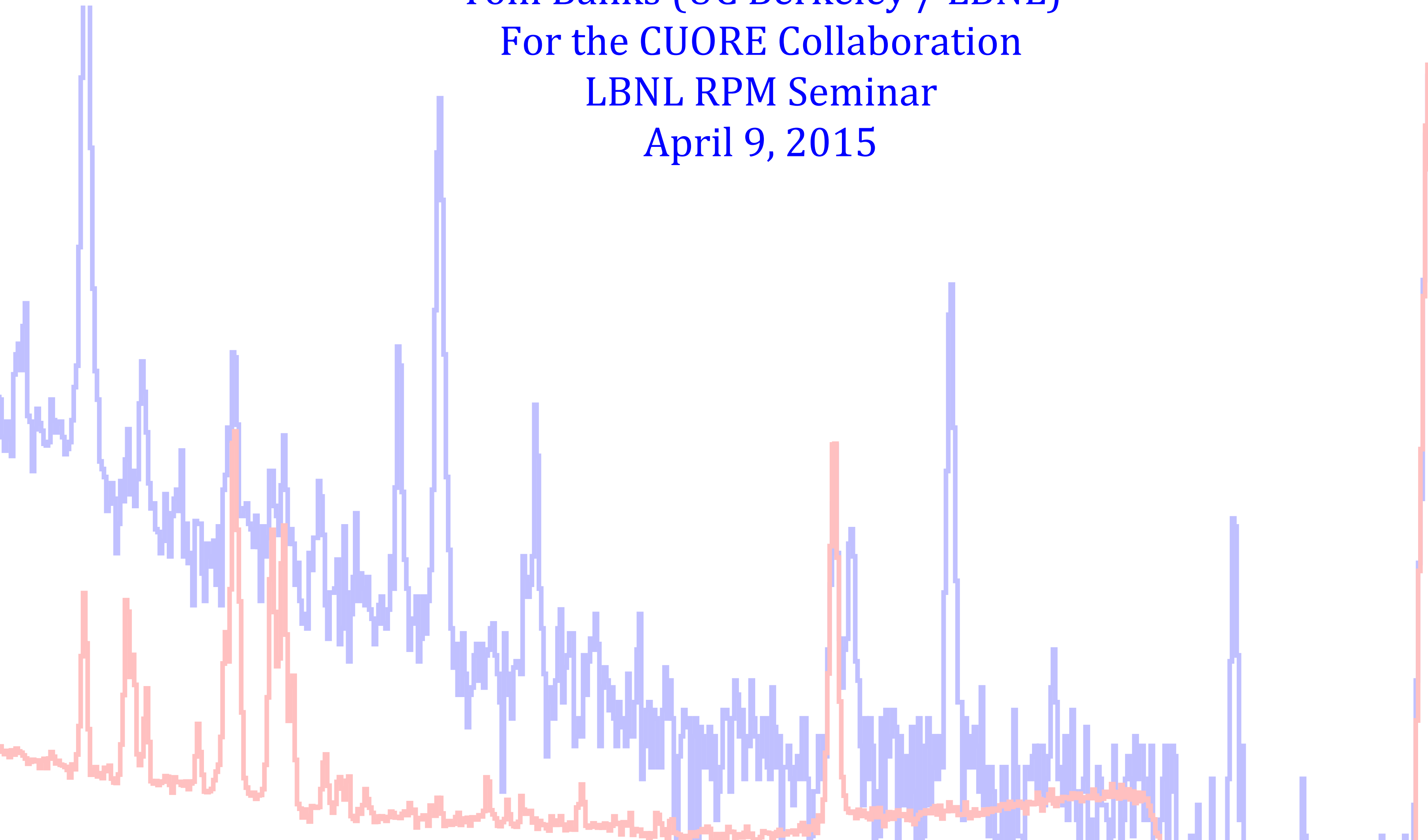
Results from the search for $0\nu\beta\beta$ decay of ^{130}Te with CUORE-0

Tom Banks (UC Berkeley / LBNL)

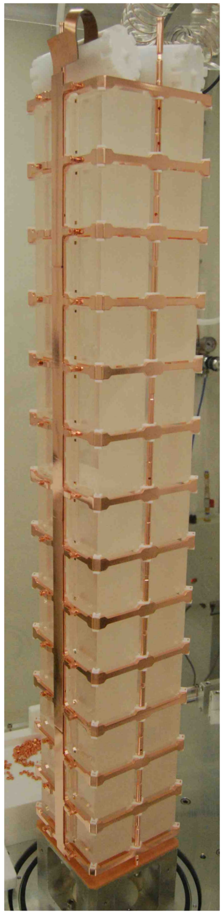
For the CUORE Collaboration

LBNL RPM Seminar

April 9, 2015



CUORE-0

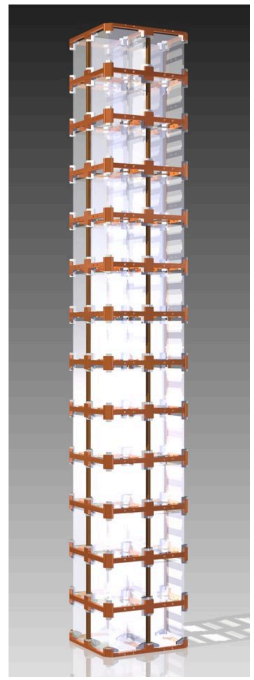


CUORE-0 is a tower of 52 TeO_2 crystals operated as independent cryogenic bolometers to search for $0\nu\beta\beta$ decay of ^{130}Te

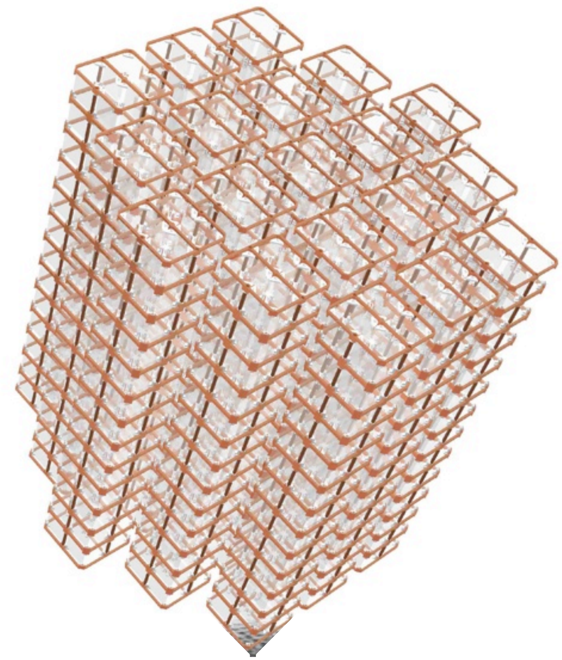
CUORE program

Cuoricino
2003–2008
11 kg ^{130}Te

COMPLETE



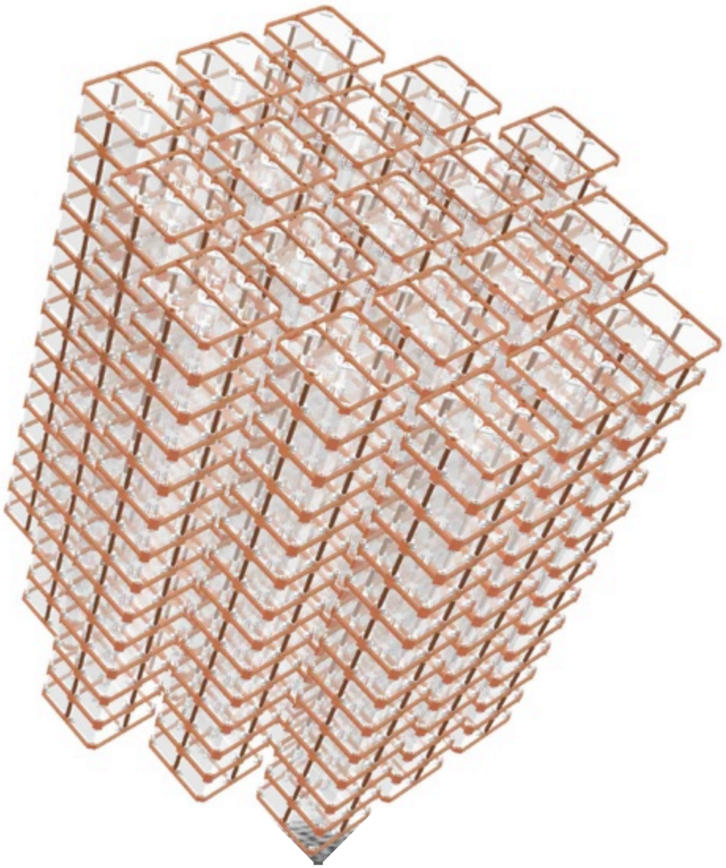
CUORE-0
2013–2015
11 kg ^{130}Te



CUORE
2015–2020
206 kg ^{130}Te

CUORE

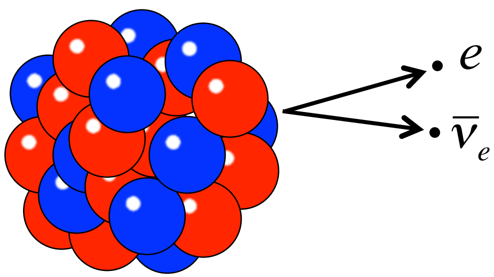
Cryogenic Underground Observatory for Rare Events



19 CUORE-0-like towers to search for $0\nu\beta\beta$ decay of ^{130}Te

Beta decay

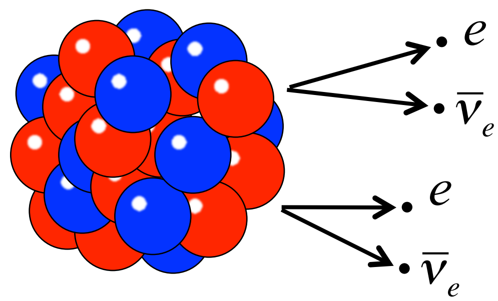
β



$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^{-} + \bar{\nu}_e$$

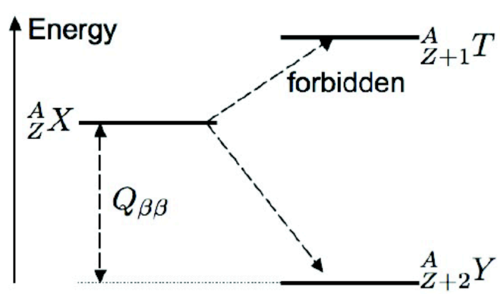
- Familiar weak process

$2\nu\beta\beta$

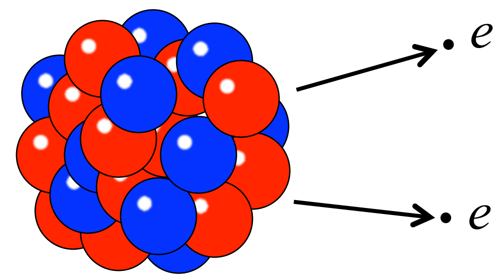


$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-} + 2\bar{\nu}_e$$

- Observed, but rare ($T_{1/2}$ > 10^{19} yr)
- Only visible in nuclei for which single β is forbidden



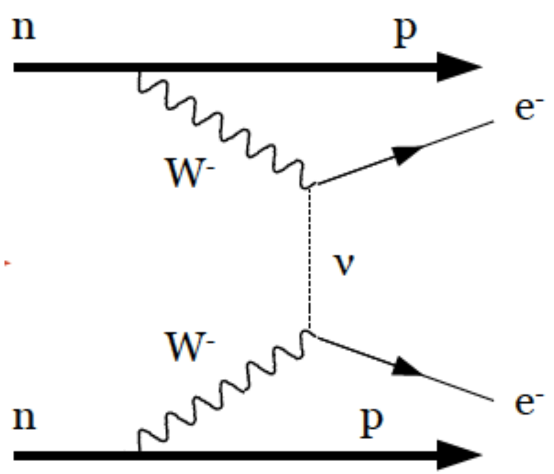
$0\nu\beta\beta$



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

- Even rarer than $2\nu\beta\beta$, (if it occurs at all)
- Only one controversial claim of observation to date

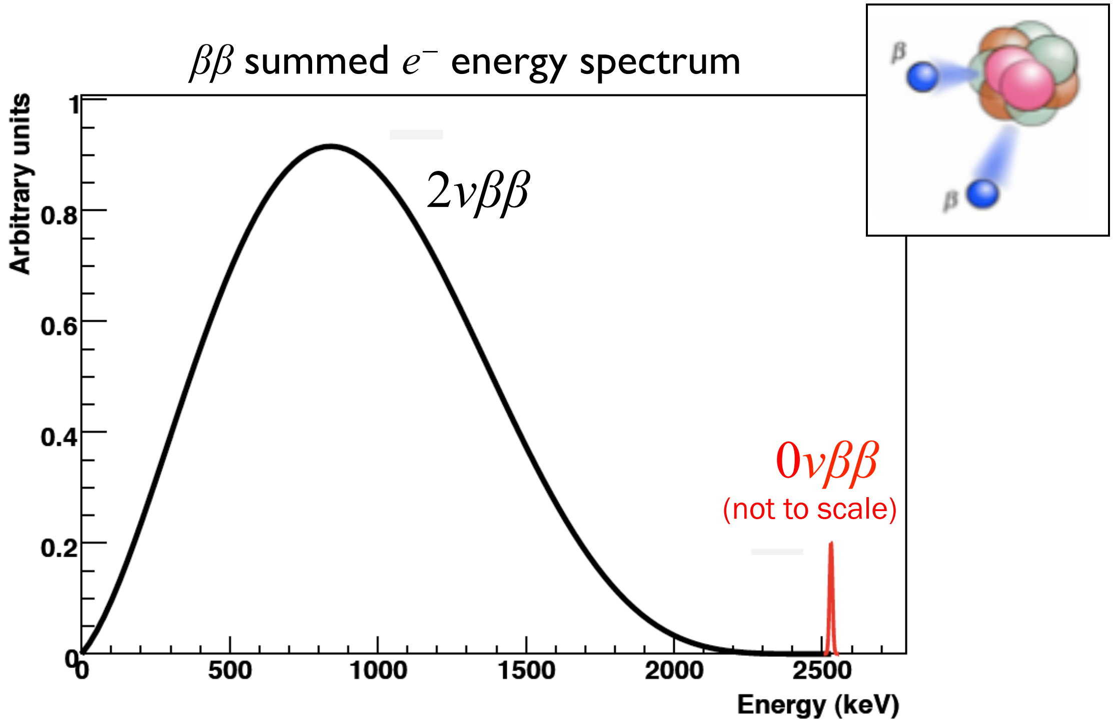
Physics motivation



If $0\nu\beta\beta$ decay is observed, it would

1. Demonstrate that lepton number is not conserved
2. Establish neutrinos as Majorana particles (i.e., $\nu = \overline{\nu}$)
3. Set constraints on the effective Majorana mass $\langle m_{\beta\beta} \rangle$ and provide info on absolute ν mass scale and hierarchy

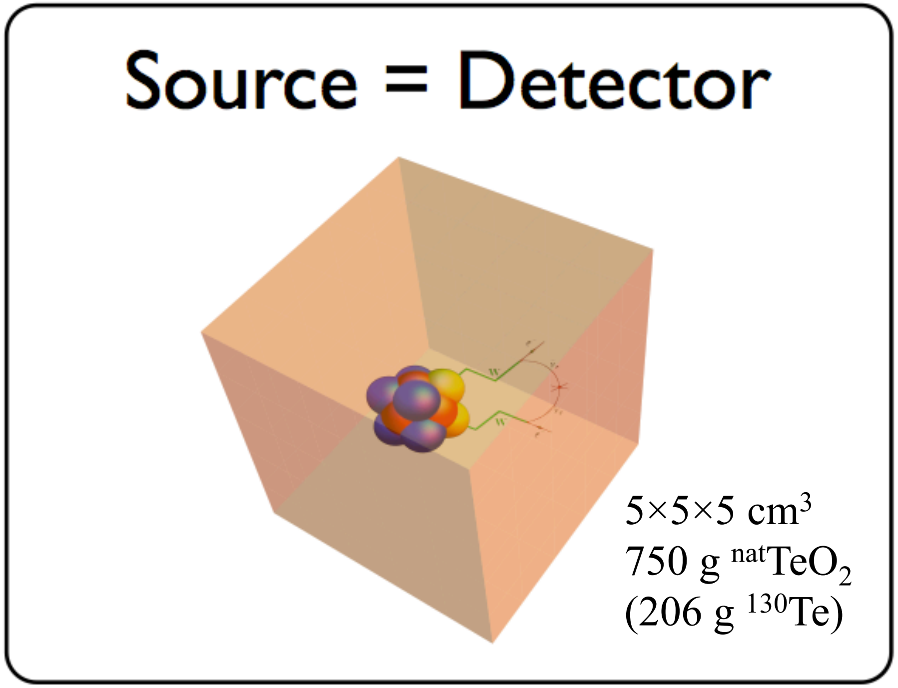
Detecting $0\nu\beta\beta$ decay



- **General approach:** Detect the two final-state electrons

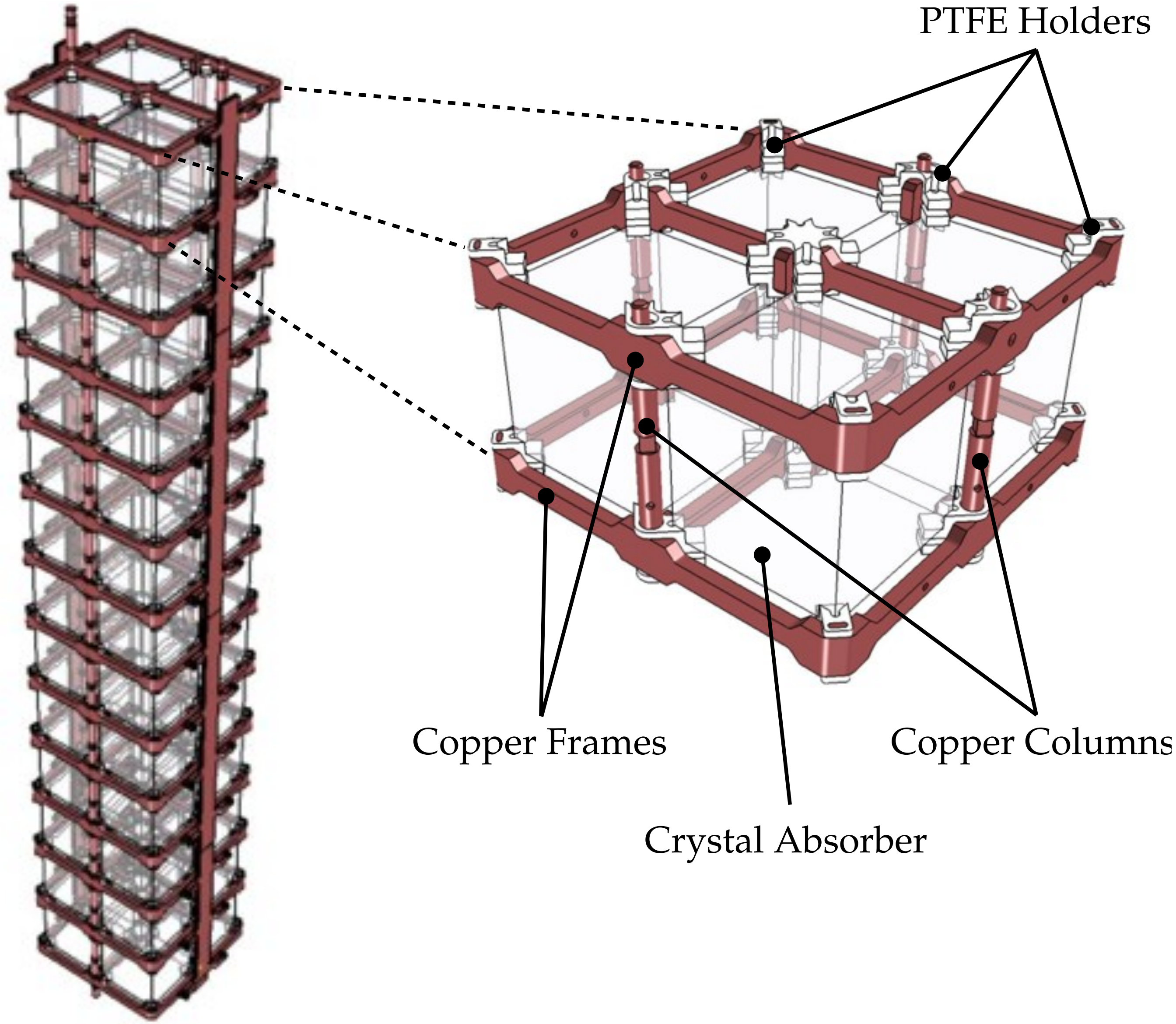
- **Signature:** Two simultaneous electrons with summed energy $Q_{\beta\beta}$, the Q-value for $\beta\beta$ decay in the isotope under study

Cryogenic bolometers

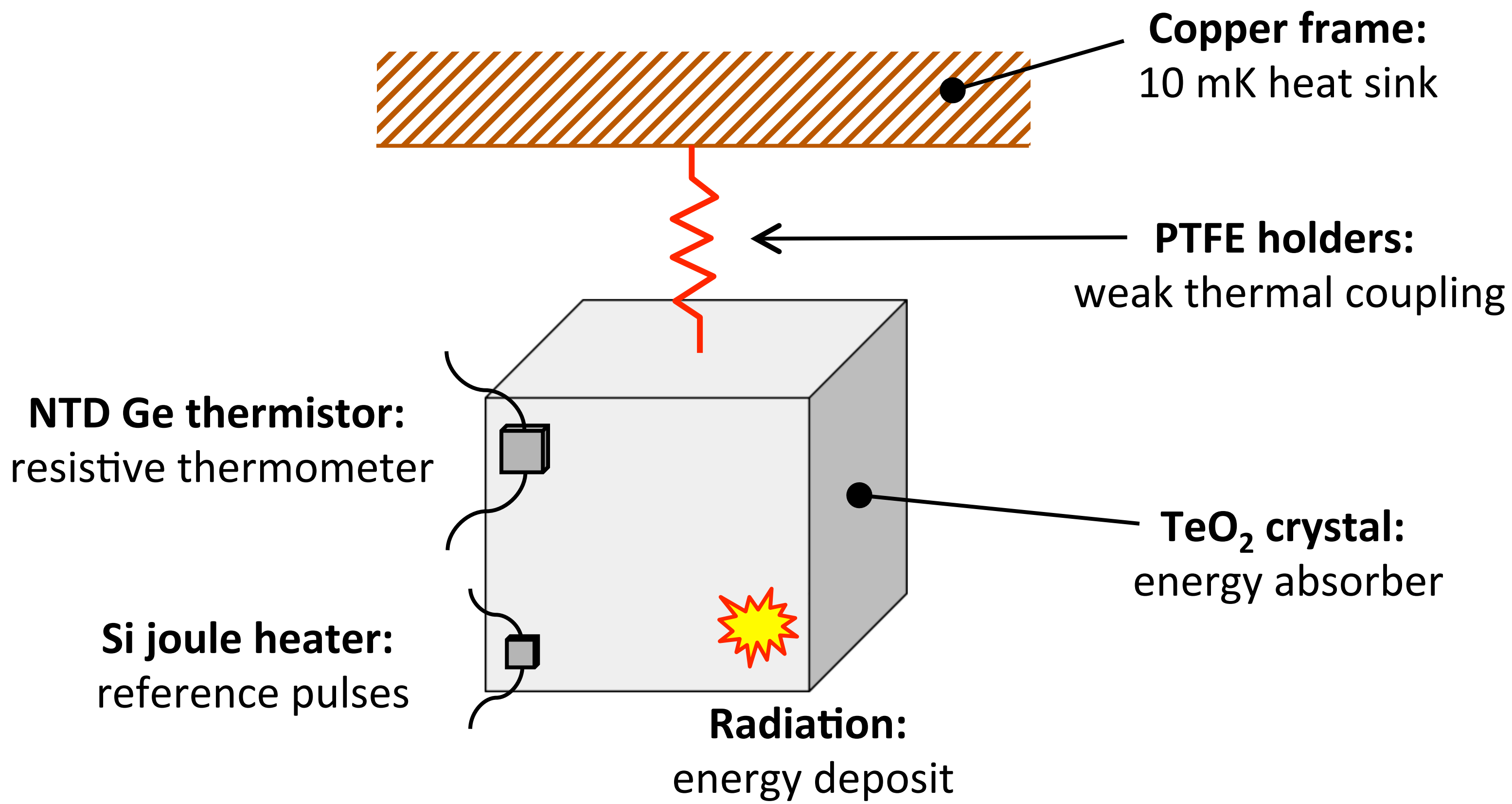


Ultracold TeO_2 crystals function as highly sensitive calorimeters

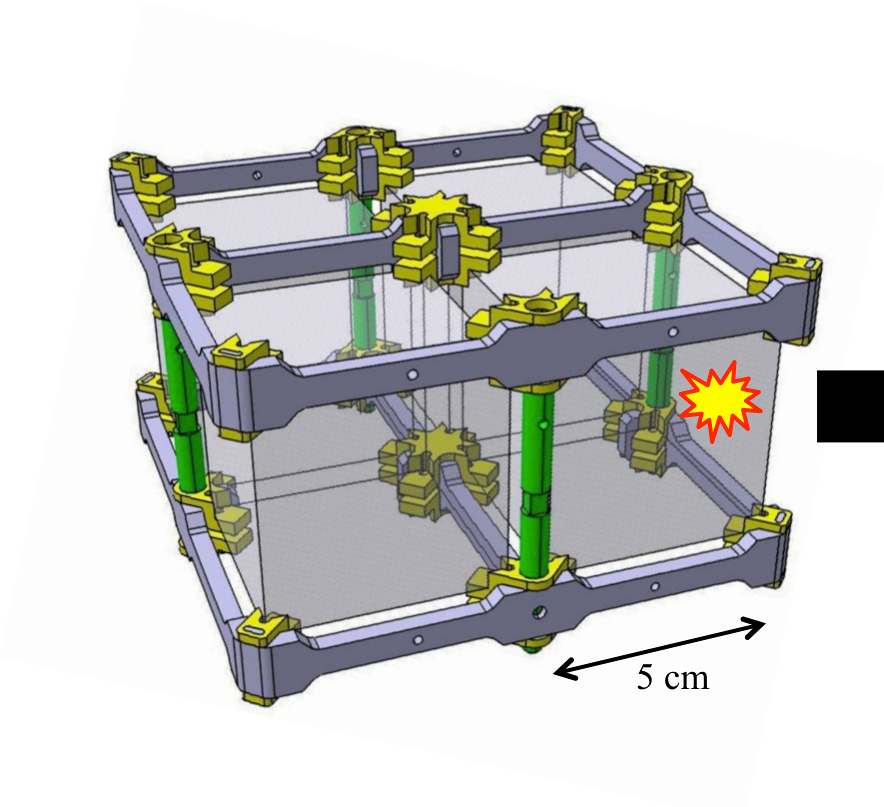
Cryogenic bolometers

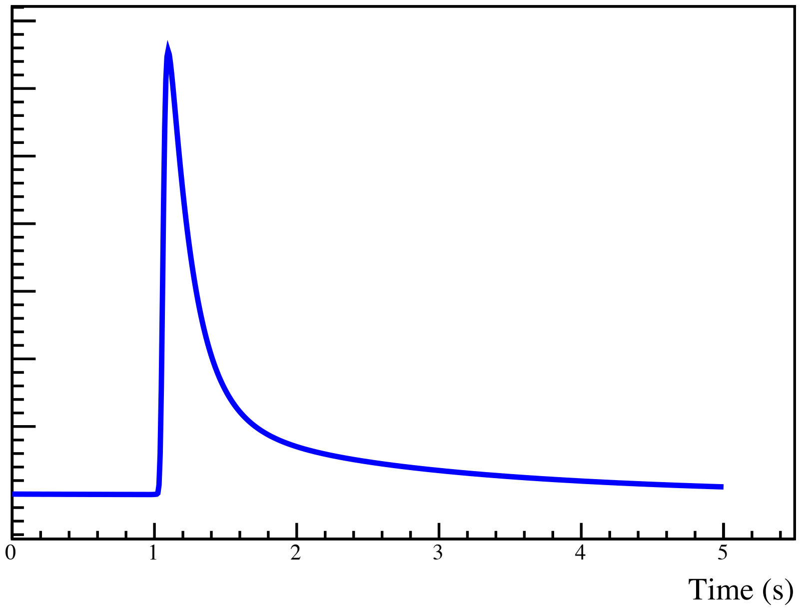


Cryogenic bolometers



Cryogenic bolometers

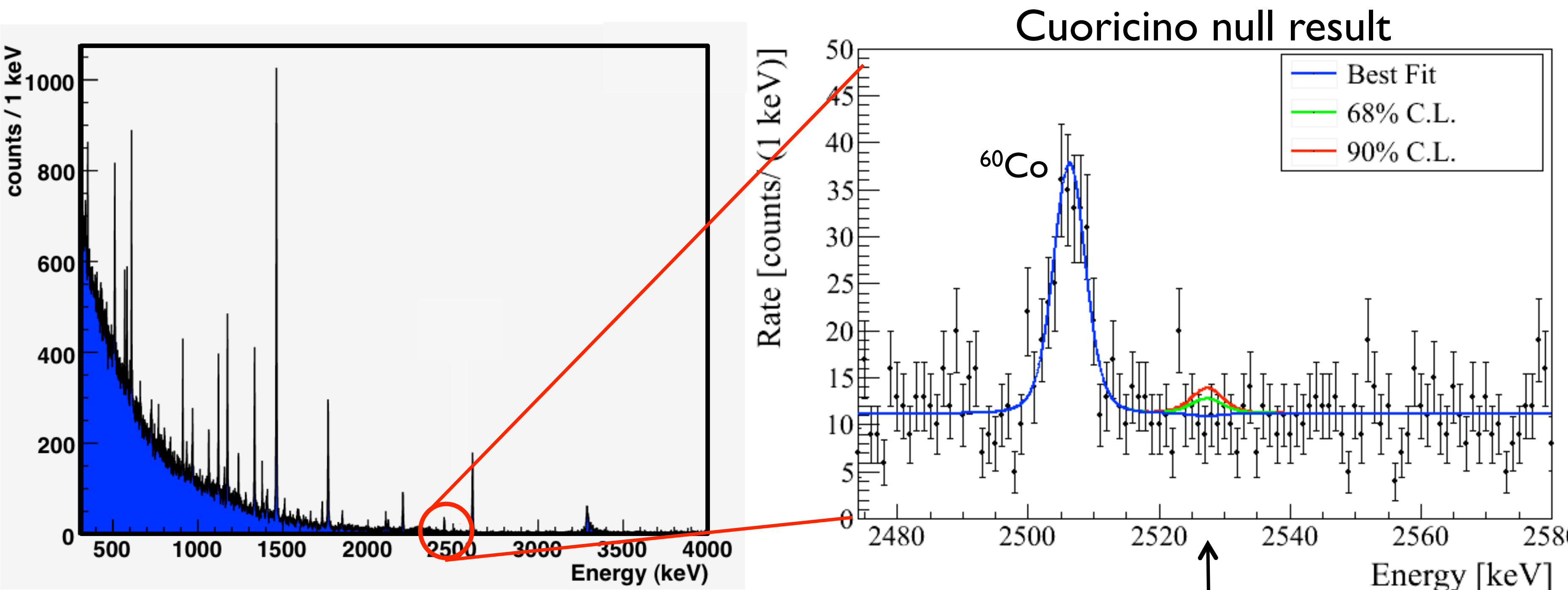




At T=10 mK, energy deposited inside a TeO_2 crystal by radiation produces a measurable rise in its temperature

Amplitude of temperature pulse is proportional to deposited energy

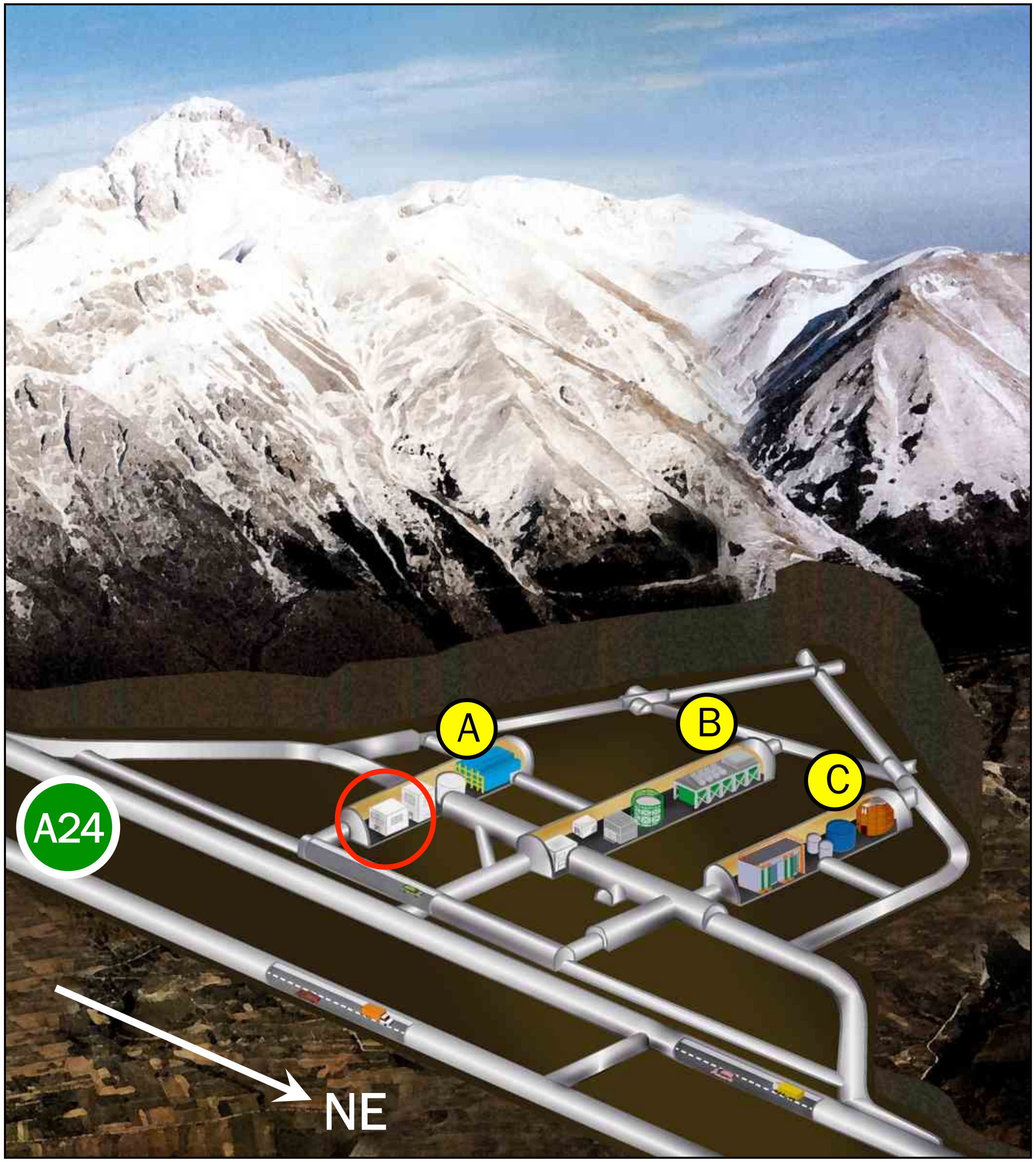
Experimental method



The energy spectrum of detected pulses is compiled...

... and the signature of $0\nu\beta\beta$ of ^{130}Te would be a small peak at 2527.5 keV.

LNGS underground lab



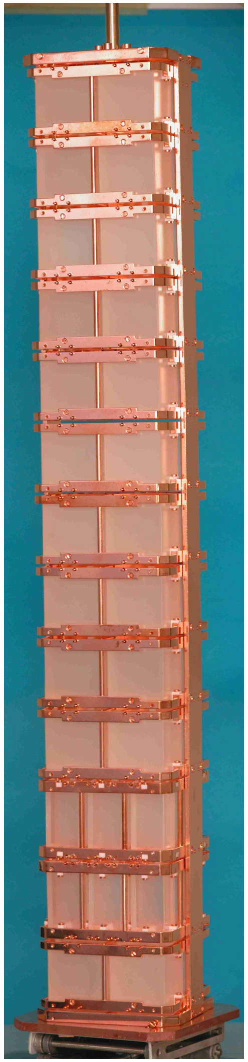
- Gran Sasso, Italy
- 1.4-km rock overburden cuts muon flux by 10^6

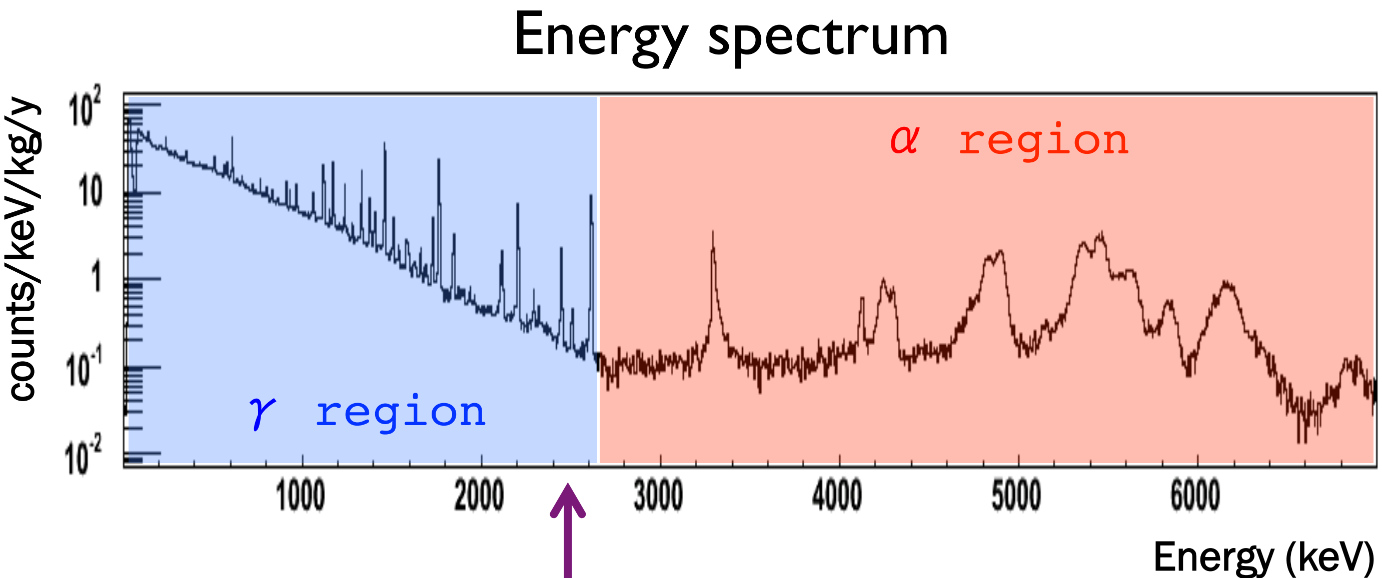
CUORE facilities in Hall A

CUORE hut

Cuoricino/
CUORE-0 hut

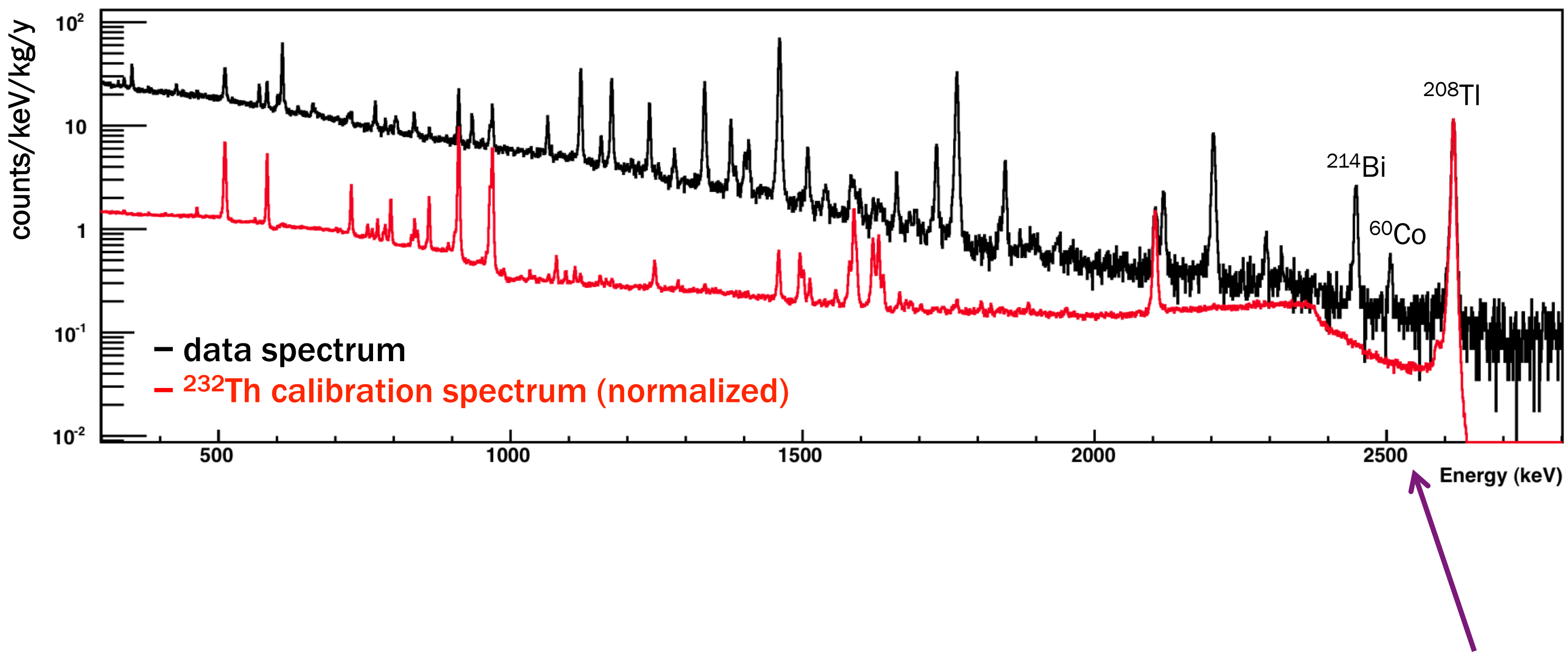
The past: Cuoricino





^{130}Te Q-value = 2527.5 keV

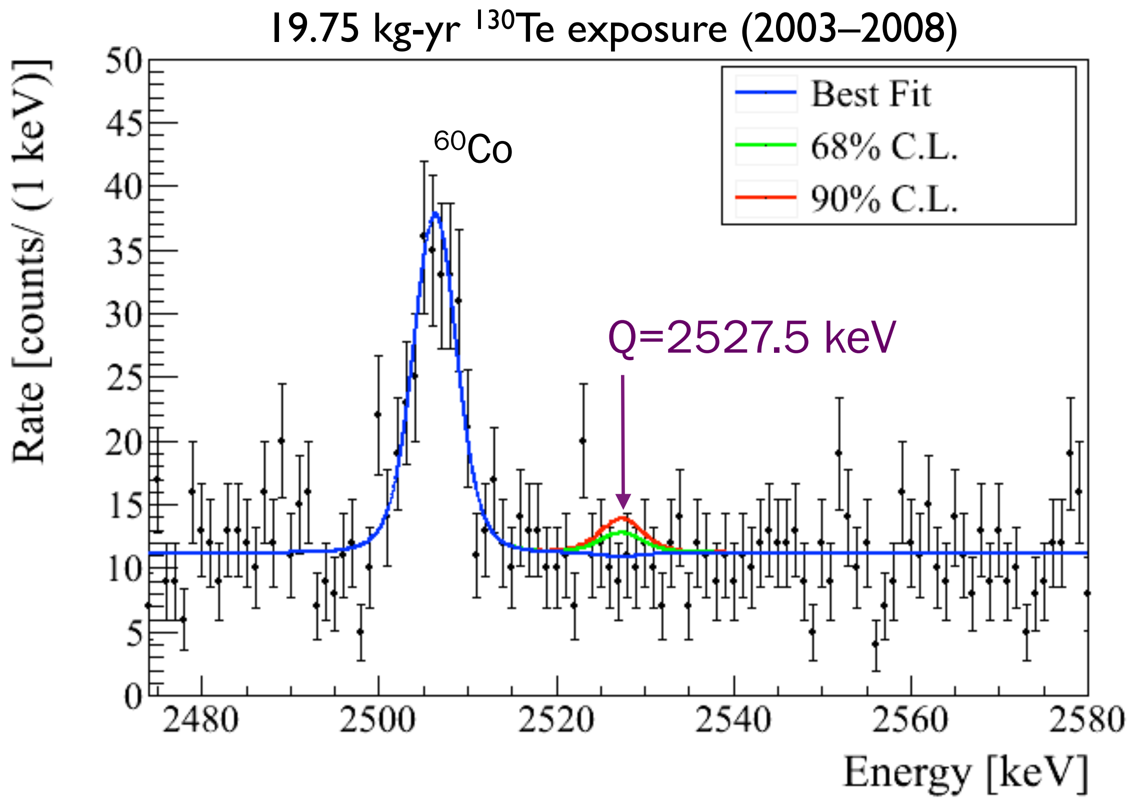
Cuoricino backgrounds



There were three main sources of background in the region around the Q value:

- (~35%) Compton gammas from ^{208}Tl, from ^{232}Th-chain decays in cryostat
- (~55%) Degraded alphas from ^{238}U- and ^{232}Th-chain decays on copper surfaces
- (~10%) Degraded alphas from ^{238}U- and ^{232}Th-chain decays on crystal surfaces

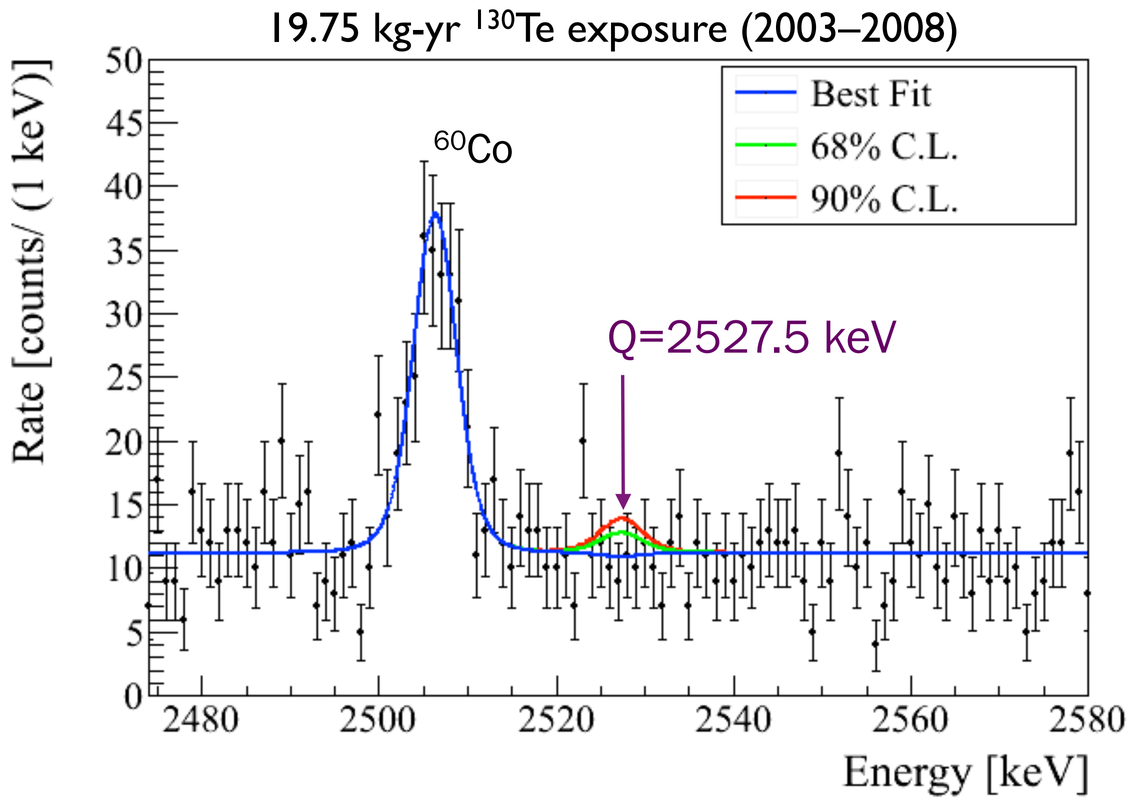
Cuoricino result



No evidence of $0\nu\beta\beta$ decay in ^{130}Te

E. Andreotti et al. (CUORICINO Collaboration), Astropart. Phys. 34: 822–831 (2011) [arXiv:nucl-ex/1012.3266].

Cuoricino result



Background: 0.169 ± 0.006 counts/keV/kg/y (^{130}Te)

Lower limit, half-life: $T_{1/2}^{0\nu\beta\beta}(^{130}\mathrm{Te}) \geq 2.8 \times 10^{24}$ y (90% C.L.)

Upper limit, Majorana ν mass: $\langle m_{\beta\beta} \rangle < 300 - 710$ meV

E. Andreotti et al. (CUORICINO Collaboration), Astropart. Phys. 34: 822–831 (2011) [arXiv:nucl-ex/1012.3266].

The future: CUORE

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

UNIVERSITÀ DEGLI STUDI DI CASSINO E DEL LAZIO MERIDIONALE – SOL PER NOCTEM – 1979

SINAP

LUX ET VERITAS

INFN Istituto Nazionale di Fisica Nucleare

CAL POLY SAN LUIS OBISPO

Lawrence Livermore National Laboratory

Massachusetts Institute of Technology

ALMA MATER STUDIORUM A.D. 1088

UCLA

SAPIENZA UNIVERSITÀ DI ROMA

CSNSM

CUORE

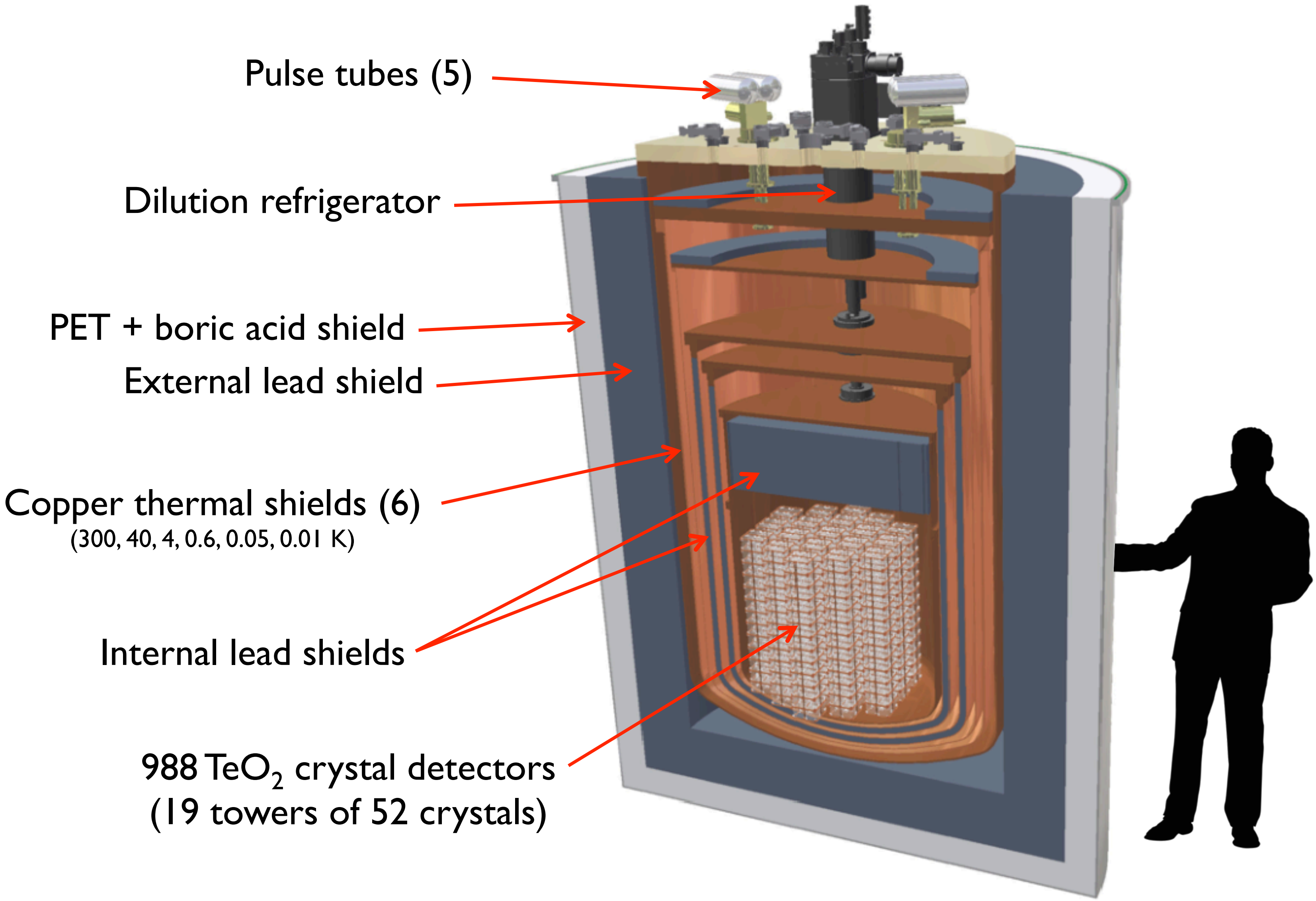
BERKELEY LAB

UNIVERSITY OF SOUTH CAROLINA

THE UNIVERSITY OF CALIFORNIA 1868

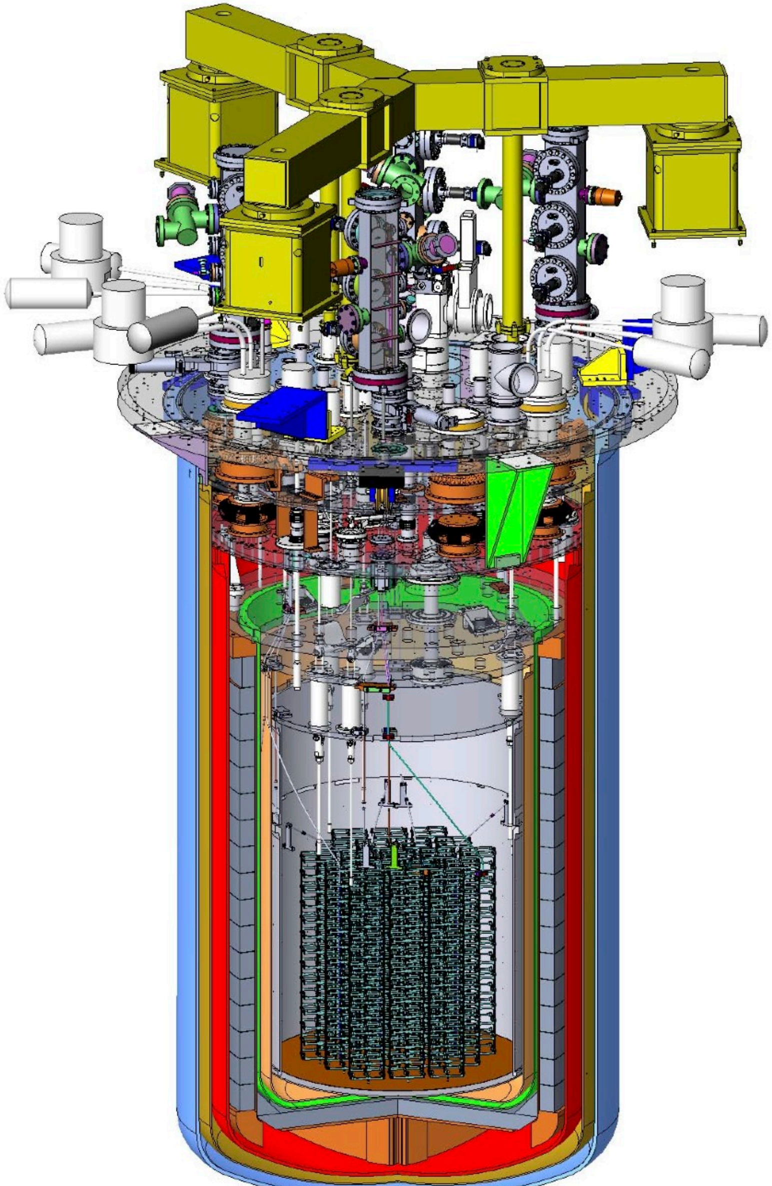
UNIVERSITAS STUDII PADUANI MCCXXII

CUORE


Pulse tubes (5)
Dilution refrigerator
PET + boric acid shield
External lead shield
Copper thermal shields (6)
(300, 40, 4, 0.6, 0.05, 0.01 K)
Internal lead shields
988 TeO_2 crystal detectors
(19 towers of 52 crystals)

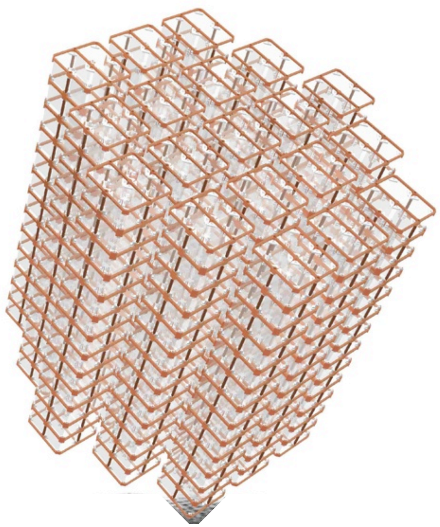
The challenge

Scale up the bolometric apparatus by 19x
while also reducing radioactive backgrounds



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

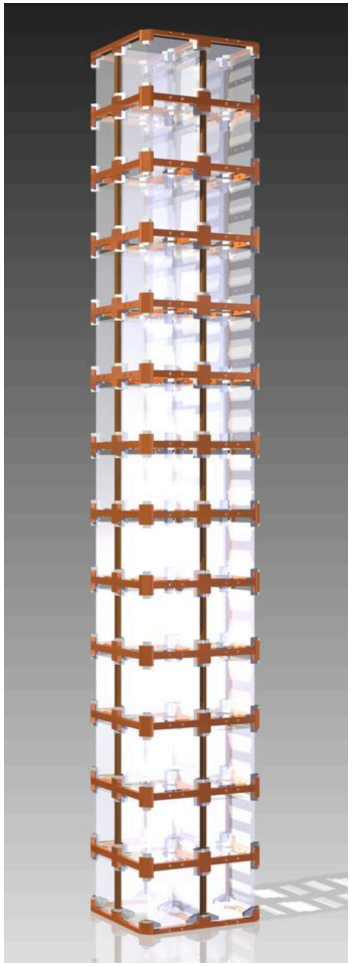


	Cuoricino	CUORE-0	CUORE
^{130}Te mass (kg)	11	11	206
Background (c/keV/kg/y) @ 2528 keV	0.17	0.06	0.01
E resolution (keV) FWHM @ 2615 keV	5.8	4.9	5
$T_{1/2}$ sensitivity (10^{24} yr) @ 90% C.L.	2.6	2.9	95

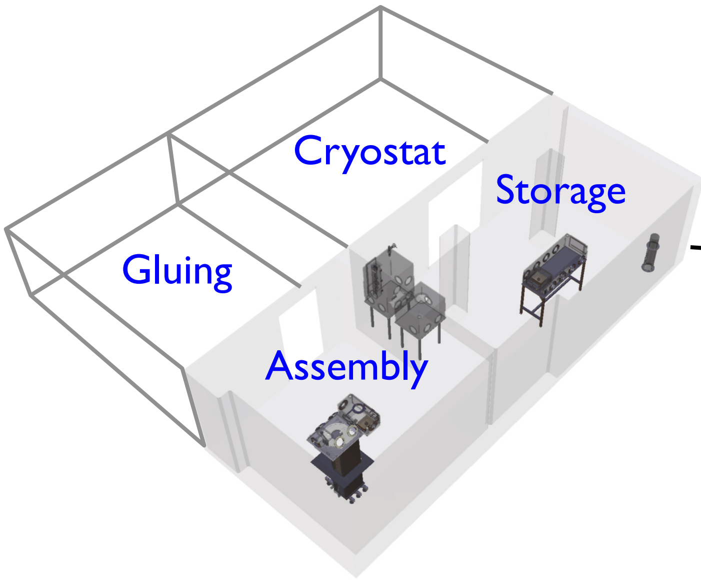
CUORE-0 overview

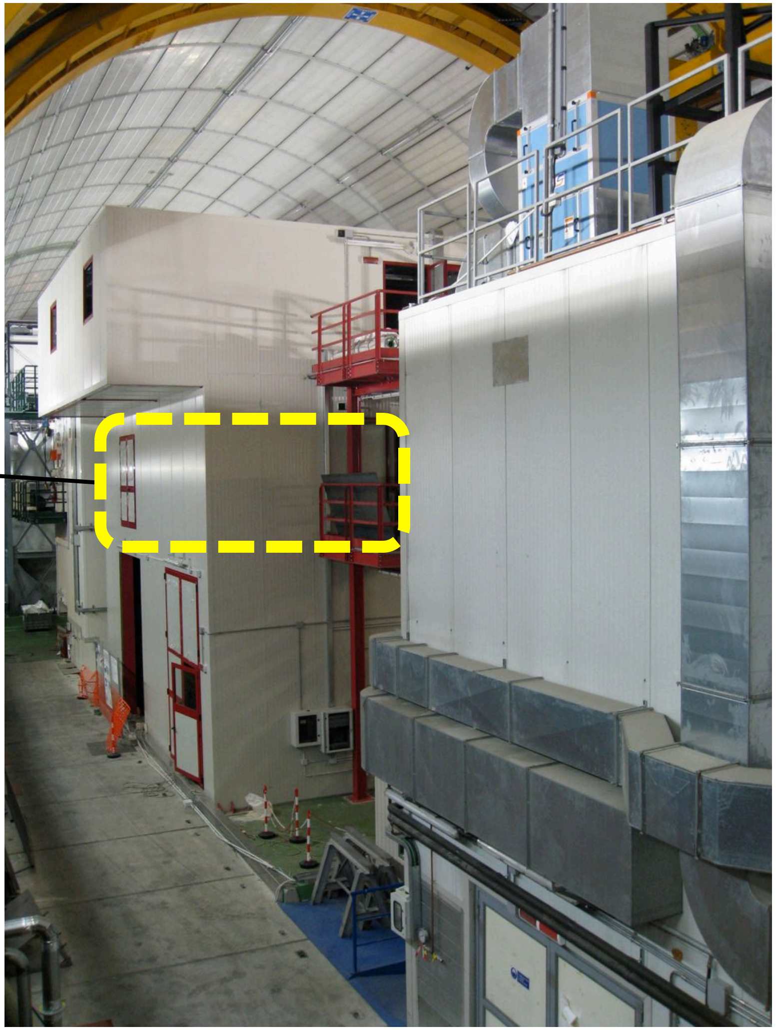
CUORE-0

- First tower from the CUORE detector assembly line
- 52 TeO_2 crystals, total mass = 39 kg TeO_2 = 10.9 kg ^{130}Te
- Purpose:
  1. Commission assembly line
  2. Run as standalone experiment while CUORE is being constructed, with aim of surpassing Cuoricino
  3. Validate CUORE detector design
  4. Provide test bed for developing DAQ & analysis framework for CUORE
- Operating in former Cuoricino cryostat since March 2013



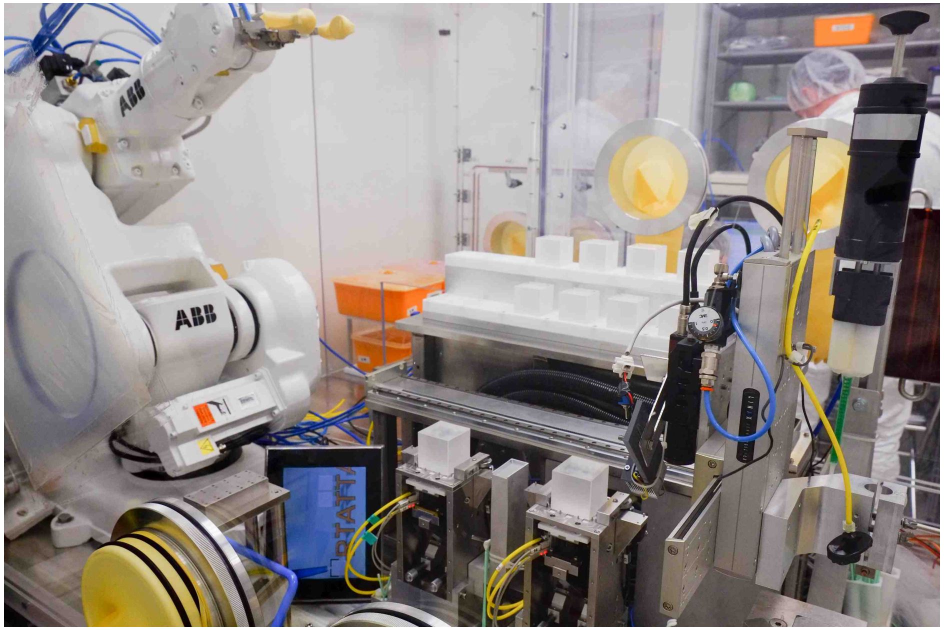
Tower construction

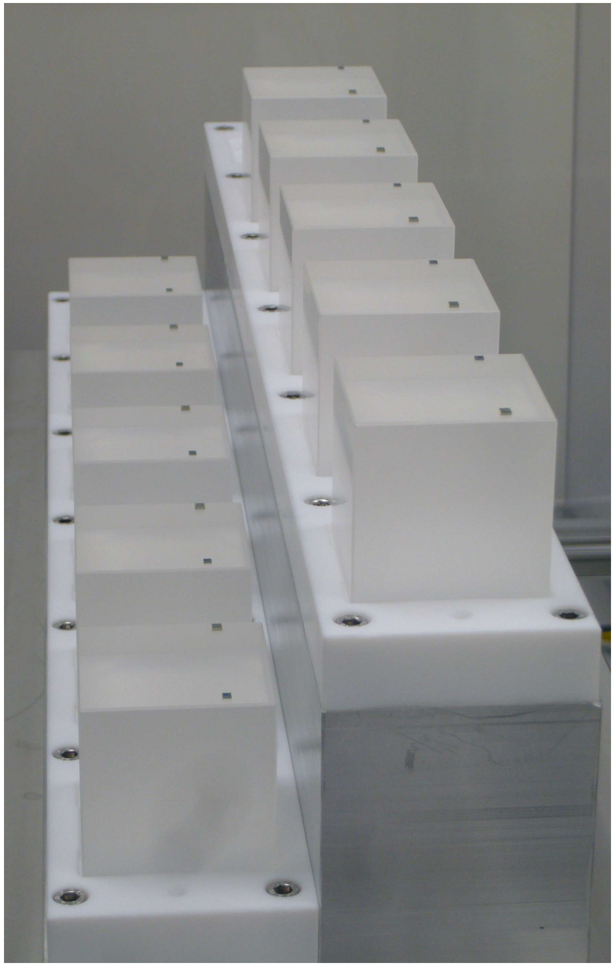


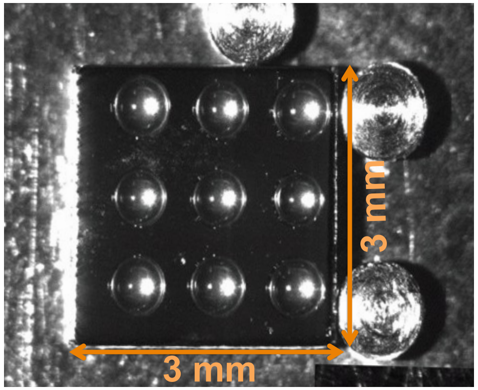


Construction was carried out inside N_2-flushed glove boxes in CUORE hut's clean room

1. Gluing sensors to crystals

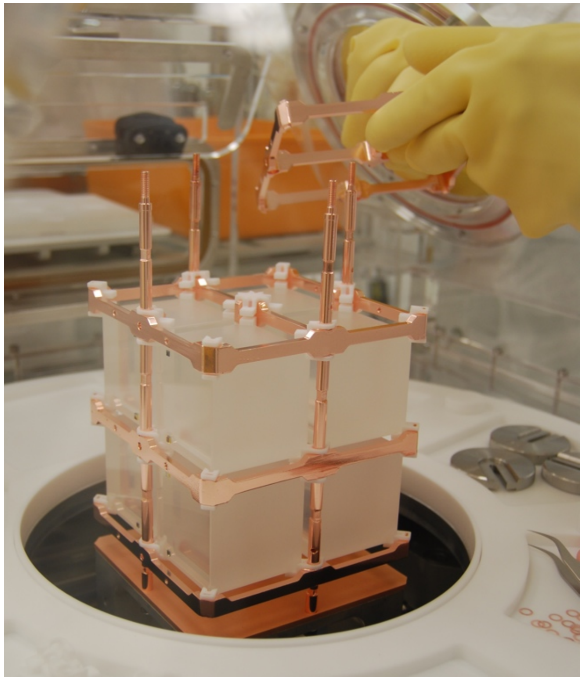




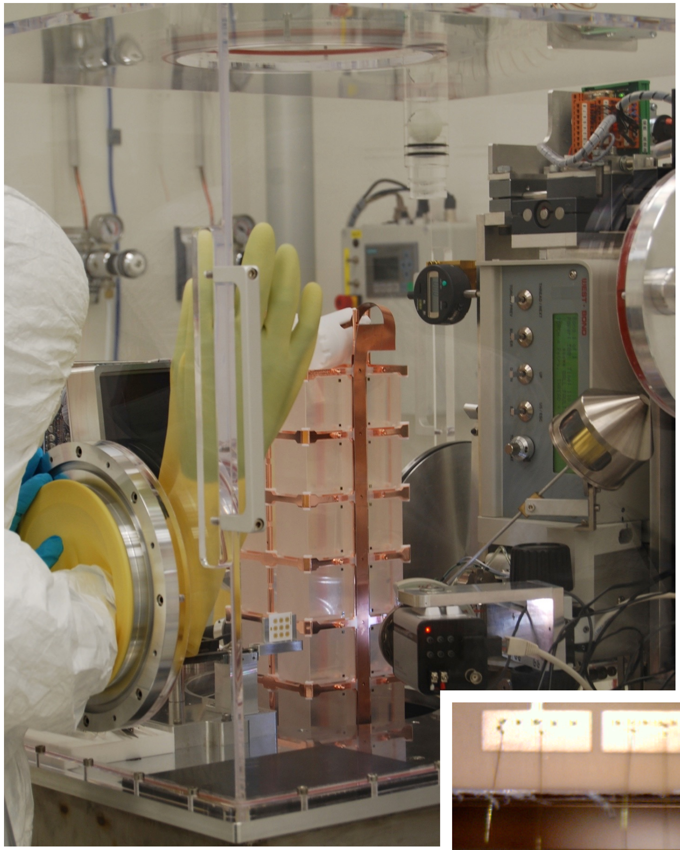


Semi-automated, glovebox-enclosed system used to glue sensors to crystals in consistent, reproducible fashion

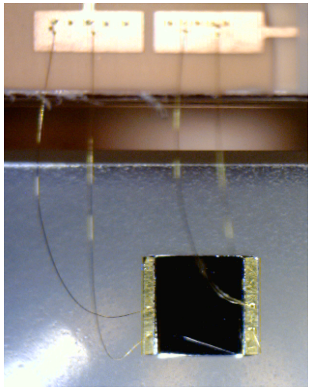
2. Tower assembly

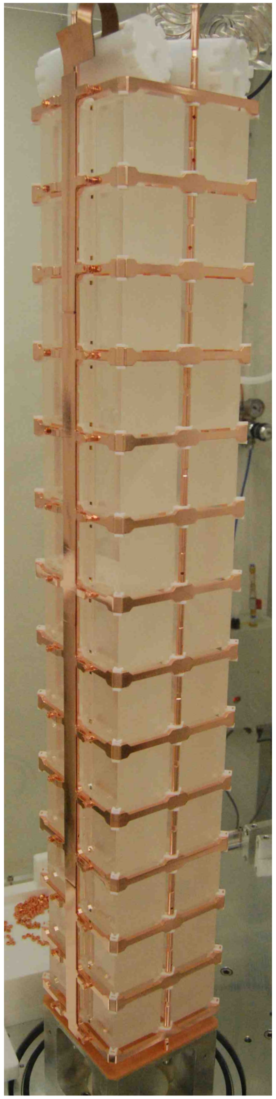


Physical assembly



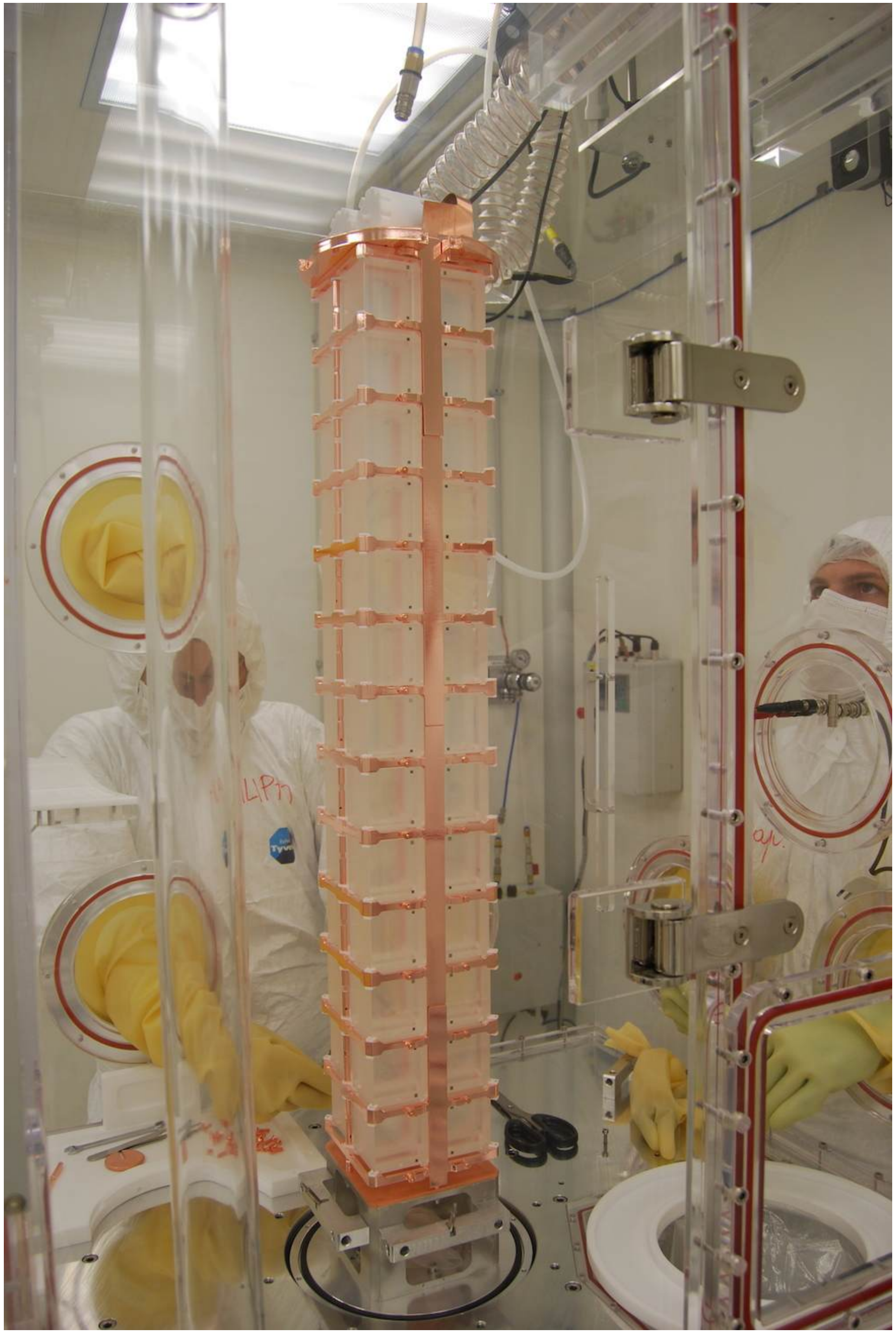
Wire bonding





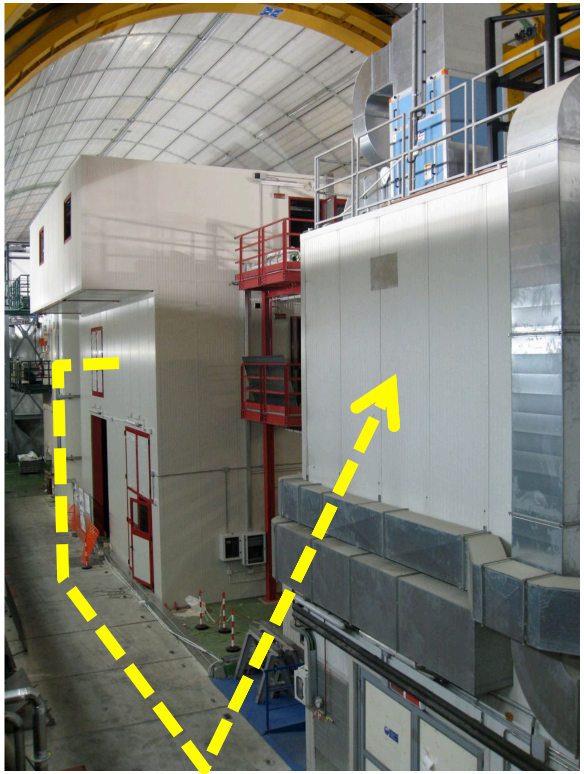
Complete

- 51/52 thermistors connected
- 51/52 heaters connected



3. Tower installation

After assembly



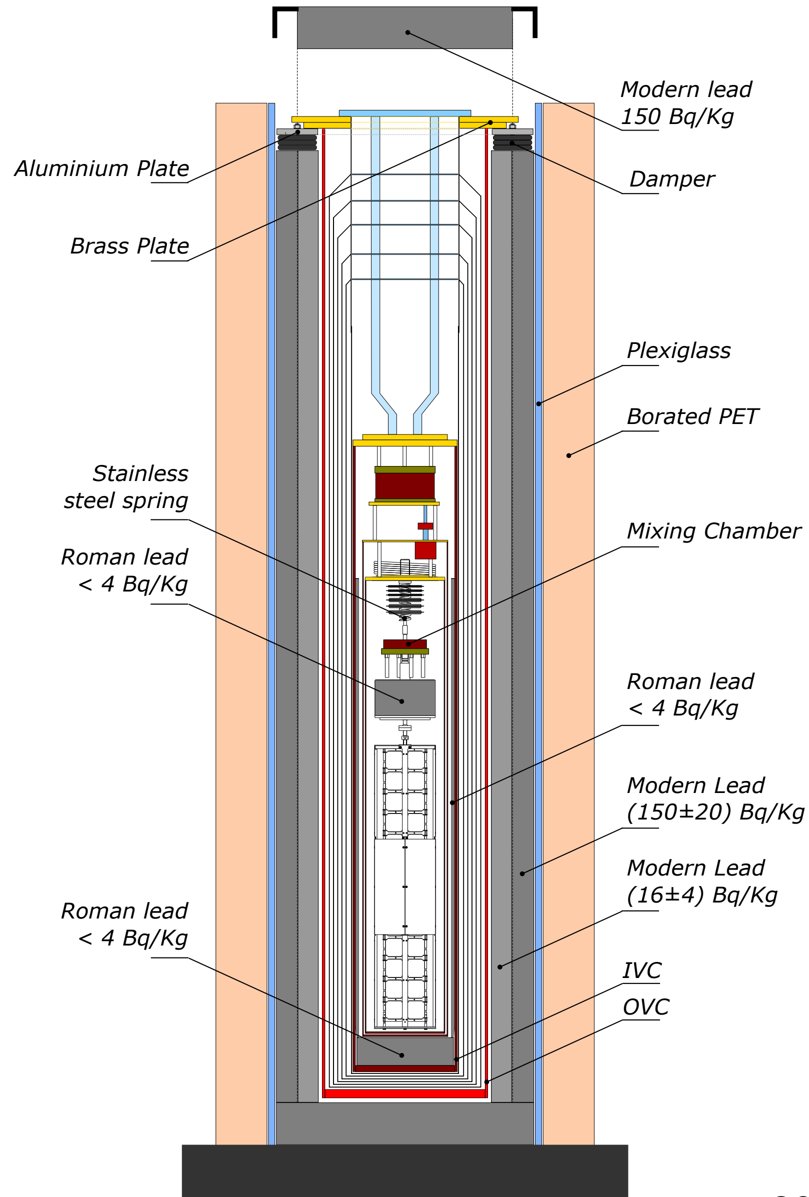
Transported from CUORE clean room to Cuoricino clean room

Attached to Cuoricino dilution rerigerator

Experimental setup

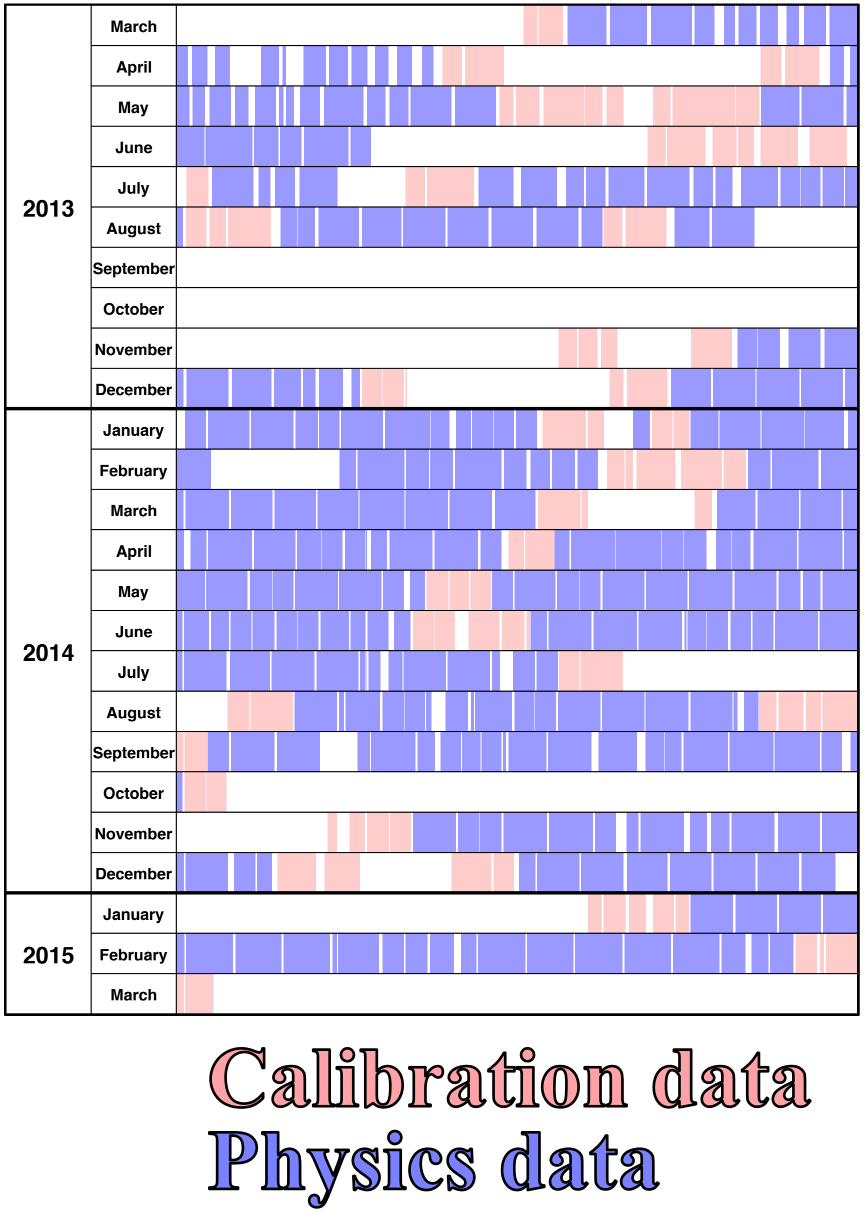
- Utilizes the same (old) cryostat as Cuoricino:
  - Inner shields of Roman lead (1 cm lateral thickness)
  - Outer shields of modern lead (20 cm lateral thickness)
  - Borated PET lateral shield
  - Faraday cage flushed with N_2 to suppress Rn

- Gamma backgrounds not expected to change compared to Cuoricino



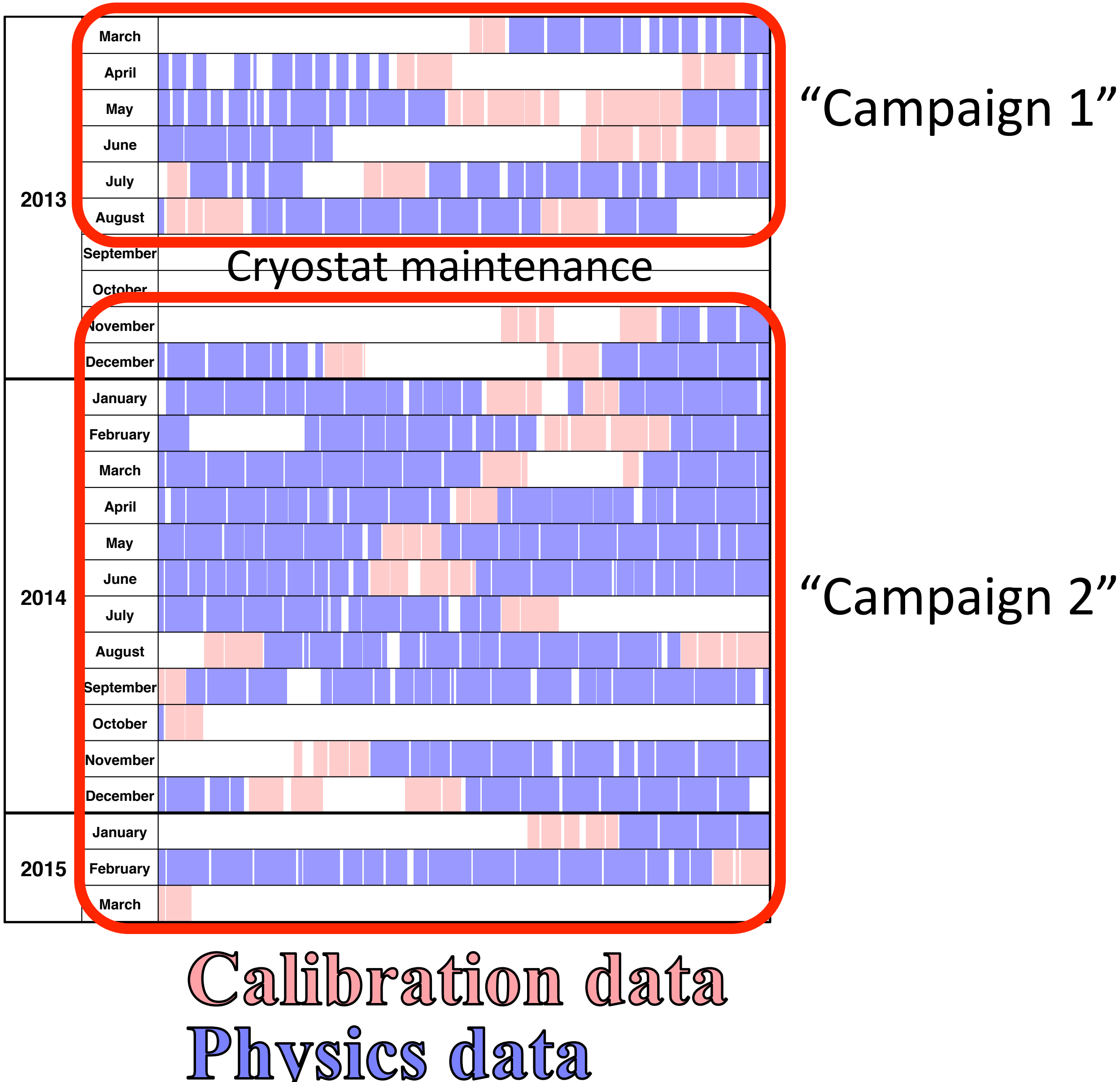
CUORE-0 performance

Data taking



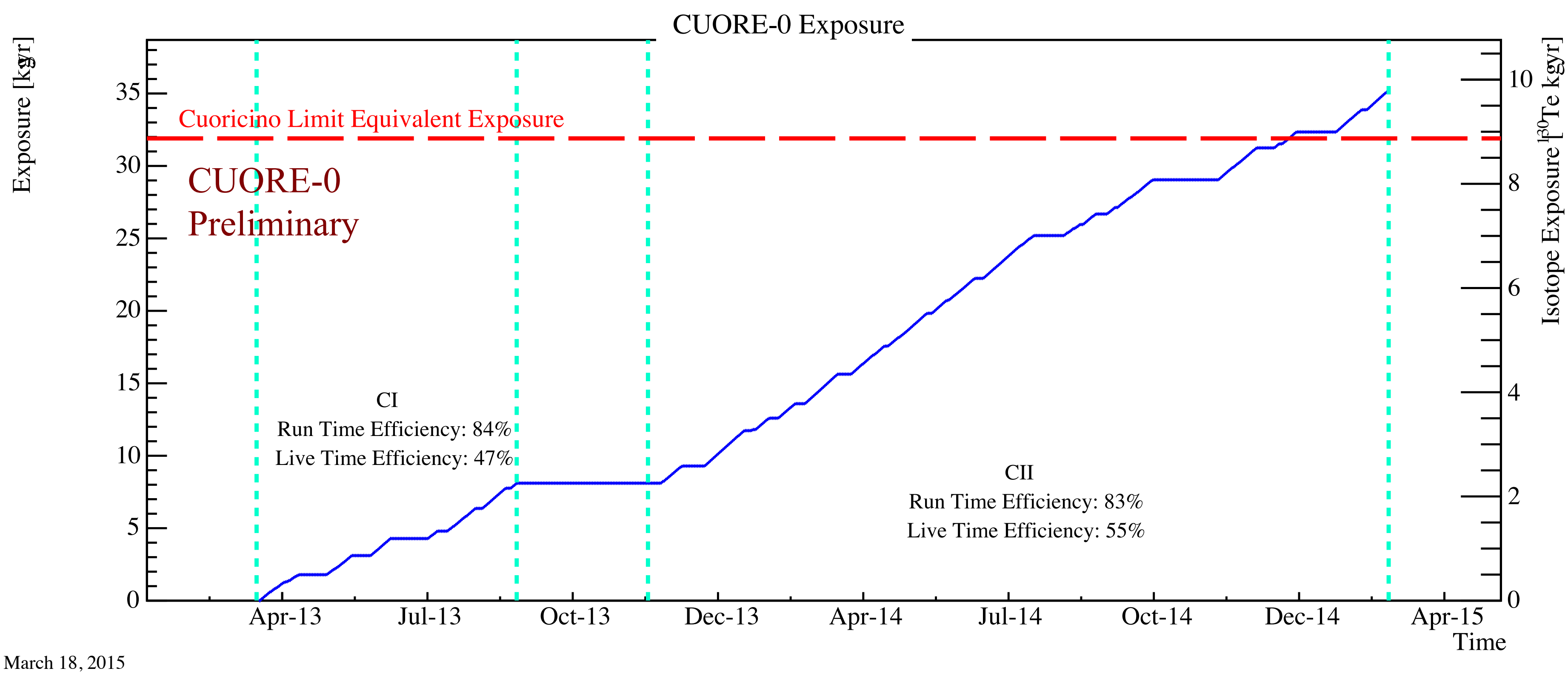
- Tower assembled Spring 2012
- First successful cooldown March 2013
- One heater lost during cooldown:
  - 51/52 thermistors operational
  - 50/52 heaters operational
- Typically 3 days/month devoted to detector calibration
- Remaining time devoted to physics data taking

Data taking



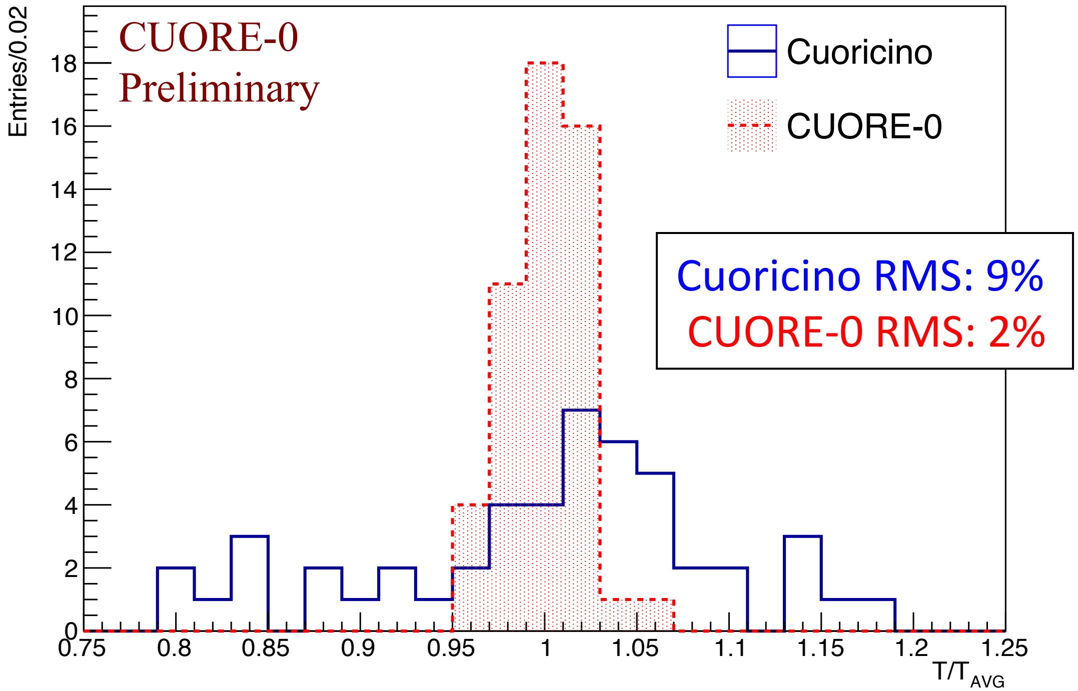
2013
March
April
May
June
July
August
September
October
November
December
2014
January
February
March
April
May
June
July
August
September
October
November
December
2015
January
February
March
Cryostat maintenance
"Campaign 1"
"Campaign 2"
Calibration data
Physics data

Exposure



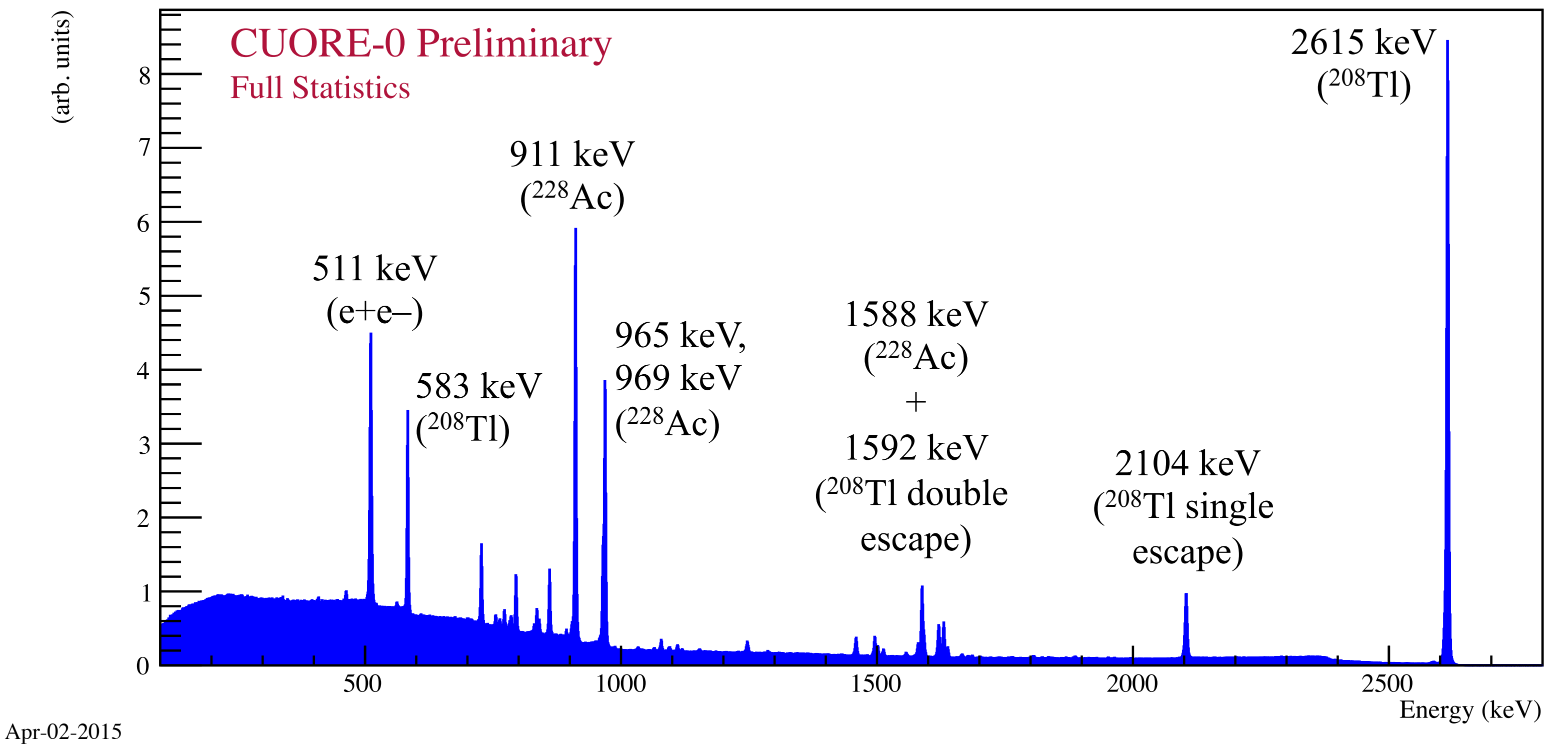
- Total exposure (TeO_2) = 35.2 kg-y
- Total exposure (^{130}Te) = 9.8 kg-y

Detector uniformity



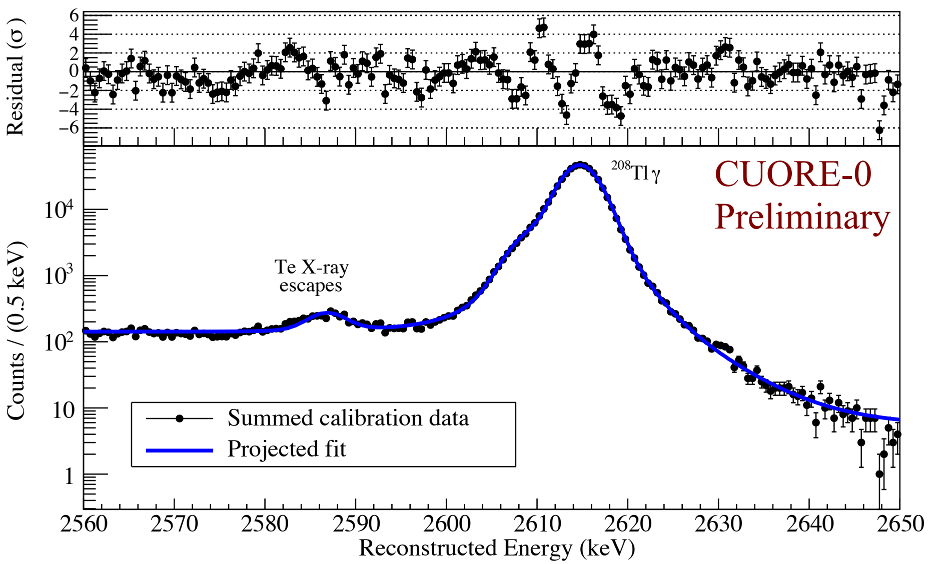
- We can convert each thermistor's resistance at 10 mK to a temperature
- CUORE-0 thermistor temperatures are much more uniform than in Cuoricino
- Demonstrates improvements in reproducibility in detector construction

Calibration spectrum

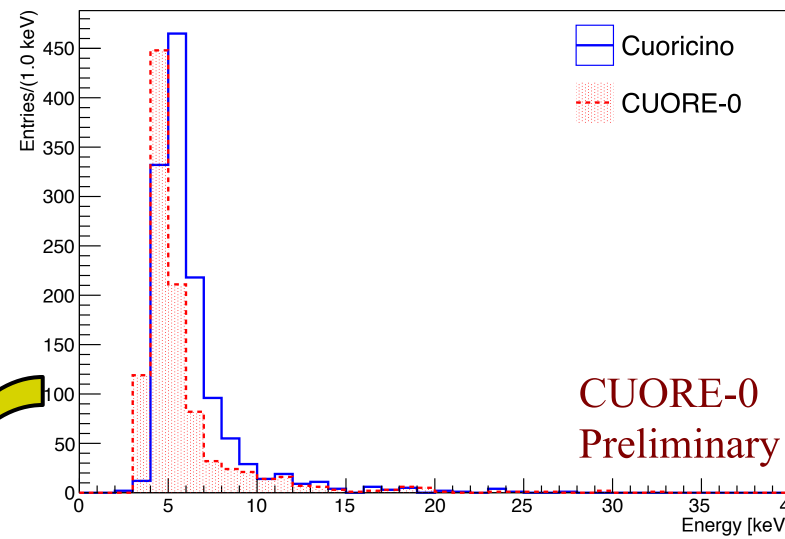


We calibrated the detector ~ once/month by lowering thoriated tungsten wires between the cryostat and the external lead shield.

Energy resolution



Bolometer-dataset FWHMs @ 2615 keV

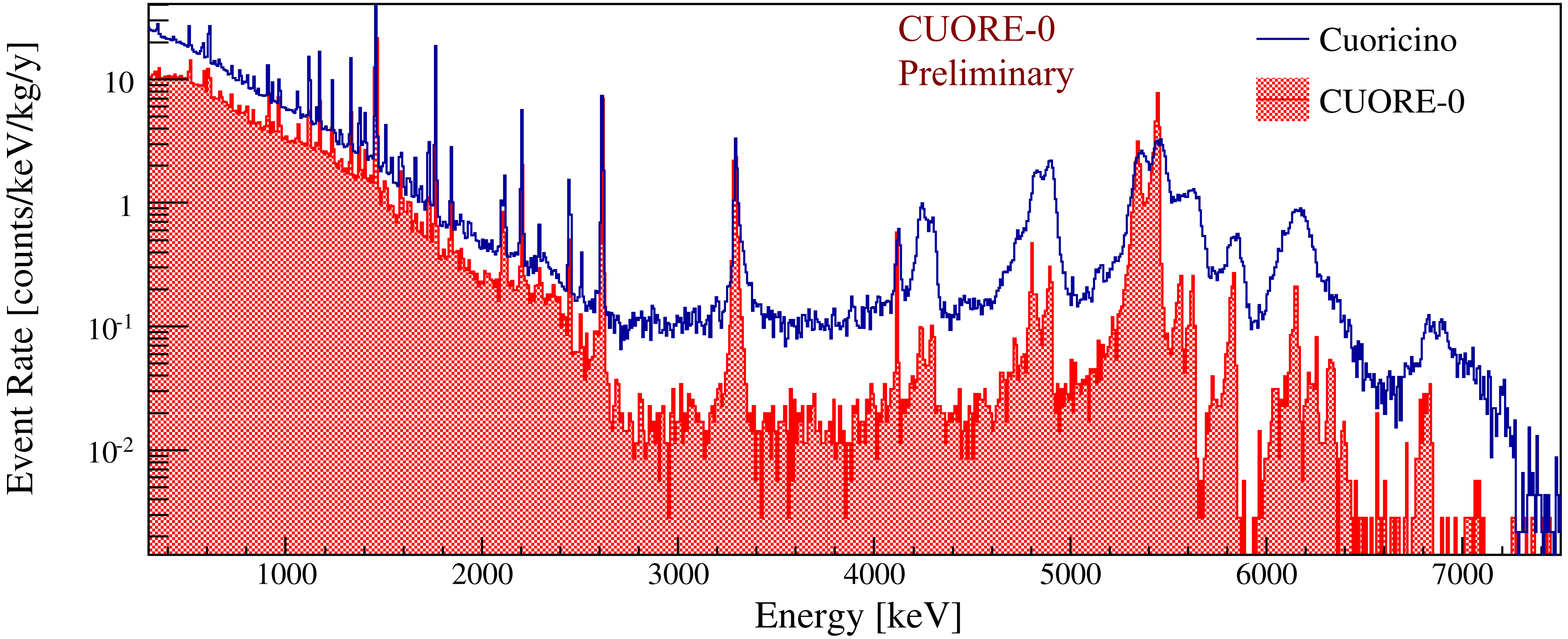


Weight FWHMs by corresponding physics exposure

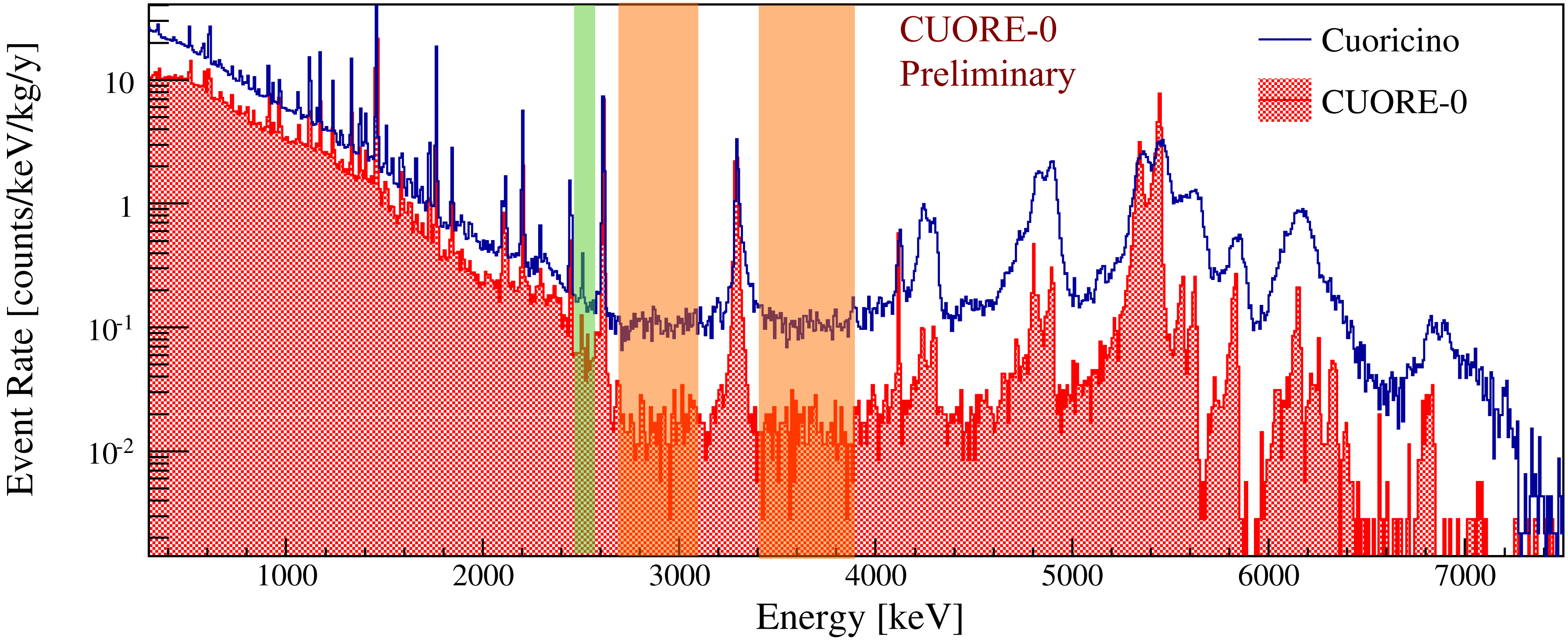
	FWHM harmonic mean (keV)	FWHM dist RMS (keV)
Cuoricino	5.8	2.1
CUORE-0	4.9	2.9

- We evaluate the energy resolution for each bolometer and dataset by fitting the ^{208}Tl photopeak in the calibration data
- We achieved the 5 keV resolution goal of CUORE!

Backgrounds

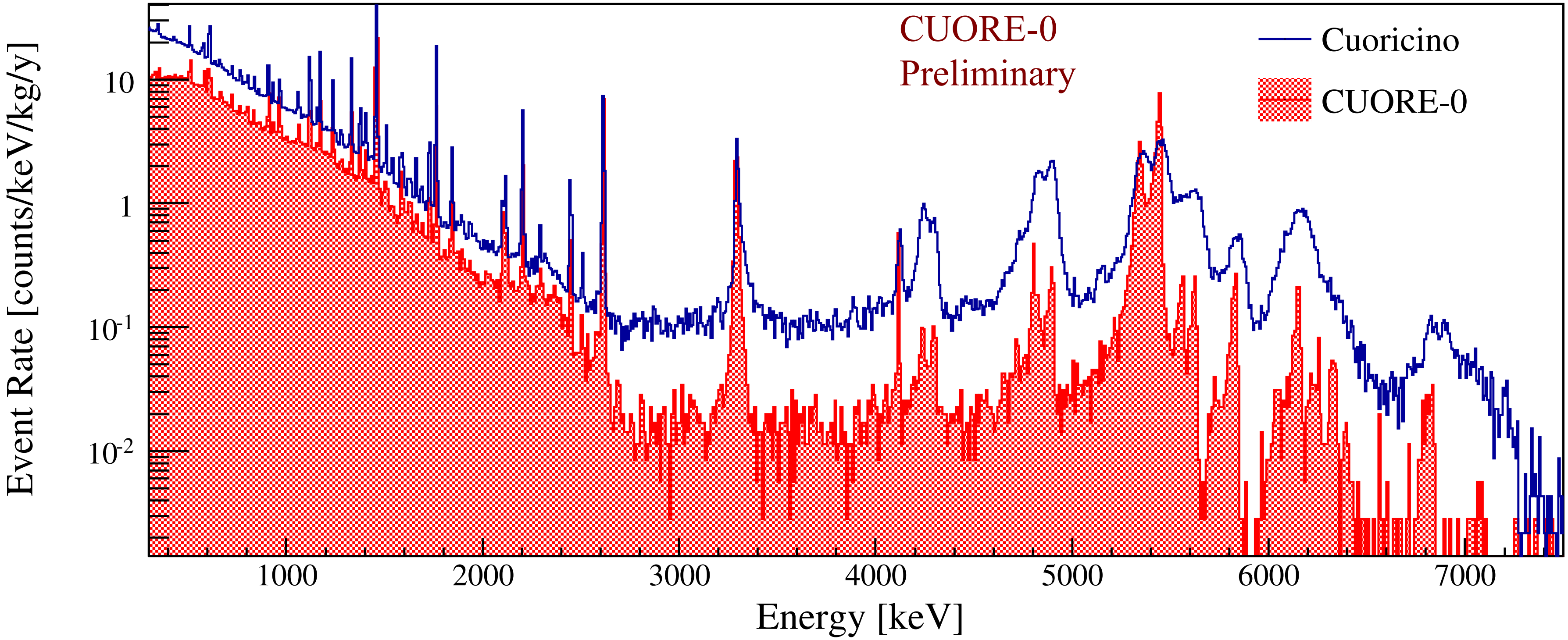


Backgrounds



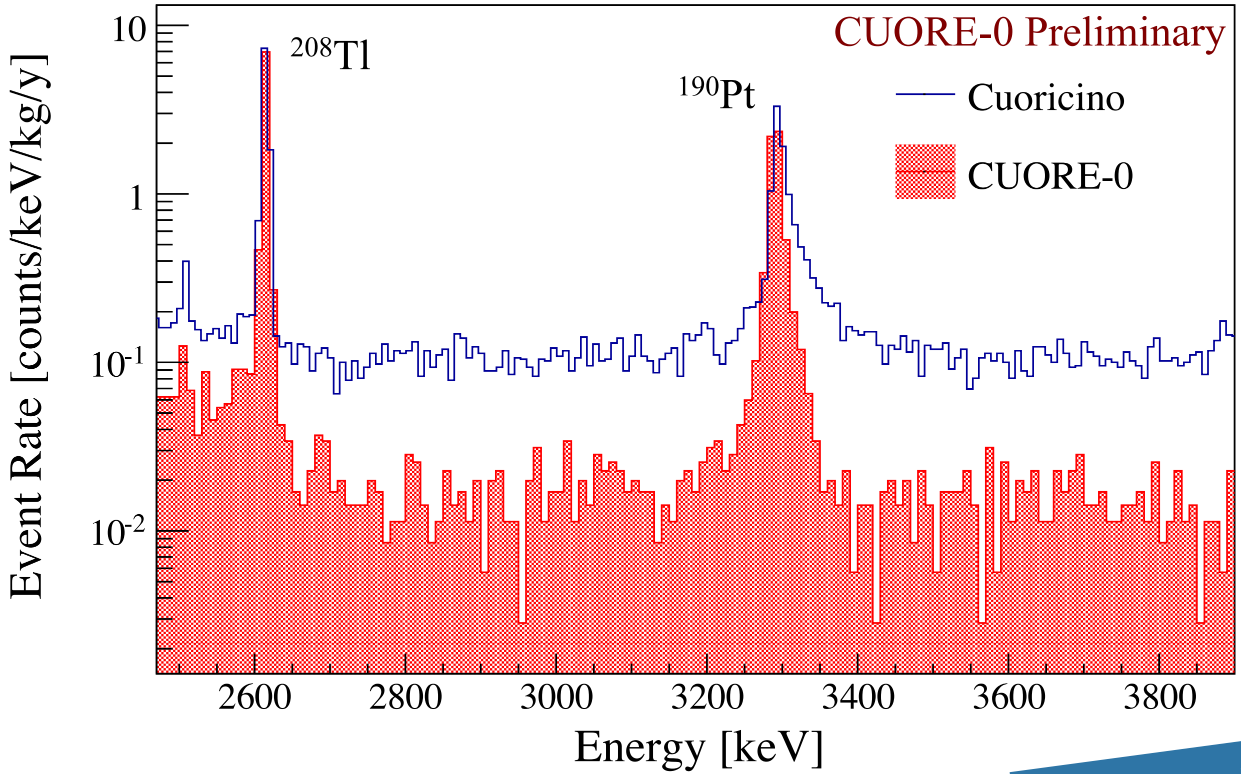
Experiment	Background rate (counts/keV/kg/y)	
	$0\nu\beta\beta$ decay region	Alpha region (excl. peak)
Cuoricino	0.169 ± 0.006	0.110 ± 0.001
CUORE-0	0.058 ± 0.004	0.016 ± 0.001

Backgrounds



- 2.5x reduction in ^{238}U-chain gammas (better radon control)
- No reduction in ^{232}Th-chain gammas (due to cryostat materials, irreducible)

Backgrounds



Paper on background model is in preparation

- 6.5x reduction in alpha continuum background!
- Validates enhanced cleaning and assembly techniques
- Confirms background model developed from Cuoricino
- Indicates CUORE sensitivity goal is within reach

CUORE-0 search for $0\nu\beta\beta$ decay

Data analysis

1. Pulse amplitude evaluation

2. Gain stabilization

3. Energy calibration

4. Event selection

5. Blinding of E spectrum

6. Analysis studies

7. Unblinding of E spectrum

8. $0\nu\beta\beta$ decay fit

Data analysis

1. Pulse amplitude evaluation

2. Gain stabilization

3. Energy calibration

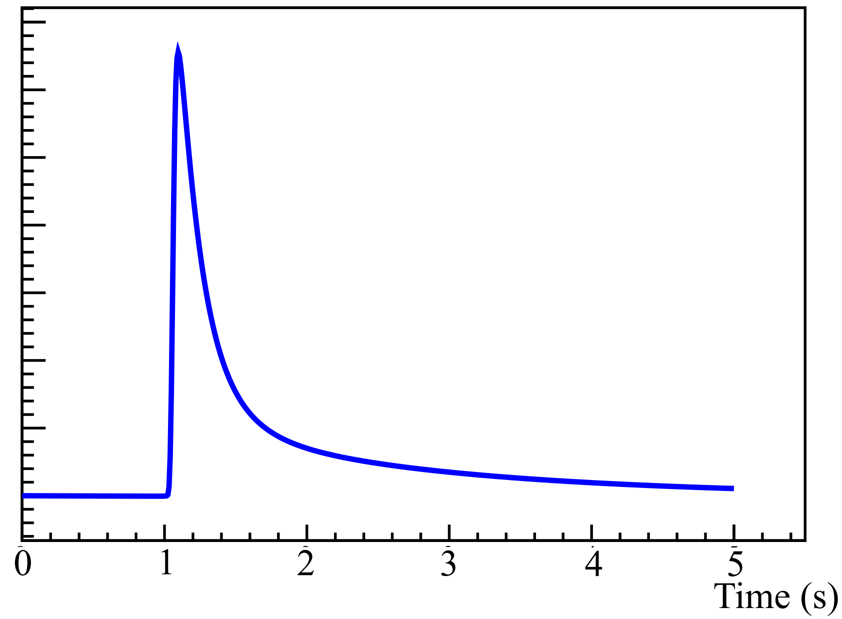
4. Event selection

5. Blinding of E spectrum

6. Analysis studies

7. Unblinding of E spectrum

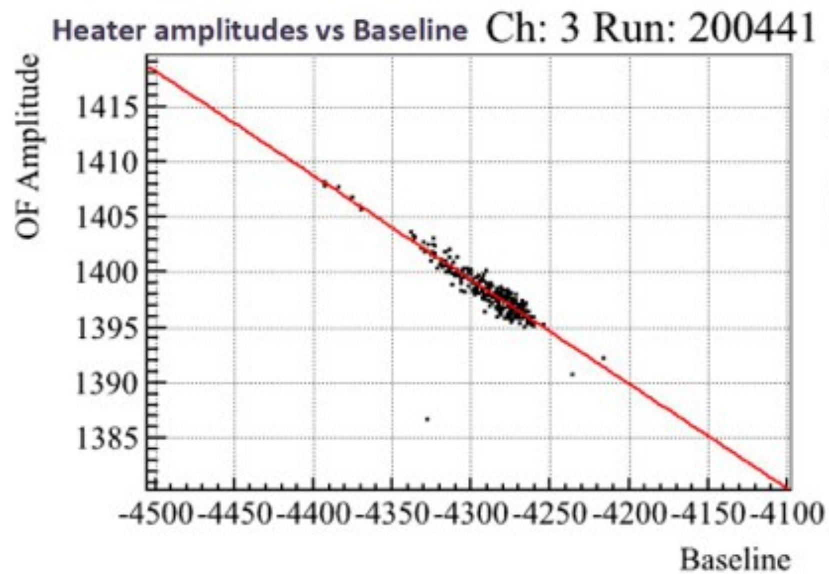
8. $0\nu\beta\beta$ decay fit



- Thermistor voltages are continuously sampled at 125 Hz
- Software threshold trigger flags 5-second intervals for study
- Pretrigger voltage is good proxy for initial bolometer temp
- Pulse is run through optimal and common-mode-noise-decorrelation filters to accurately determine its amplitude and characterize its shape

Data analysis

1. Pulse amplitude evaluation
2. Gain stabilization
3. Energy calibration
4. Event selection
5. Blinding of E spectrum
6. Analysis studies
7. Unblinding of E spectrum
8. $0\nu\beta\beta$ decay fit



- Bolometer gain is temperature-dependent, so amplitude(E) varies with drifts in temperature
- We "thermal gain stabilize" (TGS) using two parallel methods:
  - Heater-TGS: Use monoenergetic heater pulses to map pulse amplitude vs. bolometer baseline voltage
  - Calibration-TGS: Use 2.6 MeV calibration line to map pulse amplitude vs. bolometer working voltage. This method allows us to recover data from bolometers that don't have working heaters!

Data analysis

1. Pulse amplitude evaluation

2. Gain stabilization

3. Energy calibration

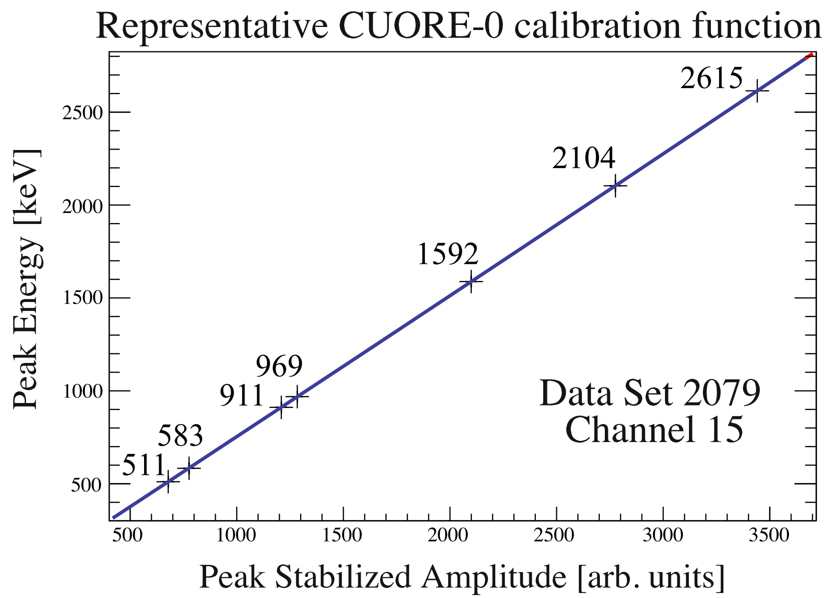
4. Event selection

5. Blinding of E spectrum

6. Analysis studies

7. Unblinding of E spectrum

8. $0\nu\beta\beta$ decay fit



- Fit most intense Th-chain gamma lines from ^{228}Ac and ^{208}Tl to obtain quadratic function mapping stabilized amplitude to energy, for each bolometer and dataset
- Apply function to data to convert pulse amplitudes to energy

Data analysis

1. Pulse amplitude evaluation

2. Gain stabilization

3. Energy calibration

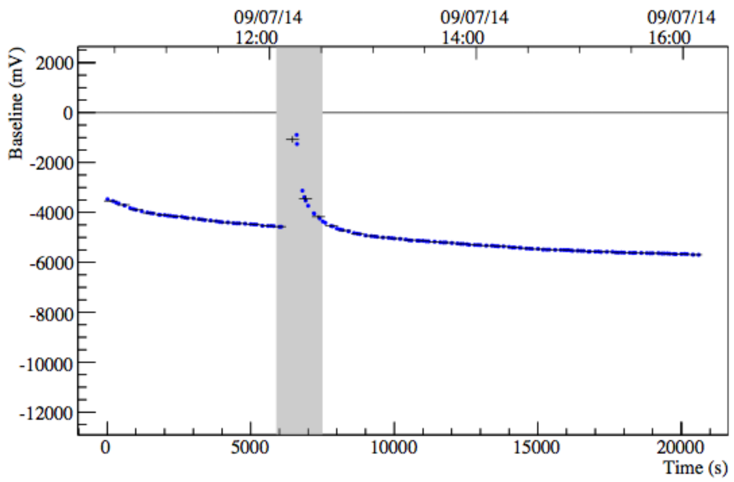
4. Event selection

5. Blinding of E spectrum

6. Analysis studies

7. Unblinding of E spectrum

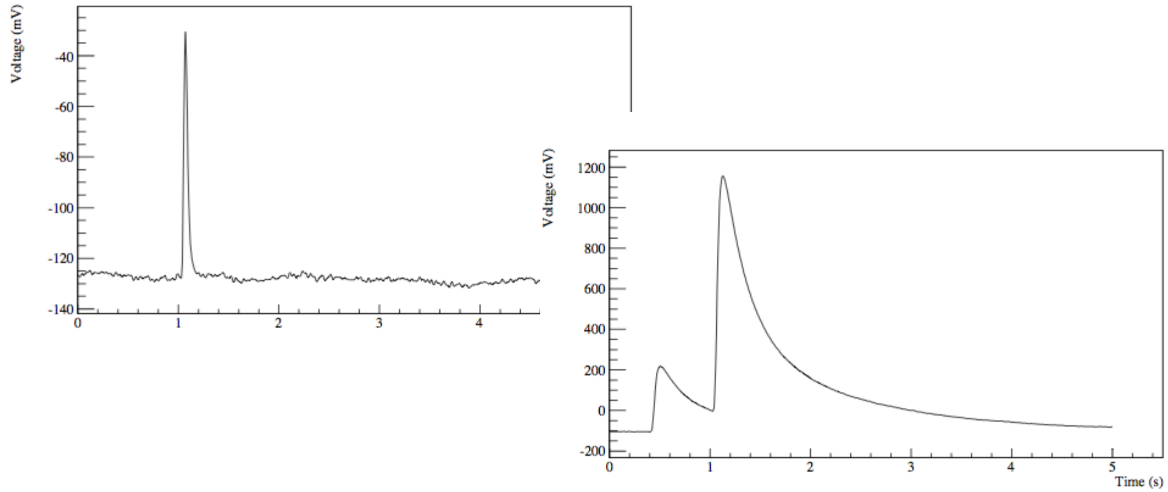
8. $0\nu\beta\beta$ decay fit



- General data quality cuts
- Pulse-shape cuts to reject unphysical noise pulses
- Pileup rejection on each channel: no signals 3.1s before or 4.0s after
- Tower-wide ±5 ms anticoincidence cut, as 88% of $0\nu\beta\beta$ decays would be single-site events

Data analysis

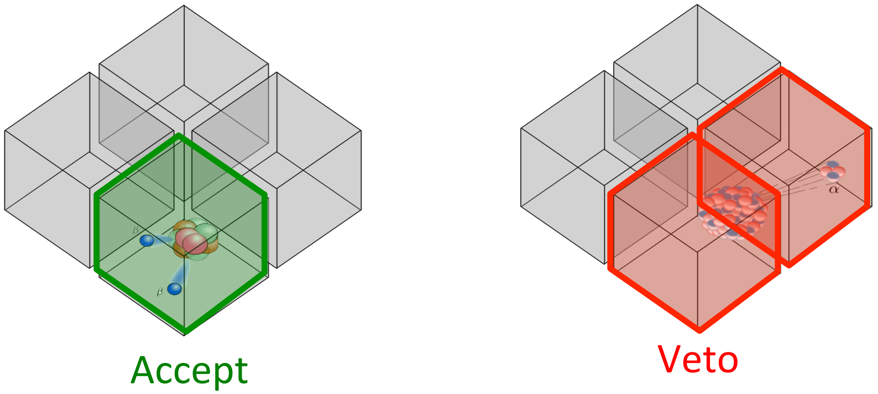
1. Pulse amplitude evaluation
2. Gain stabilization
3. Energy calibration
4. Event selection
5. Blinding of E spectrum
6. Analysis studies
7. Unblinding of E spectrum
8. $0\nu\beta\beta$ decay fit



- General data quality cuts
- Pulse-shape cuts to reject unphysical noise pulses
- Pileup rejection on each channel: no signals 3.1s before or 4.0s after
- Tower-wide ±5 ms anticoincidence cut, as 88% of $0\nu\beta\beta$ decays would be single-site events

Data analysis

1. Pulse amplitude evaluation
2. Gain stabilization
3. Energy calibration
4. Event selection
5. Blinding of E spectrum
6. Analysis studies
7. Unblinding of E spectrum
8. $0\nu\beta\beta$ decay fit



- General data quality cuts
- Pulse-shape cuts to reject unphysical noise pulses
- Pileup rejection on each channel: no signals 3.1s before or 4.0s after
- Tower-wide ±5 ms anticoincidence cut, as 88% of $0\nu\beta\beta$ decays would be single-site events

Data analysis

1. Pulse amplitude evaluation
2. Gain stabilization
3. Energy calibration
4. Event selection
5. Blinding of E spectrum
6. Analysis studies
7. Unblinding of E spectrum
8. $0\nu\beta\beta$ decay fit

	Efficiency (%)	Error (%)
Trigger	98.6	0.004
Pileup & shape	93.7	0.7
Containment	88.4	0.09
Accidental	99.6	0.1

Overall selection efficiency is (81.3 ± 0.6)%

Data analysis

1. Pulse amplitude evaluation

2. Gain stabilization

3. Energy calibration

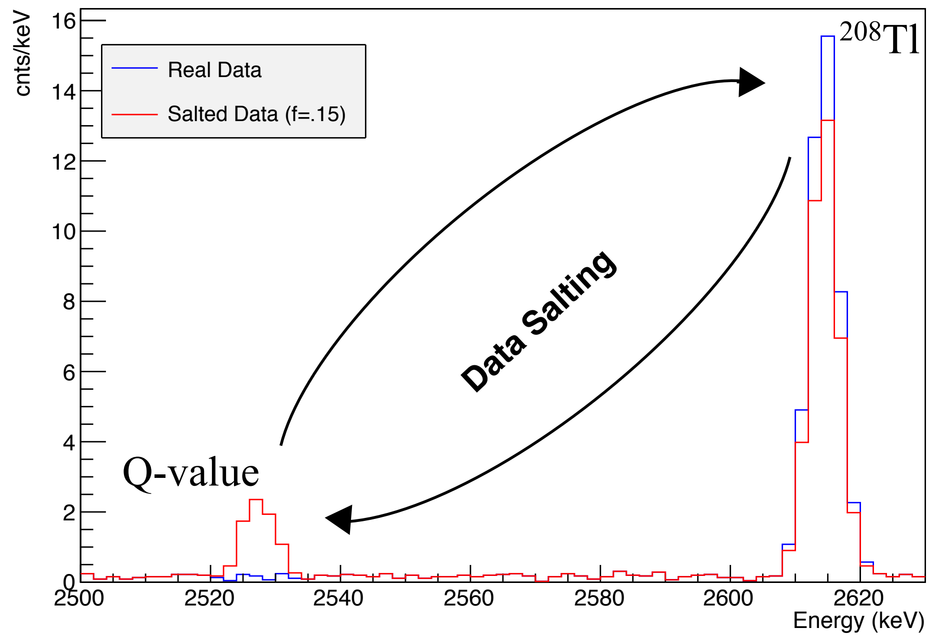
4. Event selection

5. Blinding of E spectrum

6. Analysis studies

7. Unblinding of E spectrum

8. $0\nu\beta\beta$ decay fit

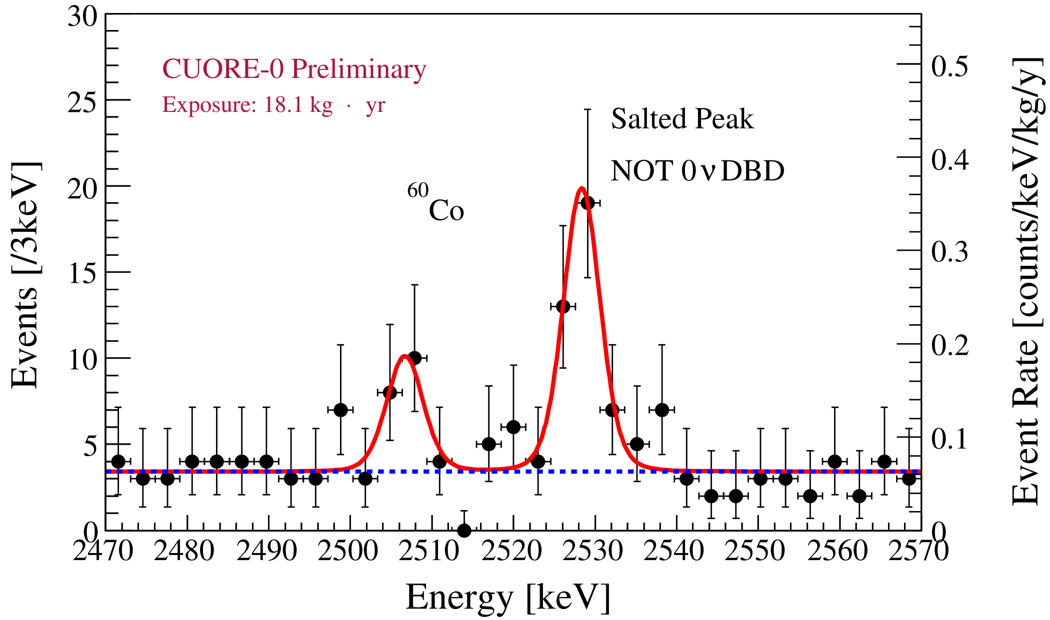


A small (and blinded) fraction of events within ±10 keV of ^{208}Tl photopeak are moved to within ±10 keV of the ^{130}Te $0\nu\beta\beta$ decay Q-value, and vice versa

Data analysis

- 1. Pulse amplitude evaluation
- 2. Gain stabilization
- 3. Energy calibration
- 4. Event selection
- 5. Blinding of E spectrum
- **6. Analysis studies**
- 7. Unblinding of E spectrum
- 8. $0\nu\beta\beta$ decay fit

(May 2014)

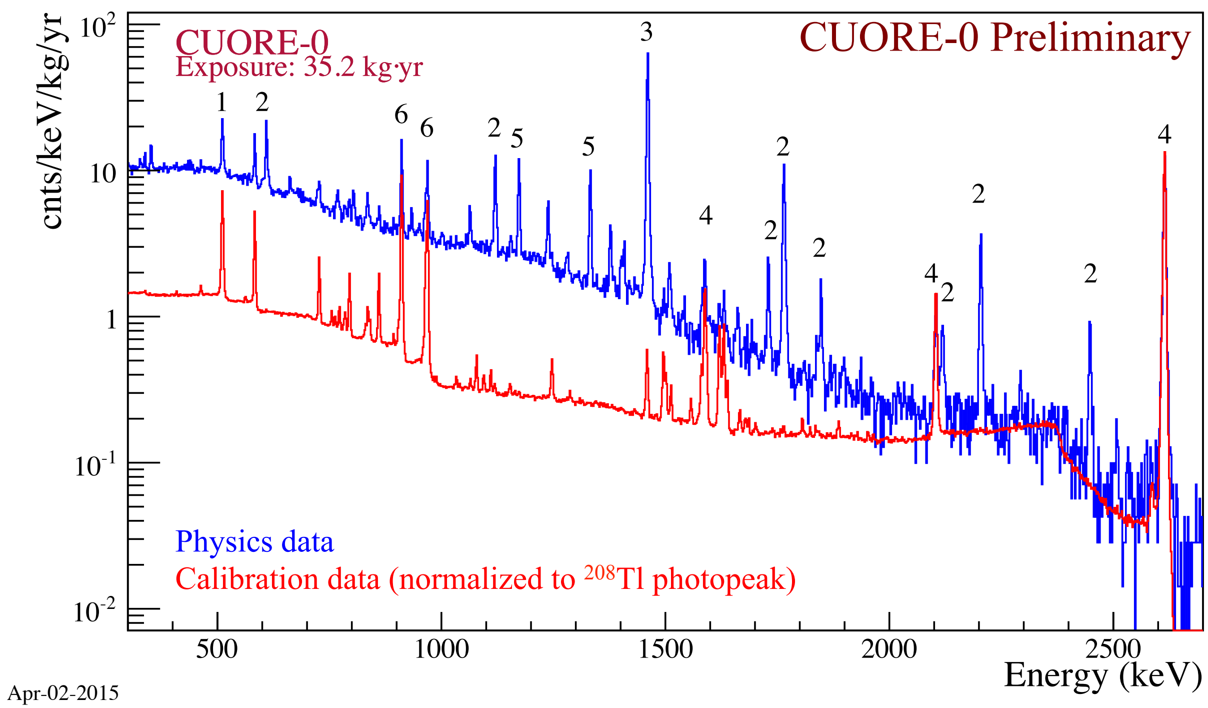


We can study and characterize the background in the region of interest (ROI) of the blinded spectrum without biasing our $0\nu\beta\beta$ decay analysis.

(CUORE-0 Collaboration) EPJC 74, 2956 (2014) [arXiv:nucl-ex/1402.0922].

Data analysis

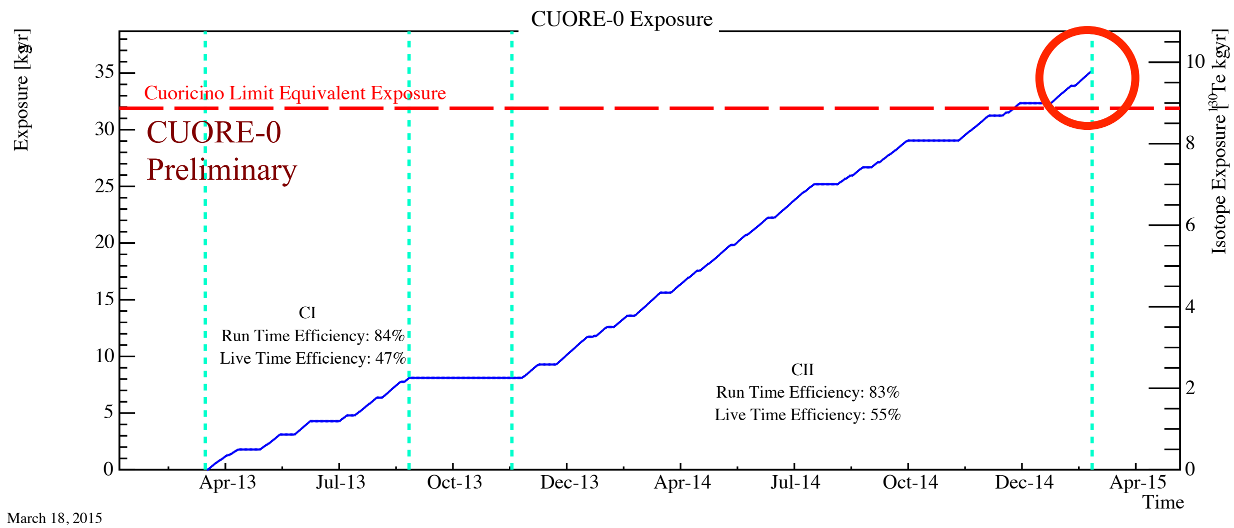
1. Pulse amplitude evaluation
2. Gain stabilization
3. Energy calibration
4. Event selection
5. Blinding of E spectrum
6. Analysis studies
7. Unblinding of E spectrum
8. $0\nu\beta\beta$ decay fit



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

Data analysis

1. Pulse amplitude evaluation
2. Gain stabilization
3. Energy calibration
4. Event selection
5. Blinding of E spectrum
6. Analysis studies
7. Unblinding of E spectrum
8. $0\nu\beta\beta$ decay fit



- We unblinded the data in February 2015, shortly after our exposure exceeded the equivalent of the Cuoricino limit
- Equivalent exposure is that yielding the same sensitivity given the experiment's resolution, detector efficiencies, and background level in the ROI

Data analysis

1. Pulse amplitude evaluation

2. Gain stabilization

3. Energy calibration

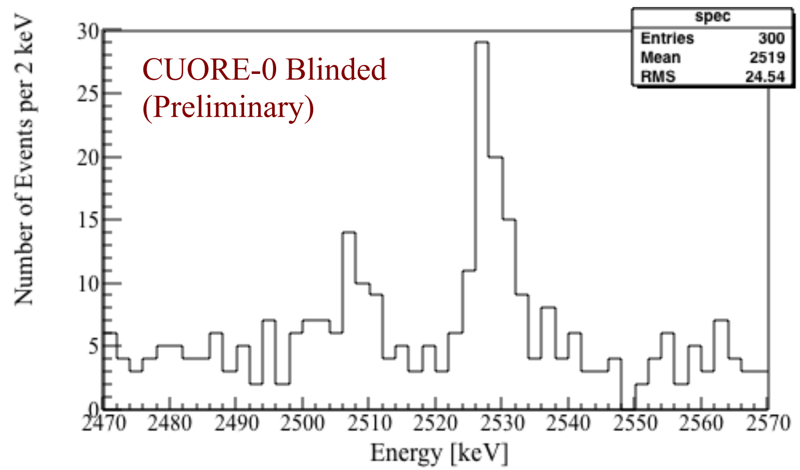
4. Event selection

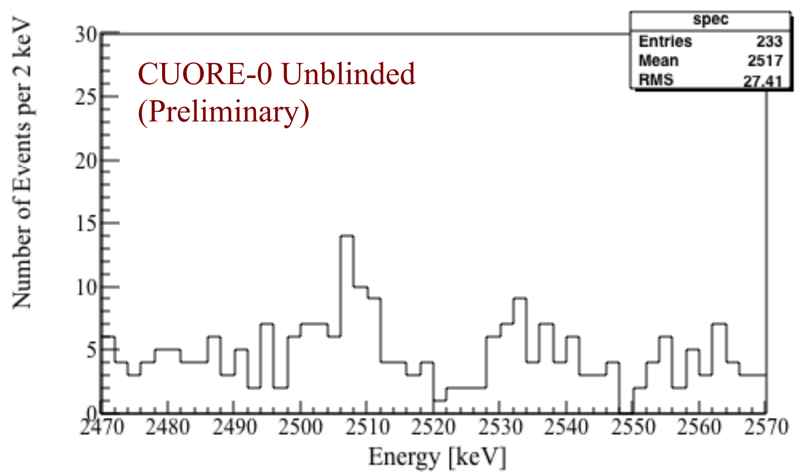
5. Blinding of E spectrum

6. Analysis studies

7. Unblinding of E spectrum

8. $0\nu\beta\beta$ decay fit





Data analysis

1. Pulse amplitude evaluation

2. Gain stabilization

3. Energy calibration

4. Event selection

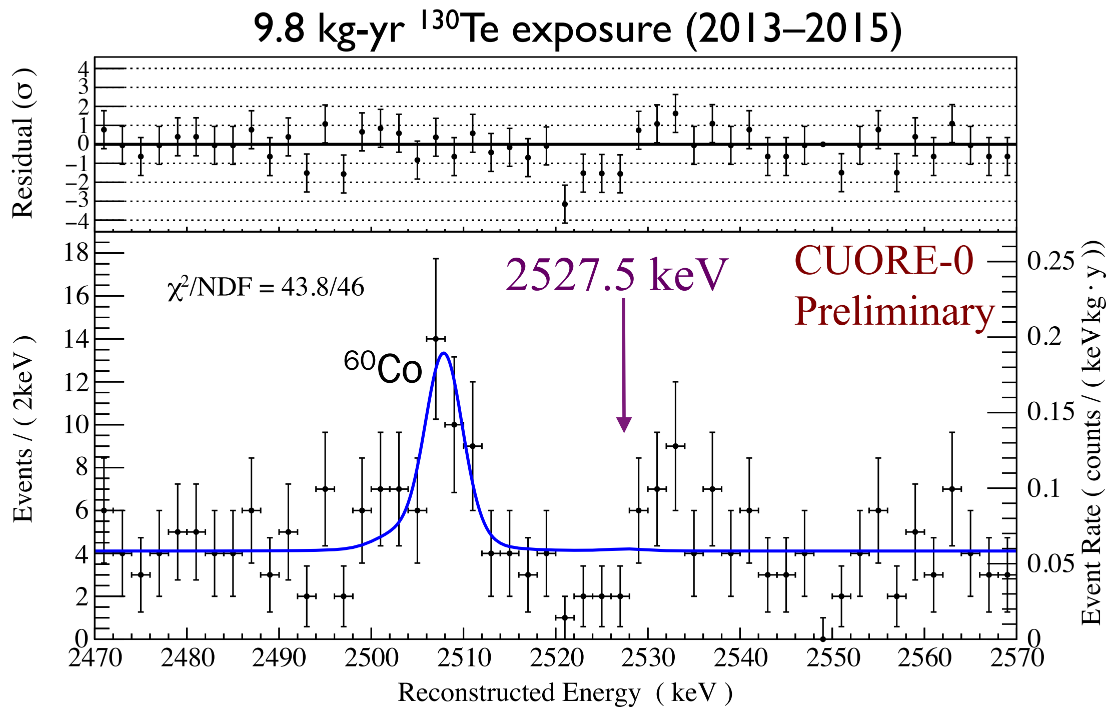
5. Blinding of E spectrum

6. Analysis studies

7. Unblinding of E spectrum

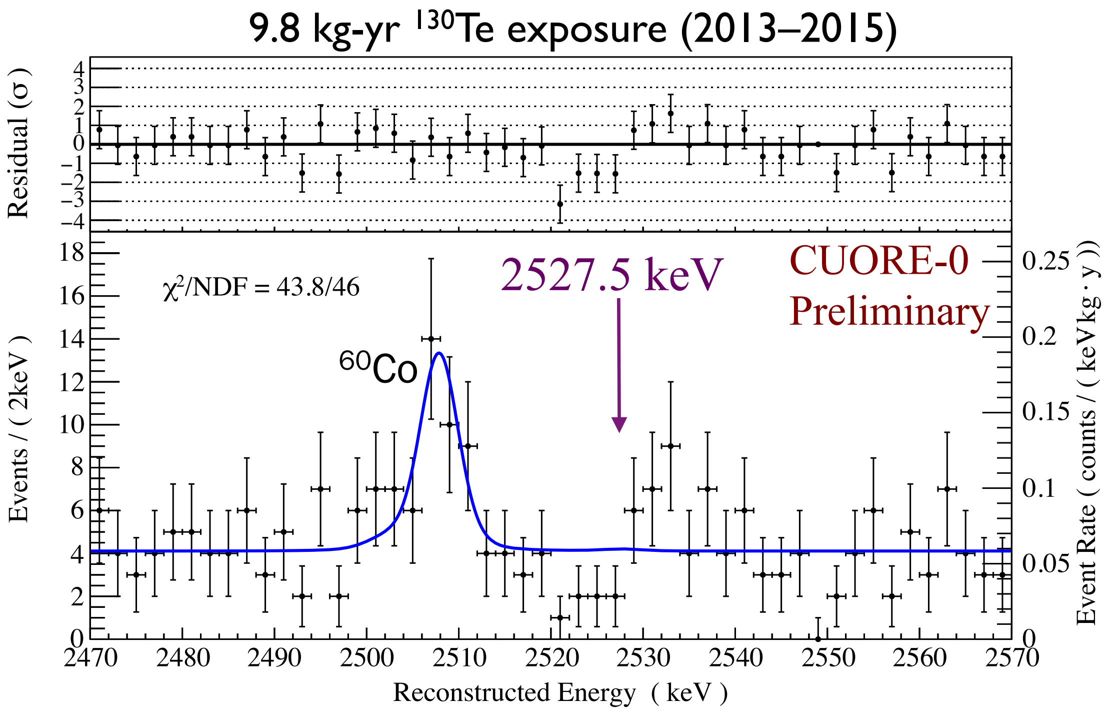
8. $0\nu\beta\beta$ decay fit

Fit to the unblinded ROI



- ▶ We perform a simultaneous unbinned extended ML fit to range [2470, 2570] keV
- ▶ Fit function has three components:
  - Calibration-derived lineshape modeling posited $0\nu\beta\beta$ peak fixed at 2527.5 keV
  - Calibration-derived lineshape modeling ^{60}Co peak floated around 2505 keV
  - Continuum background

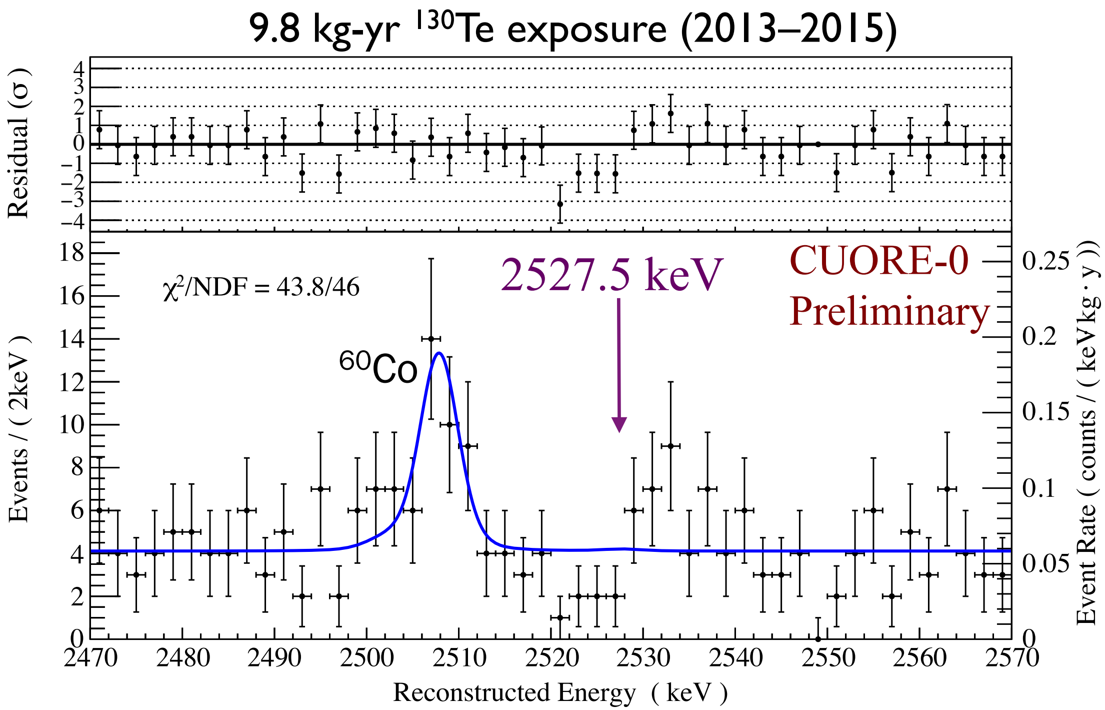
Fit to the unblinded ROI



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

Best-fit decay rate: $\Gamma^{0\nu\beta\beta}(^{130}\mathrm{Te}) = 0.007 \pm 0.123\ (\mathrm{stat.}) \pm 0.012\ (\mathrm{syst.}) \times 10^{-24}\ \mathrm{yr}^{-1}$

Fit to the unblinded ROI



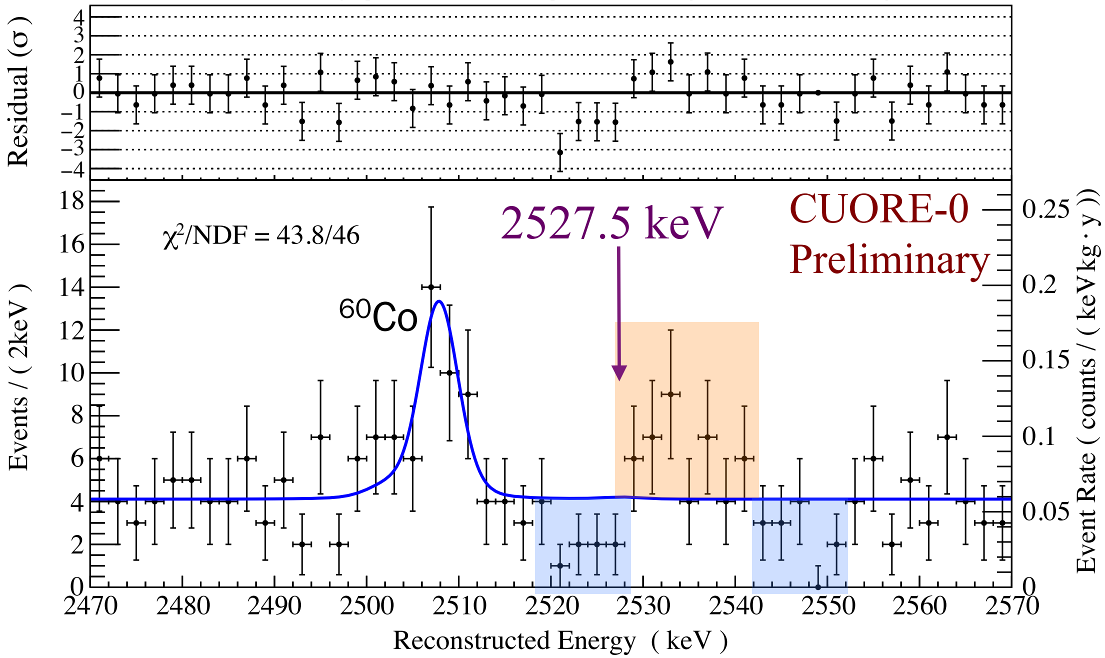
We find no evidence for $0\nu\beta\beta$ decay of ^{130}Te and report the Bayesian limits:

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

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

Background fluctuations

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



- ▶ We evaluated the statistical likelihood of observed excess and deficits in data
- ▶ Kolmogorov-Smirnov test shows data are consistent with zero-rate hypothesis
- ▶ None of the positive or negative fluctuations have signal significance > 3σ
- ▶ Probability to observe a fluctuation anywhere in the ROI as big as largest is ~ 10% (i.e., accounting for trials factor)

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
Signal normalization	0.7%	

- For each systematic, we run toy MC expts to evaluate bias on fitted $0\nu\beta\beta$ decay rate
- Bias is parameterized as $\mathrm{p0} + \mathrm{p1}\times\Gamma$, where p0="additive" and p1="scaling"
- Signal lineshape: Used variety of different lineshapes to model signal
- Energy resolution: Apply 1.05±0.05 correction to calibration-derived resolution
- Fit bias: Effect of using unbinned extended ML fit to extract values
- Energy scale: Assign 0.12 keV uncertainty derived from peak residuals in physics spectrum
- Bkg function: Treated choice of 0-, 1-, 2-order polynomial as discrete nuisance parameter

Systematics

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

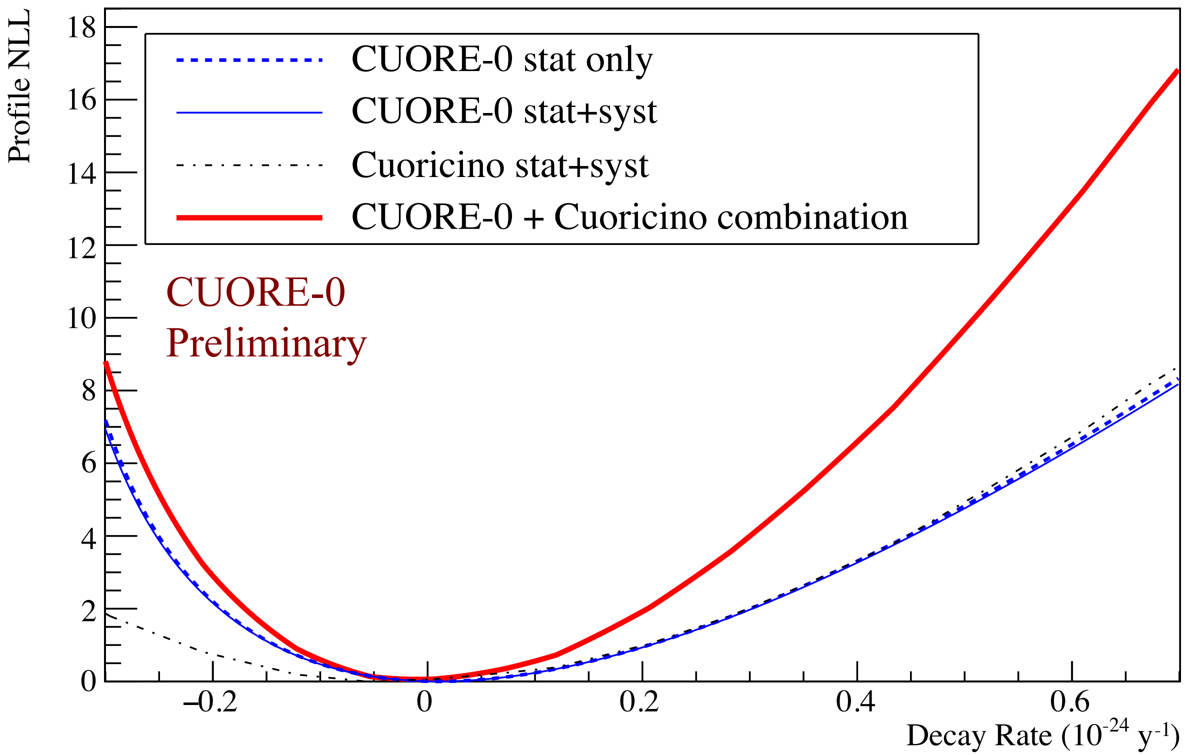
	Additive (10^{-24} y^{-1})	Scaling (%)
Lineshape	0.007	1.3
Energy resolution	0.006	2.3
Fit bias	0.006	0.15
Energy scale	0.005	0.4
Bkg function	0.004	0.8
Signal normalization	0.7%	

After accounting for systematic uncertainties we report the Bayesian limits:

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

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

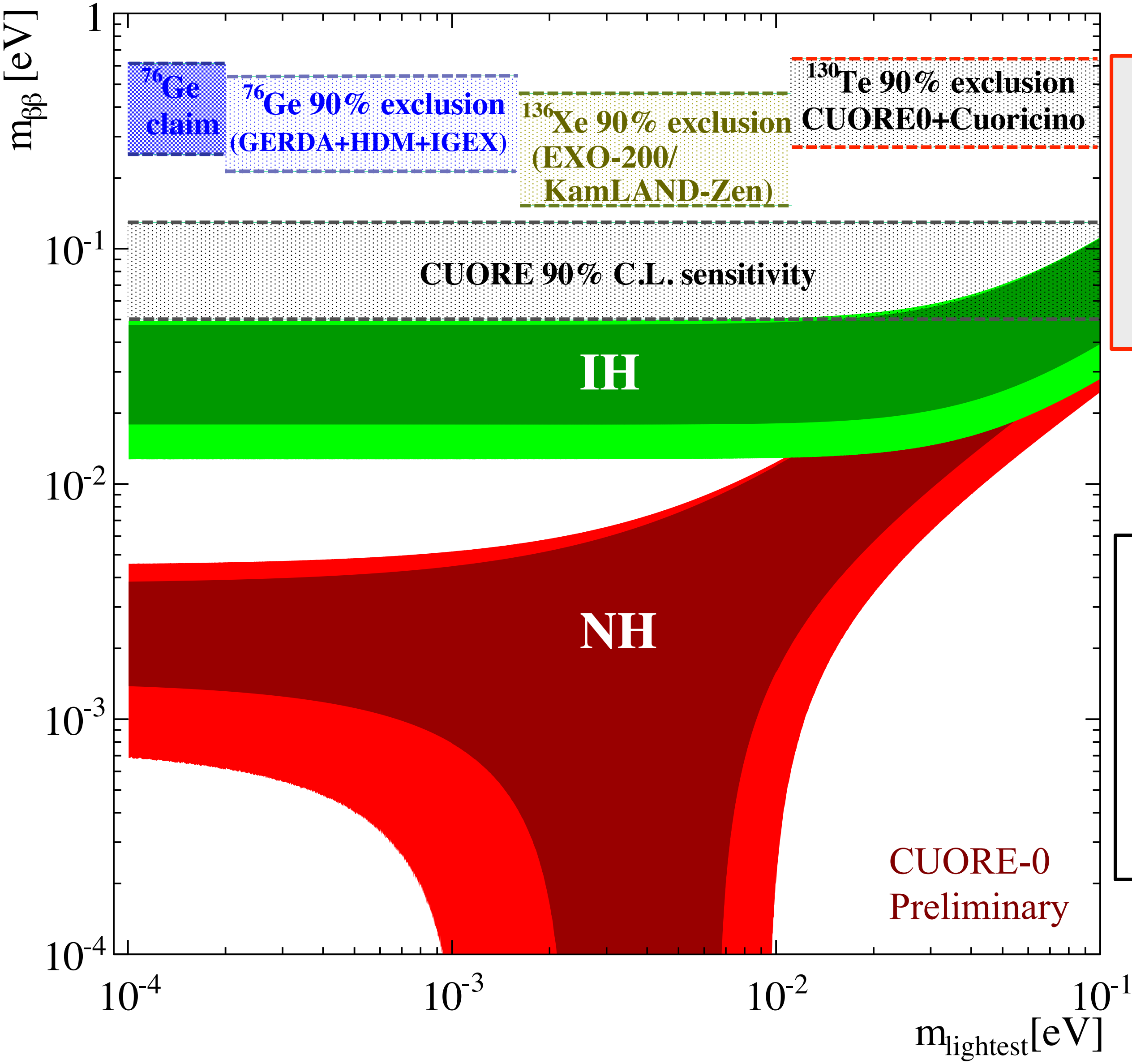
Combining Cuoricino & CUORE-0



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

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

CUORE-0 experimental reach



$\langle m_{\beta\beta} \rangle < 270 - 650$ 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))

Summary

- TeO_2 bolometers offer a well-established, competitive technique in the search for $0\nu\beta\beta$ decay
- CUORE-0 and CUORE experiments are improvements on Cuoricino (2003–2008), which did not find evidence of $0\nu\beta\beta$ decay of ^{130}Te
- CUORE-0
  - Achieved energy resolution and background reduction goals
  - Indicated CUORE sensitivity goal is within reach
  - Surpassed Cuoricino in sensitivity in ~ half the time
  - Did not find evidence of $0\nu\beta\beta$ decay
  - We posted paper to arXiv today and will submit it soon to PRL
  - We are preparing additional technical papers (re: detector, backgrounds)
- CUORE:
  - Assembly of the 19 CUORE towers is complete
  - Commissioning of the cryogenic system and experimental infrastructure is in progress
  - Plan to start operations by end of 2015

Thanks to the collaboration, and to the technical staff of our laboratories!

K. Alfonso,[1] D. R. Artusa,[2,3] F. T. Avignone III,[2] O. Azzolini,[4] M. Balata,[3] T. I. Banks,[5,6] G. Bari,[7]
J.W. Beeman,[8] F. Bellini,[9,10] A. Bersani,[11] M. Biassoni,[12,13] C. Brofferio,[12,13] C. Bucci,[3] A. Caminata,[11]
L. Canonica,[3] X. G. Cao,[14] S. Capelli,[12,13] L. Cappelli,[3,15] L. Carbone,[13] L. Cardani,[9,10,*] N. Casali,[9,10]
L. Cassina,[12,13] D. Chiesa,[12,13] N. Chott,[2] M. Clemenza,[12,13] S. Copello,[16,11] C. Cosmelli,[9,10] O. Cremonesi,[13]
R. J. Creswick,[2] J. S. Cushman,[17] I. Dafinei,[10] A. Dally,[18] S. Dell'Oro,[3,19] M. M. Deninno,[7] S. Di Domizio,[16,11]
M. L. Di Vacri,[3,20] A. Drobizhev,[5,6] L. Ejzak,[18] D. Q. Fang,[14] M. Faverzani,[12,13] G. Fernandes,[16,11] E. Ferri,[12,13]
F. Ferroni,[9,10] E. Fiorini,[13,12] S. J. Freedman,[6,5,†] B. K. Fujikawa,[6] A. Giachero,[12,13] L. Gironi,[12,13] A. Giuliani,[21]
P. Gorla,[3] C. Gotti,[12,13] T. D. Gutierrez,[22] E. E. Haller,[8,23] K. Han,[17,6] E. Hansen,[24,1] K. M. Heeger,[17]
R. Hennings-Yeomans,[5,6] K. P. Hickerson,[1] H. Z. Huang,[1] R. Kadel,[25] G. Keppel,[4] Yu. G. Kolomensky,[5,25]
K. E. Lim,[17] X. Liu,[1] Y. G. Ma,[14] M. Maino,[12,13] M. Martinez,[9,26] R. H. Maruyama,[17] Y. Mei,[6] N. Moggi,[27,7]
S. Morganti,[10] S. Nisi,[3] C. Nones,[28] E. B. Norman,[29,30] A. Nucciotti,[12,13] T. O'Donnell,[5,6] F. Orio,[10] D. Orlandi,[3]
J. L. Ouellet,[5,6] C. E. Pagliarone,[3,15] M. Pallavicini,[16,11] V. Palmieri,[4] L. Pattavina,[3] M. Pavan,[12,13] M. Pedretti,[29]
G. Pessina,[13] V. Pettinacci,[10] G. Piperno,[9,10] S. Pirro,[3] S. Pozzi,[12,13] E. Previtali,[13] C. Rosenfeld,[2]
C. Rusconi,[13] E. Sala,[12,13] S. Sangiorgio,[29] D. Santone,[3,20] N. D. Scielzo,[29] M. Sisti,[12,13] A. R. Smith,[6]
L. Taffarello,[31] M. Tenconi,[21] F. Terranova,[12,13] C. Tomei,[10] S. Trentalange,[1] G. Ventura,[32,33] M. Vignati,[10]
S. L. Wagaarachchi,[5,6] B. S. Wang,[29,30] H. W. Wang,[14] L. Wielgus,[18] J. Wilson,[2] L. A. Winslow,[24]
T. Wise,[17,18] A. Woodcraft,[34] L. Zanotti,[12,13] C. Zarra,[3] G. Q. Zhang,[14] B. X. Zhu,[1] and S. Zucchelli[35,7]
(CUORE Collaboration)

[1] *Department of Physics and Astronomy, University of California, Los Angeles, CA 90095 - USA*
[2] *Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208 - USA*
[3] *INFN - Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila) I-67010 - Italy*
[4] *INFN - Laboratori Nazionali di Legnaro, Legnaro (Padova) I-35020 - Italy*
[5] *Department of Physics, University of California, Berkeley, CA 94720 - USA*
[6] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 - USA*
[7] *INFN - Sezione di Bologna, Bologna I-40127 - Italy*
[8] *Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 - USA*
[9] *Dipartimento di Fisica, Sapienza Università di Roma, Roma I-00185 - Italy*
[10] *INFN - Sezione di Roma, Roma I-00185 - Italy*
[11] *INFN - Sezione di Genova, Genova I-16146 - Italy*
[12] *Dipartimento di Fisica, Università di Milano-Bicocca, Milano I-20126 - Italy*
[13] *INFN - Sezione di Milano Bicocca, Milano I-20126 - Italy*
[14] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800 - China*
[15] *Dipartimento di Ingegneria Civile e Meccanica, Università degli Studi di Cassino e del Lazio Meridionale, Cassino I-03043 - Italy*
[16] *Dipartimento di Fisica, Università di Genova, Genova I-16146 - Italy*
[17] *Department of Physics, Yale University, New Haven, CT 06520 - USA*
[18] *Department of Physics, University of Wisconsin, Madison, WI 53706 - USA*
[19] *INFN - Gran Sasso Science Institute, LAquila I-67100 - Italy*
[20] *Dipartimento di Scienze Fisiche e Chimiche, Università dell'Aquila, L'Aquila I-67100 - Italy*
[21] *Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, 91405 Orsay Campus - France*
[22] *Physics Department, California Polytechnic State University, San Luis Obispo, CA 93407 - USA*
[23] *Department of Materials Science and Engineering, University of California, Berkeley, CA 94720 - USA*
[24] *Massachusetts Institute of Technology, Cambridge, MA 02139 - USA*
[25] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 - USA*
[26] *Laboratorio de Fisica Nuclear y Astroparticulas, Universidad de Zaragoza, Zaragoza 50009 - Spain*
[27] *Dipartimento di Scienze per la Qualità della Vita, Alma Mater Studiorum - Università di Bologna, Bologna I-47921 - Italy*
[28] *Service de Physique des Particules, CEA / Saclay, 91191 Gif-sur-Yvette - France*
[29] *Lawrence Livermore National Laboratory, Livermore, CA 94550 - USA*
[30] *Department of Nuclear Engineering, University of California, Berkeley, CA 94720 - USA*
[31] *INFN - Sezione di Padova, Padova I-35131 - Italy*
[32] *Dipartimento di Fisica, Università di Firenze, Firenze I-50125 - Italy*
[33] *INFN - Sezione di Firenze, Firenze I-50125 - Italy*
[34] *SUPA, Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ - UK*
[35] *Dipartimento di Fisica e Astronomia, Alma Mater Studiorum - Università di Bologna, Bologna I-40127 - Italy*