Development and Characterisation of TESs and JESs for Ultra-Sensitive Low-Energy Radiation Detection

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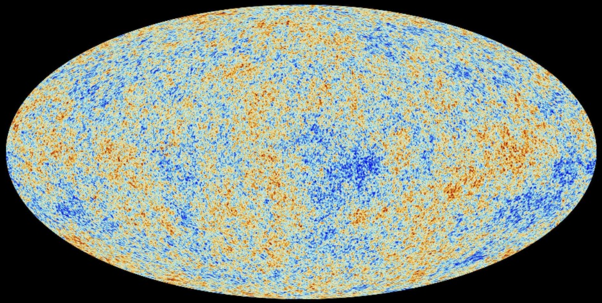
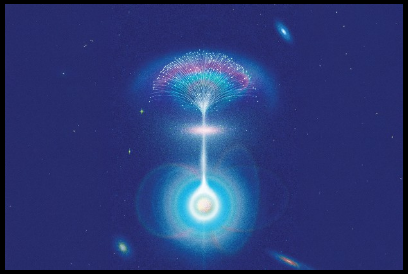
Motivation



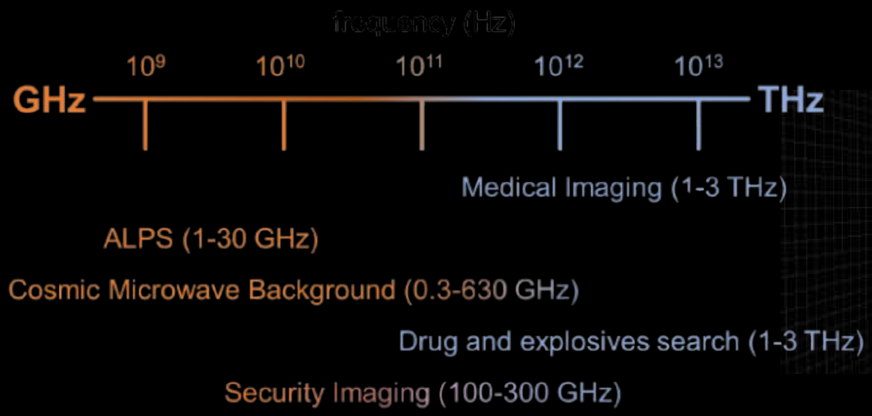


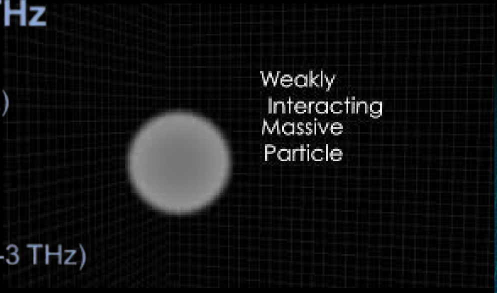
Dark Matter ?

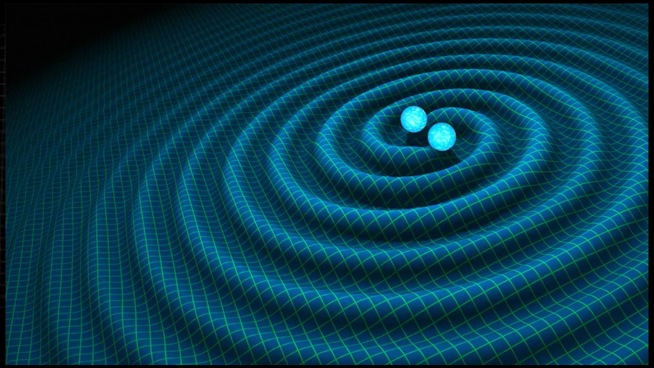
State of the art
Bol: $NEP \sim 1 \cdot 10^{-19}\, W/Hz^{1/2}$
Cal: $\delta E \sim 150\, meV$

$\Downarrow$

Aim
Bol: $NEP \sim 1 \cdot 10^{-20}\, W/Hz^{1/2}$
Cal: $\delta E \sim 400\, \mu eV$

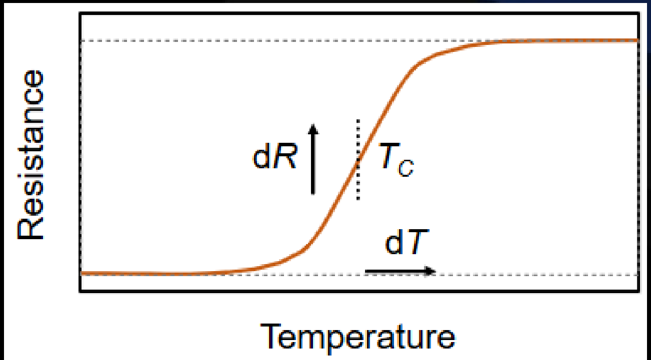


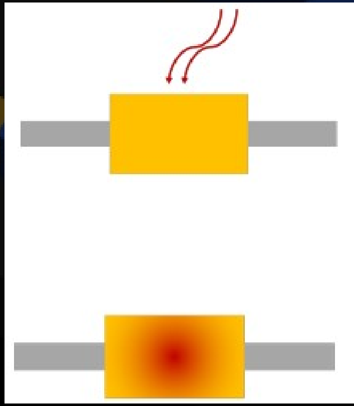


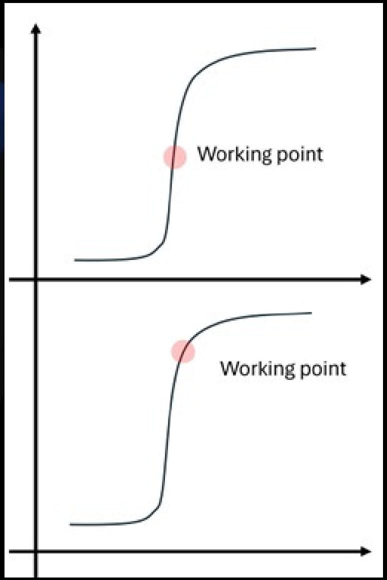


Transition Edge Sensor (TES)

TES = an ultra sensitive electronic thermometer at cryogenic temperatures, which causes a change to electric current in response to a temperature change.



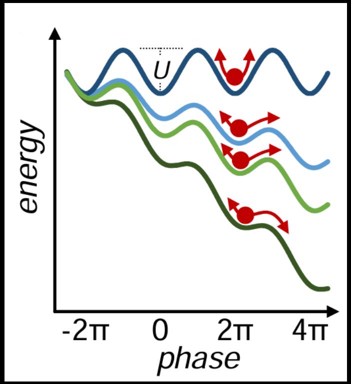


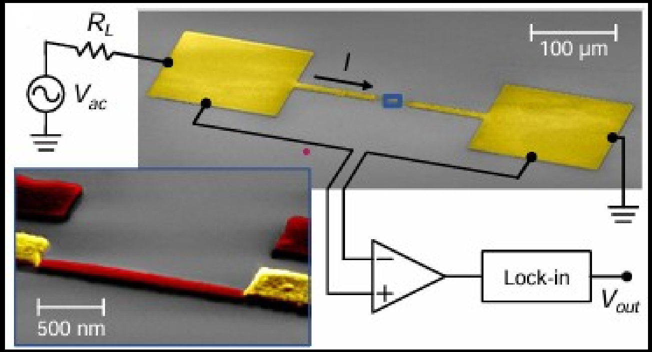


De Lucia, Mario, et al. "Transition edge sensors: Physics and applications." Instruments 8.4 (2024): 47.

Josephson Escape Sensor (JES)

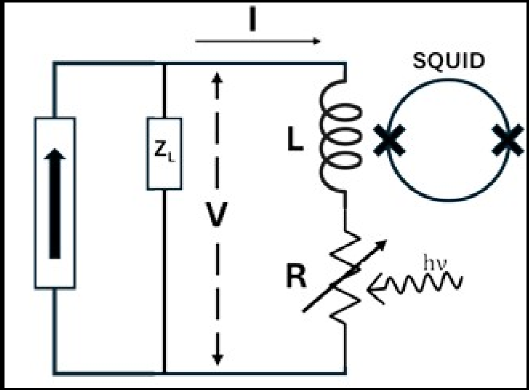
- 1D wire that operates in the fully sc state
- Operation based on the passage from the sc to the normal state
- The working point is set on a stable current not temperature
- Offers possibility to finely tune in situ the working temperature and sensitivity





Phys. Rev. Applied 14, 034055

Basic components

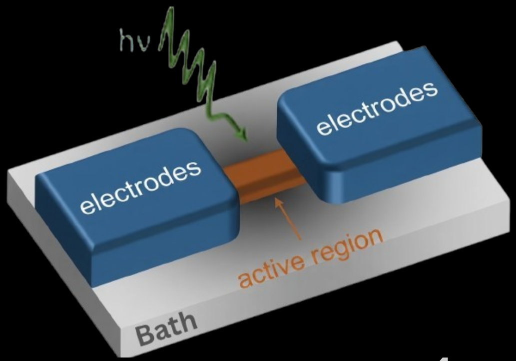


Thermal bath : Allows controlled cooling to the minimum temperature of the system

Thermistor: a sc film (sometimes a SN bilayer for sharp sc transition), measures T rise via resistance change

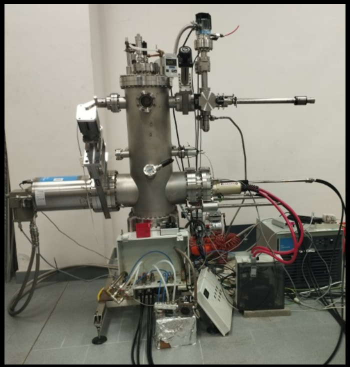
Electrodes: bias the TES and carry the read-out signal (SQUID)

Shunt resistor: a low resistor implementing a voltage-biased negative electro-thermal feedback



Fabrication Equipment

e-beam lithography



e-beam evaporator

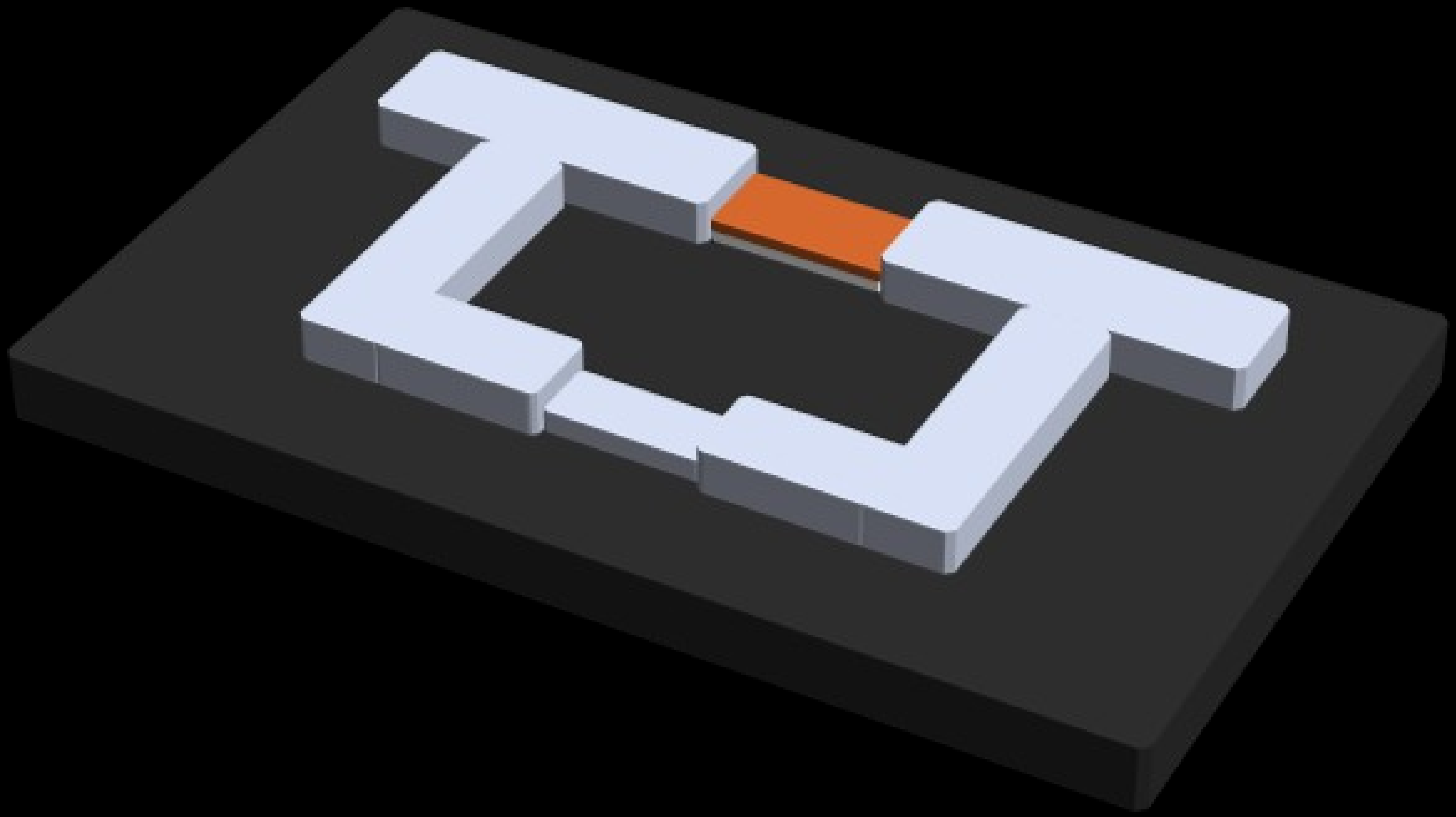
Optical lithography

Plasma etching

thermal evaporator

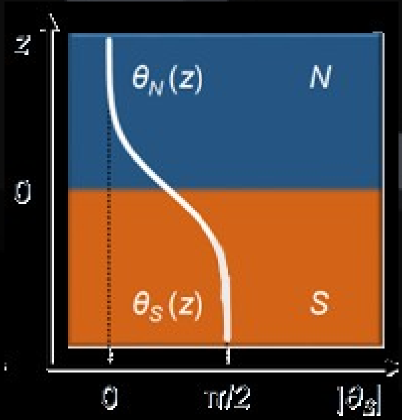
Optical microscope

Thermistor- active region



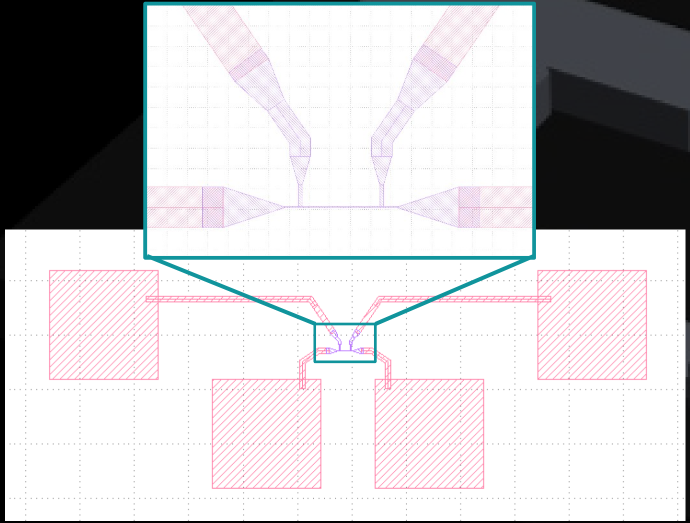
Thermistor- active region

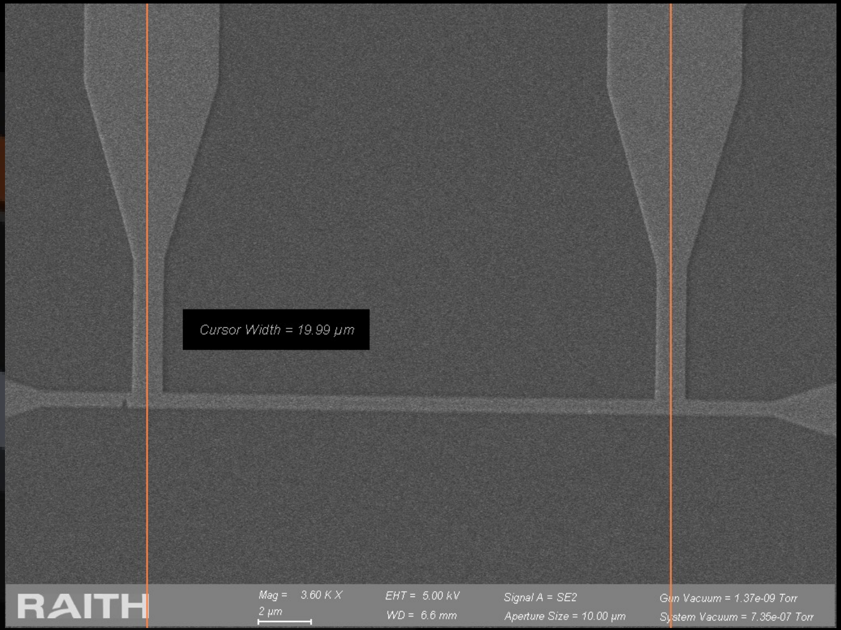
An Aluminium/ Copper Bilayer is employed for the active region, allowing the tuning of the T_c of the transition, and therefore the operation point of the detector.



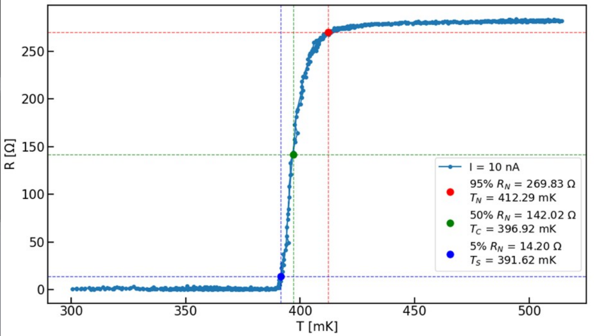
Proximity effect

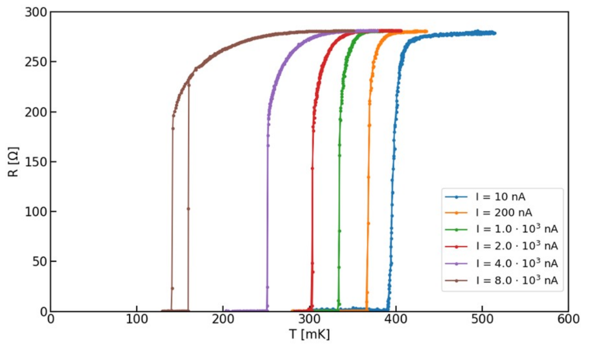
Thermistor- active region

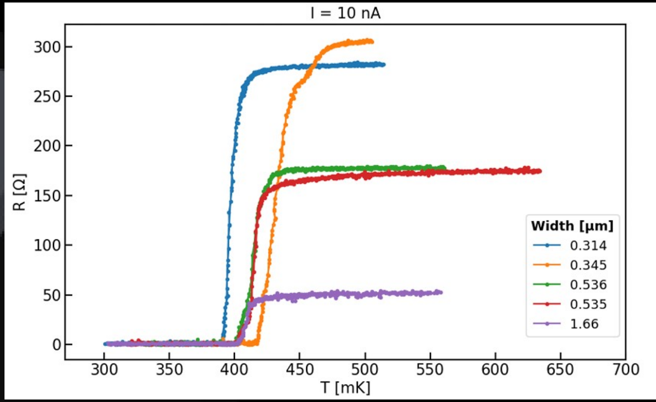




Thermistor- active region

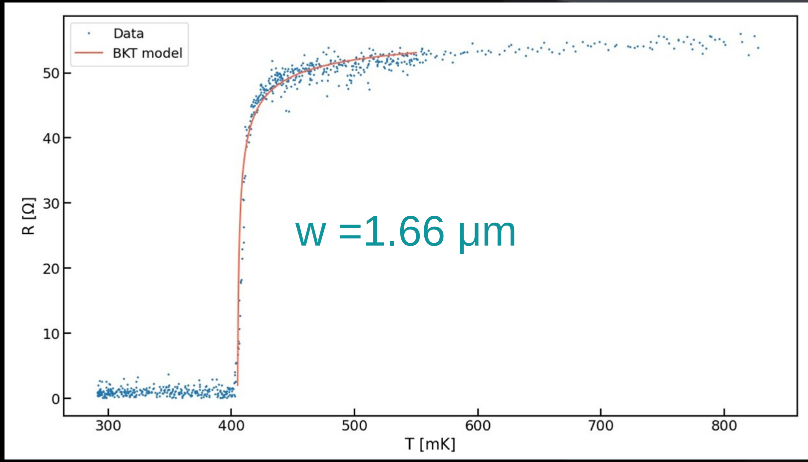


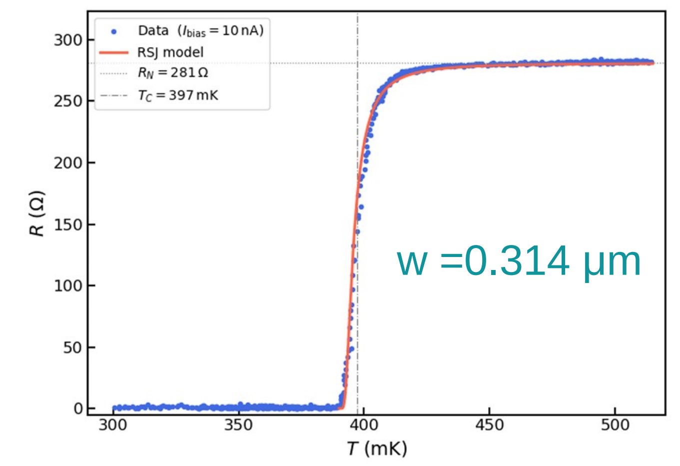




15 nm Al/ 12 nm Cu
W = 250 nm

Thermistor- active region

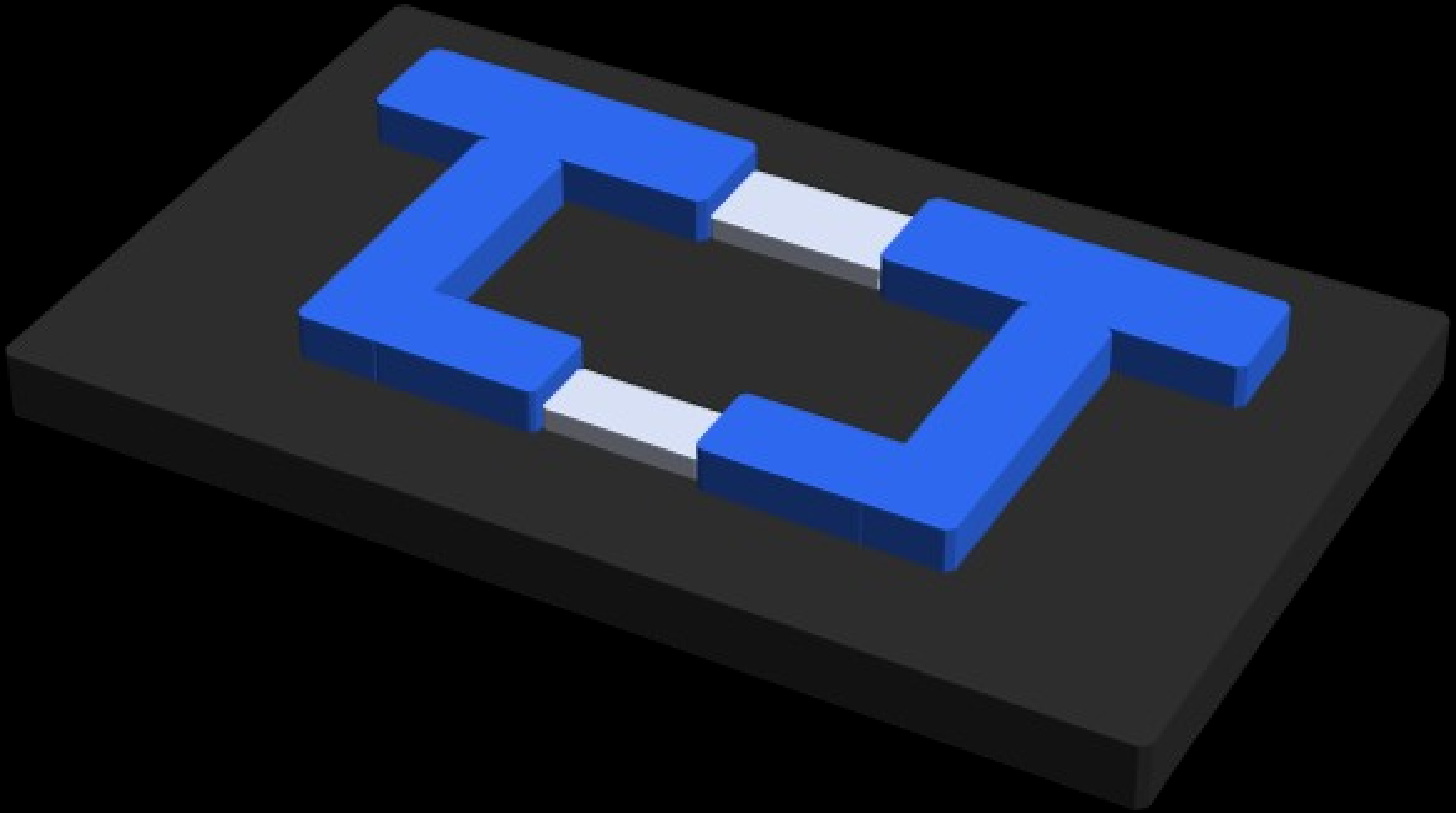




BKT model for dirty 2D superconductors

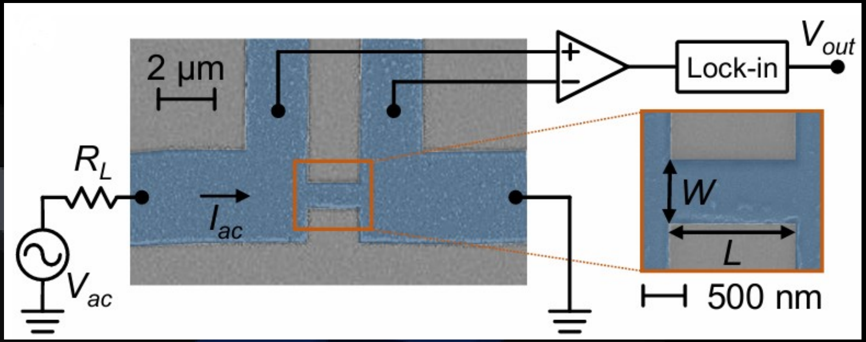
RSJ model for 1D superconducting nanowires

Electrodes



Electrodes

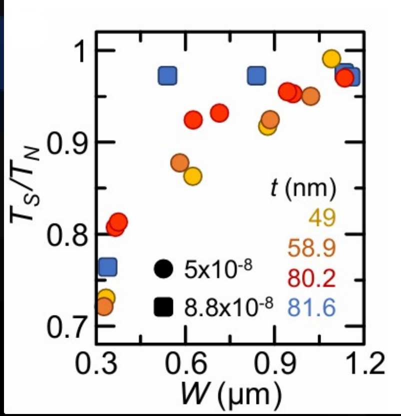
- Aluminium leads (T_c ~ 1.2 K)
- Superconducting at bath temperature



Alternative: Niobium leads

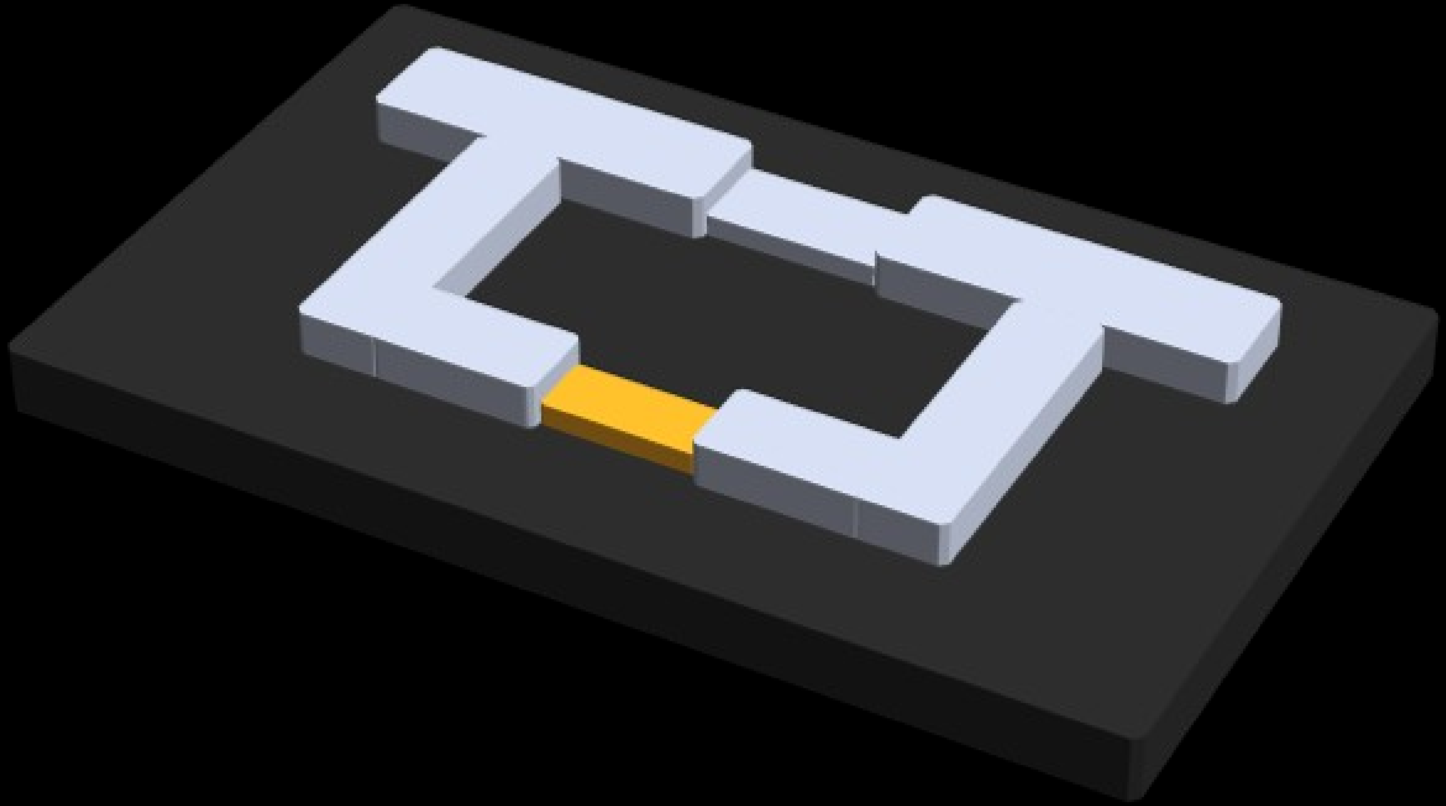
⇩

Higher (T_c ~ 9.2 K) allows higher bath temperature and operation points in higher temperatures.

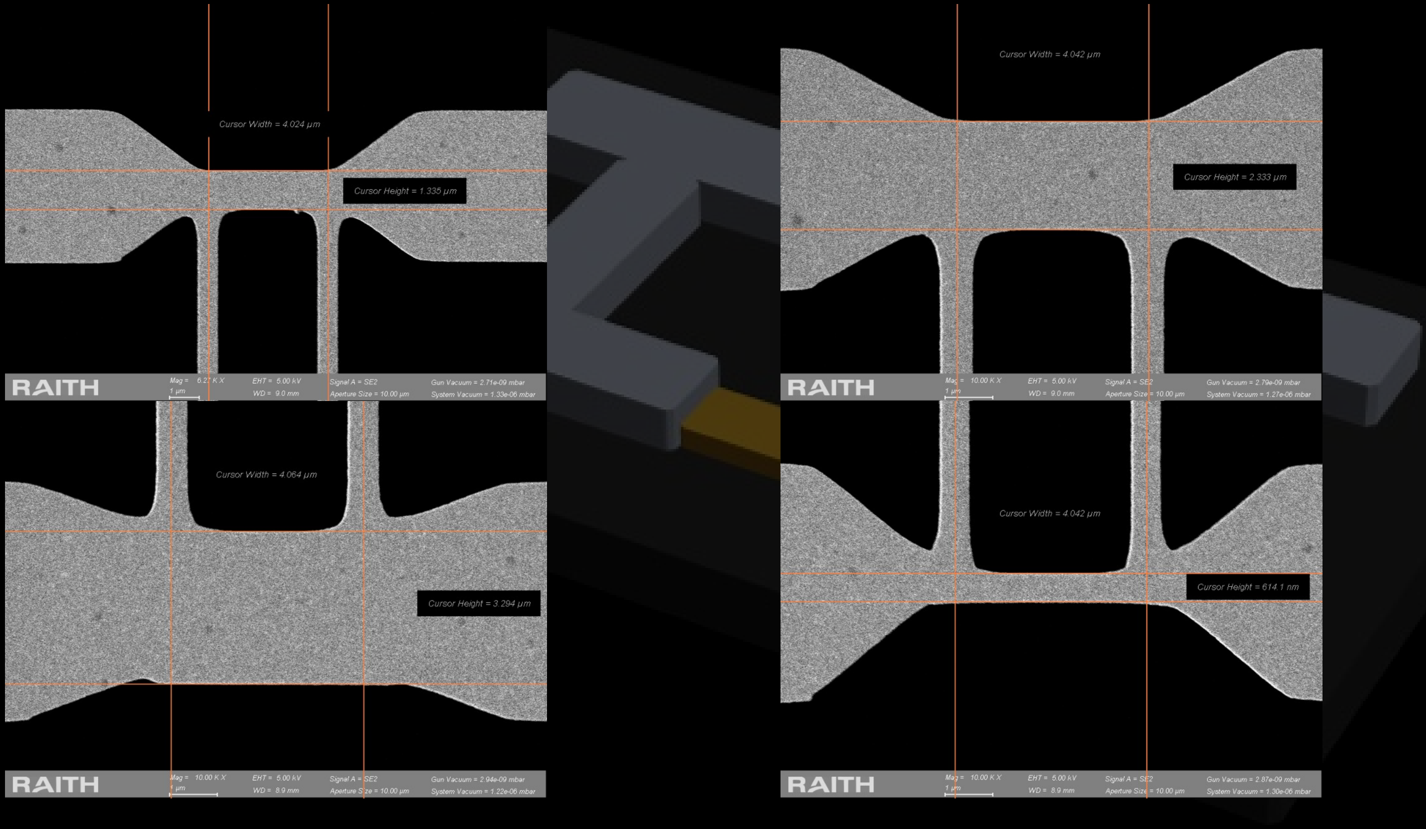


https://arxiv.org/abs/2603.24379

Shunt resistance



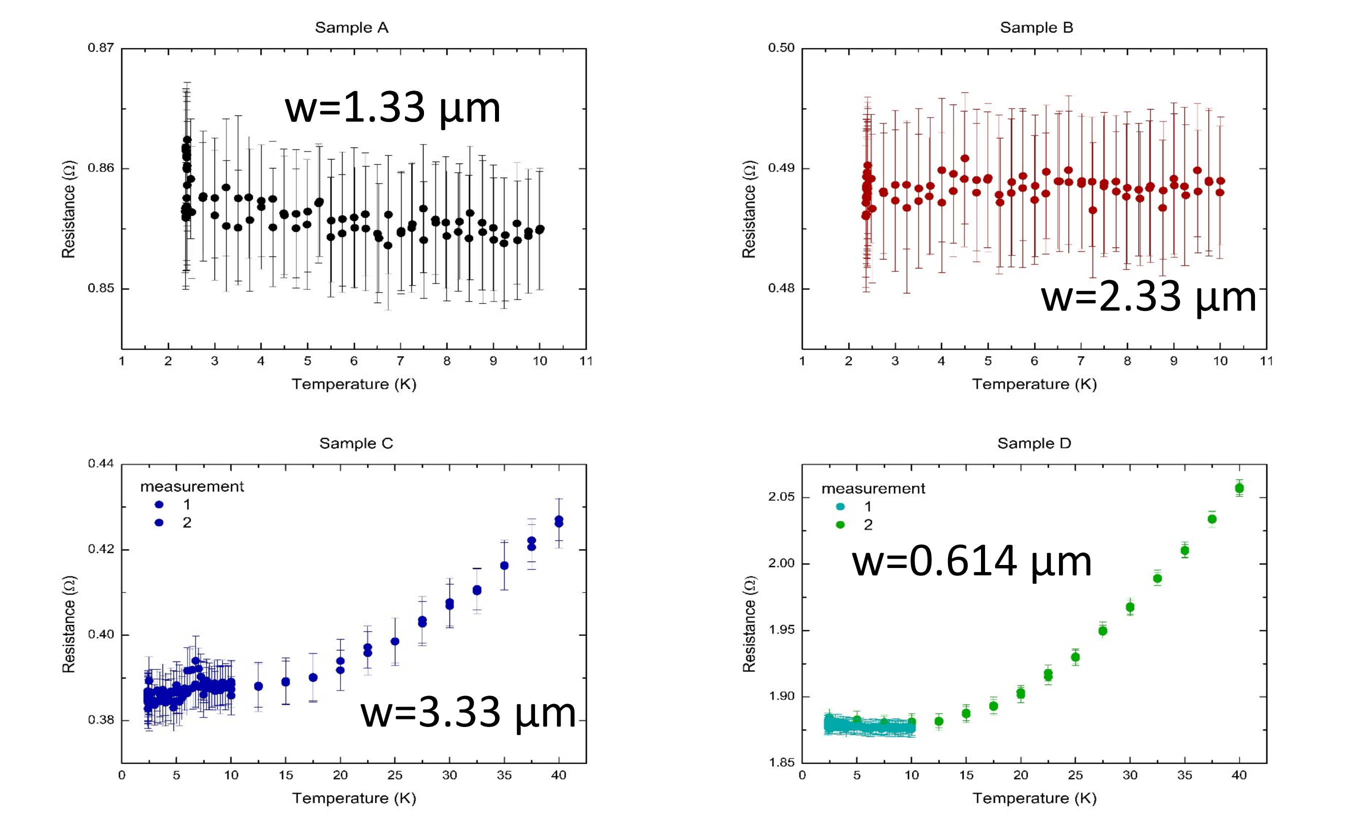
Shunt resistance



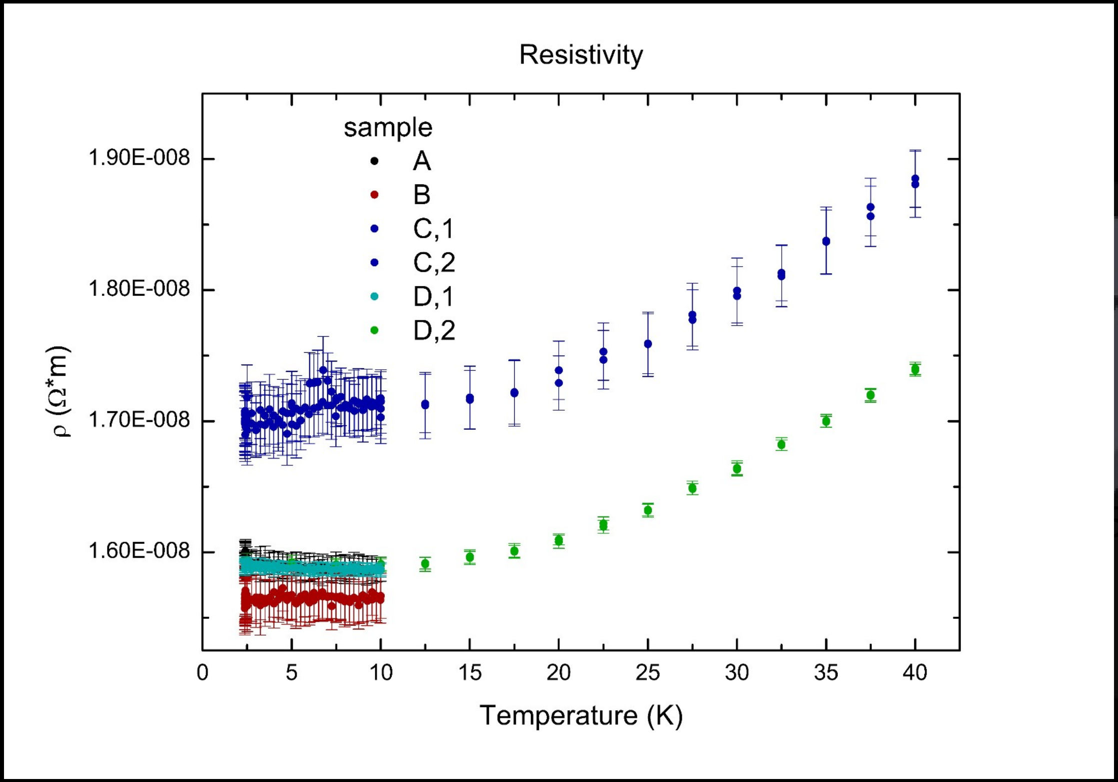
Cr (5 nm) /

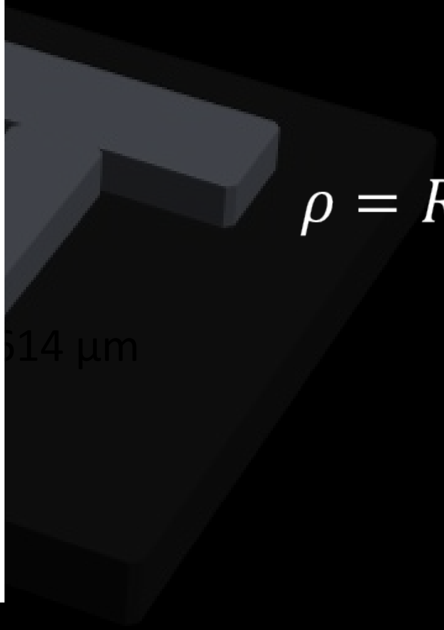
Au (55 nm)

Shunt resistance



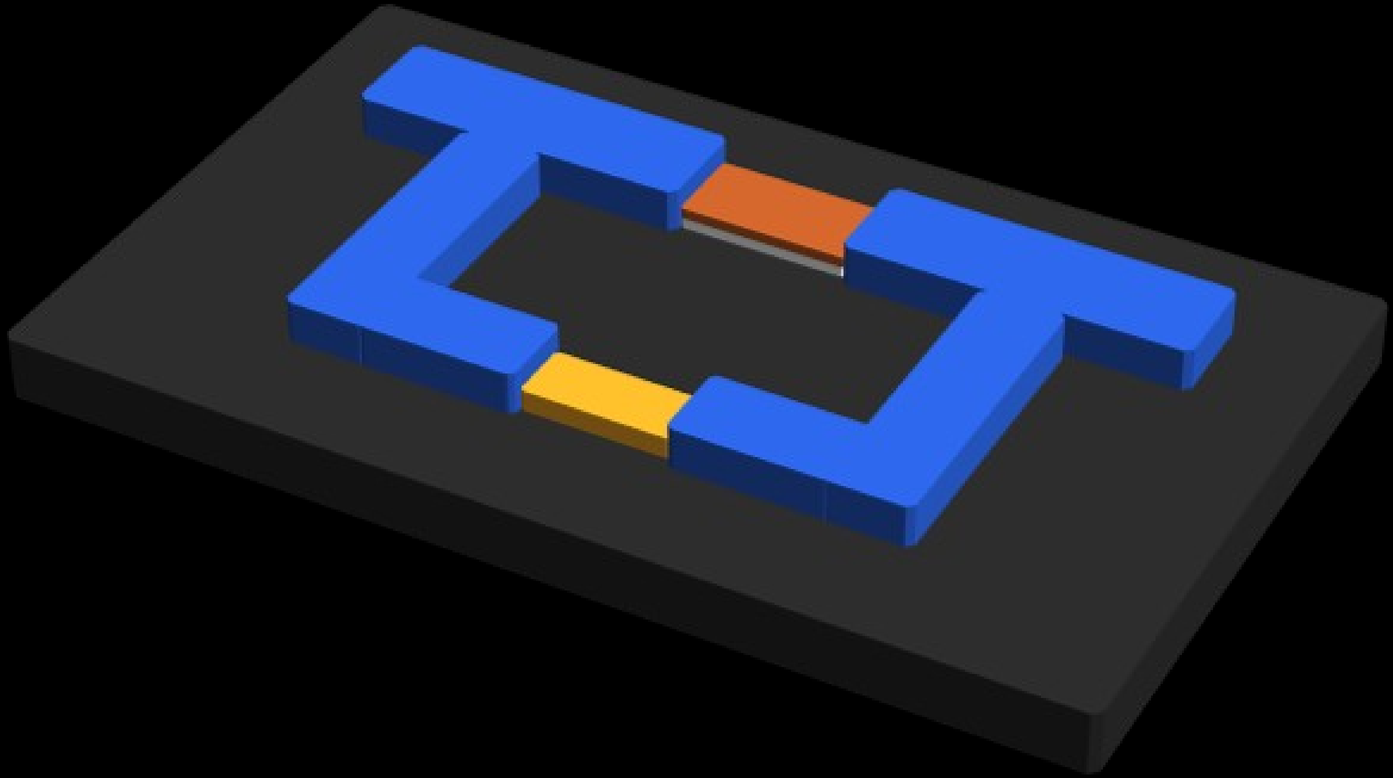
Shunt resistance





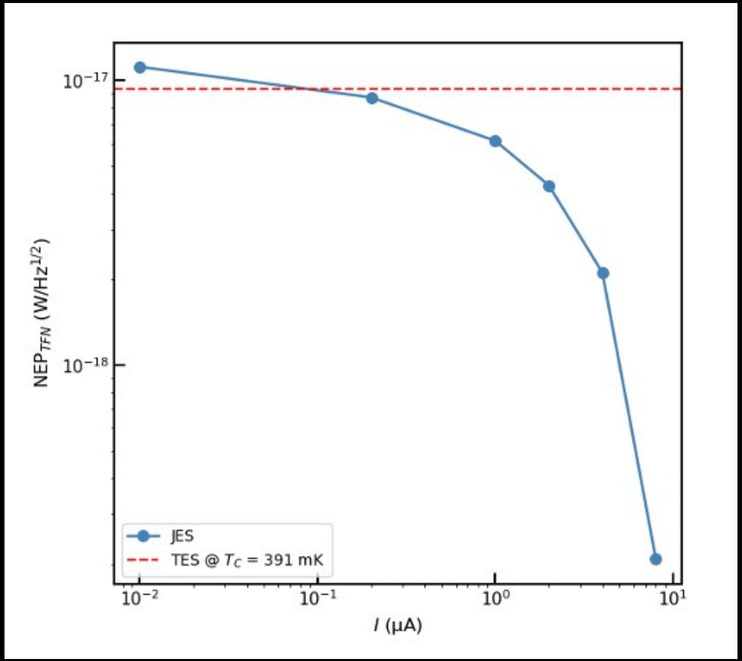
$$\rho = R\frac{t \times w}{l}$$

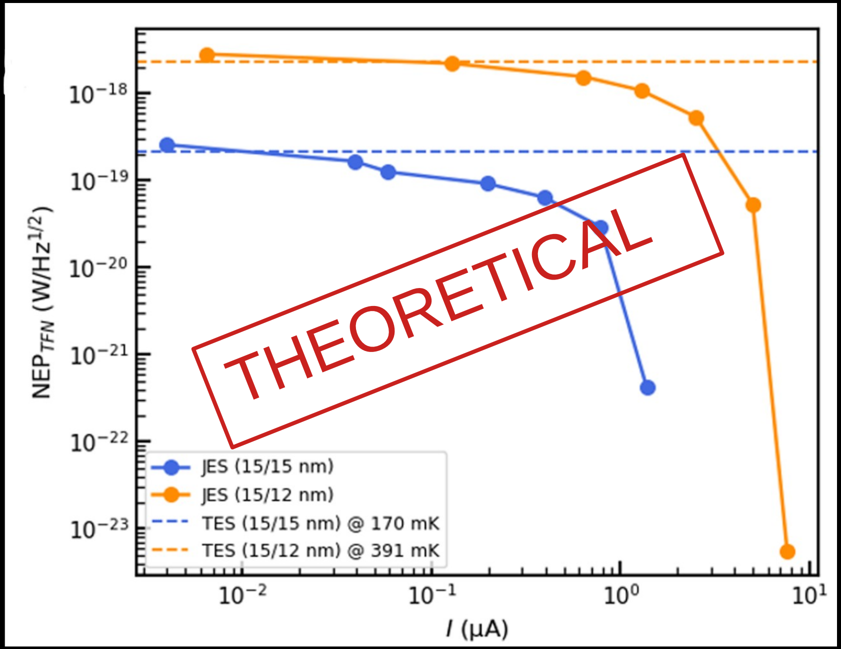
A TES



Performance

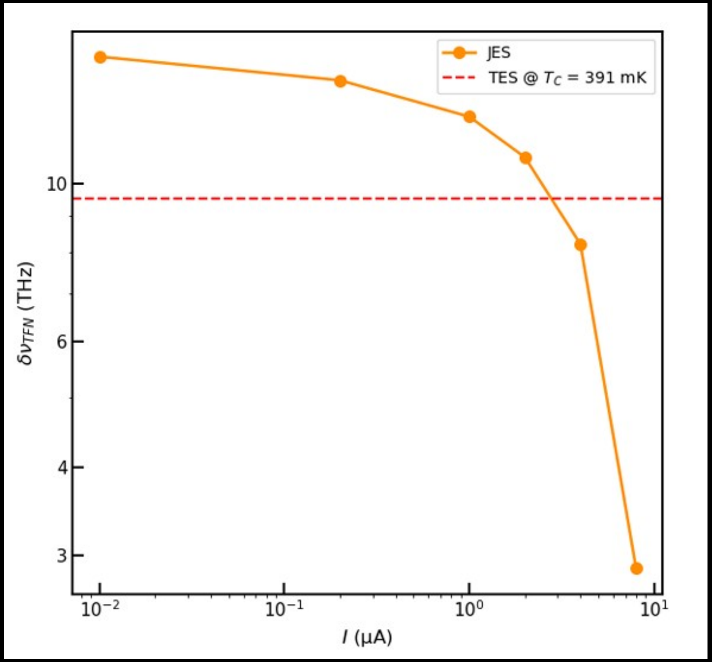
As a bolometer: $NEP_{tot} \simeq \sqrt{NEP_{TFN}^2 + NEP_{Jo}^2 + NEP_{sh}^2},$ $\quad NEP_{TFN} \propto T_c \sqrt{G}$

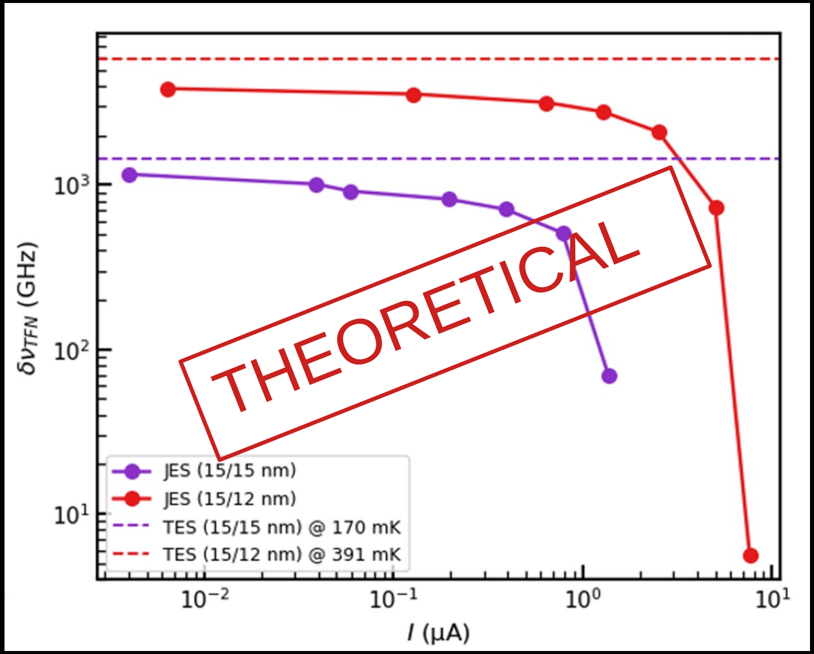




Performance

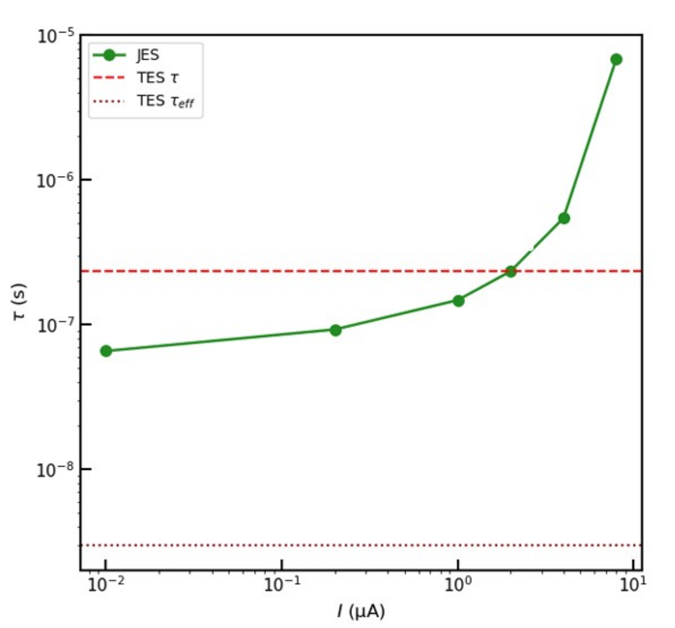
As a calometer: Frequency resolution

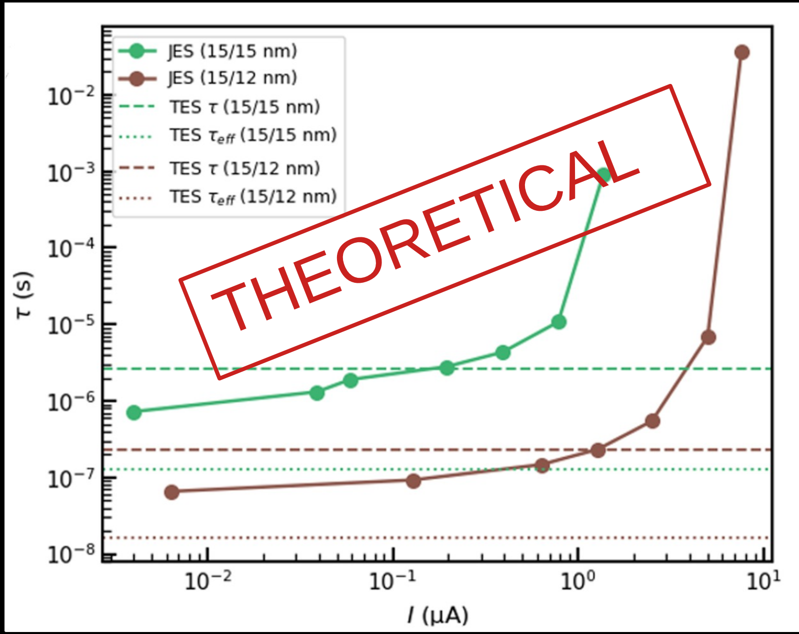




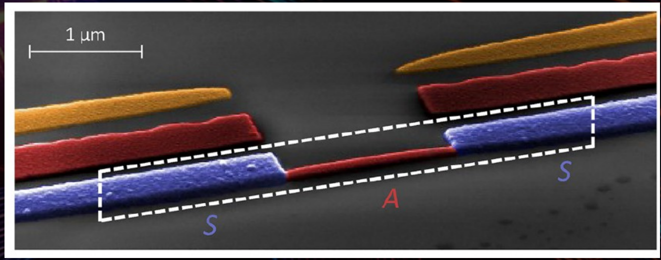
Performance

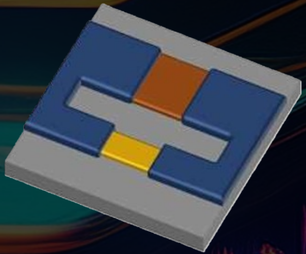
Thermal time constant

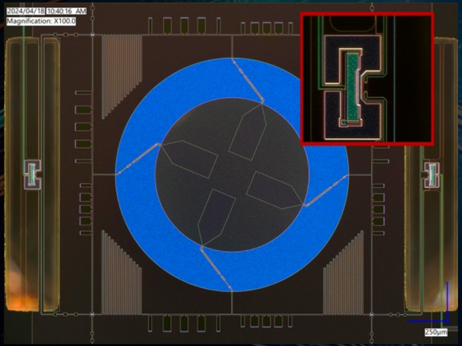


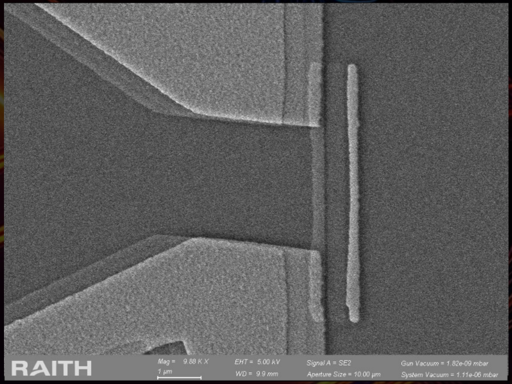


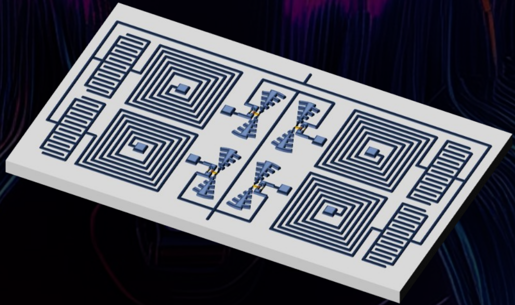
Future steps

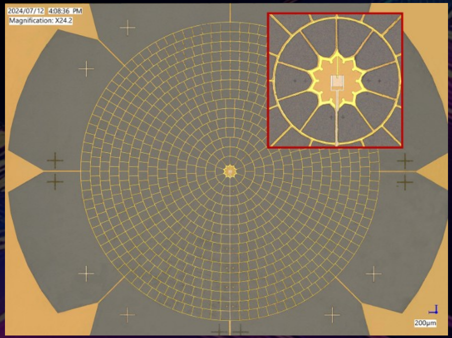












The team

Federico Paolucci	University of Pisa
Anastasia Kotsovolou	University of Pisa
Claudio Puglia	INFN, Section of Pisa
Franco Carillo	INFN, Section of Pisa
Giovanni Signorelli	University of Pisa
Andrea Tartari	INFN, Section of Pisa
Rosella Balice, MSc student	University of Pisa

INFN CSN V – Project: *Sub-kelvin Transition-Edge sensors for low Energy Physics* (*STEEP*), 2025-2027

MUR – under the call FIS2 Consolidator Grant- Project: Next Generation Quantum Detectors for Low Energy Astroparticle Physics (QuLEAP), 2025-2027

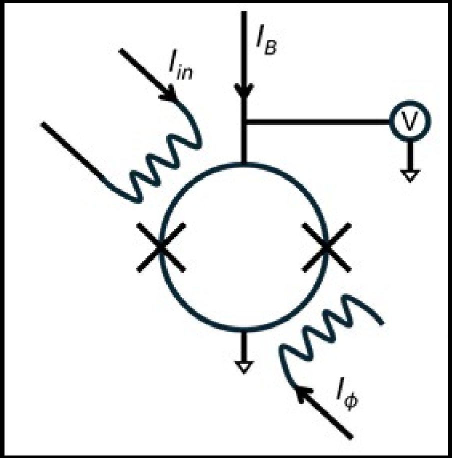

Thank you!

Appendix

SQUID – Read out

Superconducting QUantum Interference Devices

- Highly sensitive magnetometers that can detect extremely small changes in magnetic flux, related to the current flowing through the TES
- Act as an amplifier
- Low power dissipation and good noise characteristics
- Low input impedance



De Lucia, Mario, et al. "Transition edge sensors: Physics and applications." Instruments 8.4 (2024): 47.

Research Plan

- Optimization of the separate parts of the TES
    - Shunt resistance: in the order of few mΩ
    - Electrodes: superconducting, to avoid parasitic resistance effects and confine electronic heating to the thermistor
    - Thermistor: Tc $\sim$ 500 mK, very steep transition to increase sensitivity
- Combine all the parts
- Test for different frequencies
- Create 2x2 matrices via Frequency Domain Multiplexing

1D/2D models

BKT model for dirty 2D superconductors

$$R(T) = R_0 e^{-b\sqrt{\frac{T_{BKT}}{T}}}$$

RSJ model for 1D superconducting nanowires

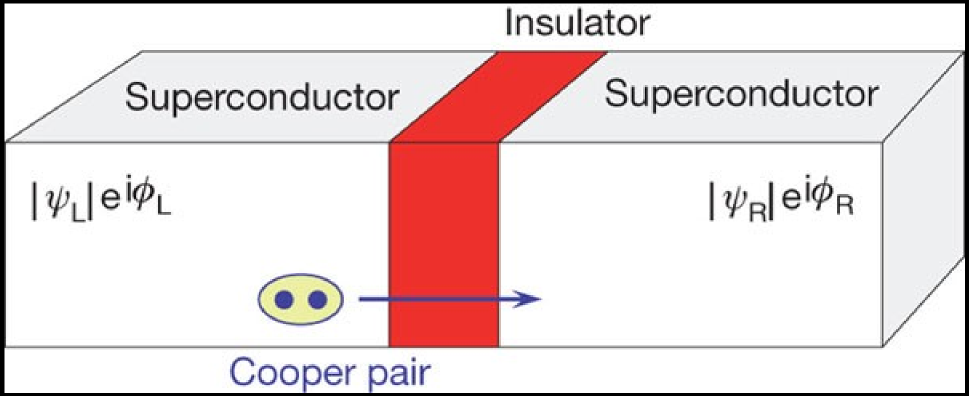
$$R(I=0, E_j, T) = \frac{R_N}{I_0\left(\frac{E_j}{k_B T}\right)^2}$$

It models a Josephson junction as an ideal non-linear superconducting element in parallel with a normal shunt resistor.

Josephson Junction

It consists of a weak barrier (e.g an insulator) that separates two superconductors.

Pairs of electrons tunnel through the barrier, producing an effective inductance that is dependent on the phase difference between the superconductors.



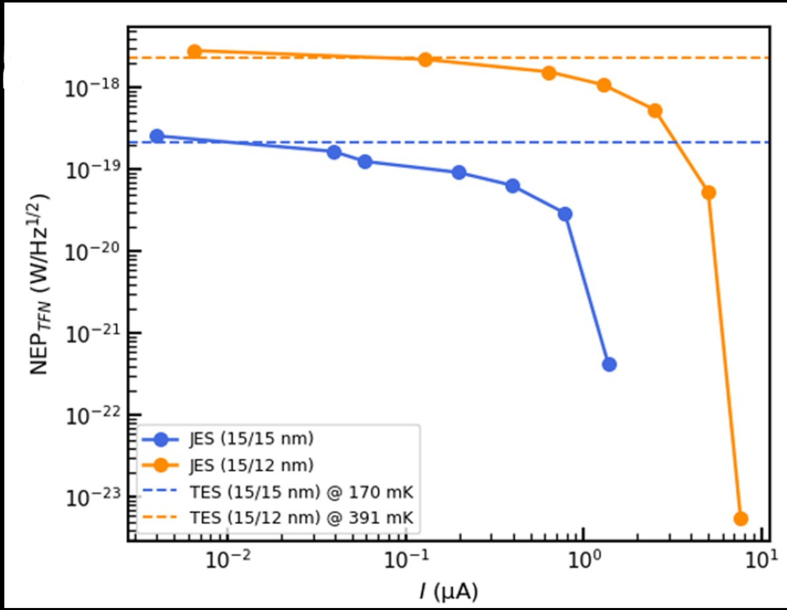
Performance

$$NEP_{tot} \simeq \sqrt{NEP_{TFN}^2 + NEP_{Jo}^2 + NEP_{sh}^2}$$

$$NEP_{TFN} = \sqrt{4 Y G_{th} k_B T_c^2} \quad , Y = \frac{2n}{2n+1}$$

$$NEP_{Jo} = \sqrt{4 k_B R(T_c) T_c \frac{G_{th} T_c}{V \alpha}} \sqrt{1 + 4\pi^2 f^2 \tau_{eff}^2}$$

$$NEP_{sh} = \sqrt{4 k_B R(T_c) T_c \frac{G_{th} T_c}{V \alpha}} \sqrt{(1 - L_0)^2 + 4\pi^2 f^2 \tau_{eff}^2}$$



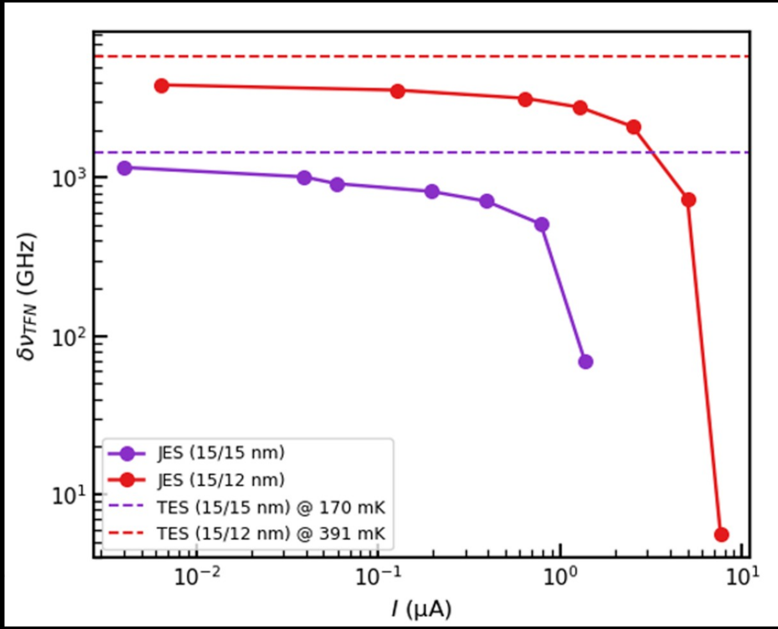
Performance

As a calometer:

Frequency resolution:

$$\delta\nu_{TES} = \frac{2.36}{\hbar}\sqrt{\frac{4}{\alpha}\sqrt{\frac{n}{2}}k_B T_c^2 C_e}$$

$$\delta\nu_{JES} = \frac{4}{\hbar}\sqrt{2\ln 2\, k_B T_e*^2 C_{e,JES}}$$

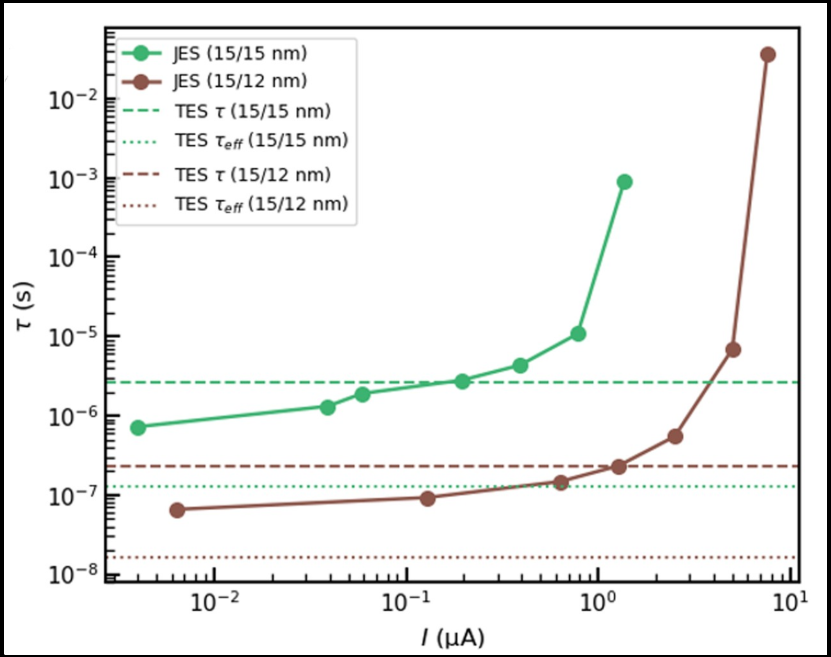


Performance

Thermal time constant:

$$\tau_{TES} = \frac{G_e}{G_{th}}$$

$$\tau_{1/2,TES} = \tau \ln 2$$



Multiplexing

Motive: reduction of the thermal load of the signal lines and the power dissipated by the SQUID, if TESs were read out individually

Steps:

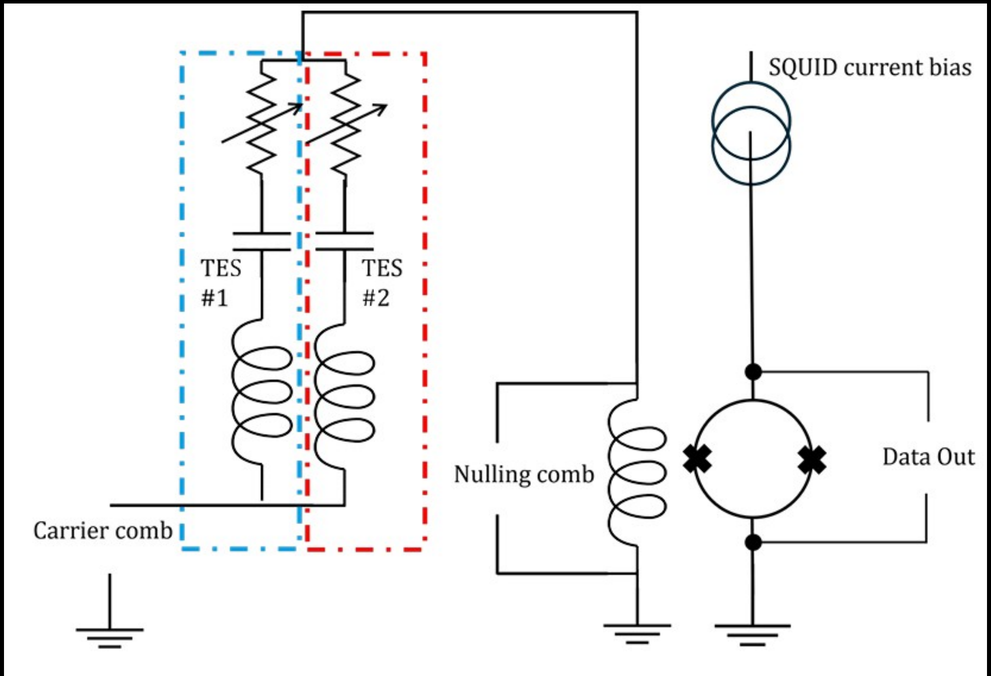
1. Bandwidth limitation
2. Encoding
3. Summation
4. De-coding

Types:

- Time-division multiplexing (TDM)
- Frequency-division multiplexing (FDM)
- Walsh code-devision multiplexing (CDM)
- Thermal multiplexing

Frequency Division Multiplexing

- Each TES connected to an inductor and a capacitor
- Generation of a comb of sinusoidal signals at the selected resonance frequencies
- Signals fed to the array on a single transmission line (decreased thermal load, lower heat dissipation)
- Number of detectors limited only by the capability of the read out electronics
- MHz-FDM, GHz-FDM, THz-FDM



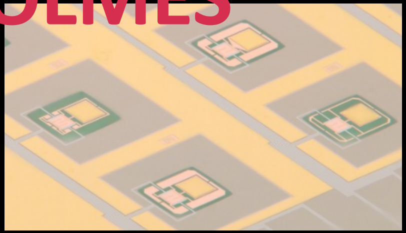
Nuclear, Particle and Astroparticle Physics

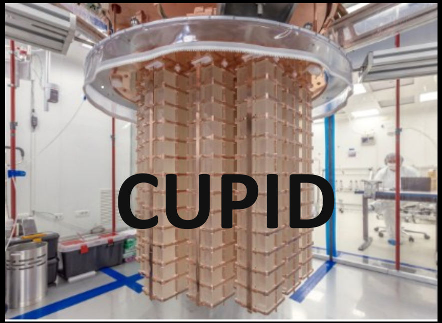
Electron Capture Decay

Rare β and Double-β Decays

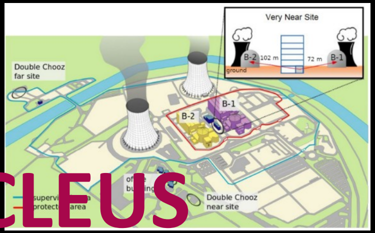
Coherent Elastic Neutrino-Nucleus Scattering

HOLMES





CUPID



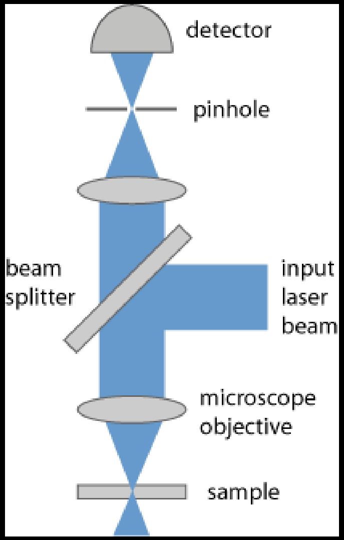
NUCLEUS

NuMECS

ACCESS

Biophysics and Medical Imaging

TES as a main detector of a Confocal Laser Scanning Microscope (CLSM)



CLSM:

- Uses point illumination, pin-hole aperture
- Excites a single point of the sample
- Detects only light produced very close to focal plane → higher optical resolution

TESs offer:

- Single phonon sensitivity- good for living cells
- Great resolution: identify different biomarkers in the same sample
- Don’t require optical filters
- Produce RBG and infrared images (less photon/pixel, lower power, faster)
- Differentiate materials based on their colour (optical properties)

-

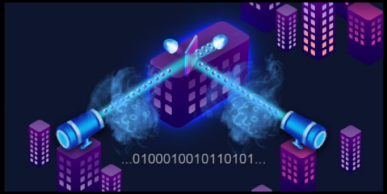
X-Ray Spectroscopy and Imaging

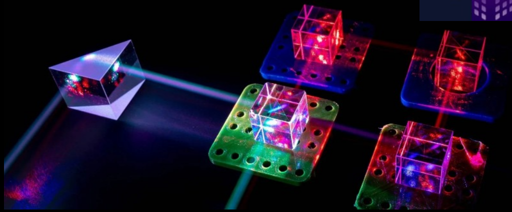
- At beam-line facilities: high energy resolution and wide bandwidth, PIXE
- For Exotic Atoms: study the shift and broadening of the energy levels at the innermost orbitals from the characteristic X-ray emission
- Nanoscale X-ray tomography of Integrated Circuits
- Nuclear Safety: for detection of trace radioactive material (plutonium)

Quantum applications

TES acts like a veto for incoming signal caused by environmental disturbance

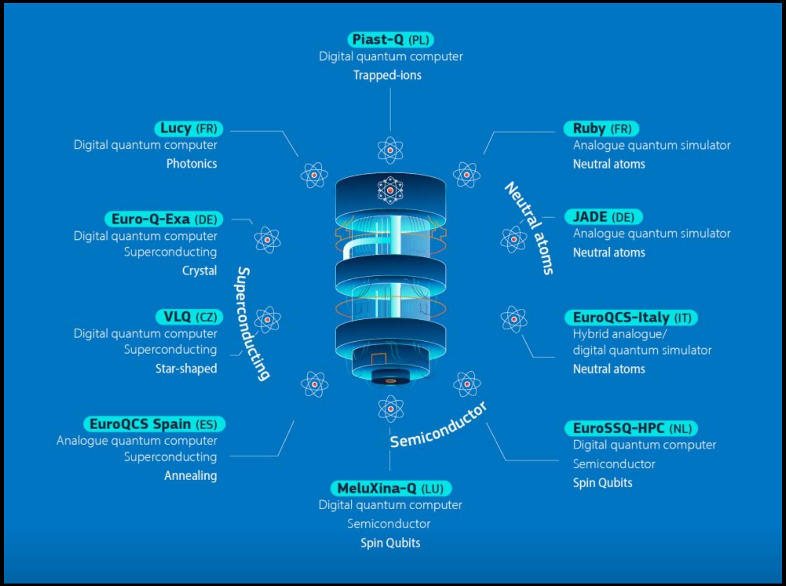
Quantum Optics and
Quantum communication





TESs for Quantum Key Distribution uses photons to generate a cyphered secret key between either end of a communication

Quantum Computing



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