# Quantum Information Science and Technology (QIST) @Unimib

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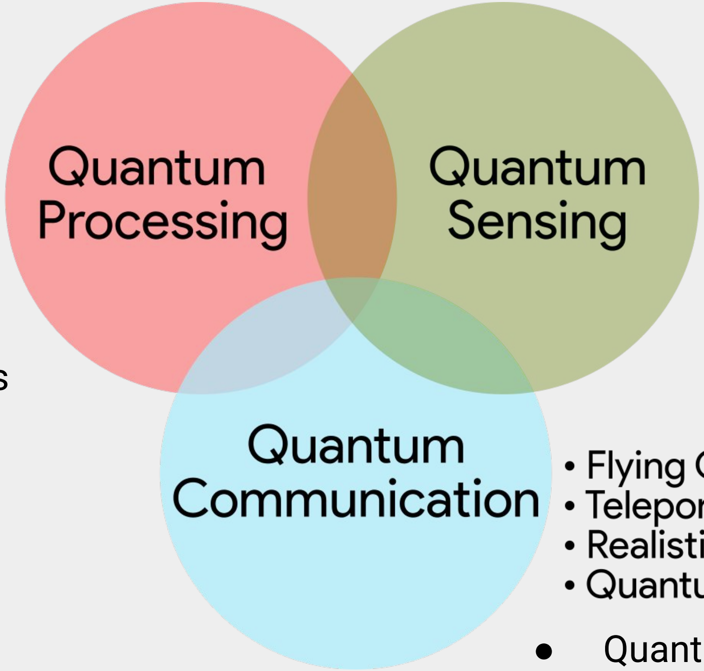
*Bicocca Quantum Technologies (BiQuTe) Centre*

# Quantum Information Science and Technology

Quantum Information Science and Technology harnesses the power of quantum mechanics for understanding, design, construction and investigation of quantum information processing systems, such as **quantum computers**, quantum communication networks, and **quantum sensors**;

- Algorithms
- Hybrid computing
- Compilers
- Error correction
- Optimization
- QC platform
- Device technology
- Materials challenges
- Complex molecules

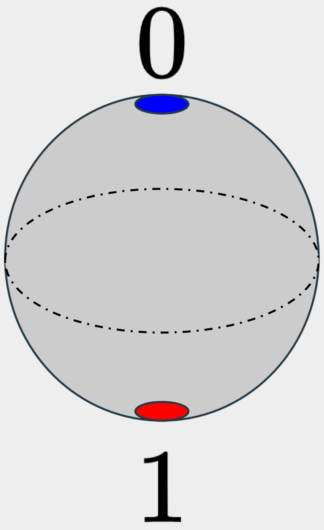



- Precision metrology
- Measurement efficiency/sensitivity
- New detectors for sensing/imaging
- Materials challenges
- Dark Matter search

- Flying Qbits/quantum networks
- Teleportation
- Realistic QC architectures
- Quantum memory
- Quantum cryptography

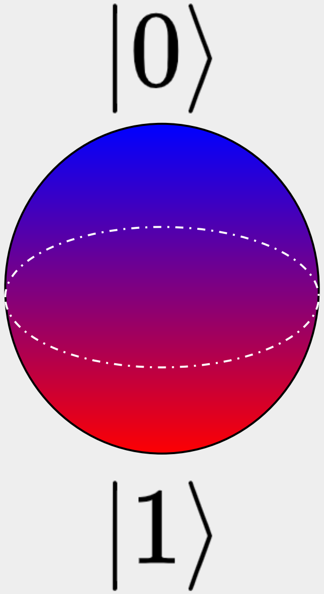
# Qubit - The building block of Quantum Information

Qubits are two-state quantum systems
They are the quantum mechanical analogous of the bit




**Classical Bit**

**Quantum Bit**



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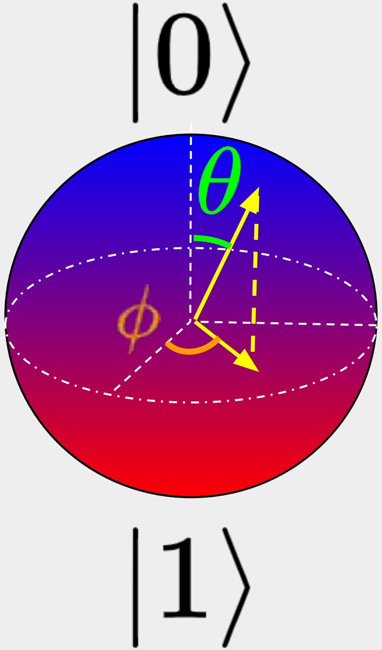
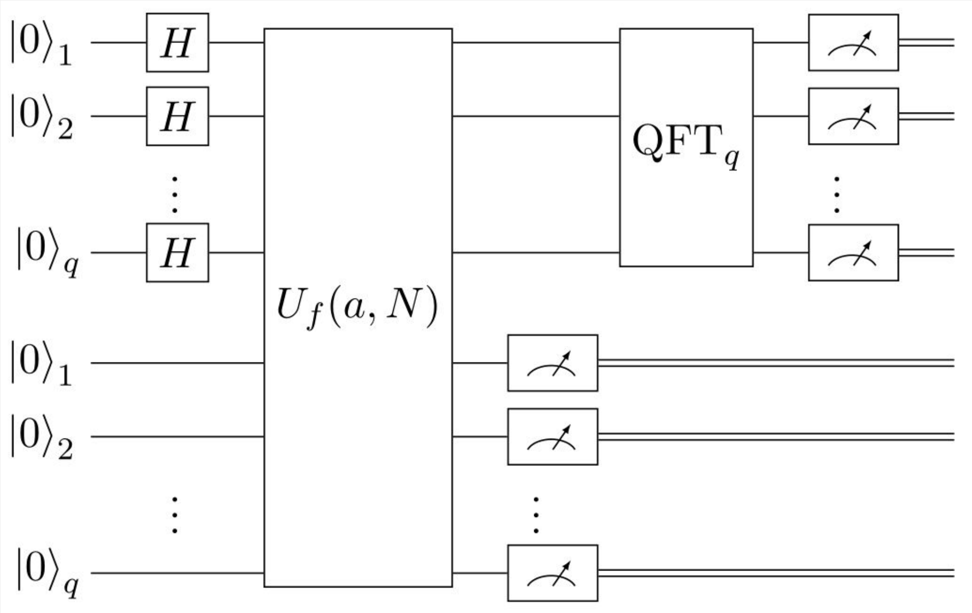


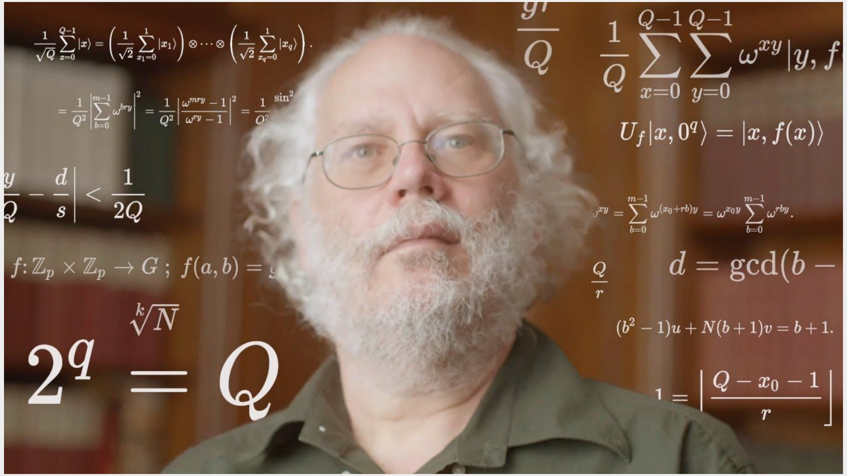

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$= \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

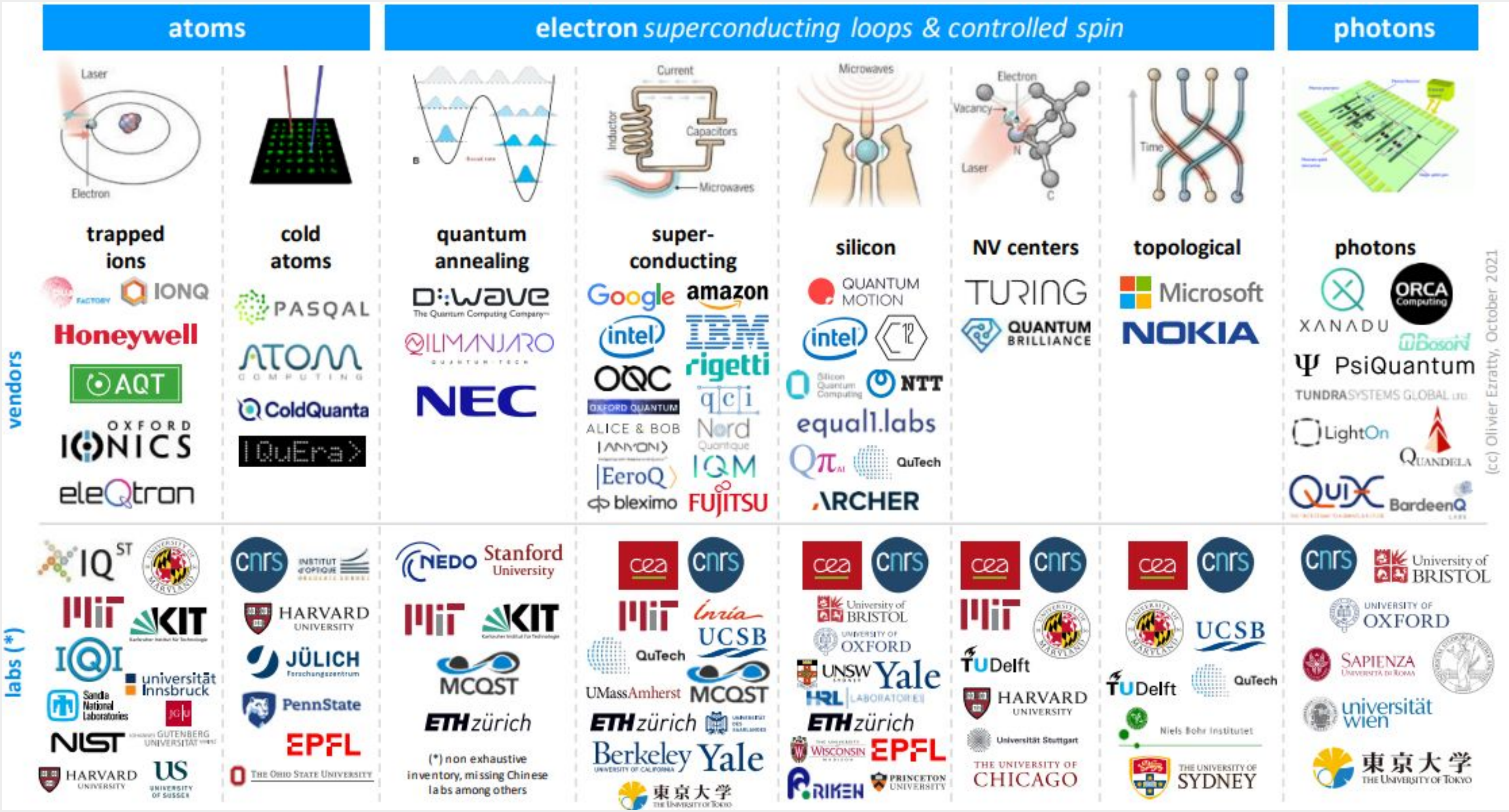
# Shor's algorithm: the first theorized Quantum Advantage

It’s a quantum algorithm for finding the **prime factors** of an integer. Shor's algorithm is **asymptotically faster than classical** factoring algorith, which works in sub-exponential time

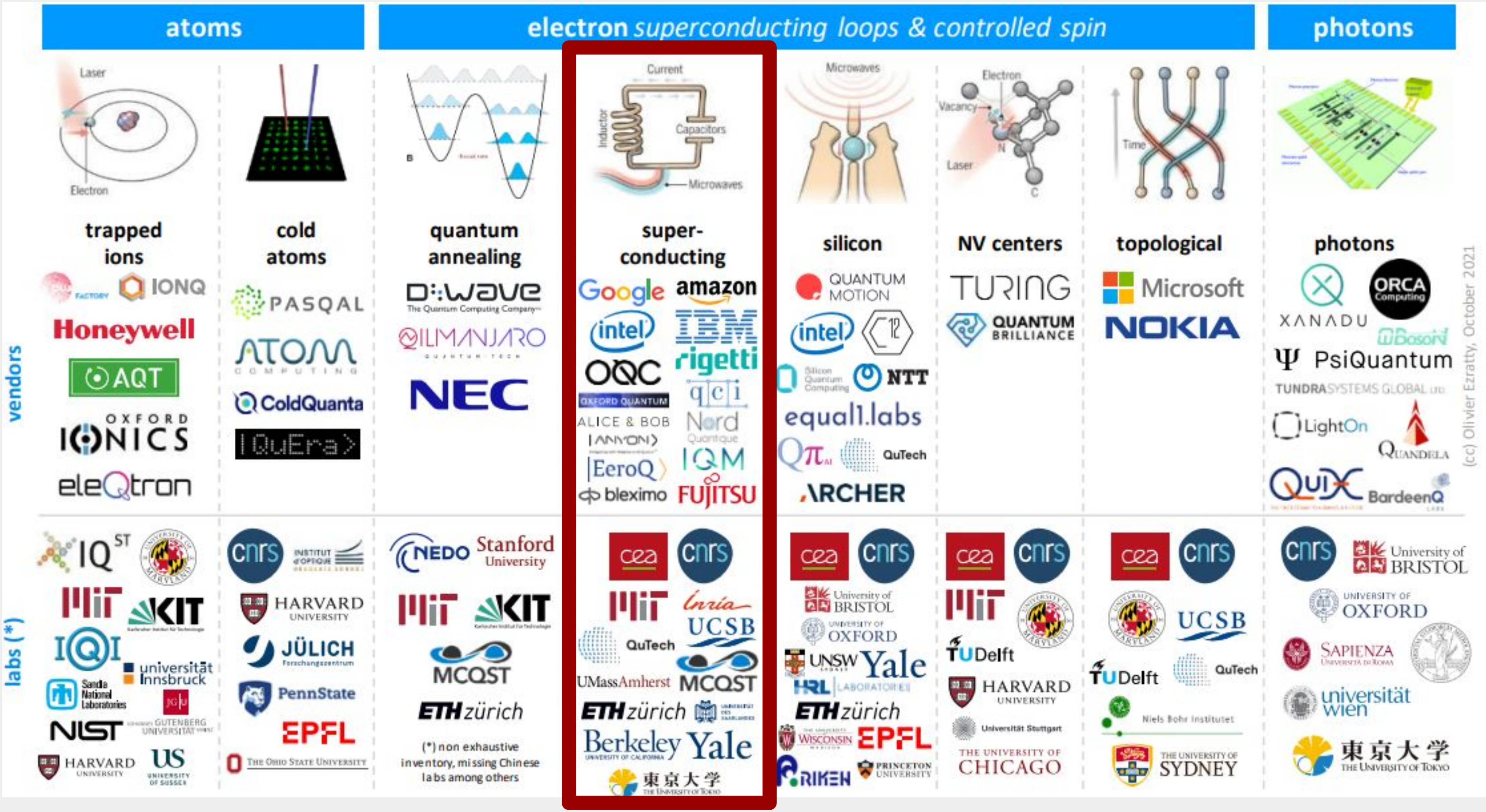


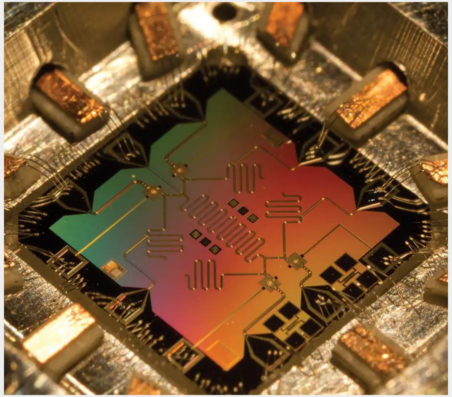
# Qubit - The building block of Quantum Information

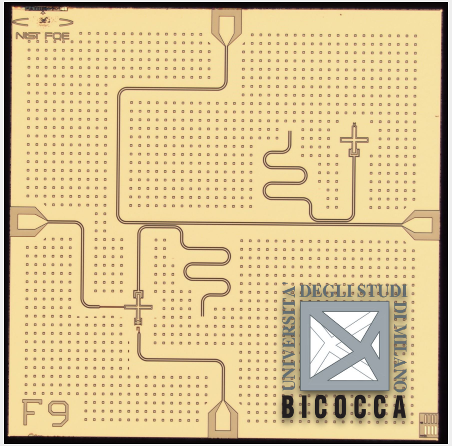


# Qubit - The building block of Quantum Information



# Superconducting Qubits



# QIST at **Unimib**

The University of Milano-Bicocca and the Department of Physics are member and leads project funded by

- the **Bicocca Quantum Technologies** (BiQuTe) Centre;
- the **National Quantum Science and Technology Institute** (NQSTI);
- the **National Centre for HPC, big data and quantum computing** (ICSC);
- the **Italian Institute of Nuclear Physics** (INFN);
- the **European Union**;
- the **CERN DRD5/RDq** roadmap for quantum sensing for particle physics;

The main activities carried out at the department of physics are:

1. Design and simulation **qubit array for quantum computing and quantum sensing**;
2. Development of **quantum sensing techniques for light dark matter search**;
3. Development of **innovative hardware and software for qubit array readout and characterization;**
4. Design and simulation of **quantum limited parametric amplifier** for **qubit read out** and **as squeezed microwave radiation source**;
5. Development of **quantum algorithms for simulations, machine learning classification, and error correction/mitigation**;

# Theses proposals in quantum “hardware”

# Superconducting qubit design and simulation

Superconducting qubit chips usually consist of a 2D architecture in which a thin film of superconducting material (e.g. Al, Nb) lay on a high-resistivity substrate (e.g. Si).

The qubit geometry must be carefully tuned to limit loss channels, i.e. spurious couplings between the qubit and the environment, which limits its coherence time. Two very important loss channels are called Purcell decay and two-level system (TLS) loss.

In this thesis **we will understand the basics of superconducting qubit design** and **create a simple layout**, learning how to simulate the most important qubit physical properties and loss channels, attempting to maximize the expected coherence time.

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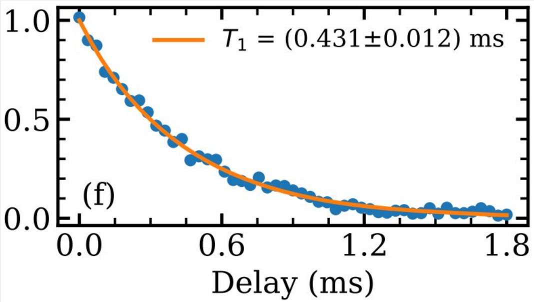
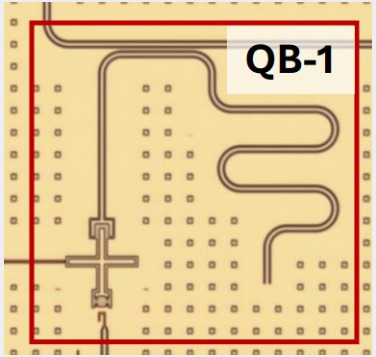



Qubit relaxation time example
*https://www.nature.com/articles/s41534-021-00510-2*




Qubit chip example
*https://arxiv.org/abs/2409.05988*

# Fast qubit readout with resonator reset

Superconducting resonators are fundamental devices in quantum technologies. One of their most widespread uses is in the readout of superconducting qubits.

In quantum computing all operations must be as fast as possible, since qubits have limited coherence times. However, **at the end of a basic readout** schema **the resonator is left in an excited state**, and waiting for its relaxation to the ground state can become dead time in some applications.

In this thesis you will learn about and simulate the effect of different readout pulses designed to reset the readout resonator as fast as possible.

As a bonus, you could investigate how much and for which applications these methods are more beneficial, for example by computing the improvement in cycle time for a quantum error correction protocol.

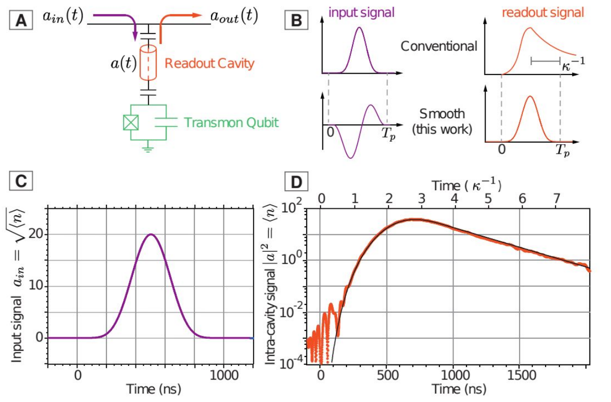



FIG. 1. (A) Simplified circuit diagram for the demonstration of dispersive readout. (B) The sketch illustrates a conventional readout with long exponential decay of the intra-cavity field and readout with shaped pulses that reset the resonator to its initial state after the pulse. $T_p$ is the pulse duration. (C and D) The conventional input read-out pulse $a_{in}(t)$ of $T_p = 1$ µs causes a long exponential decay of the intra-cavity field $|a(t)|^2$. The solid line represents a fit of experimental data to a classic response theory, see Eq.(1).

https://arxiv.org/abs/2406.04891

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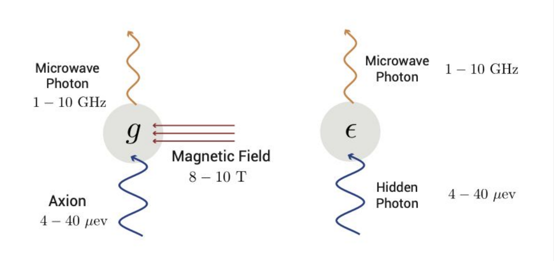
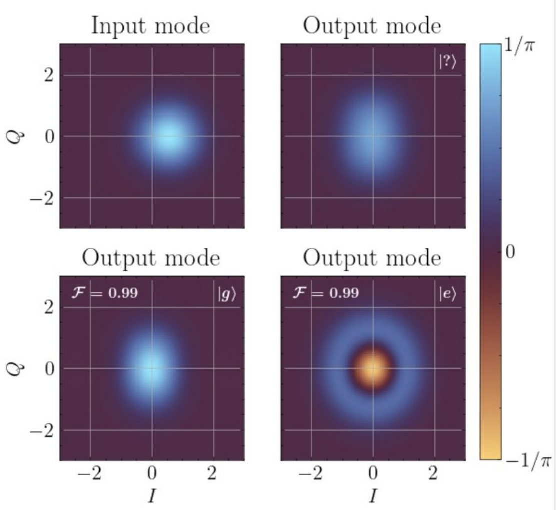
# Sensitivity analysis of a multi-qubit RF cavity experiment with QND parity detection for light dark matter searches

Superconducting qubits can also be exploited as highly sensitive **quantum sensors** for fundamental physics. They offer promising opportunities for the direct detection of light dark matter candidates such as **axions** and **dark photons** in the mass range of tens of μeV. These particles can convert into **microwave photons**, which may be stored in high-quality resonant cavities.

A compelling detection strategy consists of coupling **one or more superconducting qubits** to a microwave storage cavity in order to perform **quantum non-demolition** (QND) measurements of the coherent state.

The goal of this thesis is to perform a comprehensive sensitivity analysis. The study will investigate how the **sensitivity** scales with the number of coupled qubits and relevant experimental parameters, identify the dominant **noise sources** and **fundamental limitations**, and determine the regions of parameter space that can be probed in comparison with existing and proposed experiments. Possible strategies to mitigate these limitations and optimize the experimental design can also be explored.

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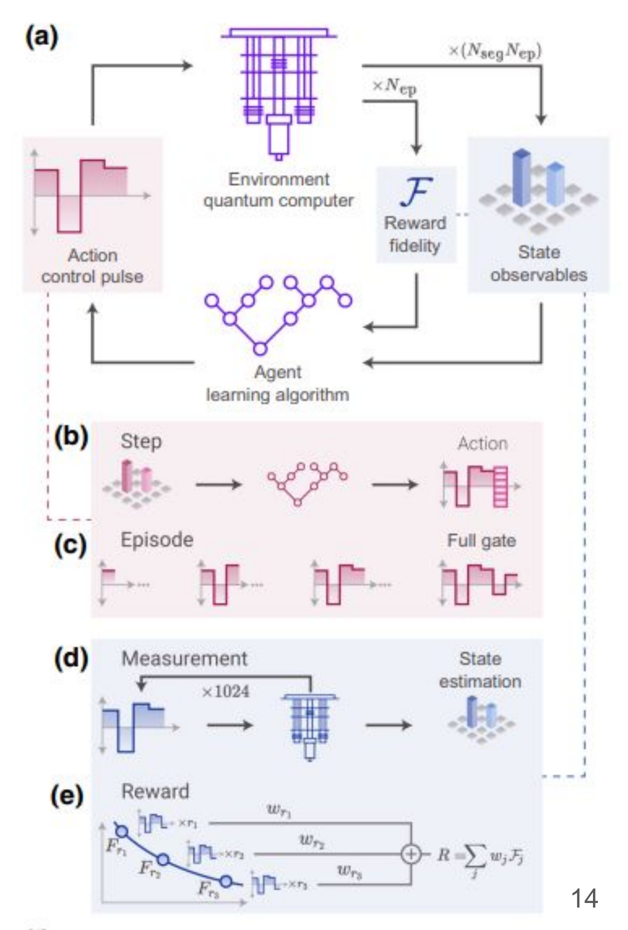
**References**
https://doi.org/10.1038/s41567-018-0066-3
https://doi.org/10.1016/j.nima.2024.170010

# Reinforcement Learning based qubit control and readout

Superconducting qubits face **key challenges such as gate errors, short coherence times, and sensitivity to noise**. Reinforcement Learning (**RL**) offers an innovative solution by allowing algorithms to autonomously **learn high-fidelity control strategies** through interaction with the quantum system.

In this thesis, the student will explore **how RL can be applied to enhance superconducting qubit performance** by designing optimized gate pulses and adaptive noise mitigation protocols. They will learn how to implement RL algorithms, simulate qubit dynamics, and analyze the results to compare RL-driven control with conventional techniques.

Through this work, the student will develop a strong foundation in quantum control, reinforcement learning, and data analysis.

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https://doi.org/10.1103/PRXQuantum.2.040324
https://doi.org/10.1103/PhysRevApplied.23.014015
https://doi.org/10.48550/arXiv.2412.04053

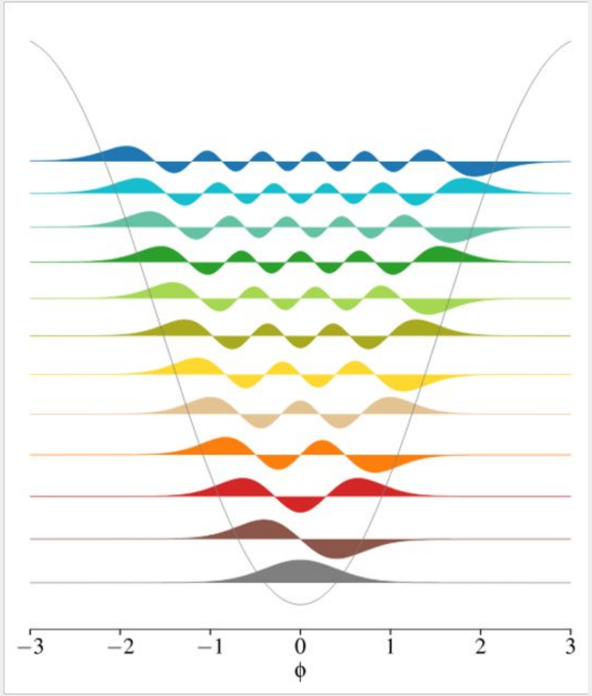
# Sensing via Superconducting QuDits

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

This is a research review project focused on quantum sensing with qudits. The goal is to survey existing literature, papers, theses, and preprints, on how multi-level quantum systems are used for sensing applications.
 Depending on the available material, the thesis will identify key approaches, technologies, and trends. Possible focuses include superconducting qudits, trapped ions, or photonic systems, comparing how higher-dimensional encoding impacts sensitivity, noise resilience, and measurement precision.

**Main goals:**

- Collect and categorize existing work on qudit-based sensing.
- Identify recurring methods, physical platforms, and target observables.
- Highlight open problems and potential directions for experimental or theoretical advances.




http://arxiv.org/abs/2407.17407
https://arxiv.org/pdf/2510.19918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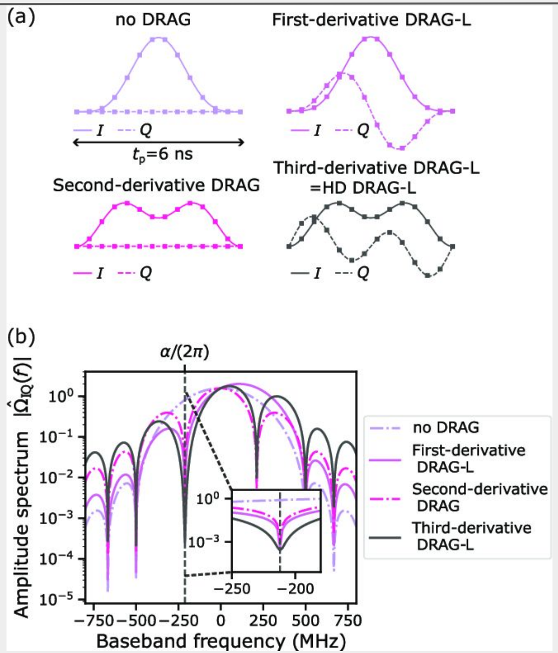
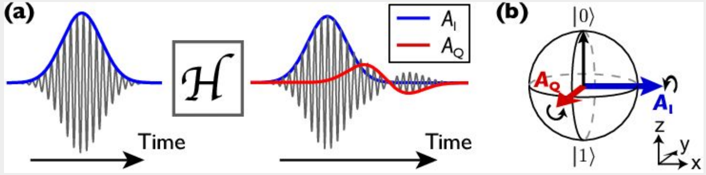
# Shaping and Optimization of Qudit Gates

This project focuses on studying and optimizing qudit gate implementations, starting from qutrits and extending to higher dimensions, on superconducting hardware.
We will analyze known universal gate sets and their physical realizations, drawing from Universal Qudit Gate Synthesis for Transmons and Speed Limits of Two-Qutrit Gates.
The goal is to understand performance limits in both ideal and realistic conditions, accounting for noise, decoherence, and finite pulse duration.

**Key questions include:**

- How do gate fidelity and operation speed scale with dimension (d)?
- What are the optimal pulse shapes for single- and two-qudit gates?
- How higher-order DRAG or Lorentzian-shaped pulses improve performance or robustness?
- Are there other reasonable/interesting shape?





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*https://doi.org/10.1103/PRXQuantum.5.030353*

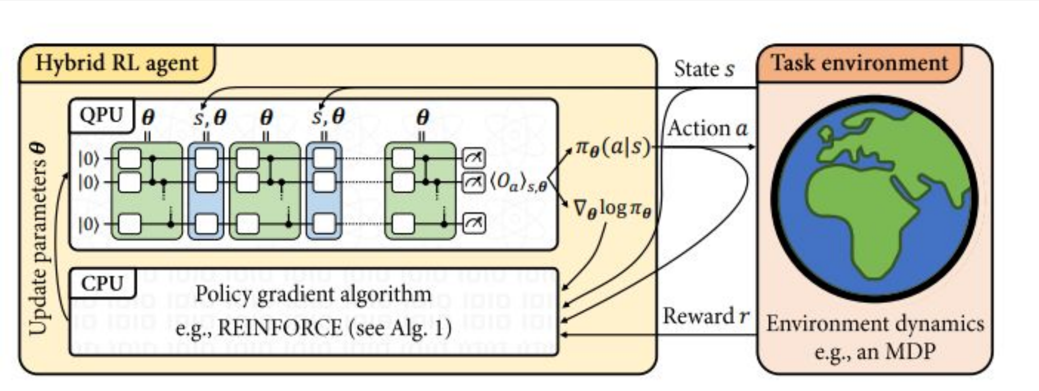
# Thesis proposals in quantum computing and quantum algorithm development

# Hybrid/Quantum Reinforcement Learning

This project explores Quantum Reinforcement Learning (QRL), which merges quantum computing with machine learning. **The objective is to implement a QRL algorithm using Variational Quantum Circuits (VQCs) and compare its performance with classical models**. The student will gain insights into how quantum technologies can enhance learning efficiency and tackle complex tasks.

By working with quantum programming libraries like PennyLane and Qiskit, the student will learn to design and implement quantum machine learning models while exploring key concepts in reinforcement learning and quantum computation.

The student will acquire practical skills in building and evaluating quantum models, along with an understanding of the challenges and future potential of quantum-enhanced machine learning.

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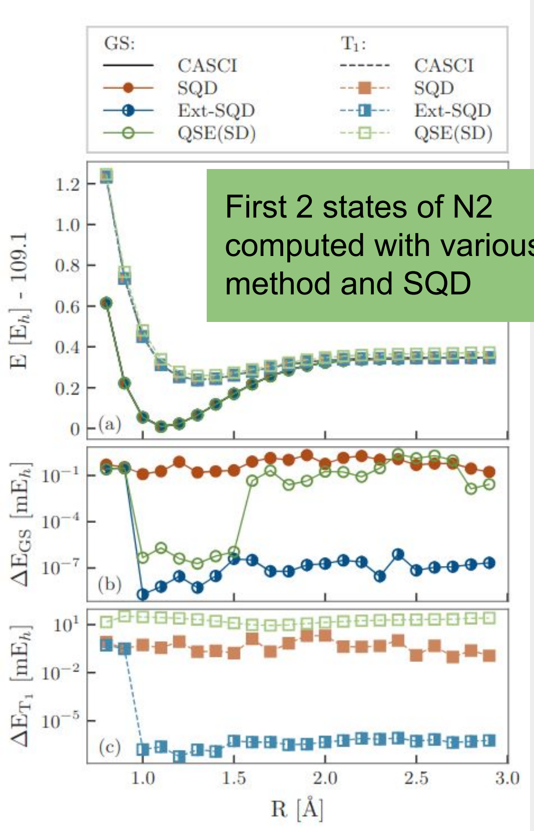
https://arxiv.org/abs/2108.06849
https://arxiv.org/abs/2211.03464
https://arxiv.org/abs/2103.05577

# Using SQD to study molecules

The Sample-based Quantum Diagonalization algorithm (SQD) uses a QPU to sample electronic configurations and a classical computer to recover signal from such noisy data and to diagonalize the Hamiltonian in a subspace defined by the recovered configurations.

In recent years it emerged as a valid alternative to the typical quantum computing variational methods, since it does not require perfect hardware and it is thus already possible to perform large computations on current devices.

In this thesis, we will study the nuances of SQD applying it to find, via simulations, the first energy states of a given molecule. If there is enough time, we will use SQD on a IBM quantum devices to confirm our simulations.




First 2 states of N2 computed with various method and SQD

https://arxiv.org/pdf/2411.00468

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THE QUANTUM INSIDER

# Quantum Computing Market Map

Non exhaustive and in no particular order. Excludes details on control systems, assembly languages, circuit design, etc.

## Users
*Select examples*

### Material Science
Merck, OTI, Airbus, BMW

### Finance
Goldman Sachs, Bank of America, J.P.Morgan, Wells Fargo

### Life Sciences
Odyssey Therapeutics, Boehringer Ingelheim, AstraZeneca, gsk

### Other
Volkswagen, Johnson Electric, Denso

## Applications
*Not mapped to verticals*

## Software offerings
*Includes control software*

### Not strictly categorized given diversity of operations[1]
Multiverse Computing, QC Ware, NQCG, 1QBit, Aliro Quantum, Horizon Quantum Computing, HQS Quantum Simulations, Zapata, QCi Ready-to-run Quantum Software, Entropica Labs, river lane, Strange Works, QuantFi, Phasecraft, aq, QunaSys, Terra Quantum, ⟨b| e, ProteinQure, Keysight Technologies, Qubit pharmaceuticals, Q-CTRL, Classiq, Quantum-South, menten.AI, ParityQC

### Cloud access to QPUs
aws, Google Cloud, Azure

### Simulators / q-inspired / etc
Atos, Fujitsu, NVIDIA, Huawei Cloud

## QPUs[2]

### Superconducting
rigetti, Google AI Quantum, OQC, IlluMAjaro Quantum Tech, IBM Q, IQM, Nord Quantique, aws, seeqc, D-Wave The Quantum Computing Company, Alibaba.com

### Ion Trap
Quantinuum, IONQ, AQT, oxford ionics, QUDOOR, eleQtron

### Neutral Atoms
Universal Quantum, atom computing, ColdQuanta, QuEra, PASQAL

### Silicon
Silicon Quantum Computing, intel, Quantum Motion, equal1, photonic

### Photonics
PsiQuantum, QC82, Xanadu, ORCA Computing, Quandela, Turing

### Other
EeroQ – Electrons on helium; Quantum Brilliance – NV Diamond

## Hardware / components
*Select examples only – not representative of entire ecosystem*

### Cryogenics (includes testing)
Oxford Instruments, FormFactor, Lake Shore Cryotronics, Blue Fors, Montana Instruments, ICE, Maybell

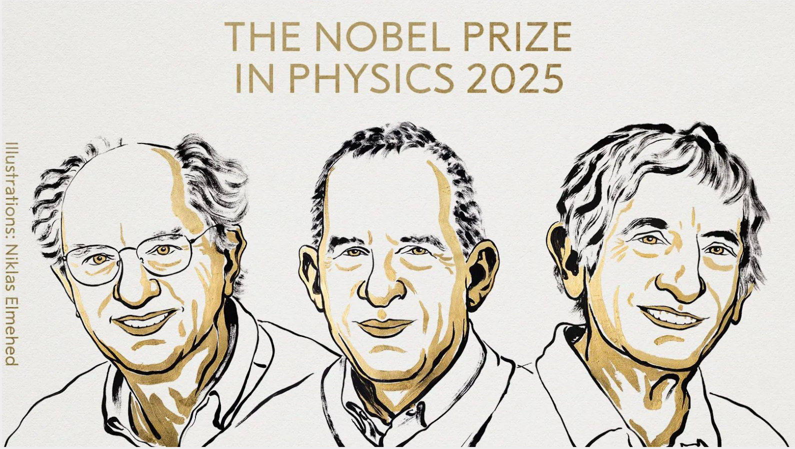
### Lights and lasers
Vescent Photonics, NKT Photonics, M Squared, Coherent, QANT, Toptica Photonics, Ligentec

### Other componentry (examples)
Delft Circuits – Hardware for quantum engineers, Keysight, Quantum Machines, Quantum Design, CryoCoax, ZNF, Qblox, QDevil, Zurich Instruments

[1] Software offerings can be further classified into SDKs, firmware / enablers, algorithms / applications, simulators etc. but many companies are offering a mixture across the stack
[2] Many QPU providers are offering full stack services (e.g. Pasqal acquired Qu&Co, Quantinuum was originally CQC prior to merger with HQS, etc.

INTERNATIONAL YEAR OF
Quantum Science
and Technology

# UN Declares 2025 International Year of Quantum Science and Technology




“For the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit” → The basis of the main platform: the superconducting qubits

# Many Thanks for your attention!!!

If you are interested in **thesis work in quantum technologies**, or if you have any questions please contact one of the following:


- Rodolfo Carobene r.carobene@campus.unimib.it (phd candidate)
- Andrea Giachero andrea.giachero@unimib.it (project leader)
- Marco Faverzani marco.faverzani@unimib.it (project leader)
- Angelo Nucciotti angelo.nucciotti@unimib.it (group leader)


**Useful links**

| | |
|---|---|
| Quantum Information Science at MIB (QISMIB) | https://qismib.github.io |
| Bicocca Quantum Technologies Centre (BiQuTe) | https://biqute.unimib.it |
| National Quantum Science and Technology Institute (NQSTI) | https://nqsti.it |
| Supercomputing ICSC | https://www.supercomputing-icsc.it/ |
| MiSS Project | https://miss.fbk.eu/ |
| DARTWARS project | https://dartwars.unimib.it/ |
| Qub-IT project | https://web.infn.it/qub-it/ |

# Quantum Information Science and Technology

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