Bolometric detectors in neutrino physics

Sergio Di Domizio
Università & INFN Genova

GDR Neutrino 2011

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Outline

- Bolometric technique
  - Working principles
  - Detector operation
  - Performances

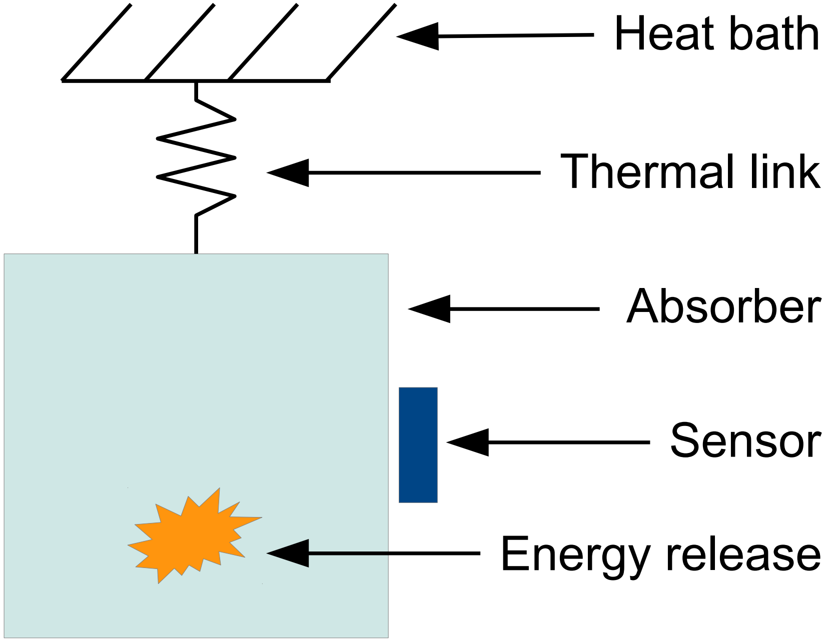
- Bolometers in neutrino physics
  - Neutrino mass measurement
  - Double beta decay
  - Background reduction in DBD bolometric experiments

Bolometers working principles

Energy release detected as a temperature rise of the absorber: $\Delta T = E/C$

Energy carried by phonons: $<\varepsilon> \sim k_B T$

Energy resolution: $\Delta E = \sqrt{k_B C(T) T^2}$

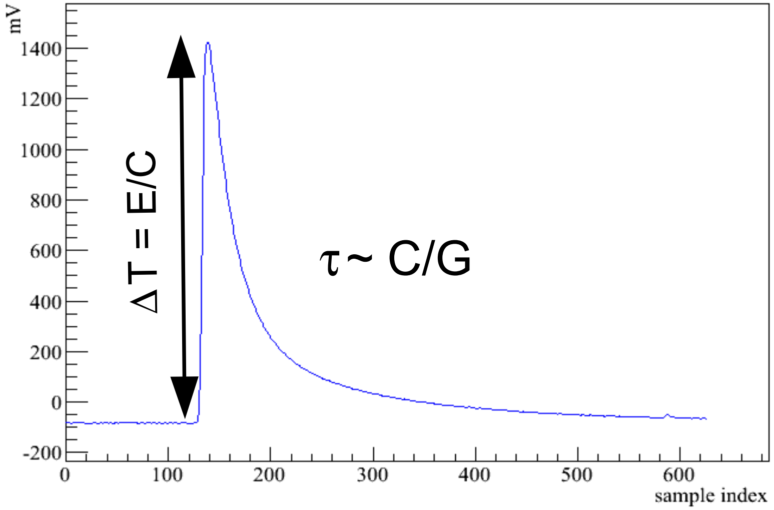

Heat bath

Thermal link

Absorber

Sensor

Energy release



Must work at temperatures cryogenic temperatures: 10 ÷100 mK

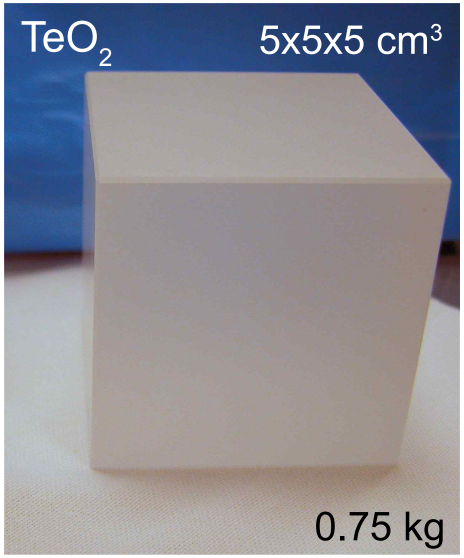
$\Delta T = E/C \Rightarrow$ prefer low C

$C(T) = \underset{\text{electrons}}{\gamma T} + \underset{\text{lattice}}{a T^3} \Rightarrow$ Prefer dielectric materials

Bolometers are intrinsically slow: signal evolution determined by thermalisation time

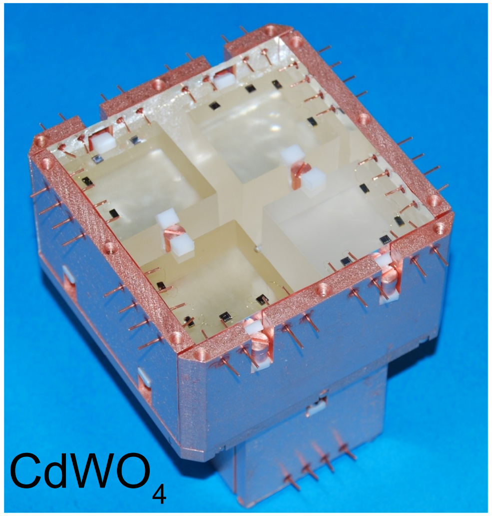
Absorber

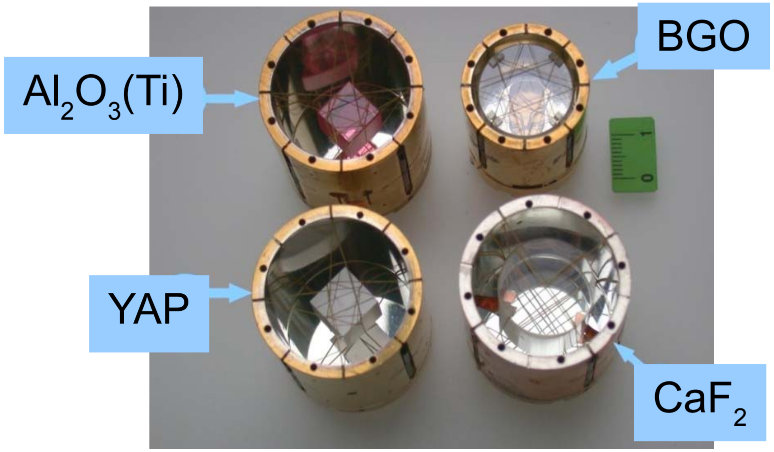
- A variety of materials
- from ~0.1 mg to ~1 kg
- Many applications

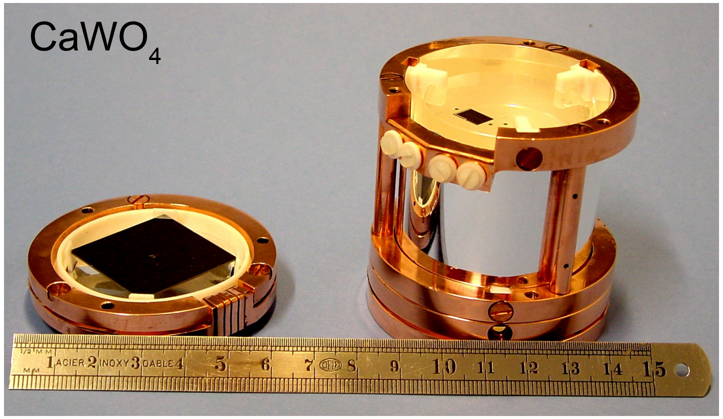

TeO_2 5x5x5 cm^3

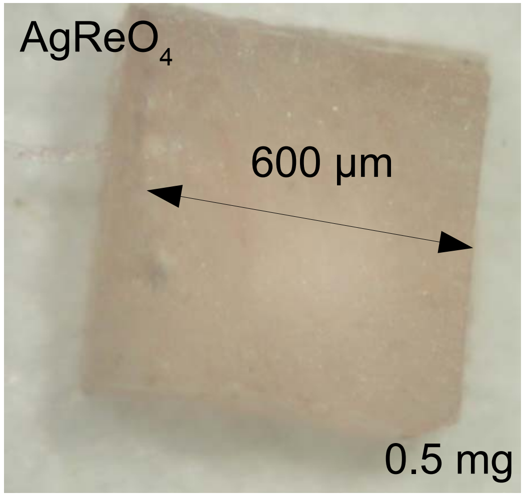
0.75 kg


Si


$CdWO_4$

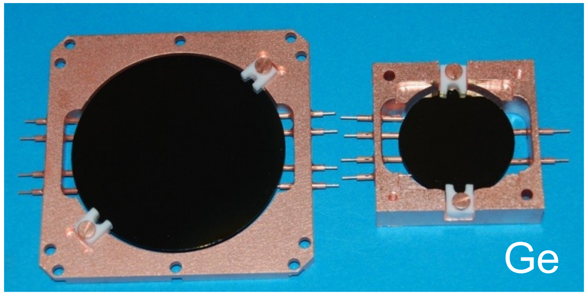


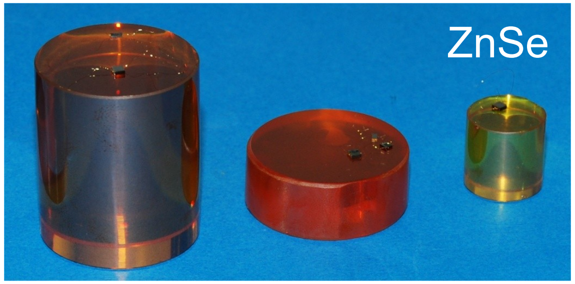

$CaWO_4$

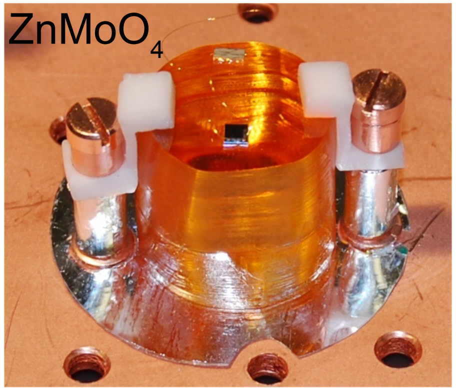

$AgReO_4$

600 µm

0.5 mg


Ge


ZnSe


$ZnMoO_4$

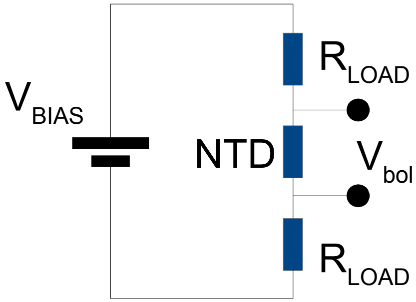
Sensor

NTD

Neutron Transmutation Doped Termistor

semiconductor with doping level slightly below MIT

$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$$



$$\alpha = \frac{d \log R}{d \log T} \simeq 10$$

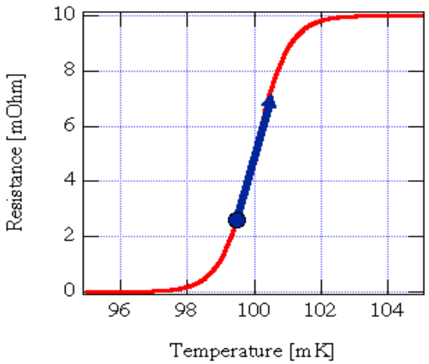
Working resistance: 100MΩ - 1GΩ

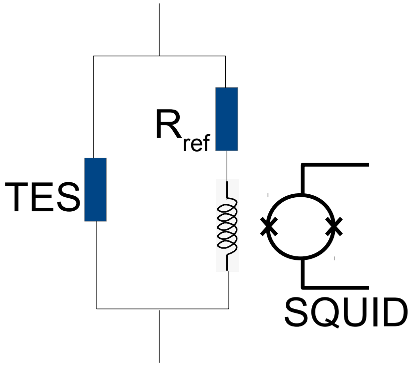
- ✓ Wide temperature range
- ✓ Easier to operate
- ✗ Slower
- ✗ Less sensible

TES

Transition Edge Sensor

Superconductor operated around T_C





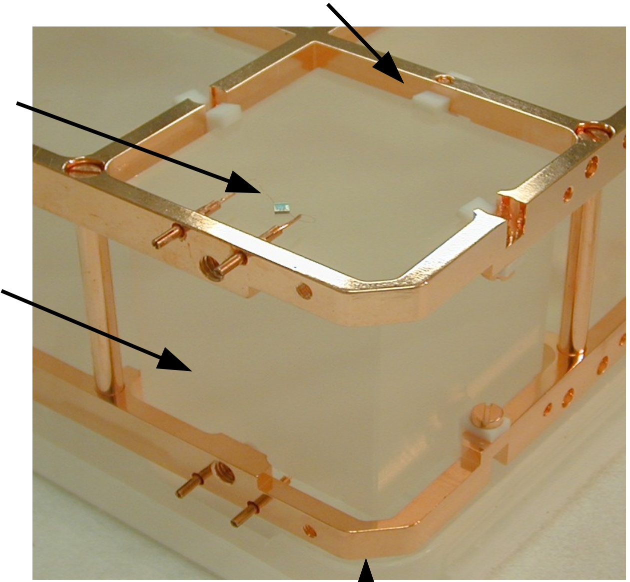
$$\alpha = \frac{d \log R}{d \log T} \simeq 100 \div 1000$$

Working resistance: 10 mΩ – 100 mΩ

- ✗ Narrow temperature range
- ✗ Harder to operate
- ✓ Faster
- ✓ More sensible

Other sensors: Metallic Magnetic Calorimeters (MMC), Kinetic Inductance detectors (MKID)

Example: CUORICINO

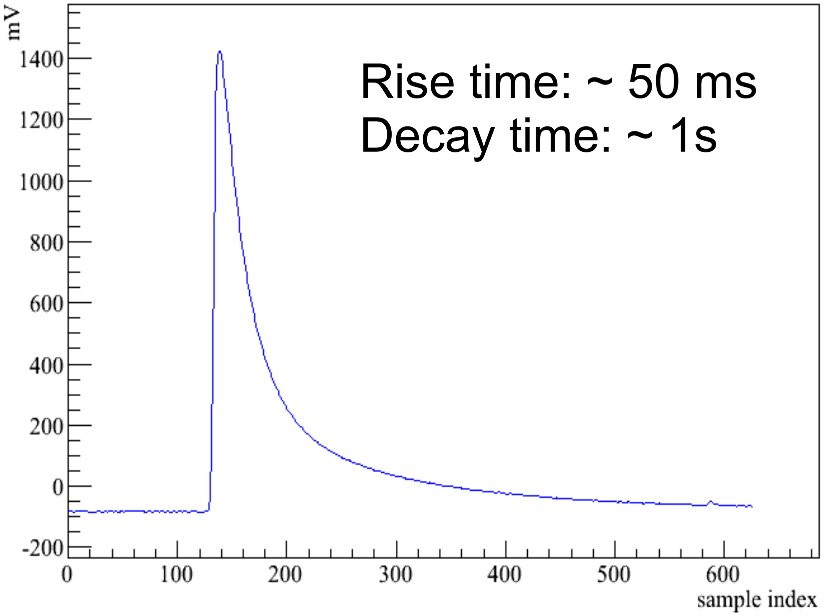


Thermal conductance: PTFE

Sensor: NTD

Absorber: TeO_2

Heat bath: OFHC Copper



Rise time: ~ 50 ms
Decay time: ~ 1s

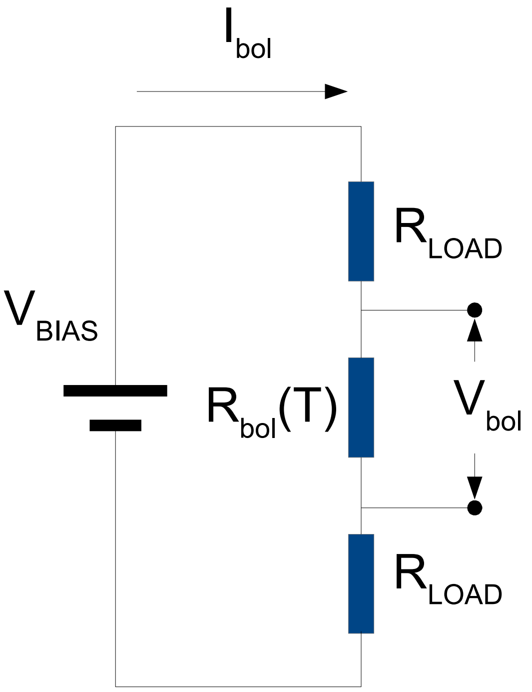
Absorber crystal: TeO_2

- M = 790 g
- C = 2 x 10^{-9} J/K
- ΔT = 0.1 mK/MeV

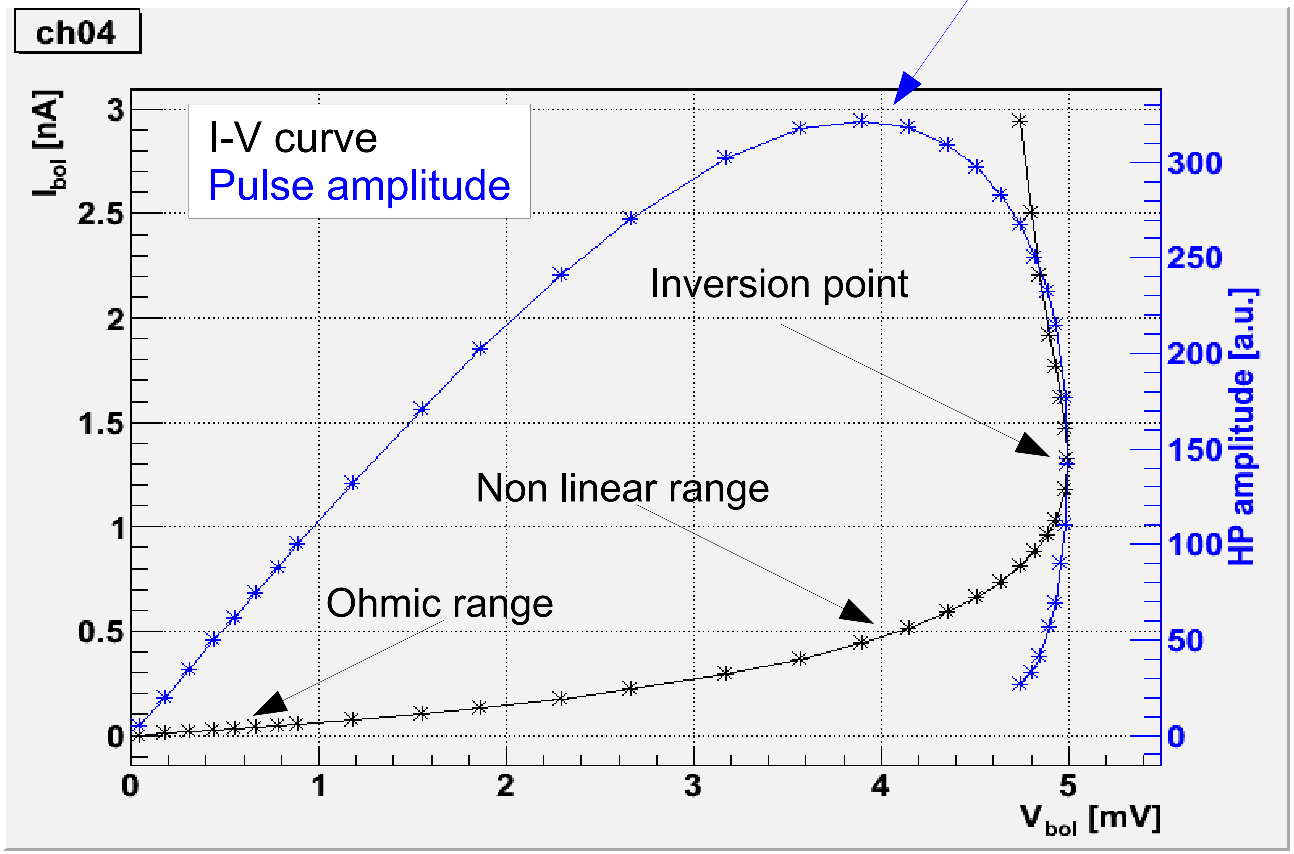
Sensor: NTD Ge thermistor

- $R = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$
- $R_0 = 1\ \Omega$, T_0 = 3 - 4 K
- R = 100 MΩ
- ΔR = 3 MΩ/MeV, ΔV = 0.3 mV/MeV

Bolometer operation



Select polarization current that maximizes the signal to noise ratio



I_{bol} induces a power dissipation on the bolometer

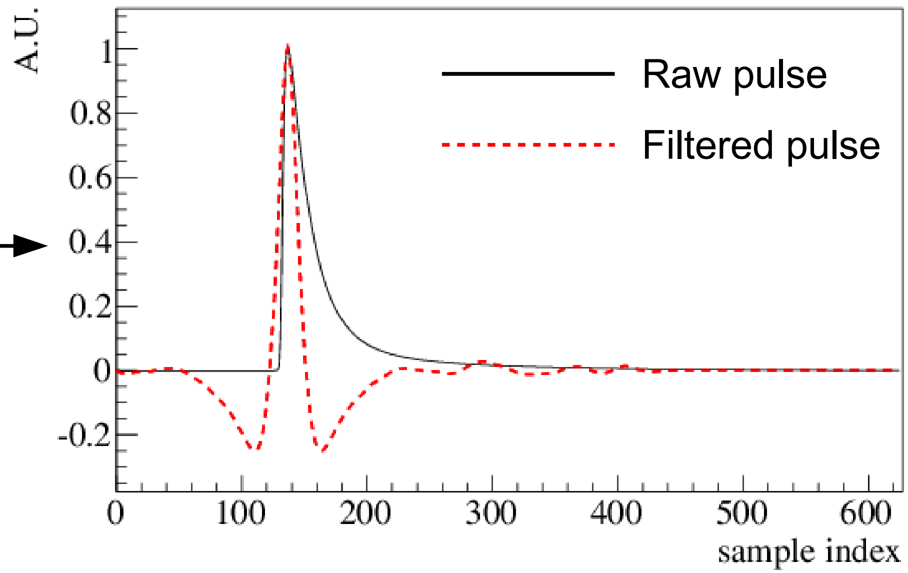
Balance between input and output power

$R(T_{bol})I^2 = G(T_{bol} – T_{bath})$

Amplitde estimation

Optimum filter: maximize signal to noise ratio

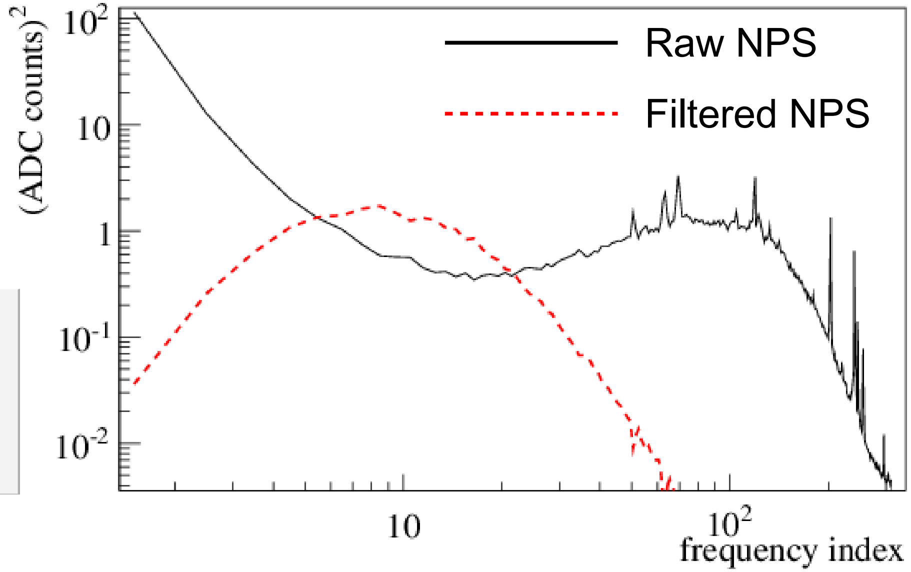
Ideal detector response: evaluated by averaging many particle pulses

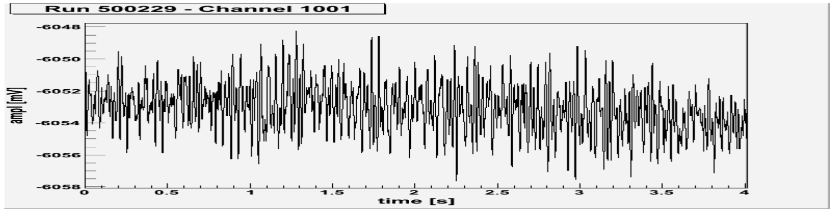


Time of maximum signal amplitude

$$H(\omega)=\frac{S^{*}(\omega)}{N(\omega)}\exp(-j\omega t_{M})$$

Noise power spectrum: average the noise power spectra of randow waveform samplings not containing pulses

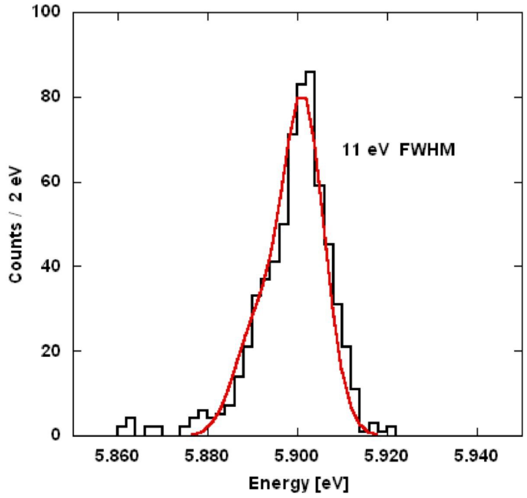




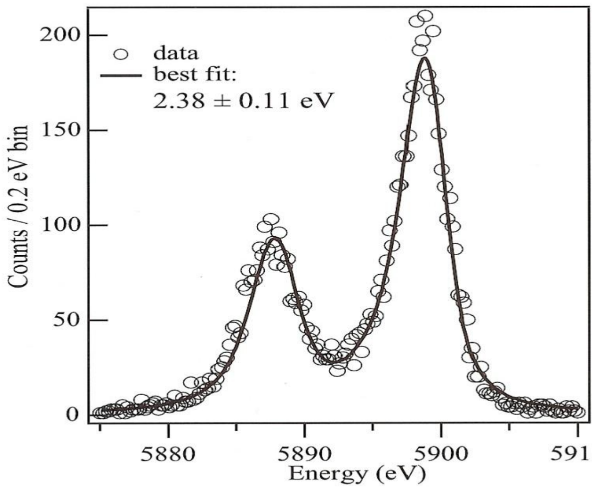
Riv. Nuovo Cim., vol. 9N1, pp. 1–146, 1986

Energy resolution

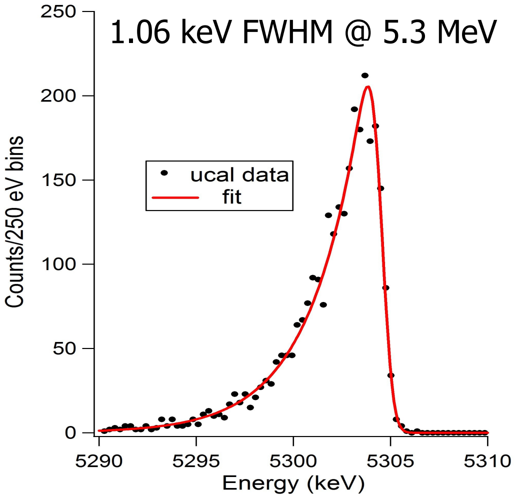
Best resolutions with micro bolometers



A. Nucciotti @ NEUTRINO 2010



NIST



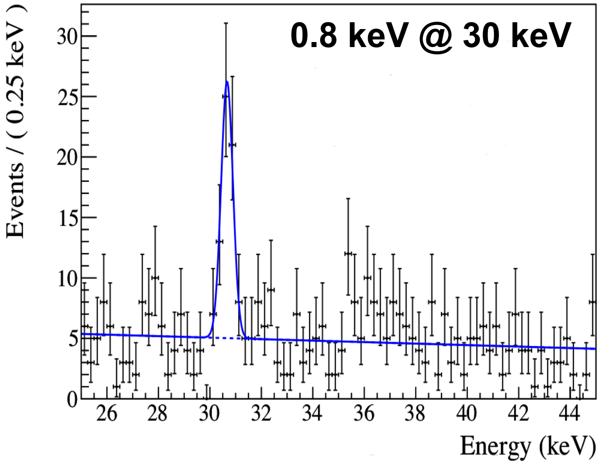
J. Ullom @ LTD13

Re absorber with TES

Bi absorber with TES

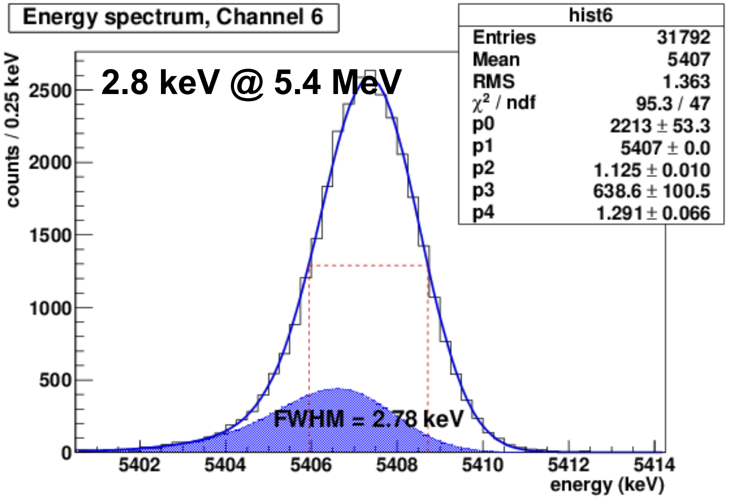
Sn absorber with TES

...but also macro bolometers have excellent performances



0.75 kg TeO_2 absorber
with NTD sensor

0.8 keV @ 30 keV
1.5 keV @ 351 keV
2.1 keV @911 keV
3.1 keV @ 2.6 MeV
2.8 keV @ 5.4 MeV



Bolometers in neutrino physics

ν-mass

- Measure the distortion of the β-decay endpoint induced by the finite ν-mass
- Energy region: ~ keV
- Detector mass: O(100 g)
- Single bolometer mass: O(mg)
- (relatively) high counting rate: O(Hz)
- Backgrounds: pile-up with events from the low energy region of the beta spectrum

Double beta decay

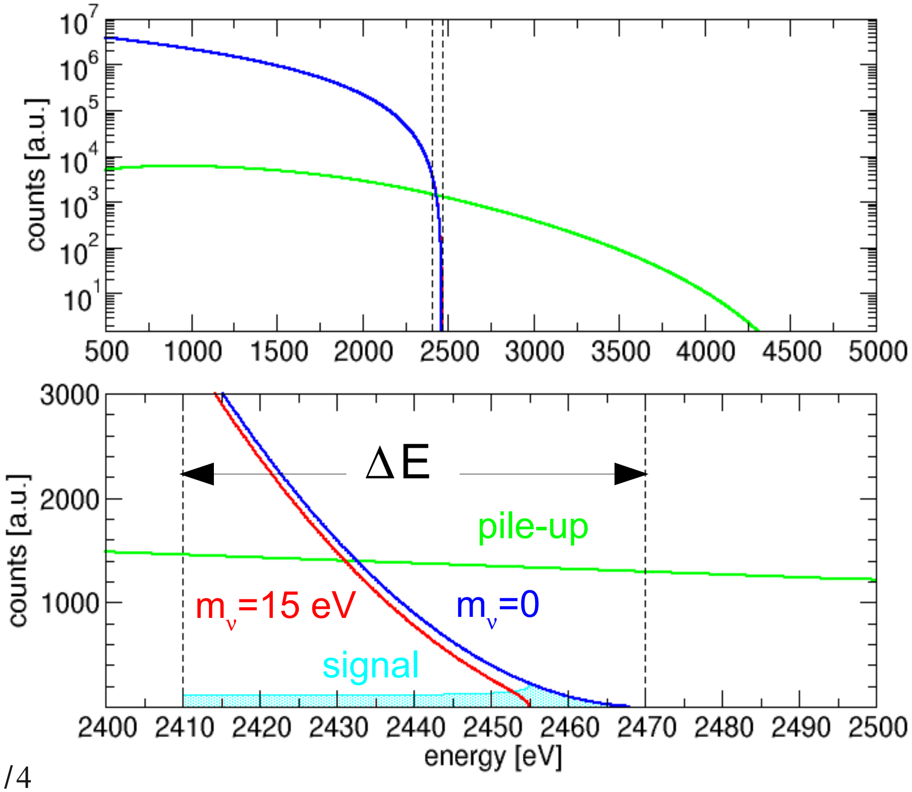
- Search for a monochromatic peak at the Q-value of the decay
- Energy region: 2 – 4 MeV
- Detector mass: O(ton)
- Single bolometer mass O(kg)
- Low counting rate: O(mHz)
- Backgrounds: natural radioactivity, cosmic muons, neutrons

ν-mass measurement

Inclusive measurement

✓ Measure all energy: $E_e + E_{exc}$

✗ Measure the whole spectrum



Fraction of events in a window ΔE

$$F(\Delta E) = \left(\frac{\Delta E}{E_0}\right)^3$$

Pile-up fraction: $f_{pile-up} = A_\beta \tau_R$

source activity resolving time

Sensitivity: $$\Sigma_{90}(m_\nu) \simeq \frac{E_0}{\sqrt{N_\beta}} \left[\frac{\Delta E}{E_0} + \frac{3}{10} \frac{E_0}{\Delta E} f_{pile-up} \right]^{1/4}$$

Best ΔE:

- Energy resolution if $f_{pile-up} \ll \frac{\Delta E^2}{E_0^2}$
- $0.55\, E_0 \sqrt{f_{pile-up}}$ If pile-up is not negligible

Best limit with spectrometers: m_ν < 2 eV
Best limit with bolometers: m_ν < 15 eV

MIBETA

MARE

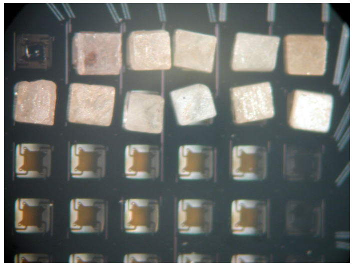
Microcalorimeter **A**rrays for a **R**henium **E**xperiment

^{187}Re

β-decay: $^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^{-} + \bar{\nu}_e$

Half life: 4.3 x 10^{10} y

E_0: 2.5 keV



MARE @MILANO

6x6 $AgReO_4$ array

m ~ 0.5 mg/pixel

ΔE ~ 30 eV

τ_R ~ 250 μs

^{163}Ho

End-point spectral distortion similar to β-decay

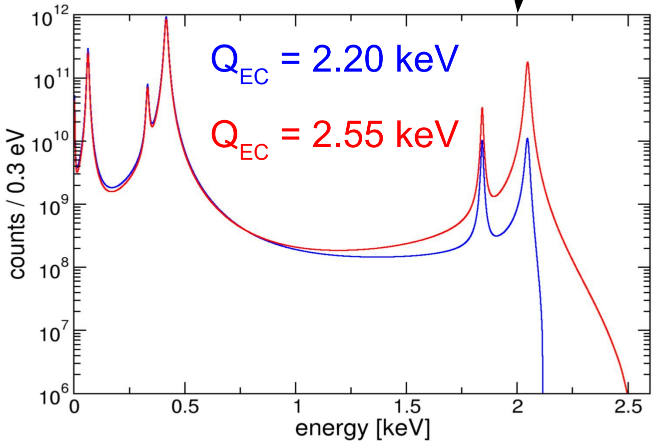
Electron capture: $^{163}\mathrm{Ho} + e^{-} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$

Half life: 4600 y

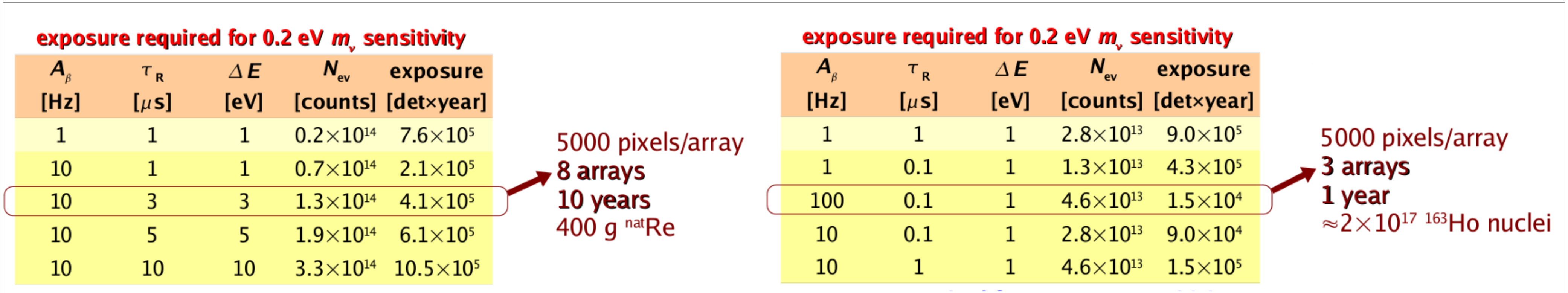
Q_{EC}: 2.3 ¿ 2.8 keV

- ✓ Lower half life
- ✓ Better τ_R
- ✗ Less expertise
- ✗ Uncertainty in Q_{EC}

Measure Dy de-excitation



Implant ^{163}Ho in bolemter arrays already developed at NIST (x-ray detection for astrophysics)



exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	0.2×10^{14}	7.6×10^{5}
10	1	1	0.7×10^{14}	2.1×10^{5}
10	3	3	1.3×10^{14}	4.1×10^{5}
10	5	5	1.9×10^{14}	6.1×10^{5}
10	10	10	3.3×10^{14}	10.5×10^{5}

5000 pixels/array
8 arrays
10 years
400 g ^{nat}Re

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	2.8×10^{13}	9.0×10^{5}
1	0.1	1	1.3×10^{13}	4.3×10^{5}
100	0.1	1	4.6×10^{13}	1.5×10^{4}
10	0.1	1	2.8×10^{13}	9.0×10^{4}
10	1	1	4.6×10^{13}	1.5×10^{5}

5000 pixels/array
3 arrays
1 year
$\approx 2\times10^{17}$ ^{163}Ho nuclei

A. NUCCIOTTI – NEUTRINO 2010

Double beta decay

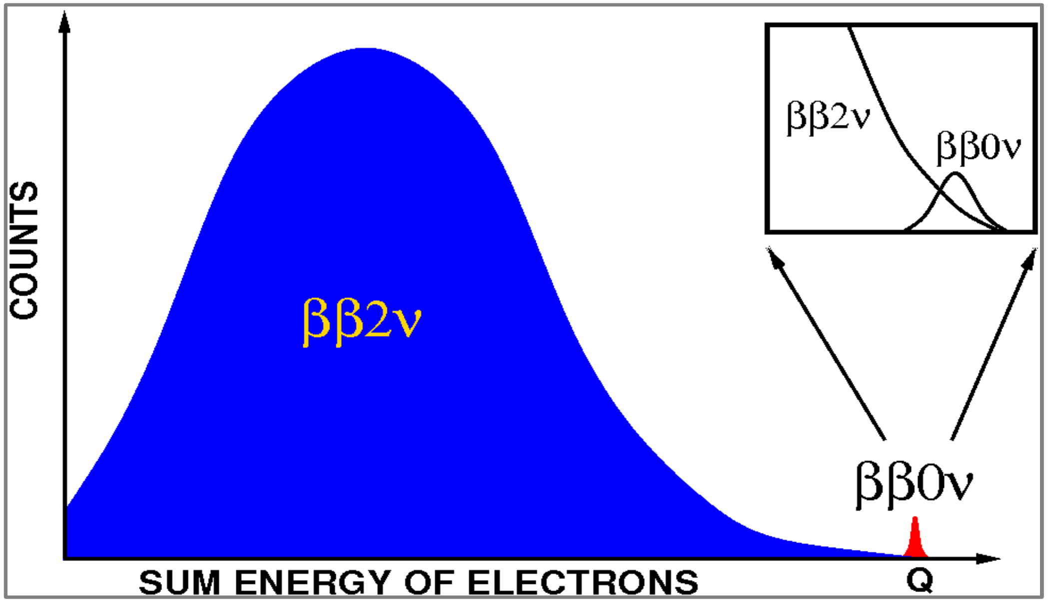
$$(A,Z)\rightarrow(A,Z+2)+2e^{-}(+2\bar{\nu})$$

Measure the sum energy of the electrons

$$\frac{1}{T^{0\nu}_{1/2}}=ln2\,F_N\frac{m^2_{\beta\beta}}{m^2_e}$$

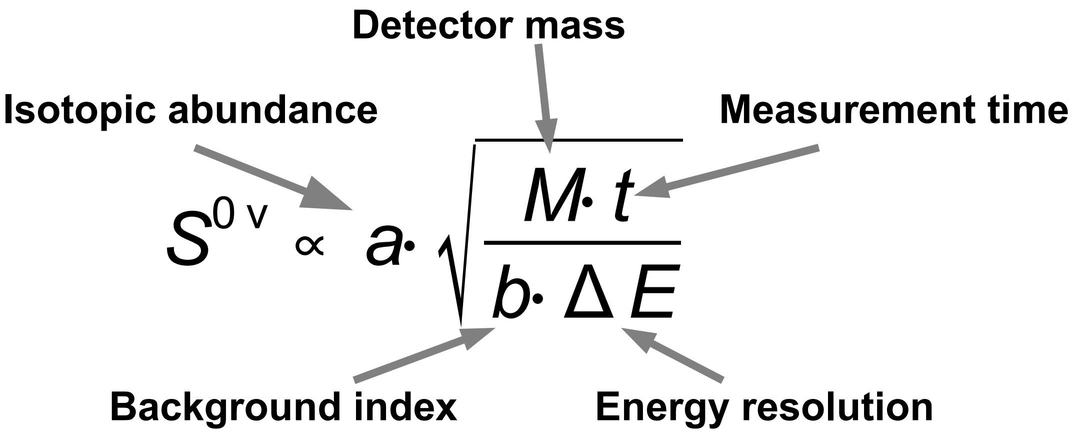
Knowledge of F_N useful for

- Comparing experiments
- Extracting information on $m_{\beta\beta}$



isotope	Q [keV]	Half life limit [y]
^{48}Ca	4271	1.4×10^{22}
^{76}Ge	2039	1.9×10^{25}
^{82}Se	2995	1.0×10^{23}
^{100}Mo	3034	4.6×10^{23}
^{116}Cd	2902	1.7×10^{23}
^{130}Te	2527	2.8×10^{24}
^{136}Xe	2479	1.2×10^{24}
^{150}Nd	3367	1.8×10^{22}

Half life sensitivity



Detector mass

Isotopic abundance

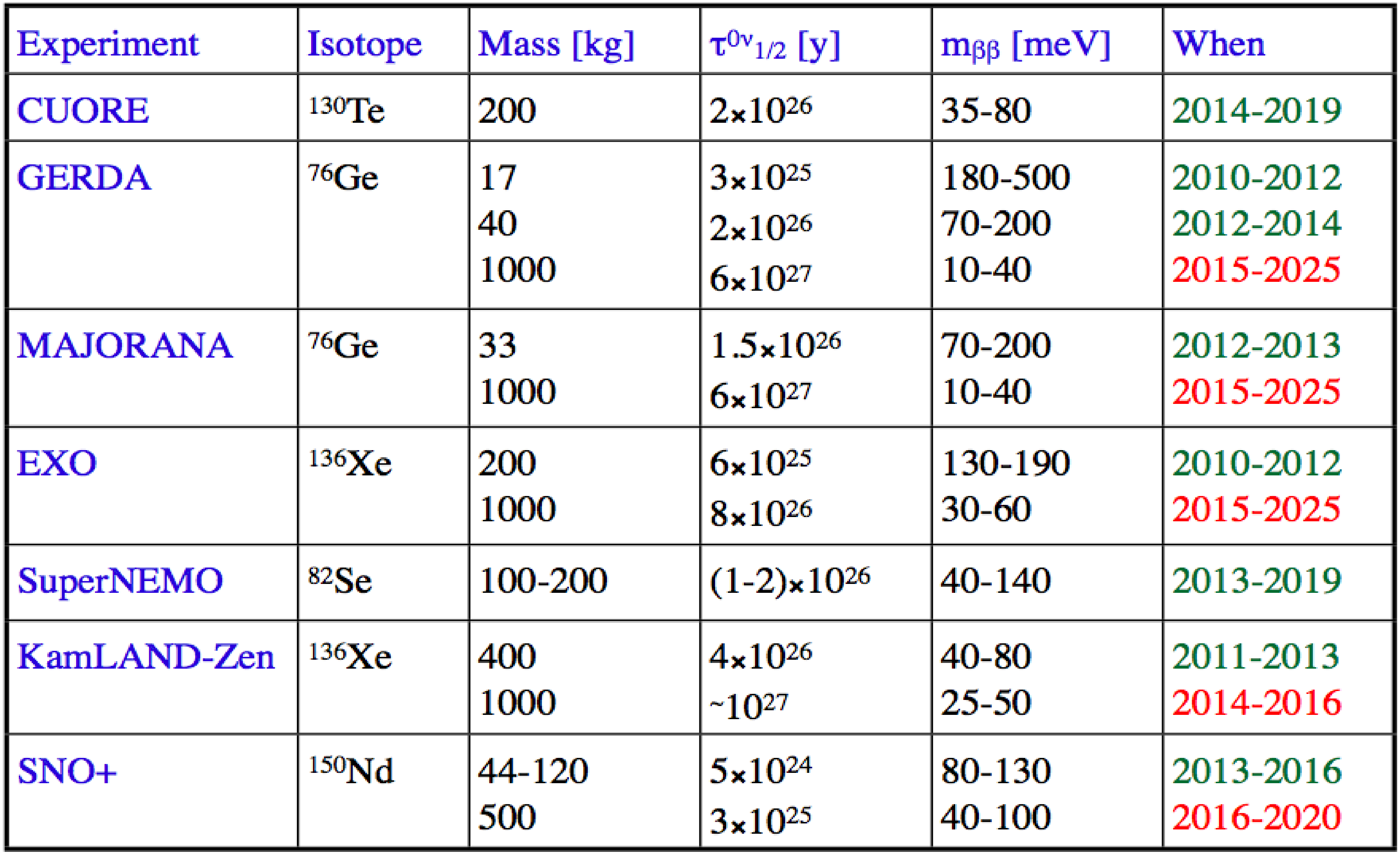
Measurement time

$$S^{0\nu}\propto a\cdot\sqrt{\frac{M\cdot t}{b\cdot\Delta E}}$$

Background index

Energy resolution

Future DBD experiments



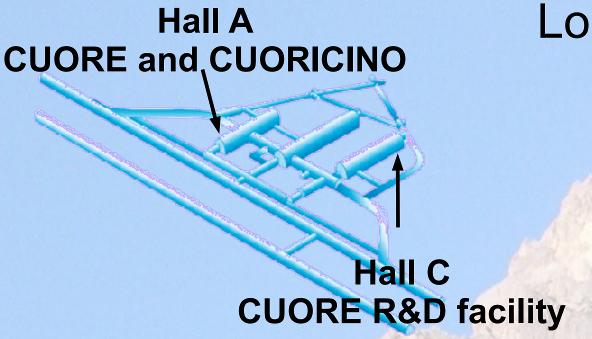
Experiment	Isotope	Mass [kg]	$\tau^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [meV]	When
CUORE	^{130}Te	200	2×10^{26}	35-80	2014-2019
GERDA	^{76}Ge	17 40 1000	3×10^{25} 2×10^{26} 6×10^{27}	180-500 70-200 10-40	2010-2012 2012-2014 2015-2025
MAJORANA	^{76}Ge	33 1000	1.5×10^{26} 6×10^{27}	70-200 10-40	2012-2013 2015-2025
EXO	^{136}Xe	200 1000	6×10^{25} 8×10^{26}	130-190 30-60	2010-2012 2015-2025
SuperNEMO	^{82}Se	100-200	$(1\text{-}2) \times 10^{26}$	40-140	2013-2019
KamLAND-Zen	^{136}Xe	400 1000	4×10^{26} $\sim 10^{27}$	40-80 25-50	2011-2013 2014-2016
SNO+	^{150}Nd	44-120 500	5×10^{24} 3×10^{25}	80-130 40-100	2013-2016 2016-2020

After A.S.Barabash, Phys.Atom.Nucl. **73**, 162 (2010)

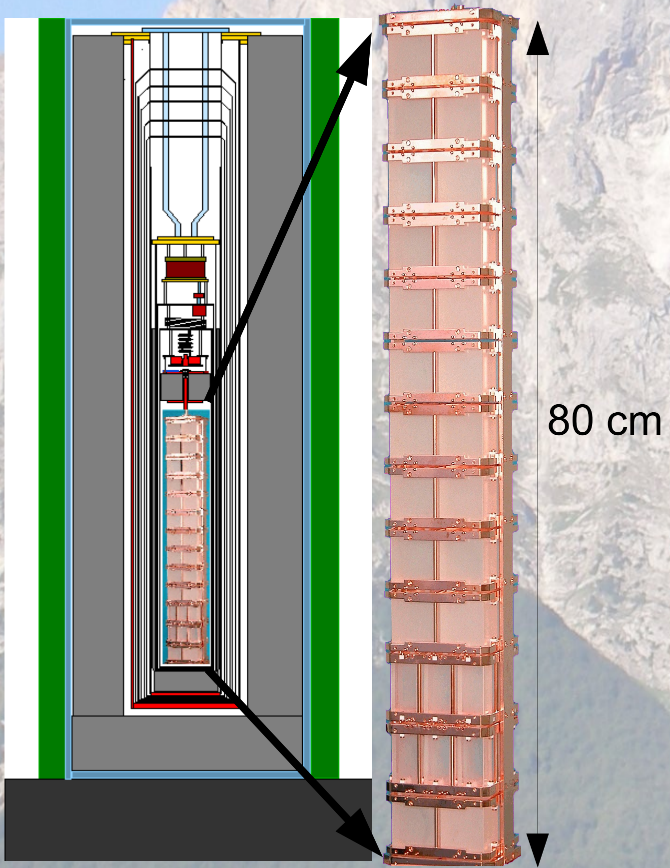
Approved R&D

CUORICINO detector

Located underground @ LNGS: 3650 m w.e. shield again cosmic rays



$^3He/^4He$ dilution refrigerator

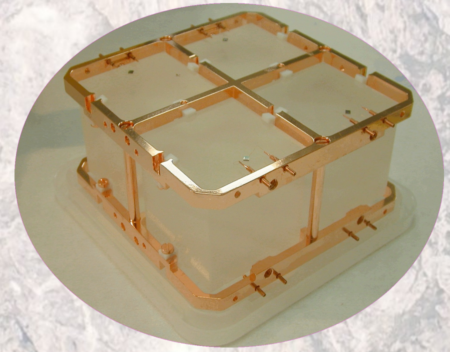


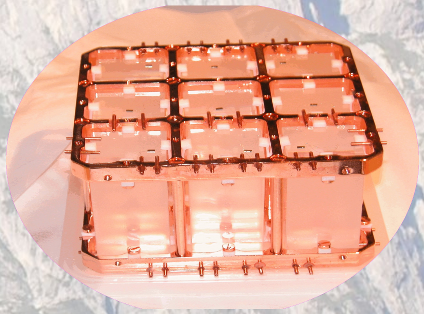
Data taking from 2003 to 2008

A tower of 62 TeO_2 crystals

11 floors made of 4 crystals
- not enriched
- Mass: 790g
- Dimensions: 5x5x5 cm^3

2 floors made of 9 crystals:
- Mass: 330g
- Dimensions: 3x3x6 cm^3
- 2 enriched in ^{128}Te (82%)
- 2 enriched in ^{130}Te (75%)





Total mass: 40.7 Kg (11.3 Kg in ^{130}Te)

Shieldings

Internal:

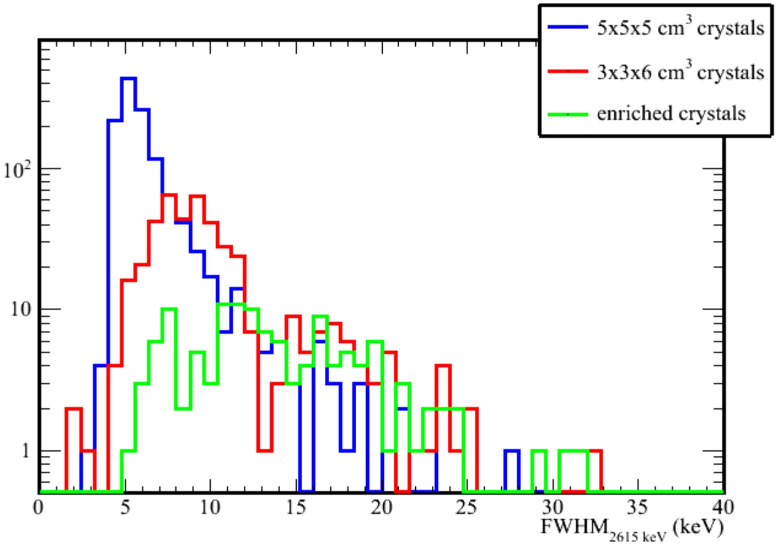
➔1cm low activity Pb
(A < 4 mBq/Kg in ^{210}Pb)

External:

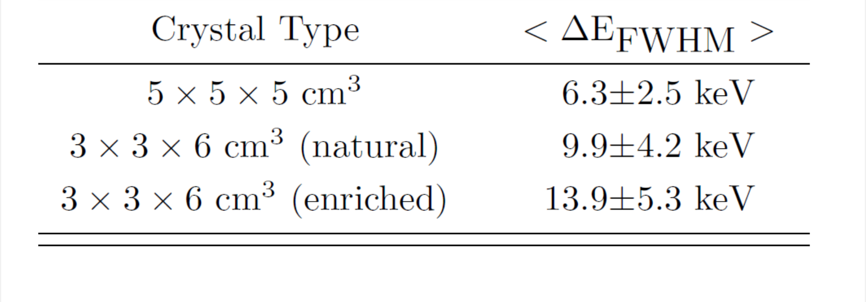
➔20cm Pb
➔20cm borated polyethylene
➔Anti-Rn box: nitrogen overpressure

CUORICINO performances and results

Energy resolution

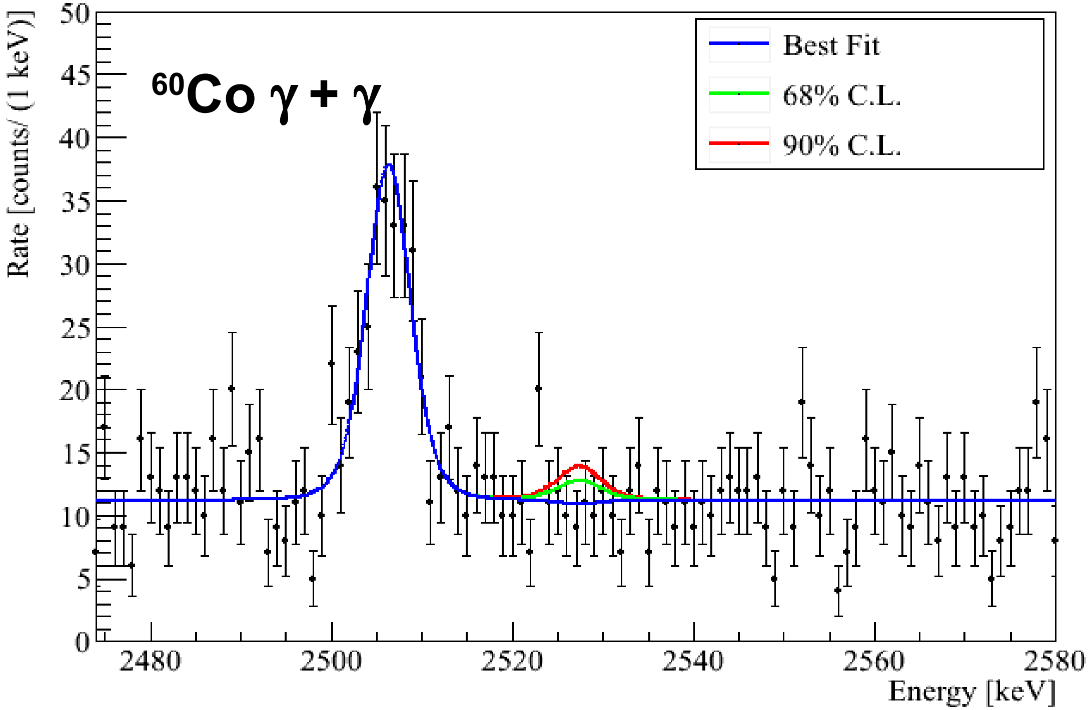


evaluated on the 2615 keV peak from ^{208}Tl



Crystal Type	$< \Delta E_{FWHM} >$
$5 \times 5 \times 5$ cm^3	6.3±2.5 keV
$3 \times 3 \times 6$ cm^3 (natural)	9.9±4.2 keV
$3 \times 3 \times 6$ cm^3 (enriched)	13.9±5.3 keV

Statistics: **19.75 kg(^{130}Te) y**



Bkg at Q-value: **0.17 counts/(keV kg y)**

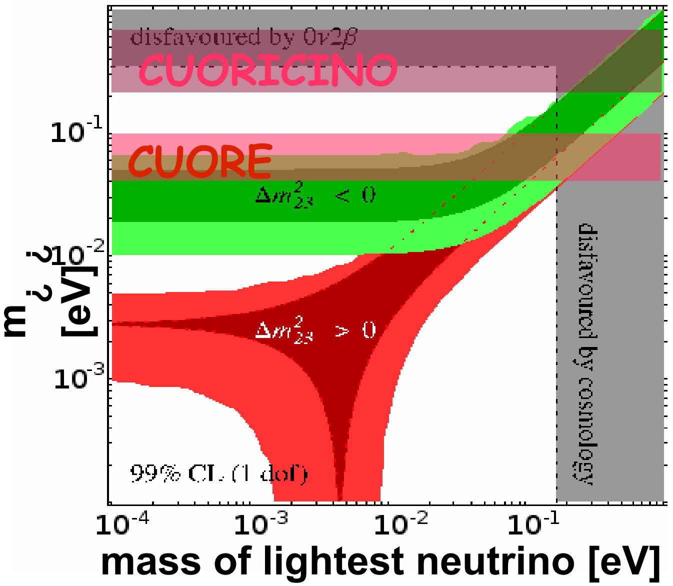
$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\ y \quad @90\%CL$$

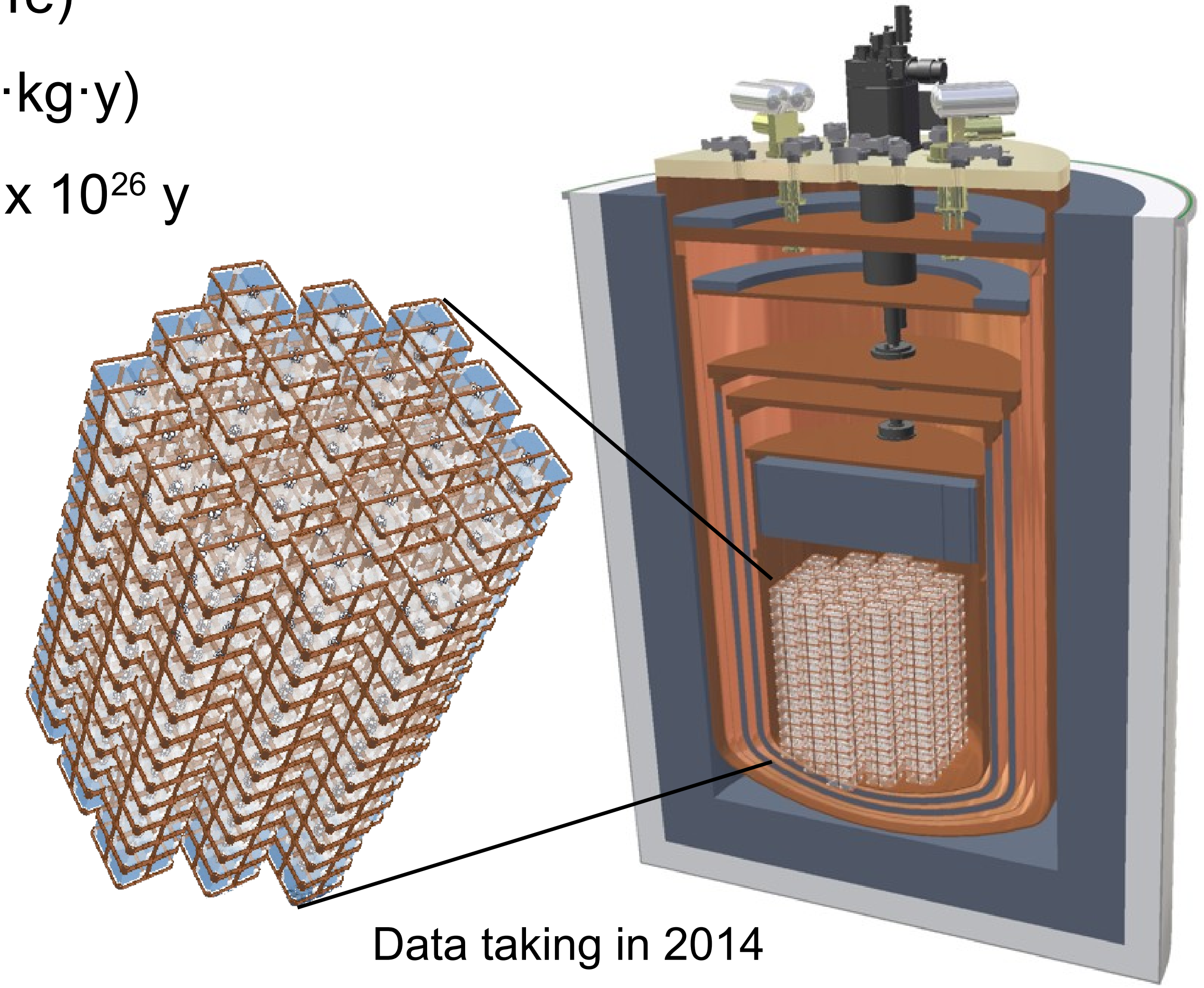
$m_{\beta\beta} < 0.3 \div 0.7$ eV

Astropart. Phys. 34 (2011) 822–831

CUORE

- 19 CUORICINO-like towers
- 988 TeO_2 crystals (5x5x5 cm^3)
- Mass: 740 kg (200 kg of ^{130}Te)
- Bkg goal: 0.01 counts/(keV·kg·y)
- 1 σ half life sensitivity: 1.6 x 10^{26} y
- $m_{\beta\beta} < 41 \div 95$ meV



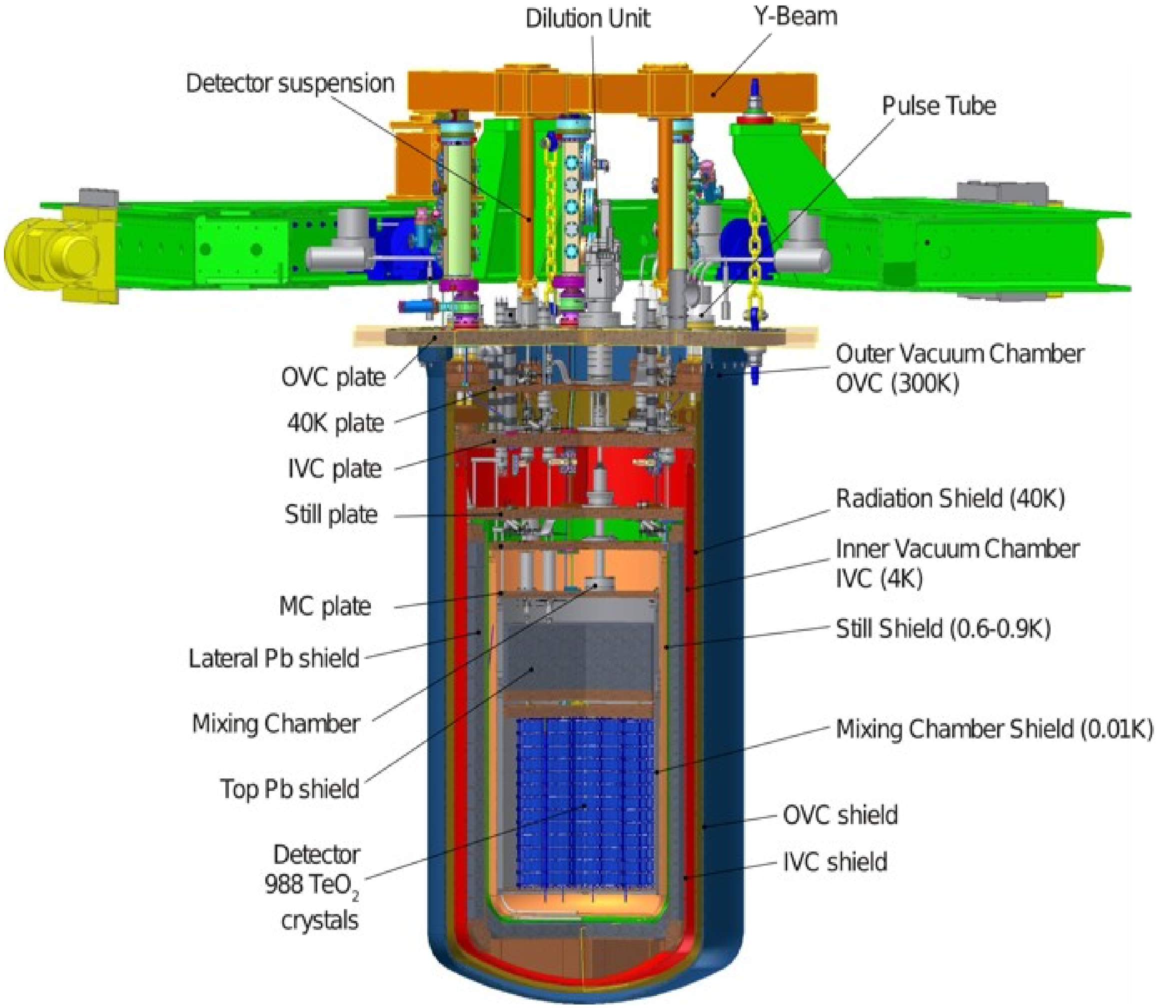


Data taking in 2014

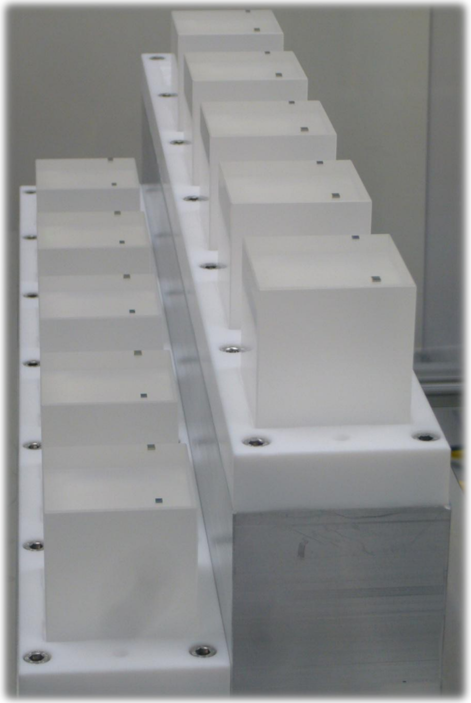
CUORE cryostat

A technological challenge

- Will be the biggest mass ever cooled down to 10 mK
- Strong radioactivity constraints on the cryostat materials
- Calibration: periodically insert Th source wires between detectors
- Multi-stage detector suspension system
- Avoid cryogenic liquids:
  - No 1-k pot
  - No liquid helium bath

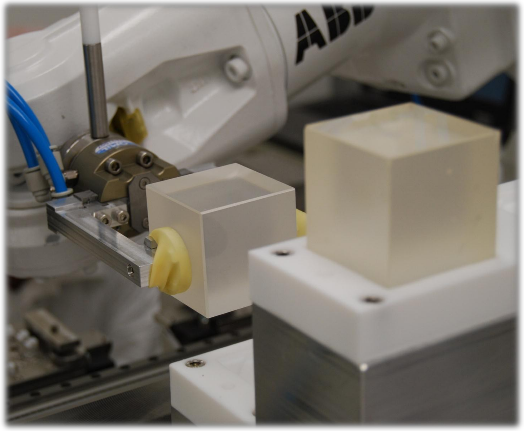


CUORE assembly line



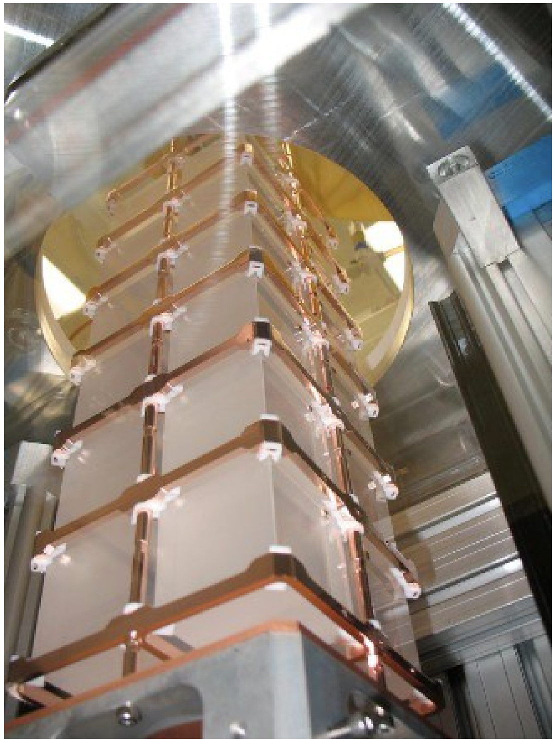
Standardized detector assembling procedure

- Handle a large number of detectors
- Improve reproducibility
- Ensure cleanliness

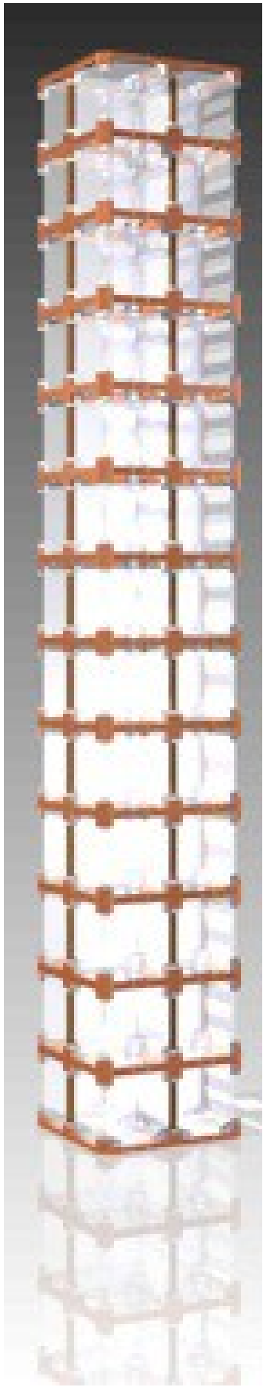


3 main steps

- Sensor gluing
- Tower assembly
- Bonding of sensor wires

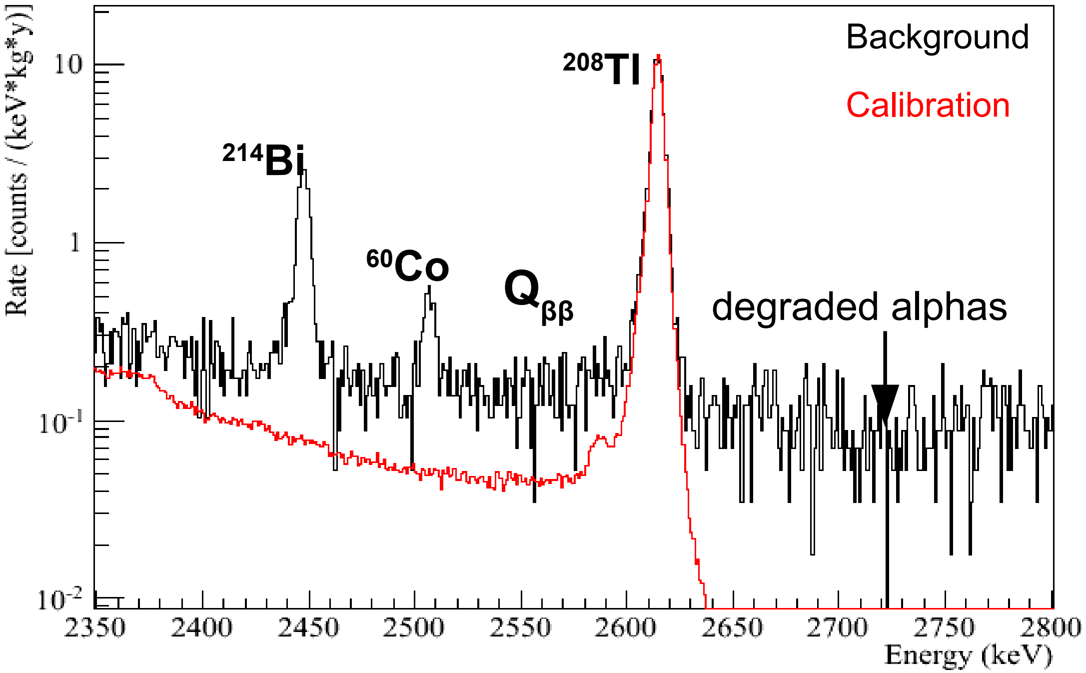


CUORE-0



- First tower of CUORE (52 TeO_2 crystals)
- Test the CUORE assembly line
- High statistics check of the radioactive background reduction
- High statistics check of the improvement in uniformity of detectors' response
- Identify operations that are critical for the success of CUORE
- Will be installed in the CUORICINO cryostat
  - Different suspension with respect to CUORE
  - Different shielding with respect to CUORE
- A sensitive double beta decay experiment by itself
- Data taking in 2012

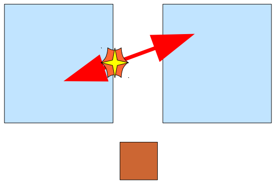
CUORICINO background



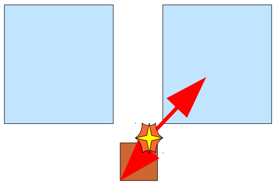
Background contributions at $Q_{\beta\beta}$

- ^{60}Co from cosmogenic activation: negligible
- Multi-Compton from ^{208}Tl (^{232}Th cont. in cryostat shields): ~40%
- Degraded alphas from crystal surfaces: ~10%
- Degraded alphas from Cu holders surfaces: ~50%
- Muon-induced background: negligible

Surface alpha contaminations produce a continuous spectrum that extends down to the $Q_{\beta\beta}$ region



Crystal contamination: double hit

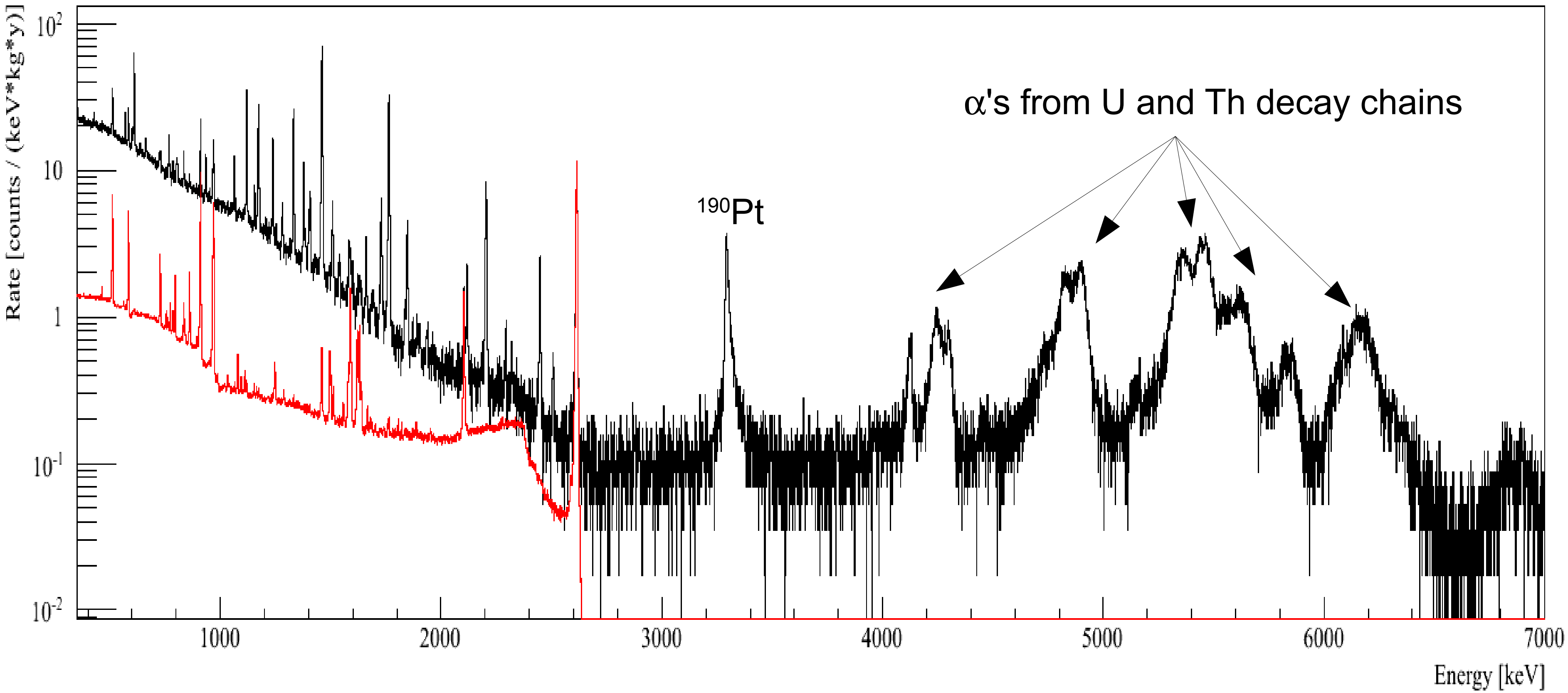


Copper contamination: single hit

Tests performed in the Hall C R&D facility showed that the alpha background can be reduced by proper cleaning procedures.

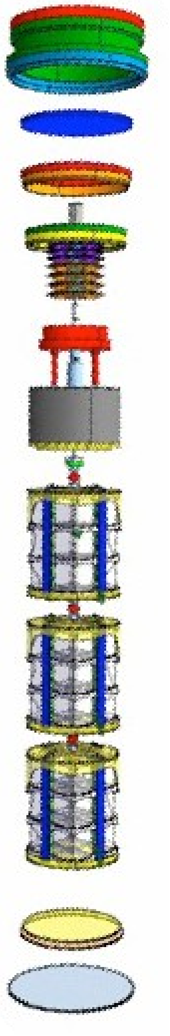
The crystal surface contribution is now under control, while the copper surface contribution is still a factor of 4 above the CUORE background goal (10^{-2} counts/(keV kg y))

Full CUORICINO energy spectrum



Degraded α's are the main source of background for CUORE

Three towers test



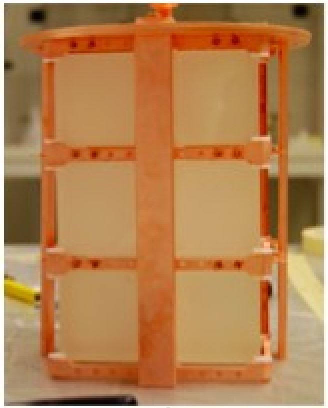
Test performed in 2008: Contemporary measurement of three identical towers in the same cryostat

The only difference was the the Cu cleaning procedure

T1

- Soap
- $H_2O_2 + H_2O$ + citric acid
- Copper covered with 7 layers of polyethylene

T2



- Soap
- 85% phosphoric acid + 5% butanol + 10% H_2O
- Nitric acid
- $H_2O_2 + H_2O$ + citric acid

T3

- Chemical erosion
- Electrochemical erosion
- Plasma cleaning

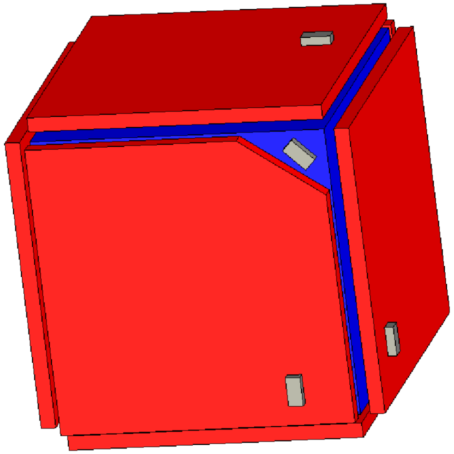
CUORE baseline

Best results from T1 and T2: 0.05 counts/(keV·kg·y) ⇨ Projection to CUORE: 0.04 counts/(keV·kg·y)

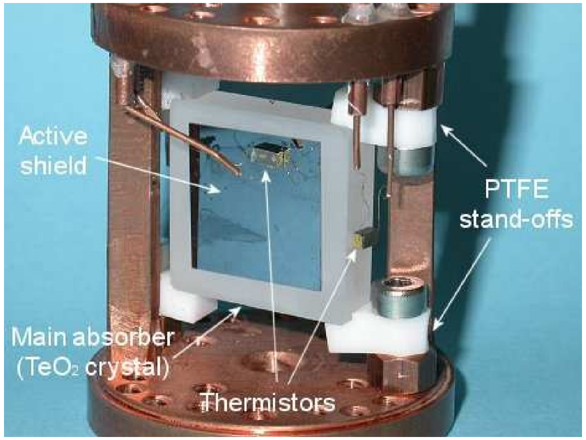
How to reduce the background?

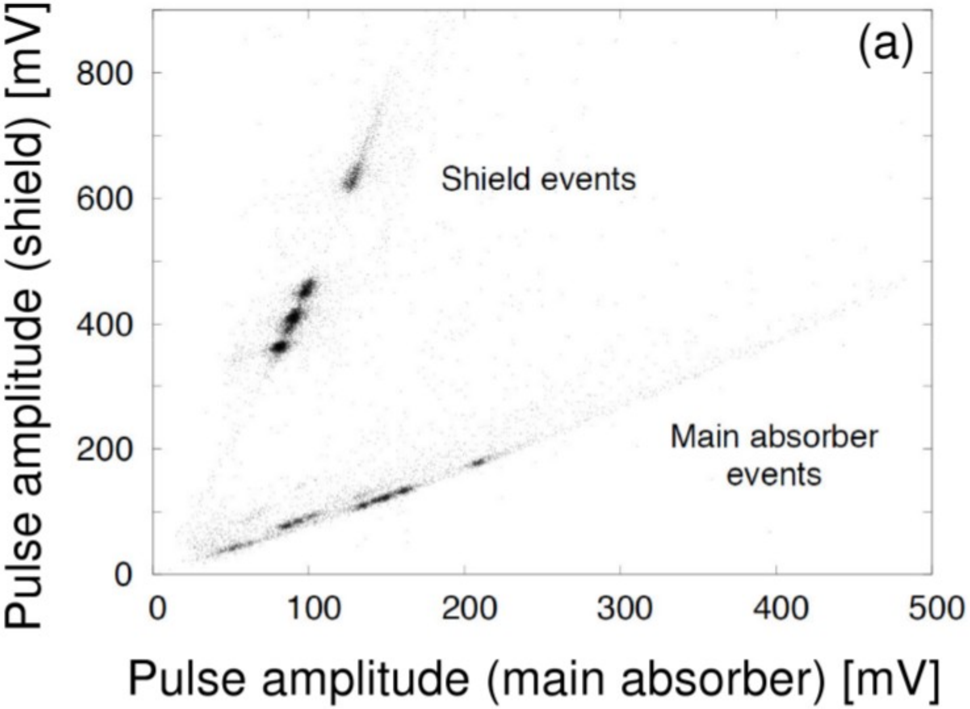
- Surface/bulk discrimination
- Particle discrimination

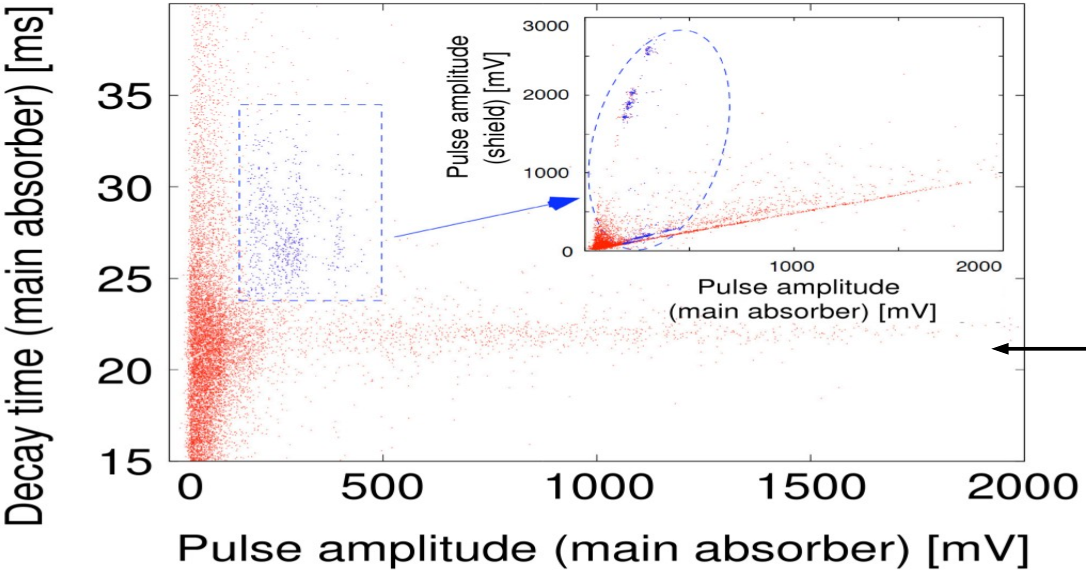
Surface sensitive bolometers



Cover the main absorber with sensitive elements provided with their own sensor, and discriminate surface/bulk events based on the relative amplitude of the signals







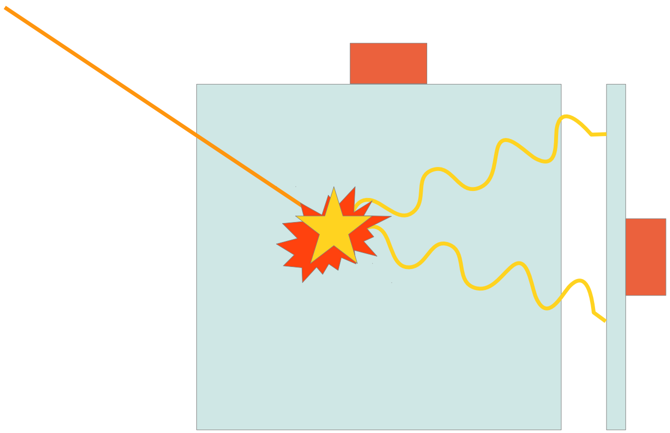
Potential to discriminate events based on the pulse shape of the main absorber: no need to read surface detectors

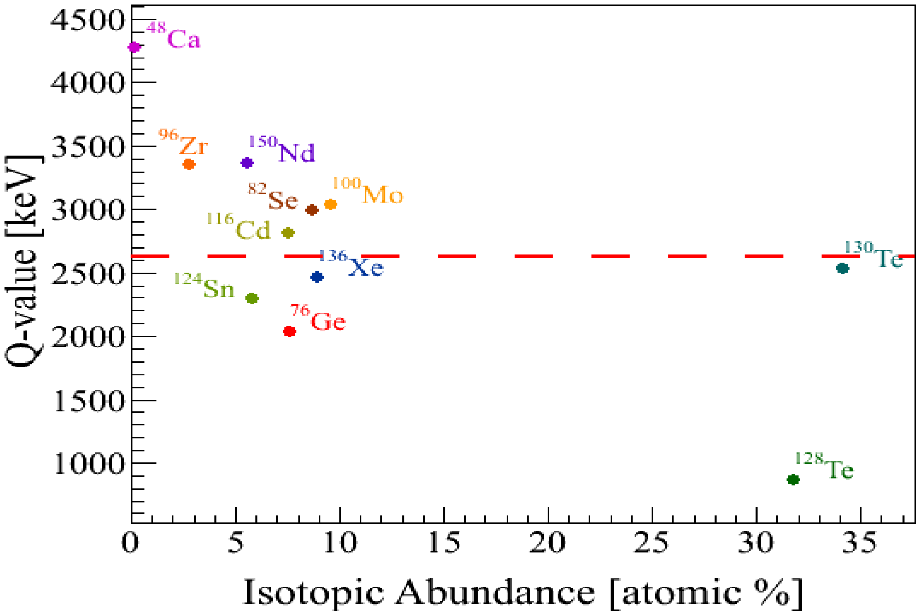
Astropart. Phys. 34 (2011) 809-821

Scintillating bolometers

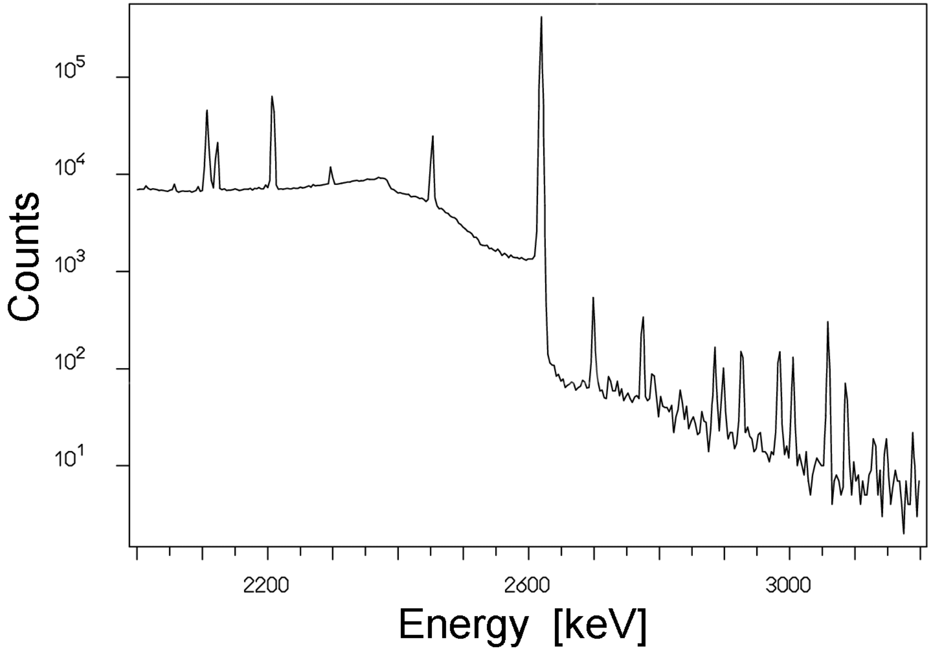
Reduce background exploiting different scintillation properties of α vs β/γ particles

Prefer isotopes with Q-value above 2615 keV (γ background is negligible)





Natural radioactivity γ spectrum



LUCIFER

Low-background Underground Cryogenics Installation For Elusive Rates

Scintillating compounds

$PbMoO_4$

$ZnSe$

$CdMoO_4$

$SrMoO_4$

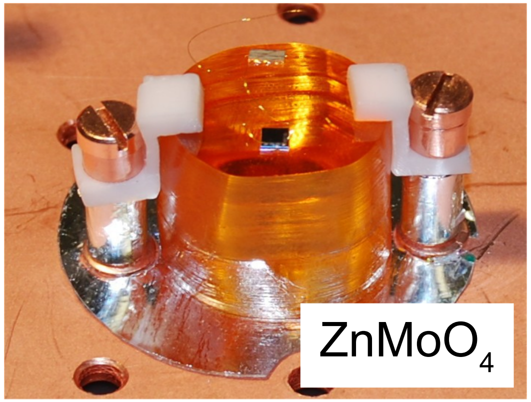
$CdWO_4$

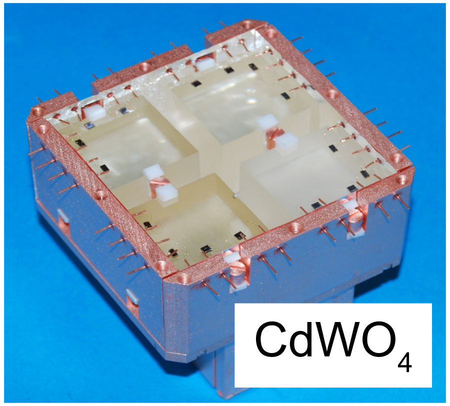
CaF_2

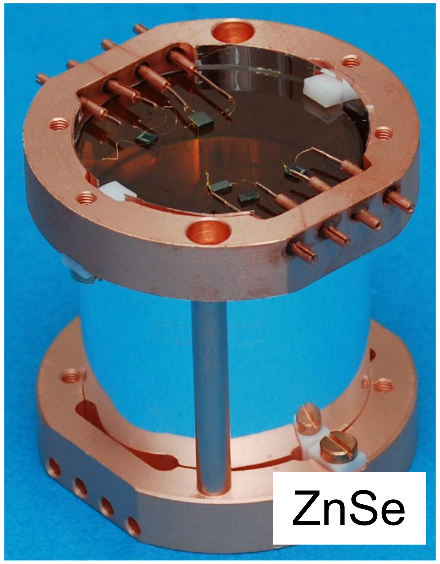
$CaMoO_4$

$ZnMoO_4$

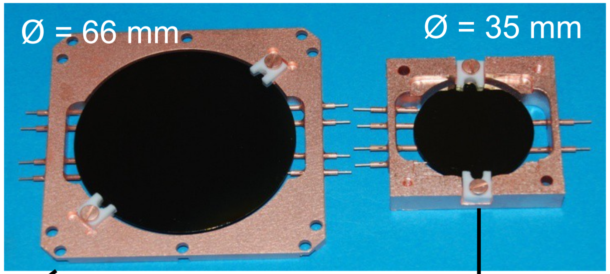
3 promising compounds based on scintillation properties and enrichment perspectives

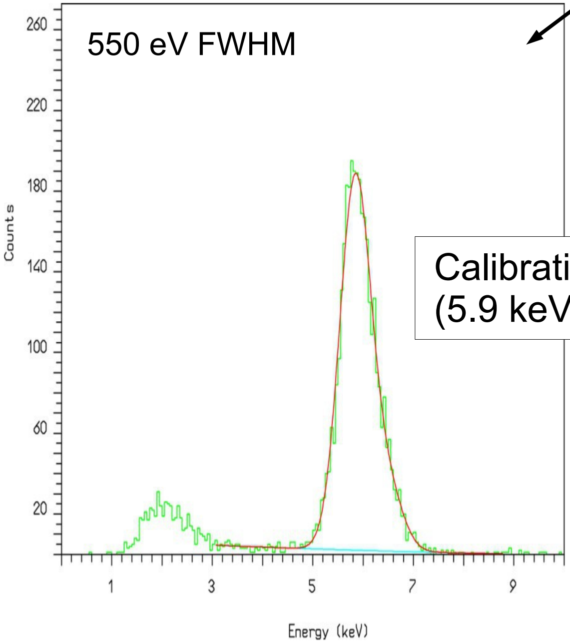


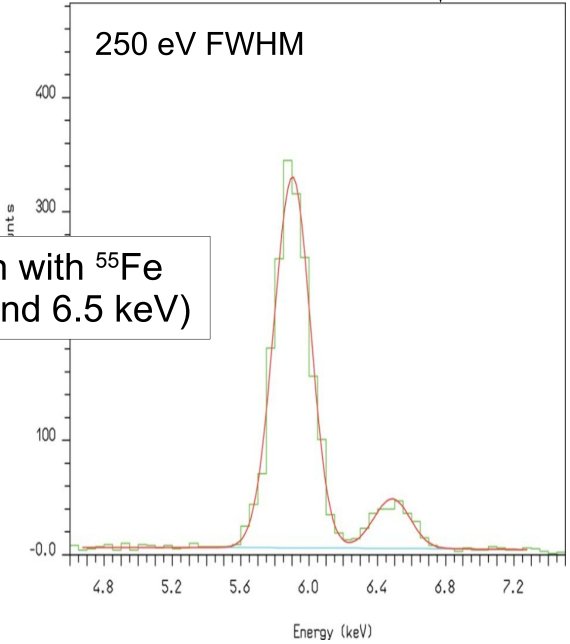




Light detector is also a bolometer (Ge slabs)

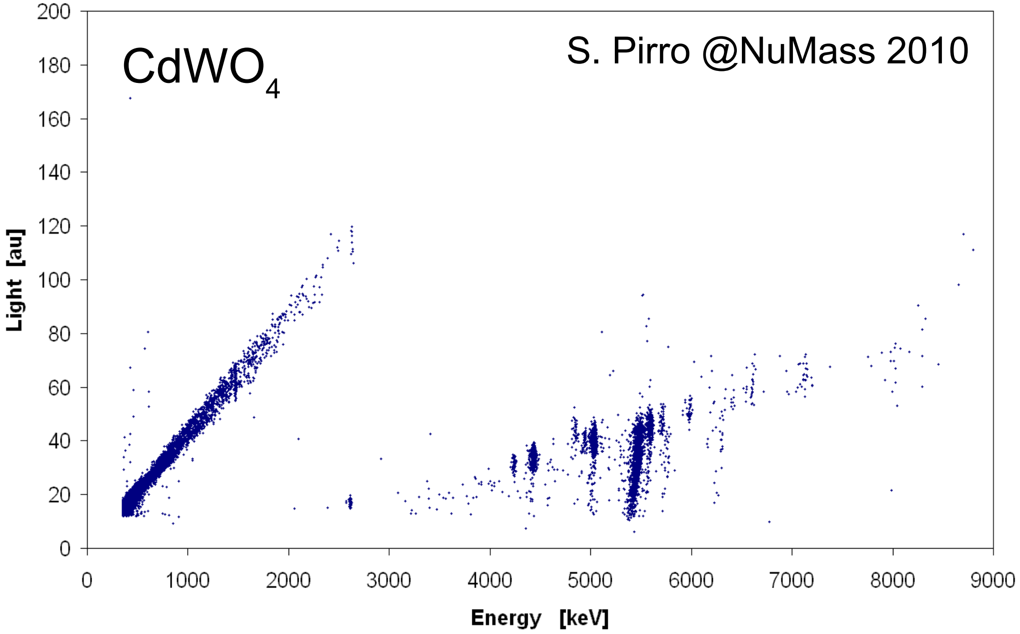




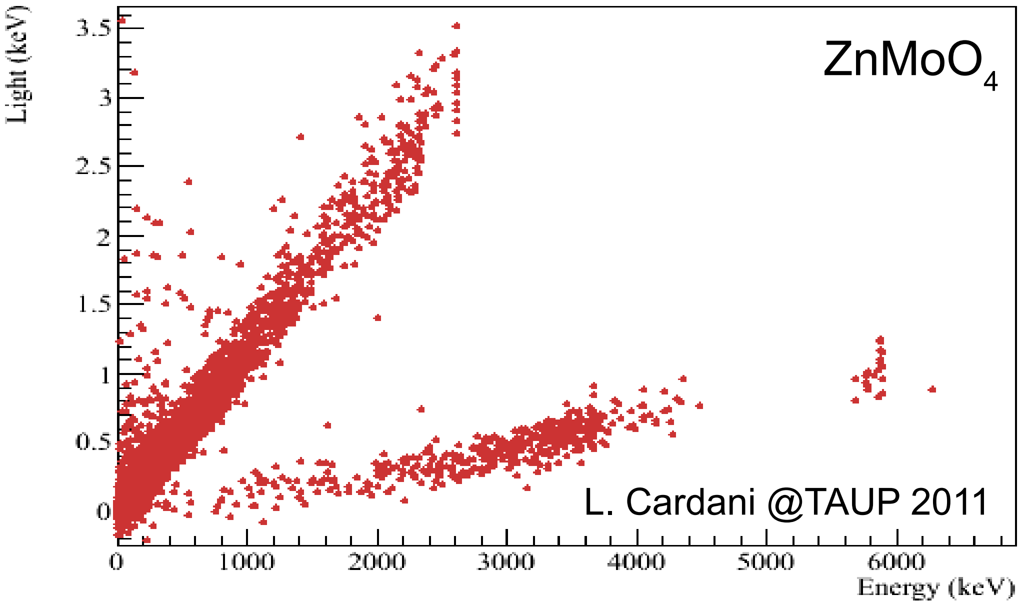


Calibration with ^{55}Fe
(5.9 keV and 6.5 keV)

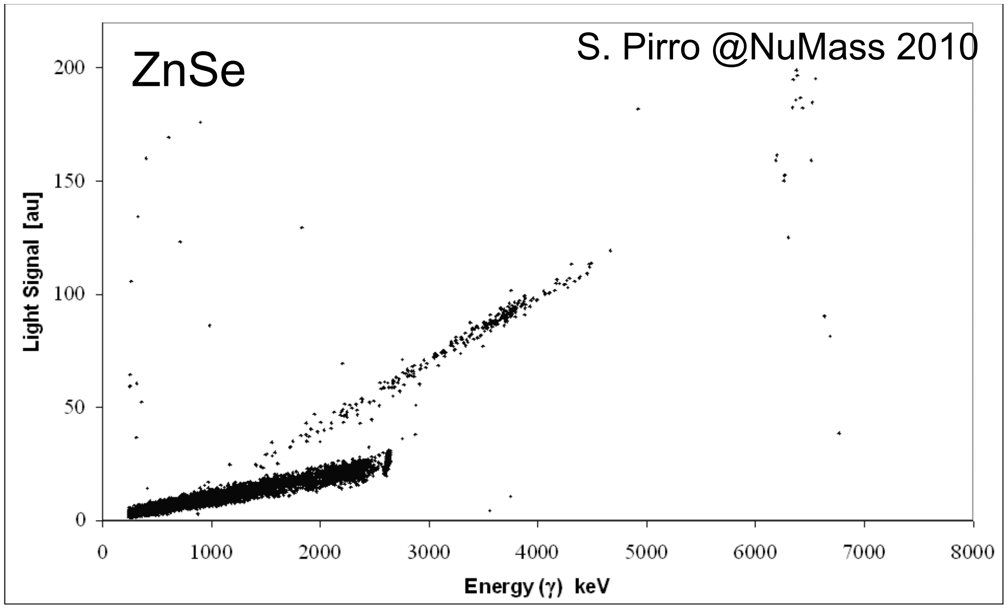
Light vs Heat signal



S. Pirro @NuMass 2010



L. Cardani @TAUP 2011

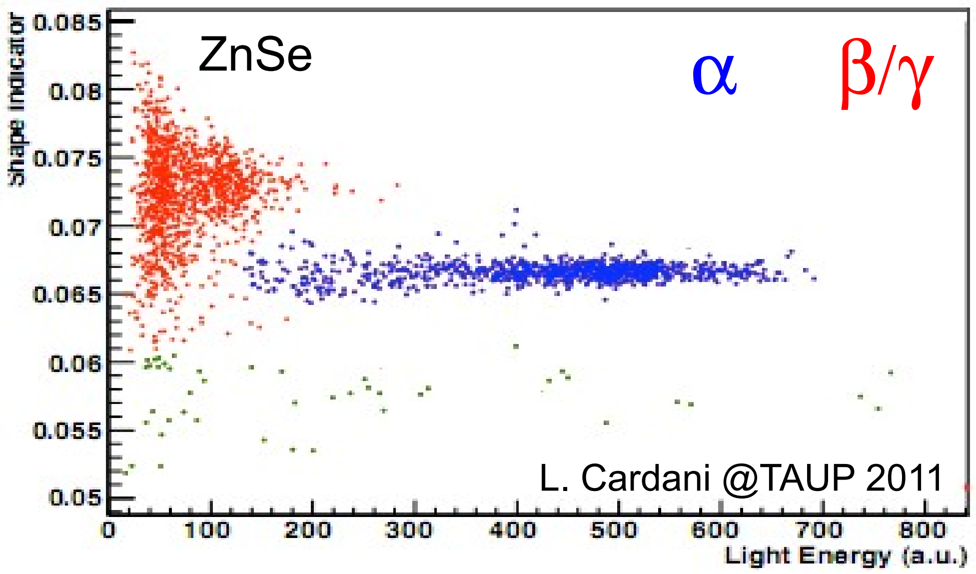


S. Pirro @NuMass 2010

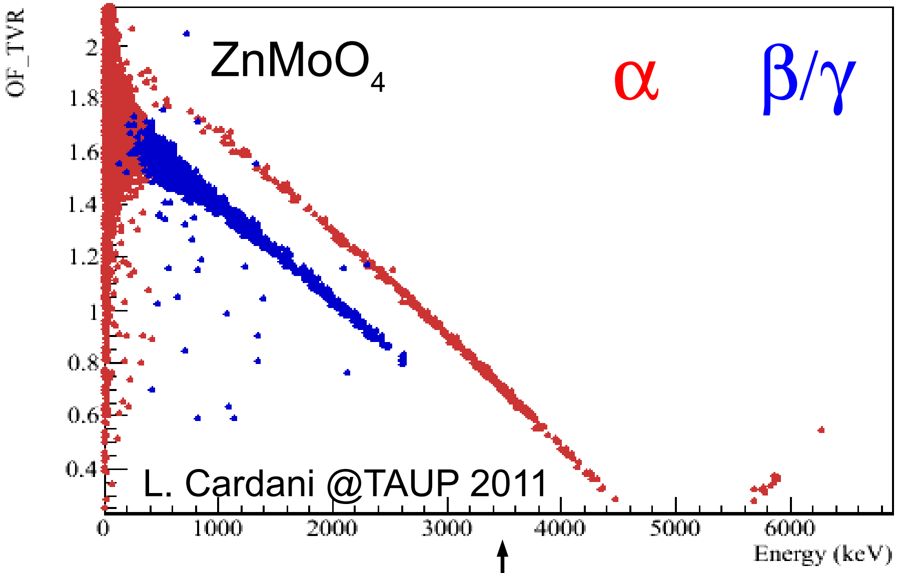
← ZnSe has a (still not understood) strange behavior: QF > 1

Astropart. Phys. 34 (2011) 344-353

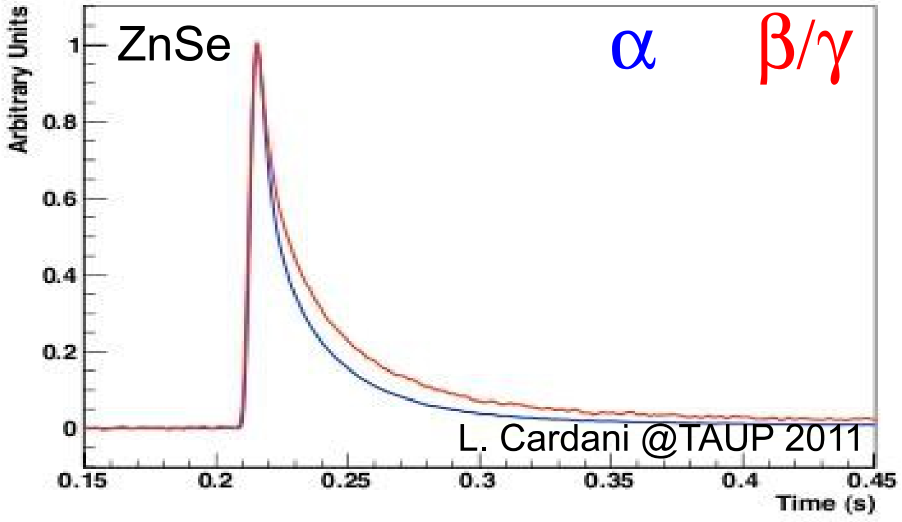
Pulse shape discrimination



L. Cardani @TAUP 2011



L. Cardani @TAUP 2011



L. Cardani @TAUP 2011

Some molibdates show the possibility to perform particle discrimination based on the heat signal only!

JINST 5 (2010) P11007

CUORE vs LUCIFER

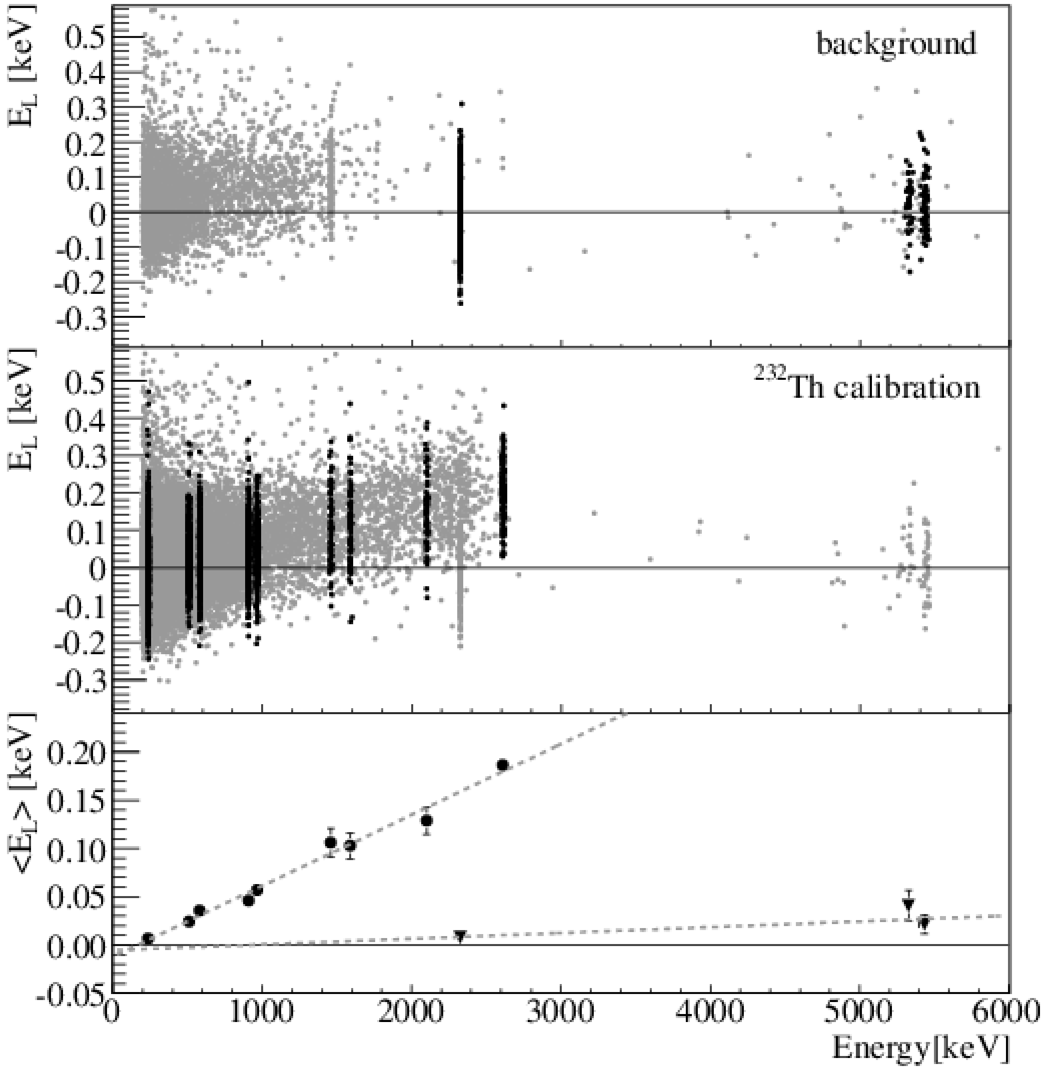
- Isotope: ^{130}Te
- Compound: TeO_2
- ΔE: 5 keV FWHM
- Data taking: 5y
- Isotope mass: 200 kg
- Bkg: 0.01 counts/(keV·kg·y)
- Half life sens: 1.6×10^{26} y
- $m_{\beta\beta}$ sens: 41-95 eV

- Isotope: ^{82}Se
- Compound: ZnSe
- ΔE: 5 keV FWHM
- Data taking: 5y
- Isotope mass: 17.6 kg
- Bkg: 0.001 counts/(keV·kg·y)
- Half life sens: 2.3×10^{26} y
- $m_{\beta\beta}$ sens: 52-65 eV

ArXiv:1109.0494v2

L. Cardani @ TAUP 20121

Particle discrimination in TeO_2



TeO_2 crystals do not scintillate
at cryogenic temperatures

It was pointed out that particle discrimination
could be based on cerenkov emission
Eur. Phys. J. ***C*** *65 (2010), p359*

Cerenkov threshold:
- 50 keV for electrons
- 400 MeV for alphas

Test with a Sm-doped TeO_2 crystal
equipped with a light detector

^{147}Sm α decay @ 2310 keV (β/γ region)

arXiv:1106.6286

Conclusions

- Bolometers can be built with a large variety of materials
- Absorber masses range from µg to kg
- The energy resolution is excellent
- Slow time response: can be used in experiments with low counting rates
- Bolometers have an important role in ν-mass and DBD experiments
- Active background rejection methods are available