3rd IBS-MultiDark-IPPP Workshop, 21-25 November 2016, Durham

Status of CUORE: a Cryogenic Underground observatory for rare events

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on behalf of the CUORE collaboration

The Cuore Collaboration

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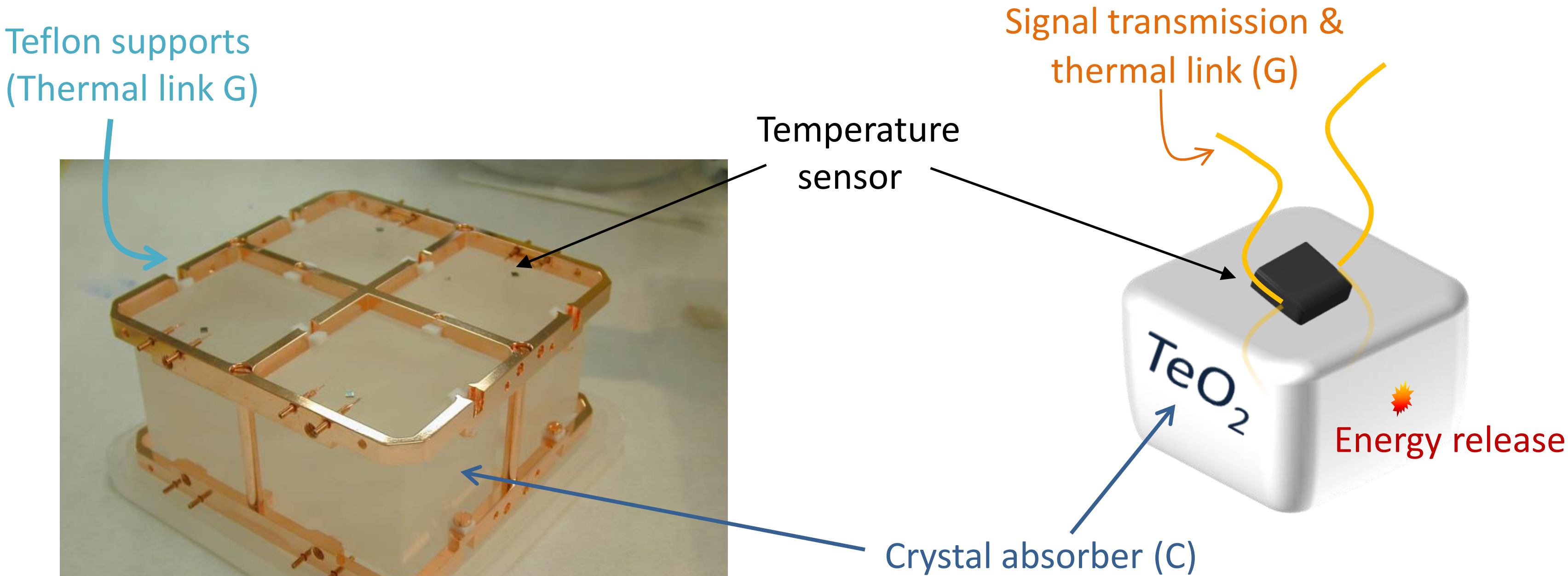
CUORE

Outline

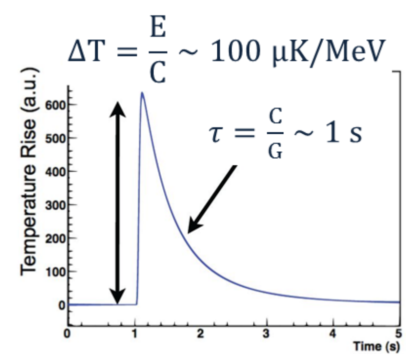
- CUORE: A ton-scale bolometric $0\nu\beta\beta$ experiment
- Other rare event searches with CUORE
  - WIMPs
  - Solar axions
- Results of the CUORE-0 demonstrator
- CUORE status
- Summary

TeO_2 bolometers as particle detectors



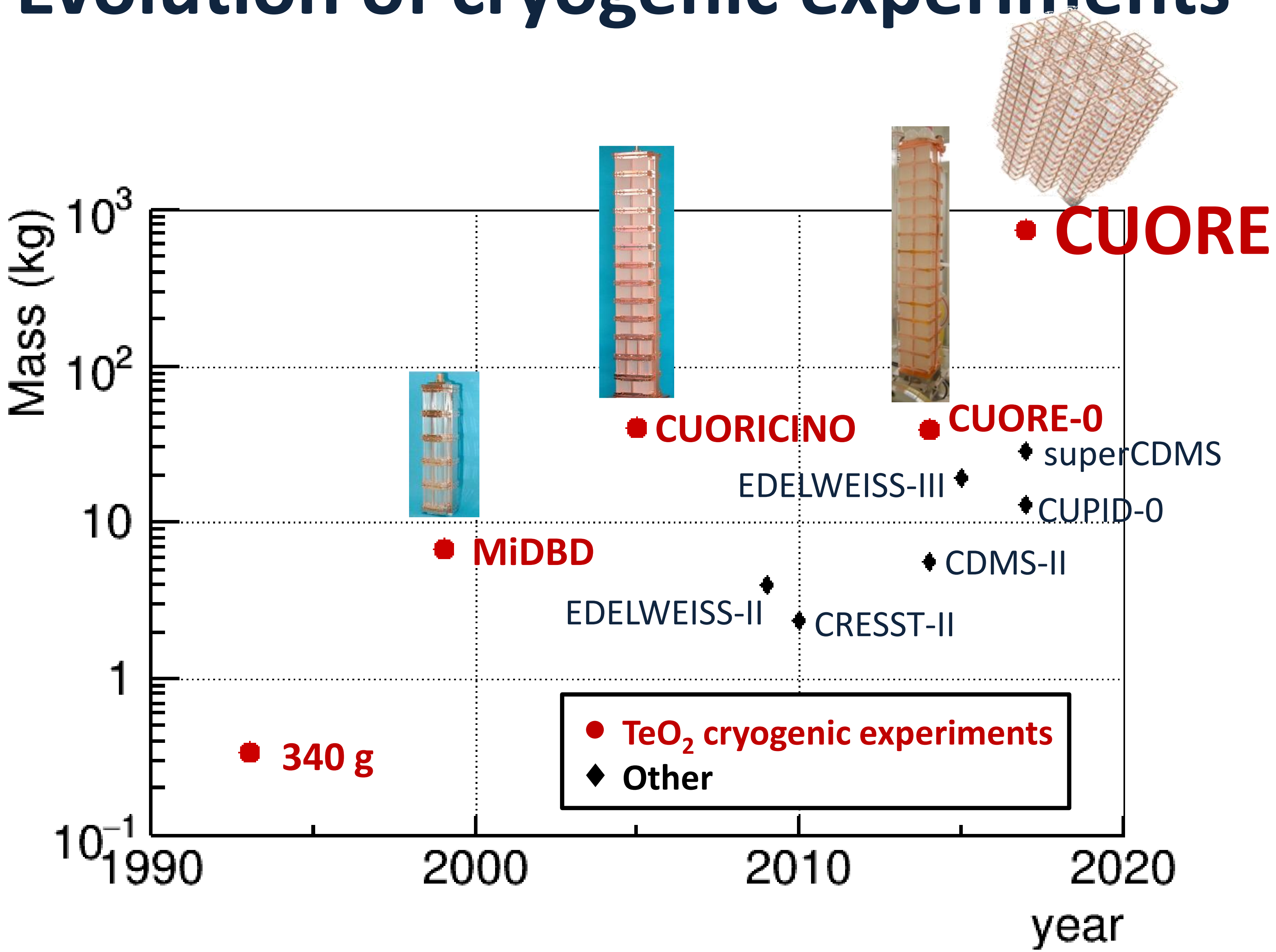
The energy release originates a temperature rise, converted by the temperature sensor in an electric signal

CUORE typical pulses:



Excellent energy resolution!!
~ 5 keV FWHM

Evolution of cryogenic experiments



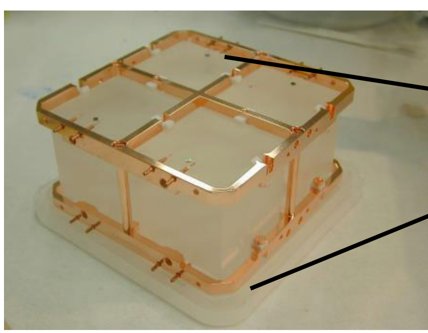
The CUORE challenge

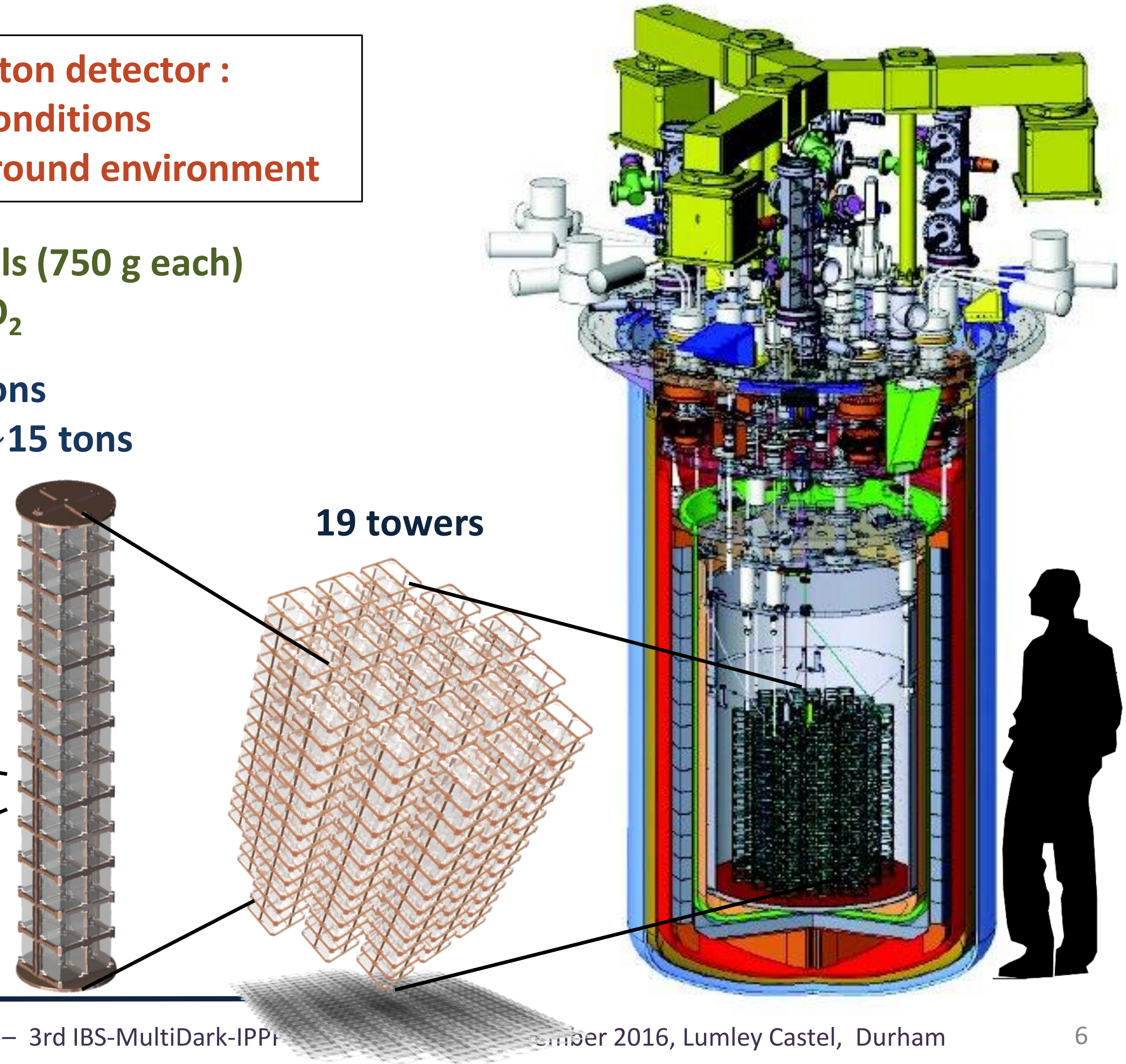
Cool down to 10 mK a ~1 ton detector :
- **stable temperature conditions**
- **extremely low background environment**

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

Cryostat total mass ~30 tons
Mass to be cooled < 4 K: ~15 tons

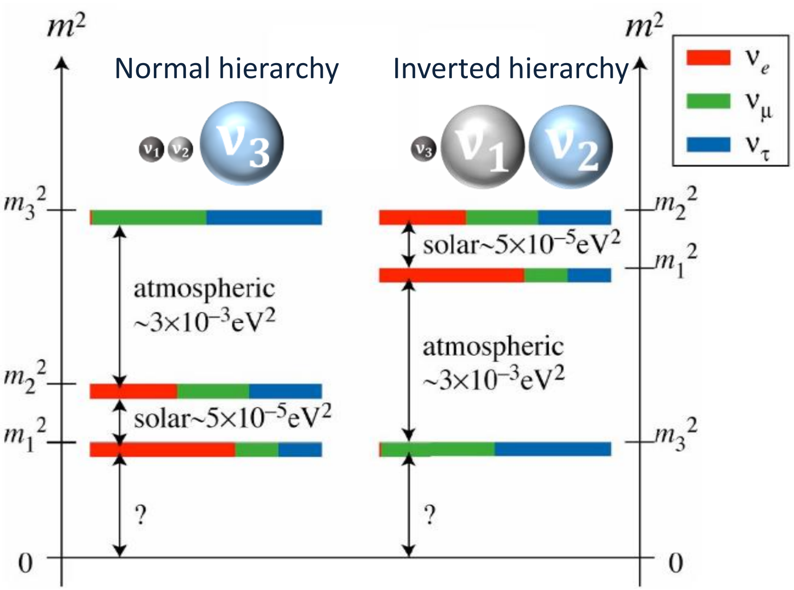
4 TeO_2 crystals:





CUORE main goal: $0\nu\beta\beta$ of ^{130}Te

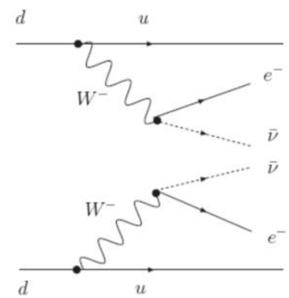
We know many things about neutrinos…



But there are still open questions:

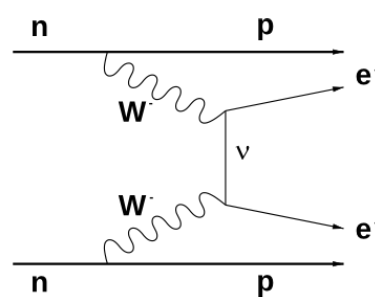
Majorana or Dirac?
why are neutrinos so light?
Hierarchy?
how many?
mass scale?
Is lepton number conserved?

In the SM, nuclei for which β decay is not energetically allowed can undergo double beta decay:



$2\nu\beta\beta$
observed for several nuclei with $T_{1/2} > 10^{18}$ y

But if $\nu \equiv \bar{\nu}$



$0\nu\beta\beta$!!
Only possible for MAJORANA neutrinos!!
(…or exotic physics)

In addition, if observed:

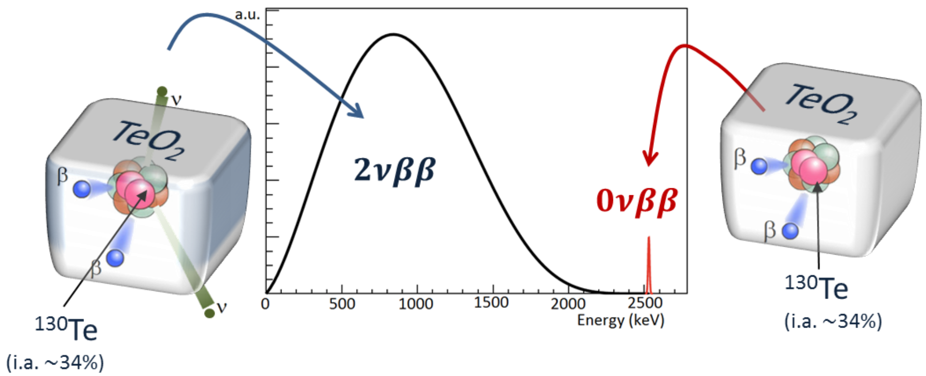
- lepton number violation
- measures effective electron neutrino mass

$$m_{\beta\beta} \equiv |e^{i\alpha_1}|U_{ei}^2|m_1 + e^{i\alpha_2}|U_{e2}^2|m_2 + |U_{e3}^2|m_3|$$

CUORE sensitivity to $0\nu\beta\beta$

^{130}Te is part of the detector (i.a.~34%)

What we are looking for:

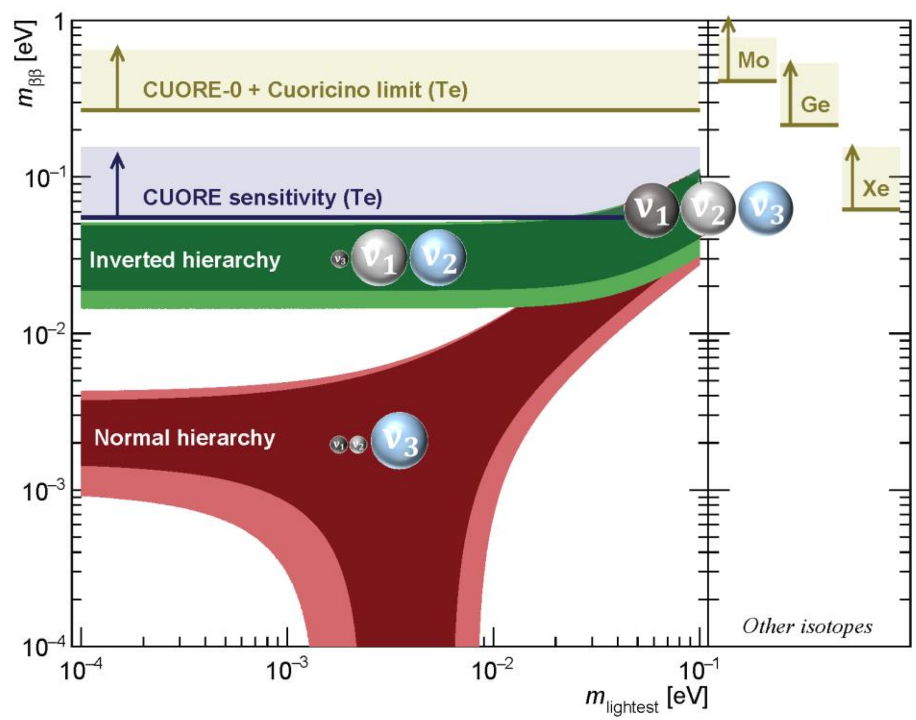


Expected energy resolution @ ROI	Background goal @ ROI
5 keV (FWHM)	0.01 (c/keV/kg/yr)

$$T_{1/2}^{0\nu} > 9.5 \times 10^{25} \text{ yr (90\% CL)}$$

Effective majorana mass

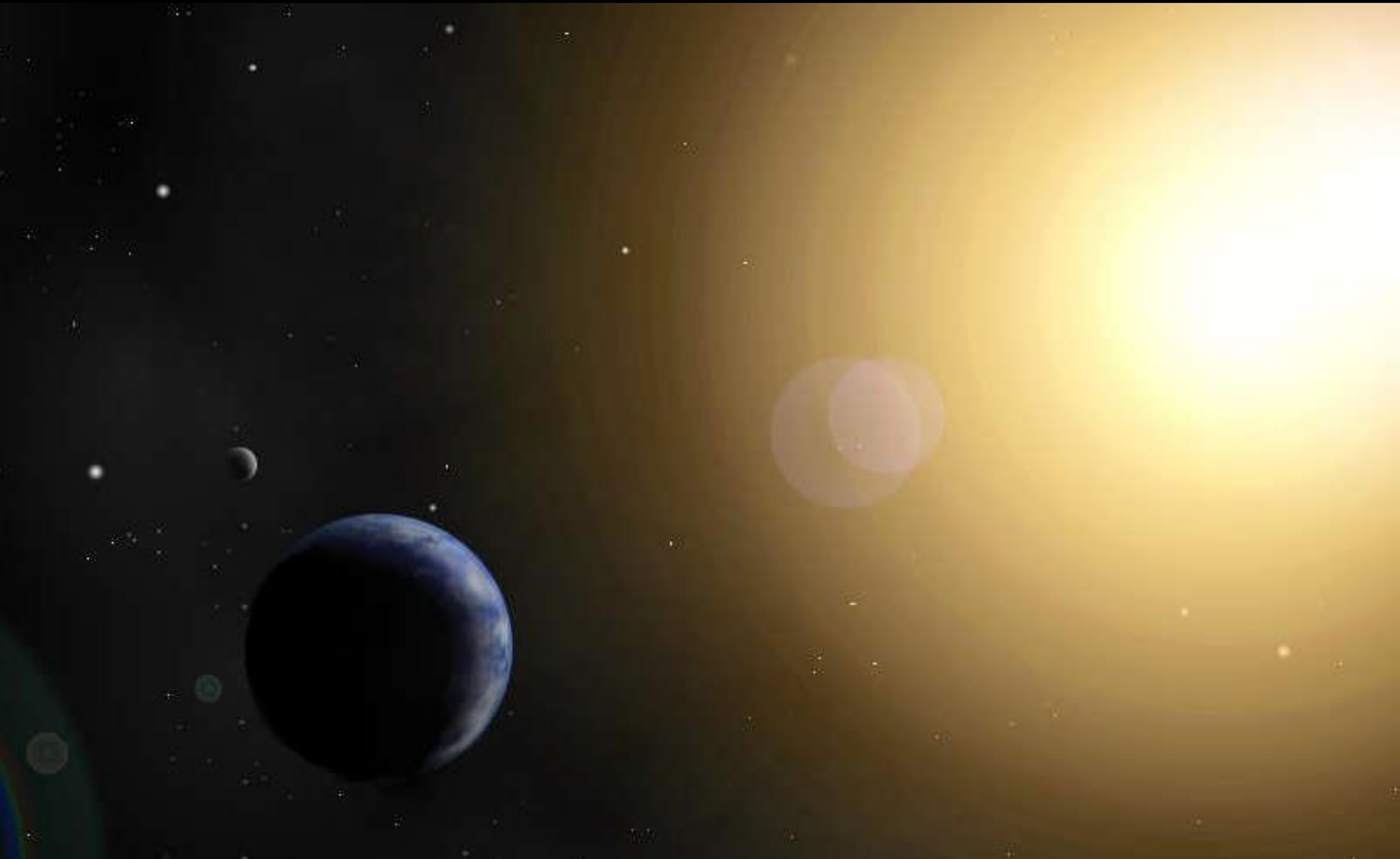
$$Rate_{0\nu} \propto \frac{1}{T_{1/2}^{0\nu}} = |\langle m_{\beta\beta}\rangle|^2 G^{0\nu}(Q,Z)|M^{0\nu}|^2 \quad (*)$$



(*) Uncertain!

Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 91, 024613 (2015)
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. Lett. 105, 252503 (2010)

OTHER SEARCHES



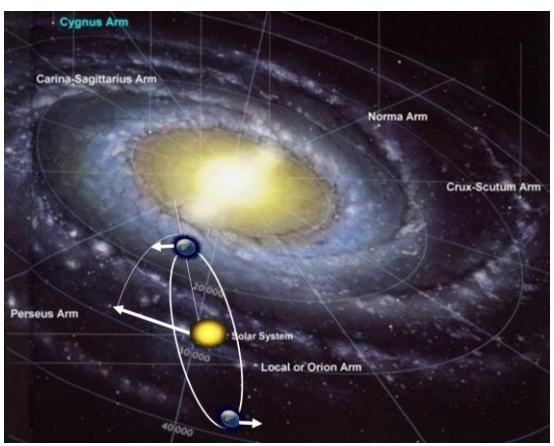
TeO_2 bolometers for WIMP detection

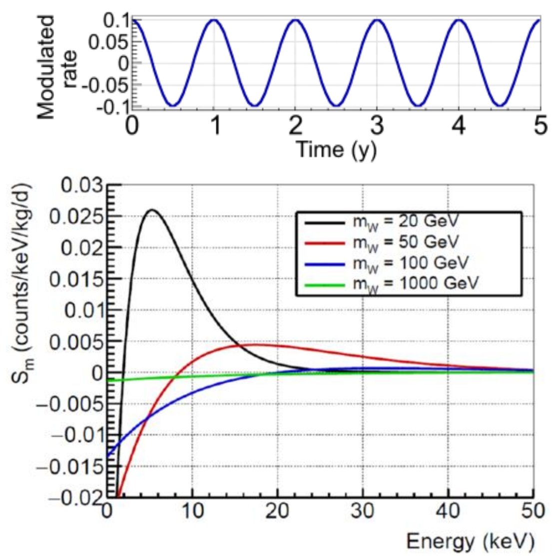
- ☺ Very good energy resolution
- ☺ Low energy threshold achievable
- ☺ Quenching factor NR/e^-R close to 1 (Phys. Lett. B 408 (1997) 465-468)
- ☺ Sensitive to light and heavy WIMPs

- ☹ 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/$\beta\gamma$)

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

➡ Look for Dark Matter ANNUAL MODULATION



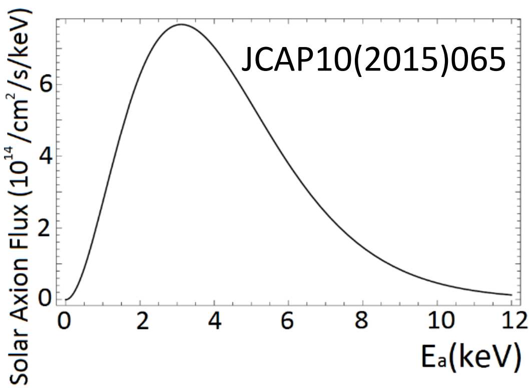


CUORICINO energy threshold: ~ tens of keV

Threshold reduction is needed for CUORE

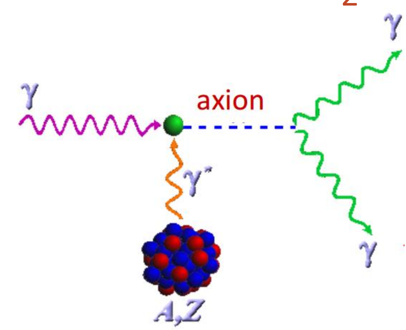
Solar axion search with TeO_2

Photons are converted to axions in solar core:



- Average energy ~4.2 keV
- ^{57}Fe M1 line at 14.4 keV

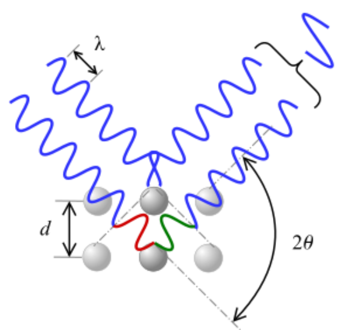
They can be detected in CUORE by Primakoff effect in TeO_2 crystal:

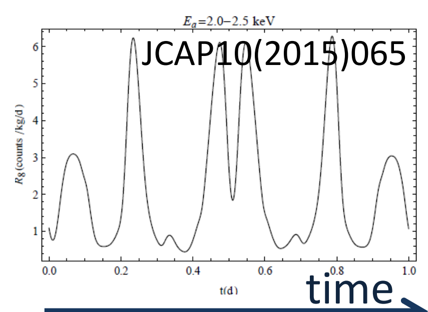


Detection strategies:

- Look for the 14.4 keV line
- Coherent Primakoff conversion in the crystal lattice:

when the incident angle fulfills the Bragg condition for a given crystalline plane the coherence enhances the scattering probability by a factor up to 10^4





signal varies in time due to Earth rotation

In both cases, threshold reduction is needed for CUORE

Lowering the energy threshold

“Optimum” trigger algorithm:

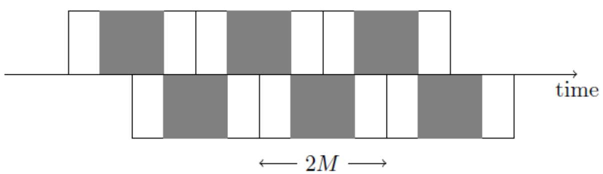
- Filter continuosly “slices” of data with Optimum Filter algorithm (improves S/N)
- Then apply simple threshold trigger to filtered data

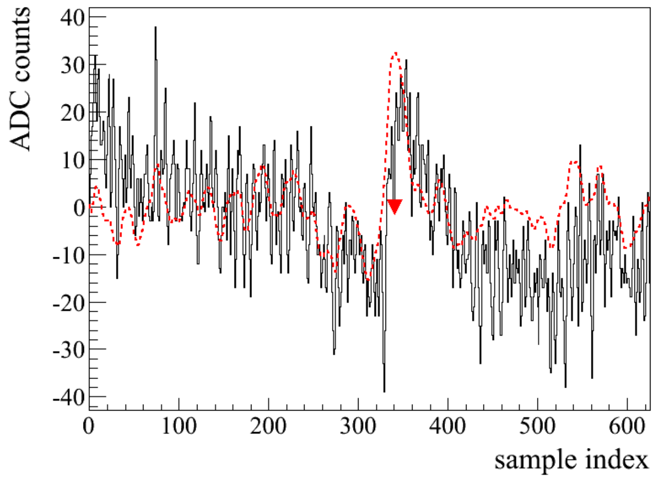
Optimum Filter:

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

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

Filter data continuously in slices





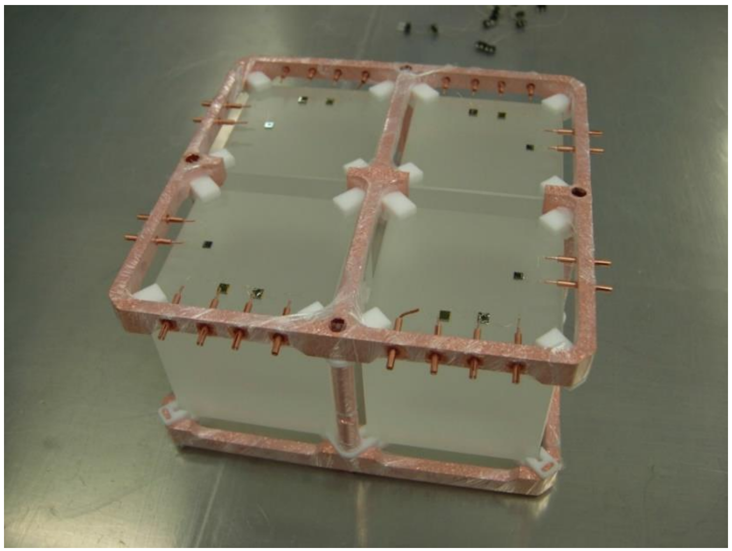
- Filtered samples (RED) are less noisy than original ones
- Baseline fluctuations are reduced
- Filter sensitive to the shape of the expected signal, suppressing non physical pulses

JINST 6 (2011) P02007

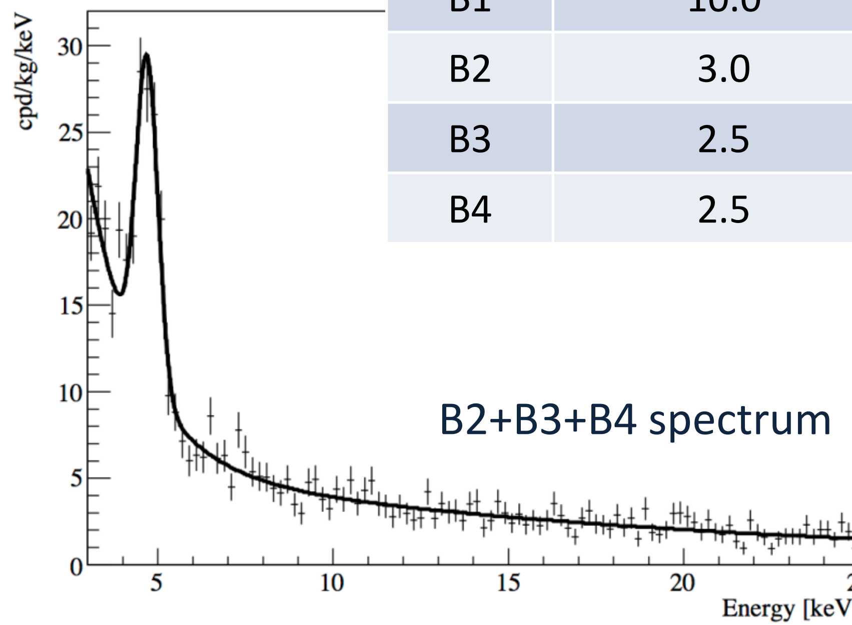
Low energy study in CUORE-like crystals

Four CUORE-like crystals (CCVR)

Total mass 3 kg x19.4 days live time



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



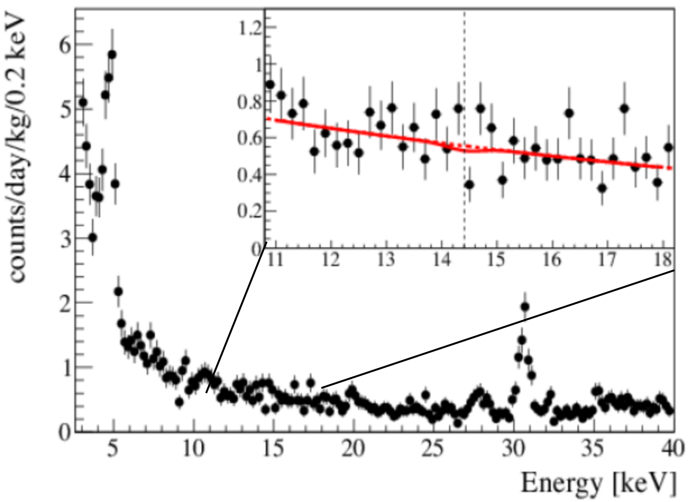
- **Background ranging from 25 c/keV/kg/d @ 3 keV to 2 c/keV/kg/d @ 25 keV**
- **A peak (presently unknown origin) at 4.7 keV**

JCAP (2013) 038

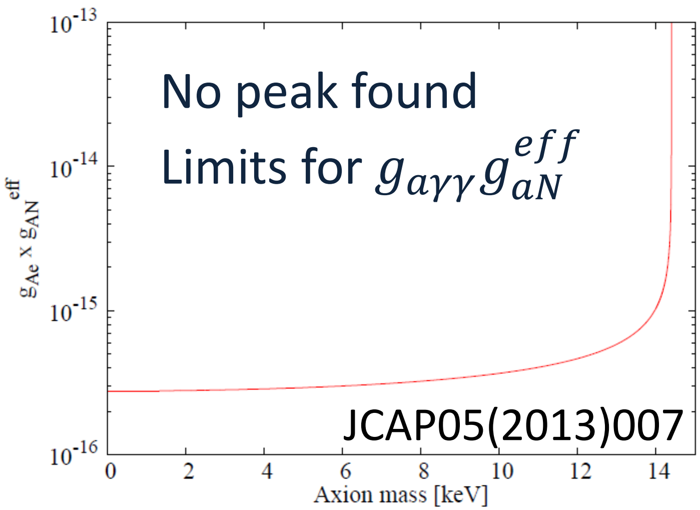
Axion search with CCVR

Look for ^{57}Fe M1 line @ 14.4 keV in CCVR:

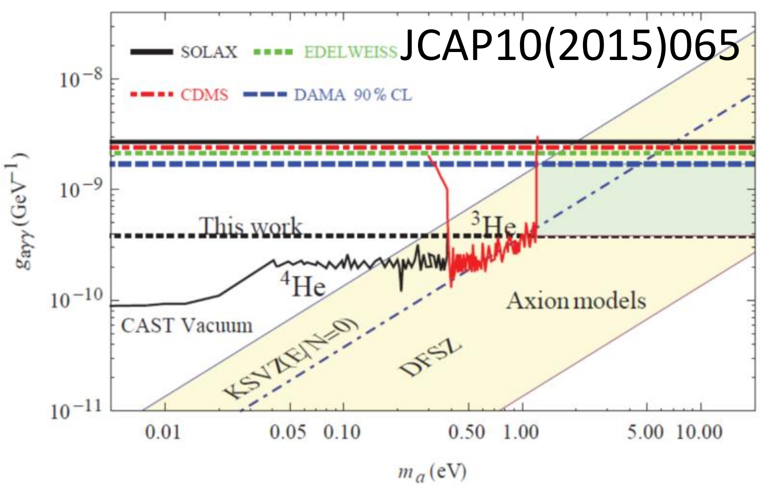
4.7 keV (?)
FWHM
~0.7 keV

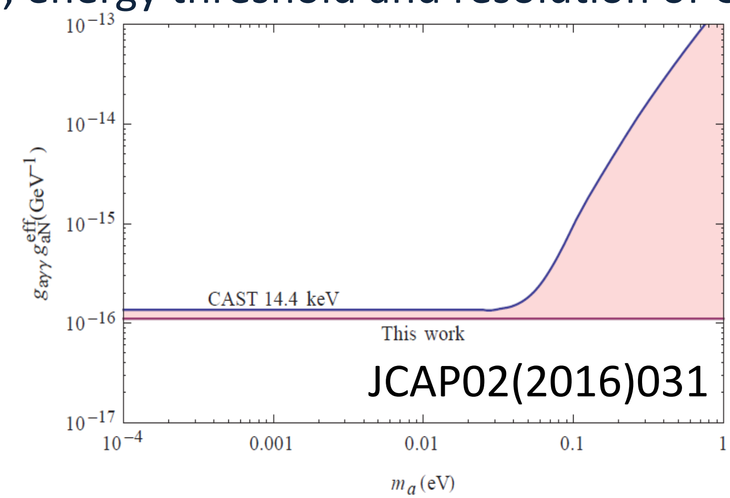


30.5 keV
FWHM
~0.6 keV



Projections for CUORE, Extrapolating background , energy threshold and resolution of CCVR:





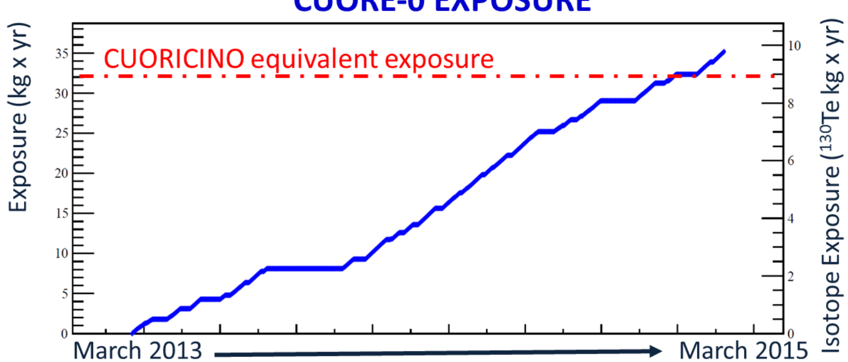
CUORE-0

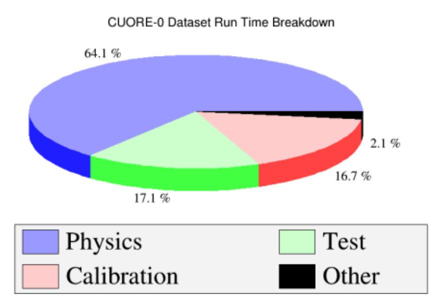
CUORE-0

- **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 (11 kg ^{130}Te)

GOALS:
- **Proof of Concept for CUORE in all stages**
  - All detector components manufactured, cleaned, stored and assembled with the same protocols defined for CUORE
  - Validation of CUORE background model & energy resolution
  - Test of the CUORE DAQ and analysis framework
- **$0\nu\beta\beta$ serch in its own**
- Demonstrate potential for DM and other rare events searches

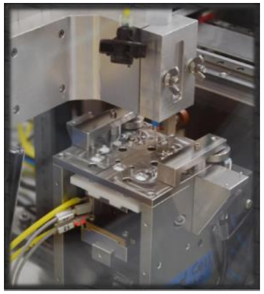
CUORE-0 EXPOSURE

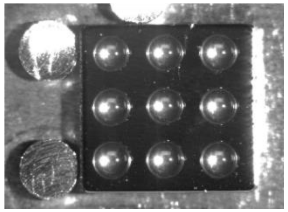




CUORE-0: test the CUORE tower assembly line

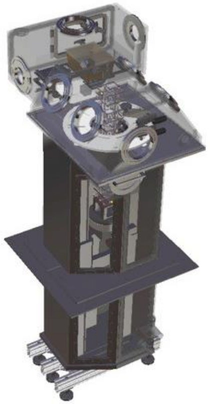
Thermistor gluing

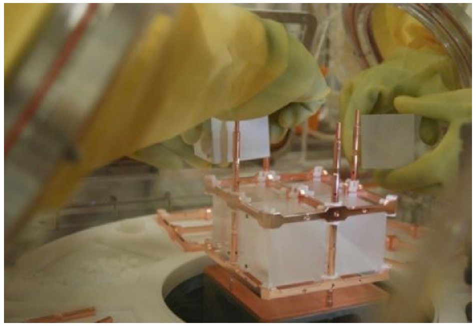




Tower assembly

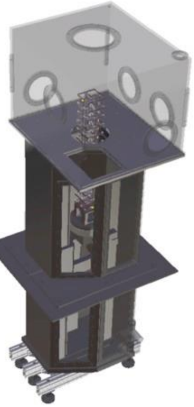
Mounting box

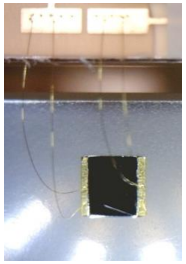




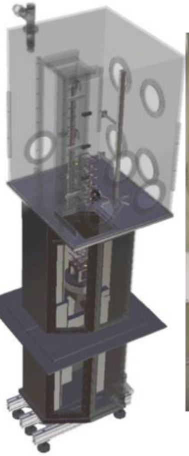
Signal wires connection

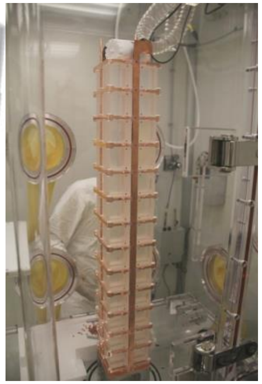
Bonding box



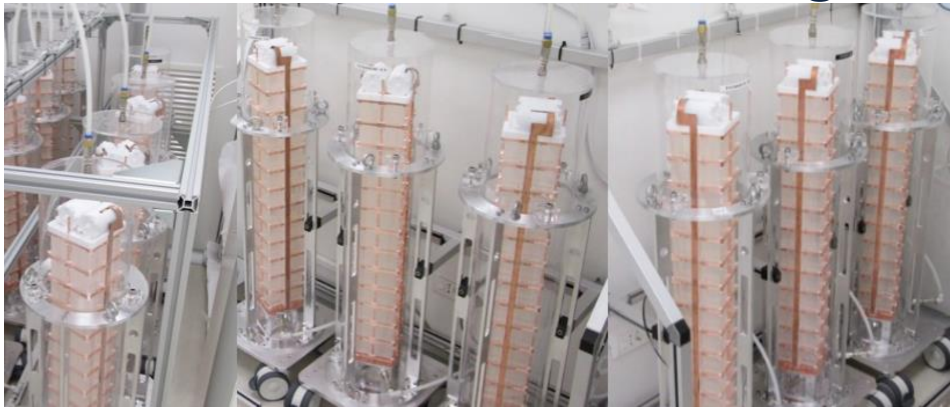


Cabling box





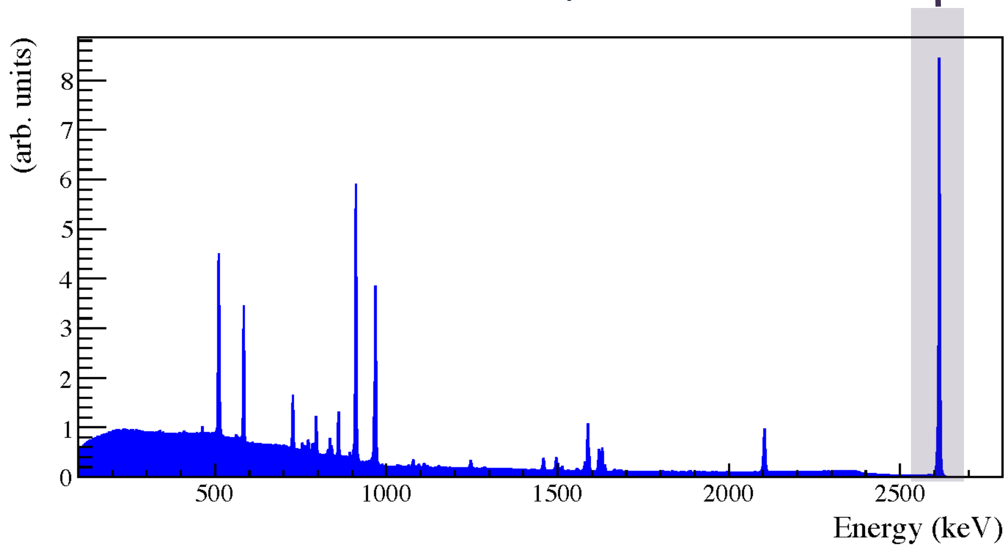
Towers storage

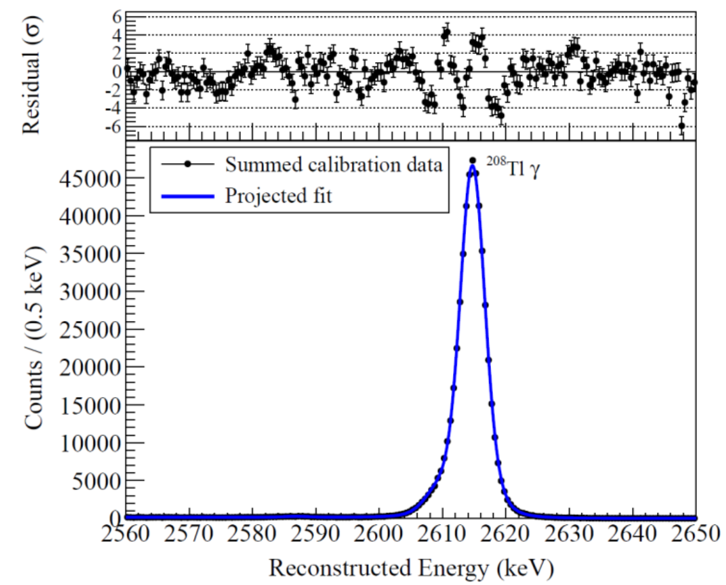


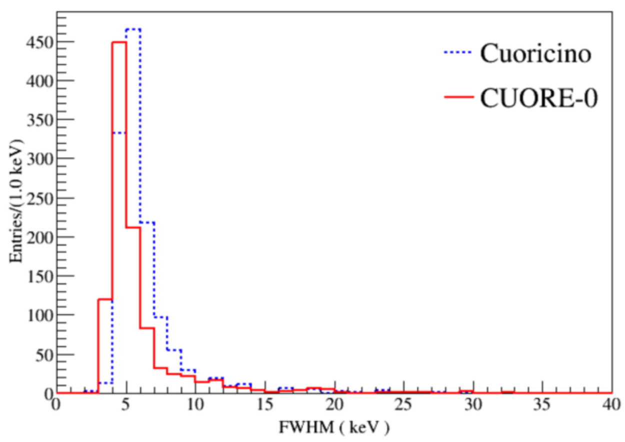
The successful operation of CUORE-0 demonstrated the validity of the CUORE tower assembly line and of the CUORE cleaning procedures.

CUORE-0 energy resolution

^{232}Th calibration spectrum



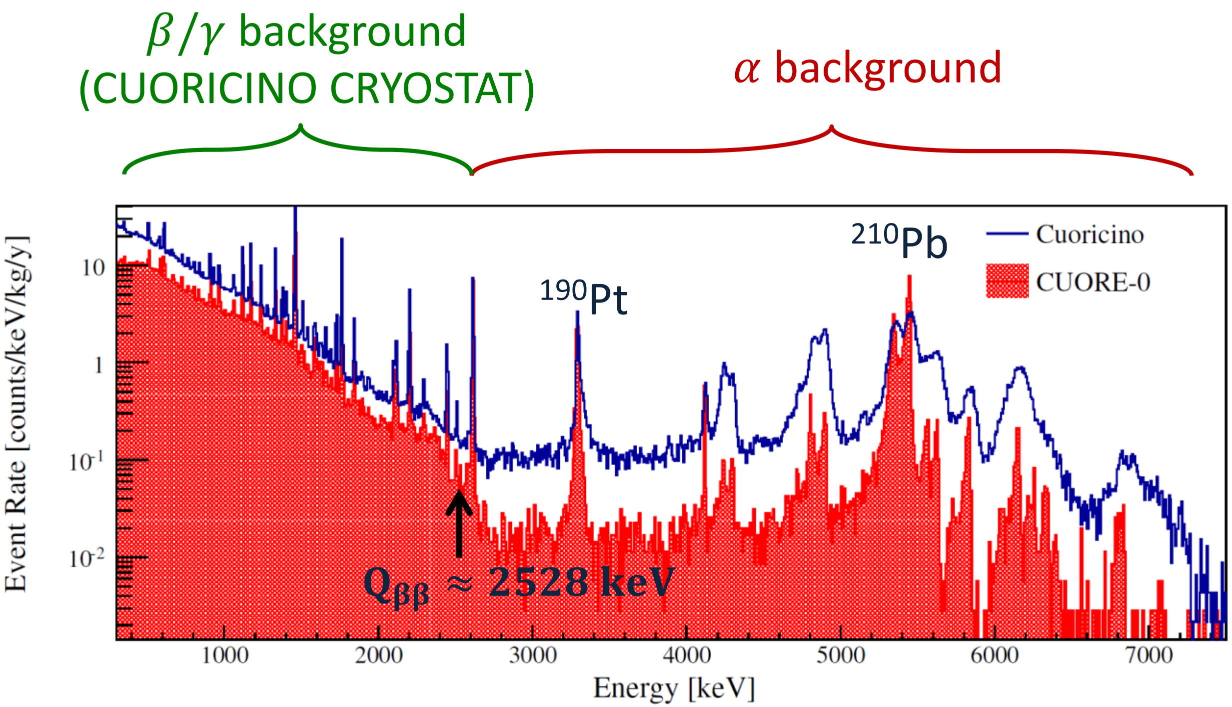




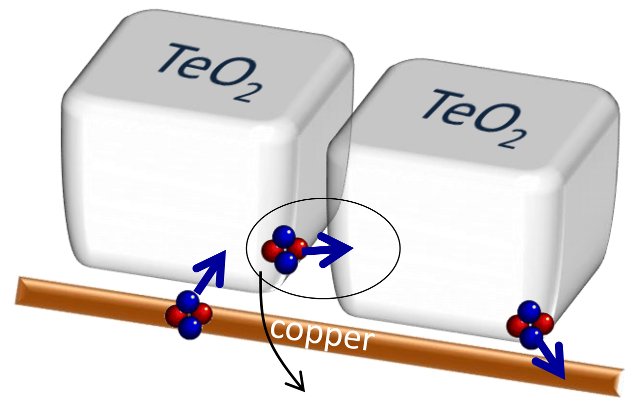
FWHM resolution estimated @ 2615 keV during calibrations ≤5 keV

CUORE goal reached!

CUORE-0 background



α background:



This can be removed by coincidence analysis

Evident background reduction with respect to Cuoricino

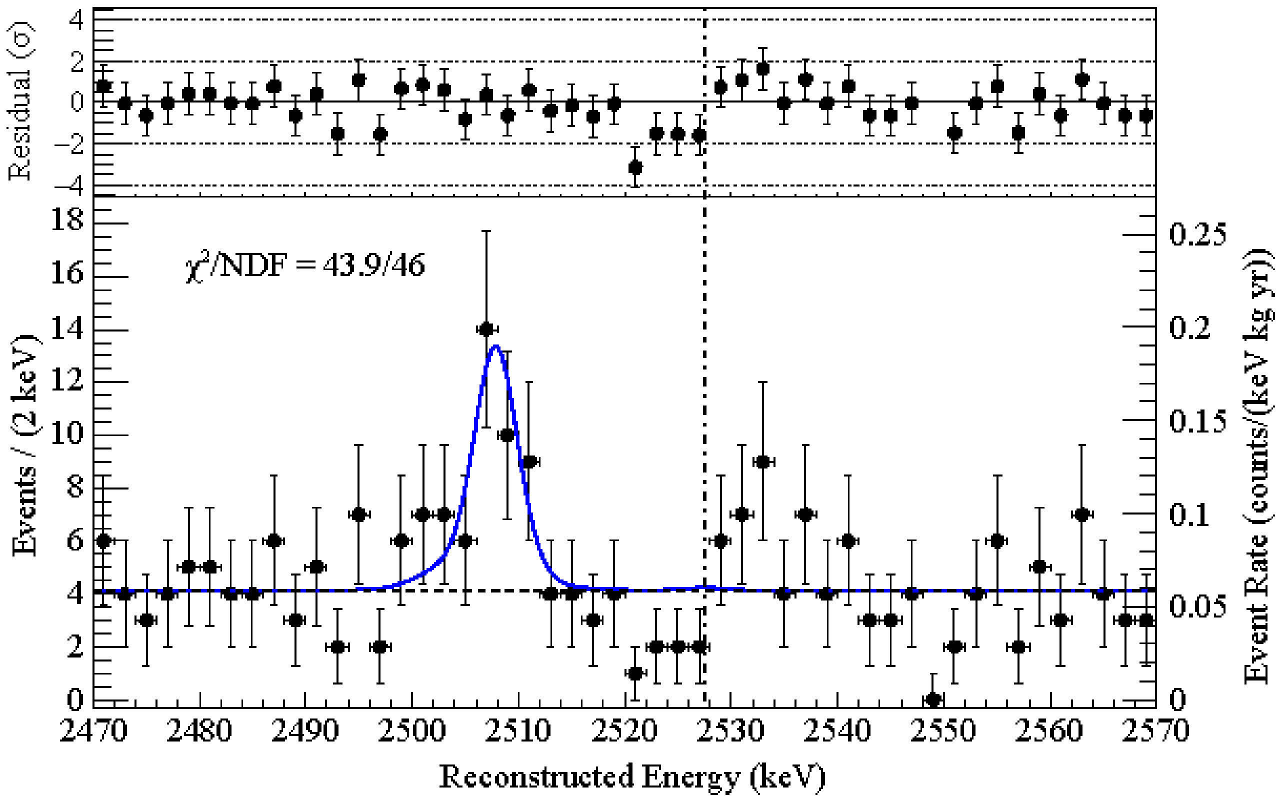
- factor ~7 for surface contaminations
- factor ~2.5 in the ROI

	$0\nu\beta\beta$ ROI c/keV/kg/y	2700-3900 keV c/keV/kg/y
Cuoricino	0.153 ± 0.006	0.110 ± 0.001
CUORE-0	**0.058 ± 0.004**	**0.016 ± 0.001**

→ CUORE ~ 0.01 c/keV/kg/y @ ROI (selfshielding!)

Background paper in preparation

CUORE-0: final $0\nu\beta\beta$ result

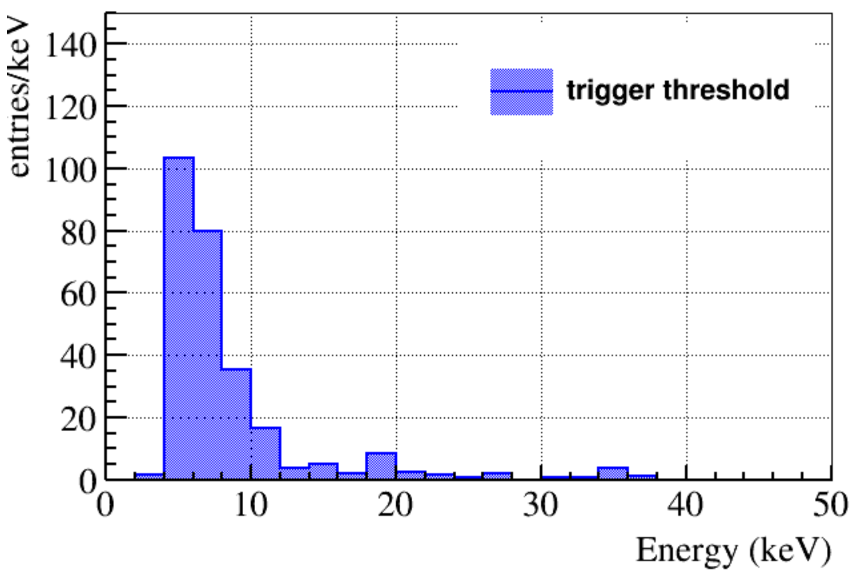


CUORE-0 Final Limit (Basyesian 90% C.L.): $T_{1/2}$(0v) > 2.7×10^{24} yr

CUORICINO + CUORE-0 limit (Bayesian 90% C.L.): $T_{1/2}$(0v) > 4.0×10^{24} yr

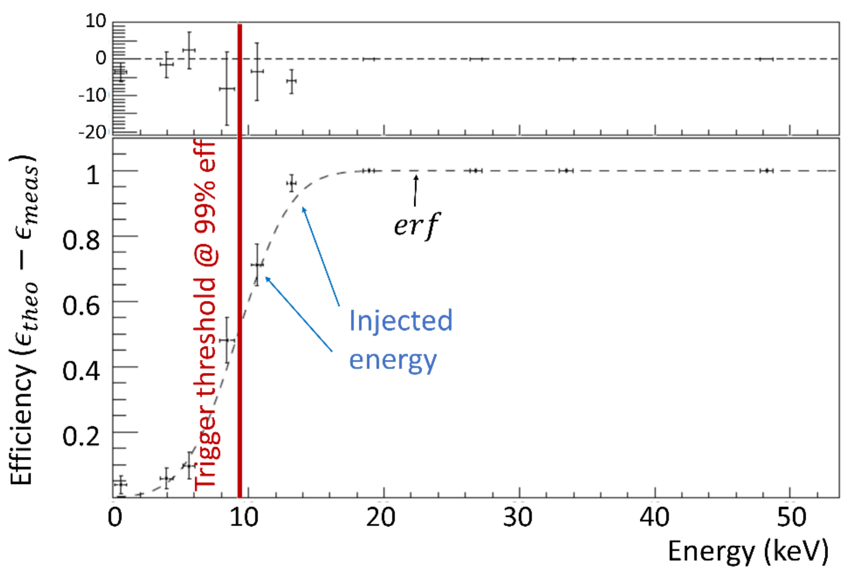
Phys.Rev.Lett. 115 (2015) 10, 102502
Phys.Rev.C 93, 045503 (2016)

Lowering the CUORE-0 threshold



Trigger threshold

Optimum trigger applied to
CUORE-0 data:
Trigger thresholds (99% eff)
between 3 -10 keV for most bolometers!



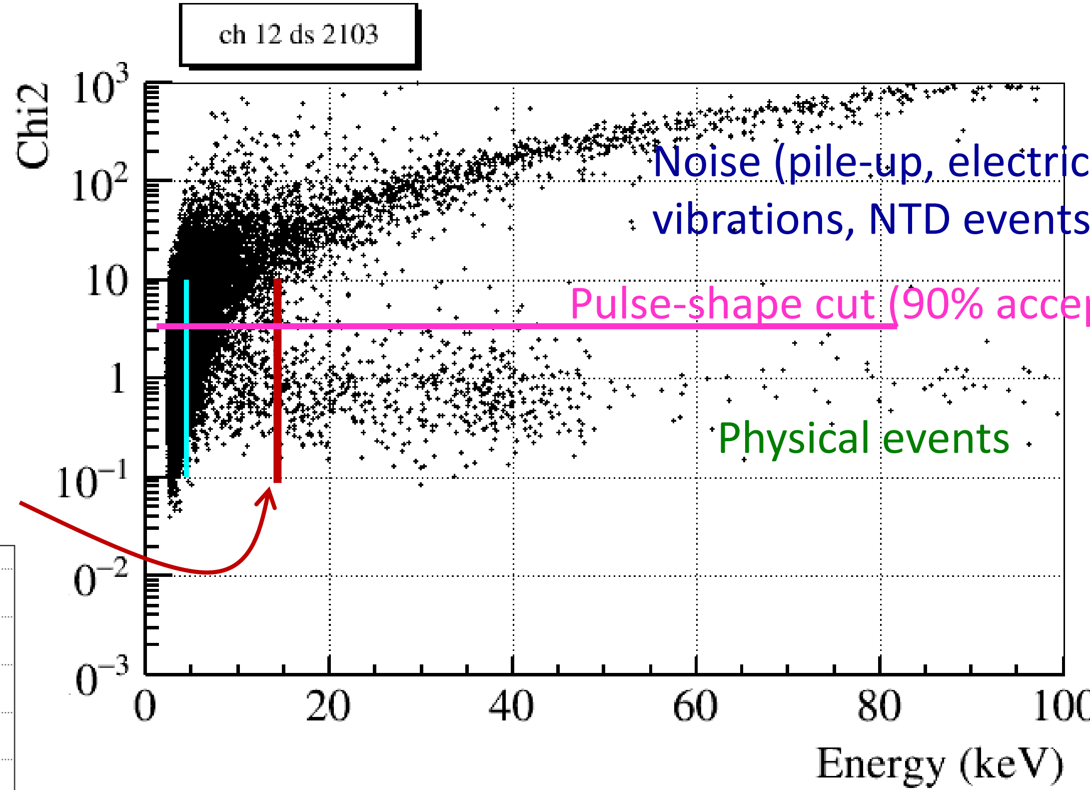
Trigger efficiency checked by injecting low energy amounts using resistors glued to the crystals

Data selection & analysis threshold

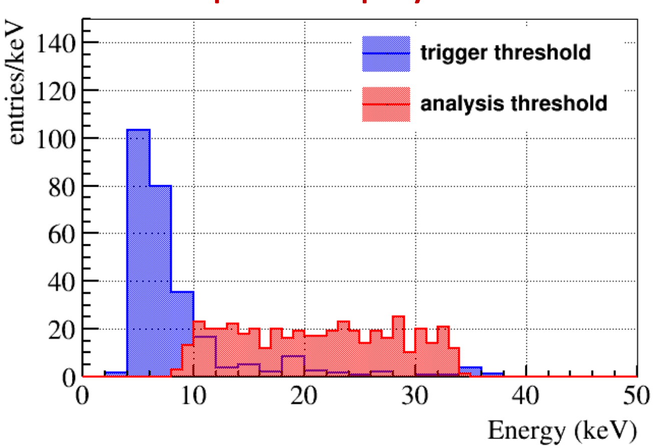
CUORICINO CRYOSTAT -> more noise than Hall C cryostat (CCVR)

Pulse-shape cut to reject noise (pile-up, electric noise, vibrations, spikes)

Pulse-shape parameter: χ^2/NDF of filtered pulses with respect the ideal one (average pulse)

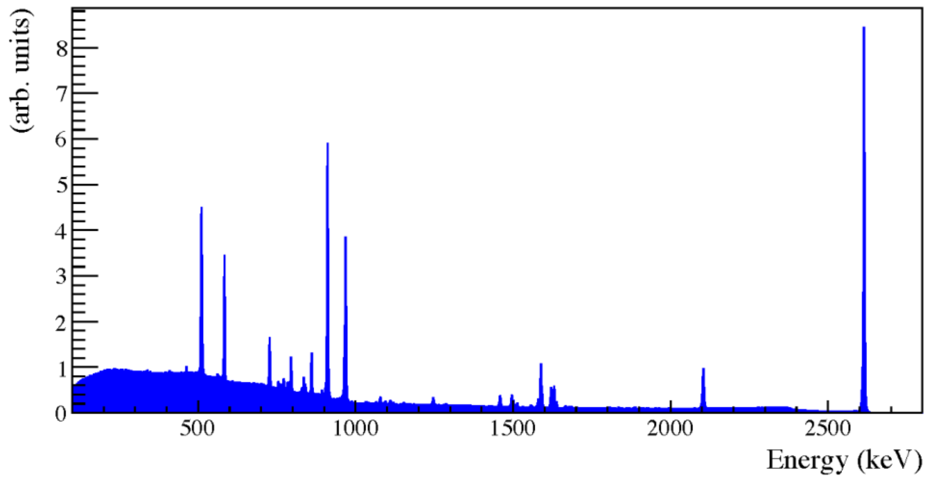


The analysis threshold is set where the noise band intercepts the physical band

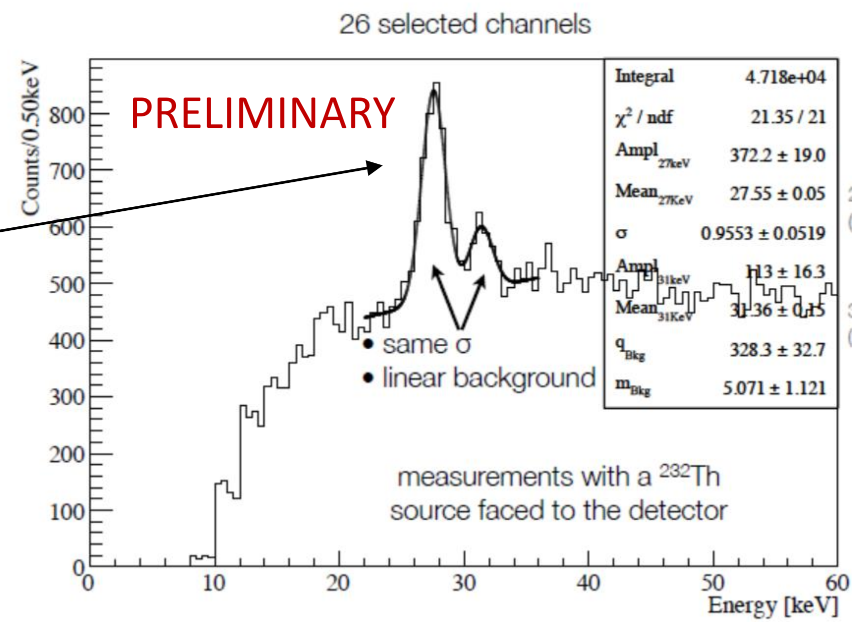


Analysis threshold between 10 – 30 keV, depending on the bolometer

Low energy calibration



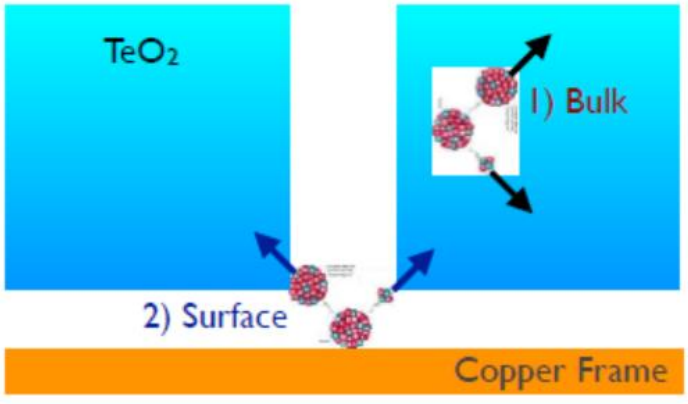
The calibration used at low energy is the same as for high energy, calculated from ^{232}Th calibration lines (lowest energy visible peak: 511 keV)

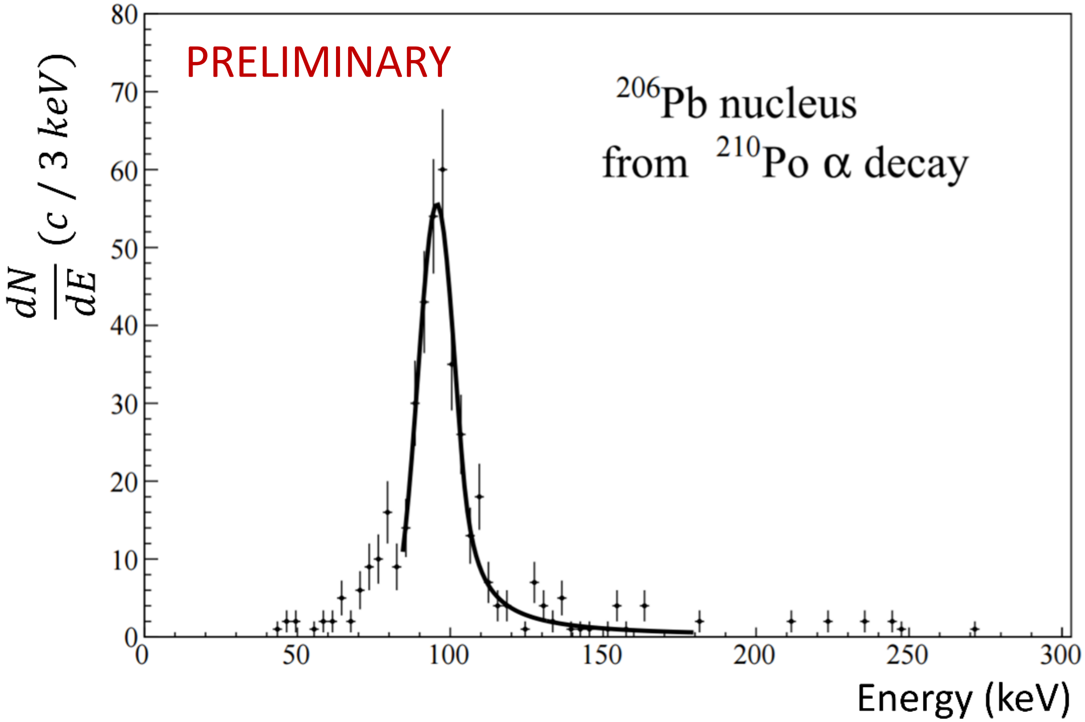


Then the 27.4 and 31 keV X-rays following Te atomic de-excitation are used to evaluate the overall energy calibration uncertainty
(of the order of 0.15 keV)

Nulcear recoil quenching of TeO2

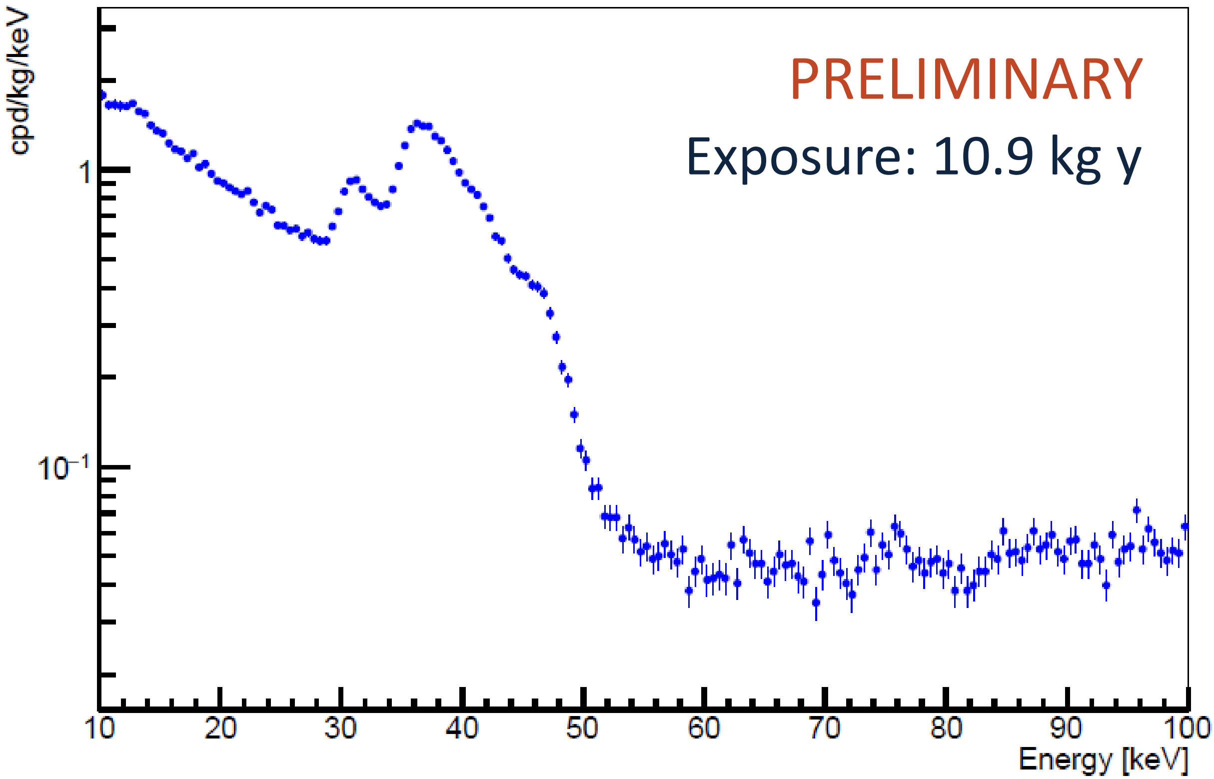
Calculated for recoiling ^{210}Pb, ^{222}Rn, ^{224}Ra and ^{218}Po after α decay





largest deviation: 7%
measured by ^{206}Pb
(0.927 ± 0.005)

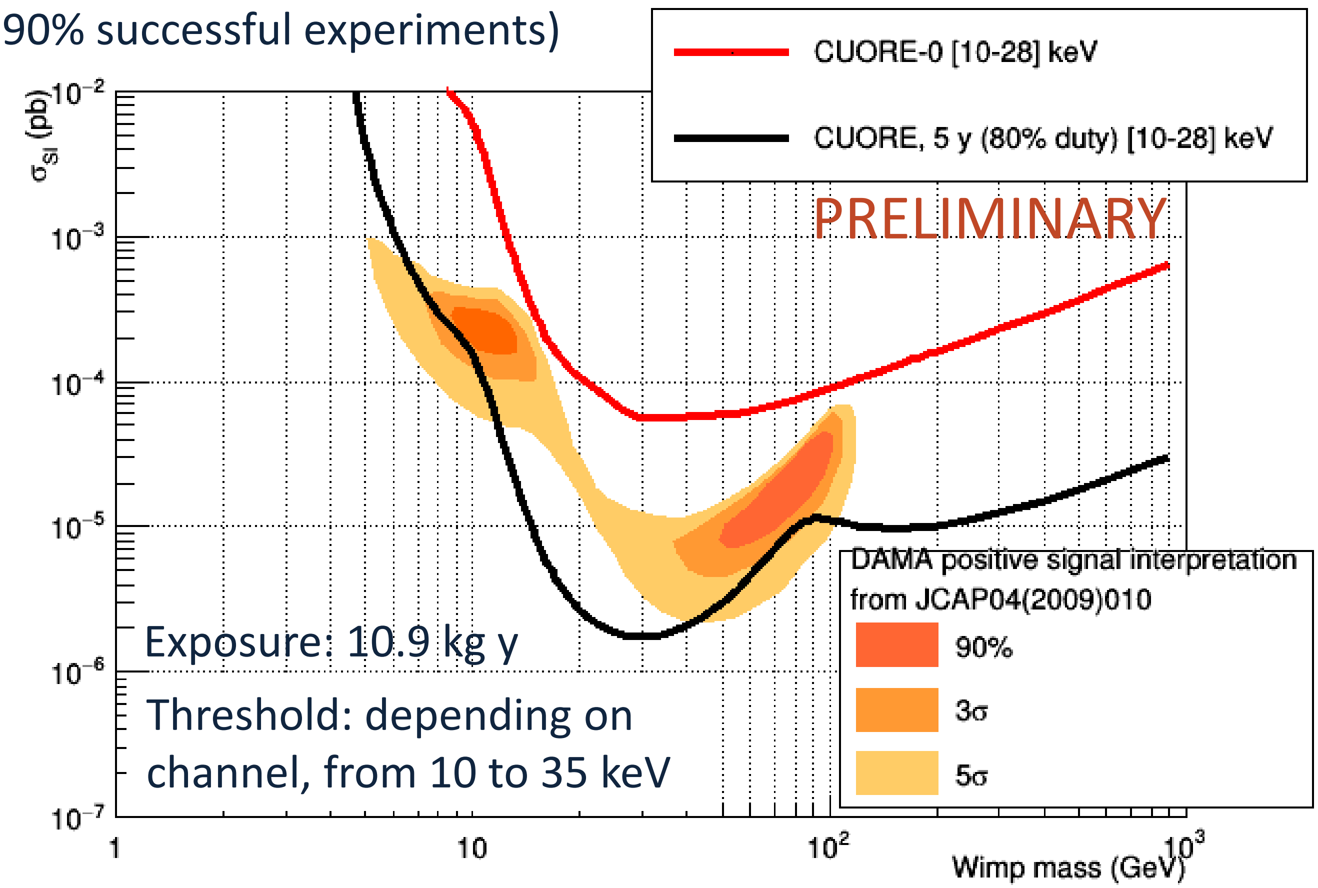
Low energy background



- Background level:
  ~1 c/keV/kg/d @ ROI → factor ~2 reduction with respect to CCVR2!
- Origin of peaks around 40 keV under investigation

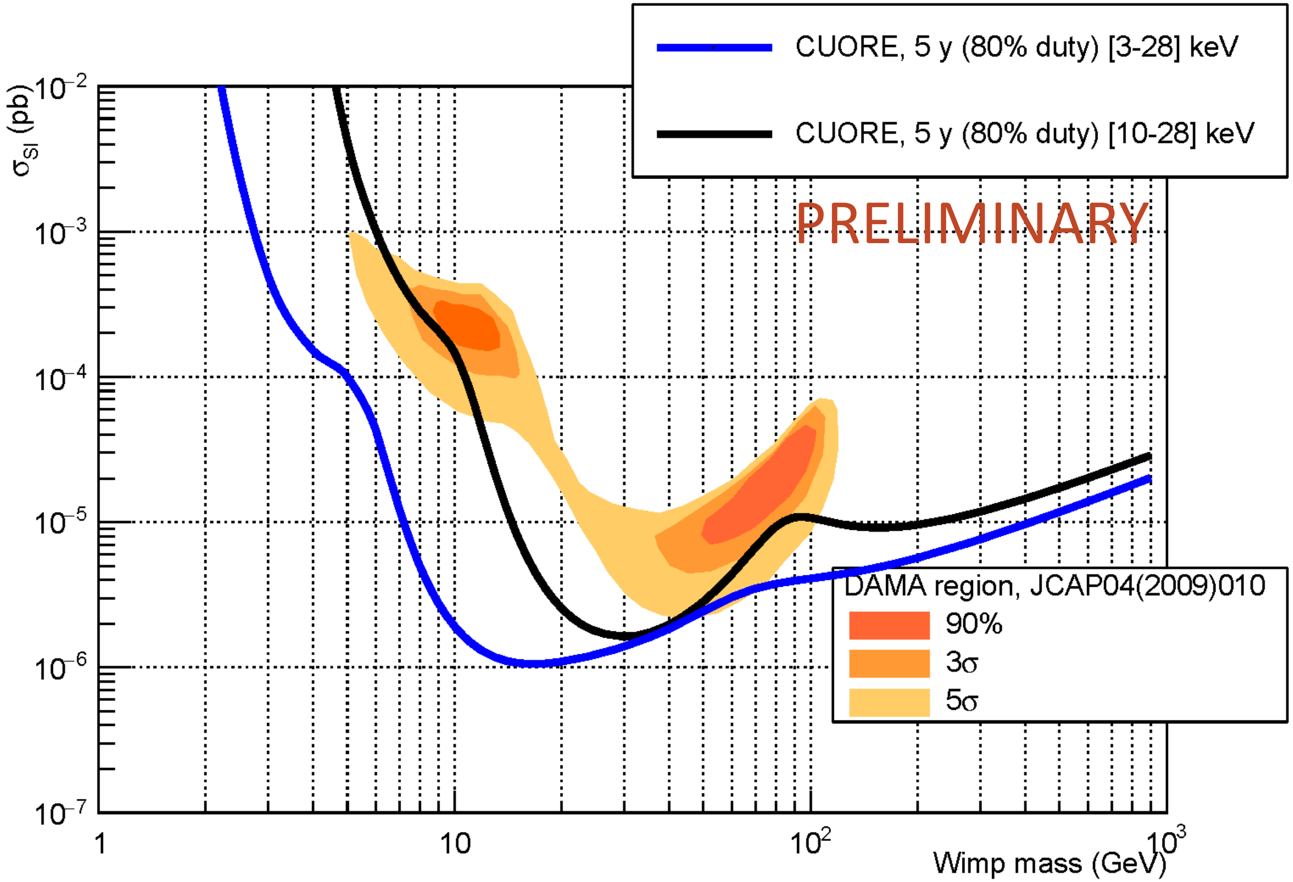
Sensitivity to annual modulation

(90% CL , 90% successful experiments)



CUORE-0: Limited sensitivity due to the low statistics
But extrapolating bkg from CUORE-0 and assuming an energy threshold of 10 keV, **CUORE could explore the DAMA/LIBRA positive signal region**

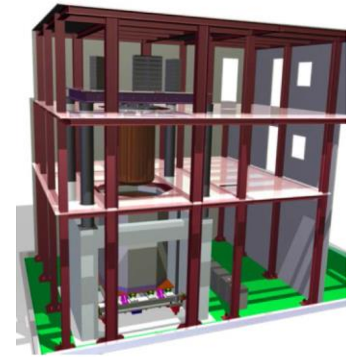
Sensitivity to annual modulation



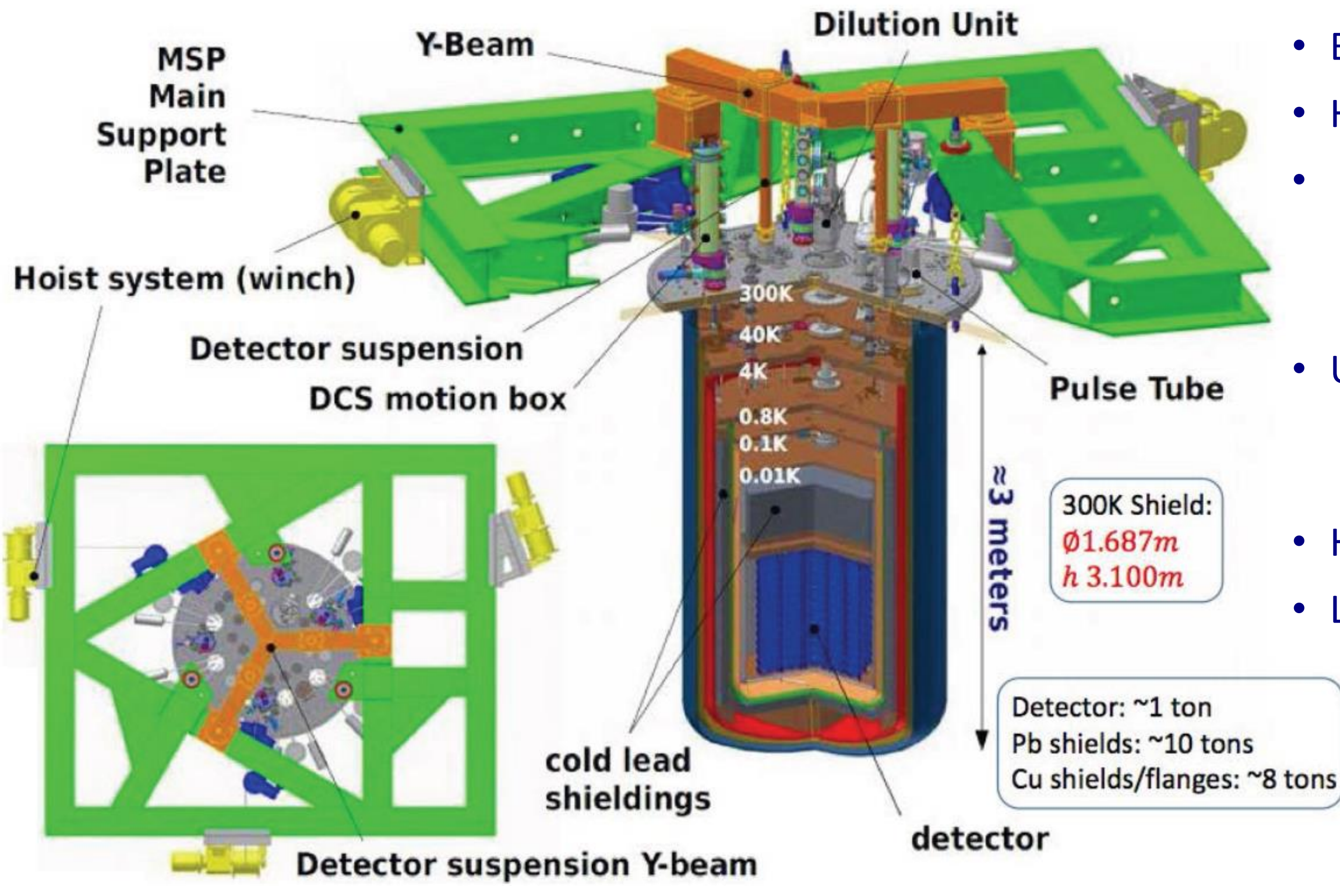
CUORE projection considering 3 keV threshold, as reached in CCVR

CUORE STATUS

Cryogenic system



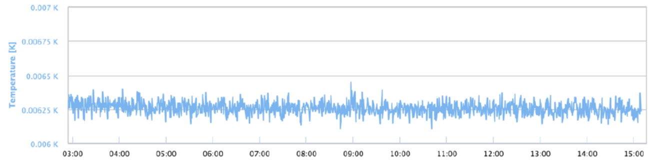
A very challenging system…



- Base temperature < 10 mK
- High temperature stability
- High cooling power
  - ~1500 kg cooled down to base T
  - 20 tons at various low T
- Ultra-low background
  - Only radiopure Cu near detectors
  - Roman lead <4mBq/kg 210Pb
- High duty-cycle (cryogen-free)
- Low mechanical vibrations.

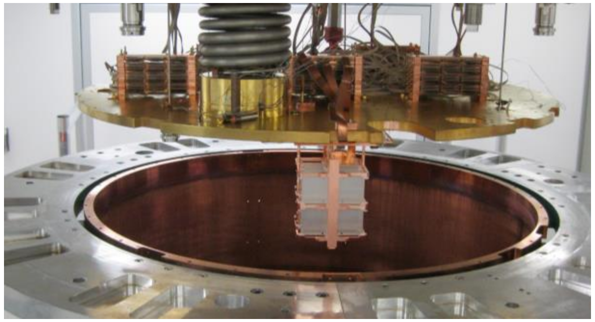
Cryogenic system commissioned!!

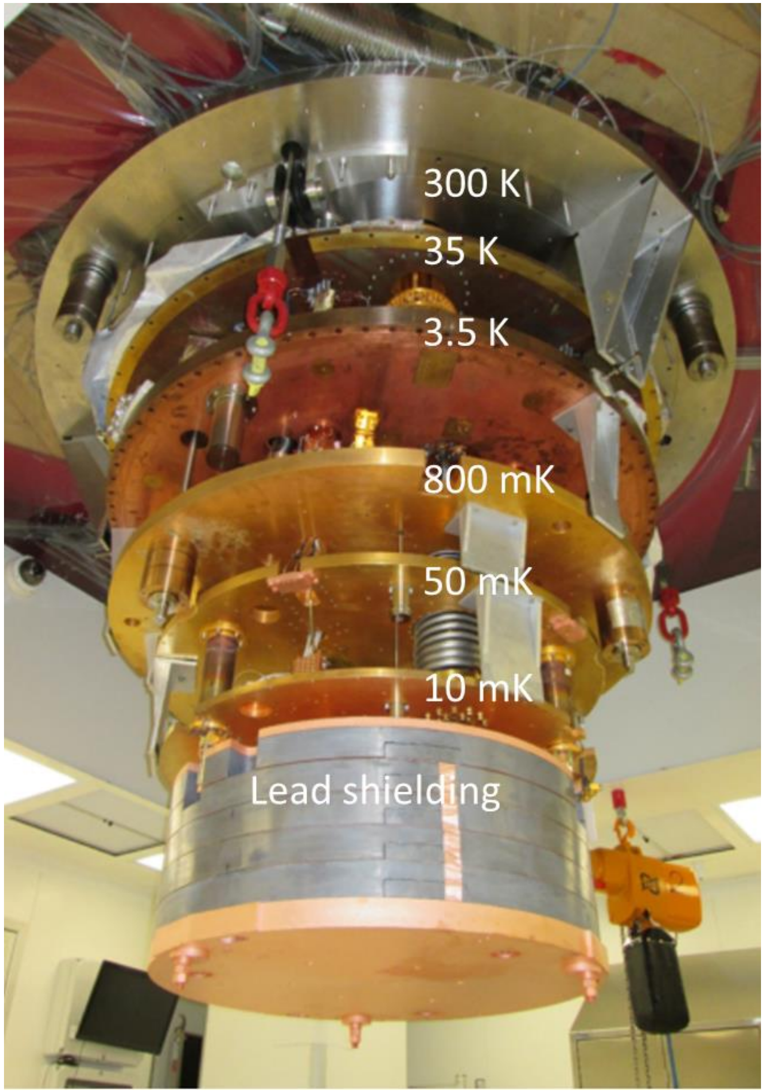
- All cryostat components thermalized (more than 15 tons of lead and copper)
- Stable base temperature **~6.3 mK** (maintained for more than 70 days)



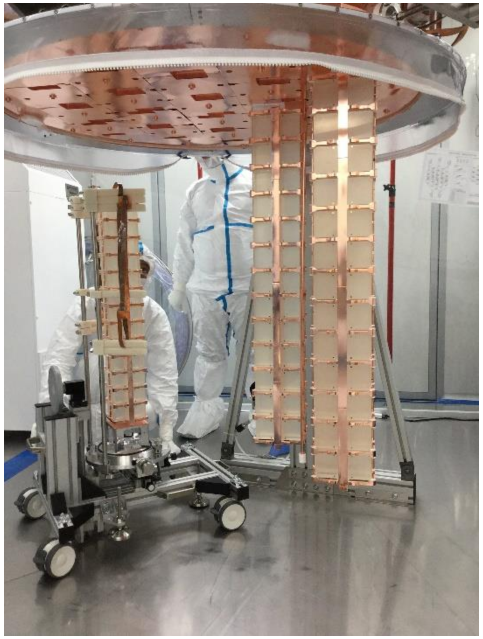
- Proved nominal cooling power: **3 μW @ 10 mK**
- First test done with 8 crystal succesfull

→ Commissioned electronics, DAQ, temperature stabilization, calibration system



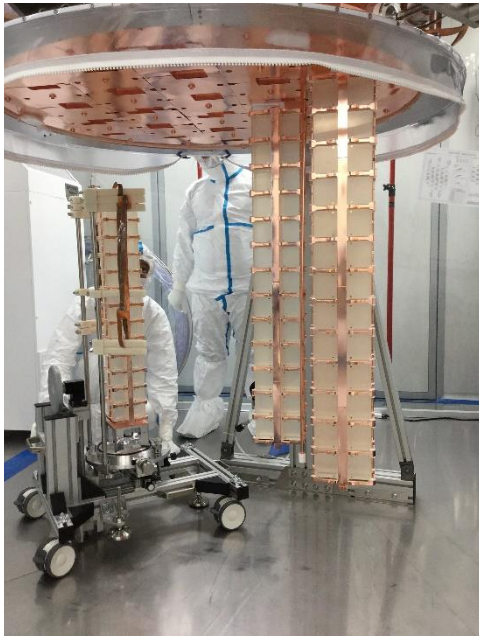


Detector installation: August 2016

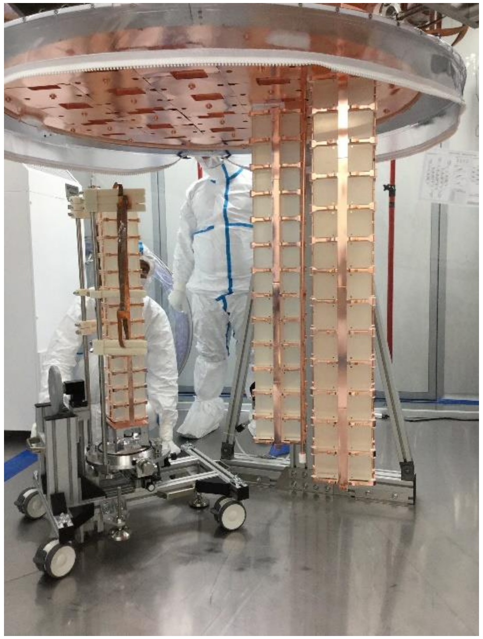


- Installation peformed in radon-free cleanroom
- Detectors stored in a nitrogen-filled protective bag until the cryostat was closed

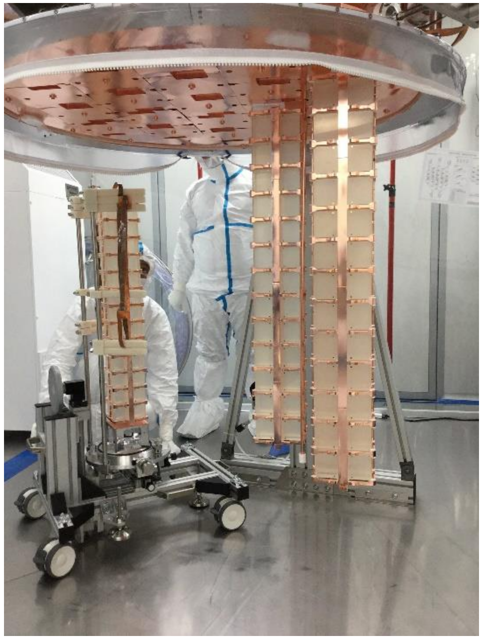
Detector installation: August 2016



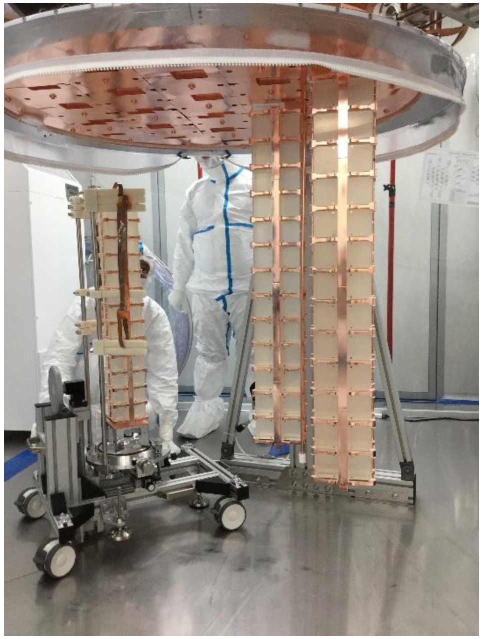
Detector installation: August 2016

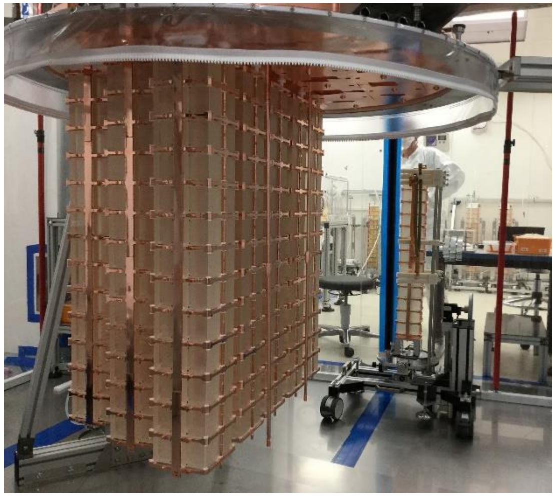


Detector installation: August 2016

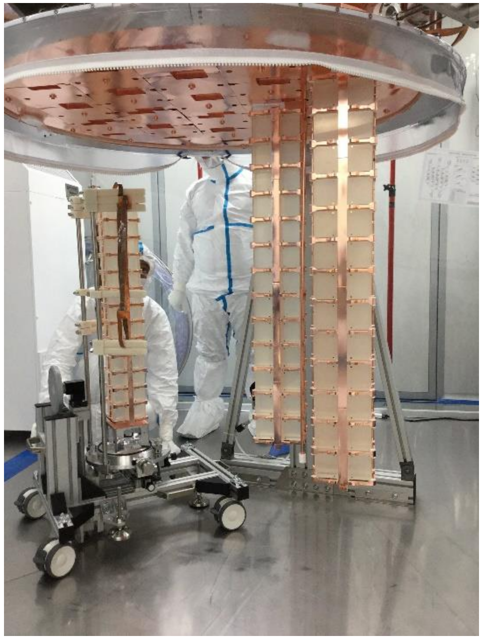


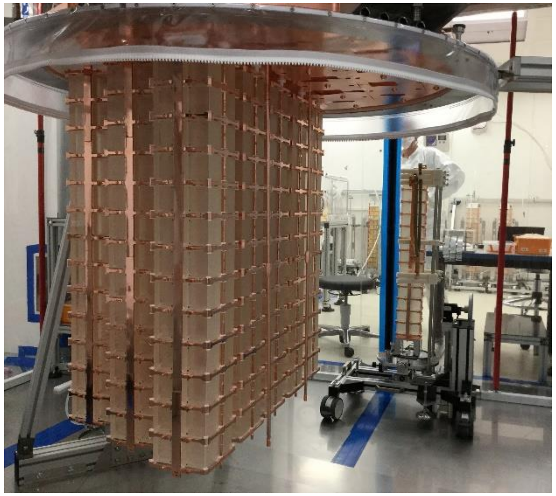
Detector installation: August 2016

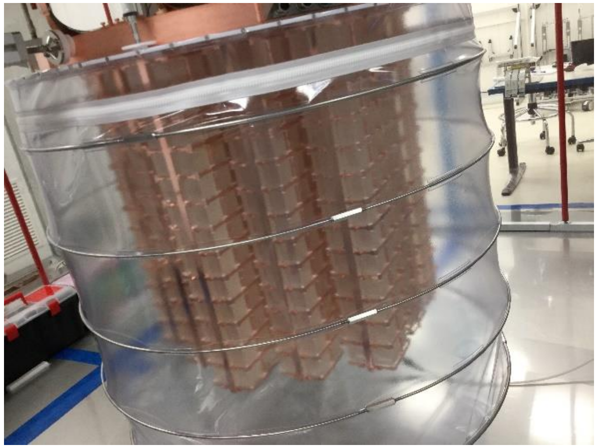




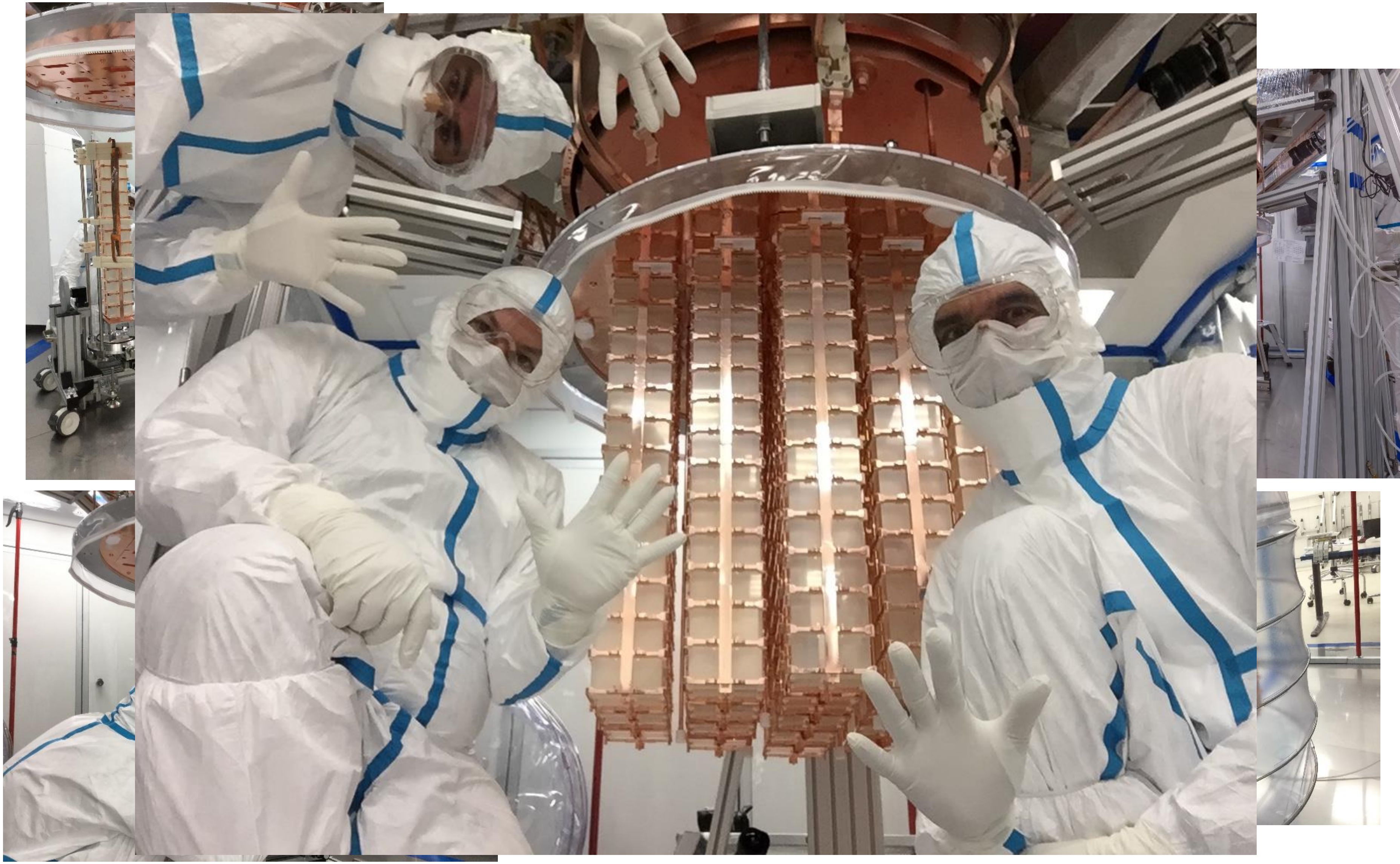
Detector installation: August 2016







Detector installation: COMPLETED!!



Summary

- **CUORE** is a TeO_2 ton-scale bolometric $0\nu\beta\beta$ experiment able to **reach the inverted hierarchy region** of the neutrino Majorana mass, but also can look for **DM annual modulation** and **solar axions via coherent Primakoff effect**.
- CUORE-0 recently concluded, achieved the **CUORE energy resolution goal** (5 keV FWHM at 2615 keV) and **validated the background reduction** protocols for CUORE. It also allowed to tune the low energy tools developed for CUORE.
- In CUORE-0 **10 keV threshold has been achieved for best crystals** with a **background ~1 cpd/kg/keV** and better results are foreseen for CUORE.
- **CUORE cryostat commissioning and detector installation completed. Start operations at the end of 2016.**


THANKS !!!

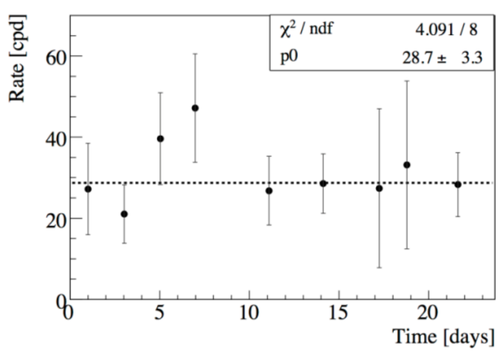
Spare

The 4.7 keV peak

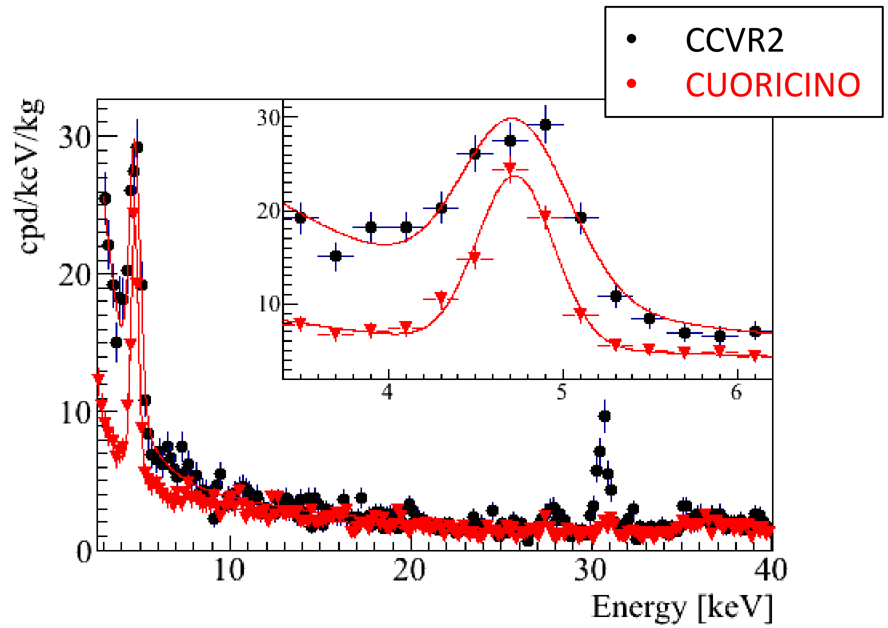
What's the origin of this peak?

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:



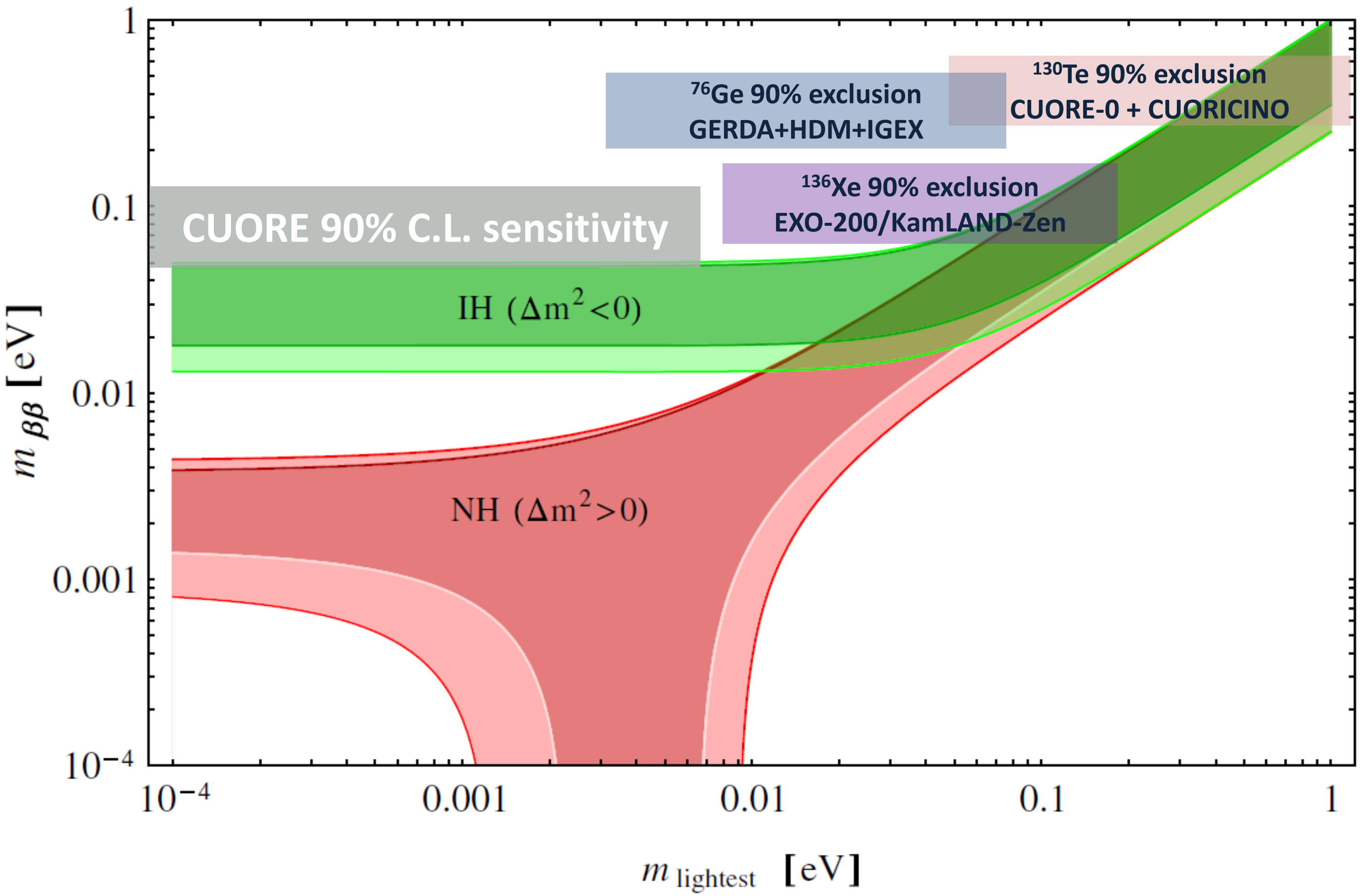
The 4.7 keV peak is also seen in a reanalysis of the last 2 months of operation of CUORICINO (only 4 bolometers with threshold < 4 keV):



(CUORICINO data not corrected for efficiency!)

CUORE 0νββ sensitivity

$$Rate_{0\nu} \propto \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

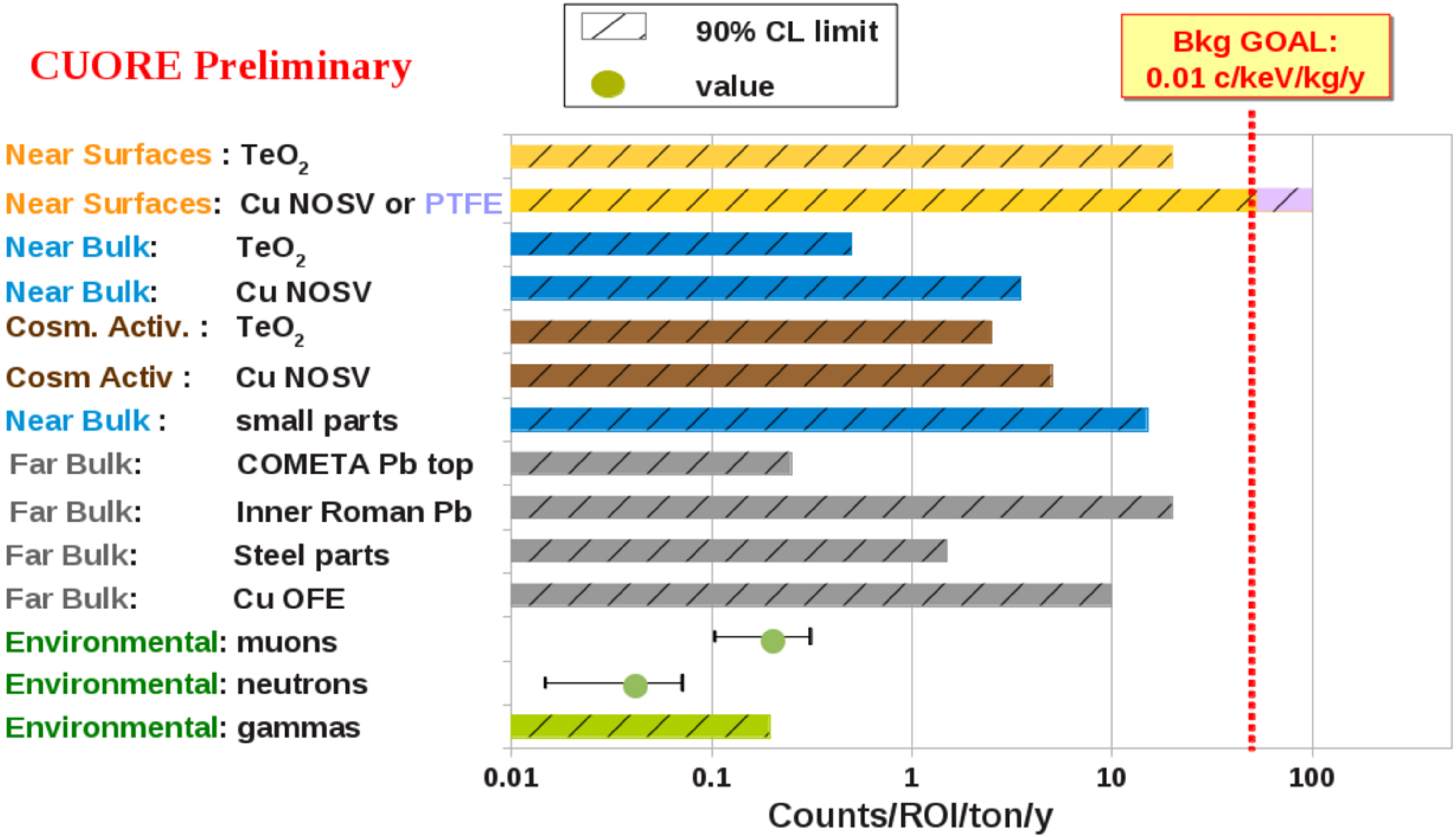


Reaching
Inverted hierarchy
~10 events/ton/yr

nuclear matrix
element estimates

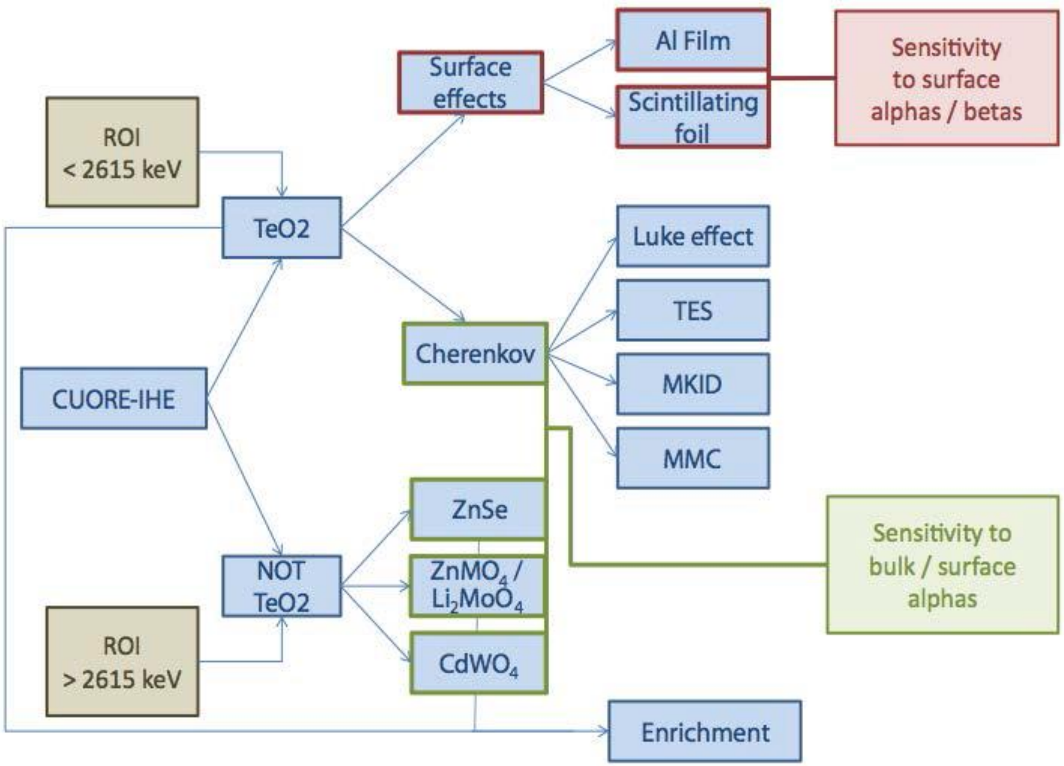
IBM-2 Phys. Rev. C 91, 034304 (2015)
RPA-TU Phys. Rev. C 87, 045501 (2013)
nQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)

Background budget

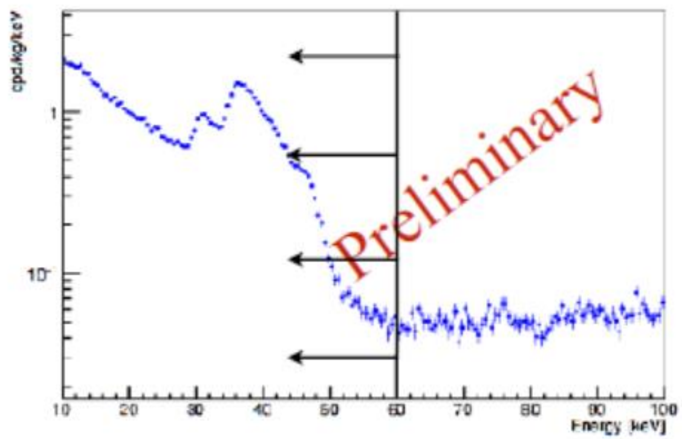


CUPID

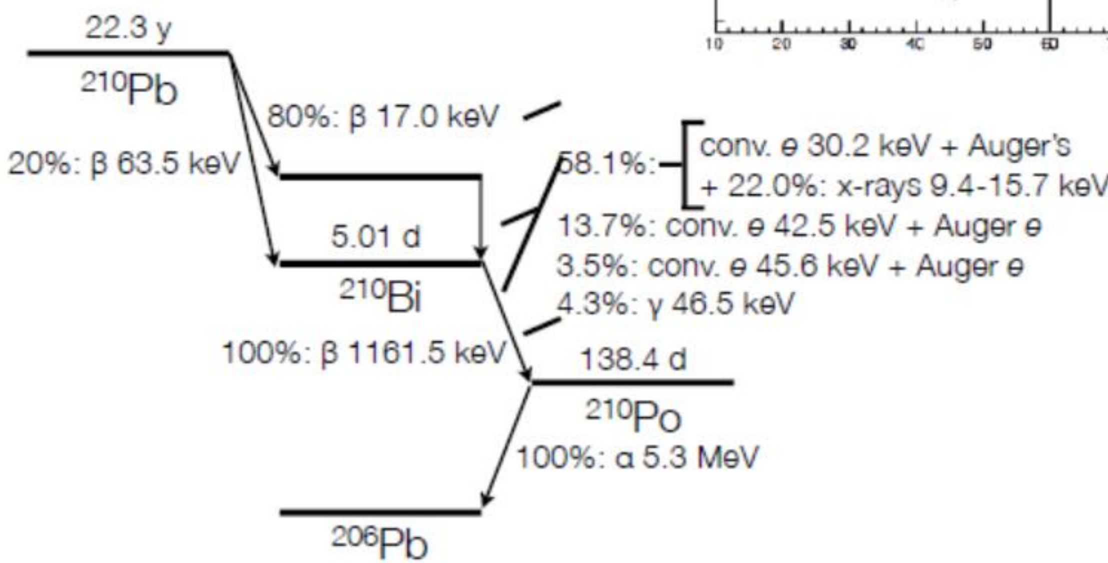
Paths to explore the IH region:



- ^{130}Te enrichment
- a discrimination
  - Cherenkov
  - Surface event tagging
- Explore other isotopes
  - scintillation



cpd/kg/keV
1
10
20
30
40
50
60
70
80
90
100
Energy [keV]
Preliminary



22.3 y
210Pb
80%: β 17.0 keV
20%: β 63.5 keV
58.1%:
conv. e 30.2 keV + Auger's
+ 22.0%: x-rays 9.4-15.7 keV
13.7%: conv. e 42.5 keV + Auger e
3.5%: conv. e 45.6 keV + Auger e
4.3%: γ 46.5 keV
5.01 d
210Bi
100%: β 1161.5 keV
138.4 d
210Po
100%: α 5.3 MeV
206Pb