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2025 *Activity Report*

RESEARCH CENTRE: **Inria Paris Centre at Sorbonne University**

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Project-Team

QUANTIC

QUANTum Information Circuits

In collaboration with Laboratoire de Physique de l'École Normale Supérieure

Project-Team QUANTIC

Creation of the Project-Team: 2015 April 01

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

Keywords

Computer sciences and digital sciences

A1.1.11. – Quantum architectures
A4.2. – Correcting codes
A6. – Modeling, simulation and control
A6.1. – Methods in mathematical modeling
A6.1.1. – Continuous Modeling (PDE, ODE)
A6.1.2. – Stochastic Modeling
A6.1.3. – Discrete Modeling (multi-agent, people centered)
A6.1.4. – Multiscale modeling
A6.2. – Scientific computing, Numerical Analysis & Optimization
A6.2.1. – Numerical analysis of PDE and ODE
A6.2.3. – Probabilistic methods
A6.2.6. – Optimization
A6.3.1. – Inverse problems
A6.3.2. – Data assimilation
A6.3.3. – Data processing
A6.3.4. – Model reduction
A6.4. – Automatic control
A6.4.1. – Deterministic control
A6.4.2. – Stochastic control
A6.4.3. – Observability and Controlability
A6.4.4. – Stability and Stabilization

Other research topics and application domains

B5.3. – Nanotechnology
B5.4. – Microelectronics
B6.5. – Information systems
B9.10. – Privacy

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2 Overall objectives

2.1 Overall objectives

The research activities of QUANTIC team lie at the border between theoretical and experimental efforts in the emerging field of quantum systems engineering. Our research topics are in direct continuation of a historic research theme of INRIA, classical automatic control, while opening completely new perspectives toward quantum control: by developing a new mathematical system theory for quantum circuits, we will realize the components of a future quantum information processing unit.

One of the unique features of our team concerns the large spectrum of our subjects going from the mathematical analysis of the physical systems (development of systematic mathematical methods for control and estimation of quantum systems), and the numerical analysis of the proposed solutions, to the experimental implementation of the quantum circuits based on these solutions. This is made possible by the constant and profound interaction between the applied mathematicians and the physicists in the group. Indeed, this close collaboration has already brought a significant acceleration in our research efforts. In a long run, this synergy should lead to a deeper understanding of the physical phenomena behind these emerging technologies and the development of new research directions within the field of quantum information processing.

Towards this ultimate task of practical quantum digital systems, the approach of the QUANTIC team is complementary to the one taken by teams with expertise in quantum algorithms. Indeed, we start from the specific controls that can be realistically applied on physical systems, to propose designs which combine them into *hardware shortcuts* implementing *robust* behaviors useful for quantum information processing. Whenever a significant new element of quantum engineering architecture is developed, the initial motivation is to prove an enabling technology with major impact for the groups working one abstraction layer higher: on quantum algorithms but also on e.g. secure communication and metrology applications.

3 Research program

3.1 Hardware-efficient quantum information processing

In this scientific program, we will explore various theoretical and experimental issues concerning protection and manipulation of quantum information. Indeed, the next, critical stage in the development of Quantum Information Processing (QIP) is most certainly the active quantum error correction (QEC). Through this stage one designs, possibly using many physical qubits, an encoded logical qubit which is protected against major decoherence channels and hence admits a significantly longer effective coherence time than a physical qubit. Reliable (fault-tolerant) computation with protected logical qubits usually comes at the expense of a significant overhead in the hardware (up to thousands of physical qubits per logical qubit). Each of the involved physical qubits still needs to satisfy the best achievable properties (coherence times, coupling strengths and tunability). More remarkably, one needs to avoid undesired interactions between various subsystems. This is going to be a major difficulty for qubits on a single chip.

The usual approach for the realization of QEC is to use many qubits to obtain a larger Hilbert space of the qubit register [130, 136]. By redundantly encoding quantum information in this Hilbert space of larger dimension one make the QEC tractable: different error channels lead to distinguishable error syndromes. There are two major drawbacks in using multi-qubit registers. The first, fundamental, drawback is that with each added physical qubit, several new decoherence channels are added. Because of the exponential increase of the Hilbert's space dimension versus the linear increase in the number of decay channels, using enough qubits, one is able to eventually protect quantum information against decoherence. However, multiplying the number of possible errors, this requires measuring more error syndromes. Note furthermore that, in general, some of these new decoherence channels can lead to correlated action on many qubits and this needs to be taken into account with extra care: in particular, such kind of non-local error channels are problematic for surface codes. The second, more practical, drawback is that it is still extremely challenging to build a register of more than on the order of 10 qubits where each of the qubits is required to satisfy near the best achieved properties: these properties include the coherence time, the coupling strengths and the tunability. Indeed, building such a register is not merely only a fabrication task but rather, one requirers to look for architectures such that, each individual qubit can be addressed and controlled independently from the others. One is also

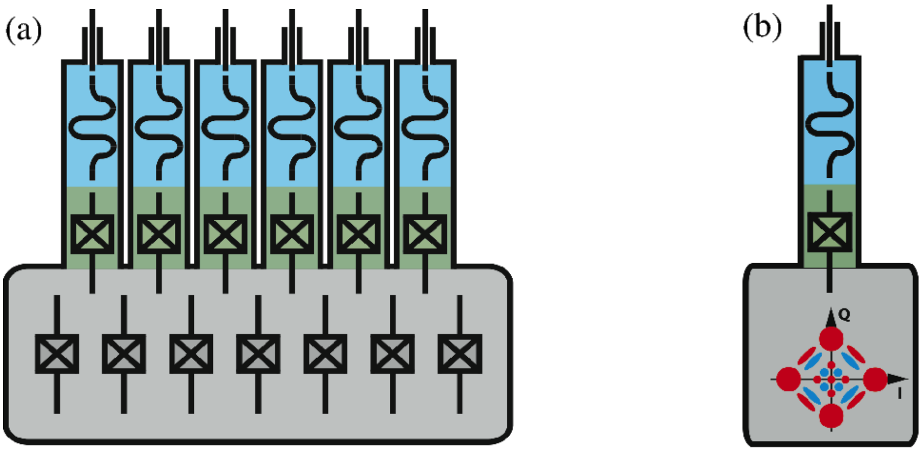

Figure 1: (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [136] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error syndromes is ensured through 6 additional ancillary qubits with the possibility of individual readout of the ancillary qubits via independent low-Q resonators. (b) Minimal architecture for a protected logical qubit, adapted to circuit quantum electrodynamics experiments. Quantum information is encoded in a Schrödinger cat state of a single high-Q resonator mode and a single error syndrome is measured, using a single ancillary transmon qubit and the associated readout low-Q resonator.

required to make sure that all the noise channels are well-controlled and uncorrelated for the QEC to be effective.

We have recently introduced a new paradigm for encoding and protecting quantum information in a quantum harmonic oscillator (e.g. a high-Q mode of a 3D superconducting cavity) instead of a multi-qubit register [97]. The infinite dimensional Hilbert space of such a system can be used to redundantly encode quantum information. The power of this idea lies in the fact that the dominant decoherence channel in a cavity is photon damping, and no more decay channels are added if we increase the number of photons we insert in the cavity. Hence, only a single error syndrome needs to be measured to identify if an error has occurred or not. Indeed, we are convinced that most early proposals on continuous variable QIP [93, 86] could be revisited taking into account the design flexibilities of Quantum Superconducting Circuits (QSC) and the new coupling regimes that are provided by these systems. In particular, we have illustrated that coupling a qubit to the cavity mode in the strong dispersive regime provides an important controllability over the Hilbert space of the cavity mode [96]. Through a recent experimental work [144], we benefit from this controllability to prepare superpositions of quasi-orthogonal coherent states, also known as Schrödinger cat states.

In this Scheme, the logical qubit is encoded in a four-component Schrödinger cat state. Continuous quantum non-demolition (QND) monitoring of a single physical observable, consisting of photon number parity, enables then the tractability of single photon jumps. We obtain therefore a first-order quantum error correcting code using only a single high-Q cavity mode (for the storage of quantum information), a single qubit (providing the non-linearity needed for controllability) and a single low-Q cavity mode (for reading out the error syndrome). An earlier experiment on such QND photon-number parity measurements [137] has recently led to a first experimental realization of a full quantum error correcting code improving the coherence time of quantum information [7]. As shown in Figure 1, this leads to a significant hardware economy for realization of a protected logical qubit. Our goal here is to push these ideas towards a reliable and hardware-efficient paradigm for universal quantum computation.

3.2 Reservoir (dissipation) engineering and autonomous stabilization of quantum systems

Being at the heart of any QEC protocol, the concept of feedback is central for the protection of quantum information, enabling many-qubit quantum computation or long-distance quantum communication. However, such a closed-loop control which requires a real-time and continuous measurement of the quantum system has been for long considered as counter-intuitive or even impossible. This thought was mainly caused by properties of quantum measurements: any measurement implies an instantaneous strong perturbation to the system's state. The concept of *quantum non-demolition* (QND) measurement has played a crucial role in understanding and resolving this difficulty [65]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [89], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [87]. Later on, this ability of performing continuous measurements allowed the same group to realize the first continuous quantum feedback protocol stabilizing highly non-classical states of the microwave field in the cavity, the so-called photon number states [11] (this ground-breaking work was mentioned in the Nobel prize attributed to Serge Haroche). The QUANTIC team contributed to the theoretical work behind this experiment [76, 55, 135, 56]. These contributions include the development and optimization of the quantum filters taking into account the quantum measurement back-action and various measurement noises and uncertainties, the development of a feedback law based on control Lyapunov techniques, and the compensation of the feedback delay.

In the context of circuit quantum electrodynamics (circuit QED) [74], recent advances in quantum-limited amplifiers [123, 140] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [90]. This ability to perform high-fidelity non-demolition measurements of a quantum signal has very recently led to quantum feedback experiments with quantum superconducting circuits [140, 122, 67]. Here again, the QUANTIC team has participated to one of the first experiments in the field where the control objective is to track a dynamical trajectory of a single qubit rather than stabilizing a stationary state. Such quantum trajectory tracking could be further explored to achieve metrological goals such as the stabilization of the amplitude of a microwave drive [107].

While all this progress has led to a strong optimism about the possibility to perform active protection of quantum information against decoherence, the rather short dynamical time scales of these systems limit, to a great amount, the complexity of the feedback strategies that could be employed. Indeed, in such measurement-based feedback protocols, the time-consuming data acquisition and post-treatment of the output signal leads to an important latency in the feedback procedure.

The reservoir (dissipation) engineering [115] and the closely related coherent feedback [103] are considered as alternative approaches circumventing the necessity of a real-time data acquisition, signal processing and feedback calculations. In the context of quantum information, the decoherence, caused by the coupling of a system to uncontrolled external degrees of freedom, is generally considered as the main obstacle to synthesize quantum states and to observe quantum effects. Paradoxically, it is possible to intentionally engineer a particular coupling to a reservoir in the aim of maintaining the coherence of some particular quantum states. In a general viewpoint, these approaches could be understood in the following manner: by coupling the quantum system to be stabilized to a strongly dissipative ancillary quantum system, one evacuates the entropy of the main system through the dissipation of the ancillary one. By building the feedback loop into the Hamiltonian, this type of autonomous feedback obviates the need for a complicated external control loop to correct errors. On the experimental side, such autonomous feedback techniques have been used for qubit reset [85], single-qubit state stabilization [108], and the creation [59] and stabilization [95, 102, 129] of states of multipartite quantum systems.

Such reservoir engineering techniques could be widely revisited exploring the flexibility in the Hamiltonian design for QSC. We have recently developed theoretical proposals leading to extremely efficient, and simple to implement, stabilization schemes for systems consisting of a single, two or three qubits [85, 99, 72, 75]. The experimental results based on these protocols have illustrated the efficiency of the approach [85, 129]. Through these experiments, we exploit the strong dispersive interaction [127] between superconducting qubits and a single low-Q cavity mode playing the role of a dissipative reservoir. Applying continuous-wave (cw) microwave drives with well-chosen fixed frequencies, amplitudes, and phases, we engineer an effective interaction Hamiltonian which evacuates the entropy of the system interacting with a noisy environment: by driving the qubits and cavity with continuous-wave drives, we induce an autonomous feedback loop which corrects the state of the qubits every time it decays out of the desired target state. The schemes are robust against small variations of the control parameters (drives amplitudes and phase) and require only some basic calibration. Finally, by avoiding resonant interactions between the qubits and the low-Q cavity mode, the qubits remain protected against the Purcell effect, which would reduce the coherence times. We have also investigated both theoretically and experimentally the autonomous stabilization of non-classical states (such as Schrodinger cat states and Fock states) of microwave field confined in a high-Q cavity mode [125, 91][6, 4].

3.3 System theory for quantum information processing

In parallel and in strong interactions with the above experimental goals, we develop systematic mathematical methods for dynamical analysis, control and estimation of composite and open quantum systems. These systems are built with several quantum subsystems whose irreversible dynamics results from measurements and/or decoherence. A special attention is given to spin/spring systems made with qubits and harmonic oscillators. These developments are done in the spirit of our recent contributions [124, 55, 134, 126, 135, 56][10] resulting from collaborations with the cavity quantum electrodynamics group of Laboratoire Kastler Brossel.

3.4 Stabilization by measurement-based feedback

The protection of quantum information via efficient QEC is a combination of (i) tailored dynamics of a quantum system in order to protect an informational qubit from certain decoherence channels, and (ii) controlled reaction to measurements that efficiently detect and correct the dominating disturbances that are not rejected by the tailored quantum dynamics.

In such feedback scheme, the system and its measurement are quantum objects whereas the controller and the control input are classical. The stabilizing control law is based on the past values of the measurement outcomes. During our work on the LKB photon box, we have developed, for single input systems subject to quantum non-demolition measurement, a systematic stabilization method [56]: it is based on a discrete-time formulation of the dynamics, on the construction of a strict control Lyapunov function and on an explicit compensation of the feedback-loop delay. Keeping the QND measurement assumptions, extensions of such stabilization schemes will be investigated in the following directions: finite set of values for the control input with application to the convergence analysis of the atomic feedback scheme experimentally tested in [145]; multi-input case where the construction by inversion of a Metzler matrix of the strict Lyapunov function is not straightforward; continuous-time systems governed by diffusive master equations; stabilization towards a set of density operators included in a target subspace; adaptive measurement by feedback to accelerate the convergence towards a stationary state as experimentally tested in [112]. Without the QND measurement assumptions, we will also address the stabilization of non-stationary states and trajectory tracking, with applications to systems similar to those considered in [90, 67].

3.5 Filtering, quantum state and parameter estimations

The performance of every feedback controller crucially depends on its online estimation of the current situation. This becomes even more important for quantum systems, where full state measurements are physically impossible. Therefore the ultimate performance of feedback correction depends on fast, efficient and optimally accurate state and parameter estimations.

A quantum filter takes into account imperfection and decoherence and provides the quantum state at time $t \geq 0$ from an initial value at $t = 0$ and the measurement outcomes between 0 and t. Quantum filtering goes back to the work of Belavkin [61] and is related to quantum trajectories [68, 73]. A modern and mathematical exposure of the diffusive models is given in [58]. In [88] a first convergence analysis of diffusive filters is proposed. Nevertheless the convergence characterization and estimation of convergence rate remain open and difficult problems. For discrete time filters, a general stability result based on fidelity is proven in [124, 134]. This stability result is extended to a large class of continuous-time filters in [54]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [62]. Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [80, 110].

We will continue to investigate stability and convergence of quantum filtering. We will also exploit our fidelity-based stability result to justify maximum likelihood estimation and to propose, for open quantum system, parameter estimation algorithms inspired of existing estimation algorithms for classical systems. We will also investigate a more specific quantum approach: it is noticed in [66] that post-selection statistics and "past quantum" state analysis [81] enhance sensitivity to parameters and could be interesting towards increasing the precision of an estimation.

3.6 Stabilization by interconnections

In such stabilization schemes, the controller is also a quantum object: it is coupled to the system of interest and is subject to decoherence and thus admits an irreversible evolution. These stabilization schemes are closely related to reservoir engineering and coherent feedback [115, 103]. The closed-loop system is then a composite system built with the original system and its controller. In fact, and given our particular recent expertise in this domain [10] [129, 85], this subsection is dedicated to further developing such stabilization techniques, both experimentally and theoretically.

The main analysis issues are to prove the closed-loop convergence and to estimate the convergence rates. Since these systems are governed by Lindblad differential equations (continuous-time case) or Kraus maps (discrete-time case), their stability is automatically guaranteed: such dynamics are contractions for a large set of metrics (see [114]). Convergence and asymptotic stability is less well understood. In particular most of the convergence results consider the case where the target steady-state is a density operator of maximum rank (see, e.g., [57][chapter 4, section 6]). When the goal steady-state is not full rank very few convergence results are available.

We will focus on this geometric situation where the goal steady-state is on the boundary of the cone of positive Hermitian operators of finite trace. A specific attention will be given to adapt standard tools (Lyapunov function, passivity, contraction and Lasalle's invariance principle) for infinite dimensional systems to spin/spring structures inspired of [10, 6] [129, 85] and their associated Fokker-Planck equations for the Wigner functions.

We will also explore the Heisenberg point of view in connection with recent results of the INRIA project-team MAXPLUS (algorithms and applications of algebras of max-plus type) relative to Perron-Frobenius theory [84, 83]. We will start with [128] and [120] where, based on a theorem due to Birkhoff [63], dual Lindblad equations and dual Kraus maps governing the Heisenberg evolution of any operator are shown to be contractions on the cone of Hermitian operators equipped with Hilbert's projective metric. As the Heisenberg picture is characterized by convergence of all operators to a multiple of the identity, it might provide a mean to circumvent the rank issues. We hope that such contraction tools will be especially well adapted to analyzing quantum systems composed of multiple components, motivated by the facts that the same geometry describes the contraction of classical systems undergoing synchronizing interactions [139] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [106].

Besides these analysis tasks, the major challenge in stabilization by interconnections is to provide systematic methods for the design, from typical building blocks, of control systems that stabilize a specific quantum goal (state, set of states, operation) when coupled to the target system. While constructions exist for so-called linear quantum systems [111], this does not cover the states that are more interesting for quantum applications. Various strategies have been proposed that concatenate iterative control steps for open-loop steering [143, 101] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [64], but without considering experimental implementations. A viable stabilization by interaction has to combine the capabilities of these various approaches, and this is a missing piece that we want to address.

3.6.1 Perturbation methods

With this subsection we turn towards more fundamental developments that are necessary in order to address the complexity of quantum networks with efficient reduction techniques. This should yield both efficient mathematical methods, as well as insights towards unravelling dominant physical phenomena/mechanisms in multipartite quantum dynamical systems.

In the Schrödinger point of view, the dynamics of open quantum systems are governed by master equations, either deterministic or stochastic [89, 82]. Dynamical models of composite systems are based on tensor products of Hilbert spaces and operators attached to the constitutive subsystems. Generally, a hierarchy of different timescales is present. Perturbation techniques can be very useful to construct reliable models adapted to the timescale of interest.

To eliminate high frequency oscillations possibly induced by quasi-resonant classical drives, averaging techniques are used (rotating wave approximation). These techniques are well established for closed systems without any dissipation nor irreversible effect due to measurement or decoherence. We will consider in a first step the adaptation of these averaging techniques to deterministic Lindblad master equations governing the quantum state, i.e. the system density operator. Emphasis will be put on first order and higher order corrections based on non-commutative computations with the different operators appearing in the Lindblad equations. Higher order terms could be of some interest for the protected logical qubit of figure 1b. In future steps, we intend to explore the possibility to explicitly exploit averaging or singular perturbation properties in the design of coherent quantum feedback systems; this should be an open-systems counterpart of works like [98].

To eliminate subsystems subject to fast convergence induced by decoherence, singular perturbation techniques can be used. They provide reduced models of smaller dimension via the adiabatic elimination of the rapidly converging subsystems. The derivation of the slow dynamics is far from being obvious (see, e.g., the computations of page 142 in [69] for the adiabatic elimination of low-Q cavity). Conversely to the classical composite systems where we have to eliminate one component in a Cartesian product, we here have to eliminate one component in a tensor product. We will adapt geometric singular perturbations [78] and invariant manifold techniques [70] to such tensor product computations to derive reduced slow approximations of any order. Such adaptations will be very useful in the context of quantum Zeno dynamics to obtain approximations of the slow dynamics on the decoherence-free subspace corresponding to the slow attractive manifold.

Perturbation methods are also precious to analyze convergence rates. Deriving the spectrum attached to the Lindblad differential equation is not obvious. We will focus on the situation where the decoherence terms of the form $L\rho L^\dagger - (L^\dagger L\rho + \rho L^\dagger L)/2$ are small compared to the conservative terms $-i[H/\hbar, \rho]$. The difficulty to overcome here is the degeneracy of the unperturbed spectrum attached to the conservative evolution $\frac{d}{dt}\rho = -i[H/\hbar, \rho]$. The degree of degeneracy of the zero eigenvalue always exceeds the dimension of the Hilbert space. Adaptations of usual perturbation techniques [92] will be investigated. They will provide estimates of convergence rates for slightly open quantum systems. We expect that such estimates will help to understand the dependence on the experimental parameters of the convergence rates observed in [85, 129, 99].

As particular outcomes for the other subsections, we expect that these developments towards simpler dominant dynamics will guide the search for optimal control strategies, both in open-loop microwave networks and in autonomous stabilization schemes such as reservoir engineering. It will further help to efficiently compute explicit convergence rates and quantitative performances for all the intended experiments.

3.7 On-chip microwave engineering

The rapid development of circuitQED over the past 20 years was enabled by commercially available microwave components such as filters, switches and circulators, which allow experimentalists to shape and route measurement and control signals in and out of quantum systems. However, these components are intrinsically bulky, lossy and are imperfectly impedance-matched, leading to spurious reflections at their ports. In order to implement a full-scale quantum computer based on superconducting circuits, it is crucial that these functionalities be enabled reliably on-chip.

On-chip filters commonly used in circuitQED experiments are far from the level of variety and refinement of commercially available components. The near exclusive strategy known as "Purcell-filtering" [121] consists in placing $\lambda/4$ stubs [116] on all feed lines. This cancels the admittance of the environment seen by a superconducting qubit at its resonance frequency, inhibiting spontaneous relaxation. An issue with this strategy is that given the modest width of the stub stopband, performances are degraded as soon as the qubit is not perfectly in resonance. Moreover, this approach is not suited for multiplexed control and measurements, in which a single feed line addresses simultaneously several qubits. Notable alternatives include highpass waveguide filters only available in 3D circuitQED [119], and a recent implementation of a bandpass filter [79].

On-chip non-reciprocal elements, such as isolators, circulators and gyrators are at a very early stage of development. So far, the most promising approach to break reciprocity without resorting to strong magnetic fields—which are incompatible with superconducting circuit technology—relies on the differential phase impinged on a signal during parametric down-conversion with respect to the reverse process of up-conversion. Combining coherently several conversion paths with well-chosen phases, one obtains a constructive forward interference, and a destructive backward one. In circuitQED, frequency conversion is enabled by a non-linear Josephson circuit [131, 71, 53], or by electromechanical coupling to nanoresonators [60, 113]. A serious drawback of this approach is that it relies on a destructive interference effect to obtain the reverse isolation, which limits the operational bandwidth: the highest value reported so far is a 23 dB isolation over a 8 MHz band [53]. For completeness, we mention a recent implementation of a forward amplifier based on resistively shunted Josephson junctions [138] that reaches a 100 MHz bandwidth at the cost of added noise, and the long term prospect of harnessing the anomalous Hall effect to implement a gyrator [142, 104].

In this project, we propose to develop novel on-chip filters and isolators based on 1D Josephson metamaterials, which could reach unprecedented bandwidth, tunable range and on/off or forward/backward transmission ratios. Such metamaterials have been routinely used over the past decade to amplify weak quantum signals [77]. It was attempted to adapt these devices to route microwave non-reciprocally (with or without amplification). However, up to now, these devices suffer from limited bandwidth, isolation and pump leakage preventing their integration in quantum circuits [118, 105, 94]. In our approach, we propose to route microwaves non-reciprocally by mixing them in a Josephson metamaterial with a pump wave propagating at a much smaller phase velocity. This allows us to activate photon conversion processes that were not previously observed, by which a propagating signal is converted into a counterpropagating one. In this configuration, the signal is exponentially attenuated as it travels down the metamaterial, providing an effective circulator with robust isolation. The device can be reconfigured into a reciprocal and adjustable filter. While the first device's generation we tested suffers from limited working bandwidth of about 200 MHz and pump leakage [117], we are currently developing a second generation to remedy these shortcomings.

3.8 Exotic circuits for qubit protection

Developing error-resilient qubits remains one of the central challenges in superconducting quantum circuits. In addition to error correction protocols and efforts to mitigate environment-induced decoherence, another avenue is to design circuits whose lowest-energy eigenstates are intrinsically protected, usually thanks to symmetry properties. Prominent examples are the so-called "$0-\pi$" qubit and the "bi-fluxon" qubit. In this project, we implement another protected qubit candidate: the "$\cos(2\varphi)$" Transmon [132]. It consists of a superconducting island connected to ground through a tunnelling element through which Cooper pairs are only allowed to travel by pairs. This Cooper-pair pairing enforces the conservation of Cooper-pair parity, making the qubit protected against certain error channels. We explore an implementation of this qubit using traditional circuit elements where the parity-preservation property is achieved through Aharonov-Bohm interference in a SQUID-like loop, known as the Kite. On the path towards the construction of our protected qubit, we have realized two experiments showcasing the physics of Cooper-pairing through a Kite element.

The first one, led by post-doc Clarke Smith, demonstrated that pairing Cooper pairs magnifies quantum phase fluctuations [133]. We accomplish this by tuning our Kite between two operating points where the potential is 2π- or π-periodic. This doubles the frequency of the corrugation and hence also the number of sites accessible to the ground state. We refer to this change of scale, resulting from a denser packing of the Josephson wells, as a magnification. The second one, led by PhD student Alvise Borgognoni and post-doc Clarke Smith, demonstrated that Cooper-pair pairing enhances photon-photon interactions [27]. Indeed, the doubling of the frequency of the Josephson corrugation results in a 2^{2n} enhancement for $n-$ photon interaction energies. From spectroscopy, we extracted two-, three-, and four-photon (eight wave-mixing) interaction energies, all of similar strength and exceeding the photon loss rate. Our results open a new regime of high-order photon interactions in microwave quantum optics. Finally, the implementation of the "$\cos(2\varphi)$" Transmon is in progress. We are in the process of measuring a device where we observe a doubling of the eigenspectrum into two parity sectors, a hallmark of quartet tunneling. We are analyzing the decay mechanisms of the ground state doublet as a function of flux and charge and reflecting on the prospects of the $\cos(2\varphi)$ Transmon as a protected qubit or charge detector.

3.9 Quantum sensing

Heavy and low frequency vibrating membranes are promising probes of gravitational effects on quantum mechanics, such as gravitational-induced decoherence. A leading expert on such membranes is Samuel Deléglise from LKB CNRS, and in recent years our team has collaborated with Deléglise to couple a membrane to a superconducting circuit. This coupling would allow not only the quantum sensing of the membrane, but also its full quantum control. The goal further ahead will then be to prepare large cat-states of phonons and seek the presence or absence of gravitational-induced decoherence. During the evaluation period, we demonstrated repeated, and high-fidelity interactions between a 4 MHz suspended silicon nitride membrane and a resonant superconducting heavy-fluxonium qubit. The qubit is initialized at an effective temperature of 27 μK and read out in a single-shot with 77% fidelity. During the membrane's 6 ms lifetime, the two systems swap excitations more than 300 times [109, 35].

Another attempt at quantum sensing was led by Zaki Leghtas and PhD student Marius Villiers in collaboration with Takis Kontos. The long-term goal was to couple a spin qubit suspended in a carbon-nanotube to a superconducting circuit. Anticipating that such a coupling would be weak, we implemented an idea of Leroux and Clerk [100], stipulating that such couplings could be amplified by antisqueezing the superconducting resonator. In our proof-of-principle implementation [141], we emulated the spin-qubit with a Transmon qubit, and demonstrated a two-fold amplification of the dispersive coupling to a resonator at 5.5 dB of squeezing. Moreover, in addition to interaction amplification, we uncovered the detrimental effects of squeezing-induced qubit decoherence. This effect dissuaded us from deploying this technique to the more complex samples containing actual carbon nanotubes.

4 Application domains

4.1 Quantum engineering

A new field of quantum systems engineering has emerged during the last few decades. This field englobes a wide range of applications including nano-electromechanical devices, nuclear magnetic resonance applications, quantum chemical synthesis, high resolution measurement devices and finally quantum information processing devices for implementing quantum computation and quantum communication. Recent theoretical and experimental achievements have shown that the quantum dynamics can be studied within the framework of estimation and control theory, but give rise to new models that have not been fully explored yet.

The QUANTIC team's activities are defined at the border between theoretical and experimental efforts of this emerging field with an emphasis on the applications in quantum information, computation and communication. The main objective of this interdisciplinary team is to develop quantum devices ensuring a robust processing of quantum information.

On the theory side, this is done by following a system theory approach: we develop estimation and control tools adapted to particular features of quantum systems. The most important features, requiring the development of new engineering methods, are related to the concept of measurement and feedback for composite quantum systems. The destructive and partial [1] nature of measurements for quantum systems lead to major difficulties in extending classical control theory tools. Indeed, design of appropriate measurement protocols and, in the sequel, the corresponding quantum filters estimating the state of the system from the partial measurement record, are themselves building blocks of the quantum system theory to be developed.

On the experimental side, we develop new quantum information processing devices based on quantum superconducting circuits. Indeed, by realizing superconducting circuits at low temperatures and using microwave measurement techniques, the macroscopic and collective degrees of freedom such as the voltage and the current are forced to behave according to the laws of quantum mechanics. Our quantum devices are aimed to protect and process quantum information through these integrated circuits.

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[1] Here the partiality means that no single quantum measurement is capable of providing the complete information on the state of the system.

5 Highlights of the year

- Pierre Rouchon was elected as a member of French Academy of Sciences.
- Alain Sarlette coordinated the conference "International Conference on Quantum Computing" at Institut Henri Poincaré.
- Alexandru Petrescu was a co-organizer of the plenary conference of GDR Quantum Mesoscopic Physics.
- Three publications in Nature Communications [21, 24, 27] and one in Physical Review X [26].

6 Latest software developments, platforms, open data

Dynamiqs Web site: `https://www.dynamiqs.org/`.

Self-assessment:

- Software Family: `research`: Software as a Vector for Knowledge (see SAE, Section 3.1).
- Audience: `universe`: wide-audience software (aims to be usable by a wide public, to become the reference software in its area, etc.).
- Evolution and maintenance: `lts`: long term support.
- Duration of the Development (Duration): 3 years
- Quantic contributors: Adrien Bocquet, Pierre Guilmin.
- Free Description: Dynamiqs is a Python library for GPU-accelerated, vectorized, and differentiable quantum simulations. The library is built with JAX and the main solvers are based on Diffrax. The code is available on GitHub at `https://github.com/dynamiqs/dynamiqs` and distributed under the Apache-2.0 license.

  The primary goal of the library is to provide a reliable, fast, and robust building block for the numerical solving of the equations governing the dynamics of closed and open quantum systems. Dynamiqs provides solvers for the most common equations used to study closed and open quantum systems, particularly: the Schrödinger equation, the Lindblad master equation, the stochastic Schrödinger equation (SSE), and the stochastic master equation (SME). These solvers are developed with three key features in mind. First, the simulations must run seamlessly on both CPUs and GPUs. Second, they can be executed simultaneously by vectorizing over multiple Hamiltonians, initial states, or jump operators. Third, they are differentiable: the gradient of functions of the state output by the simulation can be computed with respect to arbitrary input parameters. Dynamiqs can be used for understanding the dynamics of quantum systems, fitting experimental data, performing sensitivity analysis, performing quantum optimal control, and more. The library is designed to be a foundational tool for various applications.

MPSDynamics.jl Website: `https://shareloqs.github.io/MPSDynamics.jl/`.

Self-assessment:

- Software family: 2. vehicle, software as a vehicle for research
- Audience: community
- Evolution and maintenance: basic
- Duration of the Development (Duration): 2 years.
- Distribution: freely available on Github and as a package on Julia public registry (one can install it via Pkg.add).
- License: GNU General Public License v3.0
- Quantic contributors: Angela Riva.

- Free Description: MPSdynamics.jl is an open-source Julia package for simulating quantum dynamics using tensor network methods. It provides methods for time-evolving matrix product states (MPS) and tree tensor networks (TTN), using multiple time-dependent variational principle (TDVP) algorithms (including a new bond adaptive algorithm). The package supports measurement of single- and multi-site observables and data logging, making it a versatile tool for studying many-body physics.

  Originally developed to model non-Markovian open quantum system dynamics at finite temperatures using chain mapping methods, MPSDynamics.jl now handles Hamiltonians with long-range interactions, time-dependent Hamiltonians, multiple bosonic or fermionic environments.

  While general-purpose tensor network libraries (e.g. ITensors.jl) exist, MPSDynamics.jl implements chain mapping methods allowing for simulations of open quantum systems, particularly in finite-temperature settings.

  The online documentation is regularly updated. Multiple examples and tutorials benchmark MPSDynamics simulations against exact solutions. A list of publications that use MPSDynamics.jl can be found on Gihtub.

6.1 Latest software developments

7 New results

7.1 Dissipative protection of a GKP qubit in a high-impedance superconducting circuit driven by a microwave frequency comb

Participants: Lev-Arcady Sellem, , Alain Sarlette, , Zaki Leghtas, , Mazyar Mirrahimi, , Pierre Rouchon, , Philippe Campagne-Ibarcq.

Over the past decade, autonomous stabilization of bosonic qubits has emerged as a promising approach for hardware-efficient protection of quantum information. However, applying these techniques to more complex encodings than the Schrödinger cat code requires exquisite control of high-order wave mixing processes. The challenge is to enable specific multiphotonic dissipation channels while avoiding unintended non-linear interactions. In this work, we leverage a genuine six-wave mixing process enabled by a near Kerr-free Josephson element to enforce dissipation of quartets of excitations in a high-impedance superconducting resonator. Owing to residual non-linearities stemming from stray inductances in our circuit, this dissipation channel is only effective when the resonator holds a specific number of photons. Applying it to the fourth excited state of the resonator, we show an order of magnitude enhancement of the state decay rate while only marginally impacting the relaxation and coherence of lower energy states. Given that stray inductances could be strongly reduced through simple modifications in circuit design and that our methods can be adapted to activate even higher-order dissipation channels, these results pave the way toward the dynamical stabilization of four-component Schrödinger cat qubits and even more complex bosonic qubits.

This work was published in PRX [26].

7.2 Tensor-network representation of excitations in Josephson junction arrays

Participants: Emilio Rui, , Joachim Cohen, , Alexandru Petrescu.

We present a nonperturbative tensor-network approach to the excitation spectra of superconducting circuits based on Josephson junction arrays [47]. These arrays provide the large lumped inductances required for qubit designs, yet their intrinsically many-body nature is typically reduced to effective single-mode descriptions. Perturbative treatments attempt to include the collective array modes neglected in these approximations, but a fully nonperturbative analysis is challenging due to the many-body structure and the collective character of these modes. We overcome this difficulty using the DMRG-X algorithm, which extends tensor-network methods to excited states. Our key advance is a construction of trial states from the linearized mode structure, enabling direct computation of excitations, even in degenerate manifolds, which was previously inaccessible. Our results reveal significant deviations from, and allow us to improve upon, previous perturbative treatments in the regime of low array junction impedance.

7.3 Suppression of measurement-induced state transitions in $\cos\varphi$-coupling transmon readout

Participants: Alexandru Petrescu.

Drive-induced unwanted state transitions (DUST) are limiting both for microwave readout and parametric operations of superconducting qubits. Among them, measurement-induced state transitions (MIST) are due to intrinsic resonances described by the readout Hamiltonian. They were previously studied with a qubit linearly coupled to its readout mode, which constitutes the usual readout Hamiltonian. Since MIST can appear even at moderate powers, they limit the readout SNR and the QND readout fidelity. In this work [40], we study the high-power readout regime in a different transmon readout scheme, implementing a nonlinear coupling called the $\cos\varphi$-coupling. This coupling stems from a transmon molecule circuit and has symmetry properties that suppress nonparity-conserving MIST. We succeed in performing multi-state single-shot readout up to the fifth excited state of the transmon, which enables us to identify leakage pathways from the computational subspace. The measurements indicate that the system is free of MIST up to high powers, with more than 300 photons in the readout mode. The MIST can be controllably turned on by breaking the parity symmetry of the coupling using flux-tuning. These experimental results are corroborated by branch analysis and simulations of the classical chaotic dynamics, showing that the $\cos\varphi$-coupling is very robust to readout photons compared to the usual transverse coupling.

7.4 Non-perturbative switching rates in bistable open quantum systems: from driven Kerr oscillators to dissipative cat qubits

Participants: Léon Carde, , Joachim Cohen, , Alexandru Petrescu.

Accepted in Physical Review Letters.

In this work [19], we use path integral techniques to predict the switching rate in a single-mode bistable open quantum system. While analytical expressions are well-known to be accessible for systems subject to Gaussian noise obeying classical detailed balance, we generalize this approach to a class of quantum systems, those which satisfy the recently-introduced hidden time-reversal symmetry. In particular, in the context of quantum computing, we deliver precise estimates of bit-flip error rates in cat-qubit architectures, circumventing the need for costly numerical simulations. Our results open new avenues for exploring switching phenomena in multistable single- and many-body open quantum systems.

7.5 Optimal absorption and emission of itinerant fields into a spin ensemble memory

Participants: Linda Greggio, , Mazyar Mirrahimi, , Alexandru Petrescu.

Quantum memories integrated in a modular quantum processing architecture can rationalize the resources required for quantum computation. This work [36] focuses on spin-based quantum memories, where itinerant electromagnetic fields are stored in large ensembles of effective two-level systems, such as atomic or solid-state spin ensembles, embedded in a cavity. Using a mean-field framework, we model the ensemble as an effective spin communication channel and develop a cascaded quantum model to describe both absorption and emission processes. We derive optimal time-dependent modulations of the cavity linewidth that maximize storage and retrieval efficiency for finite-duration wavepackets. Our analysis yields an upper bound on efficiency, which can be met in the narrow bandwidth regime. It also shows the existence of a critical bandwidth above which the efficiency severely decreases. Numerical simulations are presented in the context of microwave-frequency quantum memories interfaced with superconducting quantum processors, highlighting the protocol's relevance for modular quantum architectures.

7.6 Strongly driven transmon as an incoherent noise source

Participants: Linda Greggio, , Rémi Robin, , Mazyar Mirrahimi, , Alexandru Petrescu.

Under strong drives, which are becoming necessary for fast high-fidelity operations, transmons can be structurally unstable. Due to chaotic effects, the computational manifold is no longer well separated from the remainder of the spectrum, which correlates with enhanced offset-charge sensitivity and destructive effects in readout. We show here [37] that these detrimental effects can further propagate to other degrees of freedom, for example to neighboring qubits in a multi-qubit system. Specifically, a coherently driven transmon can act as a source of incoherent noise to another circuit element coupled to it. By using a full quantum model and a semiclassical analysis, we perform the noise spectroscopy of the driven transmon coupled to a spectator two-level system (TLS), and we show that, in a certain limit, the interaction with the driven transmon can be modeled as a stochastic diffusive process driving the TLS.

7.7 Convergence Analysis of Galerkin Approximations for the Lindblad Master Equation

Participants: Rémi Robin, , Pierre Rouchon.

This paper [43] analyzes the numerical approximation of the Lindblad master equation on infinite-dimensional Hilbert spaces. We employ a classical Galerkin approach for spatial discretization and investigate the convergence of the discretized solution to the exact solution. Using a priori estimates, we derive explicit convergence rates and demonstrate the effectiveness of our method through examples motivated by autonomous quantum error correction.

7.8 Unconditionally stable time discretization of Lindblad master equations in infinite dimension using quantum channels

Participants: Rémi Robin, , Pierre Rouchon, , Lev-Arcady Sellem.

We examine the time discretization of Lindblad master equations in infinite-dimensional Hilbert spaces. Our study is motivated by the fact that, with unbounded Lindbladian, projecting the evolution onto a finite-dimensional subspace using a Galerkin approximation inherently introduces stiffness, leading to a Courant–Friedrichs–Lewy type condition for explicit integration schemes.

We propose and establish the convergence of a family of explicit numerical schemes for time discretization adapted to infinite dimension [44]. These schemes correspond to quantum channels and thus preserve the physical properties of quantum evolutions on the set of density operators: linearity, complete positivity and trace. Numerical experiments inspired by bosonic quantum codes illustrate the practical interest of this approach when approximating the solution of infinite dimensional problems by that of finite dimensional problems of increasing dimension.

7.9 A posteriori error estimates for the Lindblad master equation

Participants: Paul-Louis Etienney, , Rémi Robin, , Pierre Rouchon.

We are interested in the simulation of open quantum systems governed by the Lindblad master equation in an infinite-dimensional Hilbert space. To simulate the solution of this equation, the standard approach involves two sequential approximations: first, we truncate the Hilbert space to derive a differential equation in a finite-dimensional subspace. Then, we use discrete time-step to obtain a numerical solution to the finite-dimensional evolution.

In this paper [34], we establish bounds for these two approximations that can be explicitly computed to guarantee the accuracy of the numerical results. Through numerical examples, we demonstrate the efficiency of our method, empirically highlighting the tightness of the upper bound. While adaptive time-stepping is already a common practice in the time discretization of the Lindblad equation, we extend this approach by showing how to dynamically adjust the truncation of the Hilbert space. This enables fully adaptive simulations of the density matrix. For large-scale simulations, this approach can significantly reduce computational time and relieves users of the challenge of selecting an appropriate truncation.

7.10 Diffusive Stochastic Master Equation (SME) with dispersive qubit/cavity coupling

Participants: Pierre Rouchon.

A detailed analysis of the diffusive Stochastic Master Equation (SME) for qubit/cavity systems with dispersive coupling is provided [45]. This analysis incorporates clas- sical input signals and output signals (measurement outcomes through homodyne detec- tion). The dynamics of the qubit/cavity density operator is shown to converge exponen- tially towards a slow invariant manifold, parameterized via a time-varying deterministic Kraus map by the density operator of a fictitious qubit. This fictitious qubit is governed by a SME incorporating the classical input/output signals. Extension is provided where the qubit is replaced by any qudit dispersively coupled to an arbitrary set of modes with collective input/output classical signals.

7.11 Quantum Zeno dragging with application to solving the k-SAT problem

Participants: Alain Sarlette, , Artem Mamichev.

We have initialized this line of work with the group of B.Whaley at Berkeley and obtained first results in [51]. Quantum Zeno dragging is an alternative to quantum adiabatic computing, where a solution to a combinatorial problem is progressively distilled among 2^n possibilities represented by qubits. The scheme works by initially representing 0 and 1 logical states by the same physical state vectors, and progressively separating those vectors until they become orthogonal and the result can be read out. The system is measured all along this process, ensuring that it remains on a solution state if we move the vectors slowly enough. In [51], we study this scheme under continuous weak measurement and show that the critical value is a spectral gap of a related Hamiltonian, drawing a clear link with (non-standard) adiabatic computing. We also report a preliminary attempt at optimal scheduling of the time-dependent vectors. Our longer-term goals are to improve this k-SAT study in two ways: (i) find highly informed schedules — possibly qubit-dependent, constraint-dependent,... , taking all insights on the k-SAT problem into account ; (ii) integrate feedback mechanisms, thanks to the weak measurement outputs, which would allow us to go beyond the performance of adiabatic computing.

7.12 Confinement to deterministic manifolds and low-dimensional solution formulas for continuously measured quantum systems

Participants: Alain Sarlette, , Pierre Rouchon.

Several years ago, we had observed that the state of a qubit, conditioned on weak continuous measurement results, appears to jump randomly not inside the Bloch sphere but rather inside a time-dependent ellipsoid surface. Over the years, we have accumulated knowledge about other types of systems that appear in typical quantum systems and behave in this way. This includes infinite-dimensional systems (q.harmonic oscillators) and bi-partite quantum systems where only one subsystem is observed. We summarize all these findings in the paper [25] published in Phys.Rev.A. The first main point is an algebraic criterion, translated from nonlinear control theory, allowing to quickly check if a continuously monitored quantum system is confined to a low-dimensional, measurement outcome-independent manifold. As a second contribution, for a set of cases where such confinement does hold true, we take advantage of the low dimension in order to provide explicit and exact formulas for the state at time t as a function of the measurement outcomes.

7.13 Time-averaged continuous quantum measurement

Participants: Pierre Guilmin, , Pierre Rouchon,, Antoine Tilloy.

The theory of continuous quantum measurement allows to reconstruct the stateof a system from a continuous stochastic measurement record. However, this truly continuous-time signal is never available in practice. In experiments, one generally has access to its digitization, i.e., to a series of time averages over finite intervals of duration Δt. This contribution takes this digitization seriously and defines the best Bayesian estimate of the quantum state given (only) a digitized record. This allows reconstructing quantum trajectories in regimes of coarse Δt where existing methods fail, estimating parameters at fixed Δt without bias, and directly sampling digitized quantum trajectories with schemes of arbitrarily high order [38].

7.14 A relativistic continuous matrix product state study of field theories with defects

Participants: Karanbir Tiwana, , Edoardo Lauria,, Antoine Tilloy.

In this work [28], we present a method to compute expectation values in $1 + 1$-dimensional massive Quantum Field Theories (QFTs) with line defects using Relativistic Continuous Matrix Product State (RCMPS). Exploiting Euclidean invariance, we use a quantization scheme where (imaginary) time runs perpendicularly to the defect. With this choice, correlation functions of local operators in the presence of the defect can be computed as expectation values of extended operators in the no-defect vacuum, which can be approximated by a homogeneous RCMPS. We demonstrate the effectiveness of this machinery by computing correlation functions of local bulk and defect operators in the self interacting scalar theory with a magnetic line defect, in perturbative, strong coupling, critical, and symmetry-broken regimes.

7.15 Multi-Field Relativistic Continuous Matrix Product States

Participants: Karanbir Tiwana, , Antoine Tilloy.

Relativistic continuous matrix product states (RCMPS) are a powerful variational ansatz for quantum field theories of a single field. However, they inherit a property of their non-relativistic counterpart that makes them divergent for models with multiple fields, unless a regularity condition is satisfied. This has so far restricted the use of RCMPS to toy models with a single self-interacting field. We address this long standing problem by introducing a Riemannian optimization framework, that allows to minimize the energy density over the regular submanifold of multi-field RCMPS, and thus to retain purely variational results. We demonstrate its power on a model of two interacting scalar fields in dimensions [49]. The method captures distinct symmetry-breaking phases, and the signature of a Berezinskii-Kosterlitz-Thouless (BKT) transition along an -symmetric parameter line. This makes RCMPS usable for a far larger class of problems than before.

7.16 Extracting quantum field theory dynamics from an approximate ground state

Participants: Sophie Mutzel, , Antoine Tilloy.

This contribution [41] puts forward a linear-programming method to extract dynamical information from static ground-state correlators in quantum field theory. We recast the Källén-Lehmann inversion as a convex optimization problem, in a spirit similar to the recent approach of Lawrence [arXiv:2408.11766]. This produces robust estimates of the smeared spectral density, the real-time propagator, and the mass gap directly from an approximate equal-time two-point function, and simultaneously yields an a posteriori lower bound on the correlation-function error. We test the method on the -dimensional model, using a variational approximation to the vacuum – relativistic continuous matrix product states – that provides accurate correlators in the continuum and thermodynamic limits. The resulting mass gaps agree with renormalized Hamiltonian truncation and Borel-resummed perturbation theory across a wide range of couplings, demonstrating that accurate dynamical data can be recovered from a single equal-time slice.

7.17 High-performance local decoders for defect matching in 1D

Participants: Louis Paletta, , Mazyar Mirrahimi.

Local decoders, also known as cellular-automaton decoders, offer a promising path toward real-time quantum error correction by replacing centralized classical decoding, with inherent hardware constraints, by a natively parallel and streamlined architecture from a simple local transition rule. In a collaboration with Anthony Leverrier from Inria Cosmiq team and Christophe Vuillot from Inria Mocqua team, we propose two new types of local decoders for the quantum repetition code in one dimension [42]. The signal-rule decoders interpret odd parities between neighboring qubits as defects, attracted to each other via the exchange of classical point-like excitations, represented by a few bits of local memory. We prove the existence of a threshold in the code-capacity model and present numerical evidence of exponential logical error suppression under a phenomenological noise model, with data and measurement errors at each error correction cycle. Compared to previously known local decoders that suffer from sub-optimal threshold and scaling, our construction significantly narrows the gap with global decoders for practical system sizes and error rates. Implementation requirements can be further reduced by eliminating the need for local classical memories, with a new rule defined on two rows of qubits. This shearing-rule works well at relevant system sizes making it an appealing short-term solution. When combined with biased-noise qubits, such as cat qubits, these decoders enable a fully local quantum memory in one dimension.

7.18 Unfolded distillation: very low-cost magic state preparation for biased-noise qubits

Participants: Diego Ruiz, , Jeremie Guillaud, , Mazyar Mirrahimi.

Magic state distillation enables universal fault-tolerant quantum computation by implementing non-Clifford gates via the preparation of high-fidelity magic states. However, it comes at the cost of substantial logical-level overhead in both space and time. In this work [48], in collaboration with Christophe Vuillot from Alice&Bob, we propose a very low-cost magic state distillation scheme for biased-noise qubits. By leveraging the noise bias, our scheme enables the preparation of a magic state with a logical error rate of 3×10^{-7}, using only 53 qubits and 5.5 error correction rounds, under a noise bias of $\eta \gtrsim 5 \times 10^{6}$ and a phase-flip noise rate of 0.1%. This reduces the circuit volume by more than one order of magnitude relative to magic state cultivation for unbiased-noise qubits and by more than two orders of magnitude relative to standard magic state distillation. Moreover, our scheme provides three key advantages over previous proposals for biased-noise qubits. First, it only requires nearest-neighbor two-qubit gates on a 2D lattice. Second, the logical fidelity remains nearly identical even at a more modest noise bias of $\eta \gtrsim 80$, at the cost of a slightly increased circuit volume. Third, the scheme remains effective even at high physical phase-flip rates, in contrast to previously proposed approaches whose circuit volume grows exponentially with the error rate. Our construction is based on unfolding the X stabilizer group of the Hadamard 3D quantum Reed-Muller code in 2D, enabling distillation at the physical level rather than the logical level, and is therefore referred to as unfolded distillation.

7.19 LDPC-cat codes for low-overhead quantum computing in 2D

Participants: Diego Ruiz, , Jeremie Guillaud, , Mazyar Mirrahimi.

The main obstacle to large scale quantum computing are the errors present in every physical qubit realization. Correcting these errors requires a large number of additional qubits. Two main avenues to reduce this overhead are (i) low-density parity check (LDPC) codes requiring very few additional qubits to correct errors (ii) cat qubits where bit-flip errors are exponentially suppressed by design. In this work [24] published in Nature Communications, and in collaboration with Anthony Leverrier (Inria Cosmiq team) and Christophe Vuillot (Inria Mocqua team), we combine both approaches to obtain an extremely low overhead architecture. Assuming a physical phase-flip error probability $\epsilon \approx 0.1\%$ per qubit and operation, one hundred logical qubits can be implemented on a 758 cat qubit chip, with a total logical error probability per cycle and per logical qubit $\epsilon_L \leq 10^{-8}$. Our architecture also features two major advantages. First, the hardware implementation of the code can be realised with short-range qubit interactions in 2D and low-weight stabilizers, under constraints similar to those of the popular surface code architecture. Second, we demonstrate how to implement a fault-tolerant universal set of logical gates with an additional layer of routing cat qubits stacked on top of the LDPC layer, while maintaining the local connectivity. Furthermore, our architecture benefits from a high capacity of parallelization for these logical gates.

8 Bilateral contracts and grants with industry

8.1 Bilateral contracts with industry

- Four new PhD contracts with Alice&Bob: Armelle Celarier, Louis Lattier, Theo Malas Danze, Roberto Negrin.
- One new PhD contract with C12: Gregoire Charleux.

8.2 Grants with industry

BPIFrance i-Démo This project is of 22 million EUR is a partnership between Alice&Bob (20 MEUR), ENS Lyon (1.1 MEUR) and Quantic (1.1 MEUR). Zaki Leghtas is leading the effort of Quantic. The project accelerates the development of a cat-qubit quantum computer by setting technological targets that enable the emergence of an industrializable system and by reducing system costs by a factor of ten. The project's key work packages include nanofabrication, chip design, simulation tools, and control electronics.

9 Partnerships and cooperations

9.1 European initiatives

9.1.1 Horizon Europe

DANCINGFOOL

Participants: Philippe Campagne Ibarcq.

Dancingfool project on cordis.europa.eu

Title: High-impedance Superconducting Circuits Enabling Fault-tolerant Quantum Computing by Wideband Microwave Control

Duration: From December 1, 2022 to November 30, 2027

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- ECOLE NORMALE SUPERIEURE (ENS), France

Inria contact: Philippe Campagne-Ibarcq

Coordinator:

Summary: A physical system implementing a quantum bit (qubit) is never perfectly isolated from an uncontrolled environment. The system dynamics is thus noisy, modifying randomly the qubit state. This phenomenon of decoherence is the main roadblock to build a stable quantum computing platform. In order to mitigate decoherence, quantum error correction employs only a few code states within a much larger informational space, so that noise-induced dynamics can be detected and corrected before the encoded information gets corrupted. Unfortunately, most known protocols require to control dauntingly complex systems, with a degree of coherence currently out of reach. Our project is to build autonomously error-corrected qubits encoded in high-impedance superconducting circuits. In our protocol, a qubit is encoded in the vast phase-space of the quantum oscillator implemented by each circuit, in the form of Gottesman-Kitaev-Preskill (GKP) states. The novelty is that the GKP states are fully stabilized by a modular dissipation, induced by the coherent tunneling of charges through a stroboscopically biased Josephson junction. The coherence of the encoded qubit is expected to exceed that of existing superconducting qubits by orders of magnitude. Furthermore, we propose to perform protected logical gates between encoded qubits by varying adiabatically the parameters of the modular dissipation, paving the way toward fault-tolerant quantum computing. The major experimental challenge of our protocol resides in the exquisite level of control needed over a wide band in the microwave range. We propose to address this challenge by developing novel on-chip filters, tunable couplers and isolators based on periodically modulated, high-impedance, transmission lines. These on-chip components would find a wide range of applications in quantum technologies, and favor the advent of large-scale quantum computing platforms.

QFT.zip

Participants: Antoine Tilloy.

QFT.zip project on cordis.europa.eu

Title: Compressing many-body quantum states in continuous space-time with tensor networks

Duration: From January 1, 2023 to December 31, 2027

Partners:

- ARMINES, France
- INRIA, France

Coordinator: Antoine Tilloy

Summary: Many-body quantum systems with strong correlations are particularly difficult to understand in the continuum, where non-perturbative techniques are in scarce supply. Direct diagonalization methods are not available, since the Hilbert space is simply too large to be manageable. This inhibits progress in high energy physics, nuclear physics, and in the study of exotic topological phases of matter. On the lattice, tensor network states, a variational class of wavefunctions coming from quantum information theory, have allowed to compress exponentially large Hilbert spaces down to a smaller numerically manageable corner. This has allowed substantial theoretical and numerical advance on the many-body problem on the lattice. This project will develop continuous tensor network states, a new framework to extend the recent lattice progress to the continuum and quantum field theory (QFT). The originality of the approach is that it will not rely on any discretization of space-time. We will work directly in the continuum, without any cutoff. Low energy states of quantum field theories, which a priori live in a continuously infinite dimensional Hilbert space, will be compressed down to a finite and small number of parameters. This will then allow to solve numerically very generic (non-integrable) strongly coupled theories in a fully non-perturbative manner. Such a compression was long thought to be impossible, in particular in the relativistic case, but we overcame crucial theoretical hurdles in the past year, making the proposal particularly timely. We will construct this framework with 3 main applications in mind: i) non-relativistic problems in 2 space dimensions and more, including e.g. fractional quantum Hall states, ii) relativistic QFT, starting with 1+1 dimensional toy model and gradually increasing complexity to get closer to nonabelian gauge theories, iii) critical quantum systems (and classical statistical mechanics).

9.1.2 H2020 projects

ERC Advanced Grant Q-Feedback

- Program: H2020
- Type: ERC
- Project acronym: Q-Feedback
- Project title: Quantum feedback Engineering
- Duration: 2020-2026
- Coordinator: Pierre Rouchon, Mines Paristech
- Abstract : Quantum technologies, such as quantum computers and simulators, have the potential of revolutionizing our computational speed, communication security and measurement precision.The power of the quantum relies on two key but fragile resources: quantum coherence and entanglement. This promising field is facing a major open question: how to design machines which exploit quantum properties on a large scale, and efficiently protect them fromexternal perturbations (decoherence), which tend to suppress the quantum advantage?

  Making a system robust and stable to the influence of external perturbations is one of the core problems in control engineering. The goal of this project is to address the above question from the angle of control systems. The fundamental and scientific ambition is to elaborate theoretical control methods to analyse and design feedback schemes for protecting and stabilizing quantum information. Q-Feedback develops mathematical methods to harness the inherently stochastic aspects of quantum measurements. Relying on the development of original mathematical perturbation techniques specific to open quantum systems, Q-Feedback proposes a new hierarchical strategy for quantum feedback modeling, design and analysis.

The building block of a quantum machine is the quantum bit (qubit), a system which can adopt two quantum states. Despite major progress, qubits remain fragile and lose their quantum properties before a meaningful task can be accomplished. For this reason, a qubit must be both protected against external perturbations, and manipulated to perform a task. Today, no such qubit has been built. In collaboration with experimentalists, the practical ambition is to design, relying on the control tools developed here, qubits readily integrable in a quantum processing unit. The physical platform will be Josephson superconducting circuits. Q-Feedback is expected to demonstrate the crucial role of control engineering in emerging quantum technologies.

9.2 National initiatives

- **PEPR NISQ2LSQ**: Quantic is a PI and the coordinator of WP1 of this PEPR project which started in 2022. The goal is to accelerate French research on the topic of bosonic and LDPC codes for preparing the ground for hardware-efficient and fault-tolerant quantum computation.

- **PEPR RobustSuperQ**: Quantic is a PI and the coordinator of WP1 of this PEPR project which started in 2022. The goal is to accelerate French research on the topic of high quality, noise resilient, superconducting qubits.

- **Junior Research Leader chair, NISQ2LSQ**: In the framework of the PEPR NISQ2LSQ, Rémi Robin has obtained a Junior Research Leader chair consisting of 312k euros for 4 years starting in 2024.

- **ANR project Mecaflux**: Alain Sarlette is a PI of this ANR Grant that started in 2022 and runs for 4 years. This project aims to couple mechanical oscillators with superconducting circuits at the quantum level, using a new circuit architecture allowing near-resonant coupling. The project is coordinated by mechanical oscillators expert Samuel Deléglise (LKB, U.Sorbonne), other project PIs are Alain Sarlette and Zaki Leghtas (QUANTIC project-team), Emmanuel Flurin and Hélène LeSueur (CEA Saclay). Our new recruit Antoine Tilloy may join with quantum gravity expertise if the level of control attains the objective where those effects become significant. The PhD thesis of Angela Riva is funded on this ANR.

- **ANR project OCTAVES**: Mazyar Mirrahimi is a PI of this ANR Grant that started in 2022 and runs for 4 years. This project aims in studying the measurement problem in circuit QED (non QND effects in presence of probe drives) as well as limitations to the parametric driving for cat qubit stabilization. The project is coordinated by Olivier Buisson (Institut Néel, Grenoble) and other project PIs are Benjamin Huard (ENS Lyon), Mazyar Mirrahimi (Quantic project-team), and Dima Shepelyansky (LPT, Toulouse). The PhD thesis of Linda Greggio is funded on this ANR.

9.3 Regional initiatives

Alain Sarlette is amember of the steering committee of DIM Quantip.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

- Alain Sarlette has been the main coordinator of the International Conference on Quantum Computing, taking place at IHP, 12-16 May 2025.

- Alexandru Petrescu is one of the two organizers of the plenary meeting of the Groupement De Recherche (GDR) 2426 ‘Quantum Mesoscopic Physics’, Aussois, France, Dec 2025.

10.1.2 Journal

Member of the editorial boards

- Pierre Rouchon is a member of the editorial board of Annual Reviews in Control.

Reviewer - reviewing activities

- Philippe Campagne Ibarcq was a referee for Phys. Rev. X.
- Zaki Leghtas was a referee for "Comptes Rendus de l'Académie des Sciences".
- Alexandru Petrescu was a reviewer for Physical Review journals.

10.1.3 Invited talks

Philippe Compagne-Ibarcq APS March meeting , Anaheim, California, 2025.

Philippe Compagne-Ibarcq Microwave amplifiers in the quantum regime conference, Les Houches, 2025.

Philippe Compagne-Ibarcq Sherbrooke Canada, invited by Alexandre Blais.

Zaki Leghtas Walther Meissner Institute. Garching, Germany.

Mazyar Mirrahimi Physical Computation Workshop, Leuven, 2025.

Mazyar Mirrahimi CEMRACS summer school, Marseilles, 2025.

Mazyar Mirrahimi Ecole Polytechnique CMAP Colloquium.

Alexandru Petrescu FisMat 2025, Novel schemes for quantum superconducting hardware, July 2025

Alexandru Petrescu Many-body physics in superconducting devices (online MIT/Uni Mainz), January 2025

Pierre Rouchon IEEE International Conference on Quantum Control, Computing and Learning (Plenary, Hong Kong, 2025)

Pierre Rouchon 9th IFAC Symposium on System Structure and Control (Plenary, Gif-sur-Yvette, 2025)

Pierre Rouchon Workshop *Criticality and Continuous Measurements in Quantum Sensing: From Theory to Experiments* (Pisa, 2025).

Alain Sarlette Invited lecture at Quantum Winter School (Physics and Mathematics of Quantum Control), Dijon

Alain Sarlette Tutorial on Quantum Computing basics at QUEST conference, EDF Paris-Saclay

Antoine Tilloy Foundations 2025 conference; Gdansk

Antoine Tilloy Bridge QC first annual conference, Paris

Antoine Tilloy Workshop, San Vito Di Cadore, Italy

Antoine Tilloy Seminar at SPEC, Saclay, invited by Daniel Estève

Antoine Tilloy conference at Bangalore, India

Antoine Tilloy seminar at the philosophy of science workgroup, academy of sciences

10.1.4 Leadership within the scientific community

- Alain Sarlette is a board member of the DIM "QUANTIP" (Quantum Technologies in Paris Region), which has been launched in 2022.
- Mazyar Mirrahimi is leader for WP1 of the PEPR NISQ2LSQ.
- Zaki Leghtas is co-leader for WP1 of the PEPR RobustSuperQ.

10.1.5 Scientific expertise

- Philippe Campagne-Ibarcq was a reviewer for the European Research Council and the Swiss National Science fondation.
- Antoine Tilloy is a member of the HCERES evaluation committee for the CEA LETI.
- Mazyar Mirrahimi is a member of the working group of Académie des Technologies whose goal is the preparaton and updating of a report on fault-tolerant quantum computation.
- Pierre Rouchon is in the scientifc board of " laboratoire QTech " at ONERA.
- Pierre Rouchon is member of "comité de pilotage" of Paris Centre for Quantum Technologies (PCQT).
- Alain Sarlette was a member of ANR Comité d'Evaluation Scientifique on Quantum Technologies (CS 47).
- Philippe Campagne-Ibarcq, Zaki Leghtas and Mazyar Mirrahimi are members of the scientific board of the Startup Alice and Bob.

10.1.6 Research administration

- Alain Sarlette has been international relations representative for inria Paris.

10.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

10.2.1 Teaching

- Pierre Rouchon is in charge of the "Mathematics and Automatics" specialty within the ISMME-621 doctoral school.
- Pierre Rouchon is a member of the steering commitee of PSL master of Quantum Engineering with ENS-Paris.
- Philippe Campagne Ibarcq gave a short course (case study, 3h) on quantum error-correction with GKP qubits at the PSLMaster on Quantum Engineering.
- Zaki Leghtas: Circuit QED, M2 ICFP (18h).
- Zaki Leghtas: Quantum Information. EMINES, UM6P Benguerir Morocco (30h).
- Mazyar Mirrahimi: “Mathematical modelling of quantum computers”, Ecole Polytechnique (57 hours).
- Alexandru Petrescu and Pierre Rouchon give the M1 course (Mathematical method for quantum engineering) of the new PSL Master Quantum Engineering.
- Alexandru Petrescu and Pierre Rouchon give the M2 course (dynamics and control of open quantum systems) of the PSL Master Quantum Engineering.
- Alexandru Petrescu: PSL Week course on Quantum Computing: 5-day intensive course (6h/day) togshared with PhD student Emilio Rui.
- Rémi Robin: Mines Paris, TDs of Optimisation, TDs of Mathematics, and Automatics.

- Antoine Tilloy: Mines Paris, TDs of Optimisation, TDs of Introduction to quantum mechanics.
- Alain Sarlette and Antoine Tilly: M1 Course (Introduction to quantum computing) of the new PSL Master Quantum Engineering, 20 hours.
- Alain Sarlette: Robotics at Ghent university (24 hours).
- Alain Sarlette : M2 Course (Quantum Information Theory) of the new PSL Master Quantum Engineering, 10 hours.

10.2.2 Supervision

PhD defended in 2025 Thiziri Aissaoui. On-chip biasing of superconducting circuits. Supervision of Alain Sarlette and Anil Murani.

PhD defended in 2025 Adrien Bocquet. Cat-qubit: quantum coherence and macroscopic bit-flip times. Supervision of Zaki Leghtas and Raphaël Lescanne.

PhD defended in 2025 Linda Greggio. Strong drive effects in quantum superconducting circuits. Supervision of Alexandru Petrescu and Mazyar Mirrahimi.

PhD defended in 2025 Louis Paletta. Autonomous quantum error correction with cat qubits. Supervision of Mazyar Mirrahimi, Anthony Leverrier, Christophe Vuillot and Alain Sarlette.

PhD defended in 2025 Pierre Guilmin. Quantum estimation and control of cat-qubit. Supervision of Pierre Rouchon and Antoine Tilloy.

PhD defended in 2025 Leon Carde. Control and fast preparation of cat qubits, supervision of Joachim Cohen, Alexandru Petrescu, Pierre Rouchon.

PhD defended in 2025 Karanbir Singh Tiwana. Tensor networks for quantum field theory. Supervision of Antoine Tilloy.

PhD in progress Erwan Roverch'. Protected qubits. Supervision of Zaki Leghtas.

PhD in progress Angela Riva. Dynamics and control of a mechanical quantum oscillator quasi-resonantly coupled to a Heavy Fluxonium qubit. Supervision of Alain Sarlette.

PhD in progress Diego Ruiz. Scaling up a bosonic quantum processor. Supervision of Mazyar Mirrahimi and Jérémie Guillaud.

PhD in progress Emilio Rui. Cifre with Alice and Bob, Tensor network simulations for superconducting quantum circuit design. Supervision of Alexandru Petrescu and Pierre Rouchon.

PhD in progress Brieuc Beauseigneur. Supported by ERC Q-Feedback, Design and characterization of high-impedance superconducting circuits for autonomous error-correction. Supervision of Philippe Campagne-Ibarcq and Pierre Rouchon.

PhD in progress Anissa Jacob. Parametric pumping of Josephson circuits for quantum error-correction. Supervision of Philippe Campagne-Ibarcq and Anil Murani (Alice and Bob).

PhD in progress Florent Goulette. Quantum nonlinear optics with a Josephson metamaterial. Supervision of Mazyar Mirrahimi and Antoine Tilloy.

PhD in progress Thomas Decultot.Blocking error propagation in bosonic processors. Supervision of Ronan Gautier and Mazyar Mirrahimi.

PhD in progress Gustave Robichon. Solving many body open quantum systems with semi-definite relaxations. Supervision of Pierre Rouchon and Antoine Tilloy.

PhD in progress Armelle Célarier. Implementing bias-preserving gates on cat-qubits. Supervision of Zaki Leghtas.

PhD in progress Anthony Giraudo. Non-reciprocal superconducting circuits for the protection of quantum information. supervision Philippe Campagne-Ibarcq.

PhD started in 2025 Théo Malas-Danzé. CIFRE with Alice&Bob, co-supervision of Alexandru Petrescu, Joachim Cohen and Pierre Rouchon.

PhD started in 2025 Grégoire Charleux. CIFRE with C12, co-supervision of Rémi Robin et Pierre Rouchon.

PhD started in 2025 Roberto Negrin. New estimation techniques based on digitized continuous measurement, supervision by Antoine Tilloy (Cifre with Alice & Bob).

PhD started in 2025 Taha Bouwakd. Design of on-chip non-reciprocal elements for quantum information processing. Supervision Philippe Campagne-Ibarcq

PhD started in 2025 Louis Lattier, Fault-tolerant stabilization of GKP qubits in superconducting circuits, Supervision Philippe Campagne-Ibarcq and Arjan Van Loo (Cifre with Alice & Bob).

10.2.3 Juries

- Philippe Campagne-Ibarcq was a jury member for the PhD defense of Kyrylo Gerashchenko, LKB Jussieu.
- Philippe Campagne-Ibarcq was a referee for the PhD defense of Matteo Boselli, ENS Lyon.
- Philippe Campagne-Ibarcq was a referee for the PhD defense of Giulio Cappelli (Institut Néel).
- Philippe Campagne-Ibarcq was a referee for the PhD defense of Lautaro Labarca (université de Sherbrooke).
- Philippe Campagne-Ibarcq was a referee for the HDR defense of Emmanuel Flurin (CEA Saclay).
- Zaki Leghtas was a jury member of the PhD defense of Alexander Wagner, CEA Saclay.
- Zaki Leghtas was a jury member of the PhD defense of Jacob Koenig, TU Delft.
- Mazyar Mirrahimi was a jury member for the PhD defense of Hector Hutin, ENS Lyon.
- Mazyar Mirrahimi was a jury member for the PhD defense of Pierre Cussenot, CEA Saclay.
- Mazyar Mirrahimi was a referee for the PhD defense of Ruikiang Liang, Sorbonne Université.
- Mazyar Mirrahimi was a referee for the PhD defense of Kirill Dubovitskii, Grenoble.
- Alexandru Petrescu was a jury member for the PhD defense of Alessandro Chessari, CEA Saclay.

10.2.4 Educational and pedagogical outreach

- Mazyar Mirrahimi: Quantique et Business, anticiper les disruptions de demains (BPI, 2025)
- Pierre Rouchon: Quantum computing and feedback at ANDSI (April 2025, Paris)
- Pierre Rouchon: Quantum systems and control at Mines Paris – PSL, workshop L'épopé du Cosmos: hommes et machines (November 2025)
- Pierre Rouchon: keynote speaker at QUEST-IS 2025 (December 2025).
- High School presentations: Alain Sarlette under the ”Anneée quantique 2025” conference series organized by CNRS, Roubaix (09/2025) and Chevilly Larue (12/2025)
- Alain Sarlette: Tutorial on Quantum Computing basics at QUEST conference, EDF Paris-Saclay.
- Antoine Tilloy : Popular lecture at Amicale du Corps des Mines (on quantum computing)

10.3 Popularization

10.3.1 Participation in Live events

- Round table with Mazyar Mirrahimi: Calcul quantique (Vivatech, 2025)
- General Public event for ICoQC (12-16 May 2025): live and online lab visit at ENS Paris, hosted by Adrien Bocquet, Diego Ruiz, and Alain Sarlette.

10.3.2 Others science outreach relevant activities

- Interviews: Antoine Tilloy by le Monde and le Figaro on quantum computing, Zaki Leghtas on Michel Devoret's nobel prize by le Monde et le Figaro.

11 Scientific production

11.1 Major publications

[1] S. Apers and A. Sarlette. 'Quantum Fast-Forwarding: Markov chains and graph property testing'. In: *Quantum Information & Computation* (Apr. 2019). URL: `https://hal.inria.fr/hal-02394399`.

[2] P. Campagne-Ibarcq, A. Eickbusch, S. Touzard, E. Zalys-Geller, N. E. Frattini, V. V. Sivak, P. Reinhold, S. Puri, S. Shankar, R. J. Schoelkopf, L. Frunzio, M. Mirrahimi and M. H. Devoret. 'Quantum error correction of a qubit encoded in grid states of an oscillator'. In: *Nature* 584 (Aug. 2020). Text and figures edited for clarity. The claims of the paper remain the same. Author list fixed. URL: `https://hal.inria.fr/hal-03084673`.

[3] J. Guillaud and M. Mirrahimi. 'Repetition Cat Qubits for Fault-Tolerant Quantum Computation'. In: *Physical Review X* (Dec. 2019). `https://arxiv.org/abs/1904.09474` - 22 pages, 11 figures. DOI: `10.1103/PhysRevX.9.041053`. URL: `https://hal.inria.fr/hal-02413978`.

[4] Z. Leghtas, S. Touzard, I. M. Pop, A. Kou, B. Vlastakis, A. Petrenko, K. M. Sliwa, A. Narla, S. Shankar, M. J. Hatridge, M. Reagor, L. Frunzio, R. J. Schoelkopf, M. Mirrahimi and M. H. Devoret. 'Confining the state of light to a quantum manifold by engineered two-photon loss'. In: *Science* 347.6224 (Feb. 2015), pp. 853–857. DOI: `10.1126/science.aaa2085`. URL: `https://hal.inria.fr/hal-01240210` (cit. on p. 10).

[5] R. Lescanne, M. Villiers, T. Peronnin, A. Sarlette, M. Delbecq, B. Huard, T. Kontos, M. Mirrahimi and Z. Leghtas. 'Exponential suppression of bit-flips in a qubit encoded in an oscillator'. In: *Nature Physics* (Mar. 2020). DOI: `10.1038/s41567-020-0824-x`. URL: `https://hal.archives-ouvertes.fr/hal-02526631`.

[6] M. Mirrahimi, Z. Leghtas, V. V. Albert, S. Touzard, R. J. Schoelkopf, L. Jiang and M. H. Devoret. 'Dynamically protected cat-qubits: a new paradigm for universal quantum computation'. In: *New Journal of Physics* 16.4 (Apr. 2014), p. 045014 (cit. on pp. 10, 11).

[7] N. Ofek, A. Petrenko, R. Heeres, P. Reinhold, Z. Leghtas, B. Vlastakis, Y. Liu, L. Frunzio, S. Girvin, L. Jiang, M. Mirrahimi, M. H. Devoret and R. J. Schoelkopf. 'Extending the lifetime of a quantum bit with error correction in superconducting circuits'. In: *Nature* 536 (2016), p. 5 (cit. on p. 8).

[8] U. Reglade, A. Bocquet, R. Gautier, J. Cohen, A. Marquet, E. Albertinale, N. Pankratova, M. Hallén, F. Rautschke, L.-A. Sellem, P. Rouchon, A. Sarlette, M. Mirrahimi, P. Campagne-Ibarcq, R. Lescanne, S. Jézouin and Z. Leghtas. 'Quantum control of a cat qubit with bit-flip times exceeding ten seconds'. In: *Nature* 629.8013 (2024), pp. 778–783. DOI: `10.1038/s41586-024-07294-3`. URL: `https://hal.science/hal-04590249`.

[9] D. Ruiz, J. Guillaud, A. Leverrier, M. Mirrahimi and C. Vuillot. 'LDPC-cat codes for low-overhead quantum computing in 2D'. In: *Nature Communications* 16.1 (26th Jan. 2025), p. 1040. DOI: `10.1038/s41467-025-56298-8`. URL: `https://inria.hal.science/hal-04887011`.

[10] A. Sarlette, J.-M. Raimond, M. Brune and P. Rouchon. 'Stabilization of nonclassical states of the radiation field in a cavity by reservoir engineering'. In: *Phys. Rev. Lett.* 107 (2011). 010402 (cit. on pp. 10, 11).

[11] C. Sayrin, I. Dotsenko, X. Zhou, B. Peaudecerf, T. Rybarczyk, S. Gleyzes, P. Rouchon, M. Mirrahimi, H. Amini, M. Brune, J.-M. Raimond and S. Haroche. 'Real-time quantum feedback prepares and stabilizes photon number states'. In: *Nature* 477 (2011), pp. 73–77 (cit. on p. 9).

[12] L.-A. Sellem, A. Sarlette, Z. Leghtas, M. Mirrahimi, P. Rouchon and P. Campagne-Ibarcq. 'Dissipative Protection of a GKP Qubit in a High-Impedance Superconducting Circuit Driven by a Microwave Frequency Comb'. In: *Physical Review X* 15.1 (2025), p. 011011. DOI: `10.1103/PhysRevX.15.011011`. URL: `https://hal.science/hal-04988382`.

[13] W. C. Smith, A. Borgognoni, M. Villiers, E. Roverc'h, J. Palomo, M. Delbecq, T. Kontos, P. Campagne-Ibarcq, B. Douçot and Z. Leghtas. 'Spectral signature of high-order photon processes mediated by Cooper-pair pairing'. In: *Nature Communications* 16.1 (24th Sept. 2025), p. 8359. DOI: `10.1038/s41467-025-62047-8`. URL: `https://hal.science/hal-04387016`.

[14] W. C. Smith, M. Villiers, A. Marquet, J. Palomo, M. Delbecq, T. Kontos, P. Campagne-Ibarcq, B. Douçot and Z. Leghtas. 'Magnifying quantum phase fluctuations with Cooper-pair pairing'. In: *Physical Review X* 12.2 (Apr. 2022), p. 021002. DOI: `10.1103/PhysRevX.12.021002`. URL: `https://hal.inria.fr/hal-03084684`.

11.2 Publications of the year

International journals

[15] C. Behan, D. Benedetti, F. Eustachon and E. Lauria. 'Long-range minimal models'. In: *Journal of High Energy Physics* 02 (2026), p. 001. DOI: `10.1007/JHEP02(2026)001`. URL: `https://hal.science/hal-05313663`.

[16] D. Benedetti, E. Lauria, D. Mazac and P. van Vliet. 'A strong-weak duality for the 1d long-range Ising model'. In: *SciPost Physics* 20.2 (2026), p. 029. DOI: `10.21468/SciPostPhys.20.2.029`. URL: `https://hal.science/hal-05265525`.

[17] D. Benedetti, E. Lauria, D. Mazáč and P. van Vliet. 'One-dimensional Ising model with $1/r^{1.99}$ interaction'. In: *Physical Review Letters* 134.20 (2025), p. 201602. DOI: `10.1103/PhysRevLett.134.201602`. URL: `https://hal.science/hal-04874093`.

[18] T. Benoist, L. Greggio and C. Pellegrini. 'Exponentially fast selection of sectors for quantum trajectories beyond non demolition measurements'. In: *Annales Henri Poincaré* (23rd Nov. 2025). DOI: `10.1007/s00023-025-01641-4`. URL: `https://hal.science/hal-04664314`.

[19] L. Carde, R. Gautier, N. Didier, A. Petrescu, J. Cohen and A. Mcdonald. 'Non-perturbative switching rates in bistable open quantum systems: from driven Kerr oscillators to dissipative cat qubits'. In: *Physical Review Letters* 136.10 (24th July 2025), p. 100402. DOI: `10.1103/q981-pd5j`. URL: `https://inria.hal.science/hal-05364670` (cit. on p. 17).

[20] L. Carde, P. Rouchon, J. Cohen and A. Petrescu. 'Flux-pump induced degradation of T_1 for dissipative cat qubits'. In: *Physical Review Applied* 23.2 (28th Feb. 2025), p. 024073. DOI: `10.1103/PhysRevApplied.23.024073`. URL: `https://inria.hal.science/hal-04887052`.

[21] M. Praquin, A. Giraudo, V. Lienhard, T. Bouwakdh, A. Vanselow, Z. Leghtas and P. Campagne-Ibarcq. 'Mixing of counterpropagating signals in a traveling-wave Josephson device'. In: *Nature Communications* 16.1 (2025), p. 11390. DOI: `10.1038/s41467-025-66190-0`. URL: `https://inria.hal.science/hal-04887032` (cit. on p. 15).

[22] Y. Privat, R. Robin and M. Sigalotti. 'Existence of surfaces optimizing geometric and PDE shape functionals under reach constraint'. In: *Interfaces and Free Boundaries : Mathematical Analysis, Computation and Applications* 27.1 (2025), pp. 65–90. DOI: `10.4171/IFB/523`. URL: `https://inria.hal.science/hal-03690069`.

[23] R. Robin, P. Rouchon and L.-A. Sellem. 'Convergence of bipartite open quantum systems stabilized by reservoir engineering'. In: *Annales Henri Poincaré* 26 (May 2025), pp. 1769–1819. DOI: `10.1007/s00023-024-01481-8`. URL: `https://inria.hal.science/hal-04379101`.

[24] D. Ruiz, J. Guillaud, A. Leverrier, M. Mirrahimi and C. Vuillot. ‘LDPC-cat codes for low-overhead quantum computing in 2D’. In: *Nature Communications* 16.1 (26th Jan. 2025), p. 1040. DOI: `10.1038/s41467-025-56298-8`. URL: `https://inria.hal.science/hal-04887011` (cit. on pp. 15, 22).

[25] A. Sarlette, C. Elourard and P. Rouchon. ‘Confinement to deterministic manifolds and low-dimensional solution formulas for continuously measured quantum systems’. In: *Physical Review A* 112.4 (11th Mar. 2025), p. 042221. DOI: `10.1103/gdt7-2md2`. URL: `https://hal.science/hal-04994024` (cit. on p. 20).

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[27] W. C. Smith, A. Borgognoni, M. Villiers, E. Roverc’h, J. Palomo, M. Delbecq, T. Kontos, P. Campagne-Ibarcq, B. Douçot and Z. Leghtas. ‘Spectral signature of high-order photon processes mediated by Cooper-pair pairing’. In: *Nature Communications* 16.1 (24th Sept. 2025), p. 8359. DOI: `10.1038/s41467-025-62047-8`. URL: `https://hal.science/hal-04387016` (cit. on pp. 13, 15).

[28] K. Tiwana, E. Lauria and A. Tilloy. ‘A relativistic continuous matrix product state study of field theories with defects’. In: *Journal of High Energy Physics* 2025.05 (2025), p. 097. DOI: `10.1007/JHEP05(2025)097`. URL: `https://hal.science/hal-04919697` (cit. on p. 20).

Doctoral dissertations and habilitation theses

[29] T. Aissaoui. ‘Cat Qubit Stabilization with dc-biased Josephson Junctions’. Sorbonne Université, 4th June 2025. URL: `https://theses.hal.science/tel-05238591`.

[30] L. Greggio. ‘Strongly driven quantum superconducting circuits and state transfer to spin-based memories’. Université Paris sciences et lettres, 13th Oct. 2025. URL: `https://theses.hal.science/tel-05345081`.

[31] L. Paletta. ‘Local quantum memories and early fault-tolerant algorithms’. PSL University, 17th Oct. 2025. URL: `https://hal.science/tel-05488008`.

[32] A. Riva. ‘Efficient models for bipartite open quantum systems’. Sorbonne Université (Paris), 2nd Feb. 2026. URL: `https://hal.science/tel-05494955`.

Reports & preprints

[33] G. Bélanger, A. Bharucha, S. Chakraborti, R. Islam and S. Mutzel. *Probing the Phenomenology of Dark Matter from Decoupled Freeze-Out*. 3rd Dec. 2025. URL: `https://hal.science/hal-05396412`.

[34] P.-L. Etienney, R. Robin and P. Rouchon. *A posteriori error estimates for the Lindblad master equation*. 13th Mar. 2025. URL: `https://hal.science/hal-04990411` (cit. on p. 19).

[35] K. Gerashchenko, R. Rousseau, L. Balembois, H. Patange, P. Manset, W. C. Smith, Z. Leghtas, E. Flurin, T. Jacqmin and S. Deléglise. *Probing the quantum motion of a macroscopic mechanical oscillator with a radio-frequency superconducting qubit*. 28th May 2025. DOI: `10.48550/arXiv.2505.21481`. URL: `https://hal.science/hal-05088558` (cit. on p. 14).

[36] L. Greggio, T. Lorriaux, A. Petrescu, M. Mirrahimi and A. Bienfait. *Optimal absorption and emission of itinerant fields into a spin ensemble memory*. 30th June 2025. URL: `https://hal.science/hal-05345345` (cit. on p. 17).

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