Cryogenic Detectors
for particle physics

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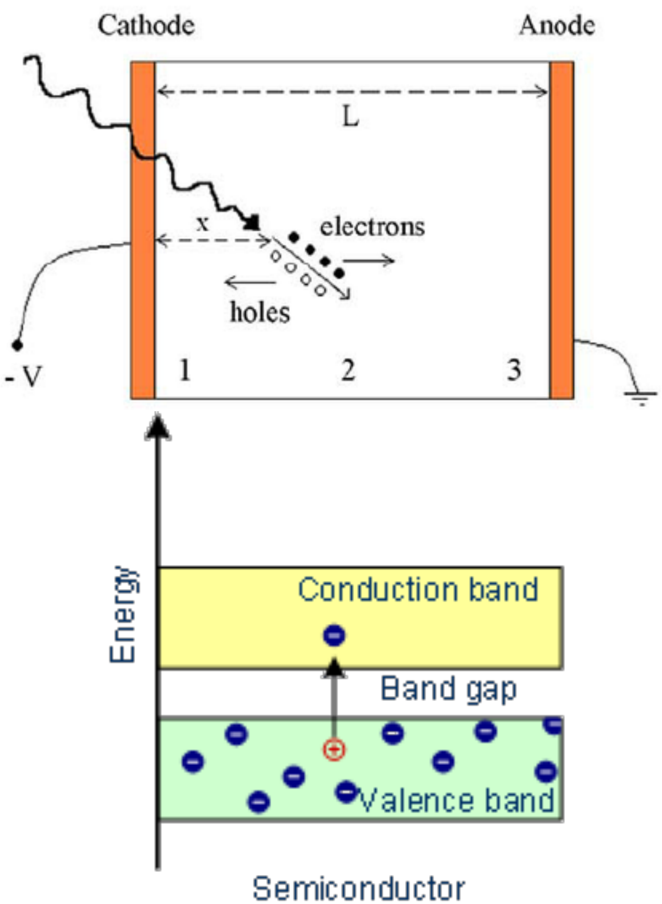
Cryogenics: when sensitivity matters

Semiconductor detectors

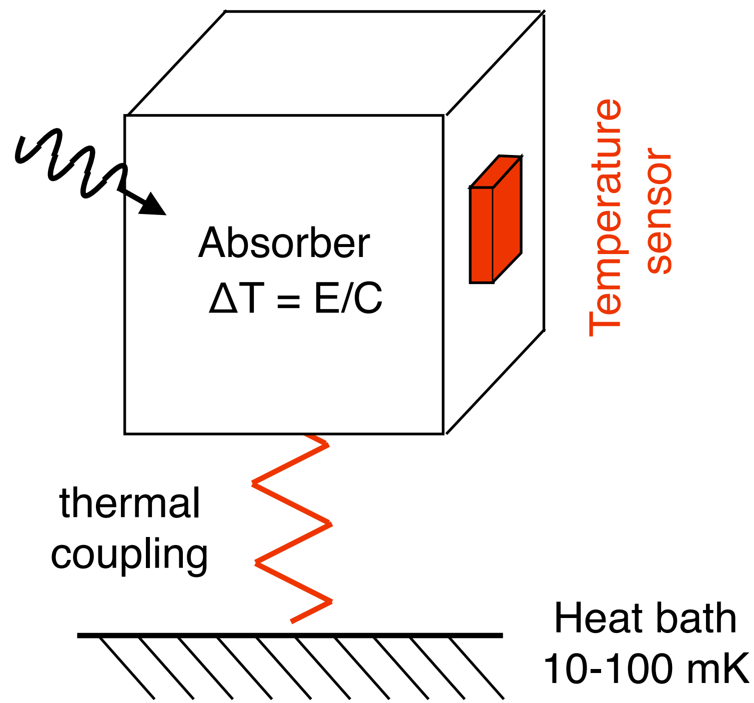


$\epsilon \sim 1\,\mathrm{eV}$

$w > \varepsilon$, quenching

$$\Delta E \propto \sqrt{\epsilon E}$$

Cryogenic detectors

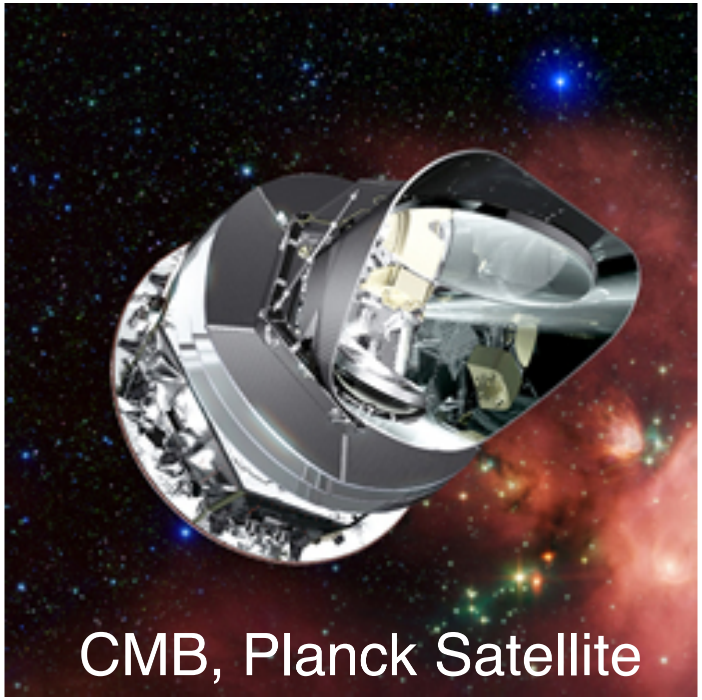


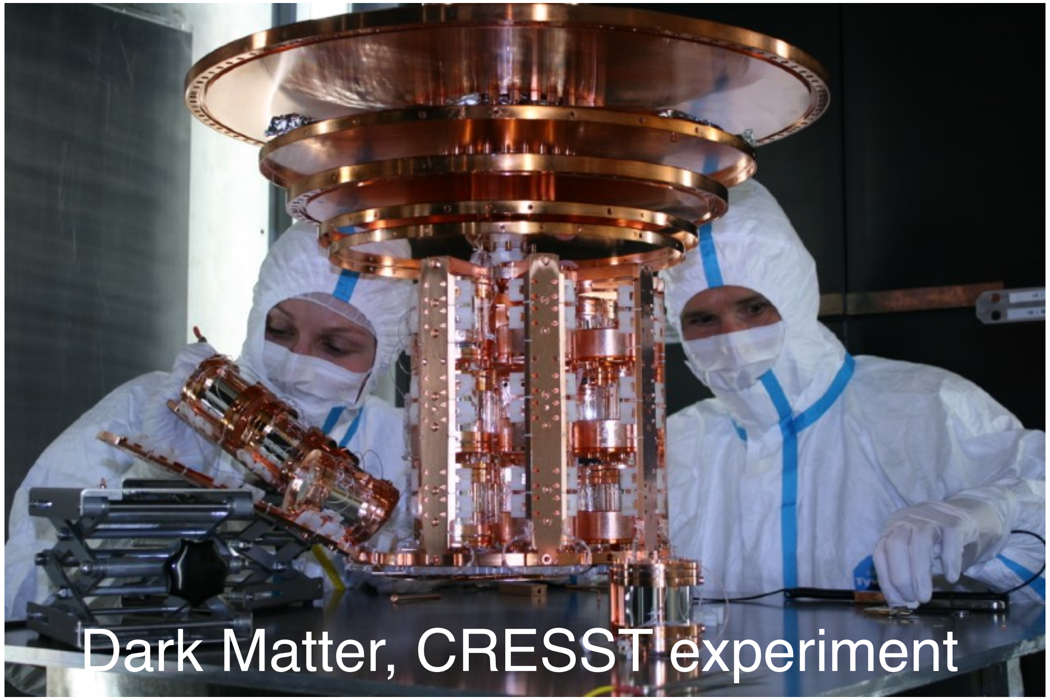
Quanta are phonons

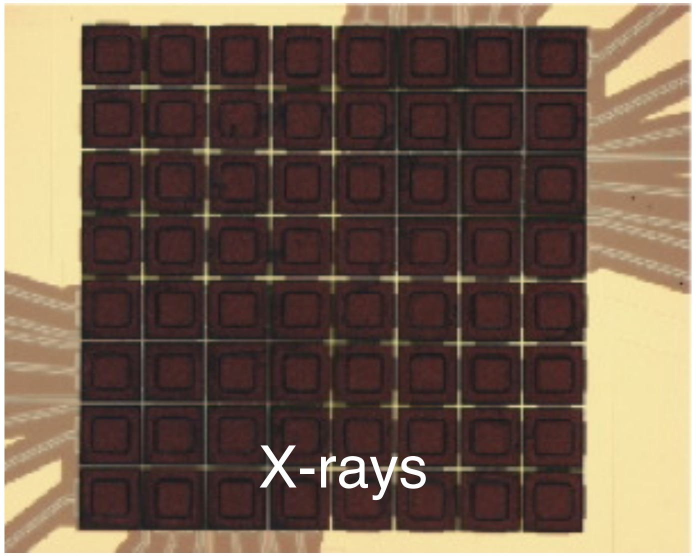
$\epsilon = k_B T(100\mathrm{mK}) \sim 10\,\mu\mathrm{eV}$

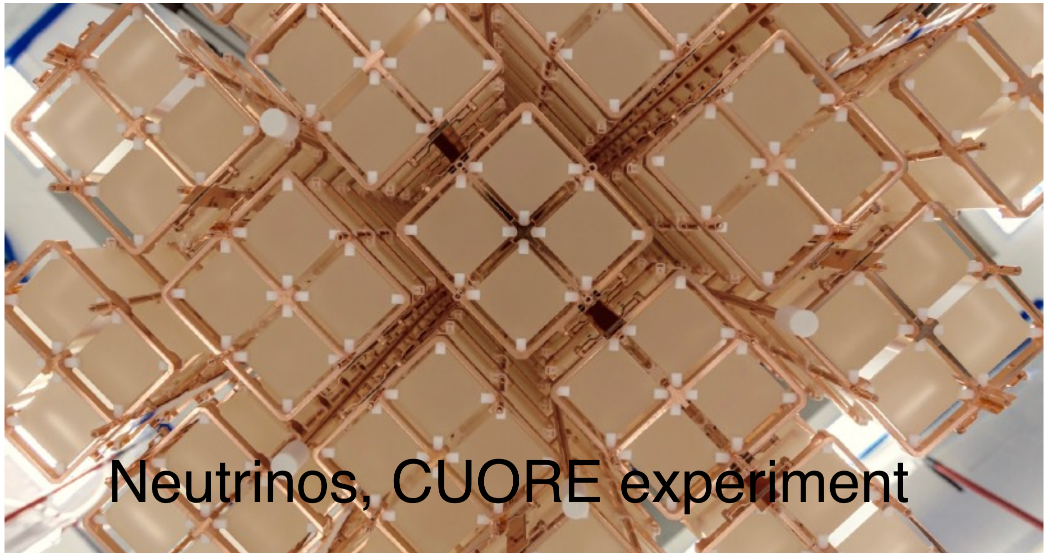
no quenching

Applications of cryogenic detectors



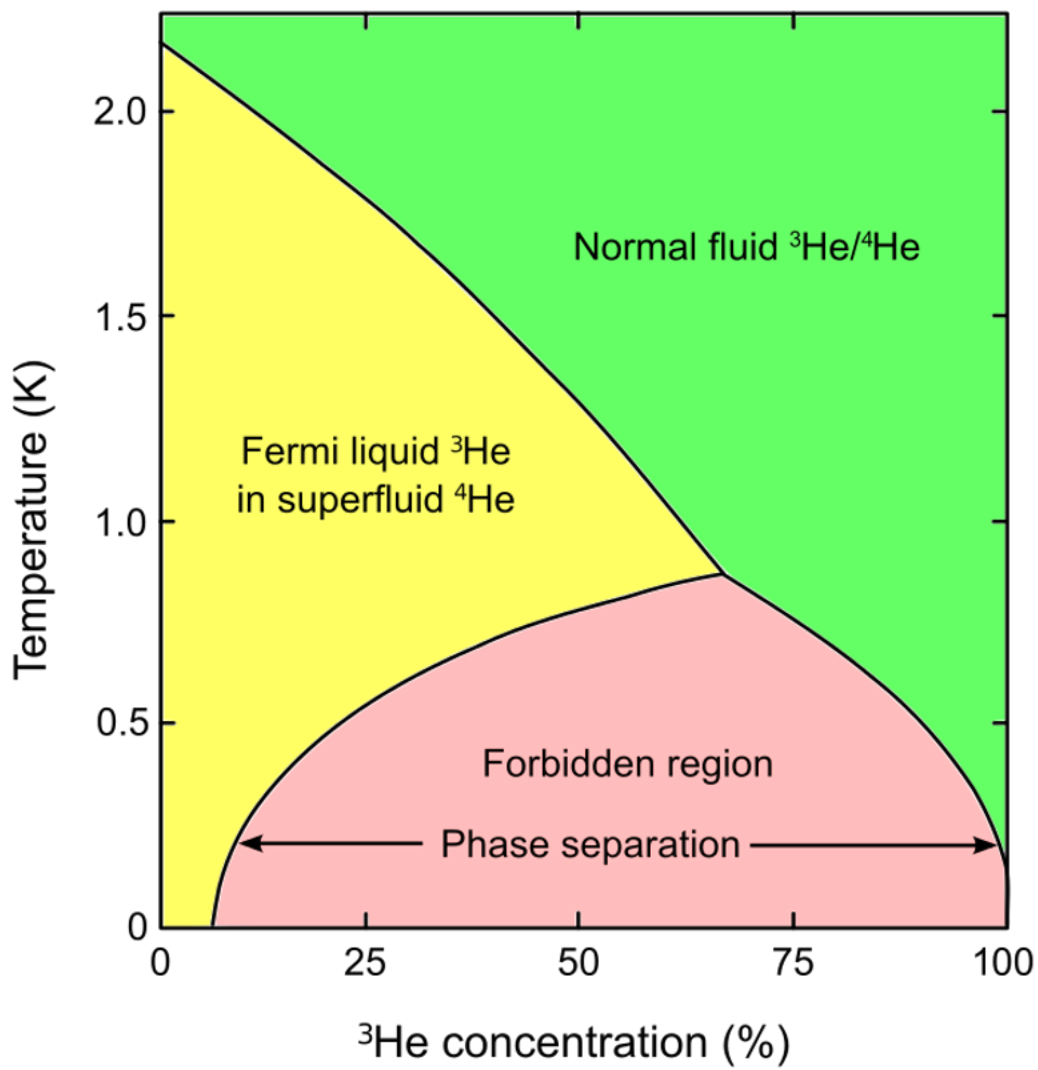






Cooling mechanism

Kelvin temperature is easily reached with Liquid He or Pulse tubes
The interesting part is from K to 0.01 K: **dilution mechanism**



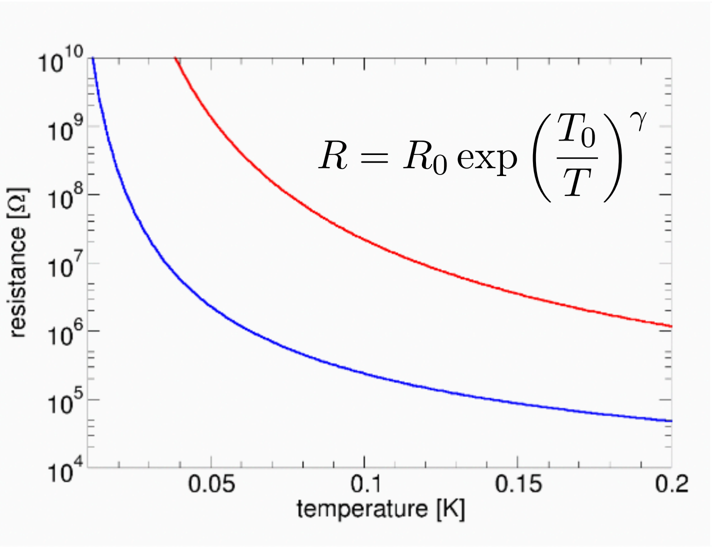
- ^4He (Bose) / ^3He (Fermi) mixture
- Phase separation below 0.87 K
  - Phase rich in ^4He
  - Phase rich in ^3He
- Work: pump ^3He gas through the ^4He condensate (evaporation)
- Evaporation absorbs heat
  - Cooling power

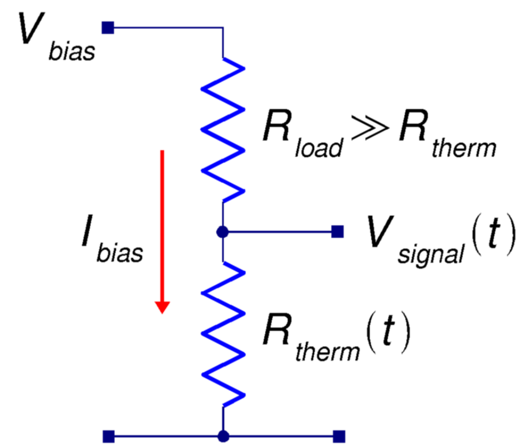
Cryolab @ Sapienza U.

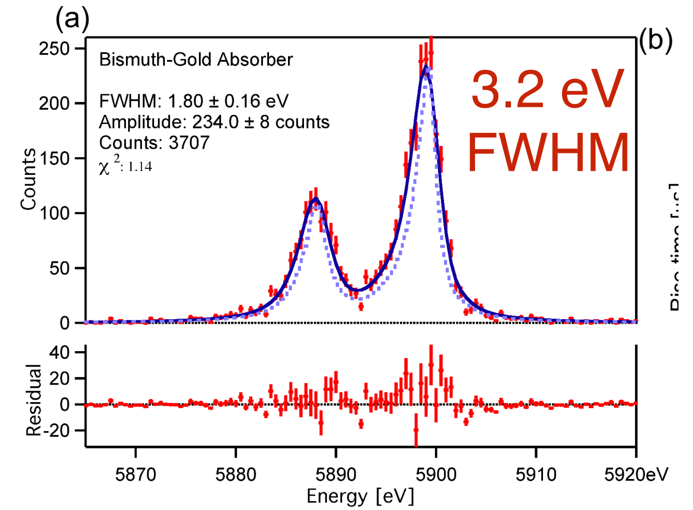
Experimental volume is few to tens of litre, typically

Most popular cryogenic sensors

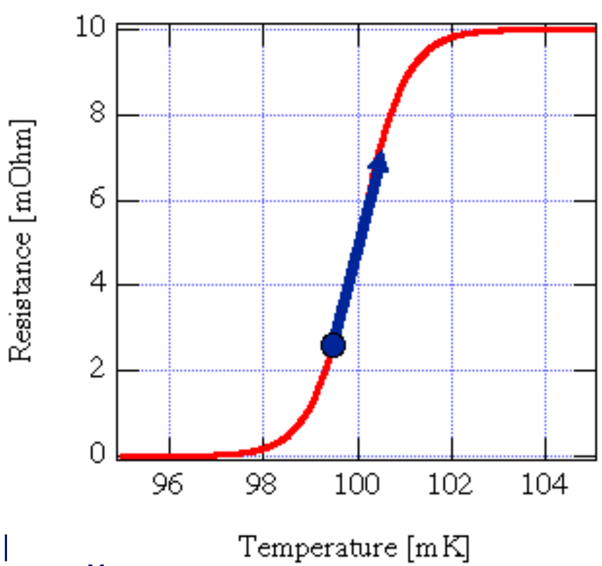
High impedance: semiconducting thermistor

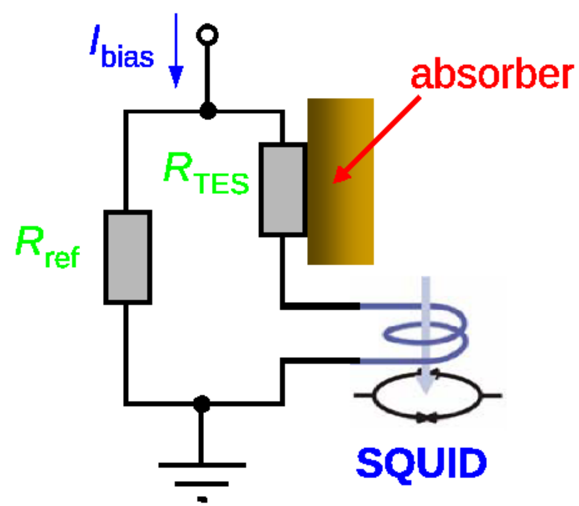


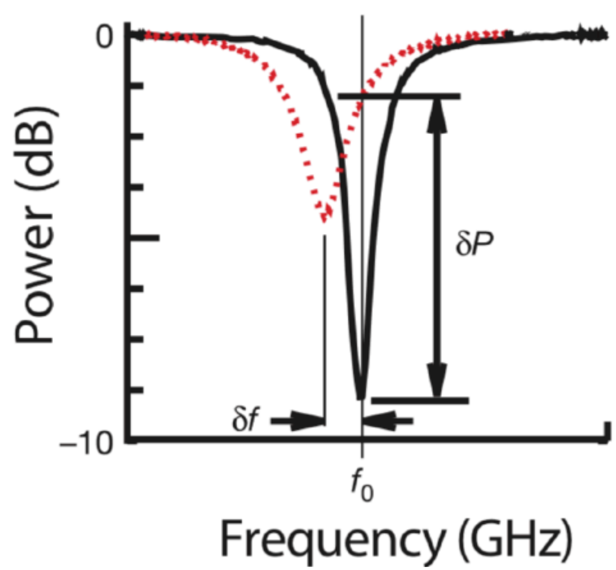




Low impedance: superconducting TES and KIDs

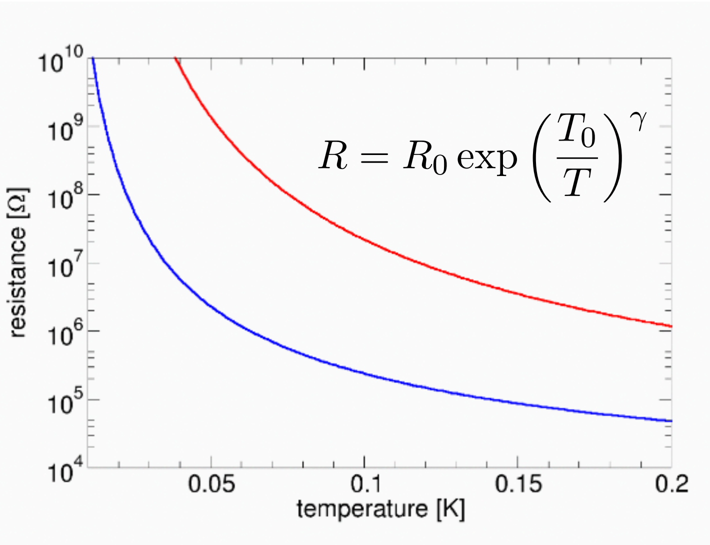


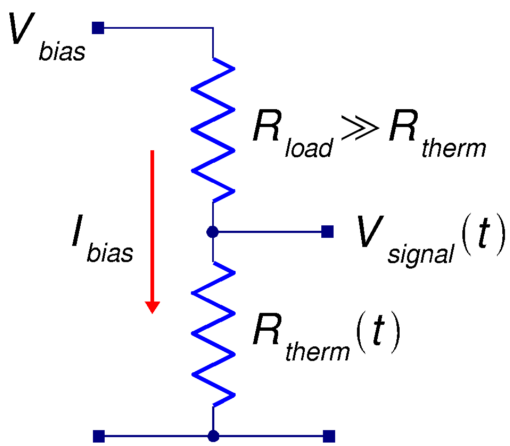


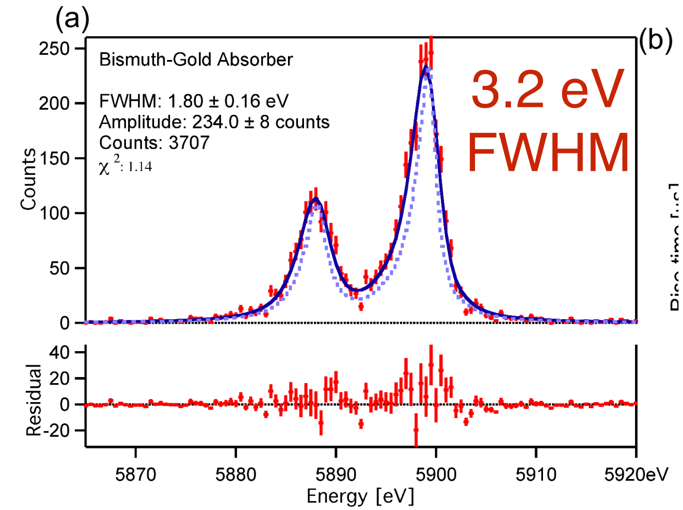


Most popular cryogenic sensors

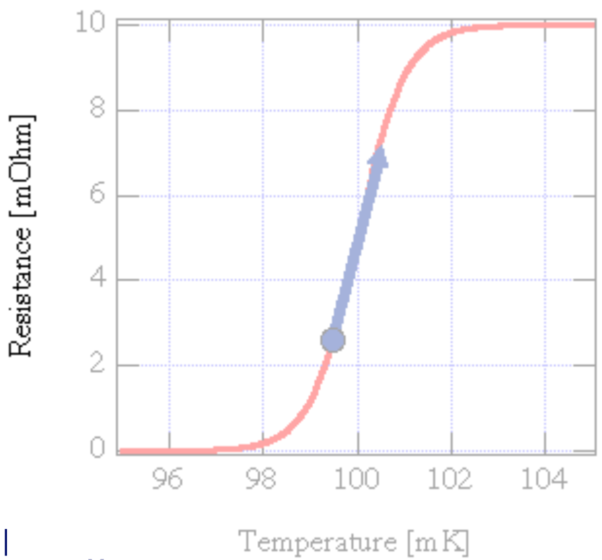
High impedance: **semiconducting** thermistor

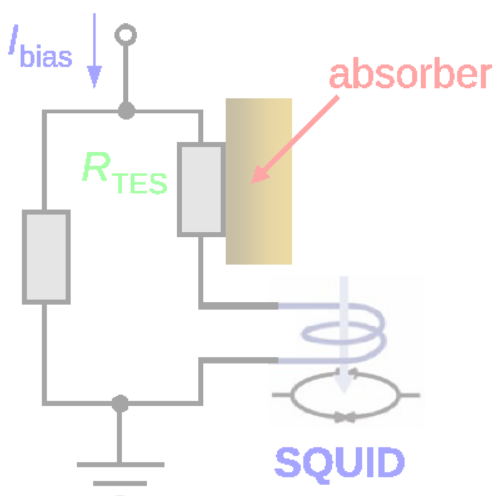


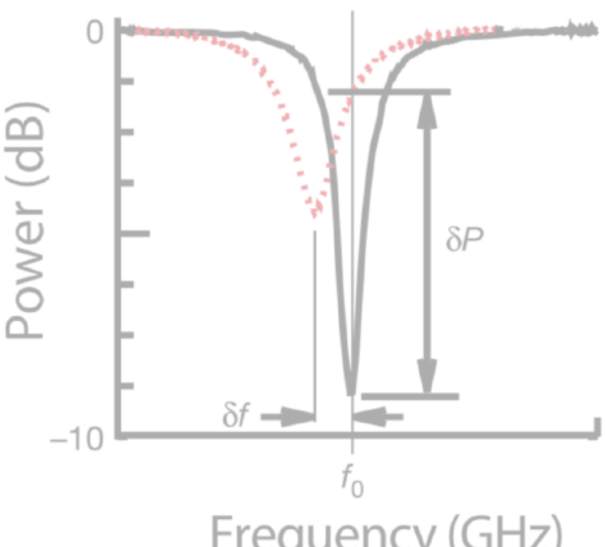




Low impedance: superconducting TES and KIDs





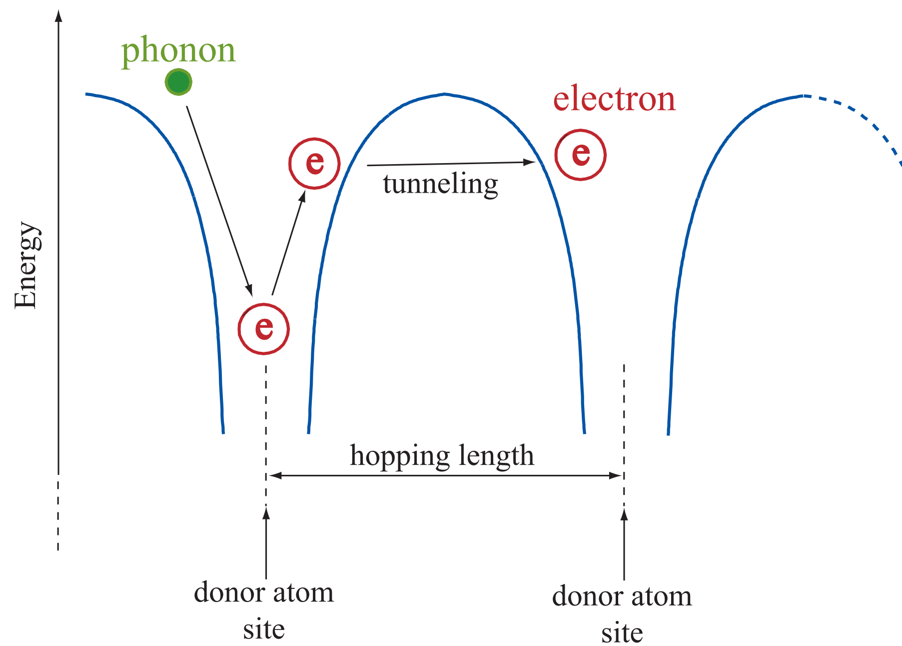


Semiconducting thermistors

Hopping conduction

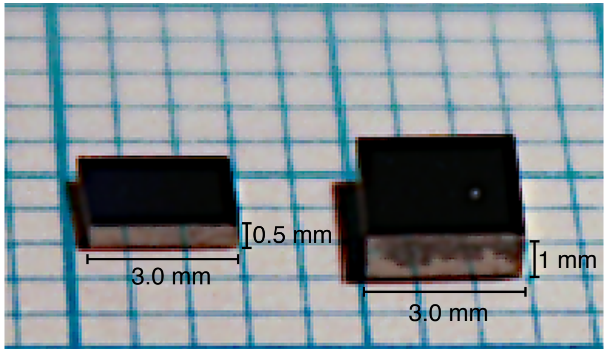
Semiconductor gap = 2 eV
Room T: 300 K = 0.027 eV

Doped semiconductor to tune the temperature of metal-insulator transition (MIT).



Mott's model:

$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{\gamma}$$



neutron-transmutation-doped germanium (NTD-Ge)

Thermistor readout

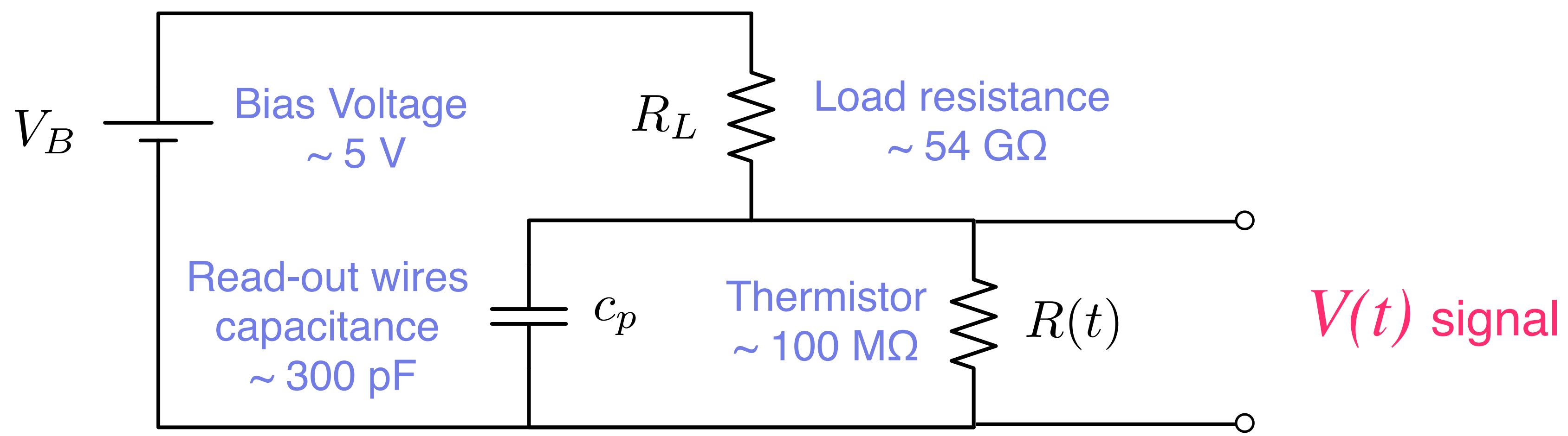
- The thermistor resistance depends on the temperature as:

$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{\gamma}$$

using parameters of CUORE experiment (R_0 = 1.15 Ω, T_0 = 3.35 K and γ = 1/2):

R (10 mK) ~100 MΩ

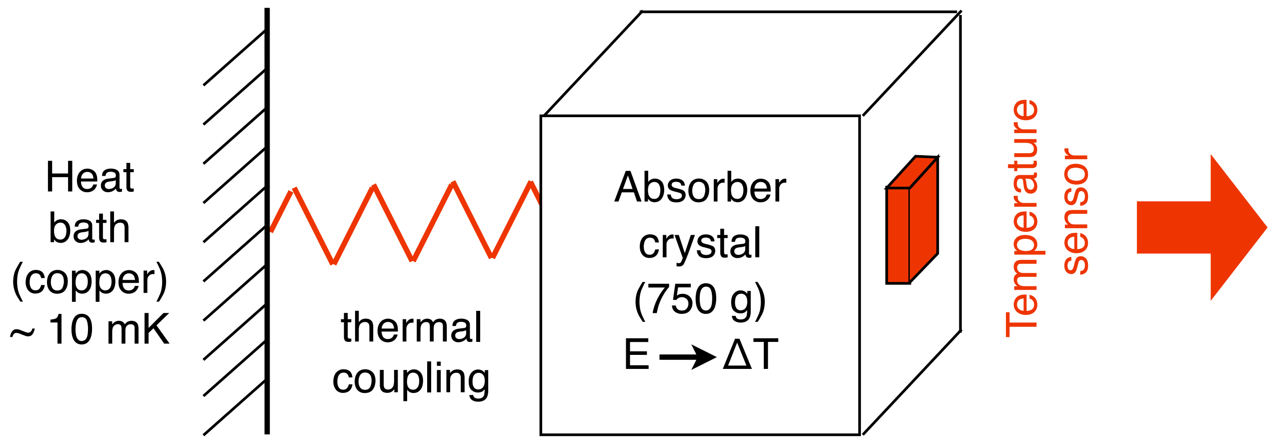
- The signal is detected biasing the resistance and reading the voltage *V(t)* across it:

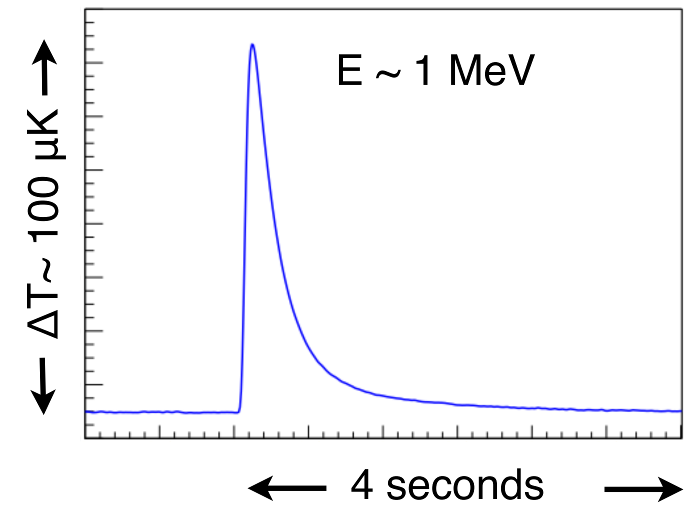


- *V(t)* is then amplified, filtered and digitised.

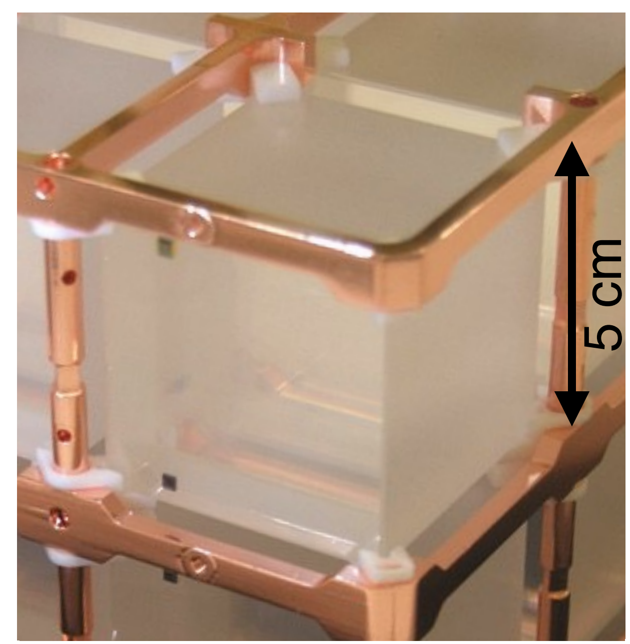
example of NTD
in particle physics

Bolometric technique in CUORE

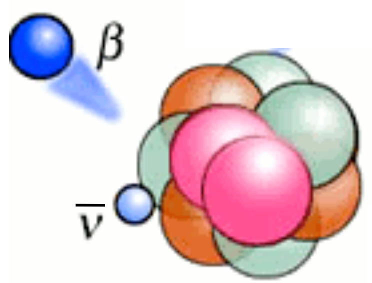




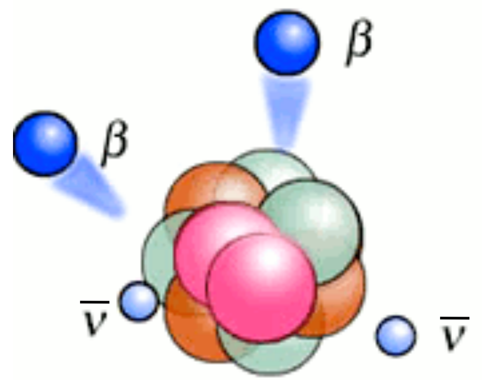
- $^{nat}TeO_2$ crystals (low heat capacitance)
  source embedded in the detector
- NTD-Ge thermistor: $R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{\frac{1}{2}}$
  R(T) = 100 - 1000 kΩ @ 10 mK
- Resolution @$0\nu\beta\beta$ energy (2528 keV):
  ΔE = 5 keV FWHM
- Detection efficiency ~ 80%



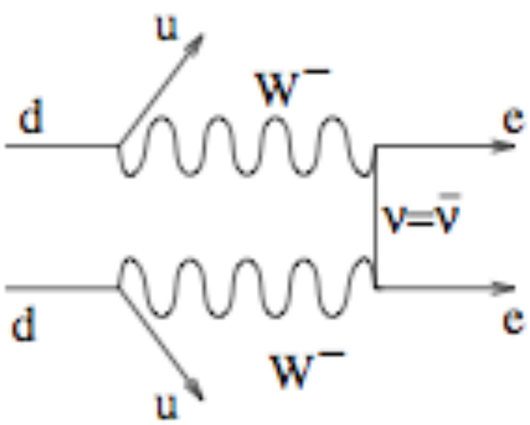
Double β decay



β-decay

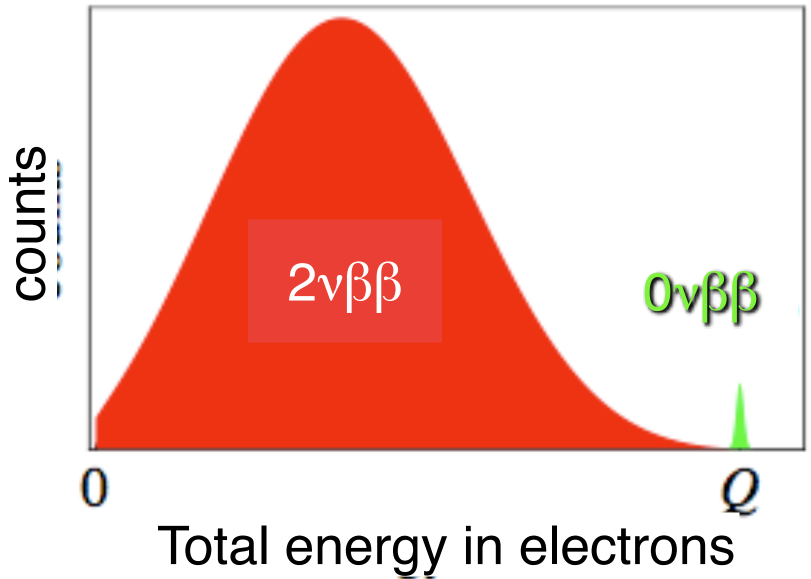


ββ-decay



0νββ-decay

only if *νs* are Majorana

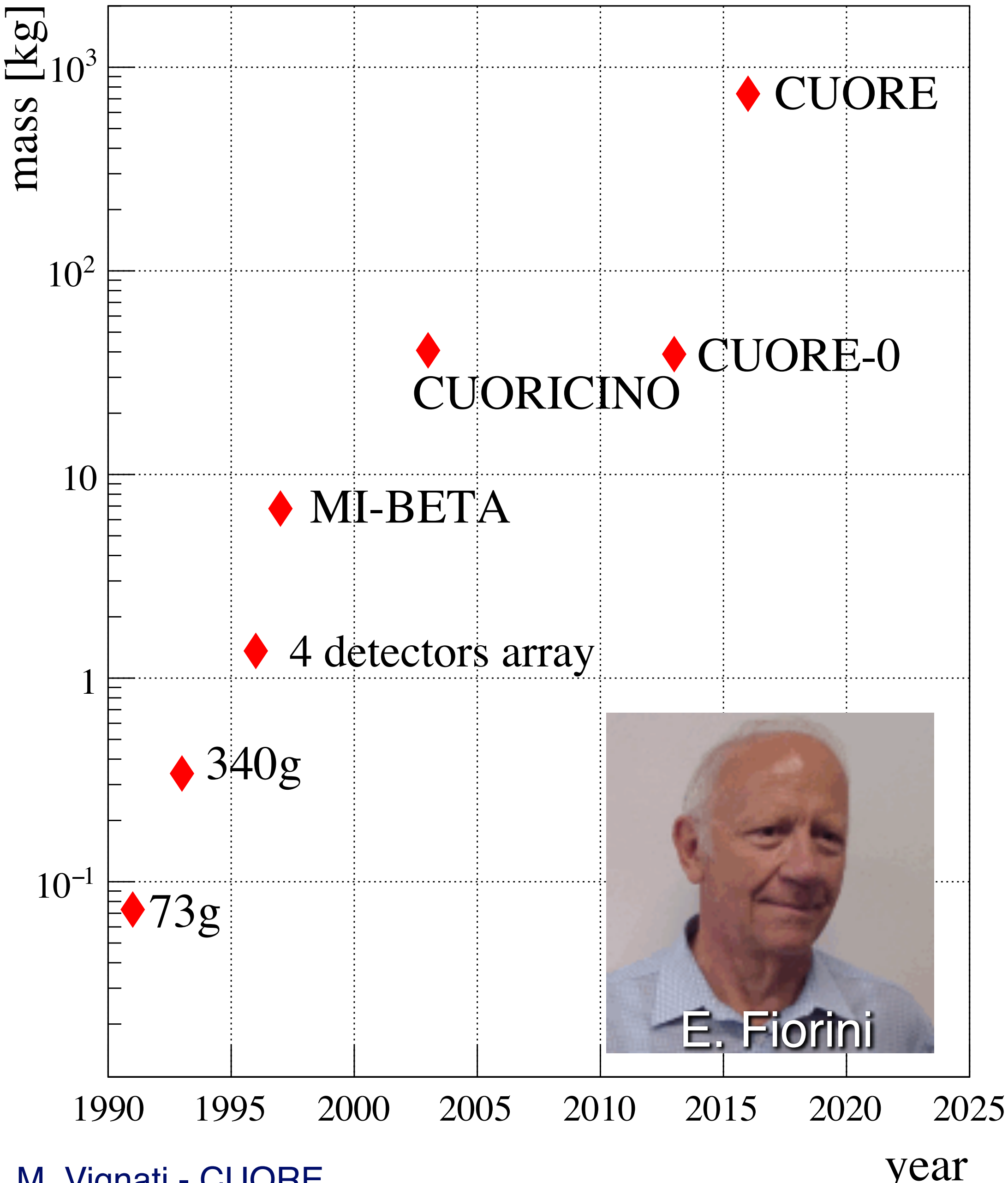


0νββ is possible only in few natural isotopes, e.g.: ^{130}Te, ^{76}Ge, ^{136}Xe,^{100}Mo,^{82}Se.

Present half-life limits are: $\tau > 10^{25\text{-}26}$ years.
Several nuclei (100 - 1000 kg) are needed.

Almost Zero background is needed.

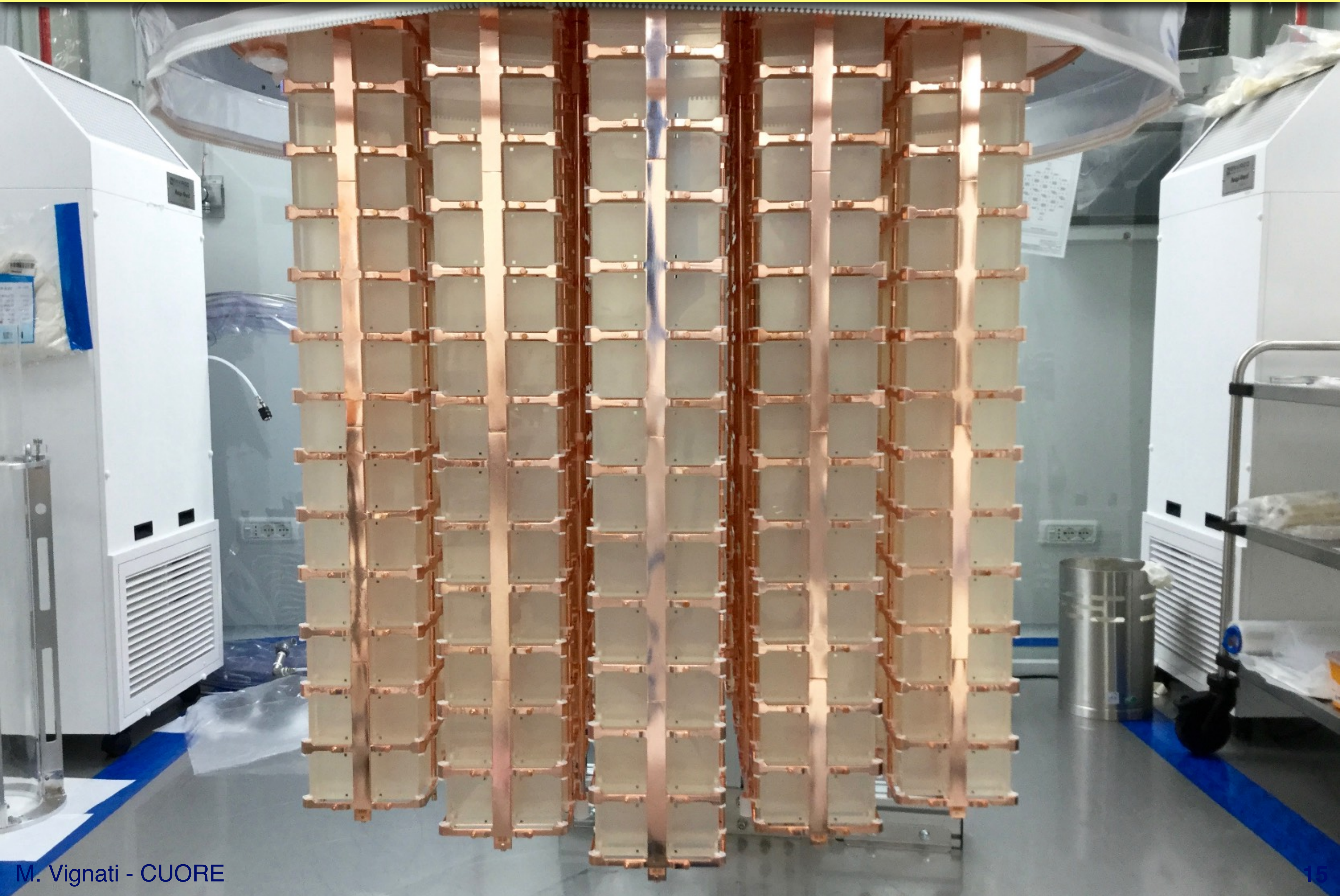
Arrays of TeO_2 bolometers



Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

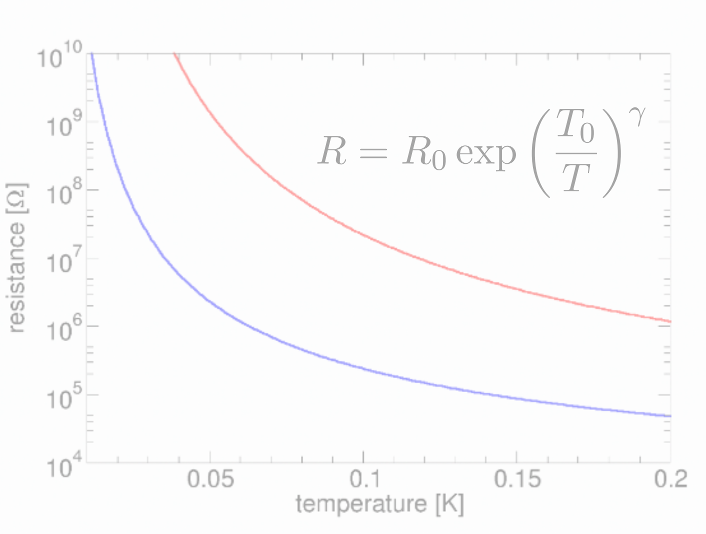
- Hosted at Gran Sasso lab in Italy.
- 988 $^{nat}TeO_2$ bolometers 19 towers, 13 floors.
- Active mass: 742 kg.
- Isotope mass: 206 kg ^{130}Te.
- Expected background: 10^{-2} c/keV/kg/year
- Sensitivity to $0\nu\beta\beta$ in 5y $T_{1/2} = 9 \times 10^{25}$ y @90% C.L.
- Sensitivity to $m_{\beta\beta}$ in 5y: 50 - 130 meV @90% C.L.

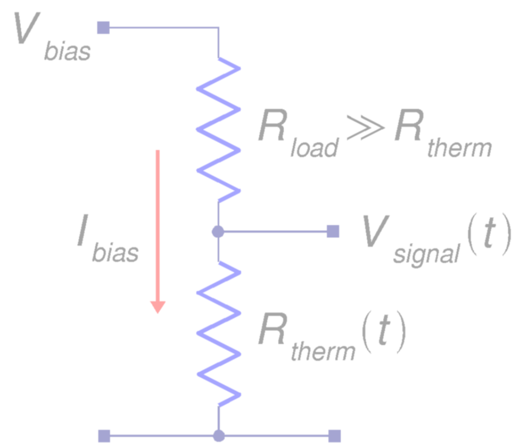
CUORE detector before cool down

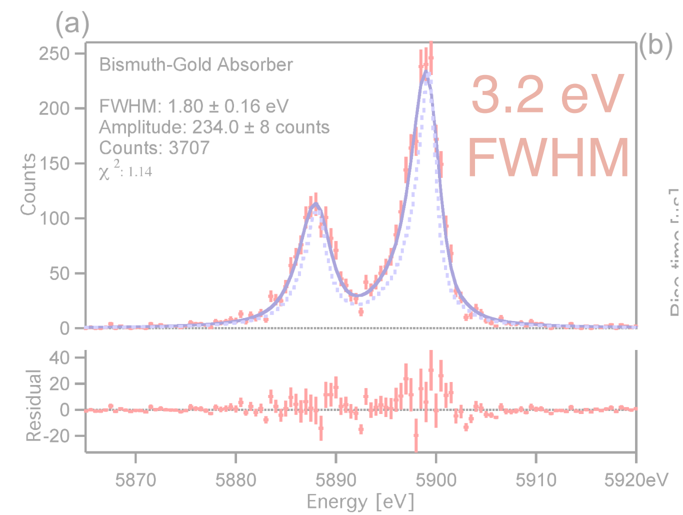


Most popular cryogenic sensors

High impedance: semiconducting thermistor







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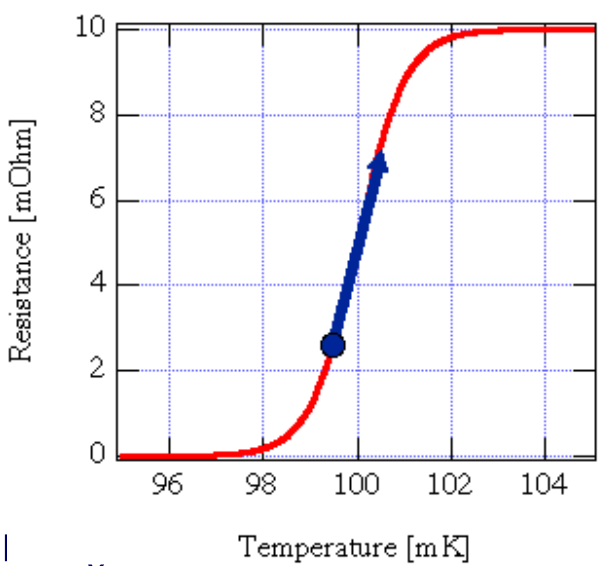
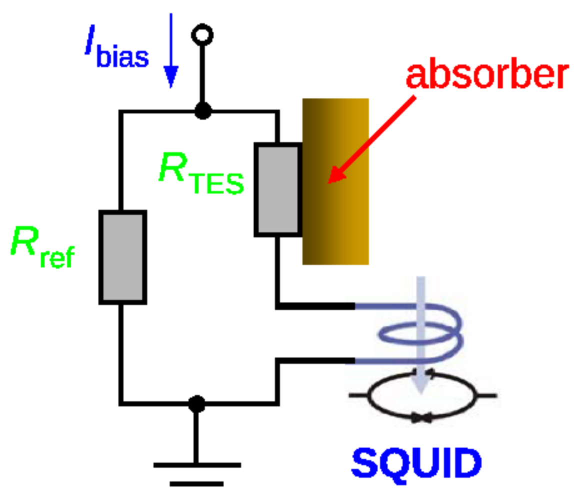
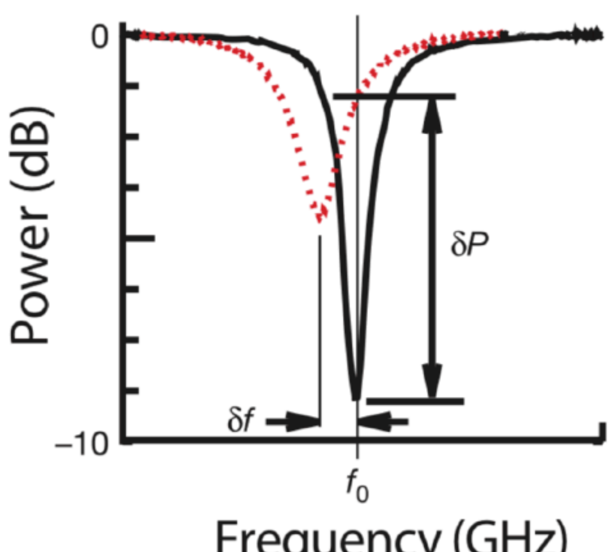




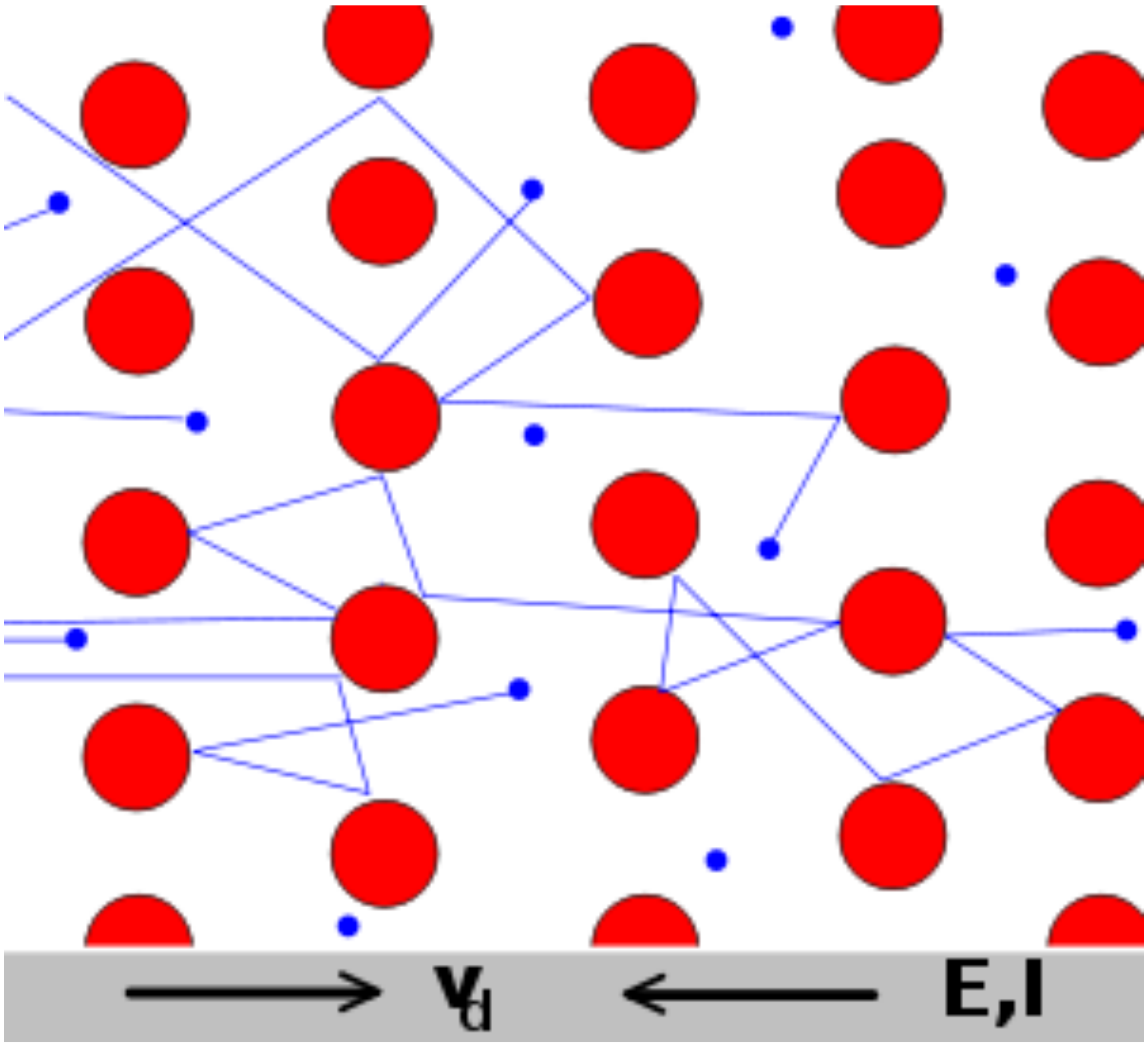


Elements of superconductivity

Conductivity - Drude model

$$\mathbf{J} = \underbrace{\left(\frac{nq^2\tau}{m}\right)}_{\sigma_0} \mathbf{E}.$$

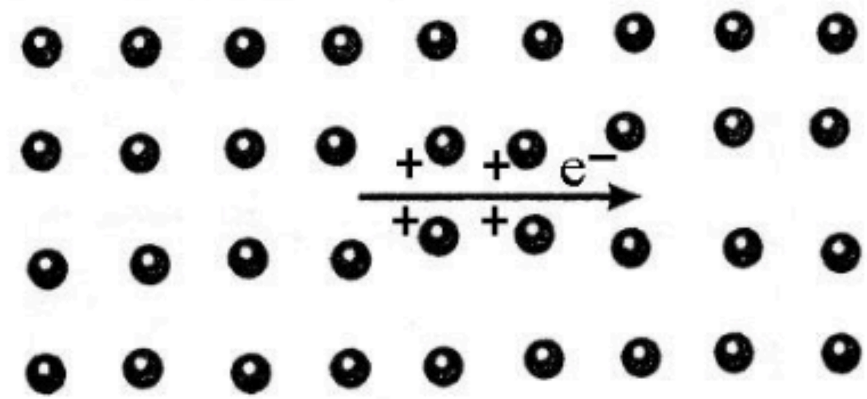
- **J** current density
- **E** electric field
- n electron density
- q electron charge
- m electron mass
- τ mean free time between collisions with phonons



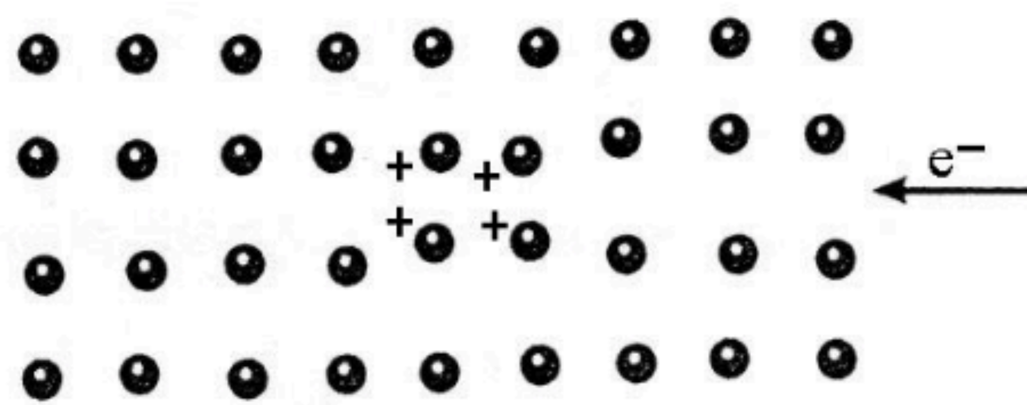
Wikipedia

Superconductivity for dummies

- Many materials at cryogenic temperatures have zero DC impedance.
- The phenomenon arises below a critical temperature, $T < T_c$.
- Below this temperature electrons do not scatter on the lattice anymore and are bound in Cooper Pairs:
  - Binding energy is small ~ 0.4 meV in aluminum.
  - Opposite electrons spins forming a Bose condensate
  - Single wave function over the condensate.



First electrons defoms part of the lattice electrostatically.



Second electron is attracted to the net positive charge of the deformation

List of superconductors (Wikipedia)

Substance	Class	T_C (K)	H_C (T)	Type	BCS
Al	Element	1.20	0.01	I	yes
Bi	Element	5.3×10^{-4}	5.2×10^{-6}	I	no
Cd	Element	0.52	0.0028	I	yes
Diamond:B	Element	11.4	4	II	yes
Ga	Element	1.083	0.0058	I	yes
Hf	Element	0.165		I	yes
α-Hg	Element	4.15	0.04	I	yes
β-Hg	Element	3.95	0.04	I	yes
In	Element	3.4	0.03	I	yes
Ir	Element	0.14	0.0016	I	yes
α-La	Element	4.9		I	yes
β-La	Element	6.3		I	yes
Li	Element	4×10^{-4}		I	
Mo	Element	0.92	0.0096	I	yes
Nb	Element	9.26	0.82	II	yes
Os	Element	0.65	0.007	I	yes
Pa	Element	1.4		I	yes
Pb	Element	7.19	0.08	I	yes
Re	Element	2.4	0.03	I	yes
Rh	Element	3.25×10^{-4}	4.9×10^{-6}	I	
Ru	Element	0.49	0.005	I	yes
Si:B	Element	0.4	0.4	II	yes
Sn	Element	3.72	0.03	I	yes
Ta	Element	4.48	0.09	I	yes
Tc	Element	7.46–11.2	0.04	II	yes
α-Th	Element	1.37	0.013	I	yes
Ti	Element	0.39	0.01	I	yes
Tl	Element	2.39	0.02	I	yes
α-U	Element	0.68		I	yes
β-U	Element	1.8		I	yes
V	Element	5.03	1	II	yes
α-W	Element	0.015	0.00012	I	yes
β-W	Element	1–4			
Zn	Element	0.855	0.005	I	yes
Zr	Element	0.55	0.014	I	yes

Then there are compounds, like YBCO with T_c = 95 K
(high -T_c superconductivity)

TES: Transition Edge Sensors

TES working principle

- Measure the temperature variations with a superconductor due to an energy release *E* in an absorber of capacitance *C:*

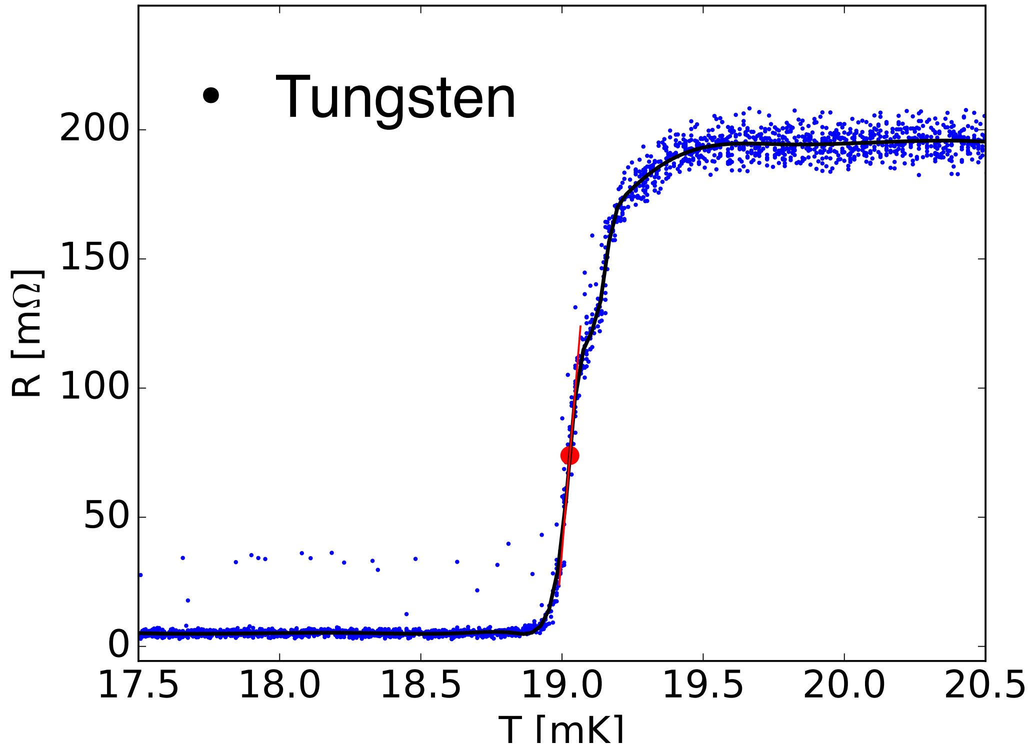
$$\Delta T = \frac{E}{C}$$

- Superconductor stabilized in temperature at the onset of the superconducting - conducting transition

- Measure tiny resistance variations

- The steeper the R vs T the higher the sensitivity

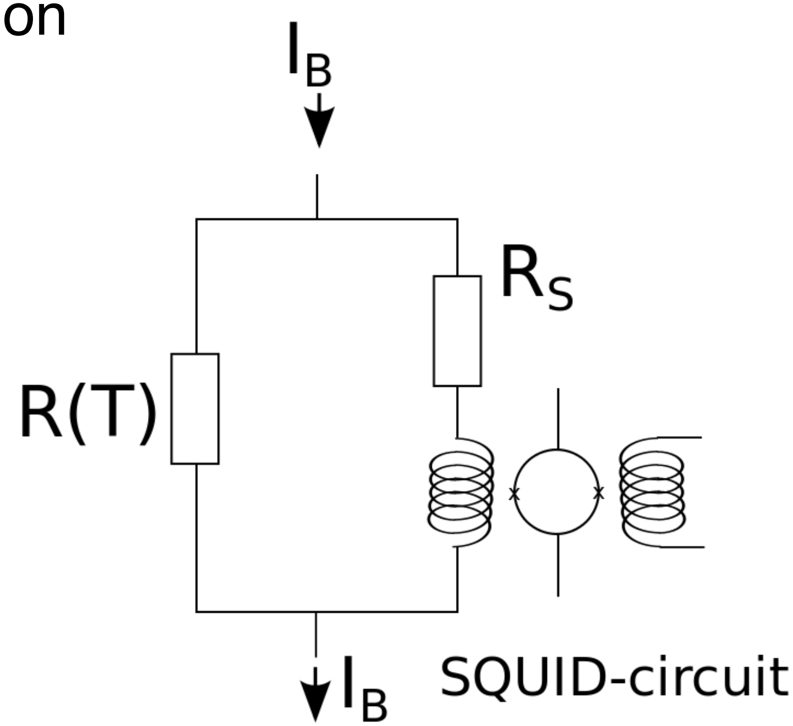
$$\alpha \equiv \frac{d(\log R)}{d(\log T)} = \frac{T}{R}\frac{dR}{dT}$$



TES readout

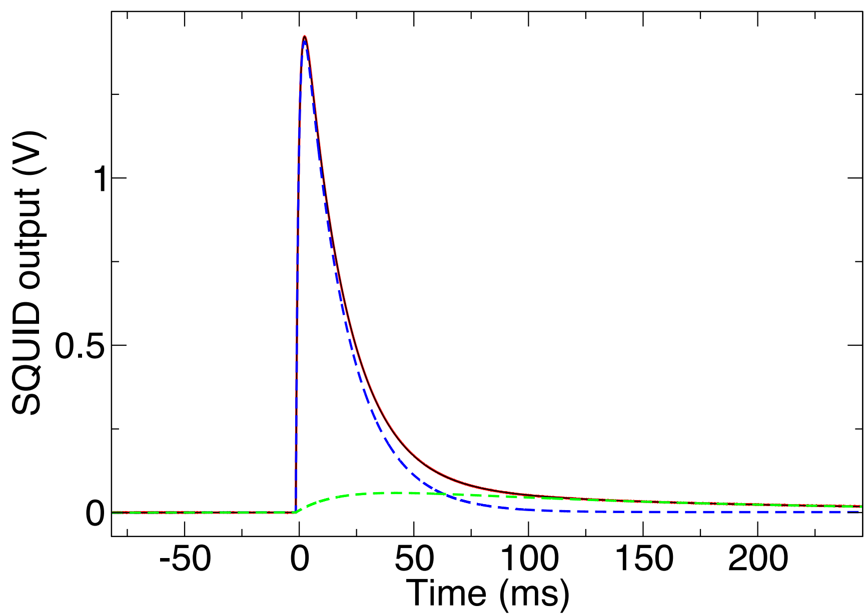
- Negative feedback circuit with constant current I_B and shunt resistor R_S for temperature stabilisation

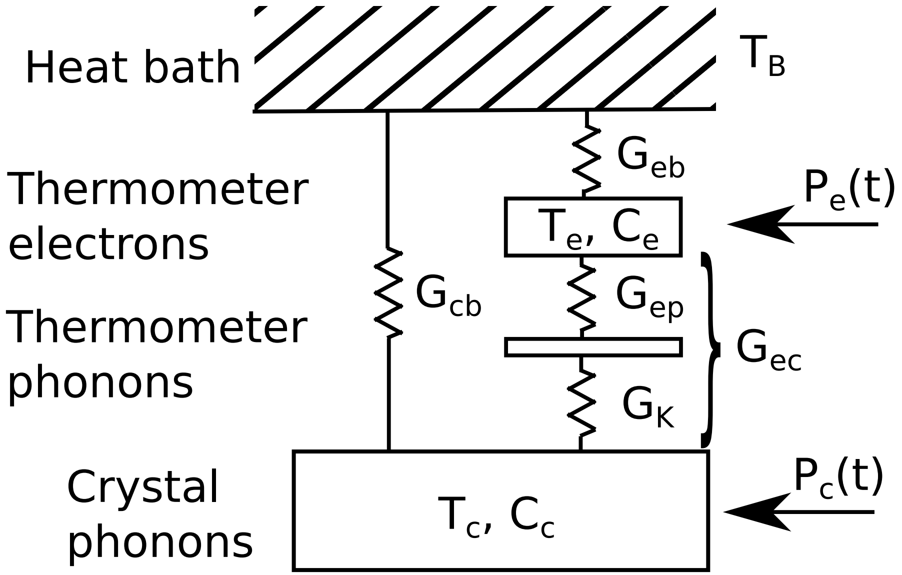
1) The higher the TES resistance R(T)
2) the lower the current and Joule heating
3) the lower the T and thus R(T)



- Current variations in R_S converted to magnetic field variations
- Magnetic field variations measured with a Superconducting Quantum Interference Device
- Complicated but very low noise (record energy resolution and threshold).

TES signal

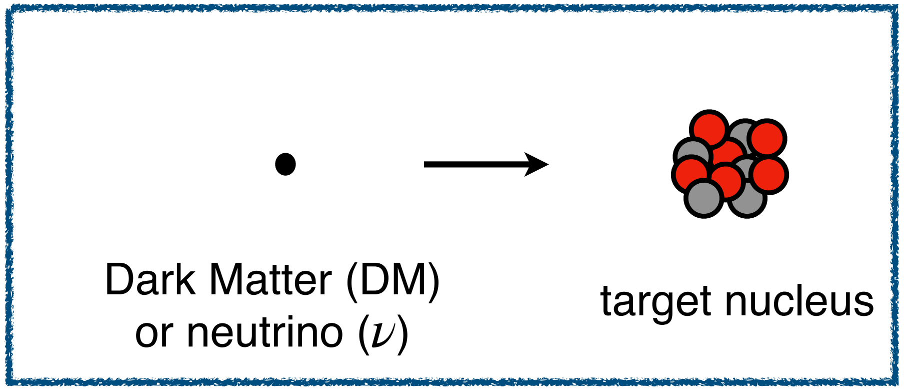


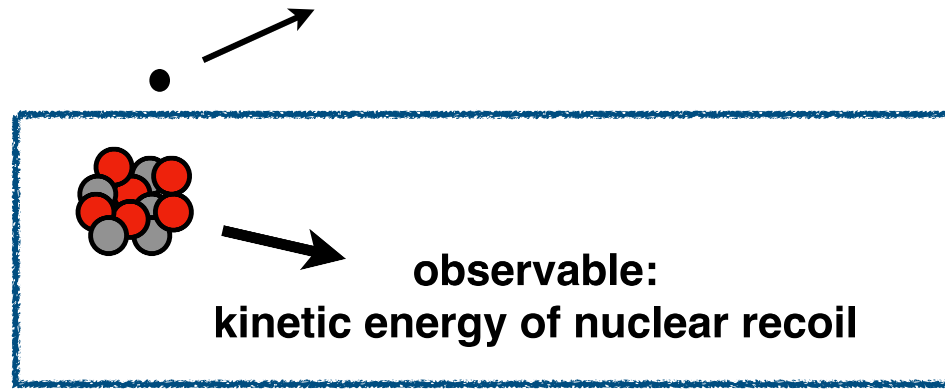


- Signal amplitude in *Volts* proportional to the energy released *E*
- Weak coupling to the thermal bath *G*
- Long relaxation times ~ *C/G*

examples of TES in particle physics

Process under observation

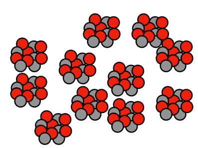


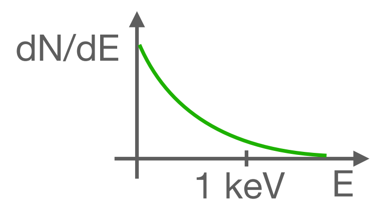


cross section $\sigma < 10^{-40}$ cm^2

energy < 1 keV

large number of targets
(large target mass)

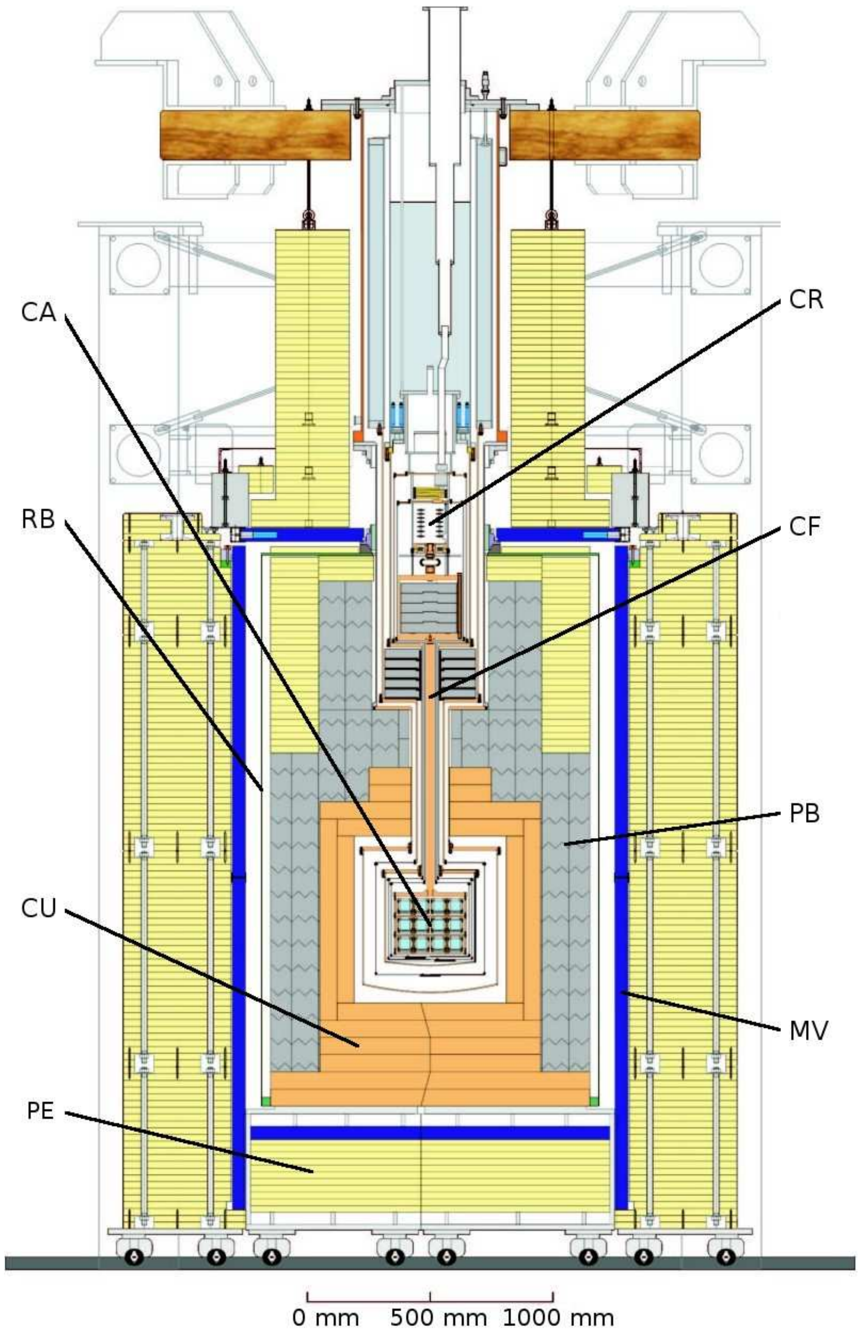




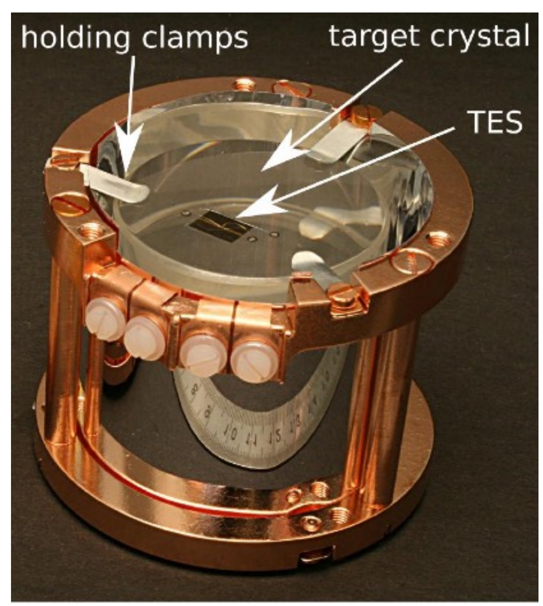
low-energy
detection threshold

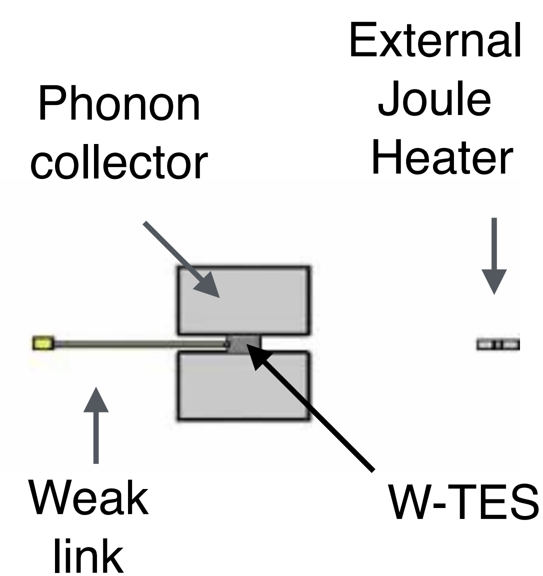
Difficult to have both in the same experiment!

Dark Matter with CRESST



- Array of $CaWO_4$ absorbers read by TES
- Operated at the Gran Sasso Laboratories in Italy.
- Leader in the low energy region of Dark Matter (energy threshold of ~30 eV)





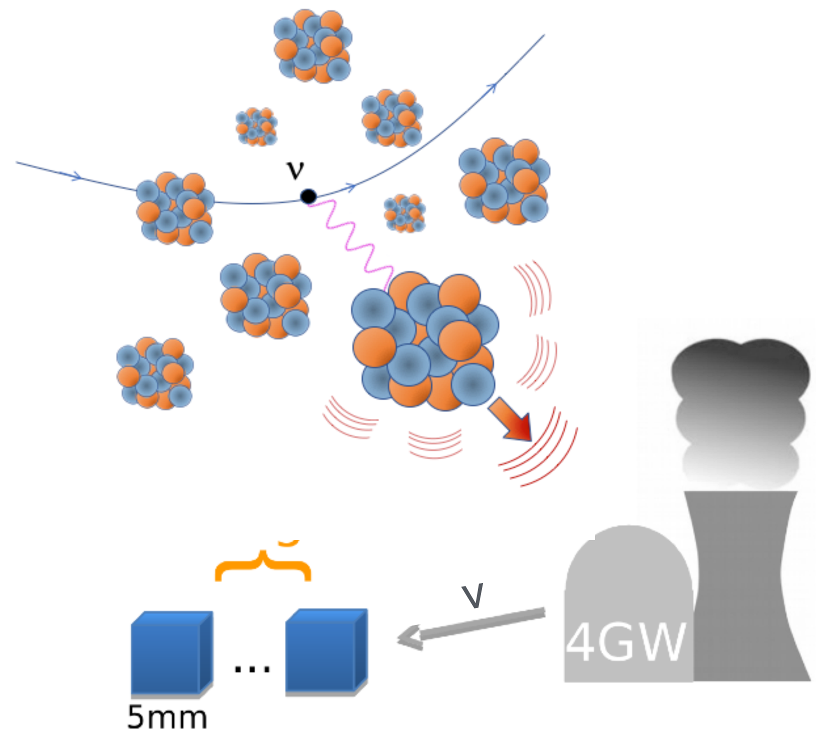
CEνNS with NUCLEUS

Coherent Elastic ν-Nucleus Scattering, discovered in 2017

$$\nu(\bar{\nu}) + A \rightarrow \nu(\bar{\nu}) + A$$

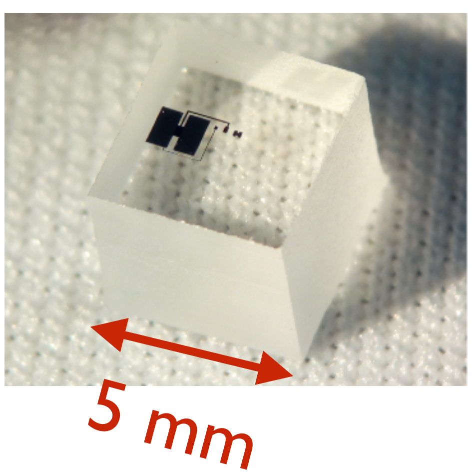
$$\sigma_{\text{CE}\nu\text{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$$

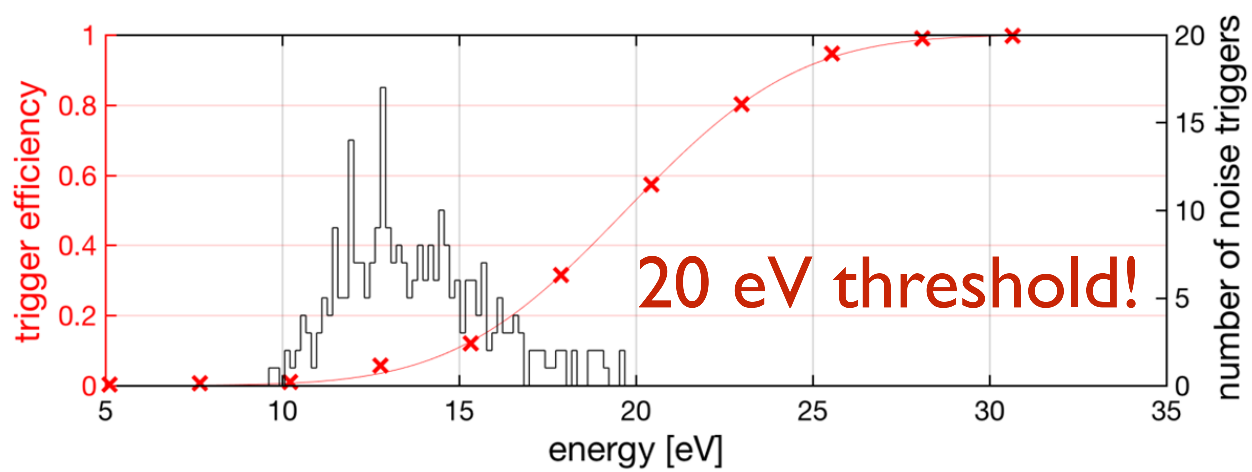
$$Q_W = N - Z(1 - 4\sin^2\theta_W) \sim N$$



NUCLEUS will measure
this process with 10% precision.

10 g of detectors with TES to observe
neutrinos from a nuclear power plant

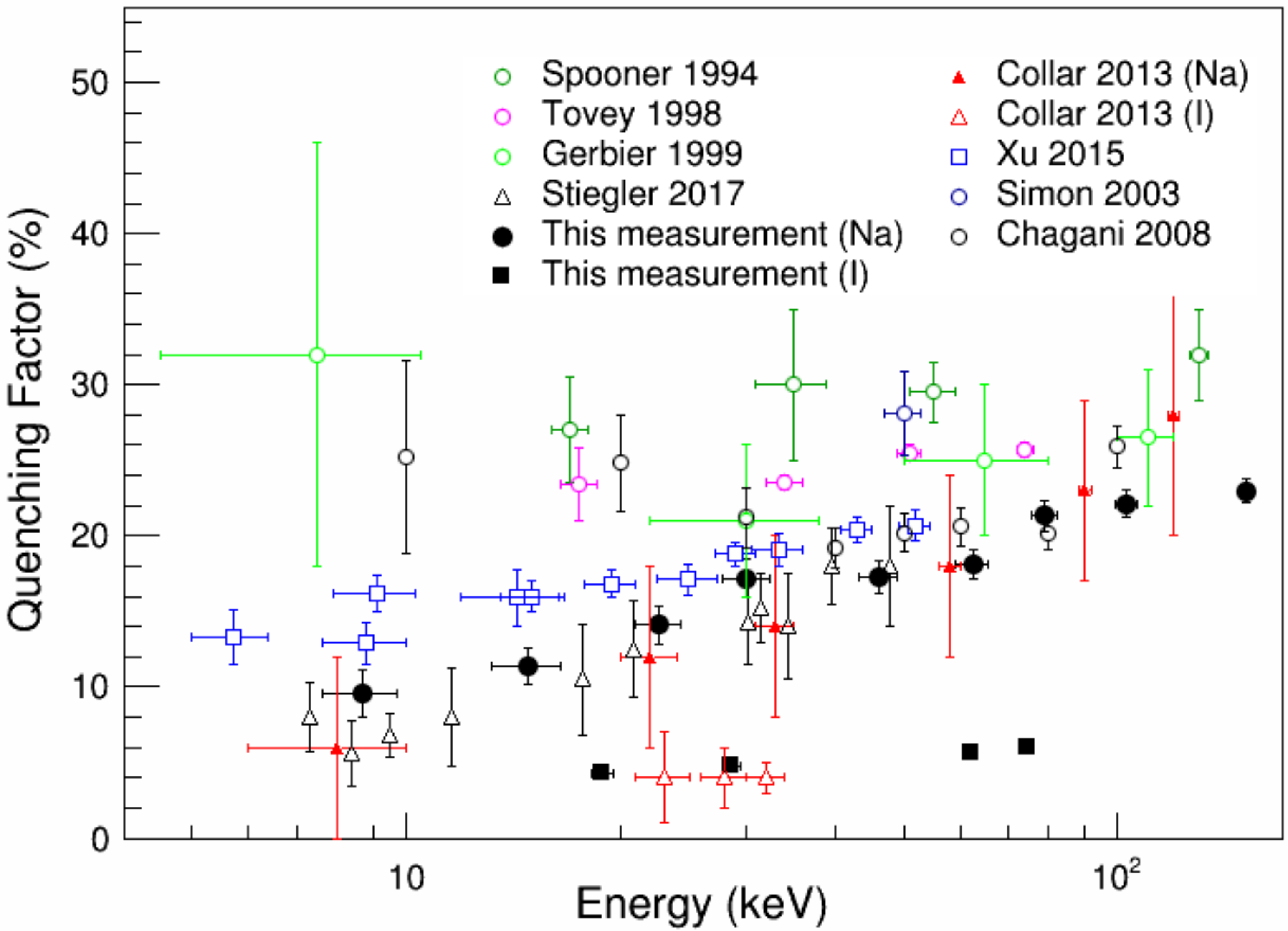




http://nucleus.roma1.infn.it

Quenching factor: NaI example

Amount of recoil energy going into visible energy

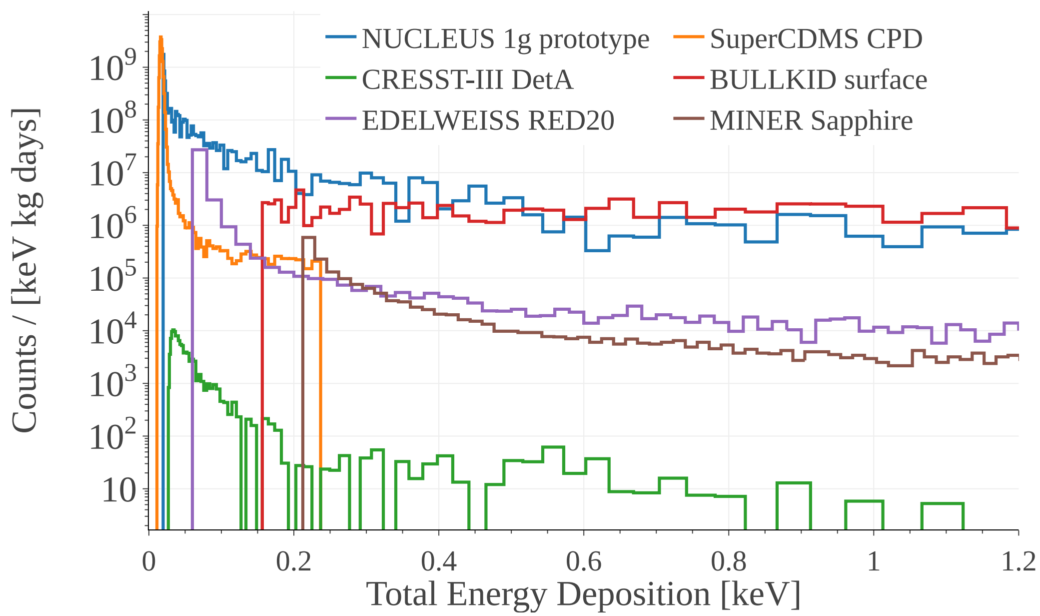


H.W. Joo, et al Astropart Phys, 108 (2019) 50

Cryo-detectors have no quenching:
entire energy eventually converted to phonons

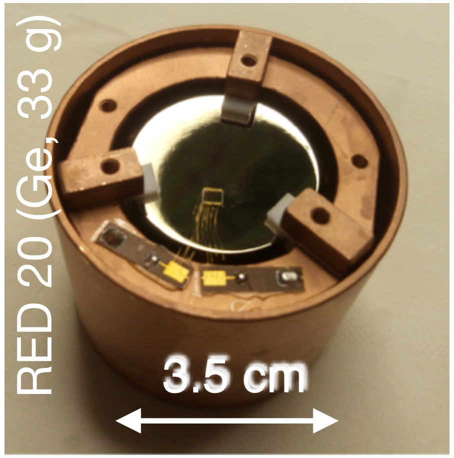
The “Excess” problem

Not understood *excess* background rising at low energies



P. Adari, et al.: EXCESS workshop: Descriptions of rising low-energy spectra SciPost Phys. Proc. 9 (2022) 001 + D. Delicato et al EPJ C 84 (2024) 353

- Phonon bursts (crystal-support friction) ?
- Lattice relaxations after cool down?
- Phonon leakage from interactions in the supports?
- ~~Neutrons (cosmic ray induced, radioactivity) ?~~



AC superconductivity

AC Conductivity

$$\sigma(\omega) = \frac{\sigma_0}{1+\omega^2\tau^2} - j\omega\tau\frac{\sigma_0}{1+\omega^2\tau^2}. \qquad \sigma_0 = \frac{nq^2\tau}{m}.$$

σ_1 σ_2

- The imaginary term σ_2 appears when $\omega \sim \frac{1}{\tau}$
- In normal conductors $\tau \sim 10^{-14} s$ which implies $f = 16\,\mathrm{THz}$!!!

- In superconductors $\tau \to \infty$ so
  - $\sigma_1 = 0$
  - $\sigma_2 = -j\frac{nq^2}{\omega m}$
- i.e. we only have the imaginary term (true at very low temperatures).

Kinetic inductance

- Let's try to understand what is this imaginary term of the conductivity

  The impedance is $Z = \frac{l}{A}\frac{1}{\sigma} = j\omega \frac{l}{A}\frac{m}{nq^2}$ *inductance L_k*

  where *l* and *A* are the length and sectional area of the conductor, respectively.

- This inductance is related to the mass of the charge carries.

  The charge carries exhibit an inertia to the variation of the field's direction because they have a mass.

  Inertias manifest themselves in a circuit as inductances, in this case it is the kinetic inductance, and is a property of the charge carriers.

  It differs from the normal magnetic inductance which is due to the geometry of the conductor.

Kinetic Energy

- We can see the phenomenon also by computing the kinetic energy stored by the charge carriers

$$E_k = \frac{1}{2} m v^2 \, n l A$$

- Reminding that the current is defined as

$$I = nqvA$$

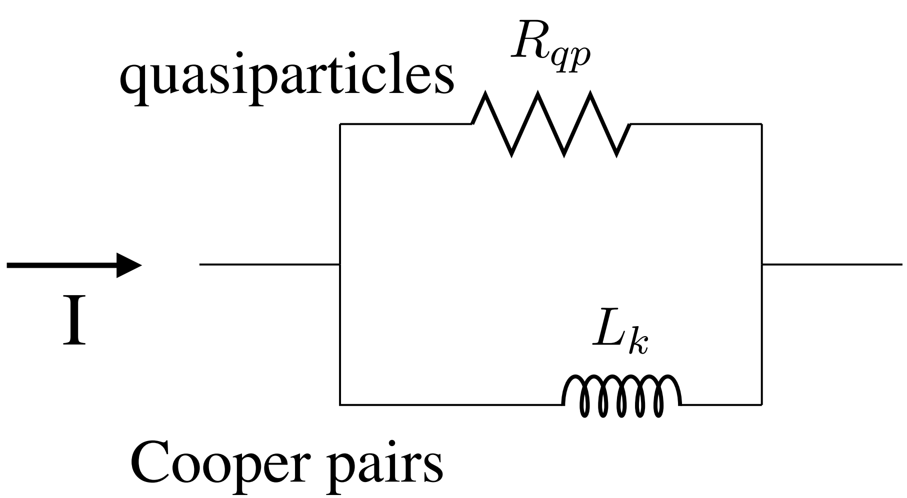
- We rewrite the energy as

$$E_k = \frac{1}{2} \frac{lm}{Anq^2} I^2 = \frac{1}{2} L_k I^2$$

- In presence of the kinetic inductance, the inertia is due to the kinetic energy stored in the charge carriers.
- In presence of the geometric inductance, the inertia is due energy stored in the magnetic field.

Two fluid model

- In a superconductor, depending on the temperature, part of the electrons may not be bound into Cooper Pairs.
- The unpaired electrons are called "quasiparticles" as they are superposition states of electrons and holes.
- Quasiparticles act as a second channel for the current, in parallel with the Cooper pairs, with high resistance.

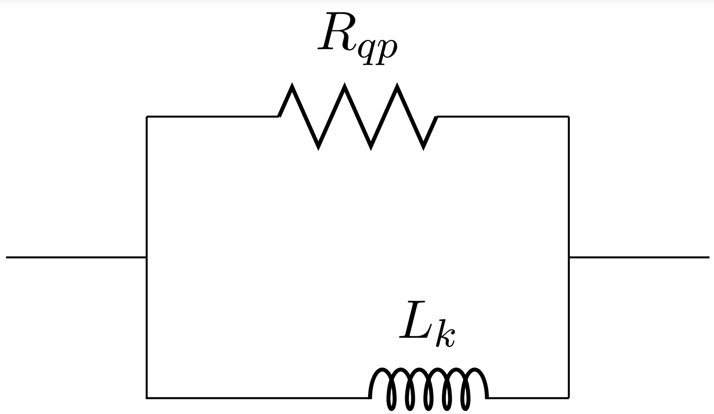


$$Z_s = (0 + j\omega L_k) \,||\, R_{qp}$$

- In DC R_{qp} is not seen, since the current flows entirely through Cooper Pairs, however in AC part of the current can flow through quasiparticles.

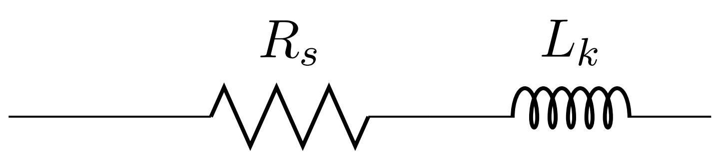
Total impedance

Original impedance



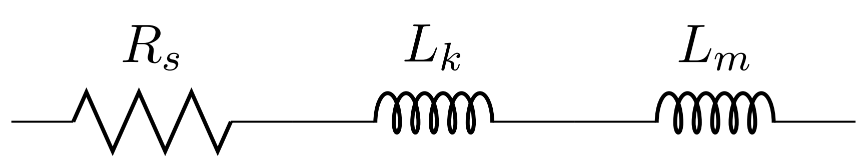
$$Z_s = (0 + j\omega L_k)\,||\,R_{qp} \underset{R_{qp} \gg \omega L_k}{\simeq} = j\omega L_k + \frac{(\omega L_k)^2}{R_{qp}}$$

Equivalent impedance



$$Z_s = j\omega L_k + R_s$$

Total impedance (+ magnetic inductance)



$$Z_s = j\omega(L_k + L_m) + R_s = j\omega L + R_s$$

Kinetic Inductance Detectors

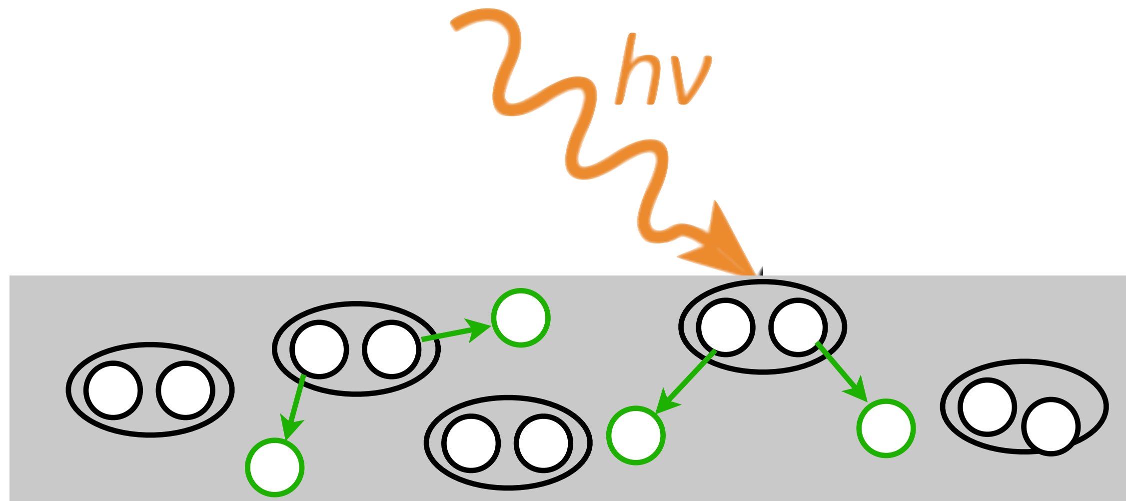
Non-equilibrium superconducting detectors invented at JPL/Caltech

Day et al., Nature 425 (2003) 817

Particle absorption

superconductor
at T<<Tc

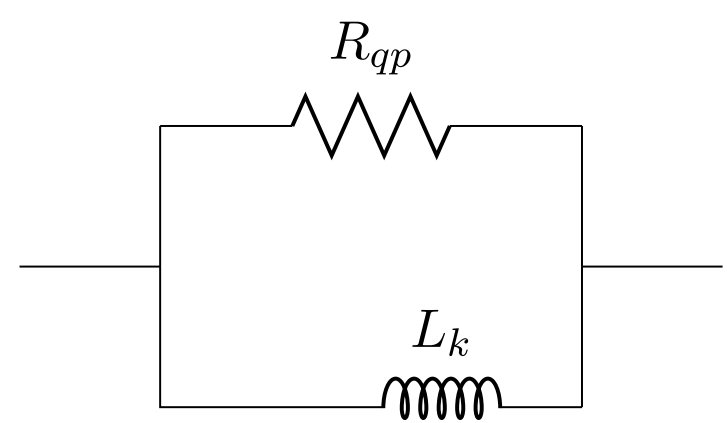
$2\Delta \sim 400\,\mu eV\,(\mathrm{Al})$



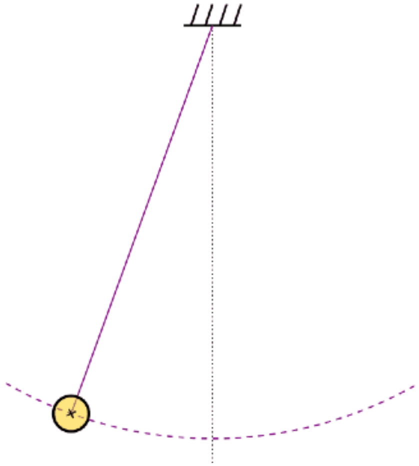
- Absorbed photons or phonons can break Cooper pairs if their energy is larger than their binding energy 2Δ.

- The number of Copper pairs decreases, thus L_k increases.

- Quasiparticles are generated, R_{qp} decreases, thus R_s increases.



Resonators

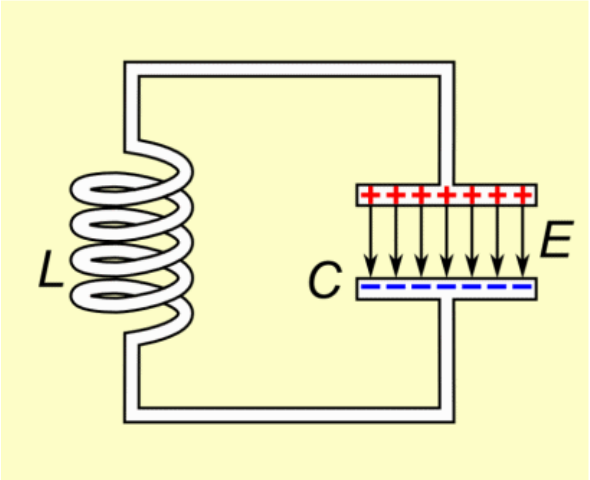


Frequency:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$

Frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

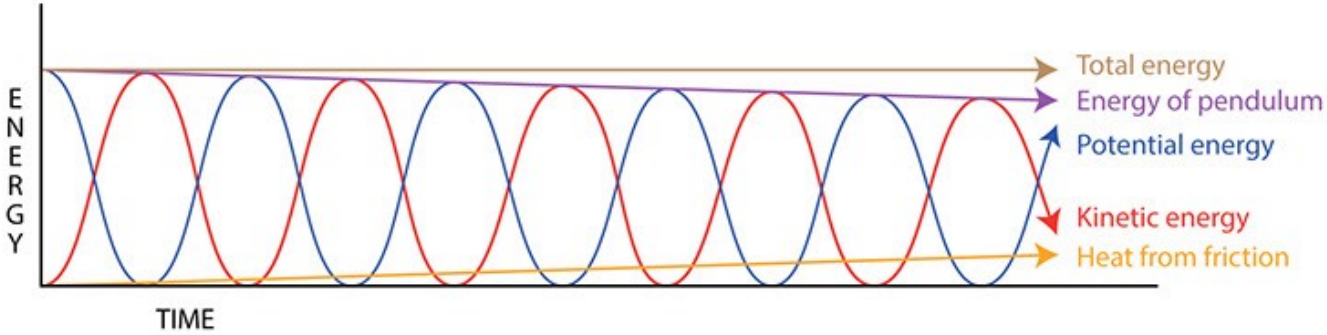


Dissipation: air friction

Dissipation: parasitic resistance

Quality factor:

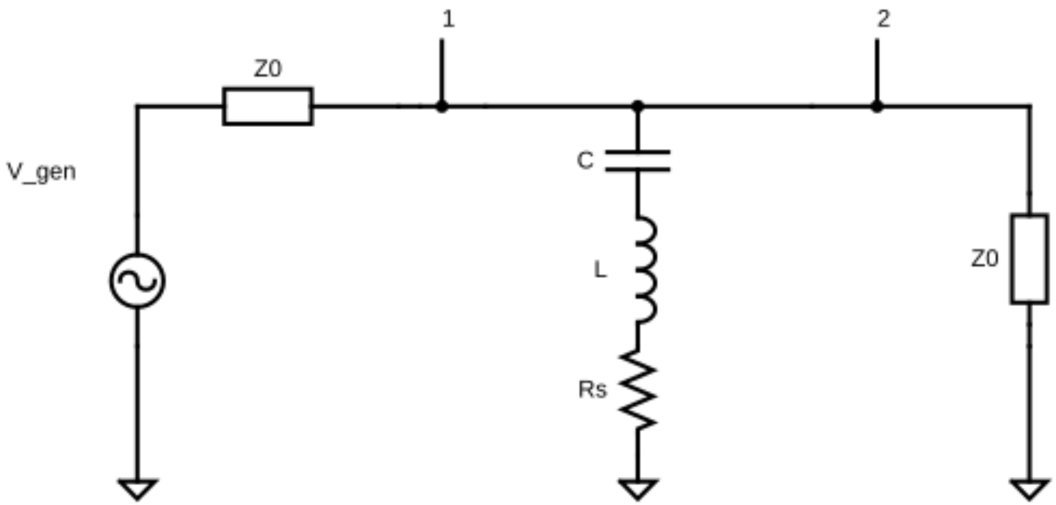
Q = 2π x number of cycles before the amplitude of oscillations drops by 1/e



The higher the Q the higher the precision on f_0

Resonant circuit

- To measure the change in *L* and R_s the superconductor is inserted in a high quality factor *(Q)* resonant circuit



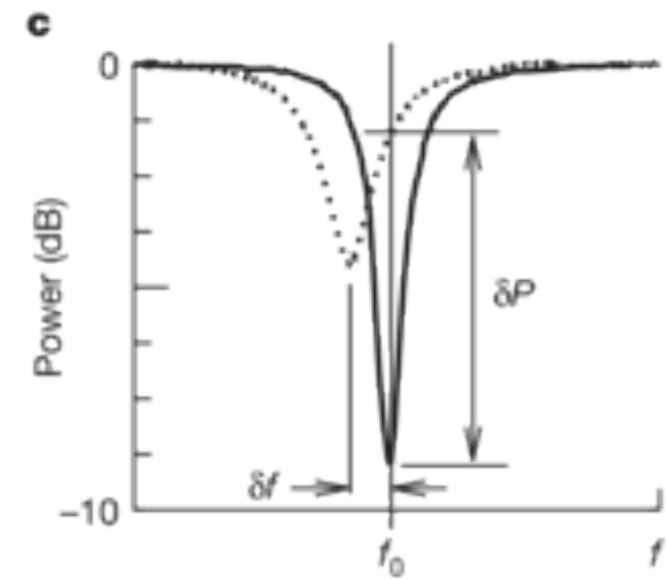
$$\frac{1}{Q} = R_s\sqrt{\frac{L}{C}} \qquad f_0 = \frac{1}{2\pi\sqrt{LC}}$$

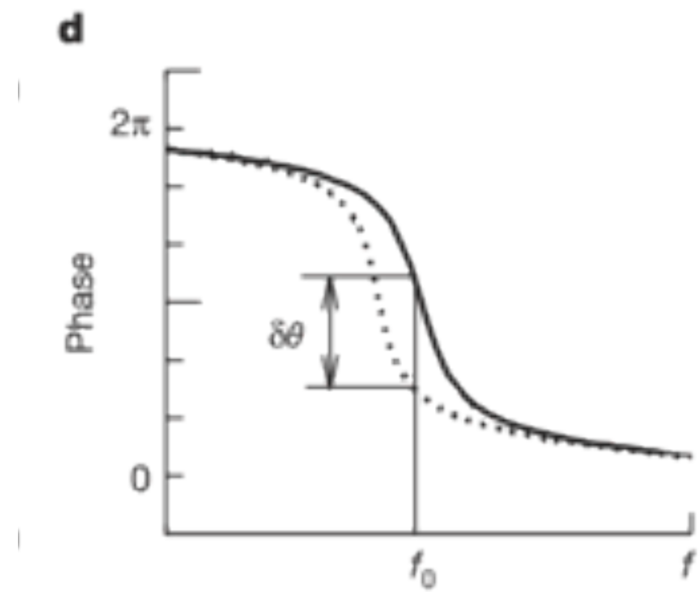
$$\frac{2V_2}{V_{gen}} \simeq 1 - \frac{1}{1 + 2jQ\frac{f_{gen} - f_0}{f_0}}$$

Variations

- Circuit constantly biased at the resonant frequency $f_{gen} = f_0$:
- Variation of R_s:
    - signal from amplitude shift $\delta(1/Q)$

$$\frac{1}{Q} = R_s\sqrt{\frac{L}{C}}$$





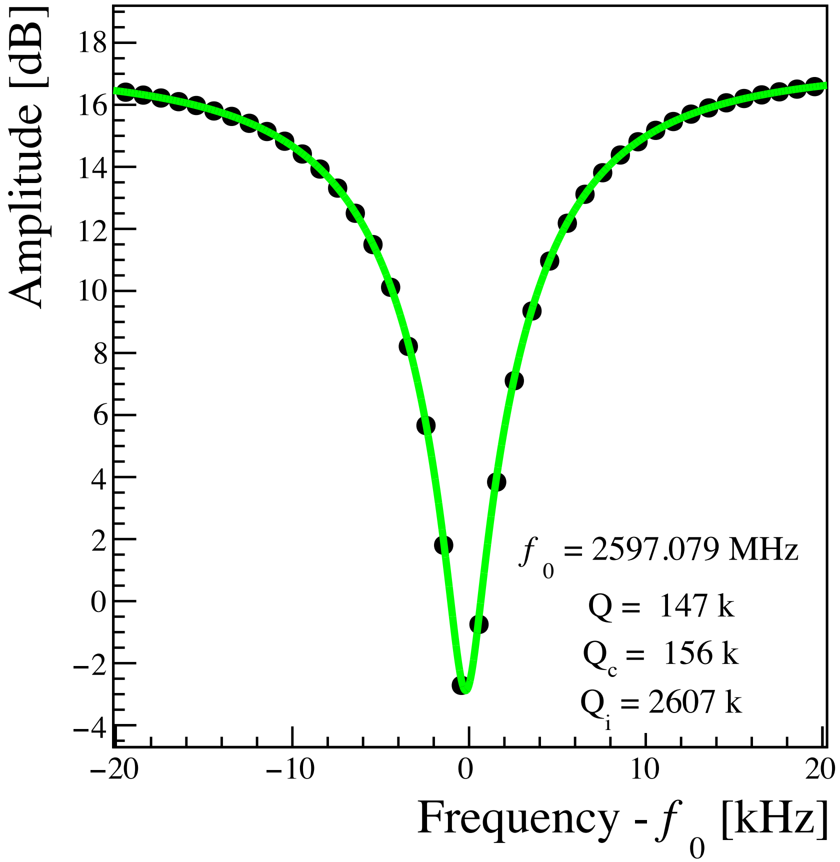
- Variation of L_k:
    - signal from frequency shift δf_0

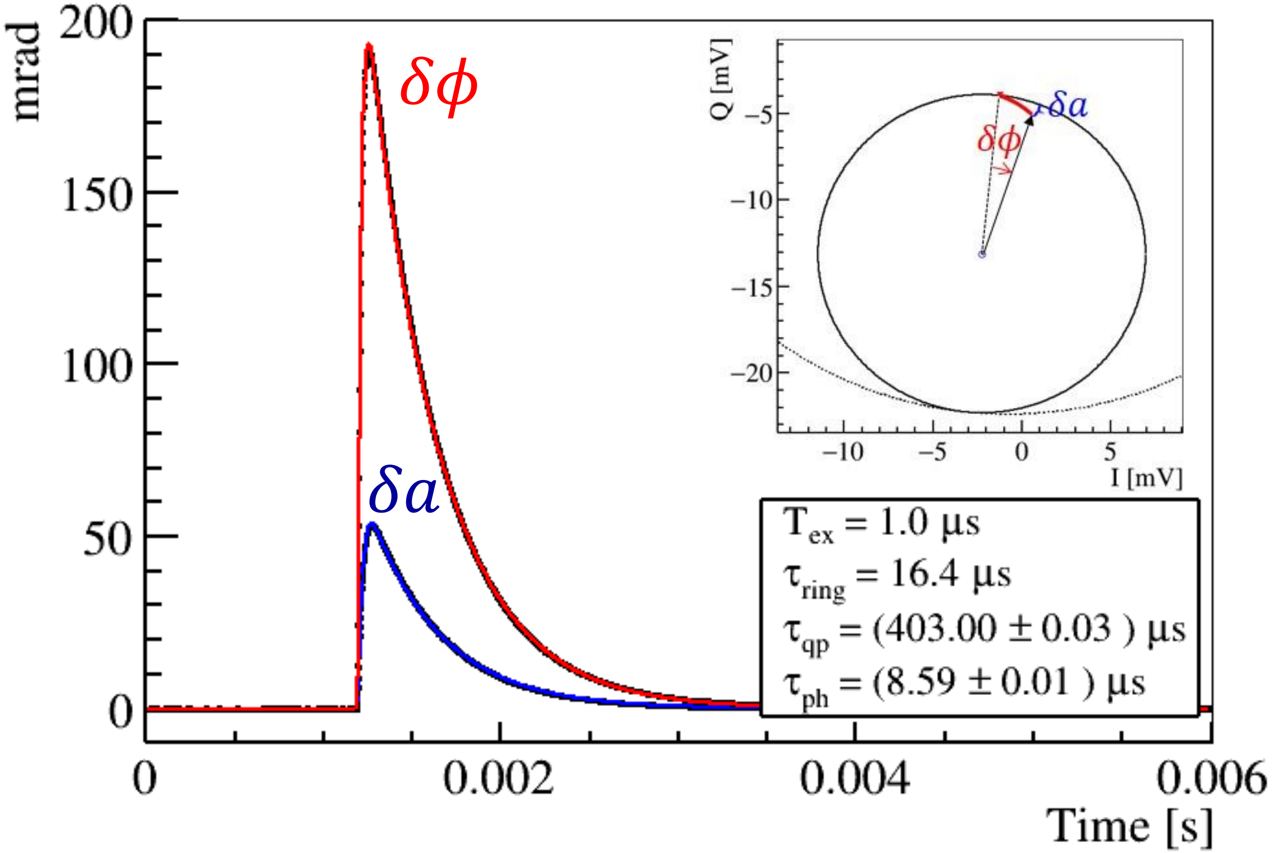
$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

    - actually measured as phase shift

KID signal

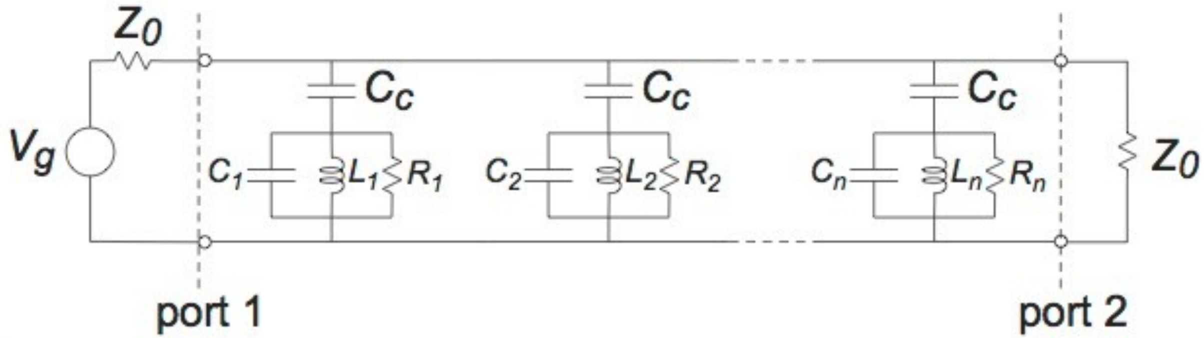
1. Frequency sweep to measure the transmission past the resonator.
2. Determine the resonant frequency and bias the detector at that frequency.
3. Measure Phase and Amplitude Modulation of the wave transmitted past the resonator

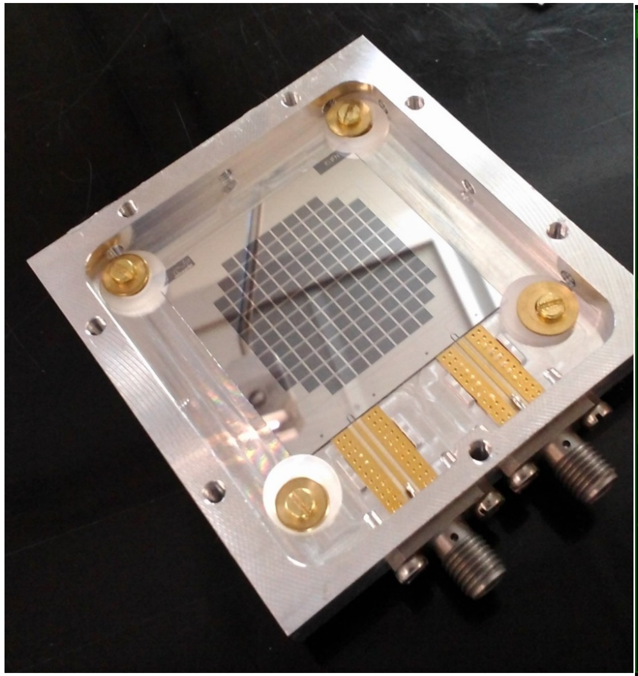


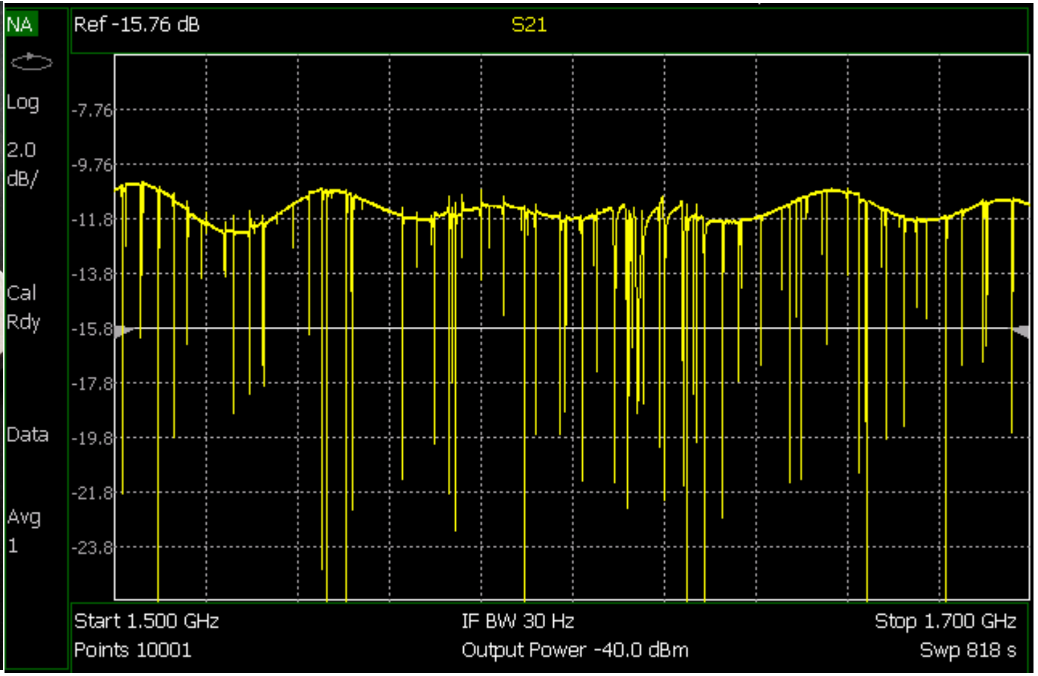


KID Multiplexing

Different resonators can be coupled to the same feedline
with slightly different resonant frequencies.
Resonant frequency modified via the capacitor (C) pattern of the circuit.







Multiplexing of 1000 KIDs with a single cryogenic amplifier demonstrated

Pros and cons of KIDs

Why KIDs:

- Ease in fabrication
- Insensitive to microphonics (almost)
- Insensitive to electromagnetic noise (almost)
- Insensitive to temperature instabilities
- Multiplexing (up to 1000 channels / line demonstrated)

Why not:

- sensitivity lower than TESs (> 2x worst depending on the application).

KIDs in Particle Physics

Requirements

To improve our neutrino and dark matter experiments we need

Several detectors

cm^2 active area

dm^3 active volume

Motivations for KIDs:
KIDs unique multiplexing
Easy to fabricate
Reproducible

High resolution

below 100 eV

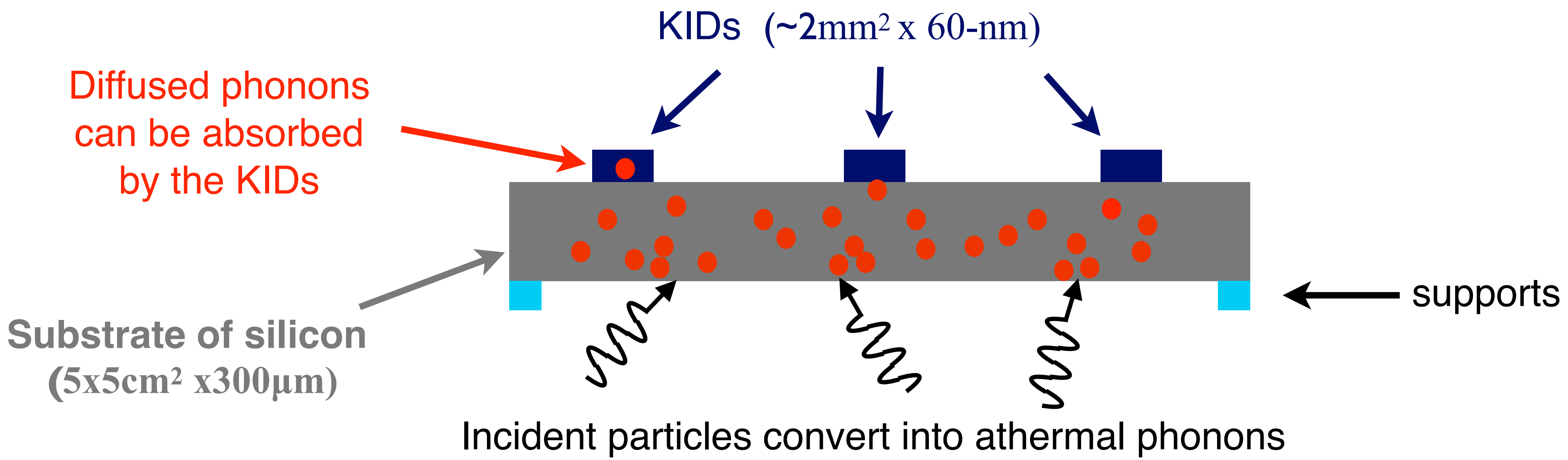
possibly 10 eV

The *difficult* part:
KIDs are today
a factor 5 off from TES

Phonon mediation

GHz operation limits the maximum sensible area of KIDs to few mm^2

Scaling to several cm^2:
indirect detection mediated by phonons



Challenge: collect as many phonons as possible

The smaller the number of pixels the better!

First phonon mediated KIDs

APPLIED PHYSICS LETTERS **96**, 263511 (2010)

High-speed phonon imaging using frequency-multiplexed kinetic inductance detectors

L. J. Swenson,[1,a)] A. Cruciani,[1,2] A. Benoit,[1] M. Roesch,[3] C. S. Yung,[4] A. Bideaud,[1] and A. Monfardini[1]
[1]*Institut Néel, CNRS–Université Joseph Fourier, BP 166, 38042 Grenoble, France*
[2]*Dipartimento di Fisica, Universitá di Roma La Sapienza, p.le A. Moro 2, 00185 Roma, Italy*
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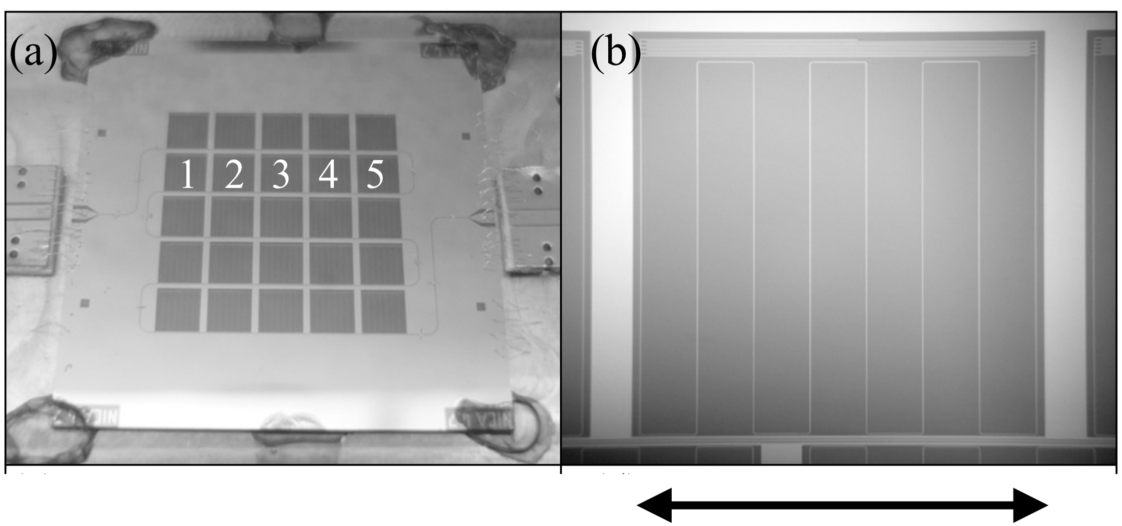
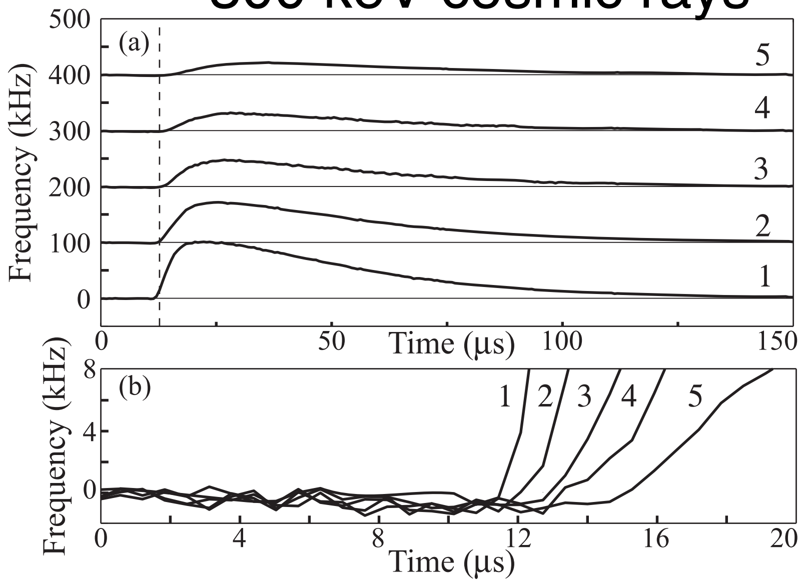
[4]*Superconductor Technologies Inc., 460 Ward Drive, Santa Barbara, California 93111, USA*

(Received 28 April 2010; accepted 11 June 2010; published online 1 July 2010)



~300 keV cosmic rays



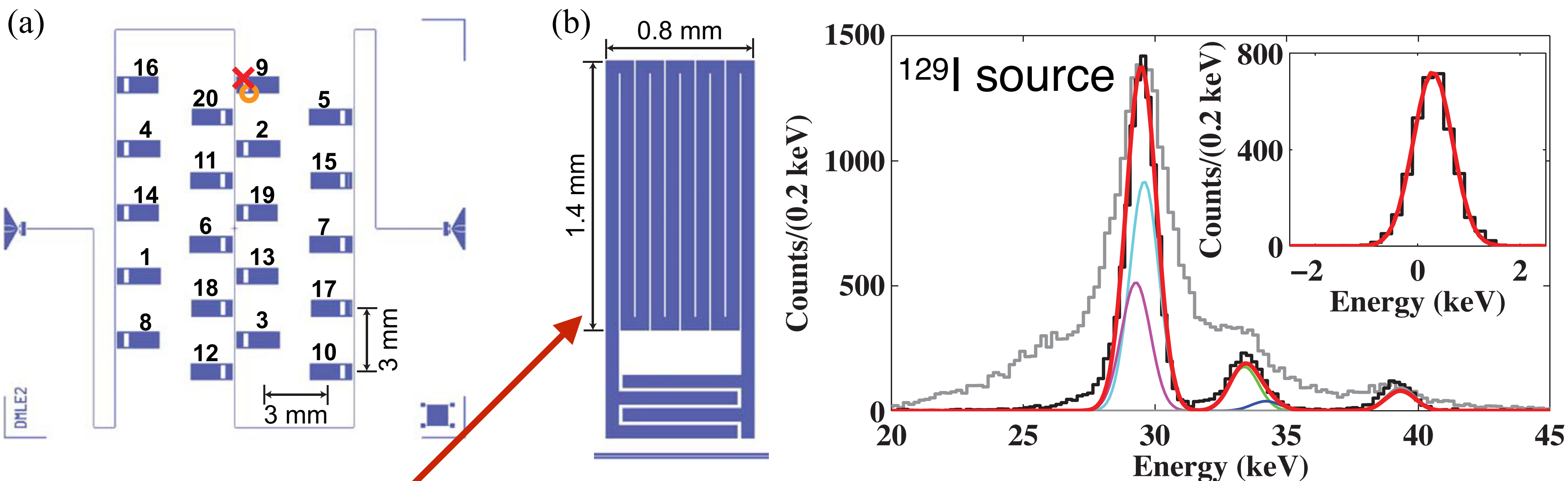
Interpretation from CALTECH

APPLIED PHYSICS LETTERS **100**, 232601 (2012)

Position and energy-resolved particle detection using phonon-mediated microwave kinetic inductance detectors

D. C. Moore,[1,a)] S. R. Golwala,[1] B. Bumble,[2] B. Cornell,[1] P. K. Day,[2] H. G. LeDuc,[2] and J. Zmuidzinas[1,2]
[1]*Division of Physics, Mathematics & Astronomy, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA*

(Received 20 March 2012; accepted 22 May 2012; published online 6 June 2012)



Filled shape, larger inductor area

ΔE (0 keV) = 380 eV

Improving the energy resolution

Superconductor gap
[180 μeV for Aluminum → 1.2 K]

Amplifier noise
HEMT: 2 - 6 K

$$\Delta E \propto \frac{T_C}{\epsilon}\sqrt{\frac{T_N}{Q L_k / L}}$$

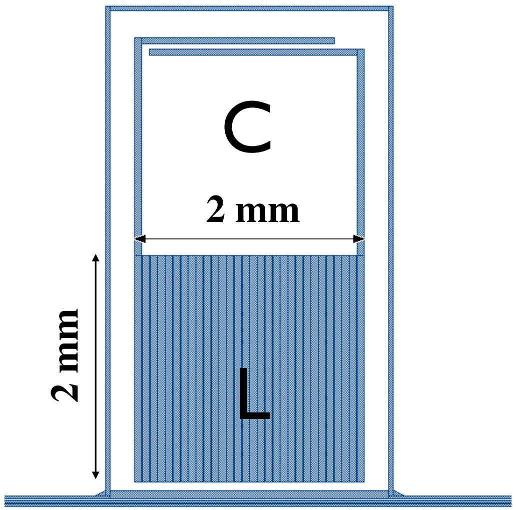
Kinetic
Inductance fraction
[few % for Al]

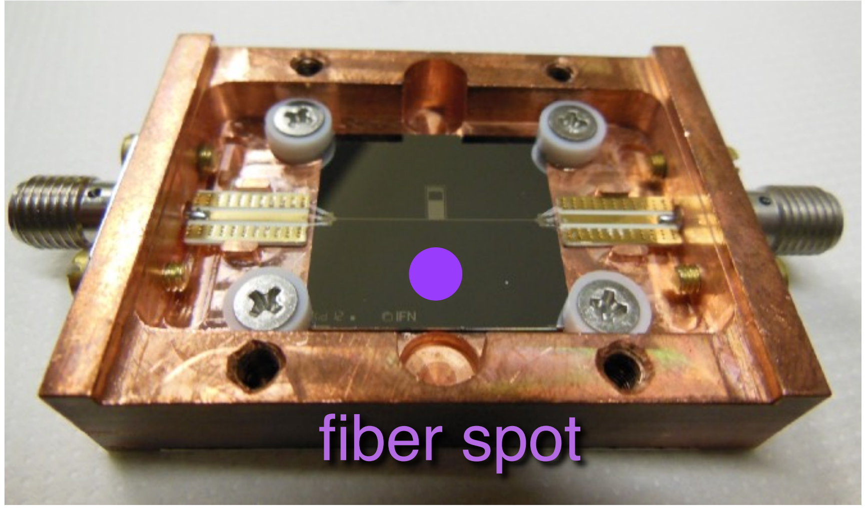
Phonon efficiency
[few % for Al]

Resonator Q [$10^{4\text{-}5}$]

CALDER project

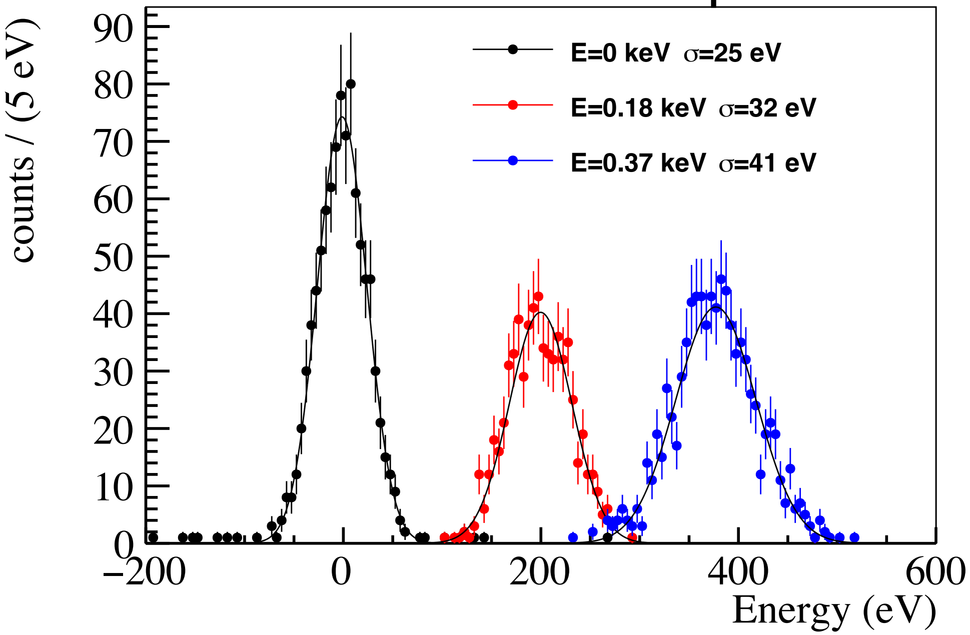
www.roma1.infn.it/exp/calder



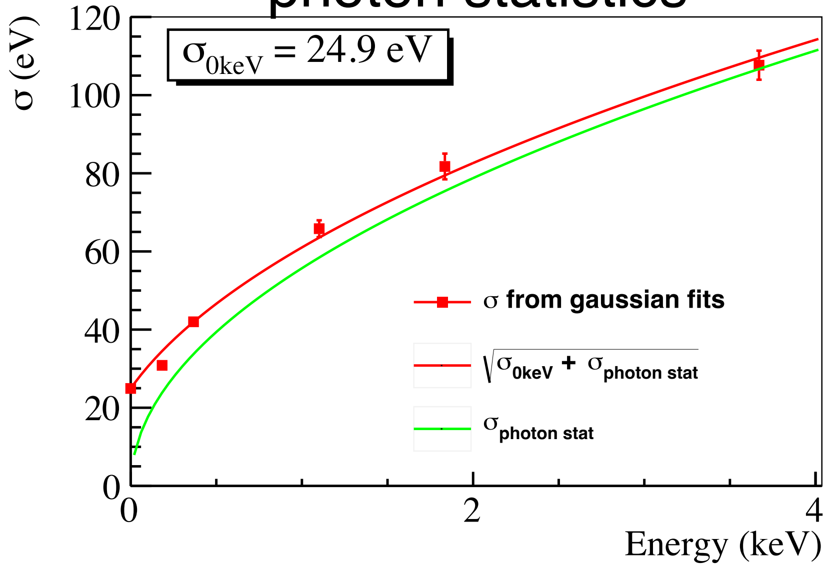


- Al(14)Ti(33)Al(30nm) resonator
- 2x2cm² x 350µm Silicon substrate
- 25 eV RMS @ 0 eV
- Phonon ε ~ 10%

Scan with LED driven optical fiber



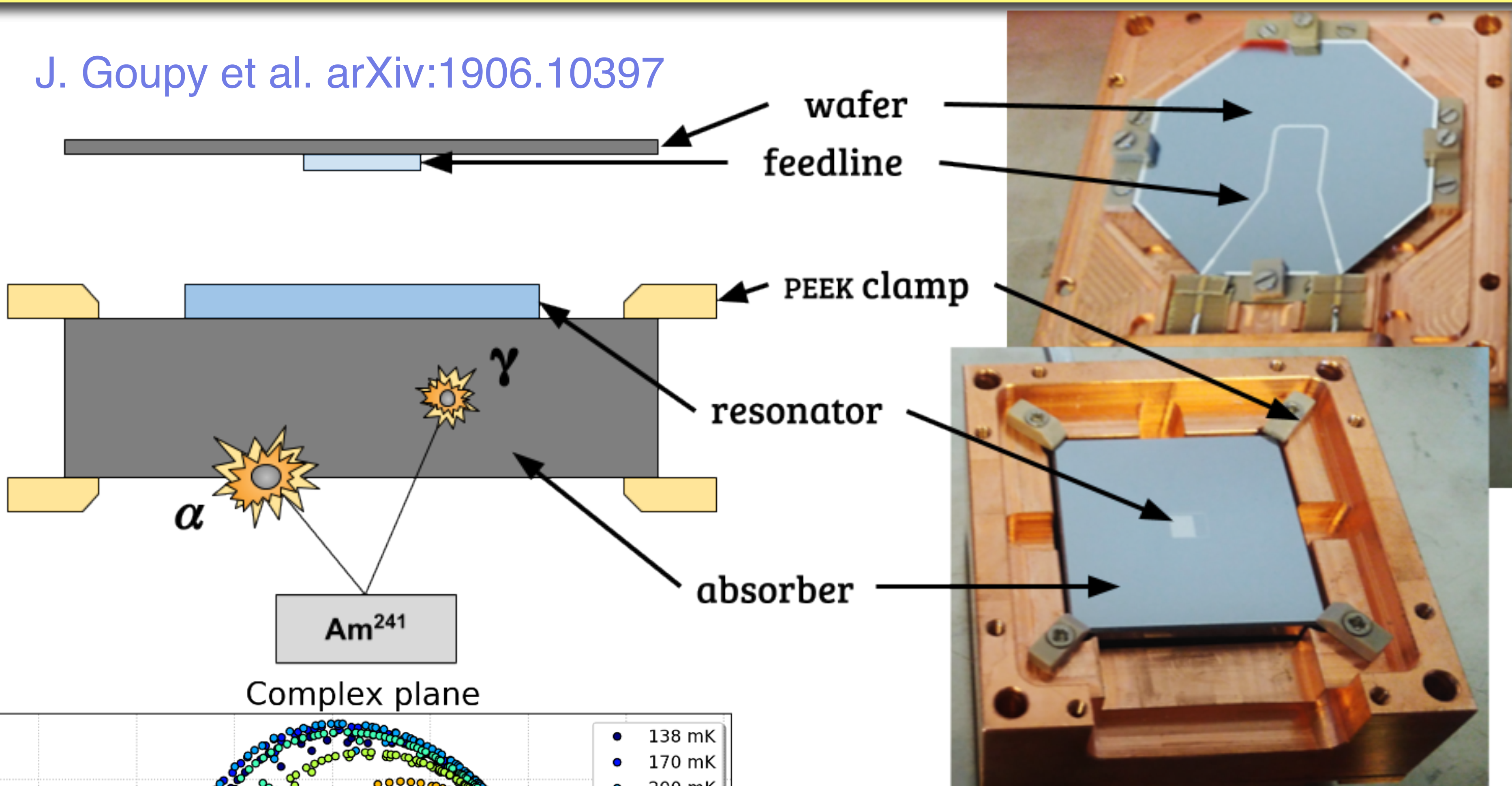
Self-calibrated with photon statistics

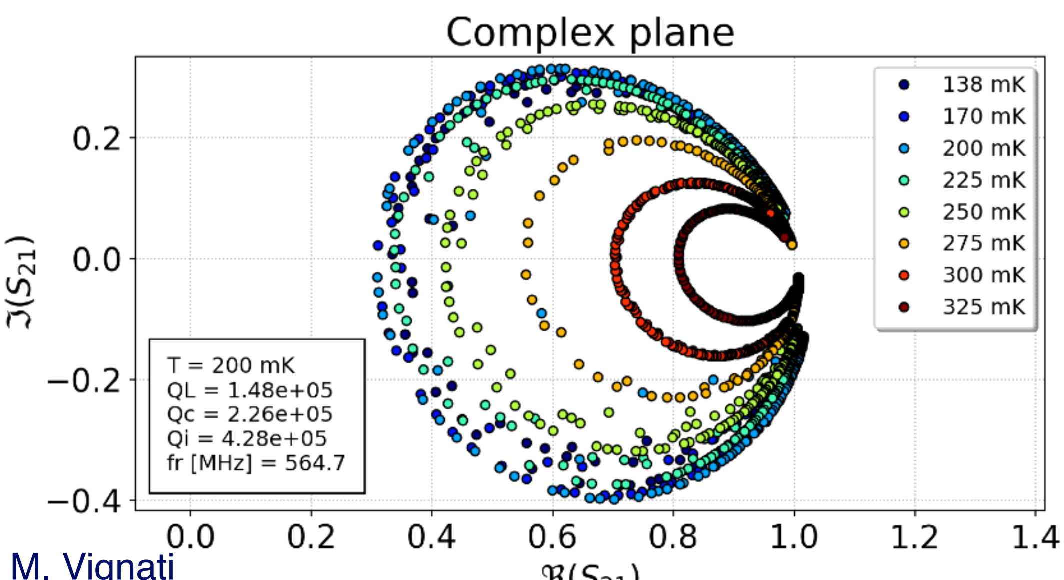


2nd R&D phase: large volumes

Wi-Fi KID at Grenoble

J. Goupy et al. arXiv:1906.10397





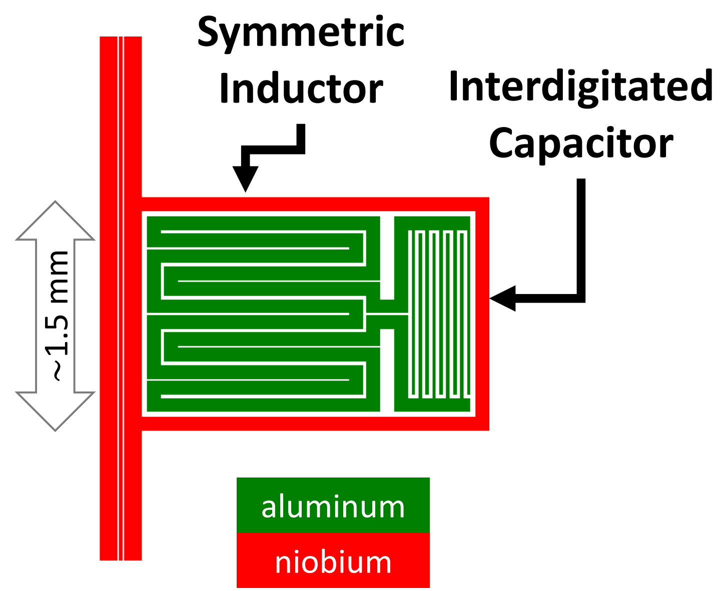
36x36x10 mm^3 absorber with Al KID, sensed by a contactless feedline

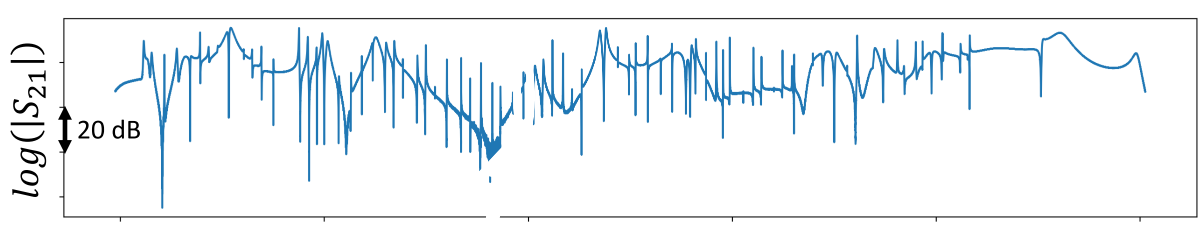
Dark Matter device at CALTECH

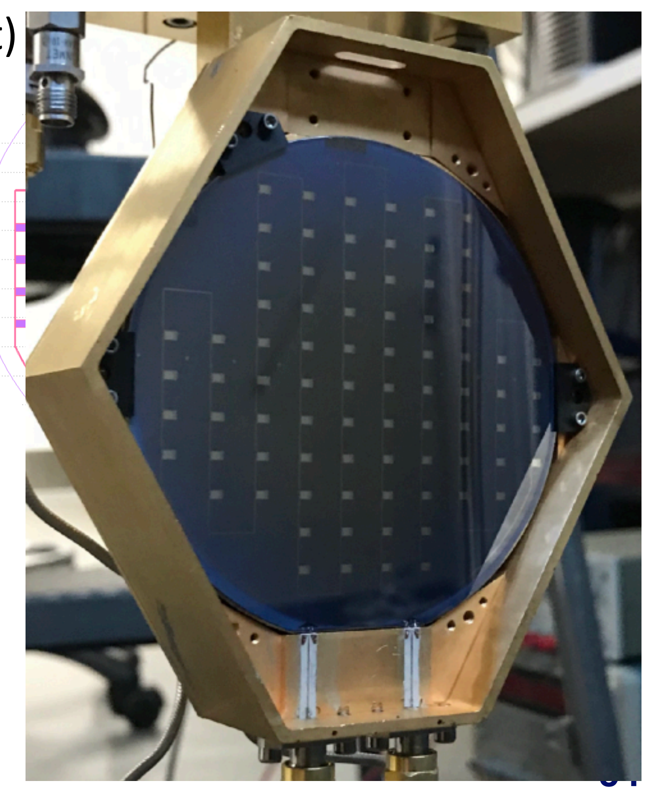
T. Aralis et al, LTD19

Design

- 80 MKIDs coupled to 1 coplanar waveguide feedline
  - KIDs are aluminum
    - $\Delta_{Al} \approx 0.2$ meV
  - Feedline is niobium
    - $\Delta_{Nb} \approx 1.5$ meV
    - Want phonon energy to be absorbed by KIDs, not feedline
    - $<$ 1% of phonons are above $2\Delta_{\rm Nb}$ (for NTL phonons) **[1]**
  - $3.0\ GHz \leq f_r \leq 3.5\ GHz$
    - For CASPER ROACH readout (potential large-scale deployment)
  - Overcoupled KIDs
    - $Q_c \ll Q_i$
    - $Q_r \ll Q_i$
    - Need bandwidth > 30 kHz to preserve phonon rise time
- High-resistivity silicon substrate
  - 75 mm diameter
  - 1 mm thick





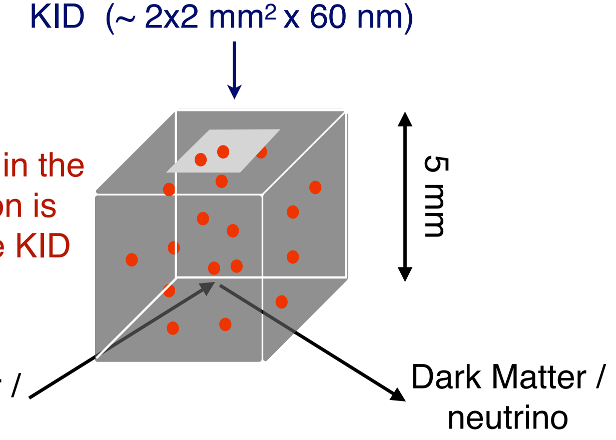


Resolution degrades as $\Delta E \propto \sqrt{N_{KID}}$

INFN way: BULLKID

Phonon mediation

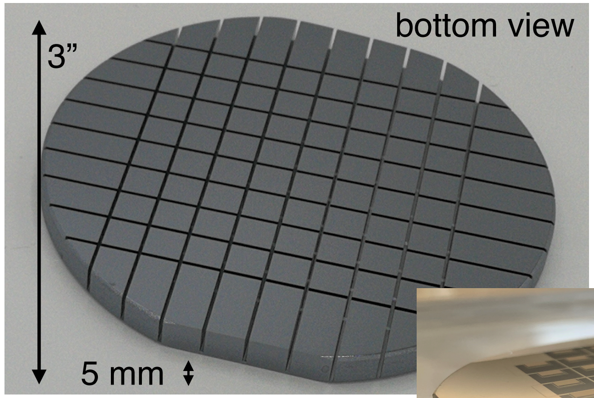
detect phonons created by
nuclear recoils in a silicon absorber

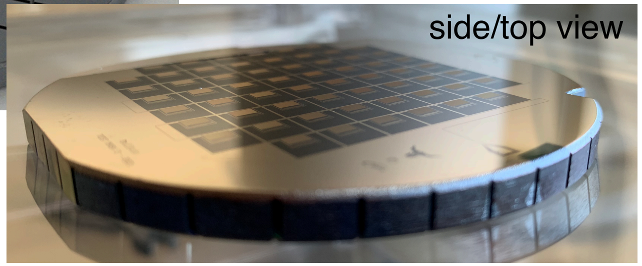


Phonon collection efficiency in the KID
is key for a good energy threshold

Scale-up of detector number

carve several absorbers in a thick silicon wafer
multiplexed KID array on opposite surface

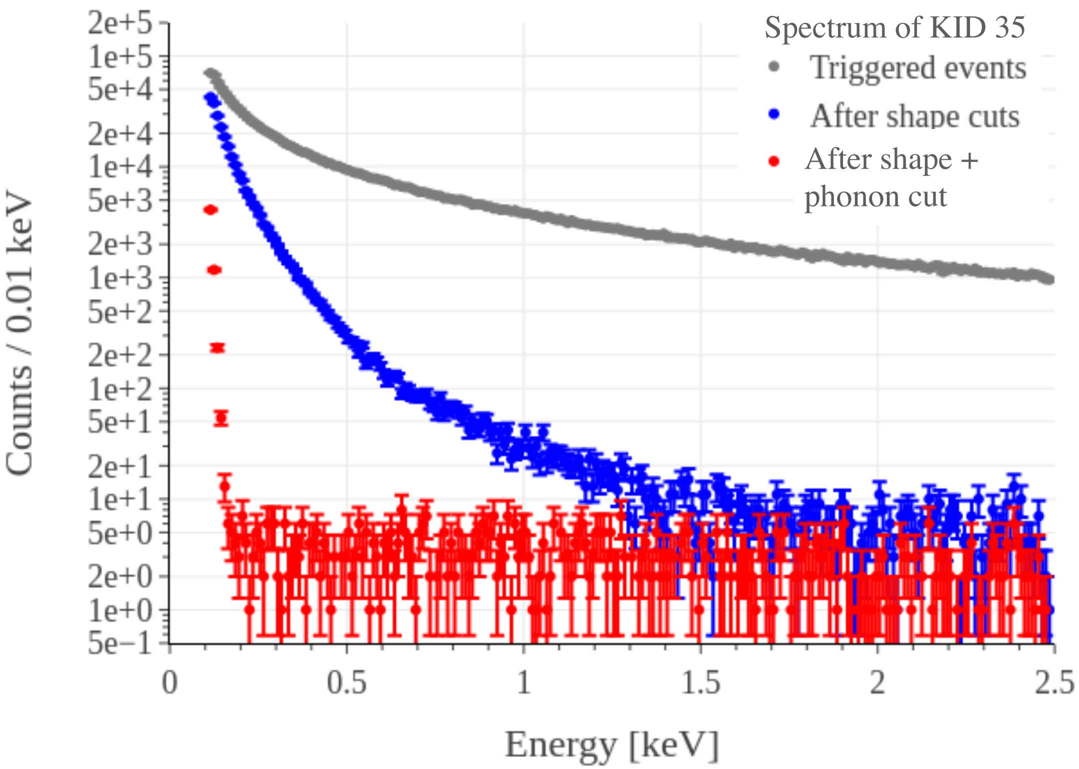


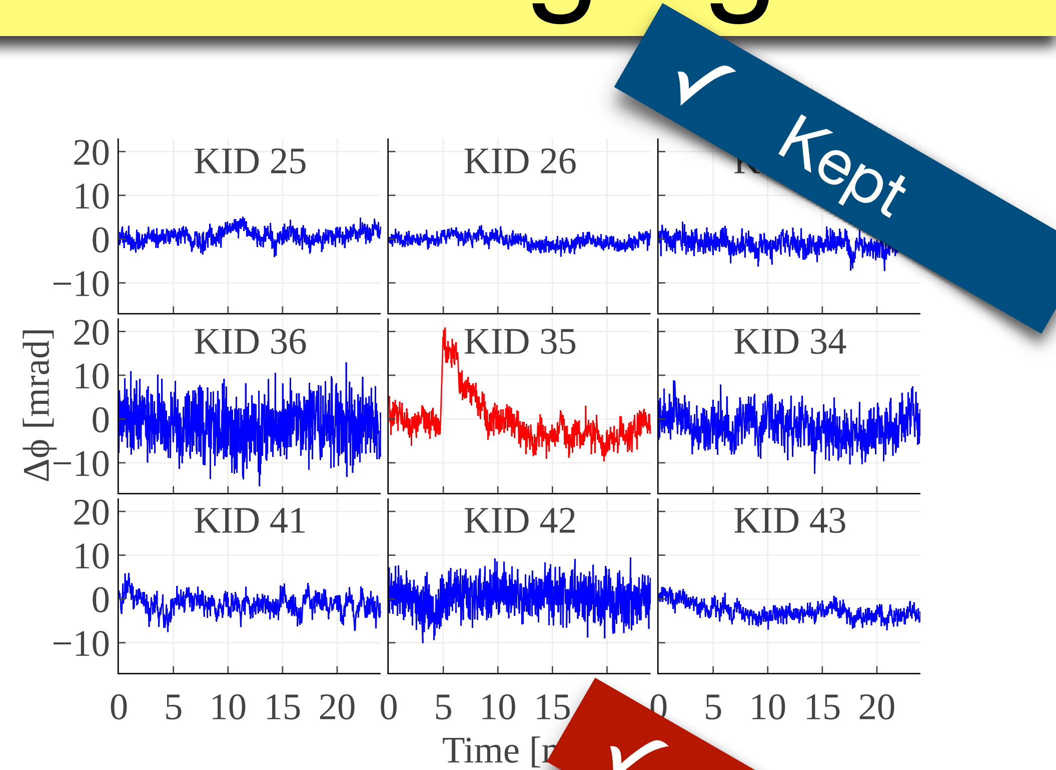


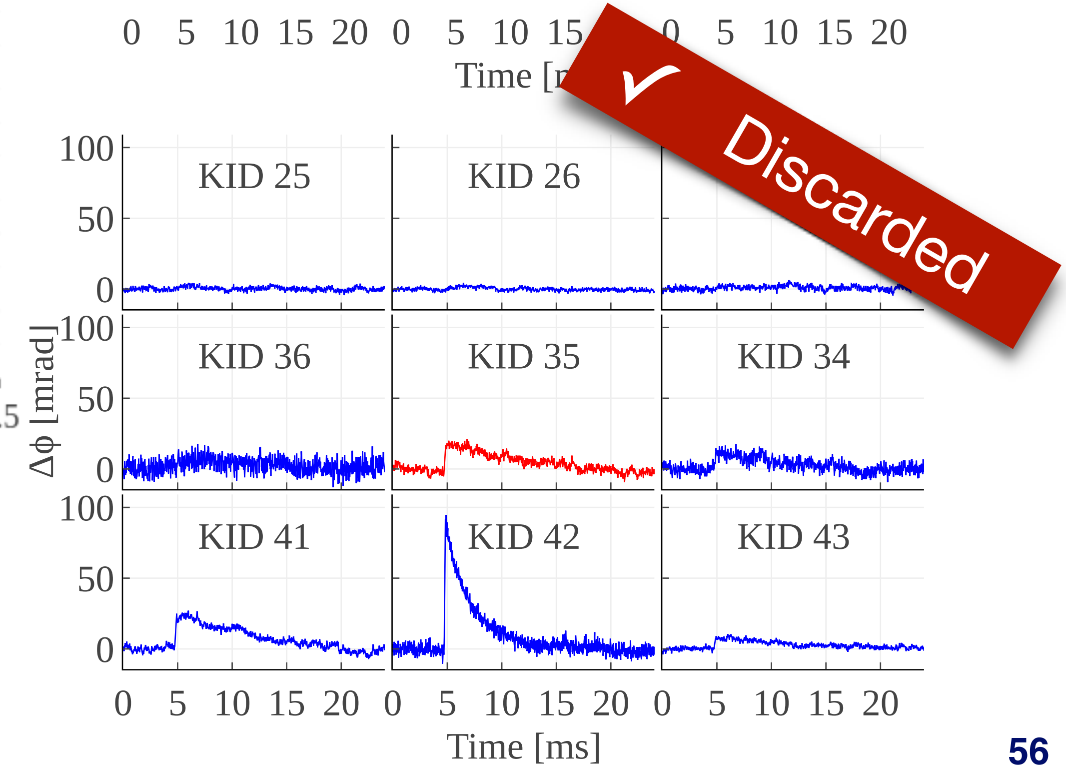
- 4.5 mm carving depth
- 60 dices 5x5x4.5 mm^3
- 60 aluminum KIDs
- 1 readout line

Feasibility study funded by the INFN project “BULLKID”

BULLKID: phonon imaging



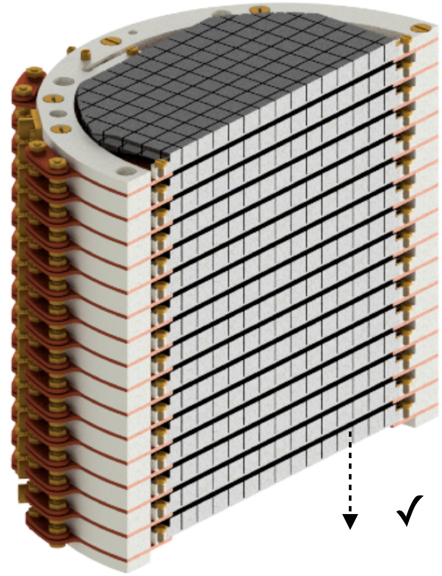




BULLKID-DM

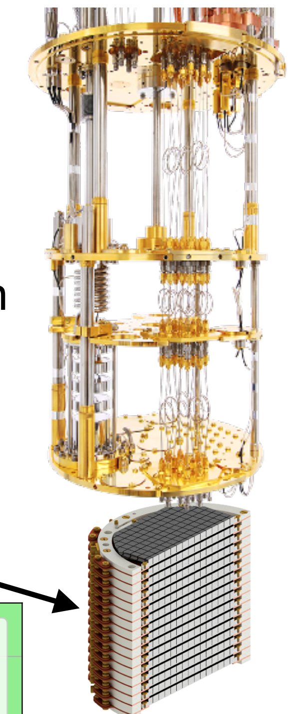
Nuclear recoil detector with:

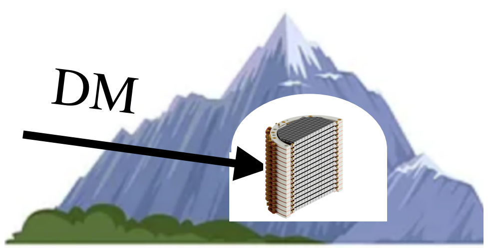
- ✓ 16 (4”) BULLKIDs (> n2000 voxels)
- ✓ 0.8 kg of silicon target
- ✓ 200 ÷ 50 eV threshold (160 eV demonstrated)

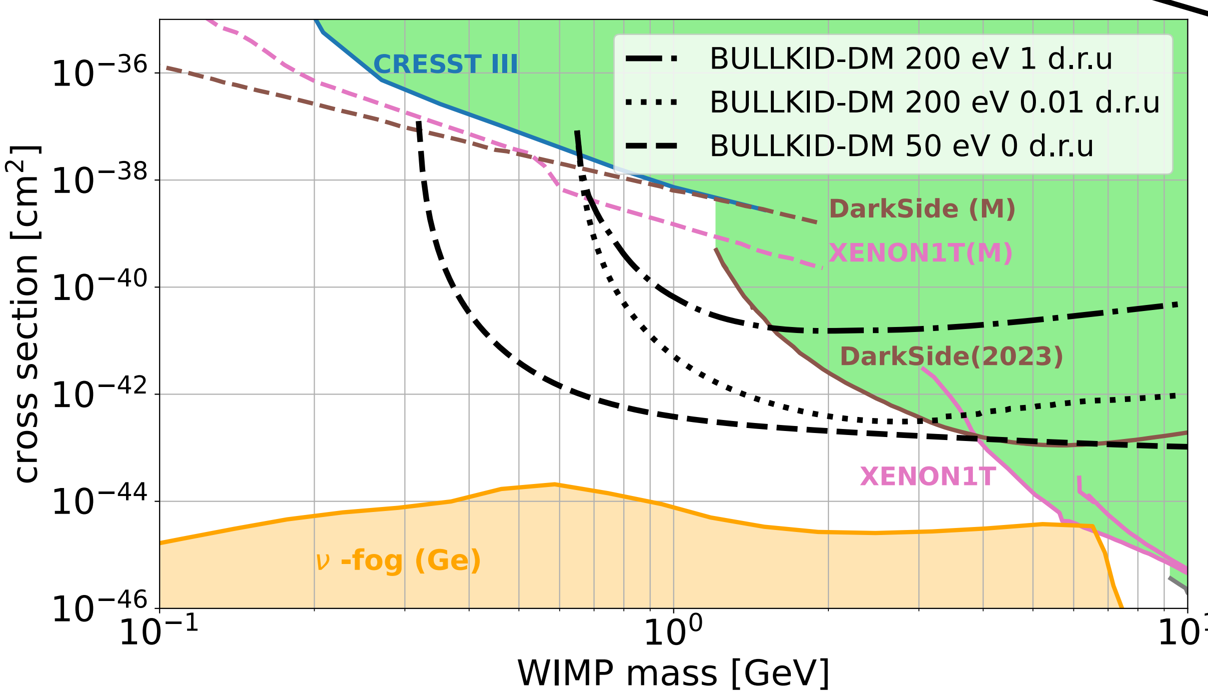


Unique features among phonon detectors:

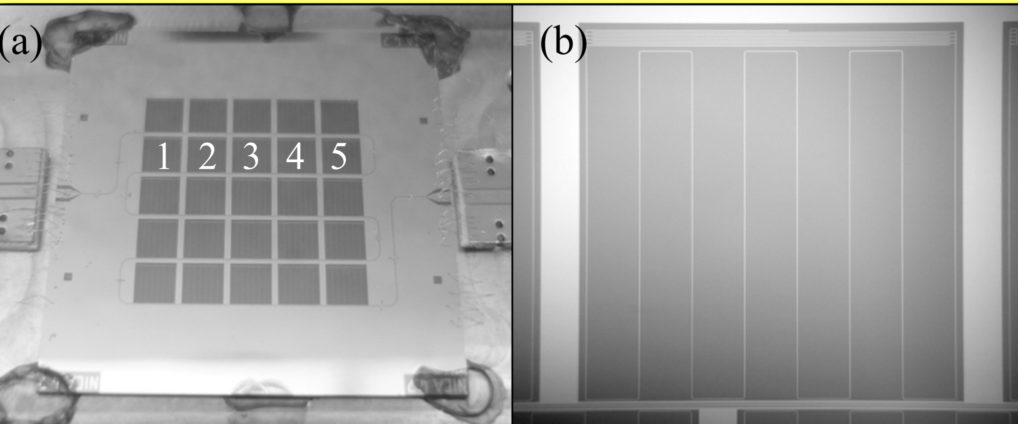
- ✓ fully active
- ✓ fiducialization
- ✓ scalable

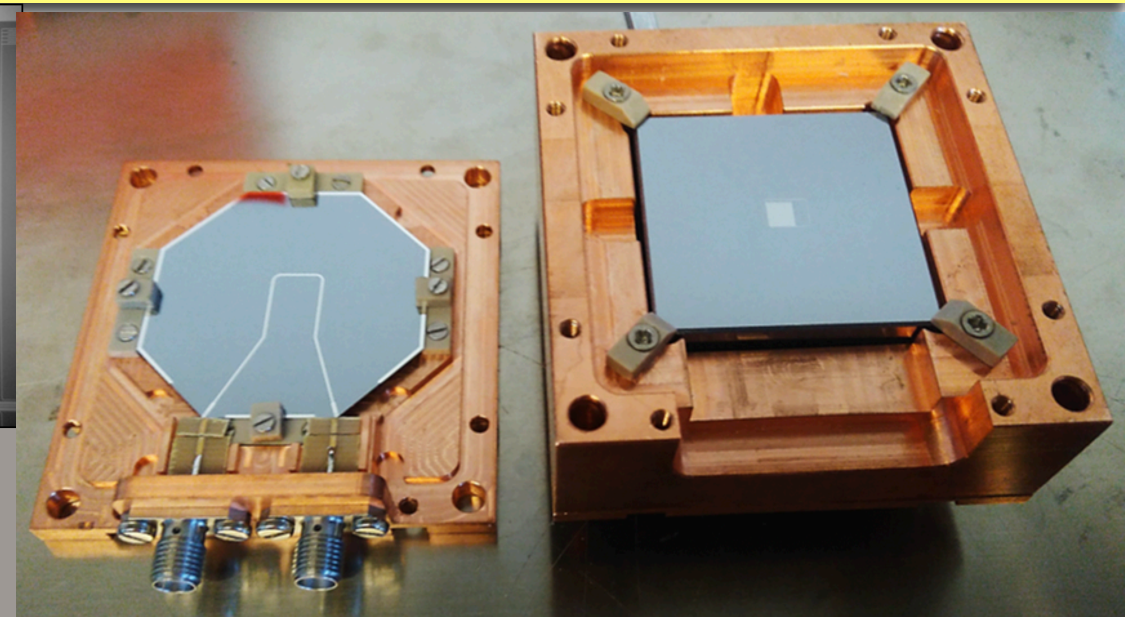


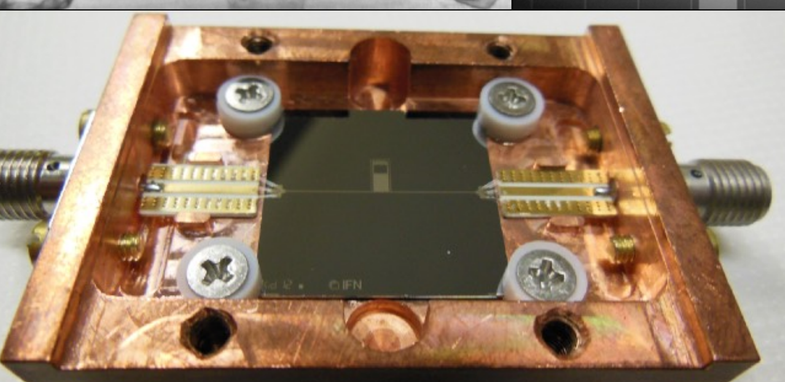




KIDs for Particle Physics







Thank you!