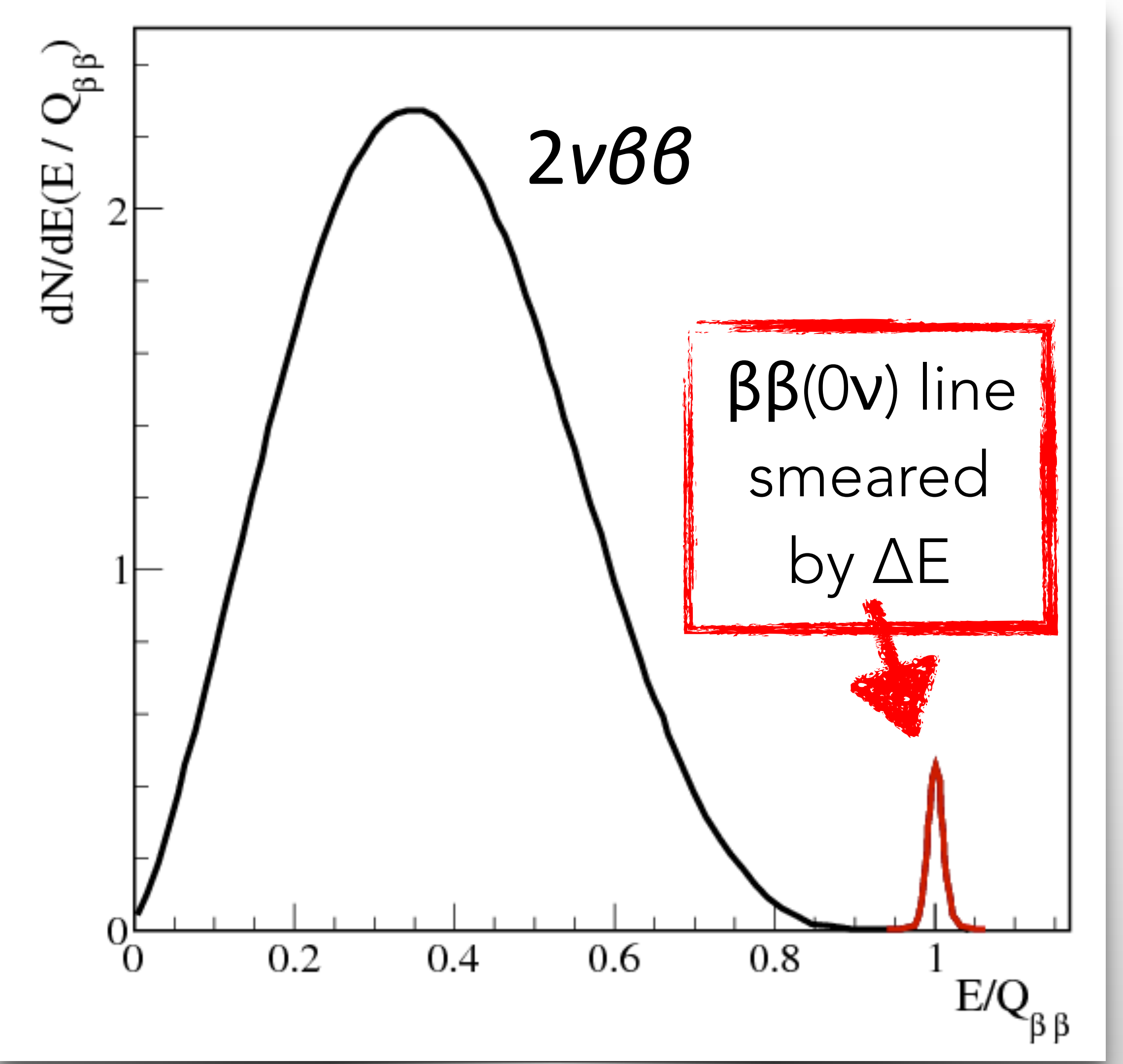
MEDEX17

Results from CUORE and CUORE0

Niccolò Moggi - Univ. and INFN Bologna
on behalf the CUORE Collaboration

Prague – May 2017

0νββ Experimental signature



Observable: line at Q-value

- Measure $E_{\beta\beta} = E_{\beta 1} + E_{\beta 2}$
- Smeared by energy resolution
- Q depends on the isotope

If observed:

$$T_{1/2}^{0\nu} = \ln(2) \cdot N_{\beta\beta} \cdot \frac{t}{N_{0\nu\beta\beta}} \cdot \varepsilon$$

exposure time

num. of active nuclei

events in the peak

efficiency

Physics Implications

- Lepton number violation $\Delta L = 2$
- $\nu = \bar{\nu}$ (some kind of Majorana mass contribution)
- $$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)\left|M_{nucl}^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}^2\rangle}{m_e^2}$$

Effective Majorana mass

Half-life (to be measured)

Phase space (calculated)

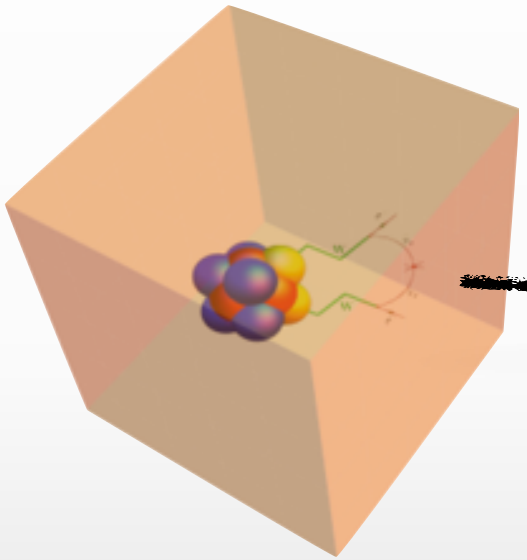
Nuclear matrix element (calculated)

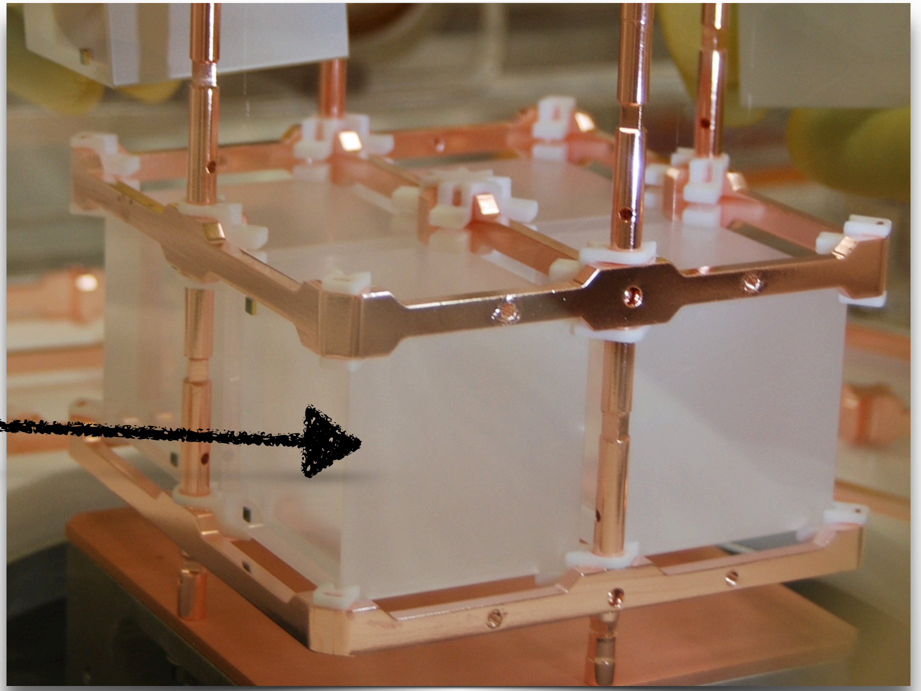
$$m_{\beta\beta} = f\left(\Delta m_{12}, \Delta m_{23}, m_1\right)$$

- perhaps indications about the mass hierarchy
- constraints on absolute mass scale

Bolometric approach: E→ΔT

Source = Detector





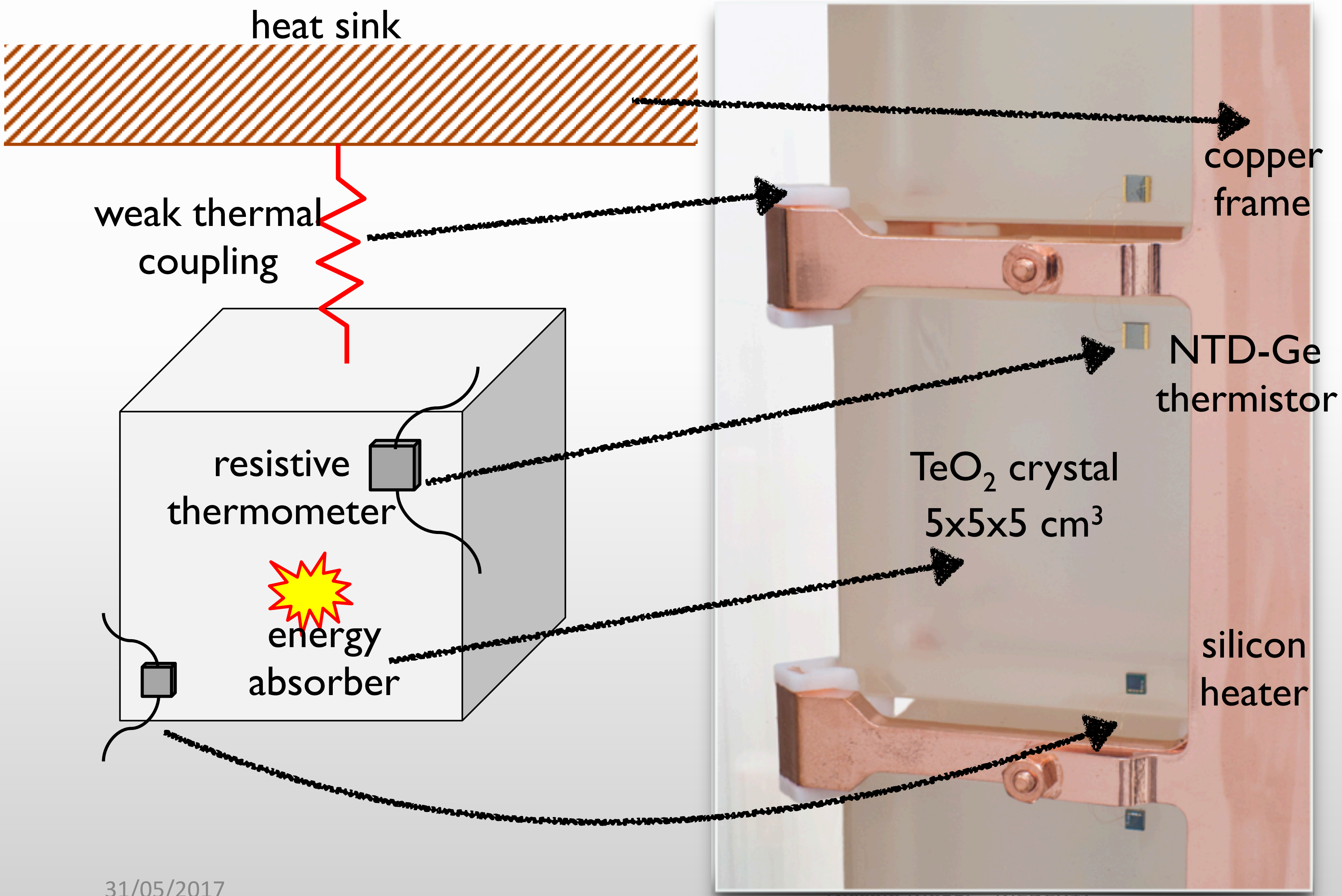
Arrangement of bolometers in 2x2 arrays

- $2e^-$ mostly contained in the bulk
- little (no) energy escape
- excellent efficiency
- excellent energy resolution
- hardly discriminate signal from bkg

$$\Delta T = \frac{E}{C\left(T\right)} \qquad C \propto \left(\frac{T}{\theta_D}\right)^3$$

Requires low heat capacity
low temperatures

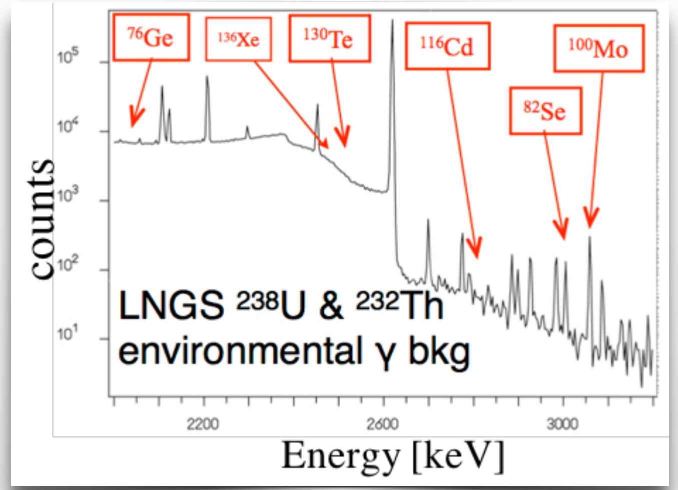
CUORE bolometers: TeO_2 crystals



TeO_2 :

^{130}Te abundance = 34%

Q = 2528.5 keV



With:

E = 1 MeV

C ~ 10^{-9} J/K at 10 mK

$$\Delta T = 0.1 \frac{mK}{MeV}$$

Thermistor Readout: ΔT →ΔV

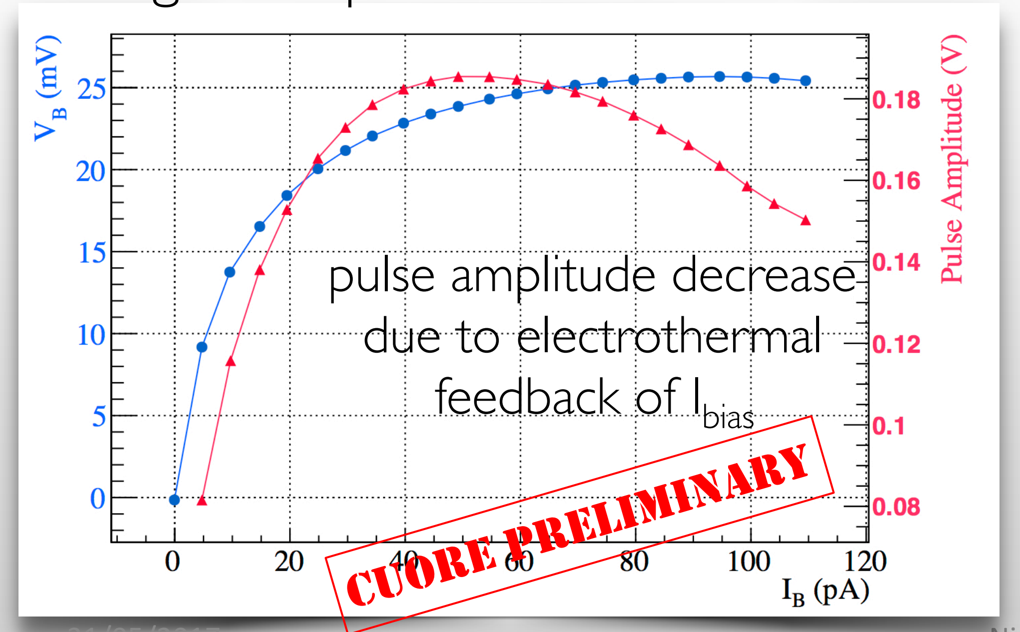
Crystals are read out by a ``Neutron Transmutation Doped'' Germanium thermistor (NTD)

$$R_{th} = R_0 e^{\left(\frac{T_0}{T}\right)^{\gamma}} = \frac{V_{th}}{I_{bias}}$$

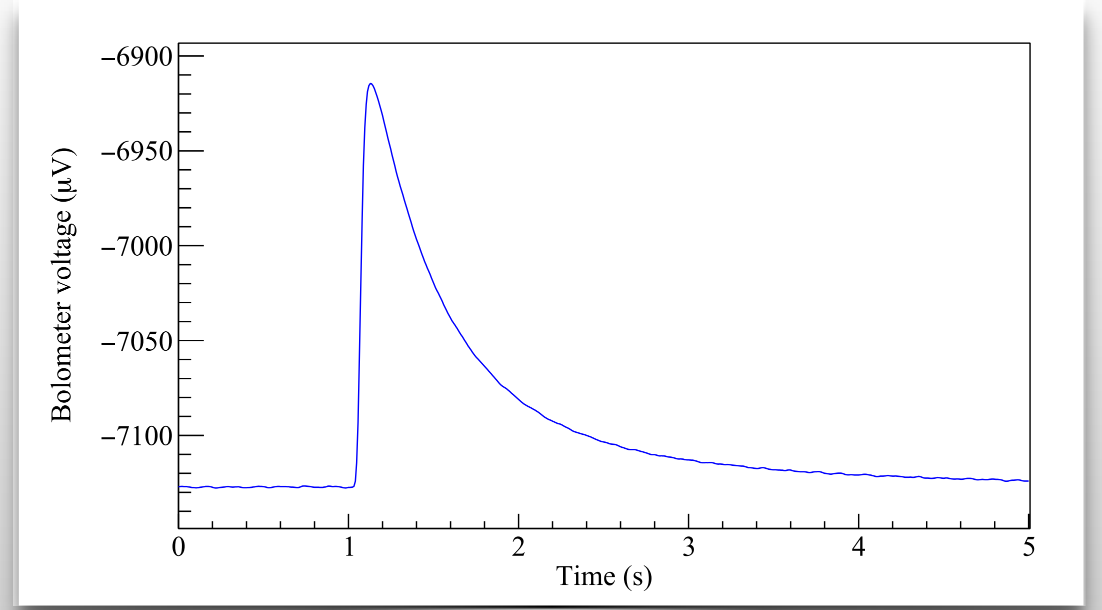
Readout ΔV

Maintain a constant current

Set I_{bias} working point where signal amplitude is maximum



Typical signal pulse shape



Sensitivity

May be expressed as the half-life that yields a signal hidden by a fluctuation of the background:

$$S_{T_{1/2}} = n_\sigma \sqrt{B}$$

For our detector the background approximately scales with the mass and the rate can be assumed to be constant

$$B = b \cdot M_{tot} \cdot t \cdot \Delta E$$

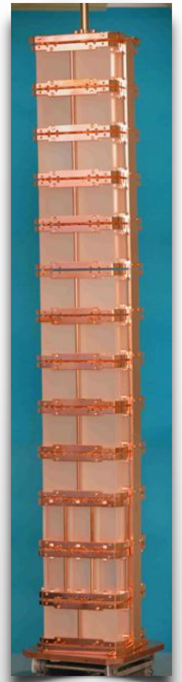
Experimental parameters where improvement produces better sensitivity

$$S_{T_{1/2}} \propto \eta \cdot \varepsilon \cdot \sqrt{\frac{M_{tot} \cdot t}{b \cdot \Delta E}}$$

Isotopic abundance (η), Efficiency (ε), Total mass (M_{tot}), Exposure time (t), Bkg rate (b), Energy resolution (ΔE)

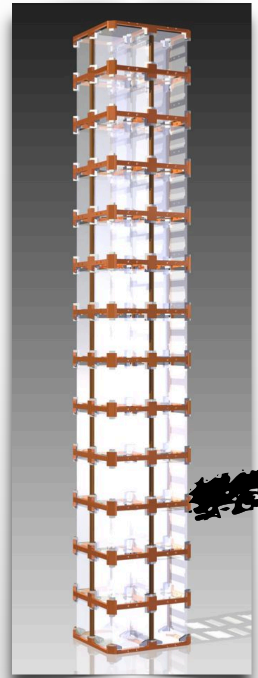
The CUORE phased program

Cuoricino
2003 - 08



Exp = 19.75 kg y of ^{130}Te
Bkg = 0.169 c/(kg keV y)
$T_{1/2}$ > 2.8x10^{24} y (90% CL)

CUORE-0
2013 - 15

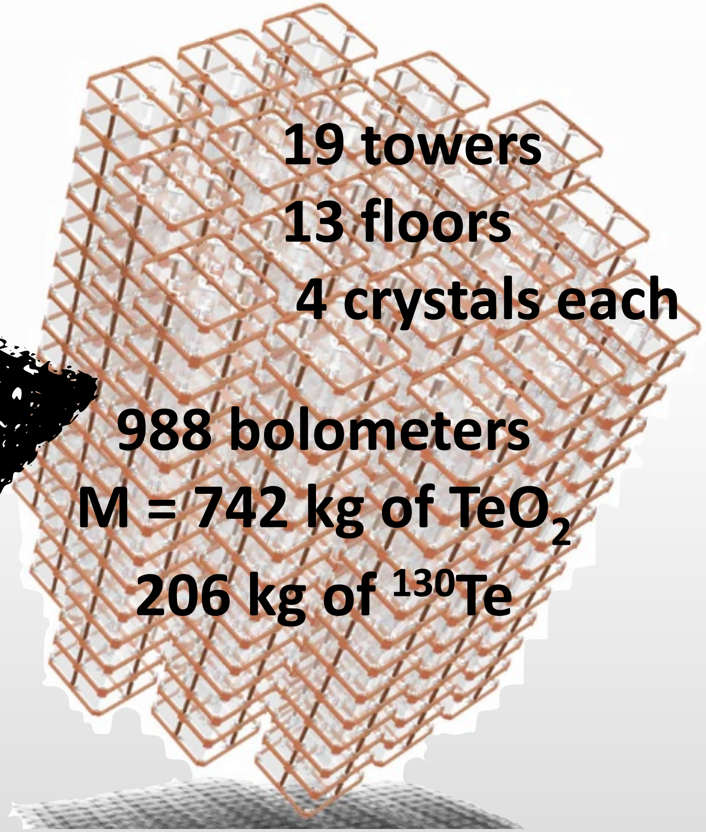


Exp = 9.8 kg y of ^{130}Te
Bkg = 0.058 c/(kg keV y)
$T_{1/2}$ > 2.7x10^{24} y (90% CL)

Same cryostat

First CUORE-like tower

CUORE
2017 -



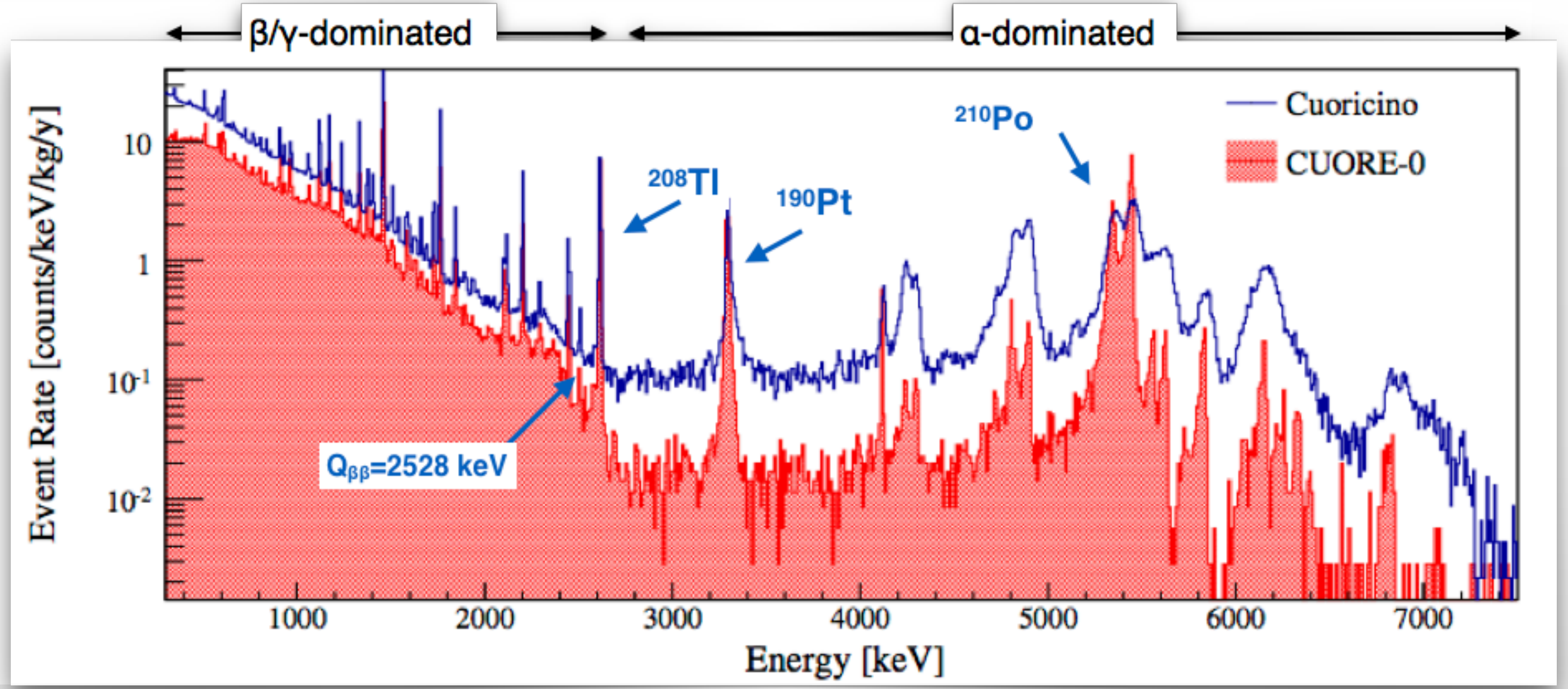
19 towers
13 floors
4 crystals each

988 bolometers
M = 742 kg of TeO_2
206 kg of ^{130}Te

Bkg GOAL = 0.01 c/(kg keV y)

New cryostat

Radioactive contamination of materials



CUORE-0:
test background reduction strategy :

- cleaning & storage
- tower assembly

c/(keV · kg · yr)	0νββ region	α region (2700-3900 keV – Pt peak)
CUORICINO	0.169 ± 0.006	0.110 ± 0.001
CUORE-0	0.058 ± 0.004	0.016 ± 0.001

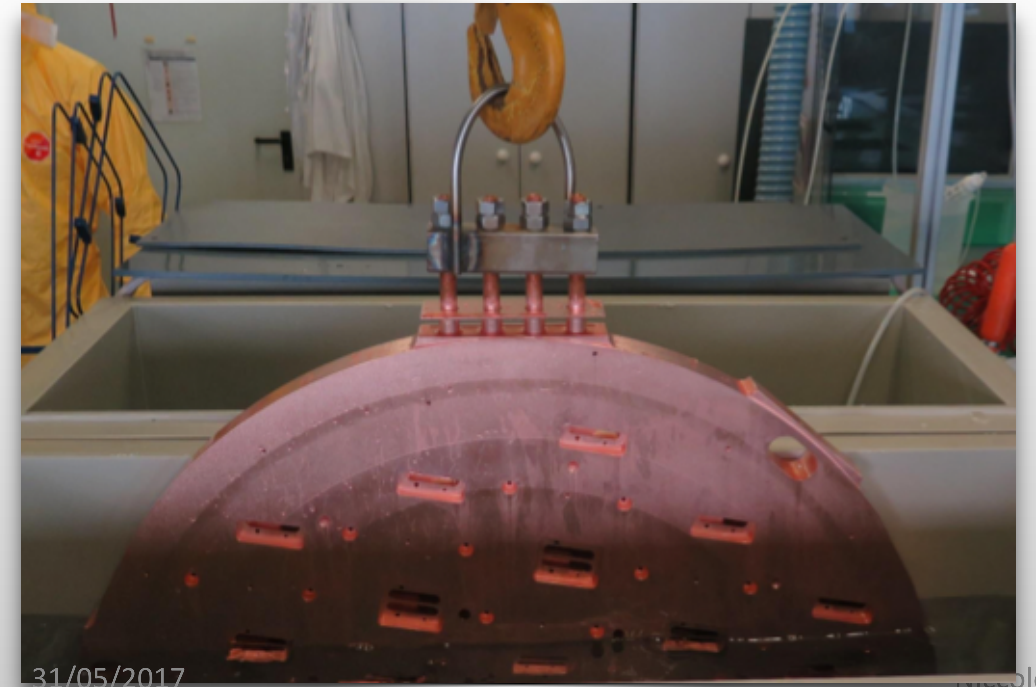
Radioactive contamination drives the Cuoricino/CUORE-0 bkg in the ROI

- γ of ^{208}Tl from cryostat
- decay products of ^{238}U and ^{232}Th from crystal and Cu surface

Parts cleaning and storage

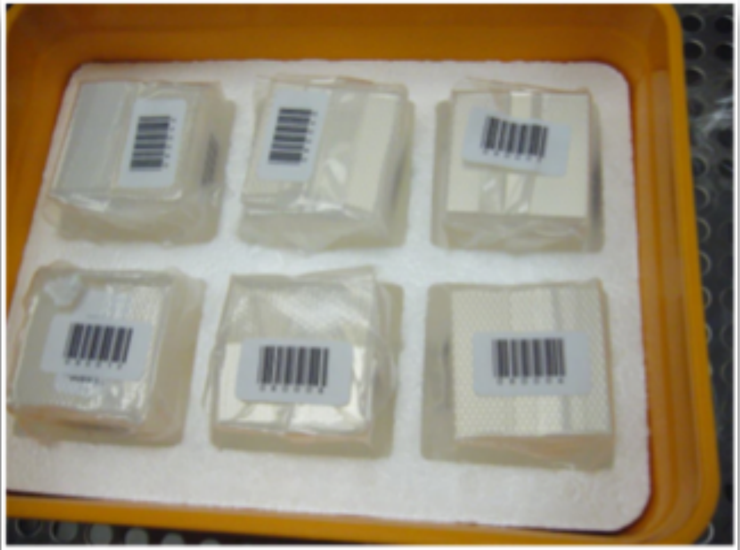
Copper:

1. Pre-cleaning (remove machining residuals)
2. Tumbling (mechanical abrasion ~1 **μ**m)
3. Electropolishing (~100 **μ**m abrasion)
4. Chemical etching (~10 **μ**m)
5. Plasma etching (2 **μ**m)
6. Packaging in vacuum

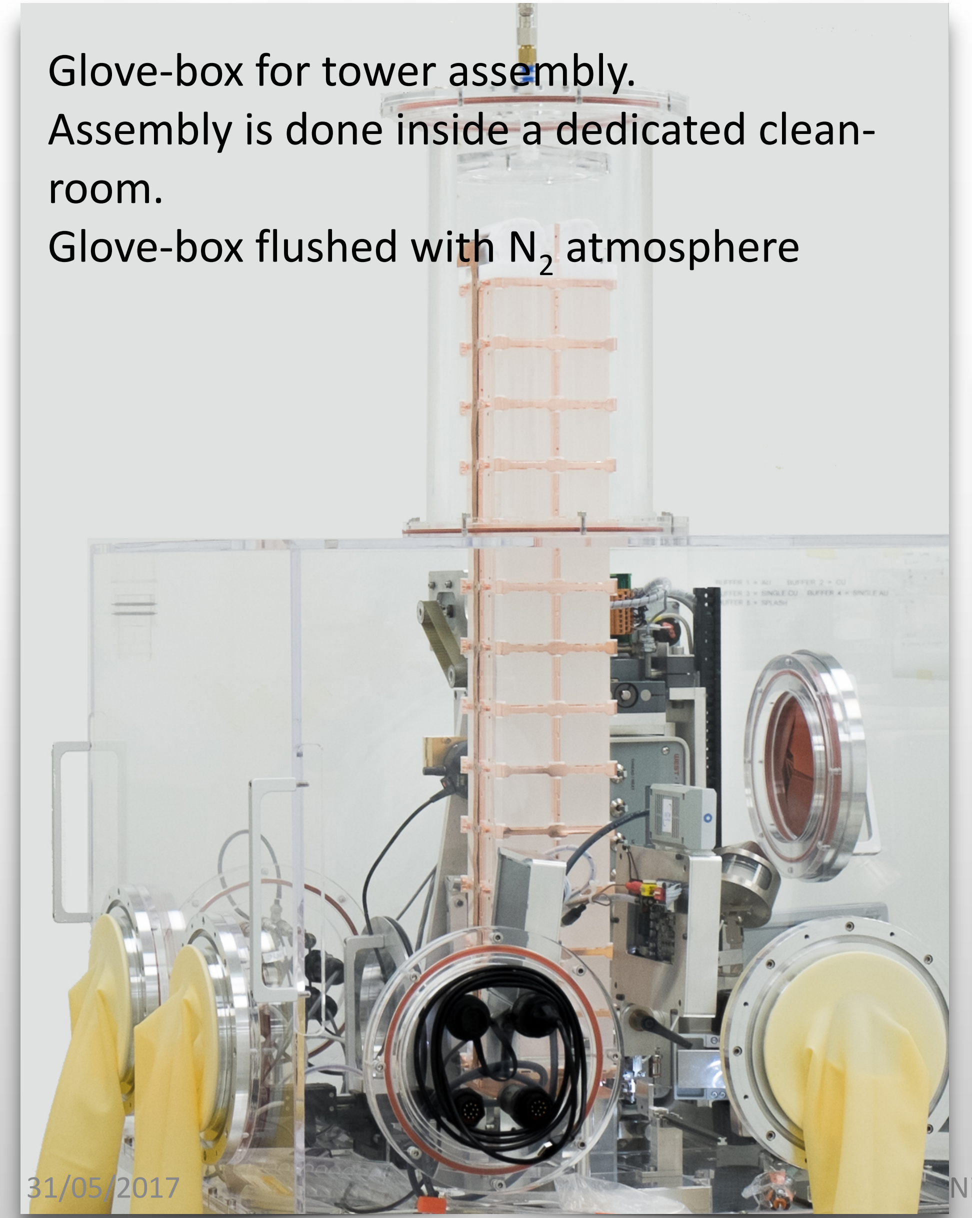


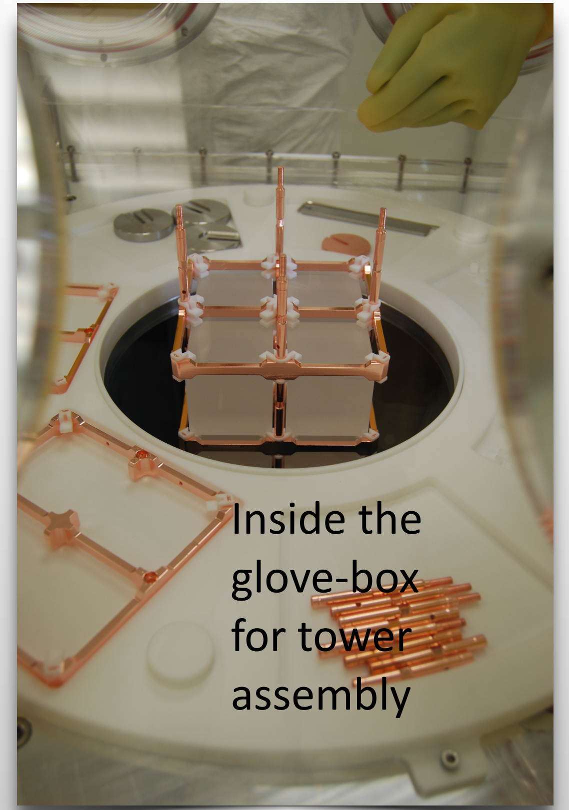
Crystals:

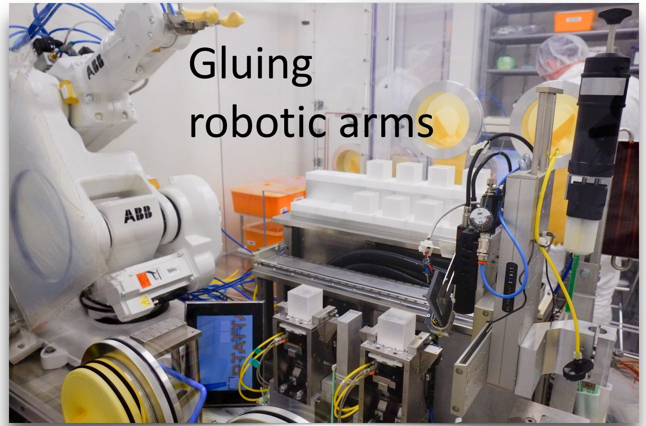
1. Produced by Shanghai Institute of Ceramics
2. Grown from high purity TeO_2 powder and Te metal
3. Shipped to LNGS by sea in vacuum bags + boxes
4. Stored underground in nitrogen-fluxed cabinets

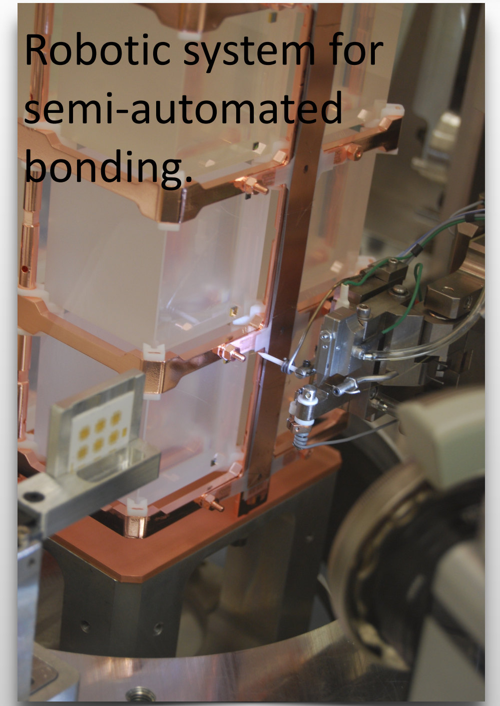


Crystal gluing, bonding and tower assembly


Glove-box for tower assembly.
Assembly is done inside a dedicated clean-room.
Glove-box flushed with N_2 atmosphere


Inside the glove-box for tower assembly

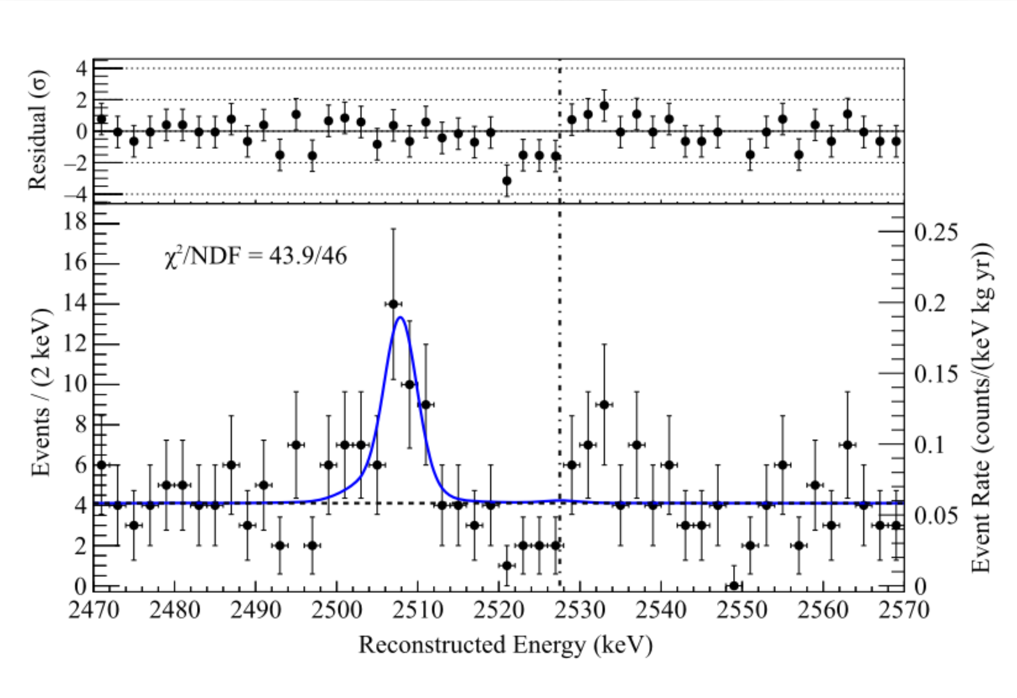

Gluing robotic arms


Robotic system for semi-automated bonding.

CUORE-0 results

CUORE-0 + Cuoricino 0νββ limit :

$$T_{1/2} > 4.0 \times 10^{24}\ \mathrm{y}\ (90\%\mathrm{C.L.})$$

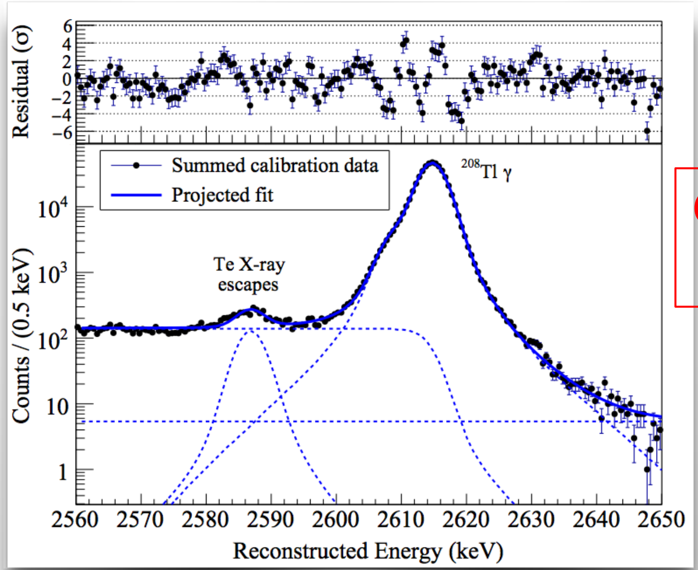


$$m_{\beta\beta} < 270 - 760\ \mathrm{meV}$$

[*Physical Review Letters* **115**, 102502 (2015)]

CUORE-0 energy resolution :

$$\Delta E = 5.1 \pm 0.3\ \mathrm{keV\ FWHM}$$



CUORE GOAL REACHED

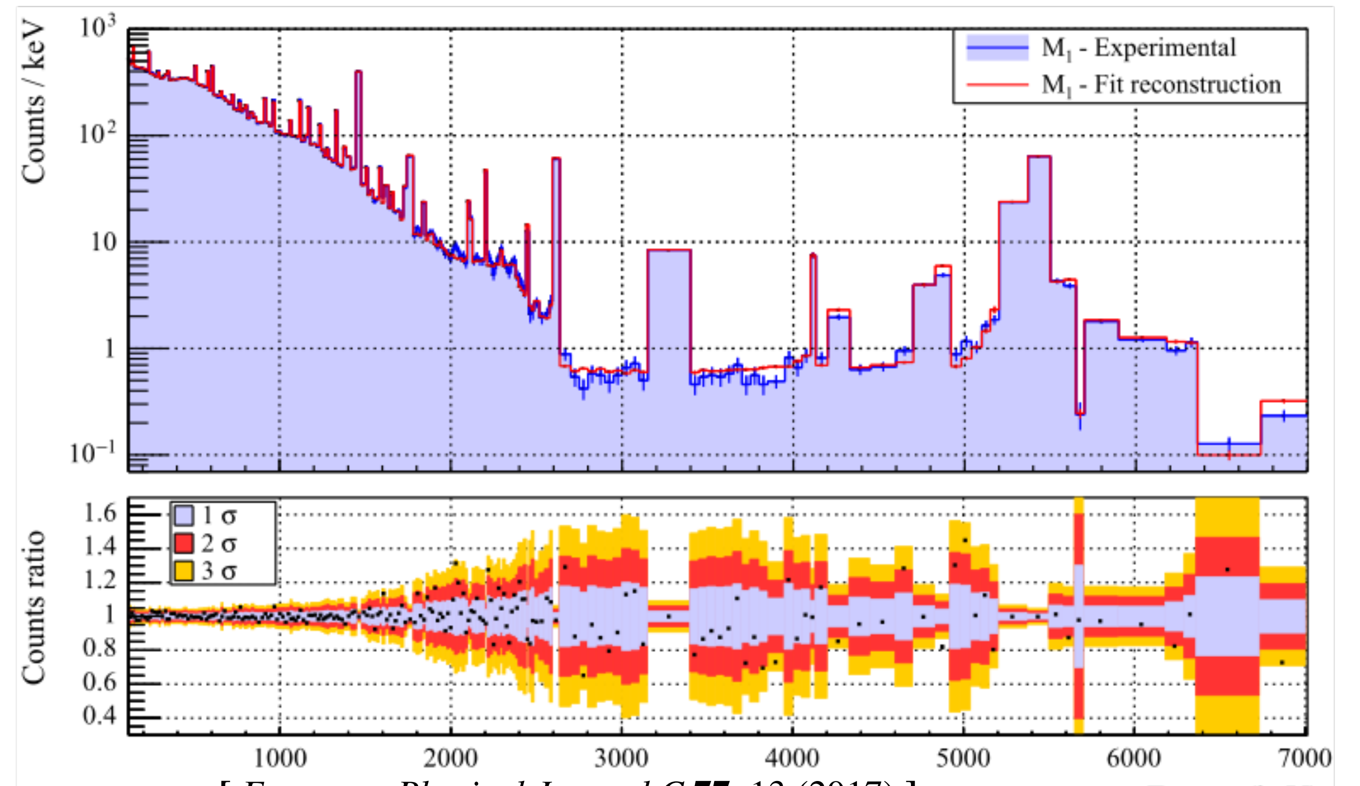
Axial coupling constant g_A = 1.269

$G^{0\nu}$: Phys. Rev. C 85, 034316 (2012)

NME : Phys. Rev. C 91, 034304 (2015) IBM-2
Phys. Rev. C 87, 045501 (2013) QRPA
Phys. Rev. C 91, 024613 (2015) QRPA
Nucl. Phys. A 818, 139 (2009) ISM
Phys. Rev. Lett. 105, 252503 (2010) EDF
Phys. Rev. C 91, 024309 (2015) ISM

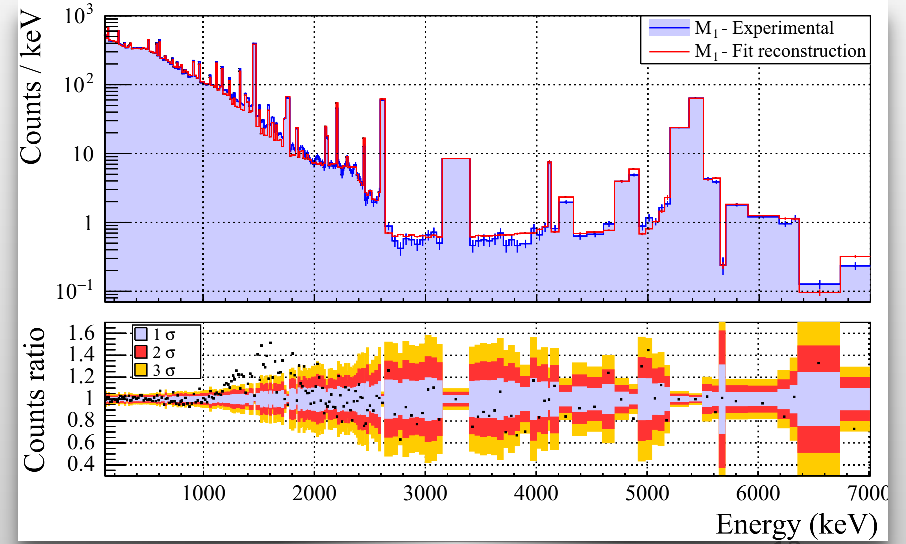
CUORE0 background model

- 56 sources of background identified and ascribed to parts of the experiment
- Found contamination levels from material screening
- All sources simulated with Geant4 through the experiment → build bkg model
- Bayesian fit to the CUORE-0 spectrum with priors from screening

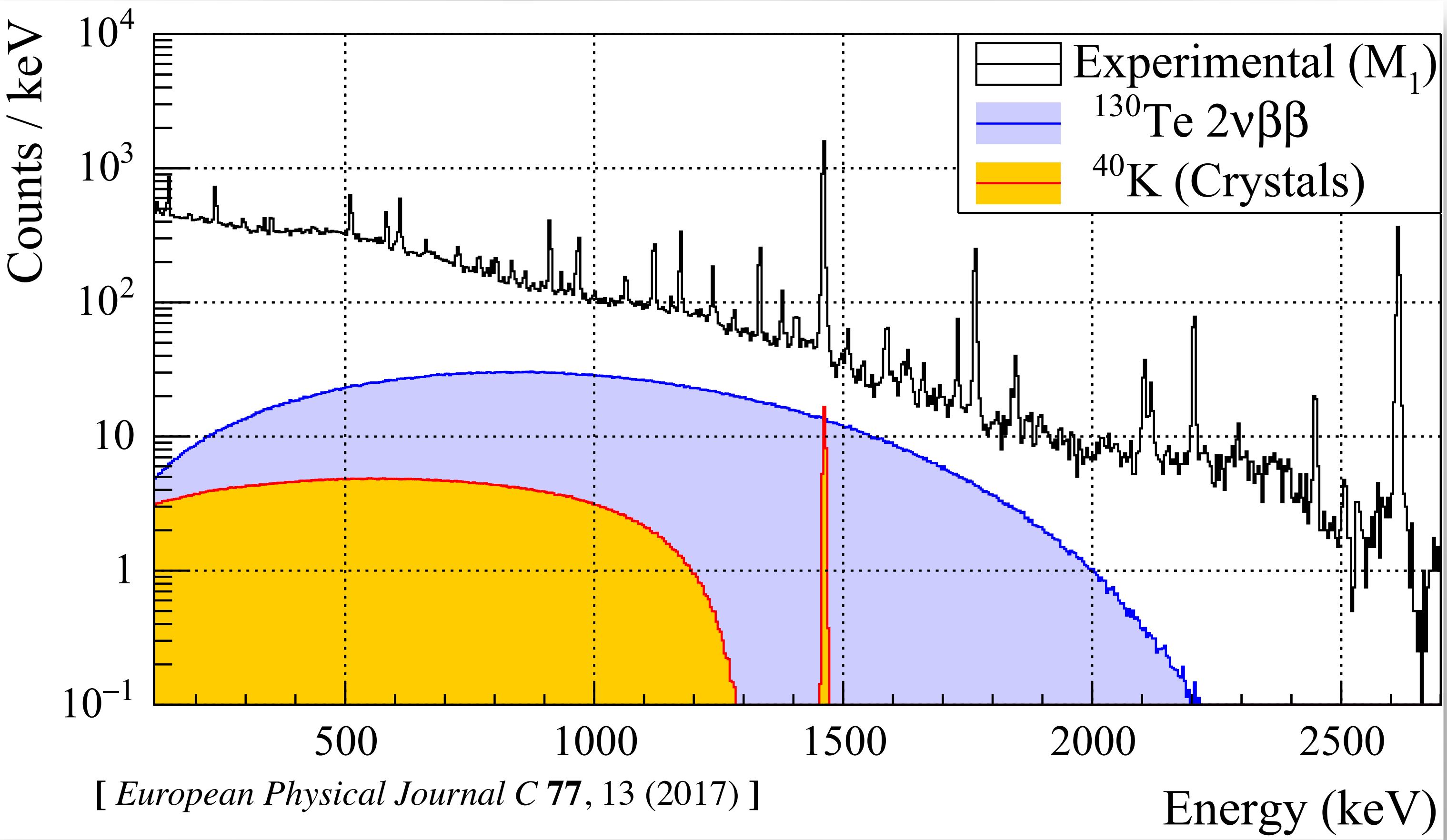


[*European Physical Journal C* **77**, 13 (2017)]

Excellent agreement of data with model when including 2νββ



CUORE-0 2νββ measure



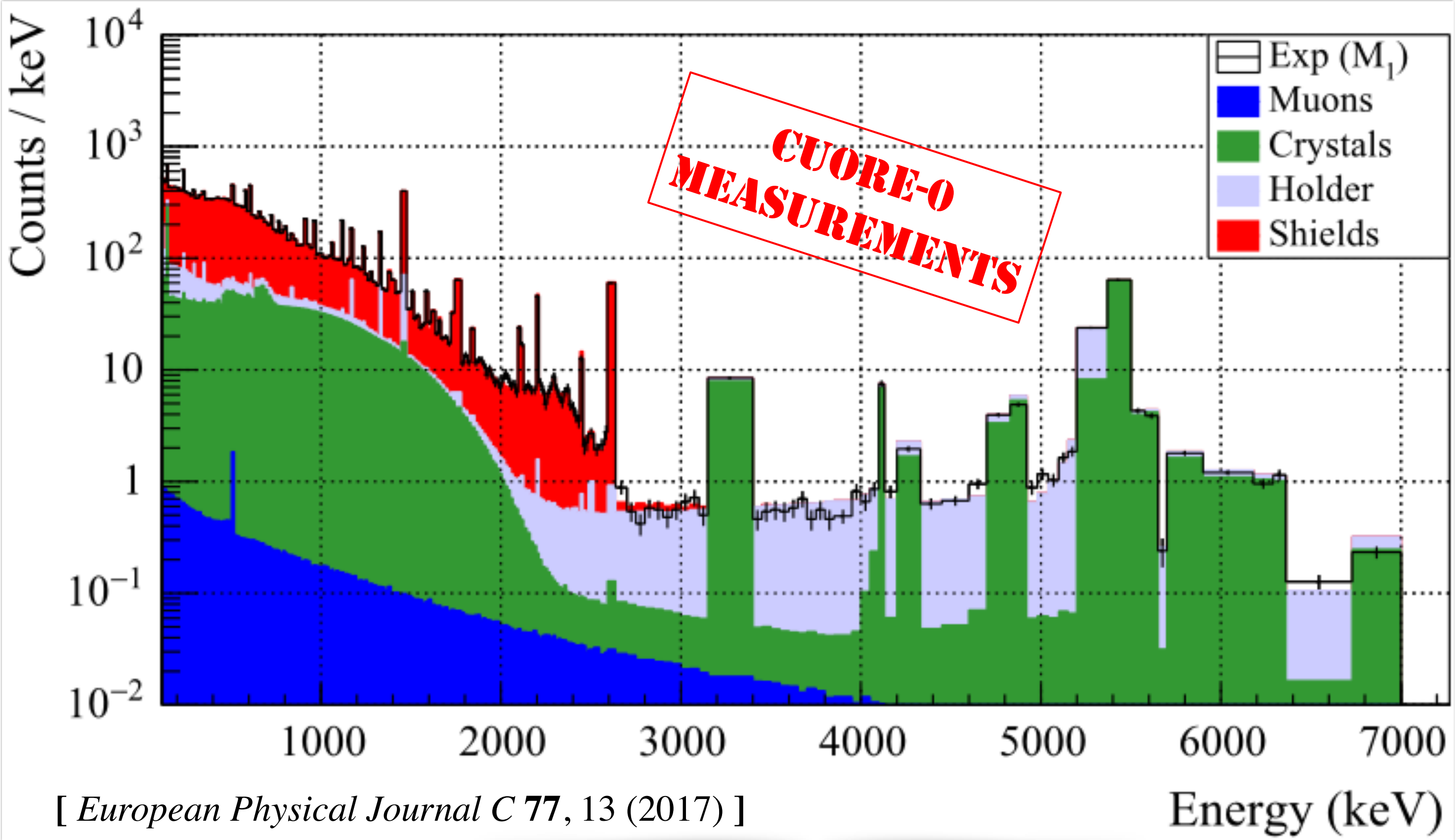
CUORE-0: $T_{1/2}$ = [8.2 ± 0.2 (stat.) ± 0.6 (syst.)] × 10^{20} y

Background estimates for CUORE

In the bkg model we can separe components by type:

- CUORE-0 = CUORE (crystals, Cu holders)
- CUORE-0 ≠ CUORE (cryo shields & Pb shield)

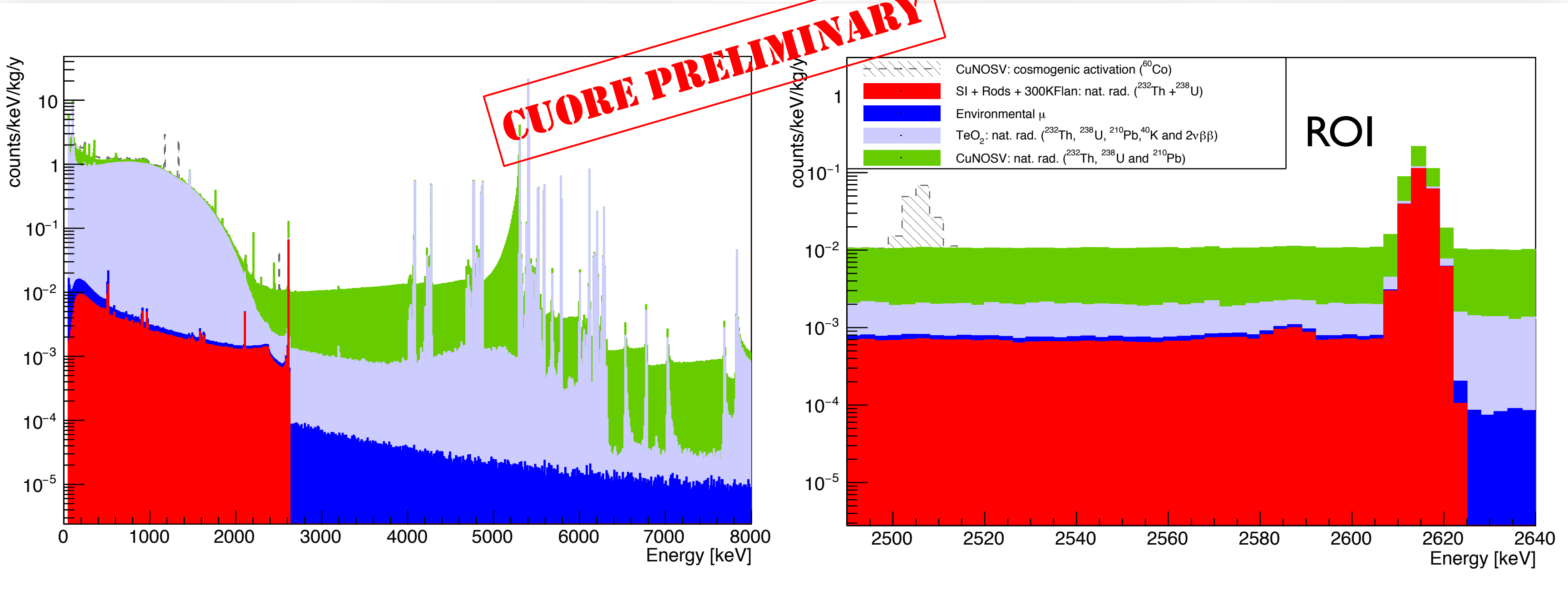
Shields are the largest contribution observed in CUORE-0 (~74%)



Component	Fraction [%]
Shields	74.4 ± 1.3
Holder	21.4 ± 0.7
Crystals	2.64 ± 0.14
Muons	1.51 ± 0.06

CUORE background projection

- CUORE-0 bkg rate is projected to the 988 CUORE bolometers
- We expect a lower BI in the ROI thanks to:
  - better granularity (anti-coincidence analysis)
  - self-shielding
  - new cryostat
  - more shielding

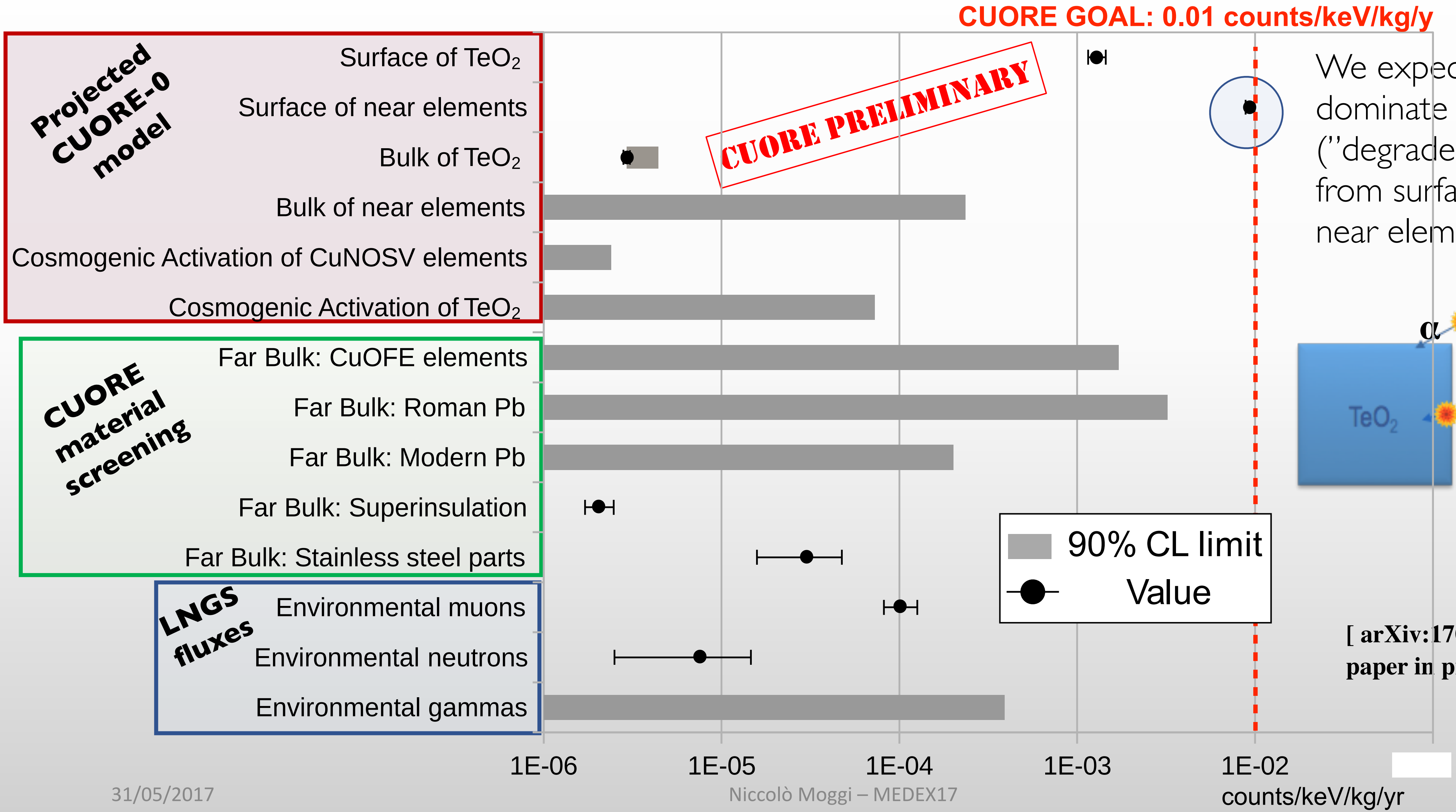


CUORE PRELIMINARY

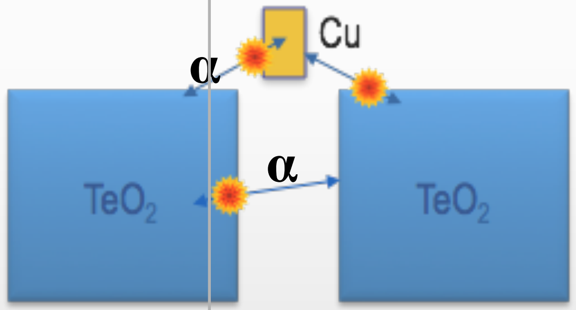
$$\left[1.00 \pm 0.03\ (\text{stat.})^{+0.23}_{-0.10}(\text{syst.})\right] \times 10^{-2}\ \frac{\text{counts}}{\text{kg} \cdot \text{keV} \cdot \text{y}}$$

c/(keV·kg·yr)	0νββ region
CUORICINO	0.169 ± 0.006
CUORE-0	0.058 ± 0.004
CUORE (projection)	0.0100± 0.0003

CUORE background budget in ROI - overall



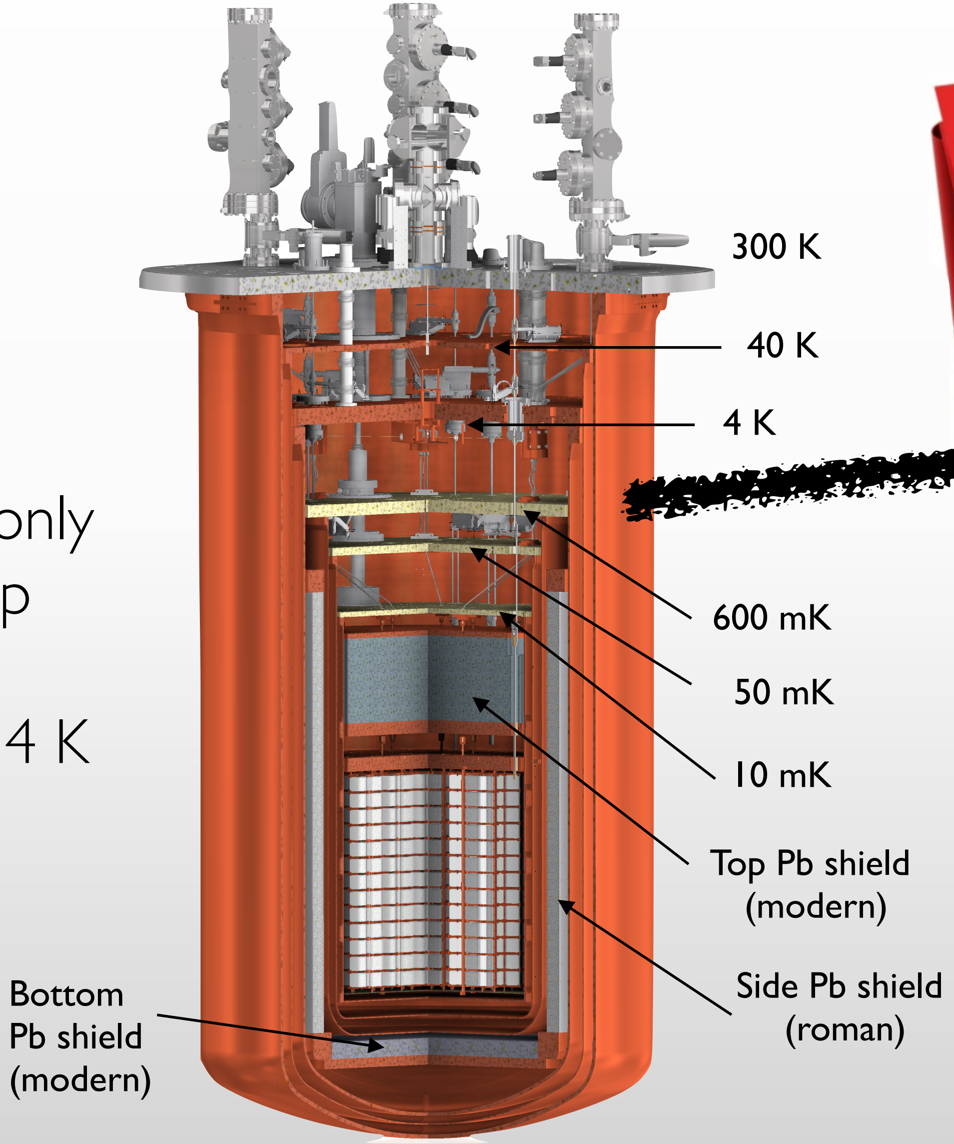
We expect α to dominate the ROI. ("degraded" α from surface of near elements)

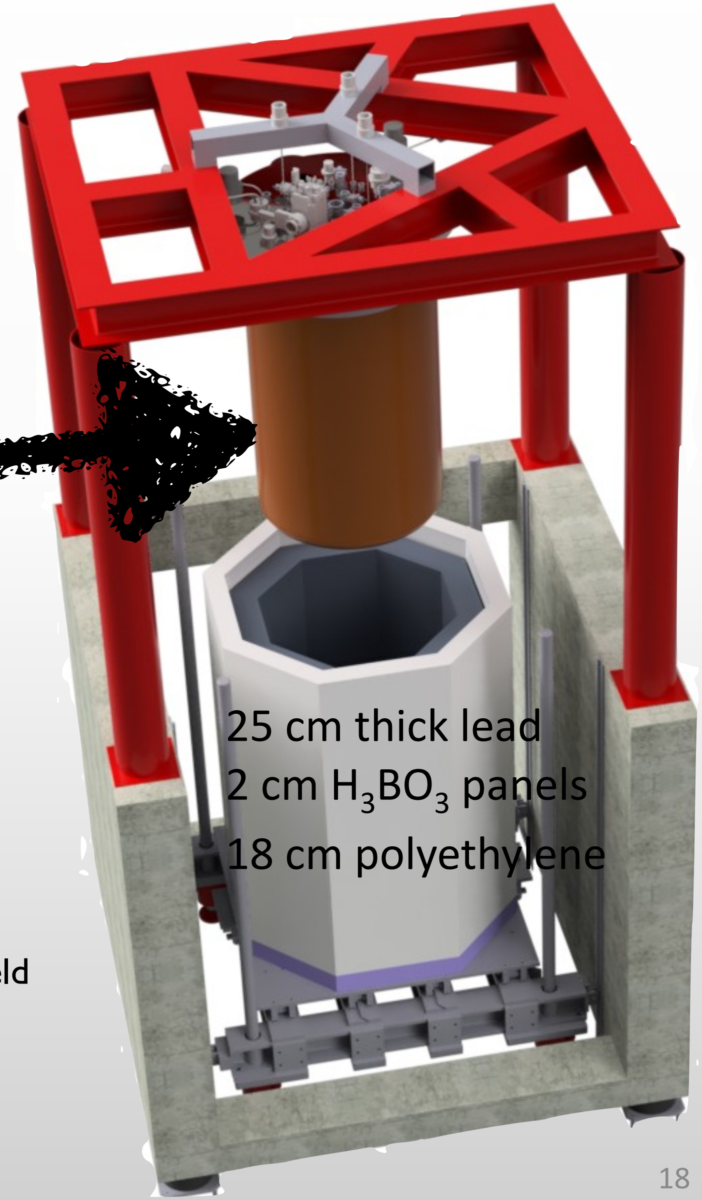


[arXiv:1704:08970]
paper in preparation

CUORE cryostat

- T~10 mK stable
- Size ~ 1 m^3
- 6 stages
- Wired ~2700
- Contains Pb shields
- Radiopure material only
- Suspensions to dump vibrations
- ~15 tons cooled to 4 K





CUORE cryostat

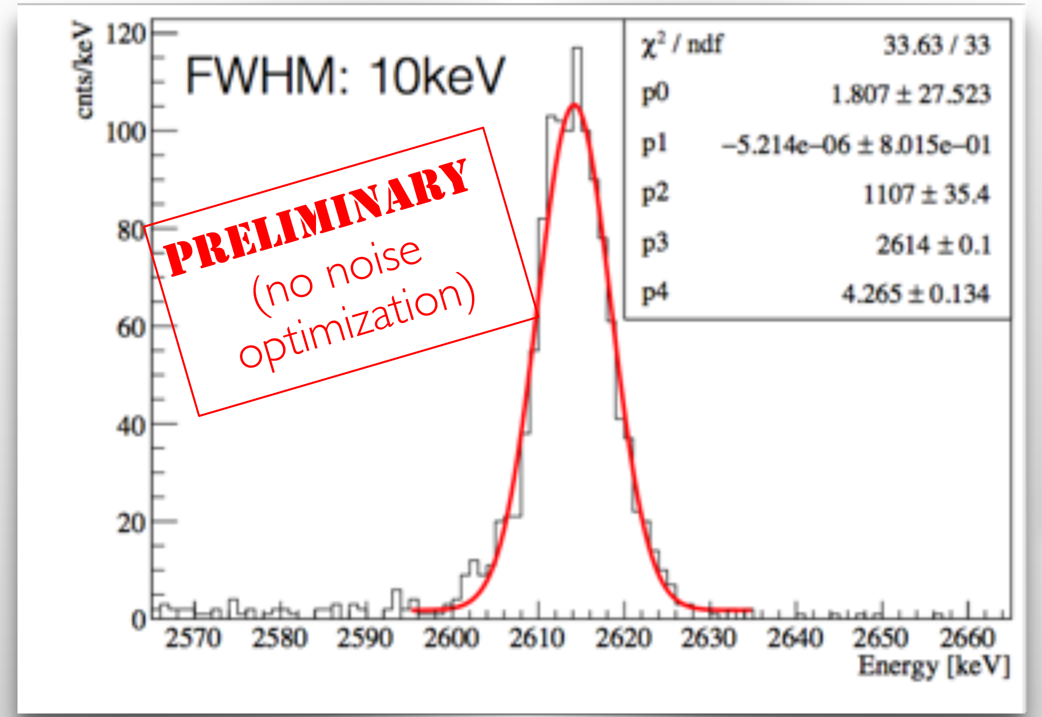
Cryostat top plates

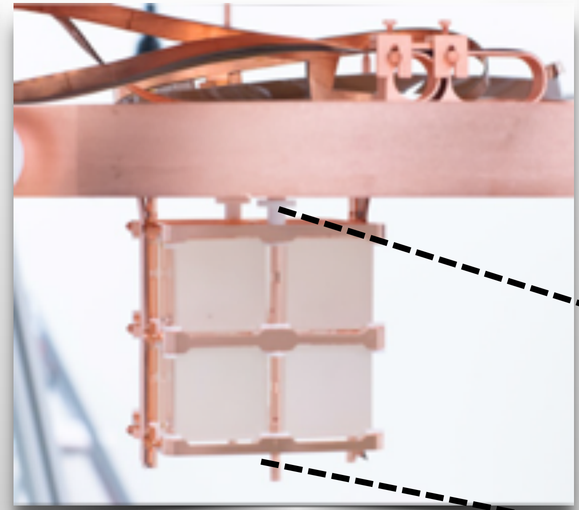
10 mK Cu shield

Cryostat roman Pb shield (4 K)

Cryostat commissioning

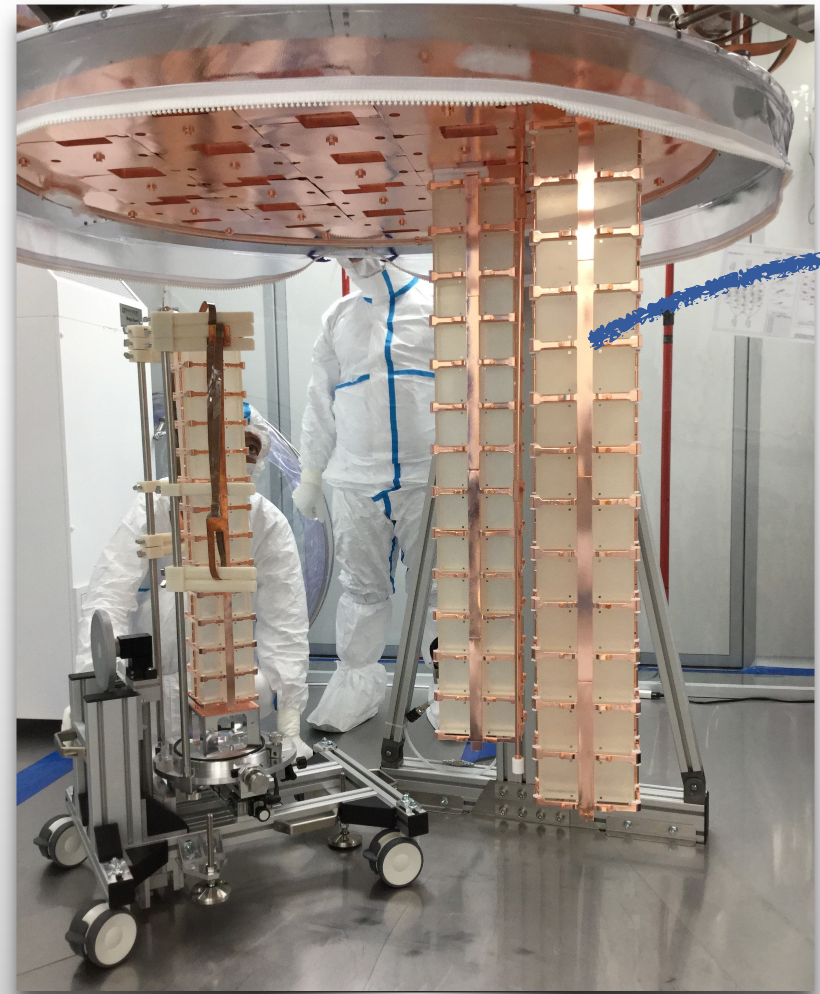
- Completed March 2016
- 6.3 mK stable base temp on ~month scale
- Succesfull test of DCS and DAQ
- "Mini-Tower" test: no unaccounted bkg sources



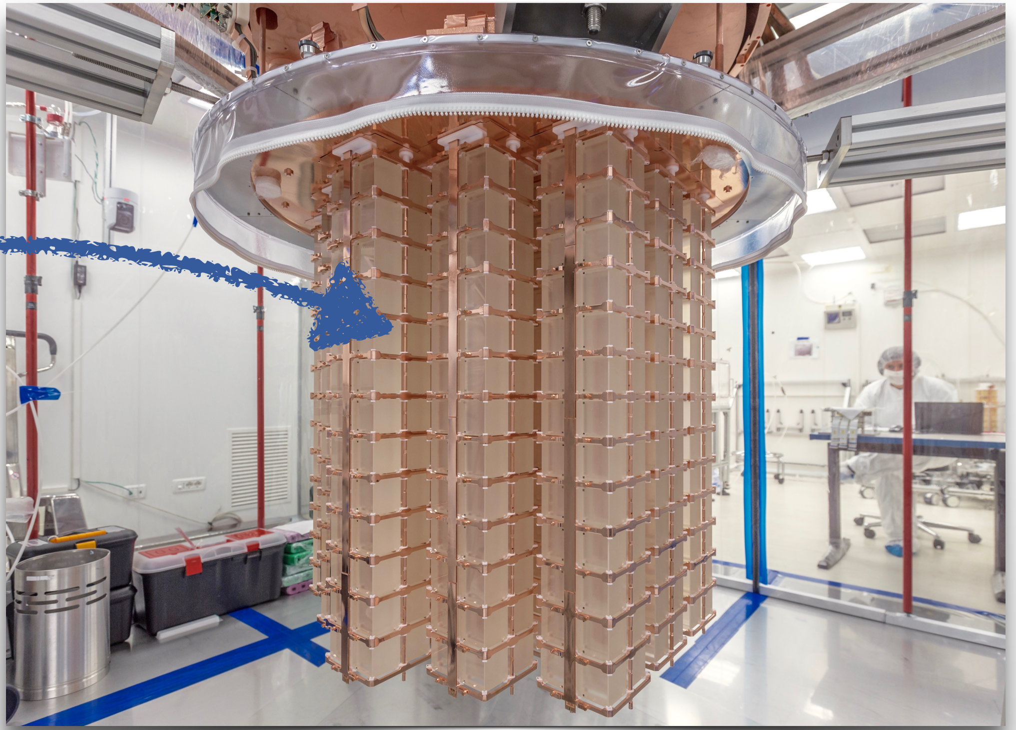


CUORE detector installation

Performed in a radon-free clean room



Installation completed in August 2016

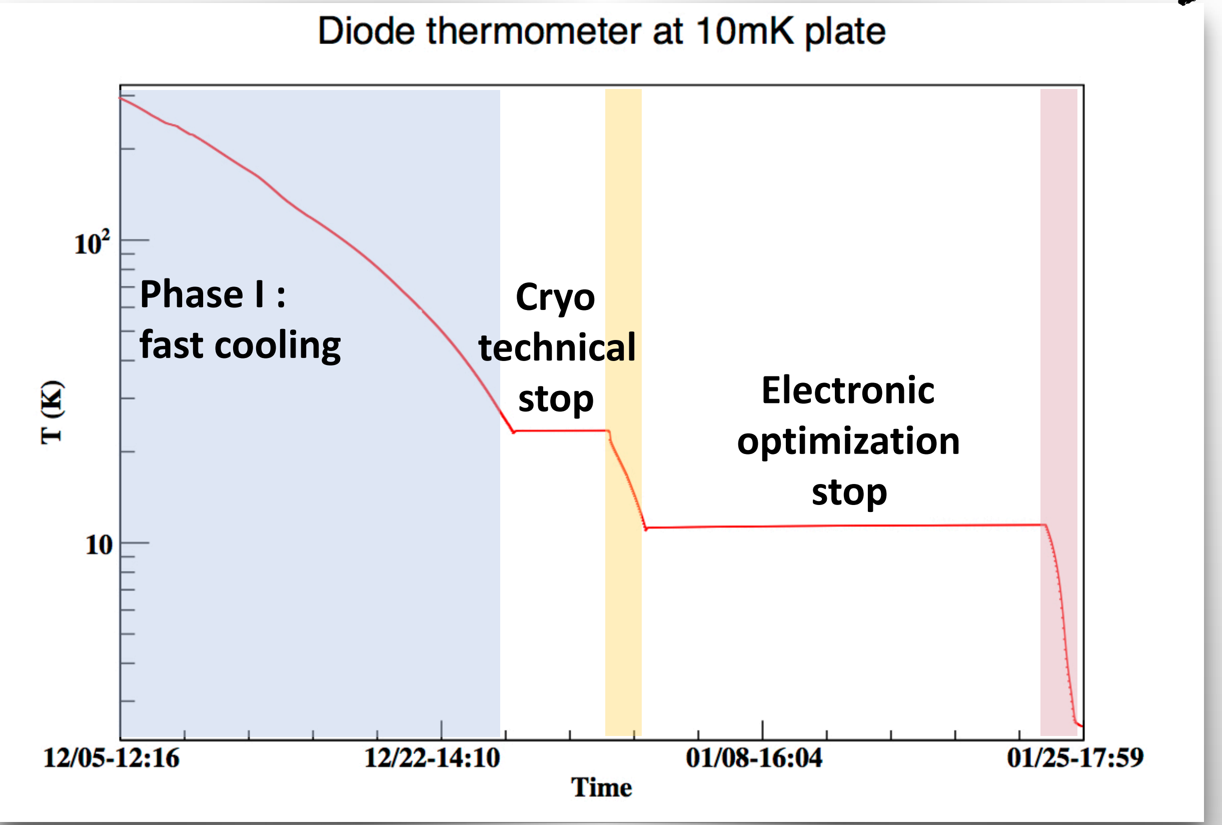


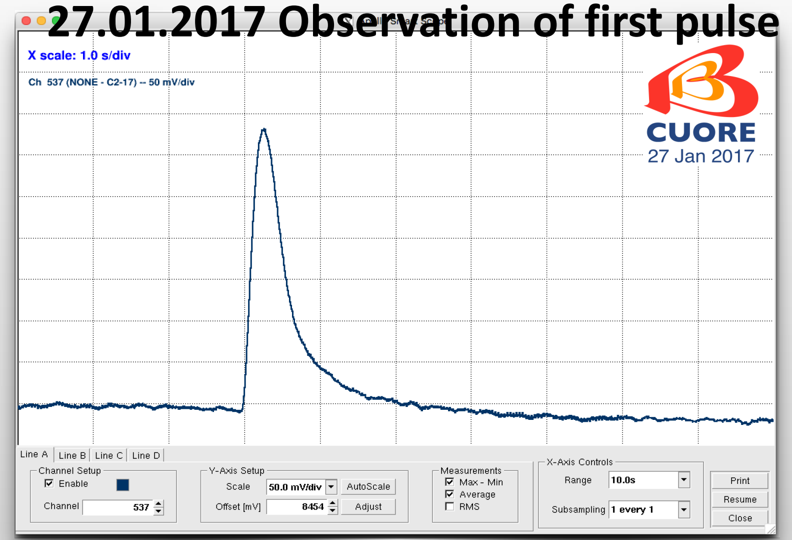
Followed (September – November) by cable routing, electronics and DAQ tests, cryostat closure.

CUORE commissioning

- Cooldown started on Dec. 5 2017
- In April 2017 started data taking
- Working on detector optimization

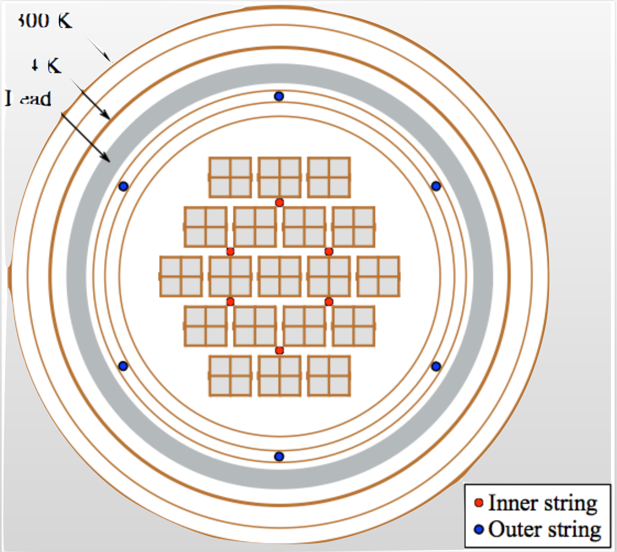
Electronic noise attenuation
Vibration reduction
Base temperature scan
Working point (find I_{bias} of max S/N ratio for each thermistor)
Detector calibration
Commissioning of analysis software

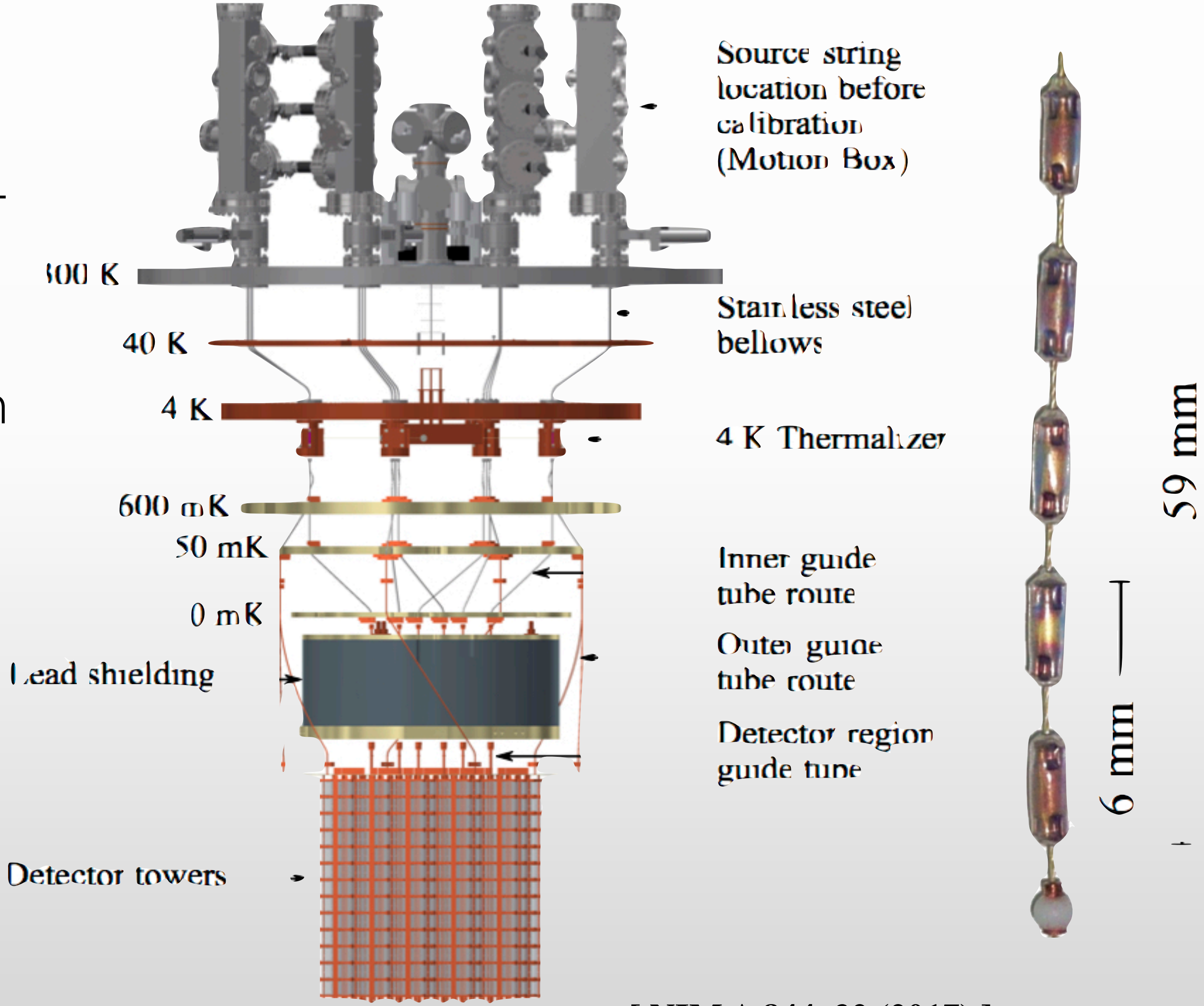




Detector Calibration System

- In-situ calibration with 12 ^{232}Th γ-ray sources (239 keV to 2615 keV)
- Sources outside detector during data-taking, lowered into the cryostat for calibration runs
- Correct for variations in detector gain





[NIM A 844, 32 (2017)]

CUORE expected sensitivity

Assuming bkg = 0.01 c/(kg keV y), ΔE = 5 keV FWHM and 5 years running

$$S_{T_{1/2}} \propto \sqrt{\frac{M_{tot} \cdot t}{b \cdot \Delta E}} \qquad S_{m_{\beta\beta}} \propto \sqrt[4]{\frac{b \cdot \Delta E}{M_{tot} \cdot t}}$$

$$T_{1/2} > 9.5 \times 10^{25}\mathrm{y} \quad (90\%\ \mathrm{C.L.})$$

$$m_{\beta\beta} < 50 - 130\ \mathrm{meV}$$

Axial coupling constant g_A = 1.269

$G^{0\nu}$: Phys. Rev. C 85, 034316 (2012)

NME :	Phys. Rev. C 91, 034304 (2015)	IBM-2
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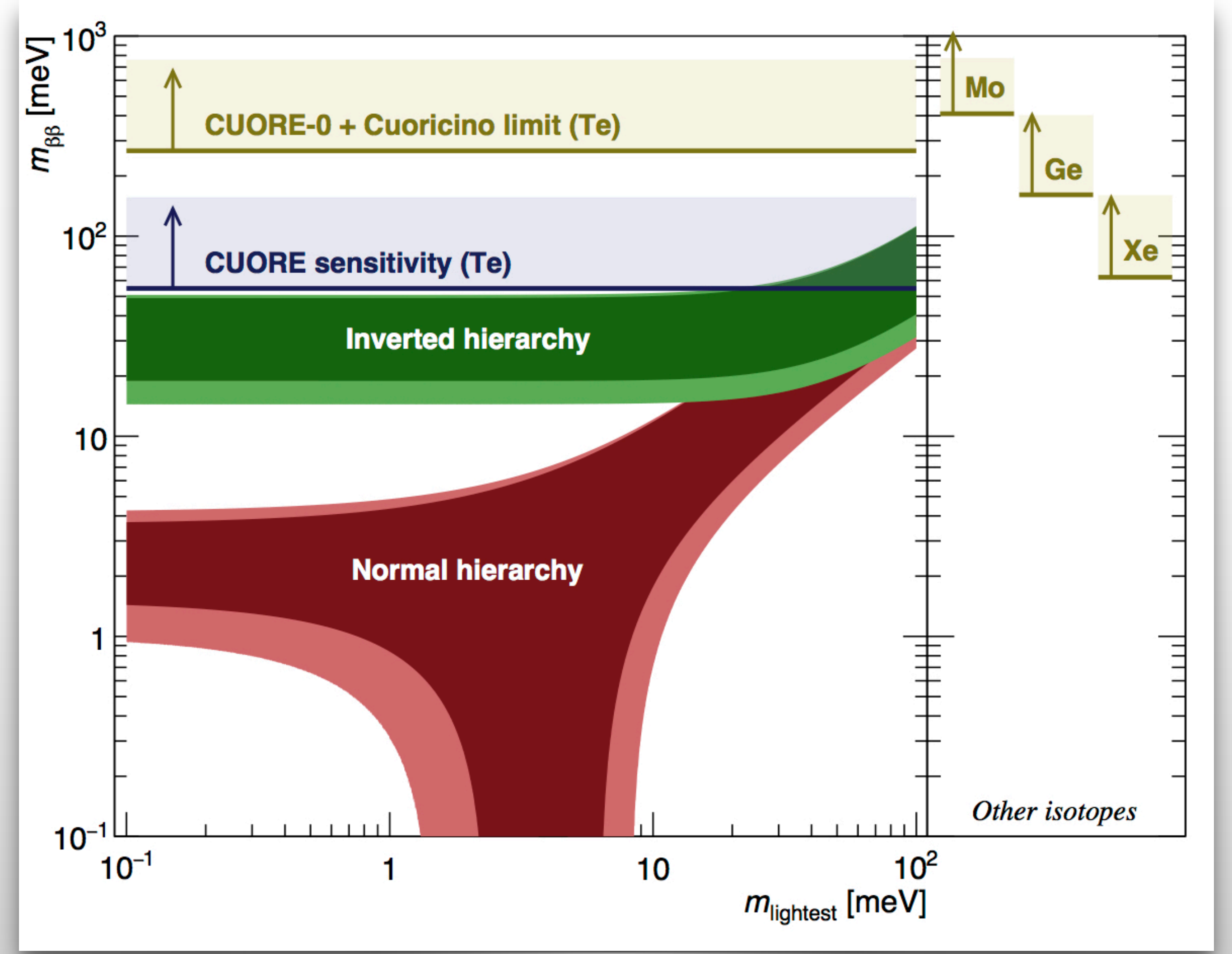
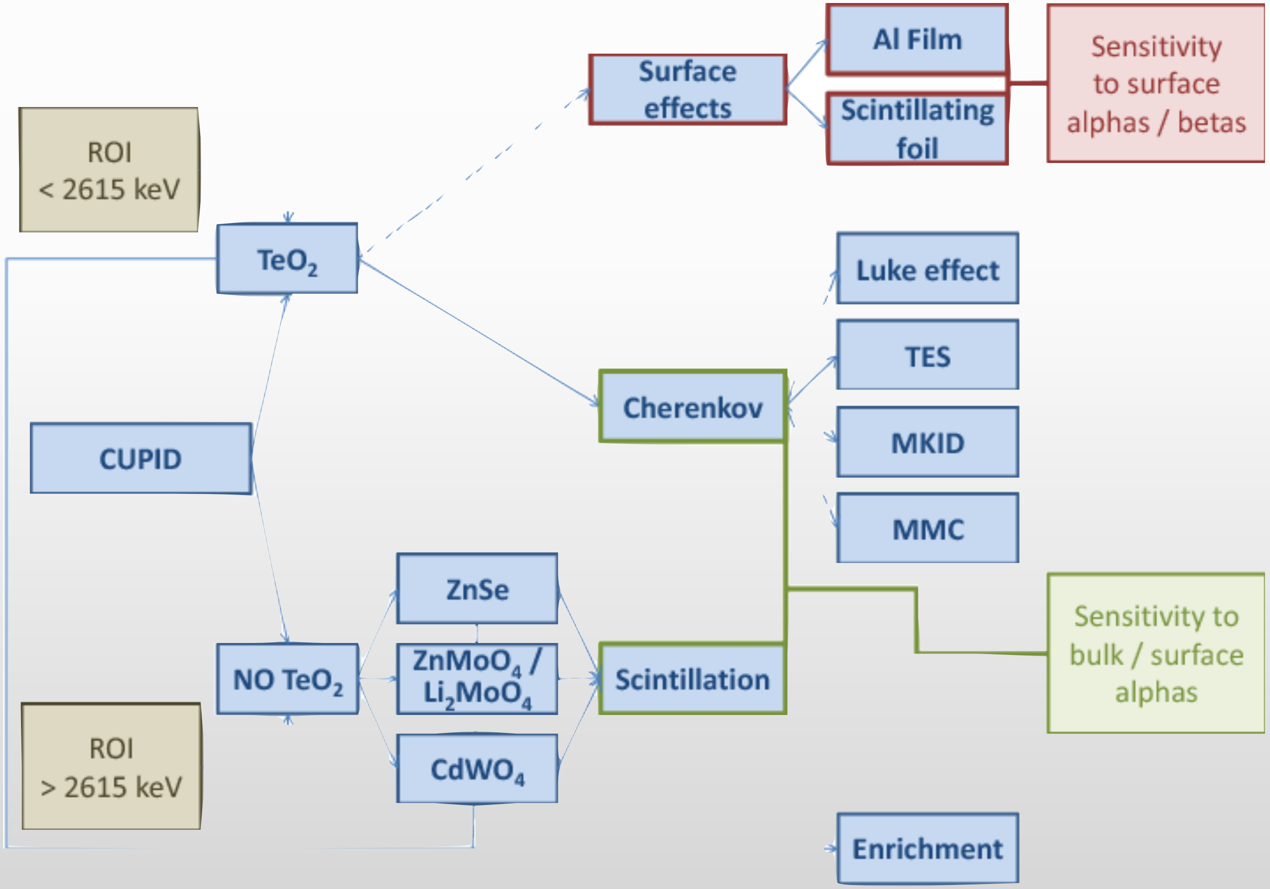
	Phys. Rev. Lett. 105, 252503 (2010)	EDF
	Phys. Rev. C 91, 024309 (2015)	ISM



CUORE R&D’s

CUPID = Cuore Upgrade with Particle IDentification

Please see Enzo Previtali presentation tomorrow



Conclusion

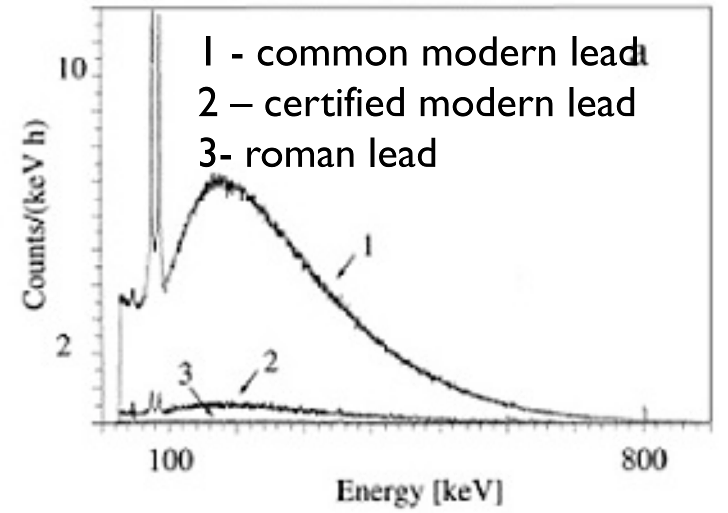
- CUORE-0
  - most stringent limit on ^{130}Te half-life
  - most precise measurement of $2\nu\beta\beta$ half-life in ^{130}Te
  - validation of the CUORE assembly technology and background model

- CUORE: first $0\nu\beta\beta$ cryogenic experiment at ton-scale
  - completed installation
  - successful cooldown
  - NOW TAKING DATA: physics results soon

Backup slides

The roman lead

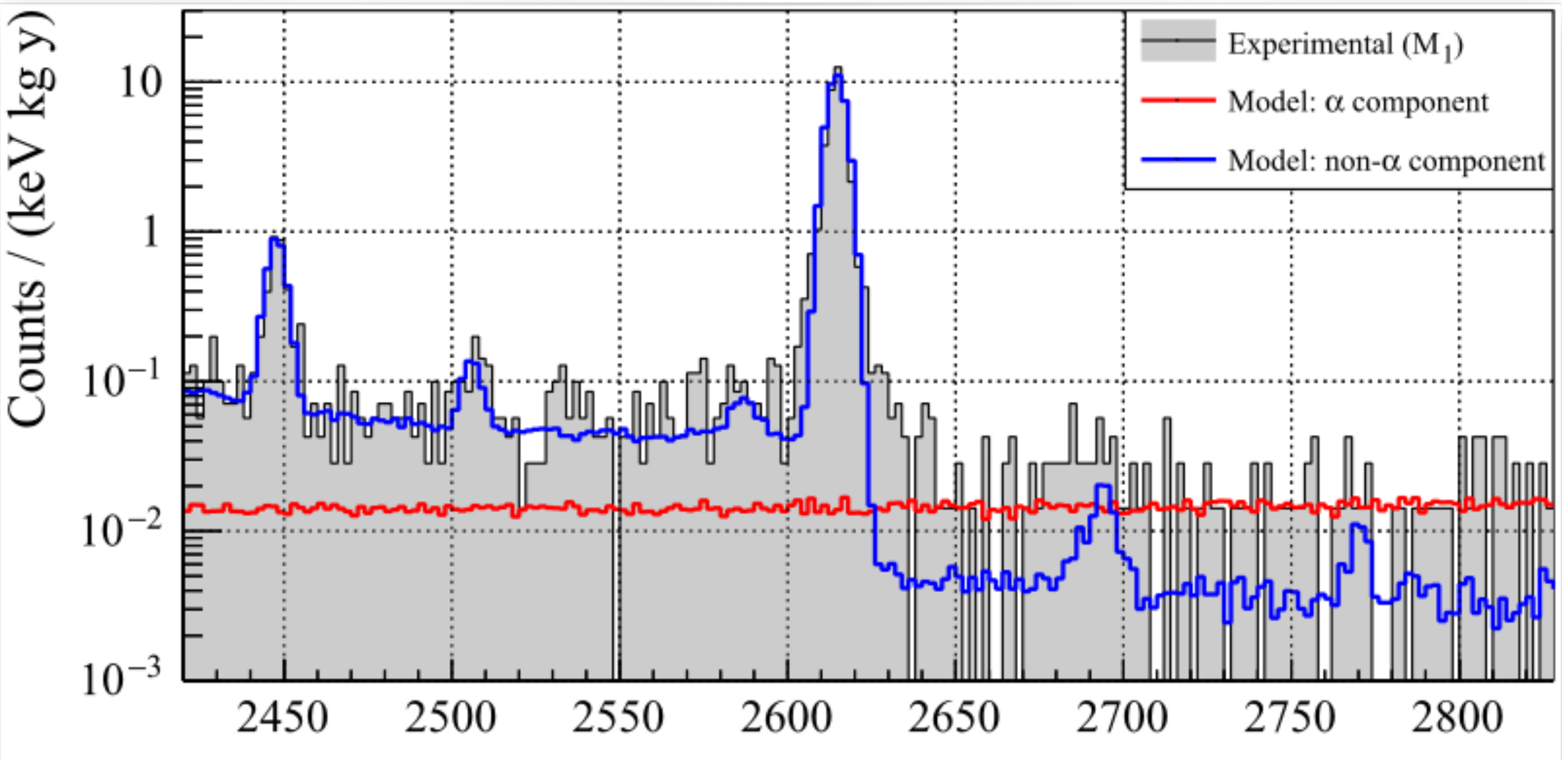
Lead ingots recovered from an ancient Roman ship sunk in ~50 b.c. offshore the west coast of Sardinia.
270 ingots, 33 kg cad = 7 tons
(after removal of the inscriptions)
Reduced content of ^{210}Pb due to ancient extraction technique and no cosmic activation.



Justification for CUPID R&D

With our MC background Model we can separe γ from α backgrounds.
α is ~24%

In CUORE the γ bkg is expected to drop thanks to the new cryostat so that capability to distinguish bkg due to α becomes crucial.

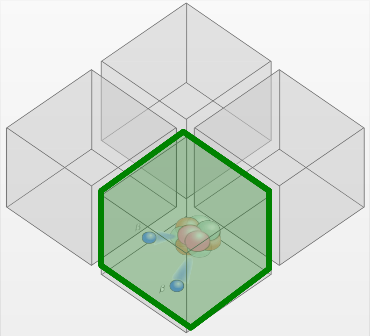


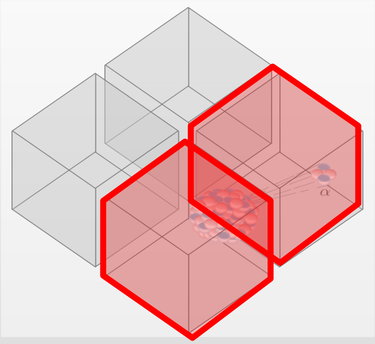
[*European Physical Journal C* **77**, 13 (2017)]

Analysis

1. Pulse amplitude evaluation
2. Gain stabilization
3. Energy calibration
4. Event selection
5. Blinding of E spectrum
6. Analysis studies
7. Unblinding of E spectrum
8. $0\nu\beta\beta$ decay fit

- General data quality cuts
- Pulse-shape cuts to reject unphysical noise pulses
- Pileup rejection on each channel: no signals 3.1s before or 4.0s after
- Tower-wide ±5 ms anticoincidence cut, as 88% of $0\nu\beta\beta$ decays would be single-site events





Only two signatures distinguish events from bkgs:

1. Energy release
2. Single hit ($0\nu\beta\beta$ signal is confined in a single crystal)

→ Multi-hit events are very likely background

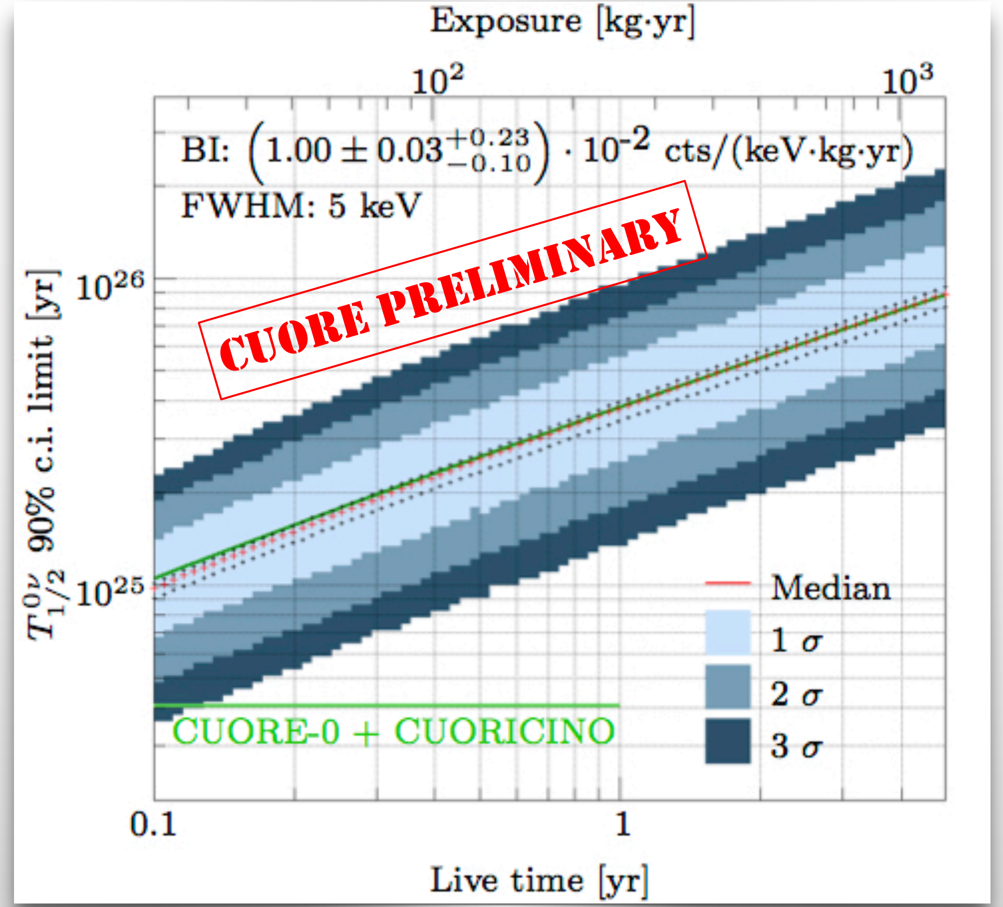
Bayesian exclusion sensitivity

Bayesian analysis on toy MC

- Generate 10^5 bkg spectra based on CUORE bkg
- Fit to bkg+0νββ model → likelihood = $P(E|T_{1/2},H^{0\nu})$ (probability of data given the model)
- compute the probability

$$P(T_{1/2}|E,H^{0\nu}) = \frac{P(E|T_{1/2},H^{0\nu})\pi(T_{1/2})}{\int_0^\infty P(E|T_{1/2},H^{0\nu})\pi(T_{1/2})dT_{1/2}}$$

- find the $T_{1/2}$ that corresponds to the 90% quantile
- The median of the distribution of the $T_{1/2}$ values is taken to be the median sensitivity



Exclusion sensitivity > Cuoricino+CUORE0 in ~days

In 5 years: $T_{1/2} \sim 9 \times 10^{25}$ y (90% C.I.)

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

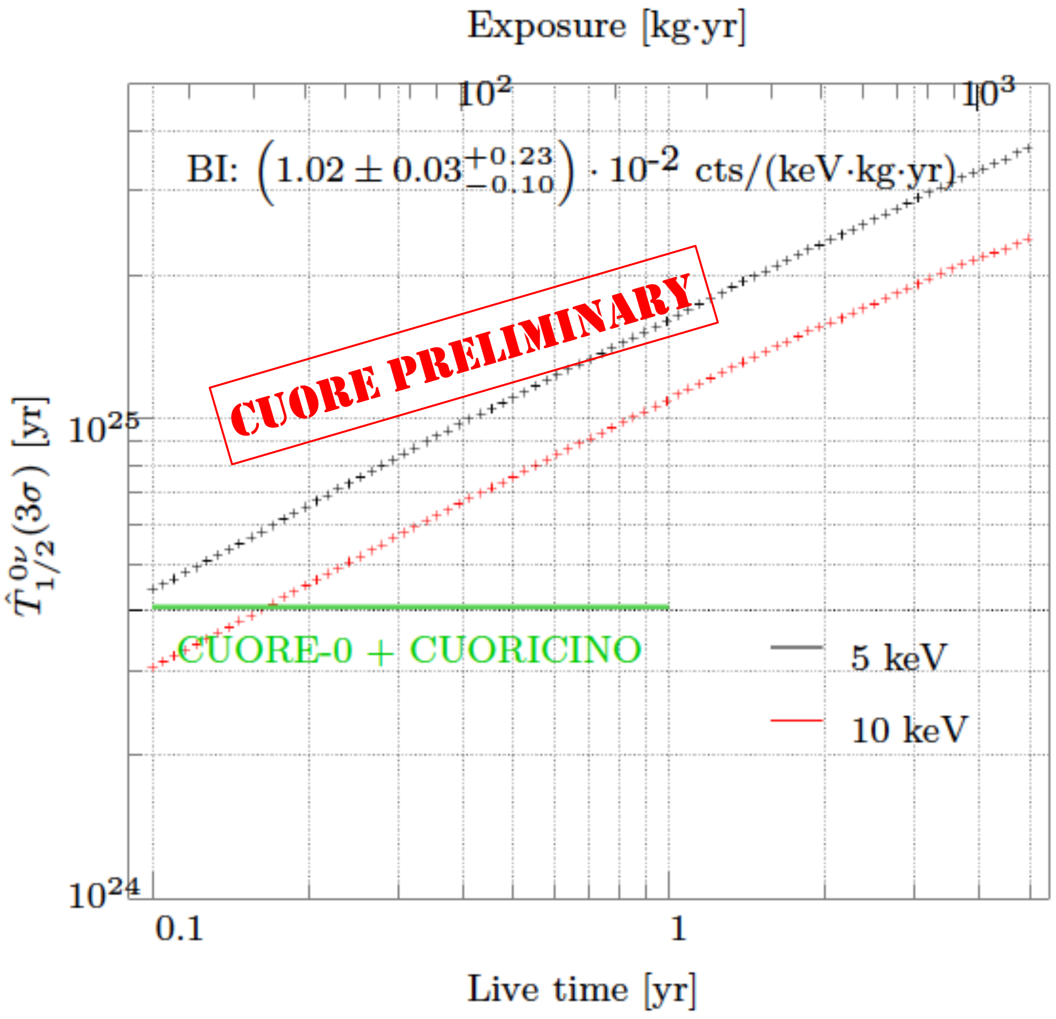
Bayesian discovery sensitivity

Bayesian analysis on toy MC

- Generate 10^5 bkg spectra based on CUORE bkg
- Fit to bkg+0νββ model → likelihood = $P(E|T_{1/2},H^{0\nu})$ (probability of data given the model)
- compute the probability

$$P(T_{1/2}|E,H^{0\nu}) = \frac{P(E|T_{1/2},H^{0\nu})\pi(T_{1/2})}{\int_0^\infty P(E|T_{1/2},H^{0\nu})\pi(T_{1/2})dT_{1/2}}$$

- find the $T_{1/2}$ that corresponds to the 90% quantile
- The median of the distribution of the $T_{1/2}$ values is taken to be the median sensitivity

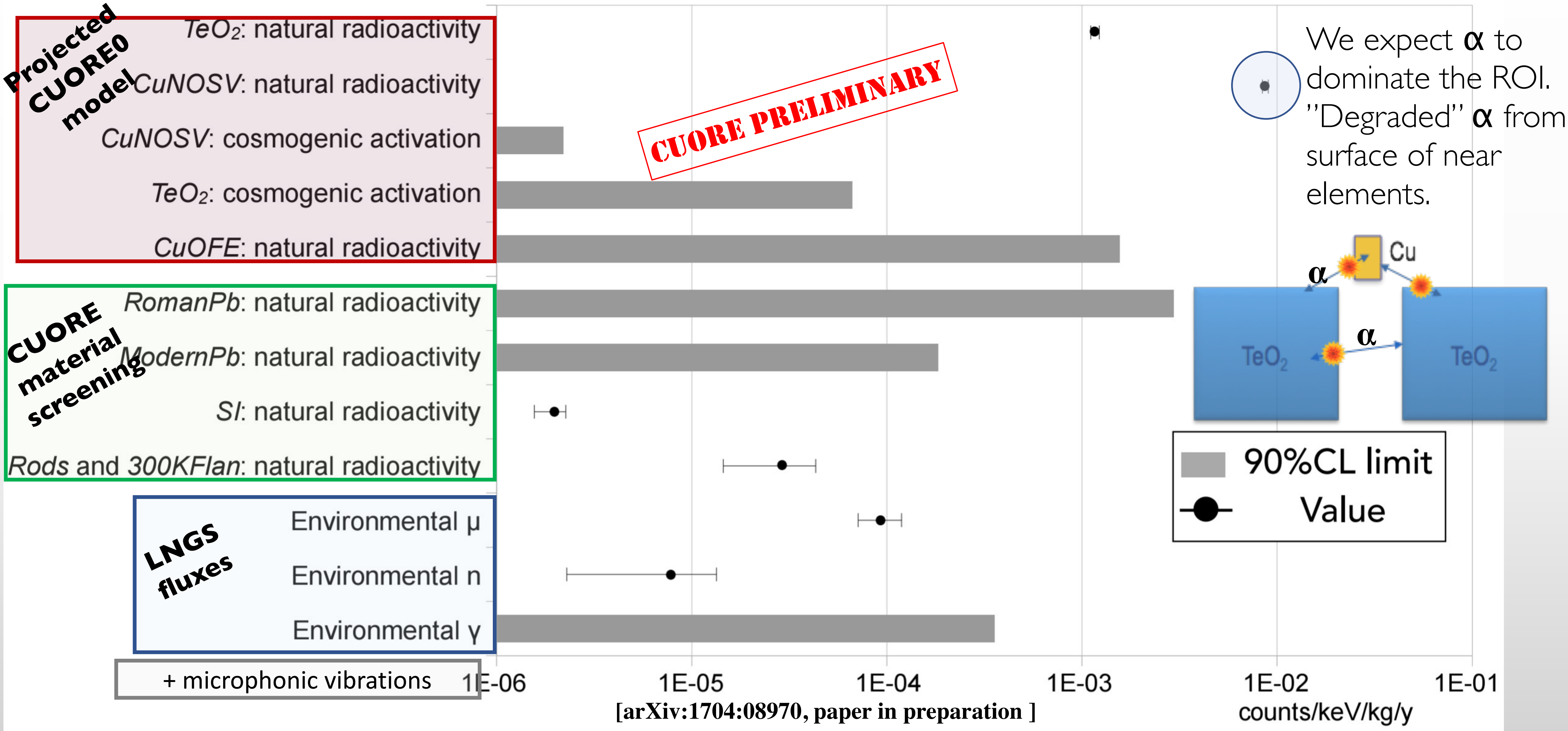


Exclusion sensitivity > Cuoricino+CUORE0 in ~days

In 5 years: $T_{1/2} \sim 3.7 \times 10^{25}$ y (90% C.L.)

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

CUORE background budget in ROI - overall

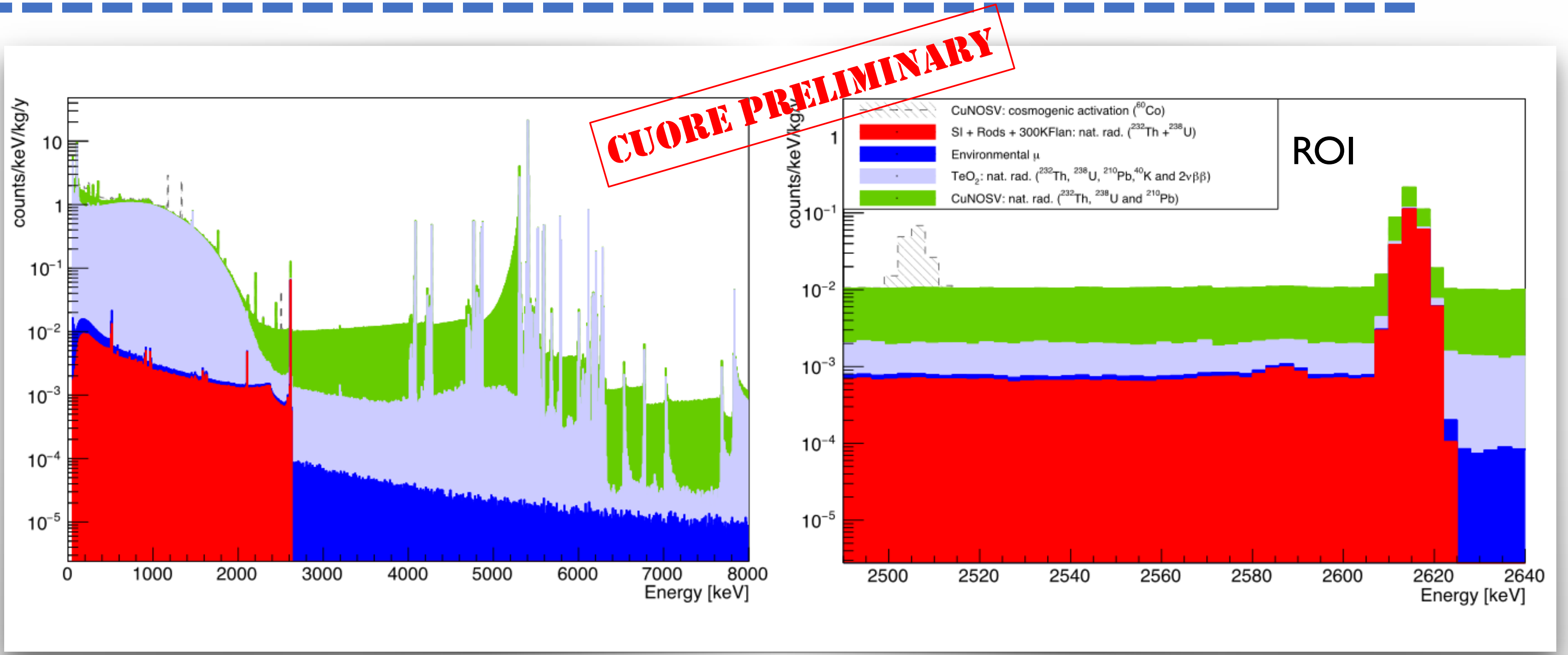


[arXiv:1704:08970, paper in preparation]

We expect α to dominate the ROI. "Degraded" α from surface of near elements.

CUORE background projection

- CUORE-0 bkg rate is projected to the 988 CUORE bolometers
- We expect a lower BI in the ROI thanks to:
  - better granularity (anti-coincidence analysis)
  - self-shielding
  - new cryostat
  - more shielding



CUORE PRELIMINARY

$$\left[1.02 \pm 0.03(\text{stat.})^{+0.23}_{-0.10}(\text{syst.})\right] \times 10^{-2} \frac{\text{counts}}{\text{kg} \cdot \text{keV} \cdot \text{y}}$$

$$\left[1.00 \pm 0.03\ (\text{stat.})^{+0.23}_{-0.10}(\text{syst.})\right] \times 10^{-2} \frac{\text{counts}}{\text{kg} \cdot \text{keV} \cdot \text{y}}$$

c/(keV·kg·yr)	0νββ region
CUORICINO	0.169 ± 0.006
CUORE-0	0.058 ± 0.004
CUORE (projection)	0.0102± 0.0003