Transition Edge Sensors

A cryogenic sensor technology for fundamental physics

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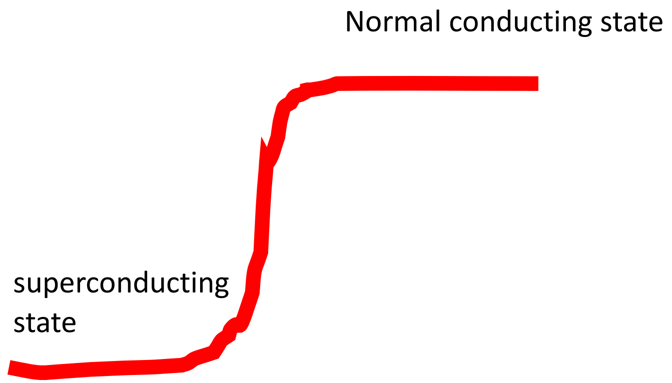
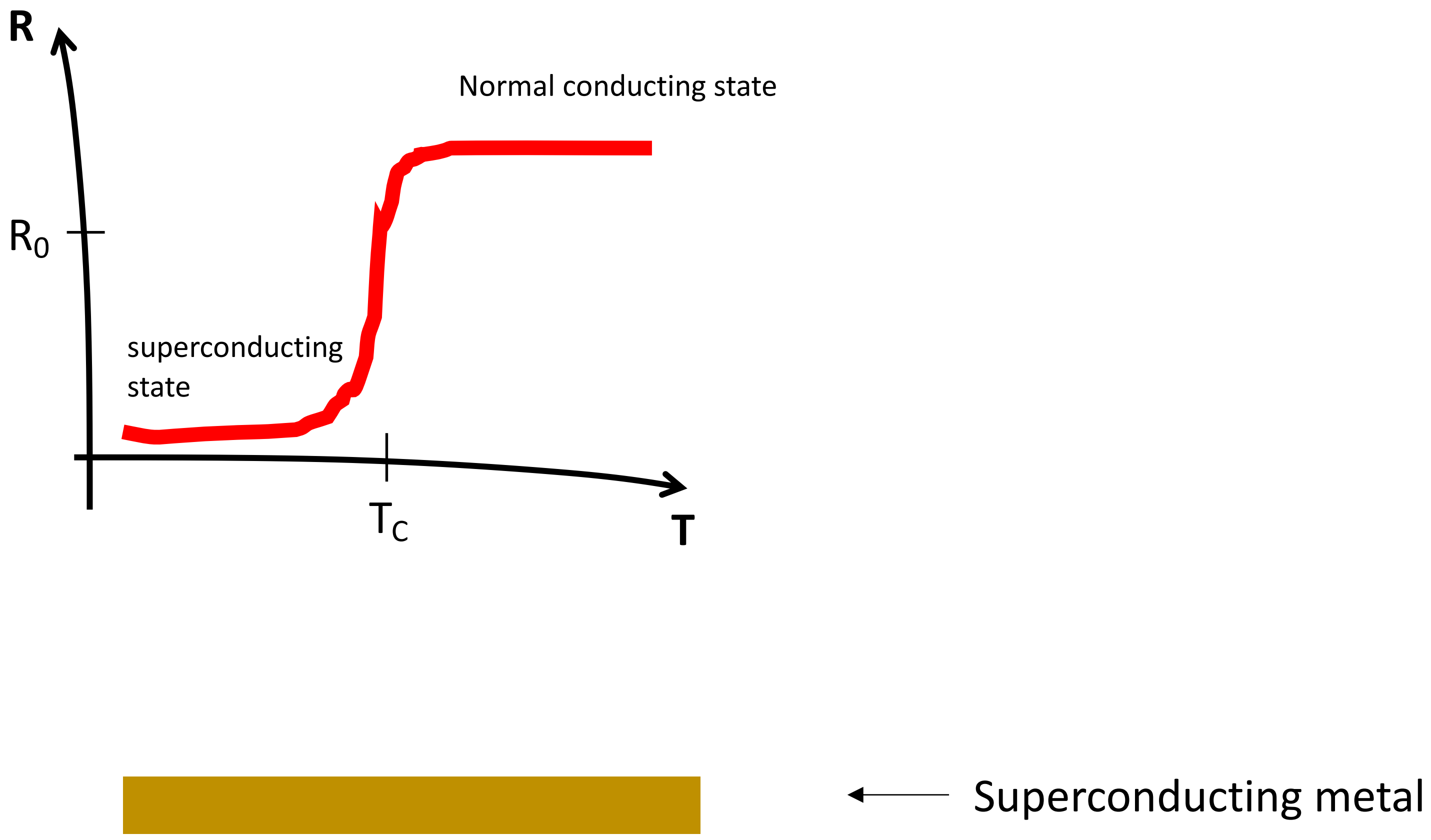
Technische Universität München

Terascale Workshop

24.Feb 2022


Normal conducting state
superconducting state

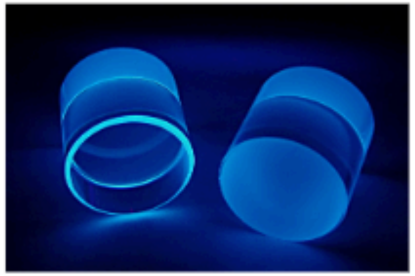


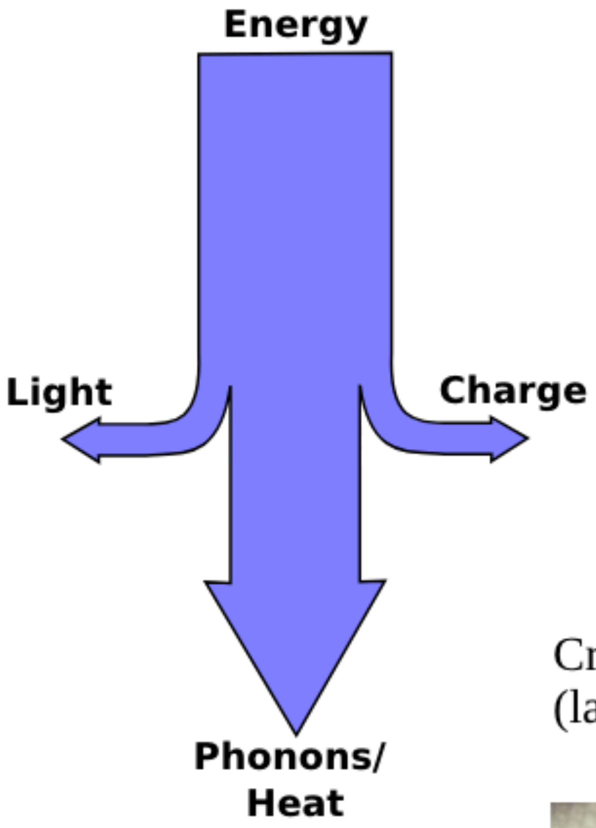
R
Normal conducting state
R_0
superconducting
state
T_C
T
Superconducting metal

Two steps back...

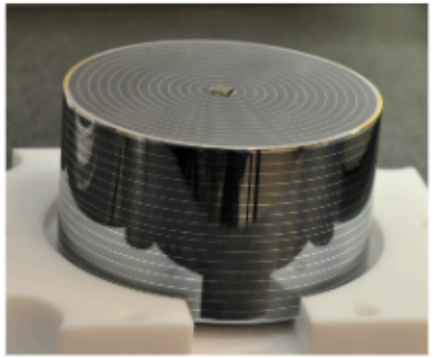
Types of Particle Detectors

Scintillators: ~eV photons

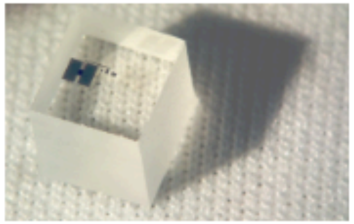




Semiconductors:
~10eV e/h-pairs

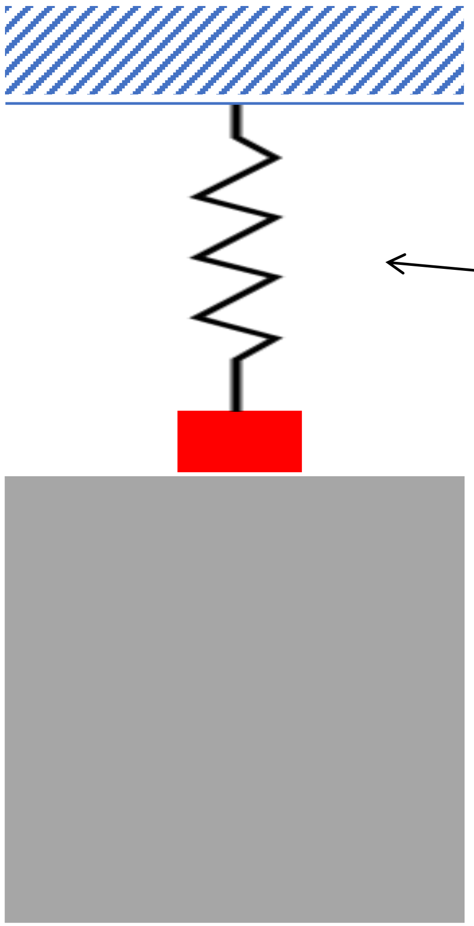


Cryogenic detectors: ~meV phonons (lattice vibrations)



→ excellent for small energies, high resolution

Cryogenic Detector



heat bath ($T \approx 10mK$)

temperature $\mathbf{T_0}$

weak thermal link

conductance **G**

thermometer

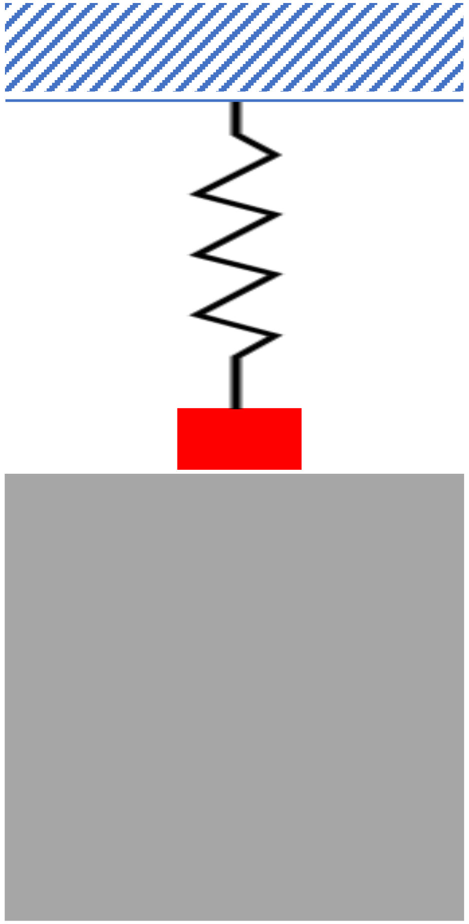
+

absorber material

heat capacity **C**

temperature **T**

Cryogenic Detector



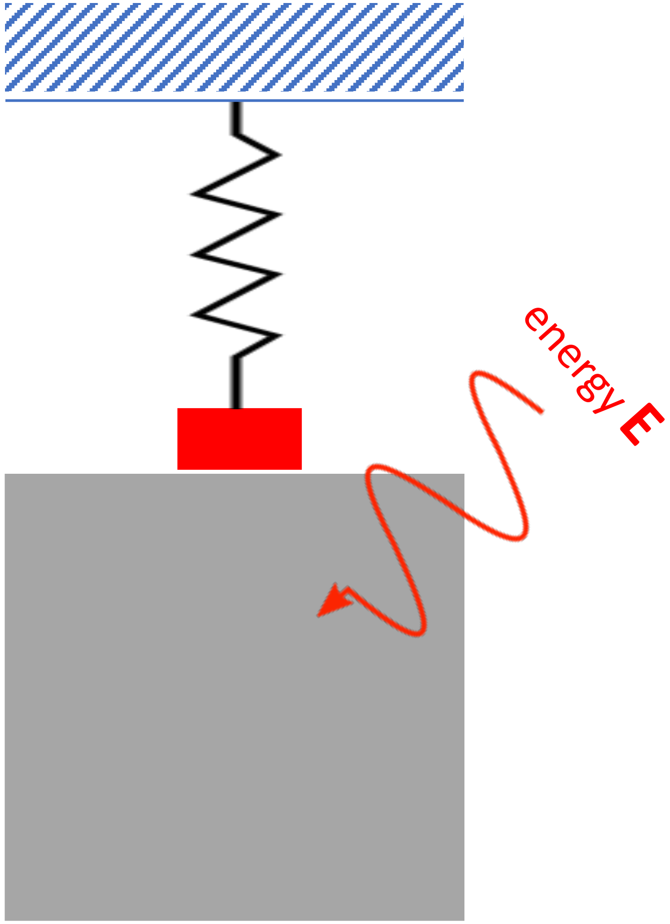
Irreducible thermal fluctuations:

$$\left\langle \Delta E^2 \right\rangle = k_B T^2 C$$

Need:

- ➢ Low temperature
- ➢ Low heat capacity

Cryogenic Detector



Irreducible thermal fluctuations:

$$\left\langle \Delta E^2 \right\rangle = k_B T^2 C$$

Need:

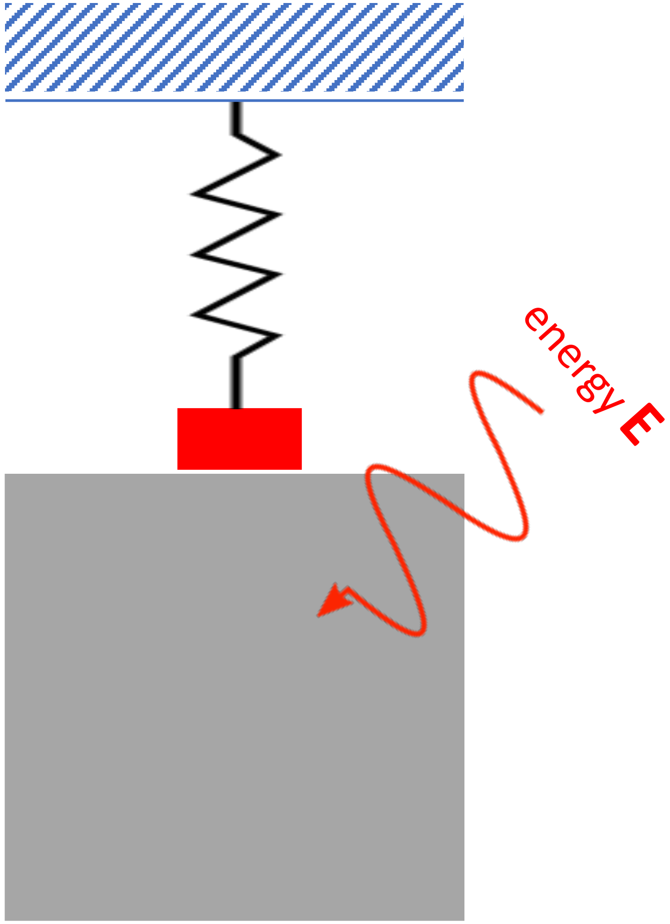
- ➢ Low temperature
- ➢ Low heat capacity

Operation at mK:

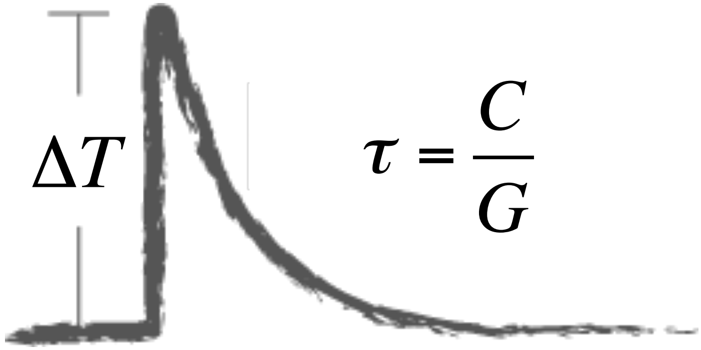
Temperature increase from particles interactions can be measured: 1keV → μK

Measurement of total deposited energy !

Cryogenic Detector



Thermometer response:

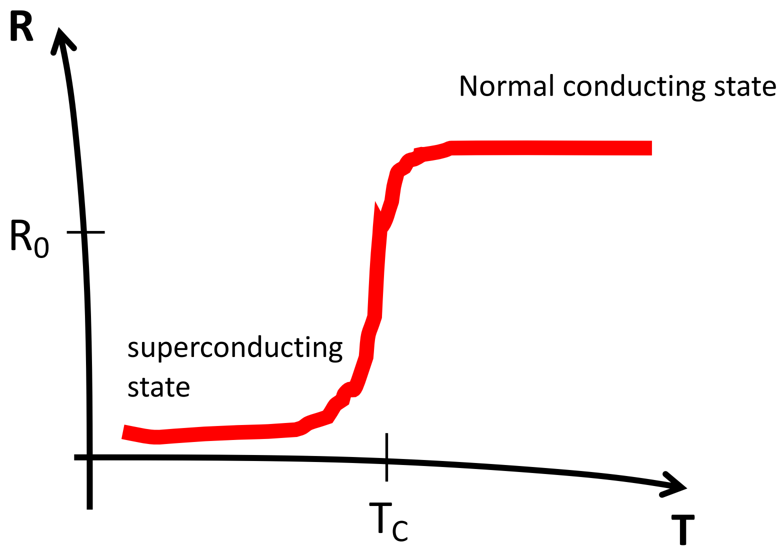


$$\tau = \frac{C}{G}$$

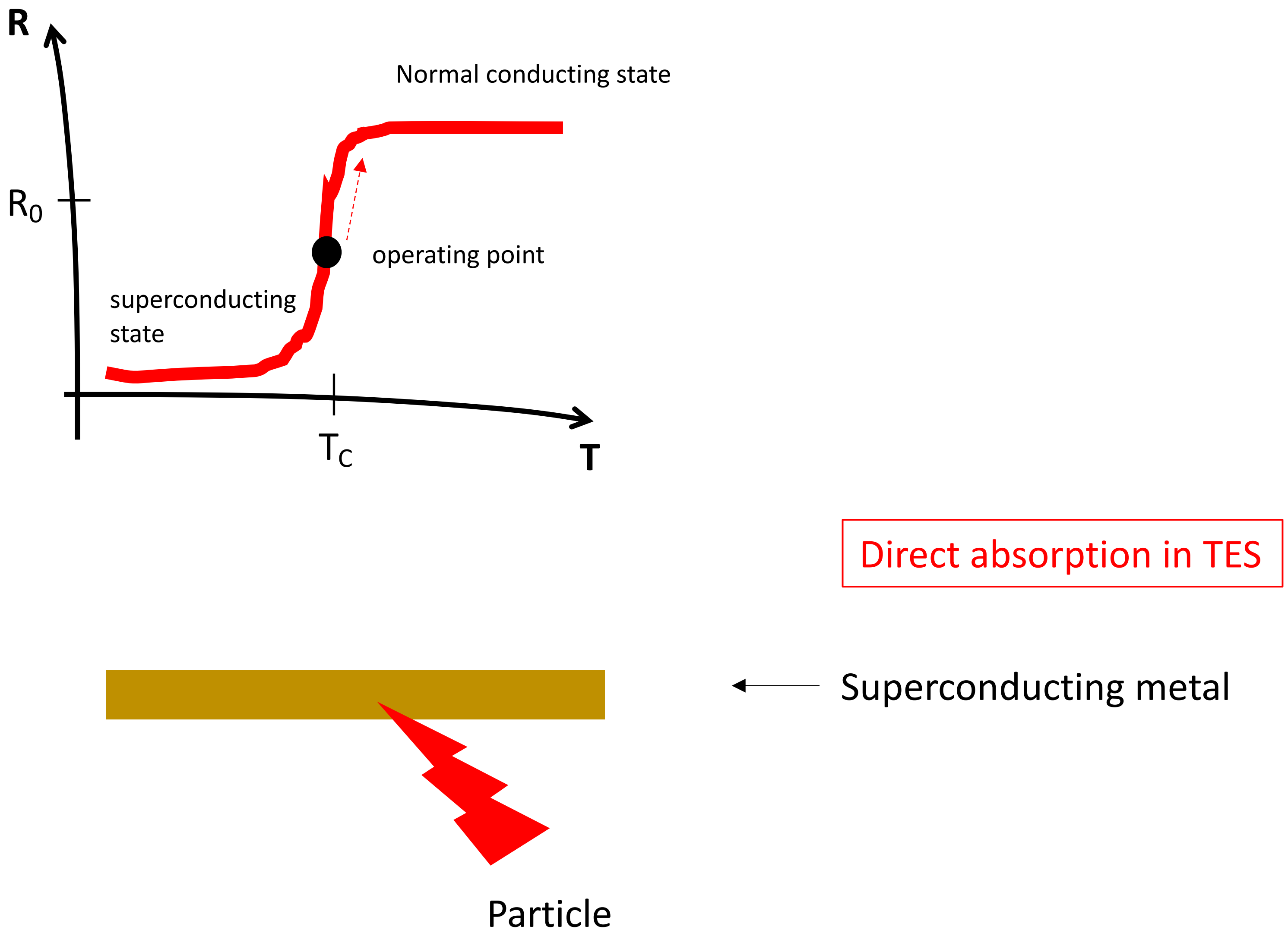
$$\boxed{\Delta T = \frac{E}{C}}$$

Needs for thermometer:

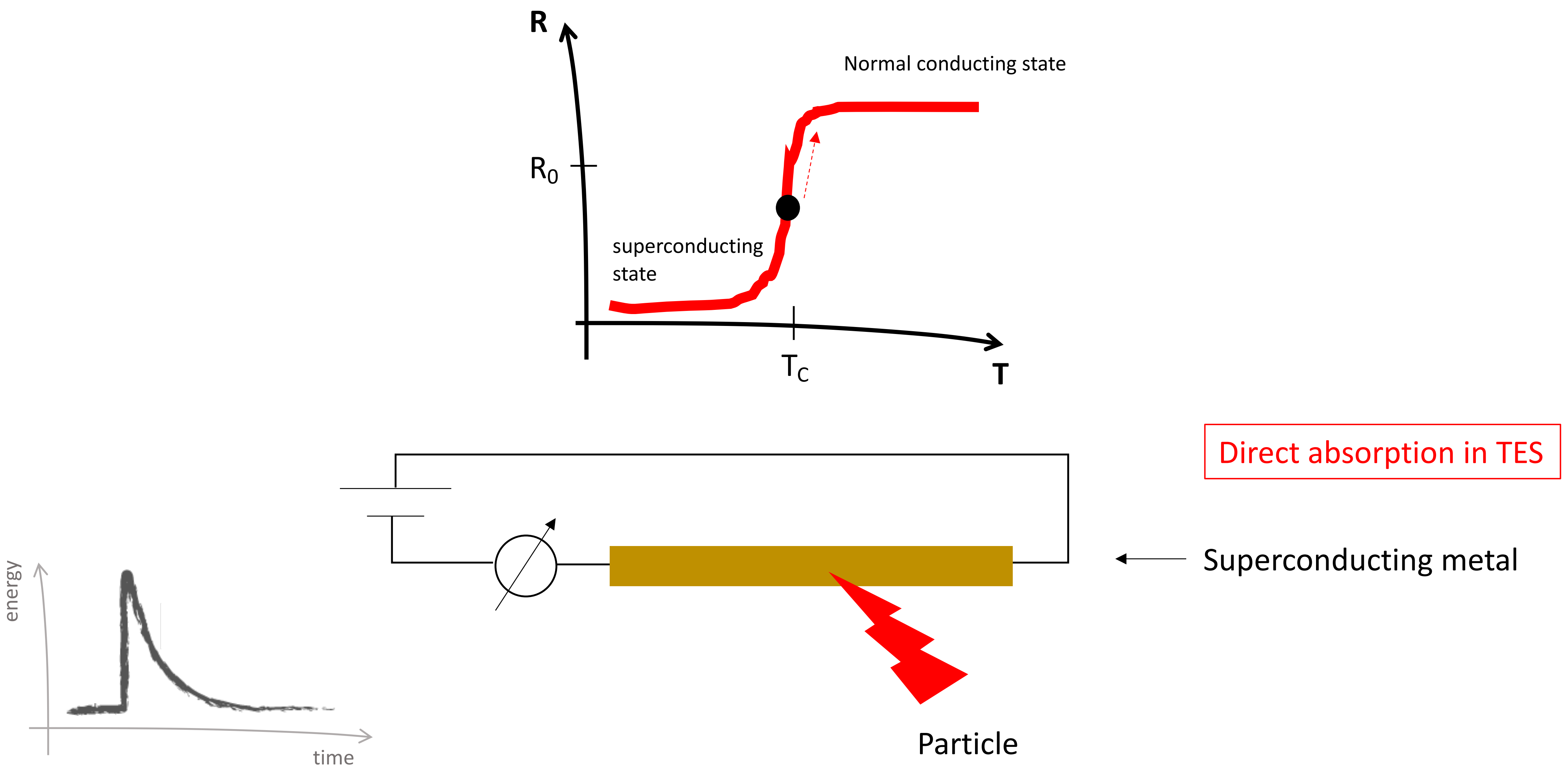
- High sensitivity
- Low heat capacity
- Operation at low temperature



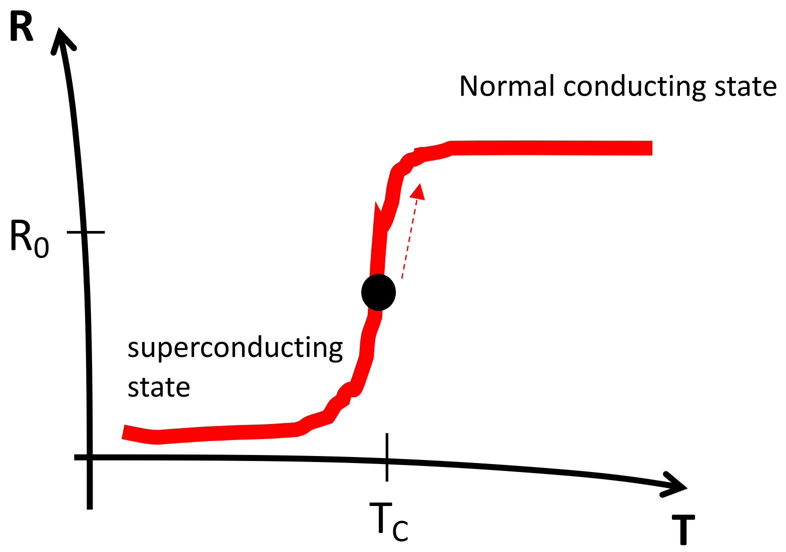
Superconducting metal

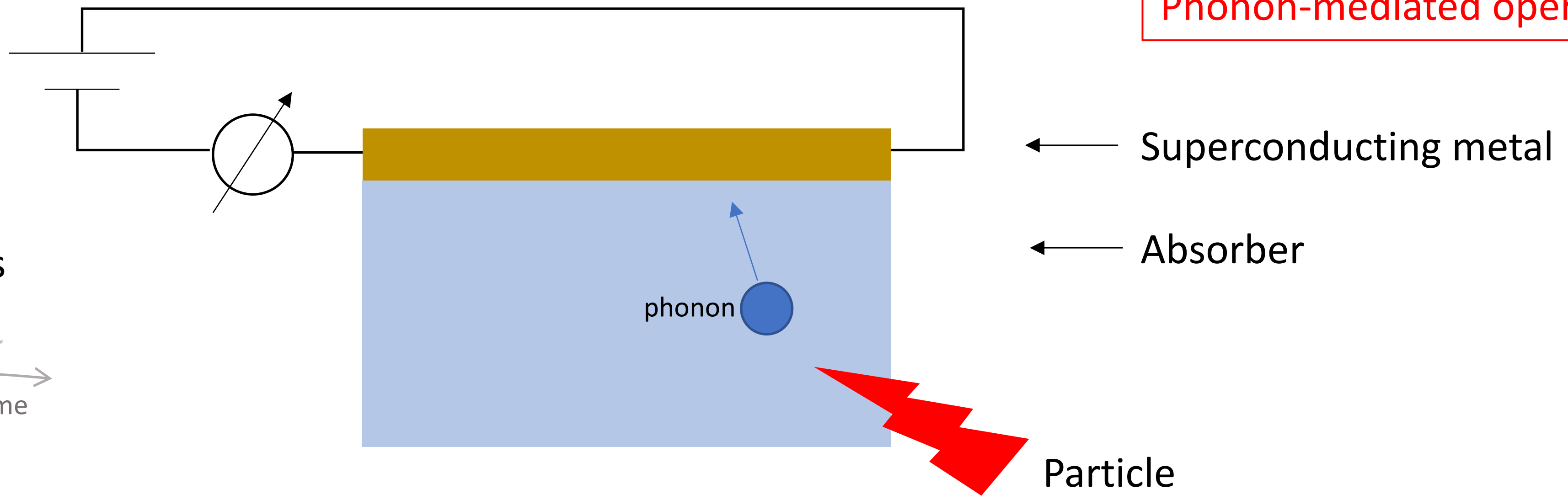


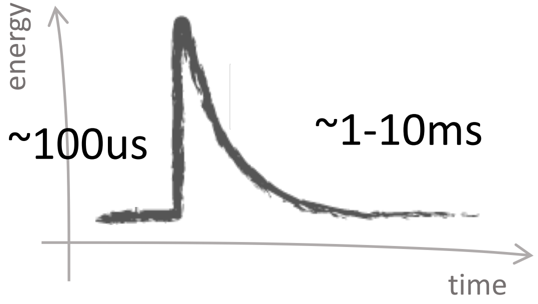
R
Normal conducting state
R_0
operating point
superconducting state
T_C
T
Direct absorption in TES
Superconducting metal
Particle


R
Normal conducting state
R_0
superconducting
state
T_C
T
Direct absorption in TES
Superconducting metal
energy
time
Particle

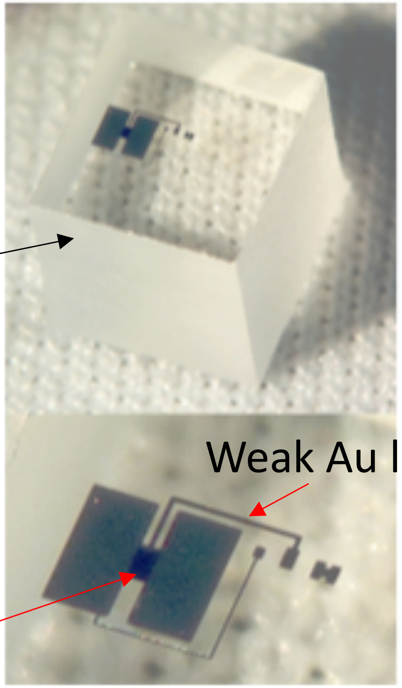
Phonon-mediated operation mode







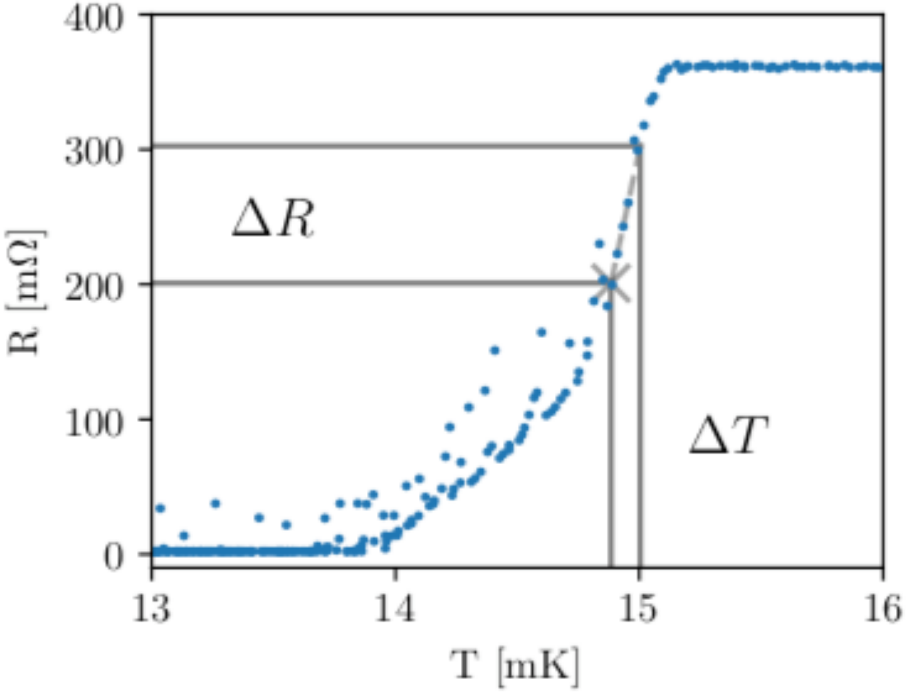
Al$_2$O$_3$ absorber crystal



W thin-film TES

J. Rothe, PhD thesis, TUM 2020

W-TES



Steepness of transition $\alpha = \frac{\mathrm{d}R}{\mathrm{d}T} \cdot \frac{T_0}{R_0}$

<u>Design goals for transition:</u>

- Steepness
- Homogeneity
- Linearity
- Dynamic range
- Temperature

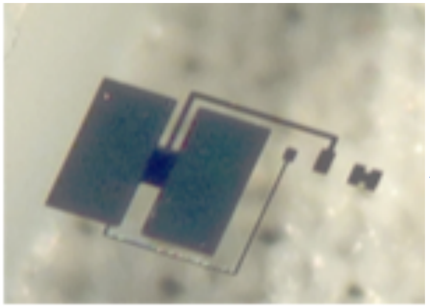
→ Outstanding sensitivity

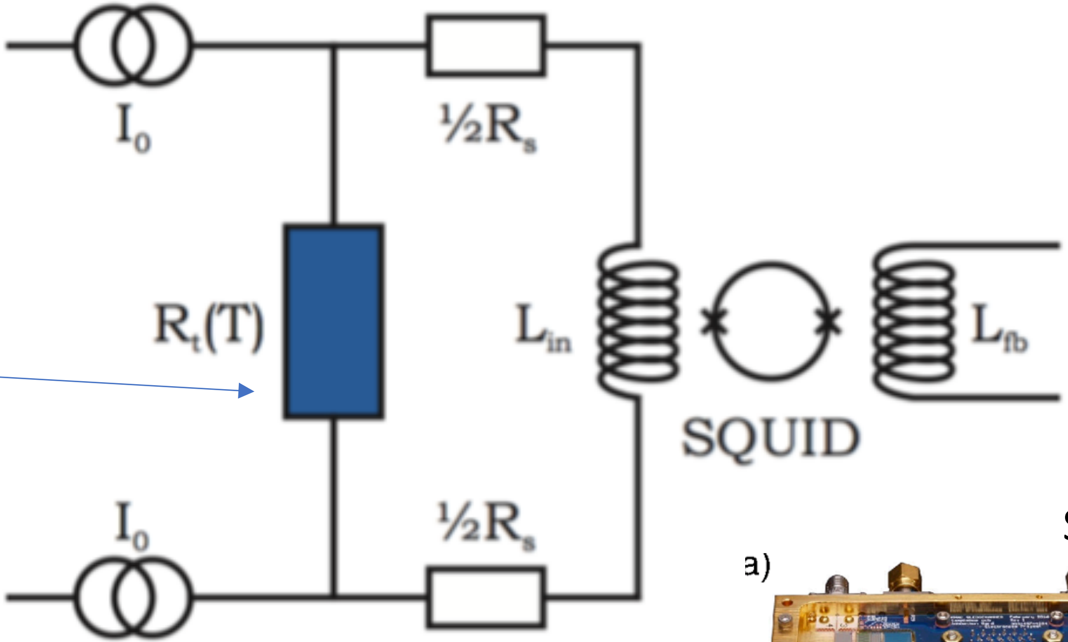
<u>Challenges:</u>

- Low impedance (SQUIDs!)
- Fabrication
- Reproducibility

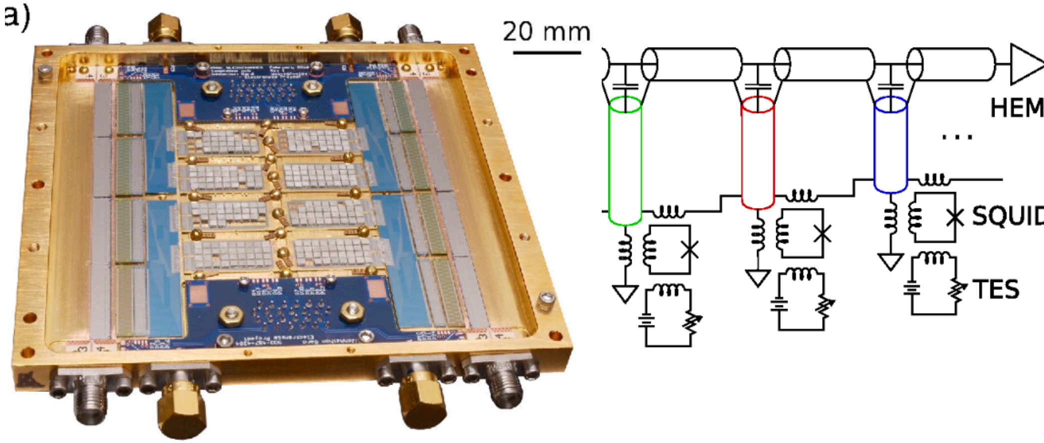
SQUID readout

Commercial single-channel SQUID





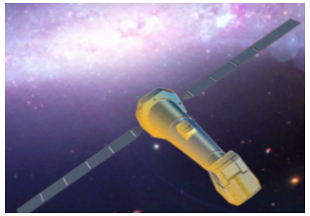
SQUID multiplexing for TES arrays



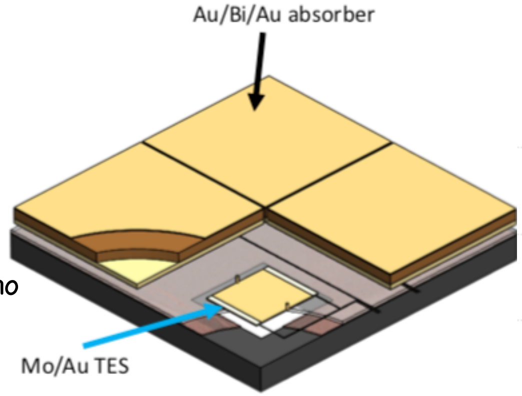
https://doi.org/10.1117/1.JATIS.5.2.021007

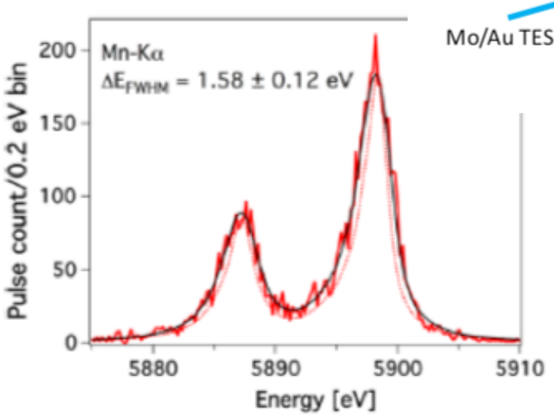
TES Micro-calorimeters

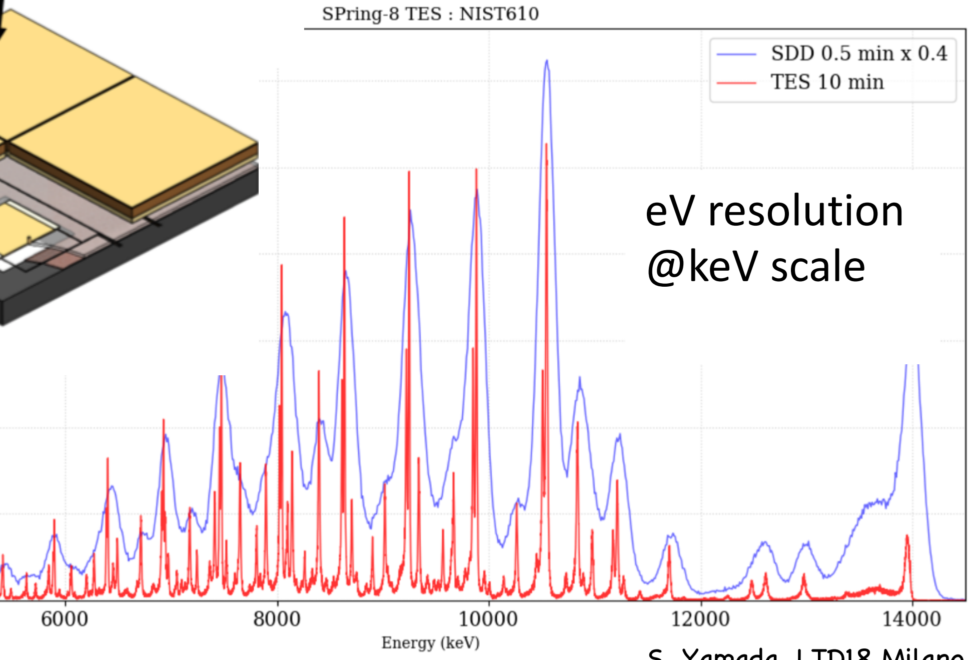
- Photon/X-ray absorption
- Large number of pixels [10k] / areas [cm]
- Applications in X-ray astronomy, spectroscopy…



N. Wakeham, LTD18, Milano







eV resolution @keV scale

S. Yamada, LTD18 Milano

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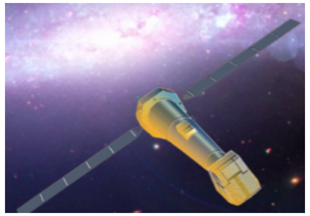
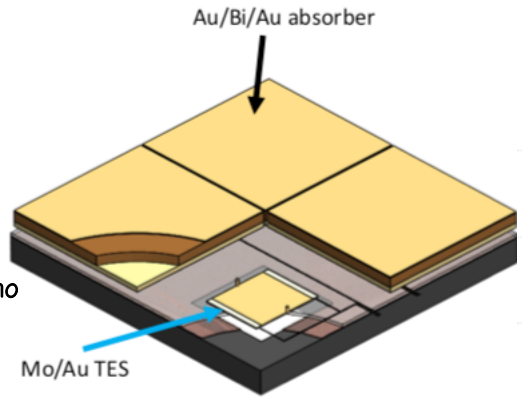
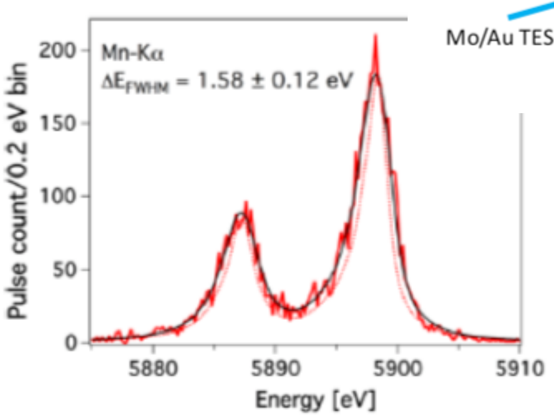
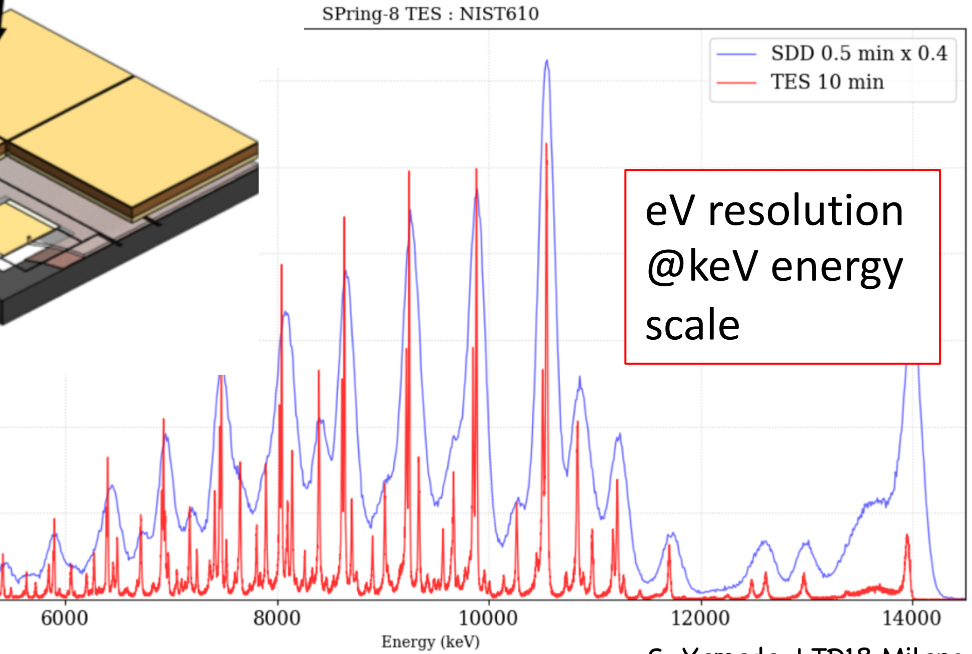




N. Wakeham, LTD18, Milano





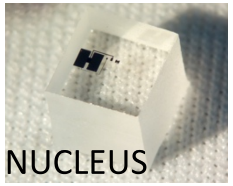
eV resolution @keV energy scale

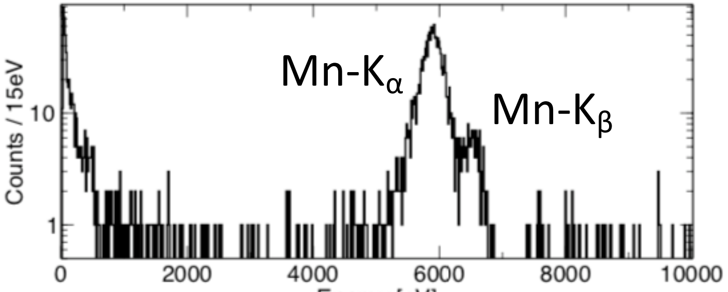
S. Yamada, LTD18 Milano

TES Macro-calorimeters

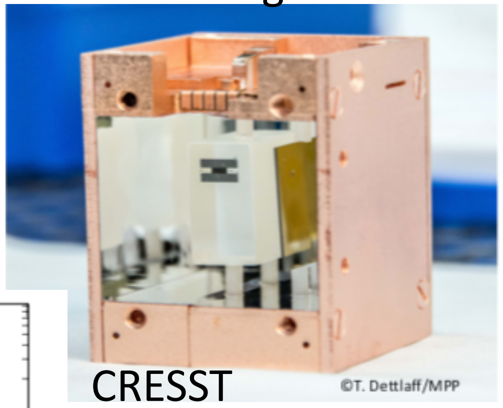
- Particle interaction in absorber [g-kg]
- Single detectors
- Applications in rare-event searches
  - Dark Matter search
  - Neutrino physics
  - Photon detection

grams

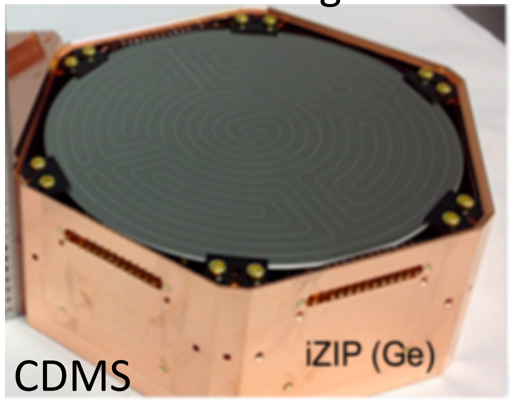




10's of grams



100's of grams



Leading energy thresholds of O(10eV)

Transition-Edge-Sensors

- TES are among most sensitive cryogenic sensors

- TES are challenging to fabricate and operate

- TES have wide application in fundamental science
  - Rare-event searches (eV resolutions, 10’s of eV thresholds)
  - Astronomy (eV resolutions, pixalated, large area)
  - X-ray spectroscopy
  - Detectors for society?

- Scalability of TES has become mature …