FONDAZIONE BRUNO KESSLER | SENSORS AND DEVICES

Quantum Technologies in Trento: Experimental platforms and recent developments

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Fondazione Bruno Kessler (FBK)
Trento, Italy

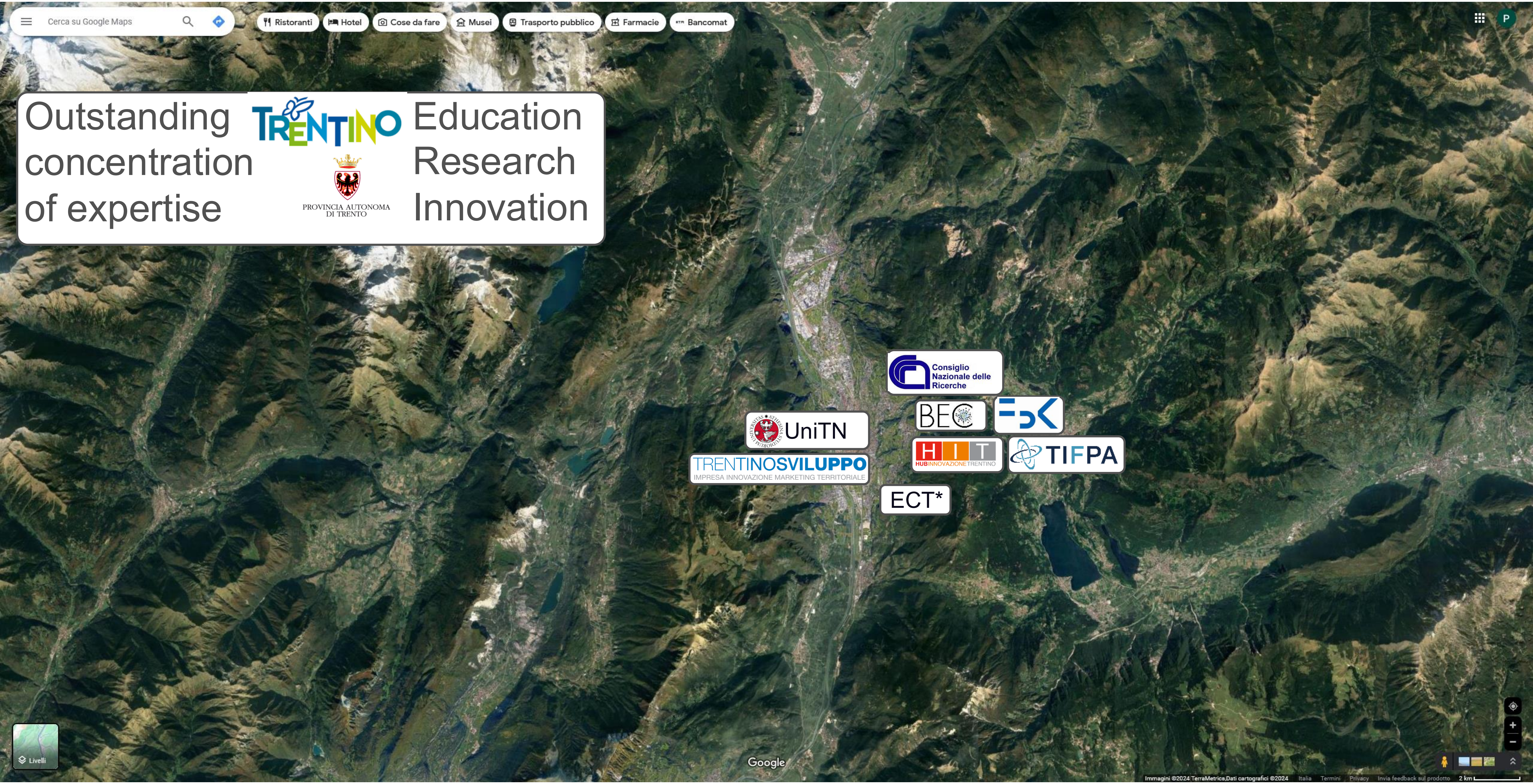
Trento, 24 June 2026

Outstanding concentration of expertise

TRENTINO

PROVINCIA AUTONOMA DI TRENTO

Education
Research
Innovation



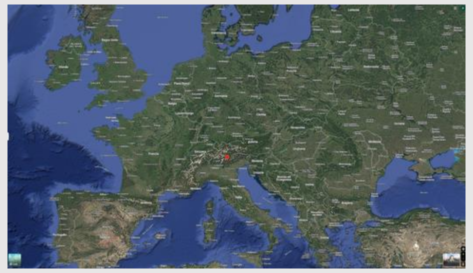
What Q@TN does

The Pillars

Research	Education	Innovation
Science and Technology	Transdisciplinary Ph.D. Program	Technology Transfer
Quantum Information, Measurement, Communication, Computation	Second Level Master in Quantum Engineering (in planning)	Prototyping Infrastructures
Open HUB and Quantum fab	Lifelong Learning, Outreach	Testing Laboratories

AIMS

- Establishment of the Q@TN initiative as a joint laboratory, leveraging on human resources and state of the art infrastructures
- Rooted in Trentino – with a European and global outlook

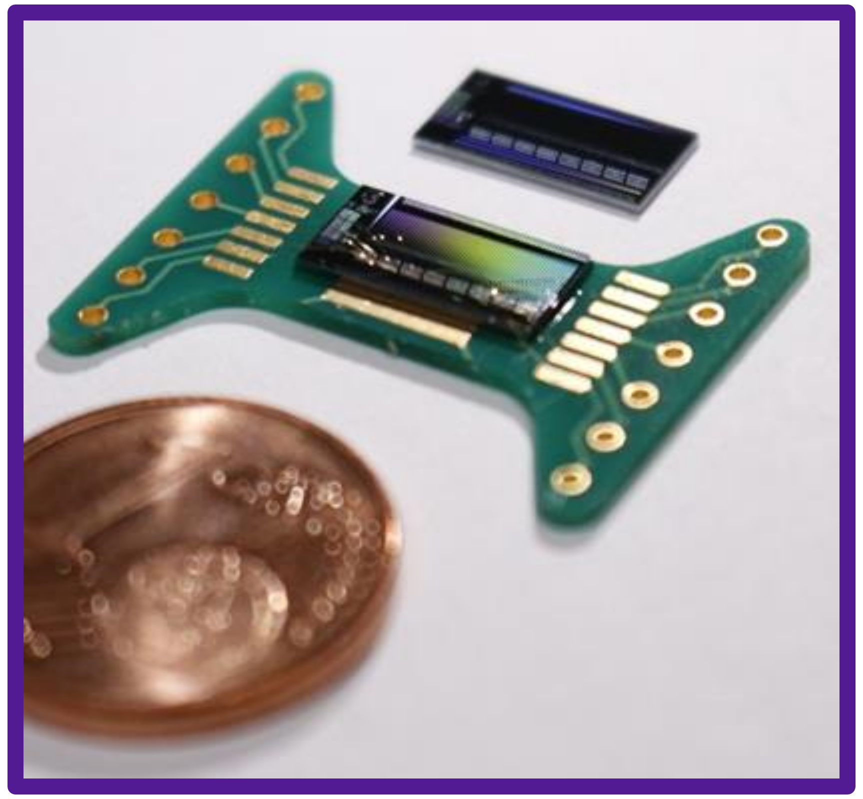


- Building a territorial ecosystem on QST as a driver for innovation
- Training new figures of researchers and professionals in QST

- Development of human, scientific, and economic values

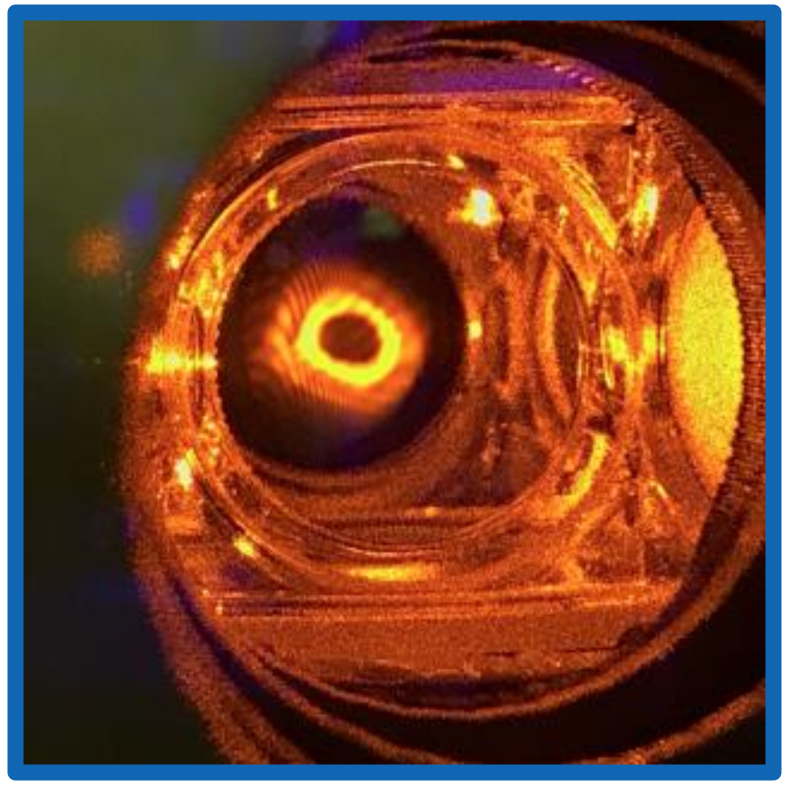
Experimental Quantum Platforms in Trento

Complementary hardware platforms

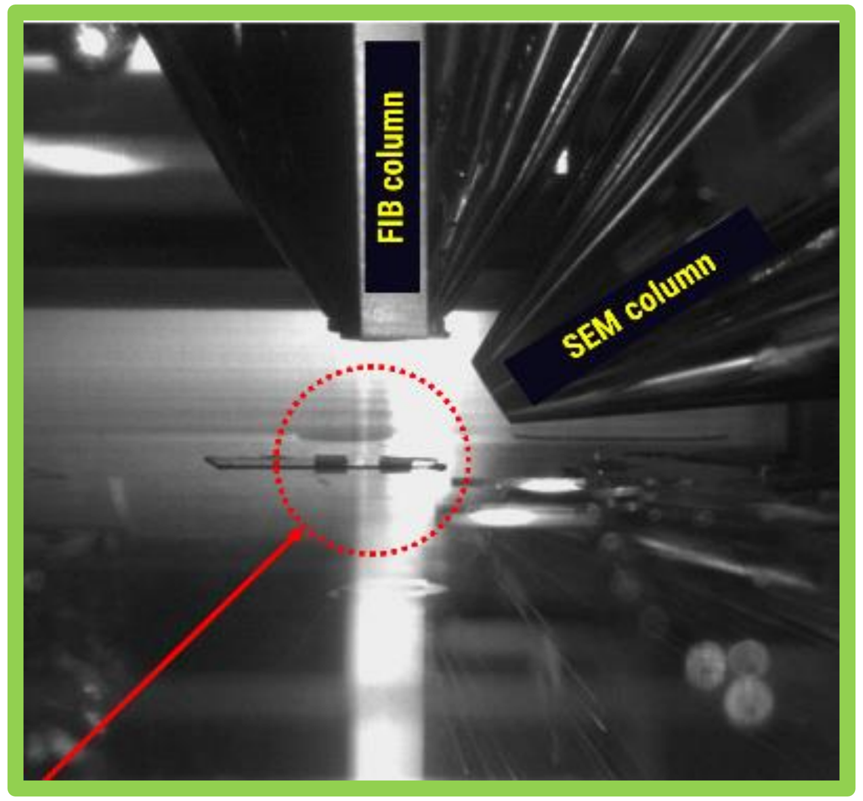


integrated photonics

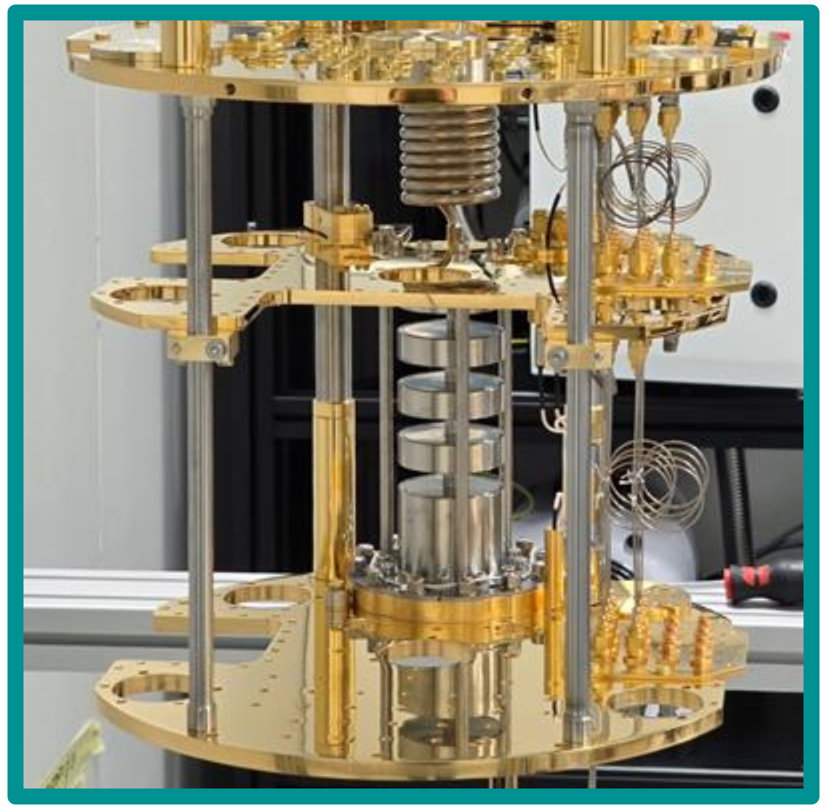
ultracold atoms



solid-state defects

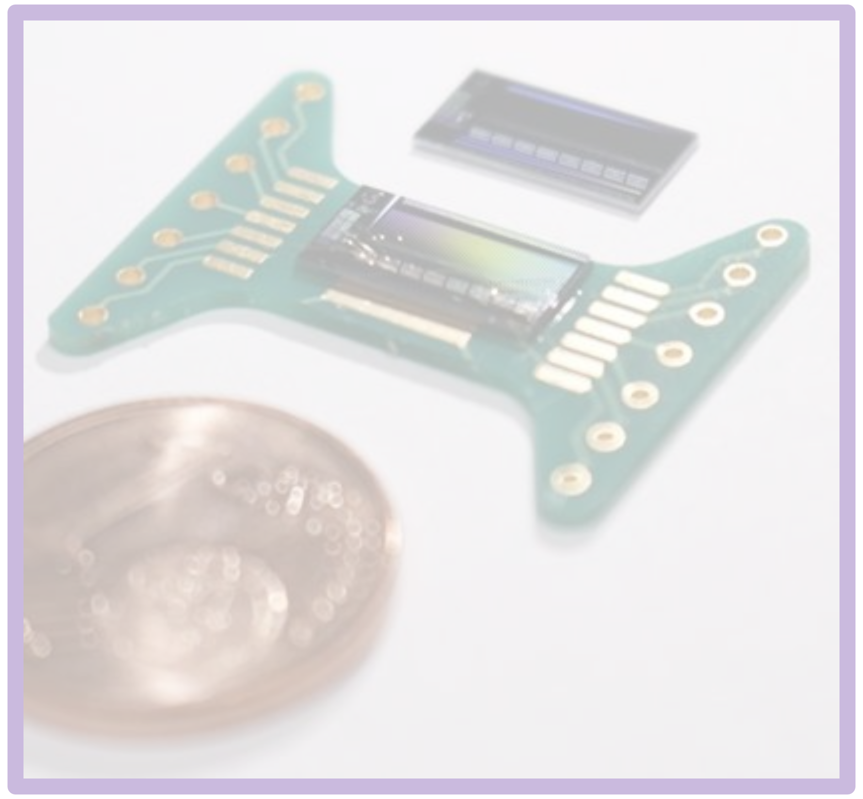


superconducting circuits



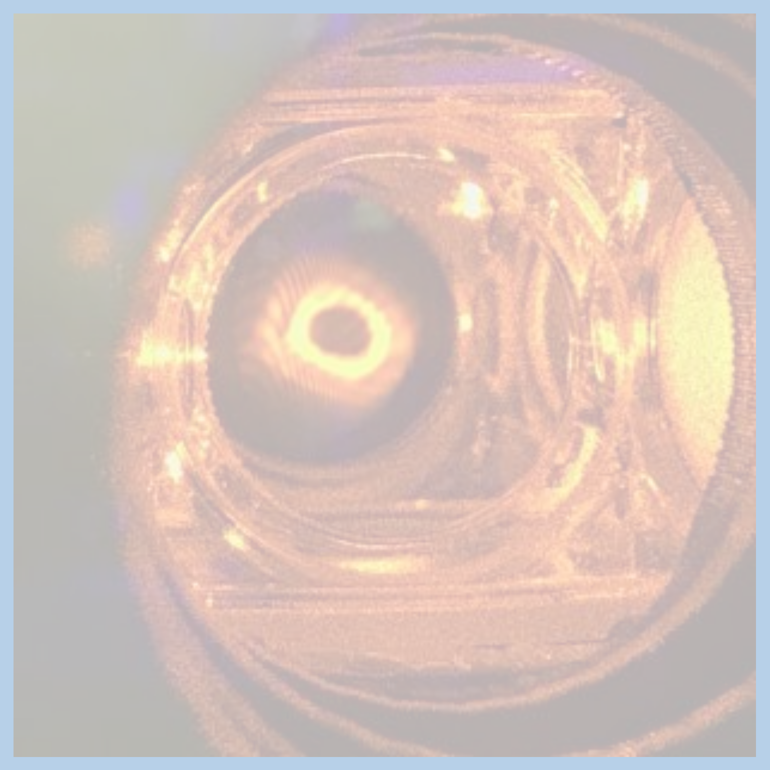
Experimental Quantum Platforms in Trento

Complementary hardware platforms

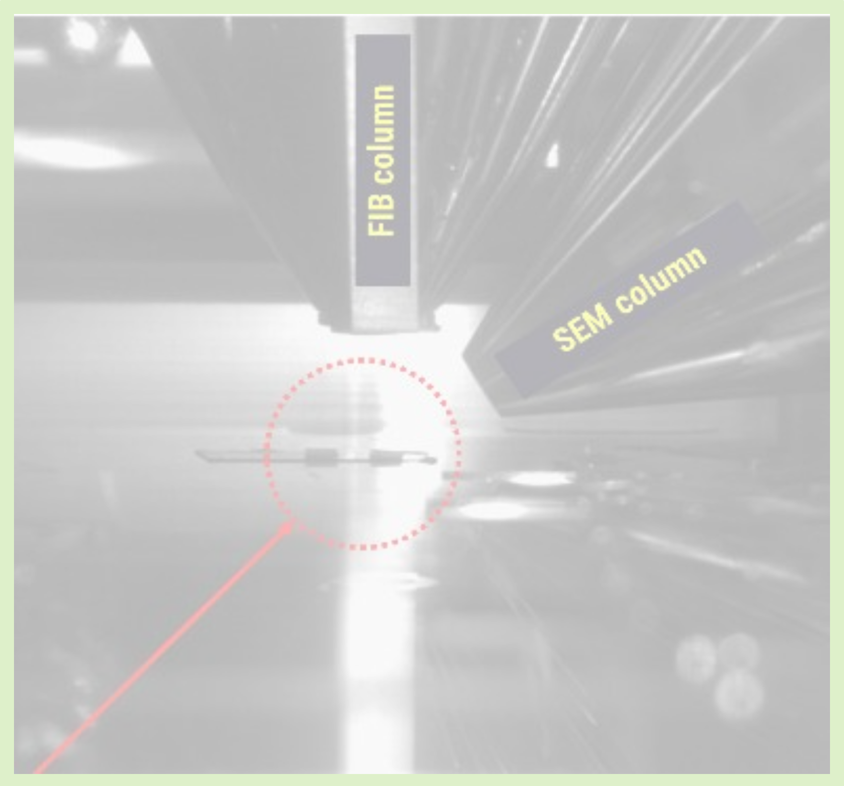


integrated
photonics

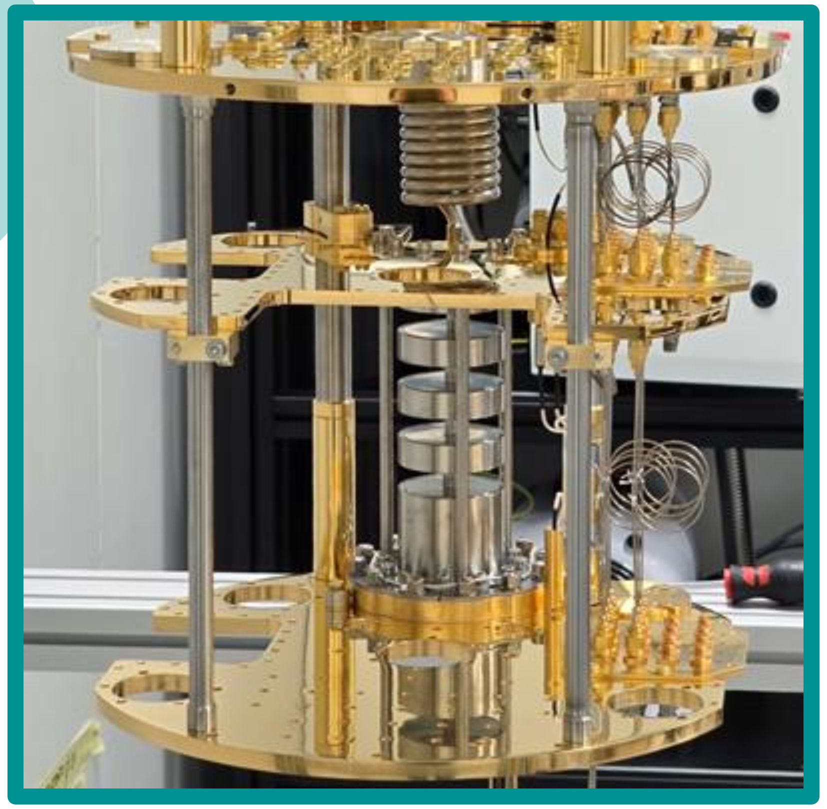
ultracold atoms



solid-state defects



superconducting
circuits



Superconducting Platform – Experimentalists in Trento

SQD
SUPERCONDUCTING
QUANTUM DEVICES

FONDAZIONE
BRUNO KESSLER

(incomplete picture…)

SQD Research Group

Felix Ahrens (Researcher)
Enrico Bogoni (PhD student)
Nicolò Crescini (Researcher)
Marcello Faggionato (Master student)
Lucas Favre (intern)
Alessandro Irace (PhD student)
Benno Margesin (Senior fellow)
Federica Mantegazzini (Researcher)

Istituto Nazionale di Fisica Nucleare
TIFPA
Trento Institute for Fundamental Physics and Applications

UNIVERSITÀ DI TRENTO

PhD scholarships: University of Milano-Bicocca, University of Trento, University of Padova

Other experimentalists in Trento:
Andrea Vinante, Renato Mezzena, Paolo Falferi, Andrea Marchese

Italian National Research Council

Quantum Computing for Nucelar Reactions

UNIVERSITÀ DI TRENTO

Research group
Francesco Pederiva
Alessandro Roggero

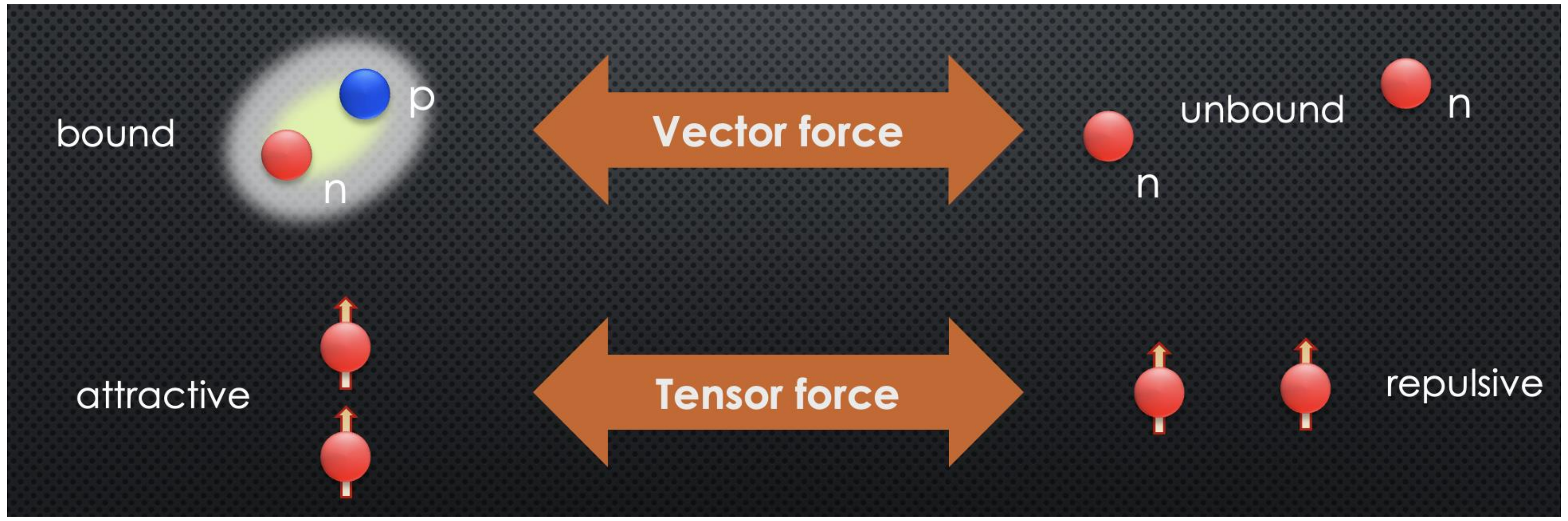
A reaction is just a time dependent process. A quantum computer is a tool that implements the time evolution of a quantum system so it should be relatively "easy" to describe a process just as it occurs, without approximations, provided that:

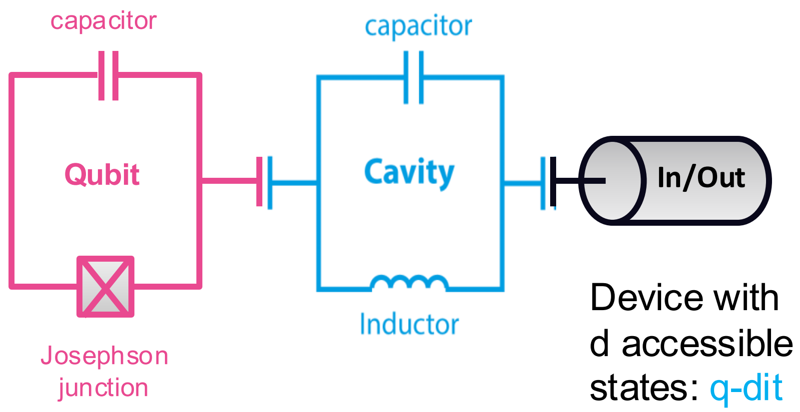
1) We actually know the Hamiltonian of the system
2) We can implement computations:
   a) In a reasonably large model Hilbert space
   b) Such that noise doesn't kill the signal over the time scale relevant for the process
3) We know how to tame dissipation (since nature gave us quasi elastic and unelastic processes…)

Example: Model two interacting neutrons

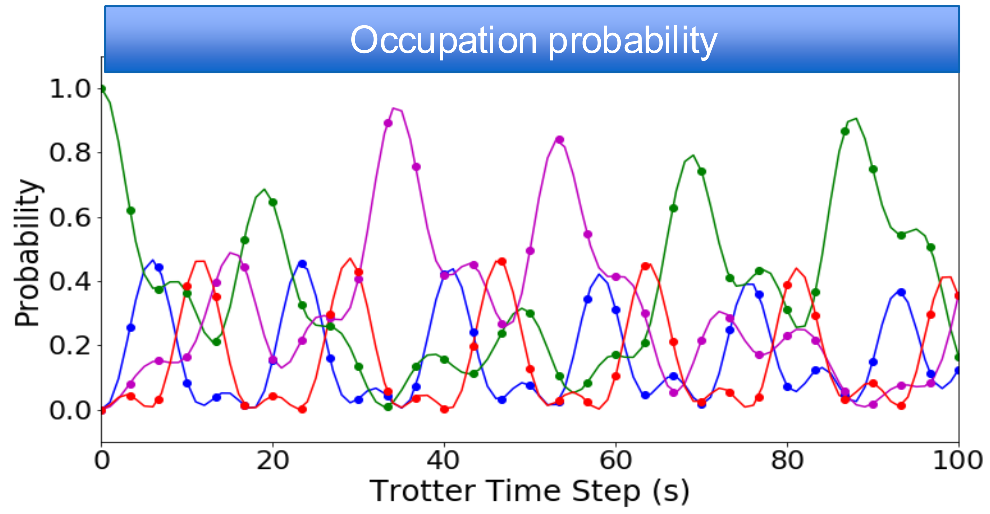
The strong nuclear interaction has a non-trivial dependence on the quantum state of the nucleons

One of the main features of the nucleon-nucleon interaction is its spin/isospin dependence.





Device with d accessible states: q-dit



First application: "frozen" nucleons → Spin/isospin Hamiltonian only

$$\exp\left[-\frac{i}{\hbar}\hat{V}_{SD}\delta t\right] = \exp\left[-\frac{i}{\hbar}\left(\sum_{i,j=1}^{A}\sum_{\alpha,\beta=x,y,z}\sigma_{i\alpha}A(r_{ij})_{ij;\alpha\beta}\sigma_{j\beta}\right)\delta t\right]$$

coordinates appear as "parameters"

Courtesy: Francesco Pederiva

BEC Center: a joint initiative of DF-UniTN and INO-CNR

UNIVERSITÀ DI TRENTO

AREE DI RICERCA:

Quantum Fluids
Quantum Simulators
Quantum Computing
Quantum Optics
Solid States
Mesoscopic Physics

THEORY

Cold Atoms

Hybrid Quantum Systems

Quantum Simulation

BEC

EXPERIMENTS

Lab BEC1
BEC &
vortices

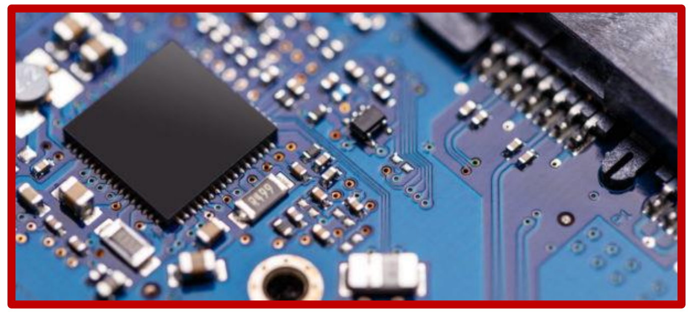
LAB BEC2
mixtures

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Fondazione Bruno Kessler

CYBERSECURITY

SENSORS & DEVICES



THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

EVALUATION OF PUBLIC POLICIES

DIGITAL SOCIETY

CENTRES

FONDAZIONE BRUNO KESSLER

RELIGIOUS STUDIES

DIGITAL INDUSTRY

ITALIAN-GERMAN HISTORICAL STUDIES

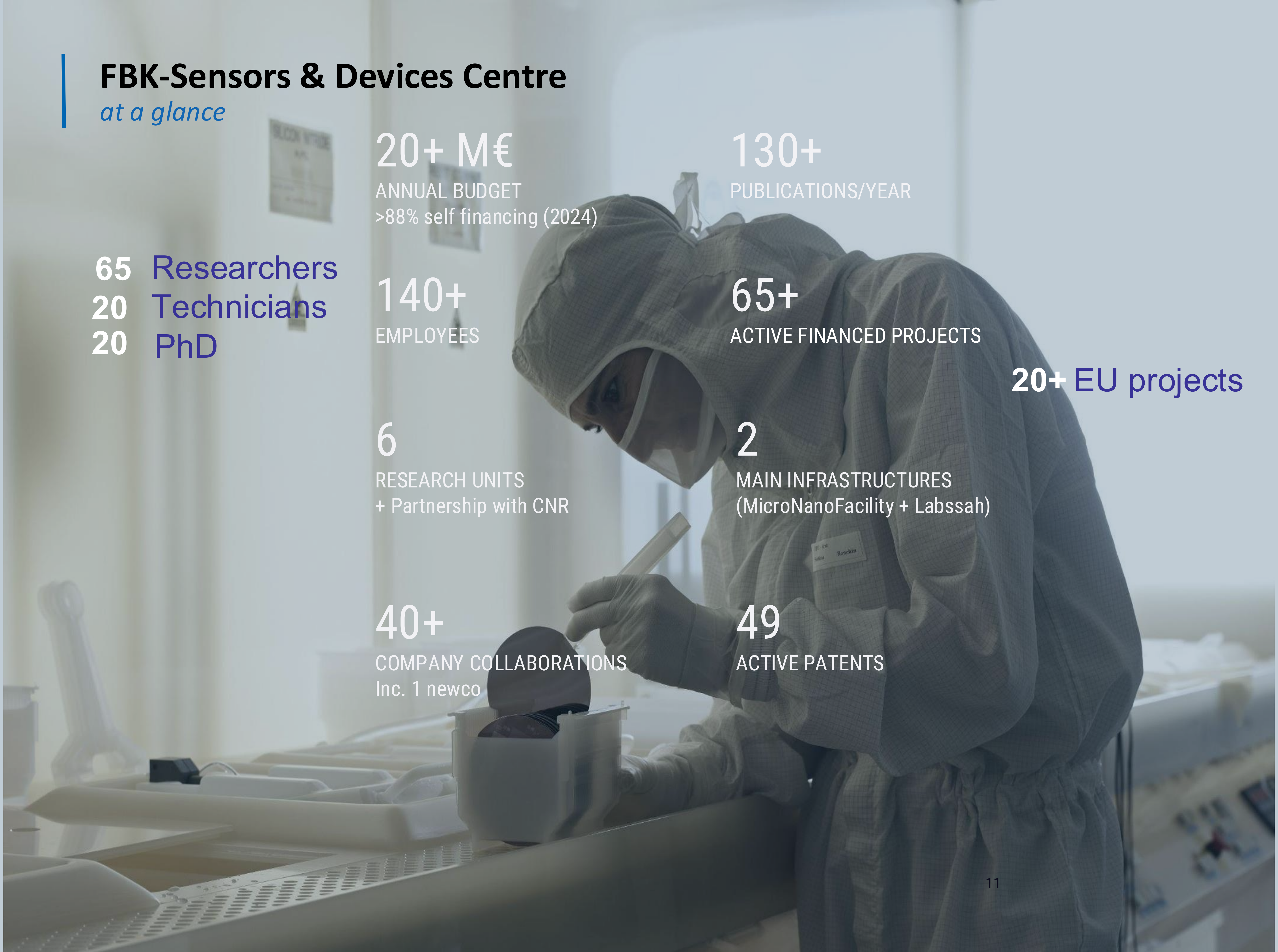
HEALTH & WELLBEING

HEALTH EMERGENCIES

SUSTAINABLE ENERGY

FBK-Sensors & Devices Centre

at a glance



20+ M€
ANNUAL BUDGET
>88% self financing (2024)

130+
PUBLICATIONS/YEAR

65 Researchers
20 Technicians
20 PhD

140+
EMPLOYEES

65+
ACTIVE FINANCED PROJECTS

20+ EU projects

6
RESEARCH UNITS
+ Partnership with CNR

2
MAIN INFRASTRUCTURES
(MicroNanoFacility + Labssah)

40+
COMPANY COLLABORATIONS
Inc. 1 newco

49
ACTIVE PATENTS

FBK-Sensors & Devices Centre

Scientific pillars

Quantum Technology

Space Industry & Big Science

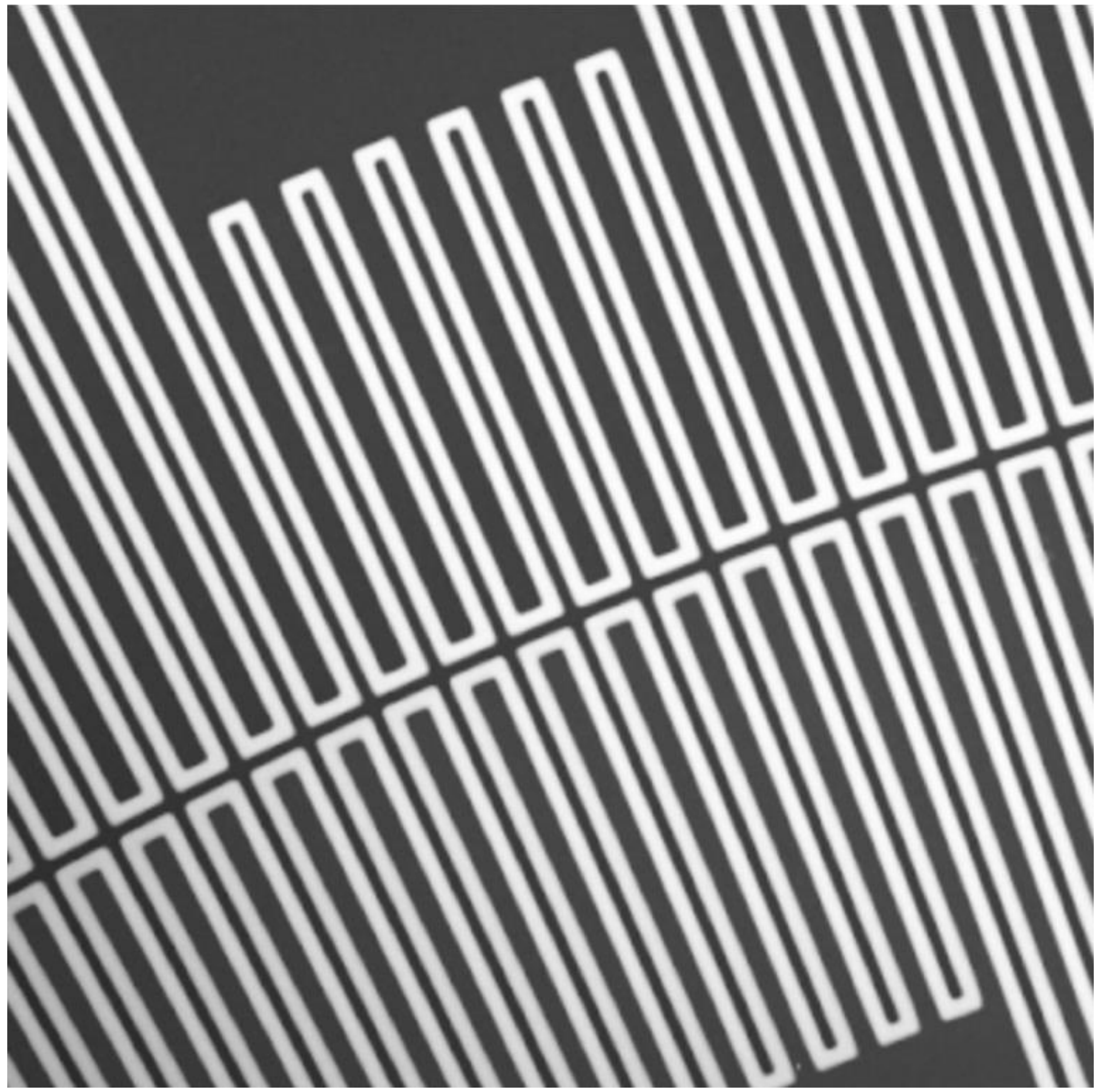
Health & Environment

Industry

Training

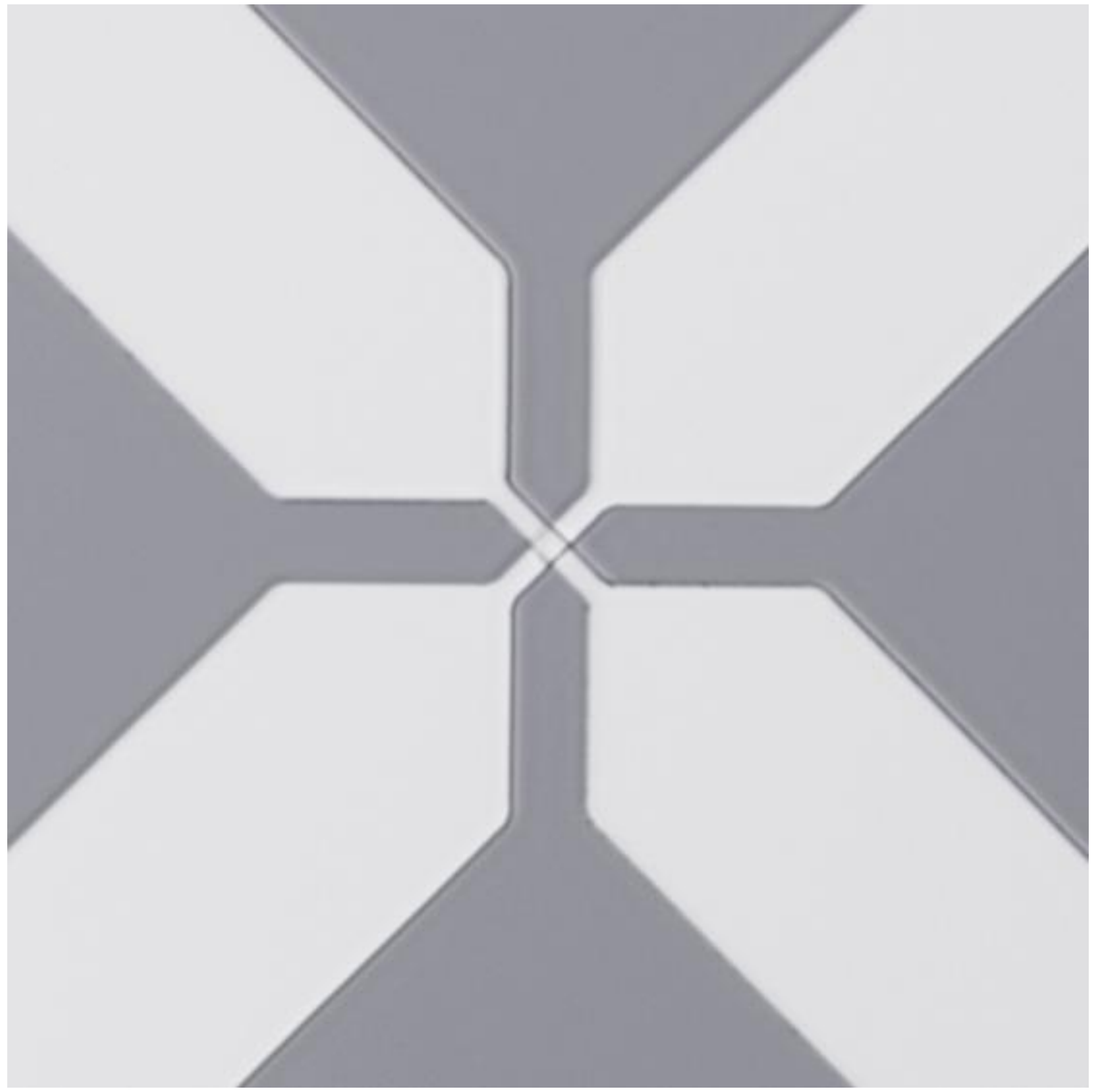
Dissemination

Superconducting technologies @FBK



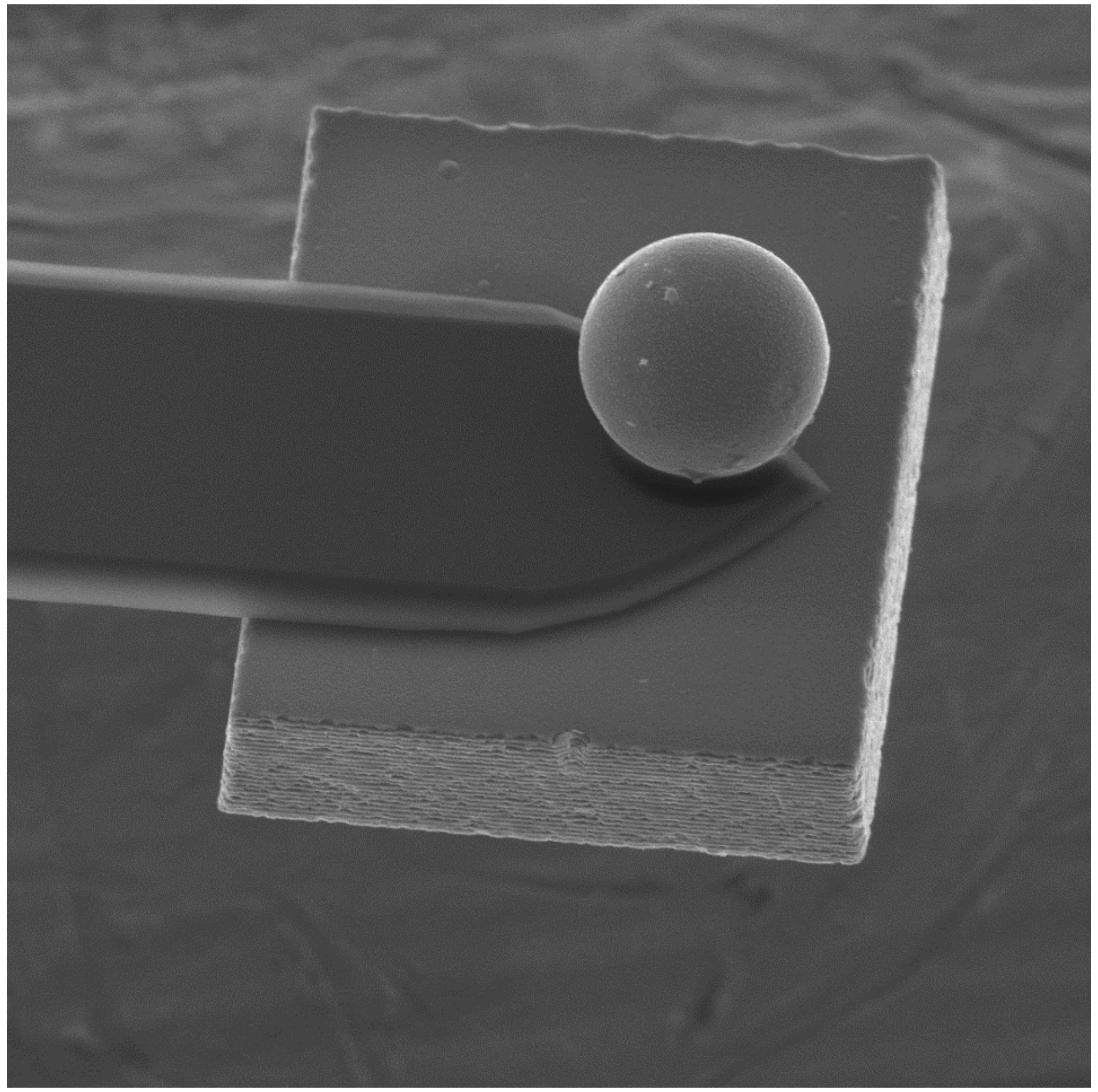
Kinetic inductance

TWPA
KICS
Microwave shifter



Josephson junctions

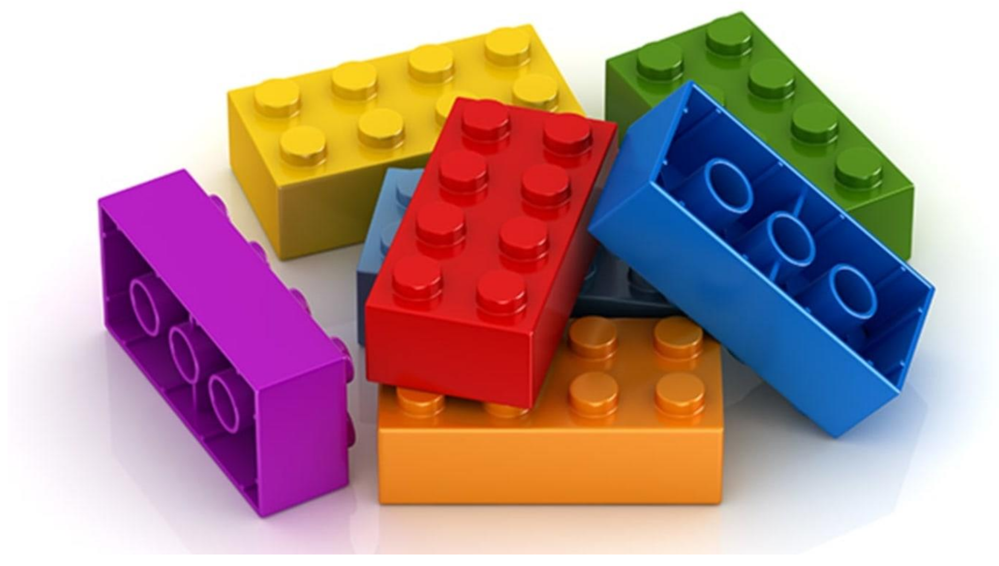
JPAs
Qubits (Transmons)
Microwave shifter

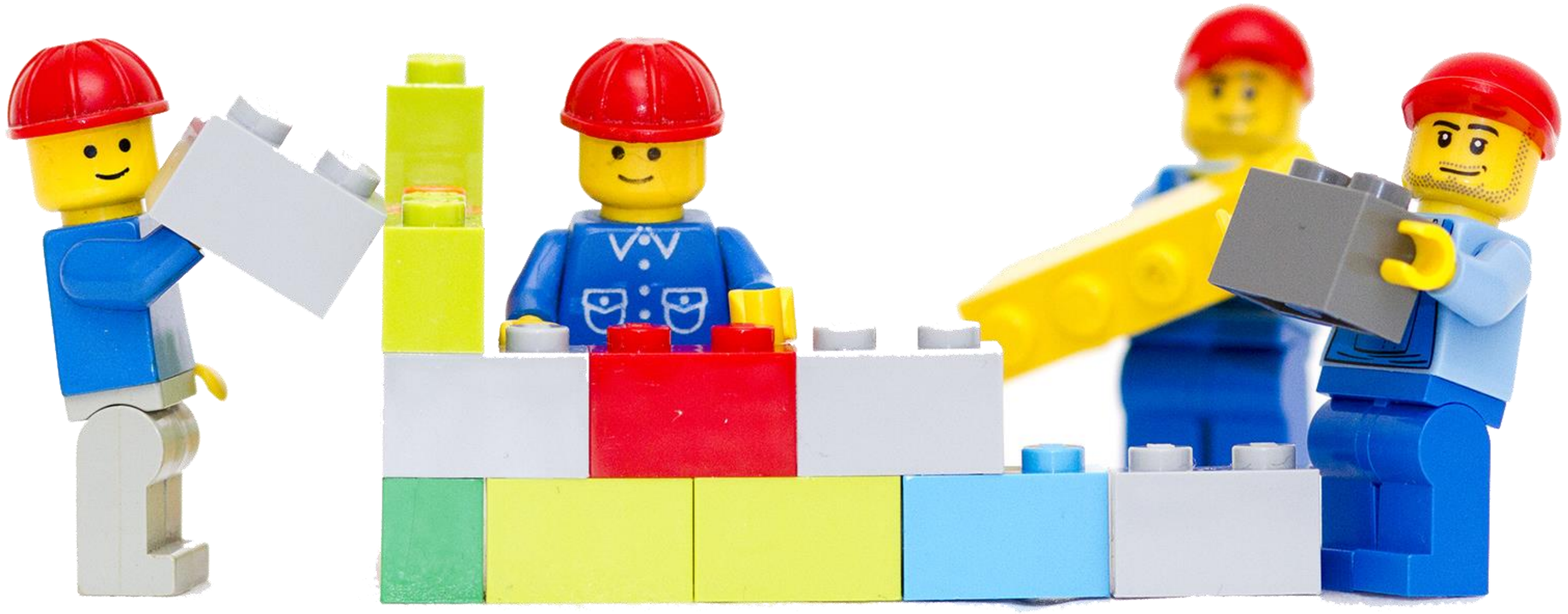


Mechanical hybrid systems

Magnetometers
Devices for funda-
mental physics

A few building blocks for many devices



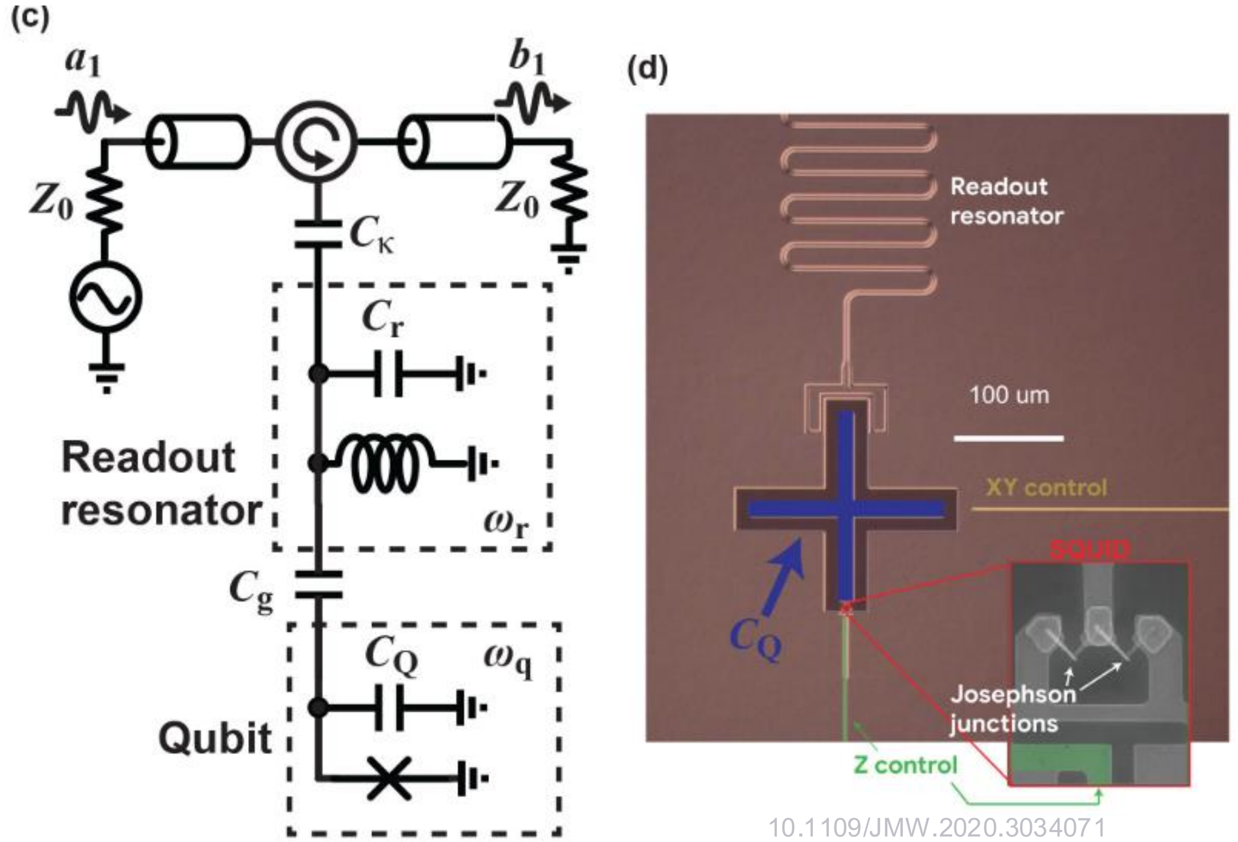


Capacitors

Inductors

Josephson junctions

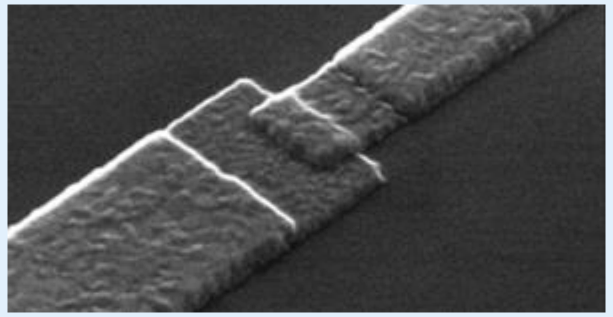
...



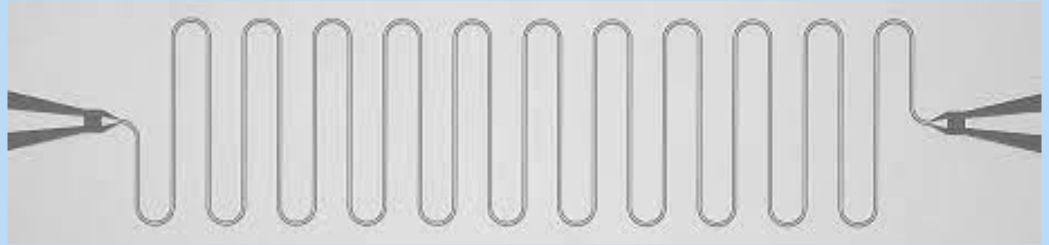
10.1109/JMW.2020.3034071

Building blocks → Devices → Applications

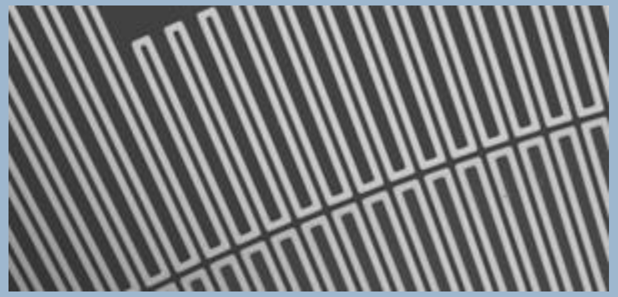
JOSEPHSON JUNCTION



SUPERCONDUCTING RESONATOR



HIGH KINETIC INDUCTANCE FILM



SQUIDs
Superc. Quantum Interference Devices

Parametric amplifiers

Tunable resonators

Qubits
Transmons

Microwave multiplexers

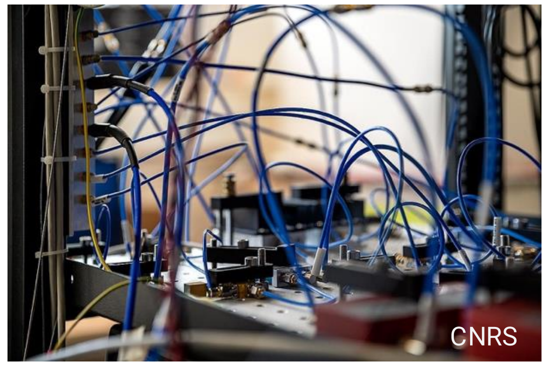
Cryogenic detectors

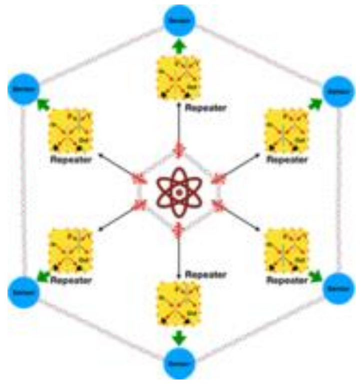
...

MICROWAVE CONTROL AND READ-OUT

Quantum-limited TWPAs
for the read-out of qubit/detector arrays

Superconducting sensors

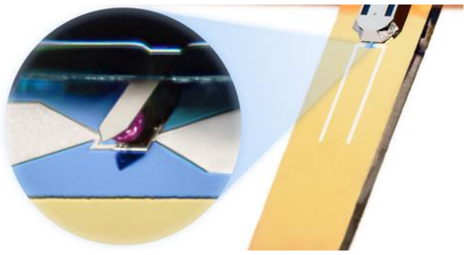




QUANTUM SENSING

Hybrid quantum systems
Dark matter searches

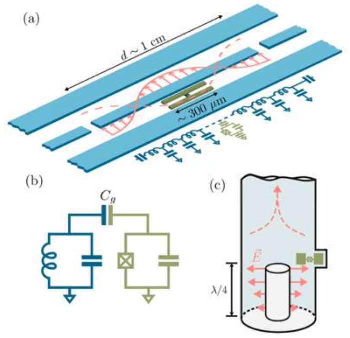
Particle detectors
Magnetometers



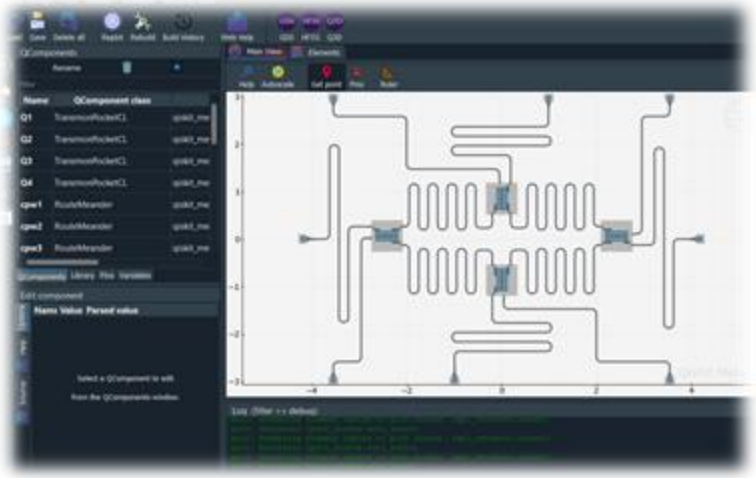
cQED & QUANTUM OPTICS EXPERIMENTS

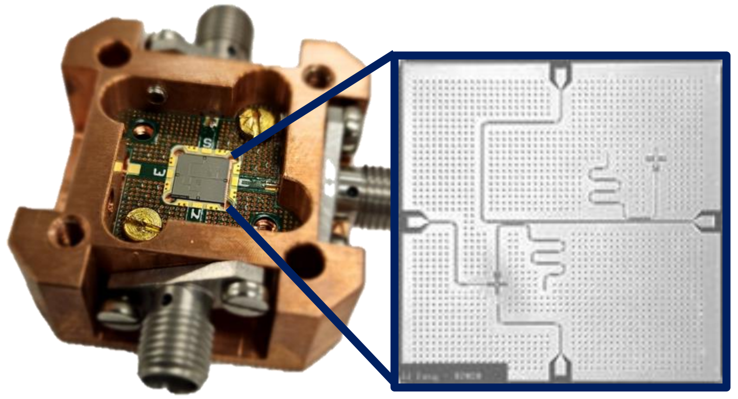
Light-matter interaction
Quantum optics in the microwave

...



Full development workflow at FBK

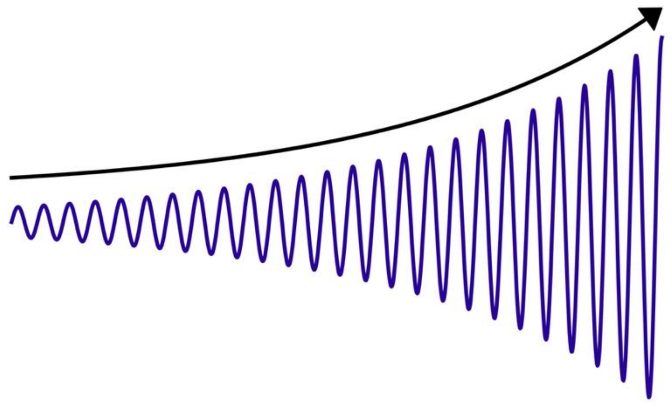
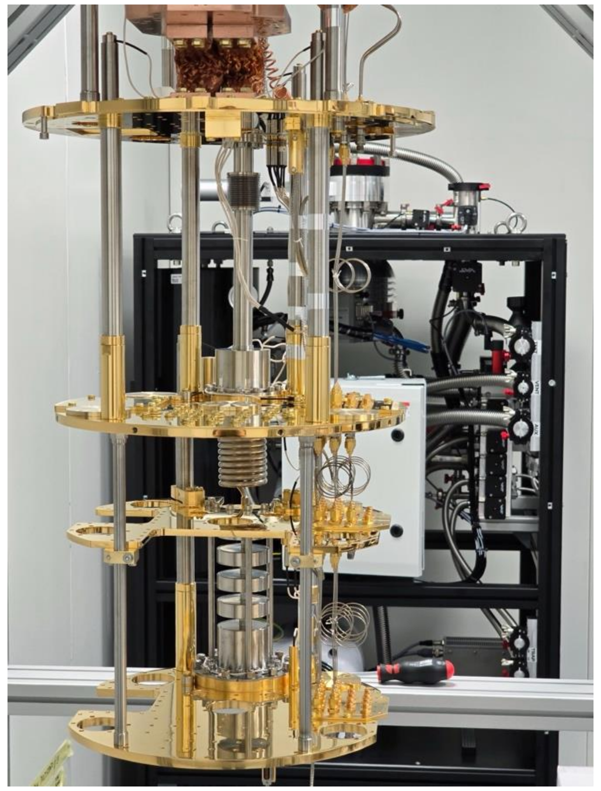




Design & Simulations → Microfabrication → Packaging

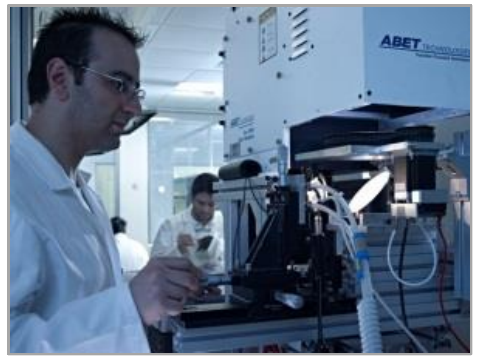
Cryogenic characterisation ← Experimental set-up

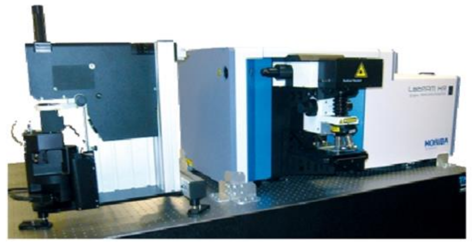
Experiment / Application

Micro and Nano fabrication Facility
1400m^2 moving to >2000m^2 ISO4-6 cleanrooms 6’’ pilot lines







ISO 9001 & 27001 certified

6” Microfabrication Area

Clean Room CR-D

700 m2; Class 10/100 CMOS pilot line: Ion Implantation, Oxidation, Diffusion, RIE, Deep RIE (silicon and oxide),

Lithography (optical: stepper, mask aligner; electron-beam), metal sputtering, optical profilometry, …

Clean Room CR-M

500 m^2 Class 100/1000: diffusion, lithography (mask aligner, direct laser writer), wafer bonding, electroplating, Si bulk micromachining, metal evaporation and sputtering, RIE, mechanical/optical profilometry, …

3D Integration Clean Room

200 m^2 Class 10/100 wafer temporary bonding/debonding, metal&fusion direct bonding, griding&polishing, metrology for 3D stacked wafers, ALD, …

Testing Area

300 m^2 manual parametric testing, automatic parametric/functional testing, optical testing, solar cells efficiency characterization, gas and pressure sensors test benches, …

Integration Area

100 m^2 clean room Class 1000 Microassembly station; screen printing, bonding (ball & wedge bonder), Shear-Pull Tester, reflow oven, CNC micro-mill, pick and place, …

Nano- and Micro- Analytical Facility

Nano Raman, FIB-SEM-EDX-EBSD, D-SIMS, TOF-SIMS, XPS, AFS, XRD/XRF

Cryogenic labs in Trento

FBK Cryogenic Lab (new!)

Fridges:

- DR Bluefors LD250, T_b < 7 mK
- Cryocooler, T_b ~ 4 K

RF instrumentation:

- VNA ZNB 26 GHz
- Signal generator SMB-100B
- Spectrum analyzer FPL
- RFSoC board 4x2 Kit

Other instruments:

- Lock-in amplifier
- Oscilloscopes
- LCR-meter
- ...

BLUEFORS

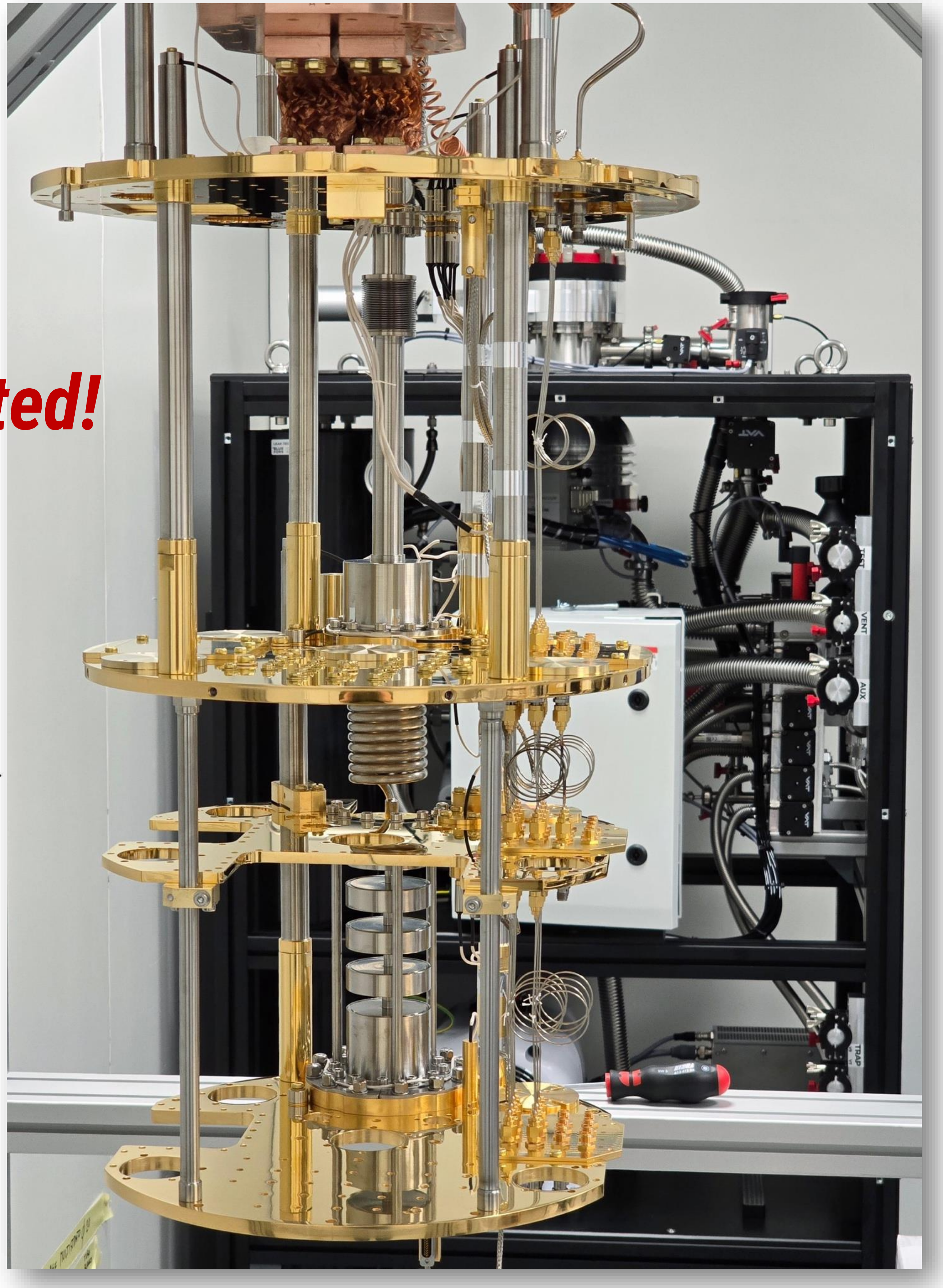
Sumitomo (SHI) CRYOGENICS OF EUROPE LIMITED

AMD

XILINX

ROHDE&SCHWARZ

Just inaugurated!

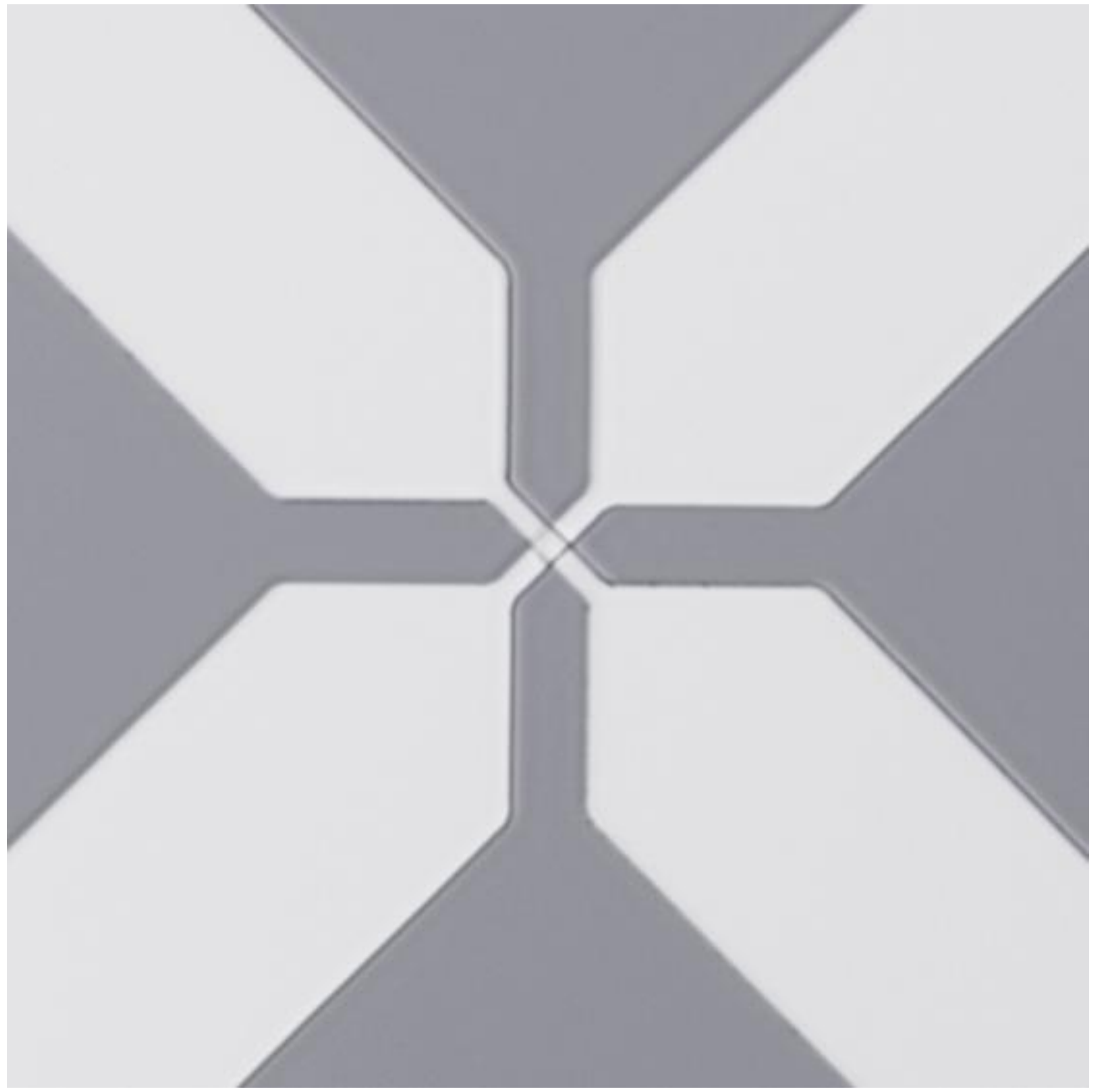


+ UniTn Cryogenic Lab Janis Fridge; Liquid He (with recovery line); RF instrumentation

Superconducting technologies @FBK

Kinetic inductance

TWPA
KICS
Microwave shifter



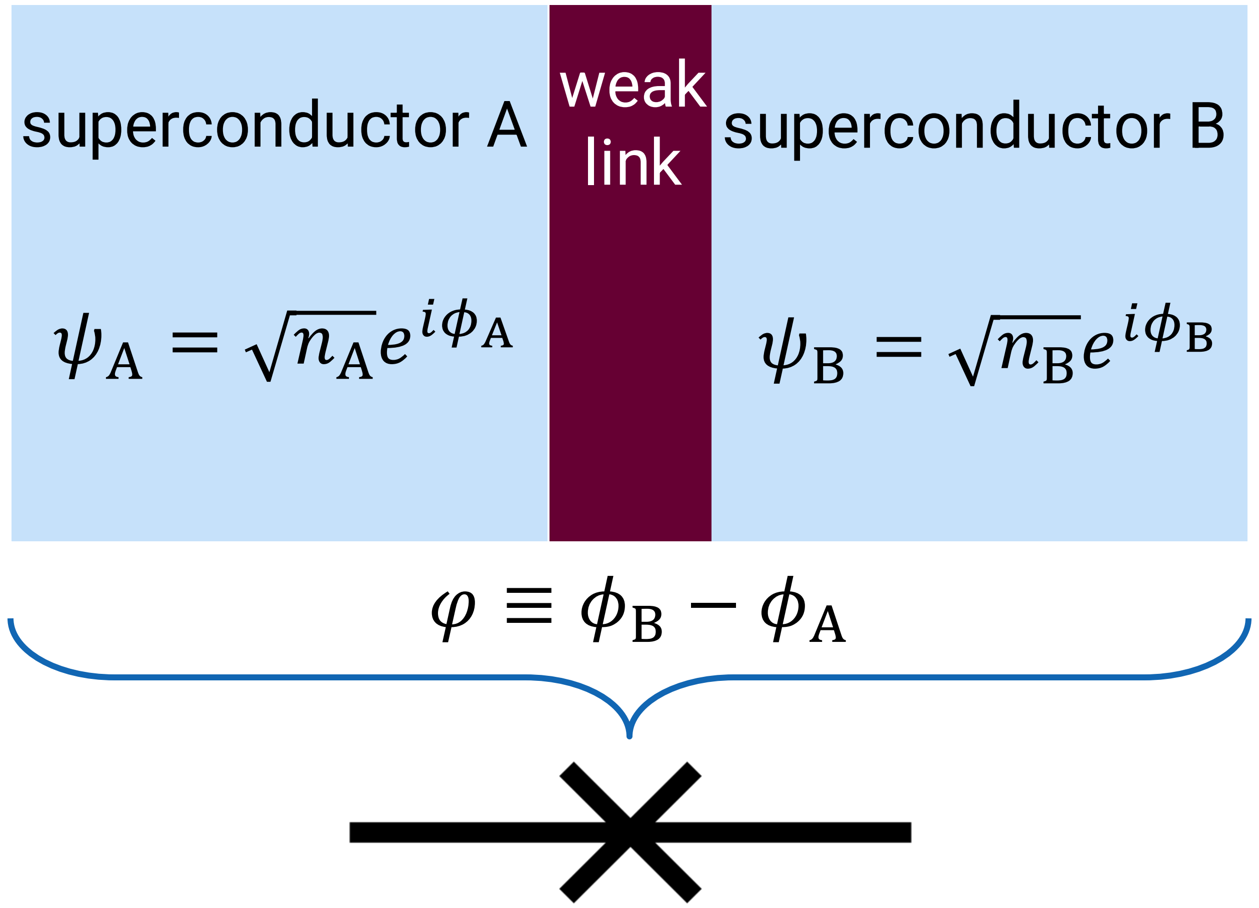
Josephson junctions

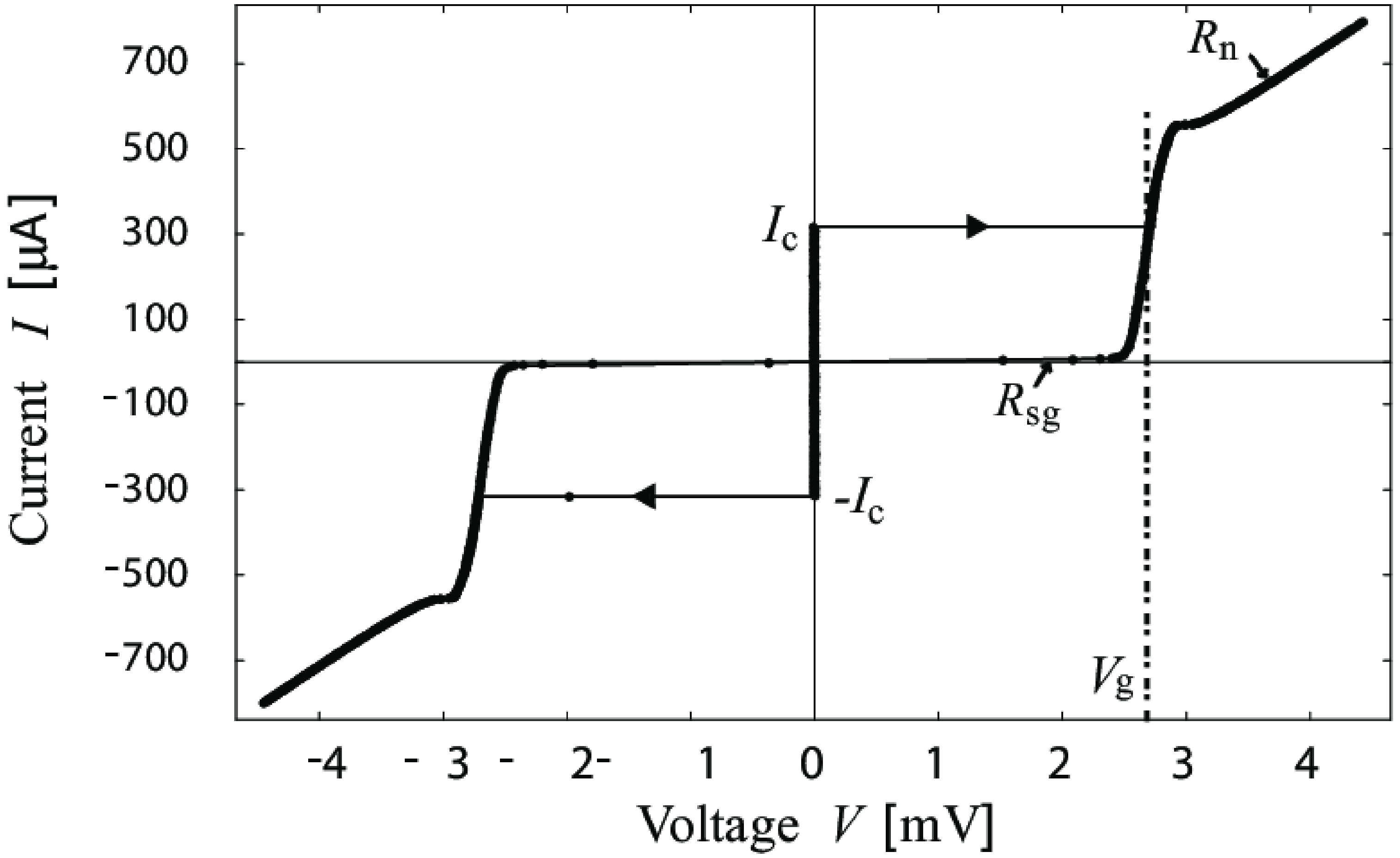
JPAs
Qubits (Transmons)
Microwave shifter

Mechanical hybrid systems

Magnetometers
Devices for funda-
mental physics

What is a Josephson junction?






Brian Josephson

Josephson equations

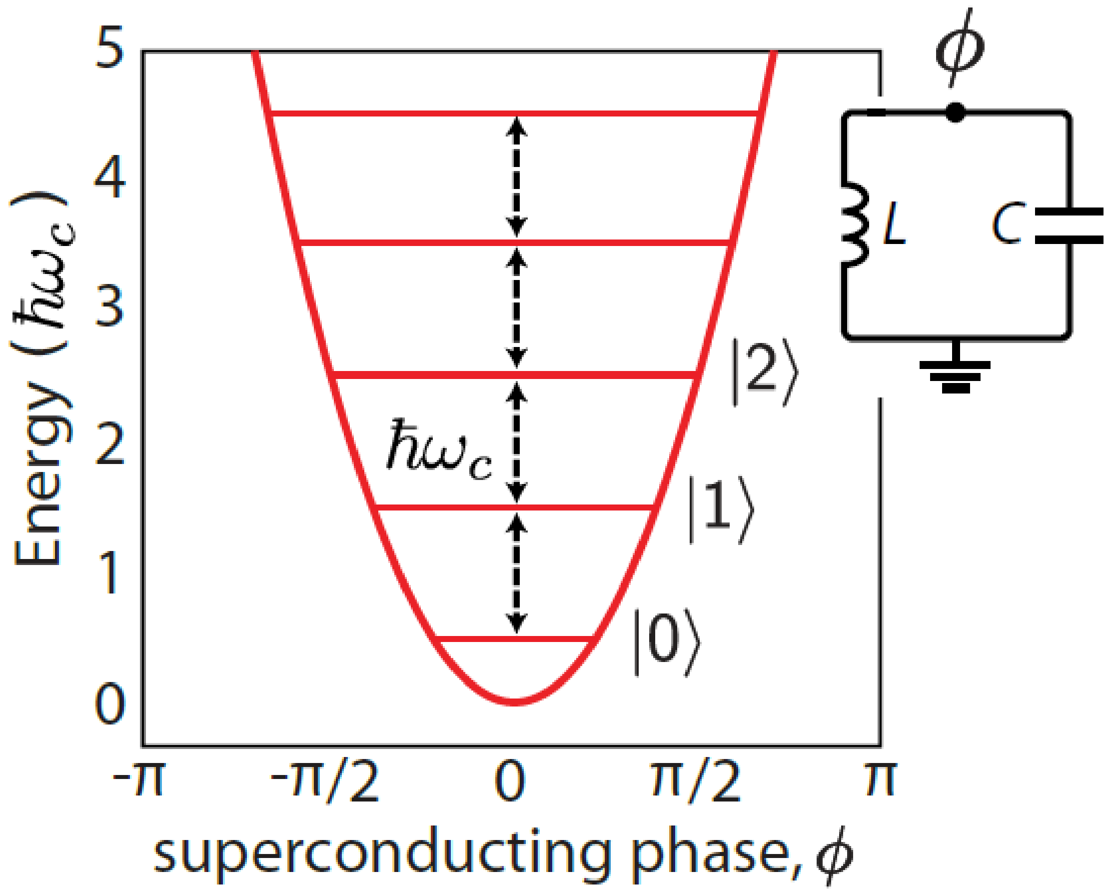
$$I(t) = I_C \sin\big(\varphi(t)\big)$$

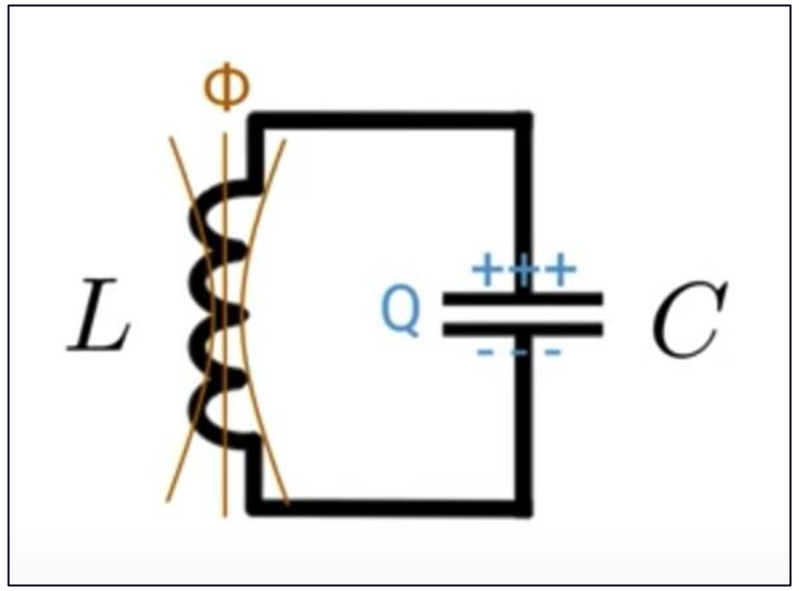
$$\frac{\partial \varphi}{\partial t} = \frac{2e\,V(t)}{\hbar}$$

$$\Rightarrow \quad V = \frac{\Phi_0}{2\pi \cdot I_c \cdot \cos\varphi} \cdot \frac{dI}{dt} = L_J(\varphi) \cdot \frac{dI}{dt}$$

→ non-linear & tunable inductance

Quantum harmonic oscillator: superconducting resonators





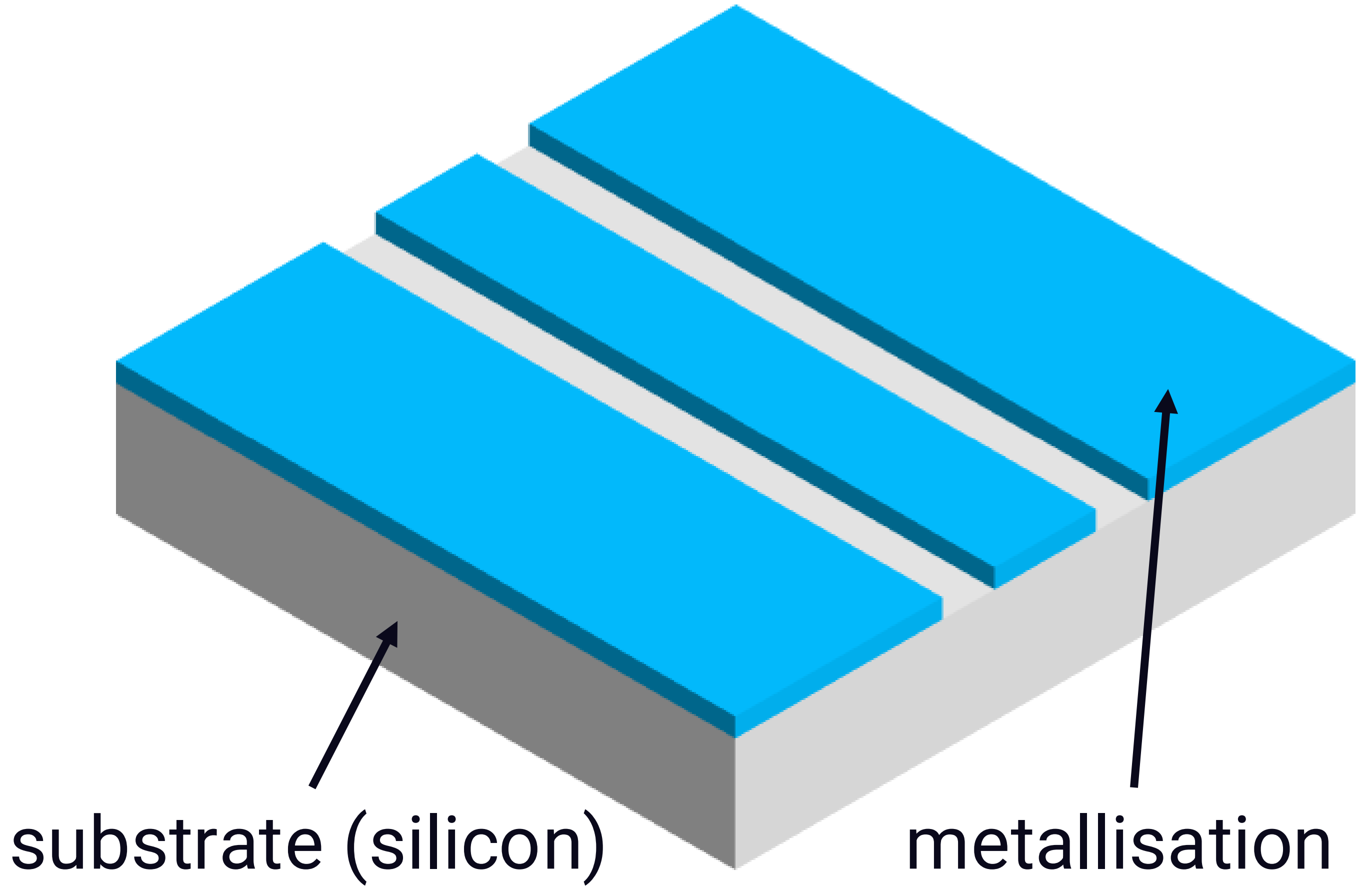
$$H = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)$$

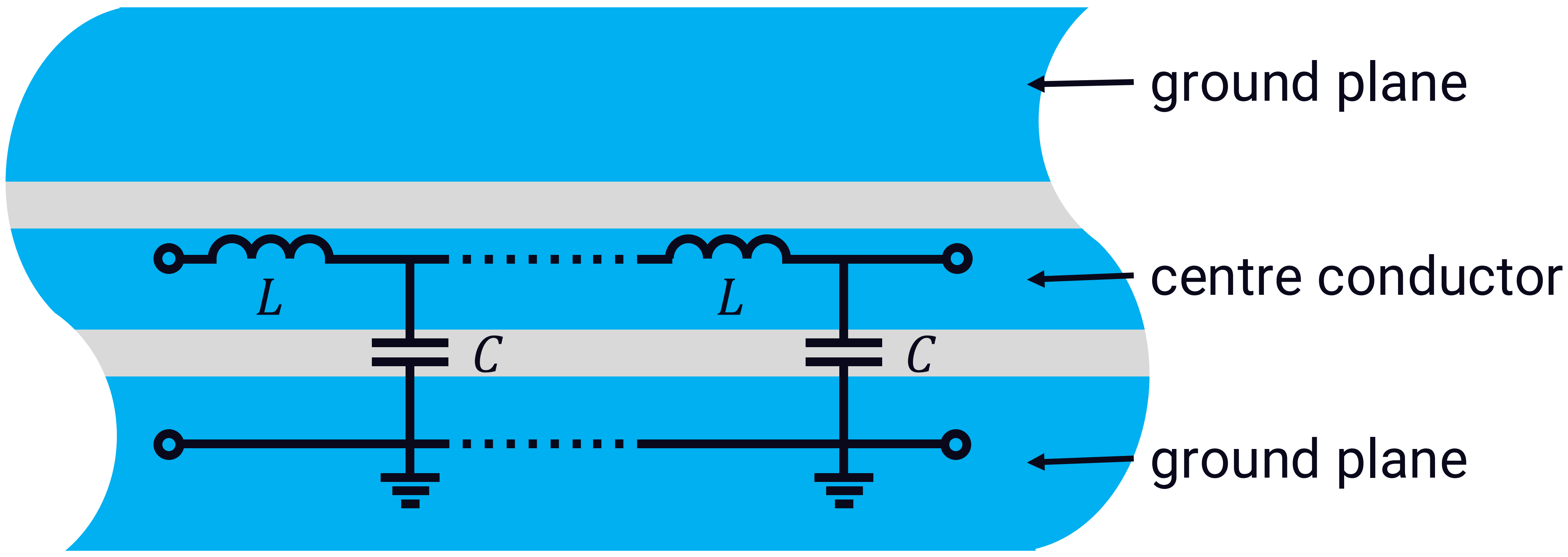
charging energy
inductive energy

→Linear harmonic oscillator

→Equidistant energy levels

Planar superconducting waveguides

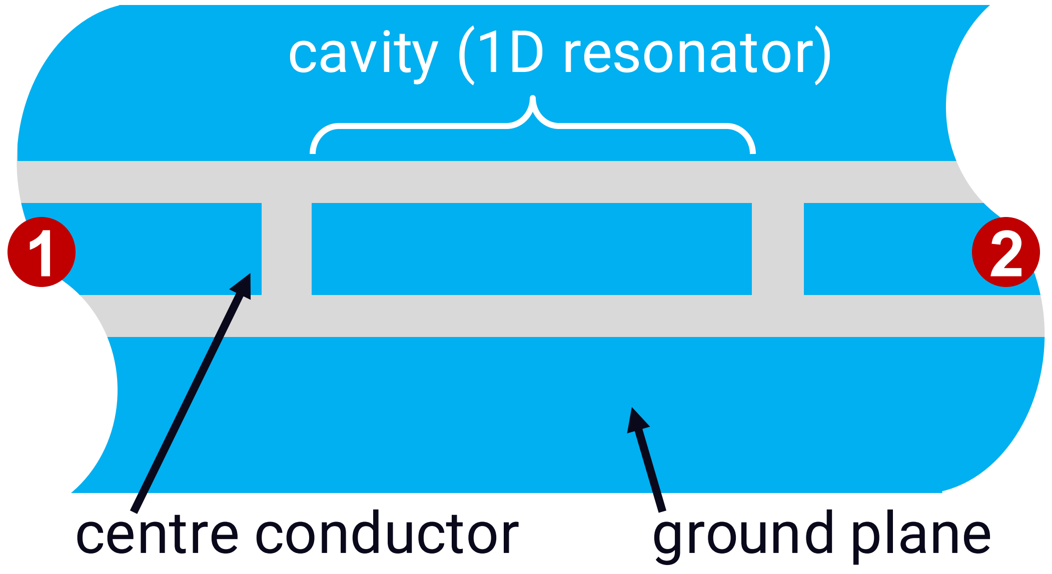




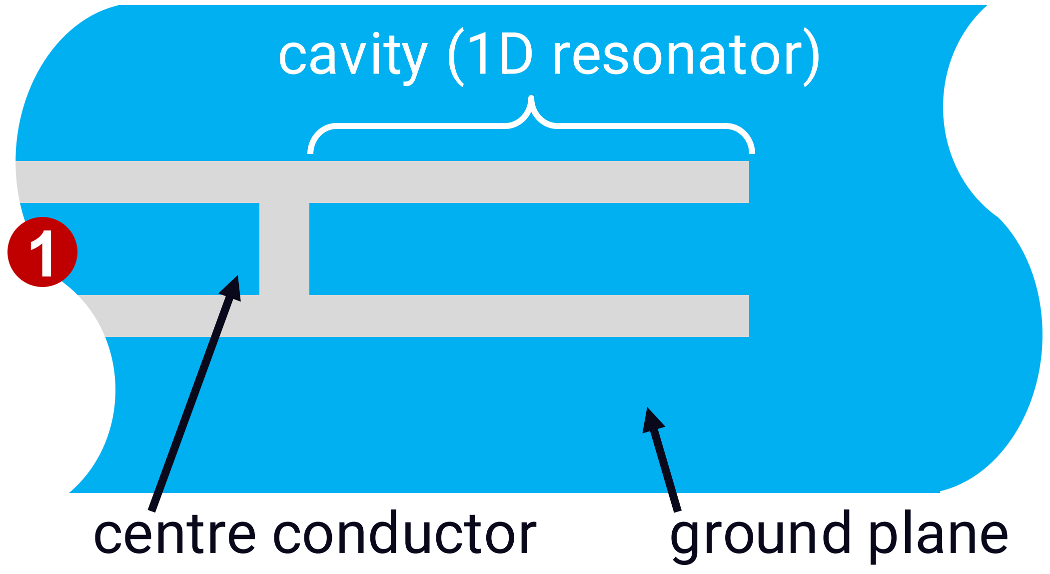
$$Z = \sqrt{\frac{L}{C}} \approx 50\ \Omega$$

Planar superconducting resonators

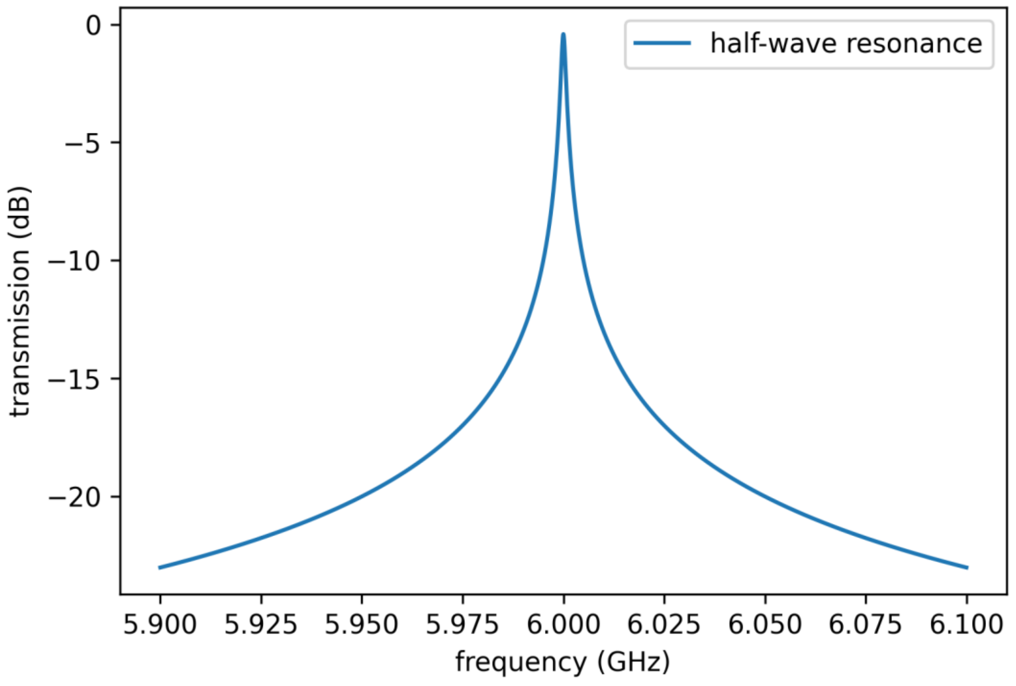
half-wave resonator



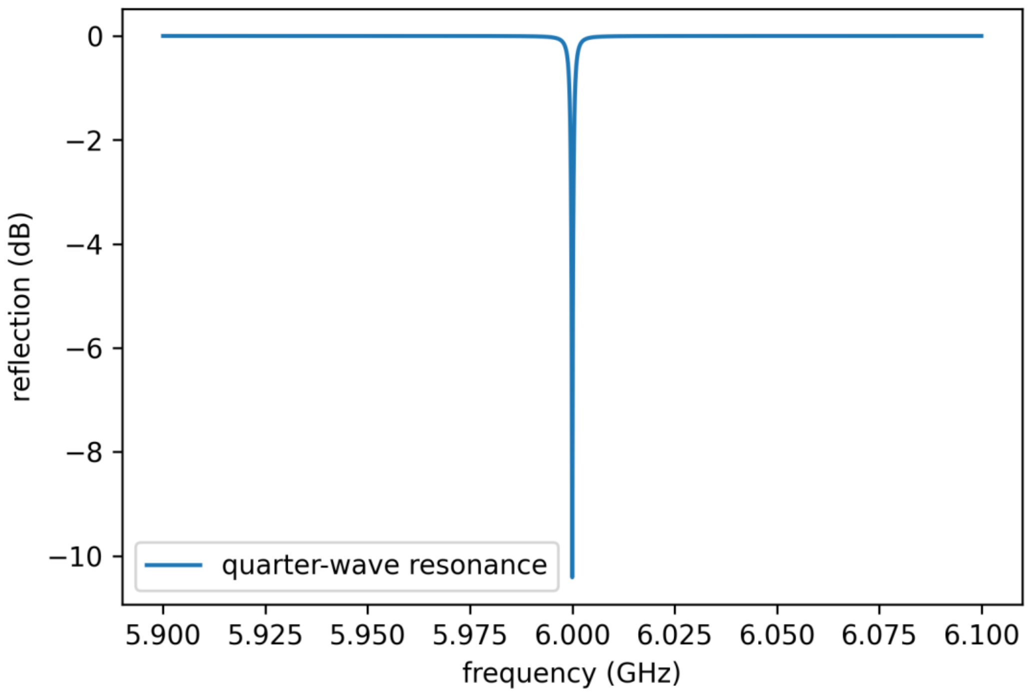
quarter-wave resonator



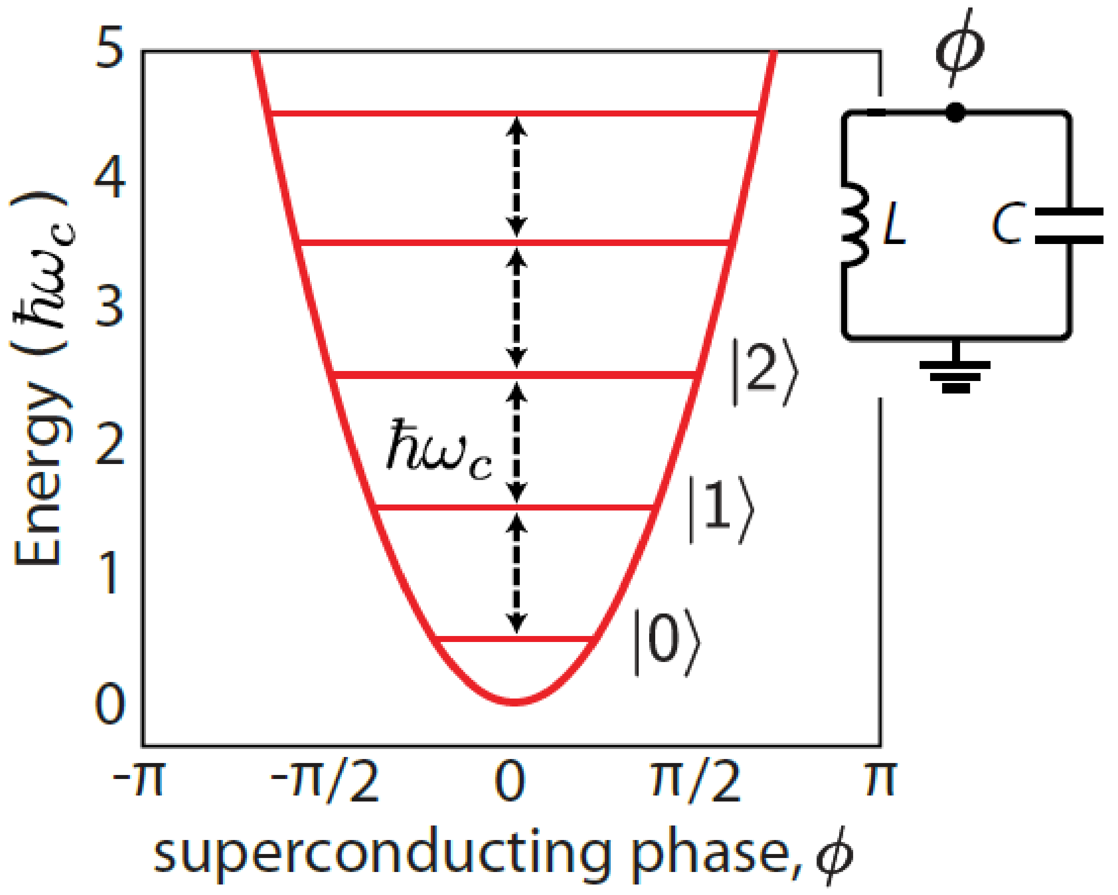
Measuring S21 transmission

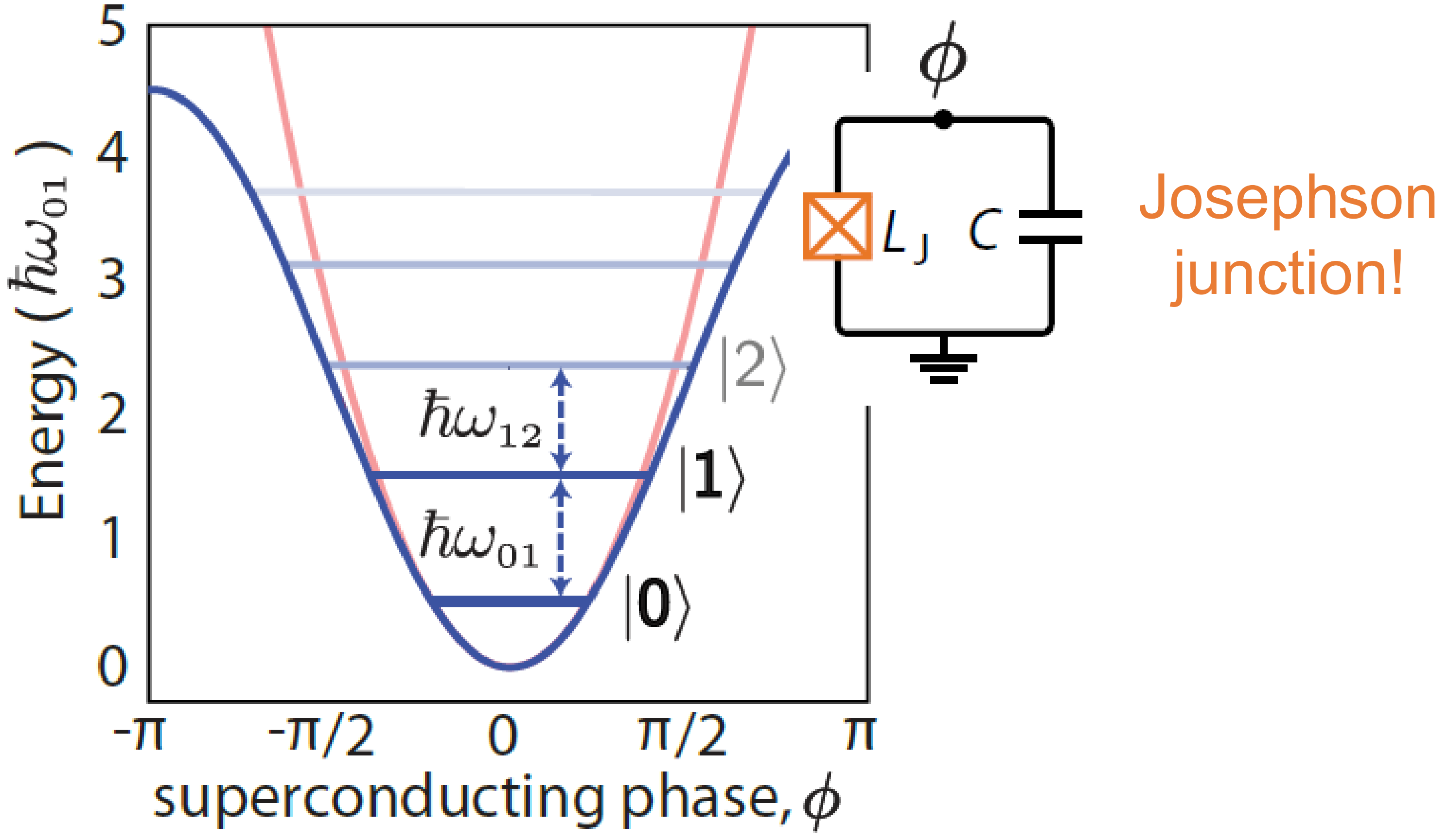


Measuring S11 reflection



Quantum circuits need non-linearity

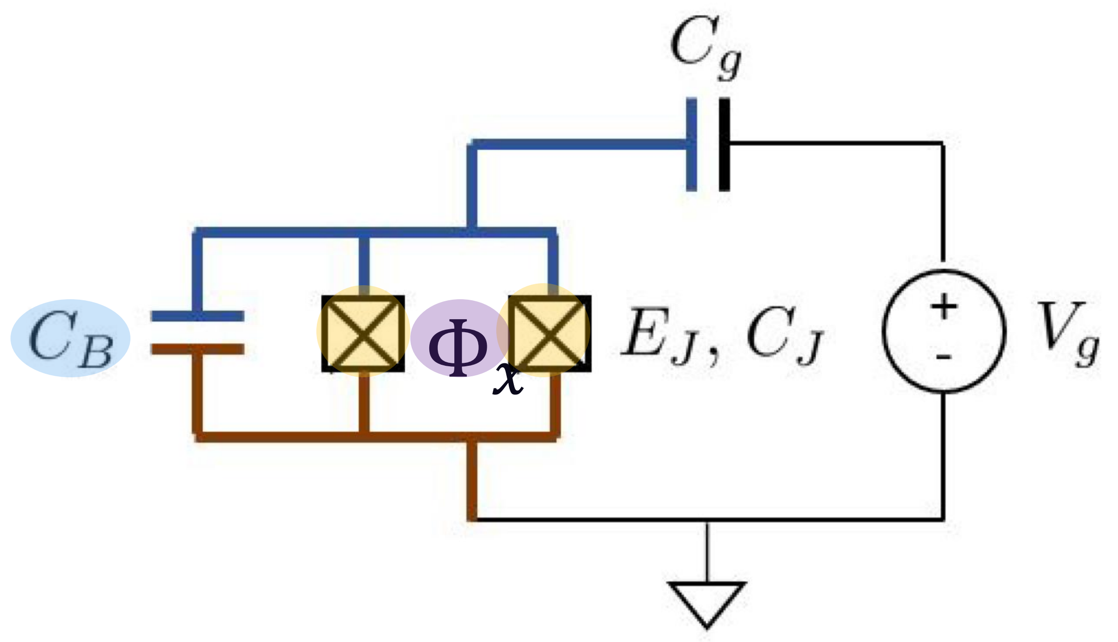




→Quantised **non**-equidistant energy levels

→Possible to address the transitions individually

Transmon qubit

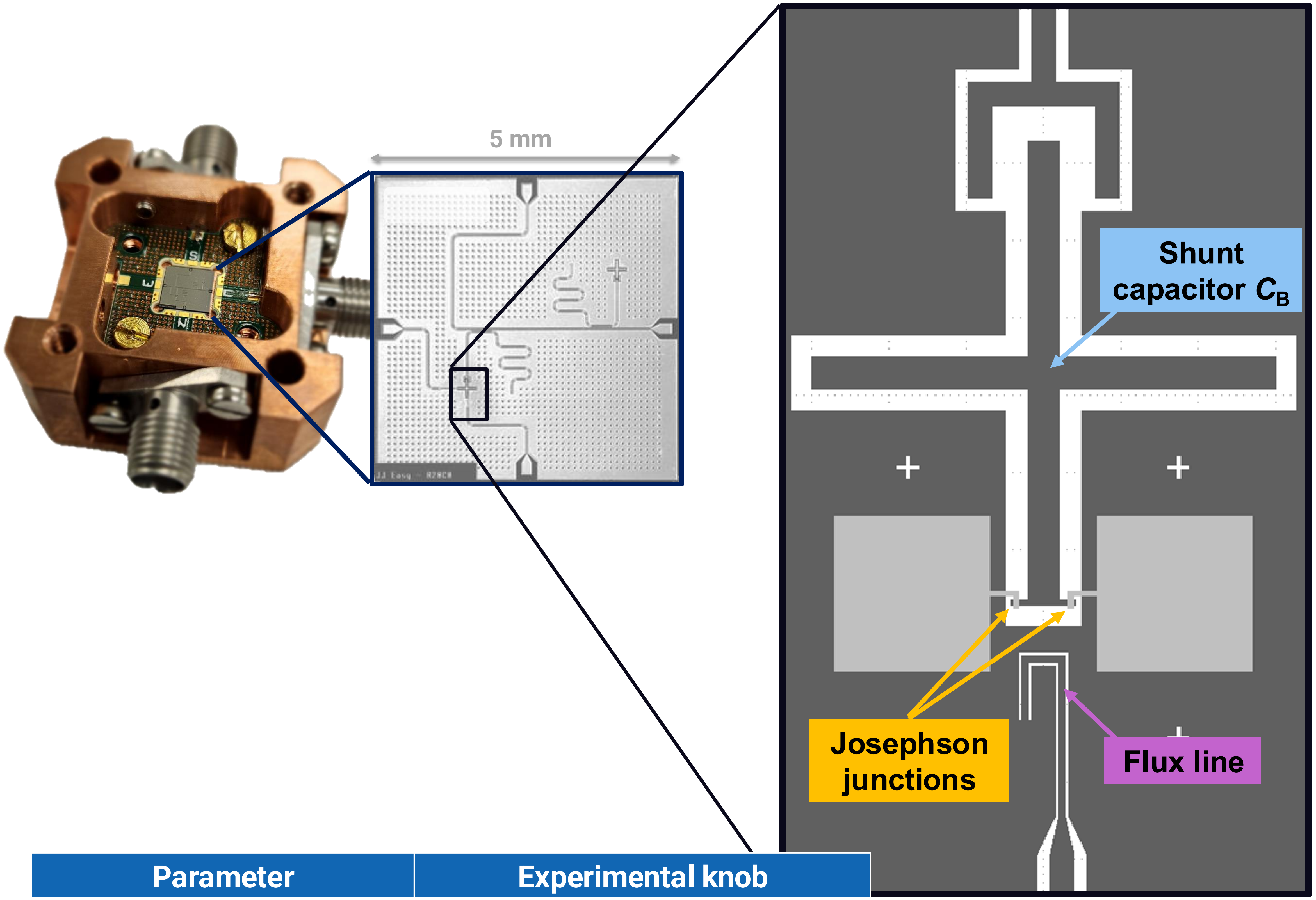


$$E_C(C) \sim \frac{1}{C}$$

$$E_J(\Phi_x) \sim E_J^{\Sigma} \cos\frac{\pi\Phi_x}{\Phi_0}$$

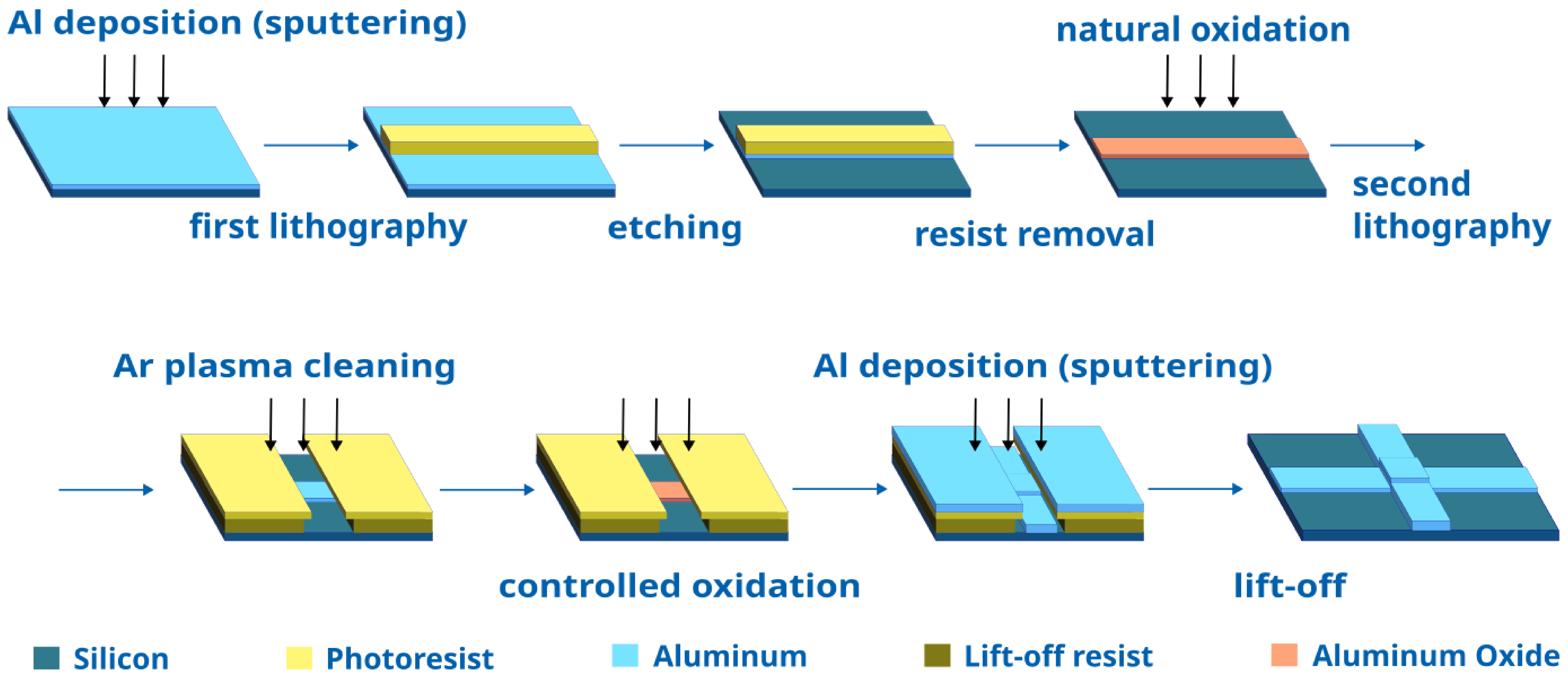
with $E_J^{\Sigma} = E_{J1} + E_{J2}$

$$E_{Ji} \propto I_c$$

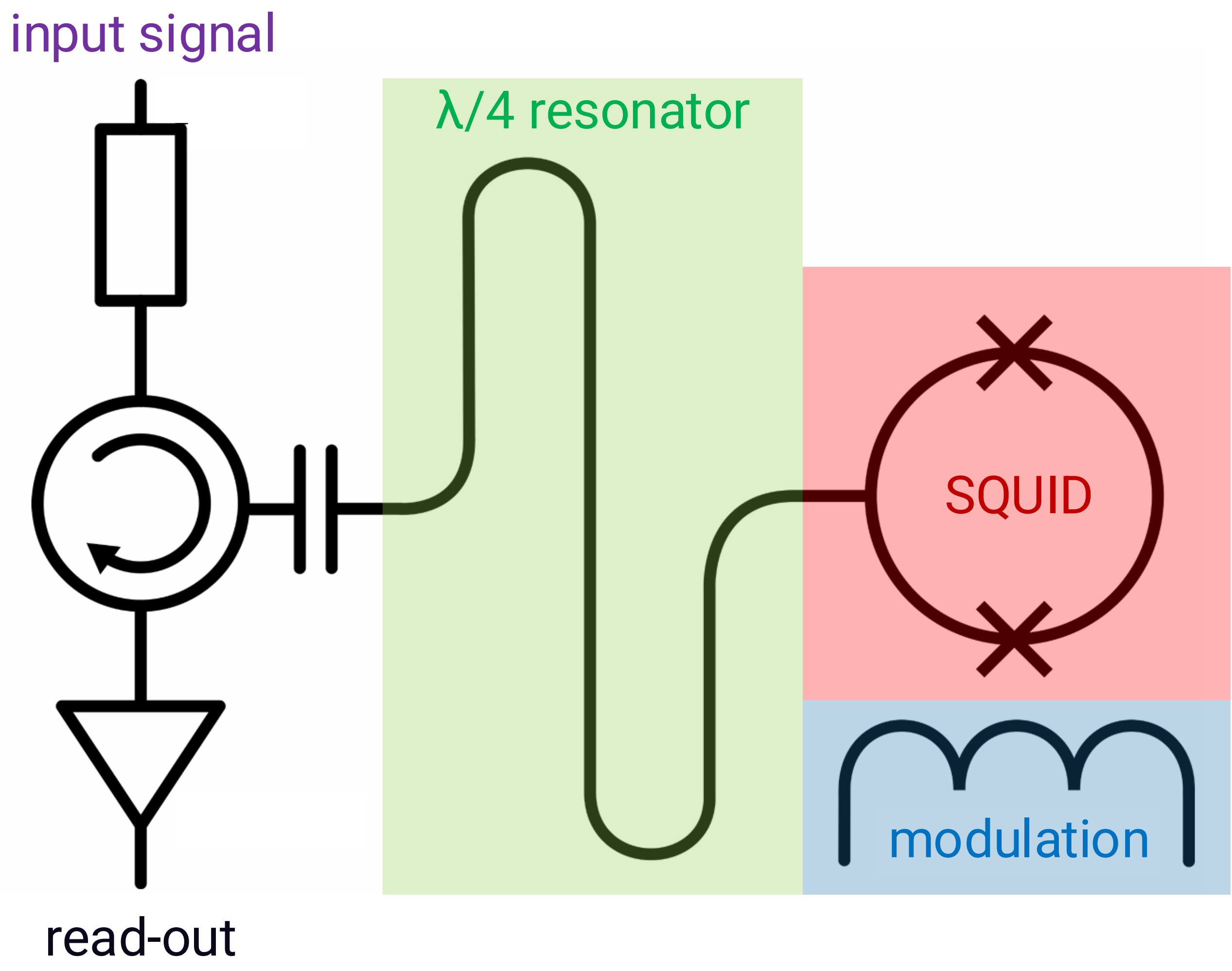


Parameter	Experimental knob
Capacitance C	Layout of shunt capacitor C_B
External magnetic flux Φ_x	Current flowing through flux line
Critical current I_c	Area and barrier of the junction

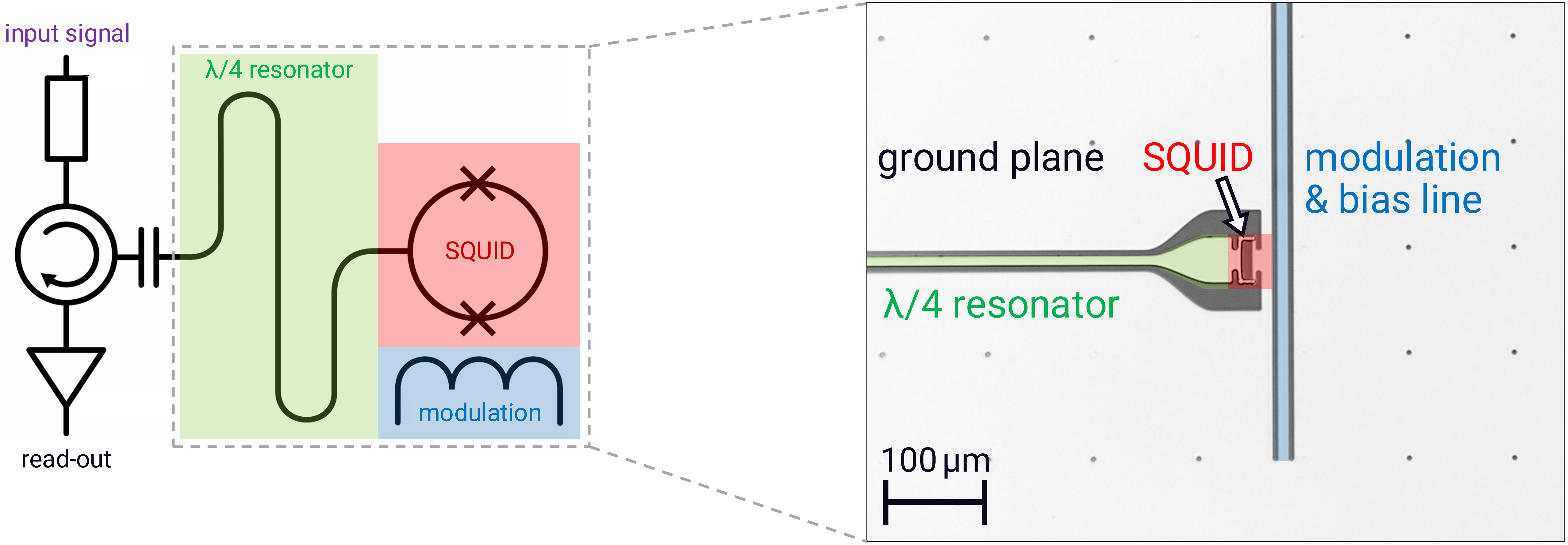
Al-AlOx-Al overlap Josephson junctions



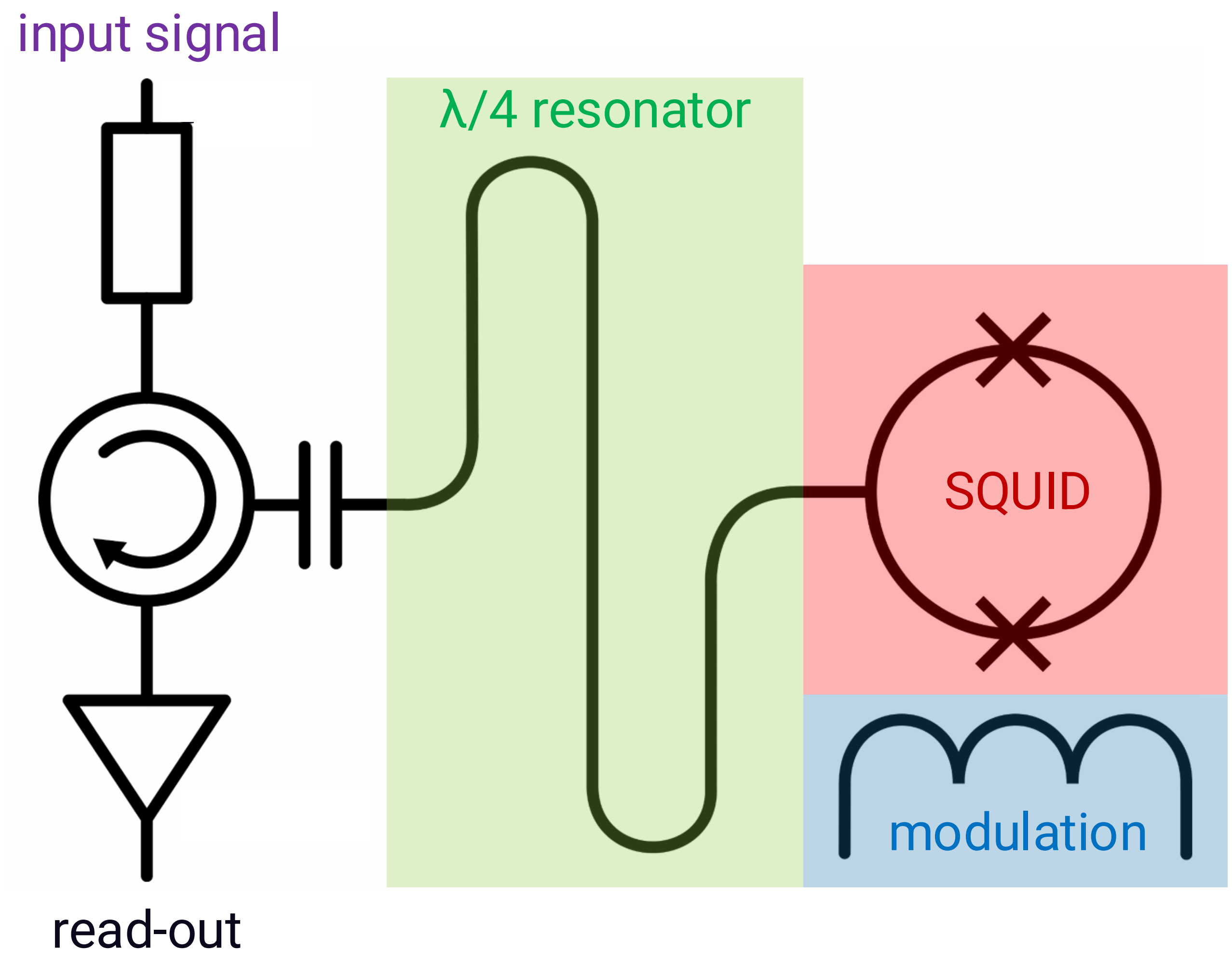
Tunable microwave cavity

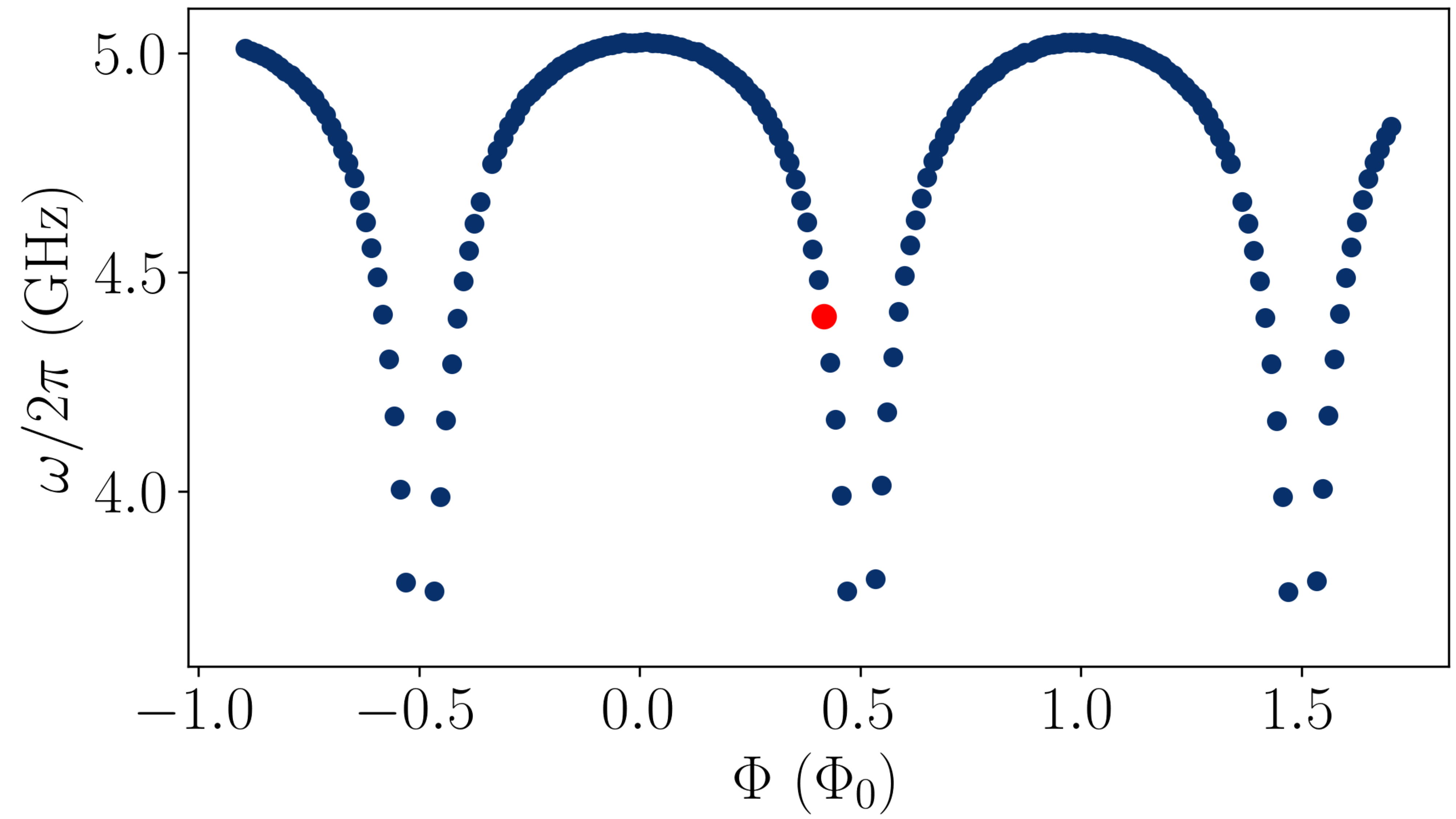


Tunable microwave cavity



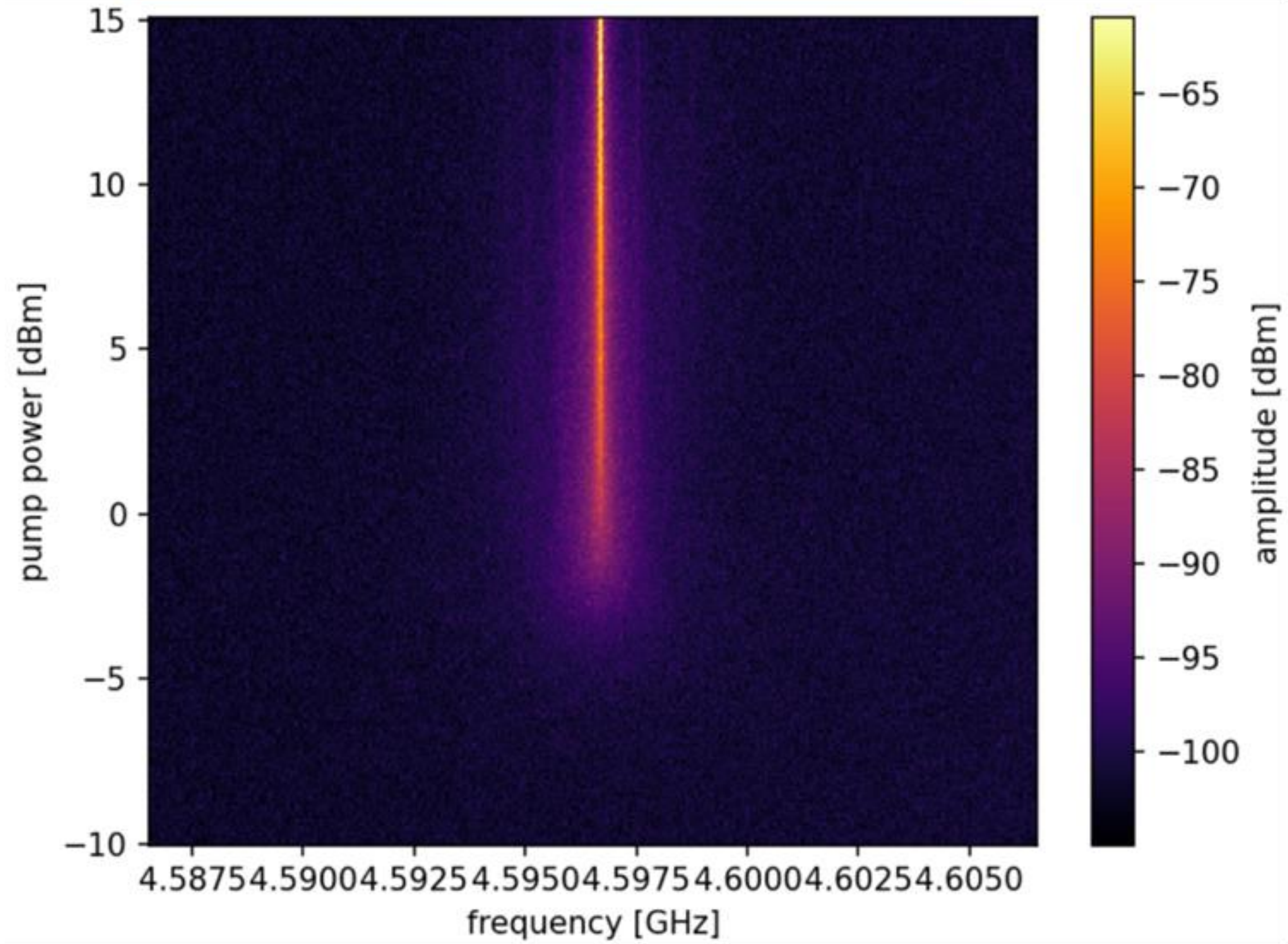
Tunable microwave cavity



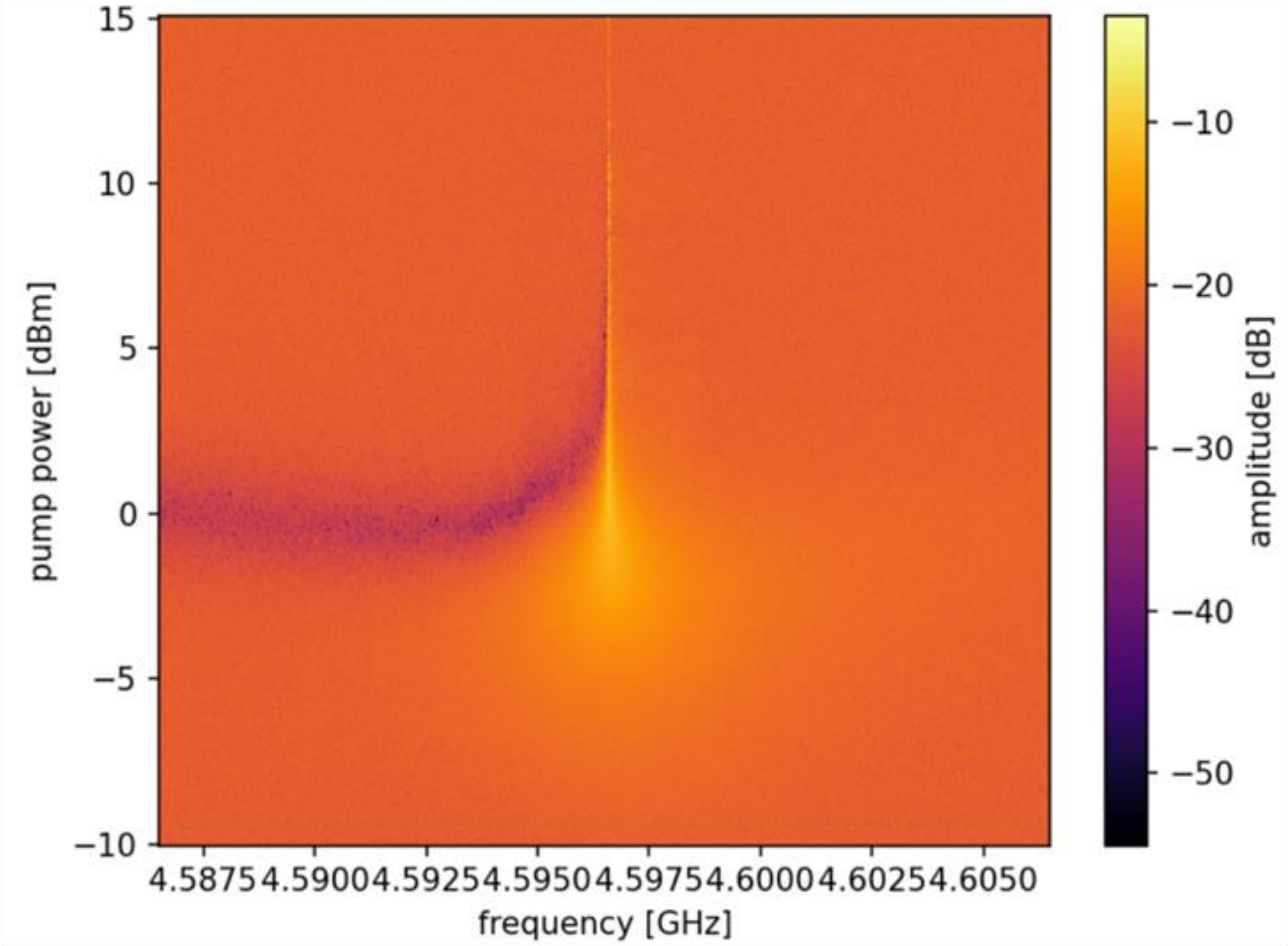


Tunable microwave cavity - JPA

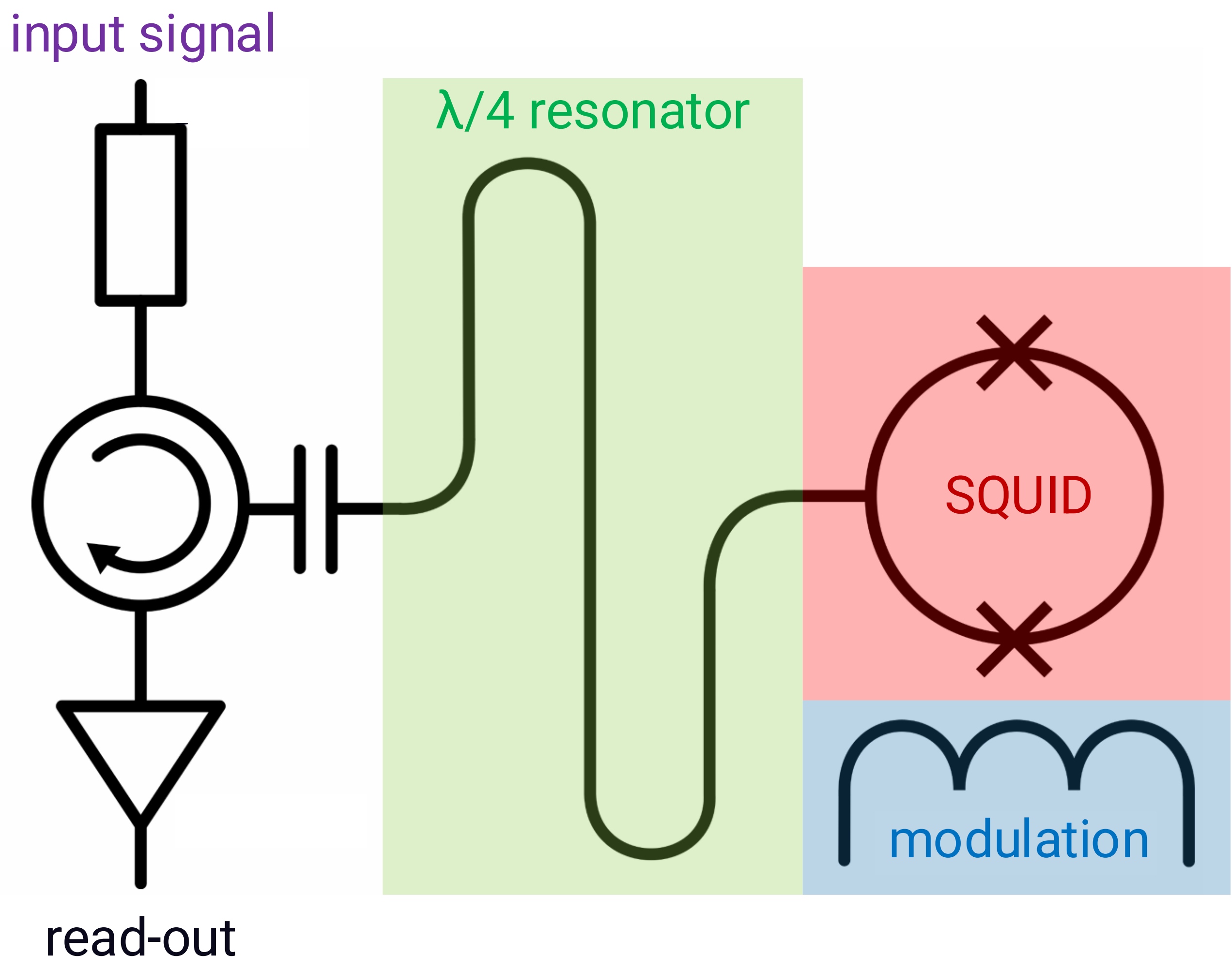
PSD

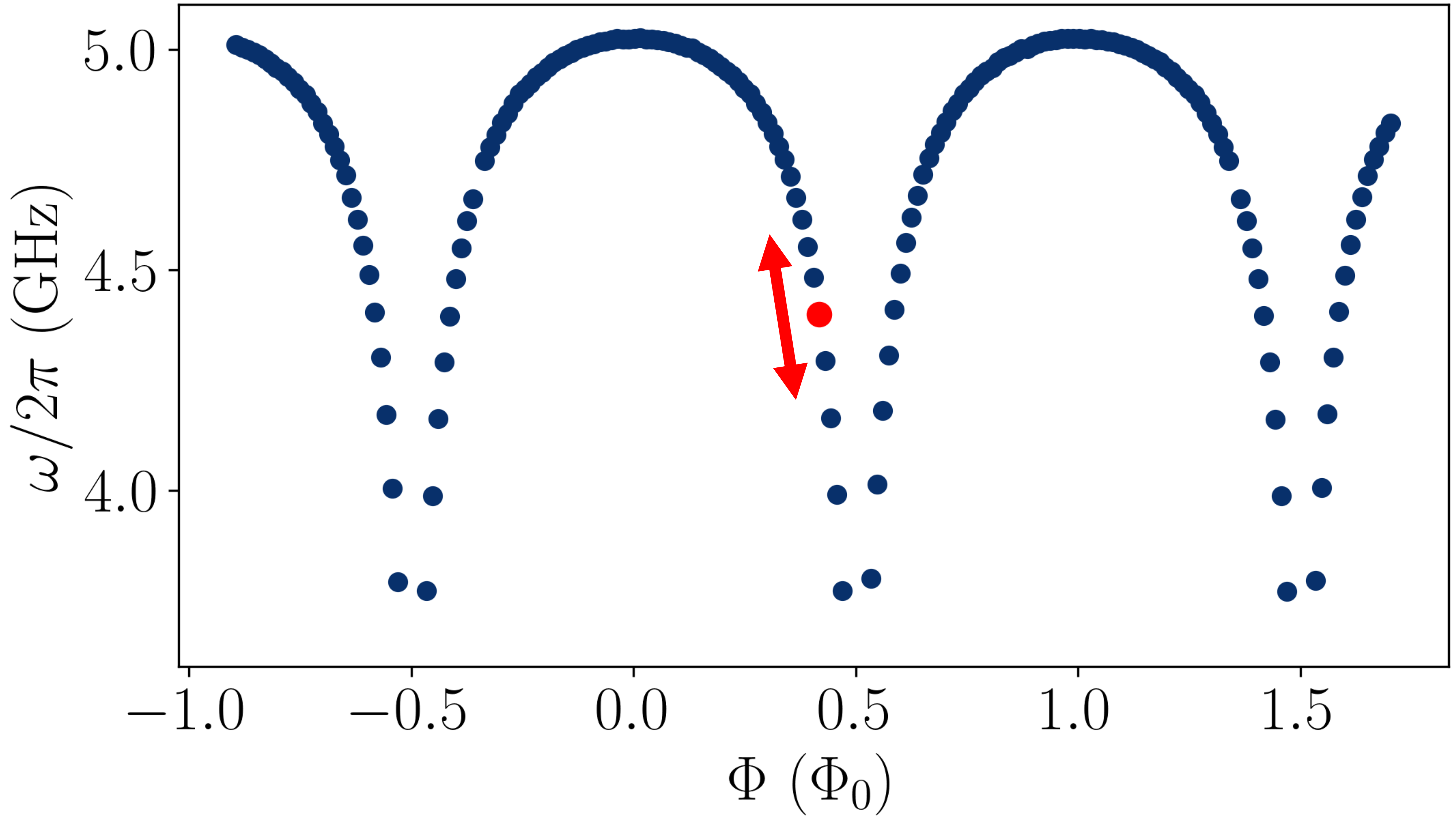


S21



Tunable microwave cavity – JPA, but not only!

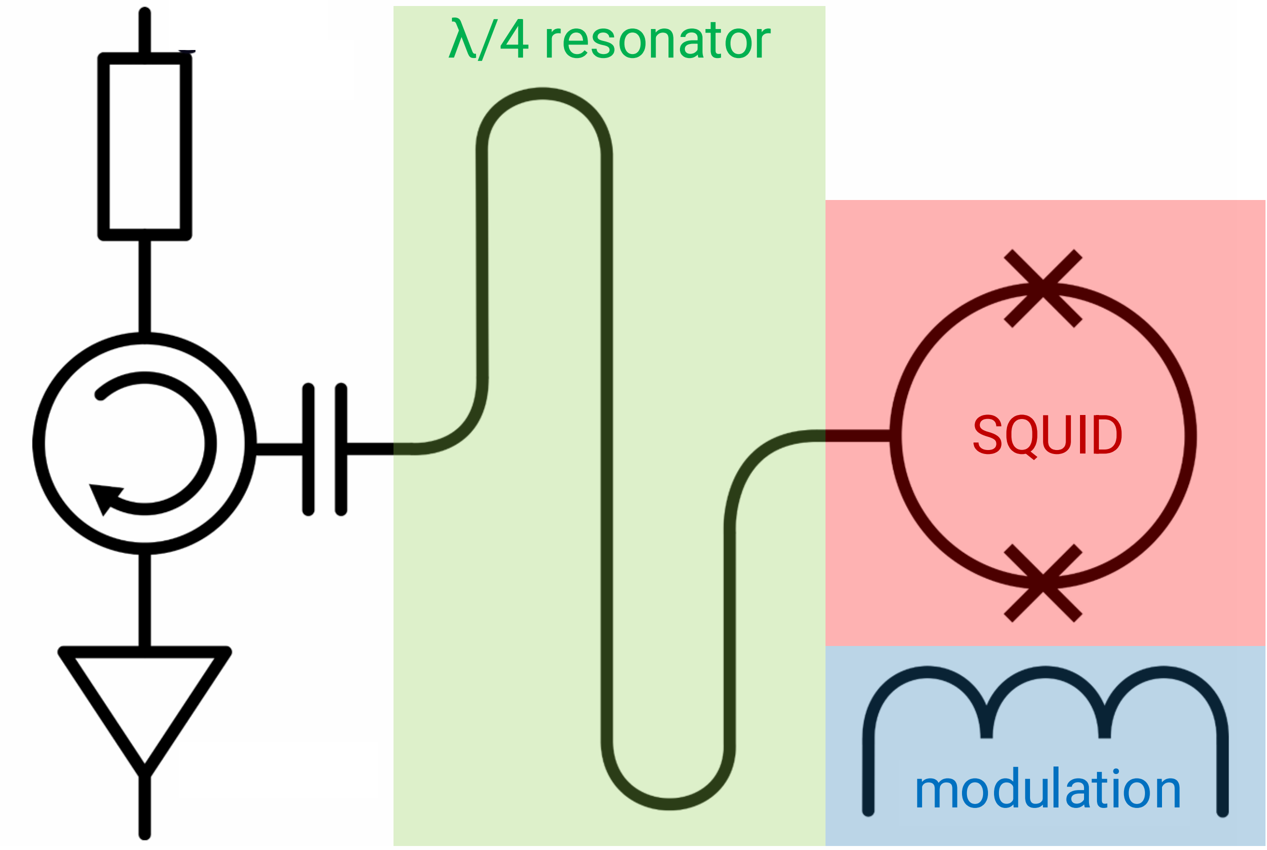




Tunable microwave cavity – JPA, but not only!

$E_{\text{in}}(t) = E_{\text{in}} e^{-i\omega_{\text{in}} t}$

input signal



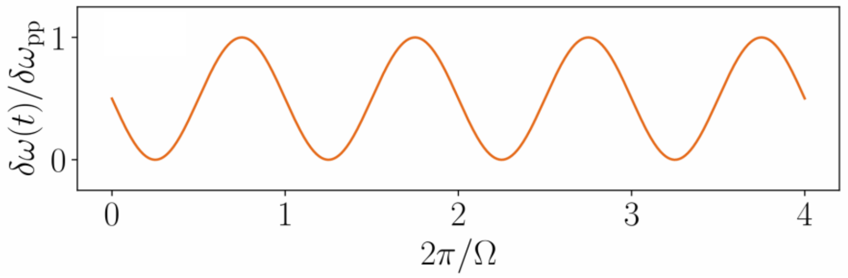
read-out

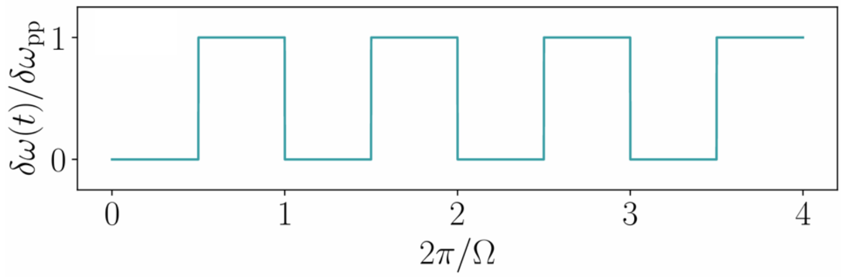
$$i\dot{\alpha}(t) = \left[\omega_0 + \delta\omega(t) - i\frac{\gamma}{2}\right]\alpha(t) + E_{\text{in}}(t)$$

Ansatz: $\alpha(t) = \sum_n \alpha_n e^{-i(\omega_{\text{in}} + n\Omega)t}$

$$\boxed{\left[\omega_{\text{in}} - (\omega_0 - n\Omega) + i\frac{\gamma}{2}\right]\alpha_n - \sum_m \delta\omega_m \alpha_{n-m} = E_{\text{in}}\delta_{n,0}}$$

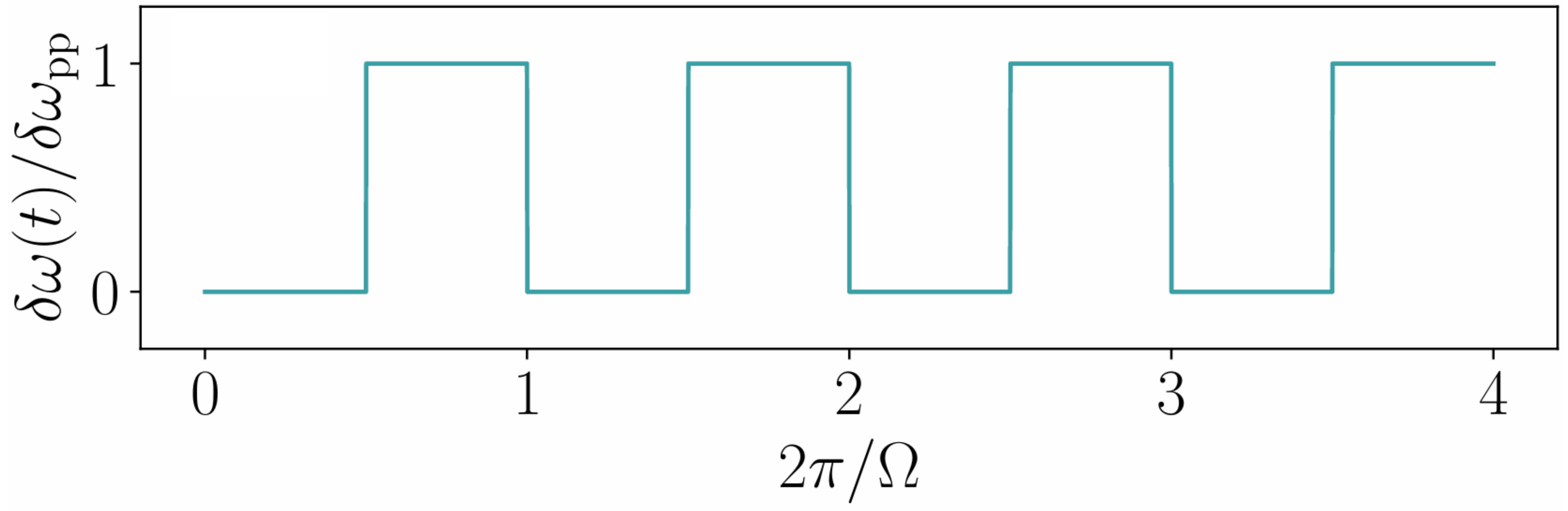
$\delta\omega(t) = \sum_m \delta\omega_m e^{-im\Omega t}$ with $\Omega \ll \omega_{\text{in}}$

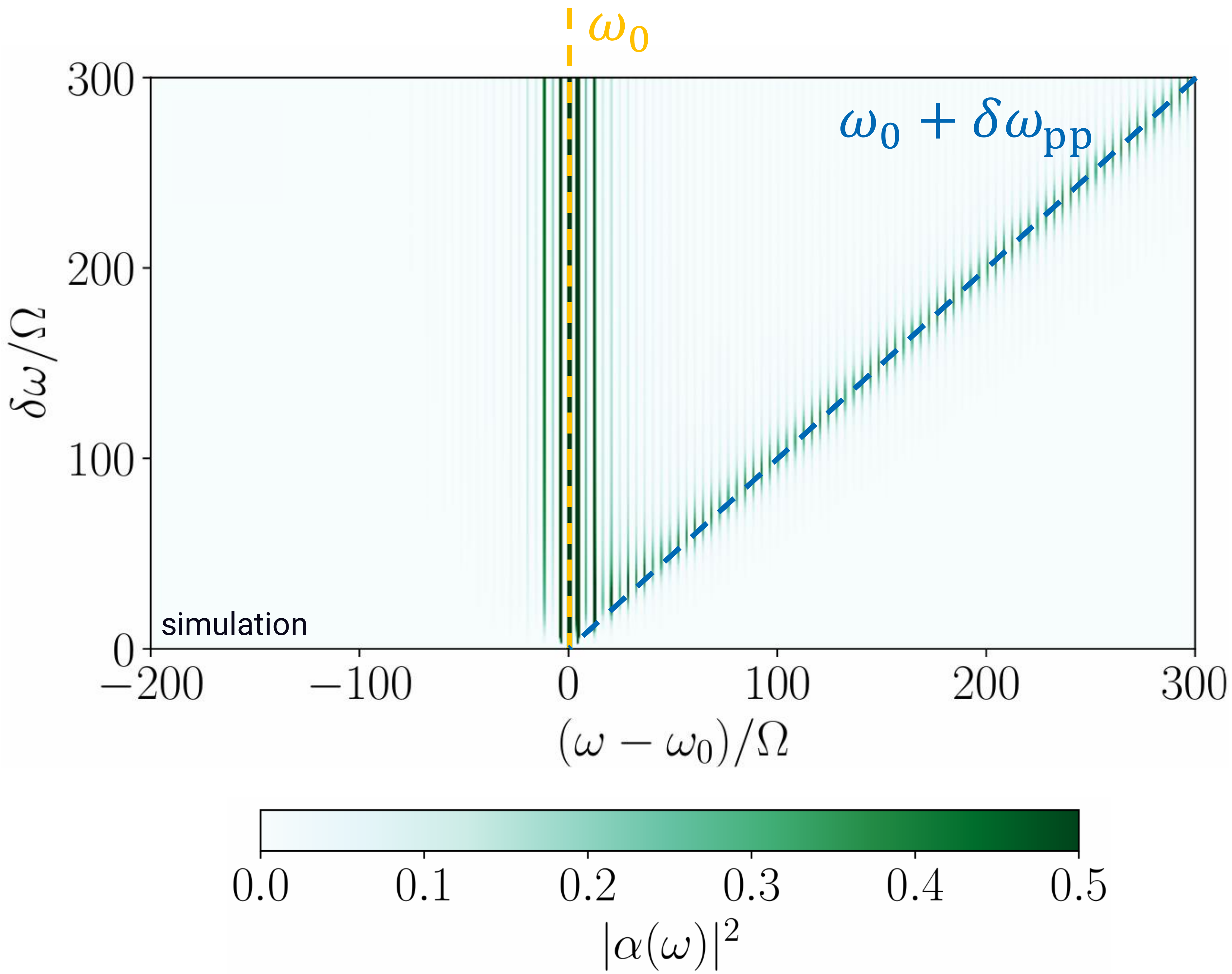




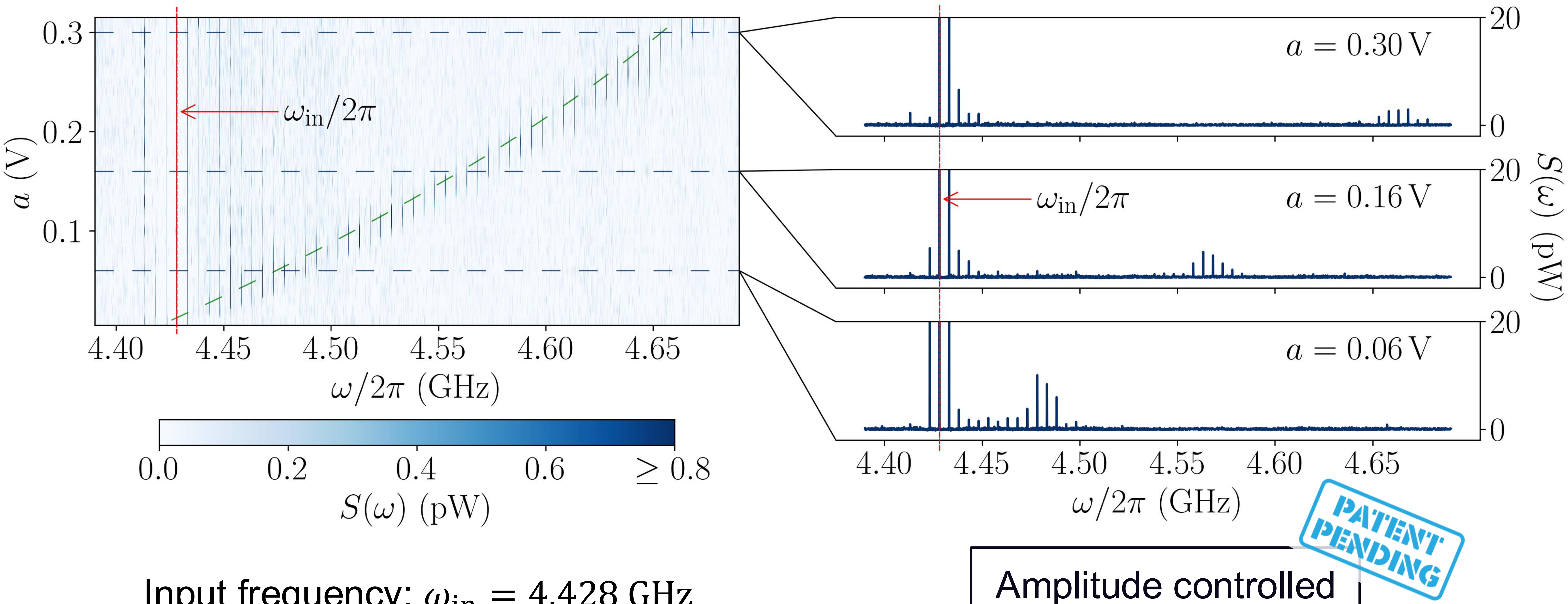
Tuning the cavity faster than the photon lifetime

$$i\dot{\alpha}(t) = \left[\omega_0 + \delta\omega(t) - i\frac{\gamma}{2}\right]\alpha(t) + E_{\mathrm{in}}(t)$$





Photon energy lifting: Experimental results

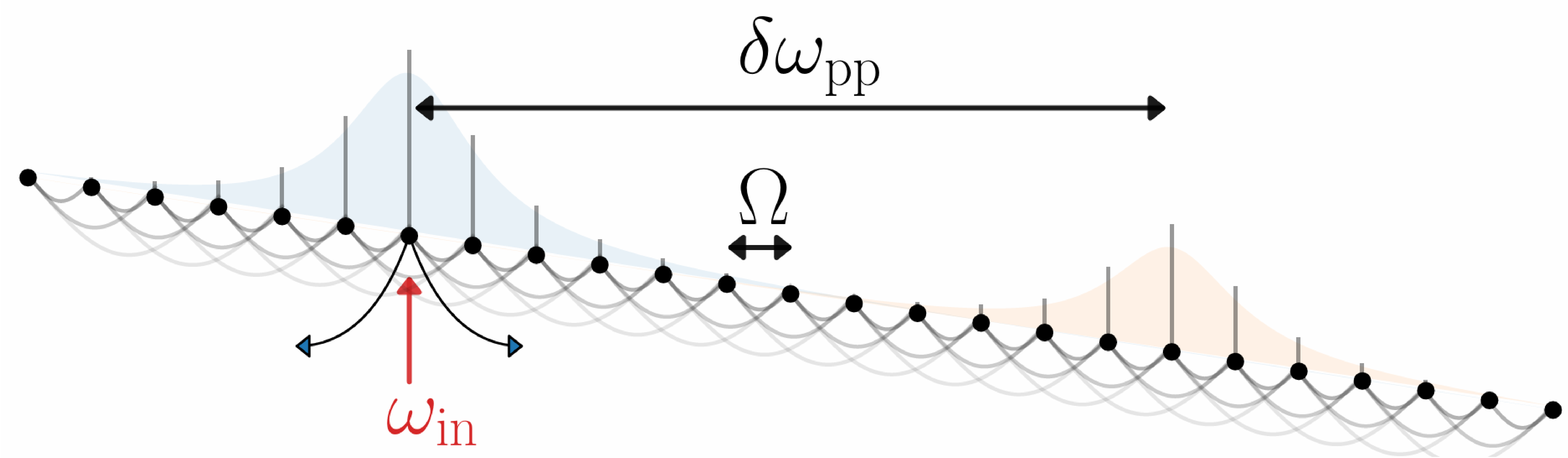


Input frequency: $\omega_{in} = 4.428\ \mathrm{GHz}$

Modulation frequency: $\Omega = 5\ \mathrm{MHz}$

Amplitude controlled frequency shifter

Synthetic lattice and Bloch oscillations

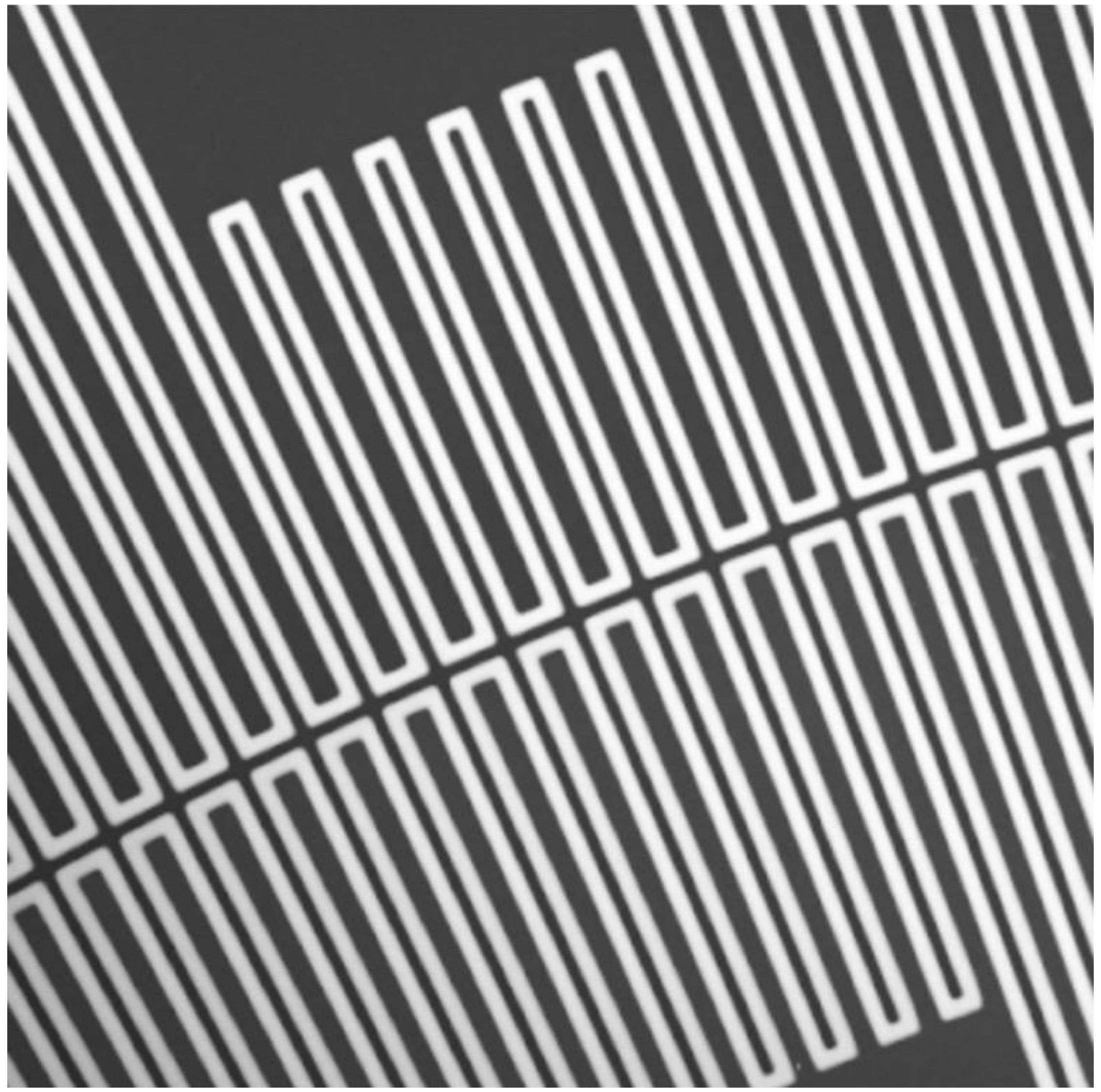


Pre-print available (arxiv:2409.00760):

F. Ahrens, N. Crescini, A. Irace, G. Rastelli, P. Falferi, A. Giachero, B. Margesin, R. Mezzena, A. Vinante, I. Carusotto, F. Mantegazzini

Synthetic-lattice Bloch wave dynamics in a single-mode microwave resonator

Superconducting technologies @FBK



Kinetic inductance

TWPA
KICS
Microwave shifter

Josephson junctions

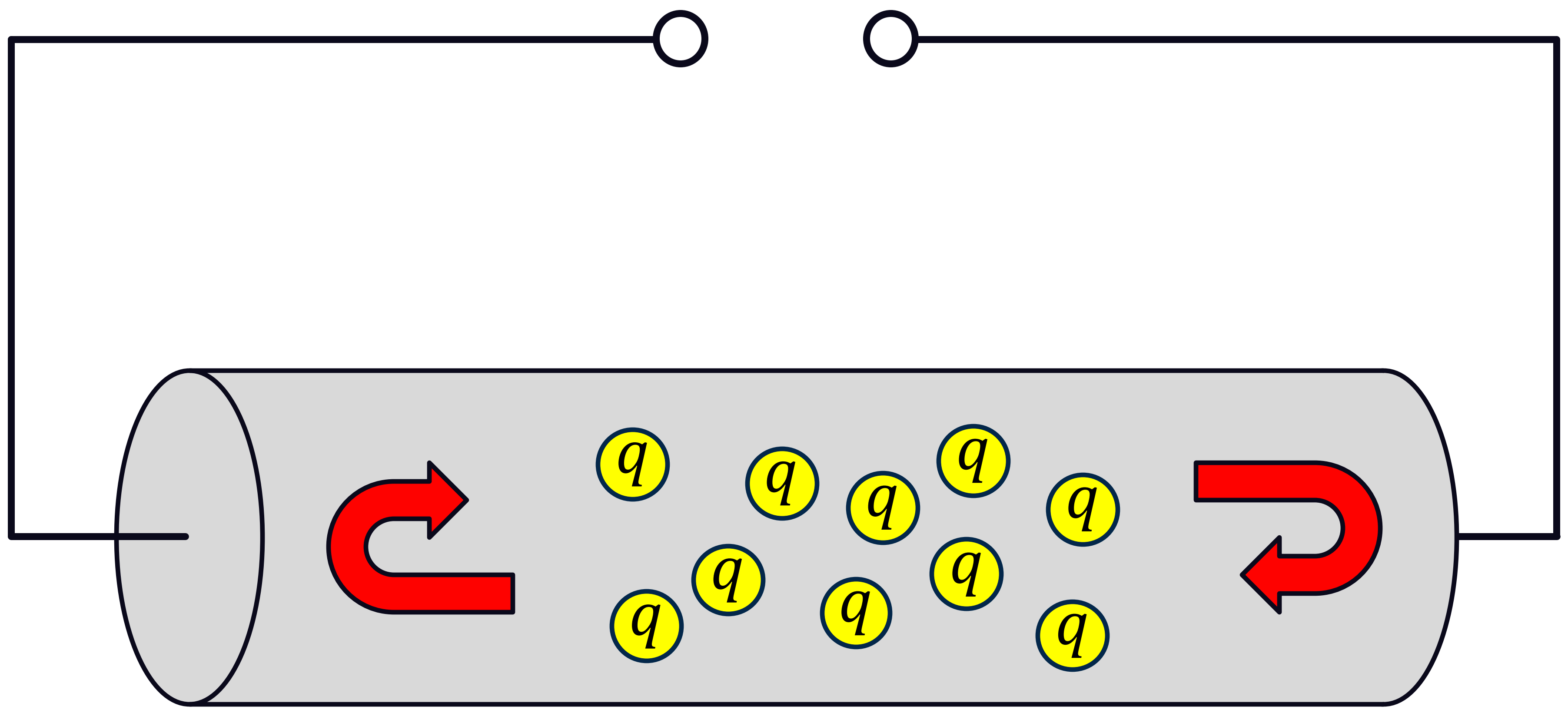
JPAs
Qubits (Transmons)
Microwave shifter

Mechanical hybrid systems

Magnetometers
Devices for funda-
mental physics

Kinetic inductance

$$U = U_0 e^{i\omega t}$$



$$\sigma = \frac{nq^2\tau}{m(1 + i\omega\tau)}$$

Kinetic inductance:
- large collision time τ
- high frequency ω

Superconductor:

$\tau \to \infty, \quad m = 2m_e, \quad q = 2e$

Cooper pair density $n = n(I)$

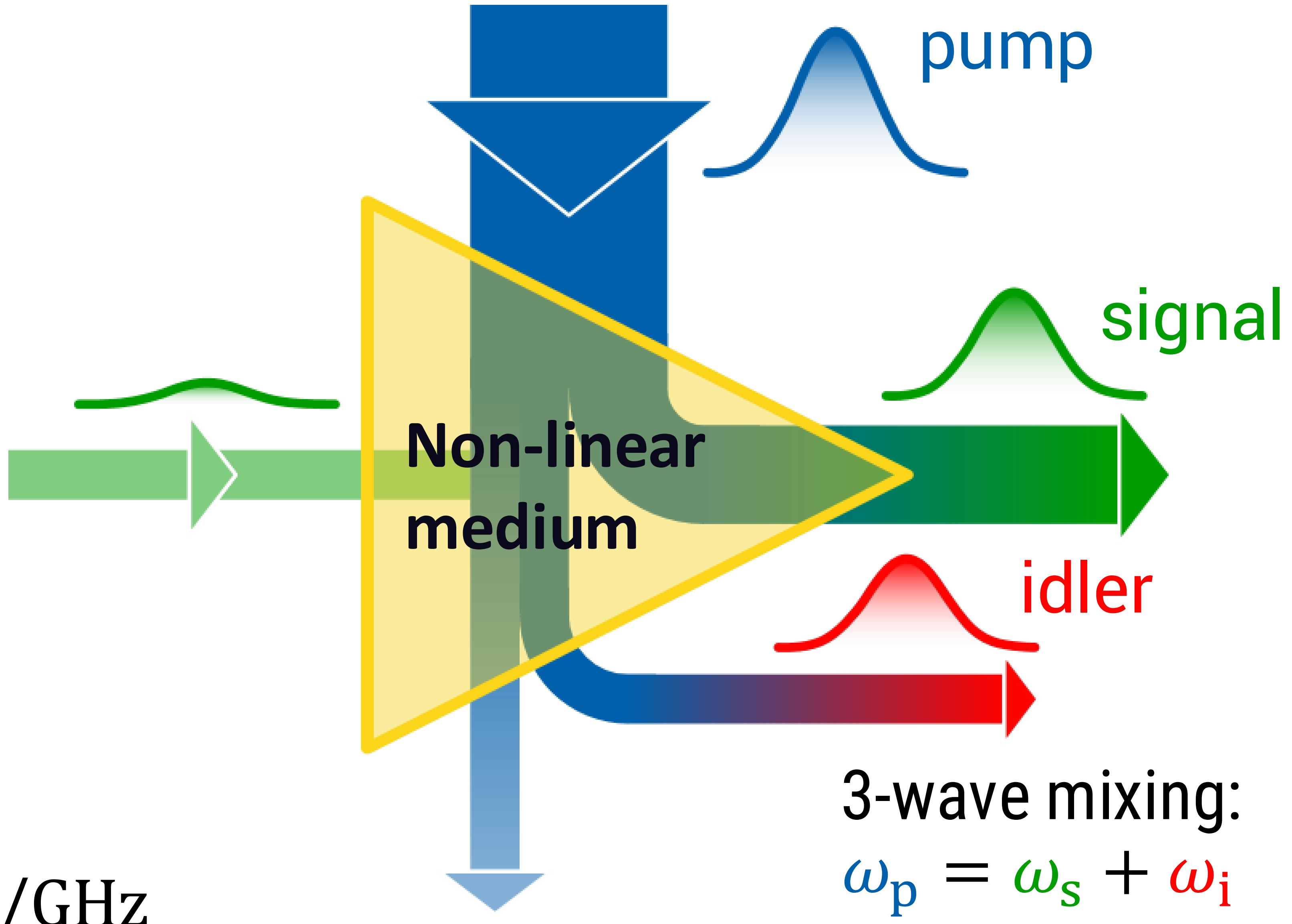
$$\Rightarrow \quad L(I) \approx L_0 \cdot \left(1 + \frac{I^2}{I_*^2}\right)$$

$$L_0 = \frac{R_S\,\hbar}{\pi\,\Delta}$$

$$I_* \propto 1/\sqrt{R_n}$$

Quantum circuits need non-linearity

Parametric amplification = wave-mixing process based on parametric **non-linearity**



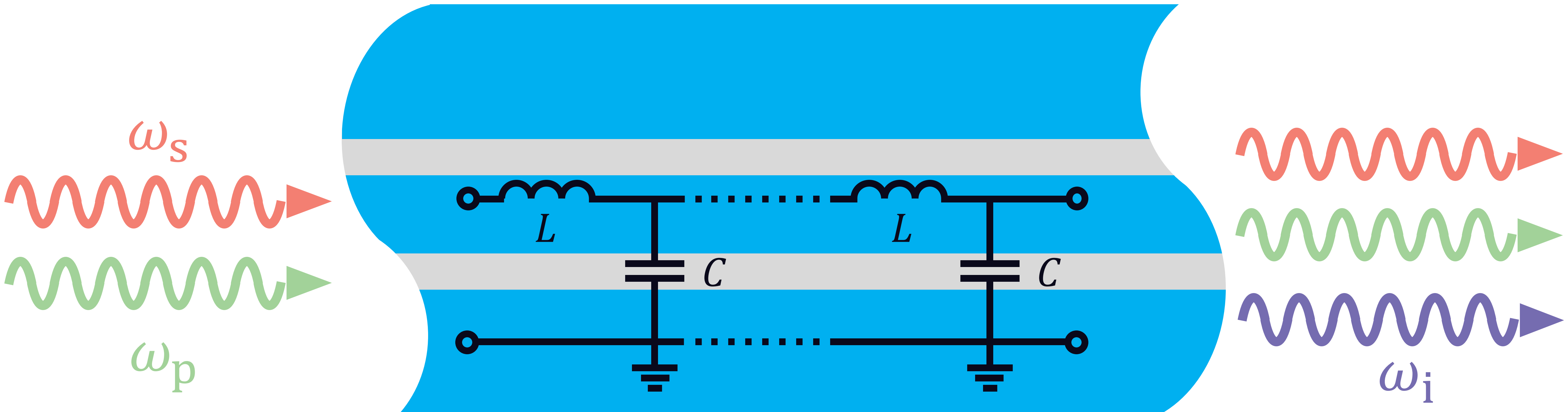
Superconducting amplifiers for microwave amplification:

- (Ideally) non-dissipative
- Ultra-low-noise amplification
  → Quantum noise limit: $T_N / f \sim h/2k_B \sim 25\ \mathrm{mK/GHz}$

Planar superconducting non-linear waveguide

Non-linear line:

- Source of **squeezed** microwave **radiation**
- Source of **entangled** microwave **photons**
- **Quantum limited** parametric microwave **amplification**
- …

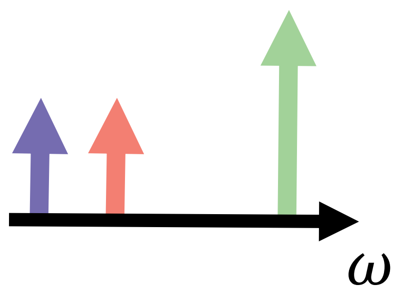


$$L(I_{\mathrm{DC}}, I_\mu) \sim L_d(I_{\mathrm{DC}})(1 + \boxed{a(I_{\mathrm{DC}})I_\mu} + \boxed{b(I_{\mathrm{DC}})I_\mu^2})$$

3-wave mixing:

$\omega_p = \omega_s + \omega_i$

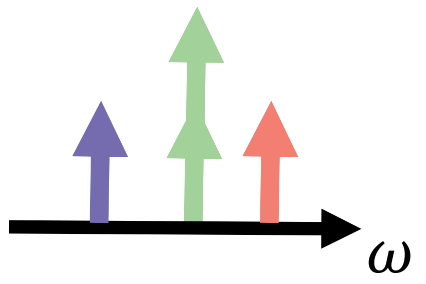
DC current bias is required



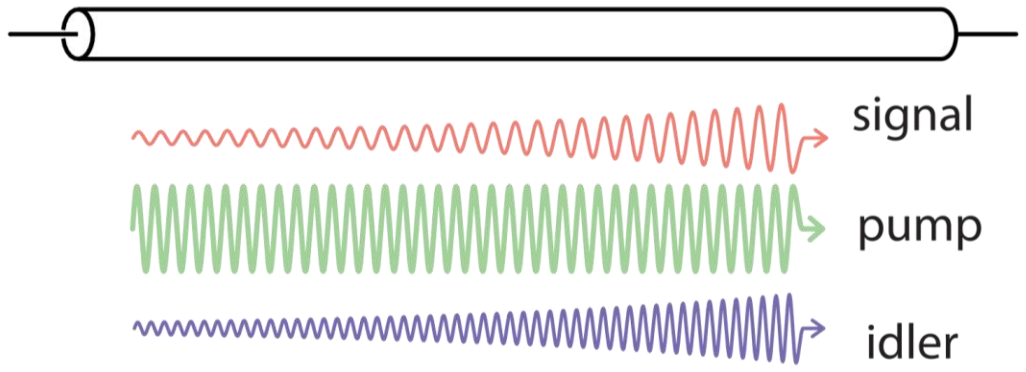
4-wave mixing:

$2\omega_p = \omega_s + \omega_i$

Pump at center of the amplification band



Travelling Wave Parametric Amplifiers
for squeezing and distributed quantum sensing



TWPA =
transmission line with embedded non-linear elements

Josephson inductance

$$L_J(I) = \frac{\arcsin(I/I_C)}{I/I_C}$$

Josephson junctions
$\Longrightarrow$ **J-TWPAs**

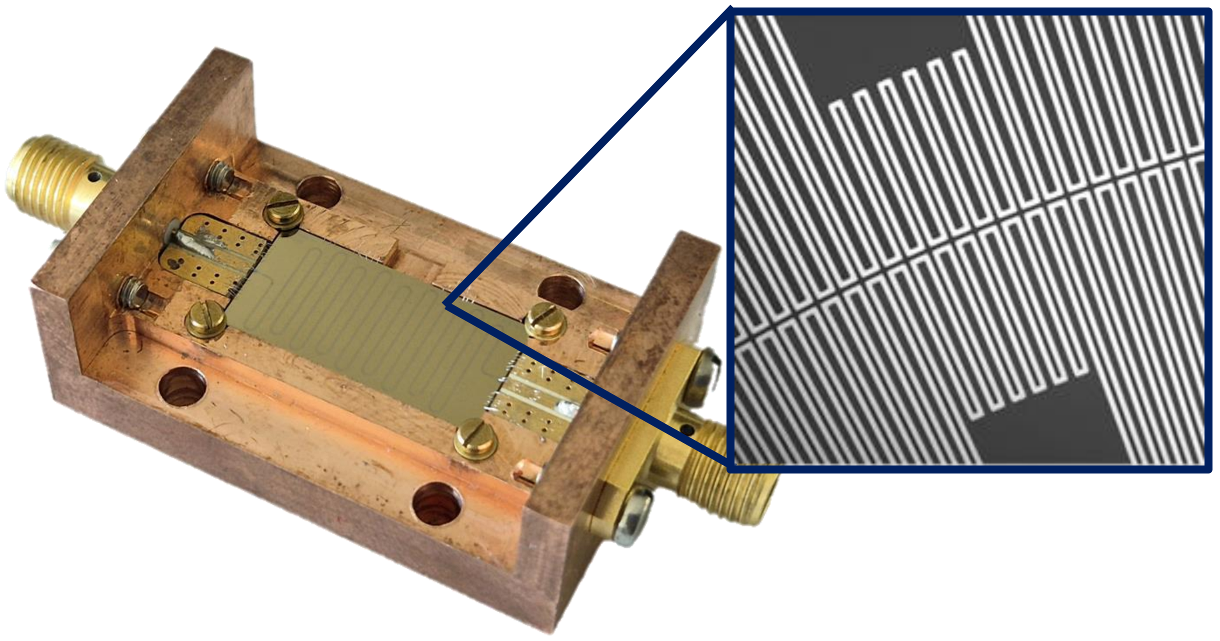
Kinetic inductance

$$L_K(I) \approx L_0 \cdot \left(1 + \frac{I^2}{I_*^2}\right)$$

High-kinetic inductance superconductor
$\Longrightarrow$ **KI-TWPAs**

Advantages

- Noise at the quantum limit
- Large bandwidth (~ 4 GHz)
- Squeezing & generation of entangled microwave photons



IMiSS

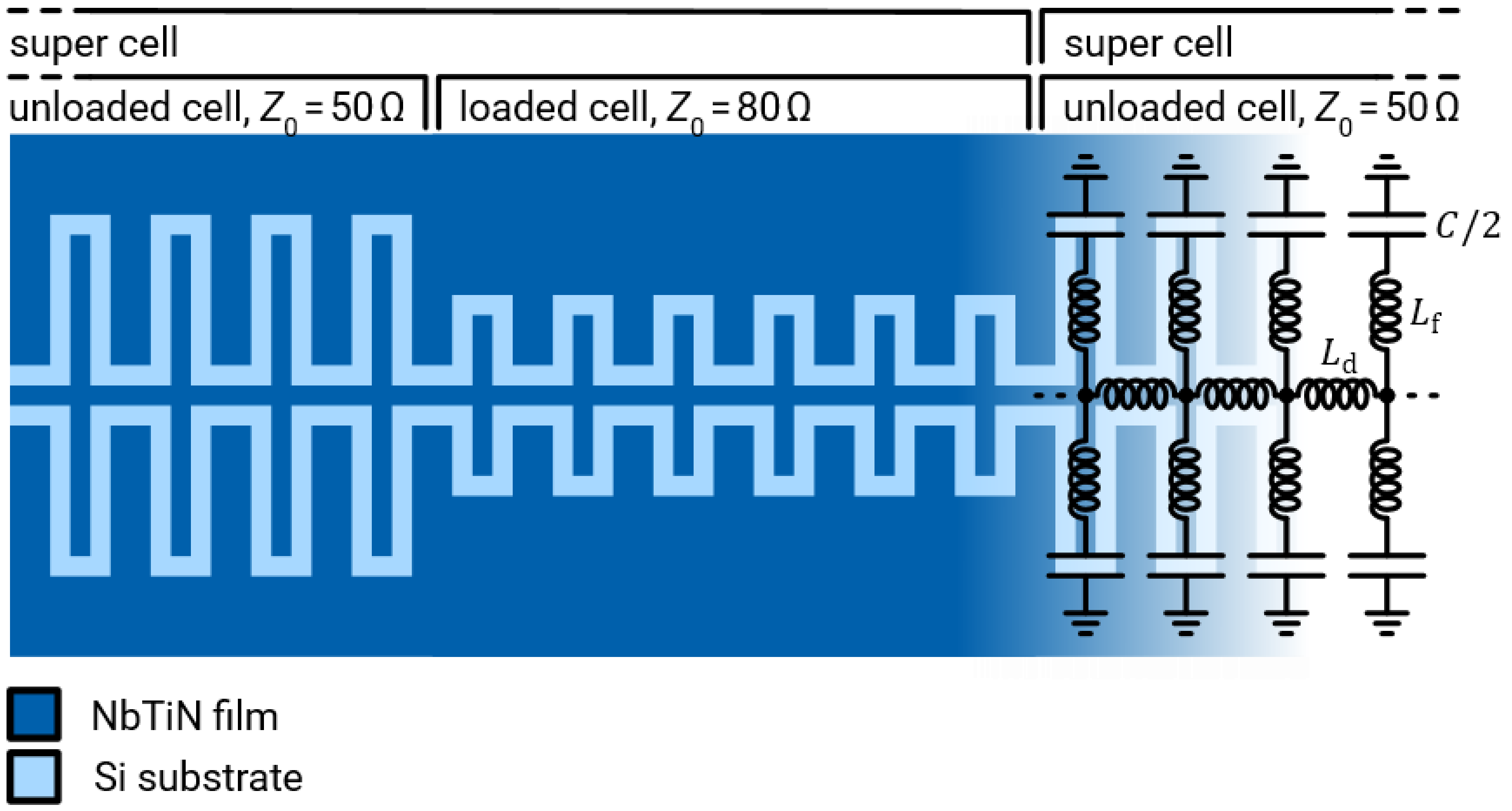
Microwave Squeezing with Superconducting (meta)materials

FONDAZIONE BRUNO KESSLER · Aalto University · SILENT WAVES · UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA · INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA · NÉEL institut

FBK develops a Travelling Wave Parametric Amplifiers for Quantum Sensing

KI-TWPA: Layout and fabrication

CPW – first generation



~10 nm NbTiN film (reactive magnetron sputtering)

+ dry etching (SF_6 plasma)

Simple fab: one lithographic layer

No need of **dielectric** layer

Low yield
(shorts central wiring / ground)

Long transmission line
(~30 cm for 20 dB gain)

Not-easy **grounding**

KI-TWPA prototype

DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

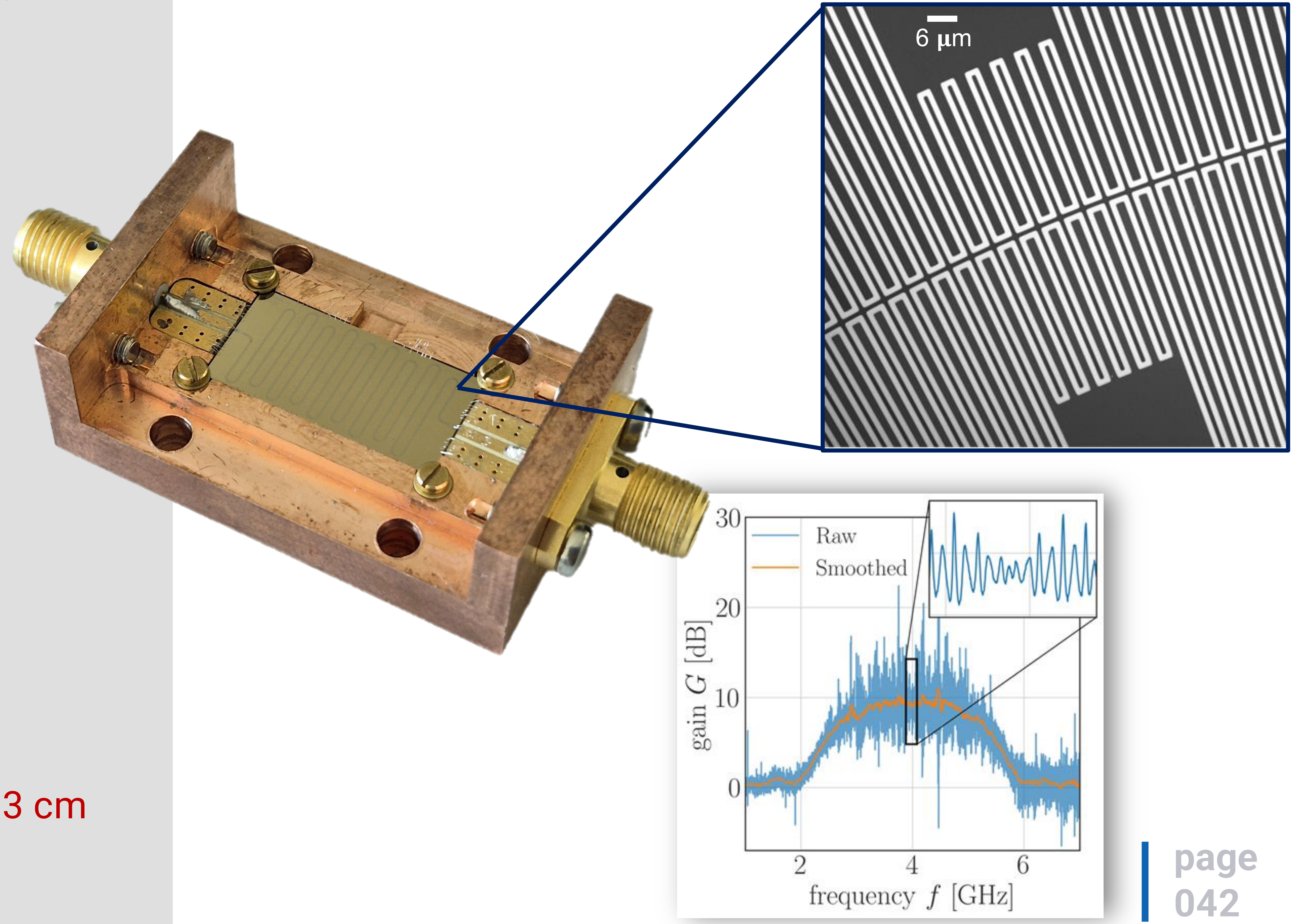
INFN

Half-size prototype to increase the fabrication yield

$\Longrightarrow$ expected gain ≈ 10 dB

Supercell =
60 unloaded cells (50 Ω)
+ 6 loaded cells (80 Ω)

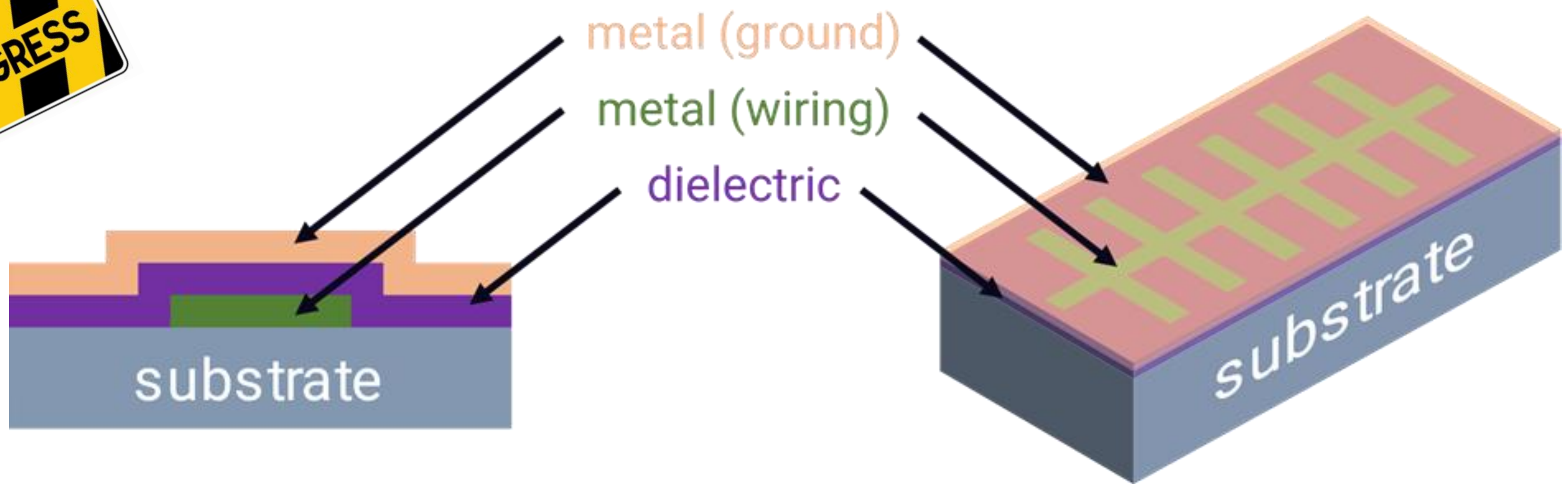
523 supercells → total length ~ 17.3 cm

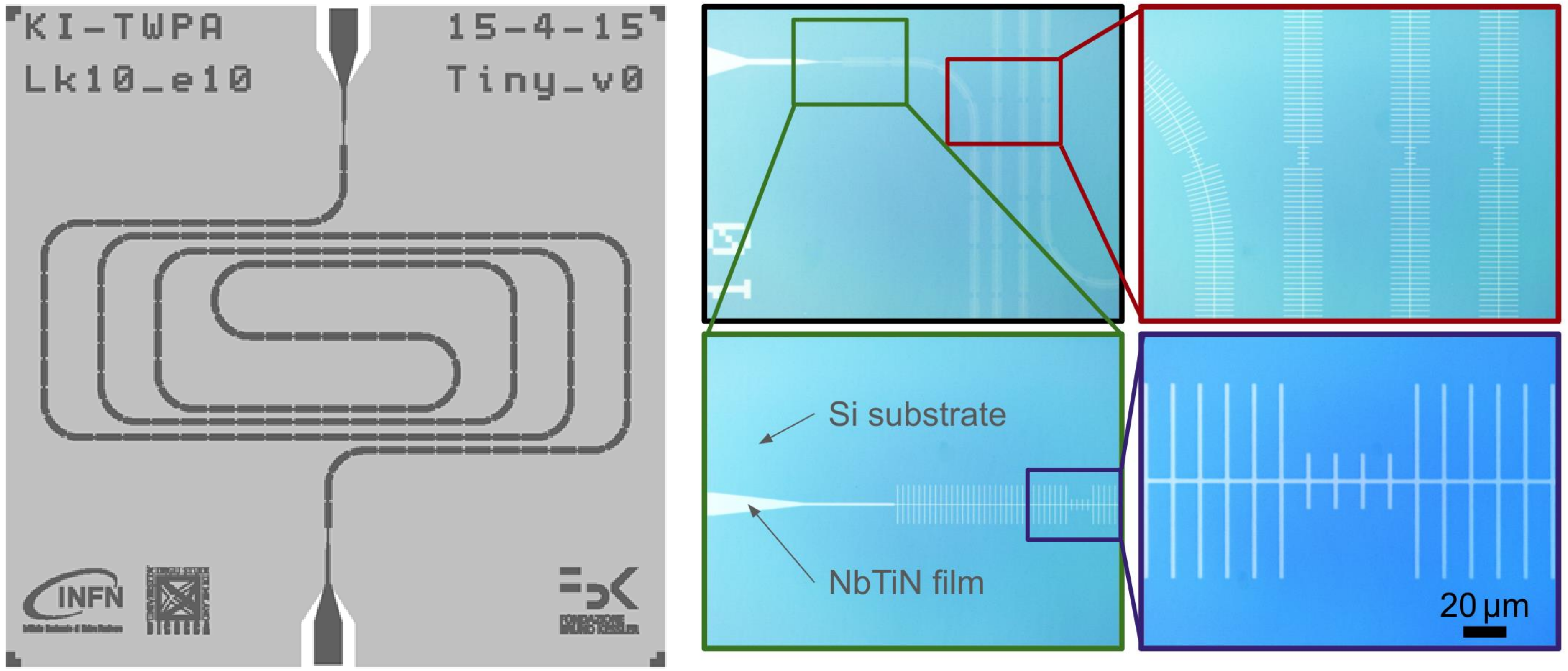


KI-TWPA: Layout and fabrication

Inverted Microstrip – second generation

WORK IN PROGRESS





First design – Uni/INFN Milano-Bicocca. Fab ongoing at FBK.

More **compact** design

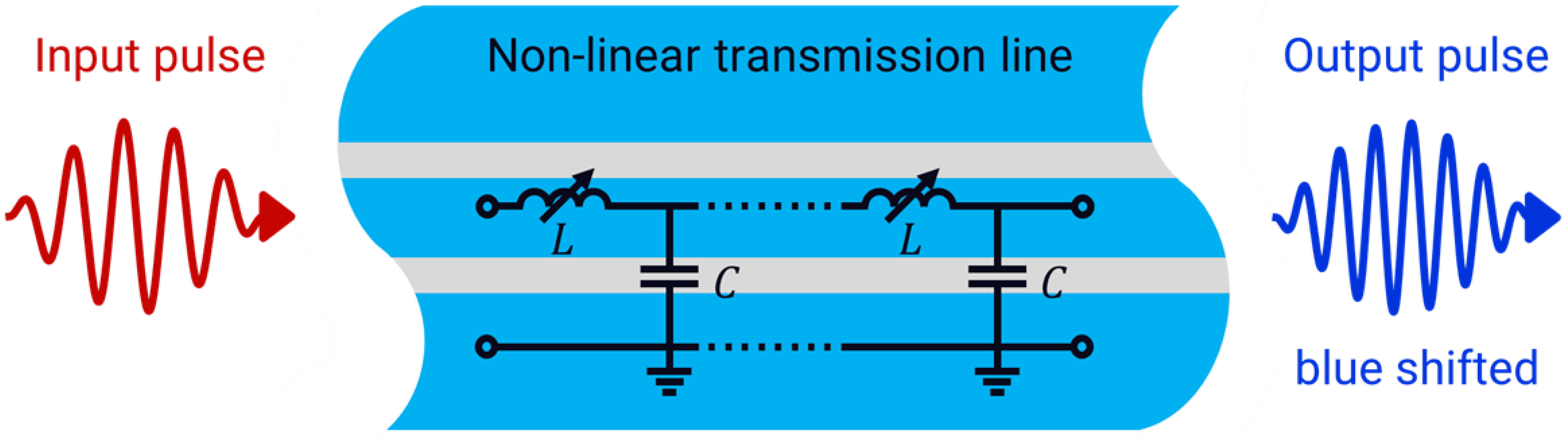
Improved **grounding**

High yield

More **complex fab**
(4 lithographic steps)

Challenge:
low-loss dielectric
- PECVD / ICP-CVD a-Si
- ALD AlOx

TWPEL – Travelling Wave Photon Energy Lifter



PATENT PENDING

A new device to **shift the frequency of microwave pulses**

Advantages

- Broadband
- Pulse shape preserving

Challenges

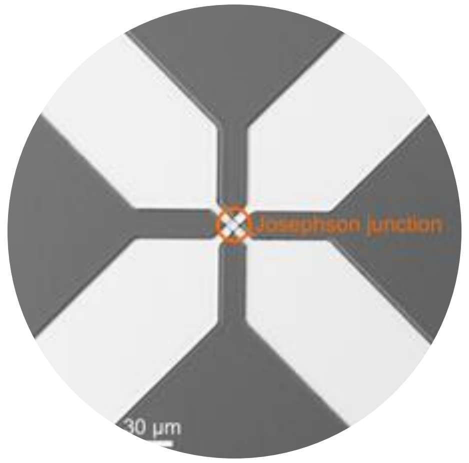
- Dedicated dispersion engineering
- Sufficient tunability and non-linearity

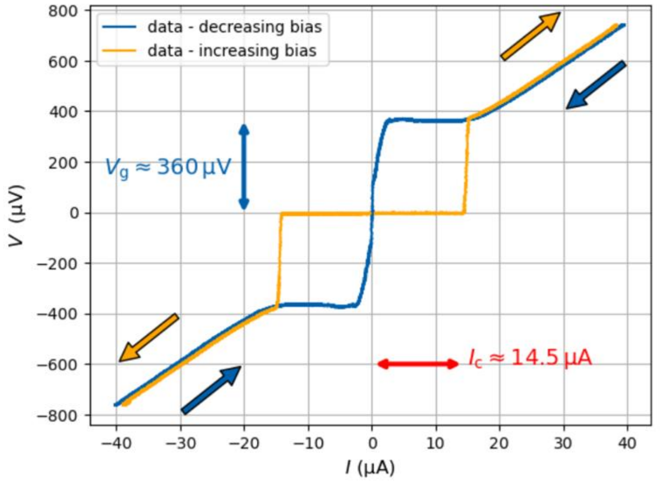
Josephson junctions-based superconducting devices

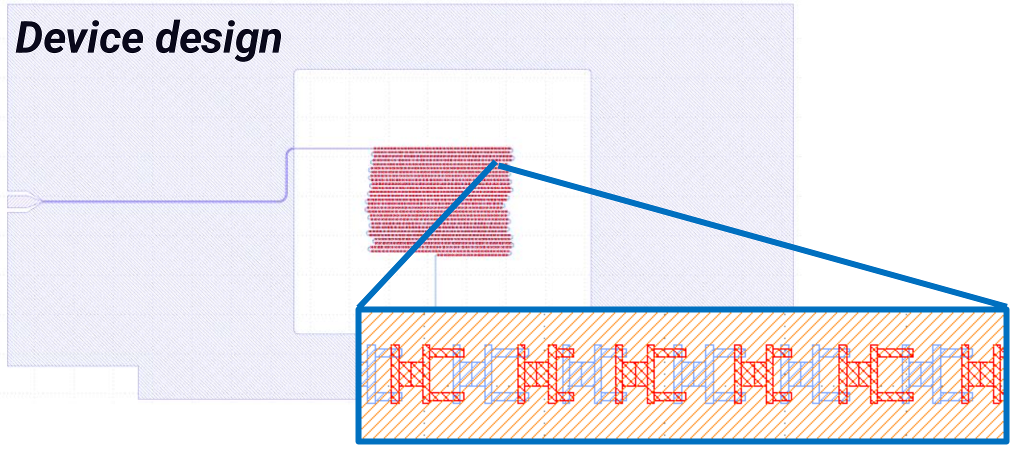
Superconducting Quantum Interference Filter (SQIF)

Receiver of signals in the C-band

→ provides a linear response in a broad frequency band
→ resilient to environmental perturbations



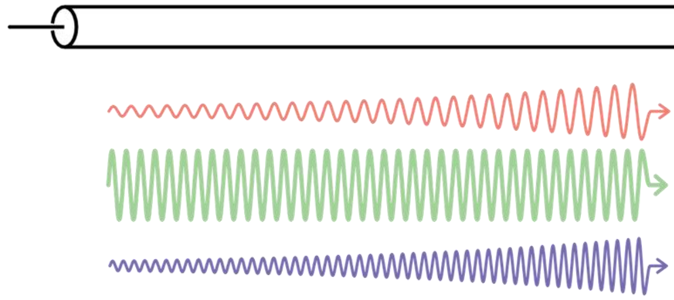


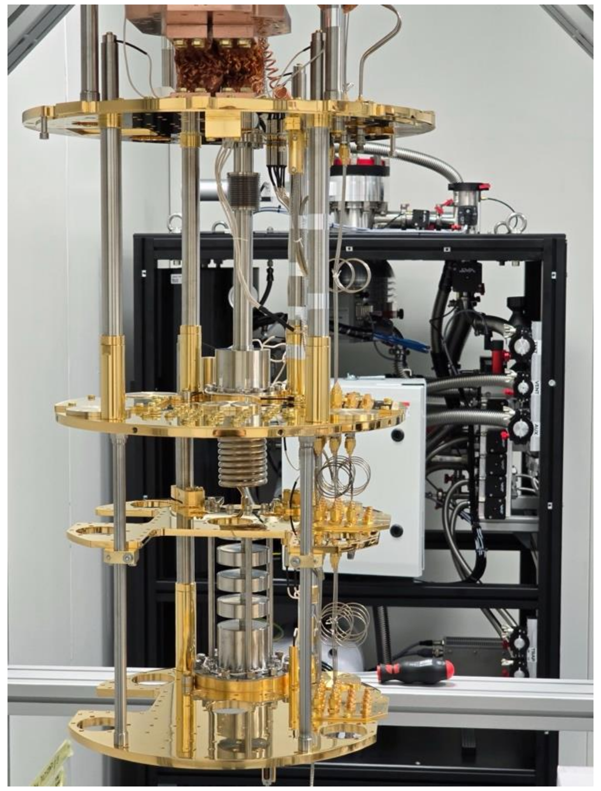


Josephson Travelling Wave Parametric Amplifiers (J-TWPAs)

Quantum-limited microwave amplifiers, e.g. for qubit read-out

→ large bandwidth and noise at the quantum limit





FONDAZIONE BRUNO KESSLER

Thales Alenia Space
a Thales / Leonardo company

QU-PILOT

Use-cases

Company: *Thales Alenia Space*

Superconducting Quantum Interference Filter (SQIF) device for sensing in space

SILENT WAVES

Company: *Silent Waves*

Quantum-limited microwave superconducting parametric amplifiers

FONDAZIONE BRUNO KESSLER | SENSORS AND DEVICES

THANK YOU!

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