

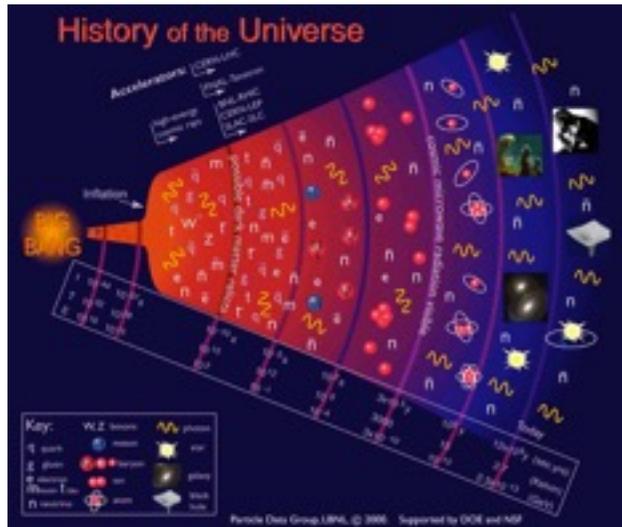
Applicazioni: La ricerca di eventi rari

Marco Vignati
9/12/2015

Indice

- Due casi di fisica delle particelle:
 - ▶ La ricerca del neutrino di Majorana
 - ▶ La ricerca di Materia Oscura
- Un rivelatore, il bolometro
 - ▶ Modello termico del bolometro (con Laplace)
 - ▶ Circuito di bias del bolometro
- Catena di lettura:
 - ▶ Amplificatori
 - ▶ Filtri analogici
 - ▶ Filtri digitali - filtro ottimo
 - ▶ Ricostruzione del segnale, risultato fisico.
- Una nuova tecnologia, i rivelatori ad induttanza cinetica.

Matter and anti-matter



Cosmology and particle physics predict an equal balance of matter and anti-matter

but

our Universe is dominated by matter.



matter
favored

Our theory:
Balance breaking from
heavy Majorana neutrinos



anti-matter
disfavored

Problem: *Ns* do not exist anymore,
they all decayed away few instants after the Big Bang.

Are neutrinos (ν) Majorana?

$$\nu \neq \bar{\nu}$$

Particle differs from anti-particle
like all other known particles



$$\nu = \bar{\nu}$$

Particle equal to anti-particle
Majorana (1937)

if we demonstrate that ν are Majorana

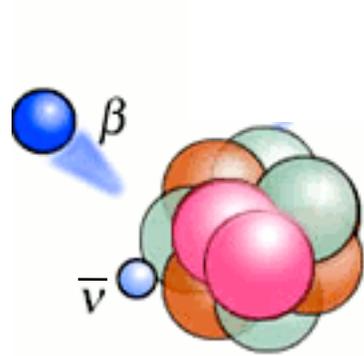


theory says that the heavy Majorana partner N existed

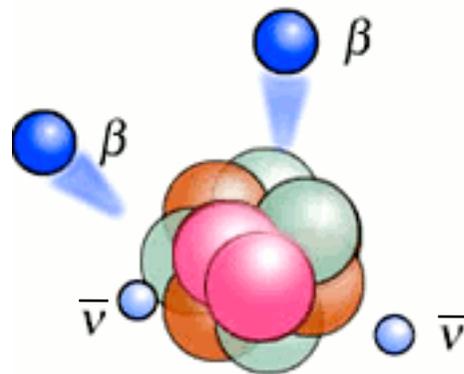


we have an evidence for N , the matter savior: the anti-matter killer!

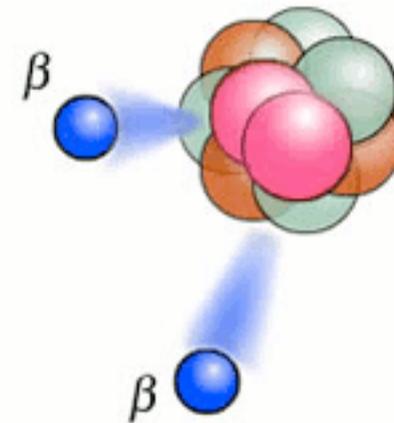
Detection principle



β -decay

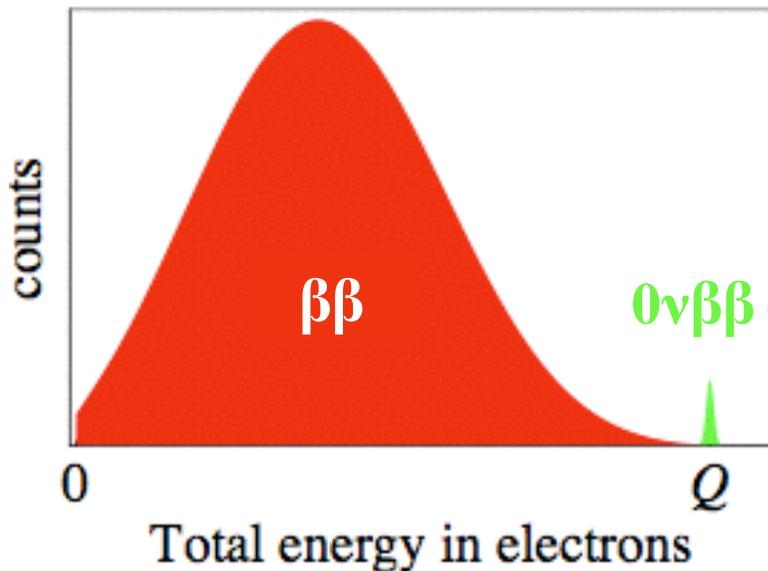


$\beta\beta$ -decay



$0\nu\beta\beta$ -decay

only if ν s are Majorana



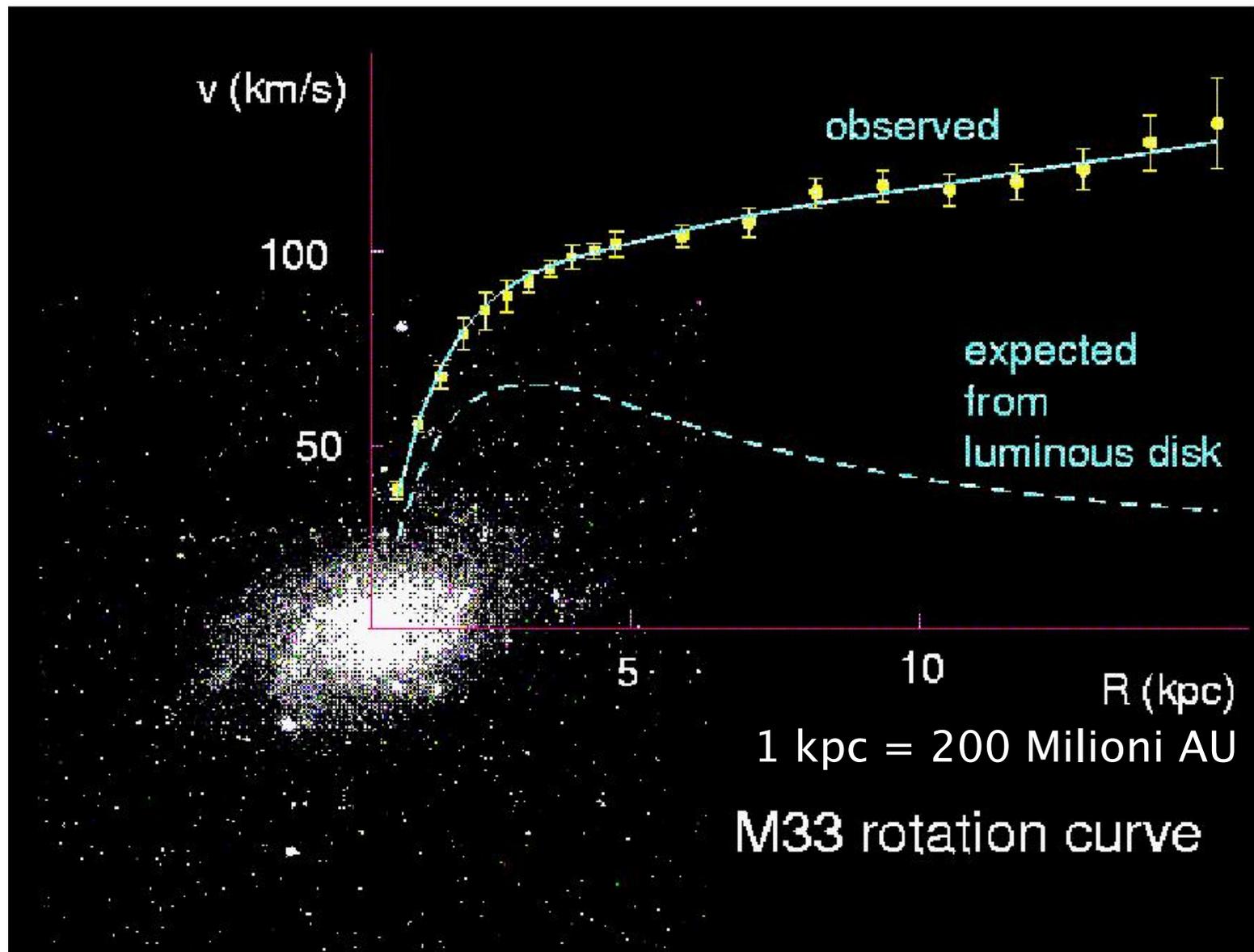
$0\nu\beta\beta$ is possible only in few natural isotopes, e.g.: ^{130}Te , ^{76}Ge , ^{136}Xe , ^{100}Mo , ^{82}Se .

Present half-life limits are: $\tau > 10^{24-25}$ years.

Several nuclei (100 - 1000 kg) are needed.

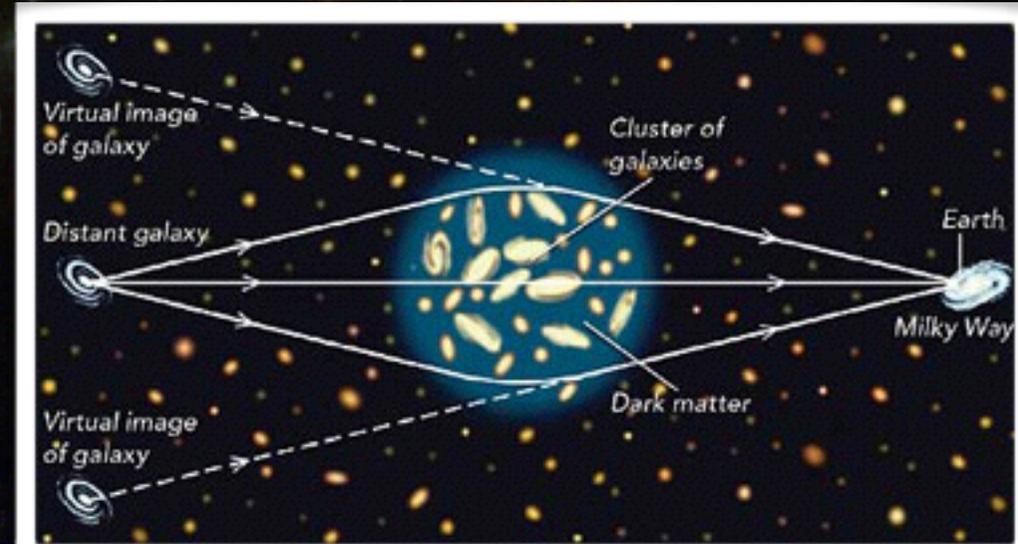
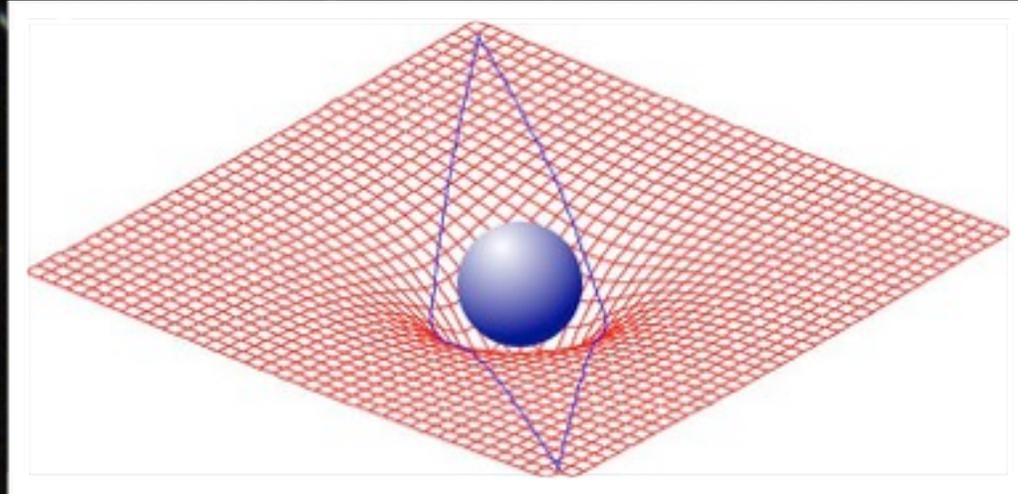
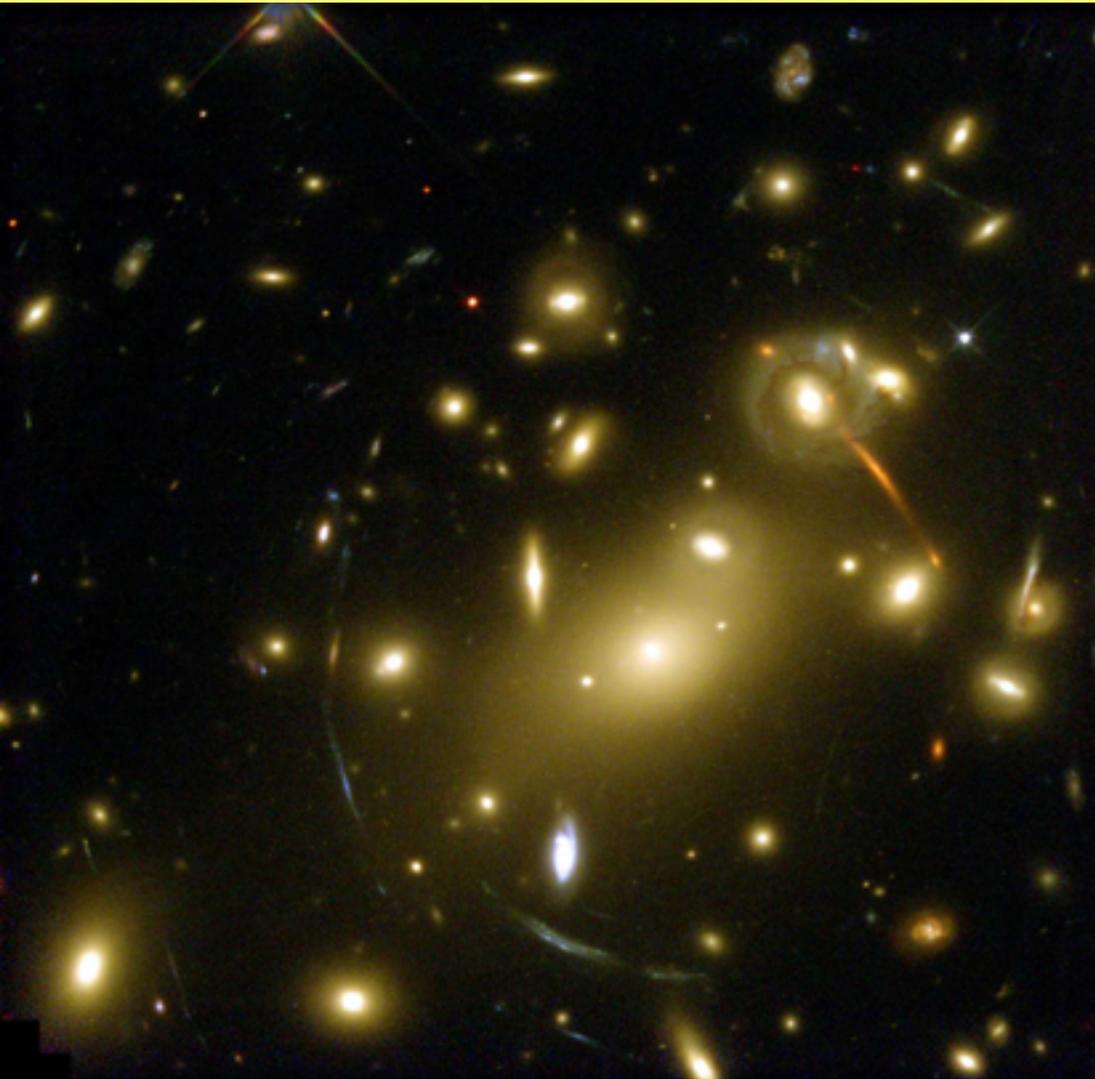
Null background is needed to detect the electrons.

Velocità di rotazione in una galassia



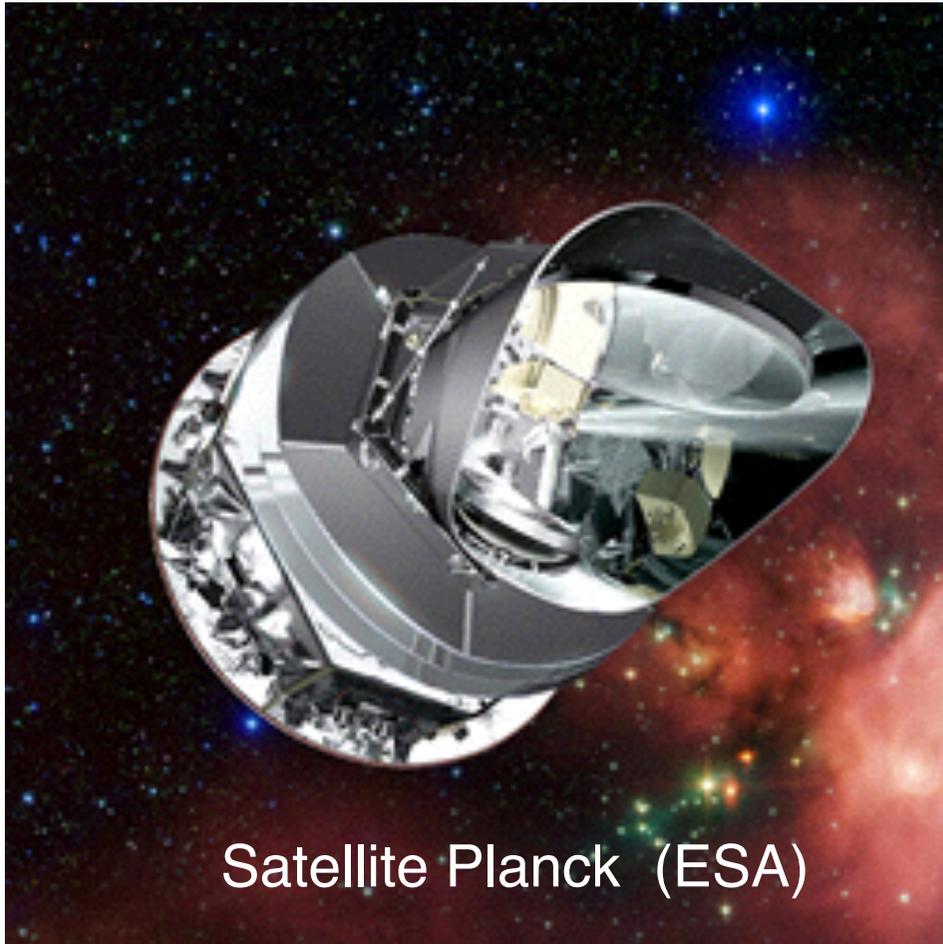
È come se ci fosse della materia in più di cui vediamo gli effetti gravitazionali ma che è invisibile.

Lenti gravitazionali

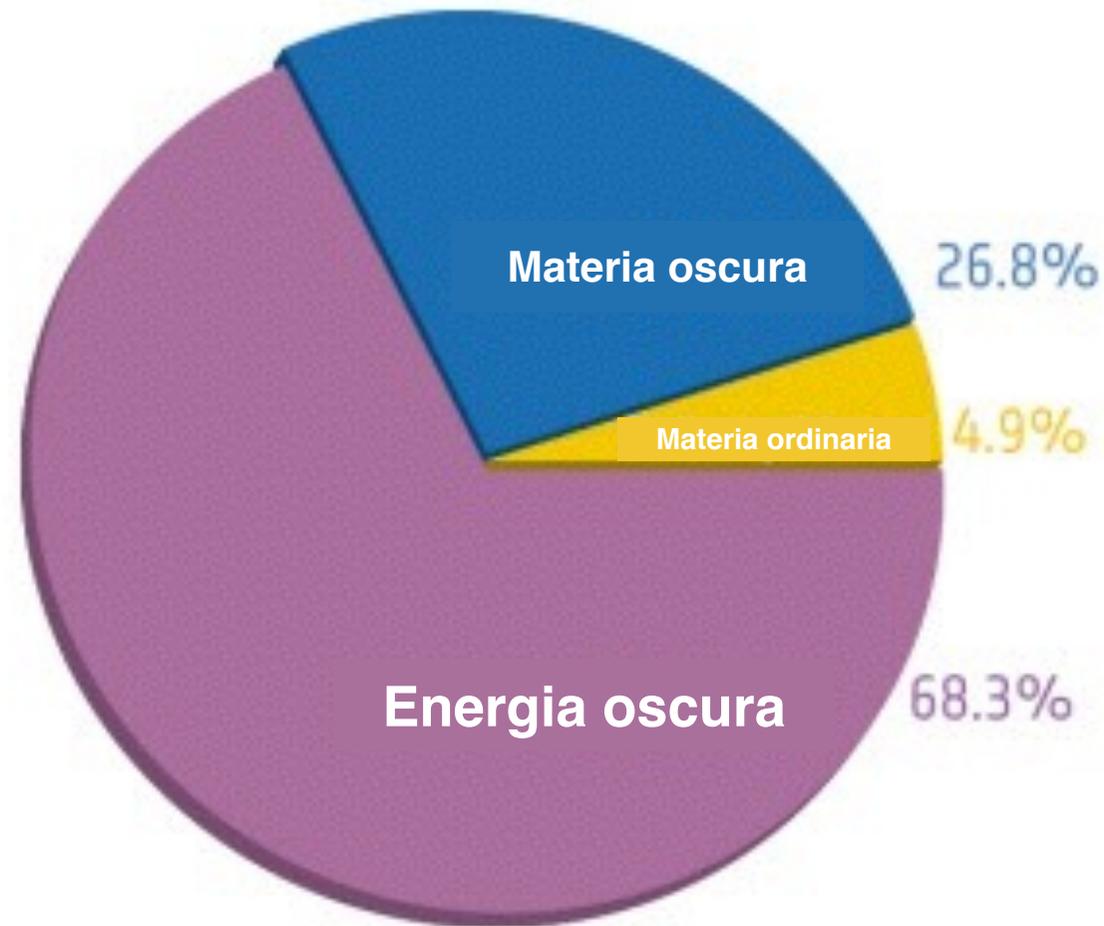


Questo metodo viene utilizzato per tracciare la mappa della materia oscura nell'Universo.

La composizione dell'Universo



Satellite Planck (ESA)



Cosa è l'energia oscura? Non ne abbiamo idea!
Per ora ci concentriamo sulla materia oscura.

Cosa è la Materia Oscura?

Cosa sappiamo:

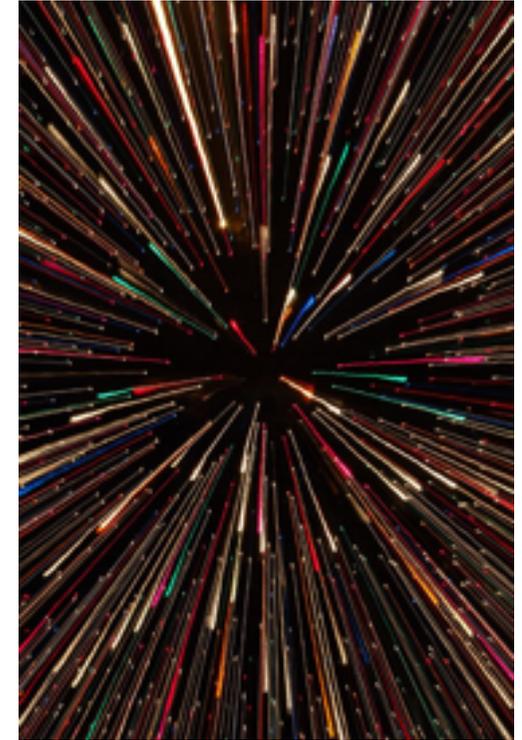
- ▶ Non emette e non assorbe luce.
- ▶ Siamo sensibili solo agli effetti gravitazionali.
- ▶ Interagisce molto poco con la materia ordinaria.
- ▶ Non è la materia ordinaria, l'antimateria o un buco nero.

Cosa potrebbe essere:

- ▶ Non esiste: le leggi della gravitazione non sono esatte (MoND).
- ▶ Una nuova particella?

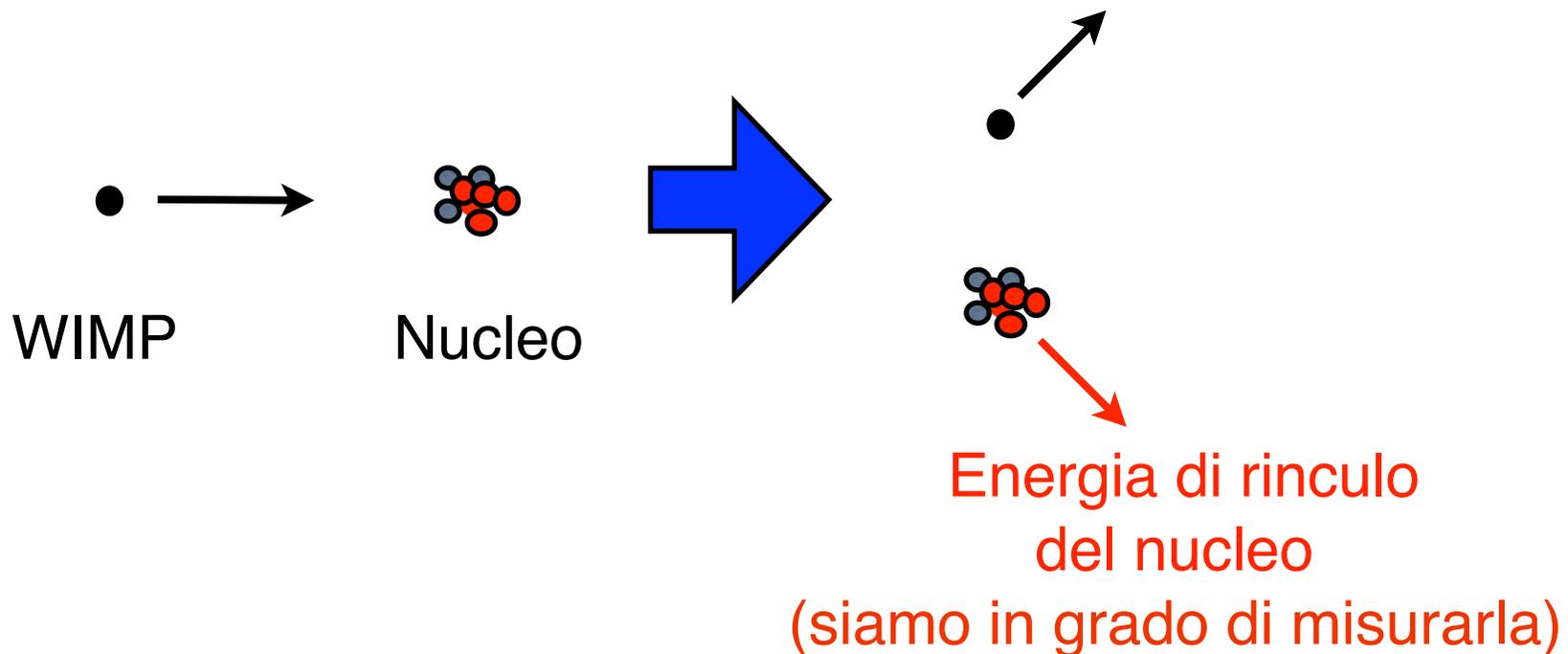
Una nuova particella?

- Problemi:
 - ▶ Non sappiamo cosa sia, quindi non sappiamo quale è il modo giusto per vederla.
 - ▶ Bassa densità: l'equivalente di 1 protone in 3 cm^3 .
 - ▶ È in grado di attraversare la terra senza interagire.
- Almeno 2 candidate:
 - ▶ Particella leggera (Assione) che può interagire con i campi magnetici.
 - ▶ **Particella pesante (WIMP).**



L'ipotesi WIMP

- Proprietà di una WIMP (Weak Interacting Massive Particle):
 - ▶ È una particella pesante $1 \div 1000$ protoni equivalenti.
- Principio di rivelazione: urto elastico con nuclei atomici di materia ordinaria.

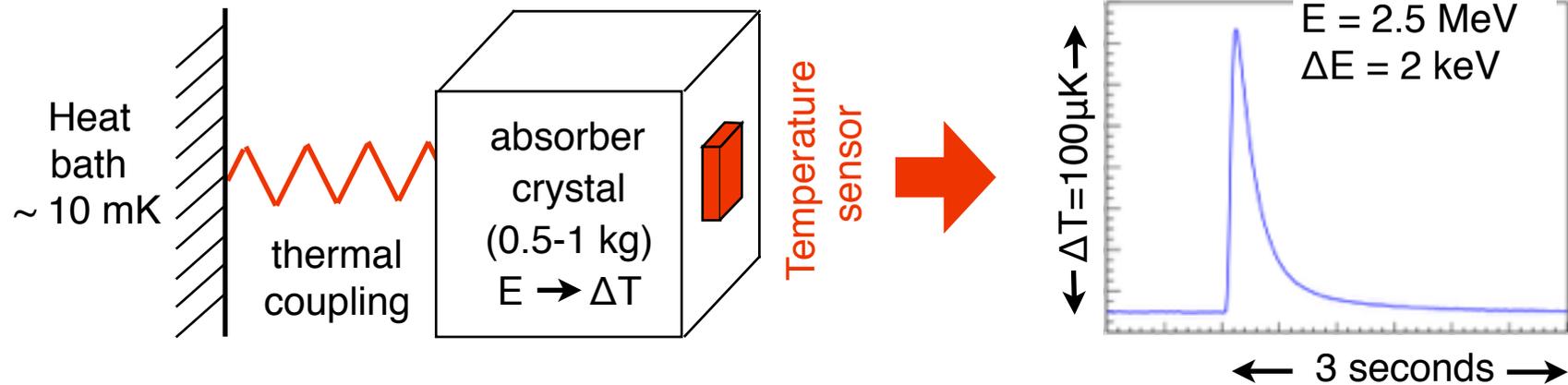


Tecniche di rivelazione

- Sia il doppio decadimento beta sia la materia oscura possono essere rivelate con la stessa tecnologia.
 - ▶ Nel caso del doppio decadimento beta vengono rivelati elettroni.
 - ▶ Nel caso della materia oscura vengono rivelati nuclei atomici.
- Oggi parliamo dei bolometri, una delle tecnologie più promettenti.

Bolometers

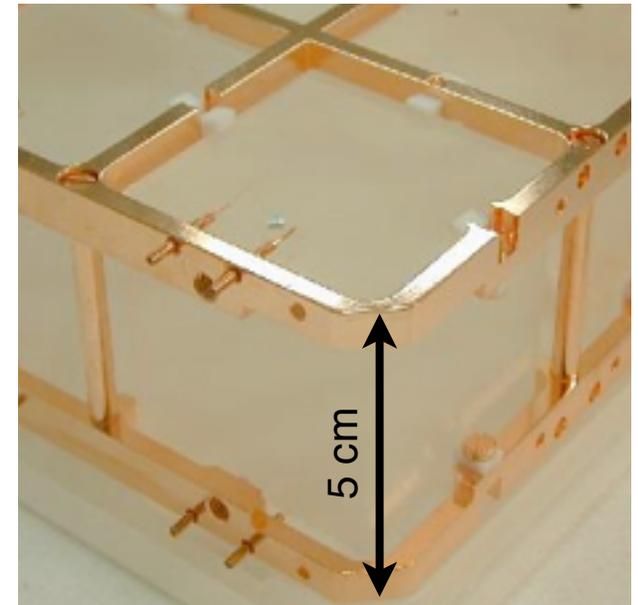
- Particle energy converted to temperature variation.
 - ▶ Cryogenic temperatures (< 20 mK).



- TeO_2 crystals: small heat capacitance.
- Sensitive thermometers, NTD-Ge thermistors:

$$R(T) \simeq 1 \Omega \cdot \exp\left(\frac{3 \text{ K}}{T}\right)^{\frac{1}{2}}$$

- Source embedded in the detector:
 $0\nu\beta\beta$ emitter: ^{130}Te (34% isotopic abundance).

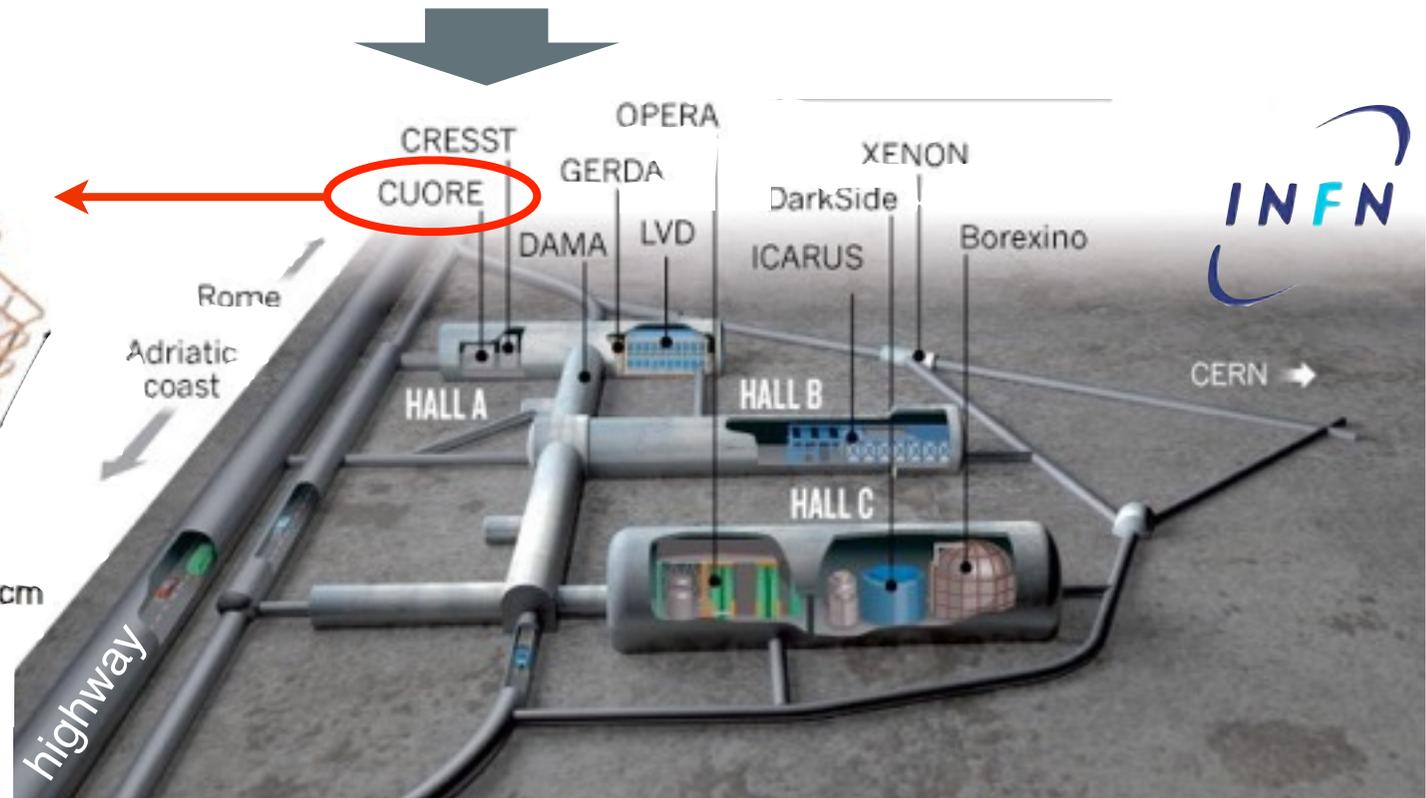
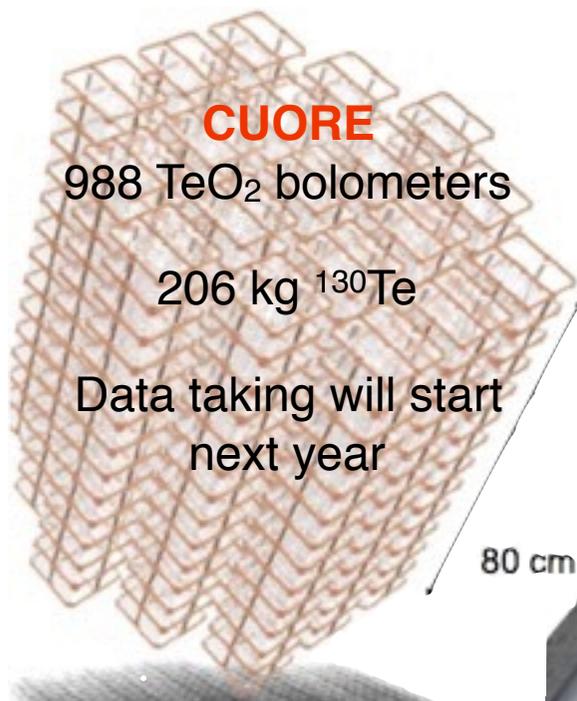


Gran Sasso lab in Italy

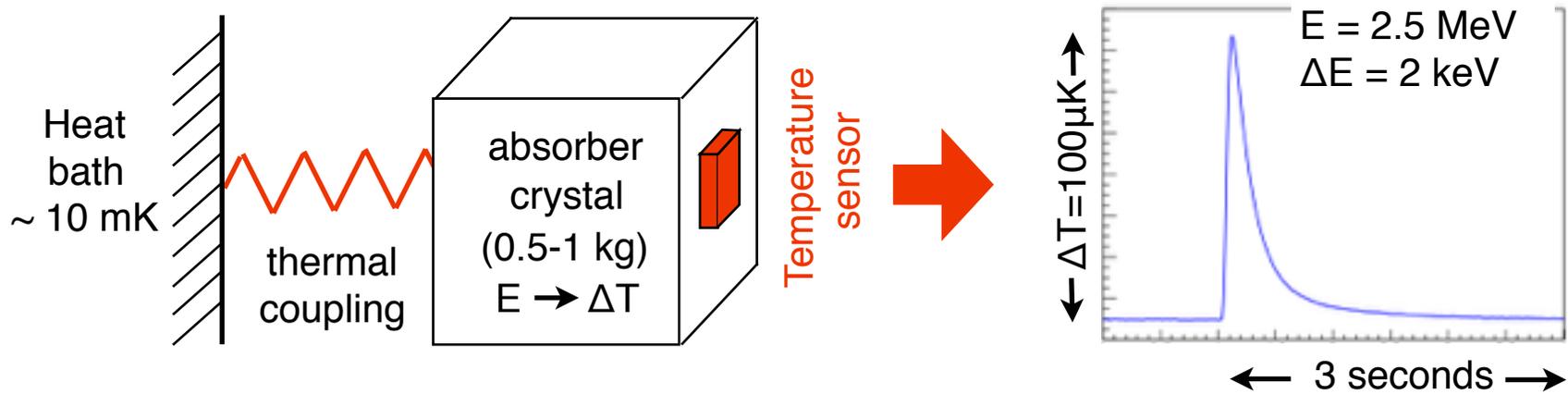
Mountain acts as cosmic rays absorber (1.4 km of rock).

Survival rate: $1 / (\text{m}^2 \text{ hour})$
($\sim 10^6$ reduction).

120 km driving from Rome.

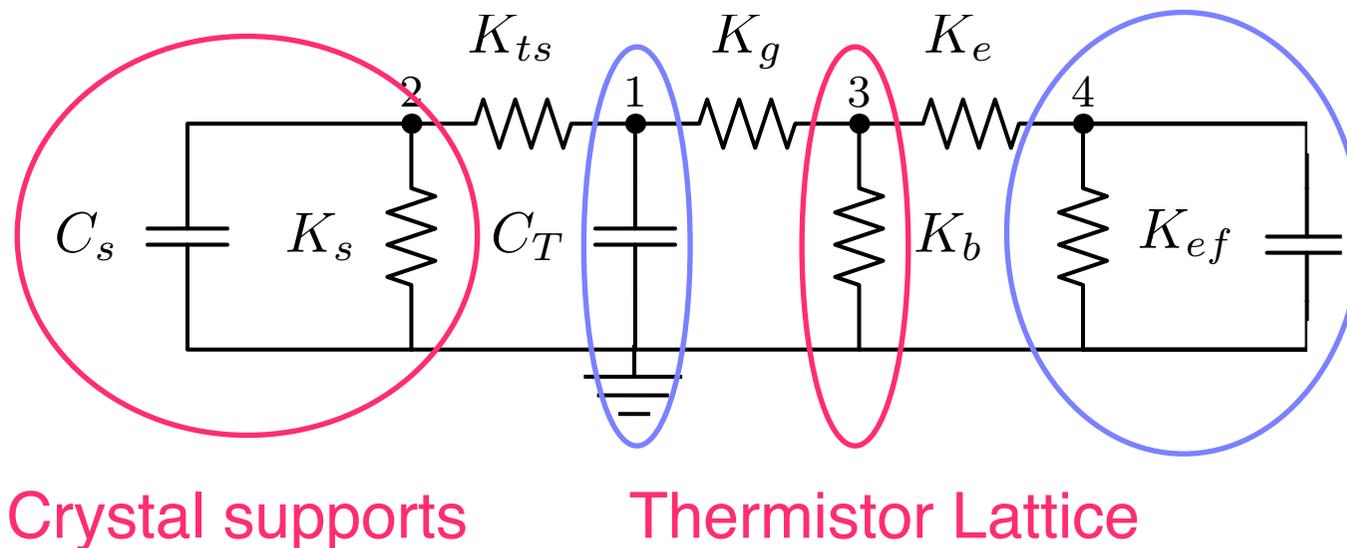


Thermal model of a bolometer



Crystal $C \propto T^3$

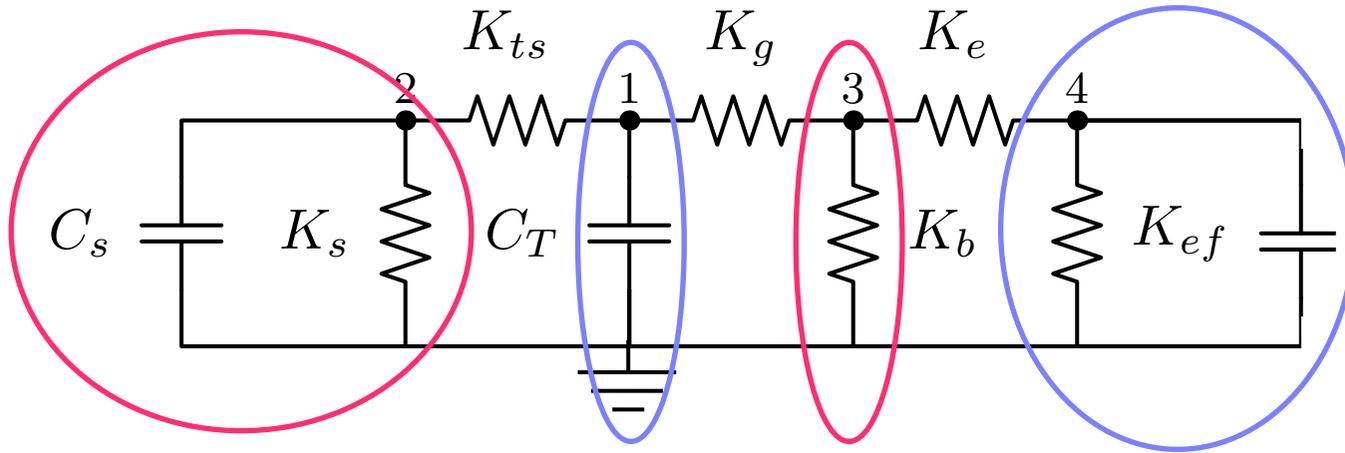
Thermistor electrons



Thermal model of a bolometer

Crystal $C \propto T^3$

Thermistor electrons



Voltage \rightarrow Temperature
Charge \rightarrow Heat (Energy)

Crystal supports

Thermistor Lattice

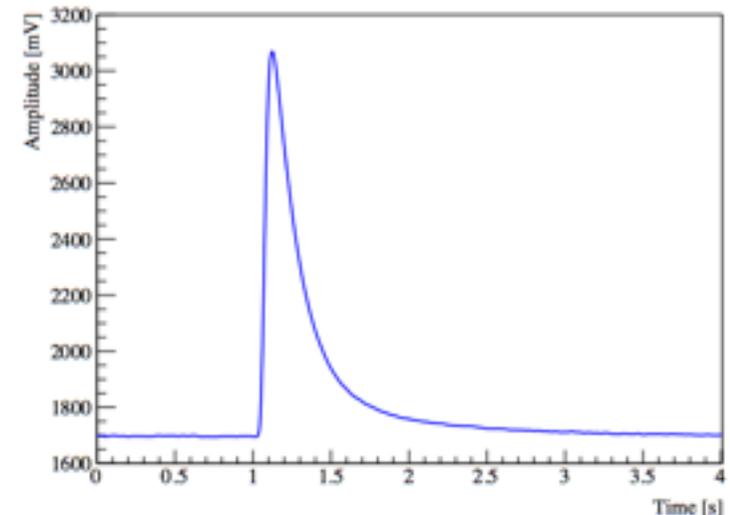
$$sC_T \Delta T_1 - E_1 + K_{ts}(\Delta T_1 - \Delta T_2) + K_g(\Delta T_1 - \Delta T_3) = 0 \quad (3.33a)$$

$$sC_s \Delta T_2 - E_2 + K_s \Delta T_2 + K_{ts}(-\Delta T_1 + \Delta T_2) = 0 \quad (3.33b)$$

$$K_b \Delta T_3 + K_e(\Delta T_3 - \Delta T_4) = 0 \quad (3.33c)$$

$$sC_{eff} \Delta T_4 - E_4 + K_{eff} \Delta T_4 + K_e(-\Delta T_3 + \Delta T_4) = 0 \quad (3.33d)$$

$$\Delta T_4(t) = A \left(-e^{-\frac{t}{\tau_r}} + \alpha e^{-\frac{t}{\tau_1}} + (1 - \alpha) e^{-\frac{t}{\tau_2}} \right)$$



Reading the bolometer signal

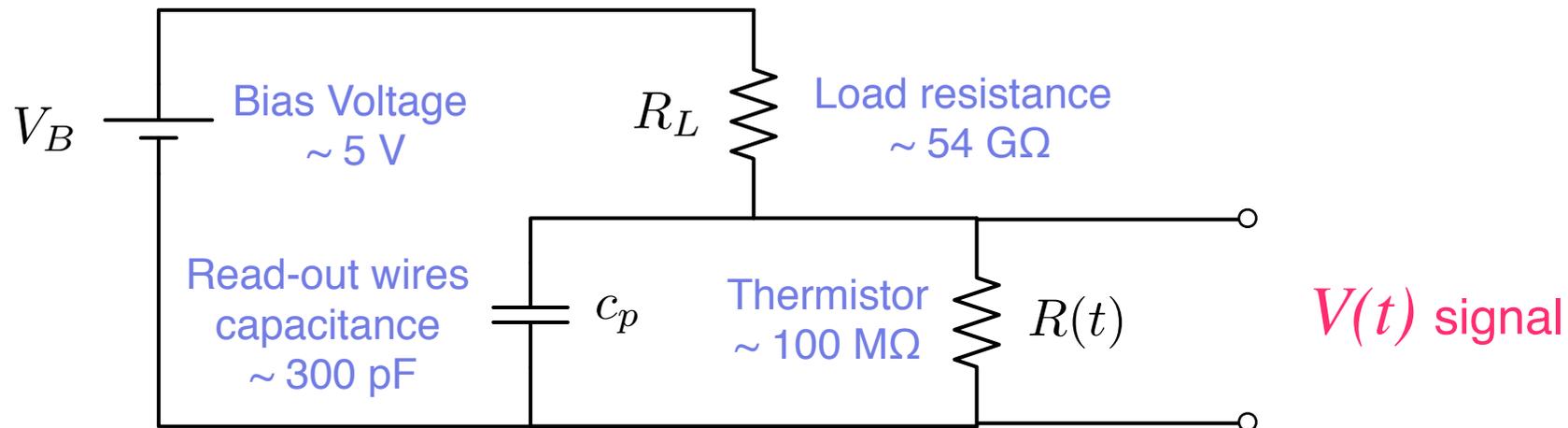
- The thermistor resistance depends on the temperature:

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

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

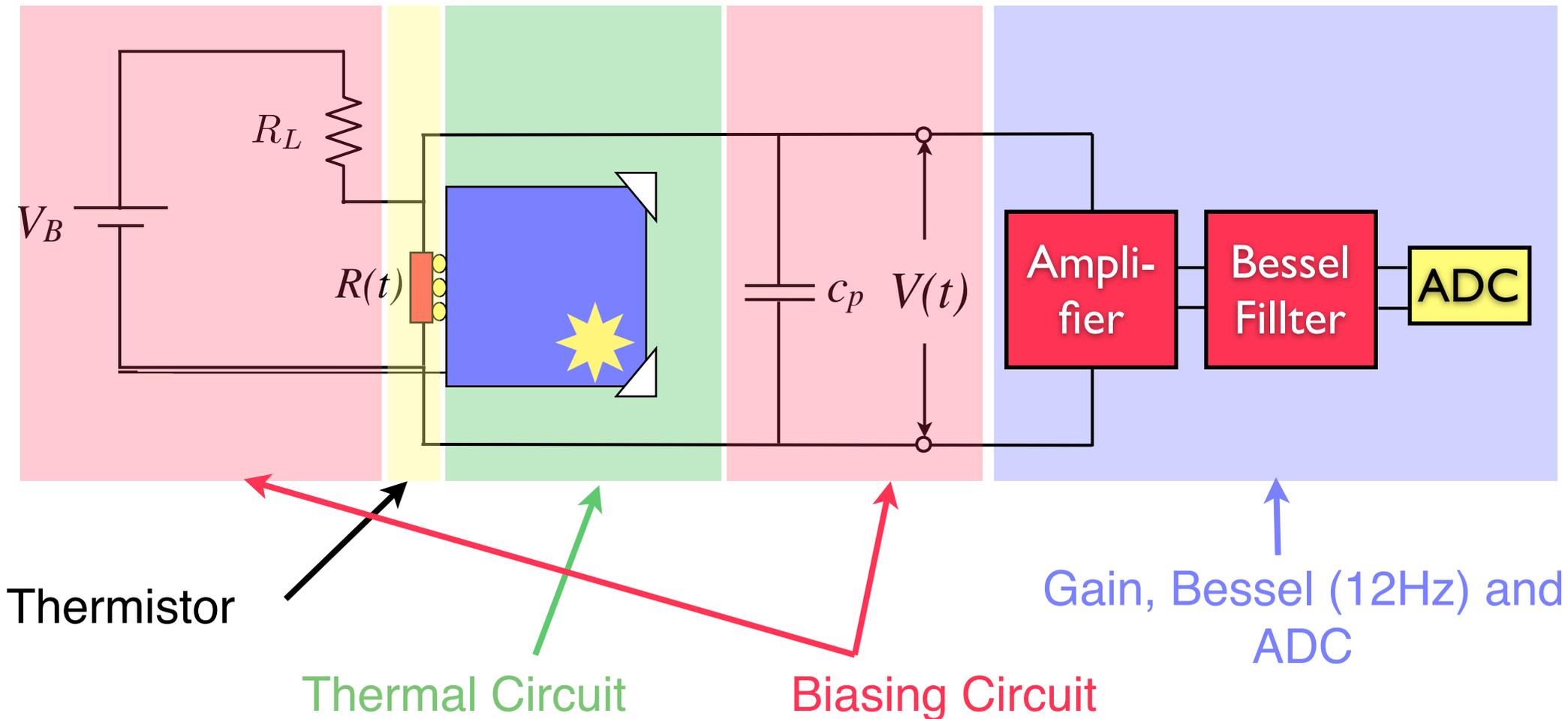
$$R(10 \text{ mK}) \sim 100 \text{ M}\Omega$$

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



- $V(t)$ is then amplified and filtered with an adaptive 6-pole Bessel filter (cutoff 12Hz).

Signal chain

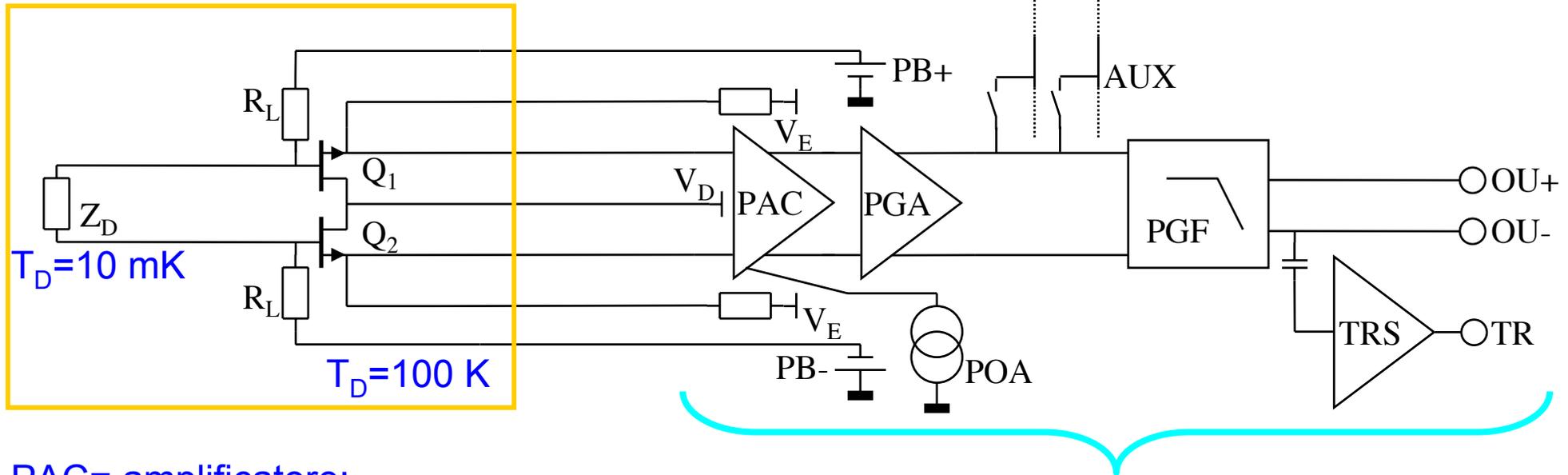


- Each element contributes to shape the signal, from the energy release in the crystal up to the ADC.

Electronics operating at cryogenic temperatures 6

Ecco qui un esempio completo di catena di acquisizione di un termistore avente uno stadio a buffer differenziale.

Refrigeratore



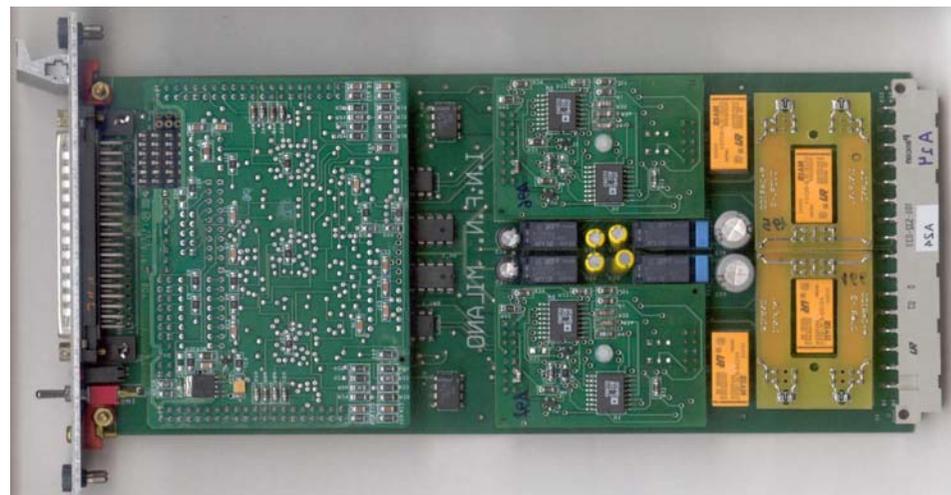
PAC= amplificatore;

POA= rete per l'aggiustamento dell'Offset;

PGA= stadio di amplificazione programmabile;

PGF= filtro antialiasing;

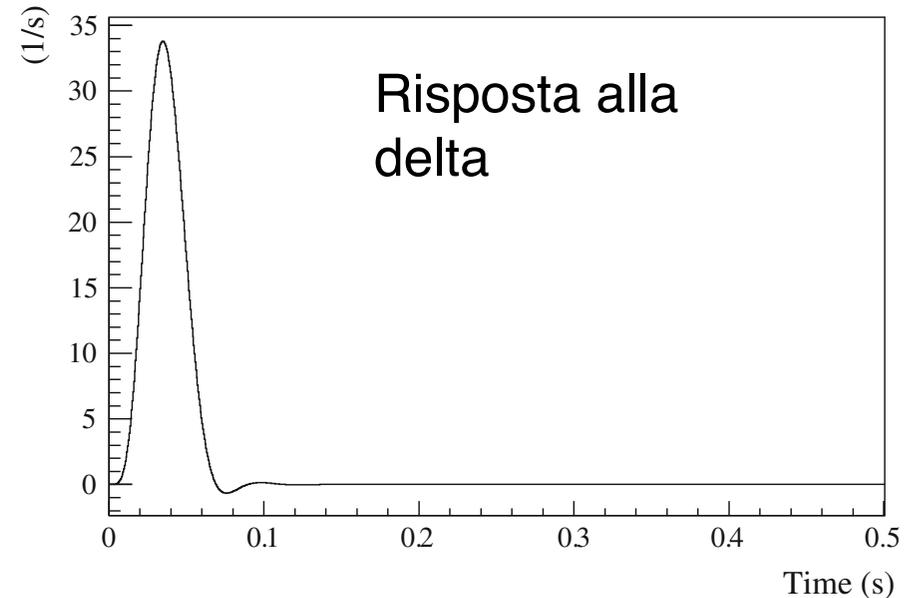
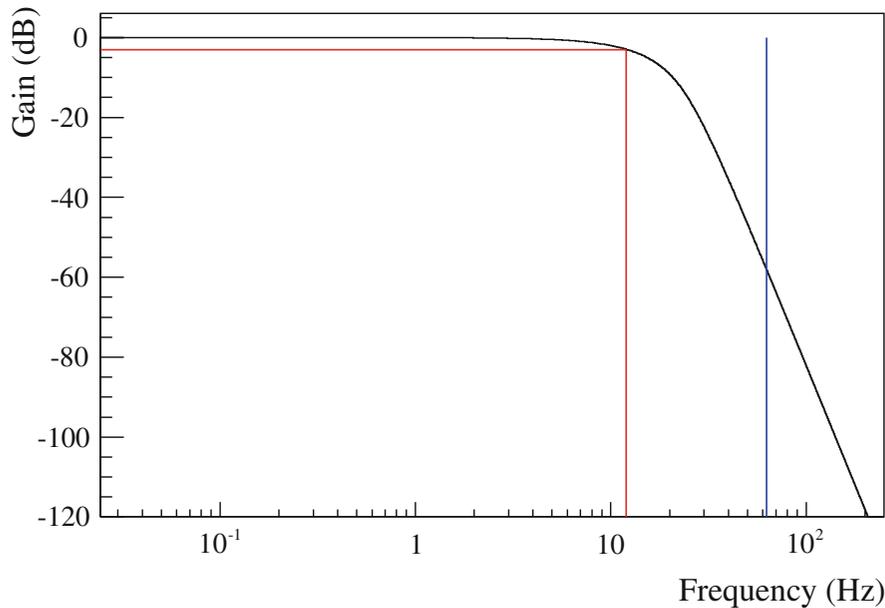
TRS= circuito analogico di trigger;



6-pole active Bessel filter

- Il segnale e' concentrato nella regione di bassa frequenza
- Questo filtro serve a rimuovere il noise ad alta frequenza, senza compromettere il segnale

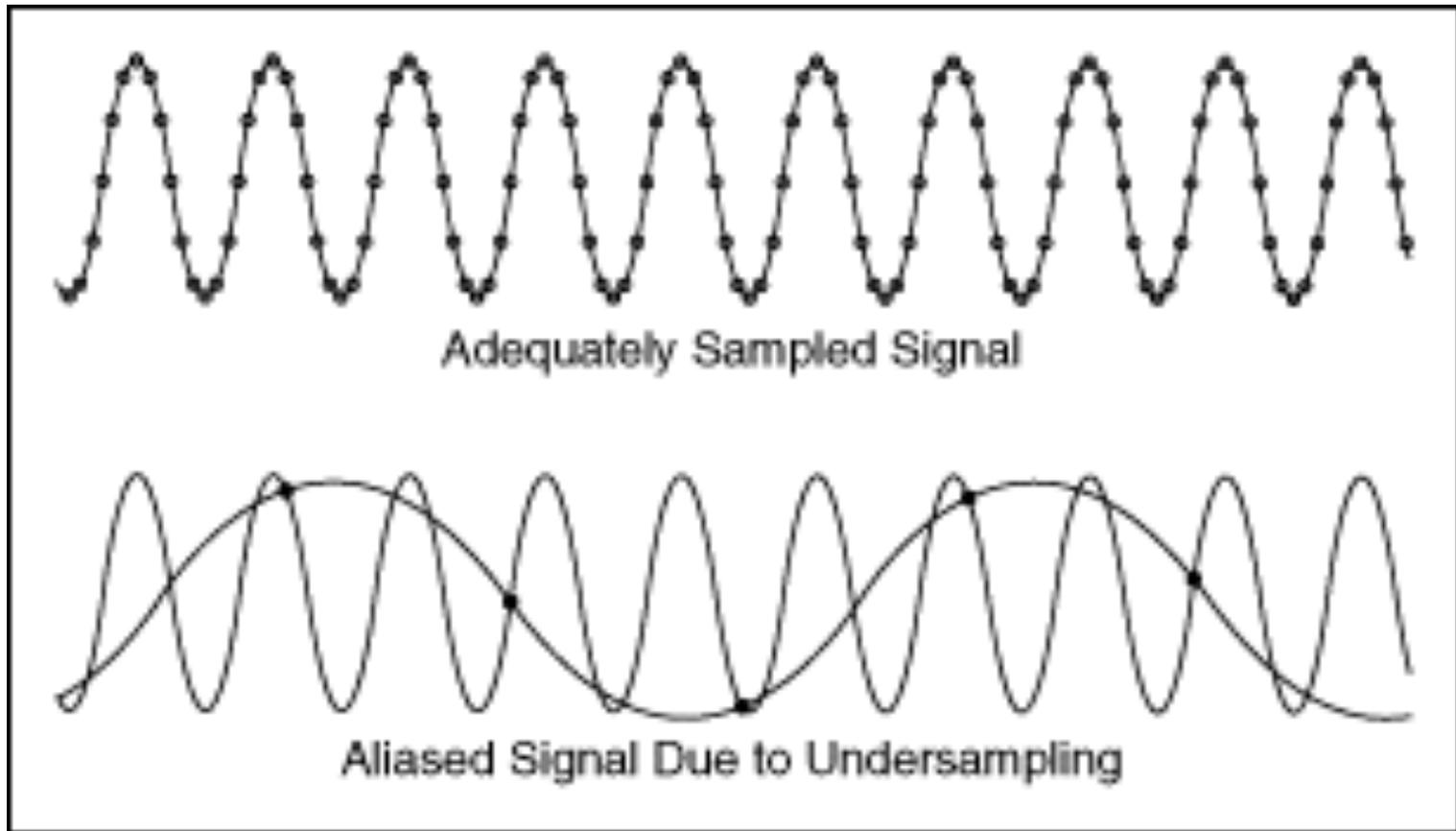
$$B(\sigma) = \frac{10,395}{\sigma^6 + 21\sigma^5 + 210\sigma^4 + 1,260\sigma^3 + 4,725\sigma^2 + 10,395\sigma + 10,395}$$



- Serve a rimuovere effetti di aliasing nell'ADC.

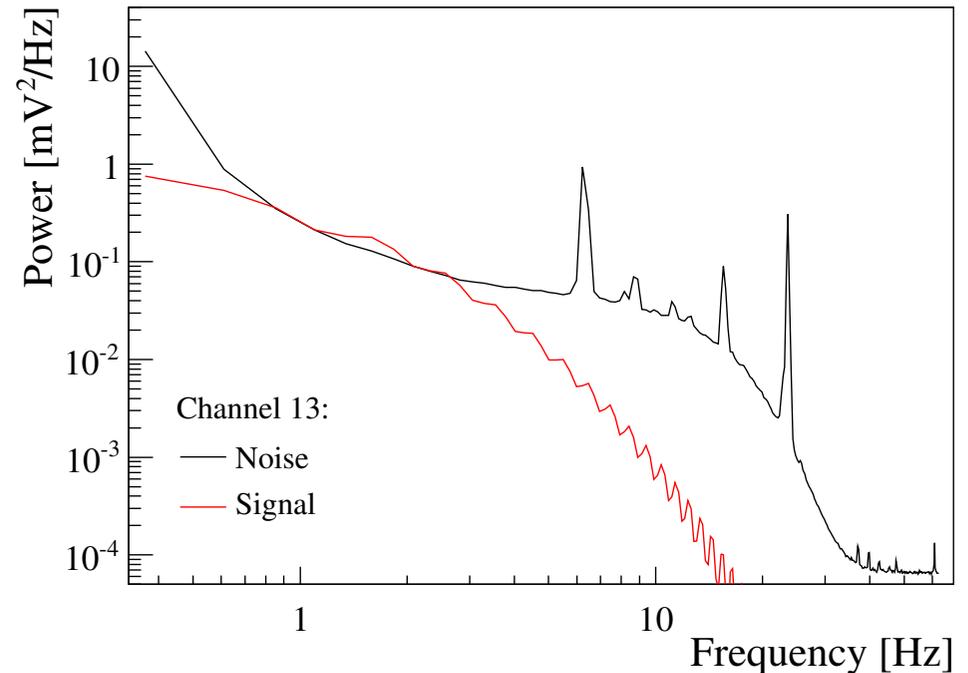
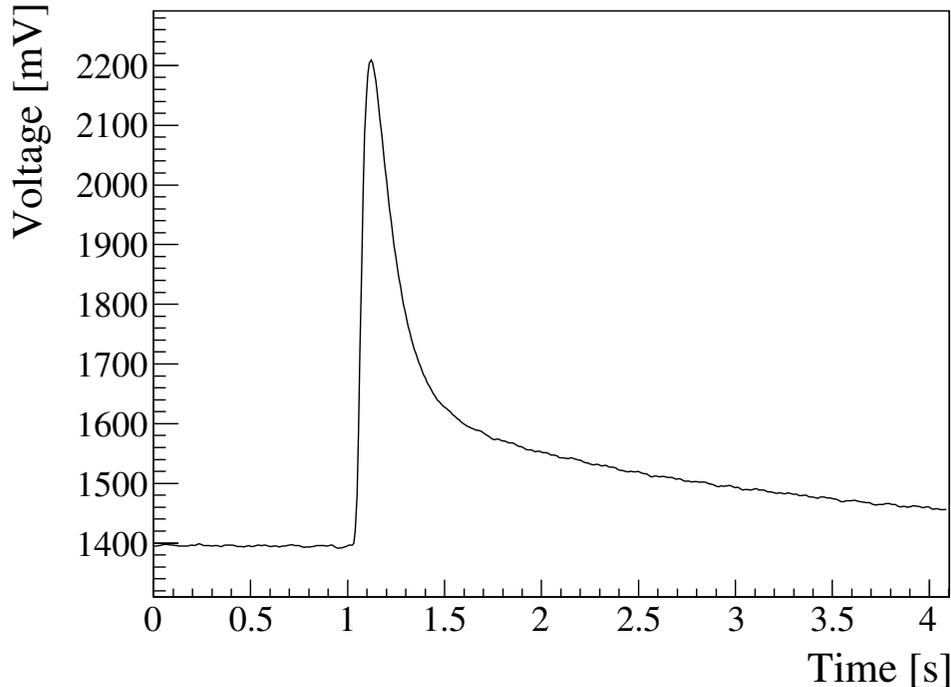
Aliasing

- Frequenze maggiori della meta' della frequenza di campionamento dell'ADC vengono ricostruite a frequenza piu' bassa.



- Il filtro passa-basso rimuove queste frequenze prima che raggiungano l'ADC. L'importante e' salvare le frequenze del segnale.

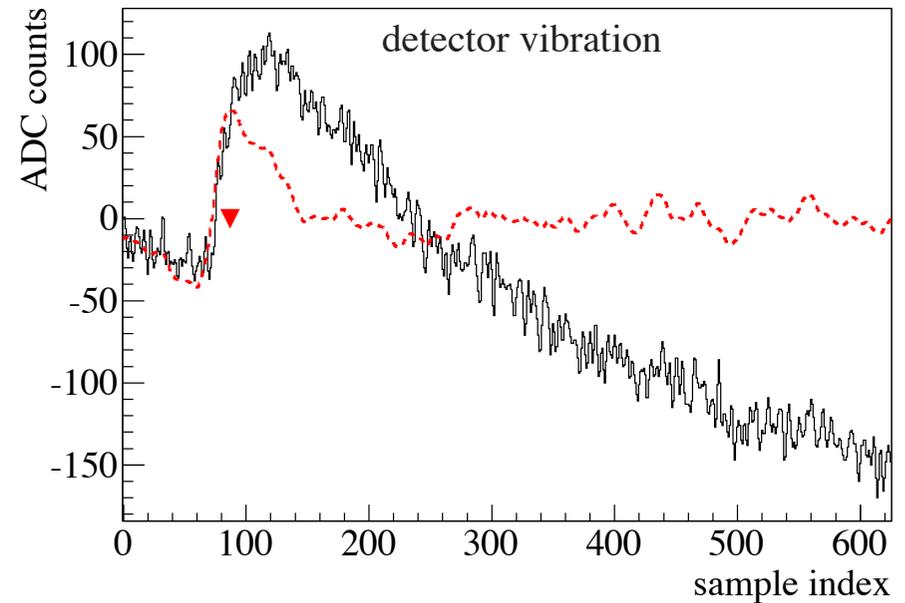
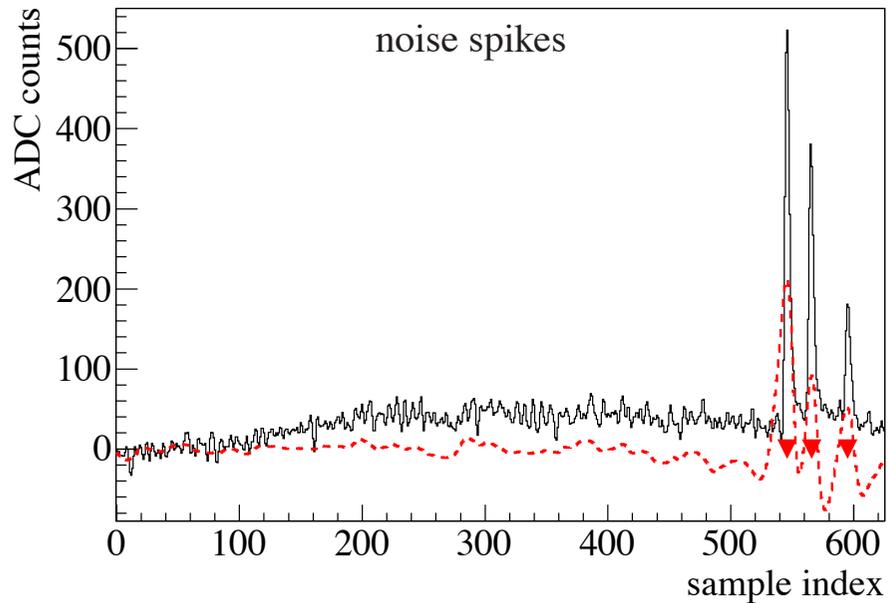
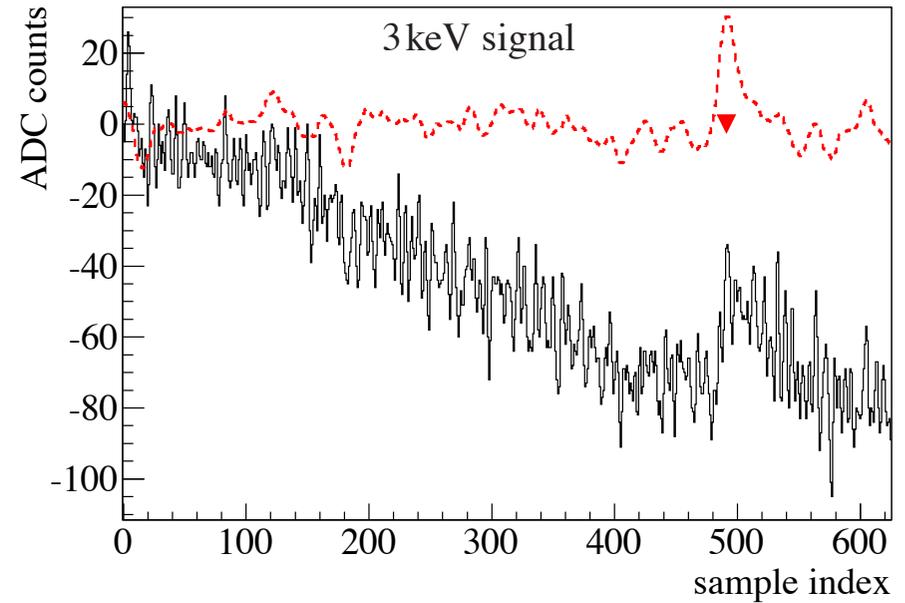
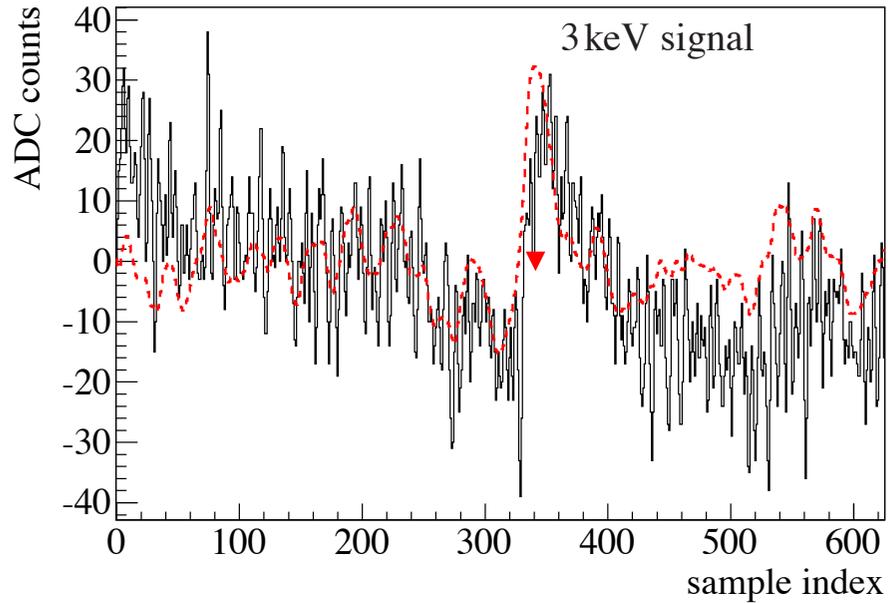
Filtri digitali: Filtro ottimo



- Il segnale (s) ha uno spettro di frequenza diverso dal noise (N).
- Lo scopo è costruire un filtro software in grado di attenuare le frequenze in cui il segnale è meno presente.
- Questo filtro è chiamato filtro ottimo. Questa è la funzione di trasferimento:

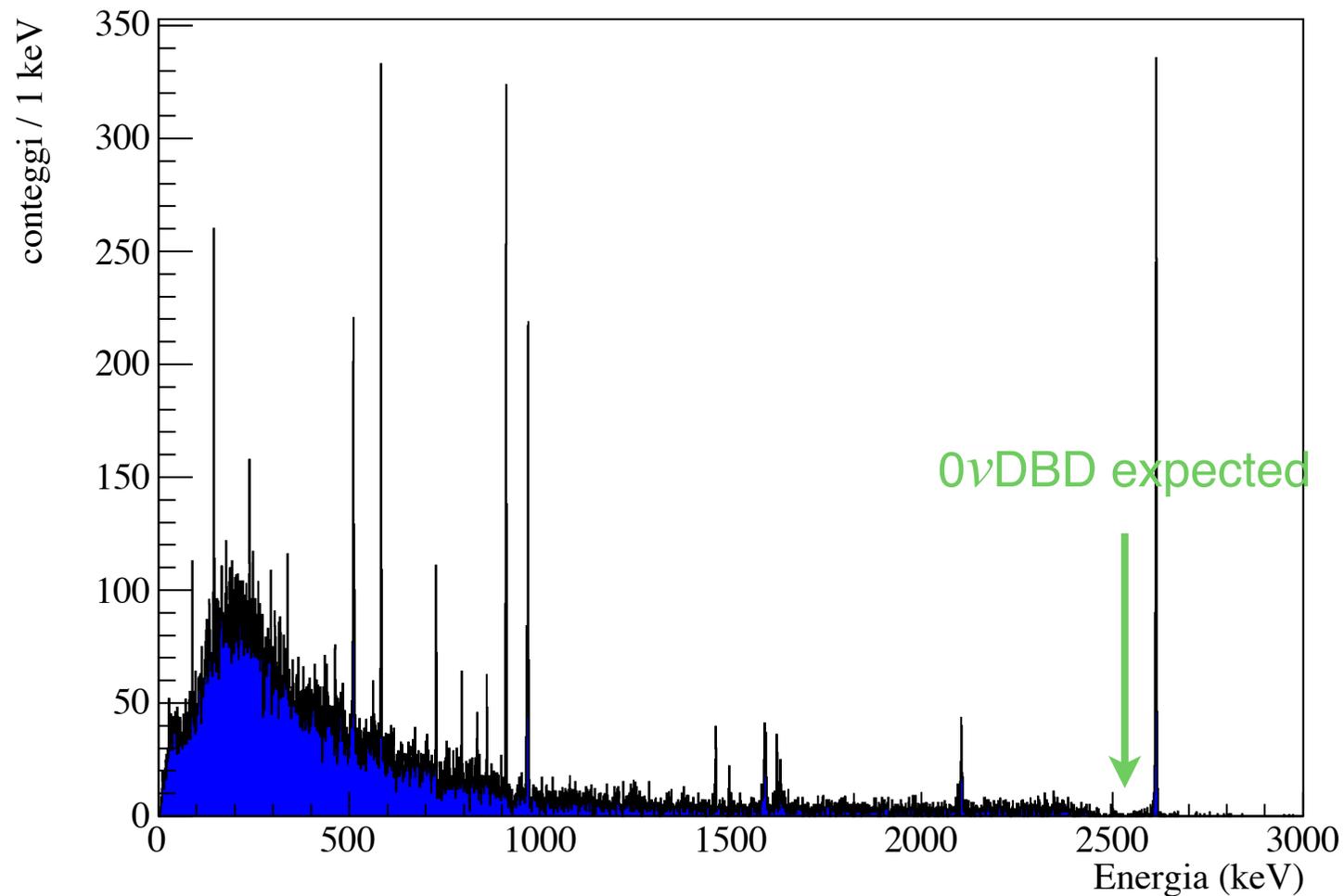
$$H(\omega) = h \frac{s^*(\omega)}{N(\omega)} e^{-j\omega t_M},$$

Filtro ottimo al lavoro



Energy spectrum

In the data analysis an energy is associated to each pulse and the spectrum is built



A Result (CUORICINO experiment)

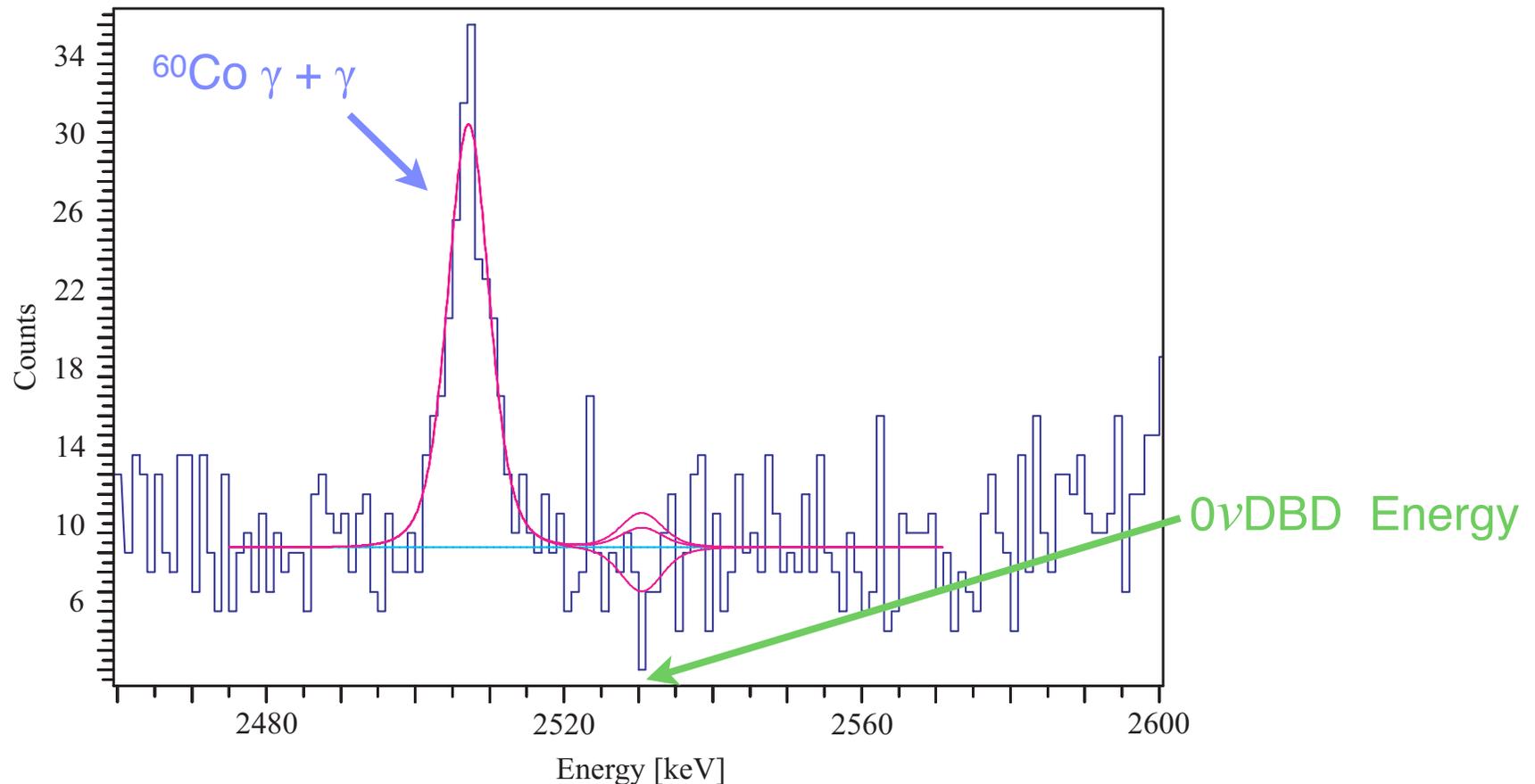
- Collected Statistics:
- Background level:
- 0ν DBD Half-life limit (90% C.L.):
- Effective neutrino mass limit:

$$t \cdot M = 18.0 \text{ y} \cdot \text{kg}^{130}\text{Te}$$

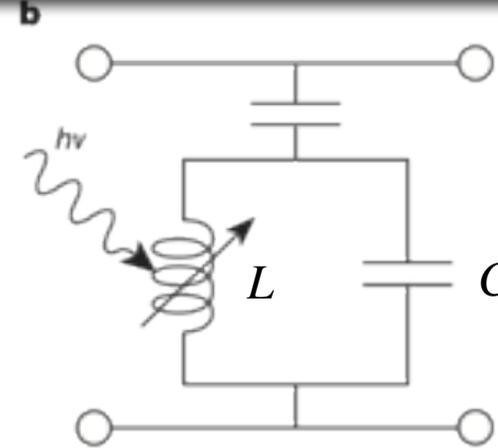
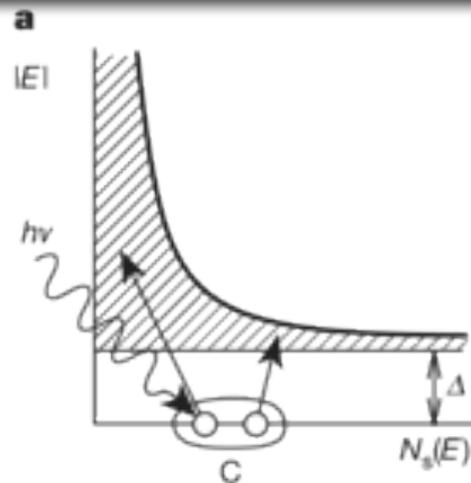
$$b = 0.18 \pm 0.01 \text{ (c/keV/kg/y)}$$

$$\tau_{1/2}^{0\nu} > 2.9 \cdot 10^{24} \text{ y}$$

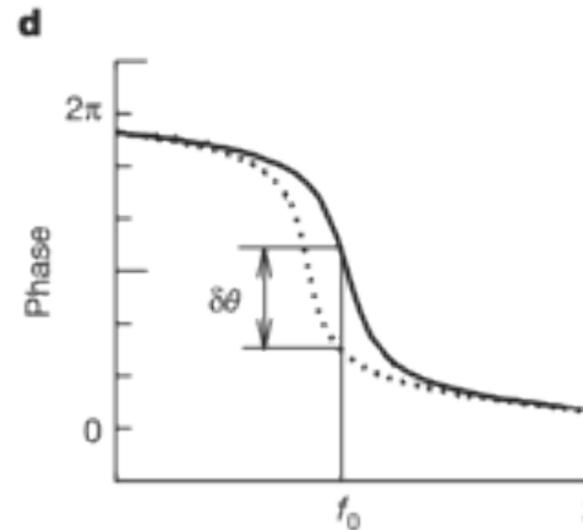
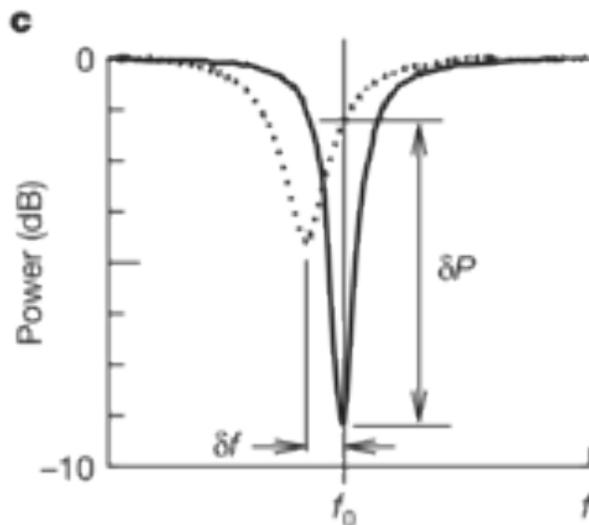
$$m_{\beta\beta} < 0.20 \div 0.69 \text{ eV}$$



Una nuova tecnologia: Kinetic Inductance Detectors (KIDs)



Cooper pairs (cp) in a superconductor act as an inductance (L).
Absorbed photons change cp density and L .

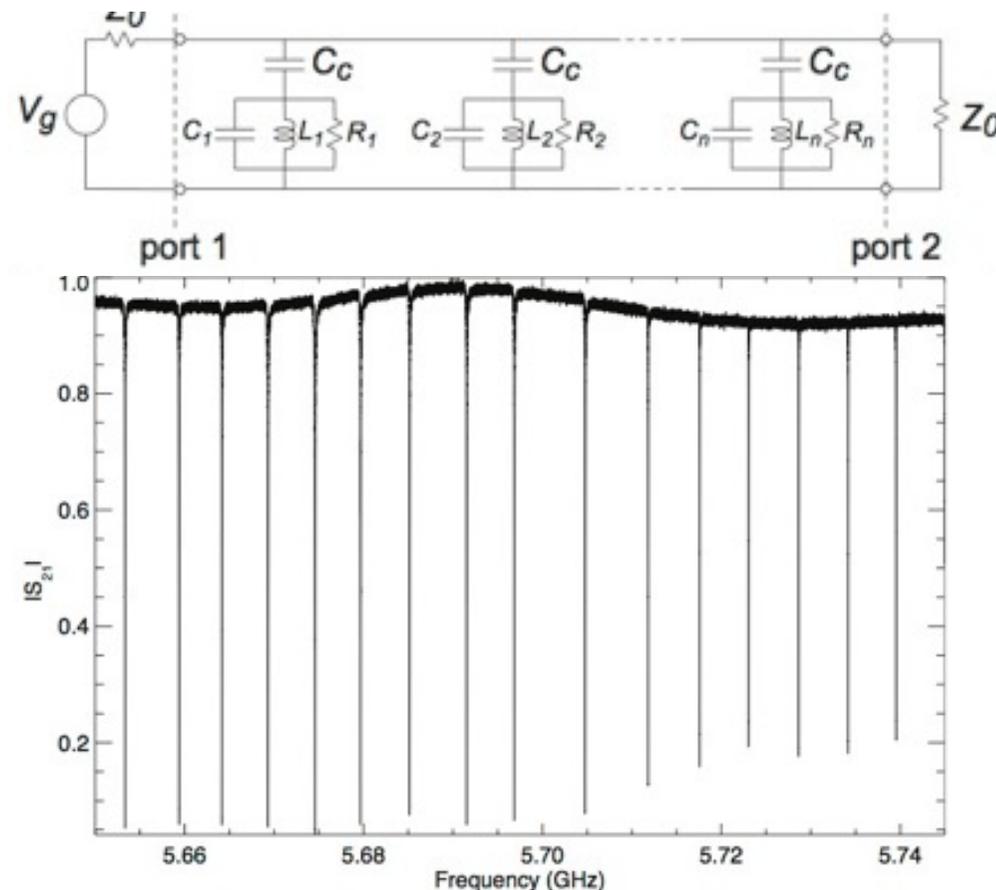


High quality factor (Q) resonating circuit biased with a microwave (GHz):
signal from amplitude and phase shift.

Day et al., Nature 425 (2003) 817

Multiplexed readout of a KID array

- Different resonators can be coupled to the same feedline by making them resonate at slightly different frequencies.
- The resonant frequency can be changed by modifying the capacitor (C) or the inductor (L) pattern of the circuit.

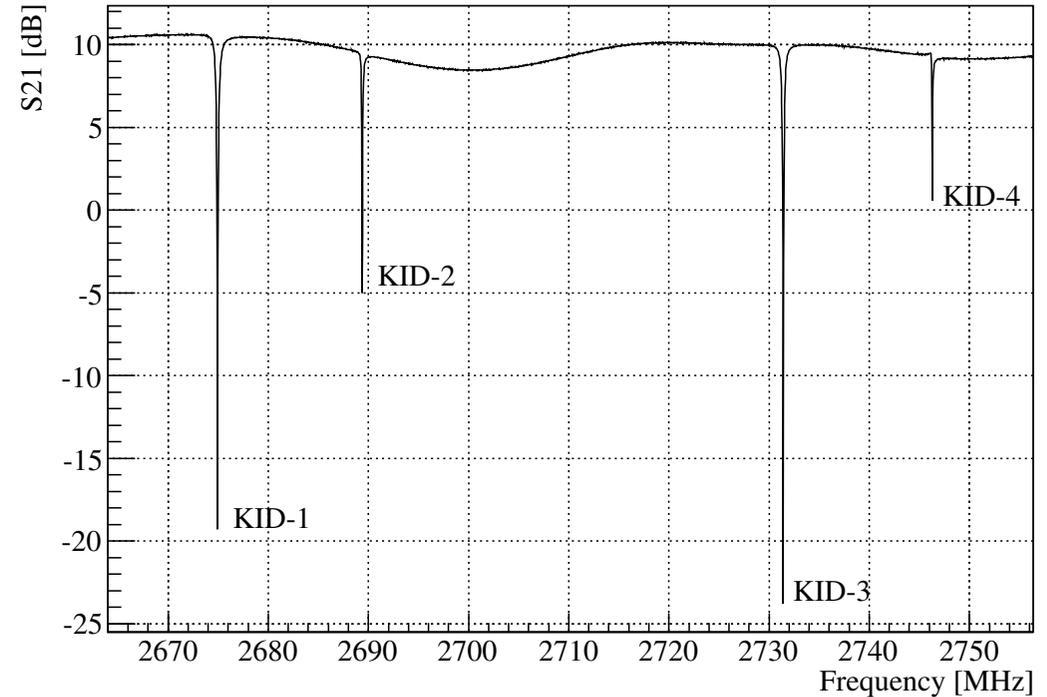
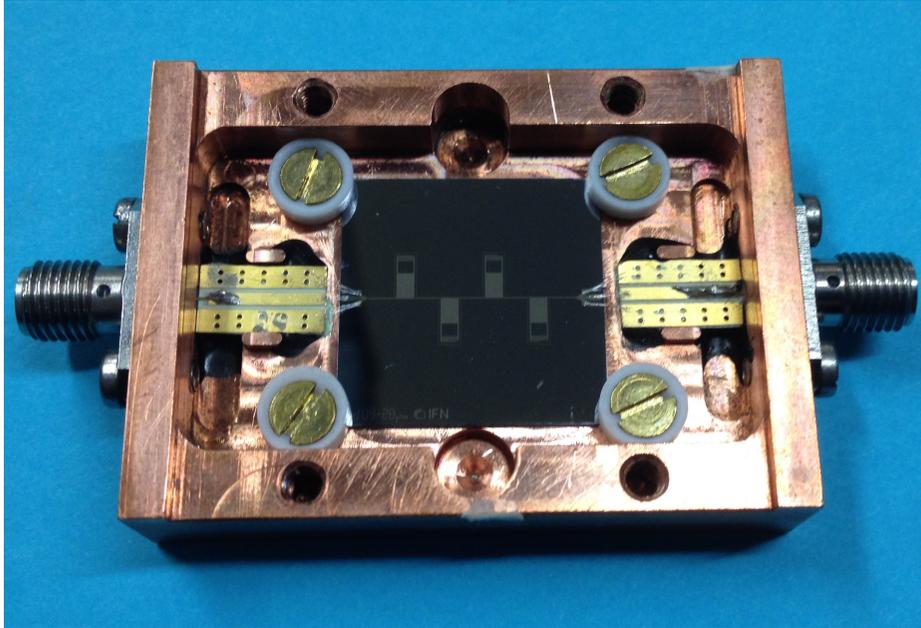


O. Bourrion et al, JINST 6 P06012 (2011)

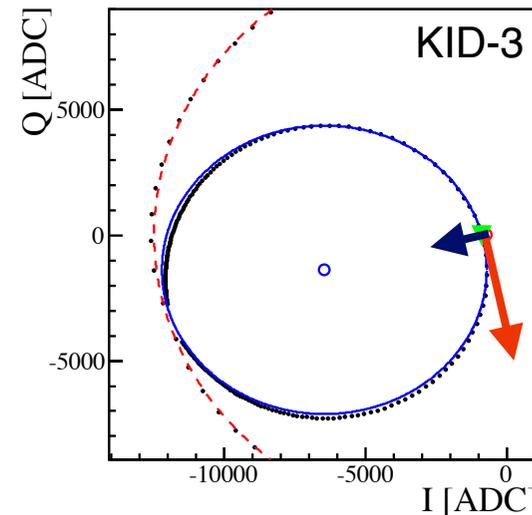
- A single cryogenic amplifier can be used to read up to 1000 detectors.

4 aluminum pixel detector

APL 107 (2015) 093508

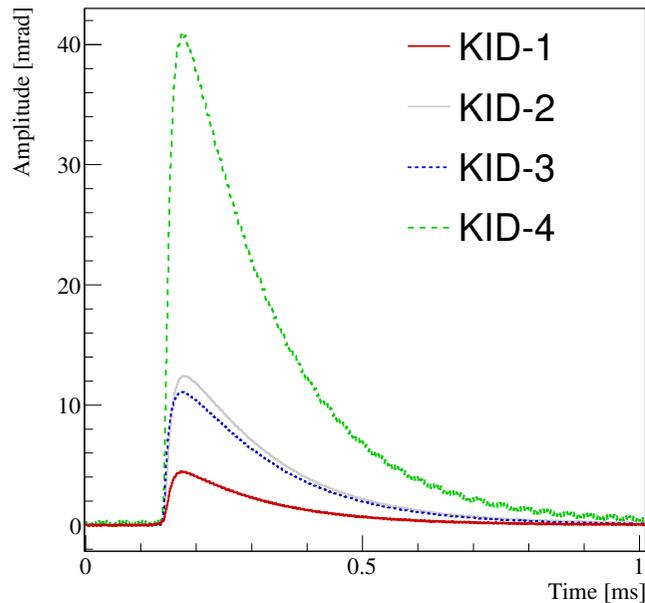


	f_0 [GHz]	Q [$\times 10^3$]
KID-1	2.675	6
KID-2	2.689	18
KID-3	2.731	8
KID-4	2.746	35



Amplitude signal
Phase signal
(3-4x higher)

Phase signal and noise



- Average phase signals at 14 keV.
- Rise time $\sim 20 \mu\text{s}$ (arrival time of phonons)
- Decay time $\sim 230 \mu\text{s}$ (recombination of quasiparticles into cooper pairs).
- KIDs with higher Q see a higher signal

- High low frequency noise, increases with Q.
- Strongly limits the sensitivity.
- Noise origin under investigation.

