

Solid State Detectors and Experiments: NTD, TES, KIDs



SAPIENZA
UNIVERSITÀ DI ROMA

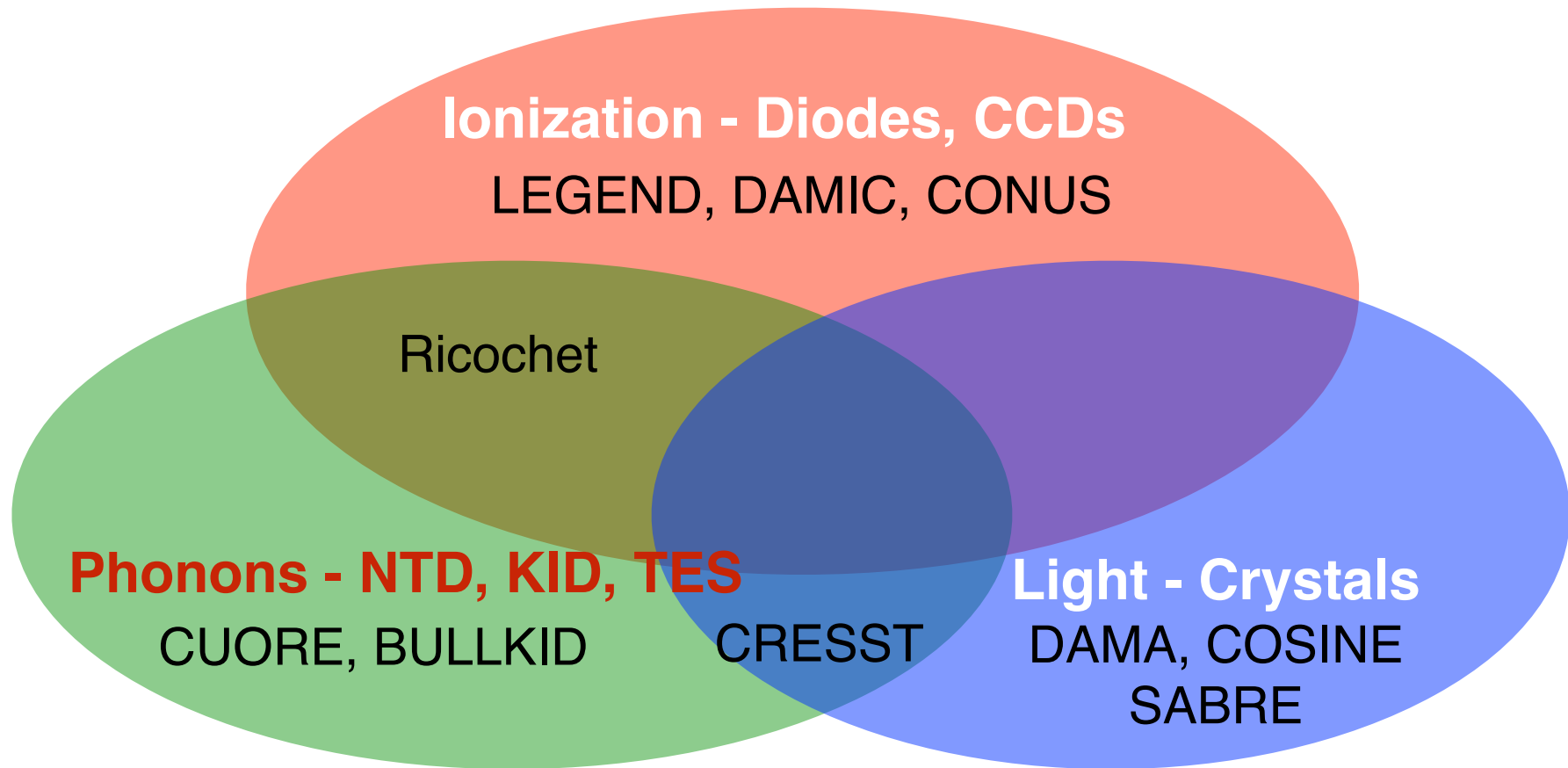
Marco Vignati, Sapienza
SOUP 2024



Istituto Nazionale di Fisica Nucleare

Detection channels

The combination of different techniques allows one to discriminate between electron and nuclear recoils, and thus to reduce the β/γ background.

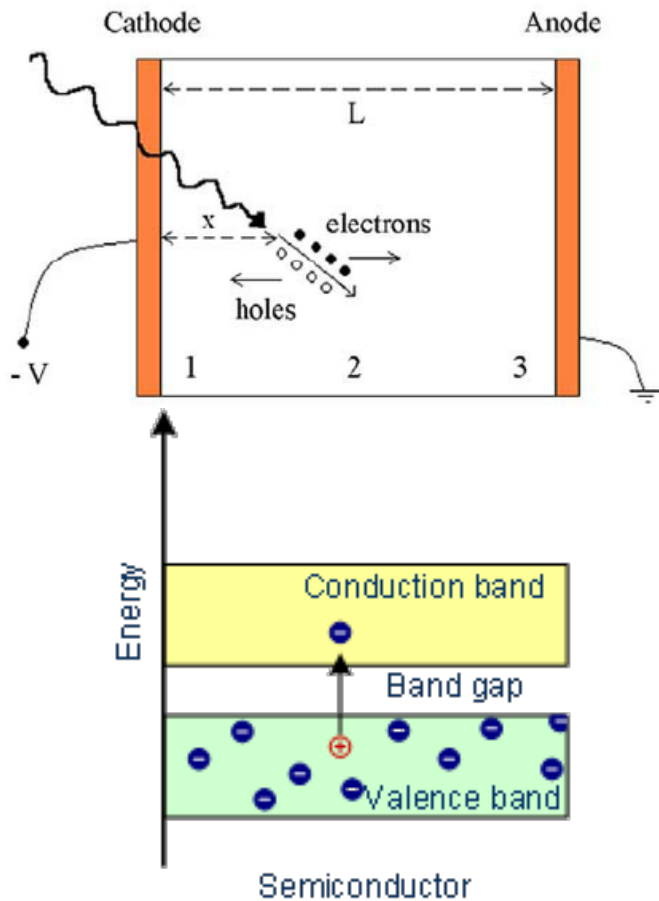


Energy calibrations are done with γ sources (electron recoils).

The relative calibration of nuclear recoils ($\text{keV}_{ee} \rightarrow \text{keV}_{nr}$), the **quenching factor** (QF), must be known with accuracy

Cryogenics: when sensitivity matters

Semiconductor detectors

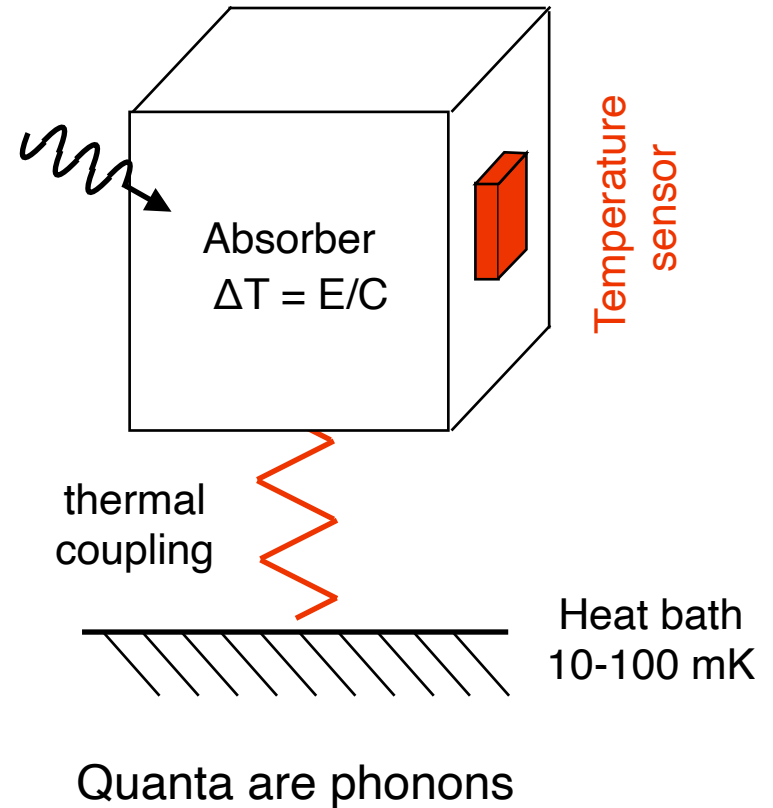


$$\epsilon \sim 1 \text{ eV}$$

$w > 3\epsilon$, quenching

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

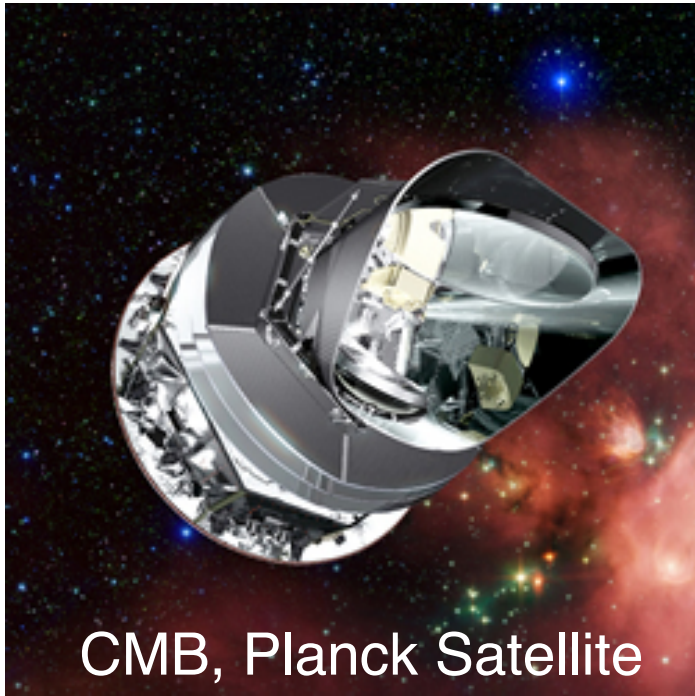
Cryogenic detectors



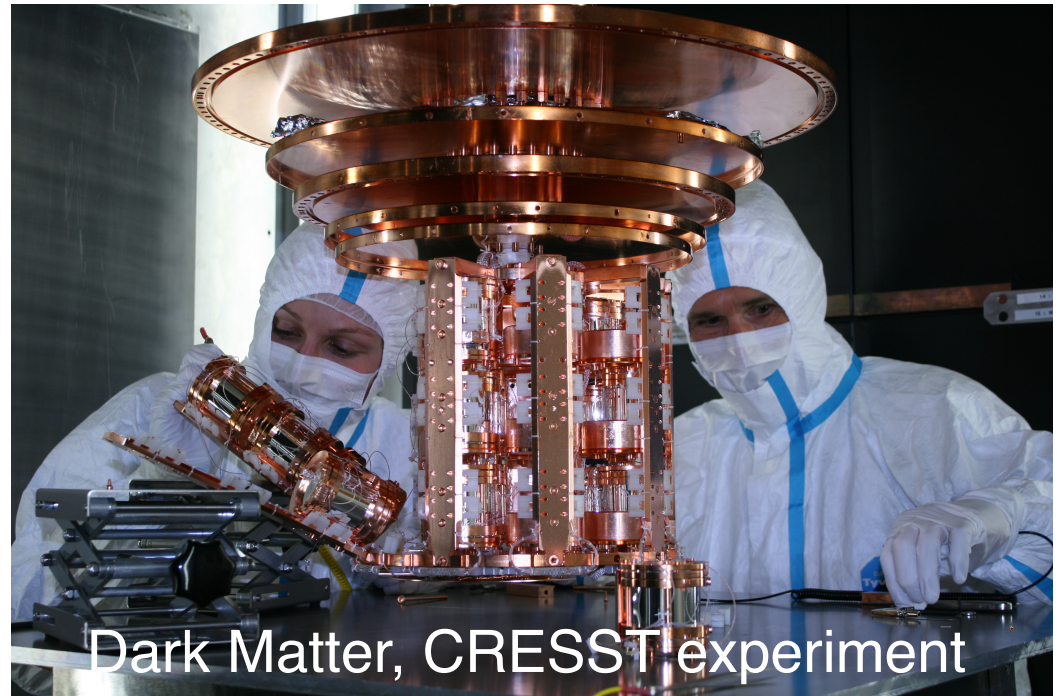
$$\epsilon = k_B T(100\text{mK}) \sim 10 \mu\text{eV}$$

no quenching

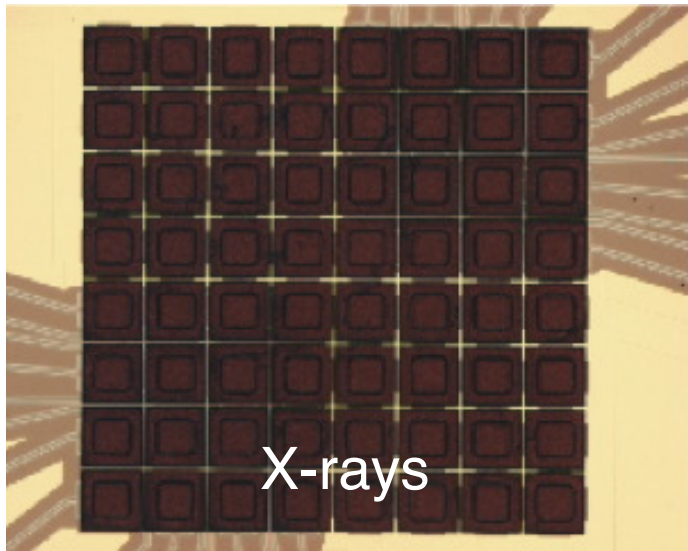
Applications of cryogenic detectors



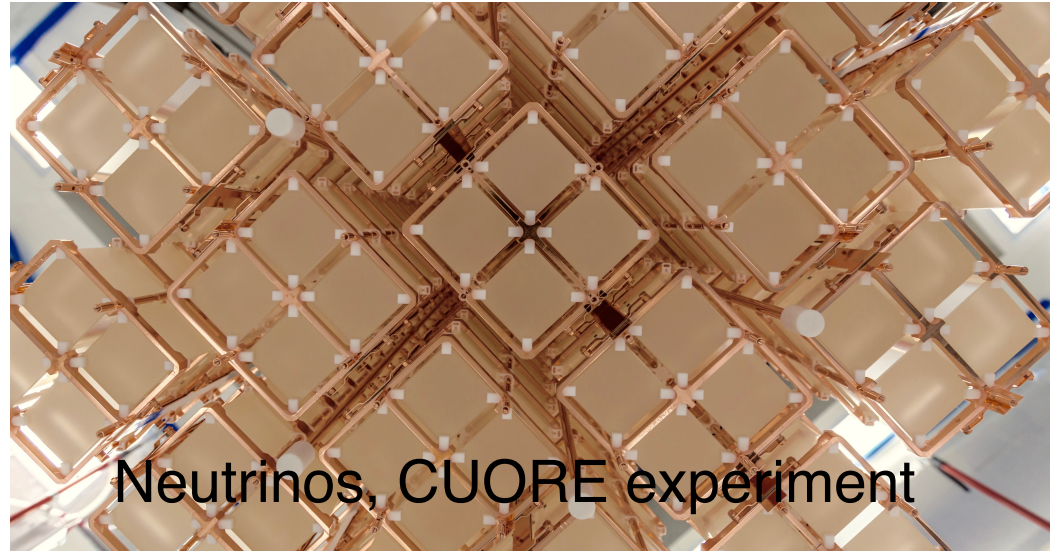
CMB, Planck Satellite



Dark Matter, CRESST experiment



X-rays

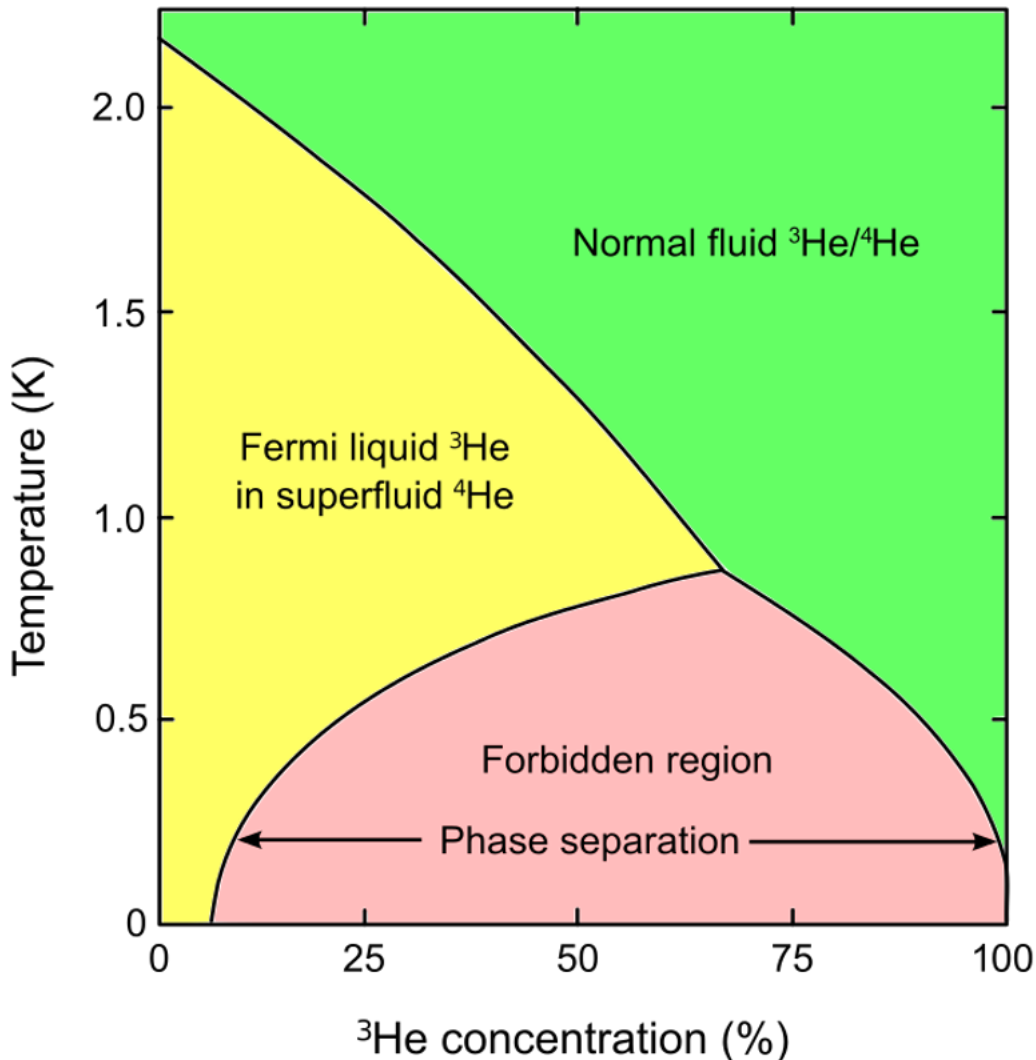


Neutrinos, CUORE experiment

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

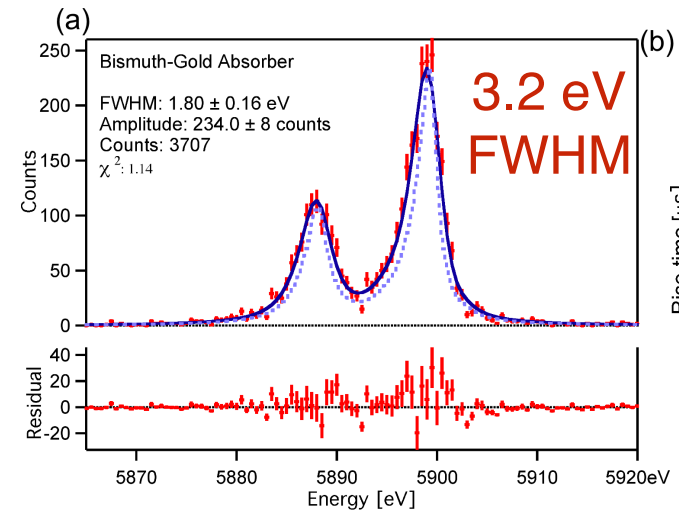
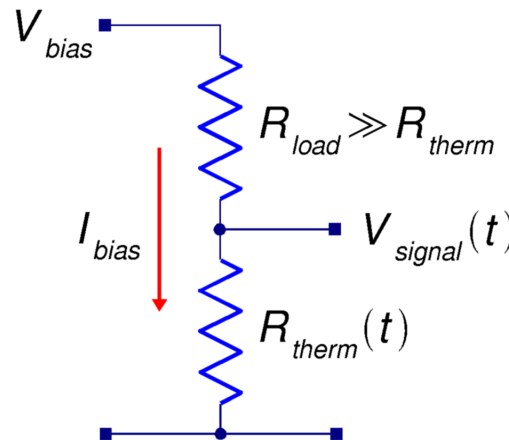
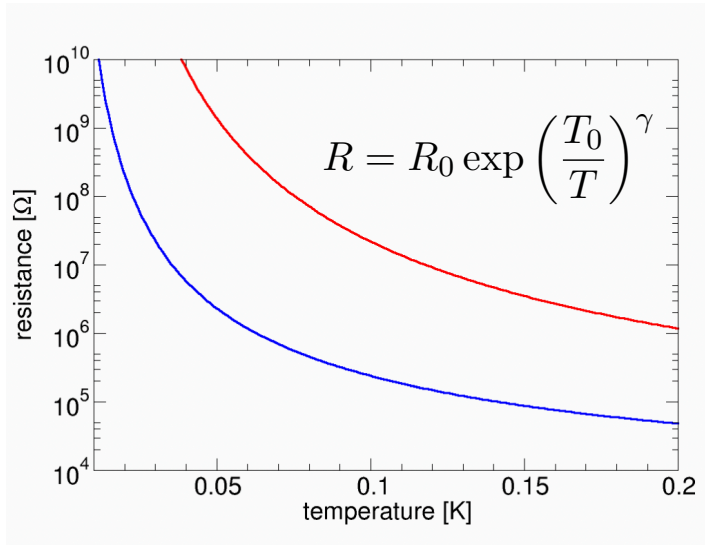
Cryolab @ Sapienza U.



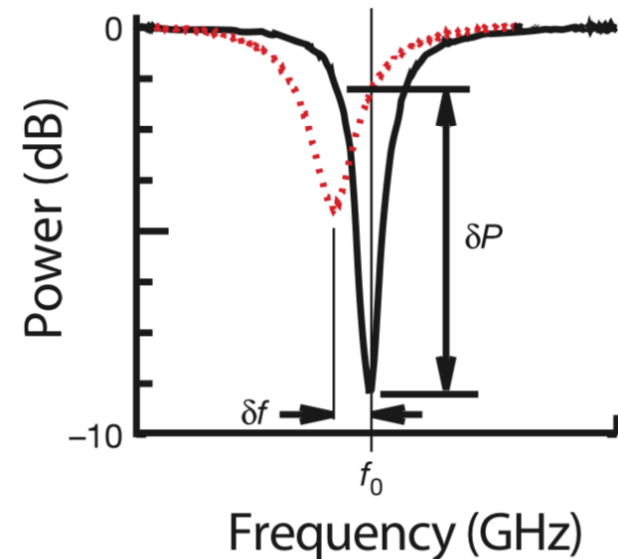
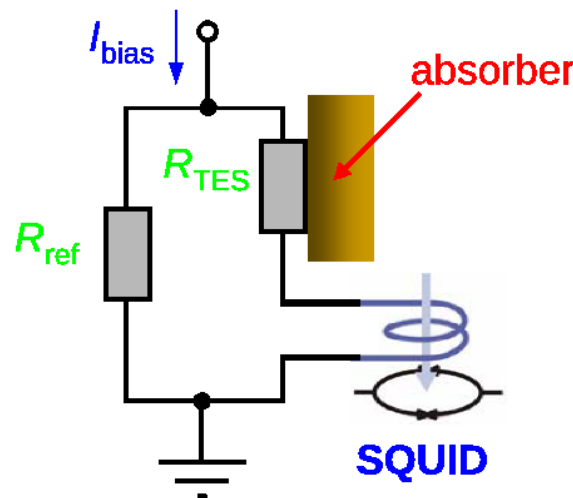
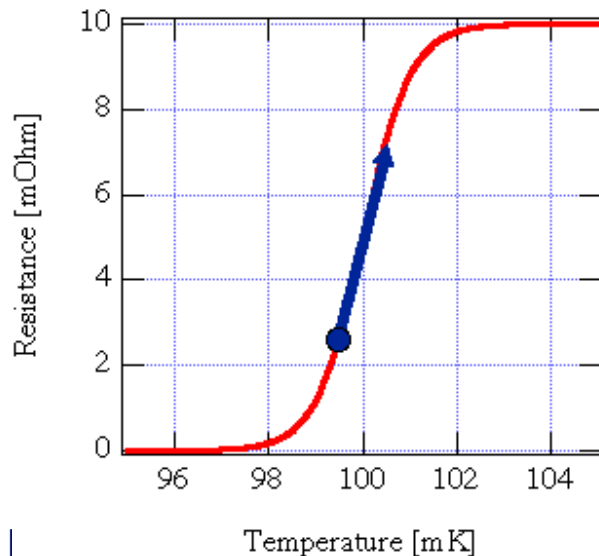
Experimental volume is few to tens of litre, typically

Most popular cryogenic sensors

High impedance: semiconducting thermistor

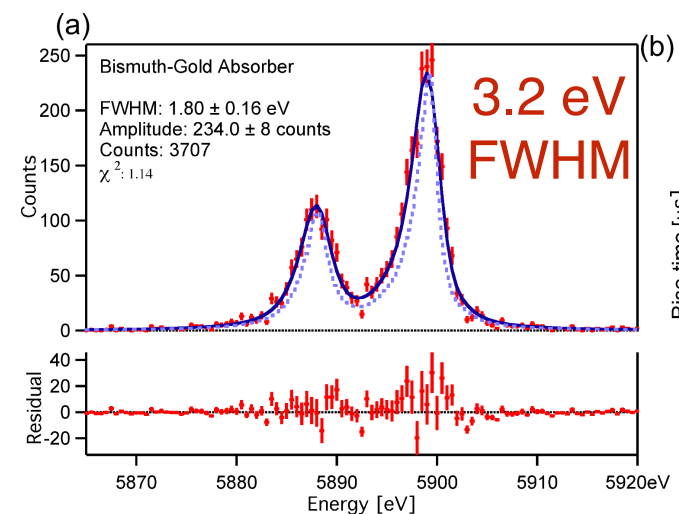
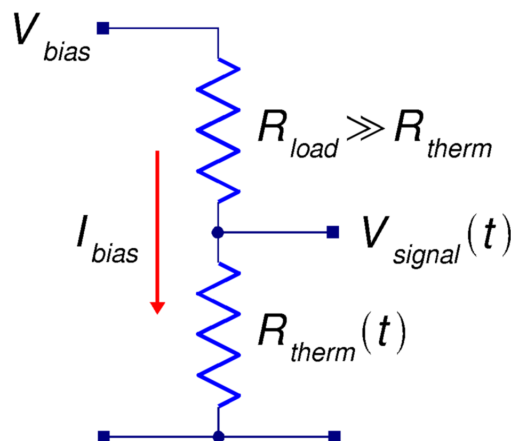
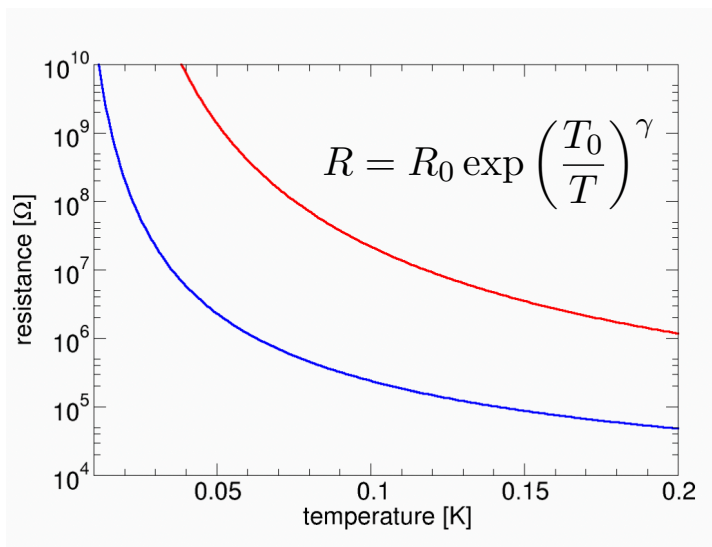


Low impedance: superconducting TES and KIDs

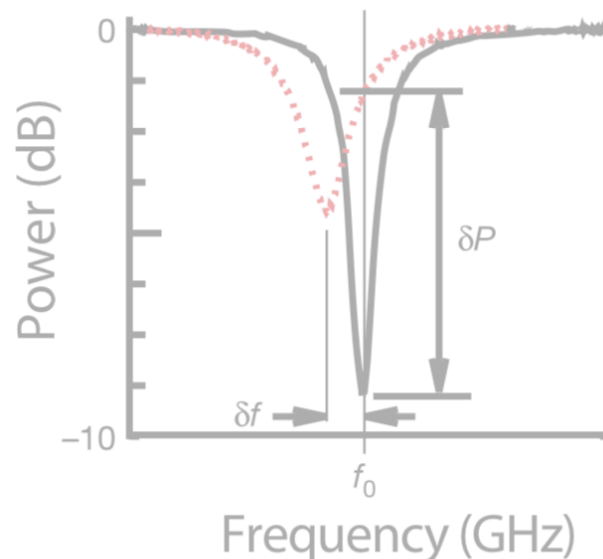
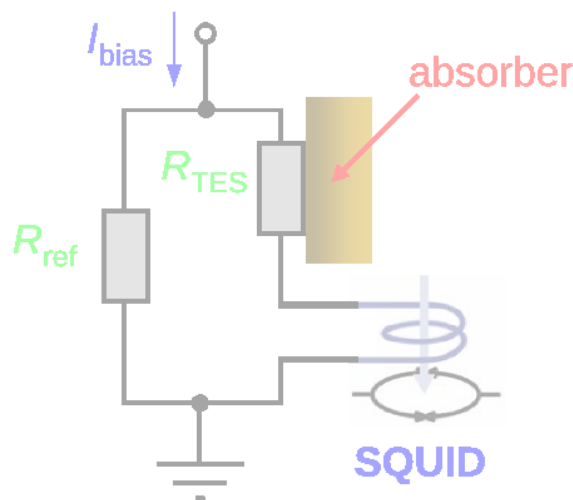
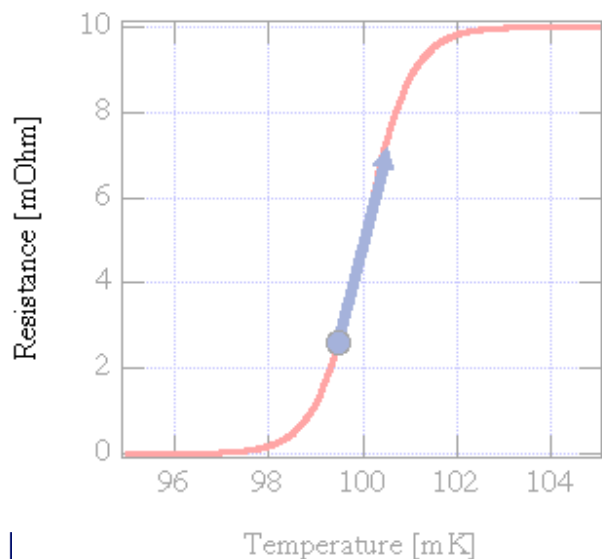


Most popular cryogenic sensors

High impedance: **semiconducting** thermistor



Low impedance: superconducting TES and KIDs



Semiconducting thermistors

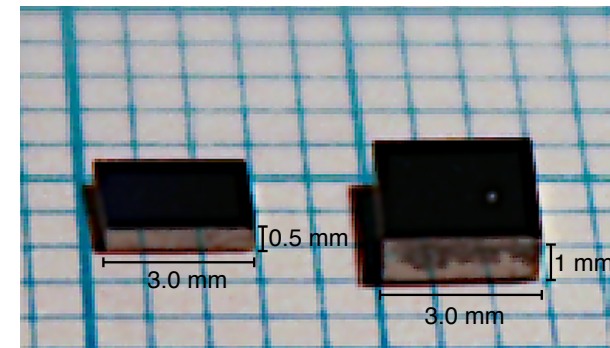
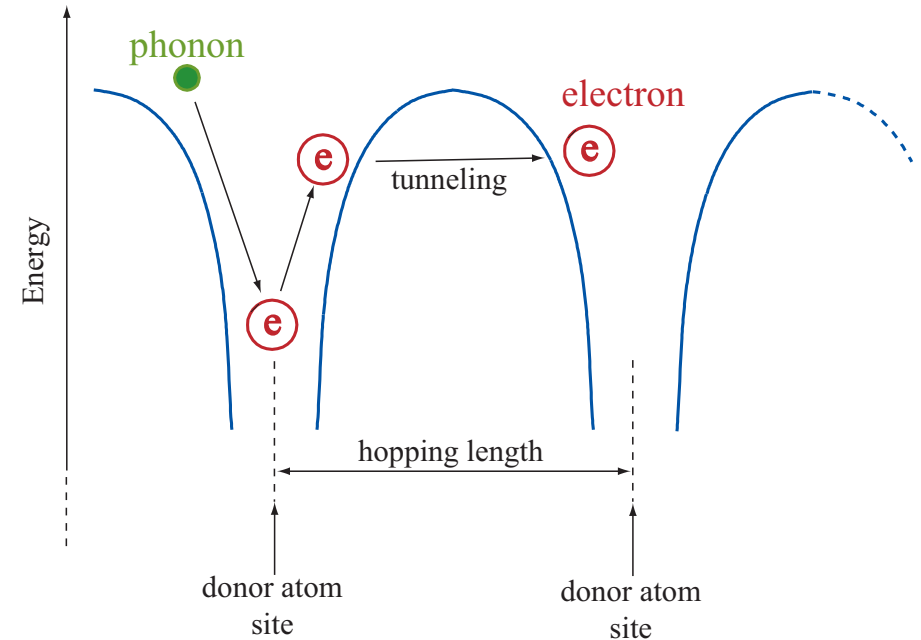
Hopping conduction

Semiconductor gap = 1 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

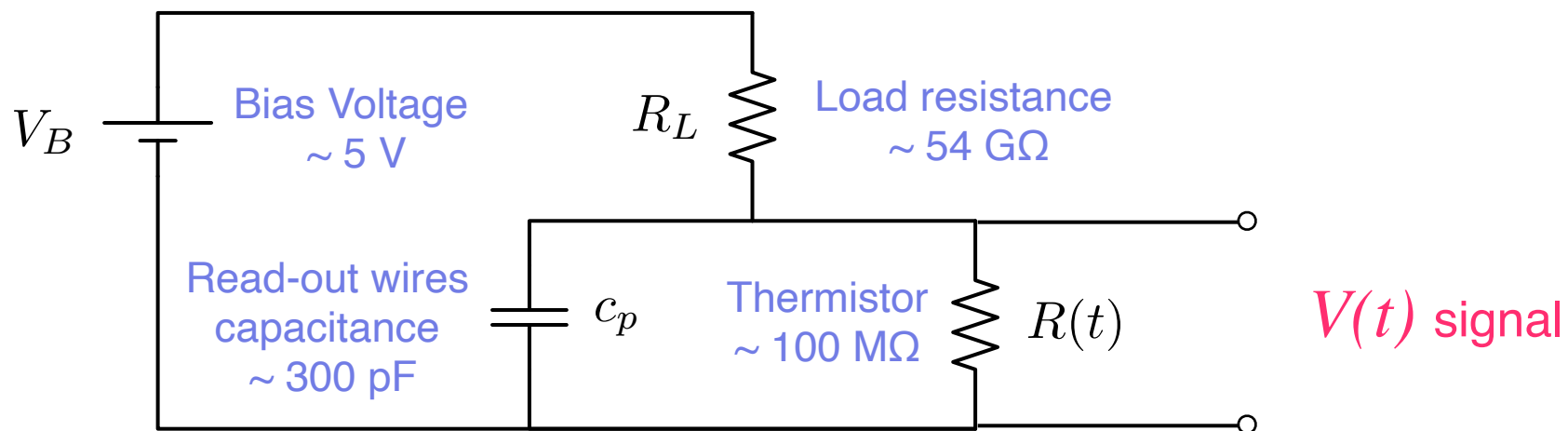
- The thermistor resistance depends on the temperature as:

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

using parameters of CUORE experiment ($R_0 = 1.15 \Omega$, $T_0 = 3.35 \text{ K}$ and $\gamma = 1/2$):

$$R(10 \text{ mK}) \sim 100 \text{ M}\Omega$$

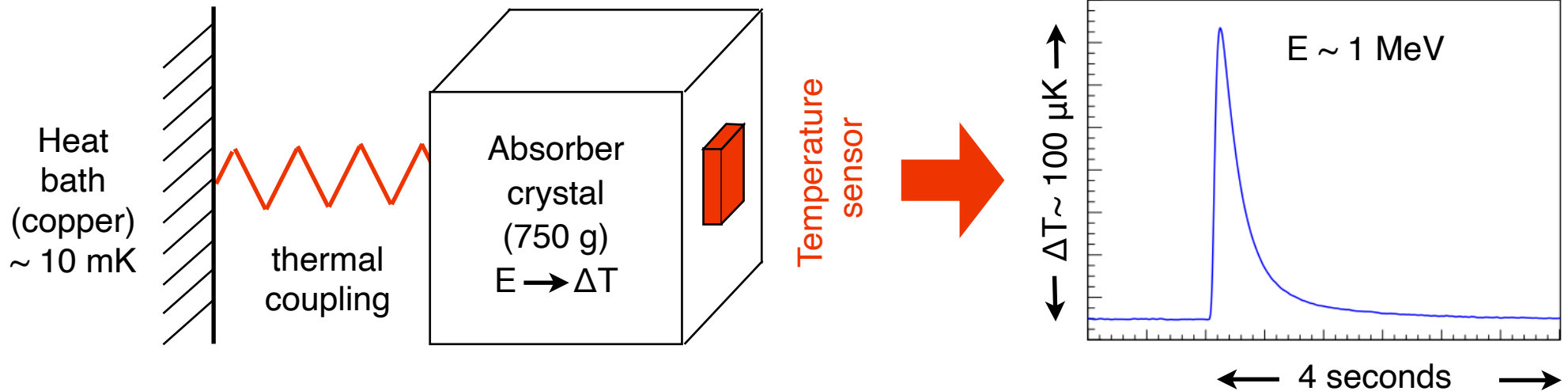
- The signal is detected biasing the resistance and reading the voltage $V(t)$ across it:



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

**example of NTD
in particle physics**

Bolometric technique in CUORE

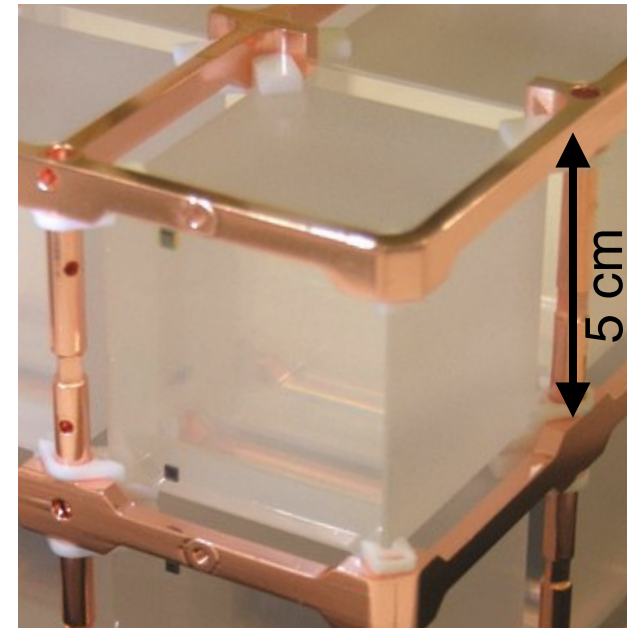


- ▶ $^{\text{nat}}\text{TeO}_2$ crystals (low heat capacitance) source embedded in the detector

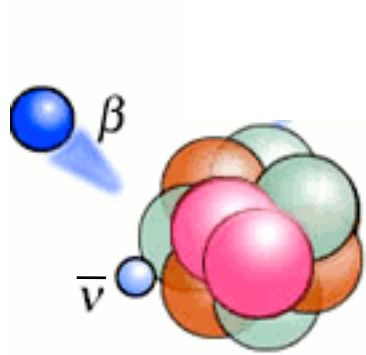
- ▶ NTD-Ge thermistor: $R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{\frac{1}{2}}$
 $R(T) = 100 - 1000 \text{ k}\Omega @ 10 \text{ mK}$

- ▶ Resolution @ $0\nu\beta\beta$ energy (2528 keV):
 $\Delta E = 5 \text{ keV FWHM}$

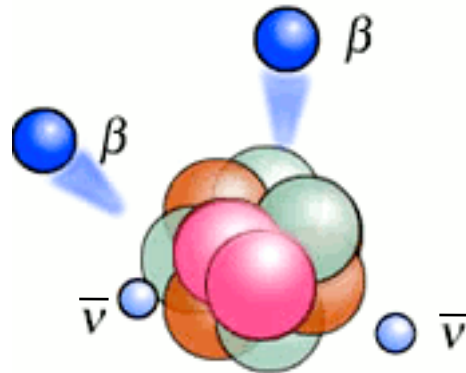
- ▶ Detection efficiency $\sim 80\%$



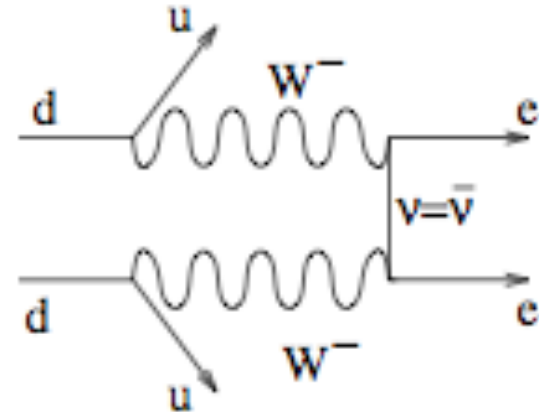
Double β decay



β -decay

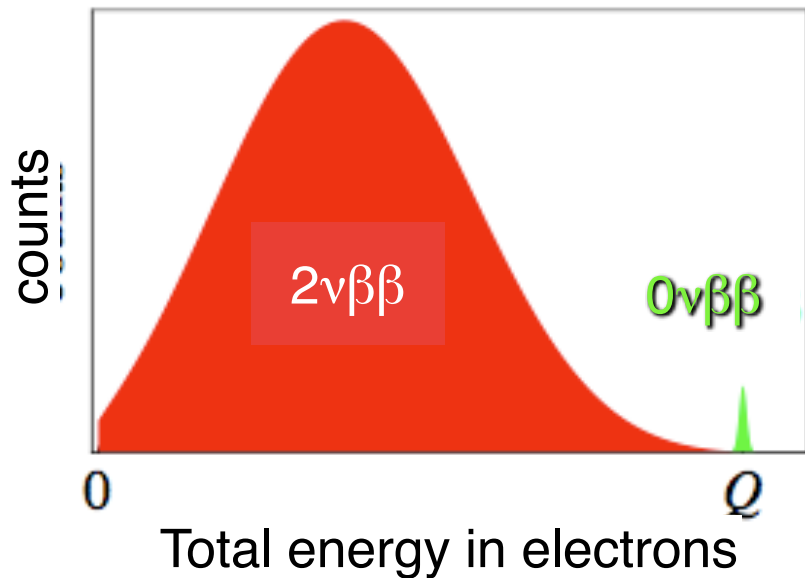


$\beta\beta$ -decay



$0\nu\beta\beta$ -decay

only if ν s are Majorana

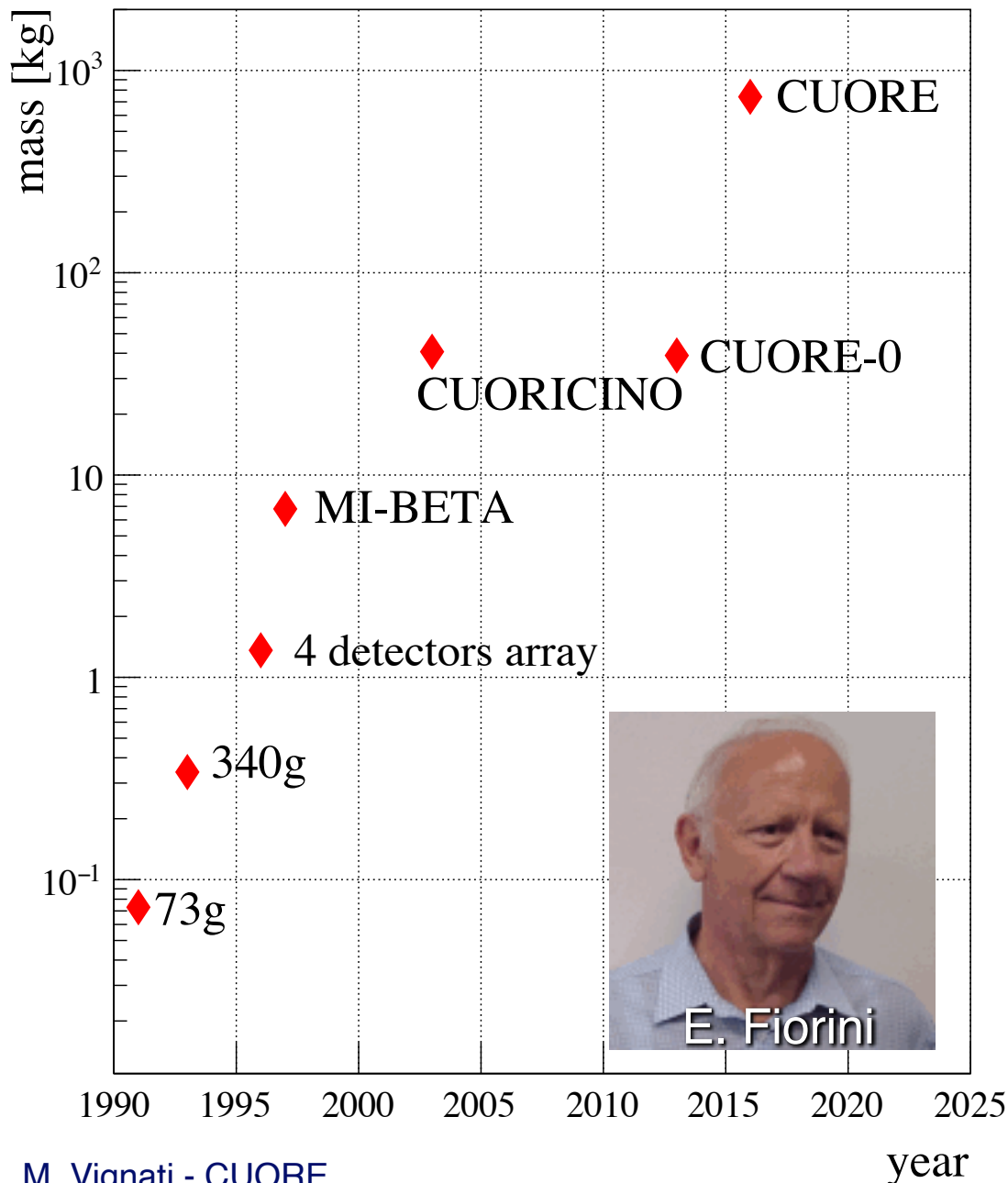


$0\nu\beta\beta$ is possible only in few natural isotopes, e.g.: ^{130}Te , ^{76}Ge , ^{136}Xe , ^{100}Mo , ^{82}Se .

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

Almost Zero background is needed.

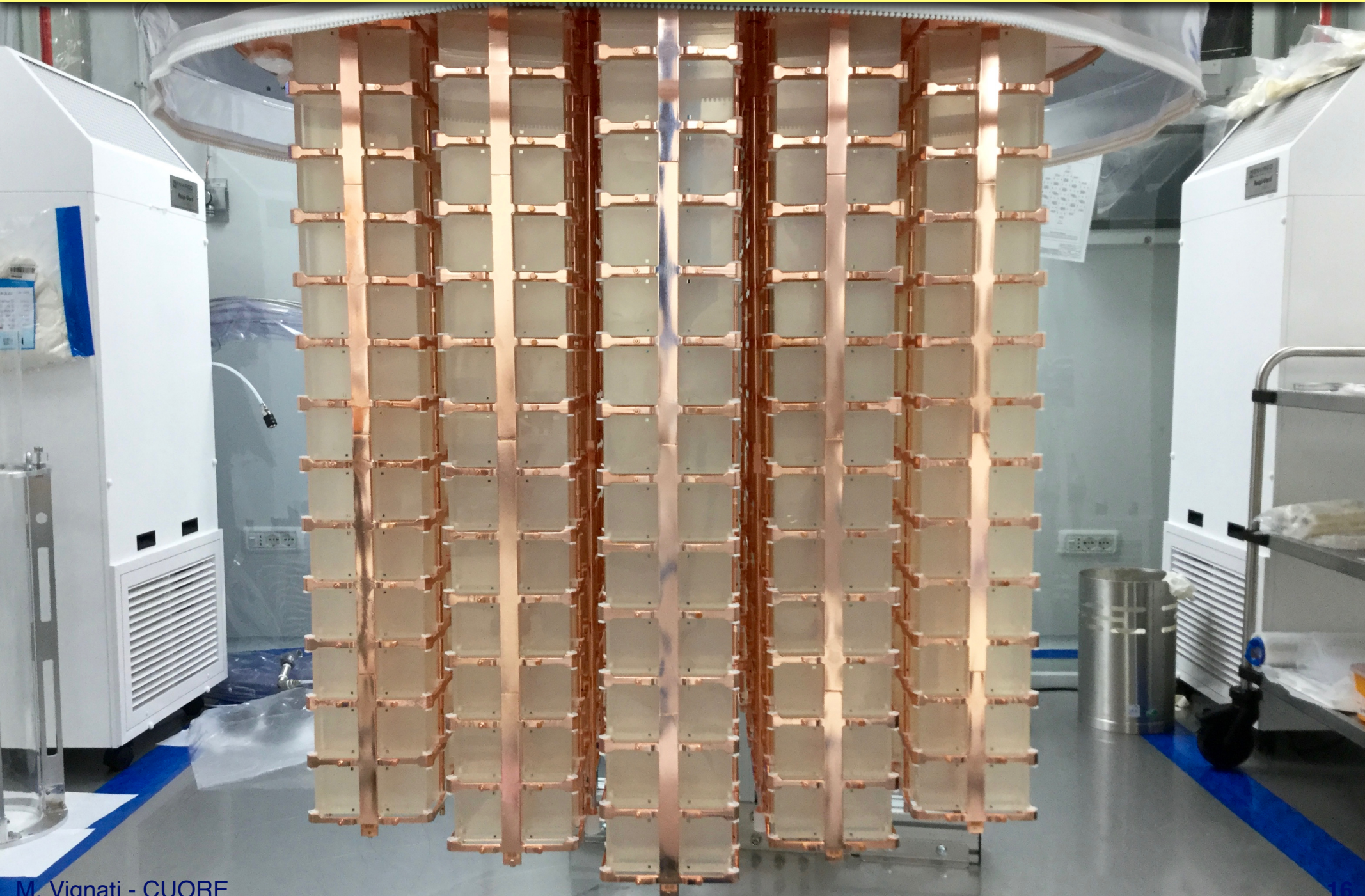
Arrays of TeO₂ bolometers



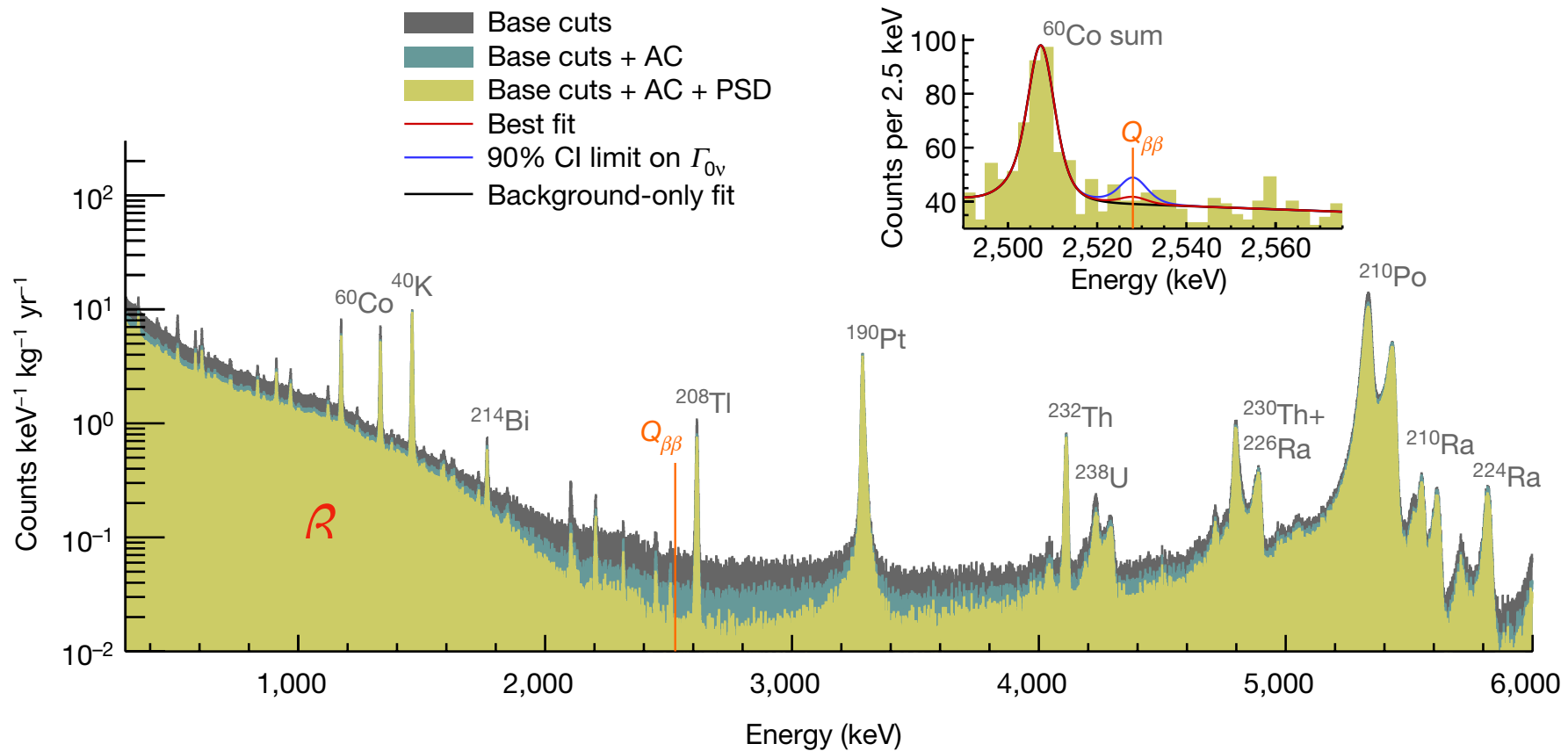
Cryogenic Underground Observatory for Rare Events

- Hosted at Gran Sasso lab in Italy.
- 988 ^{nat}TeO₂ bolometers
19 towers, 13 floors.
- Active mass: 742 kg.
- Isotope mass: 206 kg ¹³⁰Te.
- Expected background:
10⁻² c/keV/kg/year
- Sensitivity to 0νββ in 5y
T_{1/2} = 9 × 10²⁵ y @90% C.L.
- Sensitivity to m_{ββ} in 5y:
50 - 130 meV @90% C.L.

CUORE detector before cool down



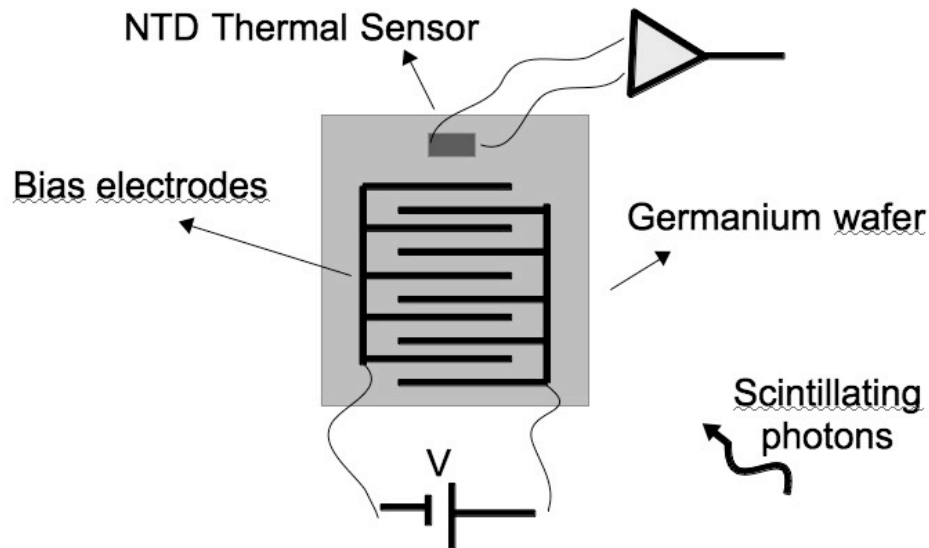
Result of CUORE (2022)



- 289 kg y ^{130}Te
- $\Delta E = 7.8$ keV FWHM
- Bkg = 0.015 counts / keV kg y
- $T_{1/2} > 2.2 \times 10^{25}$ y CI

Luke Neganov Amplification

- Combines Heat (phonons) and Ionisation (charge)
- Amplifies phonon signal in a semi-conducting crystal



$$E_{\text{heat}} = E + q V \left(\frac{E}{w} \right)$$

Number of e-h pairs

Amplified signal

- Event creates e-h pairs
- E-h pairs are drifted by V, and emit phonons.
- Phonon generation is dominated by e-h recombination: quenching factor applies!

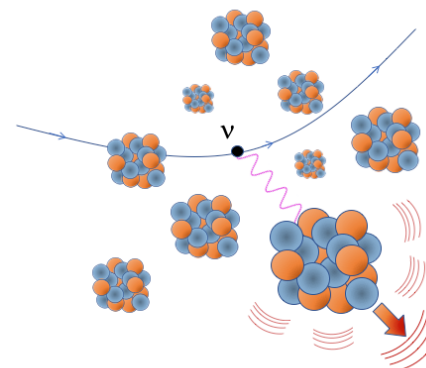
Ricochet: NTD + Ionisation

Coherent Elastic ν -Nucleus Scattering

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

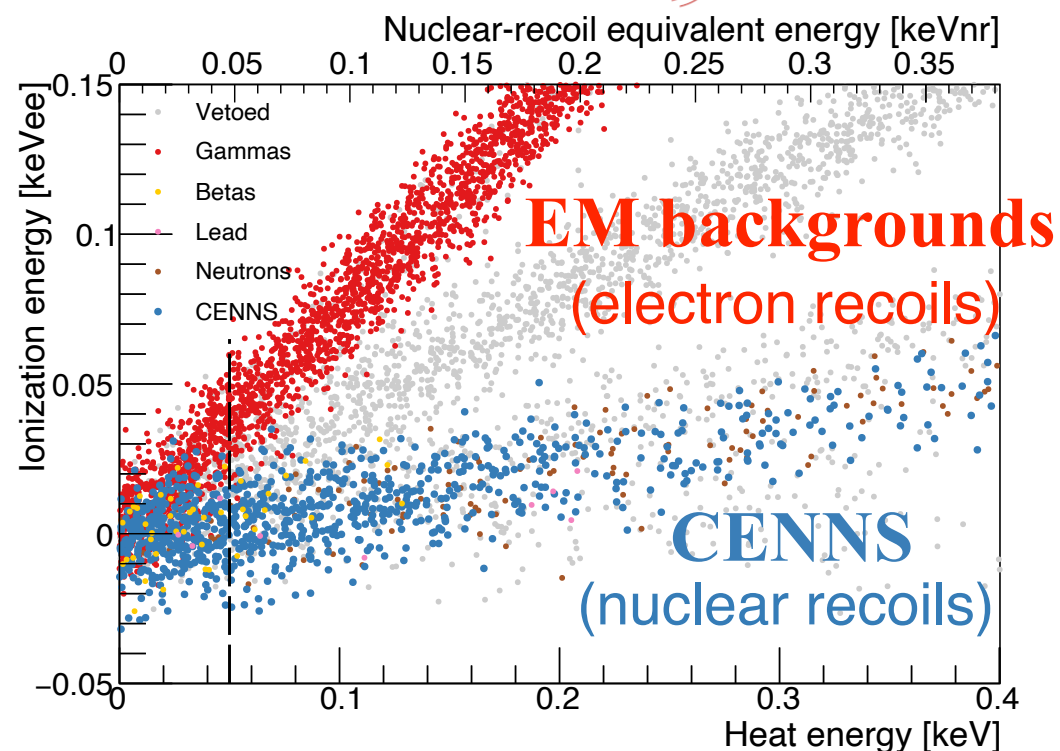
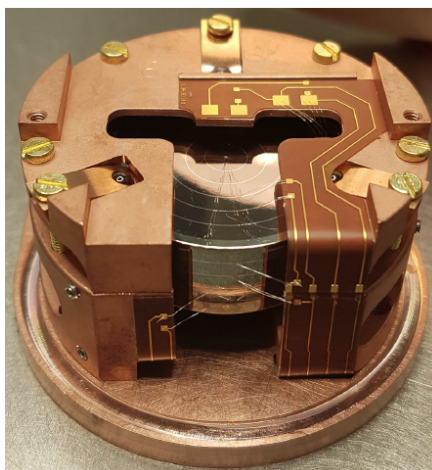
$$\sigma_{\text{CE}\nu\text{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$$

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



Ge detectors

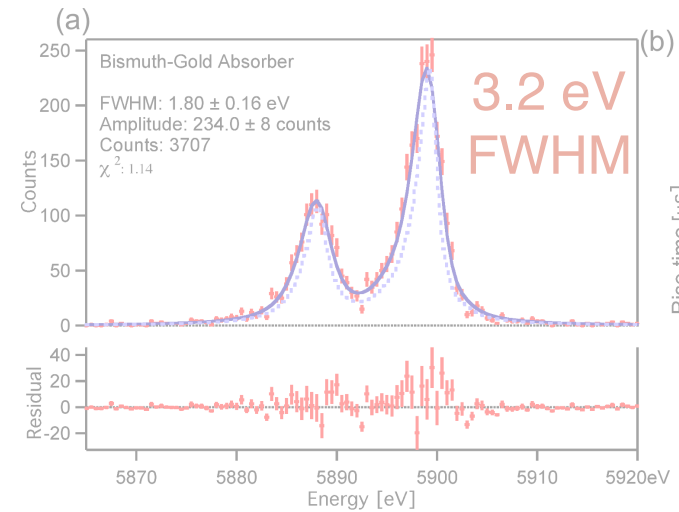
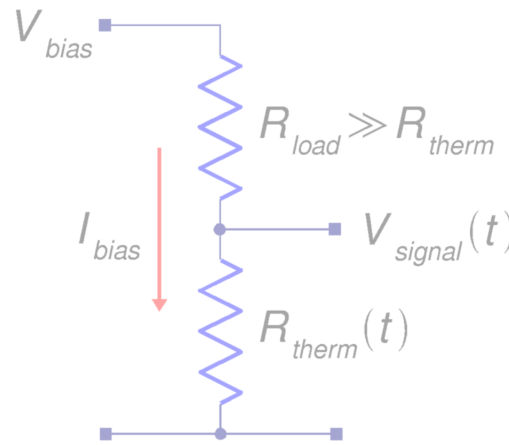
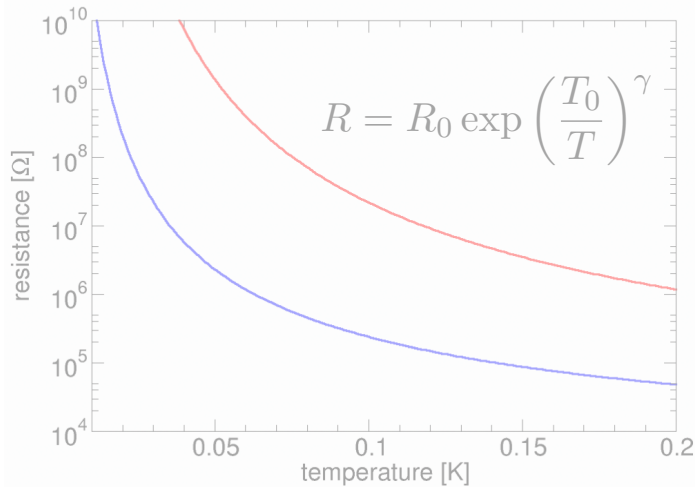
Target Mass: 42 g x 18



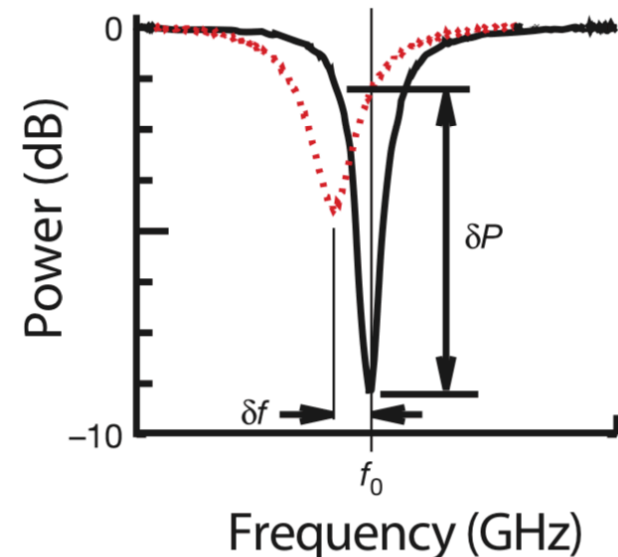
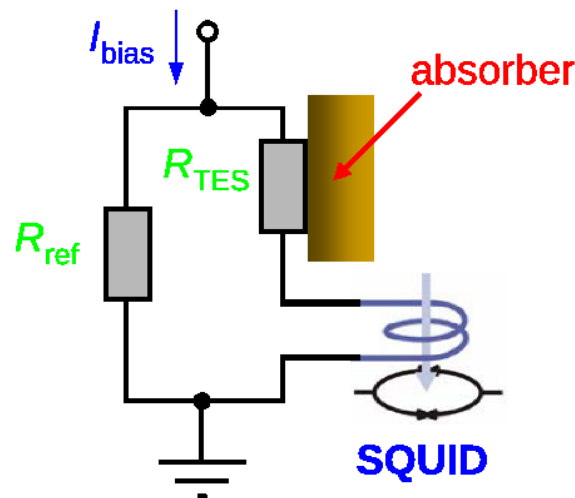
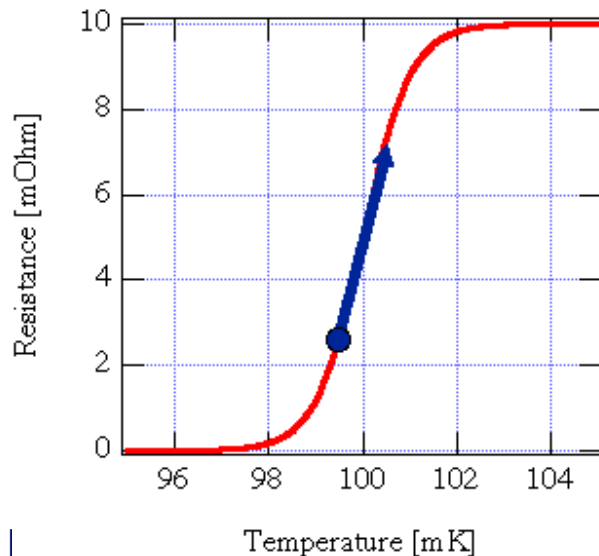
Particle ID @ < 100 eV

Most popular cryogenic sensors

High impedance: semiconducting thermistor



Low impedance: **superconducting** TES and KIDs

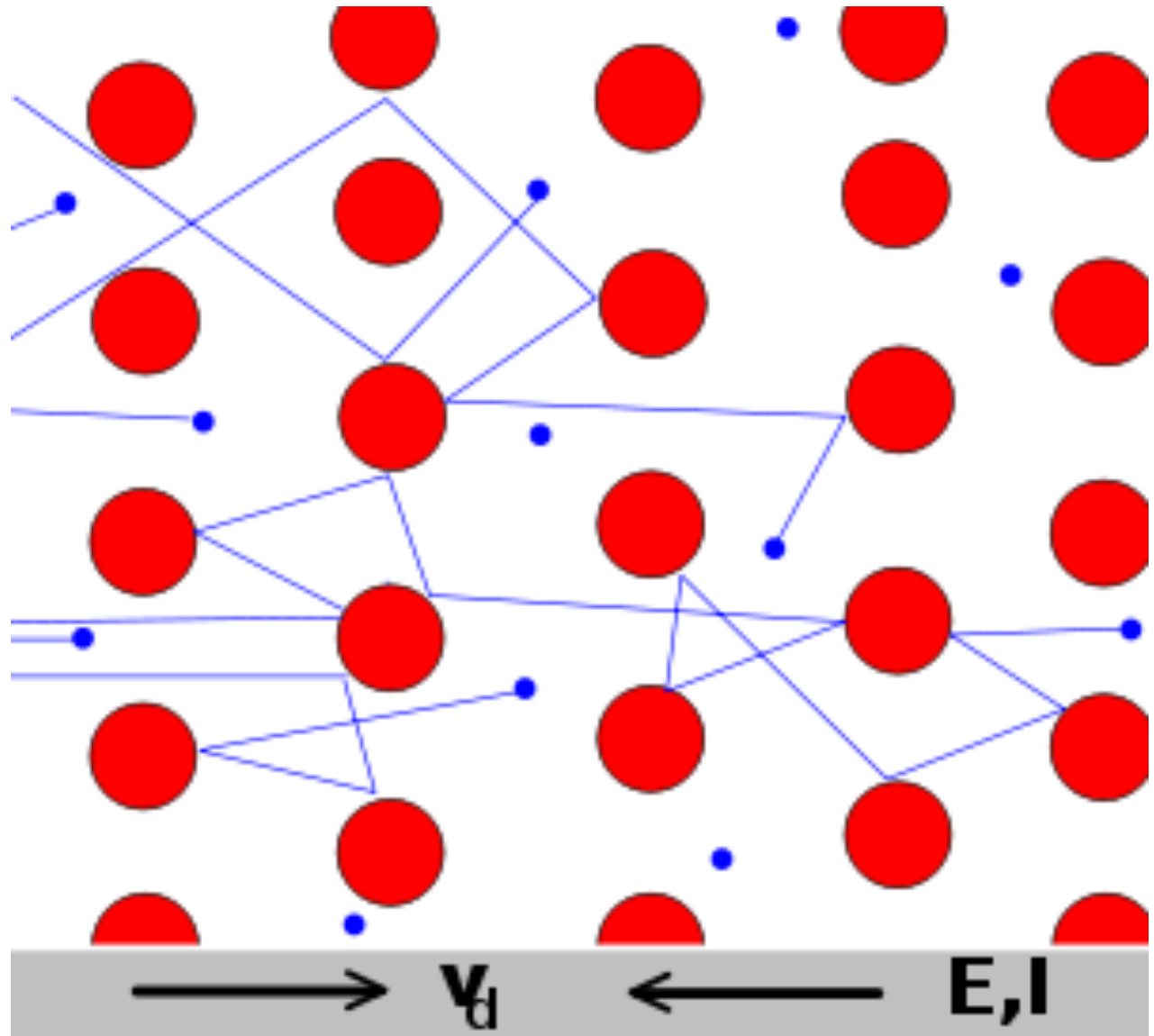


Elements of superconductivity

Conductivity - Drude model

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

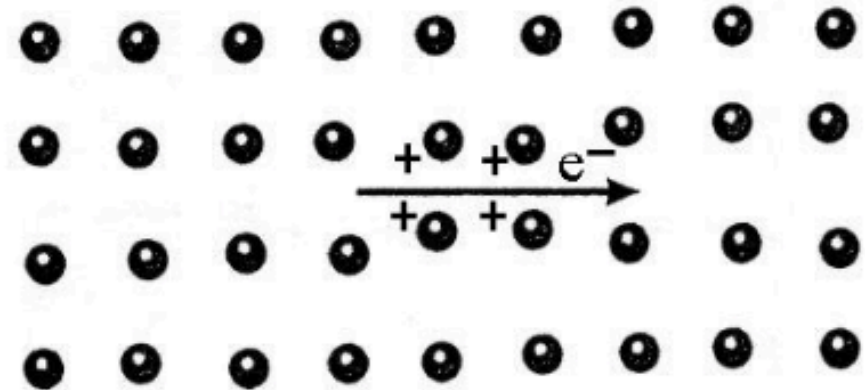
- \mathbf{J} current density
- \mathbf{E} electric field
- n electron density
- q electron charge
- m electron mass
- τ mean free time between collisions with phonons



Wikipedia

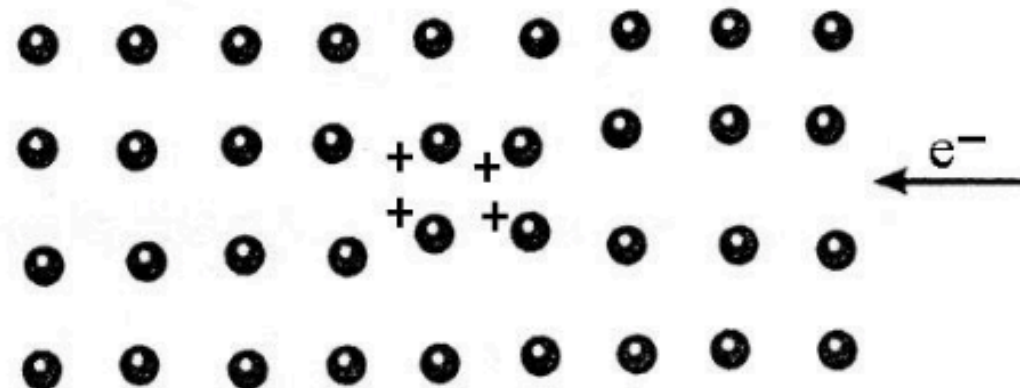
Superconductivity for dummies

- 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**:



First electron deforms part of the lattice electrostatically.

- ▶ Binding energy is small
 ~ 0.4 meV in aluminum.
- ▶ Opposite electron spins forming a Bose condensate
- ▶ Single wave function over the condensate.



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

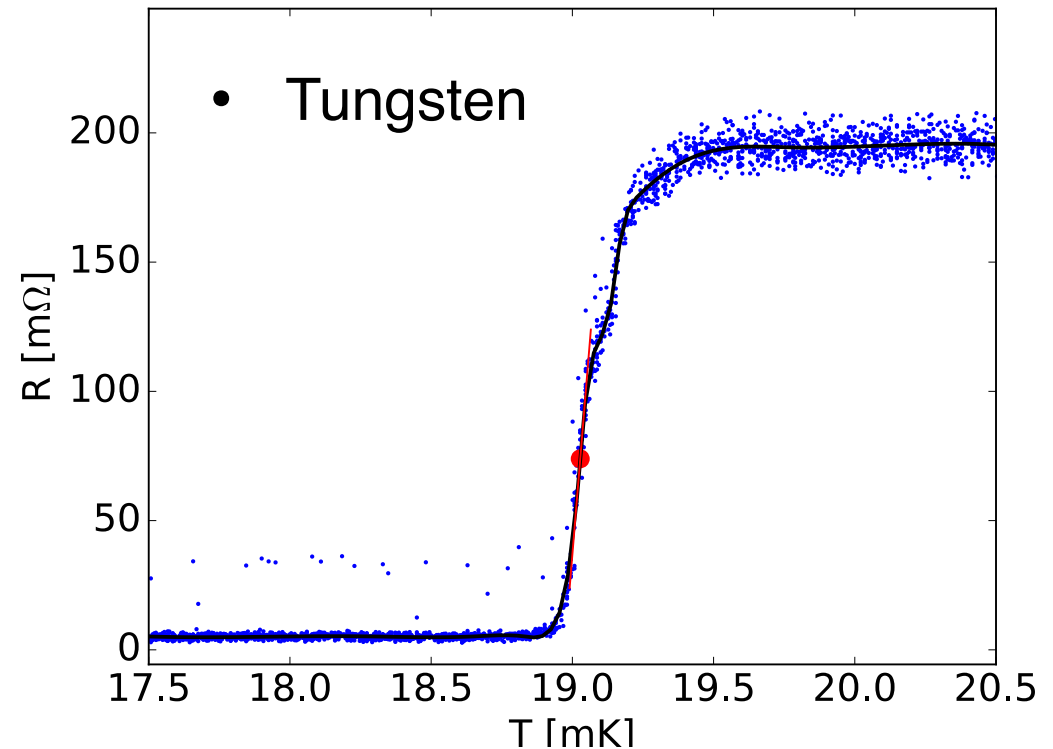
TES working principle

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

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

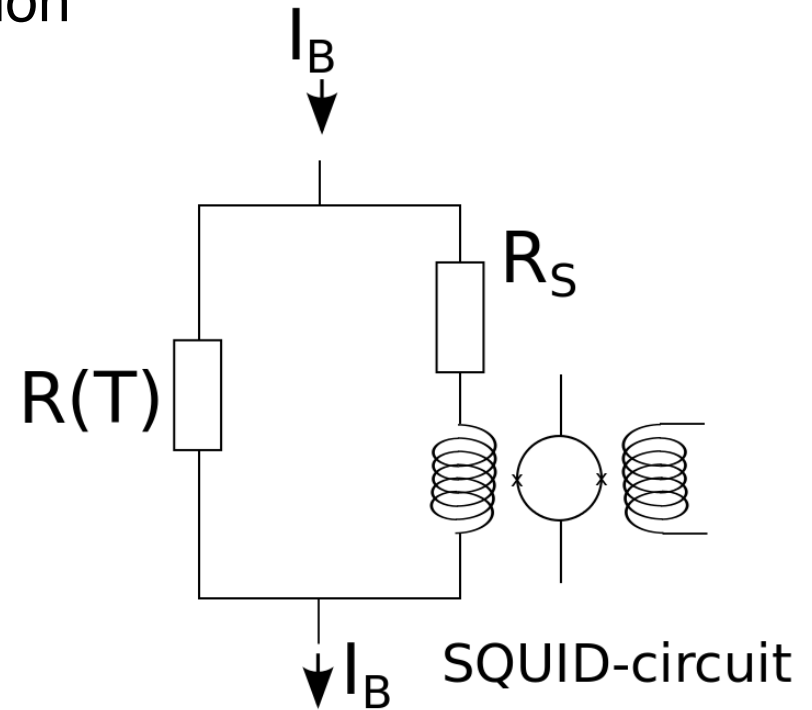
- Superconductor stabilized in temperature at the **onset of the superconducting - conducting transition**
- Measure tiny resistance variations
- The steeper the R vs T the higher the sensitivity

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

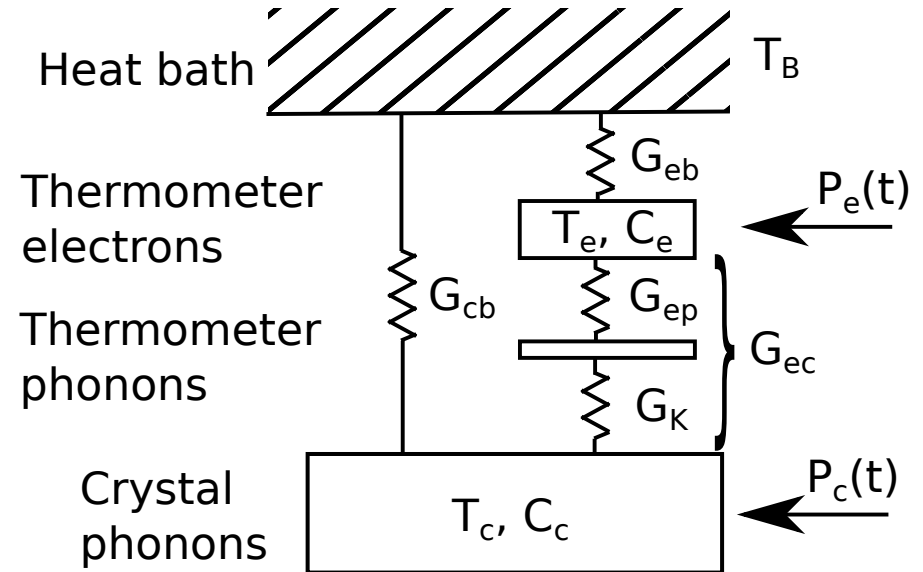
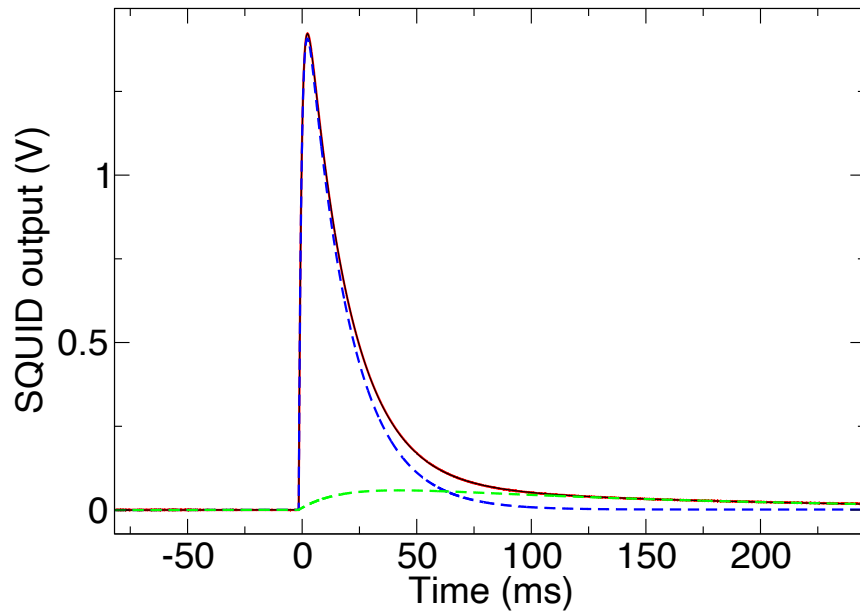


TES readout

- **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).



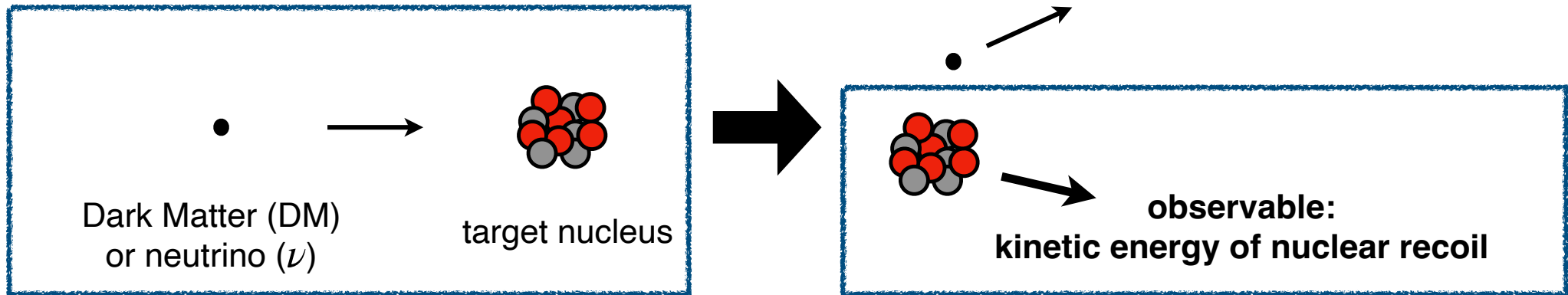
TES signal



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

**examples of TES
in particle physics**

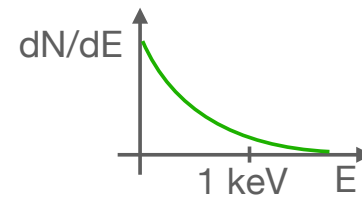
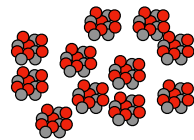
Process under observation



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

energy $< 1 \text{ keV}$

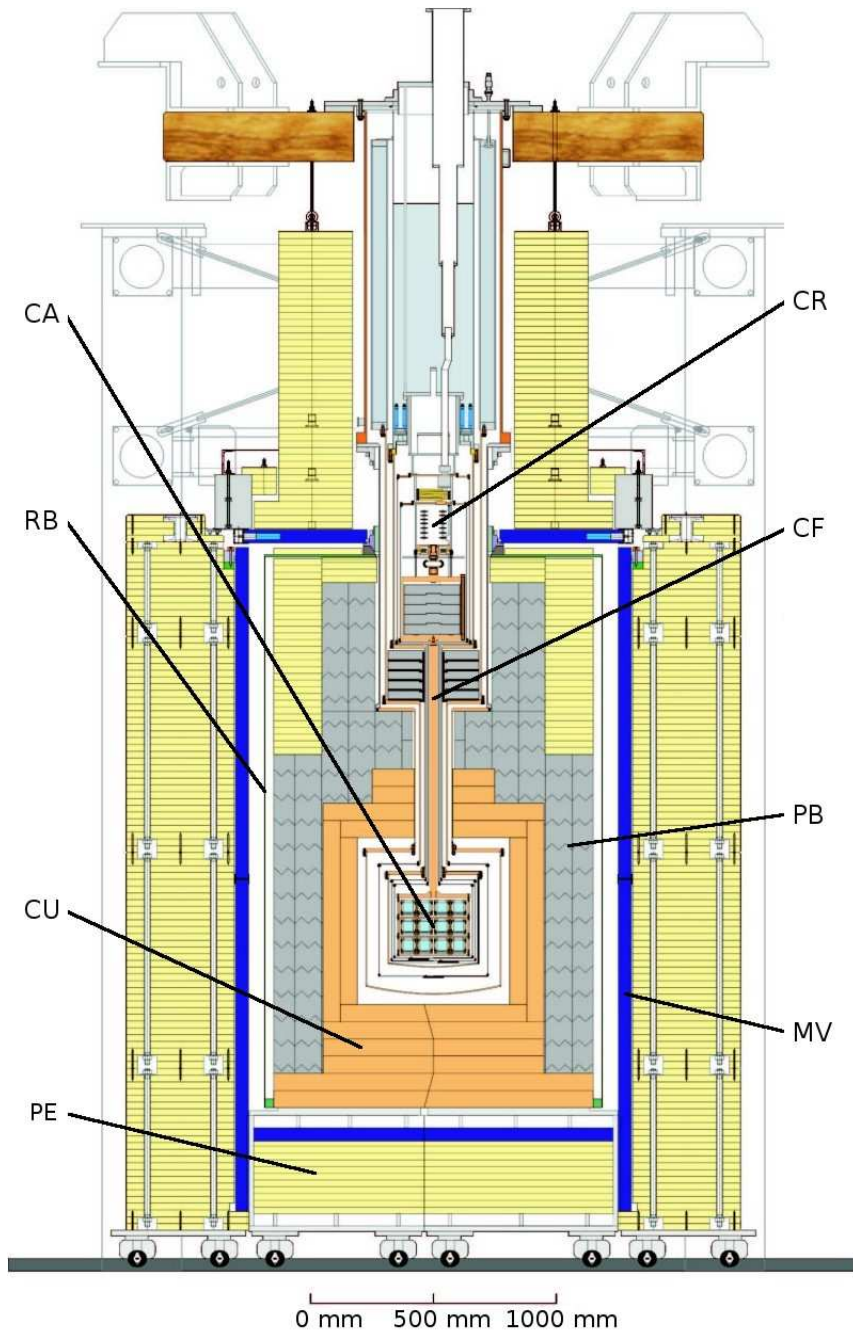
large number of targets
(large target mass)



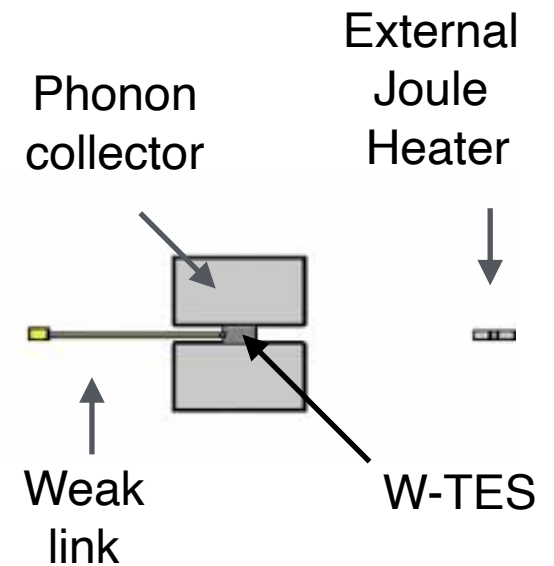
low-energy
detection threshold

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)



CE ν NS with NUCLEUS

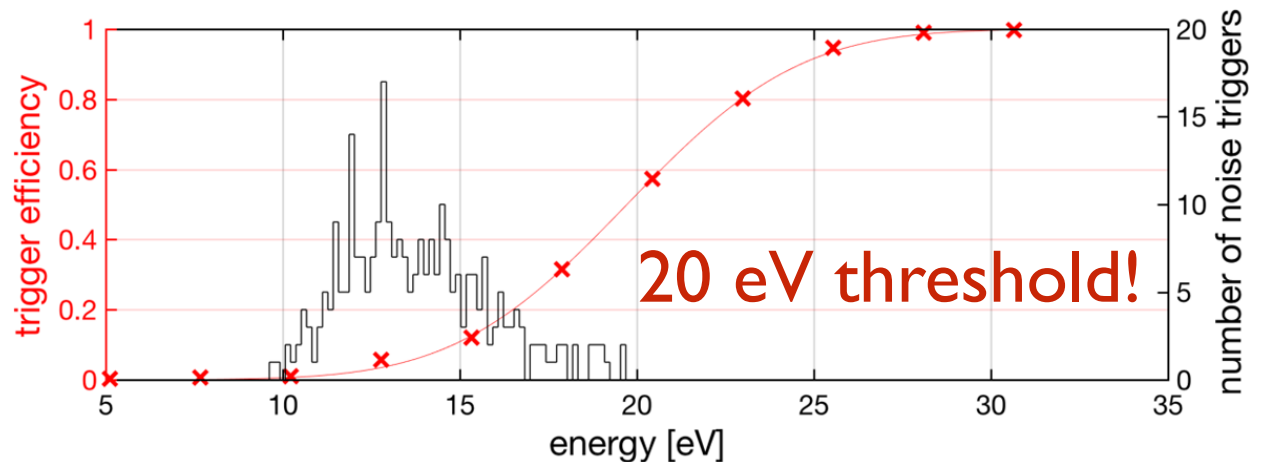
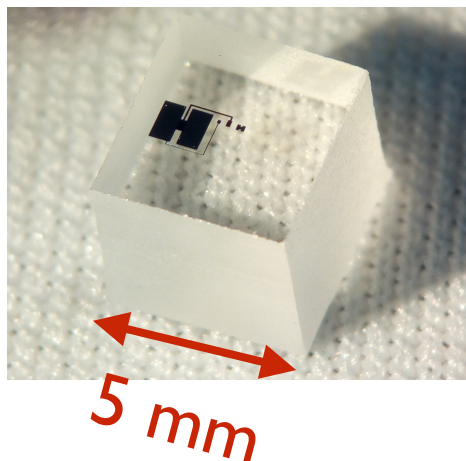
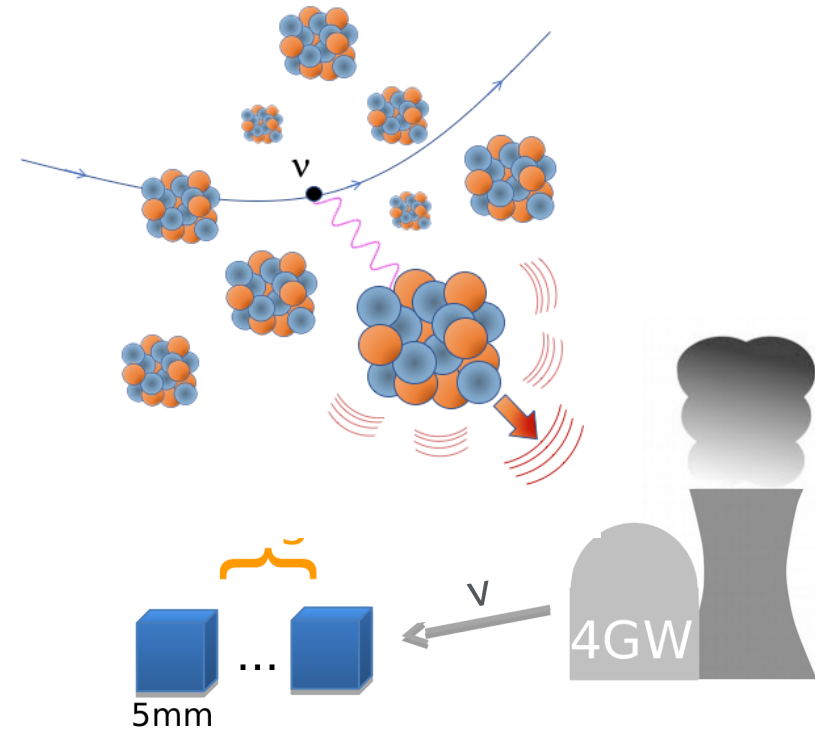
$$\nu(\bar{\nu}) + A \rightarrow \nu(\bar{\nu}) + A$$

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

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

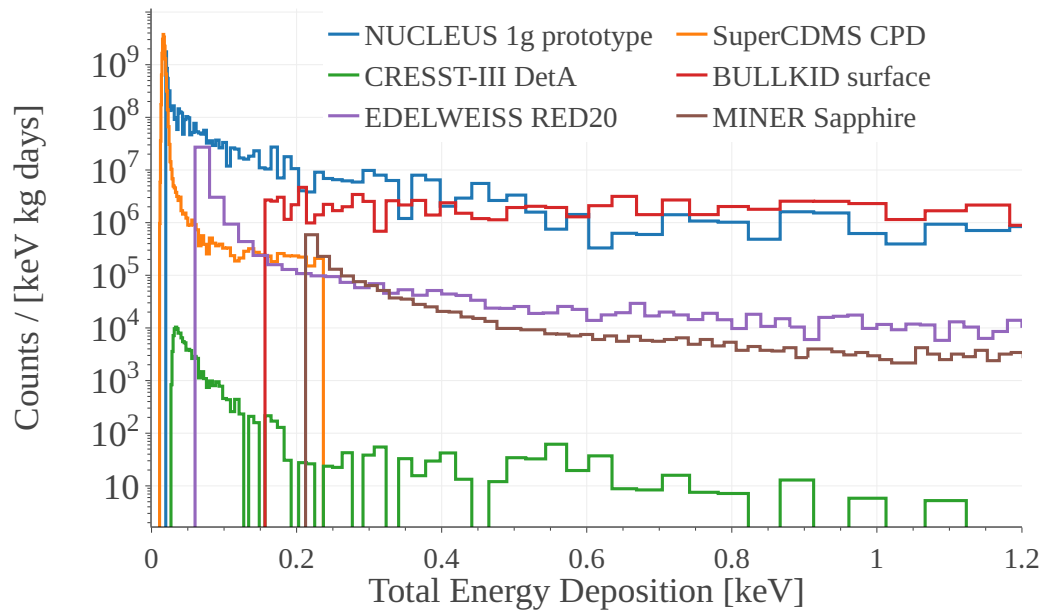
NUCLEUS will measure
this process with 10% precision.

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



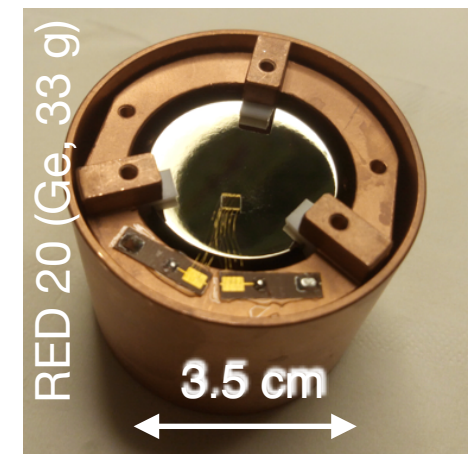
The “Excess” problem

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

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

σ_1

σ_2

- The imaginary term σ_2 appears when $\omega \sim \frac{1}{\tau}$
- In normal conductors $\tau \sim 10^{-14} \text{ s}$ which implies $f = 16 \text{ THz !!!}$
- In superconductors $\tau \rightarrow \infty$ 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 carriers.

The charge carriers 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

$$I = n q v A$$

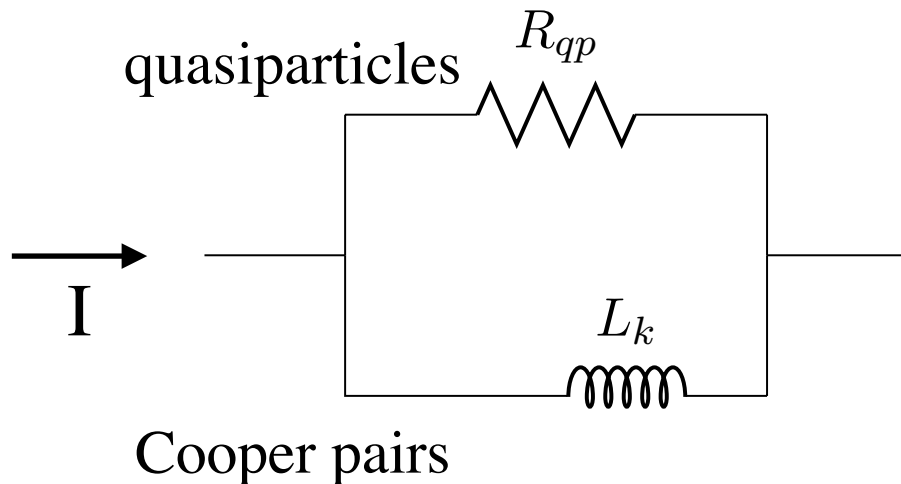
- We rewrite the energy as

$$E_k = \frac{1}{2} \frac{l m}{A n q^2} I^2 = \frac{1}{2} L_k I^2$$

- 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.

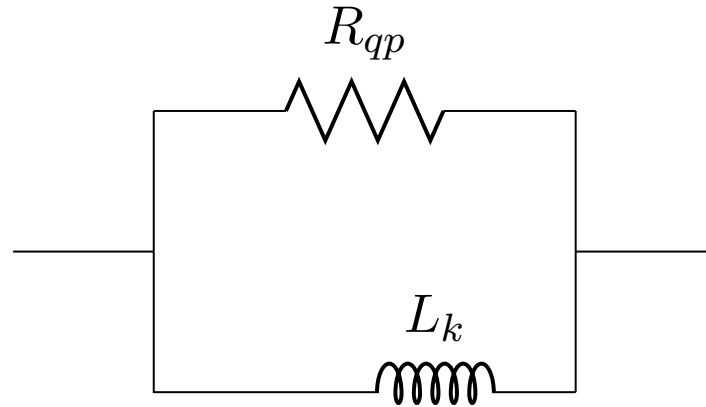


$$Z_s = (0 + j\omega L_k) || R_{qp}$$

- 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.

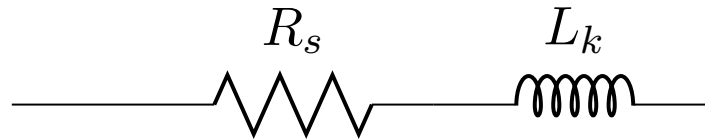
Total impedance

Original impedance



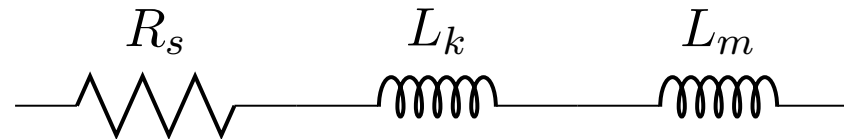
$$Z_s = (0 + j\omega L_k) \parallel R_{qp} \underset{R_{qp} \gg \omega L_k}{\approx} = j\omega L_k + \frac{(\omega L_k)^2}{R_{qp}}$$

Equivalent impedance



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

Total impedance
(+ magnetic inductance)



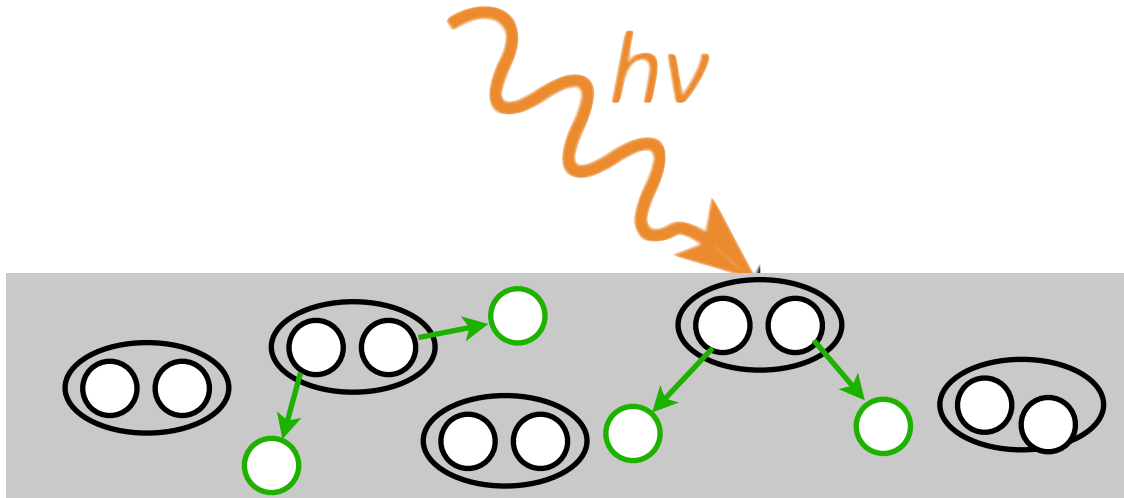
$$Z_s = j\omega(L_k + L_m) + R_s = j\omega L + R_s$$

Kinetic Inductance Detectors

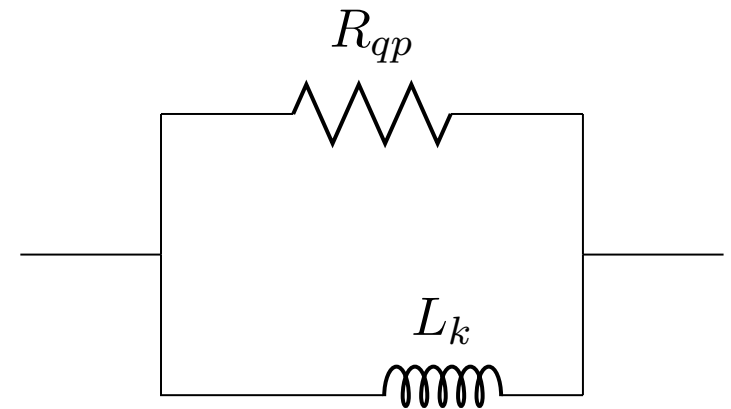
Non-equilibrium superconducting detectors invented at JPL/Caltech
Day et al., Nature 425 (2003) 817

Particle absorption

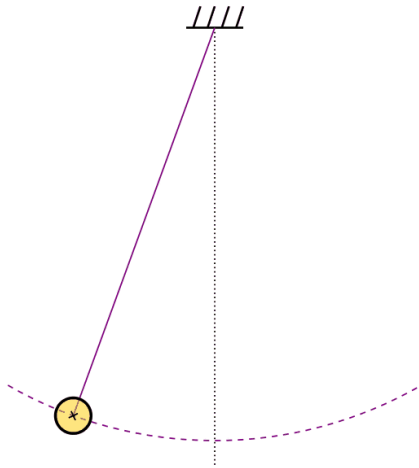
superconductor
at $T \ll T_c$
 $2\Delta \sim 400 \mu eV$ (Al)



- Absorbed photons or phonons can break Cooper pairs if their energy is larger than their binding energy 2Δ .
- The number of Cooper pairs decreases, thus L_k increases.
- Quasiparticles are generated, R_{qp} decreases, thus R_s increases.



Resonators



Frequency:

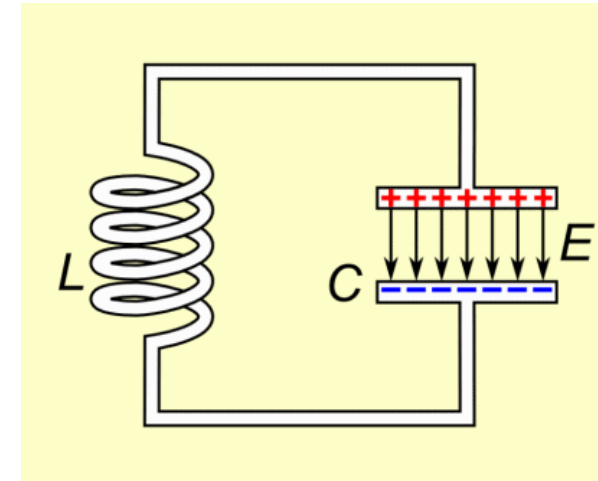
$$f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{l}}$$

Dissipation: air friction

Frequency:

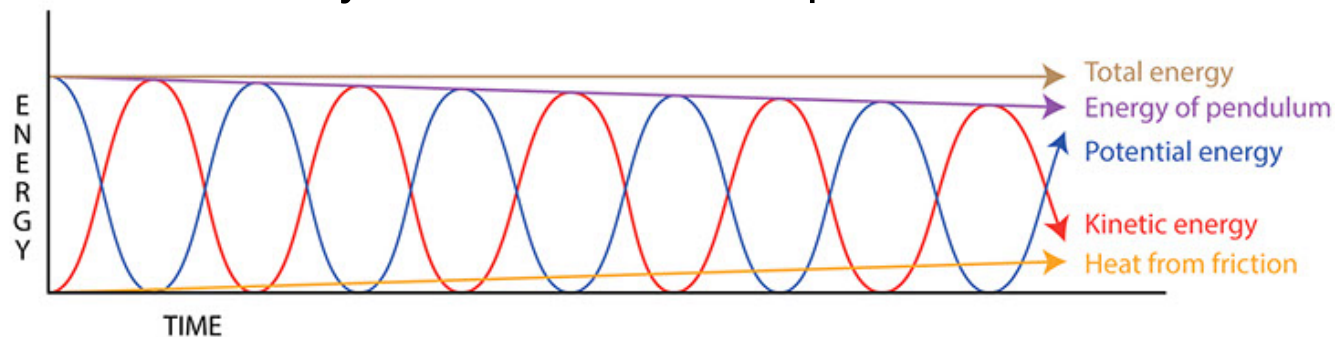
$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Dissipation: parasitic resistance



Quality factor:

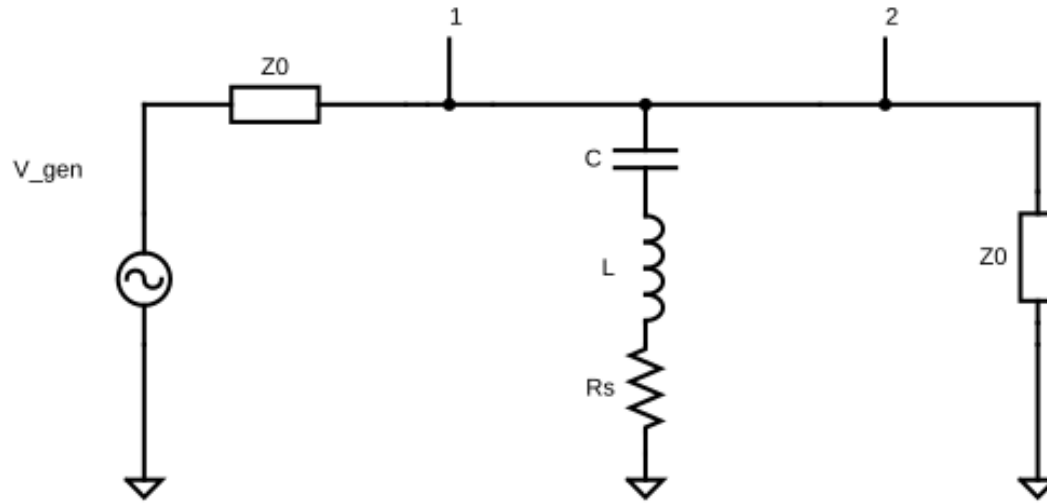
$Q = 2\pi \times$ number of cycles before the amplitude of oscillations drops by $1/e$



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



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

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

Variations

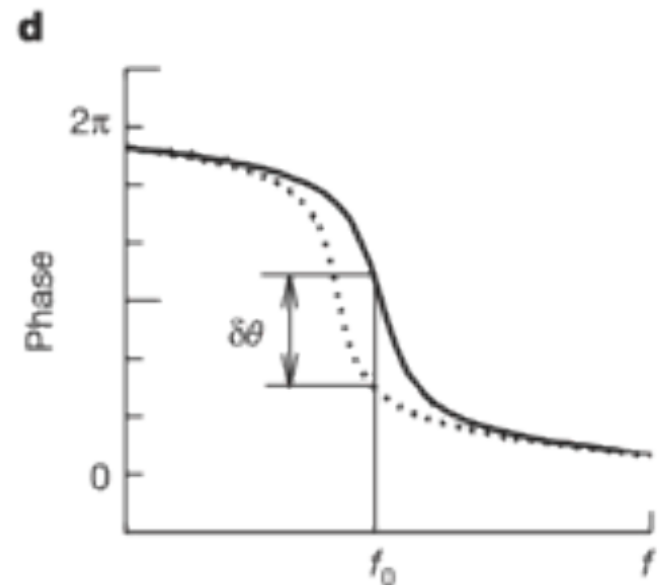
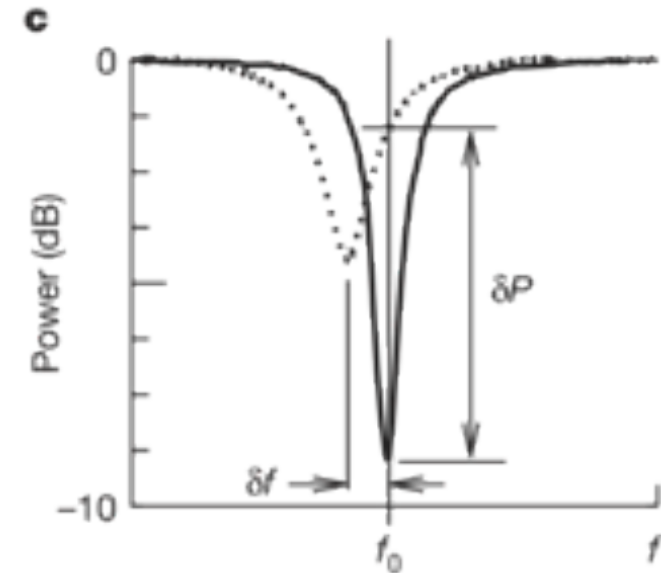
- Circuit constantly biased at the resonant frequency $f_{gen} = f_0$:
- Variation of R_s :
 - ▶ signal from **amplitude shift** $\delta(1/Q)$

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

- Variation of L_k :
 - ▶ signal from frequency shift δf_0

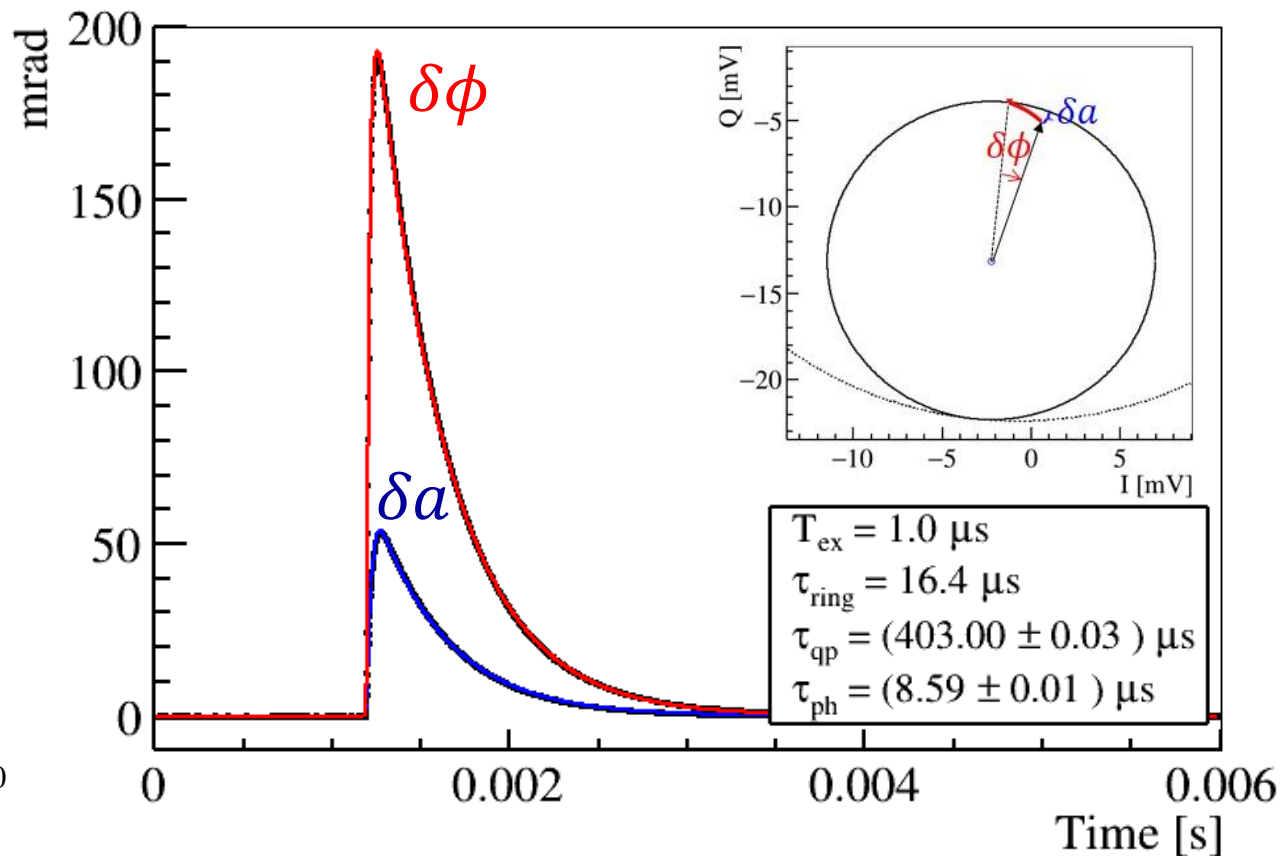
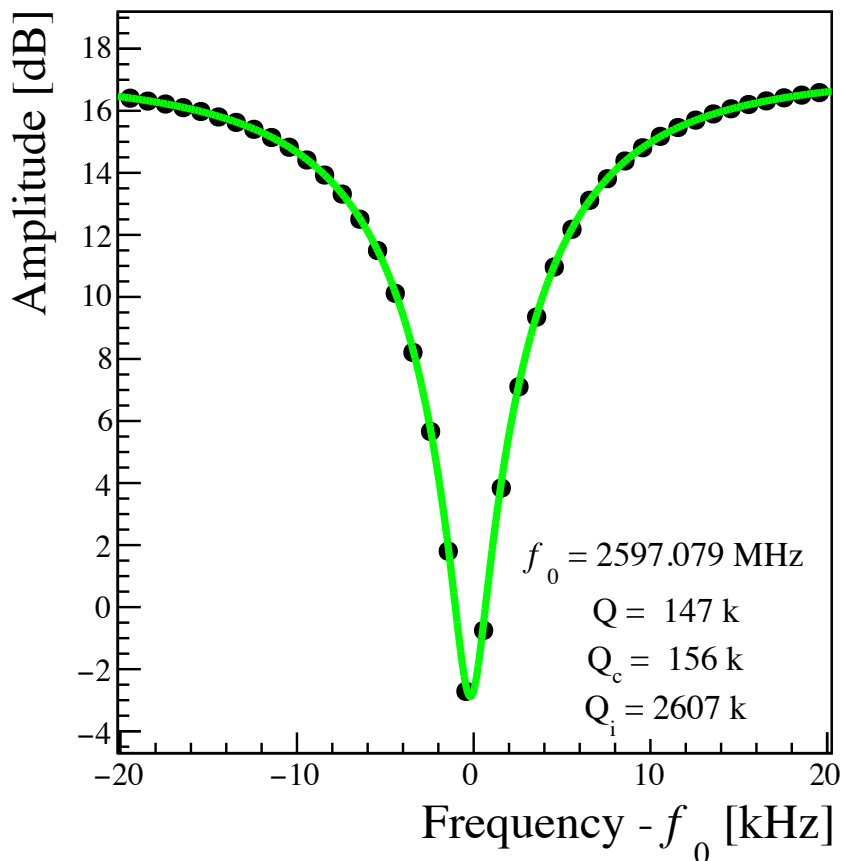
$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

- ▶ actually measured as **phase shift**



KID signal

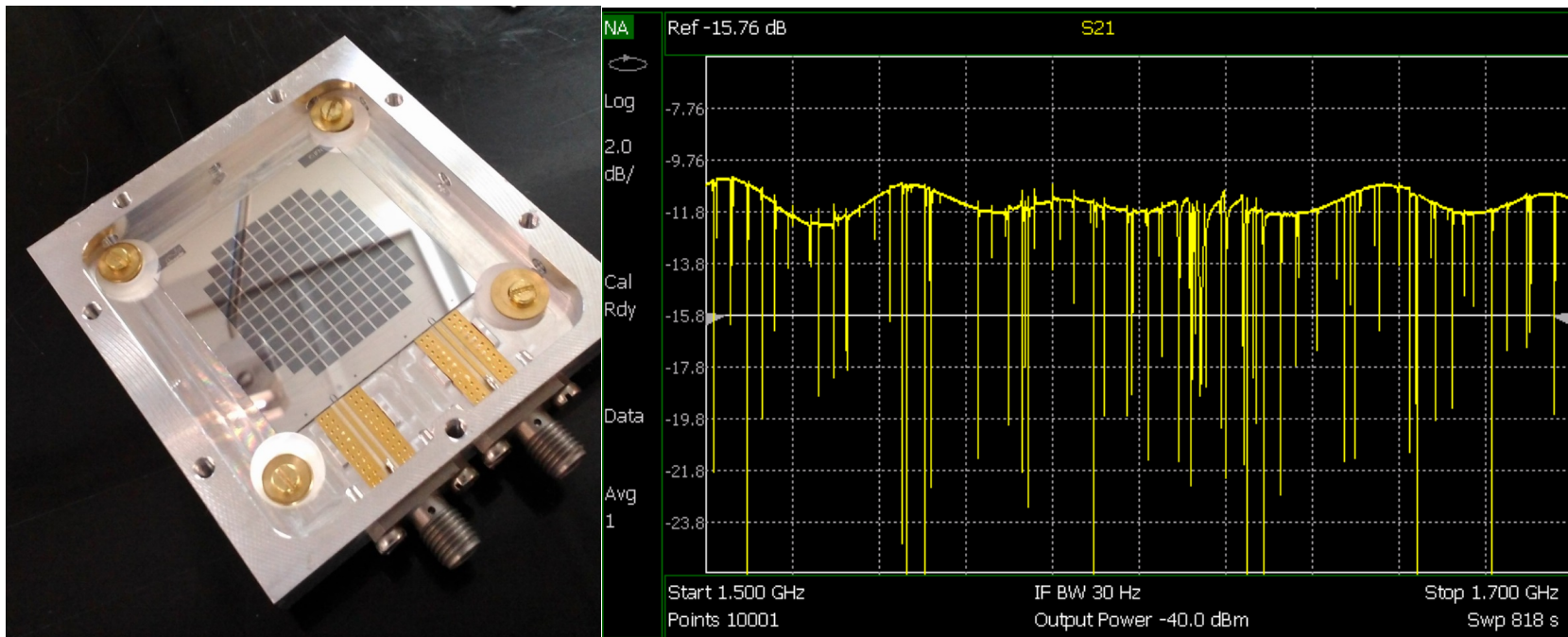
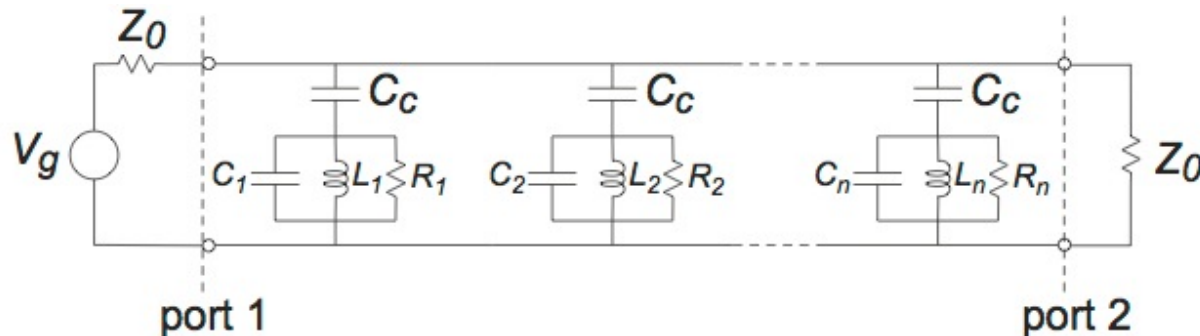
1. Frequency sweep to measure the transmission past the resonator.
2. Determine the resonant frequency and bias the detector at that frequency.
3. Measure Phase and Amplitude Modulation of the wave transmitted past the resonator



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

cm² active area

dm³ active volume

High resolution

below 100 eV

possibly 10 eV

Motivations for KIDs:

KIDs unique multiplexing

Easy to fabricate

Reproducible

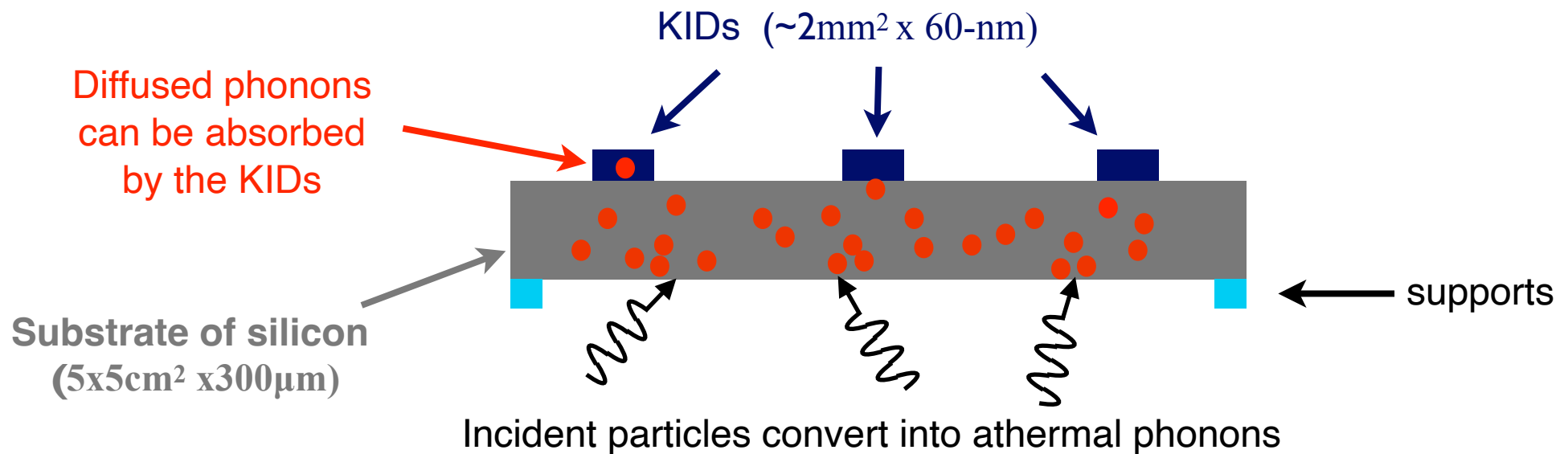
The *difficult* part:

KIDs are today
a factor 5 off from TES

Phonon mediation

GHz operation limits the maximum sensible area of KIDs to **few mm²**

Scaling to **several cm²**:
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. Monfardini¹

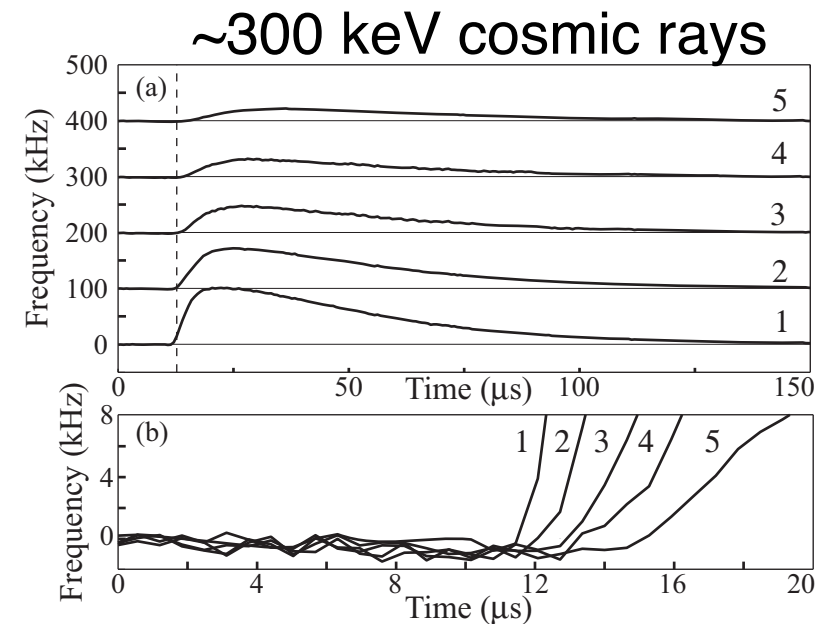
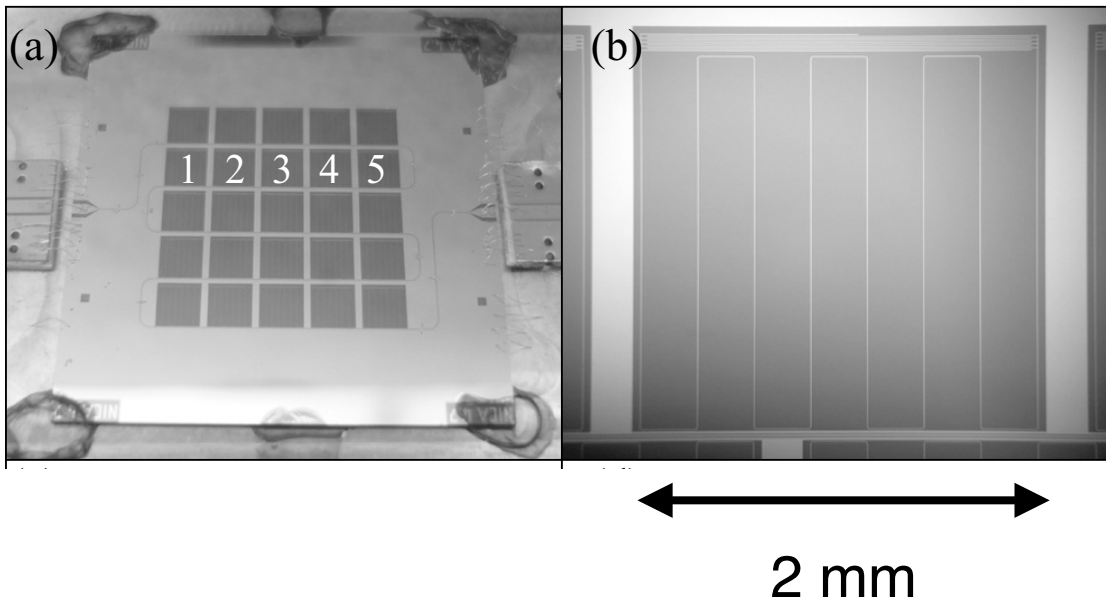
¹Institut Néel, CNRS–Université Joseph Fourier, BP 166, 38042 Grenoble, France

²Dipartimento di Fisica, Università di Roma La Sapienza, p.le A. Moro 2, 00185 Roma, Italy

³Institut de Radio Astronomie Millimétrique, 300 rue de la Piscine, 38406 Saint Martin d'Hères, France

⁴Superconductor Technologies Inc., 460 Ward Drive, Santa Barbara, California 93111, USA

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



Interpretation from CALTECH

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

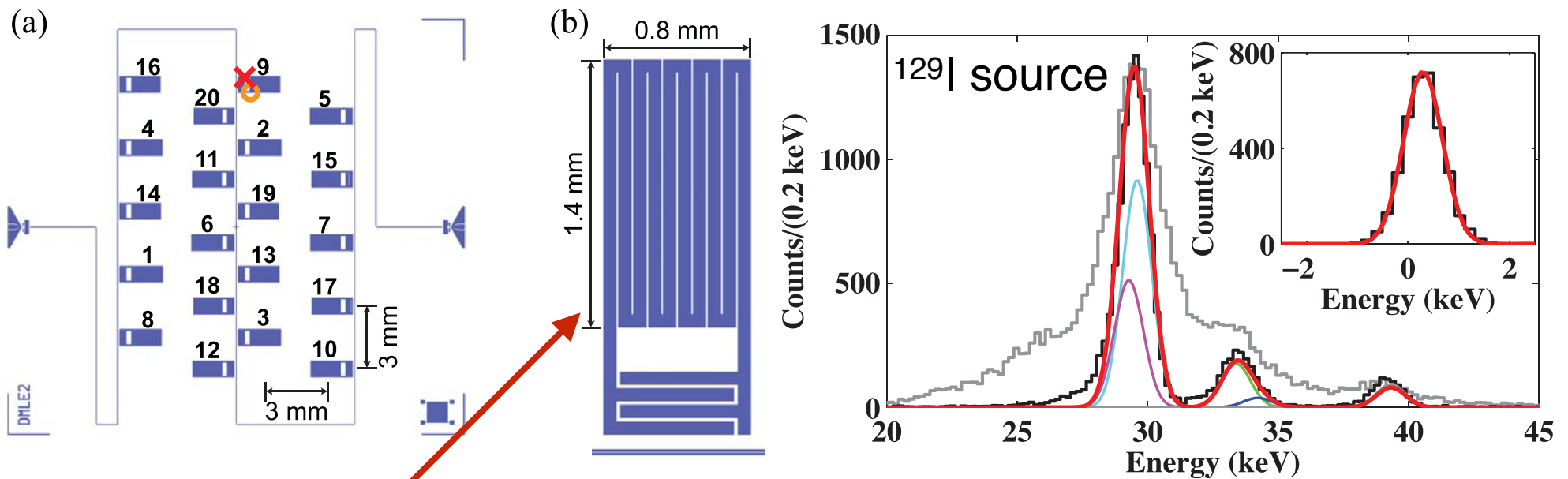
Position and energy-resolved particle detection using phonon-mediated microwave kinetic inductance detectors

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}

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

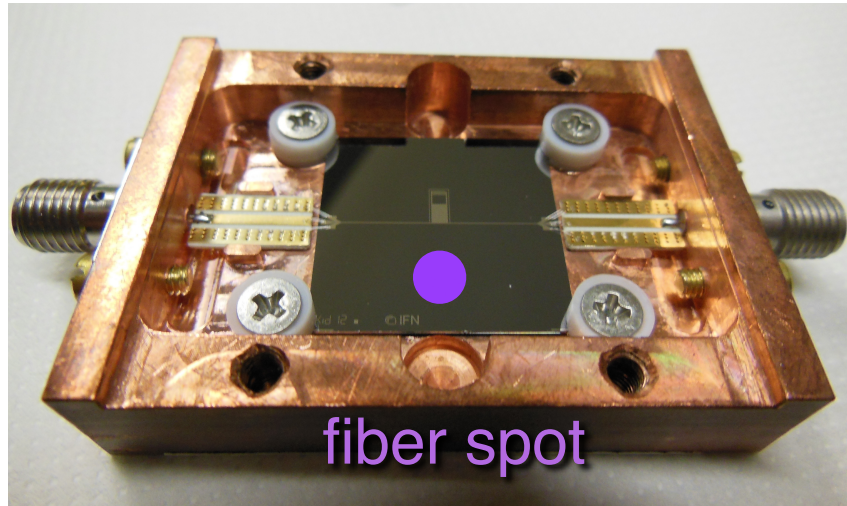
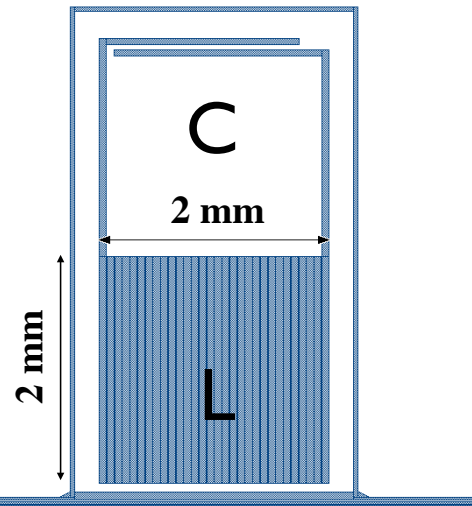


Filled shape, larger inductor area

$\Delta E (0 \text{ keV}) = 380 \text{ eV}$

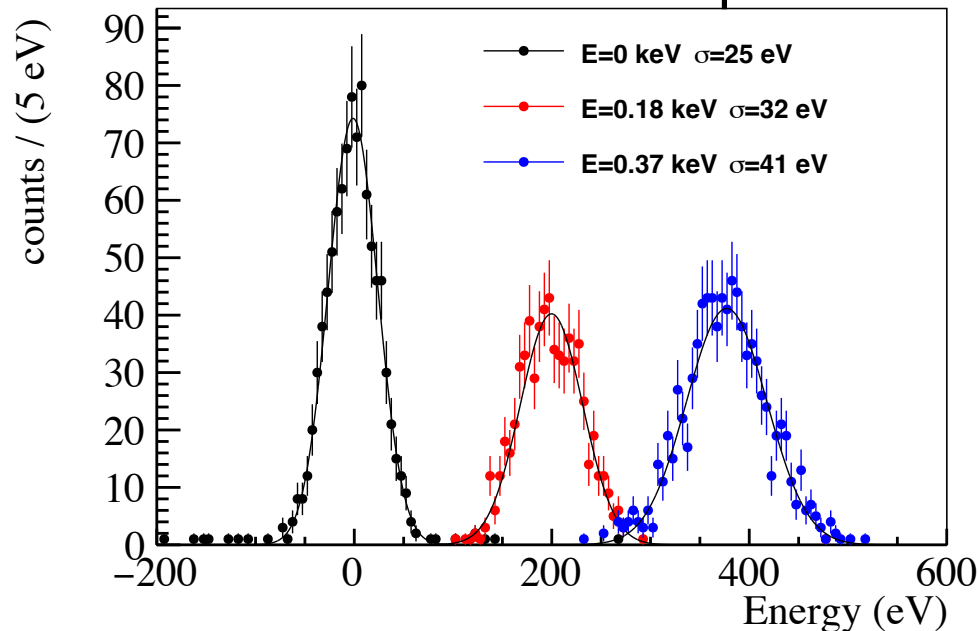
CALDER project

www.roma1.infn.it/exp/calder

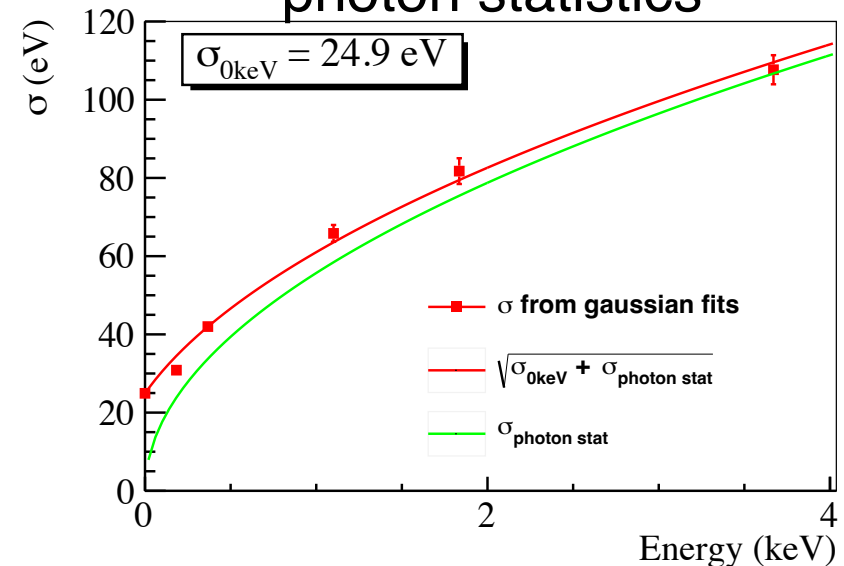


- Al(14)Ti(33)Al(30nm) resonator
- 2x2cm² x 350μm Silicon substrate
- 25 eV RMS @ 0 eV
- Phonon $\varepsilon \sim 10\%$

Scan with LED driven optical fiber

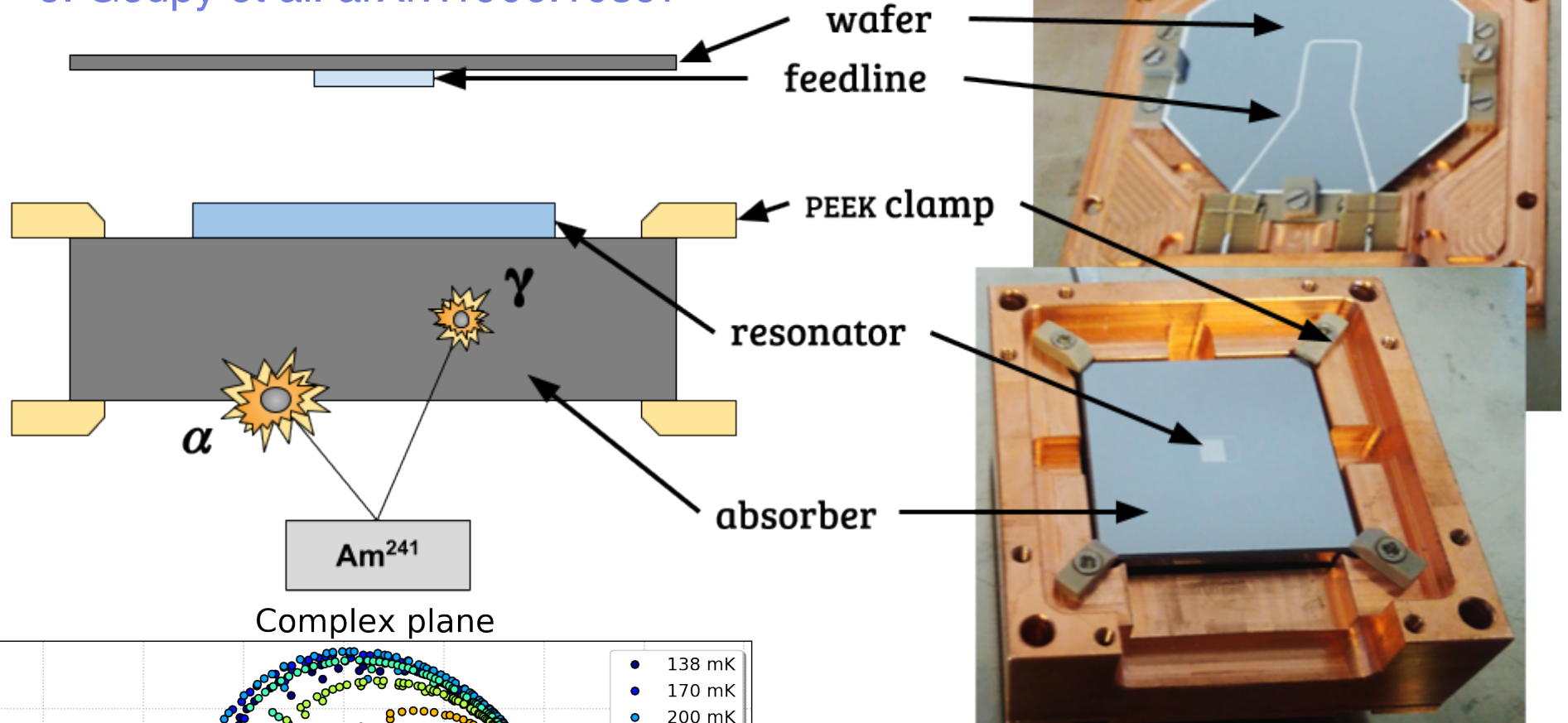


Self-calibrated with photon statistics

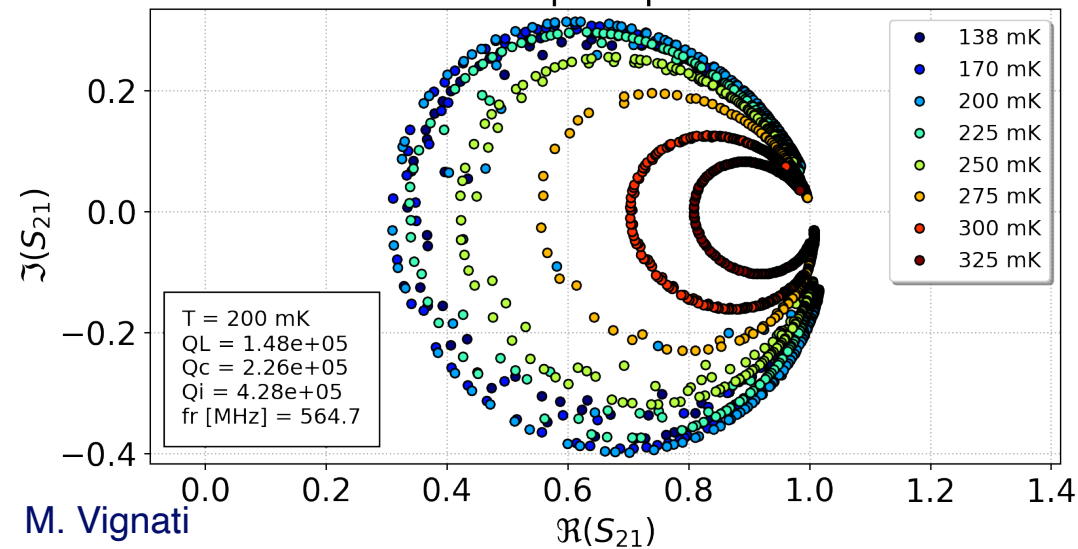


Wi-Fi KID at Grenoble

J. Goupy et al. arXiv:1906.10397



Complex plane

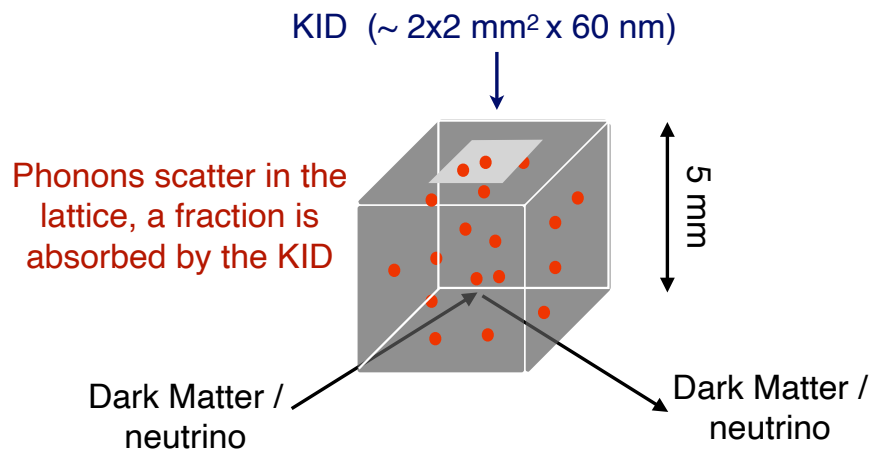


36x36x10 mm³ absorber with Al KID,
sensed by a contactless feedline

INFN way: BULLKID

Phonon mediation

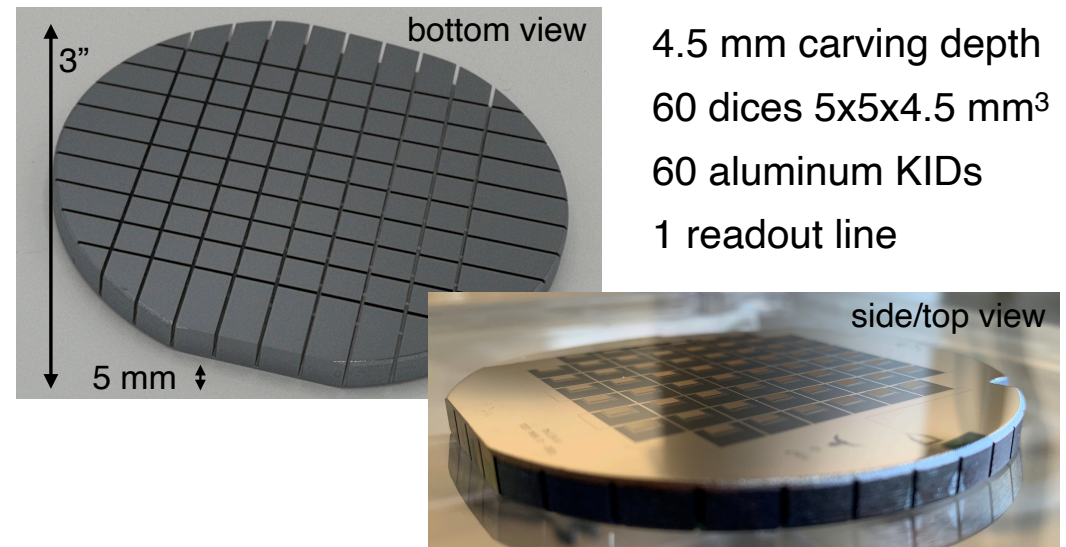
detect phonons created by nuclear recoils in a silicon absorber



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

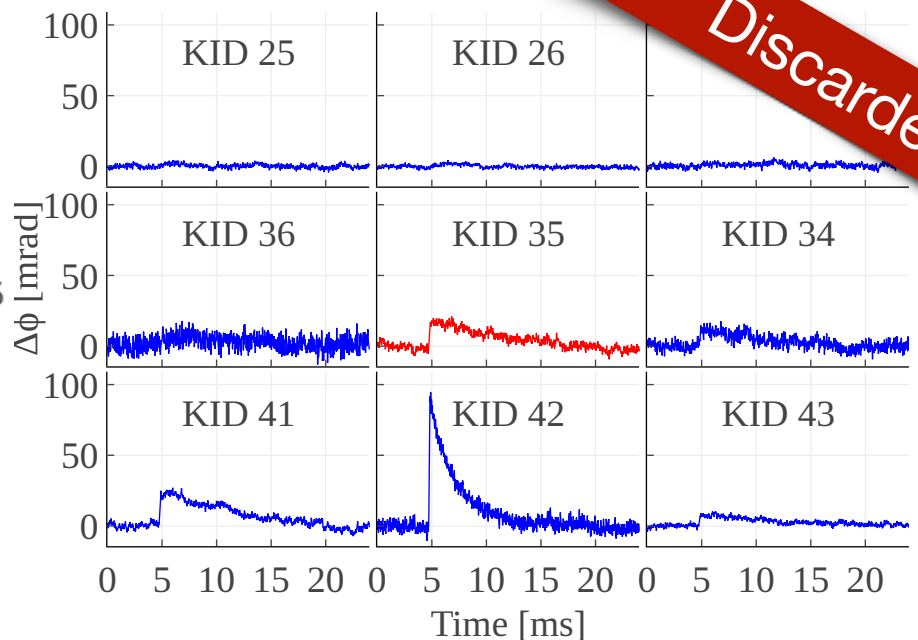
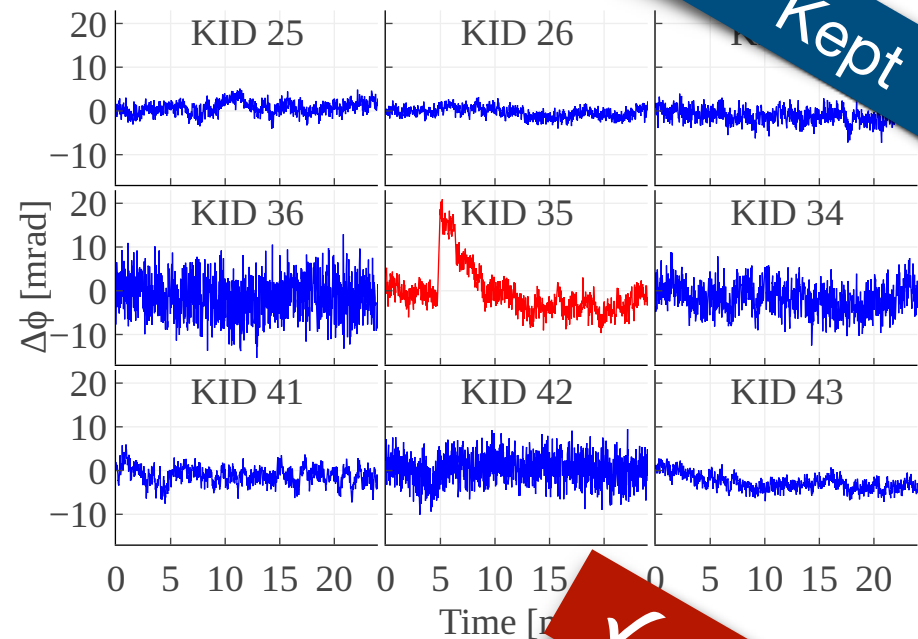
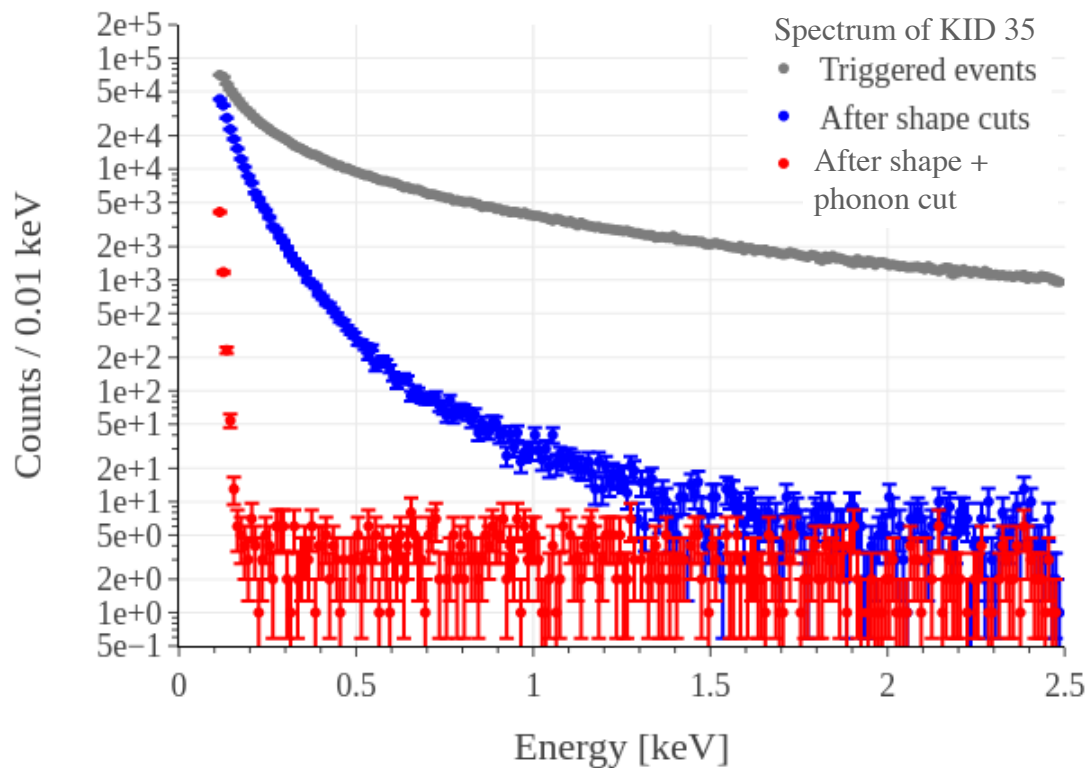
Scale-up of detector number

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



Feasibility study funded by the INFN project "BULLKID"

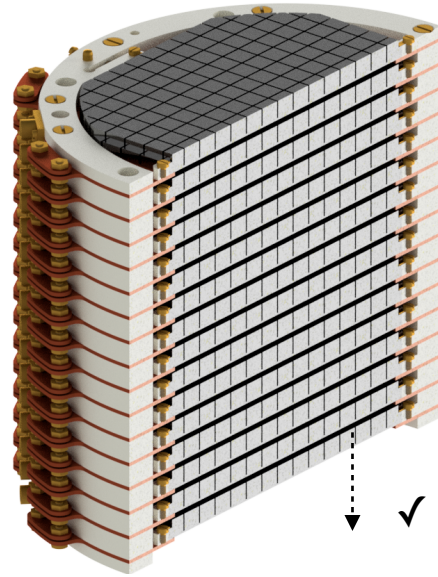
BULLKID: phonon imaging



BULLKID-DM

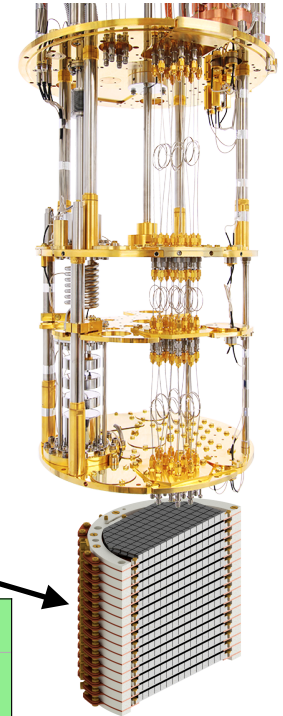
Nuclear recoil detector with:

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

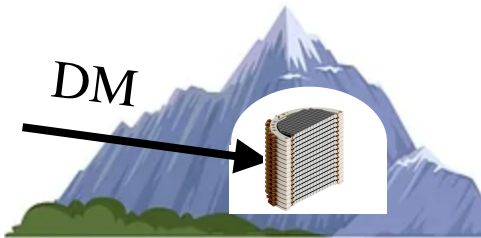


Unique features among phonon detectors:

- ✓ fully active
- ✓ fiducialization



✓ scalable



Physics run in 2027

