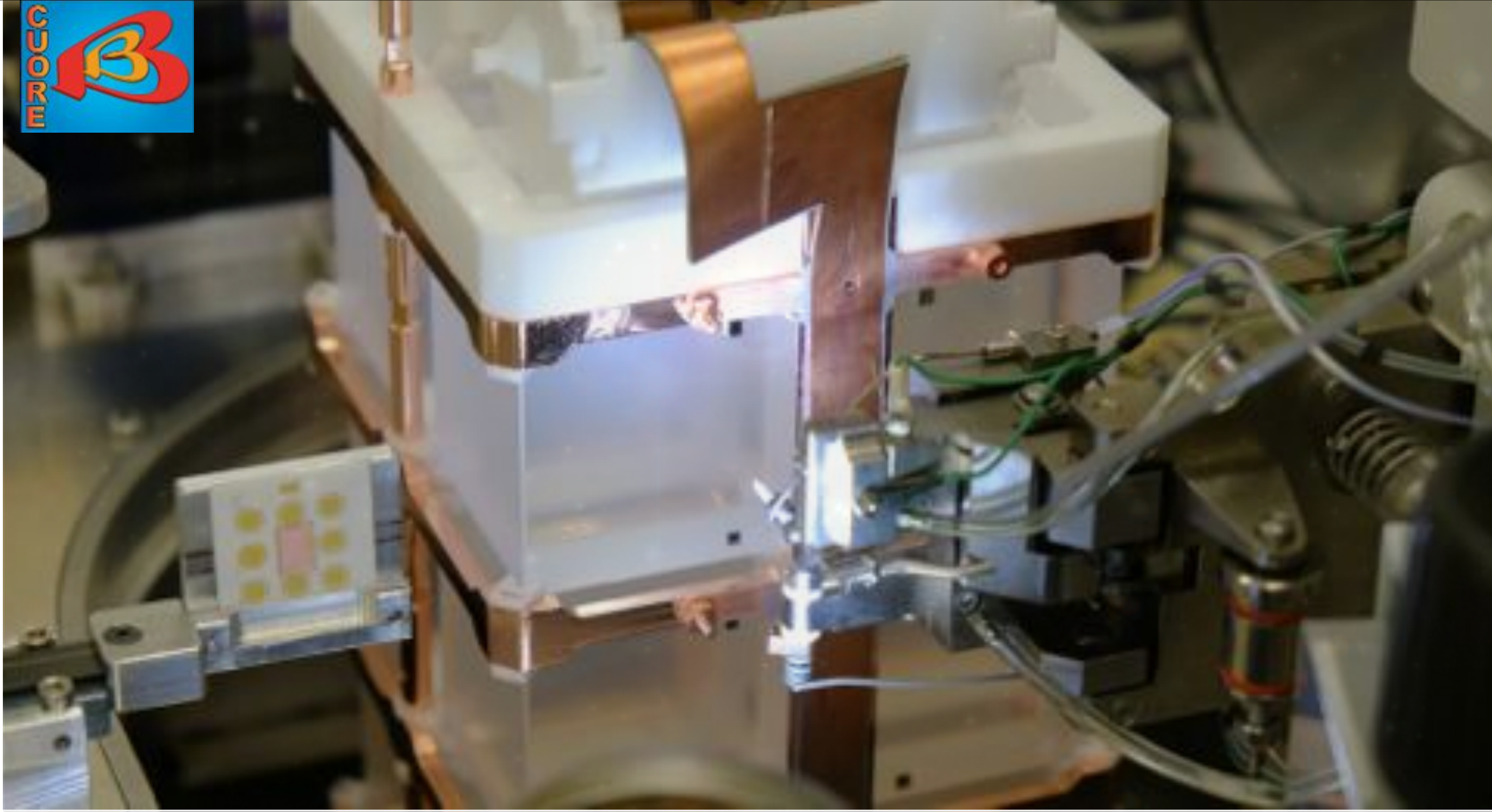
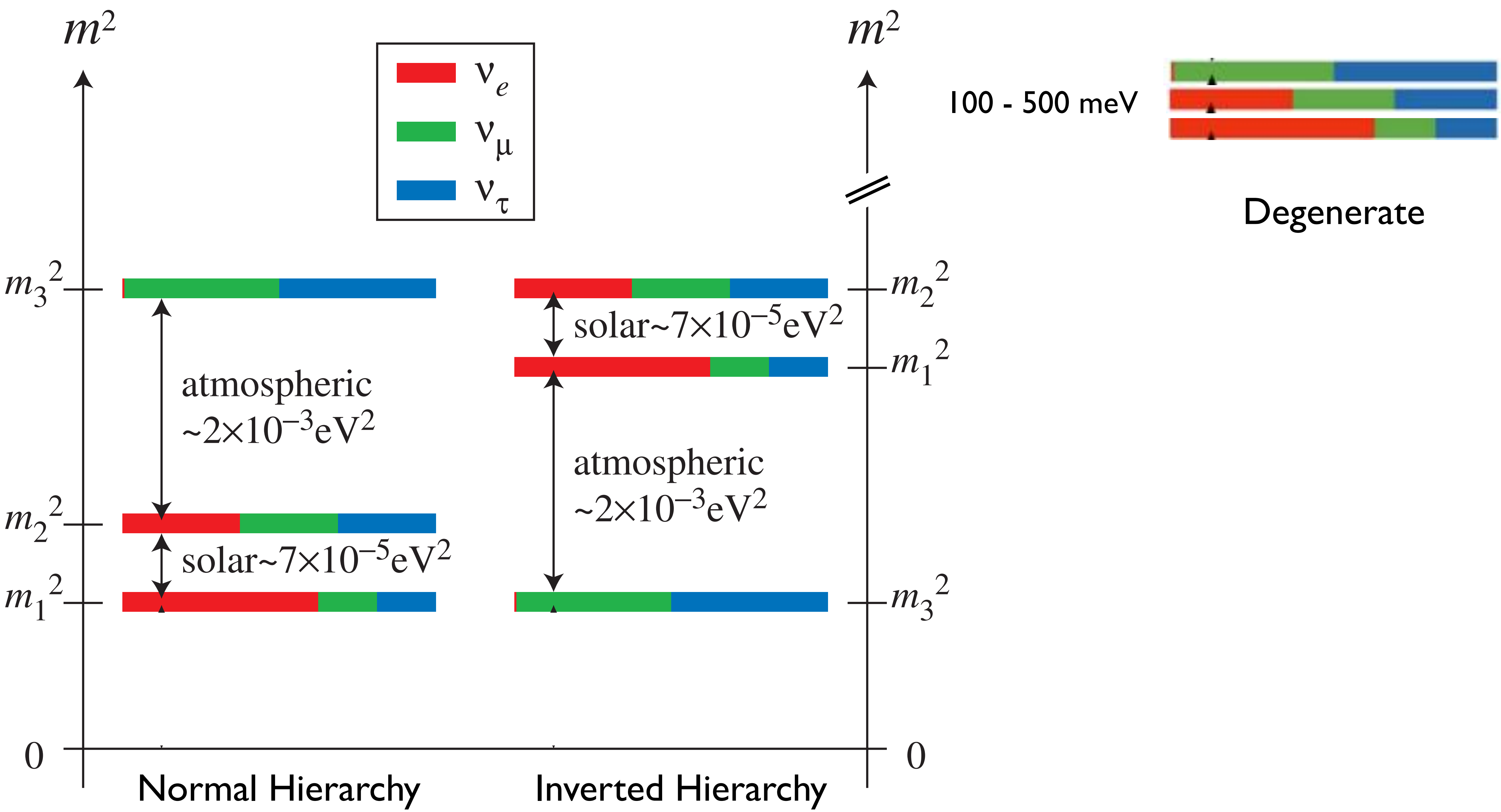


Search for Neutrinoless Double-beta Decay with CUORE-0

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

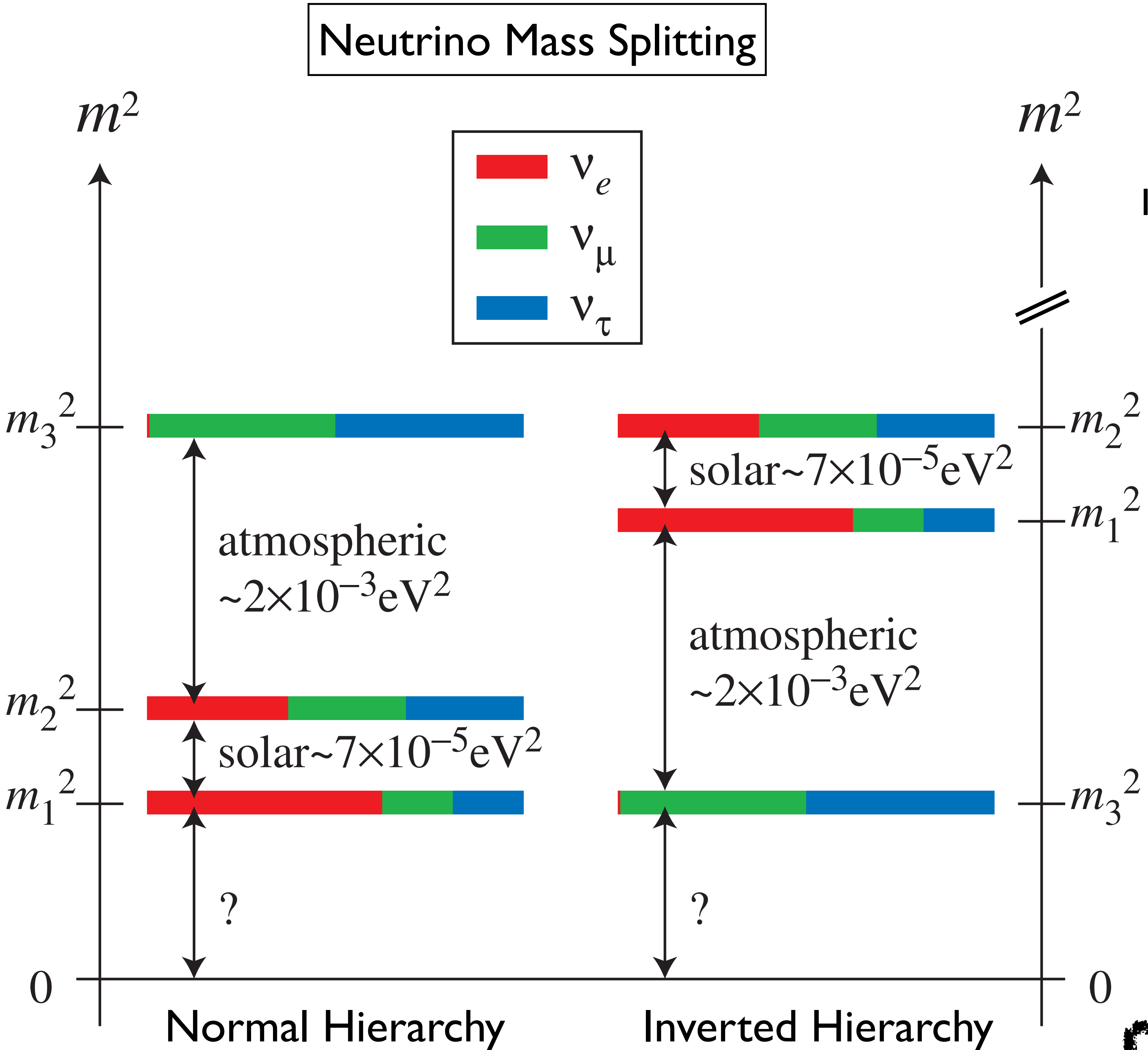
Mar. 13, 2014, Particle Physics Seminar, BNL

What we know about Neutrinos

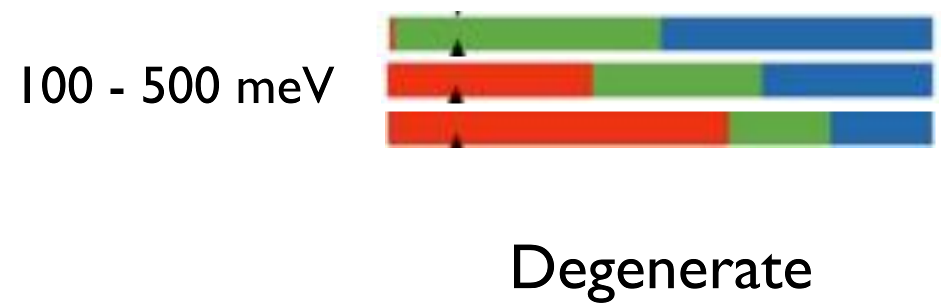


Rep. Prog. Phys. 76, 056201 (2013)

What we don't know about Neutrinos



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



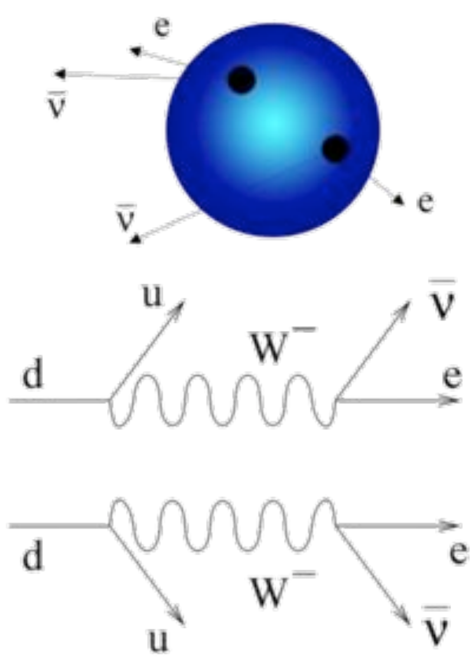
Is the neutrino its own antiparticle?

Outline

- Neutrinoless double-beta decay (0νDBD) search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : 0νDBD search w/ a single CUORE tower
  - CUORE-0 : Detector
  - CUORE-0 : Performance and Background
  - CUORE-0 : Projected Sensitivity
- Summary

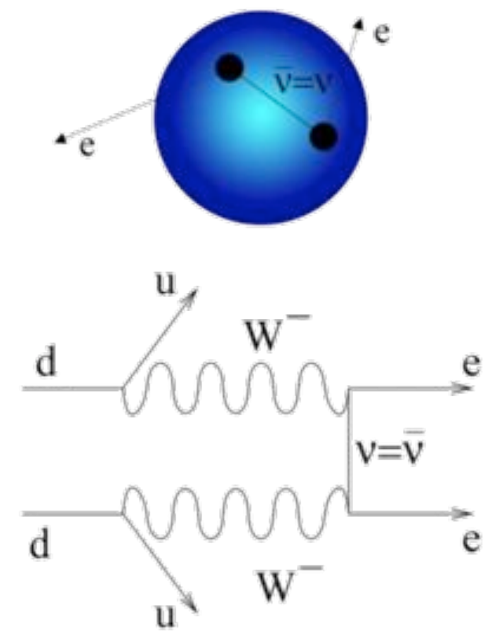
Neutrino(less) double-beta decay

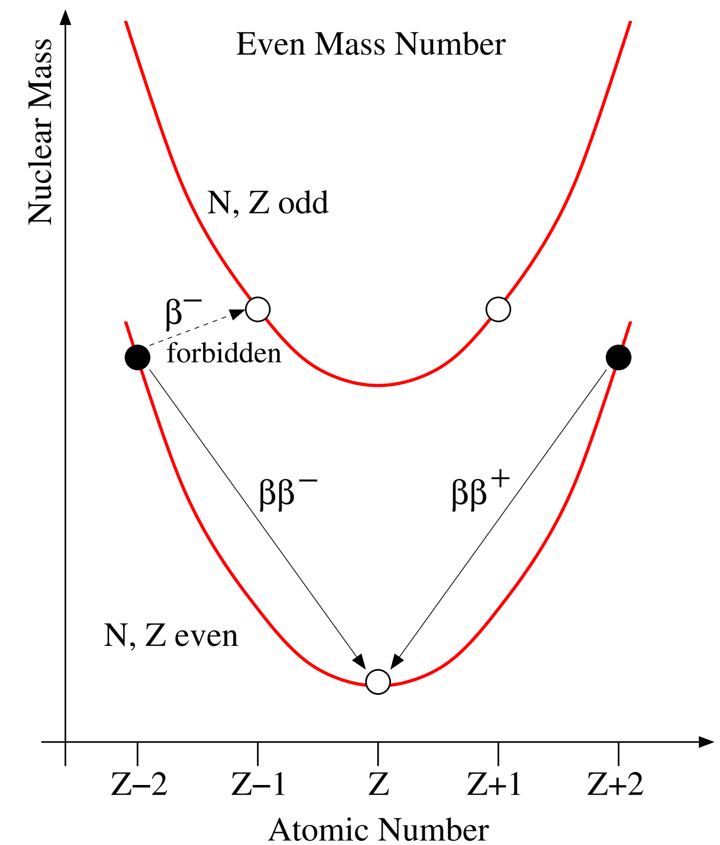
- 2νDBD



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

- 0νDBD





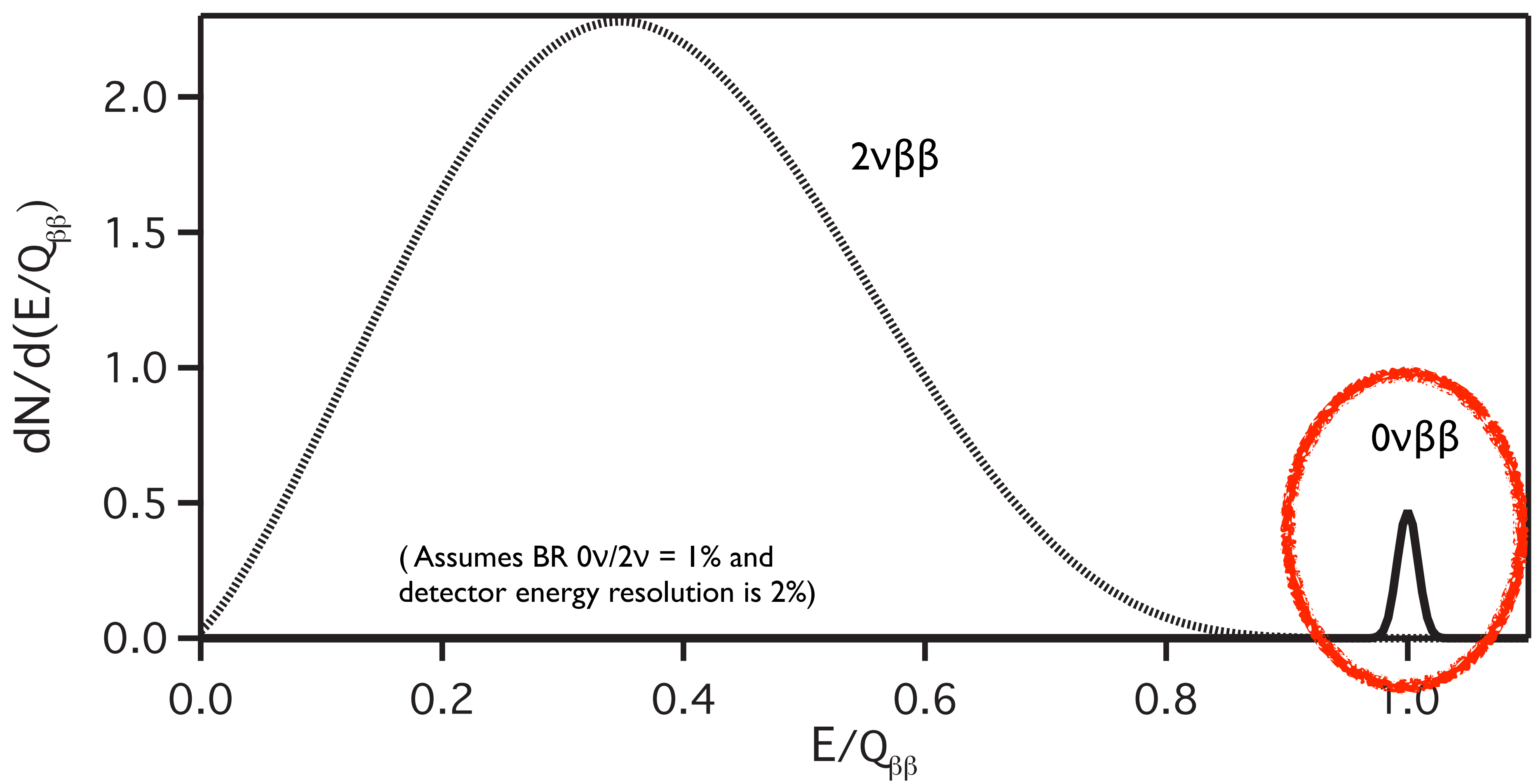
- Beyond SM (Lepton number violating process)
- Hypothetical process only if $\nu = \overline{\nu}$ and $m_\nu > 0$

Observation of 0νDBD

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

Signature of 0νDBD

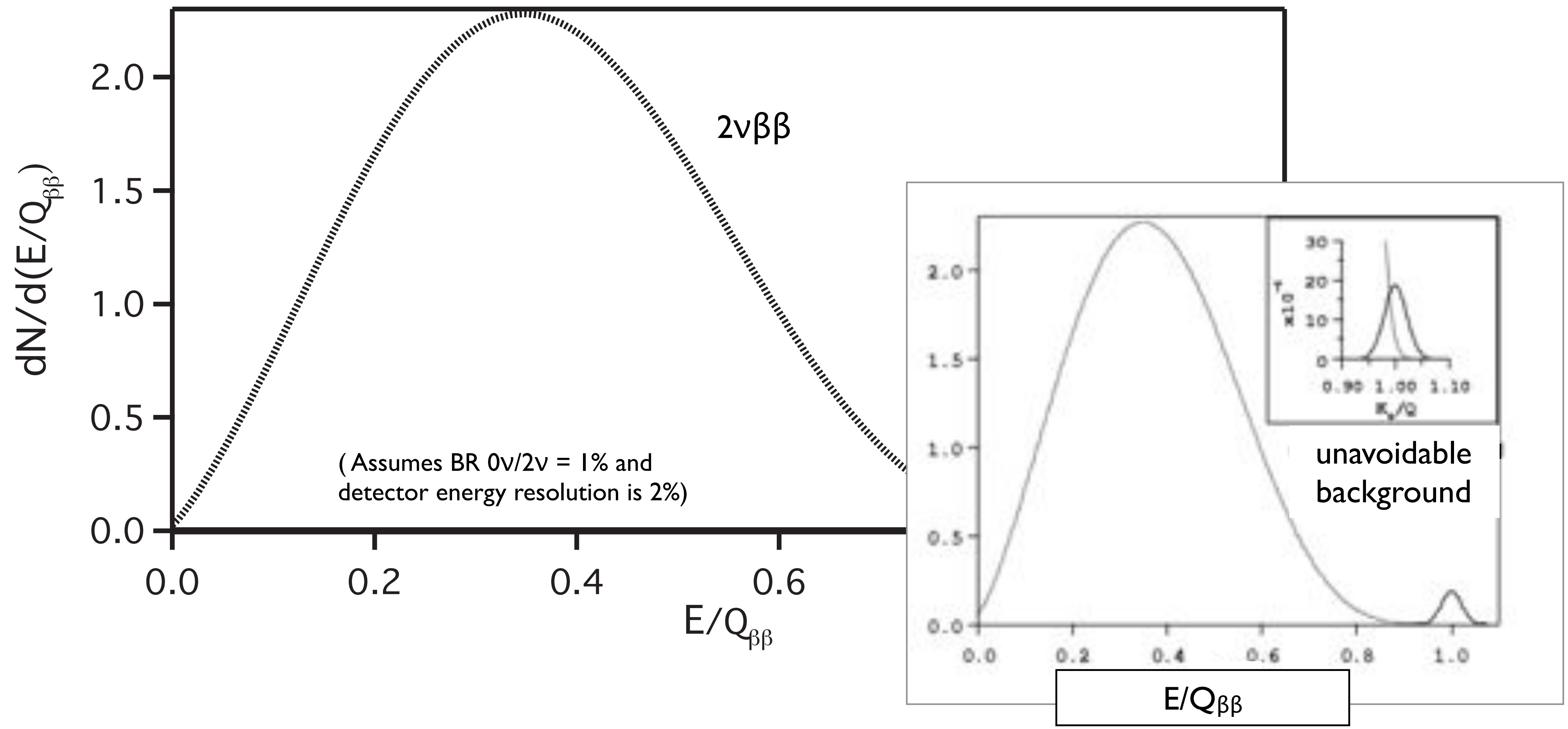
ββ summed e⁻ energy spectrum



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

Signature of 0νDBD

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 2νDBD.

Search for 0νDBD

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	0νDBD half-life
G	phase space factor $(\propto Q^5)$
M	Nuclear Matrix Element (NME)
m	effective ββ neutrino mass
m	electron mass

Search for 0νDBD

Decay rate:

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

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

T	0νDBD half-life
G	phase space factor $(\propto Q^5)$
M	Nuclear Matrix Element (NME)
m	effective ββ neutrino mass
m	electron mass

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 0νDBD

Decay rate:

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

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

T	0νDBD half-life
G	phase space factor $(\propto Q^5)$
M	Nuclear Matrix Element (NME)
m	effective ββ neutrino mass
m	electron mass

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)

Detector Building/ Source Selection Strategies

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

Search for 0νDBD

Decay rate:

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

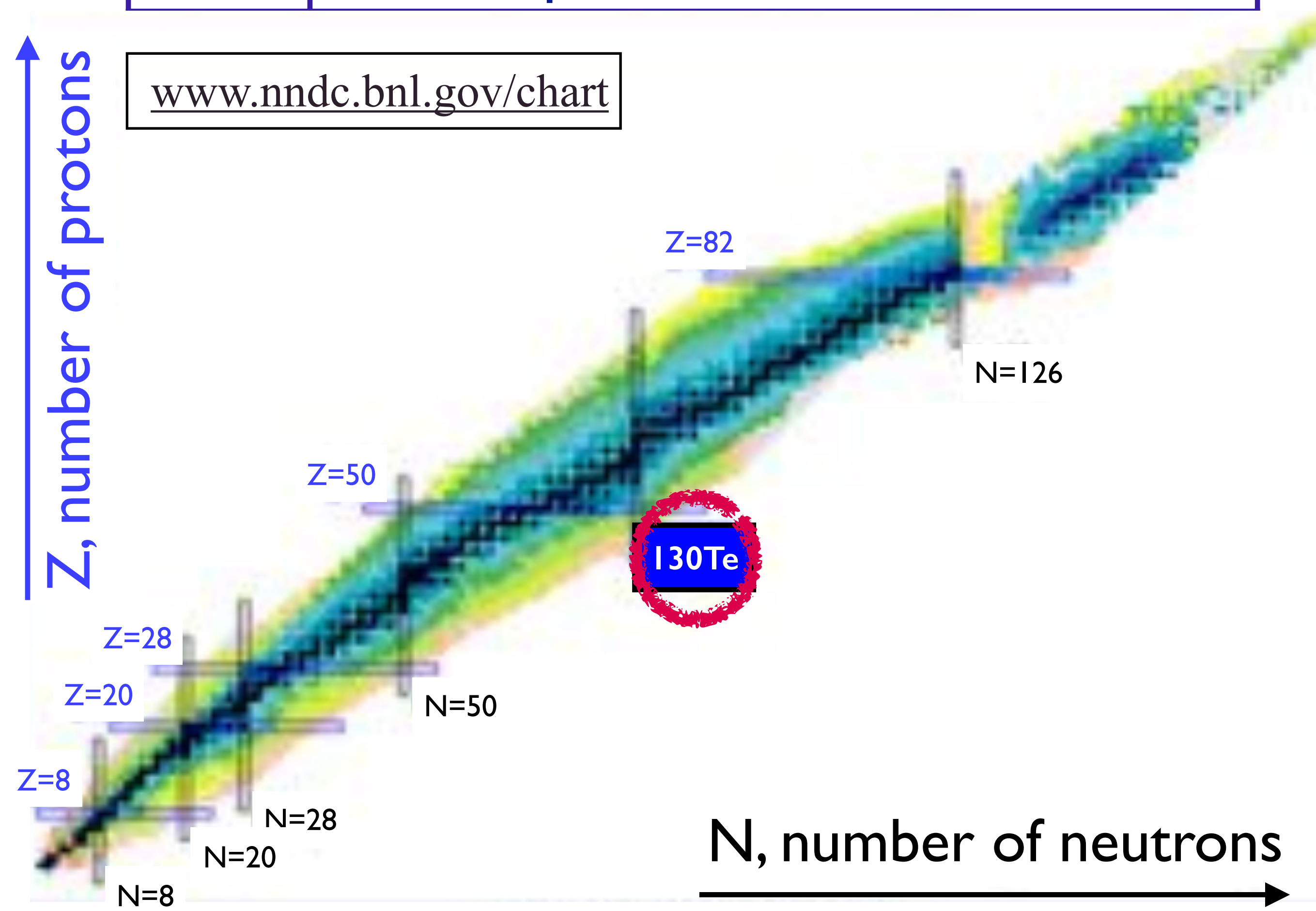
T	0νDBD half-life
G	phase space factor $(\propto Q^5)$
M	Nuclear Matrix Element (NME)
m	effective ββ neutrino mass
m	electron mass

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

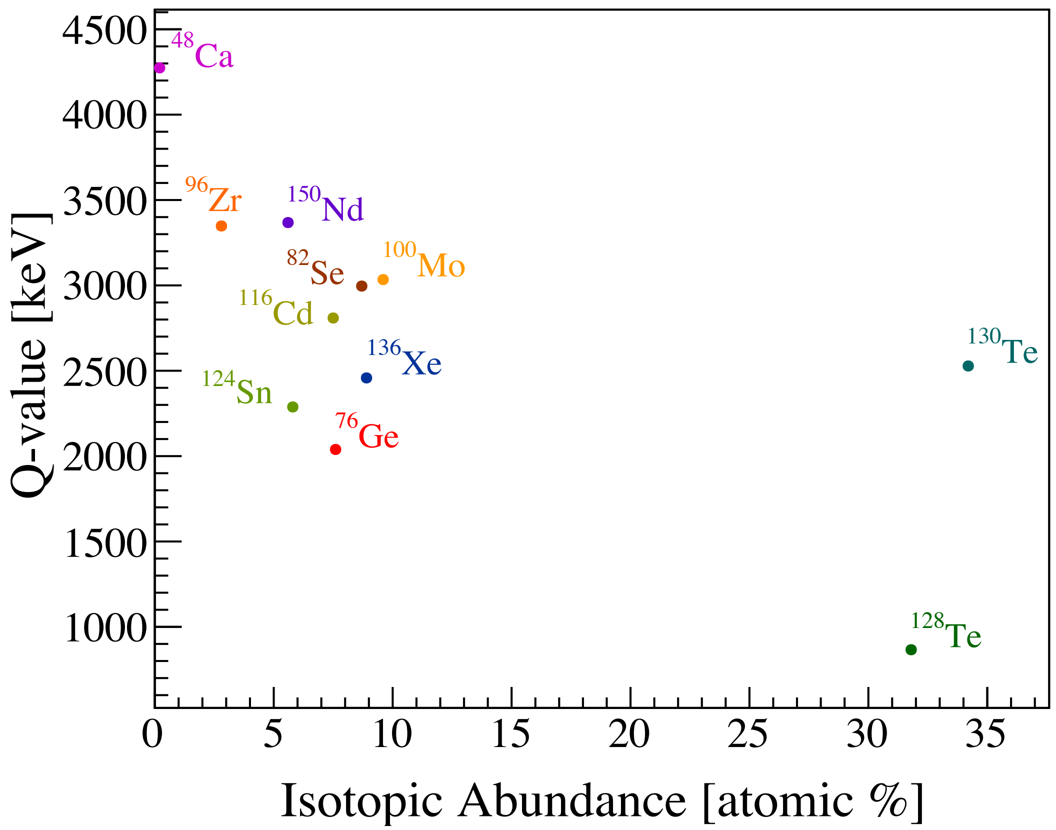
a	isotopic abundance of source

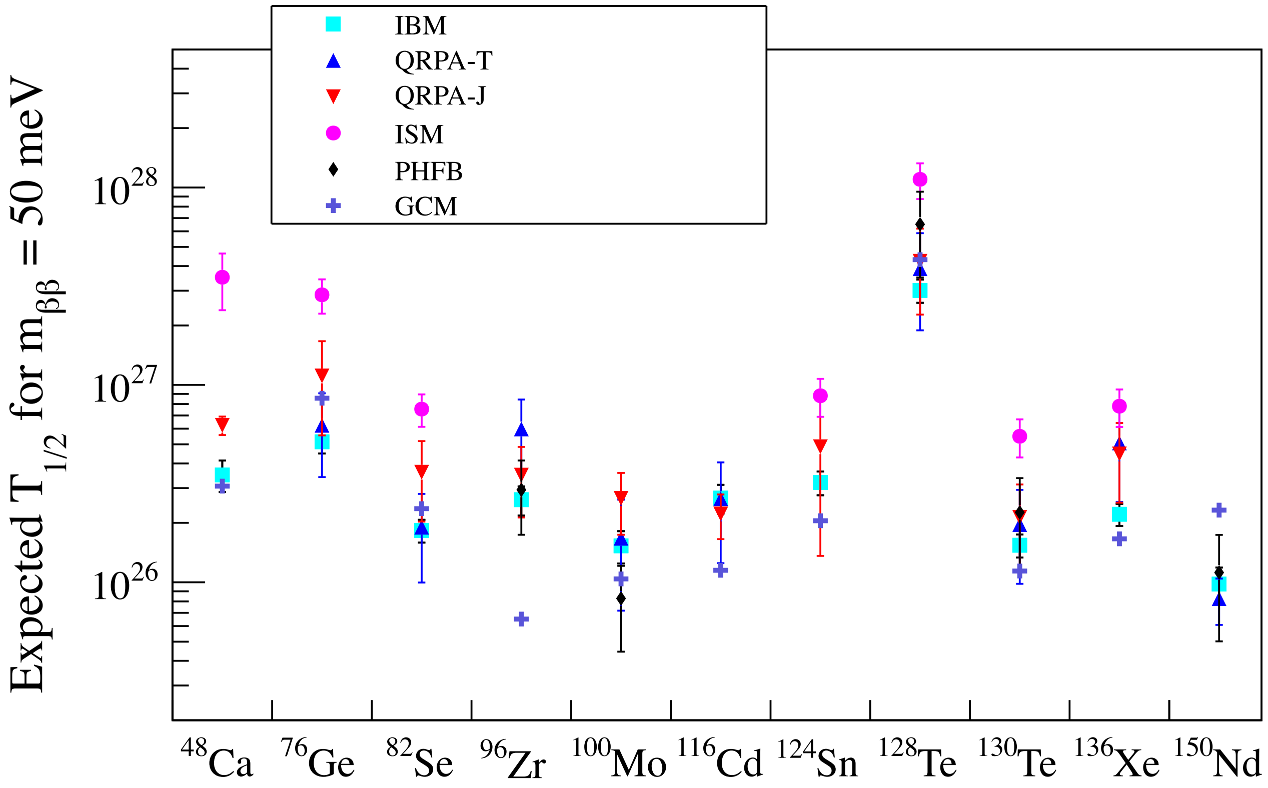
Detector Building/ Source Selection Strategies

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

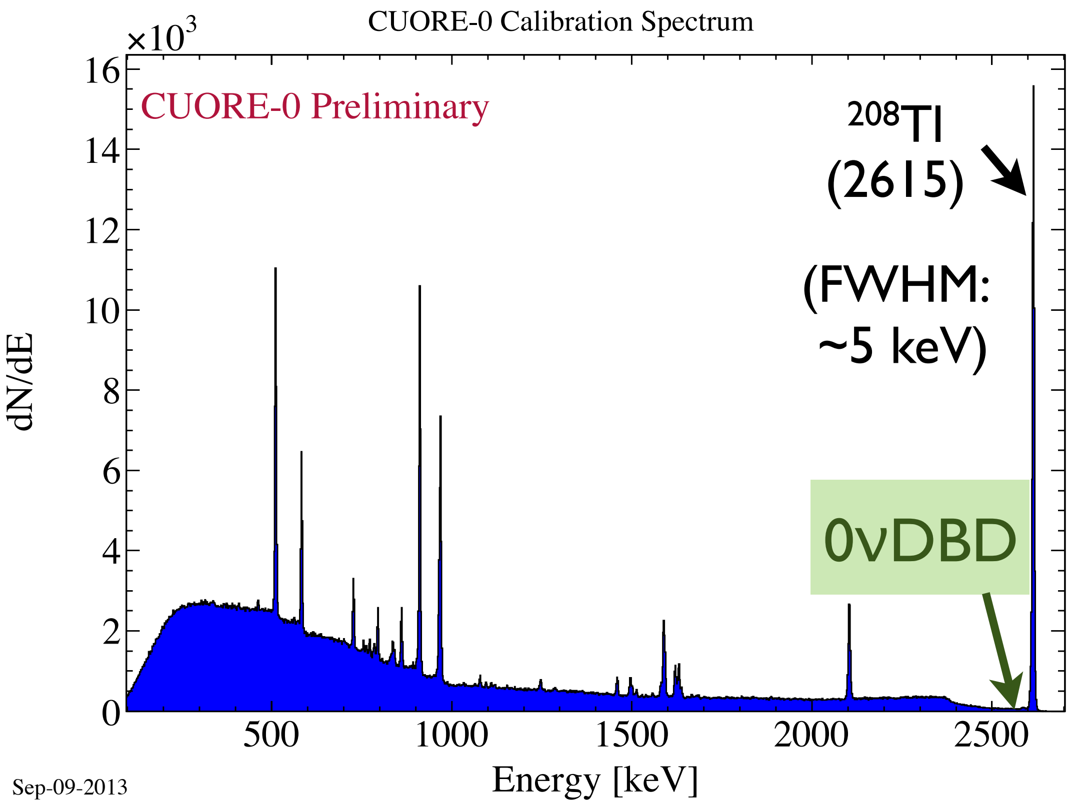


^{130}Te for 0νDBD

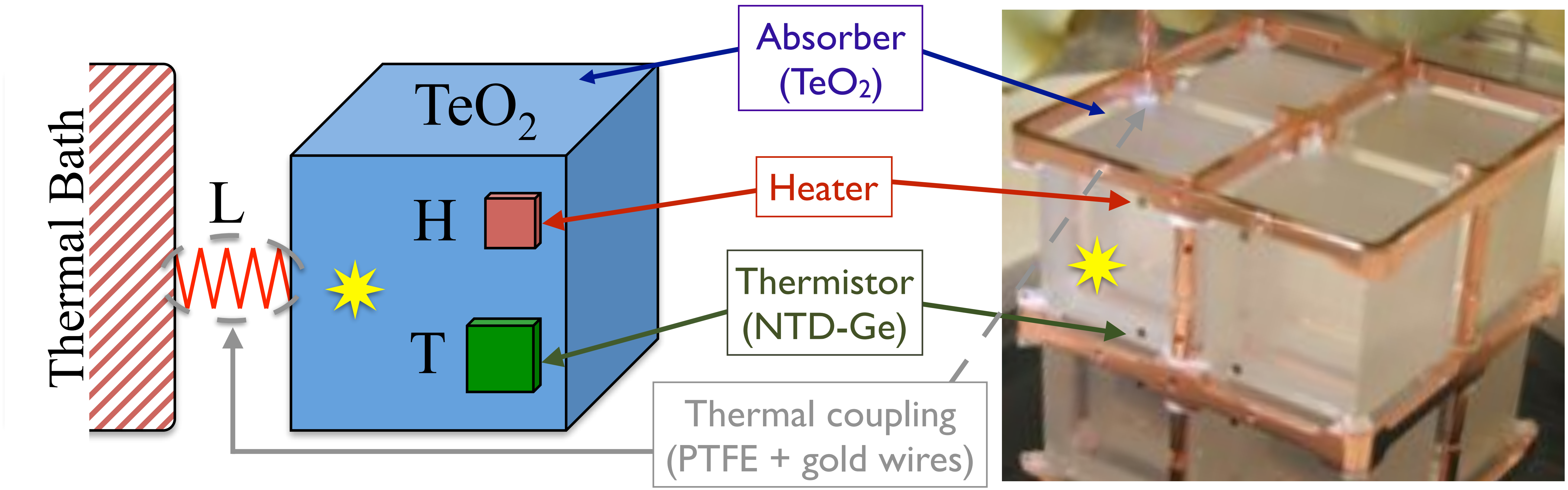




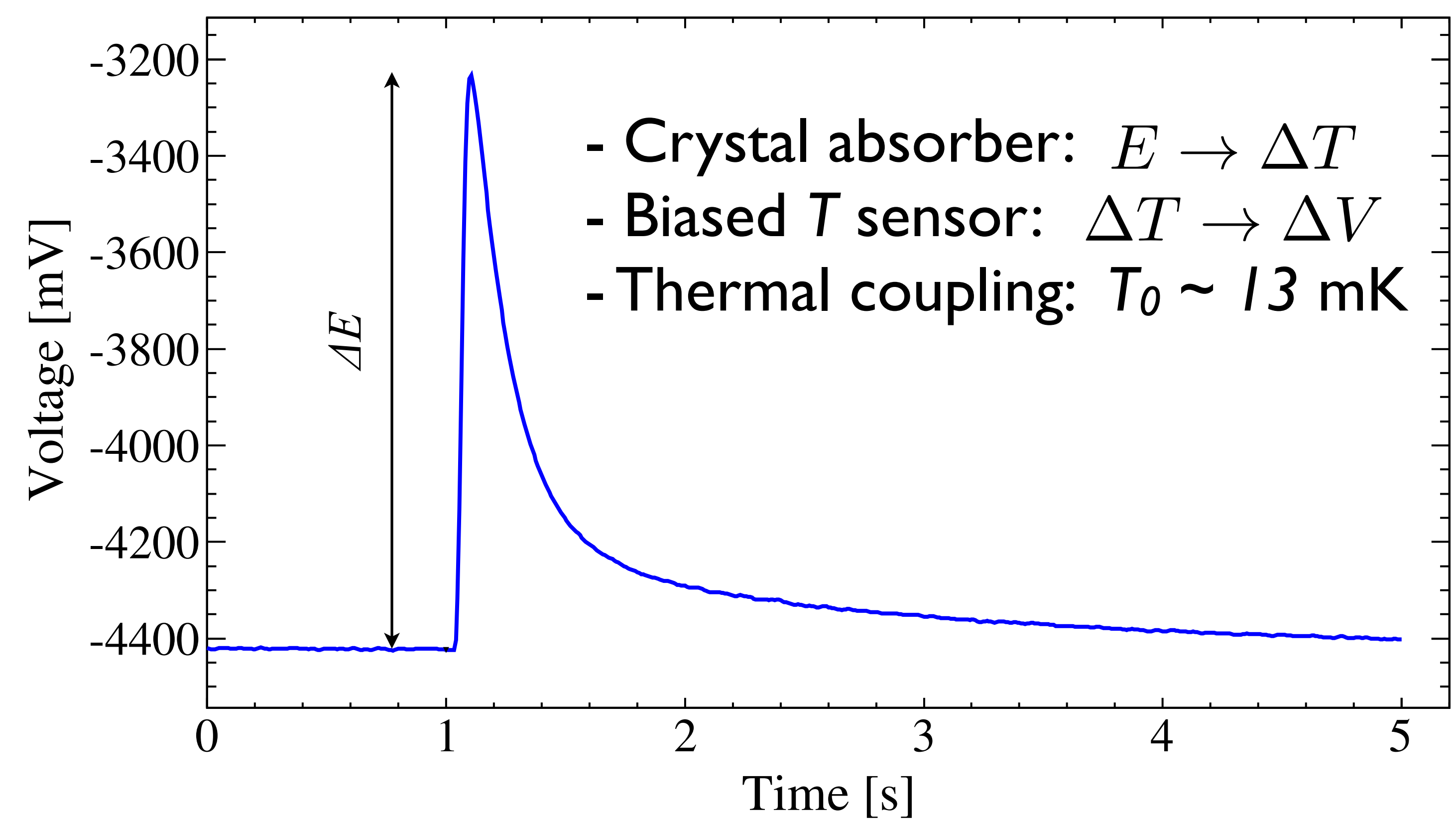
- ^{130}Te + thermal detector w/ excellent energy resolution is appealing for the 0νDBD detection.



TeO_2 Bolometers



- Measure energy deposition through temperature rise.



Outline

- Neutrinoless double-beta decay (0νDBD) search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : 0νDBD search w/ a single CUORE tower
  - CUORE-0 : Detector
  - CUORE-0 : Performance and Background
  - CUORE-0 : Projected Sensitivity
- Summary

The CUORE 0vDBD Search

CUORE: Cryogenic Underground Observatory for Rare Events

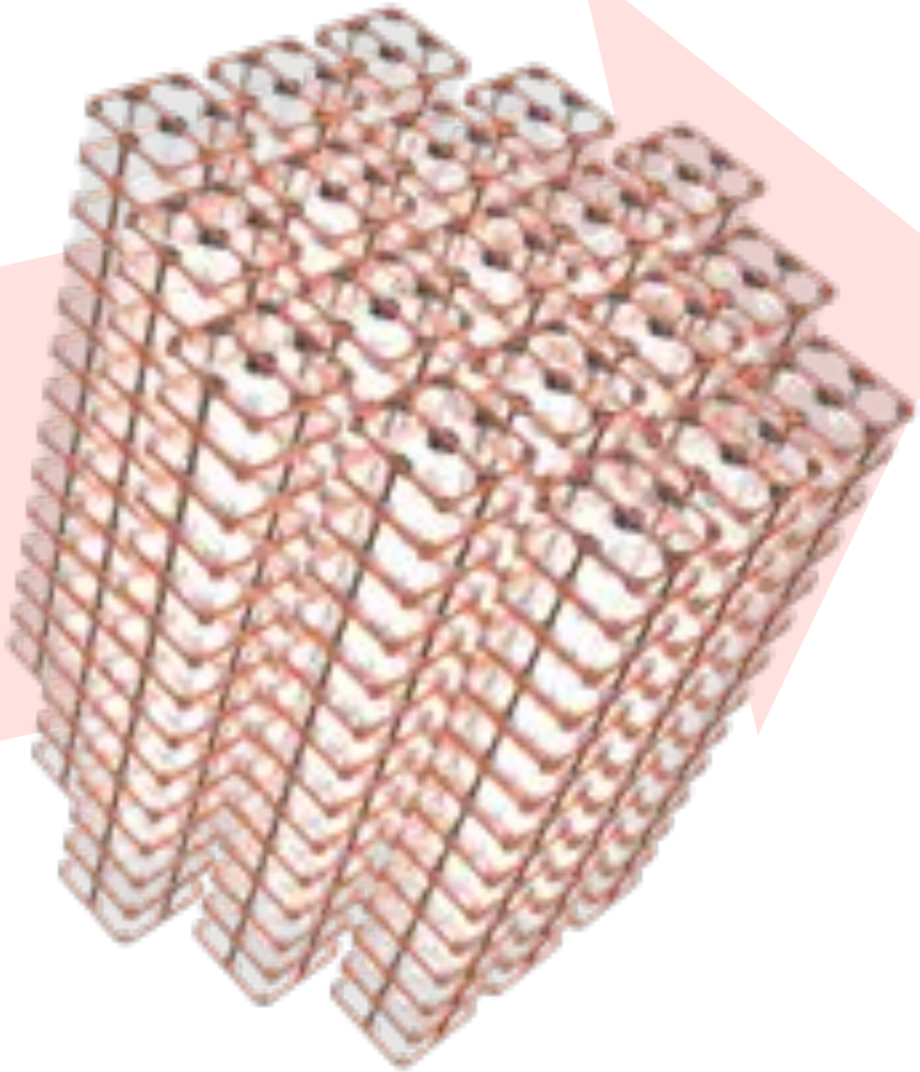
Cuoricino (2003-2008)

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)

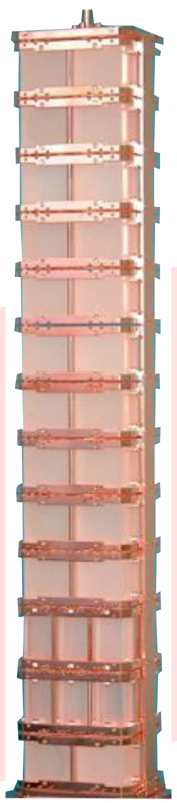


Projected (2020)
$\langle m_{\beta\beta} \rangle_{90\%\ \text{C.L.}} = 51 - 133\ \text{meV}$

The CUORE 0νDBD Search

CUORE: Cryogenic Underground Observatory for Rare Events

Cuoricino (2003-2008)

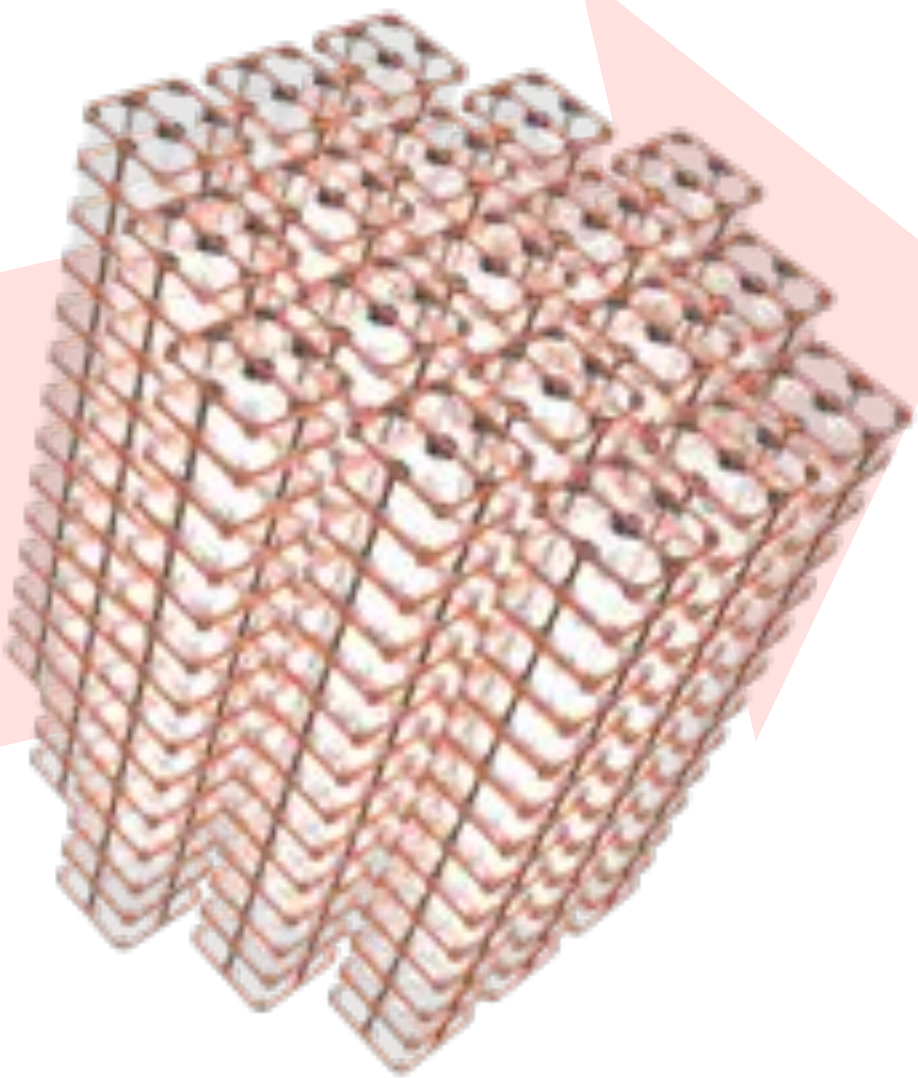


Achieved (2008)
$\langle m_{\beta\beta}\rangle_{90\%\ \mathrm{C.L.}} = 300 - 710\ \mathrm{meV}$

CUORE-0 (2013-2015)

Projected (2015)
$\langle m_{\beta\beta}\rangle_{90\%\ \mathrm{C.L.}} = 204 - 533\ \mathrm{meV}$

CUORE (2015-2020)



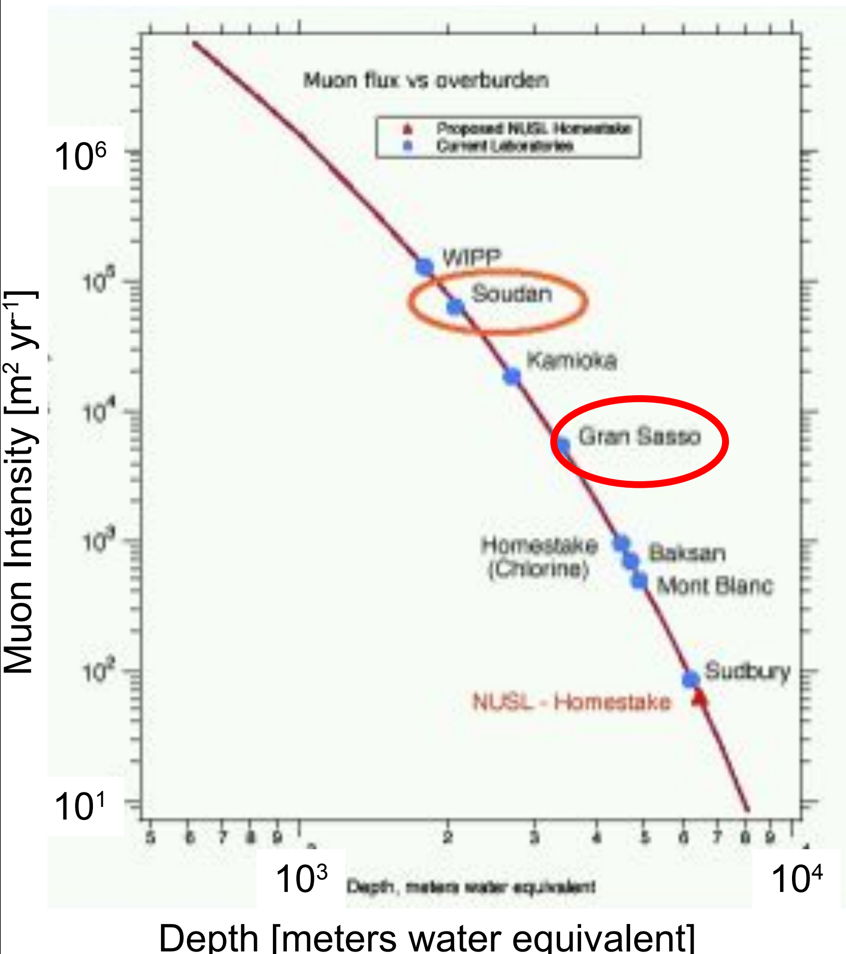
Projected (2020)
$\langle m_{\beta\beta}\rangle_{90\%\ \mathrm{C.L.}} = 51 - 133\ \mathrm{meV}$

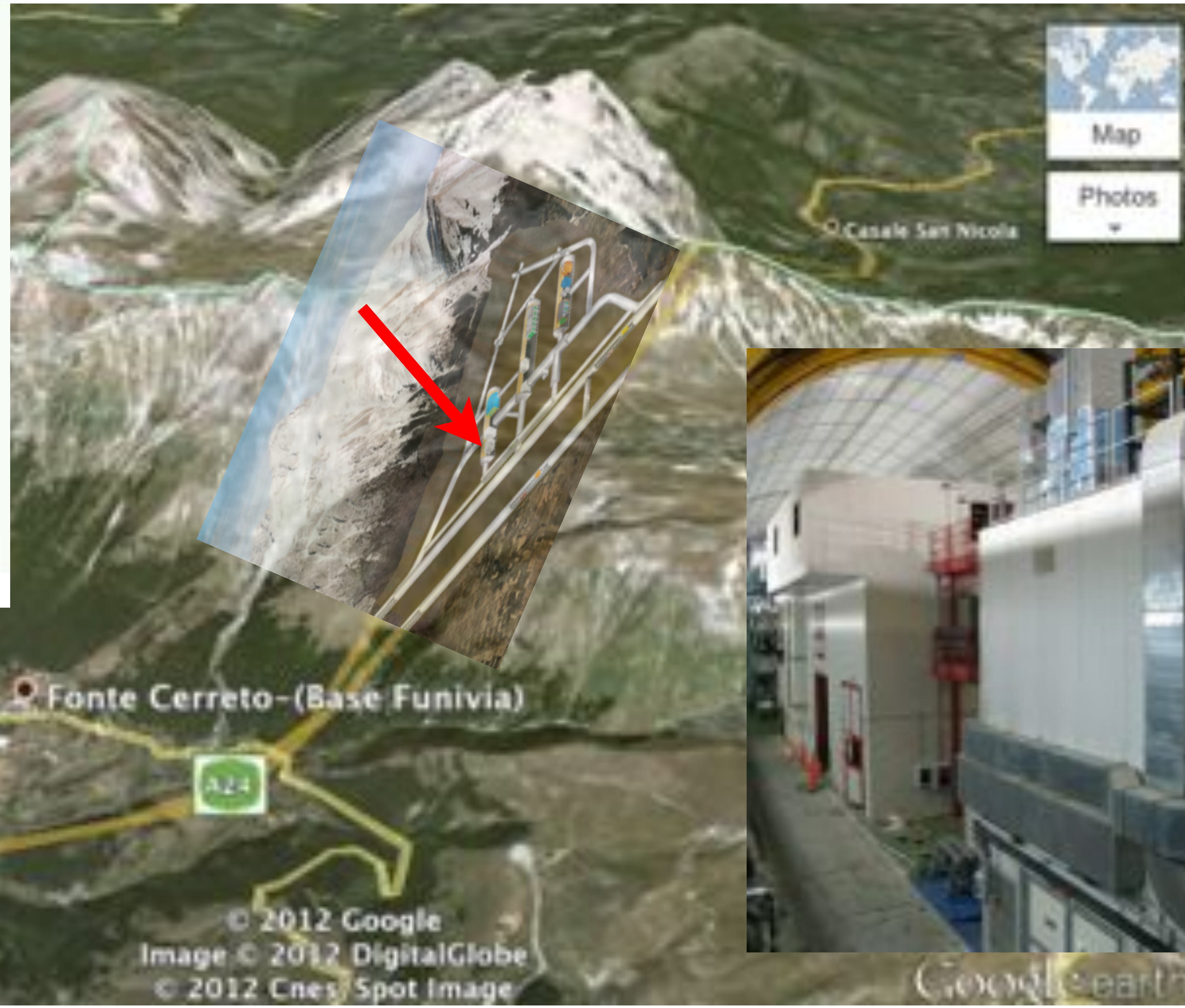
CUORE Collaboration

(Oct. 31, 2013 @ LNGS)

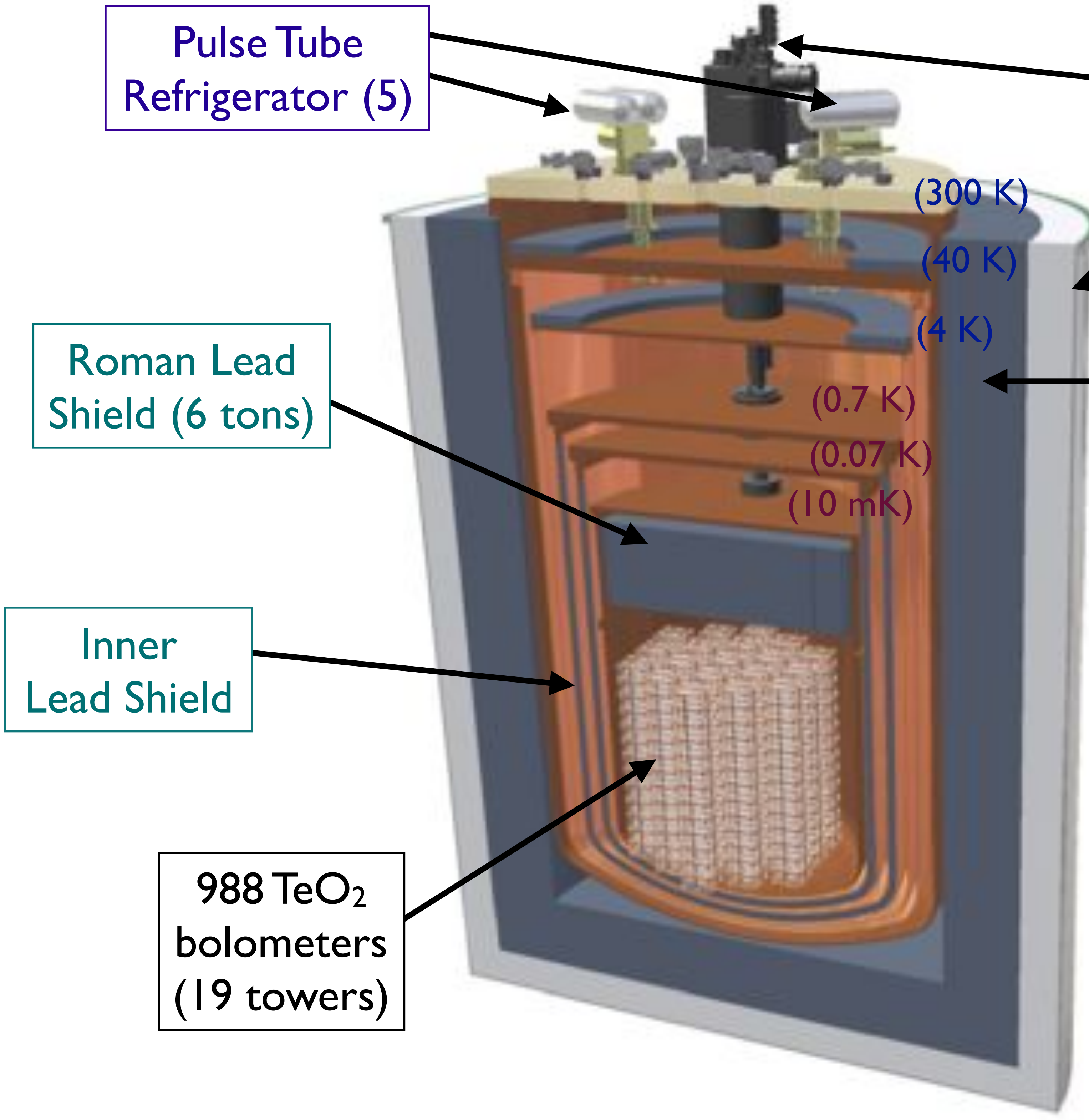
CUORE at LNGS

CUORE at LNGS



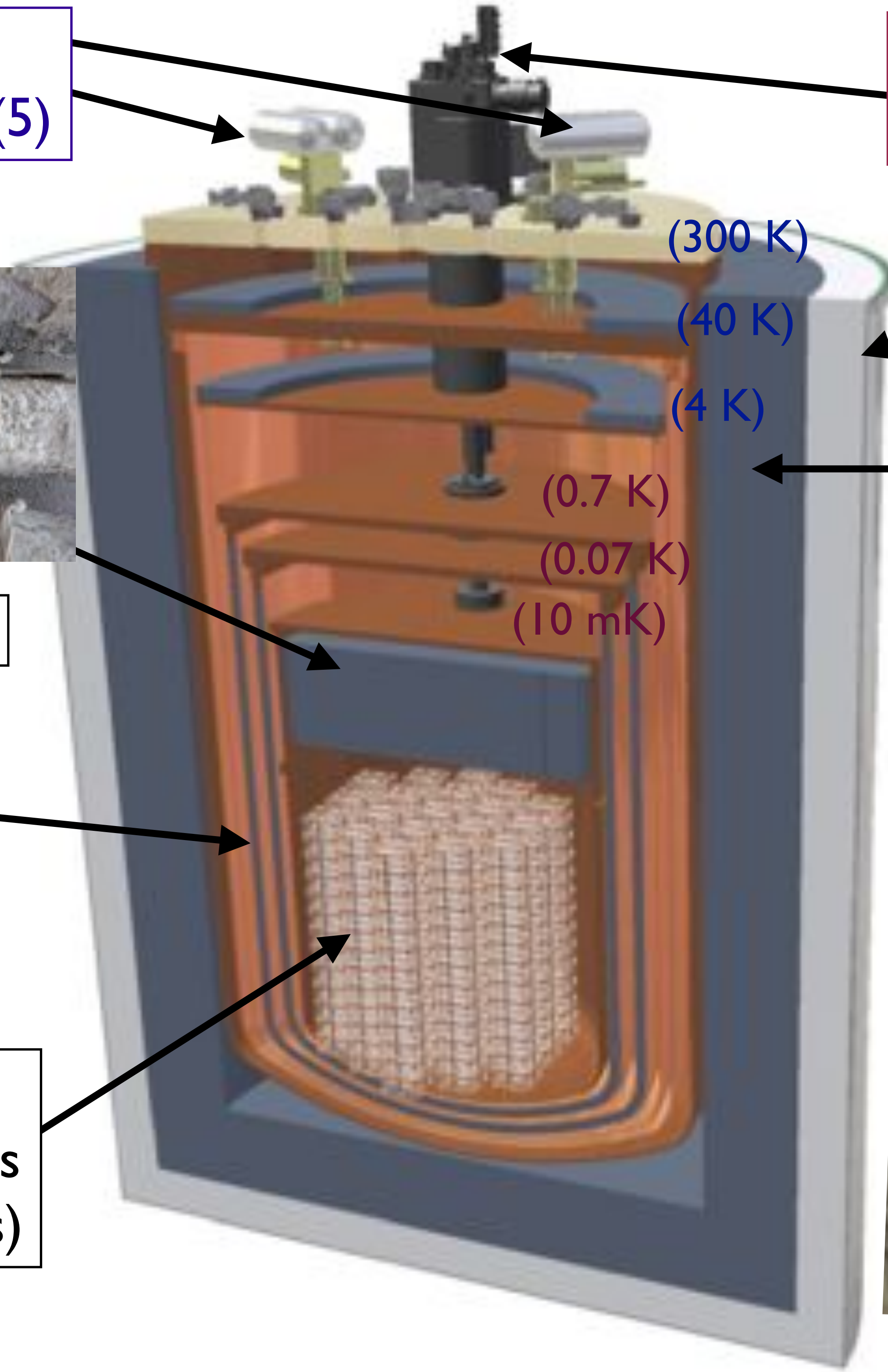


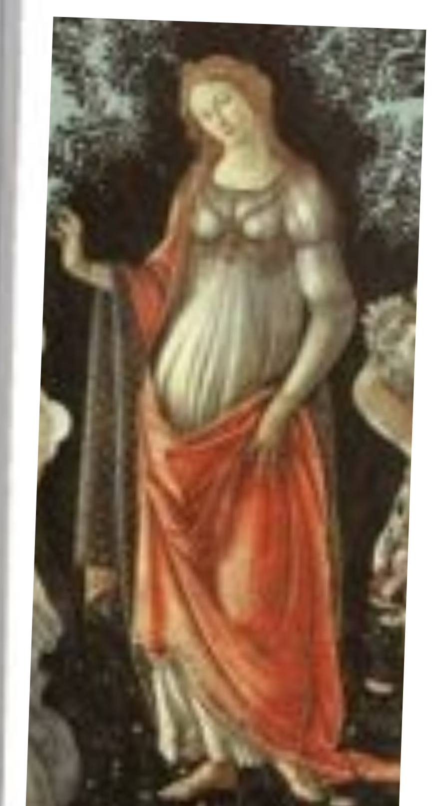
The CUORE Detector



The CUORE Detector

doi:10.1038/news.2010.186 (nature)





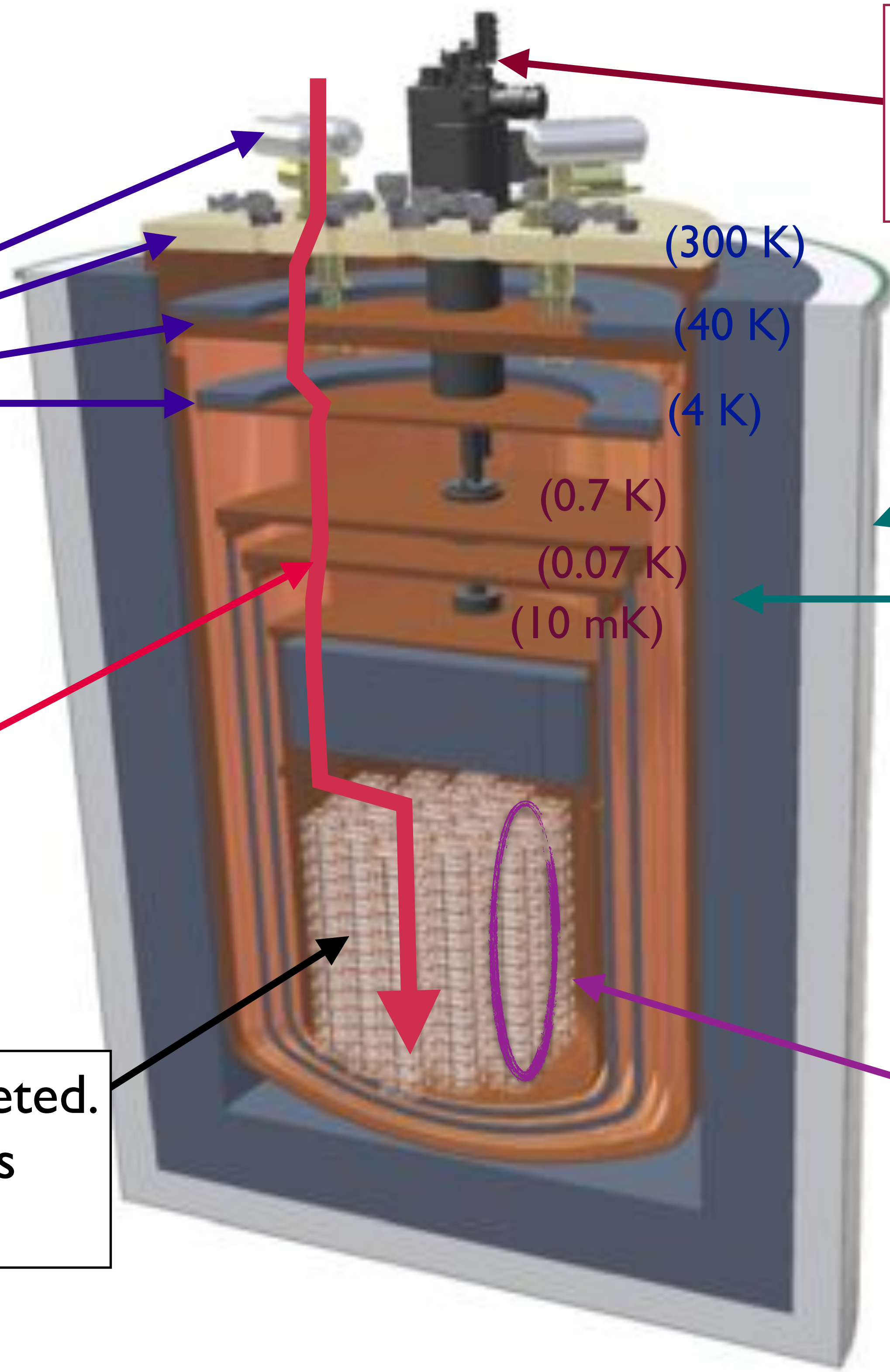
Progress towards CUORE

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.



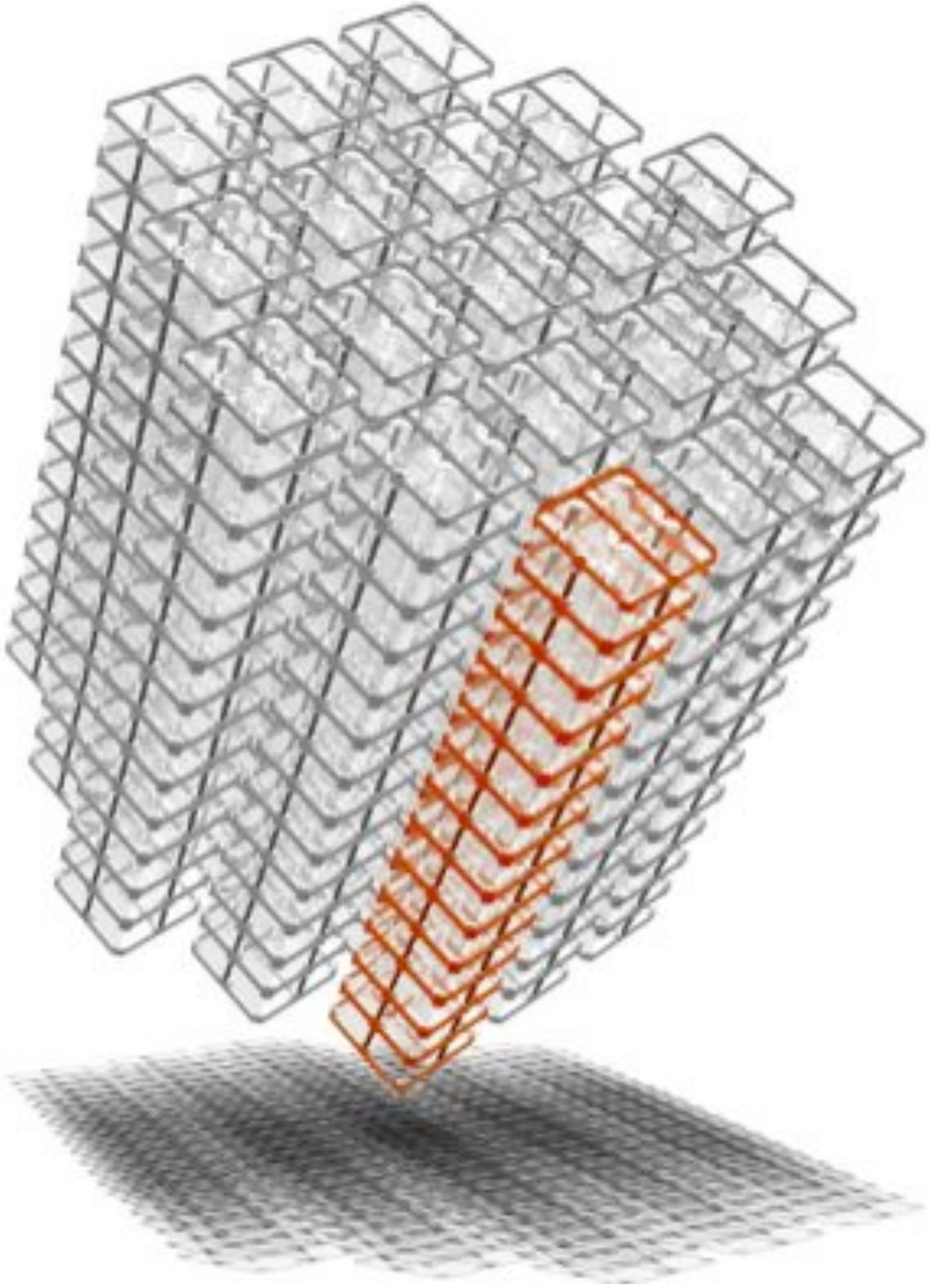
CUORE-0, the first tower from CUORE assembly line is running in the Cuoricino cryostat.

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

Outline

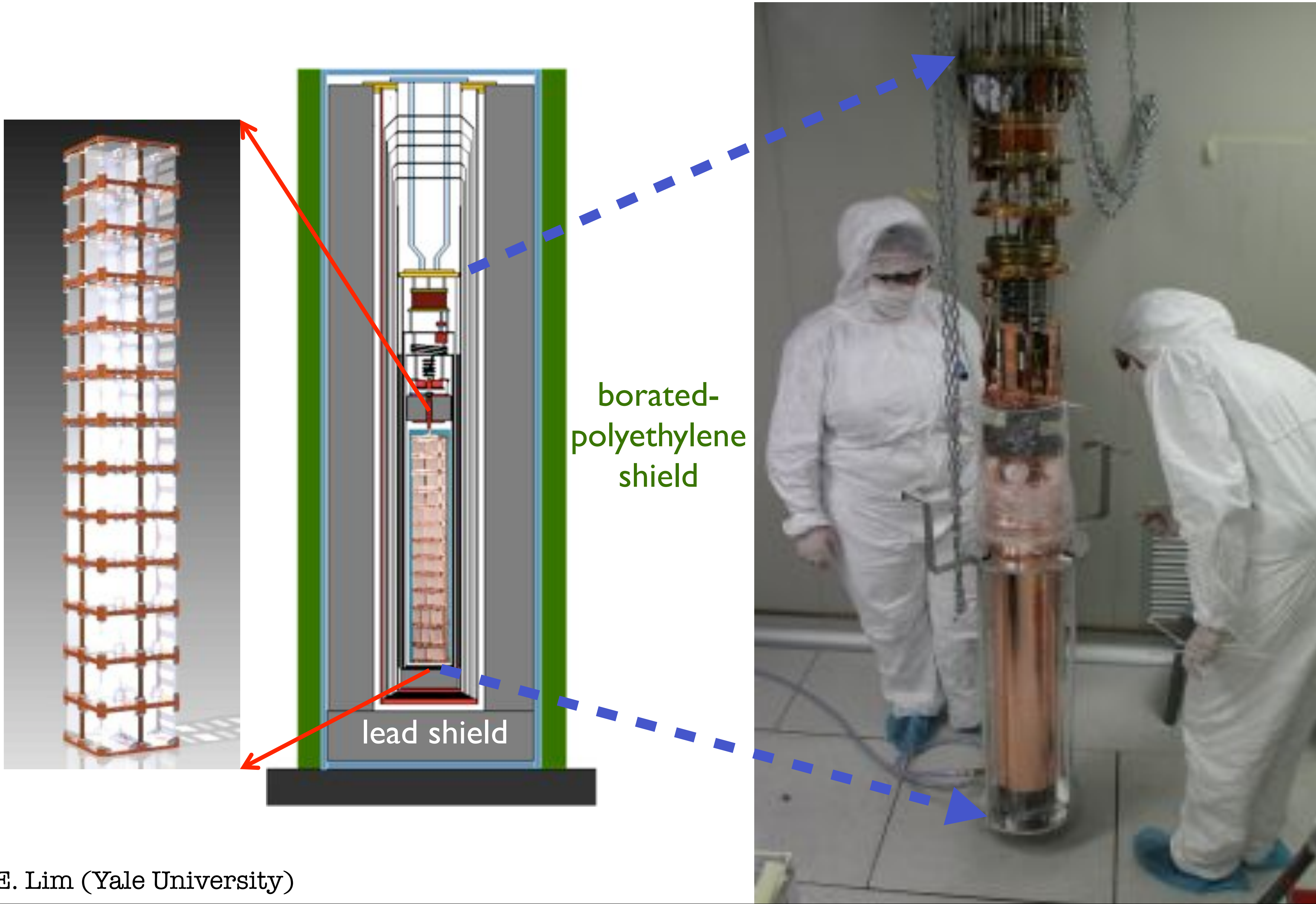
- Neutrinoless double-beta decay (0νDBD) search
- CUORE : An array of TeO_2 bolometers
- CUORE-0 : 0νDBD search w/ a single CUORE tower
    - CUORE-0 : Detector
    - CUORE-0 : Performance and Background
    - CUORE-0 : Projected Sensitivity
- Summary

CUORE-0

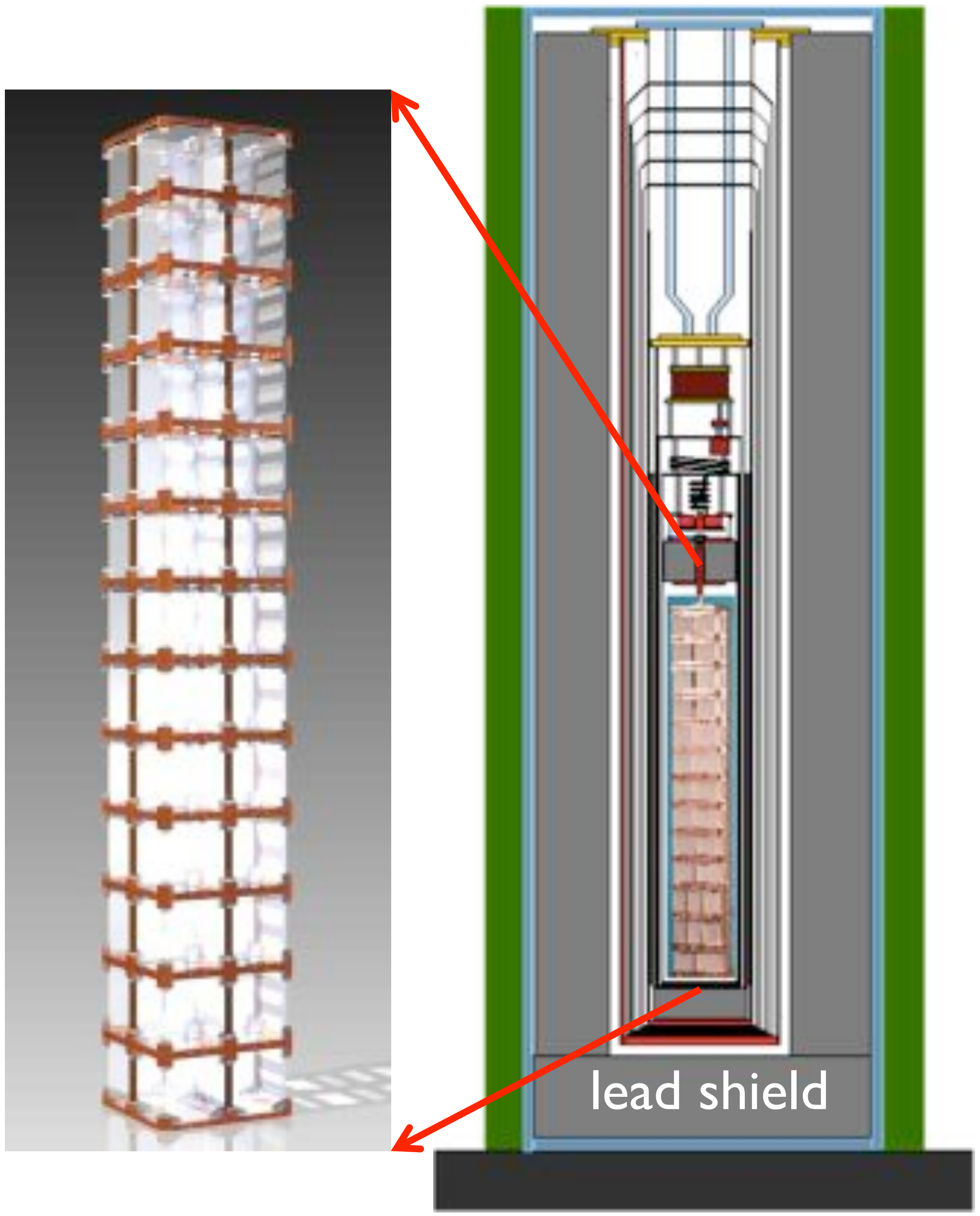


- The first CUORE-like tower hosted in old Cuoricino cryostat.

CUORE-0



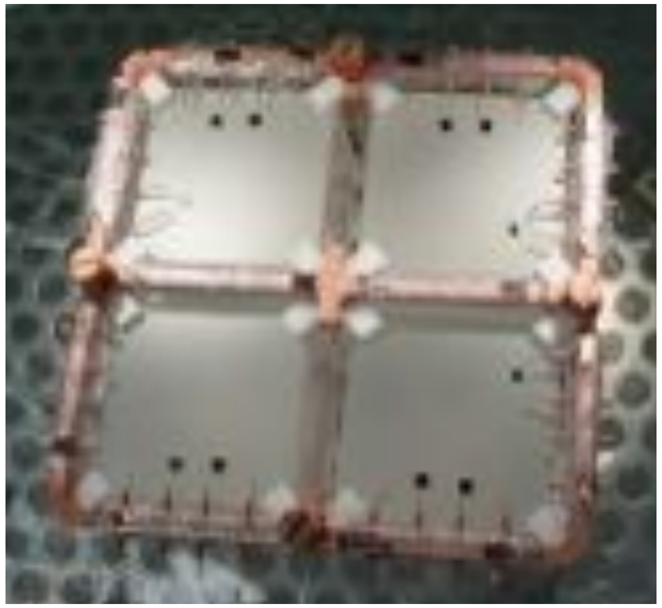
CUORE-0



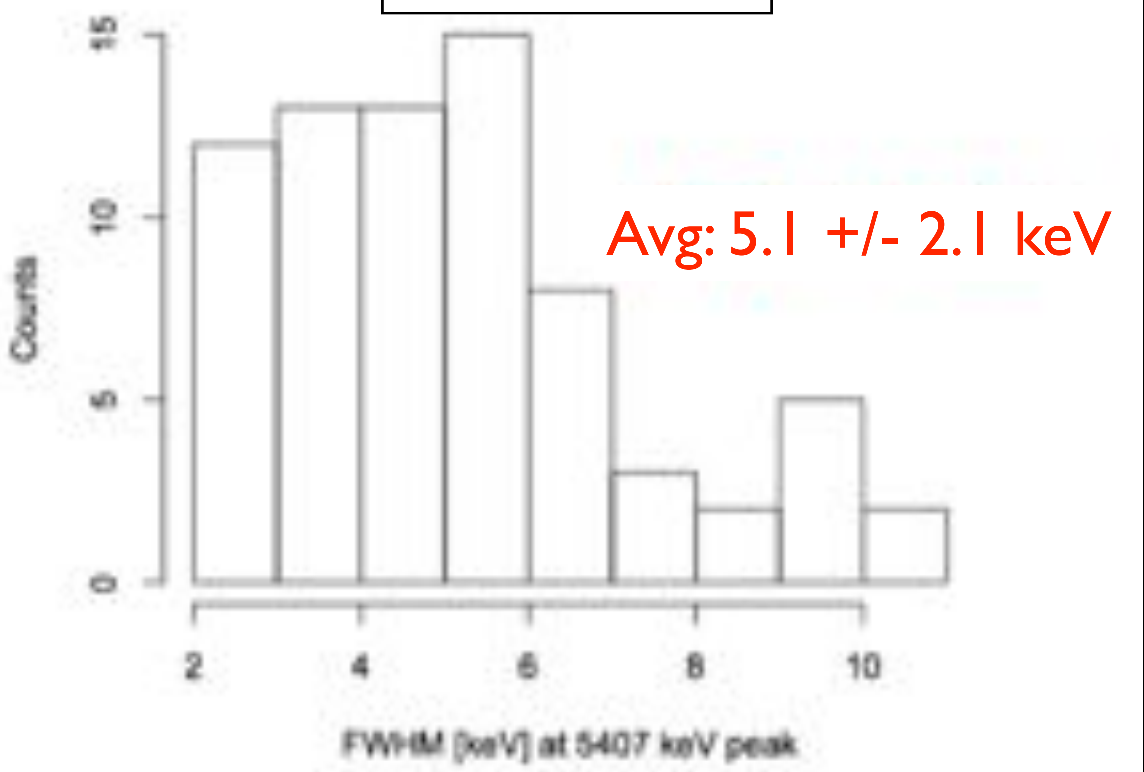
- The first CUORE-like tower hosted in old Cuoricino cryostat.
- 52 (13 x 4) crystals, 39 kg of TeO_2 (*11 kg of ^{130}Te*), 4 kg of copper structure.
- Validated new cleaning and assembly procedures for CUORE.
- Taking 0νDBD data since March 2013.
- Will surpass Cuoricino sensitivity before CUORE starts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

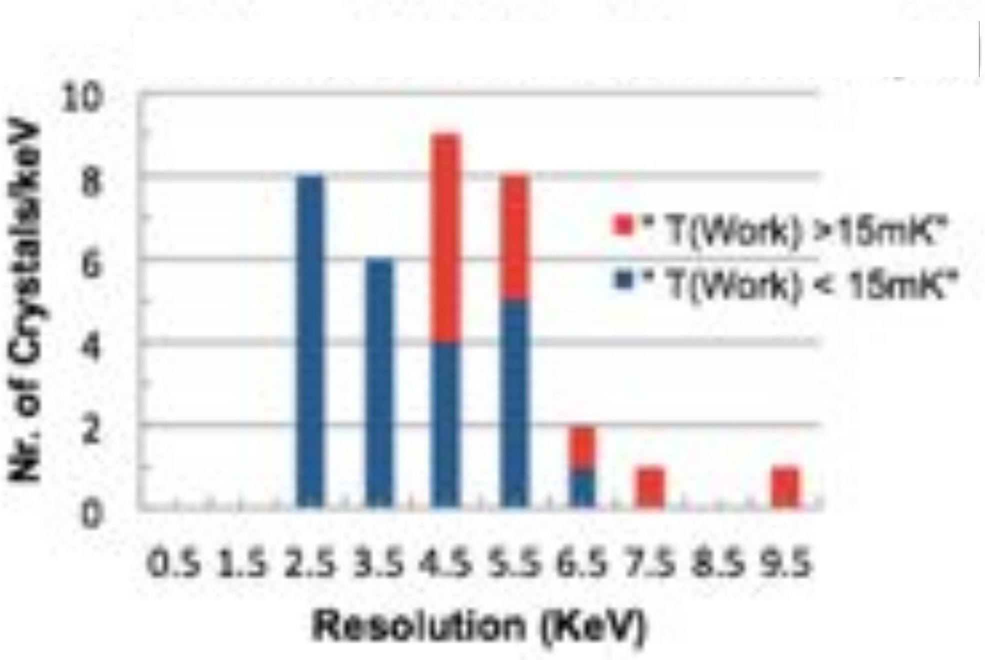
TeO_2 Crystals

- 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)



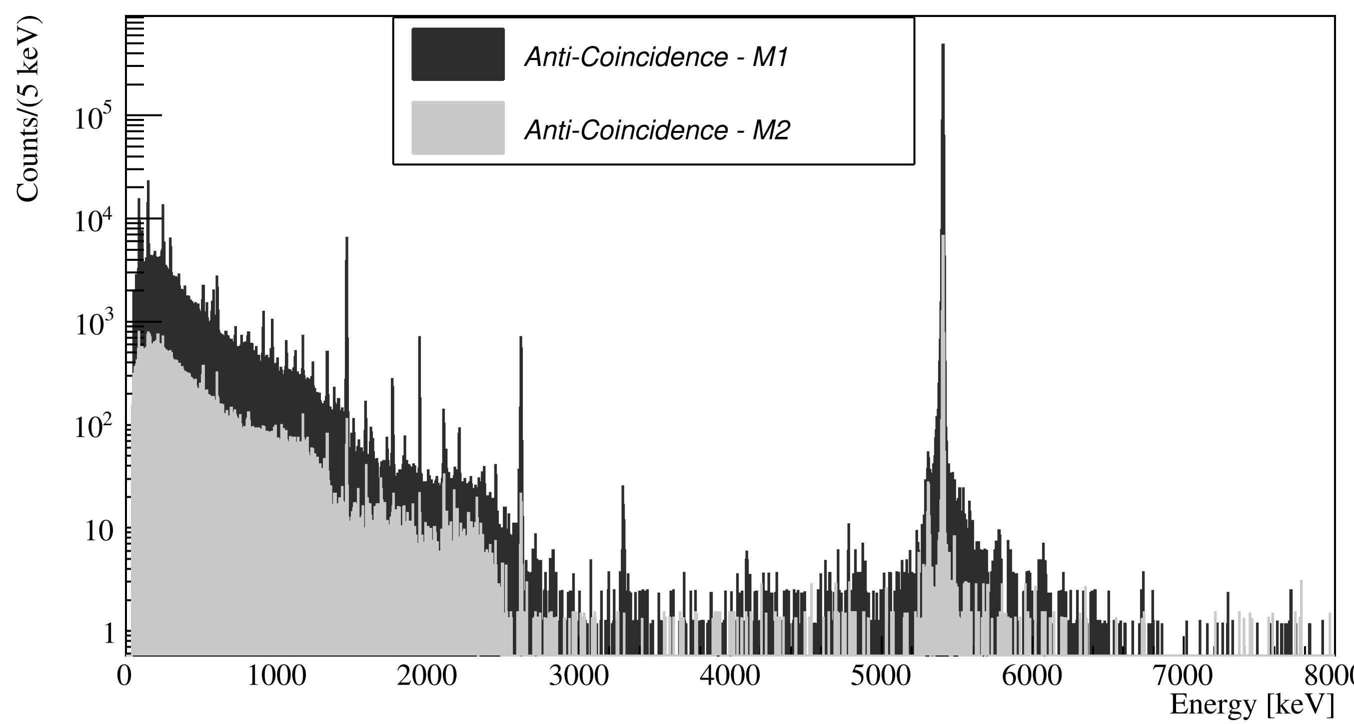
CCVR 1-9





Radioactivity of the Crystals

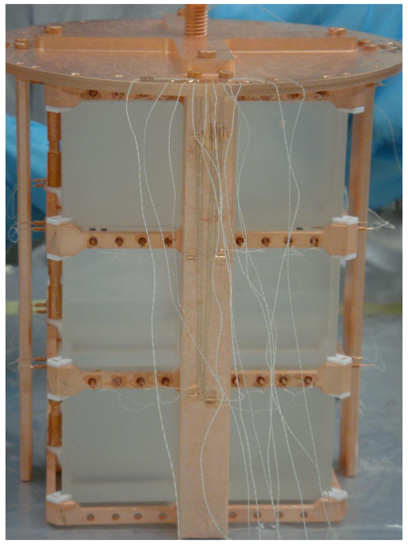
- CCVR also serves as radioactive contamination measurements of the crystals.

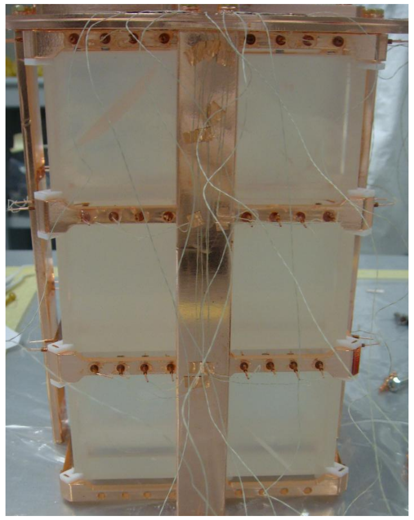


90% CL upper limit	^{232}Th	^{238}U	^{210}Po
Bulk Contaminations (Bq/kg)	< 8.4E-7	< 6.7 E-7	< 3.3 E-6
Surface Contaminations (Bq/cm^2)	< 2E-9	< 1E-8	< 1E-6

Astropart. Phys. 35, 839 (2012)

Reduction of Copper Surface Contamination

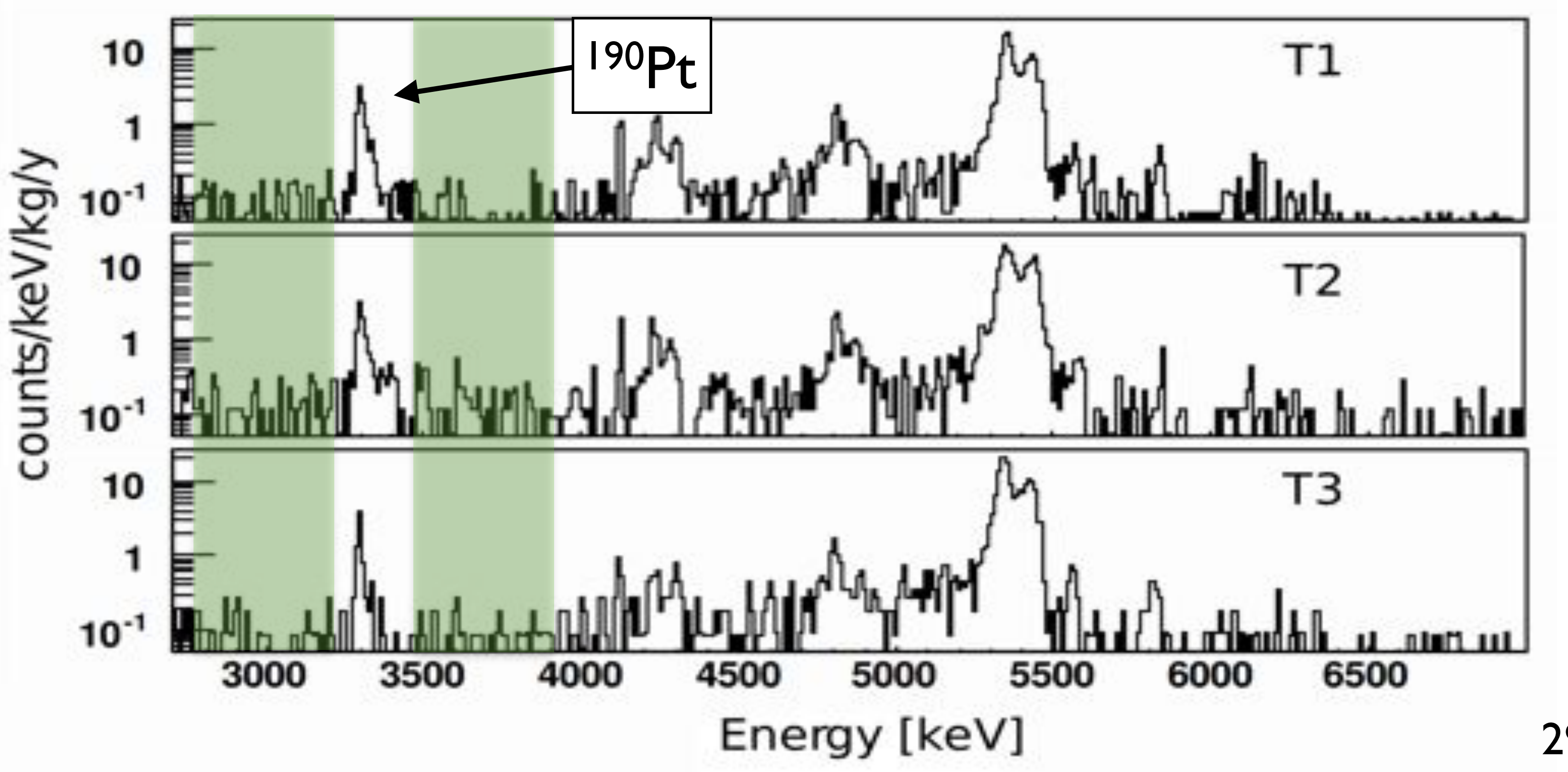




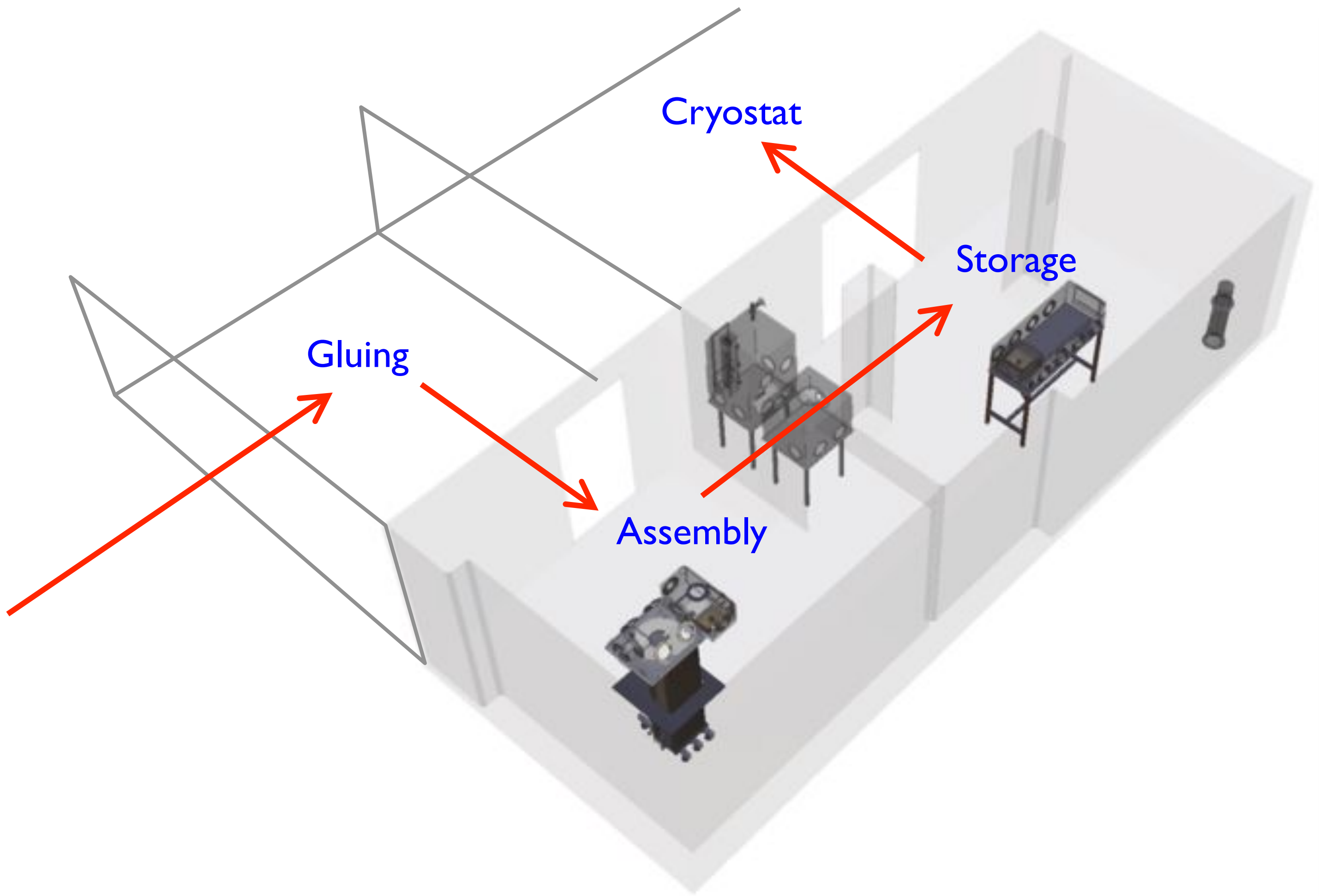
- Three Tower Test (TTT)
  - T1: Polyethylene wrapped
  - T2: Chemical etching and cleaning
  - T3: Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching (TECM) cleaning

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.
- Half the background rate of Cuoricino.

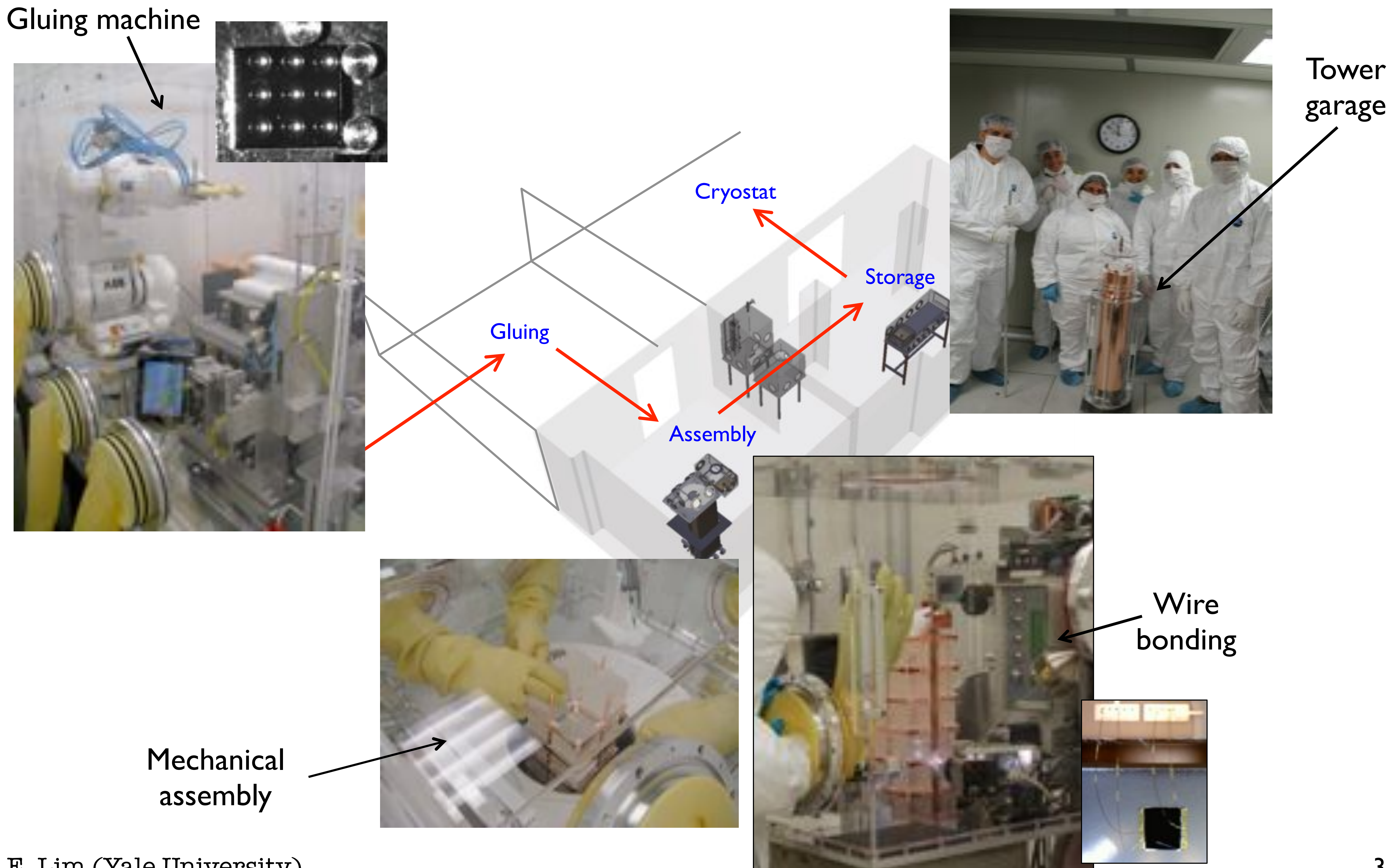


Detector Assembly



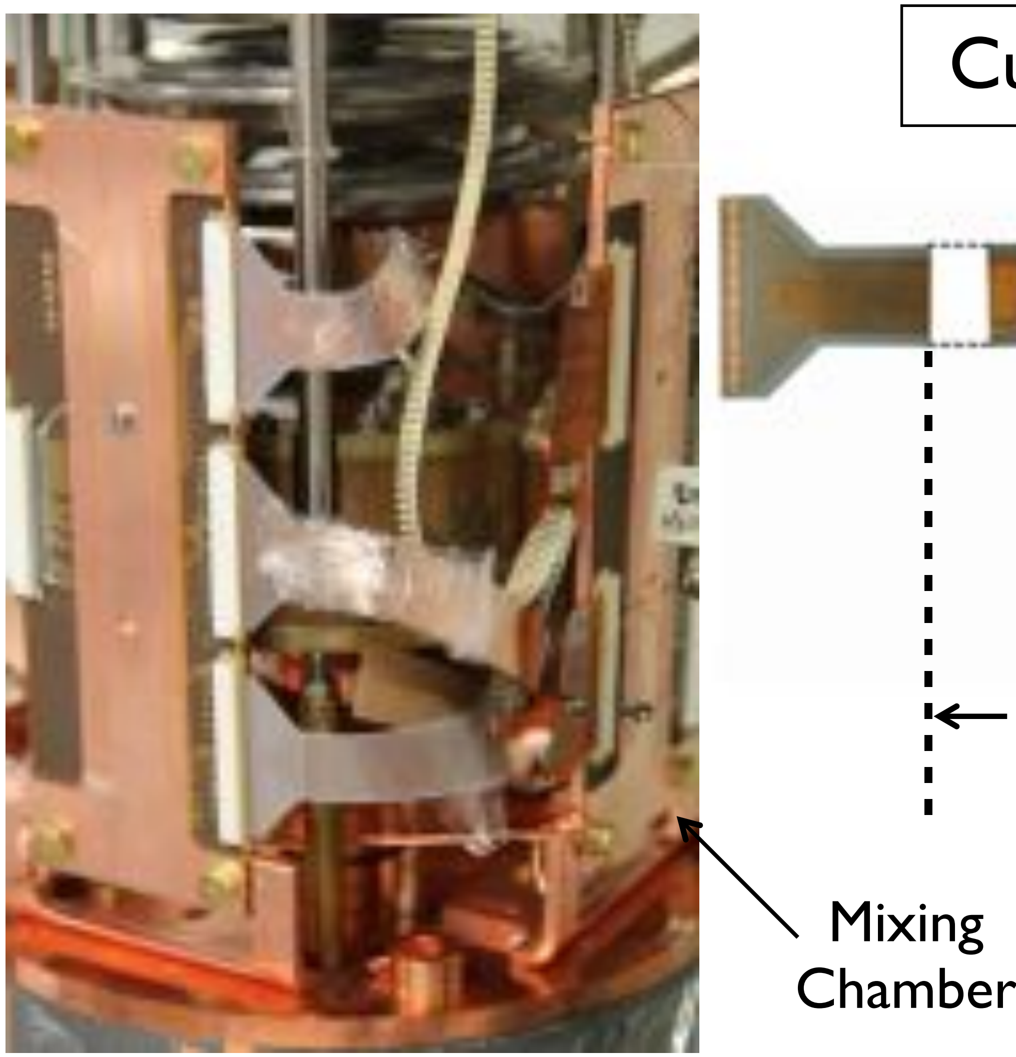
- Crystals are prepared & assembled into towers inside N_2-fluxed glove boxes in a Class 1000 clean room.

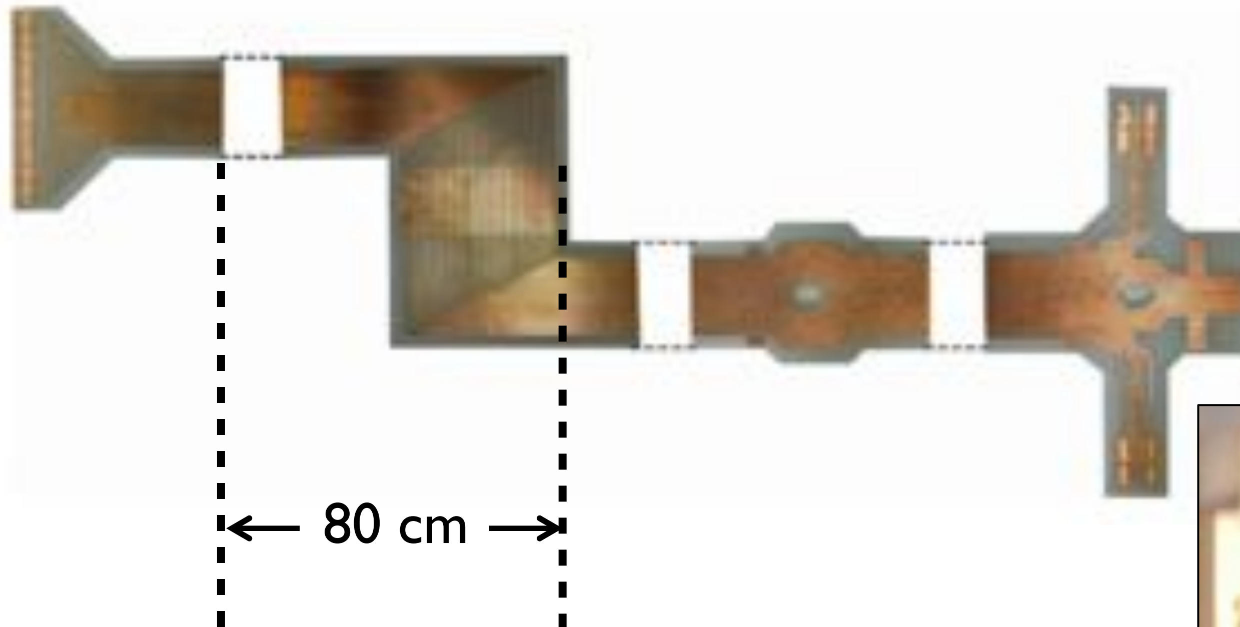
Detector Assembly



Improvements on Wiring

Cu-PEN flat flexible tape



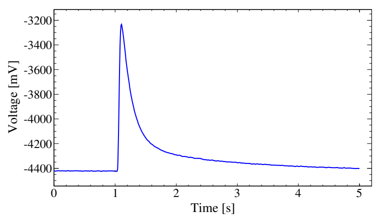


Nucl. Instrum. Meth. A 718, 211 (2013)

Analysis Procedure

Data Acquisition
continuously sample bolometer traces @ 125 S/s

Bolometer Pulse



Raw Data Processing
- software trigger (> 50-100 keV)
- signal, noise, pulser events
- signal size evaluation
- signal gain correction
- energy calibration (V → keV)

ROOT Data Trees

Event Selection
- remove low quality events
- single pulse in 7.1s window
- pulse shape
- no other pulse in coincidence in other bolometers

Analysis efficiency!

Reduced Data

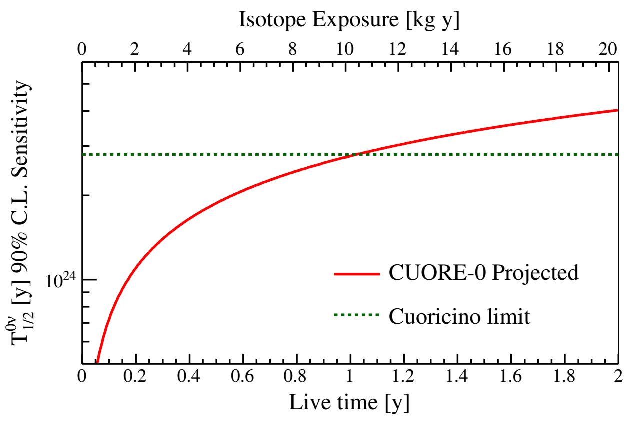
Experimental Input

0vDBD data sidebands, blind

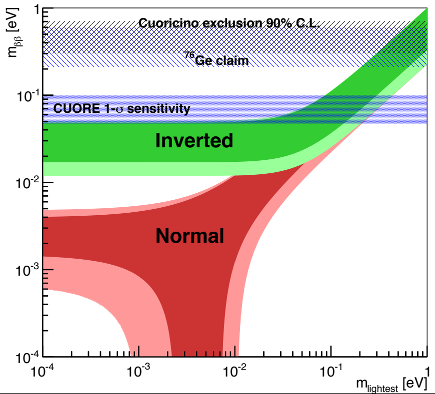
background estimation, energy resolution

Statistical Treatment

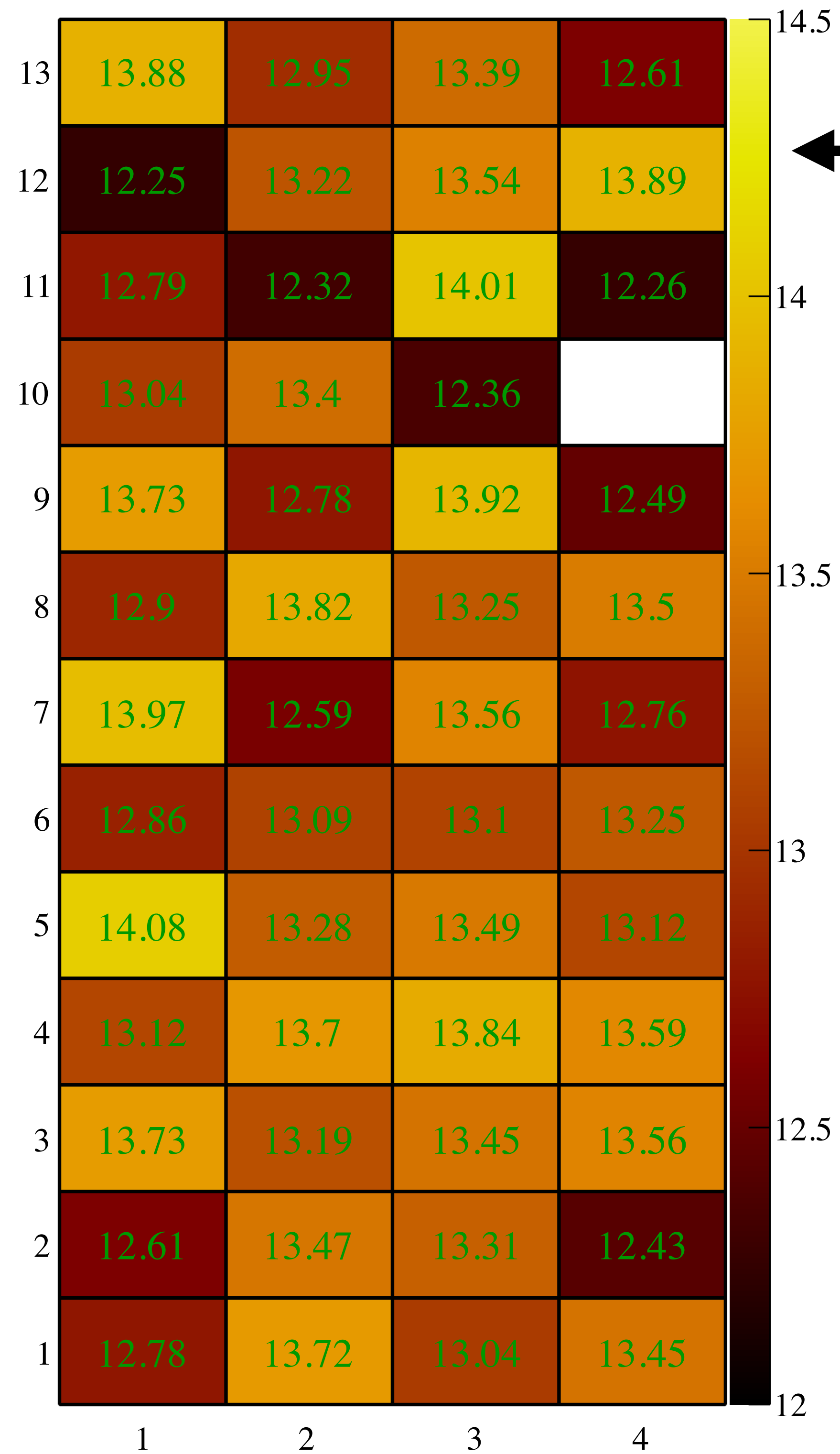
Single Bin Counting (w/ Poisson fluc)



Nuclear Physics

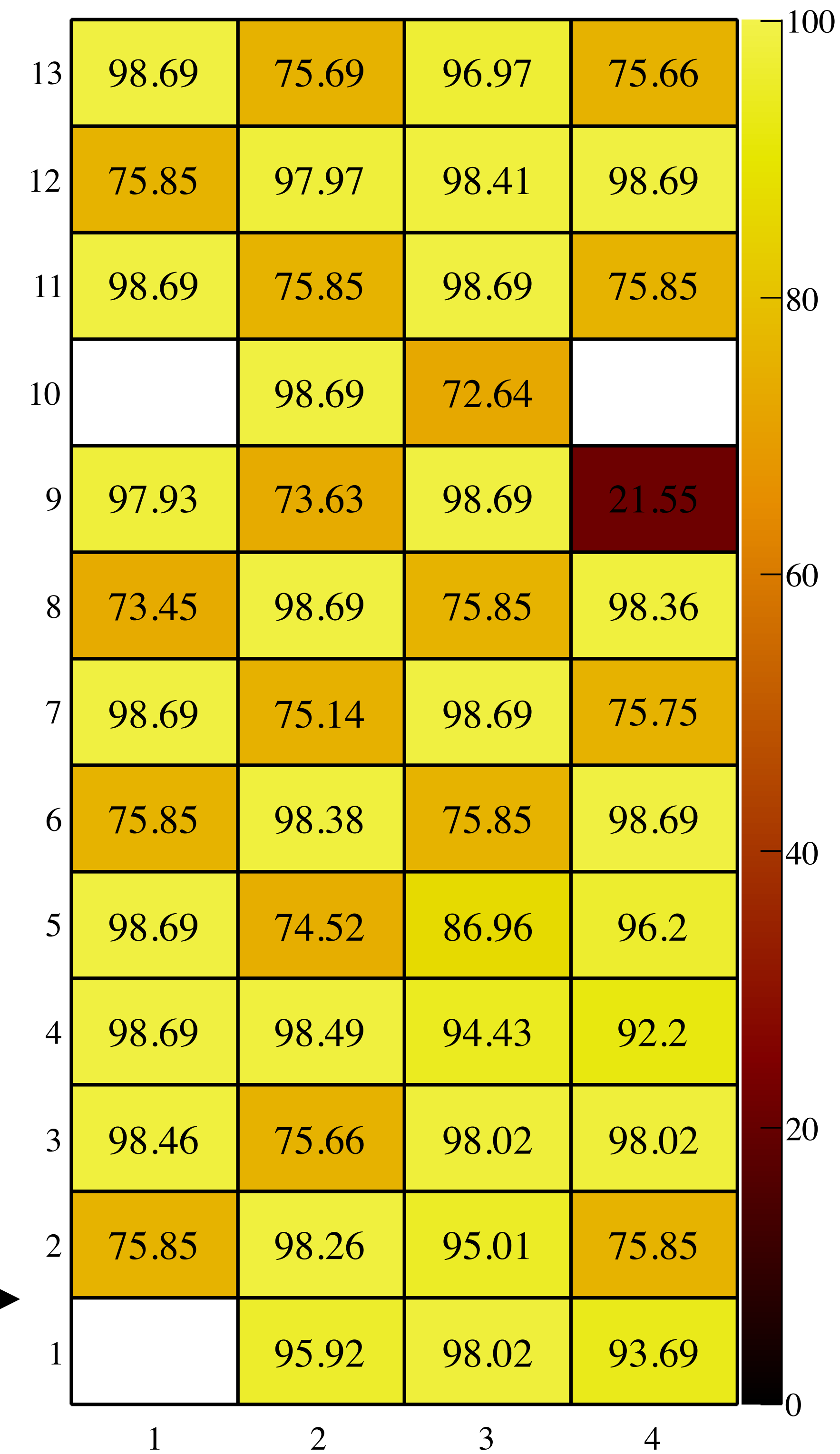


Tower Response

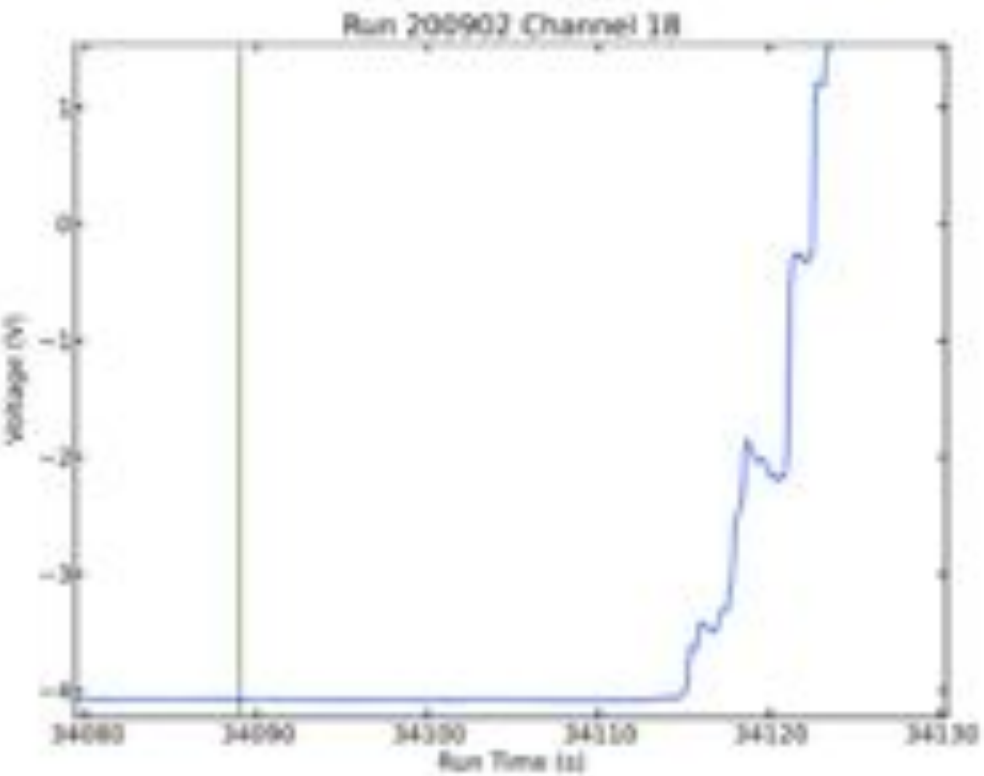


Working Temp. (mK) Run 200942

Live-time Efficiency (%)



CUORE-0 is also sensitive to Earthquake!

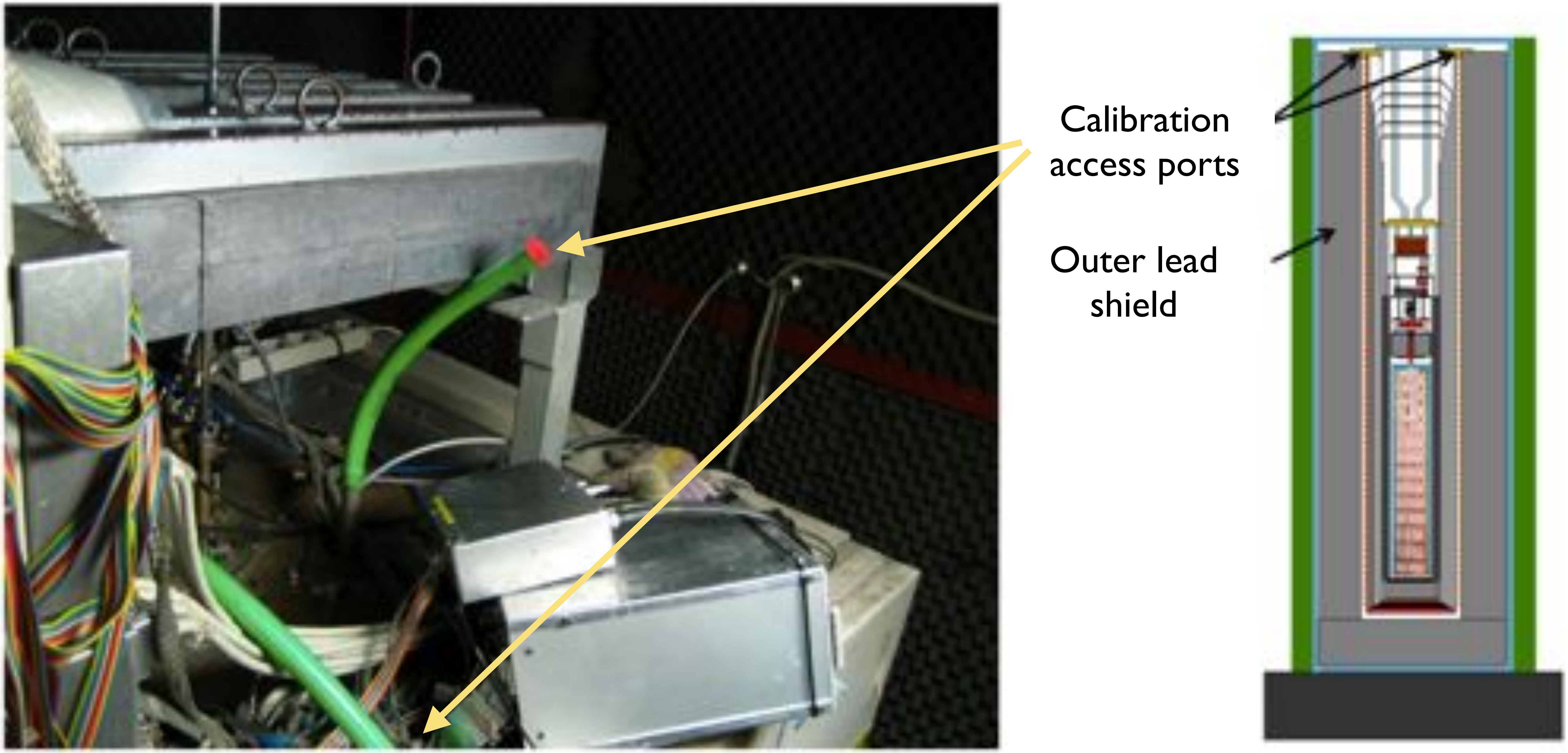


- Time of Earthquake: 2013-07-21 01:32:25 UTC.
- Time of baseline jump: 2013-07-21 01:32:47 UTC.

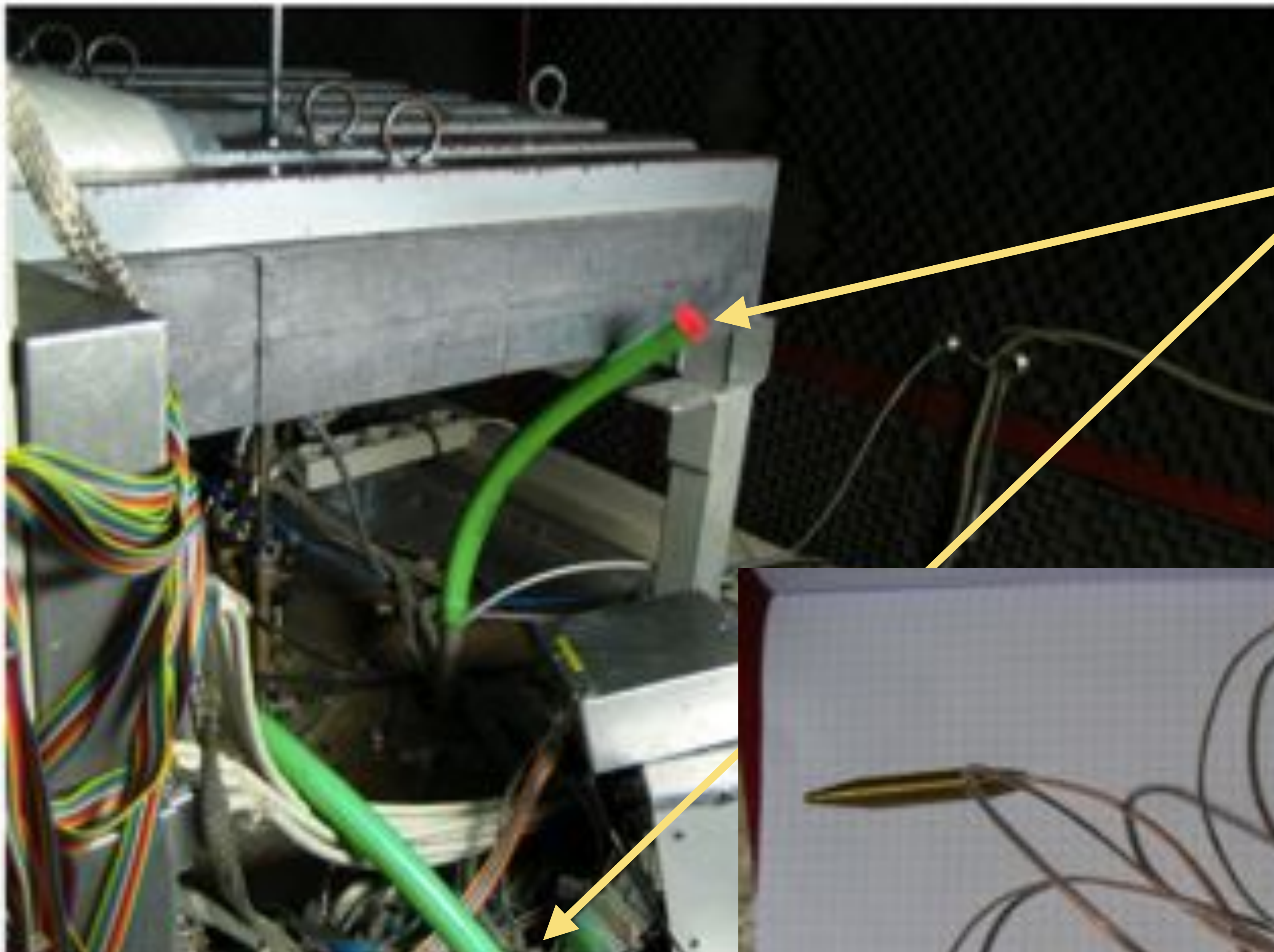
- Location of Origin: (4492.7,1099.9,4362.4) km WGS84.
- Location of Opera: (4582.167465,1106.521805,4283.602714) km.
- Baseline: 119329.0 ± 500m.
- Earthquake propogation speed: (5424 ± 245)m/s
- Typical measured values are 5200-5900 m/s.

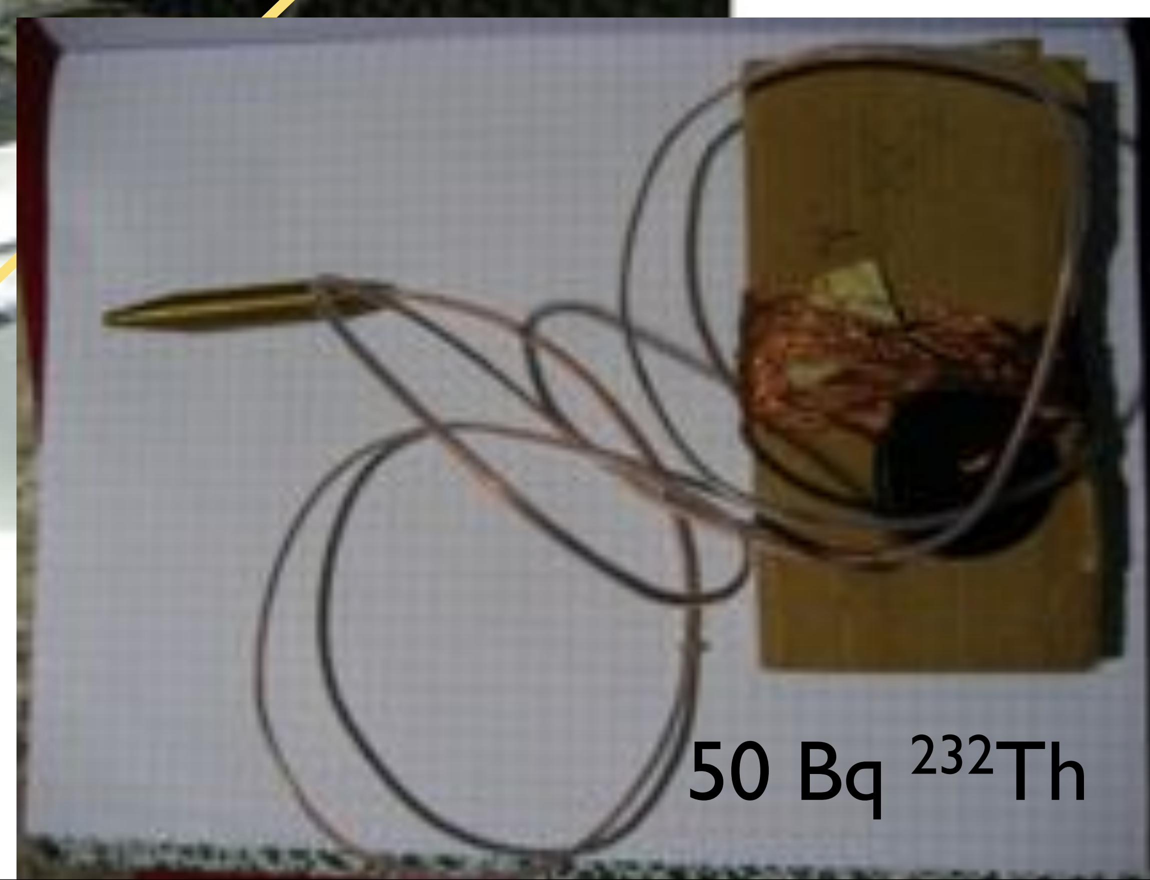
J. Ouellete, Aug 26, 2013, CUORE Analysis Meeting @ LNGS

CUORE-0: Calibration



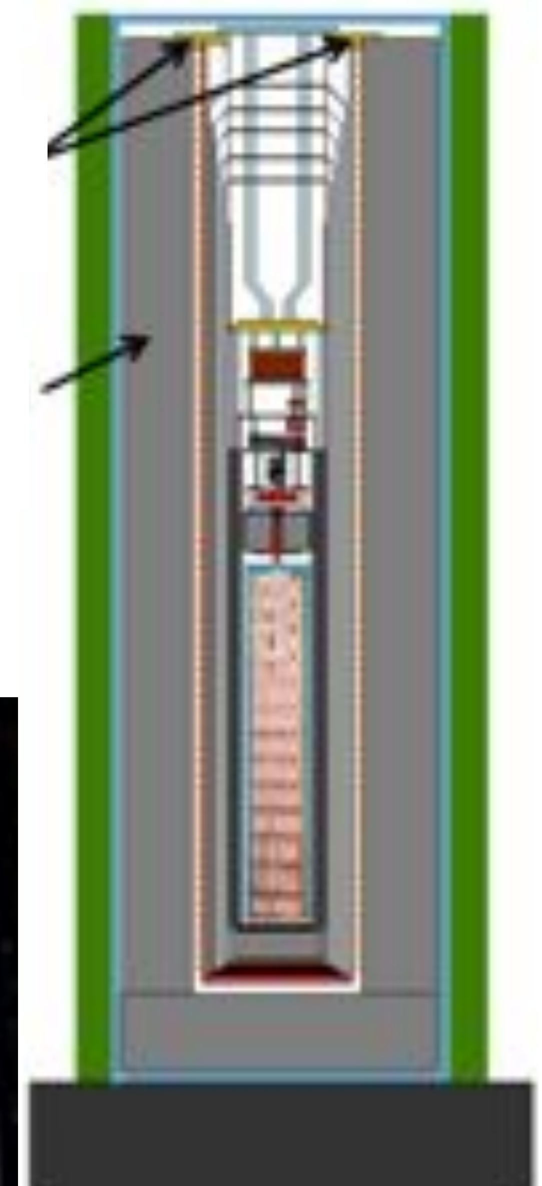
CUORE-0: Calibration



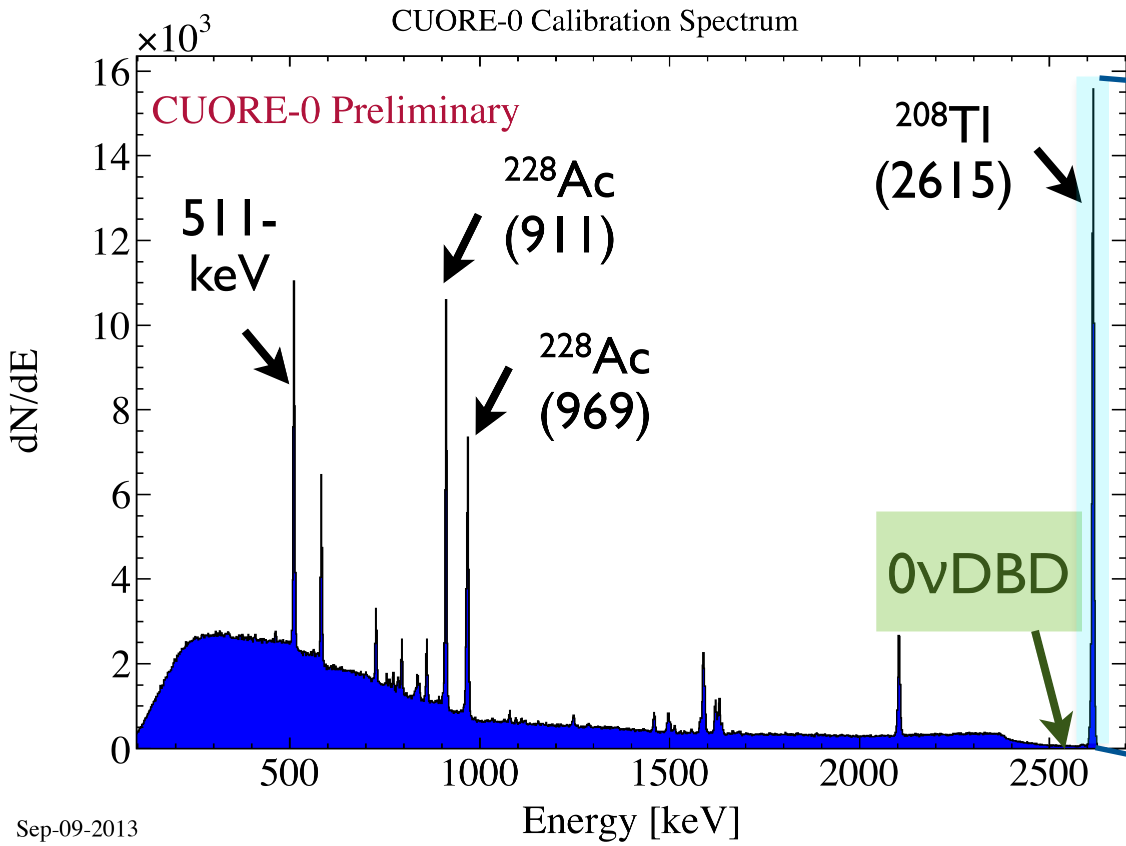


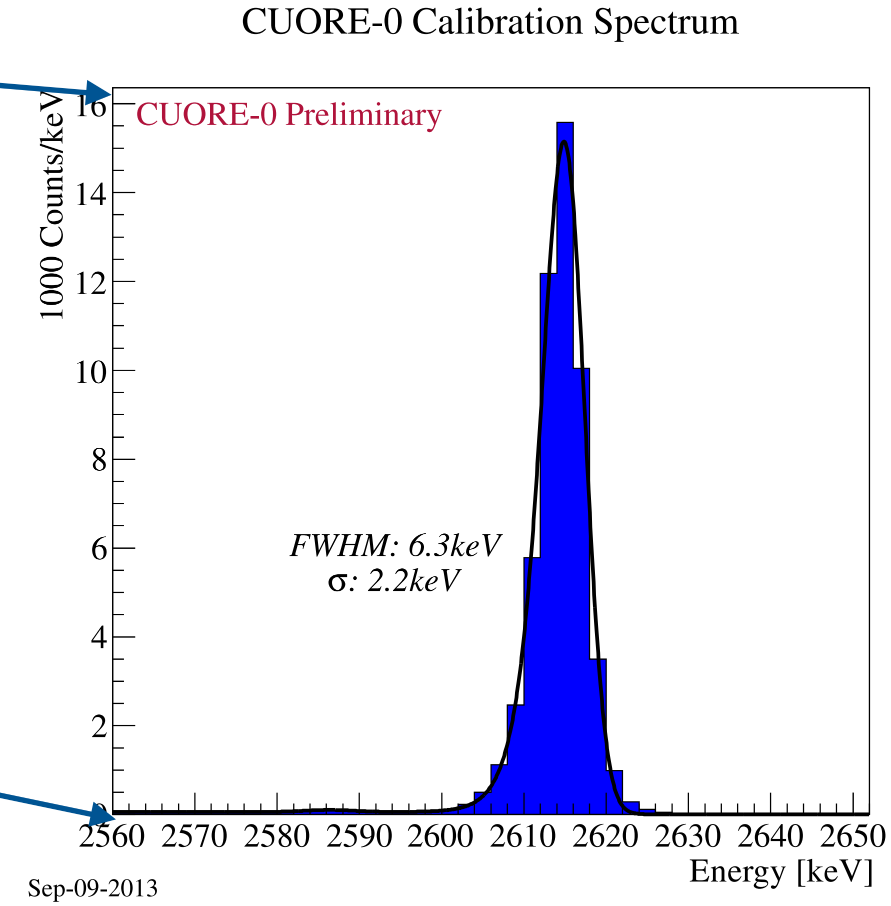
Calibration access ports

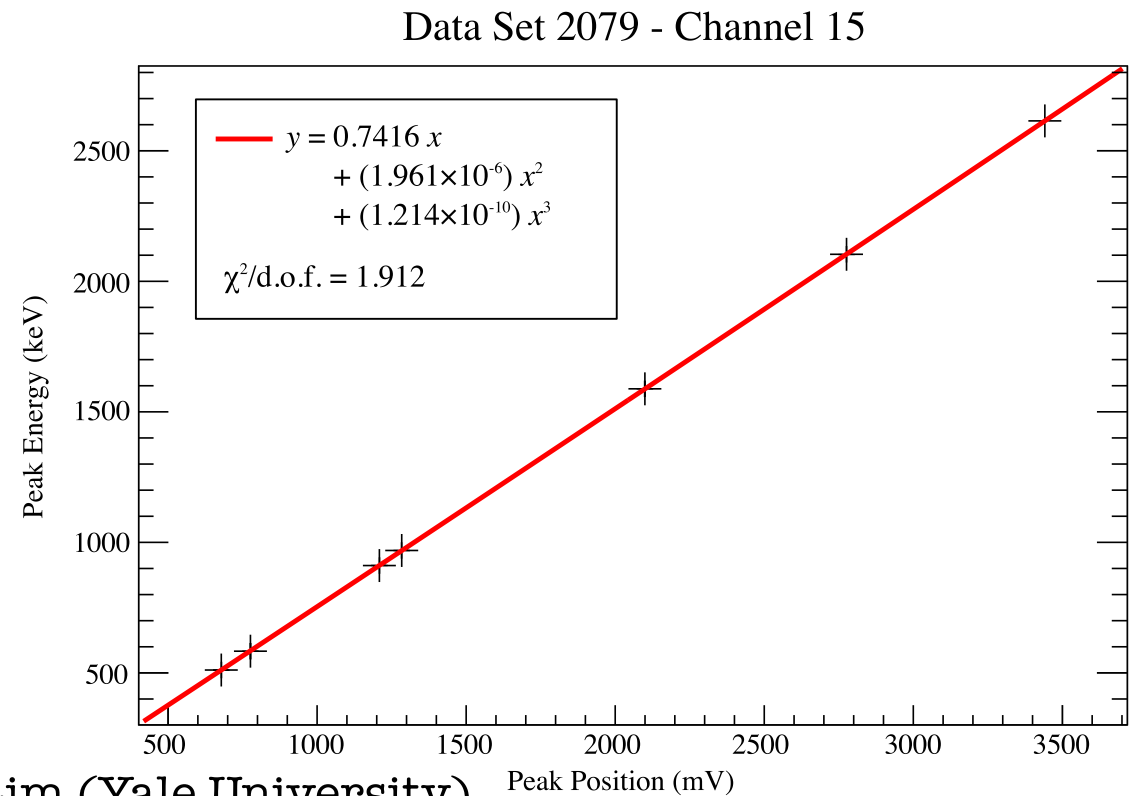
Outer lead shield

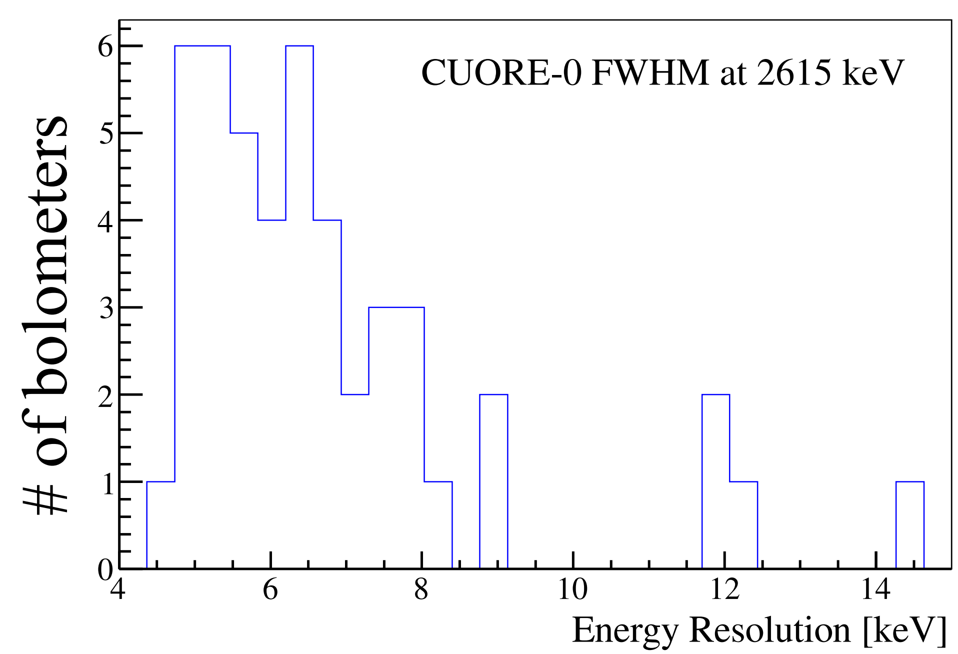


Calibration Spectrum

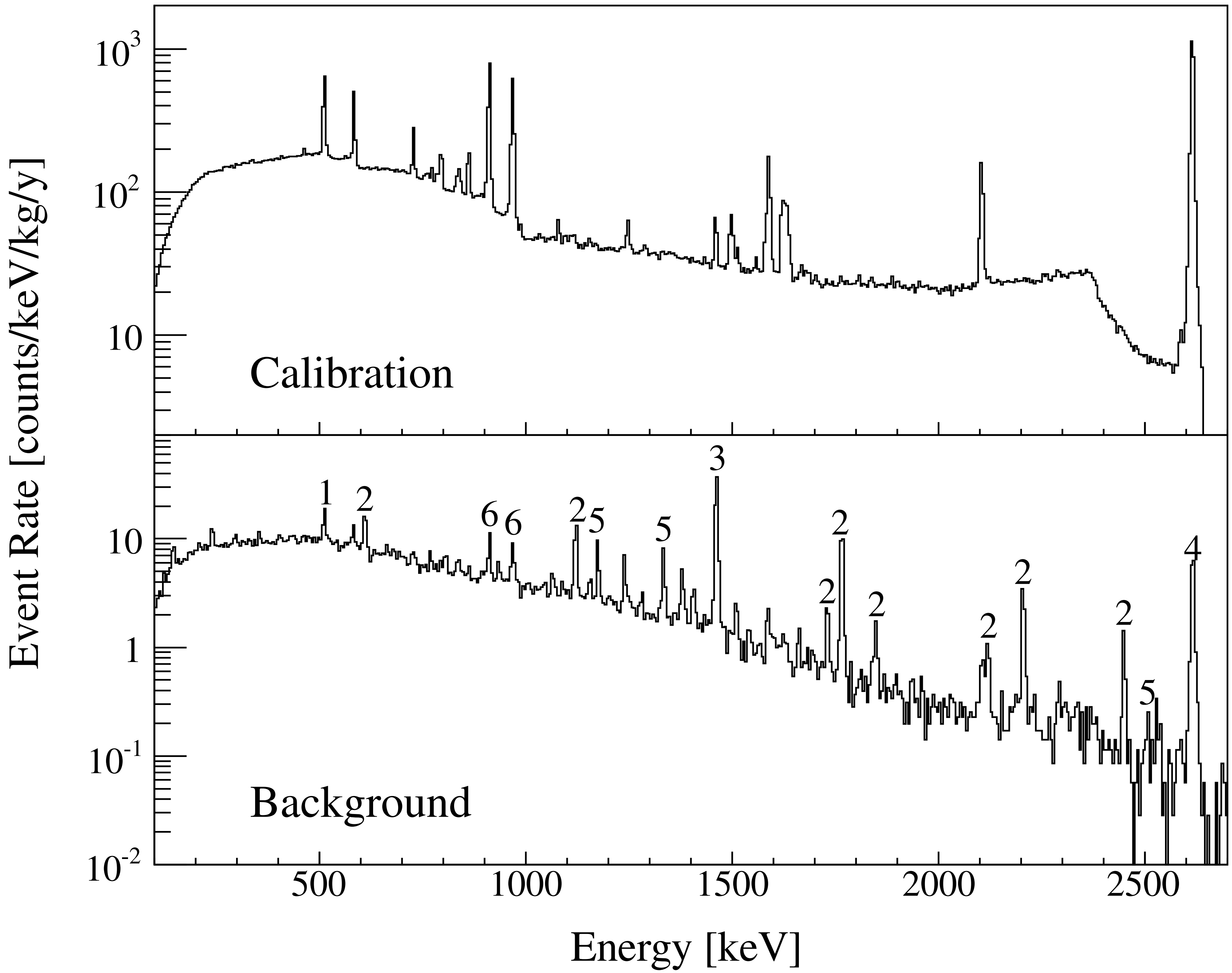


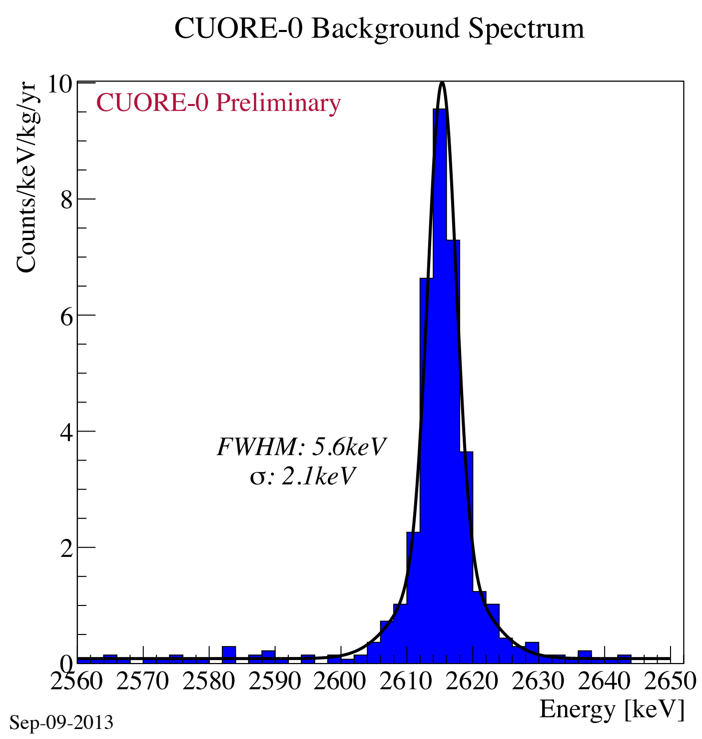




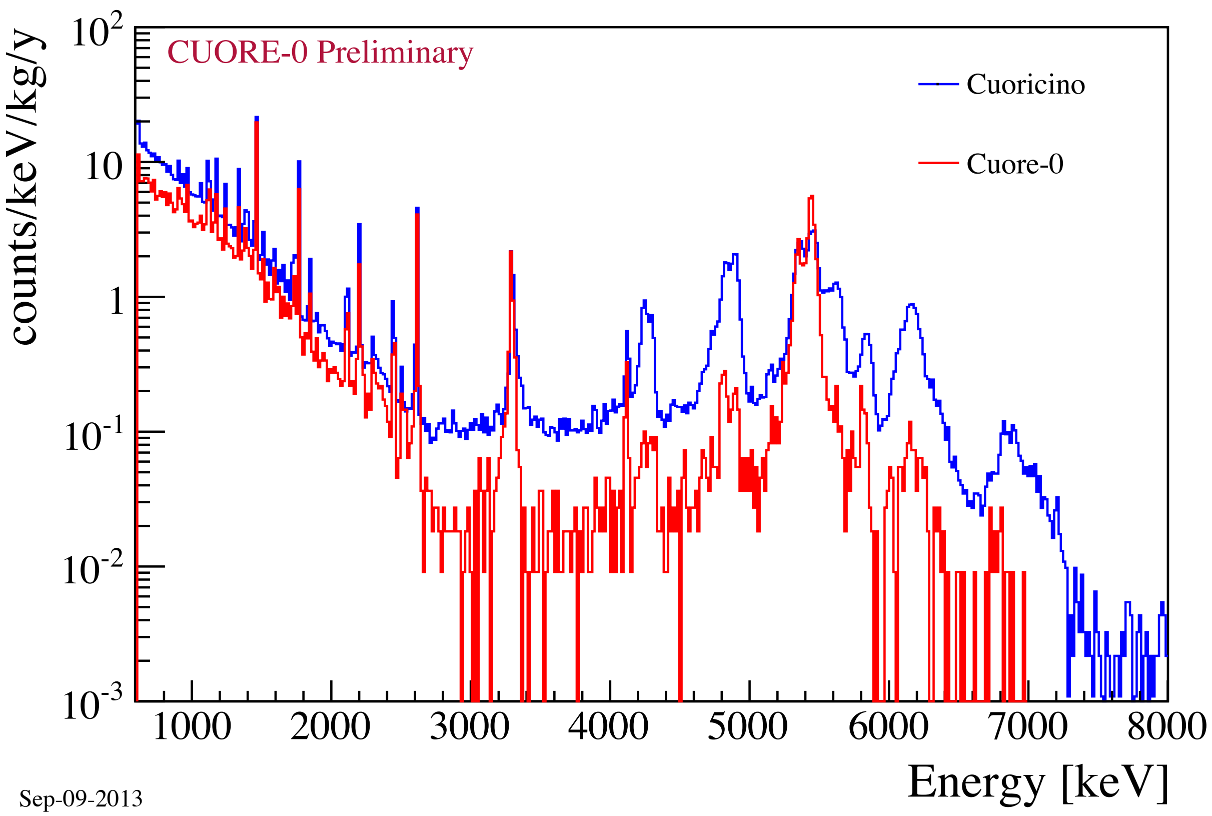


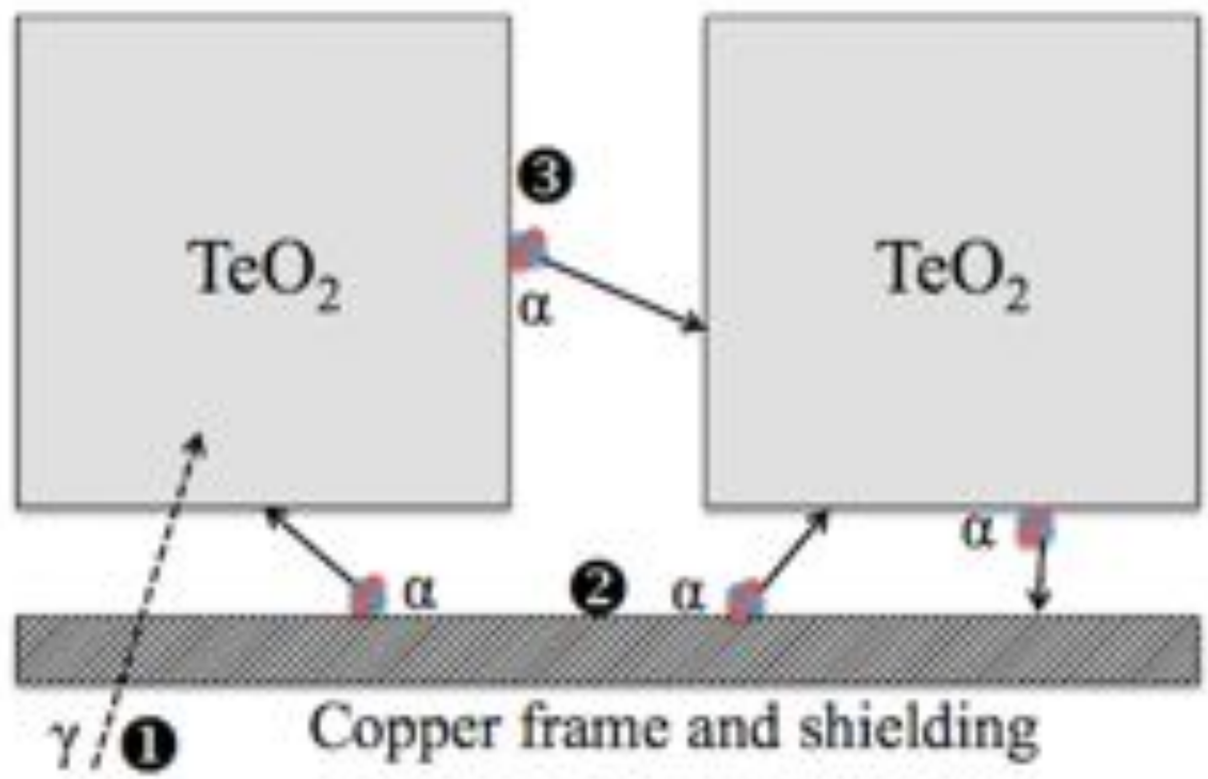
Calibration/Background Spectrum





CUORE-0: Background

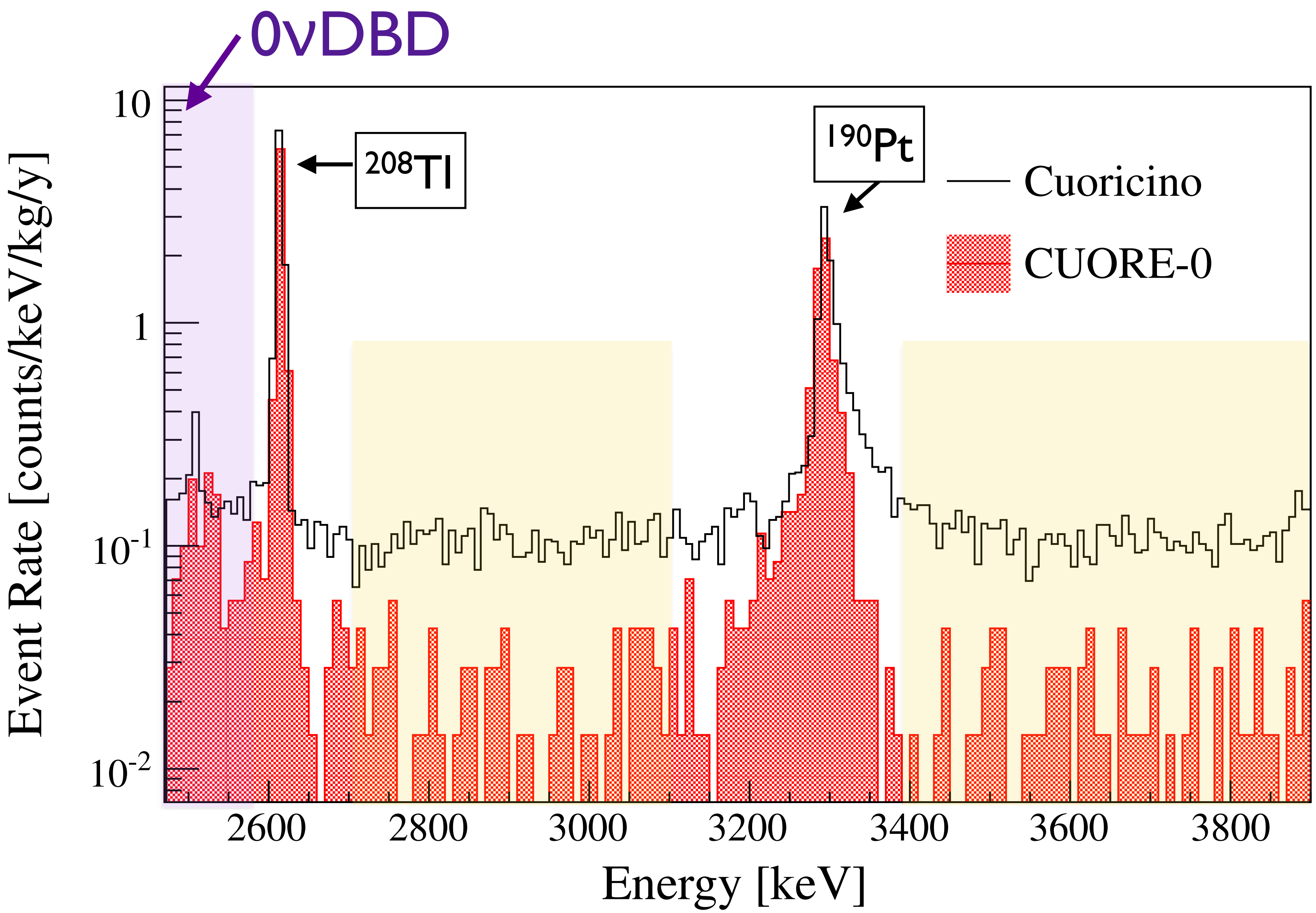




Compared to Cuoricino…

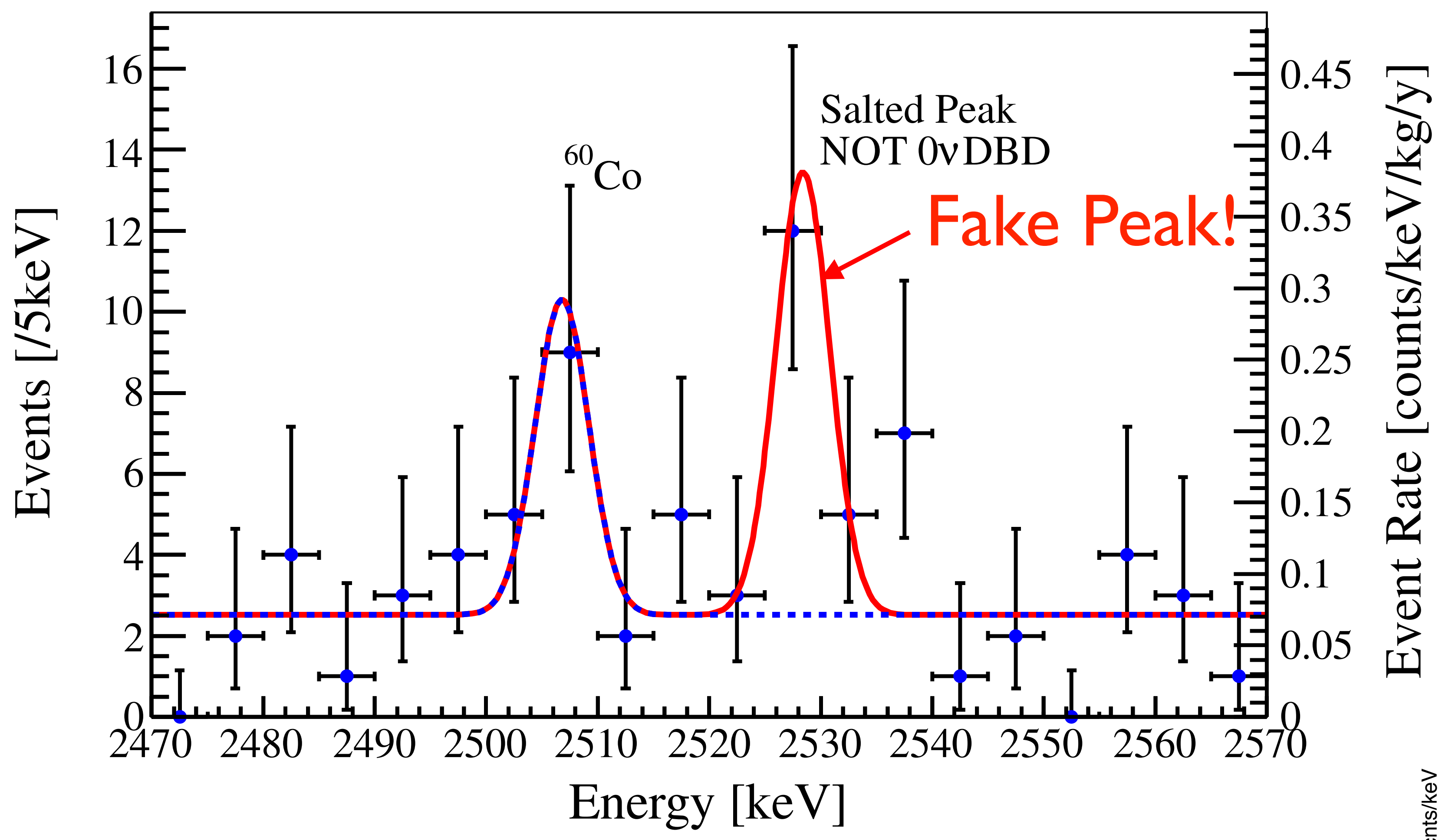
- γ background (from ^{232}Th) was not reduced since the cryostat remained the same.
- γ background (from ^{238}U) was reduced by a factor of 2 due to better radon control.
- α background from copper surface and crystal surface was reduced by a factor of 6 thanks to the new detector surface treatment.

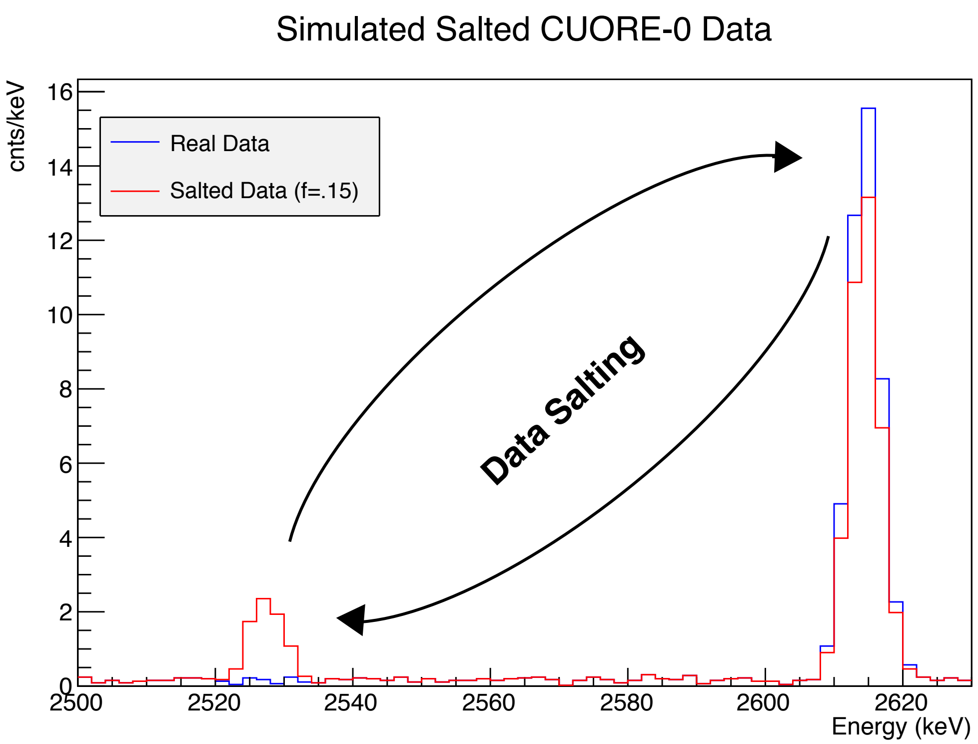
CUORE-0: Background



	Avg. flat bkg. [counts/keV/kg/y]		signal eff. [%] (detector+cuts)
	0νDBD 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

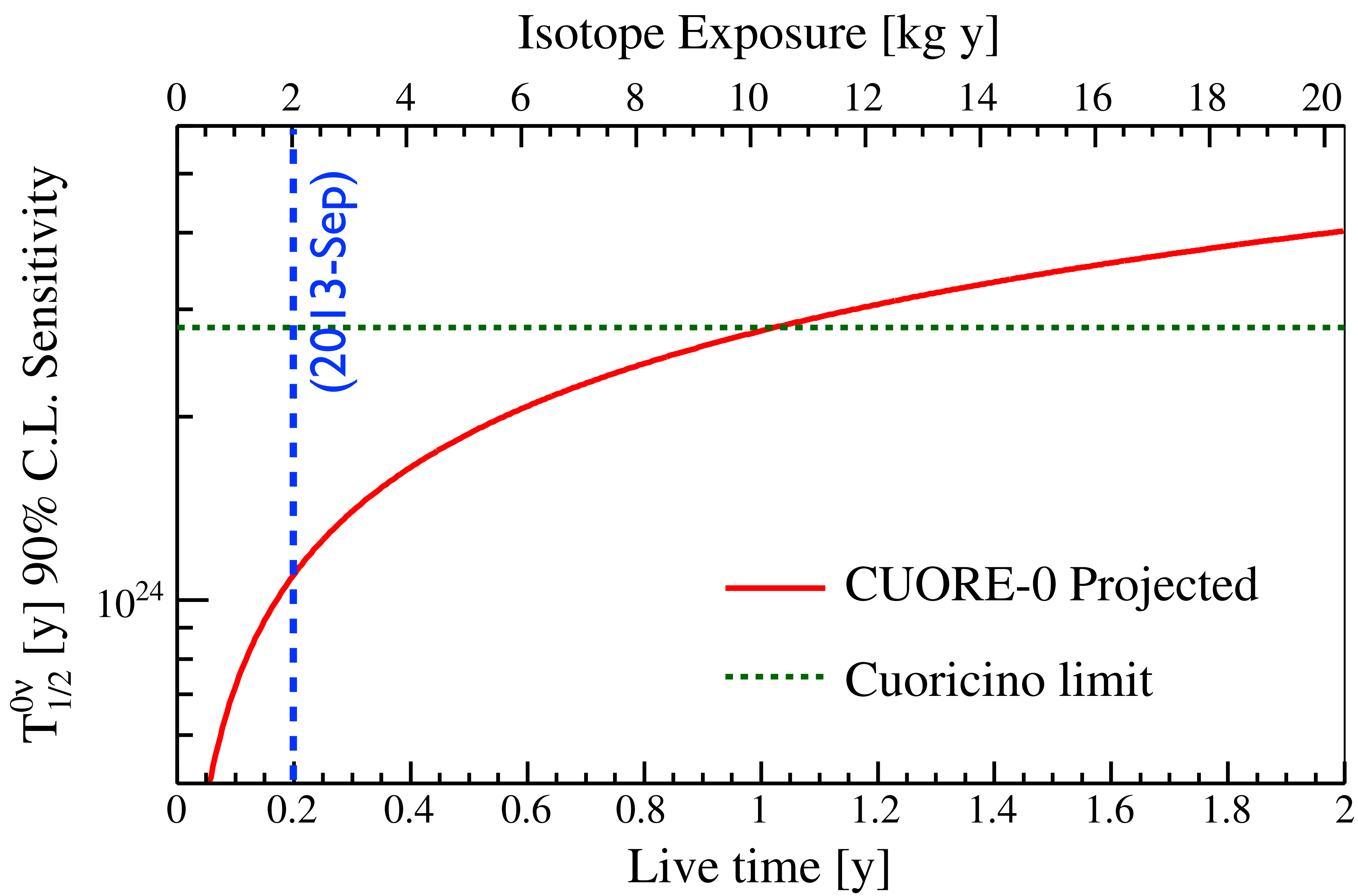
Blinding 0νDBD Region





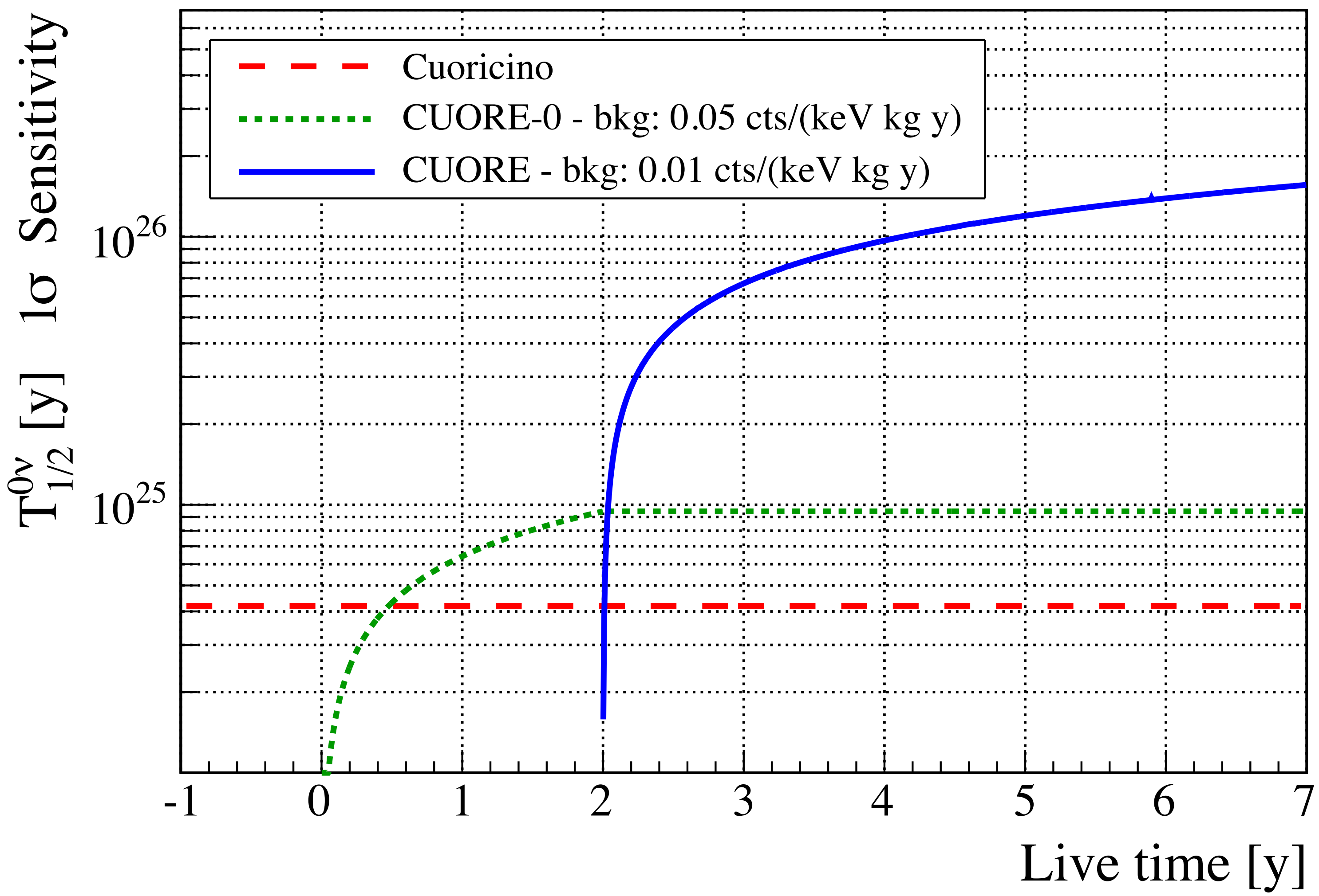
- Region of Interest was blinded by "salting" : exchange a small (and ***blinded***) fraction of the events in ^{208}Tl peak with events in the 0νDBD region to produce ***fake*** peak.

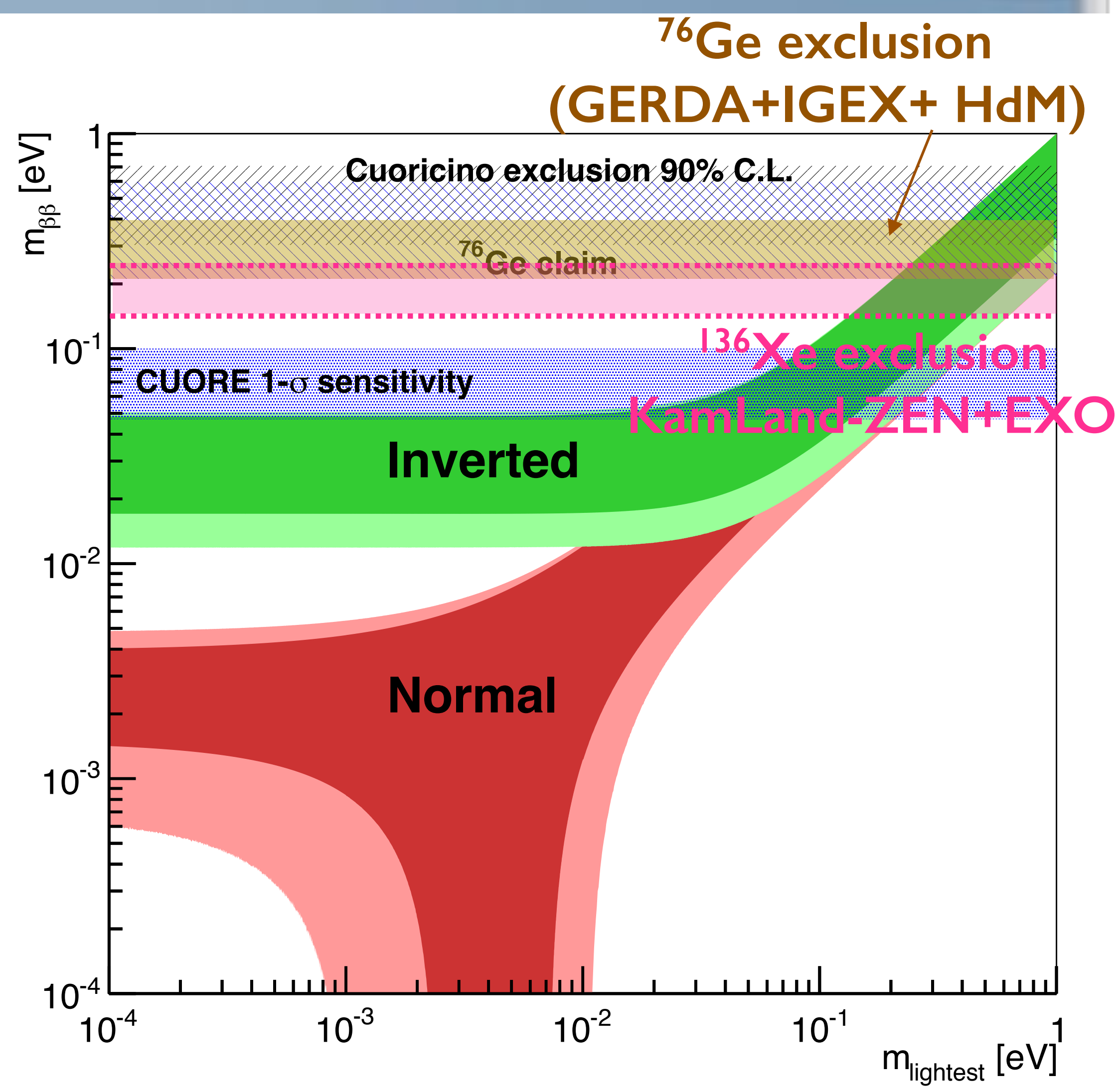
CUORE-0 Sensitivity



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

CUORE Sensitivity

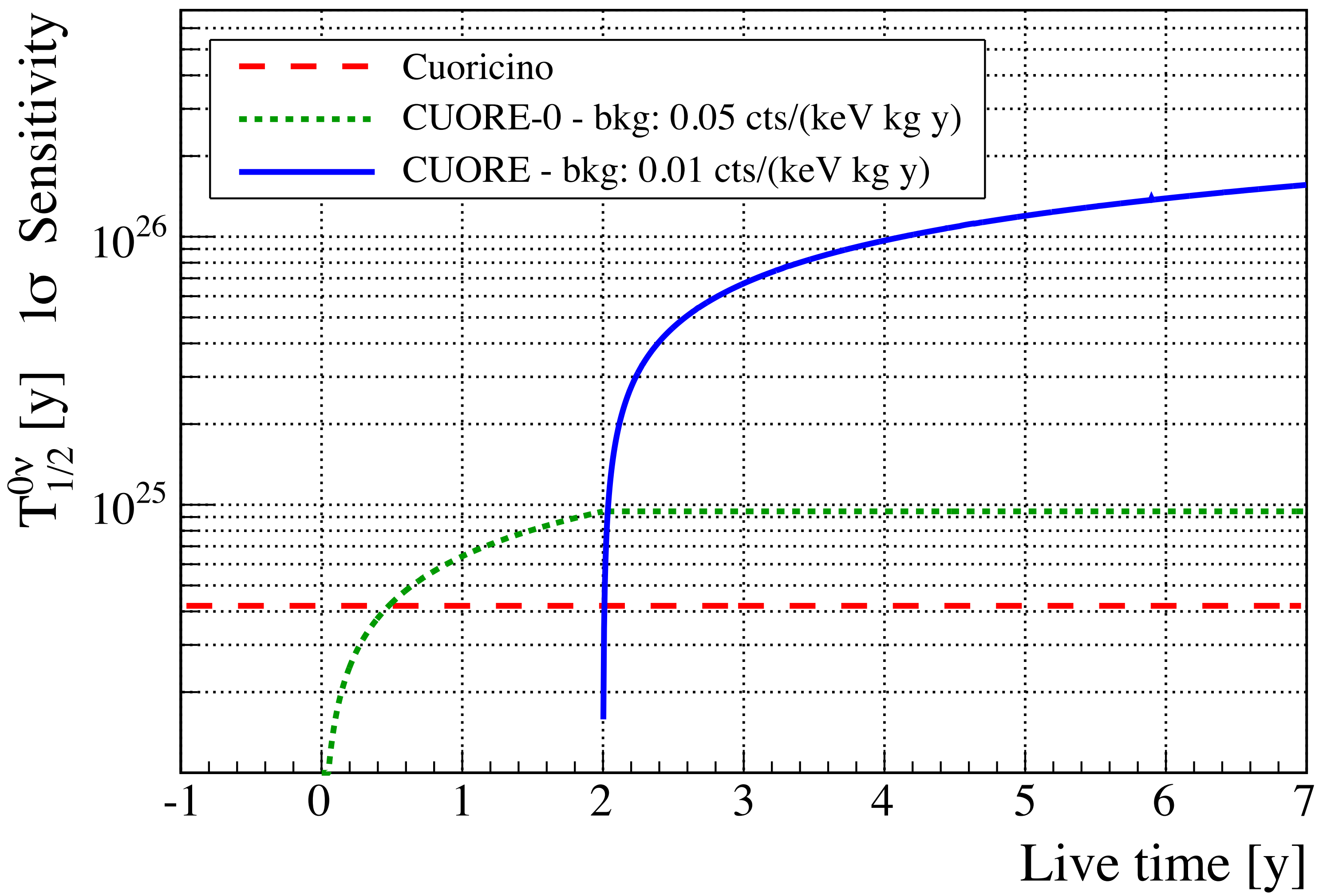


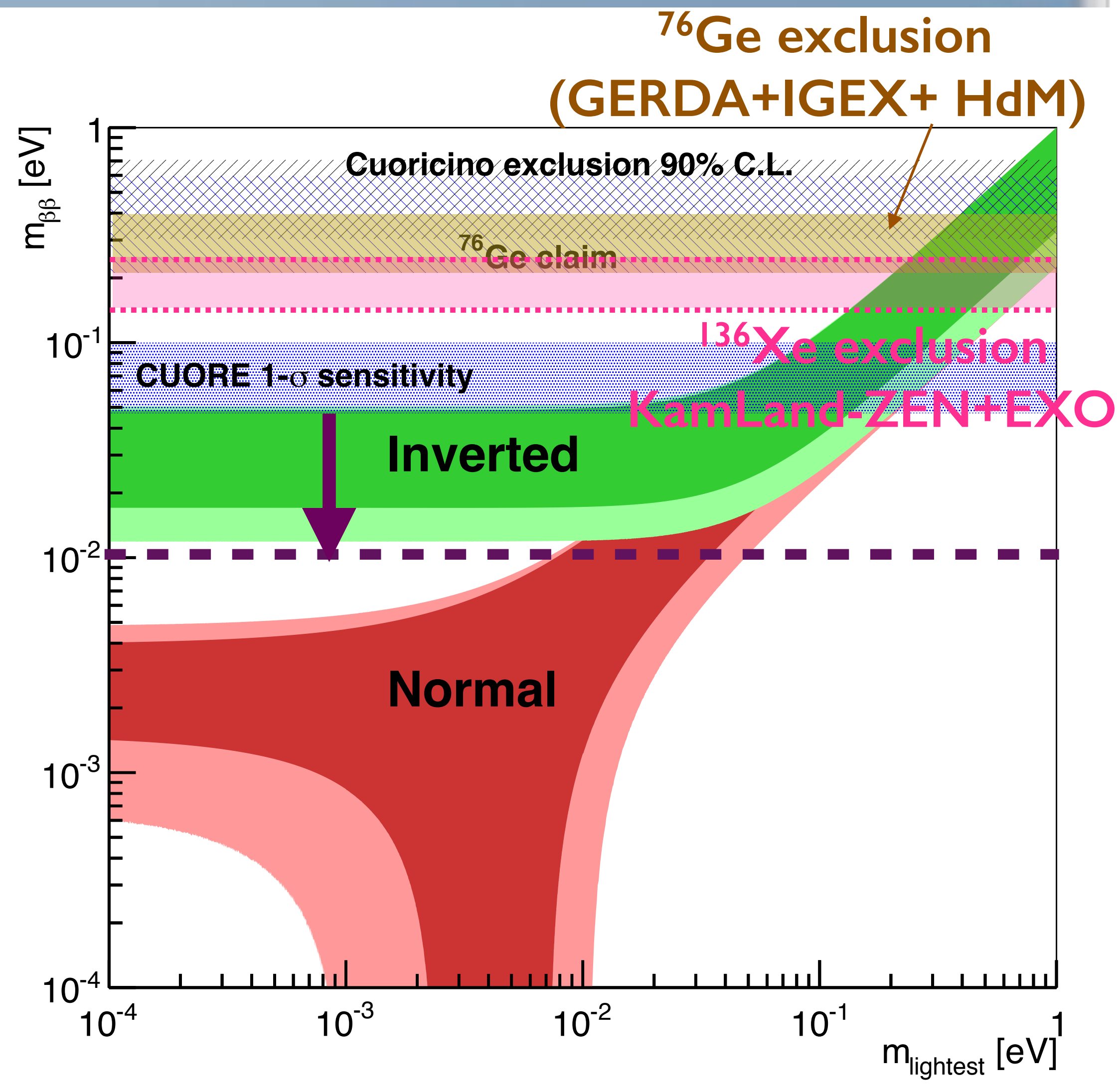


- 1σ sensitivity $T_{1/2}^{0\nu\beta\beta} = 1.6 \times 10^{26}$ yr (Effective Majorana mass 47-100 meV).
  - Assuming bg rate of 0.01 cts/(keV kg y) and 5 keV FWHM ROI resolution.
  - 5 years of live time.

arXiv:1109.0494

CUORE Sensitivity

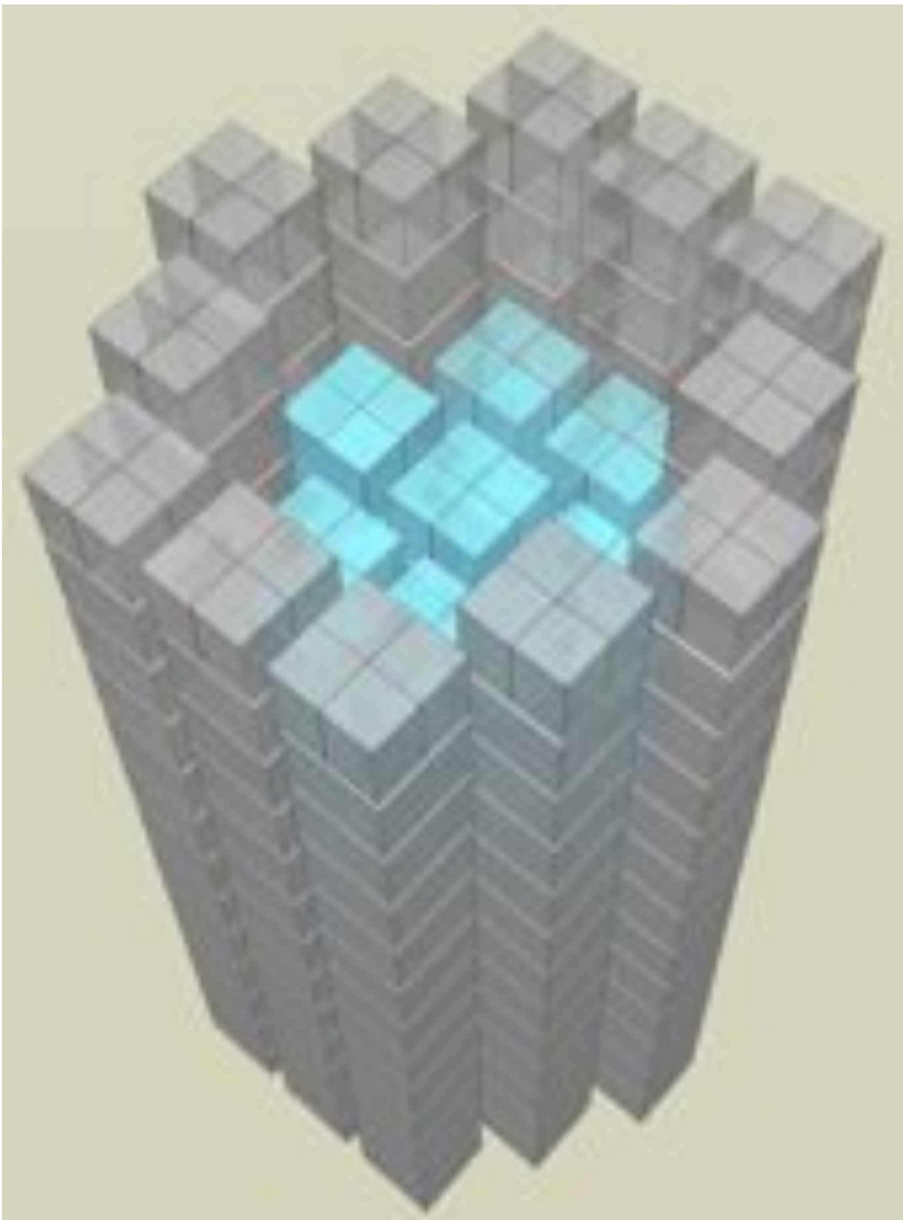


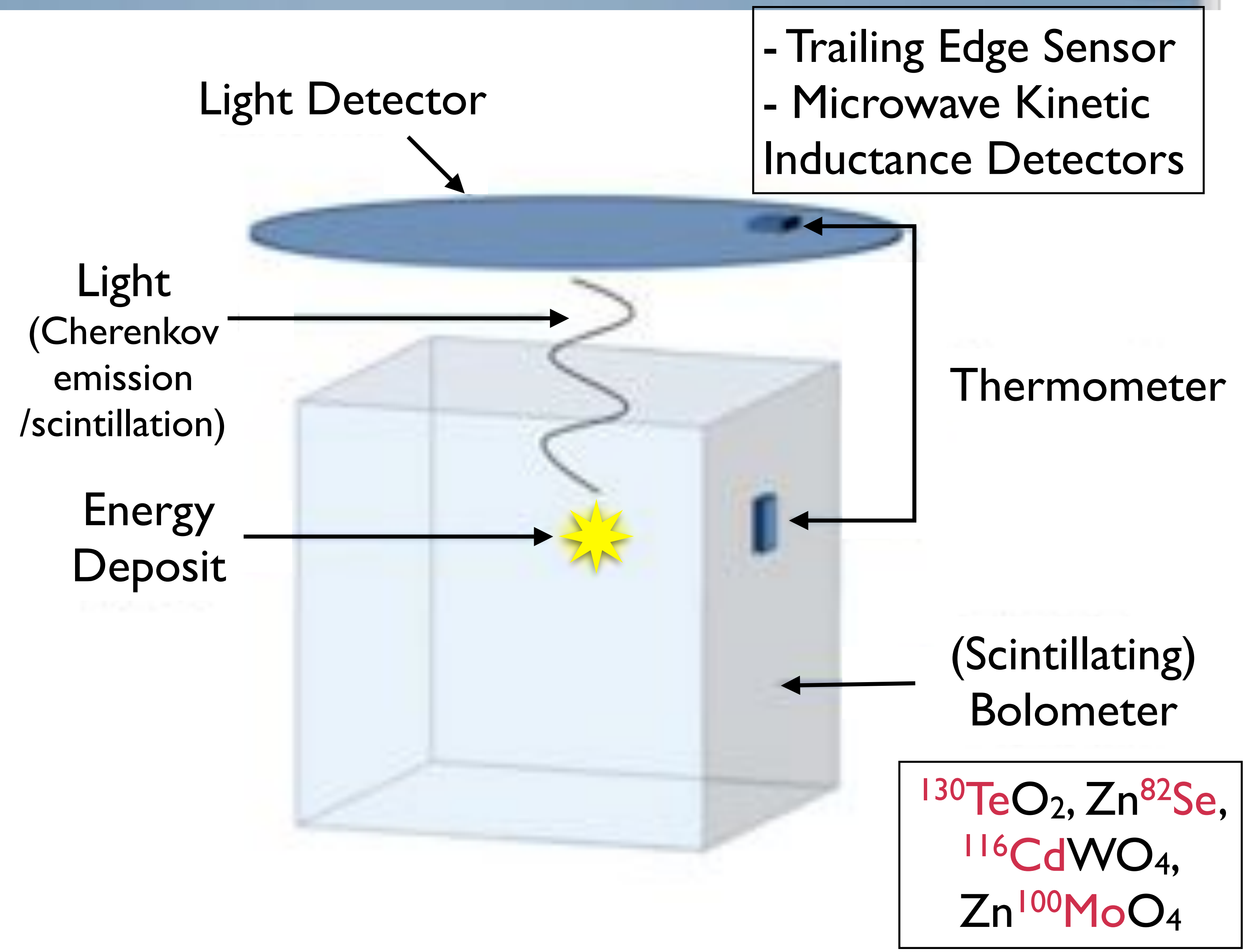


- 1σ sensitivity $T_{1/2}^{0\nu\beta\beta}$=1.6 x 10^{26} yr (Effective Majorana mass 47-100 meV).
  - Assuming bg rate of 0.01 cts/(keV kg y) and 5 keV FWHM ROI resolution.
  - 5 years of live time.

arXiv:1109.0494

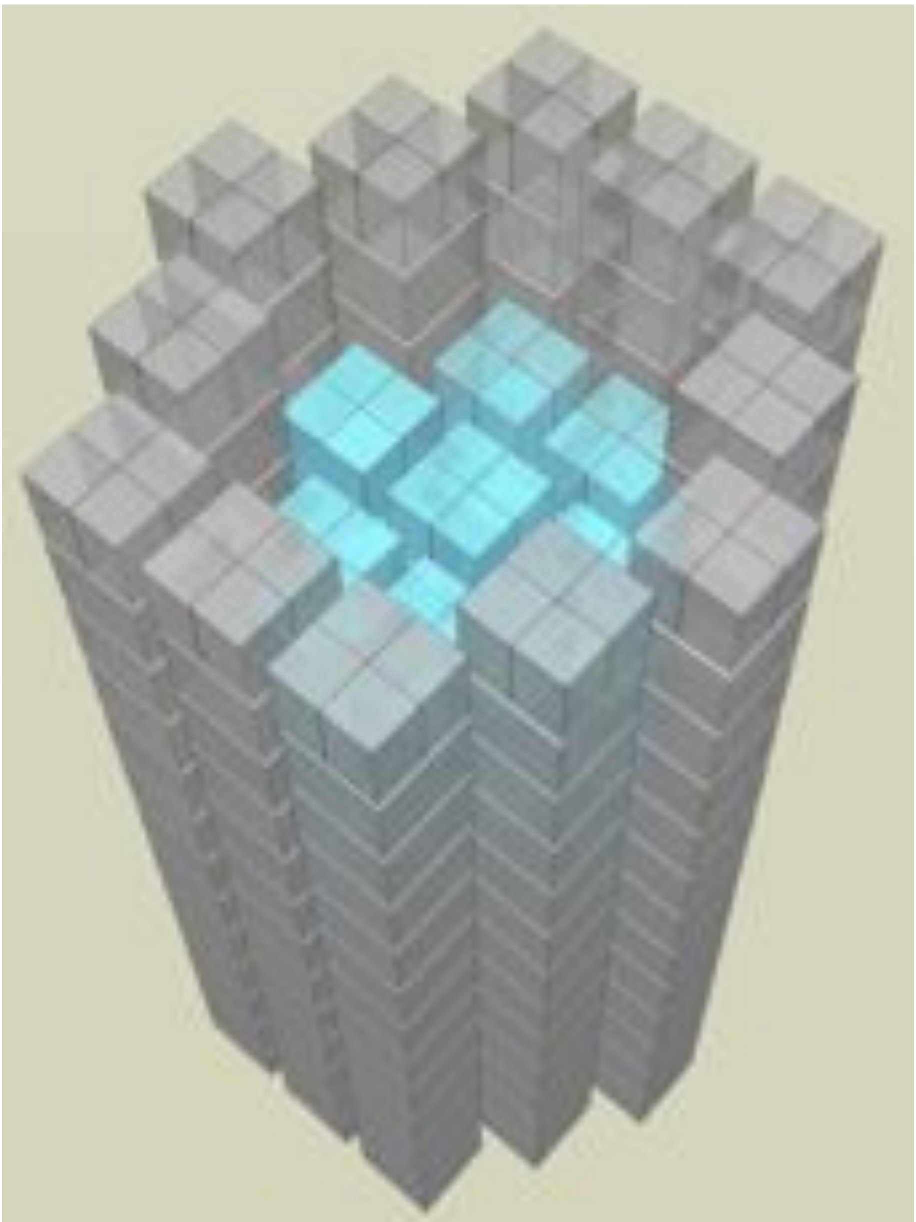
Beyond CUORE

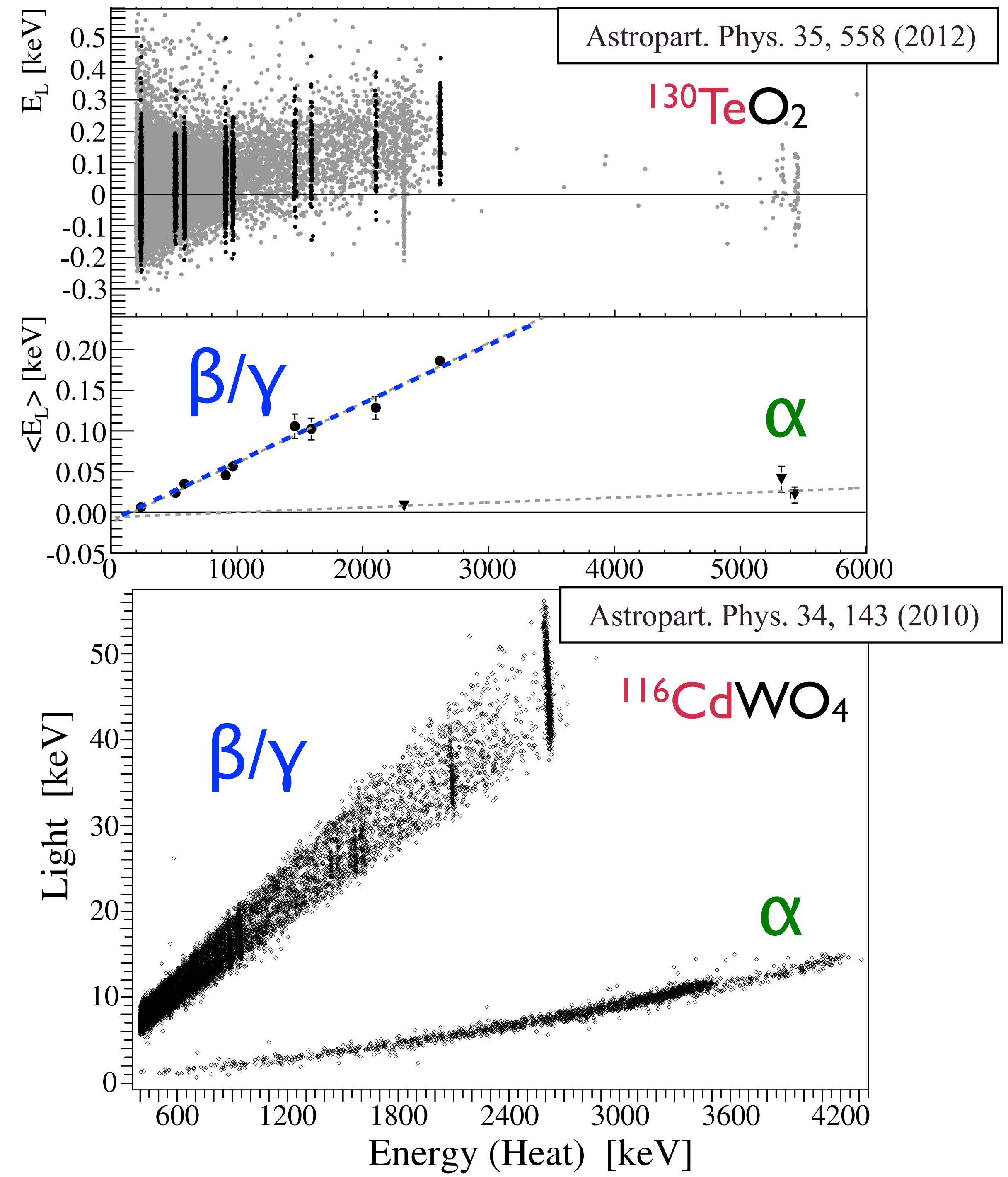




- Enrichment of the isotope.
- Particle discrimination by simultaneously measuring heat/light.

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 0νDBD.
- 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.
- CUORE-0 will surpass the sensitivity of a predecessor experiment in the coming year.
- CUORE will start to take data next year (2015).
- Various R&D projects are ongoing for searches beyond CUORE.