COSMIC WISPERS CA21106
DESY.
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
Funded by the European Union

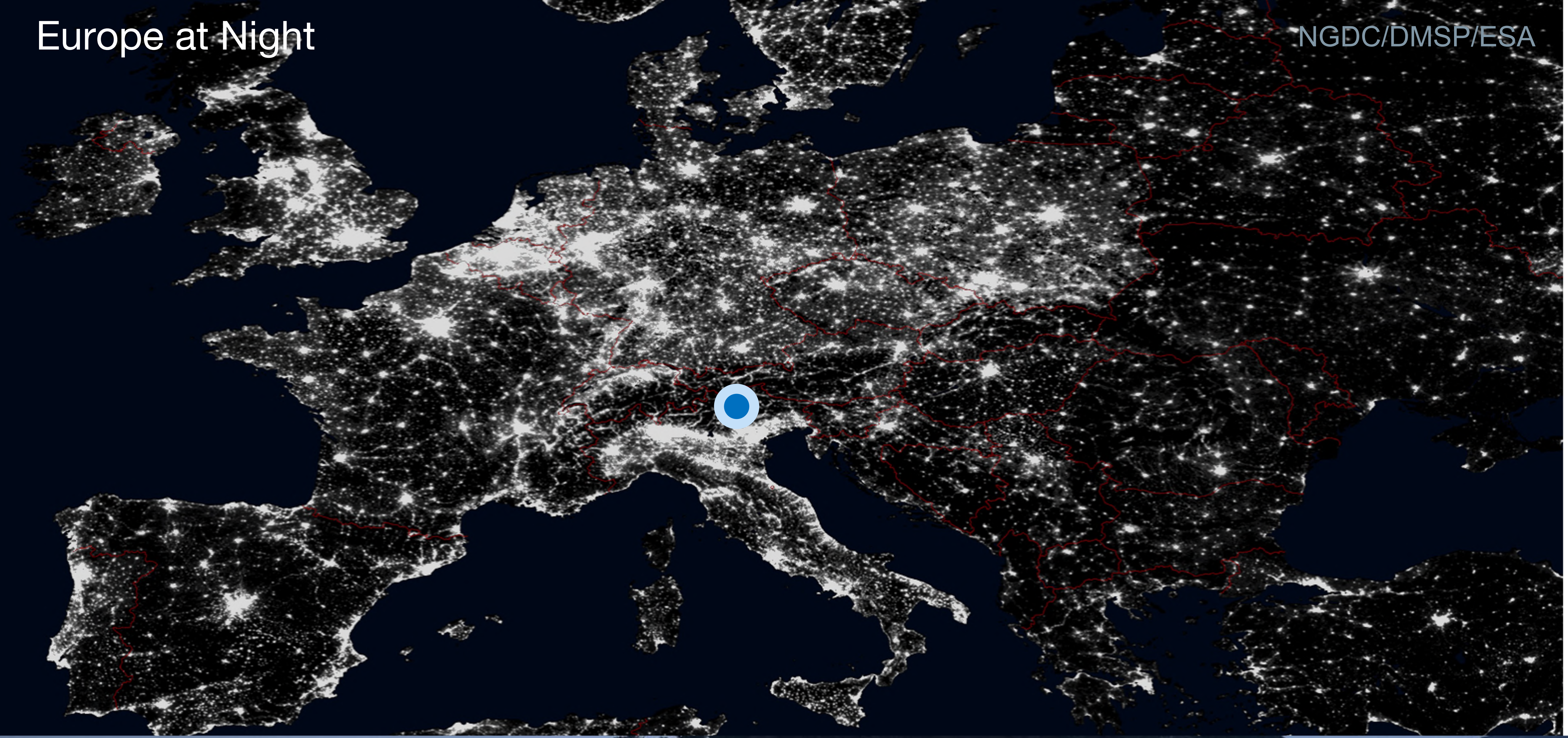
Development of superconducting circuits in Italy

2 February 2024

Federica Mantegazzini

FONDAZIONE BRUNO KESSLER
SENSORS AND DEVICES

fmantegazzini@fbk.eu
www.fbk.eu



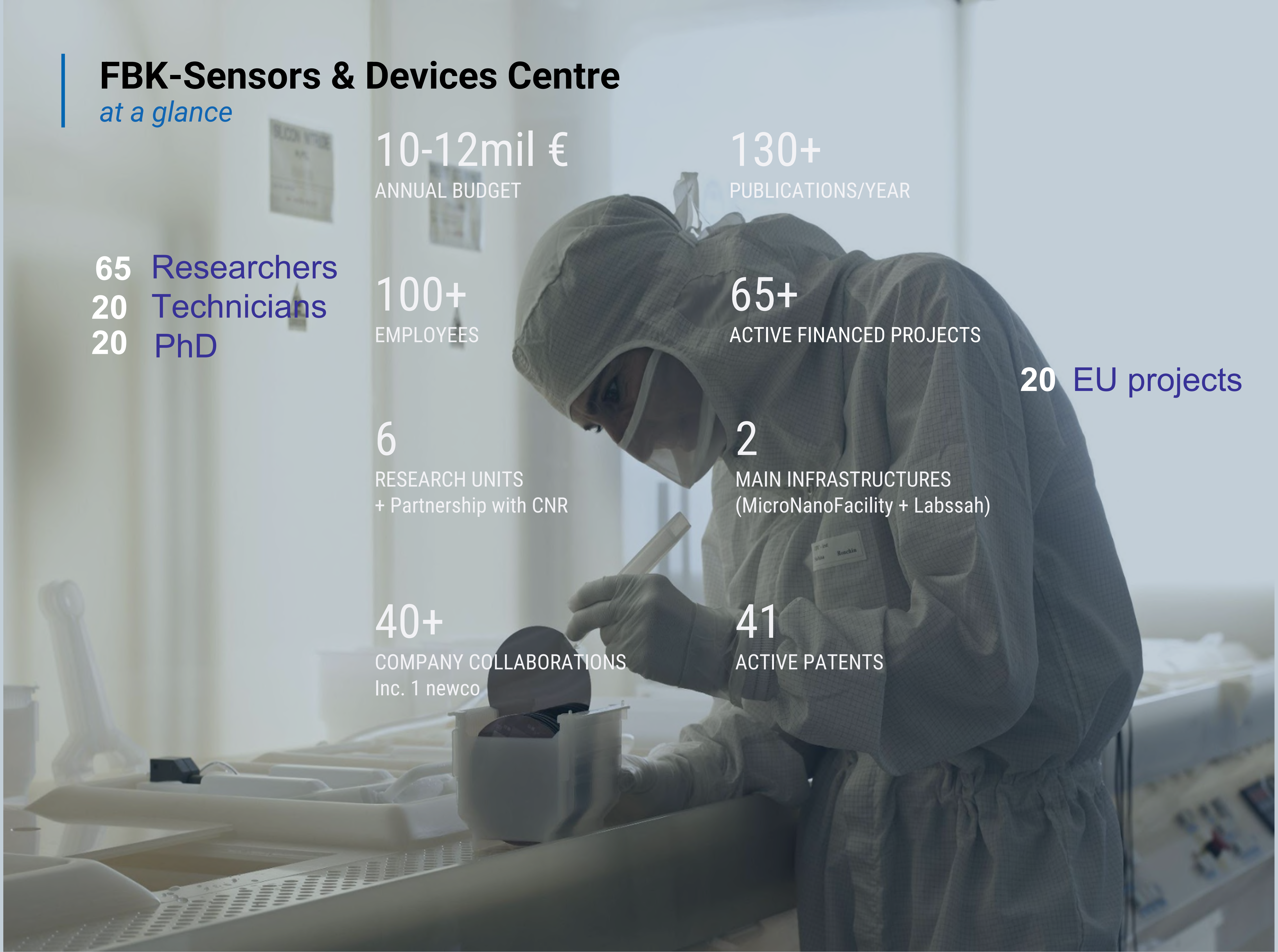
FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

Italy
Trento (Povo)
Via Sommarive 18

FBK-Sensors & Devices Centre

at a glance



65 Researchers
20 Technicians
20 PhD

10-12mil €
ANNUAL BUDGET

130+
PUBLICATIONS/YEAR

100+
EMPLOYEES

65+
ACTIVE FINANCED PROJECTS

20 EU projects

6
RESEARCH UNITS
+ Partnership with CNR

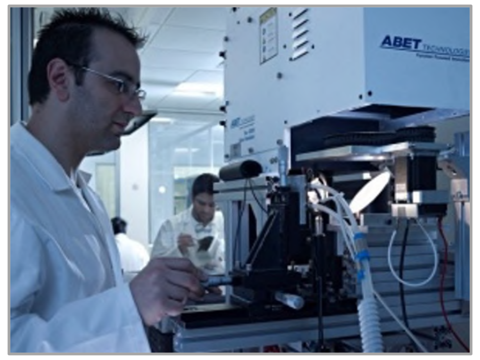
2
MAIN INFRASTRUCTURES
(MicroNanoFacility + Labssah)

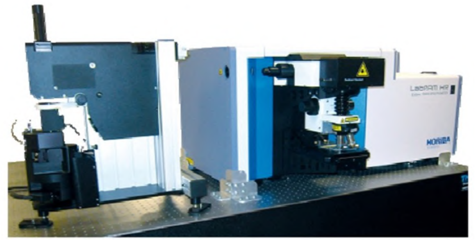
40+
COMPANY COLLABORATIONS
Inc. 1 newco

41
ACTIVE PATENTS

Micro and Nano fabrication Facility

IPCEI1: 1200m^2 moving to >2000m^2 semiconductor ISO4-6 cleanrooms





6” Microfabrication Area

Clean Room Detectors

700 m^2; Class 10/100 0,8 um CMOS pilot line: Ion Implantation, Oxidation, Diffusion, RIE, Deep RIE (silicon and oxide), Lithography (stepper 0.35 um and mask aligner), metal sputtering, optical profilometry

Clean Room MEMS

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

Testing Area

300 m^2 manual parametric testing, automatic parametric/functional testing, optical testing (spectral responsivity, quantum efficiency), 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 Ramen, FIB-SEM-EDX-EBSD, D-SIMS, TOF-SIMS, XPS, AFS, XRD/XRF

Characterisation facility

D-SIMS Dynamic Secondary Ion Mass Spectrometry

Composition depth profile
very high sensitivity: ppm-ppb
depth resolution: 1nm; lateral resolution: 1mm

ToF-SMS Time of Flight Secondary Ion Mass Spectrometry

Elemental chemical mapping
very high sensitivity: ppm-ppb
lateral resolution: 0.3 mm

XPS X-Ray Photoelectron Spectroscopy

Chemical and elemental surface analysis
sensitivity: 0.5-1%; lateral resolution: 5 mm

FIB-SEM-EDX-EBSD

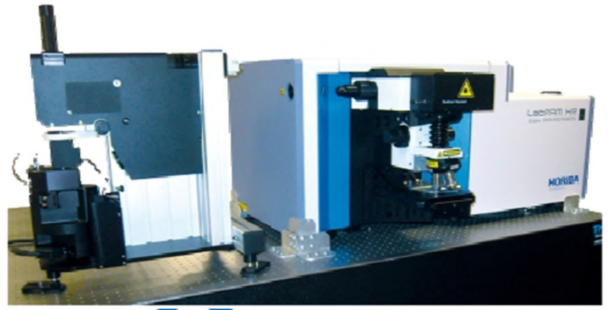
Focused Ion Beam; Electron microscopy; Energy Dispersion X-Ray; Electron Back Scattered Diffraction

AFM Atomic Force Microscopy

Surface microscopy
vertical resolution: 0.5nm; lateral resolution: 5 nm

Nano Raman

Raman Spectroscopy coupled to SPM microscopy



XRD/XRF X-ray Diffraction / X ray Fluorescence

Elemental, crystallographic phase and stress analyses
Spatial resolution: 1cm; Sensitivity: 0.1-1%

Characterisation facility

D-SIMS Dynamic Secondary Ion Mass Spectrometry

Composition depth profile
very high sensitivity: ppm-ppb
depth resolution: 1nm; lateral resolution: 1mm

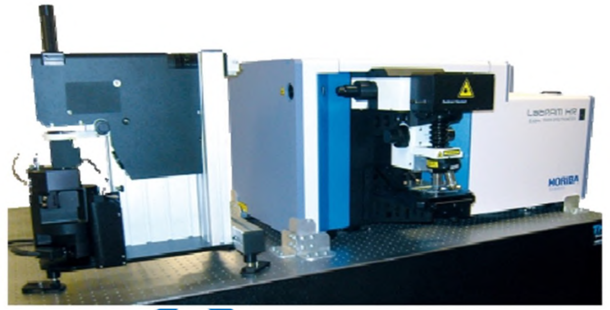
ToF-SMS Time of Flight Secondary Ion Mass Spectrometry

Elemental chemical mapping
very high sensitivity: ppm-ppb
lateral resolution: 0.3 mm

lemental surface analysis
; lateral resolution: 5 mm

; Electron microscopy; Energy
Electron Back Scattered Diffraction

y
0.5nm; lateral resolution: 5 nm

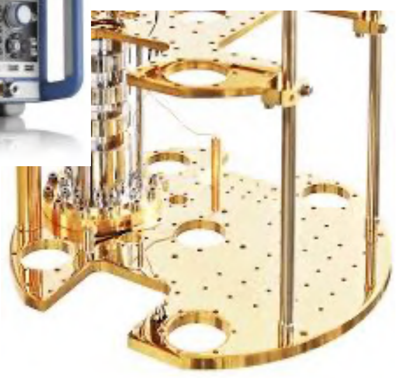


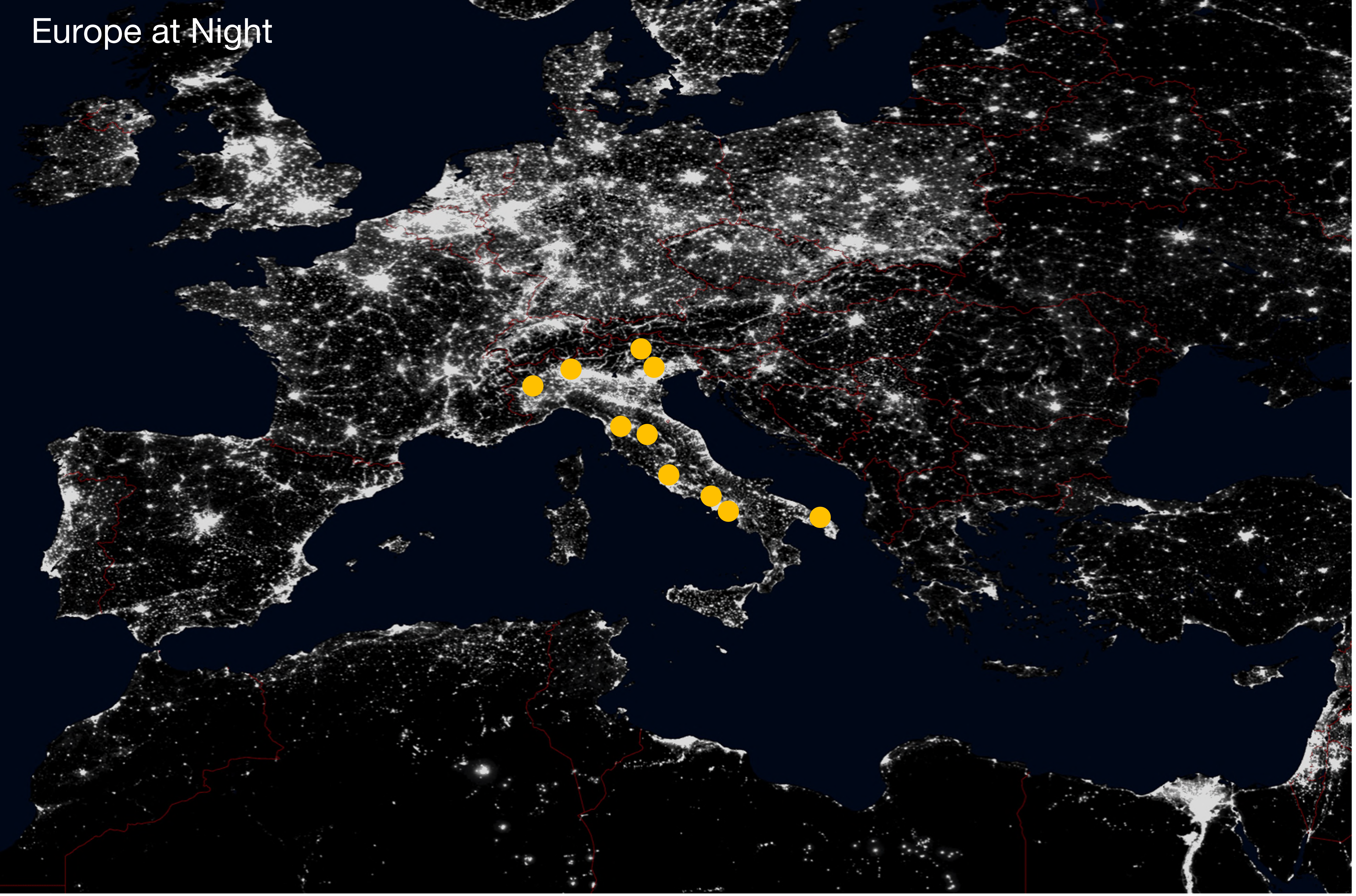
py coupled to SPM microscopy

ographic phase and stress analyses
1cm; Sensitivity: 0.1-1%

Dedicated cryogenic lab

- Dry dilution refrigerator, T_b = 10 mK
- Pulse tube cooler, T_b = 2 K
- Vector Network Analyser
- Spectrum Analyser
- Microwave generators





Superconducting circuits in Italy

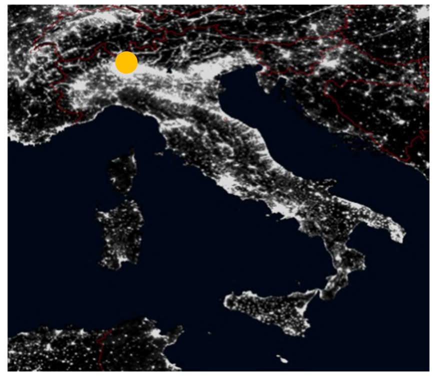
Several groups…

Fondazione Bruno Kessler, Trento
INFN TIFPA, Trento
University of Milano-Bicocca, Milan
INFN Frascati Laboratories, Rome
INFN Legnaro Laboratories, Padova
INFN Lecce
INFN Salerno
INRiM (National Metrology Institute), Turin
CNR SPIN, Naples
…

… and several projects

QU-TEST & QU-PILOT
FERROMON
ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing
INFN Istituto Nazionale di Fisica Nucleare
MARIE CURIE ACTIONS
DART WARS
Qub-IT
MiSS
TruePA
SUPERGALAX
NQSTI National Quantum Science and Technology Institute
…
Q@TN Quantum Science and Technology in Trento
European Commission

Quantum Technologies at UniMiB

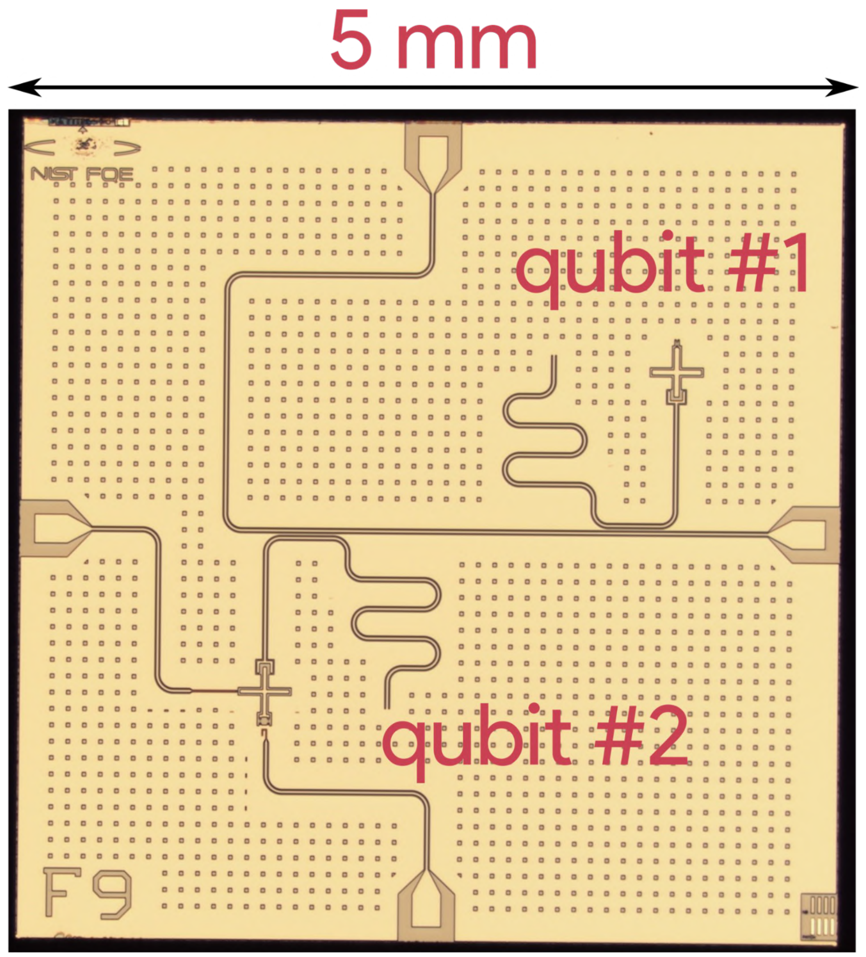


Projects:

- **DARTWARS** (Unimib, INFN, FBK, INRiM, NIST): Development of broadband quantum limited parametric amplifiers for high fidelity readout of detectors and qubit arrays;
- **Qub-IT** (Unimib, INFN, FBK, CNR): Development of qubit array for quantum sensing and quantum computing. Development of custom electronics for qubit readout;
- **CalQuStates** (Unimib, INRiM): Development of microwave metrology tools in cryogenic environments for precise characterization of qubits, resonators and parametric amplifier;
- **B-NGO** (Unimib, INFN) Development of innovative substrates for improving the resonators loss and qubit decoherence times;

Group

M.Borghesi, P. Campana, R. Carobene, M. Faverzani, E. Ferri, A. Giachero, M. Gobbo, A. Irace, D. Labranca, R. Moretti, A. Nucciotti, L. Origo



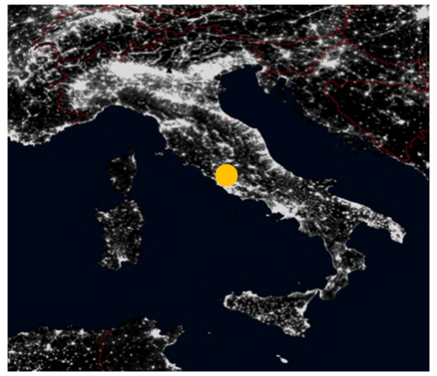
Qubit array developed in collaboration with INFN and produced at NIST

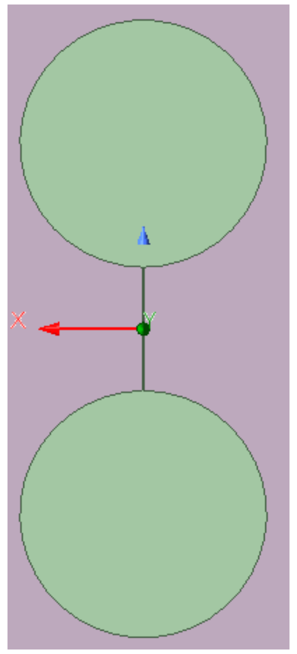
Credits: Andrea Giachero

Quantum Technologies at the INFN LNF

3D Transmon Qubits

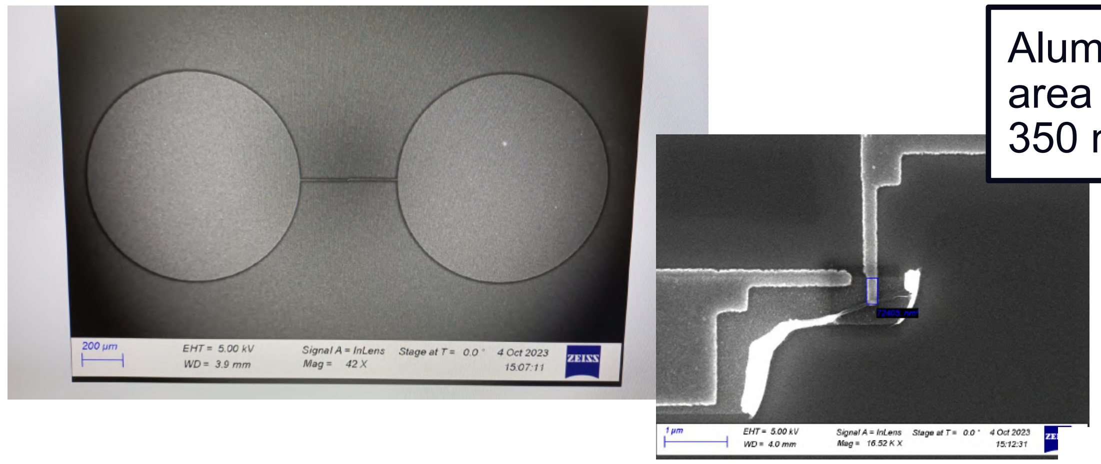
Talk by Alessio Rettaroli
1 Feb 4:10 PM





500 μm

F_q=6.57GHz
C_{tot}=100fF



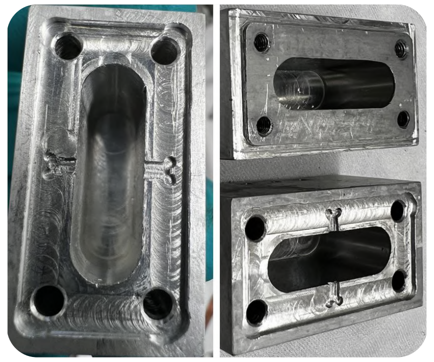
Aluminum JJ with area about 200 x 350 nm

Manufacturing of 3D qubits at IFN CNR

3D cavity fabrication at INFN LNL

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

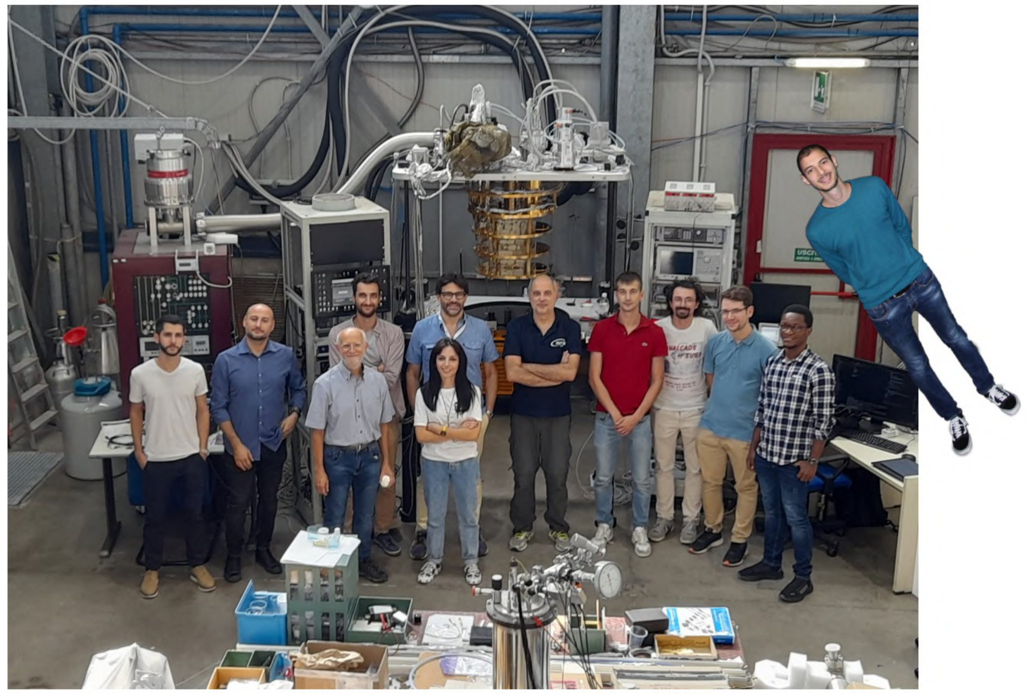
Mechanical machining



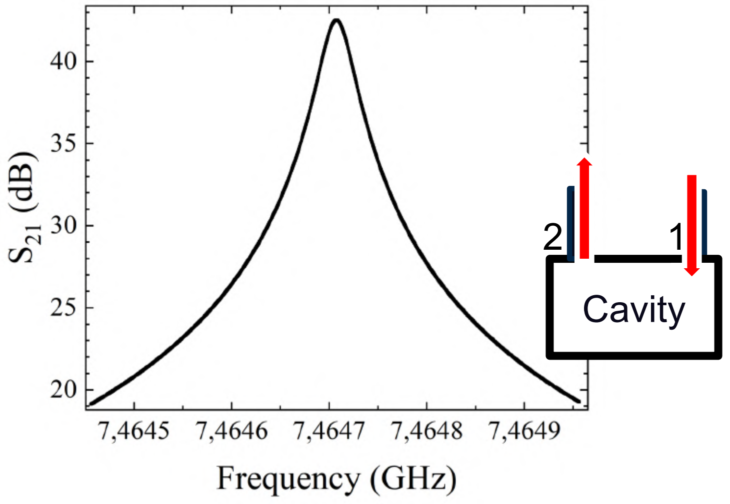
▸ Vibro-tumbling

▸ Electropolishing

Cryogenic measurements at INFN LNF



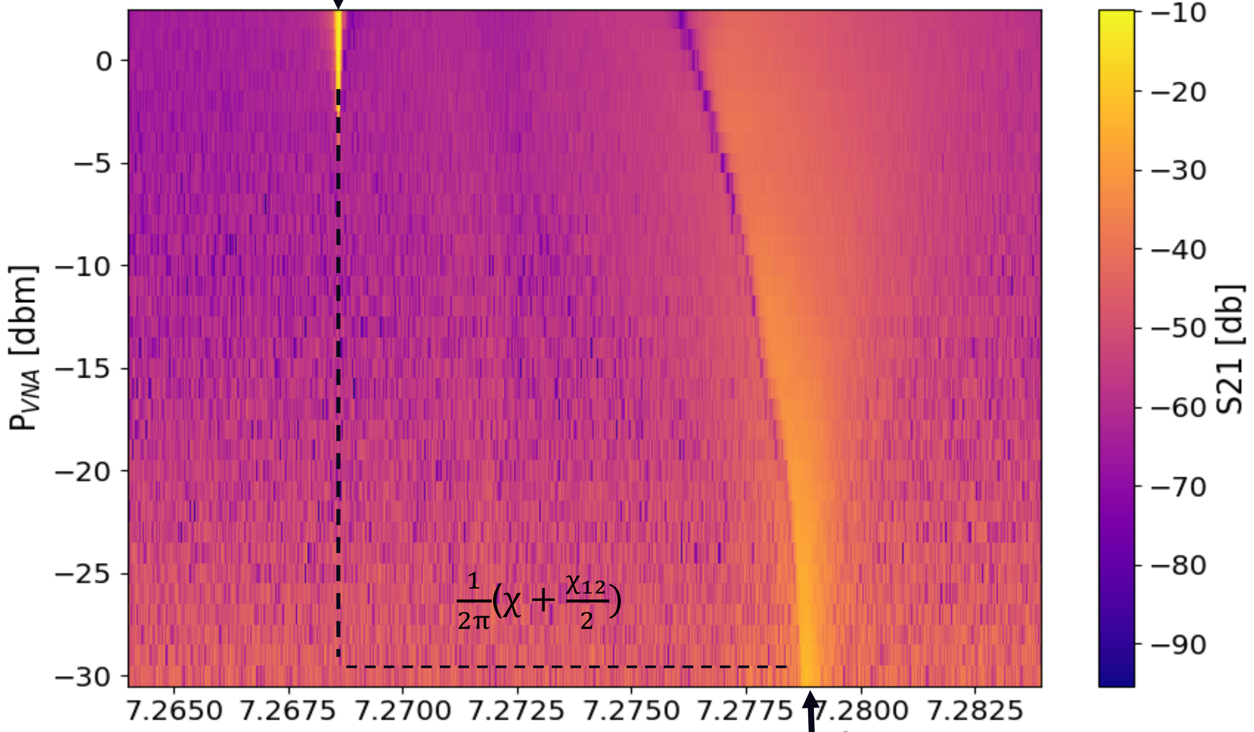
Credits: Simone Tocci



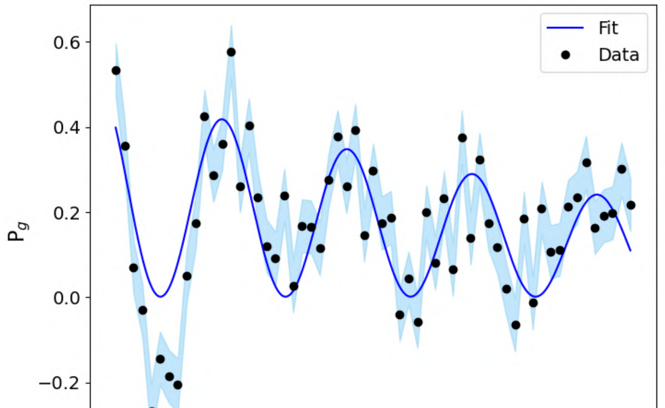
Al cavity characterisation

Bare cavity frequency
v_r= 7.268 GHz

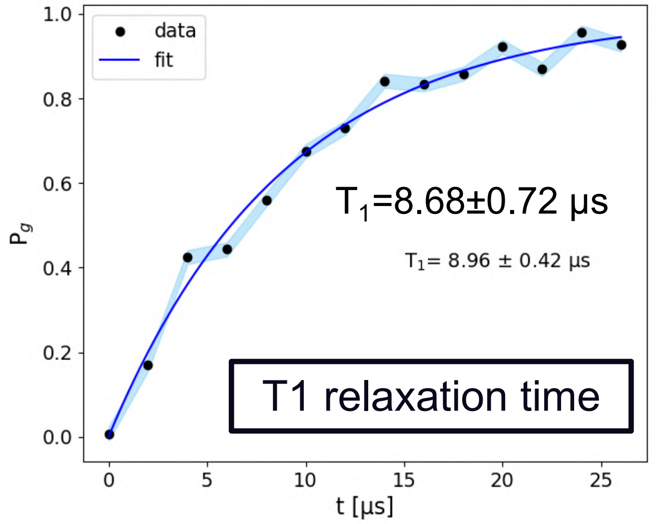
Cavity spectroscopy



Qubit in ground state



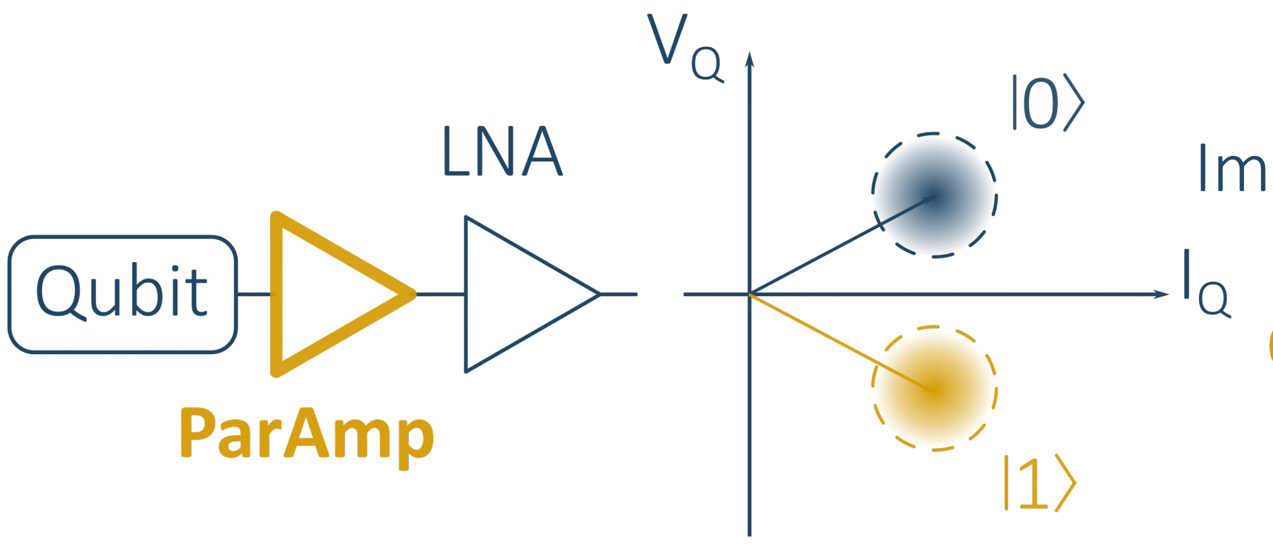
Rabi oscillations



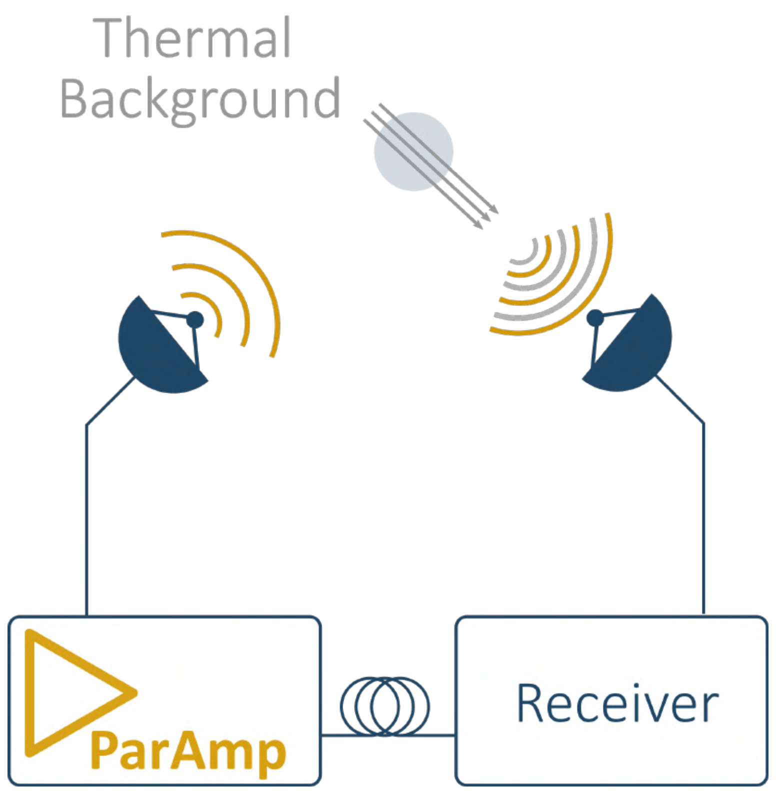
T_1=8.68±0.72 μs

T1 relaxation time

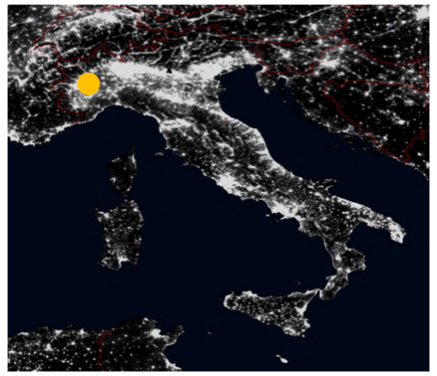
Superconducting Devices at INRiM

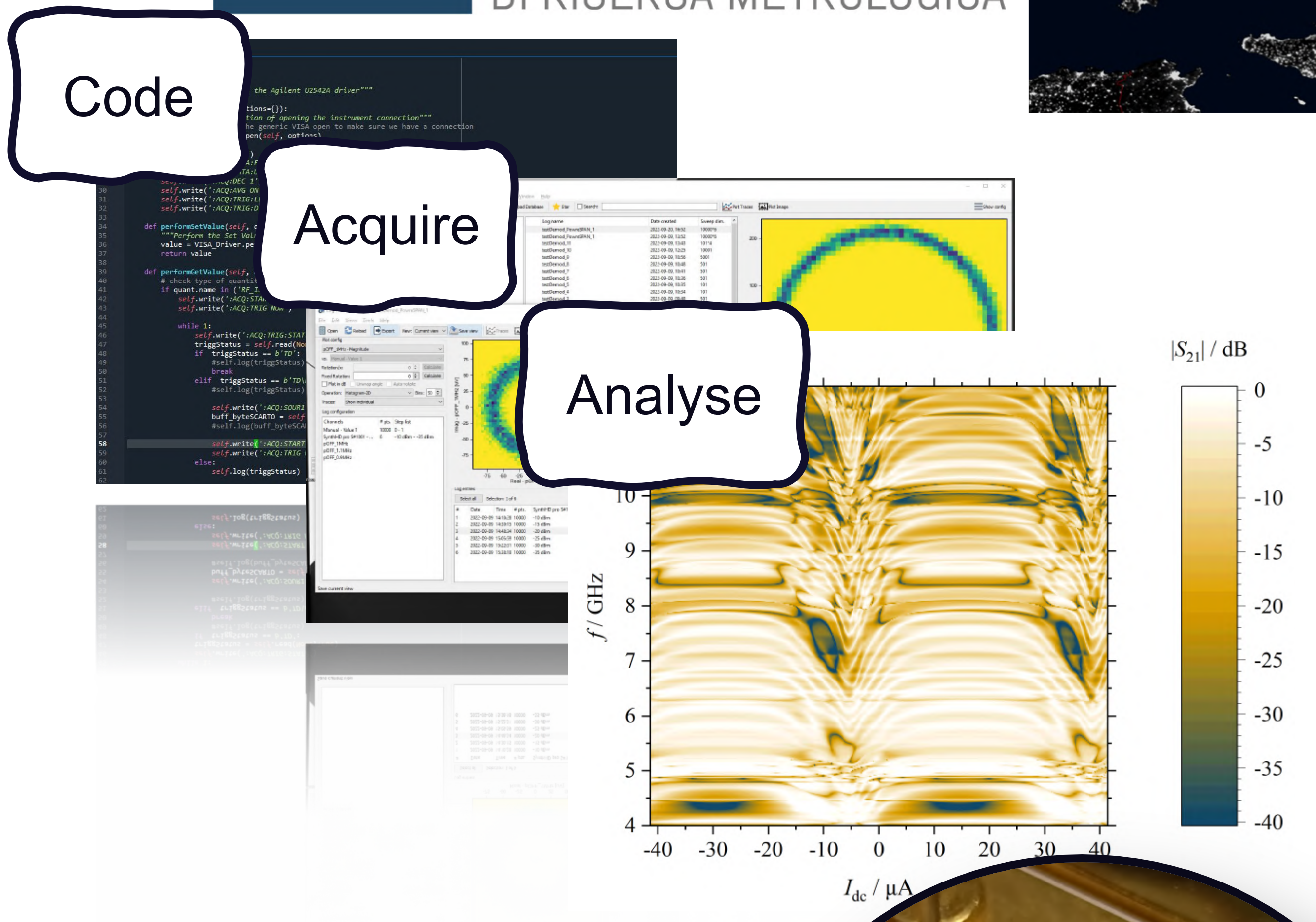


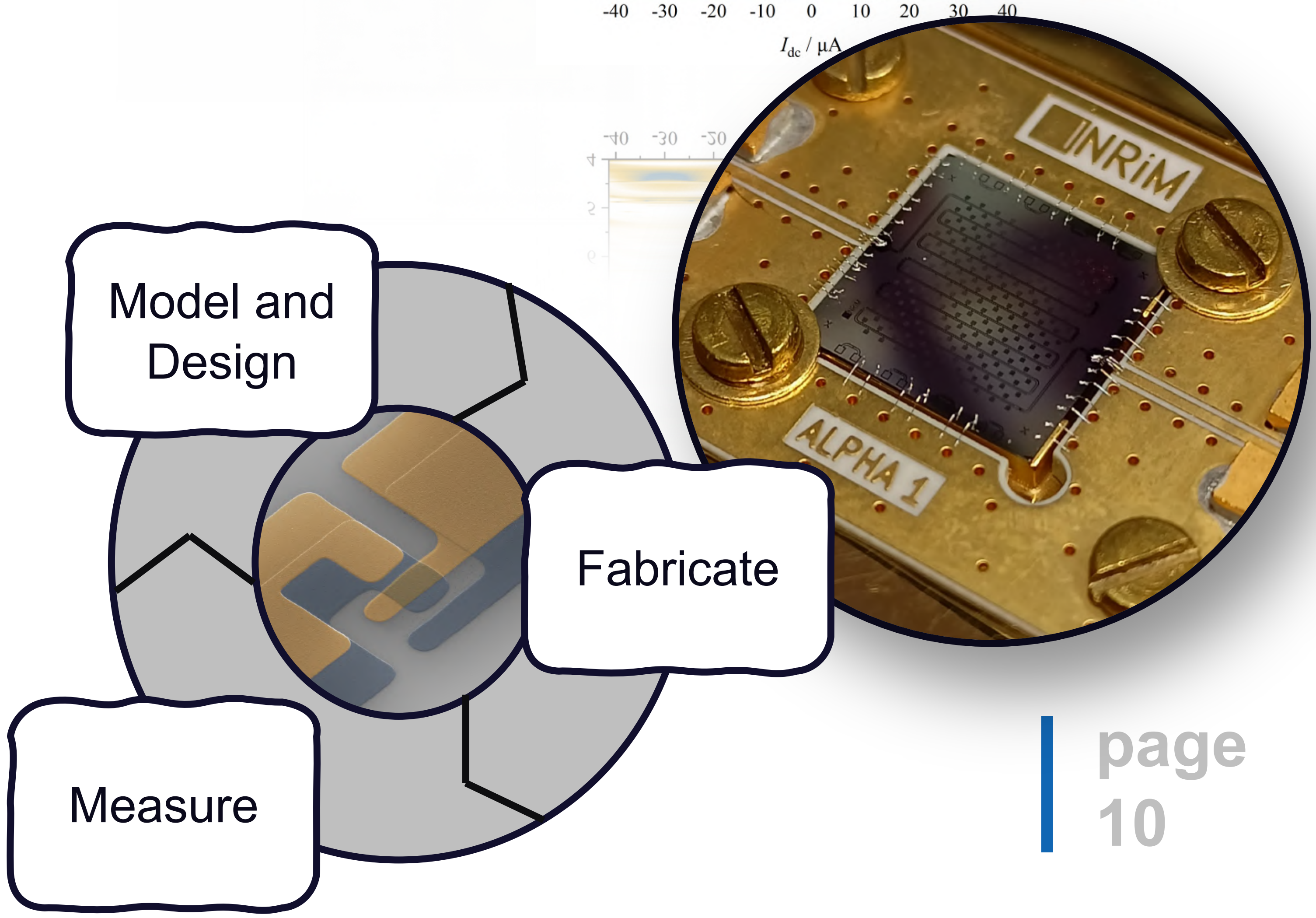
Improvement of readout of weak microwave signals with a **Quantum Limited Amplifier**



Microwave quantum illumination (**Quantum Radar**) to improve detection of low- reflectivity object or to calibrate single photon detector (**Heralding Source**)

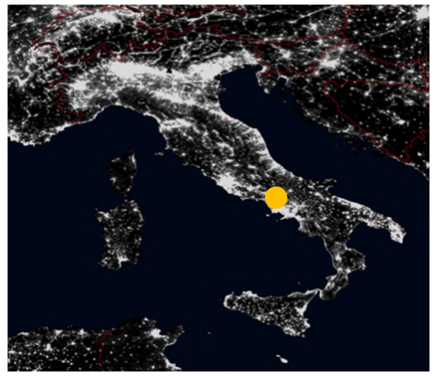






Credits: Emanuele Enrico

Superconducting Quantum Devices team in Naples



Main research activities

- **Superconducting Qubits and Hybrid quantum devices**

  Recent publications:
  [H. G. Amad et al. Condens. Matter 8(1), 29, (2023)]

  [Vettoliere et al. Nanomaterials 12(23), 4155 (2022)]

  [H. G. Amad et al. Phys. Rev. B **105**, 214522 (2022)]

- **SFQ digital qubit control and readout**

  Recent publication:
  [L. Di Palma et al. Phys. Rev. Applied 19, 064025 (2023)]

- **Superconducting Parametric Amplifiers**

  Recent publication:
  [M. Esposito. et al. Phys. Rev. Lett. 128, 153603 (2022)]

Major active projects

ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing
Finanziato dall'Unione europea NextGenerationEU
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

NQSTI National Quantum Science and Technology Institute

Funded by the European Union
FERROMON

QUANTERA
SuperLink

Funded by the European Union
TruePA

Funded by the European Union
PRIN 2022
Ministero dell'Università e della Ricerca

Università degli Studi di Napoli Federico II
Consiglio Nazionale delle Ricerche

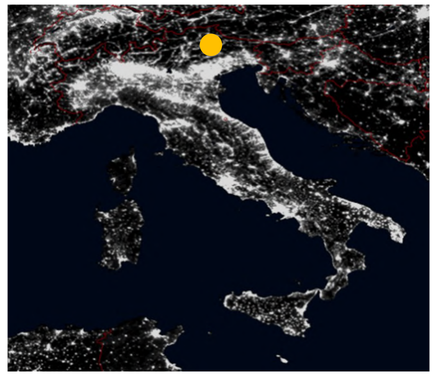
People

PIs: D. Massarotti, D. Montemurro, M. Esposito
G. Ausanio, L. Parlato, G. P Pepe, **F. Tafuri**
3 Postdoctoral researchers, 10 PhDs

Credits: Martina Esposito

Superconducting devices in Trento

Quantum Science and Technology in Trento



A growing group

Federica Mantegazzini, Felix Ahrens, Nicolò Crescini, Alessandro Irace

Paolo Falferi, Renato Mezzena, Andrea Vinante

Iacopo Carusotto, Gianluca Rastelli, Alberto Biella

Projects

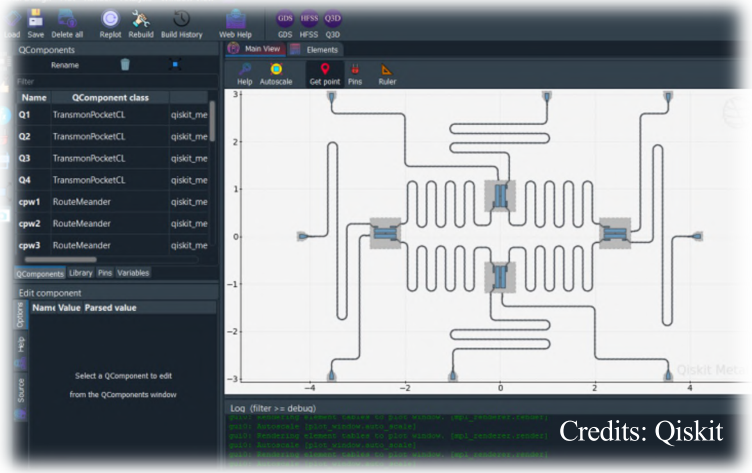
- INFN: DARTWARS, Qub-IT
- Horizon Europe: Qu-Pilot, MiSS
- PNRR NQSTI
- QuantERA: LEMAQUME
- *… and others*

Collaborators

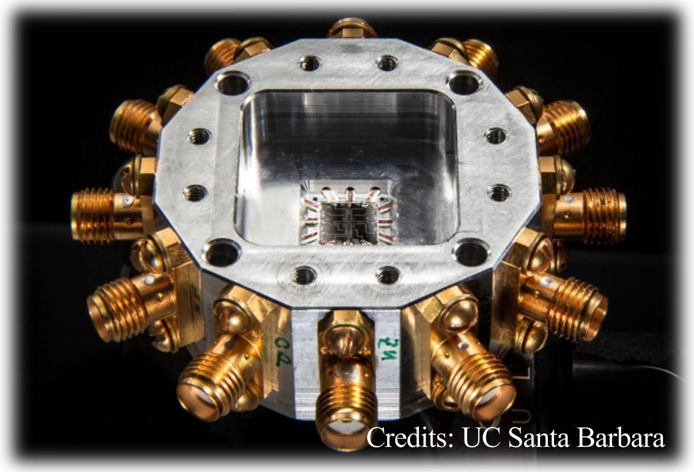
- *University of Milano-Bicocca, Italy*
- *INFN, Italy*
- *INRiM, Italy*
- *NIST, U.S*
- *CNRS, France*
- *Aalto University, Finland*

We have opening positions for PhDs and postdocs!

"Developing superconducting circuits" means…


Credits: Qiskit

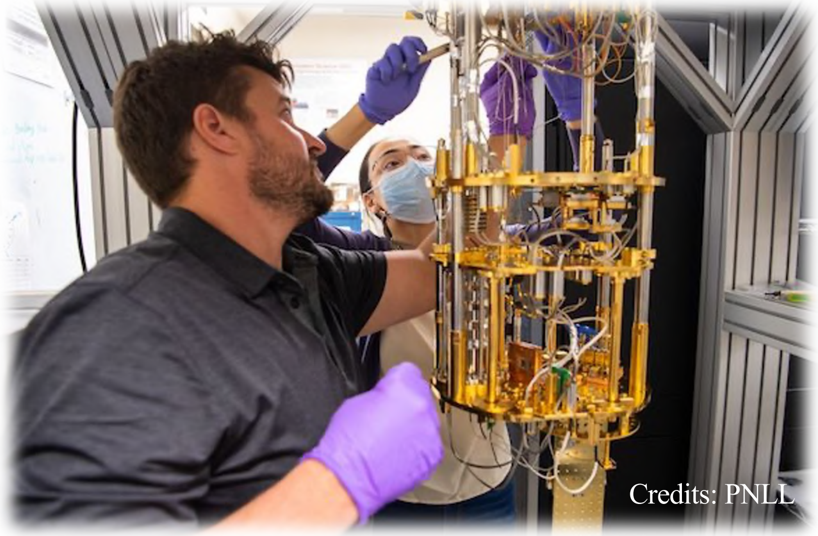

Credits: FBK

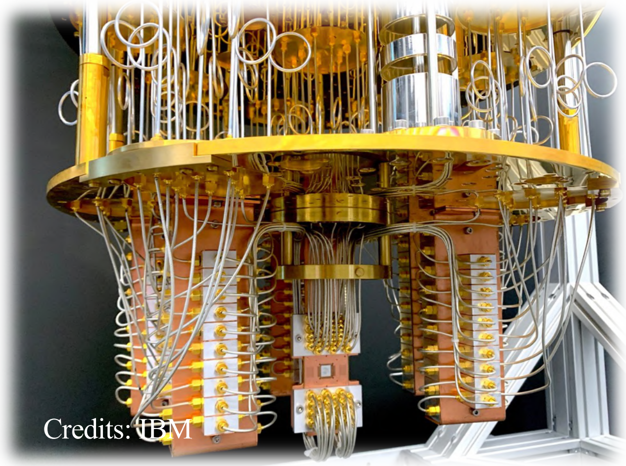

Credits: UC Santa Barbara

Design & Simulations → Microfabrication → Packaging

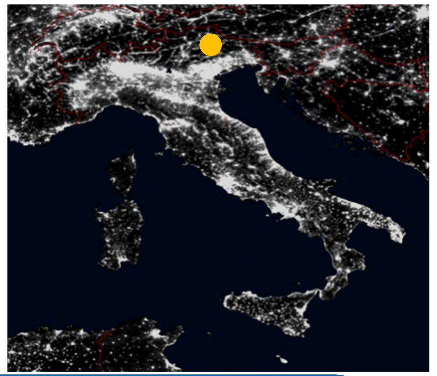
Cryogenic characterisation ← Experimental set-up

Experiment / Application

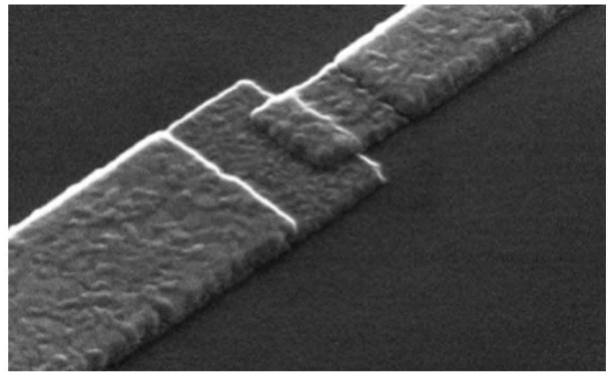

Credits: PNLL


Credits: IBM

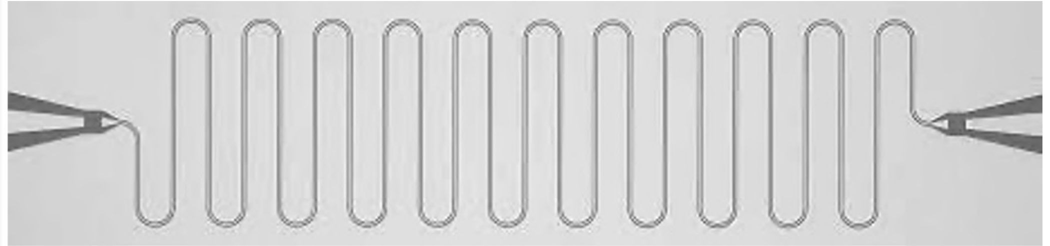
Superconducting building blocks



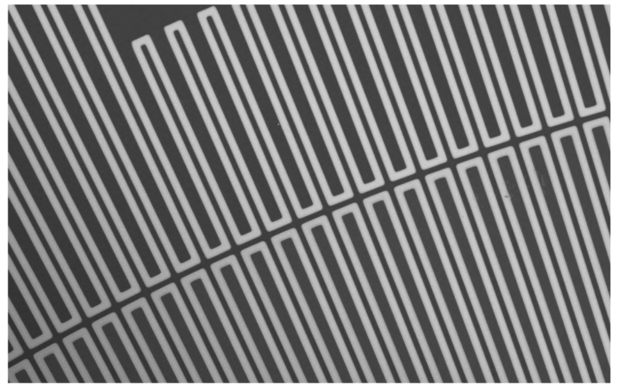
Josephson junctions



Superconducting resonators



High kinetic inductance films



SQUIDs

Parametric Amplifiers

Qubits

Cryogenic detectors

Microwave multiplexers

…

Multi-qubit systems with Quantum limited noise read-out

Hybrid superconducting magneto-mechanical systems

…

… for experimental applications

Multi-qubit systems
with
Quantum limited noise read-out

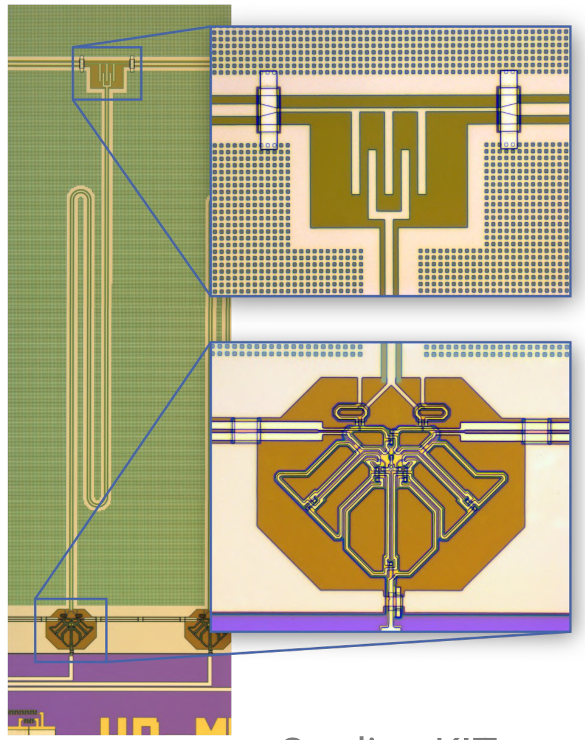
Hybrid superconducting
magneto-mechanical systems

…

READ-OUT

Neutrino mass experiments

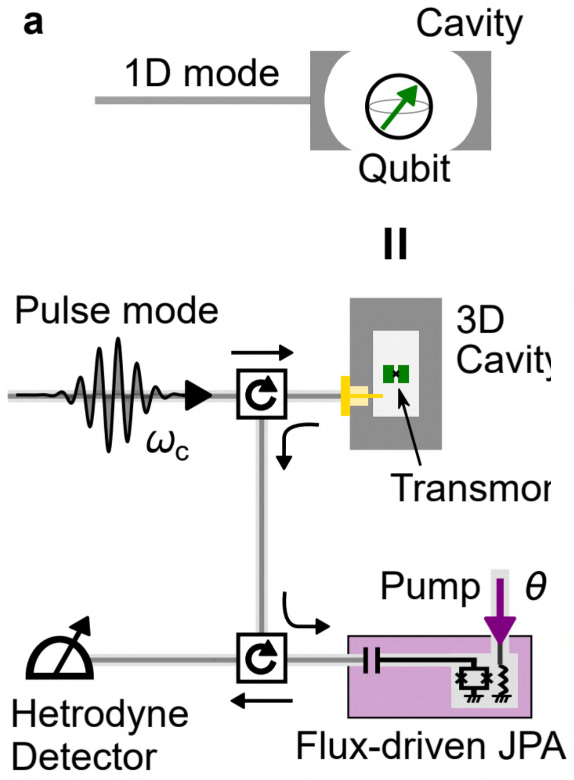
Microwave SQUID multiplexer



Credits: KIT

QUANTUM SENSING

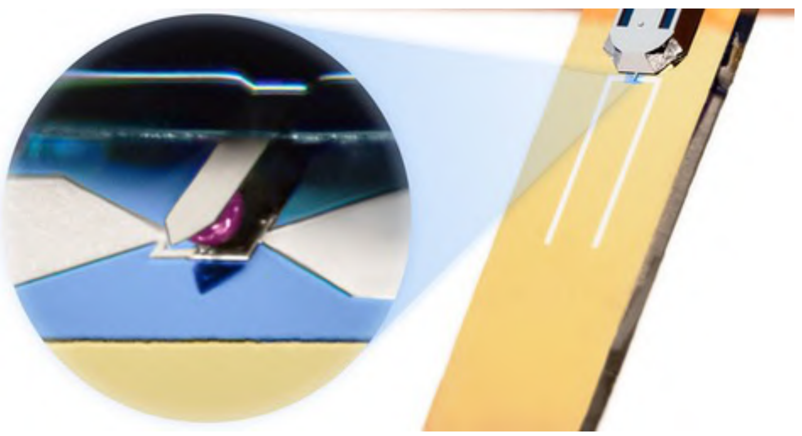
Microwave photons detection



Credits: 10.1038/s41567-018-0066-3

Hybrid quantum systems

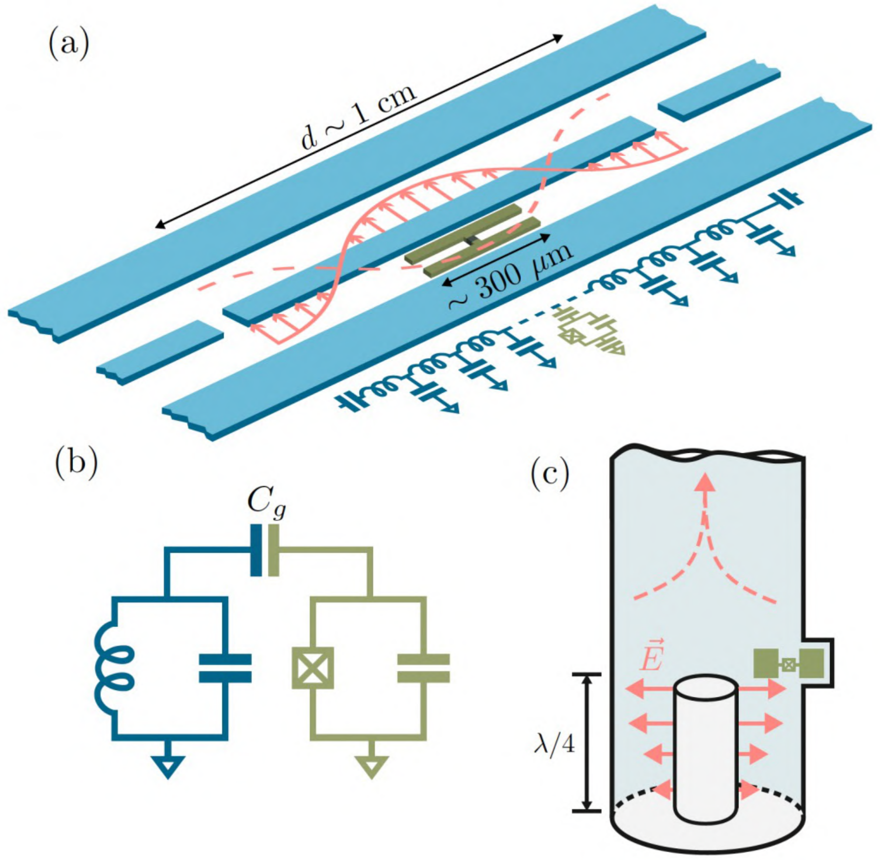
Dark matter searches



Credits: 10.1103/PhysRevLett.130.033601

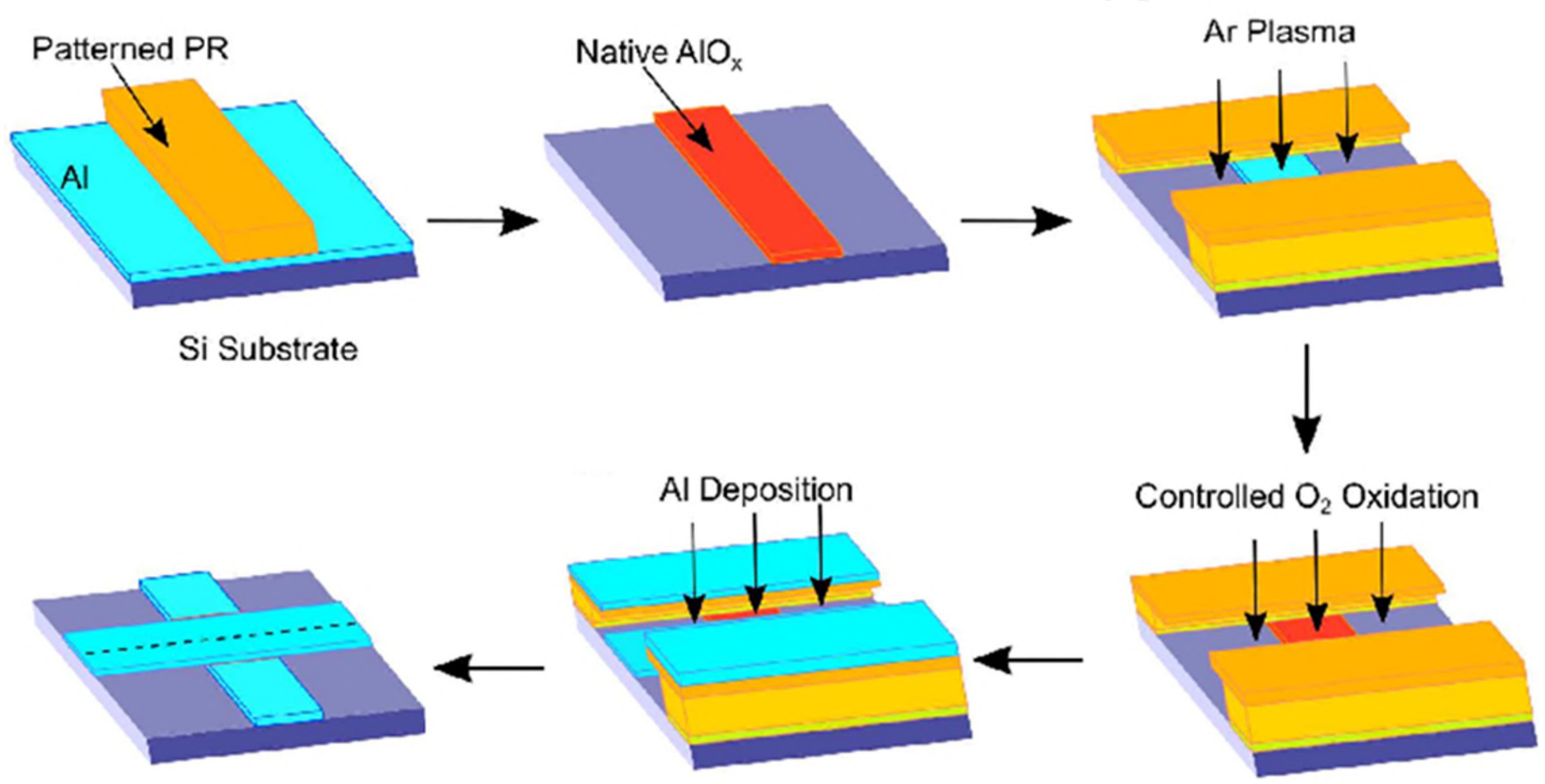
cQED EXPERIMENTS

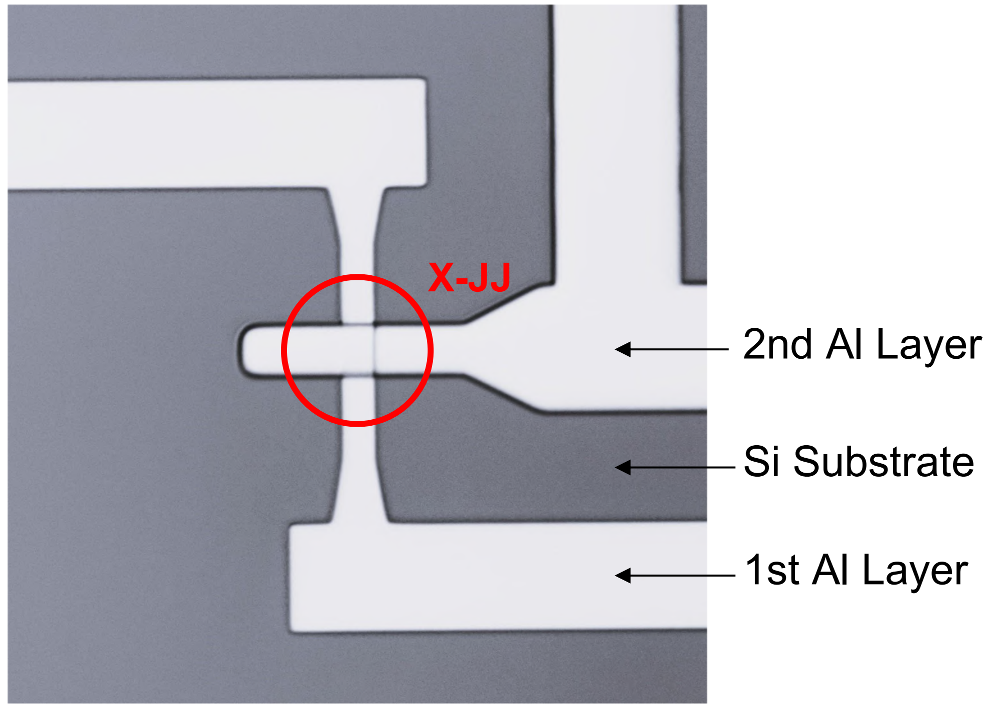
Light-matter interaction

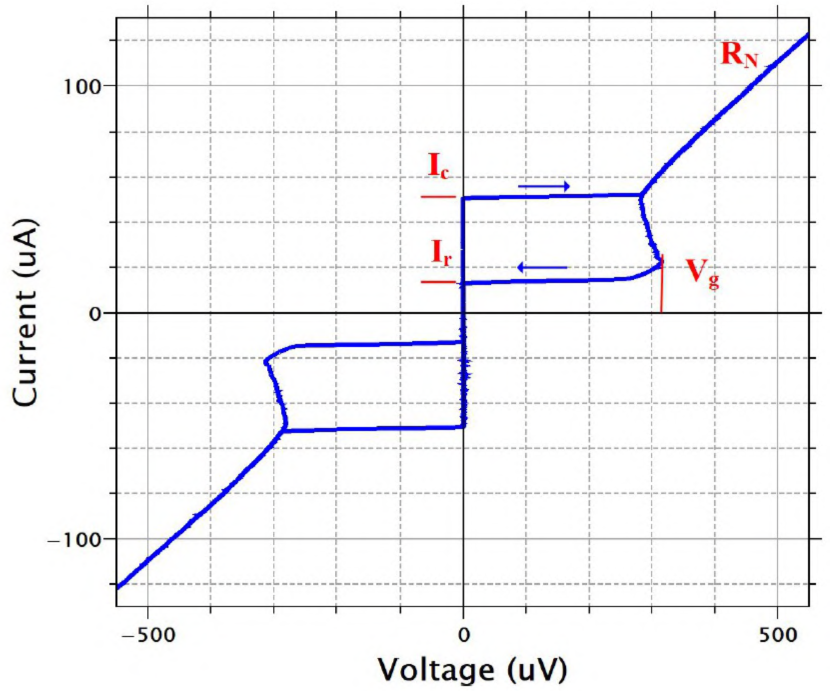


Credits: 10.1103/RevModPhys.93.025005

Cross Josephson junctions at FBK







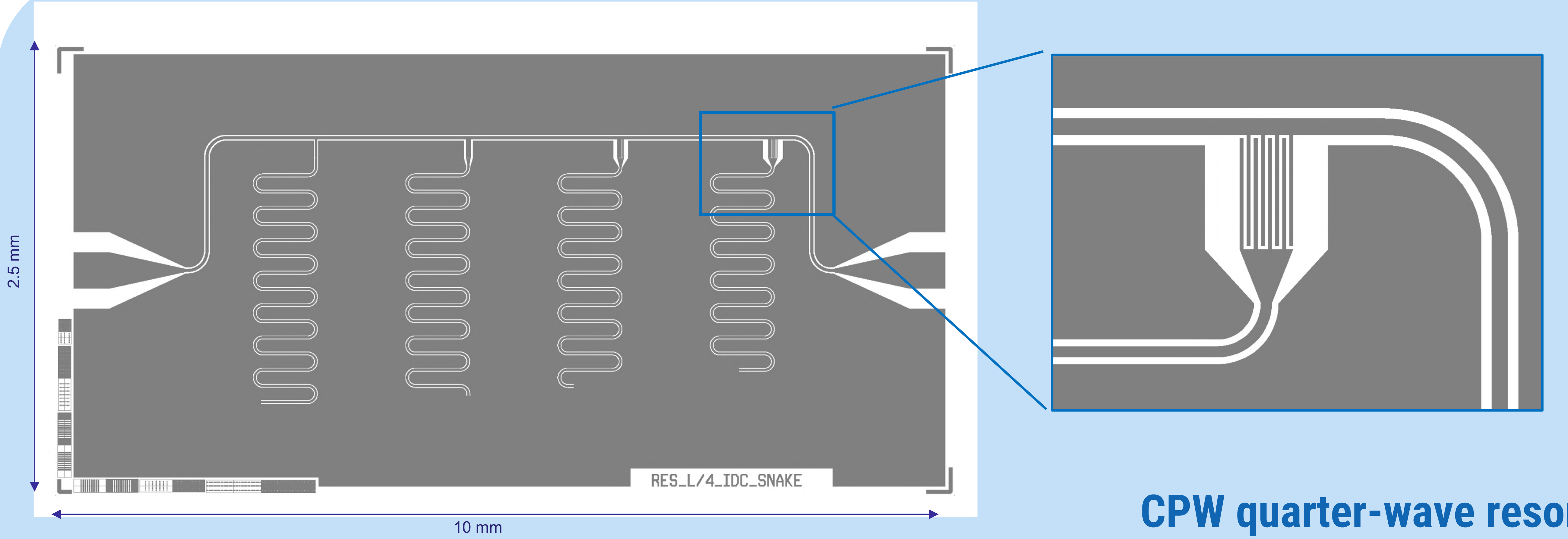
Advantages

- High control on areas (and on junction parameters)
- Two-layers process

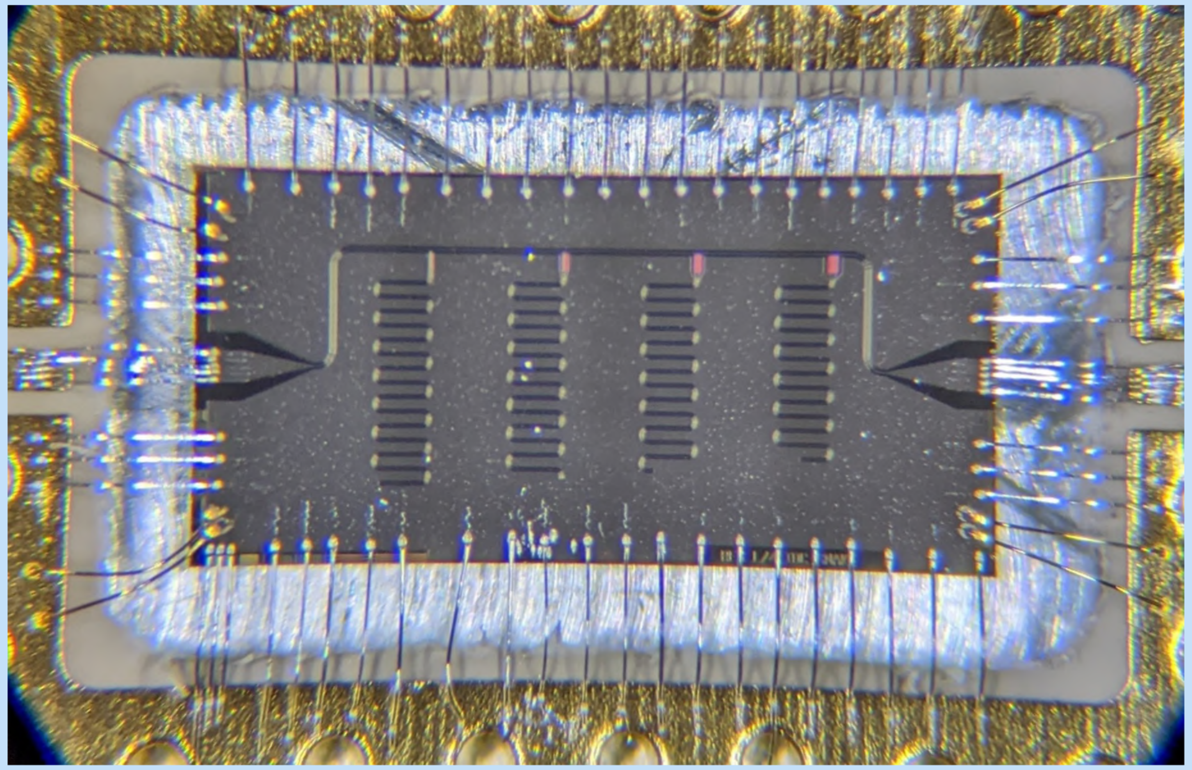
Challenge

- Develop an efficient Ar plasma cleaning
- Optimise the second lithographic step (lift-off)

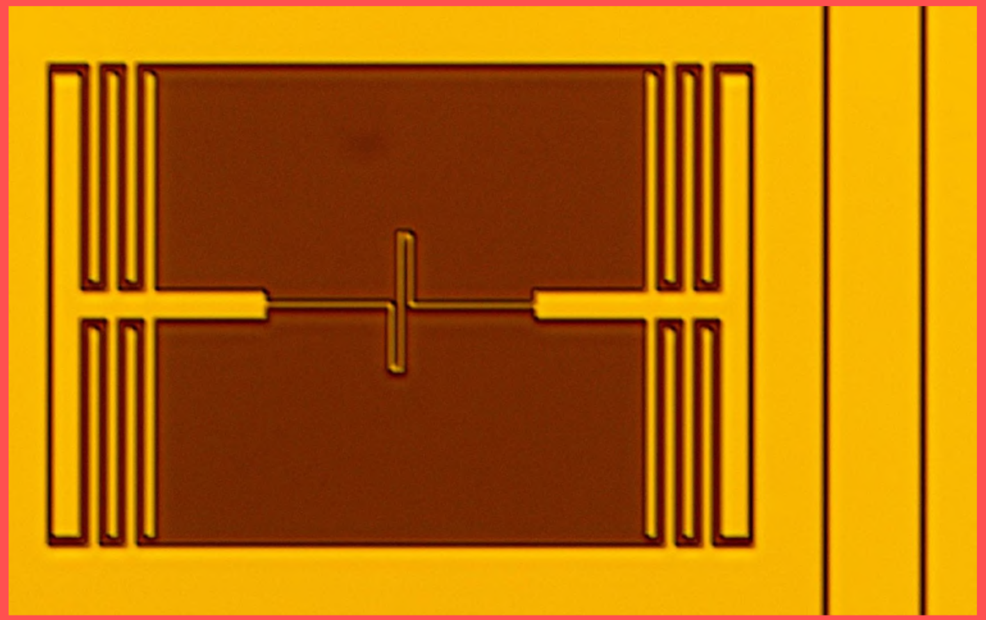
Superconducting microwave resonators



CPW quarter-wave resonators

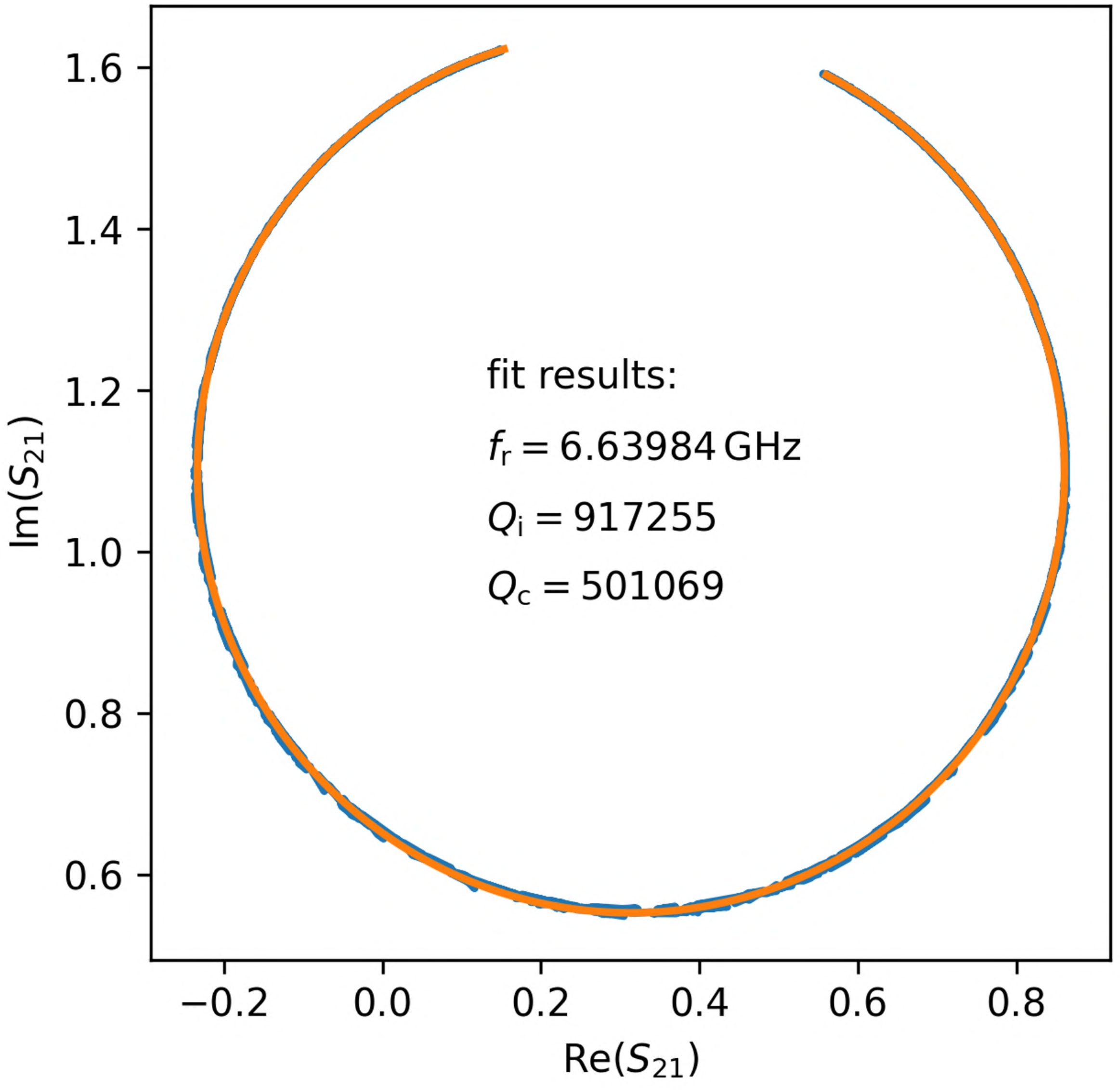


Lumped element resonators

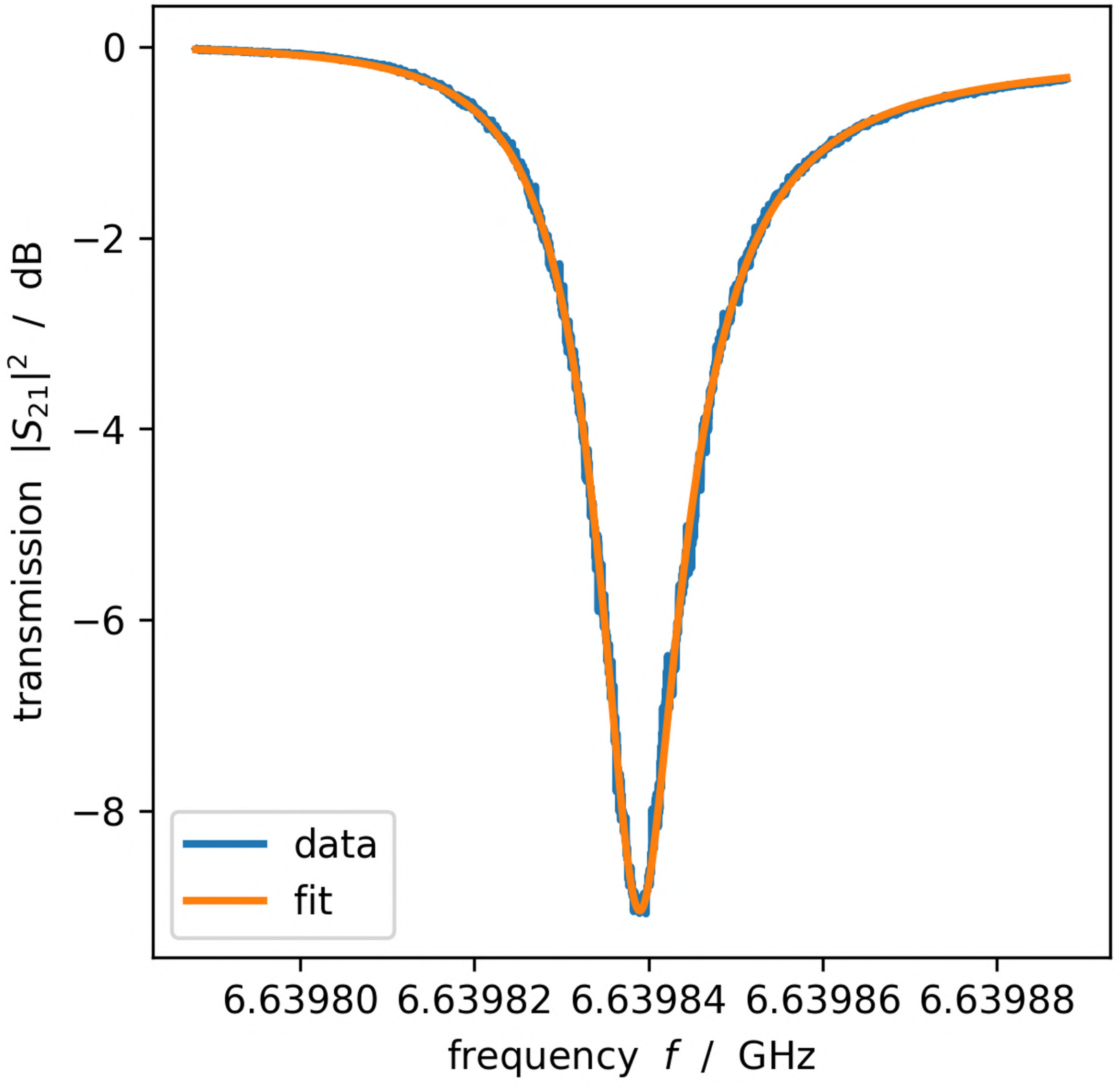


Superconducting microwave resonators

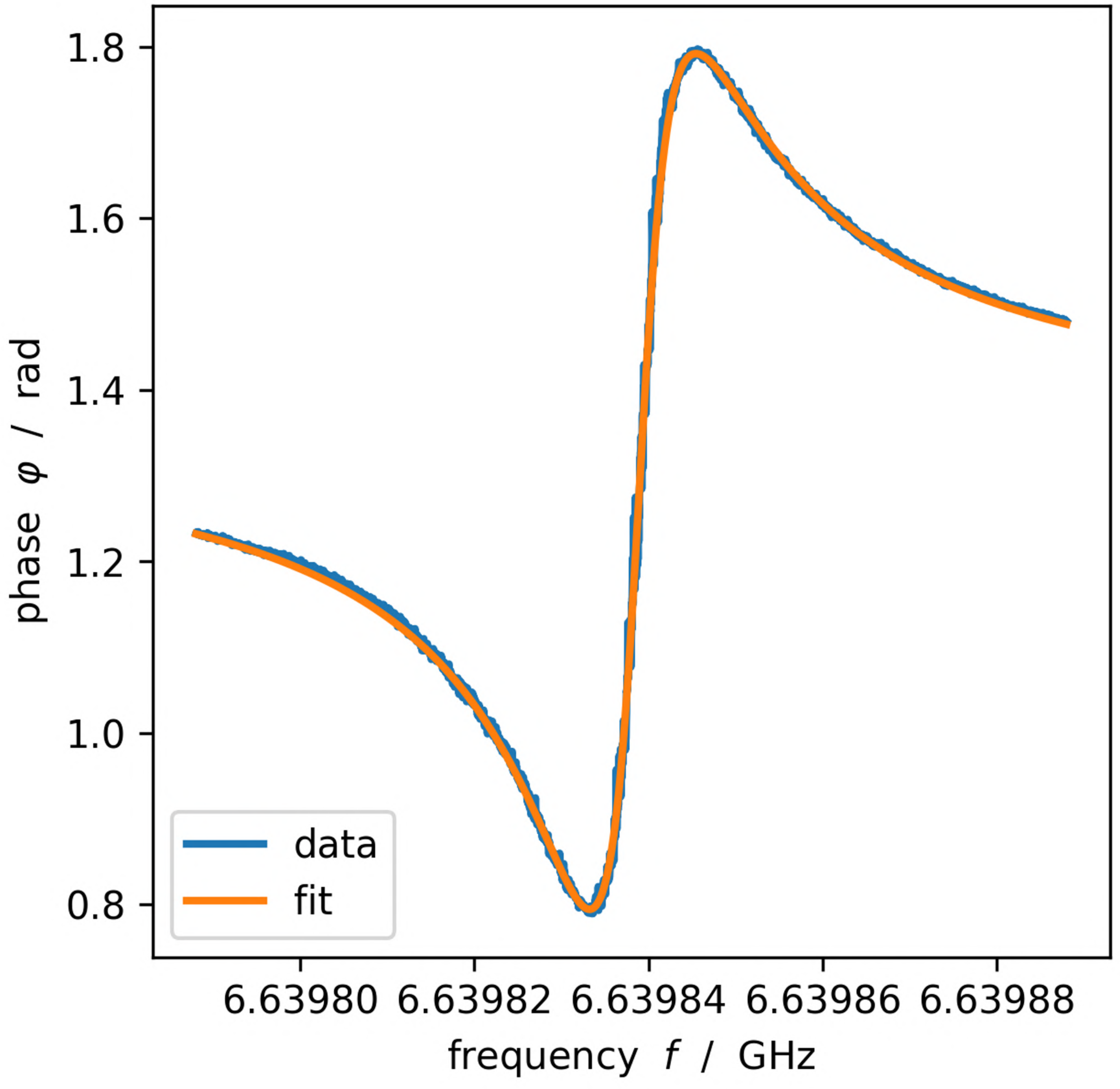
Most recent results with aluminium based lumped element resonators



Fit in complex S_{21} plane



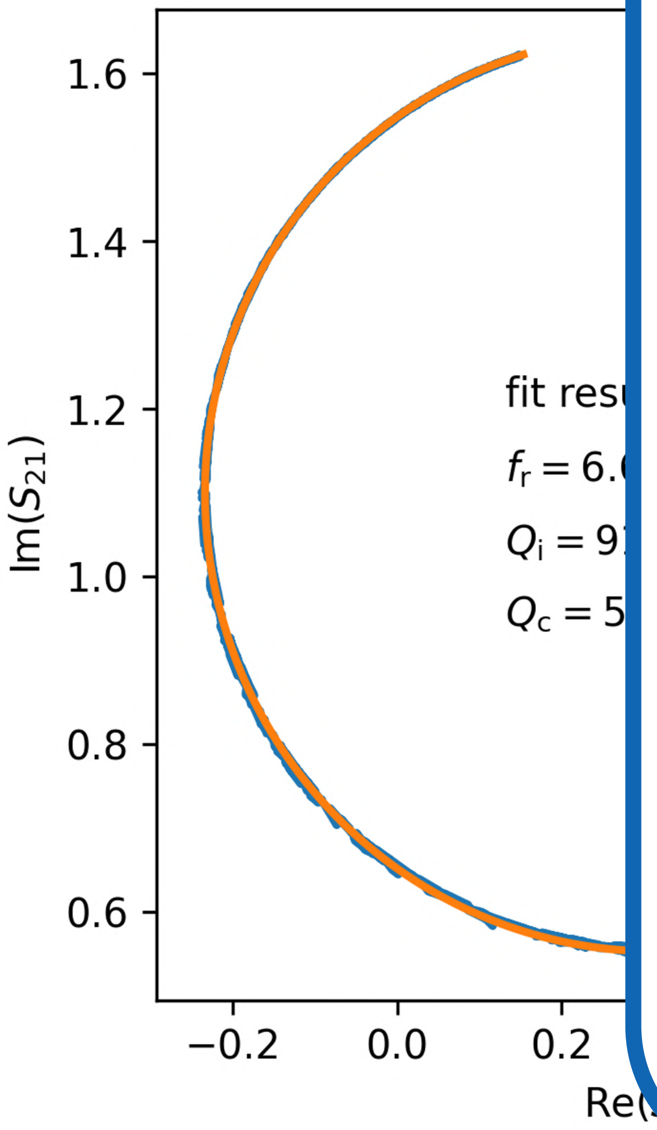
Transmission $|S_{21}|^2$

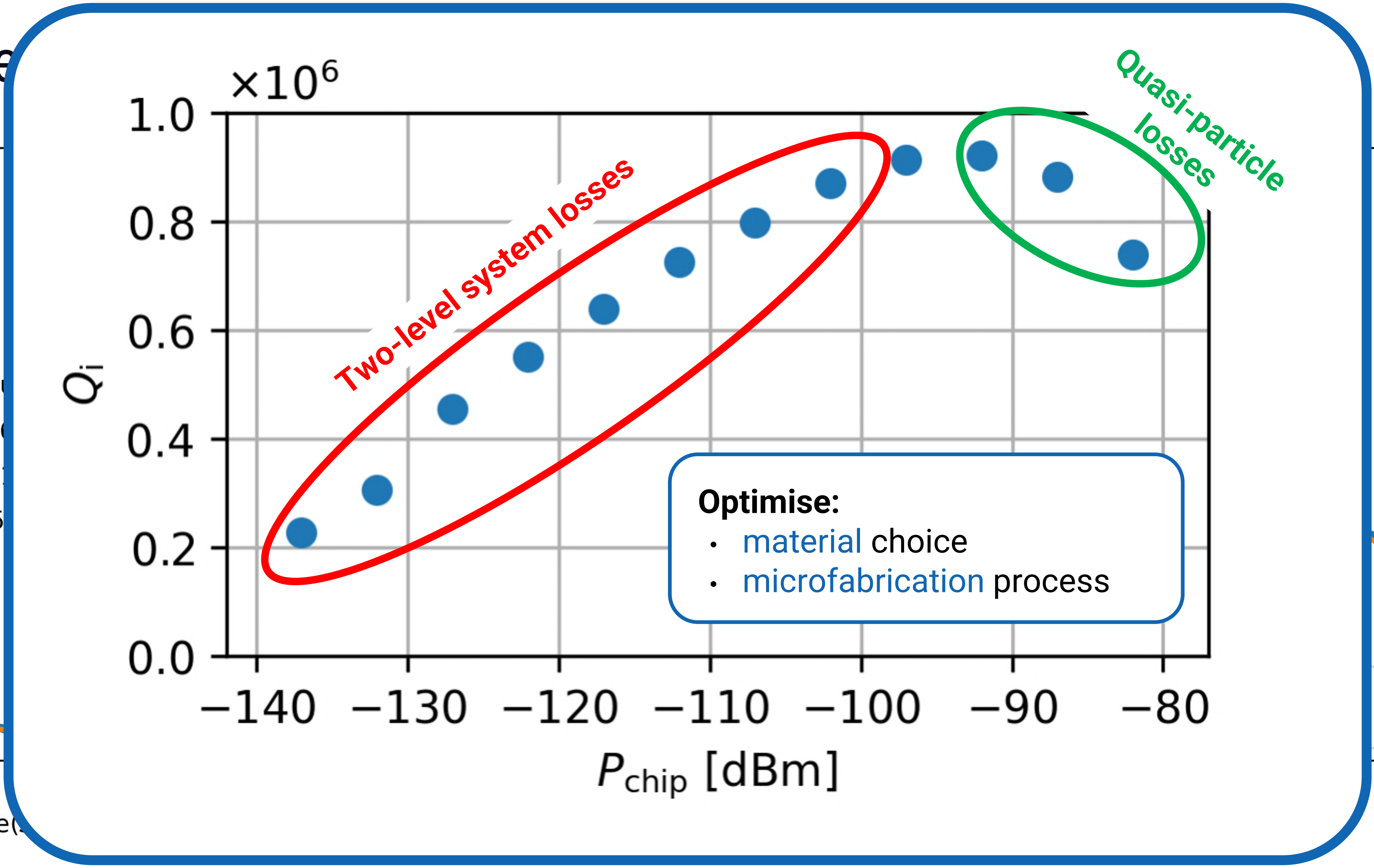


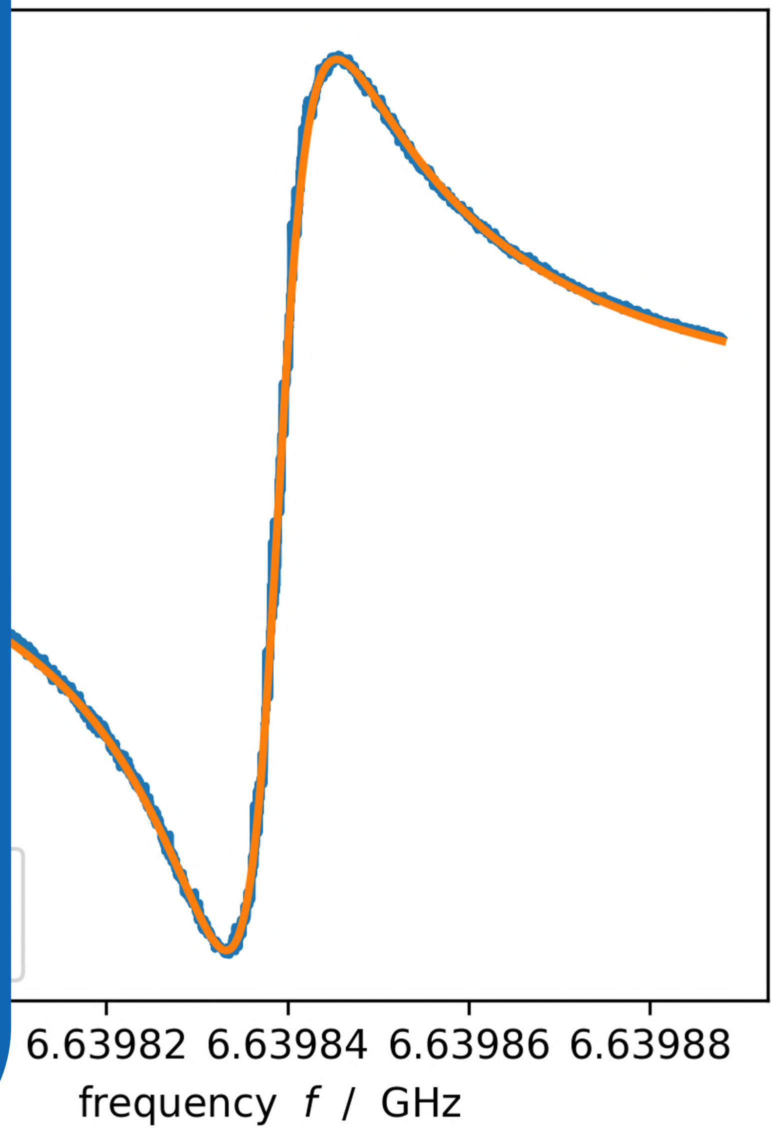
Phase arctan2[Im(S_{21}), Re(S_{21})]

Superconducting microwave resonators

Most recent re







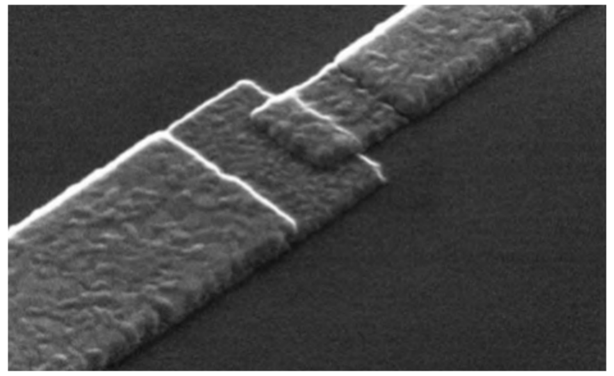
Fit in complex S_{21} plane

Transmission $|S_{21}|^2$

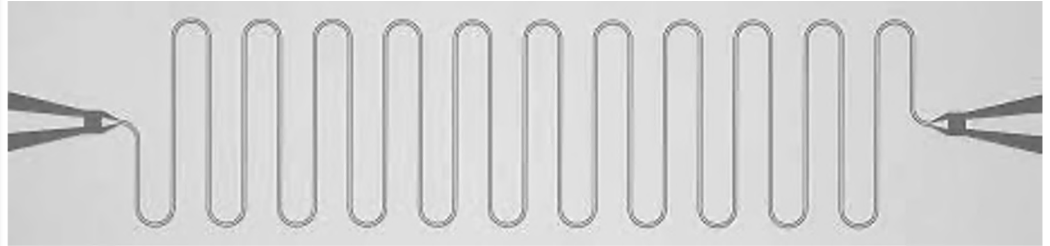
Phase arctan2[Im(S_{21}), Re(S_{21})]

Superconducting building blocks

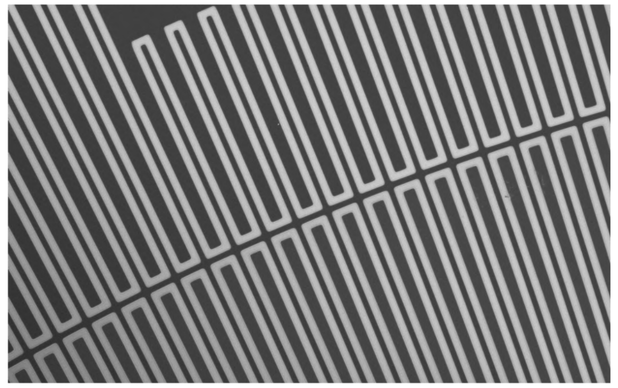
Josephson junctions



Superconducting resonators



High kinetic inductance films



SQUIDs

Parametric Amplifiers

Qubits

Cryogenic detectors

Microwave multiplexers

…

Multi-qubit systems with Quantum limited noise read-out

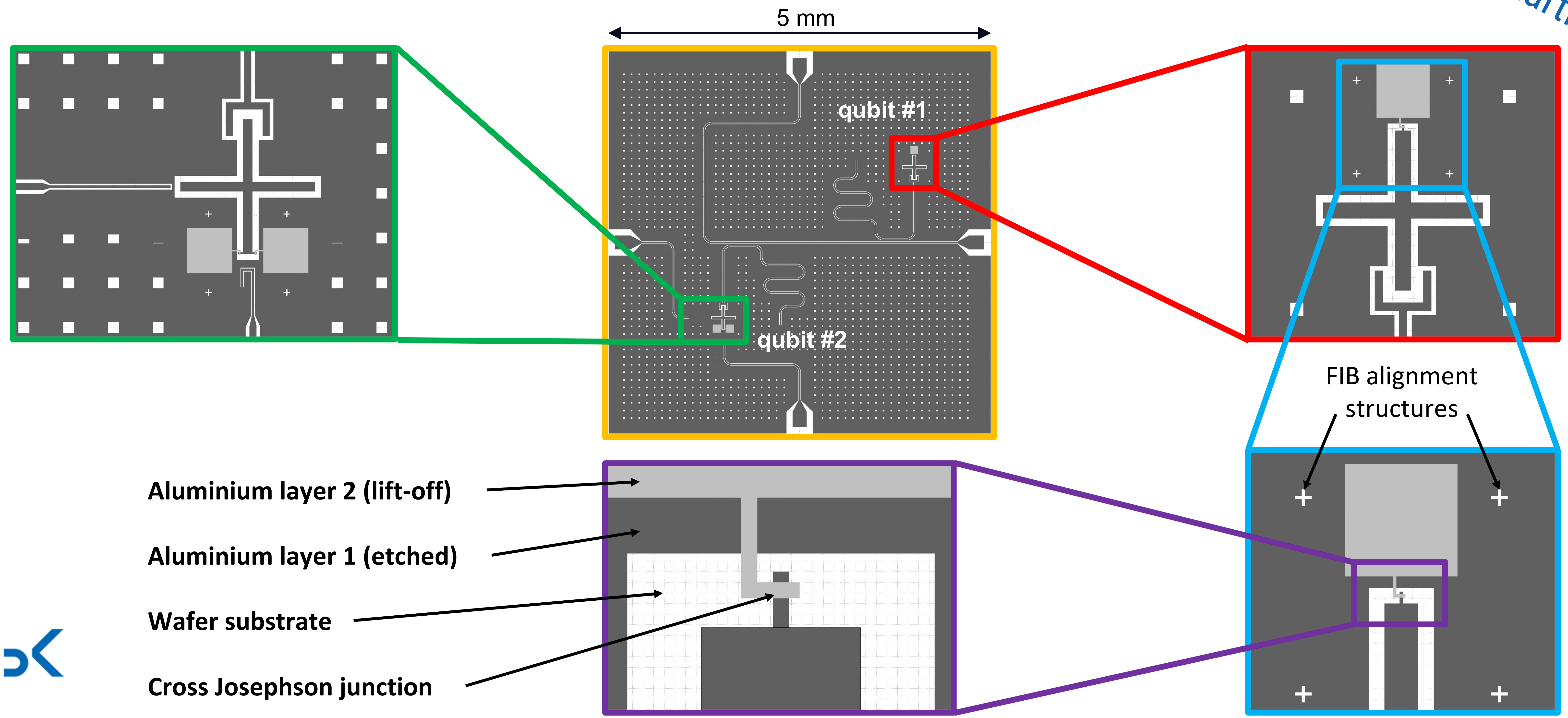
Hybrid superconducting magneto-mechanical systems

…

Superconducting transmon qubits

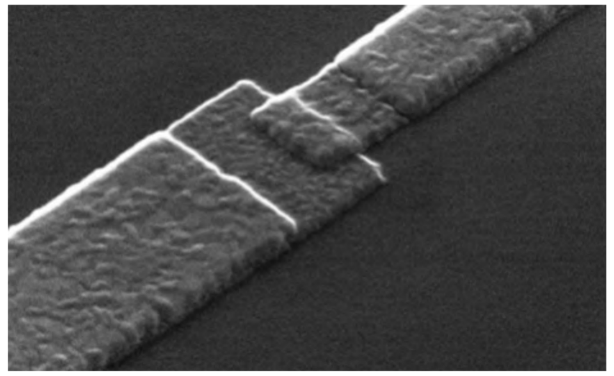
Chip design: qubit #1: fixed-frequency resonator driven transmon
qubit #2: tunable-frequency transmon with dedicated drive-line

Microfabrication starting soon!

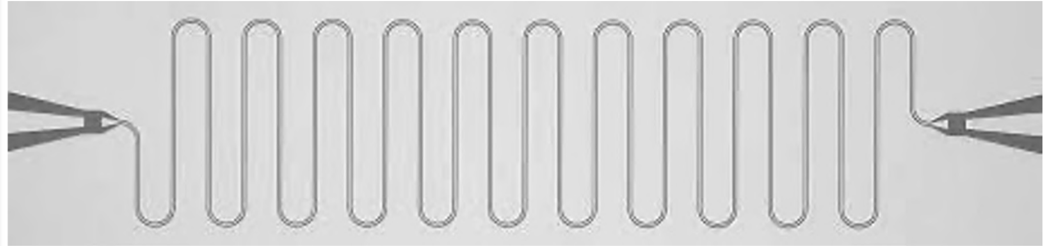


Superconducting building blocks

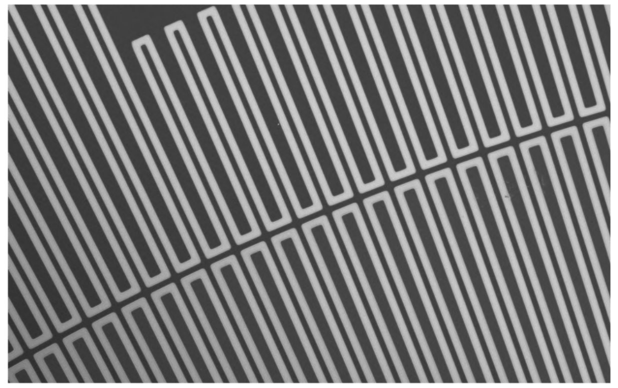
Josephson junctions

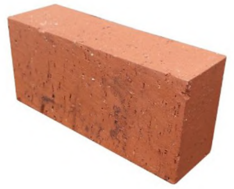


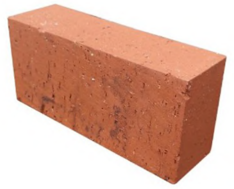
Superconducting resonators



High kinetic inductance films







SQUIDs

Parametric Amplifiers

Qubits

Cryogenic detectors

Microwave multiplexers

…

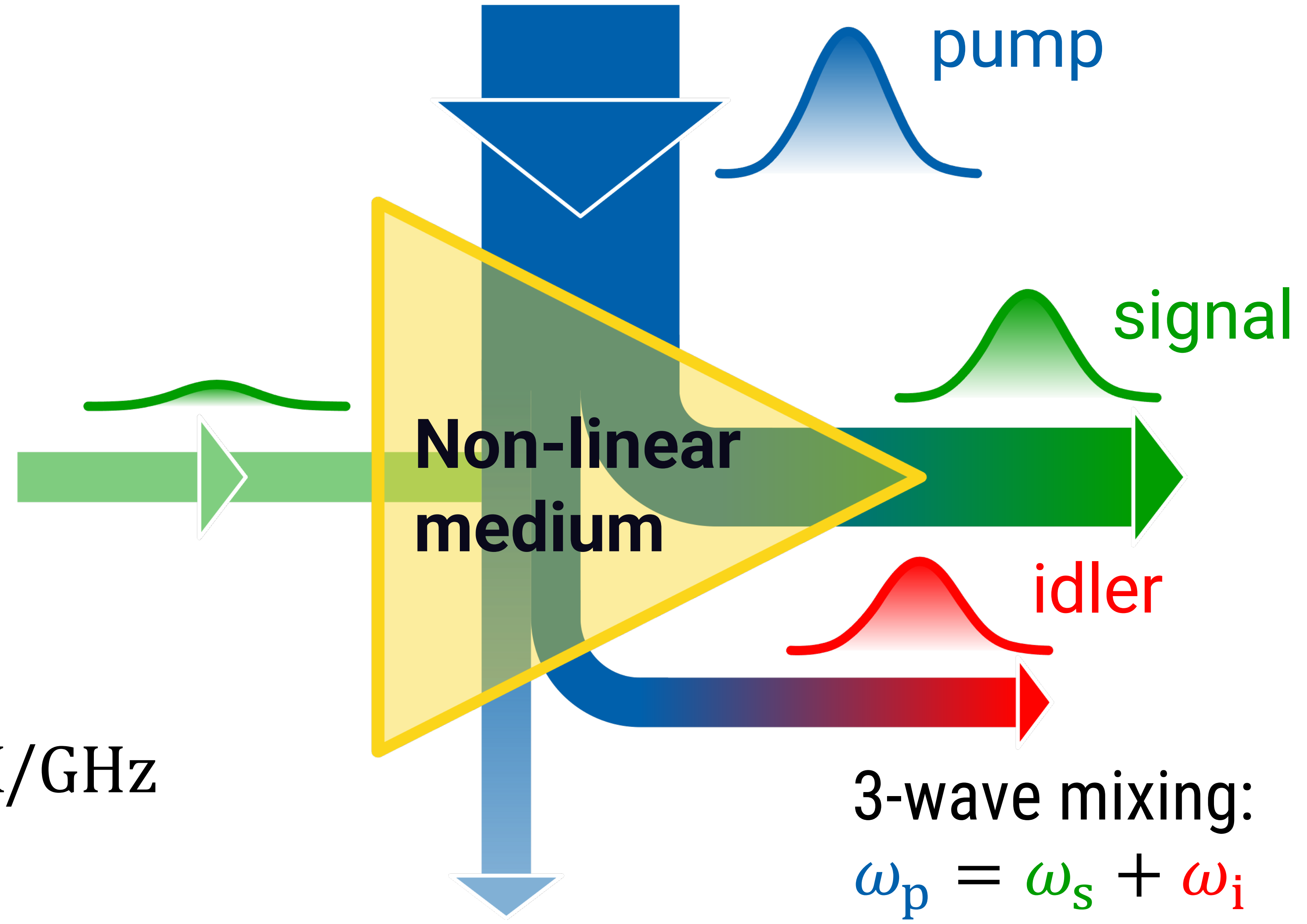
Multi-qubit systems with Quantum limited noise read-out

Hybrid superconducting magneto-mechanical systems

…

Travelling Wave Parametric Amplification (TWPA)

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: $T_N/f \sim h/2k_B \sim 25\ \mathrm{mK/GHz}$

Non-linearity given by Josephson junctions

or

Kinetic inductance of the material

NbTiN films for Superconducting Parametric Amplifiers

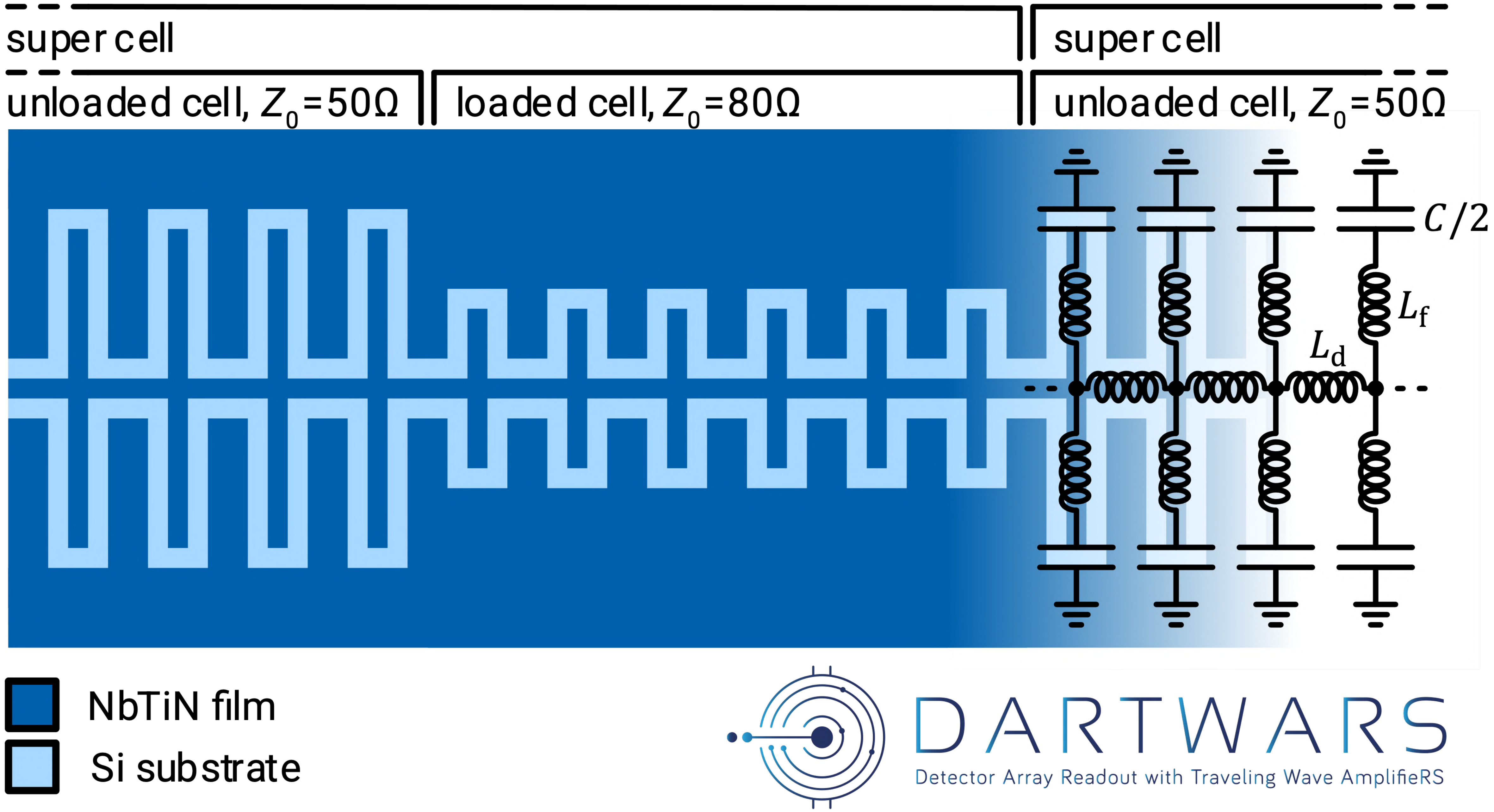
Kinetic Inductance Travelling Wave Parametric Amplifiers (KI-TWPAs)

- NbTiN thin film:
  reactive sputter deposition with $Nb_{80\%}Ti_{20\%}$ target

  → high control on film properties by fine tuning of the deposition process

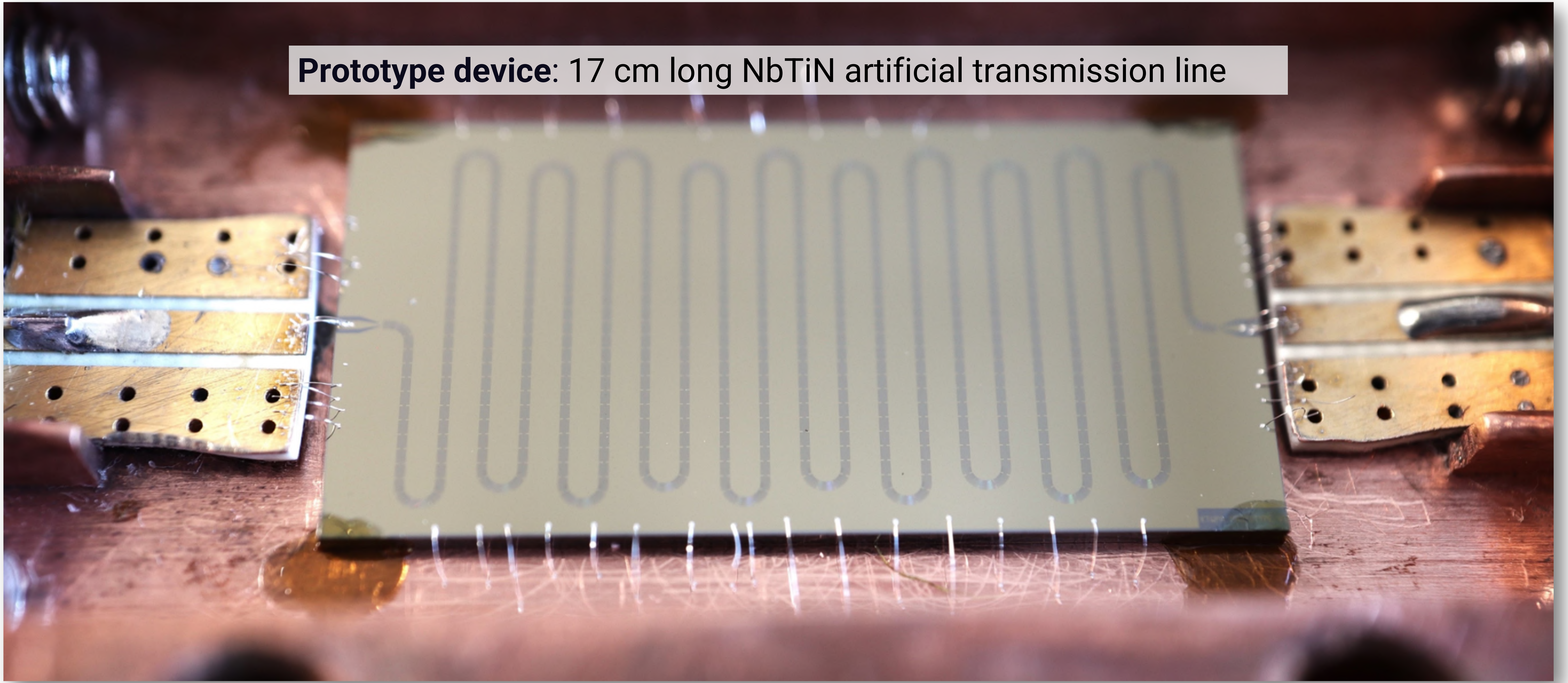
- Artificial transmission line:
  increased interaction time

- Unloaded/loaded segments:
  phase matching



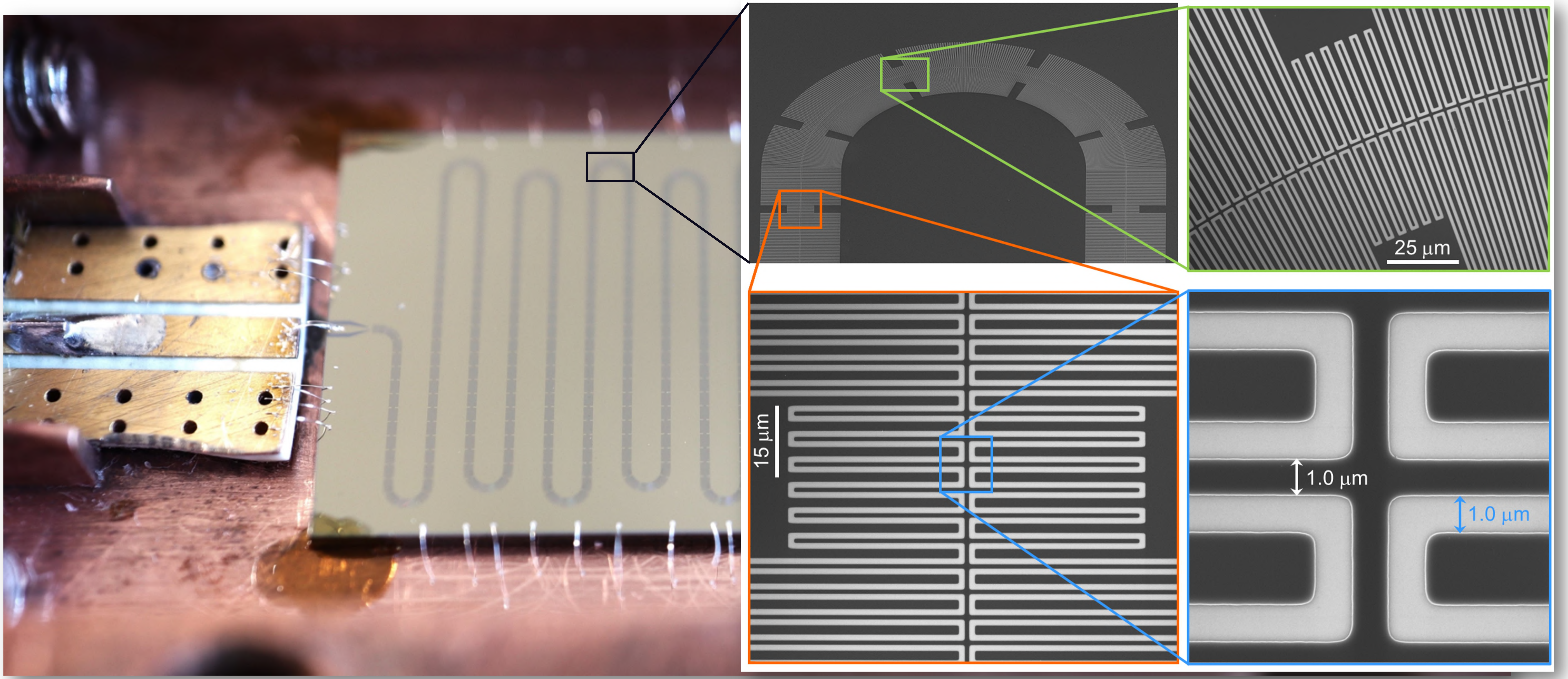
DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS

KI-TWPA prototype characterisation

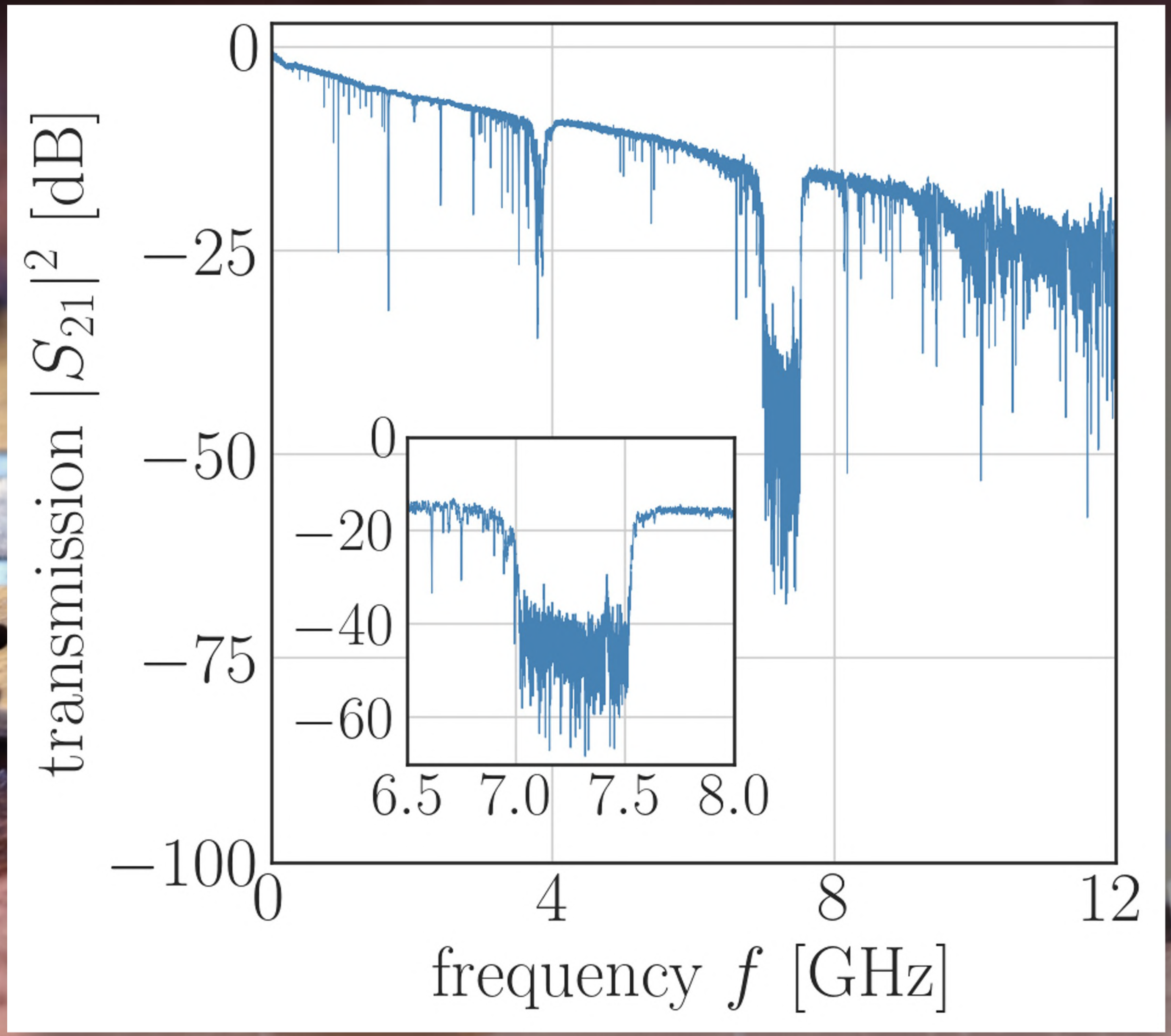


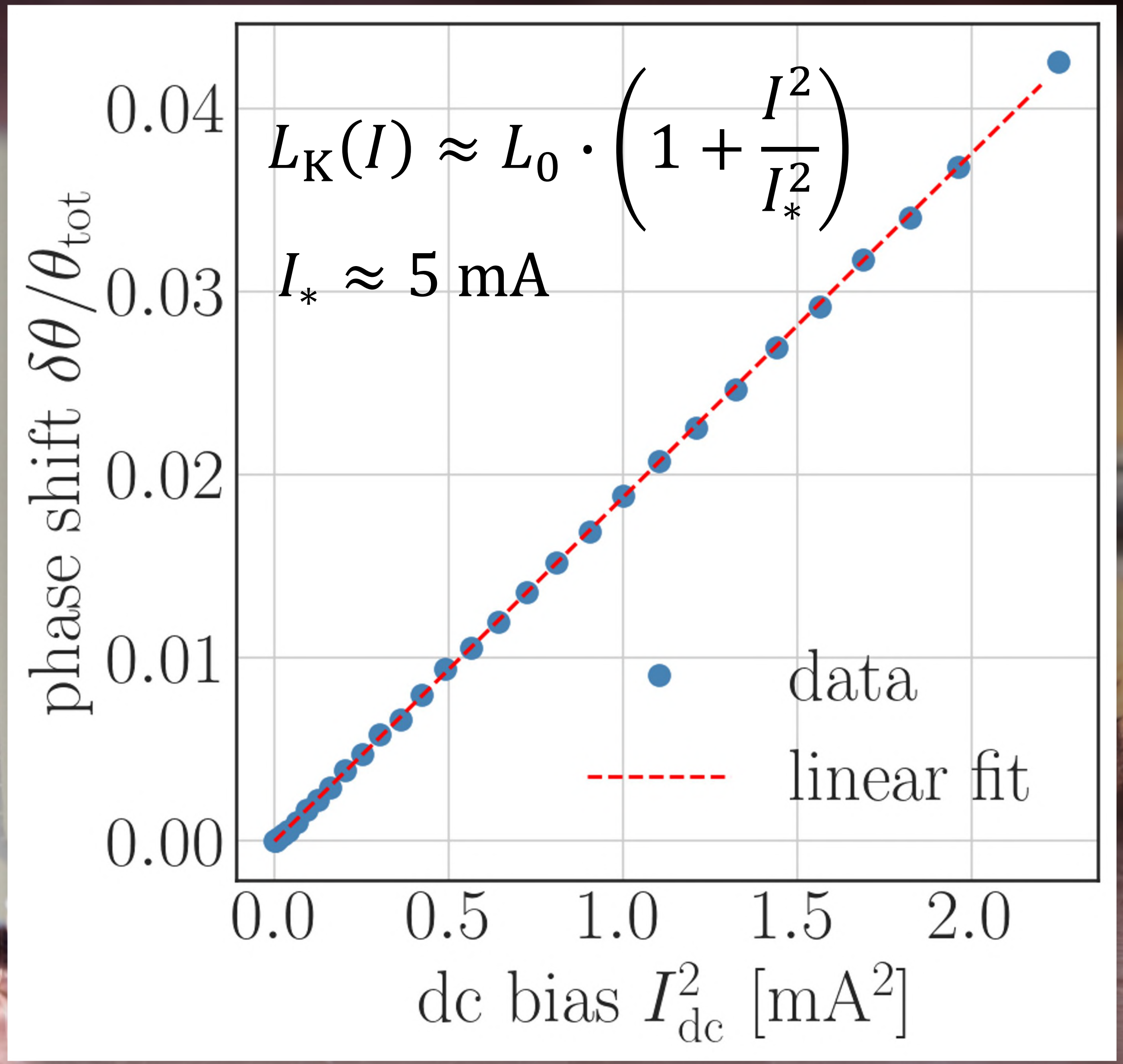
KI-TWPA prototype characterisation

DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS



KI-TWPA prototype characterisation



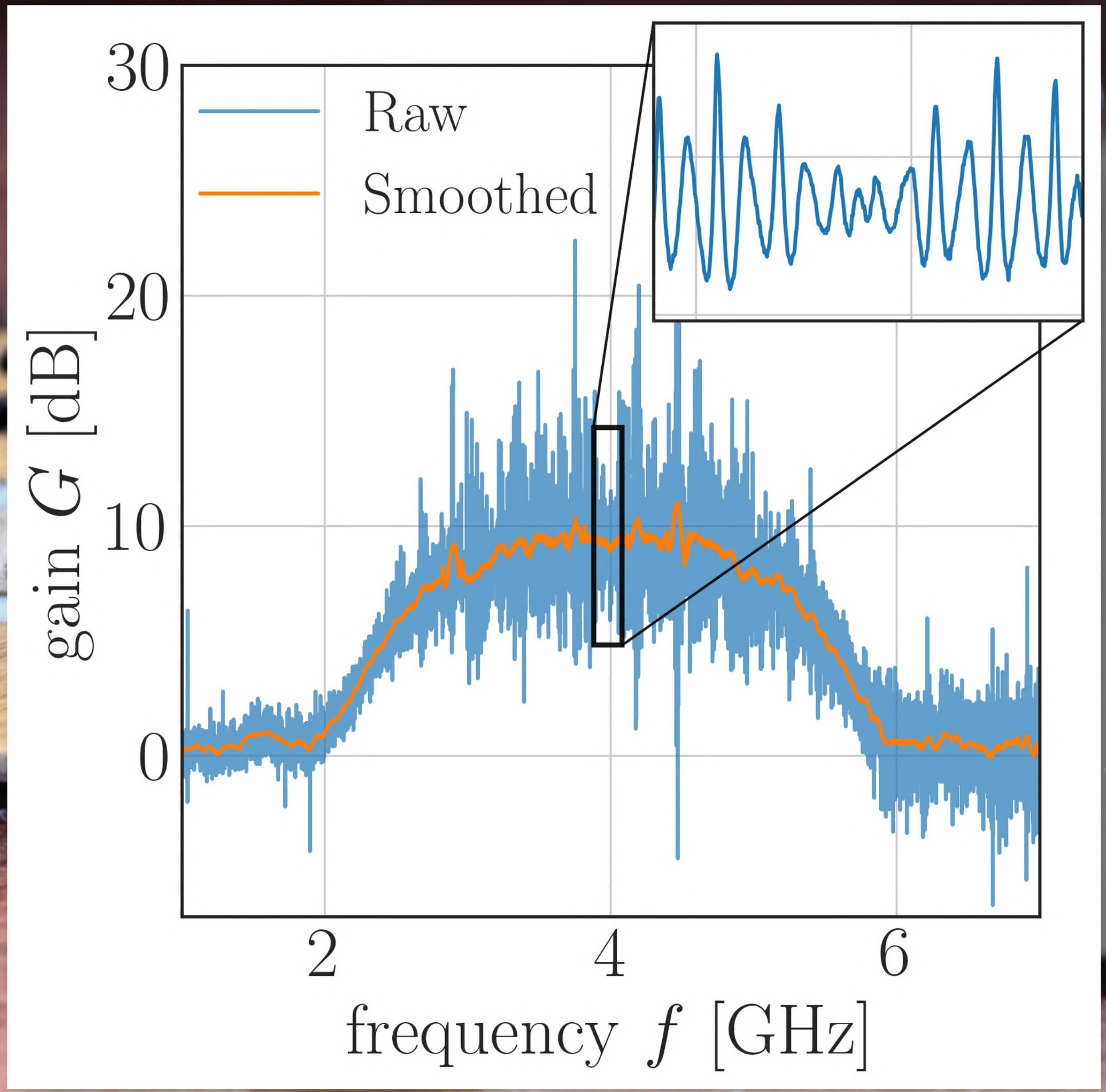


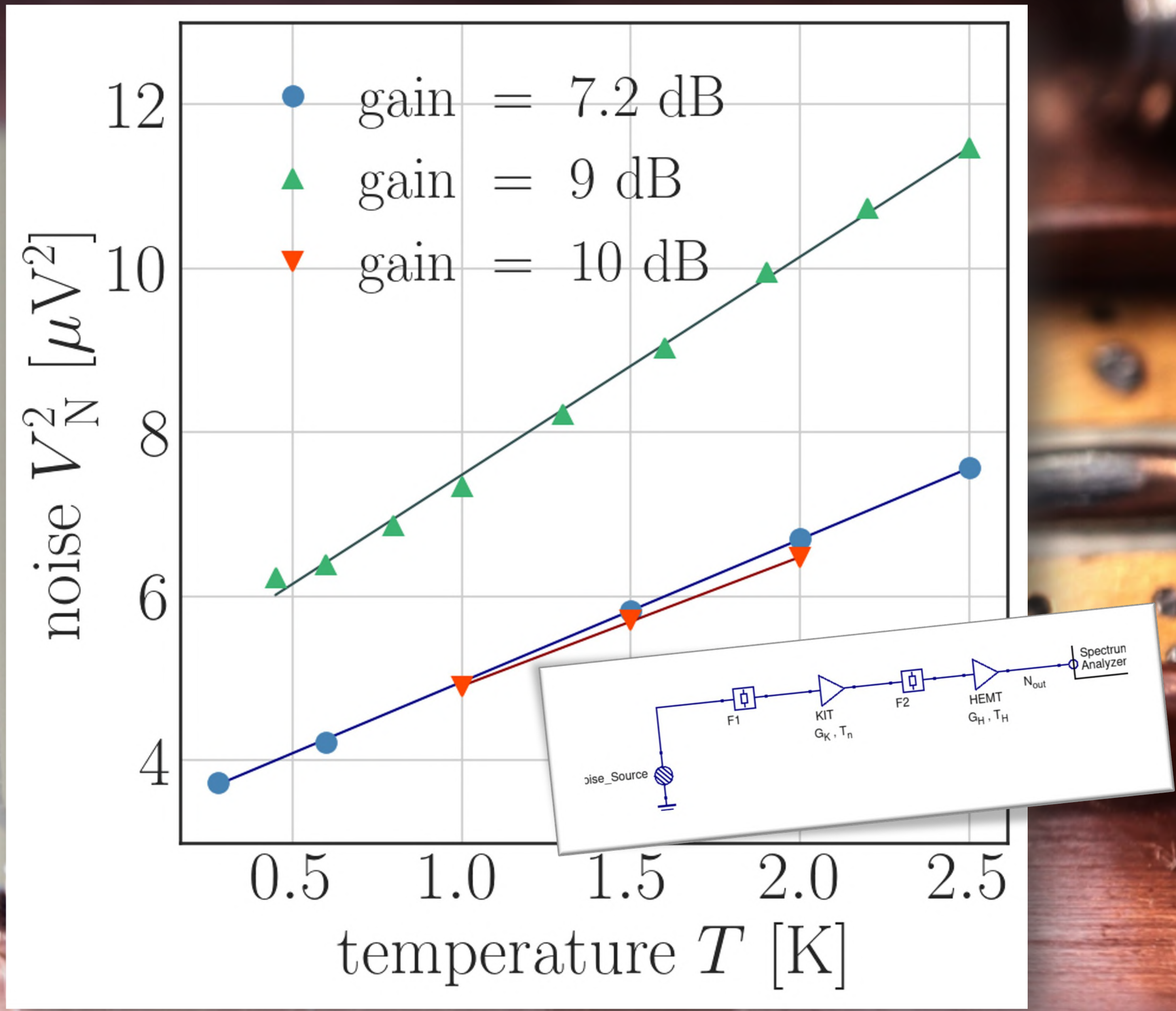
✓ Transmission with **bandgap** at ~ 7 GHz

✓ **Non-linearity** due to kinetic inductance

KI-TWPA prototype characterisation

DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS





✓ **Gain: up to ~ 10 dB** (with Idc = 1 mA)

✓ **Noise**: down to 2.5-3 noise quanta

My contacts

Federica Mantegazzini

Fondazione Bruno Kessler
Centre for Sensors and Devices
Via Sommarive 18, I-38123 Trento – Italy

E-mail: fmantegazzini@fbk.eu
Phone: +39 0461 314 141

Website: sites.google.com/fbk.eu/federica-mantegazzini

FONDAZIONE BRUNO KESSLER

SHORT SUMMARY

- Several groups in Italy are developing superconducting devices

AT FBK WE ARE OPTIMISING THE FUNDAMENTAL BUILDING BLOCKS:
JOSEPHSON JUNCTIONS, RESONATOR, HIGH KINETIC INDUCTANCE FILMS

TARGETED DEVICES:
QUBITS, PARAMETRIC AMPLIFIERS, HYBRID SYSTEMS

TARGETED APPLICATIONS:
cQED, QUANTUM SENSING, PARTICLE DETECTORS, TESTING of QUANTUM MODELS

Extra material

31 January 2024

Federica Mantegazzini

fmantegazzini@fbk.eu
www.fbk.eu

Cross Josephson junctions at FBK - 1st generation

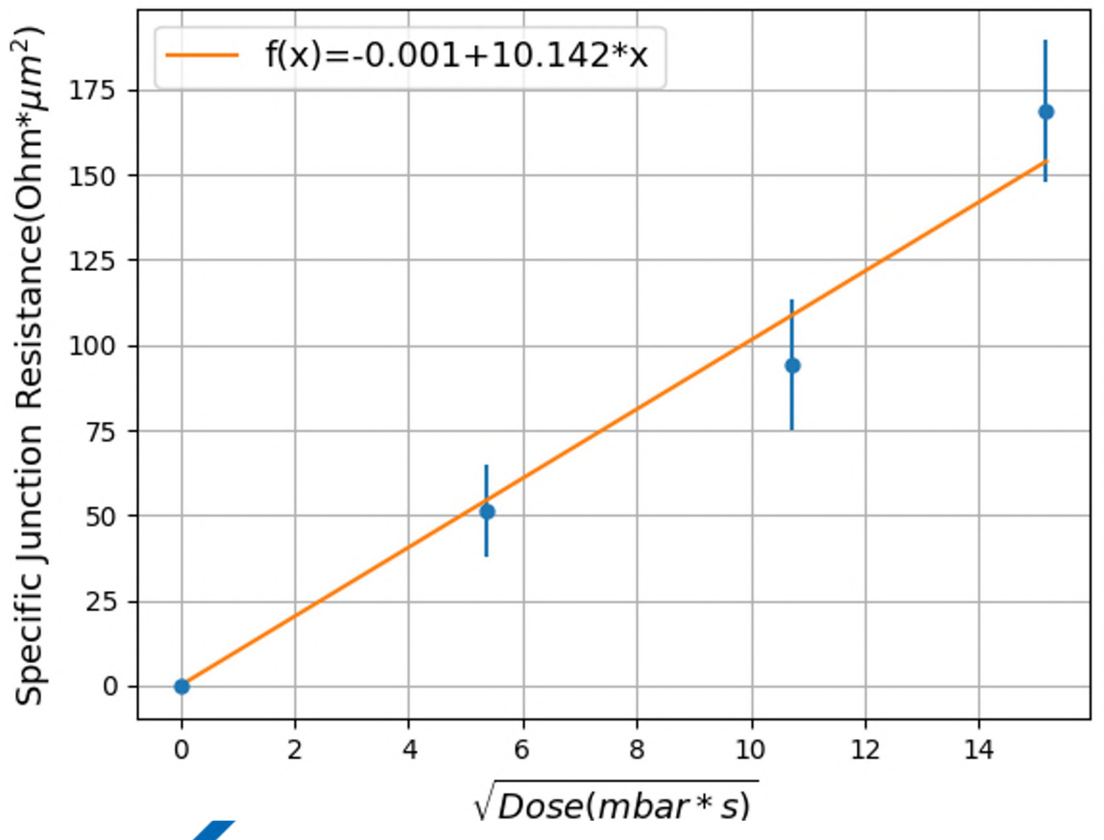
The junction normal resistance R_N is related to the critical current I_c :

$$R_N = (\pi/4) \cdot V_g$$

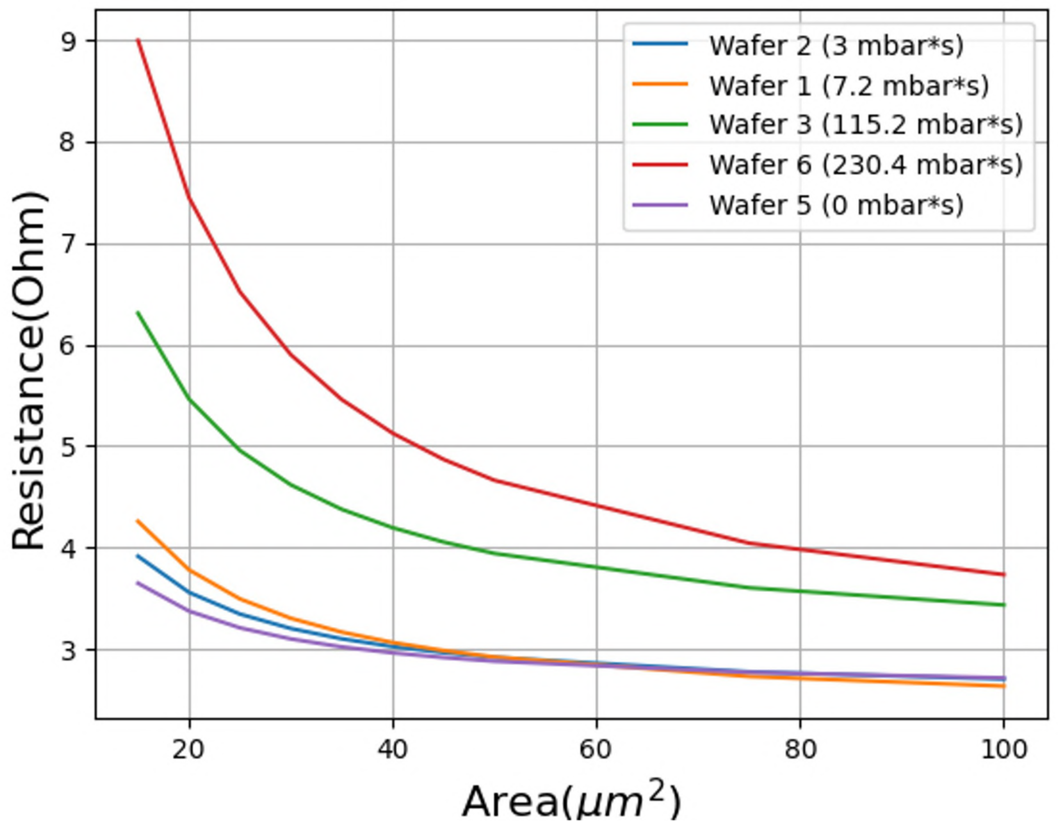
Resistance measurements at T = 300 K

Cryogenic measurements at $T_b \approx$ 20 mK

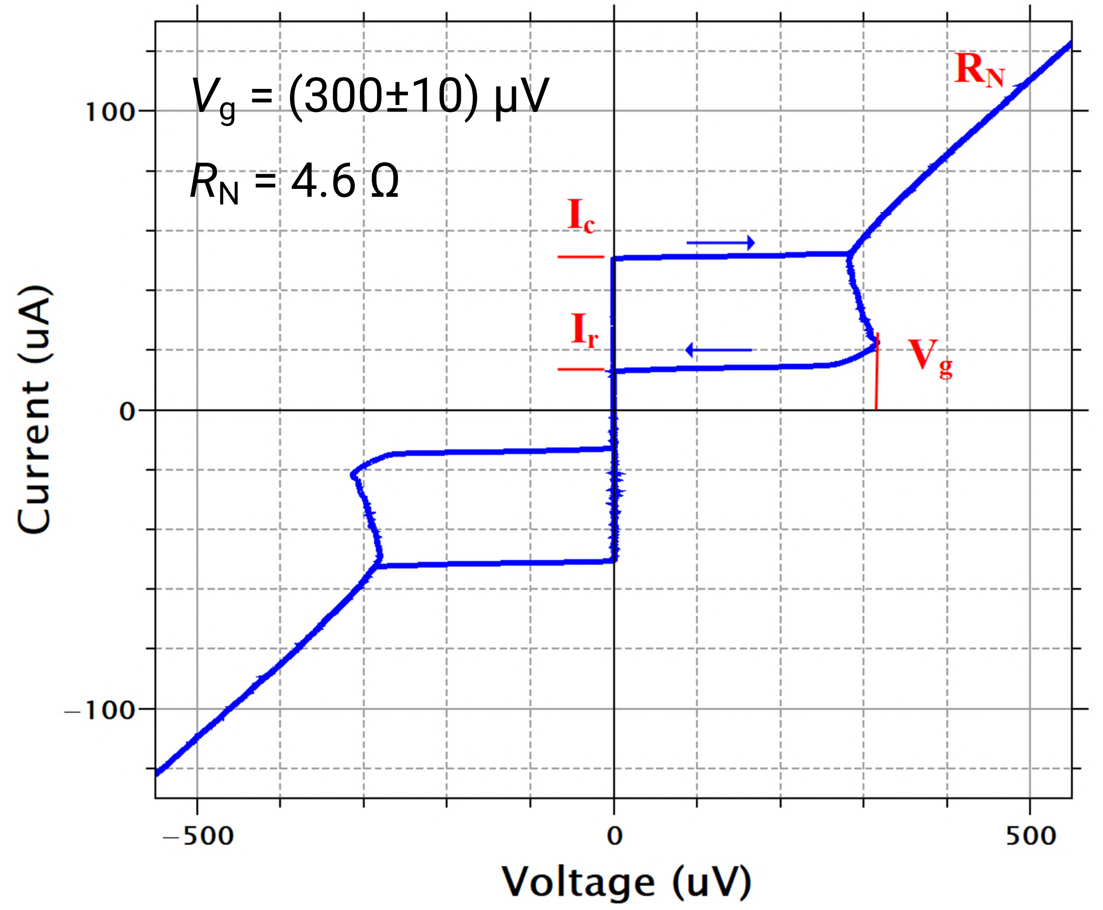
Junction resistance vs √oxidation dose



Junction resistance vs junction area (for different oxidation doses)



IV characteristics



Cross Josephson junctions at FBK - 2nd generation

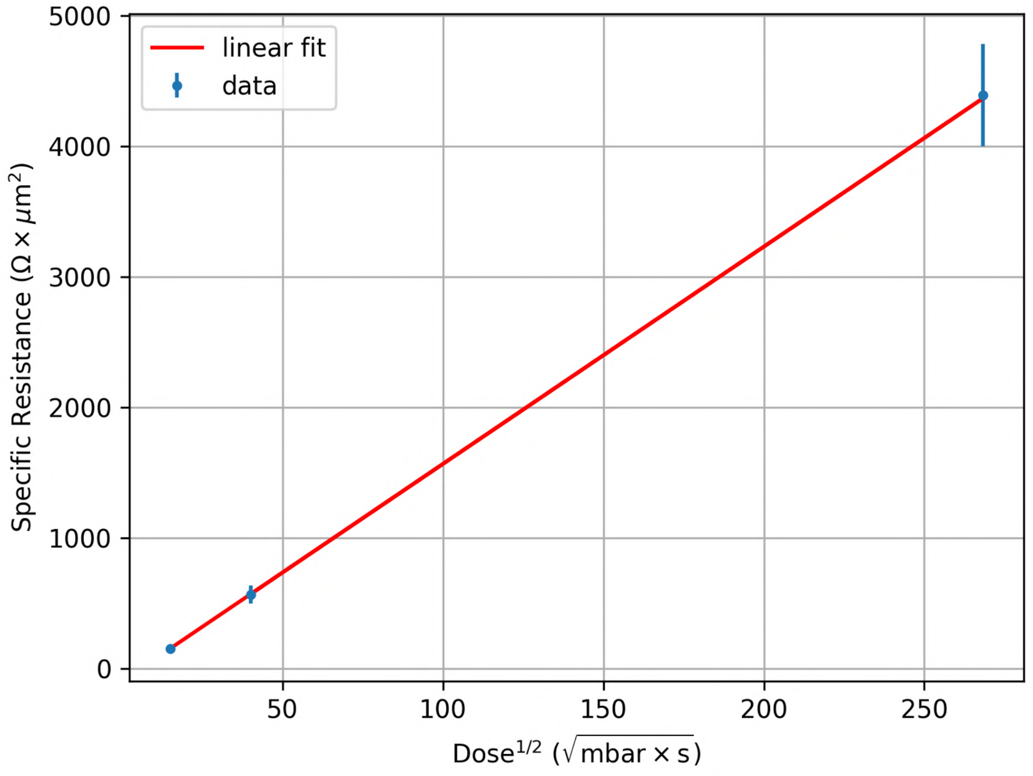
The junction normal resistance R_N is related to the critical current I_c :

$$R_N = (\pi/4) \cdot V_g$$

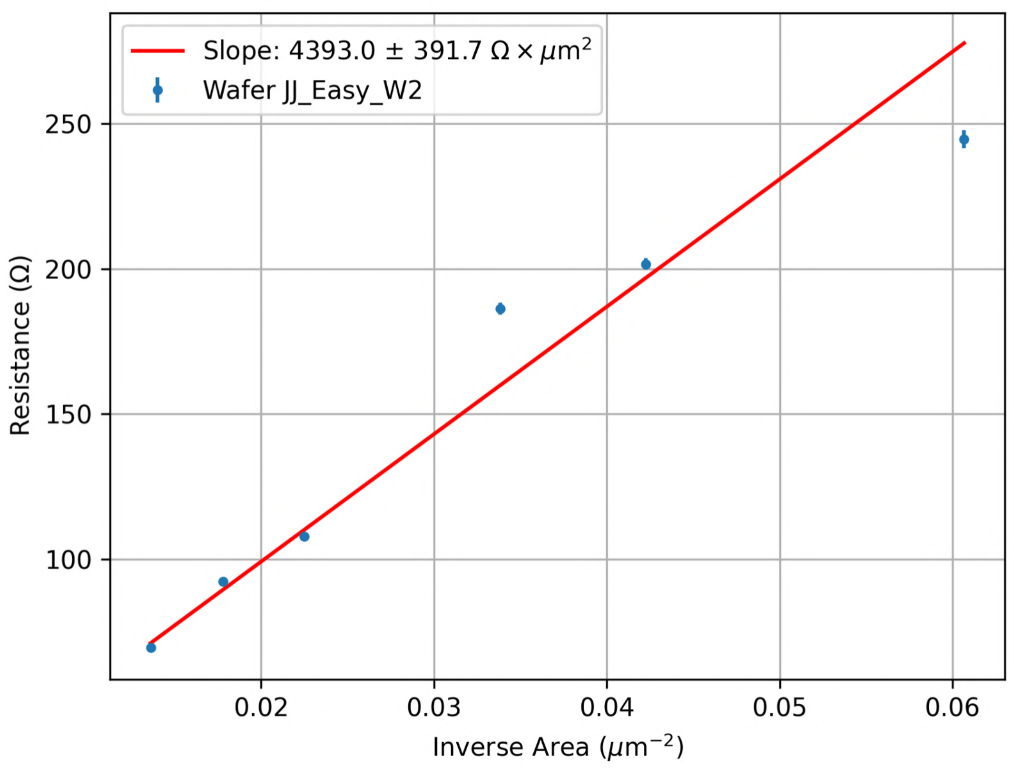
Resistance measurements at T = 300 K

Cryogenic measurements at $T_b \approx$ 20 mK

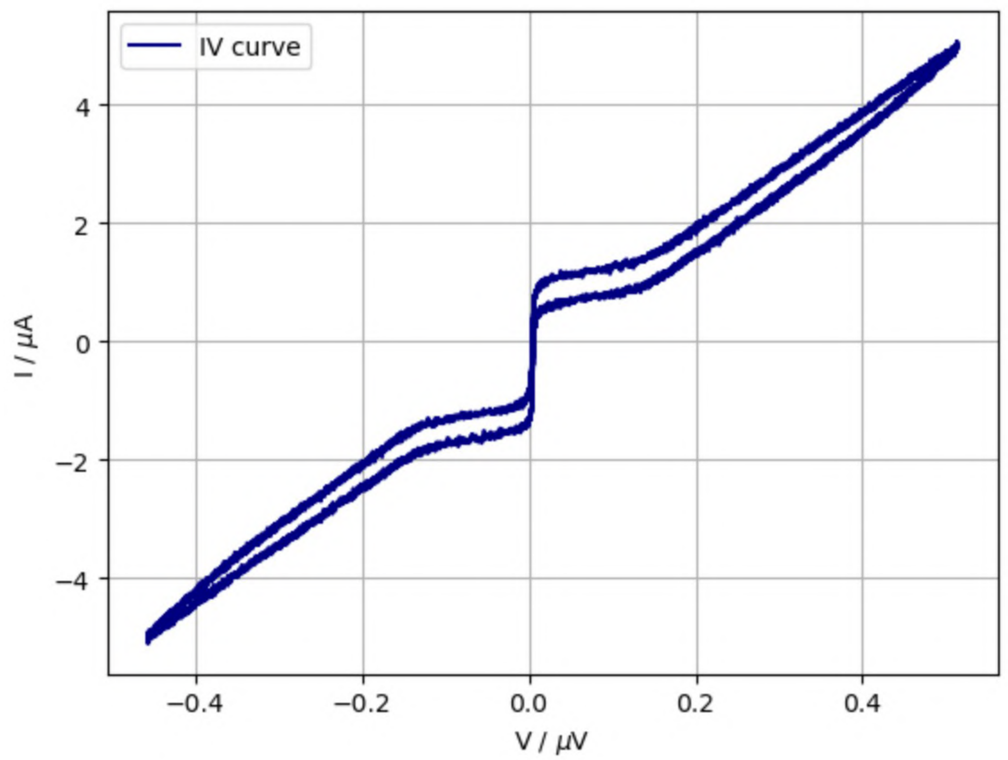
Junction resistance vs √oxidation dose



Junction resistance vs junction area (for different oxidation doses)

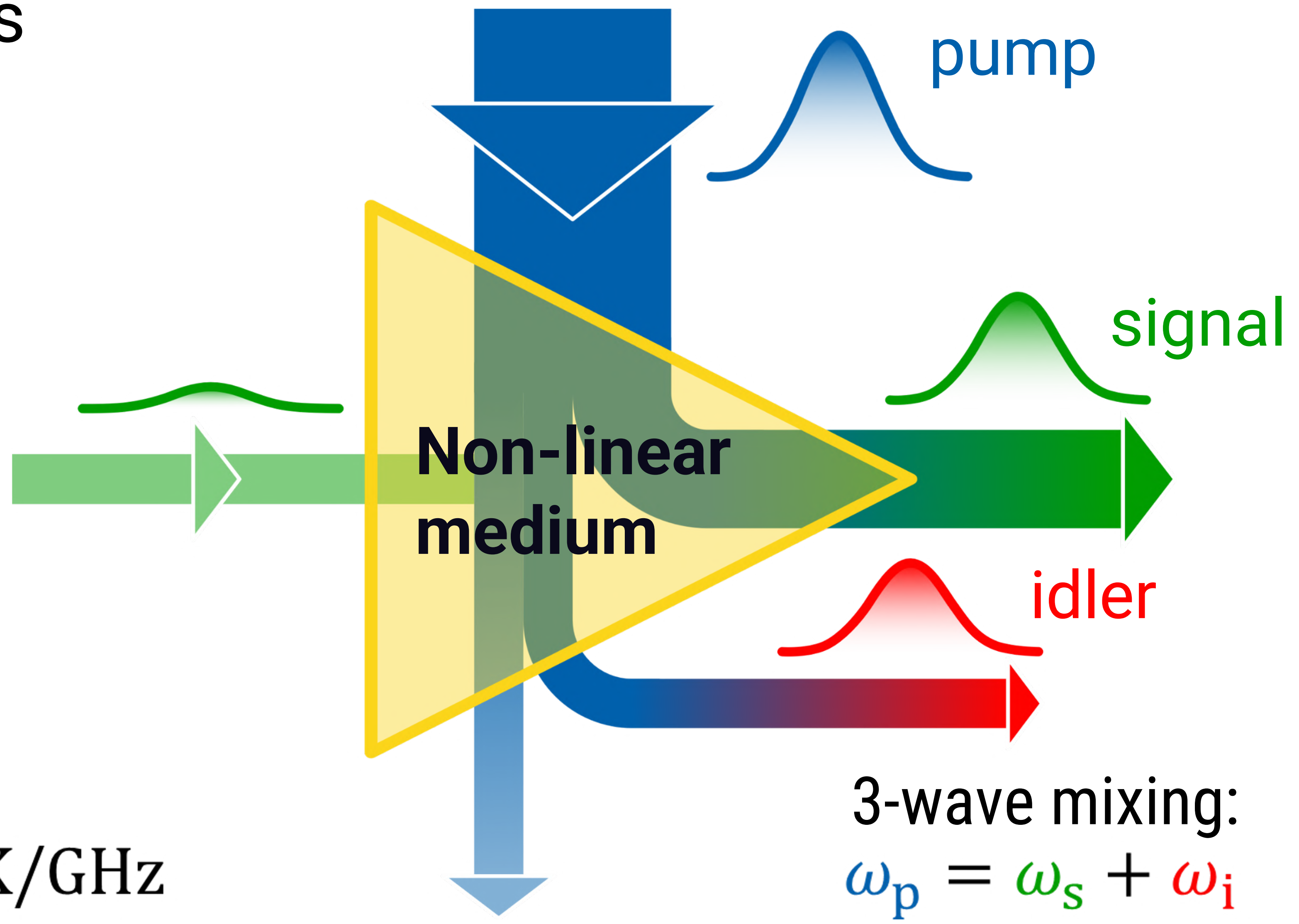


IV characteristics



Superconducting Parametric Amplifiers

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



Superconducting amplifiers

for microwave amplification:

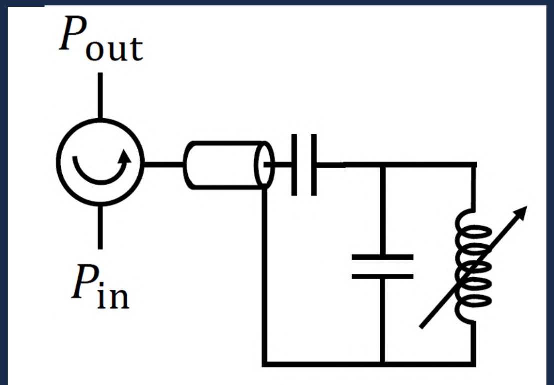
- (Ideally) non-dissipative
- Ultra-low-noise amplification
  → Quantum noise limit: $T_N/f \sim h/2k_B \sim 25\ \mathrm{mK/GHz}$

Different approaches: JPAs vs TWPAs

Increasing **signal gain** by *increasing* the **interaction time** in the non-linear medium

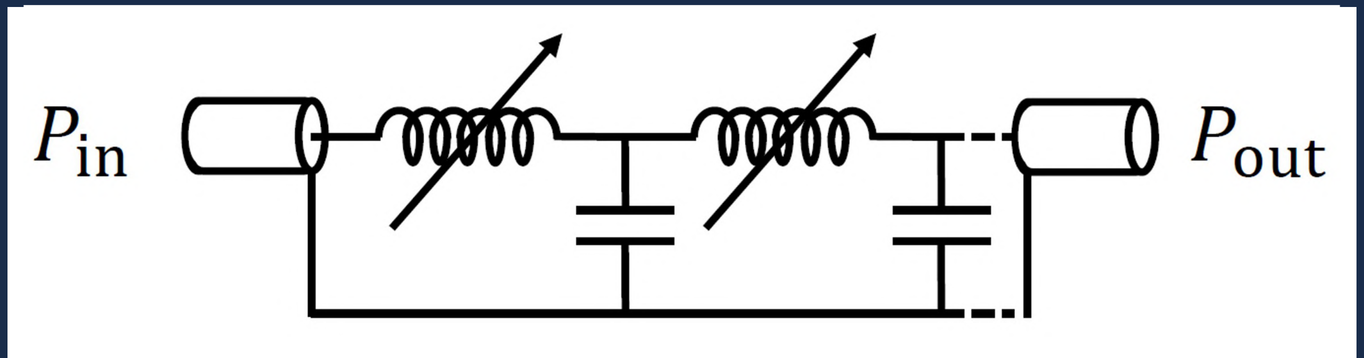
Resonator-based paramp:

Josephson Parametric Amplifiers JPAs



Long **non-linear medium**:

Travelling Wave Parametric Amplifiers TWPAs



Larger bandwidth

Larger saturation power