Results on ββ decay of ^{130}Te from CUORE-0 and Status of CUORE

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Virginia Tech
Nov 8 2016

DBD16

International Workshop on "Double Beta Decay and Underground Science"

Outline

- Overview of the CUORE experiment
- Background mitigation strategies for CUORE
- CUORE-0 ββ decay results and implications
- Status of CUORE

CUORE

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

CUORE

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

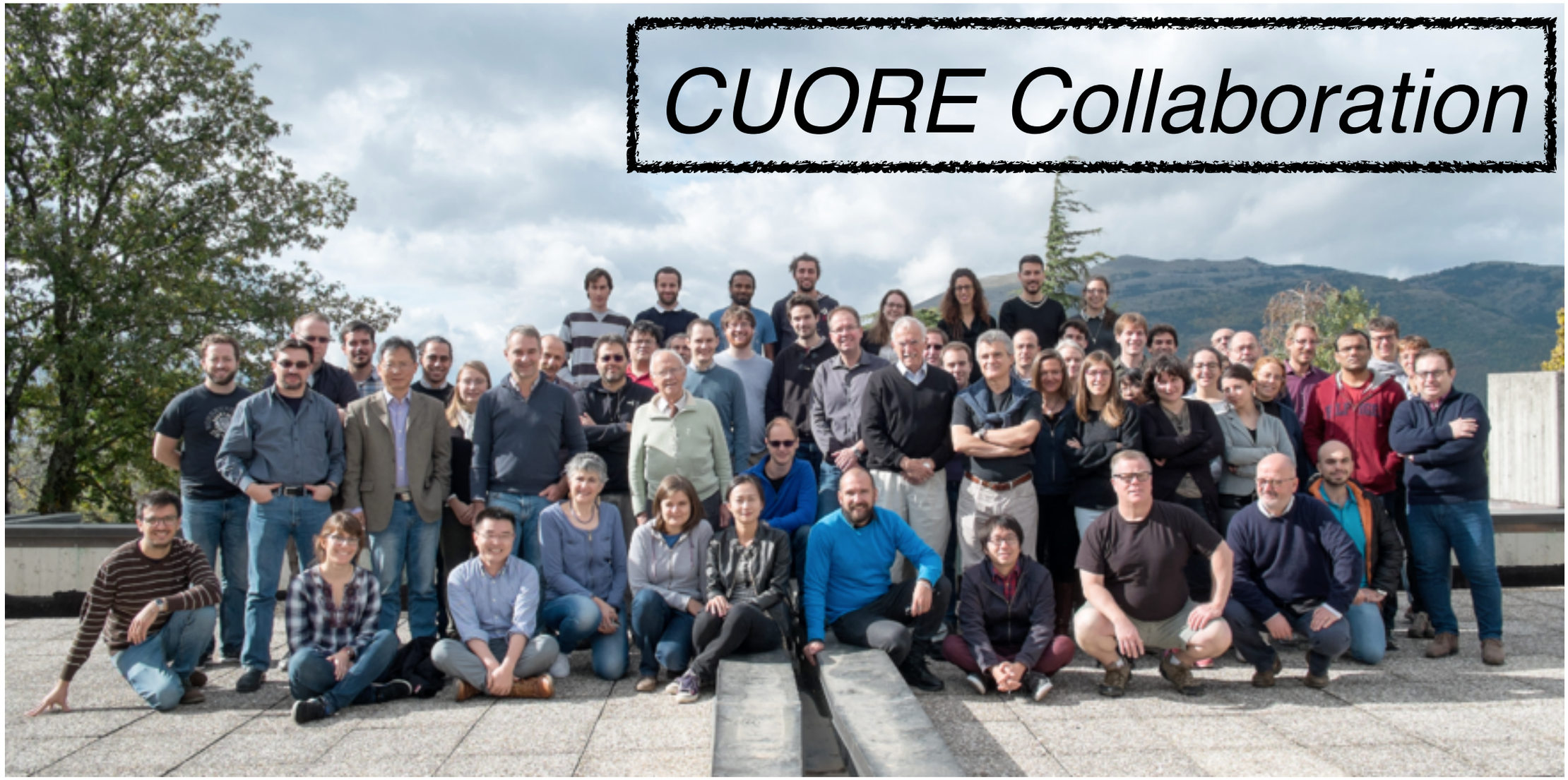
CUORE

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

- Actually … our rare event is $0\nu\beta\beta$ of ^{130}Te (Q-value = 2527.5 keV)

- The detector uses the cryogenic bolometer technique with natural TeO_2 crystals
  - Isotopic abundance ~ 34 %

CUORE Collaboration



UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

CSNSM

SINAP

UNIVERSITAS STUDII PADUANI MCCXXII

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

Lawrence Livermore National Laboratory

VirginiaTech 1872 Invent the Future®

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE SOL PER NOCTEM 1979

STVDIVM VRBIS

SAPIENZA UNIVERSITÀ DI ROMA

Yale

SHANGHAI JIAO TONG UNIVERSITY 1896

Massachusetts Institute of Technology

BERKELEY LAB

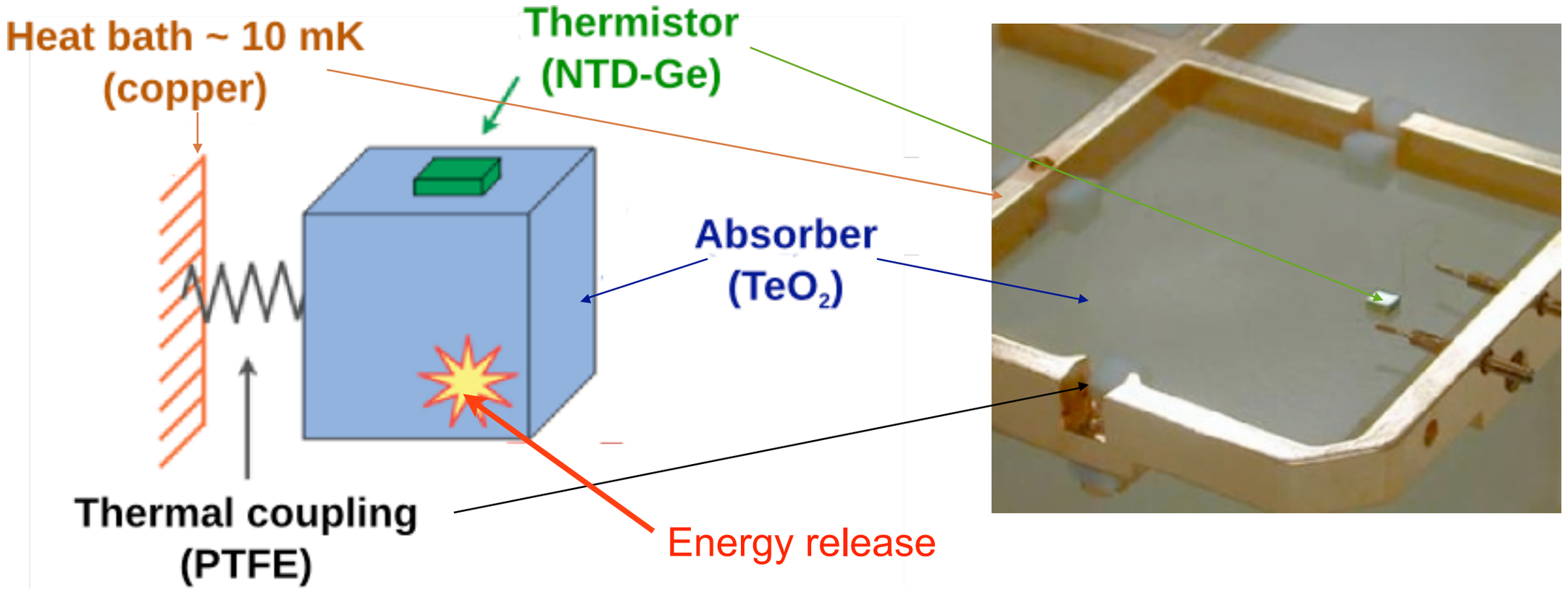
UNIVERSITY OF SOUTH CAROLINA

UCLA

THE UNIVERSITY OF CALIFORNIA 1868

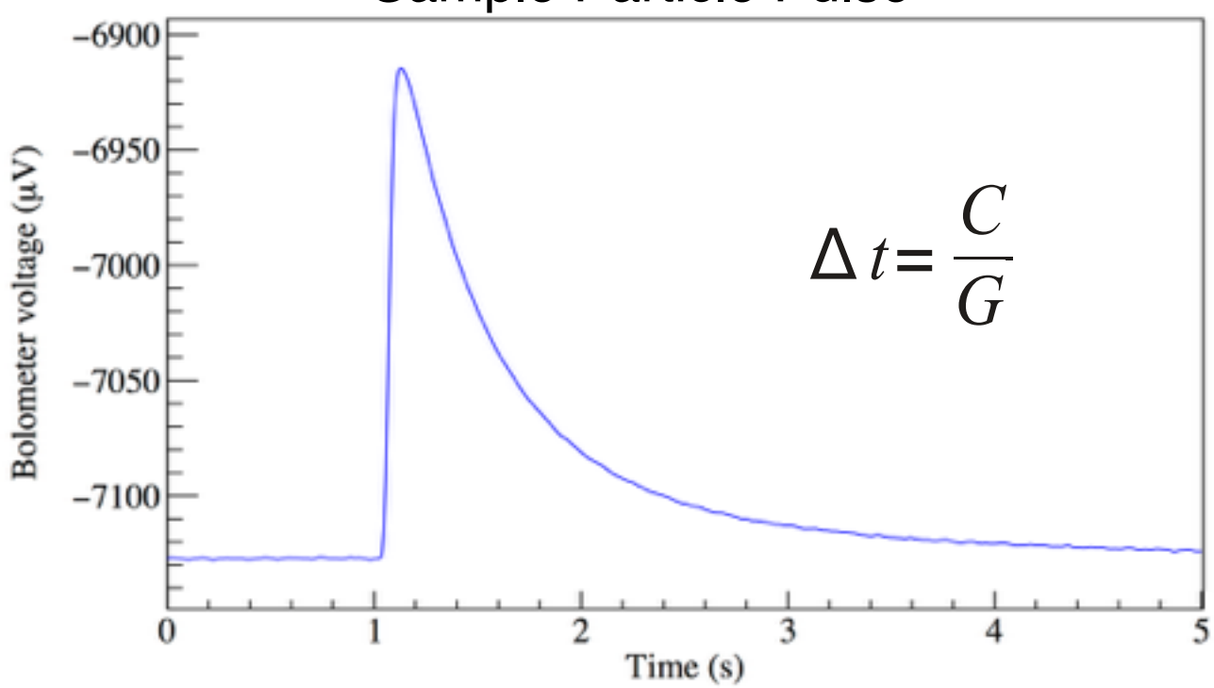
CUORE

CUORE Bolometer concept



- Energy deposit results in temperature rise
- For TeO_2 crystals configured for CUORE at ~10mK, $\Delta T \sim 0.1$mK per MeV
- Temperature change read out with NTD-Ge

Sample Particle Pulse



$$\Delta t = \frac{C}{G}$$

CUORE

- **M**: **Massive array of ^{130}Te (~20x Cuoricino)**
  - 988, 5x5x5 cm^3 $^{nat}TeO_2$ crystals
    - 742 kg of $^{nat}TeO_2$ or 206 kg of ^{130}Te
  - Assembled into 19 towers, 13 floors per tower, 4 crystals per floor

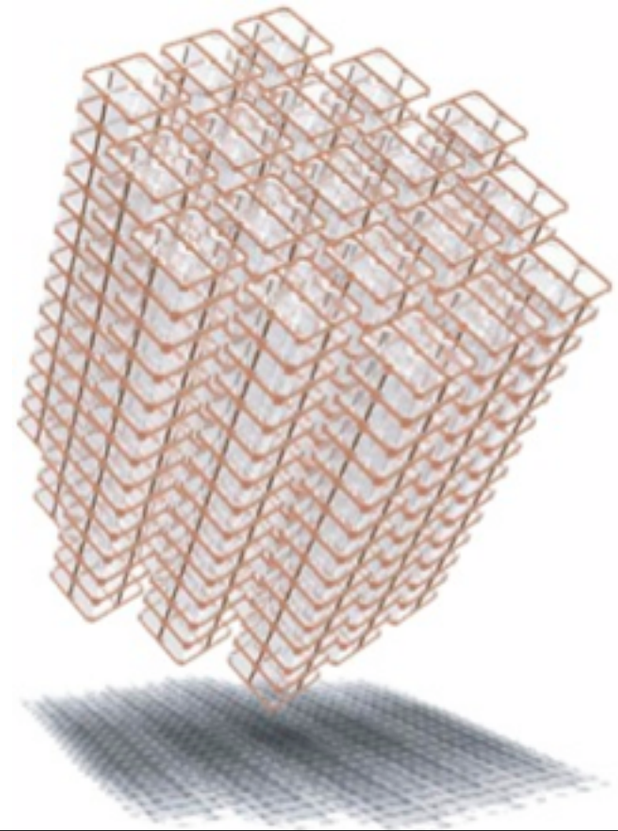
half-life sensitivity

$$\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

- **b**: **Background goal**
  - Goal 0.01 counts/keV/ky/yr (~20x lower than CUORICINO)

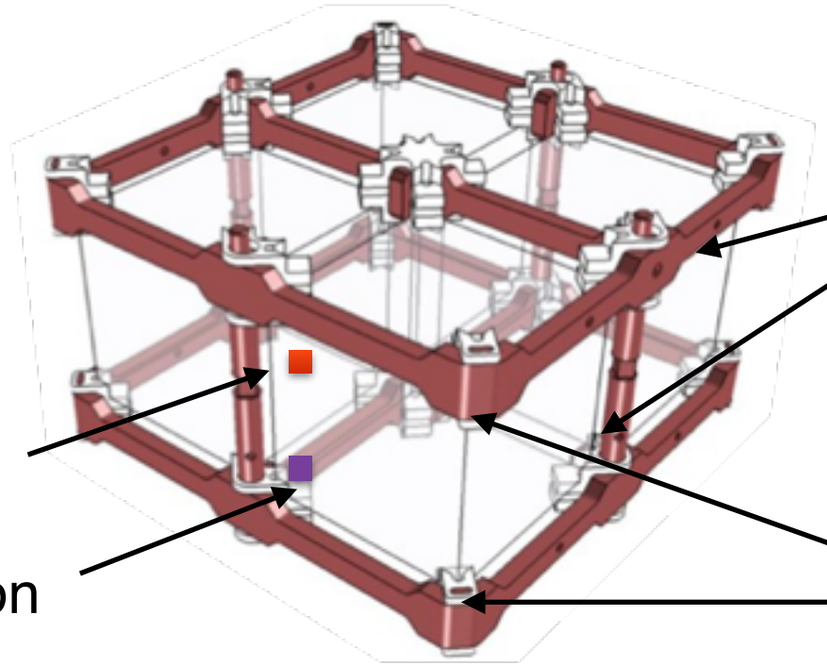
- δ**E**: **Resolution goal**
  - Resolution of TeO_2 bolometers is excellent, 5keV @ 2615keV is demonstrated

- **t**: **Cryogen-free dilution refrigerator**
  - ➡ Improves detector duty cycle
  - ➡ Improves stability

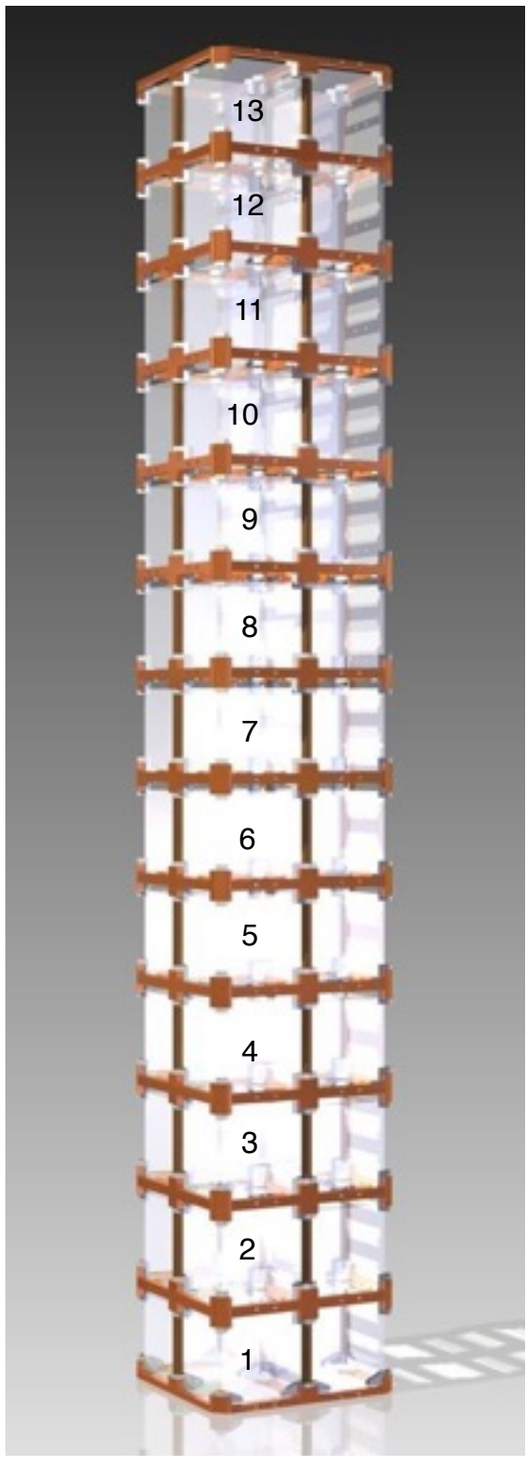


CUORE: Overview of bolometer array

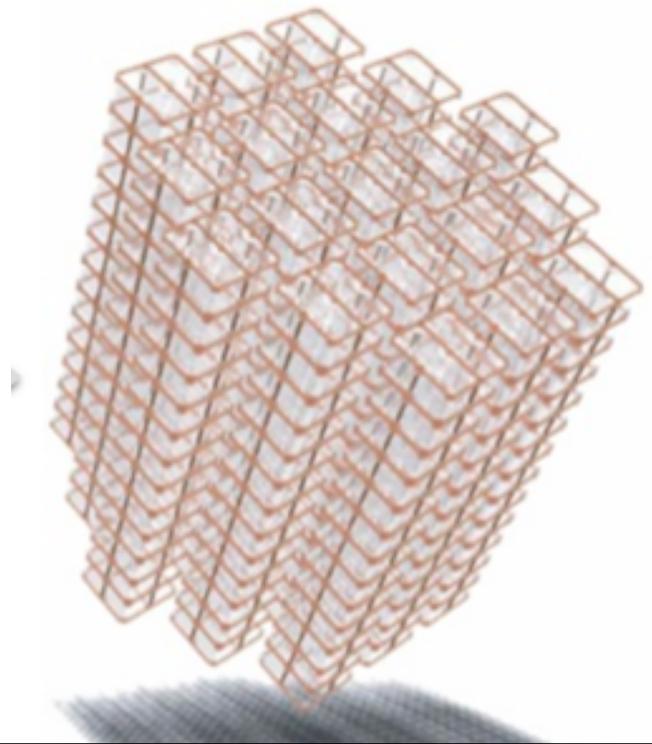
- 4 crystals per floor



- 13 floors per tower

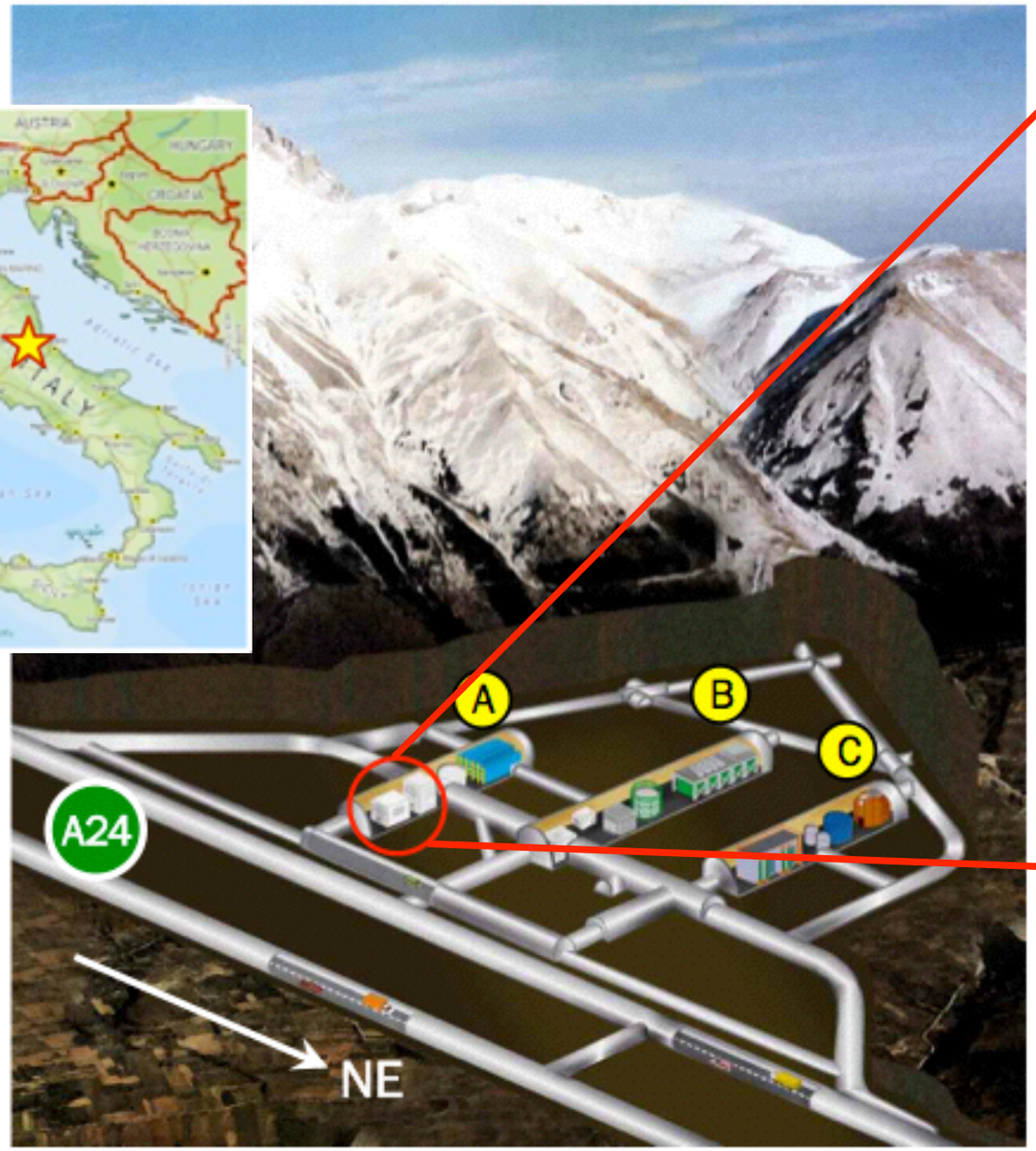


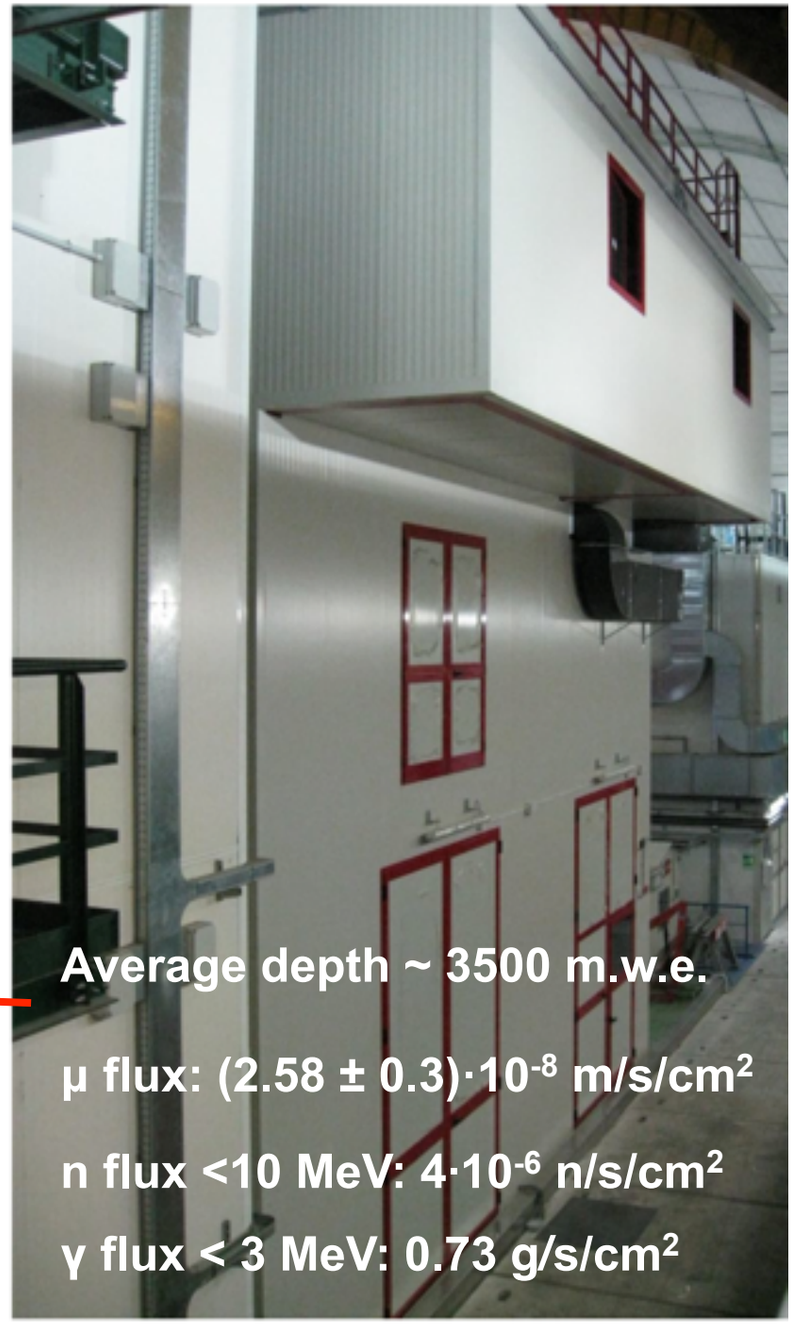
- 19 Towers
- => 742 kg TeO_2
- => 206 kg ^{130}Te



CUORE Background reduction strategies

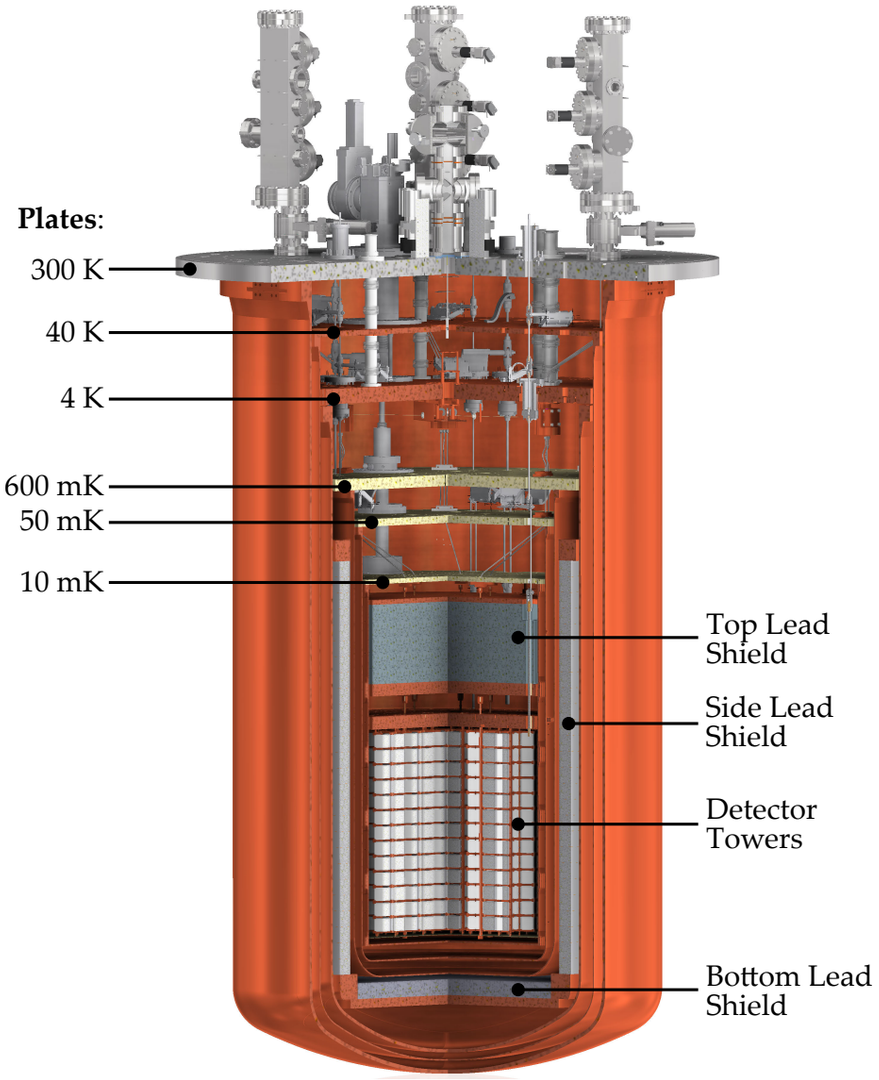
1. located in Hall A of Gran Sasso National Lab in Italy





CUORE Background reduction strategies

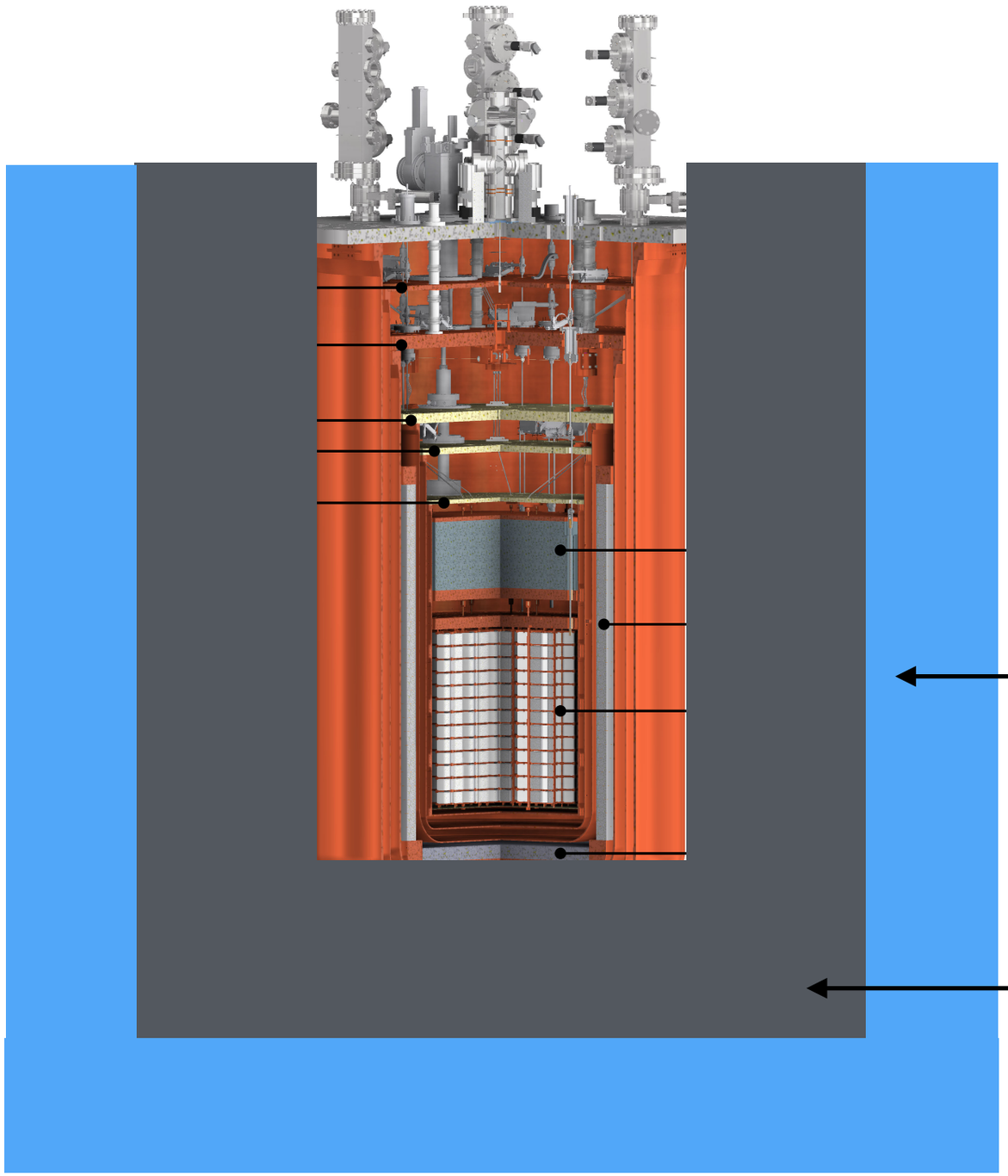
2. Shielding

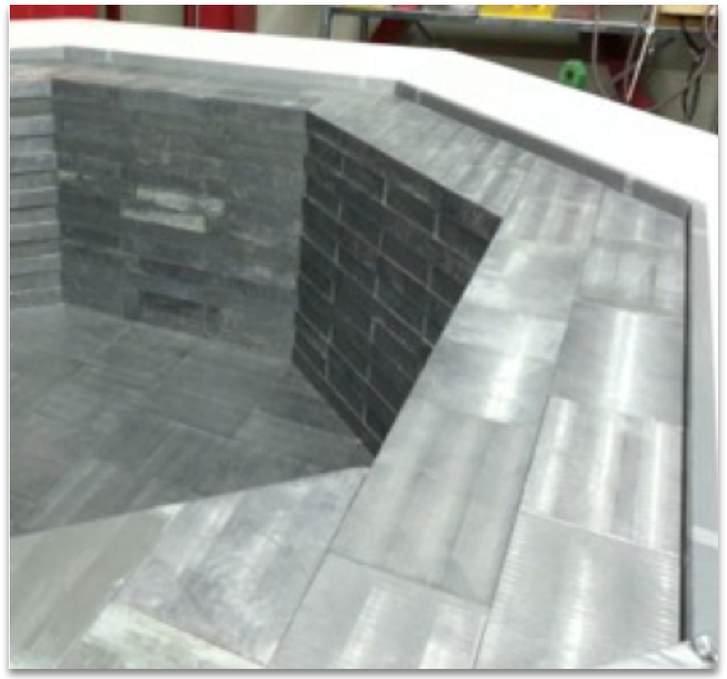


- Low background ancient lead and Cu radiation shielding inside cryostat
- Low background Cu thermal shields and structural materials

CUORE Background reduction strategies

2. … more shielding





Neutron shield (18 cm PET + 2cm of H_3BO_3)

External lead (35 cm thick)

CUORE Background reduction strategies

3. Materials selection

Bulk Screening

Component	^{232}Th [Bq/kg]	^{238}U [Bq/kg]	^{40}K [Bq/kg]
TeO_2 crystals	$<8.4\cdot10^{-7}$	$<6.7\cdot10^{-7}$	
Epoxy	$<8.9\cdot10^{-4}$	$<1.0\cdot10^{-2}$	$<47\cdot10^{-3}$
Au bonding wires	$<4.1\cdot10^{-2}$	$<1.2\cdot10^{-2}$	
Si heaters	$<3.3\cdot10^{-4}$	$<2.1\cdot10^{-3}$	
Ge thermistors	$<4.1\cdot10^{-3}$	$<1.2\cdot10^{-2}$	
PEN-Cu cables	$<1.0\cdot10^{-3}$	$<1.3\cdot10^{-3}$	$<1.3\cdot10^{-2}$
PTFE supports	$<6.1\cdot10^{-6}$	$<2.2\cdot10^{-5}$	
Cu NOSV	$<2.0\cdot10^{-6}$	$<6.5\cdot10^{-5}$	$7\pm2\cdot10^{-4}$
Pb Roman	$<4.5\cdot10^{-5}$	$<4.6\cdot10^{-5}$	$<2.3\cdot10^{-5}$
Pb Ext	$<2.6\cdot10^{-4}$	$<7.0\cdot10^{-4}$	$<5.4\cdot10^{-3}$

Surface Screening

Component	^{232}Th [Bq/cm^2]	^{238}U [Bq/cm^2]	^{210}Pb [Bq/cm^2]
TeO_2 crystals [22]	$<2\cdot10^{-9}$	$<9\cdot10^{-9}$	$<1\cdot10^{-6}$
Si heaters [23,24]	$<3\cdot10^{-6}$	$<8\cdot10^{-7}$	$<8\cdot10^{-7}$
Ge thermistors	$<8\cdot10^{-6}$	$<5\cdot10^{-6}$	$<4\cdot10^{-5}$
PEN-Cu cables	$<4\cdot10^{-6}$	$<5\cdot10^{-6}$	$<3\cdot10^{-5}$
PTFE supports	$<2\cdot10^{-8}$	$<7\cdot10^{-8}$	
CuNOSV [20]	$<7\cdot10^{-8}$	$<7\cdot10^{-8}$	$<9\cdot10^{-7}$

https://arxiv.org/abs/1609.01666

Parts screened with ICPMS, HPGe γ-counting, NAA, Si-barrier detectors, bolometric measurements, for bulk and surface contamination

CUORE Background reduction strategies

4. Material reduction, surface cleaning and materials handling protocols

- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals

- Aggressive mechanical and chemical ultra-cleaning processes developed for all Cu components:
  - Tumbling
  - Electropolishing
  - Chemical etching
  - Magnetron plasma etching

- All parts tracked, stored underground, under nitrogen after cleaning

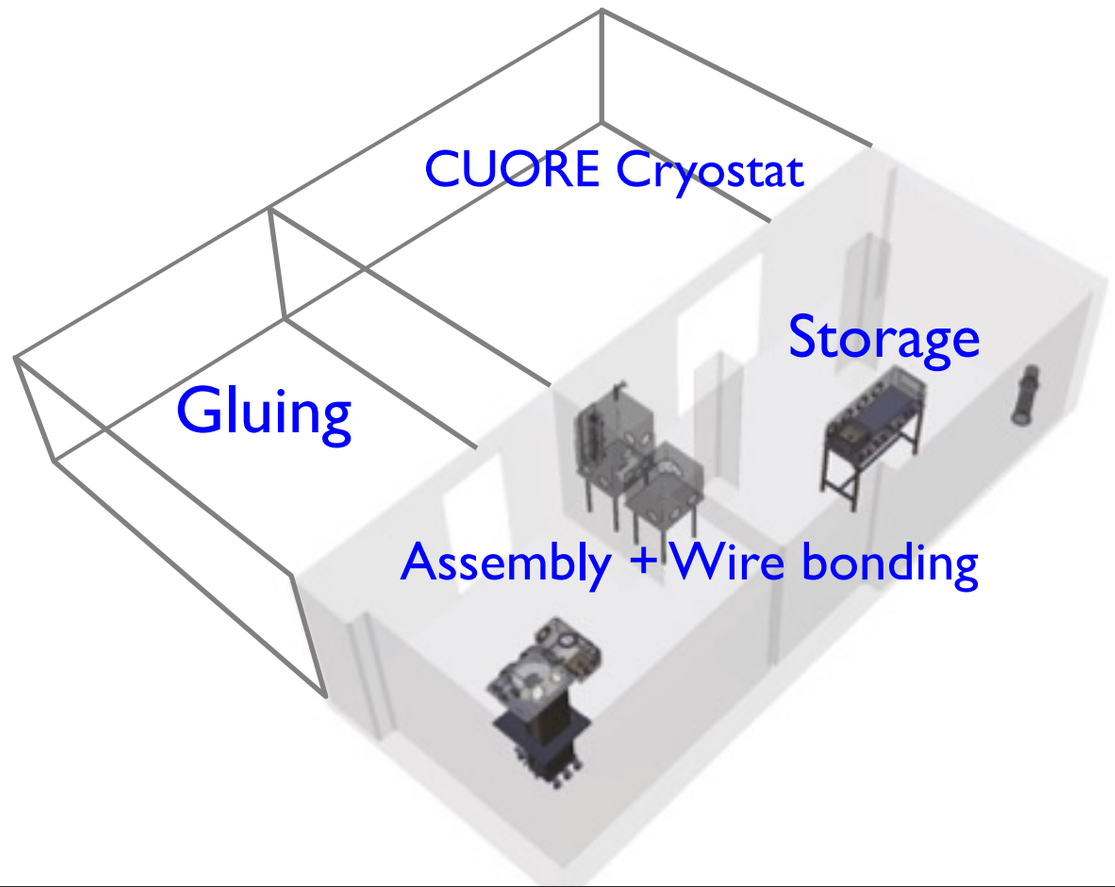
- All subsequent detector handling done in clean room, nitrogen flushed glove boxes or low-radon environment

CUORE Detector Assembly Facility

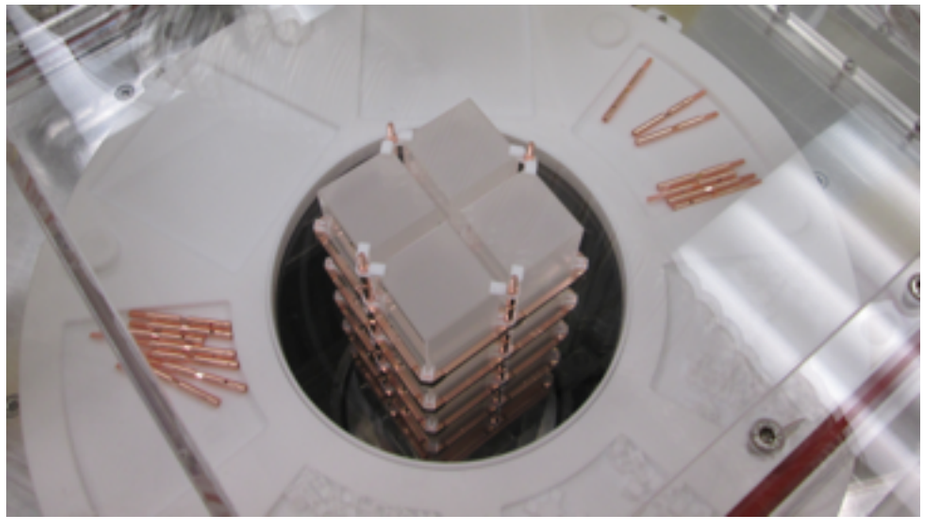
Class 1000 Clean Room for Detector Assembly and Storage

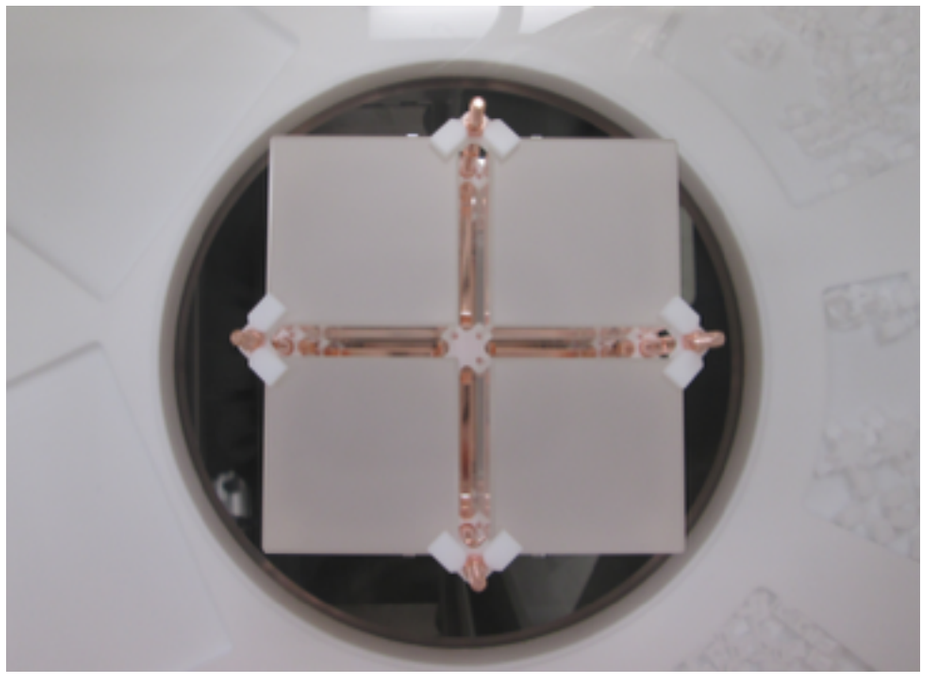
Nuclear Instruments and Methods A 768, 130-140 (2014). arxiv:1405.0852

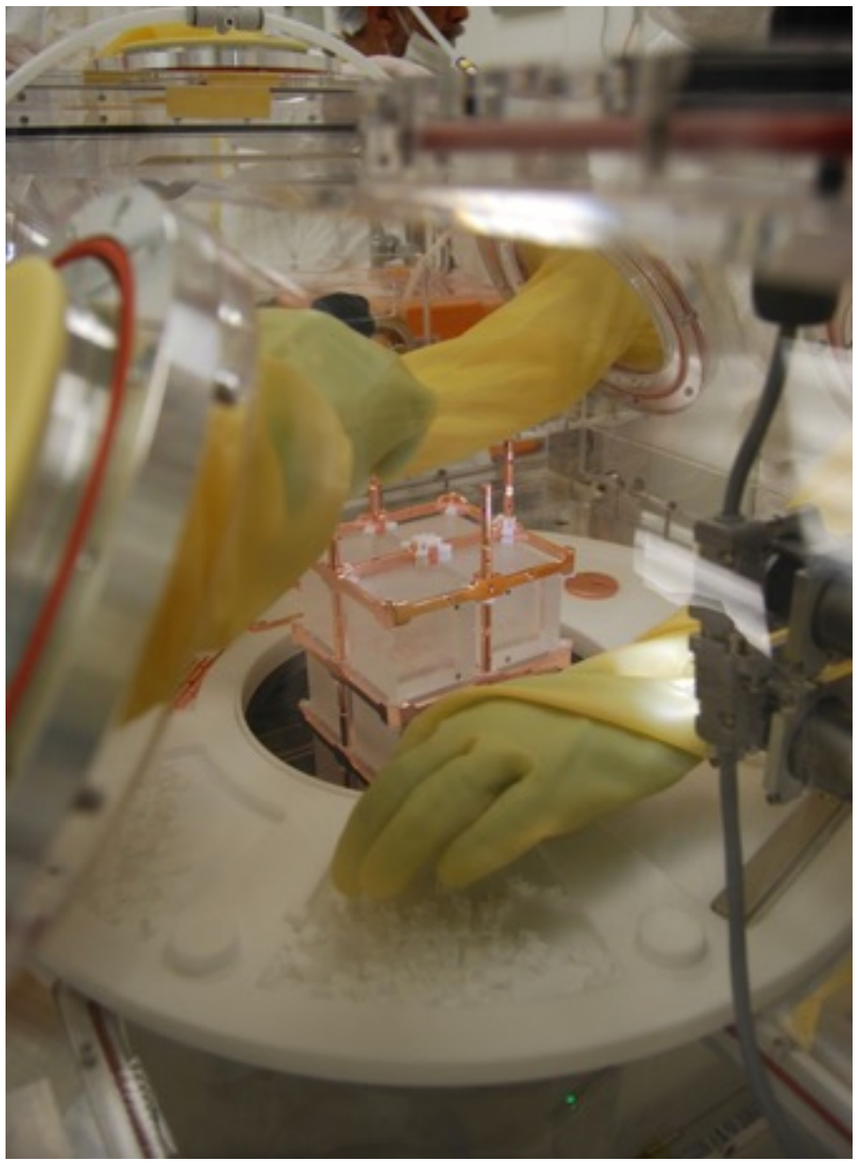
- All parts cleaned/screened according to CUORE protocol
- Underground at LNGS
- Operations in clean room in N2 flushed glove boxes

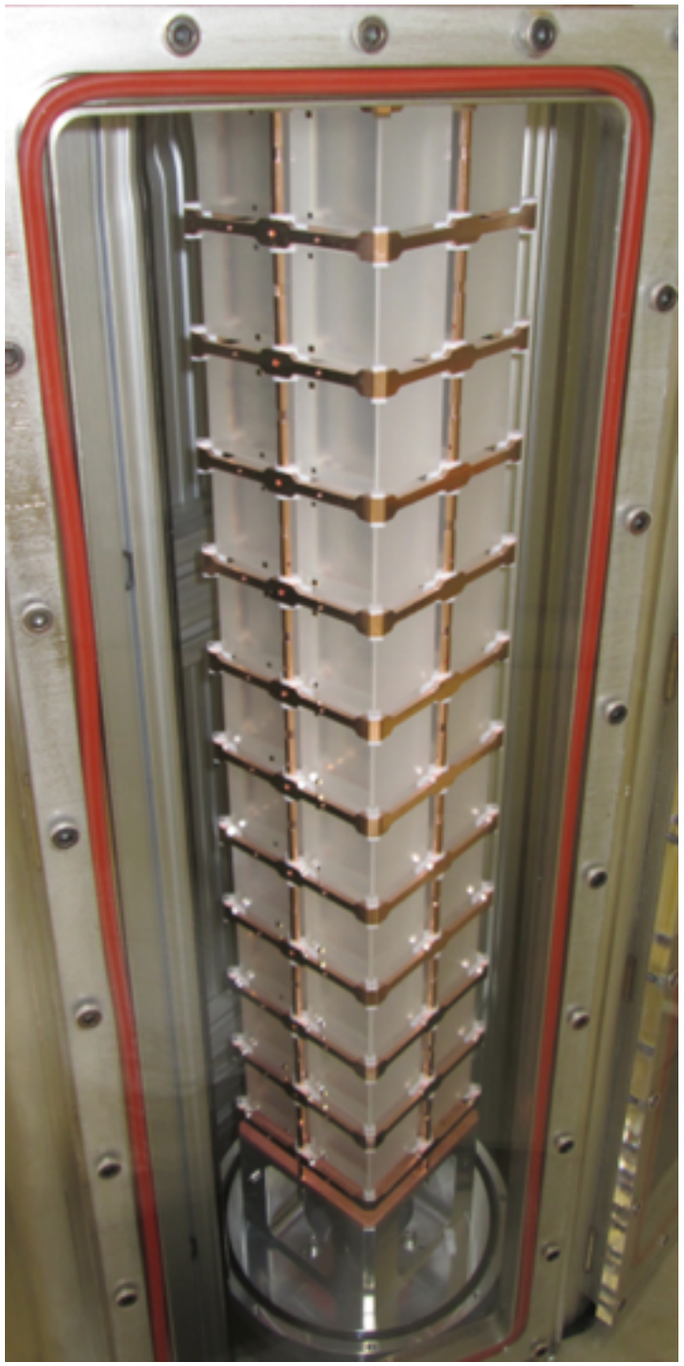


Sample of assembly steps

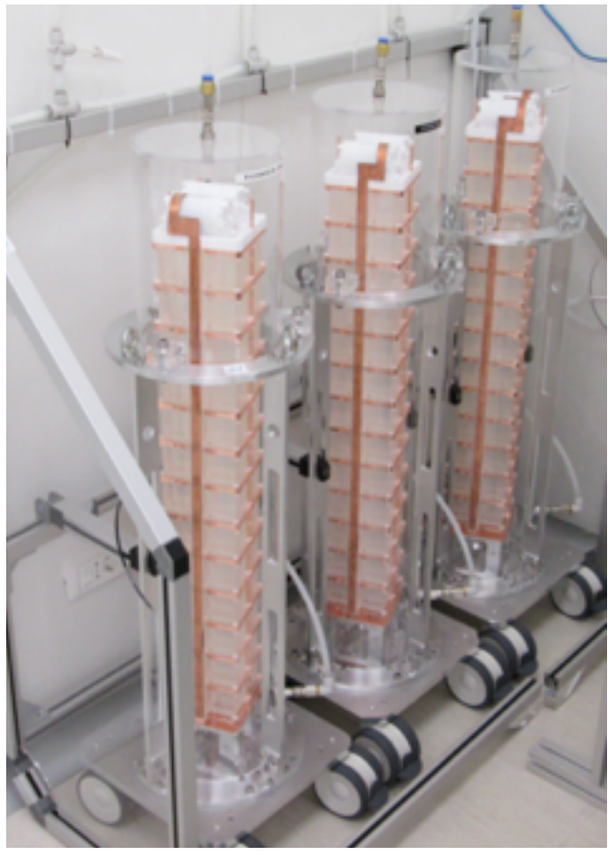




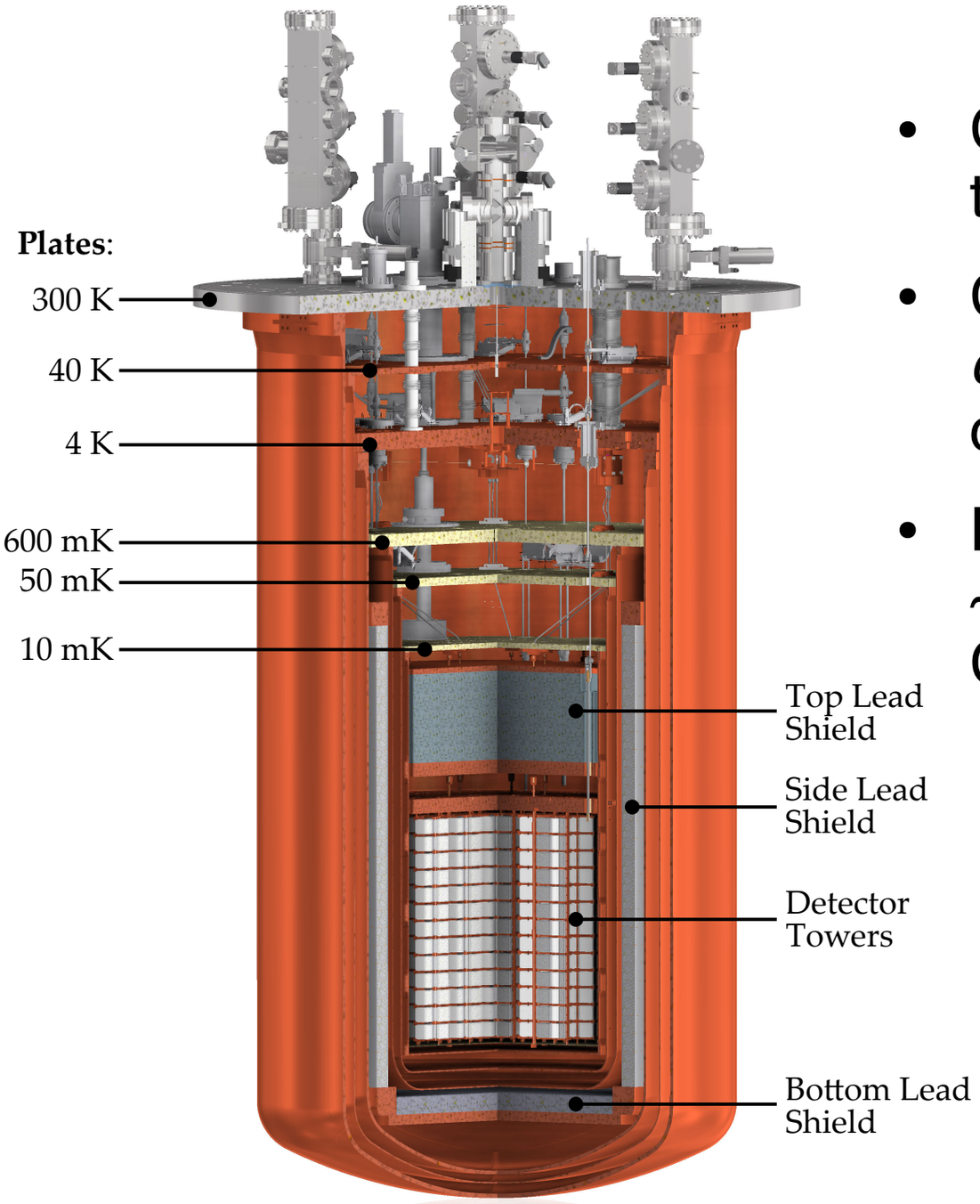




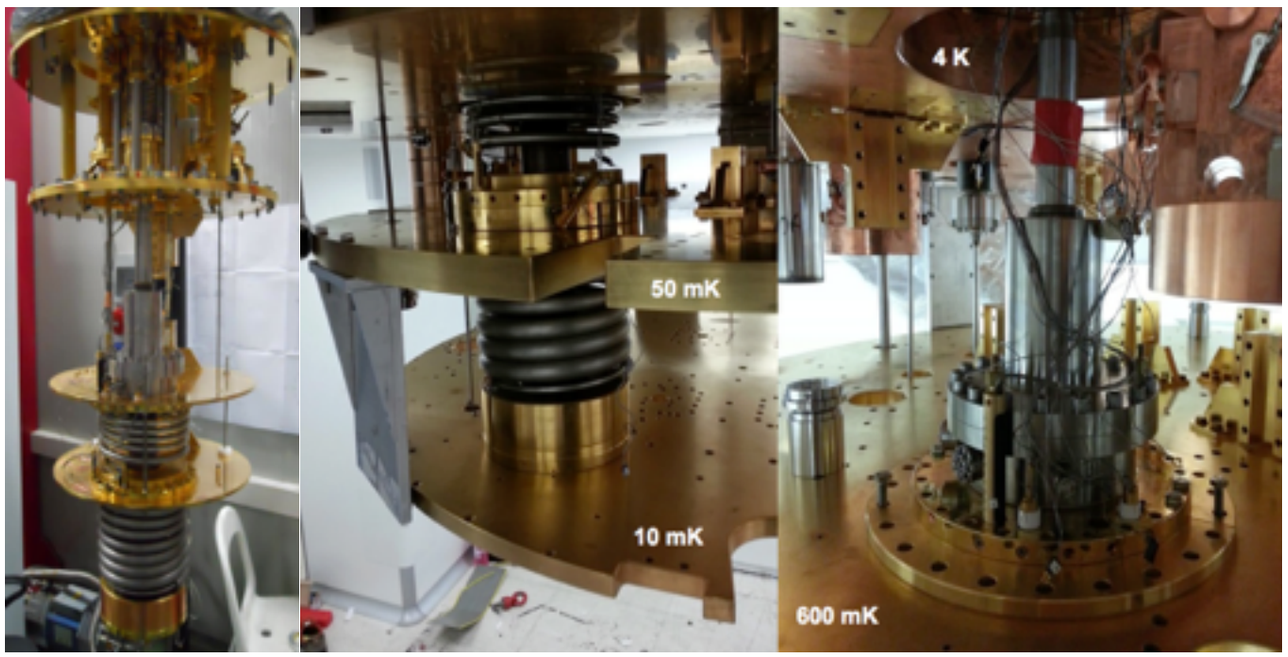
All 19 Towers Assembled



Overview of CUORE Cryogenic System



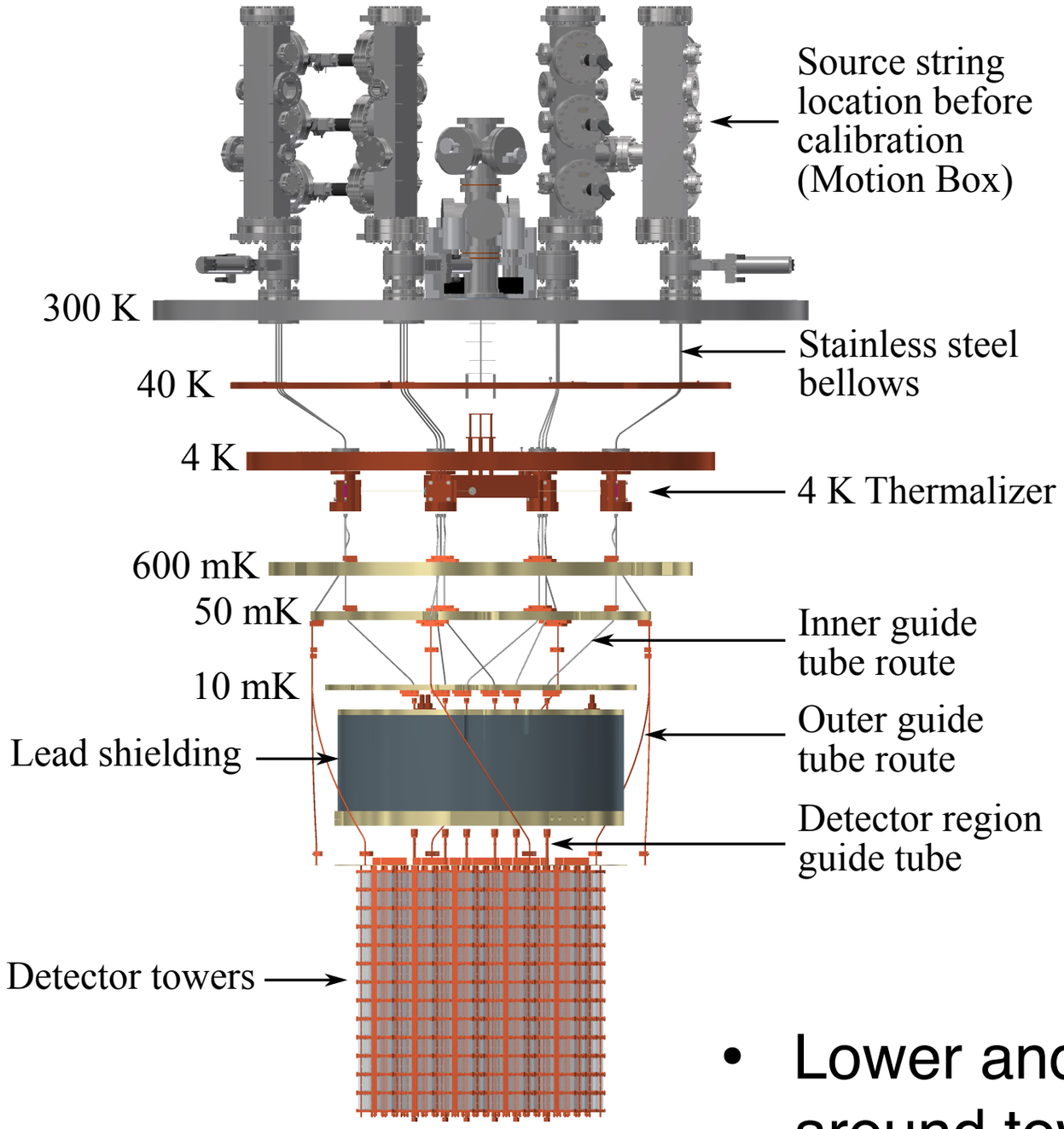
- Cooling to 4K by 5 cryomech PT415 pulse tubes (avoids liquid cryogen refills)
- Cooling (~15 tons!) to 4K accelerated by f*ast cooling system* — forced convection of pre-cooled He gas
- Dilution refrigerator cools detector stage to ~10 mK operating temp (modified DRS-CF3000 from Leiden Cryogenics)



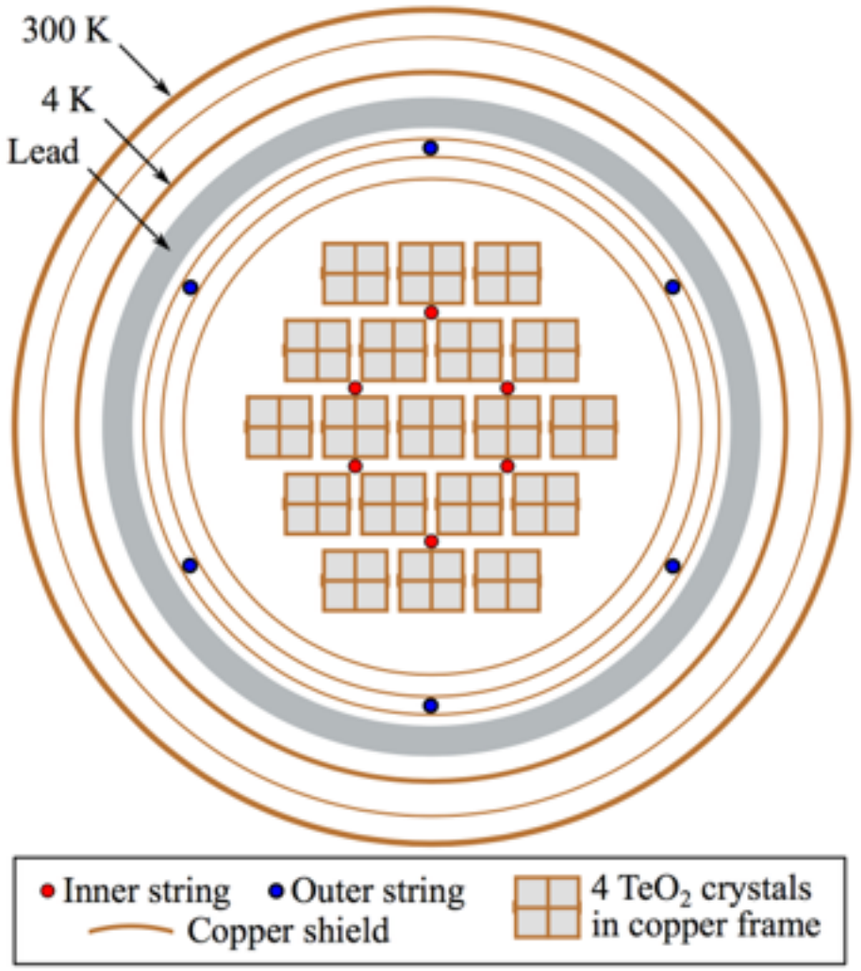
Journal of Low Temperature Physics 184, 590-596 (2016

Nuclear Instruments and Methods A 727, 65-72 (2013)

Overview of CUORE Calibration System

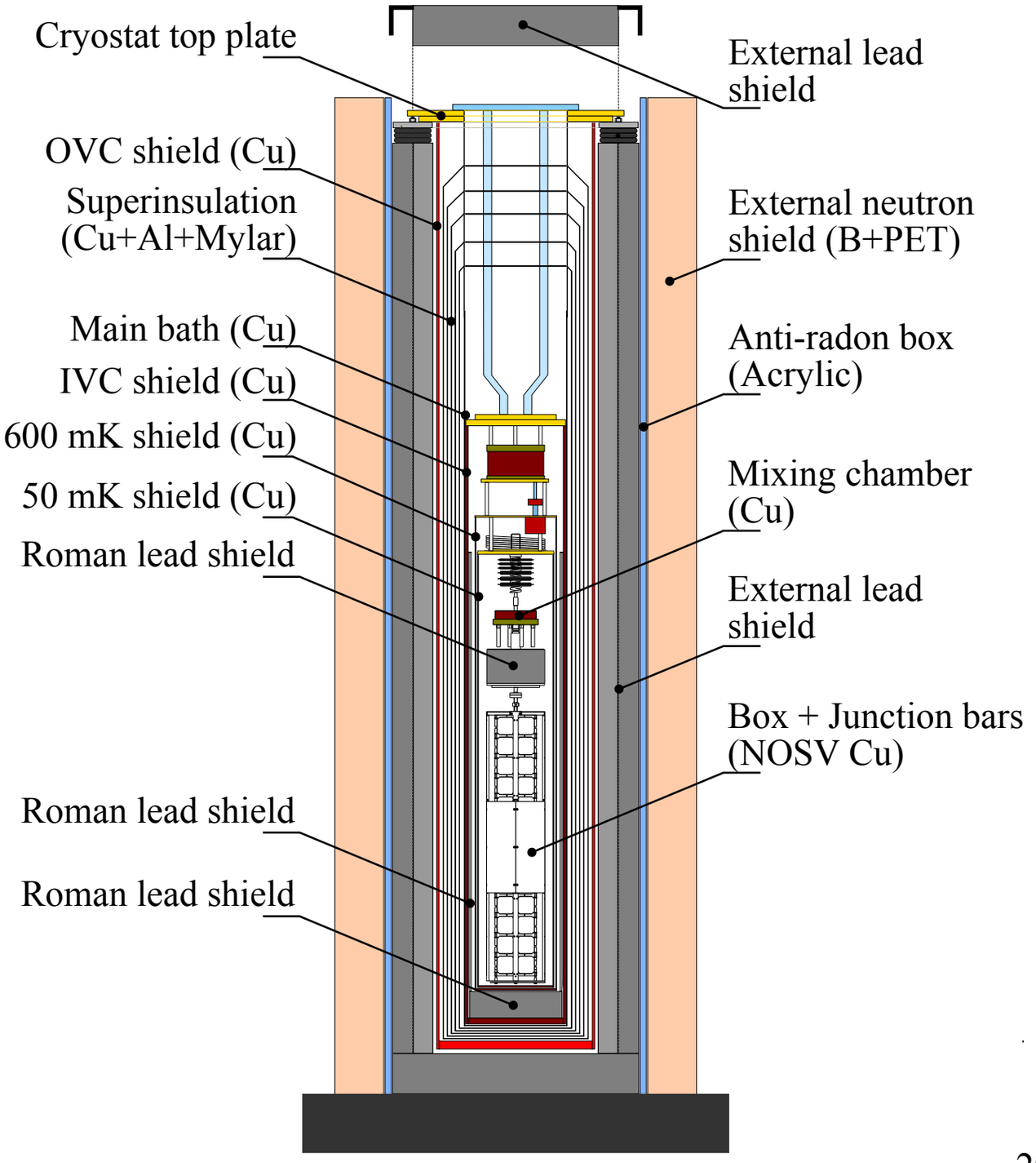


https://arxiv.org/abs/1608.01607



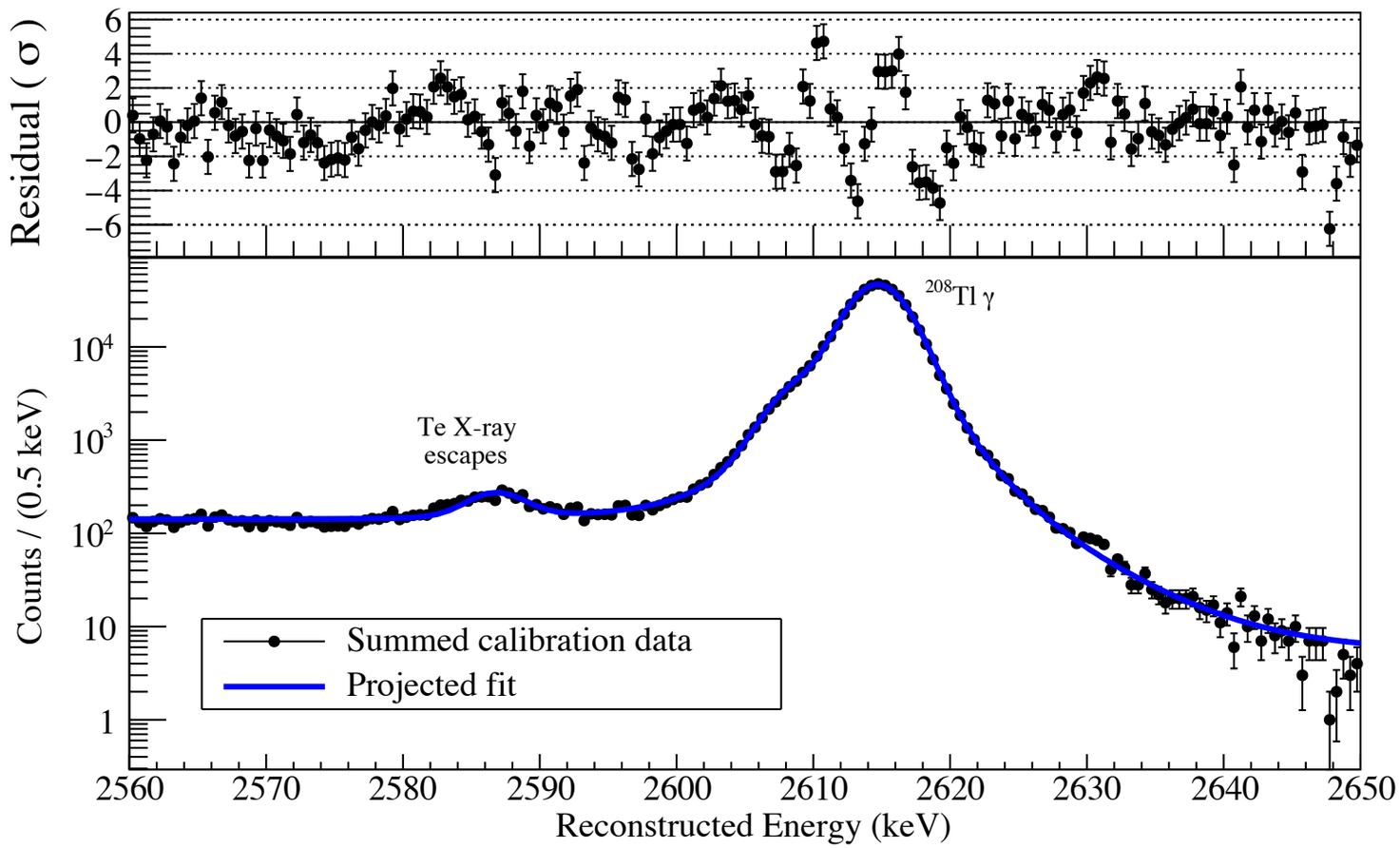
- Lower and retract calibration sources in and around tower array to uniformly “illuminate” the detectors as needed

CUORE-O



- First CUORE-like tower produced in the assembly facility
- Ran in the old CUORICINO cryostat at LNGS
- Shielding from CUORICINO
- Electronics from CUORICINO
- Operated from Mar 2013~Mar 2015
- 20 ~month-long datasets, ~1000 bolometer-datasets

CUORE-0: Energy Resolution



Calibration Data

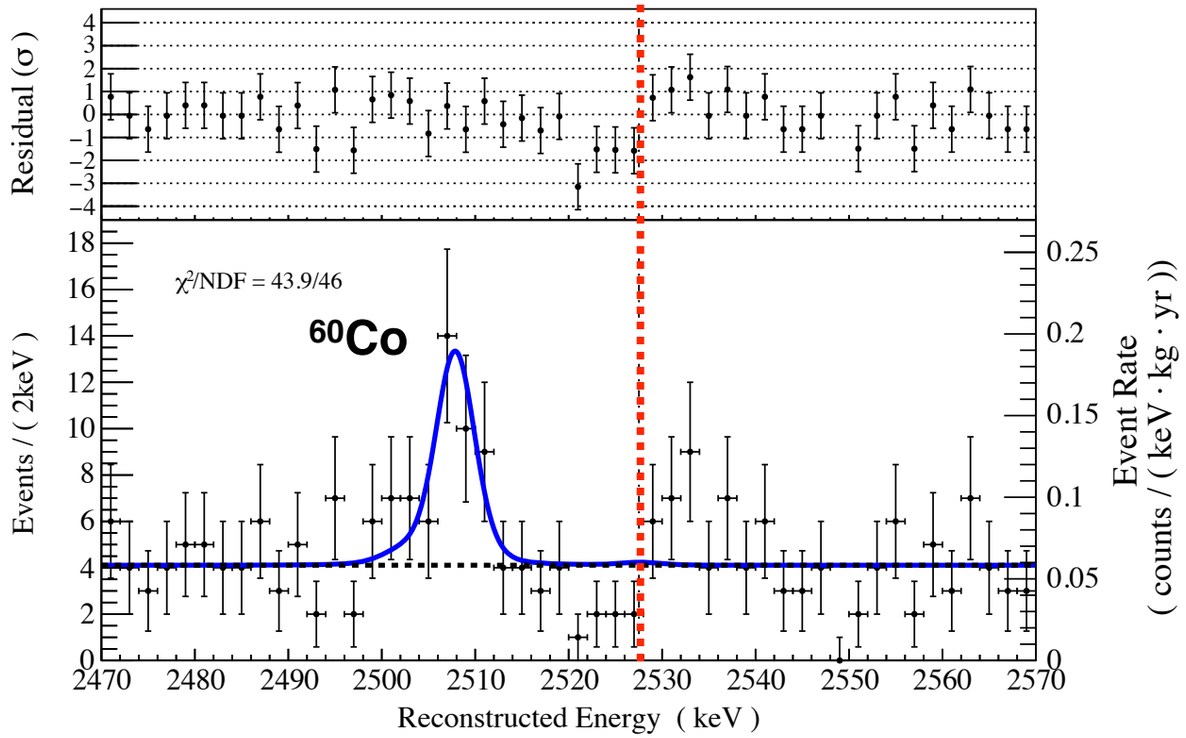
- Exposure weighted sum of the detector response function for each bolometer-dataset overlaid 2615 keV calibration data

- Characteristic energy resolution: we define as physics exposure weighted harmonic mean of FWHM of 2615 keV line over all bolometer-datasets
  - Calibration data: 4.9 keV
  - Background data: 5.1± 0.3 keV
- RMS of FWHM values is 2.9 keV

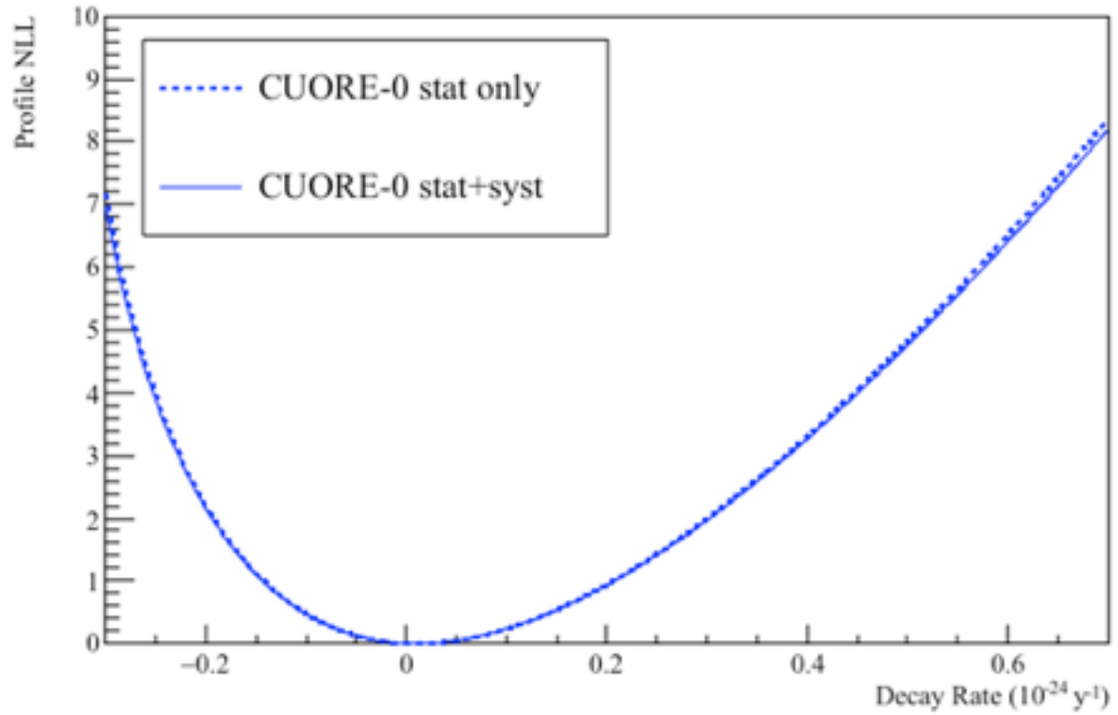
Sensitivity

$$\sim \frac{M \cdot t}{\sigma}$$

CUORE-0: 0νββ Search



$Q_{\beta\beta}$ @ 2527.5 keV



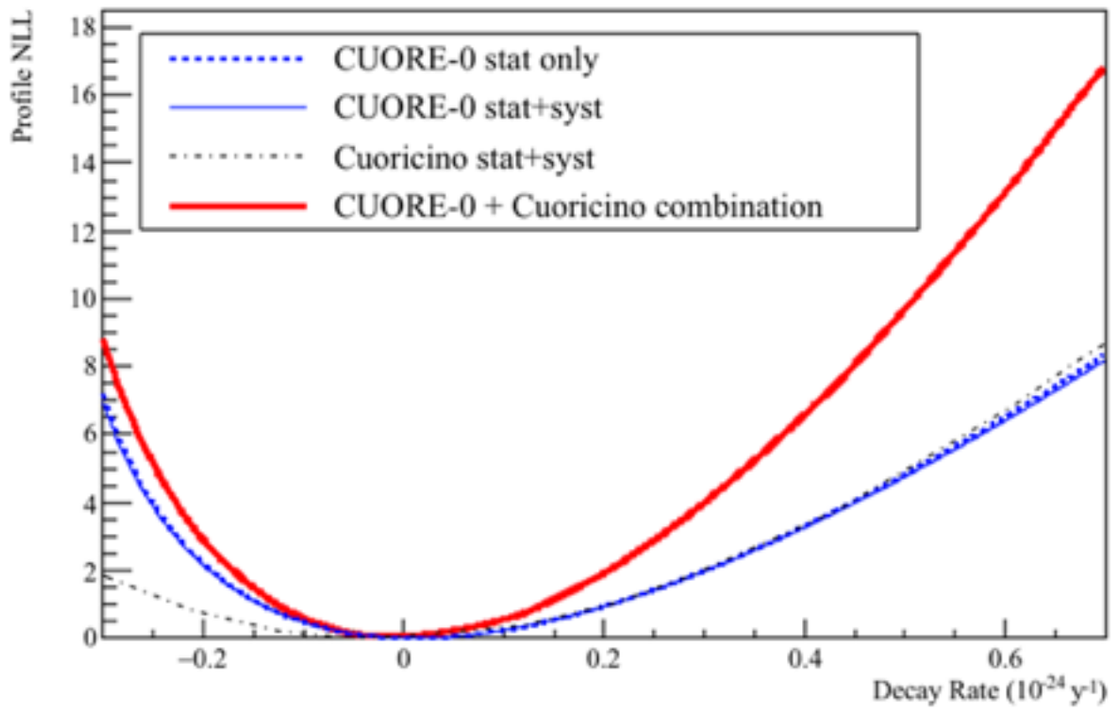
- 233 events in 9.8 kg × yr exposure of ^{130}Te in ROI [2470-2570 keV]

$\Gamma_{0\nu}$	$0\nu\beta\beta$ decay rate	$0.01 \pm 0.12\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \times 10^{-24}\ \text{yr}^{-1}$
Γ_B	Background rate	$0.058 \pm 0.004\,(\text{stat.}) \pm 0.002\,(\text{syst.})\ \text{counts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$

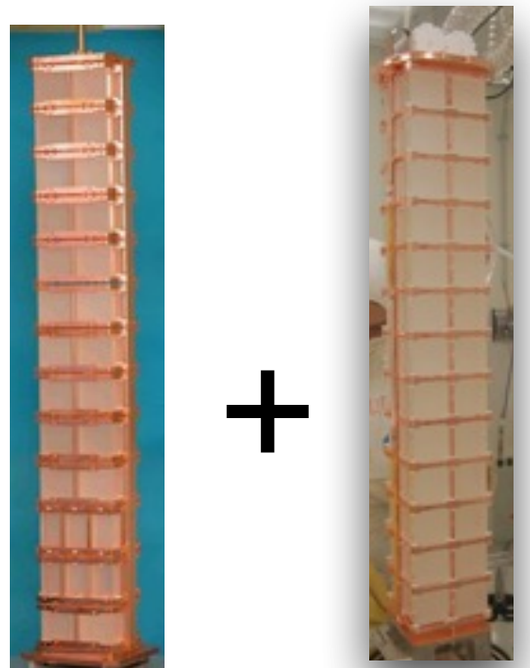
➡ Bayesian lower limit

$$T_{1/2}^{0\nu} > 2.7 \times 10^{24}\ \text{yr} \qquad 90\%\ \text{C.L.}$$

0νββ Search: CUORE-0 + CUORICINO



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



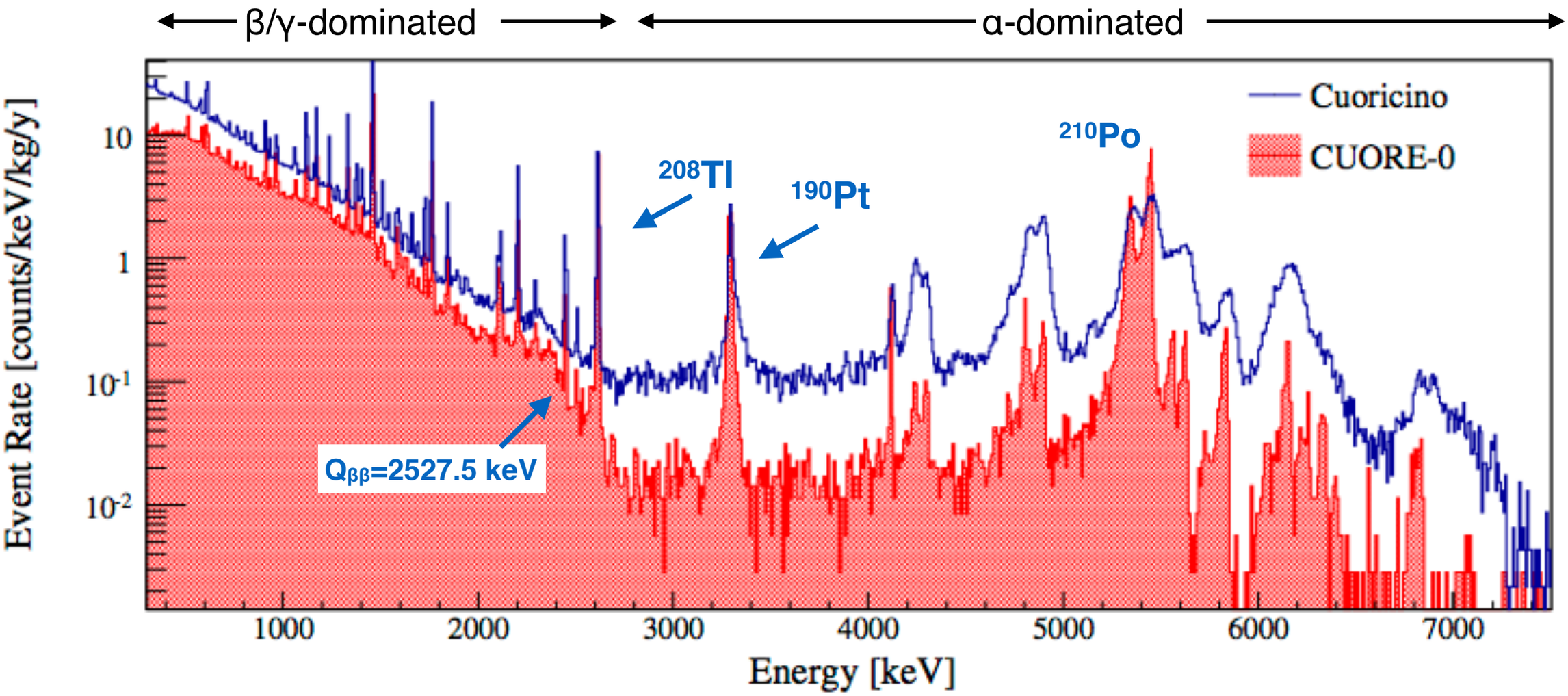
$$T^{0\nu}_{1/2} > 4.0 \times 10^{24}\ \text{yr} \quad \text{(90 \% CL)}$$

$$\langle m_{\beta\beta} \rangle < 270 - 760\ \text{meV}$$

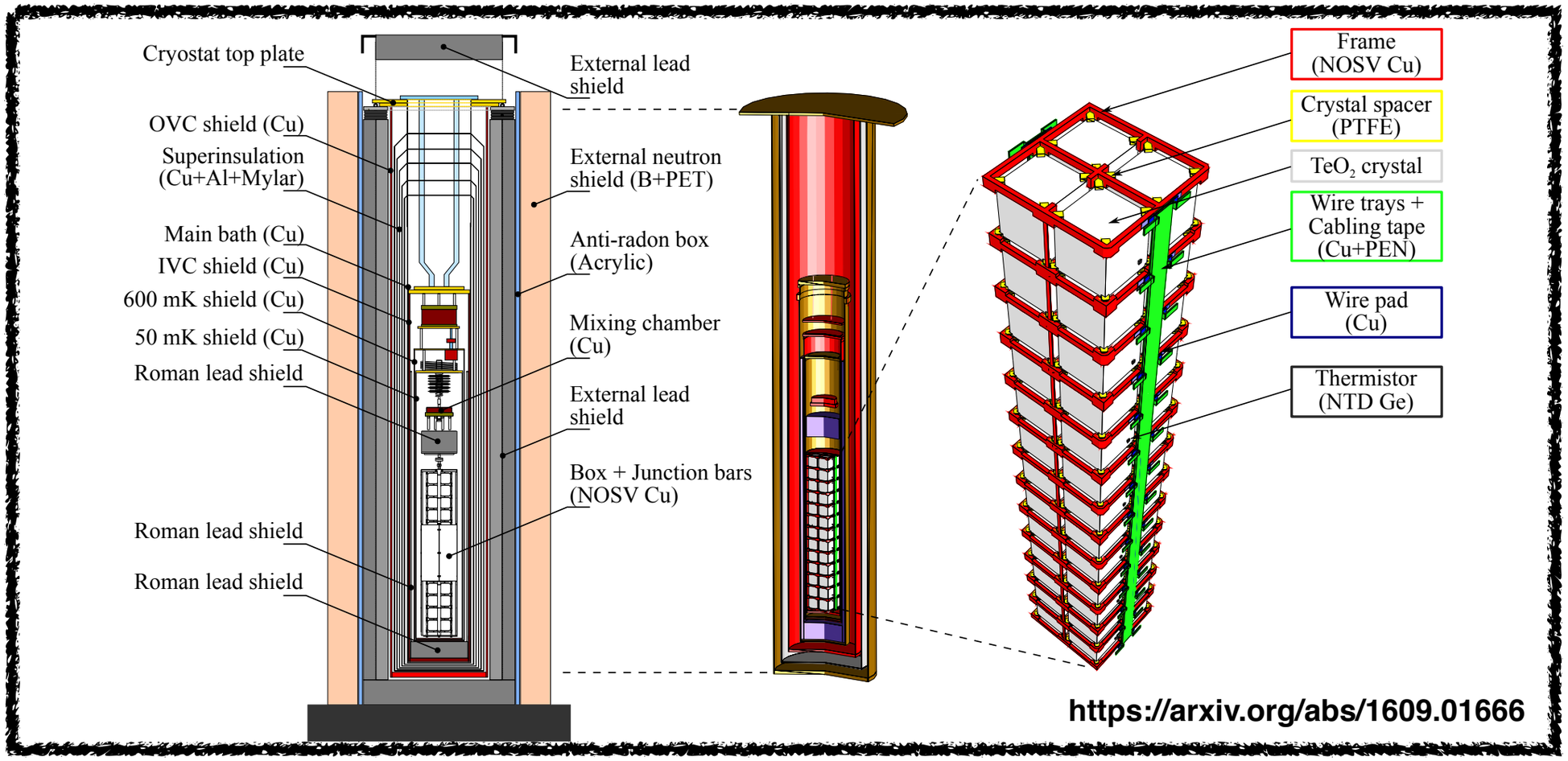
1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

	Cuoricino	CUORE-0
Exposure (kgxyr)	19.75	9.8
Background index (c/keV/kg/y)	0.169 +/-0.006	0.058 +/- 0.004
Characteristic FWHM Energy resolution (keV)	6.3	5.1

CUORE-0: 2νββ Decay + Background model



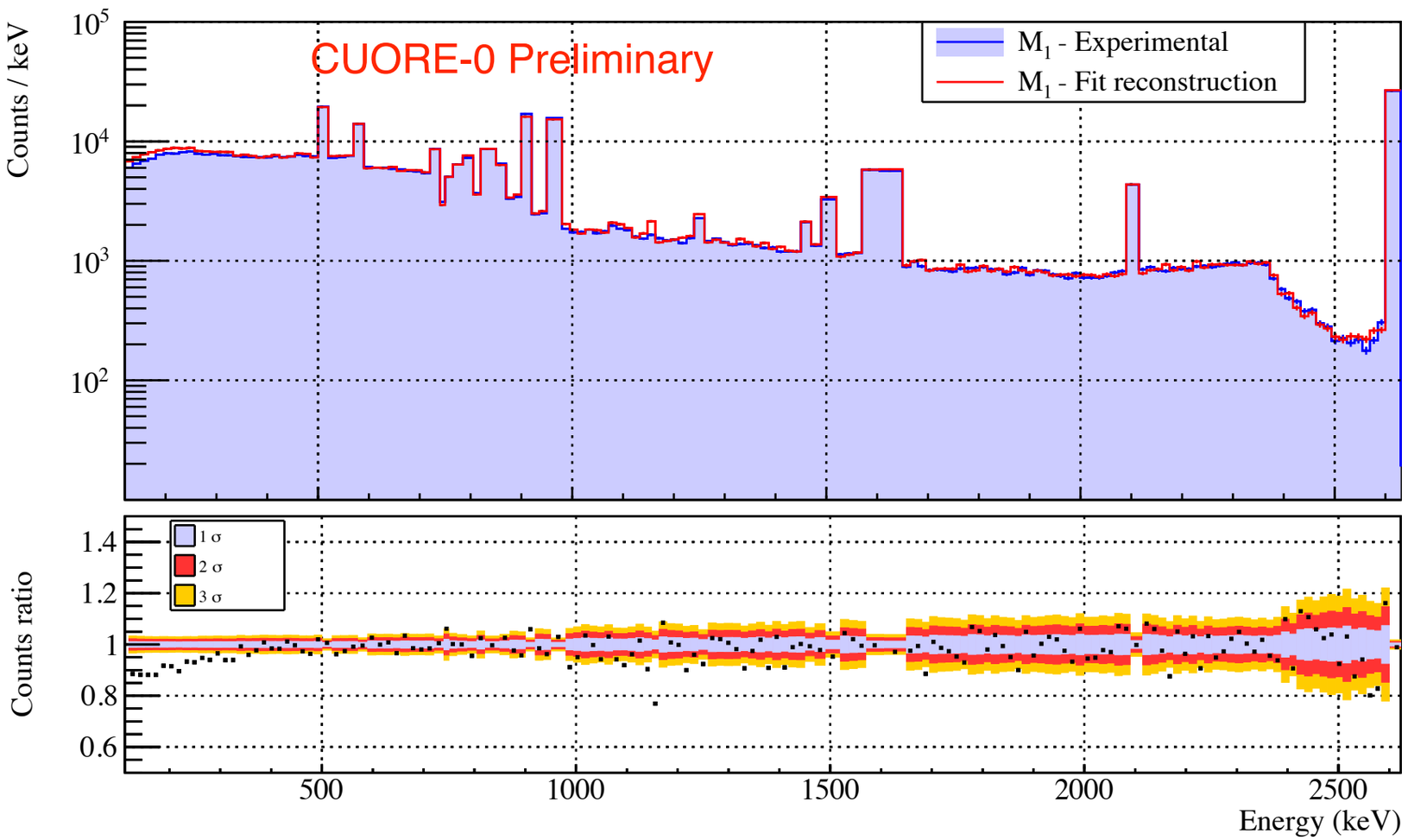
- Measurement of the 2νββ half-live requires detailed background model
- Immediately clear that surface alpha background is significantly reduced relative to earlier experiment CUORICINO



- Detailed GEANT4-based simulation implemented to model the detector
- Background model constrained by:
  - Prior radio-assay measurements on materials
  - Cosmogenic activation data on materials and data on environmental muons, gammas and neutrons at LNGS
  - Gamma and alpha lines in the CUORE-0 spectrum
  - Coincidence analysis between CUORE-0 crystals

Comparison of simulation and calibration data

Energy spectrum for single-crystal events



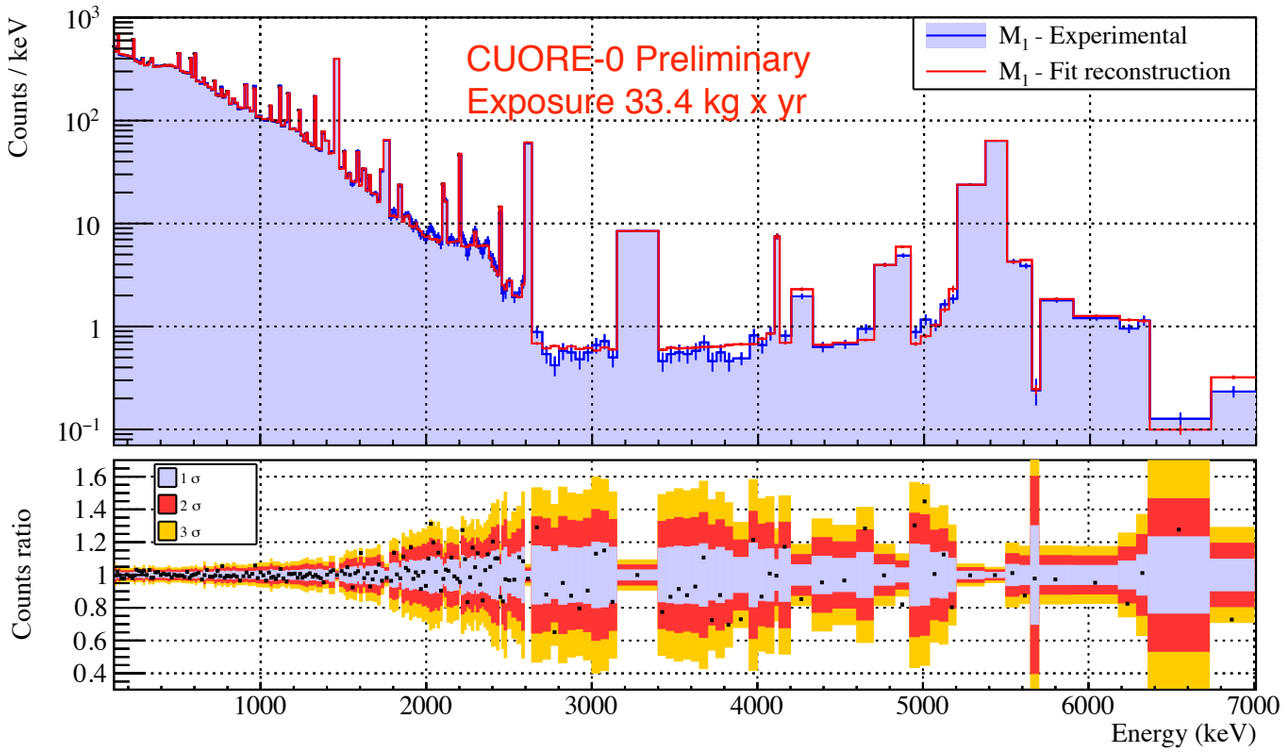
Data

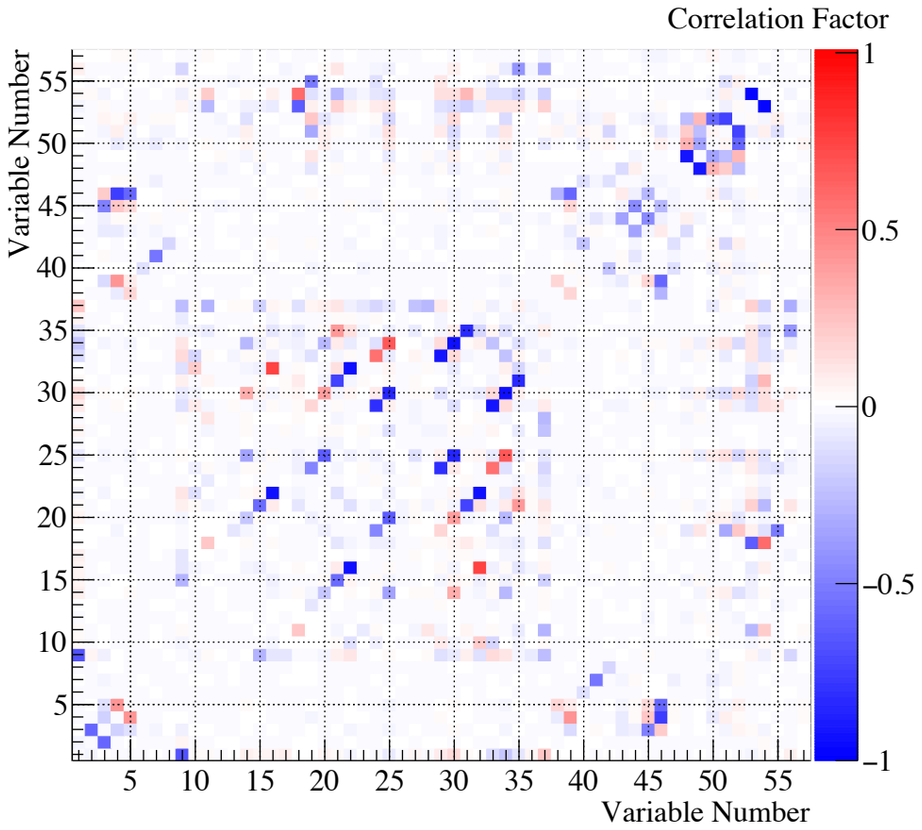
MC Fit

Residuals

https://arxiv.org/abs/1609.01666

Fit of background model + 2νββ decay



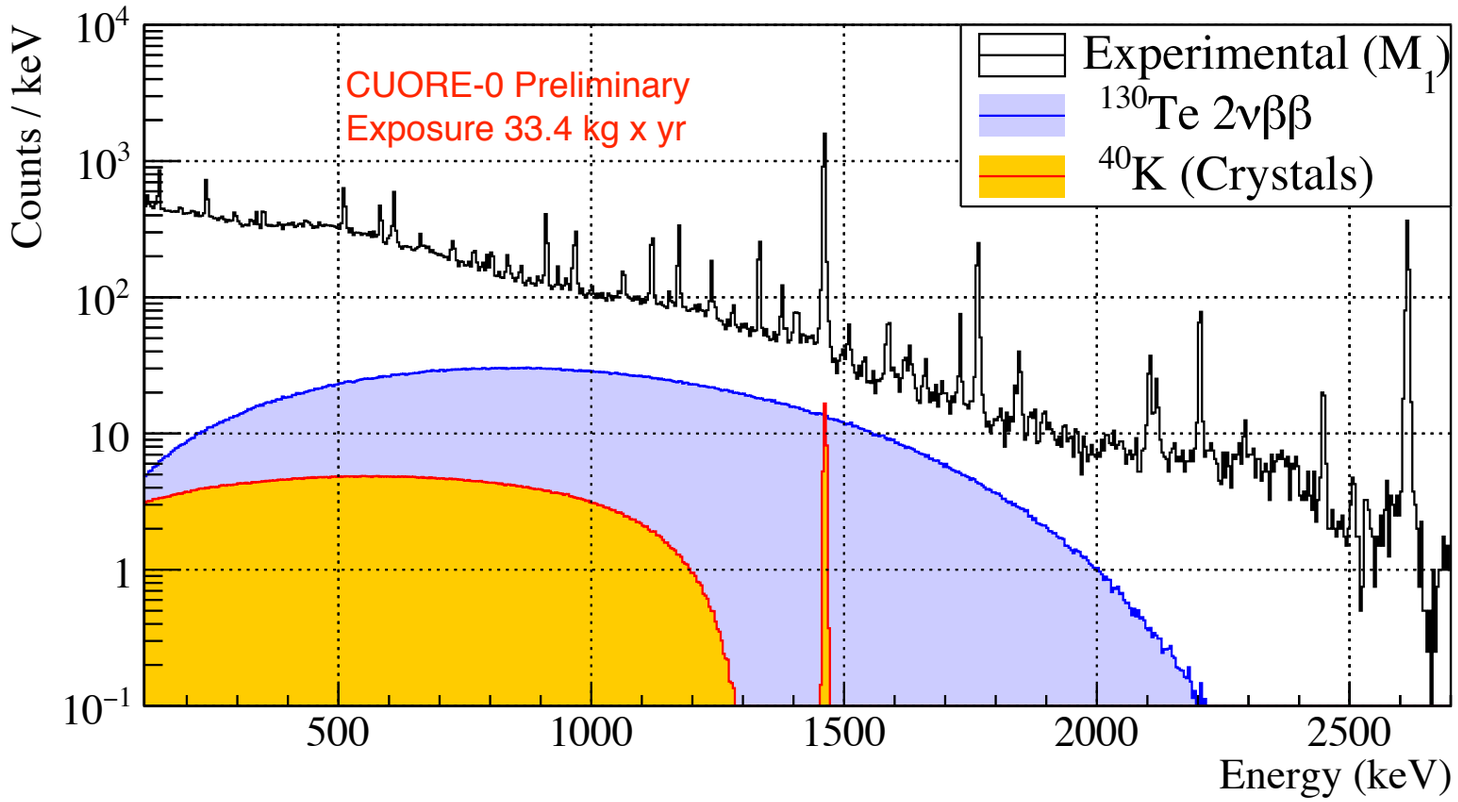


Detailed Model

Component	Index	Bulk sources
Crystals	1	^{130}Te – $2\nu\beta\beta$
	2	^{210}Po
	3	^{210}Pb
	4	^{232}Th (only)
	5	^{228}Ra – ^{208}Pb
	6	^{238}U – ^{230}Th
	7	^{230}Th(only)
	8	^{226}Ra – ^{210}Pb
	9	^{40}K
	10	^{60}Co
	11	^{125}Sb
	12	^{190}Pt
Holder	13	^{232}Th
	14	^{238}U
	15	^{40}K
	16	^{60}Co
	...	
	...	

Component		Surface sources
Crystals	38	^{232}Th (only) – 0.01 μm
	39	^{228}Ra – ^{208}Pb – 0.01 μm
	40	^{238}U – ^{230}Th – 0.01 μm
	41	^{230}Th (only) – 0.01 μm
	42	^{226}Ra – ^{210}Pb – 0.01 μm
	43	^{210}Pb – 0.001 μm
	44	^{210}Pb – 1 μm
	45	^{210}Pb – 10 μm
	46	^{232}Th – 10 μm
	47	^{238}U – 10 μm
Holder	48	^{210}Pb – 0.01 μm
	49	^{210}Pb – 0.1 μm
	50	^{210}Pb – 10 μm
	51	^{232}Th – 10 μm
	52	^{238}U – 10 μm
CryoInt	53	^{210}Pb – 0.01 μm
IntPb	54	^{210}Pb – 0.01 μm

Fit of background model + 2vBB decay



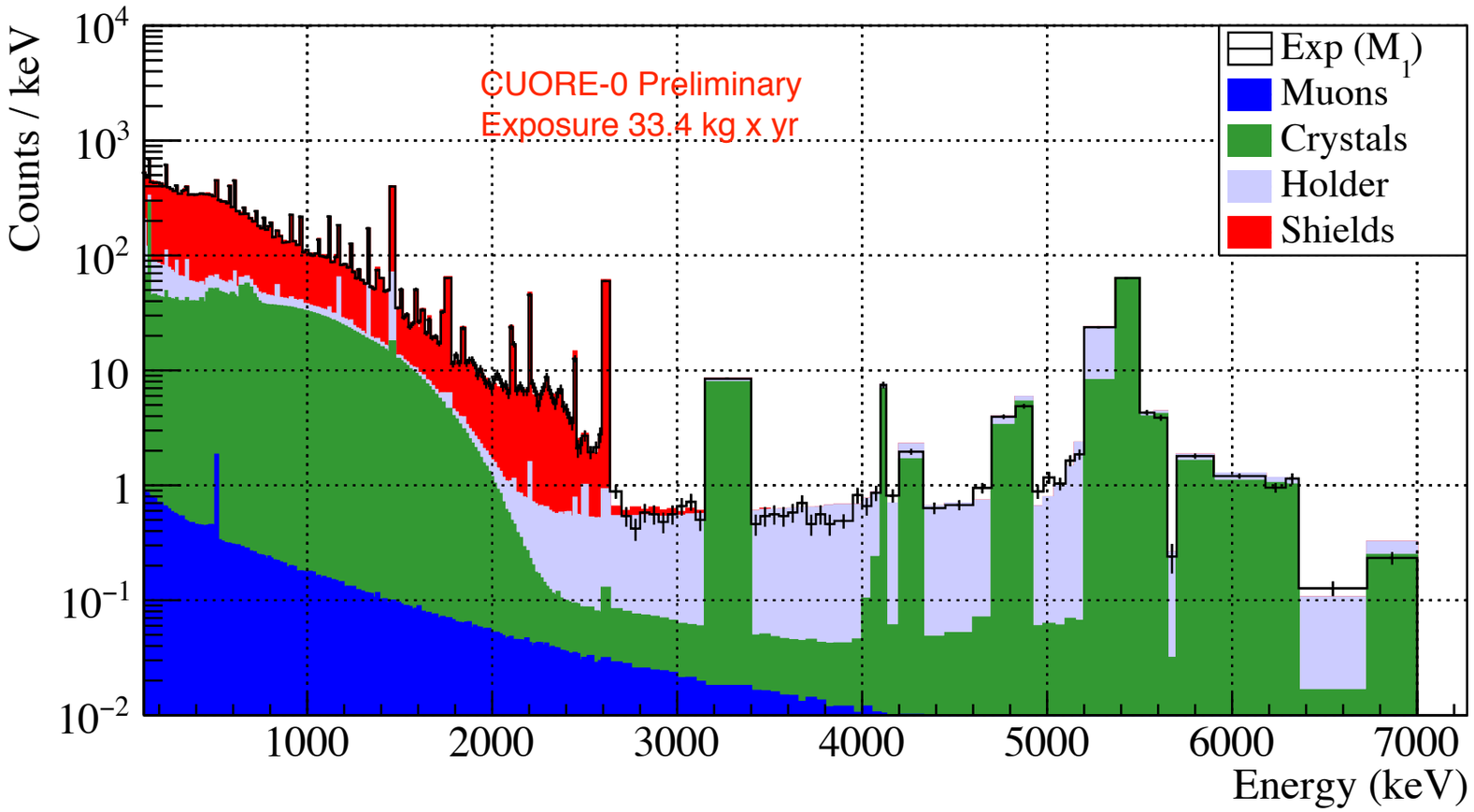
Bulk ^{40}K is most strongly correlated background to the 2νββ measurement

CUORE-0 $T^{2\nu\beta\beta}_{1/2} = 8.2 \pm 0.2\,(\text{stat.}) \pm 0.6(\text{syst.}) \times 10^{20}\,\text{yr}$

NEMO $T^{2\nu\beta\beta}_{1/2} = 7.0 \pm 0.9\,(\text{stat.}) \pm 1.1(\text{syst.}) \times 10^{20}\,\text{yr}$

MIDBD $T^{2\nu\beta\beta}_{1/2} = 6.1 \pm 1.4\,(\text{stat.})\ ^{+2.9}_{-3.5}(\text{syst.}) \times 10^{20}\,\text{yr}$

Background model

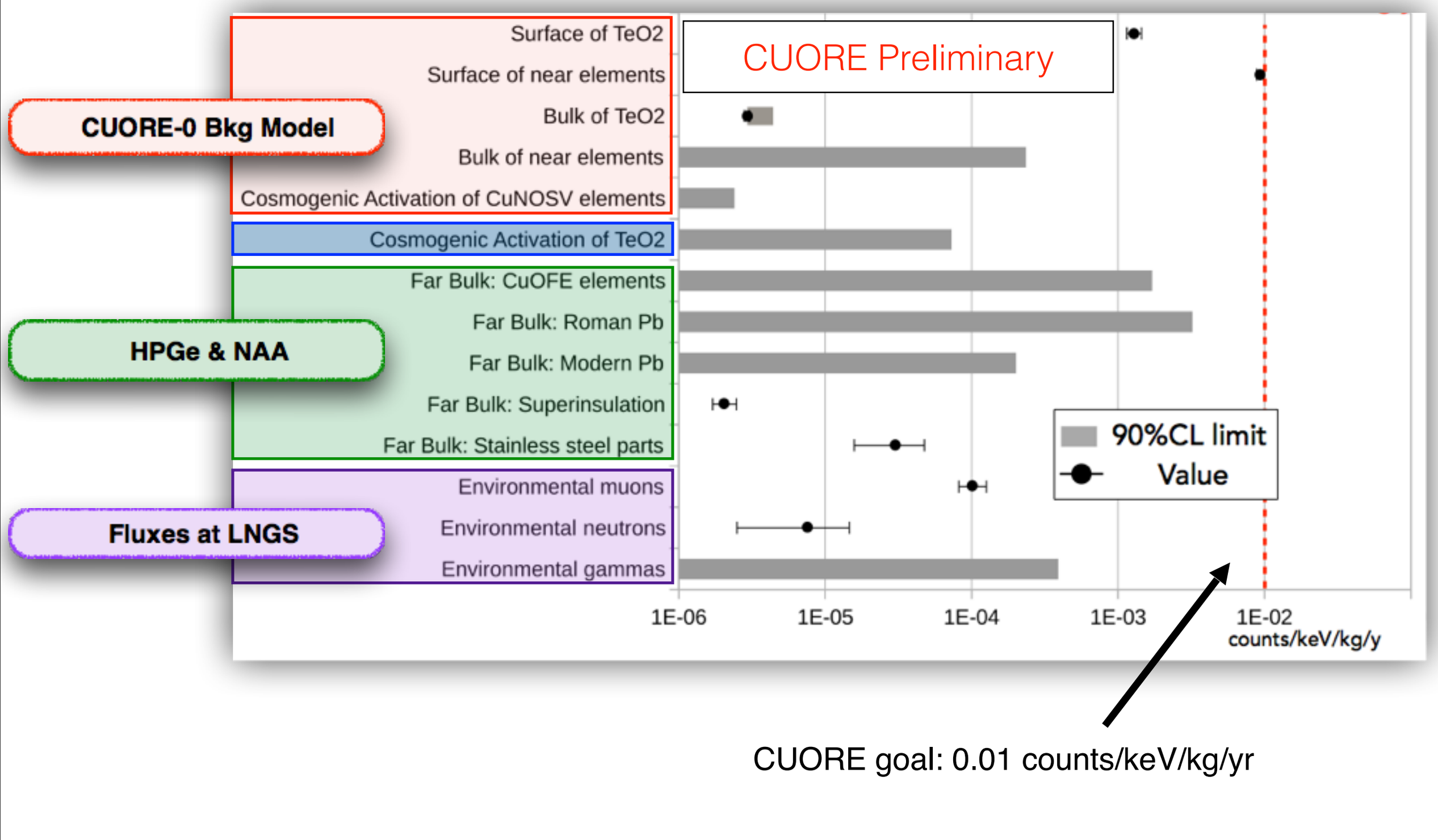


Breakdown of contributions to 0νββ ROI

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

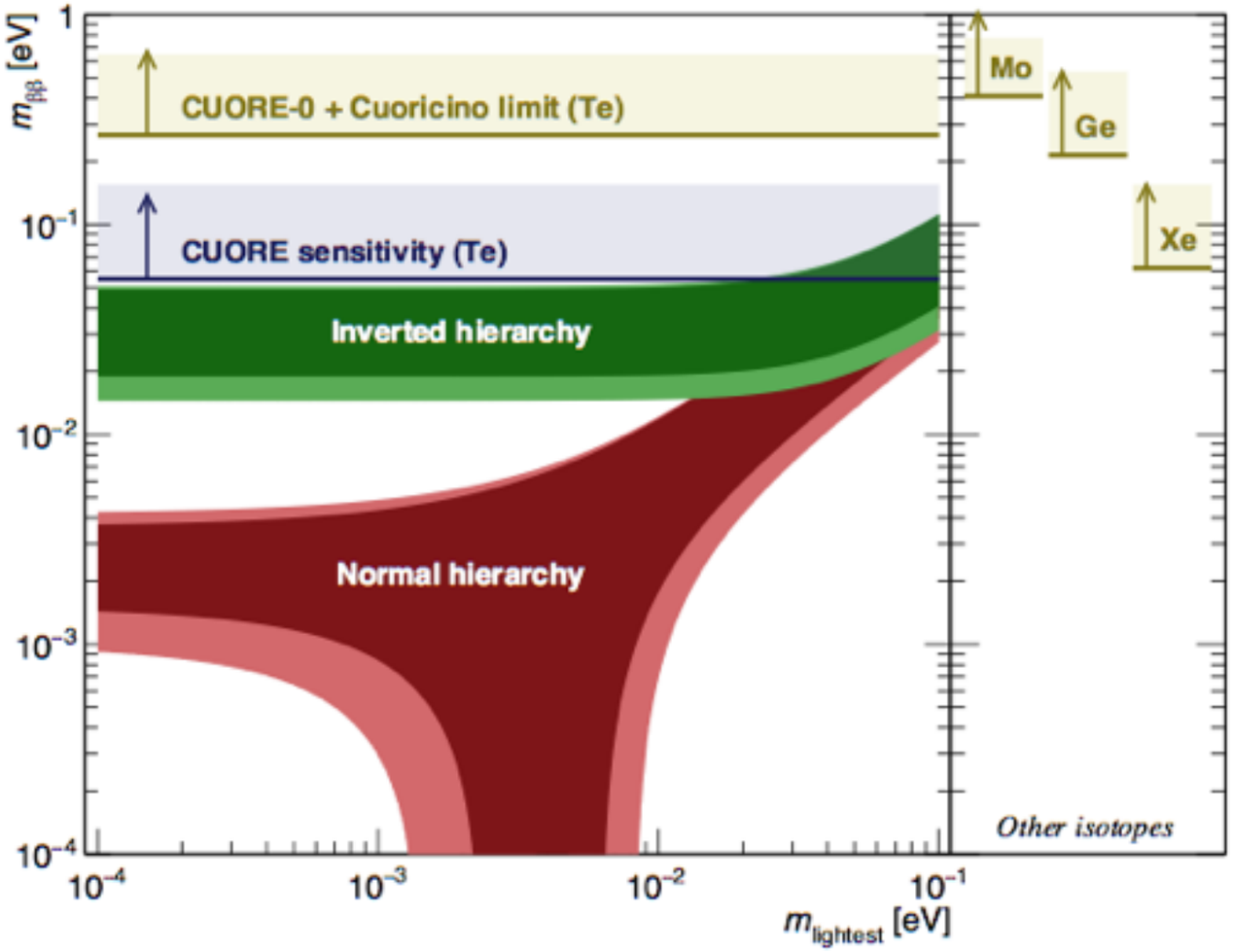
- Shields of CUORE cryostat are significantly more radio-pure than CUORICINO cryostat

CUORE Background Budget



CUORE goal: 0.01 counts/keV/kg/yr

CUORE Expected Sensitivity



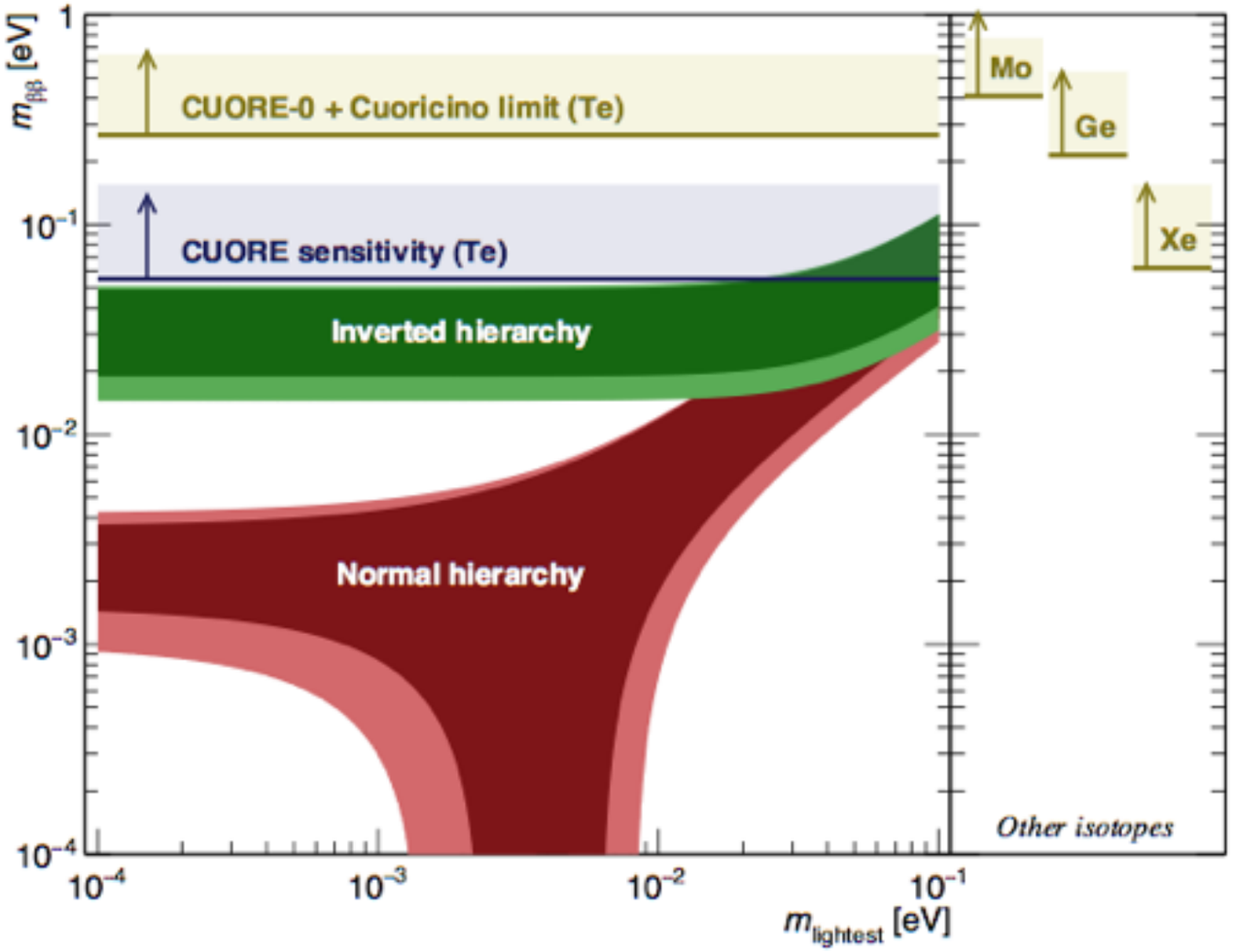
Assumptions:

- 988 bolometers
- 5 years of lifetime
- δE = 5 keV FWHM at 2615 keV
- b = 0.01 counts/(keV · kg · yr)

$$T^{0\nu}_{1/2} > 9.5 \times 10^{25} yr (90\%\text{C.L})$$

$$m_{\beta\beta} < (50 - 130\,\text{meV})$$

CUORE Expected Sensitivity



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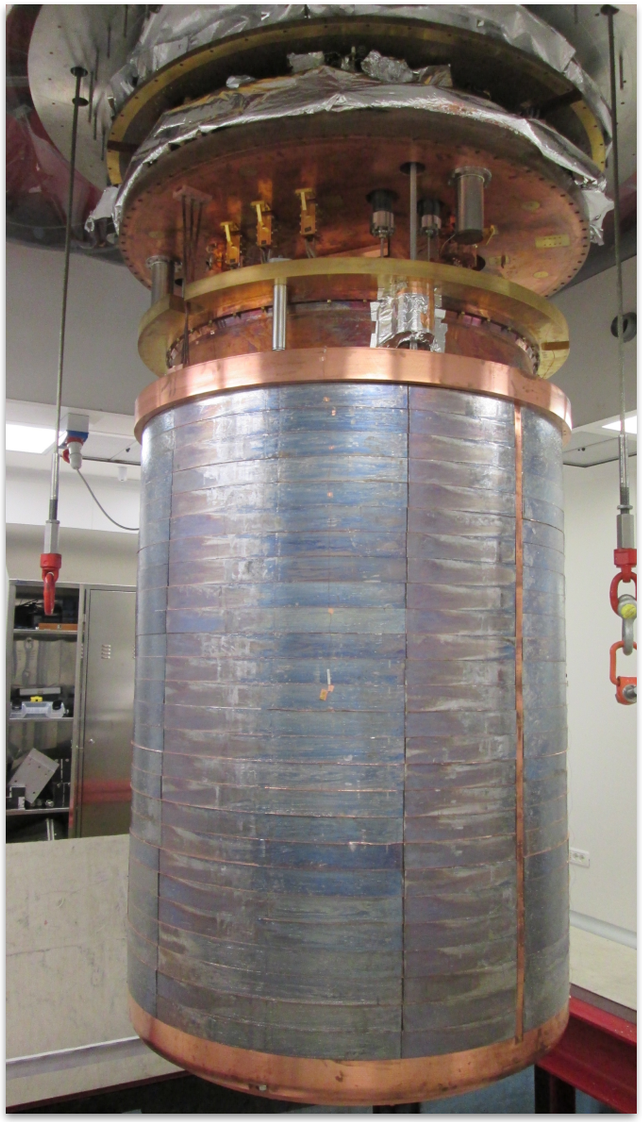
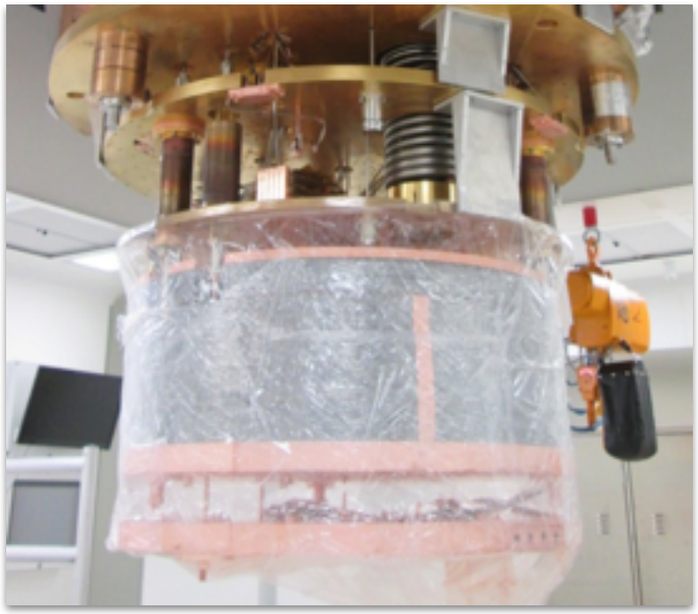
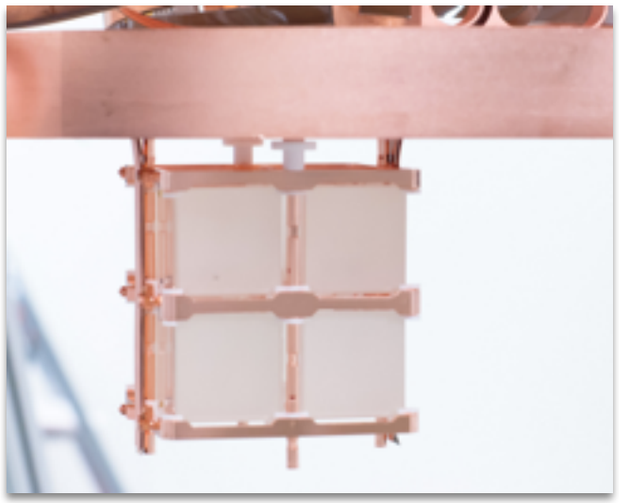
For next generation prospects
See talk of M. Vignati
CUPID @Morning session Nov 9.

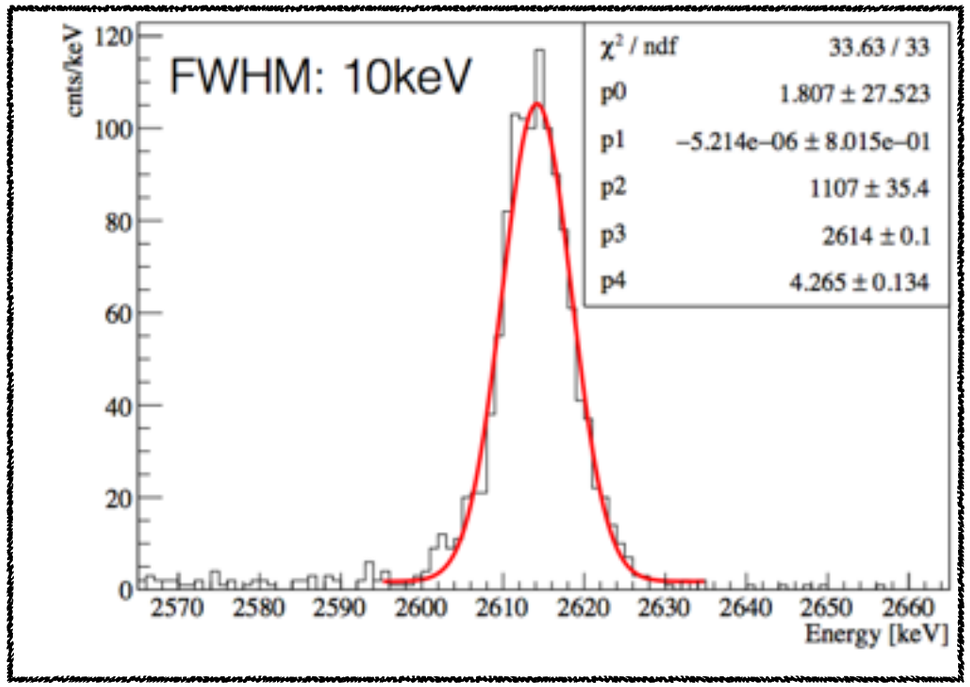
Status of CUORE: Cryogenic System



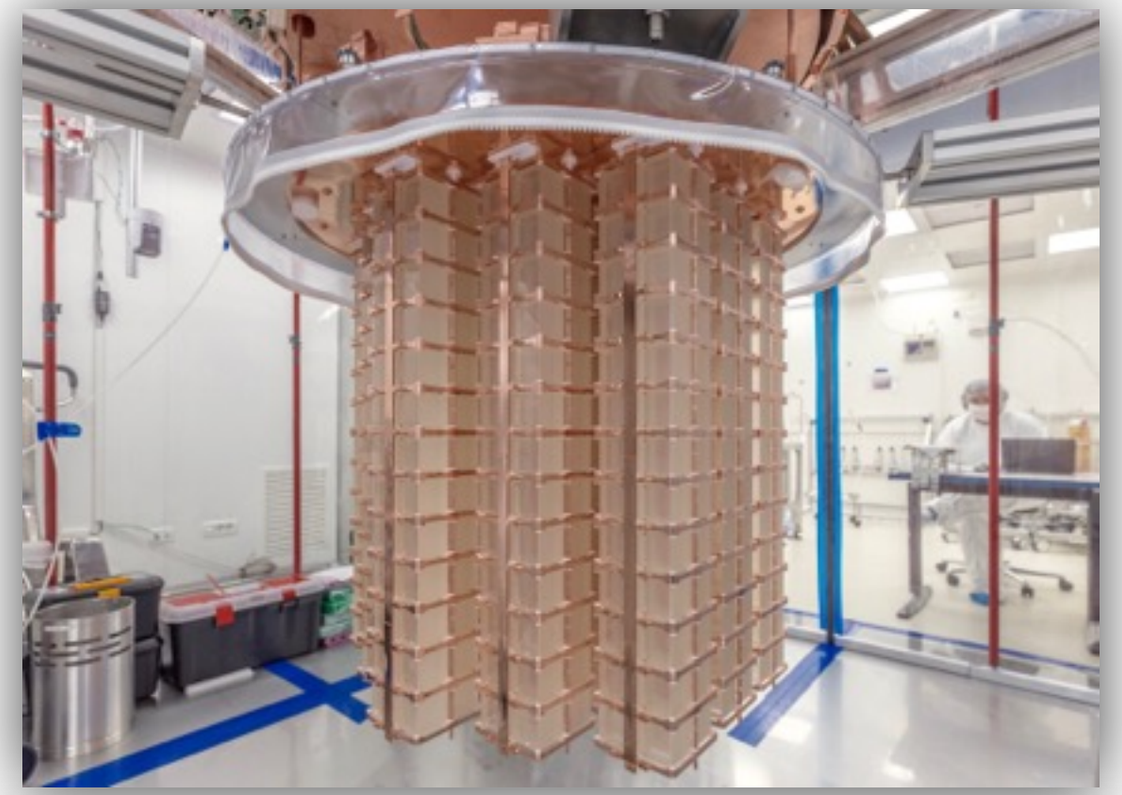


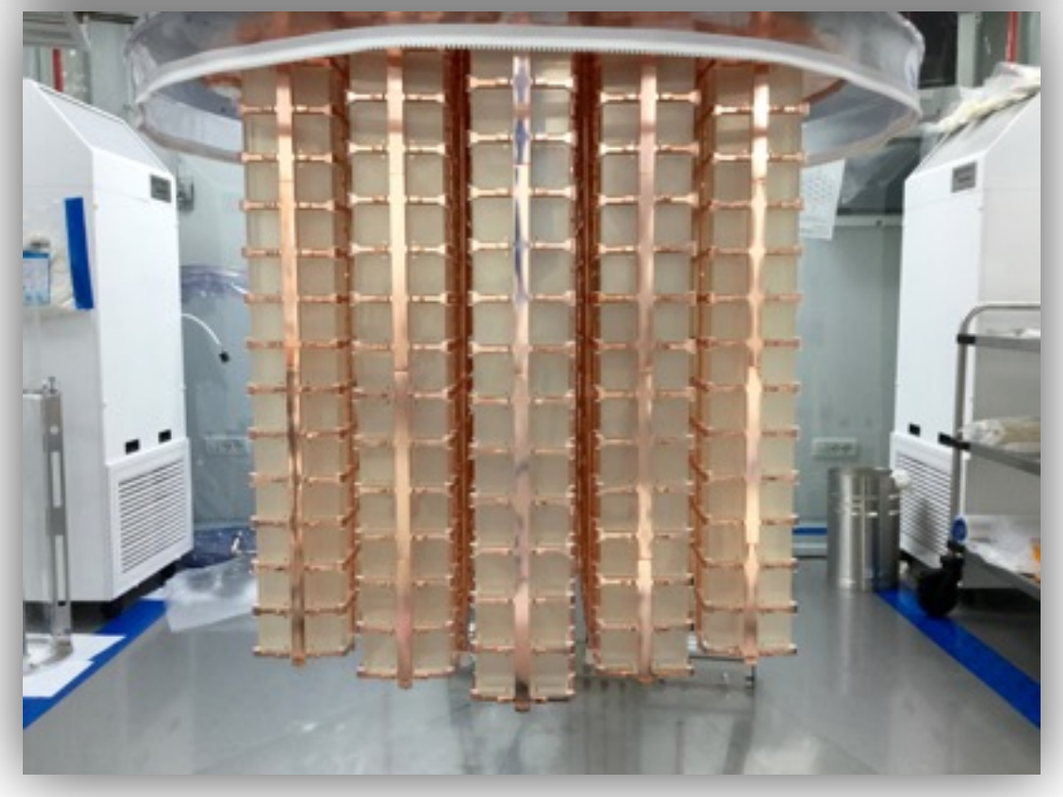


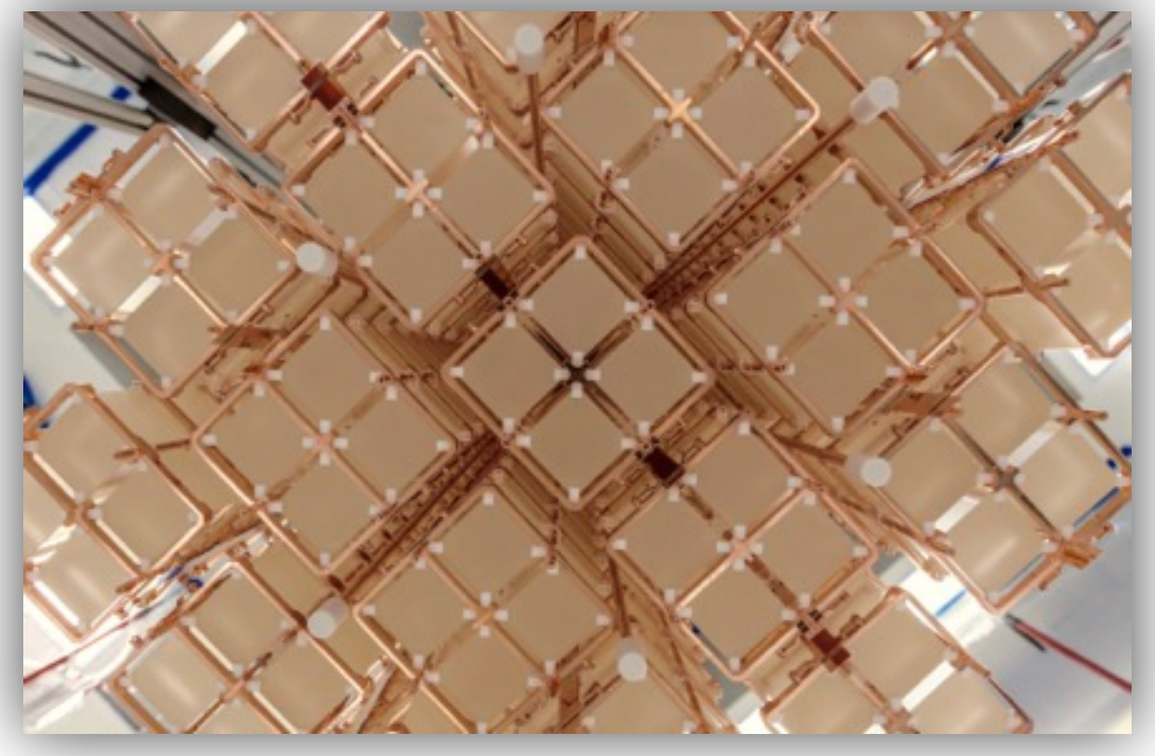
- Commissioning of full cryogenic system completed in Mar 2016, stable base temp of ~ 6.3 mK
- Operated calibration system, mini tower, test of front-end electronics, DAQ



Tower Installation on 10mK stage







Summary

- CUORE-0 combined with CUORICINO provides the most stringent limit on 0νββ decay of ^{130}Te

$$T^{0\nu}_{1/2} > 4.0 \times 10^{24}\ \mathrm{yr} \quad \text{(90\% C.L.)} \qquad \langle m_{\beta\beta} \rangle < 270 - 760\ \mathrm{meV}$$

- CUORE-0 provides the most precise measurement to date of the 2νββ decay half-live ^{130}Te

$$T^{2\nu\beta\beta}_{1/2} = 8.2 \pm 0.2\,(\mathrm{stat.}) \pm 0.6(\mathrm{syst.}) \times 10^{20}\,\mathrm{yr}$$

- CUORE-0 shows CUORE-style bolometers achieve the target energy resolution and data-driven MC shows CUORE background goal is realistic

- Cryogenic commissioning is complete and the detectors have been installed

- Commencement of CUORE operations is imminent

Acknowledgements

The CUORE Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. CUORE is supported by:

- The Istituto Nazionale di Fisica Nucleare (INFN)
- The National Science Foundation under Grant Nos. NSF-PHY-0605119, NSF-PHY-0500337, NSF-PHY-0855314, NSF-PHY-0902171, NSF-PHY-0969852, NSF-PHY-1307204, NSF-PHY-1314881, NSF-PHY-1401832, and NSF-PHY-1404205
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- The University of Wisconsin Foundation
- Yale University
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- The DOE Office of Science, Office of Nuclear Physics under Contract Nos. DE-FG02-08ER41551 and DE-FG03-00ER41138
- The National Energy Research Scientific Computing Center (NERSC)

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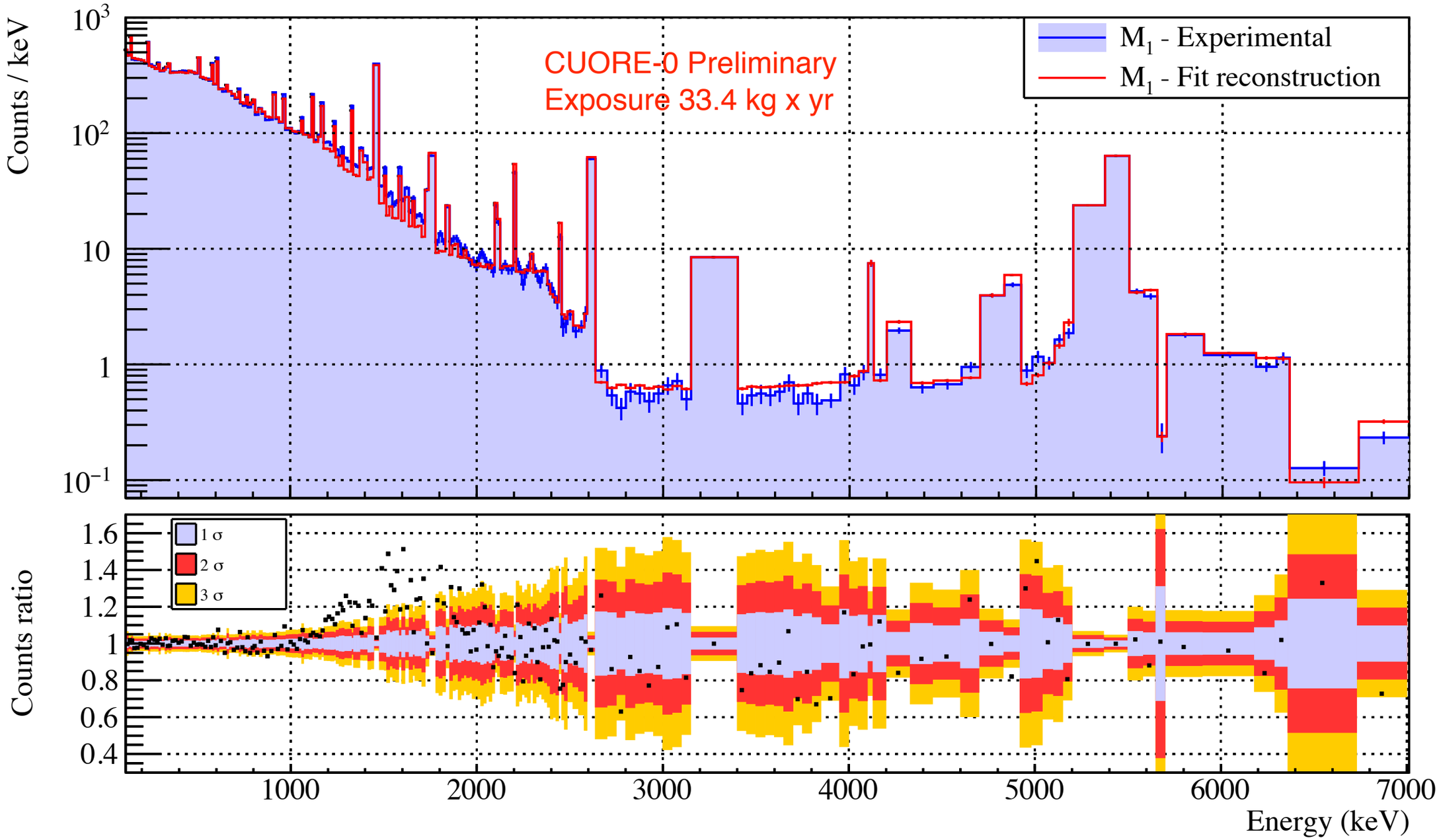
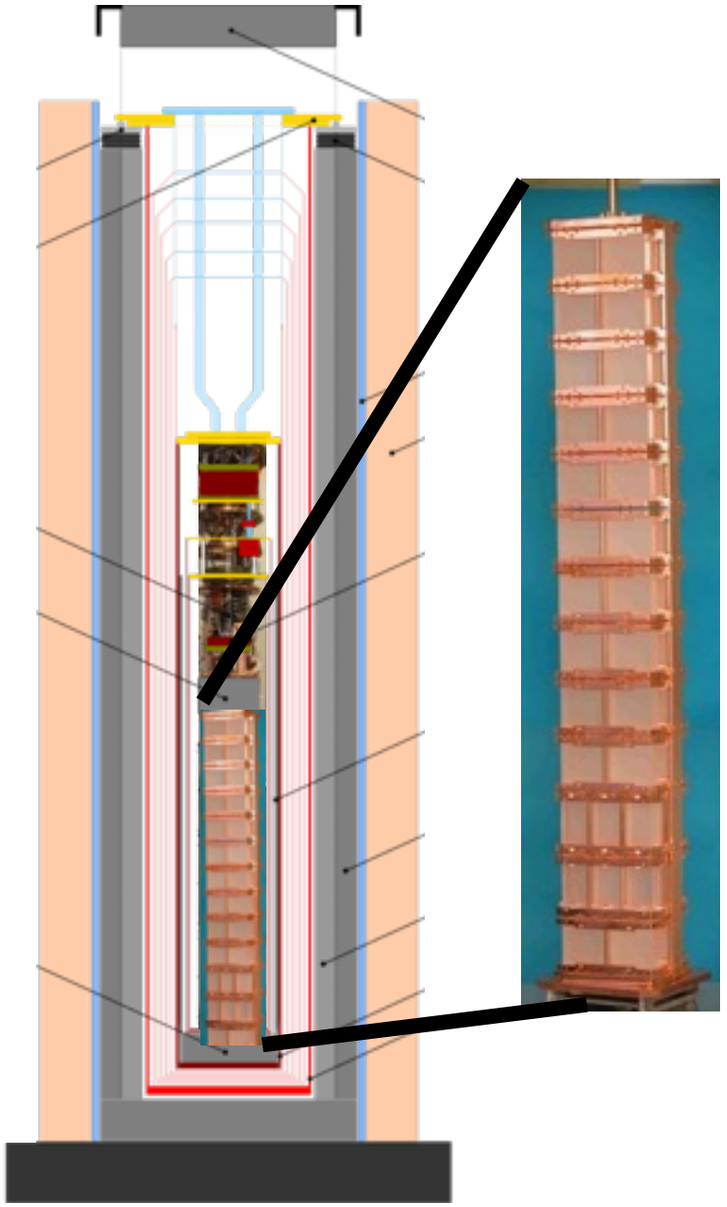
Fit of background model **without 2νββ** decay



CUORICINO (2003 - 2008)

- 62 crystal TeO_2 bolometer array operated at Gran Sasso Lab, Italy

- ^{130}Te isotopic abundance: ~34%
- ^{130}Te Q-value: 2527.5 keV



- Final results

$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\,\mathrm{yr} \quad (90\%\ \mathrm{C.L})$$
$$\langle m_{\beta\beta} \rangle < 0.3 - 0.7\,\mathrm{eV}$$

  - M.t (^{130}Te): 19.75 kg.yr
  - dE: 6.3 +/- 2.5 keV FWHM (mean +/- RMS)
  - b: 0.169 +/- 0.006 c/keV/kg/yr

Final Spectrum of CUORICINO