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Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI National Quantum Science and Technology Institute

Spokes 6 & 7

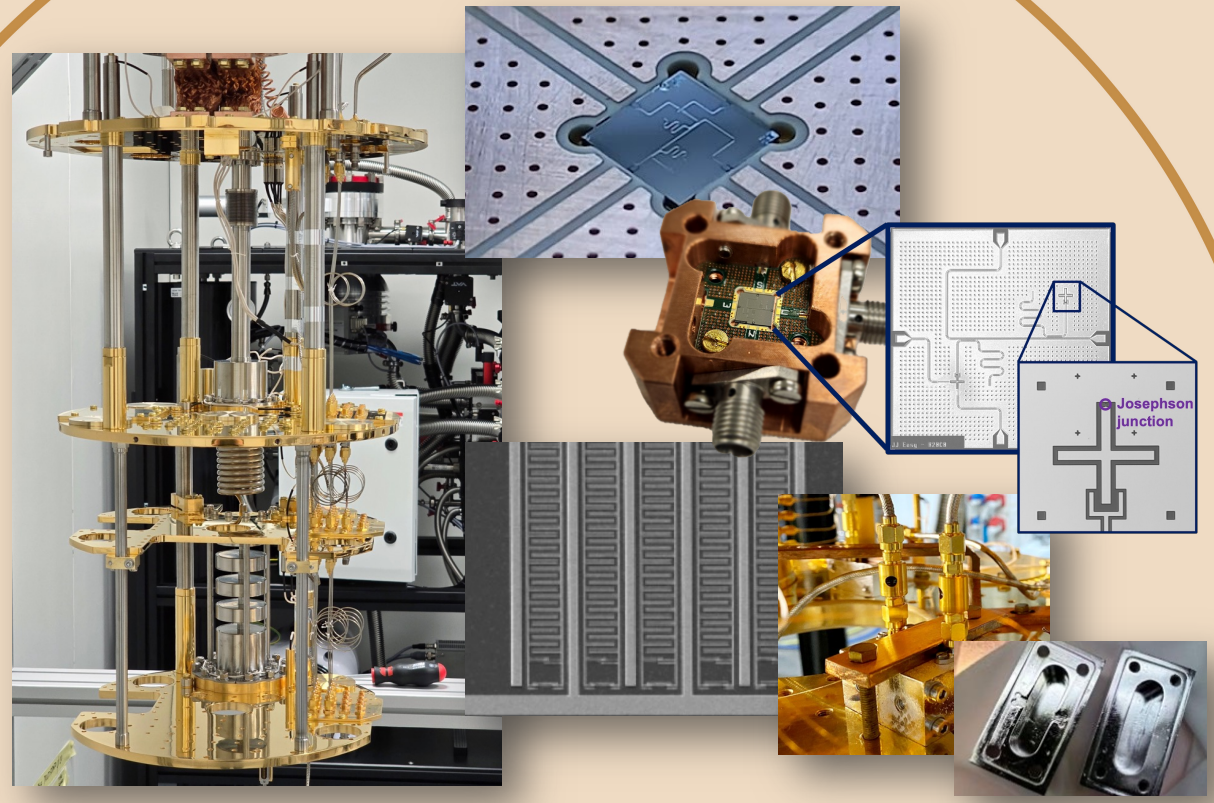
From *Integration* to *Complete Quantum Systems*

Activities on the

SUPERCONDUCTING PLATFORM

Federica Mantegazzini

Fondazione Bruno Kessler (Trento)



UMIB: M. Borghesi, G. Bosi, P. Carniti, S. Cecchi, M. Faverzani, A. Nucciotti, V. Vadalà, S. Vichi;
FBK: F. Ahrens, P. Falferi, A. Irace, F. Mantegazzini;
CNR: C. Bonavolontà, Y. Chen, V. Di Meo, E. Esposito, M. Lisitskiy, G. Panaccione, B. Ruggiero, M. Salluzzo, S. Castrignano, M. Lisitskiy, I. Ricciardi
INFN: E. Chyhyrynets, S. Garbolino, C. Gatti, L. Piersanti, C. Pira, C. Puglia, S. Tocci;
LEONARDO: M. Proietti

SPOKE 6

Integration

Integration of individual quantum objects into the building blocks of quantum architectures

Atomic, Photonic, Electronic

& Inter-platform Devices

SPOKE 7

Complete Quantum Systems

Application-oriented development of complete quantum systems

Imaging, Point Sensing,

Communication/IoT, Simulation Systems

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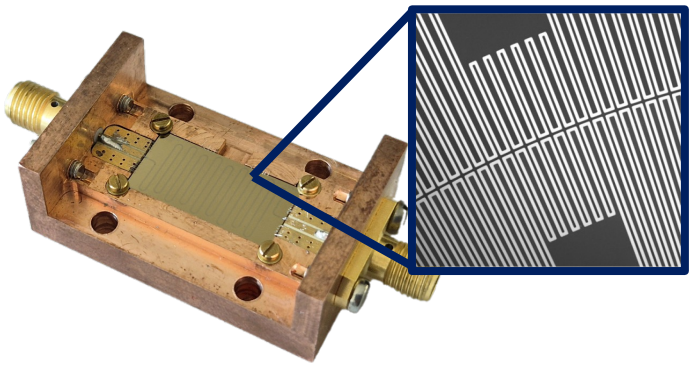
SUPERCONDUCTING PLATFORM in Spoke 6-7

Different devices and systems…

Superconducting Parametric Amplifiers

- Travelling Wave Parametric Amplifiers (TWPAs)



- Josephson Parametric Amplifiers (JPAs)

Tunable resonators

- Kinetic inductance-based current-sensitive resonators

- Josephson junction-based tunable resonators

Superconducting qubits

- 2D architectures

- 3D architectures

Unconventional superconducting platforms

- SQN devices

- Topological-superconducting systems: Josephson 2D lattices

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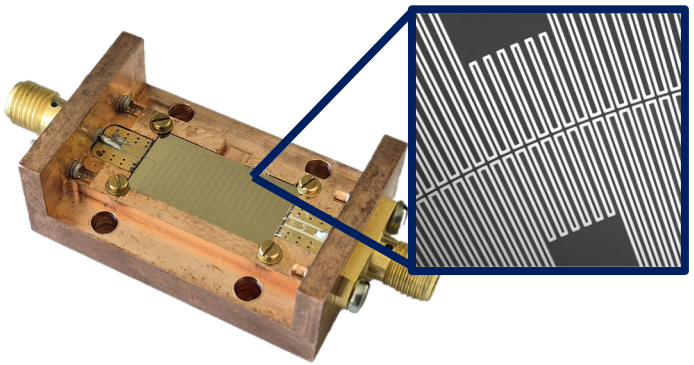

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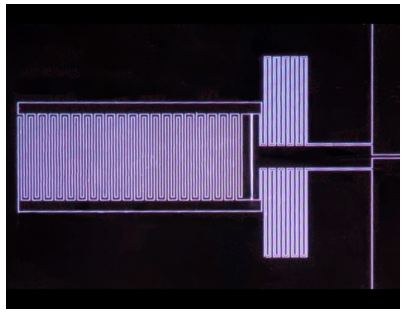

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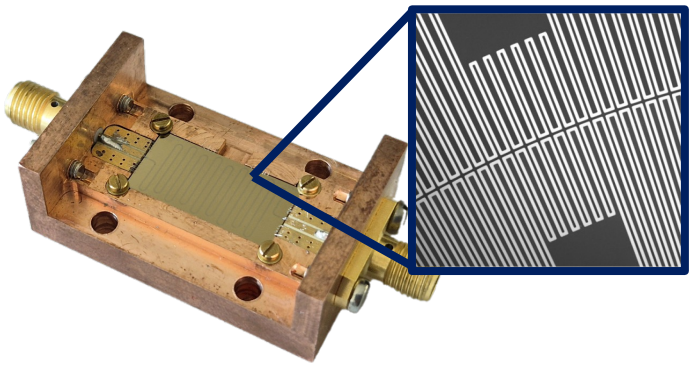

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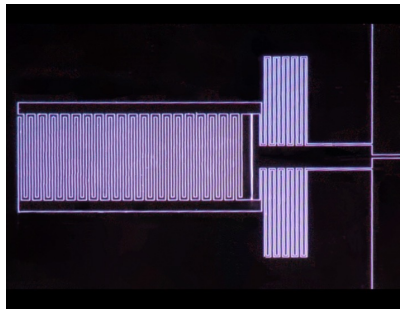

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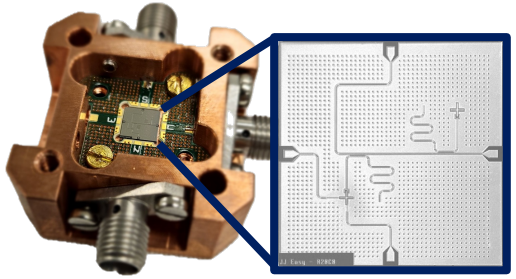

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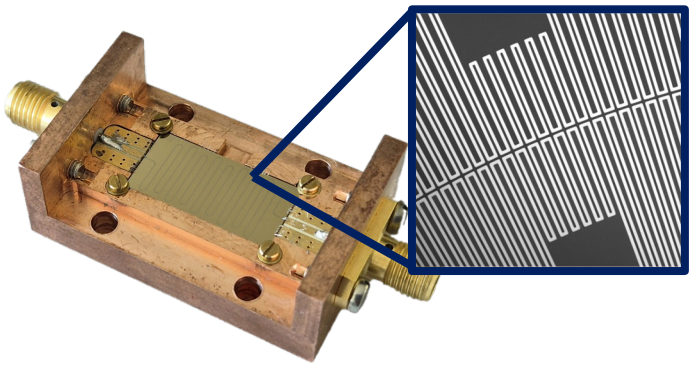

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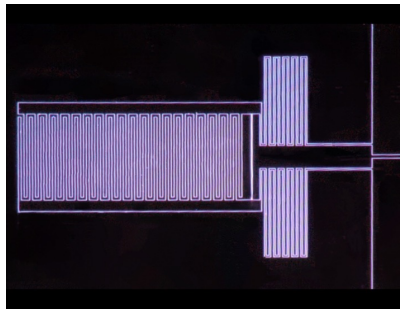

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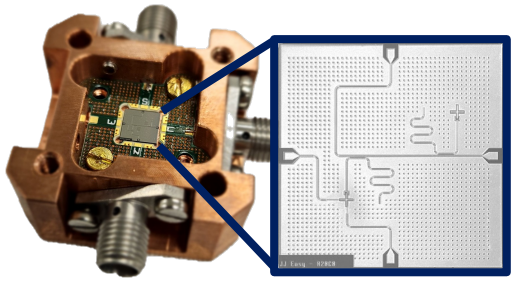

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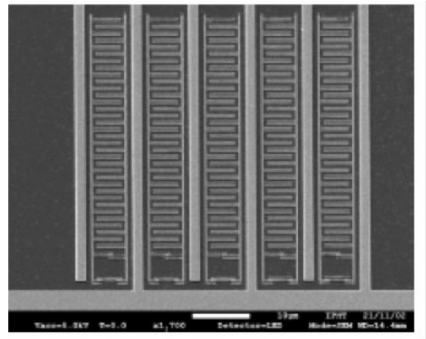

- Topological-superconducting systems:
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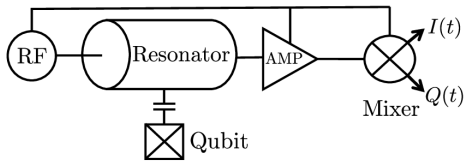
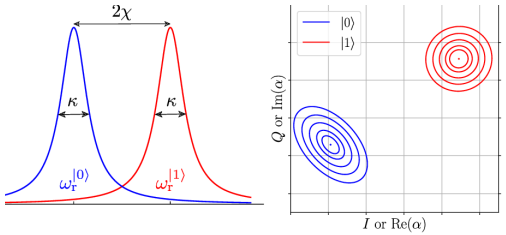
SUPERCONDUCTING PLATFORM in Spoke 6-7

… for different applications

Superconducting Parametric Amplifiers

- High-fidelity multiplexed dispersive read-out





- Sources of entangled microwave photons

Tunable resonators

- Multiplexed microwave read-out

- Pulse control

Transmon qubits

- Universal quantum gates

10.1038/s41567-022-01590-3

Unconventional superconducting platforms

- Quantum networks

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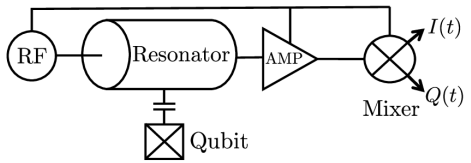

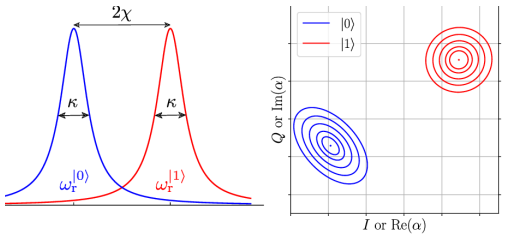

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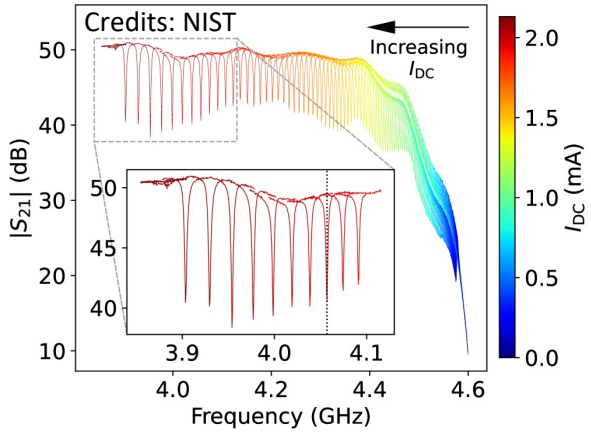

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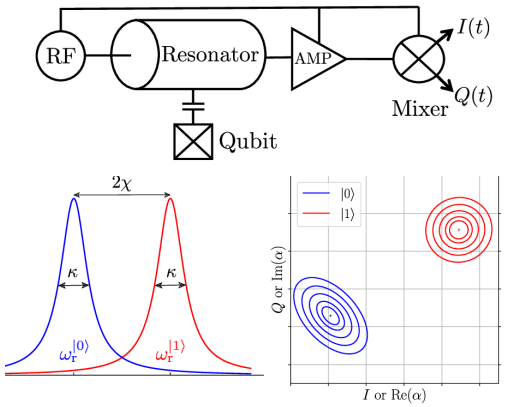

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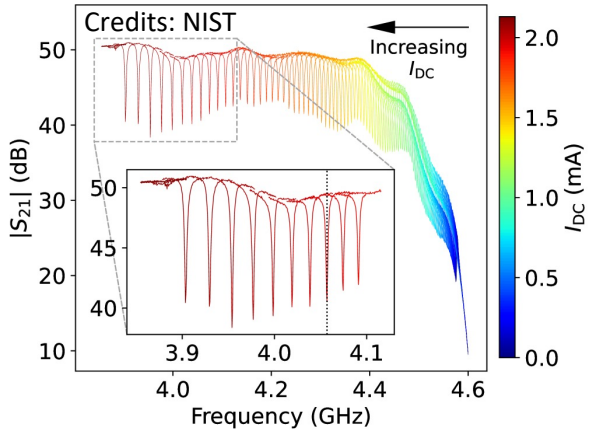

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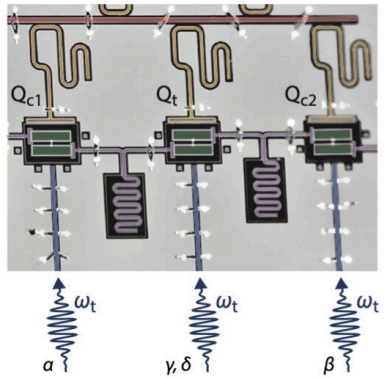

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SUPERCONDUCTING PLATFORM in Spoke 6-7

… for different applications

Superconducting Parametric Amplifiers

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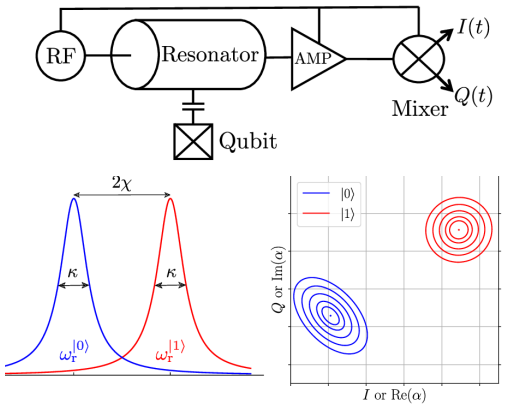

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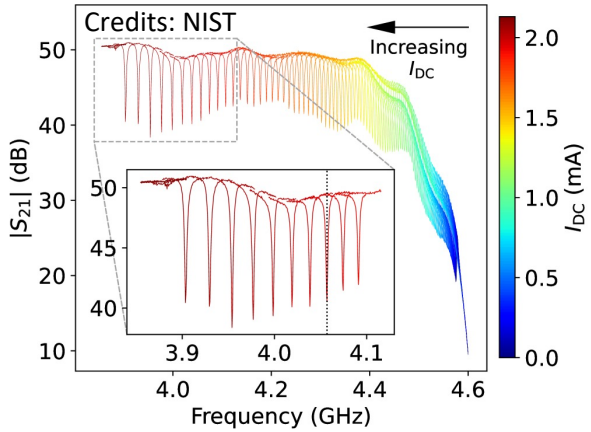

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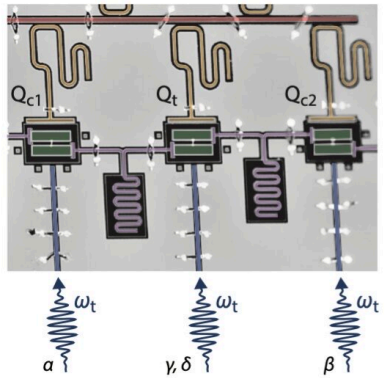

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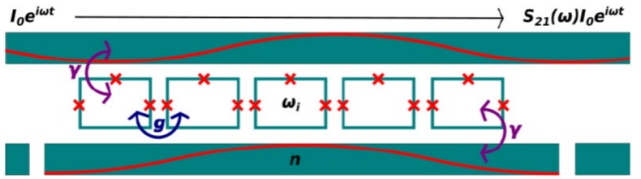

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SUPERCONDUCTING PLATFORM in Spoke 6-7

… for different applications

Supercon… Parametric …

- High-fidelity … dispersive read-out

…ble res… Multip… microwave read-out

…ducting… …niversal quantum gates

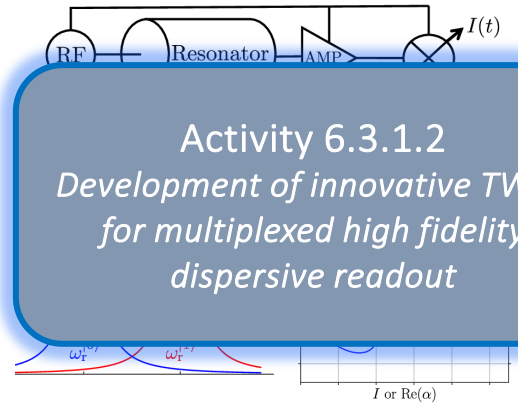
…tional …g platforms

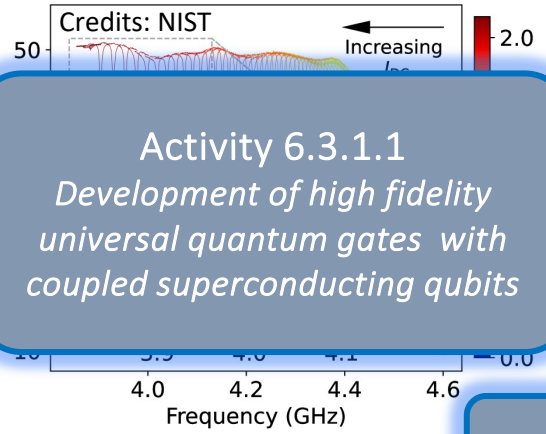
- Quantum networks

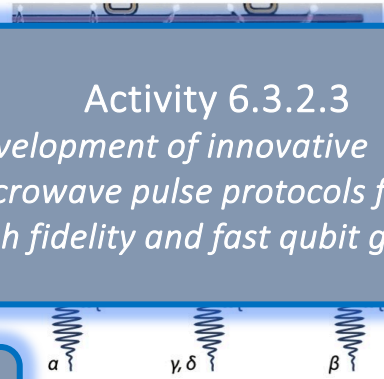
Activity 6.3.1
Superconducting quantum gates

Activity 6.3.2
Coherent control and interfacing

Activity 6.3.3
Superconducting quantum networks







Activity 6.3.1.2
Development of innovative TWPA for multiplexed high fidelity dispersive readout

Activity 6.3.1.1
Development of high fidelity universal quantum gates with coupled superconducting qubits

Activity 6.3.2.3
Development of innovative microwave pulse protocols for high fidelity and fast qubit gates

Activity 6.3.2.3
Demonstration of super-conducting quantum networks topologies - interacting Josephson junctions in 2D lattices

- Sources of entangled microwave photons
- Pulse control

… …

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SUPERCONDUCTING PLATFORM in Spoke 6-7

… for different applications

Superconducting Parametric Amplifiers

- High-fidelity multiplexed
- Sources of entangled microwave photons

Talk by A. Giachero

Talk by P. Campana

Talk by F. Ahrens

Talk by S. Pagano

Tunable resonators

- Multi… microwave read-out
- Pulse control

Talk by A. Irace

Talk by D. Labranca

Talk by C. Puglia

Talk by A. D'Elia

Superconducting qubits

Talk by M. Gobbo

Talk by R. Moretti

Talk by R. Carobene

Talk by S. Carrazza

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Talk by M. Lisitskiy

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We are successfully following

two far-reaching directions

Acquire technological expertise

as basis to

build a complete supply chain

for superconducting QT

Create scientific excellence

as basis for

research and innovation

for fundamental science and quantum applications

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An example of *integration & complete systems* towards a supply chain
The first superconducting qubit *#madeinItaly* and beyond

FONDAZIONE BRUNO KESSLER
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
INFN

Development & Microfabrication of Josephson junctions

BUILDING BLOCKS

FBK Cleanrooms

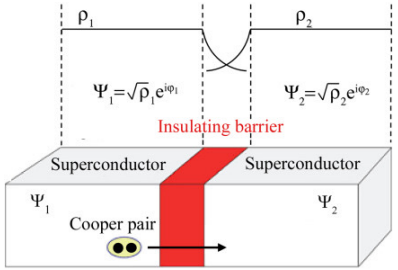
The toolbox for Quantum Circuits

- *Transmission lines*
- *Couplers*
- *Capacitors*
- *Generators*
- *Amplifiers*
- *Josephson junctions*

Josephson equations

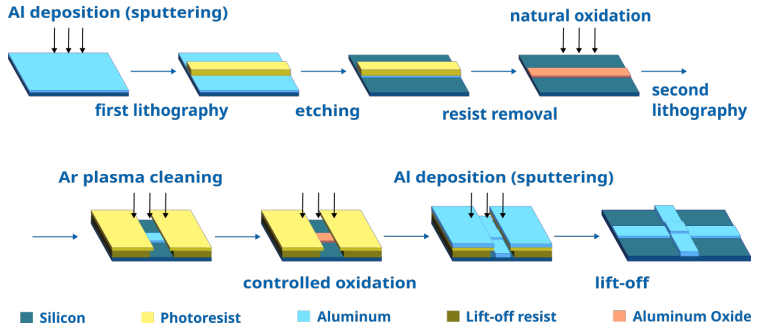
$$I = I_c sin\phi$$

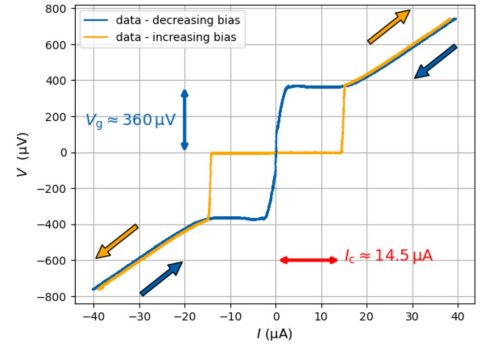
$$\frac{d\phi}{dt} = \frac{2eV}{\hbar}$$



Non-linear Josephson inductance $L = \frac{\hbar}{2e}\frac{1}{I_c cos\phi}$

Microfabrication process for Al/AlOx/Al overlap Josephson junctions





QU- PILOT
IMISS

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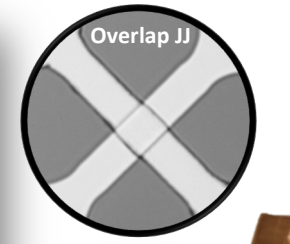
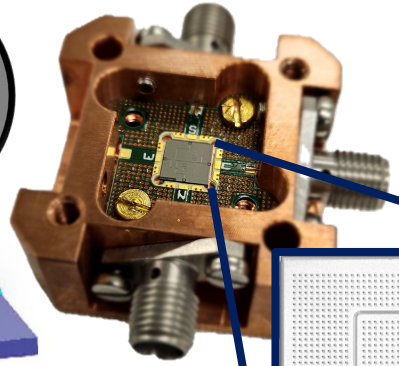
The first superconducting qubit *#madeinItaly* and beyond

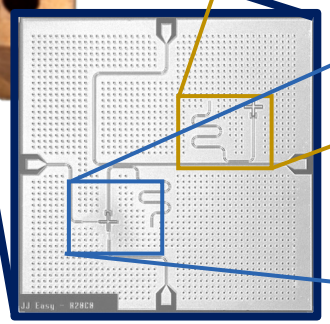
Development & Microfabrication of Josephson junctions → Design & Microfabrication of planar transmon qubits

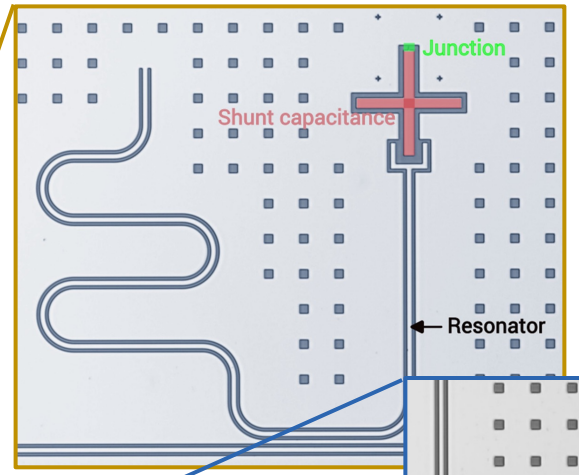
BUILDING BLOCKS → **INTEGRATION**

FBK Cleanrooms





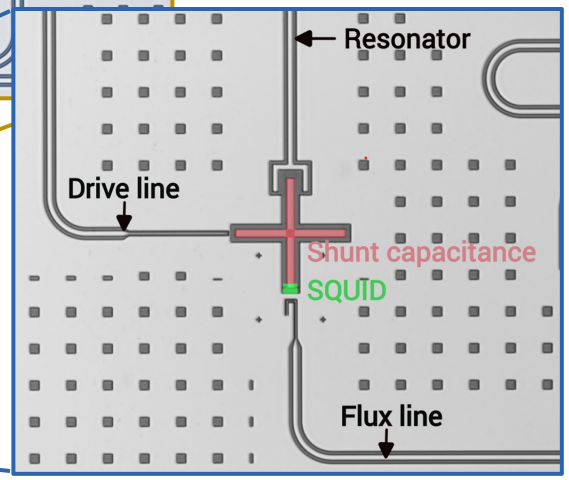




Fixed frequency transmon qubit

Talk by A. Irace

Tunable transmon qubit



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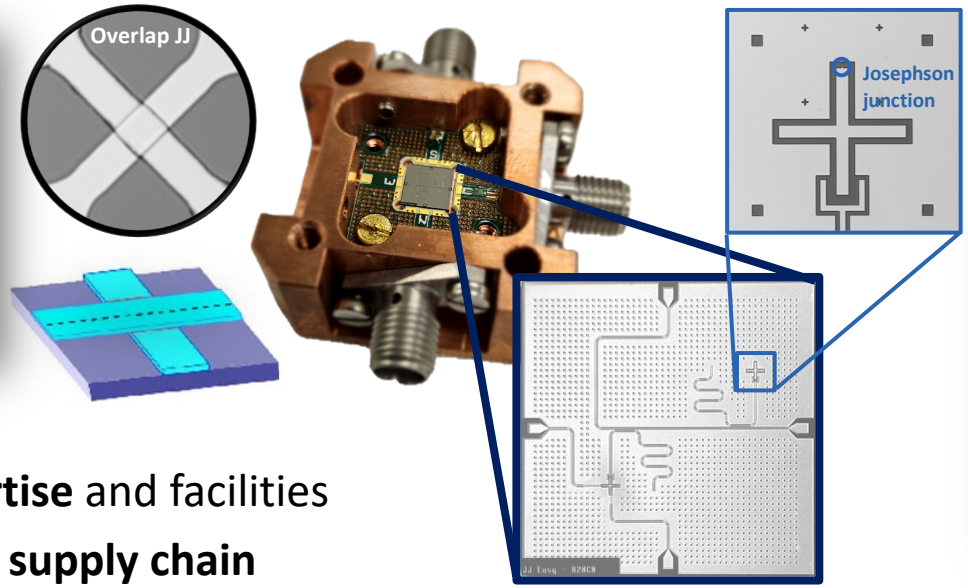
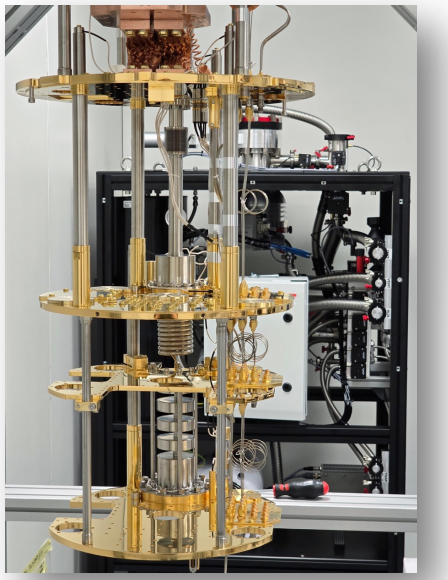
Development & Microfabrication of Josephson junctions → Design & Microfabrication of planar transmon qubits → Cryogenic set-up for mK measurements

BUILDING BLOCKS → **INTEGRATION** → **COMPLETE QUANTUM SYSTEMS**

FBK Cleanrooms





Example: FBK Cryogenic Lab

- New **technological expertise** and facilities
- Synergies for a **complete supply chain**

QU- PILOT
IMISS

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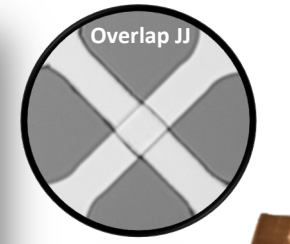
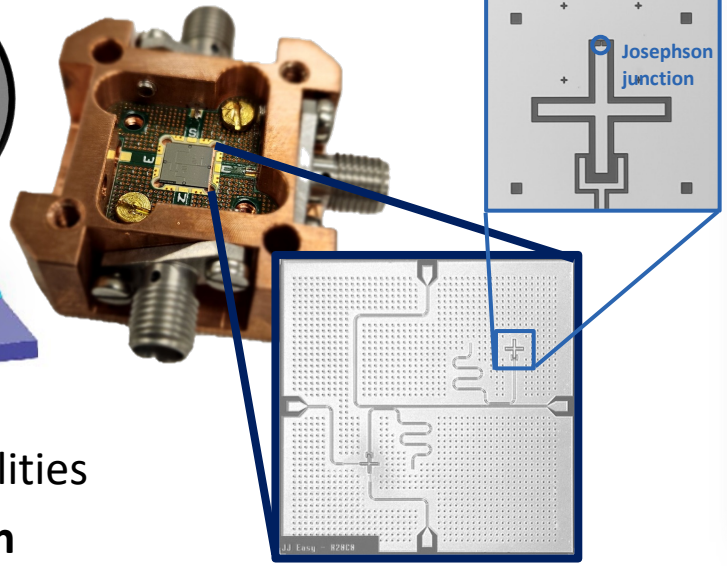
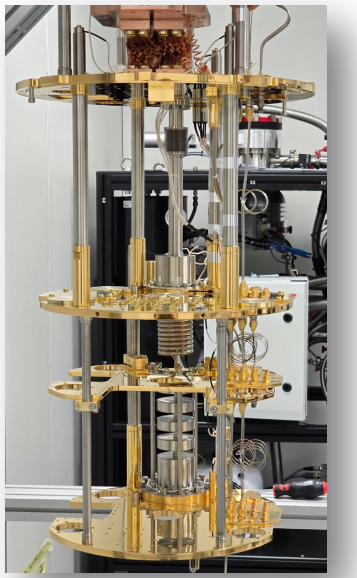
Development & Microfabrication of Josephson junctions → Design & Microfabrication of planar transmon qubits → Cryogenic set-up for mK measurements → Multi-qubit architectures

BUILDING BLOCKS → **INTEGRATION** → **COMPLETE QUANTUM SYSTEMS**

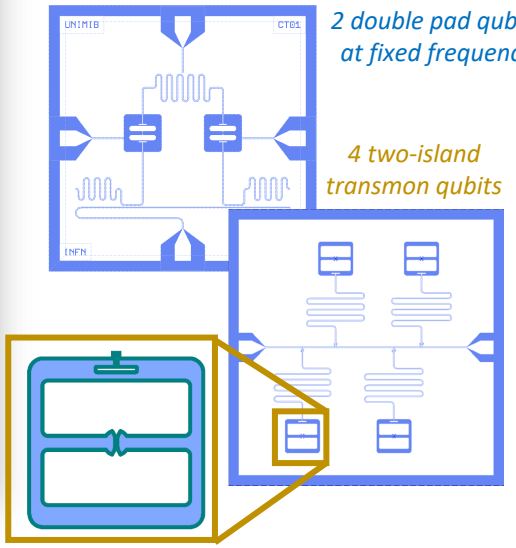
FBK Cleanrooms







Planar qubit systems



- New **technological expertise** and facilities
- Synergies for a **complete supply chain**

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Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI National Quantum Science and Technology Institute

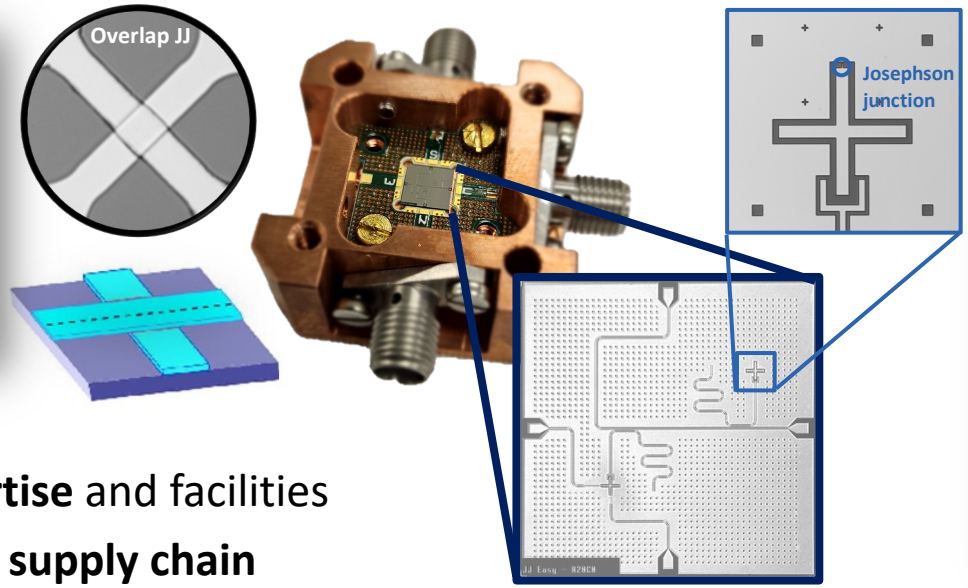
An example of *integration & complete systems* towards a supply chain
The first superconducting qubit *#madeinItaly* and beyond

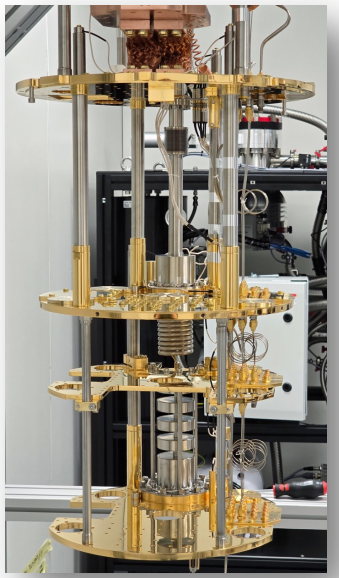
FONDAZIONE BRUNO KESSLER
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
INFN

Development & Microfabrication of Josephson junctions → Design & Microfabrication of planar transmon qubits → Cryogenic set-up for mK measurements → Multi-qubit architectures

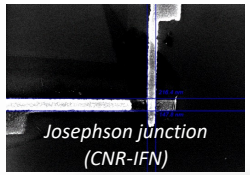
BUILDING BLOCKS → **INTEGRATION** → **COMPLETE QUANTUM SYSTEMS**

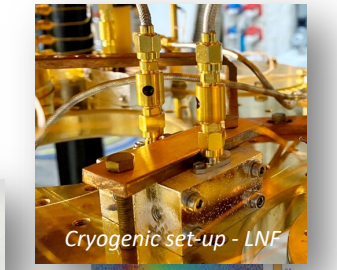
FBK Cleanrooms

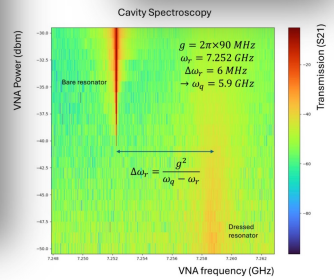


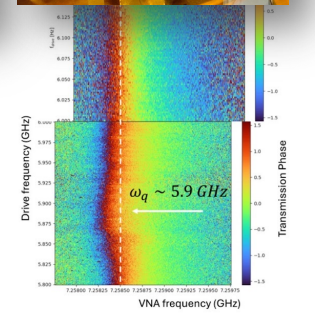


3D qubit systems









- New **technological expertise** and facilities
- Synergies for a **complete supply chain**

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SUPERCONDUCTING PLATFORM in Spoke 6-7

Synergies with other Spokes and NQSTI partners

SPOKE 5

Electron-based platform

One year ago – First NQSTI Congress: Plenary talk by Francesco Tafuri

SPOKE 6 & 7

Integration & Complete quantum systems

SPOKE 2

Simulations, sensing and metrology

Theoretical foundations and modelling

Courtesy: F. Tafuri

- ✓ Building up community
- ✓ Creating synergies across research groups
- ✓ Producing excellence

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We are successfully following

two far-reaching directions

Acquire technological expertise

as basis to

build a complete supply chain

for superconducting QT

Create scientific excellence

as basis for

research and innovation

for fundamental science and quantum applications

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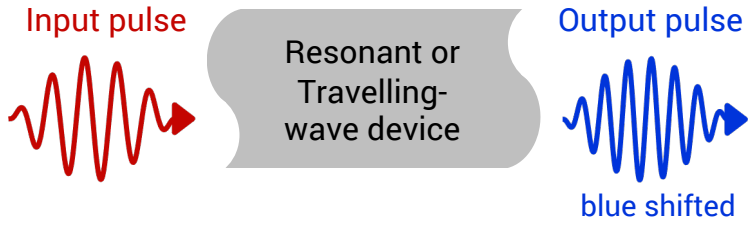
A novel device:
Microwave photon energy lifter

FONDAZIONE BRUNO KESSLER

A device to
shift the frequency of microwave photons
and to
create a synthetic frequency lattice



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

PhD students with Uni Milano Bicocca
Supervisors: Andrea Giachero, Angelo Nucciotti

SPOKE 6

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

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

SPOKE 7

Theoretical study: Gianluca Rastelli, Iacopo Carusotto

SPOKE 2

Italian National Research Council

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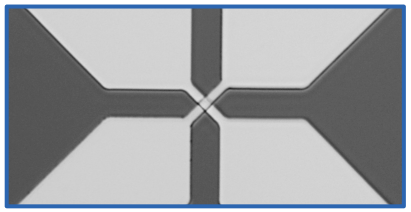
A novel device: **Microwave photon energy lifter**

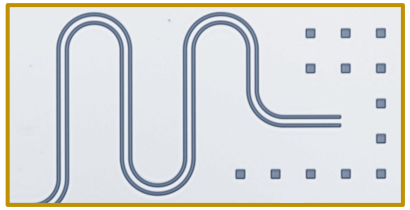
Development

BUILDING BLOCKS

Overlap Al/AlOx/Al **Josephson junctions**

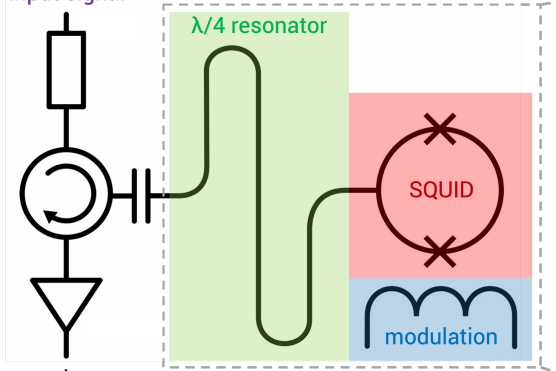


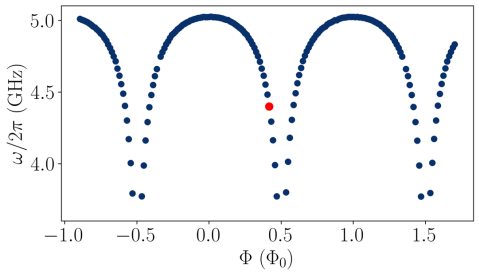
Al superconducting coplanar waveguide **resonators**



INTEGRATION

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

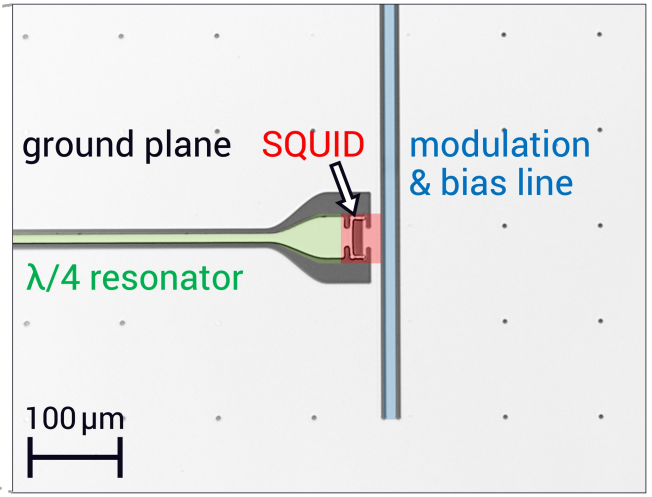




$\delta\omega(t) = \sum_m \delta\omega_m e^{-im\Omega t}$
$\Omega \ll \omega_{\mathrm{in}}$

DEVICE: Tunable resonator

Talk by A. Irace



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

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

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

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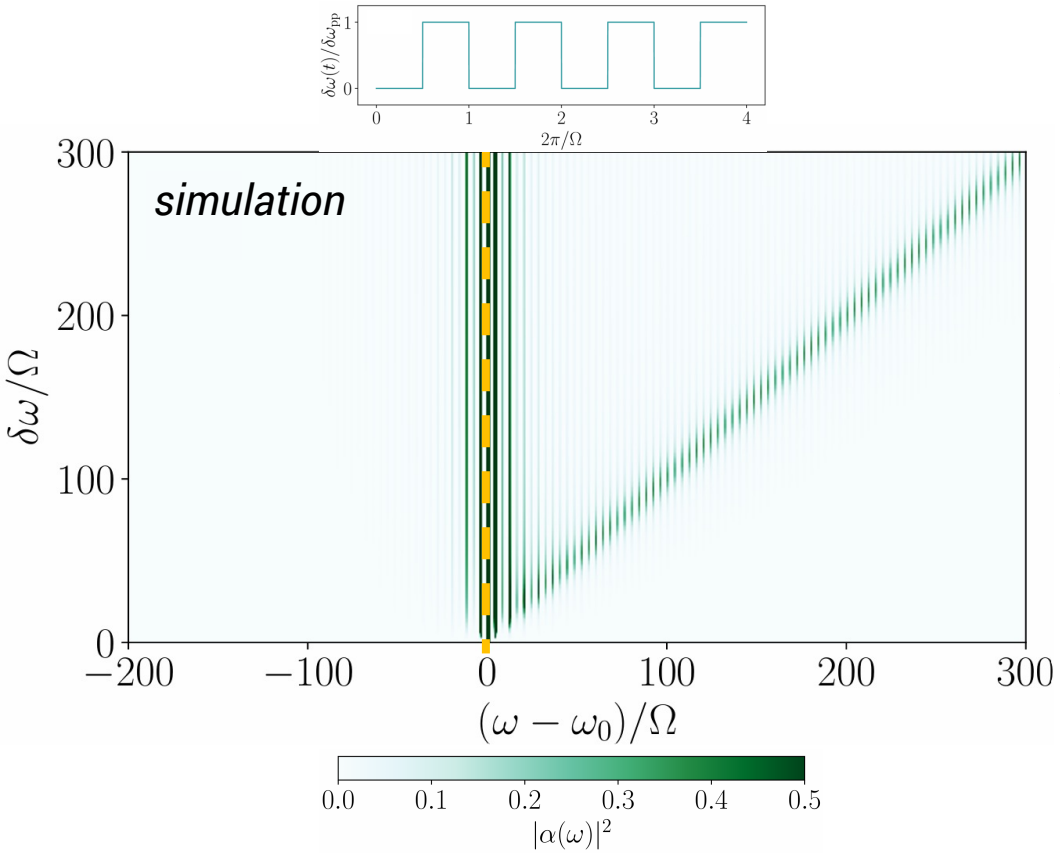
A novel device: **Microwave photon energy lifter**

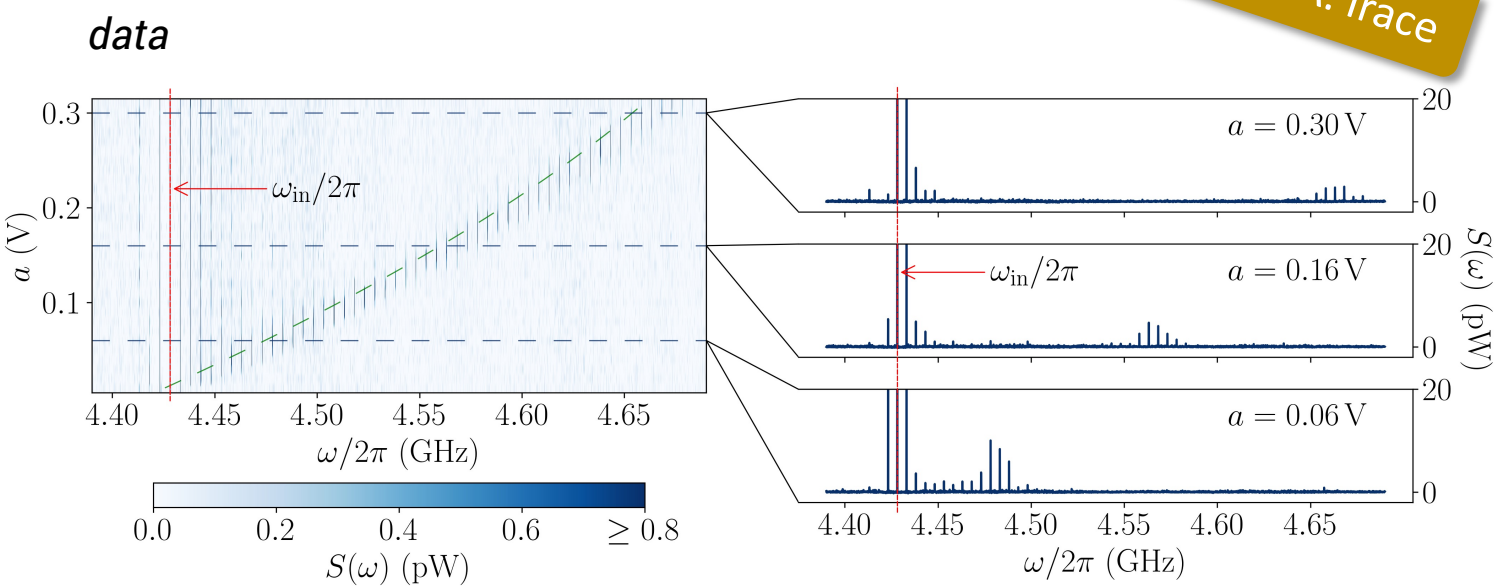
Working principle

⇒ Experimental demonstration of tunable frequency shifting

Talk by F. Ahrens

Talk by A. Irace





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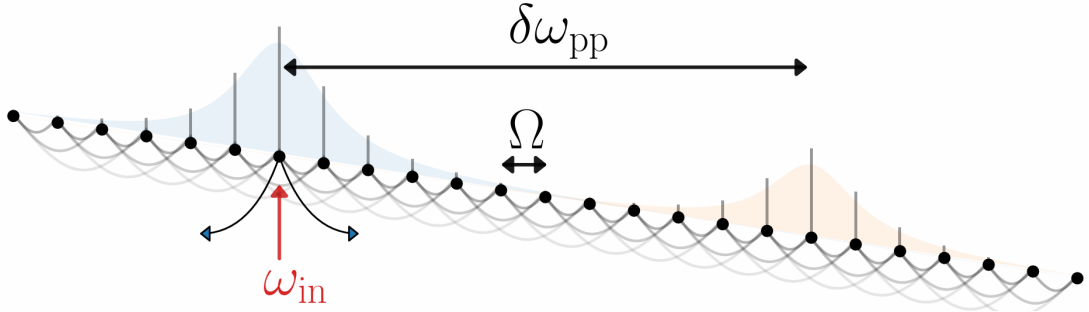
A novel device: **Microwave photon energy lifter**

Applications & Impact

Fundamental physics

- Synthetic lattice in the frequency space
- Bloch oscillation dynamics

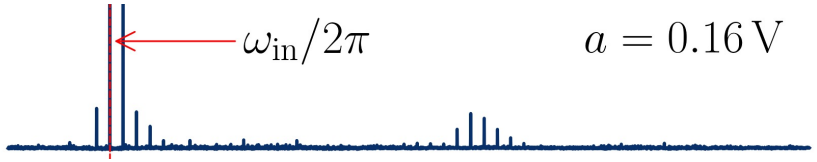
⇒ **Platform for condensed matter physics**



Pulse control

- Shift frequency of microwave photons
- Further development: pulse shape preservation

⇒ **Platform for pulse control for quantum computing**



- One publication in review – *Physical Review Letters*
- One publication in preparation – *Nature Electronics*
- One patent submitted and one patent in preparation

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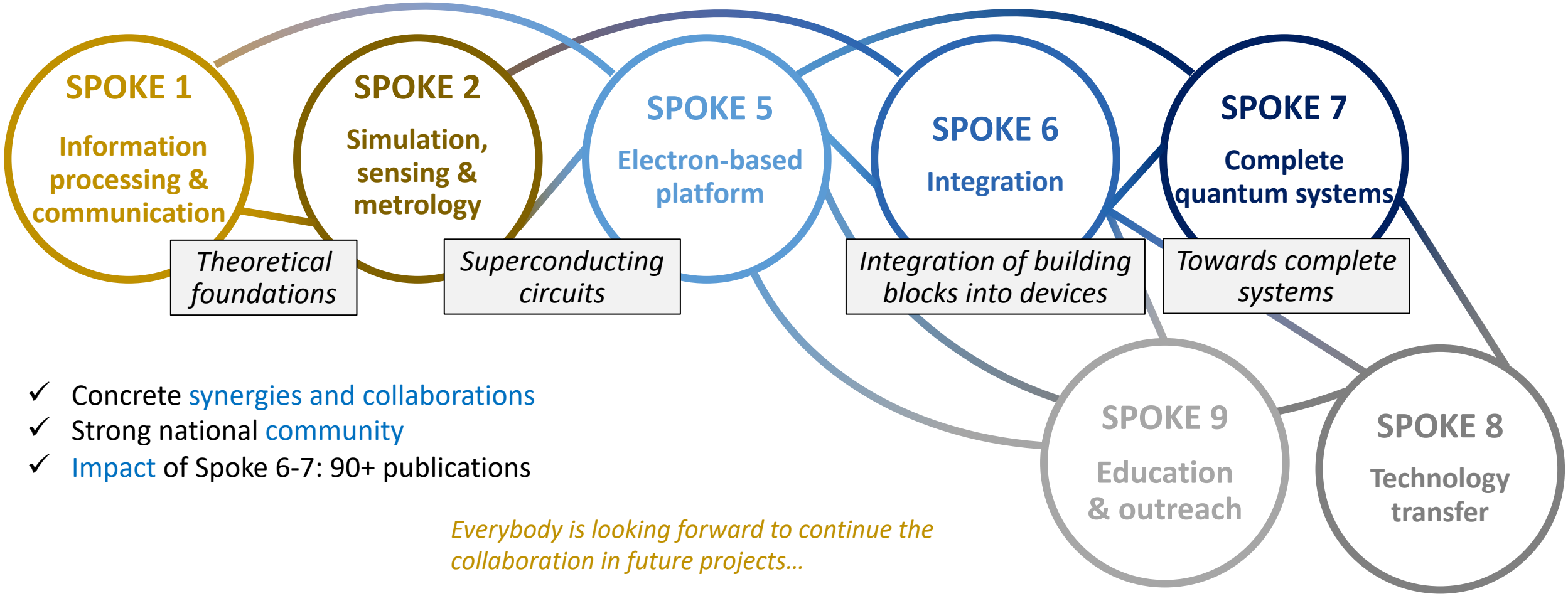
Development chain of superconducting quantum devices & systems



- ✓ Concrete synergies and collaborations
- ✓ Strong national community
- ✓ Impact of Spoke 6-7: 90+ publications

Everybody is looking forward to continue the collaboration in future projects…

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