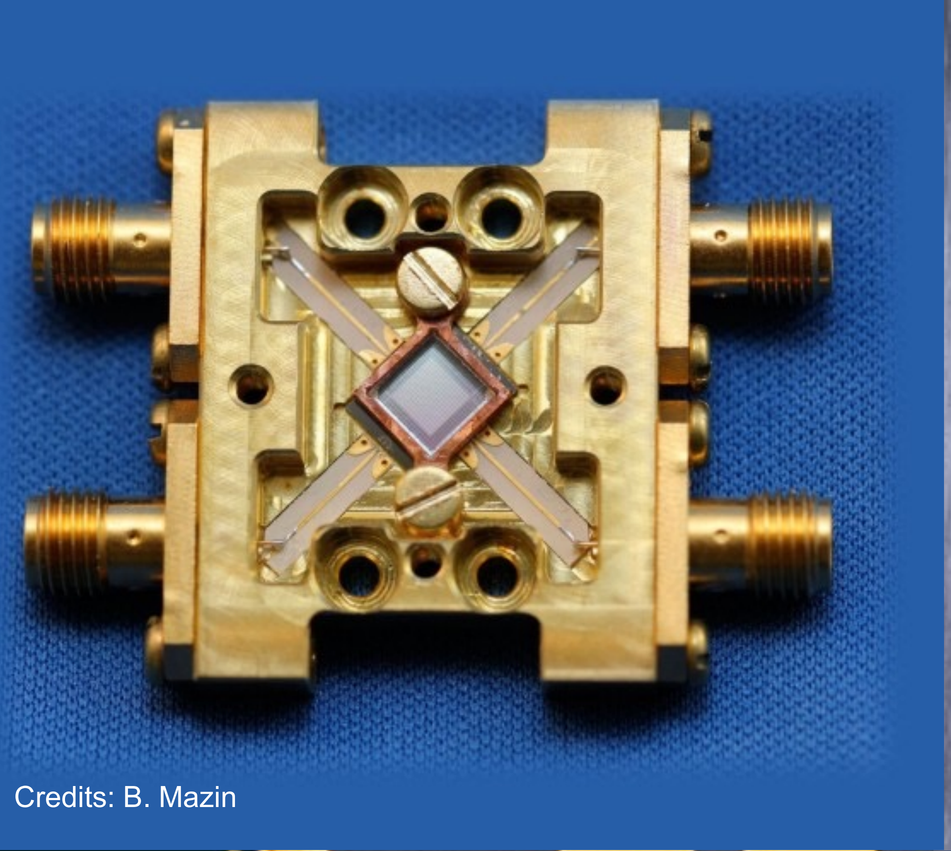
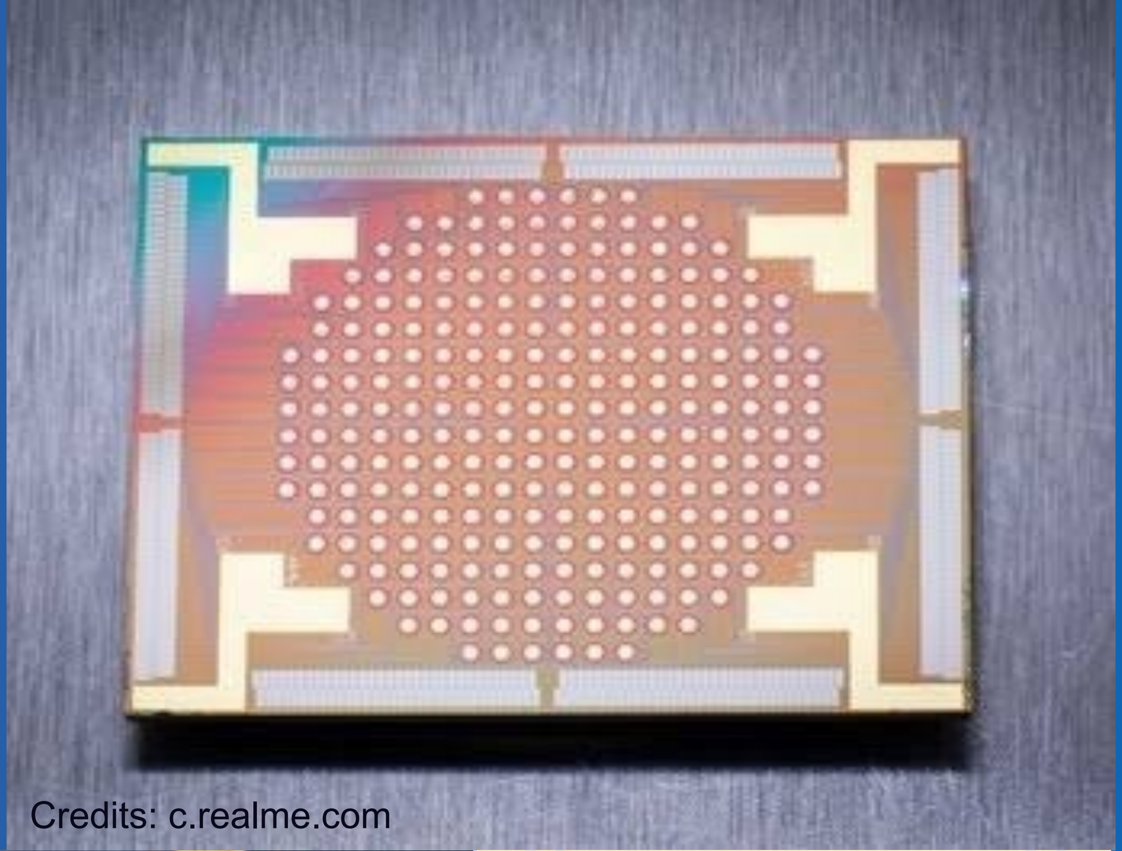
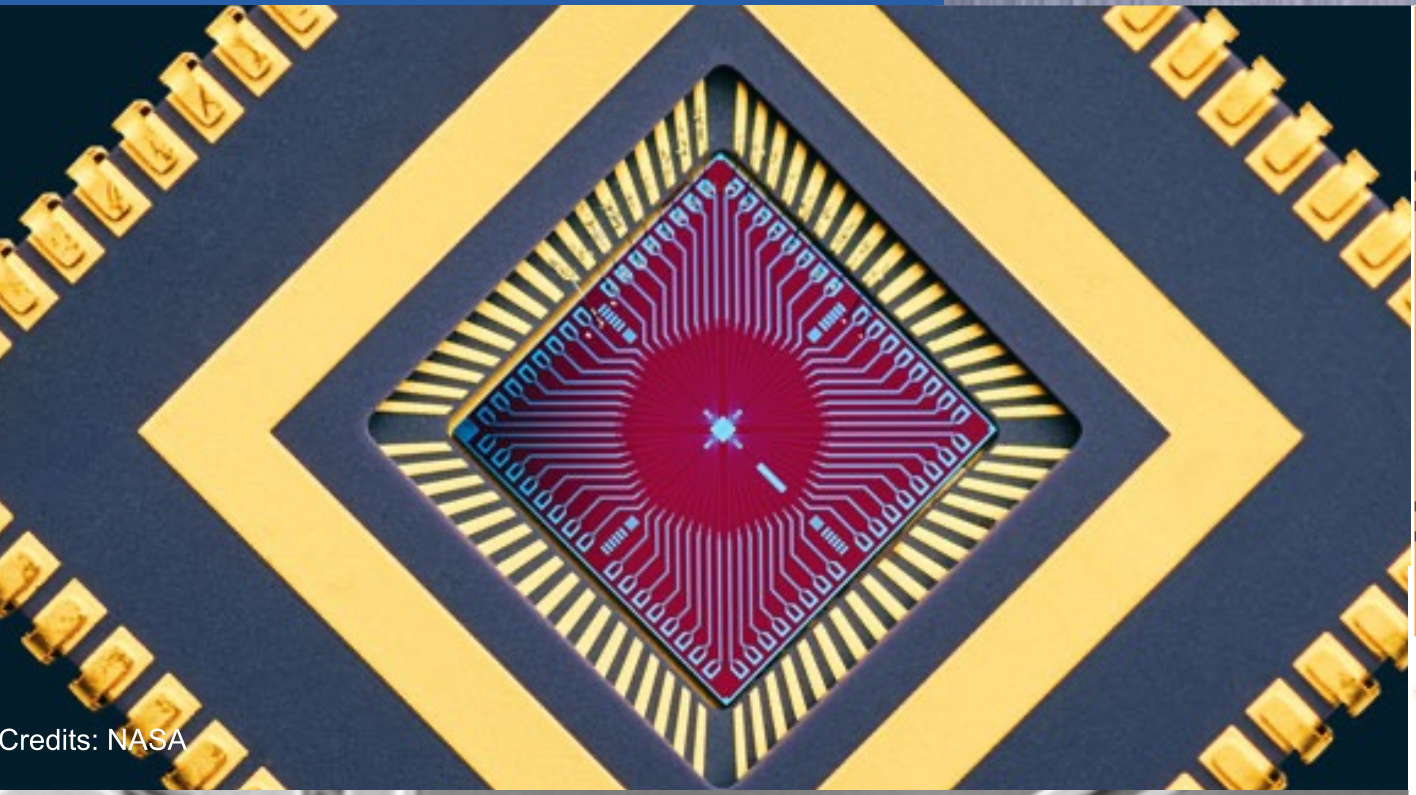
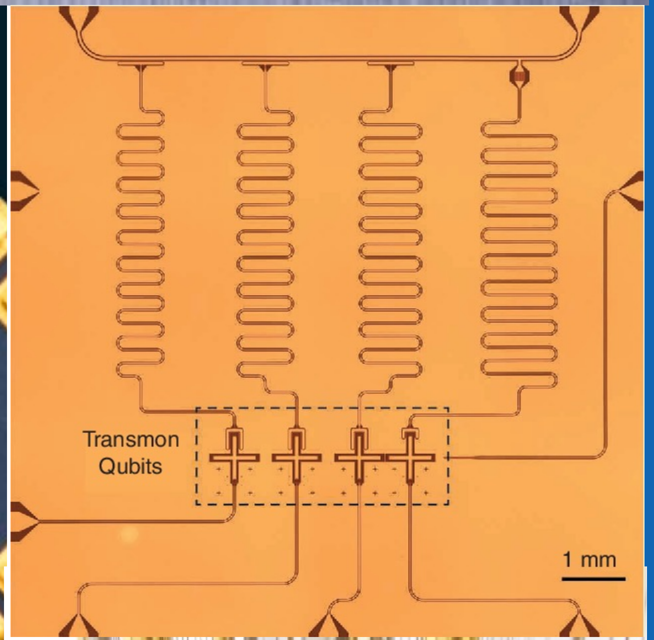
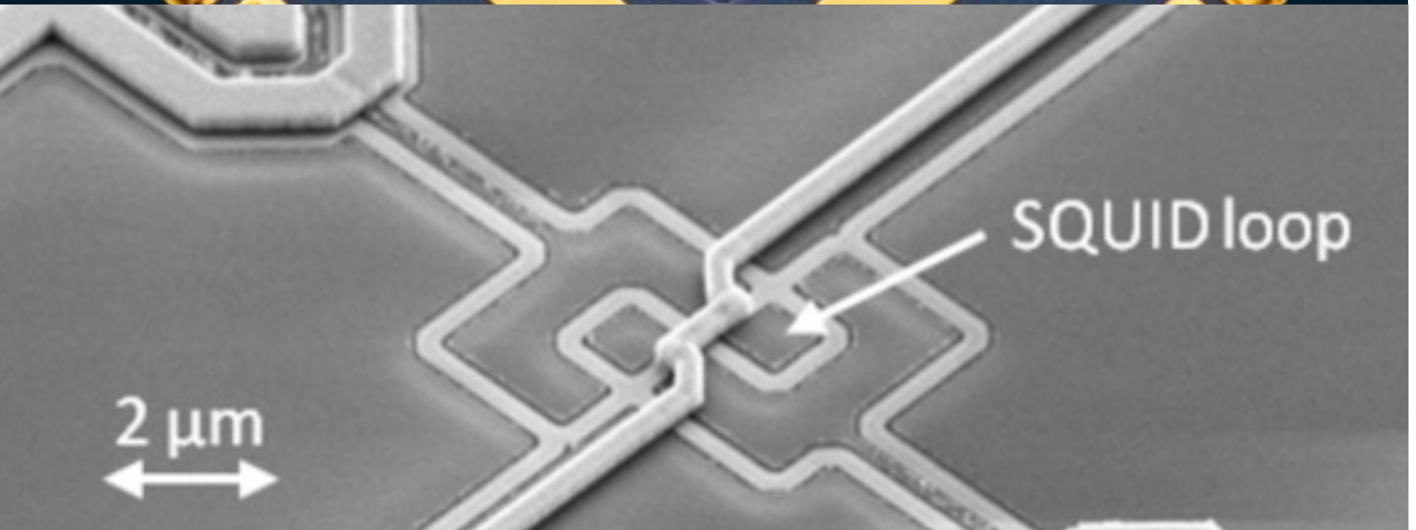

Credits: B. Mazin


Credits: c.realme.com


Credits: NASA






Credits: Bluefors

Superconducting circuits for quantum sensing: an overview

Federica Mantegazzini

17 March 2025

IFD Workshop, Sestri Levante

What is quantum sensing?

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

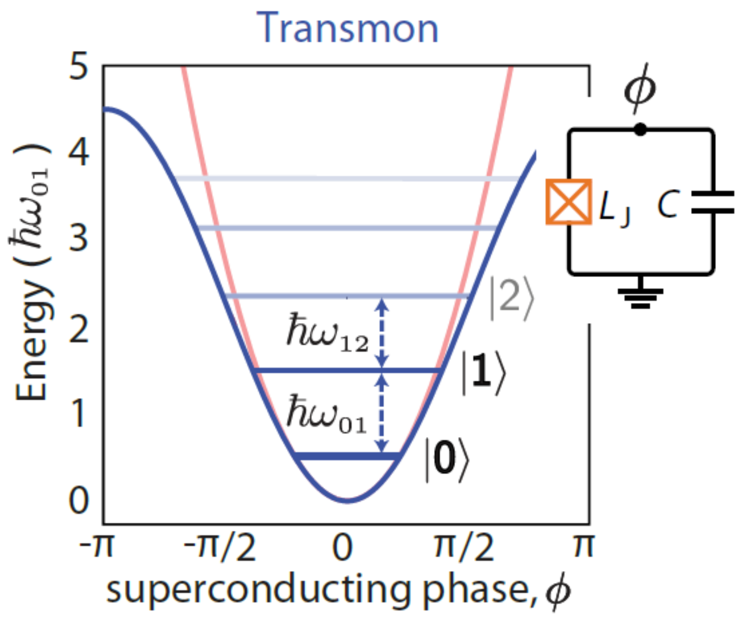
using a **quantum object** as a probe

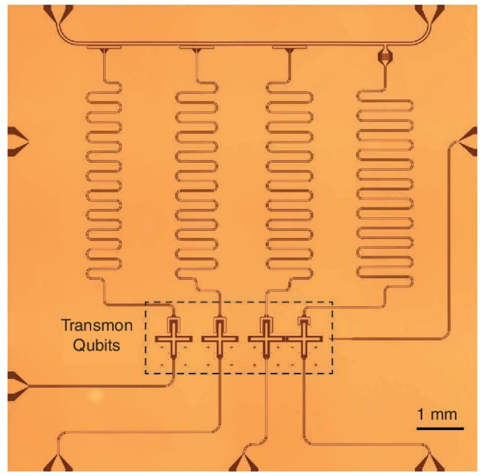
– i.e. an object in which quantum mechanical effects
can manifest and be observed –

What is quantum sensing?

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

  → **quantum circuits and qubits**

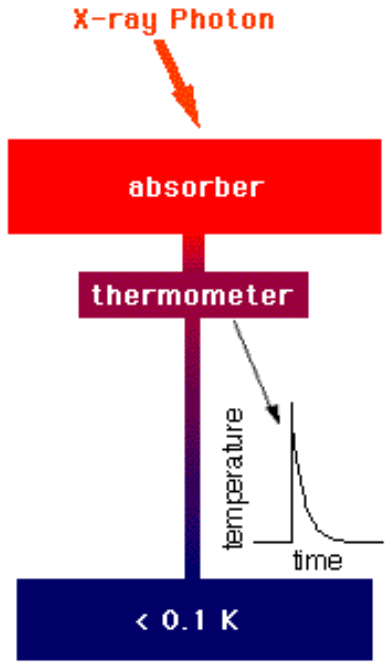


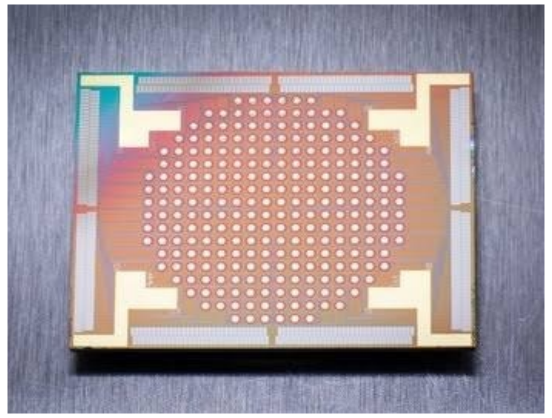


- *Broad approach*:
  Quantum sensing = making use of quantum phenomena

  (superconductivity is a macroscopic quantum phenomenon!)

  → **cryogenic detectors & sensors**





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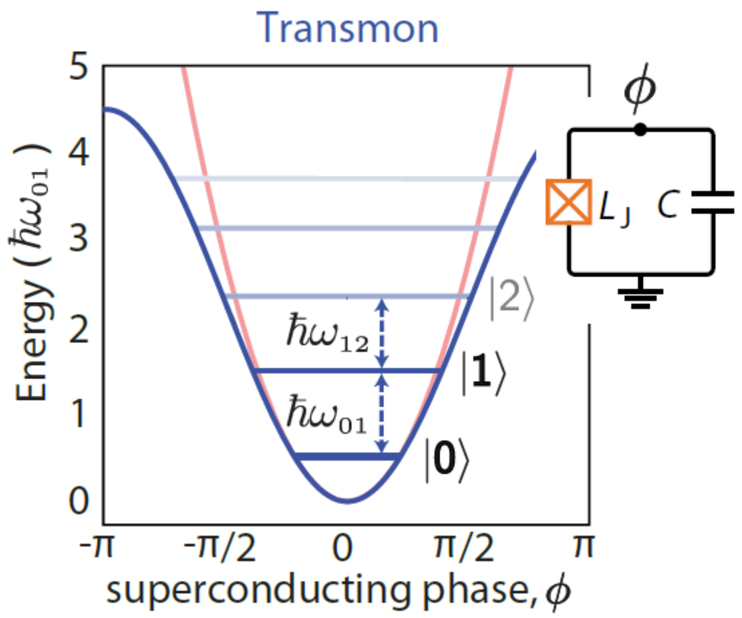

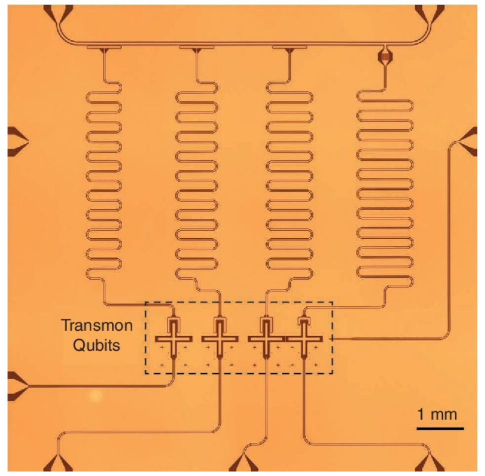

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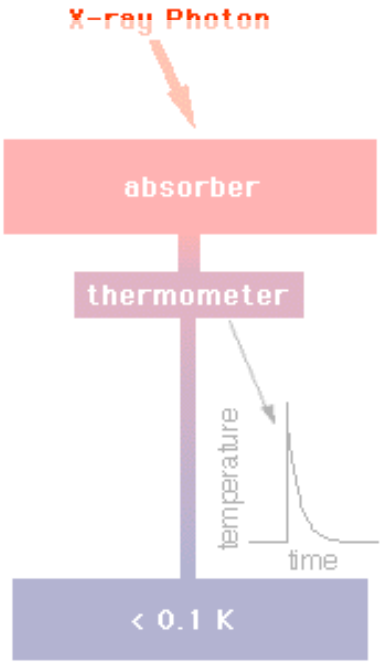
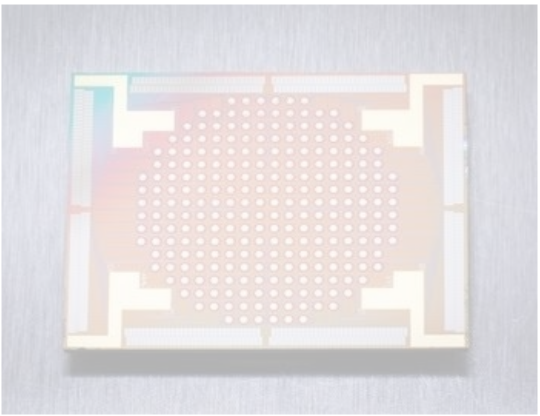
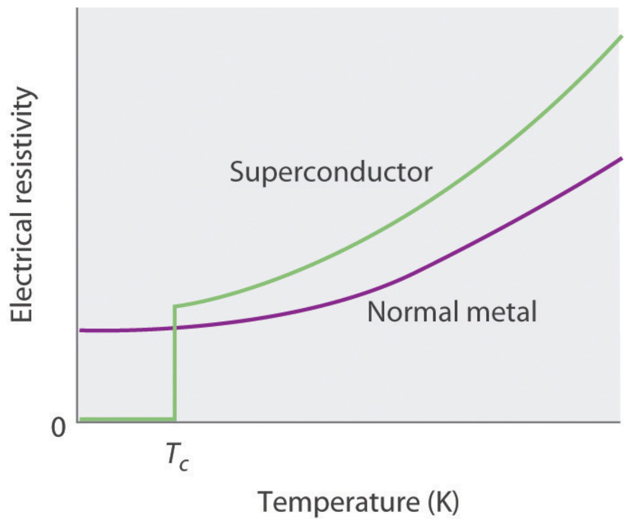




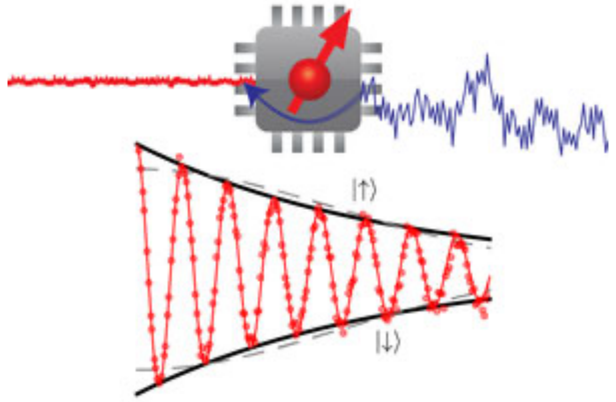
Superconducting quantum circuits: motivation

Superconducting quantum devices offer:

Lossless conduction
(R_{dc} = 0)
⇩
Ultra-low dissipation

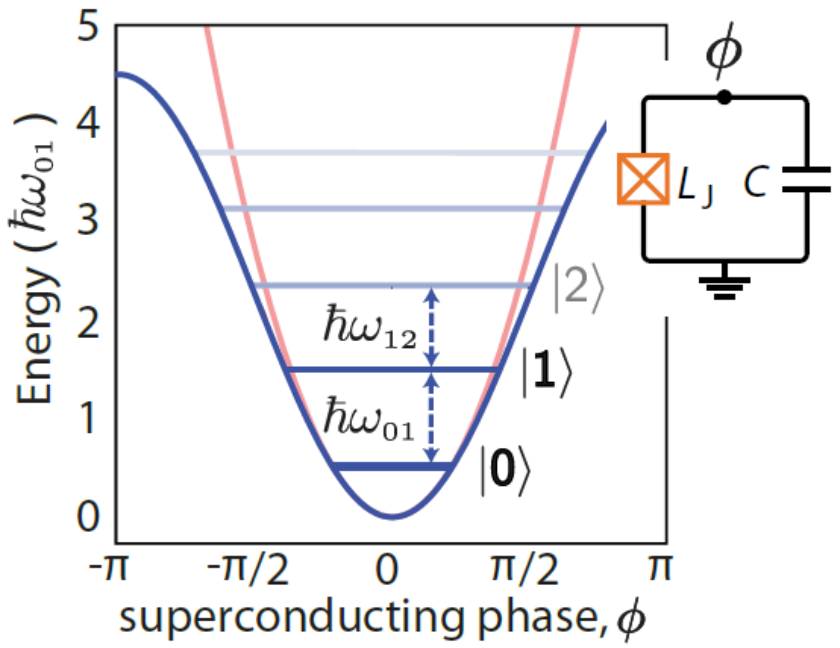


Low temperature
T ~ 20 mK
⇩
Ultra-low noise
$k_B T \ll \hbar\omega$



Scalability
Planar microfabrication techniques
⇩
On-chip circuits

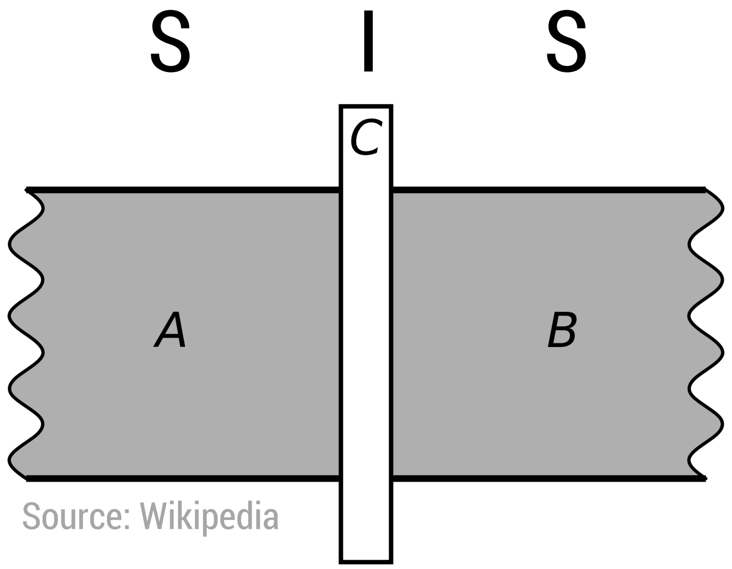
Non-linearity
Element: Josephson junction
⇩
Non-equidistant energy levels



The Josephson junction

Talk by Marcello Faggionato
Amplification-Free System for High-Resolution Josephson Junctions' Characterization

Talk by Federico Paolucci
Next Generation Quantum Detectors for Low Energy Astroparticle Physics (QuLEAP)



Source: Wikipedia

$$\psi_A = \sqrt{n_A} e^{i\phi_A} \qquad \psi_B = \sqrt{n_B} e^{i\phi_B}$$

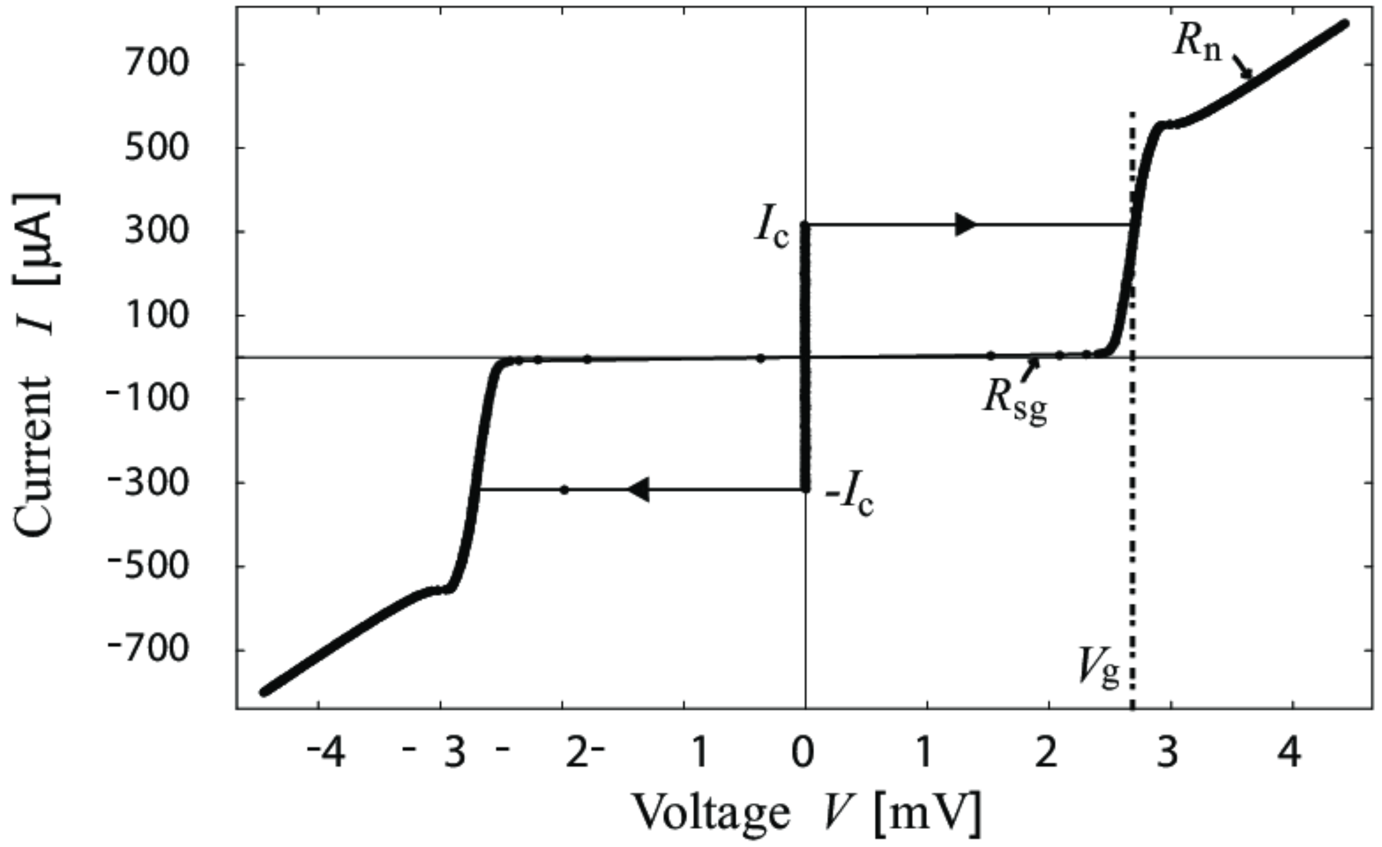
$$\varphi \equiv \phi_B - \phi_A$$

Josephson equations

$$I(t) = I_c \sin(\varphi(t))$$

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

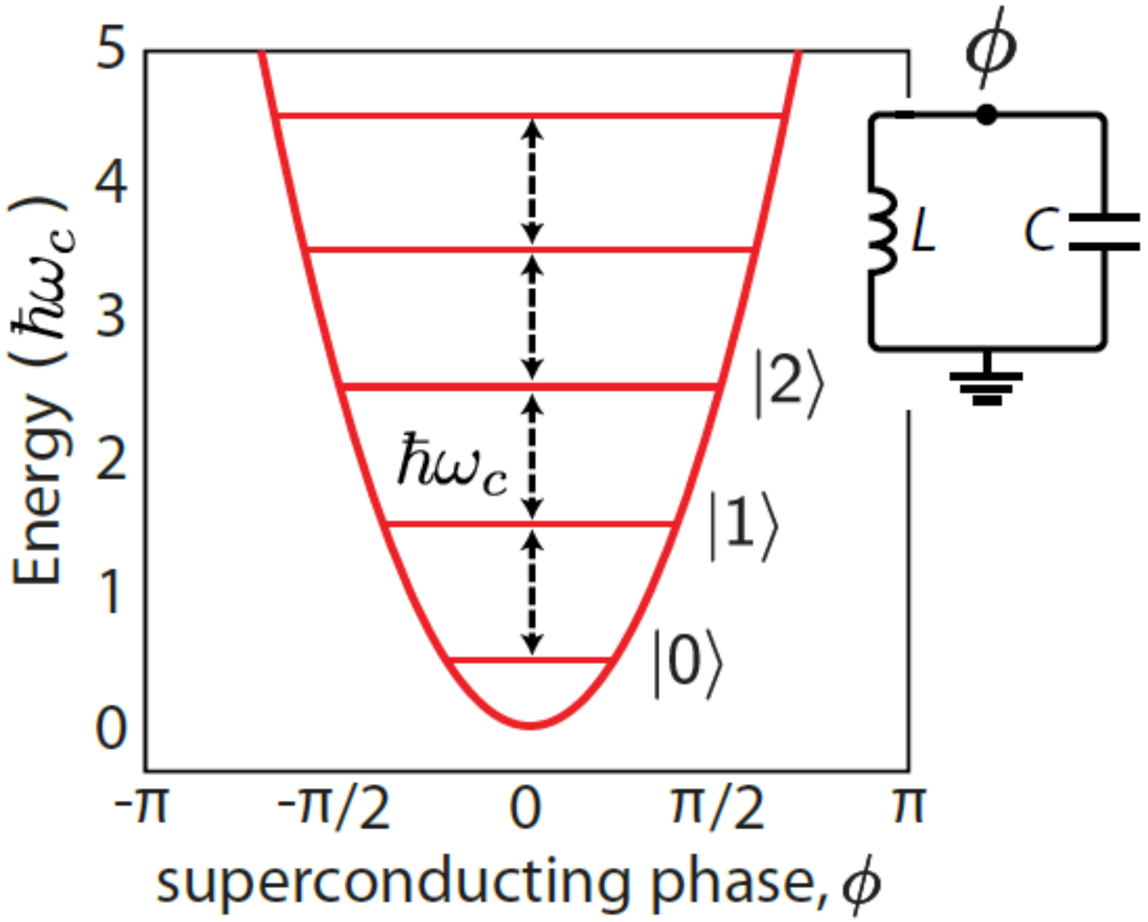
$$V = \frac{\Phi_0}{2\pi \cdot I_c \cdot cos\varphi} \cdot \frac{dI}{dt} = L_J(\varphi) \cdot \frac{dI}{dt}$$



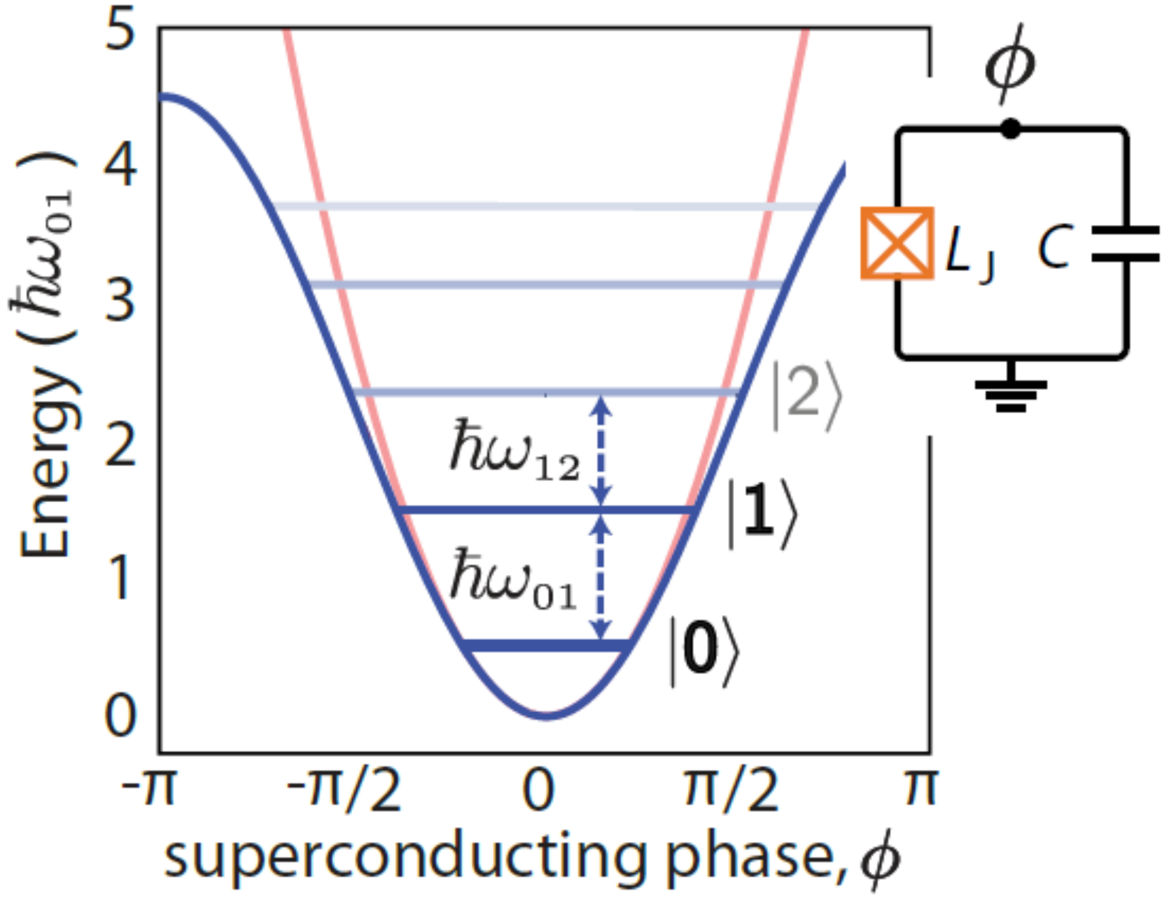
non-linear and tunable inductance

Superconducting qubits

$$H = 4E_C N^2 + \frac{E_L}{2}\varphi^2$$



$$H = 4E_C N^2 - E_J \cos\varphi$$



Josephson junction!

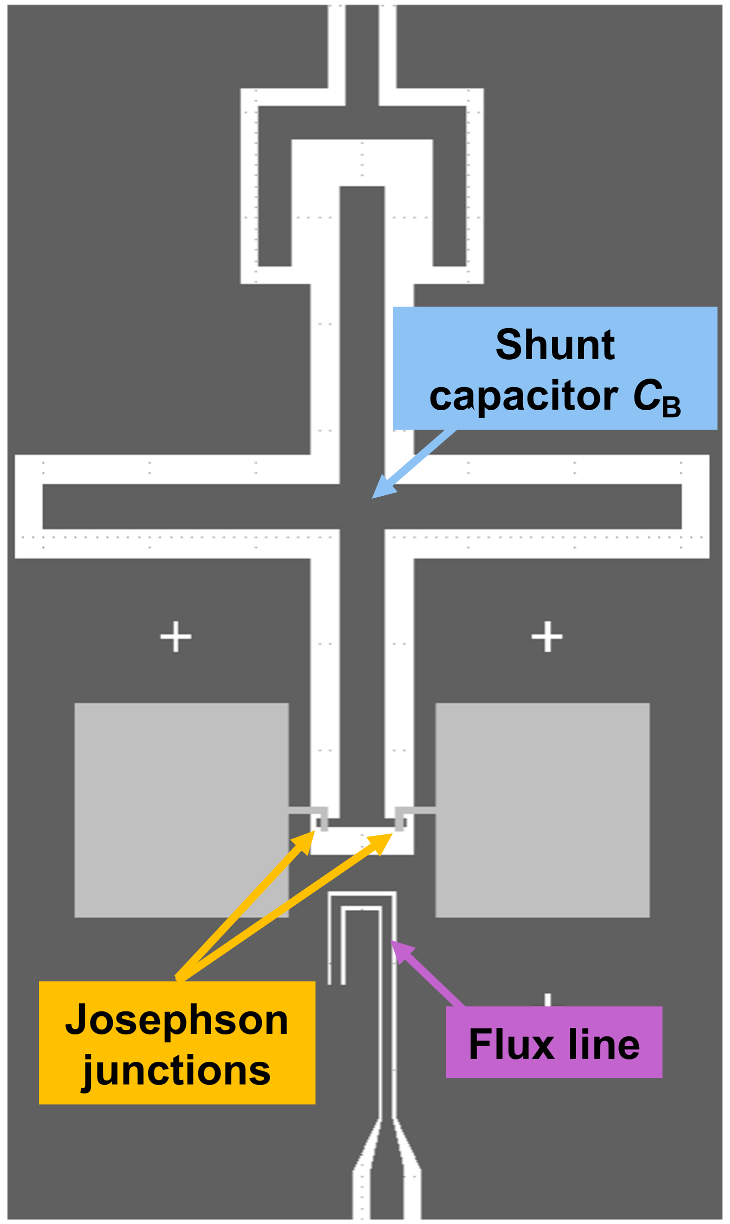
→ Quantised **non**-equidistant energy levels

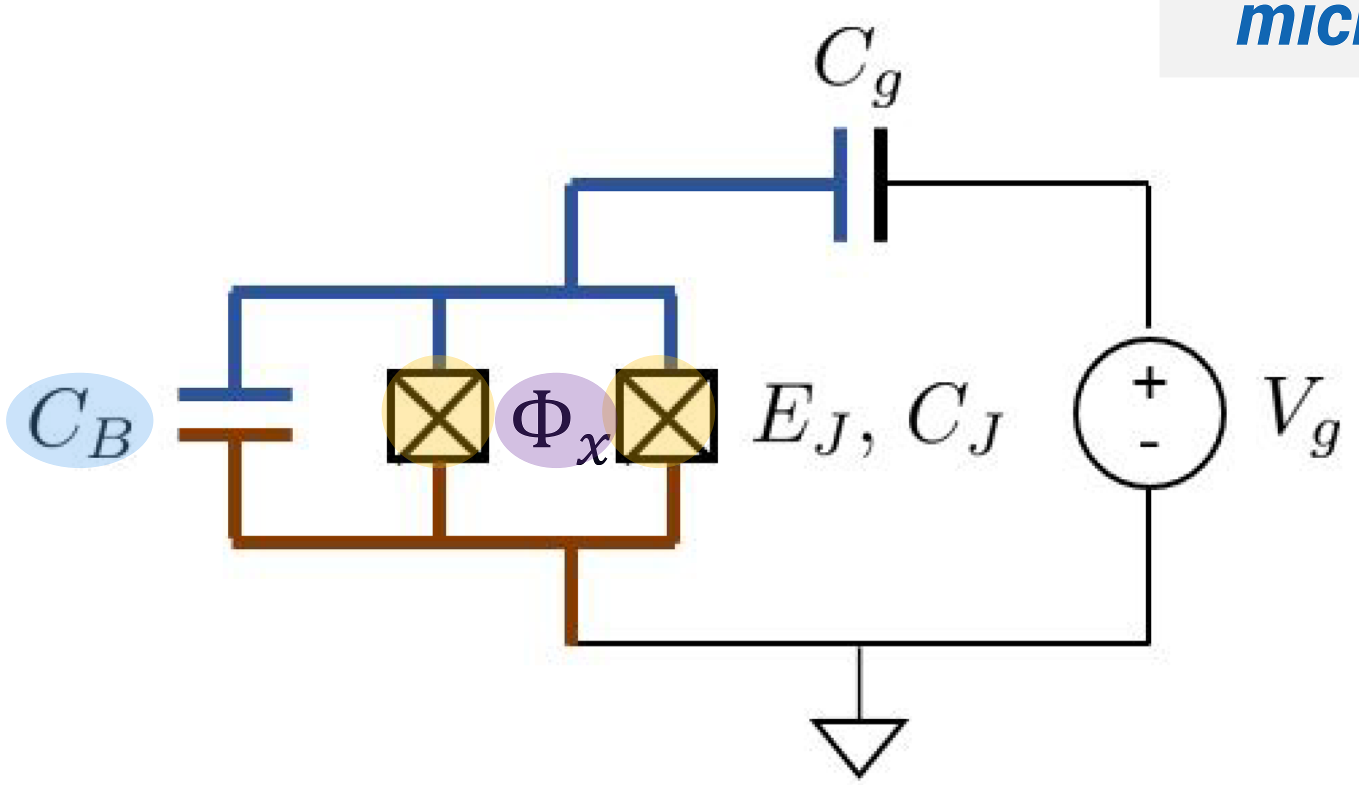
→ possible to address the transitions individually

Transmon qubits

Talk by Danilo Labranca
Development and Analysis of Transmon Qubits for Quantum Sensing applications

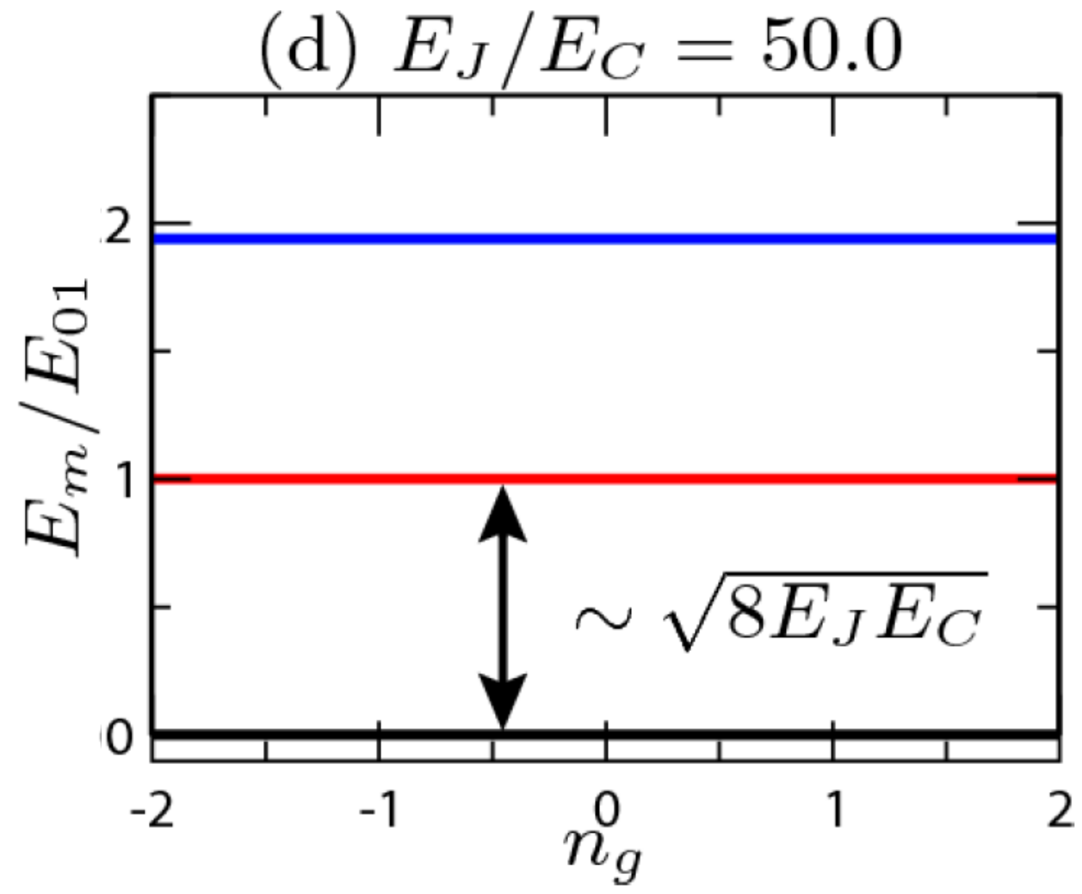
Talk by Caterina Braggio
Superconducting circuits in axion dark matter search: microwave photon counting with transmon qubits





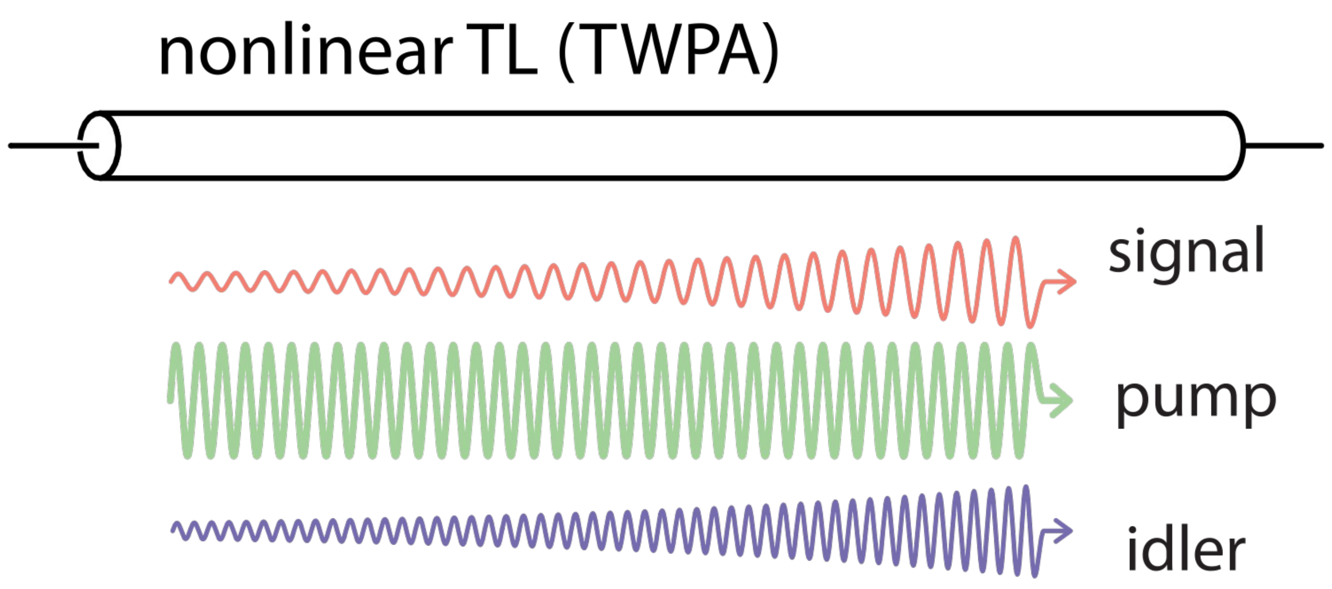
$$H = 4E_C(n - n_g)^2 - E_J \cos\varphi$$

Transmon regime: $E_J/E_C \gg 1$



Travelling Wave Parametric Amplifiers

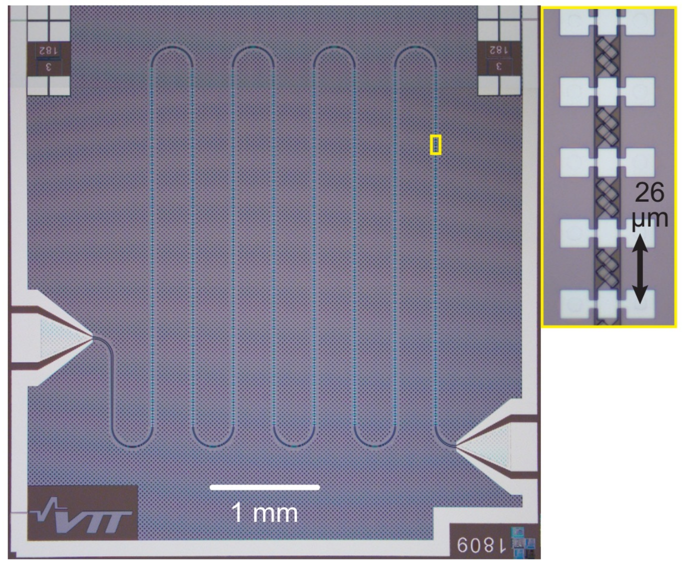
TWPA =
transmission line with embedded non-linear elements



Josephson inductance

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

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

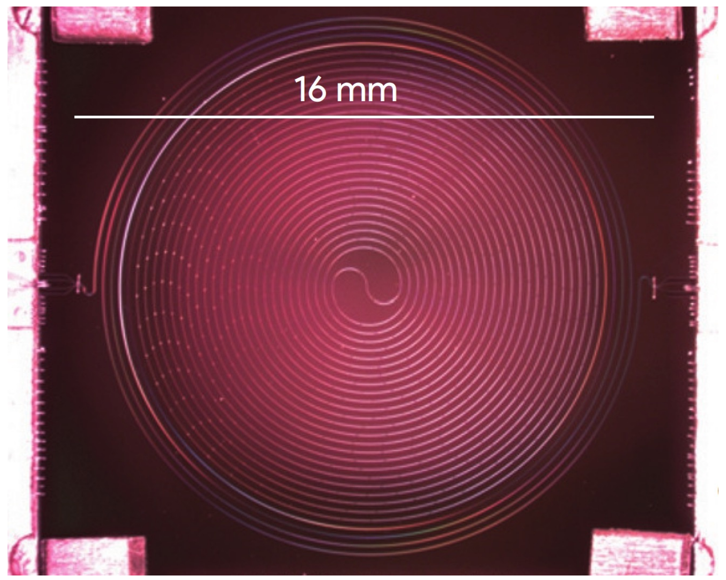


Rev. Sci. Instrum. 92, 034708 (2021)

Kinetic inductance

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

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



Nature Phys 8, 623–627 (2012)

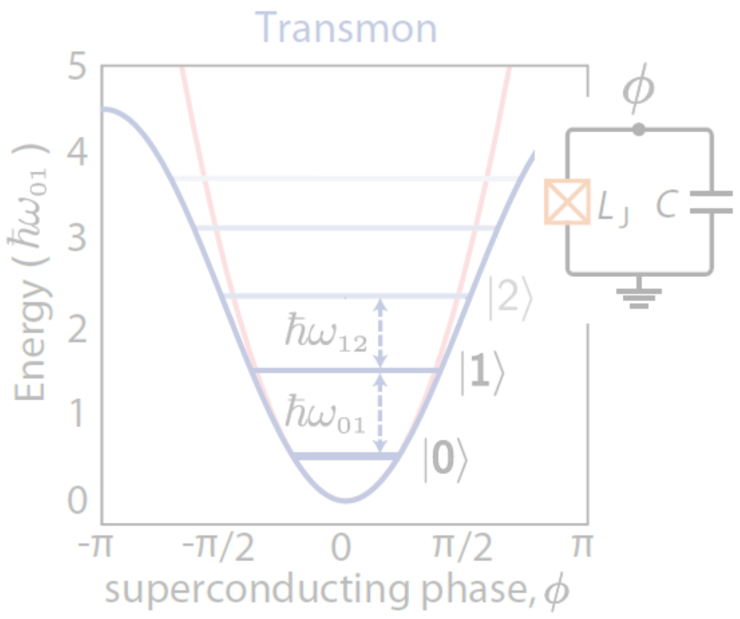
QUANTUM-LIMITED AMPLIFIERS
⇒ detectors/qubits read-out

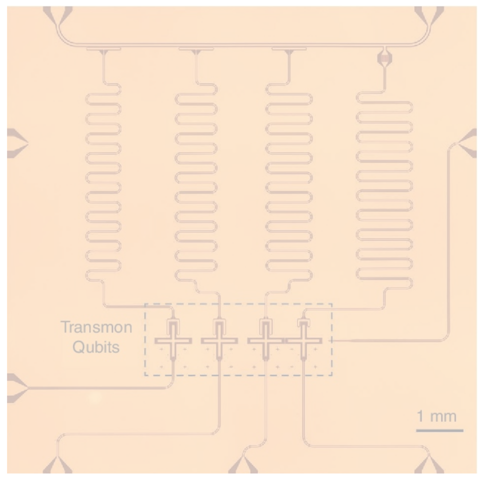
MICROWAVE SQUEEZING & ENTANGLEMENT
⇒ quantum sensing

What is quantum sensing?

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

  → **quantum circuits and qubits**





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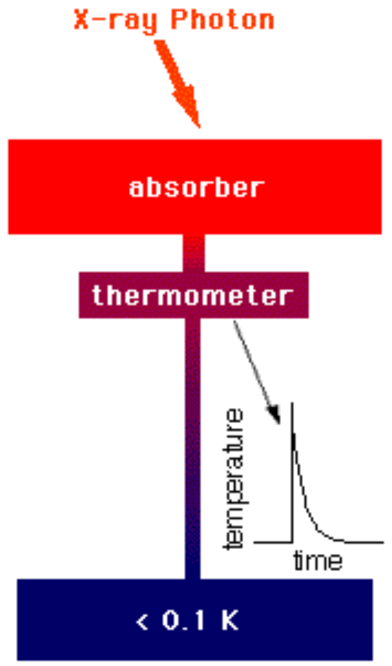
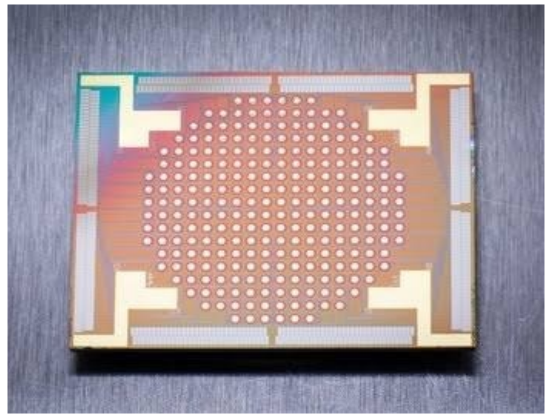




Superconducting cryogenic sensors: motivation

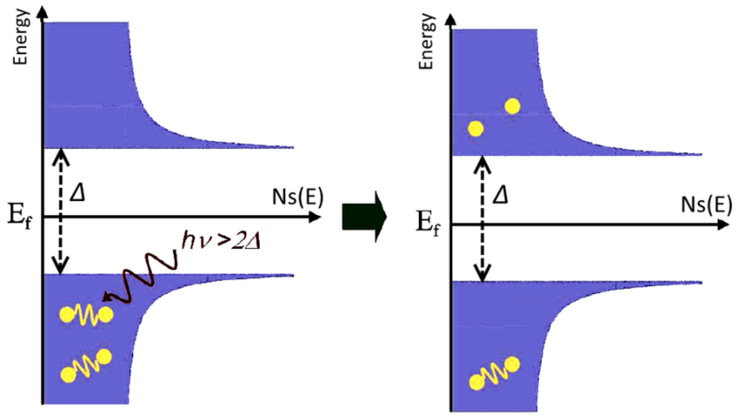
Superconductivity offers:

Small energy gap of Cooper pairs

↓

$\Delta_0 = 1.76 k_B T_c$

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



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

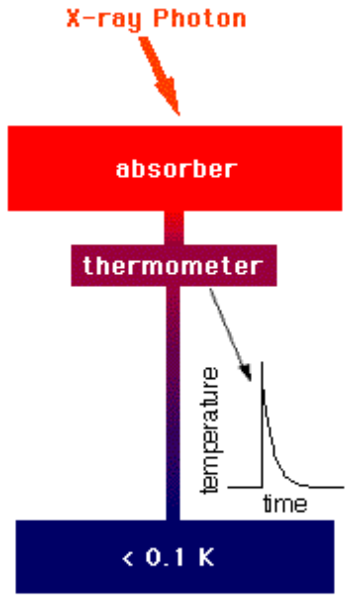
Small heat capacity

$C_e \propto T$

↓

Sensitive **calorimeters**

$\Delta T = E/C$



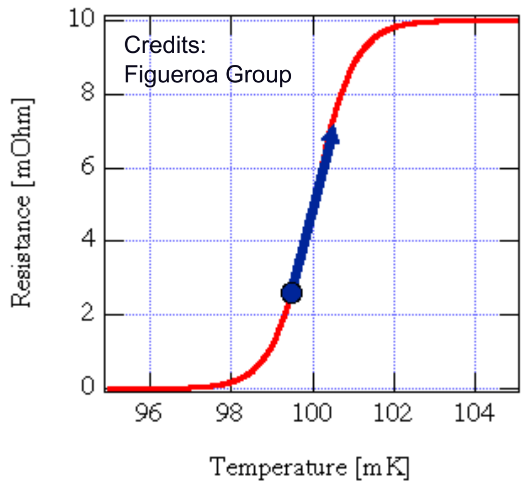
Credits: NASA

Sharp superconducting transition

↓

Sensitive **thermometer**

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



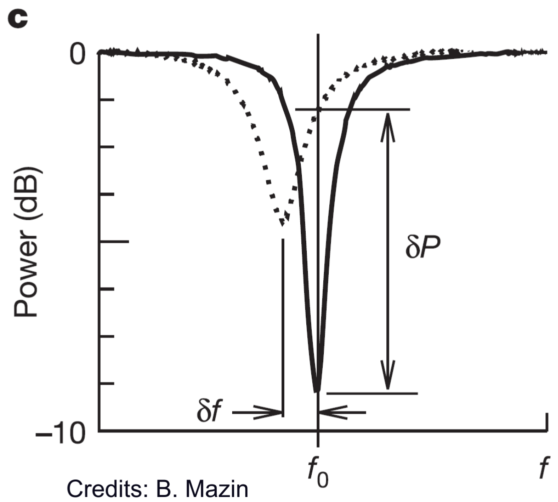
Change of kinetic inductance

$L_k \propto 1/n_S$

↓

Detection using LC **resonator**

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



Credits: B. Mazin

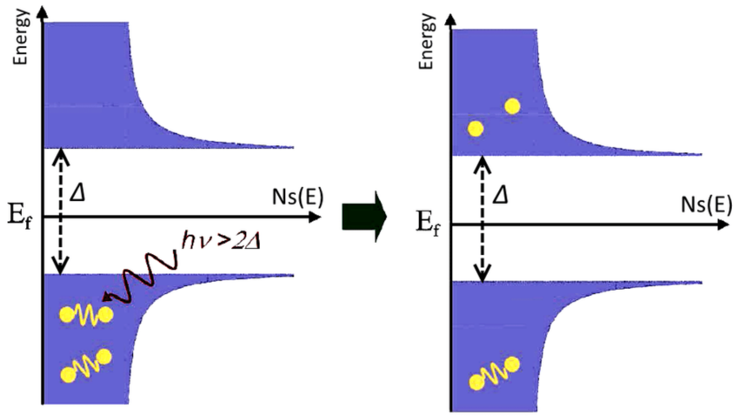
Superconducting Nanowires Single Photon Detectors

Small energy gap
of Cooper pairs

⇩

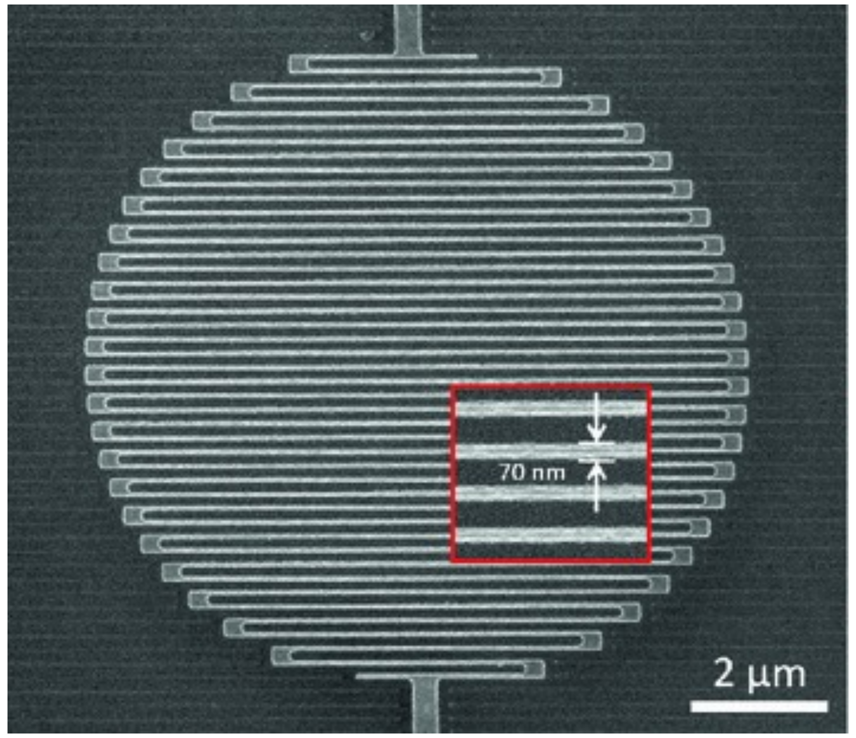
$$\Delta_0 = 1.76 k_B T_c$$

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



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

Superconducting Nanowires Single Photon Detectors (SNSPDs)



Talk by Leonardo Limongi

Photon Number-Resolving Detectors for Integrated Quantum Sensing

Superconducting cryogenic sensors: motivation

Superconductivity offers:

Small energy gap of Cooper pairs

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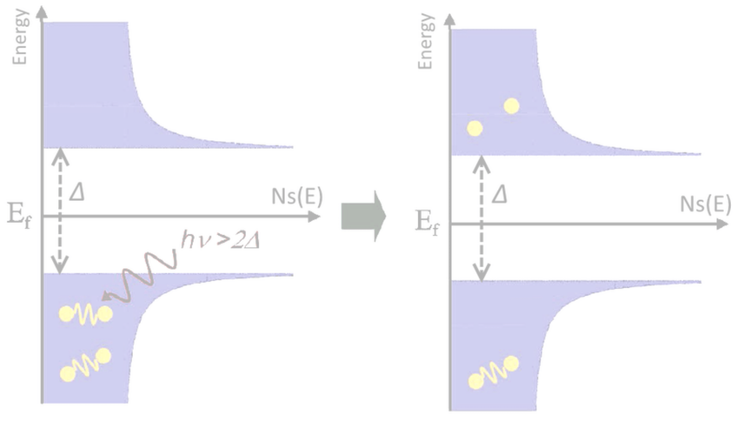


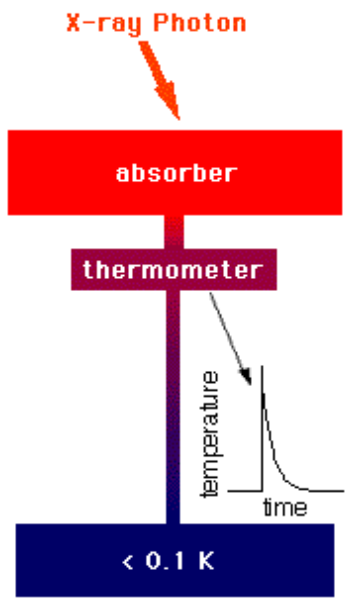
Credits: 10.1088/1742-6596/664/8/082007

Small heat capacity

$C_e \propto T$

Sensitive **calorimeters**

$\Delta T = E/C$

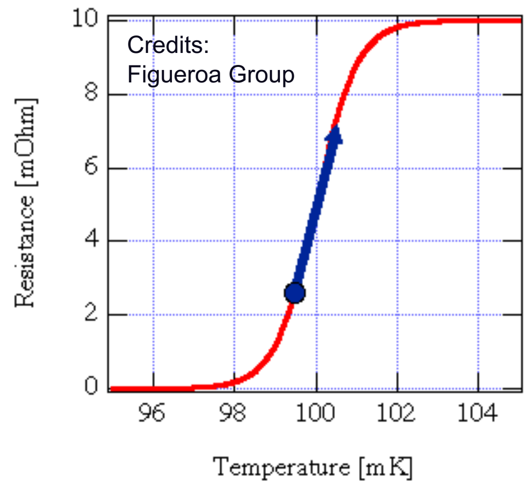


Credits: NASA

Sharp superconducting transition

Sensitive **thermometer**

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



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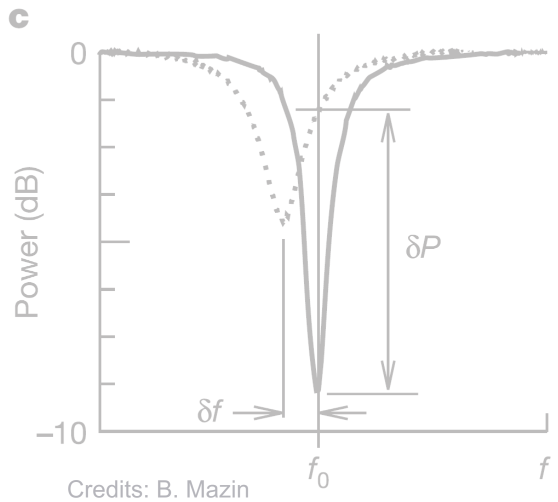

Credits: B. Mazin

Microcalorimeters

Small heat capacity
$C_e \propto T$

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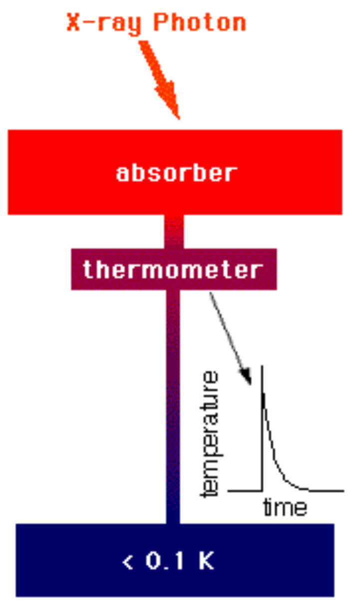
$\Delta T = E/C$



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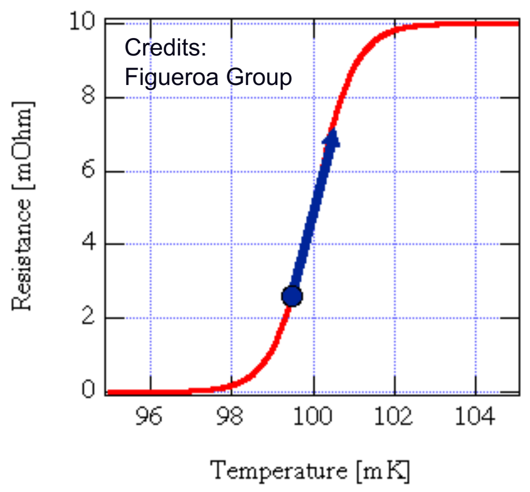
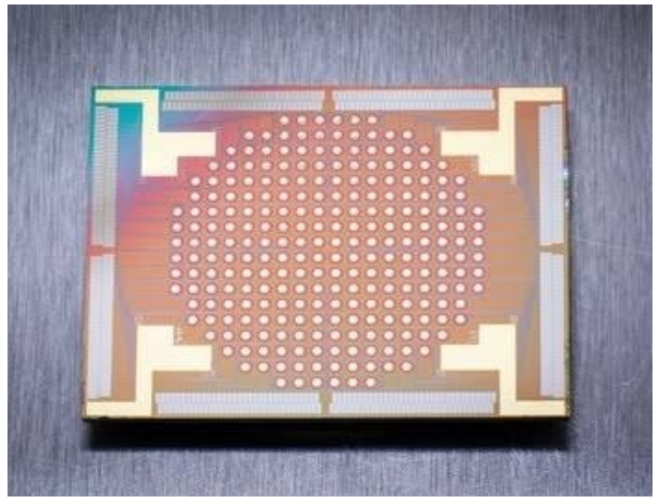
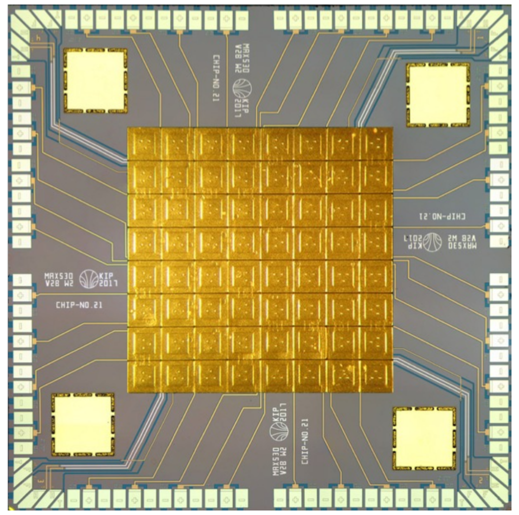


Microcalorimeters
$\Delta T = E/C$

Transition Edge Sensors (TESs)



Metallic Magnetic Calorimeters (MMCs)



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⇩

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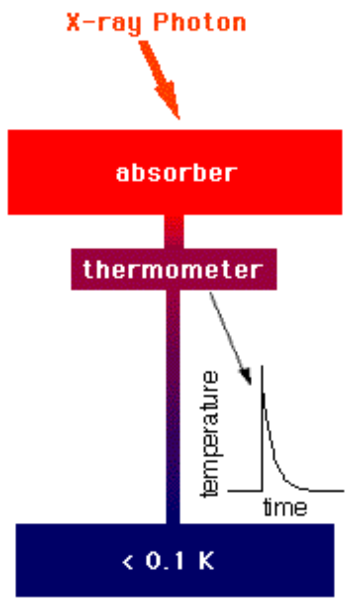

Credits: NASA

Sharp superconducting transition

⇩

Sensitive **thermometer**
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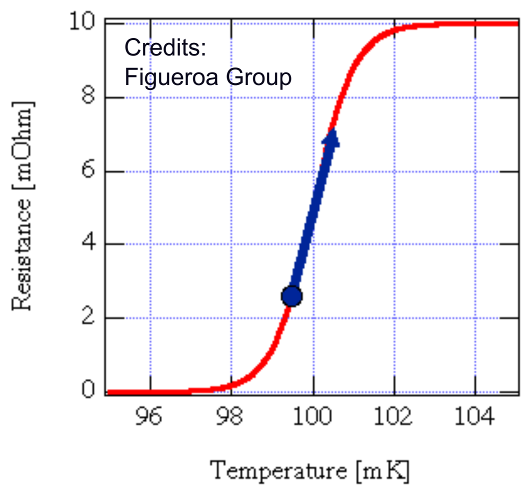

Microcalorimeters
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Transition Edge Sensors
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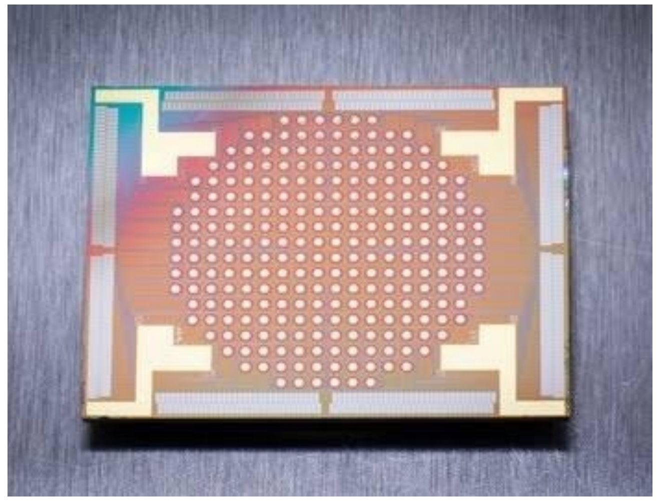
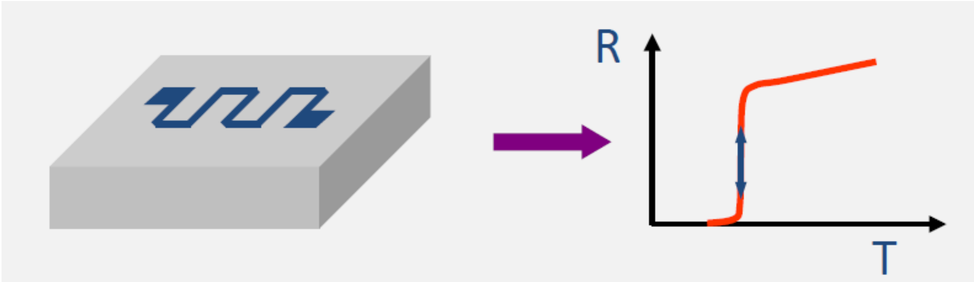


Resistance of superconducting transition



Talk by Mario De Lucia
Superconducting detectors for frontier physics

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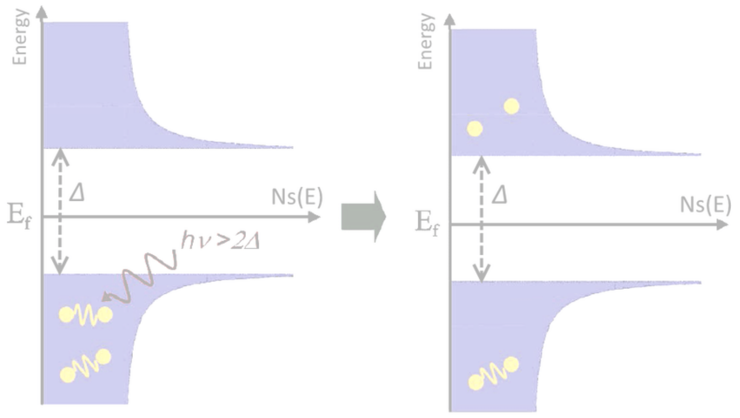

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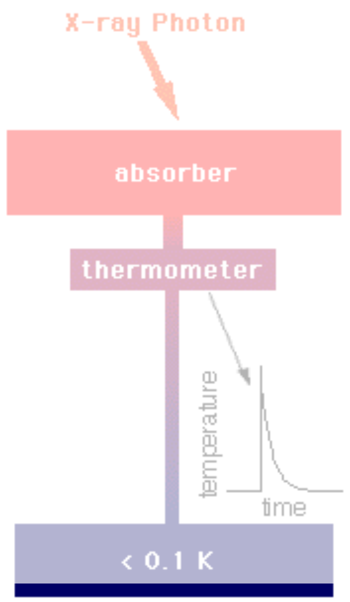
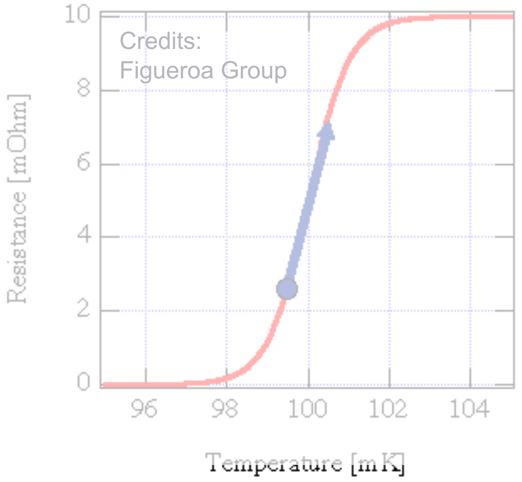


Credits: NASA

Sharp superconducting transition

Sensitive **thermometer**

dR/dT



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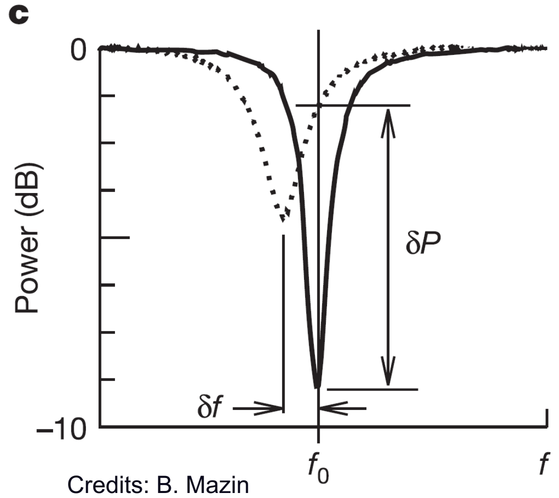


Credits: B. Mazin

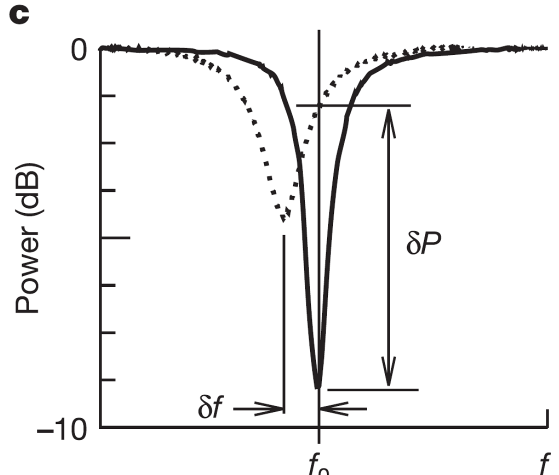
Kinetic Inductance Detectors & Current Sensors

Change of kinetic inductance

$L_k \propto 1/n_S$

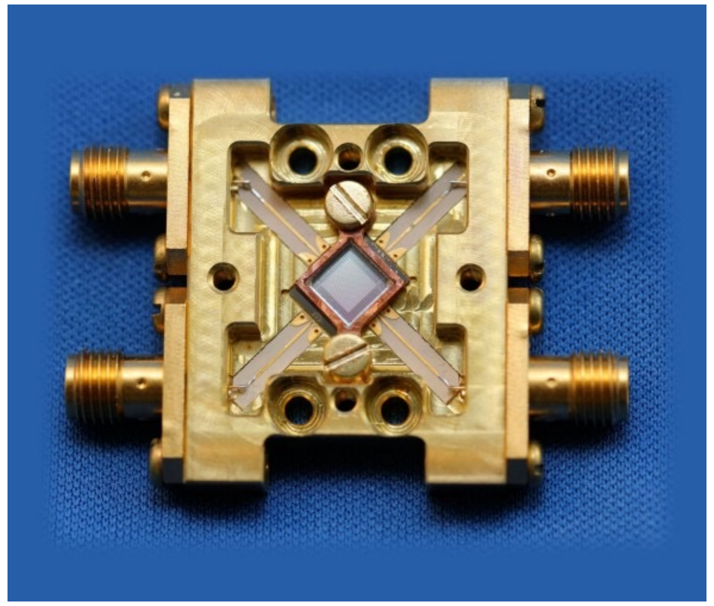
Detection using LC **resonator**

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

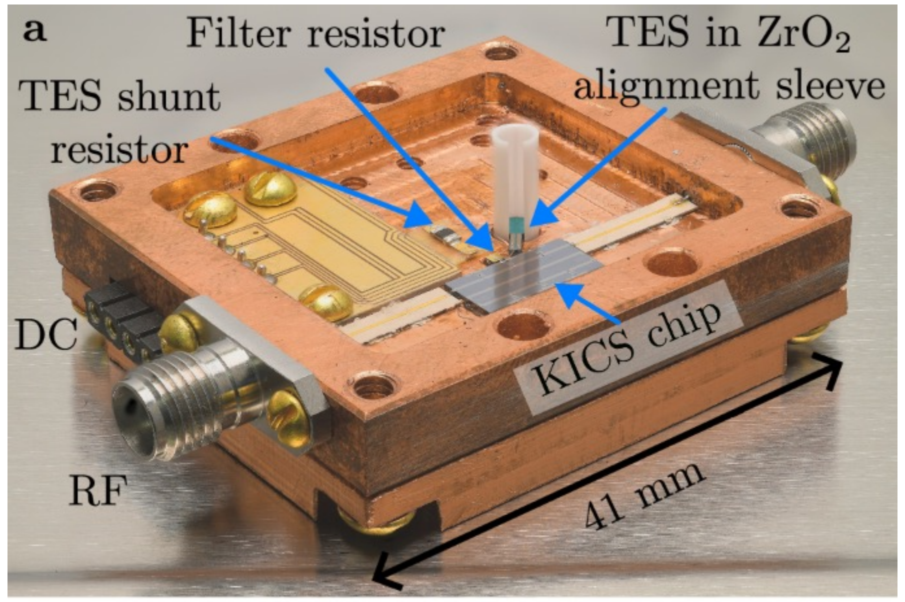


Credits: B. Mazin

Kinetic Inductance Detectors (KIDs)



Kinetic Inductance Current Sensors (KICS)



Talk by Enrico Bogoni

Kinetic inductance circuits for quantum sensing

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

Different sensing schemes exploits **different properties** of superconducting circuits

ENJOY THE SESSION!