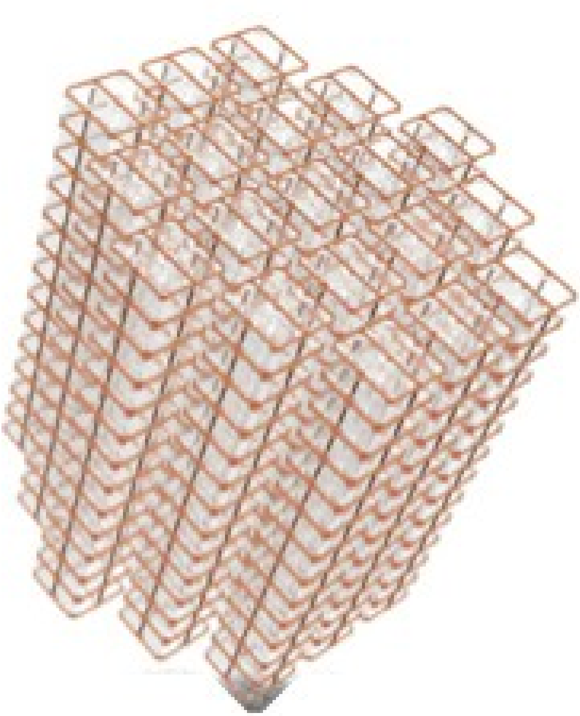
Results from the search for $0\nu\beta\beta$ decay of ^{130}Te with CUORE-0

Pablo Mosteiro
INFN – Roma
CUORE collaboration
Invisibles, June 22nd, 2015

CUORE

Cryogenic Underground Observatory for Rare Events

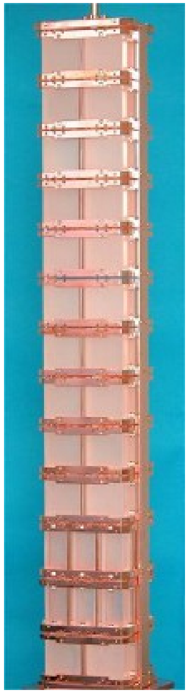


19 x 52 TeO_2 cryogenic bolometers

to search for $0\nu\beta\beta$ decay of ^{130}Te

CUORE program

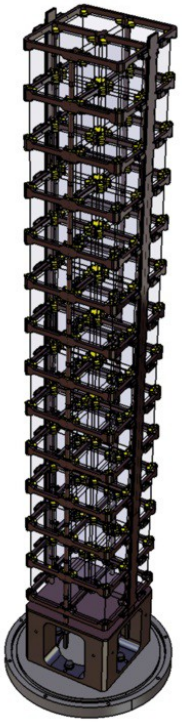
Cuoricino
11.3 kg ^{130}Te



2003-2009

COMPLETED

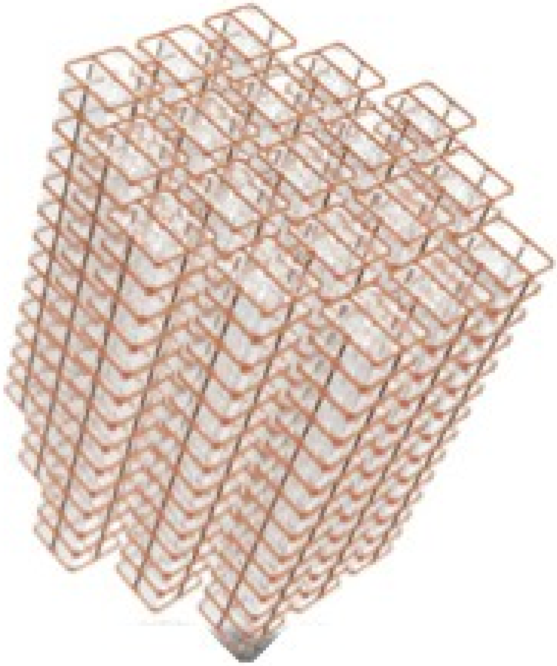
CUORE-0
11.3 kg ^{130}Te



2013-2015

COMPLETED

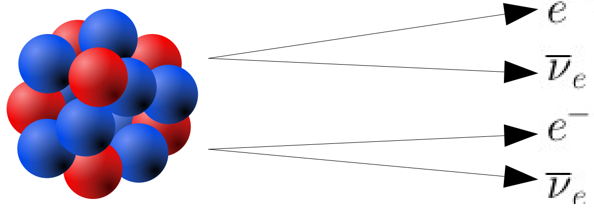
CUORE
206 kg ^{130}Te



2015-2020

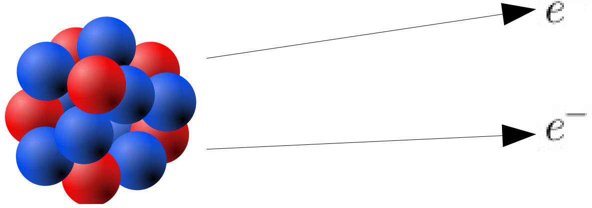
Double beta decay

2νββ



$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^- + 2\overline{\nu}_e$$

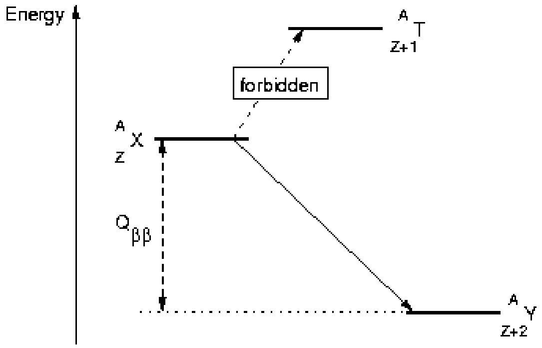
0νββ



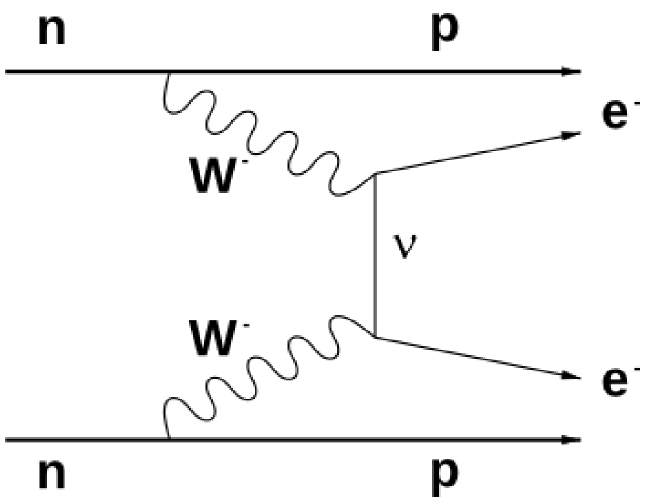
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^-$$

- Observed, but extremely rare
  $T_{1/2} > 10^{18}$ y
- Only visible in nuclei for which single β is forbidden

- Even rarer (if it exists at all)
  $T_{1/2} > 10^{22}$ y
- Only one controversial claim of observation so far



Physics motivation



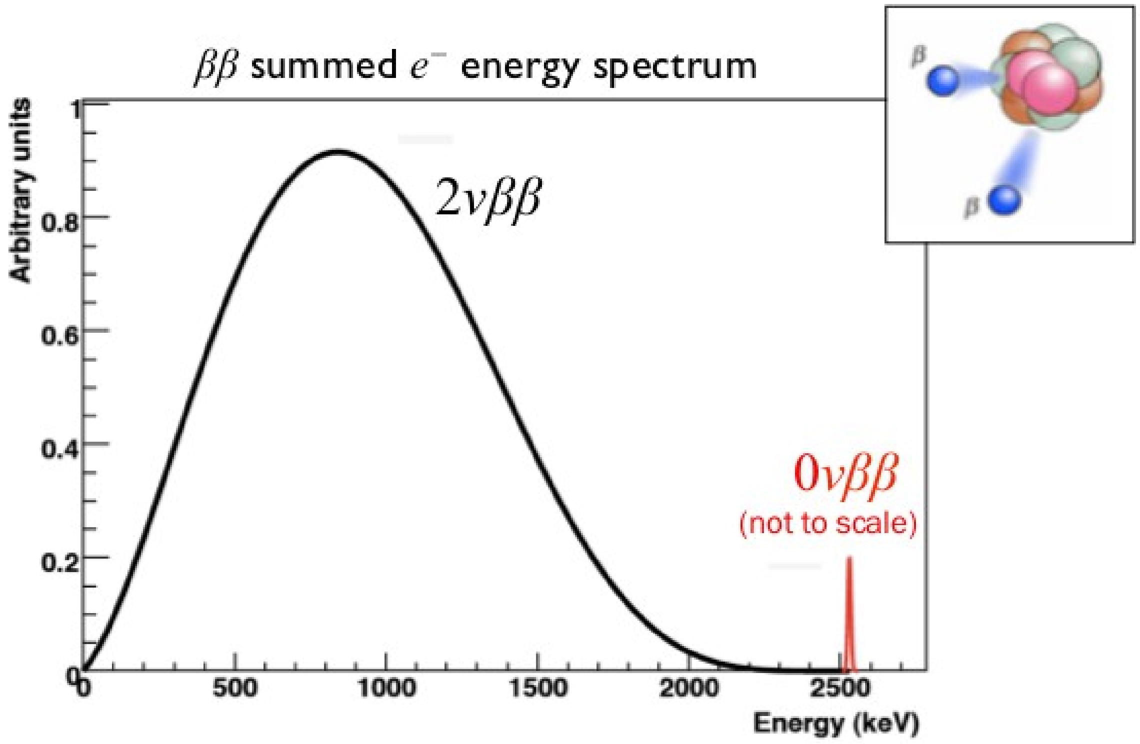
If 0νββ decay were observed, it would:

1) Disprove lepton number conservation

2) Prove that neutrinos are Majorana particles (*i*.e., $\bar{\nu}=\nu$)

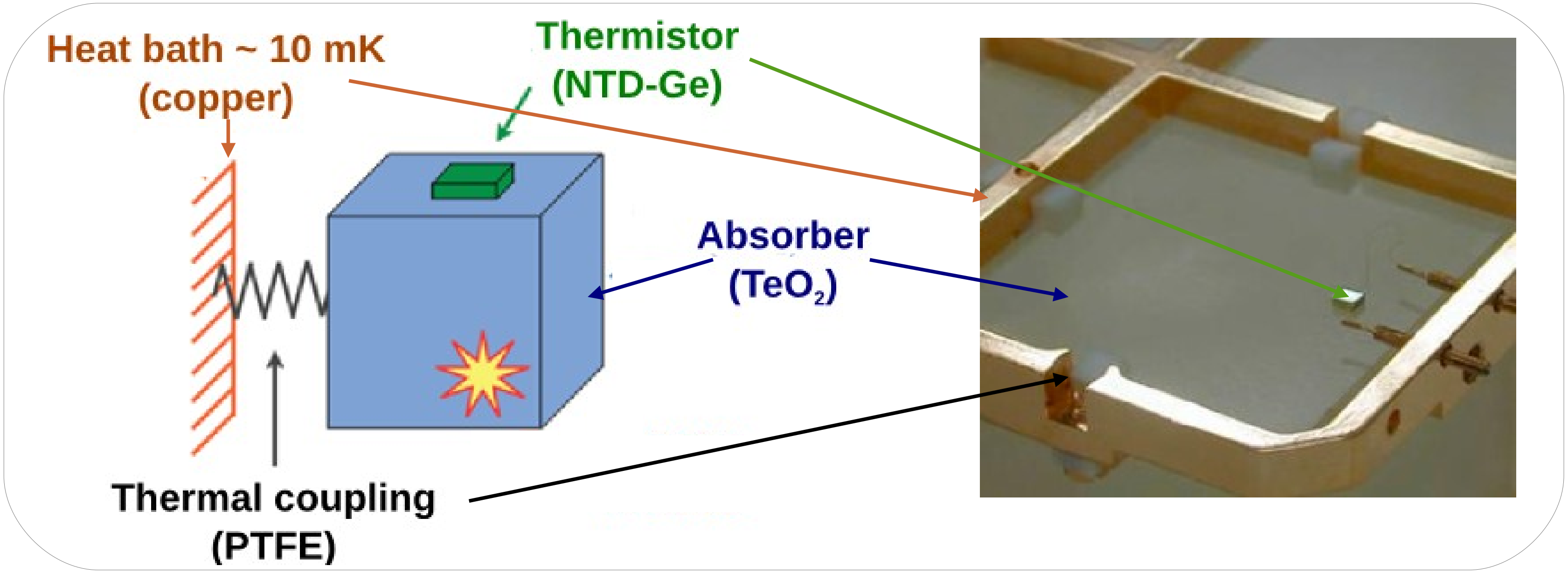
3) Provide information on neutrino mass scale and hierarchy

Detecting 0νββ decay



Signature: Two simultaneous electrons with summed energy $Q_{\beta\beta}$, the Q-value for ββ decay in the isotope under study

Cryogenic bolometers



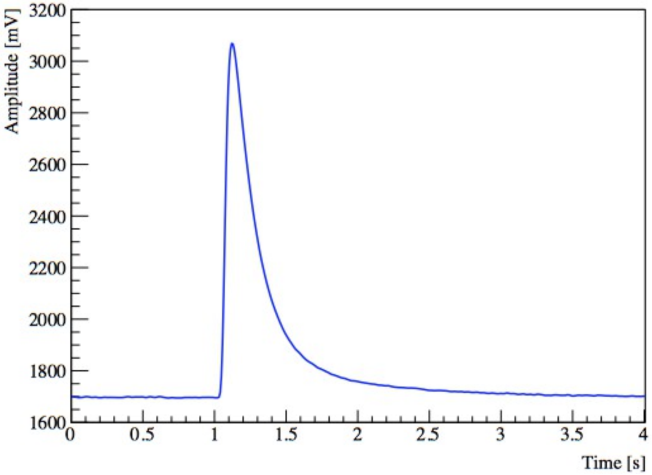
Heat bath ~ 10 mK (copper)

Thermistor (NTD-Ge)

Absorber (TeO_2)

Thermal coupling (PTFE)

$$\Delta T = \frac{E}{C(T)}$$



Particle energy is converted into phonons

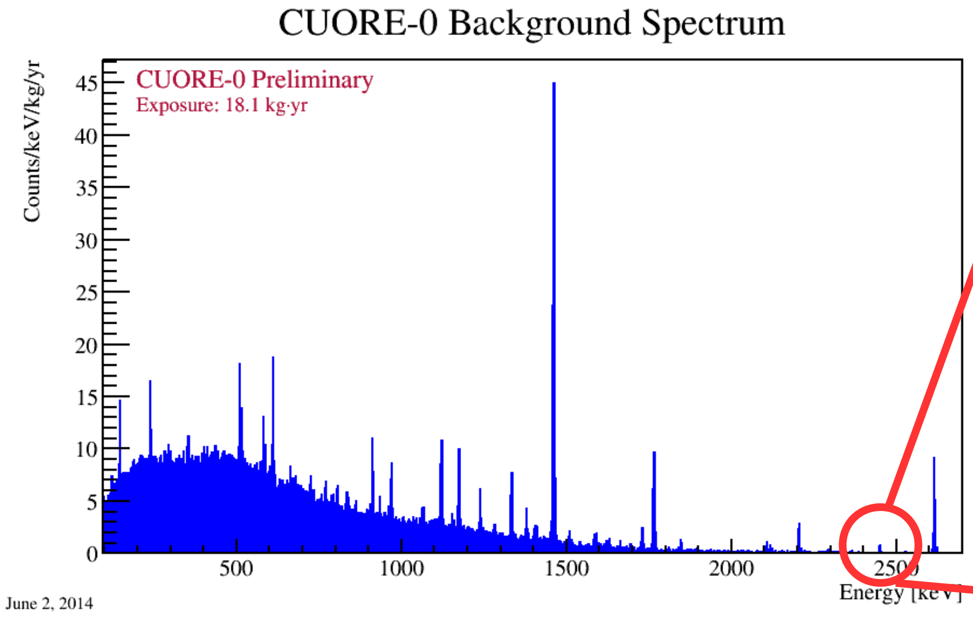
by absorbers whose heat capacity is $C \propto T^3$

(@T~10 mK: 1 MeV → ΔT~300 mK)

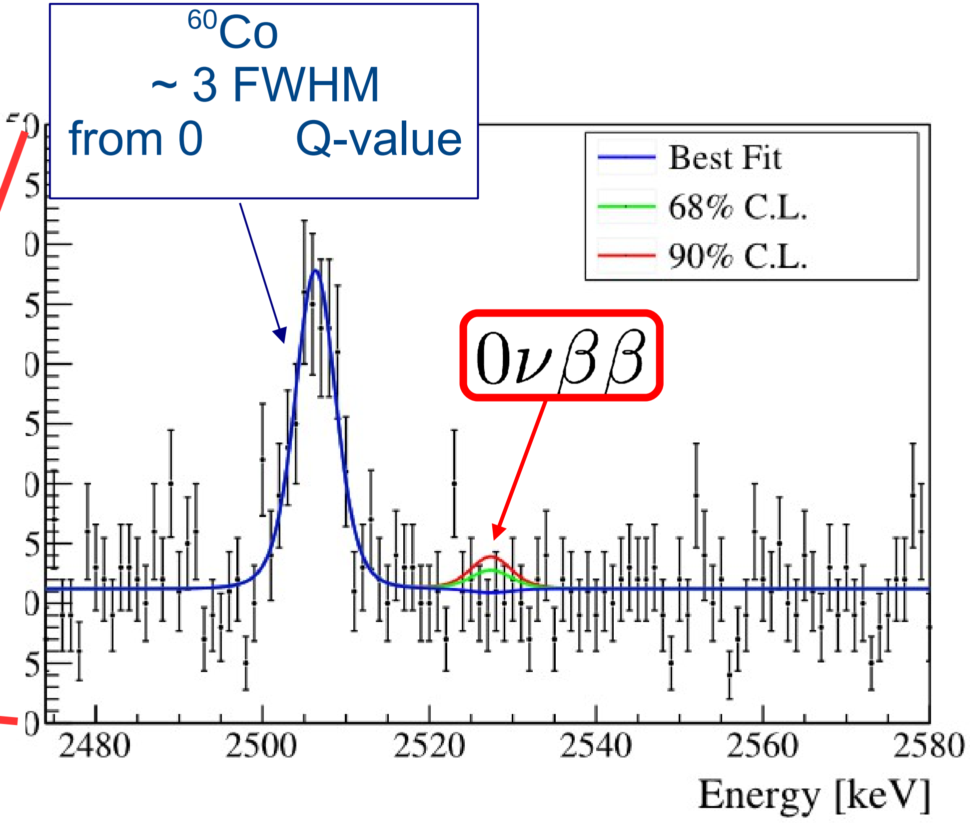
Crystal Absorber (TeO_2): E → ΔT

Biased T sensor (NTD-Ge): ΔT → ΔV

Experimental method



Cuoricino null result



^{60}Co

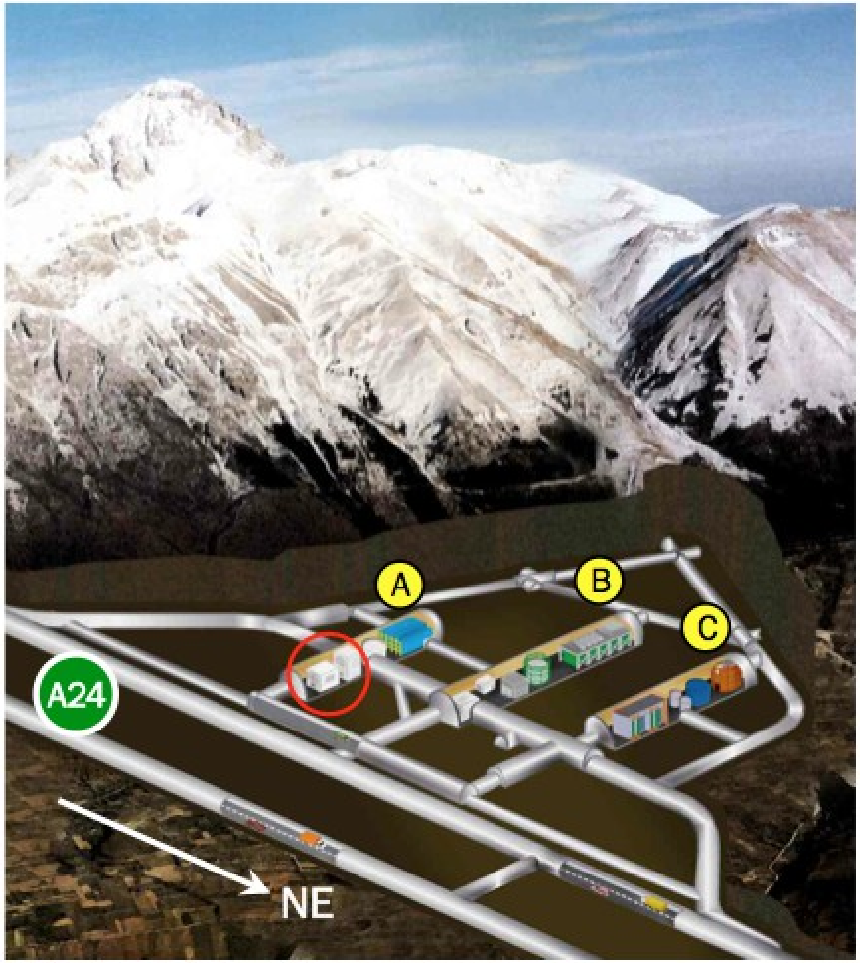
~ 3 FWHM

from 0 Q-value

1. Compile energy spectrum of detected pulses

2. Look for a small peak at 2527.5 keV [PRL 102, 212502 (2009)]

Detector location



Gran Sasso, Abruzzo, Italy

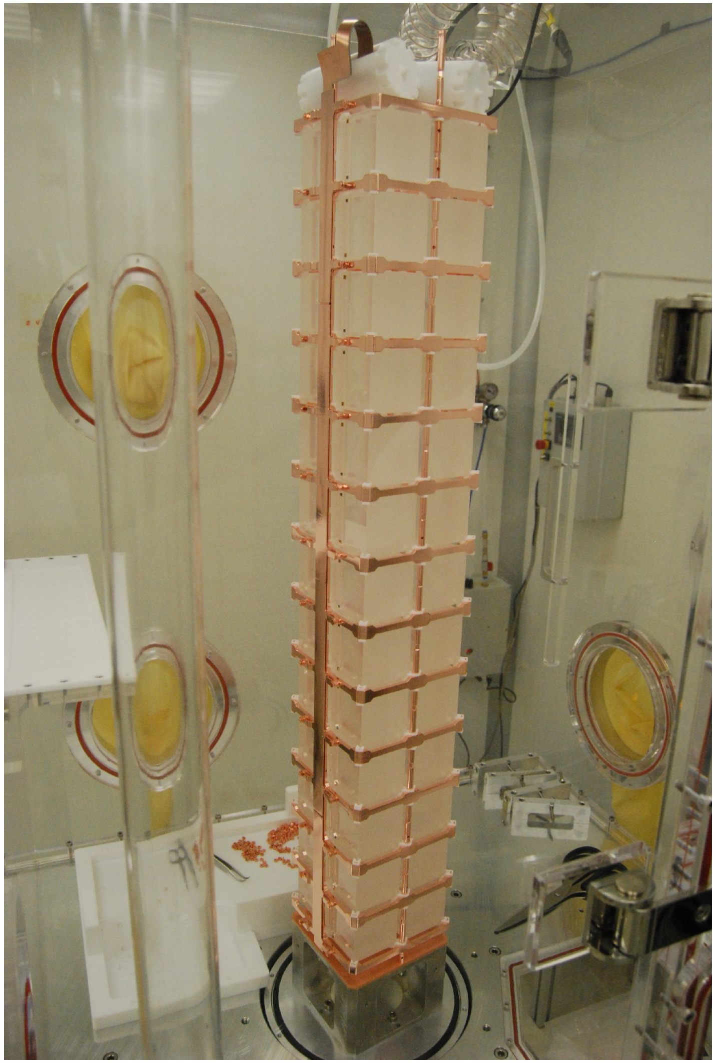
Average depth ~ 3600 m.w.e.
(1.4 km of rock)

μ flux: ~3×10^{-8} μ/(s cm^2)

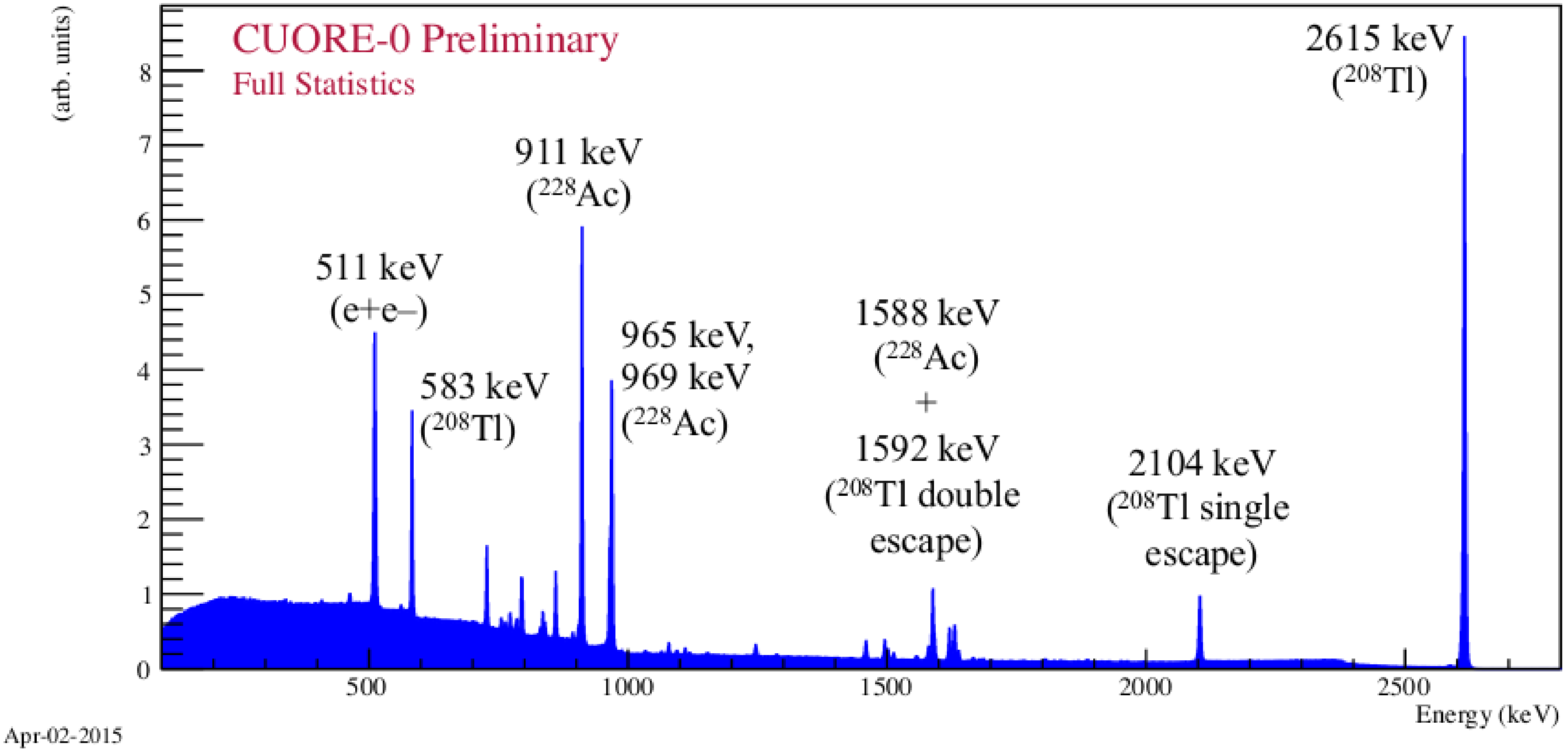
PRD 73, 053004 (2006)

CUORE-0 Goals

- First detector from the CUORE assembly line
- Total mass = 39 kg (TeO_2) = 10.9 kg (^{130}Te)
- Operating inside former Cuoricino cryostat since 2013
- Goals:
  - Commission assembly line
  - Surpass Cuoricino result while building CUORE
  - Validate CUORE detector design
  - Test bed for DAQ & analysis framework for CUORE

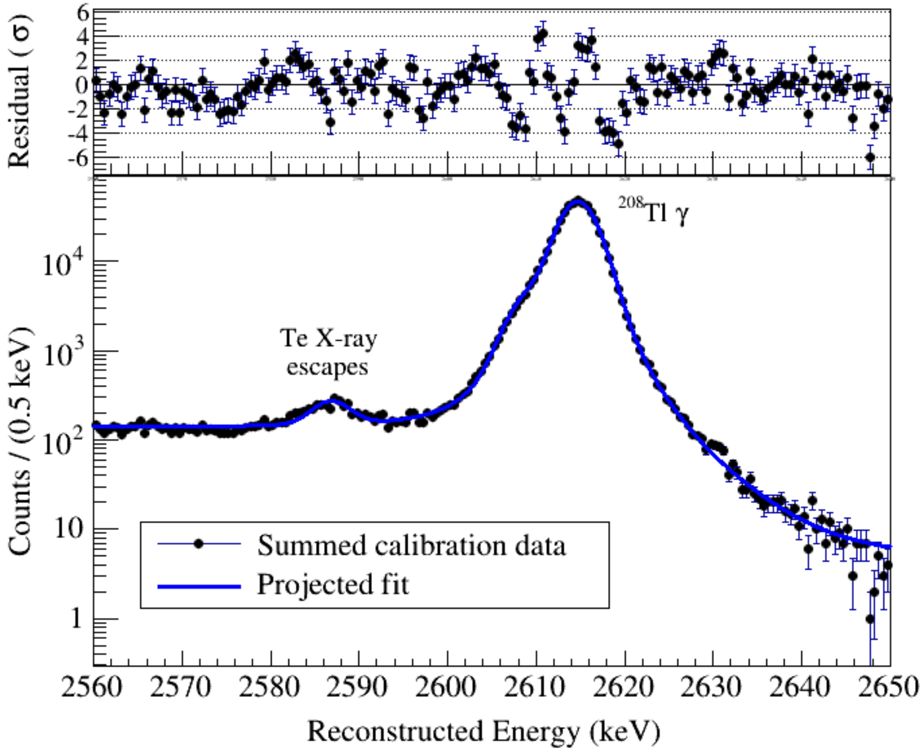


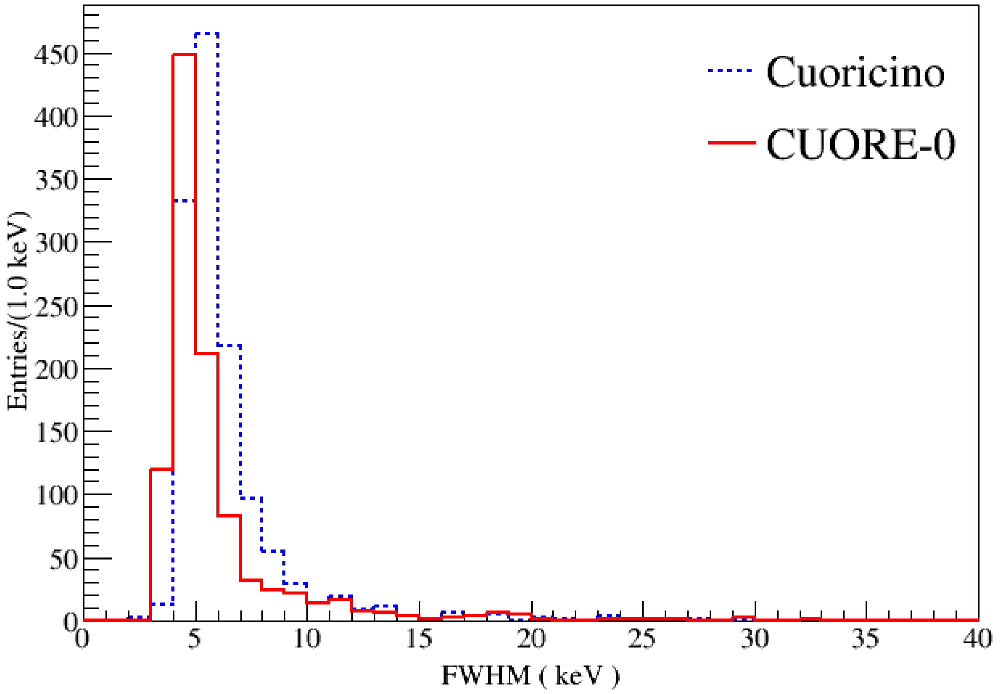
Calibration Spectrum



~1/mo: thoriated W wires between cryostat and external Pb shield

Energy Resolution

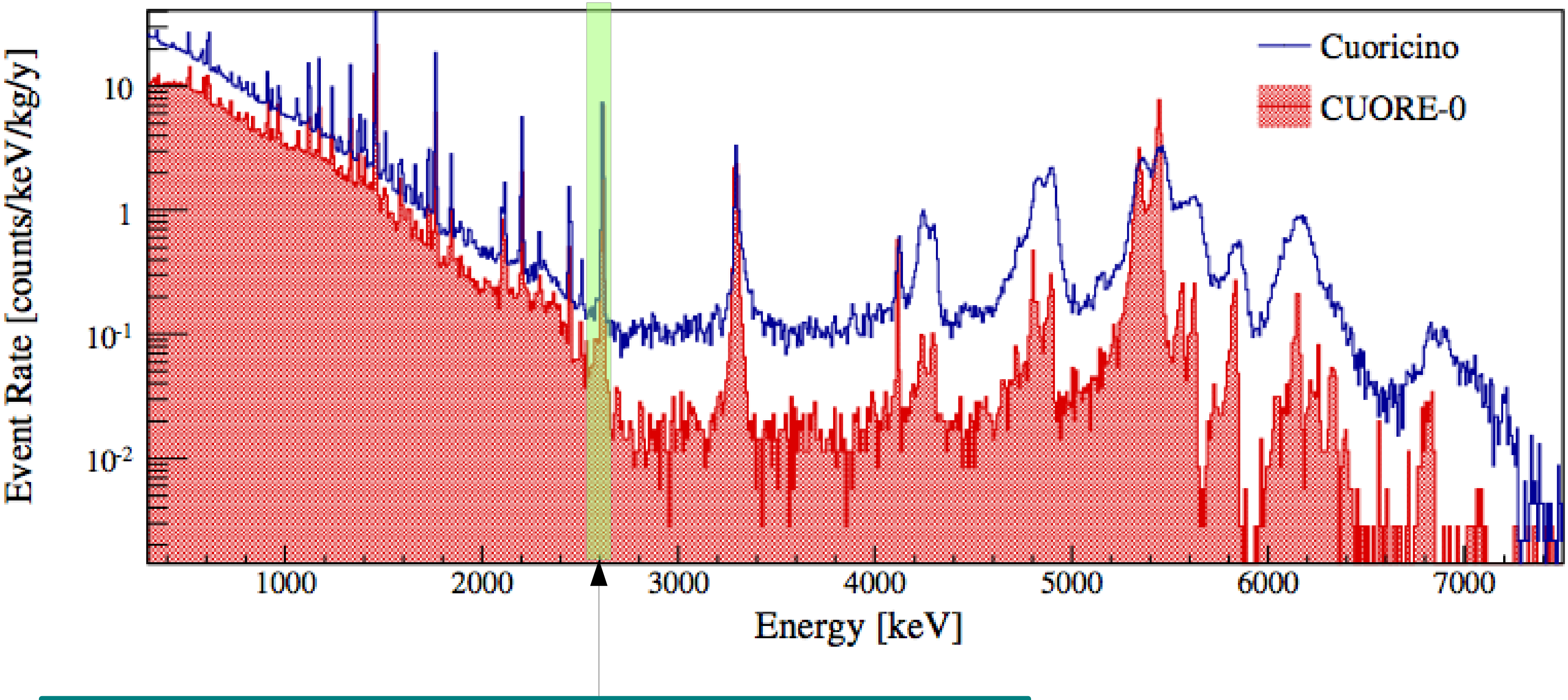




- Fit ^{208}Tl peak for each bolometer and dataset
- Weight FWHMs by corresponding exposure
- ✓ Goal of CUORE: 5 keV resolution

	FWHM harmonic mean (keV)	FWHM dist RMS (keV)
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

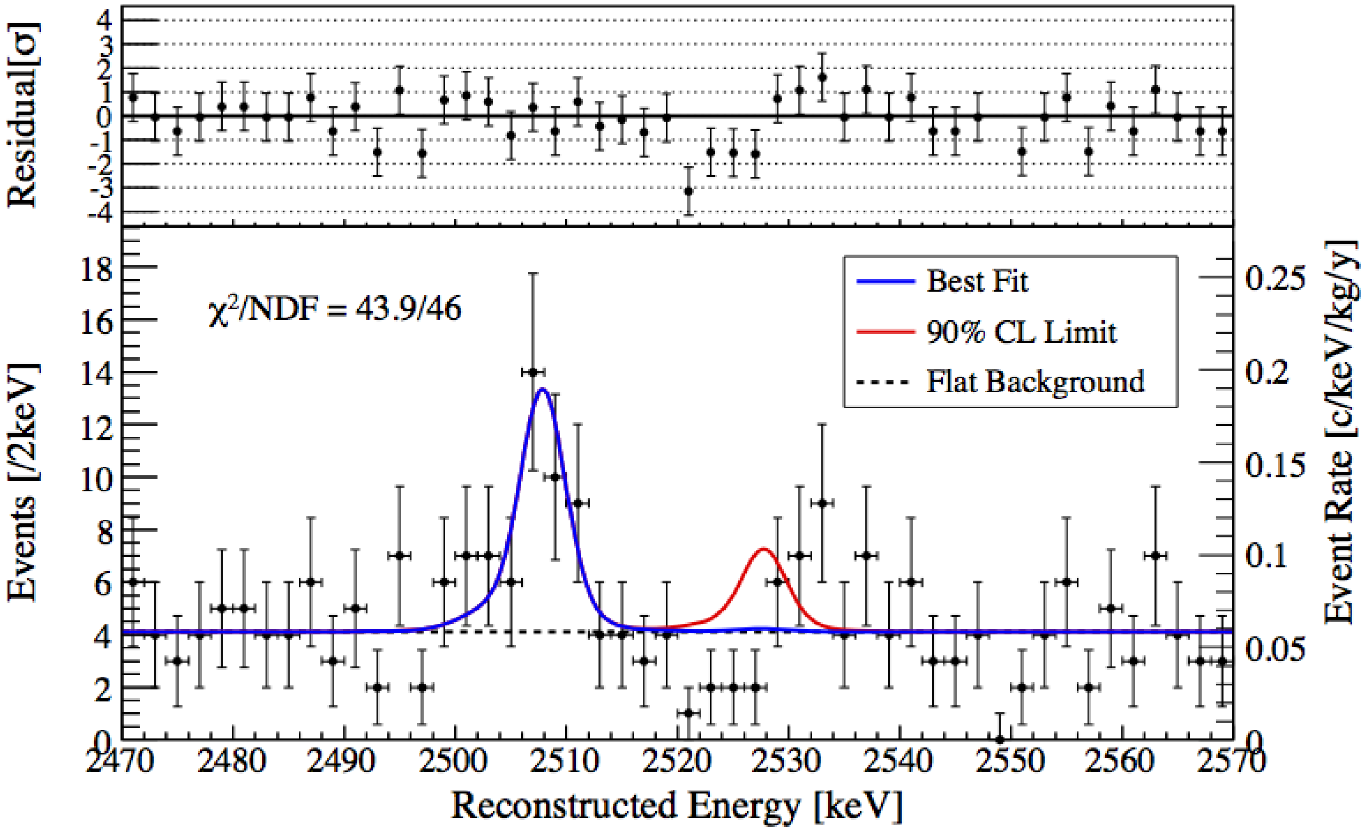
CUORE-0 Spectrum



Region Of Interest (ROI) for ^{130}Te $0\nu\beta\beta$ decay

Fit Results

35.2kg-y TeO_2 (9.8kg-y ^{130}Te) exposure (2013-2015)

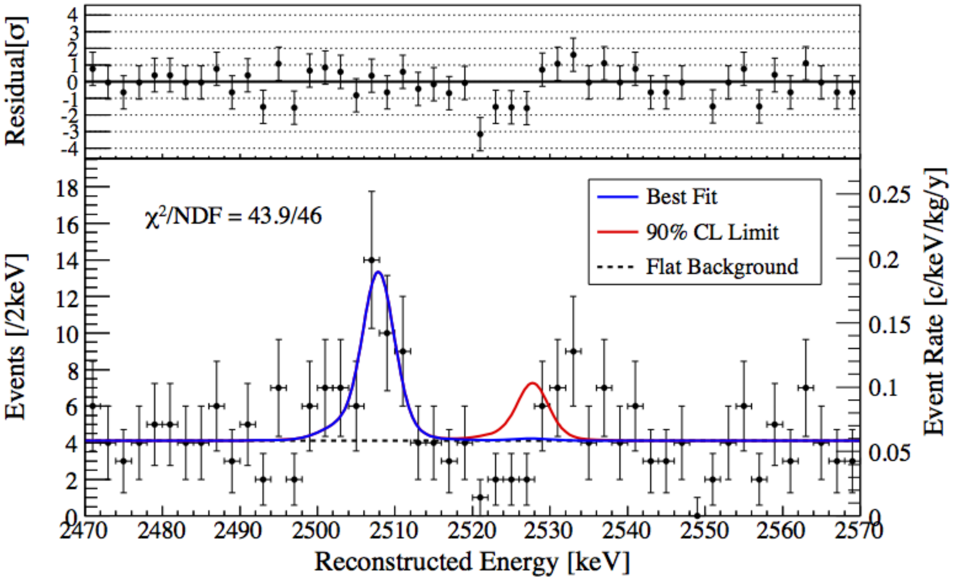


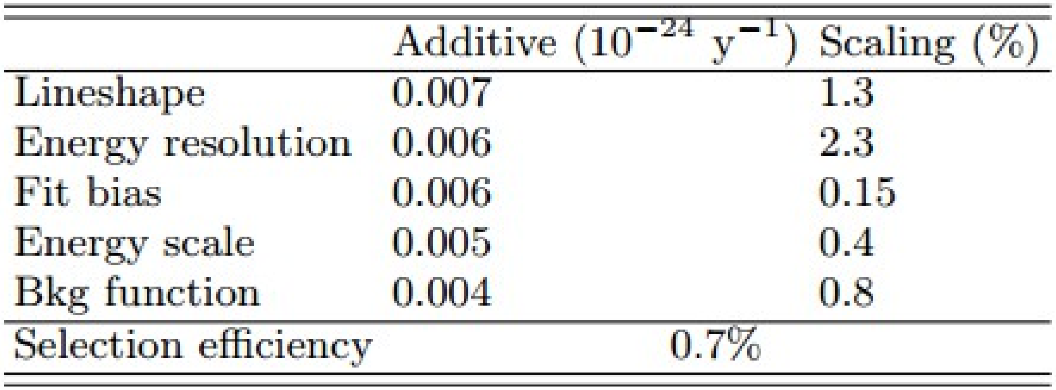
Background: 0.058 ± 0.004 (stat) ± 0.002 (syst) cpy/kg/keV

Decay rate: $\Gamma^{0\nu\beta\beta}$ (^{130}Te) = 0.007 ± 0.123 (stat) ± 0.012 (syst) x 10^{-24} y^{-1}

Final Results

9.8 kg-y ^{130}Te exposure (2013-2015)





	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%	

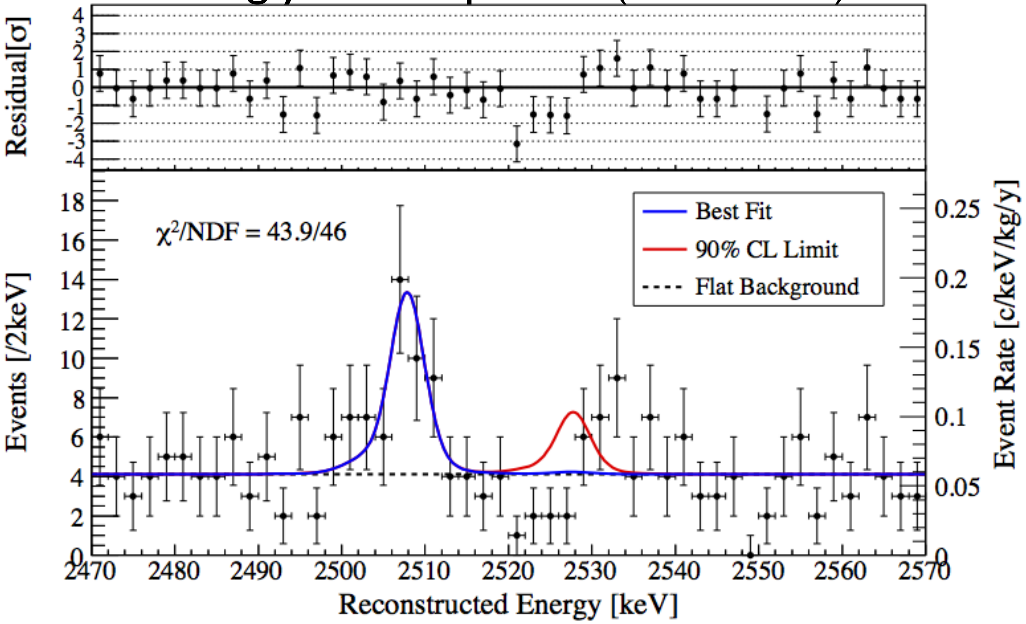
$$\Gamma^{0\nu\beta\beta} < 0.25 \times 10^{-24}\,\mathrm{y}^{-1}$$

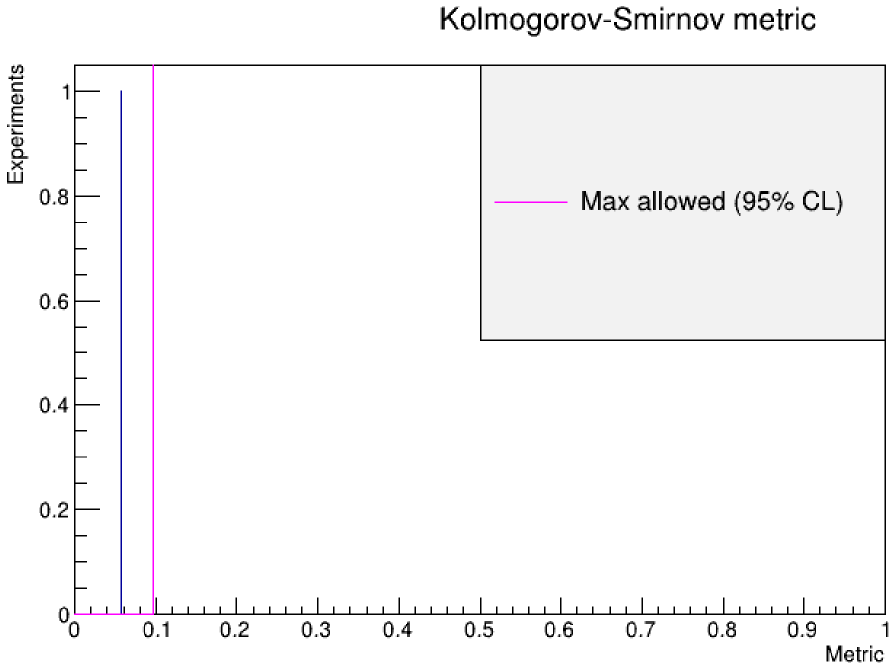
$$T_{1/2}^{0\nu\beta\beta} > 2.7 \times 10^{24}\,\mathrm{y}$$

(90% C.L., statistics + systematics)

Background Fluctuations

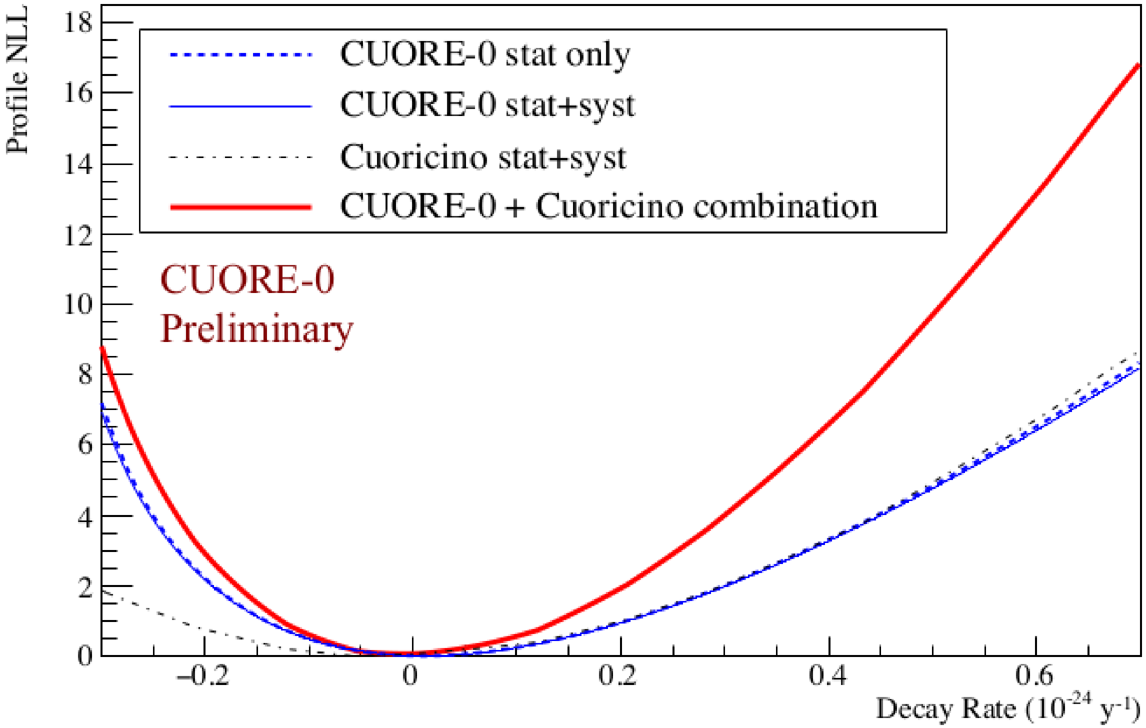
9.8 kg-y ^{130}Te exposure (2013-2015)





- Kolmogorov-Smirnov test: consistent with no peak at 95% CL
- All fluctuations <3σ from fit function
- Probability of largest fluctuation anywhere in ROI ~10%

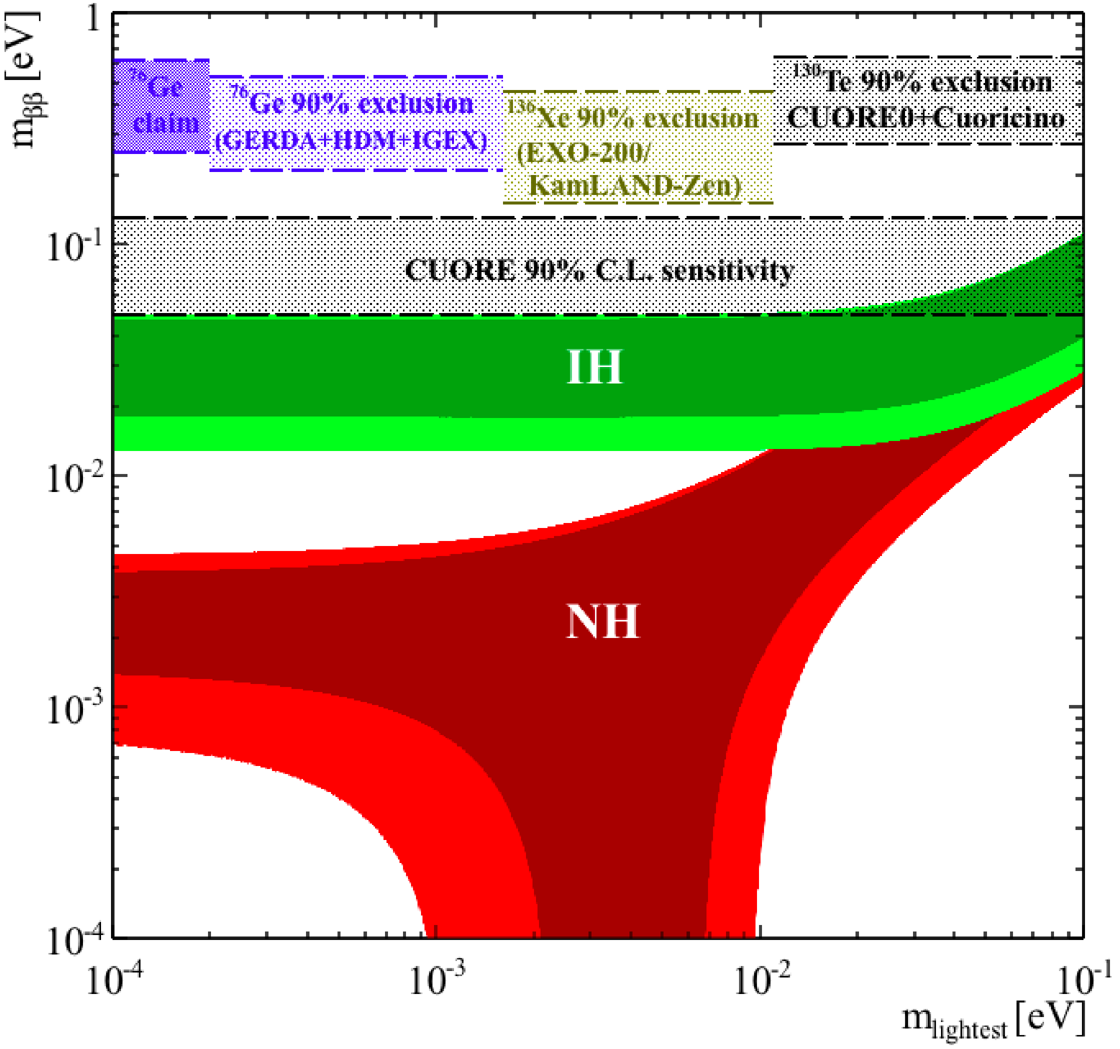
Combining with Cuoricino



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

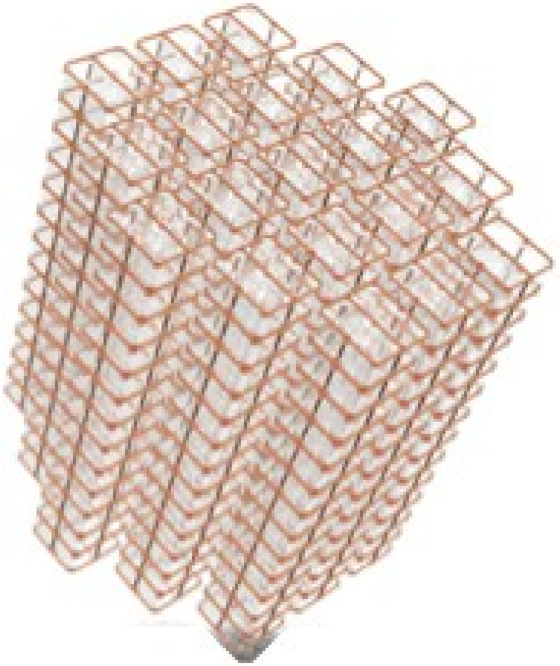
$$T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) > \ 4.0 \times 10^{24}\ \mathrm{yr} \ \ (90\%\ \mathrm{C.L.})$$

Physics Reach of CUORE



CUORE: the next challenge

- Challenge: scale up bolometric apparatus
- Advantage: larger active mass
- Advantage: Self-shielding and anti-coincidence



	Cuoricino	CUORE-0	CUORE
^{130}Te mass (kg)	11	11	206
Background (c/keV/kg/y) @ 2528 keV	0.17	0.06	0.01
E resolution (keV) FWHM @ 2615 keV	5.8	4.9	5
$T_{1/2}$ sensitivity (10^{24} yr) @ 90% C.L.	2.8	2.7/2.9	95

Conclusions

- TeO_2 bolometers good for $0\nu\beta\beta$ decay search
- CUORE-0
  - ✓ No evidence of $0\nu\beta\beta$ decay of ^{130}Te
  - ✓ Achieved energy resolution & background goals for CUORE
- CUORE
  - ● Assembly of all 19 towers complete
  - ● Commissioning cryostat and experimental infrastructure
  - ● Plan to start operations by end of 2015

The CUORE collaboration

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

SINAP

LUX ET VERITAS

INFN
Istituto Nazionale
di Fisica Nucleare

CAL POLY
SAN LUIS OBISPO

Lawrence Livermore
National Laboratory

Massachusetts
Institute of
Technology

SAPIENZA
UNIVERSITÀ DI ROMA

CSNSM

UCLA

CUORE

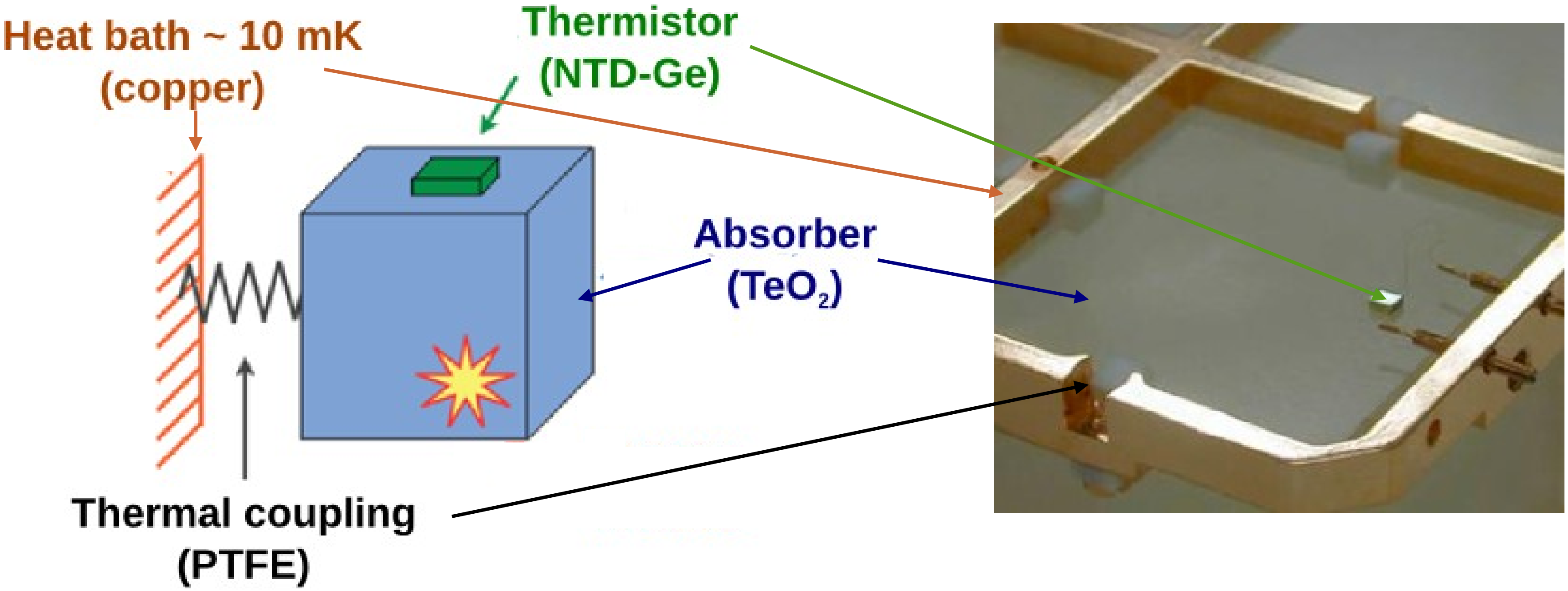
BERKELEY LAB

UNIVERSITY OF
SOUTH CAROLINA

Back-up Slides

Cryogenic bolometers

Source = Target



Heat bath ~ 10 mK (copper)

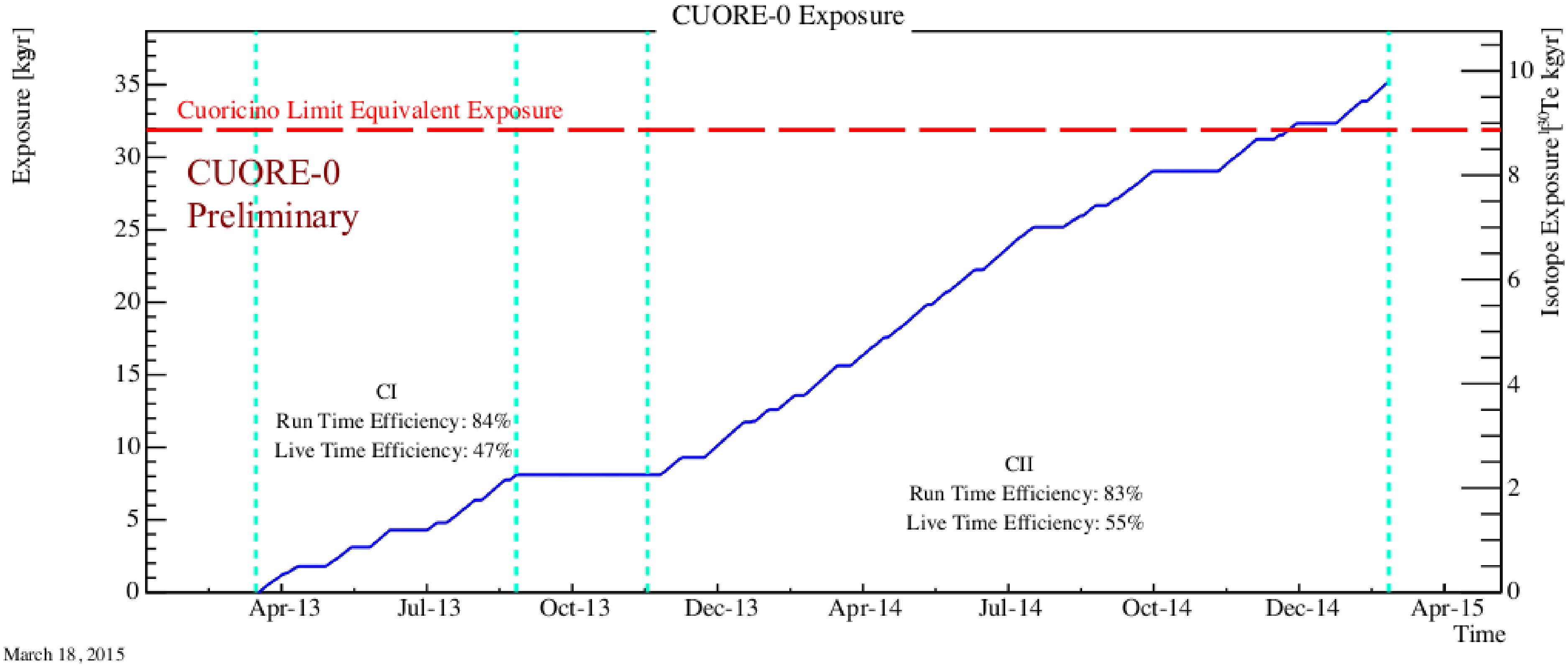
Thermistor (NTD-Ge)

Absorber (TeO_2)

Thermal coupling (PTFE)

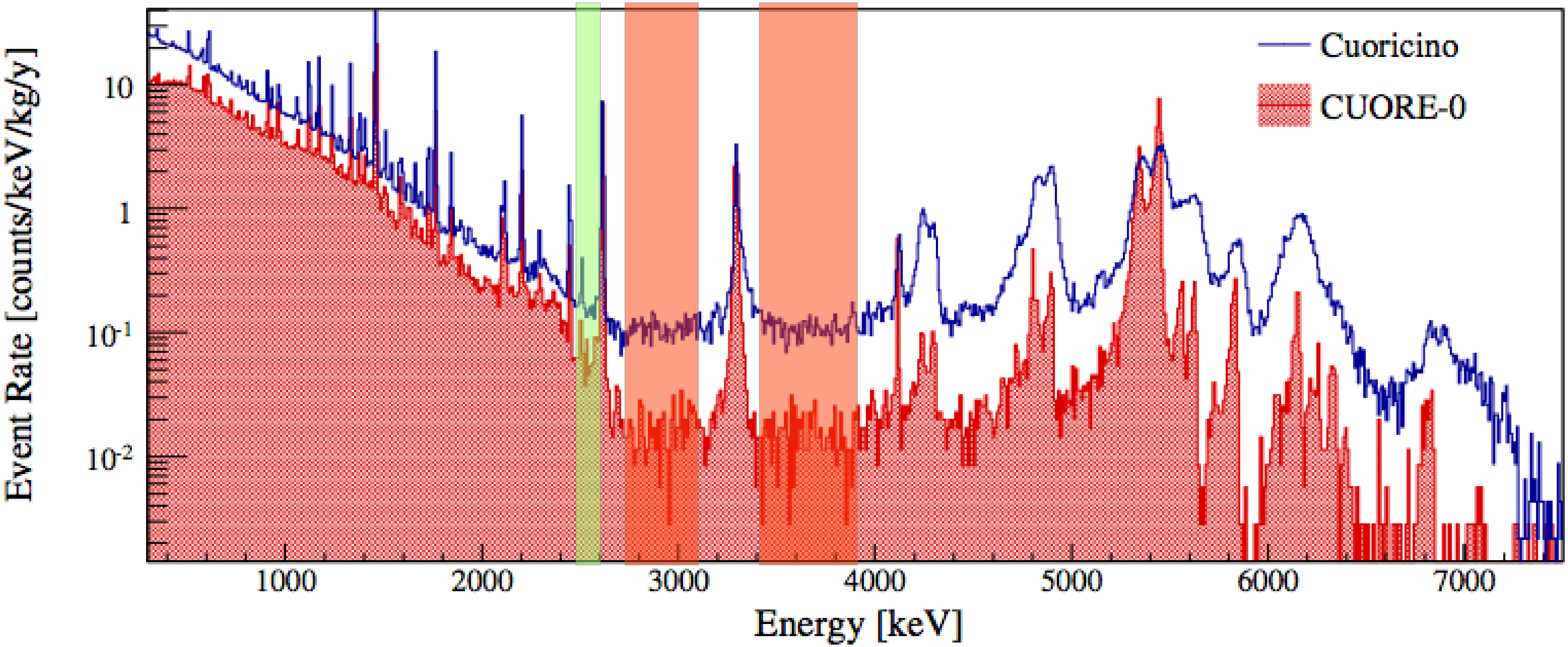
$5\times5\times5$ cm^3
750g natural TeO_2
(208g ^{130}Te)

Exposure



- Total exposure:
  - TeO_2: 35.2 kg-y
  - ^{130}Te: 9.8 kg-y

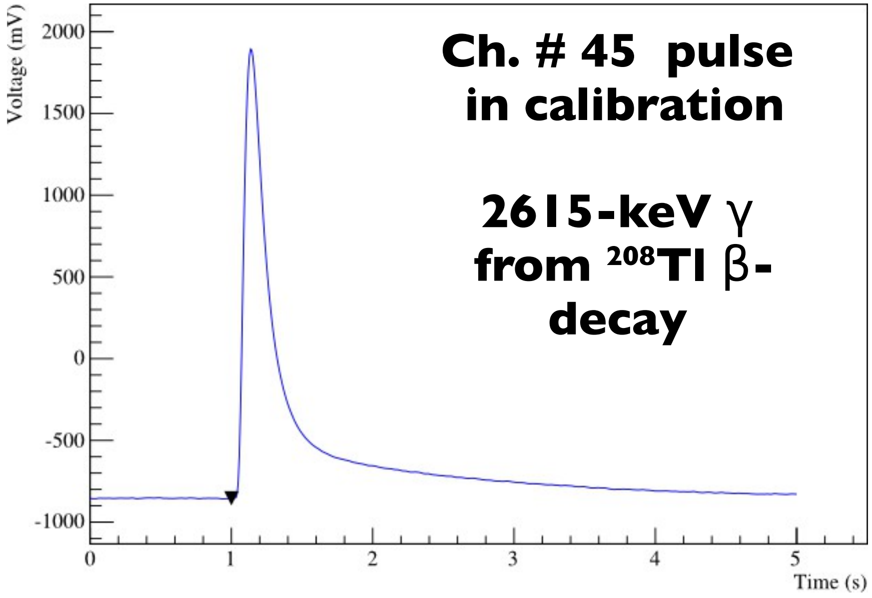
Backgrounds



- 2.5x reduction of ^{238}U-chain γs (better Rn control)
- No reduction of ^{232}Th-chain γs (cryostat materials same as Cuoricino)
- 6.5x reduction in continuum background (2.5-4 MeV)

→ Validated enhanced cleaning and assembly techniques

Data Analysis: Pulse Amplitude



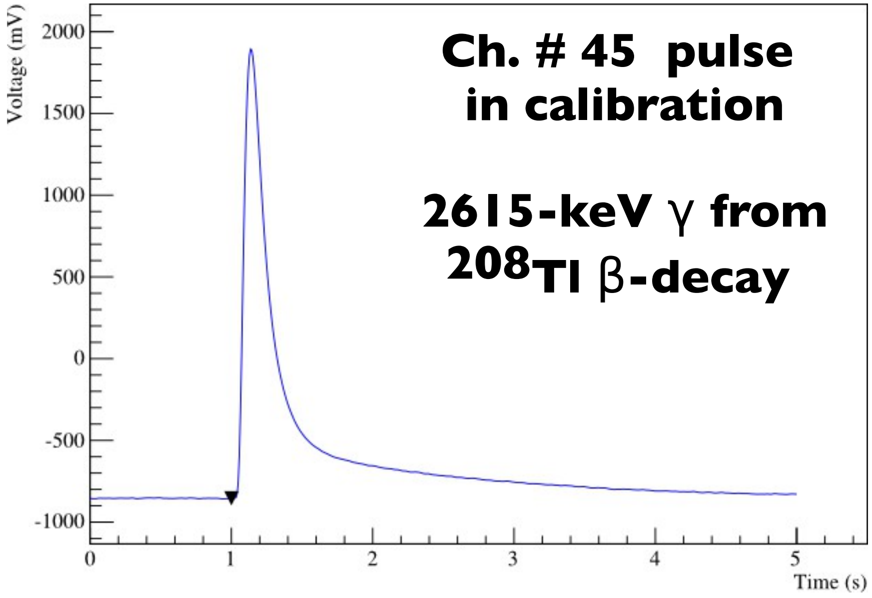
Ch. # 45 pulse in calibration

2615-keV γ from ^{208}Tl β-decay

- Sample at 125 Hz
- Software threshold trigger: 5-s events
- Run through optimum filter

→ amplitude

Data Analysis: Pulse Amplitude



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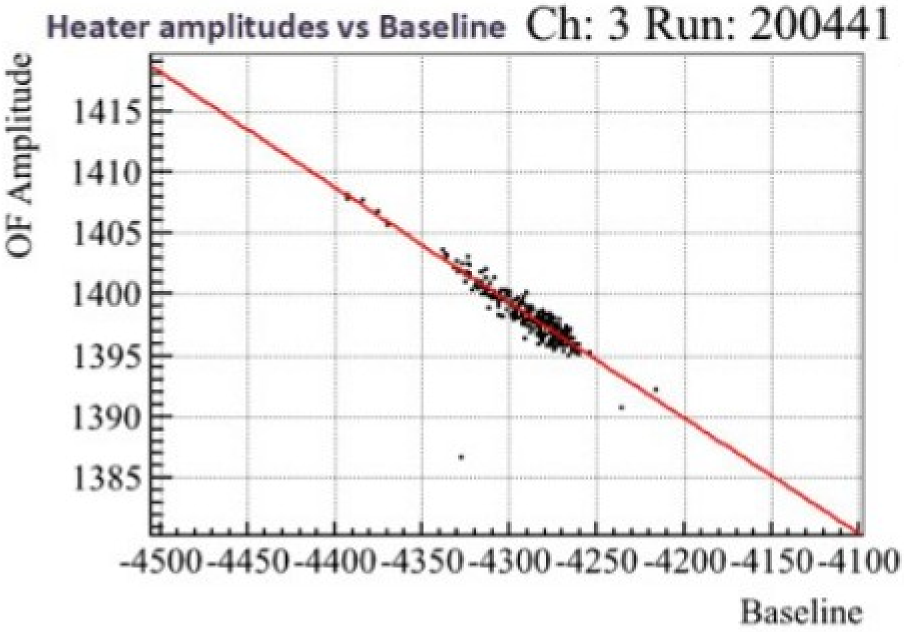
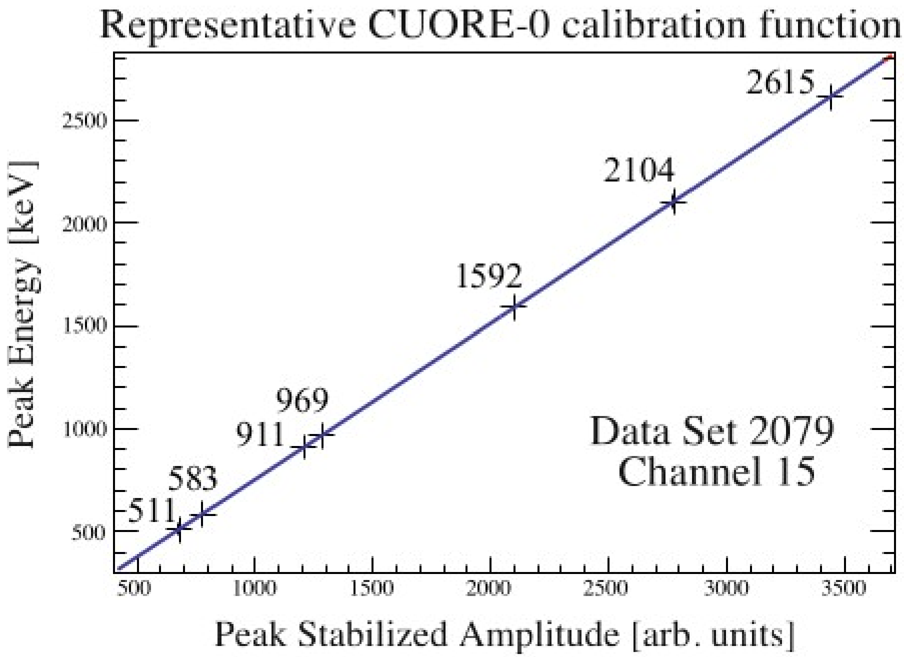


- Bolometer gain *T*-dependent

  → *A(E)* varies with *T*
- "Stabilization": correct for *T*-dep

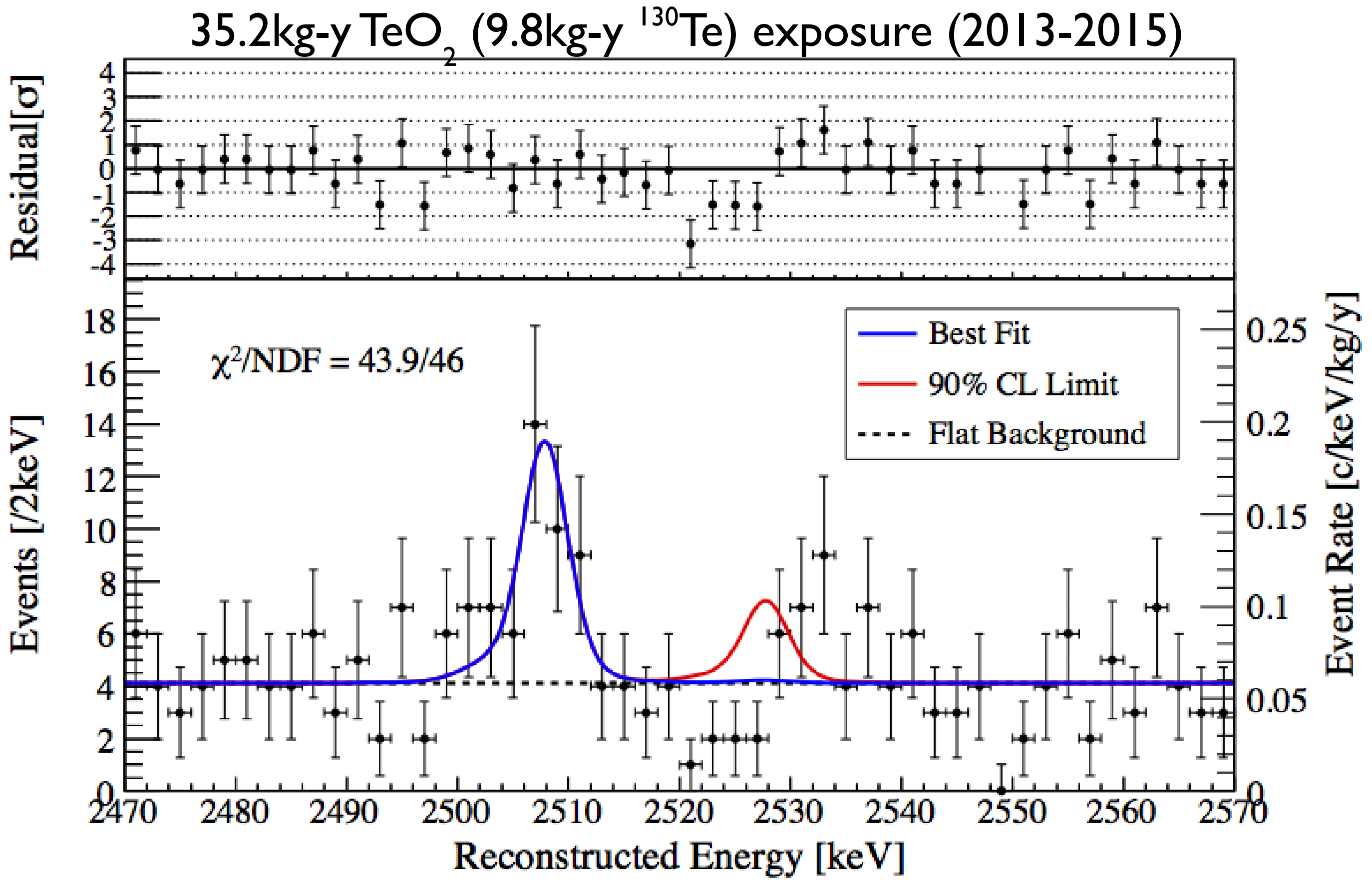
  → use monoenergetic pulsers to map *A(E,T)*

Data Analysis: Energy



- Use Th calibration data
- Quadratic *E* vs stab. *A* function

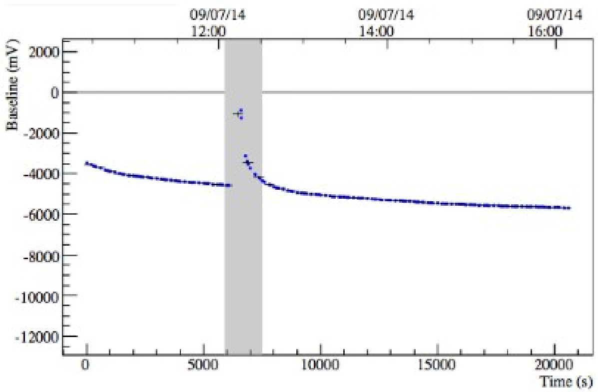
Region of interest


35.2kg-y TeO_2 (9.8kg-y ^{130}Te) exposure (2013-2015)

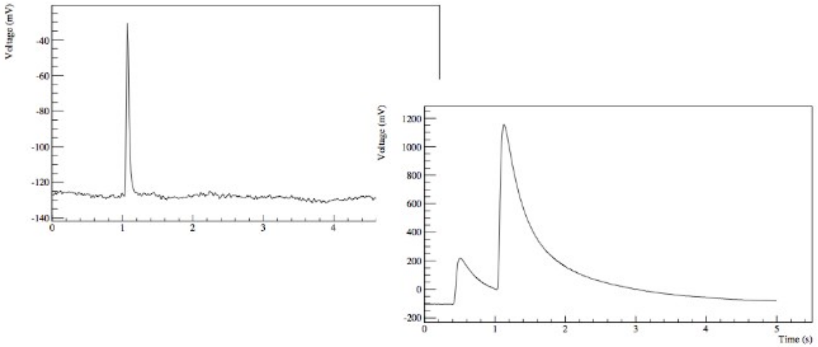
- Fit in [2470,2570] keV:
  - Model of 0νββ peak at 2527.5 keV
  - ^{60}Co peak around 2505 keV
  - Continuum background

Event Selection

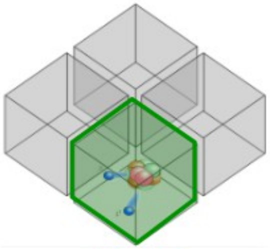
- Reject periods with detector issues

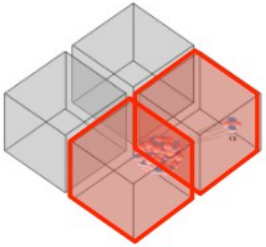


- Reject odd pulses and pile-up



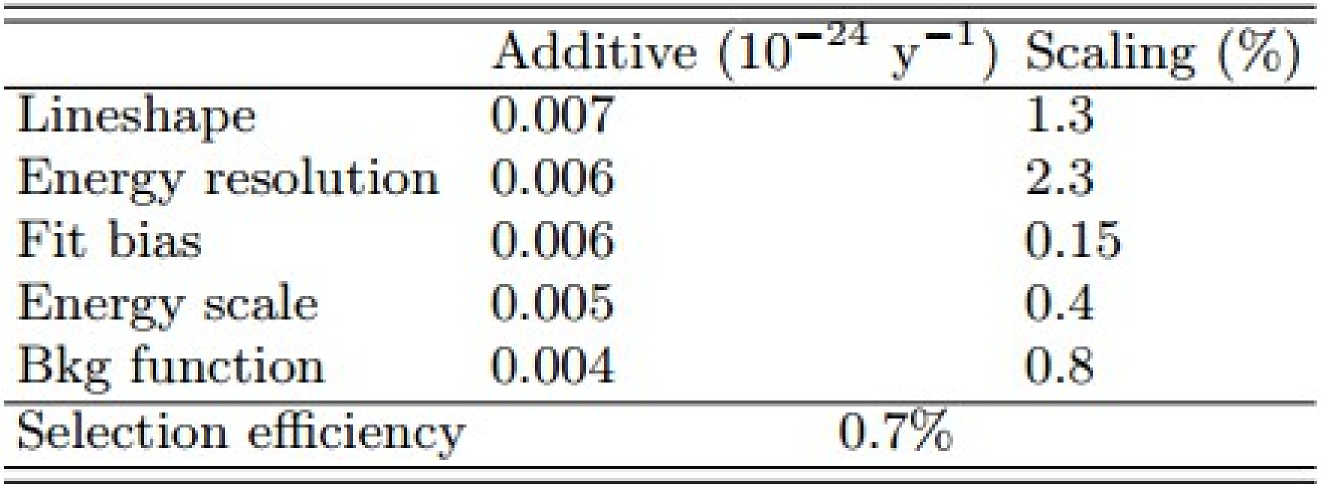
- Reject coincidences


Accept


Veto

Overall selection efficiency:
(81.3±0.6)%

Systematics



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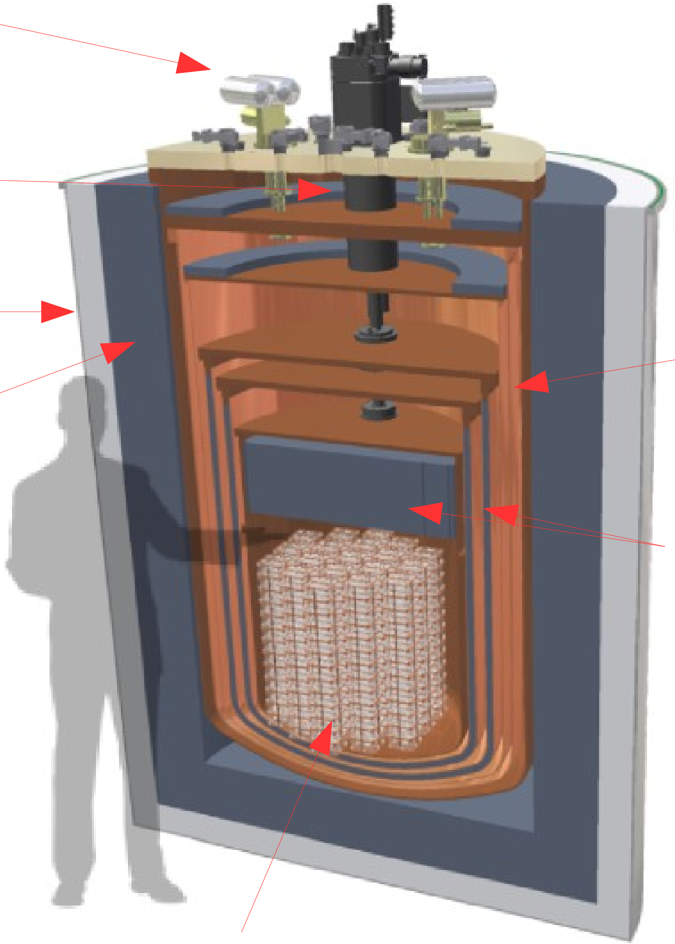
Energy resolution	0.006	2.3
Fit bias	0.006	0.15
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Selection efficiency	0.7%	

- For each source, toy MC for bias on fitted decay rate
- Bias parametrized as *(Additive)* + *(Scaling)* x Γ
  - Variety of lineshapes to model signal
  - 1.05±0.05 correction to calibration-driven energy resolution
  - Fit bias from using unbinned extended maximum likelihood
  - 0.12 keV energy scale uncertainty from peak residuals
  - Choice of polynomial order in background function (0, 1, 2)

CUORE: the next challenge



Pulse-tube refrigerators

Dilution refrigerator

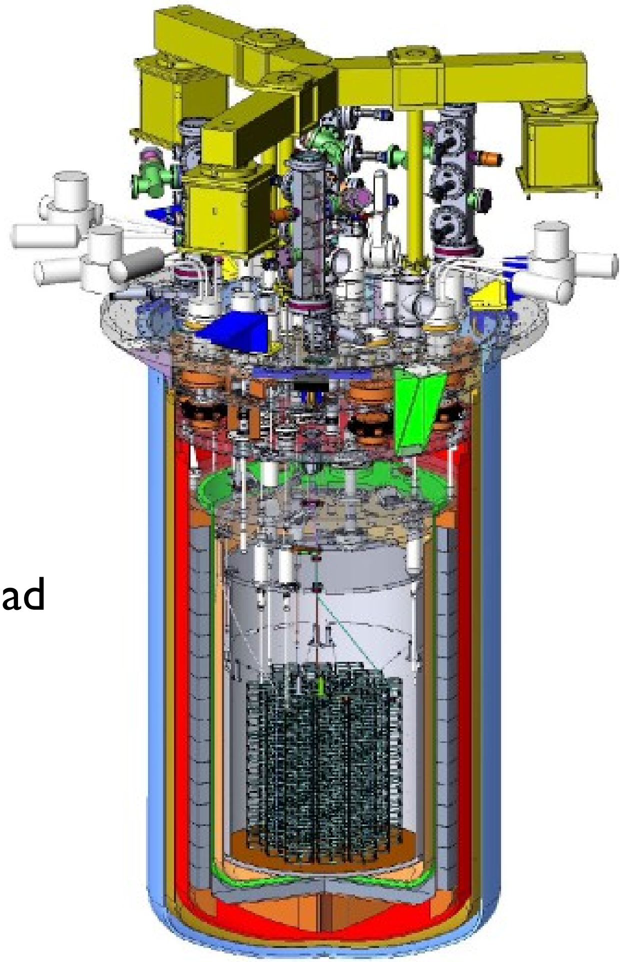
PET + boric acid shield

External lead shield

Copper thermal shields

Internal lead shields

988 (19 x 52) TeO_2 detectors



CHALLENGE:
Scale up the bolometric apparatus by 19x

Effective neutrino mass

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

F_N : Nuclear matrix element phase space factor

ϵ : Detection efficiency

η : Isotopic abundance

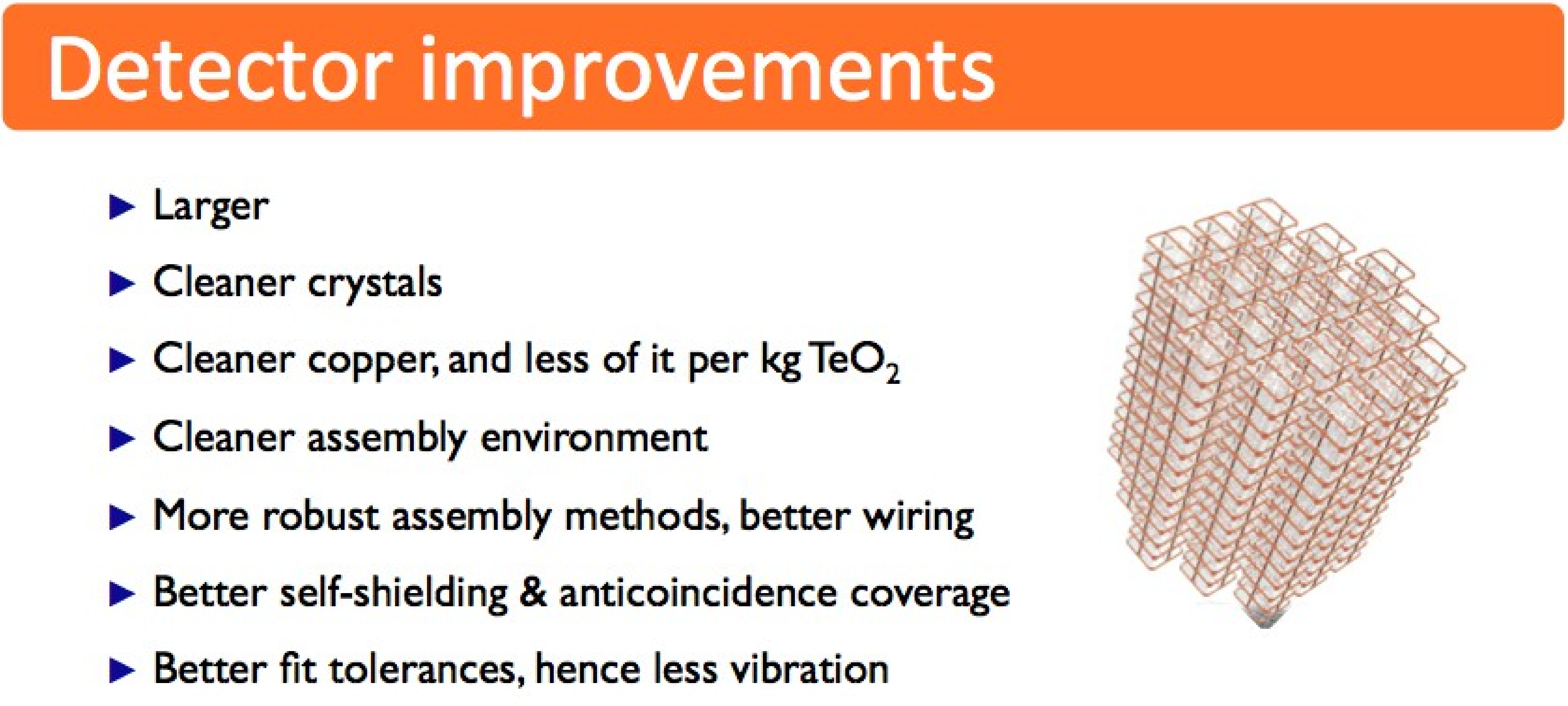
M : Detector mass

t : Live time

b : Background

δE : Energy resolution

TAUP 2013 “CUORE and Beyond” (Ke Han)



Detector improvements

- Larger
- Cleaner crystals
- Cleaner copper, and less of it per kg TeO_2
- Cleaner assembly environment
- More robust assembly methods, better wiring
- Better self-shielding & anticoincidence coverage
- Better fit tolerances, hence less vibration

2015-04-09 LBL, Tom Banks, CUORE-0 Unblinding