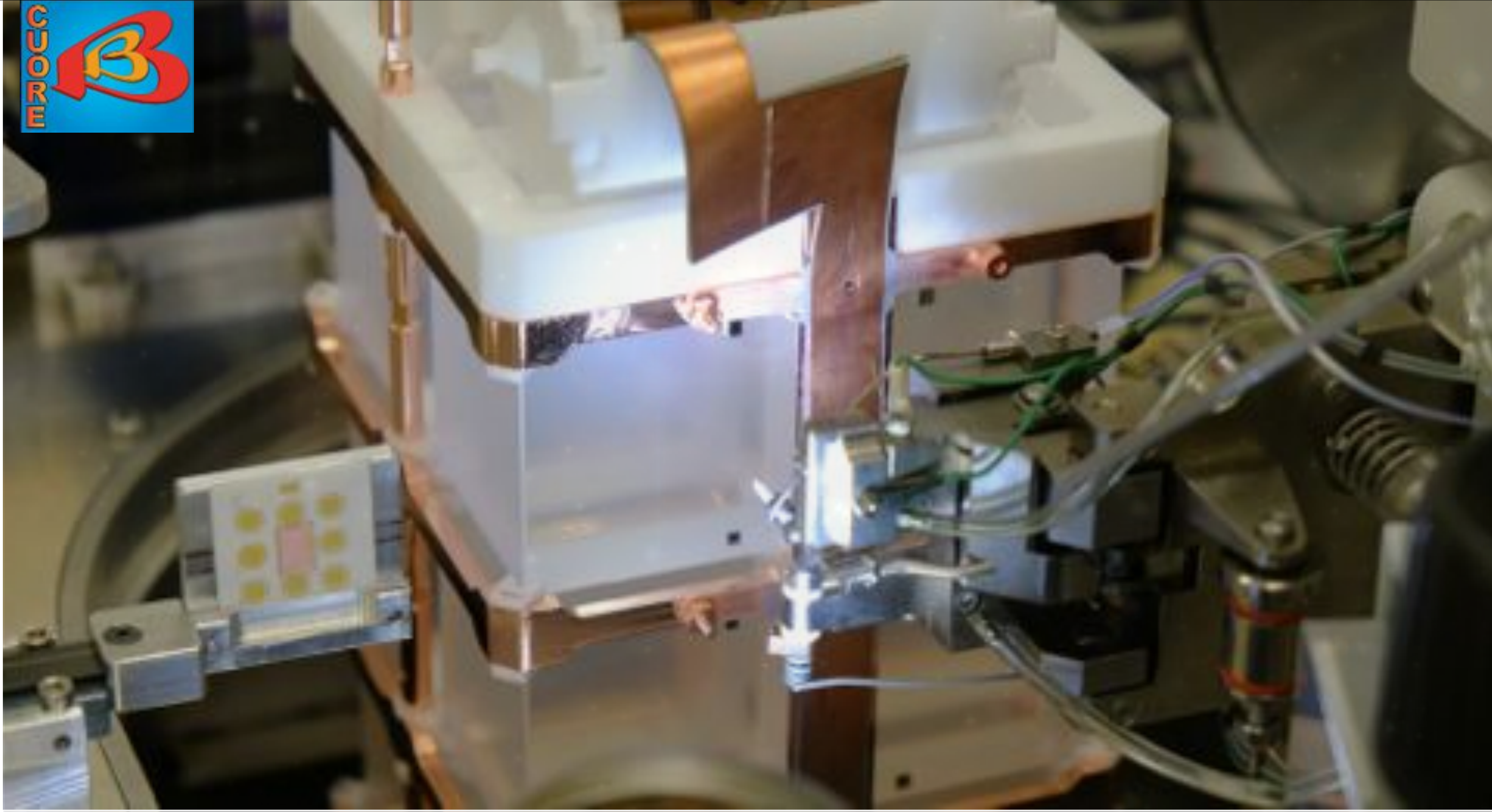


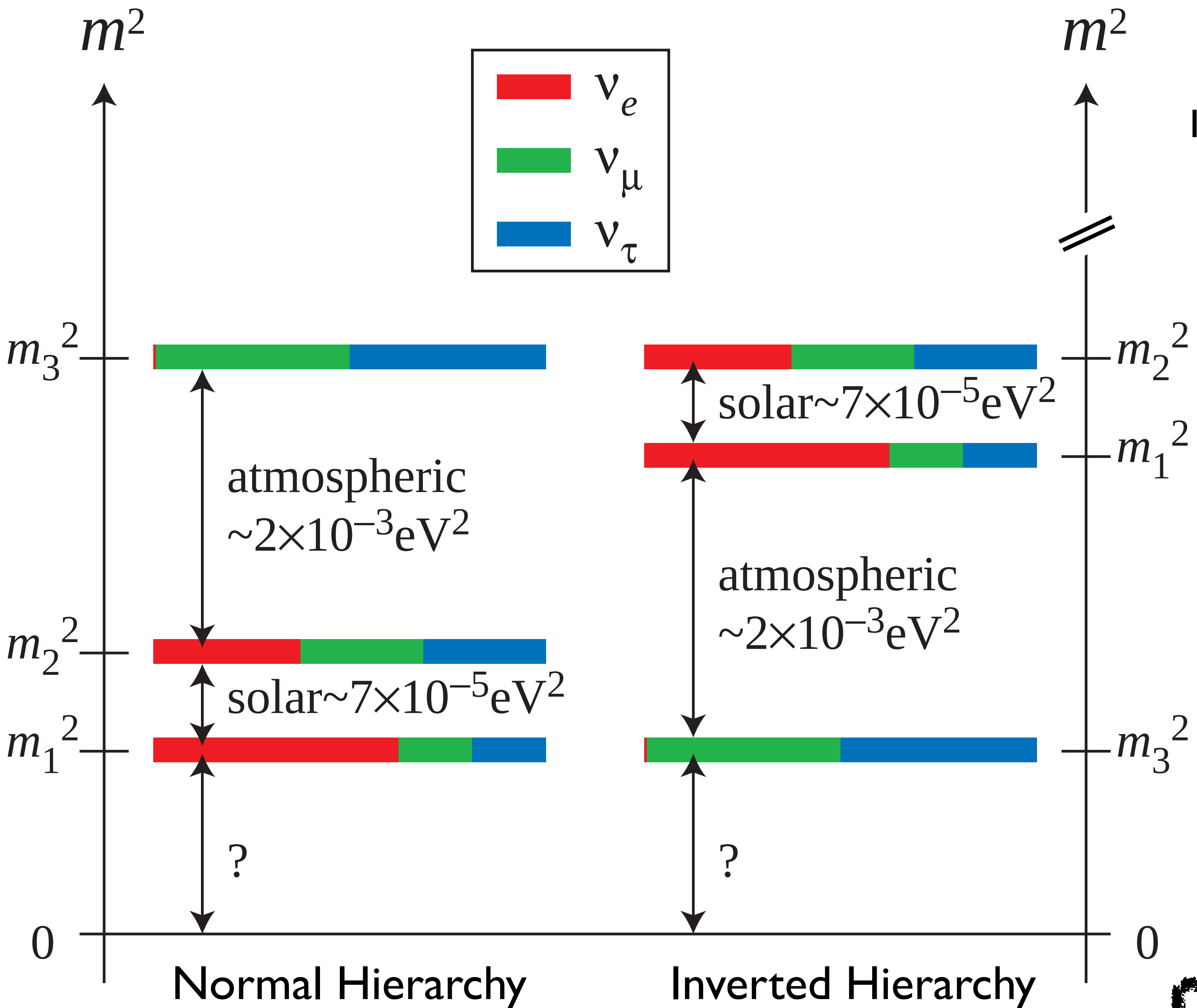
Search for Neutrinoless Double-Beta Decay with CUORE

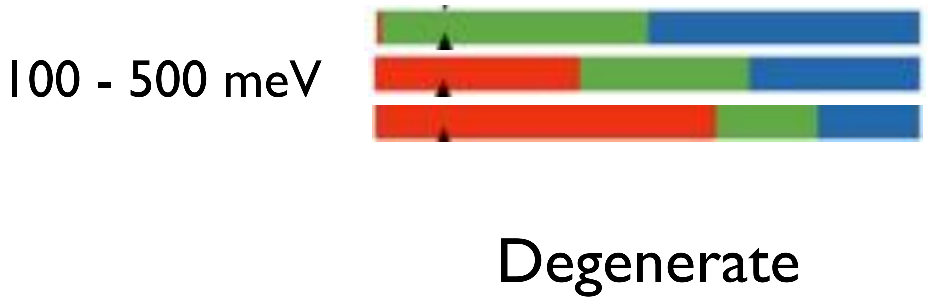
Kyungeun E. Lim (on behalf of the CUORE collaboration)

Jan. 14, 2014, WIDG Seminar, Yale University

What we (don't) know about Neutrinos

Neutrino Mass Splitting





Rep. Prog. Phys. 76, 056201 (2013)

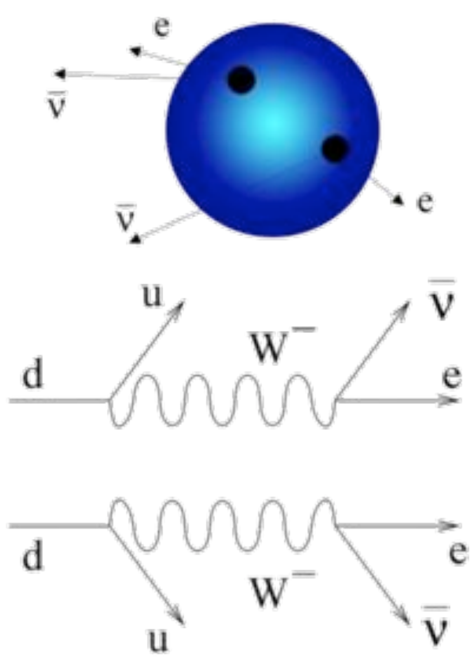
Is the neutrino its own antiparticle?

Outline

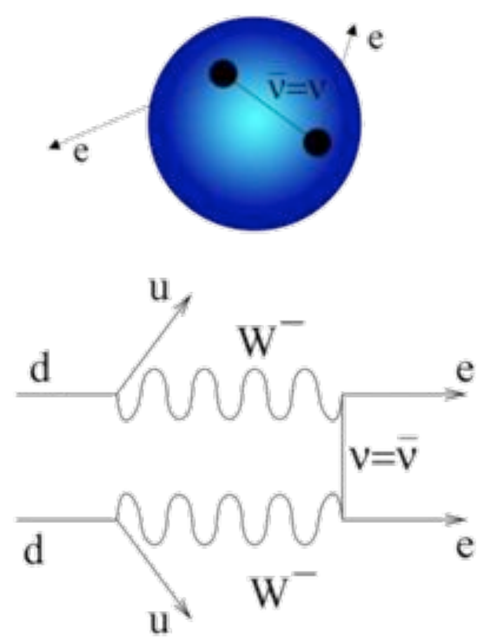
- Neutrinoless double-beta decay search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : Validation of CUORE and more
- Summary

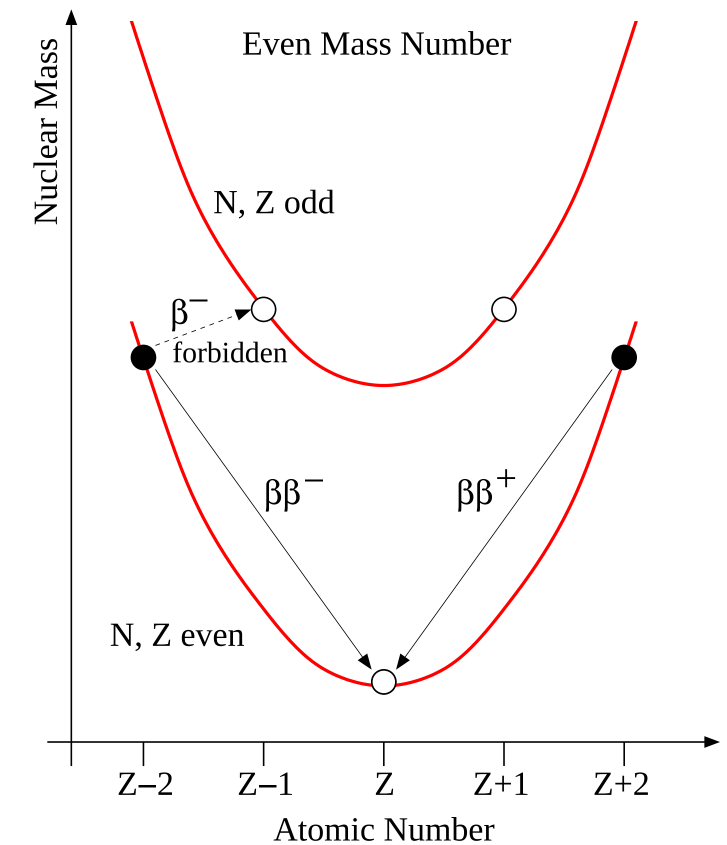
Neutrino(less) double-beta decay

- 2νββ decay



- 0νββ decay





- Allowed in SM
- Observed in several nuclei ($T_{1/2}^{2\nu} \sim 10^{18}$-$10^{21}$ yr)

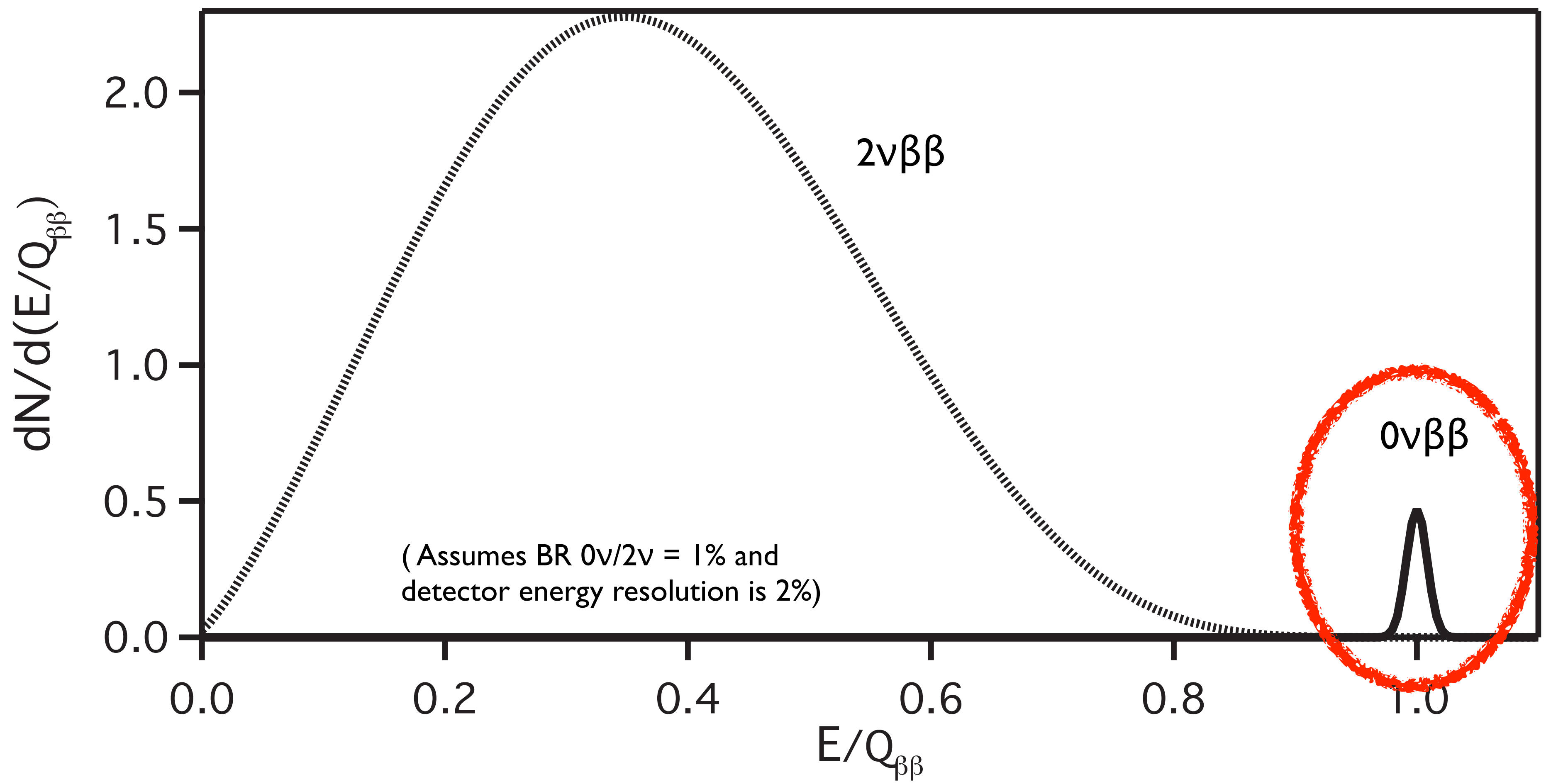
- Beyond SM (Lepton number violating process)
- Hypothetical process only if $\nu = \bar{\nu}$ and $m_\nu > 0$

Observation of 0νββ decay

1. will establish that neutrinos are Majorana Particles ($\nu = \bar{\nu}$)
2. will provide indirect info of the ν mass
3. may provide info about the mass hierarchy

Signature of 0νββ Decay

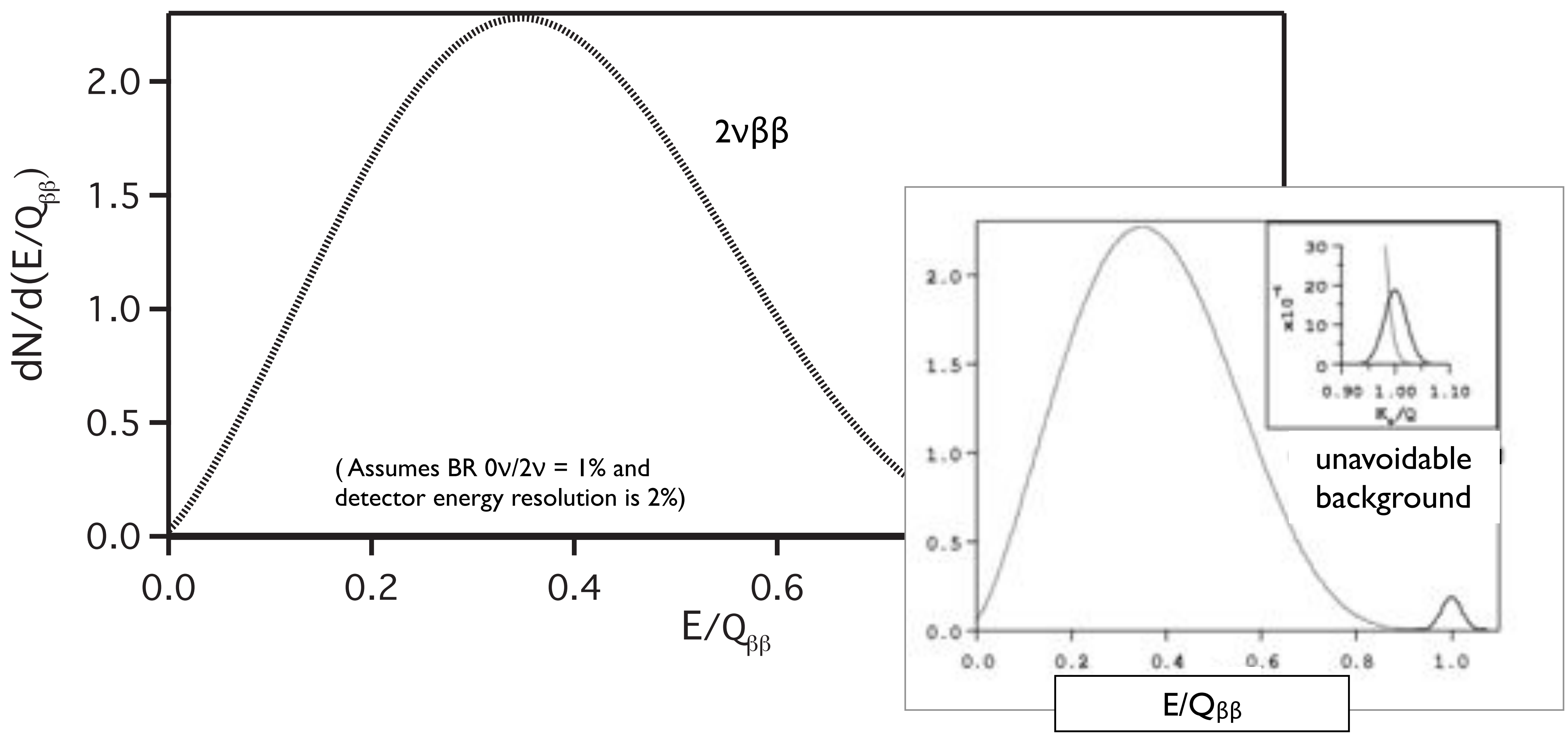
ββ summed e^- energy spectrum



- Look for peak in the detector at the Q-value of decay.
- Good energy resolution of a detector suppresses intrinsic background from 2νββ decay.

Signature of 0νββ Decay

ββ summed e⁻ energy spectrum



- Look for peak in the detector at the Q-value of decay.
- Good energy resolution of a detector suppresses intrinsic background from 2νββ decay.

Search for 0νββ Decay

Decay rate:

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

Well defined

Difficult to calculate

- Probes absolute mass scale
- Sensitive to hierarchy

$T_{1/2}^{0\nu}$	0νββ half-life
$G^{0\nu}$ (Q,Z)	phase space factor $(\propto Q^5)$
$M^{0\nu}$	Nuclear Matrix Element (NME)
$m_{\beta\beta}$	effective ββ neutrino mass
m_e	electron mass

Search for 0νββ Decay

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$T_{1/2}^{0\nu}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

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a	isotopic abundance of source
ε	detection efficiency
M	total detector mass
b	background rate /mass/energy
t	exposure time
δE	energy resolution (spectral width)

Search for 0νββ Decay

Decay rate:

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δE	energy resolution (spectral width)

Detector Building Strategies

- High Q-value
- Large total mass
- High isotopic abundance
- Ultra-low background
- Good energy resolution
- NME

Search for 0νββ Decay

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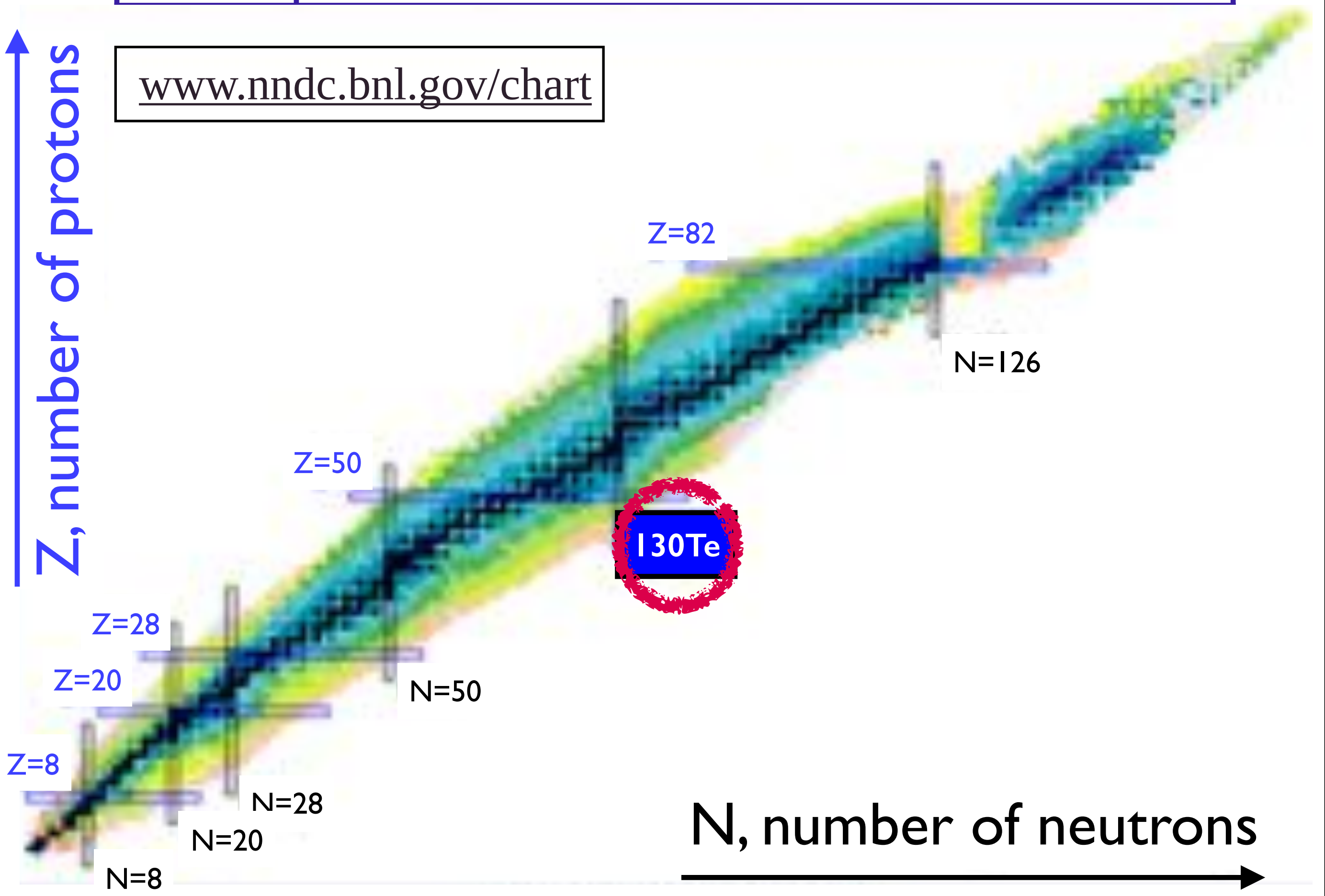
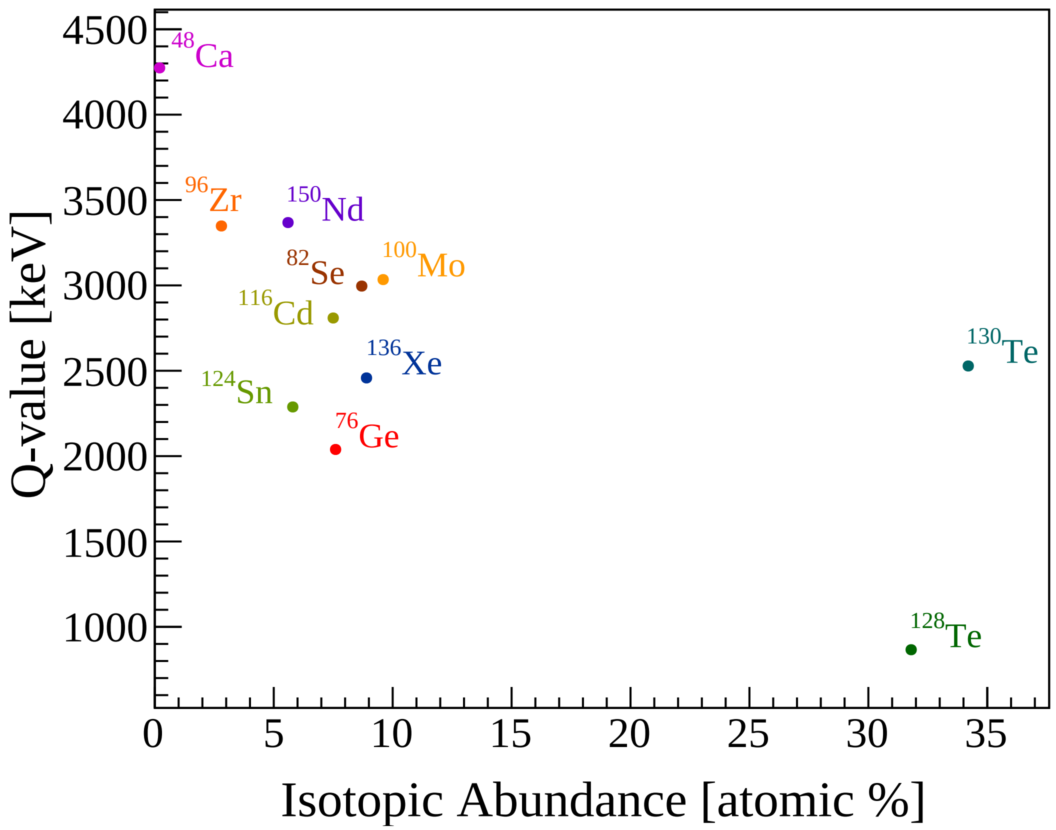
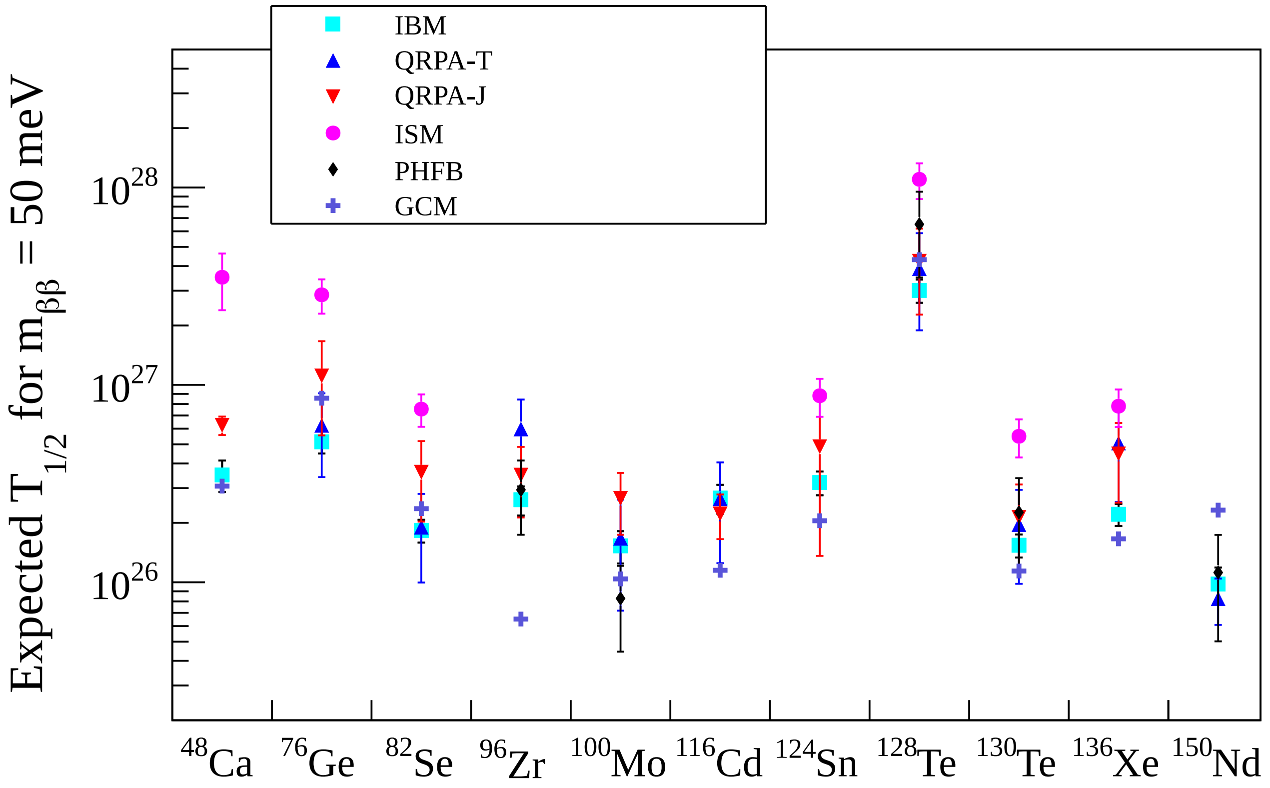
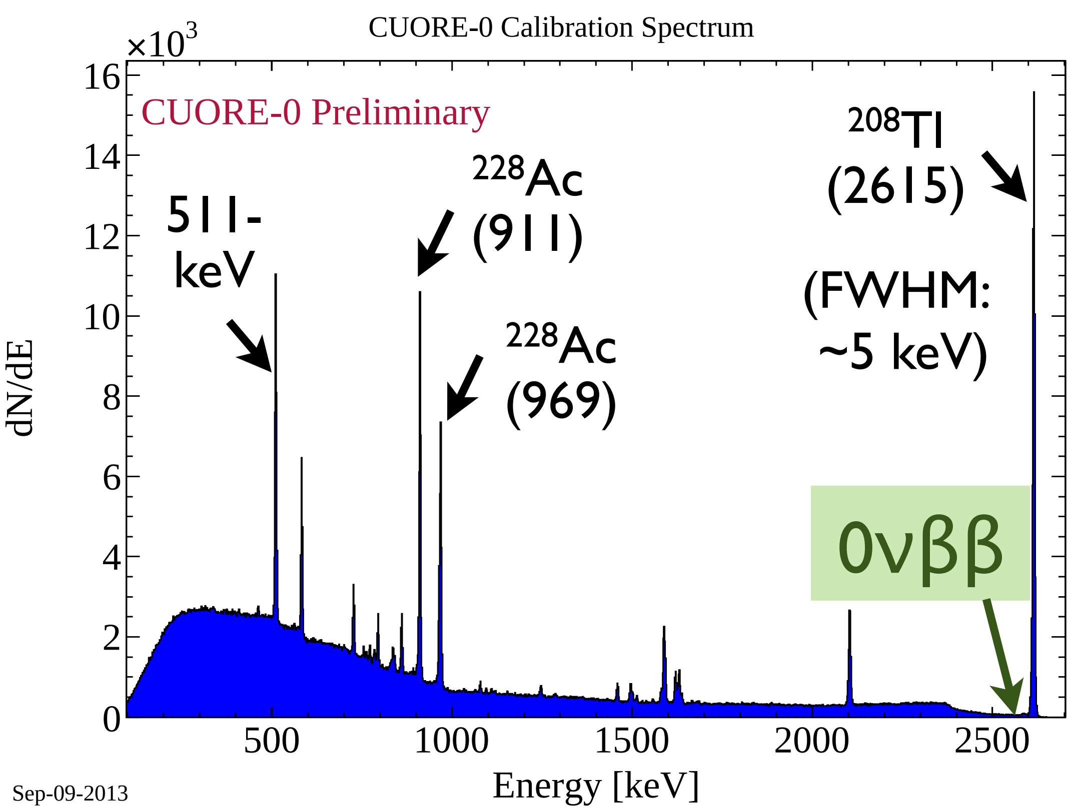


^{130}Te for 0νββ Decay

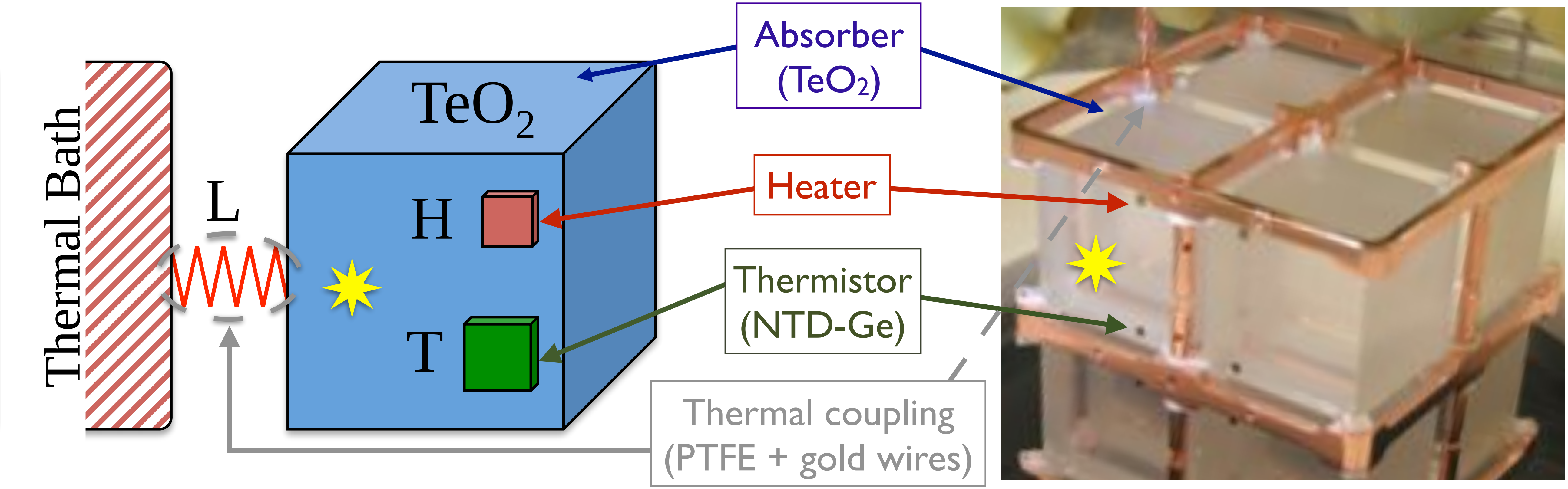




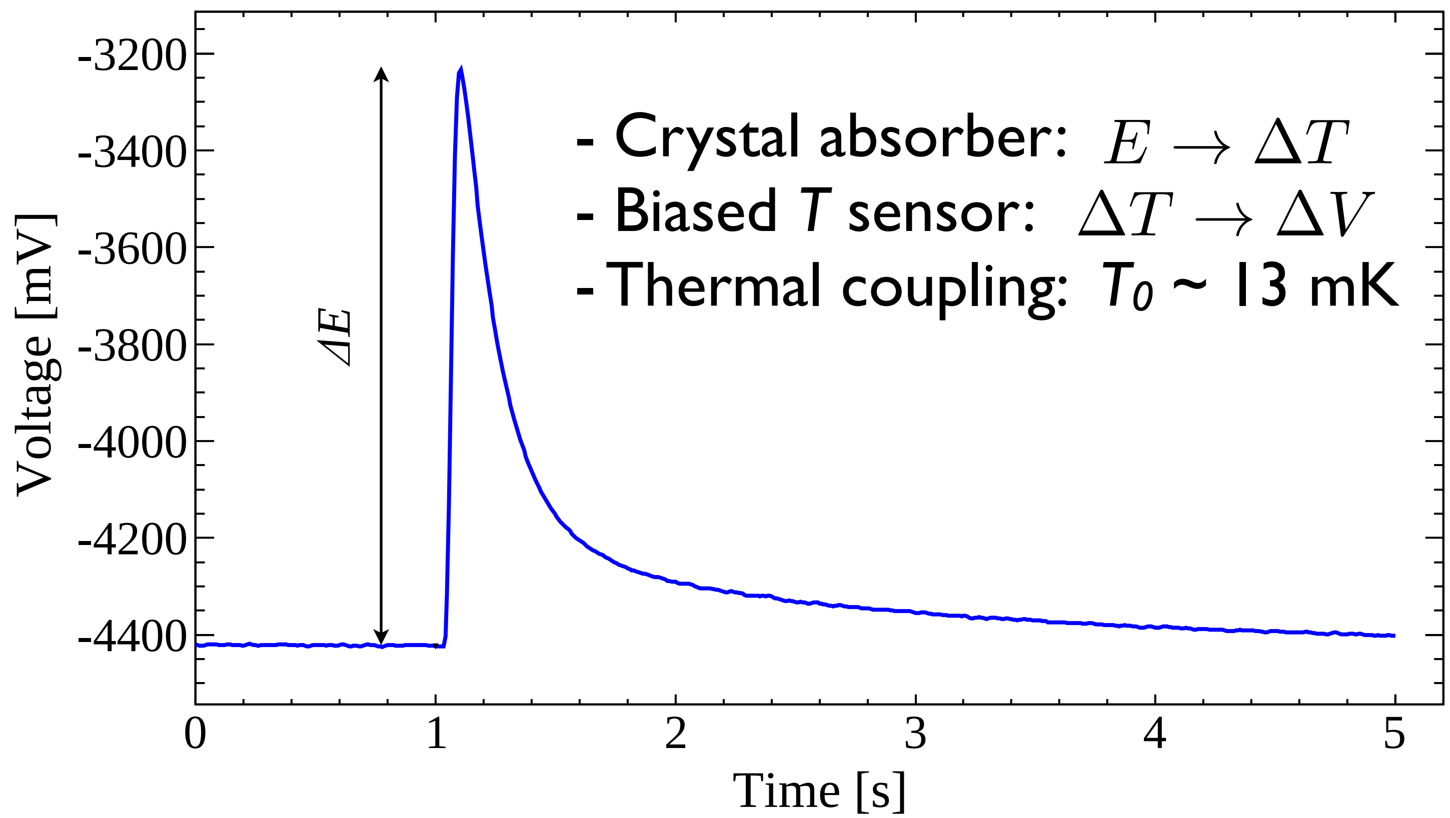
- ^{130}Te + thermal detector w/ excellent energy resolution is appealing for the 0νββ decay detection.



TeO_2 Bolometers



- Measure energy deposition through temperature rise.



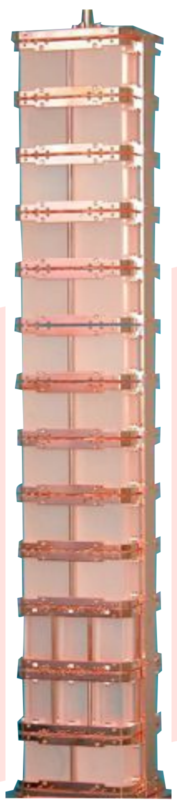
Outline

- Neutrinoless double-beta decay search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : Validation of CUORE and more
- Summary

The CUORE 0νββ Search

CUORE: Cryogenic Underground Observatory for Rare Events

Cuoricino (2003-2008)



Achieved (2008)

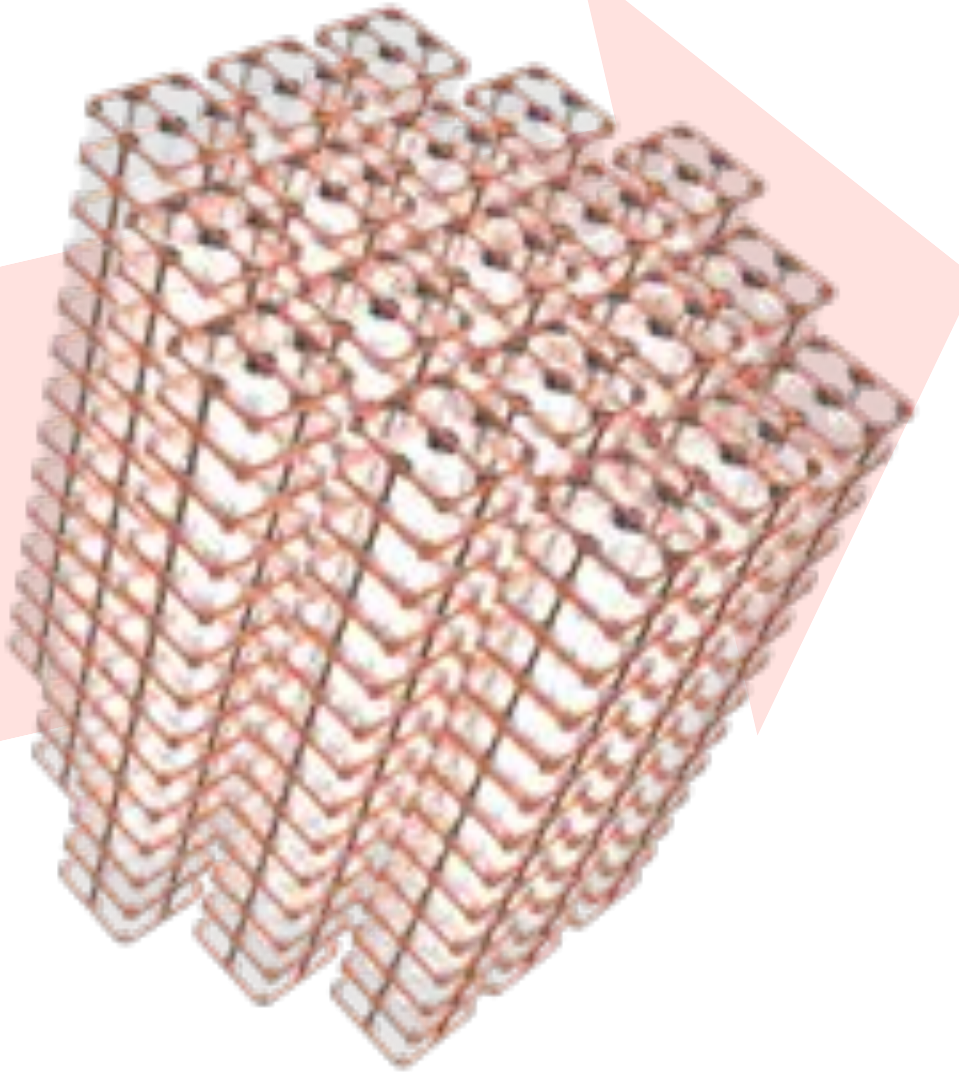
$\langle m_{\beta\beta}\rangle_{90\%\ \text{C.L.}} = 300 - 710\ \text{meV}$

CUORE-0 (2013-2015)

Projected (2015)

$\langle m_{\beta\beta}\rangle_{90\%\ \text{C.L.}} = 204 - 533\ \text{meV}$

CUORE (2015-2020)



Projected (2020)

$\langle m_{\beta\beta}\rangle_{90\%\ \text{C.L.}} = 51 - 133\ \text{meV}$

CUORE Collaboration

(Oct. 31, 2013 @ LNGS)

CUORE Yale Group

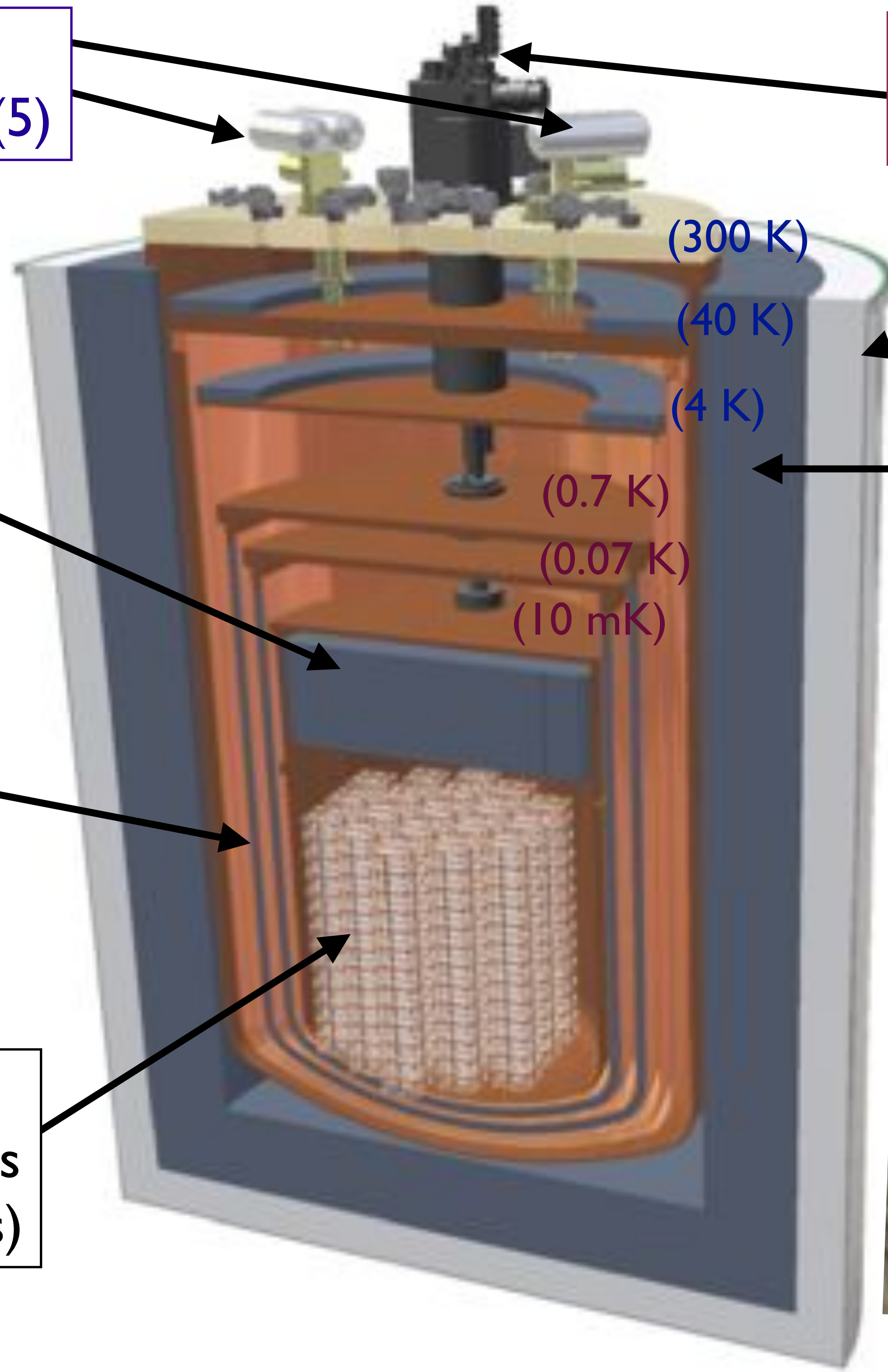
- Karsten Heeger (faculty, PI)
- Reina Maruyama (faculty)
- Tom Wise (research scientist)
- Kyungeun Lim (postdoc)
- Jeremy Cushman (grad)

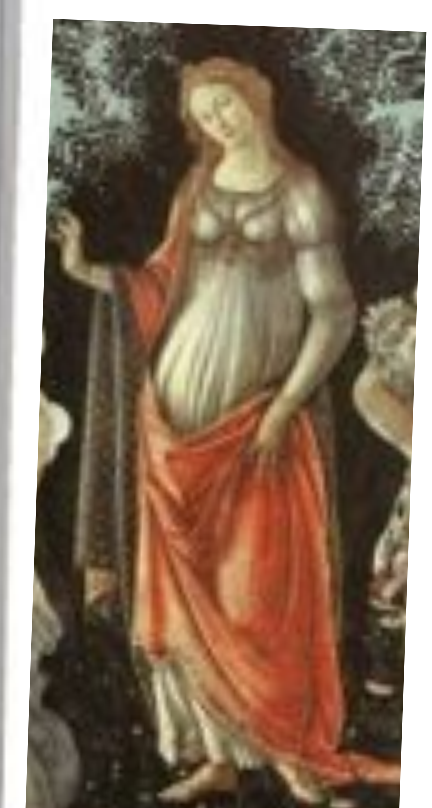
◆ Development of the CUORE detector system
◆ Calibration of CUORE
◆ Development of CUORE muon tagging system
◆ Commissioning of CUORE cryostat
◆ CUORE and CUORE-0 analysis

CUORE at LNGS

CUORE at LNGS

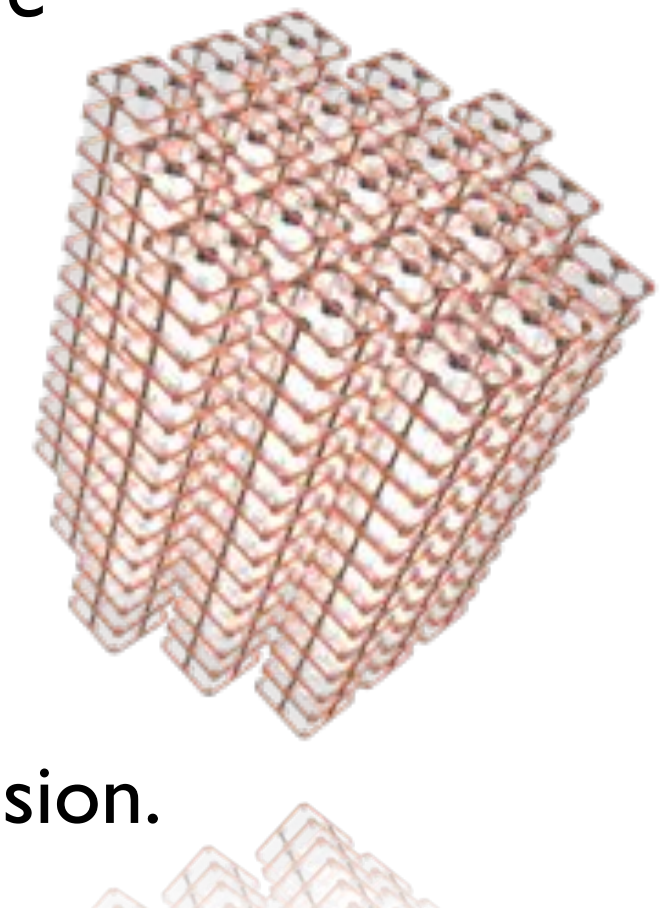
The CUORE Detector





Detector Improvements

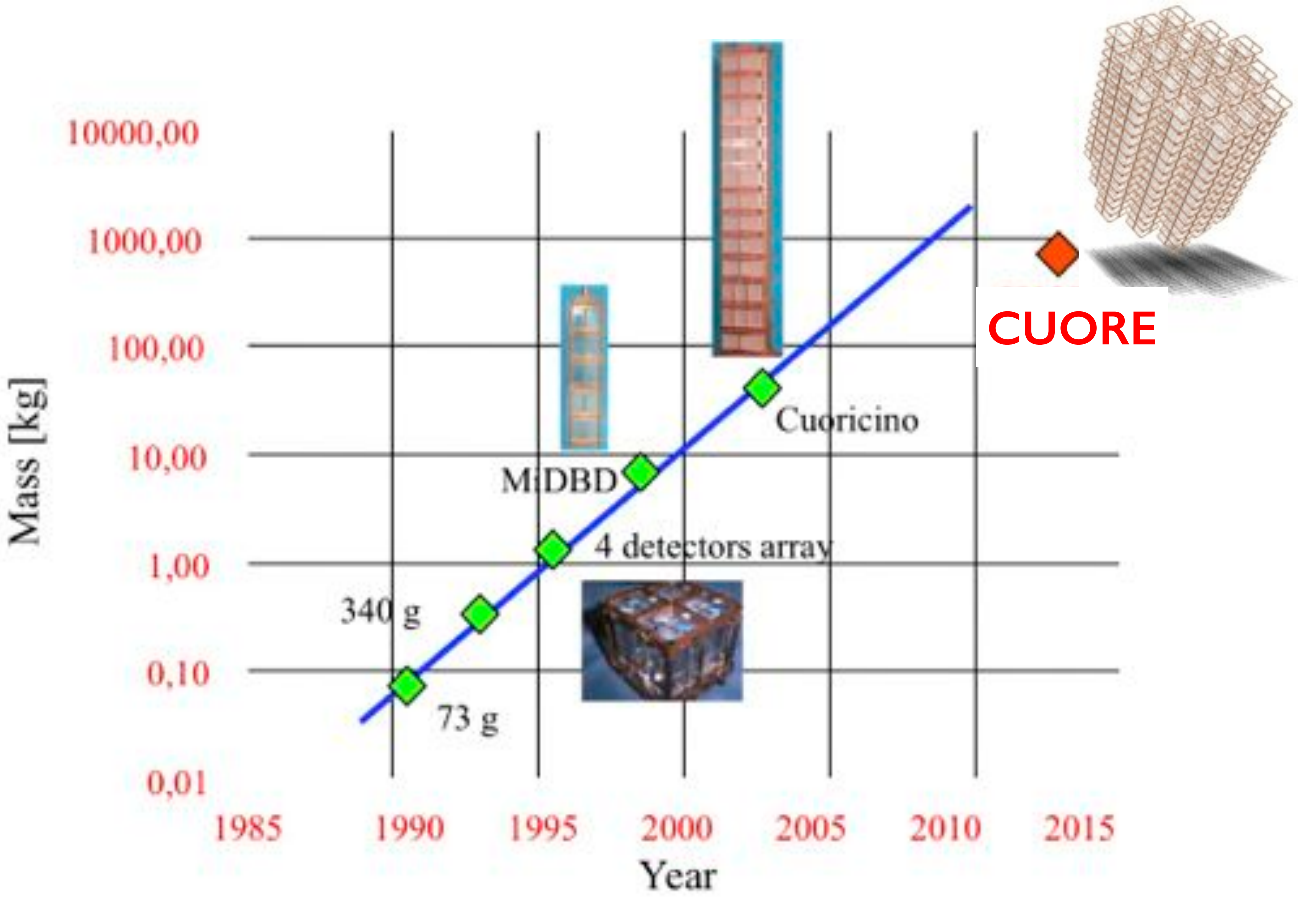
- More bolometers (Self-shielding, more powerful single crystal hit requirement).
- More radiopure crystals.
- Improved copper surface treatment, less of copper.
- Optimized tower assembly procedure.
- Radiopure materials + Roman lead shield (< 4mBq/kg ^{210}Pb) for cryostat.
- Separated DU suspension from crystal tower suspension.



	Cuoricino	CUORE-0	CUORE
^{130}Te mass [kg]	11	11	206
Background [c/keV/kg/y] @ 2527 +/- 20 keV	0.17	0.07	0.01
E resolution (FWHM) [keV] @ 2615 keV	~ 6	5.7	5
$\langle m_{\beta\beta} \rangle$ [meV] @ 90% C.L.	300 - 710	204 - 533	51 - 133

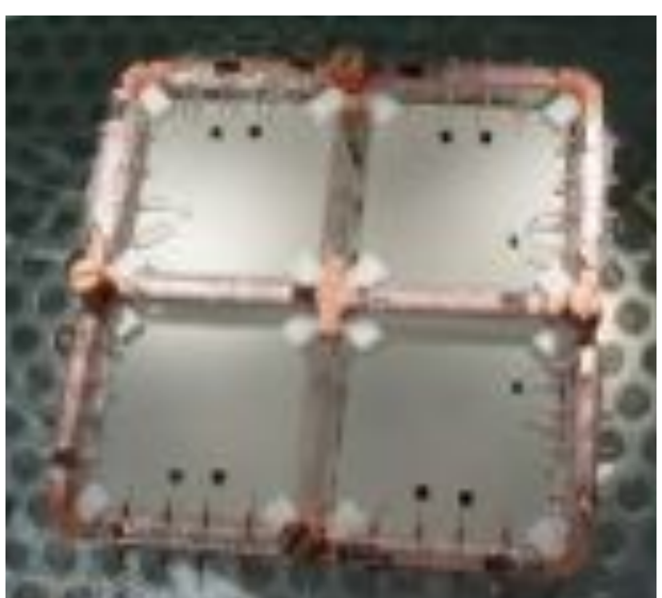
Mass: from a few kg to a ton scale

- Production of CUORE crystals started at SICASS in China in 2008.
- Transported via ship to avoid cosmogenic activation.
- All the crystals are procured.
- Stored in a dedicated storage area underground.

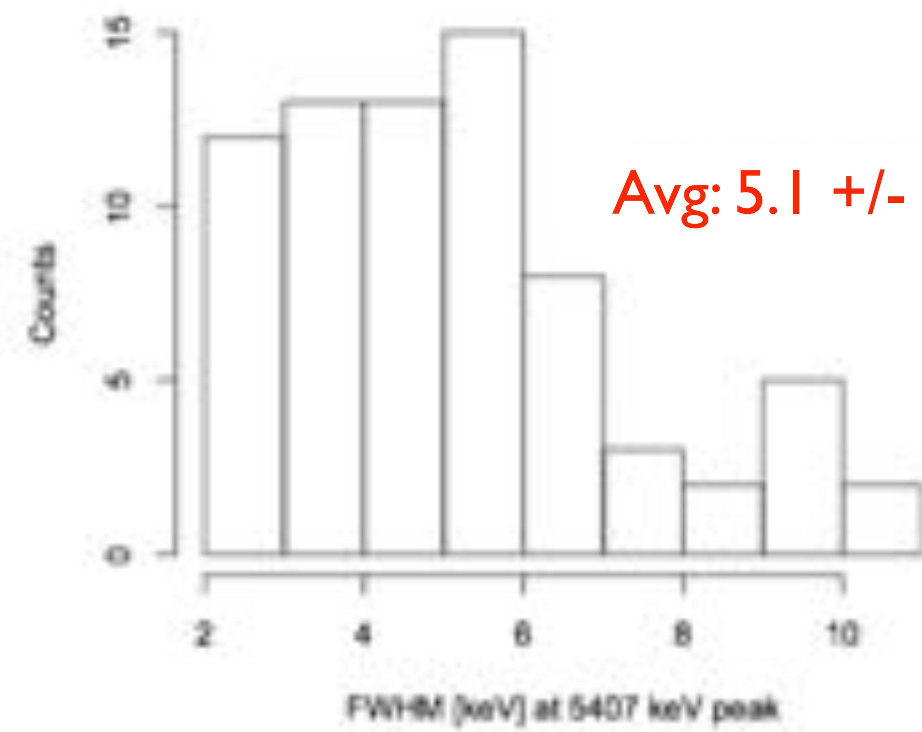


TeO_2 Crystals

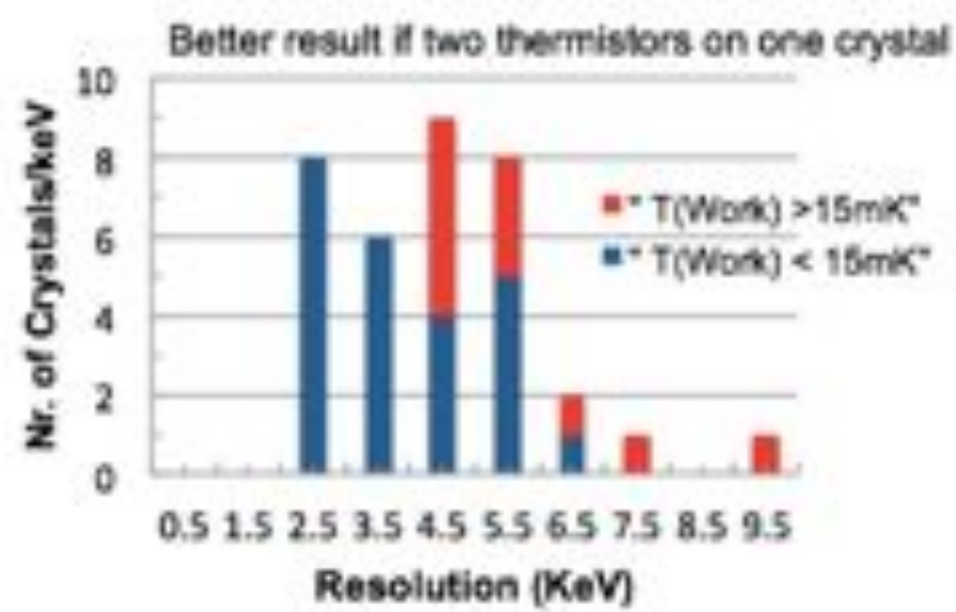
- Crystal cutting, wrapping is done in the clean room in SICASS.
- Visual Inspection (Free of precipitates/cracks/scratches)
- Randomly select 4 crystals from each production batch and test bolometric performance (CUORE Crystal Validation Runs, CCVR)



CCVR 1-9

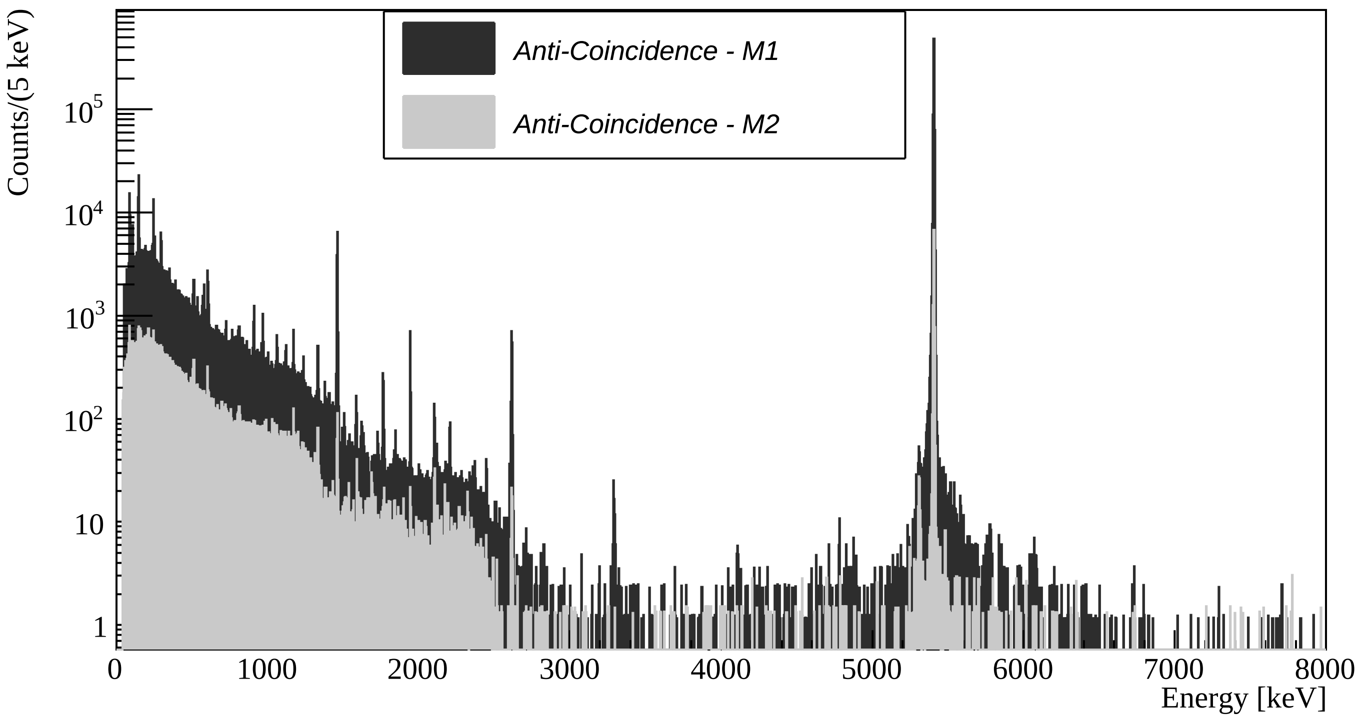


Avg: 5.1 +/- 2.1 keV



CUORE Crystal Validation Runs

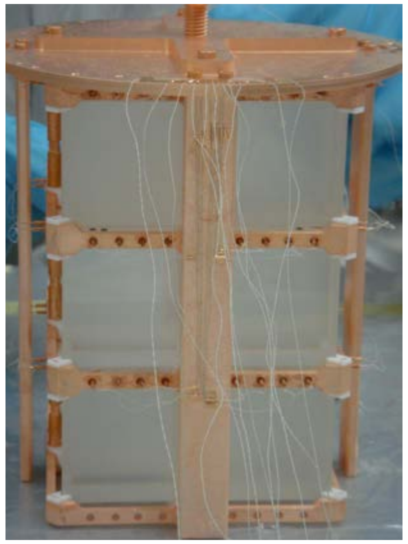
- CCVR also serves as radioactive contamination measurements of the crystals.

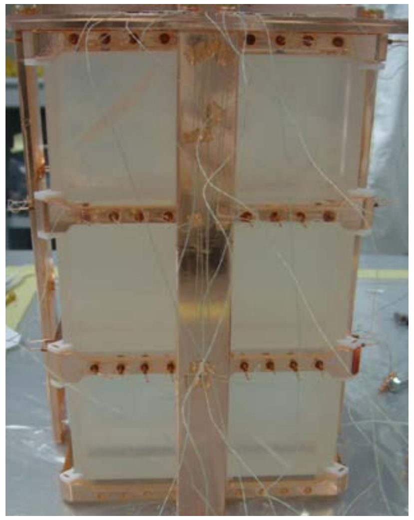


90% CL upper limit	^{232}Th	^{238}U	^{210}Po
Bulk Contaminations (Bq/kg)	< 8.4E-7	< 6.7 E-7	< 3.3 E-6
Surface Contaminations (Bq/cm^2)	< 2E-9	< 1E-8	< 1E-6

Astropart. Phys. 35, 839 (2012)

Reduction of Copper Surface Contamination

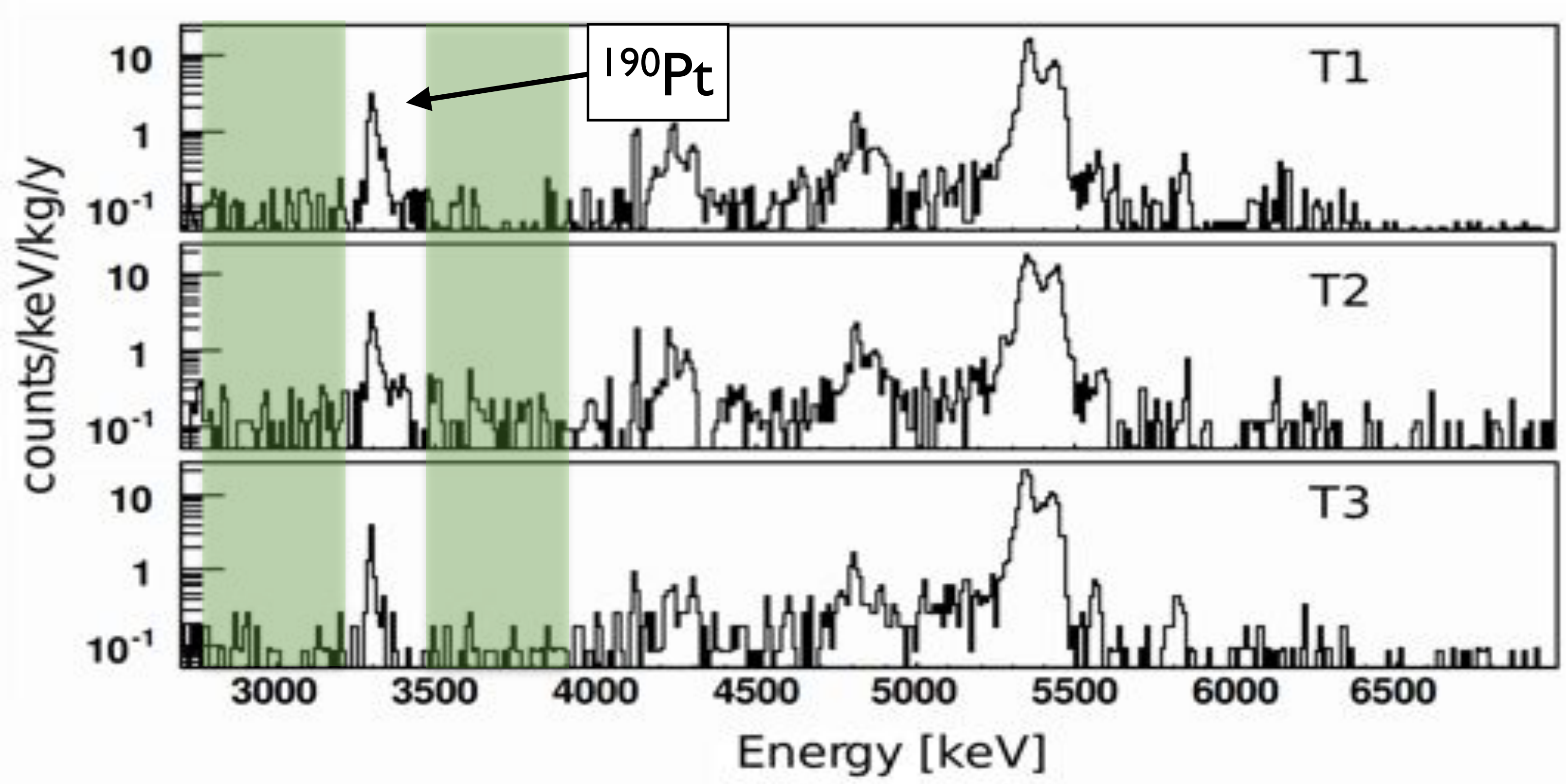




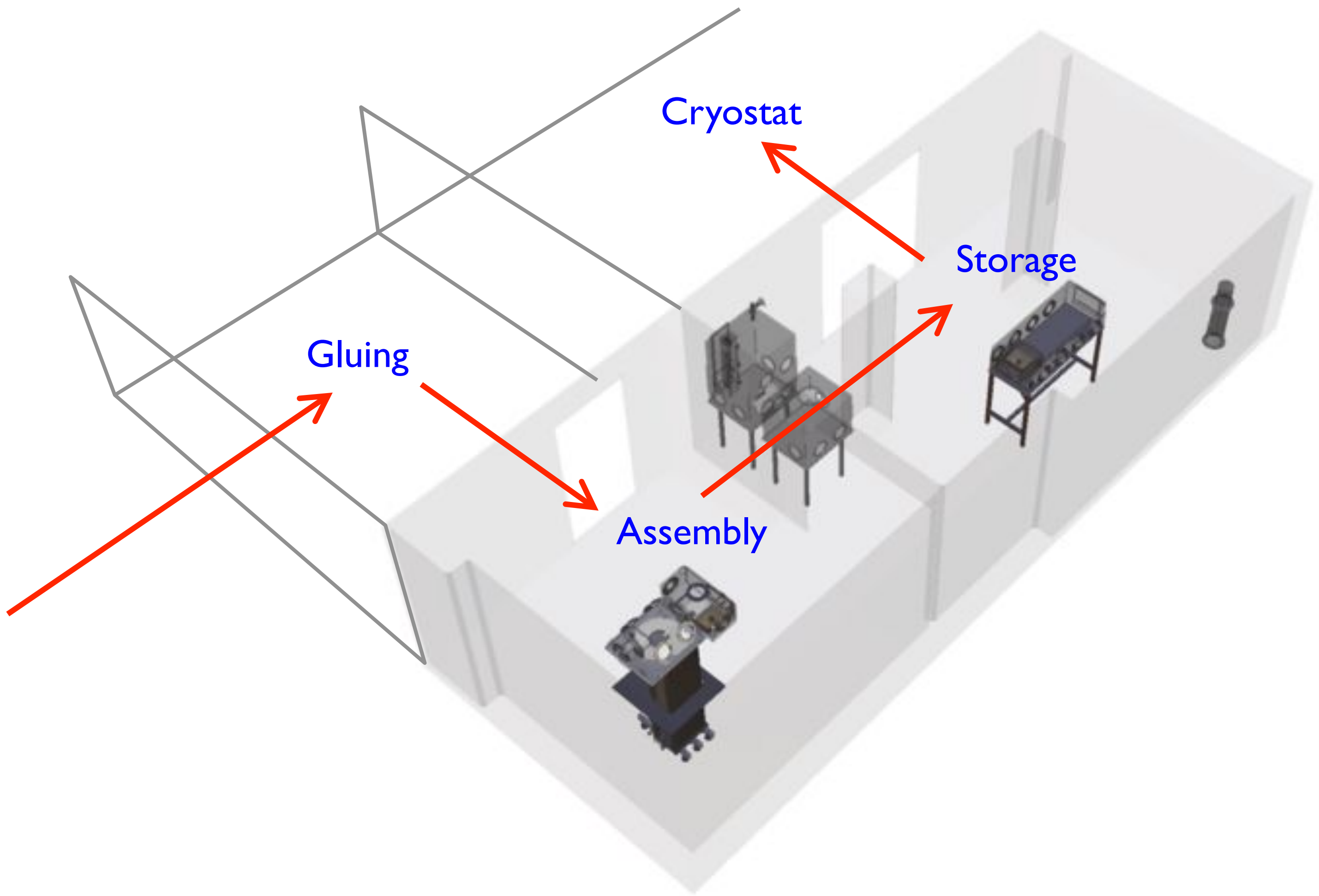
- Three Tower Test (TTT)
  - T1: Polyethylene wrapped
  - T2: Chemical etching and cleaning
  - T3: Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching (TECM) cleaning

Astropart. Phys. 45, 13 (2013)

- Best results (T1) is 0.052±0.008 c/keV/kg/yr in the 2.7 to 3.9 MeV range.
- T3 is comparable to T1.
- x2 less value compared to that of Cuoricino.

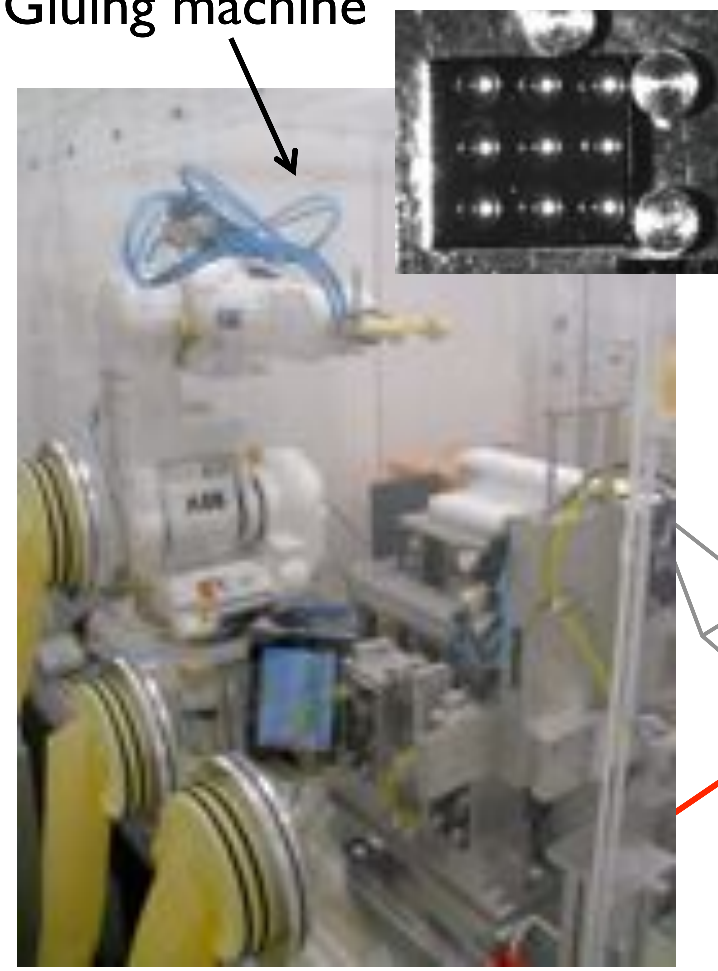


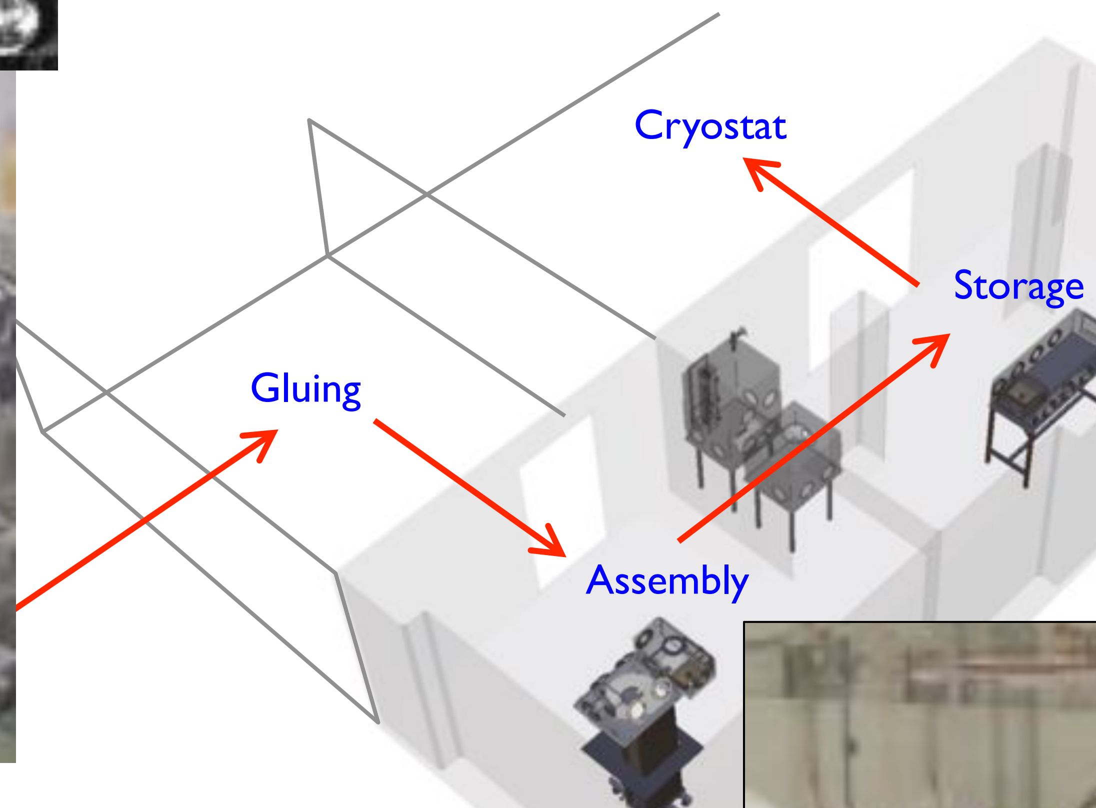
Detector Assembly

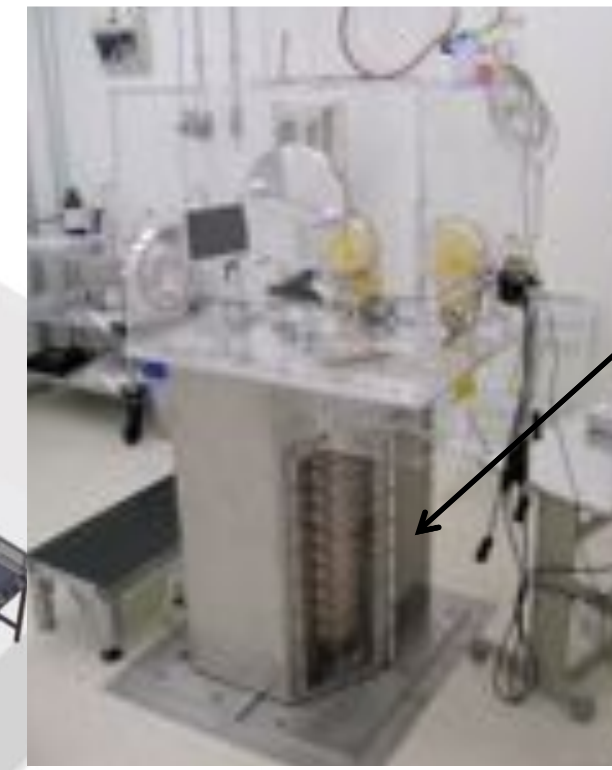


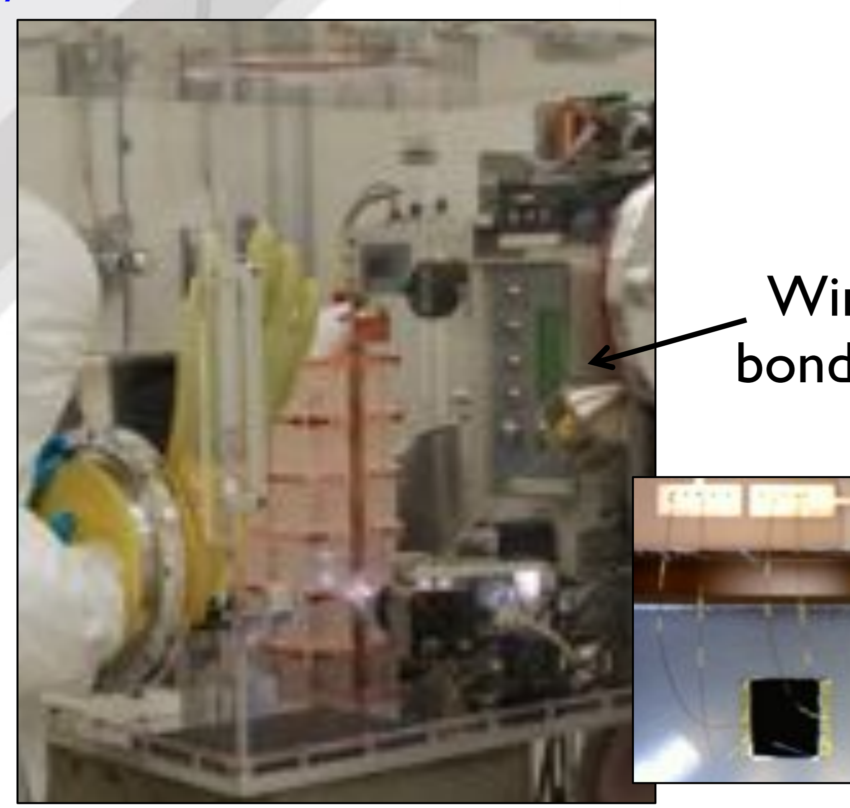
- Crystals are prepared & assembled into towers inside N_2-fluxed glove boxes in clean room.

Detector Assembly

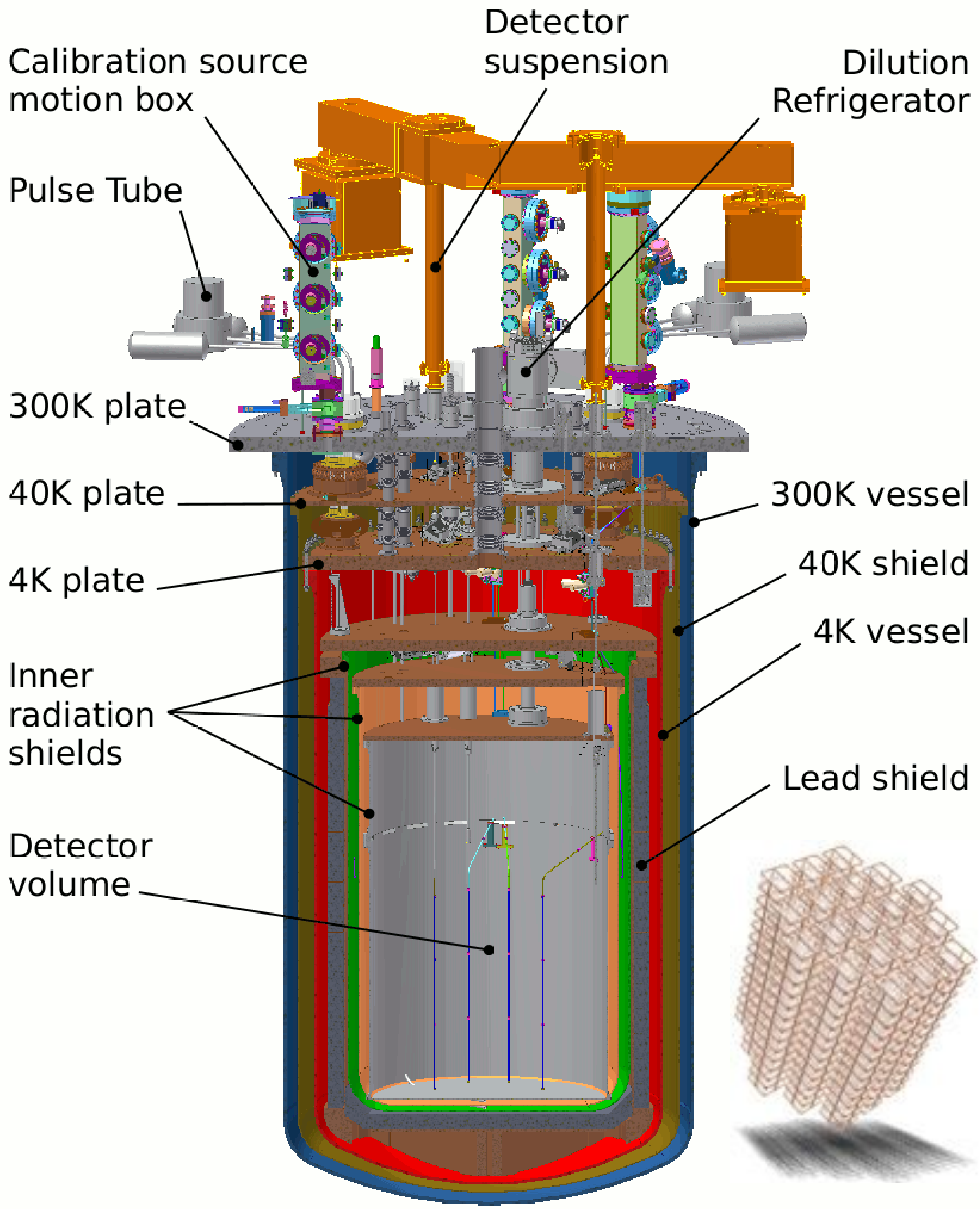








CUORE Cryogenic System



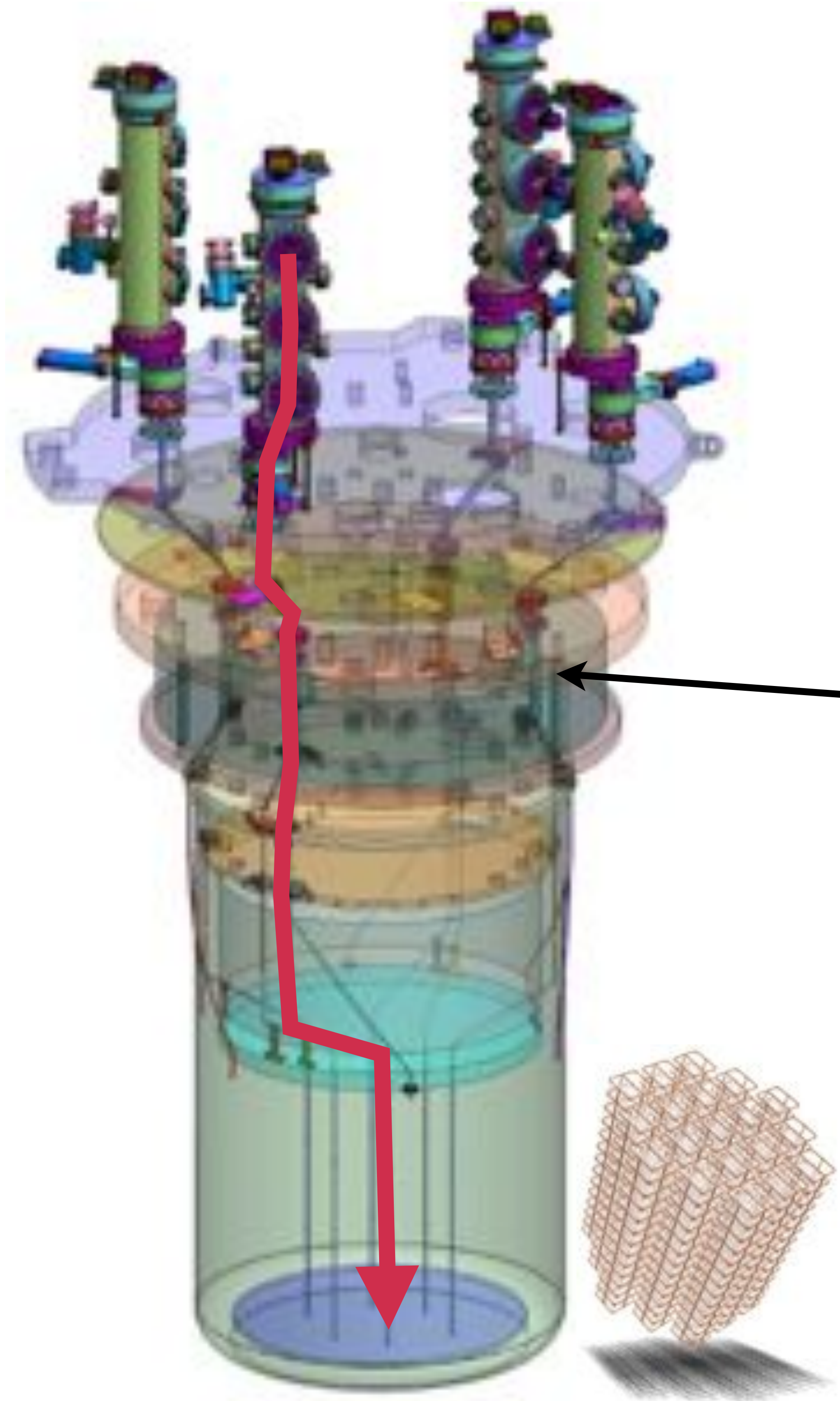
arXiv:1306.1351

- Custom, cryogen-free dilution refrigerator (minimum maintenance and dead time)
- Separation of detector suspension from the cryostat suspension
- Total mass: ~ 20 tons
- Internal Roman lead shield : 6 cm thick

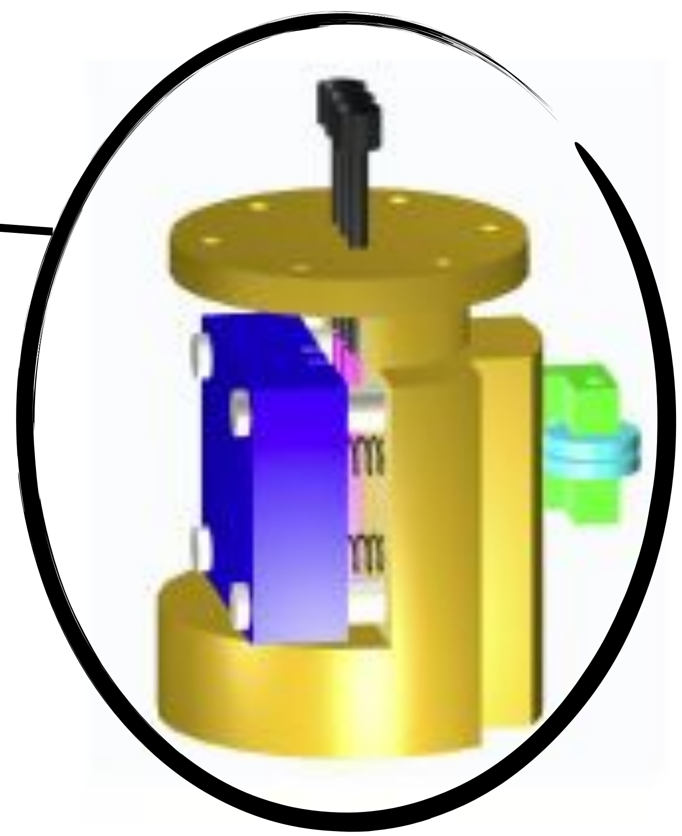
doi:10.1038/news.2010.186 (nature)

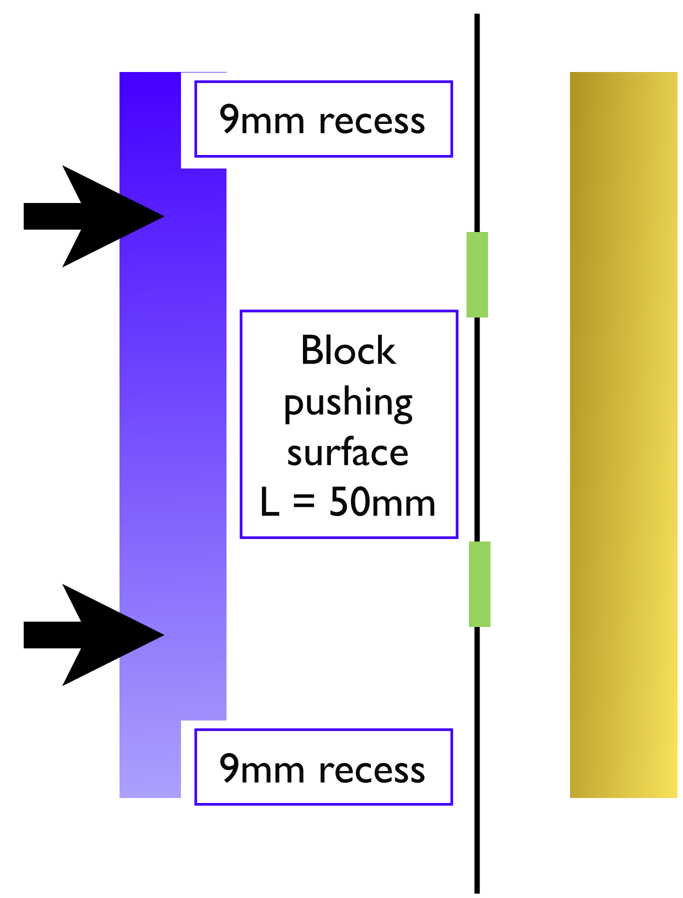
- Calibration system

CUORE Calibration System



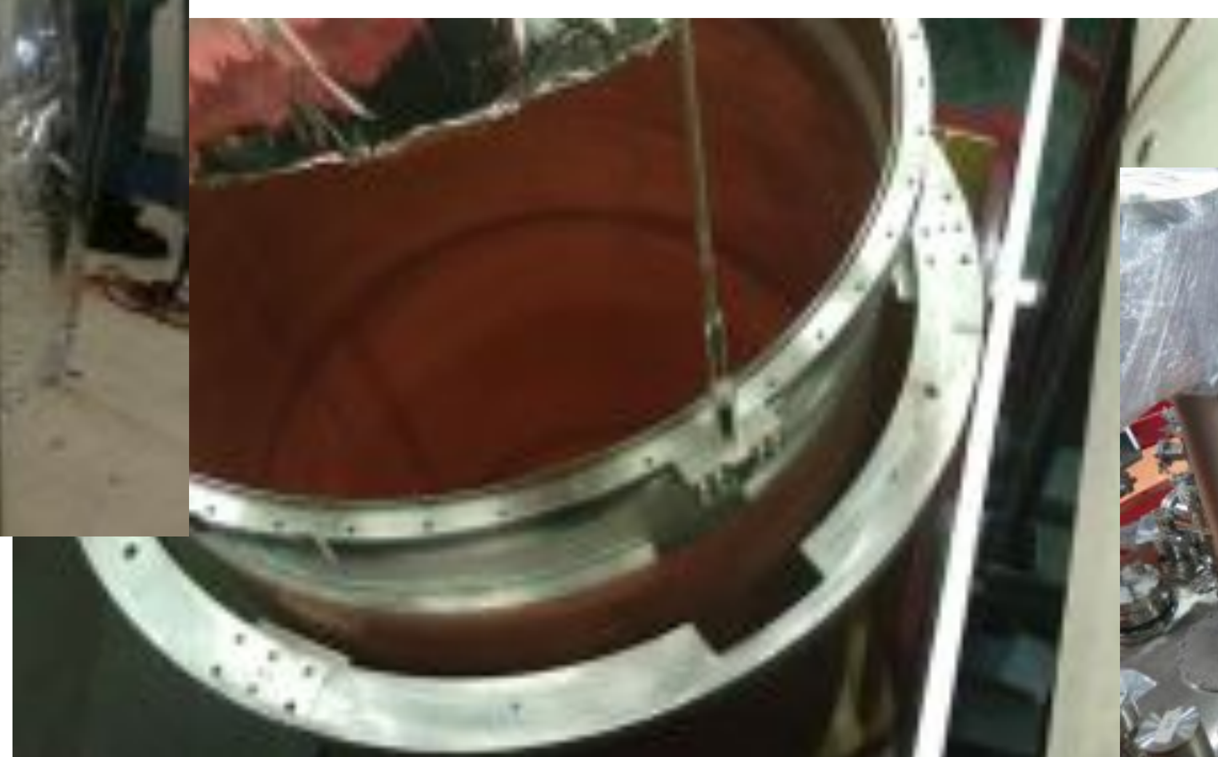
- A string with source capsules move from the top of the cryostat at 300K to the bolometer array at ~ 13mK.
- The source capsules are mechanically squeezed by a thermalizer and cooled down to 4K.

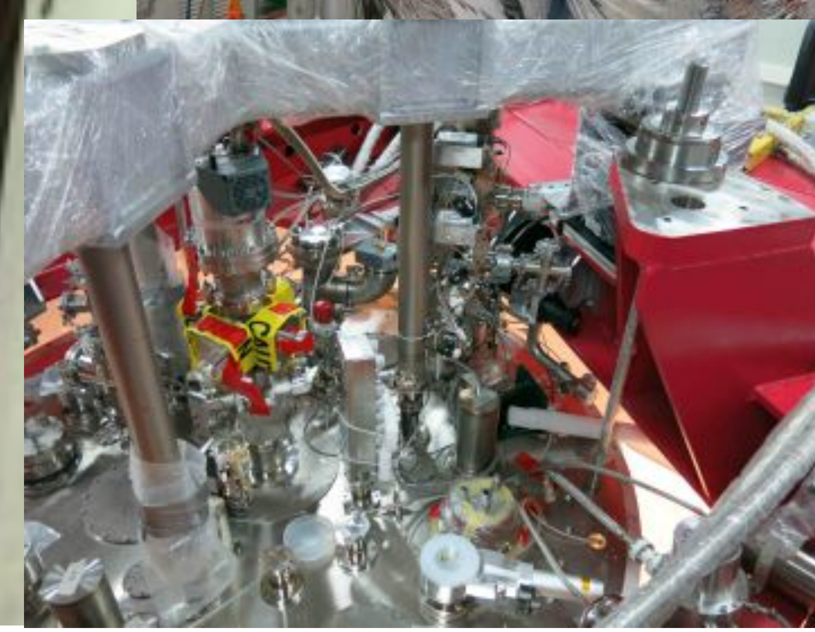




- Cooled down source capsules arrive near the bolometers to irradiate the detector.

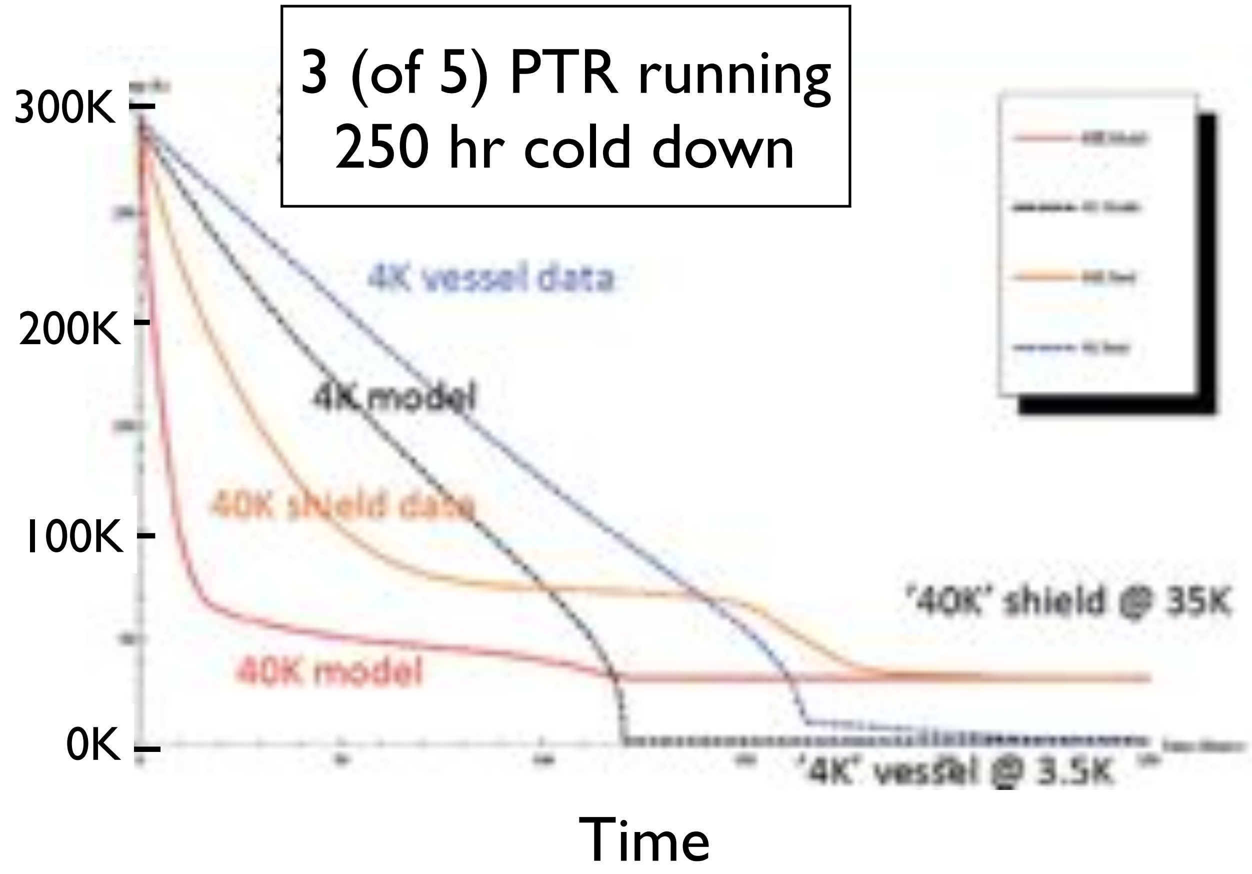
Cryostat Installation

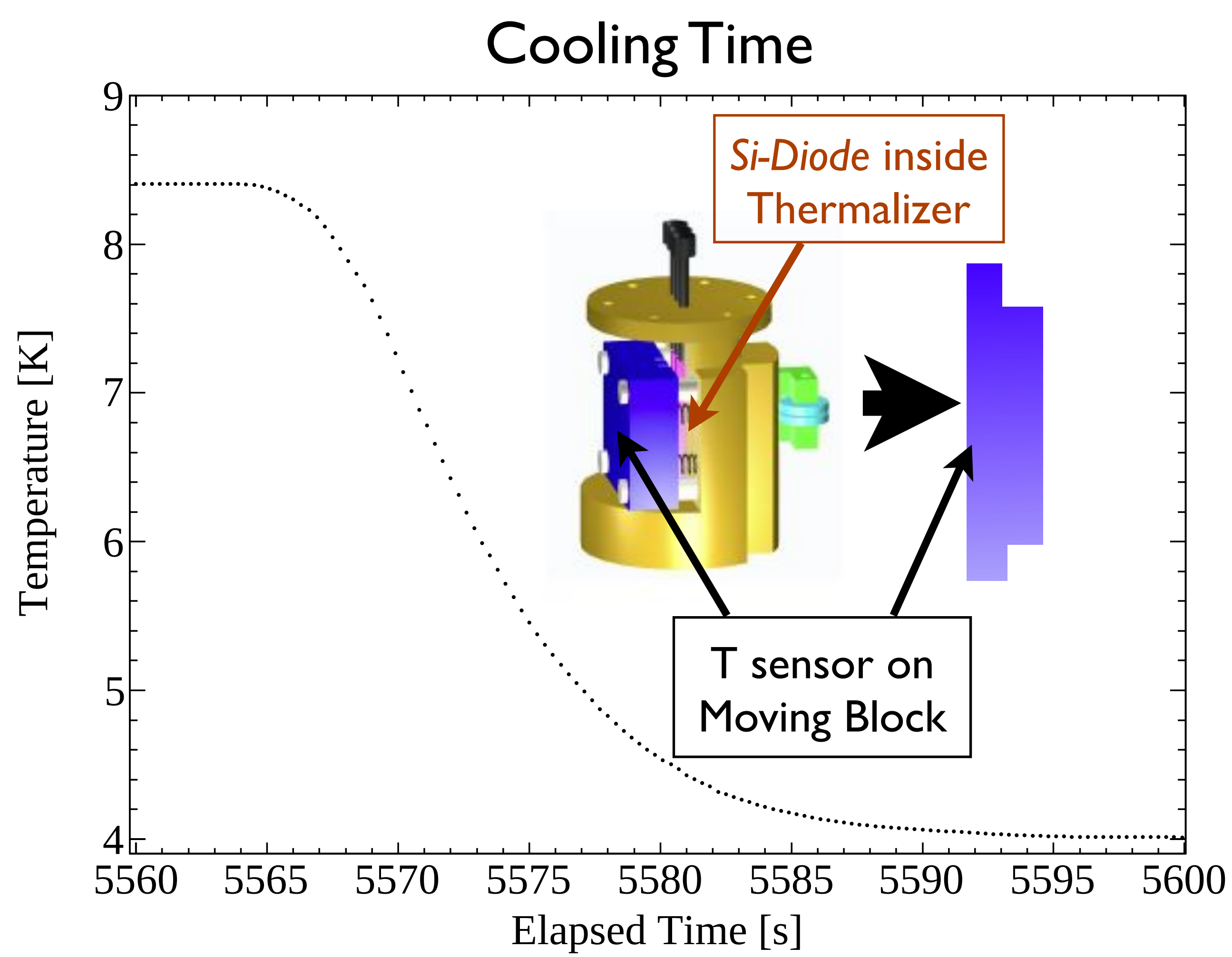




Cold Test Results

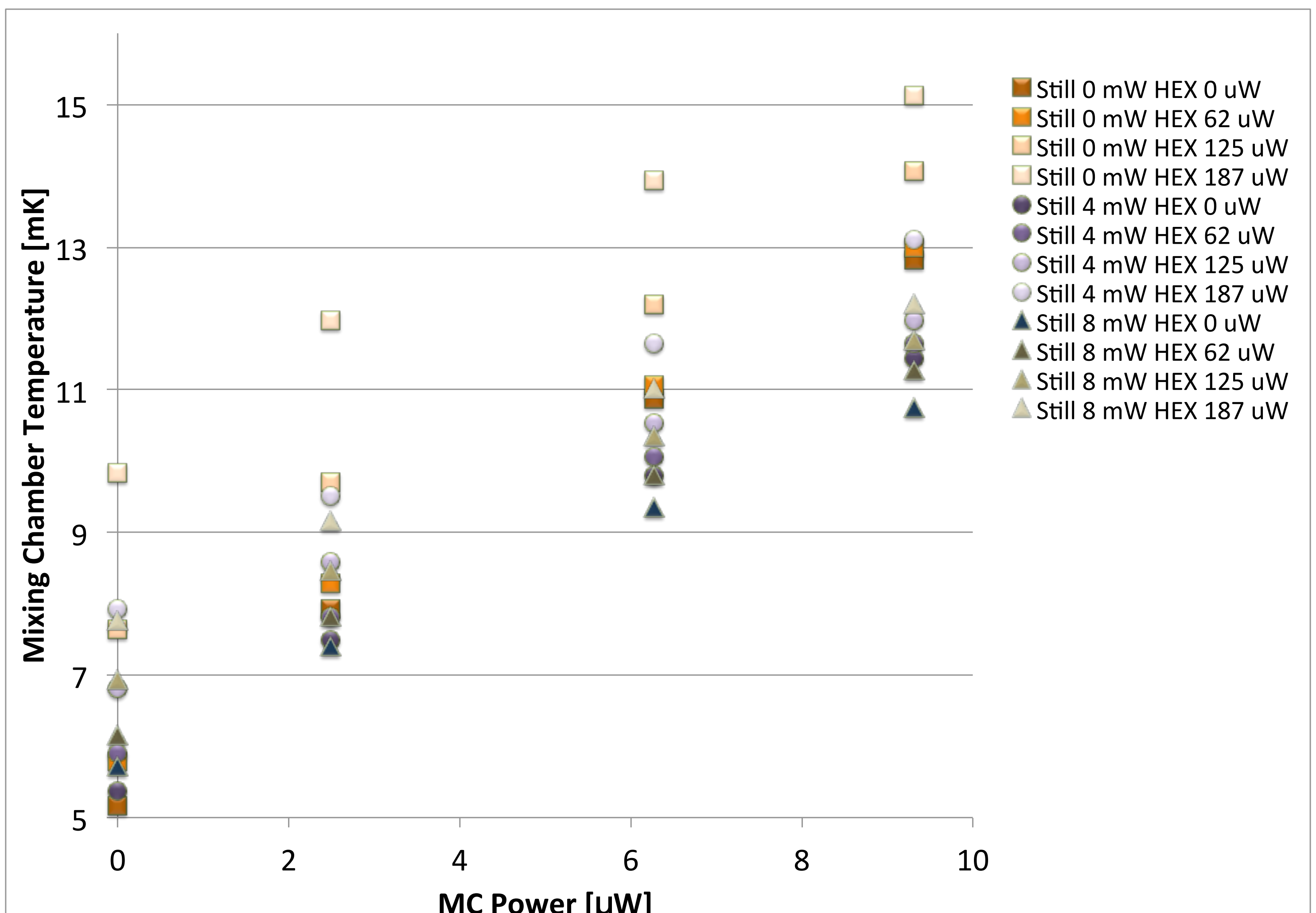
- Pulse tube refrigerators successfully cooled down the cryostat as low as 3.5 K in July 2013.
- Mechanical/thermal performance of the calibration system was verified.





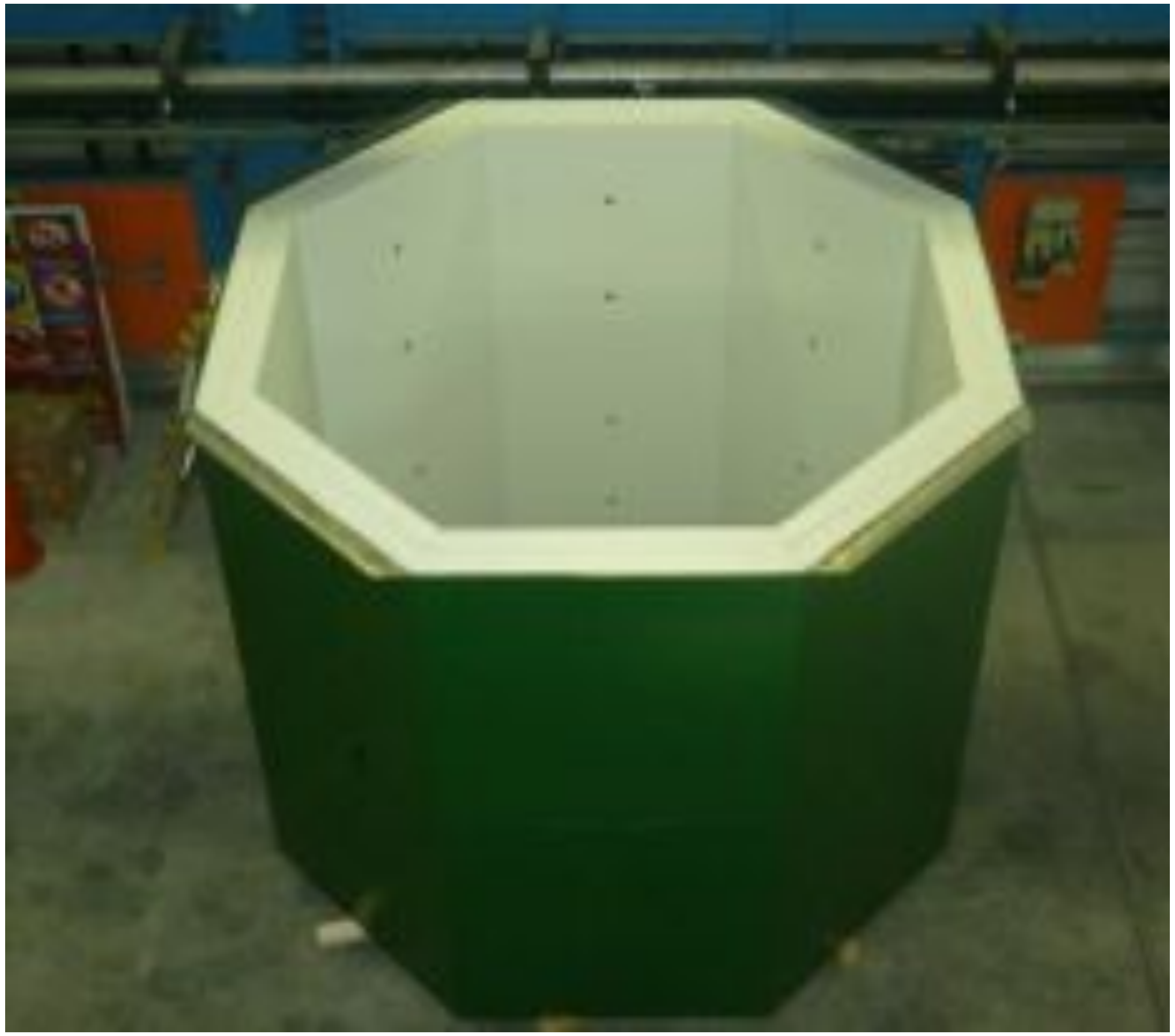
Dilution Refrigerator

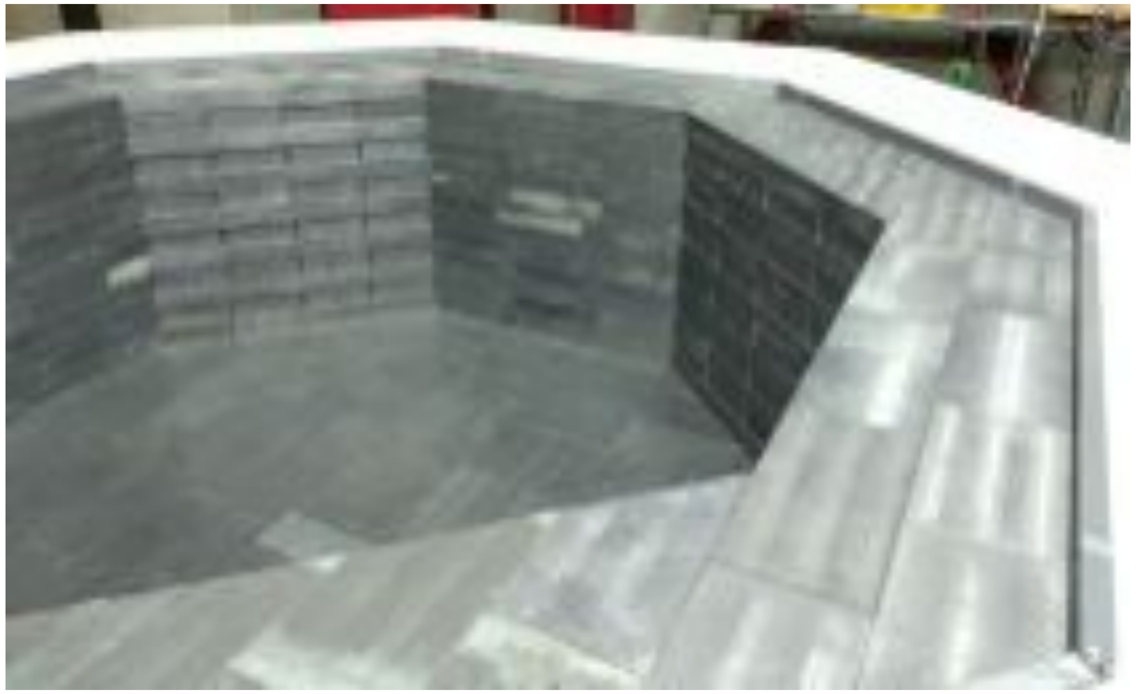
- Custom dilution refrigerator ordered from Leiden Cryogenic
  - Base temperature was measured to be as low as 5.6 mK
  - More than 5 μW of cooling power @ 10 mK



External Shields

- Installation is ongoing
  - 18 cm of Polyethylene
  - 2 cm of boric acid (H_3BO_3)
  - 25 cm of Pb
  - Steel container for N_2 flushing





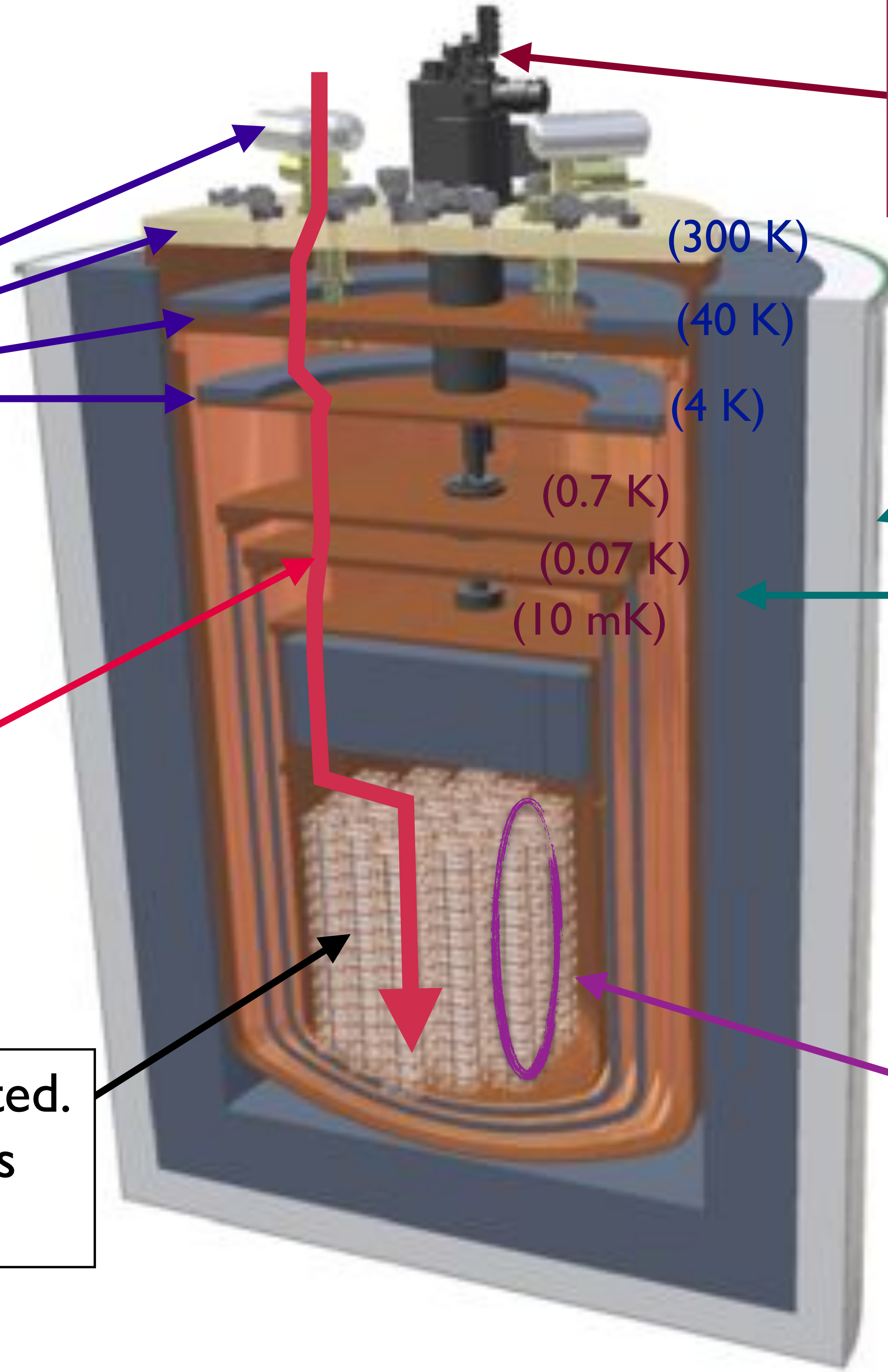
Progress towards CUORE

Dilution Refrigerator reached 5 mK for the commissioning test.

Cryostat assembled, commissioning, passed 4 K Test.

External shields installation is ongoing

Detector calibration system well underway.



CUORE-0, the first tower from CUORE assembly line is running in the Cuoricino cryostat.

- 9 out of 19 towers completed.
- Installation in the cryostat is anticipated in this year.

Outline

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- CUORE : An array of TeO_2 bolometers
- CUORE-0 : Validation of CUORE and more
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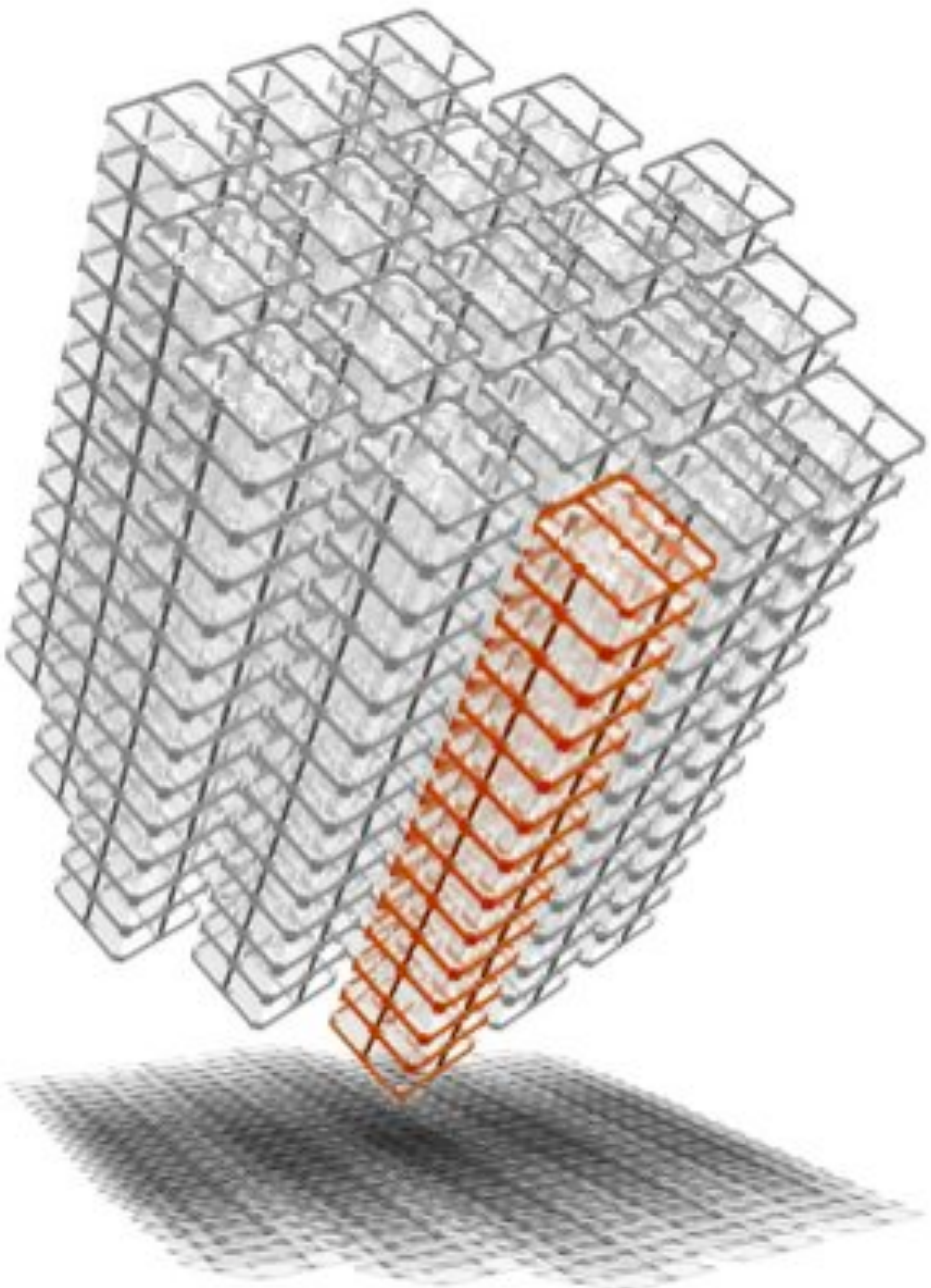
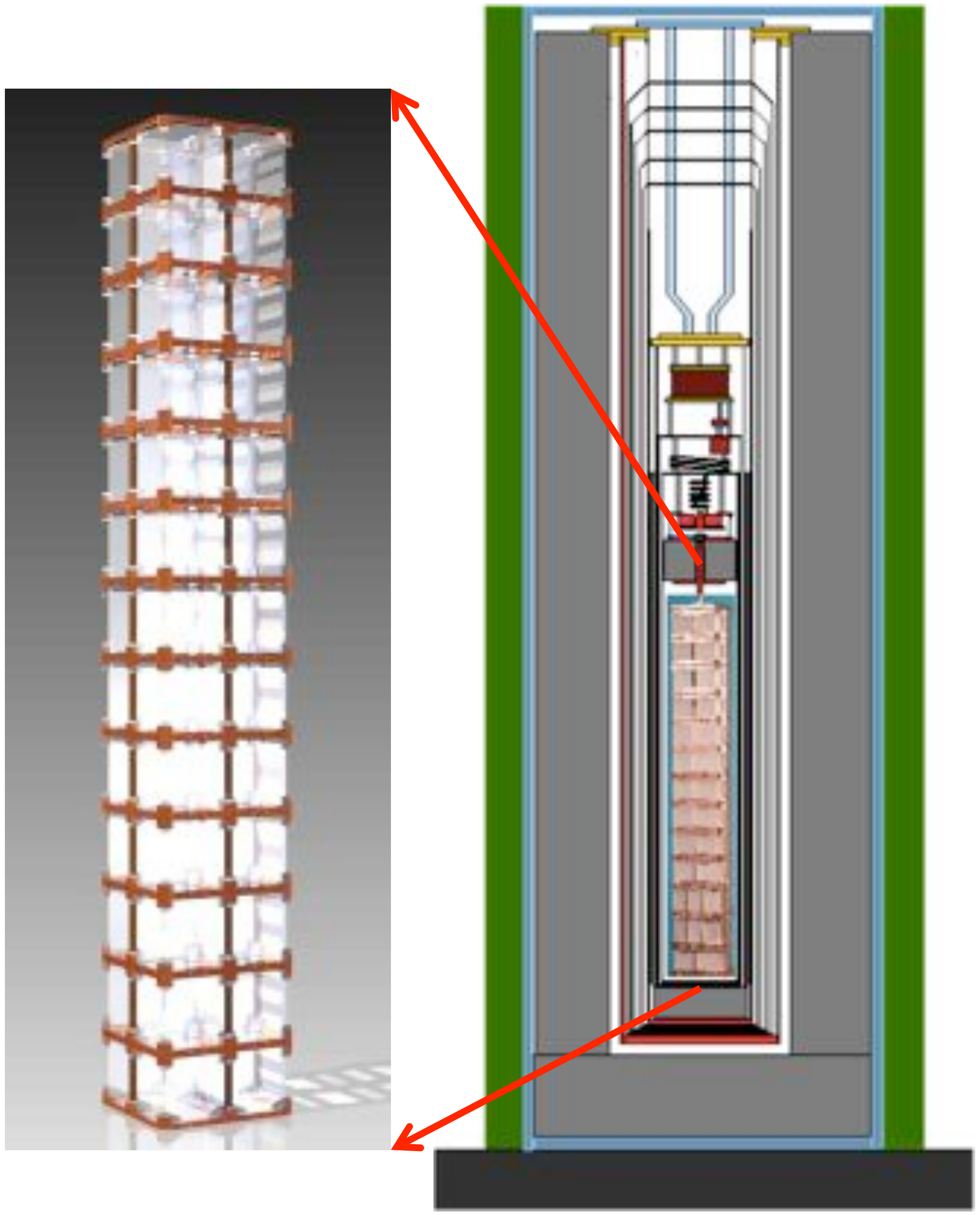
CUORE-0



- The first CUORE-like tower hosted in old Cuoricino cryostat.
- Validated new cleaning and assembly procedures for CUORE.
- Will surpass Cuoricino sensitivity before CUORE starts running.
- 52 (13 x 4) crystals, 39 kg of TeO_2 (*11 kg of* ^{130}*Te*), 4 kg of copper structure.
- Taking $0\nu\beta\beta$ decay data since March 2013.

CUORE-0



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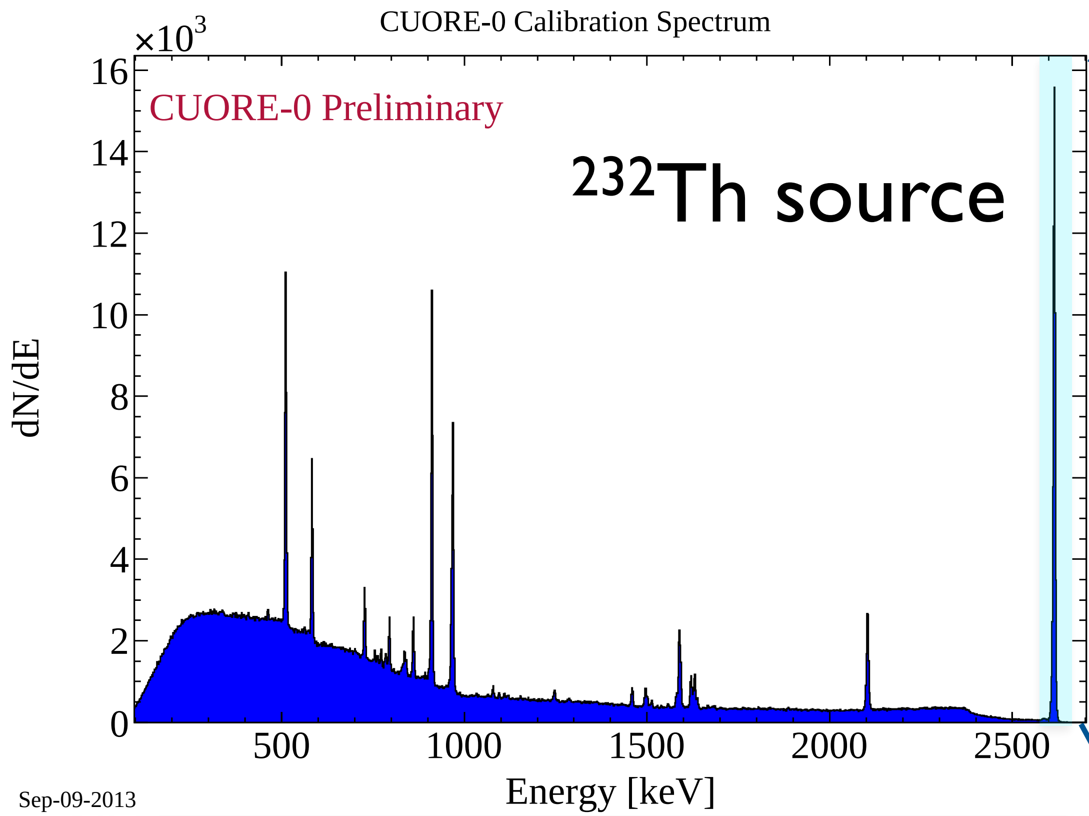
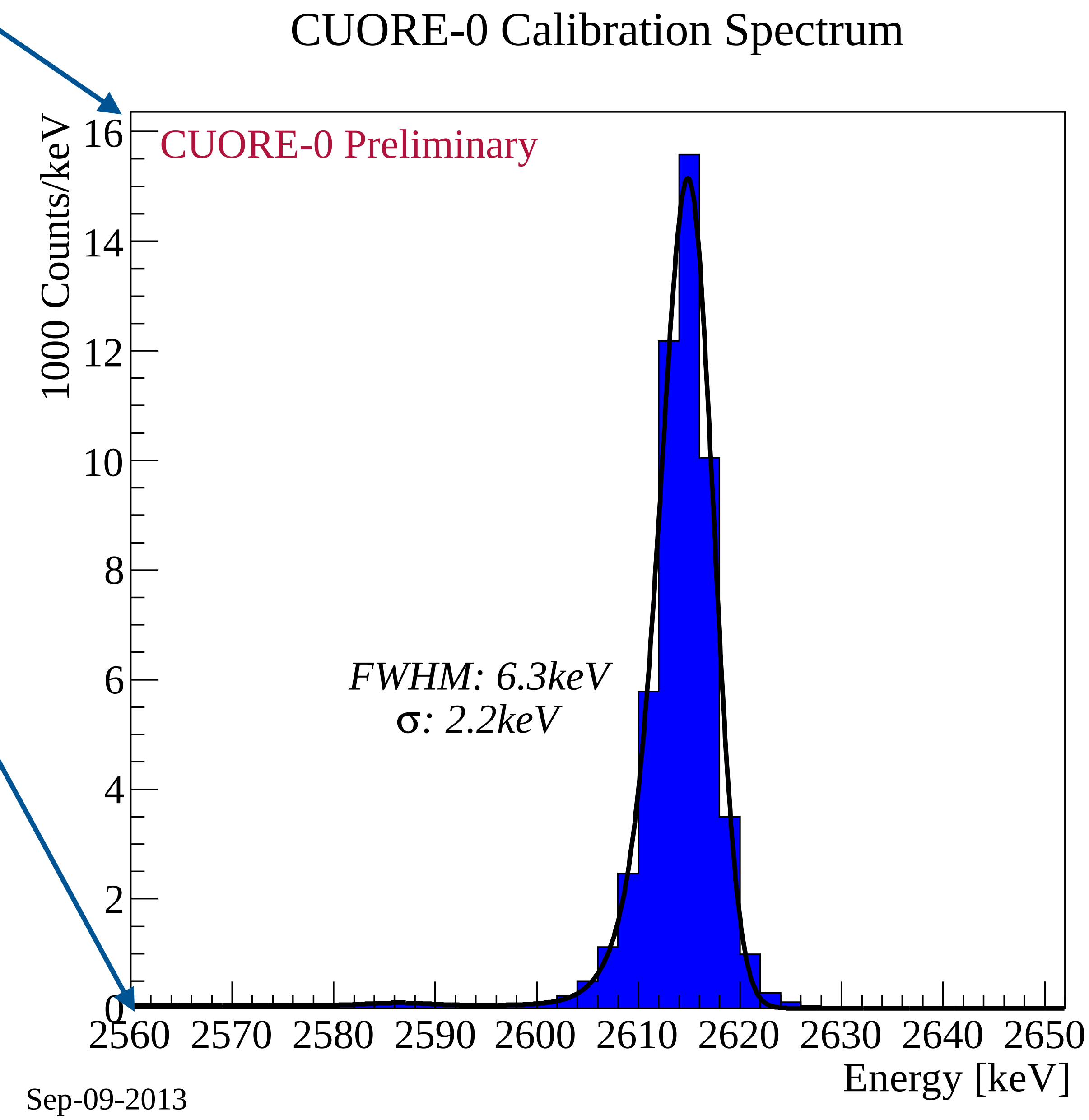
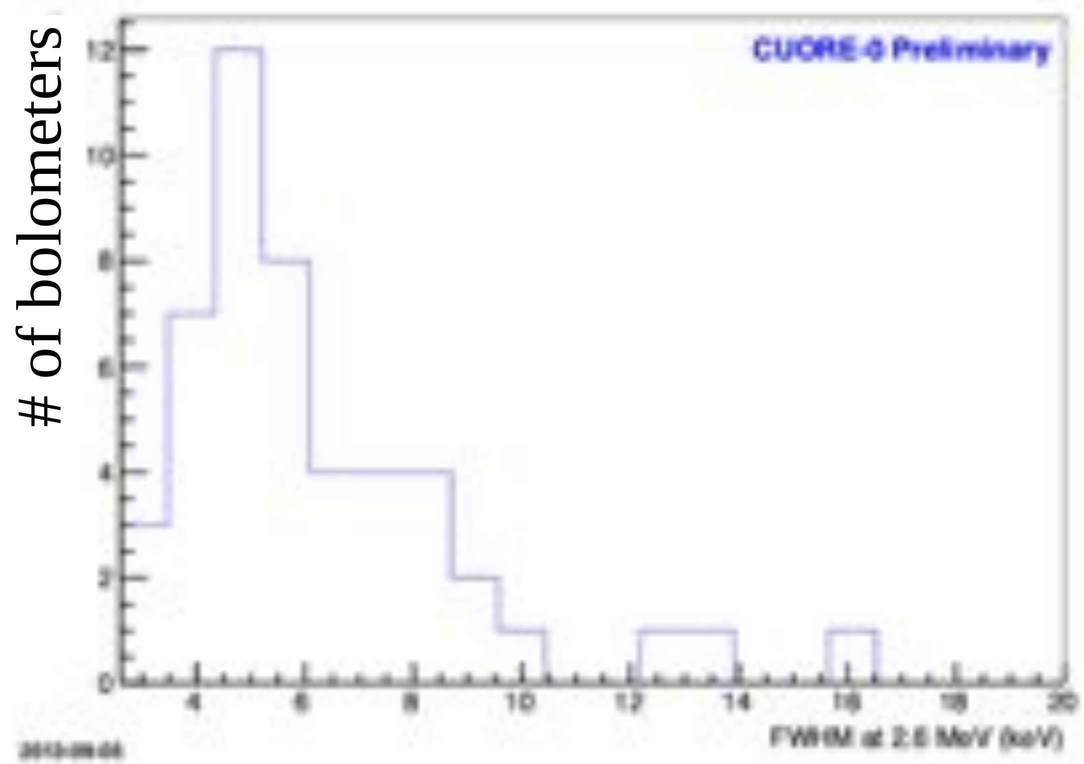
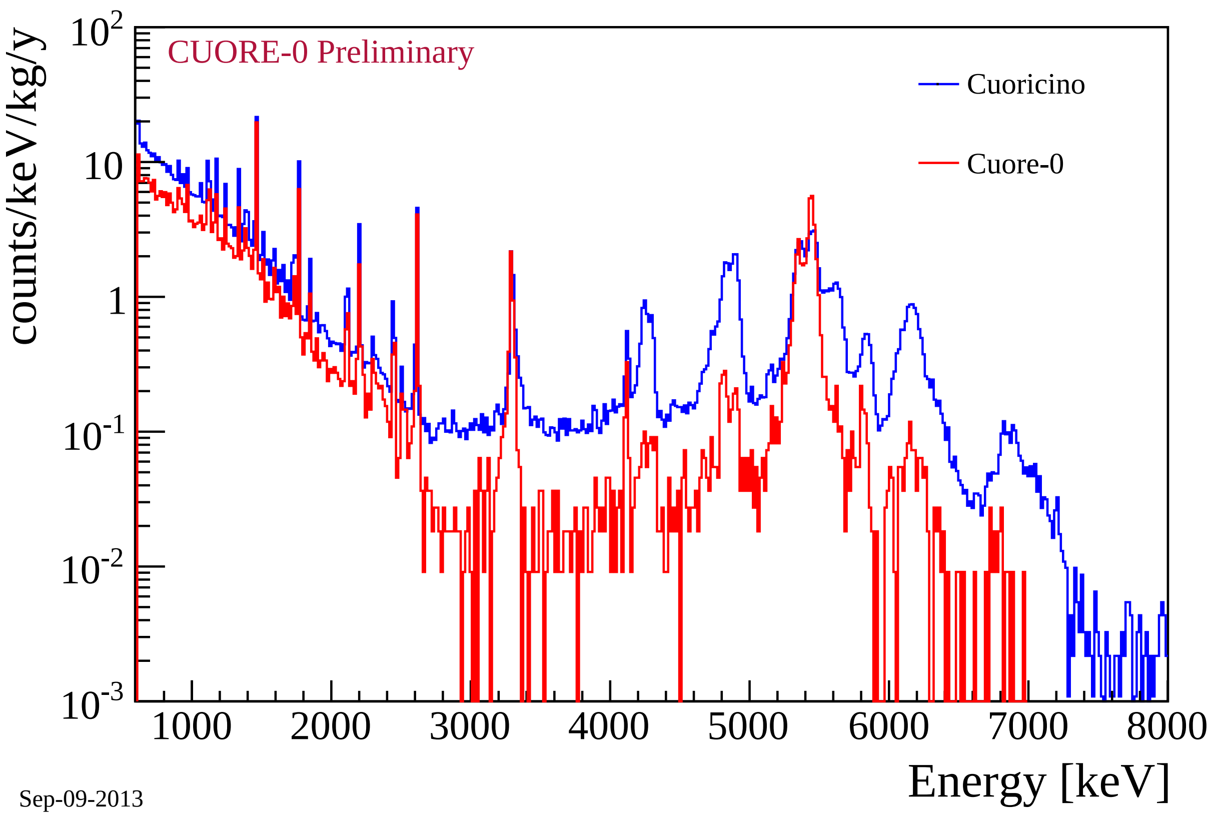
CUORE-0: Calibration

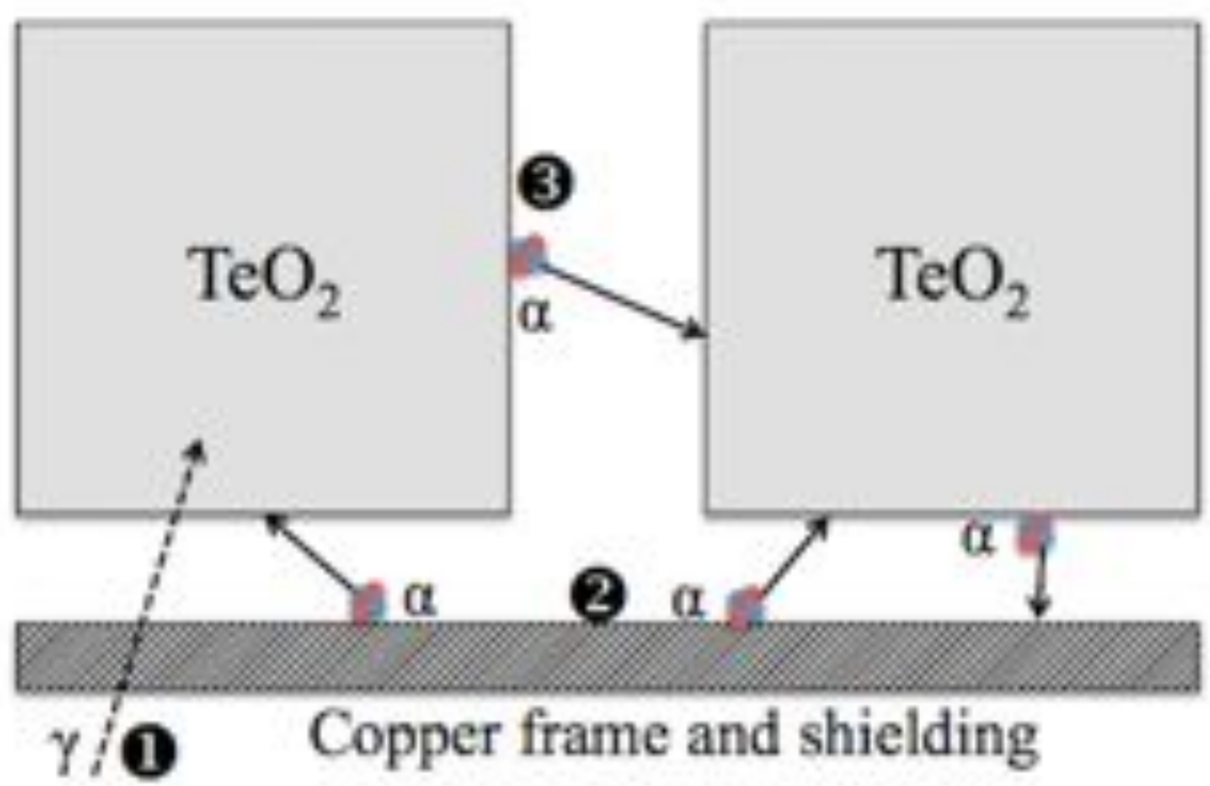






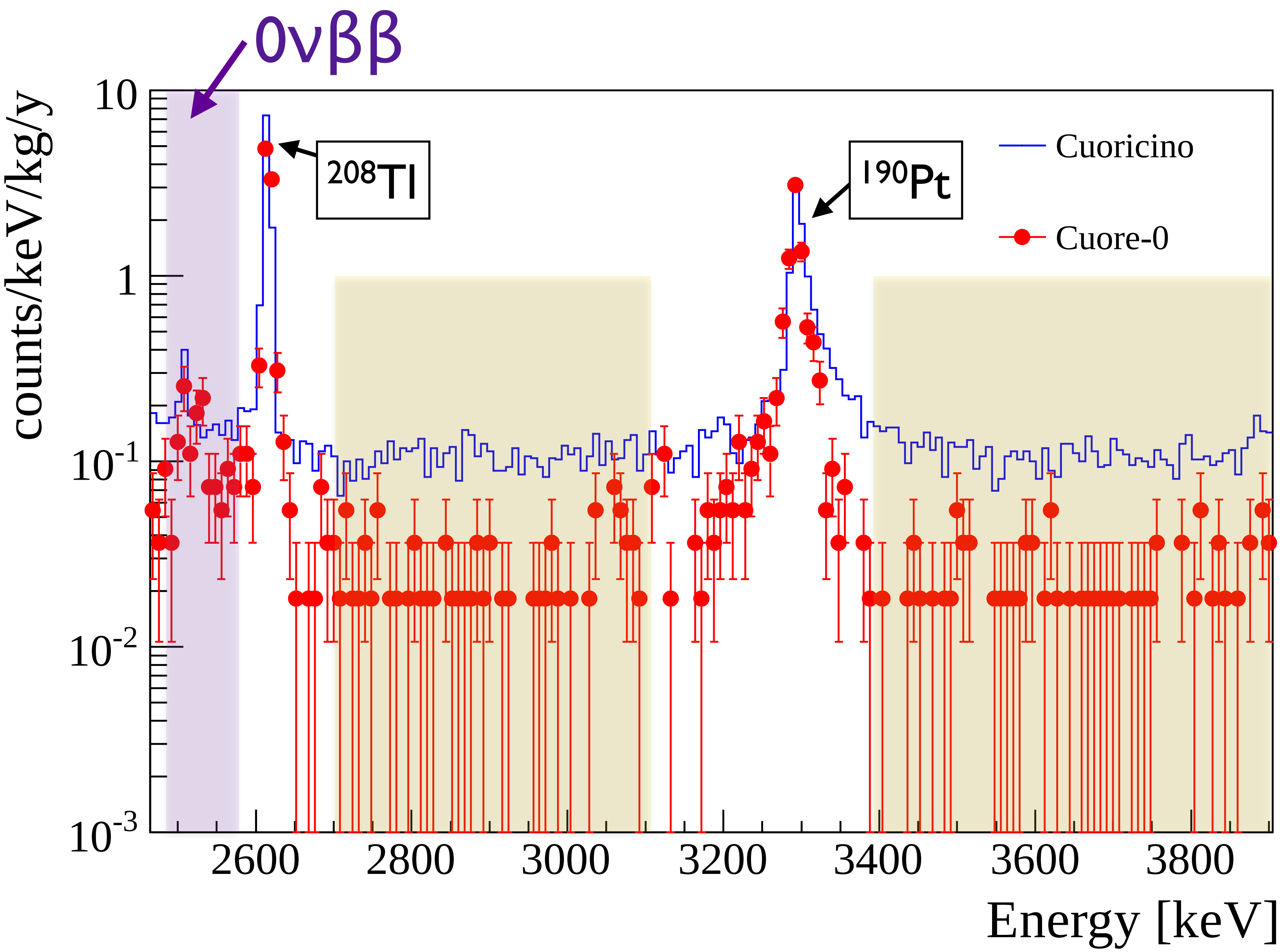
CUORE-0: Background





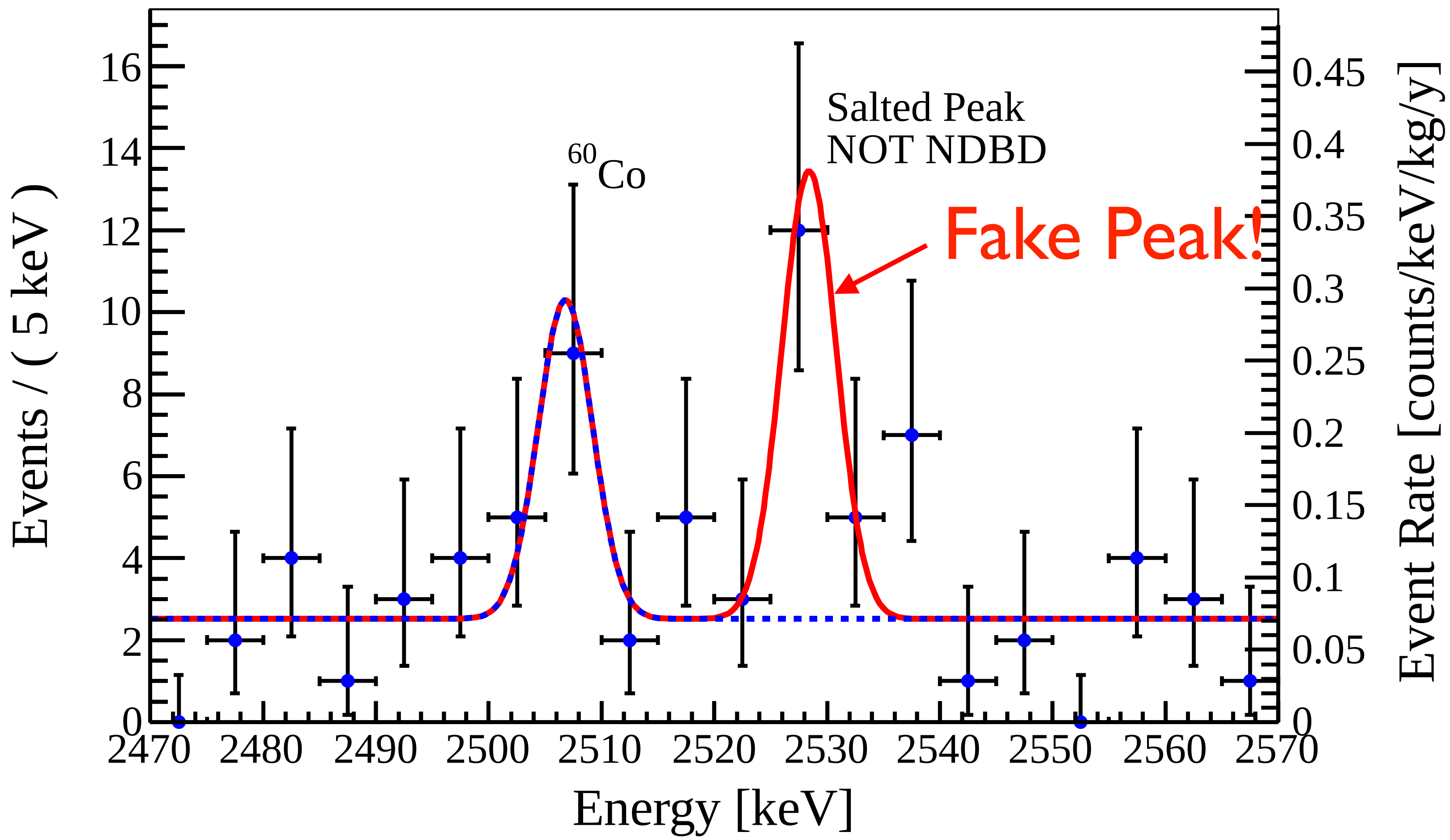
- γ background (from ^{232}Th) was not reduced since the cryostat remained the same.
- γ background (from ^{238}U) was reduced by a factor of 2 due to better radon control.
- α background from copper surface and crystal surface was reduced by a factor of 6 thanks to the new detector surface treatment.

CUORE-0: Background



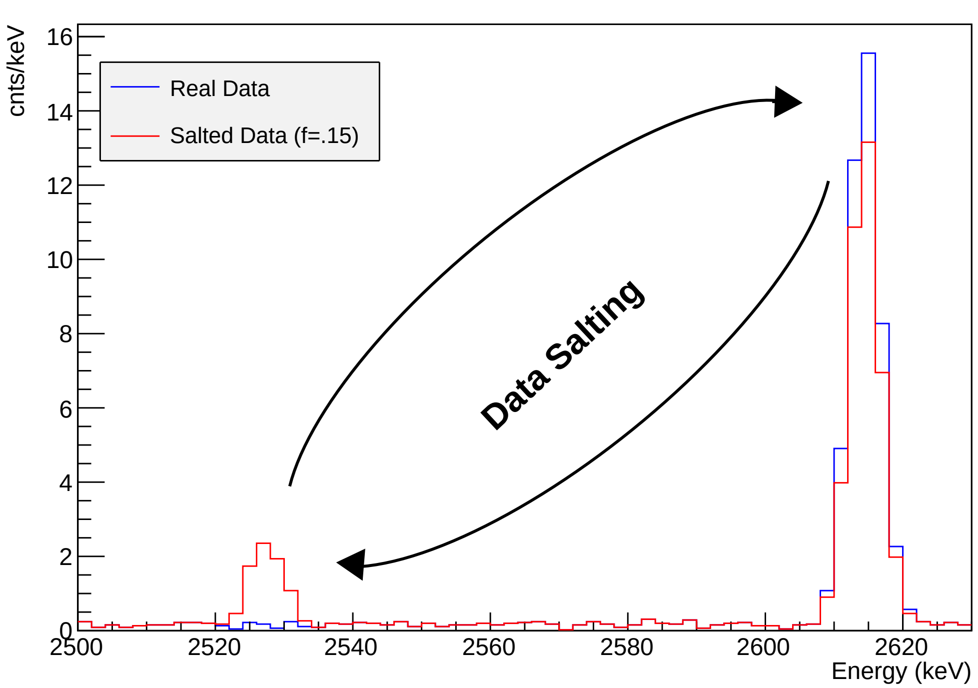
	Avg. flat bkg. [counts/keV/kg/y]		signal eff. [%] (detector+cuts)
	0νββ region	2700-3900 keV	
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	82.8±1.1
CUORE-0	0.071 ± 0.011	0.019 ± 0.002	80.4±1.9

Blinding 0νββ Region

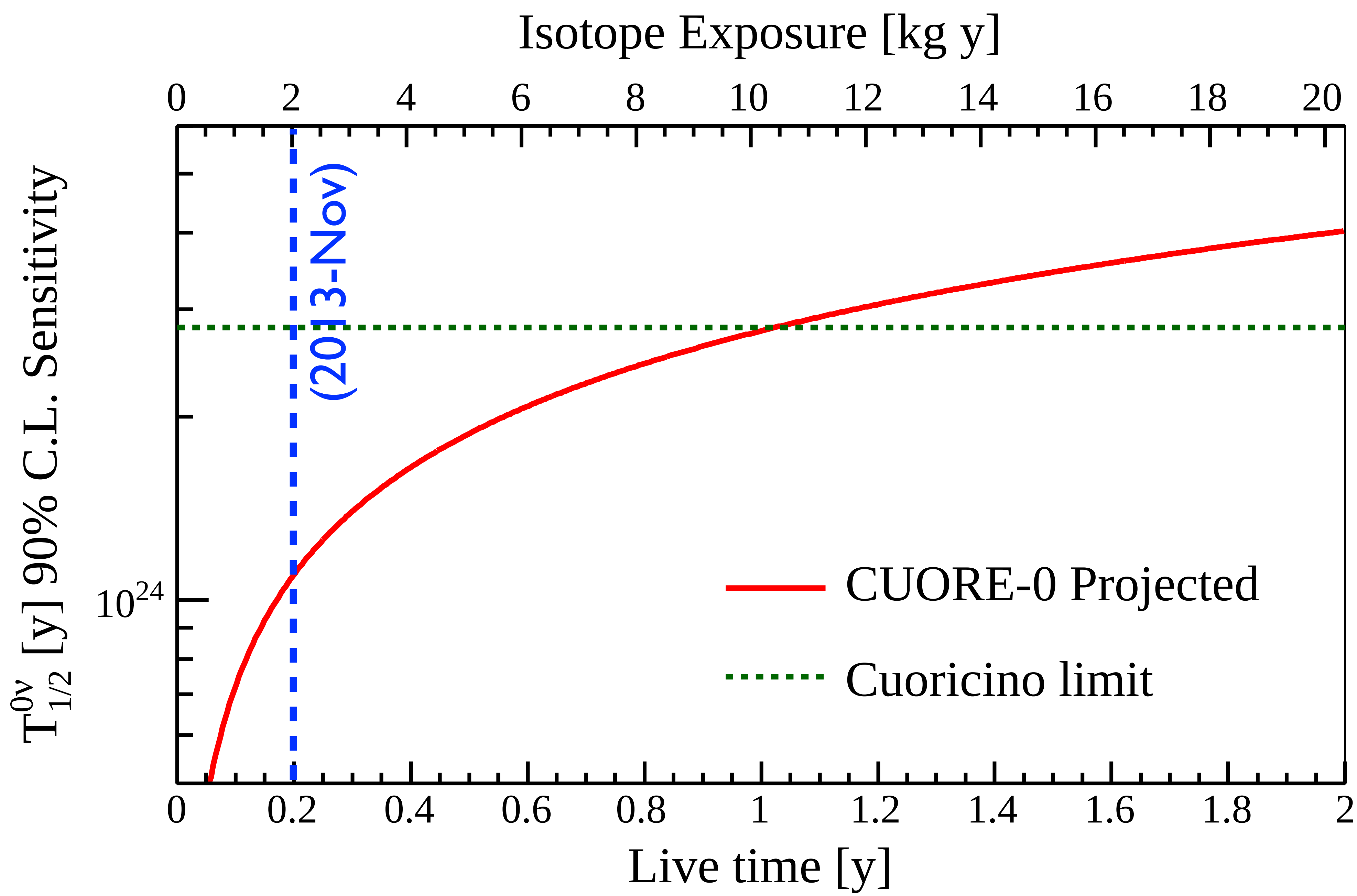


- Region of Interest was blinded by "salting" : exchange a small (and ***blinded***) fraction of the events in ^{208}Tl peak with events in the 0νββ region to produce ***fake*** peak.

Simulated Salted CUORE-0 Data

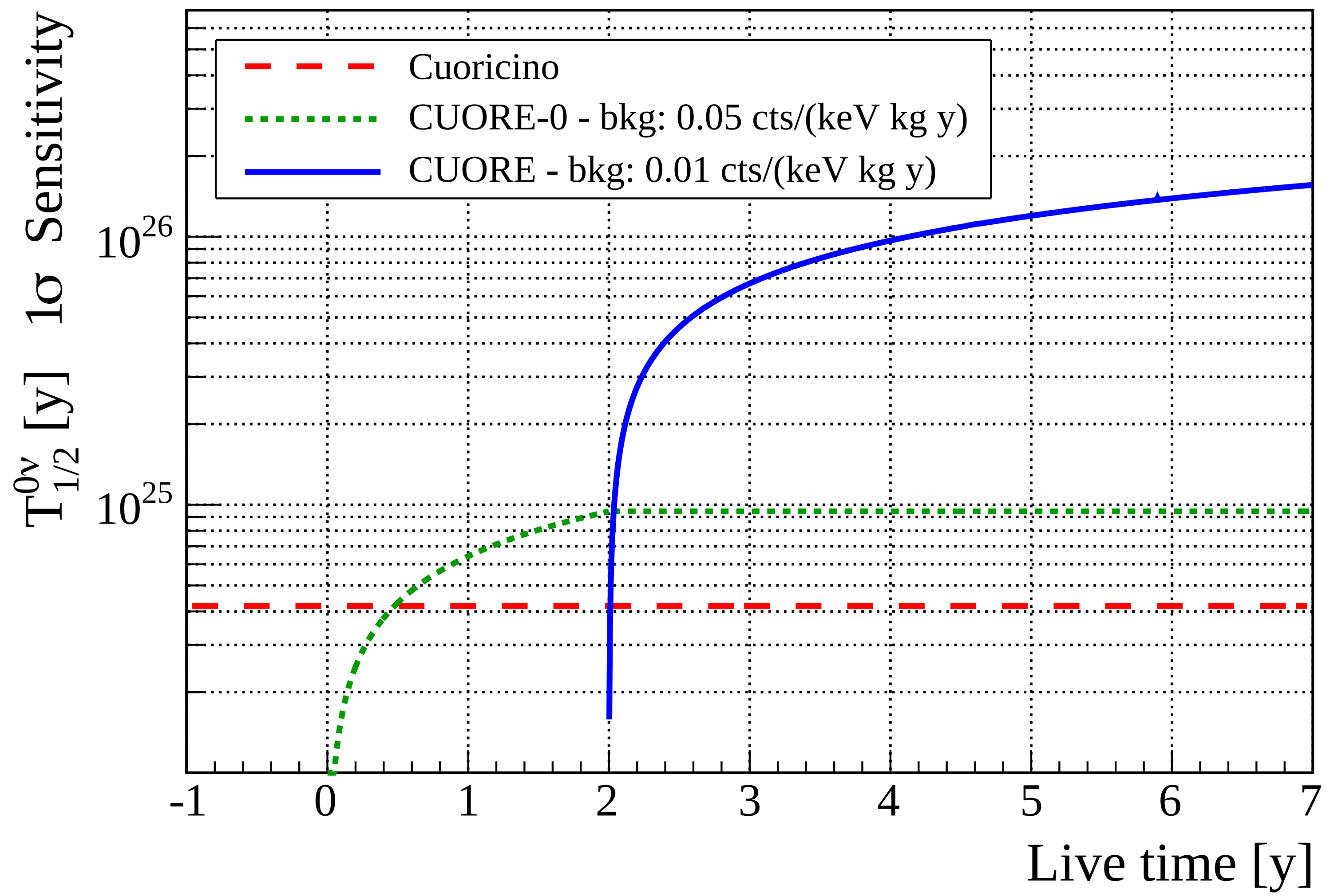


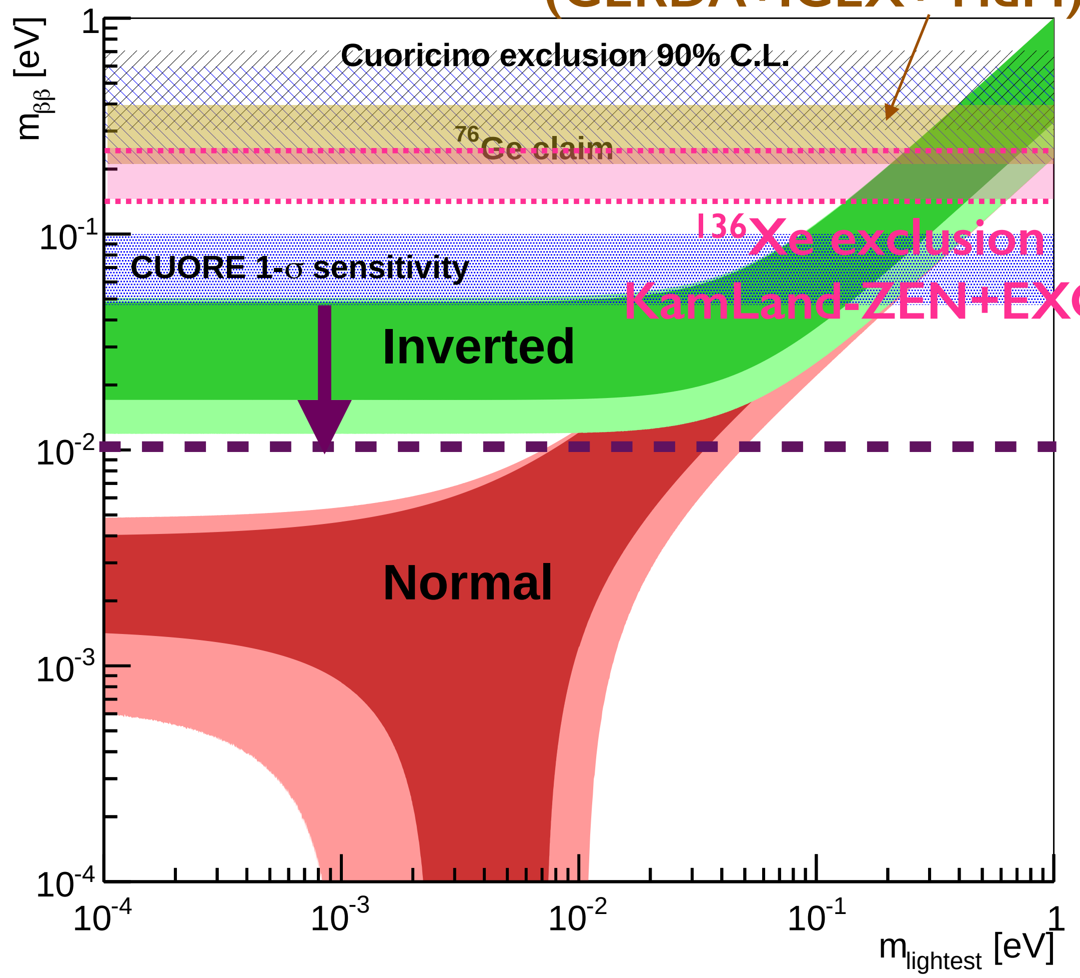
CUORE-0 Sensitivity



- Expected to surpass Cuoricino limit w/ 1.1 year of live time.

CUORE Sensitivity

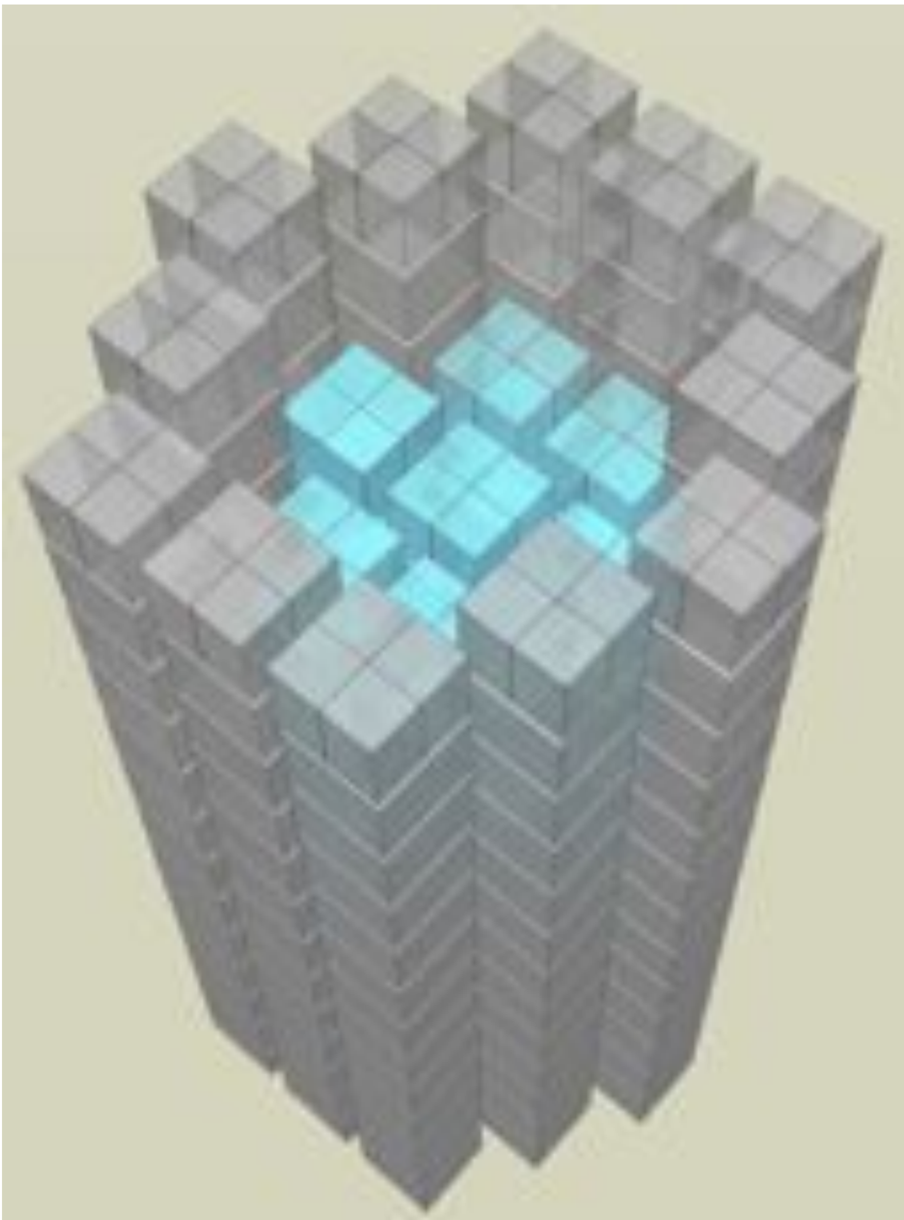


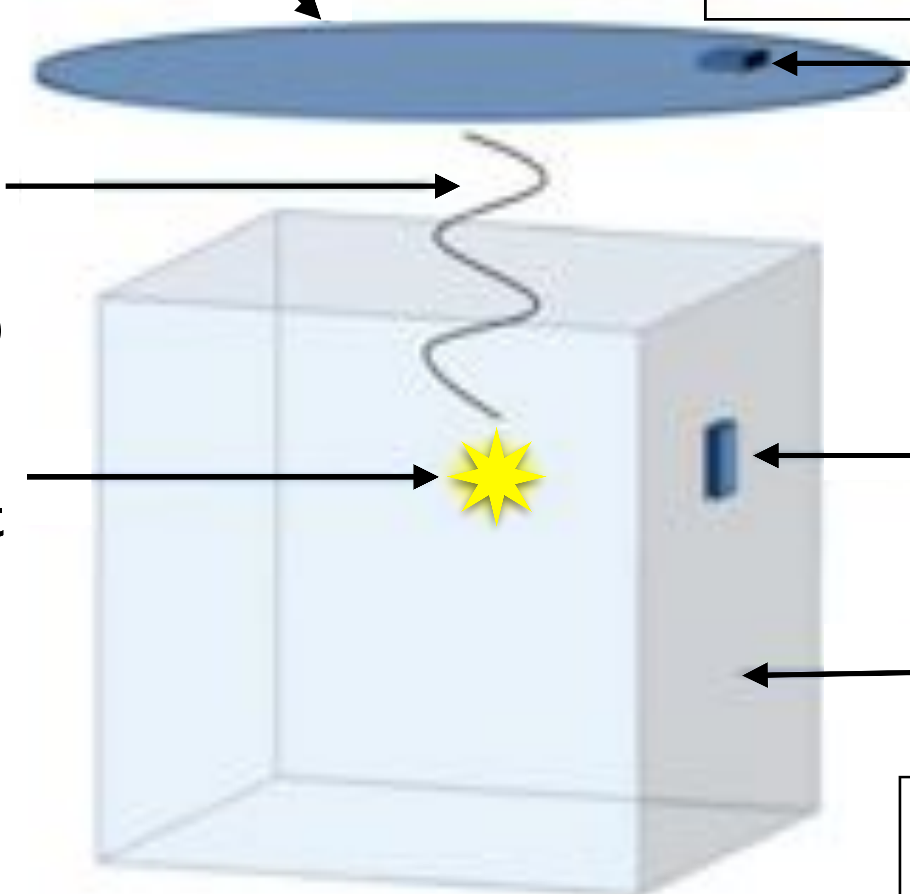


- 1σ sensitivity $T_{1/2}^{0\nu\beta\beta}$=1.6 x 10^{26} yr (Effective Majorana mass 47-100 meV).
  - Assuming bg rate of 0.01 cts/(keV kg y) and 5 keV FWHM ROI resolution.
  - 5 years of live time.

arXiv:1109.0494

Beyond CUORE



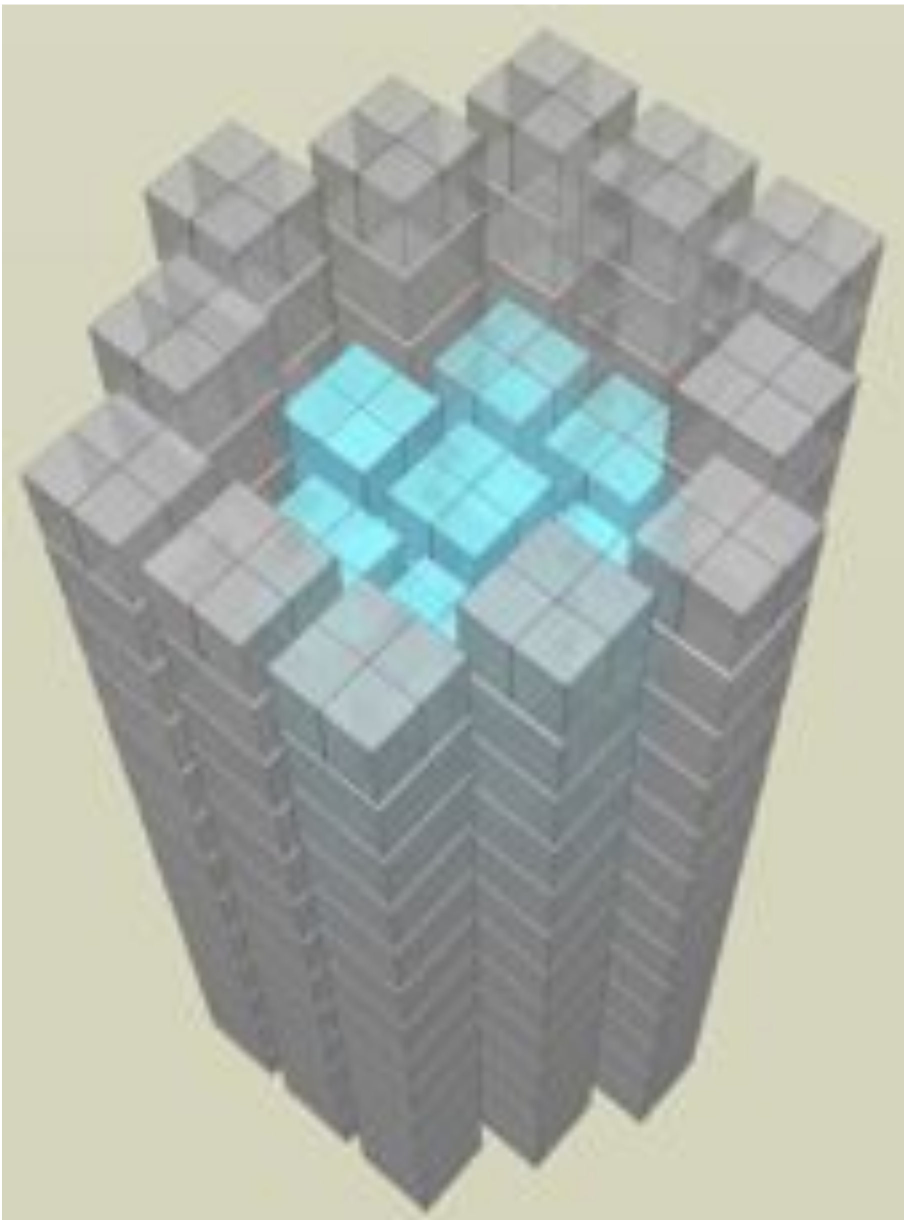


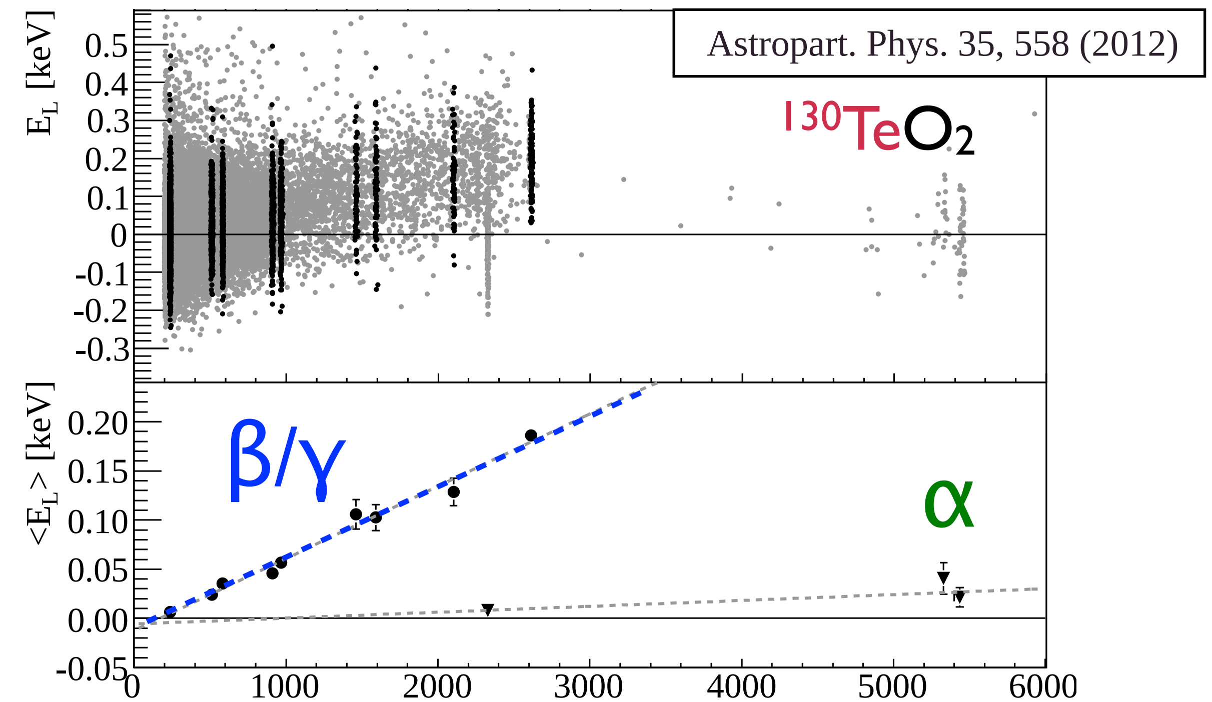
- Trailing Edge Sensor
- Microwave Kinetic Inductance Detectors

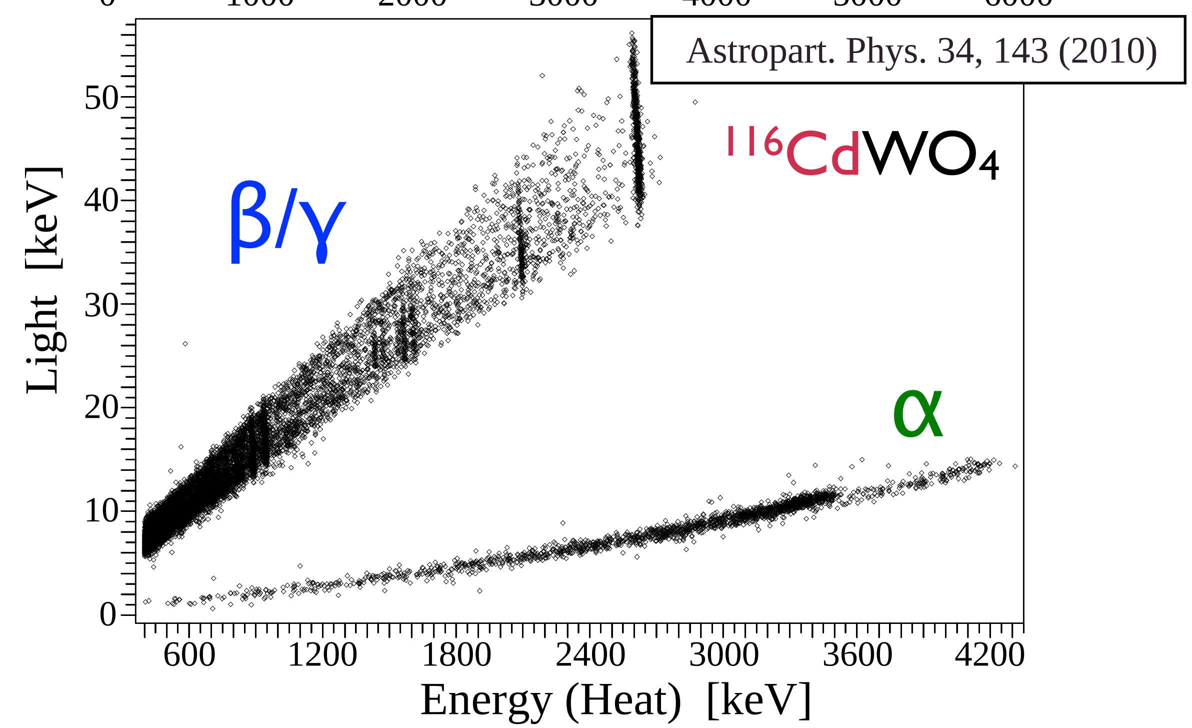
$^{130}TeO_2$, $Zn^{82}Se$, $^{116}CdWO_4$, $Zn^{100}MoO_4$

- Enrichment of the crystal (more ^{130}Te)
- Particle discrimination by simultaneously measuring heat/light.

Beyond CUORE







- Enrichment of the isotope
- Particle discrimination by simultaneously measuring heat/light.

Summary

- TeO_2 bolometers offer a well-established and competitive technique to search for $0\nu\beta\beta$ decay.
- CUORE, the largest cryogenic detector using TeO_2 bolometers with 206 kg of ^{130}Te mass, is under construction.
- Significant efforts have been made to reach very low background goals of CUORE.
- CUORE-0, the first CUORE-like tower currently operating at LNGS, demonstrated the success of background mitigation, and will surpass the sensitivity of a predecessor experiment in the coming year.
- CUORE Yale group is active on the development of calibration system, muon tagging system, calibration/commissioning of CUORE, and CUORE-0 data analysis.
- CUORE will start to take data next year (2015).
- Various R&D projects are ongoing for searches beyond CUORE.