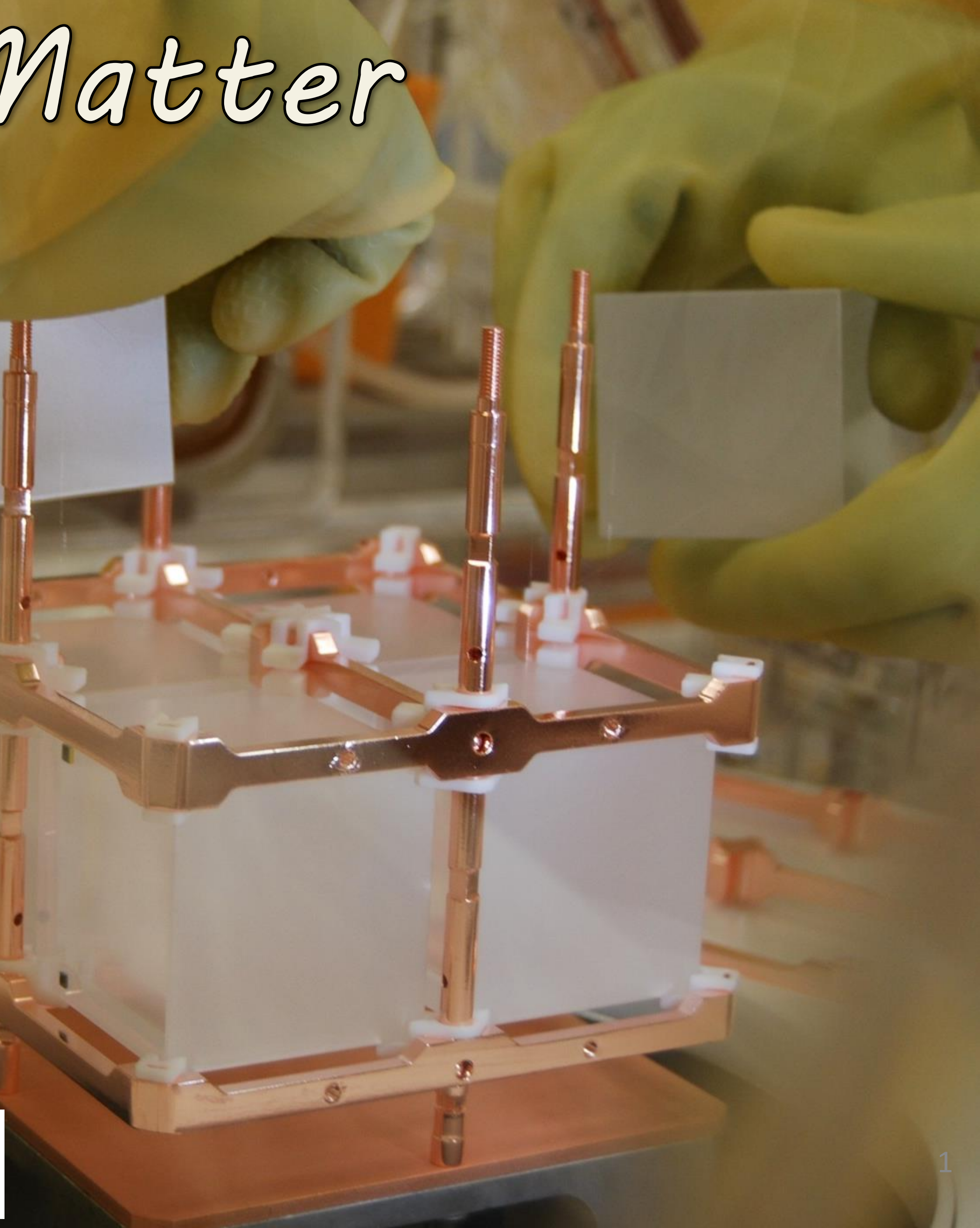
TeVPA/IDM, Amsterdam, 23-28 June 2014

$0\nu\beta\beta$ & Dark Matter Searches with CUORE-0 and CUORE



María Martínez
on behalf of the CUORE collaboration

MultiDark Multimessenger Approach for Dark Matter Detection

Universidad Zaragoza

araid FUNDACIÓN AGENCIA ARAGONESA PARA LA INVESTIGACIÓN Y EL DESARROLLO

The Cuore Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
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UNIVERSITY OF SOUTH CAROLINA
CSNSM
BERKELEY LAB
UCLA
LUX ET VERITAS
CUORE

Outline

- CUORE: $0\nu\beta\beta$ with TeO_2 bolometers
  - CUORE-0, the “CUORE demonstrator”
- DM searches with CUORE
- CUORE status
- Summary

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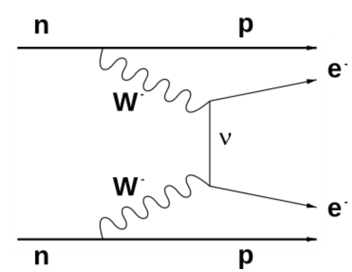
Experimental search for 0νββ

WHAT WE ARE LOOKING FOR

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

- *allowed in the SM and already observed with $T_{1/2} > 10^{18}$ y*

0νββ: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

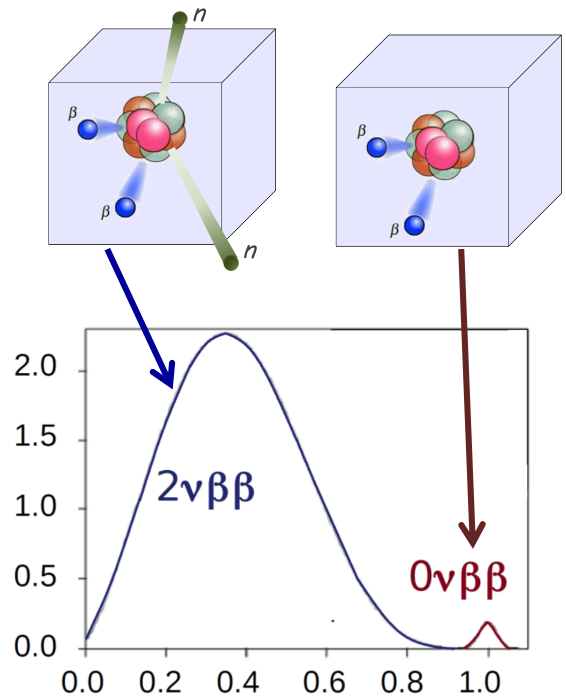


- *not allowed in the SM*
- *expected with $T_{1/2} > 10^{25}$ y*

If observed ⇒ $\nu \equiv \bar{\nu}$, $m_\nu \neq 0$

EXPERIMENTAL SIGNATURE

Approach:
SOURCE = DETECTOR



Main signature:
Peak at Q-value over 2νββ tail enlarged only by detector resolution

EXPERIMENTAL SENSITIVITY

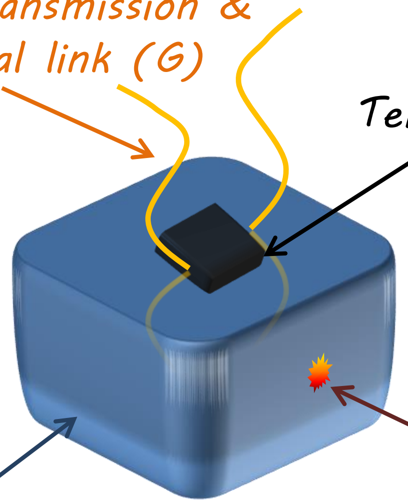
Lifetime corresponding to the minimum detectable number of events over background at a given C.L. (*):

$$S^{0\nu} \propto \frac{\epsilon\, a.i.}{A}\left(\frac{MT}{b\,\Delta E}\right)^{1/2} \qquad b \neq 0$$

- **M:** *Total active mass in kg*
- **ε:** *Detector efficiency*
- **a.i.:** *Isotopic abundance*
- **b:** *Background in c/keV/kg/y*
- **ΔE:** *Detector resolution @ ROI in keV*
- **T:** *Exposure time in y*

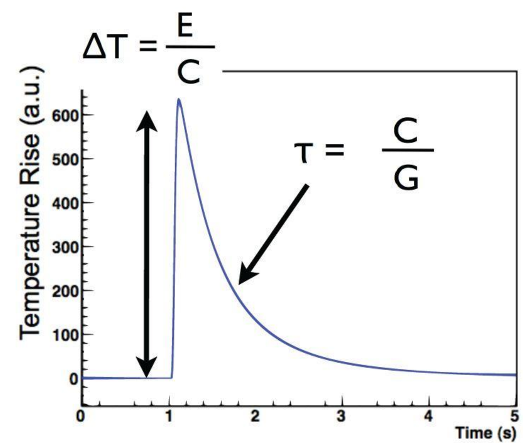
(*) Qualitative expression in the Gaussian approximation (not fully accurate for very low background experiments)

The bolometric technique

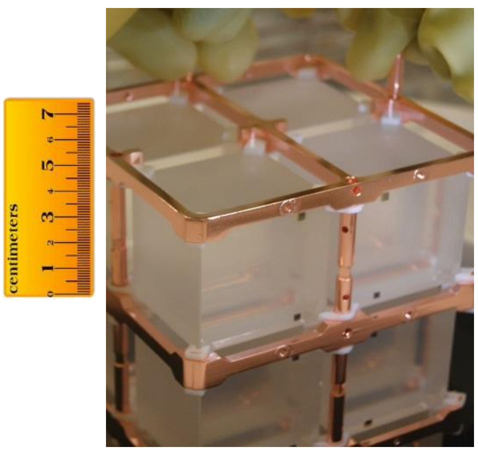


$$A = \frac{|dLog(R)|}{|dLog(T)|}$$

- The energy release originates a temperature rise: $\Delta T = \frac{E}{C(T)}$
- The temperature sensor converts the temperature rise in an electric signal:



CUORE TeO_2 bolometers:



T ~ 10 mK
M ~ 0.75 kg
C ~ 2 x 10^{-9} J/K
ΔT/ΔE ~ 100 μK/MeV
ΔV/ΔE ~ 300 μV/MeV
G ~ 2 x 10^{-9} W/K
τ = C/G ~ 1 s

- **Excellent energy resolution!**

$\uparrow\uparrow N_{phonons} = \frac{C(T)T}{K_B T} \Rightarrow$ Statistical limit to energy resolution: $\sigma = T\sqrt{C(T)K_B} \sim 10\ eV - 1\ keV$

- **Wide target choice**
  - Dielectric & diamagnetic materials
  - Intrinsic semiconductors

$$C(T) \propto \left(\frac{T}{\theta_D}\right)^3$$

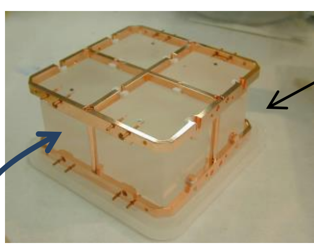
The CUORE experiment

Cryogenic Underground Observatory for Rare Events

Primary goal: search for neutrinoless double beta decay in ^{130}Te ($Q_{\beta\beta} \simeq 2528$ keV , i.a. = 34.167%)

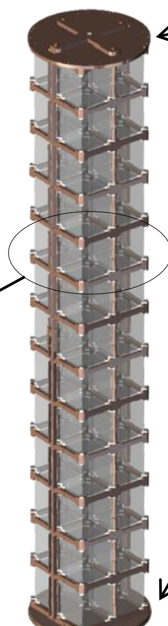
988 TeO_2 5x5x5 cm^3 crystals (750 g each)
Detector Mass: 741 kg TeO_2

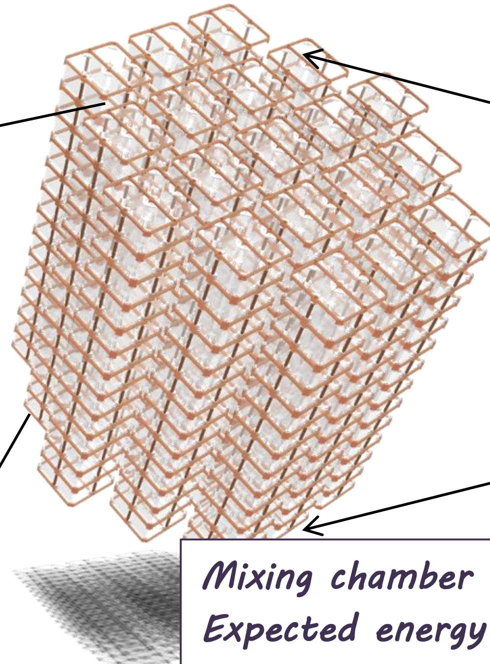
13 floors

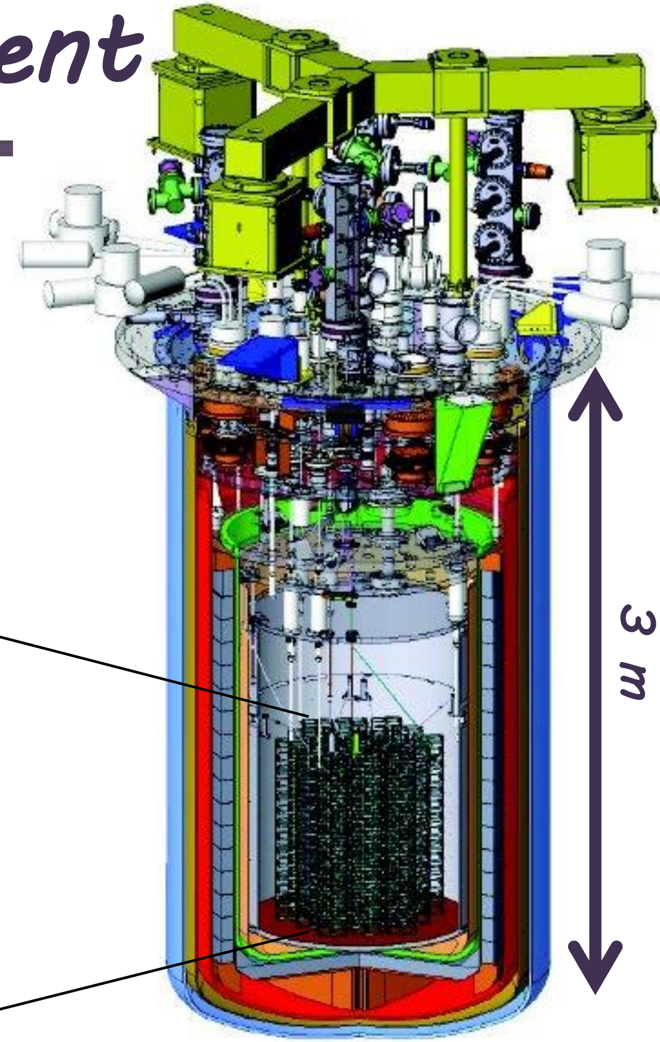


5x5x5 cm TeO_2 crystals

19 towers



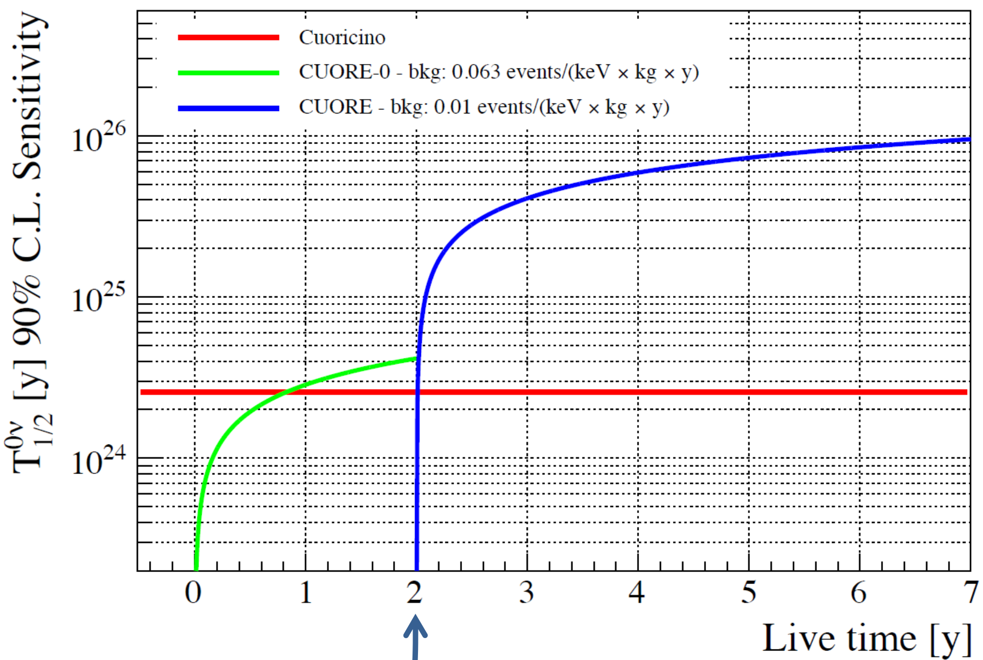




3 m

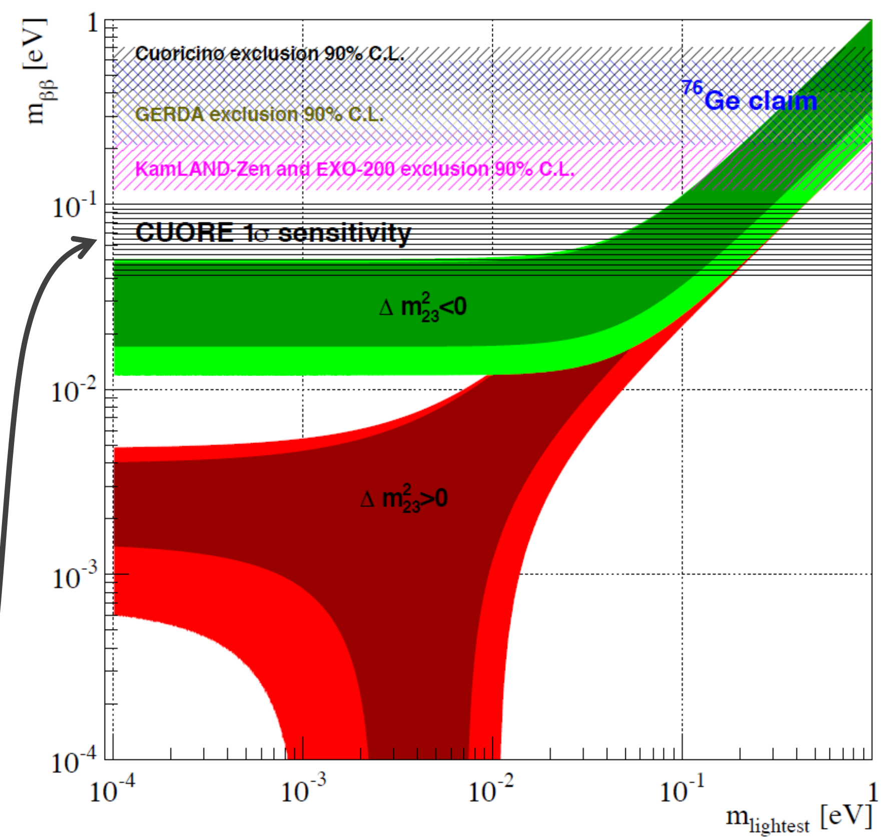
Mixing chamber T: ~ 5 mK
Expected energy resolution @ 2615 keV: 5 keV
Background goal: 0.01 c/keV/kg/y @ ROI
Projected $0\nu\beta\beta$ sensitivity (1 σ): $T_{1/2} > 1.6 \times 10^{26}$ y

CUORE sensitivity



Design sensitivity goal:

- background: 0.01 c/keV/kg/y
- 5 keV FWHM
- 5 years of live time



$S_{1/2}$ ($0\nu\beta\beta$):

1.6×10^{26} y (1 σ)

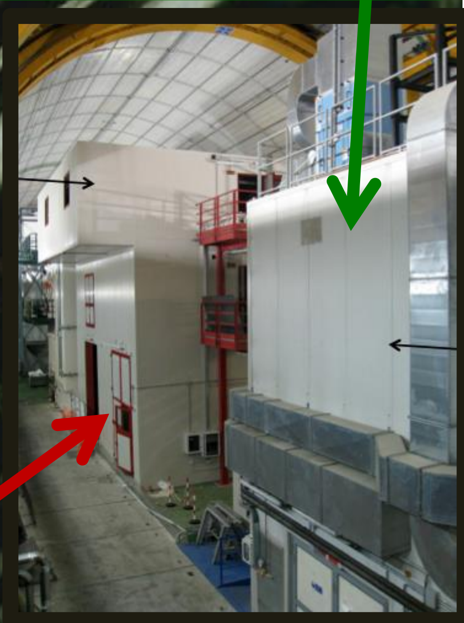
9.5×10^{25} y (90% CL)

In terms of effective Majorana mass:

$\langle m_{ee} \rangle \sim$ 40-100 meV (1 σ)

LOCATION

Laboratori Nazionali del Gran Sasso (ITALY) (3600 m.w.e.)



Evolution of TeO_2 bolometric experiments

MiDBD
6.8 kg TeO_2
(1.8 kg ^{130}Te)

1997-2001

$T_{1/2}^{0\nu} > 2.1 \times 10^{23}$ y [1]

Cuoricino
40.7 kg TeO_2
(11.3 kg ^{130}Te)

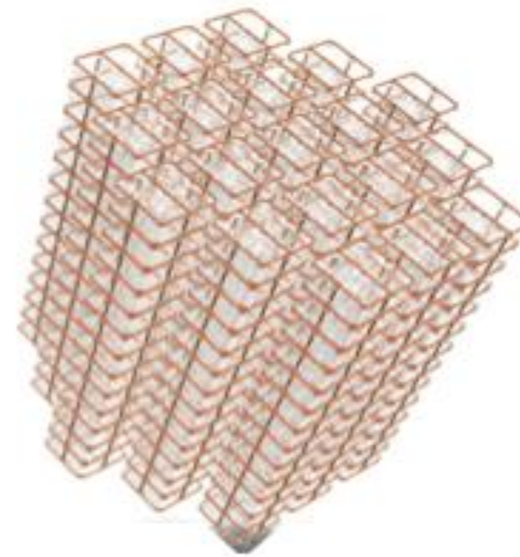
2003-2009

$T_{1/2}^{0\nu} > 2.8 \times 10^{24}$ y [2]

CUORE-0
39 kg TeO_2
(11 kg ^{130}Te)

2013···2016

CUORE
741 kg TeO_2
(206 kg ^{130}Te)



2015···

?

[1] C. Arnaboldi et al., Phys. Lett. B 557 (2003) 167-175
[2] E. Andreotti at al., Astrop. Phys. 34 (2011) 822-831

CUORE-0

1 CUORE-like tower of 13 planes - 4 crystals each
52 TeO_2 5x5x5 cm^3 crystals (750 g each)
Detector Mass: 39 kg TeO_2
^{130}Te mass (natural i.a.): 11 kg of ^{130}Te

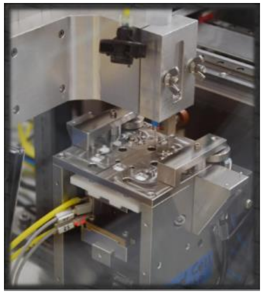
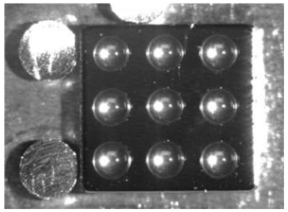
- All detector components manufactured, cleaned and stored with protocols defined for CUORE
- Assembled with the same procedures of CUORE
  … **in the 25 years-old CUORICINO cryostat**

GOALS:

- Proof of Concept for CUORE in all stages
- Test and debug the CUORE assembly line (thermistor gluing, signal wires bonding, tower assembly)
- Test of the CUORE DAQ and analysis framework
- Extend the physics reach beyond CUORICINO while CUORE is being assembled
- Demonstrate potential for DM and other rare events searches

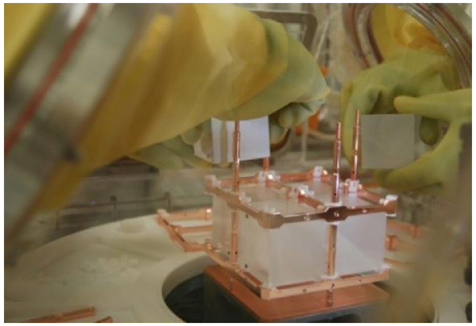
CUORE-0/CUORE tower assembly line

Thermistor gluing

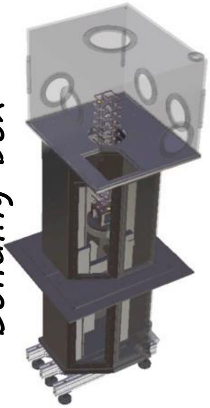
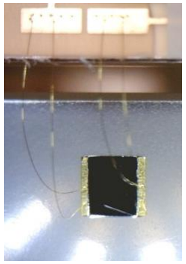
Tower assembly

Mounting box

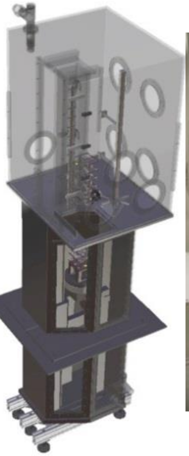
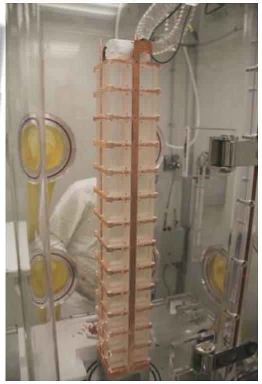



Signal wires connection

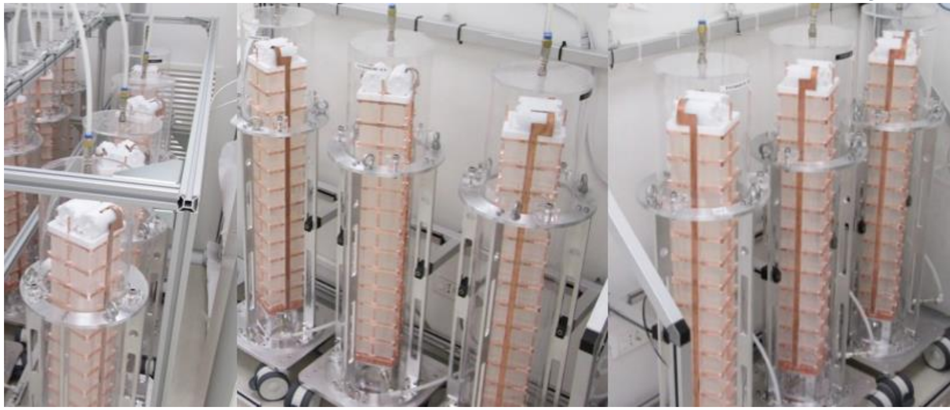
Bonding box

Cabling box

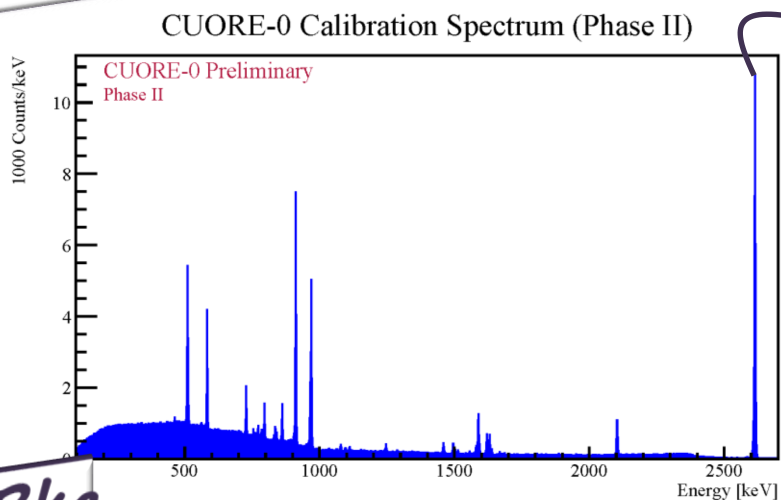
Towers storage

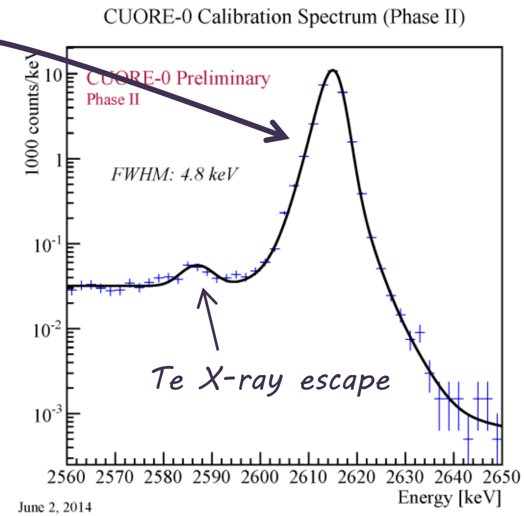


The successful operation of CUORE-0 demonstrated the validity of the CUORE tower assembly line and of the CUORE cleaning procedures.

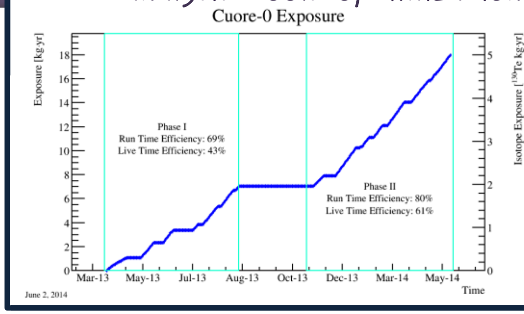
CUORE-0 energy resolution & background

FWHM





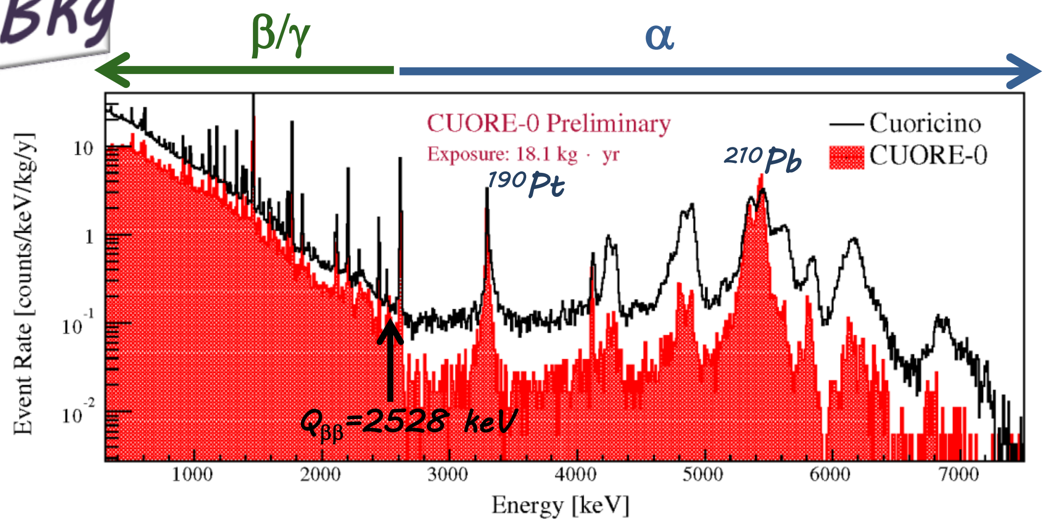
PHASE II:
Improved working conditions & analysis tools optimization



FWHM resolution estimated @ 2615 keV during calibrations ≤5 keV

CUORE goal reached!

Bkg



Cuoricino background model confirmed:

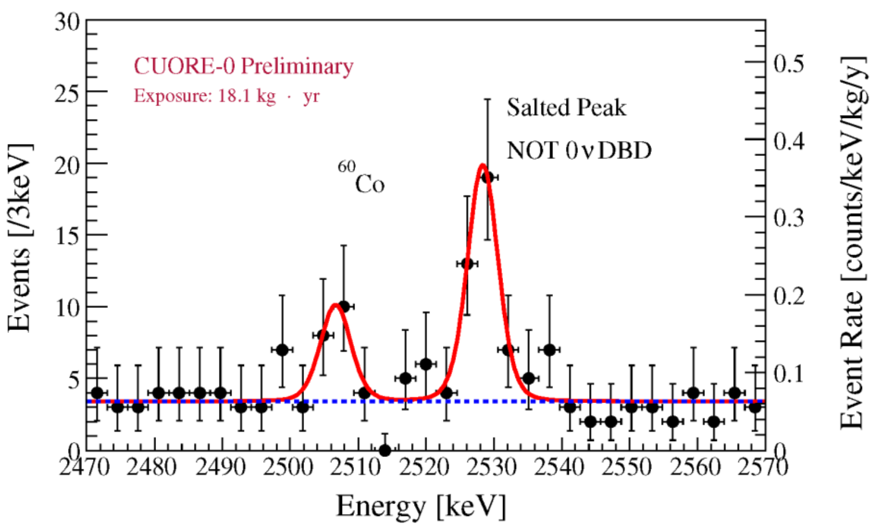
- environmental γ from material bulk contaminations
  -> mainly from cryostat (same as Cuoricino)
- surface (α) contaminations of close materials

Evident reduction with respect to Cuoricino

- factor of 6 for surface contaminations
- factor ~2.5 in the ROI

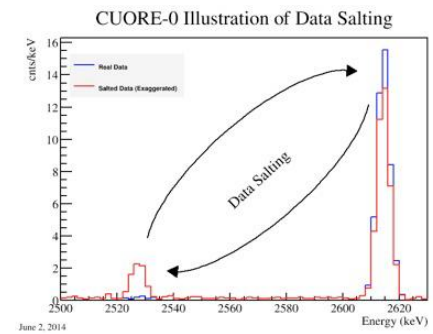
	$0\nu\beta\beta$ ROI c/keV/kg/y	2700-3900 keV c/keV/kg/y	ε(%)
Cuoricino	0.153±0.006	0.110±0.001	83
CUORE-0	0.063±0.006	0.020±0.001	78

CUORE-0 sensitivity



Bkg spc blinded!!

Blinded procedure: artificial peak generated in the ROI by exchanging some 2615 keV ⇌ $Q_{\beta\beta}$ ±10 keV events



Unblinding: early 2015

PROJECTED SENSITIVITY:

Energy resolution:

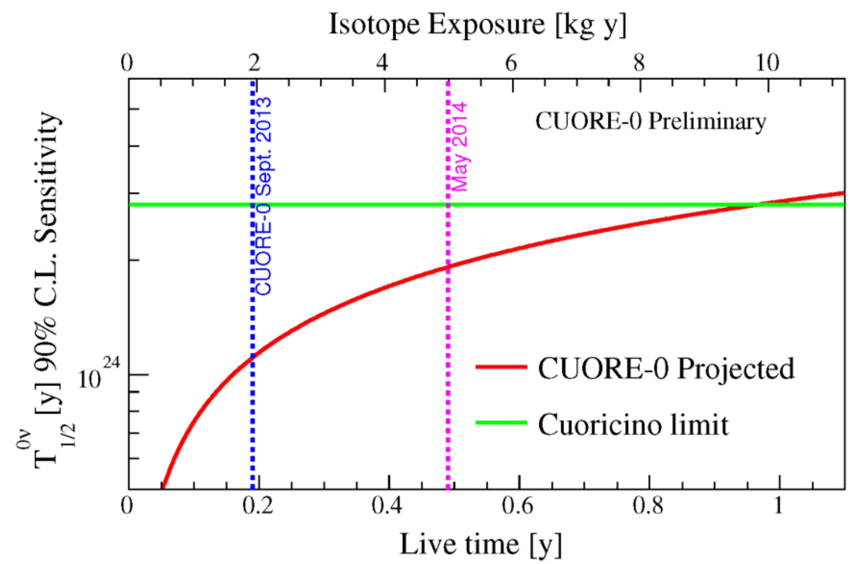
~ 5.2 keV FWHM @ 2615 keV

(corresponding to full statistics on bkg data)

Background @ ROI:

0.063 ± 0.006 c/keV/kg/y

CUORE-0 expected to surpass Cuoricino sensitivity with ~ 1 year of livetime



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  - CUORE-0, the "CUORE demonstrator"
- **DM searches with CUORE**
- CUORE status
- Summary

TeO_2 bolometers for DM

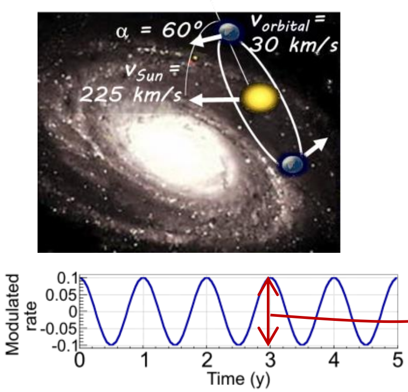
☺ Very good energy resolution
☺ Low energy threshold achievable [3]
☺ Quenching factor NR/e⁻R close to 1 [4]
☺ Sensitive to light and heavy WIMPs

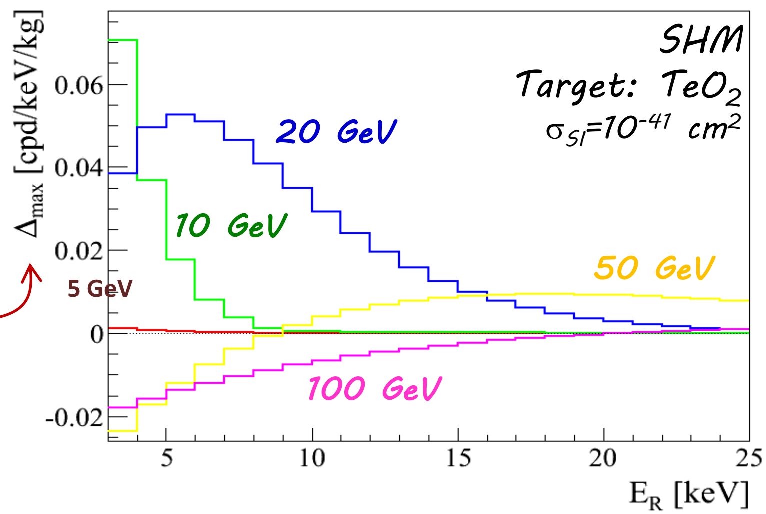
[3] Di Domizio et al., JINST 6 (2011) P02007
[4] A. Alessandrello et al., Phys. Lett. B 408 (1997) 465-468

☹ Limited sensitivity to SD interaction (^{123}Te, i.a.=0.91 %, unpaired n
^{125}Te, i.a.=7.14 %, unpaired n)
☹ No scintillation light (-> no particle discrimination NR/γ)

- Ton-scale detector mass
- Low background (material selection)
- Controlled operating conditions
- Long data-taken period scheduled

➡ Look for Dark Matter ANNUAL MODULATION





CUORICINO energy threshold: ~ tens of keV

Threshold reduction is needed for CUORE

Lowering the energy threshold

Di Domizio et al., JINST 6 (2011) P02007

New trigger algorithm for low energy events:

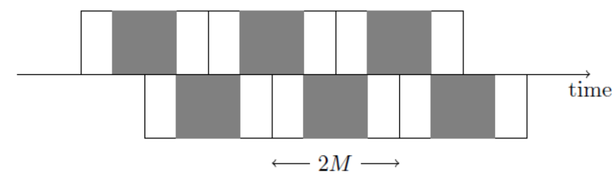
- *Filter continuosly "slices" of data with Optimum Filter algorithm (improves S/N)*
- *Then apply simple threshold trigger to filtered data*

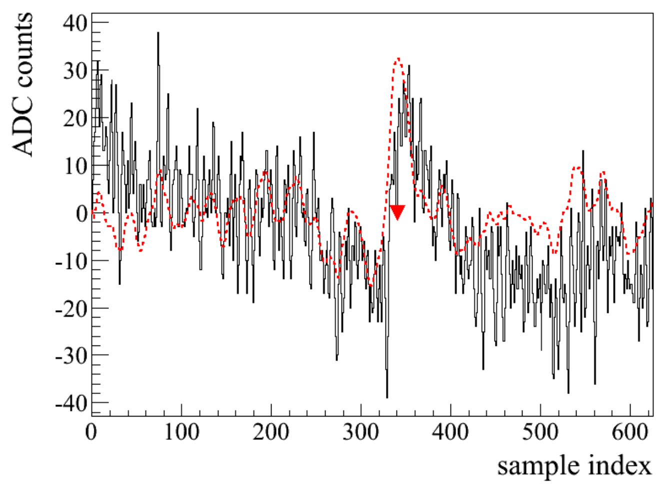
Optimum Filter:

$$H(\omega_k) = h\frac{S^*(\omega_k)}{N(\omega_k)}e^{-i\omega_k t_M}$$

Where:
$S(\omega_k)$: expected average signal (estimated from data)
$N(\omega_k)$: Noise power spectrum (estimated from data)

Filter data continuously in slices



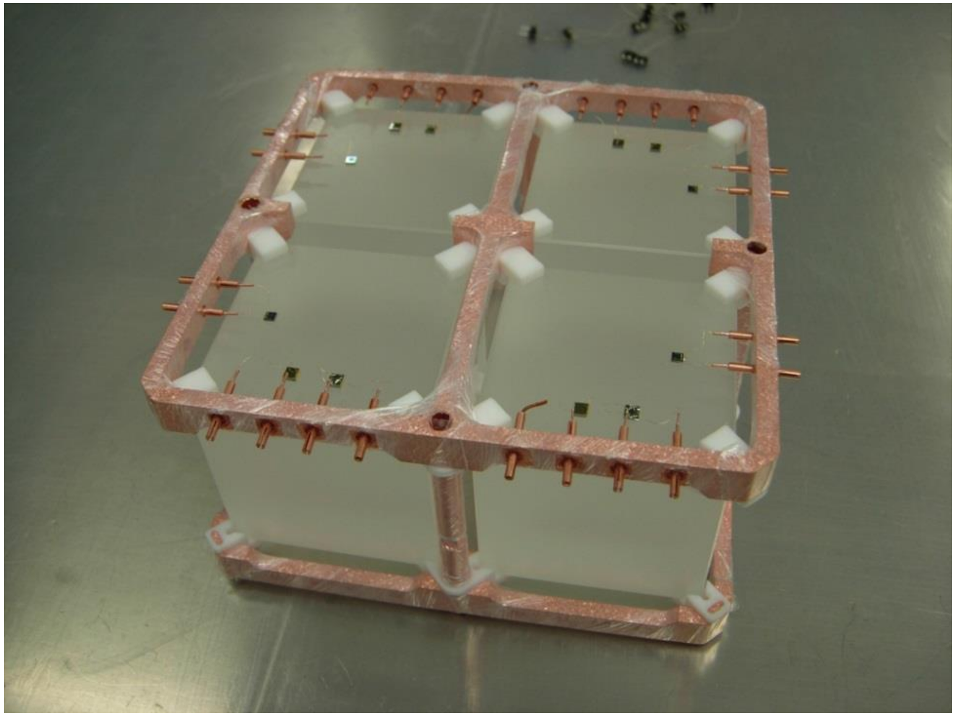


- *Filtered samples (RED) are less noisy than original ones*
- *Baseline fluctuations are reduced*
- *Filter sensitive to the shape of the expected signal, suppressing non physical pulses*

Low energy study in CUORE-like crystals

The CUORE Collaboration, JCAP (2013) 038

A low energy analysis using this trigger algorithm has been performed on CUORE crystals (CCVR2, "CUORE Crystals Validation Runs (*) No 2")



- *Four CUORE-like crystals (B1, B2, B3, B4)*
  Total mass 3 kg
- *Data taken in June 2009 in the Hall C R&D cryostat:*
  19.4 days of live time

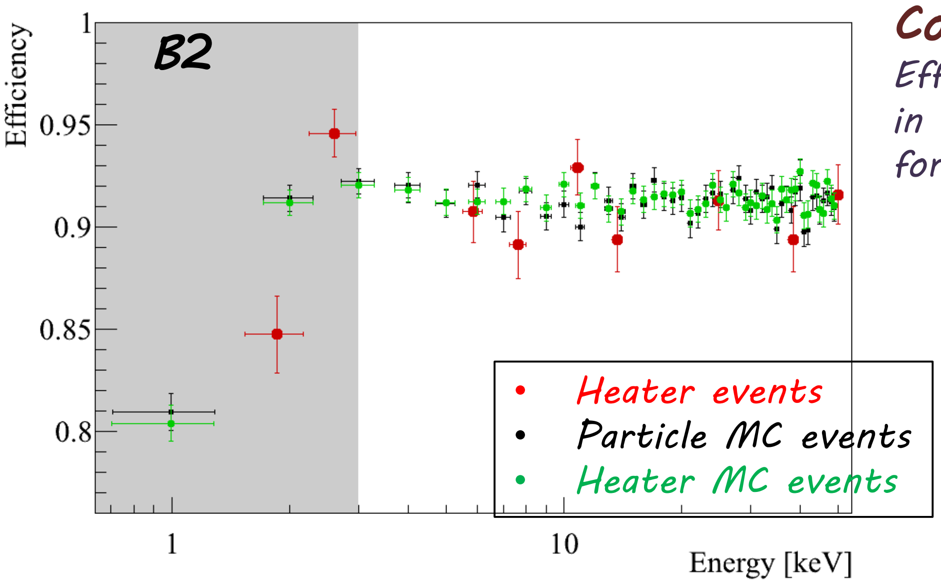
(*) Series of test of CUORE crystals arriving at LNGS (test four crystals from each batch)[6][7]

[6] Arnaboldi et al., Journal of Crystal Growth 312 (2010) 2999
[7] Alessandria et al., Astrop. Phys 35 (2012) 839-849

Trigger efficiency and energy threshold

- Physical pulses ranging from 1 to 50 keV are generated by a joule heater glued to each crystal
- The detection efficiency is estimated as the ratio detected/expected heater pulses as a function of energy
- The method is validated for particle pulses (slightly different in shape from heater pulses) by a MC event simulator[8] (pulses + noise)

[8] M. Carrettoni and M. Vignati, JINST 6 (2011) P08007



Constant efficiency ~0.9 down to ~3 keV

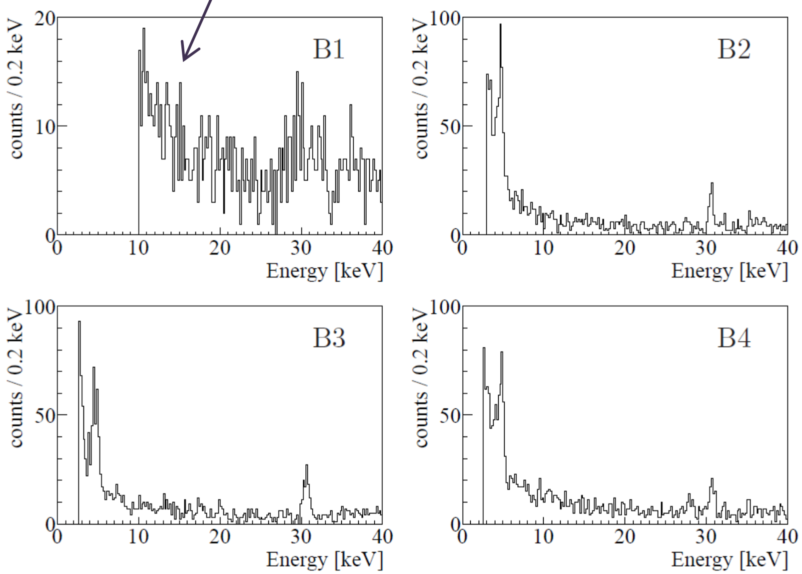
Efficiency dominated by ^{210}Po rate (usual contamination in new crystals), $T_{1/2}$= 147 days, expected to be ≈ 1 for aged crystals.

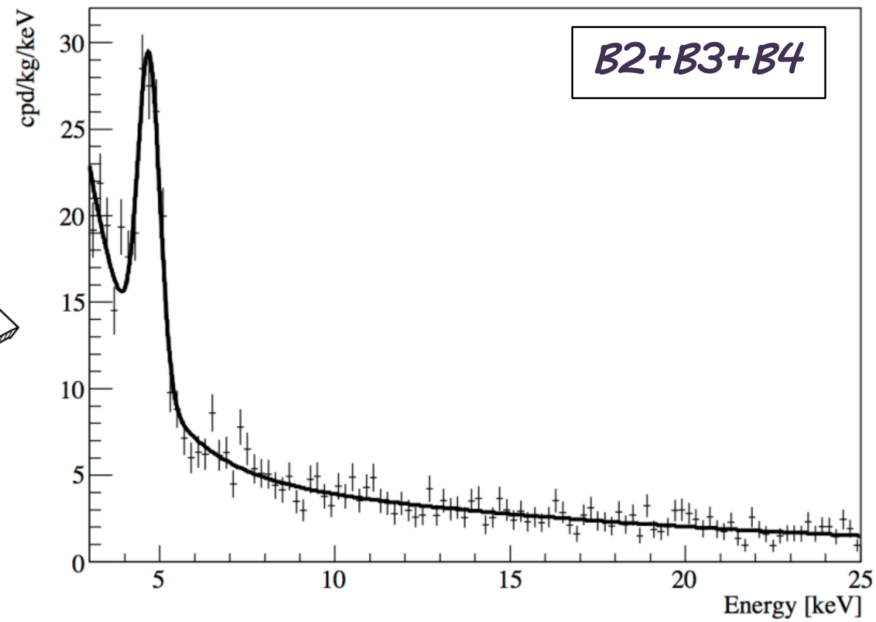
Crystal	Threshold (keV)
B1	10.0
B2	3.0
B3	2.5
B4	2.5

≤ 3 keV threshold reached in 3/4 crystals

Low energy background CCVR2

Noisy, not used in the analysis





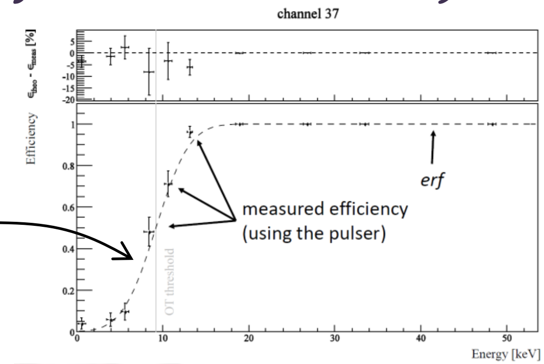
- *Background ranging from 25 c/keV/kg/d @ 3 keV to 2 c/keV/kg/d @ 25 keV*
- *A peak (presently unknown origin) at 4.7 keV*

Low energy analysis in CUORE-0

- Low energy trigger efficiency & threshold periodically monitored in dedicated runs (joule heater pulses ranging from 1 - 50 keV)

Function to model efficiency Vs E:

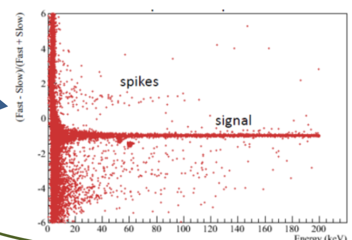
$$Eff(E) = \frac{1}{2} erf\left(\frac{E - E_{thr}}{\sqrt{2}\,\sigma}\right) + \frac{1}{2}$$

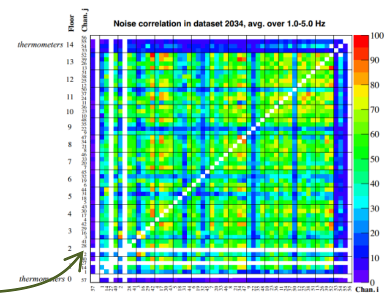


Efficiency = 1 above threshold

- Higher noise event rate than in CCVR2, specially below 10 keV (Cuoricino cryostat!!)

Need to improve PSA and noise decorrelation techniques





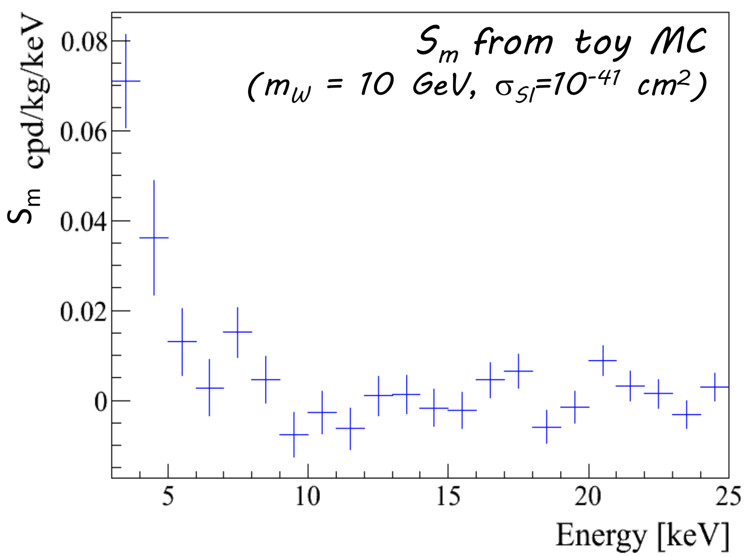
- Attained by now:
  - Threshold: 5 - 10 keV in most channels
  - Bkg level: ~ 1 - 2 c/keV/kg/d down to 4.7 keV peak **(factor ~2 reduction with respect to CCVR2)**

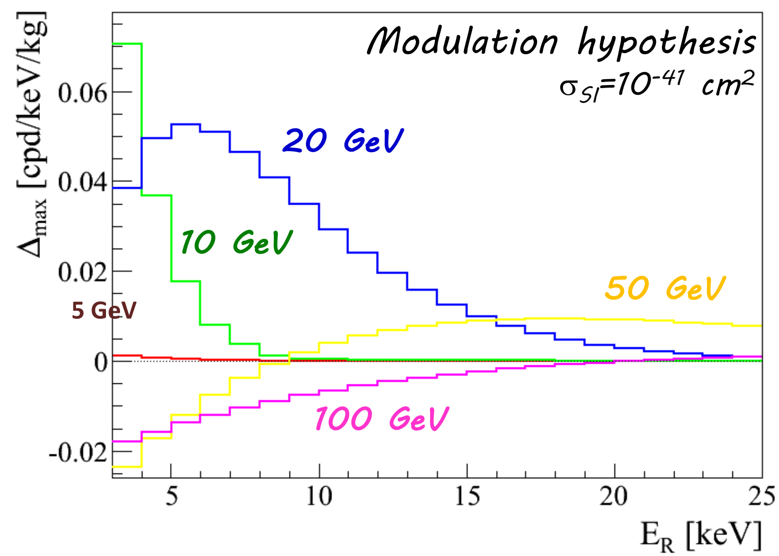
Sensitivity to annual modulation

The sensitivity to DM annual modulation in CUORE-0 /CUORE has been evaluated with toy Monte Carlo's:

For every m_W :

- *simulate bkg + signal modulated amplitude S_m (2nd December – 2nd June in 3 month-windows)*
- *find σ_{SI} that makes the probability of the modulation hypothesis greater than the absence of modulation hypothesis at least 90% of the times.*

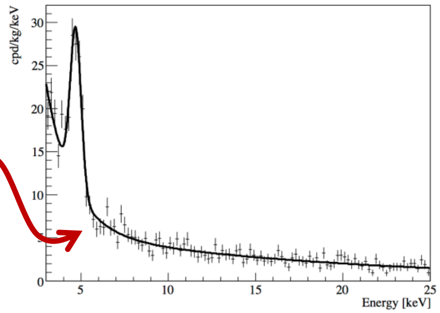


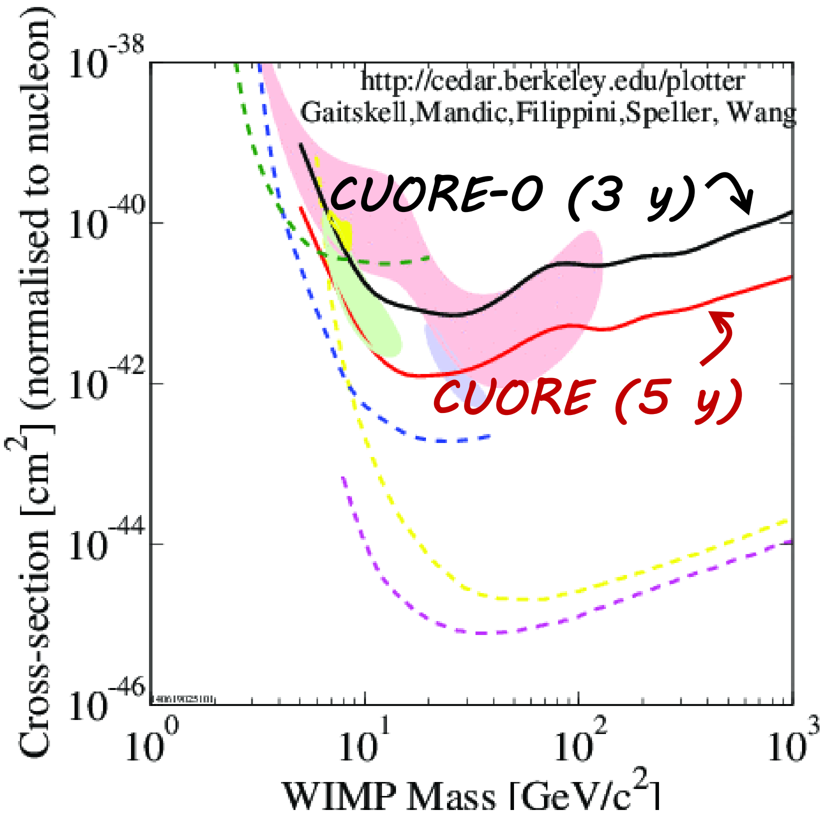


SI Sensitivity to annual modulation

ANALYSIS PARAMETERS:

- **Energy threshold: 3 keV**
- Exposure: CUORE-0 (39 kg x 3 y), CUORE (741 kg x 5 y)
- **Background: conservative approach, sampled from CCVR2**
- Halo model: Isothermal sphere
  (ρ_W = 0.3 GeV/cm^3, v_0 = 220 km/s, v_{esc}= 600 km/s)
- $Q_{NR/e-R}$ = 1





- CoGeNT Annual Modulation Search, PRL 107 (2011), ROI
- CDMSlite Soudan, Run 1 (2013)
- CUORE0 (3yr) 117 kg-y Te02 Expected Sensitivity
- CDMS-II (Soudan Silicon SI Result, R125-128, contour, 68% C.L.)
- CUORE (5yr) 3.7 Ton-y Te02, Expected Sensitivity
- DAMA/LIBRA 2008 5sigma, no ion channeling
- CRESST-II 1-Sigma Allowed Region, 730kg-days data
- SuperCDMS Soudan LT (2014), 90% C.L.
- XENON 100 Results from 225 live days of data presented at IDM
- LUX (2013) 90% U.L.

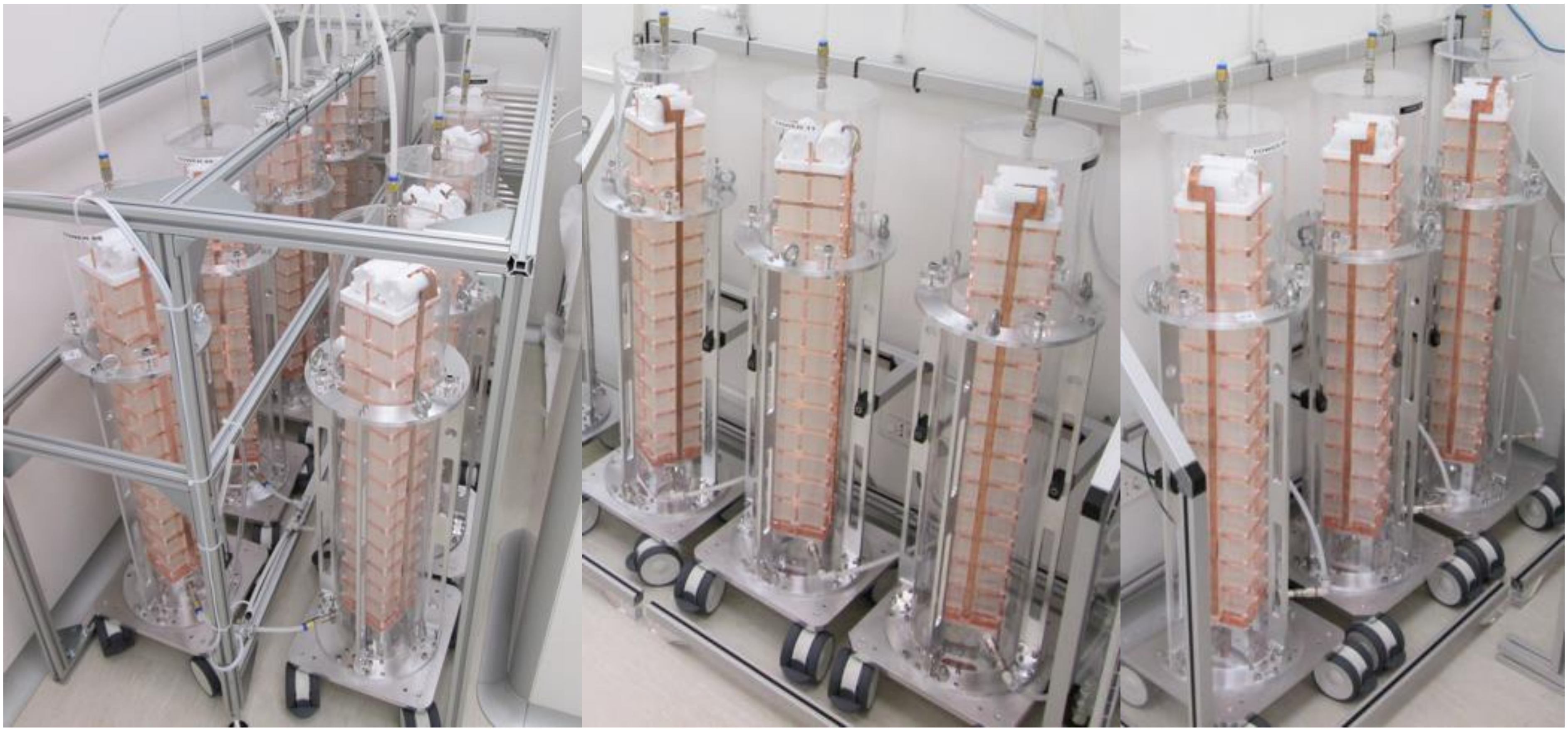
CUORE-0/CUORE could explore some of the current claims/hints of DM direct detection

Outline

- CUORE: $0\nu\beta\beta$ with TeO_2 bolometers
  - CUORE-0, the "CUORE demonstrator"
- DM searches with CUORE
- **CUORE status**
- Summary

CUORE Status: Towers assembly

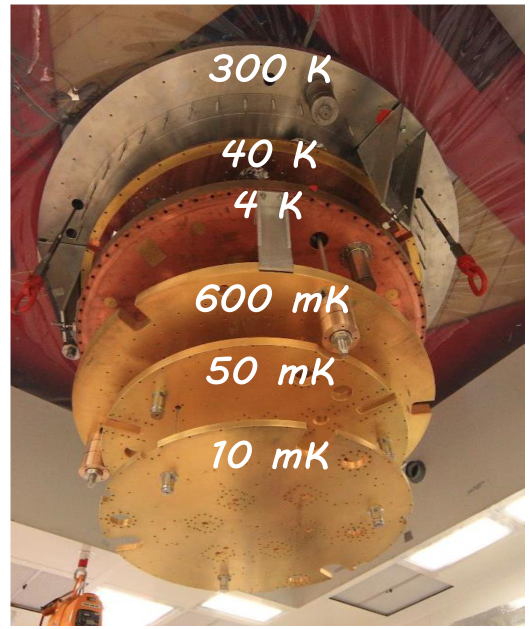
All 19 towers fully instrumented and ready to mount

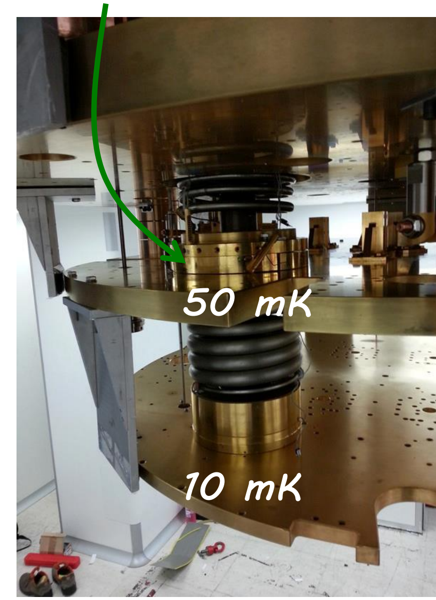


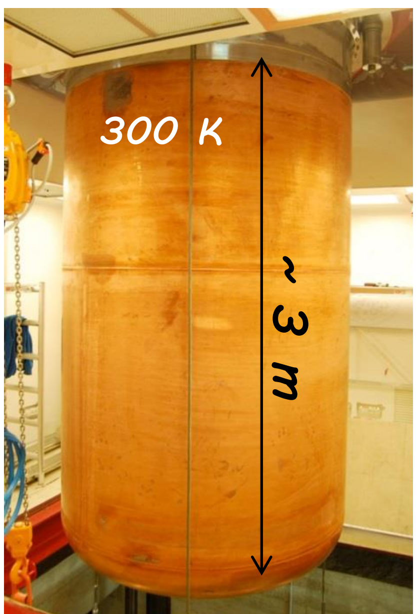
CUORE Status: Cryogenics

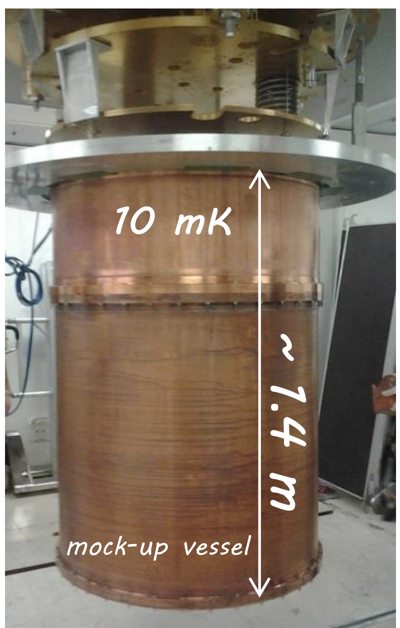
- Dilution Unit (DU) LNGS onsite testing (test cryostat with 2 PTs): Lowest temperature: **4.95 mK**

- Jan 2014: Cryostat and DU merged









- March 2014: First "complete" cryogenic run:
  - 6 shields
  - DU
  - Pulse tubes (4/5)
  - Suspensions
  - Thermalizations
  - Thermometers

Stable T ~ 14 mK

CUORE Status

Next step: detector integration (installation into the cryostat)

fall 2014 --→ spring 2015

CUORE data taking is scheduled to start in summer 2015

Summary

- ***CUORE is** a TeO_2 ton-scale bolometric $0\nu\beta\beta$ experiment able to reach 40-100 meV effective Majorana mass.*
- *CUORE is at the end of the construction stage @ LNGS. **Start data-taking in summer 2015**.*
- ***CUORE-0 is operating** as a stand alone $0\nu\beta\beta$ search. The results **verify our understanding of the background sources in CUORE-0 and demonstrate that =< 5 keV energy resolution is achievable***
- ***Low energy threshold (<3 keV) has been achieved in CUORE-like bolometers** by triggering on continuous optimum-filtered data.*
- *If low threshold level is attained, **CUORE and CUORE-0 would be sensitive to WIMPs in the galactic halo by looking for annual modulation** of the expected DM interaction rate. In particular, they can explore the light WIMP mass region pointed out by DM claims/hints.*

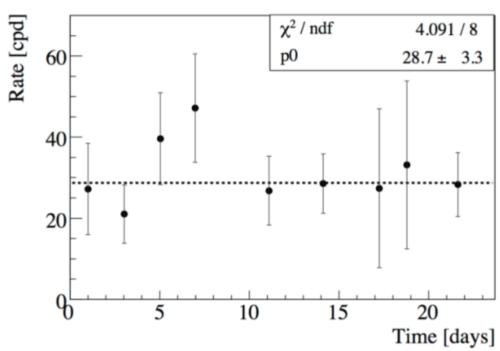
Backup Slides

The 4.7 keV peak

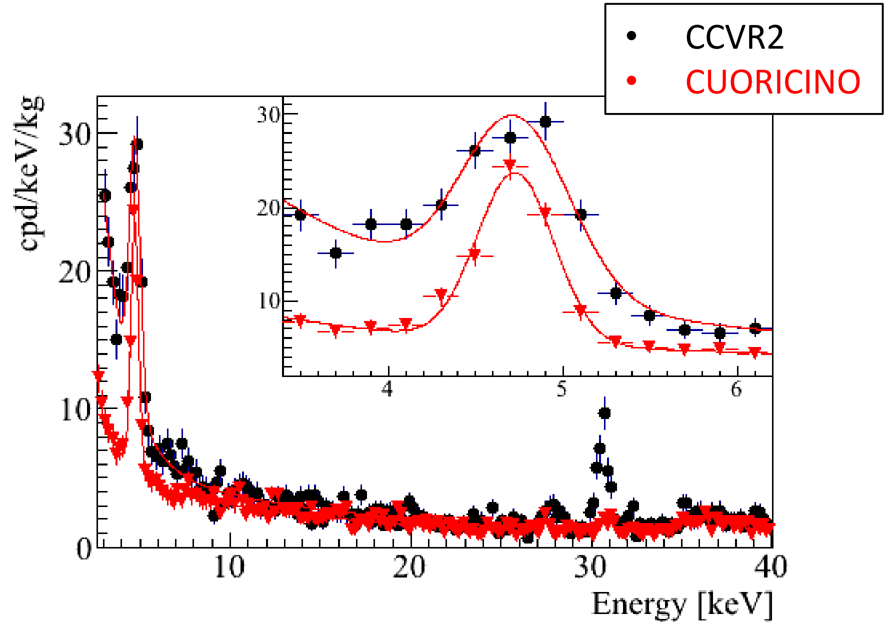
What's the origin of this peak?

4.7 keV ⇒ L1 Sb electron binding energy

- ^{123}Te (i.a. 0.9%) EC to ^{123}Sb is a 2nd forbidden unique transition that proceeds mainly from L3 shell (4.23 keV)
- ^{121m}Te and ^{121}Te EC to ^{121}Sb ($T_{1/2}$ ~154 and 17 days), but K/L intensity is inconsistent with observations
- Other EC metastable isotopes (and daughters) have $T_{1/2}$< 4.7 days, but the 4.7 keV peak intensity is constant in 20 days scale:



The 4.7 keV peak is also seen in a reanalysis of the last 2 months of operation of CUORICINO (only 4 bolometers with threshold < 4 keV):



(CUORICINO data not corrected for efficiency!)

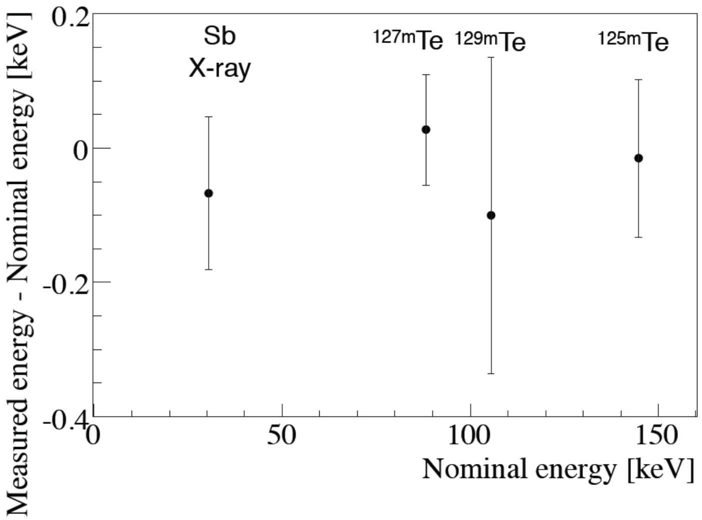
Energy calibration @ low E

The energy calibration is performed with high energy γ's (thoriated tungsten sources inserted between the cryostat and the external lead shields) and then checked at low energy:

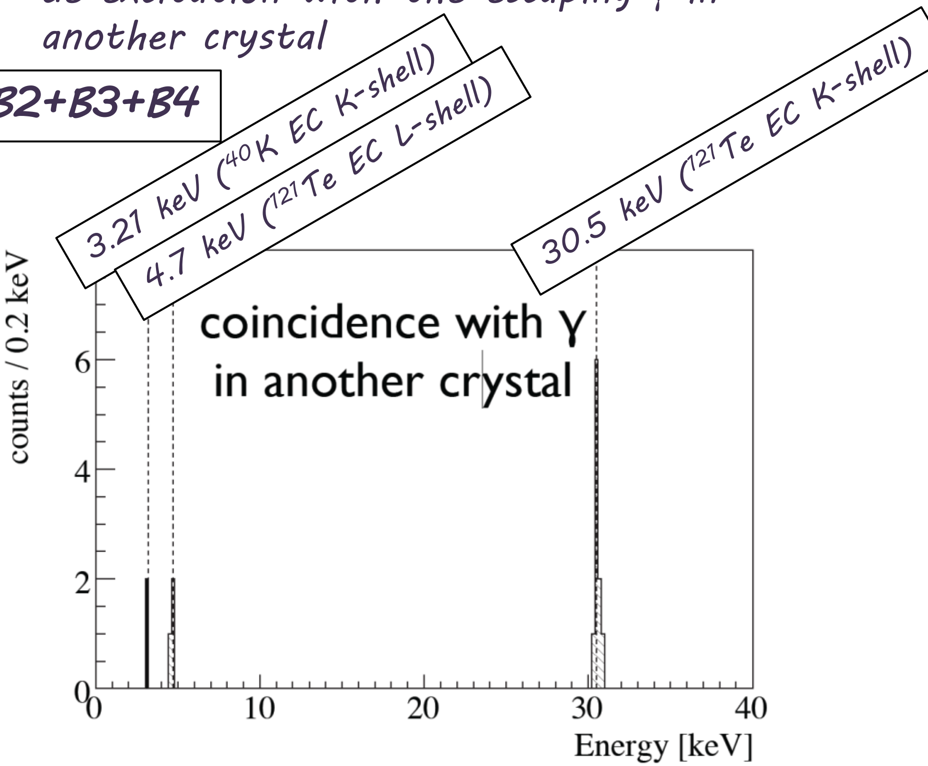
- From 30-150 keV, lines from Te metastable isotopes (cosmogenic origin)

- Below 30 keV, using ^{40}K and ^{121}Te bulk content (EC decay to excited state), looking for the coincidence of the atomic de-excitation with the escaping γ in another crystal

B2



B2+B3+B4



Pulse shape discrimination

PSA to remove non-physical pulses (electronic spikes, mechanical vibrations··)

Shape Indicator (SI) parameter based on the c^2 of the fit to the filtered average signal

$$\mathrm{SI} = \sum_{i=0}^{L-1} \frac{(y_i^f - f_i)^2}{\sigma_L^2 (L-2)} \qquad \text{where } \sigma_L^2 = \sum_{k=M/L}^{M-M/L} h^2 \frac{|s(\omega_k)|^2}{N(\omega_k)}$$