November 3-5
2021

IQFA'XII

12th colloquium on Quantum Engineering, Fundamental Aspects to Applications

ENS de Lyon
Amphithéâtre Mérieux
Place de l'École
Lyon France

Conception et réalisation Tana Puzenat / ENSmedia / ENS de Lyon / photographie Nil Hoppenot / septembre 2021

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1 What is IQFA ?

1.1 A CNRS "Research Network" on Quantum Information Science

The acronym **GDR IQFA** stands for "Groupement de Recherche Ingénierie Quantique, des aspects Fondamentaux aux Applications". It is a research network supported by the Centre National de la Recherche Scientifique (CNRS[1] GDR № 3322) through the Institutes of Physics (INP[2]), Systems & Engineering Sciences (INSIS[3]), and Computer Sciences & their interactions (INS2I[4]). This network gathers ∼60 French laboratories involving over 100 teams working on various aspects of quantum information science.

The goal of the GDR IQFA is twofold: to establish a common base of knowledge shared by different communities working in quantum engineering, and to use this shared knowledge for cross-fertilization between these communities.

IQFA's main roadmap can be summarized as follows:

- shape the discipline in order to create stronger bridges between the various thematics;
- establish a shared basis of knowledge through specific lecturing activities during the colloquiums;
- promote fundamental and applied Quantum Information Science in a "boundless laboratory" to facilitate the emergence of new projects which meet the current and future challenges of the field.

IQFA is organized along four themes - ART[5] - 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,

all based on transverse Fundamental Quantum Aspects – Fqa.

More details on those themes are provided on the IQFA webpage: http://gdriqfa.cnrs.fr/.

1.2 Scientific Committee of the GDR IQFA

Alexia Auffèves (CNRS, Univ. Grenoble Alpes),
Patrice Bertet (CEA, Univ. Paris Saclay),
Antoine Browaeys (CNRS, Inst. d'Optique Graduate School, Univ. Paris Saclay),
Thierry Chanelière (CNRS, Univ. Grenoble Alpes),
Eleni Diamanti (CNRS, Sorbonne Univ., Paris),
Anaïs Dréau (CNRS, Univ. Montpellier), Director,
Pascal Degiovanni (CNRS, ENS Lyon),
Iordanis Kerenidis (CNRS, Univ. de Paris),
Tristan Meunier (CNRS, Univ. Grenoble Alpes),
Alexei Ourjoumtsev (CNRS, Collège de France), Deputy Director
Simon Perdrix (CNRS, Univ. de Lorraine Metz-Nancy),
Nicolas Treps (ENS Paris, Sorbonne Univ., Paris)

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

2 IQFA'12 Colloquium – Scientific Information

2.1 Welcome !

IQFA'12 is organized by the IQFA Scientific Committee and by the École Normale Supérieure de Lyon[6]. Its main goal is to gather members of various communities involved in Quantum Information Science and to foster exchanges about the latest advances in the field. The colloquium will feature four types of presentations:

- 6 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,
- 3 invited talks (25'+5' discussion) on results that struck the most the scientific committee during the past year;
- 18 contributed talks (25'+5' discussion), representative of the different themes of IQFA and selected among the 85 contributions received by the scientific committee for their scientific quality and for their general interest;
- 65 contributed posters, presented during two two-hour sessions according to their theme.

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

We wish all the participants a fruitful colloquium.

On behalf of IQFA's Scientific Committee,

The organizers:

Tessa Adrian-Roux (ENS Lyon, Head of the Conference & Event Support Service),
Audrey Bienfait (CNRS, ENS Lyon),
Farah Daoulet (ENS Lyon, Conference & Event Support Service),
Pascal Degiovanni (CNRS, ENS de Lyon; President of IQFA'12),
Anaïs Dréau (CNRS, Univ. Montpellier; IQFA's Director),
Omar Fawzi (INRIA, ENS Lyon),
Benjamin Huard (ENS Lyon),
Alexei Ourjoumtsev (CNRS, Collège de France; IQFA's Deputy Director),
Tommaso Roscilde (ENS Lyon).

[6]http://www.ens-lyon.fr/

2.2 Program of the colloquium

Paris time	Wednesday the 3rd of November 2021	Thursday the 4th of November 2021	Friday the 5th of November 2021
08:30	Welcome - P. Degiovanni & A. Dréau		
09:00	**Tutorial - FQA - M. Huber (TU Vienna, AT): *The thermodynamics of measuring time***	QCOM - Y. Pelet (Univ. Côte d'Azur, CNRS, FR): *Operational entanglement-based real-field quantum key distribution*	***Tutorial - QPAC - I. Kerenidis (CNRS, Univ. Paris, FR): Quantum machine learning***
09:30		QCOM - J. Vaneecloo (CNRS, Collège de Fr., PSL Univ., FR): *A Rydberg superatom for cavity QED applications: coherent control, single-shot detection and state-dependent optical π phase shift*	
10:00	**Invited talk - FQA - H. Wiseman (Griffith Univ., AU): *Can a qubit be your friend? Why experimental metaphysics needs a quantum computer***	QCOM - F. Kaiser (Univ. Stuttgart, D): *Integrated nanophotonic multi-spin-photon interface based on silicon vacancies in silicon carbide*	QPAC - A.Shayeghi (Univ. Lyon, ENS Lyon, CNRS, Inria, FR): *A lower bound on the space overhead of fault-tolerant quantum computation*
10:30	Coffee break	Coffee break	Coffee break
11:00	FQA - A. Feller (Univ .Lille, CNRS, Centrale Lille, FR): *Emergence of a classical objective reality from a quantum observer network*	QMET - L. Garbe (TU Wien, AT): *Universal scaling laws for critical quantum sensing*	**Tutorial - QPAC - M. Veldhorst (TU Delft, NL): *Quantum information processing with semiconductor technology: from qubits to integrated quantum circuits***
11:30	FQA - I. Maillette de Buy Wenniger (CNRS, Univ. Paris-Saclay, FR)*: Coherence-enabled charge and discharge of a quantum battery*	QMET - L. Balembois (Univ. Paris-Saclay, CEA, CNRS, FR): Detecting spins by their fluorescence with a microwave photon counter	
12:00	FQA - A.Essig (Univ. Lyon, ENS Lyon, CNRS, FR): *Multiplexed photon number measurement*	QMET - A. Serafin (ENS Ulm, FR)*: Nuclear Spin-Squeezing of Helium-3 via continuous Quantum Non-Demolition measurement*	QPAC - C. Chareton (Univ. Paris-Saclay, CEA, FR): *A Deductive Verification Framework for Circuit-building Quantum Programs*
12:30	Lunch	Lunch	Lunch
14:00	FQA - H. Le Jeannic (Uni. Copenhagen, DK & Univ. Bordeaux, CNRS, FR): *Few-photons nonlinearity induced by a single quantum dot well-coupled to a photonic waveguide*	**Tutorial - QCOM - J. Thompson (Princeton Univ., USA): *Quantum technologies with single rare earth ions***	QPAC - O. Buisson (Univ. Grenoble Alpes, CNRS, FR)*: Fast high fidelity quantum non-demolition superconducting qubit readout*
14:30	QSIM - A. Raymond (Univ. Paris, CNRS, FR)*: Anyonic two-photon statistics with a semi-conductor chip*		QCOM/QPAC - B. Asenbeck (Sorbonne Univ., CNRS, ENS-Univ. PSL, FR): *Optical quantum hybrid information processing*
15:00	QSIM - Q. Fontaine (Univ. Paris-Saclay, CNRS, FR): *Observation of KPZ universal scaling in a one-dimensional polariton condensate*	**Invited talk - QCOM - A. Fedrizzi (Heriot-Watt Univ., UK): *Quantum networking with photonic graph states***	Closing session - A. Dréau
15:30	Coffee break	Coffee break	
16:00	QSIM - M. Filippone (Univ. Grenoble Alpes, CEA, FR): *Quantum simulation with solid-state quantum technologies : Observing many-body localization in a superconducting qubit array*	***Tutorial* - QMET - Ronald Walsworth (Univ. Maryland, USA): *Quantum sensing with NV centers in diamond***	
16:30	QSIM - G.Bornet (Univ. Paris-Saclay,CNRS,FR): *Microwave-engineering of programmable XXZ Hamiltonians in arrays of Rydberg atoms*		
17:00	**Tutorial - QSIM - M. Schleier-Smith (Stanford Univ., USA): Programmable Interactions and Emergent Geometry**	**Invited talk - QMET - A. Sipahigil (Berkeley Univ., USA): *Optical interconnects for superconducting quantum processors***	
17:30		Poster session 2: QMET, QSIM, QPAC	
18:00	Poster session 1: FQA, QCOM		
18:00			
19:00			
19:30		Banquet	

3 IQFA'12 Colloquium – Practical Information

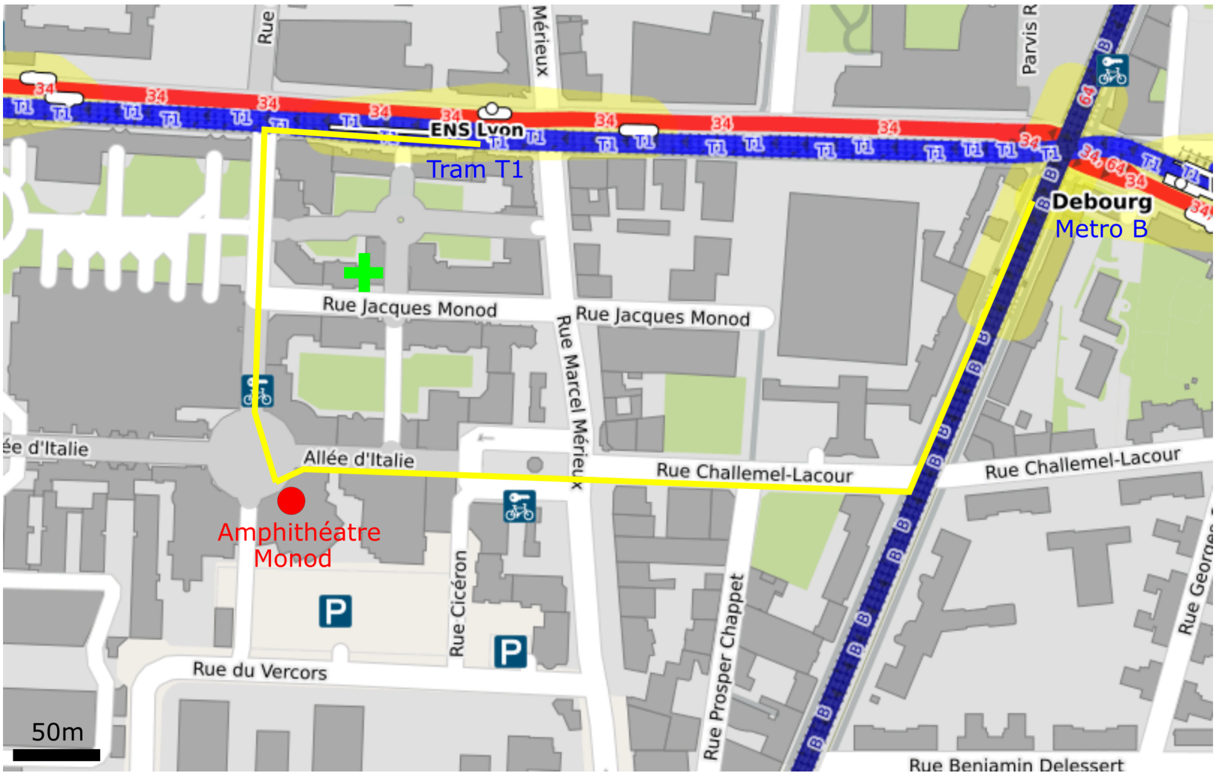
3.1 Venue

Oral sessions will take place in

Amphithéatre Mérieux, Ecole Normale Supérieure de Lyon,
Place de l'École, 69007 Lyon, France.

Poster sessions will take place in the Atrium, outside the Amphitheater. The maximal format for posters is A0, portrait orientation. Posters submitted to FQA and QCOM themes will be presented on Wednesday 3 November 2021, 18:00-20:00. Posters submitted to QMET, QSIM and QPAC themes will be presented on Thursday 4 November 2021, 17:30-19:30. Posters submitted to more than one theme will be presented during the second (Thursday) session.

Coffee breaks, lunches and the conference dinner will take place in the Atrium, next to the posters. They are free of charge for registered participants.



- **From Lyon St-Exupery airport:** Take the RhoneExpress tram to Lyon Part-Dieu train station. Change to metro line B towards Gare d'Oulins, exit at station Debourg.
- **From Lyon Part-Dieu train station:** Take the metro line B towards Gare d'Oulins, exit at station Debourg.
- **From Lyon Perrache train station:** Take the tram line 1 towards Debourg, exit at station ENS Lyon.

More information about local transportation to the conference site is available on the ENS Lyon website.

3.2 Safety & sanitary regulations

In-person participants must:

- Present a valid "Health Pass" at the entrance, on the first day of the conference. This pass will be required to enter the premises and to obtain a badge. The latter must be worn throughout the colloquium.

- Wear a face mask (mask for the general public with a filtration level of over 90% or surgical mask) during all of the event. Please note that these masks will **not** be distributed on site. The closest location where they can be purchased is the pharmacy “Pharmacie des Pavillons” located at 7 Rue Jacques Monod, about 100m from the conference site.
- Keep a distance of at least 1 meter while standing and 1 meter or one seat while seated.

National authorities encourage downloading and installing the “TousAntiCovid" contact-tracing app.

4 Host institution & sponsors of the colloquium

The École normale supérieure de Lyon, which hosts ans supports the IQFA’12 colloquium, is an elite French public institution that trains professors, researchers, senior civil servants as well as business and political leaders. Students choose their courses and split their time between training and research in sciences and humanities. Built on the tradition of the ENS de Fontenay-Saint-Cloud, founded in 1880, the ENS de Lyon also focuses on educational research. It is a symbol of French Republican meritocracy and it remains committed today to disseminating knowledge to the widest audience and to promoting equal opportunity. The ENS de Lyon is part of the Université de Lyon and supports quality research that has earned it a Fields medal (Cedric Villani, 2010) and many CNRS medals. It encourages interdisciplinary studies to foster a better understanding of complex contemporary issues.

The Centre National de la Recherche Scientifique (CNRS) is a public research institution under the responsibility of the French Ministry of Higher Education, Research, and Innovation (MESRI). The CNRS Institute of Physics (INP) focuses on research thematics related to radiation, matter, and fundamental laws. Those studies come with two main motivations : understanding the world, and answering current societal challenges. The CNRS Institutes of Engineering and System Sciences (INSIS) and of Information Sciences (INS2I) also support IQFA.

Centre Blaise Pascal, home of numerical modeling, is a place of gathering for all scientific fields around digital modeling: it takes various forms, ranging from conferences to research projects and training programs. The CBP facility consists of a wide range of computational resources (such as computing clusters, dedicated servers, collaborative work tools, a forge platform, a room for practical training, etc.), it is also equipped with offices, meeting rooms and conference rooms.

The André Marie Ampère Research Federation FRAMA encompasses the whole spectrum of activities in experimental and theoretical physics undertaken in Lyon. The participating laboratories develop research projects in the domains of condensed or diluted matter, subatomic physics, cosmology and astrophysics, optics and lasers, nanosciences, ..., with many transdisciplinary efforts oriented towards biology, biochemistry, health sciences, geophysics, mathematics, environmental science, ...

MILYON is a center of excellence in mathematics and theoretical computer science. It gathers more than 450 researchers, from five research units (UMR) of the University of Lyon located in Lyon and Saint-Etienne. MILYON focuses on four key areas: Excellence in research, especially at the interfaces of the two disciplines, and with other sciences; Education, with innovative research-oriented curriculums; Outreach with an ambitious program aimed at disseminating scientific culture among the general public and technology transfer to industry.

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 participants registered to the colloquium, and the list of authors of the presented papers.

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Tutorial talks

The thermodynamics of measuring time

Marcus Huber[1,2]*
[1]*Institute for Quantum Optics and Quantum Information - IQOQI Vienna, Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria*
[2]*Atominstitut, Technische Universität Wien, 1020 Vienna, Austria*

It is often said that time is what a clock measures. But what exactly does a clock measure ? In this tutorial I will review how the connection between the second law of thermodynamics and the arrow of time manifests in different clocks and why some of the intrinsic thermodynamic features only reveal themselves when considering the fundamental quantum nature of measurements.

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Atoms Interlinked by Light : Programmable Interactions and Emergent Geometry

Monika Schleier-Smith[1,2*]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
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Interactions govern the flow of information and the structure of correlations in quantum systems. Typical interactions decay with distance, resulting in a network of connectivity that is dictated by geometry. Yet a variety of applications in quantum state engineering, quantum simulation, and combinatorial optimization demand more versatile control of the graph of interactions, including nonlocal connectivity. I will report on the realization of programmable nonlocal interactions in an array of atomic ensembles within an optical resonator, where photons convey information between distant atomic spins. We program the coupling graph by tailoring the spectrum of an optical drive field, probing the resulting connectivity by observing spatial correlations arising from light-mediated spin mixing. As illustrative examples, we explore frustrated interactions, non-trivial topologies, and an emergent treelike geometry inspired by concepts of quantum gravity.

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Quantum technologies with single rare earth ions

Jeff Thompson[1*]
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Atomic defects in solid-state crystals are widely explored as single-photon sources and quantum memories for large-scale quantum communications networks based on quantum repeaters. Rare earth ions, in particular Er3+, have attracted recent attention because of the demonstration of extremely large Purcell enhancement in nanophotonic cavities, which overcomes the slow intrinsic photon emission rate. Using this approach, we have demonstrated the first atomic source of single photons in the telecom band, and high-fidelity single-shot readout of the Er3+ electron spin using cavity-induced cycling transitions. Furthermore, we have realized optical manipulation and single-shot readout of multiple atoms with spacings far below the diffraction limit of light, using a novel frequency-domain super-resolution technique. I will conclude by discussing some recent work on coherent control of nearby nuclear spins, as well as a systematic investigation of new host materials with the potential to realize longer spin and optical coherence times.

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Quantum sensing with NV centers in diamond

Ronald Walsworth[1]*
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The nitrogen–vacancy (NV) center in diamond is a leading modality for magnetic, electrical, temperature, and force sensing with high spatial resolution and wide field-of-view under ambient conditions. This quantum sensing technology has diverse applications across the physical and life sciences — from probing magnetic materials to fingerprinting integrated circuit activity to biomedical diagnostics. I will provide an overview of quantum diamond sensors and their diverse applications.

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Quantum machine learning

Iordanis Kerenidis[1,2*]
[1]*Université de Paris, CNRS, IRIF, F-75006, Paris, France*
[2]*QC Ware, Palo Alto, USA and Paris, France*

We will discuss the prospects and challenges of quantum machine learning, one of the most promising areas for finding real applications of quantum computing.

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Quantum information processing with semiconductor technology : from qubits to integrated quantum circuits

Menno Veldhorst[1,2*]
[1]*QuTech, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*
[2]*Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*

Our approach toward scalable quantum technology departs from the transistor, the most replicated structure made by mankind. We define qubits on the spin states of electrons and holes in silicon and germanium quantum dots. In this talk I will present our recent results in increasing the qubit quality and quantity. First, we show that even a single hole can be coherently controlled. By exploiting the strong spin-orbit interaction of holes we obtain fast qubit operation with gate fidelities of 99.99%, setting new benchmarks for quantum dot systems. Furthermore, through dynamical decoupling we obtain record coherence times for holes and by applying this technique as a band filter we are able to measure the transversal hyperfine interaction with nuclear spins. Second, we demonstrate that quantum dot qubits and control electronics can be operated in the same temperature regime. In addition, we show that qubits can be realized using a fully-industrial 300 mm wafer process. These together define a key step toward integrated quantum circuits. Third, we construct a 2×2 quantum dot array and show qubit coupling in two dimensions. We obtain universal control and demonstrate coherent execution of a quantum circuit that entangles and disentangles all four qubits. Finally, I will present our strategies to overcome qubit-to-qubit variations, aiming to build quantum systems with fewer control lines than number of qubits, targeting to achieve a quantum advantage with the same materials and techniques that enabled today's information age.

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Invited talks

Can a Qubit Be Your Friend ? Why experimental metaphysics needs a quantum computer

Howard Wiseman[1]*
[1]*Centre for Quantum Dynamics, Griffith University, Brisbane, QLD 4111, Australia*

Experimental metaphysics is the study of how empirical results can reveal indisputable facts about the fundamental nature of the world, independent of any theory. It is a field born from Bell's 1964 theorem, and the experiments it inspired, proving the world cannot be both local and deterministic. However, there is an implicit assumption in Bell's theorem, that the observed result of any measurement is absolute (it has some value which is not 'relative to its observer'). This assumption may be called into question when the observer becomes a quantum system (the "Wigner's Friend" scenario), which has recently been the subject of renewed interest. Here, building on work by Brukner, we derive a theorem, in experimental metaphysics, for this scenario [**?**]. It is similar to Bell's 1964 theorem but dispenses with the assumption of determinism. The remaining assumptions, which we collectively call "local friendliness", yield a strictly larger polytope of bipartite correlations than those in Bell's theorem (local determinism), but quantum mechanics still allows correlations outside the local friendliness polytope. We illustrate this in an experiment in which the friend system is a single photonic qubit [**?**]. I argue that a truly convincing experiment could be realised if that system were a sufficiently advanced artificial intelligence software running on a very large quantum computer, so that it could be regarded genuinely as a friend. I will briefly discuss the implications of this far-future scenario for various interpretations and modifications of quantum theory.

[1] Kok-Wei Bong, Aníbal Utreras-Alarcón, Farzad Ghafari, Yeong-Cherng Liang, Nora Tischler, Eric G. Cavalcanti, Geoff J. Pryde and Howard M. Wiseman, "A strong no-go theorem on the Wigner's friend paradox", Nature Physics **16**, 1199 (2020)

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Quantum networking with photonic graph states

Alessandro Fedrizzi[1*]
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Future quantum networks will provide multi-node entanglement enabling secure quantum communication on a global scale. Traditional two-party quantum key distribution (2QKD) consumes pairwise entanglement which is costly in constrained networks. Quantum conference key agreement (QCKA) leverages multipartite entanglement within networks to directly produce identical keys among N users, providing up to N-1 rate advantage over 2QKD. In my talk I will present work on the implementation of QCKA using photonic GHZ states distributed over telecom fibre of up to 50 km combined length. Furthermore, we implemented QCKA on a constrained network consisting of a 6-qubit photonic graph state on which we apply network coding routines to demonstrate the multi-partite advantage over the two-party paradigm.

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Optical Interconnects for Superconducting Quantum Processors

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The ability to store, transfer, and process quantum information promises to transform how we calculate, communicate, and measure. In the past two decades, superconducting microwave circuits based on Josephson junctions emerged as a powerful platform for quantum computation. However, these systems operate at low temperatures and microwave frequencies, and require coherent optical interconnects to transfer quantum information across long distances. In this talk, I will present our recent experiments demonstrating the transduction of a superconducting qubit excitation to an optical photon. I will present an integrated device platform combining superconducting qubits, piezoelectric transducers, and optomechanical transducers for converting quantum states between superconducting circuits, single phonons, and single optical photons. I will discuss how we use nanomechanical oscillators in their quantum ground states to convert single photons from microwave frequencies to the optical domain. I will conclude by discussing the prospects of this approach for realizing future quantum communication networks based on superconducting quantum processors.

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Contributed talks

Emergence of a classical objective reality from a quantum observer network

Alexandre Feller*
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Understanding the emergence of a classical picture within a quantum universe is one of the key physics questions related to the fondations of quantum theory. The development of quantum information and communication theory is shifting our views about this question by focusing on an agent based approach focused on the measuring, computing and communication resources available to many observers probing the information flow from the system to its environment [1–3]. Classicality is then viewed as a specific form of the many-body correlations within this complex quantum observer network.

In this talk, I will address two important questions arising from this paradigm shift : First, does a classical picture always exists, even when incompatible decoherence channels interact with the system ? Second, how do we characterize the ability for many observers to reconstruct a classical picture using quantum information notions.

To get an experimentally relevant and physically intuitive understanding of the underlying issues, I will consider the dispersive model of a qubit interacting with a propagating quantum electromagnetic field. Concerning the first question, I will explain how classical pointer states depends on the relative strength of the two incompatible decoherence channels, showing that number states remain the most robust states to decoherence up to a critical coupling, with a crossover exhibiting no clear classical interpretation [4]. Concerning the second question, I will discuss quantitatively how information about pointer states in a QND dispersive measurement scheme is broadcasted among various time-frequency modes of the outgoing radiation scattered by the cavity. This signal processing analysis in which the various modes play the role of an observer will enable us to discuss Zurek's quantum Darwinism picture in an experimentally relevant context. We will then conclude by commenting on the correlation structure necessary to obtain a classical picture from a quantum observer network [3, 5, 6].

[1] W.H. Zurek, Nature Physics **5**, 181 (2009).
[2] F. Brandao, M. Piani, and O. Horodecki (2015), Nature Communications **6**, 7908 (2015)
[3] A. Feller, B. Roussel, I. Frérot, O.Fawzi and P. Degiovanni, ESA Ariadna report (2021).
[4] A. Feller, G. Cœuret Cauquil and B. Roussel, Physical Review A **101**, 062107 (2020).
[5] Le, T. P. and Olaya-Castro, A., Physical Review Letters **122**, 010403 (2019).
[6] A. Feller, B. Roussel, I. Frérot and P. Degiovanni. Physical Review Letters **126**, 188901 (2021).

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Coherence-Powered Charge and Discharge of a Quantum Battery

I. Maillette de Buy Wenniger[1], S. E. Thomas[1], M. Maffei[2], S. C. Wein[2,3], M. Pont[1], A. Harouri[1], A. Lemaitre[1], I. Sagnes[1], N. Somaschi[4], A. Auffèves[2], P. Senellart[1]

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[2] *Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*

[3] *Institute for Quantum Science and Technology and Department of Physics and Astronomy, University of Calgary, Calgary, Alberta, Canada T2N 1N4*

[4] *Quandela SAS, 7 Rue Léonard de Vinci, 91300 Massy, France*

Quantum coherence has recently emerged as a key concept to describe the law of quantum thermodynamics, supporting the definition of work and governing the laws of work exchange. More specifically, recent theory predicts quantum coherence to play a crucial role in the work transfer from a quantum substance to a quantum battery [1–4].

The coupling of a two-level system to a single mode harmonic oscillator has been proposed as a toy model to explore these energy transfers [2, 3, 5]. Such system can be mapped to a two level-system (qubit) coupled to a single mode of the electromagnetic field (battery), with light emission taking place either in the spontaneous (empty battery) or stimulated regime (loaded battery) [2, 3]. In the spontaneous emission regime, it was recently predicted that the maximum amount of work extracted from the working substance to the quantum battery is limited to the coherent part of the energy carried by the initial qubit.

We experimentally study the role of coherence in the process of work transfer both in the charging and discharging of a quantum battery. We investigate the work transfer from a qubit (a two-level system of a quantum dot) into an initially empty quantum battery (a mode of the electromagnetic field). We observe that the amount of work charged into the quantum battery through spontaneous emission is proportional to the quantum coherence initially carried by the qubit and is altered by temperature. We then discharge the quantum battery into a classical coherent field, which acts as a work receiver using a homodyne-type measurement. The amount of work transferred to the work receiver is controlled by the relative fields classical optical phase, the overall quantum purity of the charged battery field as well as long term fluctuations in the qubit energy.

[1] G. Francica, F. C. Binder, G. Guarnieri, M. T. Mitchison, J. Goold, and F. Plastina, Phys. Rev. Lett. **125**, 180603 (2020), arXiv:2006.05424.

[2] J. Monsel, M. Fellous-Asiani, B. Huard, and A. Auffèves, Phys. Rev. Lett. **124**, 1 (2020), arXiv:1907.00812.

[3] M. Maffei, P. A. Camati, and A. Auffèves, , 1 (2021), arXiv:2102.05941.

[4] F. Caravelli, B. Yan, L. P. García-Pintos, and A. Hamma, Quantum **5**, 505 (2021), arXiv:2012.15026.

[5] G. M. Andolina, D. Farina, A. Mari, V. Pellegrini, V. Giovannetti, and M. Polini, Phys. Rev. B **98**, 205423 (2018).

Multiplexed photon number measurement

Antoine Essig[1], Quentin Ficheux[1], Théau Peronnin[1], Nathanaël Cottet[1], Raphaël Lescanne[2,3], Alain Sarlette[2,3,4], Pierre Rouchon[5,3], Zaki Leghtas[5,2,3], and Benjamin Huard[1*]
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[2]*Laboratoire de Physique de l'Ecole Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université Paris-Diderot, Sorbonne Paris Cité, Paris, France*
[3]*QUANTIC team, INRIA de Paris, 2 Rue Simone Iff, 75012 Paris, France*
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When a two-level system—a qubit—is used as a probe of a larger system, it naturally leads to answering a single yes-no question about the system state. Identifying what is the state of a system thus comes down to playing a game of "guess who ?" A series of binary questions are asked iteratively to refine our knowledge about the state. To give a concrete example, in order to determine how many photons are stored in a cavity, one may ask "is there an even number of photons ?" or a series of binary questions such as "are there n photons ?" for each integer n. Such experiments have been implemented with Rydberg atoms or superconducting circuits probing a microwave cavity [1,2] with the possible refinement of choosing what binary question should be optimally asked conditioned on the previous answers [3]—using a feedback loop [4,5] or advanced pulse shaping [6]. Determining an arbitrary number of photons in the cavity between 0 and 2^m-1 thus takes at least m consecutive probe measurements since each answer provides at most 1 bit of information about the system state. This limitation originates from the encoding of the extracted information into the quantum state of the qubit. But is it the best use of a qubit to determine an observable with many possible outcomes such as a photon number ?

We propose to use a qubit as an encoder of information about the state of a microwave cavity in the many propagating modes of a transmission line. Assuming an ideal detector, we show that photon counting can then be implemented in a time independent of the number of photons. We demonstrate the practicality of this approach in an experiment [7] where information about nine possible photon numbers (more than 3 bits) in a microwave resonator is simultaneously extracted by a single superconducting qubit into nine propagating modes of a transmission line. Daring an analogy with communication protocols, previous measurement schemes with time series of binary questions used time division multiplexing, while our experiment demonstrates the analog of frequency division multiplexing, where the qubit alone acts as the frequency multiplexing transducer. This experiment directly benefits from the recent bandwidth improvements of near-quantum-limited amplifiers [8], which enable us to bring the measurement process in the frequency domain. In addition, we manage to observe the multiplexed measurement backaction on the resonator using direct Wigner tomography, which allows us to measure the decoherence rate of the resonator induced by the measurement. We evidence an optimal qubit drive amplitude for information extraction, which matches the expected dynamics of a qubit under a multifrequency drive.

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Few-photons nonlinearity induced by a single quantum dot well-coupled to a photonic waveguide

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Among other solid-state emitters, single quantum dots in nanophotonics waveguides could form the backbone of a promising platform for complex quantum optical circuitry [1][2]. Reaping the benefits of this platform, for example to deterministically generate single photons [2] or exploit single photon nonlinearities [3], demands that the emitters be both efficiently coupled to photonic mode and highly coherent. The latter requirement is challenging in the solid-state, and in particular in nanophotonic systems, where decoherence processes due to phonons, charge or spin noise are typically enhanced by the presence of nearby interfaces. The first observation of near-lifetime limited transitions of quantum dots embedded in nanophotonic waveguides enabled achieve highly coherent light-matter interactions [4]. Record extinction in the transmission of light through a waveguide by a single quantum emitter, occurring due to the interference of the incident and scattered light was achieved and reached over 65% in nanobeam waveguides [4] and over 80% in photonic crystal waveguides [7]. The confirmed high coupling efficiency and coherence of our system allowed us to probe the nonlinearity of the light-matter interactions not only at the the single- but also at the two-photon level, by implementing loss-robust scattering tomography protocol [7].

These results pave the way towards deterministic and coherent single photon nonlinear optics [6] and to the realization of photon sorting protocols, efficient Bell measurements or also deterministically controlled-Z gates [5].

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Anyonic two-photon statistics with a semi-conductor chip

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We employ parametric down-conversion in an AlGaAs chip to engineer the wavefunction and exchange statistics of photon pairs directly at the generation stage, leading to the observation of fermionic and anyonic behaviours from photons.

High-dimensional entangled states of light provide novel capabilities for quantum information, from fundamental tests of quantum mechanics to enhanced computation and communication protocols. In this context, the frequency degree of freedom is attracting a growing interest due to its robustness to propagation in optical fibers and its capability to convey large scale of quantum information into a single spatial mode. This provides a strong incentive for the development of efficient and scalable methods for the generation and the manipulation of frequency-encoded quantum states. Nonlinear parametric processes are powerful tools to generate such states, but up to now the manipulation of the generated frequency states has been carried out mostly by post-manipulation, which demands complex and bulk-like experimental setups. Direct production of on-demand frequency-states at the generation stage, and preferably using a chip-based source, is crucial in view of practical and scalable applications for quantum information technologies.

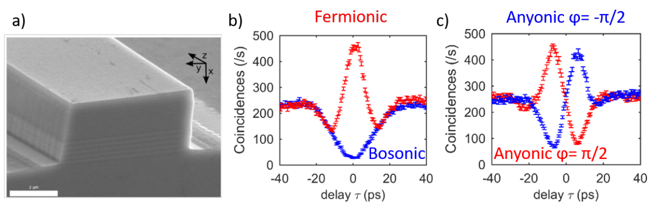

FIGURE 1. a) SEM image of an AlGaAs ridge microcavity emitting photon pairs by SPDC. b) Measured HOM interferogram of frequency-entangled biphotons exhibiting bosonic, fermionic, or c) anyonic behaviors.

Here we use an integrated AlGaAs chip (Fig.1a) to generate frequency-entangled photon pairs from parametric down-conversion. The used couterpropagating phase-matching scheme gives room for direct control of the spectral wavefunction through the spatial properties of the pump beam, directly at the generation stage [2]. Tuning the pump spatial intensity allows to produce frequency-anticorrelated, correlated and separable states, while tuning the spatial phase allows to continuously tune the symmetry of the spectral wavefunction, leading to bosonic, fermionic (Fig.1b), or anyonic (Fig.1c) behaviours of the photons as revealed by Hong-Ou-Mandel interferometry [1]. These results, obtained at room temperature and telecom wavelength, open promising perspectives for implementing quantum simulation tasks with tailored wavefunction and particle statistics in a chip-integrated platform, as well as for communication and computation protocols exploiting high-dimensional quantum states.

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Observation of KPZ universal scaling in a one-dimensional polariton condensate

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Revealing universal behaviors in different systems is a hallmark of statistical physics. At equilibrium, simple models – like the Ising model – have been pivotal in understanding the critical properties of a whole class of physical systems. Reversely, a clear description of the universal properties of several non-equilibrium systems is still missing. In this context, the Kardar-Parisi-Zhang (KPZ) equation has emerged as a quintessential model to investigate non-equilibrium phenomena and phase transitions. The KPZ equation [1] is a stochastic nonlinear partial differential equation that was originally proposed to describe the growth dynamics of an interface $h(r,t)$:

$$\partial_t h(x,t) = \nu \nabla^2 h(x,t) + \frac{\lambda}{2} \left(\nabla h(x,t)\right)^2 + \eta(x,t)$$

The first term on the right hand side describes a diffusion process. The second one is a crucial nonlinear contribution describing the growth of the interface and leads to its critical roughening. Finally, η is a Gaussian white noise stemming from intrinsic stochastic fluctuations. The spatial and temporal correlation functions of $h(x,t)$ exhibit universal power law scalings, with critical exponents that are specific to the KPZ universality class [1].

Currently available experimental observations of KPZ dynamics have mainly focused on probing the critical roughening of growing interface in classical systems [2, 3]. However, recent theoretical works suggest that the phase of a polariton condensate behaves as an interface, whose spatio-temporal evolution falls into the KPZ universality class [4, 5]. Those results are also relevant for other out-of-equilibrium systems, such as out-of-equilibrium BECs and lasers. Determining if KPZ physics governs the phase correlations in those systems is of critical importance. For instance, it would set an intrinsic limitation on the achievable coherence of large-area laser sources, beyond the standard Schawlow-Townes linewidth.

In our poster, we explore both experimentally and theoretically the spatio-temporal dynamics of the first order coherence in an extended 1D polariton condensate. We observe the stretched exponential decay of the coherence that is characteristic to KPZ physics, and evidence the collapse of the data onto the universal KPZ scaling function. Our results suggest that exciton-polariton lattices offer promising perspectives for the exploration of KPZ physics in higher dimensions.

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Quantum simulation with solid-state quantum technologies : Observing many-body localization in a superconducting qubit array

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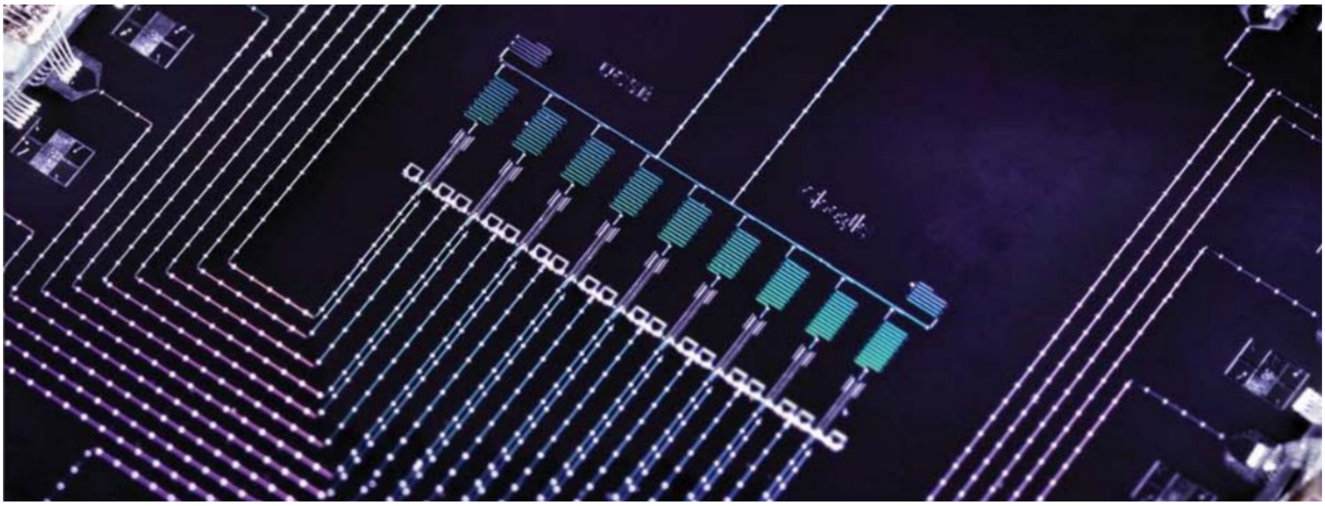
I will discuss how quantum technologies based on solid state arrays of superconducting qubits (see figure below) are now able to unveil and investigate novel fundamental phenomena by simulating interacting quantum systems. In particular, we will ask : Is it possible to harness and preserve the quantum coherent properties of many-body systems ? This project seems doomed to fail, as interactions in many-body systems generally lead to ergodicity, namely the inevitable loss of quantum coherence and memory about initial conditions. Nevertheless, the recent discovery of many-body localization (MBL) – a generalization of Anderson localization in the presence of interactions – has shown the possibility to circumvent ergodicity. I will illustrate an experiment in which an array of superconducting qubits probes the exotic dynamics of interacting and disordered bosons [1]. Relying on real-time and interferometric probes, I will discuss how we could observe and characterize the mechanism of MBL.

If time permits, I will then describe the possibility to trigger ergodicity in quantum simulators, by injecting single interacting impurities in localized and isolated quantum systems [2].



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Microwave-engineering of programmable XXZ Hamiltonians in arrays of Rydberg atoms

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Among the platforms being developed, the one based on Rydberg atoms held in arrays of optical tweezers is now a promising candidate for quantum simulation [1] and computation [2]. Recent works have demonstrated its potential through the implementation of different spin models. Here we use the resonant dipole-dipole interaction between Rydberg atoms and a periodic external microwave field to engineer XXZ spin Hamiltonians tunable anisotropies [3, 4]. The atoms are placed in 1D and 2D arrays of optical tweezers, allowing us to study iconic situations in spin physics, such as the implementation of the Heisenberg model in square arrays, and the study of spin transport in 1D [5]. We first benchmark the Hamiltonian engineering for two atoms, and then demonstrate the freezing of the magnetization on an initially magnetized 2D array. Finally, we explore the dynamics of 1D domain wall systems with both periodic and open boundary conditions. We systematically compare our data with numerical simulations and assess the residual limitations of the technique as well as routes for improvements. The geometrical versatility of the platform, combined with the flexibility of the simulated Hamiltonians, opens exciting prospects in the field of quantum simulation, quantum information processing and quantum sensing.

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Operational entanglement-based real-field quantum key distribution

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The current increase of telecommunication bandwidth and security requirements of our connected society sets a critical need for practical, absolutely secured and 24h/24h operational secret key distribution links. Since the dawn of QKD in 1984 based on single Qbit exchange, the protocols have improved and got diversified to meet all the specific requirements of practical secret key distribution in terms of security, distance and rate. Now in 2021, QKD has been demonstrated on real field implementation, exploiting free-space links toward satellites, terrestrial and underwater fiber links combined with optimized experimental protocols. For instance, the improved original QKD protocol (decoy BB84) is now used to communicate through thousands of kilometers with trusted nodes acting as repeaters in China, and can even reach satellites [1]. Twin-field QKD has set the longest distance for a repeaterless link [2] while entanglement-based protocols (BBM92) can connect many users at a time exploiting multiplexing scheme [3].

In this context, our experiment represents the first operational 3-nodes quantum link in France. It is based on entanglement sharing between two users over 50 km. We developed a broadband source of entangled photons located at a central node and distribute entanglement between two users, at remote location in Sophia-Antipolis (Bob) and Nice city center (Alice), through a standard metropolitan optical fiber network provided by Orange. We exploit energy-time entanglement for its resilience to optical fiber distribution and its multiplexing potential [4]. Energy-time entanglement has required the development of a pair of compact, stable and identical unbalanced Mach-Zehnder interferometers matching our fibre link and detectors characteristics.

We believe the strength of our implementation to be :
- Clock synchronisation for the users based on quantum signals
- Multiplexing scheme up to 40 pairs of 100GHz-ITU-channels allowing 9-users network
- Real-time sifting, error correction and privacy amplification done by user's computer

Our entanglement device is a PPLN waveguide operating at the degenerate wavelength of 1560 nm over a bandwdith of 80 nm. It produces 170×10^6 entangled photon pairs per second in a pair of 100 GHz-ITU channels and we demonstrated a continuous secure key rate of 7 kBps associated to a QBER below 4.5% since the 15th of August 2021.

Furthermore, exploiting telecom multiplexing scheme, it is possible to extend our link to multiple-users network or to increase the individual key rate. According to our 80 nm broad photon pair spectrum, we realistically estimate, using standard 100 GHz-ITU, plans to build a 9 users fully connected network or to increase the two-user rate up to 280 kBps.

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A Rydberg superatom for cavity QED applications: coherent control, single-shot detection and state-dependent optical π phase shift

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We present the first building blocks for cavity QED applications with a single Rydberg superatom. Our experimental platform is made of a small (5 µm rms) and cold (2 µK) rubidium ensemble strongly coupled to a medium-finesse resonator. The system is probed in a ladder Electromagnetically Induced Transparency scheme (EIT, Fig. 1a) to map Rydberg excitations onto photons [1]. The van der Waals interactions between Rydberg atoms are converted into strong optical nonlinearities such that the propagation of photons through the cavity becomes very dependent on the Rydberg population. For sufficiently strong interactions, one excitation is enough to blockade the presence of any other Rydberg excitation in the cloud and the atomic ensemble can then be seen as a single Rydberg superatom strongly coupled to the cavity. We have demonstrated this Rydberg blockade mechanism at the single-photon level by observing strong anti-bunching in transmission of the resonator ($g^{(2)}(0) \simeq 0.05$) [2, 3].

We have implemented a coherent control of the Rydberg superatom via a two-photon Rabi driving between the ground and the collective singly-excited Rydberg state, observing a collective enhancement of its frequency (Fig. 1b) [2]. The state of the superatom can be optically detected via the cavity transmission with a 94% efficiency, in par with results recently obtained in free-space and cavity-assisted experiments [4, 5] but with a significantly weaker residual transmission, making this system analogous to a single-excitation-controlled optical transitor with a weak leakage current.

Finally, we demonstrated that our coupled system induces π phase shift on the light reflected off of the cavity dependent on the superatom's state (Fig. 1c), allowing us to detect the latter with a 90% efficiency. This π phase rotation, together with the coherent control and the single-shot state detection, is a key ingredient for the implementation of an efficient controlled-phase gate [6] or for the deterministic generation of optical "Schrödinger's kitten" states without the need for a low-volume high-finesse cavity.

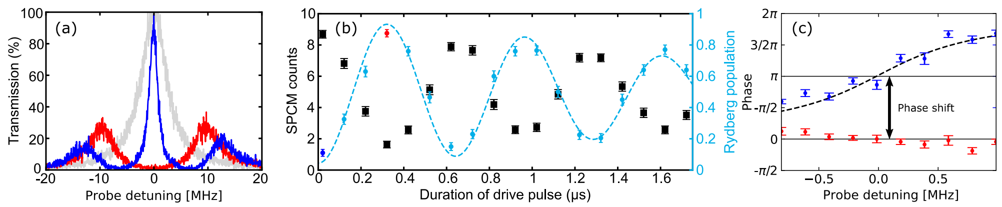

Figure 1: (a) Cavity transmission: empty cavity (grey), atom+cavity (red) and atoms+cavity+EIT (blue). (b) Rabi driving: Rydberg population in light blue (π pulse in red, no pulse in blue), SPCM counts in black and a Gaussian damping fit (dashed line). (c) Phase of the light reflected from the cavity with the superatom in the ground (blue) and Rydberg (red) state.

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Integrated nanophotonic multi-spin-photon interface based on silicon vacancies in silicon carbide

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Optically active solid-state spins demonstrated multi-node quantum networks in which nuclear spin qubits are used to implement critical features like error correction and entanglement distillation. A key challenge in the field remains the demonstration of scalability, i.e., combining all capabilities *simultaneously* after colour centre integration into scalable nanophotonic (cavity) structures [1].

Here, we show that silicon vacancy (V_{Si}) centres in semiconductor silicon carbide (SiC) [2] combine all these features [3]. Our results highlight therefore that V_{Si} centres are one of the most promising platforms towards the development of scalable quantum networks.

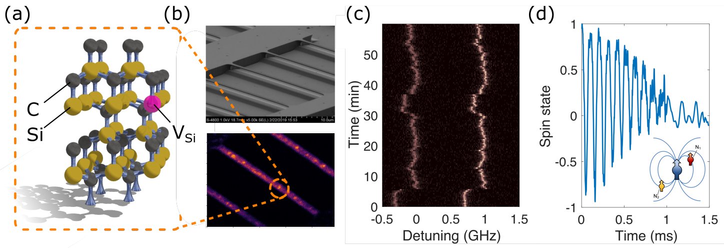

FIGURE 1. (a) 4H-SiC lattice structure and V_{Si} centre (pink). (b) SEM (top) and confocal (bottom) microscopy image of SiC waveguides. (c) Spectral stability of the two resonant absorption lines. (d) Spin Hahn echo signal, revealing coupling to two nearby ^{29}Si nuclear spins.

In particular, we introduce low-damage nanofabrication of V_{Si} centres in SiC without deterioration of their intrinsic high-quality spin-optical properties [3]. We show close-to lifetime limited optical lines and record spin coherence times for near-surface single defects generated via ion implantation and in SiC nanophotonic waveguides.

Thanks to our system's very high operation temperature ($T \sim 20\,\mathrm{K}$), we further use waveguide-integrated V_{Si} centres to control two nearby nuclear spin qubits with fidelities up to 98%. Considering the high cooling powers of standard cryostats at $T = 20\,\mathrm{K}$, the expansion to tens of nuclear spin qubits should be straightforward, and even enable direct drive via radiofrequency waves.
We will also share our upcoming plans, comprising photon collection using direct waveguide-to-fibre coupling, as well as nanophotonic cavity tuning via the electro-optic coefficient of 4H-SiC [4]. Combined with our recently-demonstrated spin-controlled generation of coherent multi-photon states [5], this promises a realistic pathway towards next-generation quantum repeater architectures based on error-corrected stationary spin memories and loss-tolerant photonic cluster states [6].

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Universal scaling laws for critical quantum sensing

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Critical systems, i.e., those undergoing a phase transition, are extremely sensitive to external perturbations. This property makes them appealing for sensing applications. For instance, a photon impinging on a piece of superconducting material can raise its temperature above the critical value, which creates a large, observable jump in resistance. This is the operating principle of transition-edge sensors [1], which can detect photons with record accuracy.

In the latter example, the operating principle can still be described (semi)-classically. *Quantum critical metrology* extend this approach by bringing together the insights from two fields. On the one hand, the field of *quantum phase transitions* [2] studies critical systems when quantum effects play a dominant role ; in particular, transitions driven by quantum fluctuations, instead of a competition between energy and entropy. On the other hand, *quantum metrology* studies how non-classical correlations (such as squeezing or entanglement) could be use to develop better sensing protocols [3, 4]. In the last few years, several works [5–8] have addressed the following question : can we exploit the non-classical properties of a system near a quantum critical point for sensing ? The goal is, on the theoretical side, to revisit some known properties of quantum phase transitions using tools coming from the quantum information and metrology community ; and, on the applied side, to develop new sensing protocols.

I will introduce the key concepts of quantum critical metrology, and discuss our recent results [8]. We have studied fully-connected models, a class of models in which phase transitions can emerge even for finite-size systems. In these systems, we have developed several protocols, which exploit either the ground state or the dynamical properties of the Hamiltonian, and drawn a connection between these different approaches. We have studied the achievable precision versus the protocol duration, and showed that universal scaling properties emerge, which depend only of the universality class of the model considered.

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Detecting spins by their fluorescence with a microwave photon counter

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Single photon counters are essential for detecting weak incoherent electromagnetic radiation. In the optical domain, they are widely used to detect spontaneous emission from individual quantum systems, with applications in fluorescence microscopy, and in numerous areas of quantum technologies. In the microwave domain, operational single photon counters have just recently been developed using superconducting quantum circuits [1], offering novel opportunities for detecting fluorescence or spontaneous emission at microwave frequencies. Here, we demonstrate the use of a microwave single photon counter to detect the photons spontaneously emitted by a small ensemble of electron spins coupled to a superconducting micro-resonator [2]. In this novel spin detection scheme, each click of the detector reveals the quantum jump of an individual spin from its excited to its ground state. Besides their fundamental interest, our results also constitute a novel methodology for Electron Spin Resonance spectroscopy well suited for the detection of small numbers of spins.

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Nuclear Spin-Squeezinf of Helium-3 via continuous Quantum Non-Demolition measurement

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Helium-3 is known for having a purely nuclear 1/2 spin in its ground-state. It means it is perfectly isolated from its environment : even as a gas in a centimetric cell at room temperature and a pressure of a few millibar, its quantum coherences can survive. In fact, polarization of 90% can be routinely prepare giving birth to a very large spin with extremely long lifetime (see [1] for a coherence time T2 of 60h). This makes the nuclear spin of Helium-3 an interesting candidate for the production, the study and the use of entangled states, and therefore a competitor of cold atomic gases and Bose-Einstein condensates in metrology and quantum information processing [2]. Of course, the high protection of the nuclear spin also means that it is difficult to attain and manipulate, in fact, the first excited state is not accessible by laser as it hangs 20 eV above the ground-state. To polarize the spin, an indirect process is used : Metastability Exchange Collisions. By applying an oscillatory discharge inside the cell, a small fraction of the gas is send to a metastable triplet state, an excellent starting point for near infrared optical transitions. From that, the collisions happening between ground state atoms and metastable ones slowly transfer (in a timescale of a second) the spin state from one population to the other. It had already been shown that quantum correlations are also transfer by those Metastability Exchange Collisions [6]. In recent years, several experimental breakthroughs have been made in the field of spin squeezing notably by means of non-demolition quantum measurements (QND) in atomic alkali gases interacting with the electromagnetic field [2],[3],[4],[5].

In the work we present, we propose to adapt those new QND techniques for Helium-3 gases, hence taking advantage of the weak coupling of ground-state helium-3 nuclear spin to its environment to produce long-lived macroscopic quantum states, nuclear spin squeezed states, in a gas cell at room temperature[8], [7]. We calculated moments of the nuclear spin squeezed component conditioned on the signal of the measurement. In a homodyne detection scheme, we solve the stochastic equation for the system state conditioned on the measurement and obtain the dependence on the signal of the squeezed component and the squeezing rate of the variance. We also included de-excitation of metastable atoms at the walls, which induces nuclear spin decoherence and found the fundamental limit of the scheme on the conditional variance.

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A lower bound on the space overhead of fault-tolerant quantum computation

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Quantum computing has been shown to be capable of solving problems for which no efficient classical algorithms are known. However, the decoherence of quantum systems due to inevitable interactions with the environment introduces a challenge in building reliable large-scale quantum computers. To circumvent this obstacle the theory of quantum error correction and fault tolerance was developed. One of the major breakthrough results in quantum computing, known as the fault-tolerant threshold theorem, states that arbitrarily long quantum computations can be reliably performed with a polylogarithmic overhead in space and time, provided the noise level is below a certain constant threshold. Since then a lot of effort has been focused on introducing new fault tolerance schemes with lower resource overheads, improving the lower bounds on the fault-tolerant threshold. A recent work by Fawzi, Grospellier and Leverrier [1] building on a result by Gottesman [2] has shown that the space overhead can be asymptotically reduced to a constant independent of the circuit, provided we only consider circuits with a length bounded by a polynomial in the width. But what is the fundamental limit on the space overhead for quantum fault tolerance as a function of the noise model ? This question in fact still remains open and widely unexplored. This is in part due to the difficulty of providing a definition encompassing the different aspects of quantum fault tolerance.

The objective of this work is to understand, given a noise model, the minimum resources required to achieve quantum fault tolerance. Towards this objective, we introduce a minimal model providing a natural characterization of quantum fault tolerance. In this model, given an arbitrary qubit channel $\mathcal{N}$, we establish a lower bound of $\frac{f(\mathcal{N})\log T}{n}$ on the space overhead of quantum fault tolerance schemes for circuits of length T and width n, against i.i.d. noise modeled by $\mathcal{N}$, where $f(\mathcal{N})$ is an explicit positive constant for any non-unitary channel $\mathcal{N}$. We show that in the extreme case where $\mathcal{N}$ has zero quantum capacity, fault tolerance is not possible even for single time step, i.e., $f(\mathcal{N}) = \infty$.

Our results apply to adaptive protocols composed of a hybrid of classical and quantum computation. By allowing classical computation to be free and perfect in our model, we address a limitation of the previous works on noisy quantum computation (see, e.g., [3–5] and the references therein) that assume classical computations are also affected by noise. The earlier results in this direction are mostly limited to a specific noise model (typically, depolarizing noise) and it is not clear if the introduced techniques can be extended to other noise models. Moreover, these works are incomparable with ours since they either focus on noise levels above the fault-tolerant threshold or prove limitations on the computational capabilities of NISQ devices.

In order to obtain our results, we use the Stokes parameterization for representing qubit channels in a basis consisting of the identity and Pauli matrices [6]. For the case of unital $\mathcal{N}$, we use a geometric argument based on convexity and the structure of the set of entanglement breaking unital qubit channels. For non-unital noise, we prove our result based on a trace distance contraction argument. Along the way, we prove an exponential upper bound on the maximal length of fault-tolerant quantum computation against amplitude damping noise, which was conjectured to hold by Ben-Or, Gottesman and Hassidim [7].

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A Deductive Verification Framework for Circuit-building Quantum Programs

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a. Quantum computing and formal verification. While testing and debugging are the common verification practice in classical programming, they become extremely complicated in the quantum case, due to both the destructive and probabilistic aspects of quantum measurement. On the other hand, nothing prevents *a priori* the formal verification of quantum programs. Formal verification [6] design a wide range of techniques aiming at mathematically proving the correctness of a system. In addition to offering an alternative to testing, it has in principle the decisive additional advantages to enable parametric proof certificates and to offer absolute guarantees for the correctness of programs.

b. Deductive program verification, based on Hoare's seminal work [9] in 1969, is probably the oldest formal method technique. In this approach, programs are *annotated* with *logical assertions*, such as pre- and post-conditions for operations or loop invariants, then so-called *proof obligations* are automatically generated in such a way that proving them ensures that the logical assertions hold along any execution of the program. These proof obligations are commonly proven by help of proof assistants or automatic solvers.

c. The hybrid model is the standard architecture for quantum computing. There, the programmer addresses a classical computer in charge of control instructions. Along an execution, this computer may address a quantum co-processor for quantum computation tasks – called *quantum circuits*.

Hence, the computational model has an higher-level savor : programmers write functions generating circuits that themselves behave as functions over quantum data. Program functional verification must then assess the correction of the calculus, for any instance of circuit possibly generated by a given program. Since automated formal verification is basically operational for first-order logic specification, **a major challenge for formal deductive verification in quantum programming is to describe and specify the higher-order behaviour of hybrid model executions into first-order logic**. In [5], we present QBRICKS : an environment for formally verified quantum programs addressing this challenge.

d. QBRICKS. Deductive verification deployment requires both an object language and a specification language, in which *pre* and *post* conditions are formalized. QBRICKS-DSL, our object language, provides the minimum necessary constructors for the circuits at stake in usual quantum algorithm. It does not contain treatment of measurement as an available operation from the object language. Still, in QBRICKS we are already able to target realistic implementations of famous quantum algorithms, and in our specification language, QBRICKS-SPEC, we can reason on the probabilistic outcome of a measurement.

Our strategy for the first-order logic specifications of quantum programs is based on the development of parameterized path-sums (PPS) instead of the standard matrix semantics. It is a generalisation of the path-sum circuit semantics [1, 2]. Then, formal reasoning about generated first-order proof obligations is eased by specific theorems libraries, featuring the mathematical material at stake with quantum computing (+14 000 LoC). These different elements are embedded in the Why3 [4, 8] environment, a platform for functional programming with deductive verification.

e. Case study : a verified implementation of `Shor-OF` in QBRICKS. Shor's algorithm [12] consists in (1) a reduction of the integer factoring problem to the order-finding problem (`Shor-OF`) for modular multiplication, (2) a quantum procedure for solving this problem. We focus on this second procedure. It consists in applying a specific quantum routine, called the *quantum phase estimation* [7, 10] (QPE), to an oracle U encoding multiplication of integers modulo N. For the implementation of U we followed Beauregard's QFT-based method [3], while the implementation of QPE is the standard one from the literature (see, eg. [11]).

f. Specifications. QBRICKS-SPEC enables to specify and verify both the functional behavior of programs and their complexity. In the `Shor-OF` case we proved the probability success of each individual run, the parameterized number of required qubits, distinguishing ancillas, and a parameterized polynomial bounding the number of required elementary operations.

g. Experimental evaluation. Benefiting from the development of PPS and derived first order reasoning rule, our development enabled a significant improvement in automation (95%, $< \frac{1}{3}*$ required human proof effort, with regards to the literature) and algorithm complexity scalability. Details about theses considerations are addressable in [5].

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Fast high fidelity quantum non-demolition superconducting qubit readout

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The most common technique of qubit readout in cQED relies on the transverse dispersive coupling between a qubit and a microwave cavity. However, despite important progresses, implementing fast high fidelity and QND readout remains a major challenge. Indeed, inferring the qubit state is limited by the trade-off between speed and accuracy due to Purcell effect and unwanted transitions induced by readout photons in the cavity. To overcome this, we propose and experimentally demonstrate a new readout scheme based on a transmon molecule inserted inside a 3D-cavity [1, 2]. The full system presents a transmon qubit mode coupled to a readout mode through an original non-pertubative cross-Kerr coupling. The readout mode, called polariton mode, results from the hybridization between the microwave cavity and the transmon molecule circuit. The direct cross-Kerr coupling is a key point of our readout scheme since it protects the qubit from Purcell effect. A first implementation, though perfectible, already enables a very efficient single-shot QND readout of the qubit in only 50ns, with a QND-ness of 99% and a fidelity of 97.4% [3]. Recent results with readout fidelity higher that 99% will be discussed.

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PACS numbers:

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Optical quantum hybrid information processing

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Quantum information technology has historically been developed from two different paradigms, known as the discrete- and continuous variables approach. Which one to use depends both on the envisioned task and chosen quantum platform which suggests that our future quantum networks will most likely be heterogeneous in both encoding and support and thus will require a way to be connected [1]. Recently a first link between discrete and continuous variables has been established by entangling an optical discrete single-photon qubit with an optical continuous cat-state qubit. For this the heralding paths of two high quality optical parametric oscillators, one outputting continuous and the other discrete states, are mixed indistinguishably [2]. As we can expect quantum networks to use flying qubits, this connection in the optical domain serves not only as a proof of principle experiment but has been pathing the way towards usable advanced hybrid protocols [3, 4].

One of the latest achievements in this direction has confirmed hybrid entanglement swapping with a negativity of $\mathcal{N} = 0.044 \pm 0.009$, performed between a discrete-discrete and discrete-continuous entangled pair as to create long distance hybrid entanglement [5] as depicted in fig. 1. Together with the initial hybrid pair the discrete entangled pair is created with one photon and the use of a delay line, which shows that the protocol has a certain resilience to losses. The Bell measurement, performed between the discrete hybrid and one of the other discrete modes, has a hybrid form itself as we are boosting its success capability via homodyne conditioning. We also report a discrete to continuous qubit converter, based on hybrid teleportation with fidelities surpassing the classical bound.

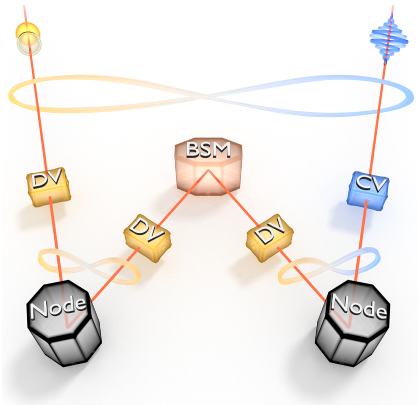

FIGURE 1 After hybrid entanglement and discrete entanglement is created on two distant nodes, a Bell-state measurement between two discrete states is applied to create remotely hybrid discrete-continuous entanglement between modes that never interacted.

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Fundamental Quantum Aspects
(FQA)

A two-qubit engine fueled by entanglement and local measurements

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Quantum measurement backaction is one of the many puzzling features of quantum physics. Not only can it disturb the state of the system being measured but it usually also comes with an energetic counterpart whereby the system gains or loses energy. This energy exchanged is called quantum heat and its microscopic origin is still in the blurry region of the quantum to classical interface.

Making use of this backaction, some quantum measurement powered engine have been proposed [1, 2]. A requirement is that the measurements are performed in a basis that does not commute with the system's Hamiltonian. Here we introduce the first bipartite quantum measurement engine by involving a two-qubit working substance playing on the fact that the local Hamiltonian of each of the qubit does not commute with the total Hamiltonian. Entanglement is also a key resource to our engine since the state of maximal entanglement between the two qubits is the one in which the demon implementing the feedback loop can gain the most information about the state of the system. Taking advantage of the quantum Zeno effect, we show that a generalisation of our engine can also be used as way to implement the frequency up-conversion of a quantum of excitation almost deterministically.

To deepen our understanding of the energy source, we include a modelling of the meter as an additional quantum system. Surprisingly, we show that the energy exchange with the measured system can be explained without invoking a classical measurement of the meter. The process during which the meter and system become correlated allows to provide the energy fueling our engine simply by turning off the interaction between the meter and system. Moreover, this work shows that the small evolution of the system during the measurement, usually thought of as detrimental, is crucial to observe the energy exchange at play.

Editor's suggestion Physical Review Letters [3]

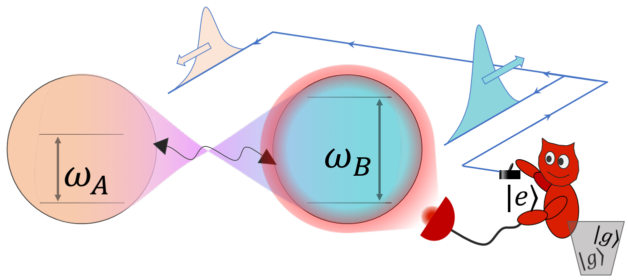

FIGURE 1. Scheme of the engine cycle.

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Certification of Non-Gaussian States using Double Homodyne Detection

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Specific properties of quantum states are necessary to unlock new technologies in quantum information. It is thus essential to be able to certify such properties. Continuous variable quantum optics provides a very promising platform where important resources such as scalable entanglement come “for free” [1]. In that context, a crucial quantum feature to look for and investigate is the so-called non-Gaussianity, which, beyond its conceptual relevance, is a necessary resource for any quantum computational advantage as well as for effective error correction, entanglement distillation for instance. Experience produced non-Gaussian states have been probed using full tomography techniques [2]. However, performing a full tomography of multimode continuous variable systems is a hard problem. Indeed, systems aimed at overcoming classical approaches are by definition too complex to be fully characterized, thus alternative approaches are required.

We derived a theoretical framework for the certification of non-Gaussian features of quantum states using double homodyne detection [3]. We exhibit witnesses for non-Gaussian properties of quantum states, such as Wigner negativity or stellar rank [4]. These witnesses provide a reliable operational characterization of the measured state in terms of its non-Gaussian properties, without the need for a full tomography.

We show using simulations in realistic experimental conditions, that certifying non-Gaussian properties can be efficiently performed from a limited number of measurement outcomes. This shows that our method can be readily employed using state-of-the-art experimental optical setups.

To conclude, we believe that the practicality and flexibility of our method will open the way to a systematic experimental investigation of the non-Gaussian properties of quantum states. Here we report on the experimental progress in demonstrating such certification protocol on photon subtracted squeezed vacuum states. This is a crucial step in the applicability of continuous variables for quantum information processing.

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Efficient spin manipulation at the Zeeman level in non-Kramers ion-doped crystals

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Rare-earth ion-doped crystals represent a very attractive platforms to implement quantum protocols, given their resonances at optical wavelengths, their large multiplexing capability and their solid-state nature. Notably, their record coherence times (up to few hours) allow performing long-duration and efficient storage of photonic qubits, and state-of-the-art experimental demonstrations were conducted along this line, by the use of so-called dynamical decoupling (DD) sequences. Up to now, the rare-earth candidates which displayed the highest performances were Kramers ions, whose energetic structure allows efficient population preparation and addressing [1, 2], without requiring the use of constraining magnetic fields, on the contrary to Kramers ions [3, 4]. Moreover, it has been witnessed that optimal coherence properties of such non-Kramers ions were obtained under the application of a small magnetic field ($\sim$1 mT), which however splits the levels due to the Zeeman effect [5, 6]. In this work, we investigate the detrimental effect of such field on the quality of spin and optical manipulation required for DD sequences, by proposing a complete theoretical model and confronting it to experimental observations [7]. It is found that three regimes can be identified for the spin dynamics, helping to determine optimal magnetic configuration in order to perform high-quality manipulation. Moreover, we investigate the case of inversion with adiabatic pulses, a commonly used set of pulses in the context of inhomogeneously broadened ensembles, and we explicit a new adiabaticity criterion based on numerical simulations.
This study will help determining optimal magnetic configurations for high-efficiency and long-duration storage of quantum photonic information in solid-state rare-earth ion-doped crystal, opening new perspectives for implementation of high-quality nodes in quantum networks.

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Spin Noise Spectroscopy of Metastable Helium

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Spin noise spectroscopy (SNS) allows to optically detect the fluctuations of a set of spins. Such fluctuations induce noise in the birefringence of the medium, which can be probed by recording polarization fluctuations of a laser beam after its propagation through the sample. The first SNS experiment was reported in the early 1980s [1], but it is only more than 20 years later that advances in narrow linewidth lasers and developments in low noise electronics lead to reconsider that technique [2]. It was then used to probe various systems, such as thermal atomic vapours, semiconductors or quantum wells [3].

We have performed spin noise spectroscopy in a metastable helium gas cell. The metastable state 2^3S_1 is composed of 3 Zeeman sublevels, with equally distributed populations. Nevertheless, random population fluctuations generate a circular birefringence noise and the associated random Faraday rotation (FR) can be recorded using a balanced photodiode. The linear birefringence noise, leading to an ellipticity noise, can also be probed by adding a quarter wave plate (QWP) in the set-up.

As spin fluctuations are centered on the zero frequency, a transverse magnetic field is applied : spin precession then shifts the spin noise resonance at the Larmor frequency, so that it is not hidden by technical noises. We add a quarter wave plate in the set up e.g. when we probe the ellipticity noise two polarization dependant resonances are visible, at ω_L and at $2\omega_L$. The observation of such a second peak had been reported recently [4], and can be understood if one remembers that the metastable state is a spin 1, with three Zeeman sublevel. Nevertheless, it can be seen only for specific polarization inputs and in the vicinity of the D_1 and D_0 transitions, and in metastable helium we could not record it below the D_2 line.

We performed simulations, which reproduce quite well the experiment.

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Electron and Hole Spin Qubits Variability in Si MOS Devices

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Semiconductor spin qubits may show significant device-to-device variability in the presence of spin-orbit coupling mechanisms. Interface roughness, charge traps, layout or process inhomogeneities indeed shape the real space wave functions, hence the spin properties. It is, therefore, important to understand how reproducible the qubits can be in order to assess strategies to cope with variability, and to set constraints on the quality of materials and fabrication. Here we model the variability of single qubit properties (Larmor and Rabi frequencies) due to disorder at the Si/SiO_2 interface (roughness, charge traps) in metal-oxide-semiconductor devices [1]. We consider both electron qubits (with synthetic spin-orbit coupling fields created by micro-magnets) and hole qubits (with intrinsic spin-orbit coupling). We unravel the microscopic mechanisms responsible for the variability of both kinds of qubits, and highlight, in particular, the relations between the characteristic sizes of the disordered dots and their Larmor and Rabi frequencies.

We show that the hole qubits are typically more sensitive to interface roughness than electron qubits due to the smaller hole confinement mass. The spread of Larmor and Rabi frequencies is proportional to the rms interface roughness and depends on a non-monotonic way on the characteristic length scales of the fluctuations. Interface fluctuations with length scales comparable to the size of the dot are indeed the most detrimental to the reproducibility of the qubits. The main sources of variability are however charged interface traps, which can scatter the Rabi frequencies of both electron and hole qubits over one order of magnitude in realistic device layouts.

The disorder also scatters the lifetimes (T_1, T_2^*) of the qubits. The speed of operation of a quantum processor will actually be limited by the qubits with smallest Rabi frequencies (at the one qubit gates level), while the overall lifetimes wil be limited by the qubits with smallest T_1 and T_2^*, which are usually different. We show that variability can, therefore, strongly impede the dynamical performances of an array of qubits.

We analyze the implications for the design of spin qubits and for the choice of materials. We discuss, in particular, the dependence of interface roughness variability on Si film thickness, and show how the impact of charge traps decreases rapidly if they can be moved away from the interface with the silicon channel (as in Si/SiGe heterostructures for example).

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Continuous variables quantum networks via single-pass femtosecond parametric process

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Photonics quantum networks arise naturally as the essential tool for measurement-based Quantum Computing (MBQC), long-distance quantum communications and the implementation of a quantum internet [1]. Here we focus on the implementation of specific Continuous Variables (CV) entanglement networks, based on a photonic setup, called CV cluster states. In this framework, the nodes of the quantum network are individual temporal/frequency modes of the electromagnetic field while the links are tailored entanglement correlations. Our setup is based on a train of ultrashort pulses that pumps a spontaneous parametric down conversion process in a non-linear periodically poled KTP waveguide, generating pairs of frequency-entangled photons. The process can be equivalently described as a collection of independently squeezed modes, named supermodes, that in our case turn out to be Hermite-Gauss frequency modes. Entangled networks (and CV clusters) of different shapes can be built by performing basis changes, which can be experimentally implemented via mode-dependent measurements, on squeezed modes. By choosing a suitable measurement basis it is possible to create an entanglement link between the frequency modes and thus to create a network of any given shape [2, 3]. We show here the recent generation of the building blocks of the quantum networks - multimode squeezed states - in our setup, shown in Fig. 1. Via homodyne detection we characterize the quadrature noise in the selected mode : thanks to an ultrafast pulse shaper we can in fact reshape the temporal/spectral components of the local oscillator reference field. We obtain preliminary results showing up to 14 squeezed Hermite-Gauss modes, with a maximum value of 0.6 dB of squeezing in the first HG mode. We also performed pulse-by-pulse measurement of the squeezed modes via a recently developed fast homodyne detector, which can resolve pulses at 156 MHz repetition rate. The pulse-by-pulse measurement of squeezing enables the generation of cluster states in the temporal domain as well, where now nodes of the cluster are individual pulses of light and the entanglement links will be generated by mixing them via linear-optics transformations. We will then go towards large clusters multiplexed both in the pulse and Hermite-Gauss basis.

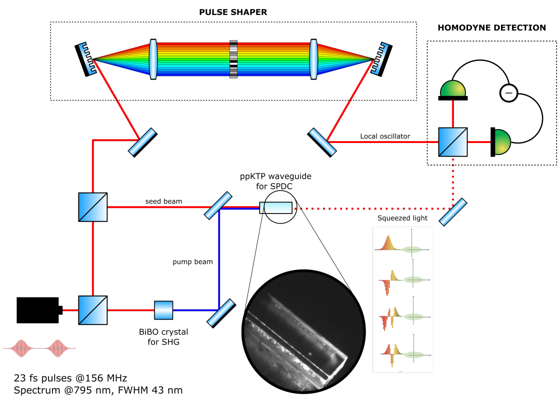

FIGURE 1: Setup of the experiment for the generation of multimode squeezed light

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Dynamics of atomic collective excitations close to a 1D nanoscale waveguide

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Nanoscale waveguides provide a tight transverse confinement of guided light, not limited by the Rayleigh range, allowing enhanced atom-photon interaction over a large sample. In our system, we interface a tapered optical nanofiber with an ensemble of cold Cesium atoms in an ultra-high vacuum chamber, trapped in a 1D lattice geometry using the evanescent field around the nanofiber.

We have studied resonant light-matter interaction in the system to demonstrate an all-fibered optical memory at the single-photon level using dynamic EIT [1]. Furthermore, tuning the interatomic distances in the one dimensional array can lead to substantial Bragg reflection from an ordered chain of atoms [2], and reflectivity up to 80% was achieved with about 2000 trapped atoms. Recently, following the seminal Duan-Lukin-Cirac-Zoller (DLCZ) protocol, we demonstrated the heralded creation of a single collective excitation, as confirmed by the measured non-classical correlations. We were able to store, and then retrieve it preferentially into the guided mode of the nanofiber [3].

In an effort to better model our system, we developed computational tools to describe the system with actual experimental parameters. We study the decay dynamics of a single collective atomic excitation coupled to a waveguide in different configurations [4]. The atoms are arranged as a linear array and only a segment of them is excited to a superradiant mode and emits light into the waveguide, as shown in Fig. 1(a). Additional atomic chains placed on one or both sides play a passive role, either reflecting or absorbing this emission. We show that when varying the geometry, such a one-dimensional atomic system could be able to redirect the emitted light, to directionally reduce or enhance it, and in some cases to localize it in a cavity formed by the atomic mirrors bounding the system. These systems are being implemented and would allow us to demonstrate cavity QED effects with an all atomic system, as shown in Fig. 1(b), as well as manifestations of subradiant and superradiant collective effects [5].

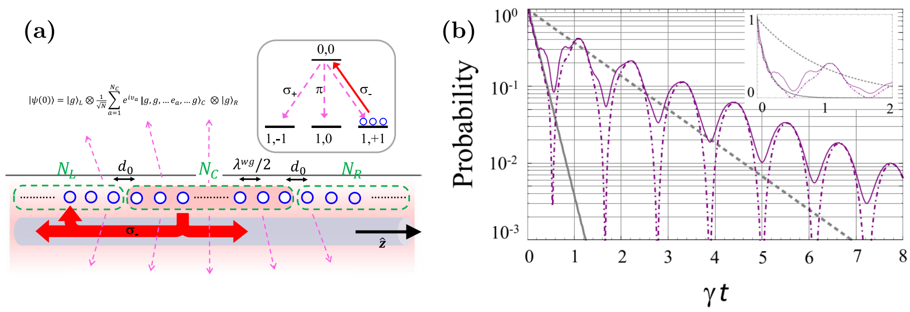

Fig. 1 (a) Schematic representation of the system. An atomic array trapped near a subwavelength dielectric waveguide is split in three segments (left, center, right) separated by a distance d_0. All atoms have a tripod level scheme, as shown in the inset. (b) Cavity-like oscillation of the collective ensemble in the non-Markovian regime, for large separations d_0.

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Inflated Graph States Refuting Communication-Assisted LHV Models

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We propose a new family of quantum states that can be used to solve computational problems with a quantum advantage. In [1], Barrett et al. present correlations in a quantum state that any local hidden variable (LHV) model assisted by a round of restricted communication fails to reproduce. Their quantum state is a graph state, which associates with a graph $G = (V, E)$ consisting of vertices V and edges $E \subset V \times V$. The construction works by taking the triangle graph with three nodes, which is locally equivalent to a GHZ state, and adding nodes along the three edges, see Fig. 1 a) for an example. The result can be phrased as a computational relational problem finding applications in distributed computation [5], randomness extraction [4], and in proving a depth complexity separation between classical and quantum circuits [2], [3], [5]. In this work we extend the result of Barrett et. al [1] to one based on any graph state by introducing what we call inflated graph states.

Given a graph state with three or more connected vertices, we form a corresponding inflated graph by adding $2d$ vertices across each edge. From the fact that there exist correlations contradicting an LHV description for any graph state with three or more vertices [6][8], we show that the inflated version gives rise to correlations that cannot be achieved with any LHV model including communication along the inflated graph's edges up to distance d, thus extending the approach of [1] to arbitrary graph states, which also leads to smaller instances, for example the 7 qubit state in Fig. 1 c).

Starting from a graph $G = (V, E)$, we construct the new graph $G' = (V', E')$ that has the same vertices as the original graph G and for every edge we add $2d$ new vertices that form a chain along the original edge. That is, the original edge is replaced by two edges that each connect to one side of the chain. We refer to the original vertices as power nodes and to the newly added vertices as chain nodes. Figure 1 b) shows an exemplary inflated graph. Graph states with more than two connected nodes escape a LHV description for sets of Pauli measurement [6][8], which measure a Pauli operator $\sigma_i \in \{\mathbb{1}_i, X_i, Y_i, Z_i\}$ on every vertex qubit i. Given such a set of Pauli measurements that are used to contradict an LHV model for the graph state $G(V, E)$, we build a new set of Pauli measurements on the inflated graph state G'. This set contains mainly measurements that have a one-to-one correspondence to the Pauli measurements on the original graph. Moreover, we add so-called dummy measurements that account for correlations along the chain nodes that do not occur on the original graph. To prove that the set of new Pauli measurements provoke a contradiction with any LHV model including a round of communication up to distance d, we evaluate submeasurements of Pauli measurement, which omit the outcome of certain vertices. In contrast, after a round of communication any LHV model accounts for the Pauli operators on all vertices within communication distance.

As a simple example consider the graph state with 7 nodes in a chain from Fig. 1 c). It can be considered as an inflated version of the graph in Fig. 1 d) that relates to the 3 qubit GHZ state. Here, no LHV model can reproduce the measurement outcome of the four Pauli products $Q_1 = Y_1X_2Y_3$, $Q_2 = Y_1Y_2Z_3$, $Q_3 = Z_1Y_2Y_3$, $Q_4 = Z_1X_2Z_3$. Then, we construct the Pauli measurements and submeasurements (omitting greyed out Pauli operators) on the left side

$$
\begin{aligned}
P_1 &= Y_1\, X_2X_3X_4X_5X_6Y_7\ , & -1 &= y_1\, x_2^Y x_3^X x_4 x_5^X x_6^Y y_7\ ,\\
P_2 &= Y_1\, X_2X_3Y_4\, \color{gray}{X_5}\color{black}{X_6Z_7}\,, & 1 &= y_1\, x_2^Y x_3^Y y_4 \quad x_6^Z z_7\,,\\
P_3 &= Z_1X_2\color{gray}{X_3}\color{black}{Y_4\, X_5X_6Y_7}\ , & 1 &= z_1x_2^Z \quad y_4\, x_5^Y x_6^Y y_7\ ,\\
P_4 &= Z_1X_2\color{gray}{X_3}\color{black}{X_4}\color{gray}{X_5}\color{black}{X_6Z_7}\,, & 1 &= z_1x_2^Z \quad x_4 \quad x_6^Z z_7\,,\\
P_5 &= X_1\color{gray}{X_2}\color{black}{X_3}\color{gray}{X_4}\color{black}{X_5}\color{gray}{X_6}\color{black}{X_7}\,, & 1 &= x_1 \quad x_3^X \quad x_5^X \quad x_7\,,\\
P_6 &= X_1\color{gray}{X_2}\color{black}{X_3}\color{gray}{Y_4}\color{black}{\, X_5}\color{gray}{X_6}\color{black}{X_7}\,, & 1 &= x_1 \quad x_3^Y \quad x_5^Y \quad x_7\,,
\end{aligned}
$$

which lead to the constraints, on the right, for any nearest-neighbor ($d = 1$) communication-assisted LHV model. The superscripts denote the information acquired from communication with the vertices that change their Pauli operator in the different measurements. Multiplying the constraints results in $-1 = 1$, a contradiction. Thus, no nearest-neighbor communication-assisted LHV model can predict all correlations for the 7 qubit chain graph state.

Concluding, we define a family of graph states for which correlations exist that no LHV model assisted by communication of distance d can describe. These inflated graph states together with the correlations can be constructed from any graph state and correlation that violate a LHV model without communication. We believe them to find applications as the one proposed by [1].

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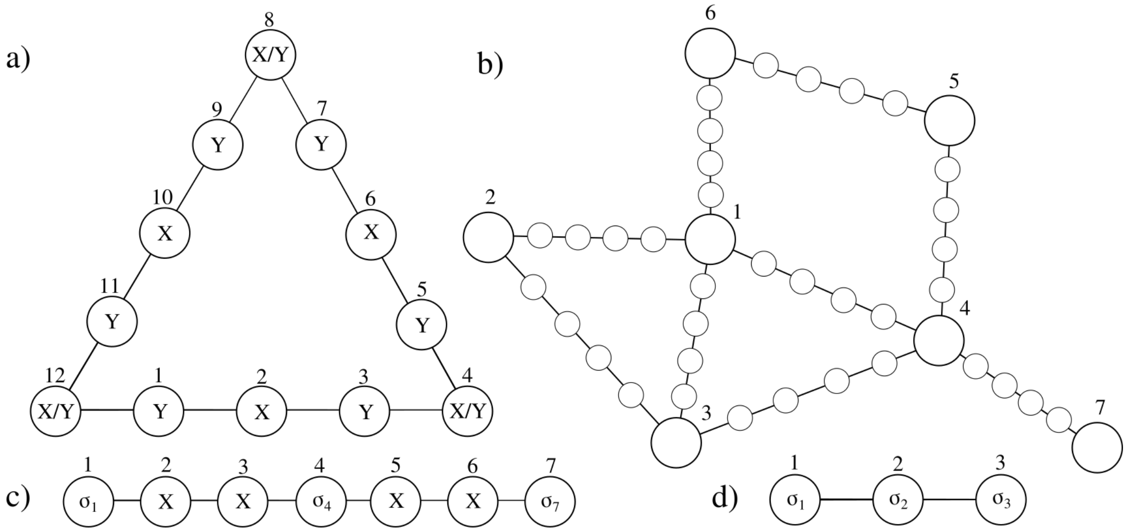

FIG. 1. For the triangle graph state a) with 12 nodes, [1] provides measurements with Pauli operators X, Y as assigned in the figure that no nearest-neighbor ($d = 1$) communication assisted LHV model can reproduce. In b) we construct an inflated graph state (for $d = 2$) from a graph with 7 nodes considering only the large balls. The graph in c) is an inflated version of the graph d) that relates to the 3 qubit GHZ state.

Geometrical description of the argument of weak values in terms of SU(N) generators

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Measurements play an important role in quantum mechanics. Amongst them, weak measurements have attracted much interest, for both theoretical and experimental reasons. Weak measurements are feasible when the interaction between a system and an ancilla is weak. After applying pre- and post-selection (which is equivalent to imposing initial and final conditions to the system evolution), the ancilla wavefunction is shifted by an amount dependent on a quantity called the weak value, multiplied by the coupling constant. Weak values depend on the initial and final states of the system, as well as on the weakly probed observable. As weak values are complex and unbounded numbers, they give rise to many applications, especially related to metrology (due to their amplification power) and to probing foundational issues in quantum mechanics (due to the non-perturbative features of weak measurements). Usually, weak values are studied in terms of their real and imaginary parts. Nonetheless, to understand their geometrical properties (related to geometric phases), their study in terms of modulus and argument becomes crucial [1, 2]. In this work, we have studied the argument of the weak values of general observables in N-dimensional quantum systems. This argument describes the area of a geodesic triangle created by three vectors representing the pre-selected state, the observable and the post-selected state on CP^{N-1}. The area of this geodesic triangle characterizes the generalization of a solid angle. This scheme can be applied, in the case of $N = 3$, to measure 3D Stokes parameters in terms of Gell-Mann matrices. Our work extends significantly previous results that were limited to weak values of qubit observables and to projectors.

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Detection of single W-centers in silicon

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The boom of silicon in semiconductor technologies was closely tied to the ability to control its density of lattice defects [1]. After being regarded as detrimental to the crystal quality in the first half of the 20th century [2], point defects have become an essential tool to tune the electrical properties of this semiconductor, leading to the development of a flourishing silicon industry [1]. At the turn of the 21st century, progress in Si-fabrication and implantation processes has triggered a radical change by enabling the control of these defects at the single level [3]. This paradigm shift has brought silicon into the quantum age, where individual dopants are nowadays used as robust quantum bits to encode and process quantum information [4]. These individual qubits can be efficiently controlled and detected by all-electrical means [4], but have the drawback of either being weakly coupled to light [5] or emitting in the mid-infrared range [6] unsuitable for optical fiber propagation. In order to isolate matter qubits that feature an optical interface enabling long-distance exchange of quantum information while benefiting from well-advanced silicon integrated photonics [7], one strategy is to investigate defects in silicon that are optically-active in the near-infrared telecom bands [8–10].

During this workshop, we will present our lastest results on the isolation of single optically-active defects in silicon [10–12]. Despite its small gap, this semiconductor hosts a large variety of emitters that can be optically detected at single scale at 10 K [13]. Research efforts have so far focused on extrinsic defects based on impurities incorporated inside the silicon lattice. Here we will show the detection of single intrinsic defects in silicon, which are linked to a tri-interstitial complex called W-center, with a zero-phonon line at 1.218 μm. Investigating their single-photon emission properties reveals new information about this common radiation damage center, such as its dipolar orientation and its photophysics. We have identified its microscopic structure and show that although this defect does not feature electronic states in the bandgap, Coulomb interactions lead to excitonic radiative recombination below the silicon bandgap. Given the advanced control over nanofabrication and integration in silicon, these results could set the stage for numerous quantum perspectives based on intrinsic luminescent defects in silicon [7], including integrated quantum photonics, quantum communications and quantum sensing.

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Comparing the quantum switch and its simulations with energetically-constrained operations

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Quantum mechanics allows processes to be superposed, leading to a genuinely quantum lack of causal structure. For example, the process known as the quantum switch consists in the superposition of applying two operations A and B in their two possible orders, A after B and B after A. The quantum switch applied to a target system S, with a control qubit C in the $|+\rangle$ state describes the following evolution of $C + S$:

$$|+_C\rangle \otimes |\psi_S\rangle \to \frac{1}{\sqrt{2}}\big(\,|0_C\rangle \otimes BA\,|\psi_S\rangle + |1_C\rangle \otimes AB\,|\psi_S\rangle\,\big). \tag{1}$$

Experimental implementations of the quantum switch have been challenged on the grounds that the operations A and B were implemented more than once, hence simulating indefinite causal order rather than actually implementing it. Motivated by such a debate, we employ a light-matter interaction model to physically describe the implementation of the quantum operations. When one restricts the energy available for the implementations, a noisy operation creating correlations between a target system and its environment is implemented instead, allowing one to distinguish processes using different numbers of operations. We consider such an energetically-constrained scenario using a light-matter interaction, as presented on Fig. 1, and compare the quantum switch to one of its natural simulations, where each operation is implemented twice. Considering a commuting-vs-anticommuting discrimination task, we find that within our model the quantum switch is more energetically efficient than its simulation. In addition to the known computational advantages of causal superpositions, our work raises the general question about their potential energetic advantage as well.

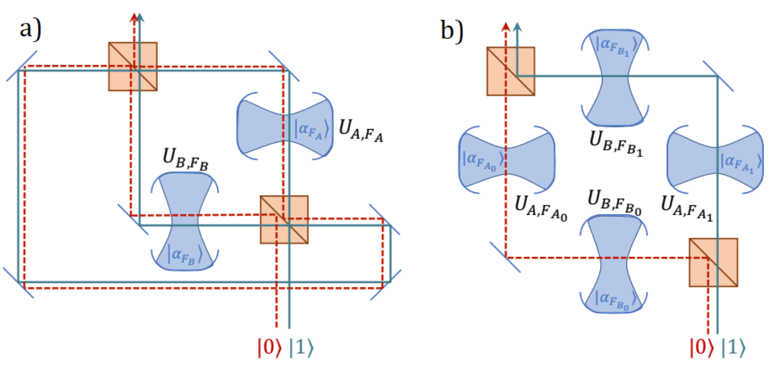

Fig. 1: Implementations of (a) the quantum switch and (b) its four-box simulation. An atom starting in the superposition of paths $|0\rangle$ and $|1\rangle$ traverses an interferometric-like setup containing polarising beam splitters and cavities. Each cavity is initially filled with a coherent field in some state $|\alpha_{F_i}\rangle$ to implement the operation i. The solid and dashed lines show the two superposed paths taken by the atom. They should be spatially superposed but are represented side by side to ease visual reading.

Single shot spin readout of the first hole in a Silicon quantum dot

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Spin qubits in semiconductors offer a promising avenue for the implementation of a scalable quantum computer. Whereas mature silicon technology has enabled rapid development of electron spin qubits in this material, their coherent manipulation still requires cumbersome ESR lines or micromagnets, which could be a bottleneck for large-scale integration. Additionally, coherence time of electrons in Silicon is limited by the nuclear spin fluctuations of naturally abundant ^{29}Si nuclei. Alternatively, hole states in semiconductors offer several appealing properties, among which their intrinsic spin-orbit coupling, allowing for fast all-electrical manipulation, which greatly simplifies large-scale integration schemes. Recent breakthrough demonstrating fast two-qubit logic [1], singlet-triplet qubit[2], and even a four-qubits quantum processor[3], have recently propelled holes to the forefront of the spin qubits scene.

Here we demonstrate single-shot spin readout of the first hole hosted in a four gates metal-oxide-semiconductor silicon-on-insulator nanowire transistor [4], made from an industrial 300mm CMOS foundry. Using drain-based reflectometry, we reach a charge-readout fidelity of 99% in 6 μs integration time. We use coherent manipulation techniques to fully characterize the connection of this hole state to its electromagnetic environment. In particular, we study its gyromagnetic tensor anisotropy [5], and find an excellent agreement with calculations, providing a deep understanding of the exact nature of this hole state.

This works paves the way to all-electrical manipulation of holes spin qubits arrays, combined with high fidelity single-shot hole spin readout in Silicon devices, fully compatible with industrial fabrication processes.

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Topological power pumping in quantum circuits

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Often, topological properties of quantum matter manifests themselves into a pumping phenomenon. However, in existing realizations the topological pumping is probed indirectly, as an anomalous velocity of the time-dependent quantum system. This anomalous velocity, which originates from a Berry curvature whose average value defines a topological Chern number, was recently measured in the cold atom and optical waveguides realizations of a topological pump. Although previous descriptions of pumping focused on the driven quantum system, they call for a key generalization that embeds the coupled degrees of freedom of the environment if one wants to model the observable topological transfer itself. I will present such a global framework that allows to characterize the actual pumping as a coupling between a fast quantum system and slow classical variables. The topological nature of this coupling induces an energy exchange between the classical systems at a stable and quantized rate. Guided by the goal of a direct measurement of the power transfer, I propose a realization of a topological pump between classical electromagnetic modes coupled to a superconducting quantum circuit. The topological pumping corresponds to a topologically protected redistribution of the power between the different frequencies of the modes which drive a fluxonium qutrit. I analyze the rich topology of the model and detail an experimental protocol enabling to experimentally probe it through direct measurement of power pumping.

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Optical coherent manipulation of alkaline-earth circular Rydberg states

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Rydberg atoms are promising tools for quantum technologies. Recent experiments have demonstrated Rydberg atom based quantum simulators with more than hundreds of particles. However, these experiments use laser accessible low angular momentum alkali Rydberg levels. Their relatively short lifetime ($\sim$ hundreds of microseconds) is currently the bottleneck that limits the size of the simulator.

Using circular Rydberg atom would enable to circumvent the problem. Circular state corresponds to levels with maximum angular momentum and have much larger lifetime (30 ms for $n \sim 50$). Nevertheless, alkali circular atoms are difficult to detect - their detection is either destructive [1] or complex [2]. They only interact with microwave field, which have much lower spatial resolution than optical light.

The use of alkaline-earth Rydberg state allows to overcome these problems. When the first valence electron is promoted to a Rydberg level, the second valence electron remains optically active and can be used to detect by fluorescence or to manipulate the atom. If the Rydberg electron is in a low angular momentum state, the probability that the two excited electrons collide with each other is high, leading to a fast auto-ionization of the atom. However, one expects the interaction between the two electrons to decrease when the angular momentum of the Rydberg electron increases and to get a negligible auto-ionization rate for circular states.

In this work, we show that we can prepare circular states of Strontium with $n = 51$ and demonstrate that the auto-ionization lifetime is larger than a few milliseconds when the ionic core electron is promoted to the $4d_{3/2}$ levels [3].

In a second experiment, we have measured the electrostatic shift due to the interaction of the ionic core electron quadrupole moment with the gradient of the electric field created by the Rydberg electron. If the ionic core is in the $4d_{3/2}$ level, this shift is on the order of a few hundreds of kilohertz. Its value depends on the principal quantum number n of the Rydberg electron and its sign depends on the sublevel m_j (Figure 1).

This allows us to encode the state of the Rydberg electron onto the second valence electron, opening the way to a state selective QND detection of the state of the atom. We also demonstrate that it enables to use optical pulses to manipulate the state of the Rydberg electron, providing a first step for a link between optical and microwave photons.

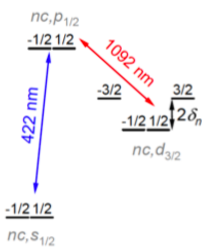

FIGURE 1: Selected energy levels of the Strontium atom when the Rydberg electron is in the circular state with principal quantum number n. The level structure i svery close to that of the Sr^+ ion, but the electrostatic coupling between the two electrons lift the degeneracy of the $51c, 4d_{3/2}, m_j$ levels by an amount $2\,\delta_n$

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Generation of non-Gaussian quantum photonic states with multimode input resources

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Non-Gaussian quantum states of light are important resources for implementing quantum information tasks, ranging from fault-tolerant optical quantum information processing [1] to long distance quantum communication [2]. These states can be generated by applying non-Gaussian operations, such as photon addition and subtraction, to an input Gaussian quantum state [3]. Also, the use of Gaussian operations (like homodyne measurement) allows the transformation of non-Gaussian input quantum states while maintaining their non-Gaussianity [4]. It has been shown that in such context, iterative tailoring of arbitrary quantum states is possible, by cascading elementary operation blocks [5]. This invitably comes at the cost of increasing the protocol complexity. Spectral modes, on the other hand, can be used to handily carry multiple quantum states in a single spatial mode. Moreover, multimode states populating such modes are readily available in commonly exploited processes such as spontaneous parametric down conversion [6].

In this work, we propose a protocol to generate non-Gaussian quantum states using spectral multiplexing of input states and Gaussian operations (Figure 1). We give the analytical expression of the output non-Gaussian state as a function of the number of input state, the Gaussian operation and the properties of spectral modes carrying the input quantum states. Taking as an example the cat breeding operation [7], we show that with a single mixing and measurement operation, we can obtain an amplified output cat state comparable to the one obtained using iterative breeding scheme with multiple mixing operations and measurements with the same number of input states. We show also that the generation of approximated GKP states [8] is possible with this protocol. We believe that the proposed protocol will have a major impact on the field of non-Gaussian quantum states generation, and can be used to extend the study beyond the cases considered in our work.

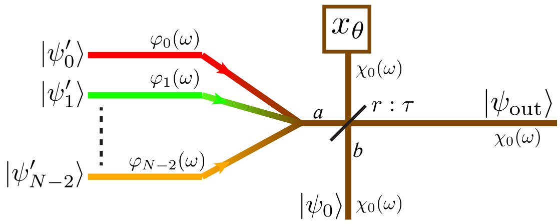

Figure 1 : Non-Gaussian state generation by mixing an input state $|\psi_0\rangle$ in a spectral mode $\chi_0(\omega)$ with several states $|\psi'_k\rangle$ in spectral modes $\varphi_k(\omega)$. According to the measured quadrature in the spatial mode b and the nature of input states, a high-amplitude non-Gaussian output state can be obtained.

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Semi-Device-Independent Certification of Causal Nonseparability with Trusted Quantum Inputs

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While the standard formulation of quantum theory assumes a fixed background causal structure, one can relax this assumption within the so-called "process matrix framework" [1]. There, the relation between parties performing local quantum operations in closed laboratories is described by a higher-order operation, the "process matrix". This formalism provides a unified description of standard quantum resources, such as quantum channels, compatible with a definite causal order. Remarkably, there are process matrices that are not compatible with a well-defined causal order between the parties. These processes are termed *causally nonseparable* [2, 3]. Explicit physical examples of processes with indefinite causal structure include some of the so-called "quantum circuits with quantum control of causal order" [5] such as the "quantum switch" [7], where the order between Alice and Bob's operations is coherently controlled by a qubit given to a third party, Fiona.

Some causally nonseparable process matrices can generate so-called noncausal correlations, allowing their causal nonseparability to be certified in a *device-independent* (DI) way by violating "causal inequalities" [1, 4]. However, not all causally nonseparable process matrices are noncausal in this strong sense [2, 8]. On the other hand, causally nonseparable process matrices can always be certified by causal witnesses [2, 3], in a *device-dependent* manner. Can one certify any causally nonseparable process matrix without fully trusting the operations performed by any of the parties, yet without violating a causal inequality ? One possible way is to trust only some of the parties [11].

In this work [6], we report progress towards the certification of causally nonseparable process matrices in a different semi-DI regime. Inspired by recent developments in the area of quantum nonlocality [9, 10], we consider a causal game scenario where the parties receive inputs in the form of trusted quantum systems (instead of classical ones), but are otherwise untrusted.

Defining the notion of causally nonseparable distributed measurements, we reduce our investigation to whether the causal nonseparability of a process matrix can be inferred by examining the induced distributed POVM generated from it by providing suitable quantum inputs. Such a possibility would constitute a *semi-device-independent with quantum inputs* (SDIQI) certification of causal nonseparability. We show how the quantum switch—a practically important process that cannot violate causal inequalities—can be certified in such SDIQI way. Moreover, by further imposing some natural structure to the untrusted operations, we show that all bipartite causally nonseparable process matrices can be certified with trusted quantum inputs.

One of the key open questions raised by our work is to understand precisely which causally nonseparable processes can be certified in an SDIQI way. Beyond understanding fully the bipartite case, an important future direction is the generalisation to multipartite process matrices, where the definition of causal (non)separability is slightly more subtle [1, 5]. Another interesting direction is whether our SDIQI approach can be combined with self-testing techniques to construct fully DI witnesses (as, e.g., in [12] for the case of entanglement). Finally, we note that the notion of causally nonseparable D-POVMS we introduced may be of independent interest to study in their own right.

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Probing non-classical light fields with energetic witnesses in Waveguide Quantum Electro-Dynamics

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We analyze energy exchanges between a qubit and a field propagating in a waveguide. The joint closed dynamics is analytically solved within a repeated interaction model [1]. This Hamiltonian approach leads to an alternative definition of work with respect to previously proposed ones based on the qubit's master equation [3, 4]. For both qubit and field, treated equally as quantum systems, we define work as the unitary, entropy-preserving, component of the local energy change. We show that under suitable initial conditions the two work flows compensate each other, allowing us to define a unique work flow. As expected, this quantity converges to its un-ambiguous classical definition in the classical limit of the field (strong coherent field). Most importantly, in the opposite regime, when the waveguide is in the vacuum, our approach is the sole capable to capture measurable work exchanges of quantum nature along the spontaneous emission process [5]. Focusing on the charging of a qubit by a pulse of light, we evidence that the work provided by a coherent field is an upper bound for the qubit ergotropy, while this bound can be violated by non-classical fields, e.g. any coherent superposition of zero- and single-photon states. Our results provide operational, energy-based witnesses to probe the non-classical nature of a light field.

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Flexible entanglement-distribution network with an AlGaAs chip for secure communications

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Quantum technologies have the potential to dramatically enhance the security of communications in network infrastructures, with applications spanning from secure communications to delegated and blind quantum computing eventually leading to the full capabilities of a quantum Internet .

In this work, we demonstrate a scalable approach to a fully-connected entanglement distribution network [1]. We use a broadband source based on an AlGaAs semiconductor chip emitting polarization-entangled photon pairs in the telecom C-band [2]. We demonstrate that the lower bound on entanglement fidelity stays above 95 % in a 30 nm wide spectral range around biphoton degeneracy and above 85 % over a 58 nm range. We deterministically separate the photons of each pair into energy matched frequency channels and distribute them to the network users. This is done using a wavelength selective switch (WSS), a technology allowing for a dynamical reconfiguration of the frequency channels, offering unprecedented flexibility in entanglement distribution.

We benchmark the performance of our quantum network by running the entanglement-based BBM92 quantum key distribution (QKD) protocol. We perform key distribution between two users with quantum bit error rate (QBER) below 2% across fibered optical links of up to 50 km including finite-key effects and we extrapolate a positive key rate for distances of up to 75 km. We then extend our study to the multi-user case, taking advantage of the flexibility offered by our setup. By reconfiguring the frequency grid, we show that our network can accommodate from 4 users over 200 GHz ITU channels up to 8 users over 50 GHz ITU channels. We further demonstrate the insensitivity of the QBER with respect to channel width, indicating that every two-user link in the network can support high-performance QKD at metropolitan-scale distances.

Finally, we showcase the flexibility of our scheme in an unbalanced network scenario, featuring several local users and one distant user. We demonstrate that the bandwidth reallocation enabled by the WSS can be used to equilibrate the resulting rates, hence materializing a smart network configuration and highlighting its potential for the deployment of flexible, scalable quantum network architectures [3].

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Quantum City : a near-term photonic metropolitan quantum network architecture towards a Quantum Internet

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The Quantum City is a proposal for metropolitan quantum communication networks that are realizable with current or near-term quantum technologies and at the same time can support several envisioned applications of quantum networks. It is a quantum network architecture that tries to minimize the necessary resources for the clients accessing the network. The Quantum City consists of two types of nodes : the **Qonnector**, a powerful node in the network that has the ability to create and share bipartite or multipartite entanglement and connect to a number of clients through quantum channels; and the **Qlients**, network users with limited photonic capabilities, who can possibly generate, receive, and measure single photons. At metropolitan scale, the Quantum City will consist of a single or a few Qonnectors, using optical fibers to send photons to a few hundred or thousand Qlients. The Quantum City architecture is flexible, allowing to choose among different protocols achieving a given functionality depending on the trust and performance requirement of the user. Using NetSquid, a quantum network simulation tool using discrete events, we perform various simulations of different QKD protocols as well as of multiparty protocols while taking into account dominant sources of errors and losses. Using state of the art but realistic parameters in our model we show that quantum-enhanced network functionalities could be efficiently achieved by such networks in the near tearm, much before high-performance quantum memories and repeaters becore available. More precisely in a realistic setting for the city of Paris, we simulate the sifted key rate, throughput and QBER of 5 QKD protocols (different BB84-based protocols, BBM92 and MDI-QKD). We also study the possible implementation of secure delegated computation to a powerful quantum device in the network. Finally we investigate GHZ state sharing between 3, 4 and 5 Qlients that would allow multipartite applications such as anonymous transmission or conference key agreement.

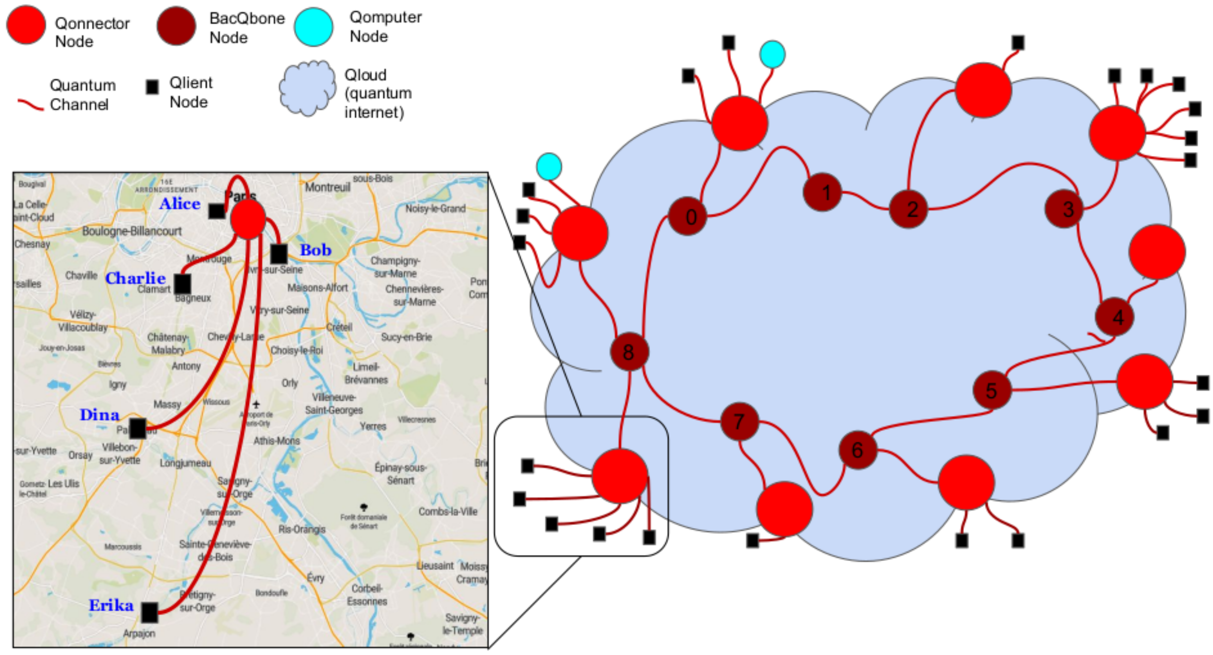

Figure 1. Representation of the Paris Quantum City (on the left) on which simulations have been performed, in a possible architecture for a future Quantum Internet (on the right).

Quantum networking with all-photonic repeaters

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The emergence of quantum communication technologies shows great promises for applications ranging from the unconditionally secure transmission of secret messages to distributed quantum computing. Due to the photon losses in fiber, long-distance quantum communication requires the use of quantum repeaters, which were initially thought around the concept of quantum memory [1]. This idea has been extended to all-photonic quantum repeaters, based on repeater graph states (RGS), which can be fabricated probabilistically solely with single-photon sources, linear optics and detectors [2]. The performances of such protocols have already been evaluated and have been shown to outperform repeater-less protocols at the expense of a significant overhead in resources. A more resource-efficient approach to produce RGS that only uses a few matter qubits has been recently proposed [3], but so far, an evaluation of its performances was lacking.

Here, we evaluate the performances of all-photonic quantum repeater protocol based on deterministic generation using a few quantum emitters [4]. We derive achievable criterions for the matter qubits, so that this protocol outperforms any memory-based and repeater-less approaches. These requirements should be met in the near term future. Finally, we propose a new all-photonic quantum repeater proposal [5] that enables error-correction, a feature that was lacking from the original proposal. Our results should pave the way towards the practical implementation of both resource-efficient and fast long-distance quantum communications.

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Receiver-Device-Independent Quantum Key Distribution

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Device-Independent (DI) Quantum Key Distribution (QKD) enables by distance separated users to establish a secret key without relying on a perfect characterization of their cryptographic devices. Theoretically, this paradigm can be argued to represent the strongest form of security for QKD achievable in quantum theory [1]. In practice, implementing DI-QKD beyond proof-of-principle demonstrations is very challenging. Nowadays a proof-of-principle experiment should be close to feasible with the best available current technology, but any practical implementation of DI-QKD is still arguably far out of reach.

This motivates the research on more general scenarios for quantum communications where trust is relaxed on some of the observers or devices. The most well-known approach is that of Measurement-Device-Independent (MDI) QKD where Alice and Bob (the honest parties) who wants to share a secret key, both send a quantum system to an intermediate third party (Charlie) performing a joint measurement [2]. Security can be demonstrated without any assumption on Charlie's device, the protocol being in this sense MDI. Another, alternative has been theoretically investigated in the context of quantum steering, where one-sided DI security can be proven [3]. Such a setup is asymmetric with respect to the sender and receiver and it is entanglement based. The implementation requires a similar level of complexity compared to a fully DI protocol (notably in terms of detector efficiency). We propose a different asymmetric approach which we term "receiver-DI" and that doesn't require any entanglement [4]. We consider a prepare-and-measure scenario, where Alice sends quantum systems to Bob. In our protocol the sender's device is (partially) trusted while the receiver's device can be treated as a black-box. In particular, our protocols do not rely on any type of fair-sampling assumption, contrary to Ref. [5]. Such an asymmetric scenario is relevant in practice when Alice and Bob have a different level of trust in their devices. For instance, Alice could be part of a large company and Bob could be an end-user. While the device of the sender (Alice) is partially characterized, the receiver's (Bob's) device is treated as a black-box. The security of the protocols is solely based on the assumption that Alice's prepared states have limited overlaps and the observed statistics, but no explicit bound on the Hilbert space dimension is required. This assumption on the overlaps is inspired from previous works in quantum random number generation. The security proof is numerical and based on computational techniques developed in [6]. The protocols are immune to attacks on the receiver's device, such as blinding attacks [7]. The users can establish a secret key while continuously monitoring the correct functioning of their devices through observed statistics. On a practical level, we report a proof-of-principle demonstration, involving mostly off-the-shelf equipment, as well as a high-efficiency superconducting nanowire detector. A positive key rate is demonstrated over a 4.8 km low-loss optical fiber with finite-key analysis. The prospects of implementing these protocols over longer distances is discussed. On a theoretical level, we show that in principle we can tolerate any amount of losses.

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Satellite-to-ground DV and CV-QKD links with adaptive optics correction

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The secure transmission of information is an important requirement of current telecommunications systems. Quantum key distribution (QKD) exploits some properties of quantum mechanics in order to allow for the exchange of unconditionally secure cryptographic keys that are subsequently used to encrypt information. The key information is encoded either into the superposition of modes of a single photon (discrete variable, DV) or into the quadratures of an electromagnetic field (continuous variable, CV). The implementation of such a system however is severely limited in distance by the attenuation in optical fiber, mainly because of the lack of mature technology in terms of quantum repeaters.

Satellite-to-ground QKD links could be an interesting way of implementing key exchange at an intercontinental scale. This has been studied as a possibility for both DV [1][2] and CV QKD [3] but the effects of turbulence on fiber coupling are not usually explored. Transmission through an atmospheric channel fluctuates and the aberrations of the transmitted wavefront affect its coupling into a single mode fiber, which is a necessary step before using either single-photon or coherent detectors for DV and CV QKD respectively. In order to mitigate at least partially the effects of turbulence, we consider correction of the perturbed wavefront with an adaptive optics (AO) system.

In this work, our purpose is to determine the feasibility of a low Earth orbit (LEO) satellite to ground QKD. We take into account trajectories with elevations between 20^o and 90^o and daytime and nighttime turbulence profiles ranging from mild to moderate. For DV-QKD we consider an efficient BB84 protocol with two decoy states while for CV we assume Gaussian modulation of amplitude and phase and heterodyne detection.

We first construct day and night turbulence profiles with statistically significant sets of measurements from different astronomical sites [4]. Using simulation tools, we then account for how this turbulence affects the signal and how its effect can be counterbalanced by AO systems of varying complexity levels, namely from 5 to 15 corrected radial orders. Next, we produce the probability distribution of the coupling efficiency of the corrected wavefront into the single mode fiber [5]. We can then compute the probability distribution of the transmission efficiency throughout the satellite orbit and including the pointing error of the satellite.

Finally, we use these results to calculate the secret key rate in the asymptotic regime and taking into account finite-size effects. The values of parameters such as excess noise (for CV) and background noise (for DV) are chosen in accordance with state of the art technology. As a first approach, we observe the evolution of the key rate as a function of the correction level of the AO system for different turbulence conditions. We determine that 15-order correction is a realistic compromise between system complexity and secret key rate. With this value in mind, we then explore the effects of other parameter variations such as satellite altitude, receiving telescope size and turbulence intensity.

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Explicit asymptotic secret key rate of continuous-variable quantum key distribution with an arbitrary modulation

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Quantum key distribution (QKD) allows two distant parties with access to a quantum channel and an authenticated classical channel to share a secret key. The information used to construct the key is either of a discrete nature, for instance, if it is encoded on the polarisation of single photons, or of a continuous nature, when the information is encoded on the quadratures of the quantified electromagnetic field. The latter case is more suitable for a large scale deployment of QKD since the technologies used are compatible with standard Telecom equipment. However, due to the infinite dimension of the Fock space now under consideration, security proofs are more challenging. The only continuous-variable (CV) protocols whose full composable security proofs are well understood use a Gaussian modulation of coherent states. In such protocols, Alice needs to draw a random complex variable from a Gaussian distribution and send the corresponding coherent state. In practice, however, the number of coherent states available is necessarily finite and a perfect Gaussian distribution is thus impossible to achieve. Protocols using a discrete modulation of states are therefore more appealing. Some recent works [1, 2] enabled to compute numerical bounds on the asymptotic secret key rate for protocols with four states. However, because these approaches were computationally intensive they could not be applied to modulations with more than a few states. In particular, the more relevant case of quadrature amplitude modulation (QAM), consisting of a grid of weighted equidistant coherent states in phase-space could not be analysed using this method. We solve this problem here: we give an explicit analytical formula for the asymptotic secret key rate of any CV QKD protocol. This result opens the way towards the derivation of a full composable security proof in the finite size regime. It also enables to compare various protocols. In particular, our bound shows that constellations of 64 states are sufficient to get a good performance (Fig.1) and are thus suitable for a large-scale deployment of CV QKD. See full version at https://doi.org/10.22331/q-2021-09-13-540.

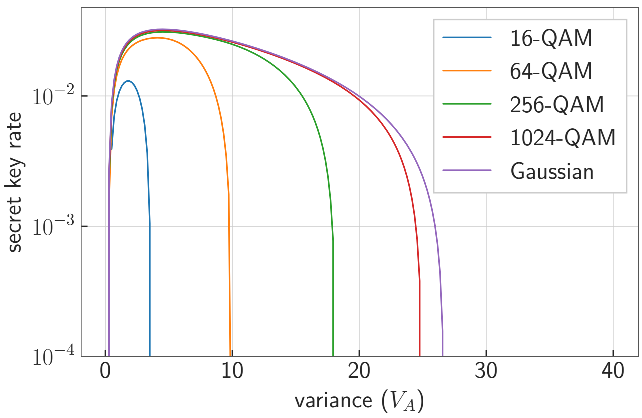

Figure 1. Secret key rate at 50 km as a function of the modulation variance V_A, for QAM of sizes 16, 64, 256, 1024 and for the Gaussian modulation (from bottom to top). The other parameters are the excess noise $\xi = 0.02$ and the reconciliation efficiency $\beta = 0.95$.

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Quantum routing in multipartite complex networks

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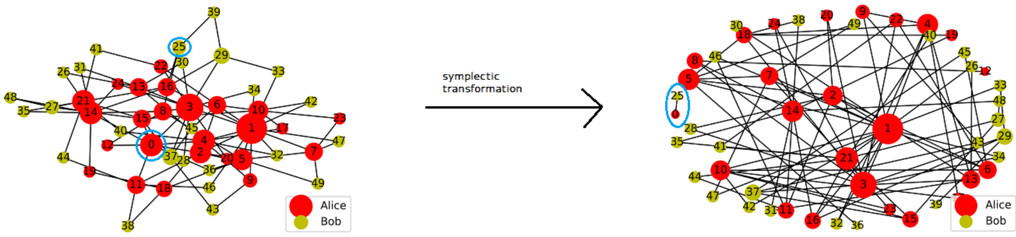
As quantum technologies become more and more mature, it is only a matter of time for them to organize into complex multipartite quantum networks also known as quantum internets, and begin to perform quantum algorithms devised with complex network structures. In this work we study the possibility of routing [1, 4] in continuous variables quantum networks toward extracting an EPR pair between two parties for quantum teleportation protocols. While methods for reshaping the network through local quadrature measurement were demonstrated recently [2] we tackle the problem in a complementary approach through local linear optic transformations. This way two parties act on their own part of the quantum network via symplectic transformation on their quadratures. To deal with the complexity of finding a global optimum in a huge parameter of space, we designed a derandomized evolutionary algorithm able to produce acceptable results within few seconds or minutes on ordinary laptops depending on the size of the problem. We demonstrate that local routing is possible in current usual complex network structures such as classical internet or protein-protein interaction graphs. This result widens our possibilities in terms of architecture toward real implementations of a quantum meta-structure. Finaly, such continuous variable entangled networks can be generated with multimode parametric processes pumped by femtosecond lasers. We present a new experimental setup for the realization of continuous variable multimode quantum states with spectro-temporal modes at telecom wavelength [3].



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High Efficiency Quantum Memory for Storage of Single photon Entanglement

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The transfer of quantum states of light and their mapping into stationary quantum nodes is one of the building blocks for future quantum networks and envisionned applications[1]. Central to this endeavor is the distribution of entanglement between the material nodes, which opens a variety of major applications[2]. For instance, to realize long-distance quantum communications one needs to divide the distance into shorter quantum repeater links connecting entangled memories. In this context, the efficiency of the entanglement mapping is a key parameter.

Recently, we realized a multiplexed quantum memory for polarization encoded qubits with high storage-and-retrieval efficiency [3]. In this experiment, we reported a quantum memory for polarization qubits that combines an average conditional fidelity above 99% and efficiency around 68%, thereby demonstrating a reversible qubit mapping where more information is retrieved than lost.

In our last experiment [4], we report for entanglement transfer between light and quantum memories and demonstrate a single mode storage-and-retrieval efficiency as high as 87%(+-5%), combined wih a very low two-photon contribution. In addition, we demonstrate that the entanglement capability of the stored quantum state is well preserved during the process as shown by the ratio of the input and output concurrences of 88%, more than a three-fold increase compared to prior works. Thanks to the realization of a comprehensive model of the storage-and-retrieval process that takes into account all the zeeman sub-levels of the involved atomic structure, we were able to better understand the physics in play and improve the overall efficiency of the process. Especially, performing the memory on the D1-line of cesium is a crucial prerequisite in order to obtain highly efficient memories. Our demonstration constitutes an important capability that is needed toward large scale networks and increased functionality.

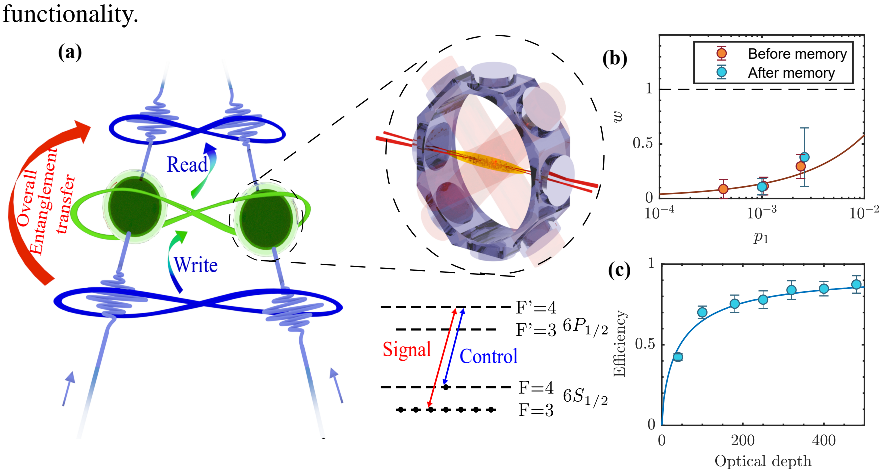

Fig. 1 (a) Single-photon entanglement is heralded, stored into two quantum memories with EIT, and read out on demand. (b) Suppression w of the two-photon component relative to a coherent state before and after retrieval. (c) Storage-and-retrieval efficiency for a single photon in one of the memories as a function of OD. The efficiency reaches $(87 \pm 5)\%$. The line corresponds to the full model (see text).

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Shaping entangled-photon correlations with an SLM

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Detecting correlations between photon pairs is an essential technique for imaging regimes that aim to exploit their entanglement. Methods have been developed to use electron multiplying CCD (EMCCD) cameras to measure these correlations, and in fact the full joint probability distribution of the photon pair source can be computed. We show that the structure of the correlations can in fact be shaped using a SLM in a manner analogous to classical beam shaping. Finally, we aim to extend this by using multiple SLMs to manipulate the structure of the JPD itself.

Practical Certification of Quantum Transmission Via Bell Theorem

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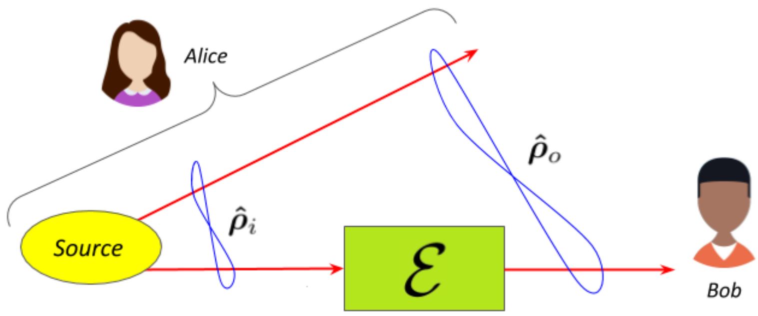
Building a quantum computer or a quantum internet relies on generating, processing, transmitting and measuring quantum information. Therefore, the ability to reliably certify such building blocks in a scalable way is of major importance in the hope of developing quantum technologies. When malicious parties or untrusted devices are involved, one might wish to make as few assumptions as possible, even regarding the dimensions of the Hilbert space involved, meaning we aim at developing device-independent certification procedures.

In this work, we provide a practical method allowing to device-independently certify the transmission of a state through an untrusted unitary quantum channel. We proceed by generalizing previous results on quantum channels [1] to any completely positive trace-decreasing map, therefore including lossy quantum channels. Showing an equivalence between Choi-Jamiołkowski and Diamond metrics for quantum processes, we show how to certify the action of a channel on any quantum state, from the sole knowledge of its action on a Bell pair. In order to account for an untrusted channel that could be controlled by a malicious operator, we build a protocol in which a finite number of states are measured, and the channel's expression might evolve through time, therefore dropping the commonly used IID assumption. This protocol relies on self-testing CHSH or steering inequalities [2], allowing one to certify a close-to-maximally entangled state, up to isometry, with the sole knowledge of measurement statistics. We base the security of this protocol on recently shown theoretical results [3] on authenticated quantum teleportation with an untrusted Bell state source. This allows use to derive bounds on the fidelity of the input state to the state that outputs the channel, up to isometry, depending on quantities that can be measured in experiments, such as the number of states sent through or received after the channel, or the deviation to the maximum violation of Bell or CHSH inequalities. This way, we not only propose a practical scheme for experimentally certified quantum transmission, but we also demonstrate some fundamental specificity in the behaviour of lossy channels, as compared to their mostly studied deterministic counterparts, also known as completely-positive trace-preserving (CPTP) maps. In the context of this study, we show a number of fundamental results regarding quantum channels, such as generalized results on probabilistic maps and or aspects of process metrics' behaviour.



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Non-Interactive and Non-Destructive Zero-Knowledge Proofs on Quantum States and Multi-Party Generation of Authorized Hidden GHZ States

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NIZKoQS. When receiving a quantum state, it is nearly impossible for the receiver to efficiently check non-trivial properties on that state without destroying it. This allows a sender to send maliciously crafted states without being detected.

To illustrate this, let us imagine the following simple goal. A receiver would like to obtain a quantum state $|\psi\rangle$ and verify, without destroying that state, that this state belongs to some "*quantum language*", say the language composed of BB84 states (so $|\psi\rangle \in \{|0\rangle, |1\rangle, |+\rangle, |-\rangle\}$). Since no measurement can answer this question (and would anyway destroy the state), a first solution could be to use a generic quantum secure multiparty computing protocol (QSMPC) between the sender and the receiver in order to generate that state. However, these protocols are interactive and require 2 messages or more (depending on the state). Therefore, the following question was left open :

Is it possible to receive via a single message a quantum state and test non-trivial properties on it non-destructively ?

In this work, we answer this question in the affirmative and propose a method to achieve Non-Interactive and Non-Destructive Zero-Knowledge Proofs on Quantum States (NIZKoQS). Notably, we prove that for some categories of states, a single message from the sender to the receiver is enough to prove (in a non-destructive way) non-trivial properties on the received quantum state. In particular, a sender can send a hidden GHZ state—a permutation of $X^{\mathbf{a}}((|0\dots0\rangle \pm |1\dots1\rangle) \otimes |0\dots0\rangle)$—and prove any property on the set of entangled qubits without revealing that set.

Multi-qubits RSP. At the heart of our method are Remote State Prepration protocols (RSP) [1, 2], which can classically fake a quantum channel ([2] being based on the groundbreaking work of [3]). However, they are particularly heavy to run : sending an n-qubits state requires the creation of at least n very expensive quantum superpositions. Therefore, a second question naturally arises :

Is it possible to classically send multi-qubits states while paying the cost of a single superposition ?

In our second orthogonal contribution, we answer this question in the affirmative and provide a method to create a state on n qubits (a hidden GHZ) using a single superposition.

Applications. We also extend this method to the multi-party setting. We show how it can prove useful to distribute a GHZ state between different parties, in such a way that only parties knowing a secret can be part of this GHZ. Moreover, the identity of the parties that are part of the GHZ remains hidden to any malicious party. A direct application would be to allow a server to create a secret sharing of a qubit between unknown parties, authorized for example by a third party Certification Authority, and this could be used to obtain Quantum Onion Routing.

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Relativistic coin flipping on a kitchen table

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Coin flipping is a cryptographic primitive which allows two mistrustful parties, Alice and Bob, to generate a random bit, such that none of the two parties can bias the outcome. The bit commitment, which is another cryptographic primitive, allows to perform coin flipping, the random bit being the XOR of the bits committed by Alice and Bob. It has been demonstrated that performing an unconditionally secure quantum bit commitment is impossible [1]. There have been though attempts to implement quantum coin flipping protocols. However, in those protocols, a dishonest party can bias the result with a non-zero success probability, which renders them quite useless in practical situations. On the other hand, relativistic bit commitment protocols have been successfully implemented [2]. Those protocols are based on special relativity and in particular on the impossibility of superluminal communication. However, they require that Alice and Bob each have two agents in remote locations. We introduce here a relativistic coin flipping protocol which is simpler to implement than a relativistic bit commitment and does not require Alice and Bob to have two agents.

The protocol proceeds as follow : Alice and Bob define two region of the space separated by a plan. Each of the two parties controls a side of this plan. They can exchange signals in two interactions points denoted X and X' and separated by a distance L. At a time t_0 Alice sends a bit a to Bob at location X. Similarly, Bob sends a bit b to Alice at location X', at a time $t_0 + \Delta_t$. The Δ_t time difference can be due to timing imperfections but also because Bob is trying to cheat by sending his bit later, once he has already learned Alice's bit. To prevent any cheating, Alice has to verify the relativistic condition, i.e. that Bob has sent the bit b at location X' before the information about the bit a could have arrived at that location. This is done by checking that $\Delta_t < L/c$, where c is the speed of light. Bob has to perform the same verification with the signal received from Alice.

We realise an experimental demonstration of this protocol by developing fast electronic boards (displayed in figure 1). Figure 2 shows a picture of the setup. Two identical electronic boards, one fore each player, are connected with coaxial cables. A third board is used to send the start signal (this board can be controlled by any player or by an untrusted third party). We set the distance L to 1 m. The temporal precision of the signals of the boards determine the minimum possible distance L, which is around 30 cm. Finally, the boards have not two but three bits in total which allows to play the game rock, paper, scissors as well.

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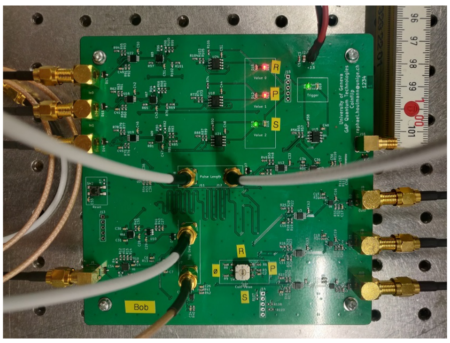

FIGURE 1. Electronic board used by each player. A switch allows for the selection of the bit sent. Light emitting diodes provide the readout of the received bit and its validity.

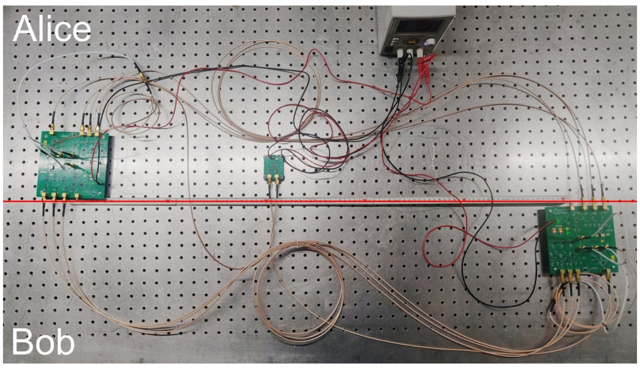

FIGURE 2. Full experimental setup. The red line represent the separation between the regions of the space controlled by Alice and Bob

Automated quantum optical experiment design for device-independent quantum key distribution

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Quantum key distribution (QKD) is the production of a shared cryptographic key between two parties, Alice and Bob, linked via a quantum communication channel [1, 2]. This communication protocol is information-theoretically secure ; i.e. a third party eavesdropper, Eve, controlling the quantum channel, can not infer information on the key. This security comes at the cost of making the assumption that (i) quantum theory is correct, (ii) Alice and Bob share an authenticated classical channel of communication and (iii) the quantum devices used by Alice and Bob to generate and measure quantum states shared via the quantum channel are truthful. Device-independent quantum key distribution (DIQKD) protocols drop the third assumption by integrating the possibility to test the key generation devices.

Although appealing, DIQKD protocols are challenging to implement experimentally. First, they rely on high quality entangled quantum states [2], which are very sensitive to noise and losses. Then, Bell tests and post-processing steps require many of these states. A mean of producing, distributing and measuring high quality entangled states is thus crucial for DIQKD and could lead to a first experimental implementation.

In this scope, optical setups, with their high repetition rates, provide a good option for such a first realization. Moreover, theoretical efforts are devoted to the development of security proofs based on individual correlation functions arising from DIQKD setups [3, 4]. The possibility of implementing complex optical setups, the demand for an optical setup producing given correlation functions and the constant evolution of DIQKD protocols push us to provide automated solutions to design experimental optical setups.

An efficient and precise way of computing the statistics arising from a given circuit is a key component for an automated search, both for scalability and reliability. In this poster, we present a numerical framework based on Gaussian operations, enabling the fast and precise computation of the statistic of any photonic setup.

Machine learning and in particular reinforcement learning (RL) was successfully used to design quantum experiments [5]. RL algorithms aim at finding the strategy, maximizing a certain goal through trials and errors in an environment. In this poster, we show how such an algorithm can learn how to apply different optical devices (actions) on an optic table (environment) in order to find a realistic and robust DIQKD implementation.

Finally, we present realistic DIQKD implementations found by our automated search. This is a simingly simple photonic setup able to produce key rates at low detector efficiency where, to our knowledge, no previous proposed implementations are able to. We also show a non-trivial photonic experiment leading to high key rate at high detector efficiency.

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A versatile and high-performance PIC-based CV-QKD receiver

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Quantum Key Distribution is a prominent application of quantum cryptography, offering security based on the laws of quantum physics. Commonly used discrete-variable (DV) QKD requires components such as single-photon detectors that are costly and require specific technology. Continuous-Variable Quantum Key Distribution (CV-QKD) on the other hand can address this issue as it only requires standard telecom laser sources and receivers. [1].

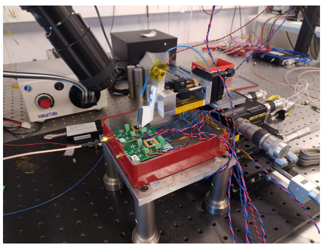
In order to reduce the cost and size of CV-QKD systems, there are significant efforts to integrate such systems on Photonic Integrated Circuits (PICs) [2]. In particular our team is part of the European quantum technologies flagship project CiViQ [3] where one of the main goals is to demonstrate fully PIC-based CV-QKD systems.

We report here on the characterization and system integration of two receiver (Rx) PICs (fig. 1a) and their specifically designed low-noise transimpedance amplifier (TIA). The chips were designed by CNRS/C2N and fabricated using a SiGe process by CEA/LETI, and each one can be used as a single-polarization homodyne or heterodyne detector. With an external Polarization Beam Splitter (PBS), we could use two chips as a full double-polarization receiver.

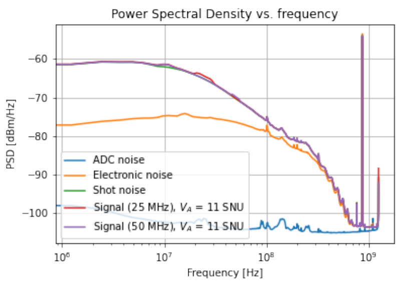
The results that we obtained demonstrate that the component characteristics relevant to CV-QKD, namely the clearance (shot-noise to electronic noise ratio), the linearity and the quantum efficiencies, on a band of several tens of MHz, are in the required range for CV-QKD and promising for a key exchange. A signal at the quantum levels required for the key exchange was also detected by the chips (fig. 1b). A special care was taken to find and eliminate unwanted sources of noise and get the best conditions for characterizing and using the PICs. We optimized the coupling to get the highest overall quantum efficiencies and the PICs internal Variable Optical Attenuators (VOAs) were also used to get the best clearance possible without saturation.

The system integration was done with a bulk transmitter (Tx) with several features akin to standard telecom technology including working with continuous wave (CW) and standard Digital Signal Processing (DSP) algorithms [4].

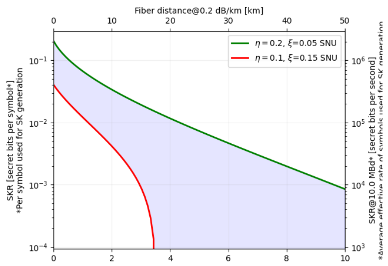
Near-term future work includes full operation with signal transmission and DSP, and system integration with other PICs of the CiViQ project with a projected Secret Key Rate (SKR) of the order of kbits/s over metropolitan area distances (fig. 1c).



(a) Picture of the chip setup.



(b) Power Spectral Density vs. frequency for different noise scenarios and signal.



(c) Projected Secret Key Rate (SKR) as a function of the channel attenuation/distance.

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Efficient telecom-band quantum frequency conversion

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Single photon sources are crucial for quantum communications. Semiconductor quantum dots (QDs) represent one of the best technology to generate single photons on-demand, with high brightness, indistinguishability, repetition rate and low multi-photon contributions. QDs emitting near infrared single photons provide the best performances [1]. To implement NIR sources on a communication network, we need to develop a quantum frequency conversion (QFC) interface to operate on telecommunication bands [2]. The combination of high performances technologies can lead to a link with high rates, low noise and widely secure.

We achieve a frequency conversion interface to coherently transmit light from a weak coherent source at 925 nm toward telecommunication C-band (Fig. 1). We demonstrate coherence preservation and an internal conversion of 62 % efficiency.

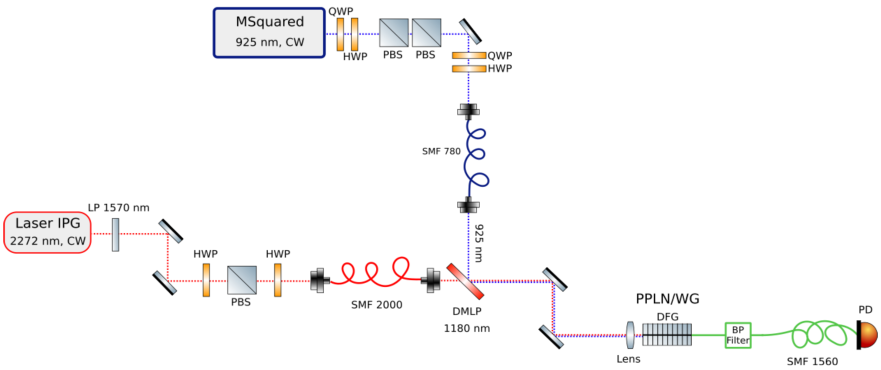

FIGURE 1: Experimental setup of the frequency conversion interface. The frequency conversion is performed by the difference frequency conversion (DFG). This non-linear process takes place in a periodically-poled lithium niobate waveguide (PPLN/WG).

We measure the internal conversion efficiency η_{int} by comparing the signal power at the output of the waveguide with several pump laser power and without. All losses are not taking into account. We also measure the external efficiency η_{ext} by calculate the ratio between the output converted power and signal power injected into the interface.We reached $\eta_{int,max} = 62(1)\%$ and $\eta_{ext,max} = 40(1)\%$. These results are at the state-of-the-art for similar downconversion interfaces [2].

Furthermore, to determine coherence preservation, we inject converted light into an unbalanced Michelson interferometer to observe single photon interference as a function of the path difference ΔL. As example, for $\Delta L = 4m$, we obtain $V = 95\pm5\%$. This result is very close to 100 % predicted by quantum theory, we conclude that our interface preserves encoded states, in particular, suitable for QKD based on single photon source.

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Complete design of an experimental platform for trapping cold atoms interfaced with slow guided light

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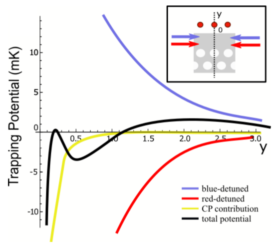
Trapping cold neutral atoms in close proximity to nanostructures has raised a large interest in recent years, pushing the frontiers of cavity-QED and boosting the emergence of the waveguide-QED field of research. Such platforms interfacing trapped cold atoms and guided light in nanoscale waveguides are a promising route to achieve a regime of strong coupling between light and atoms [2]. Experimental setups include nanofibers and photonic crystal waveguides (PCWs), owing to the large transverse confinement of their guided modes. But the design of efficient dipole trapping schemes in evanescent fields, albeit a crucial requirement, is a difficult task.

With PCWs, tuning the dispersion relation can give rise to a very low group velocity of the guided light [1], allowing for strong coupling even in single pass. While encouraging values of couplings have been observed with first corrugated devices [3], a photonic platform with trapped atoms via guided modes in the vicinity of a waveguide and in the strong coupling regime has yet to be demonstrated.

W1 waveguides (*i.e.* 2D PCWs made of a hexagonal lattice of holes with one row removed) are a powerful geometry, robust to fabrication imperfections. Building on the promises of such structures, we propose to interface ^{87}Rb atoms with a GaInP halved W1 waveguide [4] (see inset Fig.1), which significantly improves the optical access. But the tunability of the bandstructure comes with complicated field profiles, making the search for a trapping scheme an extensive procedure.

We introduce a stable trapping scheme around our Half-W1 PCW for ^{87}Rb atoms based on an evanescent two-color dipole trap formed by fast guided modes. This scheme was computed thanks to *nanotrappy* [5], a Python package developed by our group, to design, calculate and optimize dipole traps around nanoscale waveguides, making the search process faster and more systematic.



(a) FIGURE 1 : Stable trap for Rb atoms obtained after optimisation of optical powers and designs with *nanotrappy*. Trapped atoms in a few mK traps at 80 nm from the Half-W1 surface are envisioned. INSET : Scheme of a Half-W1 waveguide with atoms on the edge and trapping beams.

The coupling of the atoms to the waveguide can be characterized by the Purcell factor, which compares the decay rate of the atoms into the guided mode with respect to the one into free space. At realistic distances (see Fig. 1.), FDTD calculations reveal that Purcell factors as high as 5 can be expected. Moreover, dispersion engineering by tuning the geometrical parameters of the PCW can lead to a constant group index $n_g \sim 30$ over a range of 15 nm, centered around $\lambda_{Rb}^{D2} = 780$ nm, making the design more robust to fabrication imperfections.

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Experimental demonstration of quantum advantage in transmitted information for Euclidean distance estimation

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When considering the complexity of communication protocols, the aim is to have a protocol that performs a certain task with the smallest amount of communication resources, such as time and transmitted information. In this work, we focus on minimizing the transmitted information in a *simultaneous message passing model*, where two parties Alice and Bob are not allowed to communicate with each other but instead they send their data to a referee who performs a task and evaluates its outcome. Our starting point is the task of fingerprinting presented in [1], where is was shown that quantum and classical fingerprinting use $O(log_2(n))$ and $\Omega(\sqrt{n})$ bits respectively to perform the task within the same error margin, hence indicating a quantum advantage. Ref. [2] showed that it was in fact possible to perform quantum fingerprinting using coherent states which are readily available resources in the lab; and [3] applied this idea to propose an experimental scheme for estimating the Euclidean distance between two data sets with precision ± 0.1 and error $\delta \leq 10^{-6}$. Following these works that opened the way in theory to a possible quantum advantage for large input sizes, our goal was to implement experimentally the Euclidean distance protocol described in [3] and evaluate the quantum advantage and the error bounds.

To this end, we built a Mach Zhender interferometer, where each arm represents Alice and Bob and where the referee holds a beam splitter and two single-photon detectors. On each arm Alice and Bob encode the information on the amplitude of their coherent pulses that have a 16-ns duration. We build our data sets by dividing the amplitude of our pulses to 9 different bit values. Two superconducting nanowire single-photon detectors (SNSPDs) are then used to detect the outcome of the interference. Based on the probability of clicks at each detector, the Euclidean distance was calculated following the analysis in [3]. We tested data sets (train of pulses) with maximum distance of two and with minimum distance of zero, as well as random vectors with different Euclidean distances, and finally we also compared a set of gray scale images, which we could map to our 9 bit values scheme. Our data sets had an input size of 10^8 and all satisfied the theoretically expected precision and error bounds. Our results confirm the quantum advantage over classical protocols for this task and can find applications in a wide range of practical scenarios.

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Autonomous stabilizaion of even parity Fock states in a superconducting cavity

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Because of their coupling to the environment, physical qubits are prone to errors due to decoherence, making it necessary to use quantum error correction (QEC) protocols to preserve their quantum information. In this context, new approaches emerged using Bosonic modes where the information is delocalized across the phase space of a cavity, among which the GKP code [1],[2] or the Cat code[3]. The latter uses superpositions of coherent states to encode the quantum information, and can be efficiently protected against bit flips using a dissipation mechanism that exchanges pairs of photons with the cavity [4]. It has then been proposed to use repetition codes to correct for the remaining phase flips[5], mainly caused by the loss of single photons inside the cavity. In this work, we propose an alternative scheme to protect against such single photon losses, using a dissipative process that stabilizes states with a given parity. Similar to [6], we couple a superconducting cavity to a transmon, itself coupled to a buffer. By using two combs, temporally shifted from one another, we then transfer a photon from the cavity to the buffer whenever a Fock state with an unwanted parity is populated in the cavity. Doing so improves the lifetime of the Fock states with the desired parity, and should provide a way to autonomously protect cat qubits against phase flips errors.

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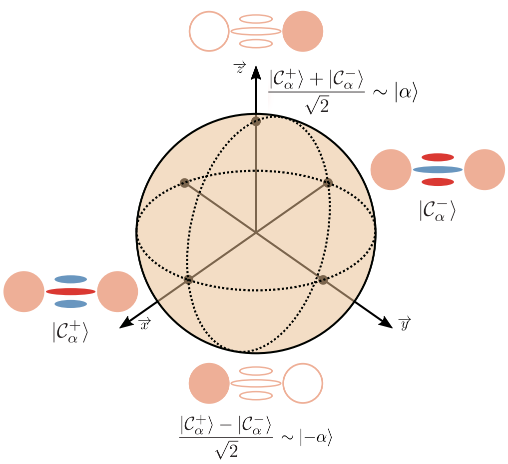

AlGaAs Bragg reflection waveguides for hybrid III-V/ Silicon quantum photonic device

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Photonic quantum technologies represent a promising platform for several quantum information applications, ranging from long-distance communications to the simulation of complex phenomena. On the one hand, the advantages offered by single photons (robustness to decoherence, propagation over very large distances) make them the candidate of choice to carry quantum information in a wide variety of domains. On the other hand, the emergence of integrated quantum Silicon photonics has led to the demonstration of photon manipulation on complex circuits with near-perfect phase stability ;

Among those platforms, SOI circuitry represents a very promising candidate thanks to its CMOS technology, however the indirect band gap of silicon waveguides prevents it from generating photon pairs with electrical injection. Our objective is to integrate on the same chip the 3-5 sources of quantum states of light and the SOI-circuitry structure through adhesive bonding [2].

We use a broadband source based on an AlGaAs semiconductor chip (figure1 (a)), benefiting from a strong non linearity, a direct bandgap and emitting polarization-entangled photon pairs in the telecom C-band [1]. The first step being to characterize the AlGaAs sources, we observed 3 types of phase matching (PM) leading to the generation of photon pairs with all 3 set of polarization in order to couple them to different kinds of silicon waveguides.

On the one hand, the type I PM, emitting parallel TE photons, is naturally compatible with CMOS SOI photonic technology. On the other hand, the type II PM, emitting orthogonal TE and TM photons can be exploited to implement polarisation entanglement, and to this aim, a specific structure of silicon waveguide has already been designed to realize the coupling of AlGaAs and Silicon waveguides for both polarizations.

The three phase matching resonances could be observed on the same AlGaAs device, the SHG measurement reported on figure 1.b has been obtained by spanning the wavelength of a telecom laser (polarized at 45 degrees in order to share the power between TE and TM polarization). It evidences a good conversion efficiency ($\eta > 10^{-3}W^{-1}$) giving soon the opportunity to demonstrate second harmonic generation on the two kinds of hybrid structures once bonded on SOI.

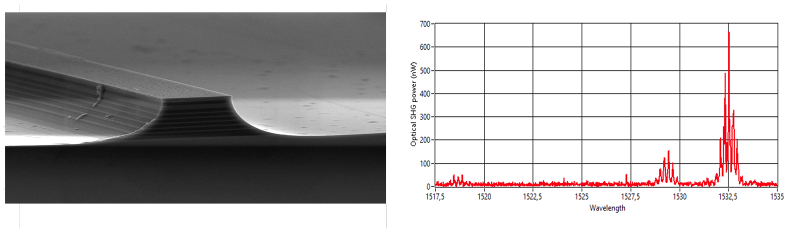

FIGURE 1. (Left) SEM image of our AlGaAs Bragg waveguide (Right) SHG measurement showing the 3 types of PM, respectively type 1,0 and 2.

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Posters 2, 04/11: Quantum Sensing & Metrology (QMET)

Dissipative stabilization of squeezing beyond 3 dB in a microwave mode.

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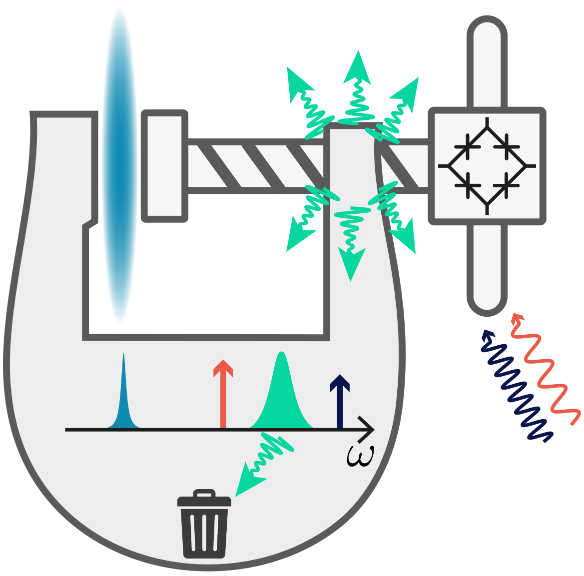
Squeezed states, whose fluctuations on one quadrature are below the zero point fluctuations (ZPF) at the expense the other, are an instrumental resource for quantum sensing and information processing. While a propagating state of light can be generated with arbitrary squeezing by pumping a parametric resonator, the intraresonator state is limited to 3 dB of squeezing.

In this work [1], we implement a reservoir-engineering method to surpass this limit using superconducting circuits. Two-tone pumping of a three-wave-mixing element implements an effective coupling to a squeezed bath [2], which stabilizes a squeezed state inside the resonator. Using an ancillary superconducting qubit as a probe allows us to perform a direct Wigner tomography of the intraresonator state. The raw measurement provides a lower bound on the squeezing at about 6.7±0.2 dB below the zero-point level. Further, we show how to correct for resonator evolution during the Wigner tomography and obtain a squeezing as high as 8.2±0.8 dB. Moreover, this level of squeezing is achieved with a purity of 0.91±0.09



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Processing Quantum Signals Carried by Electrical Currents

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Besides their interest for basics condensed matter physics, single-to-few electron excitations propagating within quantum conductors and nano-structures have been proposed for various applications in quantum technologies, ranging from interferometric sensing of time-dependent electromagnetic fields on sub-nanosecond timescales to quantum information carriers (electronic flying qubits) [1]. However, all these applications call for a general method to unravel the single-particle excitations embedded in a quantum electric current and how quantum information is encoded within it. In this talk, I will present a general signal processing algorithm to extract the elementary single-particle states, called electronic atoms of signal, present in any periodic quantum electric current [3]. These excitations and their mutual quantum coherence describe the excess single-electron coherence in the same way musical notes and score describe a sound signal emitted by a music instrument. This method, which is the first step towards the development of signal processing of quantum electric currents can therefore be used to assess the quality of single electron sources and to unravel quantum information carried by a quantum electric current. I will also present how this has effectively been implemented experimentally, leading to the first experimental determination of single electron wavefunctions propagating within quantum Hall edge channels [2]. I will then discuss some of the perspectives opened by these recent developments.

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Plug and play measurement of chromatic dispersion by means of two-photon interferometry

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Two-photon interference lies at the heart of photonic quantum information technologies. A remarkable property of is to qualify the energy-time entanglement carried by the photon pairs traveling along an interferometer, benefiting a large variety of quantum applications such as Quantum Key Distribution [1] or phase insensitive Hong-Ou-Mandel interference [2]. Here we propose a chromatic dispersion (CD) measurement method based on the acquisition of two-photon interference fringes. We highlight 3 advantages : i) The method lies in recording the free evolution of the interference fringes, neither spectrometer nor stabilisation system is needed. ii) The value of CD is directly obtained thanks on an elegant formalism linking the visibility of the fringes and the second-order dispersion value. iii) This method is versatile and can be transposed for different wavelengths.

A photon pair generated via spontaneous parametric down conversion is sent through a Michelson interferometer, creating a NOON state, carrying the information of the relative phase difference . By studying the evolution of such state through the interferometer, odd terms of the dispersion vanishes. Remarkably, provided that the two-photon spectrum shape is gaussian with a FWHM of σ, we show that the link between the visibility of the interferogram and the CD is given by :

$$V = \frac{1}{\sqrt[4]{(2\sigma^2\beta^{(2)}L)^2+1}}$$

The visibility is extracted from the Probability Density Function (PDF) of the coincidence rate according to :

$$PDF = \frac{2}{\pi V\sqrt{1+\frac{-4x^2+4x-1}{V^2}}}$$

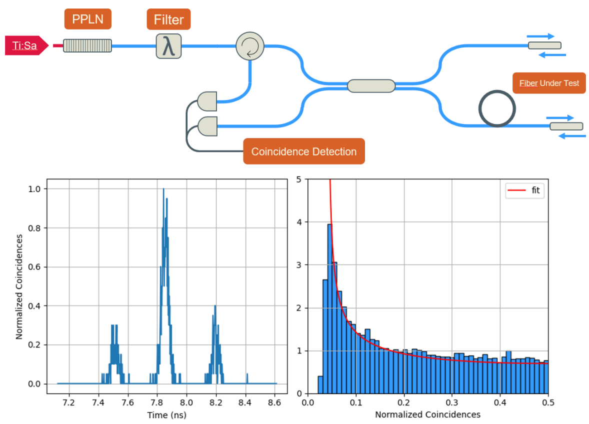

FIGURE 1. Top : Acquired interferogram after 50s with a 100ms acquisition interval. Left : Typical Franson histogram. Right : Fitted histogram using equation (2).

Where x represents the number of occurence. Figure (1) shows a 50s acquisition interferogram from a non stabilized system (top). The length of the fiber is 14,75m which creates fast fluctuations. Each point correspond to the central part of the well-known Franson histogram (left). From those values, the visibility is calculated using equation (2). While the PDF of a trigonometric function is symmetric, the Poissonian distribution associated to the pump laser creates an asymmetry of the PDF proportional to the maximum coincidence rate. In order to overcome this limitation, only the left part of the PDF is fitted, where the absolute error of the Poissonian statistic is the lowest. This work paves the way for quick and reliable measurements and clearly proves that quantum technologies are nowadays ready to adress real-world applications, potentially boosting several sectors such as fiber laser industries.

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Experiment Design for Microwave Quantum Illumination

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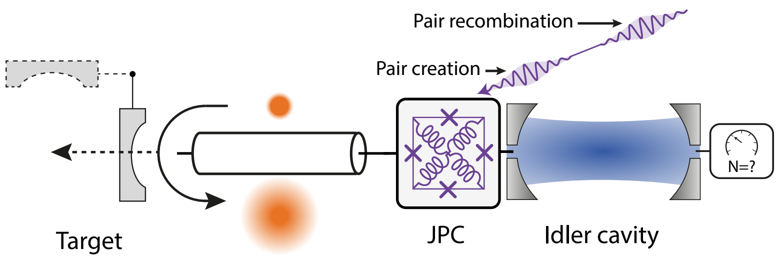
The concept of quantum illumination was introduced by Lloyd more than a decade ago [1]. It consists in using a pair of entangled photons to probe a target located in a very noisy environment. Lloyd predicted a 4x improvement in asymptotic signal to noise ratio (SNR) over the best classical setup possible. This is despite the fact that the large amount of noise completely destroys the entanglement. This is one of the few examples of an experiment able to harness quantum discord [2] — correlations that are reduced but not suppressed by large amounts of noise and that are above any form of classical correlations.

Realizing this advantage in practice has proven to be difficult with only one experiment [3] showing some SNR improvement. That experiment was however performed at optical frequencies. The interest of quantum illumination would be more drastic at microwave frequencies where there are many thermal photons at room temperature.

In this poster, we'll present the design of a new experiment that will be able to demonstrate a genuine quantum advantage in the microwave frequencies thanks to quantum illumination. The design implements both the best possible classical radar as well as a quantum radar that could show up to 2x SNR improvement following an idea of Guha and Erkmen [4]. The deterministic generation of the vacuum two-mode squeezed state is done using a superconducting circuit [5] called a Josephson Parametric Converter (JPC) cooled down to $15\,\mathrm{mK}$ inside of a dilution refrigerator. The idler mode of the JPC is able to store one half of the squeezed state for a long time while the other half is travelling to and back from the target. Once the signal comes back, the same JPC, combined with an ancillary qubit, performs a joint measurement of both modes. This joint measurement of idler and signal is required to see any quantum advantage and it is missing in all the previous attempts to demonstrate microwave quantum illumination [6].

The experiment will also feature a solid-state switch based on a Josephson junction to be able to quickly switch on and off the target. The classical radar will be implemented using a degenerate parametric amplifier able to perform essentially noiseless amplification of one of the two quadratures of the classical signal in order to implement the best possible classical radar.



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Towards a versatile and resilient detection of paramagnetic species at the micron scale using quantum circuits techniques

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Electron spin resonance is usually performed on spins embedded within a microwave resonator matching their Larmor precession frequency. In pulsed EPR spectroscopy, trains of microwave pulses are sent to trigger the emission of an echo by the spins, allowing to infer their presence. Using quantum circuits techniques, namely superconducting high-quality factor resonators, low temperatures, and quantum-limited detection, the sensitivity of such a measurement has recently been improved to a new limit of 12 spins/sqrt Hz with a probe volume of a 10 fL [1–3]. These experiments have however been limited to crystalline samples, without dielectric losses and where spins have long lifetimes, thus preventing their applications to fields of research beyond quantum information purposes. Here, we report our progress towards implementing superconducting high-quality factor resonators resilient to both magnetic fields and dielectric samples, which would enable to probe more diverse sample types, including molecular switches used as imaging probes that depict enzyme activity [4]. The resonator is designed to have a low-impedance to maximize the coupling to the spins as well as an 'active' area for the sample with maximized magnetic field and minimized electric field. It is fabricated out of NbTiN for magnetic field resilience [5]. We have validated these choices by benchmarking its quality factor against well-known designs and confirmed the magnetic field resilience. We also report on the in-situ calibration of our spectrometer using BDPA (1,3-Bis(diphenylene)-2-phenylallyl) drop.

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Probing dark spins with NV centers in CVD-grown diamond

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The electronic spin of the Nitrogen Vacancy (NV) center in diamond has given rise to a wealth of application over the past ten years, in particular in the domain of magnetic field sensing. The main reason to its rapid rise in popularity is the ability of the spin to be optically polarized and read-out at room temperature, with nothing more than a confocal microscopy setup.

Because of their point-like nature, NV centers can be placed a few nanometers away from the magnetic source, making them good candidate to probe tiny fields, such as the ones produced by other spins. Electronic and nuclear spins, both inside or outside the diamond have been detected by NV center magnetometry, down to a single spin [1].

In our work [2], we have used a diamond grown through chemical vapor deposition (CVD) with a relatively large ensemble of NV centers ($\approx$ 3 ppm) in order to probe trace amounts of other electronic spins in the diamond, in the ppb range. This technique relies on resonant dipole-dipole coupling between the spins (flip-flop) [3] and unlike many NV magnetometry protocols does not require a microwave field.

Compared to traditional electronic spin resonance technique such as EPR, besides its comparatively simpler apparatus and potential gain in sensibility, an NV-based method present the advantage not to rely on the total number of spins of the sample, but rather only on the spins in the vicinity of the probed NV centers, making the measurement applicable to micro or nano-diamond, with a spatial resolution given by the diffraction limit of the microscope.

Understanding and controlling the local environment of NV-centers is a key aspect to improve NV magnetometry and other quantum applications with NV centers. Our method could provide chemists and material scientists a quick and cheap purity test for the samples they grow.

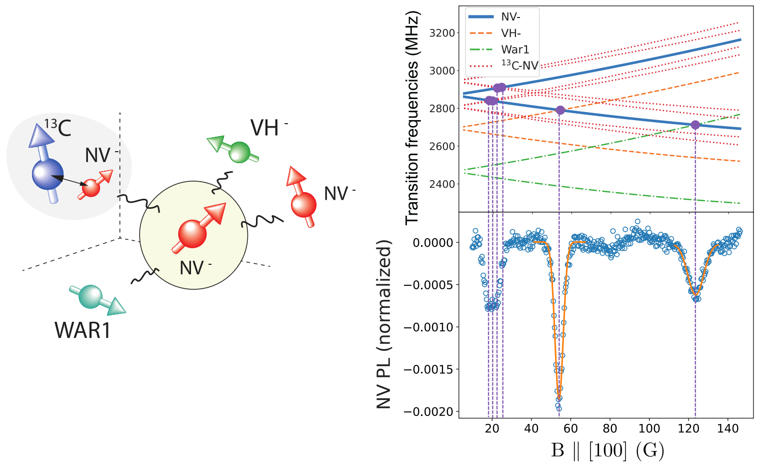

FIGURE 1. **Top Figure :** Transition energies of the NV center's spin and various dark spins as a function of the external magnetic field.
Bottom figure : Normalized photoluminescence of the NV center as a function of the external magnetic field.
Resonant dipolar coupling between polarized NV centers and unpolarized dark spins induce a depolarization of the NV spin which is detected by a drop in the NV photoluminescence

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Pixel super-resolution with spatially-entangled photons

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Pixelation occurs in many imaging systems and limits the spatial resolution of the acquired images. This effect is notably present in quantum imaging experiments with correlated photons in which the number of pixels used to detect coincidences is often limited by the sensor technology or the acquisition speed. Here, we introduce a pixel super-resolution technique based on measuring the full spatially-resolved joint probability distribution of spatially-entangled photons. Without shifting optical elements or using prior information, our technique increases the pixel resolution of the imaging system by the square of the number of correlated photons and enables retrieval of spatial information lost due to undersampling. We demonstrate its use in various quantum imaging protocols using photon pairs, including quantum illumination [1], entanglement-enabled quantum holography [2], and in a full-field version of N00N-state quantum holography [3]. Our JPD super-resolution technique can benefit any full-field imaging system limited by the sensor spatial resolution, including all already established and future photon-correlation-based quantum imaging schemes, bringing these techniques closer to real-world applications.

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Scaling laws for the sensitivity enhancement of non-Gaussian spin states

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We identify the large-N scaling of the metrological quantum gain offered by over-squeezed spin states that are accessible by one-axis-twisting, as a function of the preparation time. We further determine how the scaling is modified by relevant decoherence processes and predict a discontinuous change of the quantum gain at a critical preparation time that depends on the noise. Our analytical results provide recipes for optimal and feasible implementations of quantum enhancements with non-Gaussian spin states in existing experiments, well beyond the reach of spin squeezing [1].

[1] Y. Baamara, A. Sinatra, M. Gessner "Scaling laws for the sensitivity enhancement of non-Gaussian spin state", https ://arxiv.org/abs/2105.11421, Phys. Rev. Lett. (to appear).

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Scaling laws for the sensitivity enhancement of non-Gaussian spin states

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[1] Y. Baamara, A. Sinatra, and M. Gessner, "Scaling laws for the sensitivity enhancement of non-Gaussian spin states", arXiv :2105.11421. To appear in Physical Review Letter.

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Rapid high-fidelity charge readout in GaAs quantum dots using radio-frequency reflectometry

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A key requirement for quantum computing, in particular for a scalable quantum computing architecture, is a fast and high-fidelity qubit readout. Transport measurements across a quantum dots acting as a local electrometer have been used to demonstrate many milestones towards large scale spin qubit quantum computers [1]. However the low pass filter behaviour of classic DC cables greatly limits the possible bandwidth of the measurement to a few kHz and prevents rapid high fidelity charge readout. Moreover this technique is hardly scalable since each electrometer needs to have a dedicated line in the cryostat.

It has been shown that using Radio Frequency reflectometry allows to overcome these issues [2],[3]. In this work we opted for a source-reflectometry technique consisting in building a resonant circuit embedding a GaAs/AlGaAs gate defined quantum dot. We apply an RF-tone and monitor the reflected signal to measure variation of the quantum dot conductance. In addition we fabricated an on-chip variable capacitance to adjust precisely the matching of the tank circuit at the most sensitive conductance of the quantum dot. We demonstrate the ability to tune the total capacitance of the resonant circuit over 20 fF. We use this RF-Quantum dot to sense the charge occupancy of a neighbour dot and achieve 1e/2e charge discrimination with a SNR as high as **1.4** in 1 µs.

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Posters 2, 04/11:
Quantum Simulation (QSIM)

Effective thermalization of a many-body dynamically localized Bose gas - IQFA Quantum Abstract

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In the quantum kicked-rotor, the alternation of kicks and free propagation gives rise to exponentially localized single-particle wave-functions in momentum space [1], known as dynamical localization, which is the quantum chaos analog of the well-known Anderson localization predicted in disordered system [2].

The consequences of adding interactions in such periodically driven system remains unclear, especially for one dimensional system where mean-field theory breaks down. We study the many-body dynamical localization of a kicked Bose gas in the Tonks regime (strong interactions). We will show that the steady-state of such system at long time can be described by a thermal density matrix, with an effective temperature depending on the kicking parameters and the number of particles, while a loss of decoherence is enlightened by the one-body reduced density matrix.

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Measuring densities of cold atomic clouds smaller than the resolution limit.

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The cold atoms community explores the physics of dense cloud of atoms, which reveal interesting phenomena in extremely small and local features such as vortices, density fluctuations, etc. Resolving such structures is a difficult but rewarding problem that prompted important technical developments, using for example fluorescence imaging with high-resolution objectives [1], the newly demonstrated quantum gas magnifier [2], super-resolution imaging [3], [4]. In the case of standard absorption imaging of extremely small and dense objects, the Beer-Lambert law is non linear and cannot be averaged over the imaging resolution. This excludes the imaging of small features, and can also significantly distort large features.

We experimentally demonstrate that it is still possible to accurately measure the size and local density of an object, even when this object is smaller than the imaging resolution, taking benefit of the non-linearity of the Beer-Lambert law. The number of photons absorbed by a given number of atoms depends on the size of the sample especially when it becomes optically dense. The method relies on making an ansatz on the cloud shape along the unresolved dimension(s), and providing an additional information such as the total number of atoms. We experiment our method to measure transverse sizes as small as one fifth of our imaging resolution of *in-situ* absorption images of quasi-1D ^{87}Sr Fermi gases. The measurement is in good agreement with theoretical predictions. Moreover, we show that the distorted image of density profiles along the long axis can be reconstructed in agreement with theoretical predictions of Fermi distributions.

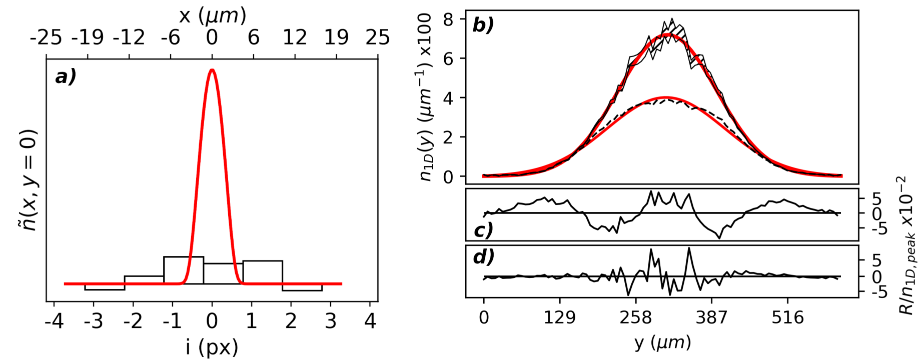

FIGURE 1: Recovering density profiles from distorted absorption images of quasi-1D tightly confined gas. a) Cross section along the unresolved short axis of the column density imaged by absorbtion imaging. The raw data (black squares) shows diffraction fringes leading to negative optical depth. The red line is the result of our method using a gaussian shape ansatz along the unresolved axis. b) Density per unit length along the resolved long axis, $n_{1D}(y) = \int dxn(x,y)$ deduced either by integrating the pixelated optical depth along the short axis ("raw data", black dashes), or by our method (black hash, the area of which describing the uncertainty). The two red lines are Gaussian fits for the raw data (upper normalized residuals at c)) and for the 1D density obtained by our method (lower normalized residuals d)). c) The residuals show that the raw data differs significantly from the expected Gaussian shape of a thermal gas. d) Our method recovers this expected Gaussian shape.

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Adiabatic spin-dependent momentum transfer in an SU(N) degenerate Fermi gas

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For the study of strongly correlated fermionic systems, ultracold alkaline-earth atoms offer original possibilities with their large ground-state spin and spin-independent collisions (SU(N) symmetry). The nuclear nature of the spins is both a strength and a complication – for example as it prevents the simple use of magnetic forces as in a Stern-Gerlach measurement. Nevertheless, the narrow lines associated with their singlet-to-triplet transitions can be used for novel spin-sensitive manipulations schemes, e.g. effective magnetic fields as in the "Optical Stern-Gerlach" (OSG) scheme [1], and spin-orbit coupling with low levels of spontaneous emission [2].

In our experiment [3], we introduce a spin-orbit coupling scheme where a retro-reflected laser beam selectively diffracts two spin components of a degenerate Fermi gas in opposite directions. Spin sensitivity is provided by sweeping through a magnetic-field sensitive transition : the intercombination line of strontium 87. The atoms follow adiabatically dark states, which significantly suppresses spontaneous emission. The adiabaticity of the scheme makes it inherently robust. We furthermore demonstrate a generalization of the scheme, and diffract in a single shot four spin states with four different momentum transfers. The spin-orbit coupling is associated with well-defined momentum transfers, set by the two-photon recoil, such that, unlike in OSG, momentum distortion is negligible. Thus, this scheme allows simultaneous measurements of the spin and momentum distributions of a strontium degenerate Fermi gas, opening the path to momentum-resolved spin correlation measurements [4] on SU(N) quantum magnets.

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Analog quantum simulation and spectroscopy in quantum dot arrays
GDR - IQFA Quantum Abstract

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I would like to present advances in analog quantum simulation and spectroscopy in semiconductor quantum dot arrays. The first part of the talk is about the experimental demonstration of Nagaoka's ferromagnetism using electrons in a GaAs quantum dot 2×2 plaquette, together with the theoretical description of the protocol [1]. In a second part I will give a theoretical analysis of recently developed dispersively probed quantum dot microwave spectroscopy techniques in silicon that permitted to measure the energies of the excited states of holes in a double quantum dot [2]. Then I will present perspectives for future developments in quantum science and technology in semiconductor and hybrid platforms.

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Degree of non Markovianity and Spectral Density Measurements via Graph State Simulation

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We present an experiment based on multimode squeezed vacuum states generation. We show how we can, via this experiment, simulate structured network and measure some of their properties. We first describe the experimental setup we call the SPOPO and then the measurements of network properties we can do : the spectral density $J(\omega)$ and non Markovian behavior.

Large multimode entangled states constitute an essential ressource in quantum information technologies. In this context, frequency comb sources of femtosecond pulsed light represent a useful solution, by providing approximately 10^5 individual frequency modes across the pulsed bandwith. It has been shown that a synchronously pumped optical parametric oscillator (SPOPO) can generate highly multimode non classical states of light [1]. Frequency doubled pulses from a Ti :Sapph laser are propagated in a nonlinear crystal (BiBO) with round trip time matched to the pump pulse train cycle time. Correlations appear among many spectral modes of the frequency comb of the down converted light, giving rise to a squeezed vacuum state at 795 nm central wavelength with a highly multimode structure. The quantum state of the output of the SPOPO is determined by the phase matching conditions, cavity resonance mode, and the spectral properties of the pump. Its quantum properties can be also tailored via spectrally resolved homodyne detection. In this context, the SPOPO represent a promising candidate for the implementation of complex networks with arbitrary topology [2].

For a given network, we can probe the reduced dynamic described by generalize quantum Langevin equation that can be described by the spectral density $J(\omega)$. Given an environment composed by n interacting harmonic oscillators of frequency ω_0 arranged in a specific graph structure, it has been shown we can probe the $J(\omega)$ function by monitoring the mean photon number of an additional harmonic oscillator that we call the probe and that is weakly coupled to the network [3] Hence, knowing the condition of the total system (structure of the graph, coupling strengths inside the total system, interaction time), we can map, for any ω, the probe on a specific mode shape of our parametric process and then measure via mode-selective homodyne detection mean photon number and reconstruct the $J(\omega)$ function.

An other Network property that we can test via our experimental setup is the degree of quantum Non Markovianity, which can be interpreted as information back flow from the environment to the probe [4]. Differently from the $J(\omega)$ measurement, the frequency of the probe is fixed and the SLM mask generated numerically are related to the interaction time. We then measure the fidelity between two orthogonal states of the probe depending on the time. If the probe's frequency is resonant with the environment, we will see oscillations of the Fidelity we can interpret as follow : when the fidelity increases, the states tend to thermalize, the energy goes from the probe to the environment ; when the fidelity decreases, the energy is going back to the probe and the states tend to be squeezed again, the system is thus non Markovian. If the probe isn't resonant, the fidelity remains flat and we don't observe any non Markovian behavior .

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Computing 256-bits elliptic curve logarithm with 258 000 qubits in 26 days with cat qubits and repetition code

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Quantum computers promise a significant speed-up for simulating quantum systems [1], for example in the context of catalytic chemistry [2]. Multiple platforms are being developed with the aim to build a large scale quantum computer to benefit from this speed up. They come with different physical architectures, various error correction codes and implementations of logical gates. A systematic comparison between these approaches can help to choose the right combination of architecture, code and gates by identifying advantages and limitations. Cryptanalysis through Shor's algorithm [3] already proved to be useful in this endeavour. In the context of RSA, the resource needed to factor a 2048-bit RSA integer with a 2D grid of superconducting qubits [4] using surface code, lattice surgery for the implementation of two-qubit gates and distillation of magic states for the non-Clifford operations has been compared with the one needed with the same approach but combined with a quantum memory [5]. The result is that the use of quantum memory reduces the number of qubits in the processor by two orders of magnitude and even more by using a 3D gauge colour code.

Here we study a platform using cat qubits and a simple repetition code [6]. Each cat qubit is made from a bosonic mode on which engineered two photon dissipation stabilizes superpositions of two coherent states with opposite phases. Those two coherent states are used as the cat's logical states 0 and 1 so that bit-flips happen with a low probability [6]. Phase errors are handled by the repetition code [6]. This architecture is evaluated in the light of Shor's algorithm for the computation of discrete logarithms on an elliptic curve. Completing such a computation would compromise the security of widely used asymmetric cryptographic systems for key-establishment and digital signature. Contrary to the RSA factorization problem, the best known classical algorithm for elliptic curve discrete logarithm computation scales exponentially with the number of bits. It is therefore recommended using elliptic curve points on integers encoded in 256 bits, which is much smaller than the recommanded 2048-bit size for RSA [7, 8]. We consider Shor's algorithm for discrete logarithm [3] implemented using Montgomery representation of integers and windowed arithmetic circuits [9]. In order to obtain an all-to-all connectivity between the logical qubits associated to the repetition code, the two qubits gates are applied via lattice surgery through routing qubits. Toffoli gates are directly applied [6] on ancillary qubits to create magical states before using gate teleportation to target any logical qubit. Using plausible physical assumptions for a large scale processor with this approach (for instance a ratio between single and double photo loss rate of 10^{-5} have been considered), our first estimations show that it would take 26 days to compute a 256-bit discrete logarithm on elliptic curve with a processor using 258 000 cat qubits. Note that a significant improvement in the runtime is expected by better exploiting the parallelization capacities of the architecture.

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Entanglement and excitations dynamics of qubit ensembles after a quench

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In this poster I will report our recent theoretical results on the non-equilibrium dynamics of quantum spin models, of direct relevance to quantum simulators. Quench dynamics of XXZ models with variable-range coupling, initialized in a coherent spin state (CSS), is found to produce spin squeezing with the same scaling as that of the paradigmatic one-axis twisting model, provided that the long-range interactions decay sufficiently slowly. At later times, approximate cat states are produced in a seemingly scalable way (up to 100 qubits), using e.g. dipolar interactions in two dimensions. Moreover the Fourier analysis of the spatio-temporal correlation pattern allows us to reconstruct the spectrum of elementary excitations. For XXZ models, this analysis reconstructs the tower of states of a quantum rotor, responsible for squeezing and cat-state generation. In the case of the quantum Ising model, quenching from the same CSS at variable field strengths we can pinpoint the ground-state critical point by the appearance of a gapless critical spectrum.

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Quantum properties of the interacting Orbital Angular Momenta in an atomic vapor
Propriétés quantiques de moments orbitaux angulaires en interaction avec les atomes

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The interplay between optical vortex beams and a vapor is studied order to understand the exchange of the Orbital Angular Momentum (OAM) of light with an atomic medium.

The OAM is a quantum variable of light, also called the 'third momentum of light' associated to the helical phase of an optical vortex. Its quantum integer $\ell \in \mathbb{Z}$, is the number of branches of the helix, its sign gives the handedness and the OAM per photon is $\hbar\ell$.

To examine the exchange of the OAM with an atomic vapor a phase-dependent interaction is chosen, namely a non-degenerated four wave mixing (FWM) in rubidium, which coherently converts two incident red input beams into a beam pair, one being infrared, the other blue (Fig.1.).

We examine the OAM of the blue wave versus the OAMs carried by the input beams and show the rules of the conversion. Depending on the relative handedness of input OAMs the blue output is single OAM or OAM-entangled due to phase-matching [1, 2].

The work will be presented in a general context of FWM with vortex beams including degenerated FWM previously realized on cesium atoms [3].

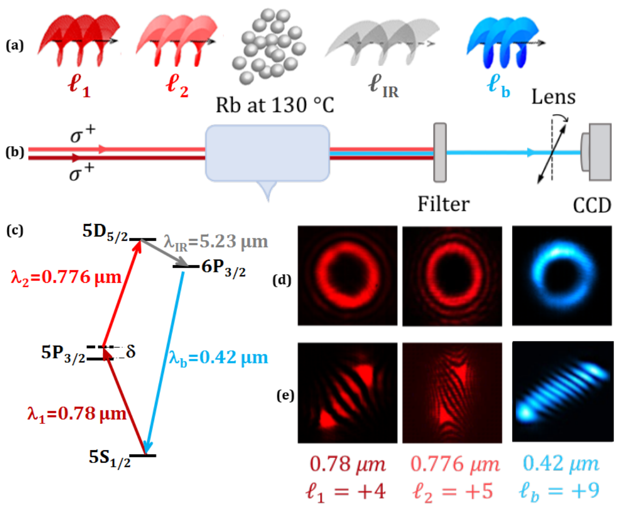

Figure 1. (a) FWM principle in a rubidium, (b) experimental scheme, (c) involved atomic levels, (d) intensity profiles of red and blue beams, (e) OAM-signatures by auto-interferences.

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Entangled states of dipolar magnetic atoms in multimode traps - IQFA Quantum Abstract

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The controlled generation and certification of entangled many-body states is a fundamental task in quantum simulation with ultracold atoms. Here we studied theoretically the generation of highly entangled states among the large spins of magnetic atoms (such as Chromium, Erbium or Dysprosium) trapped in multi-mode traps, and interacting at long distance via dipolar XXZ interactions—such systems offer a paradigmatic exemple of ensembles of interacting qudits [1] [2]. We considered two situations of experimental relevance : 1) initializing a 1d lattice of large spins (one particle per site) in a coherent spin state with alternating orientations, we show that the ensuing non-equilibrium dynamics leads to the formation of a Schrödinger's cat state [3] . The appearance of such a state in the dynamics can be proven analytically for two spins ; for a larger number of spins, we show that the cat state formation is closely related to weak ergodicity breaking of the dynamics and quantum scars in the many-body spectrum ; 2) two large spin ensembles are trapped in two separated modes, and undergo an entangling dynamics due to dipolar interactions – which is nonetheless hindered by atom losses due to dipolar relaxation (as presented in [4]). We model the dissipative dynamics of the system, and probe the robustness to losses of bipartite entanglement, as certified through a recent criterion based on collective-spin correlations [5].

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Posters 2, 04/11: Quantum Processing, Algorithm, & Computing (QPAC)

Unraveling correlated materials' properties with noisy quantum computers: solving extended impurity models with the natural-orbitalization algorithm

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We propose [1] a method for computing space-resolved correlation properties of the two-dimensional Hubbard model within a quantum-classical embedding strategy that uses a Noisy, Intermediate Scale Quantum (NISQ) computer to solve the embedded model. While previous approaches [2–5] were limited to purely local, one-impurity embedded models, requiring at most 4 qubits and relatively shallow circuits, we solve a two-impurity model requiring 8 qubits with an advanced hybrid scheme on top of the Variational Quantum Eigensolver algorithm [6]. This iterative scheme, dubbed Natural Orbitalization (NOization), gradually transforms the single-particle basis to the approximate Natural-Orbital basis, in which the ground state can be minimally expressed, at the cost of measuring the one-particle reduced density-matrix of the embedded problem. We show that this transformation tends to make the variational optimization of existing (but too deep) ansatz circuits faster and more accurate, and we propose an ansatz, the Multi-Reference Excitation Preserving (MREP) ansatz, that achieves great expressivity without requiring a prohibitive gate count, thus bridging the gap between hardware-efficient and physically-motivated strategies in variational ansatz design. The one-impurity version of the ansatz has only one parameter, making the ground state preparation a trivial step, which supports the optimal character of our approach. Within a Rotationally Invariant Slave Boson embedding scheme [7] that requires a minimal number of bath sites and does not require computing the full Green's function, the NOization combined with the MREP ansatz allow us to compute accurate, space-resolved quasiparticle weights and static self-energies for the Hubbard model even in the presence of noise levels representative of current NISQ processors. This paves the way to a controlled solution of the Hubbard model with larger and larger embedded problems solved by quantum computers.

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Si hole qubits in a cQED architecture

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Quantum computing is a major new frontier in technology promising computing power unattainable by classical computers. Among many different materials and approaches explored so far, silicon is emerging as a promising route to quantum computing with true potential in terms of scalability and manufacturability. With the recent development of spin-orbit qubit based on holes in silicon [1], it is nowadays conceivable to use a microwave photon as a « quantum bus » for long distance spin-orbit qubit interaction. The strong spin/photon coupling has been achieved using an engineered spin-orbit interaction with electron spins in silicon [2,3] and long-range microwave mediated interactions have also been demonstrated recently [4,5]. Our goal here is to use the intrinsic spin-orbit term in the valence band of silicon to achieve this coherent spin/photon coupling.

Here we will present our co-integration project : a CMOS silicon spin qubit embedded in a high-impedance NbN superconducting microwave resonator. We will describe the results of the high-impedance resonators in the coplanar waveguide geometry made of a $10\,\mathrm{nm}$ thick NbN film in the single photon regime and in magnetic fields for the many photons regime [6]. We also show the readout of a double quantum dot in the cQED architecture which paves the way to the long-range coupling of hole spin qubits in silicon.

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Entanglement-Preserving Limit Cycles from Sequential Quantum Measurements and Feedback

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Entanglement generation and preservation is a key task in quantum information processing, and a variety of protocols exist to entangle remote qubits via measurement of their spontaneous emission [1]. We here propose feedback methods, based on the information obtained by monitoring the fluorescence of two qubits and using only local pi-pulses for control, to increase the yield of and/or lifetime of entangled two-qubit states in this kind of protocols. Specifically, we describe a protocol based on photodetection of spontaneous emission (i.e. using quantum jump trajectories) which allows for entanglement preservation via measurement undoing, creating a limit cycle around a Bell states [2]. We then demonstrate that a similar modification can be made to a recent feedback scheme [4] based on homodyne measurement (i.e. using diffusive quantum trajectories), in order to increase the lifetime of the entanglement it creates. This second type of continuous monitoring fluorescence is well fitted to quantum circuits where these quantum trajectories have been observed [3]. Finally, we quantify the impact of less-than-ideal measurement efficiency on both schemes. The method we describe here combines proven techniques in a novel way, complementing existing protocols, and offering a pathway towards generating and protecting entangled states so that they may be used in various applications on demand.

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Qimaera : Type-safe (Variational) Quantum Programming in Idris

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Variational Quantum Algorithms [1, 2] are hybrid classical-quantum algorithms that consist in a back-and-forth process between classical computation (performed by a classical processor) and quantum operations executed by a quantum device. During the process, the quantum machine manipulates a set of qubits, which are measured to obtain classical bits with probabilities determined by the laws of quantum mechanics. The classical device performs further operations on these results to optimize the parameters of the quantum circuits, and the process is repeated until a satisfactory result has been obtained.

Making classical and quantum computation work in tandem to solve computational problems is a real challenge for the design of suitable programming languages. As quantum and classical information behave in very different ways, it is essential to develop a language that correctly models the manipulation of quantum resources without impacting the classical part of the language. For example, unlike classical information, quantum information cannot be uniformly copied [4]. Therefore, to avoid runtime errors, the quantum fragment of the language must be equipped with features that allow fine-grained control, where copying is restricted. However, when doing classical computation, such restrictions are unnecessary and inconvenient. One solution to this problem is to design a language with a classical non-linear fragment together with a quantum linear one, both interacting in a nice way, where "linearity" here should be understood in terms of Linear Logic [5].

In this paper, we introduce Qimaera, which is a set of libraries for the Idris 2 programming language [3] that enables the programmer to implement variational quantum algorithms where the full power of the elegant Idris language works in synchrony with quantum programming primitives that we introduce. Two key ingredients of Idris make this possible. First, dependent types allow us to represent unitary (i.e. reversible and controllable) quantum operations. The second feature, linearity, enables us to enforce fine-grained control over the execution of quantum operations, and hence allows us to statically detect erroneous quantum programs and ensure compliance with the laws of quantum mechanics.

In our intended computational scenario, we have access to both classical and quantum computers, that interact through a communication protocol. The user programs on the classical computer, which sends instructions to the quantum device and receives data from it. In our view, this is a realistic representation of a computational environment for variational quantum programming. Moreover, as we implemented libraries in an existing programming language, we already have good support for classical computation, which are often more complicated and difficult to implement compared to the quantum part of the algorithms.

To the best of our knowledge, this is the first programming language that is suitable for variational quantum programming in the sense that it provides first-class high-level support for both classical and quantum programming and that is moreover type-safe.

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Towards stabilization of Fock states using a multiplexed photon number measurement

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Stabilizing the state of a quantum system is a prerequisite to many quantum information applications. Feedback-based stabilization requires obtaining information about the state of the system, so as to correct its evolution. To stabilize a Fock state or a superposition of two Fock states in a cavity, the natural feedback signal is the cavity photon number. Here, the signal we aim to use is the multiplexed photon number measurement recently developed in our group. The number of feedback parameters being high, we plan to use a neural network embedded in a FPGA to achieve a model-free stabilization. This was already theoretically discussed in various papers [1, 2].

The experimental system we use in this work is a high quality factor superconducting cavity. To probe its photon number, we use a superconducting qubit coupled to the cavity in the photon-number-resolved dispersive regime, so that its frequency encodes the cavity photon number. The qubit is also strongly coupled to the measurement channel to generate an intense fluorescence signal. The simultaneous heterodyne detection of the fluorescence field that this qubit emits at all these frequencies allows to to continuously measure the photon number in the cavity [3]. Achieving a good Fock state stabilization requires operating in the single-shot regime. To obtain this regime, we describe the experimental improvements to bring to our previous experimental realizations, namely increasing the lifetime of the cavity by at least two orders of magnitude while preserving its strong coupling to the qubit.

Looking forward, we plan to use this experimental platform to first demonstrate high fidelity preparation of Fock states in the cavity, and then their stabilization using a continuous feedback. The ultimate goal would be to stabilize a subspace of dimension 2 of the Hilbert space, creating a logical qubit.

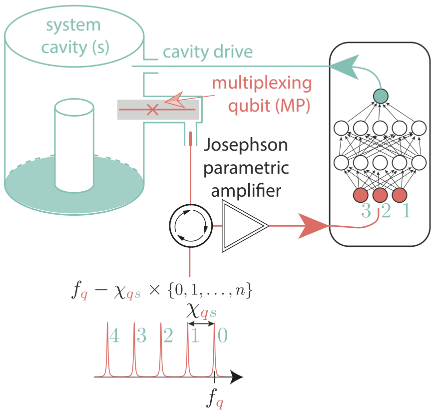

Figure 1 : Scheme of the feedback loop

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Time-Optimal Parallel Controlled-Z Gates on Rydberg atoms

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Optically trapped neutral atoms are emerging as a competitive platform for quantum computation and simulation. Qubits can be stored in hyperfine levels of the ground state manifold of an atom, single qubit gates performed via microwave fields or Raman transitions, and two qubit gates via the strong and long range interaction of atoms in Rydberg states [1]. High fidelity entangling gates are crucial for large scale computations, but current experiments only reach a fidelity of up to 97.4% for a controlled-Z (CZ) gate [2]. For many sources of error, the influence on the fidelity of the gate increases with increasing duration of the gate, so fast gates are desirable. In this work we find the shortest possible laser pulse to implement a CZ gate in two trapped neutral atoms.

Consider a setup of two atoms as follows. For each atom, we store a qubit in two states $|0\rangle$ and $|1\rangle$ and make use of an additional Rydberg state $|r\rangle$. A Van der Waals interactions between both atoms shifts the energy of the state $|r_1 r_2\rangle$ with both atoms in the Rydberg state by an energy of B. The states $|1\rangle$ and $|r\rangle$ are coupled by lasers with Rabi frequencies $\Omega_1(t)$ for the first and $\Omega_2(t)$ for the second atom. We obtain the Hamiltonian

$$H(t) = B\,|r_1 r_2\rangle\langle r_1 r_2| + \frac{\Omega_1(t)}{2}\,|1_1\rangle\langle r_1| + \frac{\Omega_2(t)}{2}\,|1_2\rangle\langle r_2| + \text{h.c.}$$

We use the GRAPE algorithm [3] to find the shortest laser pulse with a bounded maximal Rabi frequency $|\Omega_1(t)|, |\Omega_2(t)| \leq \Omega_{\max}$ that implements a CZ gate, up to single qubit rotations along the Z axis. We assume that we can control both the amplitude and the phase of the $\Omega_i(t)$ with arbitrary precision. Since many current experiments are performed in the $B \gg \Omega_{\max}$ regime we take $B = \infty$ in the following results, but similar time-optimal pulses can also be obtained for finite B. Our time-optimal pulse for a CZ gate has a duration of $7.61/\Omega_{\max}$. Interestingly, the time-optimal pulse is a parallel pulse, that is $\Omega_1(t) = \Omega_2(t)$, and can thus be performed with a single laser illuminating both atoms. Further, the amplitude is always maximal, i.e. $|\Omega_1(t)| = |\Omega_2(t)| = \Omega_{\max}$ and the phase of $\Omega_i(t)$ is given by a simple smooth curve. Our pulse is 11% faster then the fastest previously published pulse [2] (which is also a parallel pulse), showing that the pulse in [2] is already close to time-optimal. By changing the optimization objective we show that the time-optimal pulse is identical to the pulse with the smallest average occupation probability of the Rydberg states. This means that our pulse is also the pulse most robust against errors arising due to the decay of the Rydberg states.

Using the same method we find the shortest parallel pulse to implement a three qubit controlled-CZ (CCZ) gate, which is up to single qubit gates equivalent to a Toffoli gate. We consider the regime in which the van der Waals interactions between any pair of atoms in the Rydberg state is much larger then $\Omega_{\max}$. Our CCZ gate has a duration of $16.5/\Omega_{\max}$ and is thus 12% faster then the pulse proposed in [4] (duration $6\pi/\Omega_{\max}$). More importantly, our pulse for the CCZ gate is parallel and can thus be implemented without individual addressing of the atoms. Again, the pulse has maximal amplitude at all times, and the phase is described by a simple, smooth curve.

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Quantum reservoir neural network implementation on a Josephson parametric converter

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Neuromorphic computing implements neural networks in hardware to make their training more time and energy efficient. However, addressing state-of-the-art machine learning tasks requires coupling large numbers of neurons, which is challenging with physical nano-devices. It has been proposed to solve this problem using quantum hardware and encoding neurons in the basis states, whose number is exponential in the number of coupled qubits [1]. Simulation of a neural network called a quantum reservoir, implemented on a small number of qubits, showed that this quantum neural network can solve certain learning tasks with fewer neurons than an equivalent classical reservoir [2].

In this work, in order to obtain an even larger number of basis states, we use quantum oscillators instead of qubits. To go towards an experimental realization, we simulate a reservoir neural network implemented on a Josephson parametric converter [3], a well known quantum superconducting circuit. This circuit couples two superconducting oscillators through a three-wave-mixing interaction, implemented using a ring of four Josephson junctions. We encode the input data in the resonant oscillators' drives and numerically integrate quantum master equation to find the occupation probabilities of a subset of basis states that represent neural network outputs. We show that this system of two coupled quantum oscillators can solve a sine and square waveform classification task that otherwise requires 25 classical oscillators [4]. Furthermore, in order to test its memory, we train this network to perform chaotic Mackey-Glass series prediction and show that with typical experimental parameters for a Josephson parametric converter we can obtain performance comparable to other physical neural networks [5].

These results show that a simple and well known quantum circuit can realize non-trivial machine learning tasks when its dynamics is exploited. Neuromorphic computing thus promises to leverage the full computing capabilities of even small quantum systems. These simulations will guide experimental realization of a reservoir neural network on the Josephson parametric converter.

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On-chip tunable microwave components based on granular Aluminium

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For a few decades, research groups in superconducting circuit platforms have used commercial microwave components such as filters, tunable couplers, or isolators, to route and shape microwave signals in order to reach an excellent level of control on their platform. Nevertheless, this level of control and the degree of coherence could be improved by using on-chip components instead of these bulky, not impedance-matched, and more coupled to the environment, components.

In this poster, I will explain how we plan to build on-chip microwave components based on granular Aluminium (graAl) [1]. The high kinetic inductance of graAl makes it a promising candidate to realize these devices in a compact way. Using a width-modulated transmission line, we aim at realizing stop-band filters, in a very similar way as 1D photonic crystals, where the band gap and position depends on the kinetic inductance value.

The kinetic inductance of graAl can be tuned via a bias current. Consequently the aforementioned stop-band filters can be turned on and off via bias currents, turning the device into a tunable couplers. Finally, using a multi-transmission line configuration, I will show how we expect to design a microwave circulator.

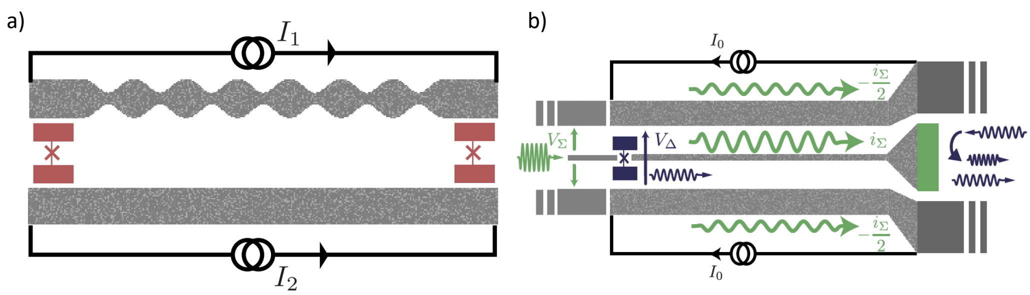

FIG. 1. On-chip microwave components with graAl. (a) : Two transmission line geometry where the two bias currents allow to tune the position and width of the stop-band filter, realizing a tunable coupler. (b) : Design for a circulator using three transmission lines.

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Micromagnetic simulations for electric-dipole spin resonance with electron spins in CMOS quantum dots

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Semiconductor quantum dots represent a promising platform for quantum computing [1]. Among the various technologies belonging to this category, silicon has low spin-orbit interaction, and can be purified into its zero nuclear spin isotopes. Electron spins in silicon therefore stand out as potential qubits given their long coherence times, and demonstrated fault-tolerant single-qubit operations [2]. In this context, quantum dots formed in CMOS classical electronics offer a path towards scalable CMOS quantum computing, by leveraging industrial fabrication foundries [3]. Building a scalable CMOS quantum processor is the goal of the "Grenoble Quantum Silicon Project", a collaboration between Institut Neel (CNRS), CEA-IRIG, and CEA-LETI, leading manufacturer of CMOS electronics.

One way of achieving qubit operations with electron spins is to engineer artificial spin-orbit coupling. This can be done by electrically displacing electrons in a magnetic field gradient generated by micro- or nano-magnets deposited on top of the quantum dots device [4, 5]. This electric-dipole spin resonance (EDSR) technique gives better qubit addressability and less sample heating than typical on-chip striplines used to flow a variable current.

I will present here preliminary micromagnetic simulations to show that in state-of-the-art silicon quantum dots devices, EDSR techniques would enable Rabi manipulations to reach operation frequencies of tens of MHz. Besides, I will present a model for another way to use micromagnets in order to drive single-qubit rotations. 500 MHz rotations can be achieved through Larmor precession, thanks to non-adiabatic transport of electrons between quantum dots seeing magnetic fields of different orientations.

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TSV-integrated Surface Electrode Ion Trap for Scalable Quantum Information Processing

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Ion traps and their geometry have seen their complexity increase for several years. Examples of this trend are the integration of waveguides, photodetectors [1] and the design of array of traps[2][3][4]. To continue in this path, significant challenges for electric signal delivery must be solved. I will present a functional trap using Through Silicon Vias (TSV) electrodes connection (both Radio-Frequency (RF) and Direct Current (DC)) which is fully foundry compatible.

In this work, we report about design, fabrication and operation of a Cu-filled through silicon via integrated ion trap. With intrinsically small resistance, Cu-filled TSVs are used here as vertical connections between all the electrodes (including RF) and an interposer underneath. Besides, a standard CMOS process on a 12-inch wafer is used, facilitating high resolution and repeatability of trap fabrication. The integration of TSVs permit a significant reduction of electrode surfaces, decreasing the trap capacitance up to 90% in comparison to a wire bonded trap of same size. A low RF dissipation is achieved in spite of the absence of a screening layer. We evaluate the trap performances by loading and laser-cooling single $88Sr^+$ ions and by measuring the trap heating-rate using the technique of Doppler re-cooling [5]. The heating rate of the trap is evaluated at $250 \pm 15mK/s$ that corresponds to $17quanta/ms$ for an axial frequency of $300kHz$. The lifetime of a laser-cooled ion in the trap is of the order of 30 minutes, compatible with the vacuum level.

This work pioneers the development of TSV-integrated ion traps, enriching the toolbox for scalable quantum computing. In particular the TSV approach is compatible with insertion of a ground screening layer to eliminate trap-heating, photonic circuit integration on which we are currently working, and in the future could be extended to glass substrates. In the future, further optimization of both TSV and multilayer metallization technologies (overlapping of alternate metal layers and dielectric materials beneath surface electrodes) is foreseen. However, a combination of the two techniques will be probably necessary to realize larger-scale ion traps with lower RF losses, and higher density of photonic components.*

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