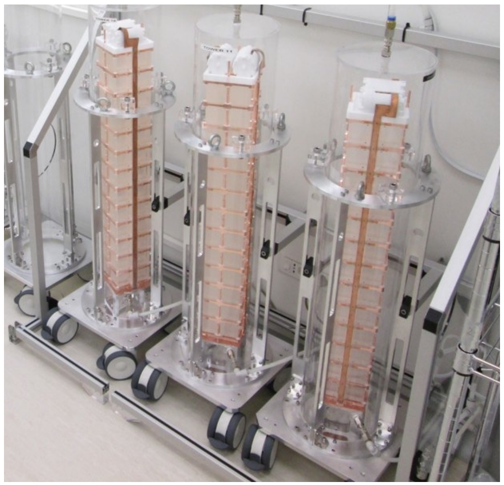
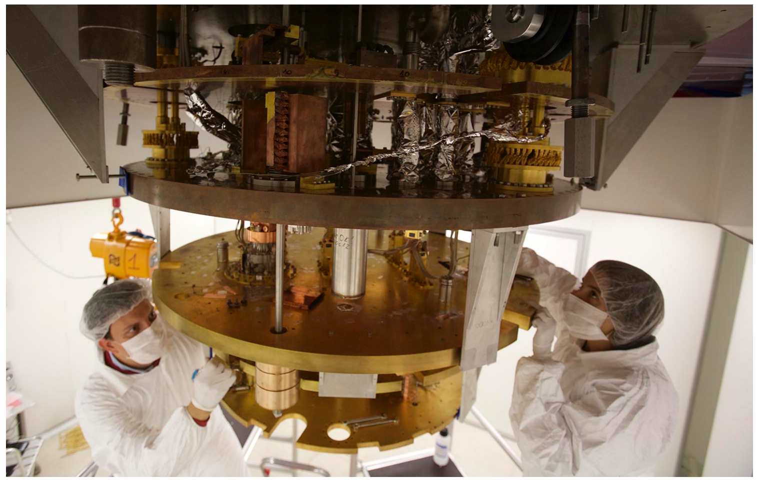
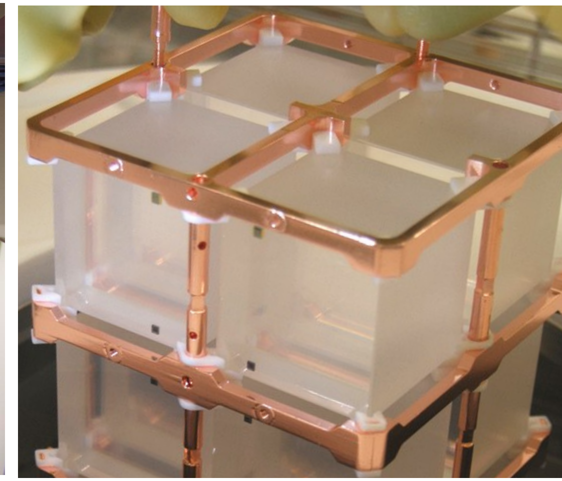
Investigation of $0\nu\beta\beta$ with Bolometers: CUORE and Beyond

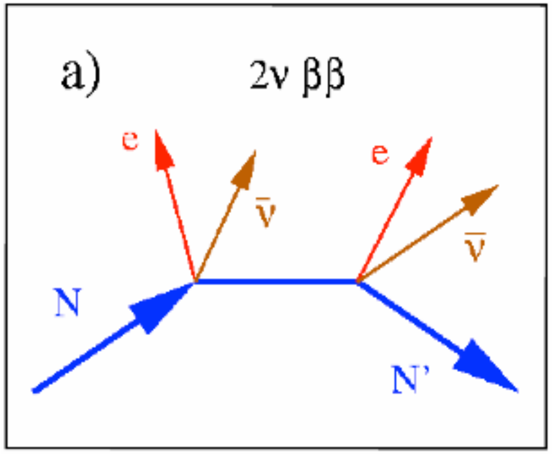




Karsten Heeger
Yale University

December 15, 2015

Yale Wright Laboratory

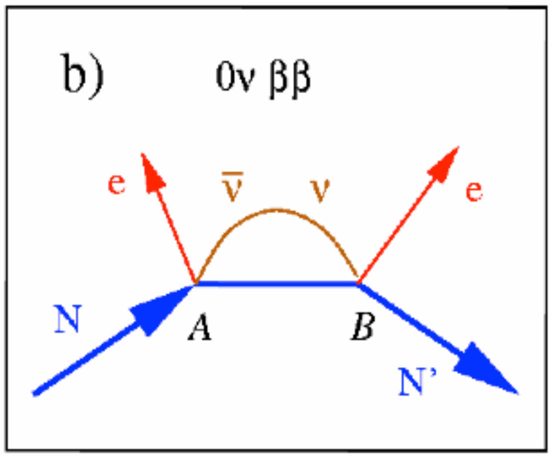
Neutrinoless Double Beta Decay: 0νββ



2ν mode: conventional 2nd order process in nuclear physics

$$\Gamma_{2\nu} = G_{2\nu} \, | M_{2\nu} |^2$$

G are phase space factors



0ν mode: hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

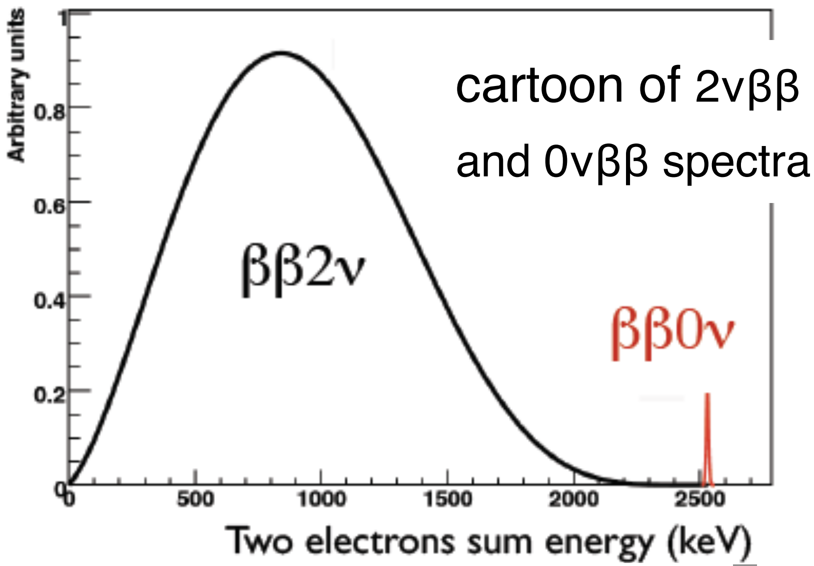
$$\Gamma_{0\nu} = G_{0\nu} \, | M_{0\nu} |^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$G_{0\nu} \sim Q^5$

0νββ would imply
- lepton number non-conservation
- Majorana nature of neutrinos

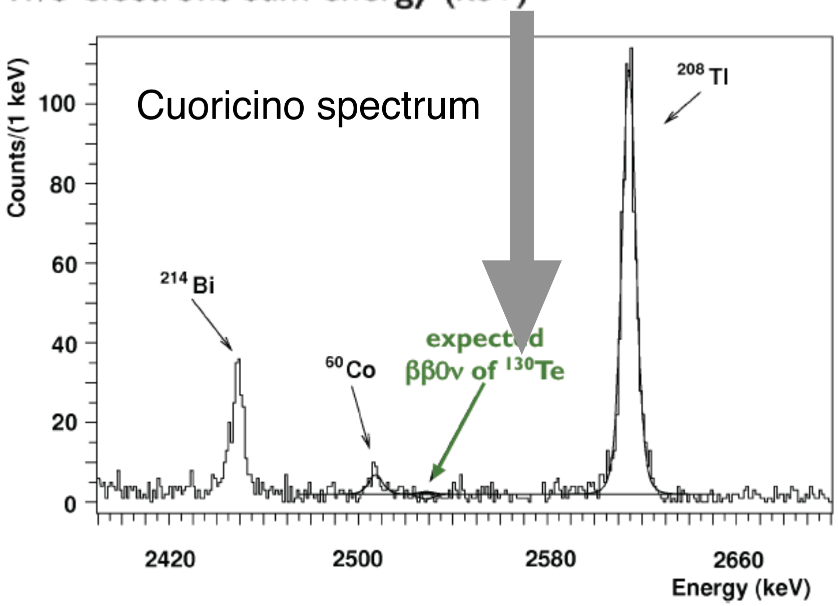
0νββ may allow us to determine
- effective neutrino mass

Search for 0νββ - Observable Signature



Experimental Signature of 0νββ

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



Example: ^{130}Te

Q(^{130}Te)=2527 keV

energy
= key event signature

energy resolution critical

Experimental Sensitivity

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

a = source isotopic abundance

ϵ = detection efficiency

M = total mass

t = exposure time

b = background rate at $0\nu\beta\beta$ energy

δE = energy resolution

0νββ source with

- **high isotopic abundance**

Detector with

- **high detection efficiency**
- **good energy resolution**
- **low-background**

Experiment

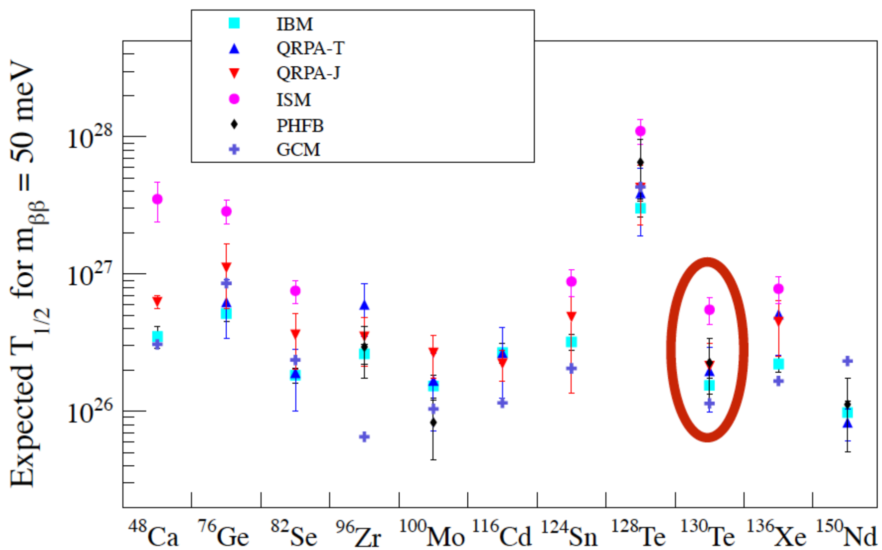
- **long exposure time**
- **large total mass of isotope**

Nuclear Structure in Double Beta Decay

Nuclear structure connects experimental rates to parameters of interaction, requires mechanism dependent nuclear matrix elements.

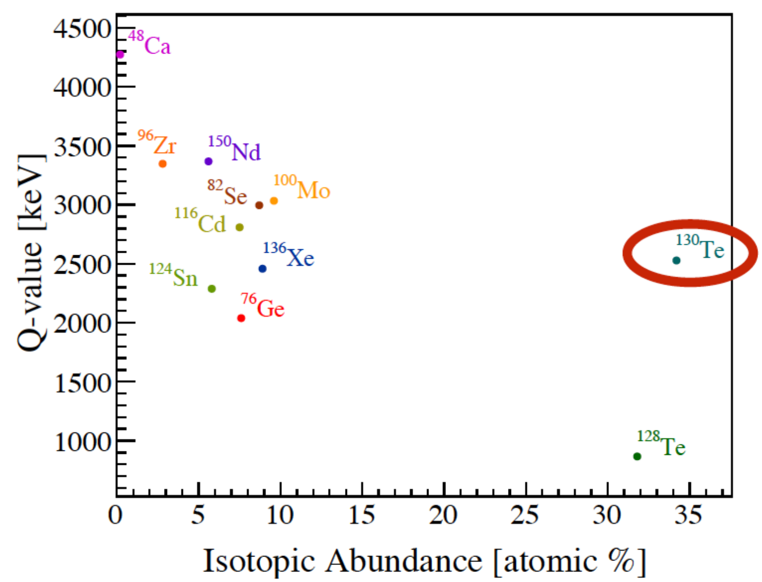
$T_{1/2}$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$



range of $T_{1/2}$ depending on nuclear matrix element

Q-value



Example: ^{130}Te

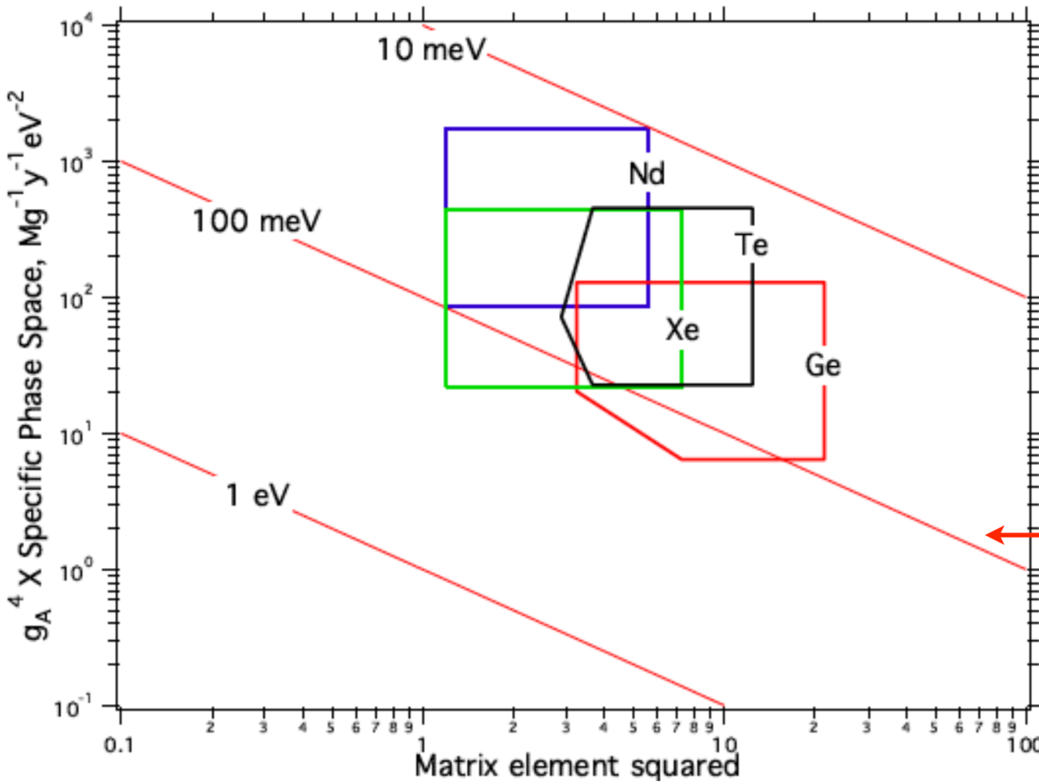
$Q(^{130}Te)$=2527 keV, good Q-value above Compton edge of 2615 keV line

High natural abundance

Isotopes and Sensitivity to $\langle m_{\nu\beta\beta} \rangle$

For Ge, Te, Xe, Nd

uncertainty on NME²



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta} \rangle}{m_e}\right|^2$$

uncertainty on value of g_A^4

Signal of 1 cnt/t-y for corresponding values of NME and g_A

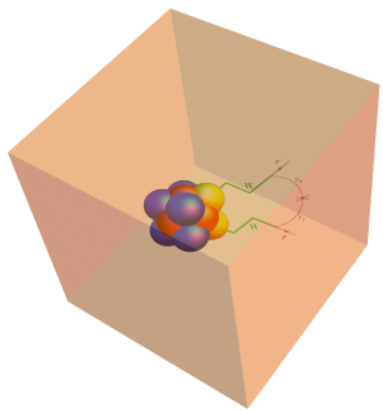
$$g_A^4 H_{0\nu} = g_A^4 \ln(2) \frac{N_A}{A m_e^2} G_{0\nu}^{(0)}$$

Isotopes have comparable sensitivities in terms of rate per unit mass

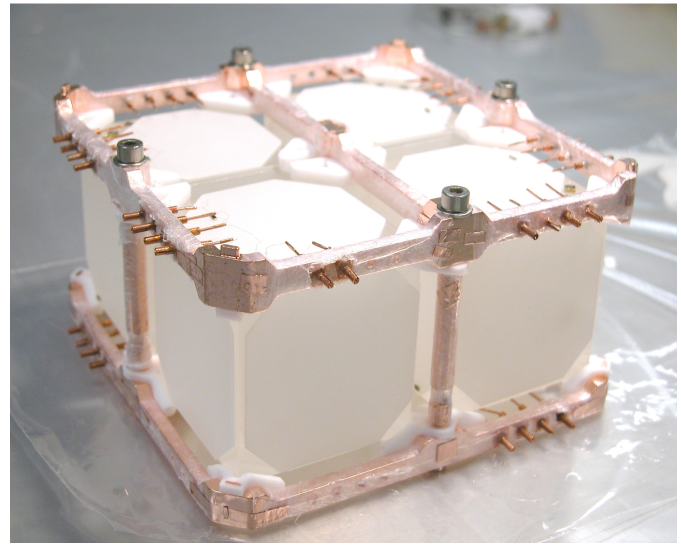
Ref: Robertson
MPL A28, 2013, 1350021
arXiv:1301.1323

CUORE Experimental Approach

Source = Detector

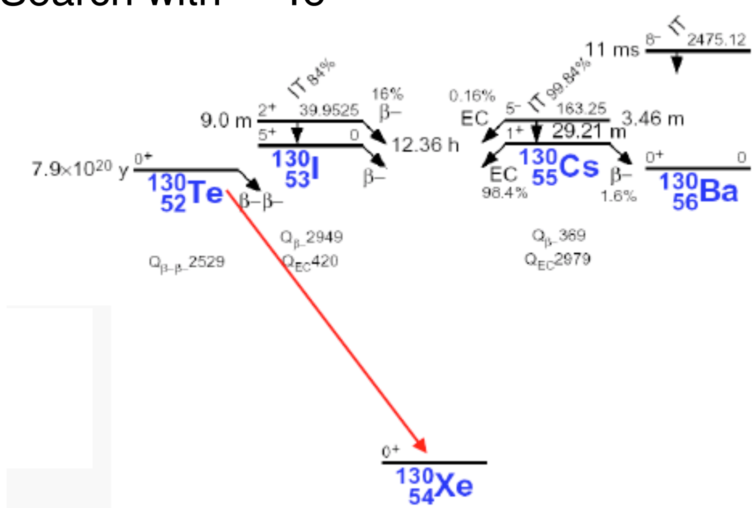


Use as calorimeter to watch for events of energy $E=Q_{\beta\beta}$



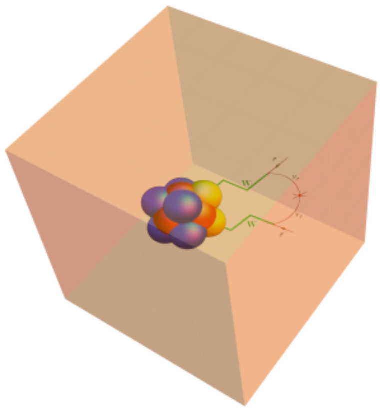
Bolometric Search with ^{130}Te

$^{130}Te \rightarrow {}^{130}Xe + 2e^-$ Q = (2527.518 +/- 0.013) keV

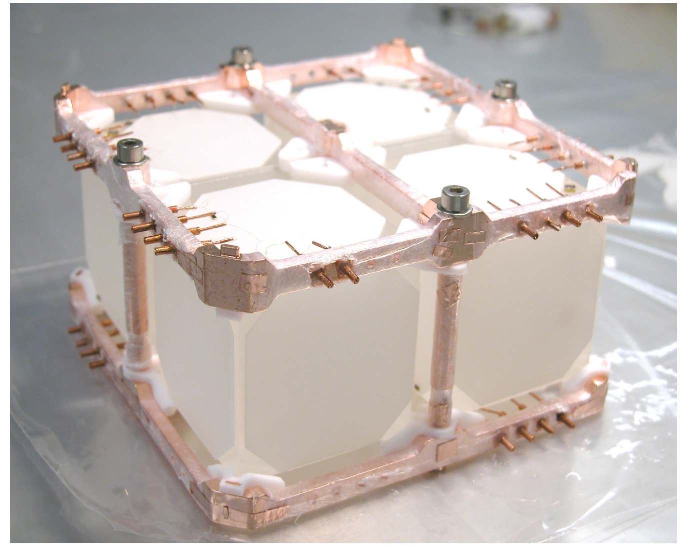


CUORE Experimental Approach

Source = Detector



Use as calorimeter to watch for events of energy $E=Q_{\beta\beta}$

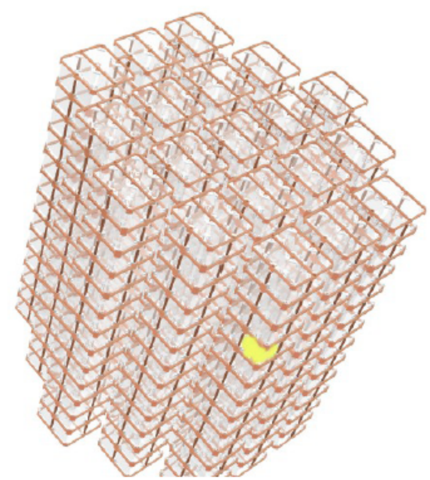


Bolometric Search with ^{130}Te

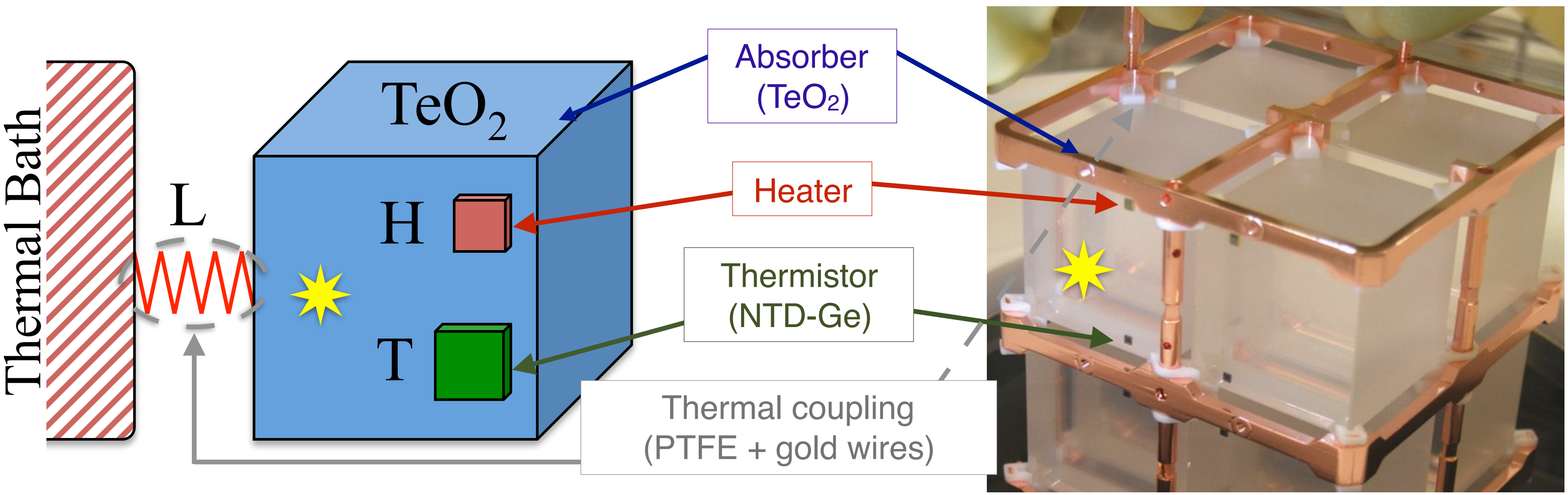
$^{130}Te \rightarrow {}^{130}Xe + 2e^-$ $Q = (2527.518 \pm 0.013)$ keV

single hit, monochromatic event

in about 87% of all cases the two electrons from are fully contained within single source crystal



TeO_2 Bolometers for 0νββ Search



- ^{130}Te is a good 0νββ source
  - high isotopic abundance
  - high Q-value
- TeO_2 bolometer provides excellent energy resolution (0.2% at Q-value)

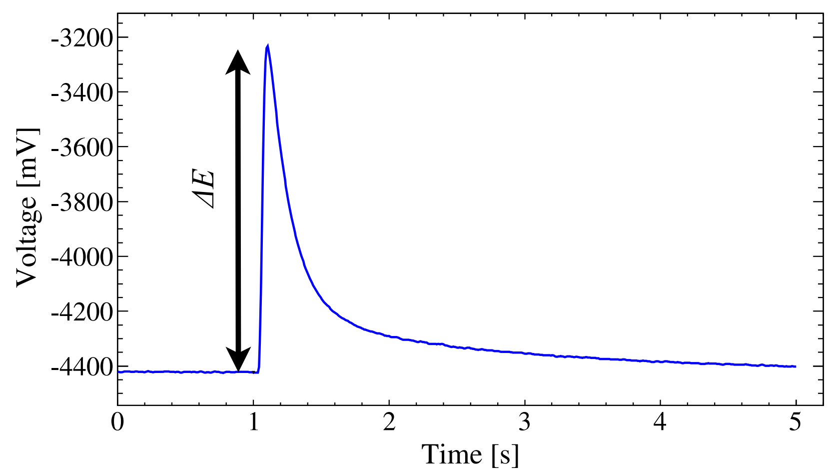
For E = 1 MeV: $\Delta T = E/C \cong 0.1$ mK

Signal size: 1 mV

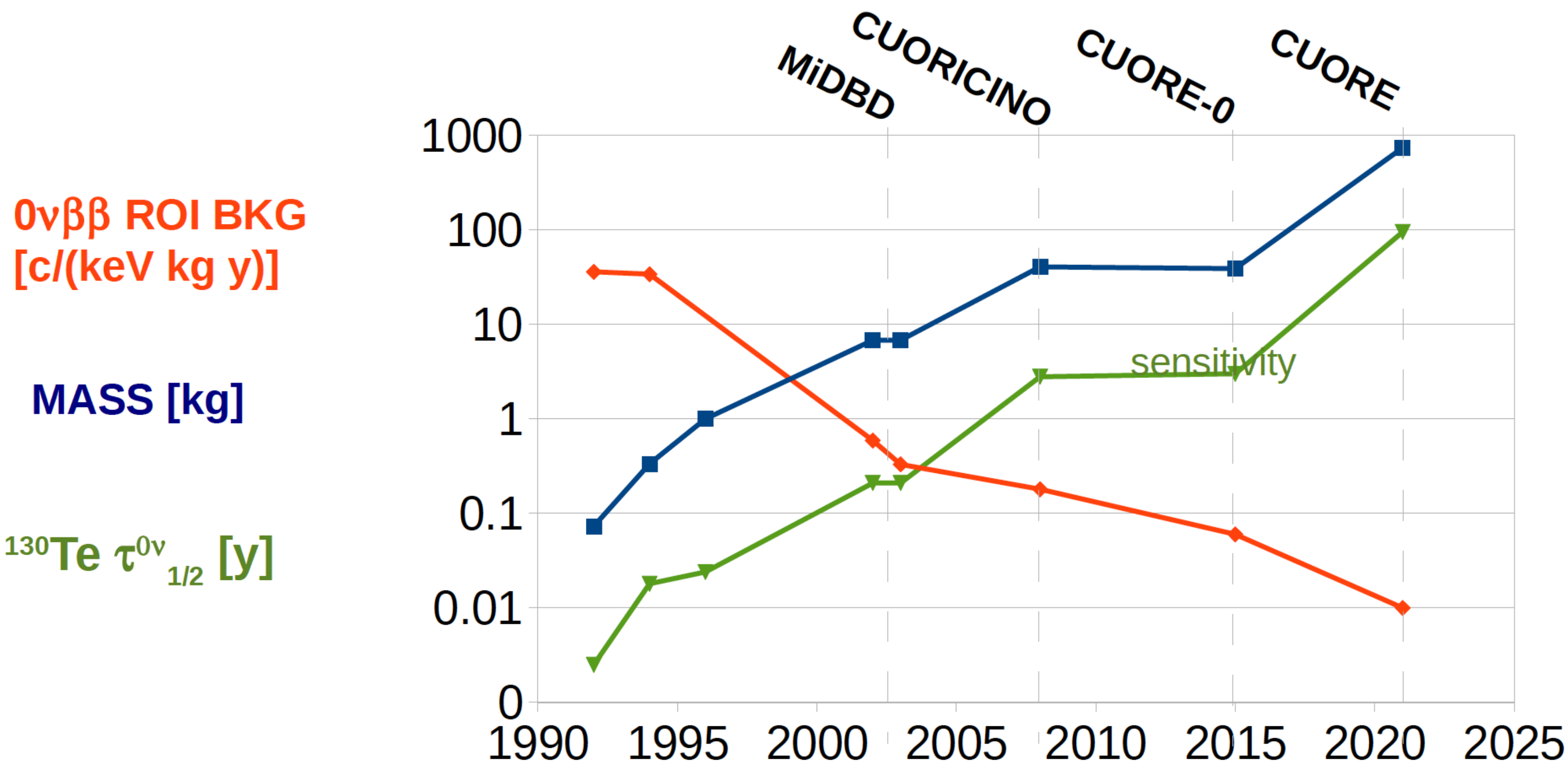
Time constant: $\tau = C/G = 0.5$ s

Energy resolution: ~ 5 keV at 2.5 MeV

$\Delta T_{crystal}$ ~ 10 - 20 μK/MeV

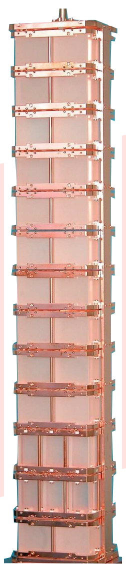


TeO_2 Bolometer - A Success Story



CUORE 0νββ Search

Cuoricino
(2003-2008)



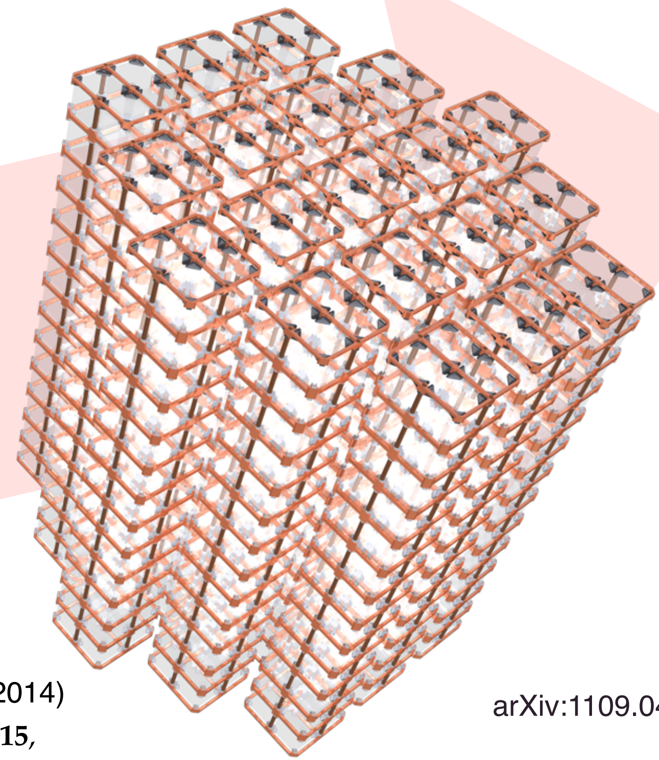
Astropart. Phys. 34 (2011) 822–831

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

CUORE-0
(2013-2015)

EPJC 74, 2956 (2014)
Phys. Rev. Lett. **115**, 102502 (2015)

CUORE
(2016-2020)



arXiv:1109.0494

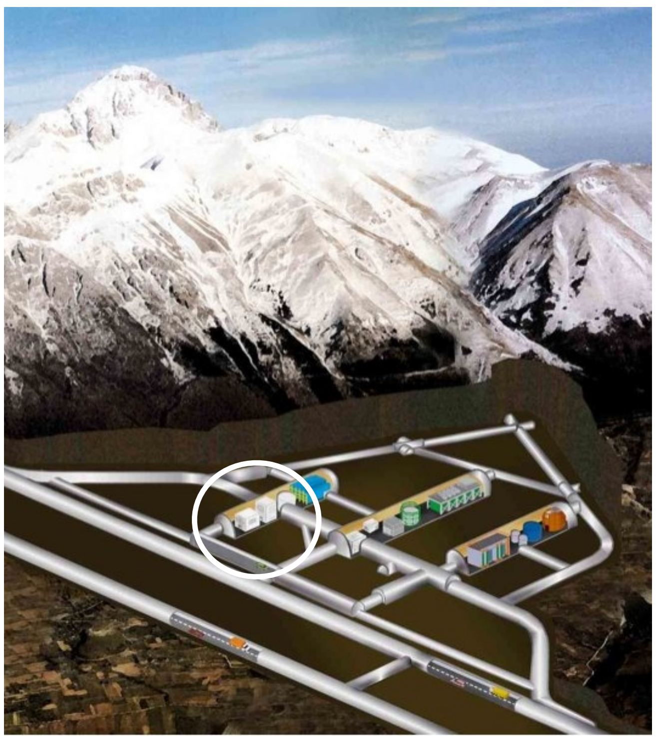
Projected:
$T_{1/2}^{0\nu\beta\beta} > 9.5 \times 10^{25}$ yr (90% C.L.)
$m_{\beta\beta} < 50 - 130$ meV

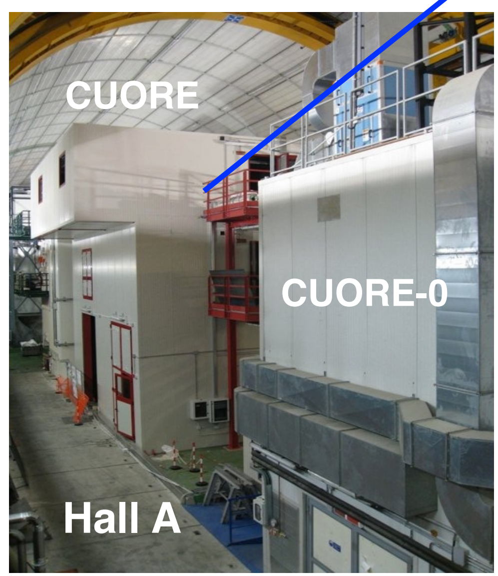
CUORE at LNGS

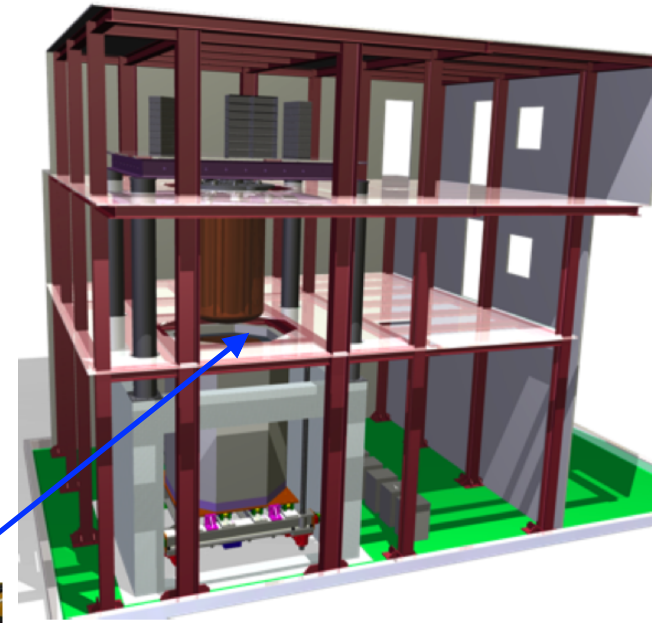
Gran Sasso National Laboratory

Average depth ~ 3600 m.w.e.

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



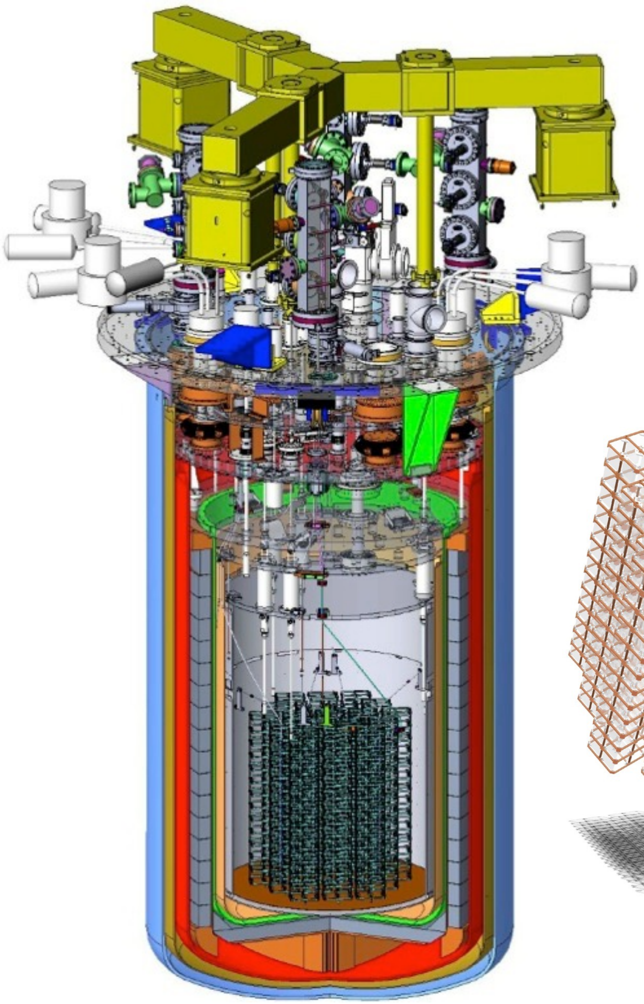




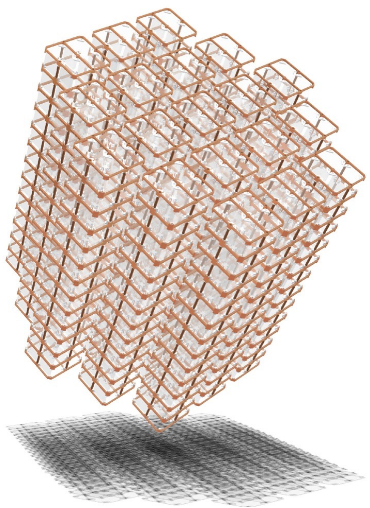
CUORE Hut

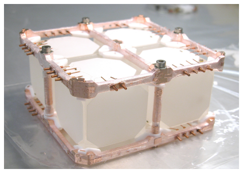
CUORE

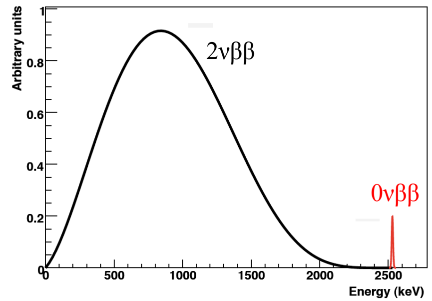
Cryogenic Underground Observatory for Rare Events



- 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

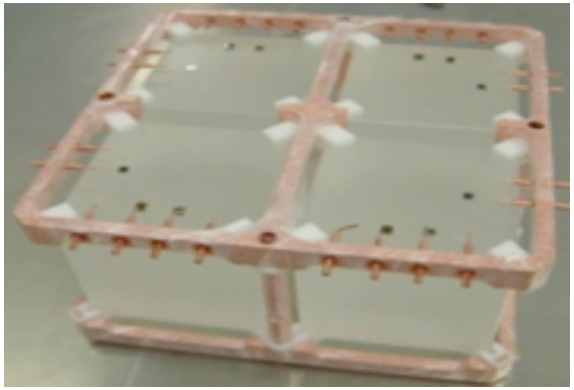






- Excellent energy resolution of bolometers
- New pulse tube dilution refrigerator and cryostat
- Radio-pure material and clean assembly to achieve low background at region of interest (ROI)

CUORE: An ultrapure TeO_2 Crystal Array



Bulk activity 90% C.L. upper limits:

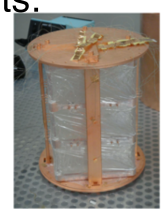
$8.4 \cdot 10^{-7}$ Bq/kg (^{232}Th), $6.7 \cdot 10^{-7}$ Bq/kg (^{238}U), $3.3 \cdot 10^{-6}$ Bq/kg (^{210}Po)

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)

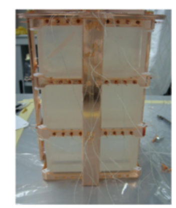
- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals

- Developed ultra-cleaning process for all Cu components:
  - Tumbling
  - Electropolishing
  - Chemical etching
  - Magnetron plasma etching

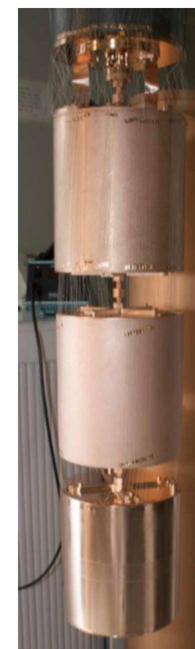


T1

T2



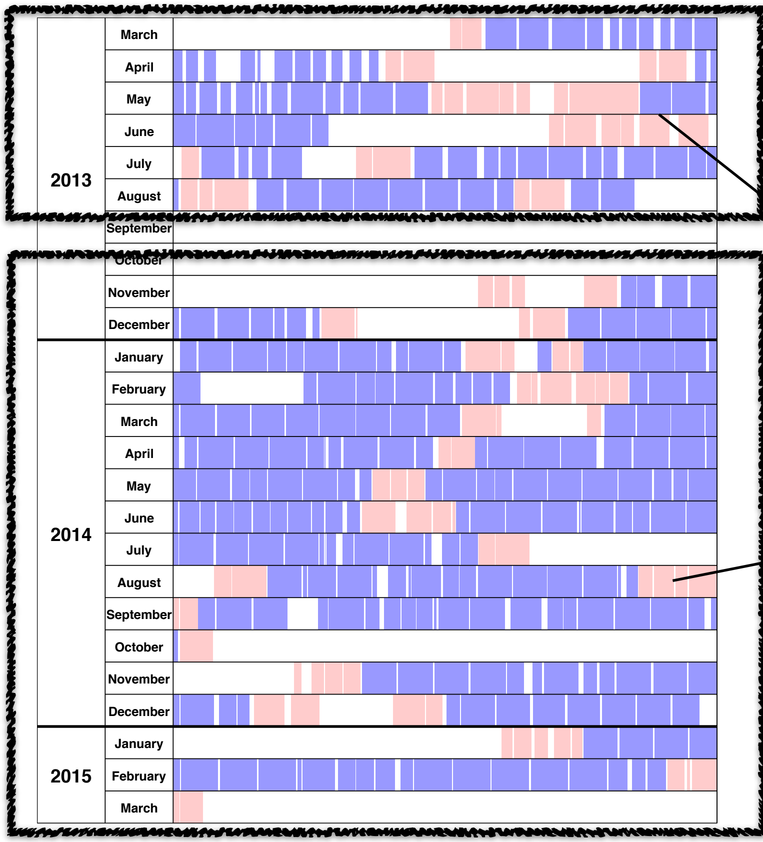
T3

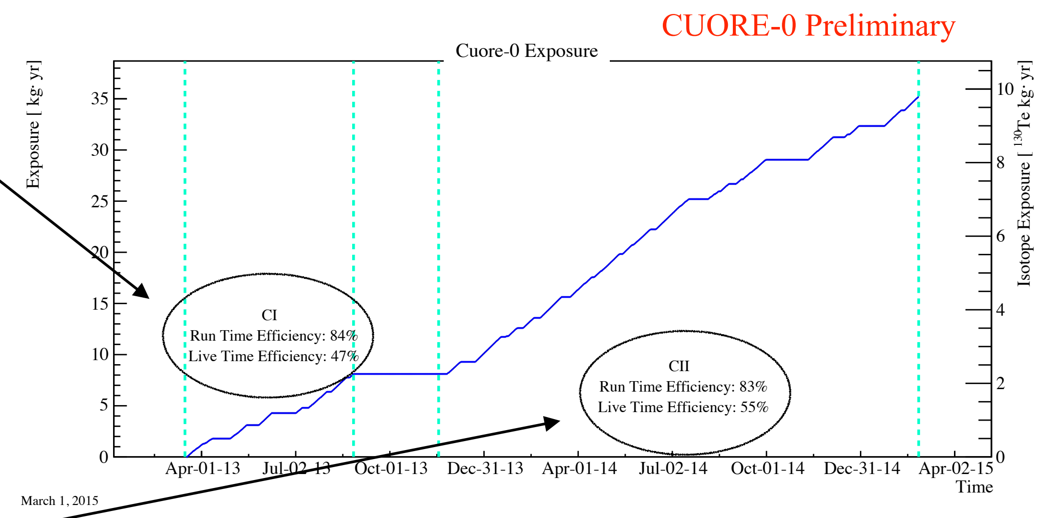


- Benchmarked in dedicated bolometer run at LNGS
  - Residual ^{232}Th / ^{238}U surface contamination of Cu: $< 7 \cdot 10^{-8}$ Bq/cm^2
- Validated by CUORE-0

- All parts stored underground, under nitrogen after cleaning

Data Run: 2013 – 2015



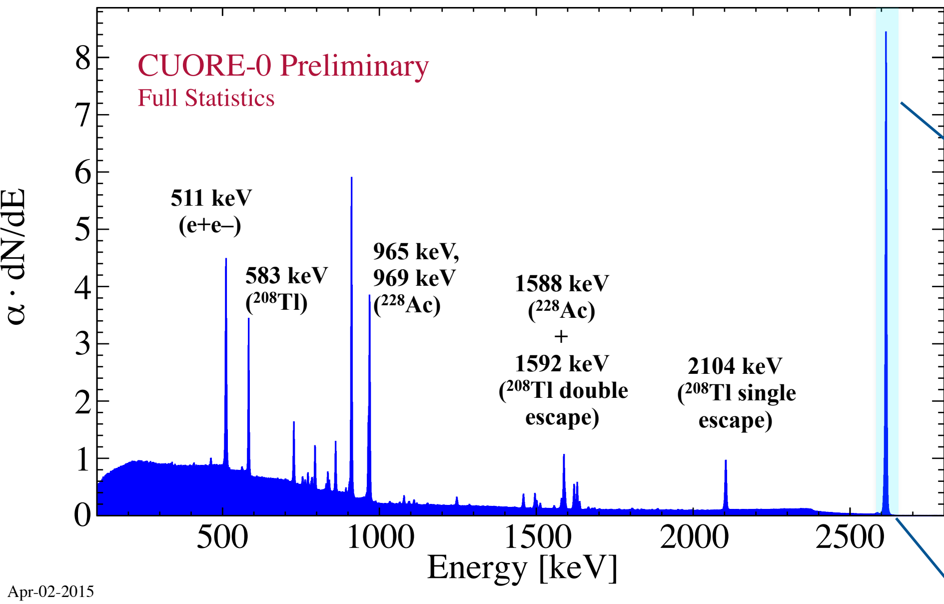


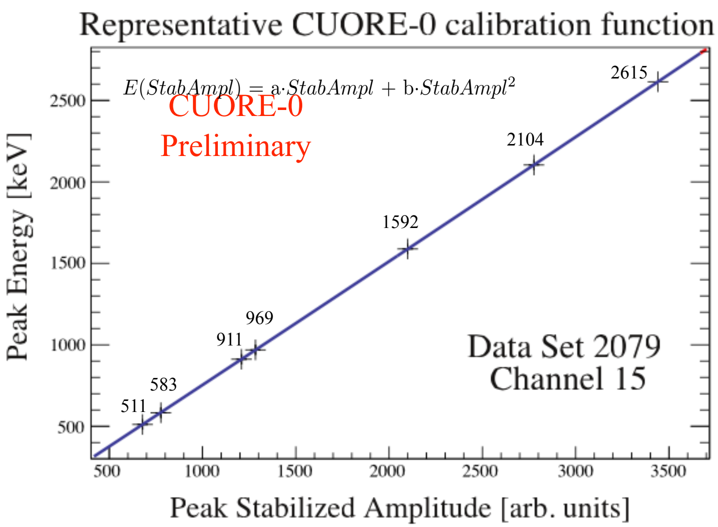
- March 2013 – March 2015
- Cryogenic maintenance between campaigns
- 35.2 kg-yr of $^{nat}TeO_2$
- 9.8 kg-yr of ^{130}Te

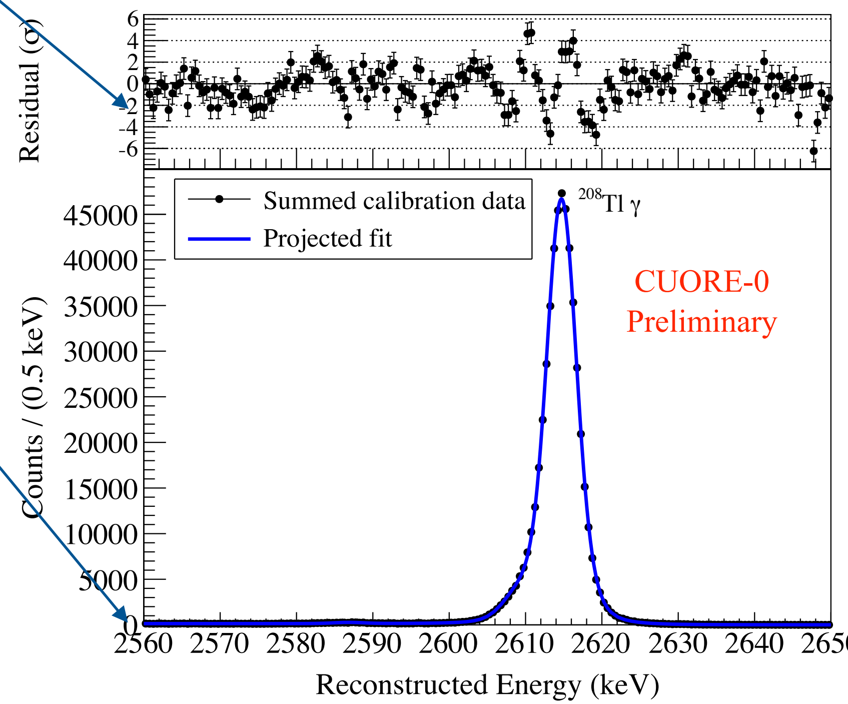
Physics data

Calibration data

Calibration

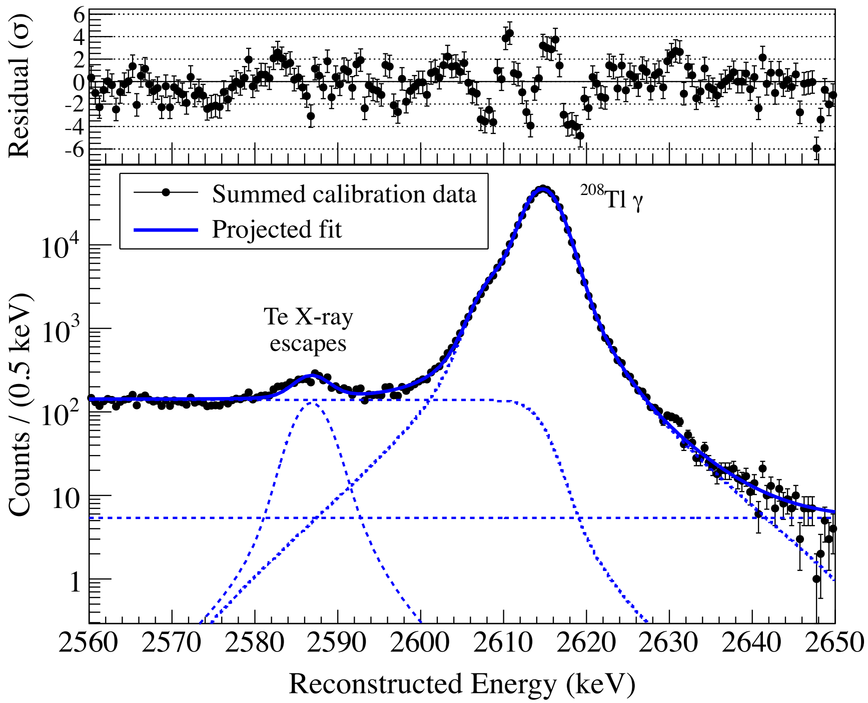




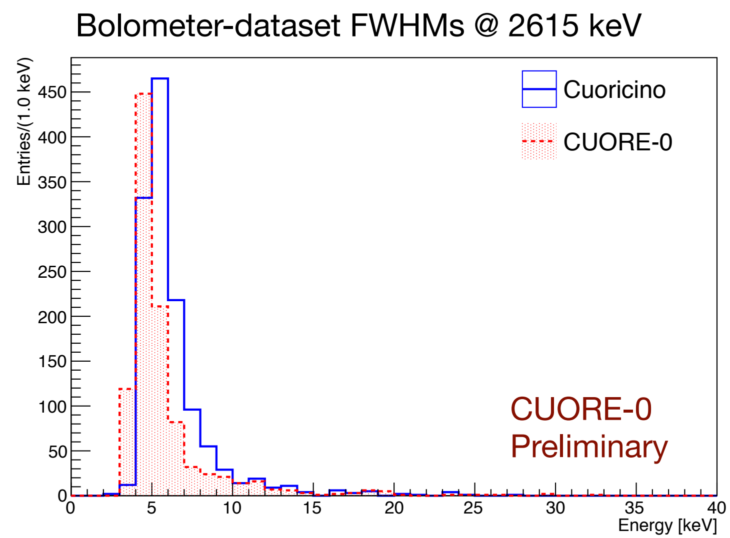


Energy Resolution

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



Phys. Rev. Lett. **115**, 102502 (2015)



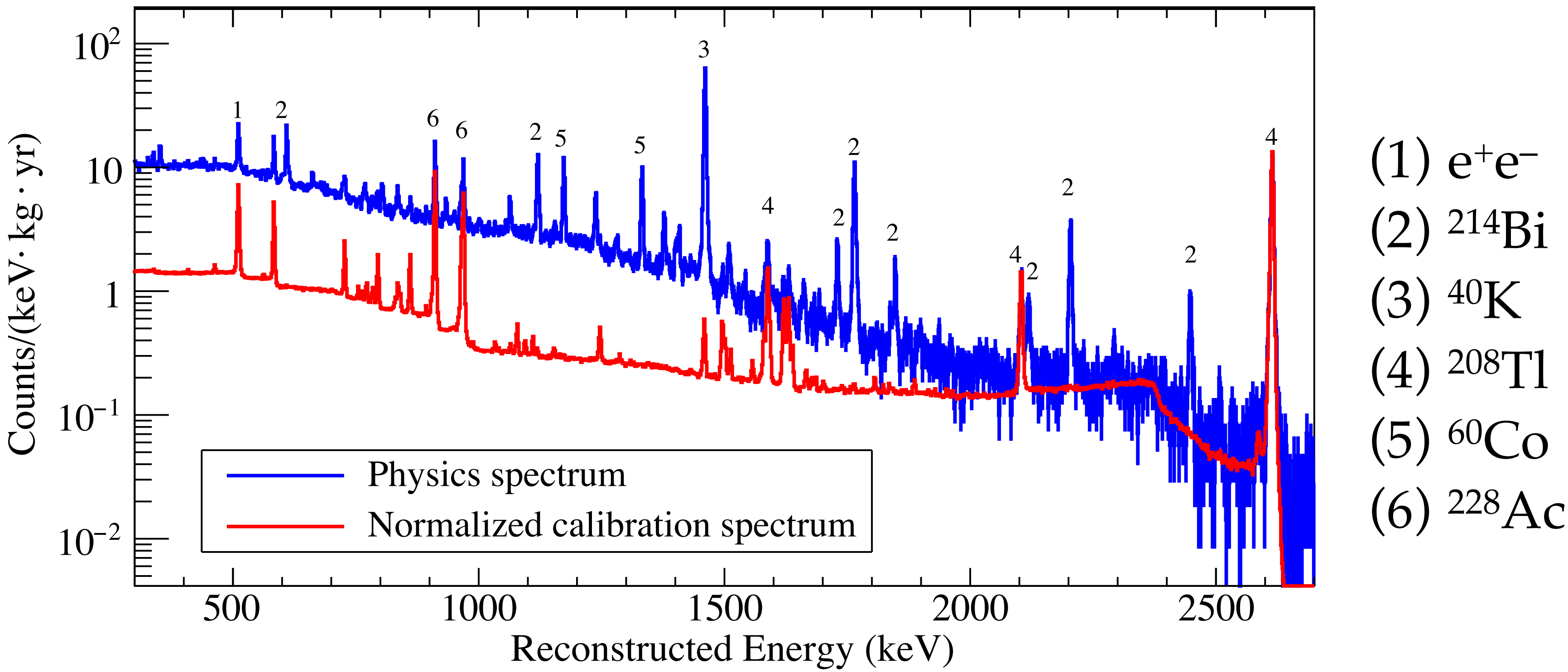
Weight FWHMs by corresponding exposure

	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.

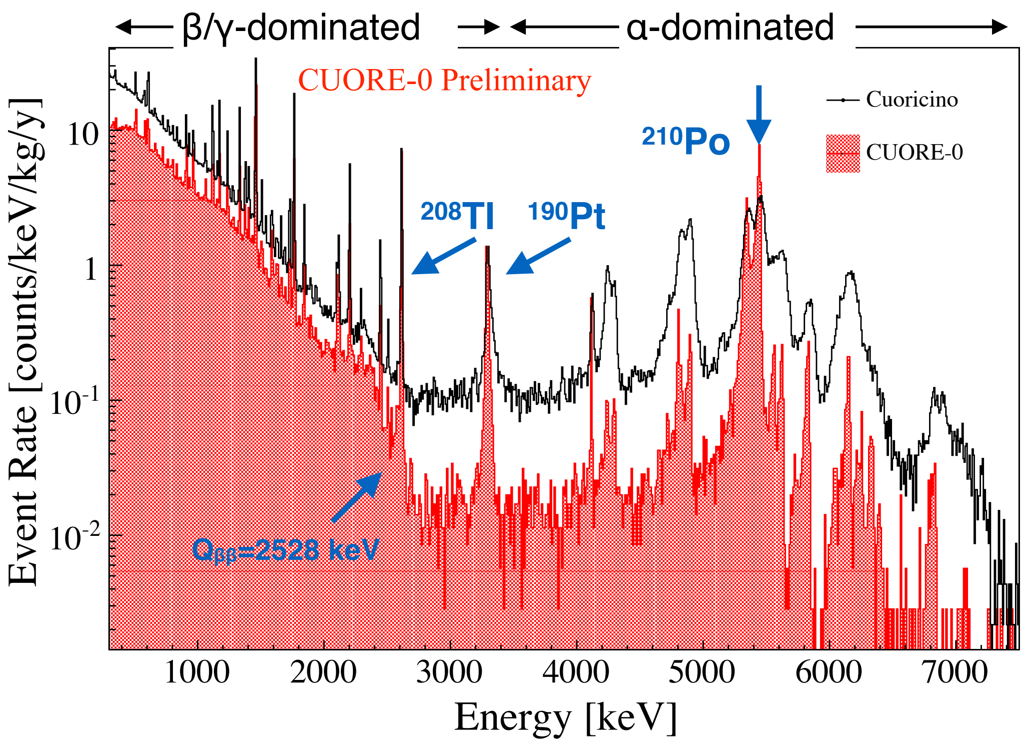
CUORE-0 Physics Spectrum

Phys. Rev. Lett. **115**, 102502 (2015)



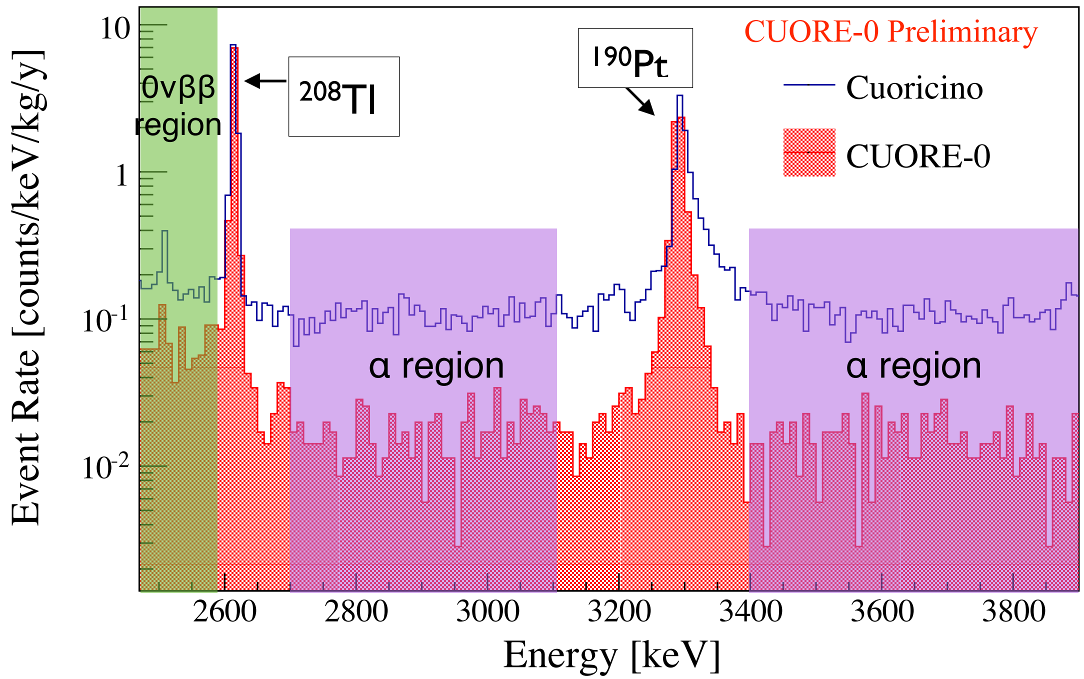
- Calibration performance is tested by measuring residuals (i.e., reconstructed energy – true energy) in the physics data
- The measured single-gamma energy scale uncertainty is 0.1 keV

CUORE-0 Background Measurement



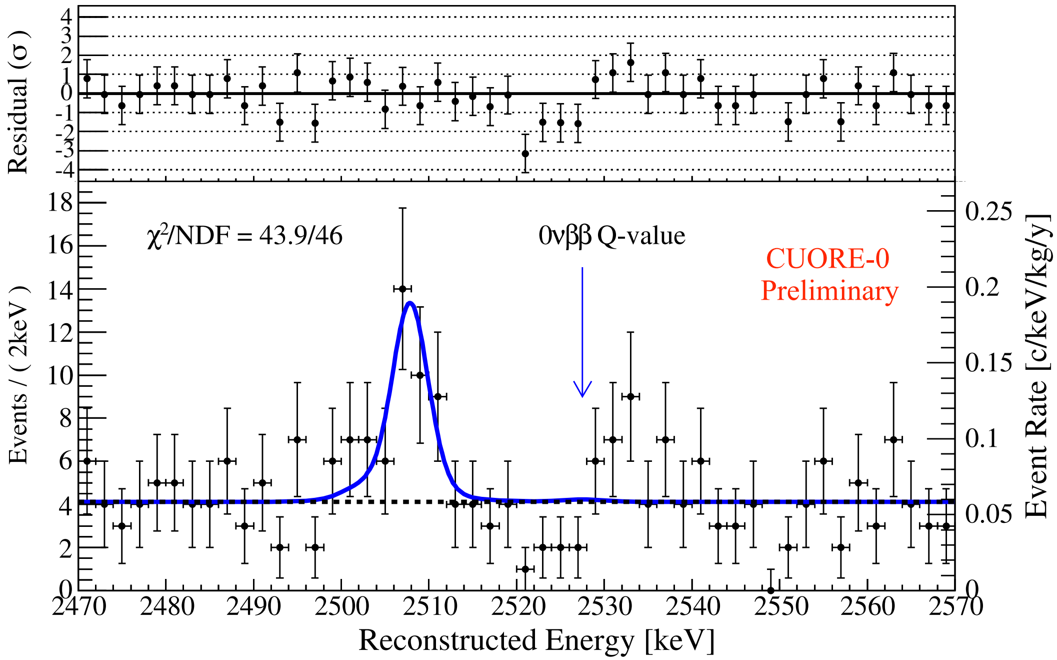
- γ background (from ^{232}Th) was not reduced since the cryostat remained the same.
- γ background (from ^{238}U chain) was reduced by a factor of 2.5 due to better radon control.
- α background from copper surface and crystal surface was reduced by a factor of 6.5 thanks to the new detector surface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

Background Rate & Reduction



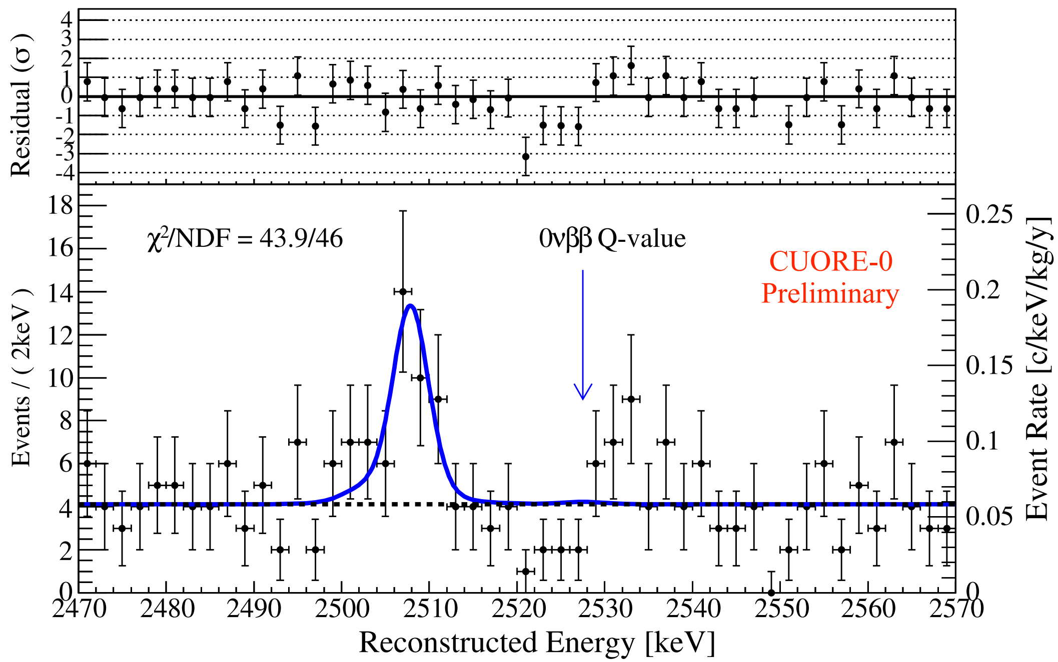
	Background rate [counts/keV/kg/y]		signal eff. [%] (detector+cuts)
	0νββ region	α region (excl. peak)	
Cuoricino	0.169 ± 0.006	0.110 ± 0.001	82.8±1.1
CUORE-0	0.058 ± 0.011	**0.016 ± 0.001**	81.3±0.6

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

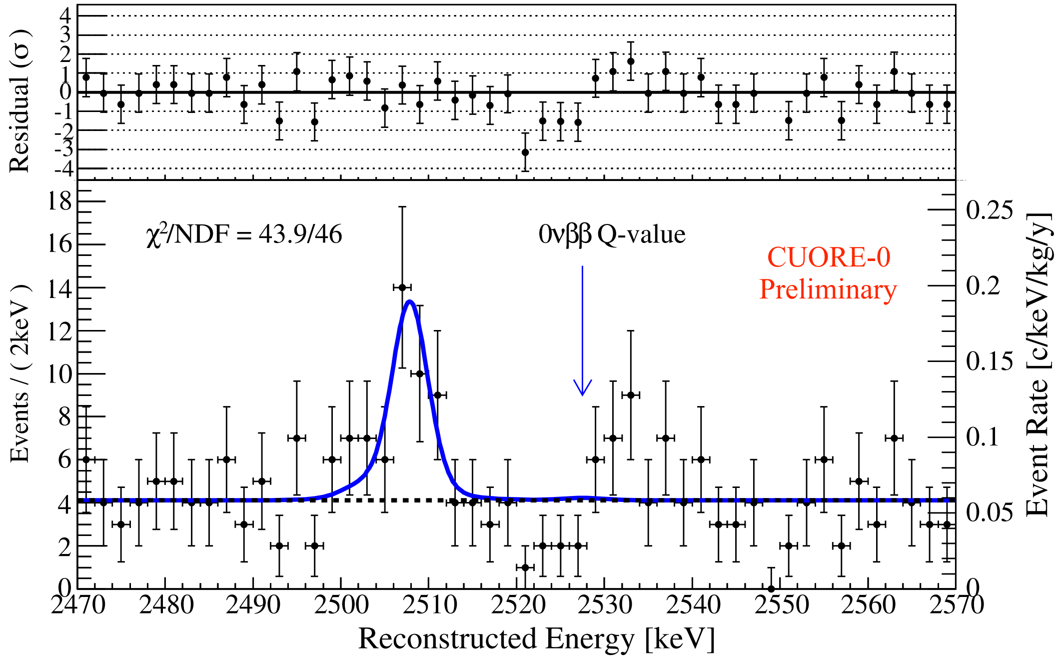
Unblinded Spectrum & Fit



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



No evidence for $0\nu\beta\beta$ of ^{130}Te found

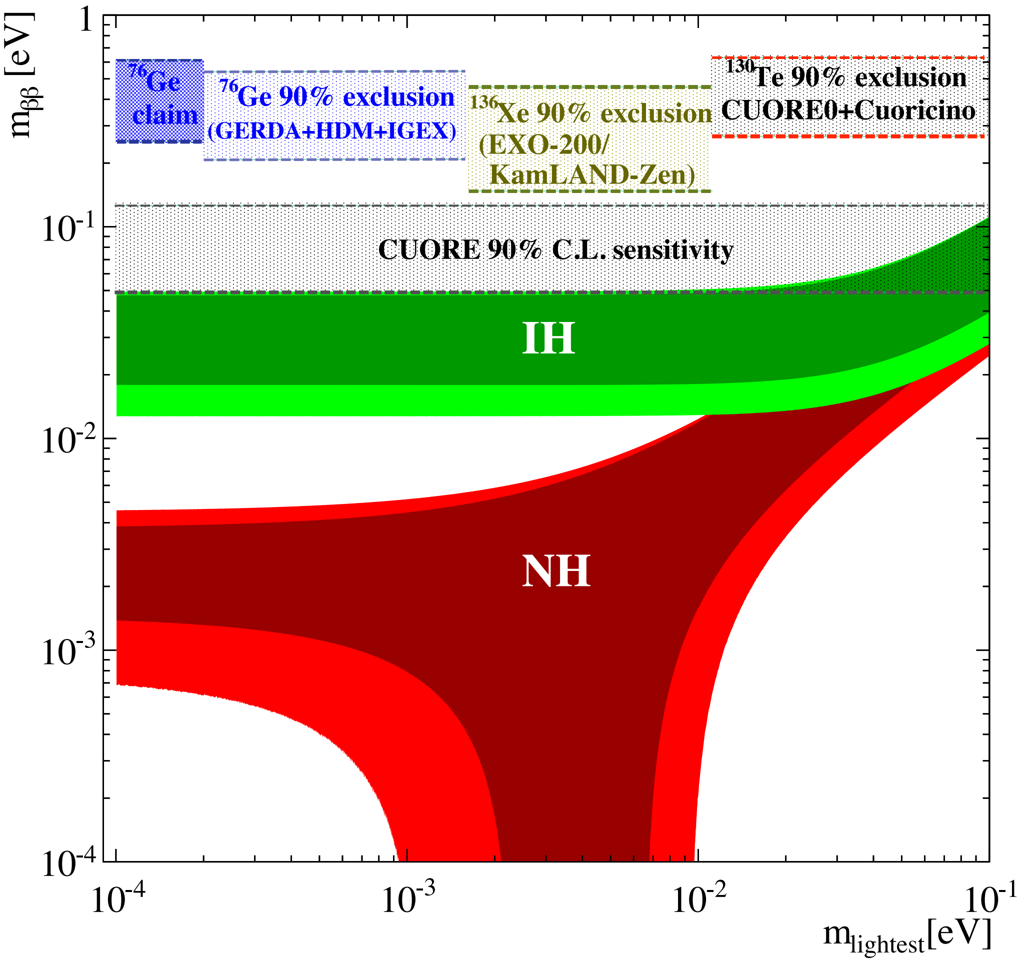
$$\Gamma^{0\nu\beta\beta}(^{130}\mathrm{Te}) < 0.25 \times 10^{-24}\ \mathrm{yr}^{-1}\ \text{(90\% C.L., statistics only)}$$

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

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

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

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

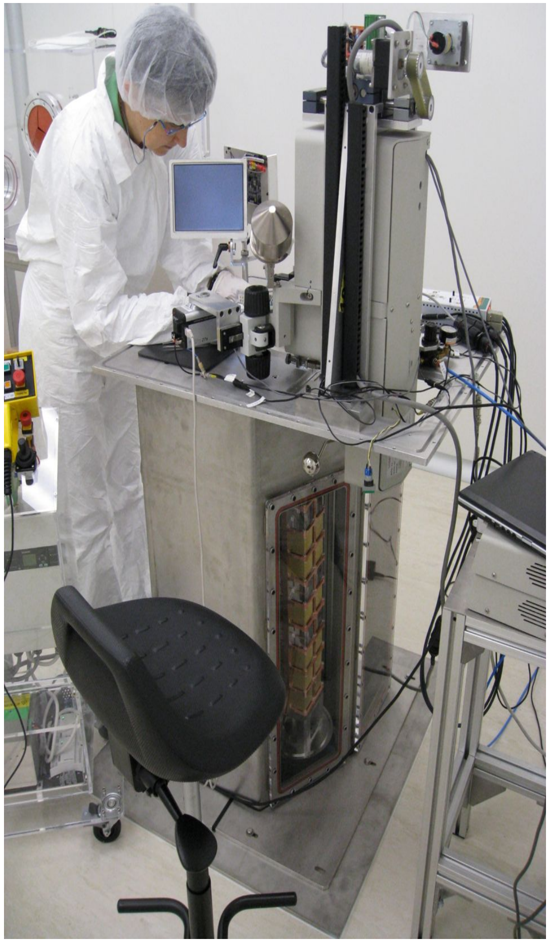
$\langle m_{\beta\beta} \rangle$ < 270 – 760 meV

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))

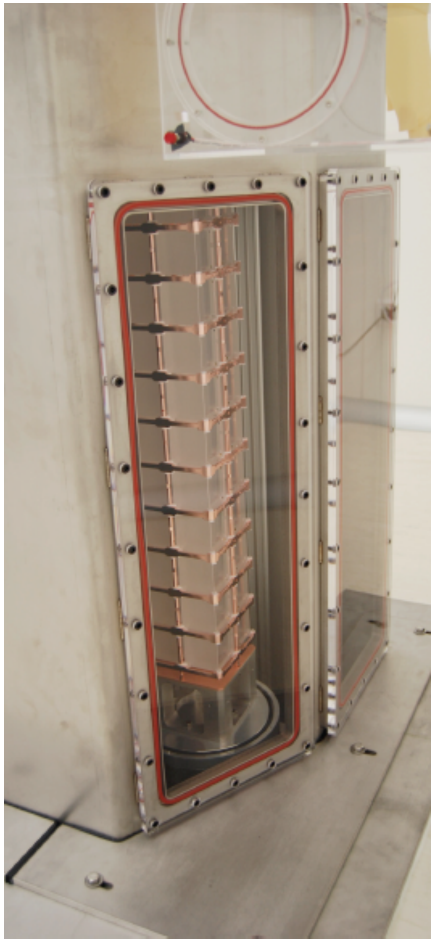
CUORE Detector Assembly

Mechanical Detector Assembly

Universal Working Plane

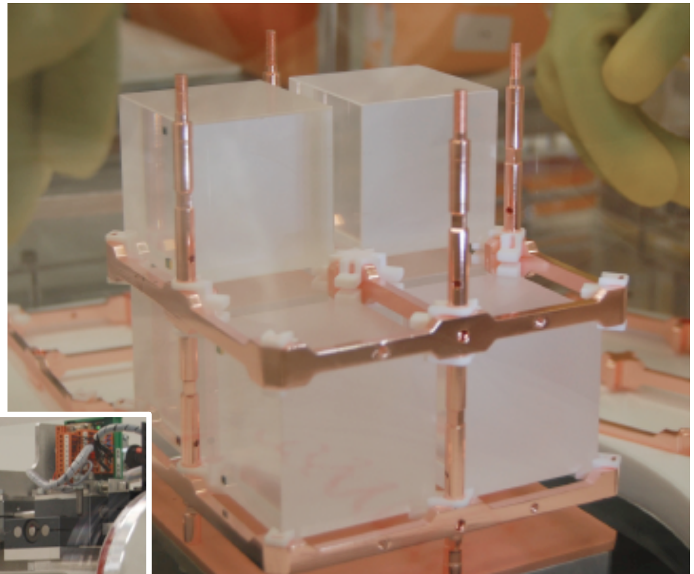


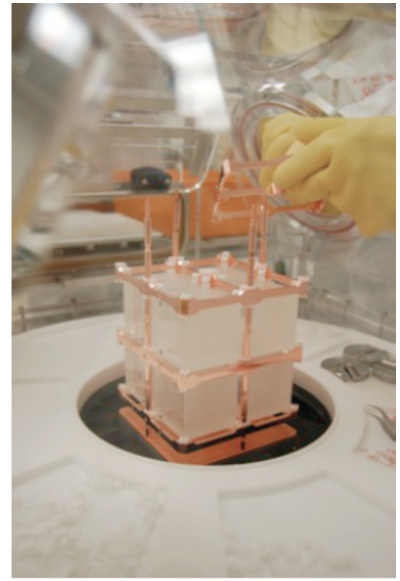
Tower garage

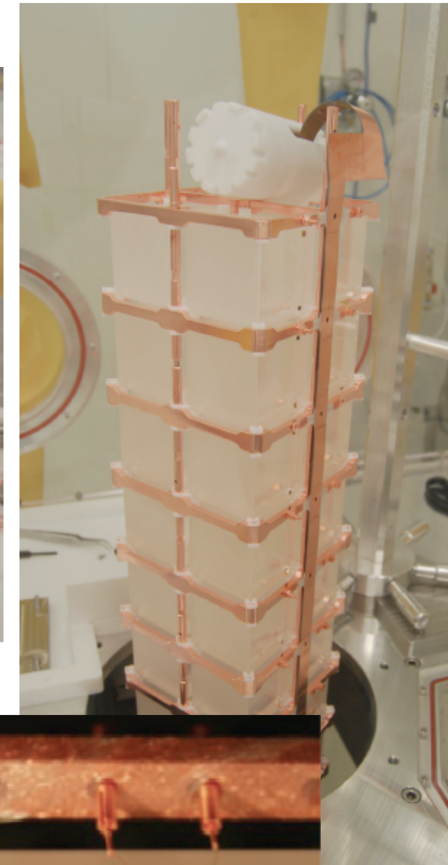


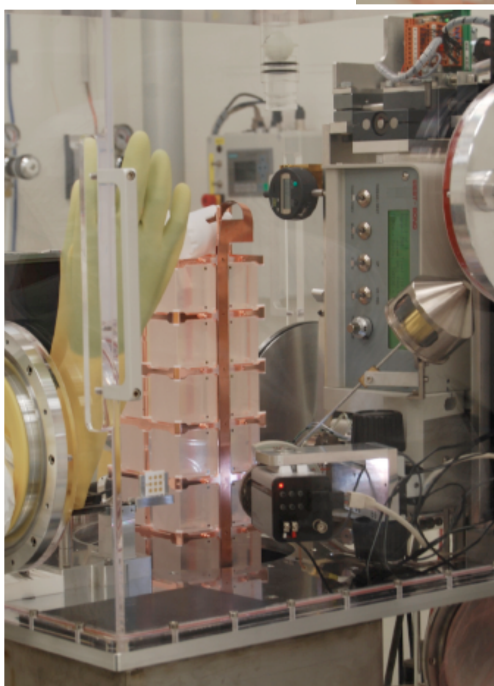
CUORE Detector Assembly

Tower Assembly

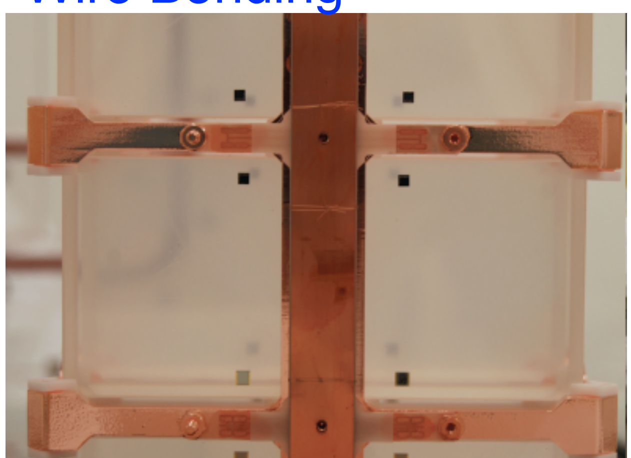


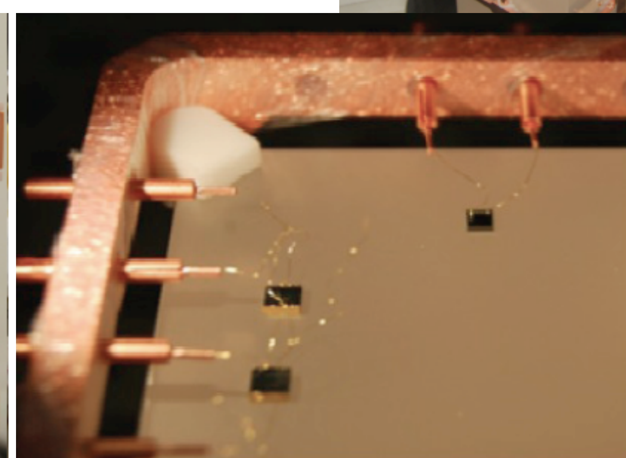






Wire Bonding

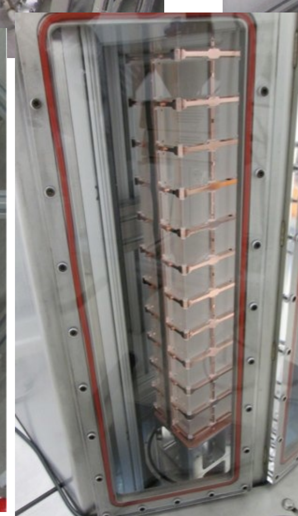
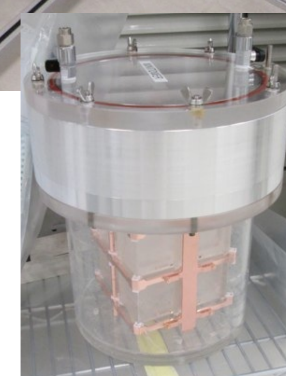




CUORE Detector Towers

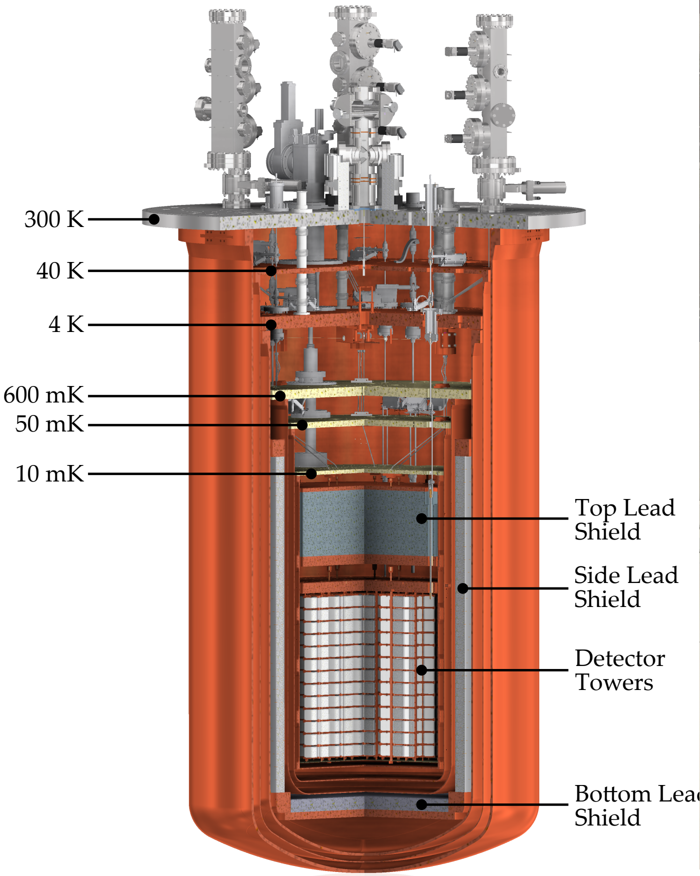
Assembly of all 19 towers is complete



CUORE Cryogenic Systems & Commissioning

Phased Commissioning

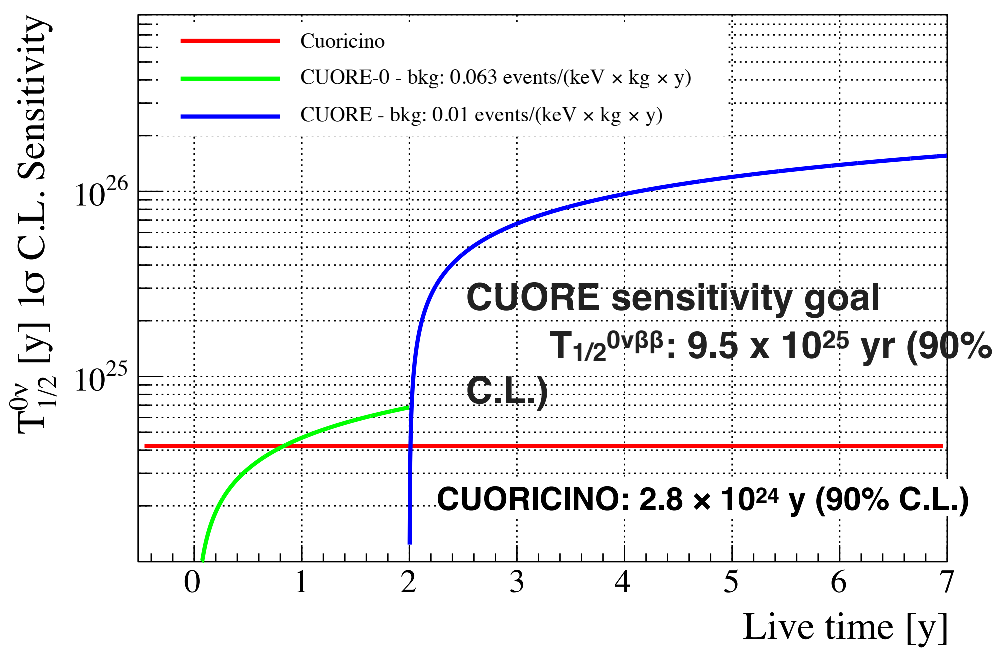


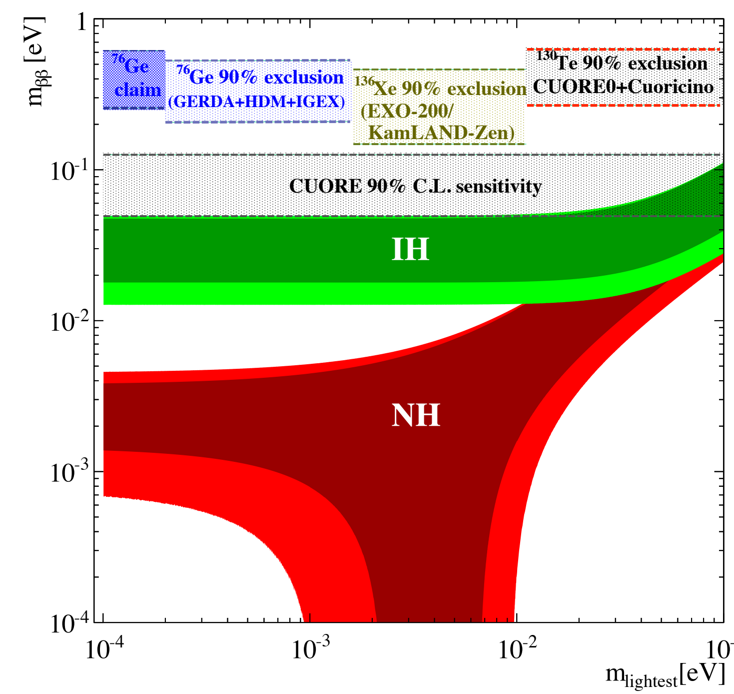
6mK stable base temperature achieved in October 2014

shielding tested during recent cooldown

CUORE Sensitivity

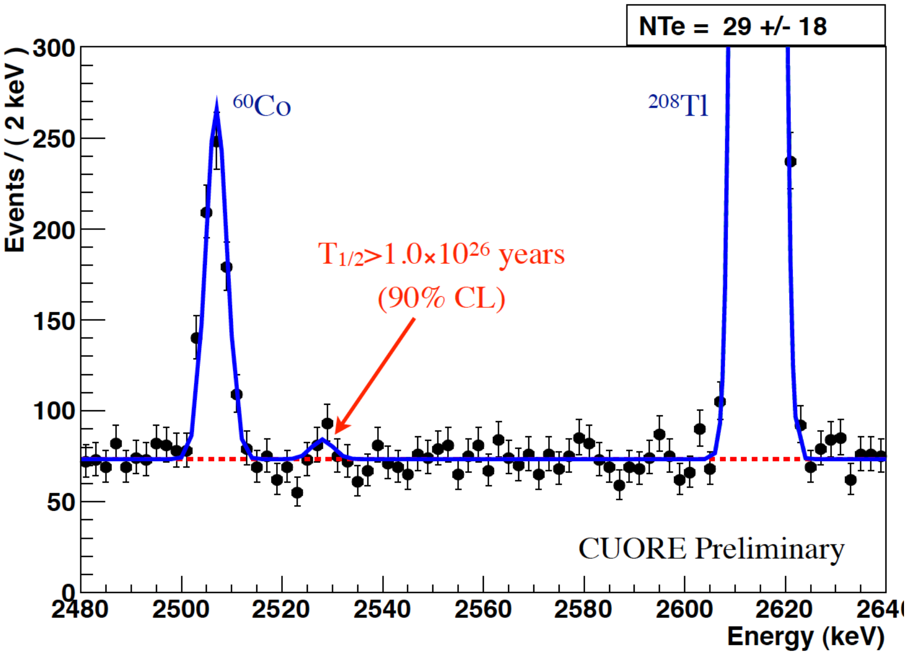
- CUORE sensitivity goal $\mathbf{T_{1/2}^{0\nu\beta\beta} > 9.5 \times 10^{25}}$ **yr** @ 90% C.L.
- Effective Majorana mass 51 - 133 meV @ 90% C.L.
  - Assumptions: 5 keV FWHM ROI resolution (δE), background rate (b) of 0.01 counts/(keV·kg·yr), 5 years of live time.

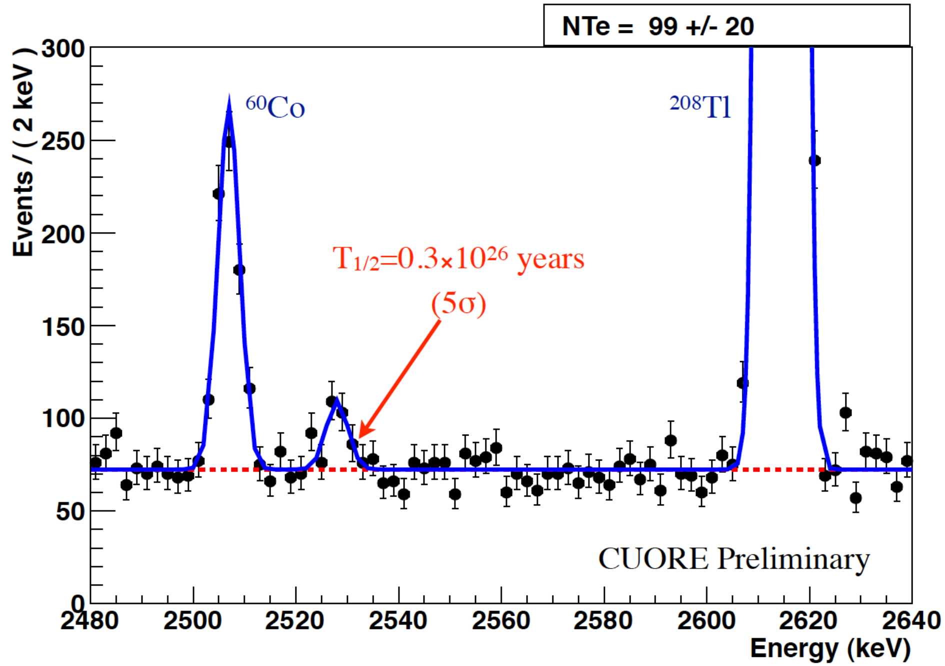




arXiv:1109.0494

CUORE - What a signal might look like…





5 years lifetime of CUORE, assuming a background index of 0.01 counts/kg/keV/y,

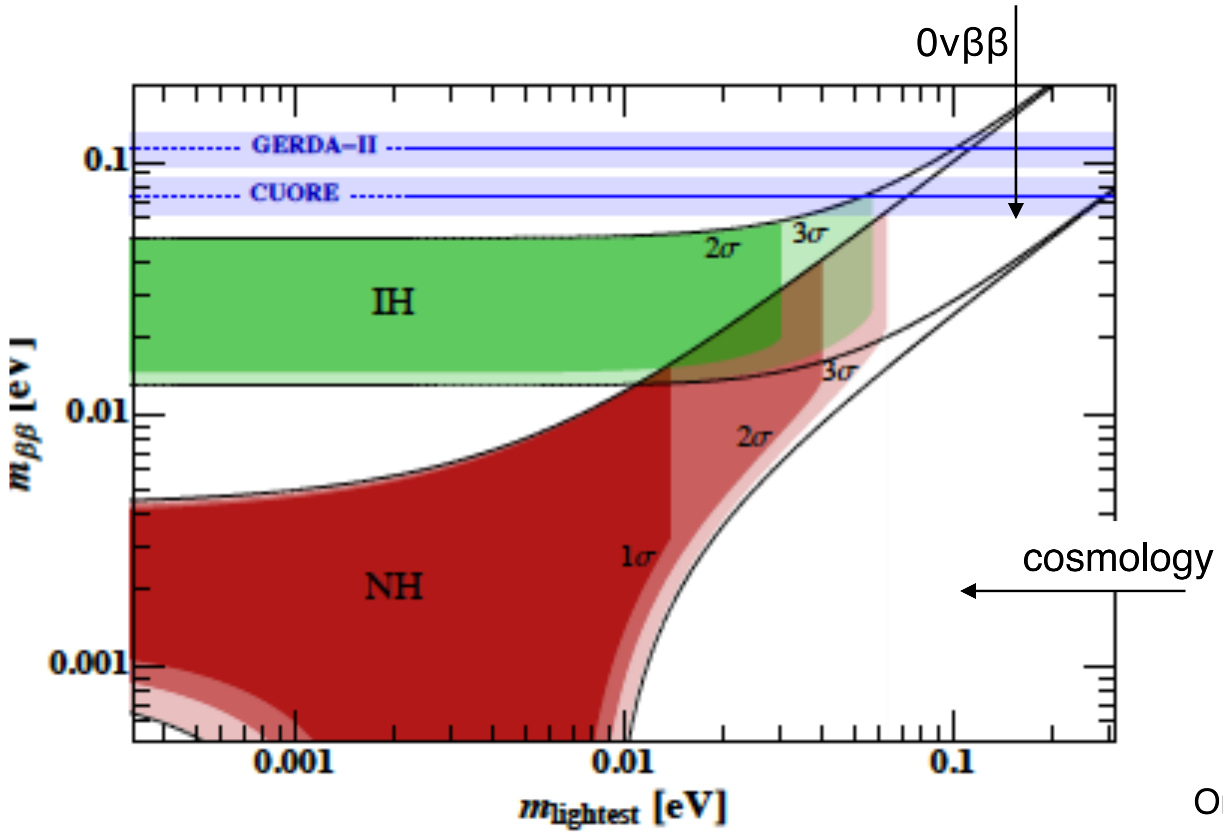
spectrum is fitted with a flat background plus 3 peaks (^{60}Co, 0νββ and ^{208}Tl).

Double Beta Decay and Cosmology

Reach of cosmology and current experiments

Palanque-Delabrouille
JCAP 1502, 045 (2015)

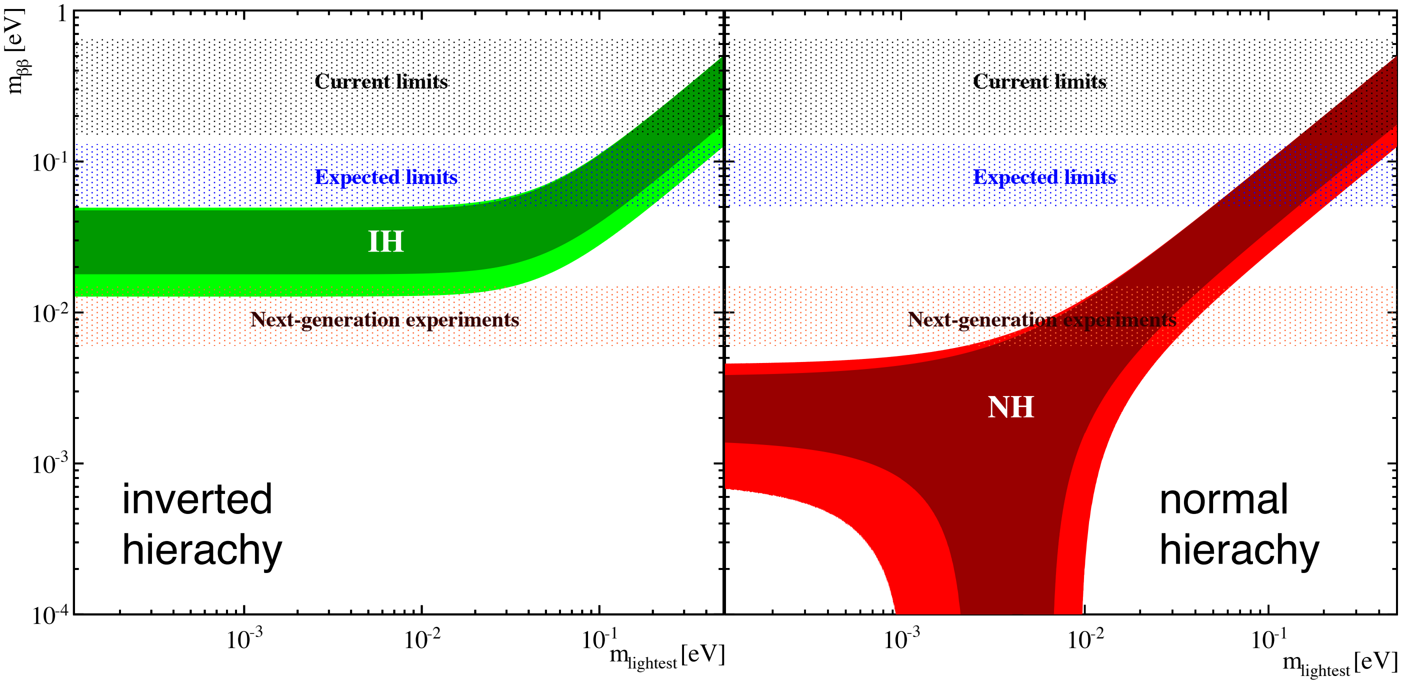
$\Sigma_\nu < 84$ meV 1σ CL



Oro et al
arXiv:1505.02722

Next Frontier - Future Searches for 0νββ

Towards Exploring the Inverted Hierarchy



$T_{1/2} \sim 10^{24}$ yrs
~1 eV
kg scale

$T_{1/2} \sim 10^{25}$ - 10^{26} yrs
~100 meV
30-200kg scale

$T_{1/2} \sim 10^{27}$ - 10^{28} yrs
~15 meV
ton scale (phased)

Ton scale experiments will make discovery if
- spectrum has inverted ordering
- $m_{lightest} > 50$ meV (irrespective of ordering)

improvement of x100 over current results

significant discovery potential

Towards a Next-Generation Experiment

Goals/Requirements

- Expect signals of **1 count/tonne-year for half-lives of 10^{27} years,** or **$\langle m_{\beta\beta} \rangle \sim$ 15 meV.**
- For discovery aim for S:B of better than 1:1 in region of interest
- Region of interest can be single dimension (e.g. energy) or multi-dimensional (e.g. energy+fiducial)

Next Steps

International collaborations are building on current efforts using multiple isotopes:

- **^{76}Ge**: large Ge experiment, HPGE crystals, ton-scale
- **^{82}Se:** SuperNEMO, tracking and calorimeter, 100kg scale
- **^{136}Xe:**
  - nEXO, liquid TPC, 5 tonnes
  - NEXT/BEXT, high pressure gas TPC, tonne-scale
  - KamLAND-Zen, scintillator
- **^{130}Te:**
  - CUPID, bolometers+scintillation/Cherenkov light
  - SNO+ phase II, scintillator
- other efforts worldwide
- staged approach possible, some experiments pursue isotopic enrichment

R&D for Future Bolometric 0νββ Searches

Goals fo future experiment: Expect signals of **1 count/tonne-year for half-lives of 10^{27} years,** or **$<m_{\beta\beta}>$~ 15 meV.** For discovery aim for S:B of better than 1:1 in region of interest

Increase mass enrich in ^{130}Te

Reduce background

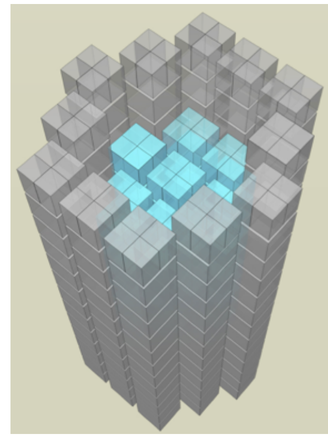
via particle ID

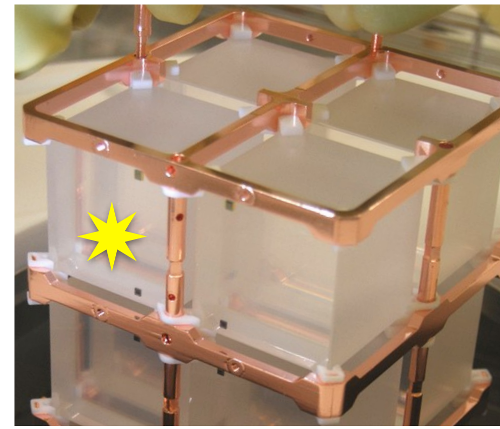
cleaner detectors,

tag backgrounds,

active veto

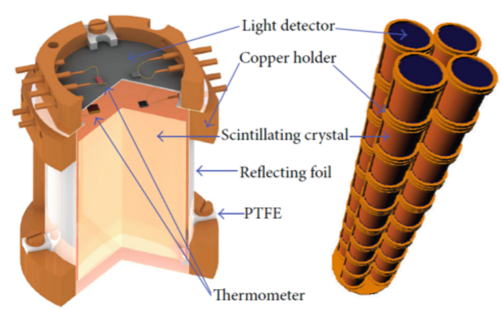
Explore other/multiple isotopes

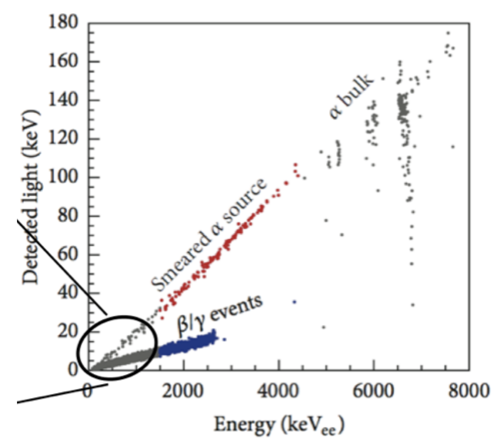




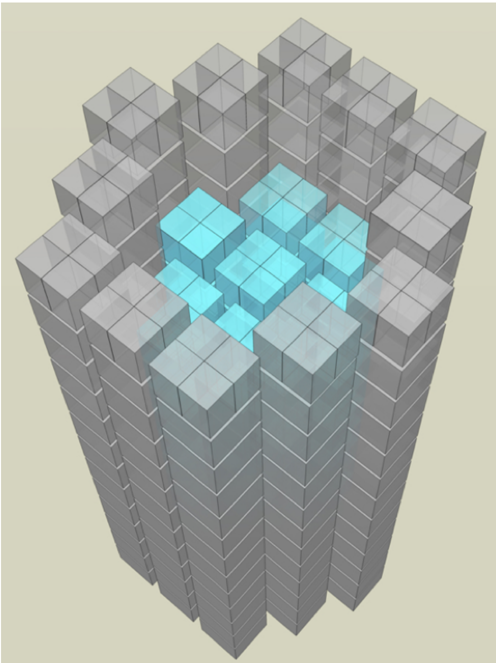
Bolometer R&D:

- CALDER
- Cherenkov/TeO_2
- LUCIFER
- LUMINEU





Beyond CUORE: ^{130}Te Enrichment

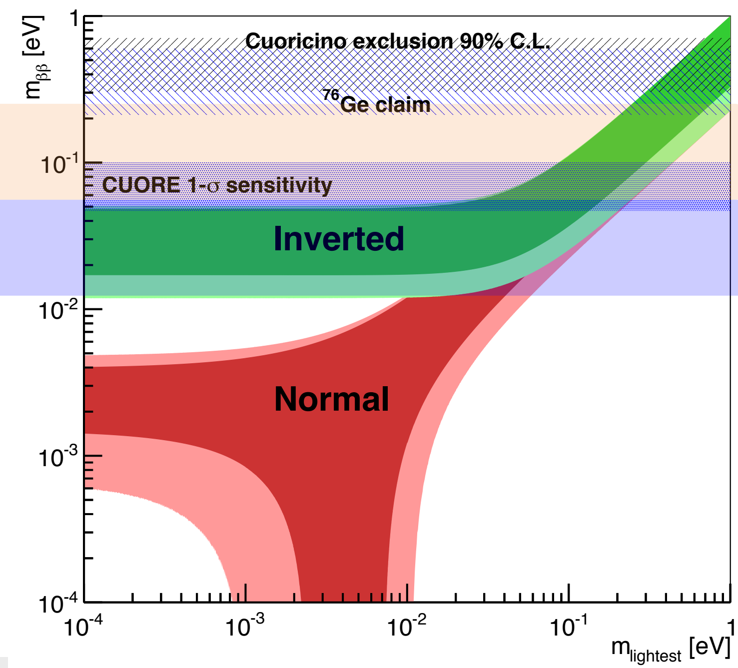


Enrichment

- **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 $100/g
- 500 gram of enriched ^{130}Te metal is sent to SICCAS for enriched crystal growth.

Current gen.

goal of next gen. experiments



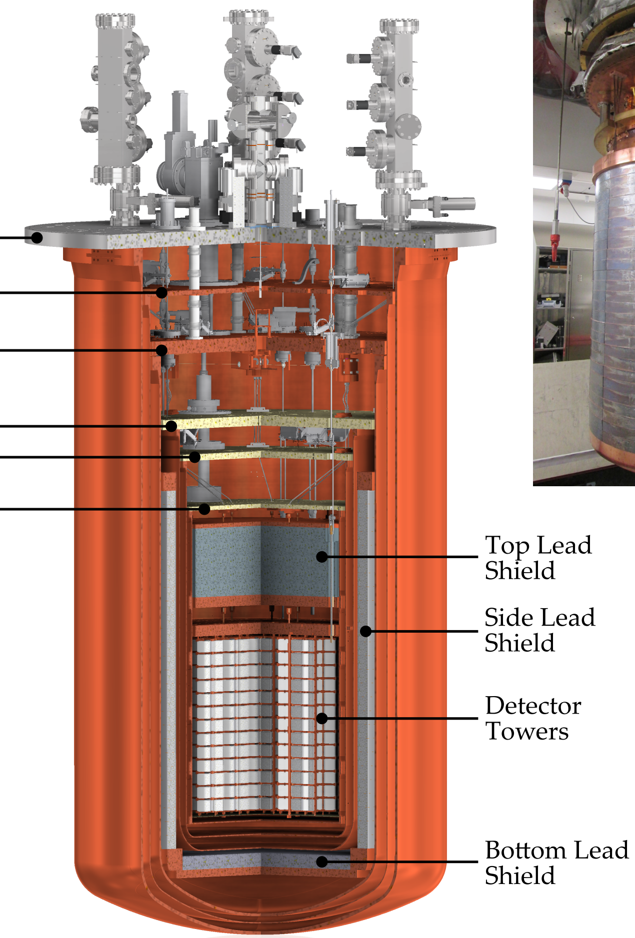
$$m_{\beta\beta} \sim \frac{m_e}{\sqrt{F_N \cdot \varepsilon \cdot \eta \sqrt{\frac{M \cdot t}{b \cdot \delta E}}}}$$

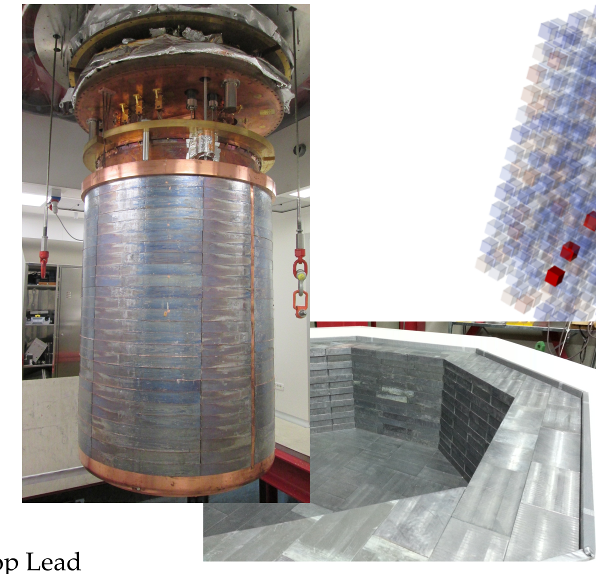
F_N	Nuclear figure of merit: nuclear matrix element x phase		
ε	Detection efficiency	t	Live time [year]
η	Isotopic abundance	b	Background [< 0.01/kg/keV/
M	Detector total mass [kg]	δE	Energy resolution [keV]

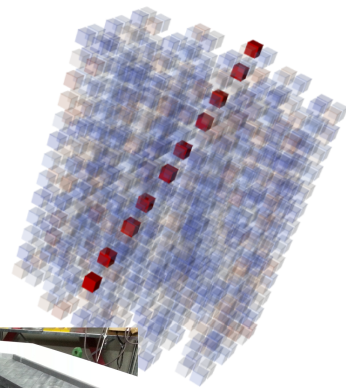
Cosmogenics Background in CUORE

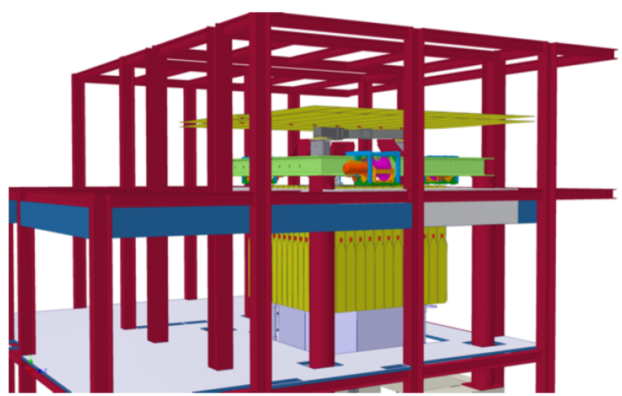
Goal: measure ROI backgrounds in situ in coincidence with CUORE

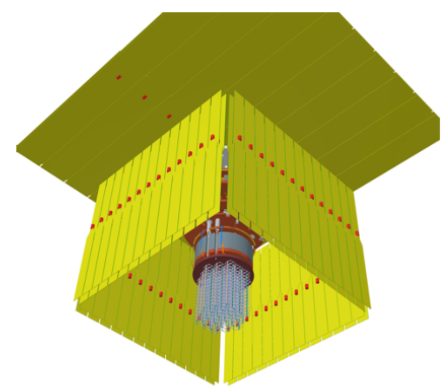
- in particular neutron spallation from external Pb shields



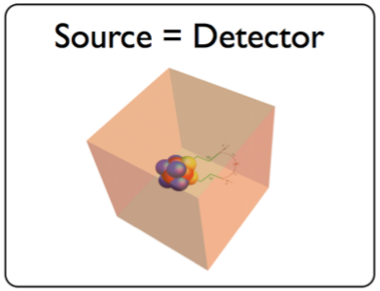


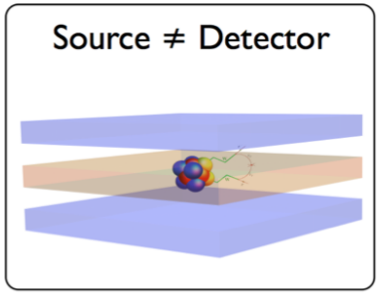




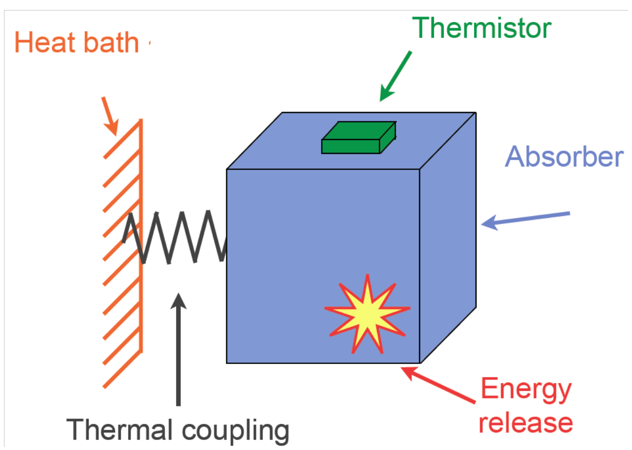


Beyond CUORE: Different Isotopes

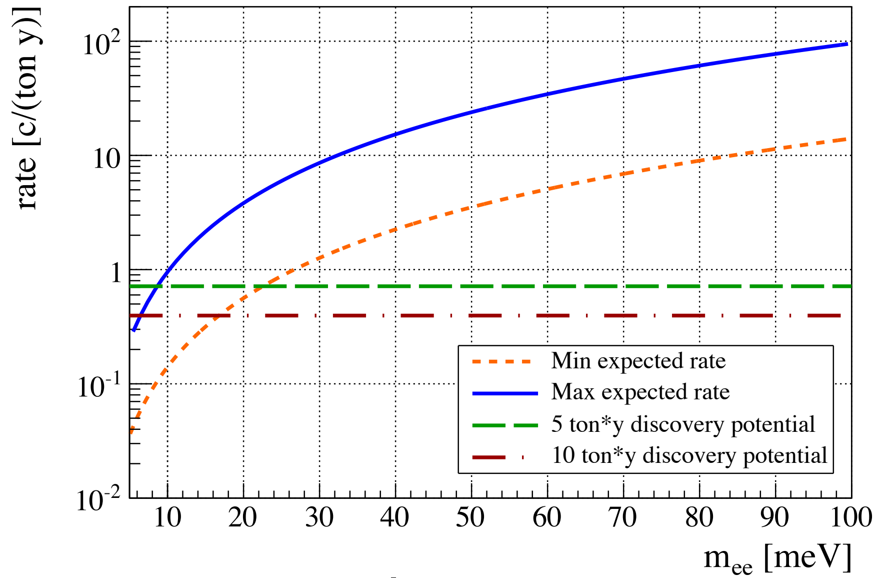




- Bolometer utilizes only the low heat capacity of dielectric crystal.
- High efficiency and flexibility in candidate isotope choices.
- Especially valuable for discovery confirmations in different isotopes.



$^{130}TeO_2$ 5σ discovery potential

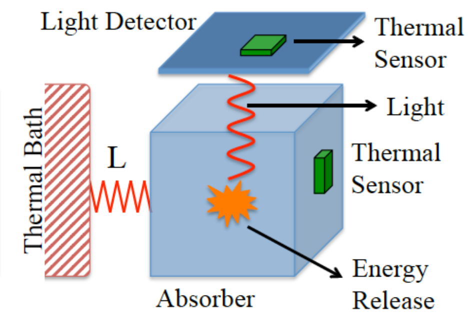


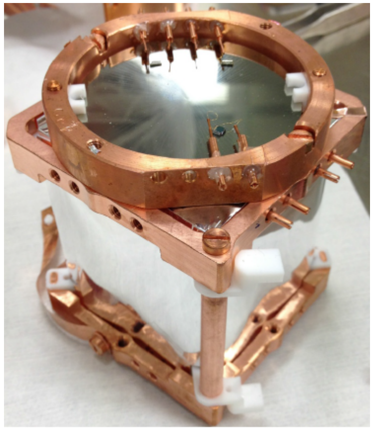
90% sensitivity limits

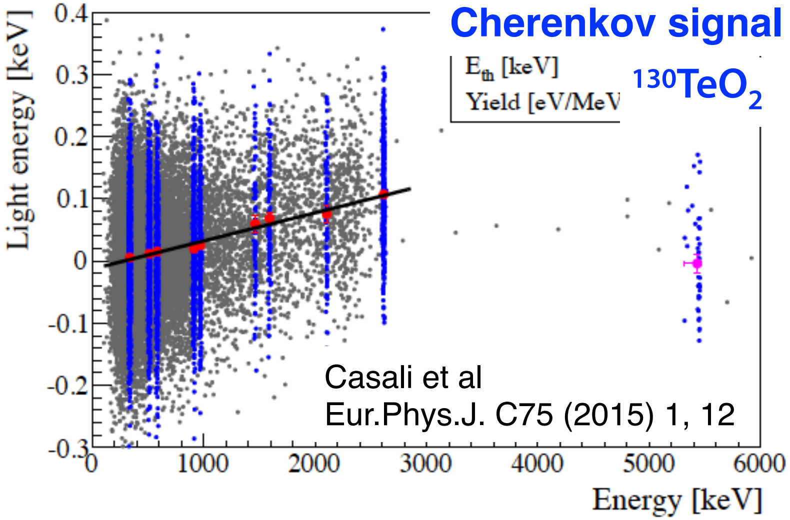
Crystal	Exposure [ton·y]	half-life sensitivity [10^{27}y]	$\lvert m_{ee}\rvert_S$ [meV]
ZnSe	5	3.3	9 - 26
	10	6.5	6 - 18
$CdWO_4$	5	1.5	14 - 26
	10	3.0	10 - 18
$ZnMoO_4$	5	0.9	11 - 32
	10	1.4	9 - 25
TeO_2	5	3.4	8 - 22
	10	6.8	6 - 16

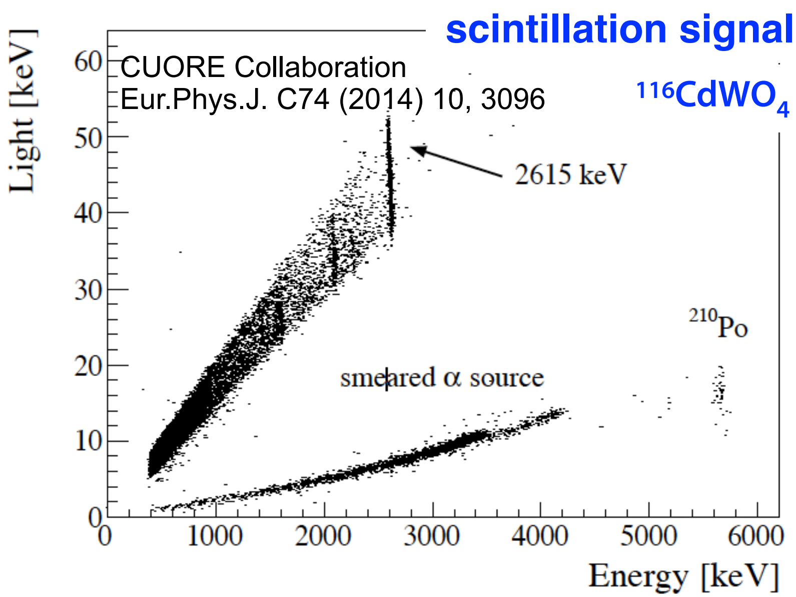
Beyond CUORE: Particle ID with Light Detectors

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 a comprehensive 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** (2016 -)
  - tower assembly is complete and cryogenic system commissioning underway.
  - physics data taking expected to start in 2016.
  - with 206 kg of ^{130}Te and 5 keV energy resolution, is able to reach 51-133 meV effective Majorana mass.
- **Beyond CUORE/CUPID**: R&D effort is underway. Large bolometers offer path towards exploring the inverted hierarchy.

CUORE Collaboration

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