Results from the CUORE experiment

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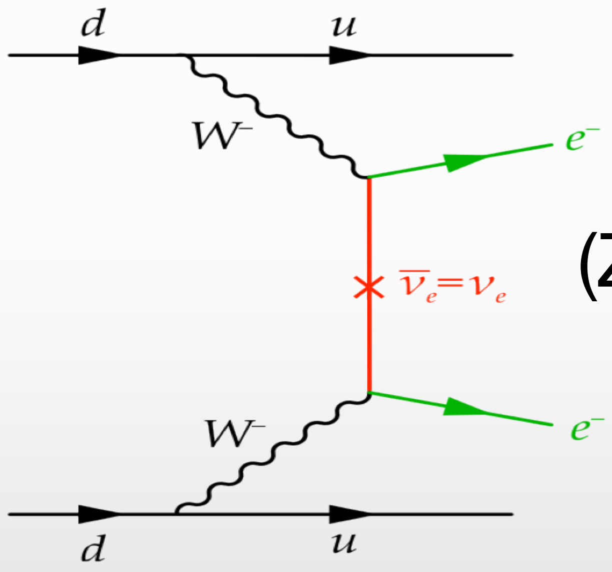
on behalf the CUORE Collaboration
Bologna – September 2018

$0\nu\beta\beta$ decay and signature

CUORE primary goal is the search

for $0\nu\beta\beta$ decay: $^{130}\mathrm{Te} \rightarrow \, ^{130}\mathrm{Xe} + 2e^-$



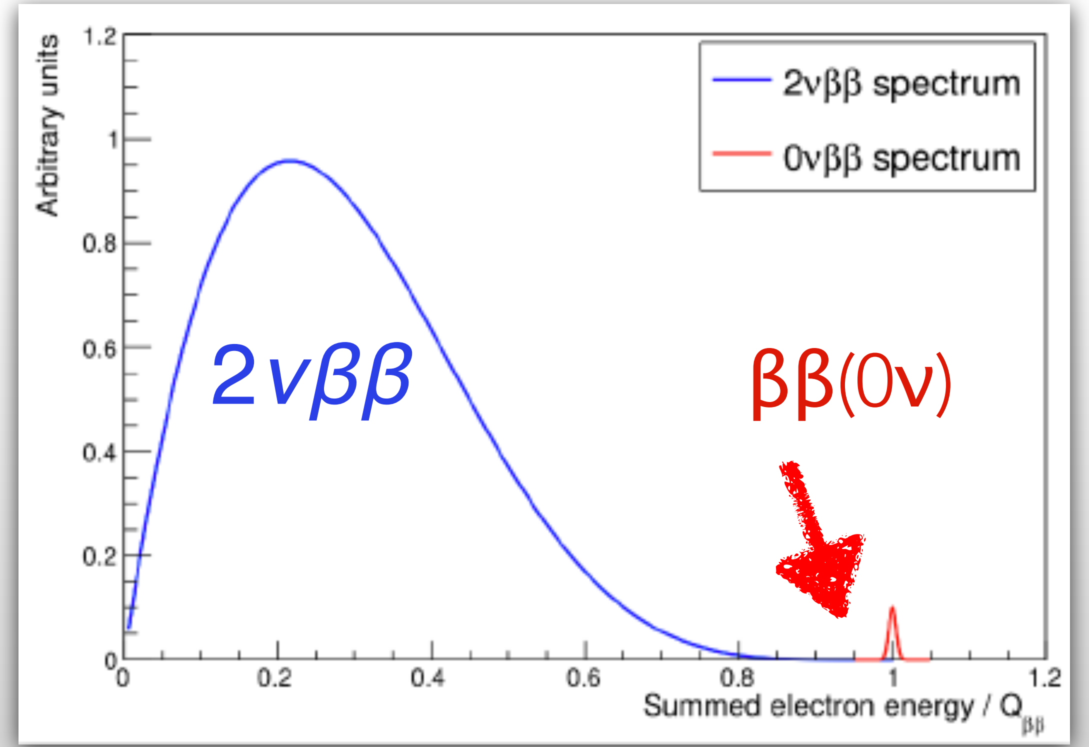
(Z,A)→(Z+2,A) +2e

(+2ν)

- SM forbidden
- $\Delta L = 2$
- If observed ⇒ ν is a Majorana particle

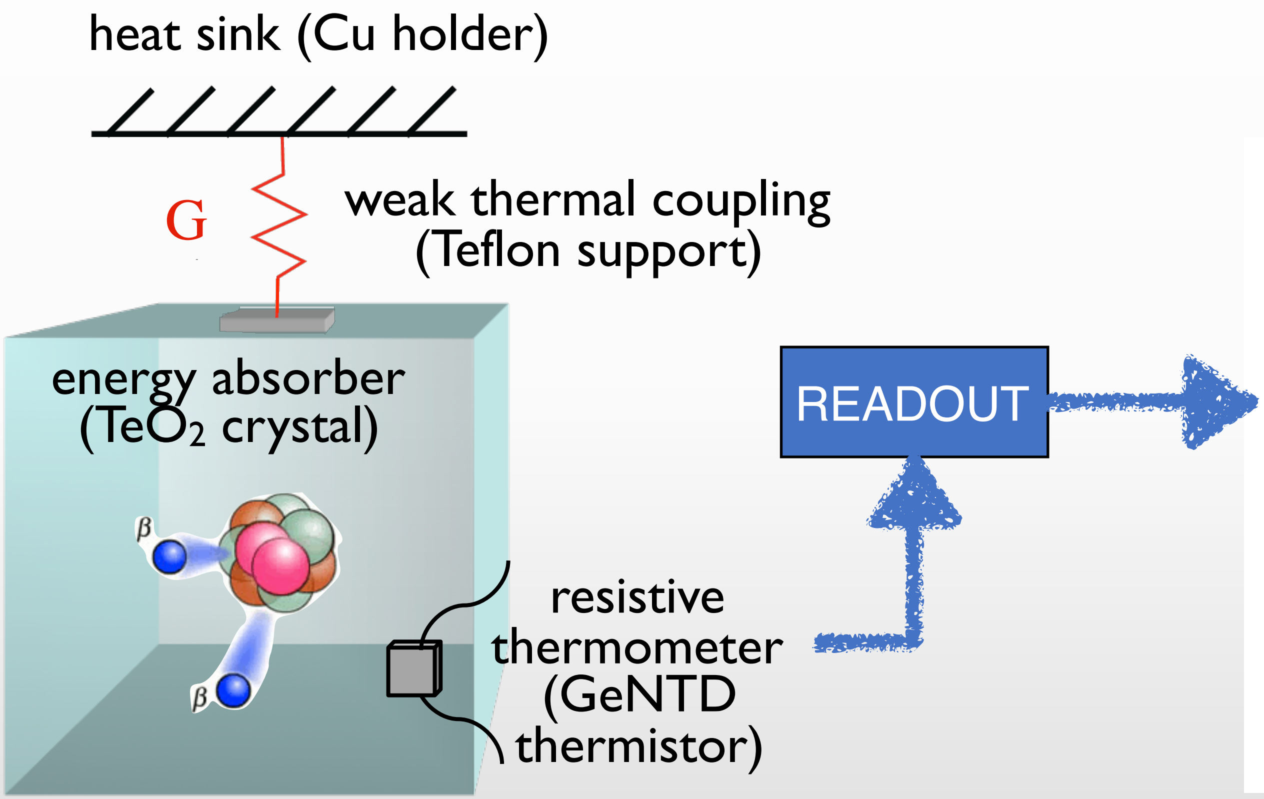
Observable: line at Q-value

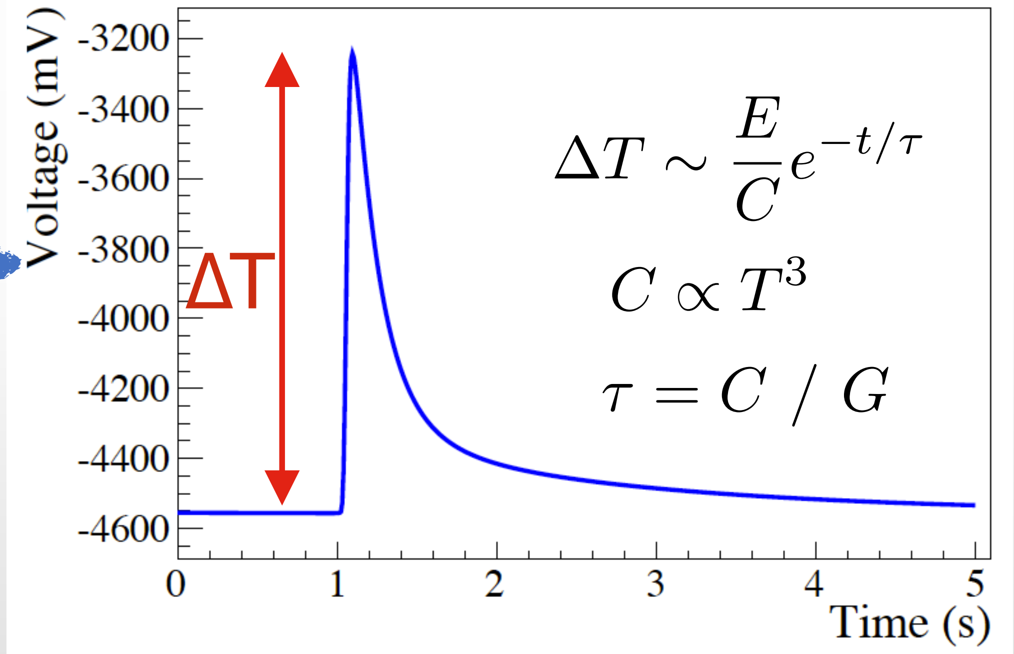
- measure $E_{\beta\beta} = E_{\beta1} + E_{\beta2}$
- smeared by energy resolution
- Q(Te) ≃ 2528 keV



The bolometric technique

The detector: 1) contains the isotope 2) absorbs the energy 3) increase its temperature





$$\Delta T \sim \frac{E}{C} e^{-t/\tau}$$

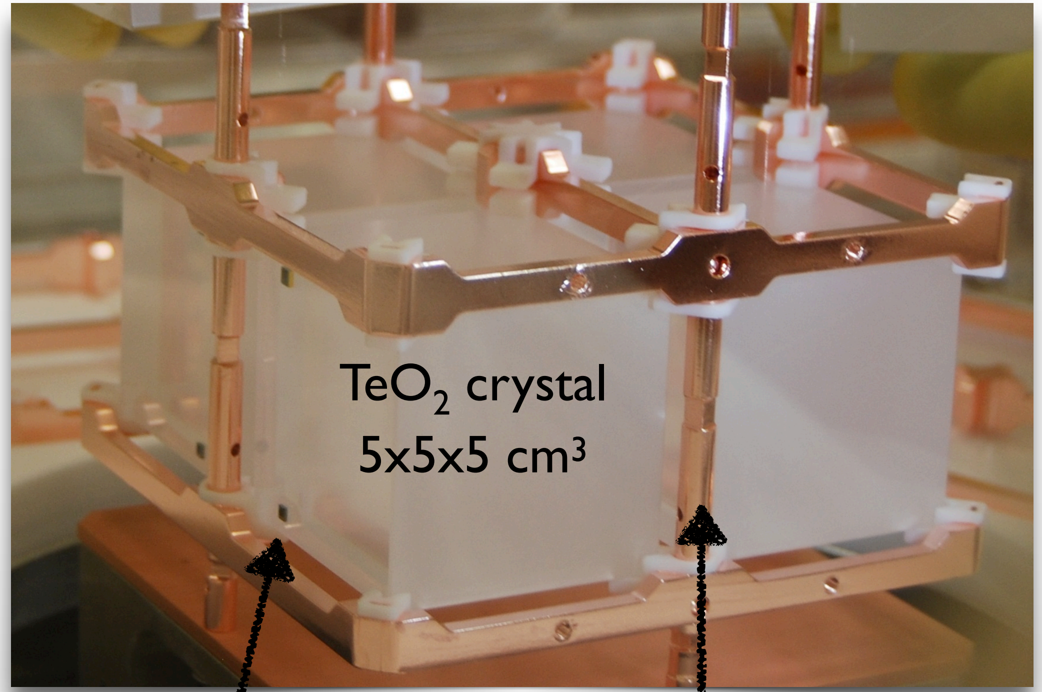
$$C \propto T^3$$

$$\tau = C \,/\, G$$

- $2e^-$ mostly contained in the bulk
- excellent efficiency & energy resolution
- hardly discriminate signal from bkg

Working temperature:
@ ~10 mK

CUORE bolometers: TeO_2 crystals

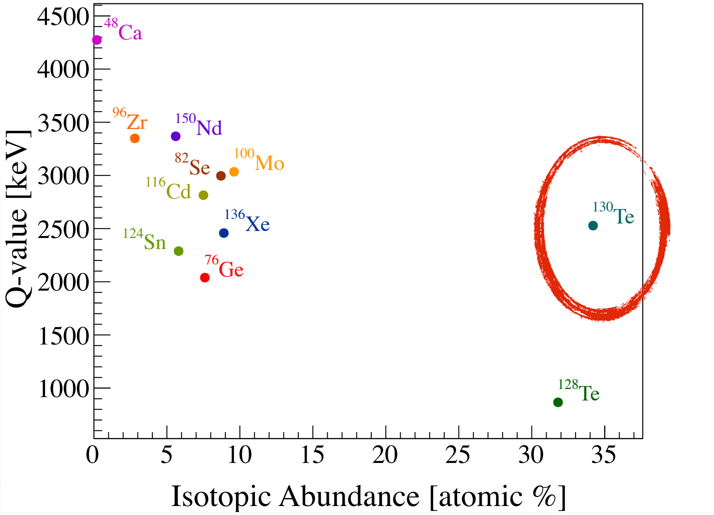


With:
E ~ 1 MeV
C ~ 10^{-9} J/K @10 mK

$\Delta T \simeq 0.1$ mK/MeV

Choice of TeO_2 :

- ^{130}Te abundance = 34%
- Q = 2527.5 keV above most of natural radioactivity
- high quality crystals and large mass scale possible



The sensitivity may be expressed as:

$$\left(T^{0\nu}_{1/2}\right)^{sens} \propto i.a. \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

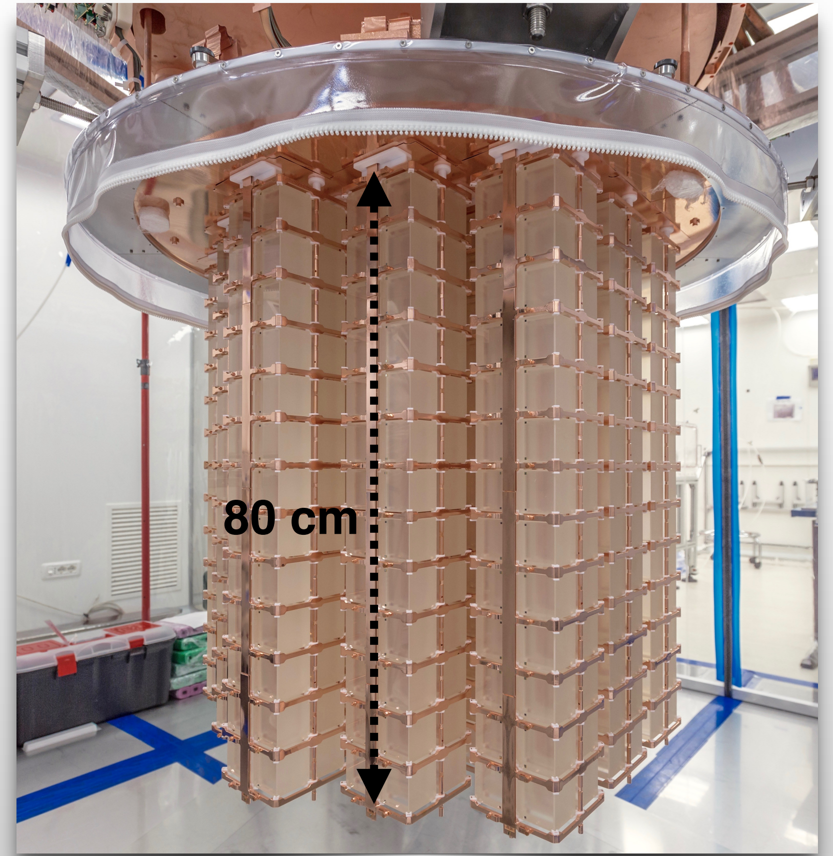
Isotopic abundance; Mass; Exposure time; Efficiency; Bkg. rate; Energy resolution

Cryogenic Underground Observatory for Rare Events

1- detector

2- cryostat

3- background mitigation + passive shielding



- 988 crystals 5x5x5 cm, closely packed
- arranged in 19 towers of 13 floors each
- 742 kg (206 kg of ^{130}Te)
- background goal: 0.01 counts/(kg keV yr)
- energy resolution goal: 5 keV FWHM in the ROI

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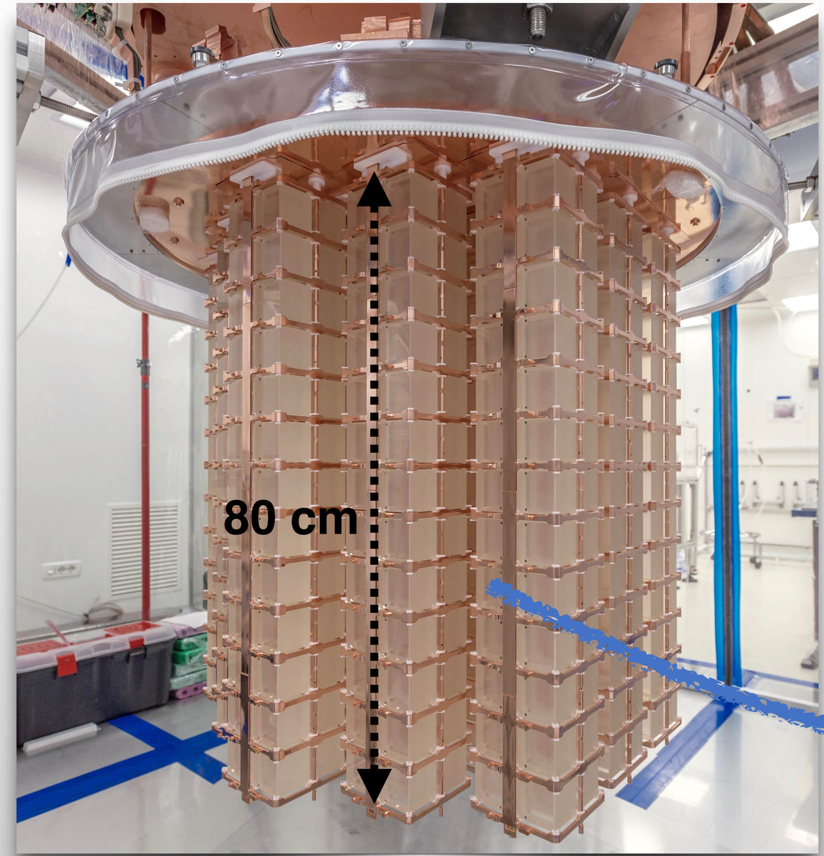

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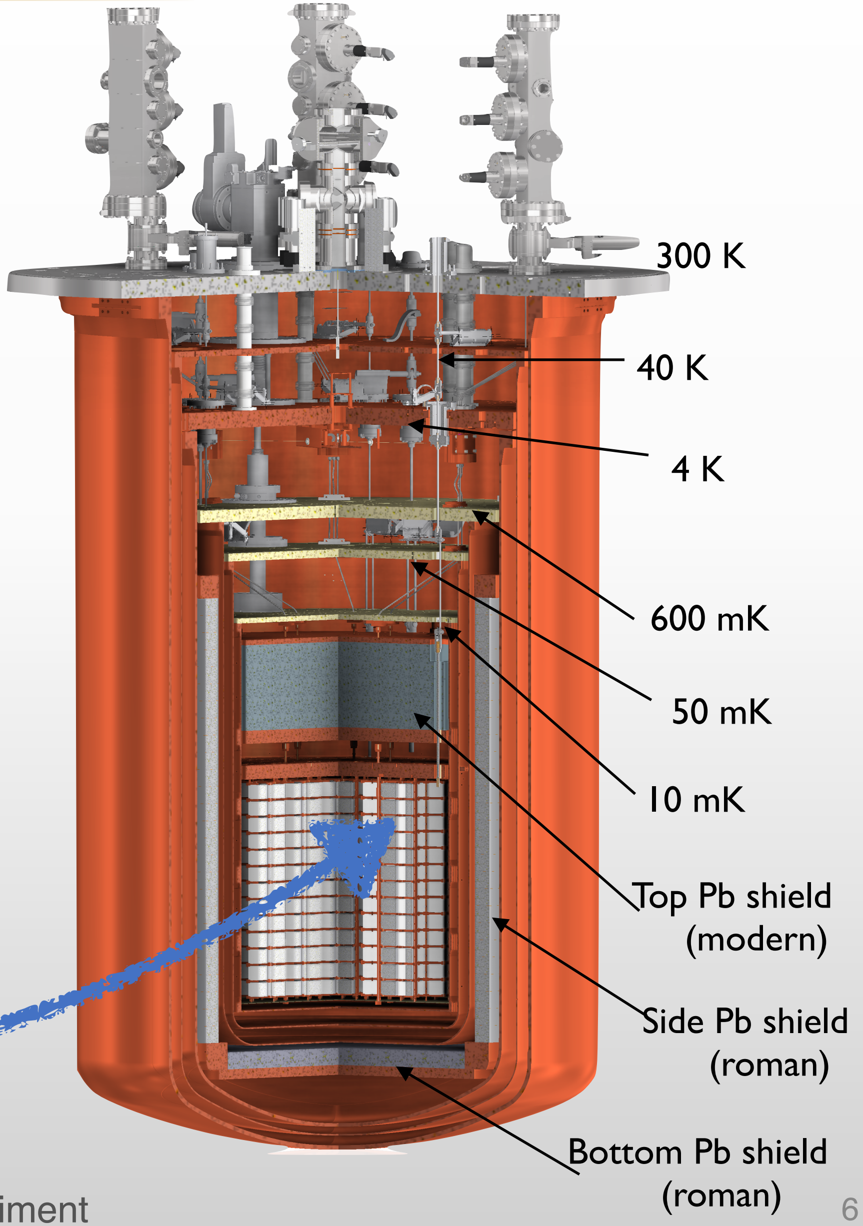

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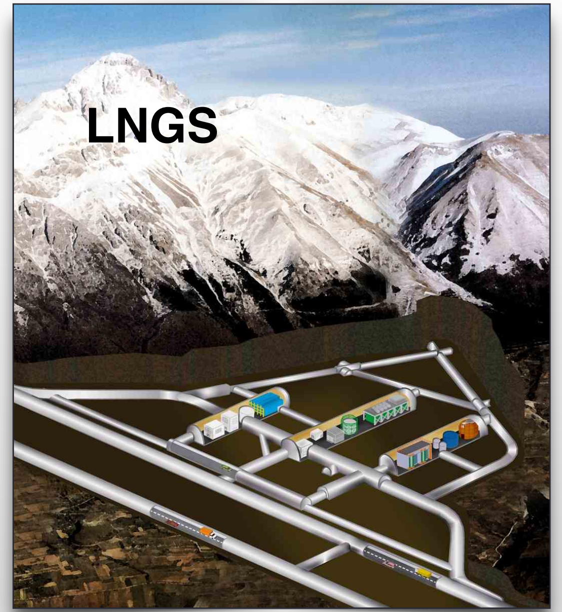
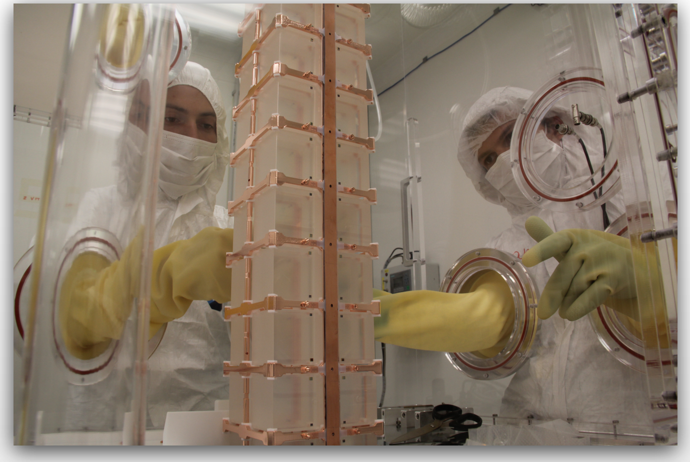
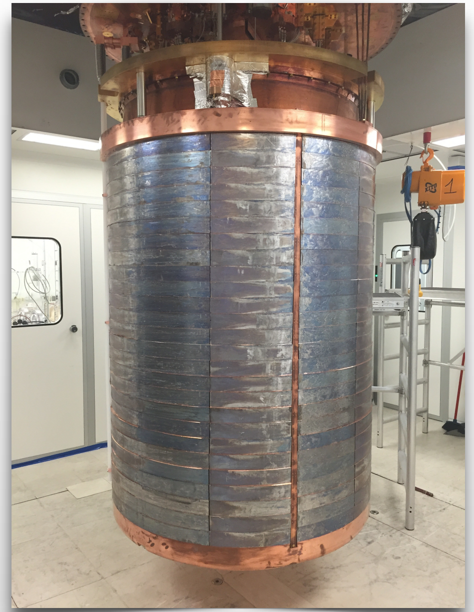


- 3600 m.w.e. deep equivalent
- 1400 m rock overburden cuts muon flux by ~10^6

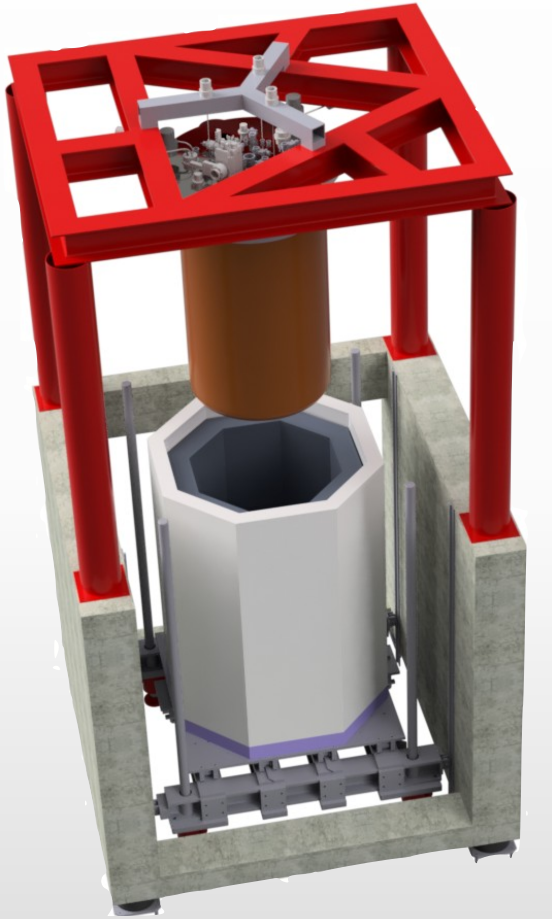


- tower assembly and storage in N_2 atmosphere @LNGS
- ✓ material selection
- ✓ crystal surface polishing
- ✓ special cleaning process for Cu and PTFE parts



Internal shields:

- 6,.5 tons ancient roman lead shied
- ✓ Cu + modern lead



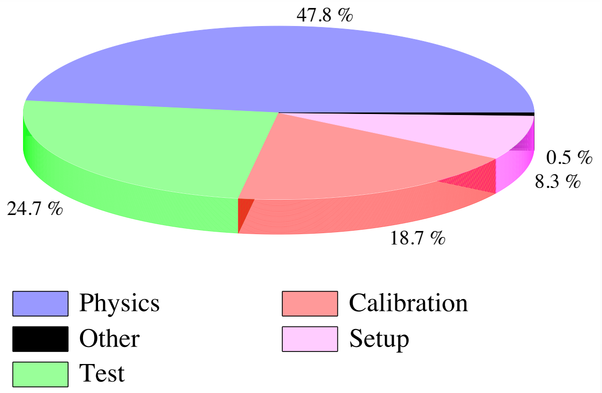
External shields:

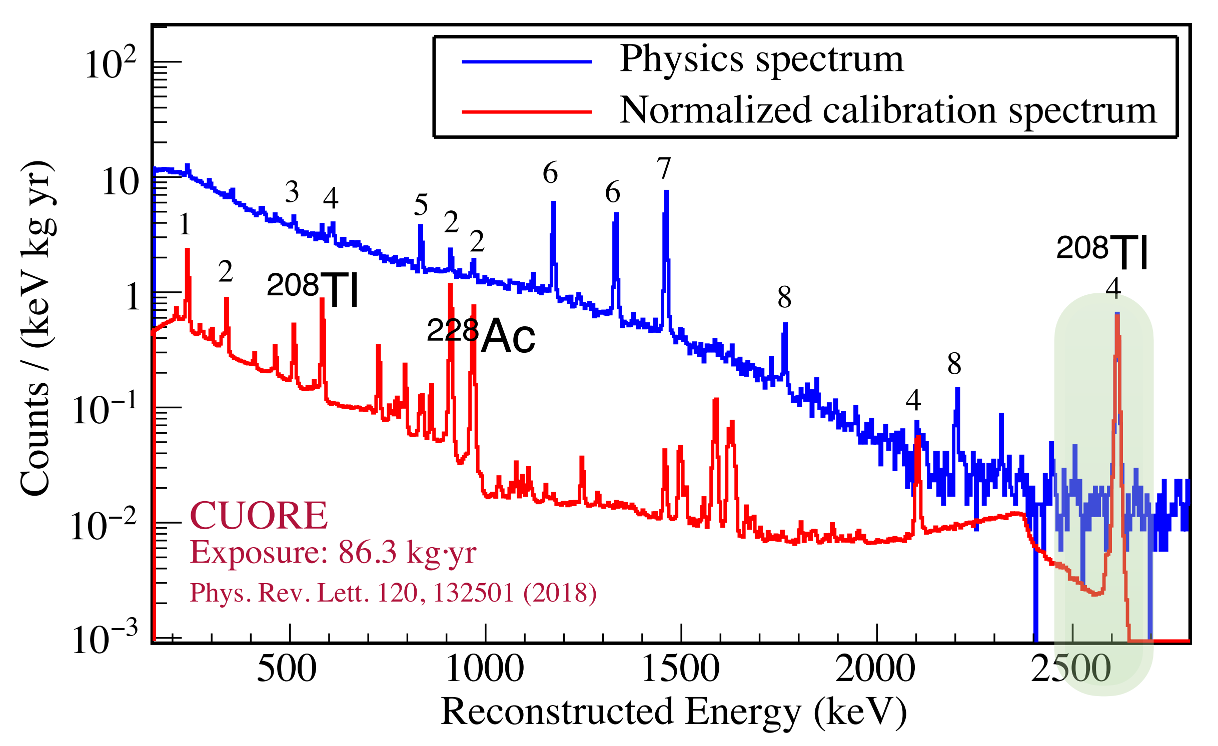
- 25 cm external Pb (γ)
- 18 cm polyethylene + 2 cm H_3BO_3 (neutrons)

CUORE data-taking 2017

- In January 2017 first pulse
- during summer 2017 two physics-data periods:
  - exposure: 86.3 kg yr of TeO_2 (37.6 + 48.7 kg yr)
  - ^{130}Te exposure: 24.0 kg yr
  - each dataset bracketed by calibrations
  - 984/988 active channels
  - 92% of channels passing analysis cuts
  - Signal efficiency ~80% (75.7±3.0 and 83.0±2.6)

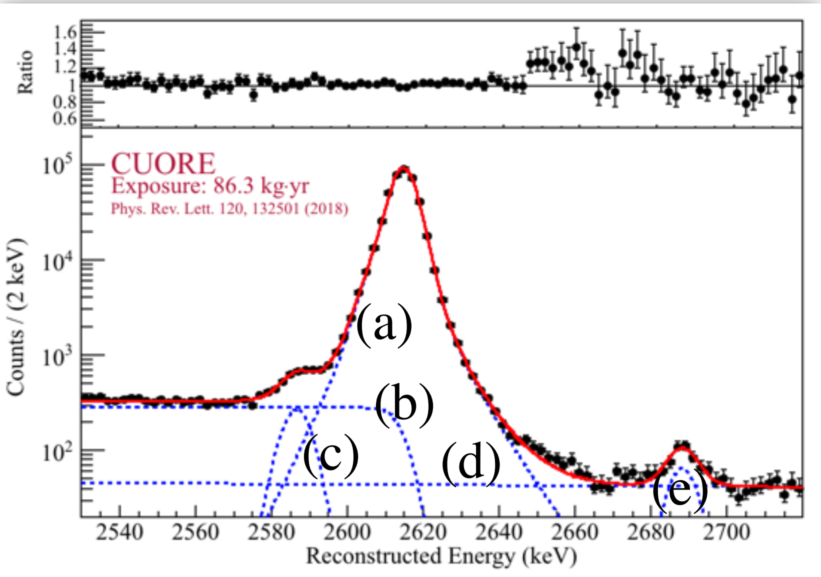
Phys. Rev. Lett. 120, 132501 (2018)





Detector performance (energy resolution)

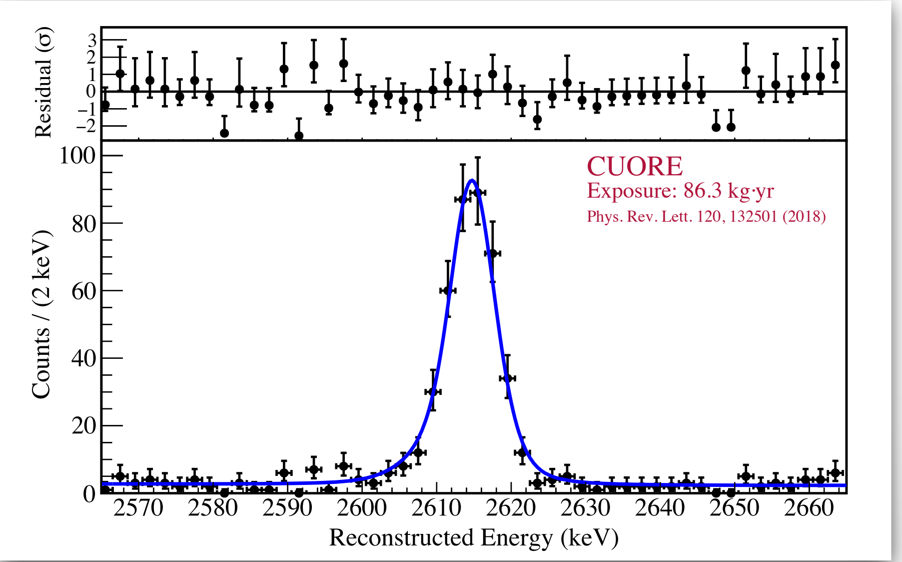
Calibration data

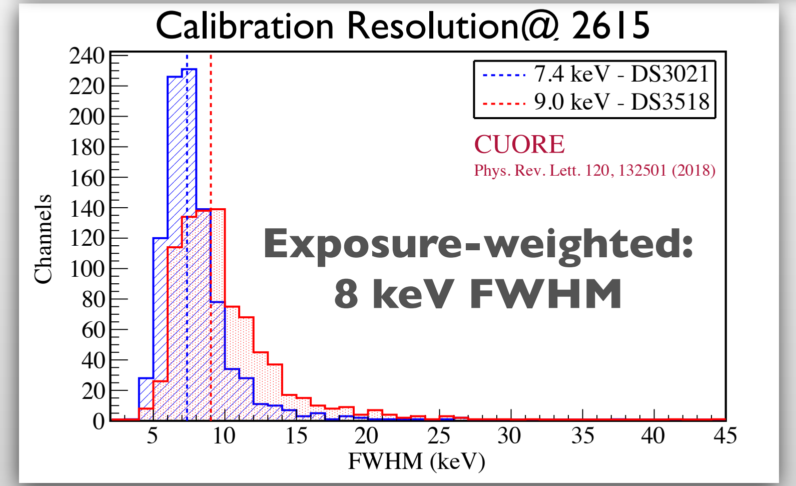


^{208}Tl 2615 keV from ^{232}Th calibration is well modelled with: (a) Gaussian photopeak, (b) Compton, (c) X-ray escape 30 KeV, (d) linear bkg, (e) 2687 keV = 2615 + 583 γ(^{232}Th) - 511γ(e^+e^-)

For calibration purpose a fit is done per bolometer-dataset.

Physics data





A scaling factor is obtained from (six) spectral lines and its value extrapolated at the Q-value

Physics data resolution@ Q-value
Dataset 1: (8.3 ± 0.4) keV FWHM
Dataset 2: (7.4 ± 0.7) keV FWHM
Exposure-weighted: (7.7 ± 0.5) keV FWHM

Event selection

1. Removal of low-quality data (~1% of the total live time)

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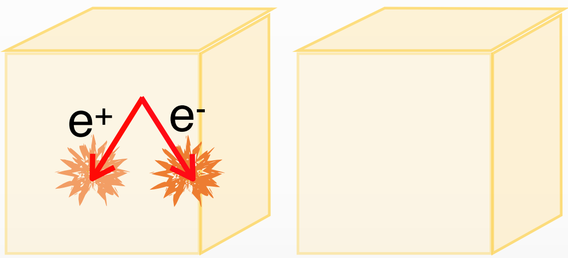
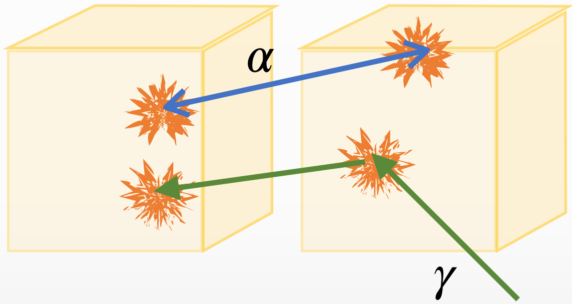
2. Select multiplicity=1 (M1) events

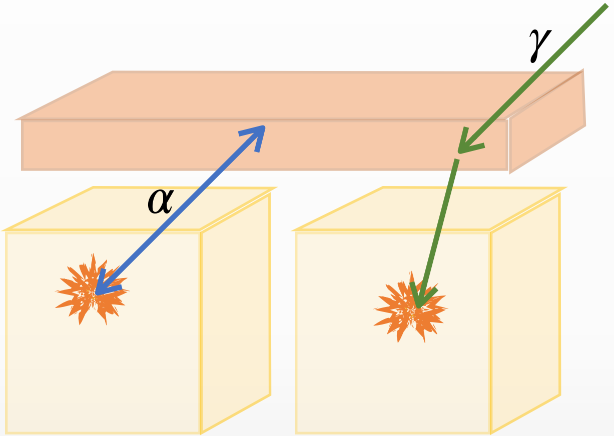


M1: signal like



M2: rejected background

Simultaneous energy deposit in two crystals is likely due to background events: we require no coincidences in a 10s time window



M1: backgrounds

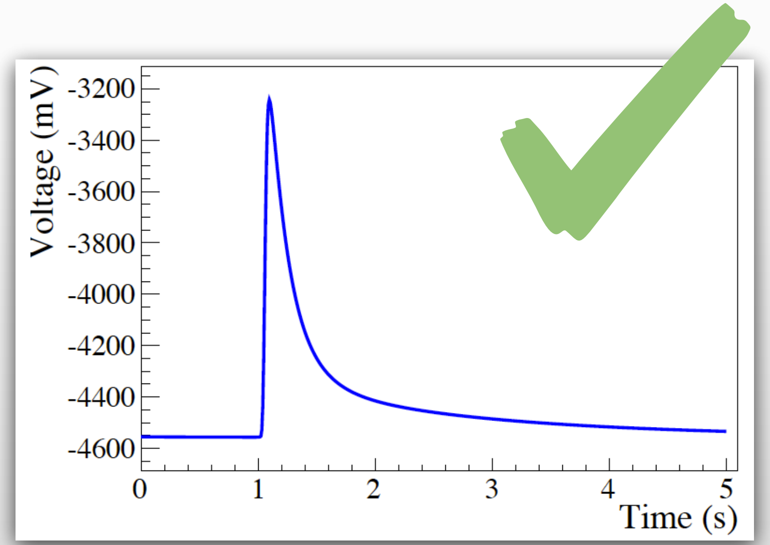
Dangerous backgrounds mimiking energy deposit in one crystal

Event selection

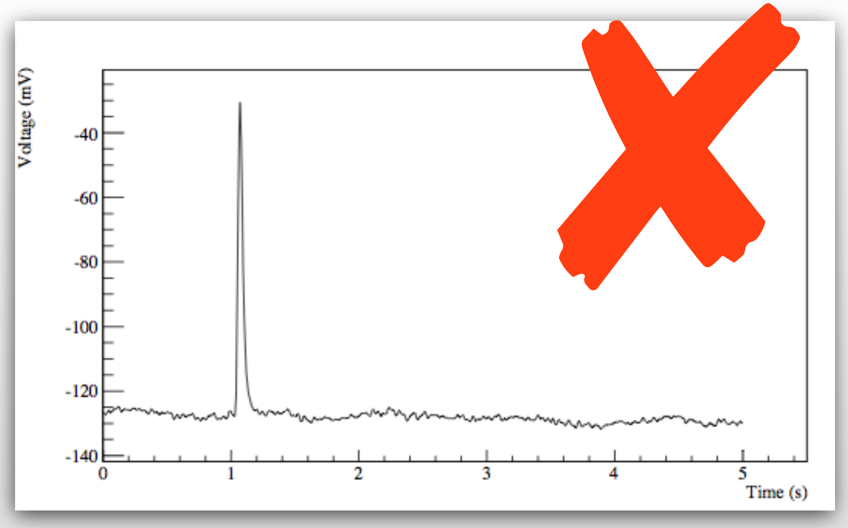
1. Removal of low-quality data (~1% of the total live time)

2. Select multiplicity=1 (M1) events

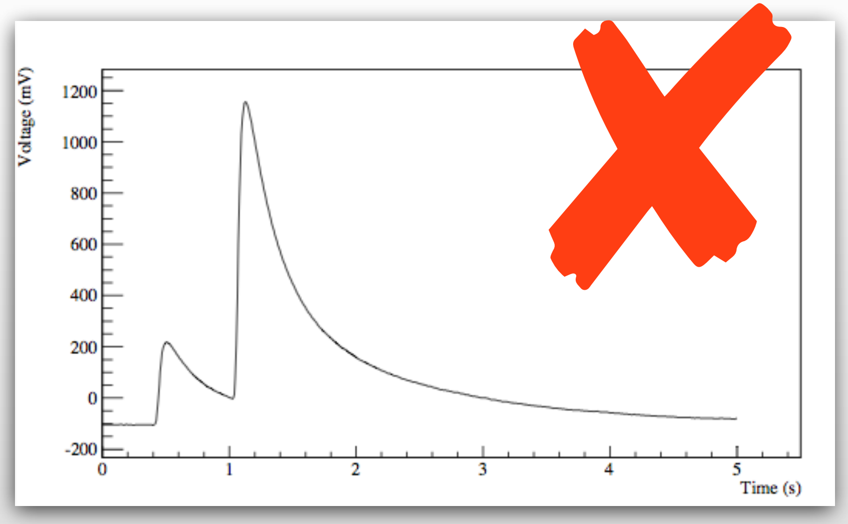
3. Pulse shape analysis



Signal



Noise



Pile-up

Event selection

1. Removal of low-quality data (~1% of the total live time)

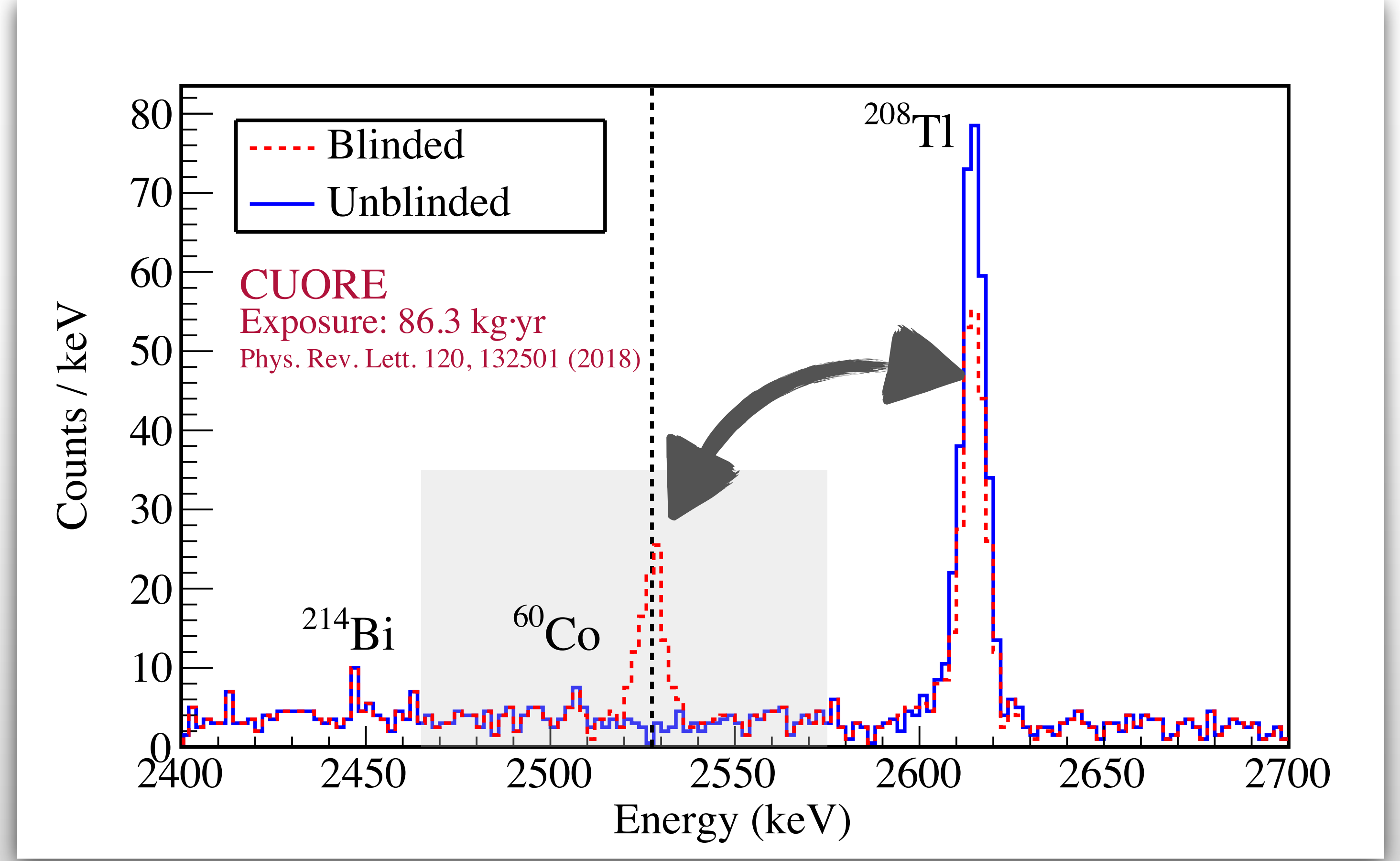
2. Select multiplicity=1 (M1) events

3. Pulse shape analysis

4. Blinding

Swap an (unknown) fraction of events from ^{208}Tl peak to the Q-value region.
Unblinding only when the full analysis procedure is fixed

155 events are left in the ROI

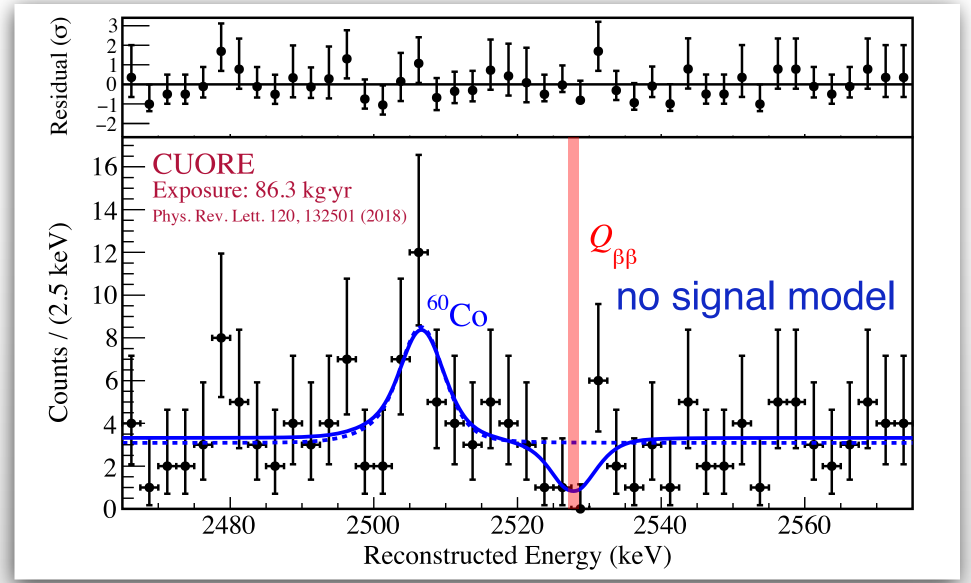


Fit and results

Phys. Rev. Lett. 120, 132501 (2018)

Extended maximum likelihood fit in 2465-2575 keV:

- ^{60}Co peak 2506 keV (floating position)
- peak at $Q_{\beta\beta}$ (fixed position, floating rate)
- flat background (dataset dependent)



Background Index in counts/(kg keV yr):

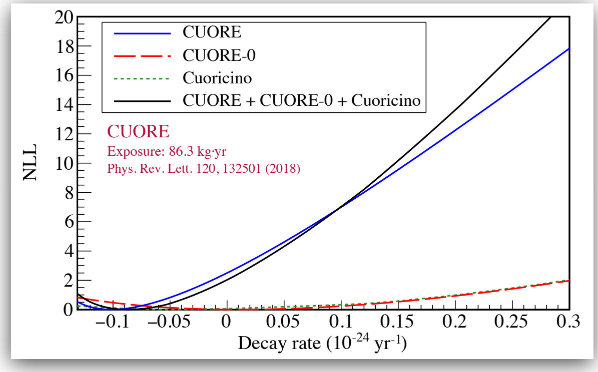
1th dataset : $(1.49^{+0.18}_{-0.17})\times10^{-2}$

2nd dataset : $(1.35^{+0.20}_{-0.18})\times10^{-2}$

Exposure weighted : 0.014 ± 0.2

Best fit decay rate:

$$\Gamma_{0\nu} = [-1.0^{+0.4}_{-0.3}(\text{stat}) \pm 0.1(\text{syst})] \times 10^{-25}\ \text{yr}^{-1}$$



No evidence for $0\nu\beta\beta$

Decay rate limit (90% C.L. incl. syst.) = 0.51×10^{-25} yr^{-1}

$T_{1/2}$ (90% C.L. including syst.) = 1.3×10^{25} yr

We combine CUORE results with Cuoricino (19.75 kg yr) and CUORE-0 (9.8 kg yr) data and obtain:

$T_{1/2}$ (90% C.L.) > 1.5×10^{25} yr

Interpretation of results

$T_{1/2}$ (90% C.L.) > 1.5x10^{25} yr

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}_{nucl}\right|^2 \frac{\langle m^2_{\beta\beta}\rangle}{m_e^2}$$

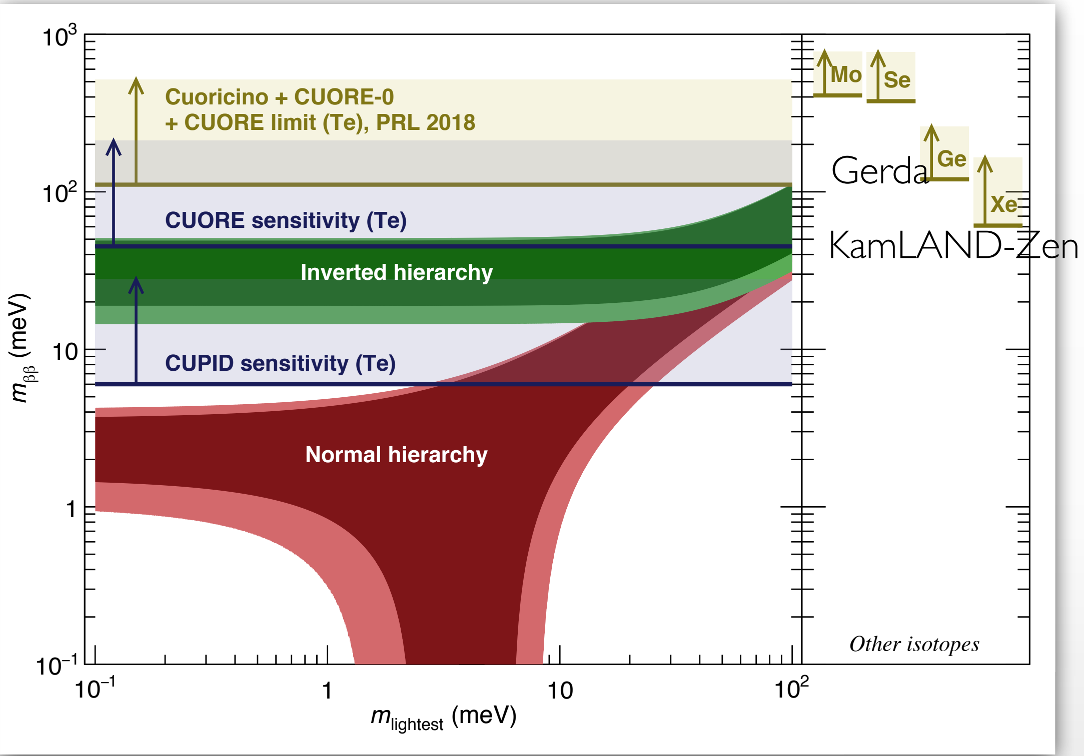
$m_{\beta\beta}$ < 110 - 520 meV (90% C.L.)

Future sensitivity

Expected in 5 yr lifetime: $T_{1/2}$ = 9 x10^{25} yr

$m_{\beta\beta}$ < 60 - 165 meV

assuming bkg = 0.01 c/(kg keV y)
and ΔE = 5 keV FWHM



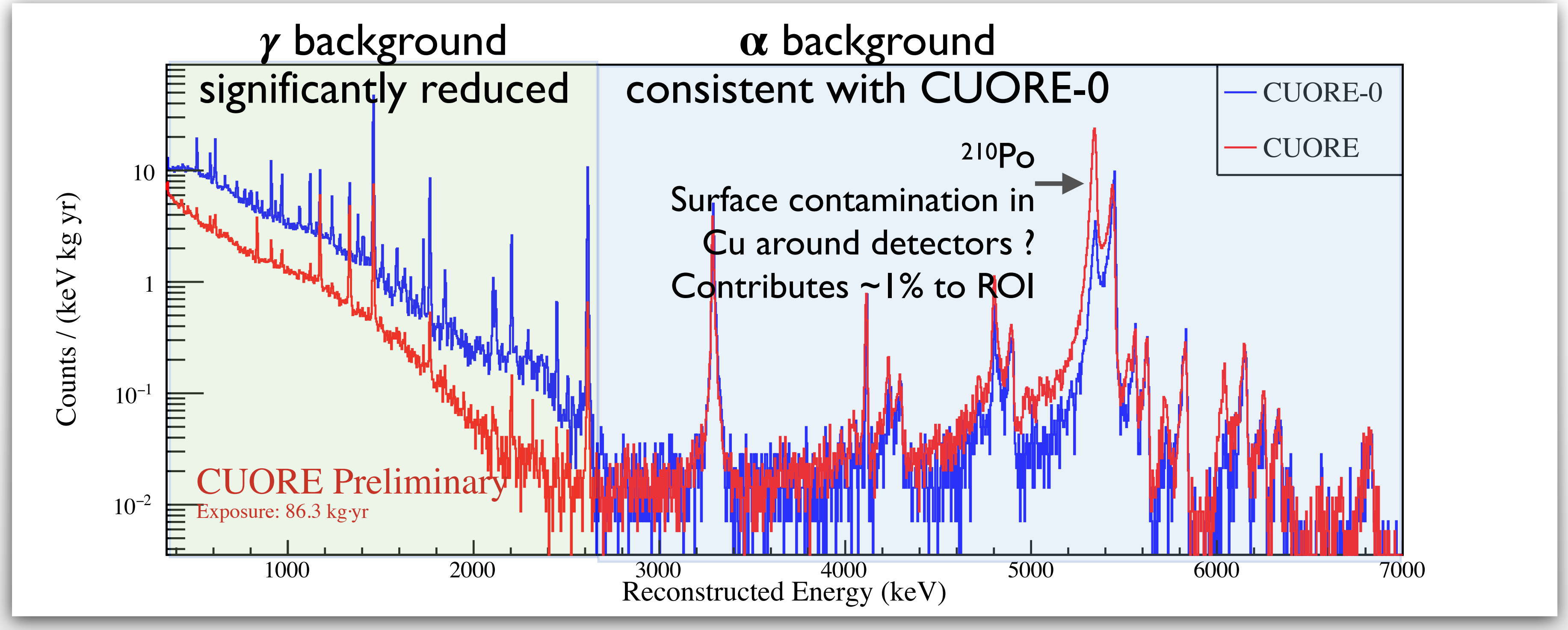
Assuming g_A=1.27 and N.M.E.

- JHEP02 (2013) 025
- Nucl. Phys. A 818, 139 (2009), ISM
- Phys. Rev. C 87, 045501 (2013), QRPA
- Phys. Rev. C 87, 064302 (2014), QRPA
- Phys. Rev. C 91, 034304 (2015), IBM-2
- Phys. Rev. C 91, 024613 (2015), pnQRPA
- Phys. Rev. C 91, 024309 (2015), SM
- Phys. Rev. C 91, 024316 (2015)
- Phys. Rev. Lett. 105, 252503 (2010), EDF
- Phys. Rev. Lett. 111, 142501 (2013) , EDF

^{130}Te: 1.5 × 10^{25} yr, this analysis
^{76}Ge: 8.0 × 10^{25} yr, PRL 120, 132503 (2018)
^{136}Xe: 1.1 × 10^{26} yr, PRL 117, 082503 (2016)
^{100}Mo: 1.1 × 10^{24} yr, PR D89, 111101 (2014)
^{82}Se: 2.4 × 10^{24} yr, PRL 120, 232502 (2018)

CUORE background

Compare to CUORE-0 (first CUORE tower tested in older cryostat)



background consistent with expectations

Origin of background:

- contamination of cryostat, shields and detector parts:
  - ^{232}Th, ^{238}U, ^{40}K natural contaminations
  - environmental ^{222}Rn resulting in ^{210}Pb surface implantation
- environmental muons and neutrons

Dominating background in ROI:

- α from surface of crystal and copper close-parts

CUORE background model

1. MC model

- Simulate the contaminations coming from different origin (= detector location + source type) using a detailed Geant4 MC simulation
- ~60 independent parameters representing various contaminations that could contribute to the CUORE background model
- detailed detector geometry description (cryostat, shieds, detector parts)

NEAR: Crystals, Cu; α, β, γ (TeO2 and CuNOSV rows)

FAR: shields+ext.; γ only (Roman lead to External rows)

Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th, ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
TeO_2	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Bulk	^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{54}Mn
CuNOSV	Surface (0.01 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (1 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
Roman lead	Bulk	^{232}Th, ^{238}U, ^{108m}Ag
Top lead	Bulk	^{232}Th, ^{238}U, ^{210}Bi
Ext. lead	Bulk	^{210}Bi
CuOFE	Bulk	^{232}Th, ^{238}U, ^{60}Co
External	-	Cosmic muons

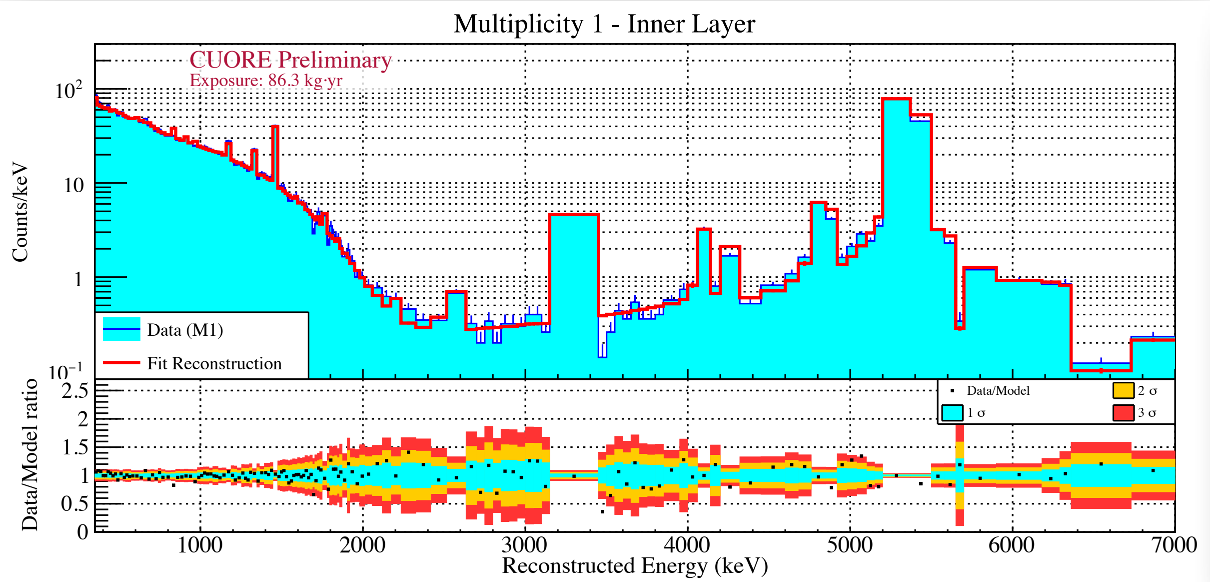
2. CUORE data

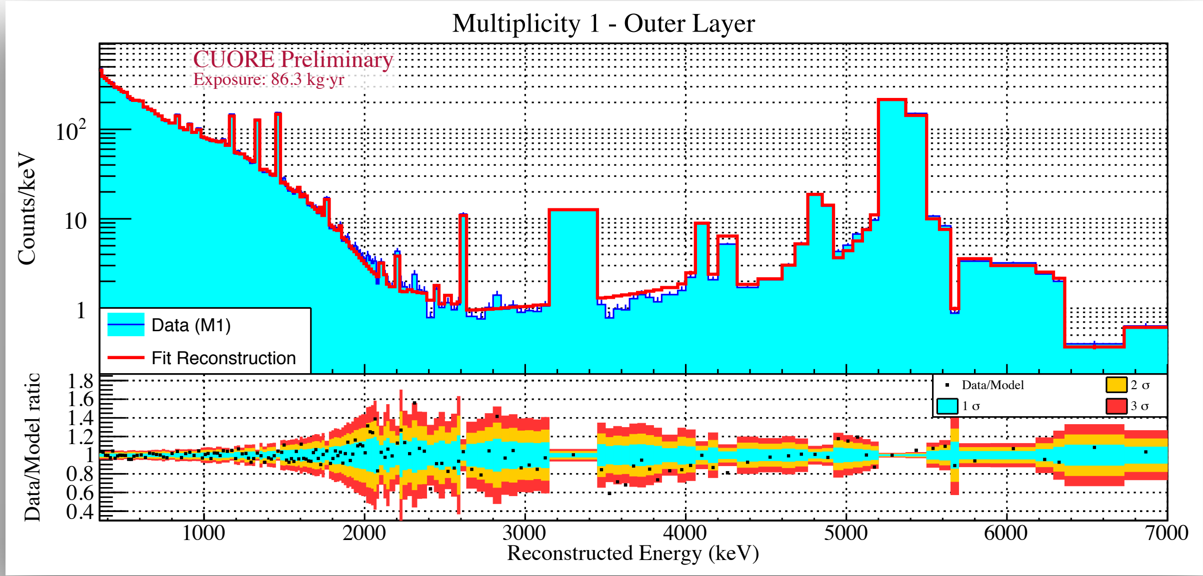
- 86.3 kg yr of TeO_2 (same as 0vBB analysis)
- split in M1, M2 and M2sum
  - M1 more sensitive to signal events
  - M2, M2sum constrain subsets of backgrounds
- split M1 between inner and outer layers (2 crystals thick)
  - outer more sensible to backgrounds originated outside the detector

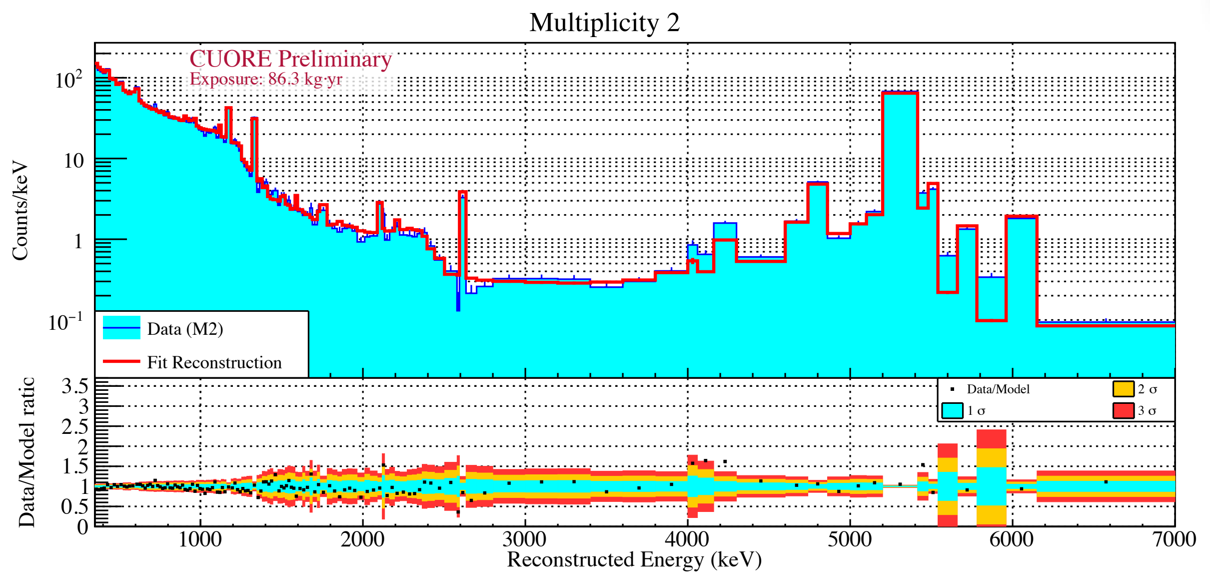
3. Fit

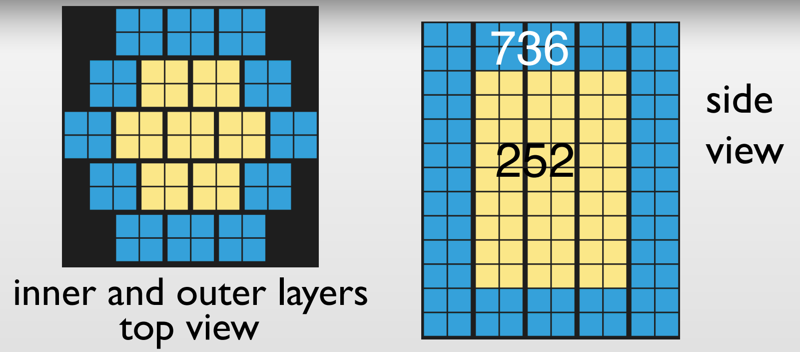
- perform a Bayesian fit of our model to the data with flat priors on all parameters (except muons which come from a cosmogenic analysis)
- simultaneous fit on M1, M1inner, M2, M2sum spectra to determine the source/location activities (MC normalisation)

CUORE background fit



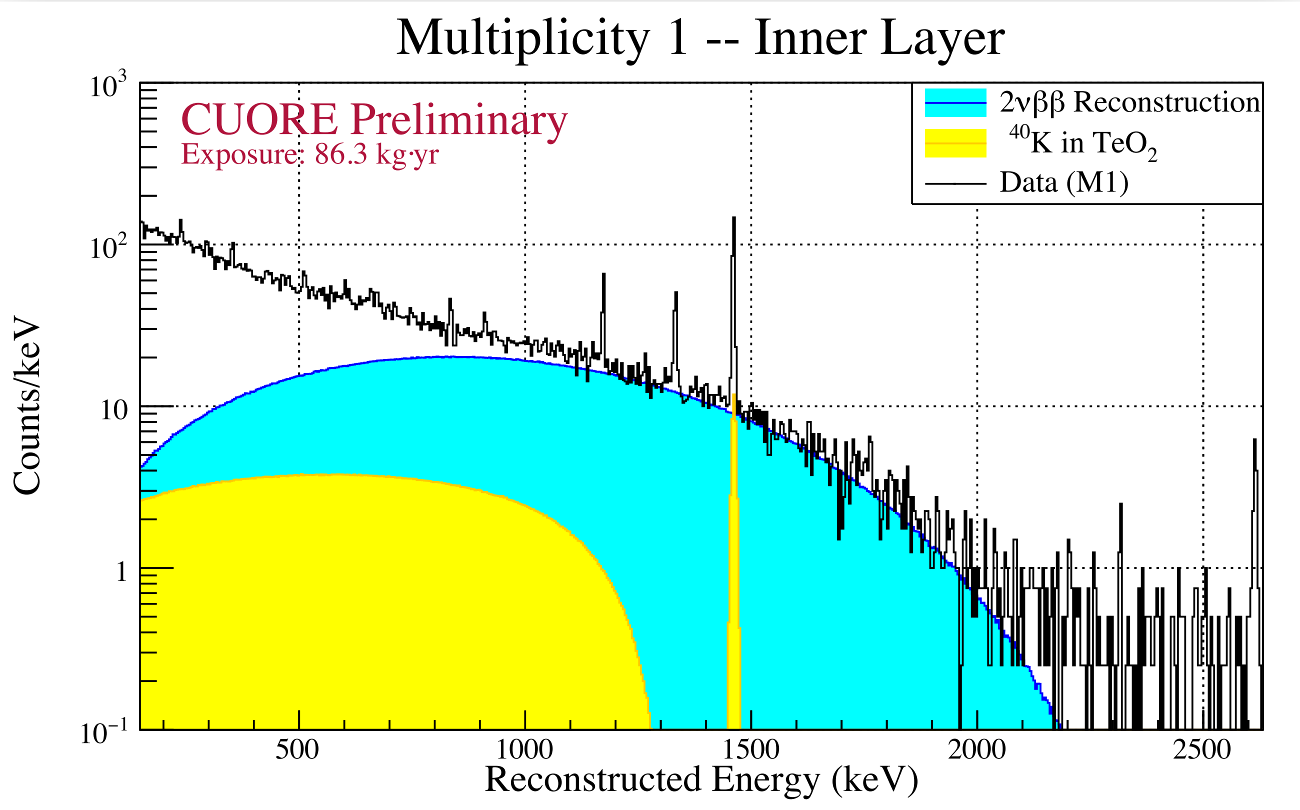






The main features of the CUORE observed spectrum are well reproduced

2νββ measurement

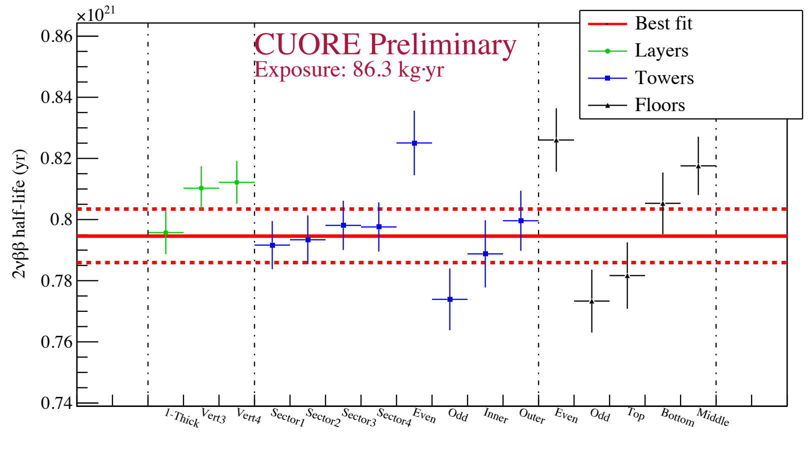


CUORE:
$T_{1/2}$= [7.9 ± 0.1(stat.) ± 0.2(syst.)]×10^{20} y

..consistent with CUORE-0 (2016):
$T_{1/2}$ = [8.2 ± 0.2 (stat.) ± 0.6 (syst.)] × 10^{20} y

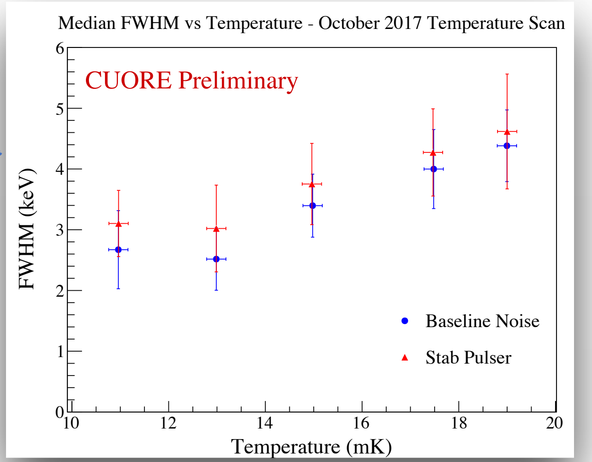
2νββ is the dominant component of the M1 background spectrum in the region ~[1-2] MeV (compare ~20% in CUORE-0)

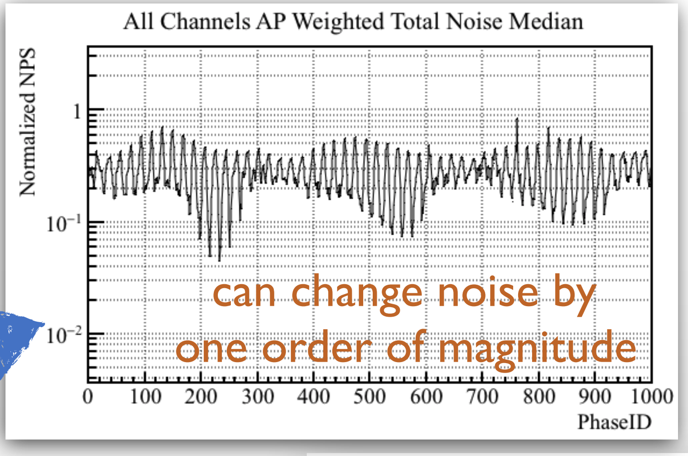
The largest systematic uncertainty due to the geometrical splitting of data (inner/outer) and is originated by the uncertainty on the origin of localised contaminations.

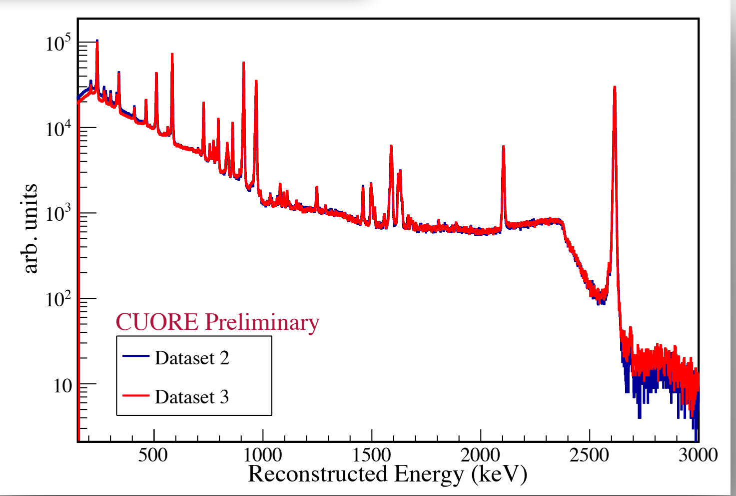


CUORE current status

- Oct-Dec 2017: scan of detector performance vs temperature:
  - new operating temperature at 11 mK
- Jan-March 2018: warm up to 100 K
  - upgrade gate valves in DCS
- March 2018:
  - return to base temperature (11 mK)
  - perform Pulse-Tube phase-scan (vary PT phase shifts and select configuration that minimises the average noise)
- April 2018:
  - calibration shows ΔE=7.6 keV FWHM
- **May 2018:**
  - **stable physics data taking**
  - **93% channels passing cuts**
  - **doubled+ 2017 data**
  - **analysis ongoing**







Conclusions

- CUORE is the first $0\nu\beta\beta$ cryogenic experiment at ton-scale
- Most stringent limit on the $0\nu\beta\beta$ half-life of ^{130}Te to date
- Most precise measurement of the $2\nu\beta\beta$ half-life of ^{130}Te to date
- We have restarted physics data taking
  - working to optimise background and energy resolution
- *CUORE will continue to be one of the most sensitive searches for $0\nu\beta\beta$ over the coming years*
- Many more potential physics searches:
  - low energy searches: Dark Matter, axions
  - other $\beta\beta$ decays and decays to excited states, $\beta+$/E.C. decays

THANK YOU !