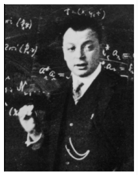
Results from the search for neutrinoless double beta decay of ^{130}Te with CUORE-0

Reina Maruyama
Yale University

NPA Seminar
Wright Lab, Yale University
April 16, 2015

History of Neutrinos



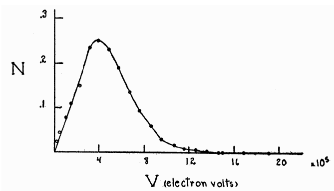
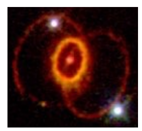


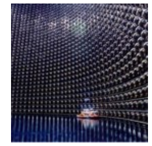
FIG. 5. Energy distribution curve of the beta-rays.

1930 Pauli postulates neutrinos

1933 Fermi names neutrinos, formulates weak interactions theory



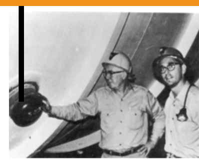
1987
SN 1987A



1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002 SNO finds evidence for solar ν_e flavor change.

2003 KamLAND discovers disappearance of reactor ν_e



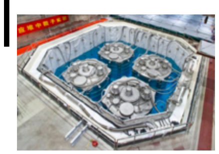
1968 Ray Davis detects solar neutrinos.

1962 Steinberger, Lederman, Schwartz, et al demonstrate ν_e & ν_μ

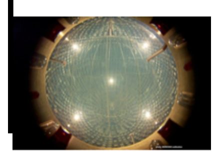
1958 Goldhaber, Grodzins, & Sunyar at BNL demonstrate left-handed helicity

1957 Pontecorvo: Neutrinos may oscillate

1956 Reines & Cowan report the first evidence of neutrinos



2012 Daya Bay, RENO, Double Chooz measure θ_{13}

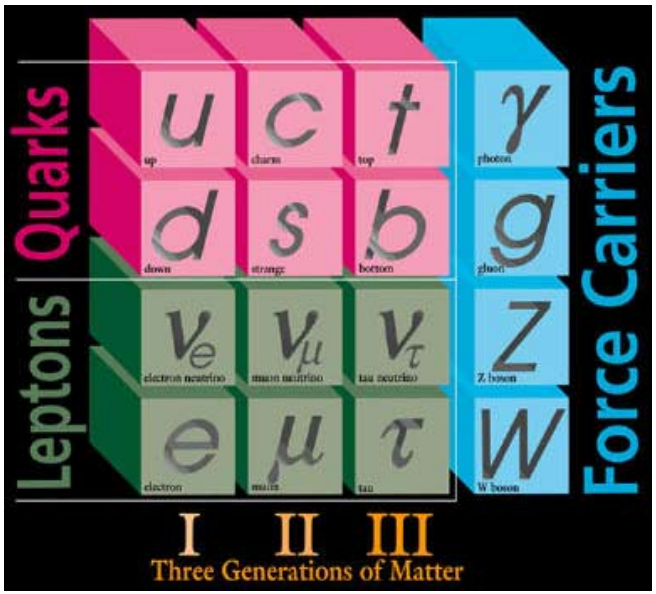


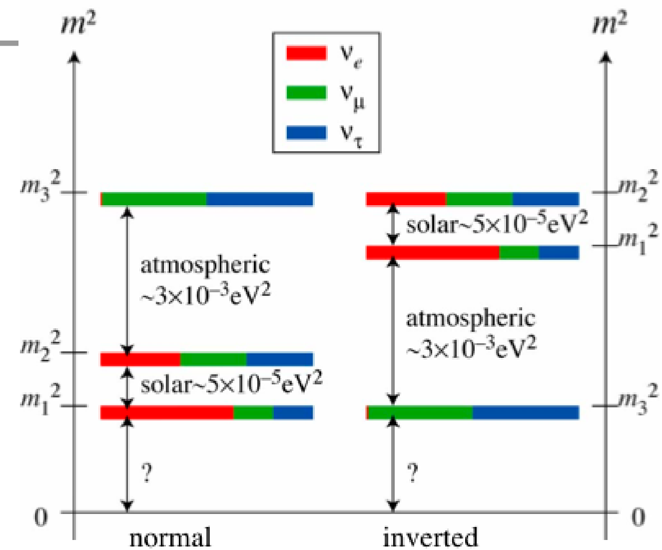
2007 Borexino detection of ^{7}Be solar neutrinos

Neutrinos have mass

Results from nu-oscillation experiments:

- Neutrinos undergo flavor-changing oscillations
- Neutrinos have finite masses





If 0νββ is observed :

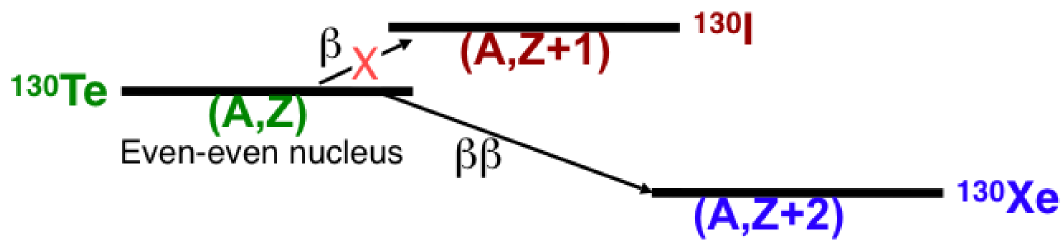
- **ν's are Majorana Particles**
- **Violates Lepton Number (& B-L)**

Also access

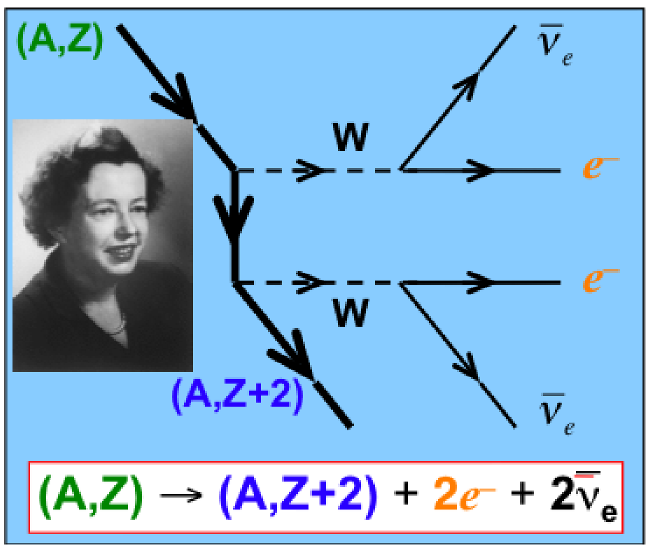
- **absolute neutrino mass scale**
- **neutrino mass hierarchy**

- Why is the mass so small?
- How small is it?
- What is the mass production mechanism?
- What is the mass hierarchy?

Double Beta Decay



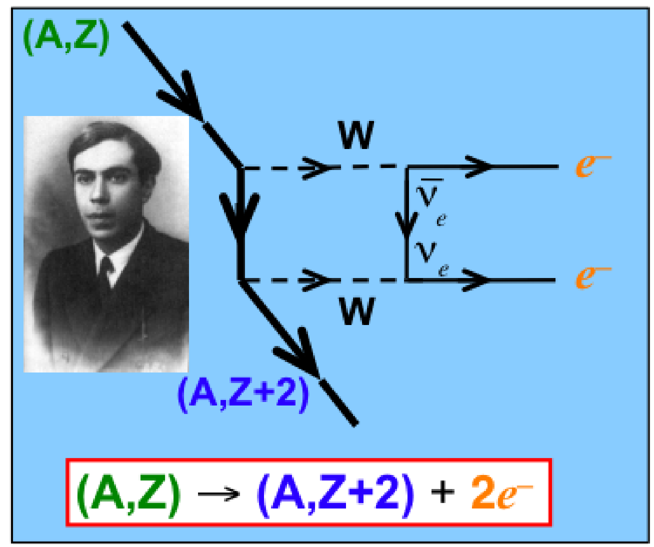
(2νββ) $T_{1/2} \sim 10^{19} - 10^{21}$ yrs



Proposed in 1935 by Maria Goeppert-Mayer

1963 nuclear shell structure

(0νββ) $T_{1/2} \geq 10^{25}$ y



Proposed in 1937 by Ettore Majorana

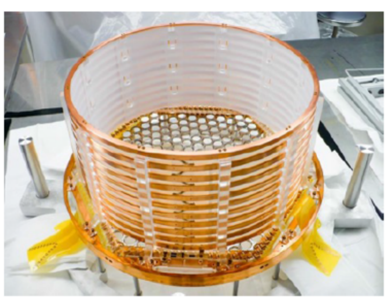
$0\nu\beta\beta$ Efforts Worldwide

^{130}Te

- Bolometer-based searches
- $T_{1/2} > 2.8 \times 10^{24}$ y
- Cuoricino / CUORE-0 / CUORE

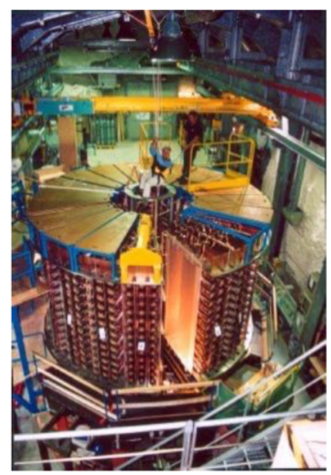
^{76}Ge

- High-purity germanium detectors
- $T_{1/2} > 2.1 \times 10^{25}$ y
- GERDA / MAJORANA



^{136}Xe

- Liquid Xe scintillation / TPC
- $T_{1/2} > 2.6 \times 10^{25}$ y
- Kamland-Zen, EXO-200, nEXO



NEMO-3 / SuperNEMO

- Source foils with tracking and calorimetry
- Half-lives on ^{48}Ca, ^{82}Se, ^{96}Zr, …

Experimental Sensitivity

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

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

- Choose a source with a high **isotopic abundance** of the 0νββ emitter
- Create a detector with a high **detection efficiency** and good **energy resolution** in a **low-background** environment
- Run experiment for a long **exposure time** with a large **total mass** of the source isotope

Half Live of 0νββ

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

$T^{0\nu}_{1/2}$ = $0\nu\beta\beta$ half-life

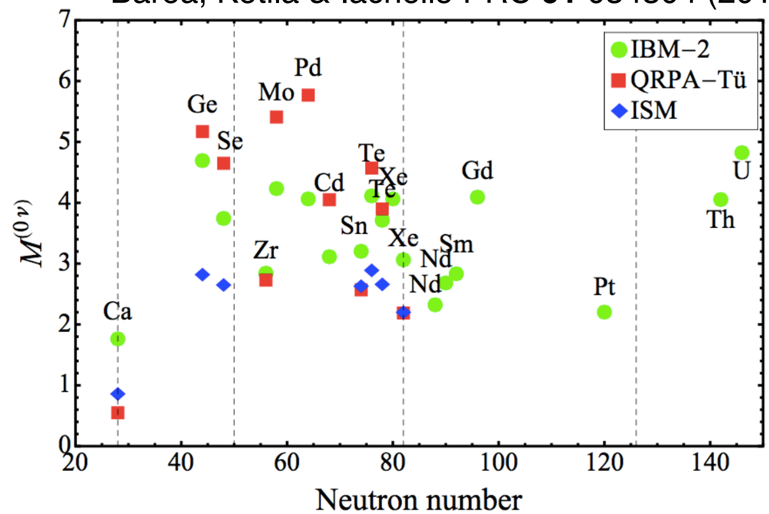
$G^{0\nu}(Q,Z)$ = phase space factor ($\propto Q^5$)

$M^{0\nu}$ = nuclear matrix element

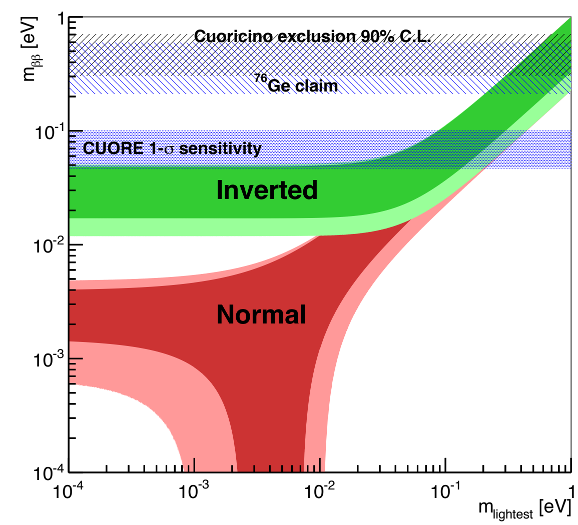
$\langle m_{\beta\beta}\rangle$ = effective $\beta\beta$ neutrino mass

m_e = electron mass

Barea, Kotila & Iachello PRC **91** 034304 (2015)



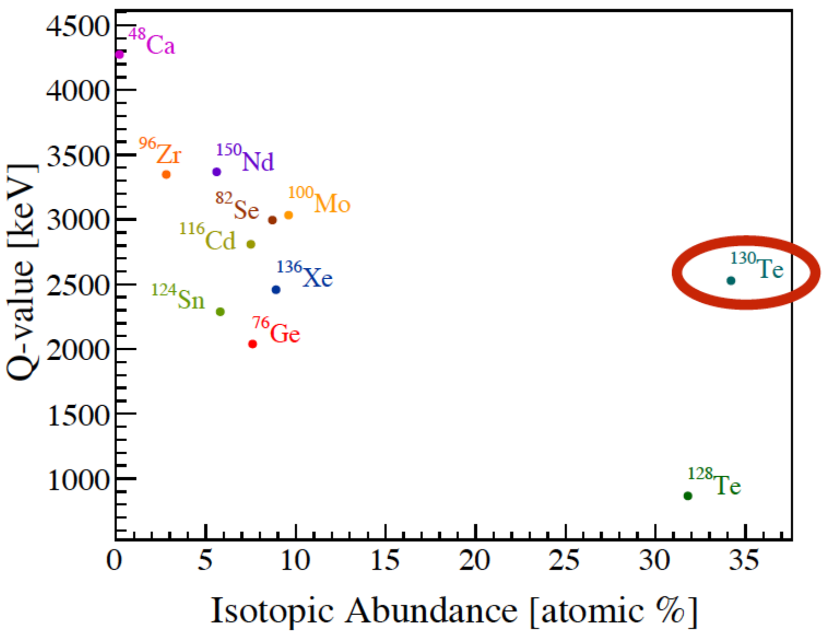
- Shorter **half-lives** are easier to measure, so choose an element with a high **phase space factor** (high Q-value for 0νββ) and high **nuclear matrix element**
- **Nuclear matrix element** is calculated theoretically, with different models
- **Effective ββ neutrino mass** gives hints about absolute neutrino mass



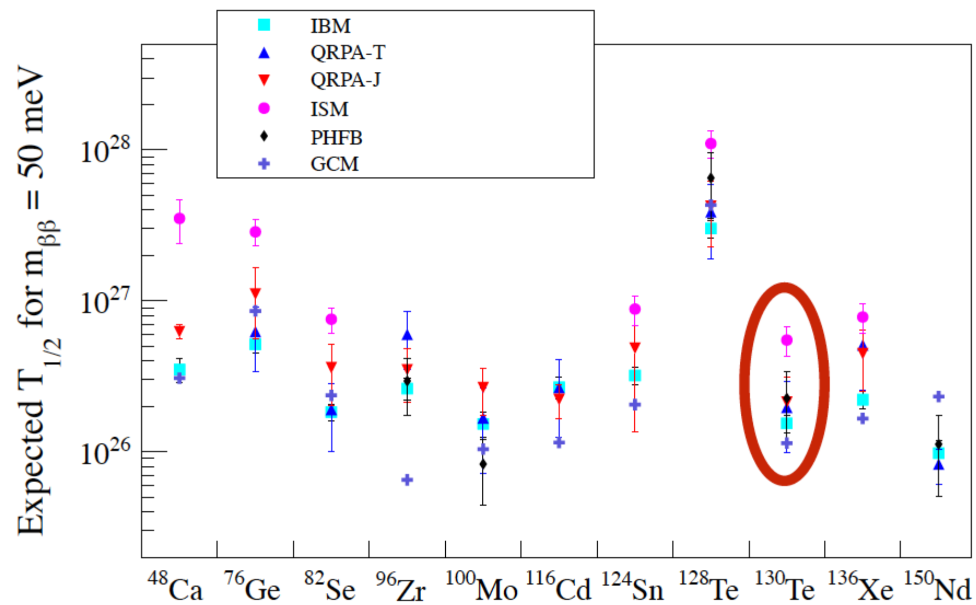
Search for Double Beta Decay in ^{130}Te

Isotope of Choice

- ^{130}Te: High natural abundance (no enrichment required), good Q-value (above Compton edge of 2615 keV line), accessible half-life

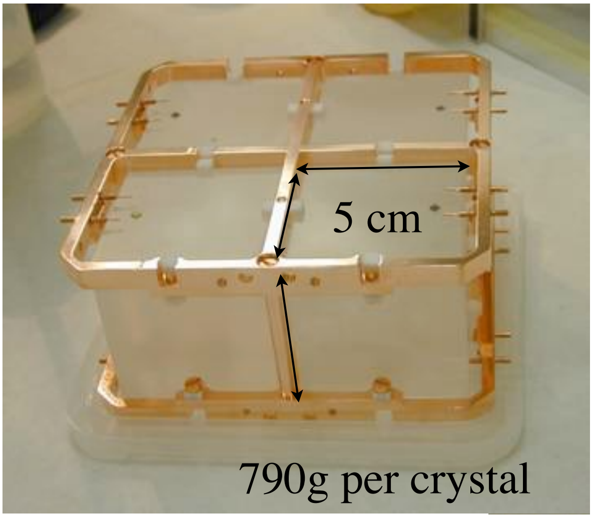


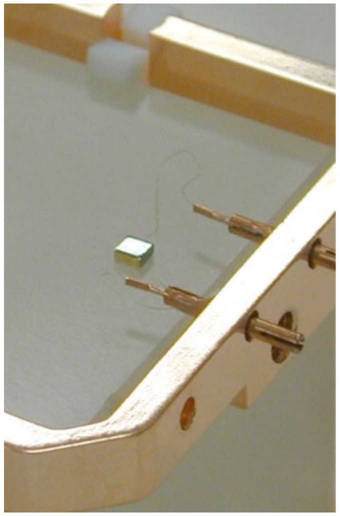
Q(^{130}Te)=2527 keV

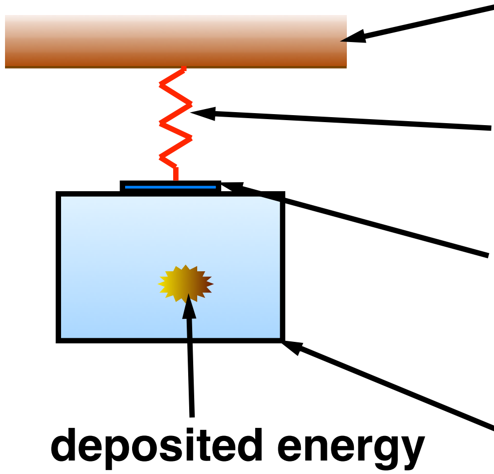


range of $T_{1/2}$ depending on nuclear matrix element

CUORE/Cuoricino 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)

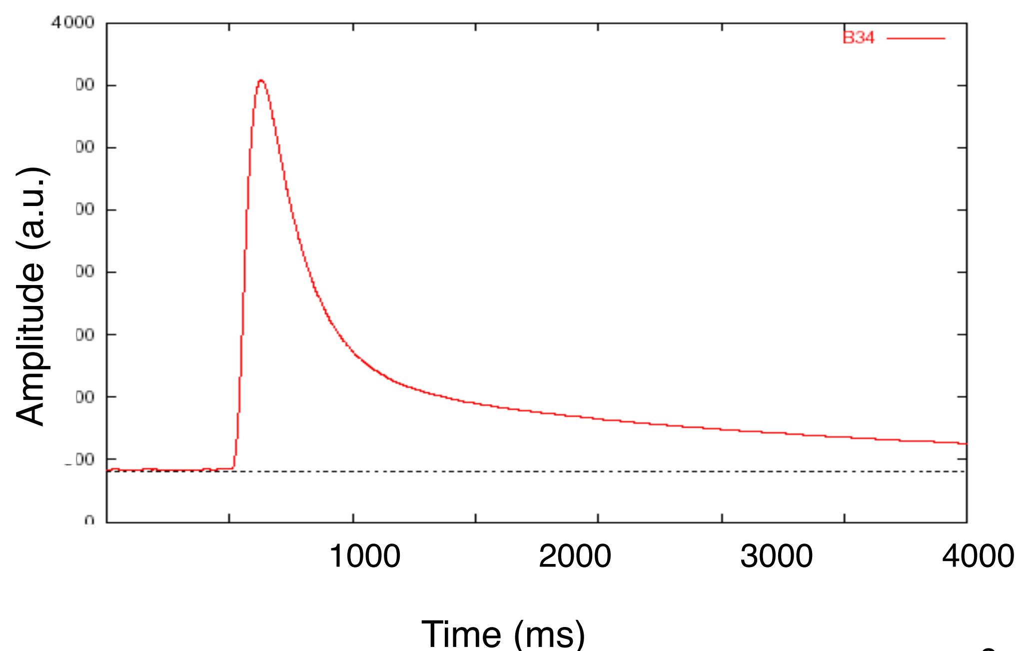
TeO_2 Bolometer: Source = Detector

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

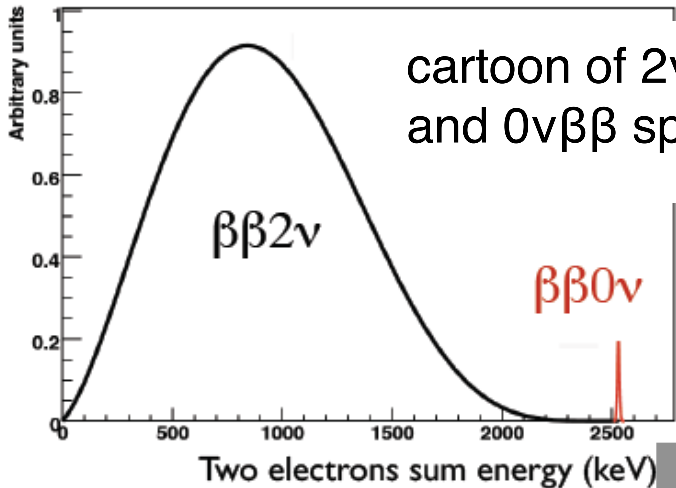
For E = 1 MeV: $\Delta T = E/C \cong 0.1$ mK
Signal size: 1 mV

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



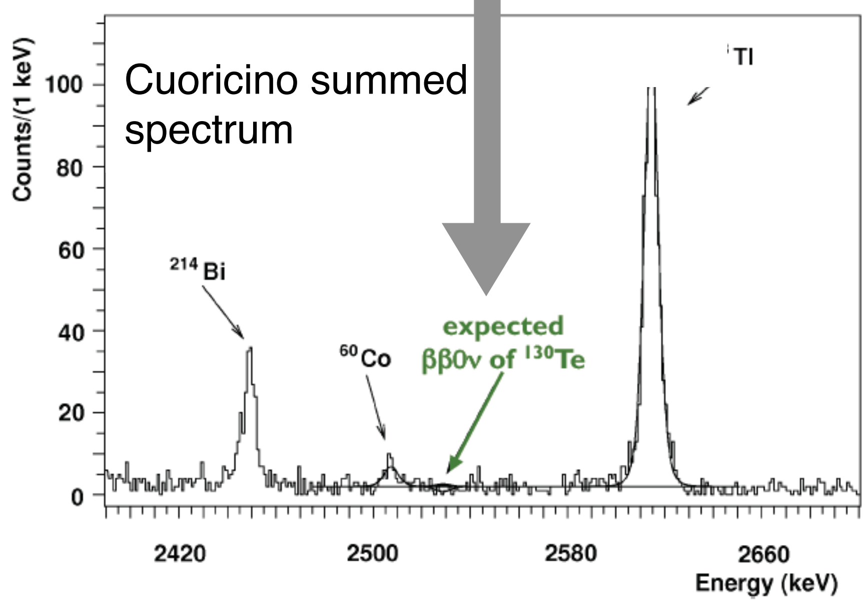
cartoon of 2νββ and 0νββ spectra

Experimental Signature of 0νββ

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

in ^{130}Te

Cuoricino summed spectrum

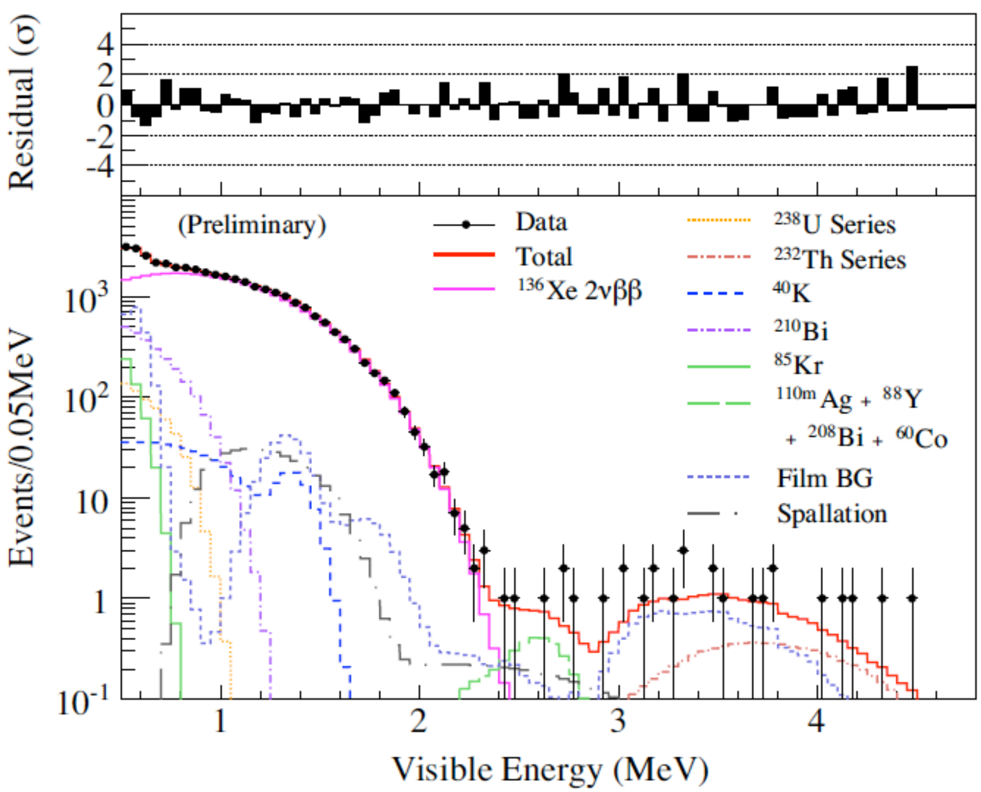


Q(^{130}Te)=2527 keV

energy
= key event signature

Search for 0νββ: ^{136}Xe

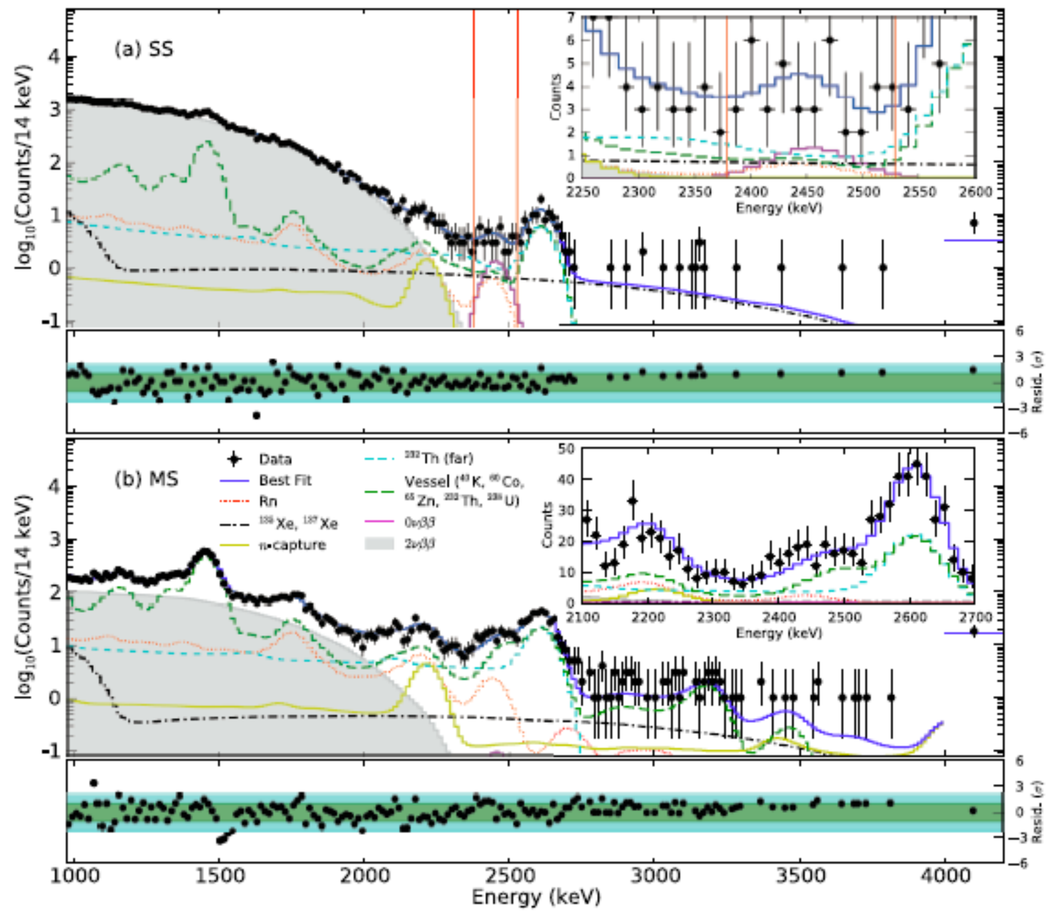
KamLAND-Zen



$T_{1/2} > 2.6\times10^{25}$ years

Phys.Rev.Lett. 111 (2013) 12, 122503

EXO-200

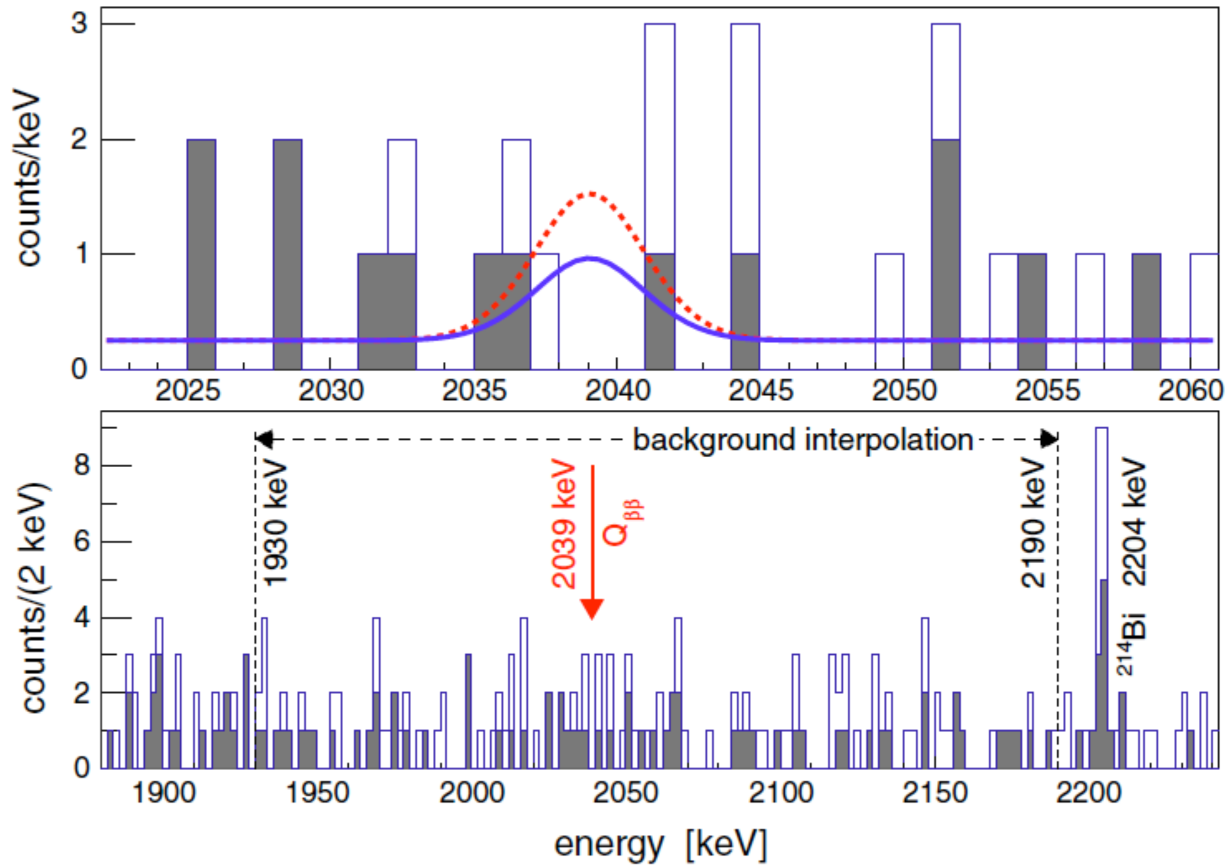


$T_{1/2} > 1.1\times10^{25}$ years

Nature 510 (2014) 229–234

Search for 0νββ: ^{76}Ge

GERDA

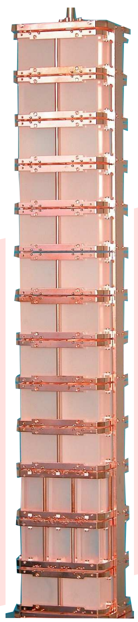


Combined ^{76}Ge $T_{1/2} > 3.0\times10^{25}$ years

Phys.Rev.Lett. 111 (2013) 12, 122503

The CUORE 0νββ Search

Cuoricino
(2003-2008)



Astropart. Phys. 34 (2011) 822–831

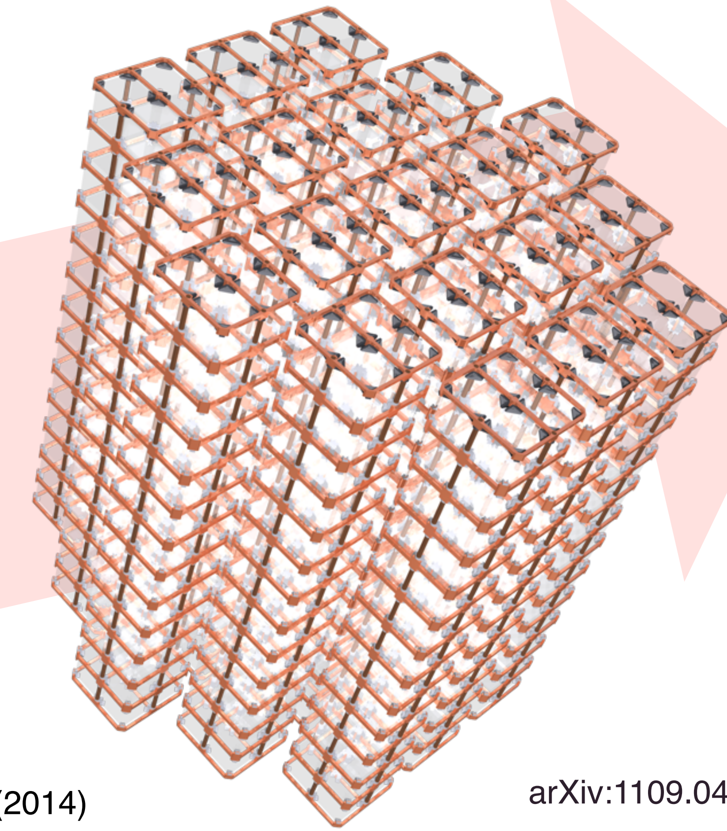
$T_{1/2}^{0\nu\beta\beta} > 2.8 \times 10^{24}$ y (90% C.L.)

CUORE-0
(2013-2015)

EPJC 74, 2956 (2014)
arXiv:1504.0245

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

CUORE
(2015-2020)

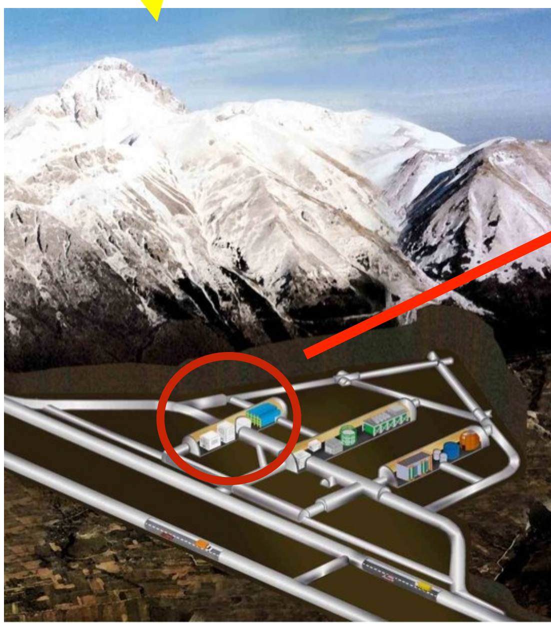


arXiv:1109.0494

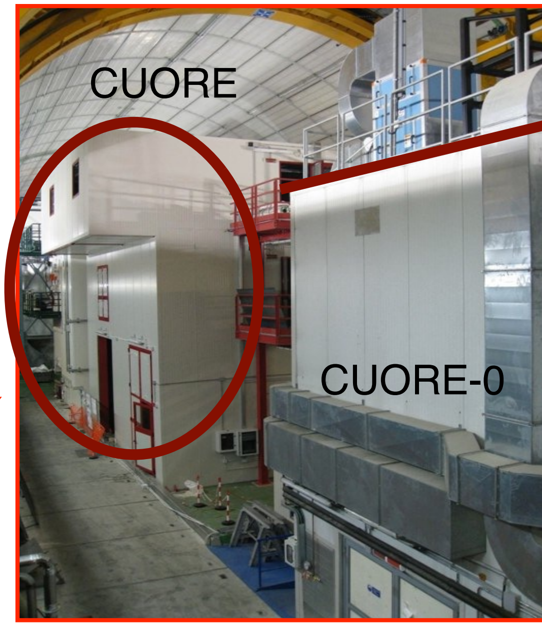
Projected
$T_{1/2}^{0\nu\beta\beta} > 9.5 \times 10^{25}$ yr (90% C.L.)

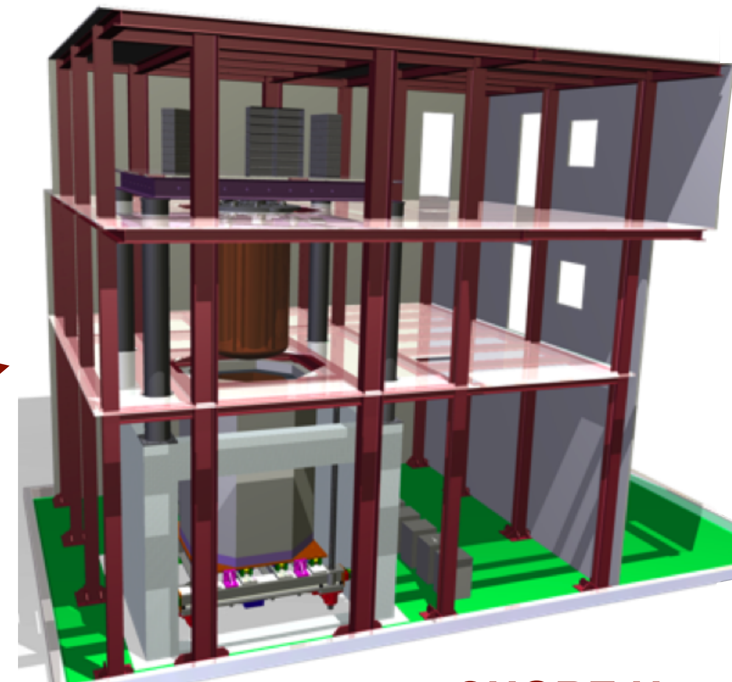
CUORE at LNGS

Gran Sasso National Laboratory



Hall A





CUORE Hut

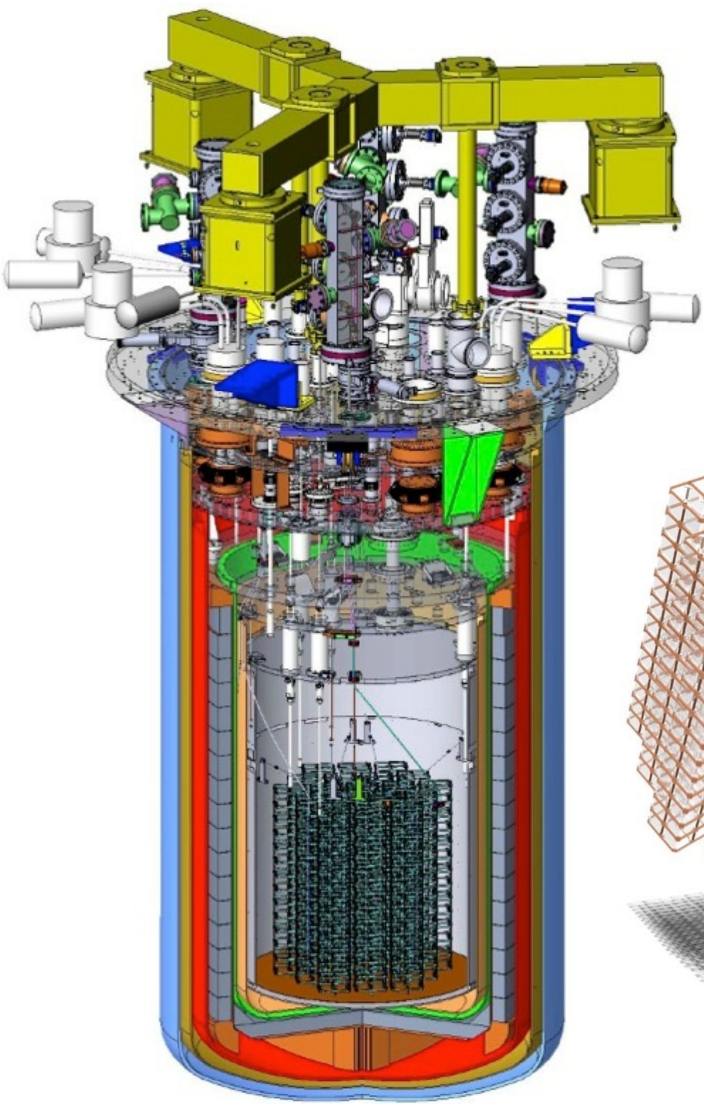
Average depth ~ 3600 m.w.e.

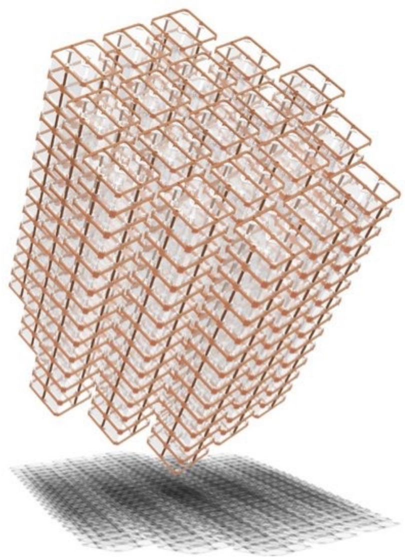
μ: 3 x 10^{-8} μ/s/cm^2

n < 10 MeV: 4 x 10^{-6} n/s/cm^2

γ < 3 MeV: 0.73 γ/s/cm^2

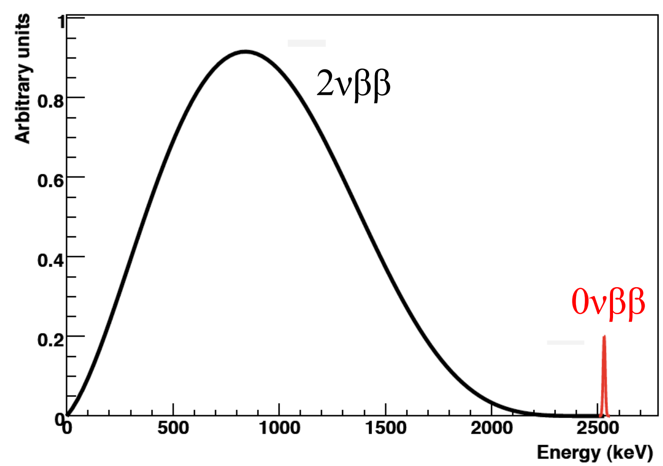
CUORE





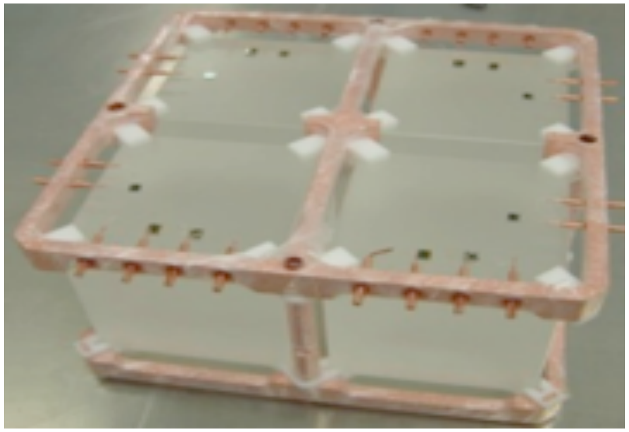
Cryogenic Underground Observatory for Rare Events

- 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)

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:

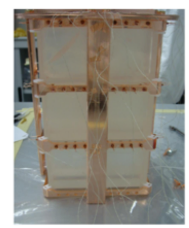
$2 \cdot 10^{-9}$ Bq/cm^2 (^{232}Th), $1 \cdot 10^{-8}$ Bq/cm^2 (^{238}U), $1 \cdot 10^{-6}$ Bq/cm^2 (^{210}Po)

- 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

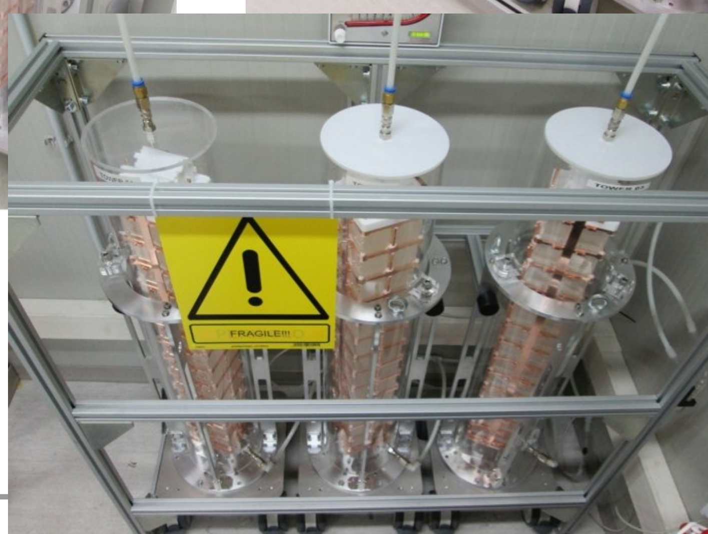
- Benchmarked in dedicated bolometer run at LNGS
    - Residual ^{232}Th / ^{238}U surface contamination of Cu: $< 7 \cdot 10^{-8}$ Bq/cm^2
- Validated by CUORE-0

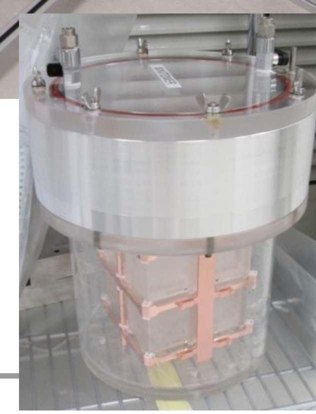
- All parts stored underground, under nitrogen after cleaning

Detector Towers

Assembly of all 19+ towers is complete!

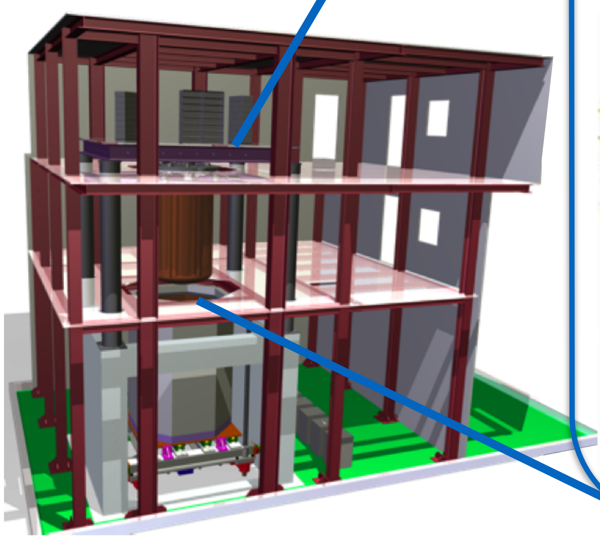


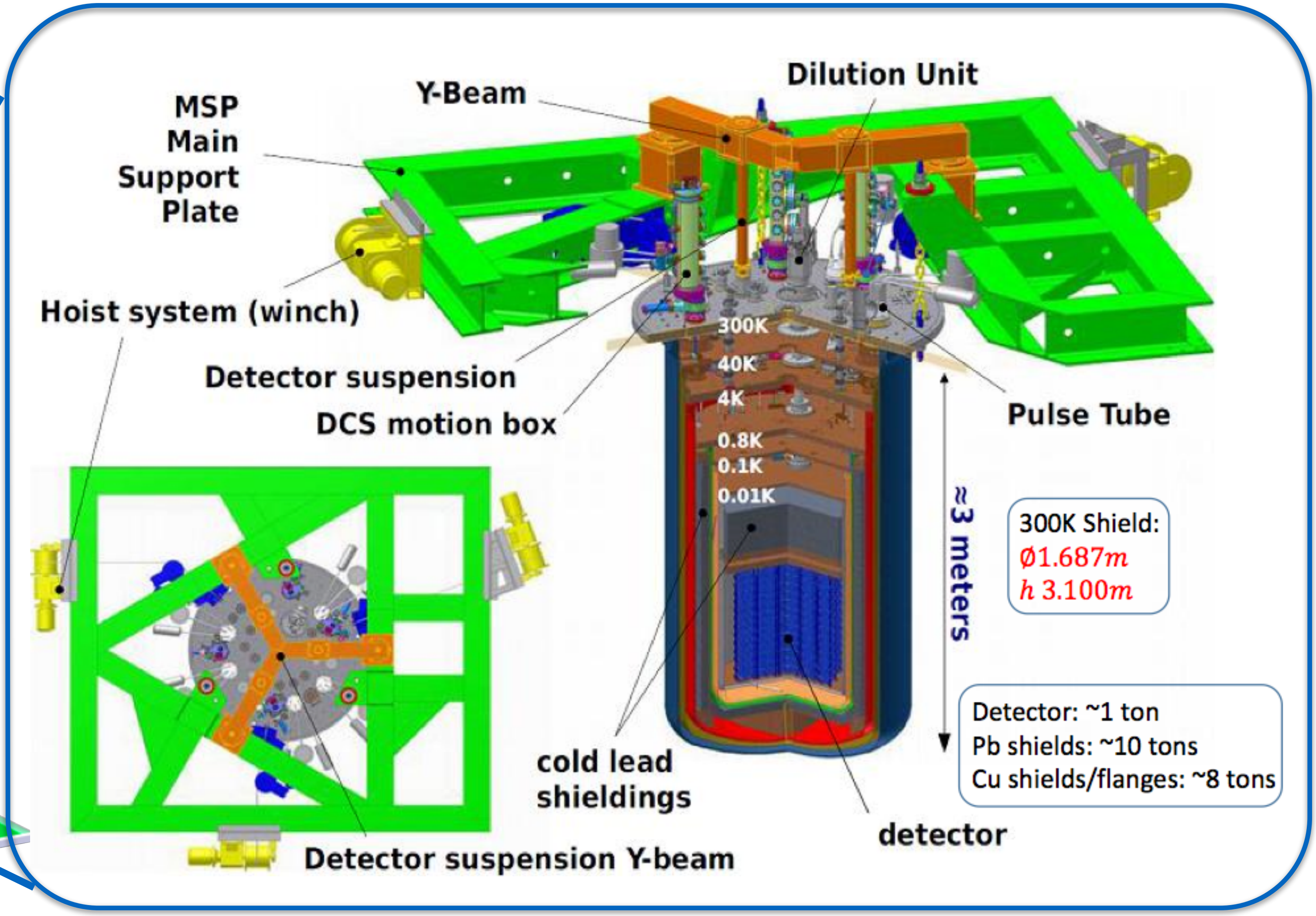



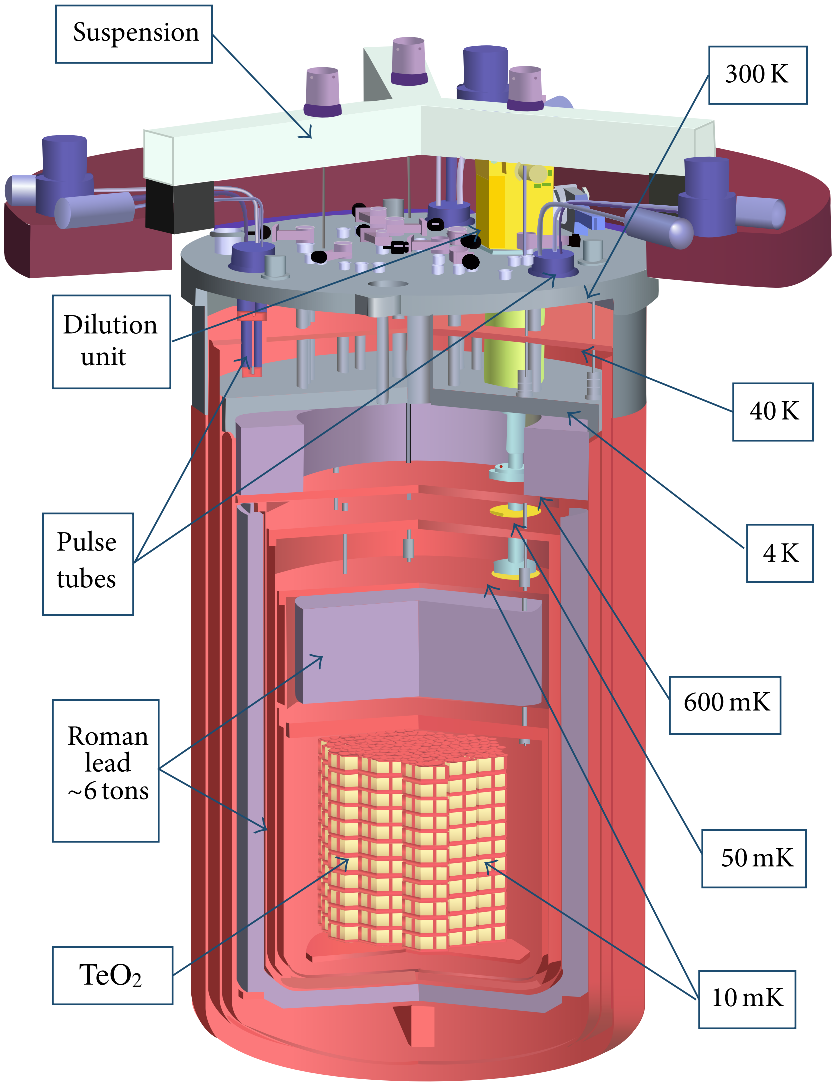
CUORE Suspension & Detector Systems

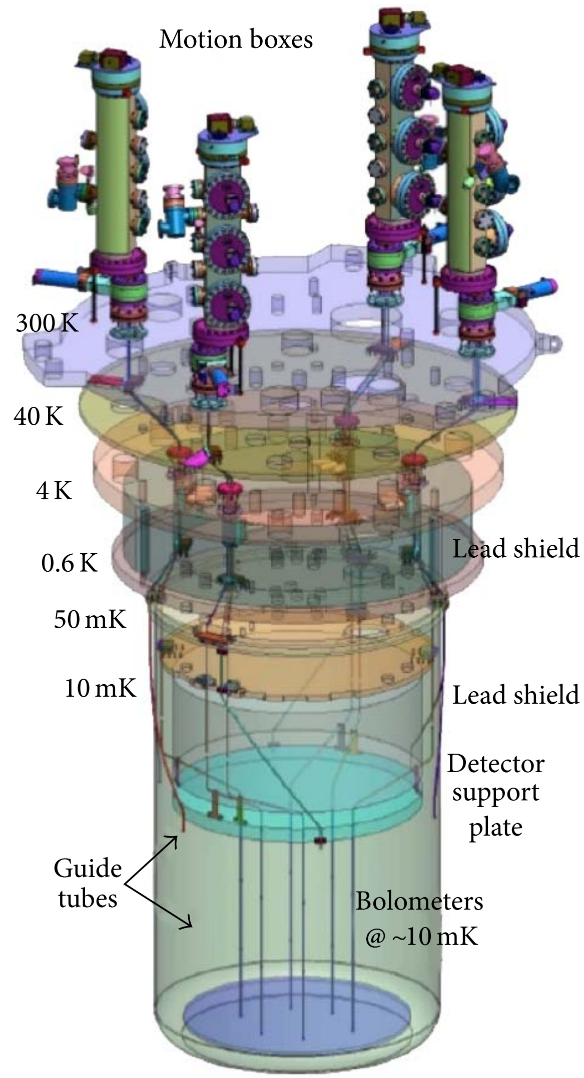
CUORE Hut

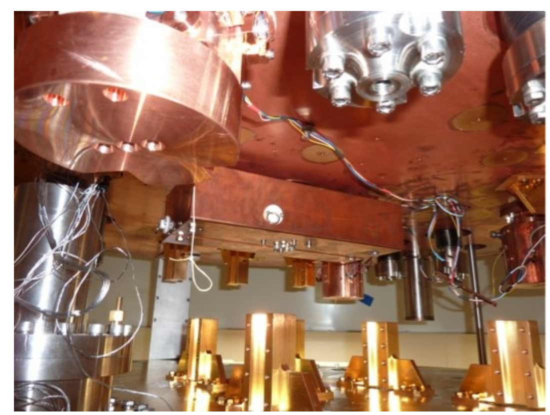




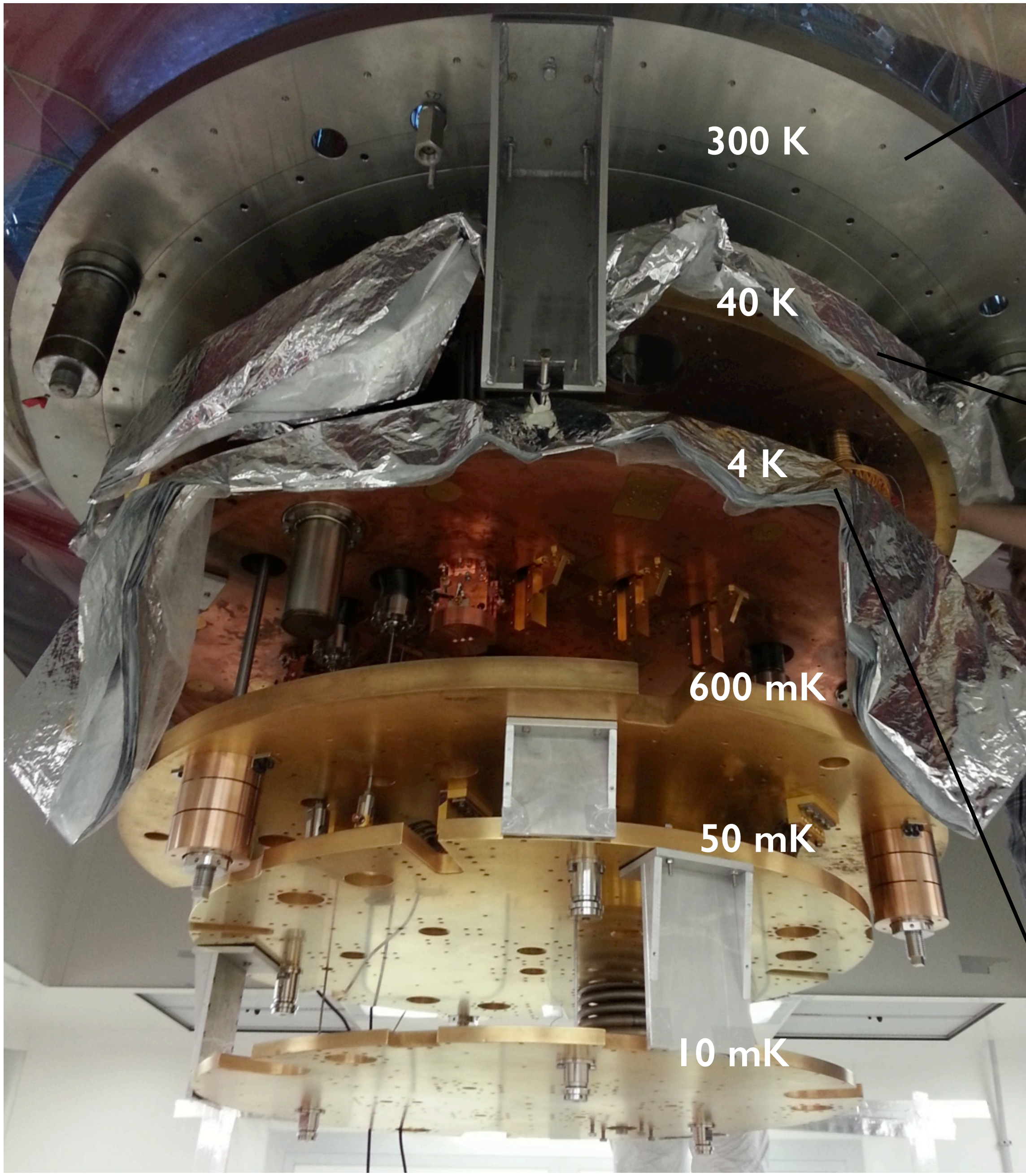
CUORE Cryostat

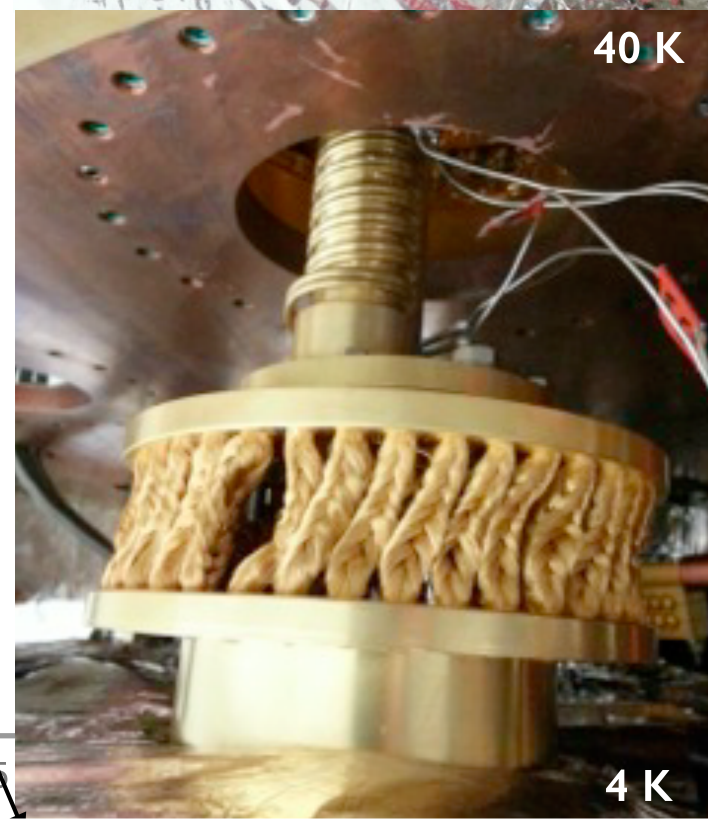






Status of CUORE: Cryogenics

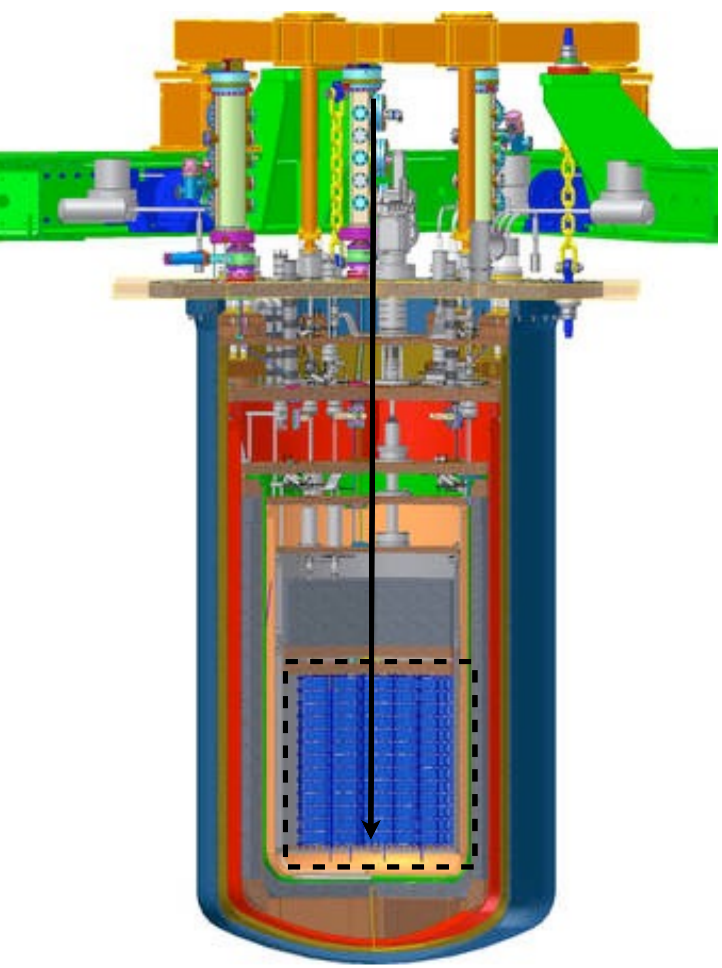




CUORE Detector Calibration System

Energy Calibration of 988 Bolometers

insertion of 12 γ sources that move under own weight

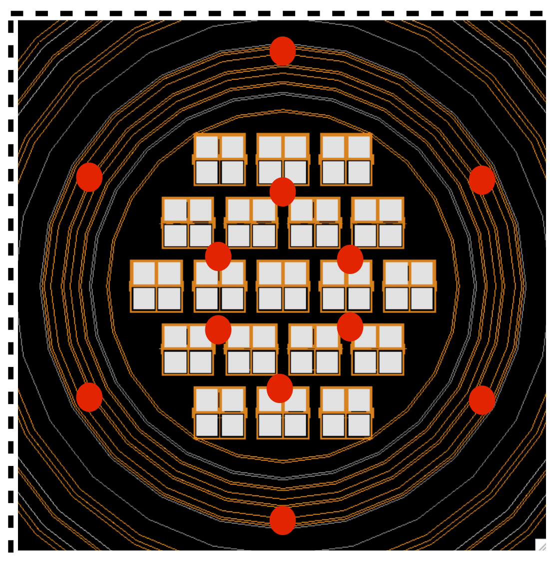


motion system:
insertion and extraction of sources in and out of cryostat

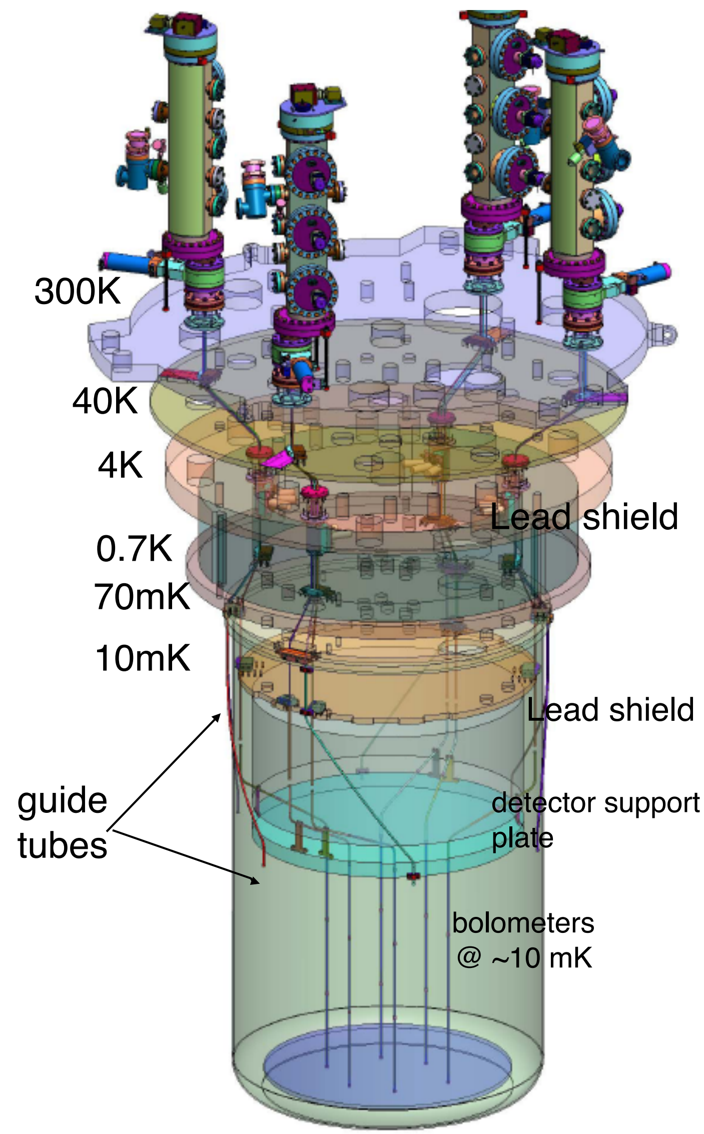
guide tubes:
no straight vertical access

source strings:
move under own weight in guide tubes

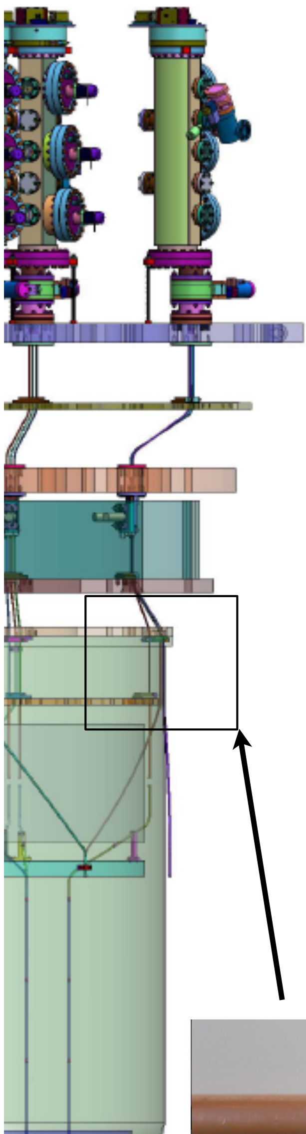
source locations

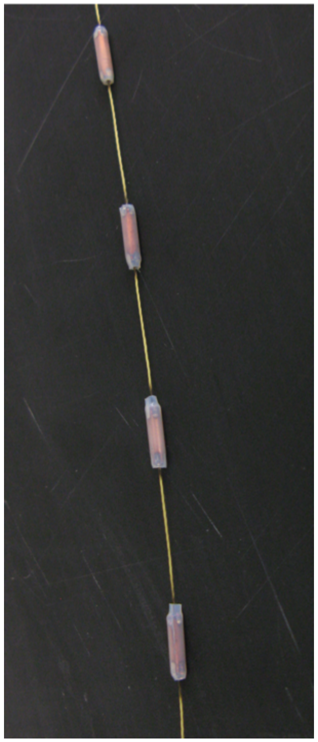


top view of detector array with source positions



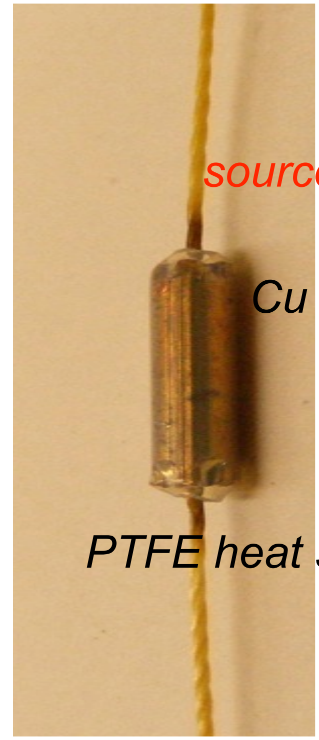
CUORE Detector Calibration

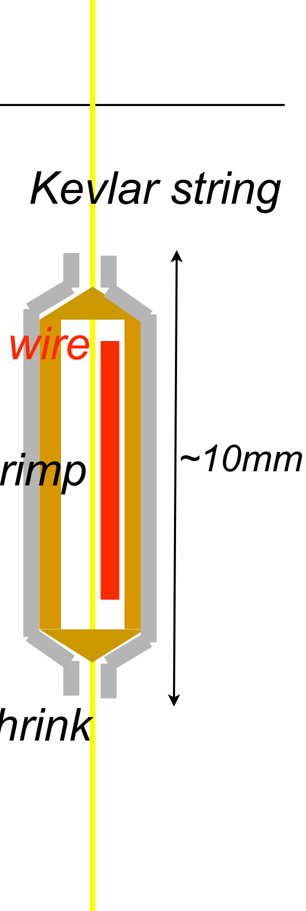




Source String

- *flexible, moves under gravity in guide tube*
- *small mass: < 5 grams*
- *vertical distribution of source activity can be adjusted*
- *30 capsules crimped and evenly spaced over 85 cm of Kevlar string*



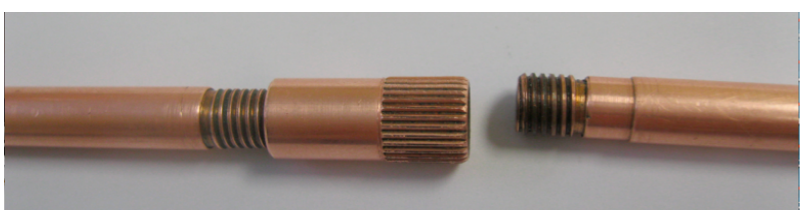


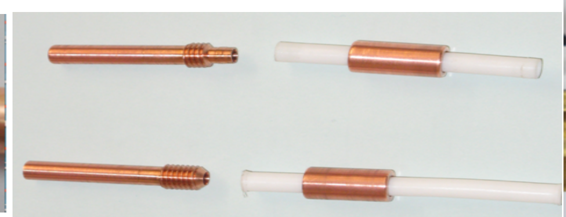
Guide Tubes

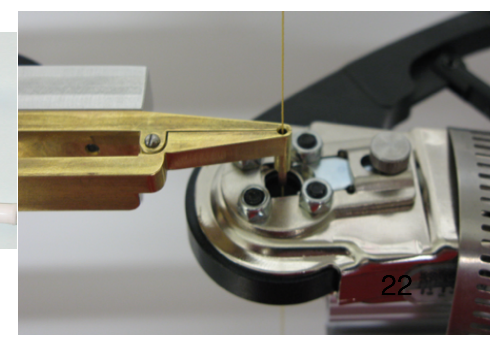
- *stainless and/or machined from solid, low-background copper*
- *can use teflon tubes for bends*

radioactive source wire

- *^{232}Th: Thoriated Tungsten wire*
- *^{56}Co: proton activated Fe wire*







CUORE Cryogenic Systems & Commissioning

Phased Commissioning

Phase I: 4K system check

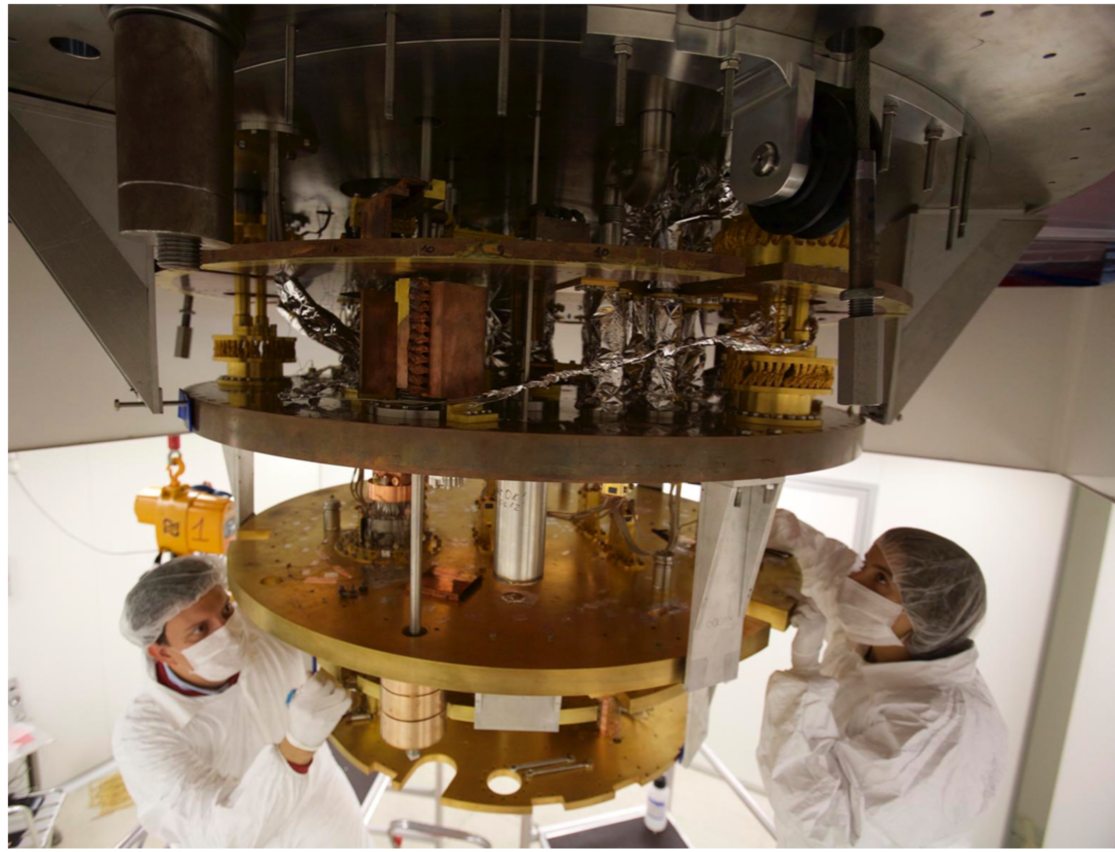
- Outer/Inner vacuum chamber test
- Cryogenic verification of detector calibration system
- Commissioning test of DU

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

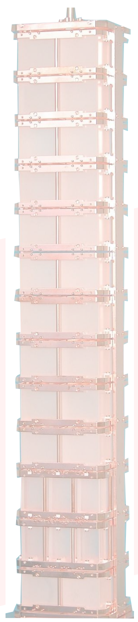
- with lead shields
- wiring
- full calibration system



6mK stable base temperature achieved in October 2014

The CUORE 0νββ Search

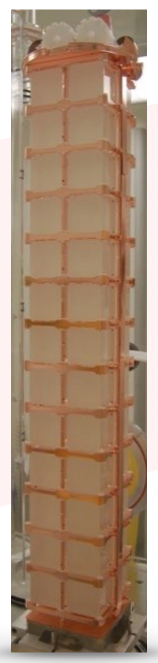
Cuoricino
(2003-2008)



Astropart. Phys. 34
(2011) 822–831

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

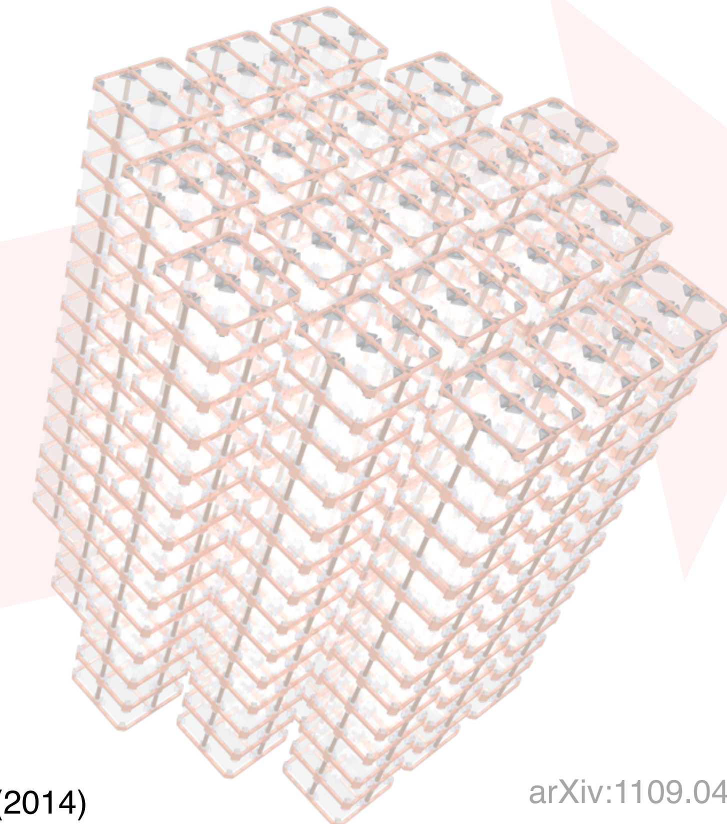
CUORE-0
(2013-2015)



EPJC 74, 2956 (2014)
arXiv:1504.0245

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

CUORE
(2015-2020)



arXiv:1109.0494

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

CUORE-0

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

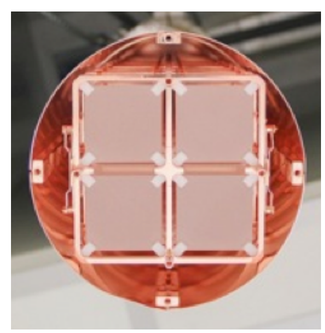
first tower of CUORE
installed in Cuoricino cryostat

PURPOSE

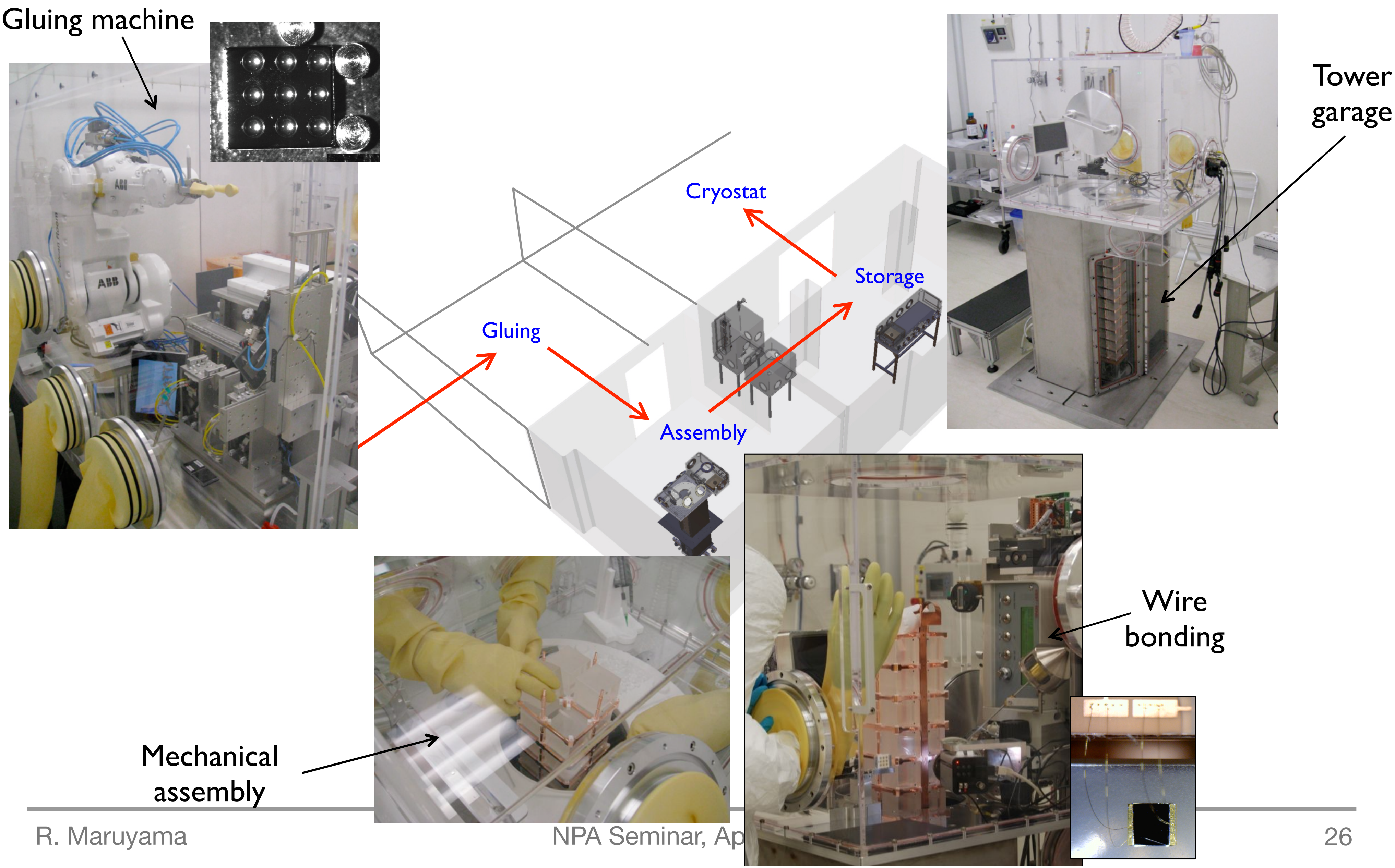
validate cleaning and assembly procedures for CUORE
- TeO2 crystal contaminations
- Cu holder surface contamination

stand-alone 0νββ experiment
- phase I data *EPJC 74, 2956 (2014)*

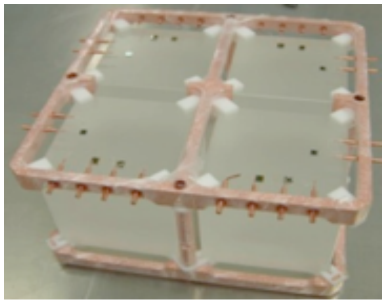
Today's result: arXiv:1504.0245



CUORE-like Detector Assembly



Lowering Background: Crystals & Copper



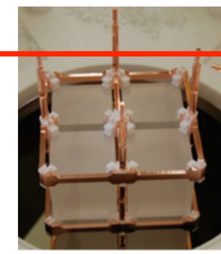
Ultra-pure TeO2 crystal array

Bulk activity 90% C.L. upper limits:

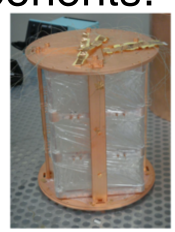
$8.4 \cdot 10^{-7}$ Bq/kg (^{232}Th), $6.7 \cdot 10^{-7}$ Bq/kg (^{238}U), $3.3 \cdot 10^{-6}$ Bq/kg (^{210}Po)

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)

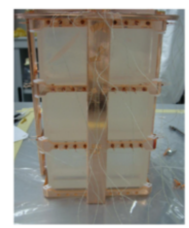


- Crystal holder design optimized to reduce passive surfaces (Cu) facing the crystals
- Developed ultra-cleaning process for all Cu components:
  - Tumbling
  - Electropolishing
  - Chemical etching
  - Magnetron plasma etching



T1

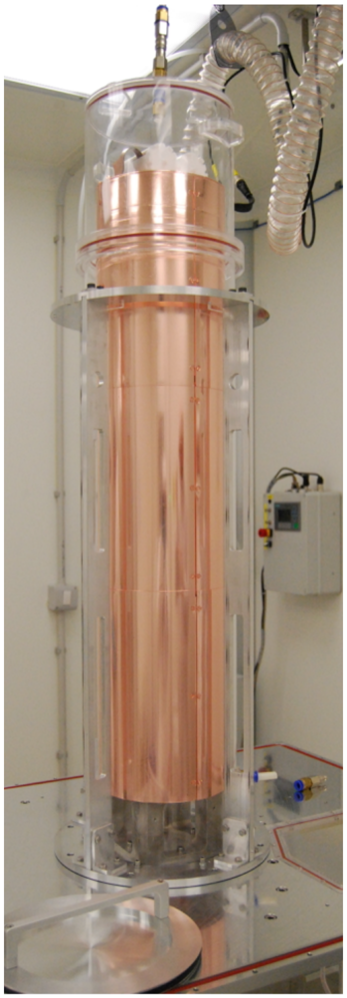
T2

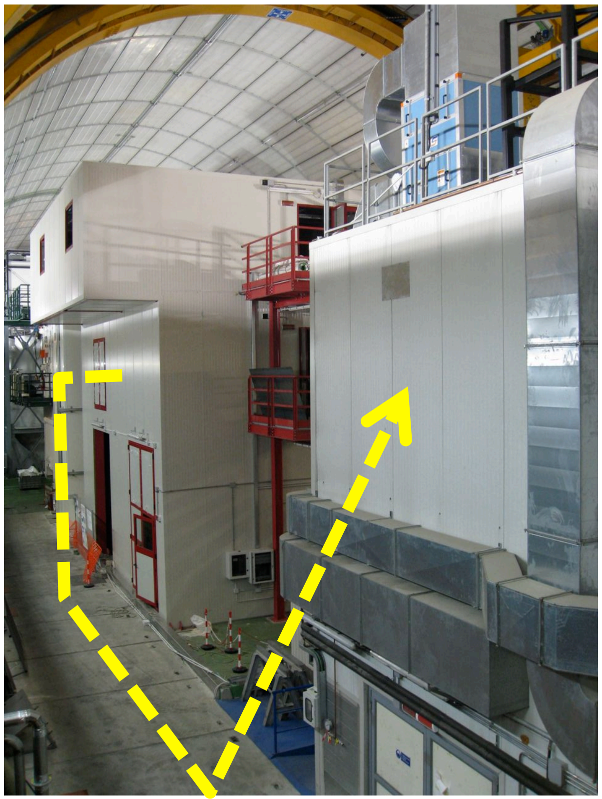


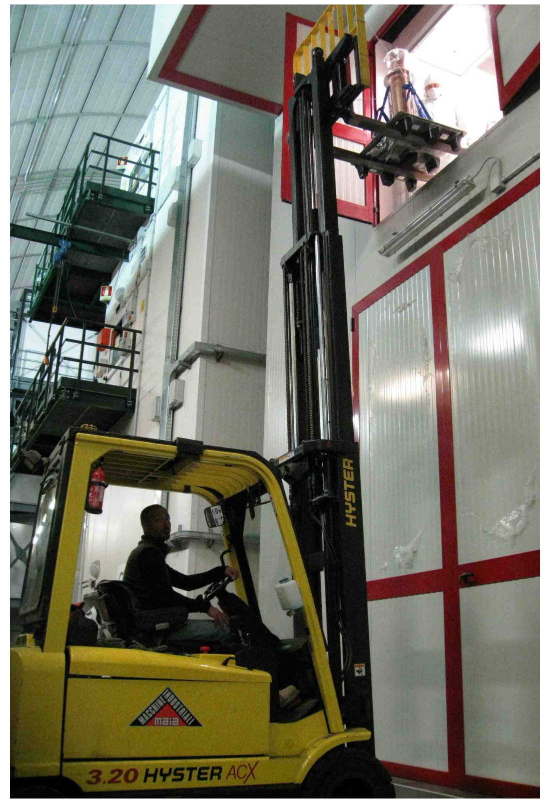
T3

- 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

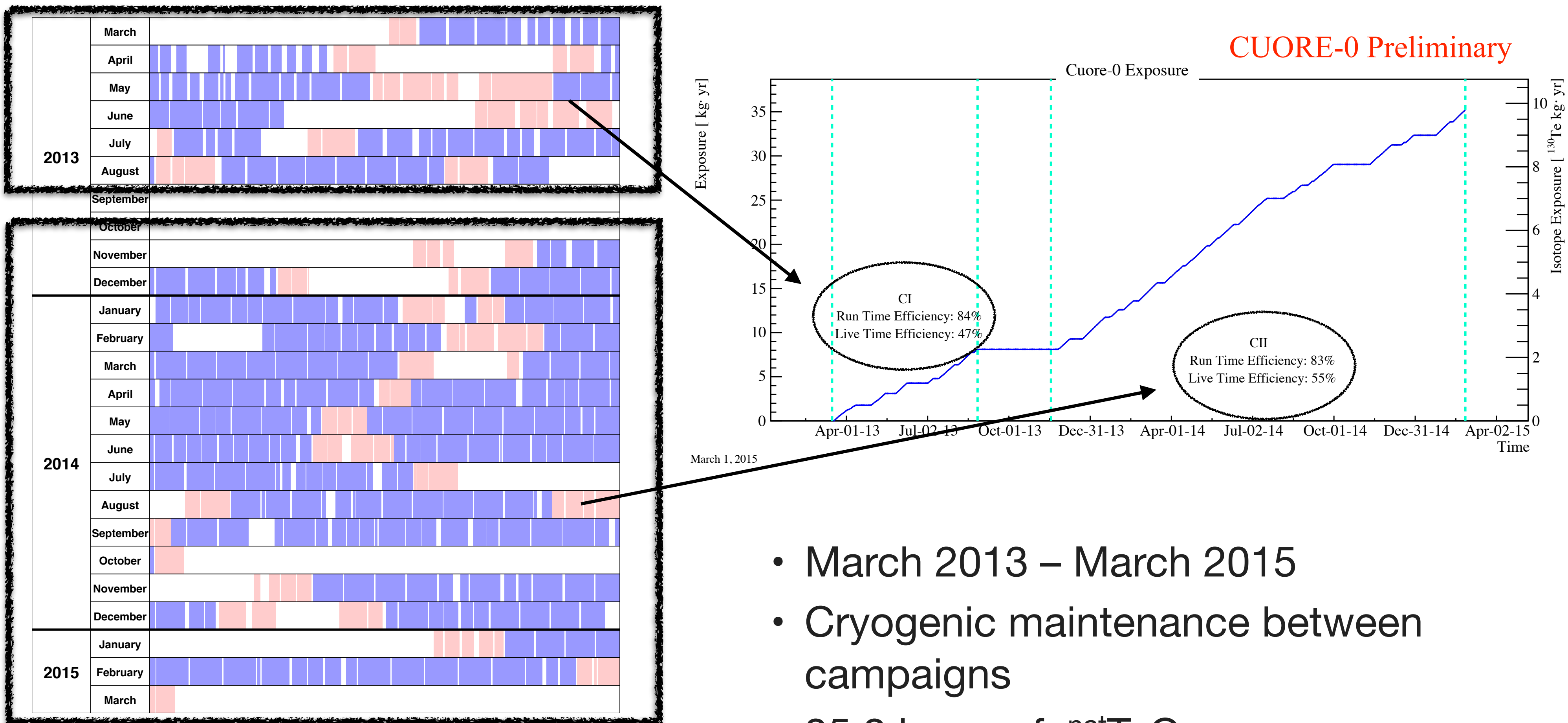






Built in CUORE Cleanroom, transported to Cuoricino cleanroom

Data Run: 2013 – 2015

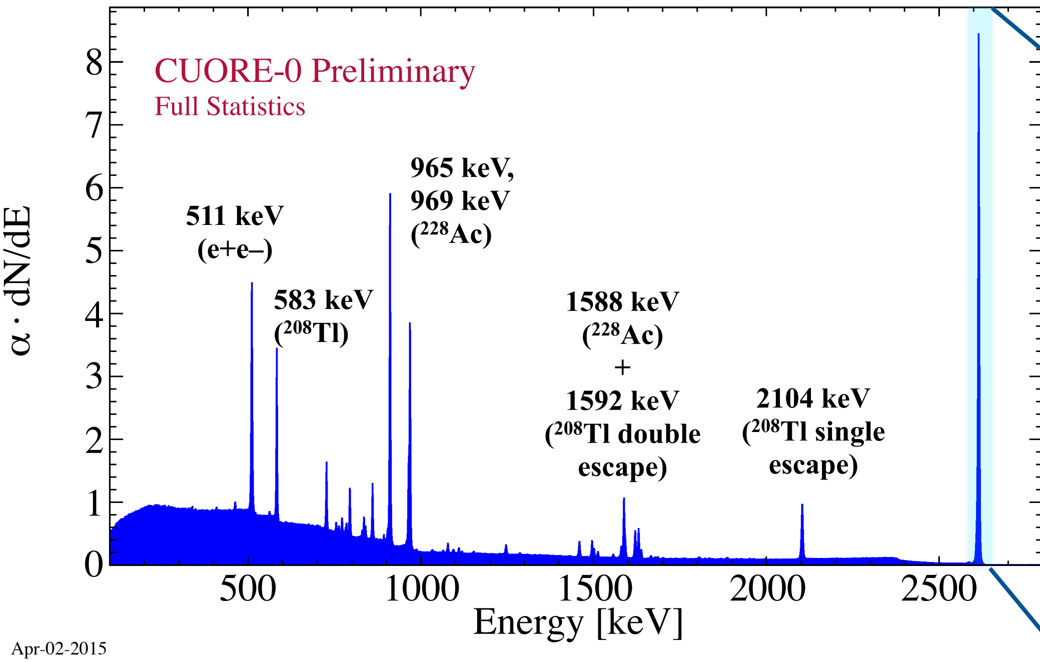


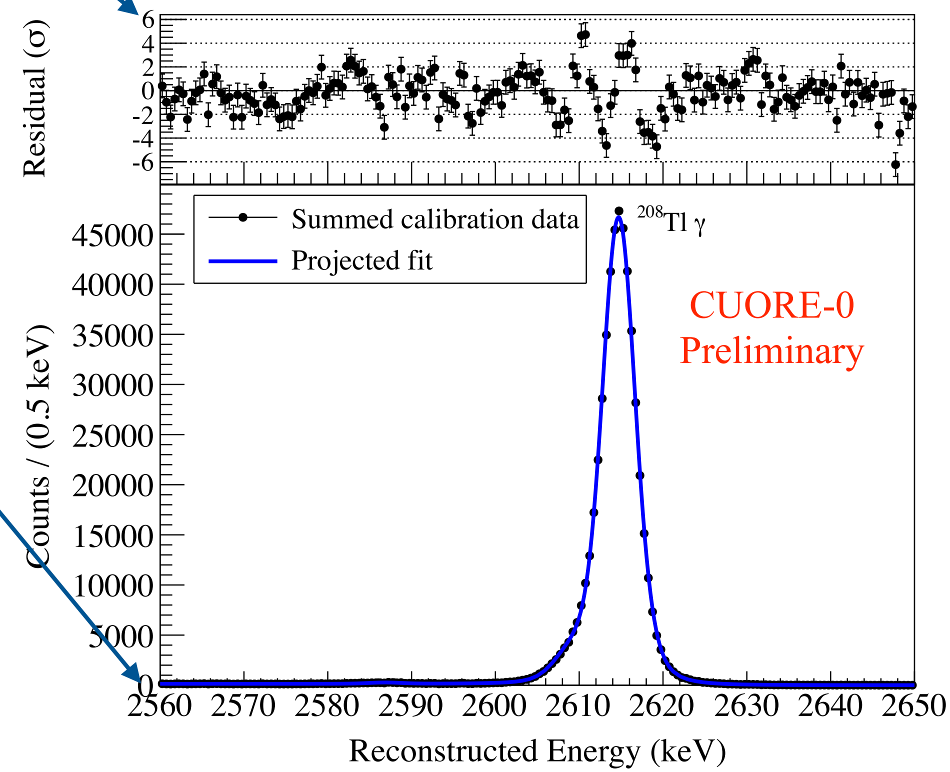
Physics data

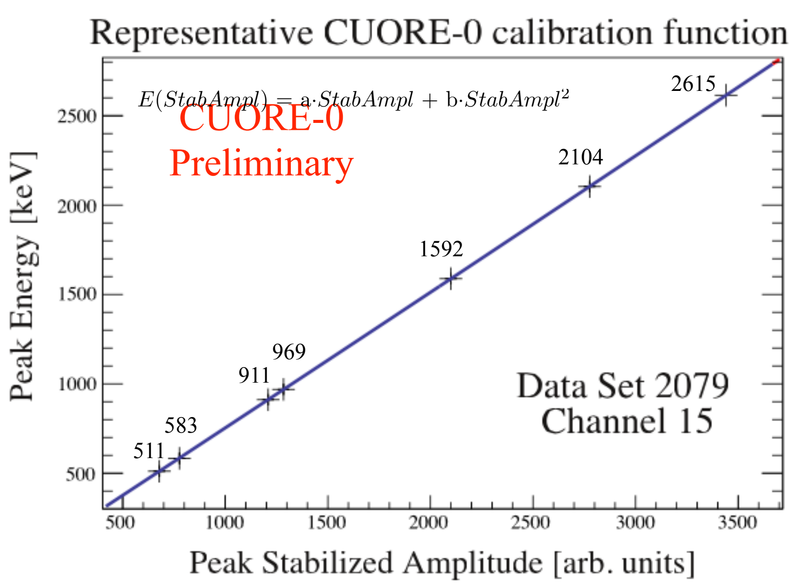
Calibration data

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

Calibration

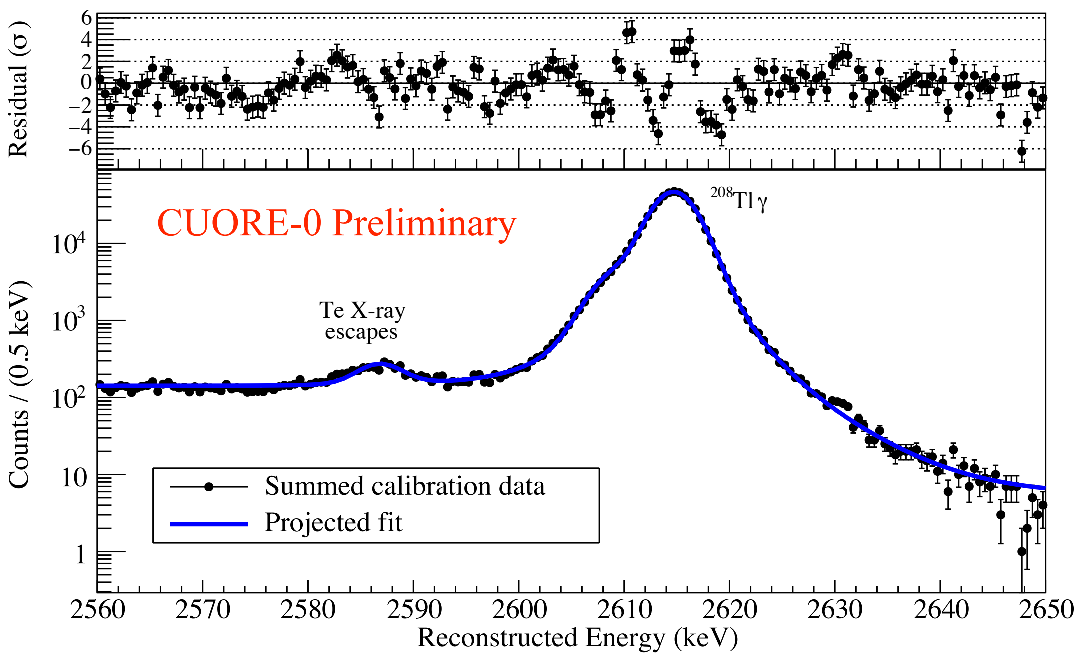


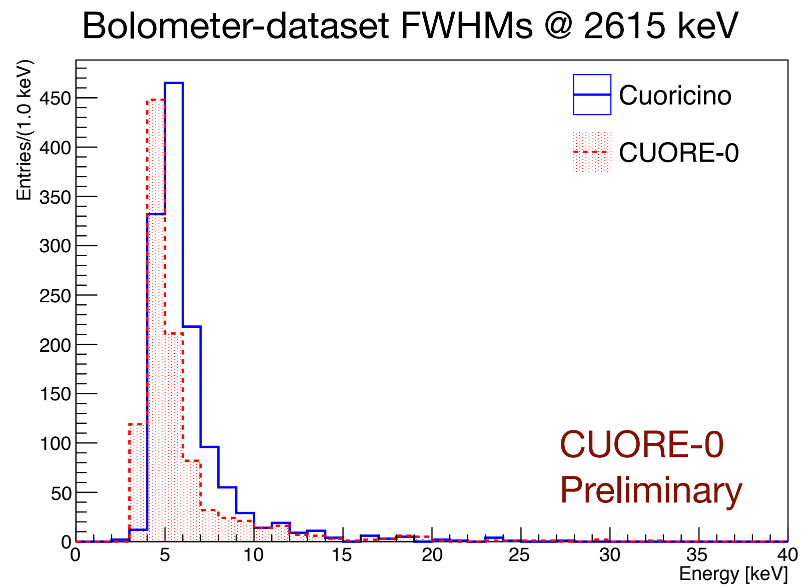




Energy Resolution

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



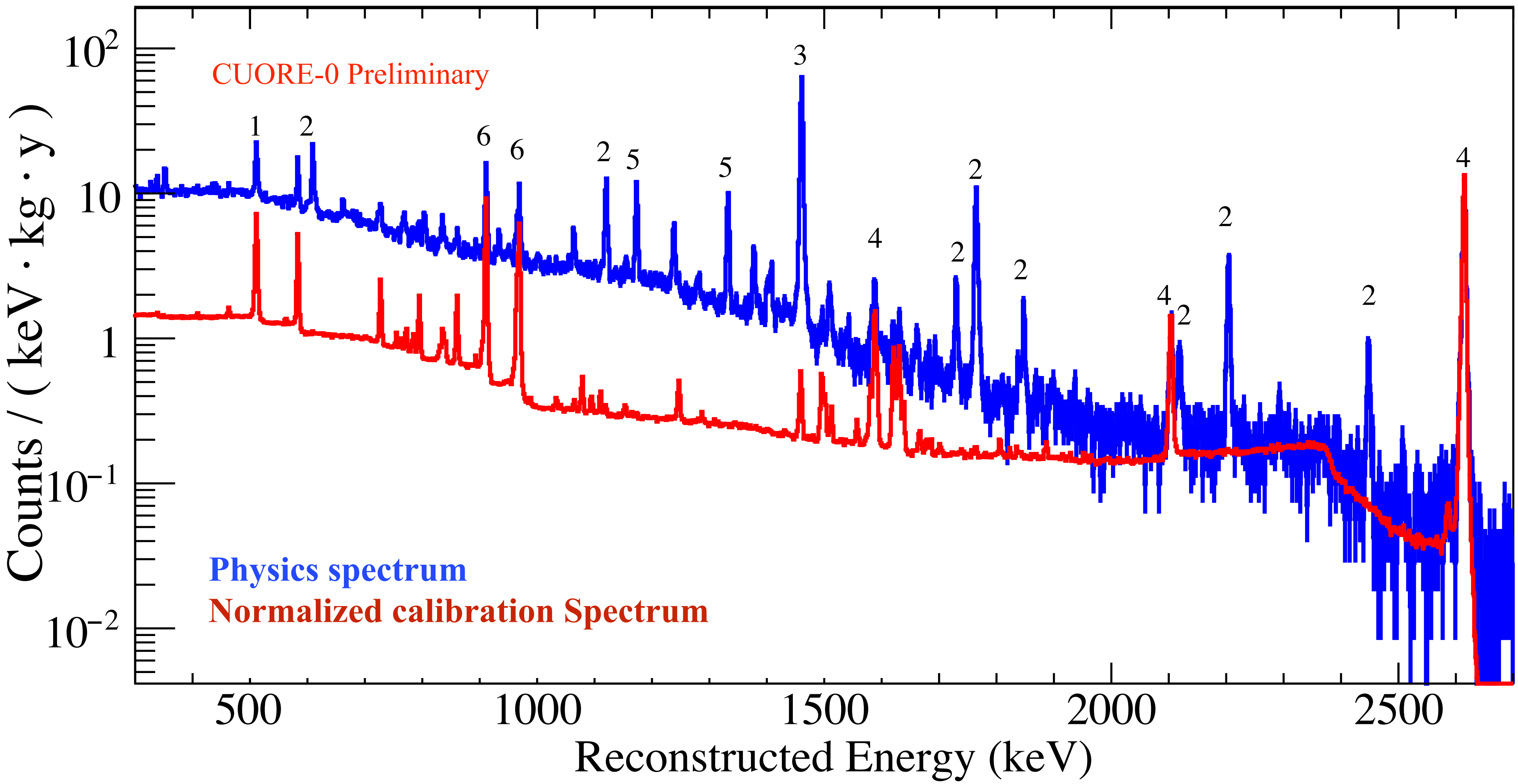


Weight FWHMs by corresponding exposure

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

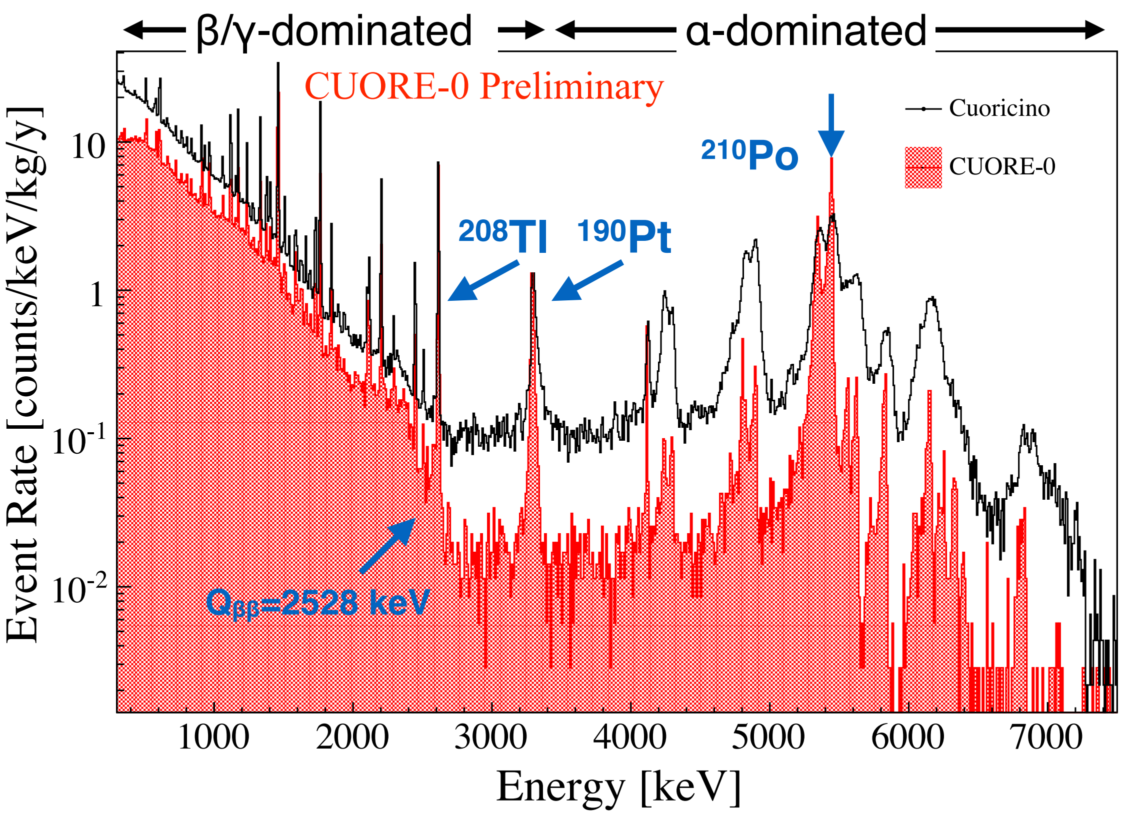
- Energy resolution is evaluated for each bolometer and dataset by fitting the 2615 keV peak from ^{208}Tl in the calibration data.
- The obtained resolution is < 5 keV, which is the CUORE goal.

“Background” Spectrum



(1)e+e-, (2)^{214}Bi, (3)^{40}K, (4)^{208}Tl, (5)^{60}Co, (6)^{228}Ac

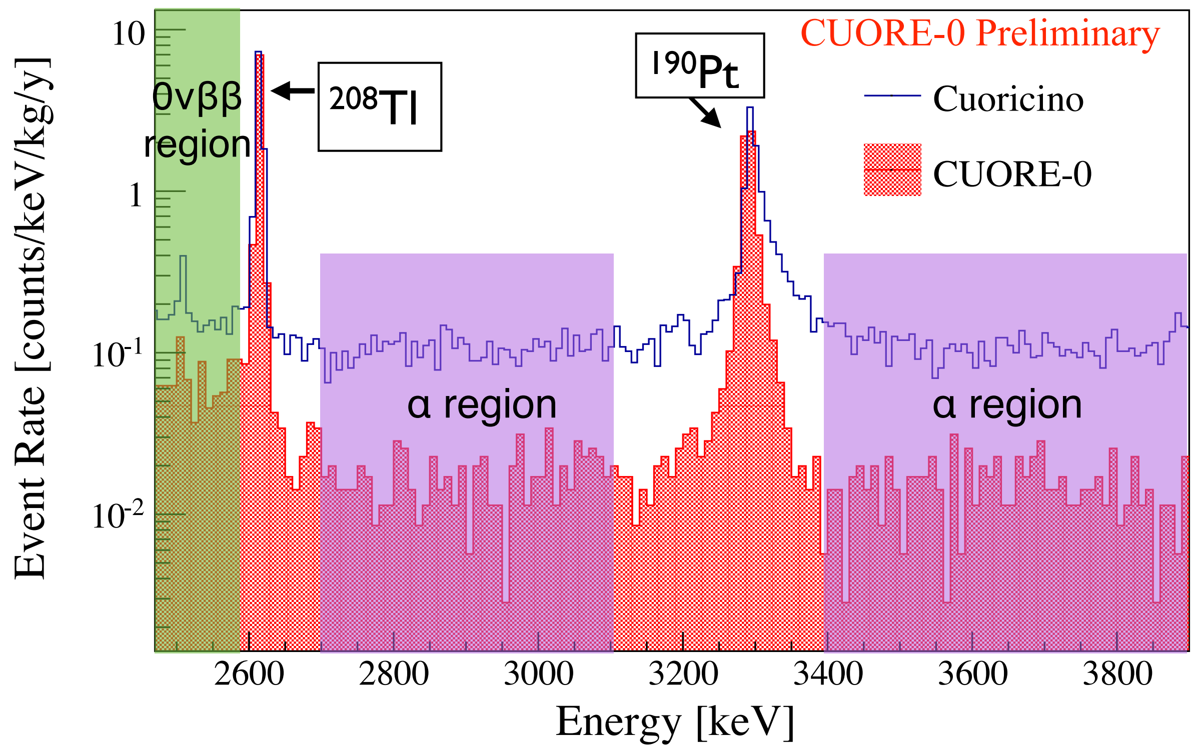
CUORE-0 Background Measurement



- 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!

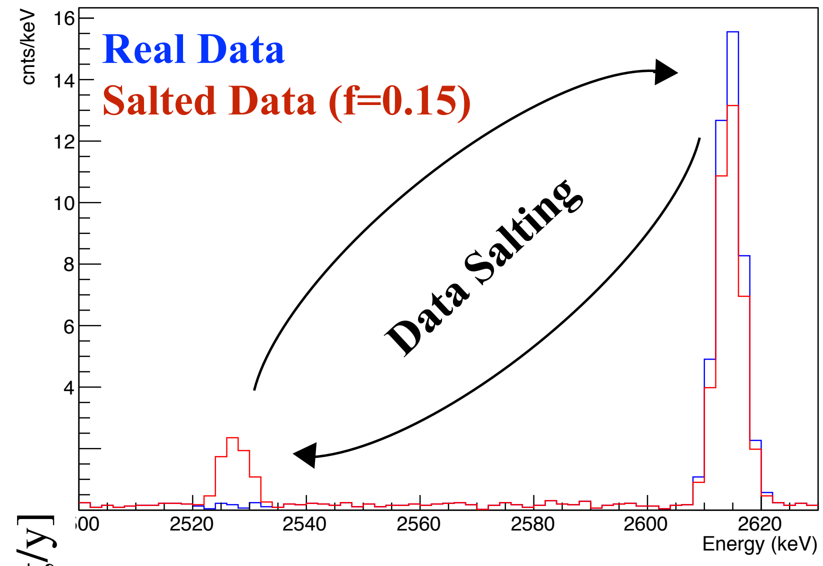
Background Rate & Reduction

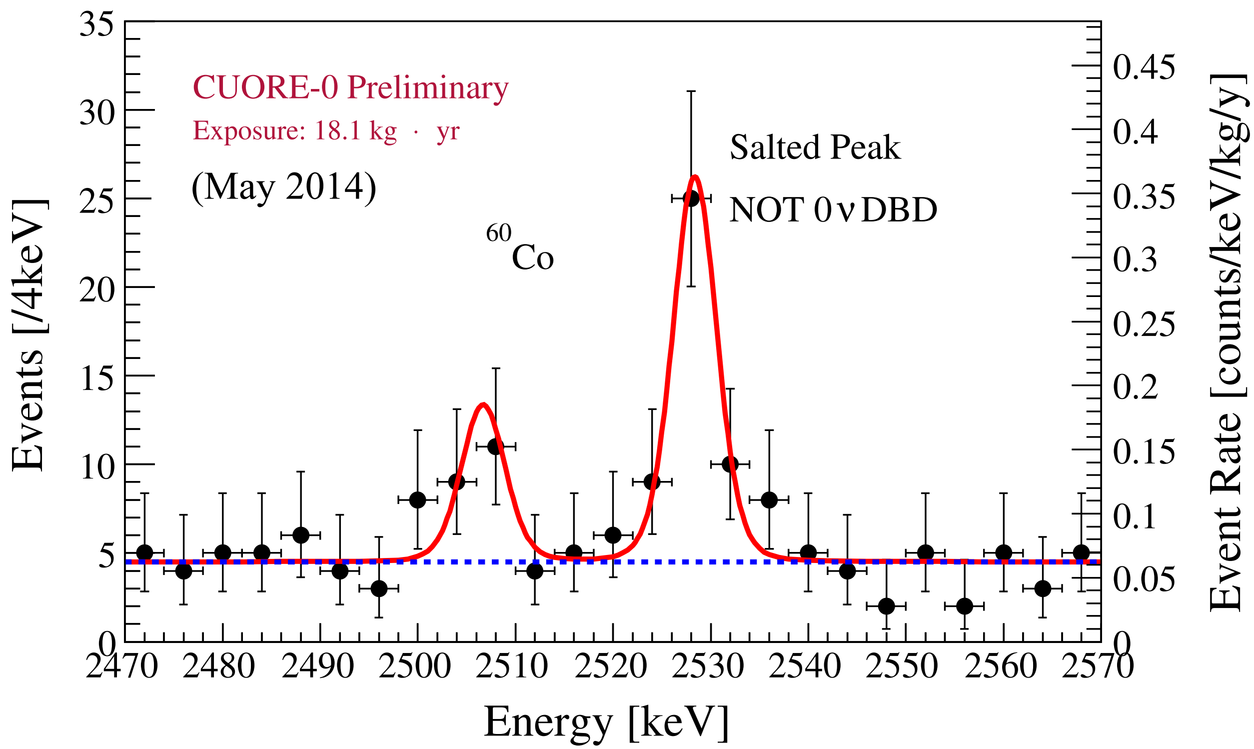


	Background rate [counts/keV/kg/y]		signal eff. [%] (detector+cuts)
	0νββ region	α region (excl. peak)	
Cuoricino	0.169 ± 0.006	0.110 ± 0.001	82.8±1.1
CUORE-0	0.058 ± 0.011	**0.016 ± 0.001**	81.3±0.6

Blind Analysis

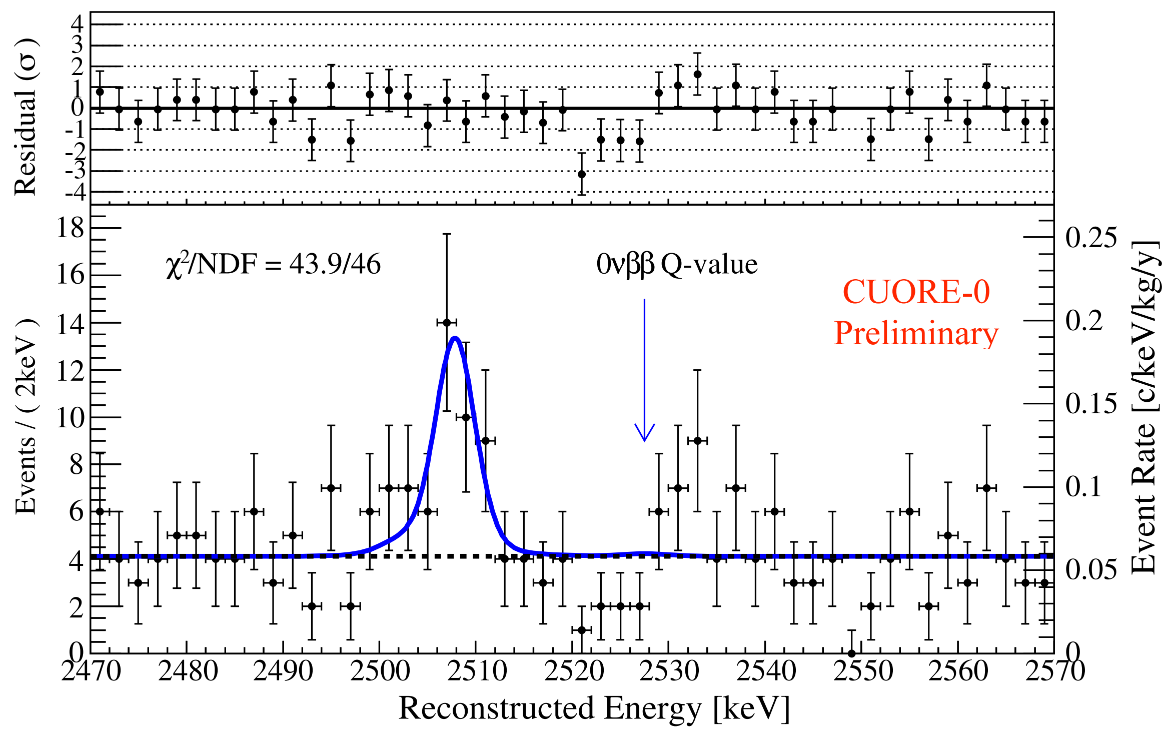
- Region of Interest was blinded by “salting” : A small (and ***blinded***) fraction of the events within ±10 keV in ^{208}Tl photopeak are exchanged with events within ±10 keV of the 0νββ Q-value to produce a ***fake*** peak.





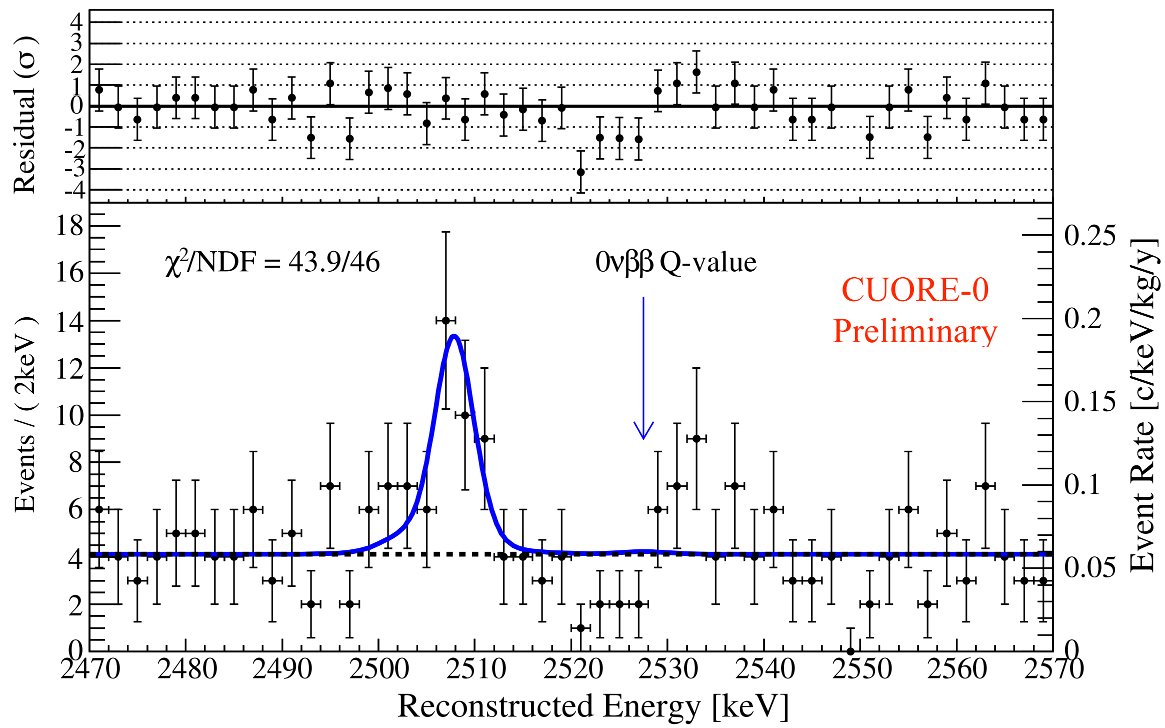
- Background at ROI characterized without biasing 0νββ analysis.

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

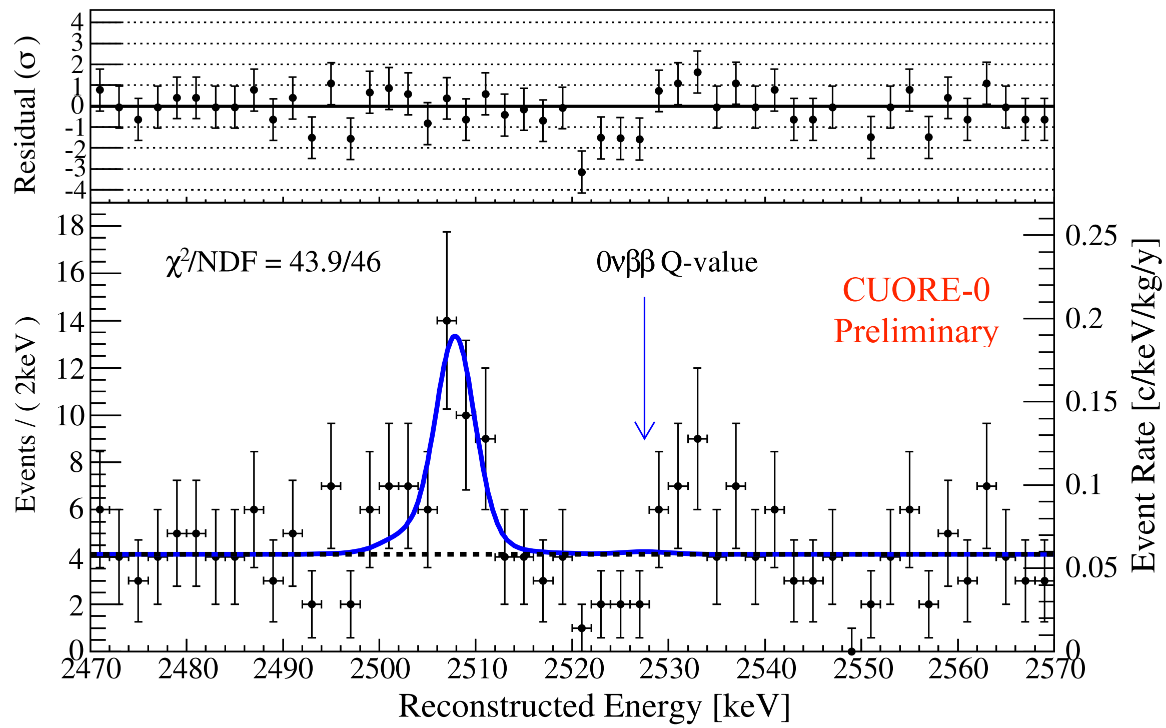
Unblinded Spectrum & Fit



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

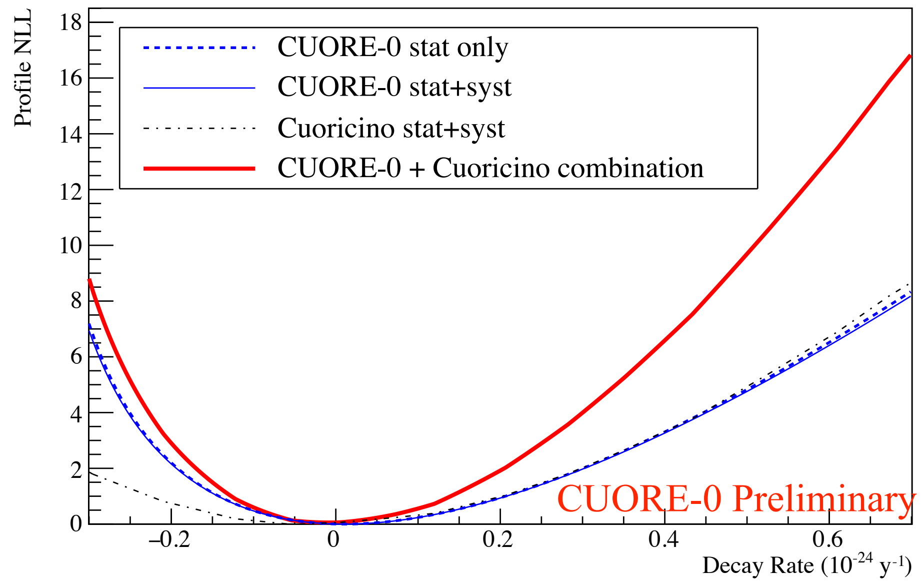


$\Gamma^{0\nu\beta\beta}$ (^{130}Te) < 0.25 × 10^{-24} yr^{-1} (90% C.L., statistics only)

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

No evidence for 0νββ of ^{130}Te found

CUORE-0 + CUORICINO



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

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

arXiv:1504.02454
Submitted to PRL

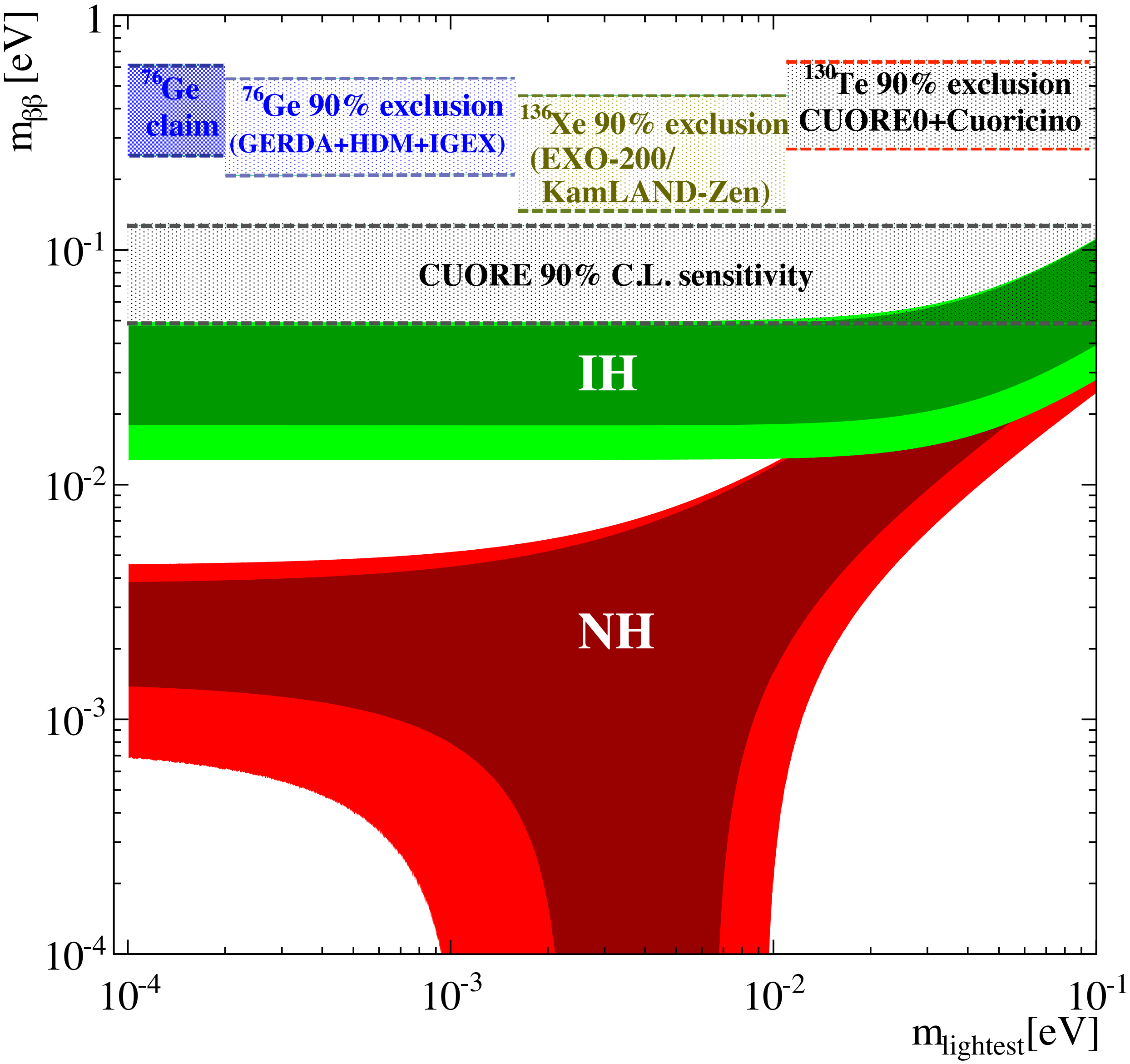
Systematics

TABLE I. Systematic uncertainties on $\Gamma_{0\nu}$ in the limit of zero signal (Additive) and as a percentage of nonzero signal (Scaling).

	Additive (10^{-24} y^{-1})	Scaling (%)
Lineshape	0.007	1.3
Energy resolution	0.006	2.3
Fit bias	0.006	0.15
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Selection efficiency	0.7%	

- For each systematic, we run toy MC exps. to evaluate bias on fitted 0νββ rate.
- Bias is parameterized as p0 + p1xΓ, where p0 =“additive” and p1=“scaling”
- Signal lineshape: Used variety of different line shapes to model signal
- Energy resolution: Apply 1.05 ± 0.05 correction to calibration-derived resolution
- Fit bias: Effect of using unbanned extended ML fit to extract values
- Energy scale: Assign 0.12 keV uncertainty derived from peak residuals in physics spectrum
- Bkg function: Choices of 0-,1-,2- order polynomial.

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))

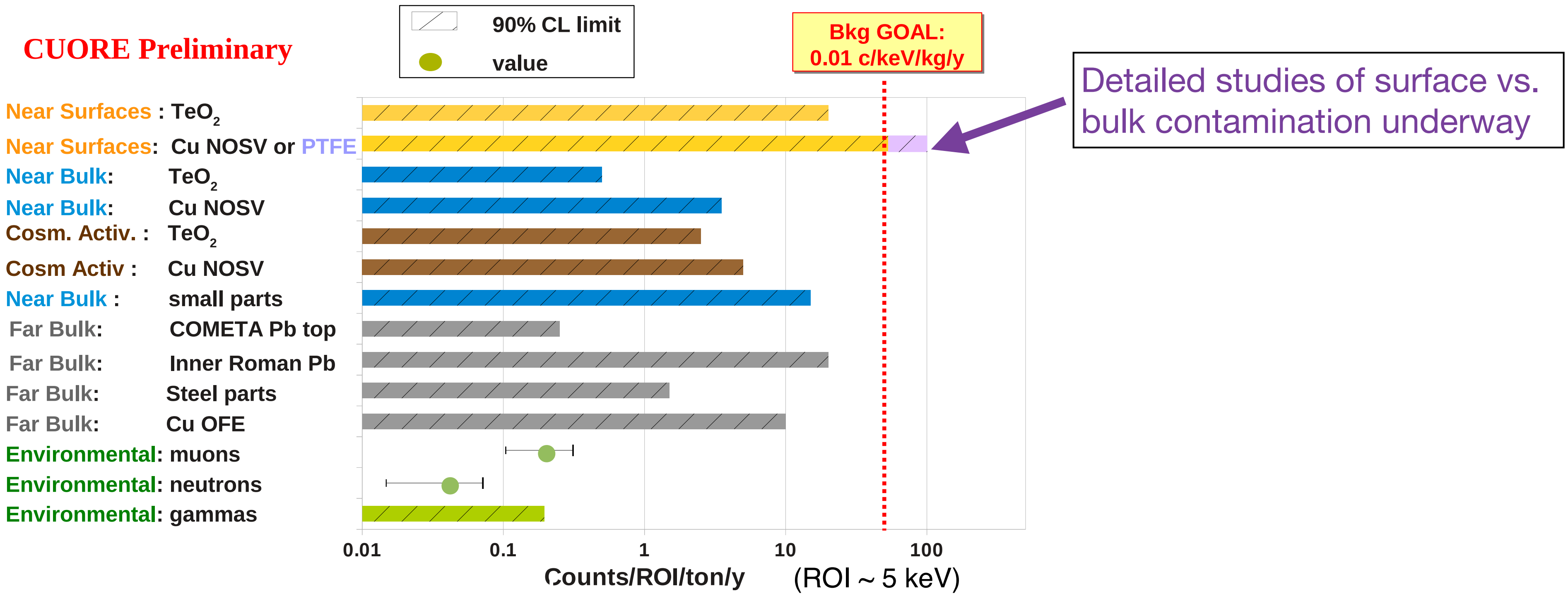
Including additional Shell-Model NME

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

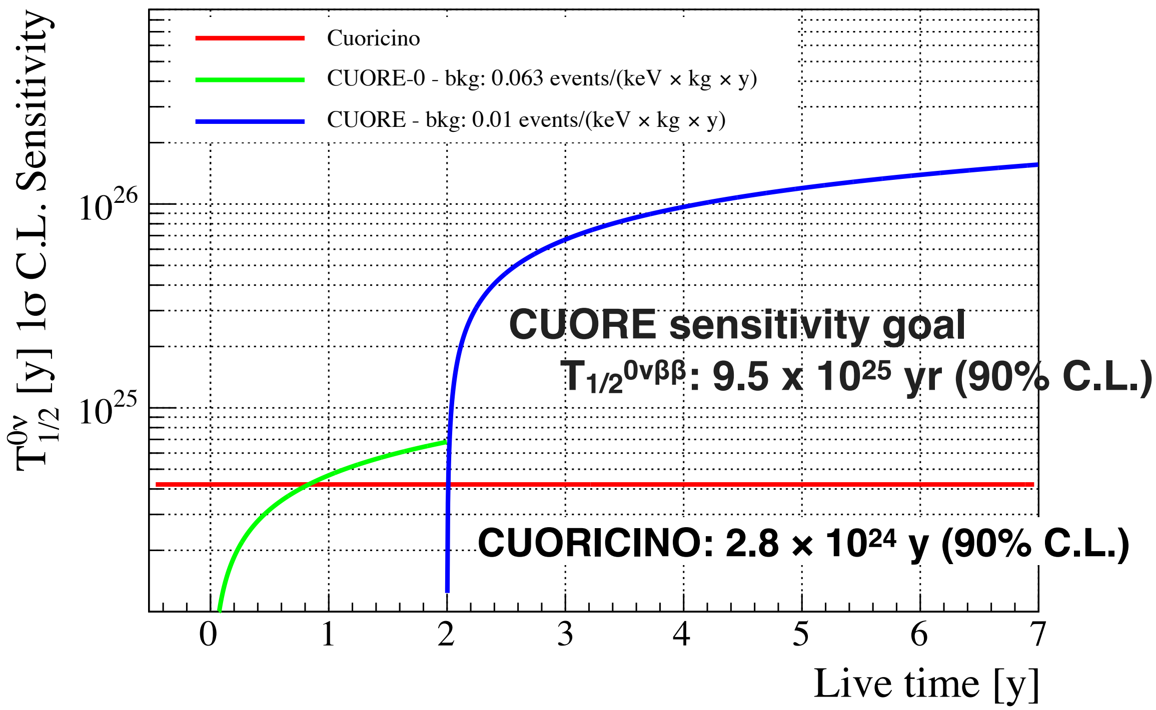
Projected CUORE Background

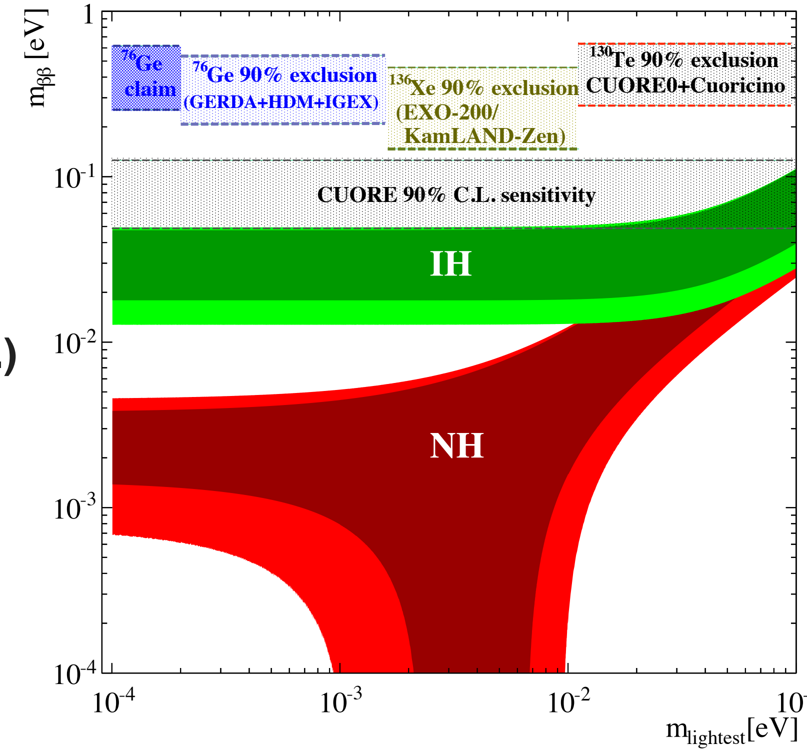
- CUORE-0 - provides bench mark for remaining background with new assembly & crystal/Cu cleaning protocols
- CUORE - results of CUORE-0 + screening campaign results -> CUORE MC



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

CUORE Sensitivity

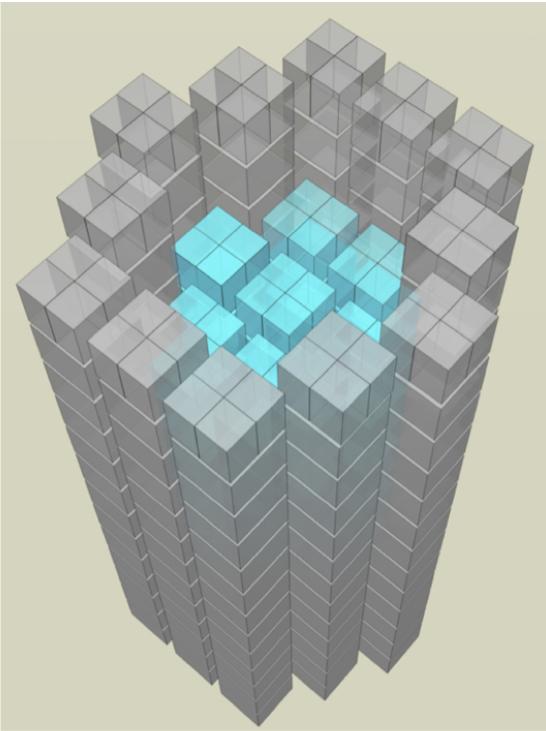




- CUORE sensitivity goal:
  - **$T_{1/2}^{0\nu\beta\beta}$ > 9.5 x 10^{25} yr** @ 90% C.L.
- Effective Majorana mass 51 - 133 meV @ 90% C.L.
  - Assumptions: 5 keV FWHM ROI resolution (δE), background rate (b) of 0.01 counts/(keV·kg·yr), 5 years of live time.

arXiv:1109.0494

Beyond CUORE: ^{130}Te Enrichment

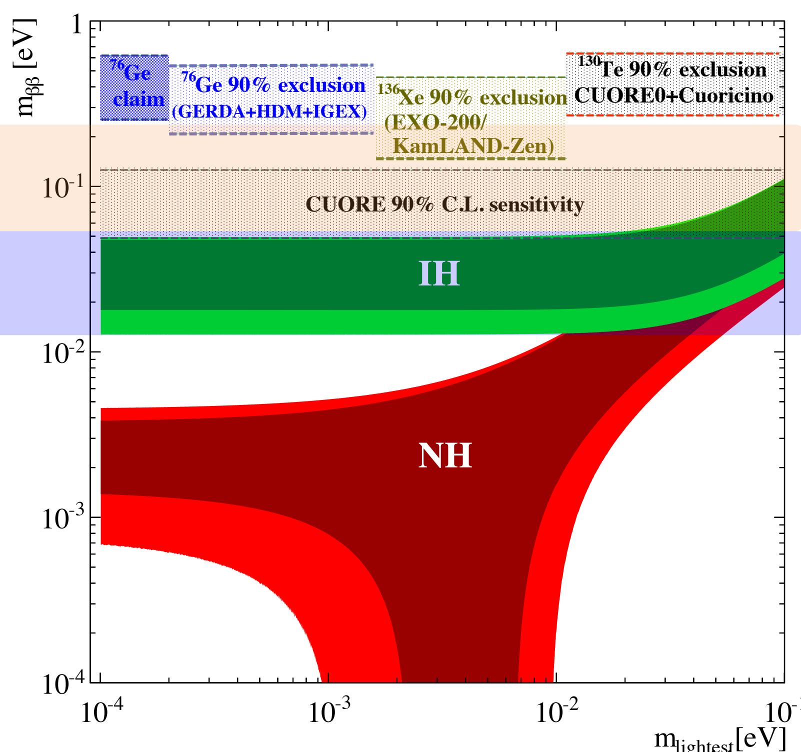


Enrichment

- **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 $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 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

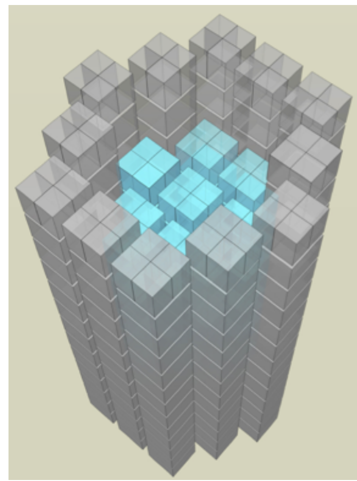
via particle ID

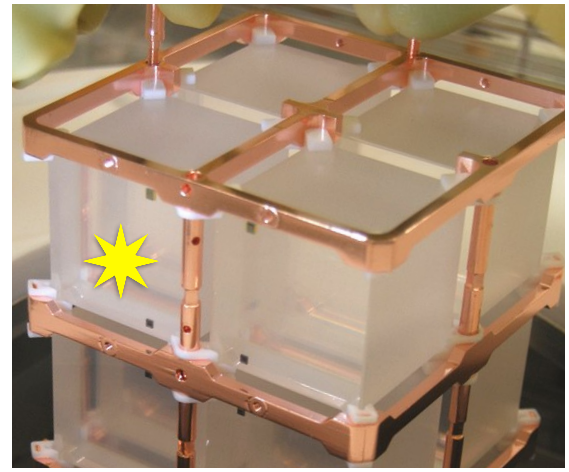
cleaner detectors,

tag backgrounds,

active veto

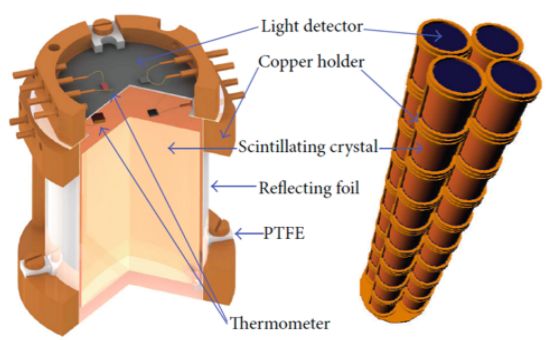
Explore other/multiple isotopes

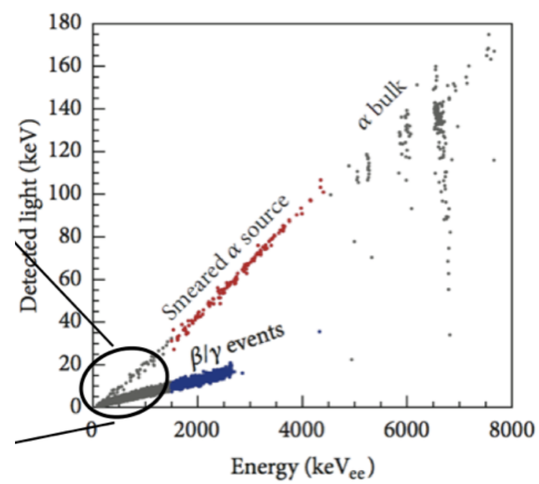




Bolometer R&D:

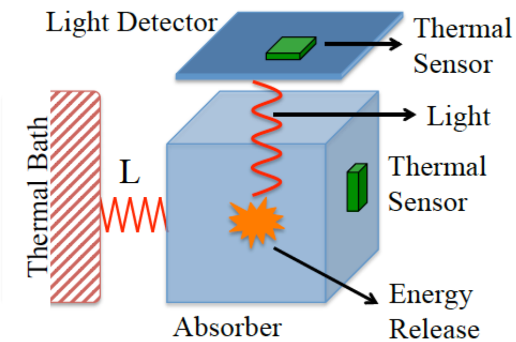
- CALDER
- Cherenkov/TeO_2
- LUCIFER
- LUMINEU

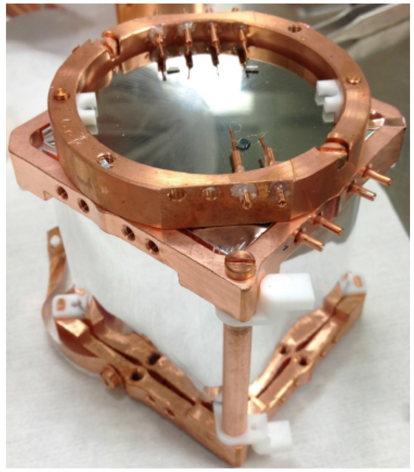


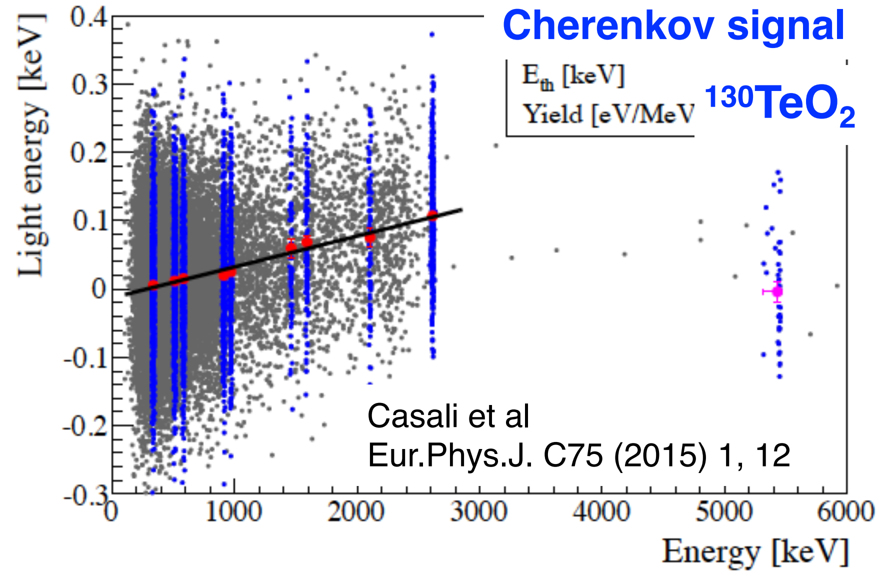


Beyond CUORE: Particle ID with Light Detectors

phonon+photon

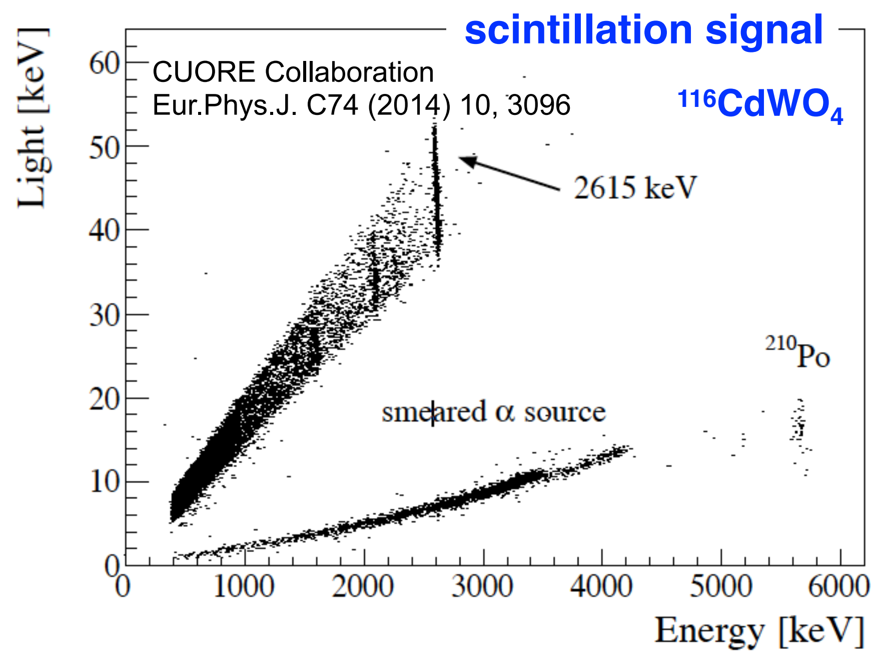






- Cherenkov light or scintillation to distinguish α from β/γ ($^{130}TeO_2$, $Zn^{82}Se$, $^{116}CdWO_4$, and $Zn^{100}MoO_4$)
- More rejection power needed: 99.9% α background suppression. Light detector R&D for better resolution.
- Background free search.

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



Conclusions

Neutrinoless double beta (0vββ) 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 (0vββ) in ^{130}Te to date.
- **CUORE**
  - tower assembly is complete and cryogenic system commissioning underway.
  - physics data taking expected to start 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!