

# Summerschool

## Nanotechnology meets Quantum Information (NanoQI) Donostia-San Sebastián

### Program

July 17, 2024

July 22 to 25, 2024



Universidad  
del País Vasco

Euskal Herriko  
Unibertsitatea

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# 1 Program

**Monday, July 22, 8h30** registration, Palacio de Miramar

**Monday, July 22, 9h30** first lecture, Palacio de Miramar

**Monday, July 22, 17h50** one-minute poster presentations, Palacio de Miramar

**Monday, July 22, 18h50** poster session, Palacio de Miramar

**Wednesday, July 24, 20h00** departure (walking) for dinner, Palacio de Miramar

**Wednesday, July 24, 20h30** school dinner, Sidrería Txirrita

**Thursday, July 25, 15h00** end of NanoQI summerschool

NanoQI'24 – Timetable							
Time	MONDAY July 22	Time	TUESDAY July 23	Time	WEDNESDAY July 24	Time	THURSDAY July 25
8:15-	Registration						
08:45-09:00	Welcome						
09:00-10:00	Pichler	09:00-10:00	Buhrman	09:00-10:00	Tarucha	09:00-10:00	Barredo
10:00-10:15	Q&A	10:00-10:15	Q&A	10:00-10:15	Q&A	10:00-10:15	Q&A
10:15-11:15	Alicea	10:15-11:15	Barredo	10:15-11:15	Kusminskiy	10:15-11:15	Alicea
11:15-11:30	Q&A	11:15-11:30	Q&A	11:15-11:30	Q&A	11:15-11:30	Q&A
11:30-12:00	Coffee Break	11:30-12:00	Coffee Break	11:30-12:00	Coffee Break	11:30-12:00	Coffee Break
12:00-12:45	Choi	12:00-12:45	Guinea	12:00-13:00	Hammerer	12:00-13:00	Kusminskiy
12:45-12:55	Q&A	12:45-13:10	Q&A+ School Photo	13:00-13:15	Q&A	13:00-13:15	Q&A
13:15-15:15	LUNCH(13:30h)	13:15-15:15	LUNCH(13:30h)	13:15-15:15	LUNCH(13:30h)	13:15-15:15	LUNCH(13:30h)
15:15-16:15	Hammerer	15:15-16:15	Pichler	15:15-16:15	Buhrman		
16:15-16:30	Q&A	16:15-16:30	Q&A	16:15-16:30	Q&A		
16:30-17:30	Poster presentation	16:30-17:00	Coffee Break	16:30-17:00	Coffee Break		
17:30-19:30	Posters & Refresh	17:00-18:00	Tarucha	17:00-17:45	Imamoglu		
		18:00-18:15	Q&A	17:45-17:55	Q&A		
				20:30	Dinner (Txirrita)		



## 2 Venue and Contact Data

**Organizers:** Géza Giedke, Alejandro, González-Tudela, Ataç İmamoğlu

**Local organizer:** Géza Giedke

**Contact:**

nanoqi@dipc.org, Tel. +34 943 01 8289 (DIPC)

**Website:** <http://nanoqi.dipc.org/>

**Venue:** Palacio Miramar

Paseo de Miraconcha, 48, E-20007 Donostia-San Sebastián

Tel.: +34 943 21 9511, fax: +34 943 21 9598, email: [udaikastaroak@ehu.eus](mailto:udaikastaroak@ehu.eus)

WLAN (eduroam) is available.



**Lunch (daily 13:10h):** Hotel Barceló “Costa Vasca”

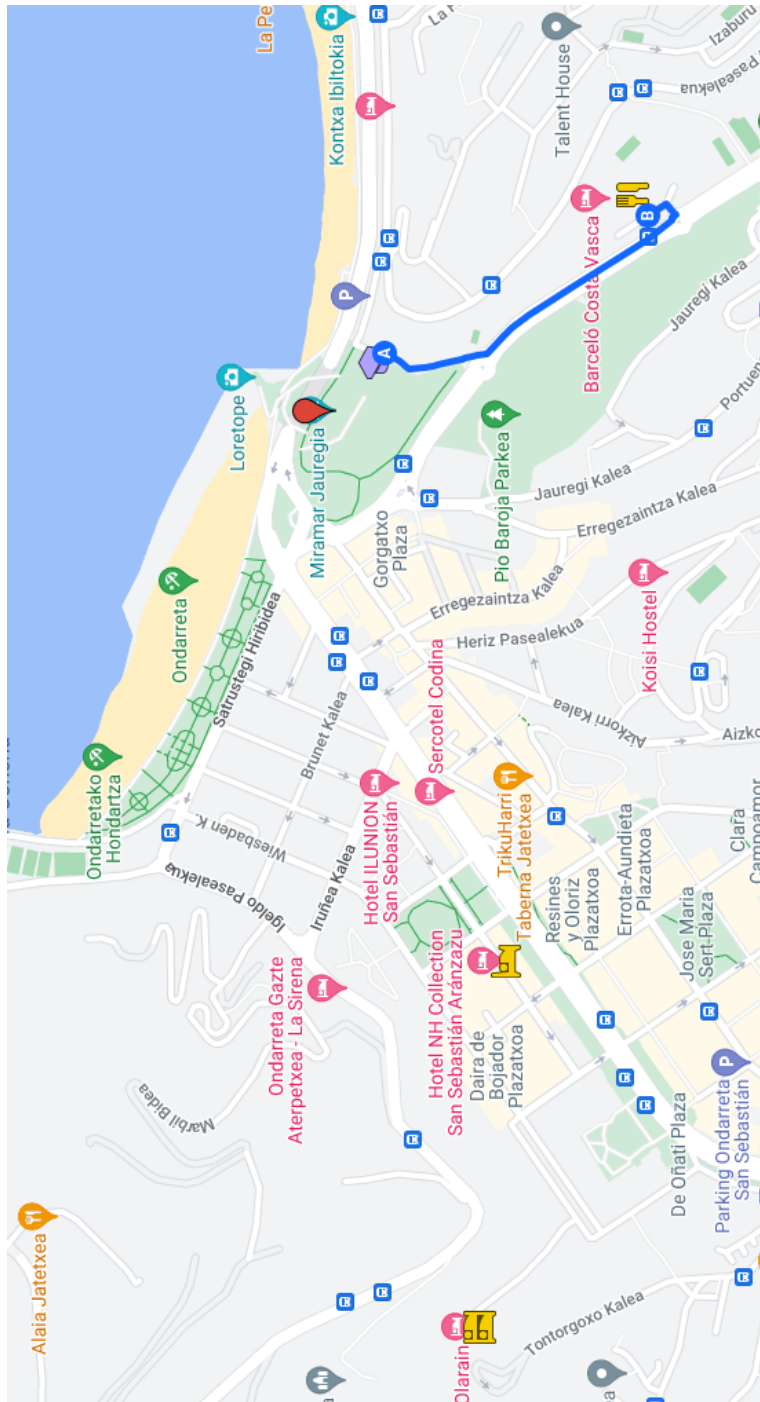
Avenida Pio Baroja, 15, 20008 San Sebastián

Tel: +34 94 331 79 50

**School Dinner (24.7., 20:30h):** Sidrería Txirrita

Calle San Bartolomé, 32, 20007 San Sebastián, Guipúzcoa

Tel. +34 943 467 638



## 3 Lectures and Talks

### 3.1 Lectures

1. Jason Alicea (California Institute of Technology)  
*Topological Qubits*
2. Daniel Barredo (Nanomaterials and Nanotechnology Research Centre (CINN-CSIC))  
*Rydberg atom arrays: expanding frontiers in quantum simulation, computation, and metrology*
3. Harry Buhrman (QuSoft, Amsterdam and Quantinuum, London)  
*Quantum Communication Beyond QKD: Position-Based Cryptography*
4. Klemens Hammerer (Universität Hannover)  
*Quantum variational optimization of optical atomic clocks*
5. Silvia Kusminskiy (RWTH Aachen)  
*Cavity Magnonics: Fundamentals and Applications*
6. Hannes Pichler (Universität Innsbruck)  
*Chiral Quantum Optics*
7. Seigo Tarucha (Center for Emergent Matter Science, Riken)  
*Spin Physics in Quantum Dots and Application to Spin-based Quantum Computing*

# Topological Qubits

JASON ALICEA

*California Institute of Technology*

Topological quantum computation aims to assemble scalable qubits that are intrinsically resilient to errors. The workhorse of a topological quantum computer are emergent particles dubbed “non-Abelian anyons” that are born in certain topological states of matter. I will survey the properties of non-Abelian anyons that underlie their utility for quantum computation, focusing largely on their manifestation in 1D and 2D topological superconductors. I will also discuss candidate experimental platforms, detection and manipulation strategies, topological qubit interrogation protocols, and future challenges and opportunities.

# Rydberg atom arrays: expanding frontiers in quantum simulation, computation, and metrology

DANIEL BARREDO

*Nanomaterials and Nanotechnology Research Centre (CINN-CSIC)*

Rydberg atoms in arrays of optical tweezers open up new horizons for quantum simulation, computation, and metrology. In these lectures, we will present an overview of this architecture. We will explore how individual atoms can be trapped and arranged, creating customizable arrays that serve as a versatile platform for various quantum applications. We will review the unique properties of Rydberg atoms, the mechanism of Rydberg blockade, and the methods to generate entanglement. These lectures will describe ongoing efforts in the community to implement different spin models with hundreds of particles for simulating quantum many-body phenomena [1,2]. We will gain insight into the role of this platform in quantum computing, highlighting its ability to implement high-fidelity quantum gates and scalable quantum circuits [3]. Furthermore, we will illustrate how entanglement in the out-of-equilibrium dynamics of these systems can be harnessed to generate scalable spin squeezing for metrological applications [4]. Finally, we will provide perspectives on the future developments of Rydberg atoms arrays in the realm of quantum science and technology.

References:

- [1] Scholl et al., *Nature* 595, 233 (2021).
- [2] Chen et al., *Nature* 616, 691 (2023).
- [3] Bluvstein et al., *Nature* 626, 58 (2024).
- [4] Bornet et al., *Nature* 621, 728 (2023).

# Quantum Communication Beyond QKD: Position-Based Cryptography

HARRY BUHRMAN

*QuSoft, Amsterdam and Quantinuum, London*

On 20 July 1969, millions of people held their breath as they watched, live on television, Neil Armstrong set foot on the Moon. Yet Fox Television has reported that a staggering 20% of Americans have had doubts about the Apollo 11 mission. Could it have been a hoax staged by Hollywood studios here on Earth? Position-based cryptography may offer a solution. This kind of cryptography uses the geographic position of a party as its sole credential. Normally digital keys or biometric features are used.

A central building block in position-based cryptography is that of position verification. The goal is to prove to a set of verifiers that one is at a certain geographical location. Protocols typically assume that messages cannot travel faster than the speed of light. By responding to a verifier in a timely manner one can guarantee that one is within a certain distance of that verifier. It was shown that position-verification protocols only based on this relativistic principle can be broken by attackers who simulate being at the claimed position while physically residing elsewhere in space.

Because of the no-cloning property of quantum information (qubits) it was believed that with the use of quantum messages one could devise protocols that were resistant to such collaborative attacks. Several schemes were proposed that later turned out to be insecure. In 2012 it was shown that also in the quantum case no unconditionally secure scheme is possible. However, many questions concerning the optimality of the attack remain open.

We will review the old results as well as some of the new sometimes very surprising connections with seemingly unconnected research areas such as holography, ADS/CFT correspondence, and classical primitives like conditional disclosure of secrets (CDS), secure message passing (SMP), and functional analysis. We will also cover some of the recent proposals for implementing position verification protocols that are secure when the attackers have a limited amount of entanglement.

# Quantum variational optimization of optical atomic clocks

KLEMENS HAMMERER

*Universität Hannover*

Employing entanglement to improve measurements limited by quantum noise is perhaps the first use case of a real quantum advantage. While this promise is already fulfilled in gravitational wave observatories, which nowadays routinely operate with squeezed states of light, other fields in quantum metrology are just beginning to profit from entanglement enhancement. In particular, the use of squeezed and, more generally, entangled states of atoms in frequency metrology and atomic clocks is under intense investigation, with experiments demonstrating significant gains in recent proof-of-principle realizations. In my lectures, I will introduce the general idea and the specific challenges of using entanglement in atomic clocks. I will also discuss the specific needs and requirements of optical atomic clocks, which use optical atomic transitions and are expected to replace the Cesium standard second within the next decade. Since optical clocks are realized with trapped ions or neutral atoms in tweezer arrays or optical lattices, they have much in common with atom-based quantum information processors. This motivates the consideration of frequency metrology protocols from the perspective of quantum variational optimization.

# Cavity Magnonics: Fundamentals and Applications

SILVIA KUSMINSKIY

*RWTH Aachen*

Cavity magnonic systems are ideally suited to explore the range of possibilities opened by tailoring the interactions between photons, phonons, and magnons. In these lectures I will go over the basic coupling mechanisms between these excitations for ferromagnetic and antiferromagnetic systems, and cover the concept of dynamical backaction. I will discuss possible applications such as the generation of quantum magnon states, transduction, and thermometry.

# Chiral Quantum Optics

HANNES PICHLER

*Universität Innsbruck*

Advanced photonic nanostructures enable novel functionalities for spin-photon interfaces. The strong light confinement in these structures can lock the local polarization of the light to its propagation direction, leading to propagation-direction-dependent emission, scattering and absorption of photons by quantum emitters. In these lectures I will develop the theoretical formalism used in quantum optics to describe such chiral light-matter interaction within the framework of the cascaded master equation.

# Spin Physics in Quantum Dots and Application to Spin-based Quantum Computing

SEIGO TARUCHA

*Center for Emergent Matter Science, Riken*

Semiconductor quantum dots (QDs) provide a promising platform for application to spin-based quantum computing and study on quantum dynamics of single electron spins. Quantum coherence and entanglement are both fundamental concepts in quantum computing and utilized to construct quantum circuits. The circuit performance depends on spin dephasing and spin-spin interaction. In Part I of my lecture I will explain basics of spin-based quantum computing and underlying physics of single spins and spin entanglement. Control and detection of single spins and entanglement, dephasing of single spins due to interaction of magnetic environment, and quantum non-demolition measurement using two-spin entanglement are the major topics.

Then in Part II, I will address advances in spin-based quantum computing in silicon (Si) QDs. Spin qubits in Si QDs have several advantages, on the grounds of a long intrinsic decoherence time ( $> \text{msec}$ ), a possible high temperature operation ( $> \text{K}$ ), and compatibility in device fabrication with industrial technologies. Motivated by these advantages, enthusiastic effort has recently been made to improve the performance of qubit devices. I will review the progress including implementation of the high-fidelity qubit gates to satisfy the fault-tolerant threshold, quantum error correction and development of multi-qubit devices.

### 3.2 Talks

1. Deung-Jang Choi (CFM-CSIC & Ikerbasque)  
*Unveiling Quantum Frontiers: Manipulating atoms and molecules to explore qubit platforms*
2. Francisco Guinea (IMDEA Madrid and DIPC)  
*Electronic structure and electronic interactions in moiré systems*
3. Atac Imamoglu (ETH Zürich)  
*Electrically defined quantum dots for excitons in two dimensional semiconductors*

# Unveiling Quantum Frontiers: Manipulating atoms and molecules to explore qubit platforms

DEUNG-JANG CHOI

*CFM-CSIC & Ikerbasque*

In the realm of quantum science and technology, harnessing individual electron spins within solid materials holds immense promise. The long-standing aspiration of constructing a quantum device with precise atomic-level connections has come to fruition in this study. We have achieved the feat of building, manipulating, and observing linked electron-spin qubits on an atom-by-atom basis, all through the ingenious use of a scanning tunneling microscope (STM) [1,2]. We also unravel the emergence of exotic states by exploring the interaction between designed structures on superconducting surfaces [3,4]. Our results shed light on Majorana bound states and their non-Abelian exchange properties, vital for the development of topological quantum computation. Within the various qubit platforms, we open the door to a realm where quantum capabilities can be harnessed, employing arrays of electron spins painstakingly assembled atom by atom upon a surface.

References:

- [1] Colloquium: Atomic spin chains on surfaces. *Review of Modern Physics* 91, 041001 (2019).
- [2] An atomic-scale multi-qubit platform, *Science* 382 (6666), 87-92 (2023).
- [3] Atomic Manipulation of In-gap States on the  $\beta$ -Bi<sub>2</sub>Pd Superconductors, *Physical Review B* 104 (4), 045406 (2021).
- [4] Calculations of in-gap states of ferromagnetic spin chains on s-wave wide-band superconductors, *Physical Review B* 104 (24), 245415 (2021).

# Electronic structure and electronic interactions in moiré systems

FRANCISCO GUINEA

*IMDEA Madrid and DIPC*

Stacks of two dimensional materials allow for the formation of moiré structures, that is, periodic crystals where the lattice length is mesoscopic, and usually exceeds 10nm. The number of atoms within the unit cell easily exceeds  $10^3$ . Moiré superlattices can be achieved by tuning the relative angle, microscopic strain, length of the microscopic lattice, of two or more two dimensional layers. They show a variety of interesting phases, from superconductivity to fractional Chern insulators (that is, systems with fractional quasiparticles, akin to the fractional Hall effect, but without the magnetic field).

The lecture will describe different moiré superlattices, and discuss models for their electronic structure, and the role of interactions, geometry, inhomogeneities, ...

# **Electrically defined quantum dots for excitons in two dimensional semiconductors**

ATAC IMAMOGLU

*ETH Zürich*

We experimentally demonstrate a new type of quantum dot where quantum confinement of excitons in two-dimensional semiconductors is achieved exclusively through applied gate voltages and ensures fully electrically tunable confinement length. Our work provides a potential solution to the scalability problem of quantum photonic technologies by establishing a new path for creating arrays of identical solid-state quantum emitters.

## 4 NanoQI'24: Poster Contributions

1. AGIRRE, ANDONI (Donostia International Physics Center (DIPC))  
**Learning QAOA energy landscapes: parameter optimization via Monte Carlo Tree Search with Iterative Search Space Restriction**
2. BECCACECI, MATTIA (Sapienza University of Rome)  
**Wavevector-resolved photonic entanglement from radiative cascades**
3. BOGACZEWICZ, RAFAŁ (Wrocław University of Science and Technology)  
**Fidelity of the acoustic control of single photon scattering with semiconductor quantum dots**
4. BUI, CHAU NGOC-QUYNH (Center for Quantum Nanoscience (QNS), Ewha Womans University, Seoul)  
**Probing picroelectronvolt avoided level crossing in a single atom with deterministic nuclear spin states**
5. CAMPBELL, CHRISTOPHER (University of Oulu)  
**Nonequilibrium dynamics in many-body supersymmetric quenches**
6. CIONI, FRANCESCO (Scuola Normale Superiore, Pisa)  
**Close to optimal refrigeration using a single-channel Andreev interferometer**
7. DEGLI ESPOSTI, DAVIDE (TU Delft)  
**Low disorder and high valley splitting in silicon**
8. DENORA, DARIO (TU Delft)  
**The Qube: beyond laterally coupled quantum dots**
9. DIAZ LOPEZ, CARLOS ALBERTO (Universität Ulm)  
**Simulation of the vortex lattice in Type-II superconductors**
10. FORGHIERI, GAIA (University of Modena and Reggio Emilia)  
**Quantum Sensing with Hole-Spin Qubits in Quantum Dots**
11. GAISER, NIKLAS (Universität Ulm)  
**High Kinetic Inductance Microstrip Networks For Integrated Quantum Information Devices**

12. HUE, BENJAMIN (Laboratoire de Physique, Ecole normale supérieure (LPENS), Paris)  
**Microsecond-lived quantum states in a carbon-based circuit driven by cavity photons**
13. IVLEV, ALEXANDER (TU Delft)  
**Eliminating barrier gates in semiconducting quantum dots**
14. KLEIDERMACHER, HANNAH C. (Stanford University)  
**Experiments in Cavity Quantum Electrodynamics with Color Centers in Diamond**
15. LEVY-YEYATI FRANZÉ, TOMÁS (Institute for Fundamental Physics (CSIC IFF), Madrid)  
**Passive photonic CZ gate with two-level emitters in chiral multi-mode waveguide QED**
16. LITZBA, LUKAS (Universität Duisburg-Essen)  
**Effective time-dependent temperature for fermionic master equations beyond the Markov approximation**
17. LÓPEZ GARCÍA, ALBERTO (University of Cartagena)  
**Arbitrary Gates on the Double Transition of NV Ground State for Low Field or High Frequency Sensing**
18. LOZANO, LIDIA (Universitat Barcelona)  
**Enhanced emission of single-photon sources based on colloidal quantum dots with printed microstructures**
19. MENTA, ROBERTO (Scuola Normale Superiore Pisa)  
**A superconducting globally driven quantum computing architecture**
20. RONCO, GIUSEPPE (Sapienza University of Rome)  
**Exciton redistribution in 2D WSe<sub>2</sub> via external strain field for positioned quantum emitters with stable magnetic response**
21. SHAJU, JASHWANTH (Neel Institute-CNRS, University of Grenoble Alpes)  
**Partitioning statistics of interacting electrons in a flying quantum dot**

22. SHAPIRO, DMITRII (FZ Jülich)  
**Superradiant phase transition and cat states in the Dicke-Ising model**
23. STEIN, ABIGAIL (Stanford University)  
**High fidelity spin control of the tin vacancy qubit in diamond**
24. TEN KATE, SOFIE (IBM Zurich)  
**Direct microwave spectroscopy of Andreev bound states in planar Ge Josephson junctions**
25. UNDSETH, BRENNAN (TU Delft)  
**Baseband control of single-electron silicon spin qubits in two-dimensions**
26. VASSELON, THOMAS (Neel Institute-CNRS, University of Grenoble Alpes)  
**Electronic flying qubits using ultrashort electronic wavepackets**

# Learning QAOA energy landscapes: parameter optimization via Monte Carlo Tree Search with Iterative Search Space Restriction

ANDONI AGIRRE

*Donostia International Physics Center (DIPC)*

Variational Quantum Algorithms (VQA) are the leading class of hybrid quantum-classical methods to cope with the limitations of near-term quantum hardware [1]. However, their effectiveness is hampered by the complexity of the classical parameter optimization, making the design of efficient optimization methods fundamental for leveraging the potential of VQAs. In this work, we propose a gradient-free parameter optimization strategy based on a modified version of the Monte-Carlo tree search (MCTS) algorithm [2] for the Quantum Approximate Optimization Algorithm (QAOA) [3], one of the most relevant algorithms in the VQA family. Our modifications allow MCTS to iteratively restrict the action space to exploit the parameter regularity inherent in optimal schedules and efficiently explore complex search domains [4]. The algorithm performs well in hard instances of 3-SAT and MaxCut problems, and exhibits remarkable robustness against noise. Our results shed light on the interplay of artificial intelligence and quantum information and provide a valuable step towards robust quantum computation with existing hardware.

References:

- [1] M. Cerezo et al., *Nat Rev Phys* 3, 625–644 (2021).
- [2] M. Świechowski et al. *Artif. Intell. Rev* 56, 2497–2562 (2023).
- [3] E. Farhi, arXiv:1411.4028 (2014).
- [4] A. Agirre, E. van Nieuwenburg, M. Wauters in preparation.

# Wavevector-resolved photonic entanglement from radiative cascades

A. Laneve<sup>1</sup>, M. B. Rota<sup>1</sup>, F. Basso Basset<sup>1</sup>, M. Beccaceci<sup>1</sup>, V. Villari<sup>1</sup>, T. Oberleitner<sup>2</sup>, Y. Reum<sup>3</sup>, T. M. Krieger<sup>2</sup>, Q. Buchinger<sup>3</sup>, S. F. Covre da Silva<sup>2</sup>, S. Stroj<sup>4</sup>, S. Hofling<sup>3</sup>, A. Rastelli<sup>2</sup>, T. Huber-Loyola<sup>3</sup>, R. Trotta<sup>1</sup>

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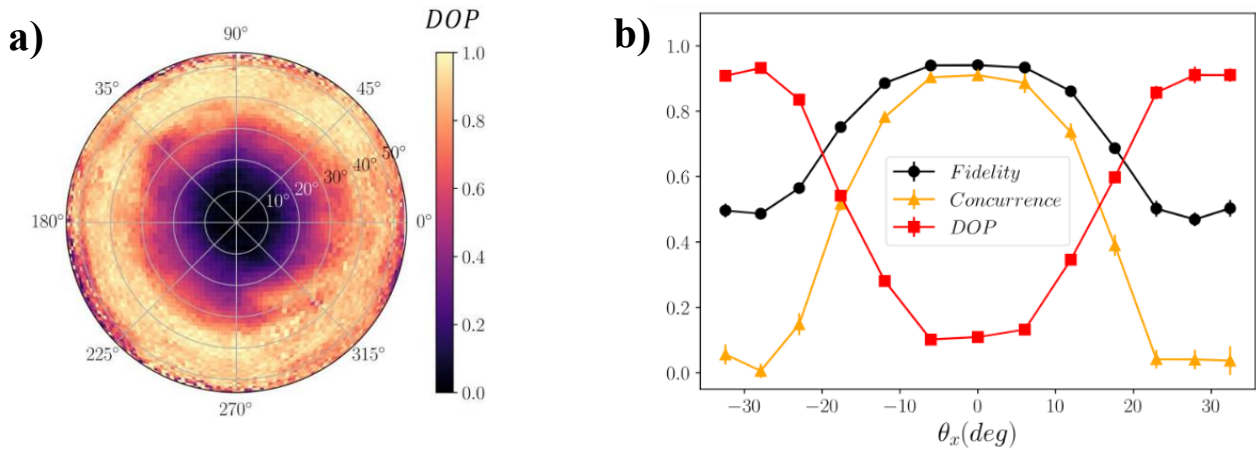
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3. Technical Physics, University of Würzburg, 97074 Würzburg, Germany

4. Forschungszentrum Mikrotechnik, FH Vorarlberg, 6850 Dornbirn, Austria

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The possibility to generate single and entangled photons have paved the way to the next quantum revolution. Among all different sources, semiconductor quantum dots (QDs) are emerging as one of the main building blocks of the newborn field of quantum networks. Their peculiar electronic structure can be exploited for the generation of polarization entangled photons via two-photon resonant excitation of the biexciton-exciton (XX-X) cascade. While massive efforts are being devoted to enhance the optical properties of quantum emitters through the integration of optical cavities [1], these very latter allowed to put into light fundamental effects that were never experienced before [2]. Here [3] we exploit  $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}/\text{GaAs}$  QDs embedded in a cavity based on circular Bragg resonators to investigate the interplay between photon polarization and emission wavevector. We observe how the polarization entanglement of the photon pairs from a XX-X cascade strongly depends on the emission wavevector. In particular, we experiment a drop in quantum correlation as the collection angles get higher due to the increasing polarization degree of the emitted photon pairs. Our experimental results, backed by a theoretical model, yield a new understanding of cascaded emission for a wide variety of quantum emitters. In addition, the model provides quantitative guidelines for designing optical microcavities that retain both a high degree of entanglement and collection efficiency, setting one further step toward an ideal source of entangled photons.



**Fig. 1** a) Experimental degree of polarization (DOP) of QDs far-field radiation, sampled through back focal plane imaging. b) Experimental fidelity of entanglement to the target state  $|\phi^+\rangle$ , concurrence and average biphoton DOP as a function of the main collection angle, for a fixed small  $\mathbf{k}$  integration range.

[1] M. B. Rota, T. M. Krieger, Q. Buchinger, M. Beccaceci, et al., arXiv:2212.12506 (2023)

[2] F. Basso Basset, M. B. Rota, M. Beccaceci, et al., Phys. Rev. Lett. **131**, 166901 (2023)

[3] A. Laneve, M. B. Rota, F. Basso Basset, M. Beccaceci, et al., in preparation

# Fidelity of the acoustic control of single photon scattering with semiconductor quantum dots

Rafał A. Bogaczewicz, Paweł Machnikowski

Institute of Theoretical Physics, Wrocław University of Science and Technology,  
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Acoustic modulation of a semiconductor self-assembled quantum dot (QD) allows one to control the scattering of photons. This is a promising solution for acousto-optic, miniaturised and multi-functional quantum hybrid systems [1], where it can be used to map the characteristics of surface acoustic waves (SAWs) onto the resonance fluorescence (RF) optical signal [2-4]. The spectrum of light scattered from an acoustically modulated QD contains a series of sidebands [2], whose intensities oscillate in the time domain [4]. The light scattered on a QD is antibunched [3], indicating the single-photon nature of the RF spectrum.

In this contribution, we characterize the fidelity of acoustic control of light scattering in the frequency domain via a two-tone acoustic field (SAW wave mixing). QD is modeled as a weakly excited two-level system whose transition energy depends on time via periodical SAW modulation and randomly changing environmental fluctuations, modeled as a white noise. We focus on the intensity at the spectral position of the first acoustic RF sideband and define the normalized contrast  $\eta$  between the maximal and minimal scattering intensities with respect to a certain relative phase  $\varphi$  between the SAW modes. We show that a high degree of control is achievable for appropriate modulation amplitude settings as long as the noise-induced phase diffusion coefficient remains one order of magnitude smaller than the acoustic frequency  $\omega_{\text{SAW}}$  (Fig. 1). Finally, using a quantitative model of optical signal collection, we determine that the acoustic phase must be stable over  $10^4$  to  $10^5$  acoustic periods for efficient control.

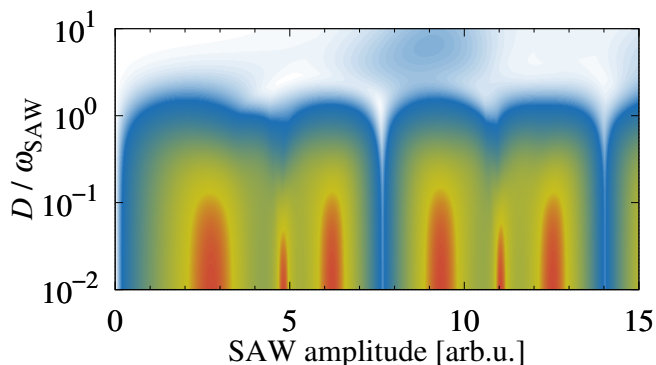


Figure 1: The contrast of the phase dependence as a function of the SAW amplitude and the noise strength.

## References:

- [1] P. Delsing *et al.*, *J. Phys. D: Appl. Phys.* **52**, 353001 (2019)
- [2] M. Metcalfe *et al.*, *Phys. Rev. Lett.* **105**, 037401 (2010)
- [3] M. Weiß *et al.*, *Optica* **8**, 291 (2021)
- [4] D. Wigger *et al.*, *Phys. Rev. Res.* **3**, 033197 (2021)

# Probing picoelectronvolt avoided level crossing in a single atom with deterministic nuclear spin states

Chau Ngoc-Quynh Bui<sup>\*\*\*</sup>, Luciano Colazzo<sup>\*</sup>, Georg A. Traeger<sup>\*\*\*</sup>, Lei Fang<sup>\*</sup>, Soo-hyon Phark<sup>\*</sup>, Andreas J. Heinrich<sup>\*\*\*</sup>, Wonjun Jang<sup>\*</sup>

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We present a novel approach using a scanning tunneling microscope to address and control the quantum tunneling of magnetization (QTM) of an individual atom on surface. Here, the QTM is controlled by the sweep rates of both external and tip-induced fields and read out by measuring the spin-polarized current using a magnetic tip in a single-shot measurement scheme. A precise control of these time-dependent fields enables us to monitor electron spin Landau-Zener (LZ) transition across an avoided level crossing, addressed to a specific nuclear spin state of the single atom. Our measurement scheme applied to a single Ho atom on MgO revealed the nature of LZ transition across its avoided level crossings of just a few picoelectronvolts, an energy resolution never ever achieved by utilizing a pure electronic measurement scheme.

# Nonequilibrium dynamics in many-body supersymmetric quenches

CHRISTOPHER CAMPBELL

*University of Oulu*

We study dynamics induced by quenching and ultracold quantum many-body system between supersymmetric partner potentials. Such a quench can be created by carefully changing the external trapping potential instantaneously and leads to a situation where the eigenspectral before and after the quench are nearly identical between the supersymmetric Hilbert spaces. By using supersymmetric partner potentials the calculations of certain thermodynamic quantities that utilize overlaps integrals can be recast to the Hilbert space of the initial Hamiltonian. For this poster we present the quenching dynamics between partner potentials of the infinite square well to demonstrate how these calculations are recast and how in particular systems emergent phenomena can arise as a consequence of this degeneracy between quenching, such as the existence of non-thermalizing systems.

# Close to optimal refrigeration using a single-channel Andreev interferometer

FRANCESCO CIONI AND FABIO TADDEI

*Scuola Normale Superiore, Pisa*

This study explores the enhancement of electron cooling with respect to conventional nanoscale metal-insulator-superconductor (NIS) junction using an Andreev interferometer (AI). To maximize the cooling power it proves necessary to reduce the Joule heating due to Andreev reflection processes. In NIS junctions, such goal is achieved by the presence of an insulating barrier which however requires a large number of transverse channel in order to obtain finite refrigeration. Here, we propose a single channel device which allows to reach similar values of the cooling power. This is achieved thanks to interference effects induced by the phase coherence in the system. This gives a cooling power per channel  $10^5$  times higher than in conventional NIS refrigerators. We also derive some analytical bounds on the maximum achievable refrigeration as a function of the number of channels. This turns out to be relevant if this number is small. We demonstrate that refrigeration in the Andreev interferometer is close to optimal value. Finally, we provide some examples of physical realizations of such device using Quantum Hall systems and 2d Topological Insulators.

## Low disorder and high valley splitting in silicon

DAVIDE DEGLI ESPOSTI

*TU Delft*

The electrical characterization of classical and quantum devices is a critical step in developing heterogeneous material stacks for semiconductor spin qubits. In the case of silicon, properties such as disorder and energy separation of conduction band valleys are commonly investigated individually upon modifications in selected parameters of the material stack. However, this reductionist approach fails to consider the interdependence between different structural and electronic properties at the danger of optimizing one metric at the expense of the others. Here, we achieve a significant improvement in both disorder and valley splitting by taking a co-design approach to the material stack. We demonstrate isotopically purified, strained quantum wells with high mobility and low percolation density. These low disorder quantum wells support quantum dots with low charge noise and large mean valley splitting energy. These findings strike the delicate balance between disorder, charge noise, and valley splitting, providing a benchmark for silicon as a host semiconductor for quantum dot spin qubits.

## **The Qube: beyond laterally coupled quantum dots**

DARIO DENORA

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Quantum dot-based spin qubits have made rapid developments in device complexity, with the scaling of qubits being a priority. Approaches towards scaling up quantum dot qubits are primarily based on one- or two-dimensional planar arrays. In the case of Ge/SiGe heterostructures, by introducing an additional quantum well, vertically coupled quantum dots can be formed. This can allow us to define a three-dimensional quantum dot lattice, which we call the Qube. Independent control of the occupation of the vertically aligned quantum dots is achieved using only top plunger and barrier gates, thanks to the different gate-to-dot capacitances due to the separation of the quantum wells in the vertical  $z$ -direction. This results in differences in electrostatic confinement. When strongly confined, only the upper quantum well is occupied, and in this regime, we can define lateral singlet-triplet qubits and electrically driving single spins (EDSR). The expansion of quantum dot devices to the third spatial dimension presents an exciting opportunity to extend the framework of gate-defined semiconductor quantum dots beyond planar implementations, facilitating the development of scalable quantum computation and simulation.

## **Simulation of the vortex lattice in Type-II superconductors**

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The Ginzburg-Landau theory of superconductivity can be used to study the non-homogeneous distribution of Cooper pairs, described by an order parameter, and the magnetic behavior of the superconductor. We develop a simulation package that uses the Ginzburg-Landau equations to relax a randomly generated initial state to a local minima in the free energy of the system. In our simulation of type-II superconductors, this has led to the observation of the vortex lattice. Both a square and triangular lattice have been observed. By plotting the free energy of these states we have found that the latter has, as predicted, a lower energy configuration than the latter.

# Quantum Sensing with Hole-Spin Qubits in Quantum Dots

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Hole-spin qubits in semiconductors represent a mature platform for quantum technological applications [1]. Holes in group IV materials present the advantage of a large spin-orbit coupling, which makes the qubit highly sensitive to the electrostatic environment. This effect not only offers the opportunity of all-electrical manipulation of the qubit, but can also be exploited for quantum sensing. Here we focus on the latter case. Specifically, our aim is to use the system in question as a sensor of the distance  $D$  of an external charge from the qubit [2]. We study different strategies for parameter estimation, based on the use of single or double quantum dots, ground states or coherent control, and rate them by means of the classical and quantum Fisher information. A crucial role is played by the multiband character of the hole state, which induces a dependence of the precision on the dot geometry.

We numerically simulate prototypical (double) quantum dots for a single hole in Si by exact diagonalization of the six-band Luttinger-Kohn Hamiltonian [3]. The comparison with a simpler analytical two-site Hubbard model confirms the generality and reliability of our conclusions. The potentialities of the hole qubit lie in the multiband character of the eigenstates, which can be significantly influenced by the electrostatic environment. This, in turn, affects its physical properties, and specifically its coupling to the external fields. Beyond those aspects that depend on the specific properties of the qubit, some general features emerge from our investigation. First, the use of double - rather than single - quantum dots allows for a significant enhancement of the precision in the estimate. In fact, the hole ground state is more polarizable, as schematically seen in Fig. 1. Consequently, the system is more sensitive to the position of the external charge, especially in the range where the charge-induced bias is comparable to the interdot tunneling amplitude. Besides, when the hole is localized in the double quantum dot, its Larmor and Rabi frequencies are more sensitive to the charge position. Second, we model a dynamic approach, where the value of  $D$  is encoded in the statistics of a Rabi or a Ramsey measurement. This method allows for better estimates than the static approach, where the distance of the charge determines the statistics of an arbitrary measurement performed on the hole ground state. Third, we compare the Rabi and Ramsey schemes, and find that the latter performs better. Indeed, the Ramsey scheme allows for a more efficient exploitation of the dependence of the Larmor frequency on the charge distance, which is stronger than that of the Rabi frequency.

Finally, while the dependence on  $D$  of the ground state and the Larmor and Rabi frequencies is specific to the hole-spin qubit, the analytical expressions of the Fisher information corresponding to the Rabi and Ramsey measurements that we have derived are completely general and apply to any physical implementation of the qubit.

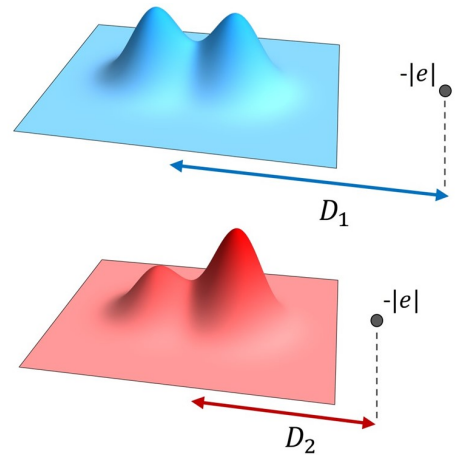


FIG. 1. The hole-charge density inside a double quantum dot is affected by additional charges inside the system, specifically by their distance  $D$ , as displayed in the picture.

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Contribution submission for the summer school NanoQI'24:

Title:

## **High Kinetic Inductance Microstrip Networks For Integrated Quantum Information Devices**

Contributors:

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Abstract:

Modern superconducting quantum information devices integrate qubits and readout resonators into complex microwave circuits.

Efficient qubit operation and fast readout require relatively strong coupling. This, however, can compromise the qubit lifetime due to spontaneous emission through the resonator. An elegant solution is provided by a Purcell filter, an added circuit element that suppresses transmission at the qubit frequency.

Here, we present a theoretical proposal for circuit architectures that realize qubit readout with Purcell filters, utilizing the highly versatile platform of high-kinetic inductance microstrip networks experimentally realized in [1]. The strongly reduced phase velocities in such materials allow compact filter designs that can be integrated on-chip.

We describe band-structure design techniques to build an efficient Purcell filter and provide quantitative estimations for the suppression of unwanted relaxation channels.

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# Microsecond-lived quantum states in a carbon-based circuit driven by cavity photons

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Electron spins in quantum dots represent an attractive path towards the realization of quantum processors. While multi-qubit gates are commonly mediated through nearest-neighbor exchange interaction, achieving coherent long-range coupling between spins remains a major challenge for such architectures. Enabling spin-photon interaction is thus appealing. Here, we manipulate the quantum state of a carbon nanotube double quantum dot with ferromagnetic contacts embedded in a microwave cavity. By performing quantum manipulations via the cavity photons, we demonstrate coherence times of the order of  $1\mu\text{s}$ , two orders of magnitude larger than what has been measured so far in any carbon quantum circuit and one order of magnitude larger than silicon based quantum dots in comparable environment. This holds promises for isotopically purified  $^{12}\text{C}$  spin qubits in circuit quantum electrodynamics.

# Eliminating barrier gates in semiconducting quantum dots

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Semiconducting spin qubits are emerging as a promising platform for scalable quantum computing, given their compatibility with industrial manufacturing and various demonstrations of beyond-threshold gate fidelities. However, a large scale qubit array has yet to be implemented due to the challenges rooted in nanometer-scale fabrication. To create a qubits array a large number of closely packed gates has to be patterned and fanned-out, which can be particularly challenging. In this work we strive to reduce this constrain by showcasing the ability to control the exchange interaction between hole spin qubits in germanium, without the need to use dedicated barrier gates. Instead we control the exchange interaction using only plunger gates in a symmetric fashion. We are able to tune the exchange interaction by over a factor of 50 using solely voltage pulses on plunger gates and staying at the charge symmetry point to maintain charge-noise insensitivity. With this approach we can reduce the gate-density of next-generation quantum dot arrays, allowing for a more scalable architecture of large 2D arrays.

# Experiments in Cavity Quantum Electrodynamics with Color Centers in Diamond

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Color centers in diamond, particularly group IV color centers like the negatively charged tin-vacancy (SnV-) center, are a promising platform for emerging quantum technologies due to their excellent optical properties and long coherence times. Recent results have demonstrated high fidelity spin control and single shot readout of the SnV- electron spin, solidifying it as a viable qubit. In order to implement the SnV- in quantum technologies, which requires a strong spin-photon interface, the color center must be integrated into high quality photonic structures. Here, we explore recent experimental efforts toward the realization of cavity quantum electrodynamics with color centers in diamond through improved diamond fabrication and materials integration.

# Passive photonic CZ gate with two-level emitters in chiral multi-mode waveguide QED

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Engineering deterministic photonic gates with simple resources is one of the long-standing challenges in photonic quantum computing. Here, we design a passive conditional gate between co-propagating photons using an array of only two-level emitters. The key resource is to harness the effective photon-photon interaction induced by the chiral coupling of the emitter array to two waveguide modes with different resonant momenta at the emitter's transition frequency. By studying the system's multi-photon scattering response, we demonstrate that, in certain limits, this configuration induces a non-linear  $\pi$ -phase shift between the polariton eigenstates of the system without distorting spectrally the wavepackets. Then, we show how to harness this non-linear phase shift to engineer a conditional, deterministic photonic gate in different qubit encodings, with a fidelity arbitrarily close to 1 in the limit of large number of emitters and coupling efficiency. Our configuration can be implemented in topological photonic platforms with multiple chiral edge modes, opening their use for quantum information processing, or in other setups where such chiral multi-mode waveguide scenario can be obtained, e.g., in spin-orbit coupled optical fibers or photonic crystal waveguides.

# Effective time-dependent temperature for fermionic master equations beyond the Markov approximation

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We consider a quantum system coupled to a fermionic environment at a fixed temperature and describe the reduced evolution of the system by means of a Redfield equation with effective time-dependent contact temperature obeying a universal law. Figure 1 shows the transition rates of the Redfield equation, along with Fermi functions that include the effective temperature, as a function of energy and for various times. At early times, after the system and environment start in a product state, the effective contact temperature appears to be much higher, yet eventually it settles down towards the true environment value. For a quantum dot coupled to an environment, we use an exact solution as a benchmark and see agreement for short times. By studying the exact correlations between the states of the environment and the quantum dot, we show that the effective temperature is related to the formation of correlations. This is related to an energy transfer between the coupling term of the Hamiltonian and the system. In this way, we obtain a method that includes some non-Markovian higher-order effects that influence the energy balance of the system and the environment, and that can be further applied to various types of GKSL equations, beyond the secular approximation and time-averaging methods.

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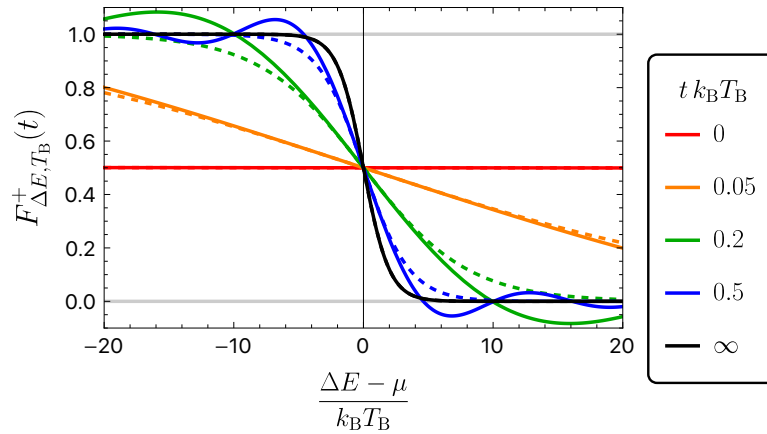


Figure 1: Transition rates of the Redfield equation as a function of energy for various times. The dashed lines show a Fermi function that include the effective temperature.



# Arbitrary Gates on the Double Transition of NV Ground State for Low Field or High Frequency Sensing

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The NV-ERC technique for control of the NV ground state exploits the spin 1 nature of the system to best initialize double quantum transition. It has been proven to be a crucial control strategy for low field or high frequency sensing. Beyond initialization and readout, the theoretical understanding of the possibility to perform  $\pi$  rotations in the transition was incomplete. We present a straightforward theoretical picture of the strategy and demonstrate a mechanism for fast arbitrary unitaries in the double quantum transition. We show it is a robust approach with respect to pulse strength and electric or strain fields in any direction.

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DOI: [10.1103/PhysRevApplied.17.044028](https://doi.org/10.1103/PhysRevApplied.17.044028)

## **Enhanced emission of single-photon sources based on colloidal quantum dots with printed microstructures**

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Single-photon emitters are at the cornerstone of most quantum communication technologies. Among existing single-photon sources (SPS), core-shell colloidal quantum dots (QDs) are particularly attractive given their small size, on-demand photon production capability, and wavelength tunability within the visible range. The QDs have an isotropic emission, limiting the coupling of the emitted photons into the optical system of interest. The goal of this project is to address these issues and develop highly efficient SPS based on QDs for future integration into quantum communication systems. Our approach is based on fabricating a resonant cavity, such as a Bragg resonator, around individual QDs by using a nanoprinter with a spatial resolution of 200 nm. This not only enhances emission rates and the Purcell effect but also reduces off-resonant emissions. Additionally, using the same nanoprinter, we can generate 3D micro-optics that improve both, the directionality of the emitted photons, as well as their quantum efficiency and stability. Here, we show our initial results on the characterization of the morphological and optical properties of individual QDs deposited on top of a substrate. The latter is achieved by using a Hanbury Brown and Twiss optical system capable of measuring their antibunching behaviour. We also compare the emission characteristics with and without resonant cavities, which are in good agreement with finite difference time domain simulations. To ease the isolation and localization of individual QDs - key for the proper performance of the resonant microstructures - we are currently working on the fabrication of polymeric arrays where QDs can be anchored. Our results show promise toward the development of controlled and enhanced SPS at targeted positions on a substrate.

# **A superconducting globally driven quantum computing architecture**

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We propose a platform for implementing a universal, globally driven quantum computer based on a 2D ladder hosting three different species of superconducting qubits. In stark contrast with the existing literature, our scheme exploits the always-on longitudinal ZZ coupling. The latter, combined with specific driving frequencies, enables the reach of a blockade regime, which plays a pivotal role in the computing scheme.

# Exciton redistribution in 2D WSe<sub>2</sub> via external strain field for positioned quantum emitters with stable magnetic response.

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Monolayer Transition-Metal Dichalcogenides (ML-TMDs) are two-dimensional semiconductors materials exhibiting unique optical and electronic properties. In addition to their easiness in fabrication, ML-TMDs can withstand up to 20% strain without breaking, being then feasible to exploit deformations to control their transport and optical properties. Furthermore, localized excitons in ML-TMDs provide single photons with high brightness<sup>[1]</sup>. Since both impurities and spatial strain gradients induce quantum emitters (QEs) in ML-TMDs<sup>[2]</sup>, dynamic control over the strain field enables to engineer the QEs properties and exploit their full potential for quantum technologies. Our piezoelectric device bursts into this context. It is a gold-covered piezoelectric material with a micro-pillars array covered by dry-transferred ML-WSe<sub>2</sub>. The QEs nucleation sites are arranged around the pillars, providing control of their position over a few microns<sup>[3]</sup>. Furthermore, deforming the piezoelectric substrate we can explore the QEs response to external strain fields. We demonstrated that the QEs energy can be precisely tuned across a spectral range as large as tens of meV without changing the multi-photon emission probability<sup>[3]</sup>. We also observed that the external strain field reversibly modifies the QEs brightness, providing theoretical simulations based on an exciton diffusion model. We found good agreement between the theory and the experimental results, confirming that strain is a valuable tool even for brightening one specific emitter rather than another<sup>[4]</sup>. We also investigated the QEs response in magnetic field. Measuring the g-factor of several single-photon lines as a function of the applied external stress, we found that despite changes in energy up to 10 meV, the variations in the g-factor always remain between the experimental errors<sup>[5]</sup>. This result ensures the robustness of the QEs spin degree of freedom, opening future possibilities in hybrid spintronic devices or photonic interfaces.

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## Partitioning statistics of interacting electrons in a flying quantum dot

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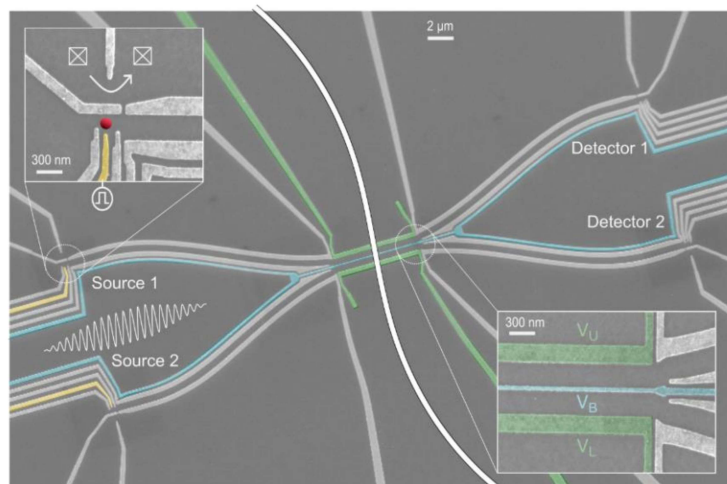
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Semiconductor quantum dots in 2D electron systems can be used to encode and process quantum information on individual electrons. Current implementations are mostly based on the electron spin which benefits from a long coherence time in purified semiconductors. Alternatively, one may think of encoding the quantum information in the orbital part of the electron wave function, when delocalized over two spatially separated quantum rails [1]. This novel approach would enable us to perform quantum operations on the flight, in a network of quantum rails with similar architecture as photonic quantum circuits [2]. Individual flying electrons in quantum rails can be obtained with surface acoustic waves creating a confining potential by piezo electric effect, thereby realizing a moving quantum dot in a depleted 1D channel [3]. After our first demonstration of the triggered injection of a single electron in a well-defined moving dot and its partitioning by a tunneling beam splitter [4], we investigated the interaction of two flying electrons transported in adjacent quantum rails, by performing a collision experiment [5]. We evidenced a clear antibunching effect in the probability distribution, that could be quantitatively attributed to Coulomb repulsion, opening the way to two-qubit operations. Here, we focus on our latest experiments where we study the partitioning statistics of up to 5 electrons launched simultaneously in the same moving dot. We interpret quantitatively the partitioning probabilities in terms of mutual Coulomb interactions between the multiple electrons, using a theoretical modelling within the mean field approximation. Thanks to the single-shot detection of our experiment, we can extract the multivariate cumulants up to 5<sup>th</sup> order associated to the partitioning statistics of a multi-electron state.



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# Superradiant phase transition and cat states in the Dicke-Ising model

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We propose a quantum protocol of Schroedinger's cat state preparation with the use of a superradiant photon condensate. In this protocol, we exploit the Dicke-Ising Hamiltonian for a chain of qubits that interact with each other and are coupled to a common single-mode photon cavity. The superradiant state is simulated via a sequence of Janes-Cummings gates and standard qubit gates. Performing selective spin measurements at the end of the Trotter evolution yields the cat's state density matrix as an outcome. We also provide a field-theoretical description of spin fluctuations around a mean-field solution. Fluctuational contribution to a profile of free energy is analyzed by means of two different methods — (i) the Jordan-Wigner fermion transformation for the case of spins  $S = 1/2$  and (ii) angular representation for larger spins  $S > 1/2$ .

# High fidelity spin control of the tin vacancy qubit in diamond

ABIGAIL STEIN

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Crystallographic defects in diamond known as ‘color centers’ present a promising platform for quantum network qubits due to their long coherence times and compatibility with integration with nanophotonic cavities to enhance emission. The negatively charged tin vacancy center (SnV<sup>-</sup>) has emerged as a leading platform. Recent results have demonstrated high fidelity spin control and single shot readout of the SnV<sup>-</sup> electron spin, which solidify the platform as a viable qubit for quantum network applications. In order to build a quantum network node with SnV<sup>-</sup>, high fidelity spin control must be demonstrated. This work constitutes progress towards realizing a high fidelity spin qubit with efficient optical readout using the tin vacancy center in diamond.

# Direct microwave spectroscopy of Andreev bound states in planar Ge Josephson junctions

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We demonstrate microwave measurements of the Andreev bound state (ABS) spectrum in planar Josephson junctions (JJs) defined in Ge high mobility two-dimensional hole gases contacted by superconducting PtSiGe. The JJs and readout circuitry are located on separate chips and inductively coupled via flip-chip bonding. For a device with 350 nm junction length, spectroscopic signatures were consistent with the short-junction limit, with an induced superconducting gap  $\Delta^* \approx 48 \mu\text{eV}$  and transmission  $\tau \approx 0.94$ . The interaction between the highest-transmission ABS and the resonator was well described by a Jaynes-Cummings model with a vacuum Rabi splitting of approximately 6 MHz. A device with junction length of 1  $\mu\text{m}$  showed an ABS spectrum consistent with a long junction model. Time-resolved monitoring of the readout resonator in the dispersive regime revealed gate-voltage tunable junction parity fluctuations on the timescale of seconds. Our work indicates a viable path towards hybrid quantum devices based on planar Ge.

## Baseband control of single-electron silicon spin qubits in two-dimensions

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Micromagnet-enabled electric-dipole spin resonance (EDSR) is an established means of high-fidelity single-spin control in silicon. However, the resulting architectural limitations have restrained state-of-the-art quantum processors to one-dimensional arrays, and heating effects from the associated microwave dissipation exacerbates crosstalk for multi-qubit operations. In contrast, spin control based on hopping spins has recently emerged as a compelling primitive for high-fidelity baseband control in sparse hole arrays in germanium [1]. In this work, we commission a  $^{28}\text{Si}/\text{SiGe}$   $2\times 2$  quantum dot array both as a 4-qubit quantum processor using established EDSR techniques and as a 2-qubit device using hopping spins in a low magnetic field regime. This control method is previously unexplored in the silicon platform but benefits from engineerable micromagnet-dominated stray fields that induce a measurable tip in quantization axis between adjacent quantum dots. The figure illustrates how the measured spin fraction after a particular shuttling sequence can be used to infer the tip when fit to the expected unitary evolution. We can directly compare the two modes of operation in terms of fidelity, coherence, and crosstalk. We find that the shuttling gate fidelity of 99.7% is on par with the benchmarked resonant gate while offering a shorter gate time. Lowering the external field to the shuttling regime nearly doubles the measured T<sub>2H</sub> suggesting a reduced coupling to charge noise. Finally, the shuttling gate circumvents the transient pulse-induced resonance shift. These results establish new opportunities for engineering spin qubit arrays in silicon.

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# Electronic flying qubits using ultrashort electronic wavepackets

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In quantum information, flying qubits are usually associated with photons. An interesting alternative is to utilize electrons instead of photons and exploit Coulomb interaction for their manipulation. To overcome the short coherence time of electrons in solid-state systems in comparison of photons in free space, generating shorter pulses ranging from GHz to THz scales is necessary.

Flying electron qubits can be made by manipulating the state of a single electron wavepackets through its propagation in an electronic Mach-Zehnder interferometer [1, 2]. The single electron can be generated by applying short voltage pulses to a two-dimensional electron gas (2DEG) [3, 4]. The current state-of-the-art for electrical pulse generation is about 20 picoseconds [5], which limits the number of quantum operations feasible in a typical 10-micron long quantum device. Despite the short time-scale (high energy scale) of the electronic wavepackets, quantum interferences can still be observed, marking an initial step towards studying the transition from adiabatic (low frequency) to an ultrafast regime.

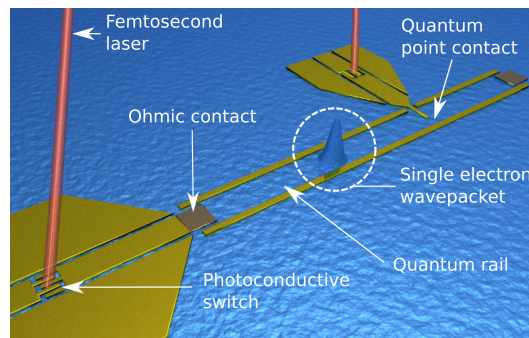


Figure 1: Single electronic wavepackets propagating in a two-dimensional electron gas (2DEG) in a quantum rail. The wavepackets are generated via a laser pulse.

To achieve even shorter pulses, a fundamentally different technology has to be used. We have developed a cryo-optoelectronic setup to convert a femtosecond optical pulse into a picosecond electrical pulse directly on-chip inside a dilution refrigerator. The opto-electronic conversion is achieved using a photoconducting switch [6] deposited on a low-temperature-grown GaAs layer with picosecond response time. We demonstrate plasmonic excitation of a 2DEG in both 2D and 1D cavities via time-resolved pump-probe measurements. These initial experiments at THz frequencies pave the way for quantum interferometry devices operating in the THz domain.

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