TeQ#2

2nd colloquium of the GdR TeQ "Quantum Technologies"

Sorbonne Université
International Conference Center
November 13-15 2024

https://gdrteq2024.sciencesconf.org/

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Table des matières

1 What is GdR TeQ ?

1.1 A CNRS “Research Network” on Quantum Technologies

The acronym **GdR TeQ** stands for "**Groupement de Recherche Technologies Quantiques**”. It is a research network supported by the Centre National de la Recherche Scientifique (CNRS[1] GDR n°2149) through the CNRS Physics[2], CNRS Engineering[3], CNRS Mathematics[4] and CNRS Computer Science[5]).

The goal of the GdR TeQ is to bring together the French community whose research activities fall within the broad spectrum of quantum technologies, ranging from physics to computer science, mathematics or chemistry. The GDR TeQ encompasses all the different types of physical support for quantum information, such as photons, trapped atoms and ions, quantum dots and point defects at the solid state, superconducting circuits, hybrid quantum systems... In particular, its scientific perimeter combines theoretical and experimental developments, including both very exploratory aspects and engineering aspects on mature technologies. The GdR TeQ network gathers more than 1000 researchers spread over ∼100 French laboratories.

GdR TeQ is organized along six research axes (ART[6]) that currently underlie the development of quantum technologies all around the world, in particular within the European Quantum Flagship project and the French Quantum Plan :

- Quantum Communication & Cryptography – Qcom,
- Quantum Sensing & Metrology – Qmet,
- Quantum Processing, Algorithms, & Computation – Qpac,
- Quantum Simulation – Qsim,
- Fundamental Quantum Aspects – Fqa,
- Transverse Engineering and Methods – Tem.

More details on these research axes are provided on the GdR TeQ webpage : `https://gdr-teq.cnrs.fr/`.

1.2 Scientific Committee of the GdR TeQ

Audrey Bienfait (CNRS, ENS Lyon),
Juliette Billy (LCAR Toulouse),
Cyril Branciard (CNRS, Institut Néel Grenoble),
Anaïs Dréau (CNRS, Laboratoire Charles Coulomb Montpellier),
Jean Etesse (CNRS, Institut de Physique de Nice),
Omar Fawzi (INRIA, LIP Lyon),
Michele Filippone (CEA Grenoble),
Hanna Le Jeannic (CNRS, LP2N Bordeaux),
Anthony Leverrier (INRIA Paris),
Damian Markham (CNRS, LIP6 Paris),
Alexei Ourjoumtsev (CNRS, Collège de France),
Sylvain Ravets (CNRS, C2N Palaiseau),
Matias Urdampilleta (CNRS, Institut Néel Grenoble),
Jérémie Viennot (CNRS, Institut Néel Grenoble),
Christophe Vuillot (INRIA, LORIA),
Mattia Walschaers (CNRS, LKB Paris).

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[1] http ://www.cnrs.fr/
[2] https ://www.inp.cnrs.fr
[3] https ://www.insis.cnrs.fr
[4] https ://www.insmi.cnrs.fr
[5] https ://www.ins2i.cnrs.fr
[6] In French : Axes de Recherche Thématiques.

2 TeQ#2 Colloquium – Scientific Information

2.1 Welcome !

TeQ#2 is organized by the GdR TeQ Scientific Committee and by the Laboratoire Kastler Brossel[7] at Sorbonne University[8].
Its main goal is to gather members of various communities involved in Quantum Technologies and to foster exchanges about the latest advances in the field. The colloquium will feature four types of presentations :

- 3 tutorial talks (50'+10' discussion), providing the participants with a clear and pedagogical perspective on significant recent advances in specific branches of fundamental and applied research in the field,
- 4 invited talks (25'+5' discussion) on results that struck the most the scientific committee during the past year ;
- 30 contributed talks (15'+5' discussion), representative of the different themes of GdR TeQ and selected among the 122 contributions received by the scientific committee for their scientific quality and for their general interest ;
- 92 contributed posters, presented during two poster sessions according to their theme.

You will find in this book the abstracts of all of these contributions.

We would like to express our warmest thanks to the CNRS, Sorbonne University, the Laboratoire Kastler Brossel and all our sponsors for their support in enabling us to organize the TeQ#2 colloquium.

We wish all the 250 participants a fruitful colloquium.

On behalf of GdR TeQ's Scientific Committee,

The organizers :

Hanna Le Jeannic (CNRS scientist, LKB),
Mattia Walschaers (CNRS scientist, LKB),
Florent Baboux (associate professor, Univ. Paris-Cité, MPQ),
Quentin Glorieux (associate professor, Sorbonne University, LKB),
Valentina Parigi (professor, Sorbonne University, LKB),
Thierry Tardieu (CNRS admin, LKB),
Alexandra Neme (CNRS admin, DR02),
Anaïs Dréau (CNRS researcher, L2C, Director of GdR TeQ),
Alexei Ourjoumtsev (CNRS, Collège de France & Deputy Director of GdR TeQ).

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[7] https ://www.lkb.fr/
[8] https ://www.sorbonne-universite.fr/

2.2 Job Fair

The GDR TeQ has teamed up with DIM QuanTiP to organize a Quantum Job Fair on Wednesday Nov. 13th morning (09 :00-12 :00), immediately before the beginning of the Colloquium. This event is designed to bring together Master 2 students, PhD students and professionals in the quantum field. It's an ideal opportunity to meet innovative companies looking for new talent, as well as researchers looking to mentor future PhD students. Whether you're looking for professional or academic opportunities, this forum offers you a privileged platform to forge links with key players in the quantum ecosystem.

MERCREDI
13.11.2024
de 9h à 12h

Inscriptions

Sorbonne Université
4 place Jussieu, 75005 Paris
Salles 107 et 109, 1er étage
Tours 44 - 54

FORUM des MÉTIERS du QUANTIQUE

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  - Start-ups

cnrs GDR <Te|Q> QuanTiP Région îledeFrance SORBONNE UNIVERSITÉ

2.3 Program of the colloquium

Wednesday, Nov. 13	Thursday, Nov. 14	Friday, Nov. 15
09:00-12:00 **Job Fair** Sorbonne University, 4 place Jussieu, towers 44-54, 1st floor, rooms 107 & 109	**09:00 Zoe Holmes** (EPFL, CH) Tutorial *Quantum process learning and variational quantum computing*	**09:00 Félicien Appas** (ICFO, ES) *Entanglement of on-demand solid-state quantum memories for quantum repeater links*
		09:20 Nicolas Laurent-Puig (LIP6, FR) *Experimental device-independent certification of a 4-qubit GHZ State*
		09:40 Othmane Meskine (MPQ, FR) *Experimental quantum triangle network nonlocality with an AlGaAs multiplexed entangled photon source*
	10:00 Paul Hilaire (Quandela, FR) *Enhanced fault-tolerance in photonic quantum computing : Floquet code outperforms surface code in tailored architecture*	**10:00 Isadora Veeren** (INRIA Saclay, FR) *Quantum advantage in distributed computing task*
	10:20 William Lam (LPMMC, FR) *Measurement of the Lindbladian of quantum computers with randomised Pauli measurements*	**10:20 George Crisan** (C2N, FR) *Reconfigurability of generation, manipulation and detection of frequency-encoded qu-d-its: towards frequency domain entanglement-based quantum networks*
	10:40-11:10 **Break**	**10:40-11:10** **Break**
	11:10 Sophie Li (Harvard, US) Invited *Logical quantum computing with neutral atom arrays*	**11:10 Gerardo Adesso** (U. Nottingham, UK) Tutorial *Quantum resources and how to use them*
	11:40 Hugo Thomas (Quandela/LIP6/DIENS, FR) *On the role of coherence for quantum computational advantage*	
12:00-13:30 **Job Fair Lunch & Arrivals**	**12:00 Eric Huang** (U. Maryland, US / Perimeter, CA) *Tailoring three-dimensional topological codes for biased noise*	**12:10 Petr Steindl** (C2N, FR) *Direct probing of the quantum-dot-emitted single-photon Wigner function*
Talks, posters, meals and breaks: Sorbonne University, 4 place Jussieu, International Conference Center (CICSU), patio towers 44-55	**12:20-13:50** **Lunch**	**12:30-13:50** **Lunch**
13:30 Welcome session		
13:50 David Awschalom (U. Chicago, US) Tutorial *Creating and controlling quantum states with spins in semiconductor*	**13:50 Christopher Wilson** (IQC, CA) *Analog Quantum Simulation of Topological Lattice Models with a Parametric Cavity*	**13:50 Lucas Tendick** (INRIA Saclay, FR) *Nature cannot be described by any causal theory with a finite number of measurements*
	14:10 Dario Ferraro (U. Genova, IT) *Cyclic solid-state quantum battery: Thermodynamic characterization and quantum hardware simulation*	**14:10 Twesh Upadhyaya** (U. Maryland, US) *Non-Abelian transport distinguishes three usually equivalent notions of entropy production*
	14:30 Andres Duran Hernandez (LKB, FR) *Interacting laser-trapped circular Rydberg atoms*	**14:30 Victor Barizien** (IPhT, FR) *Quantum statistics in the minimal Bell scenario*
14:50 Hugo Defienne (INSP, FR) *Adaptive optical imaging with entangled photons*	**14:50 Romain Martin** (LCF, FR) *Luttinger-liquid behavior in a Rydberg-encoded spin chain*	**14:50 Antoine Debray** (LKB, FR) *Resourceful gates for photonic quantum computation*
15:10 Eloi Descamps (MPQ, FR) *Exploring spectral multipartite entanglement*	**15:10 Kévin Falque** (LKB, FR) *Polariton fluids as quantum field theory simulators on tailored curved spacetimes*	**15:10-15:40** **Break**
15:30-16:00 **Break**	**15:30-16:00** **Break**	**15:40 Anton Potočnik** (IMAC, BE) Invited *Superconducting qubit control with ultra-low-power CryoCMOS multiplexer at millikelvin temperatures*
16:00 Ilaria Gianani (U. Roma III, IT) Invited *Characterization of biphoton states: ultrafast metrology and machine learning*	**16:00 Ofer Firstenberg** (WIS, IL) Invited *Strong photon-photon interactions: from conditional phase flip to quantum vortices*	**16:10 Félix Cache** (L2C, FR) *Coherent spin control of G centers in silicon*
16:30 Diego Lancheros (SYRTE, FR) *Doppler phases in counter-propagating geometry of atom Interferometers*	**16:30 Clara Piekarski** (LKB, FR) *Two-component fluids of light in a Rubidium vapor*	**16:30 Sacha Welinski** (Thales RT, FR) *Toward wideband optical waveform generation for optically addressable quantum systems*
16:50 Jacques Ding (APC, FR) *General quantum input-output theory through the conjugate symplectic group*	**16:50 Tristan Lorriaux** (LP ENS Lyon, FR) *Addressing a spin-ensemble for storing microwave quantum states*	**16:50 Marion Bassi** (PHELIQS, FR) *Tunable sweetlines for hole spin qubits*
17:10 Julien Basset (LPS, FR) *Towards photoelectric detection of single microwave photons*	**17:10 Aziza Almanakly** (MIT, US) *Deterministic remote entanglement using a chiral quantum interconnect*	**17:10 Closing remarks**
17:30-19:30 Posters FQA/QPAC/QMET	**17:30-19:30 Posters QCOM/QSIM/TEM**	
	19:30-21:00 Banquet	

3 TEQ#2 Colloquium – Practical Information

3.1 Venue

The colloquium (oral and poster sessions, breaks and meals) will take place in

International Conference Center of Sorbonne University (CICSU)
4 place Jussieu, 75005 Paris.

The Jussieu SU campus follows a grid plan centered on the Zamansky tower. The entrance of the campus is located 4 place Jussieu ; please have your bags ready for security inspection. Once on campus, you will find the entrance of CICSU on the right (east) of the Zamansky tower, at the Patio between towers 44 and 55.

PLAN D'ACCÈS AUX ESPACES DU CICSU
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The maximal format for posters is A0, portrait orientation. Posters submitted to FQA, QPAC, and QMET themes will be presented on Wednesday 13 November 2023, 17 :30-19 :30. Posters submitted to QCOM, QSIM and TEM themes will be presented on Thursday 14 November 2023, 17 :30-19 :30.

Getting to the campus

The campus is located at the metro station Jussieu served by lines 7 and 10, as well as many city bus lines. It can be accessed from the Charles de Gaulle airport via a connection with the RER (suburban train) line B, from Orly airport via the metro line 14, and from all Parisian train stations with at most one metro connection. More details, and a route planner, are available on the website of the Parisian public transport agency RATP, https://www.ratp.fr. If you have a phone with NFC, metro tickets can be purchased via the RATP app. This can avoid you some long waits at the train station upon arrival.

4 Host institution & sponsors of the colloquium

4.1 Parent institution

The Centre National de la Recherche Scientifique (CNRS) is an interdisciplinary public research organisation under the administrative supervision of the French Ministry of Higher Education, Research, and Innovation (MESRI). The CNRS chooses to pursue research excellence that explores natural and social phenomena in greater depth, in an effort to push back the frontiers of knowledge.

The research network "Quantum Technologies" (GdR TeQ) is linked to and supported by CNRS Physics. CNRS Physics's research themes relate to the fundamental laws of physics, understanding radiation, matter, and their interactions. Those studies come with two main motivations : understanding the world, and answering current societal challenges.

The GdR TeQ also benefits from secondary support from the CNRS Engineering, CNRS Mathematics and CNRS Computer Science.

4.2 Host institution

Sorbonne Université is a public university, created on January 1, 2018 by the merging of Université Paris-Sorbonne and Université Pierre et Marie Curie. A multidisciplinary research university in the heart of Paris, it is structured into three faculties, in the fields of humanities, languages and social sciences, science and engineering, and health.

Sorbonne Université pioneers the paths of knowledge and tackles major contemporary challenges, such as climate change and sustainability, digital transformation and the data revolution, personalized medicine, open science... Strengthened by its shared values of quality and integrity, freedom, transparency and collegiality, diversity and exchange, the University is ambitious in its mission to serve the public, create and develop knowledge at the heart and intersection of disciplines.

4.3 Sponsors

The Kastler Brossel Laboratory (LKB) is a joint research unit of the Ecole Normale Supérieure, Sorbonne University, Collège de France and CNRS It is one of the main leaders worldwide in the domain of fundamental physics of quantum systems, covering numerous subjects from fundamental tests of quantum theory to applications, with an internationally recognized expertise throughout its 65 years history, including three Nobel Prize winners.

The traditional activities of the laboratory is in atomic physics and optics, with a particular emphasis in fundamental issues of light-matter interaction, quantum states of light and precision spectroscopy. One of the important developments in recent decades concerns cooling and trapping of neutral atoms, which have opened up a rich field of study on quantum gases and liquids, at the boundary between atomic and condensed matter physics.

QuanTiP - a short name for Quantum Technologies in Paris Region - was founded in May 2022 as one of the Major Research and Innovation Networks (DIM) funded by Région Ile-de-France (Paris Region).

QuanTiP acts in all fields of quantum technologies : computing, simulation, communications, sensing, and all the scientific and technological resources necessary to develop these fields. QuanTiP pays particular attention to technology transfer from the academy to the industry, with dedicated valorization and training program. They also develop targeted communication towards the general public, students and pupils.

QuanTEdu-France, led by Université Grenoble Alpes, brings together a consortium of 21 academic institutions nationwide, professionals in initial and continuing education, and players in industry and innovation. QuanTEdu-France aims to meet the objectives set out in the national strategy for quantum technologies, as part of a drive to accelerate the development of skills and human capital. QuanTEdu-France is implementing concrete actions to meet the growing need for quantum technology skills among engineers, researchers, teacher-researchers and professors, technicians and managers, while consolidating interactions between academics, researchers and local and national economic players. Indeed, the emergence of new professions encouraged by the national quantum strategy, such as quantum engineer-doctors, calls for in-depth reflection on the teaching methods to be adopted. These methods preserve the generalist nature of disciplinary and fundamental teaching, while promoting interdisciplinarity, a spirit of innovation and integration into the job market.

At the heart of a global network of knowledge and innovation, Université Paris Cité is France's leading multidisciplinary university. It covers a wide range of disciplines, with one of the most comprehensive and ambitious educational offerings available in the world. Université Paris Cité is part of the incarnation of a world city, aware of its place and missions, open to youth and knowledge.
Born in 2019 from the merger of the universities of Paris Diderot, Paris Descartes and Institut de physique du globe de Paris, the ambition of Université Paris Cité is to lead and develop an exceptional potential to meet the challenges of tomorrow's society.

Quandela is a leading technology company in the field of quantum technologies. Using the world's most efficient single-photon emitters, the company has developed and brought to market photonic quantum computers. The company, based in the Paris region, employs more than 80 experts in semiconductors, optics, electronics, quantum information theory and computer science.
Quandela's extremely efficient and high-quality single-photon source technology is based on the use of cavity semiconductor quantum dots. These sources have been on the market since 2017. Since 2023, Quandela has been supplying MosaiQ, modular, scalable, energy-efficient photonic quantum computers that can be accessed both in the cloud and on Quandela's own site. Our team specialises in developing software and hardware solutions for a variety of quantum computing applications.

Welinq is a pioneering Quantum Networking company that develops and commercializes quantum links based on laser-cooled neutral atom quantum memories to interconnect quantum computers in order to drastically increase their computational power and to ensure their deployment in clusters on customer premises. Welinq is a spin-out from Sorbonne Université, CNRS and PSL-University, founded in 2022 by Tom Darras, Prof. Julien Laurat, Dr. Eleni Diamanti and Jean Lautier-Gaud.

Pasqal is a leading Quantum Computing company that builds quantum processors from ordered neutral atoms in 2D and 3D arrays to bring a practical quantum advantage to its customers and address real-world problems. Pasqal was founded in 2019, out of the Institut d'Optique, by Georges-Olivier Reymond, Christophe Jurczak, Professor Dr. Alain Aspect – Nobel Prize Laureate Physics, 2022, Dr. Antoine Browaeys and Dr. Thierry Lahaye. Pasqal has secured more than €140 million in financing to date. To learn more about us, visit www.pasqal.com

Founded in 2013, Cailabs designs, manufactures and develops innovative photonic solutions for space, industry, telecommunications and defence. A global specialist in laser shaping, the company has seen its growth accelerate in the space sector with turnkey optical ground stations that incorporate atmospheric turbulence compensation technology. This makes Cailabs one of the first companies to exploit the very high throughput enabled by optics in a ground station on an industrial scale. Today, Cailabs has more than 120 employees, including 32 PhDs. With 26 patent families registered, the company is one of France's most innovative SMEs. It is based in Rennes, with offices in Paris and Washington (USA). For more information : https://www.cailabs.com/.

THORLABS is a vertical integrated photonics products manufacturer serving the Photonics Industry from research to industrial, life science, medical, and defense segments. Its manufacturing assets include fabrication facilities for semiconductors, optical fibers, epitaxial wafer growth, glass and metal shops, thin film deposition, and optomechanical as well as optoelectronic shops.

KWAN-TEK develops and markets metrology solutions based on diamond quantum sensors. The Company offers a range of sensitive and stable instruments for various industrial and research applications. KWAN-TEK's technology is based on the optical interrogation of a particular defect in diamond, which allows to measure magnetic fields with high accuracy. KWAN-TEK was founded with the conviction that Quantum Sensing will become mainstream in critical applications that require precision measurements. The diamond sensor technology uniquely combines robustness and accuracy to be deployed in Industries. Based in Lorient (Brittany, West of France), KWAN-TEK's team of 24 people is highly multidisciplinary, with experts in quantum physics, photonics, electronics, mechanics and software, working closely with the marketing to drive innovation.

C12 was founded in January 2020 by twin brothers Matthieu and Pierre Desjardins. Based in Paris, our technology is the fruit of ten years of research into the use of carbon nanotubes for quantum electronics at LPENS. Driven by a powerful ambition to develop the next-generation quantum computer to solve the world's most complex problems, we are the only startup to develop this kind of disruptive technology with carbon nanotubes. Backed by two rounds of financing - the latest of €18m in June 2024 - we have assembled a team of 45 talents, including 37 researchers and engineers and 18 different nationalities.

Qubit Pharmaceuticals brings unparalleled accuracy and precision to drug discovery and design, using quantum physics to develop life-changing treatments for major diseases. No target is undruggable.
Our proprietary technologies, the fruit of over 30 years of research, make it possible to develop novel drug candidates and innovative modes of action against targets previously considered too complex.

5 Abstracts, Participants and Authors

The following section contains the abstracts of the tutorial talks, the invited talks, the contributed talks, and all the posters sorted according to their session and theme. They are followed by the list of authors of the presented papers.

Table of contents

Tutorial talks

Creating and controlling quantum states with spins in semiconductors

David Awschalom[1]
[1] *University of Chicago, USA*

Traditional electronics are rapidly approaching the length scale of atoms and molecules. In this regime, a single atom out of place can have outsized negative consequences and so scaling down classical technologies requires ever-more perfect control of materials. Surprisingly, one of the most promising pathways out of this conundrum may emerge from current efforts to embrace these atomic ‘defects’ to construct devices that enable new information processing, communication, and sensing technologies based on the quantum nature of electrons and atomic nuclei. In addition to their charge, individual defects in semiconductors and molecules possess an electronic spin state that can be employed as a quantum bit. These qubits can be manipulated and read using a simple combination of light and microwaves with a built-in optical interface and retain their quantum properties over millisecond to second timescales. With these foundations in hand, we discuss emerging opportunities and the importance of collaborating with industry to atomically-engineer qubits in a broad range of materials for nuclear memories, entangled registers, sensors and networks for science and technology.

Quantum process learning and variational quantum computing

Zoe Holmes[1]*
[1]*Institute of Physics, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*

Parameterized quantum circuits serve as ansätze for solving variational problems and provide a flexible paradigm for programming near-term quantum computers. Here we discuss three fundamental criteria for this paradigm to be effective : expressibility, trainability and generalisability. We will introduce these concepts and present recent analytic progress quantifying to what extent these criteria can be achieved. While more generally applicable, the discussion will be framed around the example of trying to variationally learn an unknown quantum process. We will end with some more open-ended dreaming about the applications of these ideas for experimental quantum physics and quantum compilation.

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Quantum resources and how to use them

Gerardo Adesso[1]*
[1] *School of Mathematical Sciences, University of Nottingham,*
University Park, Nottingham, NG7 2RD, United Kingdom

What makes quantum technologies tick ? Advantages in communication, computation, metrology and other applications can be traced back to distinct manifestations of quantum theory, such as coherence and entanglement. In this tutorial we show how to characterise these elusive quantum signatures and their operational power under the unifying lens of resource theories. We then show that every quantum resource yields an advantage in a channel discrimination task, enabling a strictly greater success probability than what is achievable by any state without the given resource. We further discuss recent progress in untapping these benefits for practical quantum-enhanced imaging and sensing tasks.

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Invited talks

Characterization of biphoton states : ultrafast metrology and machine learning

Ilaria Gianani[1]*
[1]*Dipartimento di Scienze, Universit'a degli Studi Roma Tre, Via della Vasca Navale 84, 00146 Rome, Italy*

Encoding information in the time–frequency domain demonstrates its potential for quantum information processing. It offers a novel scheme for communications with large alphabets, computing with large quantum systems, and new approaches to metrology and spectroscopy. It is then crucial to secure full control on the generation of time–frequency quantum states and their properties. Characterizing the spectral phase in particular poses a great challenge, one that has similarly been taken up by classical ultrafast metrology to control ultrashort pulses in the femtosecond and attosecond timescales. In this talk we will look at a method for the characterisation of biphoton states and explore how machine learning techniques can serve for spectral phase reconstruction.

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Logical quantum computing with neutral atom arrays

Sophie Li[1]*
[1]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*

Suppressing errors is a central challenge for useful quantum computing, with quantum error correction required for large-scale processing. However, the overhead in the realization of error-corrected 'logical' qubits, poses substantial challenges to large-scale quantum computing. In this talk, I'll describe our experiment, which combines hundreds of atomic qubits with high two-qubit gate fidelities, arbitrary connectivity, fully programmable qubit rotations, mid-circuit measurement and feedforward. I will describe our demonstration of improving a two-qubit logic gate by scaling the surface code and the preparation of color-code qubits. Furthermore, using 3D code-blocks, we realize computationally complex sampling circuits with up to 48 logical qubits entangled with hypercube connectivity. Finally, I will highlight ongoing work exploring new opportunities with state-selective qubit readout and qubit reuse which are necessary to enable deep circuits on our platform.

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Strong photon-photon interactions : from conditional phase flip to quantum vortices

Ofer Firstenberg[1]*
[1] *Weizmann Institute of science, Department of Physics of Complex Systems, Rehovot 76100, Israel*

Imagine dragging a plate across the surface of a tranquil water pool. Quite excitingly, you would form a pair of swirling vortex and antivortex, propagating steadily across the surface. In optics, vortices materialize as phase twists of the electromagnetic field. While traditionally optical vortices arise from interactions between light and matter, we have recently reached a new extreme regime of optical nonlinearity where quantum vortices – phase dislocations in the few-photon wavefunction – form due to effective, strong interactions between the photons themselves [1]. These interactions are realized in a "quantum nonlinear optical medium" based on ultracold Rydberg atoms. Analogous to the water pushed by the plate, the excess phase accumulating due to the photon-photon interaction gives rise to pairs of quantum vortices, vortex lines, and rings, within the photonic wavefunction. The "conditional" phase flip localized between these vortices can be used for deterministic quantum logic operations.

[1] Lee Drori, Bankim Chandra Das, Tomer Danino Zohar, Gal Winer, Eilon Poem, Alexander Poddubny and Ofer Firstenberg, "Quantum vortices of strongly interacting photons", Science **381**, 193–198 (2023).

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Superconducting Qubit Control with Ultra-Low-Power CryoCMOS Multiplexer at Millikelvin Temperatures

A. Potočnik[1], R. Acharya[1,2], S. Brebels[1], A. Grill[1], Ts. Ivanov[1], D. Perez Lozano[1], J. Van Damme[1,2], A. M. Vadiraj[1], M. Mongillo[1], D. Wan[1], J. Craninckx[1], K. De Greve[1,2],

[1] *Imec, Kapeldreef 75, Leuven, B-3001, Belgium*
[2]*Department of Electrical Engineering (ESAT), KU Leuven, Leuven, B-3000, Belgium*

Quantum computing has the potential to revolutionize the way we process information, but scaling up the number of qubits presents a formidable challenge. The instrumentation and hardware required to control and manipulate qubits scale approximately linearly with the number of qubits, imposing significant economic, spatial, and thermal constraints on the dilution refrigerators where superconducting qubits operate. An intriguing solution to this problem is to place custom-designed control electronics at the same temperature stage as the qubits, thereby reducing the wiring problem. However, this presents a challenge for superconducting qubits, which are extremely sensitive to thermal noise at microwave frequencies [1]. In this talk, we will present our work on a cryoCMOS multiplexer for superconducting qubits [2], [3], with a power consumption of only 0.6 µW (Fig. 1). This low power consumption allows the multiplexer to interface with superconducting qubits at millikelvin temperatures without affecting single qubit gate fidelity, which remains as high as 99.93%. This approach has the potential to ease the wiring problem and open up new possibilities for scalable quantum computing architectures.

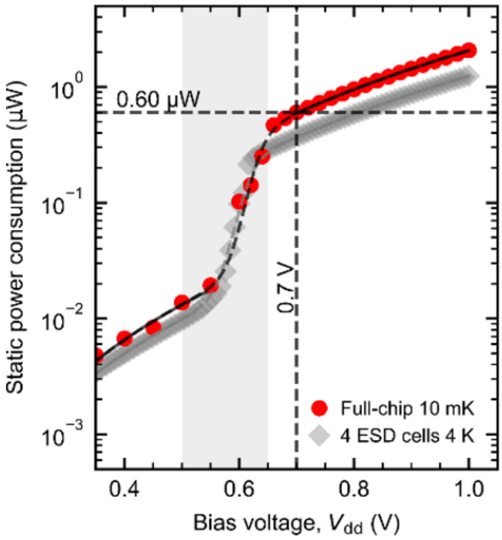

Fig. 1: *Static power consumption of the bulk 28nm cryoCMOS multiplexer at 10 mK temperature. A significant portion of the static power consumption can be attributed to leakage in the standard ESD protection cells.*

References

[1] A. Potočnik *et al.*, *Quantum Sci Technol*, **7**, 015004, (2021).
[2] R. Acharya *et al.*, *2022 IEEE Symposium on VLSI Technology and Circuits.*
[3] R. Acharya *et al.*, *Nat. Electron.*, **6**, 900, (2023).

Contributed talks

Adaptive optical imaging with entangled photons

Patrick Cameron[1], Baptiste Courme[2,3],Chloé Vernière[2], Raj Pandya[2,3,4], Daniele Faccio[1] and Hugo Defienne[1,2]*
[1] *School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK*
[2] *Sorbonne Université, CNRS, Institut des NanoSciences de Paris, INSP, F-75005 Paris, France*
[3] *Laboratoire Kastler Brossel, ENS-Universite PSL, CNRS,*
Sorbonne Universite, College de France, 75005 Paris, France
[4] *Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*

Adaptive optics enables the correction of aberrations in imaging systems and has revolutionized applications from astronomy to microscopy. Typically, this process requires a "guide star," with a deformable mirror or spatial light modulator used to correct distortions in the propagating wavefront, producing a sharp image. However, not all imaging systems or samples can accommodate a guide star. In our work, we demonstrate that entangled photons can be employed in adaptive optics, effectively removing aberrations in biological samples without the need for a guide star. This quantum approach to adaptive optics offers a powerful tool for imaging biological samples in the presence of aberrations. More details in [1].

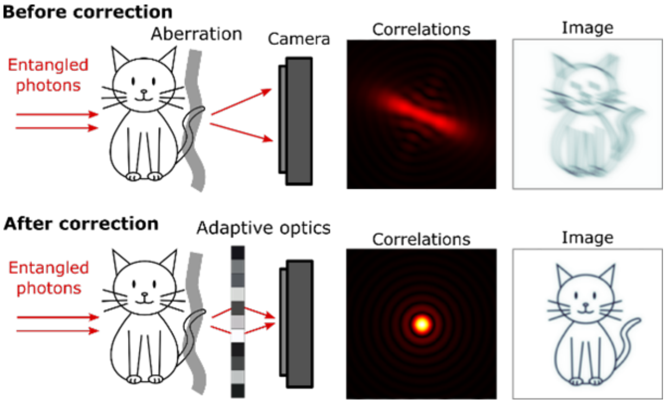

FIGURE 1. **Principle of the technique** The decrease in correlations between entangled photons allows quantification of aberrations in the microscope. An adaptive optics algorithm then restores the correlations, thus producing a clear image on the camera.

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Exploring Spectral multipartite entanglement

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Entanglement is a cornerstone of quantum mechanics, with profound implications for both foundational research and practical applications in quantum information science. While bipartite entanglement has been extensively studied, further investigation into multipartite entanglement is crucial for advancing our understanding of complex quantum systems. In particular, frequency, as a continuous degree of freedom, remains relatively unexplored. Thus, our research focuses on studying spectral multipartite entanglement.

In a metrological study [1], we demonstrate that the spectral properties of single photons can be exploited to achieve quantum enhancements in parameter estimation. This challenges the traditional perspective in continuous variable systems, where spectral properties are often treated as classical resources. Our findings reveal that the spectral entanglement necessary for quantum advantage in parameter estimation can be described as entanglement along a collective variable.

Building on these results, we propose a further application of this form of entanglement. In a subsequent work [2], we show how this perspective can be applied to develop more robust error-correcting codes based on a time-frequency comb state, by improving the Gottesman-Kitaev-Preskill (GKP) code. Similar to the metrological case, where entanglement offers a quadratic improvement in measurement precision over separable states, we demonstrate that our approach enhances the robustness of the GKP code against time-frequency shift errors.

Interestingly, similar types of entanglement have been studied in other contexts, such as in finite-dimensional systems. To offer a broader perspective, we introduce a unifying framework [3] that presents a new measure of multipartite entanglement. This framework not only sheds new light on existing results through a geometrical perspective inspired by the time-frequency setting, but it is also particularly relevant to the concept of k-entanglement, a specific type of multipartite entanglement.

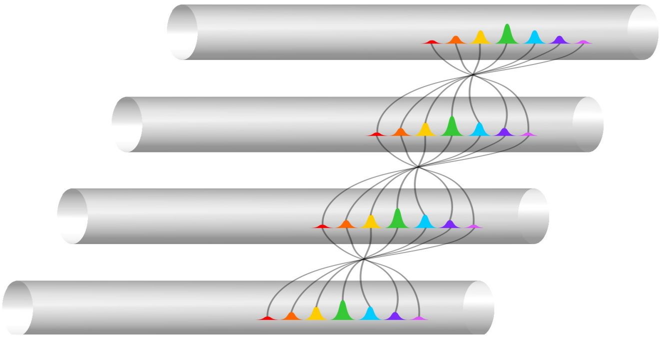

Figure 1. Spectrally entangled single photons propagating in parallel fibers.

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Doppler phases in Counter-propagating Geometry of Atom Interferometers.

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Atom Interferometry techniques allows the control of the wave-packets of massive particles. Through the superposition of different momentum states labeled by electronic states it is possible the formation of different types of interferometers whose fringes give information of the inertial properties of the involving particles. As such manipulation are performed with laser beams, this has allowed us to access unprecedented levels of sensitivity that opens the possibility of local gravity measurements[1], probing tests for General Relativity[2], QED[3] and the development of the Quantum Simulation and Quantum Computing[4].

We present the Quantum Gravimeter at LNE - SYRTE as the most fundamental example of the application of these principles and also as the illustration of the study of the important sources of the systematic errors in the measurement which limits the accuracy of these type of instruments. Specifically we focus in the role of the power and polarization of the lasers in a counter-propagating geometry[5]. We propose a method, solving the dynamics of the multilevel system, that links the population of undesired states with the accumulation of nonlinear phases at the output ports of the interferometer.

The complete development of the couplings permits a generalization of the adiabatic approximation in the case of phases dependent of the wave-vector of the driving fields as well as contribute to the insights of the phase accumulation in other systems, specially in Bragg Interferometry[6], which is an open question that has attracted increased interest recently[7]. In addition, we present the strategies to suppress these systematic errors and we formulate further inquiries related to the inherent asymmetry of these systems and the implications in the techniques of manipulation of momentum states such as optimal control[8] and momentum Squeezing[9].

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General quantum input-output theory through the conjugate symplectic group

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A general problem in science is to produce a minimal model of a "black box" system based on a set of response measurements from its inputs to its outputs. The classical theory of linear time-invariant (LTI) systems has been widely successful in classical engineering, but does not account for fundamental quantum noise sources, which must be added to preserve the canonical commutation relations of the output quadratures. Previous attempts at a quantum LTI theory have relied on restrictive hypotheses such as Markovianity or a well-defined state-space representation of the inaccessible internal modes of such a "black box" [1–3].

From first principles, we theoretically characterize the set of all LTI, not necessarily Markovian, frequency dependent transformations of a N-mode bosonic quantum system. These transformations constitute the conjugate symplectic group. Whereas the oft-studied real symplectic group emerges in the limit that the transformation is frequency-independent, we show that features of explicit frequency-dependence, such as complex correlations between quadratures, arise in general and can be physically interpreted.

We prove several structural theorems of the conjugate symplectic group that shed light on the physical resources necessary to implement such a transformation, as well as a tight uncertainty principle which reflects the "self back-action" of multimode quantum-limited systems. Our framework unifies the quantum linear response theory developed by the quantum control community [4], with the matrix group theory approach of gaussian quantum information [5, 6] and the recent developments in integrated quantum photonics [7]. As a result, any desired linear response function for a quanutm system may be implemented by a chain of devices readily constructed in the lab.

The states of closed LTI quantum systems, characterized by their spectral density matrices, may be written in a conjugate-symplectic version of the Williamson theorem, and these states are naturally more general than states of frequency independent LTI quantum systems. This more general class of states includes ones with "complex squeezing" [8], a type of squeezed state undetectable with traditional homodyne or heterodyne measurements. We introduce a new measurement scheme, "symplectodyne detection" which allows for full state tomography of LTI quantum systems, including measuring complex squeezing.

As examples, we apply our results to the mitigation of quantum noise in gravitational wave interferometers, the broadband evasion of the Schawlow-Townes limit in feedback oscillators [9], and the recovery of squeezing below the shot noise level in systems with frequency-dependent loss [10].

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Towards photoelectric detection of single microwave photons

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In this talk i will present our recent efforts towards realizing the photoelectric detection of single microwave photons, a key missing element in microwave quantum optics. I will start first by explaining our approach to realize an efficient and continuous microwave photon-to-electron converter with large quantum efficiency (83%) and low dark current [1]. I will insist on the fact that these unique properties were enabled by the use of a high kinetic inductance disordered superconductor, granular aluminium, to enhance light-matter interaction and the coupling of microwave photons to electron tunneling processes. As a consequence of strong coupling, we could observe both linear and nonlinear photon-assisted processes where two, three, and four photons are converted into a single electron at unprecedentedly low light intensities. Theoretical predictions, which require quantization of the photonic field within a quantum master equation framework, reproduce well the experimental data. I will then proceed by explaining how we used our new tool to detect individual microwave photons using charge-based detection techniques.

* equal contribution

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Enhanced Fault-tolerance in Photonic Quantum Computing : Floquet Code Outperforms Surface Code in Tailored Architecture

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In the pursuit of practical fault-tolerant quantum computing, i.e. reliable information processing even in the presence of physical noise, the interplay between hardware architecture and quantum error-correcting codes is a crucial consideration. In this article we evidence the point with a comparative performance of two kinds of code – the surface code (SC) and the honeycomb Floquet code (HC) [1] – when implemented with two variants of the spin-optical quantum computing (SPOQC) architecture [2]. This modular architecture has been designed specifically for, but not restricted to, computing platforms consisting of quantum dot photon emitters, photon routers and small linear optical circuits.

In the original version of the SPOQC architecture linear optical circuits were used to perform "repeat-until-success" (RUS) controlled-Z gates. These are especially convenient for running error correction, for example via the popular SC. The SC allows fault-tolerance and is attractive for its versatility and simplicity, admitting a 2D planar layout and good error thresholds. Combined with the SPOQC architecture the SC was shown to allow a photon loss threshold of 2.8% [2]. However, a limitation of the SC is that it relies on the measurement of weight-4 Pauli operators to check for errors, and high-weight measurements are challenging to implement in practice. In this context, the recent development of a new family of codes known as Floquet codes opens exciting new possibilities. Through periodic sequences of weight-2 measurements, such codes dynamically generate effective stabilizers of higher weight over time. This makes them well-suited to technological platforms for which such operations are native, i.e. easy to implement, such as photonic platforms or Majorana-based qubits.

An existing comparison indicates that the HC performs significantly better than the SC on hardware with native two-qubit measurements [3]. However, the comparison relied on different noise models for the native operations used to implement the respective codes. We establish conclusively that the SC is outperformed by its Floquet counterpart, the HC, when implemented with appropriate variants of the SPOQC architecture – specifically with controlled-Z gates for the SC and with RUS ZZ measurements for the HC. Crucially, the same noise model applies to both two-qubit gates and two-qubit measurements. Remarkably, we obtain a photon loss threshold of 6.4%, which to our knowledge is the best that has been reported to date for photonic platforms [2] that do not rely on large-scale multiplexing. This is all the more important given that photon loss is the primary source of errors in photon-mediated quantum computing platforms.

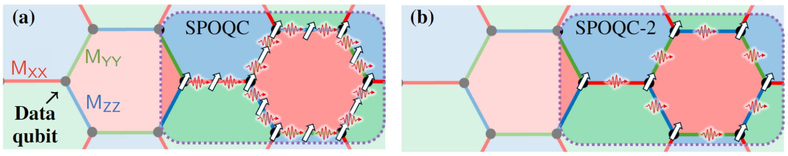

Figure : Honeycomb Floquet code defined by a sequence of M_{XX}, M_{YY} and M_{ZZ} measurements on red, green and blue edges of a tri-colorable hexagonal lattice, with architecture layout for the **(a)** SPOQC and **(b)** SPOQC-2 architectures. The white arrows represent quantum emitters and the undulating red arrows represent linear-optical RUS operations.

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Measurement of the Lindbladian of quantum computers with randomised Pauli measurements

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In the work we propose a scalable Lindbladian measurement protocol for multi-qubits systems. Having a generic characterisation protocol of the Lindbladian, i.e. without strong assumptions about its form, is crucial in quantum computing and simulation platforms.

We have studied how the protocol described in Daniel Stilck França's entilted ”Efficient and robust estimation of many-qubit Hamiltonian" [1], can be implemented with randomised Pauli measurements. In this work we will assume that the qubits are subject to a Markovian quantum evolution, described by a time-independent Lindbladian. The method is applicable to any qubit architecture. The only device requirements are to be able to initialise the state of each qubit and to measure early-time derivatives of the correlations with precision.

Qubits will be randomly initialised from products of Pauli operators eigenstates, evolved in the quantum computer for a given time, and finally measured in random Pauli basis. The experiment will be performed for many configurations (set of initials states and measured basis) and evolution times. From the N qubit data, the states populations and then the dynamics of the expected values of all the k-body Pauli observables, with $k < N$, can be constructed efficiently [2]. The initial time derivatives (evolution time zero) are estimated and stored. Given the configurations, the Lindbladian of each k-set of qubits can be extracted by solving a closed system of equations.

The system being, most of the time, overdetermined we proposed to use the pseudo-inverse of the tomography matrix to obtain the least squares solution of the system. We computed an ’inversion distance’ to measure how good the solution is. For random configurations and random Lindbladians, our numerical results show that both the reconstruction error and the inversion distance tend to zero for an infinite number of measurements. For a finite number of measurements, the reconstruction errors arise from finite data sampling, and hardware capabilities to measure early time dynamics.

We are currently analyzing the data from a 10 qubit system with a two body Hamiltonian and local dissipation.

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On the role of coherence for quantum computational advantage

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Understanding the origin of quantum advantage is crucial to grasp the gap between classical and quantum computations. Beyond its fundamental relevance, it is of great interest when it comes to designing quantum algorithms which could by no mean be ran efficiently by classical devices. Pinpointing the core differences between these two models is a challenging task which has been addressed from various perspectives. One prominent approach is based on the study of *computational resources*, i.e., the quantum properties allowing for a computational advantage with respect to classical computers. In particular, resource theory seeks to quantify the amount of quantum resources a quantum state comprises while undergoing in a certain process. If this process is a computational task, widely studied resources include entanglement [1], coherence [2], and magic [3], arising from quantum gates such as CNOT, Hadamard and T respectively. Their significance for quantum computations follows from the evidences that as soon as one of these resources is absent from a quantum computation, then one can show that that computation may in fact simulated efficiently by classical computers. Coherence enables quantum superposition and gives rise to interference effects. Its in quantum computation has been related to the the success probability of the computation [4–6], yet no link to classical simulability is made, and little is known about how classical simulation algorithms behave with respect to coherence.

In this work, we address this knowledge gap and investigate the role of coherence for quantum computational advantage. Leveraging the celebrated *sum-over-paths* formalism — introduced in [7] as a discrete version of Feynman path integral formulation of quantum mechanics [8] — we introduce the notion of *path coherence*, which characterizes the effective number of coherent paths involved in a quantum computation.

We show that estimating an arbitrary transition amplitude of such an n-qubit quantum circuit can be done in polynomial time if the path coherence is low enough, which we prove to be almost always the case provided the number of Hadamard gates is less than $2n + \mathcal{O}(\log n)$, so that low path coherence implies classical simulability.

We identify a sharp computational complexity transition from $\oplus\mathsf{L}$ to BQP characterized by a new resource interpretation of those complexity classes. This transition is remarkable in that $\oplus\mathsf{L}$ is *weaker* than universal classical computation, and path coherence has the power of promoting it to universal quantum computation.

Beyond their fundamental significance, our results have practical applications for simulating with classical computers large classes of quantum computations, including quantum machine learning algorithms, for which probability estimation is a common subroutine.

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Tailoring Three-Dimensional Topological Codes for Biased Noise

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Tailored topological stabilizer codes in two dimensions have been shown to exhibit high-storage-threshold error rates and improved subthreshold performance under biased Pauli noise. Three-dimensional (3D) topological codes can allow for several advantages including a transversal implementation of non-Clifford logical gates, single-shot decoding strategies, and parallelized decoding in the case of fracton codes, as well as construction of fractal-lattice codes. Motivated by this, we tailor 3D topological codes for enhanced storage performance under biased Pauli noise. We present Clifford deformations of various 3D topological codes, such that they exhibit a threshold error rate of 50% under infinitely biased Pauli noise. Our examples include the 3D surface code on the cubic lattice, the 3D surface code on a checkerboard lattice that lends itself to a subsystem code with a single-shot decoder, and the 3D color code, as well as fracton models such as the X-cube model, the Sierpiński model, and the Haah code. We use the belief propagation with ordered statistics decoder (BP OSD) to study threshold error rates at finite bias. We also present a rotated layout for the 3D surface code, which uses roughly half the number of physical qubits for the same code distance under appropriate boundary conditions. Imposing coprime periodic dimensions on this rotated layout leads to logical operators of weight $O(n)$ at infinite bias and a corresponding $\exp[-O(n)]$ subthreshold scaling of the logical failure rate, where n is the number of physical qubits in the code. Even though this scaling is unstable due to the existence of logical representations with $O(1)$ low-rate and $O(n^{2/3})$ high-rate Pauli errors, the number of such representations scales only polynomially for the Clifford-deformed code, leading to an enhanced effective distance.

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Analog Quantum Simulation of Topological Lattice Models with a Parametric Cavity

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There has been a growing interest in realizing quantum simulators for physical systems where perturbative methods are ineffective. The scalability and flexibility of circuit quantum electrodynamics (cQED) make it a promising platform to implement various types of simulators, including lattice models of strongly-coupled field theories. Here, we use a multimode superconducting parametric cavity as a hardware-efficient analog quantum simulator, realizing a lattice in synthetic dimensions. Lattices sites are linked by applying pump tones at special frequencies, realizing both hopping and pairing interactions, both of which can have complex amplitudes. The coupling graph, i.e., the realized model, can be programmed in situ. The realization of complex-valued interactions further allows us to simulate, for instance, gauge potentials and topological models. As a demonstration, we simulate small realizations of a number of paradigmatic topological models including the bosonic Creutz ladder [1], the bosonic Kitaev chain [2], and the SSH model. [3] We characterize the lattices with scattering measurements, reconstructing the experimental Hamiltonian and observing important precursors of topological features including chiral transport, Ahranov-Bohm caging, and the non-Hermitian skin effect. This platform can be easily extended to larger lattices and different models involving other interactions.

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Cyclic solid-state quantum battery : Thermodynamic characterization and quantum hardware simulation

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We introduce a cyclic quantum battery model, based on an interacting bipartite system, weakly coupled to a thermal bath. The working cycle of the battery consists of four strokes : system thermalization, disconnection of subsystems, ergotropy extraction, and reconnection. The thermal bath acts as a charger in the thermalization stroke, while ergotropy extraction is possible because the ensuing thermal state is no longer passive after the disconnection stroke. Focusing on the case of two interacting qubits, we show that phase coherence, in the presence of non-trivial correlations between the qubits, can be exploited to reach working regimes with efficiency higher than 50% while providing finite ergotropy. Our protocol is illustrated through a simple and feasible circuit model of a cyclic superconducting quantum battery. Furthermore, we simulate the considered cycle on superconducting IBM quantum machines. The good agreement between the theoretical and simulated results strongly suggests that our scheme for cyclic quantum batteries can be successfully realized in superconducting quantum hardware [1].

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Interacting laser-trapped circular Rydberg atoms

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Rydberg atoms are particularly well suited for quantum simulation, thanks to their strong dipole-dipole interactions even at a few microns. Circular Rydberg atoms, the natural lifetime of which reaches several $10\,\mathrm{ms}$, hundred times longer than laser-accessible Rydberg states, offer the perspective to run quantum simulation over unprecedented timescales [1].

Here, I will report on the first experimental study of the resonant dipole-dipole interaction between two circular Rydberg atoms [2]. We laser trap pairs of individual circular Rydberg atoms in arrays of bottle beams [3] and characterize their interaction through microwave spectroscopy.

We use the interaction between the circular Rydberg atoms as a meter for the interatomic distance, and record the relative motion between two atoms in their traps. This motion, that we induce through the interaction between Rydberg levels with permanent electric dipoles, transiently populated during the preparation of the circular states, is a signature of spin-motion coupling [4].

Finally, I will discuss our latest results, in which we use the dipole-dipole inpteraction to locally control and measure the state of the circular Rydberg atoms.

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Luttinger-liquid behavior in a Rydberg-encoded spin chain

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Physics in one dimension can be very different than in higher dimensions, due to the strong role of quantum fluctuations [1] that tend to suppress long-range order. Over the past decades, experimental progress made it possible to create and manipulate one-dimensional (1D) systems with high controllability and single-particle resolution [2], enabling precise tests of our understanding of 1D physics.

A cornerstone for describing the low-energy properties of many gapless 1D systems with short-range interactions is the so-called Tomonaga-Luttinger liquid (TLL) theory [1, 3]. The power of this theory relies on its capability to predict a large number of experimentally-relevant observables from two numbers, the Luttinger parameter K and the velocity of sound u. This universality has been observed in such diverse observables as the electrical conductance, relaxation times in nuclear magnetic resonance, the spectrum of excitations, the momentum distribution, etc.

In this work, we report a new example of this broadband range of applicability, on a 1D chain of interacting Rydberg atoms. More specifically, our system [4] can be mapped onto effective spins 1/2 interacting under the dipolar XY Hamiltonian. Unlike nearest-neighbor interactions, dipolar interactions lead to an asymmetry between the ferromagnetic (FM) ground state and the antiferromagnetic (AFM) ground state : while the AFM ground state is predicted to be a TLL, the FM ground state lies at the boundary between TLL and a phase with continuous symmetry-breaking [5]. We perform two different experiments to explore the low-energy properties of our system. Firstly, making use of the single-atom resolution [6], we adiabatically prepare low-energy ferromagnetic and antiferromagnetic states. We are then able to directly probe the spatial profile of the spin-spin correlations in different measurement bases. In all bases, we measure a power-law decay, a textbook prediction of the TLL theory, although it is multiplied by a small exponential correction. Some of the power-law exponents agree with the simulated ground state value, and some others show deviations that can be quantitatively explained by various experimental errors in the state preparation. Secondly, we monitor the dynamics of correlations in a quench experiment starting from a low-energy product state. Correlations propagate in the system with a characteristic velocity that corresponds to the Luttinger velocity.

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Polariton Fluids as Quantum Field Theory Simulators on Tailored Curved Spacetimes

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Quantum field theory (QFT) in curved spacetimes predicts the amplification of field excitations and the occurrence of classical and quantum correlations, as in the Hawking effect [1] for example. This raises the interest for experiments in which the curvature of spacetime can be controlled and correlations measured [2]. Such analogue simulations are typically done with fluids accelerating from sub- to supersonic speeds : acoustic excitations are dragged by the supersonic flow, effectively trapped inside an acoustic horizon [4–8]. Quantum fluctuations of the acoustic field are predicted to yield entangled emission across the horizon [10], as in black holes [2]. Here we introduce such a QFT simulator in a one-dimensional polaritonic fluid of light [11]. We demonstrate the unique tunability of our system by engineering smooth and steep horizons, which respectively have quasi-thermal, but weak, and strong Hawking radiation. We exploit the driven-dissipative nature of polaritons with a recently developed coherent probe spectroscopy method [12] to measure the spectrum on either side of the horizon and evidence the excitation of negative energy waves for the first time. Notably, we explicitly show that, beyond phononic excitations as in other systems, our simulator also supports excitations with a massive, relativistic dispersion. This benchmarks and thereby establishes a QFT simulator of a new class. In the future, quantum optics techniques offer the possibility to measure entanglement in unexplored regimes, giving insight in this outstanding prediction of relativistic QFT.

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Two-component fluids of light in a Rubidium vapor

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Quantum fluids of light are based on the mathematical analogy between the Gross-Pitaevskii equation (GPE), which describes Bose-Einstein condensates, and the propagation of a laser through a nonlinear Kerr medium – in our case a Rubidium vapor. This work focuses on how this analogy can be pushed to the realization of a two-component fluid. The two-component GPE naturally arises when considering the propagation of the field's circular polarization components. We can then define intra- and inter-component interaction terms, of which the signs and relative weights determine whether the mixture is stable or unstable, miscible or immiscible.

I will present different measurements to establish which regimes can be achieved in our system. In particular, I will show experimental results on the density and spin dispersion branches measurements in the miscible regime, where we also use the saturation of the medium to transition between attractive and repulsive inter-component interactions. I will also share numerical results on domain formation dynamics in the immiscible case.

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Addressing a spin-ensemble for storing microwave quantum states

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Superconducting qubits are strong candidates for quantum information processing, yet their scalability is a current challenge. Multimode quantum memories have been proposed to alleviate the resource requirement of quantum architectures [1]. Such memories could be also used in quantum repeaters to improve long-distance quantum communication [2] or be a resource for improved quantum sensing [3]. They require high storage density, long-coherence time and the ability to write and read on-demand an arbitrary register. Different platforms have demonstrated quantum state storage : clouds of atoms or ions [4], spins in crystals [5], mechanical oscillators [6] as well as superconducting circuits [7] [8].

Ensembles of electron spins for microwave quantum state storage combines three advantages. Firstly, they can offer extanded storage times compared to superconducting qubits. For instance, the coherence of electronic and nuclear spins of donors in silicon can last seconds at clock transition sweet-spots where the impact of spin-spin interactions is significantly reduced [9] [10]. Then, they present a compact footprint. Finally, similarly to optical memories, protocols exist for creating multimode storage [11] [12].

The main challenge in realizing these proposals is to achieve strong, adjustable coupling between the spin and superconducting circuit. By exploiting a kinetic inductive non-linearity, we can active a parametric process to dynamically control the virtual bandwidth of the resonator, demonstrating coupling rate tuning range over a factor of 15 and thus enabling catch-and-release of microwave photons. We can also observe a coherence time of $T_2 = 450$ ms at the clock transition. We are able to show how this circuit enables radiative relaxation of the spins, allowing us to implement in-situ nuclear level cooling. We can therefore assess the ability of the system to implement a complete quantum memory protocol.

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Deterministic remote entanglement using a chiral quantum interconnect

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Quantum interconnects facilitate entanglement distribution between non-local computational nodes. For superconducting processors, microwave photons are a natural means to mediate this distribution. However, many existing architectures limit node connectivity and directionality. In this work, we construct a chiral quantum interconnect between two nominally identical modules in separate microwave packages. We leverage quantum interference to emit and absorb microwave photons on demand and in a chosen direction between these modules [1, 2]. We optimize the protocol using model-free reinforcement learning to maximize absorption efficiency. By halting the emission process halfway through its duration, we generate remote entanglement between modules in the form of a four-qubit W state with $62.4 \pm 1.6\%$ (leftward photon propagation) and $62.1 \pm 1.2\%$ (rightward) fidelity, limited mainly by propagation loss. This quantum network architecture enables all-to-all connectivity between non-local processors for modular and extensible quantum computation.

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Entanglement of on-demand solid-state quantum memories for quantum repeater links

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Heralded entanglement of shared excitations between two remote matter nodes is a primitive for quantum repeater links [1]. This type of architecture relies on quantum nodes consisting of sources of entanglement and quantum memories (QM). Entanglement is created by heralding at intermediate locations via the detection of a telecom photon, then stored in quantum memories and manipulated locally. Some of the main requirements for practical quantum links are high heralding rates with photons at telecom wavelength and multiplexed operation to boost communication rates. Most importantly, the ability to retrieve stored excitations on-demand is a crucial feature for synchronization of repeater links across a network. Recently, memory-memory entanglement over telecom channels has been achieved using rare-earth doped crystal QMs [2] or cold atomic clouds [3]. However none of these works featured quantum nodes combining simultaneously on-demand storage and multimodality.

In this talk, we report on recent progress towards remote entanglement of two on-demand and multimode solid-state quantum memories using cavity-enhanced non-degenerate spontaneous parametric downconversion (cSPDC) sources and Pr^{3+} rare-earth doped QM. The sources emit entangled photon pairs with one idler photon in the telecom band and one signal photon at 606 nm, that is stored in a Pr^{3+} QM. Upon detection of an idler click at one of the detectors of the central station, an entangled state is heralded at the memories. To verify entanglement, it is necessary to show that we operate in the single excitation regime and that the excitation is in a coherent superposition of the two memories By retrieving the excitations from the QMs and interfering the photons at a beam splitter, state tomography can be carried out.

We measure the conditional single-photon interference fringes obtained at the signal detectors proving quantum coherence between the two QMs of Alice and Bob. The estimated concurrence of the detected heralded state is of $4.54 \times 10^{-4} \pm 7.21 \times 10^{-5}$ showing entanglement by more than six standard deviations. The single photon purity goes as low as $h_c^{(2)} = 0.22 \pm 0.01$ with an associated total heralding rate of 550 cps indicating the successful heralding of a genuinely entangled state at high rate. Finally, we illustrate the multiplexing capacity of the Pr^{3+} QM by storing up to 10 temporal modes and showing linear scaling of the heralding rate with the number of modes.

Altogether, our system combines most requirements for efficient quantum repeater links thus paving the way towards real-world deployment of quantum networks.

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Experimental Device-Independent Certification of a 4-qubit GHZ State

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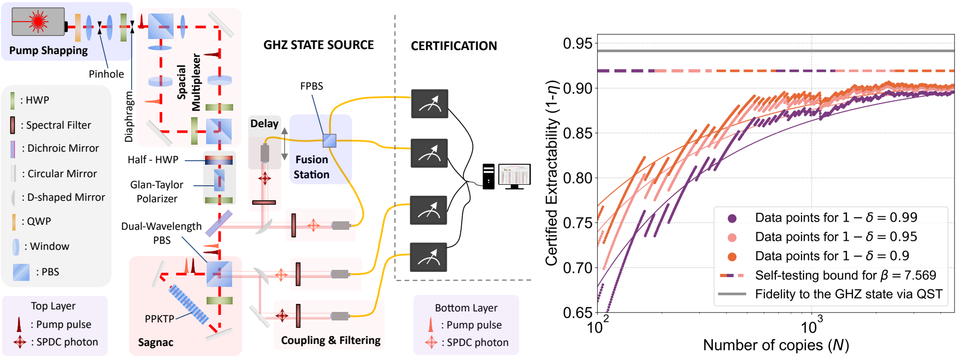
In this work, we present a compact and efficient setup for generating high-quality Greenberger-Horne-Zeilinger (GHZ) states at telecom wavelength and then use then for a crucial quantum information task. Photonic platforms using spontaneous parametric down-conversion (SPDC) in Sagnac interferometers have demonstrated remarkable intrinsic stability and the generation of high-quality entangled Bell states. Here [1], we develop a source that employs spatial multiplexing in a Sagnac configuration, producing high-fidelity four-photon GHZ states, based on the fusion of independent SPDC photon pairs from two parallel layers in the same crystal (see Fig. 1(a)), therefore displaying high indistinguishability between photons. This results in a fidelity of $\mathscr{F} = (94.73 \pm 0.21)\%$ to the target ideal state, for a generation rate of 1.7 Hz, indicating the potential for practical applications in real-world quantum networking. We further use this setup to demonstrate the device-independent (DI) certification of a GHZ state in the few-copies regime, while avoiding the identically and independently distributed samples (iid) assumption [2]. Fully DI certification is crucial for ensuring the reliability of quantum resources, particularly when deployed in untrusted environments. In our implementation, the generated GHZ states are divided into two sets, with one set used to certify the quantum properties of the unmeasured one. This certification is a critical step for determining whether the quantum state can be trusted for use in subsequent protocols. By leveraging robust self-testing methods, we establish a lower bound on the average extractability of the states based on the violation of a carefully selected Bell-type inequality. Furthermore, based on its quantum and algebraic bounds, it is possible to estimate the number of states required to achieve a certain extractability, with a confidence level of $1-\delta$. Our experimental results, shown in Fig. 1(b), demonstrate the fully-DI certification of a GHZ state, with a high level of confidence (0.99) and achieving an extractability beyond 0.89, with a few more than 10^4 samples, highlighting the practicality of our setup for quantum communication tasks. This work marks a significant step towards scalable quantum networks by demonstrating a sample-efficient, device-independent certification method that can be implemented in real-world settings.



(a) (b)

FIGURE 1. **(a)** Experimental setup. Photon pairs are probabilistically generated via type-II SPDC in a ppKTP crystal and entangled in polarization in the Sagnac loop, resulting in the output state $(|H\rangle_s |V\rangle_i + e^{i\theta} |V\rangle_s |H\rangle_i)/\sqrt{2}$. Both idler photons (from the top and bottom layers) arrive simultaneously to the FPBS. If they are each transmitted to different outputs of the FPBS, and conditioned on fourfold coincidences, a GHZ state $(|HHHH\rangle + e^{i\delta} |VVVV\rangle)/\sqrt{2}$ is generated. **(b)** Fully DI protocol implementation results for different confidence levels.

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Experimental Quantum Triangle Network Nonlocality with an AlGaAs Multiplexed Entangled Photon Source

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The exploration of the concept of nonlocality beyond standard Bell scenarios in quantum network architectures unveils fundamentally new forms of correlations that hold a strong potential for future applications of quantum communication networks [1]. It is necessary to adapt theoretical advances to realistic configurations to materialize this potential. Here we consider a quantum triangle network, illustrated in Fig.1, for which it was shown in theory that, remarkably, quantum nonlocality without inputs can be demonstrated for sources with an arbitrarily small level of independence [2]. We realize experimentally such correlated sources, ρ_{AB}, ρ_{AC}, and ρ_{BC}, by carefully engineering the output state of a single AlGaAs multiplexed entangled-photon source [3], exploiting energy-matched channels cut in its broad spectrum. This simulated triangle network is then used to violate a Bell-like inequality that we derive to capture the effect of noise in the correlations present in our system [4]. We also rigorously validate our findings by analyzing the mutual information between the generated states. Our results allow us to deepen our understanding of network nonlocality while also pushing its practical relevance for quantum communication networks.

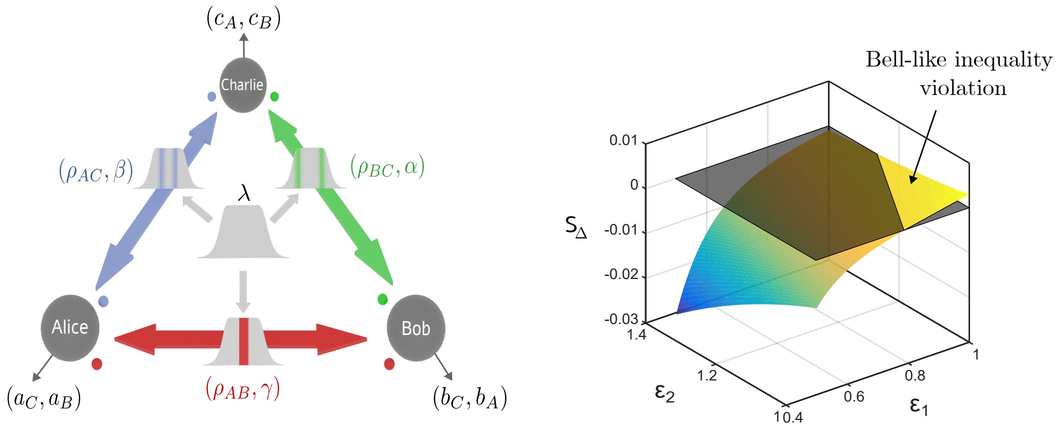

FIGURE 1. (Left) Scheme of a triangle network using one physical source. (Right) Experimental violation of a Bell-like inequality ($S_\Delta < 0$) as a function of two parameters ϵ_1 and ϵ_2 related to the degree of sources independence.

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Quantum advantge in distributed computing task

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In this work, we introduce a task of distributed computing, formalized in the structure of a game, that can be proved to have a quantum advantage.

One can approach distributed computing tasks as a game, played by a collection of agents scattered on a network. Some agents share pairwise communication channels according to the network that connects them, and they must all collaborate to perform a single task such as computing a global function. The difficulty of performing such computations lies in the fact that the inputs for the task are scattered across agents, such that they must communicate and exchange information in order to come up with a valid answer to the problem.

In the typical setting for distributed computing, one assumes that each agent has access to unlimited computation power, and that the channel that two agents may share has infinite capacity. However, they can only communicate with their neighbors at specific time intervals. Given that the community is interested in tasks where communication is crucial for cooperation towards a collective solution, one must look for the strategy that will optimize the number of time steps necessary (and consequently, minimize the iterations with neighbors).

We introduce a game we dub GHZ^d, a generalization of the GHZ game played now by a collection of overlapping agents. In the GHZ game, a trio of players receive individual inputs and must produce outputs that recover the correlations of a GHZ state [1]. Now, each party must play d GHZ games with different colleagues : everyone receives an input for their first game and produce an output. Now, the output of the first game is forwarded as the input for the second game, and so on until all d games have been played.

While in [2] it was shown that no quantum advantage can be obtained in the task of approximate graph coloring, here we explore the frontier with computer science and prove that quantum strategies outperform classical ones in GHZ^d, meaning that quantum agents require fewer communication steps to win the game. We find a lower bound for the number of communication steps necessary for any classical strategy, and indicate how a quantum strategy can, intuitively, outperform this bound.

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Reconfigurability of generation, manipulation and detection of frequency-encoded qu-d-its : towards high dimensional frequency domain entanglement-based quantum networks

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Quantum networks enhance quantum communication schemes by linking multiple users. Harnessing high dimensional quantum states - i.e. qu-d-its - allows for a denser transfer of information with increased robustness to noise compared to qubits [1], their binary counterparts, usually at the expense of the simplicity of the hardware.

Frequency encoding is a good candidate for quantum networks as it enables access to a high dimensional Hilbert space where qu-d-its are manipulated with off-the-shelf fibered devices such as Electro-Optic Modulators (EOMs) and Programmable Filters (PF) [2].

In this work, we use Bell states of dimension d=2 (qubits) and d=3 (qutrits) to implement a frequency-domain proof of concept of entanglement-based quantum key distribution network as [5] did with qubits in polarization encoding. We build on reconfigurability and control of our simple implementation to boost the network and protocol performances. Using a silicon microresonator parametric photon pair source, via Four Wave Mixing (FWM), we access up to 70 frequency modes in, and independently manipulate 15 frequency-bin entangled qu-d-its, interconnecting up to 6 users [6]. We benchmark and optimize the source (via pump power), the signal processing (via coincidence window size) and qu-d-it encoding (d=2 or 3) with a single hardware depending on interconnection lengths.

We thus propose an adaptive strategy to exploit reconfigurability to increase the transmitted secret key rate at short distances, taking advantage of the dense encoding capacity of a qutrit, and benefiting from the higher signal to noise ratio afforded by qubits to communicate up to 260km. This demonstration paves the way for larger dimensionality implementations deployed on metropolitan fiber links.

We thus position frequency-bin encoding with respect to other encodings viable for high dimensional QKD networks : in time-bin encoding increasing state dimension reduces symbol generation rate [3] and orbital angular momentum encoding is subject to crosstalk or requires expensive multicore fibers [4]. In contrast, frequency encoding is robust against phase or polarization fluctuations and compatible with telecom fiber infrastructure. We demonstrate a competitive communication distance range and realistic architecture for a trusted-node free network, stable during over 20 hours.

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Direct probing of the quantum-dot-emitted single-photon Wigner function

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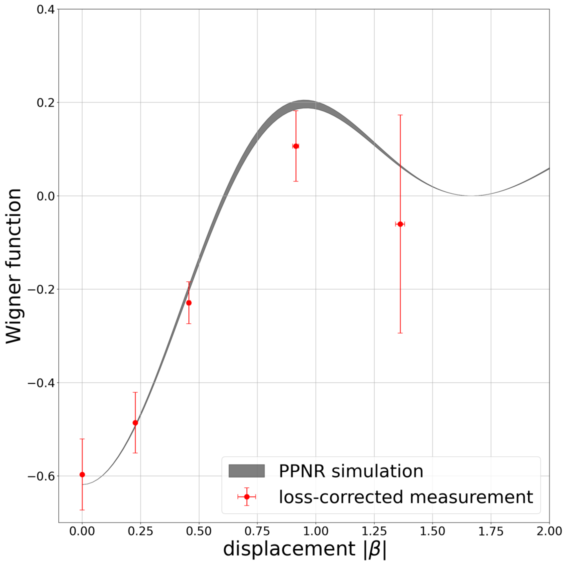

FIGURE 1. Radial cut of the loss-corrected single-photon WF and simulation [8].

Semiconductor quantum dot (QD) devices are forefront and versatile quantum light sources that exhibit high in-fiber single-photon brightness [1], strong single-photon level nonlinearities [2], and can produce controllable photon-number superpositions [3]—these assets position QD-based platforms as promising hardware for continuous-variable (CV) quantum information processing. In the CV framework, homodyne detection is a crucial technique to measure the Wigner function (WF), which fully describes a quantum state, including its non-classicality and non-Gaussianity.

We use the direct probing method to infer the WF [4] of a single photon generated by an InGaAs QD embedded in a micropillar cavity [7]. This tomography method requires the measurement of the photon-number statistics at different points in the quadrature phase space, which is achieved by displacement of the quantum state by interference with a weak amplitude- and phase-controlled coherent state on a beam splitter (BS). We probe the pseudo-photon-number resolved (PPNR) statistics of the photonic states after the interference by spatially demultiplexing into four superconducting nanowire single-photon detectors (SNSPD) [4].

On the one hand, the quality of the direct probing method depends on the optical losses in the system, which are compensated for in post-processing by binomial loss modeling [4]. On the other hand, it is affected by the quality of displacement operation on the BS controlled by the maximal mean wavepacket overlap M between the laser and quantum light [4]. Thus to access and maximize the overlap M, we developed two photon-correlation methods measured at the outputs of the BS during the WF tomography acquisition to monitor the photon bunching effect. The first method, monitoring the overlap during the WF acquisition, relies on an adapted Hong-Ou-Mandel experiment, where the bunching is inferred from photon cross-correlations between the two BS outputs [5]. The second method used between acquiring individual phase-space data points of the WF, enables optimizing M (up to 76%) by looking at the two-photon correlation in only one BS output [6].

By correcting for optical loss and displacement efficiency, we reconstruct the Wigner function of the QD-emitted single photon, including its Wigner-negative part.

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Nature cannot be described by any causal theory with a finite number of measurements

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The goal of theoretical physics is it to devise a model of nature that accurately explains past observations and allows to make experimentally verifiable predictions. Quantum theory is the most successful and accurately tested description of nature that exists in physics. Despite 100 years of proving its success over and over again, quantum theory's success is still surprising from a theory building perspective. That is, quantum theory is primarily a mathematical theory with a set of mathematical rules leading to observable predictions. However, the concise physical principles obeyed by nature that lead to the corresponding mathematical framework remain unknown. While several physical principles, such as causality [1], have been proposed to motivate or even derive the mathematical formalism of quantum theory, to our current knowledge, there is still room for theories beyond quantum theory.

These, experimentally unobserved post-quantum theories, might describe nature more accurately. This possibly more accurate description of nature is not only of foundational appeal, but is also of practical interest. Consider for instant the context of quantum cryptography, where a malicious eavesdropper is usually assumed to obey the laws of quantum theory. It is therefore of crucial importance to understand whether quantum mechanics is the theory that describes nature most accurately and how to rule-out possible extensions of the quantum framework. This work follows this line of research by considering post-quantum correlations with a restricted degree of freedom [2–4]. More precisely, we consider the following question: *Can nature possibly be described by a (maybe very exotic) causal theory that only requires a finite number of measurements?*

In this work, we answer this question in the negative, that means we show that nature *cannot* be described by any causal theory that involves only a finite number of measurements. In particular, we show the existence of quantum correlations obtained from performing n different dichotomic measurement on an bipartite entangled quantum state that cannot be reproduced by any theory of nature (classical, quantum, and beyond), which is compatible with causality (i.e., it does not allow for super luminal signalling) involving only $n-1$ measurements for every finite n. Consequently, every possible way to come up with a, maybe very exotic, causal theory of nature in which there is an (arbitrarily large but finite) upper limit on the number of different measurement settings, can be falsified (in principle also experimentally).

From a technical perspective, we make use of the relation between Bell nonlocality and measurement incompatibility. Bell nonlocality allows us to characterize experiments solely based on the correlations produce in it, without even assuming the physical theory (as long as theory obeys the no-signaling principle). On the other hand, measurement incompatibility is the notion that two (or more) observable quantities that cannot be measured jointly. Its recent generalization to incompatibility structures [5] allows for a device-and-theory-independent verification of the number of *genuine* (i.e., not reducible) number of measurements used in a Bell experiment. We use this groundwork to analytically analyze the M_{nn22} Bell inequality [6]. We show, for any finite $n \geq 2$, that the M_{nn22} inequality cannot be violated by any causal theory that has only access to genuinely $n-1$ measurements. However, we give an explicit quantum model for its violation for any n, resulting in the statement that *Nature cannot be described by any causal theory with a finite number of measurements.* Finally, we discuss relations to previous works [5] and possible experimental implications of our result, based on high-dimensional entanglement experiments [7].

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Non-Abelian transport distinguishes three usually equivalent notions of entropy production

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We analyze entropy produced by arbitrarily far-from-equilibrium exchanges of noncommuting charges [1]. Three formulae for entropy production, which equal each other when all charges commute, have been used widely [2]. We show that these formulae fail to equal each other when charges fail to commute. This incommensurability stems from measurement disturbance : Noncommuting charges' currents cannot be measured simultaneously.

Consider a unitary transporting conserved quantities ("charges") between two systems initialized in thermal states (generalized Gibbs ensembles). A classical example would be energy and particles being exchanged between two systems initialized in grand canonical ensembles. Any charge entering or leaving a system produces entropy. The entropy produced in a trial—the *stochastic entropy production* (SEP)—is a random variable. The SEP is well-studied for classical system : its average over trials is non-negative, according to the second law of thermodynamics, and it obeys constraints called *exchange fluctuation theorems* which are tightenings of the second law of thermodynamics [3].

But for quantum systems, the measurements required to probe currents disturb the systems being measured. We consider using *weak measurements* instead of strong measurements, disturbing the systems less at the price of extracting less information. As probabilities describe strong-measurement experiments, *quasiprobabilities* describe weak-measurement experiments. Quasiprobabilities have recently proven useful across quantum thermodynamics [4].

We generalize the SEP to accommodate a deeply quantum regime, that of noncommuting charges. Our starting point is conventional thermodynamics, where there are three equivalent formulae for the SEP : entropy is cast as an extensive thermodynamic variable by a "charge formula," as quantifying missing information by a "surprisal formula," and as quantifying irreversibility by a "trajectory formula." To accommodate charges' noncommutation, we generalize all three formulae using quasiprobabilities. If the charges commute, the generalizations reduce to the usual formulae. Yet we find deductively that noncommuting charges break the equivalence, generating three species of SEP. Each highlights a different way in which charges' noncommutation impacts transport :

1. *Charge SEP :* Charges' noncommutation enables individual stochastic trajectories to violate charge conservation. These violations underlie commutator-dependent corrections to a fluctuation theorem.
2. *Surprisal SEP :* Initial coherences, relative to eigenbases of the charges, enable the average surprisal entropy production to become negative. Such negativity, a product of charges' noncommutation, simulates a reversal of time's arrow.
3. *Trajectory SEP :* The generalized trajectory SEP can become nonreal. A nonzero imaginary component of the entropy signals contextuality, which is a strong form of nonclassicality.

This work opens up stochastic thermodynamics to noncommuting—and so particularly quantum—charges. Furthermore, our work advances the widespread research program of critically comparing thermodynamic with information-theoretic entropies.

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Quantum statistics in the minimal Bell scenario

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The unpredictability of quantum theory is today considered a resource and in light of this new perspective, a natural question arises : what are the fundamental limits of quantum theory's probabilistic predictions ? Addressing this question requires distinguishing probabilistic predictions that can admit a quantum explanation from those which don't. Interestingly, because quantum statistics can violate Bell inequalities when measurements can be freely chosen, determining whether a given set of probability distributions is compatible with quantum theory turns out to be a highly nontrivial task [1].

The problem of determining the quantum set – the set of quantum statistical predictions – was initially considered in the 1980s by Tsirelson, who obtained the first analytical bounds on quantum statistics [2]. Since then, several advances were made on this problem, including works by Landau and Masanes [3, 4] as well as the celebrated NPA method based on moment matrices [NPA], but a complete and explicit analytical description of a quantum set has remained to be found ever since.

Determining the quantum set is known to have wide-ranging consequences. From a fundamental point of view, knowledge of the quantum set is crucial for the search of a principle-based formulation of quantum theory. A profound understanding of the quantum set in Bell scenarios is also key for applications to device-independent quantum protocols, such as entanglement detection and quantification, or the security of adversarial protocols.

In this work, we provide an exact and explicit characterization of a complete quantum set [5]. We derive our results in the widely used Bell scenario which involves two users in a bipartite setting, Alice and Bob, each having access to a shared quantum state and performing one of two possible measurements, each with two possible outcomes. Due to the convexity of the quantum set, its explicit description amounts to identifying all extremal quantum behaviors. We consider this question from the perspective of self-testing [6]. Concretely, we show that a nonlocal behavior is extremal iff it satisfies the conditions

$$\epsilon_{00}\arcsin[\tilde{A}_0^{\mathsf{s}}B_0]+\epsilon_{01}\arcsin[\tilde{A}_0^{\mathsf{s}}B_1]+\epsilon_{10}\arcsin[\tilde{A}_1^{\mathsf{t}}B_0]+\epsilon_{11}\arcsin[\tilde{A}_1^{\mathsf{t}}B_1]=\pi$$

for all $\mathsf{s},\mathsf{t}\in\{-1,+1\}$, where $\epsilon_{xy}\in\{\pm1\}$ such that $\prod_{x,y}\epsilon_{xy}=-1$, and $[\tilde{A}_x^{\mathsf{a}}B_y]=\frac{\langle A_xB_y\rangle+\mathsf{a}\langle B_y\rangle}{1+\mathsf{a}\langle A_x\rangle}$. In doing so, we provide a complete characterization of all extremal points of the quantum set in this minimal scenario. We also indentify the quantum realizations behind these points in terms of measurements on two-qubit states. A consequence of our findings is that all extremal points in this scenario self-test a quantum realization.

Our result closes a long-standing open question. It relies on both mathematical tools from convex geometry and physically driven intuitions. One of the key ingredient of our result is a non-linear steering transformation that we introduce at the level of statistics, which allows to study a quantum behavior obtained from measuring a partially entangled state in light of four different behaviors obtained from measuring a maximally entangled one. We expect these new tools and methods to generalize naturally to broader scenarios.

This first characterization is of foremost fundamental interest as it can be used to test alternative theories of physics claiming to reproduce the predictions of quantum theory. It is also important on the application side, where it provides all possible statistics that can be used to test and verify the proper functioning of a given quantum device in a device-independant fashion.

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Resourceful gates for photonic quantum computation

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It has long been known that Gaussian states of light are not enough to achieve universal quantum computation with photons nor a possible quantum advantage over classical computers [1]. Indeed, an hallmark of non-Gaussianity, Wigner negativity, is provably necessary for any photonic quantum computation aiming at a quantum advantage, yet more stringent criteria to decide which Wigner-negative states are actually useful are lacking. The traditional argument concerning Wigner negativity relies on the decomposition of the quantum circuit in states, gates and positive operator-valued measures (POVMs), each of which can be represented by an appropriate *Wigner function* on phase space. If these functions are all positive, then the whole quantum computational process has a neat interpretation in terms of probabilities over multi-mode phase-space being updated through positive-semidefinite transition kernels and it can be thus simulated efficiently by sampling. However, the Wigner representation is only one of a continuous 1-parameter family of quasi-probability distributions (quasi-PD), called s-ordered quasi-PD [2], indexed by a parameter $s \in [-1, 1]$. The original Wigner function corresponds to $s = 0$, while for $s = -1$ the resulting function is always a true probability distribution, known as the Husimi Q-function. For values of $s > 0$, instead, the s-ordered quasi-PD of a quantum state will in general be a distribution and not necessarily a regular function. Each quantum state will then have a maximum value s^* such that all its s-ordered quasi-PDs with $s \leq s^*$ are positive probability distributions and all those with $s > s^*$ either attain negative values or they are distributions that are more singular than the Dirac delta ; this maximum value s^* determines the *nonclassicality* of the quantum state. Importantly, the s-parameter can be assigned independently for each mode and one can also describe quantum channels with the same formalism, assigning a set of s-parameters to the input modes and another set for the output modes. By assuming that we have a decomposition of the quantum computation process into an initial M-modes factorized quantum state, a series of k quantum gates $\mathcal{E}_{j\in\{1,\ldots,k\}}$ acting on at most m each and finally a factorized POVM measurement on each mode, we can compute the outcomes probability by matching the ordering parameters of consecutive quasi-PDs such that if $\mathcal{E}_j$ is parametrized by the pair of vectors $(-\boldsymbol{s}_j, \boldsymbol{s}_{j+1})$, the first relative to the input modes and the second relative to the output modes, it must be followed by the $(-\boldsymbol{s}_{j+1}, \boldsymbol{s}_{j+2})$-parametrized function of $\mathcal{E}_{j+1}$ [3]. We then iteratively look for the bet candidate set of s-parameters at each step to find a decomposition of the whole process into positive-semidefinite PDs : in this way, we can just study the conditions for positivity of s-ordered quasiprobability distributions of quantum gates independently of the exact input states. If such a choice of ordering parameters exist, then the quantum process will be simulable through sampling, otherwise we can exclude the possibility of efficient simulability with phase-space functions and sampling. After showing that unitary operators cannot make every input state more classical (i.e. cannot always increase the maximum value of $\boldsymbol{s}$), we focus our analysis on a universal set of unitary gates, namely Gaussian unitary gates and the cubic phase gate, a prototypical non-Gaussian gate and we provide the relation between their output and input order parameters that guarantees the positivity of the phase-space function describing the given gate, therefore simulable. Relying on the fact that the loss channel, as opposed to unitary ones, does increase the maximum allowed value of s for any input state, we are able to interpret the relations found for the quantum gates order parameters as bound on the amount of losses that can be tolerated before each gate before that it becomes simulable.

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Coherent spin control of G centers in silicon

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Silicon is the major semiconductor of the information society. It is at the heart of devices in microelectronics and computer technology, and as such one of the most desired platforms for the development of next-generation applications in quantum technologies. The discovery of telecom single-photon emission from several families of isolated individual optically active defects in silicon [1–6] has open up new perspectives. Among them, erbium ions [1] and T centers [6] are of particular interest for their electron spin doublet ground state. Their weak light-matter coupling has been overcome by integration into silicon nanophotonic cavities to enhance photon emission rate and light extraction. This has allowed the recent demonstration of coherent control and optical single-shot readout of single spins interfaced with light in silicon [8, 9].

In this work, we focus on the G center in silicon, a well-known and widely studied carbon-based defect recently observed at single scale [7]. It possesses a telecom emission around $1.3\,\mu\mathrm{m}$ and an excited metastable electron spin triplet that has been detected optically on ensembles in the 80s [10]. We present the coherent control and characterization of the spin coherence properties of an ensemble of G centers in silicon. We determine the spin-dependant metastable-lifetimes and identify in which spin states the G defects are prepared following optical excitation.

These results are a first step towards the optical detection of the magnetic resonance of the G center in silicon down the single defect scale. Moreover, the strong hyperfine interaction with intrinsic ^{29}Si and ^{13}C nuclear spins (respectively 300 and 30 MHz) [11] could be used to address and control these memory qubits. As the G center ground state is electron spin free, these nuclear spins could benefit of extended coherence times in isotopically purified silicon, similar to ionized donors [12].

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Toward wideband optical waveform generation for optically addressable quantum systems

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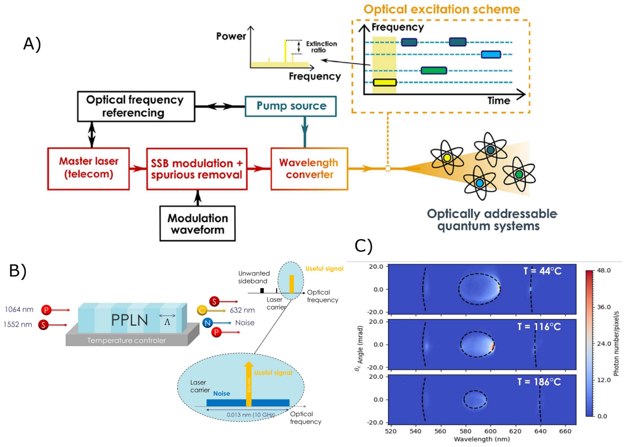
Optical manipulation of quantum systems requires stable laser sources able to produce complex waveforms over a large frequency range [1, 2]. In the visible region, such waveforms can be generated using an acousto-optic modulator driven by an arbitrary waveform generator, but these suffer from a limited tuning range typically of a few tens of MHz. Visible-range electro-optic modulators are an alternative option offering a larger modulation bandwidth, however they have limited output power which drastically restricts the scalability of quantum applications. There is currently no architecture able to perform phase stabilized waveforms over several GHz in the visible or near infrared region while providing sufficient optical power for quantum applications. In this presentation, I will first present a modulation and frequency conversion set-up able to deliver optical waveforms over a large frequency range, with a high spurious extinction ratio, scalable to the entire visible/near infrared region with high optical power. The optical waveforms are first generated at telecom wavelength and then converted to the emitter wavelength through a sum frequency generation process [3]. By adapting the pump laser frequency, the optical waveforms can be tuned to interact with a broad range of optical quantum emitters or qubits such as alkali atoms, trapped ions, rare earth ions, or fluorescent defects in solid-state matrices. Using this architecture, we were able to detect and study a single erbium ion in a nanoparticle. We also generated high bandwidth signals at 606 nm, which would enable frequency multiplexing of on-demand read-out $Pr^{3+}:Y_2SiO_5$ quantum memories [4, 5]. In a second time, I will present a study of the noise generated during the frequency conversion processes. We perform both a theoretical and experimental analysis of the different nonlinear processes arising from the nonlinear mixing, and able to analyse the parasitic photon emission close to the signal of interest, generated at the Pr^{3+} quantum memory wavelength. We quantify the rate of the generated parasitic photons per spectral width of the SFG process, and conclude on the effect on the memory performances.



A) Overall architecture of the optical waveform generator, described in the main text. B) Sum frequency generation and parasitic non linear processes creating noise photons. C) Noise spectra with respect to PPLN temperature, dashed lines correspond to model

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Tunable sweetlines for hole spin qubits

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Recent scaling up efforts have brought hole spin qubits to the forefront of the scene as promising semiconductor-based qubits [1]. Thanks to their strong spin-orbit coupling, hole spins are manipulated through their transverse electrical dipole. As a drawback, spin-orbit also brings a longitudinal hole spin susceptibility opening channels for decoherence through charge noise. Fortunately, for peculiar magnetic field orientations, the longitudinal coupling can vanish, yielding to sweet spots where hole spin qubits coherence times is greatly enhanced [2]. In this work, we show that these sweet spots form in fact three-dimensional lines, whose geometries can be tailored by electrical fields. We demonstrate our ability to align two neighboring qubits at a shared sweet spot, offering a promising route for larger scale integration. Finally, we show that the transverse interaction can be maximized when the longitudinal one cancels out [3], therefore maximizing their Rabi frequency. This yields qubits optimized at the same time for large coherence and fast manipulation, which greatly enhances single qubit gate fidelities.

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Posters 1, 13/11/2024: Quantum Fundamental Quantum Aspects (FQA)

Biphoton speckles in the deep Fresnel region

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Speckles are random patterns formed when a laser light is transmitted through a scattering medium. Classical studies of thin-film scattering typically take place in the far field of the scatterer. In this regime, the average speckle size scales with propagation length, a direct consequence of the van Cittert-Zernike theorem. In contrast, speckles observed closer to the scatterer, in the so-called deep Fresnel zone, maintains a constant size, regardless of the axial position of the detector [1, 2]. This zone can be generalized to obtain information hiding behind the scatterer, such as 3D imaging of objects [3], or even sensing scatterer properties [1].

Here, we study these two zones for the scattering of entangled photon pairs, for which speckle patterns are seen in coincidence measurements. We discover that the biphoton speckles too exhibit qualitatively different behavior with propagation. We show theoretically and experimentally that they are rectangular-shaped in the deep Fresnel zone, rather than the previously observed elliptical speckles in the far field [4], with propagation behavior that depends only on the properties of the scatterer. Further, we compare classical and entangled correlations over all propagation distances and discuss the novel aspects that arise due to the higher dimensionality of the latter. This study advances our fundamental understanding of entanglement propagation, thereby having implications for improved quantum imaging and communication through scattering media.

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Thermodynamics of weak continuous measurements

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The central aim of this work is to quantify fundamental energy costs of a quantum measurement. To do so, we analyze a minimal model of quantum measurement involving the steps of relevance for the thermodynamic and energetic properties. We describe measurements where partial or complete information is extracted from the system of interest, spanning from weak to strong measurements, and varying in detection efficiency from fully efficient to highly inefficient. Our model involves the measured quantum system, S, and an ancilla, A, which is used to extract information about the primary system. After initializing the ancilla ((1) in Fig. 1), the system interacts with it, allowing information to be extracted from the system and transferred to the ancilla ((2) in Fig. 1). The amount of information extracted from the measurement, which determines its strength, depends on the interaction coupling constant. Although the information is transferred to the ancilla in quantum form, only classical information can be read out, which can be achieved by applying a dephasing process. In this step ((3) in Fig. 1), the ancilla undergoes complete dephasing, establishing the measurement basis and eliminating all coherences in the energetic eigenbasis. The final step ((4) in Fig. 1) involves reading out the ancilla by measuring a property of its state and storing all the information in a classical memory. Finally, both the classical memory and the ancilla state are reset.

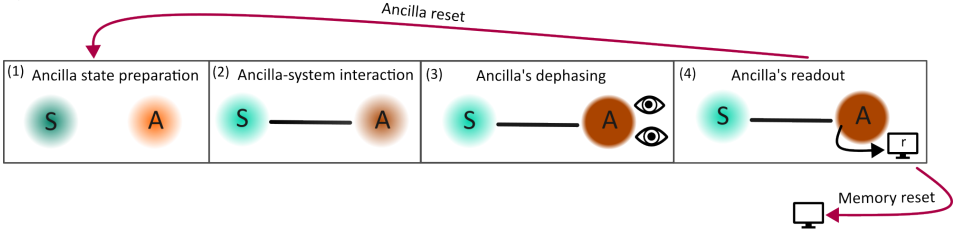

FIGURE 1 – Procedure to model quantum measurements. The change of colours of both the system and the ancilla represents a change of state.

We analyze the lower bound on the work cost of the protocol and compare it to a scenario where dissipation, rather than dephasing, is employed to convert quantum information into classical form [1]. Our findings indicate that the work bound in the dephasing case is greater than or equal to that in the dissipation case.

A strong, efficient measurement can be achieved in several ways. One approach is to directly apply the measurement protocol in a strong manner, while another is to perform multiple consecutive weak measurements. We compare the work bounds for both cases. The work bound for the consecutive weak measurements, $W_{N\epsilon}$ is significantly larger than that of a single strong measurement, W_1 (Fig. 2).

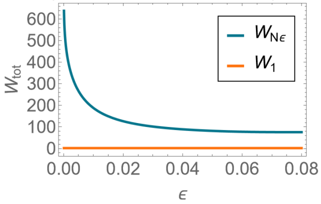

FIGURE 2 – Total work bound required to achieve a strong, efficient measurement by concatenating weak measurements, $W_{N\epsilon}$, in terms of ϵ, a parameter determining the measurement strength. The work bound for a single strong measurement $W_1 = 1.946$ has been added to the plot.

Our work provides insights into the relationship between energy resources and measurement performance, as well as the links between measurement-induced dynamics and thermodynamic irreversibility.

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Extremal Tsirelson inequalities

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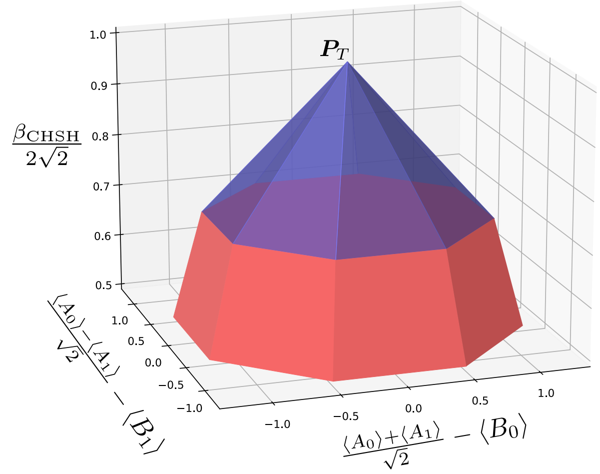
Bell's theorem provides a unique basis to certify the proper working of quantum devices directly from observed quantum statistics [1–3]. Despite decades of efforts, the set of quantum statistics $\mathcal{Q}$ remains hard to describe in general. This constitutes a fundamental obstacle to the application of the device-independent method to the certification of quantum communication and quantum computing apparatuses.

In this work [4], we propose to study the set of quantum statistics from a dual picture. Namely, we consider the dual of the quantum set $\mathcal{Q}^*$, defined by the Tirelson bounds of Bell inequalities [5]. As expected, characterizing the full dual $\mathcal{Q}^*$ is a challenging task since it amounts to finding the maximal quantum value of every Bell expression. As a first step, we restrict our interest to Bell expressions whose maximum value is attained by the Tsirelson point P_T, i.e. by the statistics obtained upon applying the measurements $A_0 = \sigma_z$, $A_1 = \sigma_x$ and $B_y = (\sigma_x + (-1)^y \sigma_z)/\sqrt{2}$ on the maximally entangled two-qubits state $|\phi^+\rangle = (|00\rangle + |11\rangle)/\sqrt{2}$. This point maximizes the CHSH expression β_{CHSH} [6] and its realization is the target of numerous experimental endeavors.

Surprisingly, we show that other Bell expressions than the CHSH one are also maximized by the Tsirelson point. We fully characterize the set of these expressions analytically, proving that they form a convex manifold of dimension two, with 8 extremal points. This yields the first complete description of a slice of the quantum dual $\mathcal{Q}^*$.

One consequence of our findings is that the CHSH expression is not extremal with respect to the quantum set. Rather, it can be decomposed in terms of the 8 extremal Tsirelson inequalities that we identified. Geometrically speaking, this implies that the Tsirelson point is an angulous point of the quantum set. In particular, there is a 3-dimensional projection in which this point lies at the summit of an 8-sided pyramid, as depicted below. This challanges the common representation of the Tsirelson point as a smooth boundary of the quantum set [7].



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A toy model for the generation of photon-number coherence in quantum dot-based single photon sources

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The development of semiconductor Quantum Dot (QD)-based sources generating single photons of high purity and indistinguishability at high rates [1] has enabled the implementation of quantum computing protocols [2] with increasing number of single photons. In 2019, the emission of coherent superpositions of vacuum and single photons $|\psi\rangle = \sqrt{1-p}\,|0\rangle + \mathrm{e}^{\mathrm{i}\varphi}\sqrt{p}\,|1\rangle$ with controlable population p and phase φ was evidenced for a coherently excited quantum dot in a pillar cavity [3]. Such ability opens exciting perspectives for advanced quantum information processing protocols [4].

In this work, we study the generation of such photon-number superposition as a function of the QD electronic state configuration. We consider exciton and trion states where the QD ground state before the laser excitation is empty or occupied by a single charge, respectively. To probe the photon number coherence, we send the emitted light states into an unbalanced Mach-Zehnder interferometer. The observation of anti-correlated oscillations of count rates as a function of the interferomer phase [3] attests the presence of quantum coherence between the vacuum and the single photon component of the state. From the visibility of these oscillations, the photon-number coherence C can be measured. Our experiments show that neutral QDs i.e. exciton-based sources usually allow for superposition states generation with high photon-number coherence (up to 97%). In contrast, photon-number coherence usually remains limited for trion-based sources, as shown in Fig. 1.

To tackle this phenomenon, we have developed a time-averaged density matrix model describing the generation of the photonic superposition states from exciton- and trion-based sources. First, our model demonstrates full coherence transfer from the quantum dot energy levels to the photonic field for exciton-based sources. Second, it demonstrates a reduction of photon-number coherence originating from the optical selection rules at the core of spin-photon entanglement in trion-based QD devices.

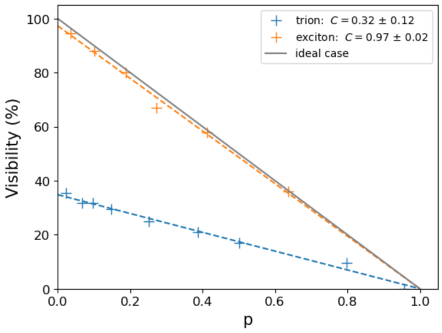

Figure 1 : Experimental visibility of superposition states in a Mach-Zehnder interferometer as a function of their population p mapped to the strength of the coherent excitation. The visibility at $p = 0$ gives access to the photon number coherence C.

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Collective light scattering in ordered 1D chains of dysposium atoms

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Understanding and controlling the light-matter interaction is crucial for many applications ranging from quantum metrology to quantum computing. While the interaction of light with a single quantum emitter is well understood, an ensemble of many emitters coupled by a resonant probe is a complex open quantum system. To explore these kinds of systems, programmable arrays of atoms in optical tweezers are particularly appealing, since the geometrical ordering offers the possibility to enhance the collective behavior exploiting the constructive and destructive interference between the emitters.

Here we present a novel experimental apparatus working with single dysprosium atoms trapped in one-dimensional tweezer arrays [1, 2]. We employ a magic wavelength for the 626 nm intercombination transition, allowing for high-fidelity imaging of single dysprosium atoms. We then build defect-free atomic arrays with variable interparticle distances, reaching spacings of the order of a few transition wavelengths. In this regime, we report recent measurements of collective light scattering, manifesting in frequency shifts of the 626 nm transition, that we detect both in the weak and strong excitation limits.

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Characterizing the spin-orbit interactions in PbTe nanowire quantum dots with negligible charging energy

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A broadly useful quantum processor is likely to require a very large number of qubits—foreseeably millions—to allow for error correction [1]. Spin qubits in quantum dots are an increasingly attractive candidate for such systems due largely to their promise of scalability, but the development of a practical quantum computer would still demand great progress in spin qubit research. Investigating new and promising materials is a crucial part of this effort with the potential to dramatically expedite overall progress. Lead telluride (PbTe) is one such material that has received relatively little attention in quantum research despite its potential utility. Here we report on several fundamental transport properties of quantum dots (QDs) defined in PbTe nanowires, with a focus on the observed spin-orbit interactions.

PbTe is a IV-VI narrow-bandgap semiconductor with an assortment of unique properties of interest for quantum research. One of the most important, and striking, of these is that its static dielectric constant exceeds 1000 at cryogenic temperatures [2]. This results in the suppression of electrostatic charging energy in QDs, effectively eliminating Coulomb blockade and allowing for the direct spectroscopy of spin-orbital states. This effect is predicted to improve qubit coherence times through charge noise reduction, but the full consequences have yet to be established.

We observe that PbTe has strong spin-orbit interactions (SOI) and a large effective Landé g-factor, which are both desirable for spin qubits. Both of these properties are anisotropic, with observed maximum magnitudes exceeding $500 \mu eV$ and 30, respectively, in our nanowire devices [3]. We characterized this anisotropy through transport measurements done in externally-applied magnetic fields with variable direction, and found it to be highly significant. As the magnetic field is rotated approximately in-plane, the SOI energy typically varies from its maximum value of order $100 \mu eV$ to near-zero, and the effective g-factor typically varies by a factor of 2 or more. This represents a major degree of freedom which could have relevance for spin qubits as well as for other quantum technologies based on this material.

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Breaking Local Indistinguishability with Superposition of Classical Communications

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Local indistinguishability, also known as "quantum nonlocality without entanglement" (QNLWE) [1], refers to the phenomenon where a set of perfectly distinguishable product states cannot be perfectly discriminated using local operations and classical communications (LOCC) [2]. Remarkably, [3] recently demonstrated that definite causal order (causality of correlations) can be traded for restauring local distinguishability : an example of determinisitic, logically consistent (under free operations), classical communications without global past [4, 5] - the tripartite “Lugano process” [6], can be used with local operations to perform the QNLWE “SHIFT” measurement.

In this work (in preparation), we surprisingly demonstrate that the SHIFT measurement can also be performed by local operations with a quantum control of two classical communication channels, known as the “quantum switch” [7]. Our set up involves sending one qubit of the SHIFT state to be measured to Alice, one to Bob, and using the last one as a control of the classical communications between Alice and Bob’s operations, which is measured by a third final party, Fiona. The causally nonseparable distributed measurement [8] based on the SHIFT ensemble thus has two realisations with local operations and classical communications : using the Lugano process or the quantum switch.

Unlike the Lugano process, the quantum switch, despite being causally nonseparable, cannot produce noncausal correlations [9, 10]. Our result may thus initially seem to be in contradiction with the previously established correspondence between noncausality and QNLWE, but, under analysis, this conflict is illusory. By examining the Lugano process realization of the SHIFT measurement in terms of time-delocalized subsystems [11, 12], we demonstrate its equivalence to a classical switch circuit between two parties (Alice and Bob), controlled by the qubit from the SHIFT basis received by the third party (Charlie), who is “time-delocalized”, i.e. acts “before and after” Alice and Bob. By judiciously dividing Charlie into two parties representing a global past and a global future, the Lugano process performing the SHIFT measurement can then be transformed into a quantum switch, revealing how the exotic noncausal structure of classical communications can be simulated with a superposition of classical communications.

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Spatial localization of single photons: impact of the rotating wave approximation

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Photons are currently among the best candidates to be used as qubits in quantum information processing, especially for quantum communication. Experimentally, the ability to produce single photons on demand is now accessible to many platforms and to any quantum optics laboratory. However, some properties of these promising objects have been overlooked both theoretically and experimentally. Indeed, it was shown first by Knight [1], and then by Bialynicki-Birula [2] that a single-photon state cannot be spatially localized in a finite volume $\mathcal{V}$, i.e., even though the state function representing the photon is zero outside a certain volume, one can always find an local observable for which the expectation value of the *a priori* localized photon-state is not equal to the vacuum expectation value outside $\mathcal{V}$. In other words, there is a nonzero probability to detect the state that should be localized in $\mathcal{V}$ with a detector that is placed anywhere outside $\mathcal{V}$. Recently, we have shown that the energy density of the electromagnetic field is a physical observable for which the spatial nonlocality is explicit [3]. The proof was done using an intrinsic property of the photon helicty operator. This result rises some questions regarding the production of perfect single-photon states in actual experiments. Indeed, assuming that a single-photon is produced by an interaction taking place in a finite volume, as soon as it is produced, there will be a nonzero probability to detect it anywhere in space, clearly violating causality. In order to address such problem, we consider the spontaneous emission of a Hydrogen atom in a Weisskopf-Wigner like model meaning that we work in the subspace of single-photon states. This assumption, essentially equivalent to the rotating wave approximation (RWA), as well as a coupling term beyond the dipolar approximation [4], allow us to compute the expectation value of the energy density, and to characterize the spatial nonlocality of the produced state. We find, in the asymptotic limit, that it decays like r^{-6} where r is the radial distance from the atom [5]. This result, that is far from an exponential decay, is an illustration of the spatial nonlocality assuming the production of single photons only. However, from a meticulous analysis of the full minimal coupling between the atom and the quantized field, one can see that the dynamics couples the atom with N-photon states for $N = 2, 3, \ldots, +\infty$. Consequently, the model considering the full coupling should not violate causality. Another question arising from these analyses, is how close to perfect single-photon states one can get in an experiment. We thus consider a cavity QED system where a two-level atom is interacting with a single bosonic cavity mode. In order to discuss the impact of multiphoton contribution, we consider two descriptions of this system: the Jaynes-Cummings model which includes the RWA and therefore predicts only the emission of single photons, and the Rabi model which breaks the RWA and therefore predicts the emission of higher photon components. We show then using adiabatic control theory and topological argument on the eigenenergy surfaces that, in the adiabatic limit, the same control parameters can be used to reach the target state which is the emission of a single-photon in the cavity [6]. This result tells us that any single-photon source using adiabatic processes to emit the photons, can produce states that are as close as desired to perfect single-photon states. The contribution of the multiphoton components will thus be given by the correction terms to the adiabatic evolution which scale as $1/\tau$ where τ is the typical duration of the control pulses [7].

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Developing InAs based hybrid nanowires for Quantum devices

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We study the transport properties of hybrid semiconductor-superconductor nanowire devices, in which a superconductor is grown on top of a semiconductor nanowire to create a SNS junction with the weak link being a semiconductor. The junction is achieved by in-situ shadowing of nanowires using nearby nanowires, resulting in etch-free junctions which increases the likelihood of ballistic devices. One of the challenges in fabricating these devices is the immediate formation of a natural oxide layer on the semiconductor surface upon exposure to ambient air. This oxide layer hinders the quality of the superconductor-semiconductor interface, which is essential for creating transparent junctions with strong proximity effects. To resolve this, atomic hydrogen cleaning is employed to remove the oxide layer before depositing the superconductor. This process is monitored in real-time using techniques like Reflection High-Energy Electron Diffraction (RHEED) and Auger spectroscopy, allowing precise control over the cleaning process. Atomic hydrogen cleaning of InAs surfaces has been extensively studied, and we apply this technique to our devices, ensuring an atomically clean interface that enhances transport properties.

Previous studies has predominantly focused on aluminum (Al) as the superconductor in these hybrid devices, for instance Al-InAs devices in which the latter possess strong spin-orbit coupling, an essential ingredient for the emergence of Majorana bound states. Other materials, such as tin (Sn) on InSb nanowires, have also been explored, demonstrating promising results for topological superconductivity [1]. Semiconducting nanowire based superconducting qubit have been studied [2]. Recent studies in our group has explored Sn-InAs nanowire devices, utilizing the non-linearity of the Josephson junction to create gate-tunable transmon qubits. Sn exhibits higher superconducting gap compared to aluminum providing potential intrinsic protection against non-equilibrium quasiparticles. Additionally, their high magnetic field compatibility fosters integration with various quantum systems.

In our research, we are exploring a new material combination, in which tantalum (Ta) is used as the superconductor on InAs nanowires. Tantalum, a type 1 superconductor, has two crystalline phases, out of which the alpha phase has a higher critical temperature (T_c) of 4.48K while beta-tantalum exhibits T_c less than 1K. It also has higher superconducting gap compared to Aluminum [3]. These offers distinct advantages and makes tantalum as a potential candidate for study. By using Ta in proximity with InAs nanowires, we aim to create devices that support the formation of Majorana bound states as well as Ta based josephson junctions to create gate-tunable transmon qubits.

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Detection of mode-intrinsic quantum entanglement

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Major efforts are being conducted worldwide to harness the power of quantum mechanics for technological applications. The use of these systems for performing computations beyond the capabilities of classical processors stands as one of the most encouraging perspectives. A wide variety of physical platforms are being considered for this purpose, among which optical systems prove to be a promising framework given its potential for scalability. In particular continuous variable optical settings offer a huge potential for the generation of very large entangled states.

Identifying and characterizing the necessary resources for computational advantage with this kind of systems remains a challenging task. Entanglement is clearly a necessary resource, but on itself it is not enough. It is known that a non-Gaussian statistics with a negative Wigner function [1], is also necessary to develop protocols that can not be simulated efficiently with classical resources. Moreover, in Ref. [2] it was shown that in a certain family of sampling protocols a strong form of quantum entanglement is required : not passive separability, i.e., the fact that entanglement cannot be undone with optical passive transformations (beamsplitters and phase shifters).

In this work [3], we propose a witness, based on previously known relations between metrological power and quantum correlations [4], to detect such a strong form of entanglement, i.e. entanglement in all mode bases, that only non-Gaussian states possess. Furthermore, our method has a more practical experimental application. In quantum optics experiments that use multiplexing in time and/or frequency, some mode bases are experimentally inaccessible for direct measurements with state-of-the-art techniques. Our new method allows to nevertheless access entanglement between such inaccessible modes.

The strength of our witness is two-fold : it only requires measurements in one basis to check entanglement in any arbitrary mode basis ; it can be made applicable experimentally using homodyne measurements and without requiring a full tomography of the state.

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Realistic Bell tests and DIQKD with homodyne detectors

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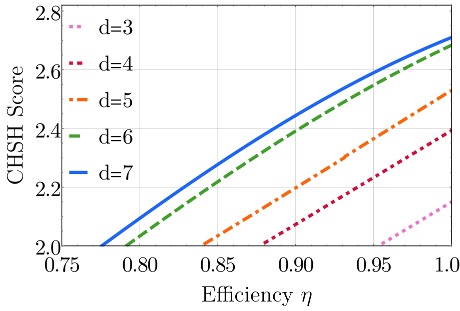
Bell non-locality is one of the most fascinating aspect of Quantum Information, not only as a foundational problem, but also as a core resource for quantum communication in a device-independent (DI) manner, *i.e.* without making assumptions about the underlying quantum mode [1–3].

By 2017, three different Bell experiments had been carried out which closed the main "loopholes", *i.e.* experimental problems that affect the validity of Bell tests [4–6]. However, these tests involve measurements devices relying on superconducting nanowire single-photon detectors, which require cryogenic temperatures to operate efficiently. This stands in contrast with the practical and commercial expecta- tions for the implementation of DI protocols, where on- chip integration is highly desirable.

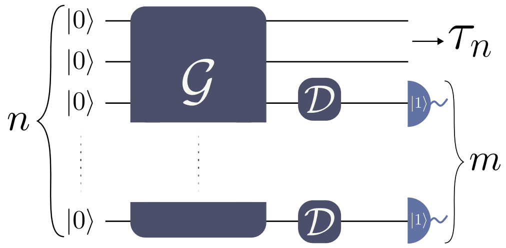
We consider set-ups with standard photonic devices, notably restricting the detecting apparatus to homodyne detectors. We look for the largest possible Bell violations in bipartite experiment for which each party can possess up to four measurements. For every Bell inequality, we run optimisations to obtain the maximum quantum bound, by playing on three different parameters :

- The dimension of the observables
- The angles of the homodyne measurements
- The choice of binning (discretization of the outcome).

For local qudit Fock spaces of increasing dimensions, we found states that yield the largest violations observed in the literature [7]. We focus on the experimental feasibility, first by deriving thresholds of efficiency required to enable Bell inequalities violations, as displayed in Fig.(a), then by proposing realistic set-ups which can produce such violations, as displayed in Fig.(b). Finally, we derived key-rates for Device Independent Quantum Key Distribution (DIQKD) protocols.



(a) CHSH score with respect to the overall efficiency of the protocol η. We plot the curves of the different ordered local Fock spaces $\{|0\rangle, ..., |d\rangle\}$.



(b) n-mode bosonic parameterized circuits. The modes are initialized to the vacuum $|0\rangle$. A Gaussian process $\mathcal{G}$ is applied on all modes. $m = n - 2$ displacement operations $\mathcal{D}$ are performed on the last modes, before heralding operations on single photon count. The state $\mathcal{T}_n$ is then send to Alice and Bob.

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Towards antibunching from a large three-dimensional atomic cloud

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The light radiated by a quantum emitter, such as an atom, generally features quantum correlations and squeezing, which are at the heart of many applications in quantum technologies. In particular, antibunching is the key ingredient for single-photon sources, and which naturally occurs in the light emitted by a single quantum emitter and vanishes when the light originates from many emitters. Still, antibunching can be obtained using many atoms [1], when, instead of collecting the atoms' fluorescence, one uses the light transmitted through the ensemble. This has been demonstrated recently by the group of Arno Rauschenbeutel in Germany with a one-dimensional array of cold atoms [2].

The goal of this project is to take advantage of a simpler platform, with a 3D atomic cloud generated by a standard magneto optical trap, and see if antibunching can be still observed. The first step is thus to tackle the question of the effect of the dimensionality of the atomic medium, going from the initial realization in 1D to a 3D atomic ensemble, and in particular to study the impact of multiple scattering.

To this end, we first investigate the light transmitted and scattered by our cloud of cold atoms. Our approach includes measuring light transmission to identify deviations from the Beer-Lambert law, signaling either the presence of technical artifacts such as background light or multiple scattering effects by our system. Additionally, we analyze photon correlations in the scattered light to assess the impact of multiple scattering on our observations. Furthermore, we conduct simulations using both random walk and coupled-dipole models to compare to our experimental results.

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Detection limitations in CV measurement of non-Gaussian states

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Non Gaussian (NG) quantum states and operations belong to the basic set of tools needed in numerous quantum information protocols including measurement based quantum computation and quantum communication [1]. Usual schemes rely on heralding via photon-counting measurement on a subsystem from an entangled state. The heralded NG state can be then reconstructed via quantum state tomography after quadrature measurements with homodyne detectors [2]. However, these protocols are sensible to losses, detection efficiency and detection bandwidth. Notably, in multiple situations optical filtering steps are required on the heralding path to comply with spectral multimode features [3–5].This leads to a time envelop that needs to be resolved to observe the produced NG state [6]. In this context, the performances of detectors play a critical role on both the heralding and heralded path [7]. In recent works, high performance (bandwidth and detection efficiency) detectors are used to avoid this issue. Here, we analyze experimental data to characterize the boundary between optimal working parameters and unoptimal experimental resources.

We focus on the data acquisition strategy used in our work on the plug'n'play generation of non-Gaussian states of light at a telecom wavelength [5]. Considering a continuous wave laser for the local oscillator, data are post treated to make the detection mode on the homodyne used to measure the produced the NG state match the heralding detection mode determined by the optical filters.

Simulating digital data treatments with varying parameters allowed us to identify, for a fixed heralding bandwidth, the conditions to respect to retrieve NG and negative quantum states out of the entire detection process. We compare reconstructed Wigner functions with homodyne detection bandwidth f_c varying from 11 MHz to 301 MHz and sampling frequency f_s going from 10 Msps to 5 Gsps as shown in figure 1 .Our analysis shows that, provided Shannon-Nyquist criterium is respected, NG features are preserved even when the detection bandwidth is closer to the optical bandwidth of filters on the heralding path, here 10 MHz. The state negativity is however degraded by the loss of information associated to temporal responses.

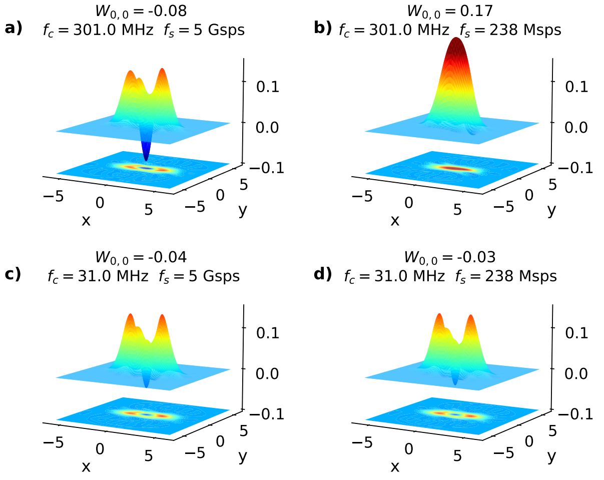

Figure 1 Reconstructed Wigner functions $W_{NG}(x, p)$ of the heralded non-Gaussian state.

By assessing and quantifying these effects, our analysis allows to understand results that can be achieved by exploiting standard devices with limited performance and paves the way to a more efficient and aware use of experimental resources.

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GRAPHENE QUANTUM DOTS AS PROMISING BRICKS TO TAILOR SUPER(SUB) RADIANT STATES IN COUPLED QUANTUM EMITTERS

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In the race for efficient quantum emitters, graphene quantum dots (GQDs) have a lot to offer. Indeed, bottom-up chemistry allows a total control on the structure, which opens the possibility to customize their optical properties [1–3]. We have recently shown that GQDs can be efficient sources of single photons [4] whose properties can be tuned by playing with both the symmetry and the size [5]. In particular, we designed a new family of elongated GQDs showing linear transition dipoles up to 16 Debye [6].

In this poster, we will investigate the potential of these new GQDs in the context of building coupled quantum emitters to tailor super and sub radiant states. In fact, there is recently a renewed interest in the study of dimers of molecules coupled by dipole-dipole interaction leading to entangled states at low temperature [6, 7]. In these papers, the authors report the control of the entanglement through the tuning of the molecules emission energy, through either Stark effect [6] or laser tuning [7]. Here, we will present some simulations to demonstrate how the strong dipoles of GQDs can be an asset in this context, in particular to get rid of the constrain of the detuning between the emitters.

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Spin properties of type-II excitons in a single GaAs/AlAs quantum dot

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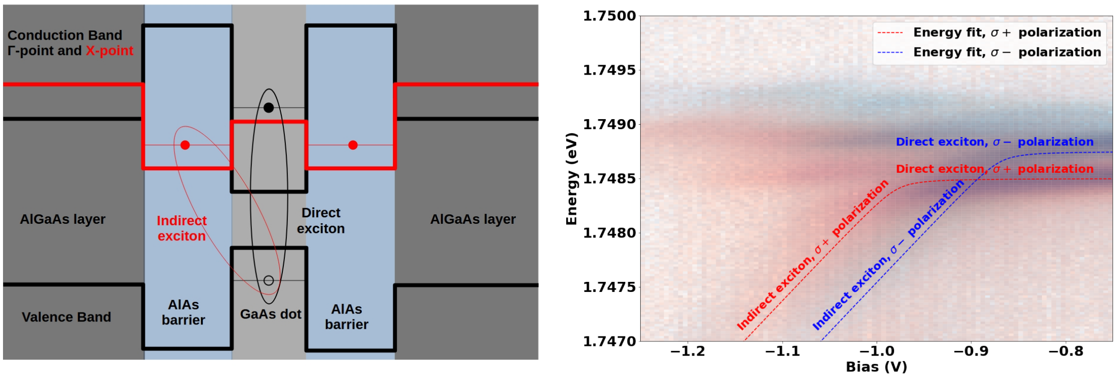
The control of individual quantum systems and their mutual interaction is a fundamental focus for the development of quantum information technologies. Quantum dot molecules (QDMs) are of great interest as a system allowing for the realisation of delocalized excitons with a spatial separation between the hole and electron, whose properties are tunable through the application of an external electric field, enabling the realisation of entangled states [1, 2] and quantum gates [3, 4]. The study and understanding of the indirect exciton is thus of capital importance in the exploitation of this sytem.

We here present an architecture for type-II GaAs/AlAs quantum dots, offering an alternative way to generate indirect excitonic states, with the electron either located inside the dot itself or in the AlAs barrier. QDMs are complex objects whose properties may vary with fabrication, making it a sensitive system to engineer, while our type-II have a simpler electronic structure, making them a viable platform for the experimental study of indirect excitons.

Our system consists of a GaAs quantum dot grown using nanohole infilling technique [5] between two AlAs barriers on top and at the bottom of the dot. The system is embedded in a Schottky diode structure. Because of the high Al content of the barriers, electrons can be confined inside the barrier at the bottom of the X-valley of the conduction band, leading to the creation of indirect excitons where the hole is located in the dot and the electron in the AlAs barrier, as sketched on Fig1(a)).

Due to the large dipolar moment of the indirect exciton, its energy level is highly sensitive to external electric field applied inside the diode. When the energy of the indirect exciton crosses that of the direct one, an anticrossing appears, evidencing coherent coupling between the two eigenstates of the system. Under the influence of an external magnetic field, the energy levels of the system undergo Zeeman splitting. The indirect and direct branches of the excitonic lines exhibit opposite signs of the effective Landé factors for the X-valley electron in the AlAs barrier and the Γ-valley electron in the GaAs dot. This enables us to experimentally demonstrate continuous tunability of the effective Landé factor of the exciton through the application of an external electric field using the transition at the anticrossing from a pure indirect to a pure direct exciton, as shown on Fig1(b). This study opens perspectives for a better understanding of the interface coupling mechanisms between the X- and Γ-valleys in AlAs/GaAs heterostructures.



(a) (b)

FIGURE 1. (a) Schematic band diagram of the type-II GaAs quantum dot without an external electric field. (b) Experimental spectroscopy map of the type-II GaAs quantum dot for the $\sigma+$ (red) and $\sigma-$ (blue) polarizations as a function of the applied bias. The indirect exciton lines are faintly visible because of their low intensity and their energies vary greatly with the applied bias.

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Distortions in Flat-Band Type-II Superconductor ZrV2

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Type-II superconductors have long been studied as candidates for where superconductivity arises from spin-fluctuations. [1] ZrV2 is one such candidate for spin-fluctuations giving rise to changes in the superconductive properties.

Using floating zone growth methods we synthesised single crystal samples of ZrV2, a Type-II superconductor with Tc = 8.9K and Hc=14T, in a high pressure floating zone laser furnace. These samples show an electronic transition around 100K and an unusually high RRR of 0.94 that agrees with observations in the literature. [2] However, Our samples do not show a structural distortion seen in the literature in polycrystalline or twinned samples. [3] Our work on single crystal X-Ray diffraction performed at CHESS (Cornell High Energy Synchrotron Source) seeks to explain the electronic transition as it correlates to diffuse scattering observed to onset alongside the electronic transition. Continuing work on this flat-band material will be to explore the transition between the distorted superconducting parent compound ZrV2 and non-distorted parent compound HfV2.

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Vortex optique pour le mélange à 4 ondes : Laguerre Gauss, Bessel Gauss et vortex parfaits

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Les vortex optiques sont des ondes lumineuses ayant un front d'onde en hélice, dont le sens et le nombre de branches est caractérisé par $\ell \in \mathbb{Z}$. Les vortex possèdent deux propriétés principales : une intensité annulaire – forme intéressante pour faire des pièges ou de la microscopie STED- et un moment orbital angulaire (OAM) photonique quantifié et valant $\hbar\ell$ par photon [1]. Ce qbit photonique trouve des applications en technologies quantiques notamment par sa base étendue. L'intrication de deux OAM se fait par processus non-linéaire.

Dans nos études, on exploite le mélange à quatre ondes (FWM) non dégénéré en fréquences, réalisé dans une vapeur de rubidium. Il est connu pour produire des paires photoniques. Par exemple si le rubidium est excité par deux lasers sur la transition 5S-5D il produit une paire IR-bleue. Réalisé avec des vortex optiques, il donne deux vortex et des paires d'OAM [2]. Comme il conserve l'OAM total mis à l'entrée il produit plusieurs paires d'OAM en sortie, ce qui ouvre vers de la multi-intrication. Par ailleurs, l'efficacité du FWM est crucialement lié au recouvrement des vortex en jeu, i.e. recouvrement de leurs anneaux. Là intervient la famille de vortex choisie et ses propriétés pour faire les expériences. La famille des modes de Laguerre-Gauss (LG) est la plus couramment utilisée, et a permis de convertir de grands OAM [3] mais il en existe d'autres : Bessel-Gauss (BG), Zernike, etc.

Notre projet vise à réaliser le FWM avec des vortex dits « parfaits » (PVB pour Perfect Vortex Beams) [4] car les PVB, à l'instar des LG ou des BG, ont un anneau dont le rayon est indépendant de ℓ et peuvent garantir un recouvrement optimal. Cela permettrait d'étendre l'espace des paires d'OAM. Le poster présentera une étude comparée des LG, BG et PVB réalisés par phase-shaping (et SLM). On discutera leurs propriétés, leur fabrication et leur propagation et par des éléments prévisionnels on donnera les attendus du FWM réalisé avec des PVB.

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Modal Analysis of a Multimode Displaced Squeezed State from High-Harmonic Generation

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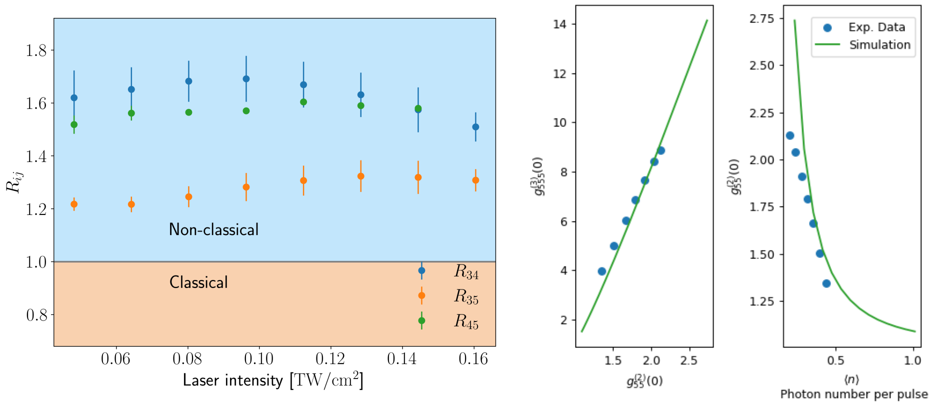
The ongoing second quantum revolution aims to harvest the properties of non-classical systems for applications in quantum metrology and quantum information. The key properties to realize these applications are entanglement and squeezing. Using these properties, the promise is to achieve secure communication and high precision in sensing to a level, that is unreachable with systems relying on classical physics. Still, the generation of systems with appropriate properties poses a challenge. One propitious system is a bosonic platform made out of non-classical states of light. High-harmonic generation (HHG) could have suitable properties to form the basis of such a bosonic platform. Still, the experimental perspectives on the quantum properties of HHG are scarce. Theoretical [1–3] and experimental [4] investigations have demonstrated that solid-state high-harmonic generation (SHHG) creates non-classical states of light. In this study, we perform an experimental analysis of the non-classical properties of solid state harmonic high-harmonic generation (SHHG) in Cadmium Telluride (CdTe). Extending upon recent work [4], we confirm non-classicality in the bipartite states created from three harmonic orders by pairwise violation of the multimode Cauchy-Schwarz inequality and estimate the multimode squeezing distribution.



In detail, we investigate three high-harmonic orders in CdTe and confirm non-classical properties in the non-perturbative generation regime by measuring the broadband Glauber correlation function $g^{(n)}$ for $n = 2$ and $n = 3$ in a Hanbury-Brown-Twiss like configuration using single photon sensitive diodes. Besides observing a characteristic transition in the photon statistics dependent on the driving laser intensity, we evaluate the parameter $R_{ij} := \frac{\left[g^{(2)}_{\mathrm{ij}}\right]^2}{g^{(2)}_{ii}\, g^{(2)}_{jj}}$, where the indices refer to the harmonic order. A violation of the Cauchy-Schwarz is obtained for $R_{ij} > 1$ for all bipartite reductions, a strong sign of non-classicality. Additionally, we compare the experimental data for the simultaneous measurement of the broadband $g^{(2)}_{ii}$ and $g^{(3)}_{iii}$ to the statistics obtained from a multimode displaced squeezed state. The theoretically obtained curves match the experimental data very well. From the simulation, we extract the squeezer distribution and estimate the squeezing strength.

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Two convergent NPA-like hierarchies for the quantum bilocal scenario [24]

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Characterising the set of probability distributions allowed by quantum theory in different scenarios is central to understand quantum nonlocality [1], which is crucial to both the foundation and the application of quantum theory [2–10]. This requires effective methods for the characterisation of quantum correlations. In the usual Bell scenario, where many distant parties share a single entangled state distributed by one common source, the inner approximation to the set of quantum correlations can be done by sampling all Hilbert spaces and operators. The outer approximation, on the other hand, can be achieved with the *Navascues-Pironio-Acin (NPA) hierarchy* [11–13], which provides a hierarchy of Semidefinite Programs (SDP) converging to the set of feasible correlations.

More recently, there has been a growing interest in studying quantum nonlocality in network scenarios, where multiple sources that distribute independent states among distant observers are considered [14–18]. In particular, the *bilocal scenario*, the simplest network scenario where two independent sources are distributed to three parties—one between Alice and Bob and the other between Bob and Charlie—has received increased attention [19–23]. This requires generalising the NPA hierarchy to characterise bilocal quantum correlations. While there are promising candidates, such as the *inflation-NPA hierarchy*, no proof of convergence existed before the first draft of our manuscript.

In [24], we first introduce a new non-SDP NPA-like hierarchy, the *factorisation bilocal NPA hierarchy*, and show its convergence to the set of *Projector Bilocal Quantum Distribution*, a relaxation of quantum correlations in bilocal scenarios. Then, building upon the original scalar extension method [25], we propose the *scalar extension bilocal NPA hierarchy*, which can be solved by SDP, and show its convergence to the same set of Projector Bilocal Quantum Distribution. Finally, we show the equivalence of our two hierarchies and the inflation-NPA hierarchy in bilocal network scenarios.

Our first draft has triggered interest from other groups of physicists and mathematicians [26, 27], which, in turn, inspired an important correction leading to the current version of the manuscript. Along with [26, 27], we provide converging SDP hierarchies to the set of quantum correlations arising from bilocal network scenarios as axiomatised in the C^*-algebra formulation of quantum information theory. This means that the characterisation of quantum correlations for bilocal networks is complete in the Heisenberg picture, and sets the first step towards the generalisation of even more complex quantum networks.

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Posters 1, 14/11/2024: Quantum Processing, Algorithm, & Computing (QPAC)

Using qubit noise to our advantage for the quantum computation of Dynamical Mean Field Theory

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The bottleneck of the numerical resolution of Dynamical Mean Field Theory (DMFT) is the solution of the impurity model, which becomes exponentially difficult with the number of correlated orbitals. Hybrid quantum classical methods have been proposed that set out to solve this problem on ever-improving quantum processors. Yet, all previous approaches neglect the fact that the number of requisite bath sites in DMFT is very large and is thus unsuitable for a computation on near-term processors. This work addresses this issue by showing that noise can be used to reduce the number bath sites thanks to a more economical fitting of the DMFT hybridization function, up to a certain point. This paves the way for a solution of DMFT equations with a mixed quantum-classical algorithm.

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Quantum Ripple-Carry Addition with Polylogarithmic Depth

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A number of techniques for performing addition on a quantum computer are known, with the arguably simplest one being the quantum ripple-carry addition. It has the advantage of requiring a linear number (in the size of the input) of classical gates, without ancilla. However, it has the significant disadvantage of having a linear depth, which is in contrast to other adders, which have a logarithmic depth (but also have their own shortcomings, such as the use of many ancillae or the use of quantum gates and approximations). This is a consequence of the use of operators that are naively implemented by means of CNOT ladders and Toffoli ladders, that have a linear depth.

CNOT ladders are closely related to the quantum Fan-Out and Fan-In operators, and they share the well-known result that they can be replaced with a circuit of logarithmic depth. They appear to be building blocks of many algorithms, whether in quantum arithmetic [5] and cryptanalysis [1] or even in quantum chemistry [4] and physics [6]. However, a comprehensive and detailed study of these operators seems to be lacking.

With regard to Toffoli ladders, we are unaware of any paper that presents a depth-optimized alternative circuit. It is noteworthy though that on one hand, Toffoli ladders appear when considering the implementation of generalized Toffoli gates with a circuit involving only Toffoli gates, and on the other hand, it has been recently shown [2, 3] that generalized Toffoli gates can be implemented in logarithmic depth with few ancillae. The conjunction of these two facts suggests the possibility of a depth-optimized circuit that could replace Toffoli ladders.

We precisely address the aforementioned shortcomings in our paper :

1. Pseudocode and a precise complexity analysis of the implementation of a logarithmic-depth circuit to replace CNOT ladders is unavailable in the literature. We address this gap by showing that there exists such a circuit. On n qubits, it has a logical depth of at most $2\log n$ and a number of CNOT gates $< 2n$ (more precise values in our paper) ;

2. A review of the literature reveals no prior work on a depth-optimized implementation to replace Toffoli ladders. We address this gap by proving that there exists such a circuit. On n qubits, it has a logical depth of $O(\log^2 n)$ and a number of Toffoli gates of $O(n \log n)$. To prove this result, we build up on the recently published works [2, 3] on the technique of *conditionally clean ancillae* ;

3. Quantum ripple-carry adders do not need any ancilla nor inherently quantum gates, and have a linear gate count. However, they have a linear depth. We address this drawback by applying the two previous results to the quantum ripple-carry adder proposed by Takahashi *et al.* [5], and prove that quantum ripple-carry addition can be done in polylogarithmic time, instead of linear time. Namely, we can compute the sum of two n-bit integers in place with only classical gates, a depth of $O(\log^2 n)$ and $O(n \log n)$ Toffoli gates.

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Controlling the generation of large cluster states with partially post-selected measurements

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Entanglement is a fundamental resource for advancing photonic quantum technologies, particularly in quantum computing and quantum communications [1]. We present a resource-efficient method for generating large-scale photonic linear cluster (LC) states using a bright single-photon source an InGaAs quantum dot embedded in a micropillar cavity [2] and a fiber-based entanglement setup (see Fig. 1a) [3]. The entanglement scheme is composed of a polarizing beam splitter and a fiber delay loop, acting as a quantum memory to entangle sequentially the photons.

To scale up the number of entangled photons, we introduce an optimization strategy based on residual visibility measurements. This technique allows us to monitor and enhance the quality of the generated LC states by analyzing partially post-selected (PPS) data showing visibility of 2 to n-1 photons in an n-photon experiment. This significantly reduces acquisition time compared to conventional post-selection methods, where only the same number of input and output photons are measured. By optimizing the PPS visibilities, we attest precise alignment of the experiment and gather valuable insights into the performances of the system comprised of the source and the loop.

Using this approach, we show a 6-photon visibility fitted with information fitted from PPS data. This method offers a promising path for scaling up photonic entanglement and could be applied to larger cluster states for measurement-based quantum computing (MBQC) and other quantum technologies.

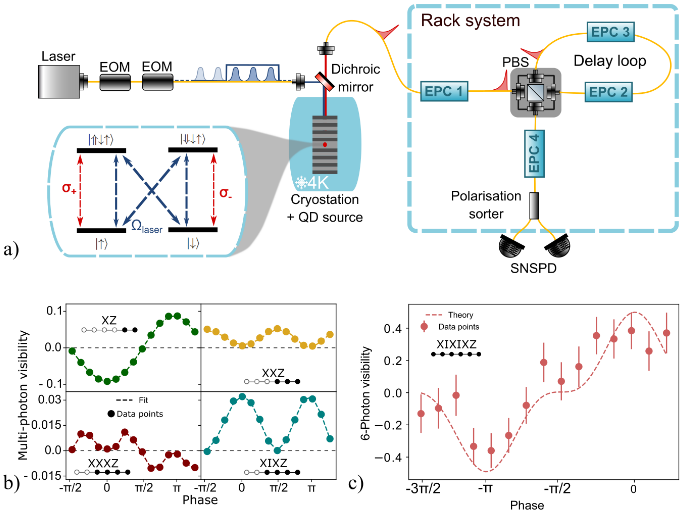

Figure 2 : a) Experimental setup for sequential entanglement of single photons from an InGaAs quantum dot source in a micropillar cavity. Inset : Energy level structure of the negative trion device - Red - Optical transitions of the QD - Blue - Laser drive with H or V polarization. b) Partially post-selected visibilities of 2 (top-left), 3 (top-right) and 4 (bottom) photon cluster states measured in a 6-photon experiment. c) 6-photon visibility measurement reaching $V = 39 \pm 5\%$. The theoretical model fits the data from the 6-photon experiment with parameters from the 2-photon partially post-selected fit.

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Study and experimental measurement of non-classical correlations in the multimode regime

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Developing new models of quantum computing and quantum communication protocols is requiring advanced technologies that are more compact, loss tolerant, and that allow us to have higher scalability to match the complexity of tasks [1]. This can be done in quantum optics with observables in the Continuous Variables regime (CV) by encoding information on the entanglement of frequency-time modes of the electromagnetic field [2]. An example of this approach is the use of highly multimodal states called cluster states that can be used for one-way quantum computing protocols [3].

For our project, we aim to tailor the quantum correlations between modes of light we generate via the process of Parametric Down Conversion (PDC). We are engineering the spectral envelope of the pump we send to a Periodically Poled KTP crystal (PPKTP). These correlations are completely described by the Joint Spectral Amplitude (JSA). This function is governed by the spectral amplitude of the pump and the phasematching of the crystal. Consequently, spectral modulations of the pump will modulate the JSA and engineer the correlations between multiple modes [4].

In our experimental setup (Fig.1), the main laser is a pulsed picosecond laser at 1556 nm. It is the pump of a Periodically Poled Lithium Niobate crystal (PPLN) used to generate the Second Harmonic (SHG) at 778 nm. This generated light is, then, the pump of the PDC. We tailor the 778 nm light spectrum by adding a Wave Shaper directly after the main telecom laser. The experimentally tailored spectra is numerically implemented in a code to simulate the output of the PDC. This code computes the expected JSA conditioned by the parameters of our experiment. Then, to evaluate and quantify the weights of the correlations, we map the entanglement onto another basis known as the Schmidt basis.

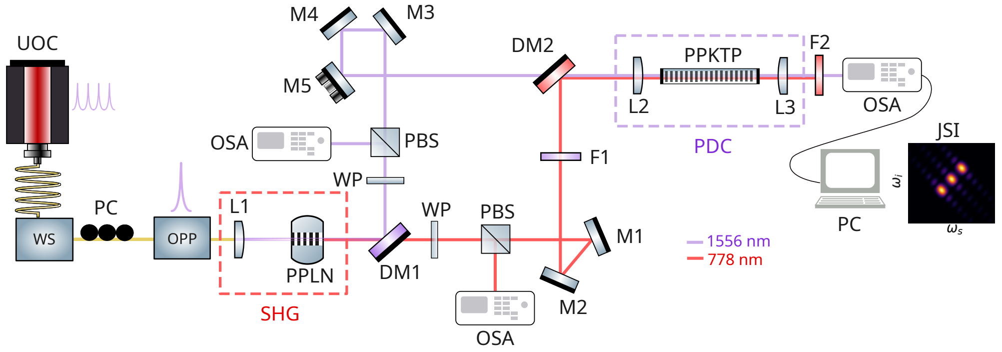

FIGURE 1. Experimental setup. UOC : ultrafast optical clock ; WS : wave shaper ; PC : polarisation controller ; OPP : optical pulse picker ; L1-3 : lenses ; DM1 : dichroic mirror-shortpass ; DM2 : dichroic mirror-longpass ; WP : half wave plate ; PBS : polarisation beam splitters ; M1-5 : mirrors ; F1-2 : filters ; OSA : optical spectrum analyser ; JSI : joint spectral intensity.

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Robust Quantum Optimal Control in a Two-Level System

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Today, quantum optimal control is a key tool in the development of quantum technologies to perform specific operations with efficiency and in a short time. [1]. A major limitation in the experimental implementation of optimal control procedures is the high dependency of the control on system parameters, which therefore need to be known with precision [2]. The design of robust control with respect to parameter variations is an important requirement which has been explored in many different works, particularly for two-level quantum systems. Different approaches based on a geometric [3] or an analytical [4] study of the dynamics have been proposed. We have shown that these different methods can be described in a unified way based on the Pontryagin Maximum Principle, which allows us to give a complete description and to generalize the results obtained in [3, 4]. We also extend this approach to the case of robust universal control where the system parameter against which the control must be robust is unknown. A Bose-Einstein condensate in an optical lattice is used as an illustrative example to show the efficiency of the control procedure [2].

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Adaptive mesh refinement with quantum computing

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The Finite Element Method (FEM) [1] is a widespread method to solve partial differential equations and design complex systems. In the domain of electromagnetic wave scattering, accurate simulations are necessary to ensure that radar and antenna meet strict requirements.

Many developments have improved the efficiency of the FEM on classical High Performance Computing (HPC) clusters, leveraging parallelism to treat large problems with millions of degrees of freedom. However, this numerical method suffers from a large algorithmic complexity and requires important computing power on clusters. Quantum algorithms to solve linear systems, such as HHL [2] and improved versions [3], can be applied to the FEM [4]. Although promising, they have to fit within specific numerical schemes already in production. A numerical strategy that falls into this category is adaptive mesh refinement (AMR) which refines the mesh iteratively where, and only where it will most improve the accuracy of the solution. This is predicted by deriving local a posteriori error estimates from the solution computed on each mesh.

The present work investigates the introduction of the HHL algorithm in the AMR framework. In order to do so, we consider the output of the HHL algorithm to be given in a quantum register at each iteration of the AMR loop. The classical representation of the electric field is needed to compute the a posteriori error estimates. As a first step in our analysis, the entire quantum state is *sampled*. Since it is a stochastic procedure, we obtain a classical register containing the *approximated field*. We study the impact of the field's uncertainties on the convergence rate of the mesh adaptation loop. Resources required by standard sampling and sampling with amplitude estimation [5] are compared.

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New tools for verification of quantum computations in the circuit model

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a. Context **Verification of Quantum Computations** by clients restricted to single-qubit operations has mostly been relying on the Measurement Based Quantum Computation model [1]. Building upon the VBQC protocol [2] (Verifiable and Blind Quantum Computation), a generic framework has been developed recently [3] and yields a modular construction for verification protocols with composable security, negligible security error and some noise-robustness.

b. Overview of results **In the circuit model**, only few protocols have been described, the most proeminent one being [4]. In this work, we show that [4] can be seen as an instance of [3] when rewritten in MBQC. This has notable consequences. For decision problems, the security error in [4] can be made negligible with respect to the total number of rounds of the protocol, and the correctness is robust up to a constant amount of global noise. Furthermore, following this method we introduce the first composable verification protocol in the circuit-model, and improve over [4] by reducing the amount of quantum communication between the Verifier and the Prover.

c. Tools and techniques Inspired by [4], we transform the delegated quantum computation by implementing the non-Clifford gates using **magic-state injection** provided by the Verifier. By one-time-padding the injected states, the Verifier is able to secretely either instruct the initial computation or a deterministic computation that can be used to detect a malicious behaviour from the Prover. More importantly, we show that there is enough freedom in the deterministic computations to **detect all possible harmful deviations** by the Prover. This shows that the results from [3] can be applied without requiring the computation to be fully blinded in order to yield composable verification with a negligigble security error and noise-robustness.

d. Perspectives Our work shows that an essential resource required to verify quantum computations is the ability to prepare magic states, pointing towards a potential resource theory. Also, by introducing robustness in the circuit model, one can hope for expanding the proof of concept experiments [5] for deeper circuits. Finally, this work opens the way to further develop applications of verification for circuit-based quantum computers such as those linking MBQC verification and quantum device benchmarking [6].

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Training an analog quantum bosonic neural network through backpropagation

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In the quest for a quantum neural network, quantum systems have been utilized either through parameterized quantum circuits or analog quantum reservoirs. The latter can be implemented on qubit ensembles or bosonic systems, which offer a larger Hilbert space for feature embedding. However, QRC is limited by the fact that training occurs after measurement, thus requiring a large number of observables to be measured and ultimately reducing its expressivity. In this work, we propose a method for training complex drive and interaction parameters directly within an analog bosonic quantum system. Our results show that these parameters can be optimized via backpropagation, reducing the number of observables to measure compared to QRC. Furthermore, we demonstrate that a trained system can learn tasks of increasing complexity, with data encoding in entanglement drives proving to be the most efficient. We introduce a technique for encoding higher-dimensional data and show that using local variables in the loss function, rather than global ones, accelerates training convergence, likely due to the mitigation of barren plateaus.

Capacities of quantum Markovian noise for large times

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In this paper[1], we examine the capacities of quantum Markovian noise models to understand the limits of information storage over arbitrarily long periods. We specifically investigate how much classical or quantum information can be reliably stored within a system that is subject to Markovian noise, focusing on the infinite-time limit. Unlike the conventional fixed-time setting, we establish that, in the infinite-time regime, both the classical and quantum capacities can be effectively characterized by the properties of the peripheral spectrum of the quantum channel, which are efficiently computable.

Our analysis reveals that the classical and quantum capacities exhibit additivity when subjected to the tensor product of channels. This result implies that the one-shot capacity, which considers a single use of the channel, is equivalent to the asymptotic i.i.d. capacity, where multiple independent uses of the channel are considered over time. This additivity simplifies the understanding of information transfer in quantum systems in the infinite-time context.

Additionally, we present an improved algorithm for computing the structure of the peripheral subspace of a quantum channel. This advancement has practical implications, as it offers a more efficient means of determining the infinite-time capacities of noisy quantum channels compared to previous methods. Our findings contribute to a deeper understanding of long-term information storage and retrieval in quantum systems and offer insights into the potential development of more robust quantum memories and error correction strategies.

[1] Omar Fawzi, Mizanur Rahaman, and Mostafa Taheri. Capacities of quantum markovian noise for large times. arXiv preprint arXiv :2408.00116, 2024.

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Memory-Assisted Quantum Computing with Rare-Earth ion-doped Crystals

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We investigate a potential paradigm change by means of a memory-assisted quantum computation scheme, which has been shown to reduce the amount of physical qubits needed by several orders of magnitude [1]. This scheme demands a suitable quantum processor and an efficient and long-lived multimode quantum memory. To this end, we assess the capabilities of rare-earth ion-doped crystals. This choice is motivated by the complexity of the memory-assisted QC scheme relying mainly on high-quality quantum information storage, where rare-earth ion-doped crystals have already proven to represent state-of-the-art : they have shown promising capabilities as both efficient and long-lived ensemble memories [2–4]. Furthermore, they are the natural choice for the processor qubits as well, in order to optimise their coupling with the memory.

In particular, we study a suitable protocol to implement a high-fidelity universal set of gates. We analyse the performance of a two-color excitation single-qubit gate and blockade two-qubit gates by means of the dipole-dipole interaction of the individual ions [5], including the corresponding modelling and estimation of errors. We also simulate and subsequently optimise the readout processes [6]. We comparatively study the performance of different rare-earth qubits to be able to choose the best candidate material. We conclude that $Eu^{3+}:Y_2SiO_5$ stands out as a perfect candidate both for processing, storage and readout using a single rare-earth ion species. We believe these results can bring fault tolerant QC closer to realisation.

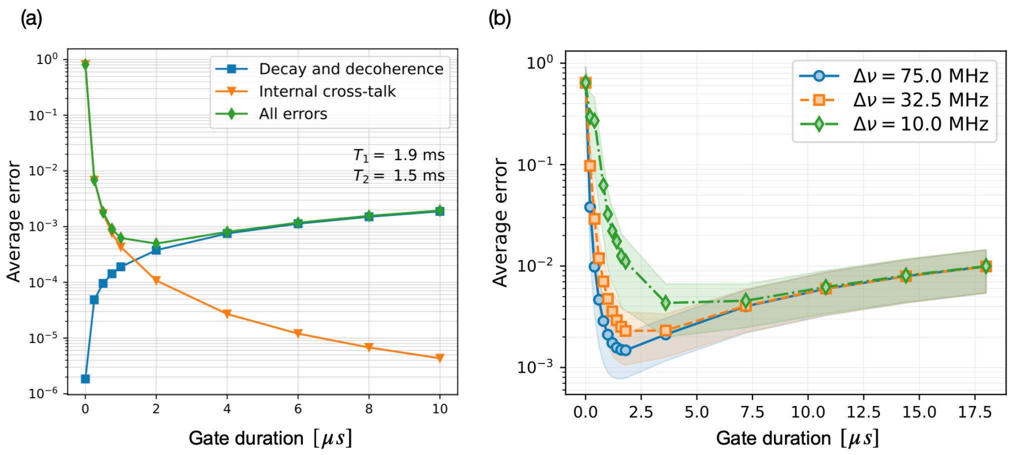

FIGURE 1. Average gate error versus total gate duration. We model two main errors : decay and decoherence, specified by the measured T_1 and T_2 times in $Eu^{3+}:Y_2SiO_5$ [7], and internal cross-talk between neighboring energy levels in the ion. (a) Average error over six single-qubit gates belonging to the Clifford group, performed over six different initial states. (b) Average error of a CNOT gate performed over the same six initial states, including decay and decoherence and internal cross-talk error, for different energy shifts $\Delta\nu$ induced through dipole-dipole interaction.

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Posters 1, 13/11/2024: Quantum Sensing & Metrology (QMET)

Quantum sensing and control with organic molecules

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Developing controlled quantum systems as local probes for their environment and research platforms for fundamental physics is a topic of prime interest. In that regard, organic molecules, such as dibenzoterrylene embedded in a molecular matrix, are an easy-to-produce and highly sensitive quantum system that can be isolated, providing lifetime-limited linewidth at liquid helium temperature in the wavelength-range from the visible to the near-infrared [1].

First, this system couples to the phonons of the environment. We show that the broadening of the zero-phonon line through the interaction with phonons offers a non-invasive probe for temperatures in the range of three to a few tens of Kelvins [2]. Furthermore, this sensitivity to the hardly-explored local phononic environment could enable the use of organic molecules as a transducer for optomechanical experiments.

Second, these molecules are sensitive to electric fields, displaying a shift of their main emission line due to the Stark effect. This well-known property can be used to tune the molecule through laser-induced long-lived charge state in the matrix [3]. Applying an external electrical field we could shed light on the microscopic charge distribution within the crystal and demonstrate control over the spectral diffusion of the zero-phonon line [4]. This suppression by a factor of 12 of the spectral diffusion of tuned molecular systems with respect to traditional tuning methods is a promising advancement towards molecule-based single-photon sources.

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Towards single-quanta detection of surface acoustic wave phonons

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The single photon “click” detector (SPD) is an essential component in experimental quantum optics, serving as a way to measure the arrival time of a photon with high resolution. Many familiar SPD technologies, such as the avalanche photodiode or superconducting nanowire SPD, rely on material properties that make them best suited for photonic platforms with energy scales at or above infrared frequencies. Microwave quantum platforms, including certain spin systems, superconducting qubits, and quantum acoustics, operate at energy scales several orders of magnitude lower and thus do not benefit from integration with these technologies. We are implementing a single microwave photon detector (SMPD) based on dissipation engineering [1, 2] that is coupled to a surface acoustic wave channel using flip-chip integration, thus aiming for a single microwave acoustic *phonon* detector. The detector will use a parametric microwave-frequency pump tone to irreversibly convert an incoming phonon into a qubit excitation, which can then be measured using standard dispersive readout. We have characterized our implementation first as a *photon* detector, separated from the acoustic channel, and find a detection efficiency of 68.7% and a dark count rate of $5.10\ \mathrm{ms}^{-1}$, the former limited by the qubit T_1 and the latter by heating due to the parametric pump. Demonstration and characterization of a detector coupled to an acoustic channel is in progress. We aim to develop this device as a building block for experiments in linear mechanical quantum computing [3], for solid-state based quantum sensing of massive particles, as well as other condensed matter applications.

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Towards quantum microscopy of neuron electric signals

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Quantum sensors based on negatively charged Nitrogen-Vacancy (NV-) centers in diamond have been an emerging platform for sensing external electromagnetic fields, stress, and temperature. The sensing relies on the laser manipulation and optical detection of NV- electronic spin in its ground state, and it takes advantage of the few tens of microseconds long T_2 coherence duration. NV- in diamond has been widely applied to magnetometry in near-field and wide-field configurations, addressing questions not accessible to other methods. One promising application is the wide-field detection of neuron electrical activity, going beyond the proof of principle experiment of Barry *et al.* [1], which demonstrated the time-resolved detection with a photodiode, of action potentials (AP) from the giant axon of a marine worm. However, a detailed modeling of magnetic field associated to mammalian neurons AP predicts a magnetic field amplitude at the axon membrane of about 1 nT, lasting a few milliseconds [2]. Such a value is not detectable with the best wide-field NV-magnetometers, requiring to increase their sensitivity by a few orders of magnitude. Several groups currently explore refined pulsed sensing approaches (i.e. double quantum Ramsey interferometry) and high signal-to-noise array sensors to overcome the sensitivity limitation [3–5].

Here we consider an alternative approach for the detection of electrophysiological activity of neurons in a wide-field configuration with NV- centers in diamond, using electrometry instead of magnetometry. Following the proposal of Ref. [2], we use a dense diamond nanopillar array with NV- implanted at a depth of $\approx$100 nm. The nanopillar geometry ensures the perfect contact between the neurites and the diamond required to avoid $\boldsymbol{E}$-field screening by ions of the medium. Furthermore, the nanopillar arrays improve the optical collection efficiency. The peak-to-peak AP-associated electric field amplitude within one diamond nanopillar at 100 nm distance from its surface was predicted in Ref. [2] to be more than two orders of magnitude larger than the smallest detectable one as established by Dolde *et al.* [6].

In order to validate the electrometry wide-field sensing protocol, we use a diamond plate sensor doped volume with NV- centers. A key element of our setup is a pixel-wise lock-in array sensor capable of demodulation rate fast enough for time-resolved AP detection, and providing a large signal to noise ratio. We will show our ability to image Rabi oscillations and Hanh echoes T_2 coherence time all over the active diamond sensor part, and present how we will implement double quantum Ramsey to evaluate the sensitivity of our device using reference source of electric field. In parallel to the sensor development, we validated our ability to grow neurons derived from induced pluripotent stem cells.

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Photonic integration of diamond materials for quantum sensing applications with spin ensembles

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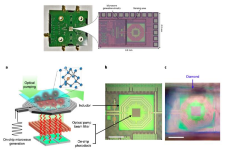
Nitrogen-Vacancy (NV) centers in diamond are rapidly gaining ground as some of the most versatile quantum sensors we have today. These tiny defects in diamond lattices can sense magnetic and electric fields, pressure, and even temperature, across a broad range of scales—from nanometers to millimeters. Their precision is unmatched ; for example, NV-based magnetometers are now being used to probe materials at the nanometer scale, providing an exciting new window into condensed matter research [1]. What sets NV sensors apart from other quantum technologies, like SQUIDs or atomic gas sensors, is their ability to operate at room temperature, all while being housed in the robust, solid-state diamond material. This makes them ideal candidates for a wide array of cutting-edge applications, from biomedical imaging to non-destructive industrial testing and autonomous navigation systems.

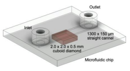
Yet despite the exciting potential, the road to commercializing NV-sensing technology remains challenging. While some impressive prototypes—such as endoscopic fiber sensors and C-MOS integrated devices—have been demonstrated, the ability to fully integrate high-performance NV centers into micro- and nano-scale devices is still evolving. Progress in the field of diamond photonics, including the development of nanostructures hosting individual NV spins, has been significant[2]. However, to push these sensors into mainstream use, especially for ensemble-based sensing, we need to improve diamond processing techniques to create low-loss, diamond-based optical structures on low-index substrates[3].

In this colloquium, we'll share updates from our ongoing research, including innovative projects like a diamond-based sensor for imaging neuronal activity (in collaboration with LuMIn labs) and an endoscopic fiber sensor designed for non-destructive testing (with Kwantek). We'll also dive into the latest results from the Institut FOTON, where we're applying cutting-edge clean-room technology to overcome these integration challenges, and charting the path to the next generation of quantum sensors.

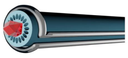
Existing devices



CMOS-Integrated sensor
From Kim et al. *Nature Electronics* **7**, 284-289 (2019)

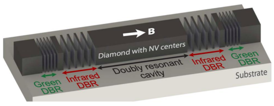


Microfluidic Chip with diamond materials
From Allert et al. *Lab Chip* **22,** 4831-4840 (2022)

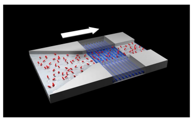


Fiber optic magnetometer
I. V. Fedotov et al. *Opt. Lett.* , **41**, 472-475 (2016)

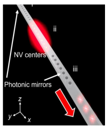
Proposed devices



Highly sensitive integrated magnetometer
From Gazzano et al. *Phy.Rev.*B 95, 115312 (2017)



Velocimeter for microfluidic channel
From Cohen et al., *Scientefic Reports* **10**, 5298 (2020)



Nanocavity based diamond magnetometer
Ryota Katsumi et al. *Japanese Journal of Applied Physics* 61, 082004 (2022)

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Magnetic imaging under high pressure with a spin-based sensor integrated in a van der Waals heterostructure

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Spin defects with optically detectable magnetic resonances in hexagonal boron nitride (hBN) are currently attracting a deep scientific interest for the deployment of quantum sensing technologies on a two-dimensional (2D) material platform [1]. Among several optically active spin defects recently discovered in hBN, the negatively-charged boron vacancy ($\mathrm{V_B^-}$) centre stands out due to its well-established atomic structure and ease of creation by various irradiation methods [2, 3]. This defect features a spin triplet ground state whose electron spin resonance (ESR) frequencies can be interrogated by optical means even in the limit of atomically-thin hBN layers [4], and strongly depends on external perturbations such as magnetic and electric fields, strain, and temperature [5, 6]. Such properties make the $\mathrm{V_B^-}$ center in hBN a promising candidate for the design of a flexible 2D quantum sensing unit, which could offer an ultimate atomic-scale proximity between the spin-based sensor and the probed sample.

Recent proof-of-concept experiments have shown that $\mathrm{V_B^-}$ centers can be integrated into van der Waals (vdW) heterostructures and used to image the magnetic field produced by 2D ferromagnets [7–9]. Interestingly, the properties of 2D magnets can be tuned by applying hydrostatic pressure. As an example, the magnetic order of $\mathrm{CrI_3}$ switches from an antiferromagnetic interlayer coupling to a ferromagnetic interlayer coupling for a pressure in the range of few GPa [10, 11]. In this work, we study the optical and spin properties of $\mathrm{V_B^-}$ centers in hBN under high pressure and we analyze their performances for magnetic imaging of pressure-induced phase transitions of 2D magnets. As an example, we analyze pressure-induced variations of the Curie temperature of $1T$-$\mathrm{CrTe_2}$, a layered ferromagnet with in-plane magnetic anisotropy. Our work highlights the potential of $\mathrm{V_B^-}$ centers in hBN for magnetic sensing and imaging in high pressure physics.

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Non-local wavefront shaping using entangled photons

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Wavefront shaping is a crucial technique in optics, traditionally used to correct aberrations and scattering that an optical beam may encounter along its propagation path [1][2]. In a conventional wavefront shaping architecture, the optical signal passes through the complex medium, and an aberration correction device - typically a spatial light modulator (SLM) - is positioned along the same optical path (Figure 1a).

One challenge of this approach is to properly integrate the SLM into the optical system to efficiently correct aberrations by developing suitable algorithms. To overcome this challenge, and also explore a new avenue in optical wavefront control, we developed a *non-local* wavefront shaping approach using entangled photons (Figure 1b).

The photon pairs are produced by Spontaneous Parametric Down Conversion, therefore exhibiting strong spatial correlations. In this method, one of the photon of the pair is sent through an aberrant or scattering medium, while its twin propagates through a SLM. By shaping the photon that hasn't interacted with the medium to mimic the scattering effects experienced by its pair, we demonstrate the restoration of strong correlations and entanglement between the pairs. This approach decouples the wavefront shaping from the system containing the aberrations, enabling the development of new correction algorithms that may surpass existing methods and opening up new possibilities for applications in communication and imaging.

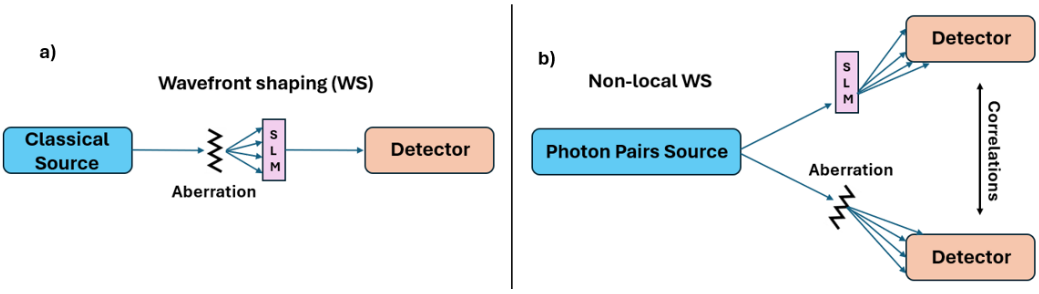

FIGURE 1. Simplified schemes of a **(a)** Classical AO configuration and a **(b)** non-local AO configuration.

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Matter-wave collimation to picokelvin energies with scattering length and potential shape control

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In atom interferometers, achieving long pulse separation times and minimizing contrast loss are critical for enhancing sensitivity. In this study [1, 2], we examine the influence of atomic interactions on collimation using a lensing protocol with a ^{39}K Bose-Einstein condensate at varying scattering lengths. By manipulating the interactions, we measure an expansion energy of (340 ± 12) pK in one direction. This value is confirmed by numerical simulations, which also predict a 2D ballistic expansion energy of (438 ± 77) pK. Based on these findings, we propose a protocol for achieving 3D expansion energies below 16 pK by introducing an additional pulsed delta-kick. This advanced scenario offers the potential for the realization of ensembles exceeding 1×10^5 atoms with 3D energies in the double-digit pK range in typical dipole trap setups, eliminating the need for a microgravity environment.

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Room temperature GeSn nanowire array SWIR photodetectors on Si

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GeSn semiconductors grown on a Si wafer offer a scalable material platform to engineer a variety of photonic devices (photodetectors, lasers, LEDs) operating in the short-wave infrared (SWIR : $1.5 - 3\mu m$) and beyond.[1] These GeSn devices are the essential building blocks to develop high-performance infrared sensing and imaging technologies using Si-compatible fabrication processes. The ability to incorporate Sn atoms in Ge at concentrations about one order of magnitude higher than the $1 at.\%$ equilibrium solubility is at the core of these emerging technologies. Importantly, texturing GeSn into nanowire (NW) arrays enhances SWIR optical absorption and results in tunable leaky-mode resonance peaks controlled by the NWs geometrical parameters.[2] Furthermore, structuring the device into NW arrays confines the electromagnetic field within the depletion region of the p-i-n junction, resulting in an increased signal to noise ratio compared to planar GeSn devices of the same size.

Herein, we discuss the structural and optoelectronic properties of GeSn NW arrays obtained from a $Ge_{0.9}Sn_{0.1}$ p-i-n heterostructure, using a directional Cl_2-based ICP-RIE etching technique. We fabricate NW-based SWIR photodetectors by embedding the NWs into a planarization layer and then depositing a top transparent contact. This device architecture enables room temperature operation in the $2\mu m$ band with enhanced performance compared to conventional planar GeSn technologies. The impact of NW geometry on device performance is assessed through a range of electrical and optical measurements. Optoelectronic characterization, via photocurrent measurements with a FTIR spectroscopy system, of the photodetectors is performed at room temperature to investigate the emergence of leaky-mode resonance in the NWs. FDTD simulations are conducted to optimize the NW geometry, aiming to maximize the device absorption and ensure the confinement of the resonant mode within the depletion region of the p-i-n junction.

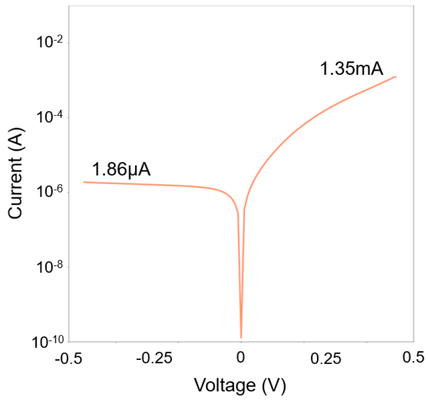

FIGURE 1 – I(V) curve of a device.

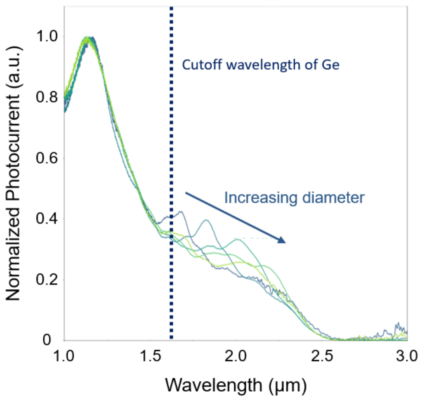

FIGURE 2 – Normalized photocurrent of devices with different nanowire diameters.

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Towards an integrated entangled photons source for mid-infrared ghost spectroscopy

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Quantum metrology for biological and chemical applications focuses on quantum photonics, as photons can penetrate aqueous environments without damaging delicate specimens, enabling precise chemical analysis with minimal disruption [1]. Quantum integrated photonics platforms, offering stability, accuracy, and compact designs, further enhance this potential. We aim to develop an integrated quantum source for mid-infrared (MIR) spectroscopy, using telecom components to identify chemicals via their spectral fingerprints. Quantum entanglement allows the transfer of infrared information to the telecom range, overcoming current MIR limitations. Specifically, the probability of detecting a signal photon from a nonlinear crystal can be expressed as [2] :

$$I_s \propto \Big(1 + |r_i||\tau_i||\mu(\Delta t)|\cos(\phi_s + \phi_i - \phi_p)\Big) \tag{1}$$

Here, μ_i and τ_i represent the reflectivity and transmittance at the idler photons' wavelength, respectively, while ϕ_s, ϕ_i, and ϕ_p are the phases acquired by the signal, idler, and pump photons. Eq. 1 shows that the interference pattern of the signal photons depends on the phase shifts and losses experienced by the idler photons. Consequently, the sample's properties at the idler photons' wavelength can be inferred by measuring the interference pattern of the signal photons, without the need for direct detection of the idler photons.

The preliminary step involves demonstrating a spectrum in both spectral domains. To achieve this, we set up the experimental apparatus depicted in Fig.1. We demonstrate a nonlinear process known as differential frequency generation (DFG) by pumping a nonlinear crystal which is phase-matched for 900 nm $\rightarrow$ 1560 nm + 2127 nm. We first proceed with parametric amplification to generate a 2127 nm spectrum from a 900 nm pump and a 1560 nm signal (Fig.2).

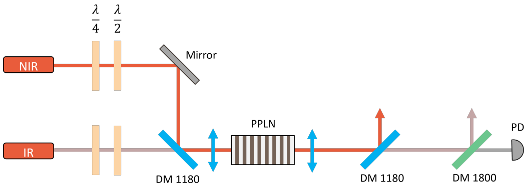

FIGURE 1 – Experimental setup for DFG caracterization. A series of dïchroic mirrors (DM) are used to separate each wavelength at the output of the cristal.

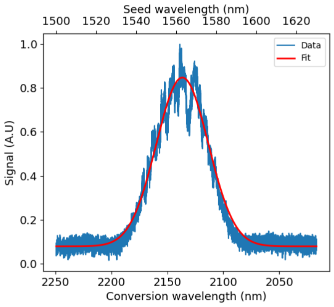

FIGURE 2 – Experimental setup for DFG caracterization. A series of dïchroic mirrors (DM) are used to separate each wavelength at the output of the cristal.

By energy conservation, the corresponding part of the spectrum lies in the telecom band. After this preliminary characterization, the next phase of the experiment will involve implementing a nonlinear interferometer in a folded configuration to ensure identical emission spectra from both crystal passes. The challenge will be in managing the different wavelengths while ensuring the indistinguishability of the two probability amplitudes, in both the forward and return paths. Ultimately, we will measure phase variations introduced in the MIR arm by detecting the telecom photons.

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Impact of Raman Beam Wavefront on the Accuracy of an Atomic Gravimeter

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The cold atom gravimeter of LNE-SYRTE is an atom interferometer, based on a $\pi/2 - \pi - \pi/2$ sequence of Raman transitions separated by a free evolution time T. These pulses successively split, redirect and recombine ^{87}Rb atoms into a superposition of $\left|5S_{1/2}, F=1, \vec{p}\right\rangle$ and $\left|5S_{1/2}, F=2, \vec{p}+\hbar\vec{k}_{\text{eff}}\right\rangle$ states, with $\vec{k}_{\text{eff}} = \vec{k}_1 - \vec{k}_2$ the difference between the two laser beam wavevectors. During each light-matter interaction, the phase ϕ_i of the light field is imprinted on the atomic wavepacket. For free-falling atoms in the gravity field g and Raman counter-propagating laser fields aligned along the vertical axis with a linear sweep α of their angular frequency difference, the interferometer phase is given by

$$\Delta\phi = \phi_1 - 2\phi_2 + \phi_3 = (k_{\text{eff}} g - \alpha)\, T^2 + \Delta\varphi,$$

with $\Delta\varphi$ the interferometer phase shift relative to the ideal case. Thanks to a sequence of four measurements, most systematic shifts are eliminated, the remaining effects being the Coriolis phase shift, which can be evaluated by rotating the gravimeter of 180° or suppressed by compensating the Earth rotation, and the one resulting from wavefront aberrations, in particular those induced by imperfections of the retro-reflecting optics [1]. The accuracy of the LNE-SYRTE cold atom gravimeter is therefore limited by an uncertainty of the order of 10^{-8} m s^{-2}.

To assess the contribution of wavefront aberrations to the interferometer phase, experimental approaches have involved making measurements while modifying the parameters of the atomic cloud or laser beam, and fitting the measurements with numerical simulation, see [2] for example. However, these simulations are generally carried out with two approximations. Firstly, wavefront aberrations are represented by low-order Zernike polynomials, as these are the ones commonly used in surface analyzers such as the Fizeau interferometer or the Shack-Hartmann wavefront sensor, which generally correspond to aberrations whose typical variation length is greater than the size of the atomic cloud. Secondly, the evolution of aberrations during laser beam propagation is not taken into account, so that the aberrated wavefronts at the position of the three pulses are identical. As this second approximation is valid for aberrations with low spatial frequencies, non-negligible corrections are brought when the product of the propagation length and the wavelength are of the order of the characteristic size of the aberrations.

Using both an arbitrary mirror surface described by Zernike polynomials and raw data from a Fizeau interferometer analysis of a commercially available mirror surface, we demonstrate that simulations based on the two aforementioned approximations lead to errors of the order of 10^{-8} m s^{-2} in the gravimeter simulation. Furthermore, the typical shifts obtained through the simulations are in agreement both with the variation of the order of 10^{-8} m s^{-2} experimentally observed [1, 2] and with the gradient of the gravity bias with respect to the fluctuation of the initial position of the atomic cloud, which is of the order of 10^{-8} m s^{-2} mm^{-1} [1].

Thanks to these simulations and their future comparisons with the experiment, we hope to be able to improve the characterization of the LNE-SYRTE cold atom gravimeter and determine the needed correction. More generally, the evaluation of wavefront aberrations will also be necessary to achieve better accuracy and complement the error budget of other atom interferometry inertial sensors, such as the ones embarked in space missions, which target beyond state-of-the-art performances.

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Scanning NV thermometry

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Scanning NV center microscopy relies on a single nitrogen-vacancy (NV) defect in diamond, which exhibits an electronic spin resonance (ESR) that can be optically detected [1]. The ESR frequency is highly sensitive to external perturbations, making NV centers powerful quantum sensors. Scanning-NV microscopy is already used as an efficient magnetometer with a sensitivity of $\eta_\mathrm{B} \approx 1\ \mu\mathrm{T}/\sqrt{\mathrm{Hz}}$ and a spatial resolution of approximately 50 nm. Its functionalities can be extended to temperature measurements by exploiting the temperature dependence of the ESR frequency [2]. A possible application of scanning NV thermometry is the detection of hot spots in microelectronics, which can degrade device performances. In this work, we show how to simultaneously map the Joule heating and the Oersted field generated by an electrical current flowing through a semiconductor nanowire with a scanning NV center microscope.

We first show that scanning-NV thermometry reaches a thermal sensitivity of $\eta_\mathrm{T} \approx 600\ \mathrm{mK}/\sqrt{\mathrm{Hz}}$. We then discuss the impact of a bias magnetic field on the temperature measurement. We show that the component of the magnetic field perpendicular to the NV's quantization axis competes with the effect of the temperature on the position of the ESR frequency, making quantitative temperature measurements challenging. To illustrate this, we explain how we can obtain accurate magnetic field and temperature maps of a semiconductor nanowire carrying an electrical current despite the presence of a misaligned field during the measurements. Finally, we propose solutions to improve the overall performances of scanning NV thermometry through the design of optimized diamond probes [3].

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Leveraging Space-Time Couplings in Ultrafast Pulses to Obtain Sub-Diffraction Limited Imaging: Optical Resonance Imaging

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Optical sub-diffraction limited imaging is currently limited to micro-millisecond timescales for temporal resolution. Optical Resonance Imaging (ORI) [1] will allow femtosecond resolution below the diffraction limit by exploiting pulse front tilt to couple pulse arrival time to the lateral spatial coordinate of the sample plane, analogous to the coupling between spatial coordinate and Larmore precession frequency in MRI. This technique enables high-precision time resolution and simultaneous sub-diffraction limited spatial resolution. ORI offers a vacuum-free, all-optical, wide-field spatially resolved technique with a temporal resolution at or below the relevant time-scales for ultrafast energy flow processes. As a technique, ORI enables the direct experimental observation of nanoscale, ultrafast energy flow for a wide range of samples. Here, I will present current progress on the design and commissioning of the first ORI spectrometer.

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Cascaded single microwave photon detector

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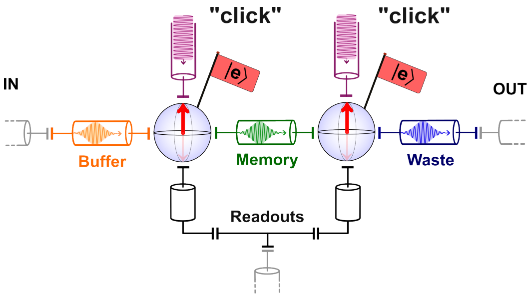
Detecting single photons in the optical frequency band is a well-established practice; however, this capability is just emergent at microwave frequencies. Single microwave photon detectors (SMPDs) are instrumental for efficiently detecting weak signals from incoherent emitters, with applications in axion searches [1], hybrid quantum systems [3], and superconducting quantum computing [4]. At microwave frequencies, SMPDs rely on superconducting qubits to encode the presence or absence of an itinerant photon [5–7]. Such quantum interaction provide a quantum non-demolition (QND) measurement of the photon state, in constrast with absorptive optical Single Photon detectors (SPDs). In this work, we leverage the QND nature of this interaction to repeatedly measure the photon state in a cascaded manner [2]. By encoding the information on multiple qubits, we mitigate the intrinsic local noise of individual qubits, achieving a two-order-of-magnitude reduction in intrinsic detector noise at the cost of a slight reduction in efficiency. The photon detector concatenates two four wave mixing process coherently on a single chip. This scheme ensures fully quantum coherent dynamic of photon detection, enabling dynamical tuning of the detector's bandwidth — a critical feature for practical use in setups affected by thermal photons.

We show how to balance the strengths of the parametric processes to maximize sensitivity and evaluate the core metrics of such a device. We demonstrate a sensitivity of $(5.9\pm0.6)\times10^{-23}$ W/$\sqrt{\text{Hz}}$ at 8.798 GHz, with the detector noise entirely dominated by the thermal noise of the input resonator. The bandwidth tunability is 100 kHz. Current limitations are discussed.



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Recovery of Two-Photon Interference Visibility in Imperfect Mach Zehnder Interferometers

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Quantum metrology stands out as one of the most promising fields of experimental study, aiming to demonstrate the advantages associated with the utilization of non classical states of light. These advantages manifest in achieving supersensitive measurements, beyond the Standard Quantum Limit, and super resolution. For this purpose, the use of perfectly entangled states, such as N00N states, has been extensively explored in recent decades [1]. However, supersensitivity is vulnerable to experimental imperfections, such as absorption or unbalanced interferometric systems [2]. Indeed, an imbalance in losses due to the measurement arm of the Mach Zehnder interferometer leads to a reduction in the visibility of two-photon interferences and therefore to the device sensitivity.

Here we present a theoretical and experimental study on compensating for these relative losses by appropriately adjusting the coupling ratio of the first beam splitter. We demonstrate that in the case of non-zero relative losses, i.e., an interferometer with imbalanced losses, the maximum visibility does not correspond to the case of a balanced beam splitter. In the case of a photon pair entering the MZI by the same mode, the coincidence probability can be expressed as :

$$P_{11}(\varphi) = \left((1-P)^2R_1^2 + (1-R_1)^2\right)\left[1 + \frac{2(1-P)(1-R_1)R_1}{(1-P)^2R_1^2 + (1-R_1)^2}\cos(2\varphi)\right], \tag{1}$$

where R_1 and P correspond to the first beam splitter reflectivity and the relative losses.

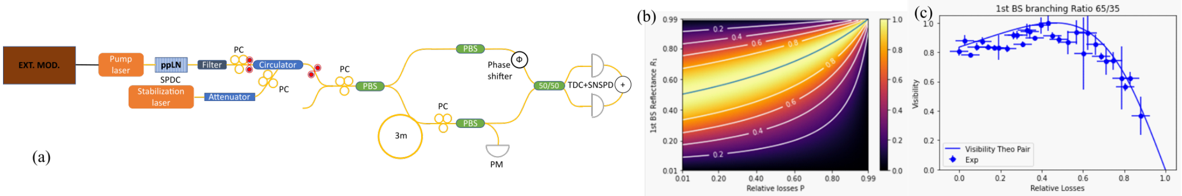

FIGURE 1. (a) Experimental scheme of our MZI with unbalanced beam splitters and linear losses in each arms. The acronyms are PBS : polarizing beam splitter, WDM : Wavelength Demultiplexer, TDC : Time to Digital Converter, PC : Polarization control. (b) Visibility as function of the relative losses and the first beam splitter branching ratio. (c) Experimental two photon visibility versus theoretical visibility obtained from equation (1)

From equation (1), we show that for a given value of the relative losses, a perfect two photon fringes visibility (V=1) can be recovered by adjusting the coupling ratio of the first beam splitter (Fig.1(b)). We then study experimentally the MZI resilience using an unbalanced interferometer (Fig.1.(a) in which photon pairs are injected in the same mode. We confirm that the maximum of visibility can indeed be recovered by unbalancing the relative losses (Fig.1.(c)), which is equivalent to counter the relative losses by unbalancing the first beam splitter branching ratio.

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Characterization of ultrafast charge-state switching dynamics in NV centers of diamond

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The negatively charged nitrogen-vacancy (NV^-) center in diamond has been established as a promising platform for quantum sensing due to its spin-dependent photoluminescence at room temperature. However, improving the sensitivity of these techniques requires a deeper understanding of the processes driving charge state conversion between NV^- and the neutral charge state (NV^0). This study investigates the ultrafast dynamics of photoluminescence and infrared (IR) absorption, and their dependence on IR fluence. Using pump-probe and time-resolved photoluminescence techniques with joint excitation at 515 nm and 1030 nm, and a temporal resolution on the order of hundreds of femtoseconds, we observe a significant IR-induced enhancement of the NV^- population. Our results also reveal the presence of an IR power threshold reversing the direction of the charge state conversion dynamics. Additionally, the time-resolved photoluminescence method proves to be a promising approach for investigating the photophysics of NV centers, and these findings open new pathways for optimizing high-precision quantum sensing applications.

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Posters 2, 04/11:
Quantum Communications (QCOM)

A Linear Algebraic Framework for Dynamic Scheduling Over Memory-Equipped Quantum Networks

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Quantum Internetworking is a recent field that promises numerous interesting applications, many of which require the distribution of entanglement between arbitrary pairs of users. This work deals with the problem of scheduling in an arbitrary entanglement swapping quantum network — often called first generation quantum network — in its general topology, multicommodity, loss-aware formulation. We introduce a linear algebraic framework that exploits quantum memory through the creation of intermediate entangled links. The framework is then employed to apply Lyapunov Drift Minimization (a standard technique in classical network science) to mathematically derive a natural class of scheduling policies for quantum networks minimizing the square norm of the user demand backlog. Moreover, an additional class of Max-Weight inspired policies is proposed and benchmarked, reducing significantly the computation cost at the price of a slight performance degradation. The policies are compared in terms of information availability, localization and overall network performance through an ad-hoc simulator that admits user-provided network topologies and scheduling policies in order to showcase the potential application of the provided tools to quantum network design.

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A QKD-oriented tuning toolbox for photon number statistics with semiconductor quantum dots

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Single-photon sources are a resource of key importance for enabling technologies such as quantum computing and quantum communications [1]. Among them, quantum cryptography appears to be one of the most prominent. For this application, brightness and purity of the source are fundamental parameters to take into account. While high brightness allows to maintain high rate over a long distance, high purity ensures security by preventing any eavesdropper to retrieve information without introducing errors. Gathering these demanding performances in one device has been at the heart of fabrication research for decades, but semiconductor quantum dots (QD) proved to be promising during the last years [2, 3].

We introduce a method to tune the purity of a single-photon stream to optimize the performances of a Quantum Key Distribution (QKD) protocol with semiconductor quantum dot sources. We produce single photons by exciting a charged quantum dot embedded in a micropillar cavity off-resonantly. This phonon-assisted excitation scheme enables to reject the laser with a set of three narrow bandpass filters [4]. The single photons are then horizontally polarized to encode the information. After passing through a programmable attenuator, they are measured in two orthogonal bases with a polarization analyzer. By doing so, we are able to measure the relevant parameters in assessing performances of QKD, namely the count rate, the single-photon purity and the quantum bit error rate (QBER).

In this setup, we mounted filters on motorized stages to control their tilt angle in a precise and reproducible manner. Adding this feature is allowing us to let some of the excitation laser pass, at the price of a worse purity. This additional, and previously unexplored, tuning feature enables us to find the optimal trade-off between achievable purity and count rate to maximize the Secret Key Rate (SKR). Moreover, we can also send only laser light into the apparatus to characterize the quantum channel.

Depending on the optical link's length, two main functionning regimes arise from our capability to tune the purity. When emulating short distances, the main contribution to the SKR is the count rate. Yet, for longer distances, reaching the best possible SKR requires the purest single photons.

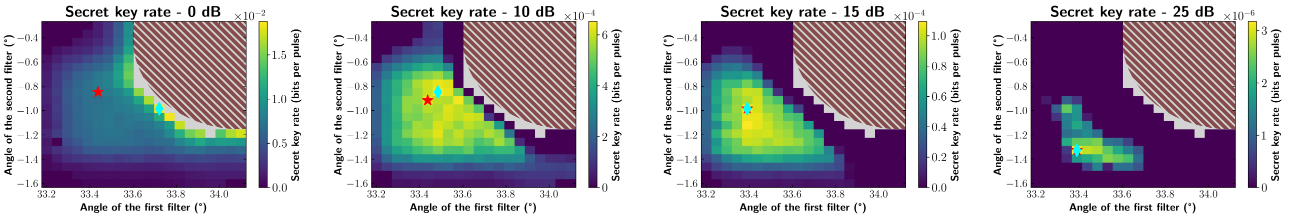

FIGURE 1. Scans of the secret key rate as a function of the filters' angles for different attenuations. The global optimal secret key rate is marked with a blue diamond, and the optimal point within the single photon regime ($g^{(2)}(0) \leqslant 5\%$) is marked with a red star. The hatched area indicates an absence of data due to the saturation of the detectors.

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Certifying high dimensional quantum entanglement with a time-stamping camera

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High-dimensional entanglement is a promising resource for quantum technologies [1],[2]. Being able to certify it for any quantum state is essential. However, to date, experimental entanglement certification methods are imperfect and leave some loopholes open, due to the necessity of accidentals subtraction [3],[4]. We present here experimental results showing that high dimensional entanglement certification can be obtained without accidentals subtraction and with relatively short acquisitions (16 seconds) by making use of a single-photon-sensitive time-stamping Tpx3Cam camera. More precisely, we measure position-momentum Einstein-Podolsky-Rosen (EPR) [5] correlations in pairs of photons generated by Spontaneous Parametric Down Conversion (SPDC) by collecting all spatial output modes simultaneously. In this preliminary setup we obtain an EPR factor of 0.13 < 1/2, which allows us to certify entanglement.

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Coexistence of Counter-Propagating Quantum and Classical Signals through Time-Multiplexing

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Quantum Key Distribution (QKD) is a cryptographic technology that enables the secure transmission of cryptographic keys, with security based on the principles of quantum mechanics rather than computational assumptions. We are currently at a critical juncture in the development of global quantum networks, and many countries are building infrastructure compatible with quantum technologies in anticipation of future cyber threats [1] [2].The preferred medium for transporting quantum information is optical fibers. For economic reasons, it can be advantageous to integrate quantum communications into optical fibers already used by classical traffic. However, this coexistence leads to the presence of noise generated by classical power levels, with Raman backscattering noise being the most significant, which can heavily impact quantum communications [3]. Managing this noise is therefore crucial to ensuring the reliability of quantum networks, and several mitigation strategies have been developed. The first approach was to place the quantum signal in the O-band, minimizing Raman noise but increasing quantum signal losses [4] [5]. Alternatively, placing the quantum signal in the C-band often necessitates the use of narrow spectral filters [6], temporal filters [7], or optimized allocation of quantum channels [8], in addition to reduce the classical signal power. Specialized fibers, such as multicore fibers [9] or hollow-core fibers [10], show promise in significantly reducing noise but introduce new challenges related to manufacturing and deployment costs. Our proposal consists of applying time division multiplexing (TDM), previously studied in the context of co-propagation in [11], to minimize the effects of Raman backscattering. Specifically, we propose the insertion of an empty classical frame, allowing the quantum signal to be received in counter-propagation without impairment from classical signals. We developed a simple model based on dispersion to describe backscattering Raman noise in the temporal domain, and we applied it to the BB84 protocol to evaluate the performance of our scheme. For simplicity, we consider that classical and quantum frames have the same duration of 500 µs. Finally, we compared our proposal to the two main coexistence strategies : the first involves placing the quantum signal in the O-band, and the second involves using a narrow spectral filter in the C-band. We considered the same classical channels (wavelength and power) and a standard APD detector (η = 20% and $p_{dc} = 10^{-5}$). Our results demonstrate that our proposed scheme can be effectively applied over longer distances compared to common coexistence strategies. In particular, the counter-propagating TDM strategy outperforms the O-band quantum signal approach beyond 40 km and the C-band quantum signal approach with a narrowband filter beyond 26 km, with TDM potentially reaching distances greater than 120 km. In conclusion, we believe that such an approach will be beneficial in the context of quantum communication network deployment within existing infrastructure and could contribute to the development of cost-effective and scalable quantum networks.

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Crystalline waveguides for highly efficient integrated quantum memories

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Rare-earth (RE) doped crystals are a promising platform for quantum memories : at cryogenic temperatures they feature narrow optical transitions, long hyperfine coherence time [1], while maintaining very large inhomogeneous absorption lines, allowing for higher degrees of multiplexing. Current storage experiments in bulk RE doped crystal display limited efficiency for long storage time due to low absorption [2] and poor light-matter interaction strength due to free space beam divergence, especially when optically long samples are needed. Waveguides in RE doped crystals appear as a good solution to enhance memory performances : the optical Rabi frequency remains constant in the material, and the interaction length can be extended to match the desired absorption depth [3] to reach maximum efficiency, together with an improved scalability [4]. For this reason, many techniques for fabricating integrated quantum memories in RE ensemble have been investigated. Most of them either show poorer spectroscopic performances [5] or can't allow for complex functions [6] such as couplers, curvatures or cavities.

Here we present the fabrication of single-crystalline Y2SiO5 waveguides. Those structures are made from bulk crystals and should be able preserve the bulk properties. We describe our recent progresses on different steps of the fabrication process including recent results on crystal bonding, YSO layer thinning down to micrometric thicknesses and dry-etching of YSO [7]. Simulations have been performed to determine the geometry and dimensions of the waveguide's structure. Cryogenic fiber coupling is verified and erbium spectroscopy at low temperature in crystalline waveguides is under progress. A preliminary quantitative study of the advantages of waveguides over bulk crystal for the Atomic Frequency Comb (AFC) protocol will also be presented.

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Deterministic nanostructuring of tapered optical nanofibers towards high coupling efficiency integrated single-photon sources

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Tapered optical nanofibers (TONFs) are a widely used platform in applications ranging from sensing to quantum optics. By appropriately designing their profile, the so-called "adiabatic transmission regime" is achieved, whereby most of the energy injected at one end of the TONF is transferred to an evanescent field strongly confined around its surface and then up to 99% of light is transmitted to the other end with negligible losses. Due to this property, efficient interaction with solid-state single-photon emitters deposited on the TONF's surface can be promoted. Despite these premises, the collection efficiency of such systems is limited to around 20% to 30% [1]. For this reason, several top-down nanofabrication strategies have been developed to enable radiative pattern redirection of quantum emitters, e.g., milling from focused ion beam of Ga [2] or He [3], but also from femtosecond laser beam [4]. They require patterning of extensive sections of the fiber and are sensitive to small fabrication inaccuracies. In the case of ion beam milling, ion implantation also modifies the properties of the fiber, introducing further loss channels that lower the system's efficiency. Here, we present a bottom-up fabrication technique based on Electron Beam Induced Deposition that enables the deterministic deposition of nanostructures directly onto the nanofiber surface. We simulated a simple pattern consisting of a small number of dielectric pillars grown on the nanofiber surface, that has been shown to improve the collection efficiency up to 60%. This requires extensive control over the geometry and the refractive index of the pillars. Here we first demonstrate how the refractive index of deposited structures can be controlled by acting on fabrication parameters. Then we demonstrate the fabrication of arrays according to the design simulated in Figure 1.A (Figure 1.B). The developed technique, combined with advanced quantum emitters deposition techniques, such as AFM pick-and-place, holds the promise to realize highly efficient single-photon sources and, by exploiting TONF's features, easily integrable into complex optical fiber networks.

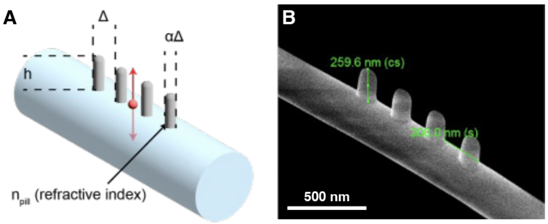

FIGURE 1. A) Sketch and B) SEM micrograph of a dielectric nanopillar array fabricated on a TONF.

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Dual wavelength Sagnac source of entanglement and polarization stabilization device for space and ground quantum communication applications

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In the field of secure communication, classical encryption techniques rely on complex mathematical algorithms which are being threatened by the rise of quantum computers. In this context, new encryption techniques are being developed to maintain confidentiality and security in modern day communications. One of these solutions is Quantum Key Distribution (QKD), which allows two parties to share encryption keys with unprecedented levels of security. Over the last few years, the feasibility of QKD has been widely proven at a metropolitan scale but connecting different metropolitan QKD networks remains a challenge[1] because of the losses in optical fibers. Moreover, the quantum nature of the QKD signals makes it impossible to use amplifiers and quantum repeaters are still in an experimental stage of development. Another solution is to create free space QKD segments between metropolitan networks and satellites. The first layout for this promising solution was realized with the decoy state protocol in 2018[2], shortly before an entanglement based protocol was proved to be feasible for a spatial link in 2020[3]. In this work, we present a bi-color entangled photon source compatible with existing fiber communication networks (at telecom wavelength) and with astronomical tools, which are highly developed and efficient at visible wavelength. This source bridges the gap between fiber network and free space link and offers two degrees of encoding : polarization and energy-time.

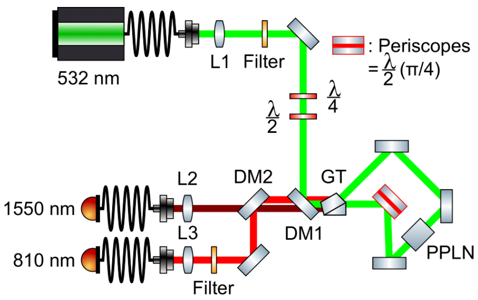

FIGURE 1. Schematic of the source : half-waveplate ($\frac{\lambda}{2}$), dichroic mirror (DM1/DM2), Glan-Thompson polarizer (GT), periodically poled lithium niobate (PPLN).

In Figure 1, the source design is composed of : a high coherence continuous-wave laser (at 532nm) pumping a PPLN crystal nested inside a Sagnac loop, allowing for the generation of horizontally polarized photon pairs in the clockwise path and vertically polarized photon pairs at 810nm and 1550nm in the counterclockwise path. We managed to obtain a coupling efficiency above 60% for both wavelength and a brighness of $2.0 \cdot 10^2$ pairs.s^{-1}.mW^{-1}.GHz^{-1}. Energy-time and polarisation entanglement have been qualified using a Franson experiment and a state tomography, respectively. Two-photon interference fringes (energy-time) have been measured with a raw visibility of 98%, and the polarization state tomography led to a purity of 98,1% and a fidelity of 99%, making the source an ideal candidate for QKD applications. For the real field distribution of entanglement, a calibration and stabilisation technique of time and polarization was developed to compensate for transformations happening during the propagation in a fiber or in free space.

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Entanglement Swapping in Orbit : a Satellite Quantum Link Case Study

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Satellite quantum communication is a promising way to build long distance quantum links, making it an essential complement to optical fiber for quantum internetworking beyond metropolitan scales. A satellite point to point optical link differs from the more common fiber links in many ways, both quantitative (higher latency, strong losses) and qualitative (nonconstant parameter values during satellite passage, intermittency of the link, impossibility to set repeaters between the satellite and the ground station). We study here the performance of a quantum link between two ground stations, using a quantum-memory-equipped satellite as a quantum repeater. In contrast with quantum key distribution satellite links, the number of available quantum memory slots m, together with the unavoidable round-trip communication latency t of at least a few milliseconds, severely reduces the effective average repetition rate to m/t — at most a few kilohertz for foreseeable quantum memories. Our study uses two approaches, which validate each other : 1) a simple analytical model of the effective rate of the quantum link ; 2) an event-based simulation using the open source Quantum Internet Simulation Package (QuISP). The important differences between satellite and fiber links led us to modify QuISP itself. This work paves the way to the study of hybrid satellite- and fiber-based quantum repeater networks interconnecting different metropolitan areas.

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Experimental Implementation of Quantum Oblivious Transfer from One-Way Functions

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Secure multiparty computation (SMPC) is a cryptographic protocol that allows the communicating parties to compute the result of a given function without disclosing their input parameters. It has been shown that SMPC [1] can be based on the oblivious transfer (OT) functionality. In OT, Alice has two messages $\{m_0, m_1\}$ while Bob has a choice bit $b \leftarrow \{0, 1\}$. At the end of the interaction, Bob retrieves only m_b and Alice has no information on b [2]. As shown in [3], classically, one-way functions (OWF) do not imply OT. In the attempt of overcoming this limit, [4] proposed the first quantum OT (QOT) scheme, which exploited BB84 [5] and a bit commitment (BC) subroutine to guarantee security against a malicious receiver. Unfortunately, unconditional security for BC (and consequently for QOT) is prevented by [6, 7]. However, [8] proved the possibility of achieving computational security in a simulation-based framework by providing BC schemes with two properties : *extractability* and *equivocality*. For the first time, [9, 10] showed how to build computationally-secure BC schemes from OWF by leveraging quantum communication, hence obtaining computationally-secure QOT from OWF and surpassing the classical limit of [3]. Unfortunately, both [9] and [10] constructions are not noise tolerant and their resource consumption scales rapidly with the required security, making an experimental implementation unpractical. To solve these problems, we proposed a practical, noise-tolerant QOT protocol [11], based on *equivocal* and *relaxed-extractable* bit commitments and proven secure in a simulation-based framework. In our scheme, Alice and Bob exchange BB84 states bidirectionally over a quantum channel. Experimentally, we implement it by allowing the parties to send transmission and reception queries to the *Control Station* of a single polarization-based weak coherent pulse source, which prepares the qubits polarization states and measures them with a passive setup. The *Transmitter* uses an electro-optic amplitude modulator to carve ns-pulses in a $4\ mW$ continuous-wave laser at $1550\ nm$. Two variable optical attenuators are then used to simulate single-photon pulses and their polarization is changed via an electro-optic polarization modulator. The *Receiver* passively measures the states through two polarizing beam splitters, then the photons are detected with a superconducting nanowire single-photon detector (SNSPD), with a maximum detection rate of 10 MHz. The performance of our protocol has been assessed by comparing several figures of merit with BCKM21 benchmark. The number of queries to computationally-demanding functions – such as PRGs, hashes and RNGs – is a crucial aspect for determining the protocol execution time and memory consumption and has been reduced by seven orders of magnitude. However, the key factor has been identified in the total number of required BB84 states, as the major bottleneck is represented by the the SNSPD detection rate. In fact, while in BCKM21 the total number of states is given by $N_{BB84} \in \Omega(\lambda_{CK88}^2)$, our protocol only requires $N_{BB84} \in \Omega(\lambda_{CK88})$, allowing for a remarkable reduction of the qubits acquisition time, from 19 $days$ to 210 ms.

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Generation of time-frequency entanglement with an effective quantum dot-waveguide two-photon quadratic interaction

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Similarly to classical information-based technologies, quantum technologies require information to be carried by a physical unit. At the research forefront, several are being considered [1], such as superconductors or photons. Quantum information encoding with photons typically uses either discrete variables like photon polarization or continuous variables such as the field quadratures using the photon number statistical distribution. The latter offer a large continuous Hilbert space and more efficient deterministic mode entanglement compared to discrete variables [2]. However, quantum information with the field quadratures continuous variables is sensitive to photon losses [3] and require challenging non-Gaussian operations implementation. Single-photon time-frequency continuous variables [4] serve as a middle ground, encoding continuous variables in the single-photon subspace. This approach uses a formalism analogous to that of the field quadratures' while physically dealing with single photons. Nevertheless, like other photonic quantum information frameworks, two-photon entanglement - a key component to photonic quantum information - remains difficult. Two-photon entanglement can be achieved either probabilistic methods [5] using linear optics or deterministic methods [6] exploiting non-linear effects. The former employs post-selection and is unlikely to be a viable option in the near-future while the non-linear schemes are not yet efficient enough for scaling. Nonetheless, this work addresses two-photon entanglement using non-linearity with the aim of generating a highly efficient deterministic gate. In the single-photon time-frequency continuous variables framework, this operation, referred to as the non-linear frequency beam-splitter (NFBS), is quartic in bosonic operators [4], involving the destruction of two photons and the generation of two entangled ones. Such transformation is at the core of four-wave mixing or spontaneous parametric down-conversion (SPDC) which are perturbative and therefore inefficient and not scalable. We thus opted for an effective transformation to shape a separable two-photon distribution into an entangled one, in other words to effectively output the NFBS operation. To that end, we derived a microscopic model for an artificial atom quadratically coupled to a continuum of frequency modes, considering the biexctionic structure of a quantum dot embedded in a photonic crystal waveguide. In the line of the proposal [7], we then developed a photonic scattering input-output model demonstrating the effective implementation of the two-photon entanglement NFBS. The entanglement properties were further analyzed using the Schmidt decomposition for continuous variables. We finally studied the action of the effective NFBS on time-frequency grid states, that are expected to be crucial for time-frequency quantum metrology and communication protocols.

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Krames-Kronig detection in the quantum regime

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We investigate, in [1], the quantization of the Kramers-Kronig detection initially developed in classical coherent communications [2]. This detection technique begins by combining the state of interest of the field with a local oscillator into a beamsplitter. Direct detection is then performed on only one output making it fundamentally different from most used balanced detection schemes such as double homodyne detection and heterodyne detection [3]. Kramers-Kronig detection being a direct detection scheme based on signal processing might be more compact, less onerous and simpler to implement than traditional balanced detection schemes.

It has been shown in classical optics that intensity measurement in the case of spectrally engineered fields allows measuring digitally the phase of the signal. Knowing the phase and the intensity, we show that Kramers-Kronig detection reconstructs both quadratures of the field even in the quantum regime. Therefore Kramers-Kronig detection is a Gaussian measurement in the same way as the better known double homodyne detection and heterodyne detection. This detection scheme may be used in place of traditional balanced detection schemes in quantum protocols such as quantum sensing, quantum tomography, quantum random number generators and quantum key distribution for example.

We investigate in details what is the phase measured with Kramers-Kronig detection in the quantum regime for bosonic coherent states [4] and pure single mode and mixed states. This is the relative phase between the local oscillator and the state of interest, where from the latter, the phase is composed of both the particle-number statistics and the temporal mode structure.

Finally, we propose an alternative spectral tomography technique for single photon states [5] inspired from Kramers-Kronig detection and relying on single photon state engineering.

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Long-distance device-independent quantum key distribution using single-photon entanglement

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Device-independent quantum key distribution (DIQKD) provides the strongest form of quantum security, as it allows two honest users to establish secure communication channels even when using fully uncharacterized quantum devices. The security proof of DIQKD is derived from the violation of a Bell inequality, mitigating side-channel attacks by asserting the presence of nonlocality. This enhanced security comes at the cost of a challenging implementation. As photons in fibers are the natural carriers of quantum information, channel losses represent the main challenge for DIQKD : growing exponentially with distance, they become already at short distances too large for the honest users to be able to observe any Bell inequality violation. To circumvent channel losses, a heralding scheme can be used, where entanglement is generated between the parties' systems conditioned on the detection of photons at a central heralding station performing a joint measurement. Losses therefore reduce the key generation rate, but not its security. Heralding schemes have been used in recent proof-of- principle demonstrations of DIQKD [1]. In this experiment, the honest users locally generate light-matter entanglement, so that the state at the local stations is encoded in material qubits. Despite these successful demonstrations, the light- matter entanglement generation process required in this approach typically has low repetition rates, limiting its scalability over large distances. Purely photonic platform can offer a good repetition rate but they typically require 2 photon interference at the central station which make the key rate proportional to the efficiency of the channel between the two parties and thus limit the maximum distance at which one can perform DIQKD. We propose a photonic realization of DIQKD [2], utilizing a heralded preparation of a single-photon path entangled state between the honest users. Being based on single-photon interference effects, the obtained secret key rate scales with the square root of the quantum channel transmittance. This leads to positive key rates over distances of up to hundreds of kilometers, making the proposed setup a promising candidate for securing long-distance communication in quantum networks.

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Multimode squeezed states in telecom and prospects of mode-selective non-Gaussian processes

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Our project focuses on generating continuous-variable multimode squeezed states in the telecom regime. In the initial phase, we successfully achieved squeezing across 21 frequency modes, marking an important result in the development of multimode squeezed light sources [1]. To further improve the squeezing values, we are upgrading key elements, such as enhancing the spectral width of the local oscillator (LO) within the homodyne detection scheme. Additionally, we have implemented important progress towards pulse-by-pulse measurements. A self-optimizing wavefront shaping scheme is also being implemented to increase coherence between the LO and the squeezed light and give higher resolution to the measurement scheme.

As a next step, we aim to incorporate non-Gaussian processes into our system by applying mode-selective single-photon addition and subtraction processes [2]. Our theoretical framework models the quantum optical nonlinearities determining joint spectral amplitudes for mode-selective single-photon addition and transfer functions for subtraction processes, respectively. These models offer valuable insights into how different waveguide configurations can generate and control non-Gaussian states. We further include purity analysis of expected realizations.

By advancing both our experimental techniques and theoretical simulations, we expect to contribute to the development of reconfigurable quantum networks at telecommunication wavelengths.

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QOSST : A Highly Modular Open Source Software for Continuous-Variable Quantum Key Distribution

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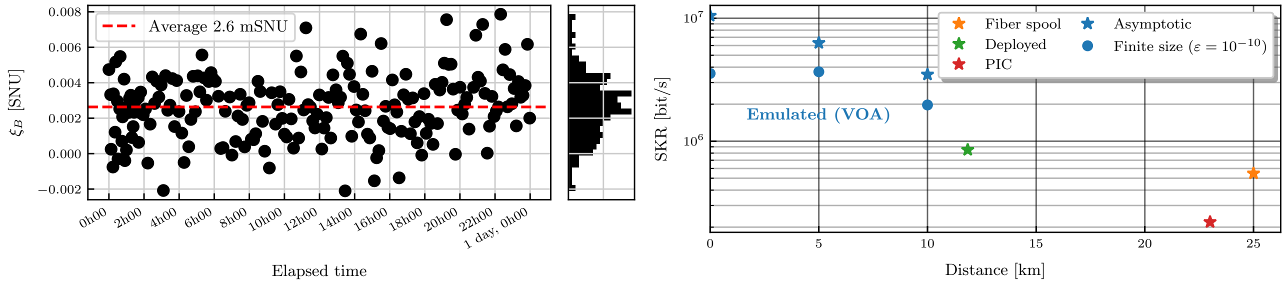
Quantum Key Distribution (QKD) is one of the most mature and prominent applications of quantum cryptography. It refers to protocols where two trusted users, Alice and Bob, use a public quantum channel and an authenticated classical channel, both accessible to the eavesdropper Eve, to exchange a secret key with information-theoretic security. Continuous-Variable (CV) protocols, as opposed to Discrete Variable protocols, encode the information on continuous degrees of freedom, in practice on the quadratures of Gaussian states, and the detection is carried out using coherent detection, working at high rate and high efficiency at room temperature.

Since 2015, CV-QKD systems have gradually shifted towards resembling classical coherent communication systems, with two different laser sources at the transmitter and receiver sides, requiring precise synchronisation that can be achieved through digital signal processing (DSP). Here we present the first open source software for experimental CV-QKD : the Quantum Open Software for Secure Transmissions (QOSST) [1]. The software is written in Python, and performs hardware control, DSP for Alice and Bob (including clock, frequency and phase synchronization), parameter estimation, secret key rate computation, classical communication and automatic optimization of the DSP parameters for CV-QKD with modulated coherent states. It is hardware agnostic and fully documented allowing adaptation to several scenarios and setups.

After optimization, our software was benchmarked on our CV-QKD experimental platform implementing the Gaussian Modulated Coherent States protocol with dual-quadrature RF heterodyne detection [2, 3]. Tested on emulated distances and a fiber spool of 25 km, our system was able to yield an excess noise in the mSNU order with good stability (see Fig. (a)) and asymptotic secret key rates (SKR) in the order of 1-10 MBit/s (1.17 MBit/s at 25 km fiber spool, see Fig. (b) for SKR summary). Our software was also benchmarked on a 11.85 km deployed fiber between two remote testbed nodes in the Paris area, achieving an asymptotic key rate of 0.85 MBit/s. Furthermore, it was used with a silicon-based photonic integrated receiver yielding an asymptotic key rate of 220 kbit/s at an emulated distance of 23 km [4]. This shows the capabilities of our software to be used in a variety of experimental setups giving positive key rates at metropolitan distances. It is also currently being used for investigation of free-space based channels and certification of QKD systems.

Our software is released to the community, in the hope that it can lower the barriers for performing experiments on CV-QKD from other groups, and hoping that it can also be improved and enriched by interested researchers. It has recently prompted the open source release of a software for information reconciliation [5].



(a) Excess noise results in the deployed fiber.

(b) Summary of secret key rate results.

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Secure communication based on sensing with undetected photons

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We introduce a secure optical communication protocol using quantum correlations in entangled photon pairs. The message is encoded on one photon of the pair and can be decoded by measuring only the other photon. We demonstrate secure communication through both amplitude and phase modulation, using single-photon measurements. Our approach remains resilient to noise, withstanding noise in the optical link up to 10^5 times greater than the signal, and we successfully use it to securely transfer an image.

Quantum physics provides a very good framework for secure communication methods, but current protocols, like Quantum Key Distribution (QKD) [1], rely on complex protocols with many moving parts, as well as complex post-treatment methods. We propose a novel communication method that consists in concealing messages within a bright, meaningless optical beam and using quantum correlation in entangled photon pairs to retrieve the messages [2], making it extremely challenging for eavesdroppers to access the communication. This technique differs from traditional quantum illumination protocols, as it does not rely on coincidence measurements, which are vulnerable to noise [3].

Our secure communication scheme uses a quantum interferometer designed for sensing with undetected photons [4, 5]. A 532 nm continuous-wave laser pumps a PPLN crystal, generating entangled photon pairs at 1550 nm (idler) and 810 nm (signal). The pump, signal, and idler photons are split into different paths. In the signal path, Bob (the sender) encodes the message using an object modeled as a beam-splitter with tunable reflectivity α and phase shift $\Delta\phi$. A strong 810 nm laser is overlapped with the returning signal to hide the message within its shot noise. The pump, idler, and signal modes are then recombined and redirected into the crystal, inducing quantum coherence between photon pairs generated in the first and second pass and leading to interference at the single-photon detectors. Alice retrieves the message by measuring the idler photons, while the signal photons remains concealed in the noise.

We measured the signal-to-noise ratio (SNR) of our communication protocol, showing that unauthorized users (Eve) cannot extract useful information from the signal photon as long as the noise level exceeds the quantum signal by a factor of 100, and it shows that detection is unaffected at Alice's detector up to a factor of 10^5. Our scheme was also used to securely transfer an image by encoding it in the photon pair and retrieving it through the quantum interference, while an eavesdropper only sees the noise.

In summary, we demonstrate a secure quantum communication method based on single-photon measurements, achieving high resilience to noise and successfully transferring an image. This protocol can be adapted for fiber-based communication systems, providing a secure and practical alternative to traditional methods.

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SiV centers in photonic nanowaveguide in diamond for light matter interaction

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Single photon sources of different types have been widely studied in the past years for quantum information and the development of quantum networks. Solid-state single photon sources can be compact compared to traditional atomic systems, and can be integrated in photonic chips, which could be more practical and efficient for device implementation. However, collecting efficiently their single photon emission into conventional optical fibers remains a challenge. Our work focuses on the coupling of a diamond nanowaveguide with embedded group IV-color centers and specifically silicon-vacancy (SiV) centers, to a nanofiber (cf. figure (a)). Optical nanofibers, with their sub-wavelength diameters, can interact with their surrounding environment through an evanescent field at their surface. Objects within this field can couple to the fiber. By tapering adequately the diamond nanowaveguide and placing it on top of the nanofiber, we can reach high outcoupling efficiency [1]. For this, We apply the theoretical principle of adiabatic transfer [2] by tapering the two ends of the diamond nanowaveguide, to ensure a smooth transition between the two eigenstates, without incurring energy losses through change in the eigenvalue. This approach enables a pure geometrical photon transfer **??**.

Following this design and fabrication step, we developed a pick-and-place setup for the deposition of waveguides onto the surface of the nanofiber. A tungsten tip is positioned in proximity of the waveguide, to lift it via Van der Waals interaction. Once the waveguide adheres to the tungsten tip, it can be deposited precisely onto the nanofiber. As at low temperatures,the quality and directionality of emitted photons are significantly improved, we will then proceed into the integration of the platform into cryogenic environements Future studies will consider other shapes of waveguides [3] as well as focusing on exploring interactions such as giant nonlinearities between single photons and quantum emitters [4] to develop a functional optical control switch for single-photon.

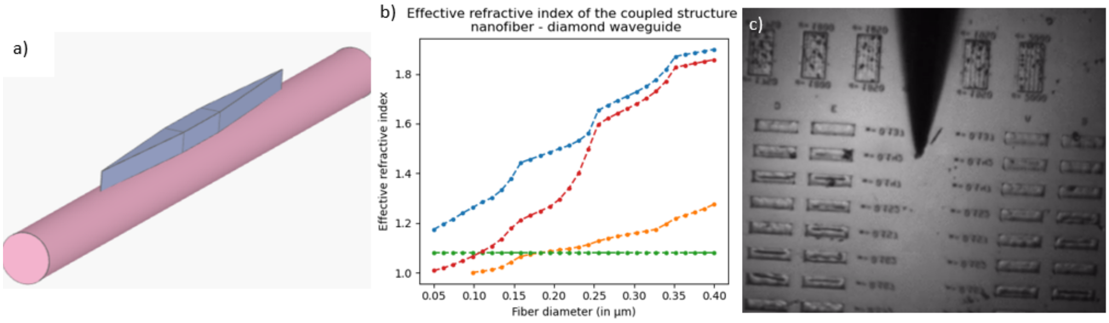

FIGURE 1 – a), b) Tunsten tip depositing on a nanofiber, c) Microscope image of the tip picking waveguides c) light through a nanofiber under the microscope

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Spin relaxation dynamics of telecom emitters in silicon carbide

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Optically active spin defects are a promising class of quantum systems for implementing scalable quantum networking technologies due to their intrinsic spin-photon interfaces and compatibility with lithographically fabricated devices. One such system that has recently drawn interest for this application is the vanadium (V^{4+}) dopant in silicon carbide (SiC) due to favorable properties including bright emission in the telecom O-band (1278-1388 nm), an optically addressable electron-nuclear spin system, and the mature fabrication techniques available for SiC. Here we address crucial questions about the mechanisms that govern the spin state lifetime of this defect. We first demonstrate efficient optical spin polarization and readout which facilitate all-optical measurements of the spin relaxation rate at different temperatures. Our measurements reveal a strong temperature dependence of the spin T_1 time with lifetimes exceeding 15 seconds at 100 mK for multiple of the inequivalent lattice sites. Furthermore, the form of the temperature dependence allows us to identify the underlying relaxation mechanisms that dominate at different temperatures. At higher temperatures we find that a 2-phonon Orbach process between the low lying orbital states dominates, which offers an opportunity to exponentially suppress the relaxation through strain tuning. These results enable further development of V^{4+} in SiC as a prime candidate for implementing future quantum networking nodes.

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Tailoring epitaxial interfaces in quantum materials

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Engineering materials and devices for solid-state quantum technologies requires a careful control of the interface quality between materials with different physical properties. [1] Any disorder at these interfaces (defects, impurities, and roughness) is a detrimental source of noise and dissipation, and compromises the ability to generate, detect, and manipulate quantum states. Here, we will discuss novel epitaxial heterostructures between superconductor/semiconductor and superconductor/topological materials by performing the epitaxial growth in a high purity molecular beam epitaxy (MBE) system and down to cryogenic temperatures (below -100°C). Specifically, we will evaluate the structural properties of superconducting Tin layers (β-Sn phase) that are epitaxially-grown on III-V and group IV substrates. β-Sn is a promising candidate to fabricate superconducting contacts in solid-state quantum devices due to combination of high critical temperature and resilience to high magnetic fields. [2, 3]

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Towards Efficient coupling of single nanodiamonds to an optical fiber for single photon emission

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The development of integrated quantum technologies greatly benefits from efficient, scalable single-photon sources and deterministic quantum operations. Solid-state quantum emitters coupled to nanophotonic structures offer a promising solution to these challenges. This work explores color centers in nanodiamonds, particularly those containing group IV color centers, such as GeV and MgV, at both room and cryogenic temperatures. These nanodiamonds are selected for their stability and excellent coherence properties at cryogenic temperatures [1], outperforming other colloidal quantum emitters. When deposited on a tapered optical nanofiber, they couple to the nanofiber mode through the strongly confined evanescent field. However, the collection efficiency of such systems is currently limited to 30To achieve this, we are investigating the deterministic nanofabrication of dielectric and plasmonic nanostructures on the nanofiber surface, a technique recently developed in our group. By optimizing the composition, design, and positioning of these nanostructures, we show that a pattern of a few pillars around the quantum emitter can increase coupling efficiency up to 60Currently, nanodiamonds are deposited on nanofibers using a non-deterministic technique involving a diluted droplet gently contacting the nanofiber [4]. To address the lack of precise control and selection, we are developing a "pick and place" technique using AFM tip, enabling precise control over emitter choice and positioning [5]. This work contributes to the development of integrated photonic devices for single-photon sources and addresses key challenges in achieving nonlinear operations for photonic quantum computing. [3]

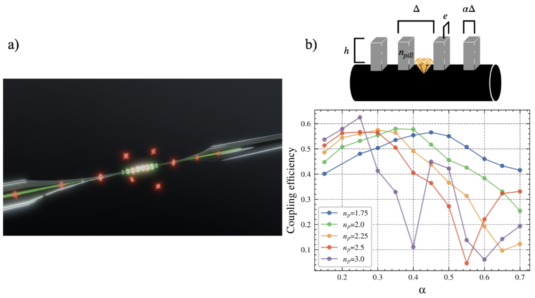

FIGURE 1. a) Nanofiber single photon source (conceptual illustration).b) Coupling efficiency enhancement simulations.

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Posters 2, 14/11/2024: Quantum Simulation (QSIM)

Combining Matrix Product States and Noisy Quantum Computers for Quantum Simulation

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Matrix Product States (MPS) and Operators (MPO) have proved to be powerful tools to simulate quantum many-body systems. While MPS can efficiently find ground states of 1D systems, they fail to simulate their dynamics, where the entanglement can increase ballistically with time. On the other hand, quantum devices are natural platforms to perform time evolution but are strongly hampered by noise. In this work [1], we use the best of both worlds : the short-time dynamics is efficiently performed by MPSs, compiled into short-depth quantum circuits, and is performed further in time on a quantum computer thanks to efficient MPO-optimized quantum circuits (Fig. 1). In this scheme (that we call “QMPSO”), tensor networks provide all the ingredients to the quantum computer for a resource-efficient quantum simulation, and drastically lower the noise requirements for a practical advantage. Finally, we successfully demonstrate our method on an actual quantum device (Fig. 1) from IBM : we simulate experimentally a 10-qubit system over a longer time scale than low-bond-dimension MPSs and purely quantum Trotter evolution.

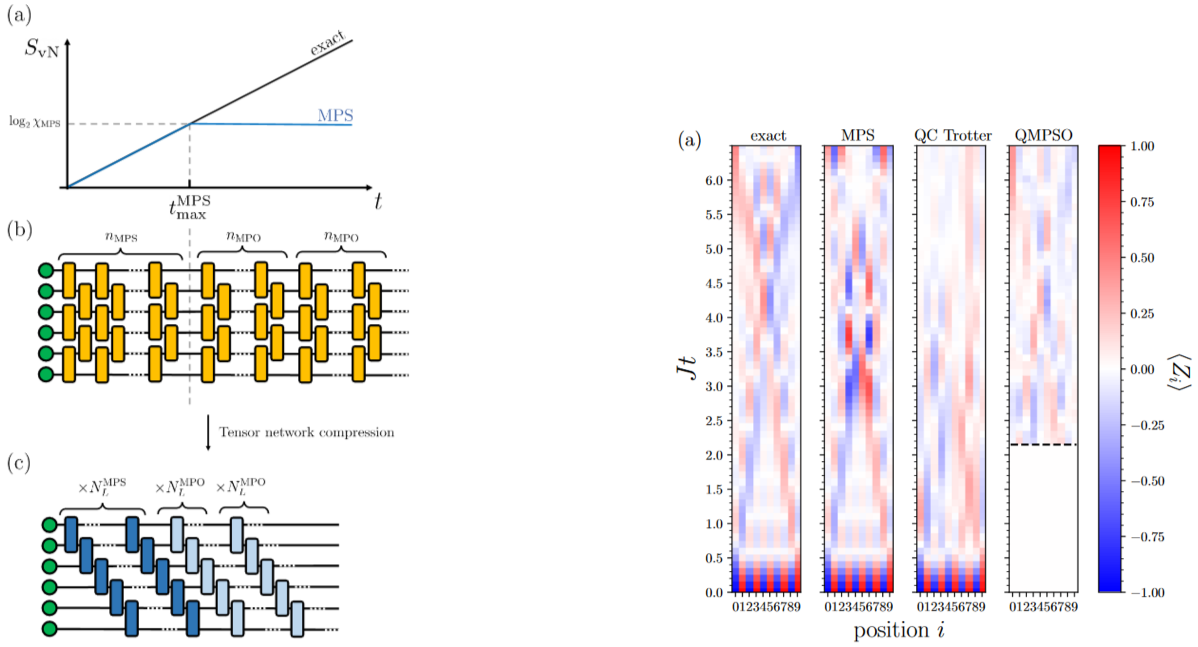

FIGURE 1. Left : (a) The entanglement entropy increases with time using the Trotter quantum circuit in (b). Using tensor network techniques, we compress the circuit (b) into a short-depth entanglement-efficient quantum circuit (c). Right : Evolution in time of the local magnetization in time for a L = 10 quantum Ising chain for the exact solution versus MPS, Trotter and QMPSO simulations on IBM devices

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Controlled dissipation for Rydberg atom experiments

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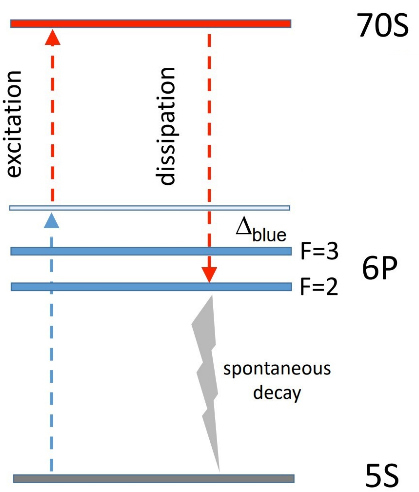
In ultracold Rydberg atoms studies in the context of quantum computation and simulation, dissipation and decoherence are usually detrimental and need to be minimized [1]. However, in the study of driven-dissipative systems exhibiting nonequilibrium phase transitions [2] or in the dissipative preparation of entangled states, the dissipation is a feature. In Rydberg atom experiments dissipation arises naturally from spontaneous decay to the ground state and black-body radiation induced transitions between Rydberg levels. Here, we demonstrate a simple technique for adding controlled dissipation (decay to the ground state) to Rydberg atom experiments [3]. Our approach involves exciting cold rubidium atoms trapped in a magneto-optical trap to 70-S Rydberg states while concurrently inducing forced dissipation. This dissipation is achieved by resonantly coupling the Rydberg state to a hyperfine level of the short-lived 6-P state as shown in the above figure. The resulting effective dissipation can be controlled in time during within a single experimental cycle.



Scheme for simultaneous excitation and controlled dissipation in rubidium Rydberg atoms. The 6P level is used both as an intermediate state for two-photon excitation (blue and red arrows on the left) and resonant depumping from the 70S Rydberg state (red arrow on the right).

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Reservoir computing has emerged as a novel way to implement machine learning on analog machines. The large Hilbert space of quantum systems could be harnessed to achieve quantum advantage. Using spatial light modulator - the propagation of light in complex media - coincidences measurements with SPAD arrays, we explore the difference of performance between classical and quantum light, i.e. distinguishable and indistinguishable photons, for various tasks. We demonstrate experimental proof of concepts results and explore the quantum advantage in simulations, for classification and timeseries prediction.

Inhibition of circular Rydberg atoms decay : towards the realization of quantum simulation of slow processes

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Being able to describe quantum properties of many body microscopic systems is one of the key ingredients for better understanding matter on a deeper level. However, the computational complexity of such systems prevents us from performing ab intio calculations with classical computers. If fully programmable quantum computers would be a way to study such systems, another path has been found which is the one of analog quantum simulation. Indeed, through a quantum system that is fully controllable it is possible to acquire knowledge about a system that can't be directly studied, provided that there is a formal equivalence between their models [1].

In our group, the platform chosen to perform quantum simulation is based on circular Rydberg atoms.These atoms show dipole-dipole interactions that can be harnessed to have the same Hamiltonian as a spin chain with a XXZ model [2]. The interaction strength provided by the Rydberg state, around tens of MHz at few $\mu\mathrm{m}$ distances, allows for atoms spacing which are achievable with optical trapping techniques [3]. Experiments with elliptical (low-l) states are already showing promising simulation results, but study of some slow dynamics remains limited by the interaction cycles number [4]. Additionally, using maximal angular momentum (circular) states allow for longer lifetime, that can for example go up to $30\,\mathrm{ms}$ for circular state $n = 50$ at cryogenic temperatures, which is two order of magnitudes above elliptical states in similar conditions. Using two conductive plates, it is possible to inhibit the photons emission, increasing the lifetime of circular states [5]. Recent work of our group studied this effect in a room temperature experiment, where inhibition of stimulated and spontaneous emission allowed to observe millisecond lifetime even at such temperatures [6]. This lifetime can be further increased by getting rid of black body radiations responsible for photons stimulated emission and absorption.

The goal of my PhD project is to design and build an experiment to push this idea one step further by going to a cryogenic environment to get rid of black body radiations. Theoretical simulations of such an experiment suggest that lifetime in the minute range could be reached, which would allow for simulation duration way larger than the characteristic interaction time [2]. In order to implement this idea, we want to cool down and transport ground state atoms in between the two plates, where the Rydberg excitation and circularisation will take place. Detection through ionisation will then allow to measure atoms lifetime.

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Quantum Matter Synthesizer : an ultracold cesium quantum simulation platform

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The Quantum Matter Synthesizer is an ultracold atom quantum simulation apparatus that combines an optical lattice with optical tweezers [1]. We prepare and perform site-resolved fluorescence imaging of individual cesium atoms in a triangular optical lattice. We aim to rearrange atoms between lattice sites using a moving optical tweezer array. The combined advantages of optical lattices and optical tweezers make this a promising platform to study many body physics. We plan to study novel quantum phases and phenomena such as quantum transport.

Enhanced loading : A highly filled lattice is an ideal starting point for rearranging atoms since it minimizes the tweezer moves. We observe that a high lattice filling fraction in excess of 70% can be prepared by introducing a blue-detuned Raman sideband cooling optical pumping beam. The blue-detuned beam causes one atom to be ejected from the lattice site when two or more atoms are loaded into a single lattice site. The atom might also redistribute into a neighboring site. During imaging, atoms are ejected in pairs from the lattice sites by light assisted collisions until the site occupancy is either 0 or 1. Given a thermal distribution, the pairwise ejection yields a filling fraction of 50%. The blue-detuned optical pumping changes the initial distribution such that the filling fraction is enhanced.

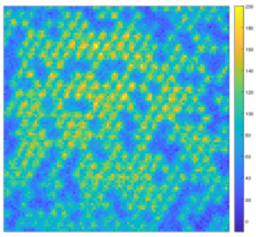

FIGURE 1 – Atoms in the triangular lattice.

Progress toward custom rearrangement : We will use an optical tweezer array to arrange the atoms into custom patterns. A digital micromirror device (DMD) in the image plane is used to project arbitrary patterns of 532 nm light through a high NA (0.8) microscope objective onto the atoms. This approach to optical tweezer creation enables merging and splitting of the tweezer potentials. We project static patterns of light onto the atoms and confine them into those patterns. We are implementing tweezer rearrangement of atoms with the following workflow : 1. Image the atoms. 2. Program the tweezer moves. 3. Play the tweezer movie on the atoms. 4. Image the atoms again. This will allow us to create arbitrary atom arrangements in the lattice for quantum simulation.

Quantum networking : We also aim to use the Quantum Matter Synthesizer as a node in a quantum network for distributed quantum processing. We are currently working to generate narrow linewidth pairs of entangled photons on the cesium D2 line. We will interact them with atoms in the QMS to generate atom-photon entanglement. We then aim to send one photon to the QMS and send another photon to a different apparatus to create distant atom-atom entanglement between qubits.

This work is supported by the U.S. DOE, Office of Science, Office of Basic Energy Sciences, under Award No. DE-SC0019216, by the NSF Graduate Research Fellowship under Grant No. DGE 1746045 and by the Hybrid Quantum Architectures and Networks Quantum Leap Challenge Institute.

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Quantum Simulation with Rydberg Synthetic Dimensions

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A synthetic dimension is an internal or external degree of freedom in a quantum system that can be mapped to a spatial dimension. Recently, the Rydberg states of an ultracold strontium atom were used as a one-dimensional system to realize the Su-Schrieffer-Heeger (SSH) model, where the states were coupled with microwaves to implement tunneling between the synthetic sites [1]. Fundamental dynamics of the SSH model were observed, including edge-to-edge tunneling and bulk oscillations. Here, we report on these past studies and our current efforts toward building an experiment that will employ optical tweezers to introduce tunable dipole-dipole interactions between pairs of Rydberg atoms. The new system will enable the study of interacting, many-body systems by allowing us to observe coherent dynamics in the synthetic space and engineer Hamiltonians that are difficult to realize with real-space systems.

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Quantum simulation of spin models in a two-dimensional Rydberg atom array

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I will present our Rydberg atom array experiment, our latest results on the study of interacting spin models, and our plans to build an improved version of this experiment.

In the context of quantum simulation of many-body spin Hamiltonians, we have developed a method called quench spectroscopy [1], which allows us to extract the dispersion relation of elementary excitations in many-body systems. We also have extended the range of systems we can study by implementing arbitrary local control in arrays of dipolar Rydberg atoms [2]. These improvements have enabled us to implement the $t - J$ spin model using Rydberg states. In particular, this makes it possible to study parameter ranges that are unreachable in optical lattices or in condensed matter physics, where this model is generally studied.

In parallel, we are building an improved version of this experiment. The main upgrade consists in using under-vacuum microscope objectives, enabling us to manipulate larger arrays of atoms with less optical aberration and a larger field of view.

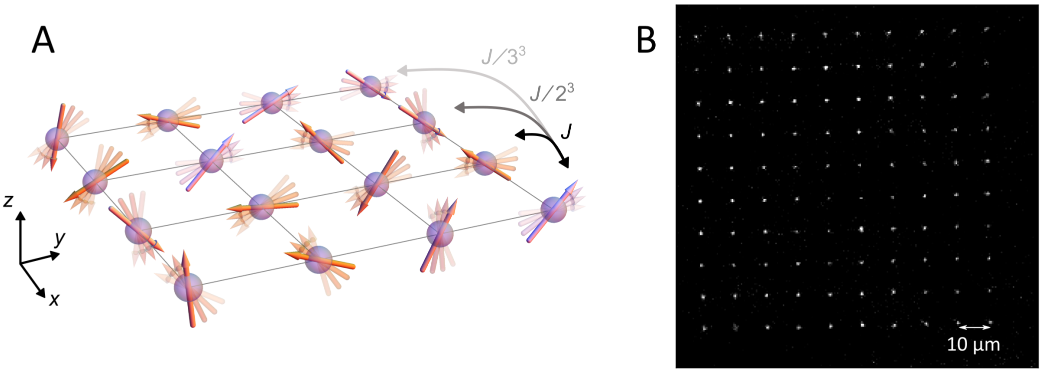

FIGURE 1. **A** : Schematic representation of a square array of spins interacting under the dipolar XY model. The red arrows depict the average direction of the spins, and the black arrows represent the coupling between the spins, which decays as $1/R^3$ with R the inter-spin distance. **B** : Fluorescence image of an assembled atomic array.

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Quantum simulations with a register array coupled to an optical fiber Fabry-Perot microcavity

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The study of N two-level systems involved in long-range interactions holds interest for quantum simulations and information. An ideal candidate would be N individually controlled neutral atoms interacting via the resonant photons of a Fabry-Perot cavity, in a Cavity Quantum Electrodynamics (CQED) scenario.

In our group, high-finesse Fibre Fabry-Perot Cavities (FFPCs) are made with laser-machined mirrors, allowing small mode cross-section and thus strong light-matter coupling for a single emitter. The N atoms are separately trapped using an array of far-off-resonance, tightly-focused laser beams (optical tweezers).

We are currently working on the characterization of quantum states in the low-excitation regime, which involve a hybrid light-matter mode : the polariton. This quantum state is comprised of a superposition between a single atomic excitation shared by all emitters and a single photon in the resonant field mode. It has been shown that polaritons can emerge even when the qubit frequency distribution is inhomogeneous. Experimental investigation of the transition from disordered to polaritonic regime remains mostly unexplored.

In this poster, I will discuss about the generation of large tweezer arrays with acousto-optic deflectors and the coupling between single atoms and cavity mode. I will also present the different methods we have to detect state of the system. One by single photon detector with a quantum non demolition process and one by background-free fluorescence imaging. These methods will allow to analyse quantum simulations of polaritonic chemistry that is a disordered system.

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Strain engineering in Ge/GeSi spin qubits heterostructures

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The heavy-holes in Ge/GeSi heterostructures show highly anisotropic gyromagnetic response with in-plane g-factors $g^*_{x,y} \lesssim 0.3$ and out-of-plane g-factor $g^*_z \gtrsim 10$ [1, 2]. As a consequence, Rabi hot spots and dephasing sweet lines are extremely sharp and call for a careful alignment of the magnetic field in Ge spin qubit devices [3]. We investigate how the g-factors can be engineered by strains [4]. We show that uniaxial strains can raise in-plane g-factors above unity while leaving g^*_z essentially constant. We discuss how the etching of an elongated mesa in a strained buffer can actually induce uniaxial (but inhomogeneous) strains in the heterostructure. This broadens the operational magnetic field range and enables spin manipulation by shuttling holes between neighboring dots with different g-factors.

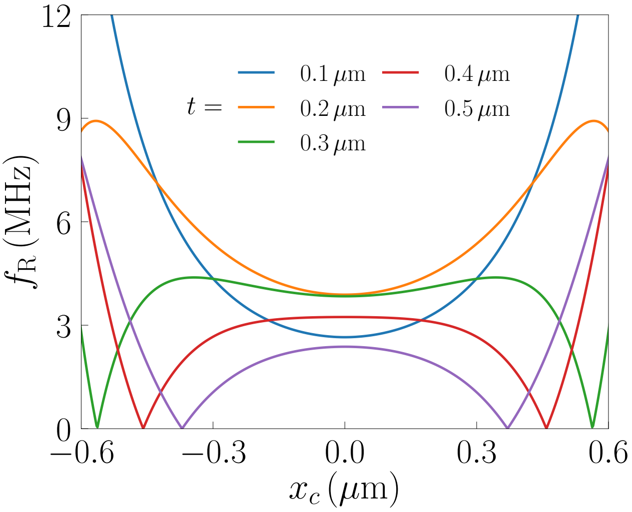

FIGURE 1. Shuttling Rabi frequency $\bar{f}_\mathrm{R}$ as a function of the average position of the dots $x_c = (x_1 + x_2)/2$ for mesas with width $W = 2\,\mu$m and different depths t.

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Interacting Rice-Mele quantum cellular automaton : edge states

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Unitary dynamics allow for a greater range of dynamics than Hamiltonian ones. They can be used to engineer quantum states with desirable properties. A class of such unitary dynamics are quantum cellular automata (QCA), which are local rules that act on a lattice of qubits and update their states. They are translation invariant Floquet systems and have been shown to be universal for quantum computing.

The Su-Schrieffer-Heeger (SSH) model [1] is a toy model showing topological effect. An intrinsic topological invariant can be found which allows for edge states to exist in the system in open boundary conditions. Adding an on-site potential, the model is called the Rice-Mele model [2, 3].

Interacting versions of the SSH model were proposed in the litterature, two-body edge bound states were found to be made possible by interactions in a bosonic model [4]. By solving the Lippmann-Schwinger equation, explicit expressions were found for the bound states. It was also shown there that local interaction could affect edges of the system. In [5], using center of mass coordinates and in the limit of strong nearest-neighbor interactions with spinless fermions, the two-body sector was diagonalized and topological states were identified.

The split-step quantum walk was proposed as an analogue of the SSH model in a Floquet setting. Such driven systems have quasienergies which are periodic, allowing for a rich topological phenomenology. An experimental realization of this model was done on a photonics split step quantum walk, bound states predicted by the theory were observed [6].

Studies with two particles in Floquet systems were proposed and bound states were shown to exist when interaction is present [7, 8]. A two particle generalization of the split-step quantum walk with interaction was also shown to exhibit topological effects [9].

It is of interest to study a many-body generalization of the Rice-Mele model with interaction in a Floquet setting, in order to study the interplay between interaction and edge phenomenology.

We define a quantum cellular automaton in open boundary conditions, breaking translation invariance in the model and allowing for edge phenomena. By construction, our QCA recovers the nearest-neighbor interacting Rice-Mele model in the Trotter limit [10]. Moreover, in the one particle sector, it reproduces Kitagawa's split-step quantum walk phenomenology, therefore making the link between the split-step quantum walk and the SSH model explicit. We then compute explicitly the eigenstates in the non-interacting one particle sector.

We study the multiparticle case, beginning with the two particles case, and exhibit a relationship between interaction and edge localization.

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Toward microwave-induced Feshbach resonance

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Controlling interatomic interactions is a powerful tool for the study of quantum phases of degenerate Bose gases. This has become accessible in experiments relying on Feshbach resonances. This phenomenon occurs as soon as the energy of two free atoms is brought to resonance with the energy of a bound state of their interaction potential. This is commonly achieved thanks to a homogeneous magnetic field relying on the Zeeman effect. In 2010, Papoular et al. [1] have proposed to realize microwave-induced Feshbach resonances for alkaline atoms.

On our experimental setup at LPL, we are currently investigating this possibility. We rely on an atom chip in order to confine extremely elongated Bose-Einstein condensates of sodium atoms. The atom chip also encompasses a coplanar waveguide allowing the production of large amplitude microwave fields at the position of the trapped atoms. In a first step, we have characterized a molecular bound state lying about 200 MHz below the hyperfine splitting energy. Microwave spectroscopy allows us to reach a much better accuracy on the measurement of the energies of the different spin states of the molecular bound state, with respect to previous results [2]. We have also been able to study the effect of large amplitudes microwave dressing on these energies.

We are currently investigating the effect of the microwave field on the scattering length of the trapped atoms. Pulsing the microwave field, we are able to excite the radial breathing mode of the condensate and observe slight differences in its characteristics across the molecular resonance.

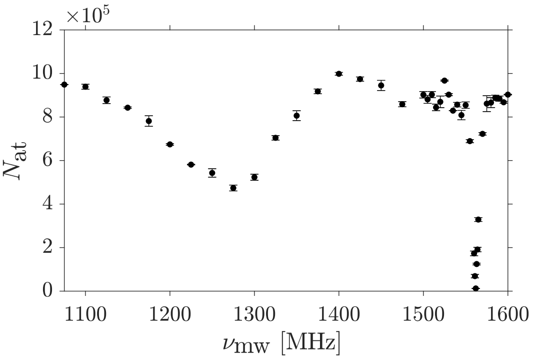

FIGURE 1. Spectroscopy of a sodium molecular state. We can observed a broad resonance and a very narrow one corresponding to different spin states.

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Ultra-cold single Potassium atoms excited to Rydberg states for quantum computing and quantum simulation

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In this poster, I will report on a recent experimental achievement on trapping single Potassium atoms in optical tweezers and progresses with the implementation of a new laser system for future experiments.

Trapping single atoms in optical tweezers is one of the first steps in making quantum registers. We recently benefited from experimental upgrades to get our first stable single-atom signal in a 1x11 tweezer array. Along with improving our trap depth, a stroboscopic imaging sequence has been implemented : turning *off* the tweezer light while cooling and collecting fluorescence to image the atoms ; turning it *on* again to re-catch them. This sequence avoids the influence of energy light shifts from the tweezer light so one can rely on the simpler free-space Potassium spectral properties [1, 2].

These single atoms can then be grouped all within a Rydberg blockade radius to realize Jaynes-Cummings (JC) and Jaynes-Cummings-Hubbard (JCH) cavity quantum-electrodynamics Hamiltonians, hence without the need of a cavity [3, 4]. To reach a stronger coupling to the Rydberg states, I am working on a new laser system to implement an alternative 2-photon Rydberg excitation scheme called the “inverted-scheme” : a UV laser at 405 nm couples the atoms from the ground to the first excited state, and the excitation to the Rydberg states is achieved via an infrared transition at 976 nm [5]. The advantages of this excitation ladder lie in the longer lifetime of the first excited state and the higher Rabi frequency coupling expected from a 10 W infrared laser. This new laser system includes two laser seeds, an infrared high-power fiber amplifier, and a second-harmonic generator cavity to generate UV light. The laser frequencies will be locked with the Pound–Drever–Hall technique using an ultra-low expansion Fabry-Perot cavity and a Potassium hot vapor cell as a frequency reference.

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Posters 2, 14/11/2024: Transverse Engineering and Methods (TEM)

Focusing entangled state through scattering media via coincidence-based feedback

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Adaptive optics has revolutionized imaging in fields ranging from astronomy to microscopy by correcting optical aberrations. However, disturbances often become too strong and fall into the scattering regime. Fifteen years ago, Vellekoop and Mosk implemented the first experimental refocusing of classical light through a scattering medium by optimizing the incident wavefront [1]. In our work, we extend these wavefront shaping methods to the quantum domain to transmit high-dimensional entangled states of light through scattering layers. To manipulate high-dimensional entangled quantum states, the techniques developed so far use only correction patterns learned with classical light. In practice, however, these approaches are limited because they do not consider the specific properties of the states, such as their strong correlations or entanglement [2, 3]. Here, we report the first experimental realization of focusing a high-dimensional two-photon entangled state through a scattering medium using wavefront shaping algorithms based on photon coincidence feedback. The two-photon state is produced by Spontaneous Parametric Down Conversion in a thin nonlinear Beta Barium Borate crystal. This state exhibits strong spatial correlations in high dimensions that we aim to preserve after passing through the medium. The photons are modulated by a Spatial Light Modulator (SLM), and a Single Photon Avalanche Diode camera is used to measure the spatial coincidences between the pairs after the medium. Analogous to the classical case, where intensity can be modulated by a phase mask, the output coincidence rate of the photon pairs can also be modulated. We theoretically investigated this modulation by examining the various quantum interference processes occurring in the medium. As a result, we provide a comprehensive description, enabling efficient signal modulation and identification of the optimal SLM phase mask to maximize the targeted spatial coincidence feedback signal. In addition, an intriguing phenomenon occurs as the classical light remains scattered and uncorrected, highlighting the potential of these techniques in quantum communication and imaging.

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Towards perfect spin projection in a QD-based spin-photon interface

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Charged quantum dots (QD) are promising candidate platforms for quantum information processing applications. Entanglement between the spin degree of freedom of a charged confined in the QD (acting as a stationary qubit) and the polarization of single photons (flying qubits) allows for deterministic spin-photon and photon-photon quantum gates [1]. However, this requires an efficient read-out of the matter qubit state. A promising strategy, in this respect, is to take advantage of the giant rotation induced by a single spin on the polarization state of single photons as in micropillar cavity-based spin-photon interfaces [2, 3].

In our work, we explore an InAs negatively charged QD deterministically coupled to a microcavity [4]. An attenuated linearly polarized CW laser is sent to the cavity-QD system and tuned close to resonance from the trion transition. The output polarization of the reflected photons is rotated with respect to the incoming one, providing a spin-state dependent effect. In our protocol, the spin qubit is projected into one of its eigenstates by a projective measurement on a first photon reflected from the interface. We then perform time-resolved intensity measurements of the reflected photons polarization to track the spin evolution towards the steady state. Doing so, we can infer the state of the spin in the Bloch sphere and demonstrate efficient measurement induced back-action.

This work paves the way for novel entanglement schemes, where a single spin gets entangled with single incoming photons in QD-based systems, the next step towards deterministic spin-photon gates working at the single photon level.

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Hybrid III-V/Silicon quantum photonic device generating broadband entangled photon pairs

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Photonic quantum technologies represent a promising platform for several quantum information (QI) applications: the implementation of integrated devices able to efficiently generate, manipulate and detect quantum states of light is a major objective [1]. Among the available material platforms, silicon stands out as one of the leaders in linear integrated photonics, thanks to its moderate optical losses, large-scale high-yield production capability and fabrication maturity [2]. Although nonlinear effects are accessible through its strong third order susceptibility, it intrinsically lacks of second order nonlinearity; furthermore, its indirect bandgap practically prevents it from achieving laser action. AlGaAs, on the other hand, features both strong second order nonlinearity and direct bandgap, suitable for electrically injected photon-pair production [3], resulting perfectly complementary to silicon for the implementation of a compact photonic chip for QI applications.

We demonstrate a hybrid AlGaAs/silicon-on-insulator (SOI) source operating at room temperature [4], whose working principle is sketched in Figure 1.a: the photon pairs are generated, upon optical pumping, via spontaneous parametric down-conversion (SPDC) in an AlGaAs waveguide based on Bragg reflectors (grey, on top) and then transferred, through evanescent adiabatic coupling, to the SOI circuitry (blue, beneath), preserving the properties of the produced quantum state, while the pump beam is automatically filtered out.

Both type 0 and type 2 conversion processes are accessible via SPDC, attesting the polarization versatility of the source. We estimate the amount of photon pairs injected into the silicon waveguides to be $>10^5$ pairs/s in the two cases, with a coincidence-to-accidental ratio (CAR) up to 10^2 (Figure 1.b) over a bandwidth of 90 nm. The non-classicality of the quantum state of light is characterized through an energy-time entanglement measurement, using a fibered Franson interferometer: The obtained visibility is larger than 90% for a 20 nm-broad state (Figure 1.c), demonstrating the high entanglement quality of the produced photons and establishing the potentiality of the proposed hybrid photonic circuit in view of QI applications.

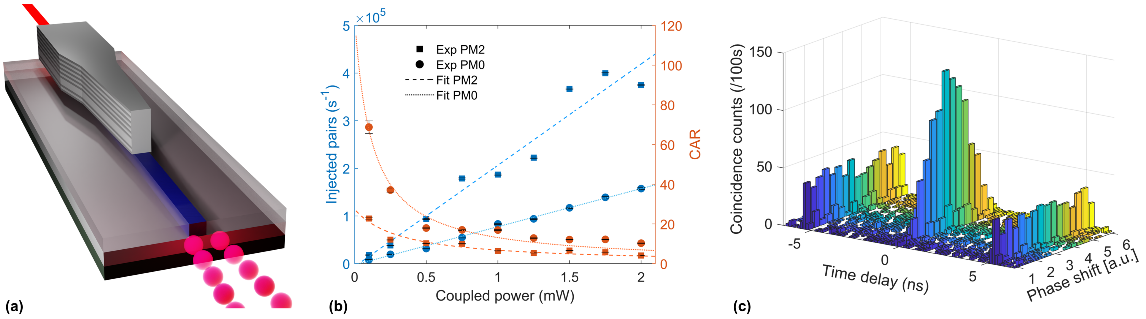

Figure 1. (a) Sketch of the device. Measured (b) injected pairs into the silicon waveguide and CAR, (c) energy-time entanglement visibility.

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Ultra-precise holographic optical tweezers array

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Over the past five decades, optical tweezers have evolved into versatile tools for manipulating microscopic particles across various scientific fields. Among their numerous applications, the trapping of neutral atoms using optical tweezers has emerged as a powerful platform in quantum science. These atomic arrays are now essential for research in quantum simulation, computation, and metrology, which is the primary focus of this work [1–3].

Creating arrays of optical tweezers involves both adjustable and fixed devices. Adjustable devices such as Spatial Light Modulators (SLMs), acousto-optic deflectors, and digital micromirror devices offer flexibility in generating arbitrary geometries. Fixed tools like intensity masks and microlens arrays provide stable configurations. Among these, SLMs are particularly effective due to their ability to generate arbitrary geometries with high efficiency, as demonstrated in recent advancements scaling up to thousands of tweezers.

A critical factor for precise atom manipulation is maintaining homogeneity across the tweezer array in terms of intensity, shape, and position. While this challenge has been addressed previously, we report an improved hologram optimization method that utilizes *in situ* measurements to achieve high uniformity. Our approach involves using feedback from the atoms themselves to refine the computer-generated holograms (CGHs) that control the tweezer arrays.

The presentation begins with a brief overview of CGHs and introduces a simplified formalism specific to optical tweezer arrays. We then detail our optimization procedures for each parameter—intensity, shape, and position—highlighting how feedback methods enhance the precision of CGH optimization. The use of *in situ* measurements derived from atomic signals is discussed extensively, showcasing its role in achieving our results.

As a highlight, we have achieved remarkable uniformity in the tweezer arrays : intensity inhomogeneity of 0.3%, shape inhomogeneity below 0.5%, and positional inhomogeneity of 70 nm, measured using root mean square deviation. These improvements represent a significant step forward in the precise manipulation of atoms and have promising implications for future quantum science research.

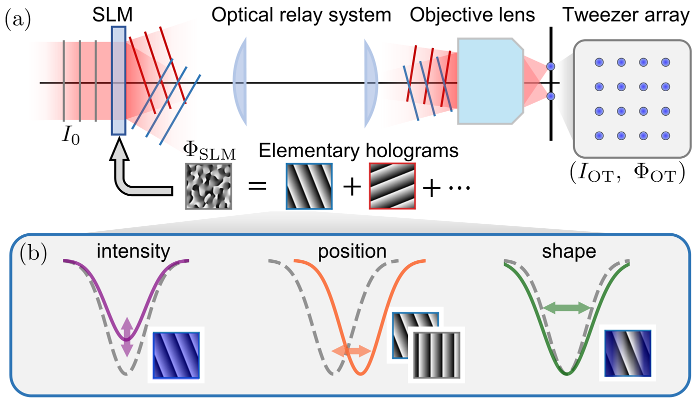

FIGURE 1. **Generation of optical tweezers arrays using an SLM**. (a) A schematic of the setup we consider. An SLM is employed to modulate spatially the incoming laser beam and create an array of optical tweezers. The phase of the SLM can be reduced to a superposition of elementary holograms for our specific array. (b) The parameters to homogeneize considered in this work. Imperfections lead to intensity, position and shape inhomogeneity between tweezers. Specific modifications of the elementary holograms in the SLM phase calculation can correct these inhomogeneities.

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A cat qubit stabilization scheme using a voltage biased Josephson junction

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Recent works have used DC voltage biased Josephson junctions [1],[2] for Hamiltonian engineering in superconducting circuits, demonstrating microwave signal amplification or entangled photon generation. Compared to more conventional approaches based on parametric pumps, this solution typically enables larger interaction strengths. In the context of quantum information, cat qubits [3],[4] rely on a two-to-one photon interaction to exponentially suppress bit-flips errors, promising significant resource savings for quantum error correction. This work investigates how the DC bias approach to Hamiltonian engineering can benefit cat qubits. We find a simple circuit design that is predicted to showcase a two-to-one photon exchange rate larger than that of the parametric pump-based implementation while dynamically averaging typically resonant parasitic terms such as Kerr and cross Kerr. In addition to addressing qubit stabilization, we propose to use injection locking with a catqubit adapted frequency filter to prevent long-term drifts of the cat qubit angle associated to DC voltage noise. The whole scheme is simulated without rotating-wave approximations, highlighting for the first time the amplitude of related oscillatory effects in cat-qubit stabilization schemes. This study lays the groundwork for the experimental realization of such a circuit.

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Pulse by pulse and frequency multiplexed quantum states for continuous variables protocols

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Photonics quantum networks are essential for quantum information processing, as quantum states of light enable efficient distribution and manipulation of information. Femtosecond pulses offer specific temporal and spectral structures, yielding entangled multimode outputs when combined with nonlinear interactions. The entanglement relies on mixing squeezed optical modes and can be enhanced through mode-selective homodyne measurements, facilitating the creation of quantum networks. Reconfigurable entangled networks have been demonstrated in frequency modes [1], and the largest entangled structures, comprising over a million nodes, have been realized by exploiting temporal modes. We have recently shown the generation of frequency-multiplexed and pulse-by-pulse multiplexed squeezed quantum states using nonlinear waveguides pumped by femtosecond pulsed lasers [2–4]. Optimization of the experiments hinges on sufficient squeezing and stabilization through electronic locking, and it involves annealing simulations assessing the impact of waveguide characteristics such as aperiodic poling. Pulse shaping instead is pivotal for mode-selective detection and encoding. Applications are found in machine learning tasks such as quantum reservoir computing (in collaboration with the theory group of R. Zambrini at Institute for Cross-Disciplinary Physics and Complex Systems), facilitated by continuous variables gates as the Cz. Recent findings indeed suggest that Gaussian states provide universal reservoir computing resources and that quantum Gaussian resources, like squeezed states, offer greater information capacity than classical states [5].

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Experimentally exploring physical limitations of phase-flip error rates in Schrödinger cat qubits for enhanced quantum error correction

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The realization of a universal, fault-tolerant quantum computer is one of the foremost challenges in modern physics. Such a computer would possess the capability to solve computational problems that are intractable for classical computers, with far-reaching applications in fields such as cryptography, materials design, and drug discovery. However, a significant challenge arises due to the inherent fragility of quantum bits, or qubits, which are highly susceptible to errors. Quantum error correction theory provides a framework to mitigate these errors and enables the precise manipulation of quantum information. Nonetheless, current implementations demand substantial physical and material resources.

A novel approach developed by Alice & Bob involves the use of a new type of qubit, termed the Schrödinger cat qubit. This qubit architecture substantially simplifies quantum error correction by exploiting engineered dissipation mechanisms. Specifically, the cat qubit undergoes two-photon dissipation, which is induced by pumping a nonlinear circuit element functioning as a four-wave mixer at an appropriate frequency. In this process, photons in the electromagnetic resonator, which encodes the cat qubit, are dissipated in pairs. This two-photon dissipation mechanism exponentially suppresses bit-flip errors in the cat qubit, thereby leaving only phase-flip errors, which can be corrected using a repetition code.

The goal of this thesis is to investigate the physical mechanisms that limit the phase-flip rate. Hypotheses under consideration include parametric processes, the influence of two-level systems (TLS), and the presence of quasiparticles. The objective is to experimentally identify the dominant processes contributing to the phase-flip rate, develop a quantitative understanding of these processes, and propose new quantum circuit designs to mitigate their impact

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Measure of charge noise on micropillar single photon sources

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Epitaxial quantum dots embedded in a micropillar cavity have proven to be high-performance single photon sources with high purity, high indistinguishability and high brightness [1]. The next technological challenge relies on the emission of indistinguishable photons from independent sources. One of the main limitations comes from the fluctuating charges around the quantum dot, known as charge noise, that vary differently over time for independent micropillars. The charge noise results in a wandering of the resonance frequency and causes the detuning of the quantum dot relative to the micropillar cavity mode. In this study, we investigate the charge noise in our micropillars devices by using the resonant fluorescence of the quantum dot [2]. We study both the influence of laser power and excitation time on the noise density spectra on various devices presenting different doping structures.

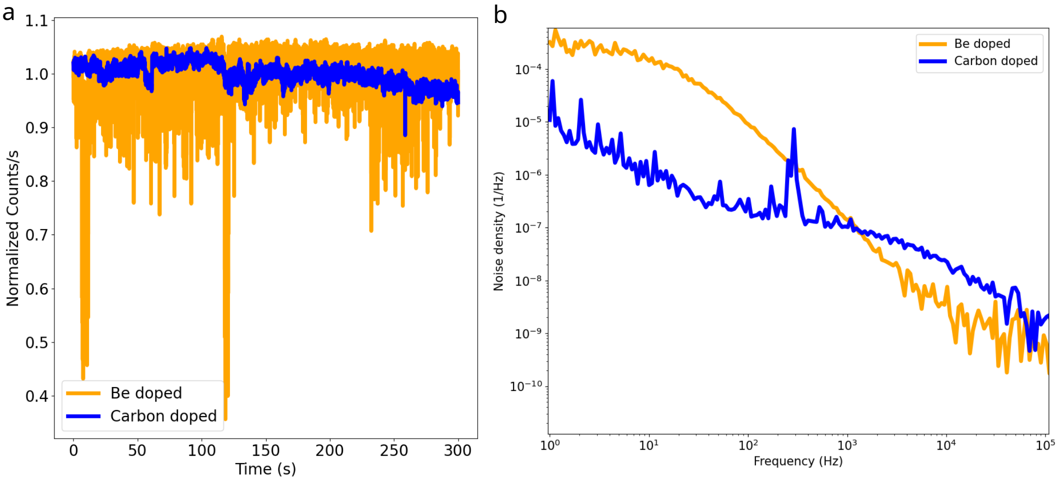

FIGURE 1 – **(a)** Normalized resonance fluorescence timetrace of a quantum dot embedded in a micropillar with different P-doping type (Beryllium and Carbon). **(b)** Corresponding noise density spectra.

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Hiding images in quantum correlations

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Photon-pair correlations in spontaneous parametric down conversion (SPDC) processes are ubiquitous in quantum photonics applications. Therefore, the ability to engineer and tailor their properties for a specific task is essential. In this work, we investigate the potential for encoding and retrieving information in the second order correlations of spatially entangled photon pairs produced by type-I SPDC in a non-linear crystal.

To encode an image of an arbitrary object, we project its Fourier transform directly onto the crystal, embedding the image in the photon correlations. After propagation, photons are detected using an Electron Multiplier Charge-Coupled Device camera to reveal the correlation-encoded image. This information remains undetectable by conventional intensity measurements. Our approach proves effective for both amplitude and phase objects, even when the beam intensity is spatially modulated [1].

Additionally, we make this technique resistant to optical scattering by employing it with wavefront shaping. When introducing a scattering media after the crystal, we recover the shaped correlation by learning the transmission matrix of the scattering media and compensating for it by adjusting accordingly the phase with a Spatial Light Modulator (SLM) [2].

Moreover, we find that certain phase patterns can refocus through the scattering medium exclusively with photon pairs, and not with classical coherent light. Consequently, when we correct with this model, the transmission of an image through the scattering medium is only possible if it is correlation encoded, and coherent light alone cannot reconstruct the image.

Our approach enables the transmission of complex, high-dimensional information using quantum spatial correlations of photons, offering significant potential for advancing quantum communication and imaging protocols.

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Defect engineering of single G centers in silicon using co-implantation method

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Silicon, the cornerstone of integrated photonics and microelectronics, is today becoming increasingly important for developing quantum technologies due to its compatibility and ease of integration with existing CMOS architectures. Optical quantum technologies rely on creation and manipulation of single photons [1]. Recentely, silicon wafers have been shown to host diverse near-infrared single-photon emitters [2, 3], such as G center [4], W center [6], T center [7], Er dopant [8] and many other unidentified defect centers [9]. This has opened a new exploration path for quantum integrated photonics with atomic-like single-photon sources directly integrated in silicon. Among these defects, the G center is of particular interest due to its emission in the telecom O-band [4, 5], and a metastable spin triplet that could be used as a qubit [10, 11]. Single G centers have been shown to be created via lab-facility ion implantation [4] and focused ion beam [12]. However, to develop large scale applications, a fundamental requirement is the controlled fabrication of G defects compatible with existing ion implantation semiconductor foundries.

In this work, we investigate the engineering of single G centers in silicon-on-insulation (SOI) samples using commercial ion implantations performed by II-VI. Our implantation method comprises (i) carbon implantation, followed by (ii) flash annealing at 1000°C in nitrogen atmosphere for cristal repair, and finally (iii) proton irradiation [4]. We characterize the defect properties by their zero-phonon line spectra, polarization diagrams and single-photon count rates, to identify the optimal carbon and proton fluences for creating well-isolated single G centers. Moreover, although our studies are primarily focused on G centers, we also observe and characterize other fluorescent defects created by this method. To achieve defect creation with sub-100-nm spatial resolution, this co-implantation technique, in addition to being commercially available and easily accessible, could be combined with implantation through PMMA masks [12]. This could unlock the deterministic fabrication of nanophotonic cavities around preselected single G centers and open up prospects for scalable integration of color centers in silicon quantum photonic chips.

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Non-Markovian dynamics of collectively-encoded qubits

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Collectively-encoded qubits are widespread in quantum technologies, for example in atomic or solid-state quantum memories. However, they suffer from uncontrolled inhomogeneous dephasing which couples them to a large bath of dark states. This significantly limits the coherence time of the qubit. In most cases, this process is not Markovian and thus cannot be encompassed in a standard master equation with time-independent coefficients, making its description either tedious or inaccurate.

We develop a new approach that enables us to understand this dephasing by considering it as a displacement in time-frequency phase space. In addition to the collective excited state, we introduce a small number of states generated through successive applications of the dephasing Hamiltonian, followed by orthonormalization. The last state of the system is then coupled to a Markovian bath, with a decay rate and a Lamb shift derived from the resolvent operator formalism. By doing so, we can reformulate the dynamics within the framework of a standard master equation and efficiently simulate numerically the evolution of the system for any kind of broadening.

Furthermore, we investigate this phenomenon both theoretically and experimentally using a Rydberg superatom : a small ensemble of cold atoms where interactions between Rydberg-state atoms limit the number of excitation to one, thus defining a collectively-encoded qubit[1]. the Rydberg superatom is coupled to an optical cavity enabling efficient mapping of its excited state to a photon. Therefore, by driving the superatom to its excited state, waiting for a given storage duration and mapping it to a photonic qubit, we can observe the decoherence of the collective qubit. We highlight the regime of strong driving where coherent dynamics of a Gaussian inhomogenously-broadened qubit occurs over times strongly exceeding its coherence time. This remarkable behavior is reminiscent of a phenomenon previously observed in systems with cavity coupled to inhomogeneous ensemble of emitters, commonly referred to as cavity protection [2][3]. Our "drive protection" precluding decoherence is a strong natural enhancement for such qubits fot quantum technologies.

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Coherence of a spin qubit coupled to photons

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Owning to their long lifetime and coherence time, spins in semiconductor quantum dots constitute a promising platform for scalable quantum information processing. These qubits generally rely on the spin-exchange interaction for 2-qubit gates, and on spin-charge conversion for the readout. While these methods have achieved high fidelities, they both have drawbacks as the former constrains the distance between qubits and the latter doesn't allow for fast quantum non demolition readout. [1]

One potential solution to these challenges is to engineer a coupling between spins and photons. Photons could serve as dispersive probes of the quantum state, and as mediators of a long-distance exchange interaction, similarly to what is routinely done for superconducting qubits [2]. However, a new interaction also brings new means of losing the quantum information.

We present a hole spin qubit delocalized in a Si double quantum dot coupled to a microwave cavity, currently holding the world-record for spin-photon coupling [3], and study the coherence times of this spin susceptible to photons. The strong coupling allows-us to measure its lifetime (Fig. 1a) and dephasing time (Fig. 1b) as a function of magnetic field and gate voltage on a wide scale. We span its energy over a range of 15GHz, crossing several cavity modes and identify photon emission (multimode Purcell) as one of the limiting mechanisms for the lifetime.

This system can be tuned to a point where it is protected to first-order from charge-noise. Surprisingly, even at this optimal point, the dephasing time is limited by charge noise due to second order coupling. In addition, photons may also contribute to dephasing as the fast dephasing is maximal close to the optimal point, which is also where spin-photon coupling is maximized. Further studies are needed to fully clarify the situation.

We generally find the qubit performances to be limited by its coupling to photons and to charge noise. Engineering the circuit architecture to reduce the coupling of the qubit to its photonic environment would then improve the spin lifetime by possibly orders of magnitude, drastically increasing the readout fidelity. Additionally, reducing second-order coupling to charge noise, which can be done by adjusting the magnetic field direction, would improve the coherence.

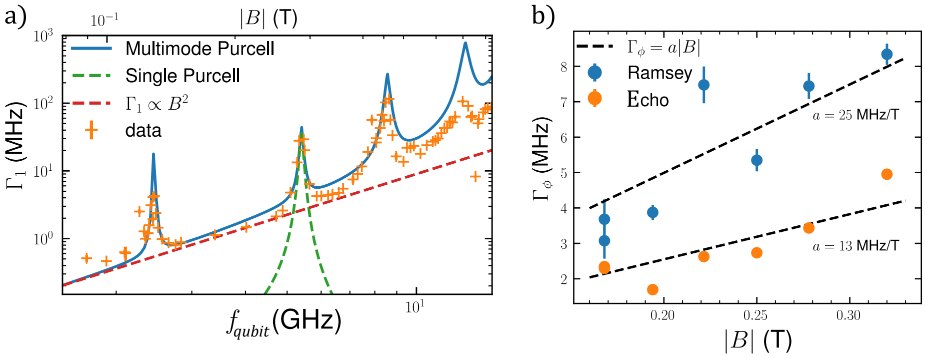

FIGURE 1. (a) Relaxation rate as a function of qubit frequency. (b) Echo and Ramsey dephasing rates as a function of magnetic field.

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Exploring Non-Linear Kinetic Inductance in Disordered Superconducting NbN thin films

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We present our investigation of non-linear kinetic inductance circuits based on superconducting disordered niobium nitride (NbN) films. This material is promising for advanced electronic applications due to its magnetic field and temperature resilience at microwave frequencies [1].

In our study, we have characterized DC-current-biased microwave resonators fabricated from a thin NbN film with high kinetic inductance. We analyze the relationship between the nonlinearity of the kinetic inductance, measured through the frequency dependence of our resonator at GHz frequencies and the depairing current, measured with DC current via the magnetic field film critical temperature dependence [2].

Our findings contribute to the growing body of knowledge on high kinetic inductance superconducting materials and their potential in quantum technologies.

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Approaching optimal microwave-acoustics transduction on lithium niobate using SQUID arrays

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Acoustic waves play an essential role in a wide variety of quantum systems such as microwave-to-optics transducers, quantum acoustics devices or devices using strain to couple to spin defects. For surface acoustic waves and Lamb waves, control and detection are commonly achieved using interdigital transducers (IDTs) on piezoelectric materials. However conventional IDTs are either inefficient or have narrow bandwidth and are not tunable in-situ.

Here we demonstrate an acoustic transducer showing both high efficiency (>60%) and wide bandwidth (hundreds of MHz), as well as in-situ tunability in the 4-8 GHz band. This transducer is based on IDTs fabricated on suspended lithium niobate, integrated with SQUID arrays on Si. We pattern lithium niobate structures to obtain basic acoustic networks such as waveguides and resonators for Lamb waves. On the other hand, SQUID arrays serve as lossless tunable matching circuits for the IDTs.

This technique is directly compatible with the quantum toolbox of superconducting circuits (parametric amplifiers, photon counters, etc.) and completes it with a highly sensitive acoustic probe. Among other experiments, it could be used to perform the acoustics spectroscopy of 2D-material or to sense phonons emitted by spin relaxation.

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