GDR-DI2I
Groupement De Recherche
Détecteurs et Instrumentation pour les 2 Infinis

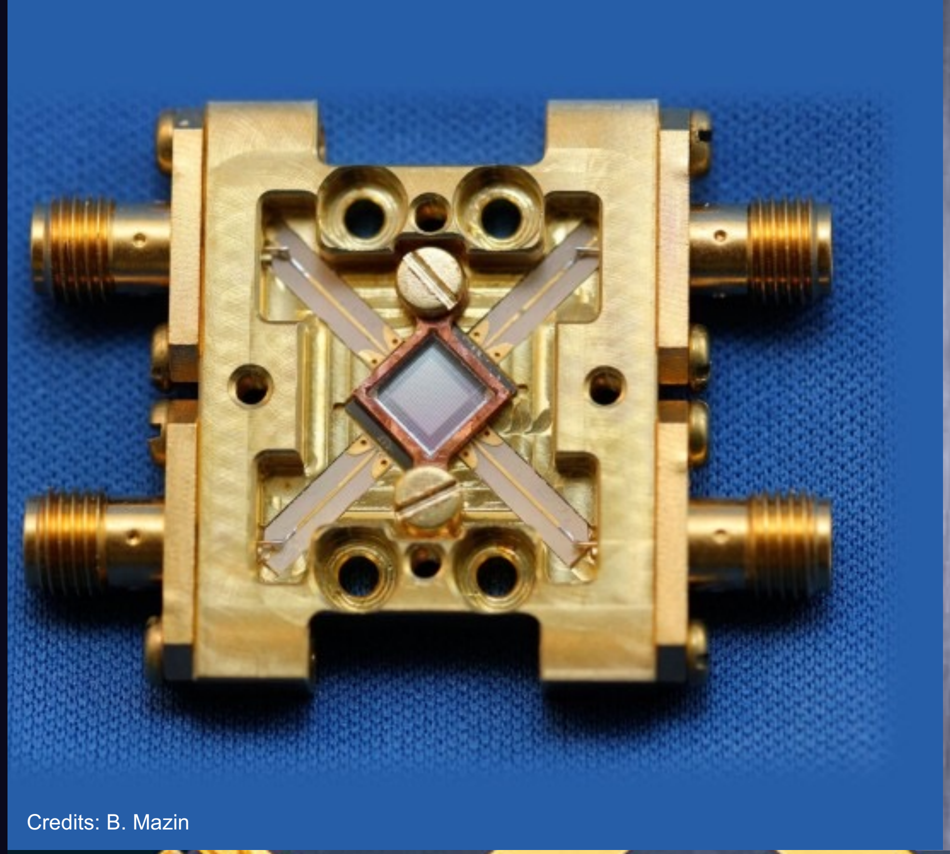
Quantum sensing:

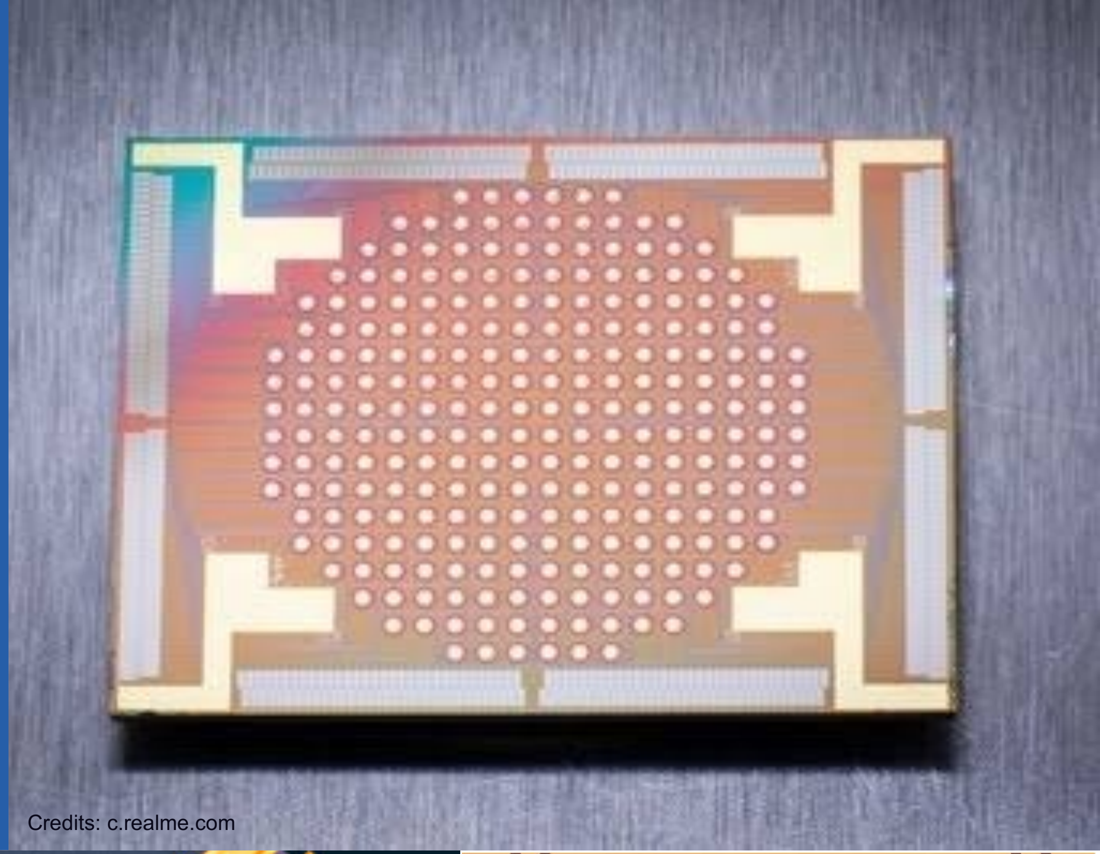
a new paradigm for particle physics and beyond

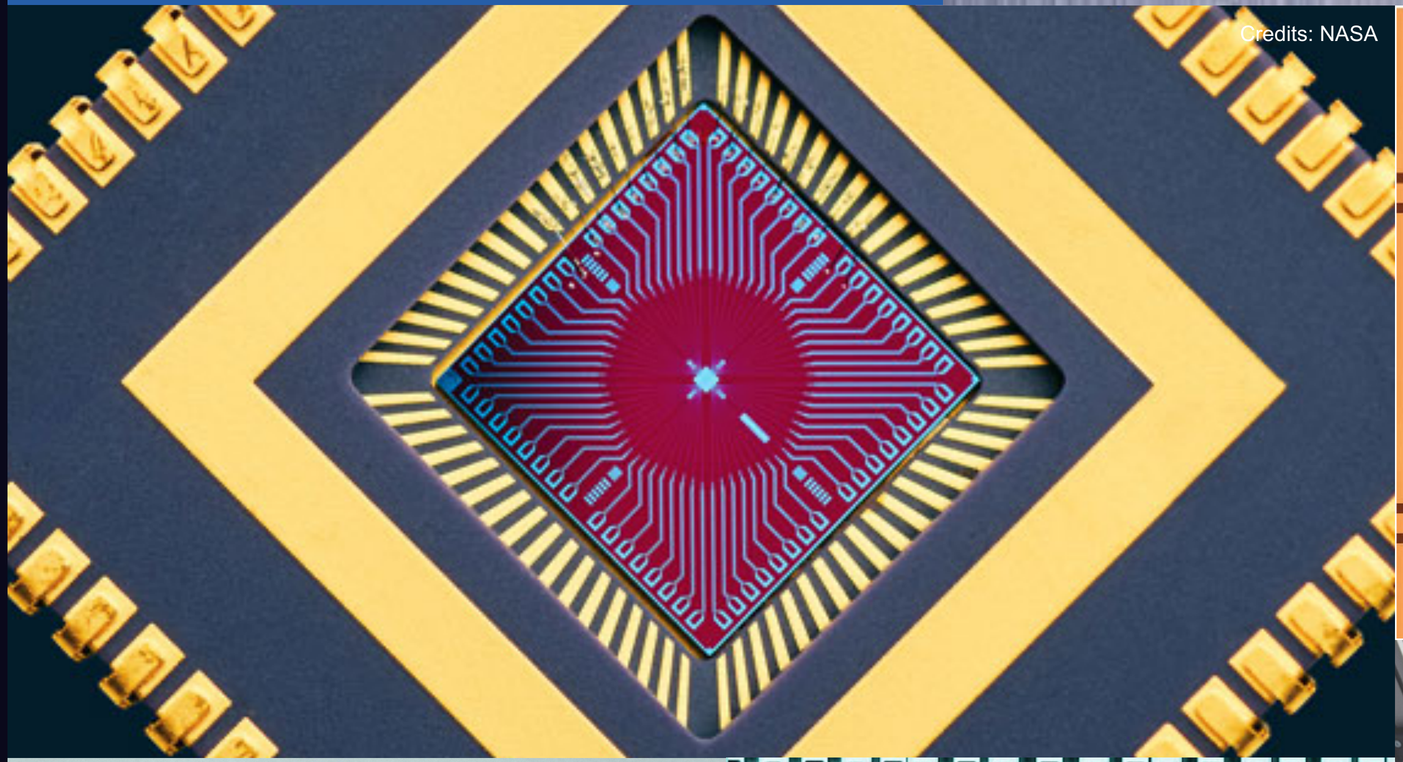
Federica Mantegazzini

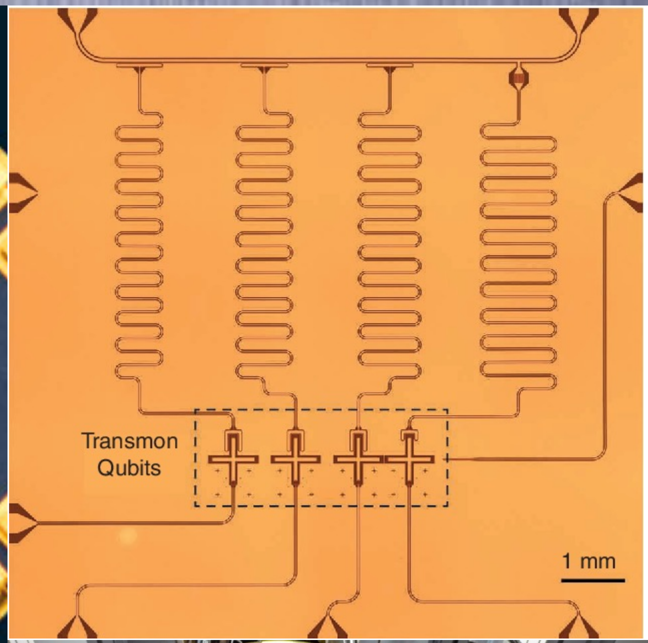
FBK & INFN-TIFPA (Trento, Italy)

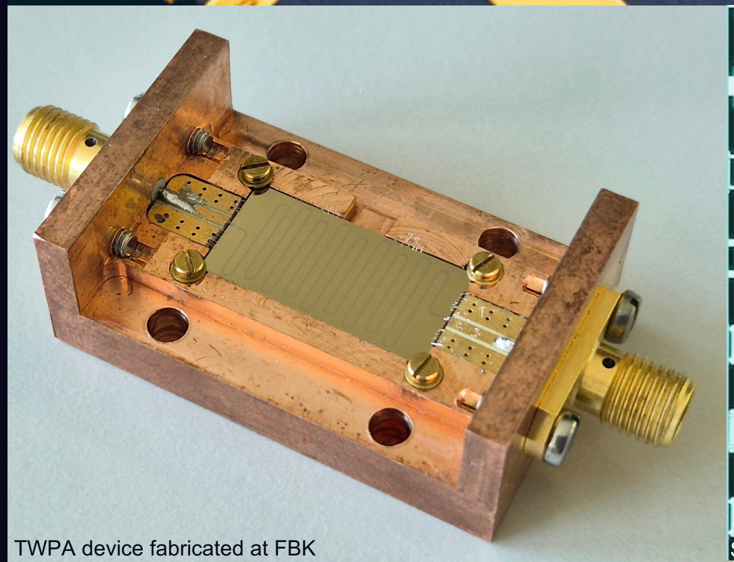
Paris, 19 November 2025

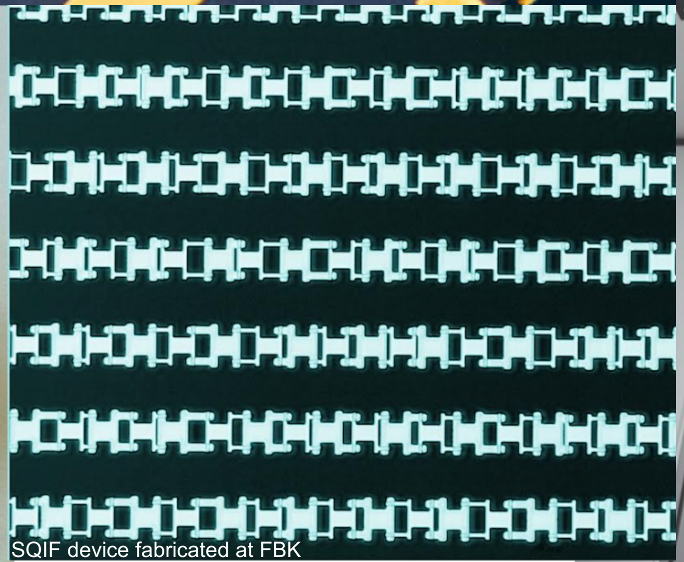

Credits: B. Mazin

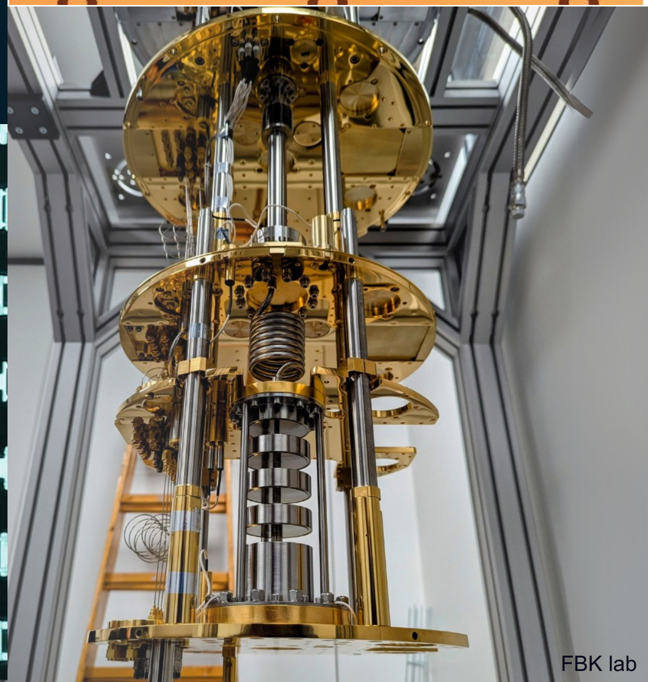

Credits: c.realme.com


Credits: NASA




TWPA device fabricated at FBK


SQIF device fabricated at FBK


FBK lab

What is quantum sensing?

Quantum sensing is the procedure of measuring an unknown quantity of an observable

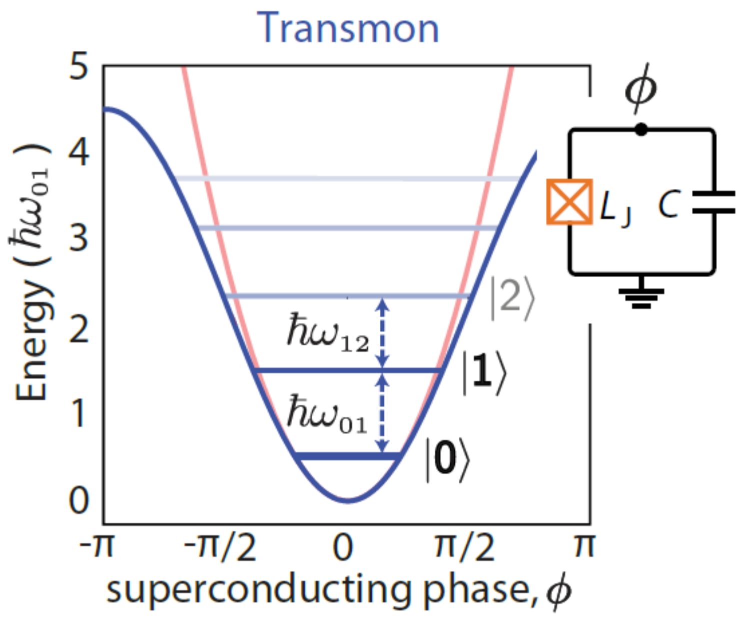
using a **quantum object** as a probe

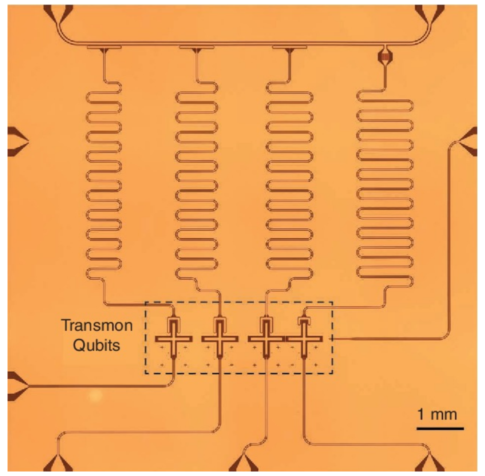
– i.e. an object in which quantum mechanical effects can manifest and be observed –

What is quantum sensing?

- *Strict definition*:
  Quantum sensing = making use of quantised energy levels and/or entanglement of a quantum system

  → **quantum circuits and qubits**





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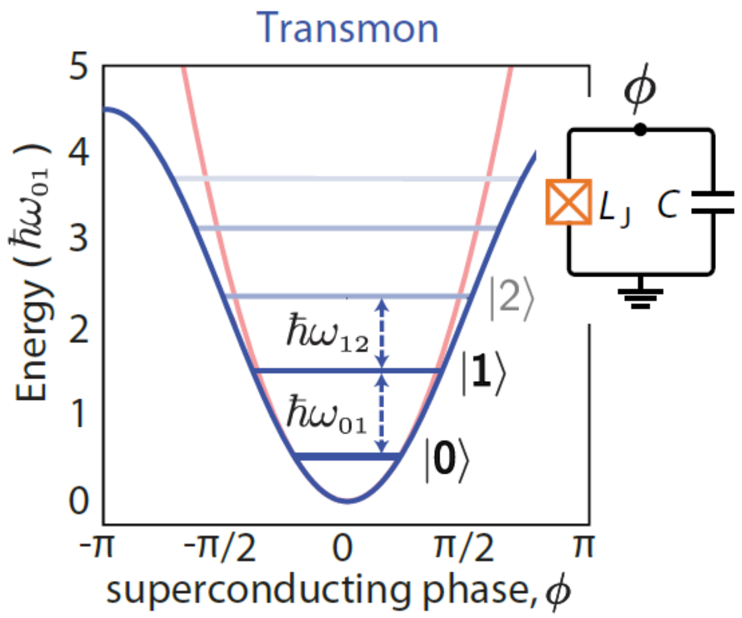
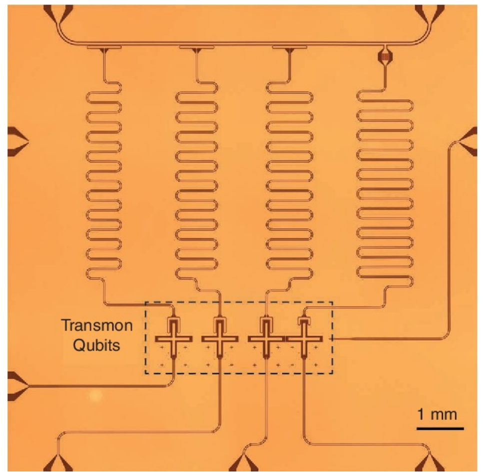
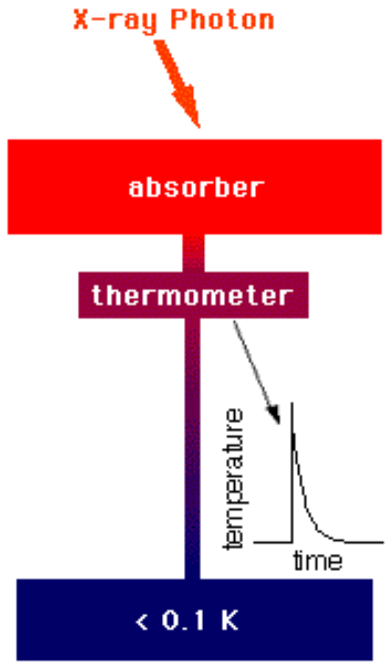


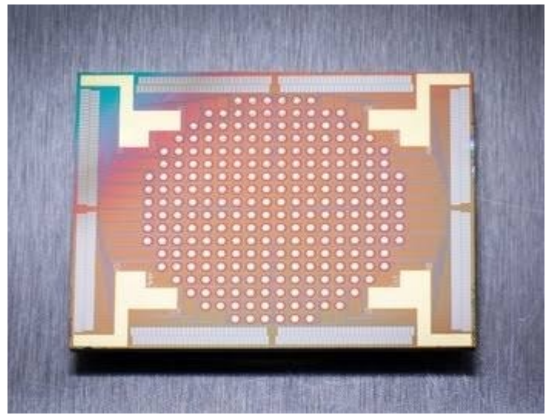


- *Broad definition*:
  Quantum sensing = making use of quantum phenomena

  (superconductivity is a macroscopic quantum phenomenon!)

  → **cryogenic detectors & sensors**





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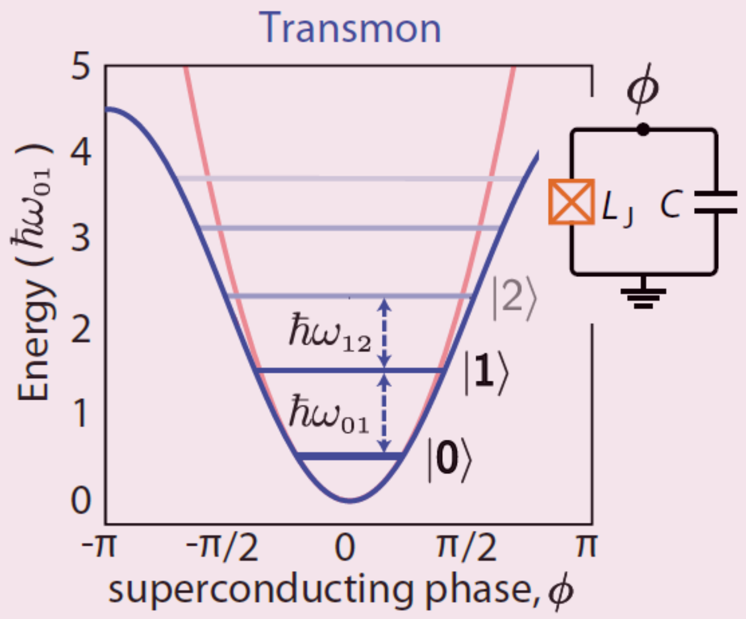

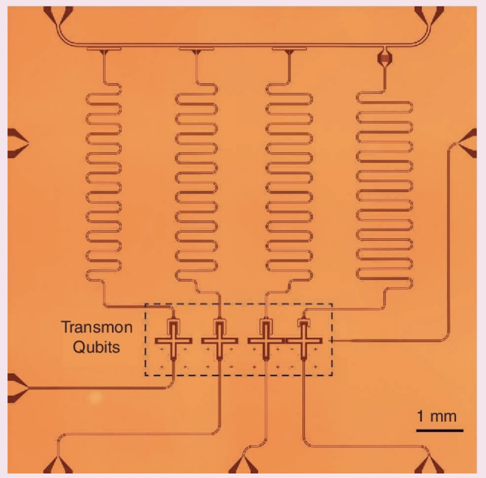

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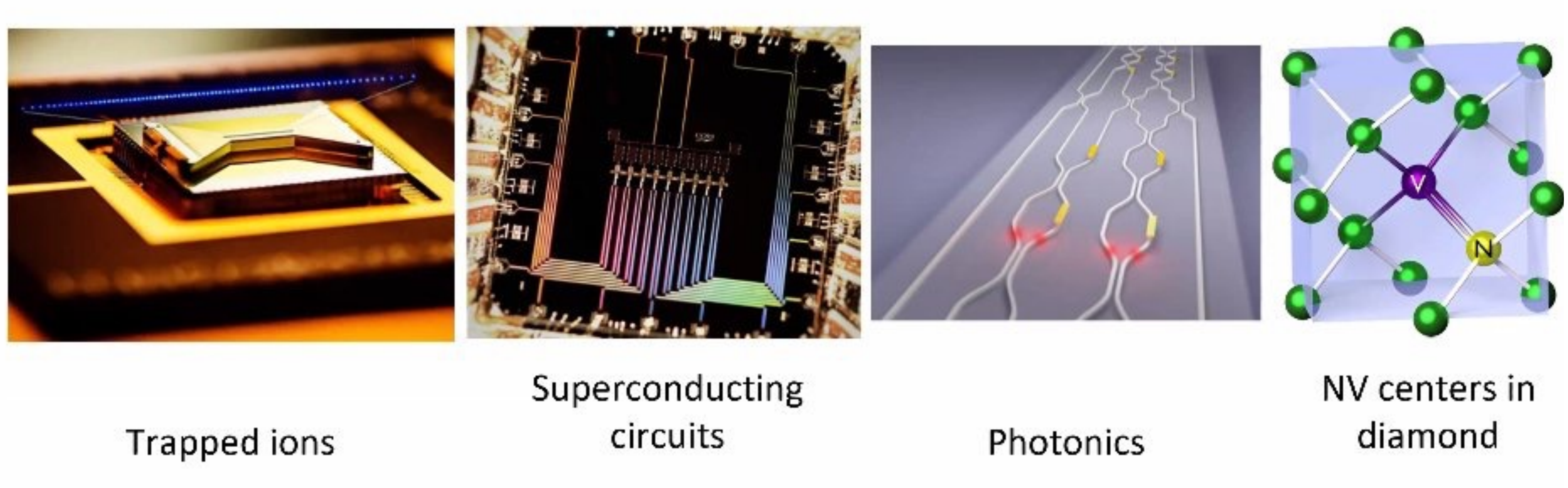
Quantum platforms

Different "quantum objects":



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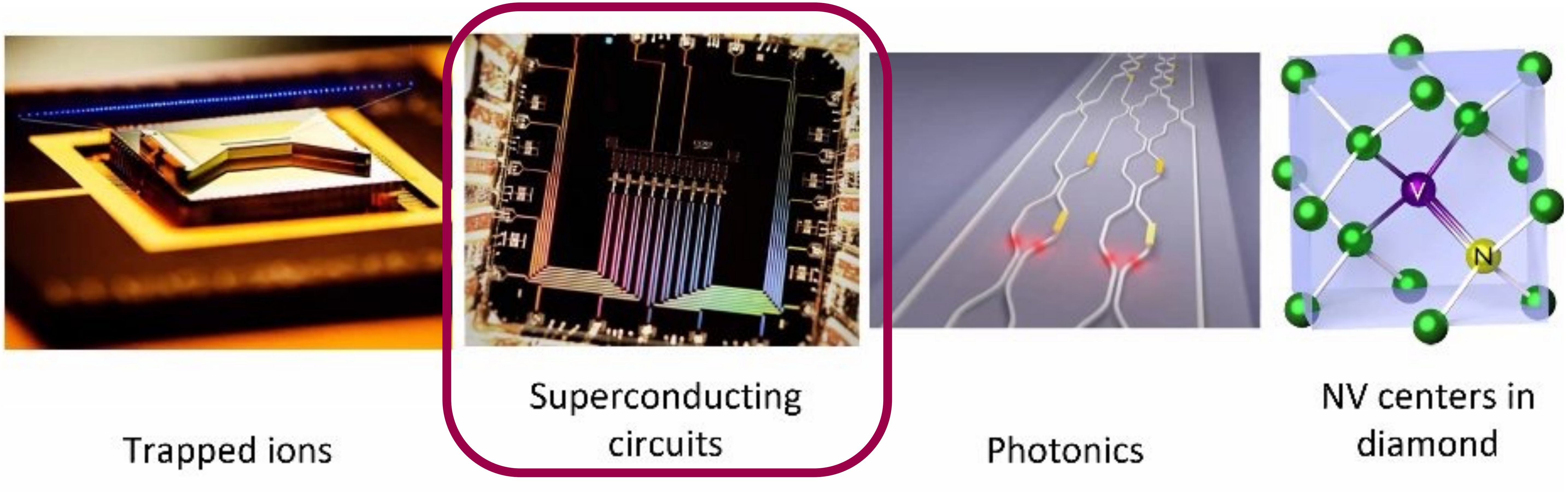

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Artificial circuits
→ flexible engineering of their properties

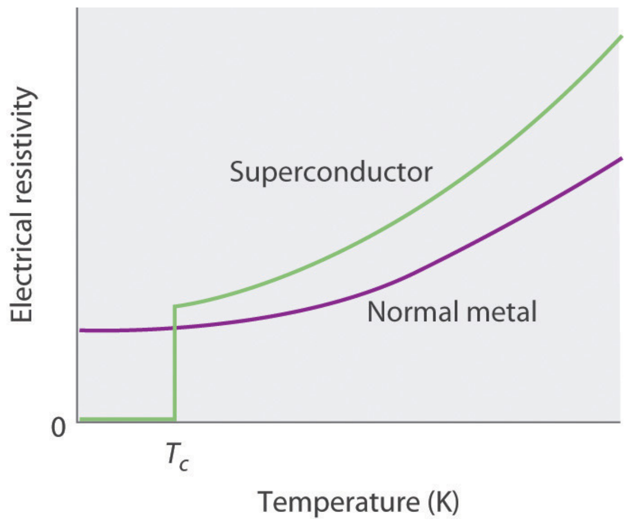
Superconducting quantum circuits: why?

Lossless conduction

(R_{dc} = 0)

⇩

Ultra-low dissipation



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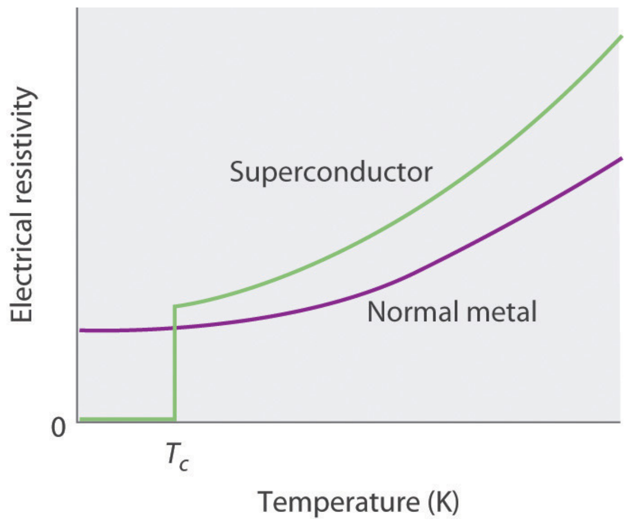
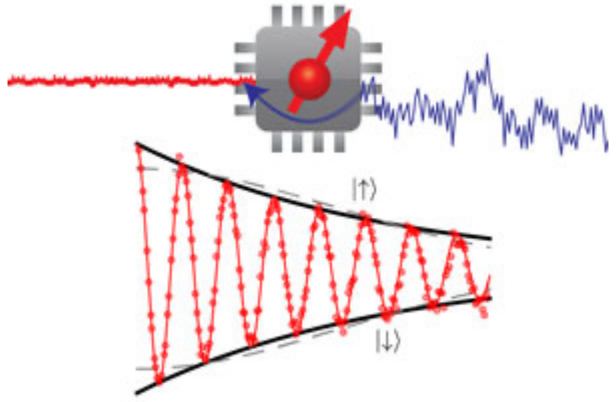


Low temperature
$T \sim 20$ mK

⇩

Ultra-low noise
$$k_B T \ll \hbar\omega$$



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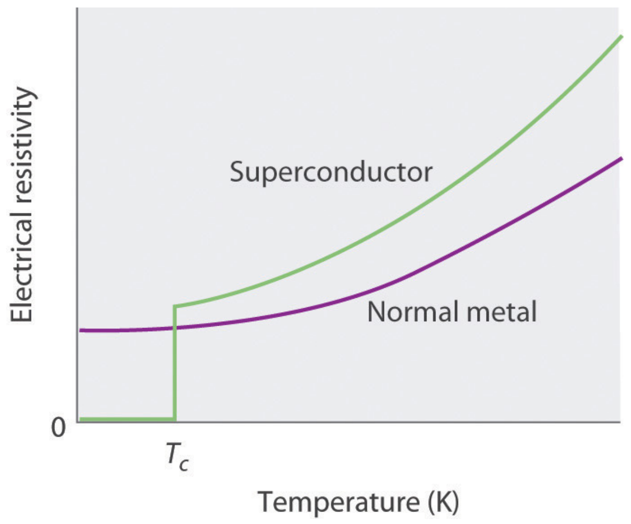

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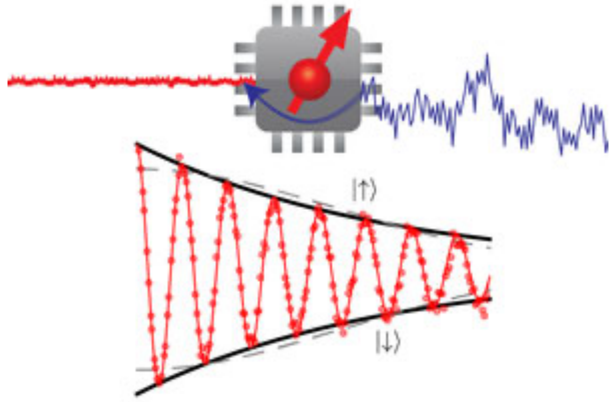

Scalability
Planar microfabrication techniques

⇩

On-chip circuits

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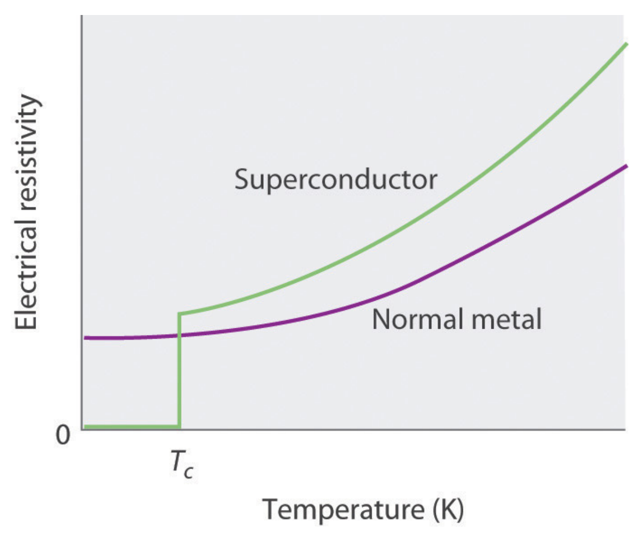
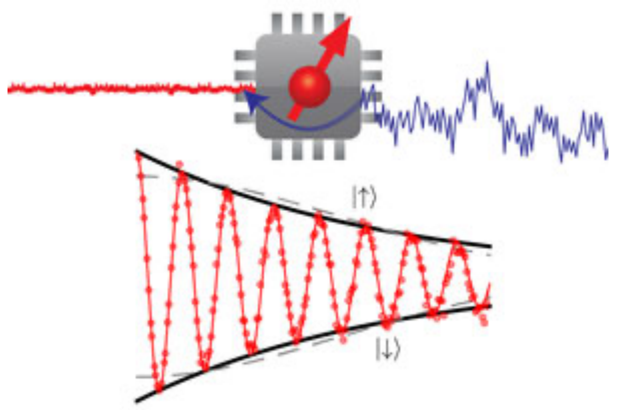
On-chip circuits

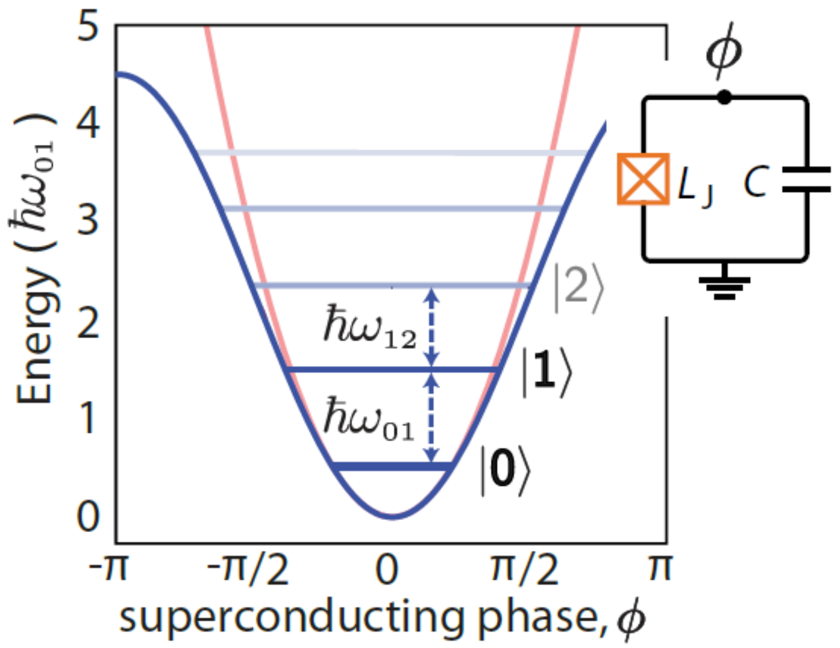
Non-linearity
Element: Josephson junction

⇩

Non-equidistant energy levels







Superconducting quantum circuits: why?

SOME EXAMPLES...

Lossless conduction
(R_{dc} = 0)

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T ~ 20 mK

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icrofabrication

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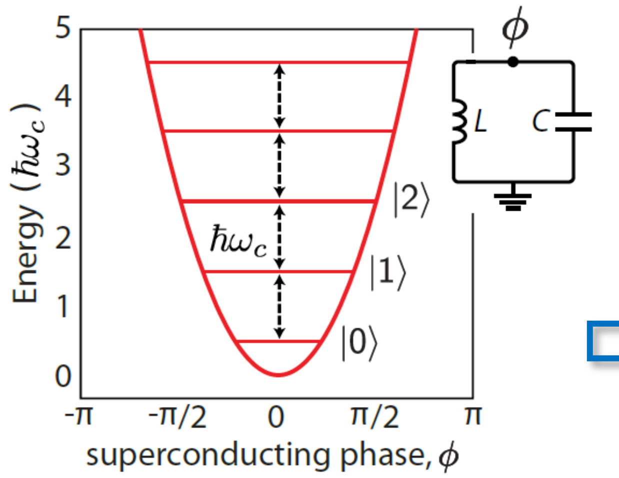
n-equidistant energy levels

Transmon qubits

Non-linear circuits that behave as "artificial atoms" ⇒ quantized energy levels

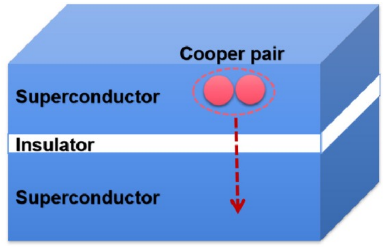
Harmonic oscillator



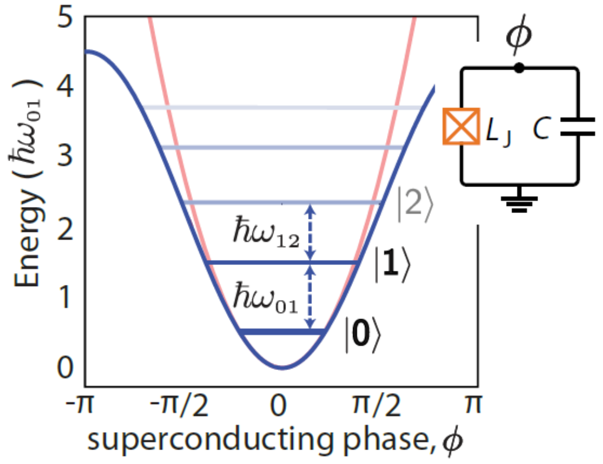
$$\hat{H} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L} = \hbar\omega\left(\hat{a}^\dagger\hat{a}\right)$$

charging energy — inductive energy

+ Josephson junction

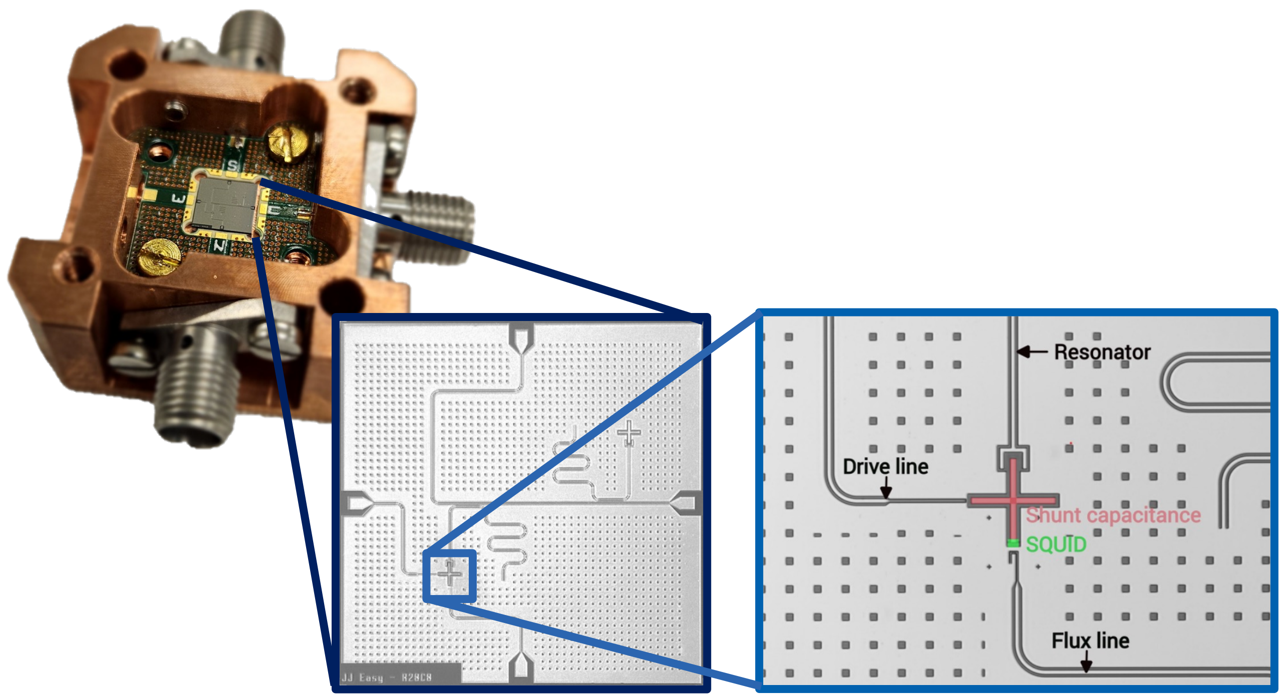


= transmon qubit



$$\hat{H} = \frac{\hat{Q}^2}{2C} - E_J \cos\left(\frac{2\pi}{\Phi_0}\hat{\Phi}\right)$$

$$= 4E_C\hat{n}^2 - E_J\cos\hat{\varphi}$$



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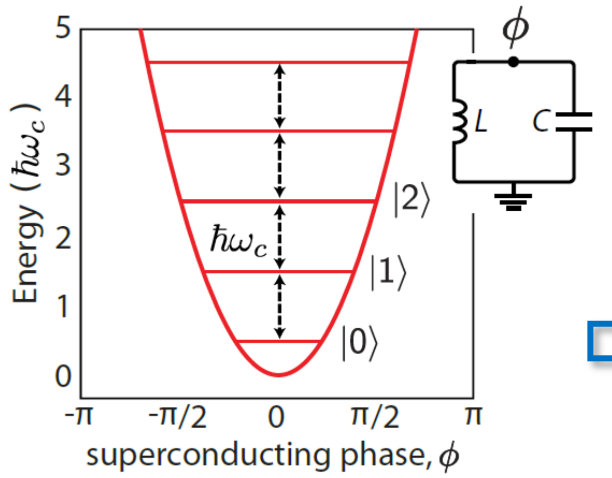

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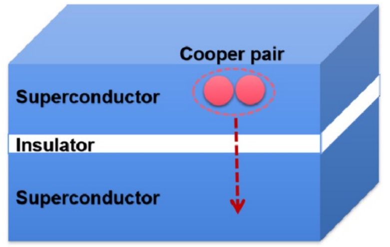

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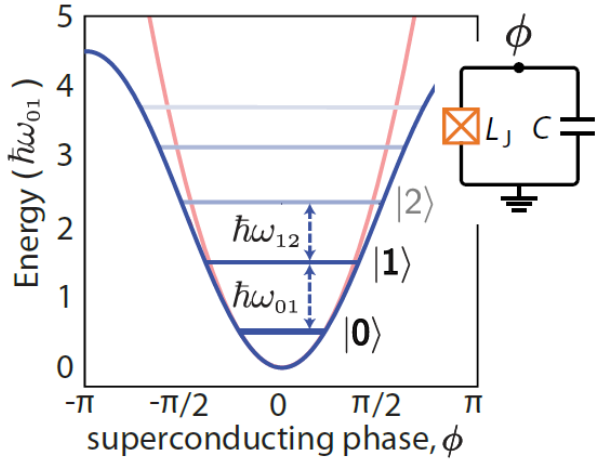

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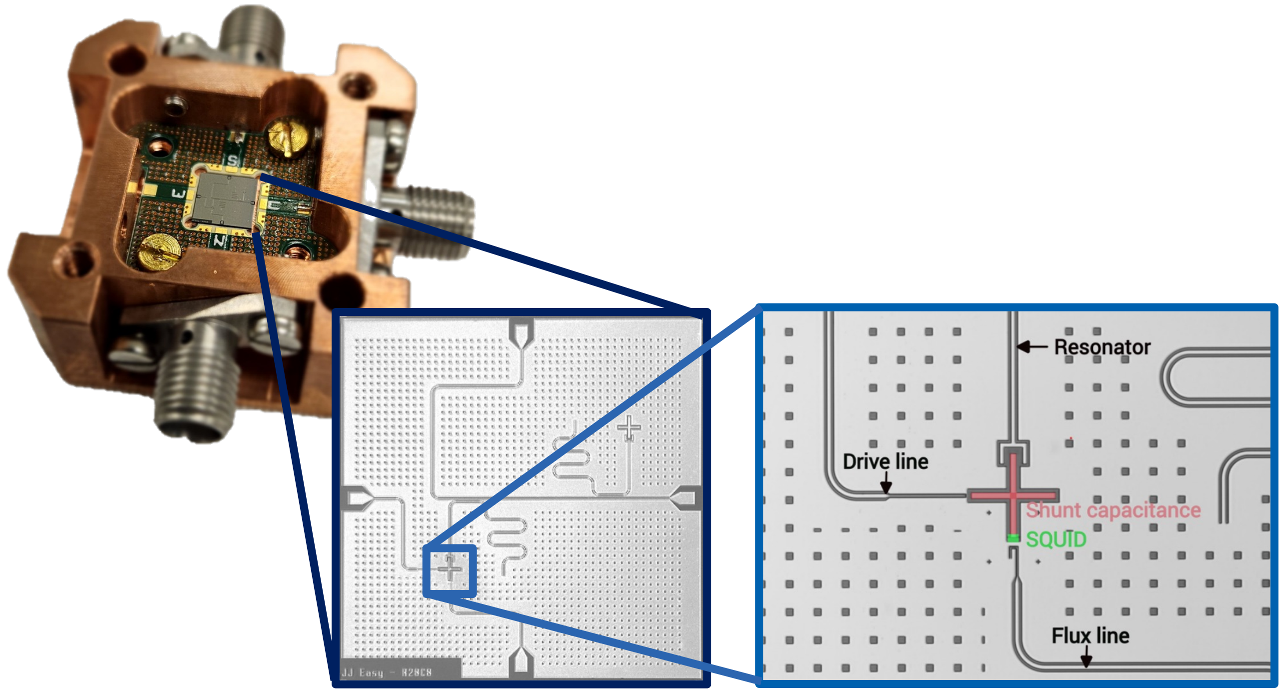


Qubits: mainly used as two-level systems

⇩

QUANTUM COMPUTING

Qubits: extremely sensitive to the electromagnetic environment

⇩

QUANTUM SENSING

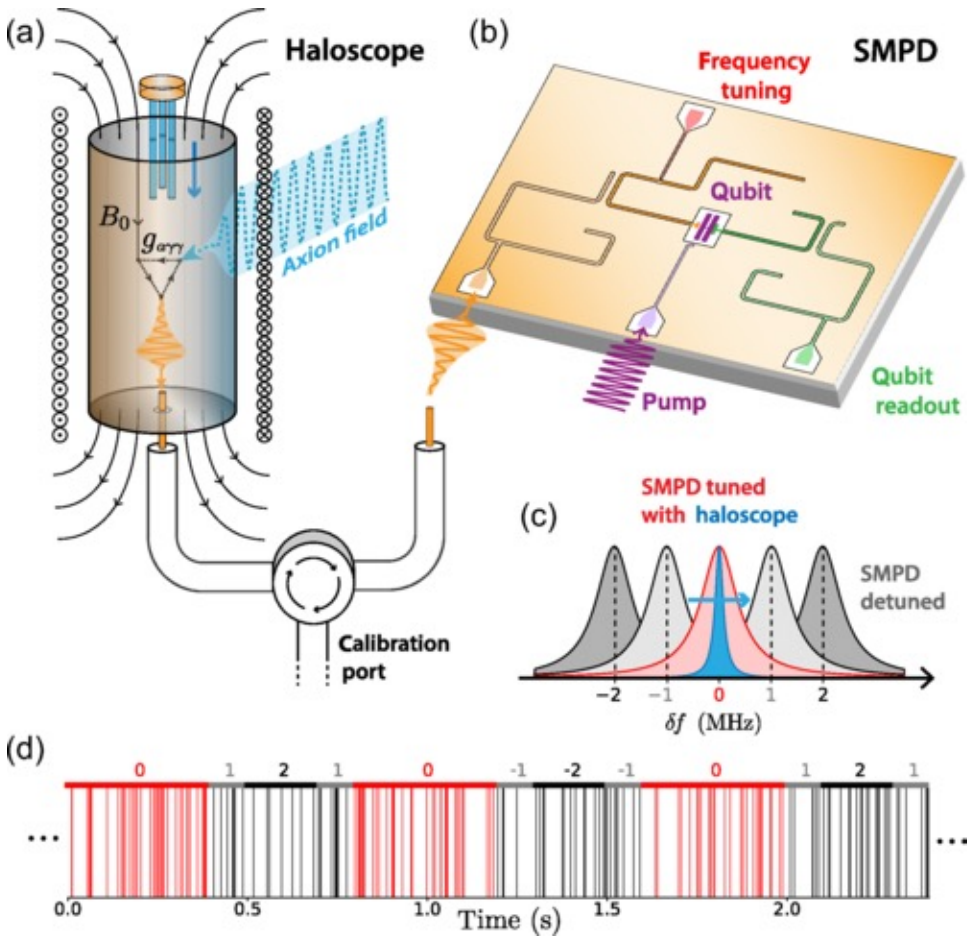
QUART&T — QUANTUM ARCHITECTURES FOR THEORY & TECHNOLOGY
INFN
CSN5 Ricerca Tecnologica
QU- PILOT
European Commission

Transmon qubits
as sensors

Applications for particle physics:

- **Dark matter detection (axions):** single **microwave photon counter**

C. Braggio et al, *Quantum-Enhanced Sensing of Axion Dark Matter with a Transmon-Based Single Microwave Photon Counter*, Phys. Rev. X **15**, 021031, 2025



INFN LNL
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Transmon qubits
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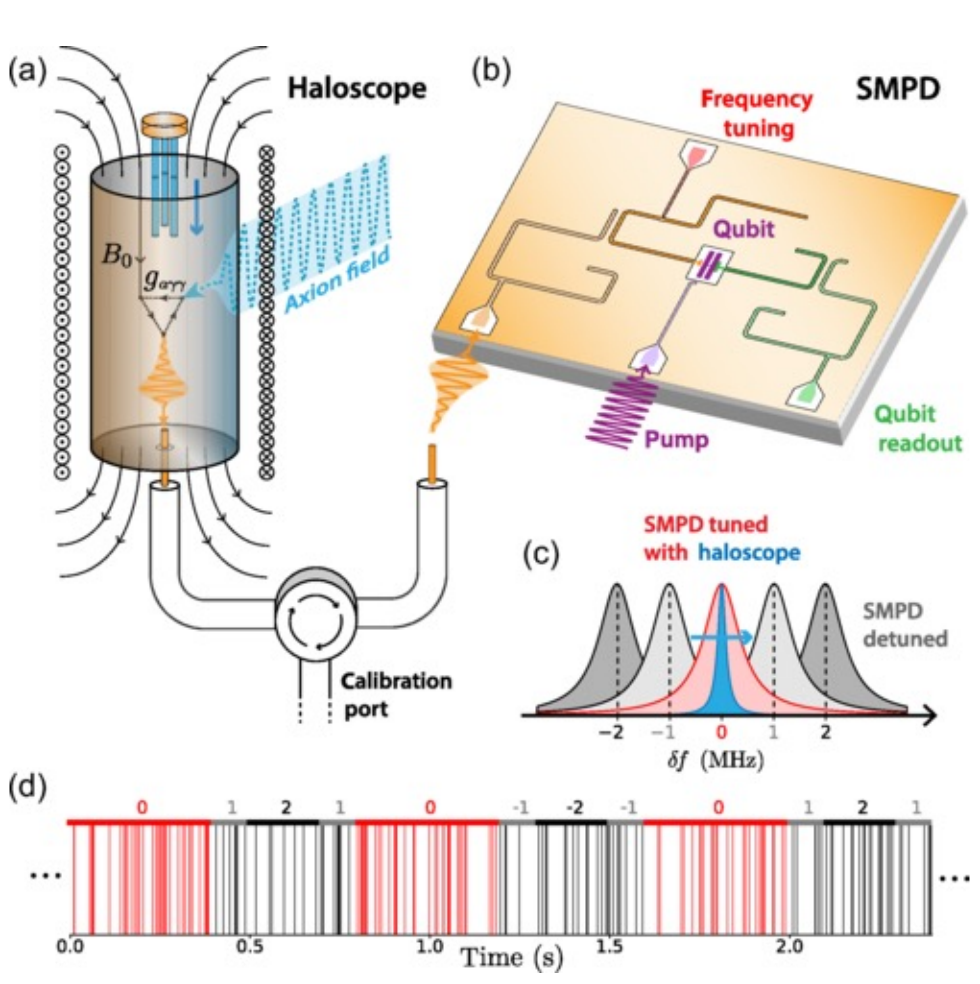

- **Rare-event detection:** Ultra-sensitive **calorimetry** (zJ) with quantum-limited noise

- **Precision tests for QED:** **energy levels** spectroscopy, ultra-strong **couplings** (beyond perturbation theory)

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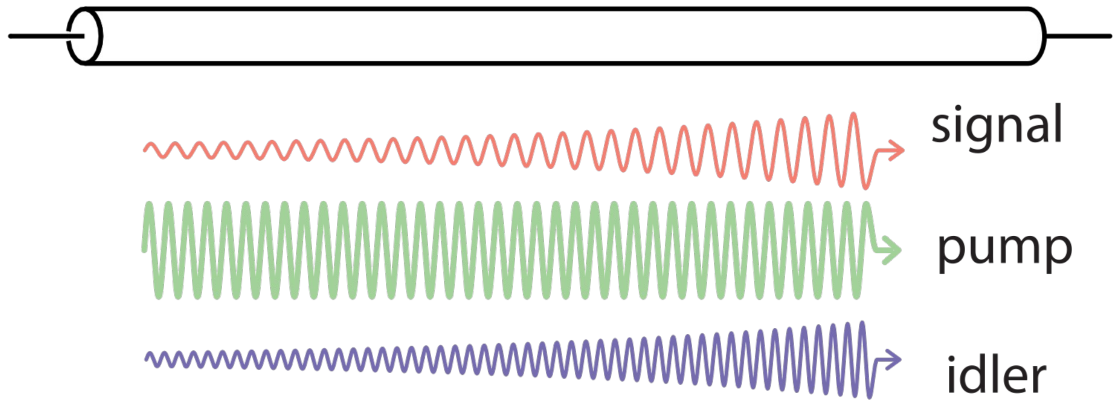
TWPAs
Travelling Wave Parametric Amplifiers

TWPA = non-linear transmission line



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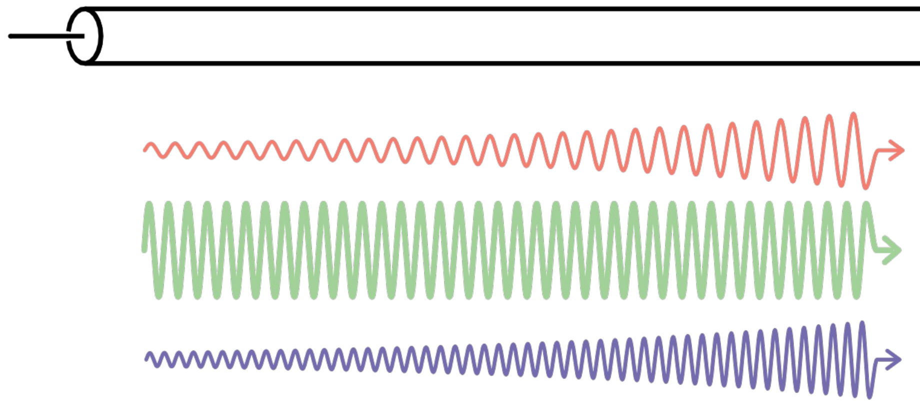
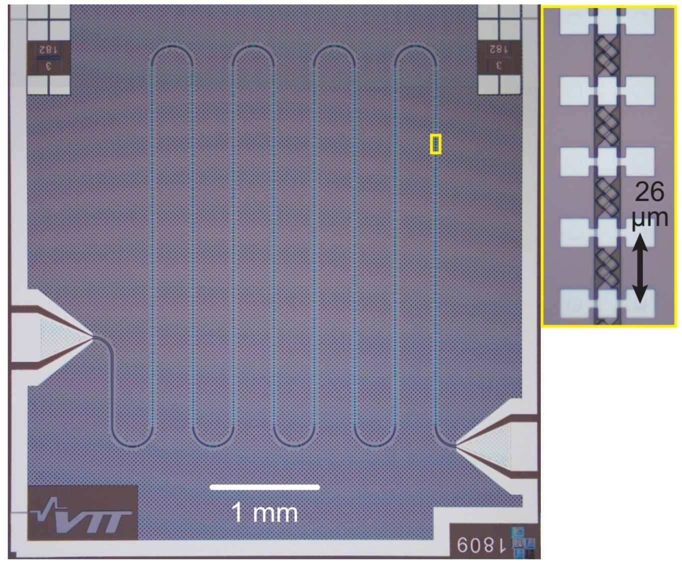


Non-linear elements

Josephson inductance

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

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

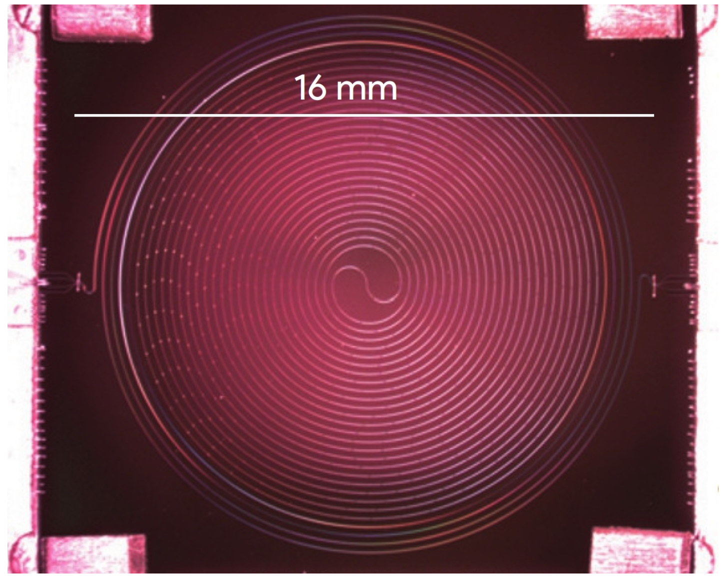


Rev. Sci. Instrum. 92, 034708 (2021)

Kinetic inductance

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

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



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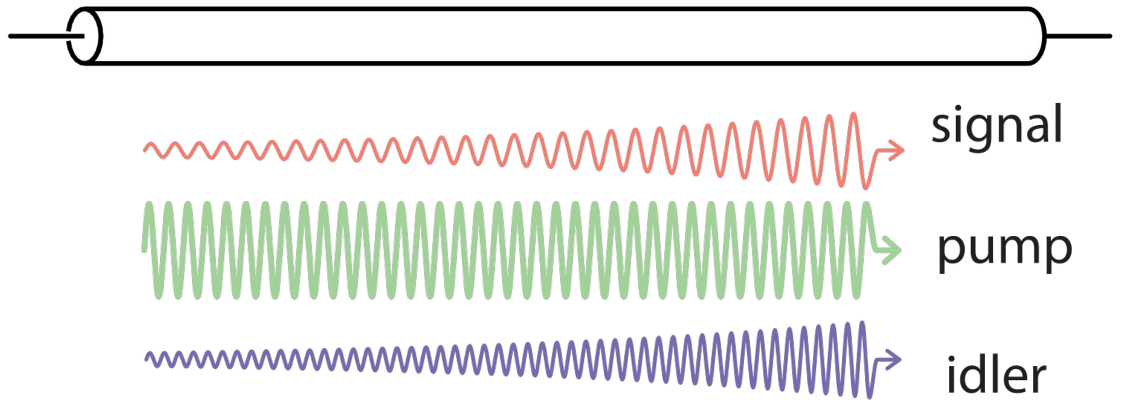

QUANTUM-LIMITED AMPLIFIERS
⇒ detectors/qubits read-out

MICROWAVE SQUEEZING & ENTANGLEMENT
⇒ quantum sensing

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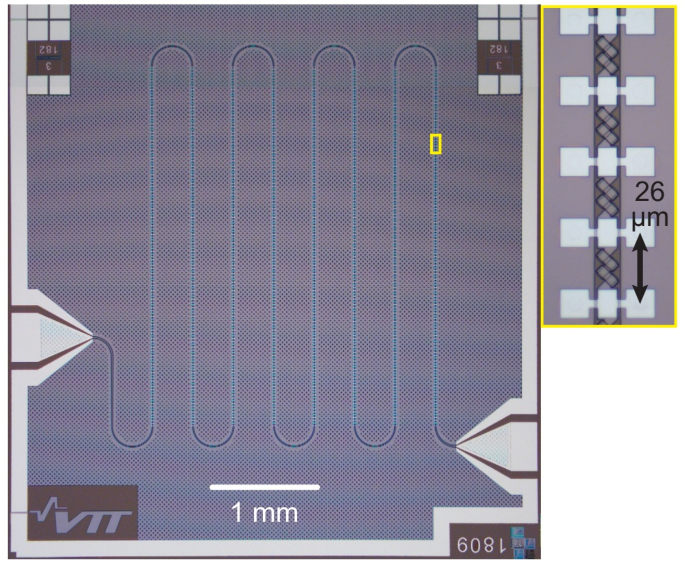

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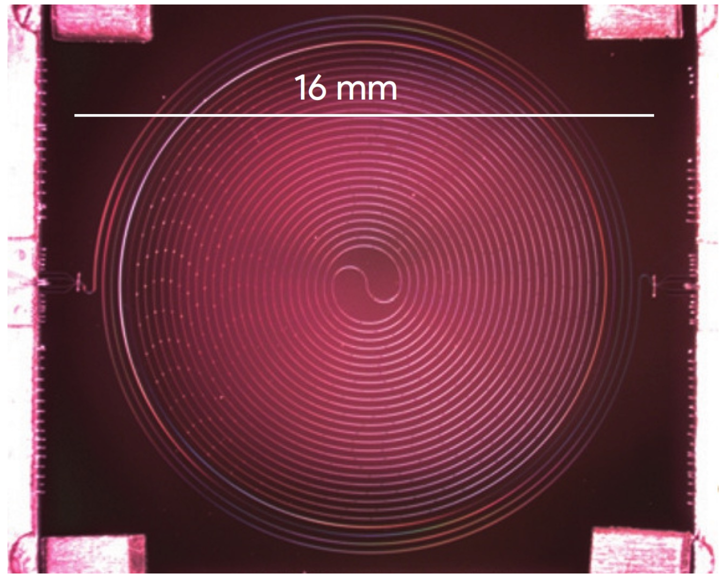

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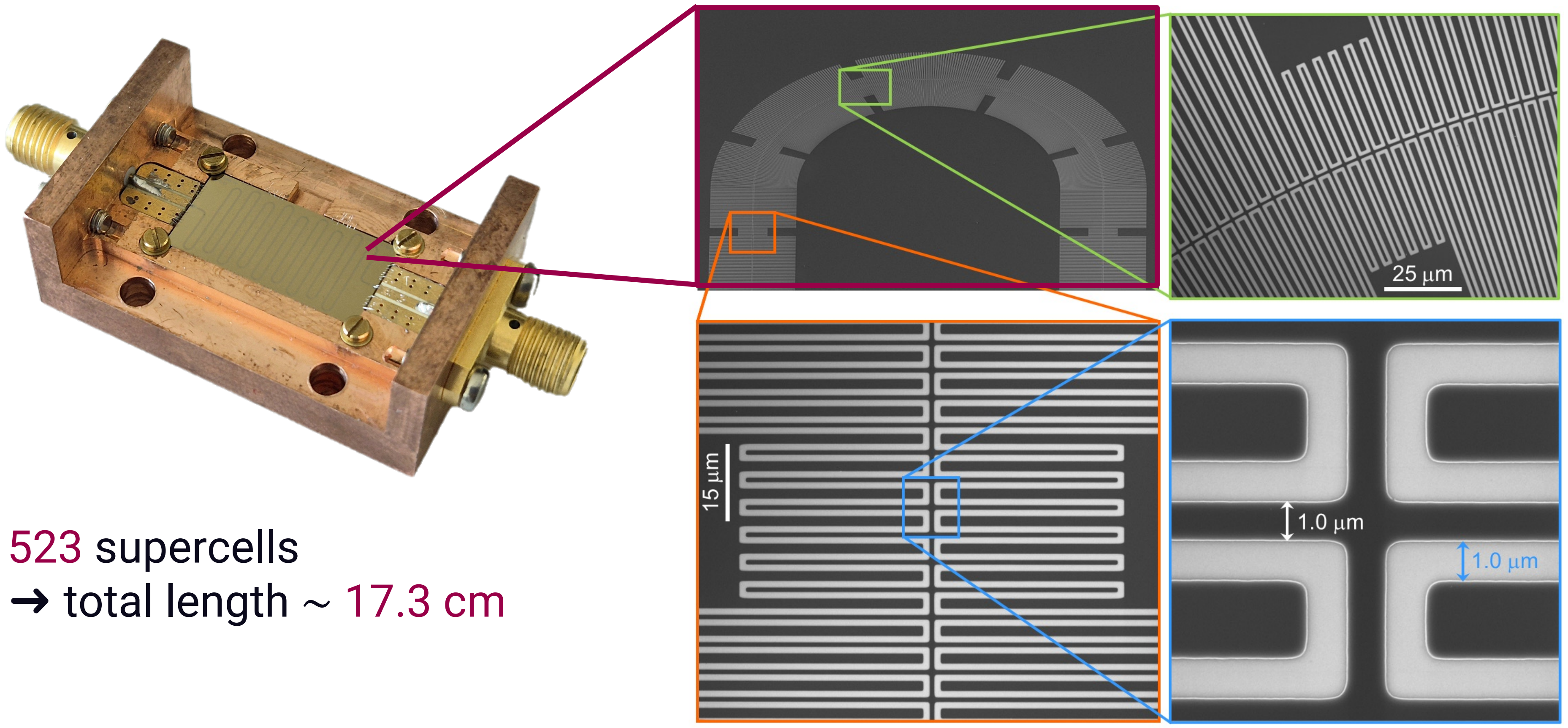
1st GENERATION



523 supercells
→ total length ~ 17.3 cm

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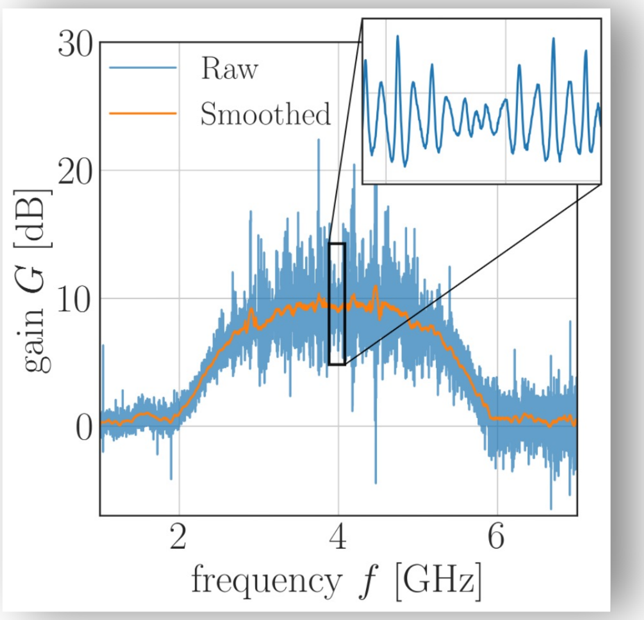
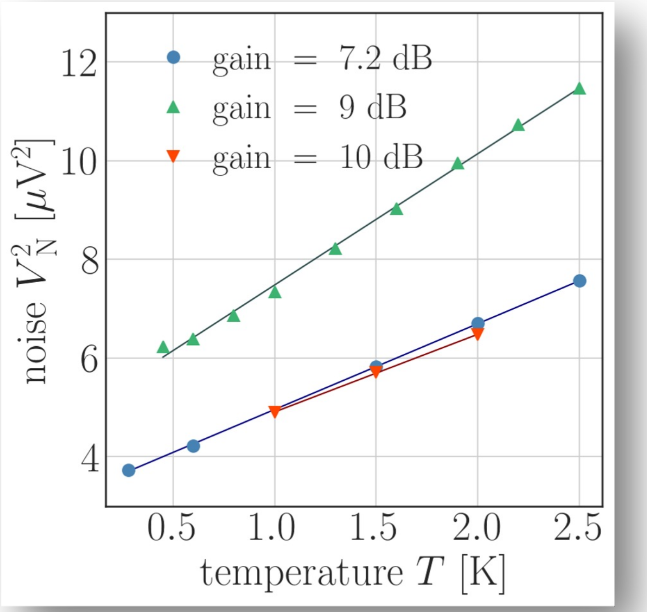


Gain: up to ~ 10 dB



Noise: down to 2.5-3 noise quanta

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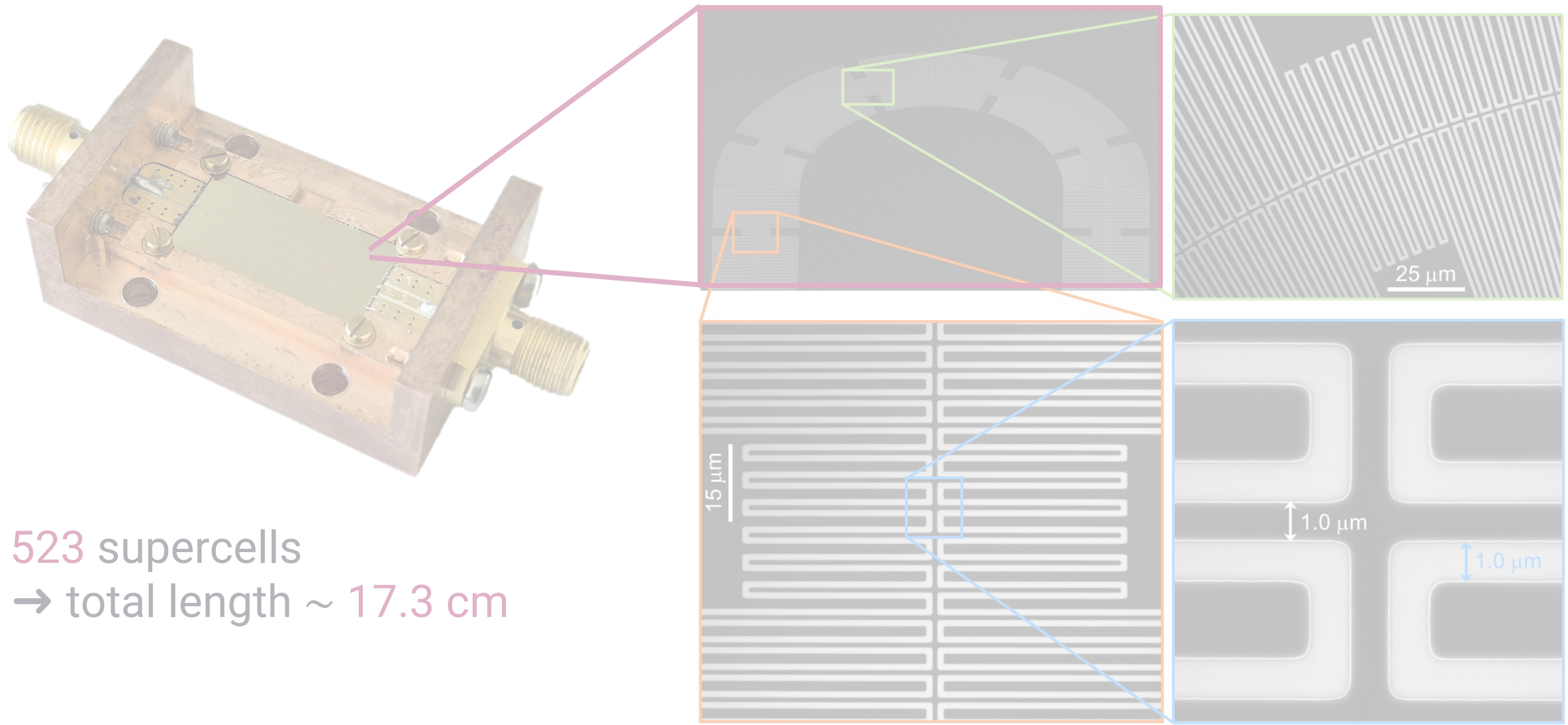

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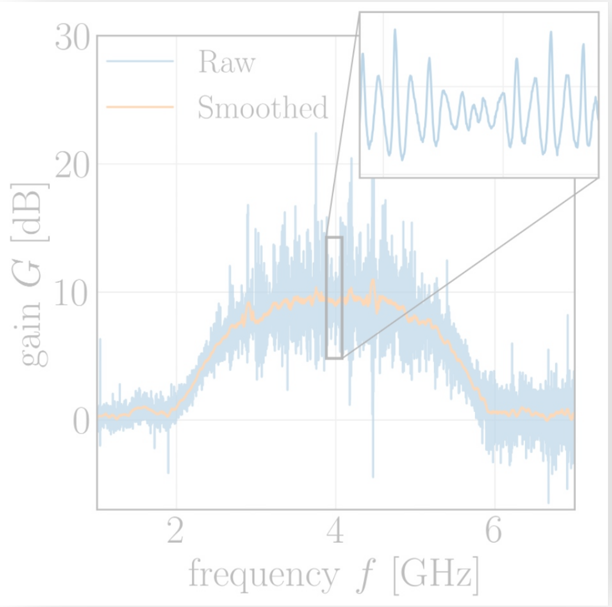

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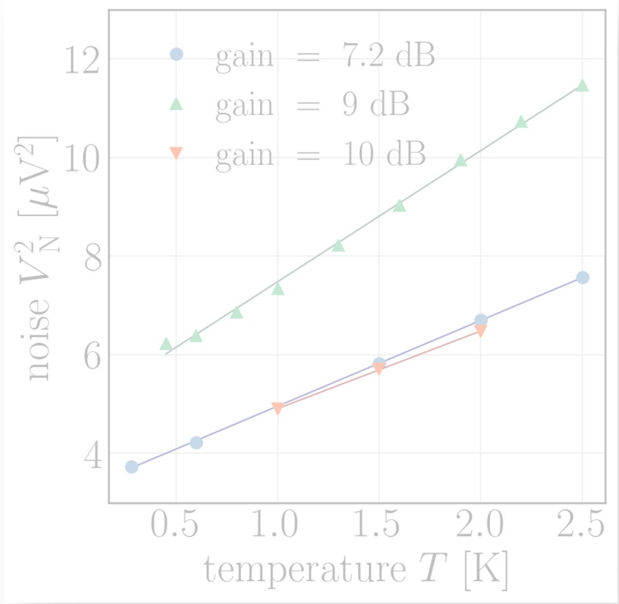

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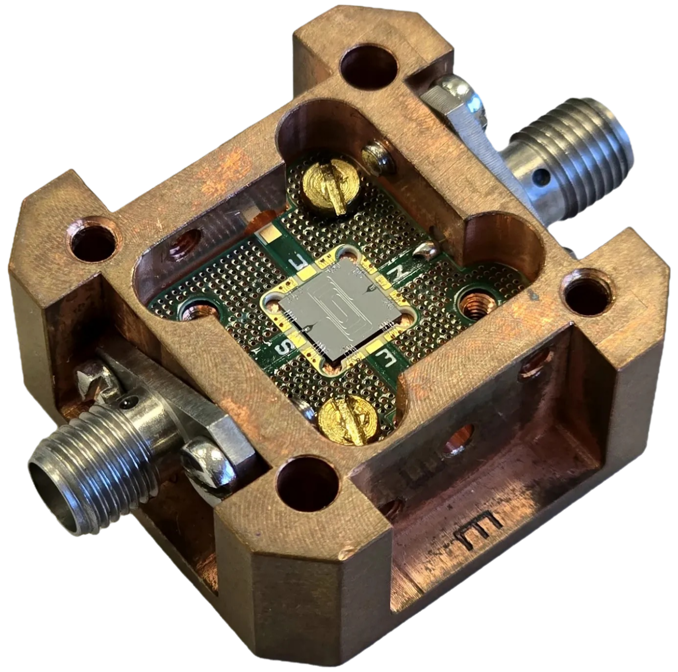
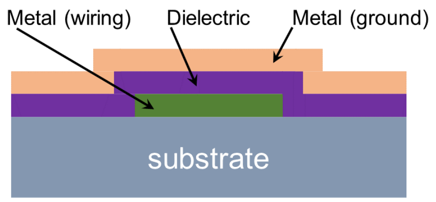
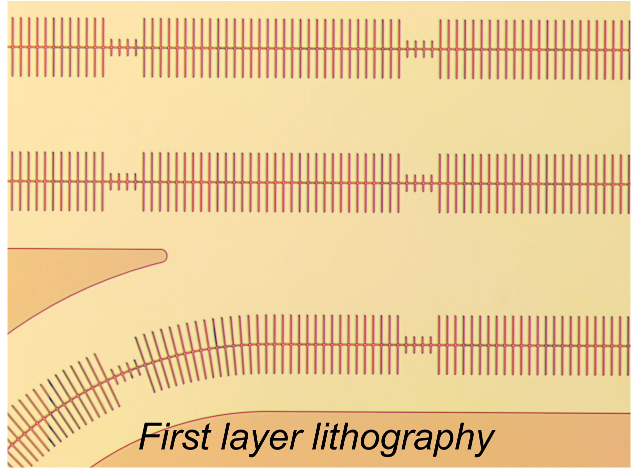


Inverted microstrip geometry
➜ higher yield, more compact device





Entanglement generation

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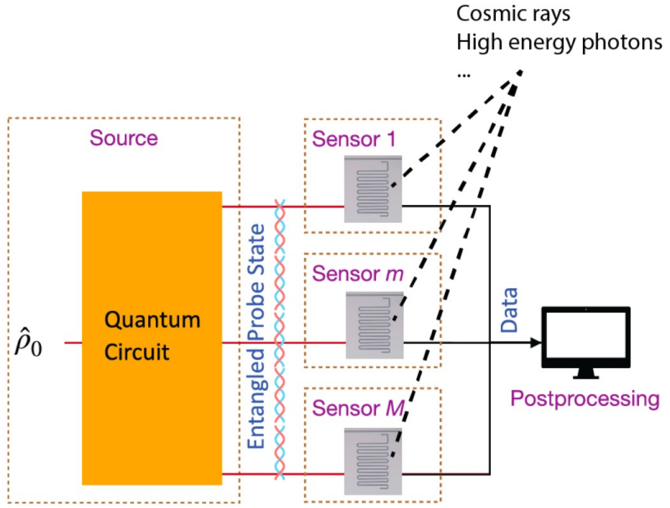
DQS
Distributed Quantum Sensing



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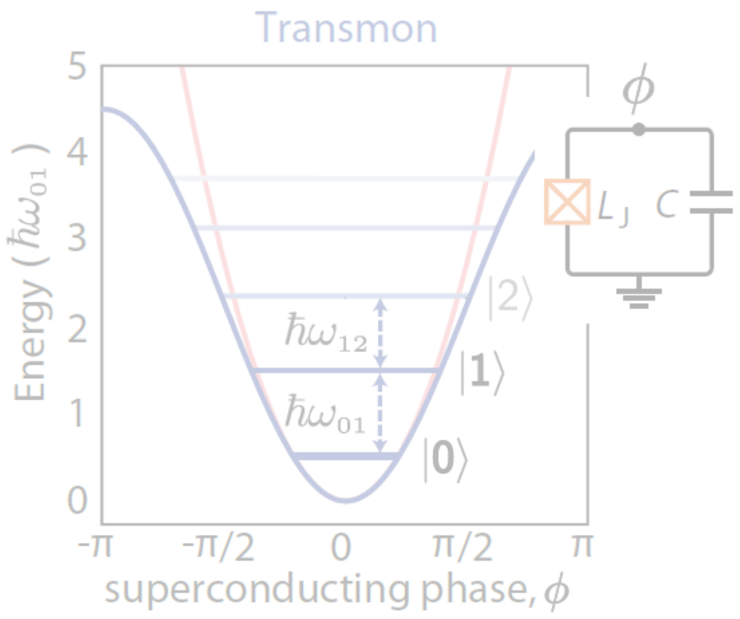

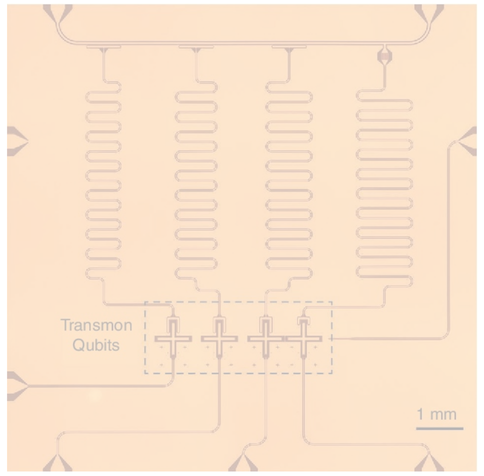

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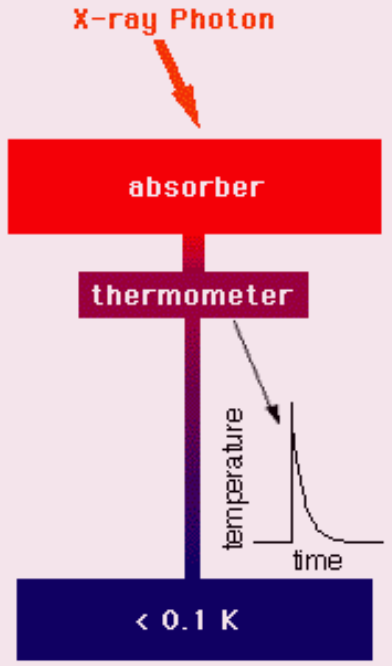
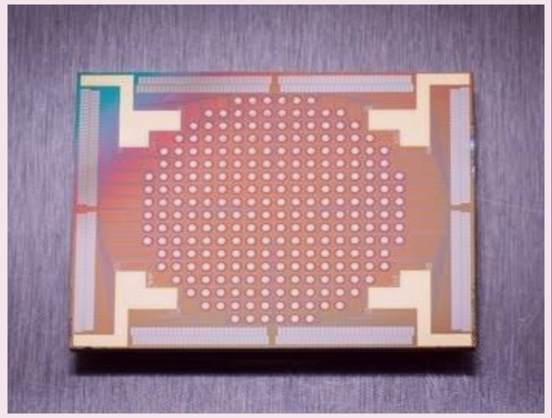




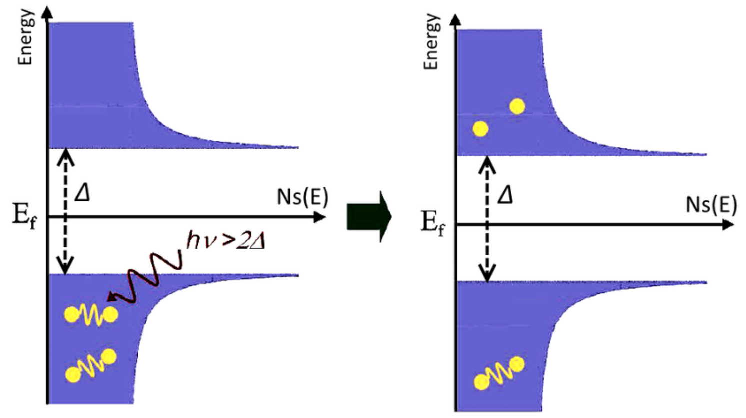
Superconducting cryogenic sensors: why?

Small energy gap
of Cooper pairs

⇩

$$\Delta_0 = 1.76 k_B T_c$$

$$\boldsymbol{\Delta_0}\left(T_c^{\mathrm{NbN}} = 16.5\ \mathrm{K}\right) = \mathbf{2.5\ meV}$$



Credits: 10.1088/1742-6596/664/8/082007

SNSPDs

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⇩

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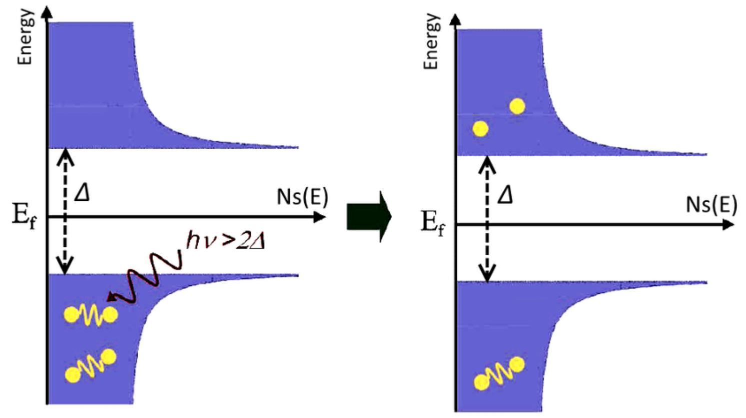
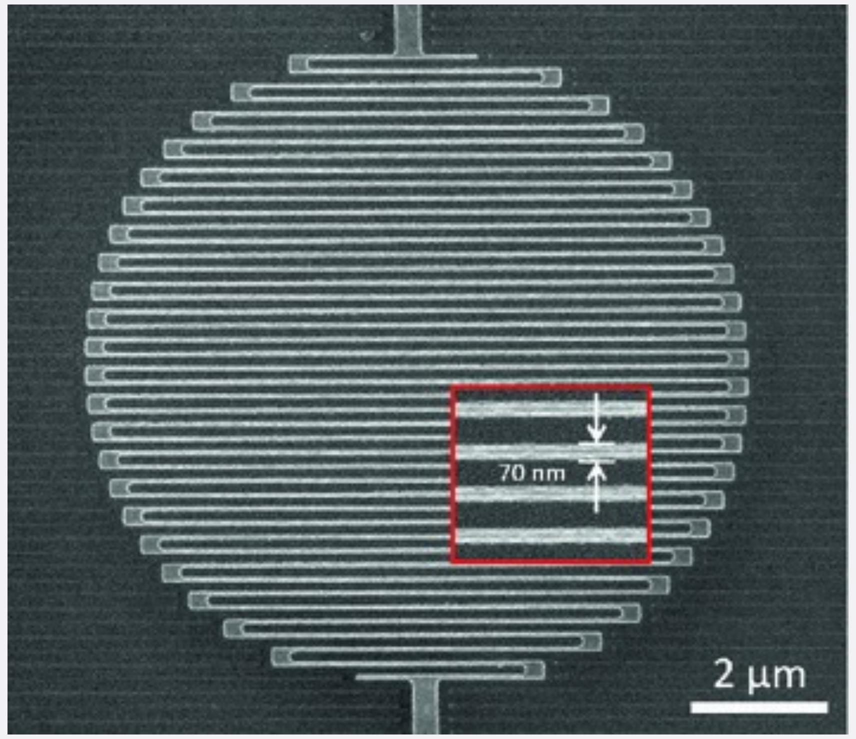


Credits: 10.1088/1742-6596/664/8/082007

Superconducting Nanowires Single Photon Detectors (SNSPDs)



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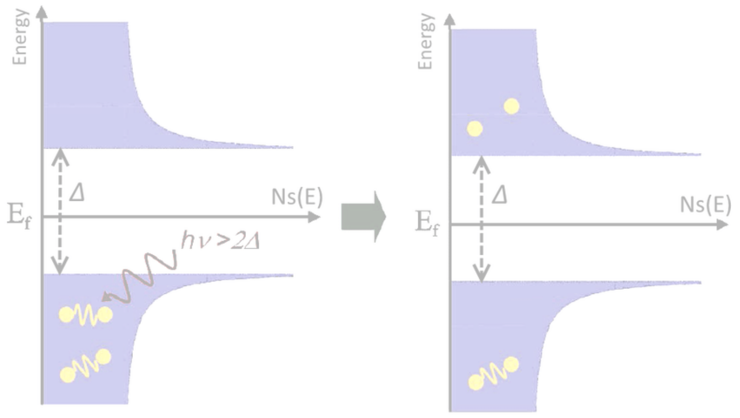
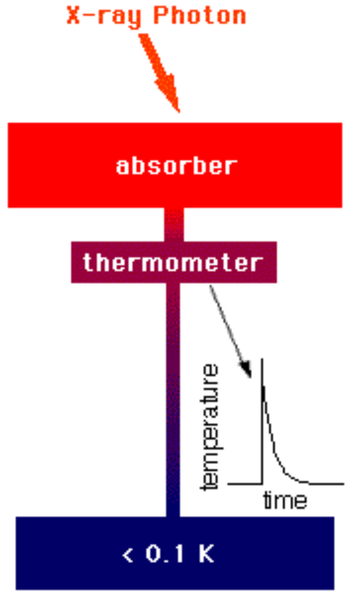


Credits: 10.1088/1742-6596/664/8/082007

Small heat capacity
$C_e \propto T$

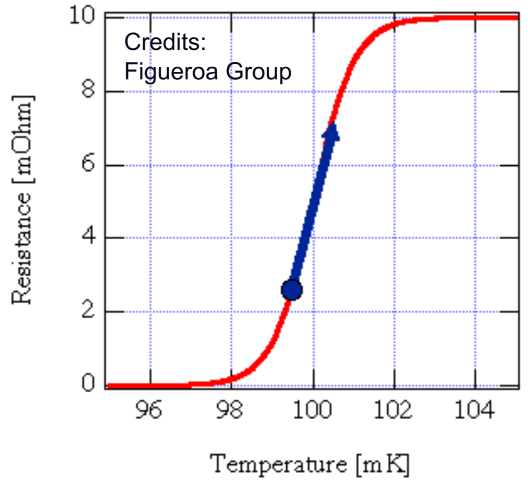
Sensitive **calorimeters**
$\Delta T = E/C$



Credits: NASA

Sharp superconducting
transition

Sensitive **thermometer**
$\mathrm{d}R/\mathrm{d}T$



Cryogenic microcalorimeters

Small energy gap
of Cooper pairs

⇩

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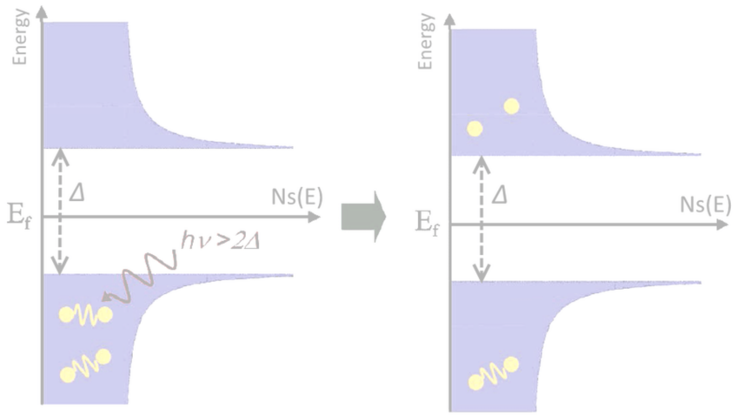

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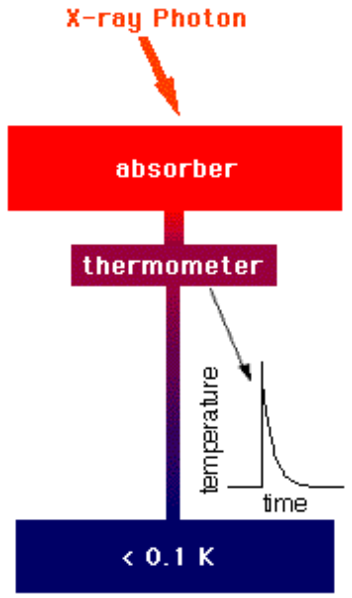

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Sharp superconducting
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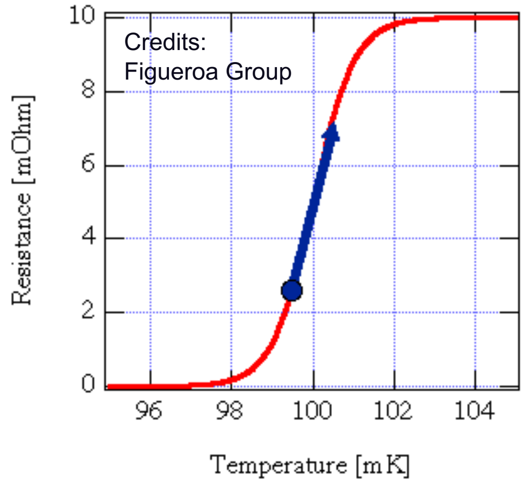
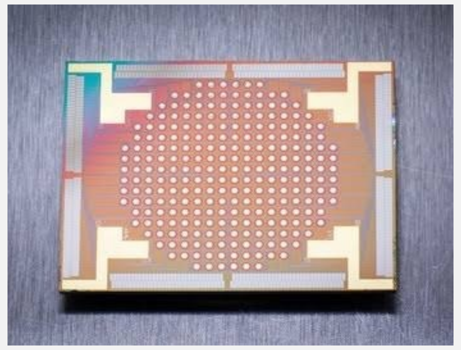
⇩

Sensitive **thermometer**

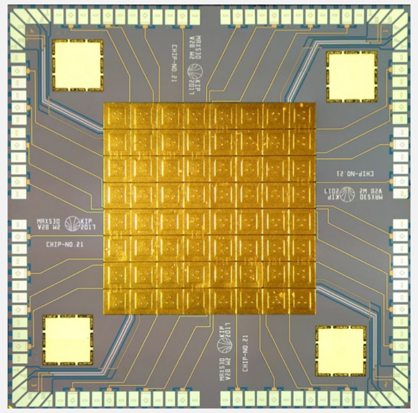
$\mathrm{d}R/\mathrm{d}T$



Transition Edge Sensors (TESs)



Metallic Magnetic Calorimeters (MMCs)



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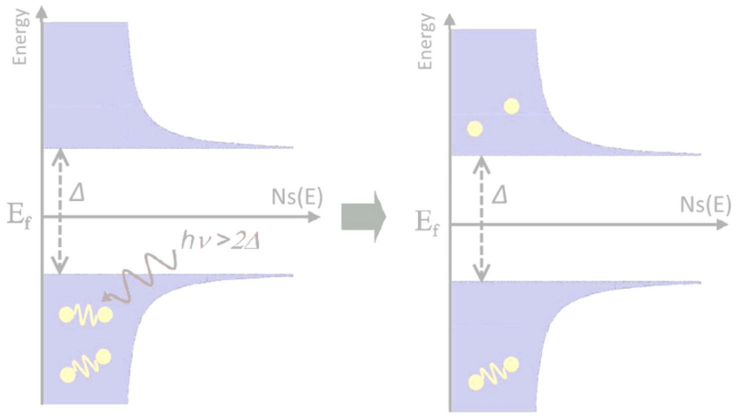

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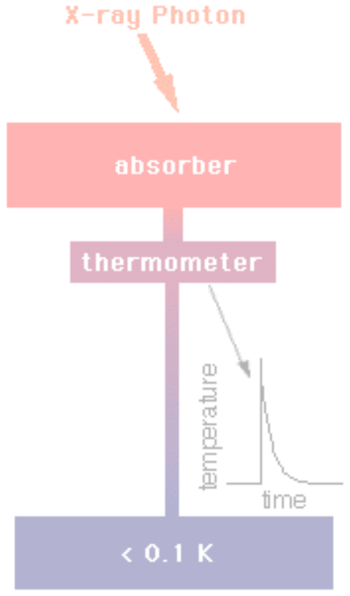

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Sharp superconducting transition

⇩

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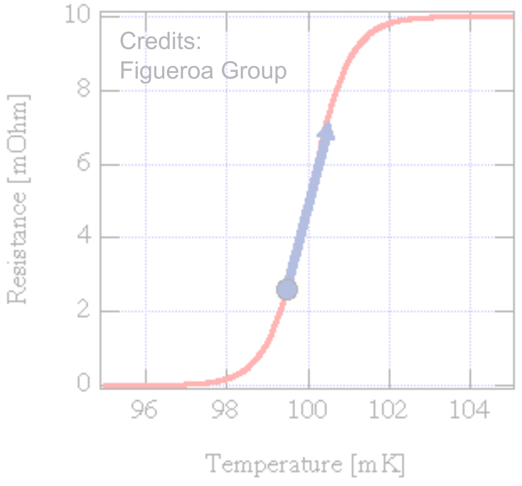


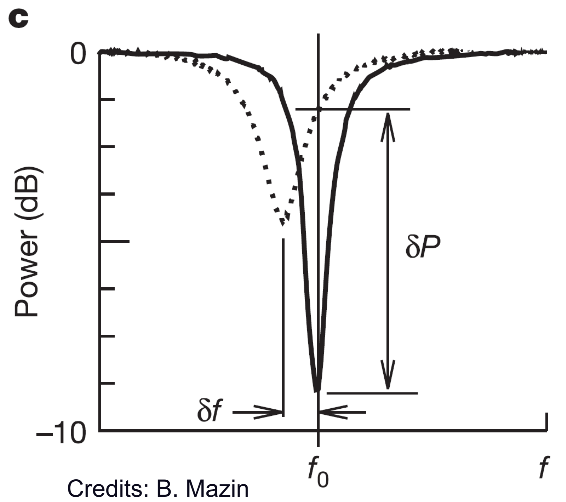
Change of kinetic inductance

$L_k \propto 1/n_S$

⇩

Detection using LC **resonator**

$f_R = 1/(2\pi\sqrt{LC})$



Credits: B. Mazin

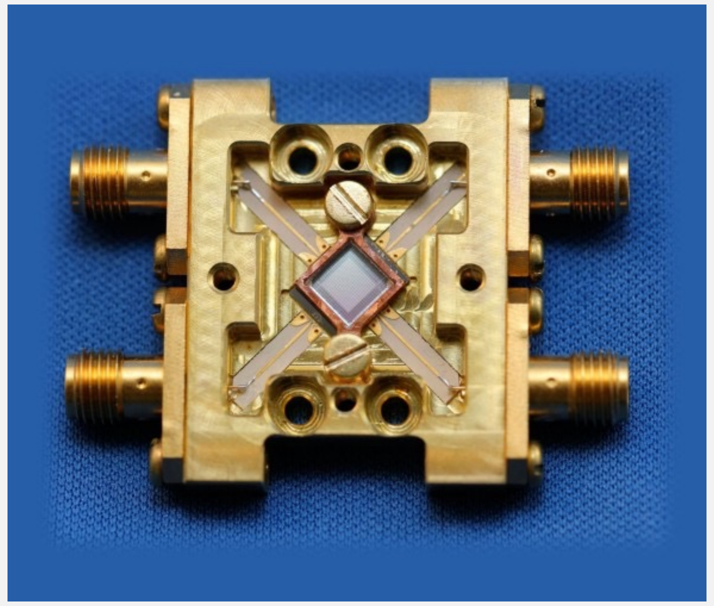
KIDs & KICS

Small energy gap

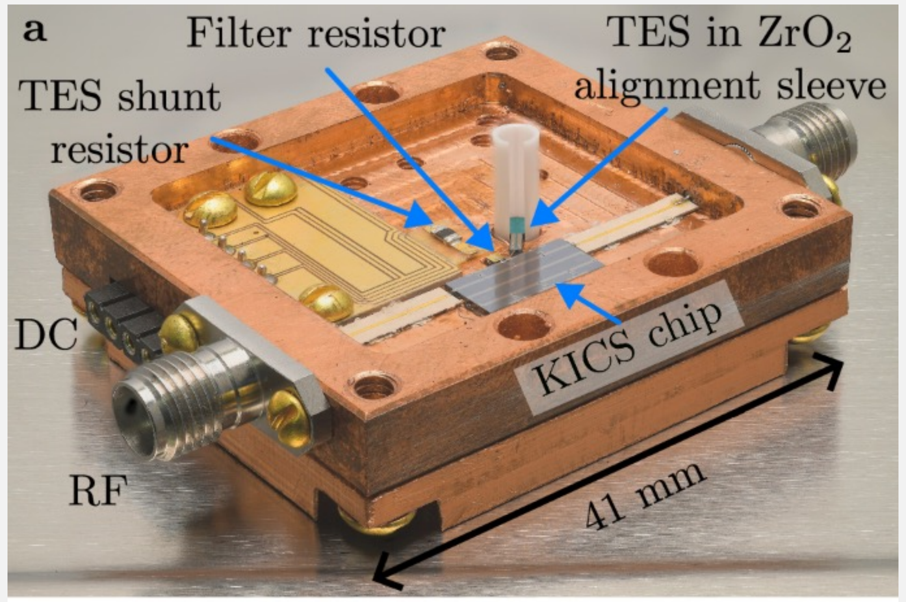
Small heat capacity

Sharp superconducting

Kinetic Inductance Detectors (KIDs)



Kinetic Inductance Current Sensors (KICS)



Credits: 10.1088/1742-6596/664/8/082007

Credits: NASA

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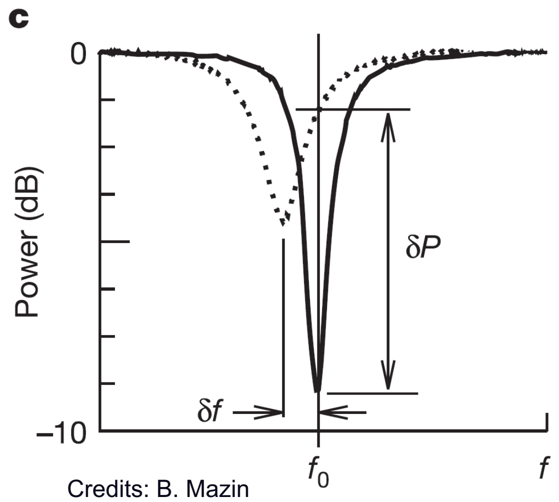


Credits: B. Mazin

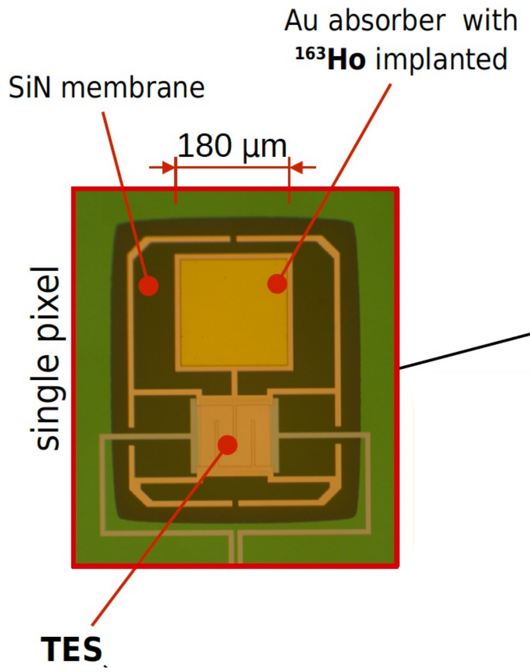
KICS for neutrino mass experiments

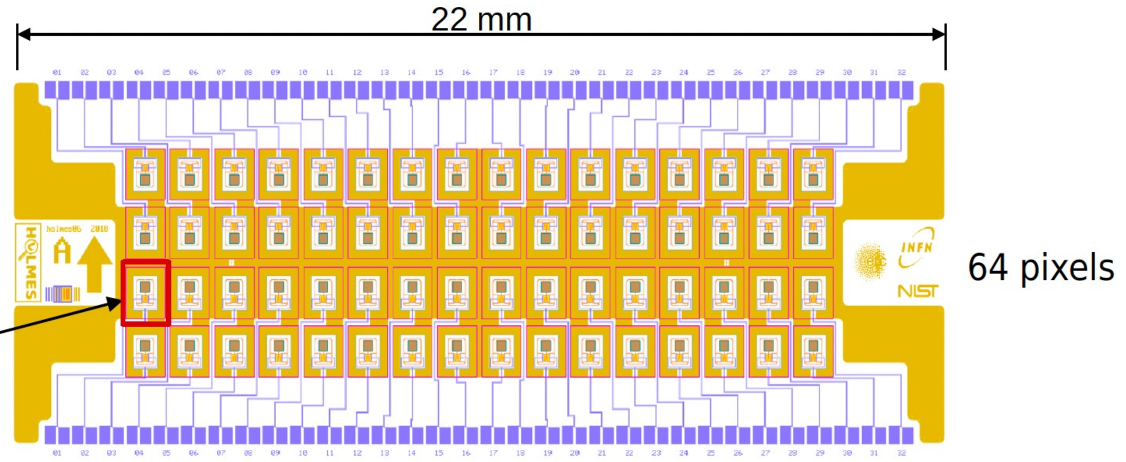
HOLMES+

INFN CSN2 Fisica delle Astroparticelle

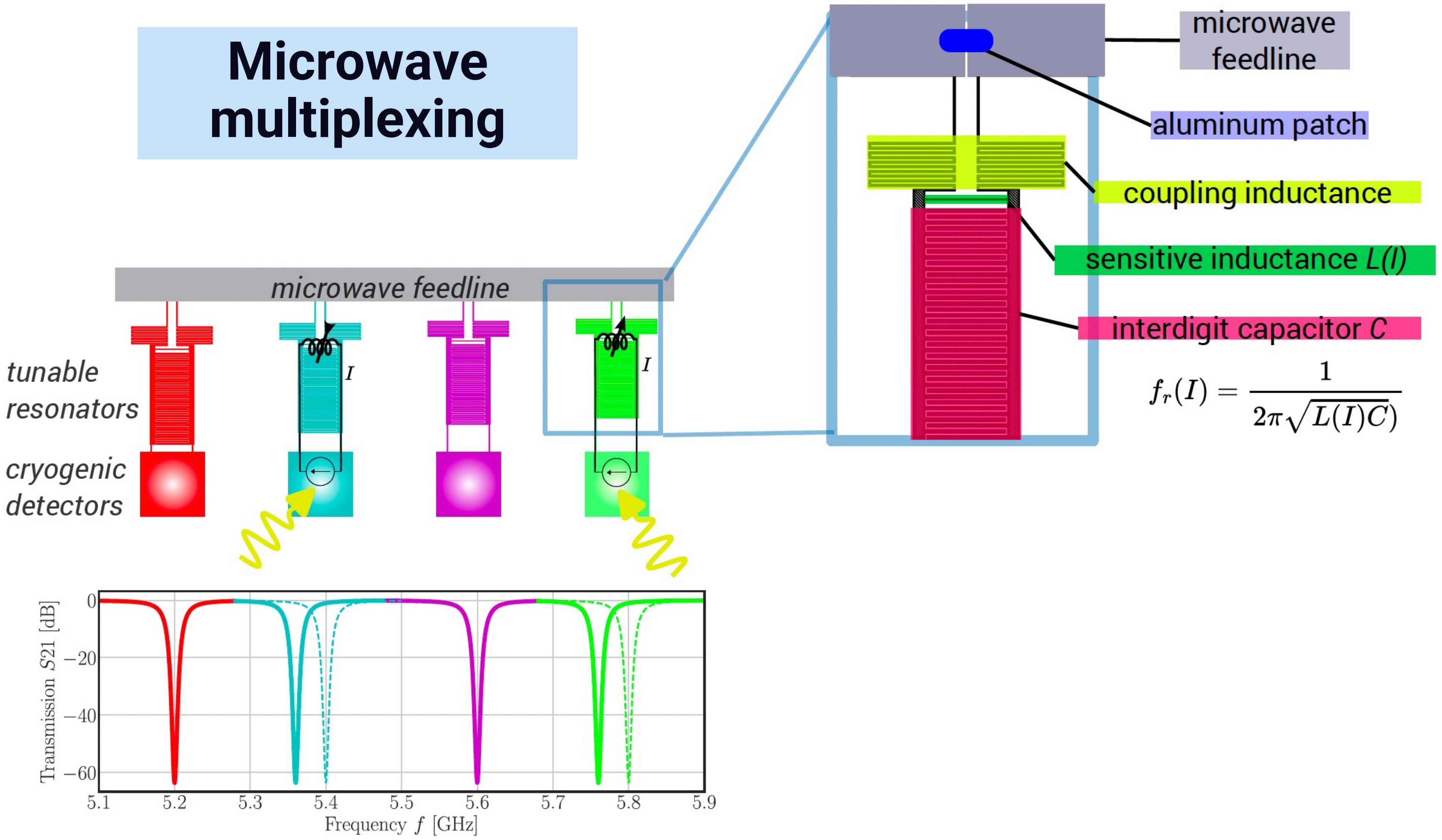
Goal: determination of the electron neutrino mass

→ arrays of TES detectors implanted with Ho-163





Microwave multiplexing



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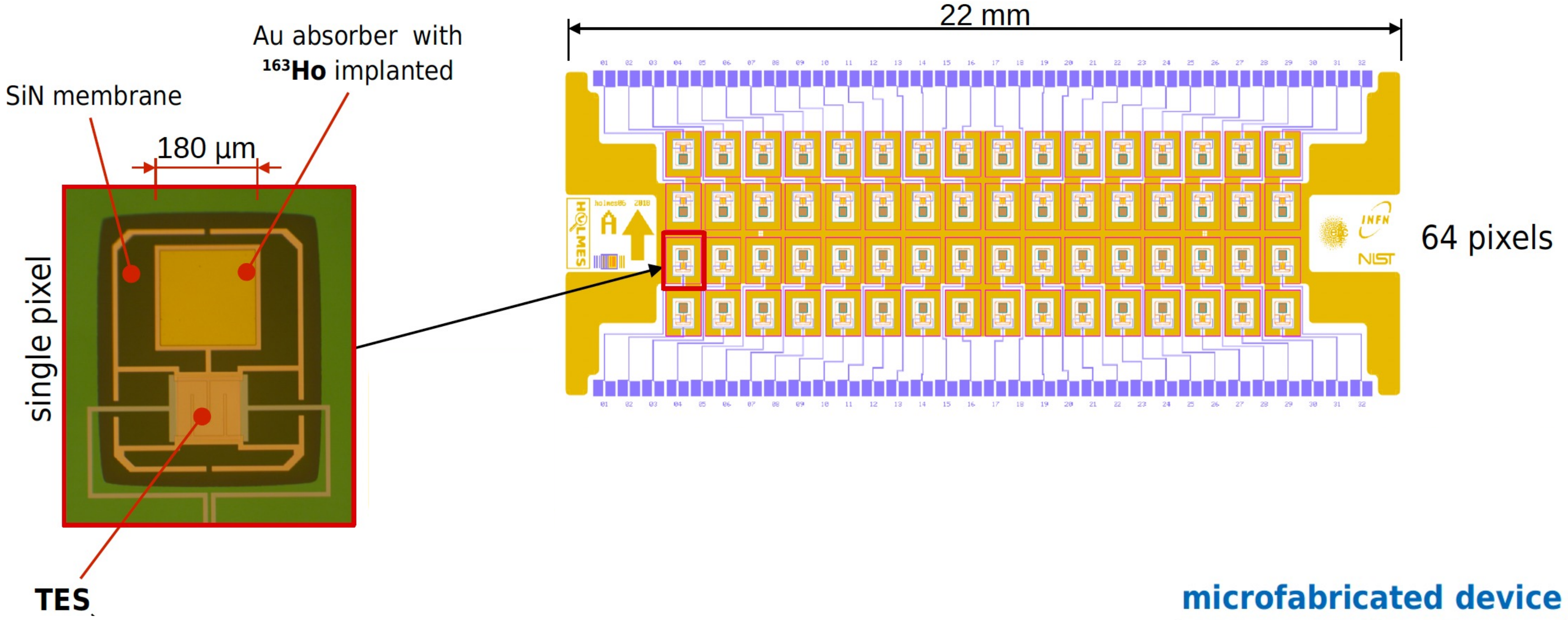

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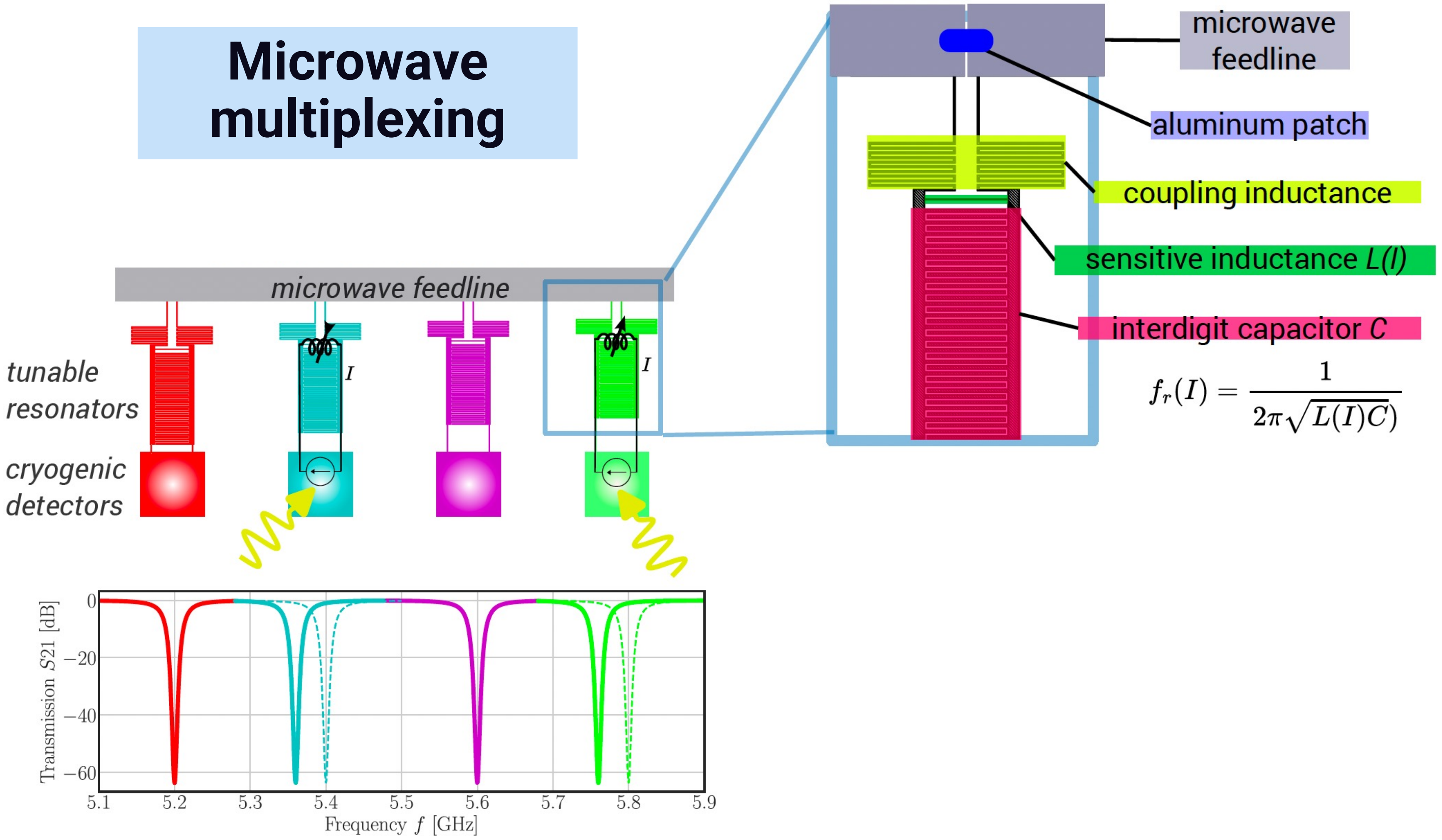
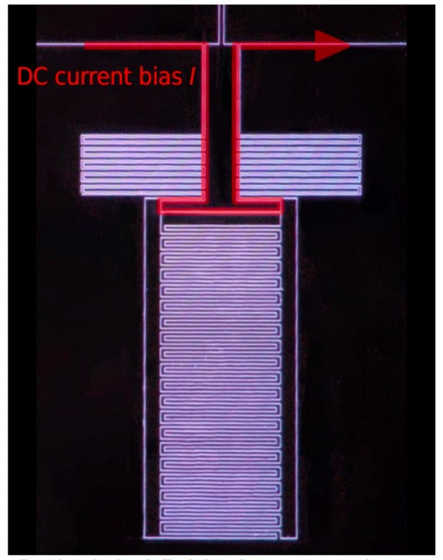


First prototypes realised at **FBK-TIFPA**:

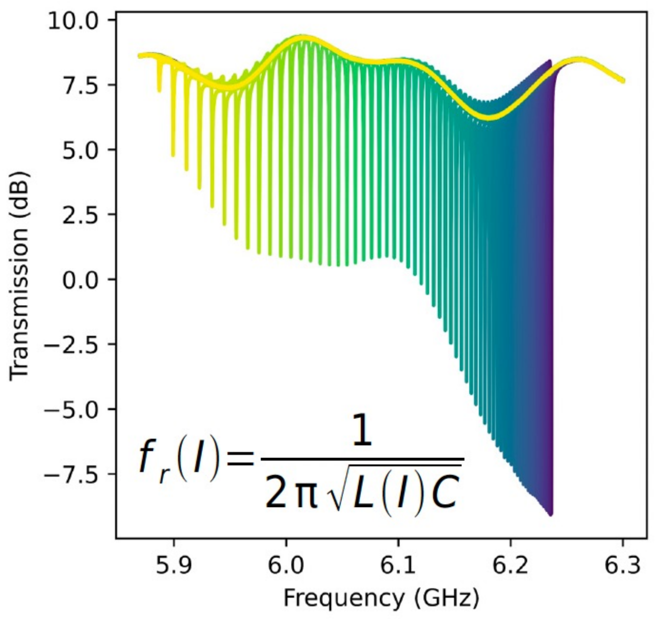
- Microfabrication of tunable resonators
- Cryogenic characterisation

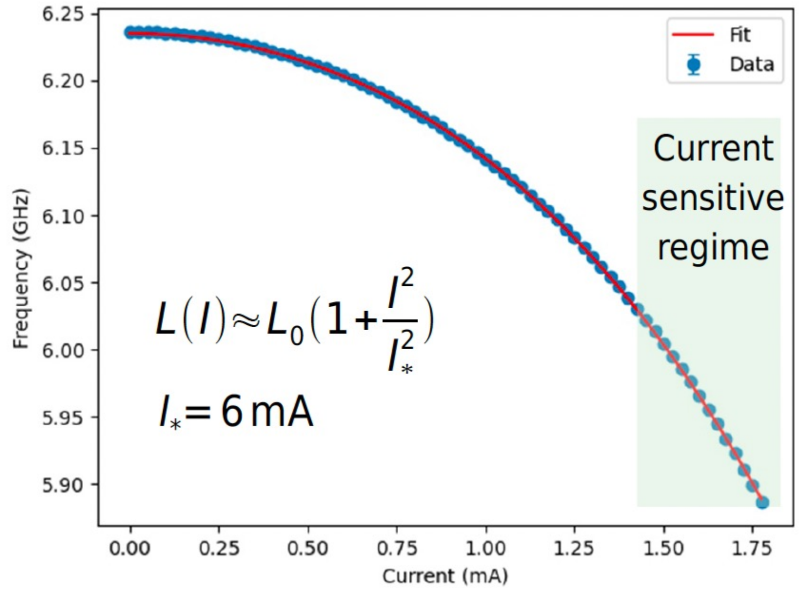
→ expected resonance response
→ good agreement with simulations

microfabricated device



Optical darkfield microscope image





Conclusions

Quantum sensing with superconducting circuits is a broad field

Quantum circuits:
manipulation of quantum states

Cryogenic detectors:
Response of superconducting circuits upon energy input

Next talk
by A. Monfardini
Cryogenic detectors in France

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Many activities ongoing within INFN

State-of-the-art cleanroom facility available

not only quantum sensors… but also **silicon detectors**:
large arrays, scalability, R&D for custom radiation sensors:
SiPM, **LGADs**, **SDDs**, **…**

Poster
by M. Centis Vignali
Silicon Sensors Development: the INFN-FBK Collaboration

Talk
by E. Rovati
Innovative Back-Side Illuminated SiPMs (BSI-SiPMs): …

Outlook

Quantum sensing, *"a new paradigm for particle physics"* … ?

Challenges

Superconducting devices suffer
magnetic fields
radiation
…

often slow response time

Opportunities

High sensitivity
Low threshold
Quantum-limited noise
New detection mechanisms
⇒ explore ***new physics***

Acknowledgments

Projects and funding

The SQD Research Unit

Felix Ahrens, Enrico Bogoni, Giulio Cappelli, Nicolò Crescini, Marcello Faggionato, Alessandro Irace, Benno Margesin, Federica Mantegazzini