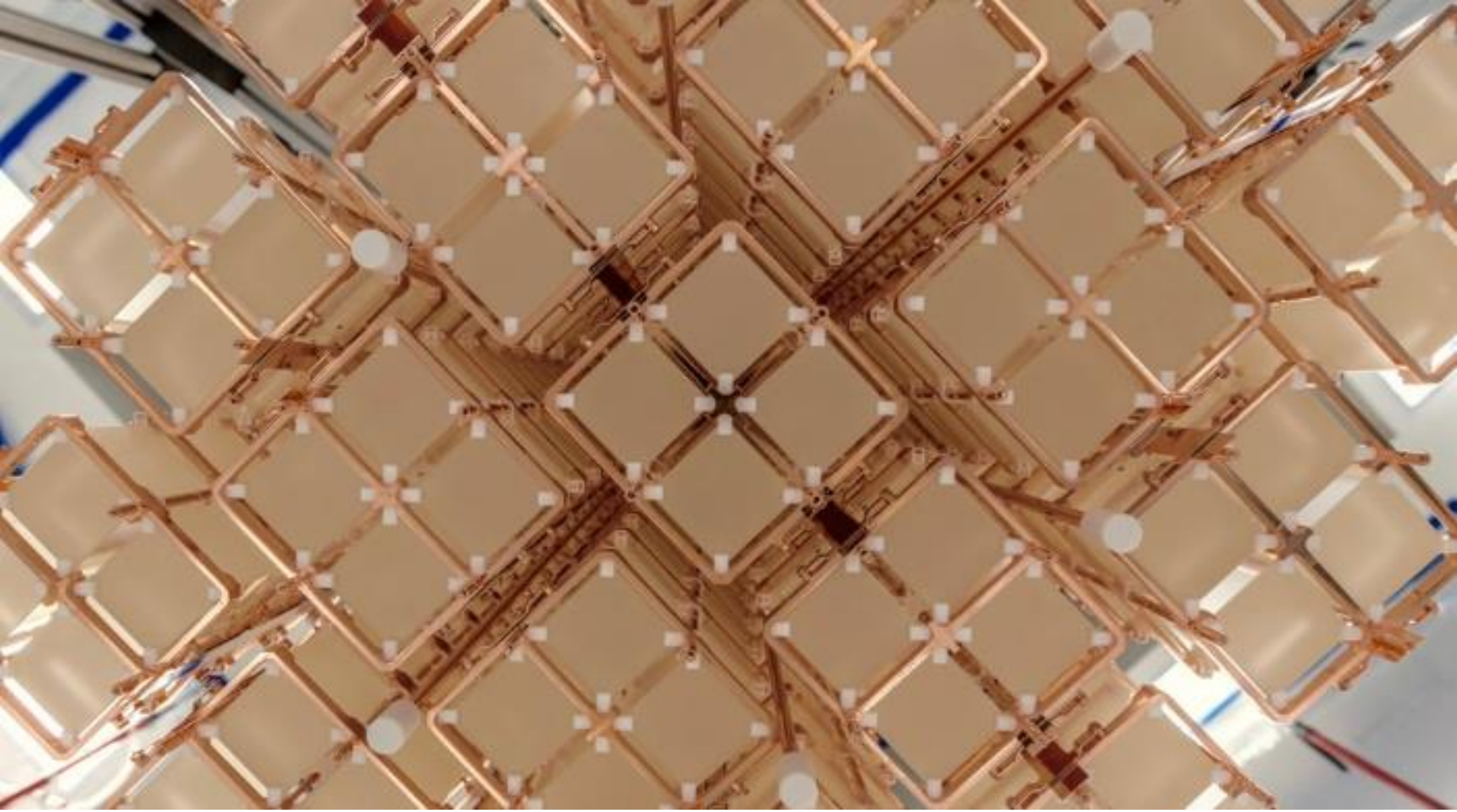
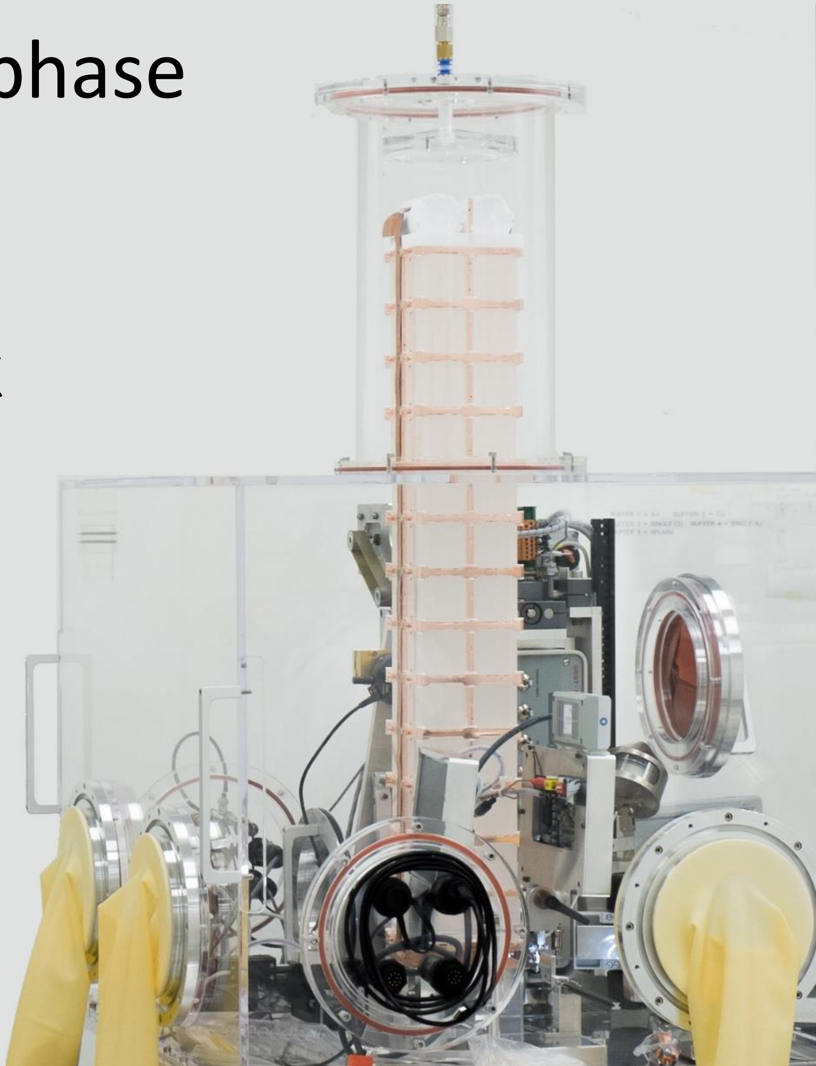


Latest Results from CUORE

Ke Han
Shanghai Jiao Tong Univ.
June 29, 2018

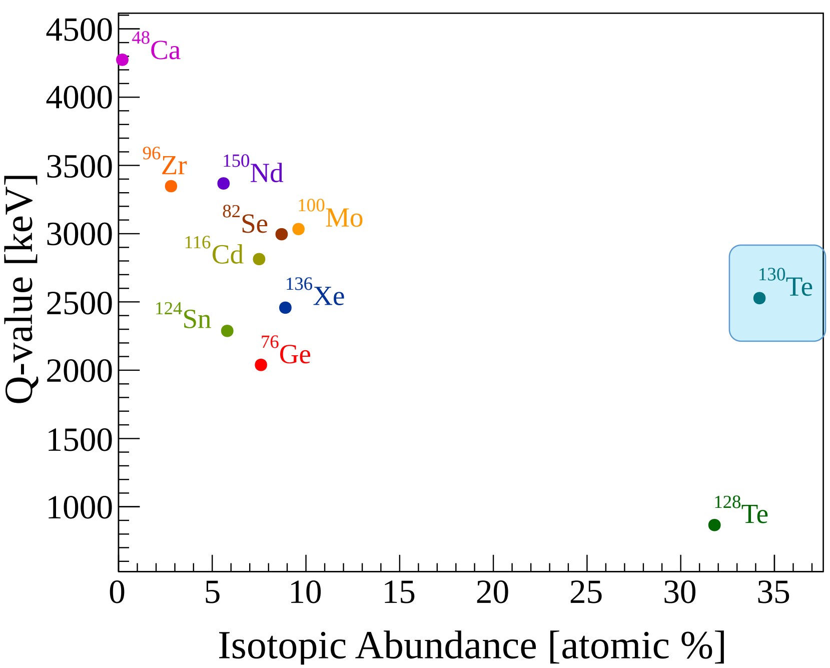
Outline

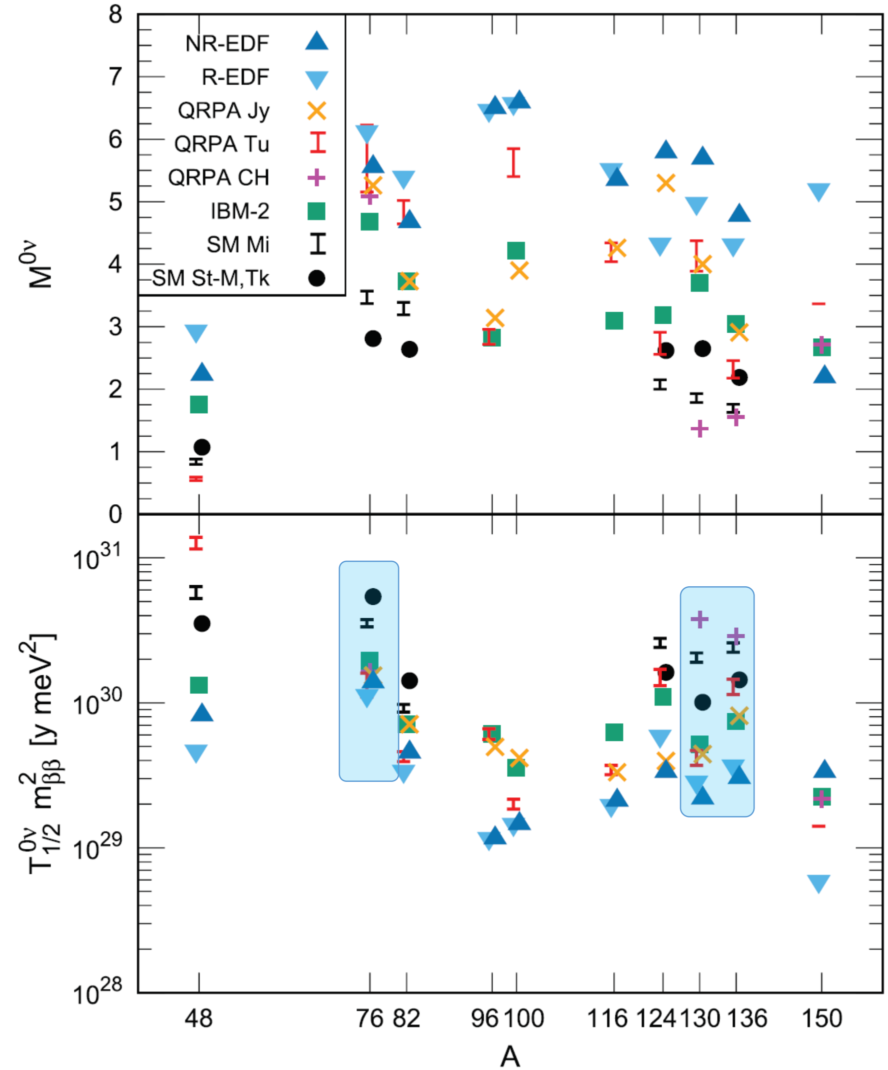
- CUORE Project overview
- $0\nu\beta\beta$ result from the first phase
- Recent $2\nu\beta\beta$ result
- CUORE status and outlook



Double beta decay in experiments

- Extremely rare events $T_{1/2} > 10^{24}$ year.
- Experimentally try to search for a peak on the spectrum of total energy of electrons.
- ^{130}Te: isotopically abundant and favorable in terms of half-life requirement



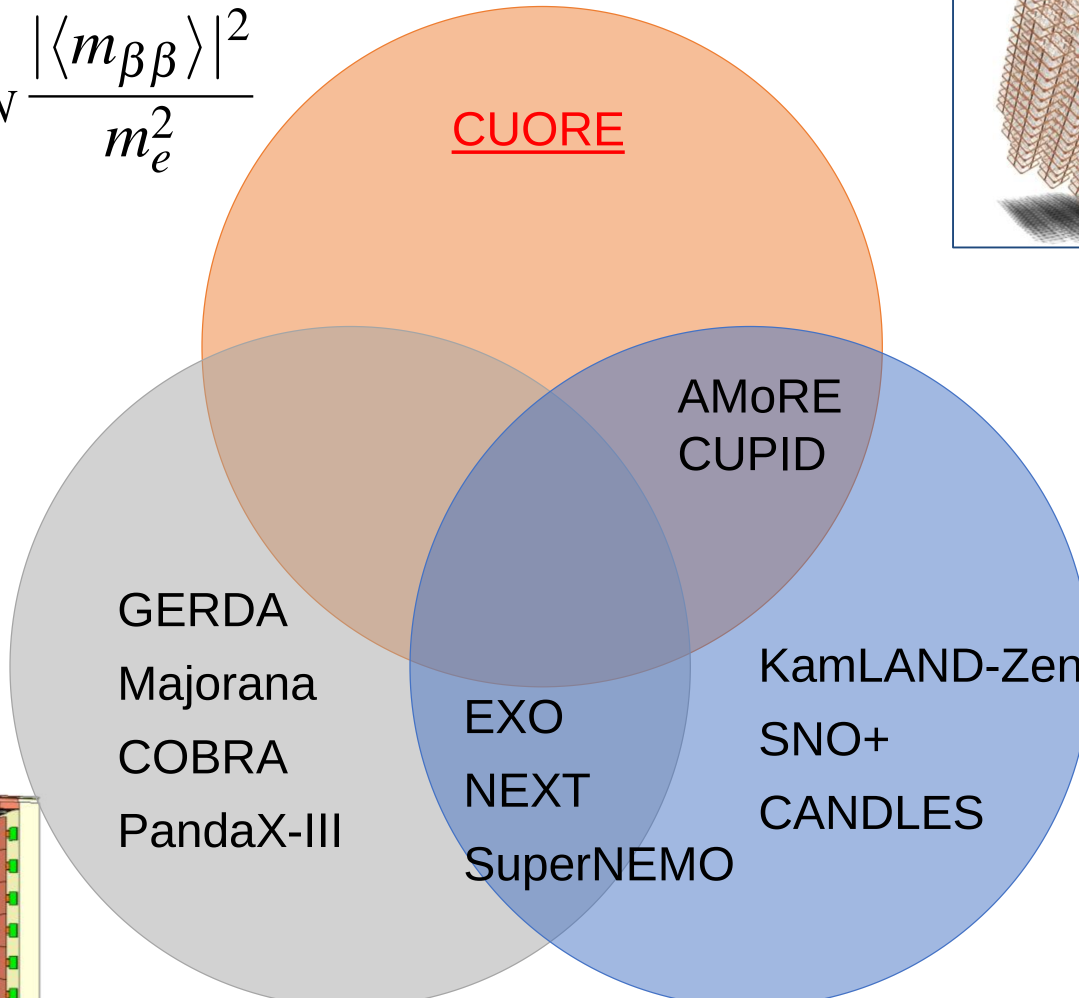


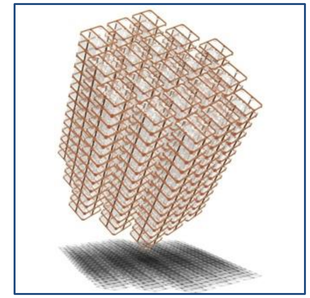
J. Engel and J. Menéndez 2017 Rep. Prog. Phys. 80 046301

Detection channels

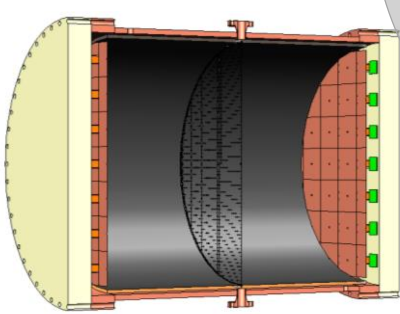
$$(T^{0\nu}_{1/2})^{-1} = F_N \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phonons

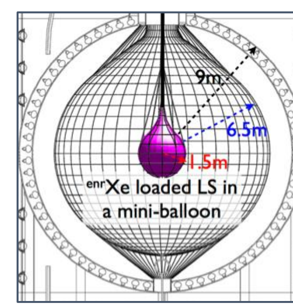




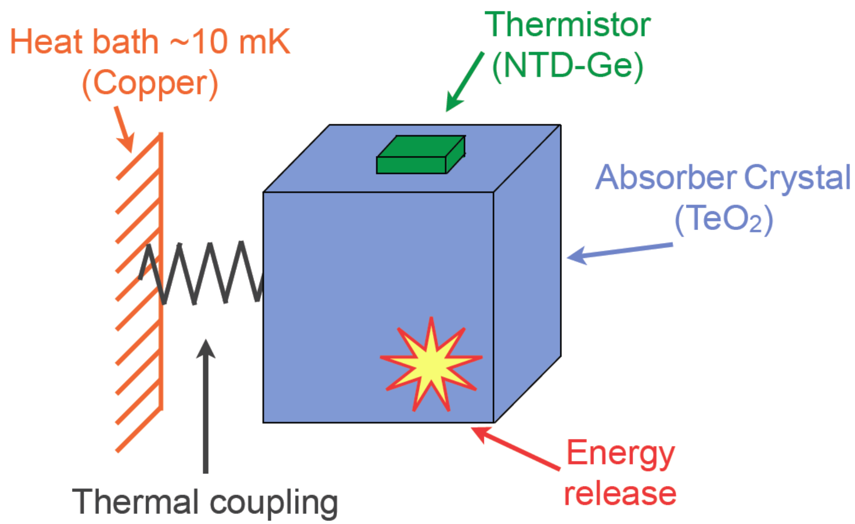
Electrons
Holes

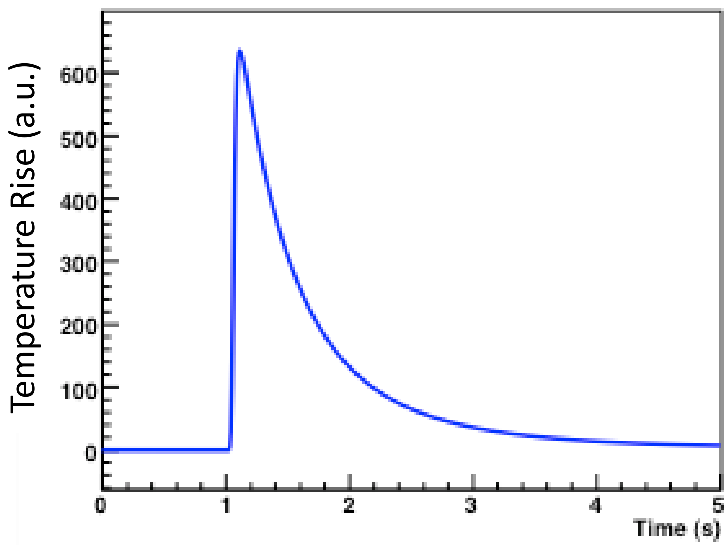


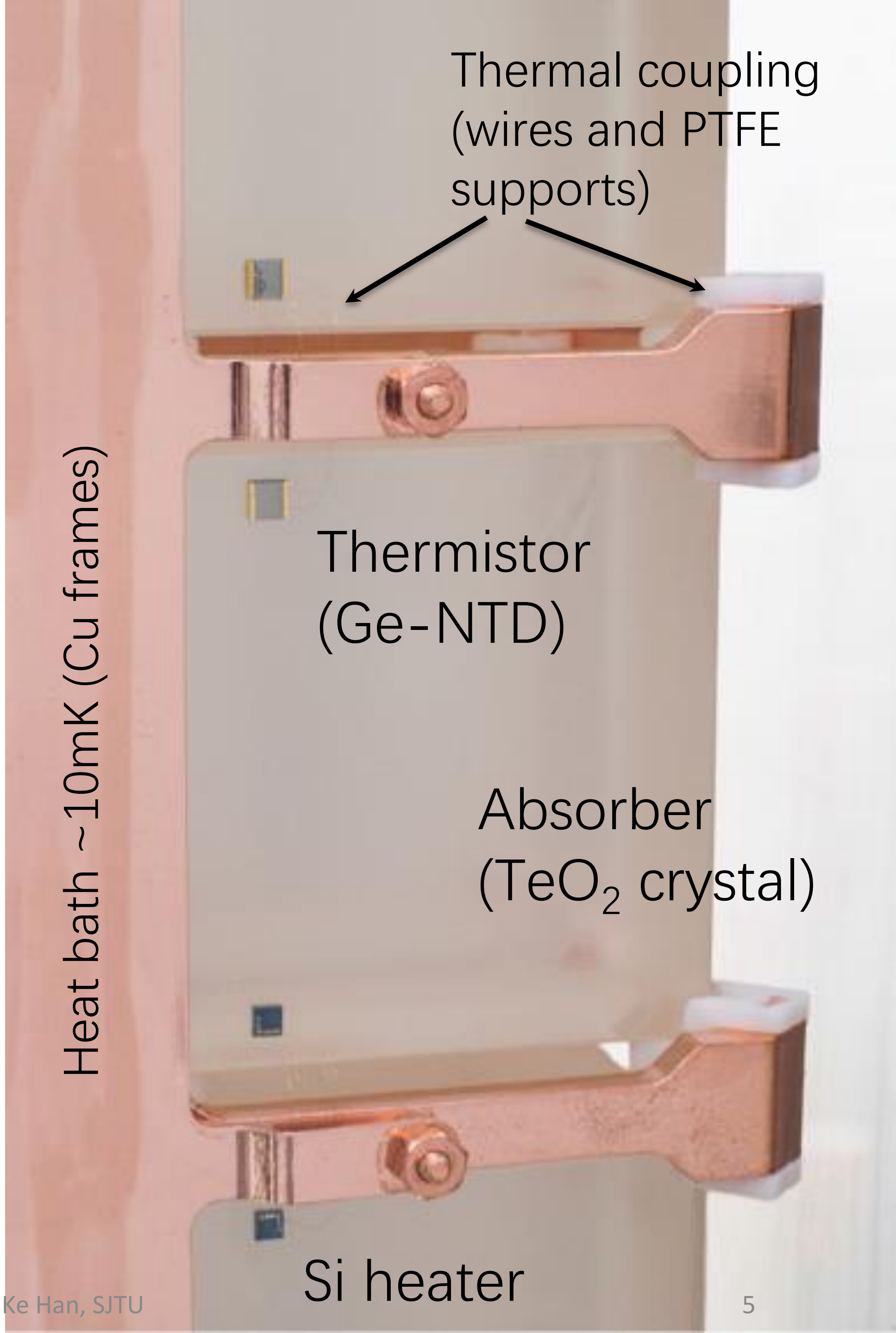
Photons



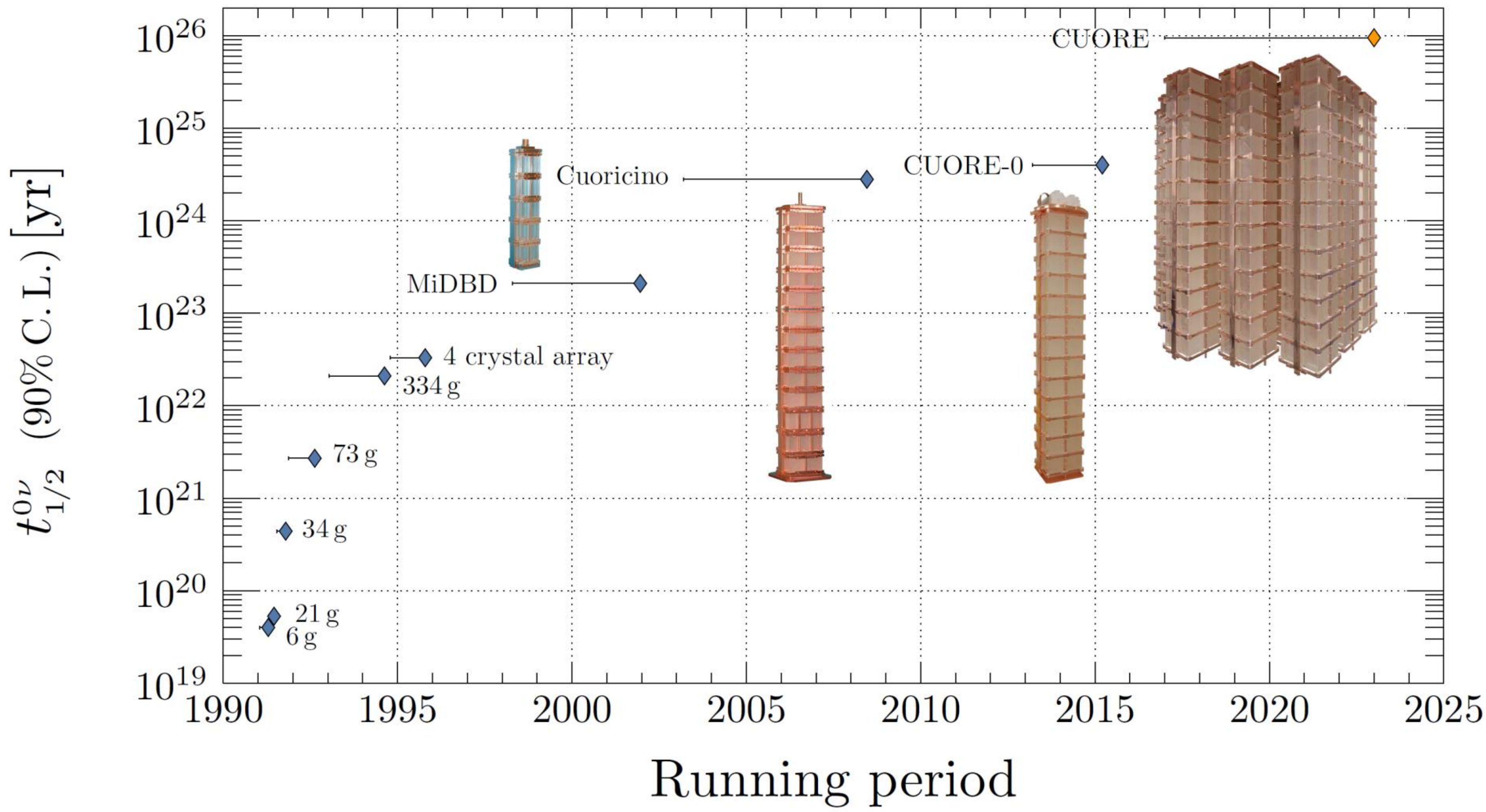
Large mass bolometer



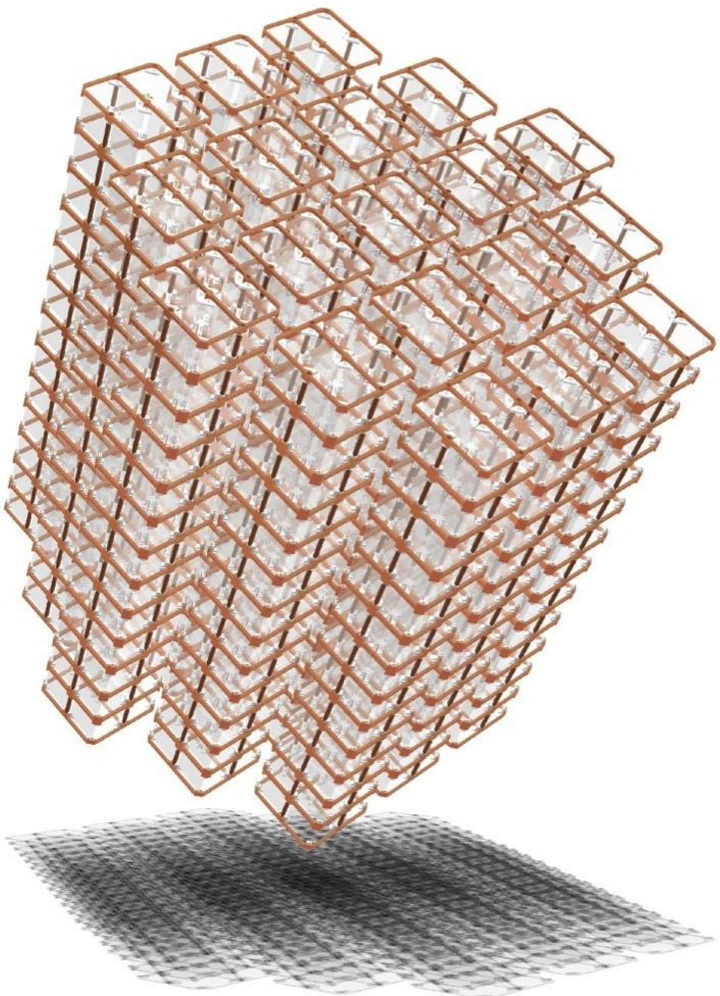




Arrays of TeO_2 bolometers

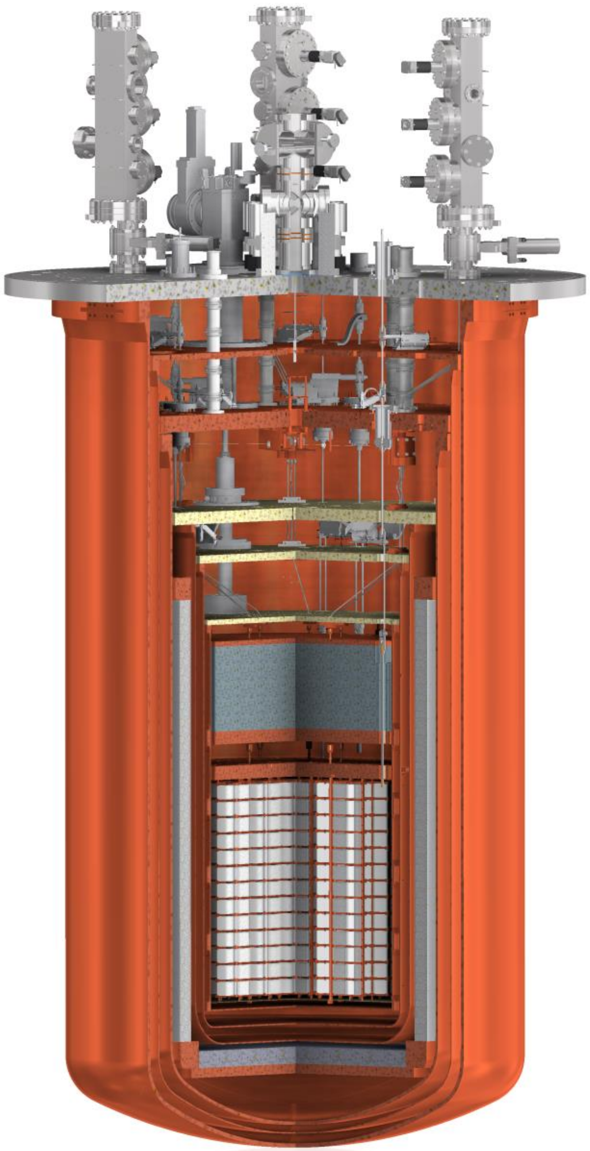


Cryogenic Underground Observatory for Rare Events



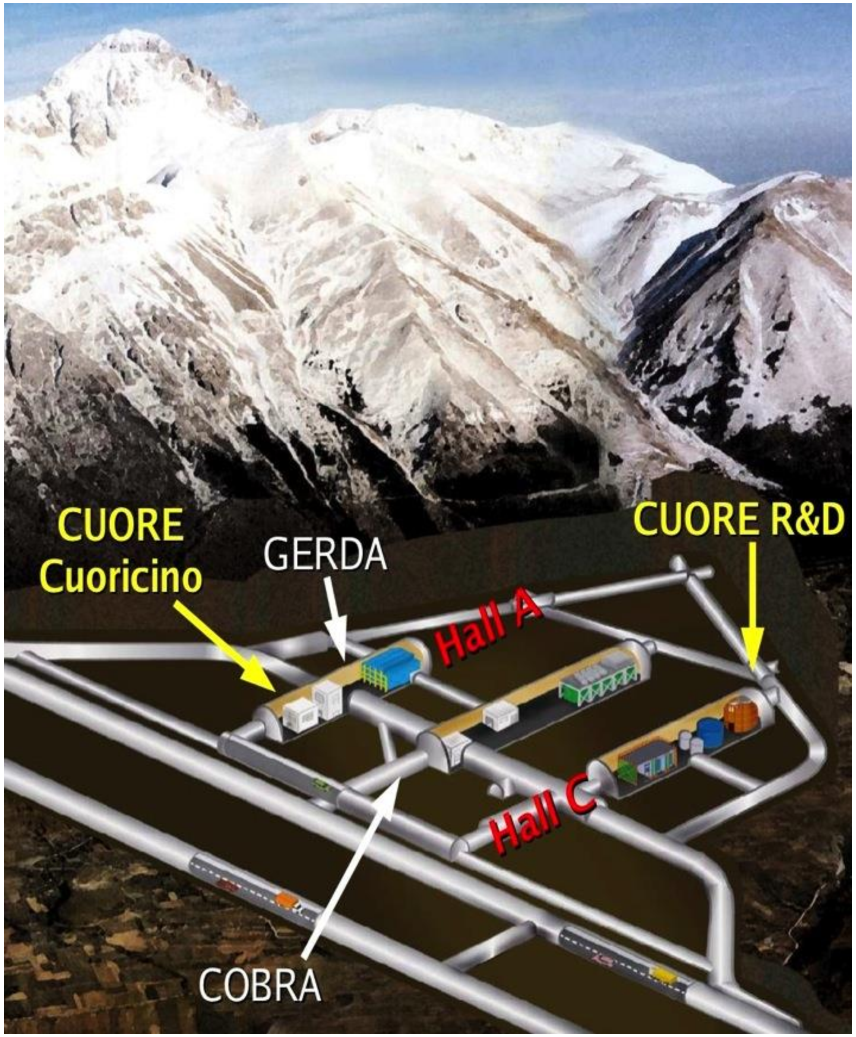
- Search for $0\nu\beta\beta$ of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array
  - 19 Towers
  - 13 floors
  - 4 modules per floor
  - 741 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- 10 mK base temperature in a custom dilution refrigerator
- Gran Sasso underground lab (LNGS), Italy

Cryogenic Underground Observatory for Rare Events



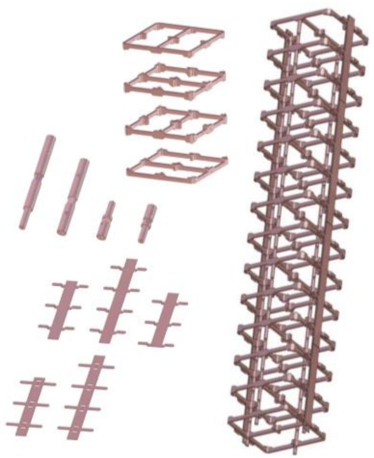
- Search for $0\nu\beta\beta$ of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array
  - 19 Towers
  - 13 floors
  - 4 modules per floor
  - 741 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- 10 mK base temperature in a custom dilution refrigerator
- Gran Sasso underground lab (LNGS), Italy

Cryogenic Underground Observatory for Rare Events

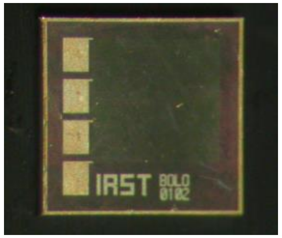


- Search for $0\nu\beta\beta$ of ^{130}Te and other rare events
- 988 TeO_2 crystals run as a bolometer array
  - 19 Towers
  - 13 floors
  - 4 modules per floor
  - 741 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- 10 mK base temperature in a custom dilution refrigerator
- Gran Sasso underground lab (LNGS), Italy

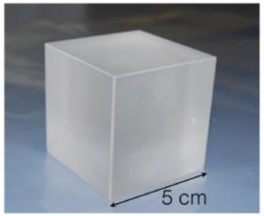
CUORE-module: a tower



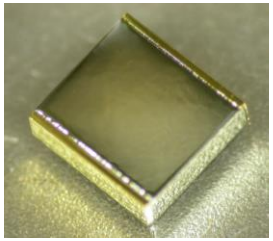
~2000 Cu NOSV components



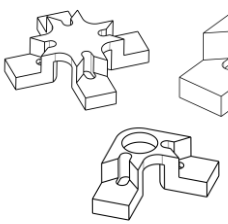
52 Si heaters



52 TeO_2 crystals



52 Ge thermistors



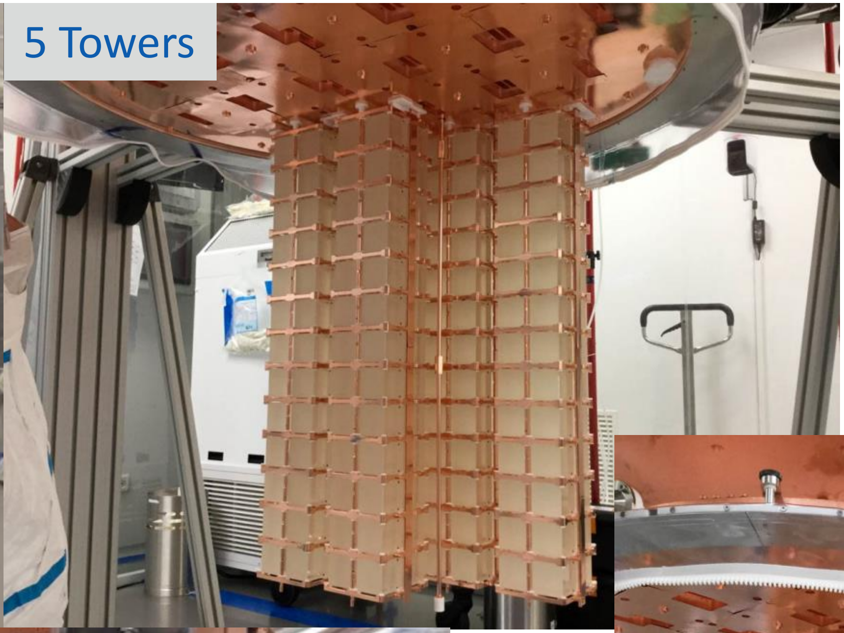
234 PFTE holders

8 Cu-PEN cables

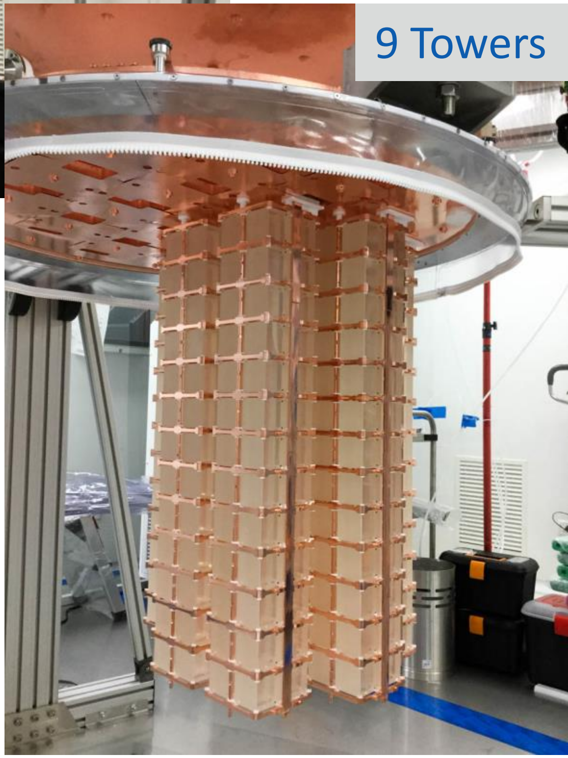
- New detector design structure
- Strict material selection (e.g. raw materials)
- Strict surface cleaning technique for Cu and TeO_2
- Minimization of Rn exposure (Glove Box assembly)

Detector installation (Summer 2016)

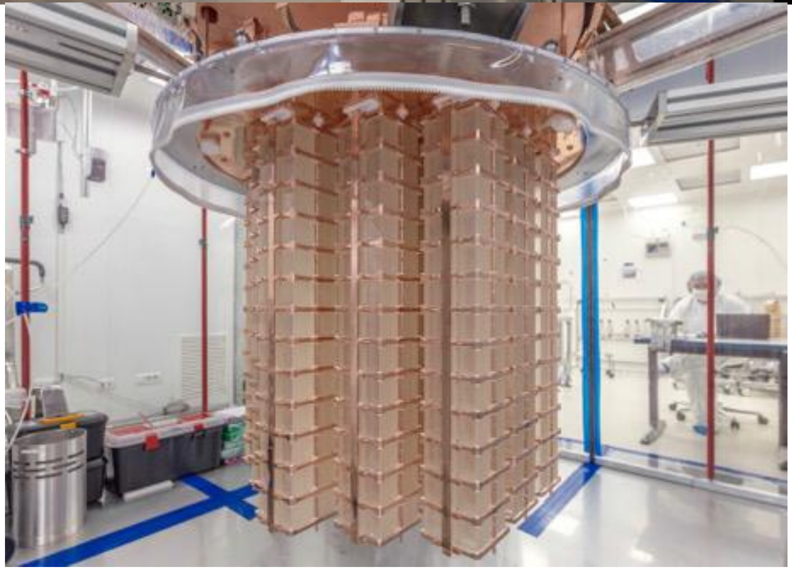
First Tower



5 Towers



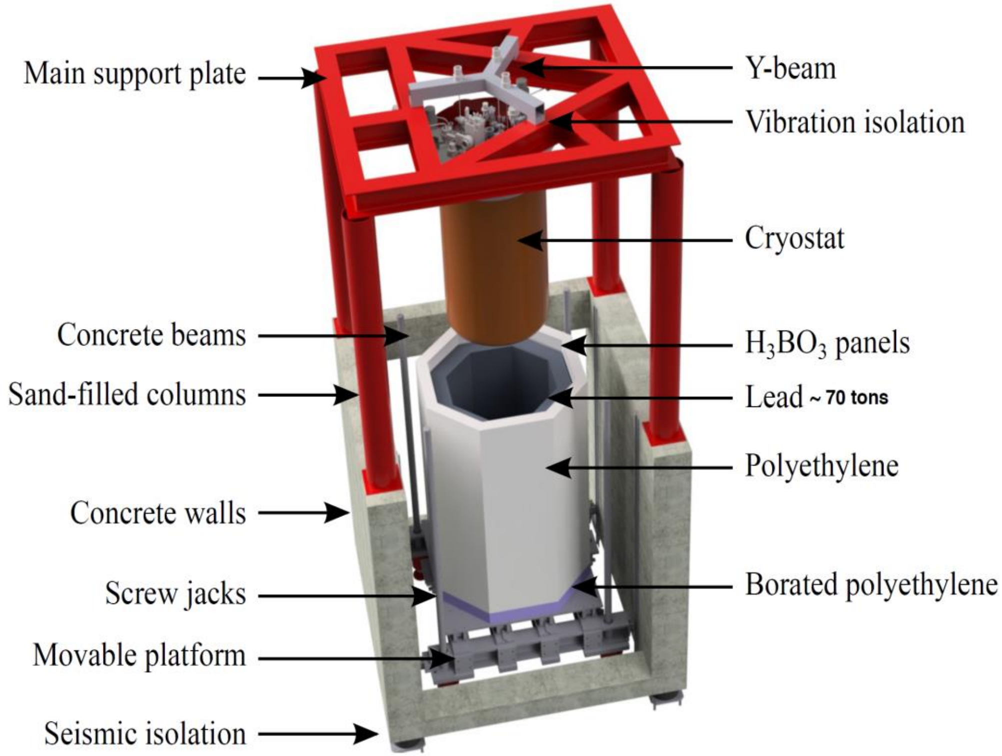
9 Towers



19 Towers

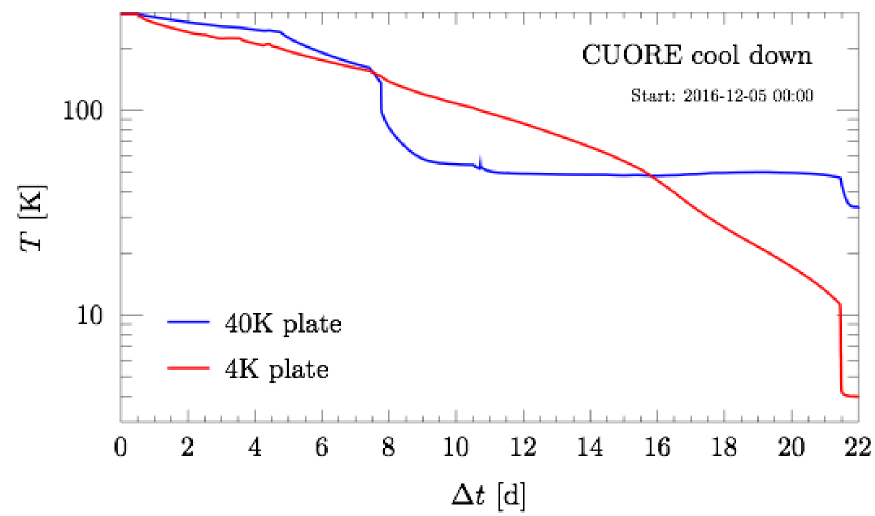
Passive shielding

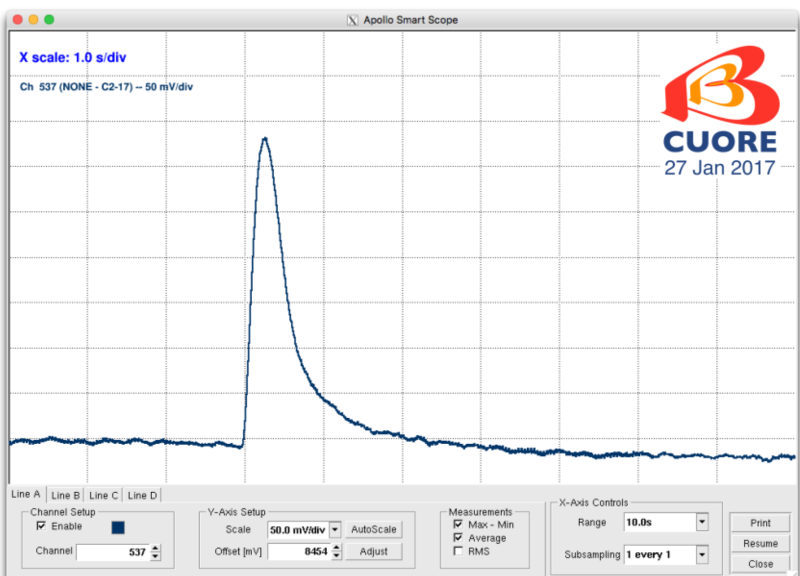
- External gamma and neutron shielding with ~70 tons lead + H_3BO_3
- Internal ancient roman lead and selected NOSV copper
- Internal shielding at low temperature: 2.5 tons @ 50mK + 5.5 tons @ 4K

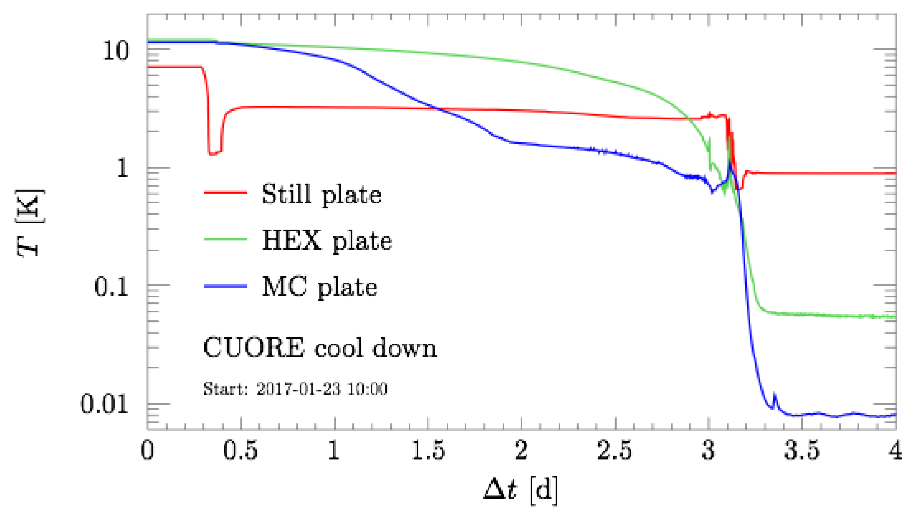


CUORE cooling down

- Fast cooling system (4He gas) allows quick cool down to ~40 K
- All 5 PT coolers activated to bring cryostat to ~4 K
- DU brings temp down to ~6.3 mK
- Residual cooling power at 10 mK: 3 µW

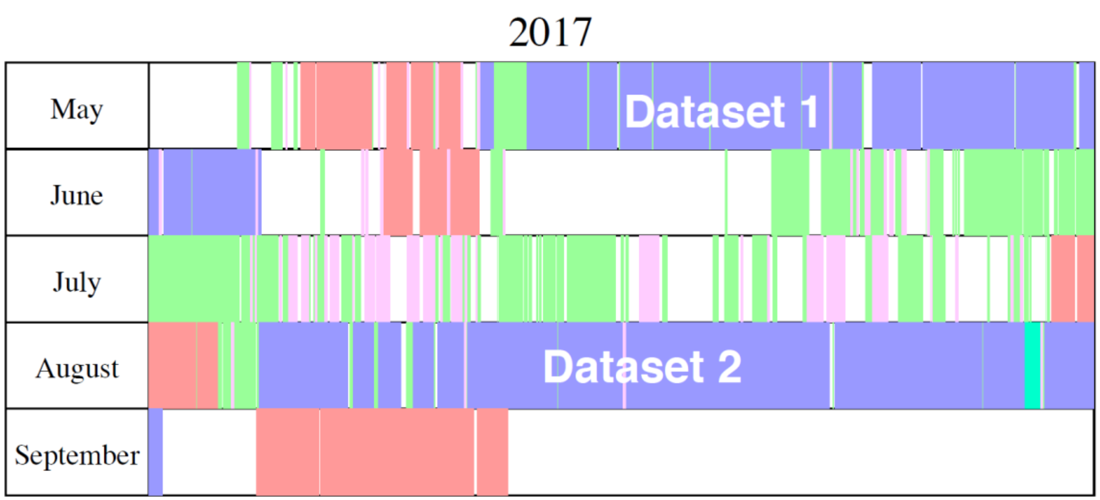


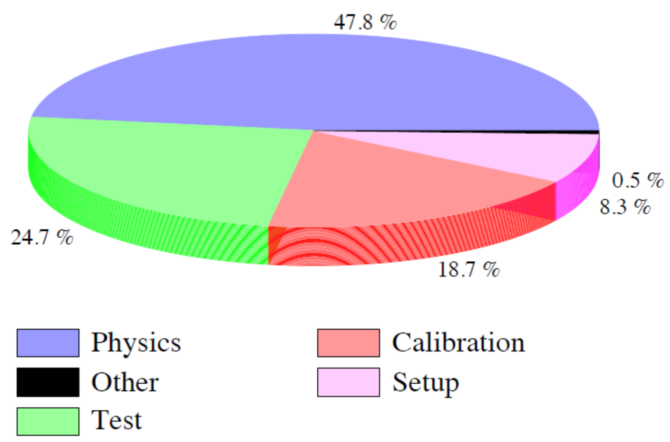




Science runs

- Science operations started on April 14, 2017
- 984/988 operational channels
- Excellent data-taking efficiency when in operations
- Calibrations/physics data ratio still to be optimized
- $^{nat}TeO_2$ exposure: 86.3 kg yr (37.6 + 48.7)
- ^{130}Te exposure: 24.0 kg yr

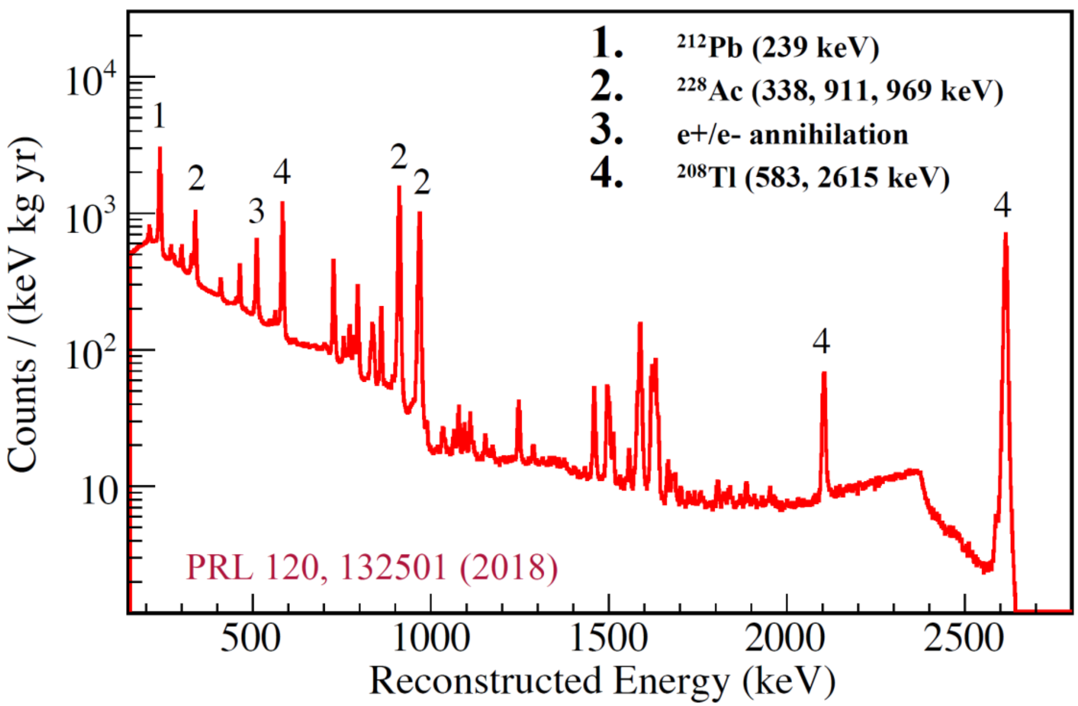


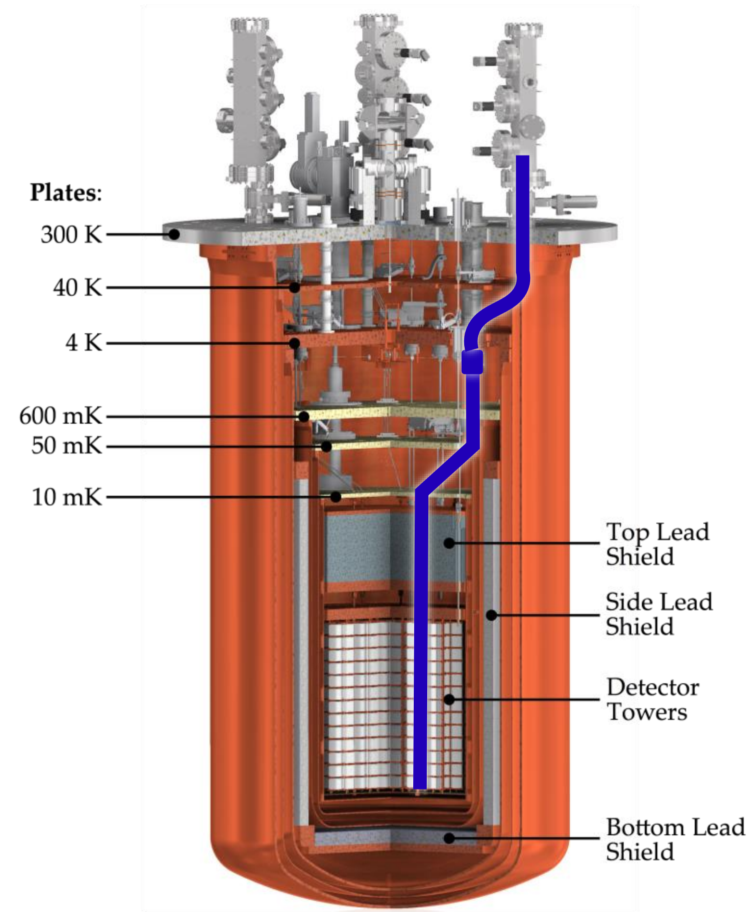


Physics, Calibration, Test, Special Configuration runs

Calibration and gain stabilization

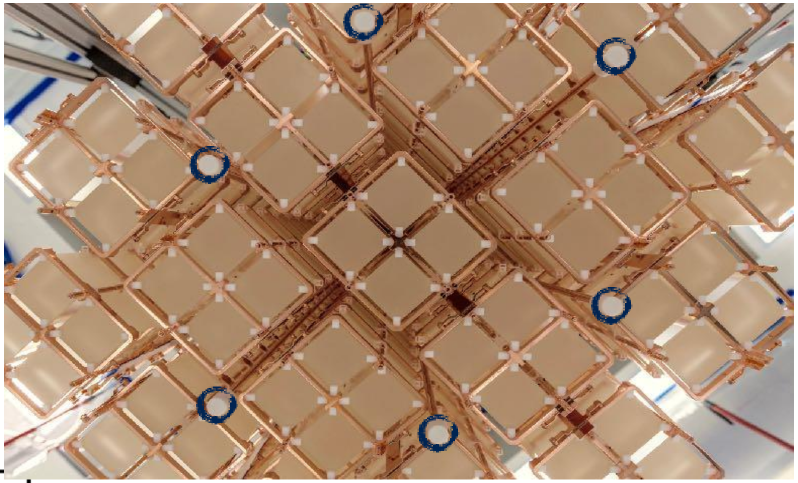
- ^{232}Th source （lower down from 10mK）
  - Energy scale calibration
- Silicon heater (pulser)
  - Thermal gain stabilization
- Detector response (line shape) study

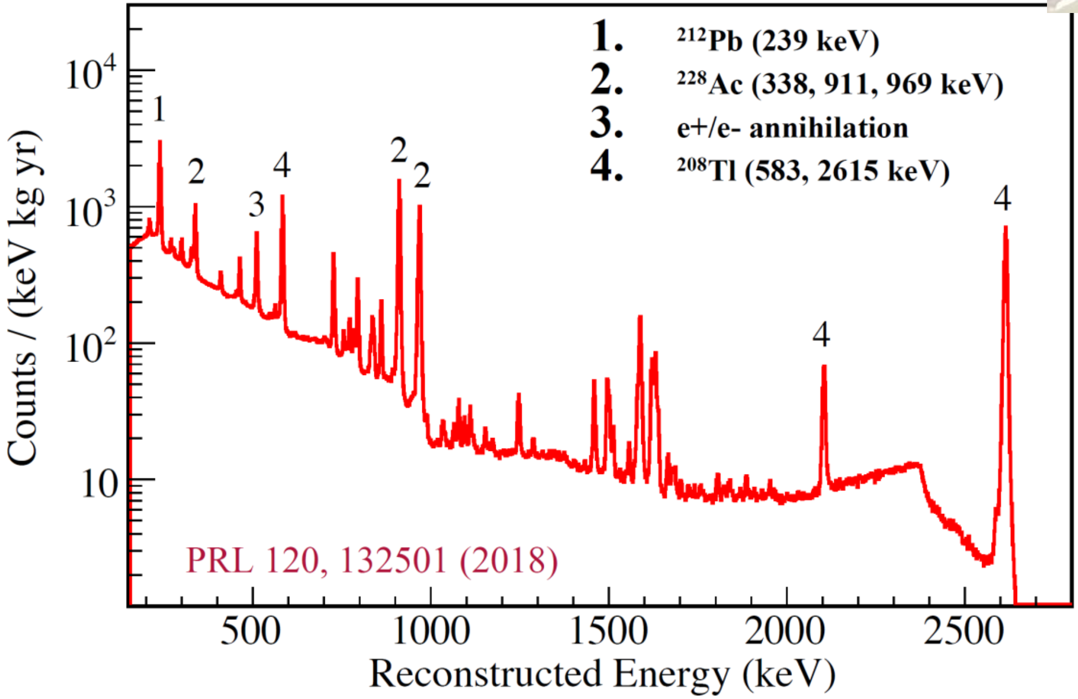


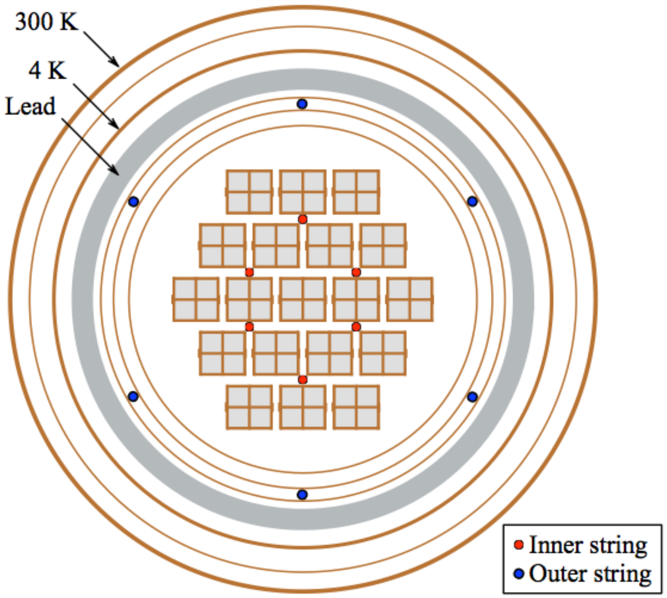


Calibration and gain stabilization

- ^{232}Th source （lower down from 10mK）
  - Energy scale calibration
- Silicon heater (pulser)
  - Thermal gain stabilization
- Detector response (line shape) study

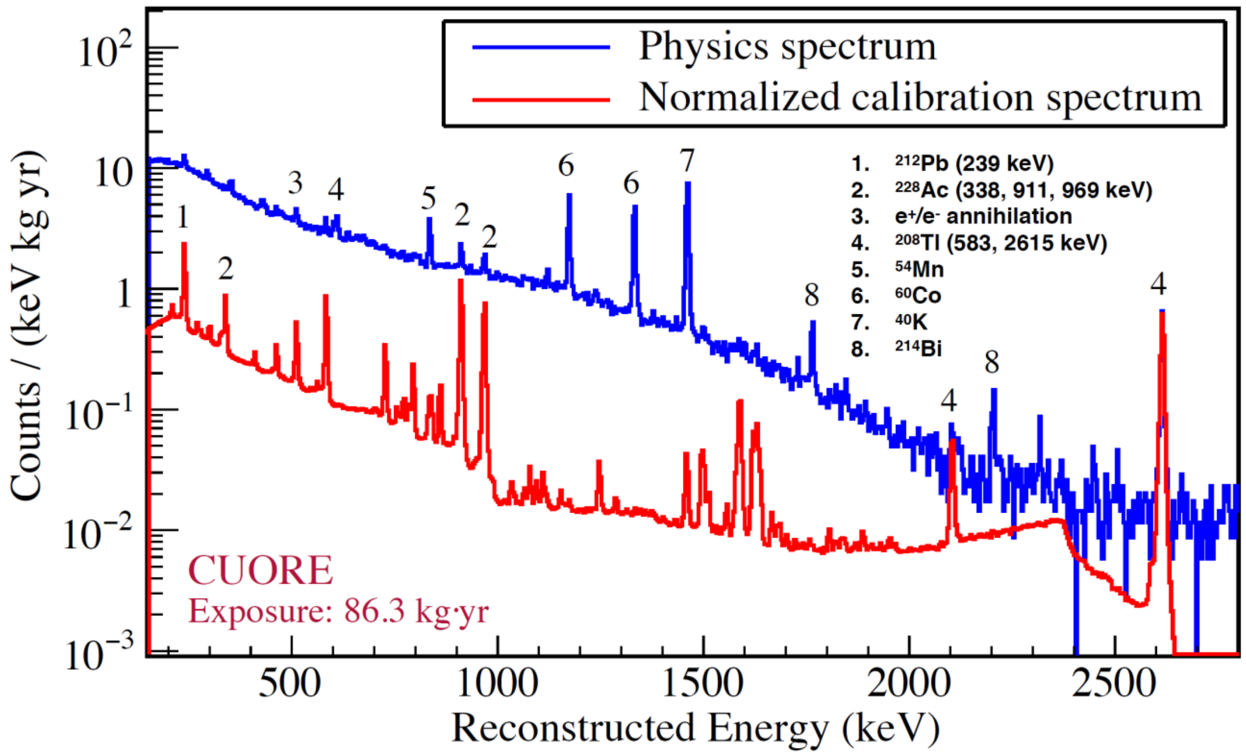






Physics spectrum

- 1811 channel-dataset pairs utilized
  - 92% of active channels
- Energy spectrum from sum of all active channels used in 0νββ search

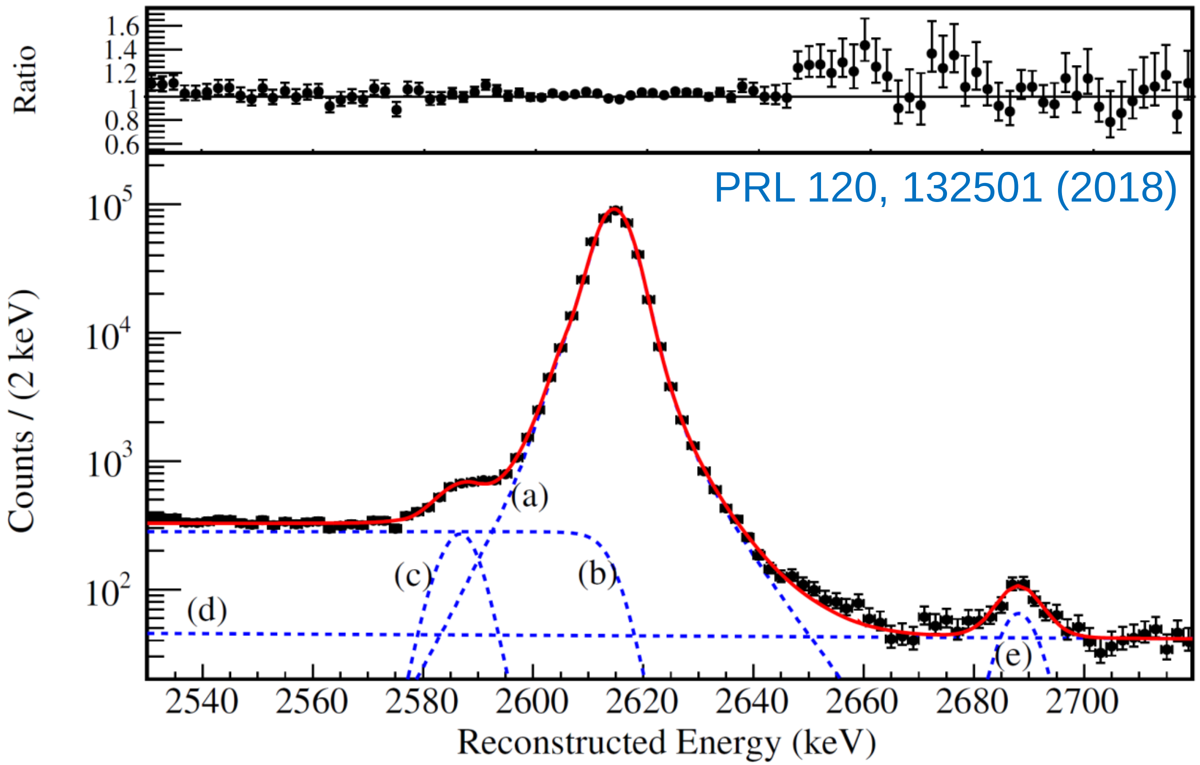


Line shape studies

CUORE

Model the ^{208}Tl 2615 keV line

- The most prominent peak from ^{232}Th calibration
- Close to the 0νββ Q-value for ^{130}Te in the background spectrum



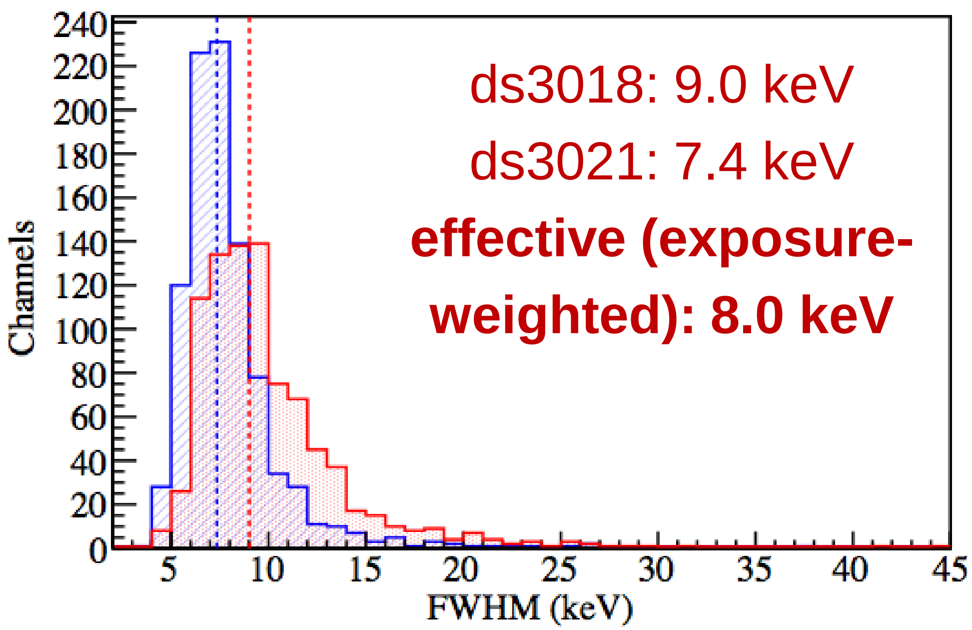
Fit for 2615 keV summed over all channels

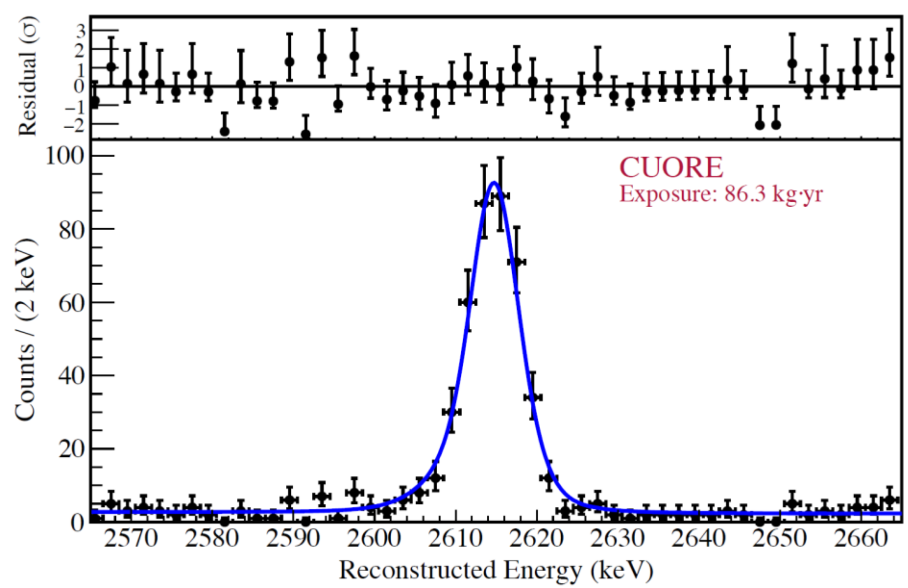
a) Triple Gaussian for main peak
b) Step-wise multi-Compton background
c) X-ray escape peak (~30 keV)
d) Linear background
e) 2687 (2615 + 583 - 511) keV peak

Energy resolution

- 1811 (92% of live channels) channels-dataset
- Obvious improvements in ds3021
- Exposure weighted average resolution at Q-value of 7.7 ± 0.5 keV FWHM

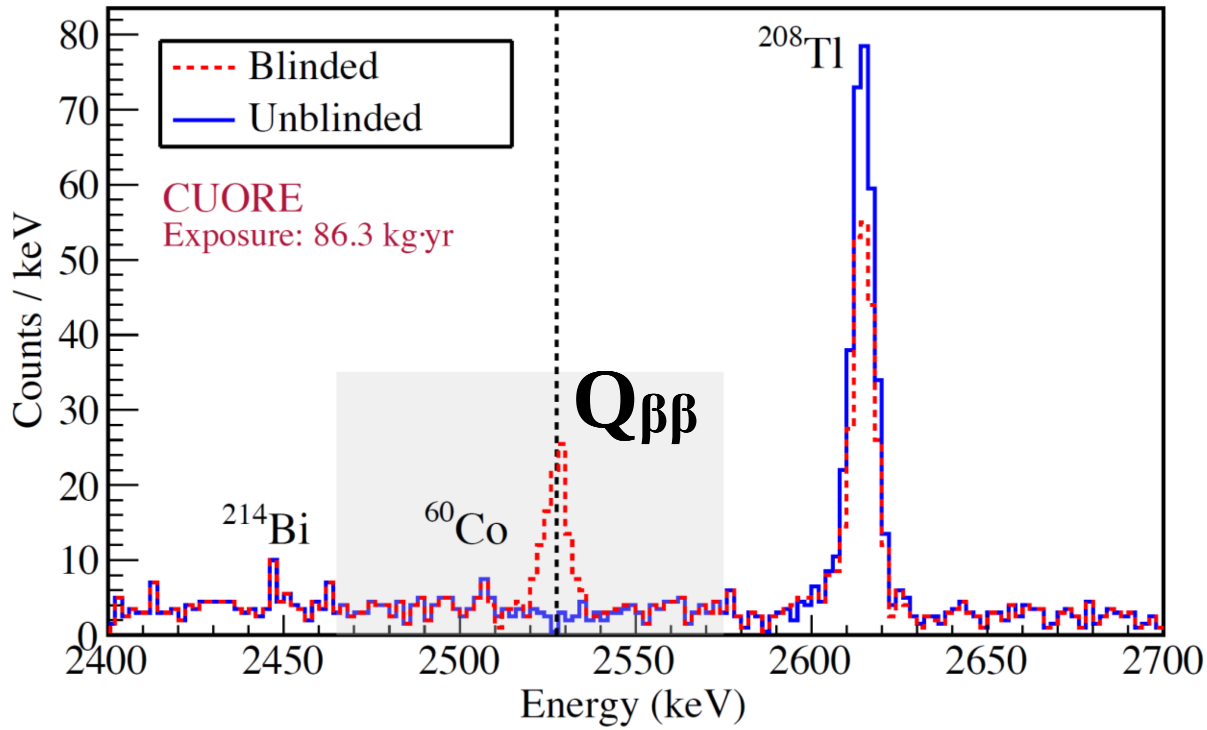
Resolution at 2615 keV gamma peak





Blinding procedure

- To blind our data we randomly move a fraction of events from +/- 20 keV of 2615 keV to the Q-value and vice versa
- The blinding algorithm produces an artificial peak around the 0νββ Q-value hiding the real 0νββ rate of ^{130}Te
- When all data analysis procedures are fixed the data are eventually unblinded

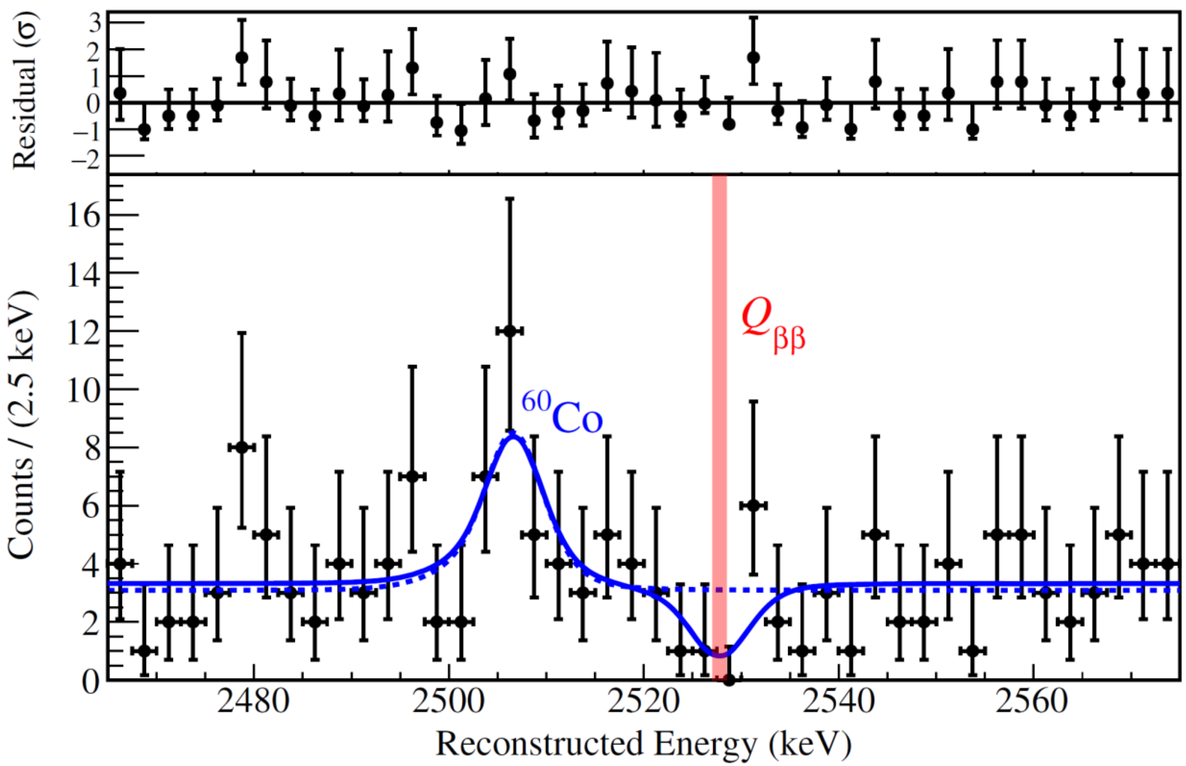


Event selection

- 155 (65+90) events survive cuts in the unblinded region of interest

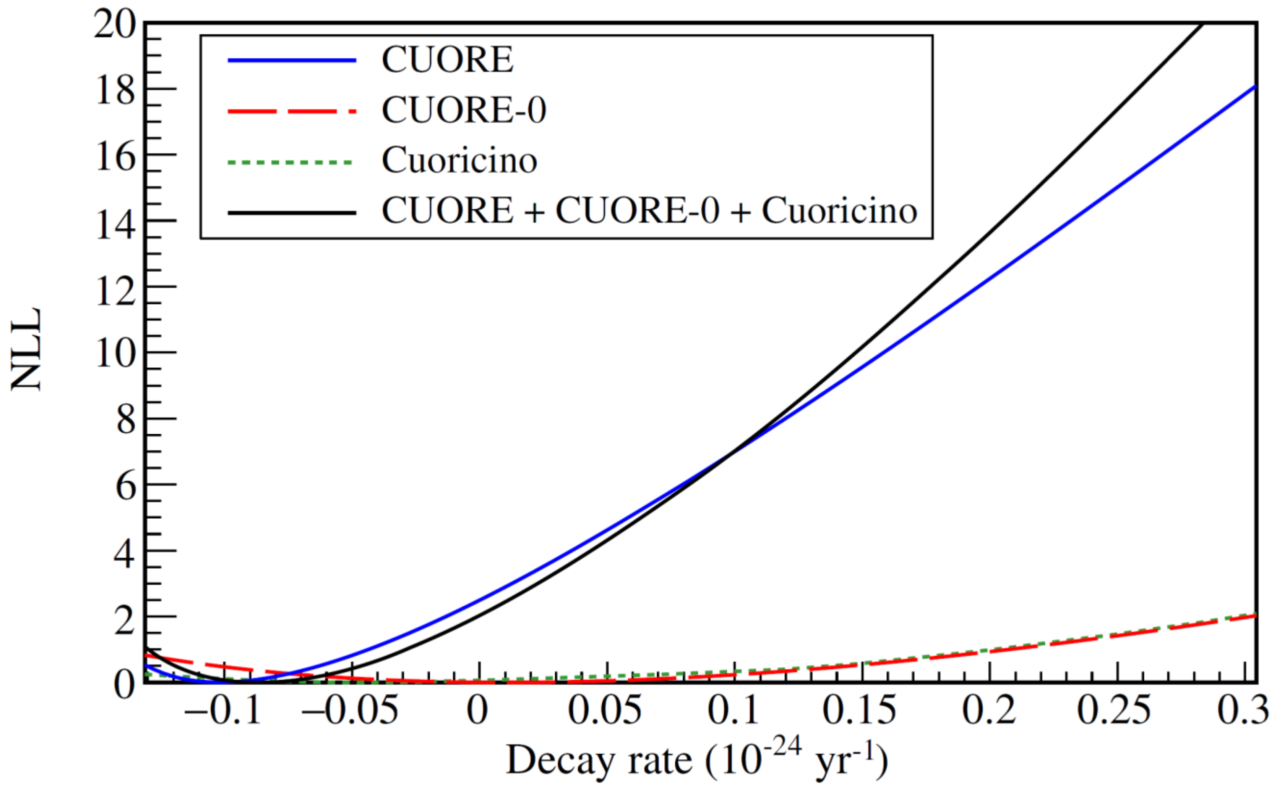
ROI fit

- Region of interest: 2465 to 2575 keV
- Signal efficiency (75.7 ± 3.0)% - ds3018 [(83.0 ± 2.6)% - ds3021]
- Background index (c/(keV·kg·yr)): $(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ [$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$]
- Best Fit Signal Decay Rate: $(-1.0_{-0.3}^{+0.4}$ (stat.) ± 0.1 (syst.)$)\times10^{-25}$ / yr



0νββ results

- No 0νββ signals found
- Half-life limit established
- Profile likelihood integrated on the physical region ($\Gamma^{0\nu} > 0$)



Decay rate limit (90% CL, including systematics):
0.51×10^{-25} / yr

Half-life limit (90% CL, including systematics):
1.3×10^{25} yr

Median expected sensitivity:
7.0×10^{24} yr

Combining with previous ^{130}Te results

CUORE

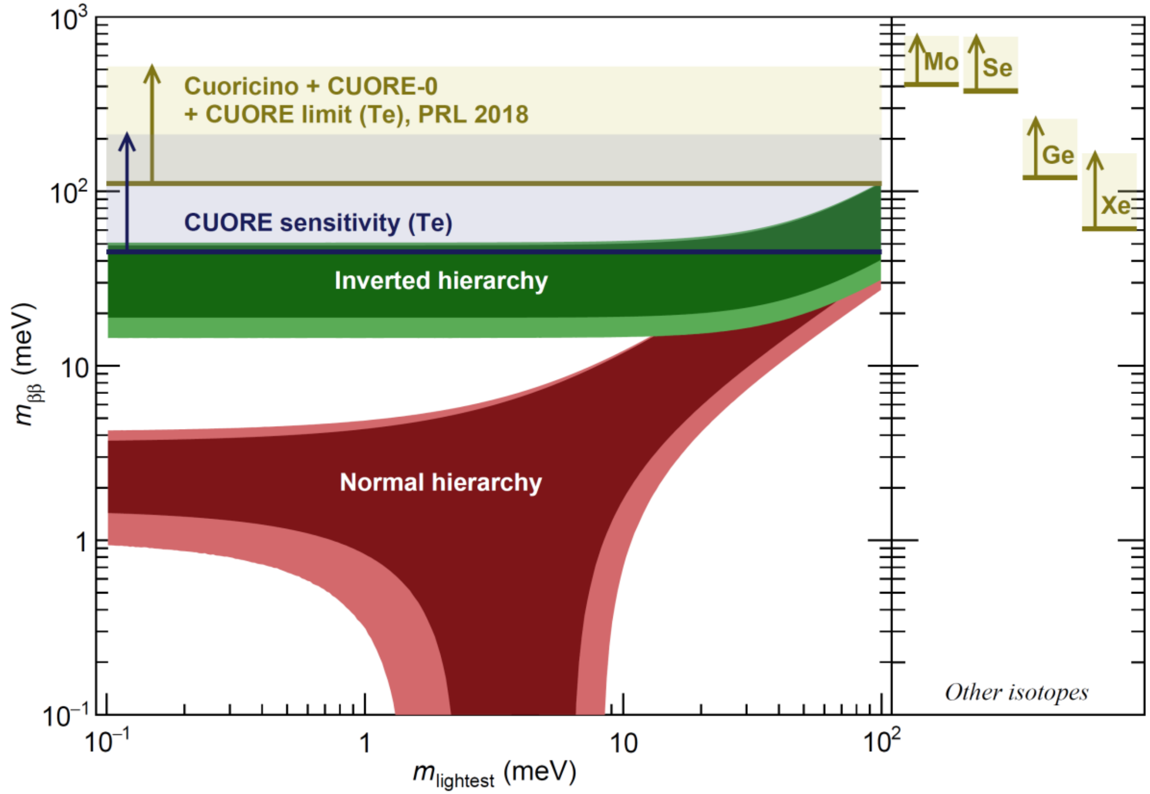
We combined the CUORE result with the existing ^{130}Te

- 19.75 kg·yr of Cuoricino
- 9.8 kg·yr of CUORE-0

- The combined 90% C.L. limit is

$T_{0\nu} > 1.5 \times 10^{25}$ yr

$m_{\beta\beta} <$ 110–520 meV



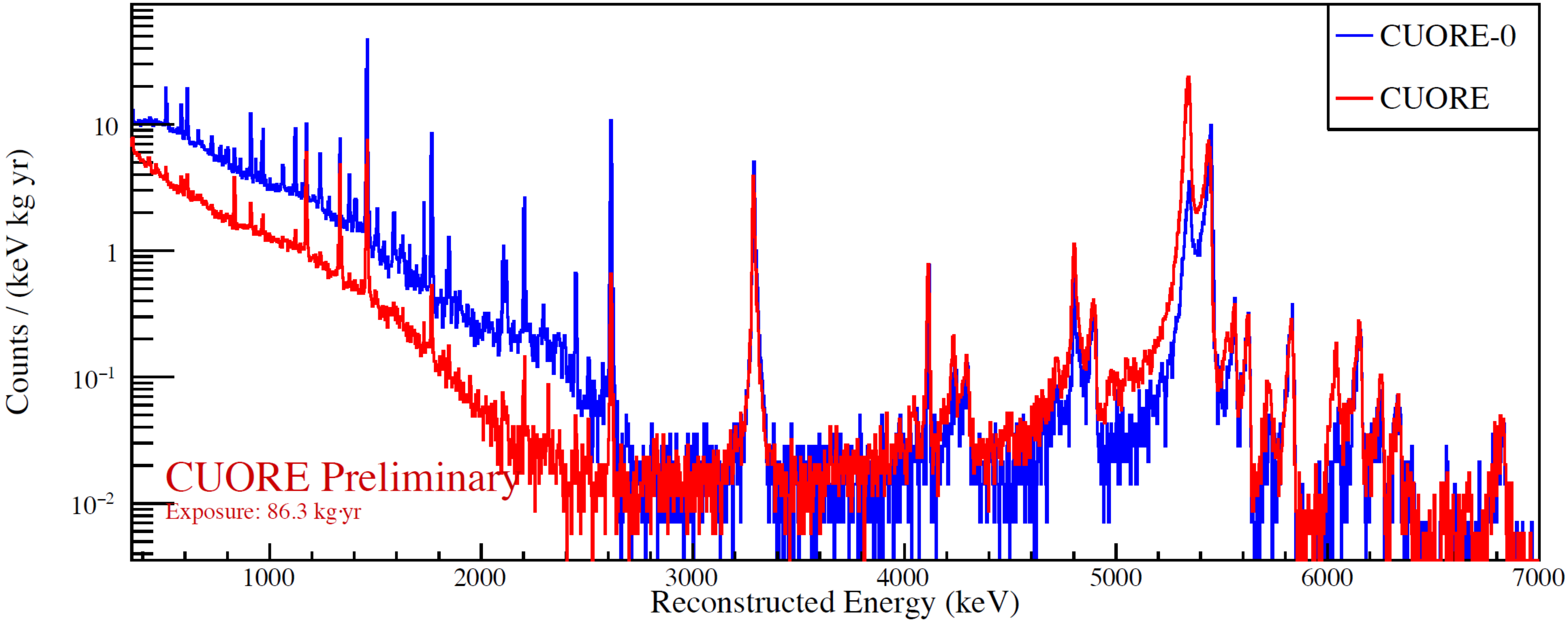
^{130}Te: 1.5×10^{25} yr from this analysis PRL 120, 132501 (2018)
^{76}Ge: 8.0×10^{25} yr from PRL 120, 132503 (2018)
^{136}Xe: 1.1×10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1×10^{24} yr from Phys. Rev. D 89, 111101 (2014)
^{82}Se: 2.4×10^{24} yr from Phys. Rev. Lett 120, 232502 (2018)
CUORE sensitivity: 9.0×10^{25} yr
CUPID sensitivity: 5.1×10^{27} yr

NME:

JHEP02 (2013) 025
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 87, 064302 (2014)
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 91, 024613 (2015)
Phys. Rev. C 91, 024309 (2015)
Phys. Rev. C 91, 024316 (2015)
Phys. Rev. Lett. 105, 252503 (2010)
Phys. Rev. Lett. 111, 142501 (2013)

CUORE background

- Significant reduction in the gamma region with respect to CUORE-0
- ^{210}Po excess appears to be from shallow contamination in copper around the detectors
  - Estimated contribution to ROI at the level of ~ 10^{-4} c/(keV kg yr)

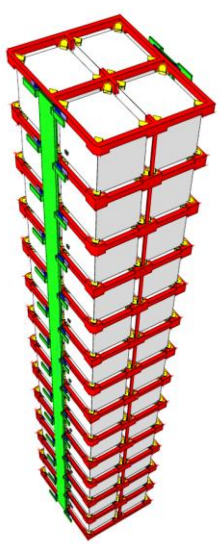


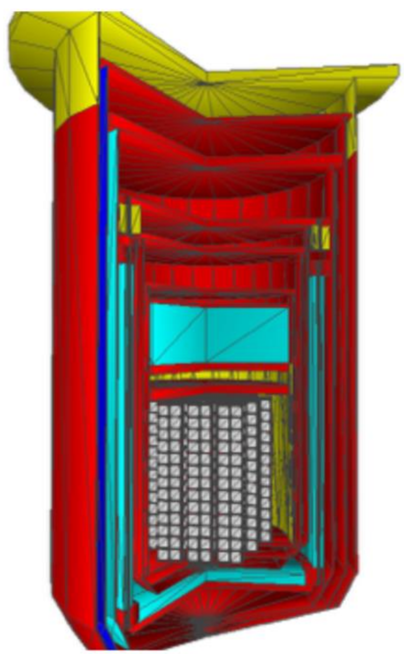
Fitting the CUORE Background Model

- Simulate the contaminations coming from different cryostat components using a detailed Geant4 MC simulation
- ~60 independent parameters representing various contaminations that

could contribute to the CUORE background model

- Bayesian fit to data with flat priors except for muons which come from a cosmogenic analysis

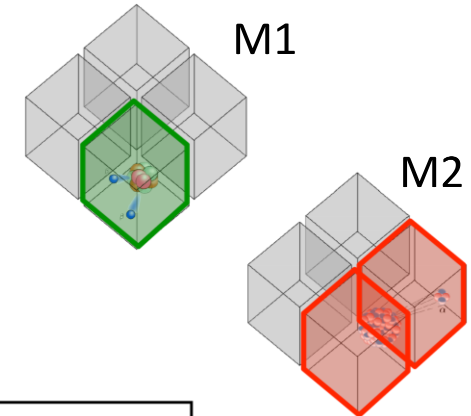


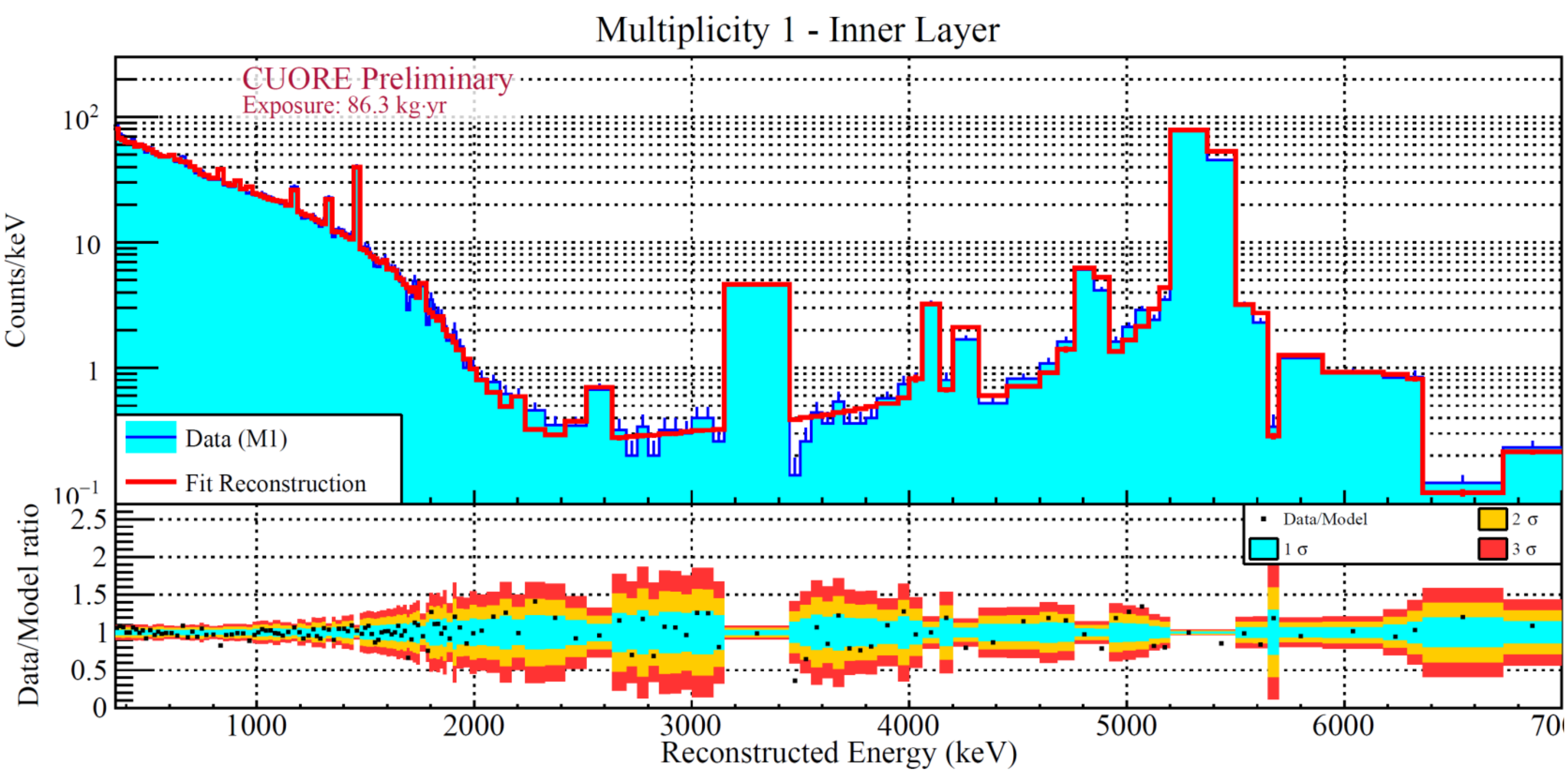


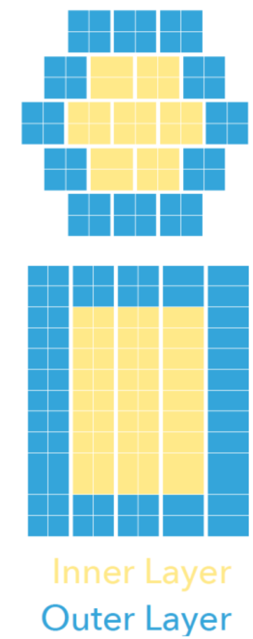
Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
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

More recent runs

- Multiplicity 1 spectra very sensitive to signal events
- Many contaminations constrained by the higher multiplicity spectra

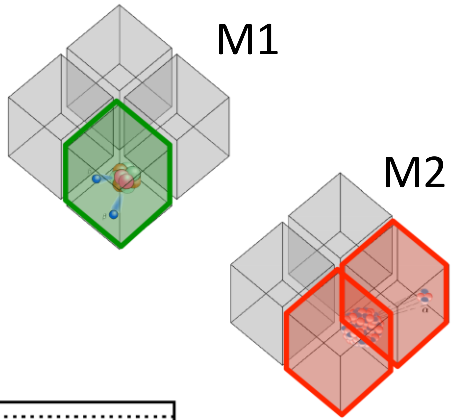


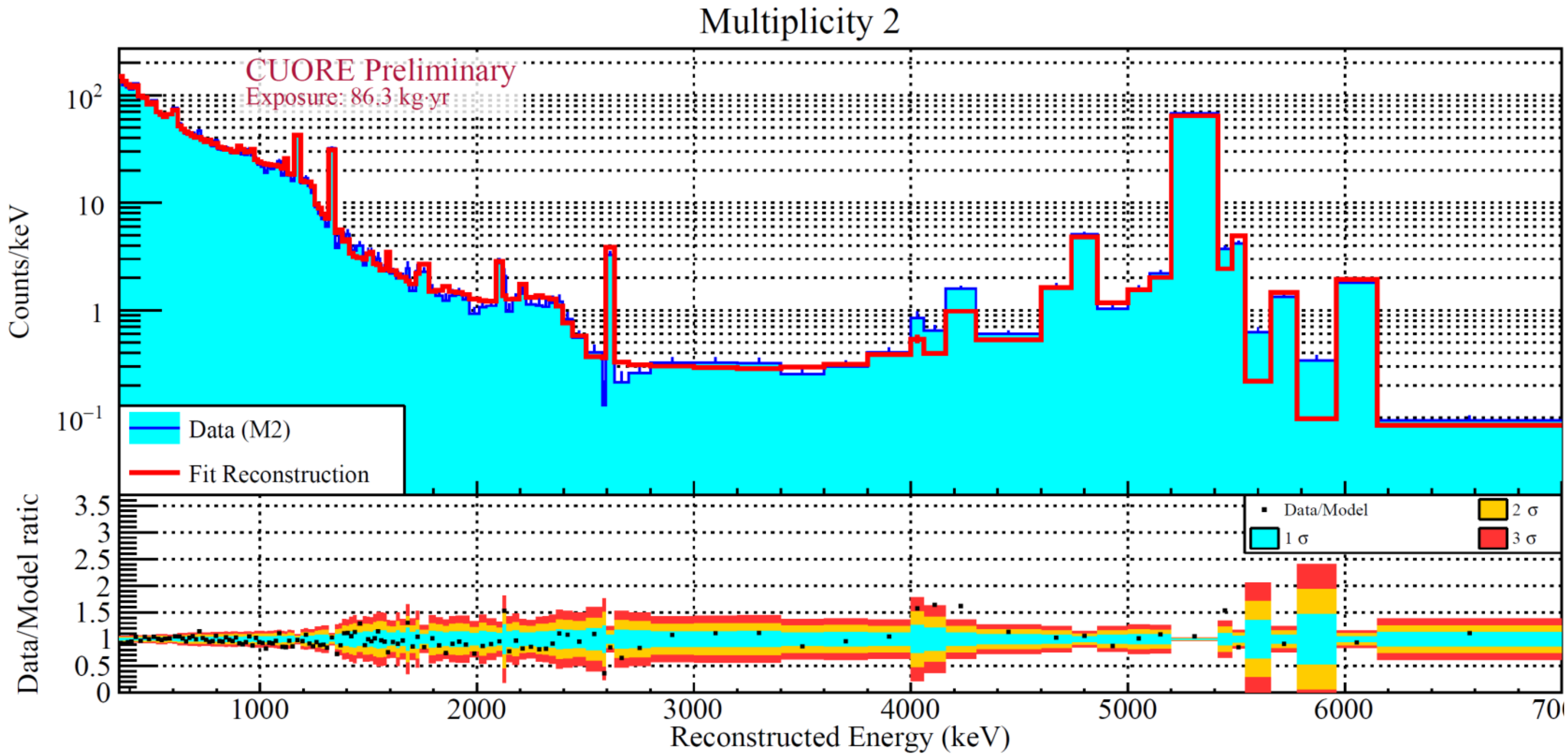


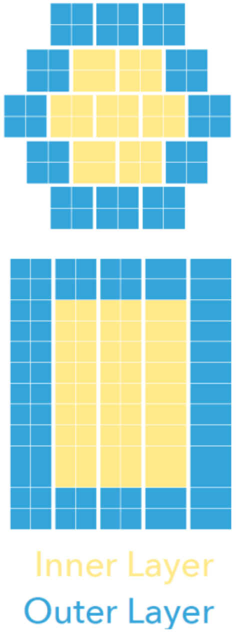


More recent runs

- Multiplicity 1 spectra very sensitive to signal events
- Many contaminations constrained by the higher multiplicity spectra

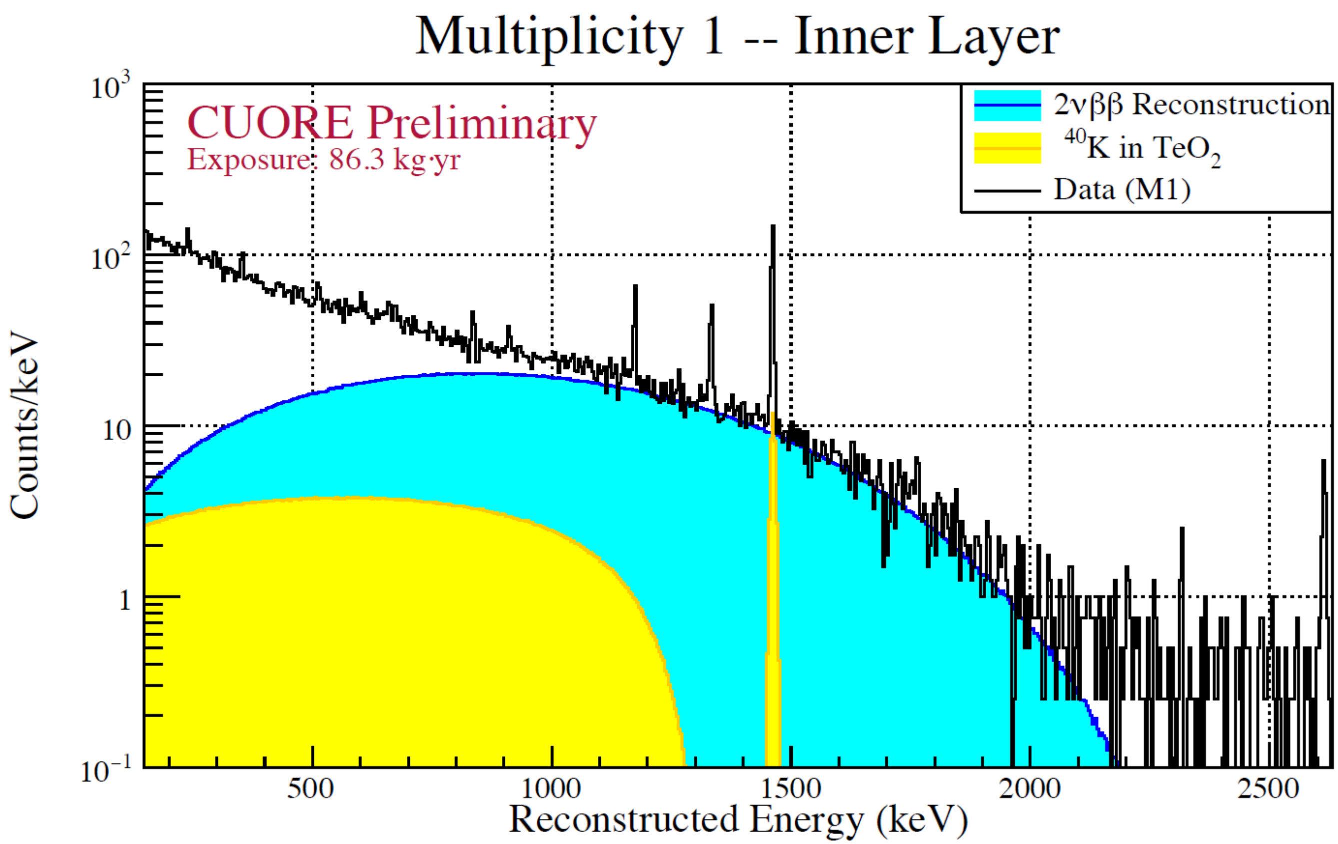






Measuring precisely 2νββ half-life

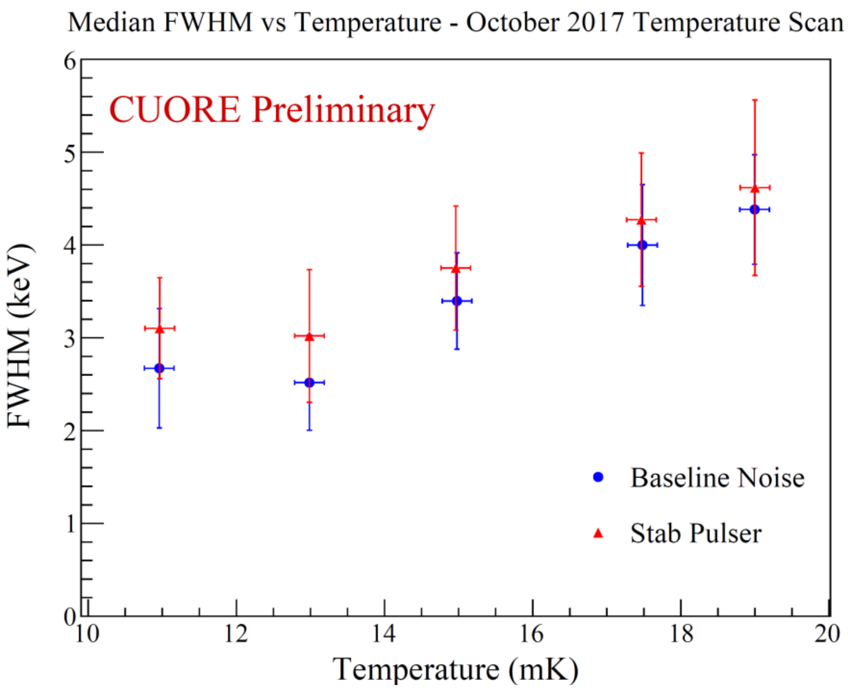
- 2νββ decay rate: [8.7 ± 0.1 (stat.) ± 0.2 (syst.)] × 10^{-21} yr^{-1}
- Half-life: [7.9 ± 0.1 (stat.) ± 0.2 (syst.)] × 10^{20} yr

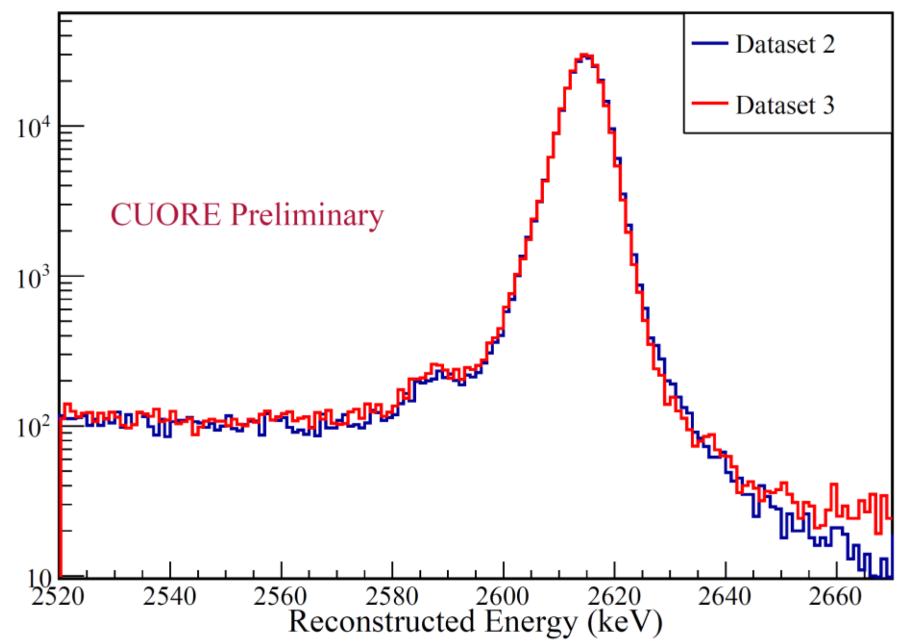


CUORE-0 : [8.2 ± 0.2 (stat.) ± 0.6 (syst.)] × 10^{20} yr; NEMO-3 : [7.0 ± 0.9 (stat.) ± 1.1 (syst.)] × 10^{20} yr

More recent data taking

- Detector temperature scan and cryostat optimization after the first PRL result
- Stable physics data taking since May 2018 at 11 mK.
- Data quality on par with previous datasets.





What's next for CUORE

- We set the most stringent limit on the 0νββ half-life of ^{130}Te and had the most precise measurement of the 2νββ half-life of ^{130}Te
- More physics analysis in the pipeline:
  - Double beta decay with Majoron emission
  - Dark Matter WIMP and axion searches with low energy analysis
  - ββ decays to excited states, β^+/E.C. decays
- CUORE will continue to be one of the most sensitive searches for 0νββ for the next few years.
- Sensitivity to 0νββ half-life with 5 year live time reaches 9×10^{25} yr
- CUORE Upgrade with Particle ID (CUPID) R&D is on-going.

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

CSNSM

SINAP

UNIVERSITAS STUDII PADUANI MCCXXII

Massachusetts Institute of Technology

Lawrence Livermore National Laboratory

VirginiaTech 1872 Invent the Future®

INFN

ALMA MATER STUDIORUM UNIVERSITA DI BOLOGNA A.D. 1088

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

Yale

SHANGHAI JIAO TONG UNIVERSITY 1896

CAL POLY SAN LUIS OBISPO

CUORE

SAPIENZA UNIVERSITÀ DI ROMA

UCLA

BERKELEY LAB

UNIVERSITY OF SOUTH CAROLINA

THE UNIVERSITY OF CALIFORNIA 1868 LET THERE BE LIGHT