Highly sensitive, low-temperature sensors

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Marco Faverzani

University & INFN Milano - Bicocca

INFN Istituto Nazionale di Fisica Nucleare

Introduction

(main) Low Temperature Detectors technologies

- semiconductors
  - ➢ Neutron Transmutation Doped (NTD) Germanium

- superconductors
  - ➢ Transition Edge Sensors (TES)
  - ➢ Microwave Kinetic Inductance Detectors (MKIDs)

- others
  - ➢ Magnetic Metallic Calorimeters

Neutron Transmutation Doped (NTD) Germanium sensors

- well **established technology**
- conduction band engineered to have **large sensitivity at very low temperature** (~10 mK)
- coupled to large crystals (see I. Nutini's talk) for **rare event searches**
- current biased → electro-thermal feedback → **thermal stability**
- **great energy resolution** $\Delta E \approx \mathcal{O}$(keV) @ MeV
- also coupled to thin absorbers, to **detect light** (particle identification)
- large impedance → signal integration (stray capacitance) → **slow signals**

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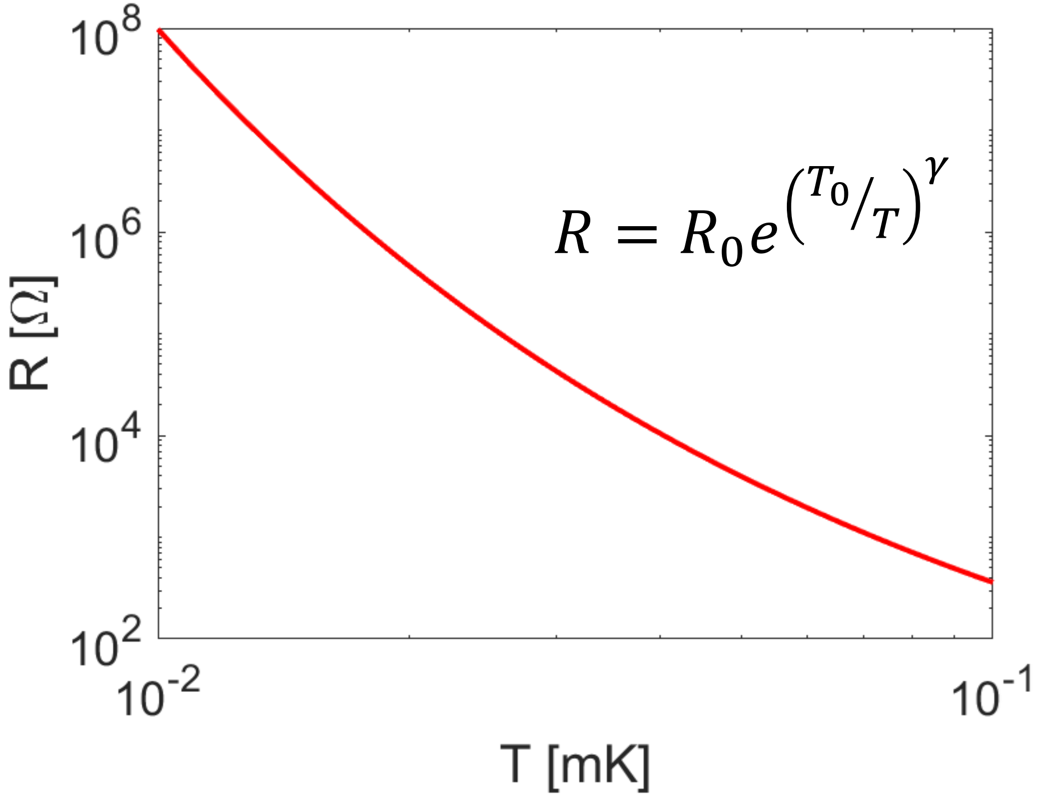
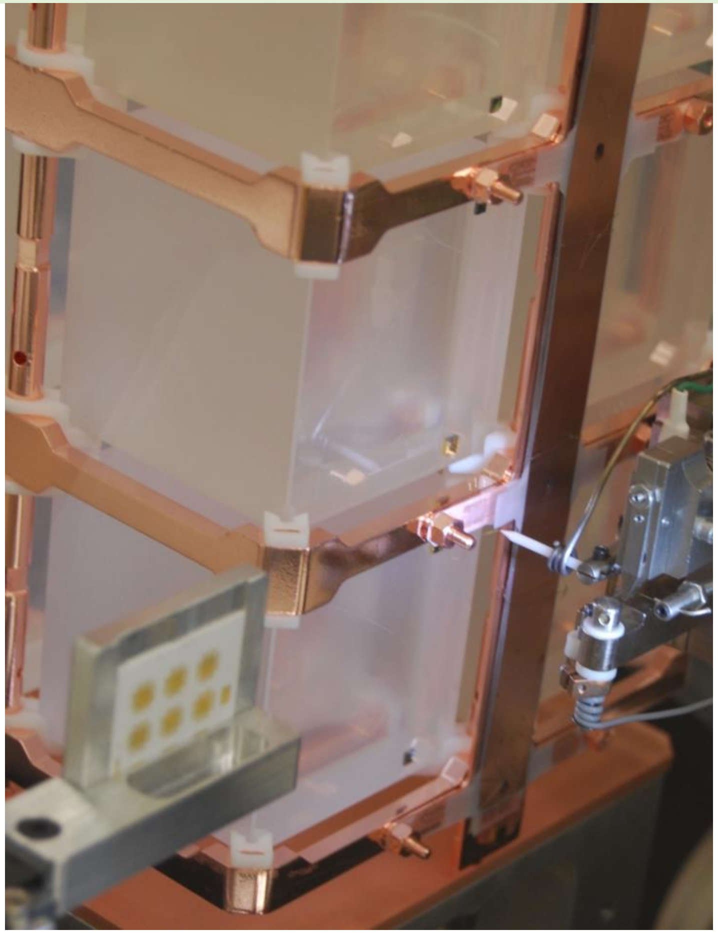
aims:

- ➢ decrease heat capacity to increase sensitivity
- ➢ increase thermal coupling to light absorber (eutectic bonding?)

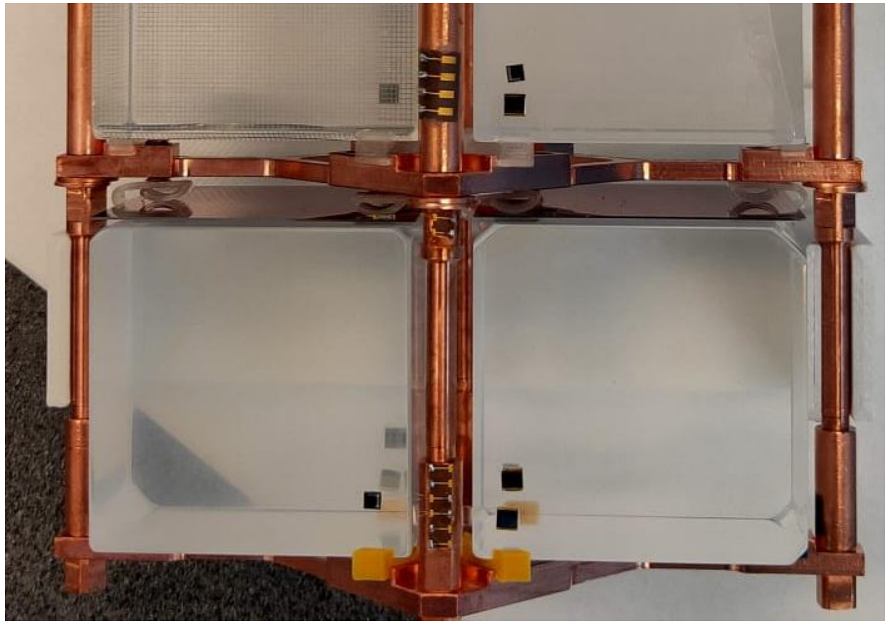


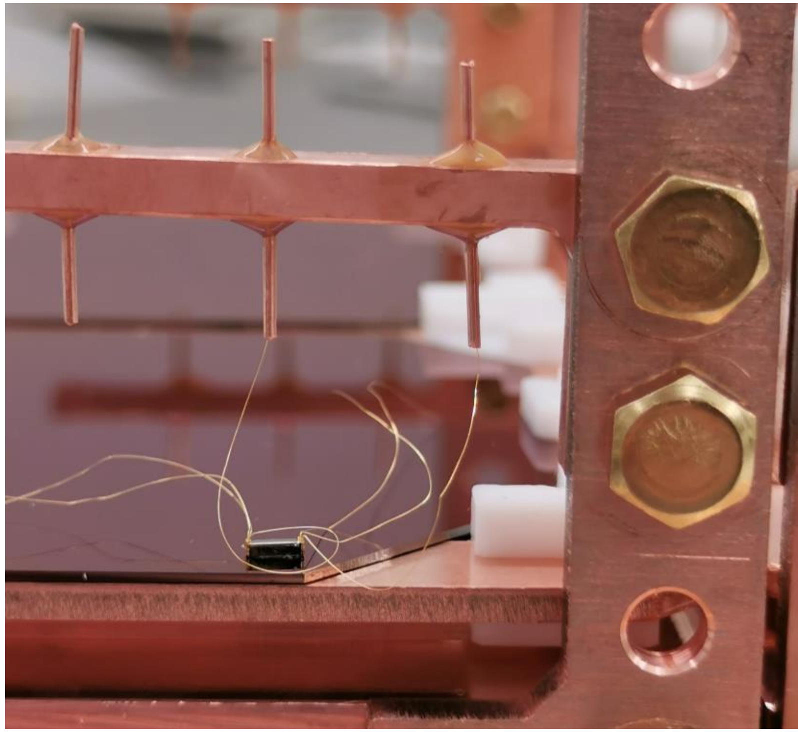
Neutron Transmutation Doped (NTD) Germanium sensors



CUORE

CUPID (thermal channel)

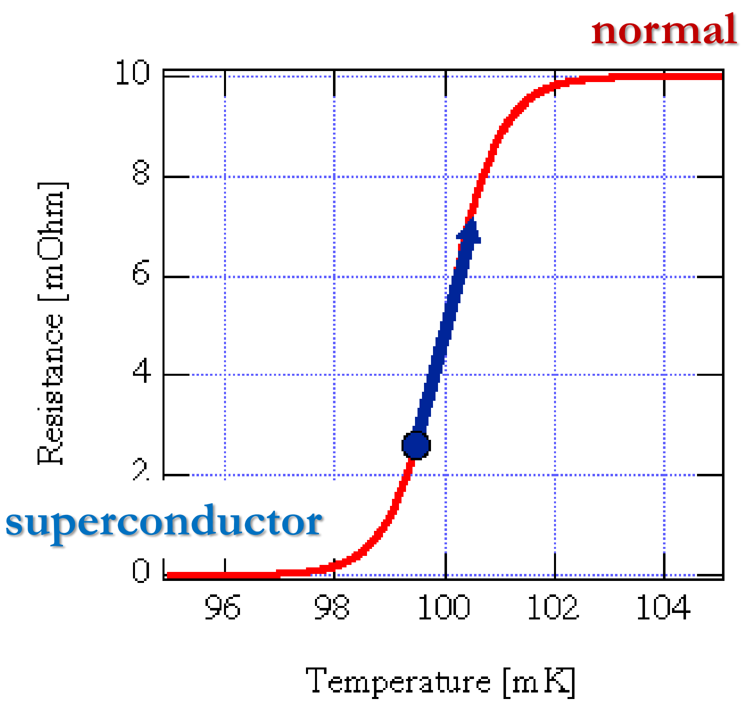


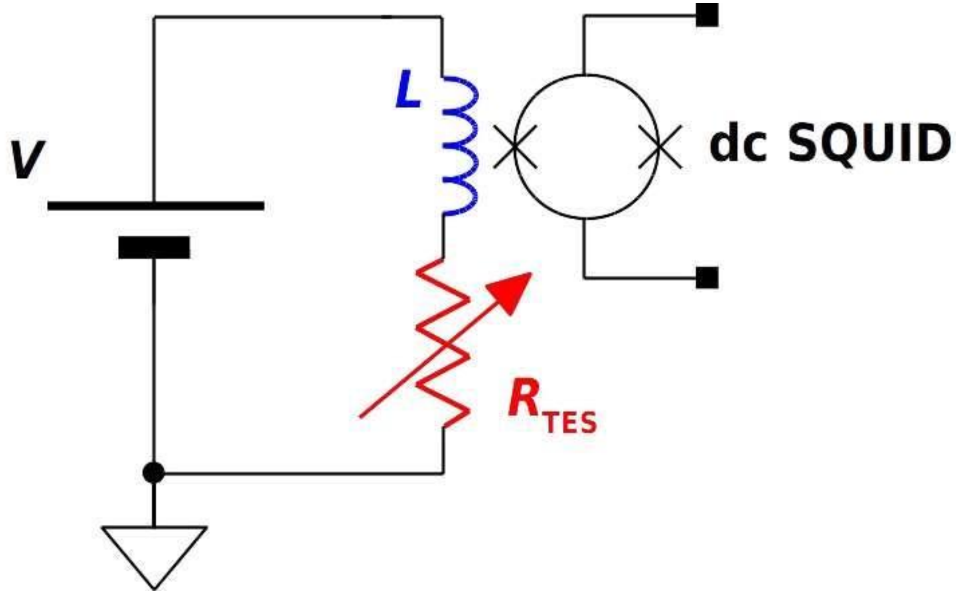


CUPID (light channel)

Transition Edge Sensors (TESs)

- superconductive films within transition at $T = T_c$ → high sensitivity → **high energy resolution** $\Delta E \approx \mathcal{O}$(eV) @ keV
- thermodynamic limit $\sigma_E^2 \approx \xi^2 k_B T^2 C(T) \xrightarrow{if\ C \propto T} \propto T_c^3$
- metal/superconductor bilayers: Mo/Cu, Ti/Au, Ir/Au, Ti/Al, … → **tunable T_c** (20÷200) mK
- voltage biased → electro-thermal feedback → **thermal stability**
- **intrinsically fast**, but ultimately time profile tuned by L/R to match bandwidth
- low impedance → SQUID readout → **multiplexing schemes** for large arrays (TDM, FDM, CDM, µwave mux)
- narrow transition region → **limited dynamics**

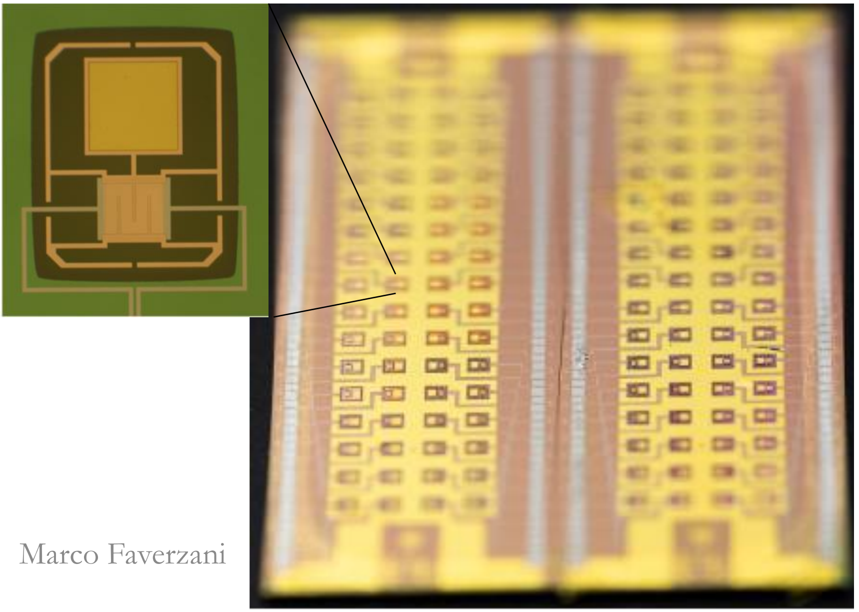




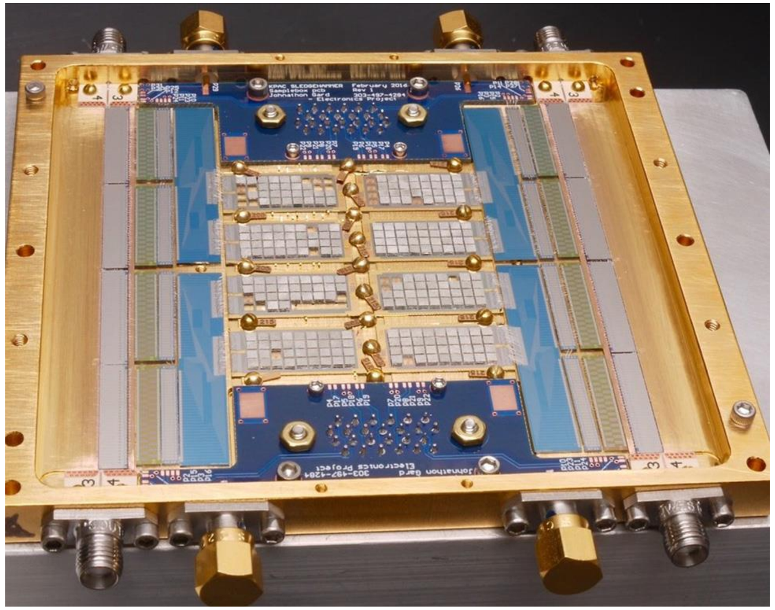
Transition Edge Sensors (TESs)

- direct (and calorimetric) assessment of neutrino mass
  - ➢ measurement of decay energy in a beta process
- dark matter searches
  - ➢ nuclear recoils due to WIMPs scatter
- photon detection
  - ➢ X-ray spectroscopy, single photon detection, CMB (bolometers)

HOLMES



SLEDGEHAMMER



Micorwave Kinetic Inductance Detectors (MKIDs)

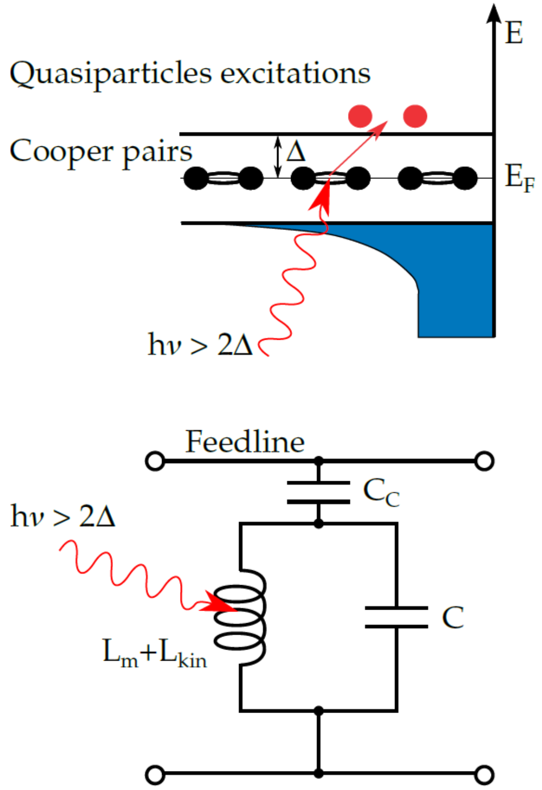
pair breaking detectors:
$E = h\nu > 2\Delta$ (≈ meV)

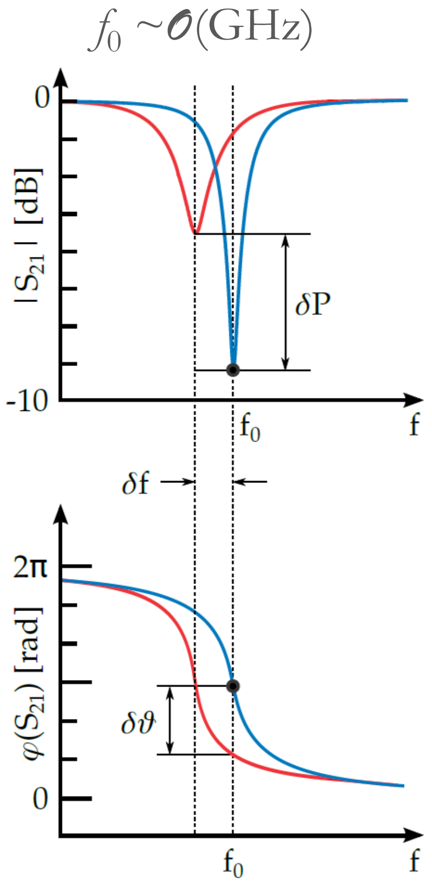
increase in quasiparticles
$N_{qp} \approx \eta\, h\nu/\Delta$
change in sheet impedance $Z_s = R_s + i\omega L_s$

$$\frac{\delta f_r}{f_r} = -\frac{\alpha}{2}\frac{\delta L_s}{L_s} \qquad \delta Q^{-1} = \alpha\frac{\delta R_s}{\omega L_s}$$

α = *surface inductance fraction*

relaxation time after qp recombination time τ_{qp}





demonstrated single photon detection $\Delta E_{FWHM} \approx 0.5$ eV @ 0.8 eV

J Low Temp Phys 199, 73–79 (2020)

Nature, 425:817 (2003)

MKIDs operated in thermal mode

equivalence of temperature change and external pair breaking

J Low Temp Phys (2008) 151: 557–563

radiation interacts in absorber coupled to the sensor

sensor detects increase of absorber's temperature $\Delta T \approx h\nu / C$

$$n_{qp} = 2N_0\sqrt{2\pi kT\Delta}e^{-\frac{\Delta}{kT}}$$

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$$\frac{\delta f_r}{f_r} = -\frac{\alpha}{2}\frac{\delta L_s}{L_s} \qquad \delta Q^{-1} = \alpha\frac{\delta R_s}{\omega L_s}$$

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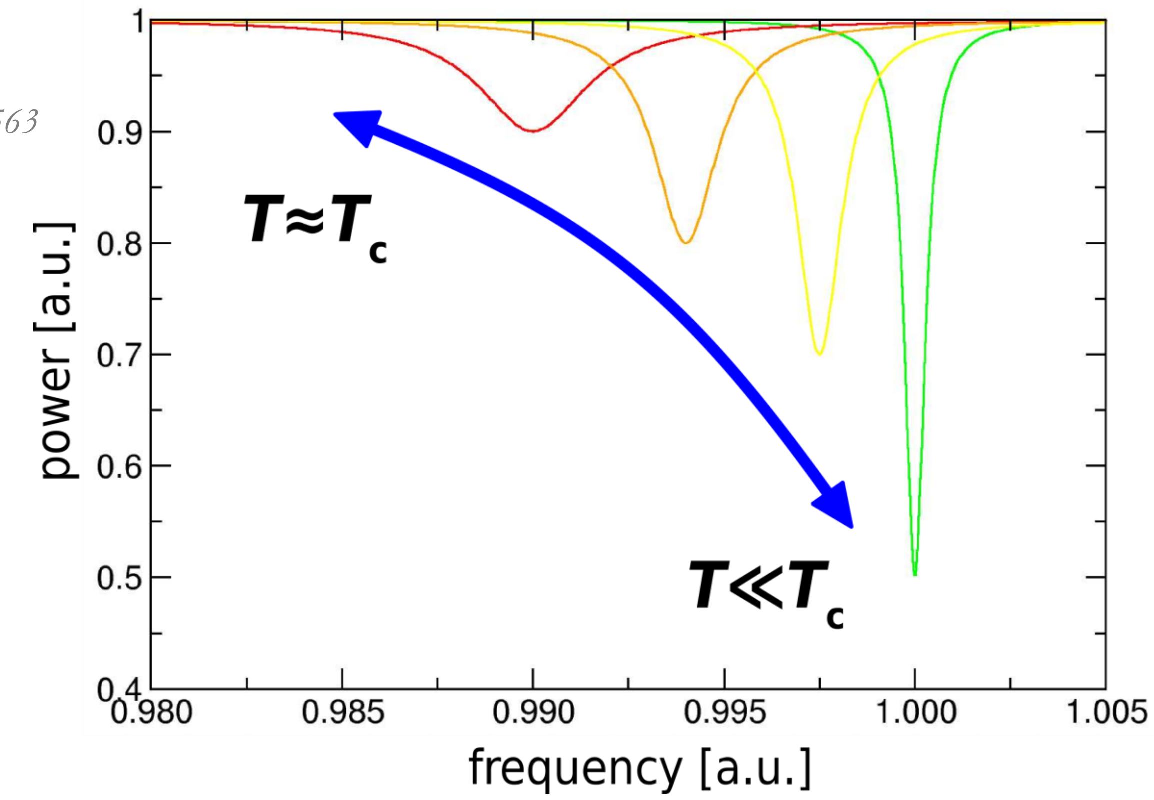
thermal relaxation time $\tau = C/G$



possible TES replacement?

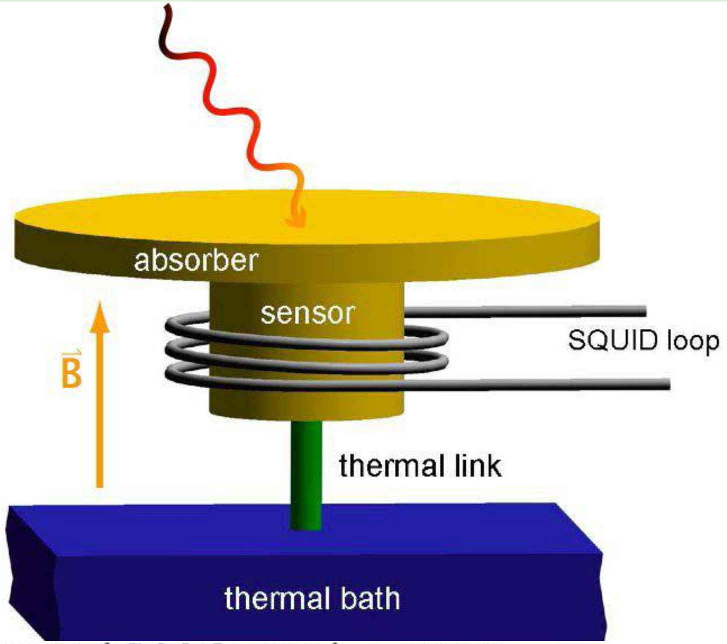
- in principle $\Delta E \approx$ thermodynamic limit
- simple read-out
- natural multiplexing

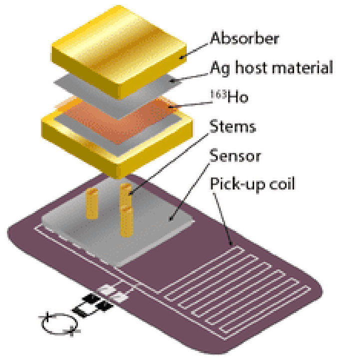
so far ΔE = 75 eV @ 5.9 keV

Appl. Phys. Lett. 106, 251103 (2015)

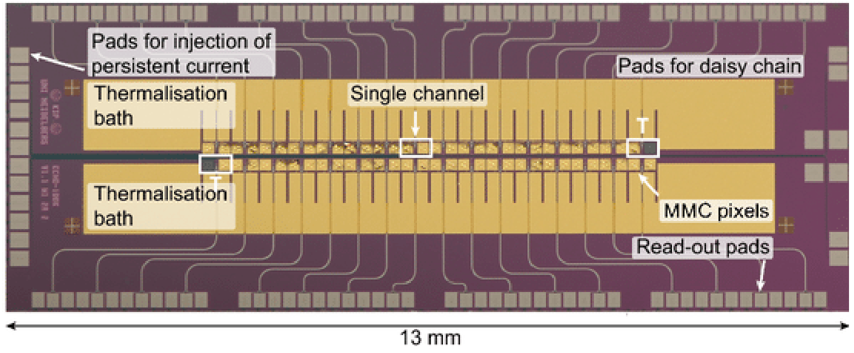
Magnetic MicroCalorimeters

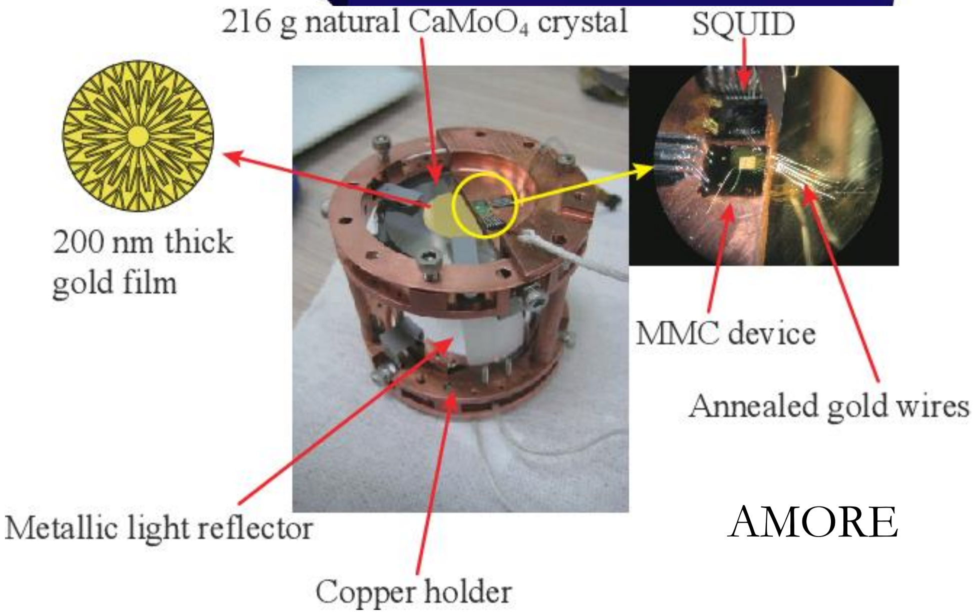
- paramagnetic temperature sensors (Au:Er, Ag:Er, …): **$\delta E \rightarrow \delta M \rightarrow \delta\phi$**
- dc-DQUID readout
  - **high energy resolution**
  - **fast rise** time ≈ 100 ns
- **high linearity**
- **no power dissipation** in the sensor
- possible **frequency multiplexing**





ECHO

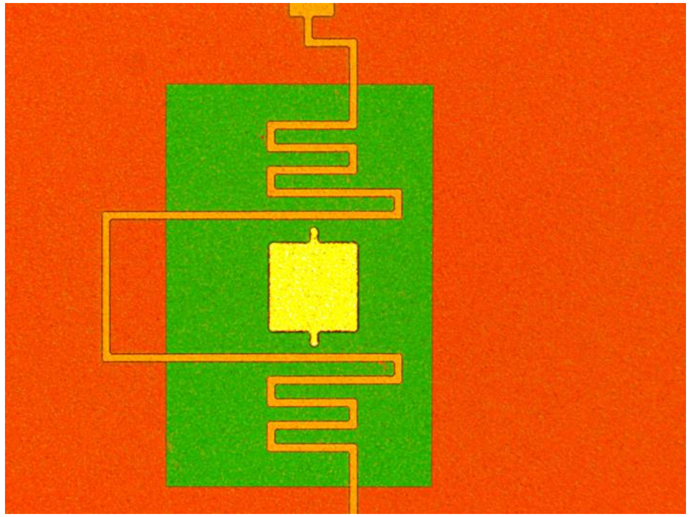




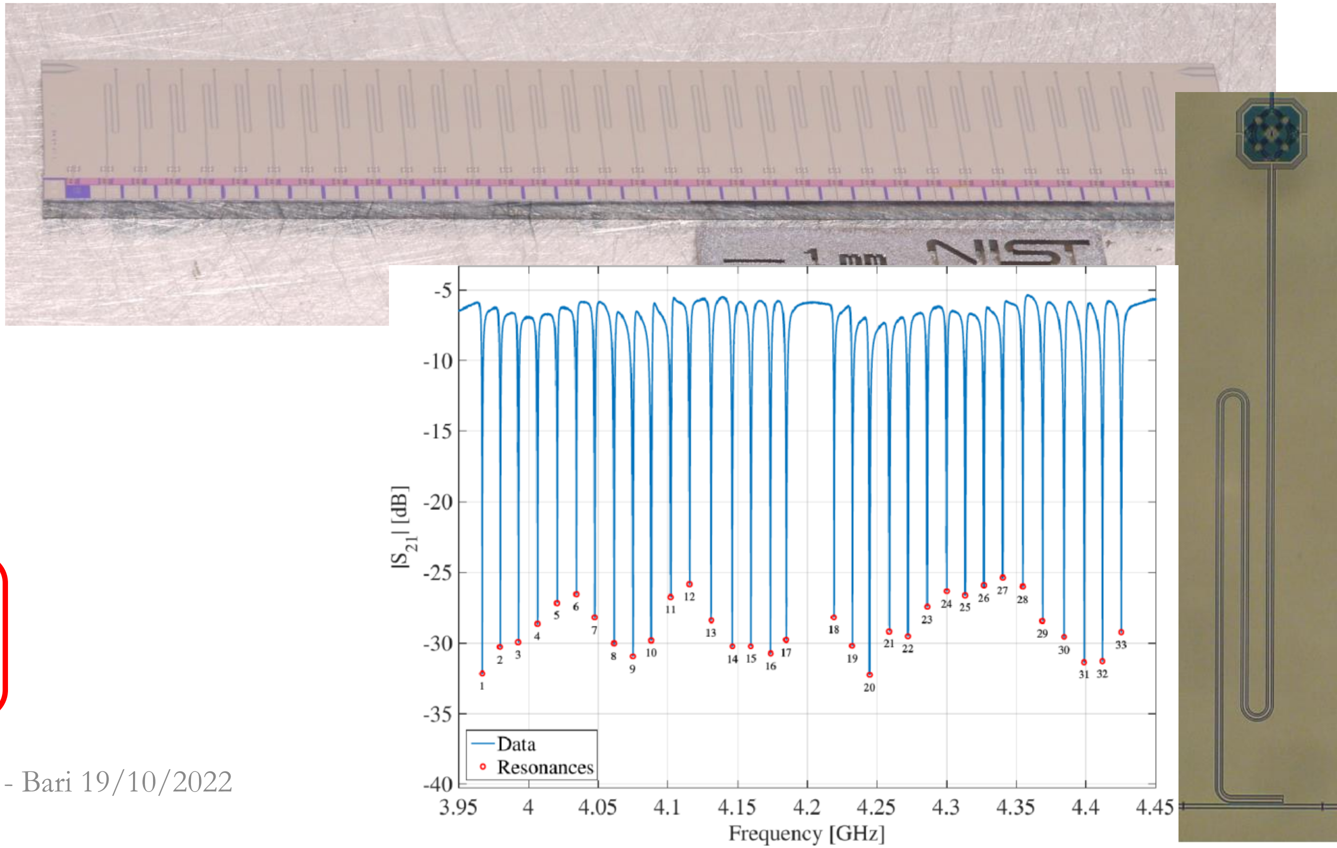
AMORE

Future challenges

- **NTDs:**
  - decrease sensors' heat capacity as much as possible
  - improve coupling to the absorber
- **MKIDs**
  - R&D
  - …



- **TESs**
  - multiplexed readout: $\mathcal{O}(10^6)$ detectors, $\tau_R \sim \mu s$
  - large scale producing facility closely related to Italian community
- **MMCs**
  - demonstration of multiplexed readout



- **Sensors and readout techniques strongly synergetic with quantum technologies!**