

RESEARCH CENTRE

**Inria Paris Centre
at Sorbonne University**

IN PARTNERSHIP WITH:

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

2023

ACTIVITY REPORT

Project-Team

QUANTIC

QUANTum Information Circuits

IN COLLABORATION WITH: Laboratoire Pierre Aigrain, Centre
Automatique et Systèmes

DOMAIN

**Applied Mathematics, Computation and
Simulation**

THEME

**Optimization and control of dynamic
systems**

Inria

Contents

Project-Team QUANTIC	1
1 Team members, visitors, external collaborators	2
2 Overall objectives	3
2.1 Overall objectives	3
3 Research program	4
3.1 Hardware-efficient quantum information processing	4
3.2 Reservoir (dissipation) engineering and autonomous stabilization of quantum systems . .	5
3.3 System theory for quantum information processing	6
3.4 Stabilization by measurement-based feedback	6
3.5 Filtering, quantum state and parameter estimations	7
3.6 Stabilization by interconnections	7
3.6.1 Perturbation methods	8
3.7 On-chip microwave engineering	9
4 Application domains	10
4.1 Quantum engineering	10
5 Highlights of the year	10
6 New results	11
6.1 Designing High-Fidelity Zeno Gates for Dissipative Cat Qubits	11
6.2 Stabilization of approximate GHZ states with quasi-local couplings	11
6.3 Stability and decoherence rates of a GKP qubit protected by dissipation	11
6.4 Complete Positivity Violation in Higher-order Quantum Adiabatic Elimination	12
6.5 Correlation functions for realistic continuous quantum measurement	12
6.6 Heisenberg formulation of adiabatic elimination for open quantum systems with two time-scales	12
6.7 Adiabatic elimination for composite open quantum systems: reduced model formulation and numerical simulations	12
6.8 Convergence of bipartite open quantum systems stabilized by reservoir engineering	13
6.9 High-sensitivity AC-charge detection with a MHz-frequency fluxonium qubit	13
6.10 Quantum control of a cat-qubit with bit-flip times exceeding ten seconds	13
6.11 Observation of Josephson Harmonics in Tunnel Junctions	14
6.12 Robust suppression of noise propagation in Gottesman-Kitaev-Preskill error correction . .	14
6.13 A GKP qubit protected by dissipation in a high-impedance superconducting circuit driven by a microwave frequency comb	15
6.14 Robust sparse IQP sampling in constant depth	15
7 Bilateral contracts and grants with industry	15
7.1 Bilateral contracts with industry	15
8 Partnerships and cooperations	16
8.1 International research visitors	16
8.1.1 Visits of international scientists	16
8.2 European initiatives	17
8.2.1 Horizon Europe	17
8.2.2 H2020 projects	18
8.3 National initiatives	20
8.4 Regional initiatives	20

9 Dissemination	21
9.1 Promoting scientific activities	21
9.1.1 Scientific events: selection	21
9.1.2 Journal	21
9.1.3 Invited talks	21
9.1.4 Leadership within the scientific community	22
9.1.5 Scientific expertise	22
9.1.6 Research administration	22
9.2 Teaching - Supervision - Juries	23
9.2.1 Teaching	23
9.2.2 Supervision	23
9.2.3 Juries	24
9.3 Popularization	25
9.3.1 Interventions	25
10 Scientific production	25
10.1 Major publications	25
10.2 Publications of the year	26
10.3 Cited publications	28

Project-Team QUANTIC

Creation of the Project-Team: 2015 April 01

Keywords

Computer sciences and digital sciences

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

Other research topics and application domains

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

1 Team members, visitors, external collaborators

Research Scientists

- Mazyar Mirrahimi [Team leader, INRIA, Senior Researcher]
- Philippe Campagne Ibarcq [INRIA, Researcher]
- Alain Sarlette [INRIA, Senior Researcher, from Oct 2023, HDR]
- Alain Sarlette [INRIA, Researcher, until Sep 2023, HDR]

Faculty Members

- Zaki Leghtas [ENSMP, Associate Professor]
- Tudor-Alexandru Petrescu [MINESPARISTECH]
- Pierre Rouchon [ARMINES, Professor, HDR]
- Antoine Tilloy [MINESPARISTECH]

Post-Doctoral Fellows

- Yousra Bouasria [INRIA, Post-Doctoral Fellow, until Feb 2023]
- Edoardo Lauria [ENSMP, Post-Doctoral Fellow, from Mar 2023]
- Vincent Lienhard [ENS PARIS, Post-Doctoral Fellow]
- Remi Robin [ARMINES, Post-Doctoral Fellow]

PhD Students

- Thiziri Aissaoui [ALICE ET BOB, CIFRE]
- Brieuc Beauseigneur [ARMINES, from Sep 2023]
- Leon Carde [ARMINES, CIFRE]
- Ronan Gautier [INRIA, until Aug 2023]
- Linda Greggio [INRIA]
- Pierre Guilmin [ALICE ET BOB]
- Anissa Jacob [ALICE ET BOB, CIFRE, from Nov 2023]
- François-Marie Le Regent [ALICE ET BOB]
- Louis Paletta [INRIA]
- Matthieu Praquin [ENS PARIS]
- Angela Riva [INRIA]
- Emilio Rui [ALICE ET BOB, from Oct 2023]
- Diego Ruiz [ALICE ET BOB, CIFRE]
- Lev-Arcady Sellem [ARMINES, from Sep 2023]
- Lev-Arcady Sellem [ENS PARIS-SACLAY, until Aug 2023]
- Christian Siegele [INRIA, until Feb 2023]
- Karanbir Tiwana [ARMINES]
- Aron Vanselow [INRIA]

Interns and Apprentices

- Brieuc Beauseigneur [INRIA, Intern, from Apr 2023 until Jul 2023]
- Leonardo Cardinale [ENSMP, Intern, from May 2023 until Aug 2023]
- Vania Clesca Dedieu [MINESPARISTECH, Intern, until Feb 2023]
- Robin Geiller [ENS DE LYON, Intern, from May 2023 until Jul 2023]
- Philippe Gigon [INRIA, Intern, from Feb 2023 until Jun 2023]
- Danilo Nascimento Guimaraes [INRIA, Intern, from Apr 2023 until Jul 2023]
- Etienne Parcollet [ENS Paris, Intern, from Apr 2023 until Jun 2023]
- Tom Perrin [MINESPARISTECH, Intern, from Dec 2023]

Administrative Assistant

- Derya Gok [INRIA]

Visiting Scientists

- Henrik Clausen [UNIV AALBORG, from Sep 2023]
- Birgitta Whaley [UNIV BERKELEY, from May 2023 until Jul 2023]

External Collaborators

- Ronan Gautier [ALICE ET BOB, from Sep 2023]
- Jeremie Guillaud [ALICE ET BOB]

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 [109, 113]. By redundantly encoding quantum information in this Hilbert space of larger dimension one makes 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 requires 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 [81]. 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 [78, 71] 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 [80]. Through a recent experimental work [120], we benefit from this controllability to prepare superpositions of quasi-orthogonal coherent states, also known as Schrödinger cat states.

In this Scheme, the logical qubit is encoded in a four-component Schrödinger cat state. Continuous quantum non-demolition (QND) monitoring of a single physical observable, consisting of photon number parity, enables then the tractability of single photon jumps. We obtain therefore a first-order quantum error correcting code using only a single high-Q cavity mode (for the storage of quantum information), a single qubit (providing the non-linearity needed for controllability) and a single low-Q cavity mode (for reading out the error syndrome). An earlier experiment on such QND photon-number parity measurements [114] has recently led to a first experimental realization of a full quantum error correcting code improving the coherence time of quantum information [7]. As shown in Figure 1, this leads to a significant hardware economy for realization of a protected logical qubit. Our goal here is to push these ideas towards a reliable and hardware-efficient paradigm for universal quantum computation.

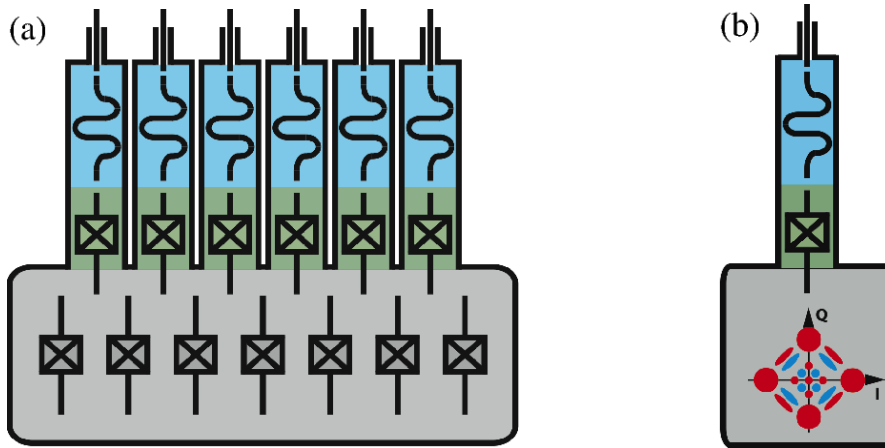


Figure 1: (a) A protected logical qubit consisting of a register of many qubits: here, we see a possible architecture for the Steane code [113] consisting of 7 qubits requiring the measurement of 6 error syndromes. In this sketch, 7 transmon qubits in a high-Q resonator and the measurement of the 6 error 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.

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 [51]. In the context of cavity quantum electro-dynamics (cavity QED) with Rydberg atoms [74], a first experiment on continuous QND measurements of the number of microwave photons was performed by the group at Laboratoire Kastler-Brossel (ENS) [72]. 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 [9] (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 [62, 41, 112, 42]. 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) [60], recent advances in quantum-limited amplifiers [102, 117] have opened doors to high-fidelity non-demolition measurements and real-time feedback for superconducting qubits [75]. 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 [117, 101, 53]. 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 [89].

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 [96] and the closely related coherent feedback [86] 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 [70], single-qubit state stabilization [90], and the creation [45] and stabilization [79, 85, 108] 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 [70, 83, 58, 61]. The experimental results based on these protocols have illustrated the efficiency of the approach [70, 108]. Through these experiments, we exploit the strong dispersive interaction [106] 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 [104, 76][6, 4].

3.3 System theory for quantum information processing

In parallel and in strong interactions with the above experimental goals, we develop systematic mathematical methods for dynamical analysis, control and estimation of composite and open quantum systems. These systems are built with several quantum subsystems whose irreversible dynamics results from measurements and/or decoherence. A special attention is given to spin/spring systems made with qubits and harmonic oscillators. These developments are done in the spirit of our recent contributions [103, 41, 111, 105, 112, 42][8] 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 [42]: 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 [121]; 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 [93]. 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 [75, 53].

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 [47] and is related to quantum trajectories [54, 59]. A modern and mathematical exposure of the diffusive models is given in [44]. In [73] 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 [103, 111]. This stability result is extended to a large class of continuous-time filters in [40]. Further efforts are required to characterize asymptotic and exponential stability. Estimations of convergence rates are available only for quantum non-demolition measurements [48]. Parameter estimations based on measurement data of quantum trajectories can be formulated within such quantum filtering framework [65, 91].

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 [52] that post-selection statistics and “past quantum” state analysis [66] 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 [96, 86]. 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 [8] [108, 70], 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 [95]). 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., [43][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 [8, 6] [108, 70] 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 [69, 68]. We will start with [107] and [99] where, based on a theorem due to Birkhoff [49], 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 [116] and by our recent generalized extension of the latter synchronizing interactions to quantum systems [88].

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 [92], 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 [119, 84] with experimental limitations. The characterization of Kraus maps to stabilize any types of states has also been established [50], 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 [74, 67]. 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 [82].

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 [55] 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 [63] and invariant manifold techniques [56] 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 [77] 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 [70, 108, 83].

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" [100] consists in placing $\lambda/4$ stubs [97] 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 [98], and a recent implementation of a bandpass filter [64].

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 [110, 57, 39], or by electromechanical coupling to nanoresonators [46, 94]. 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 [39]. For completeness, we mention a recent implementation of a forward amplifier based on resistively shunted Josephson junctions [115] 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 [118, 87].

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 su-

perconductors. Extending the numerical simulation methods developed in this 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 or 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 partial¹ nature of measurements for quantum systems lead to major difficulties in extending classical control theory tools. Indeed, design of appropriate measurement protocols and, in the sequel, the corresponding quantum filters estimating the state of the system from the partial measurement record, are themselves building blocks of the quantum system theory to be developed.

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

5 Highlights of the year

- Successful PhD defense of Christian Siegele on February 24th.
- Successful PhD defense of Camille Berdou on March 14th.
- Successful PhD defense of Marius Villiers on May 15th.
- Successful PhD defense of Ronan Gautier on December 4th.

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

- Installation of a new experimental laboratory space at ENS Paris with a new dilution cryostat.
- Promotion of Alain Sarlette to DR2.

6 New results

6.1 Designing High-Fidelity Zeno Gates for Dissipative Cat Qubits

Participants: Ronan Gautier, Mazyar Mirrahimi, Alain Sarlette.

This paper [15], published in PRX Quantum, gathers several different system design possibilities in order to perform fast operations on cat qubits while strongly reducing the decoherence induced by the fast actuation on the system. The decoherence is due to the fact that a dissipative element is present on purpose in order to stabilize the qubit, while simple enough actuation Hamiltonians cannot drive all necessary system operations without activating this stabilizing dissipation; in this way, fast actuation would also induce rather fast information loss. One proposed solution, also submitted for patenting, is to introduce back-action from the output of the main dissipation channel, thus re-injecting the part of the evacuated entropy which correlates to qubit information which we want to maintain. Other proposed solutions include the engineering of small nonlinearities in the actuation Hamiltonian, or designing jump-activated operations. This has been a major part of the thesis of Ronan Gautier, successfully defended in December 2023.

6.2 Stabilization of approximate GHZ states with quasi-local couplings

Participants: Vincent Martin, Alain Sarlette.

This work [30], currently under review, comprises essentially 3 contributions. First, we solve the objective of stabilizing intrinsically long-range entanglement, for which impossibility results have been known, on a prototypical example. Second, our solution proposes and investigates the use of engineered reservoirs — thus an autonomous system with steady couplings — whose aim is to mimic the behavior of automata with little but nonzero memory. We establish the effectiveness of several options and workings, involving: introducing one auxiliary system per data qubit; adding a third level to the data qubit for operation purposes ; and inducing waves of effects propagating through the overall system at stochastic speeds. A third contribution concerns the analysis method, where we bound the Lindblad master equation evolution by a Markov chain involving hypothetical measurements of the dissipation channels, and then analyze the associated classical Markov chain.

6.3 Stability and decoherence rates of a GKP qubit protected by dissipation

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

In this communication at the IFAC WC 2023[20], We analyze an experimentally accessible Lindblad master equation for a quantum harmonic oscillator. It approximately stabilizes finite-energy periodic grid states called Gottesman-Kitaev-Preskill (GKP) states, that can be used to encode and protect a logical qubit. We give explicit upper bounds for the energy of the solutions of the Lindblad master equation. Using three periodic observables to define the Bloch sphere coordinates of a logical qubit, we show that their dynamics is governed by a diffusion partial differential equation on a 2D-torus with a Witten Laplacian. We show that the evolution of these logical coordinates is exponentially slow even in presence of small diffusive noise processes along the two quadratures of the phase space. Numerical simulations indicate similar results for other physically relevant noise processes.

6.4 Complete Positivity Violation in Higher-order Quantum Adiabatic Elimination

Participants: Masaaki Tokieda, Alain Sarlette, Pierre Rouchon.

This communication at the IFAC WC 2023 [21] addresses quantum adiabatic elimination and complete-positivity. When a composite Lindblad system consists of weakly coupled sub-systems with fast and slow timescales, the description of slow dynamics can be simplified by discarding fast degrees of freedom. This model reduction technique is called adiabatic elimination. While second-order perturbative expansion with respect to the timescale separation has revealed that the evolution of a reduced state is completely positive, this paper presents an example exhibiting complete positivity violation in the fourth-order expansion. Despite the non-uniqueness of slow dynamics parametrization, we prove that complete positivity cannot be ensured in any parametrization. The violation stems from correlation in the initial state.

6.5 Correlation functions for realistic continuous quantum measurement

Participants: Pierre Guilmin, Pierre Rouchon, Antoine Tilloy.

This communication at the IFAC WC 2023 [25] proposes a self-contained and accessible derivation of an exact formula for the n-point correlation functions of the signal measured when continuously observing a quantum system. The expression depends on the initial quantum state and on the Stochastic Master Equation (SME) governing the dynamics. This derivation applies to both jump and diffusive evolutions and takes into account common imperfections of realistic measurement devices. We show how these correlations can be efficiently computed numerically for commonly filtered and integrated signals available in practice.

6.6 Heisenberg formulation of adiabatic elimination for open quantum systems with two time-scales

Participants: François-Marie Le Regent, Pierre Rouchon.

This communication at the IEEE CDC 2023 [19], considers an open quantum system governed by a Gorini, Kossakowski, Sudarshan, Lindblad (GKSL) master equation with two time-scales: a fast one, exponentially converging towards a linear subspace of quasi-equilibria; a slow one resulting from perturbations (small arbitrary decoherence and Hamiltonian dynamics). Usually adiabatic elimination is performed in the Schrödinger picture. We propose here an Heisenberg formulation where the invariant operators attached to the fast decay dynamics towards the quasi-equilibria subspace play a key role. Based on geometric singular perturbations, asymptotic expansions of the Heisenberg slow dynamics and of the fast invariant linear subspaces are proposed. They exploit Carr's approximation lemma from center-manifold and bifurcation theory. Second-order expansions are detailed and shown to ensure preservation, up to second-order terms, of the trace and complete positivity for the slow dynamics on a slow time-scale. Such expansions can be exploited numerically.

6.7 Adiabatic elimination for composite open quantum systems: reduced model formulation and numerical simulations

Participants: François-Marie Le Régent, Pierre Rouchon.

This preprint under review in Physical Review A [32] proposes a numerical method for simulation of composite open quantum systems. 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.

6.8 Convergence of bipartite open quantum systems stabilized by reservoir engineering

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

This preprint [34] considers 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 proposed for the stabilization of so-called cat qubits, a system that received considerable attention in recent years due to its potential applications in quantum information processing.

6.9 High-sensitivity AC-charge detection with a MHz-frequency fluxonium qubit

Participants: Angela Riva, Marius Villiers, Alain Sarlette, Zaki Leghtas.

This work [31], provisionally accepted in PRX, is the first step of results in the framework of the ANR project MecaFlux led by Samuel Deléglise, whose ultimate goal is to stabilize quantum states in a mechanical oscillator thanks to its coupling to a superconducting circuit in so-called "heavy fluxonium" configuration. The first step demonstrates the capabilities of such a fluxonium, in terms of actively cooling it down to the ground state, maintaining qubit-type quantum states, reading out such state. It also demonstrates experimentally how this circuit does couple to the degree of freedom (MHz charge fluctuations) where the mechanical oscillator is to be placed; thus we have a fully operational building block for the overall project, and which may be of independent interest.

6.10 Quantum control of a cat-qubit with bit-flip times exceeding ten seconds

Participants: Ulysse Reglade, Adrien Bocquet, Ronan Gautier, Lev-Arcady Sellem, Pierre Rouchon, Alain Sarlette, Mazyar Mirrahimi, Philippe Campagne-Ibarcq, Zaki Leghtas.

Binary classical information is routinely encoded in the two metastable states of a dynamical system. Since these states may exhibit macroscopic lifetimes, the encoded information inherits a strong protection against bit-flips. A recent qubit - the cat-qubit - is encoded in the manifold of metastable states of a quantum dynamical system, thereby acquiring bit-flip protection. An outstanding challenge is to gain quantum control over such a system without breaking its protection. If this challenge is met, significant shortcuts in hardware overhead are forecast for quantum computing. In this experiment, we implement a cat-qubit with bit-flip times exceeding ten seconds. This is a four order of magnitude improvement over previous cat-qubit implementations, and six orders of magnitude enhancement over the single photon lifetime that compose this dynamical qubit. This was achieved by introducing a quantum tomography protocol that does not break bit-flip protection. We prepare and image quantum superposition states, and measure phase-flip times above 490 nanoseconds. Most importantly, we control the phase of these superpositions while maintaining the bit-flip time above ten seconds. This work demonstrates quantum operations that preserve macroscopic bit-flip times, a necessary step to scale these dynamical qubits into fully protected hardware-efficient architectures.

This work has given rise to the preprint [33].

6.11 Observation of Josephson Harmonics in Tunnel Junctions

Participants: Zaki Leghtas.

Superconducting quantum processors have a long road ahead to reach fault-tolerant quantum computing. One of the most daunting challenges is taming the numerous microscopic degrees of freedom ubiquitous in solid-state devices. State-of-the-art technologies, including the world's largest quantum processors, employ aluminum oxide (AlOx) tunnel Josephson junctions (JJs) as sources of nonlinearity, assuming an idealized pure $\sin\phi$ current-phase relation ($C\phi R$). However, this celebrated $\sin\phi$ $C\phi R$ is only expected to occur in the limit of vanishingly low-transparency channels in the AlOx barrier. Here we show that the standard $C\phi R$ fails to accurately describe the energy spectra of transmon artificial atoms across various samples and laboratories. Instead, a mesoscopic model of tunneling through an inhomogeneous AlOx barrier predicts %-level contributions from higher Josephson harmonics. By including these in the transmon Hamiltonian, we obtain orders of magnitude better agreement between the computed and measured energy spectra. The reality of Josephson harmonics transforms qubit design and prompts a reevaluation of models for quantum gates and readout, parametric amplification and mixing, Floquet qubits, protected Josephson qubits, etc. As an example, we show that engineered Josephson harmonics can reduce the charge dispersion and the associated errors in transmon qubits by an order of magnitude, while preserving anharmonicity.

This work has led to the preprint [38].

6.12 Robust suppression of noise propagation in Gottesman-Kitaev-Preskill error correction

Participants: Christian Siegele, Philippe Campagne Ibarcq.

The recently reported generation and error-correction of GKP qubits in trapped ions and superconducting circuits thus holds great promise for the future of quantum computing architectures based on such encoded qubits. However, these experiments rely on error-syndrome detection via an auxiliary physical qubit, whose noise may propagate and corrupt the encoded GKP qubit. In [Siegele, C., & Campagne-Ibarcq, P. (2023). Robust suppression of noise propagation in Gottesman-Kitaev-Preskill error correction. *Physical Review A*, 108(4), 042427.], we propose a simple module composed of two oscillators and a physical qubit, operated with two experimentally accessible quantum gates and elementary feedback controls to implement an error-corrected GKP qubit protected from such propagating errors. In the idealized setting of periodic GKP states, we develop efficient numerical methods to optimize our

protocol parameters and show that errors of the encoded qubit stemming from flips of the physical qubit and diffusion of the oscillators state in phase-space may be exponentially suppressed as the noise strength over individual operations is decreased. Our approach circumvents the main roadblock towards fault-tolerant quantum computation with GKP qubits.

This work was published in Phys. Rev. A [18].

6.13 A GKP qubit protected by dissipation in a high-impedance superconducting circuit driven by a microwave frequency comb

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

In the preprint [35], we propose a novel approach to generate, protect and control GKP qubits. It employs a microwave frequency comb parametrically modulating a Josephson circuit to enforce a dissipative dynamics of a high impedance circuit mode, autonomously stabilizing the finite-energy GKP code. The encoded GKP qubit is robustly protected against all dominant decoherence channels plaguing superconducting circuits but quasi-particle poisoning. In particular, noise from ancillary modes leveraged for dissipation engineering does not propagate at the logical level. In a state-of-the-art experimental setup, we estimate that the encoded qubit lifetime could extend two orders of magnitude beyond the break-even point, with substantial margin for improvement through progress in fabrication and control electronics. Qubit initialization, readout and control via Clifford gates can be performed while maintaining the code stabilization, paving the way toward the assembly of GKP qubits in a fault-tolerant quantum computing architecture.

6.14 Robust sparse IQP sampling in constant depth

Participants: Louis Paletta, Alain Sarlette, Mazyar Mirrahimi.

Between NISQ (noisy intermediate scale quantum) approaches without any proof of robust quantum advantage and fully fault-tolerant quantum computation, we propose a scheme to achieve a provable superpolynomial quantum advantage (under some widely accepted complexity conjectures) that is robust to noise with minimal error correction requirements. We choose a class of sampling problems with commuting gates known as sparse IQP (Instantaneous Quantum Polynomial-time) circuits and we ensure its fault-tolerant implementation by introducing the tetrahelix code. This new code is obtained by merging several tetrahedral codes (3D color codes) and has the following properties: each sparse IQP gate admits a transversal implementation, and the depth of the logical circuit can be traded for its width. Combining those, we obtain a depth-1 implementation of any sparse IQP circuit up to the preparation of encoded states. This comes at the cost of a space overhead which is only polylogarithmic in the width of the original circuit. We furthermore show that the state preparation can also be performed in constant depth with a single step of feed-forward from classical computation. Our construction thus exhibits a robust superpolynomial quantum advantage for a sampling problem implemented on a constant depth circuit with a single round of measurement and feed-forward.

This work [23] has been accepted for a plenary presentation at the conference QIP 2024 in Taipei and is under revision for Quantum.

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

- New PhD contracts with Alice&Bob for 2 new students: Emilio Rui, Anissa Jacob.

8 Partnerships and cooperations

8.1 International research visitors

8.1.1 Visits of international scientists

Other international visits to the team

Birgitta Whaley

Status: Professor

Institution of origin: Univ. of Berkeley

Country: USA

Dates: May 5th to June 18th.

Context of the visit: Collaborations with Pierre Rouchon.

Paulo Sérgio Pereira da Silva

Status: Professor

Institution of origin: Univ. of Sao Paolo

Country: Brasil

Dates:

Context of the visit: Collaborations with Pierre Rouchon.

Philippe Lewalle

Status: PhD

Institution of origin: Univ. of Berkeley

Country: USA

Dates: May 4th to June 18th.

Context of the visit: Collaborations with Pierre Rouchon.

Henrik Clausen

Status: PhD

Institution of origin: Aalborg University

Country: Denmark

Dates: Sept 11th to Dec 8th.

Context of the visit: Collaborations with Pierre Rouchon.

8.2 European initiatives

8.2.1 Horizon Europe

DANCINGFOOL

Participants: Philippe Campagne Ibarcq, Matthieu Praquin, Vincent Lienhard, Aron Vanselow.

[DANCINGFOOL project on cordis.europa.eu](https://cordis.europa.eu/project/DANCINGFOOL)

Title: High-impedance Superconducting Circuits Enabling Fault-tolerant Quantum Computing by Wide-band 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, Karanbir Tiwana, Edoardo Lauria.

[QFT.zip project on cordis.europa.eu](https://cordis.europa.eu/project/QFT.zip)

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 from external 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.

Quantera Grant QuCos

- Program: H2020
- Type: Quantera
- Project acronym: QuCos
- Project title: Quantum Computation with Schrödinger cat states
- Duration: 2019-2023
- Coordinator: Gerhard Kirchmair, University of Innsbruck, Austria.

- Inria contacts: Zaki Leghtas and Mazyar Mirrahimi
- Other partners: ENS Lyon (France), Karlsruhe Institut of Technology (Germany), Quantum Machines (Israel), National Institute for Research and Development of Isotopic and Molecular Technologies, Romania.
- Abstract: This project seeks to establish a radically new, alternative approach to realizing the fundamental building blocks of quantum computers with superconducting qubits. In the next 3 years, we plan to employ only a handful of realistic components to realize robust error-corrected logical quantum bits. We aim to demonstrate the same level of protection provided by a few hundreds of qubits (with properties beyond the state of the art) in today's mainstream approach of the so-called surface code architecture. Our alternative approach is known as cat codes, because it employs multiple interconnected high coherence cavity modes with non-linear dissipation, to encode a qubit in superpositions of Schrödinger cat states. Our project combines realizing the quantum processor architecture as well as the control system and the protocols that drive it, building towards a full-stack error-corrected quantum computer. The partners in our collaboration form a strong synergetic group that has the full range of expertise needed to design and realize these systems, and to obtain these challenging goals. Furthermore, all partners of our project, including both industry and academia, have worked together and published works in the fields of quantum computing and quantum information processing. We aim to implement error protected qubits, fault tolerant operations, and demonstrate the scalability of this approach by realizing a repetition code. Our project will enable quantum experiments towards the ambitious and well-defined goal of constructing a logical qubit, on which we can perform gates, and most importantly, quantum error-correction (QEC).

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.
- **ANR project HAMROQS**: In the framework of the ANR program JCJC, Alain Sarlette has received a funding for his research program "High-accuracy model reduction for open quantum systems". This grant of 212k euros started on april 2019 and will run for 4 years.
- **ANR project Mecaflex**: 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 a member of the steering committee of DIM Quantip.

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific events: selection

Reviewer

- Pierre Rouchon was a referee for IEEE and IFAC conferences.
- Alain Sarlette was a referee for IEEE and IFAC conferences.

9.1.2 Journal

Member of the editorial boards

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

Reviewer - reviewing activities

- Philippe Campagne Ibarcq was a referee for PRL, PRX, Nature Physics.
- Zaki Leghtas was a referee for PRL and Nature Communications.
- Mazyar Mirrahimi was a referee for PRL and npj Quantum Information.
- Tudor-Alexandru Petrescu was a referee for Physical Review and Quantum.
- Pierre Rouchon was a referee for Journal of differential equation, PRX.
- Alain Sarlette was a referee for IEEE Transactions, PRL, PRX Quantum, PRA.
- Antoine Tilloy was a referee for PRL, PRX, Physics Letters A, and Foundations of Physics.

9.1.3 Invited talks

- Philippe Campagne Ibarcq: BBQ conference in Boulder, Colorado, on bosonic error correction.
- Philippe Campagne Ibarcq: Erlangen University (remote).
- Philippe Campagne Ibarcq: Chalmers University.
- Zaki Leghtas: Hebrew University of Jerusalem. Invited by Alex Retzker (2023).
- Zaki Leghtas: Weizmann Instiute. Invited by Fabien Lafont and Serge Rosenblum (2023).
- Zaki Leghtas: Institut Néel. Invited by Jérémie Viennot (2023).
- Zaki Leghtas: C2N. Invited by Rebeca Ribeiro-Palau (2023)
- Zaki Leghtas: Les Houches. France. Invited by Benjamin Sacépé (2023)
- Mazyar Mirrahimi: BBQ conference in Boulder, Colorado, on bosonic error correction.
- Mazyar Mirrahimi: ENS-Mitsubishi Heavy Industry meeting.
- Mazyar Mirrahimi: University of Glasgow Centre for Quantum Technology (remote) invited by Kaveh Delfanazari.
- Mazyar Mirrahimi: Workshop "Feedback control of Quantum Machines", Okinawa Institute for Science and Technology, Japan.
- Mazyar Mirrahimi: Conference "Quantum PhotonIX", Jinhua, China.

- Tudor-Alexandru Petrescu: APS March Meeting 2023 in New Orleans
- Tudor-Alexandru Petrescu: MPQ
- Tudor-Alexandru Petrescu: Université Paris-Cité
- Tudor-Alexandru Petrescu: Institut Néel, Grenoble
- Pierre Rouchon: Feedback and autonomous Quantum Error Correction (QEC). Innovations in Nonlinear Control 13-17 February 2023, IIT Bombay.
- Pierre Rouchon: Feedback and quantum error corrections: Séminaire de Mathématiques Appliquées, Collège de France, 9 juin 2023.
- Pierre Rouchon: Feedback et correction d'erreurs quantiques: Stratégie Nationale Quantique Journée du 30 mars 2023, Paris; Académie des Technologies, 21 novembre 2023, Paris.
- Antoine Tilloy: IFT Madrid.
- Antoine Tilloy: Capital Fund Management.
- Antoine Tilloy: "Entangle This 5" conference in Benasque.
- Antoine Tilloy: Maspin event in Besançon.

9.1.4 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.

9.1.5 Scientific expertise

- Pierre Rouchon 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.

9.1.6 Research administration

- Alain Sarlette has been a member of the selection committees at inria Paris (invited professors, PhD and postdoc grants).
- Philippe Campagne-Ibarcq has been a member of the selection committee at Inria Paris-Saclay for Junior Researcher (CRCN) positions.
- Mazyar Mirrahimi has been a member of the selection committee at Inria Paris for Junior Researcher (CRCN) positions.

9.2 Teaching - Supervision - Juries

9.2.1 Teaching

- 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).
- Pierre Rouchon is a member of the steering committee 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 2023 Marius Villiers. Enhancing qubit-photon interactions with anti-squeezing. Supervision Zaki Leghtas.

PhD defended in 2023 Camille Berdou. Cat-qubit: macroscopic bit-flip times. Supervision of Zaki Leghtas.

PhD defended in 2023 Christian Siegele. Quantum error correction with grid states of light. Supervision of Philippe Campagne-Ibarcq and Mazyar Mirrahimi.

PhD defended in 2023 Ronan Gautier. Efficient protection and fast gates in bosonic quantum codes. Supervision of Alain Sarlette.

PhD in progress Alvis Borgognoni. Non-local quantum dynamics. Supervision of Zaki Leghtas.

PhD in progress Ulysse Réglade. 3D cat-qubit. Supervision of Zaki Leghtas and Raphaël Lescanne.

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 Aron Vanselow. Autonomous stabilization of GKP grid states in high impedance circuits. Supervision of Philippe Campagne-Ibarcq and Mazyar Mirrahimi.

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

PhD in progress Lev-Arcady Sellem. Mathematical methods for simulation and control of open quantum systems. Supervision of Claude Le Bris and Pierre Rouchon.

PhD in progress Thiziei Aissaoui. On-chip biasing of superconducting circuits. Supervision of Alain Sarlette and Anil Murani.

PhD in progress Matthieu Praquin, Reconfigurable microwave photonics crystals based on granular superconductors. Supervision of Philippe Campagne-Ibarcq and Zaki Leghtas.

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).

9.2.3 Juries

- Zaki Leghtas has been referee for the HDR of Jean-Damien Pillet.
- Mazyar Mirrahimi has been the jury president for the PhD defense of Valentin Heyraud at Univ. Paris Cité.
- Mazyar Mirrahimi was a jury member for the PhD defense of Leo Balembois at Univ. Paris Saclay.
- Alexandru Petrescu was external reader for the PhD thesis of Xu Xiao at Yale University.
- Pierre Rouchon was referee of the "mémoire d'habilitation de François Ollivier" on Effective Formal Resolution of Systems of Algebraic Differential Equations at Université Paris-Saclay.
- Pierre Rouchon was member of the jury of the "mémoire d'habilitation de Amaury Hayat" on Stabilization of 1D evolution systems at Université Paris-Dauphine.
- Antoine Tilloy was in the PhD committee of Manuel Campos, UNIVERSIDAD AUTÓNOMA DE MADRID.

9.3 Popularization

9.3.1 Interventions

- Alain Sarlette participated in an afternoon roundtable discussion on "quantum computing" at EFREL, Villejuif.

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] J. Guillaud and M. Mirrahimi. 'Repetition Cat Qubits for Fault-Tolerant Quantum Computation'. In: *Physical Review X* (Dec. 2019). <https://arxiv.org/abs/1904.09474> - 22 pages, 11 figures. DOI: 10.1103/PhysRevX.9.041053. URL: <https://hal.inria.fr/hal-02413978>.
- [4] Z. Leghtas, S. Touzard, I. M. Pop, A. Kou, B. Vlastakis, A. Petrenko, K. M. Sliwa, A. Narla, S. Shankar, M. J. Hatridge, M. Reagor, L. Frunzio, R. J. Schoelkopf, M. Mirrahimi and M. H. Devoret. 'Confining the state of light to a quantum manifold by engineered two-photon loss'. In: *Science* 347.6224 (Feb. 2015), pp. 853–857. DOI: 10.1126/science.aaa2085. URL: <https://hal.inria.fr/hal-01240210>.
- [5] R. Lescanne, M. Villiers, T. Peronnin, A. Sarlette, M. Delbecq, B. Huard, T. Kontos, M. Mirrahimi and Z. Leghtas. 'Exponential suppression of bit-flips in a qubit encoded in an oscillator'. In: *Nature Physics* (Mar. 2020). DOI: 10.1038/s41567-020-0824-x. URL: <https://hal.archives-ouvertes.fr/hal-02526631>.
- [6] M. Mirrahimi, Z. Leghtas, V. V. Albert, S. Touzard, R. J. Schoelkopf, L. Jiang and M. H. Devoret. 'Dynamically protected cat-qubits: a new paradigm for universal quantum computation'. In: *New Journal of Physics* 16.4 (Apr. 2014), p. 045014.
- [7] N. Ofek, A. Petrenko, R. Heeres, P. Reinhold, Z. Leghtas, B. Vlastakis, Y. Liu, L. Frunzio, S. Girvin, L. Jiang, M. Mirrahimi, M. H. Devoret and R. J. Schoelkopf. 'Extending the lifetime of a quantum bit with error correction in superconducting circuits'. In: *Nature* 536 (2016), p. 5.
- [8] 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.
- [9] 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.
- [10] 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

- [11] C. Berdou, A. Murani, U. Reglade, W. C. Smith, M. Villiers, J. Palomo, M. Rosticher, A. Denis, P. Morfin, M. Delbecq, T. Kontos, N. Pankratova, F. Rautschke, T. Peronnin, L.-A. Sellem, P. Rouchon, A. Sarlette, M. Mirrahimi, P. Campagne-Ibarcq, S. Jezouin, R. Lescanne and Z. Leghtas. ‘One hundred second bit-flip time in a two-photon dissipative oscillator’. In: *PRX Quantum* 4.2 (2023), p. 020350. DOI: [10.1103/PRXQuantum.4.020350](https://doi.org/10.1103/PRXQuantum.4.020350). URL: <https://hal.science/hal-03662636>.
- [12] J. Cohen, A. Petrescu, R. Shillito and A. Blais. ‘Reminiscence of classical chaos in driven transmons’. In: *PRX Quantum* 4.2 (2023), p. 020312. DOI: [10.1103/PRXQuantum.4.020312](https://doi.org/10.1103/PRXQuantum.4.020312). URL: <https://hal.science/hal-03758792>.
- [13] L. C. Contamin, T. Cubaynes, W. Legrand, M. Margańska, M. Villiers, M. Desjardins, V. Vinet, Z. Leghtas, S. Rohart, A. Cottet, A. Thiaville, M. Dartailh, M. R. Delbecq and T. Kontos. ‘Inhomogeneous magnetic fields interacting with spinful states in a double quantum dot: Evidence for a staggered spin-orbit interaction’. In: *Physical Review B* 107.8 (15th Feb. 2023), p. 085152. DOI: [10.1103/PhysRevB.107.085152](https://doi.org/10.1103/PhysRevB.107.085152). URL: <https://hal.science/hal-04094062>.
- [14] A. Gasull, A. Tilloy, J. I. Cirac and G. Sierra. ‘Symmetries and field tensor network states’. In: *Physical Review B* 107.15 (3rd Apr. 2023), p. 155102. DOI: [10.1103/PhysRevB.107.155102](https://doi.org/10.1103/PhysRevB.107.155102). URL: <https://minesparis-psl.hal.science/hal-03858060>.
- [15] R. Gautier, M. Mirrahimi and A. Sarlette. ‘Designing High-Fidelity Zeno Gates for Dissipative Cat Qubits’. In: *PRX Quantum* 4.4 (25th Oct. 2023), p. 040316. DOI: [10.1103/PRXQuantum.4.040316](https://doi.org/10.1103/PRXQuantum.4.040316). URL: <https://inria.hal.science/hal-04378911>.
- [16] F.-M. L. Régent, C. Berdou, Z. Leghtas, J. Guillaud and M. Mirrahimi. ‘High-performance repetition cat code using fast noisy operations’. In: *Quantum* 7 (6th Dec. 2023), p. 1198. DOI: [10.22331/q-2023-12-06-1198](https://doi.org/10.22331/q-2023-12-06-1198). URL: <https://inria.hal.science/hal-03918298>.
- [17] D. Ruiz, R. Gautier, J. Guillaud and M. Mirrahimi. ‘Two-photon driven Kerr quantum oscillator with multiple spectral degeneracies’. In: *Physical Review A* 107.4 (6th Apr. 2023), p. 042407. DOI: [10.1103/PhysRevA.107.042407](https://doi.org/10.1103/PhysRevA.107.042407). URL: <https://inria.hal.science/hal-03918293>.
- [18] C. Siegele and P. Campagne-Ibarcq. ‘Robust suppression of noise propagation in GKP error-correction’. In: *Phys.Rev.A* 108.4 (2023), p. 042427. DOI: [10.1103/PhysRevA.108.042427](https://doi.org/10.1103/PhysRevA.108.042427). URL: <https://hal.science/hal-04017937>.

International peer-reviewed conferences

- [19] F.-M. L. Régent and P. Rouchon. ‘Heisenberg formulation of adiabatic elimination for open quantum systems with two time-scales’. In: 62nd IEEE Conference on Decision and Control. Singapore, Singapore, 2023. URL: <https://inria.hal.science/hal-04379140>.
- [20] L.-A. Sellem, R. Robin, P. Campagne-Ibarcq and P. Rouchon. ‘Stability and decoherence rates of a GKP qubit protected by dissipation’. In: *22nd World Congress of the International Federation of Automatic Control*. IFAC 2023 - 22nd World Congress of the International Federation of Automatic Control. Yokohama, Japan, 7th Apr. 2023. DOI: [10.48550/arXiv.2304.03806](https://doi.org/10.48550/arXiv.2304.03806). URL: <https://inria.hal.science/hal-04071008>.
- [21] M. Tokieda, C. Elouard, A. Sarlette and P. Rouchon. ‘Complete Positivity Violation in Higher-order Quantum Adiabatic Elimination’. In: *IFAC-PapersOnLine*. IFAC 2023 - 22nd World Congress of the International Federation of Automatic Control. Vol. 56. 2. Yokohama, Japan, 2023, pp. 1333–1338. DOI: [10.1016/j.ifacol.2023.10.1779](https://doi.org/10.1016/j.ifacol.2023.10.1779). URL: <https://inria.hal.science/hal-04379080>.

Conferences without proceedings

- [22] L. Paletta, A. Leverrier, A. Sarlette, M. Mirrahimi and C. Vuillot. ‘Robust sparse IQP sampling in constant depth’. In: QIP2024. Taipei, Taiwan, 20th July 2023. URL: <https://hal.science/hal-04320801>.

- [23] L. Paletta, A. Leverrier, A. Sarlette, M. Mirrahimi and C. Vuillot. ‘Robust sparse IQP sampling in constant depth’. In: QIP2024 The international conference on Quantum Information Processing. Taipei, Taiwan, 20th July 2023. URL: <https://hal.science/hal-04312163>.

Scientific book chapters

- [24] J. Guillaud, J. Cohen and M. Mirrahimi. ‘Quantum computation with cat qubits’. In: *SciPost Physics Lecture Notes*. 2019-07: Quantum Information Machines Collection in the Les Houches Summer School Lecture Notes Series. 16th June 2023, p. 72. DOI: [10.21468/SciPostPhysLectNotes.72](https://doi.org/10.21468/SciPostPhysLectNotes.72). URL: <https://inria.hal.science/hal-03918283>.

Edition (books, proceedings, special issue of a journal)

- [25] P. Guilmin, P. Rouchon and A. Tilloy, eds. *Correlation functions for realistic continuous quantum measurement*. IFAC-PapersOnLine. Vol. 56. 2. 22nd Nov. 2023, pp. 5164–5170. DOI: [10.1016/j.ifacol.2023.10.110](https://doi.org/10.1016/j.ifacol.2023.10.110). URL: <https://hal.science/hal-03882949>.

Doctoral dissertations and habilitation theses

- [26] C. Berdou. ‘Macroscopic bit-flip times in two-photon dissipative oscillator’. Université Paris sciences et lettres, 14th Mar. 2023. URL: <https://pastel.hal.science/tel-04235044>.
- [27] R. Gautier. ‘High-Fidelity Control and Stabilization of Cat Qubits’. Inria Paris, 4th Dec. 2023. URL: <https://hal.science/tel-04362128>.
- [28] C. Siegele. ‘Robust suppression of back-propagating noise in GKP error syndrome measurements’. ENS Paris - Ecole Normale Supérieure de Paris, 24th Feb. 2023. URL: <https://theses.hal.science/tel-04385083>.
- [29] M. Villiers. ‘Dynamically Enhancing Qubit-Photon Interactions with Anti-Squeezing’. Sorbonne Université, 15th May 2023. URL: <https://hal.science/tel-04209718>.

Reports & preprints

- [30] V. Martin and A. Sarlette. *Stabilization of approximate GHZ state with quasi-local couplings*. 22nd June 2023. URL: <https://hal.science/hal-04137276>.
- [31] 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*. 24th July 2023. URL: <https://hal.science/hal-04169999>.
- [32] F.-M. L. Régent and P. Rouchon. *Adiabatic elimination for composite open quantum systems: reduced model formulation and numerical simulations*. 8th Jan. 2024. URL: <https://inria.hal.science/hal-04379147>.
- [33] U. Réglade, A. Bocquet, R. Gautier, 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. Jezouin and Z. Leghtas. *Quantum control of a cat-qubit with bit-flip times exceeding ten seconds*. 13th July 2023. URL: <https://hal.science/hal-04189479>.
- [34] R. Robin, P. Rouchon and L.-A. Sellem. *Convergence of bipartite open quantum systems stabilized by reservoir engineering*. 16th Nov. 2023. URL: <https://inria.hal.science/hal-04379101>.
- [35] L.-A. Sellem, A. Sarlette, Z. Leghtas, M. Mirrahimi, P. Rouchon and P. Campagne-Ibarcq. *A GKP qubit protected by dissipation in a high-impedance superconducting circuit driven by a microwave frequency comb*. 3rd Apr. 2023. DOI: [10.48550/arXiv.2304.01425](https://doi.org/10.48550/arXiv.2304.01425). URL: <https://inria.hal.science/hal-04070996>.
- [36] W. C. Smith, A. Borgognoni, M. Villiers, E. Roverc’H, J. Palomo, M. Delbecq, T. Kontos, P. Campagne-Ibarcq, B. Douçot and Z. Leghtas. *Spectral signature of high-order photon processes mediated by Cooper-pair pairing*. 22nd Dec. 2023. URL: <https://hal.science/hal-04387016>.

- [37] 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-oscillator interactions with anti-squeezing*. 2nd Jan. 2023. URL: <https://inria.hal.science/hal-03918303>.
- [38] D. Willsch, D. Rieger, P. Winkel, M. Willsch, C. Dickel, J. Krause, Y. Ando, R. Lescanne, Z. Leghtas, N. T. Bronn, P. Deb, O. Lanes, Z. K. Mineev, 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. P. Divincenzo, K. Michielsen, G. Catelani and I. M. Pop. *Observation of Josephson Harmonics in Tunnel Junctions*. 23rd Aug. 2023. URL: <https://hal.science/hal-04387195>.

10.3 Cited publications

- [39] B. Abdo, O. Jinka, N. T. Bronn, S. Olivadese and M. Brink. ‘On-chip single-pump interferometric Josephson isolator for quantum measurements’. In: *arXiv preprint arXiv:2006.01918* (2020).
- [40] H. Amini, C. Pellegrini and P. Rouchon. ‘Stability of continuous-time quantum filters with measurement imperfections’. In: *Russian Journal of Mathematical Physics* 21 (2014), pp. 297–315.
- [41] H. Amini, M. Mirrahimi and P. Rouchon. ‘Stabilization of a delayed quantum system: the Photon Box case-study’. In: *IEEE Trans. Automatic Control* 57.8 (2012), pp. 1918–1930.
- [42] H. Amini, A. Somaraju, I. Dotsenko, C. Sayrin, M. Mirrahimi and P. Rouchon. ‘Feedback stabilization of discrete-time quantum systems subject to non-demolition measurements with imperfections and delays’. In: *Automatica* 49.9 (2013), pp. 2683–2692.
- [43] S. Attal, A. Joye and C.-A. Pillet, eds. *Open Quantum Systems III: Recent Developments*. Springer, Lecture notes in Mathematics 1880, 2006.
- [44] A. Barchielli and M. Gregoratti. *Quantum Trajectories and Measurements in Continuous Time: the Diffusive Case*. Springer Verlag, 2009.
- [45] J. Barreiro, M. Muller, P. Schindler, D. Nigg, T. Monz, M. Chwalla, M. Hennrich, C. Roos, P. Zoller and R. Blatt. ‘An open-system quantum simulator with trapped ions’. In: *Nature* 470 (2011). 486.
- [46] S. Barzanjeh, M. Wulf, M. Peruzzo, M. Kalae, P. Dieterle, O. Painter and J. M. Fink. ‘Mechanical on-chip microwave circulator’. In: *Nature communications* 8.1 (2017), pp. 1–7.
- [47] V. Belavkin. ‘Quantum stochastic calculus and quantum nonlinear filtering’. In: *Journal of Multivariate Analysis* 42.2 (1992), pp. 171–201.
- [48] T. Benoist and C. Pellegrini. ‘Large Time Behavior and Convergence Rate for Quantum Filters Under Standard Non Demolition Conditions’. In: *Communications in Mathematical Physics* (2014), pp. 1–21. URL: <http://dx.doi.org/10.1007/s00220-014-2029-6>.
- [49] G. Birkhoff. ‘Extensions of Jentzsch’s theorem’. In: *Trans. Amer. Math. Soc.* 85 (1957), pp. 219–227.
- [50] S. Bolognani and F. Ticozzi. ‘Engineering stable discrete-time quantum dynamics via a canonical QR decomposition’. In: *IEEE Trans. Autom. Control* 55 (2010).
- [51] V. Braginski and F. Khalili. *Quantum Measurements*. Cambridge University Press, 1992.
- [52] P. Campagne-Ibarcq, L. Bretheau, E. Flurin, A. Auffèves, F. Mallet and B. Huard. ‘Observing Interferences between Past and Future Quantum States in Resonance Fluorescence’. In: *Phys. Rev. Lett.* 112 (18 May 2014). 180402. DOI: [10.1103/PhysRevLett.112.180402](https://doi.org/10.1103/PhysRevLett.112.180402). URL: <http://link.aps.org/doi/10.1103/PhysRevLett.112.180402>.
- [53] P. Campagne-Ibarcq, E. Flurin, N. Roch, D. Darson, P. Morfin, M. Mirrahimi, M. H. Devoret, F. Mallet and B. Huard. ‘Persistent Control of a Superconducting Qubit by Stroboscopic Measurement Feedback’. In: *Phys. Rev. X* 3 (2013). 021008.
- [54] H. Carmichael. *An Open Systems Approach to Quantum Optics*. Springer-Verlag, 1993.
- [55] H. Carmichael. *Statistical Methods in Quantum Optics 2: Non-Classical Fields*. Springer, 2007.
- [56] J. Carr. *Application of Center Manifold Theory*. Springer, 1981.
- [57] B. J. Chapman, E. I. Rosenthal, J. Kerckhoff, B. A. Moores, L. R. Vale, J. Mates, G. C. Hilton, K. Lalumiere, A. Blais and K. Lehnert. ‘Widely tunable on-chip microwave circulator for superconducting quantum circuits’. In: *Physical Review X* 7.4 (2017), p. 041043.

- [58] J. Cohen and M. Mirrahimi. ‘Dissipation-induced continuous quantum error correction for superconducting circuits’. In: *Phys. Rev. A* 90 (2014), p. 062344.
- [59] J. Dalibard, Y. Castin and K. Mølmer. ‘Wave-function approach to dissipative processes in quantum optics’. In: *Phys. Rev. Lett.* 68.5 (1992), pp. 580–583.
- [60] M. H. Devoret, A. Wallraff and J. Martinis. *Superconducting Qubits: A Short Review*. arXiv:cond-mat/0411174. 2004.
- [61] N. Didier, J. Guillaud, S. Shankar and M. Mirrahimi. ‘Remote entanglement stabilization and concentration by quantum reservoir engineering’. In: *Physical Review A* (July 2018). <https://arxiv.org/abs/1703.03379> - 5 pages, 4 figures. DOI: 10.1103/PhysRevA.98.012329. URL: <https://hal.inria.fr/hal-01652766>.
- [62] I. Dotsenko, M. Mirrahimi, M. Brune, S. Haroche, J.-M. Raimond and P. Rouchon. ‘Quantum feedback by discrete quantum non-demolition measurements: towards on-demand generation of photon-number states’. In: *Physical Review A* 80: 013805-013813 (2009).
- [63] N. Fenichel. ‘Geometric singular perturbation theory for ordinary differential equations’. In: *J. Diff. Equations* 31 (1979), pp. 53–98.
- [64] V. S. Ferreira, J. Banker, A. Sipahigil, M. H. Matheny, A. J. Keller, E. Kim, M. Mirhosseini and O. Painter. ‘Collapse and Revival of an Artificial Atom Coupled to a Structured Photonic Reservoir’. In: *arXiv preprint arXiv:2001.03240* (2020).
- [65] J. Gambetta and H. M. Wiseman. ‘State and dynamical parameter estimation for open quantum systems’. In: *Phys. Rev. A* 64.4 (Sept. 2001). 042105. URL: <http://link.aps.org/doi/10.1103/PhysRevA.64.042105>.
- [66] S. Gammelmark, B. Julsgaard and K. Mølmer. ‘Past Quantum States of a Monitored System’. In: *Phys. Rev. Lett.* 111.16 (Oct. 2013). 160401. URL: <http://link.aps.org/doi/10.1103/PhysRevLett.111.160401>.
- [67] C. Gardiner and P. Zoller. *Quantum Noise*. third. Springer, 2010.
- [68] S. Gaubert and Z. Qu. ‘Checking the strict positivity of Kraus maps is NP-hard’. In: *arXiv:1402.1429* (2014).
- [69] S. Gaubert and Z. Qu. ‘The contraction rate in Thompson’s part metric of order-preserving flows on a cone - Application to generalized Riccati equations’. In: *Journal of Differential Equations* 256.8 (Apr. 2014), pp. 2902–2948. URL: <http://www.sciencedirect.com/science/article/pii/S0022039614000424>.
- [70] K. Geerlings, Z. Leghtas, I. Pop, S. Shankar, L. Frunzio, R. Schoelkopf, M. Mirrahimi and M. H. Devoret. ‘Demonstrating a Driven Reset Protocol of a Superconducting Qubit’. In: *Phys. Rev. Lett.* 110 (2013). 120501.
- [71] D. Gottesman, A. Kitaev and J. Preskill. ‘Encoding a qubit in an oscillator’. In: *Phys. Rev. A* 64 (2001). 012310.
- [72] C. Guerlin, J. Bernu, S. Deléglise, C. Sayrin, S. Gleyzes, S. Kuhr, M. Brune, J.-M. Raimond and S. Haroche. ‘Progressive field-state collapse and quantum non-demolition photon counting’. In: *Nature* 448 (2007), pp. 889–893.
- [73] R. van Handel. ‘The stability of quantum Markov filters’. In: *Infin. Dimens. Anal. Quantum Probab. Relat. Top.* 12 (2009), pp. 153–172.
- [74] S. Haroche and J.-M. Raimond. *Exploring the Quantum: Atoms, Cavities and Photons*. Oxford University Press, 2006.
- [75] M. Hatridge, S. Shankar, M. Mirrahimi, F. Schackert, K. Geerlings, T. Brecht, K. Sliwa, B. Abdo, L. Frunzio, S. Girvin, R. Schoelkopf and M. H. Devoret. ‘Quantum back-action of an individual variable-strength measurement’. In: *Science* 339 (2013), pp. 178–181.
- [76] E. Holland, B. Vlastakis, R. Heeres, M. J. Reagor, U. Vool, Z. Leghtas, L. Frunzio, G. Kirchmair, M. H. Devoret, M. Mirrahimi and R. Schoelkopf. ‘Single-photon-resolved cross-Kerr interaction for autonomous stabilization of photon-number states’. In: *Phys. Rev. Lett.* 115 (2015), p. 180501.

- [77] T. Kato. *Perturbation Theory for Linear Operators*. Springer, 1966.
- [78] E. Knill, R. Laflamme and G. Milburn. ‘A scheme for efficient quantum computation with linear optics’. In: *Nature* 409 (2001). 46.
- [79] H. Krauter, C. Muschik, K. Jensen, W. Wasilewski, J. Petersen, J. Cirac and E. Polzik. ‘Entanglement Generated by Dissipation and Steady State Entanglement of Two Macroscopic Objects’. In: *Phys. Rev. Lett.* 107 (2011). 080503.
- [80] Z. Leghtas, G. Kirchmair, B. Vlastakis, M. H. Devoret, R. J. Schoelkopf and M. Mirrahimi. ‘Deterministic protocol for mapping a qubit to coherent state superpositions in a cavity’. In: *Phys. Rev. A* 87 (2013). 042315.
- [81] 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 (2013). 120501.
- [82] Z. Leghtas, A. Sarlette and P. Rouchon. ‘Adiabatic passage and ensemble control of quantum systems’. In: *J. Phys. B* 44 (2011). 154017.
- [83] Z. Leghtas, U. Vool, S. Shankar, M. Hatridge, S. Girvin, M. H. Devoret and M. Mirrahimi. ‘Stabilizing a Bell state of two superconducting qubits by dissipation engineering’. In: *Phys. Rev. A* 88 (2013). 023849.
- [84] J.-S. Li and N. Khaneja. ‘Ensemble control of Bloch equations’. In: *IEEE Trans. Autom. Control* 54 (2009), pp. 528–536.
- [85] Y. a. J. G. Lin, F. Reiter, T. Tan, R. Bowler, A. Sorensen, D. Leibfried and D. Wineland. ‘Dissipative production of a maximally entangled steady state of two quantum bits’. In: *Nature* 504 (2013), pp. 415–418.
- [86] S. Lloyd. ‘Coherent quantum feedback’. In: *Phys. Rev. A* 62 (2000). 022108.
- [87] A. C. Mahoney, J. I. Colless, L. Peeters, S. J. Pauka, E. J. Fox, X. Kou, L. Pan, K. L. Wang, D. Goldhaber-Gordon and D. J. Reilly. ‘Zero-field edge plasmons in a magnetic topological insulator’. In: *Nature communications* 8.1 (2017), pp. 1–7.
- [88] L. Mazzarella, A. Sarlette and F. Ticozzi. ‘Consensus for quantum networks: from symmetry to gossip iterations’. In: *IEEE Trans. Automat. Control* (2014). in press.
- [89] M. Mirrahimi, B. Huard and M. H. Devoret. ‘Strong measurement and quantum feedback for persistent Rabi oscillations in circuit QED experiments’. In: *IEEE Conference on Decision and Control*. IEEE Conference on Decision and Control, 2012.
- [90] K. Murch, U. Vool, D. Zhou, S. Weber, S. Girvin and I. Siddiqi. ‘Cavity-assisted quantum bath engineering’. In: *Phys. Rev. Lett.* 109 (2012). 183602.
- [91] A. Negretti and K. Mölmer. ‘Estimation of classical parameters via continuous probing of complementary quantum observables’. In: *New Journal of Physics* 15.12 (2013). 125002. URL: <http://stacks.iop.org/1367-2630/15/i=12/a=125002>.
- [92] H. Nurdin, M. James and I. Petersen. ‘Coherent quantum LQG control’. In: *Automatica* 45 (2009), pp. 1837–1846.
- [93] B. Peaudecerf, T. Rybarczyk, S. Gerlich, S. Gleyzes, J.-M. Raimond, S. Haroche, I. Dotsenko and M. Brune. ‘Adaptive Quantum Nondemolition Measurement of a Photon Number’. In: *Phys. Rev. Lett.* 112.8 (Feb. 2014). 080401. DOI: [10.1103/PhysRevLett.112.080401](https://doi.org/10.1103/PhysRevLett.112.080401). URL: <http://link.aps.org/doi/10.1103/PhysRevLett.112.080401>.
- [94] G. A. Peterson, F. Lecocq, K. Cicak, R. W. Simmonds, J. Aumentado and J. D. Teufel. ‘Demonstration of efficient nonreciprocity in a microwave optomechanical circuit’. In: *Physical Review X* 7.3 (2017), p. 031001.
- [95] D. Petz. ‘Monotone Metrics on matrix spaces’. In: *Linear Algebra and its Applications* 244 (1996), pp. 81–96.
- [96] J. Poyatos, J. Cirac and P. Zoller. ‘Quantum Reservoir Engineering with Laser Cooled Trapped Ions’. In: *Phys. Rev. Lett.* 77.23 (1996), pp. 4728–4731.

- [97] D. M. Pozar. *Microwave engineering*. John Wiley & Sons, 2011.
- [98] M. Reagor, W. Pfaff, C. Axline, R. W. Heeres, N. Ofek, K. Sliwa, E. Holland, C. Wang, J. Blumoff, K. Chou et al. ‘Quantum memory with millisecond coherence in circuit QED’. In: *Physical Review B* 94.1 (2016), p. 014506.
- [99] D. Reeb, M. J. Kastoryano and M. M. Wolf. ‘Hilbert’s projective metric in quantum information theory’. In: *Journal of Mathematical Physics* 52.8 (Aug. 2011). 082201. arXiv: [1102.5170 \[math-ph\]](https://arxiv.org/abs/1102.5170). URL: <http://dx.doi.org/10.1063/1.3615729>.
- [100] M. D. Reed, B. R. Johnson, A. A. Houck, L. DiCarlo, J. M. Chow, D. I. Schuster, L. Frunzio and R. J. Schoelkopf. ‘Fast reset and suppressing spontaneous emission of a superconducting qubit’. In: *Applied Physics Letters* 96.20 (2010), p. 203110.
- [101] D. Ristè, J. Leeuwen, H.-S. Ku, K. Lehnert and L. DiCarlo. ‘Initialization by measurement of a superconducting quantum bit circuit’. In: *Phys. Rev. Lett.* 109 (2012). 050507.
- [102] N. Roch, E. Flurin, F. Nguyen, P. Morfin, P. Campagne-Ibarcq, M. H. Devoret and B. Huard. ‘Widely tunable, non-degenerate three-wave mixing microwave device operating near the quantum limit’. In: *Phys. Rev. Lett.* 108 (2012). 147701.
- [103] P. Rouchon. ‘Fidelity is a Sub-Martingale for Discrete-Time Quantum Filters’. In: *IEEE Transactions on Automatic Control* 56.11 (2011), pp. 2743–2747.
- [104] A. Roy, Z. Leghtas, A. Stone, M. Devoret and M. Mirrahimi. ‘Continuous generation and stabilization of mesoscopic field superposition states in a quantum circuit’. In: *Phys. Rev. A* 91 (2015), p. 013810.
- [105] A. Sarlette, Z. Leghtas, M. Brune, J.-M. Raimond and P. Rouchon. ‘Stabilization of nonclassical states of one- and two-mode radiation fields by reservoir engineering’. In: *Phys. Rev. A* 86 (2012). 012114.
- [106] D. Schuster, A. Houck, J. Schreier, A. Wallraff, J. Gambetta, A. Blais, L. Frunzio, J. Majer, B. Johnson, M. H. Devoret, S. Girvin and R. J. Schoelkopf. ‘Resolving photon number states in a superconducting circuit’. In: *Nature* 445 (2007), pp. 515–518.
- [107] R. Sepulchre, A. Sarlette and P. Rouchon. ‘Consensus in non-commutative spaces’. In: *Decision and Control (CDC), 2010 49th IEEE Conference on*. 2010, pp. 6596–6601.
- [108] S. a. M. H. Shankar, Z. Leghtas, K. Sliwa, A. Narla, U. Vool, S. Girvin, L. Frunzio, M. Mirrahimi and M. H. Devoret. ‘Autonomously stabilized entanglement between two superconducting quantum bits’. In: *Nature* 504 (2013), pp. 419–422.
- [109] P. Shor. ‘Scheme for reducing decoherence in quantum memory’. In: *Phys. Rev. A* 52 (1995), pp. 2493–2496.
- [110] K. Sliwa, M. Hatridge, A. Narla, S. Shankar, L. Frunzio, R. Schoelkopf and M. Devoret. ‘Reconfigurable Josephson circulator/directional amplifier’. In: *Physical Review X* 5.4 (2015), p. 041020.
- [111] A. Somaraju, I. Dotsenko, C. Sayrin and P. Rouchon. ‘Design and Stability of Discrete-Time Quantum Filters with Measurement Imperfections’. In: *American Control Conference*. 2012, pp. 5084–5089.
- [112] A. Somaraju, M. Mirrahimi and P. Rouchon. ‘Approximate stabilization of infinite dimensional quantum stochastic system’. In: *Reviews in Mathematical Physics* 25 (2013). 1350001.
- [113] A. Steane. ‘Error Correcting Codes in Quantum Theory’. In: *Phys. Rev. Lett* 77.5 (1996).
- [114] L. Sun, A. Petrenko, Z. Leghtas, B. Vlastakis, G. Kirchmair, K. Sliwa, A. Narla, M. Hatridge, S. Shankar, J. Blumoff, L. Frunzio, M. Mirrahimi, M. H. Devoret and R. J. Schoelkopf. ‘Tracking photon jumps with repeated quantum non-demolition parity measurements’. In: *Nature* 511 (2014), pp. 444–448.
- [115] T. Thorbeck, S. Zhu, E. Leonard Jr, R. Barends, J. Kelly, J. M. Martinis and R. McDermott. ‘Reverse isolation and backaction of the SLUG microwave amplifier’. In: *Physical Review Applied* 8.5 (2017), p. 054007.

-
- [116] J. Tsitsiklis. 'Problems in decentralized decision making and computation'. In: *PhD Thesis, MIT* (1984).
 - [117] R. Vijay, C. Macklin, D. Slichter, S. Weber, K. Murch, R. Naik, A. Korotkov and I. Siddiqi. 'Stabilizing Rabi oscillations in a superconducting qubit using quantum feedback'. In: *Nature* 490 (2012), pp. 77–80.
 - [118] G. Viola and D. P. DiVincenzo. 'Hall effect gyrators and circulators'. In: *Physical Review X* 4.2 (2014), p. 021019.
 - [119] L. Viola, E. Knill and S. Lloyd. 'Dynamical decoupling of open quantum system'. In: *Phys. Rev. Lett.* 82 (1999), pp. 2417–2421.
 - [120] B. Vlastakis, G. Kirchmair, Z. Leghtas, S. Nigg, L. Frunzio, S. Girvin, M. Mirrahimi, M. H. Devoret and R. J. Schoelkopf. 'Deterministically encoding quantum information using 100-photon Schrödinger cat states'. In: *Science* 342 (2013), pp. 607–610.
 - [121] X. Zhou, I. Dotsenko, B. Peaudecerf, T. Rybarczyk, C. Sayrin, S. Gleyzes, J.-M. Raimond, M. Brune and S. Haroche. 'Field locked to Fock state by quantum feedback with single photon corrections'. In: *Physical Review Letter* 108 (2012). 243602.