RESEARCH CENTRE

**Inria Paris Centre at Sorbonne University**

**IN PARTNERSHIP WITH:**

**CNRS, Ecole normale supérieure de Paris, Mines ParisTech, Sorbonne Université**

2024
ACTIVITY REPORT

# Project-Team
# QUANTIC

## QUANTum Information Circuits

**IN COLLABORATION WITH: Laboratoire de Physique de l'École Normale Supérieure**

**DOMAIN**

**Applied Mathematics, Computation and Simulation**

**THEME**

**Optimization and control of dynamic systems**

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# Project-Team QUANTIC

*Creation of the Project-Team: 2015 April 01*

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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 [133, 137]. 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 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 [105]. 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 [102, 95] 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 [104]. 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.

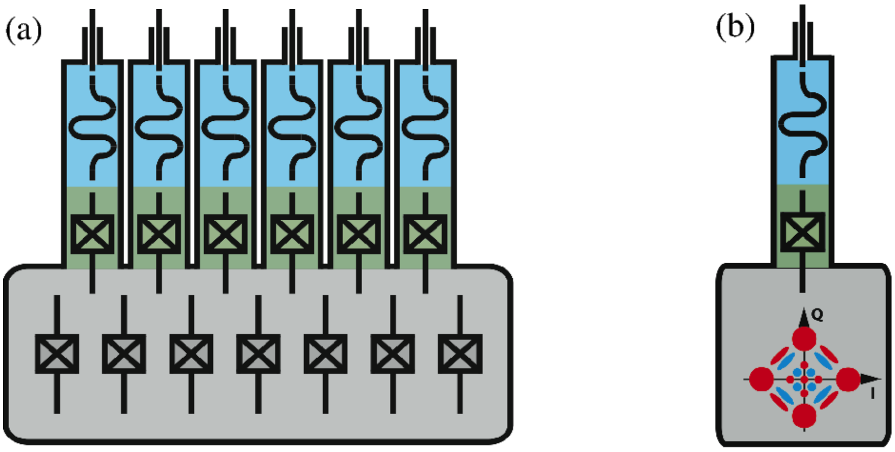

Figure 1: (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [137] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error 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.

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 [138] has recently led to a first experimental realization of a full quantum error correcting code improving the coherence time of quantum information [9]. 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 [75]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [98], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [96]. 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 [12] (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 [86, 65, 136, 66]. 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) [84], recent advances in quantum-limited amplifiers [126, 141] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [99]. 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 [141, 125, 77]. 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 [113].

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 [120] and the closely related coherent feedback [110] 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 [94], single-qubit state stabilization [114], and the creation [69] and stabilization [103, 109, 132] 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 [94, 107, 82, 85]. The experimental results based on these protocols have illustrated the efficiency of the approach [94, 132]. Through these experiments, we exploit the strong dispersive interaction [130] 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 [128, 100][8, 6].

## 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 [127, 65, 135, 129, 136, 66][11] 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 [66]: 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 [117]. 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 [99, 77].

### 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 [71] and is related to quantum trajectories [78, 83]. A modern and mathematical exposure of the diffusive models is given in [68]. In [97] 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 [127, 135]. This stability result is extended to a large class of continuous-time filters in [64]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [72]. Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [89, 115].

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 [76] that post-selection statistics and “past quantum” state analysis [90] 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 [120, 110]. 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 [11] [132, 94], 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 [119]). 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., [67][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 [11, 8] [132, 94] 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 [93, 92]. We will start with [131] and [123] where, based on a theorem due to Birkhoff [73], 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 [140] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [112].

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 [116], 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, 108] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [74], 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 [98, 91]. 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 [106].

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 [79] 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 [87] and invariant manifold techniques [80] 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 [101] 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 [94, 132, 107].

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" [124] consists in placing $\lambda/4$ stubs [121] 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 [122], and a recent implementation of a bandpass filter [88].

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 [134, 81, 63], or by electromechanical coupling to nanoresonators [70, 118]. 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 [63]. For completeness, we mention a recent implementation of a forward amplifier based on resistively shunted Josephson junctions [139] 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, 111].

In this project, we propose to develop novel on-chip filters and isolators based on 1D photonic crystals, which could reach unprecedented bandwidth, tunable range and on/off or forward/backward transmission ratios. The central idea is that a microwave transmission line with periodically modulated electrical properties behaves as a robust stopband filter, with attenuation scaling exponentially with the line length.

By fabricating lines whose properties are modulated by design, we plan to demonstrate the efficiency of this novel type of stopband filters. These lines will be fabricated in a high-kinetic inductance material (such as chains of Josephson junctions or granular aluminium), we will overcome the main weakness of this approach, which is the large on-chip footprint required when fabricating with conventional superconductors. Extending the numerical simulation methods developed in thsi work, we plan to design other types of filters (bandpass, highpass, lowpass) based on a similar technology.

We will then change perspective and modulate a line properties parametrically instead of by design to implement non-reciprocal elements. The idea is to design a line that possesses two traveling mode 1 and 2, with different propagation phase-velocity $v_1 \ll v_2$. If a low-frequency pump wave propagates on 1 modulates the electrical properties of the mode 2 thanks to shared non-linear inductance—for instance Josephson junction participating in both modes inductance—we obtain a situation in which mode 2 has spatially modulated electrical properties, with the phase of this modulation slowly evolving in time with at the pump period. A stopband appears in the transmission of a probe signal on mode 2, whose central frequency depends on whether the probe propagates in the same direction as the pump or not. It is then straightforward to turn this non-reciprocal filter into an isolator on circulator.

# 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.

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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.

Our quantum devices are aimed to protect and process quantum information through these integrated circuits.

# 5 Highlights of the year

- A new publication in Nature [28]: The QUANTIC team, in collaboration with start-up company Alice and Bob, have demonstrated quantum operations on a very stable qubit: its measured bit-flip time exceeds 10 seconds. A communication on this result can be read at `https://www.lpens.ens.psl.eu/quantum-control-of-a-cat-qubit-with-bit-flip-times-exceeding-ten-seconds/?lang=en`
- Quantic team has obtained a BPI idemo grant (1100 kEUR) as a part of a consortium with Alice and Bob and ENS Lyon.
- Mazyar Mirrahimi and Pierre Rouchon were co-organizers of a thematic semester at Institute for Mathematical and Statistical Innovation, University of Chicago, in fall 2024. The theme of the semester was "Statistical Methods and Mathematical Analysis for Quantum Information Science" and included 5 workshops and a long program.

## 5.1 Awards

- Pierre Rouchon was elected member of French Academy of Sciences.

# 6 New results

## 6.1 Explicit formulas for adiabatic elimination with fast unitary dynamics

**Participants:** Angela Riva, Alain Sarlette, Pierre Rouchon.

This contribution extends the range of results in our line of work about reducing the dimension of quantum models thanks to adiabatic elimination. The most usual reduction is to eliminate all fast, converging dynamics. Here, we allow fast unitary dynamics (non-converging), which typically appears in quantum systems before going to a rotating frame or when applying drives for operations. The corresponding degrees of freedom are kept, and the formulas for the reduced model must be modified. Our series expansion approach becomes nontrivial as the unitary dynamics adds mathematical couplings in the unknown operators. However, special properties in the typically encountered systems of quantum electrodynamics, composed of qubits and harmonic oscillators, allow us to develop explicit solutions. This work has been presented at IEEE CDC 2024 [39] (special session co-organized by A.Sarlette) ; its extended version is being prepared for journal submission.

## 6.2 A cat qubit stabilization scheme using a voltage biased Josephson junction

**Participants:** Thiziri Aissaoui, Alain Sarlette.

This work [46], in collaboration with Alice and Bob, proposes a new way to stabilize the "cat qubit" with reservoir engineering (see team description). The main idea is to replace an AC external signal by the use of the AC Josephson effect: when applying a DC bias on a Josephson Junction (JJ), it induces an oscillating current whose frequency is proportional to the voltage. The expected advantage of this scheme is that it generates a "cleaner" reaction of the JJ circuit, with less spurious frequencies and nonlinearities. Thanks to this fact, it should be possible to push the parameter regime to stronger values, resulting in stronger stabilization. Our analysis also comports two important side results. First, we add and analyze an 'injection locking' mechanism, to reject long-term drift by reservoir engineering too. This drift concerns the angle of the cat-frame and is particularly important here, because in absence of locking signal it is floating without reference. Second, for the first time to our knowledge, we perform detailed simulations without assuming the rotating wave approximation (RWA). This both confirms RWA-based design ideas, and uncovers some details which are important to minimize phase-flip errors, the unprotected part of cat qubits.

## 6.3 Spectral signature of high-order photon processes mediated by Cooper-pair pairing

**Participants:** Alvise Borgognoni, Erwan Roverc'h, Marius Villiers, Philippe Campagne-Ibarcq, Zaki Leghtas.

Inducing interactions between individual photons is essential for applications in photonic quantum information processing and fundamental research on many-body photon states. A field that is well suited to combine strong interactions and low losses is microwave quantum optics with superconducting circuits. Photons are typically stored in an LC circuit, and interactions appear when the circuit is shunted by a Josephson tunnel junction. Importantly, the zero-point fluctuations of the superconducting phase across the junction control the strength and order of the induced interactions. Superconducting circuits have almost exclusively operated in the regime where phase fluctuations are smaller than unity, and two-photon interactions, known as the Kerr effect, dominate. In this experiment, we shunt a high-impedance LC oscillator by a dipole that only allows pairs of Cooper pairs to tunnel. Phase fluctuations, which are effectively doubled by this pairing, reach the value of 3.4. In this regime of extreme fluctuations, we observe transition frequencies that shift non-monotonically as we climb the anharmonic ladder. From this spectroscopic measurement, we extract two-, three- and four-photon interaction energies of comparable amplitude, and all exceeding the photon loss rate. This work explores a new regime of high-order photon interactions in microwave quantum optics, with applications ranging from multi-photon quantum logic to the study of highly correlated microwave radiation.

## 6.4 Flux-pump induced degradation of T1 for dissipative cat qubits

**Participants:** Léon Carde, Pierre Rouchon, Alexandru Petrescu.

Dissipative stabilization of cat qubits autonomously corrects for bit flip errors by ensuring that reservoir-engineered two-photon losses dominate over other mechanisms inducing phase flip errors. To describe the latter, we derive an effective master equation for an asymmetrically threaded SQUID based superconducting circuit used to stabilize a dissipative cat qubit [48]. We analyze the dressing of relaxation processes under drives in time-dependent Schrieffer-Wolff perturbation theory for weakly anharmonic bosonic degrees of freedom, and in numerically exact Floquet theory. We find that spurious single-photon decay rates can increase under the action of the parametric pump that generates the required interactions for cat-qubit stabilization. Our analysis feeds into mitigation strategies that can inform current experiments, and the methods presented here can be extended to other circuit implementations.

## 6.5 General quantum-classical dynamics as measurement based feedback

**Participants:** Antoine Tilloy.

This work [34] derives the stochastic differential equations and partial differential equation of general hybrid quantum–classical dynamics from the theory of continuous measurement and general (non-Markovian) feedback. The advantage of this approach is an explicit parameterization, without additional positivity constraints. The construction also neatly separates the different effects: how the quantum influences the classical and how the classical influences the quantum. This modular presentation gives a better intuition of what to expect from hybrid dynamics, especially when used to construct possibly fundamental theories.

## 6.6 Bootstrapping the stationary state of bosonic open quantum systems

**Participants:** Gustave Robichon, Antoine Tilloy.

In this work [52], we propose a method to compute expectation values of observables in the stationary state of a (Markovian) bosonic open quantum system. Using a hierarchy of semi-definite relaxations, we obtain finer and finer upper and lower bounds to any expectation value of interest. The bounds are rigorous, robust to stationary state degeneracies, and numerically improve as the occupation number increases on the examples we considered. This makes it adapted to the simulation of stationary states of bosonic qubits and in particular dissipatively stabilized cat qubits.

## 6.7 Parameter estimation by fitting correlation functions of continuous quantum measurement

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

In this work [50], we propose a simple method to estimate the parameters of a continuously measured quantum system, by fitting correlation functions of the measured signal. We demonstrate the approach in simulation, both on toy examples and on a recent superconducting circuits experiment which proved particularly difficult to characterise using conventional methods. The idea is applicable to any system whose evolution is described by a jump or diffusive stochastic master equation. It allows the simultaneous estimation of many parameters, is practical for everyday use, is suitable for large Hilbert space dimensions, and takes into account experimental constraints such as detector imperfections and signal filtering and digitisation. Unlike existing methods, it also provides a direct way to understand how each parameter is estimated from the measured signal. This makes the approach interpretable, facilitates debugging, and enables validating the adequacy of a model with the observed data.

## 6.8 Mixing of counterpropagating signals in a traveling-wave Josephson device

**Participants:** Matthieu Praquin, Vincent Lienhard, Anthony Giraudo, Aron Vanselow, Zaki Leghtas, Philippe Campagne-Ibarcq.

In the work [51], we present a novel on-chip microwave isolator based on a 1-dimensional Josephson metamaterial. Unlike conventional isolators, our approach uses a low-phase-velocity pump wave to mediate asymmetric frequency conversion, enabling the input signal to attenuate while converting into an output wave traveling in the opposite direction. This method eliminates the need for strongly magnetic components, making it compatible with superconducting circuits and scalable quantum systems.

The device operates across a wide range (5.5–8.5 GHz) with over 15 dB isolation in a 100 MHz bandwidth, matching the best current on-chip isolators. It is also reconfigurable in situ, functioning alternately as an isolator or a reciprocal, tunable coupler, offering unique versatility. Design improvements and better fabrication could further enhance its performance. This work provides a practical and flexible approach for signal routing and noise isolation in superconducting circuits, with potential applications in microwave technologies and quantum computing architectures.

## 6.9 Gate generation for open quantum systems via a monotonic algorithm with time optimization

**Participants:** Pierre Rouchon.

We present a monotonic numerical algorithm including time optimization for generating quantum gates for open systems [33]. Such systems are assumed to be governed by Lindblad master equations for the density operators on a large Hilbert-space whereas the quantum gates are relative to a sub-space of small dimension. Starting from an initial seed of the control input, this algorithm consists in the repetition of the following two steps producing a new control input: (A) backwards integration of adjoint Lindblad-Master equations (in the Heisenberg-picture) from a set of final conditions encoding the quantum gate to generate; (B) forward integration of Lindblad-Master equations in closed-loop where a Lyapunov based control produced the new control input. The numerical stability is ensured by the stability of both the open-loop adjoint backward system and the forward closed-loop system. A clock-control input can be added to the usual control input. The obtained monotonic algorithm allows then to optimise not only the shape of the control imput, but also the gate time. Preliminary numerical implementations indicate that this algorithm is well suited for cat-qubit gates, where Hilbert-space dimensions (2 for the Z-gate and 4 for the CNOT-gate) are much smaller than the dimension of the physical Hilbert-space involving mainly Fock-states (typically 20 or larger for a single cat-qubit). This monotonic algorithm, based on Lyapunov control techniques, is shown to have a straightforward interpretation in terms of optimal control: its stationary conditions coincides with the first-order optimality conditions for a cost depending linearly on the final values of the quantum states.

## 6.10 Online Parameter Estimation for Continuously Monitored Quantum Systems

**Participants:** Pierre Rouchon.

In this work [17], we consider the problem of online (real-time, single-shot) estimation of static or slow-varying parameters along quantum trajectories in quantum dynamical systems. Based on the measurement signal of a continuously monitored quantum system, we propose a recursive algorithm for computing the maximum likelihood (ML) estimate of unknown parameters using an approach based on stochastic gradient ascent on the log-likelihood function. We formulate the algorithm in both discrete-time and continuous-time and illustrate the performance of the algorithm through simulations of a simple two-level system undergoing homodyne measurement from which we are able to track multiple parameters simultaneously.

## 6.11 Adiabatic elimination for composite open quantum systems: Reduced-model formulation and numerical simulations

**Participants:** Francois-Marie Le Régent, Pierre Rouchon.

A numerical method is proposed for simulation of composite open quantum systems [22]. It is based on Lindblad master equations and adiabatic elimination. Each subsystem is assumed to converge exponentially towards a stationary subspace, slightly impacted by some decoherence channels and weakly coupled to the other subsystems. This numerical method is based on a perturbation analysis with an asymptotic expansion. It exploits the formulation of the slow dynamics with reduced dimension. It relies on the invariant operators of the local and nominal dissipative dynamics attached to each subsystem. Second-order expansion can be computed only with local numerical calculations. It avoids computations on the tensor-product Hilbert space attached to the full system. This numerical method is particularly well suited for autonomous quantum error correction schemes. Simulations of such reduced models agree with complete full model simulations for typical gates acting on one and two cat-qubits (Z, ZZ and CNOT) when the mean photon number of each cat-qubit is less than 8. For larger mean photon numbers and gates with three cat-qubits (ZZZ and CCNOT), full model simulations are almost impossible whereas reduced model simulations remain accessible. In particular, they capture both the dominant phase-flip error-rate and the very small bit-flip error-rate with its exponential suppression versus the mean photon number.

### 6.12 Monitoring the energy of a cavity by observing the emission of a repeatedly excited qubit

**Participants:** Pierre Rouchon.

The number of excitations in a large quantum system (harmonic oscillator or qudit) can be measured in a quantum nondemolition manner using a dispersively coupled qubit. It typically requires a series of qubit pulses that encode various binary questions about the photon number. Recently, a method based on the fluorescence measurement of a qubit driven by a train of identical pulses was introduced to track the photon number in a cavity, hence simplifying its monitoring and raising interesting questions about the measurement backaction of this scheme. A first realization with superconducting circuits demonstrated how the average number of photons could be measured in this way. Here we present an experiment that reaches single-shot photocounting and number tracking owing to a cavity decay rate 4 orders of magnitude smaller than both the dispersive coupling rate and the qubit emission rate. An innovative notch filter and pogo-pin-based galvanic contact makes possible these seemingly incompatible features. The qubit dynamics under the pulse train is characterized. We observe quantum jumps by monitoring the photon number via the qubit fluorescence as photons leave the cavity one at a time. Additionally, we extract the measurement rate and induced dephasing rate and compare them to theoretical models. Our method could be applied to quantum error correction protocols on bosonic codes or qudits [19].

### 6.13 Convergence of Bipartite Open Quantum Systems Stabilized by Reservoir Engineering

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

In this work [29], we study a generic family of Lindblad master equations modeling bipartite open quantum systems, where one tries to stabilize a quantum system by carefully designing its interaction with another, dissipative, quantum system—a strategy known as quantum reservoir engineering. We provide sufficient conditions for convergence of the considered Lindblad equations; our setting accommodates the case where steady-states are not unique but rather supported on a given subspace of the underlying Hilbert space. We apply our result to a Lindblad master equation modeling engineered multi-photon emission and absorption processes, a setting that received considerable attention in recent years due to its potential applications for the stabilization of so-called cat qubits.

## 7 Bilateral contracts and grants with industry

### 7.1 Bilateral contracts with industry

- One new PhD contract with Alice&Bob: Thomas Decultot.

## 7.2 Grants with industry

Quantic team has obtained a BPI idemo grant (1100 kEUR) as a part of a consortium with Alice and Bob and ENS Lyon.

# 8 Partnerships and cooperations

## 8.1 International research visitors

### 8.1.1 Visits of international scientists

**Other international visits to the team**

**Christopher Wilson**

**Status** Professor

**Institution of origin:** University of Waterloo

**Country:** Canada

**Dates:** August-Sept 2024

**Context of the visit:** Collaborations with Zaki Leghtas and Philippe Campagne-Ibarcq

**Birgitta Whaley**

**Status** Professor

**Institution of origin:** University of Berkeley

**Country:** USA

**Dates:** June-July 2024

**Context of the visit:** Collaboration with A.Sarlette (quantum computing and quantum information protection with non-hermitian Zeno-type dynamics)

**Philippe Lewalle**

**Status** PhD student

**Institution of origin:** University of Berkeley

**Country:** USA

**Dates:** June-July 2024

**Context of the visit:** Collaboration with A.Sarlette (quantum computing and quantum information protection with non-hermitian Zeno-type dynamics)

### 8.1.2 Visits to international teams

**Research stays abroad**

**Linda Greggio**

**Visited institution:** ENS Lyon

**Country:** France

**Dates:** Since May 2024

**Context of the visit:** Collaborations with the team of Audrey Bienfait

**Pierre Guilmin**

**Visited institution:** University of Griffith

**Country:** Australia

**Dates:** Feb-Sept 2024

**Context of the visit:** Collaborations with Prof. Howard Wiseman

**Louis Paletta**

**Visited institution:** University of Chicago

**Country:** USA

**Dates:** Oct-Nov 2024

**Context of the visit:** Semester on "Statistical Methods and Mathematical Analysis for Quantum Information Science"

**Diego Ruiz**

**Visited institution:** University of Chicago

**Country:** USA

**Dates:** Oct-Nov 2024

**Context of the visit:** Semester on "Statistical Methods and Mathematical Analysis for Quantum Information Science"

**Alexandru Petrescu**

**Visited institution:** University of Chicago

**Country:** USA

**Dates:** Oct-Nov 2024

**Context of the visit:** Semester on "Statistical Methods and Mathematical Analysis for Quantum Information Science"

**Rémi Robin**

**Visited institution:** University of Chicago

**Country:** USA

**Dates:** Oct-Nov 2024

**Context of the visit:** Semester on "Statistical Methods and Mathematical Analysis for Quantum Information Science"

**Angela Riva**

**Visited institution:** University of Chicago

**Country:** USA

**Dates:** Oct-Nov 2024

**Context of the visit:** Semester on "Statistical Methods and Mathematical Analysis for Quantum Information Science"

**Emilio Rui**

**Visited institution:** University of Chicago

**Country:** USA

**Dates:** Oct-Nov 2024

**Context of the visit:** Semester on "Statistical Methods and Mathematical Analysis for Quantum Information Science"

## 8.2 European initiatives

### 8.2.1 Horizon Europe

**DANCINGFOOL** 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:** Philippe Campagne-Ibarcq

**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).

### 8.2.2 H2020 projects

**ERC Starting Grant ECLIPSE**

- Program: H2020
- Type: ERC
- Project acronym: ECLIPSE
- Project title: Exotic superconducting circuits to probe and protect quantum states of light and matter
- Duration: 2019-2024
- Coordinator: Zaki Leghtas, Mines Paristech
- Abstract: Quantum systems can occupy peculiar states, such as superposition or entangled states. These states are intrinsically fragile and eventually get wiped out by inevitable interactions with the environment. Protecting quantum states against decoherence is a formidable and fundamental problem in physics, which is pivotal for the future of quantum computing. The theory of quantum error correction provides a solution, but its current envisioned implementations require daunting resources: a single bit of information is protected by encoding it across tens of thousands of physical qubits. This project intend to encode quantum information in an entirely new type of qubit with

two key specificities. First, it will be encoded in a single superconducting circuit resonator whose infinite dimensional Hilbert space can replace large registers of physical qubits. Second, this qubit will be rf-powered, continuously exchanging photons with a reservoir. This approach challenges the intuition that a qubit must be isolated from its environment. Instead, the reservoir acts as a feedback loop which continuously and autonomously corrects against errors. This correction takes place at the level of the quantum hardware, and reduces the need for error syndrome measurements which are resource intensive. The circuits I will develop manipulate quantum states of light, whose utility transcends the long term goal of quantum computing, and can readily be used to probe fundamental properties of matter. In mesoscopic physics where a large number of particles exhibit collective quantum phenomena, the measurement tools to characterize subtle quantum effects are often lacking. Here, the project proposes to measure the spin entanglement of a single Cooper pair, by coupling a superconductor to a circuit composed of microwave resonators and a carbon nanotube. The spin entanglement can be swapped into microwave photons, which can be detected by deploying the arsenal of quantum limited microwave measurement devices.

**ERC Advanced Grant Q-Feedback**

- Program: H2020
- Type: ERC
- Project acronym: Q-Feedback
- Project title: Quantum feedback Engineering
- Duration: 2020-2025
- 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.

## 8.3 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 will run 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.

## 8.4 Regional initiatives

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

# 9 Dissemination

## 9.1 Promoting scientific activities

### 9.1.1 Scientific events: organisation

- Mazyar Mirrahimi and Pierre Rouchon were co-organizers (with Liang Jiang and Aashish Clerk, Univ. Chicago) of a thematic semester at Institute for Mathematical and Statistical Innovation, University of Chicago, in fall 2024. The theme of the semester was "Statistical Methods and Mathematical Analysis for Quantum Information Science" and included 5 workshops and a long program. Here is the link to the program: `https://www.imsi.institute/activities/statistical-methods-and-mathematical-analysis-for-quantum-information-science/`
- Mazyar Mirrahimi and Pierre Rouchon were co-organizers (with Liang Jiang, Univ. Chicago) of a one-week workshop "quantum error correction" in the framework of the above semester at University of Chicago. Here is the link to the program: `https://www.imsi.institute/activities/statistical-methods-and-mathematical-analysis-for-quantum-information-science/quantum-error-correction/`
- Mazyar Mirrahimi co-organized (with Hideo Mabuch, Univ. Stanford) a workshop on "Wave Mixing: Microwave, Optical, Broadband, Quantum" at University of Stanford. Here is the program: `https://qfarm.stanford.edu/events/conference-symposium/wave-mixing-microwave-optical-broadband-quantum`
- Alain Sarlette was co-oreganizer of a special session "open quantum systems" at IEEE Control and Decision Conference, 2024.
- Alain Sarlette was a principal organizer of "(quantum computing: physicists talk to) Math-Info day" on June 10, 2024 at Sorbonne Université. (ou le mettre e 9.1.1)

- Alexandru Petrescu selected at the GDR meeting on Mesoscopic physics Aussois, December 2024 to be one of two co-organizers of the next edition in December 2025.
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### 9.1.2 Scientific events: selection

**Reviewer**

- Pierre Rouchon and Alain Sarlette were referees for IEEE and IFAC international conferences.

### 9.1.3 Journal

**Reviewer - reviewing activities**

- Philippe Campagne Ibarcq was a referee for Nature, PRX Quantum.
- Zaki Leghtas was a referee for Nature.
- Rémi Robin has been a referee for Nuclear Fusion and Quantum.
- Pierre Rouchon was a referee for Journal of differential equation and PRX.
- Alain Sarlette has been a referee for IEEE Transactions, PRL, PRX Quantum, PRA, Nature communications.
- Antoine Tilloy received the APS Reviewer Excellence Award for contributions in Phys. Rev. X
- Antoine Tilloy has been a regular reviewer in Phys. Rev. X, Phys. Rev. Lett., and Foundations of Physics (among others).

### 9.1.4 Invited talks

- Zaki Leghtas: Sorbonne Université. Invited by Nabil Guarroum.
- Zaki Leghtas: Université Paris Diderot. Invited by Edouard Boulat.
- Zaki Leghtas: Institute of Science and Technology Austria. Invited by Johannes Fink.
- Zaki Leghtas: Workshop "Frontiers of Condensed Matter". Les Houches, France.
- Zaki Leghtas: Workshop "Quantum Cavities". Canada.
- Mazyar Mirrahimi: Workshop "Quantum Hardware", Institute for Mathematical and Statistical Innovation, University of Chicago.
- Mazyar Mirrahimi: Workshop "Wave Mixing: Microwave, Optical, Broadband, Quantum", Stanford University.
- Mazyar Mirrahimi: New York University, Invited by Javad Shabani.
- Mazyar Mirrahimi: University of Erlangen, Invited by Christopher Eichler.
- Mazyar Mirrahimi: ENS-Rice University meeting, Invited by Carlo Sirtori.
- Mazyar Mirrahimi: GDR Mesoscopic Physics Plenary Sesssion, Tutorial talk.
- Rémi Robin: University of New Mexico (remote)
- Rémi Robin: Université Clermont Auvergne
- Rémi Robin: Université d’Avignon

- Pierre Rouchon: A tutorial introduction to quantum feedback, 58th Control Engineering Colloquium in Boppard, Germany.
- Pierre Rouchon: Quantum Error Correction and Feedback, Rencontre printanière 2024 de l'INTRIQ, Bromont Québec.
- Pierre Rouchon: Quantum filtering and estimation based on stochastic master equations, Sherbrooke, Canada.
- Pierre Rouchon: Quantum Gate generation for open quantum systems via a monotonic algorithm with time optimization, A Lighthearted Conference on Control Theory, Celebrating Witold Respondek's (Partial) Retirement. INSA Rouen Normandie.
- Pierre Rouchon: Quantum Optimal Control: From Mathematical Foundations to Quantum Technologies Zuse Institute Berlin.
- Pierre Rouchon: Mini-course on quantum control engineering: dynamics, estimation and feedback. UniCA QuantAzur days, Nice.
- Pierre Rouchon: Laboratoire de Mathématiques d'Orsay Université Paris-Saclay.
- Antoine Tilloy: FU Berlin (group of Jens Eisert)
- Antoine Tilloy: ECT Trento (workshop "A modern Odyssey")
- Antoine Tilloy: Vienna quantum foundations conference
- Antoine Tilloy: Séminaire Ballades quantiques ENS
- Antoine Tilloy: Seed seminar kick-off at Institut Henri Poincaré
- Antoine Tilloy: Ateliers du LKB
- Antoine Tilloy: Séminaire Subatech à Nantes

### 9.1.5 Leadership within the scientific community

- Alain Sarlette is a board member of the new 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.

### 9.1.6 Scientific expertise

- Philippe Campagne-Ibarcq was a reviewer for the Swiss National Science fondation.
- Philippe Campagne-Ibarcq and Mazyar Mirrahimi were co-authors of a report on the impact and scalability of quantum computing platforms for the Académie des technologies and the Secrétariat Général Pour l'Investissement.
- Mazyar Mirrahimi was a member of the working group of Académie des Technologies in the preparaton 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.

#### 9.1.7 Research administration

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

## 9.2 Teaching - Supervision - Juries

### 9.2.1 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 (14h).
- Mazyar Mirrahimi: Quantum Feedback at Ecole Polytechnique (60 hours), Ecole Polytechnique bachelor program thesis instructor (20 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.
- Philippe Campagne-Ibarcq : 12h of préceptorat at ESPCI.
- Alex Petrescu Automatics at Mines ParisTech (12 hours).
- Rémi Robin: Mines Paris, TDs of Optimisation, TDs of Mathematics, and Automatics.
- Pierre Rouchon is a member of the steering commitee of PSL master of Quantum Engineering with ENS-Paris.
- Pierre Rouchon is in charge of the "Mathematics and Automatics" specialty within the ISMME-621 doctoral school.
- 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.

#### 9.2.2 Supervision

**PhD defended in 2024** Alvise Borgognoni. Mediating high-order photon-photon interactions by Cooper-pair pairing. Supervision of Zaki Leghtas.

**PhD defended in 2024** François-Marie Le Régent. Quantum computing architecture with cat-qubits. Supervision of Mazyar Mirrahimi and Jérémie Guillaud.

**PhD defended in 2024** Vincent Martin. Entangled state stabilization by local couplings through reservoir-engineering methods. Supervision of Alain Sarlette.

**PhD defended in 2024** Matthieu Praquin. Mixing of counterpropagating signals in a traveling-wave Josephson device. Supervision of Philippe Campagne-Ibarcq.

**PhD defended in 2024** Ulysse Réglade. quantum control of a dissipative cat-qubit with macroscopic bit-flip time. Supervision of Zaki Leghtas and Raphaël Lescanne.

**PhD defended in 2024** Lev-Arcady Sellem. Bosonic qubits and quantum reservoirs: taming the environment. Supervision of Claude Le Bris and Pierre Rouchon.

**PhD defended in 2024** Aron Vanselow. High-impedance superconducting circuits for the dissipative stabilization of four-component Schrödinger cat states. Supervision of Philippe Campagne-Ibarcq.

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

**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** Thiziri Aissaoui. On-chip biasing of superconducting circuits. Supervision of Alain Sarlette and Anil Murani.

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

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

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

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

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

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

**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 started in 2024** Florent Goulette. Quantum nonlinear optics with a Josephson metamaterial. Supervision of Mazyar Mirrahimi and Antoine Tilloy.

**PhD started in 2024** Thomas Decultot.Blocking error propagation in bosonic processors. Supervision of Ronan Gautier and Mazyar Mirrahimi.

**PhD started in 2024** Gustave Robichon. Solving many body open quantum systems with semi-definite relaxations. Supervision of Pierre Rouchon and Antoine Tilloy.

**PhD started in 2024** Armelle Célarier. Implementing bias-preserving gates on cat-qubits. Supervision of Zaki Leghtas.

**PhD started in 2024** Anthony Giraudo. Non-reciprocal superconducting circuits for the protection of quantum information. supervision Philippe Campagne-Ibarcq.

### 9.2.3 Juries

- Mazyar Mirrahimi was a jury member for the PhD defense of Hector Hutin, ENS Lyon.
- Pierre Rouchon was a jury member for the PhD defense of Maël Bompais, Université Paris Saclay.
- Alain Sarlette was a jury member for the PhD of Maël Bompais at Univ. Paris Saclay.
- Alain Sarlette was a jury member for the PhD of Tommaso Grigoletto at Univ. Padova.
- Antoine Tilloy was reviewer for the PhD thesis of Mustafa Kemal Döner (university of Jena).

## 9.3 Popularization

### 9.3.1 Productions (articles, videos, podcasts, serious games, ...)

- Antoine Tilloy: Article in Pour la Science "Réseaux de tenseurs, les ordinateurs classiques contre-attaquent"
- Antoine Tilloy: Regular advisor for Pour la Science (quoted in some articles)

### 9.3.2 Participation in Live events

- Antoine Tilloy: Popular lecture at the Université Permanente de Nantes (on Quantum computing)
- Antoine Tilloy: Popular lecture at the Société d'Astronomie de Nantes (on Quantum and non-Quantum gravity)

### 9.3.3 Others science outreach relevant activities

- Antoine Tilloy: Interview with le Monde journalist (appeared in 2025).

# 10 Scientific production

## 10.1 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] P. Campagne-Ibarcq, P. Six, L. Bretheau, A. Sarlette, M. Mirrahimi, P. Rouchon and B. Huard. 'Observing Quantum State Diffusion by Heterodyne Detection of Fluorescence'. In: *Physical Review X* 6 (Jan. 2016). 011002. DOI: 10.1103/PhysRevX.6.011002. URL: https://hal-mines-paristech.archives-ouvertes.fr/hal-01264326.

[4] 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.

[5] Z. Leghtas, G. Kirchmair, B. Vlastakis, R. J. Schoelkopf, M. H. Devoret and M. Mirrahimi. 'Hardware-Efficient Autonomous Quantum Memory Protection'. In: *Phys. Rev. Lett.* 111 (12 Sept. 2013), p. 120501. DOI: 10.1103/PhysRevLett.111.120501. URL: https://link.aps.org/doi/10.1103/PhysRevLett.111.120501.

[6] 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. 6).

[7] 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`.

[8] 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. 6, 8).

[9] 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. 5).

[10] 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`.

[11] 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. 6–8).

[12] 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. 5).

[13] 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`.

## 10.2 Publications of the year

### International journals

[14] A. Antunes, E. Lauria and B. C. van Rees. 'A bootstrap study of minimal model deformations'. In: *Journal of High Energy Physics* 2024.05 (2024), p. 027. DOI: `10.1007/JHEP05(2024)027`. URL: `https://hal.science/hal-04446841`.

[15] L. Balembois, J. Travesedo, L. Pallegoix, A. May, E. Billaud, M. Villiers, D. Estève, D. Vion, P. Bertet and E. Flurin. 'Practical Single Microwave Photon Counter with $10^{-22}\mathrm{W}/\sqrt{\mathrm{Hz}}$ sensitivity'. In: *Physical Review Applied* 21.1 (2024), p. 014043. DOI: `10.1103/PhysRevApplied.21.014043`. URL: `https://hal.science/hal-04161810`.

[16] C. Behan, E. Lauria, M. Nocchi and P. van Vliet. 'Analytic and numerical bootstrap for the long-range Ising model'. In: *Journal of High Energy Physics* 03 (2024), p. 136. DOI: `10.1007/JHEP03(2024)136`. URL: `https://hal.science/hal-04289006`.

[17] H. G. Clausen, P. Rouchon and R. Wisniewski. 'Online Parameter Estimation for Continuously Monitored Quantum Systems'. In: *IEEE Control Systems Letters* 8 (2024), pp. 1247–1252. DOI: `10.1109/LCSYS.2024.3407608`. URL: `https://inria.hal.science/hal-04887075` (cit. on p. 14).

[18] L. Di Pietro, E. Lauria and P. Niro. 'Conformal boundary conditions for a 4d scalar field'. In: *SciPost Physics* 16 (3rd Apr. 2024). DOI: `10.21468/scipostphys.16.4.090`. URL: `https://hal.science/hal-04773157`.

[19] H. Hutin, A. Essig, R. Assouly, P. Rouchon, A. Bienfait and B. Huard. ‘Monitoring the energy of a cavity by observing the emission of a repeatedly excited qubit’. In: *Physical Review Letters* 133.15 (11th Oct. 2024), p. 153602. DOI: `10.1103/PhysRevLett.133.153602`. URL: `https://hal.science/hal-04743685` (cit. on p. 15).

[20] T. Lacroix, B. Le Dé, A. Riva, A. J. Dunnett and A. W. Chin. ‘MPSDynamics.jl: Tensor network simulations for finite-temperature (non-Markovian) open quantum system dynamics’. In: *The Journal of Chemical Physics* 161.8 (2024), p. 084116. DOI: `10.1063/5.0223107`. URL: `https://hal.science/hal-04631554`.

[21] E. Lauria, M. Milam and B. C. van Rees. ‘Perturbative RG flows in AdS: an étude’. In: *Journal of High Energy Physics* 2024.03 (2024), p. 005. DOI: `10.1007/JHEP03(2024)005`. URL: `https://hal.science/hal-04228539`.

[22] F.-M. Le Régent and P. Rouchon. ‘Adiabatic elimination for composite open quantum systems: reduced model formulation and numerical simulations’. In: *Physical Review A* 109.3 (6th Mar. 2024), p. 032603. DOI: `10.1103/PhysRevA.109.032603`. URL: `https://inria.hal.science/hal-04379147` (cit. on p. 14).

[23] V. Martin and A. Sarlette. ‘Stabilization of approximate GHZ state with quasi-local couplings’. In: *Journal of Physics A: Mathematical and Theoretical* 57.27 (2024), p. 275303. DOI: `10.1088/1751-8121/ad52d7`. URL: `https://hal.science/hal-04137276`.

[24] B.-L. Najera-Santos, R. Rousseau, K. Gerashchenko, H. Patange, A. Riva, M. Villiers, T. Briant, P.-F. Cohadon, A. Heidmann, J. Palomo, M. Rosticher, H. Le Sueur, A. Sarlette, W. C. Smith, Z. Leghtas, E. Flurin, T. Jacqmin and S. Deléglise. ‘High-Sensitivity ac-Charge Detection with a MHz-Frequency Fluxonium Qubit’. In: *Physical Review X* 14.1 (2024), p. 011007. DOI: `10.1103/physrevx.14.011007`. URL: `https://hal.science/hal-04777888`.

[25] L. Paletta, A. Leverrier, A. Sarlette, M. Mirrahimi and C. Vuillot. ‘Robust sparse IQP sampling in constant depth’. In: *Quantum* 8 (6th May 2024), p. 1337. DOI: `10.22331/q-2024-05-06-1337`. URL: `https://inria.hal.science/hal-04696925`.

[26] A. Peugeot, H. Riechert, S. Annabi, L. Balembois, M. Villiers, E. Flurin, J. Griesmar, E. Arrighi, J.-D. Pillet and L. Bretheau. ‘Two-tone spectroscopy of high-frequency quantum circuits with a Josephson emitter’. In: *Physical Review Applied* 22.6 (2024), p. 064027. DOI: `10.1103/PhysRevApplied.22.064027`. URL: `https://hal.science/hal-04632209`.

[27] 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* (24th June 2024). DOI: `10.4171/IFB/523`. URL: `https://inria.hal.science/hal-03690069`. In press.

[28] 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` (cit. on p. 11).

[29] R. Robin, P. Rouchon and L.-A. Sellem. ‘Convergence of bipartite open quantum systems stabilized by reservoir engineering’. In: *Annales Henri Poincaré* (20th Nov. 2024). DOI: `10.1007/s00023-024-01481-8`. URL: `https://inria.hal.science/hal-04379101` (cit. on p. 15).

[30] R. Robin and R. Roussel. ‘Shape optimization of harmonic helicity in toroidal domains’. In: *Journal of Optimization Theory and Applications* 204.10 (29th Dec. 2024), `https://doi-org.minesparis-psl.idm.oclc.org/10.1007/s10957-024-02588\bibrangedashy`. DOI: `10.1007/s10957-024-02588-y`. URL: `https://hal.science/hal-04419547`.

[31] 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`.

[32] 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`.

[33] P. S. P. D. Silva and P. Rouchon. ‘Gate generation for open quantum systems via a monotonic algorithm with time optimization’. In: *Mathematical Control and Related Fields* 14.4 (29th Mar. 2024), pp. 1684–1704. DOI: `10.3934/mcrf.2024053`. URL: `https://inria.hal.science/hal-04887070` (cit. on p. 14).

[34] A. Tilloy. ‘General quantum-classical dynamics as measurement based feedback’. In: *SciPost Physics* 17.3 (18th Sept. 2024), p. 83. DOI: `10.21468/SciPostPhys.17.3.083`. URL: `https://hal.science/hal-04541218` (cit. on p. 12).

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[36] M. Villiers, W. C. Smith, A. Petrescu, A. Borgognoni, M. Delbecq, A. Sarlette, M. Mirrahimi, P. Campagne-Ibarcq, T. Kontos and Z. Leghtas. ‘Dynamically Enhancing Qubit-Photon Interactions with Antisqueezing’. In: *PRX Quantum* 5.2 (2024), p. 020306. DOI: `10.1103/prxquantum.5.020306`. URL: `https://hal.science/hal-04774096`.

[37] D. Willsch, D. Rieger, P. Winkel, M. Willsch, C. Dickel, J. Krause, Y. Ando, R. Lescanne, Z. Leghtas, N. Bronn, P. Deb, O. Lanes, Z. Minev, B. Dennig, S. Geisert, S. Günzler, S. Ihssen, P. Paluch, T. Reisinger, R. Hanna, J. H. Bae, P. Schüffelgen, D. Grützmacher, L. Buimaga-Iarinca, C. Morari, W. Wernsdorfer, D. Divincenzo, K. Michielsen, G. Catelani and I. Pop. ‘Observation of Josephson harmonics in tunnel junctions’. In: *Nature Physics* 20.5 (4th Apr. 2024), pp. 815–821. DOI: `10.1038/s41567-024-02491-3`. URL: `https://hal.science/hal-04891568`.

### International peer-reviewed conferences

[38] E. Marolleau, P. Martin, P. Rouchon and P. Ullah. ‘Can a Perfect Vibratory Gyroscope Provide a Drift-Free Angle Estimation?’ In: ISA 2024 DGON Inertial Sensors and Applications. Braunschweig, Germany: IEEE, 17th Dec. 2024. DOI: `10.1109/ISA62769.2024.10786089`. URL: `https://minesparis-psl.hal.science/hal-04876977`.

[39] A. Riva, A. Sarlette and P. Rouchon. ‘Explicit formulas for adiabatic elimination with fast unitary dynamics’. In: CDC 2024 - IEEE Conference on Decision and Control. Milan, Italy, 2nd Apr. 2024. URL: `https://inria.hal.science/hal-04530303` (cit. on p. 11).

### Conferences without proceedings

[40] L. Paletta, A. Leverrier, A. Sarlette, M. Mirrahimi and C. Vuillot. ‘Robust sparse IQP sampling in constant depth’. In: QIP2024. Taipei, Taiwan, 6th May 2024, p. 1337. DOI: `10.22331/q-2024-05-06-1337`. URL: `https://inria.hal.science/hal-04312163`.

### Doctoral dissertations and habilitation theses

[41] A. Borgognoni. ‘Mediating high-order photon-photon interactions by Cooper-pair pairing’. Université PSL, 27th May 2024. URL: `https://hal.science/tel-04901986`.

[42] P. Campagne-Ibarcq. ‘Design and control of Josephson circuits for the protection and processing of quantum information’. ENS Paris - Ecole Normale Supérieure de Paris, 28th Mar. 2024. URL: `https://hal.science/tel-04901822`.

[43] F.-M. Le Régent. ‘Analytical and numerical methods for optimizing quantum computing architectures based on stabilized bosonic qubits’. Université PSL Paris Sciences & Lettres (PSL Research University), 14th Mar. 2024. URL: `https://theses.hal.science/tel-04891145`.

[44] V. Martin. ‘Entangled state stabilization by local couplings through reservoir-engineering methods’. Sorbonne Université, 8th Feb. 2024. URL: `https://theses.hal.science/tel-04562042`.

[45] L.-A. Sellem. 'Bosonic qubits and quantum reservoirs: taming the environment'. Université Paris sciences et lettres, 21st Mar. 2024. URL: https://pastel.hal.science/tel-04976541.

### Reports & preprints

[46] T. Aissaoui, A. Murani, R. Lescanne and A. Sarlette. *A cat qubit stabilization scheme using a voltage biased Josephson junction*. 10th Dec. 2024. URL: https://inria.hal.science/hal-04887025 (cit. on p. 11).

[47] T. Benoist, L. Greggio and C. Pellegrini. *Exponentially fast selection of sectors for quantum trajectories beyond non demolition measurements*. 26th July 2024. URL: https://hal.science/hal-04664314.

[48] L. Carde, P. Rouchon, J. Cohen and A. Petrescu. *Flux-pump induced degradation of* $T_1$ *for dissipative cat qubits*. 1st Oct. 2024. URL: https://inria.hal.science/hal-04887052 (cit. on p. 12).

[49] 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.

[50] P. Guilmin, P. Rouchon and A. Tilloy. *Parameters estimation by fitting correlation functions of continuous quantum measurement*. 15th Oct. 2024. URL: https://inria.hal.science/hal-04887056 (cit. on p. 13).

[51] M. Praquin, V. Lienhard, A. Giraudo, A. Vanselow, Z. Leghtas and P. Campagne-Ibarcq. *Mixing of counterpropagating signals in a traveling-wave Josephson device*. 28th June 2024. URL: https://inria.hal.science/hal-04887032 (cit. on p. 13).

[52] G. Robichon and A. Tilloy. *Bootstrapping the stationary state of bosonic open quantum systems*. 9th Oct. 2024. URL: https://inria.hal.science/hal-04887077 (cit. on p. 13).

[53] R. Robin, P. Rouchon and L.-A. Sellem. *Unconditionally stable time discretization of Lindblad master equations in infinite dimension using quantum channels*. 3rd Mar. 2025. URL: https://hal.science/hal-04990415.

[54] A. Sarlette, C. Elouard and P. Rouchon. *Confinement to deterministic manifolds and low-dimensional solution formulas for continuously measured quantum systems*. 11th Mar. 2025. URL: https://hal.science/hal-04994024.

[55] P. S. P. da Silva and P. Rouchon. *On encoded quantum gate generation by iterative Lyapunov-based methods*. 2nd Sept. 2024. URL: https://inria.hal.science/hal-04887064.

[56] M. Tokieda and A. Riva. *Time-Convolutionless Master Equation Applied to Adiabatic Elimination*. 12th Sept. 2024. URL: https://inria.hal.science/hal-04887096.

[57] A. Vanselow, B. Beauseigneur, L. Lattier, M. Villiers, A. Denis, P. Morfin, Z. Leghtas and P. Campagne-Ibarcq. *Dissipating quartets of excitations in a superconducting circuit*. 10th Jan. 2025. URL: https://hal.science/hal-04891415.

### Scientific popularization

[58] J. Joliclerc, A. Decarpigny, A. Sarlette, C. Leininger and J. Grapin. *À la conquête des qubits*. Ed. by C. Touati. 12th Feb. 2025. URL: https://inria.hal.science/hal-04935426.

### Patents

[59] P. Combes, D. Surroop, P. Martin and P. Rouchon. 'Accionador de velocidad variable para el control de PWM sin sensores de un motor de ca mediante la explotación de artefactos inducidos por PWM'. ES2975522T3 (Spain). 8th July 2024. URL: https://minesparis-psl.hal.science/hal-04877134.

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