Results from CUORE-0, Status of CUORE

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BLV 2015
International Workshop on Baryon and Lepton Number Violation
University of Massachusetts, Amherst
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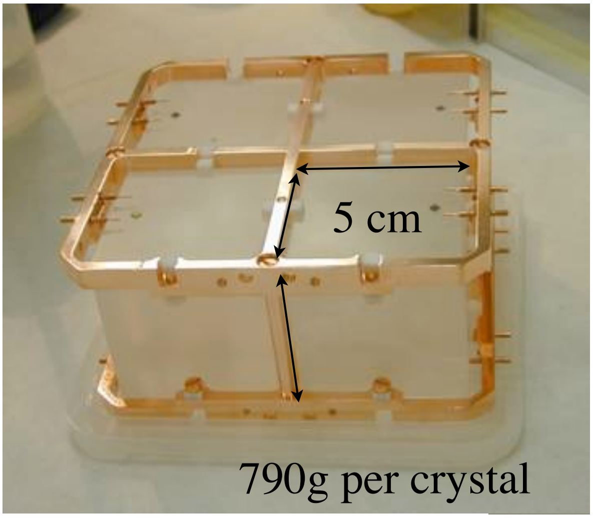
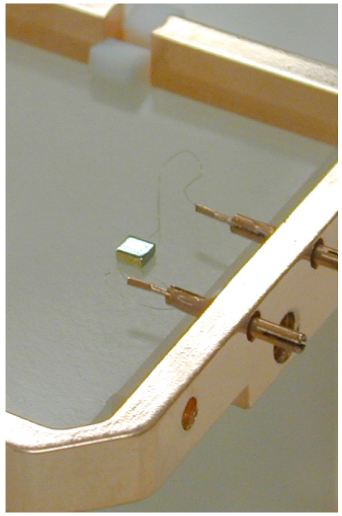
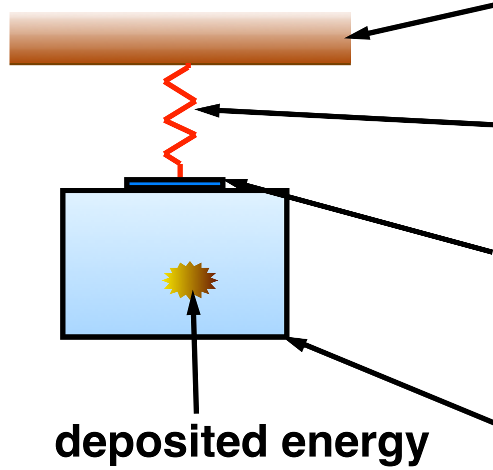
CUORE Bolometer







Heat sink:
Cu structure (8-10 mK)
Thermal coupling:
Teflon (G = 4 pW/mK)
Thermometer:
NTD Ge-thermistor (100 kΩ/μK)
Absorber:
TeO_2 crystal
(C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

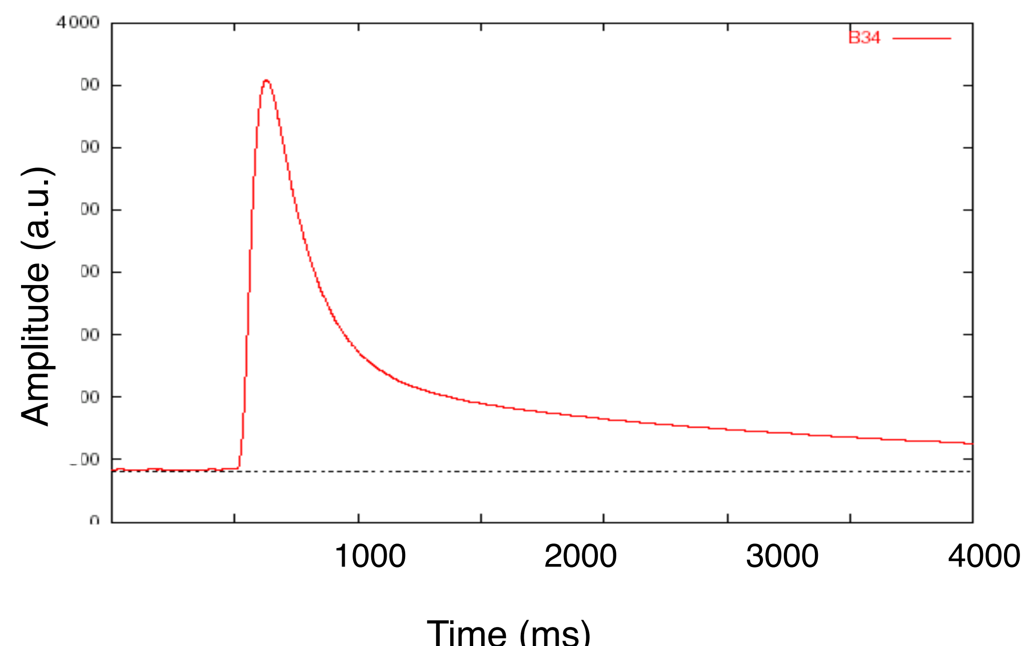
TeO_2 Bolometer: Source = Detector

main candidate isotope: ^{130}Te
Q-value: 2530 keV
Isotopic abundance: 34%

For E = 1 MeV: $\Delta T = E/C \cong 0.1$ mK
Signal size: 1 mV

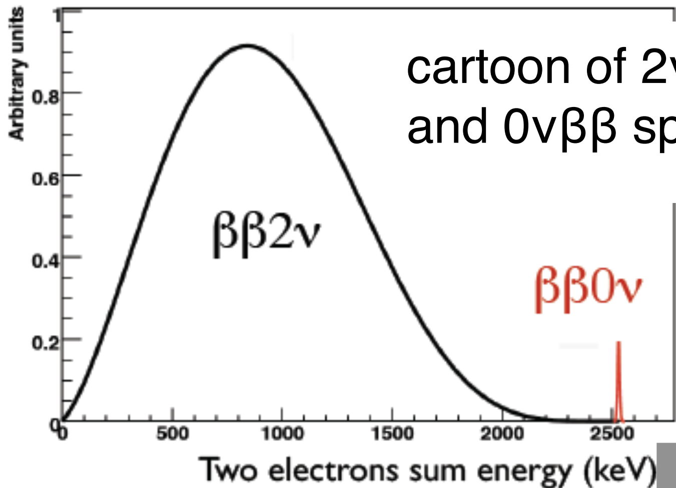
Time constant: $\tau = C/G = 0.5$ s
Energy resolution: ~ 5-10 keV at 2.5 MeV

Single pulse example



Search for 0νββ in ^{130}Te

cartoon of 2νββ and 0νββ spectra

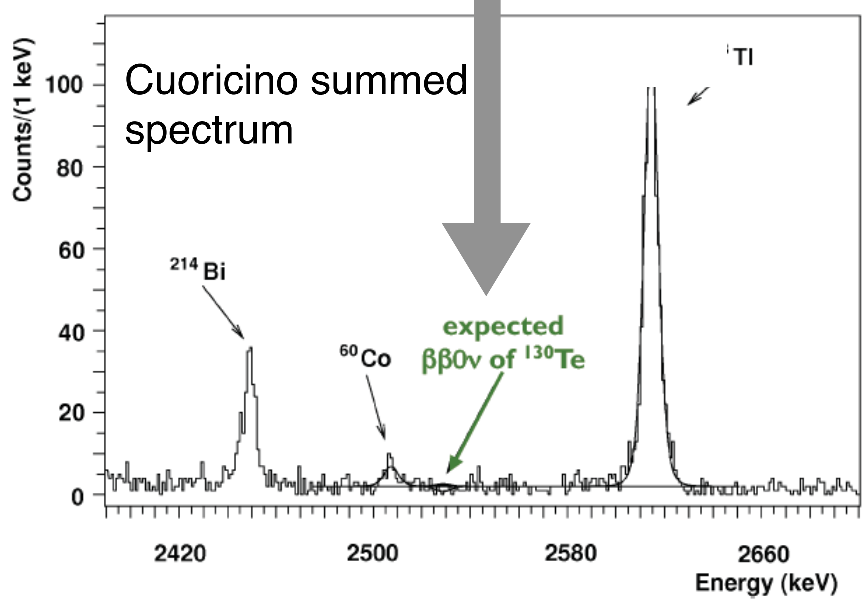


Experimental Signature of 0νββ

- peak at the transition Q-value
- enlarged by detector resolution
- over unavoidable 2νββ background

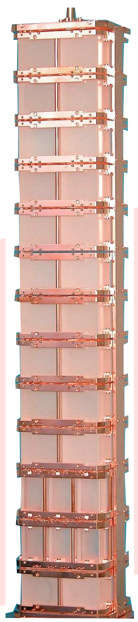
in ^{130}Te

Cuoricino summed spectrum



The CUORE 0νββ Search

Cuoricino
(2003-2008)



Astropart. Phys. 34 (2011) 822–831

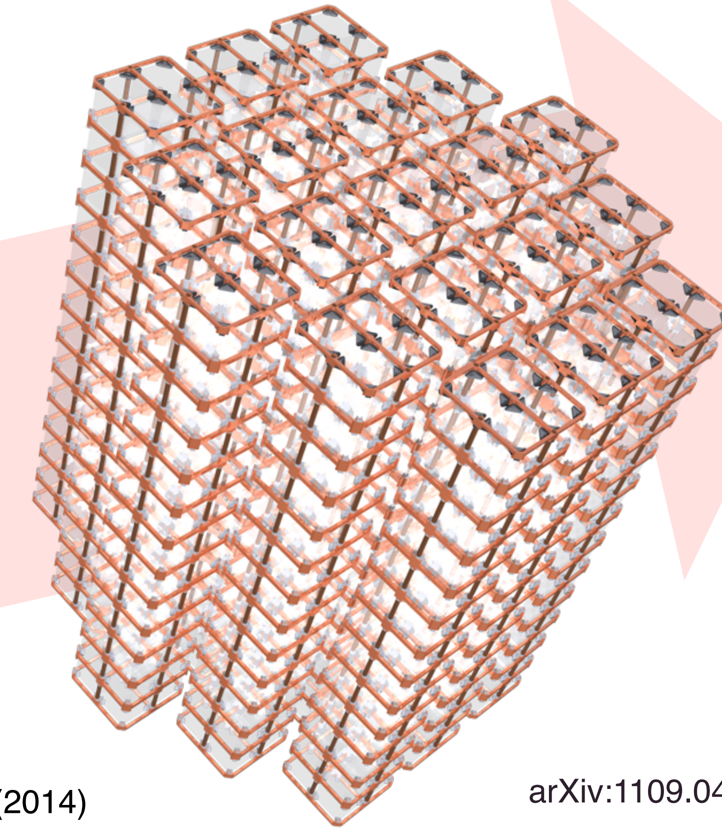
$T_{1/2}^{0\nu\beta\beta}$ > 2.8 × 10^{24} y (90% C.L.)

CUORE-0
(2013-2015)

EPJC 74, 2956 (2014)
arXiv:1504.0245

$T_{1/2}^{0\nu\beta\beta}$ > 4.0 × 10^{24} y (90% C.L.)

CUORE
(2015-2020)

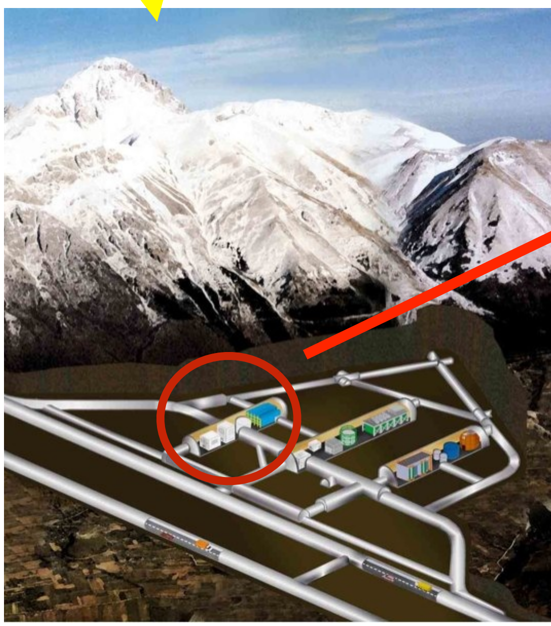


arXiv:1109.0494

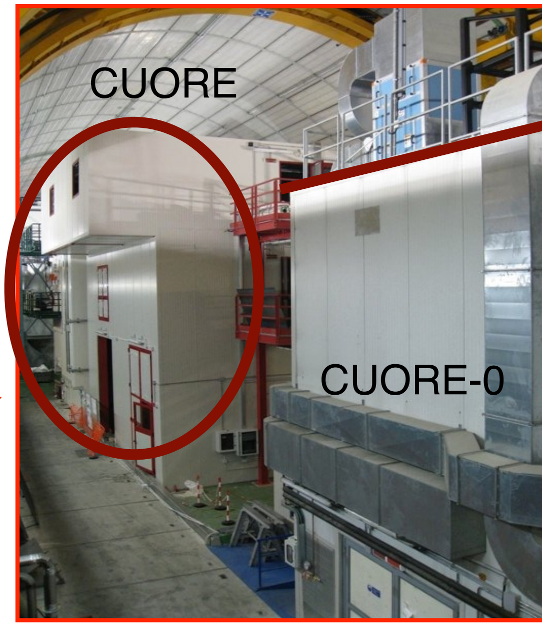
Projected
$T_{1/2}^{0\nu\beta\beta}$ > 9.5 x 10^{25} yr (90% C.L.)

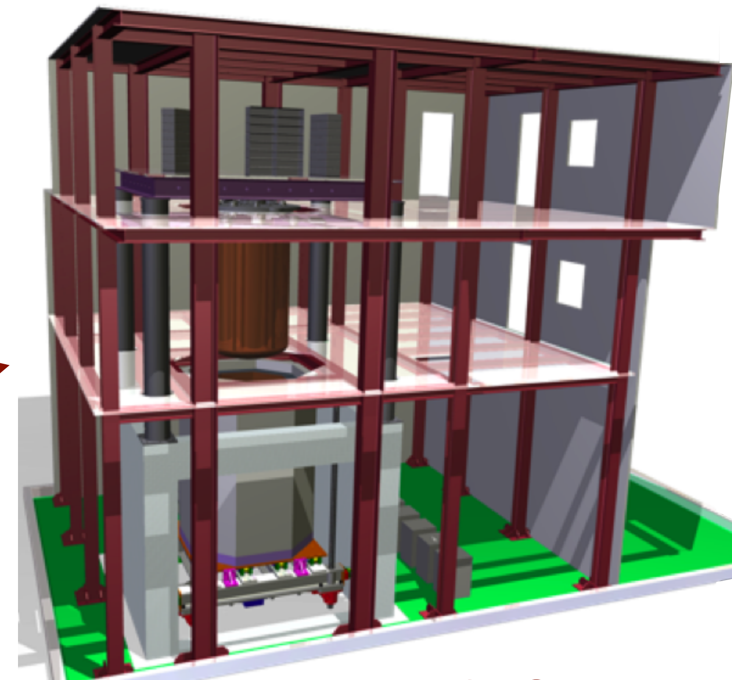
CUORE at LNGS

Gran Sasso National Laboratory



Hall A



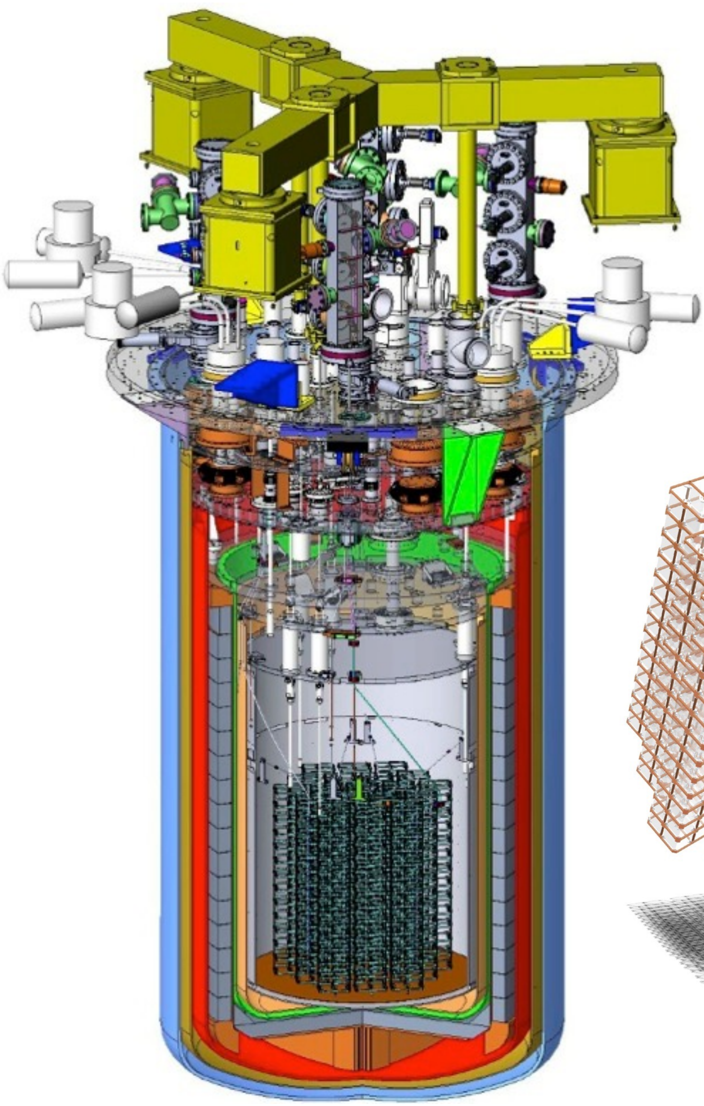


CUORE Hut

Average depth ~ 3600 m.w.e.

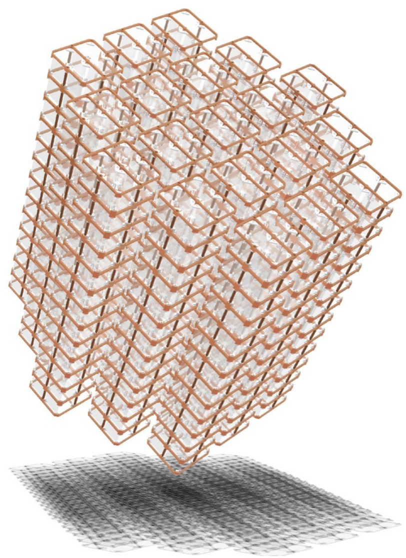
- **μ: 3 x 10^{-8} μ/s/cm^2**
- **n < 10 MeV: 4 x 10^{-6} n/s/cm^2**
- **γ < 3 MeV: 0.73 γ/s/cm^2**

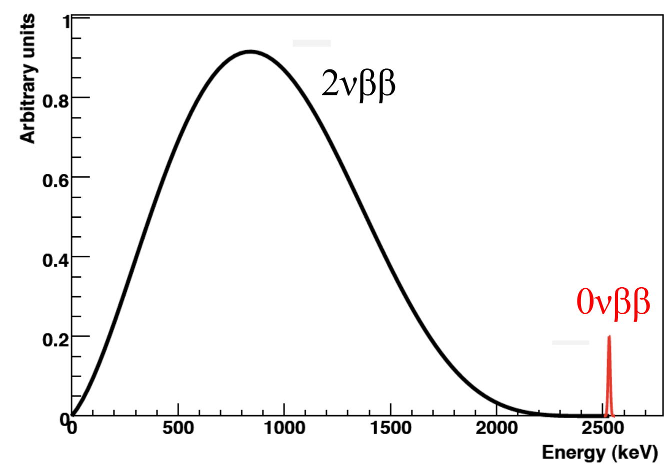
CUORE



Cryogenic Underground Observatory for Rare Events

- 988 TeO_2 crystals run as a bolometer array
  - 5x5x5 cm^3 crystal, 750 g each
  - 19 Towers; 13 floors; 4 modules per floor
  - 741 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei

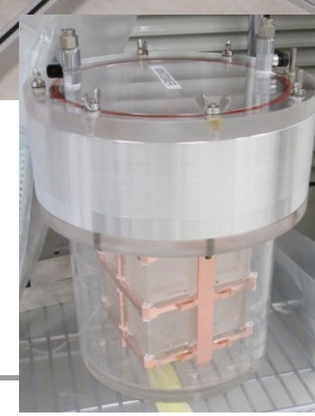




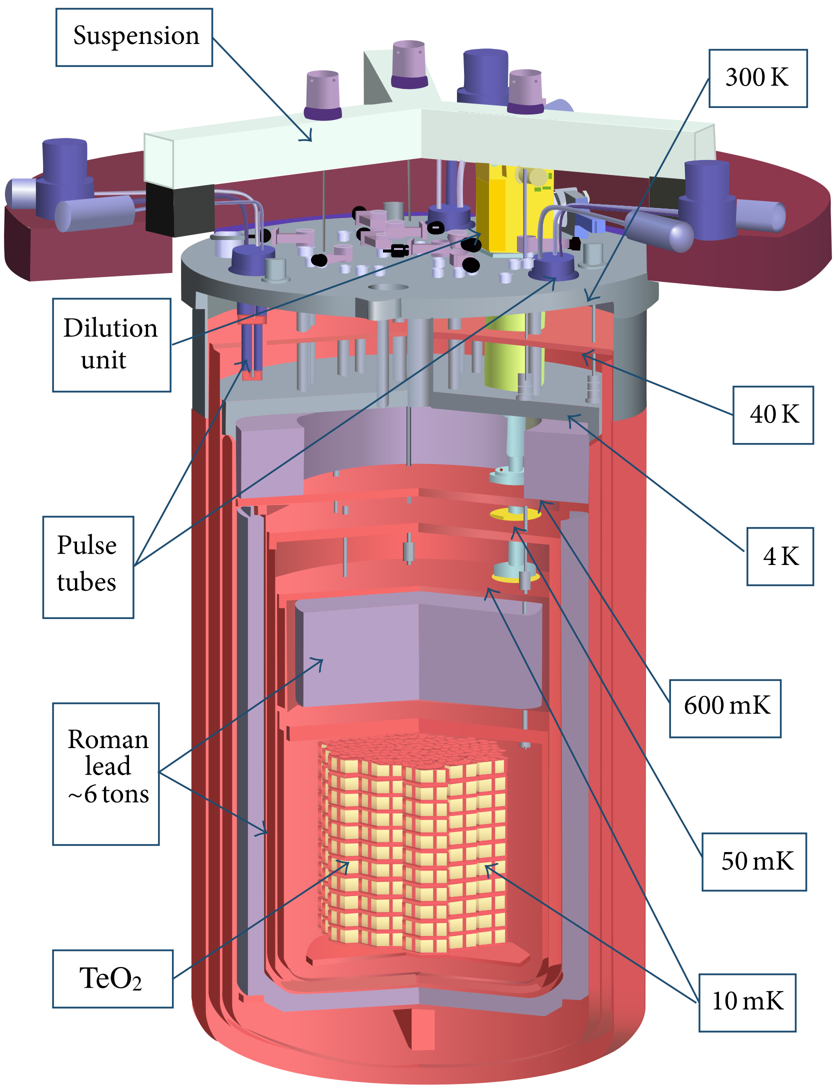
- Excellent energy resolution of bolometers
- New pulse tube dilution refrigerator and cryostat
- Radio-pure material and clean assembly to achieve low background at region of interest (ROI)

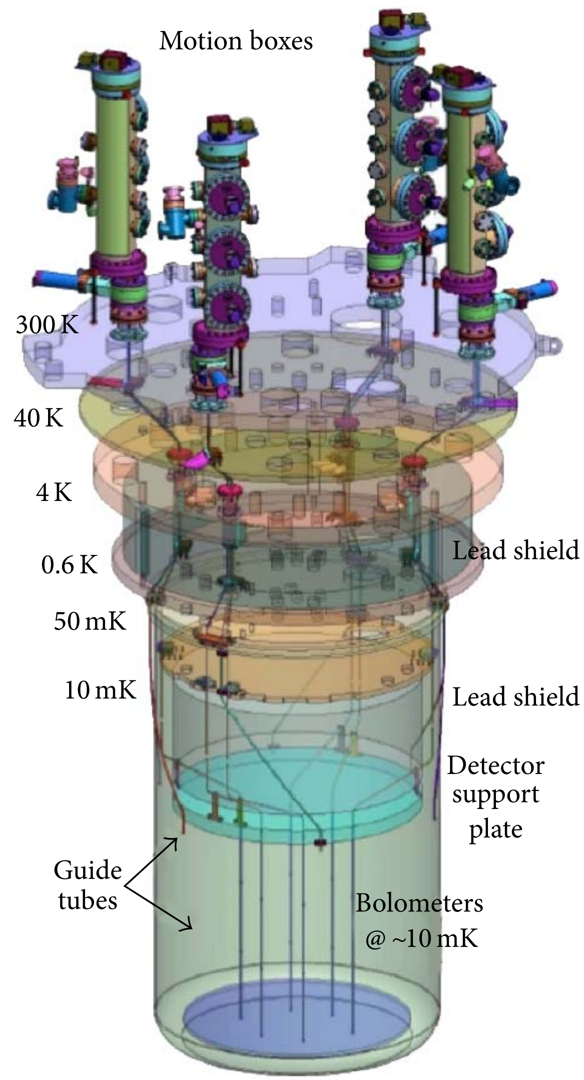
Detector Towers

Assembly of all 19+ towers is complete!



CUORE Cryostat





CUORE Cryogenic Systems & Commissioning

Phased Commissioning

Phase I: 4K system check

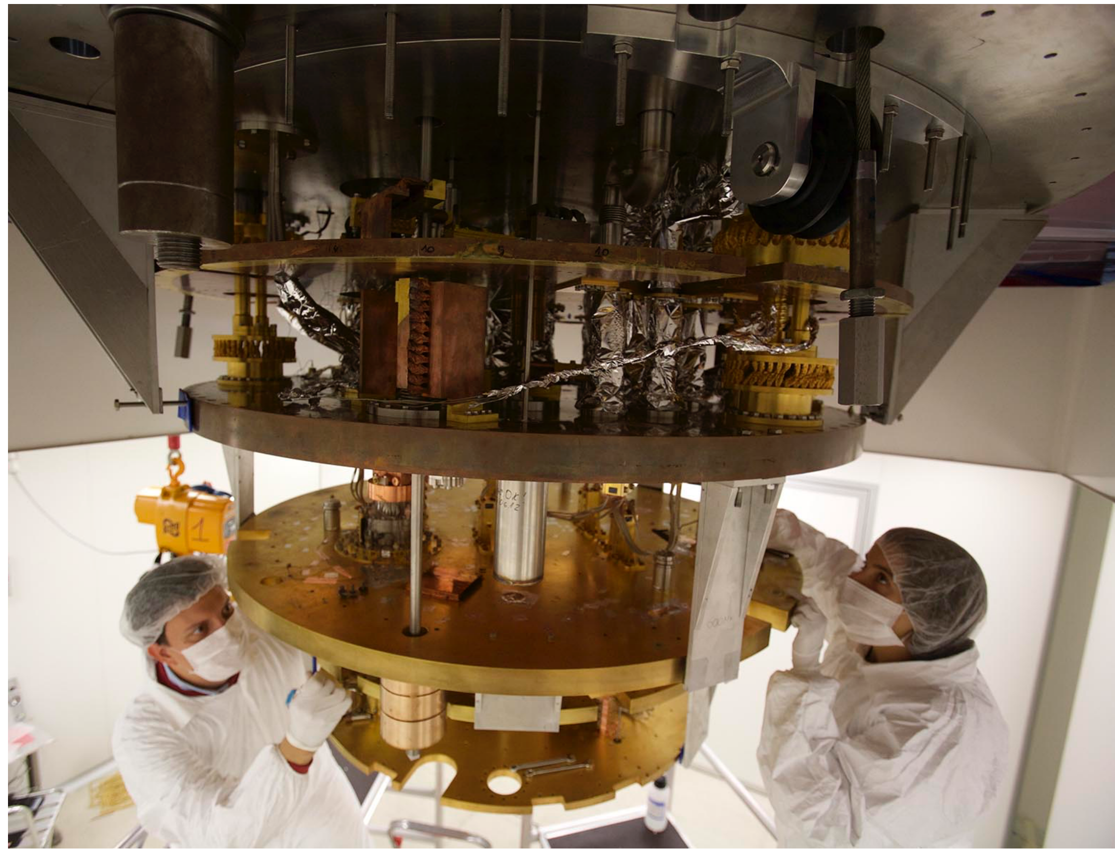
- Outer/Inner vacuum chamber test
- Cryogenic verification of detector calibration system
- Commissioning test of DU

Phase II: full cryostat vessel check

- Full assembly of cryostat
- Cool down of cryostat
- Integration of test tower
- Detector wiring
- calibration system

Preparing for Phase III: integrated cryogenic test

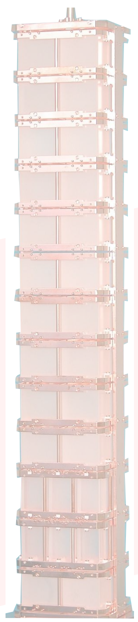
- with lead shields
- wiring
- full calibration system



6mK stable base temperature achieved in October 2014

The CUORE 0νββ Search

Cuoricino
(2003-2008)



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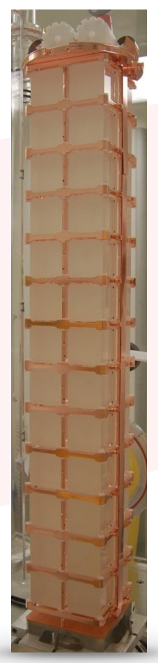
CUORE-0
(2013-2015)



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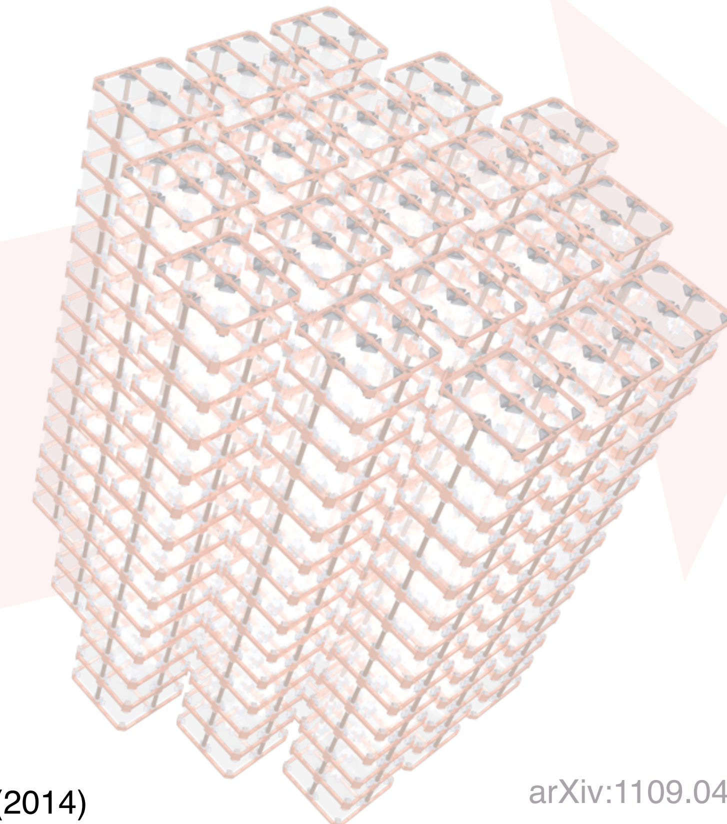
$T_{1/2}^{0\nu\beta\beta}$ > 4.0 × 10^{24} y (90% C.L.)

CUORE
(2015-2020)



arXiv:1109.0494

Projected
$T_{1/2}^{0\nu\beta\beta}$ > 9.5 x 10^{25} yr (90% C.L.)

CUORE-0

first tower of CUORE
installed in Cuoricino cryostat

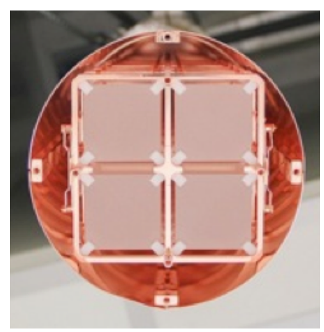
52 TeO_2 crystals
39 kg TeO_2
~ 11 kg of ^{130}Te

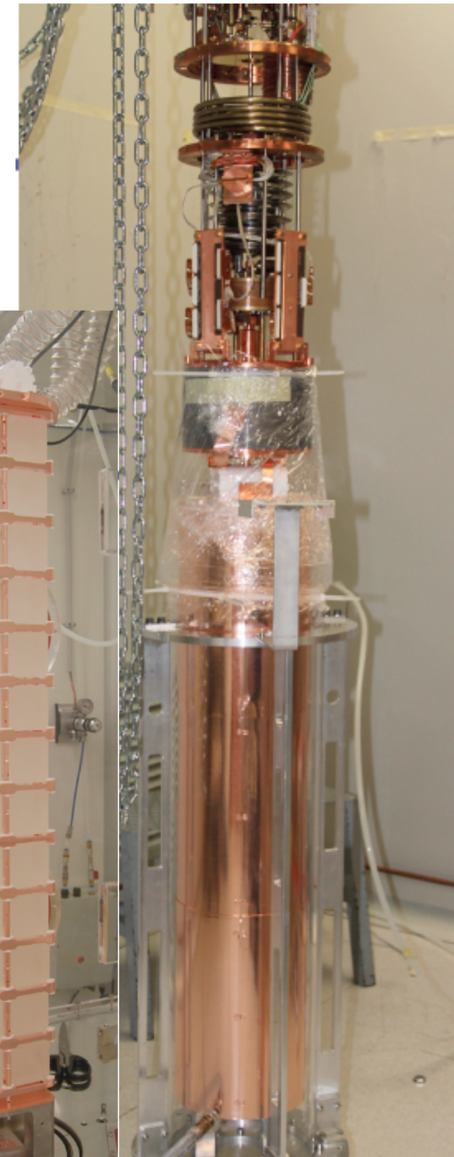
PURPOSE

validate cleaning and assembly procedures for CUORE
- TeO2 crystal contaminations
- Cu holder surface contamination

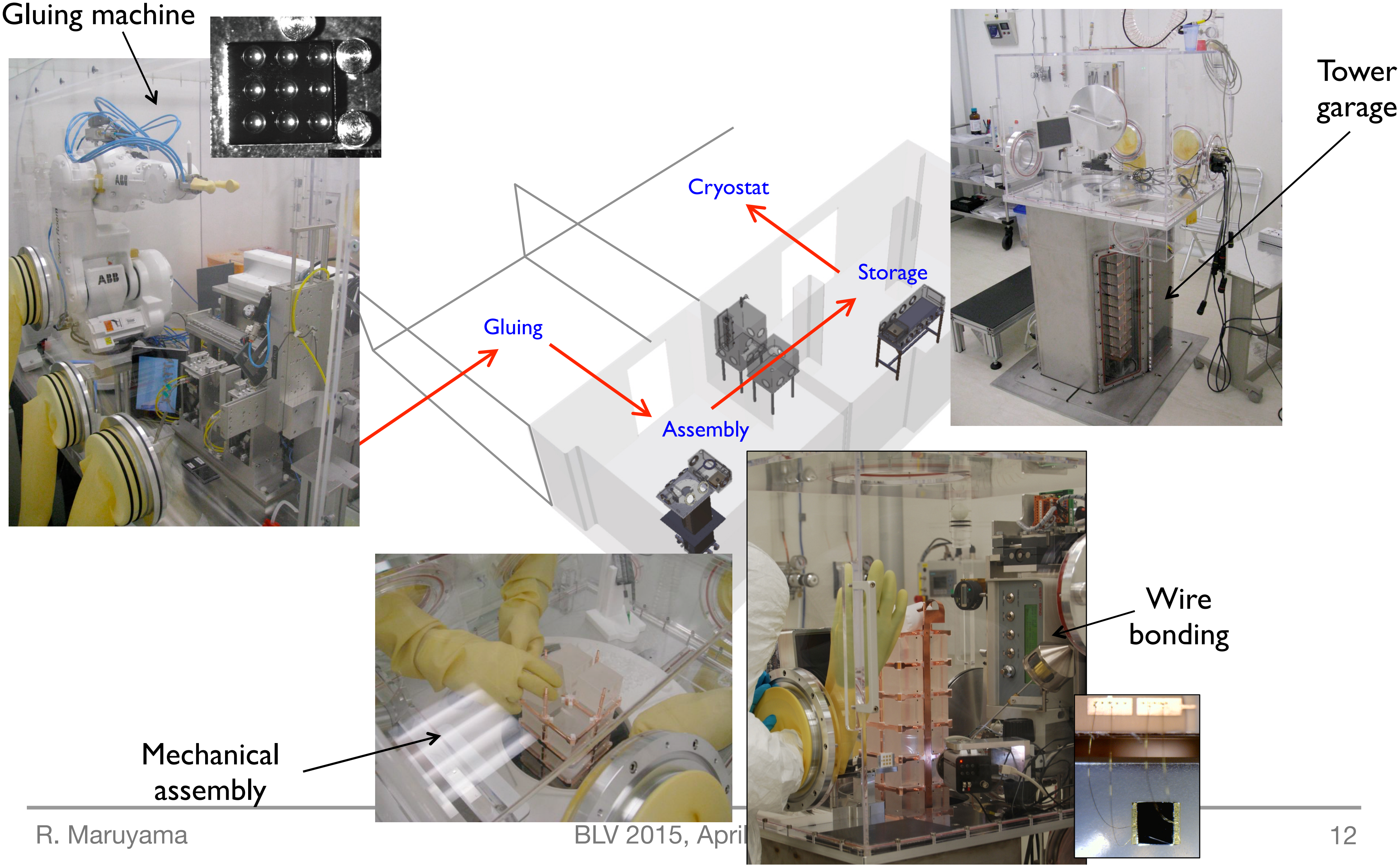
stand-alone $0\nu\beta\beta$ experiment
- phase I data *EPJC 74, 2956 (2014)*

Today's result: arXiv:1504.0245

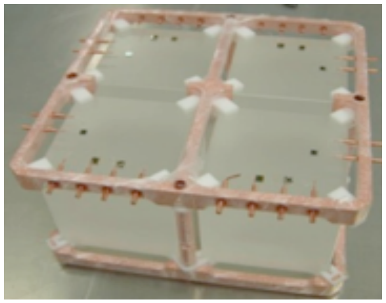




CUORE-like Detector Assembly



Lowering Background: Crystals & Copper



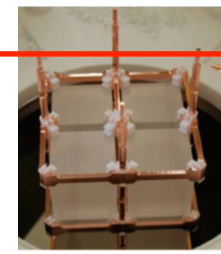
Ultra-pure TeO2 crystal array

Bulk activity 90% C.L. upper limits:

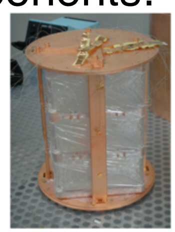
$8.4 \cdot 10^{-7}$ Bq/kg (^{232}Th), $6.7 \cdot 10^{-7}$ Bq/kg (^{238}U), $3.3 \cdot 10^{-6}$ Bq/kg (^{210}Po)

Surface activity 90% C.L. upper limits:

$2 \cdot 10^{-9}$ Bq/cm^2 (^{232}Th), $1 \cdot 10^{-8}$ Bq/cm^2 (^{238}U), $1 \cdot 10^{-6}$ Bq/cm^2 (^{210}Po)

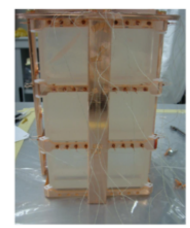


- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals
- Developed ultra-cleaning process for all Cu components:
  - Tumbling
  - Electropolishing
  - Chemical etching
  - Magnetron plasma etching



T1

T2

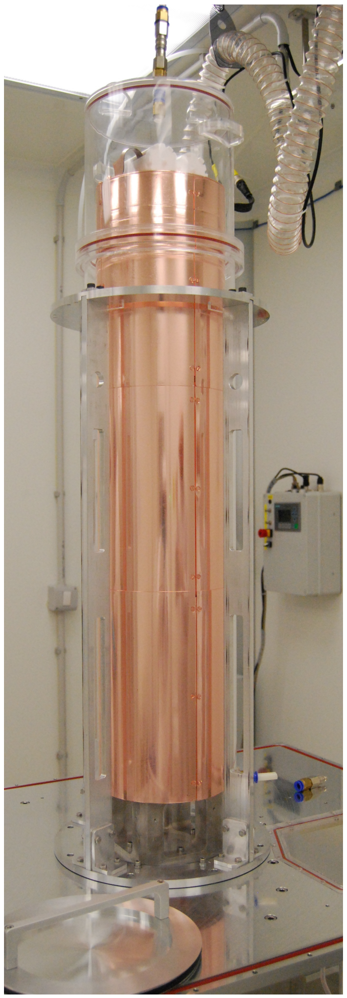


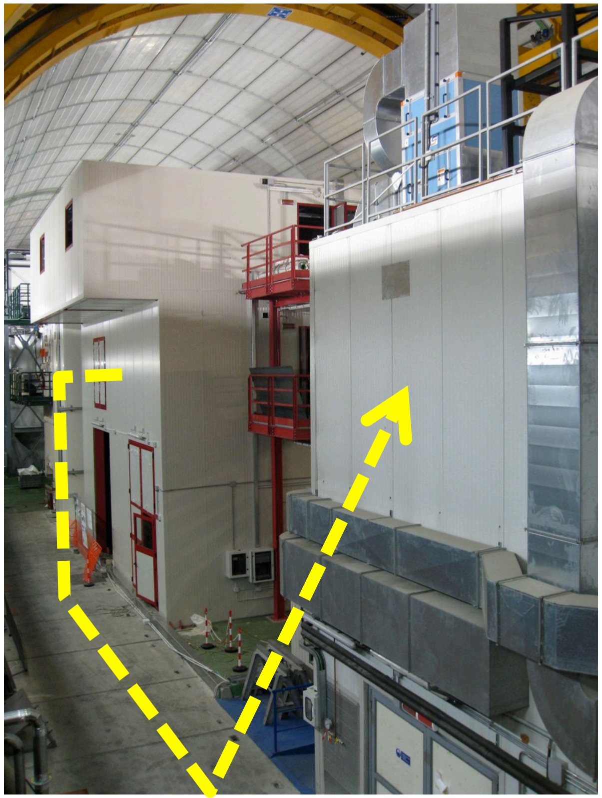
T3

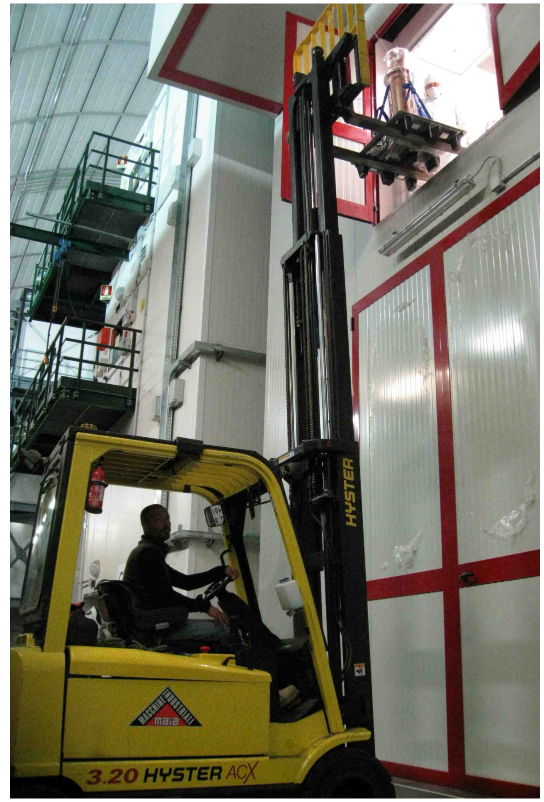
- Benchmarked in dedicated bolometer run at LNGS
  - Residual ^{232}Th / ^{238}U surface contamination of Cu: $< 7 \cdot 10^{-8}$ Bq/cm^2
- Validated by CUORE-0

- All parts stored underground, under nitrogen after cleaning

Tower Installation

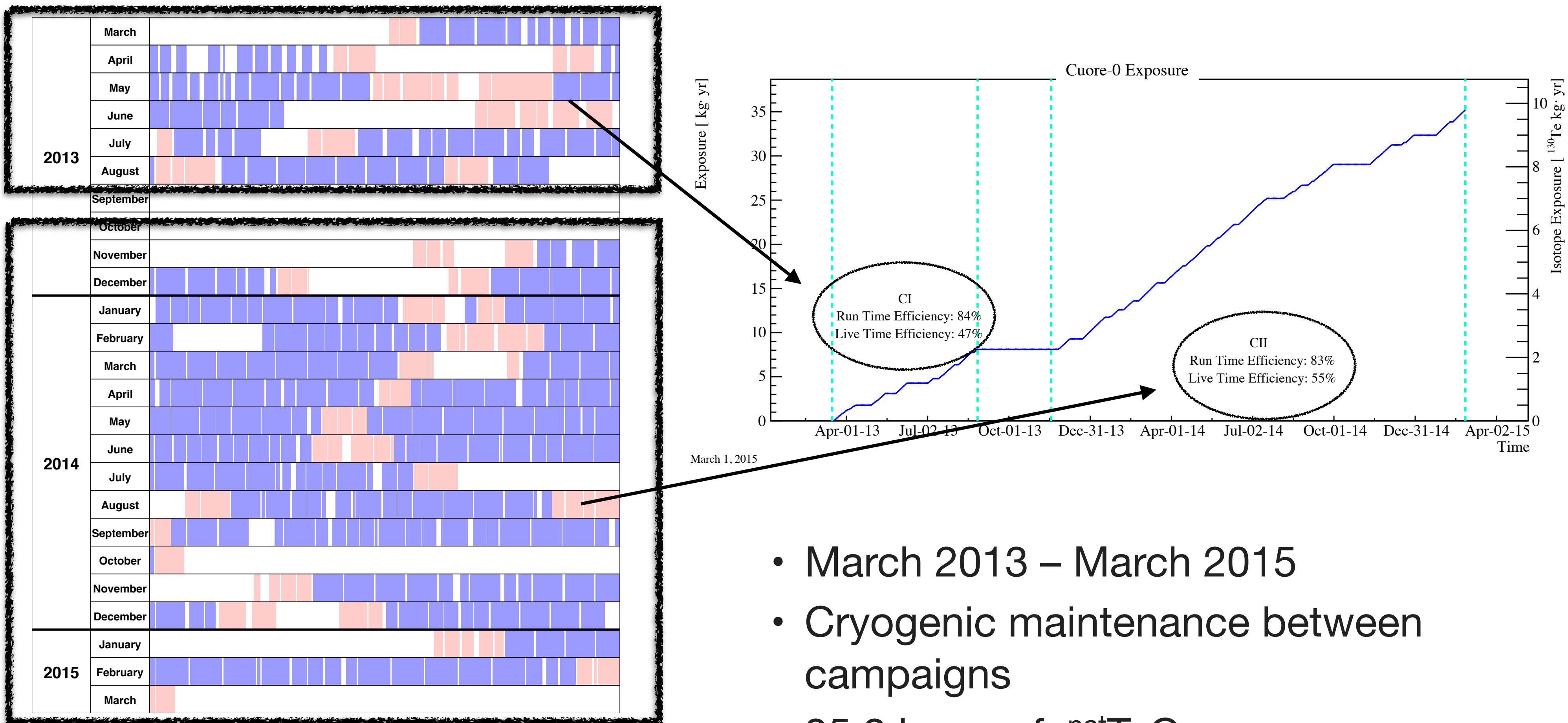






Built in CUORE Cleanroom, transported to Cuoricino cleanroom

Data Run: 2013 – 2015

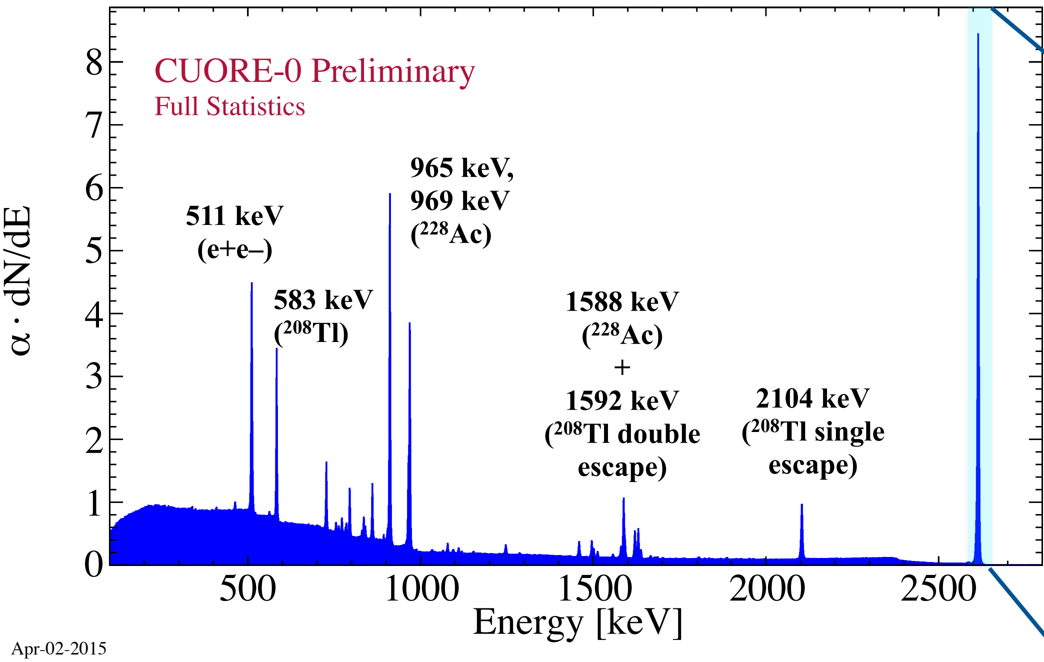


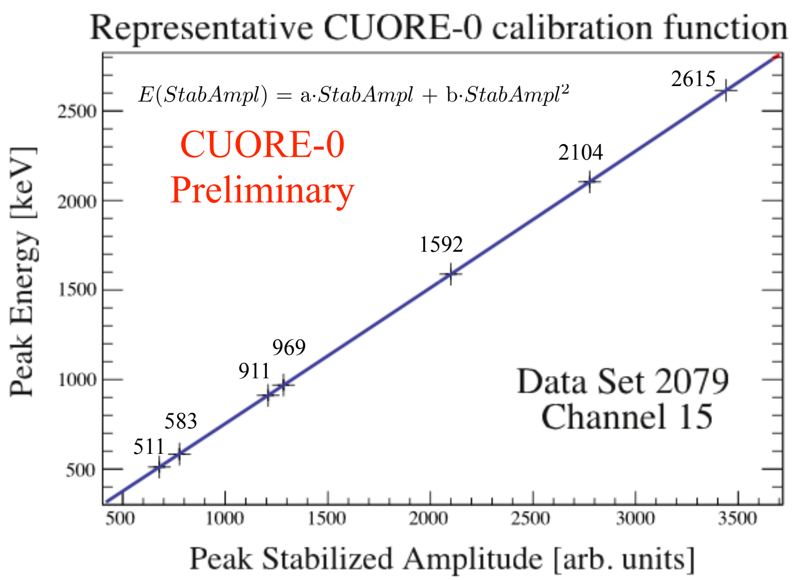
Physics data

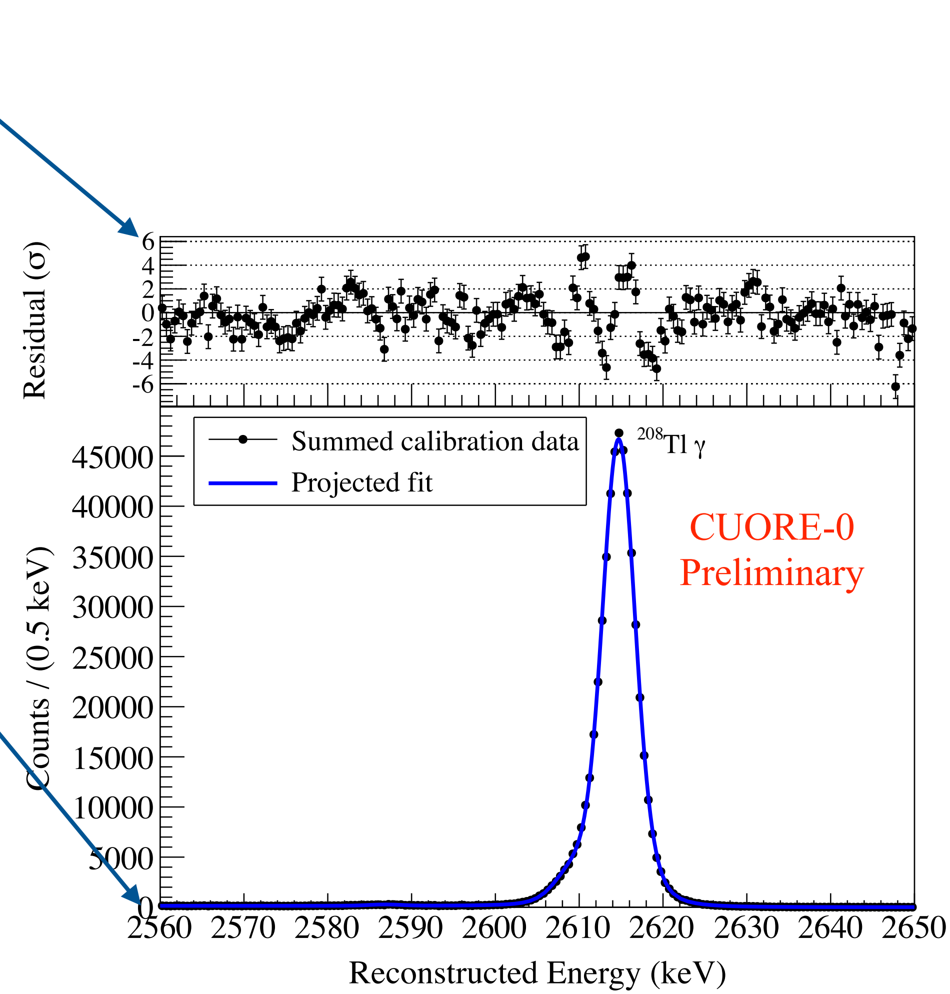
Calibration data

- March 2013 – March 2015
- Cryogenic maintenance between campaigns
- 35.2 kg-yr of $^{nat}TeO_2$
- 9.8 kg-yr of ^{130}Te

Calibration

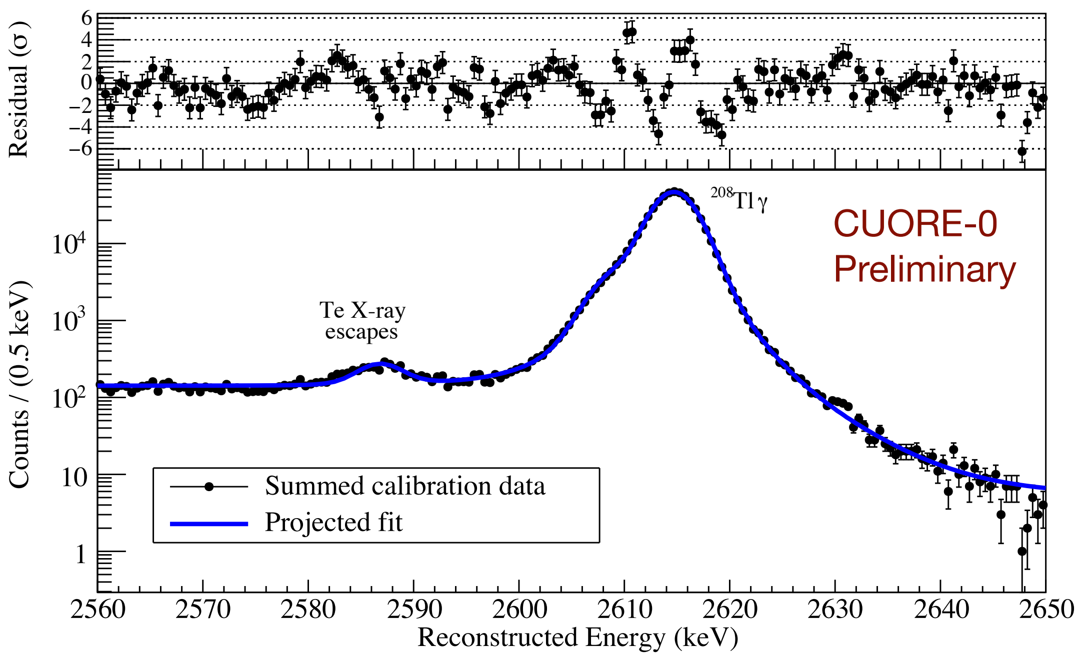


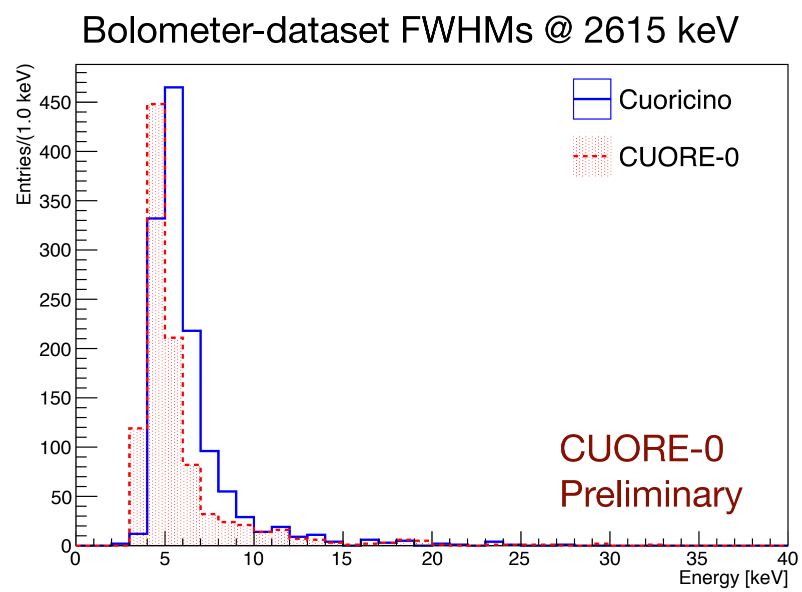




Energy Resolution

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



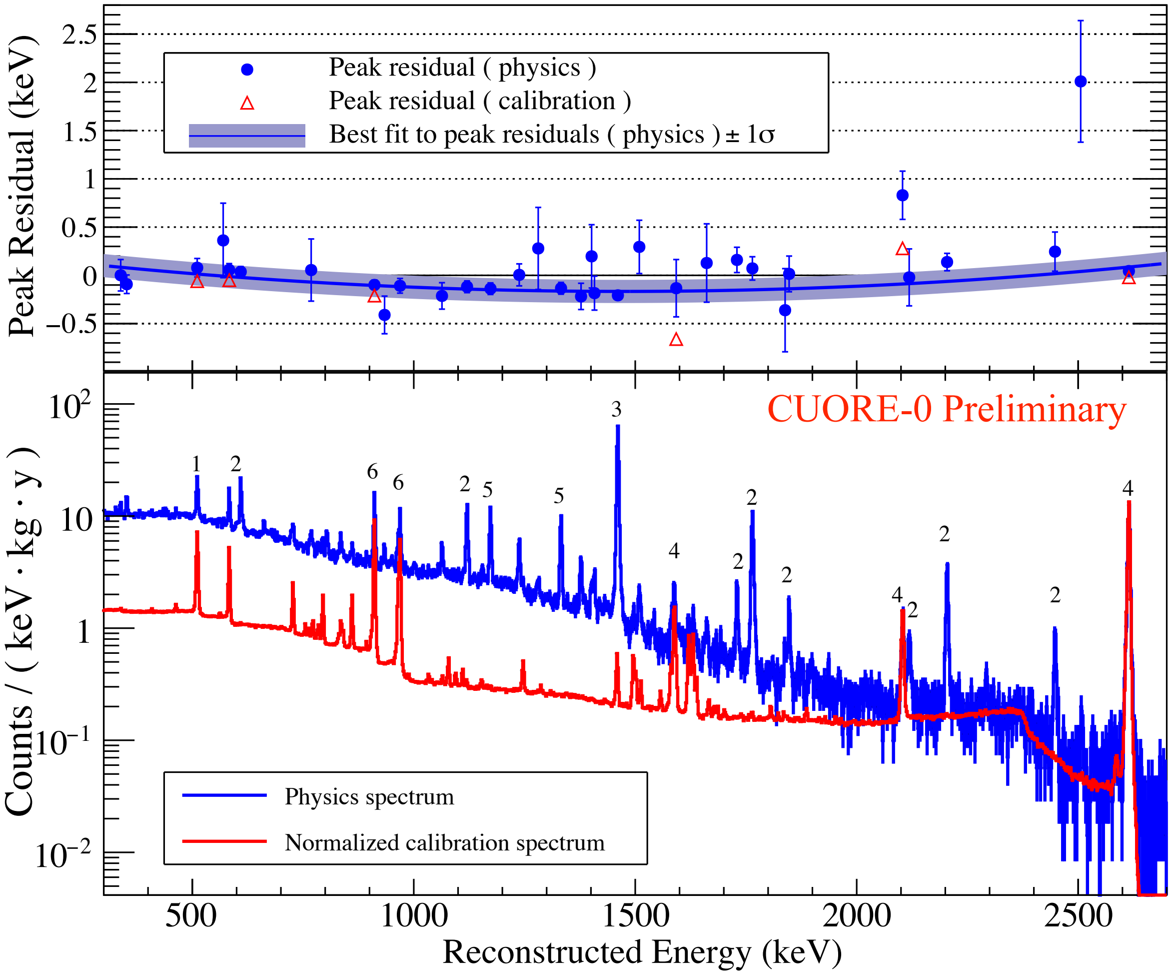


Weight FWHMs by corresponding exposure

	FWHM harmonic mean [keV]	FWHM dist RMS [keV]
Cuoricino	5.8	2.1
CUORE-0	**4.9**	**2.9**

- Energy resolution is evaluated for each bolometer and dataset by fitting the 2615 keV peak from ^{208}Tl in the calibration data.
- The obtained resolution is < 5 keV, which is the CUORE goal.

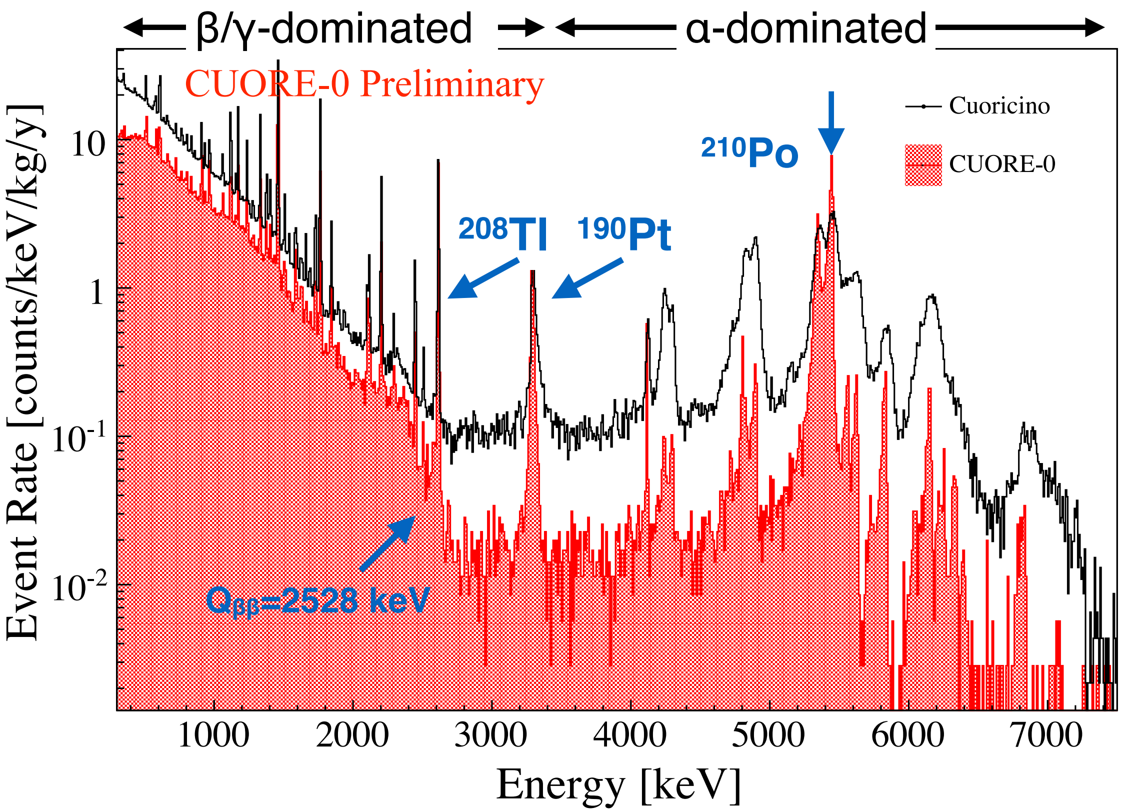
Energy spectra and Peak Residuals



- Two outliers are:
  - ^{60}Co, which reconstruct at 2507±0.6 keV, 2.0±0.6 keV higher than the nominal value
  - ^{208}Tl single-escape line, which reconstruct 0.84±0.22 w.r.t the nominal value at 2103.51 keV.
- Double escape from Tl-208 at 1592 keV in line with other peaks.

- **We determined a global calibration offset function, by performing a parabolic fit to the peak residual (excluding the two outliers).**
- **We take the standard deviation of the fit residuals (0.12 keV) as a global systematic uncertainty on the reconstructed energy.**

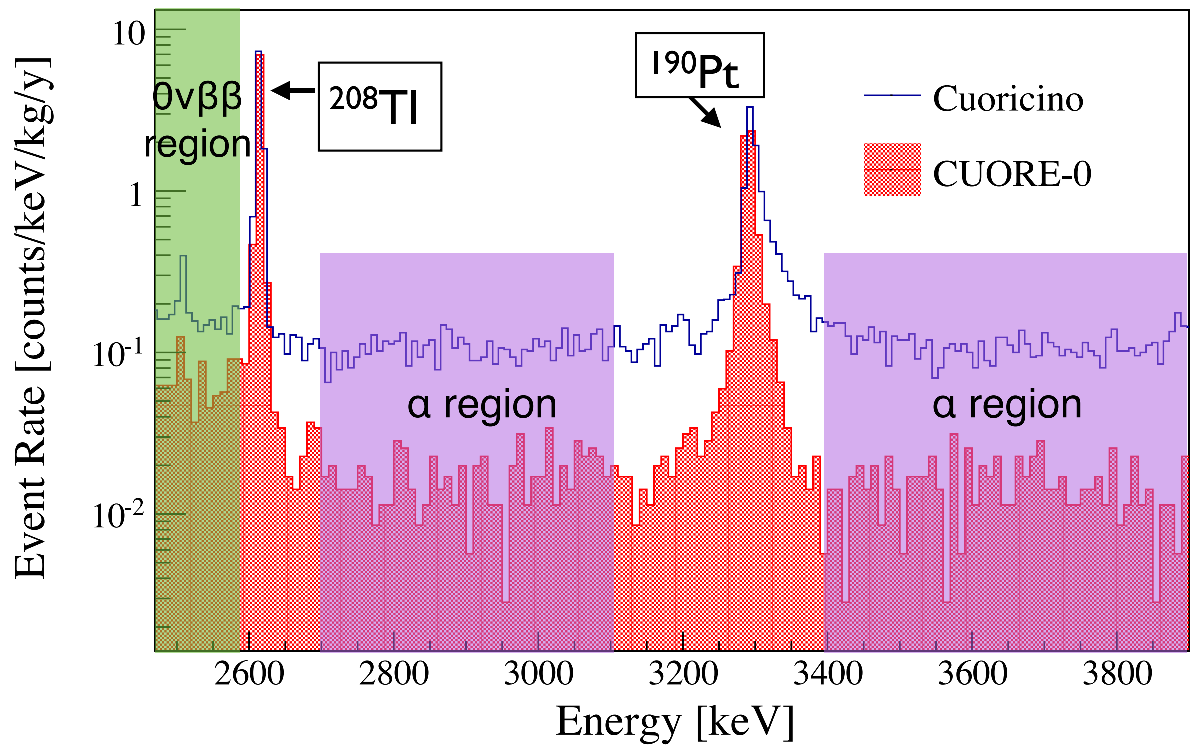
CUORE-0 Background Measurement



- γ background (from ^{232}Th) was not reduced since the cryostat remained the same.
- γ background (from ^{238}U chain) was reduced by a factor of 2.5 due to better radon control.
- α background from copper surface and crystal surface was reduced by a factor of 6.5 thanks to the new detector surface treatment.
- Demonstrate CUORE sensitivity goal is within reach.

Background paper in preparation!

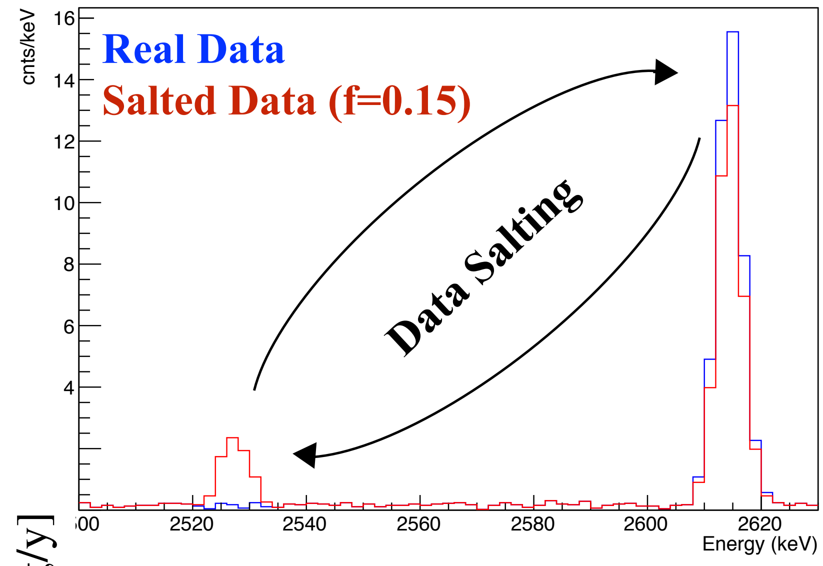
Background Rate & Reduction

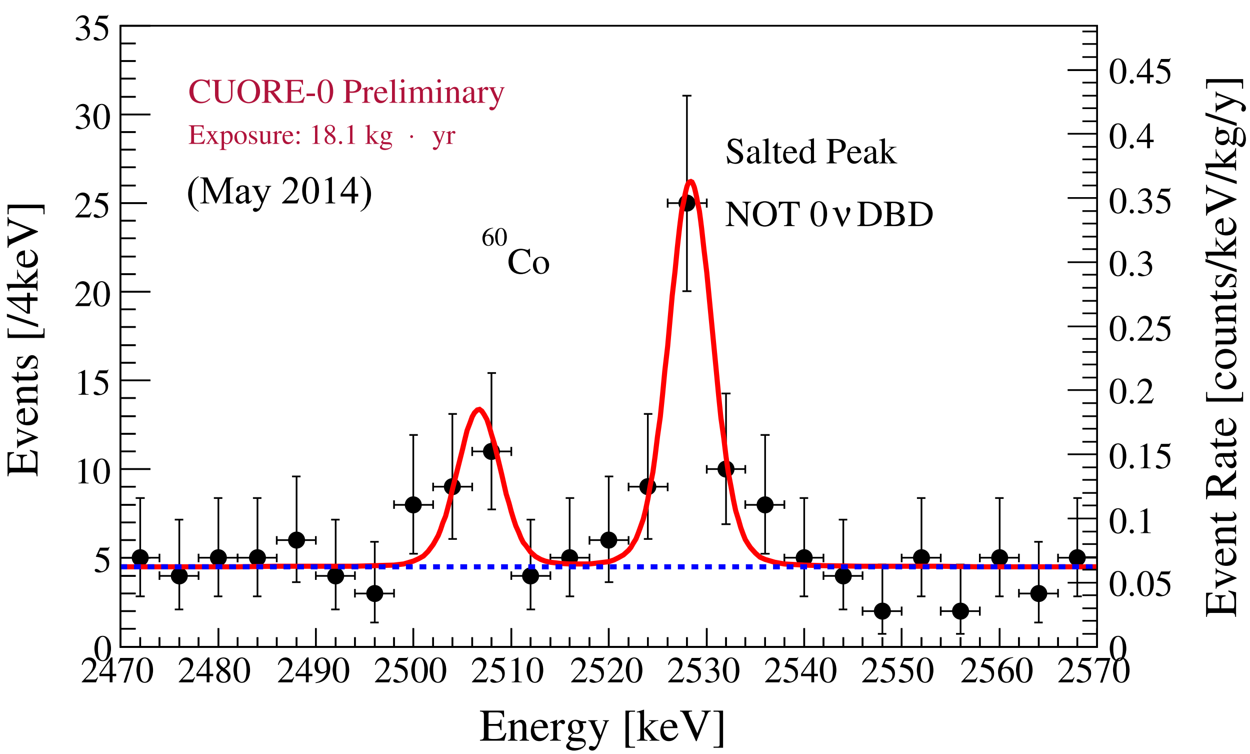


	Background rate [counts/keV/kg/y]		signal eff. [%] (detector+cuts)
	0νββ region	α region (excl. peak)	
Cuoricino	0.169 ± 0.006	0.110 ± 0.001	82.8±1.1
CUORE-0	0.058 ± 0.011	**0.016 ± 0.001**	81.3±0.6

Blind Analysis

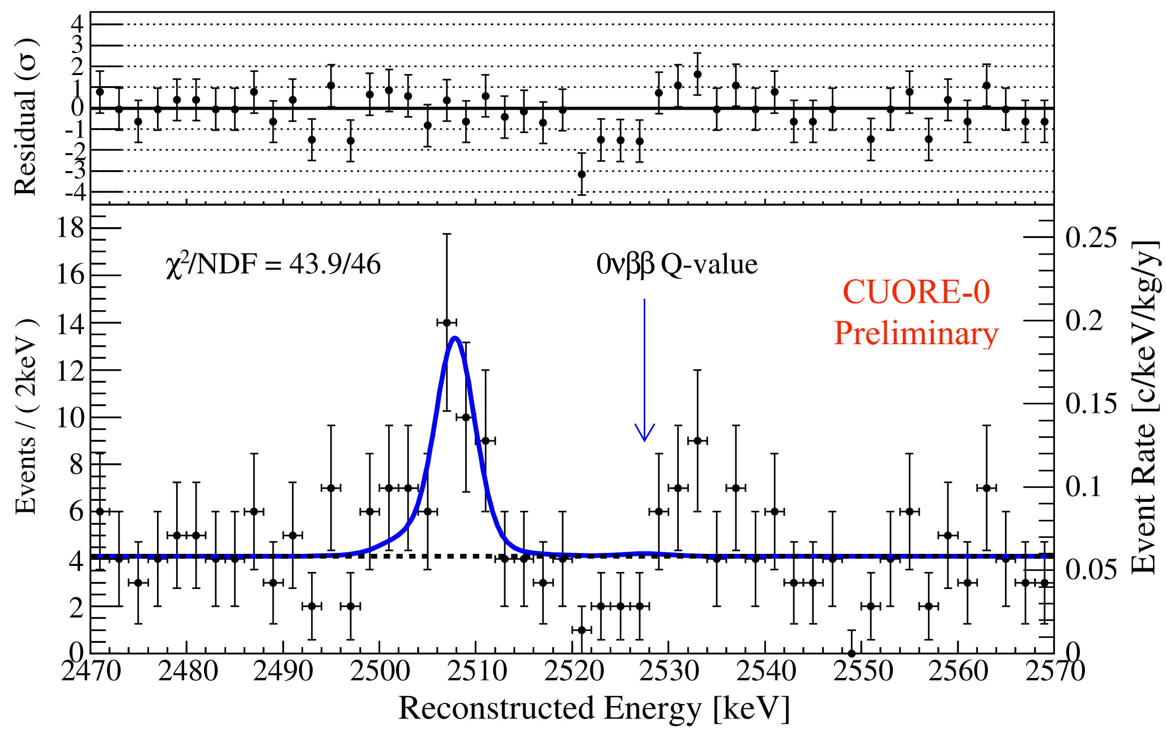
- Region of Interest was blinded by "salting" : A small (and ***blinded***) fraction of the events within ±10 keV in ^{208}Tl photopeak are exchanged with events within ±10 keV of the 0vββ Q-value to produce a ***fake*** peak.





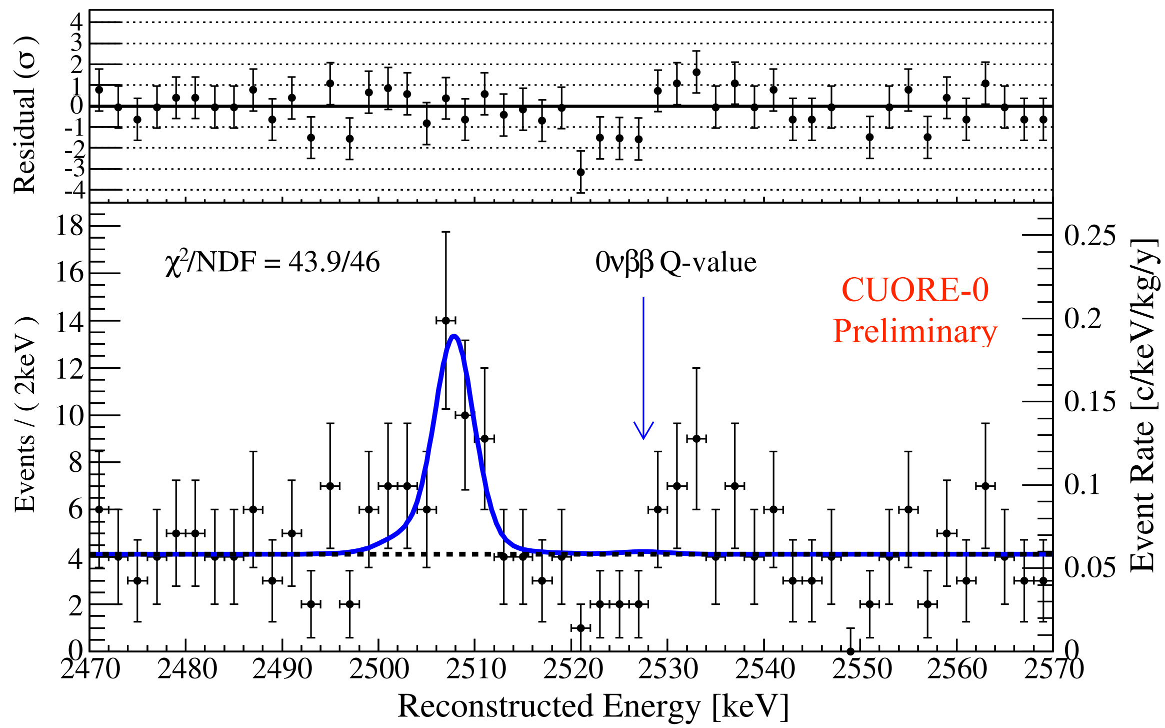
- Background at ROI characterized without biasing 0vββ analysis.

Unblinded Spectrum & Fit



- Simultaneous unbinned extended ML fit to range [2470,2570] keV
- Fit function has 3 components:
  - Calibration-derived lineshape modeling posited fixed at 2527.5 keV
  - Calibration-derived lineshape modeling Co peak floated around 2505 keV
  - Continuum background

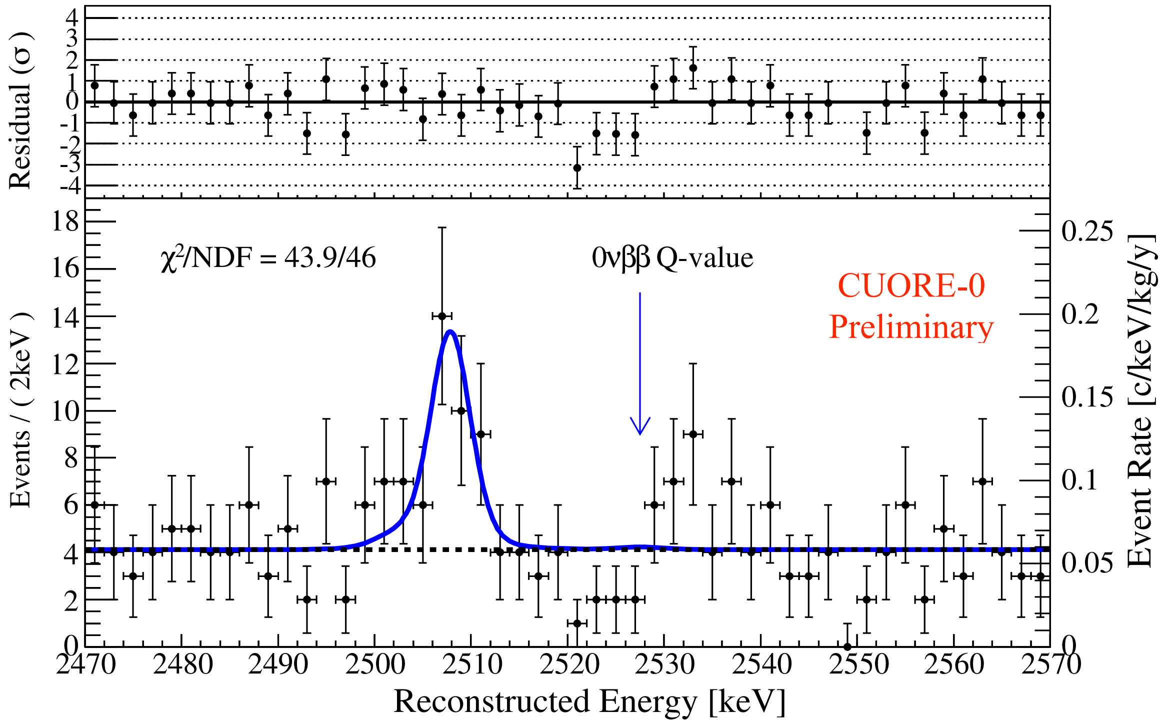
Unblinded Spectrum & Fit



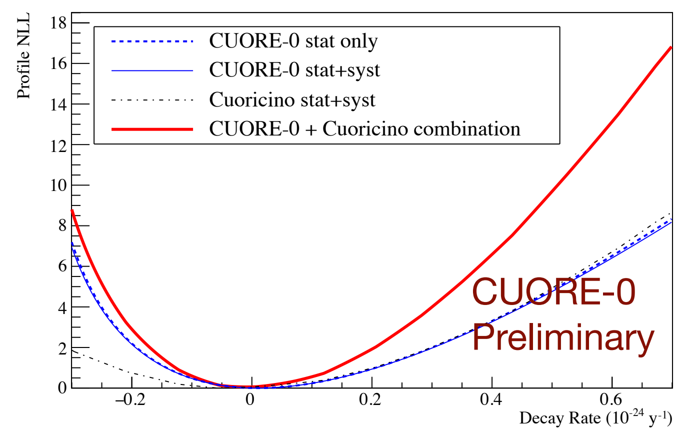
Fitted background: 0.058 ± 0.004 (stat.) ± 0.002 (syst.) counts/keV/kg/yr

Best-fit decay rate: $\Gamma^{0\nu\beta\beta}$ (^{130}Te) = 0.01 ± 0.12 (stat.) ± 0.01 (syst.) × 10^{-24} yr^{-1}

Unblinded Spectrum & Fit



CUORE-0 result combined with Cuoricino result from 19.75 kg-yr of ^{130}Te exposure yields the Bayesian lower limit:



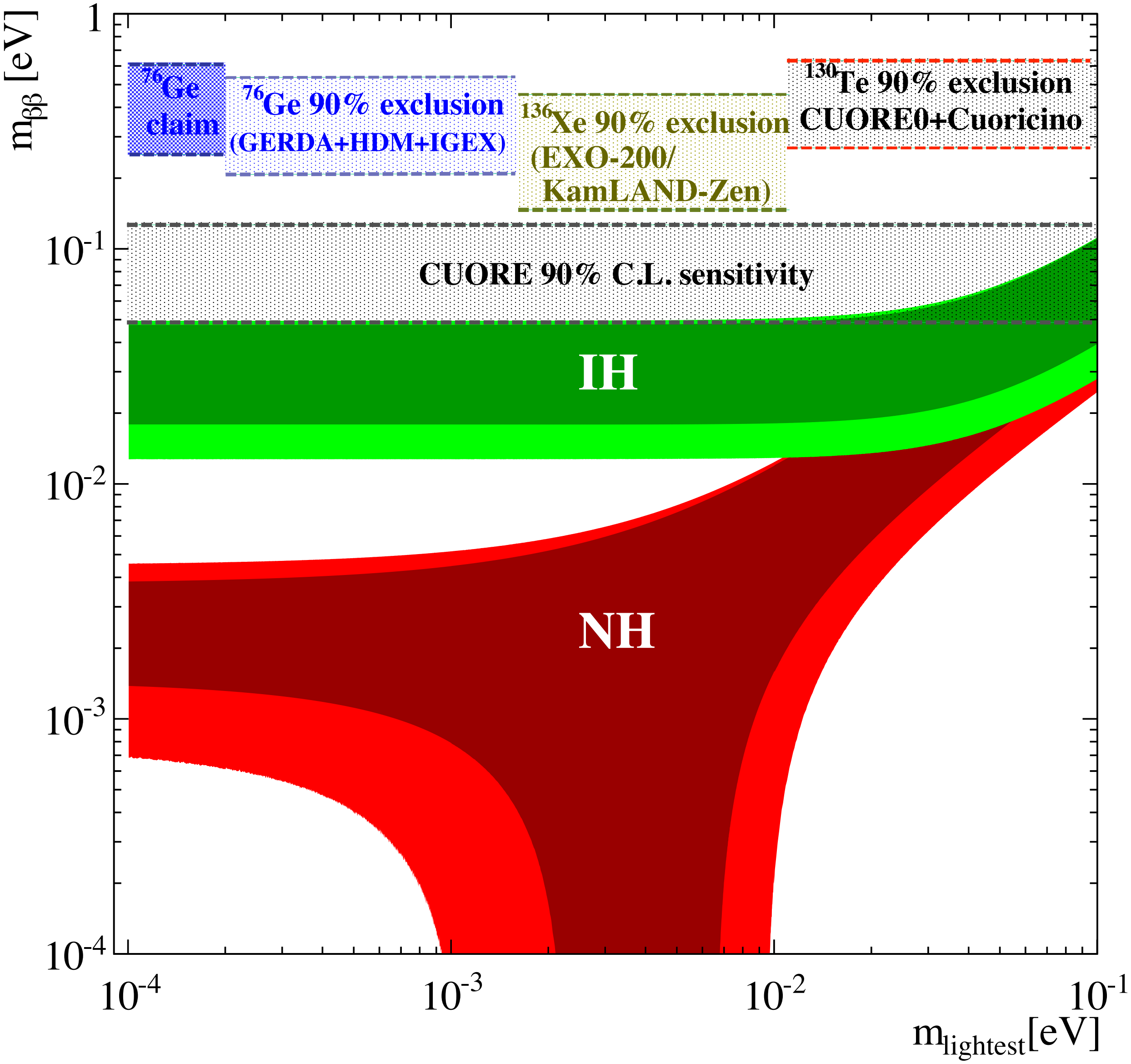
$\Gamma^{0\nu\beta\beta}(^{130}Te) < 0.25 \times 10^{-24}$ yr^{-1} (90% C.L., statistics only)

$T_{1/2}^{0\nu\beta\beta}(^{130}Te) > 2.7 \times 10^{24}$ yr (90% C.L., statistics only)

arXiv:1504.02454
Submitted to PRL

$T_{1/2}^{0\nu\beta\beta}(^{130}Te) > 4.0 \times 10^{24}$ yr (90% C.L., stat.+sys.)

Limits on Effective Majorana Mass



$\langle m_{\beta\beta} \rangle$ < 270 – 650 meV

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

Including additional Shell-Model NME

$\langle m_{\beta\beta} \rangle$ < 270 – 760 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))

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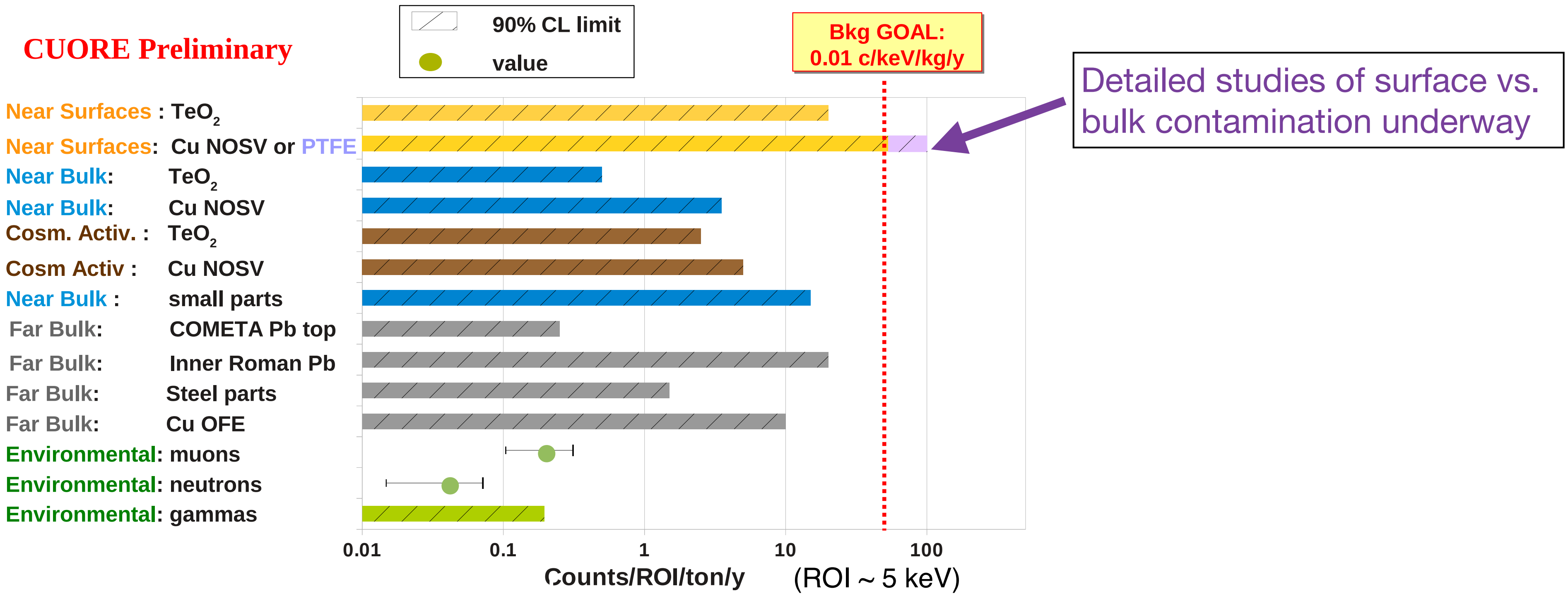
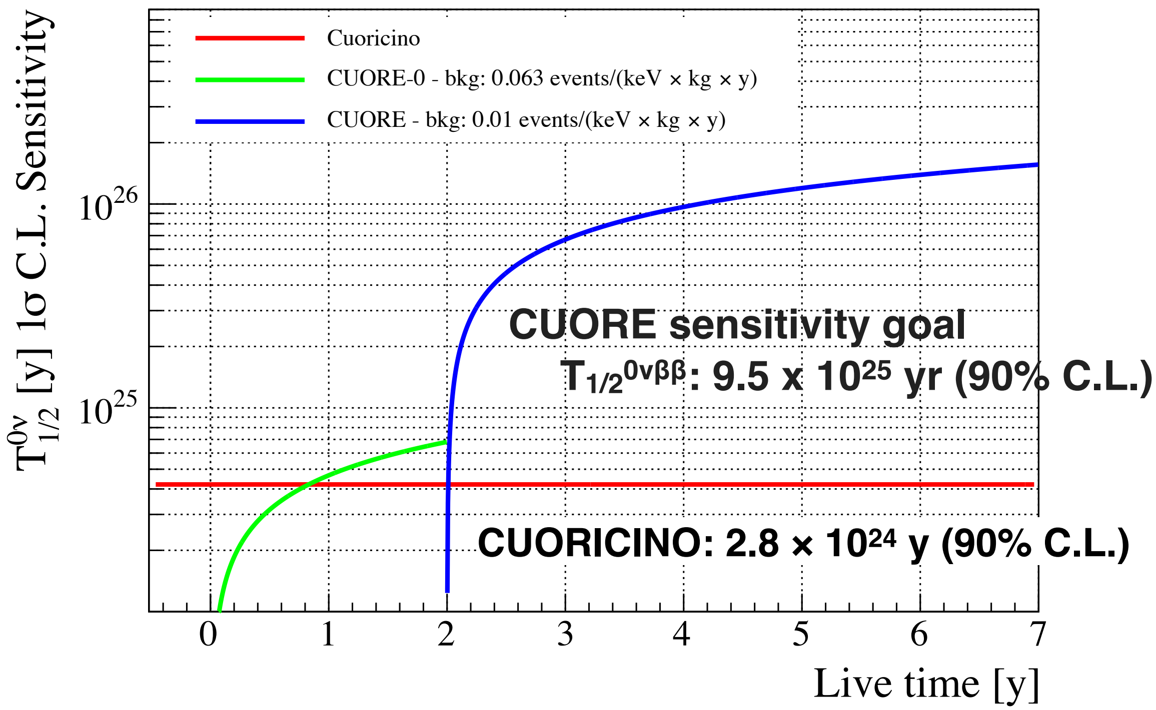
Projected CUORE Background

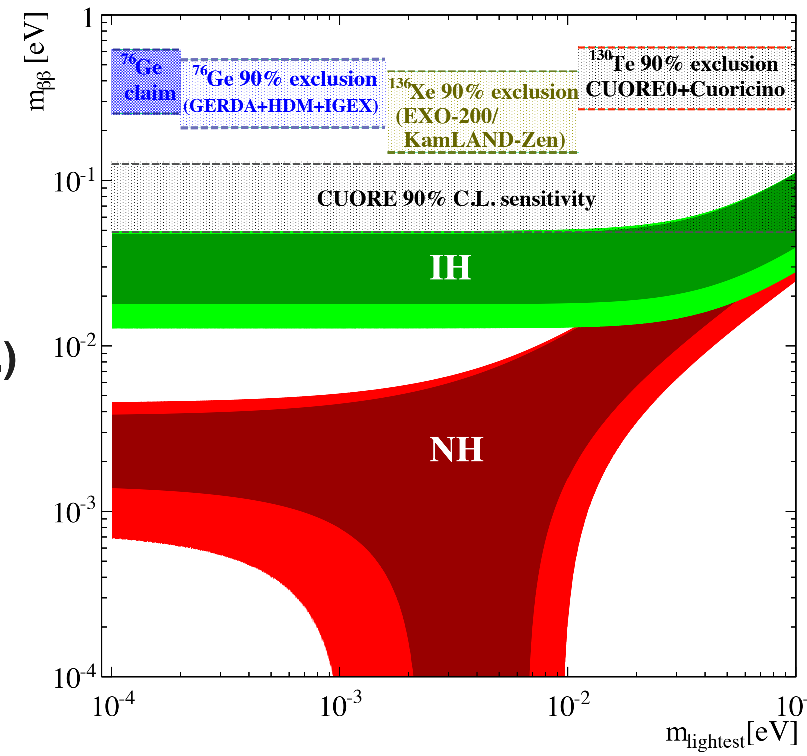
- CUORE-0 - provides bench mark for remaining background with new assembly & crystal/Cu cleaning protocols
- CUORE - results of CUORE-0 + screening campaign results -> CUORE MC



Conservatively extrapolate measured α-region bkg from CUORE-0 assuming all bkg is from $^{238}U/^{232}Th/^{210}Po$ individually

CUORE Sensitivity

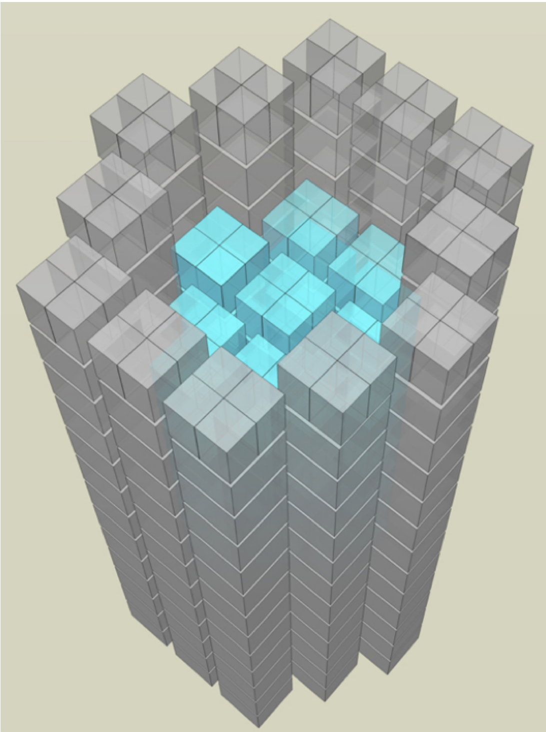




- CUORE sensitivity goal:
  - **$T_{1/2}^{0\nu\beta\beta}$ > 9.5 x 10^{25} yr** @ 90% C.L.
- Effective Majorana mass 51 - 133 meV @ 90% C.L.
  - Assumptions: 5 keV FWHM ROI resolution (δE), background rate (b) of 0.01 counts/(keV·kg·yr), 5 years of live time.

arXiv:1109.0494

Beyond CUORE: ^{130}Te Enrichment

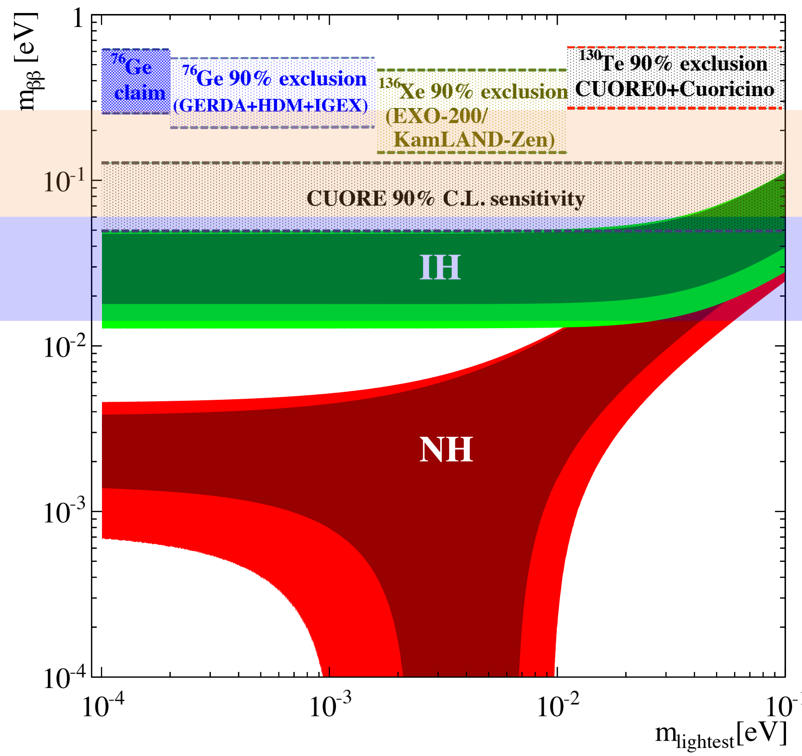


Enrichment

- **Natural next step for CUORE**
  - Increase # of parent nuclei, not the detector mass (# of background events)
- **^{130}Te enrichment is relatively cheap at $17K/kg**
  - Compared to ^{76}Ge enrichment at $100k/kg
- 500 gram of enriched ^{130}Te metal is sent to SICCAS for enriched crystal growth.

Current gen.

goal of next gen. experiments



$$m_{\beta\beta} \sim \frac{m_e}{\sqrt{F_N \cdot \varepsilon \cdot \eta \sqrt{\frac{M\cdot t}{b\cdot \delta E}}}}$$

F_N	Nuclear figure of merit: nuclear matrix element x phase space factor		
ε	Detection efficiency	t	Live time [year]
η	Isotopic abundance	b	Background [< 0.01/kg/keV/y]
M	Detector total mass [kg]	δE	Energy resolution [keV]

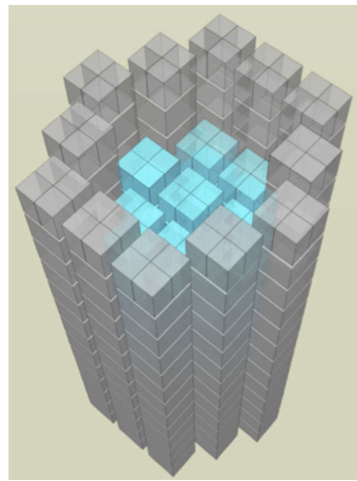
R&D for Future Bolometric 0νββ Searches

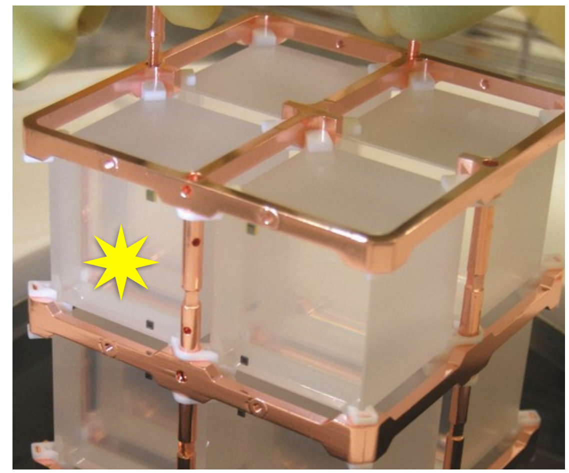
Increase mass enrich in ^{130}Te

Reduce background

- via particle ID
- cleaner detectors,
- tag backgrounds,
- active veto

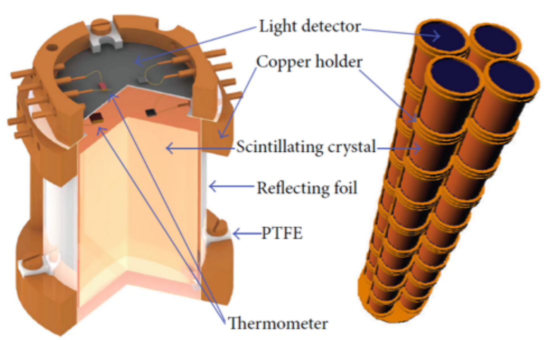
Explore other/multiple isotopes

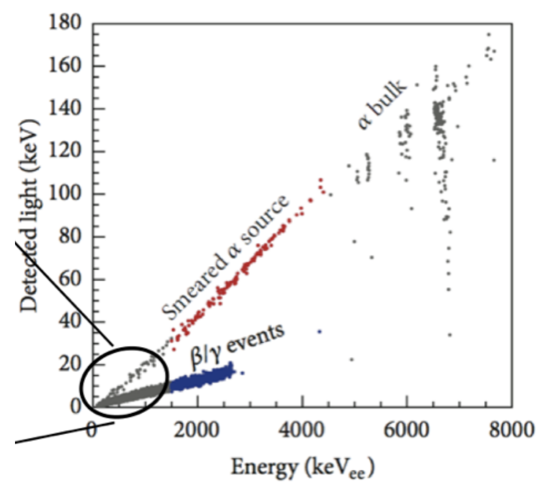




Bolometer R&D:

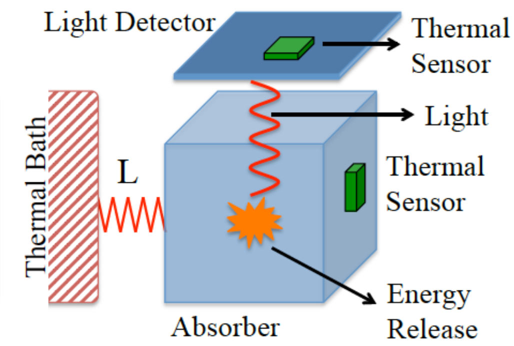
- CALDER
- Cherenkov/TeO_2
- LUCIFER
- LUMINEU

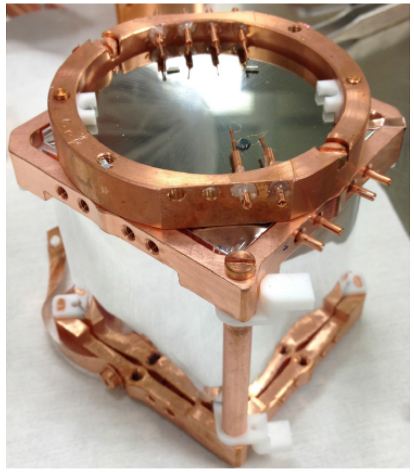


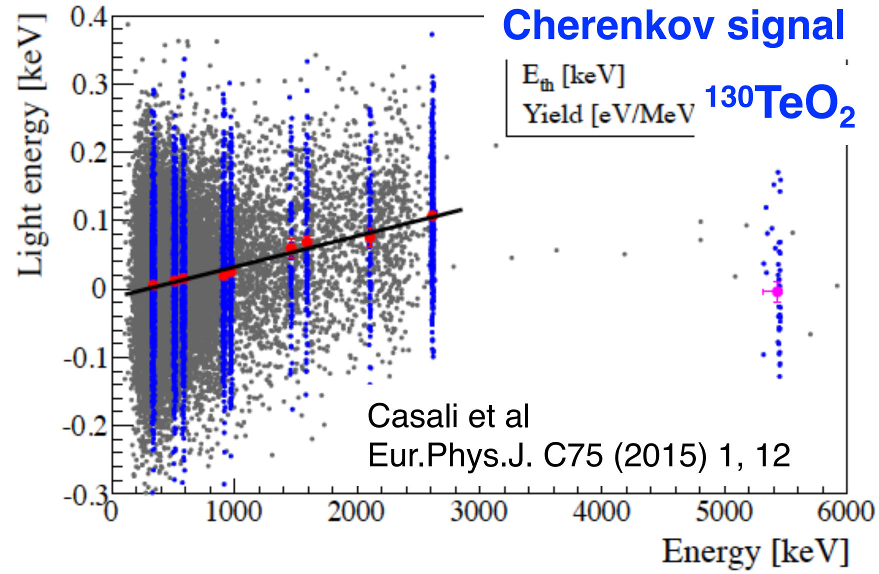


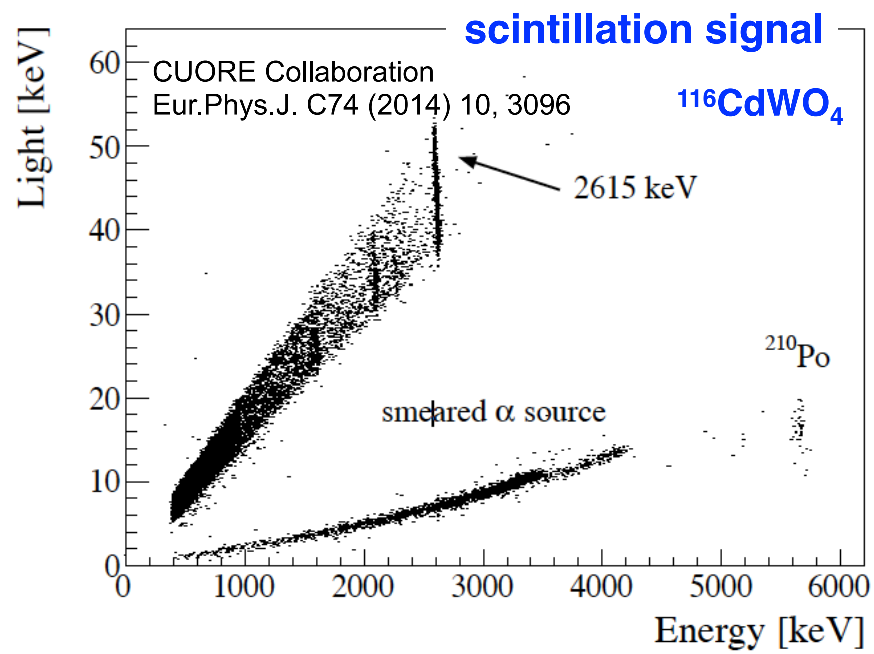
Beyond CUORE: Particle ID with Light Detectors

phonon+photon









- Cherenkov light or scintillation to distinguish α from β/γ ($^{130}TeO_2$, $Zn^{82}Se$, $^{116}CdWO_4$, and $Zn^{100}MoO_4$)
- More rejection power needed: 99.9% α background suppression. Light detector R&D for better resolution.
- Background free search.

$$m_{\beta\beta} \sim (M\cdot t)^{-1/2}, \text{ not } (M\cdot t)^{-1/4}$$

Conclusions

Neutrinoless double beta (0νββ) is the only method for probing the Majorana nature neutrinos. Observation would establish lepton number violation and physics beyond Standard Model.

CUORE program builds on the success of CUORICINO and predecessors

- **CUORE-0** (2013 - 2015)
  - confirms successful background mitigation and Cuoricino background model
  - energy resolution of < 5 keV FWHM for ROI reached
  - provides the most sensitive limit for (0νββ) in ^{130}Te to date.
- **CUORE**
  - tower assembly is complete and cryogenic system commissioning underway.
  - Start operation in late 2015.
  - with 206 kg of ^{130}Te and 5 keV energy resolution, is able to reach 51-133 meV effective Majorana mass.
- **Beyond CUORE**: R&D effort is underway. Large bolometers offer path towards exploring the inverted hierarchy.

Stay tuned!