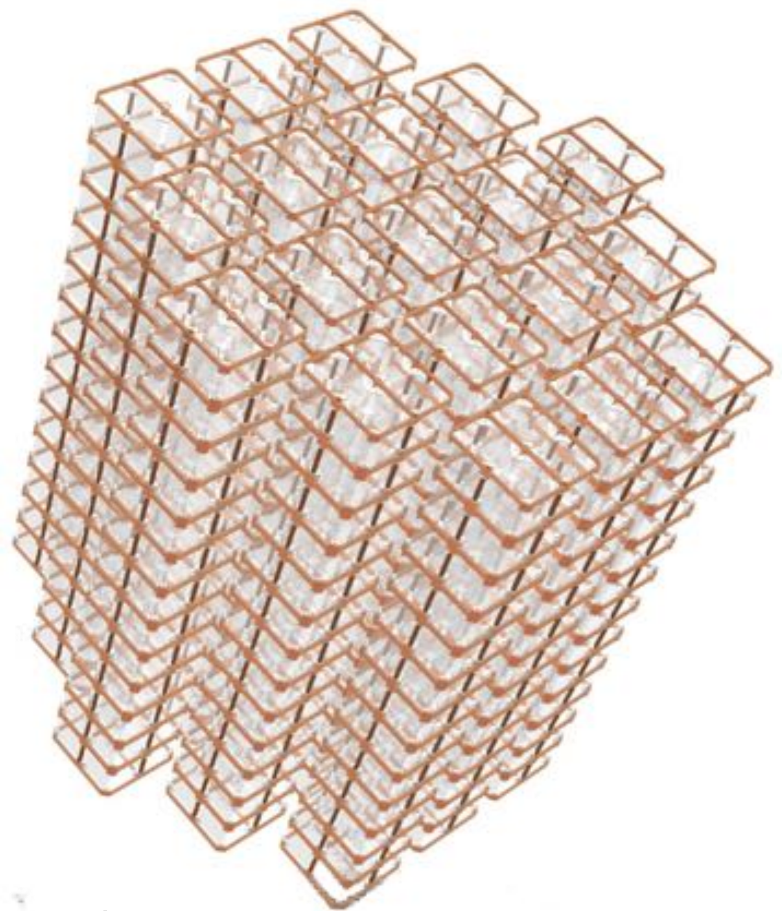
Search for 0νββ decay of ^{130}Te with CUORE-0 and CUORE



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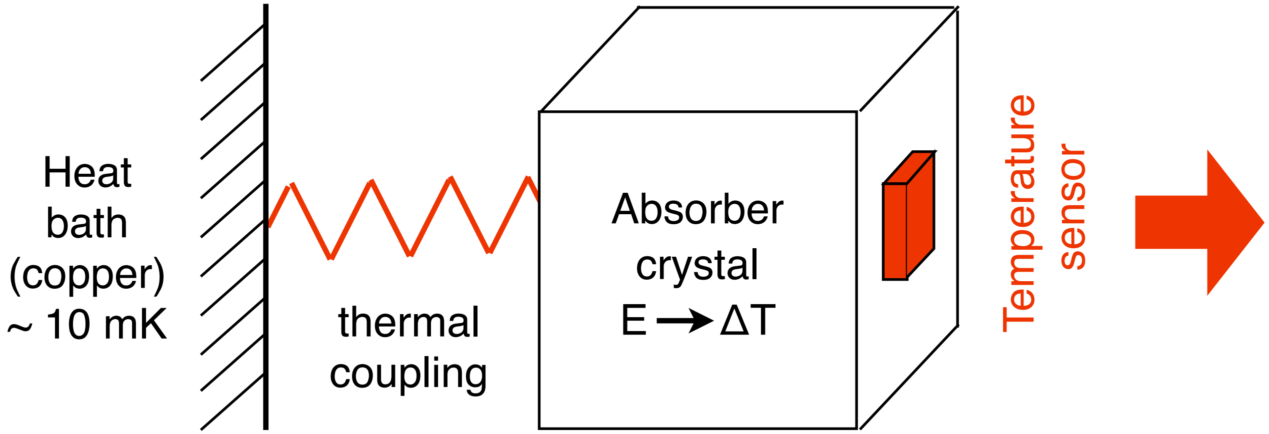
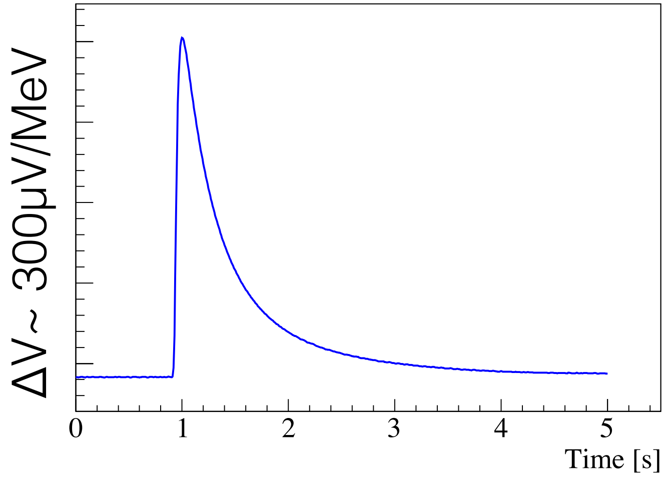
25th International Workshop on Weak Interactions and Neutrinos

Heidelberg, 8-13 June 2015

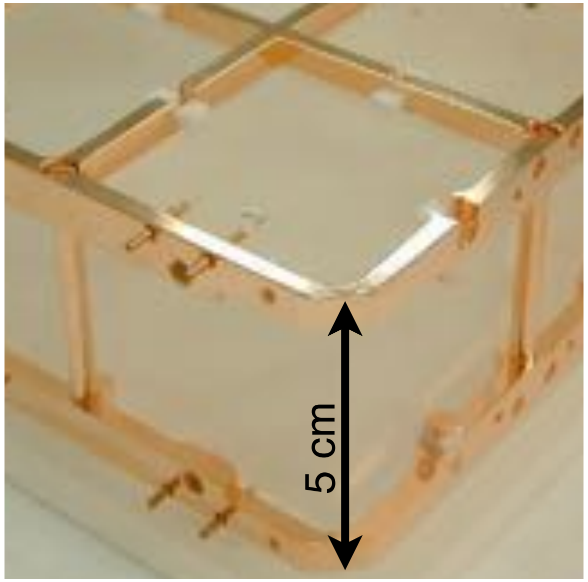
TeO_2 bolometers

- CUORE searches for 0νββ decay of ^{130}Te in $^{nat}TeO_2$ bolometers





- 0.75 Kg $^{nat}TeO_2$ crystals
  - C~10^{-9} J/K →ΔT/ΔE~100μK/MeV

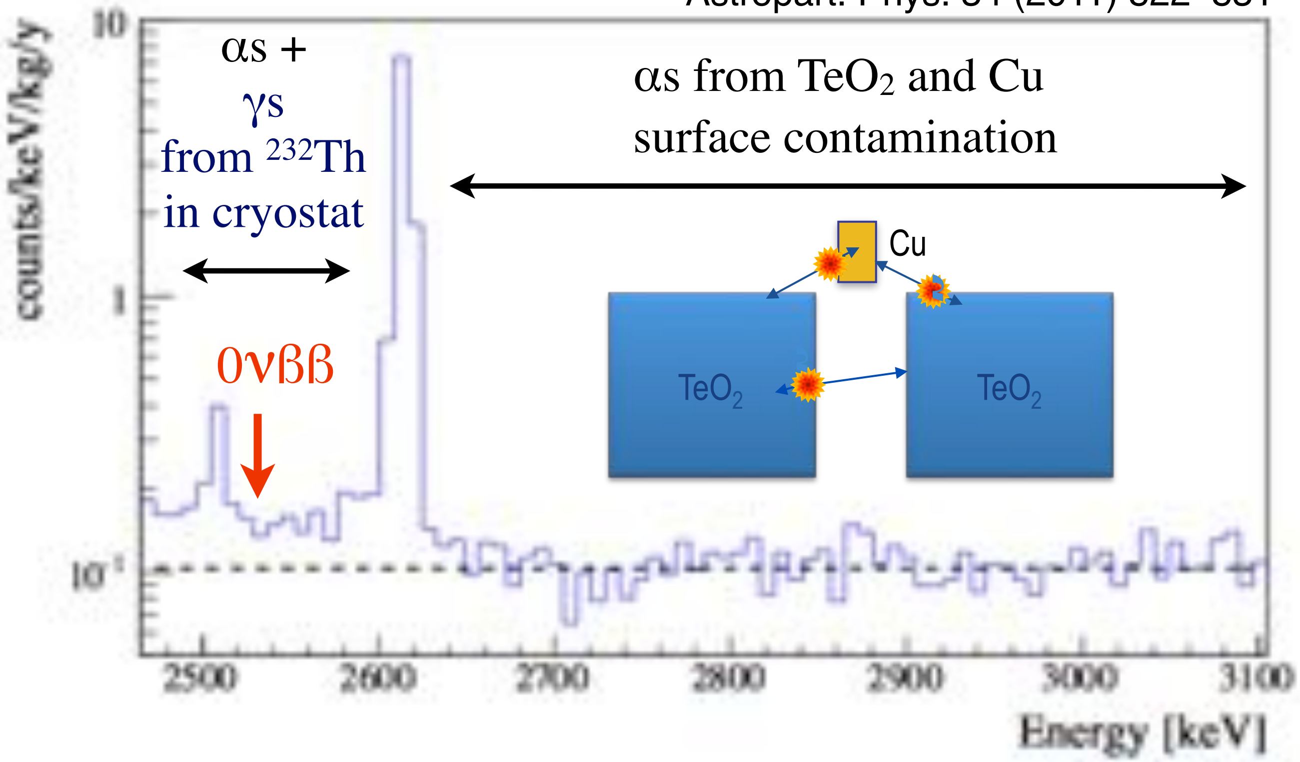


- NTD-Ge thermistor: $R=R_0\exp(T_0/T)^{1/2}$
  - R~ 100 MΩ →ΔR/ΔE~3MΩ/MeV
- Resolution @ 0νββ energy (~2528 keV): ΔE_{FWHM} = 5-7 keV

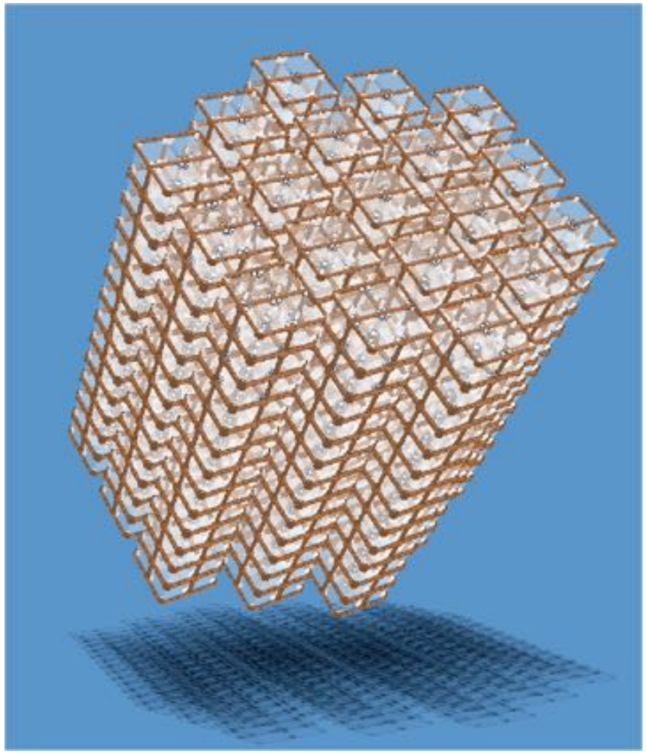
The CUORICINO experience

- 62 TeO_2 crystals operated at LNGS
- ^{130}Te: i.a.~34%, $Q_{\beta\beta}$~2528 keV
- Exposure: 19.75 $kg \cdot yr$ ^{130}Te
- $T^{0\nu}_{1/2} > 2.8 \cdot 10^{24}$ yr (90% CL) $m_{\beta\beta} <$ (300-710) meV
- Bkg level: 0.169 ± 0.006 c/(keV · kg · yr)

Astropart. Phys. 34 (2011) 822–831



CUORE at LNGS

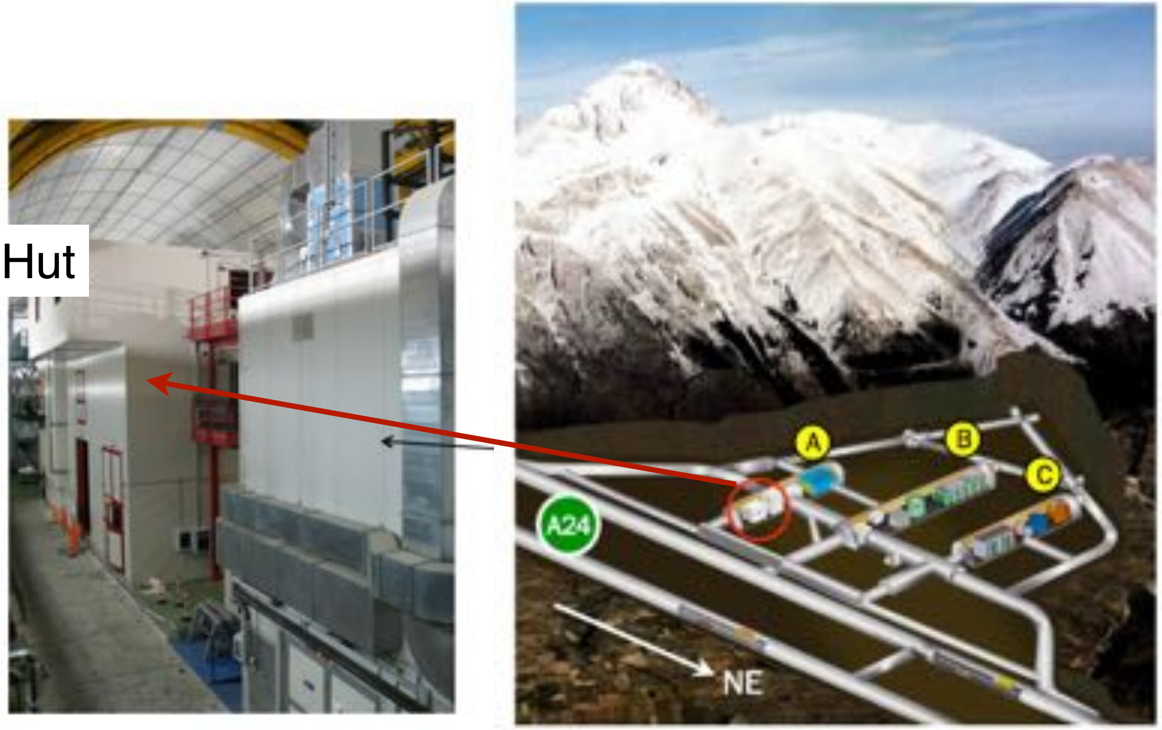


Array of 988 TeO_2 crystals, each crystal 5x5x5 cm^3 (750 g)

- 19 towers - 13 floors - one 4 crystal module per floor
- 741 kg total mass - 206 kg of ^{130}Te (~10^{27} ^{130}Te nuclei)

Bkg goal: 0.01 c/(keV · kg · yr) (~17 lower than CUORICINO)

Energy resolution goal: $\Delta E_{FWHM} = 5$ keV



CUORE Hut

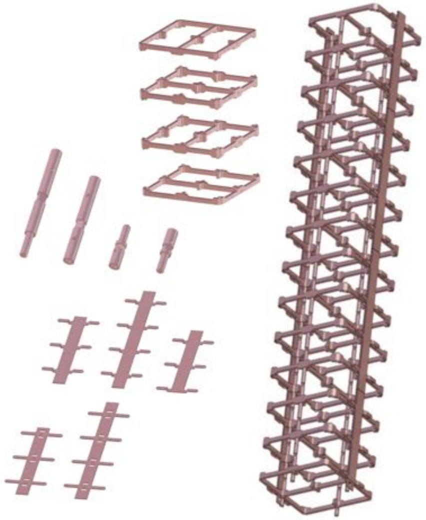
3.6 km.w.e. average deep

μs: ~3×10^{-8}/(s cm^2)

γs: ~0.73/(s cm^2)

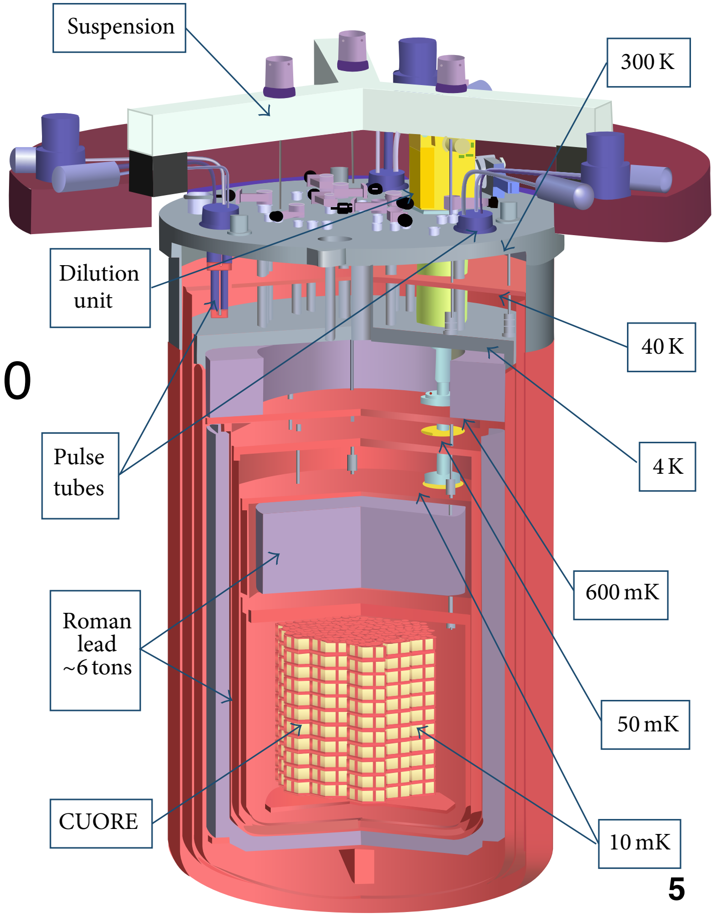
neutrons: 4×10^{-6} n/(s cm^2)

CUORE: main challenges



- Cleaning
    - Strict radio-purity control protocol to limit bulk and surface contaminations in crystal production
    - TECM (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) cleaning for copper surfaces

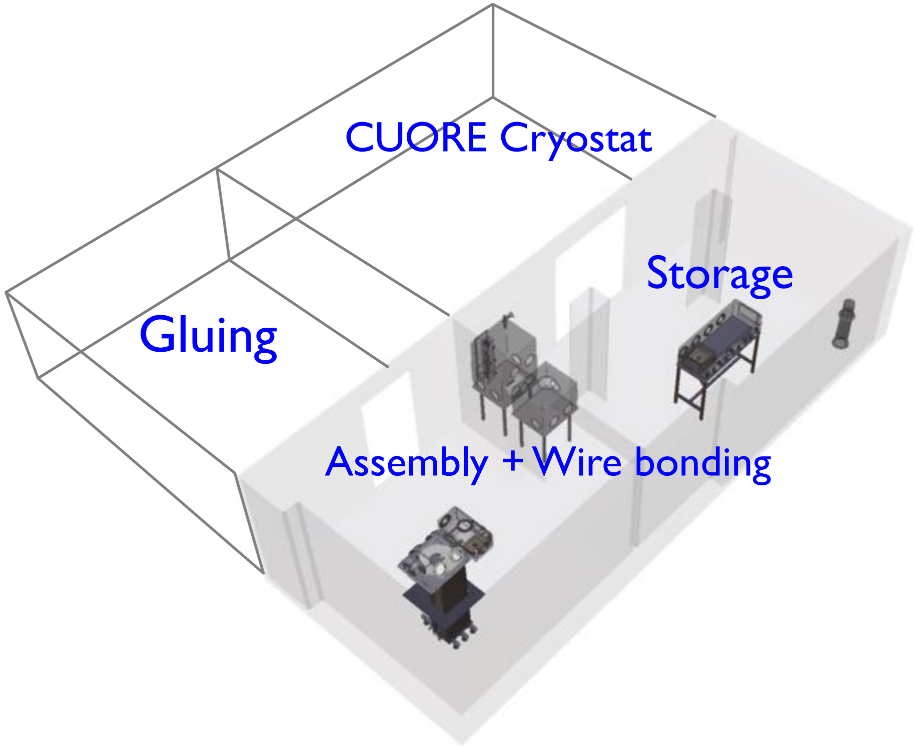
- Cryostat:
    - Custom pulse tube dilution refrigerator and cryostat. Technologically challenging: ~1 ton of detectors at 10 mK
    - Stringent radioactivity constraints on materials and clean assembly
    - Independent suspension of the detector array from the dilution unit



CUORE Assembly Line

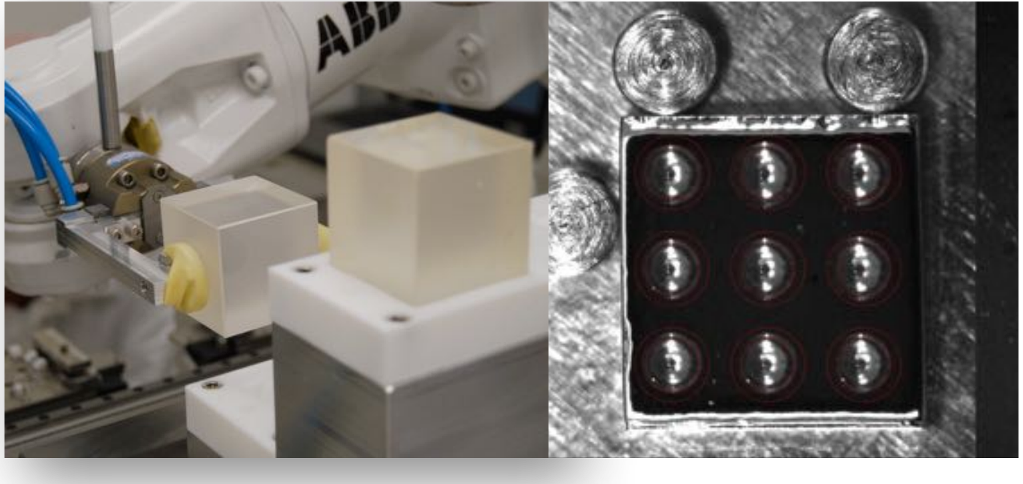
Class 1000 Clean Room for Detector Assembly and Storage

- All parts cleaned/screened according to CUORE protocol
- Stored underground at LNGS
- Assembly carried in N_2-flushed glove boxes in CUORE clean room

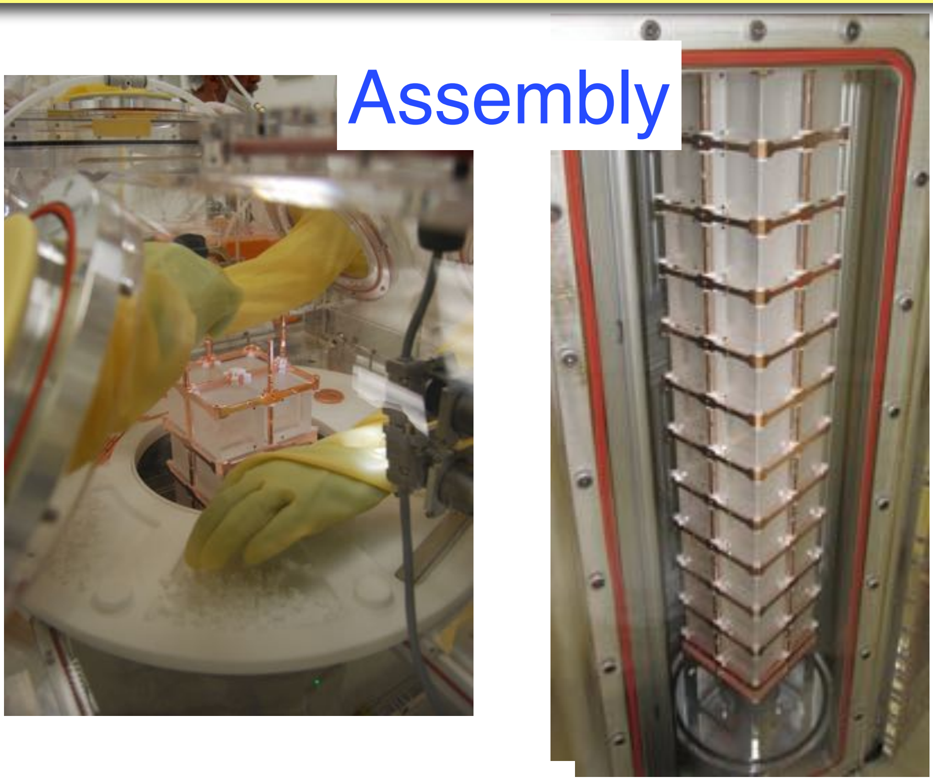


CUORE Assembly Line

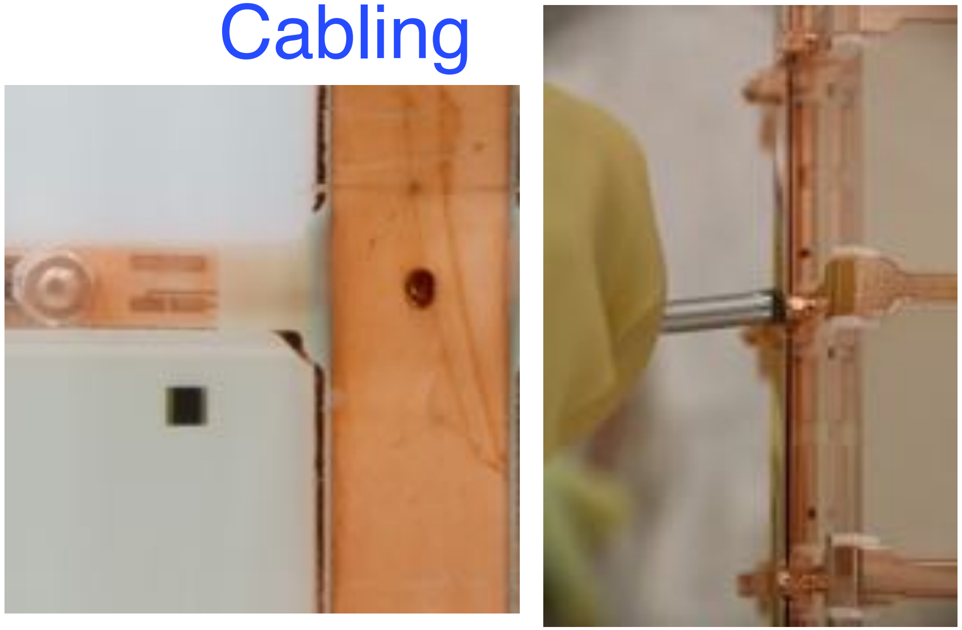
Gluing



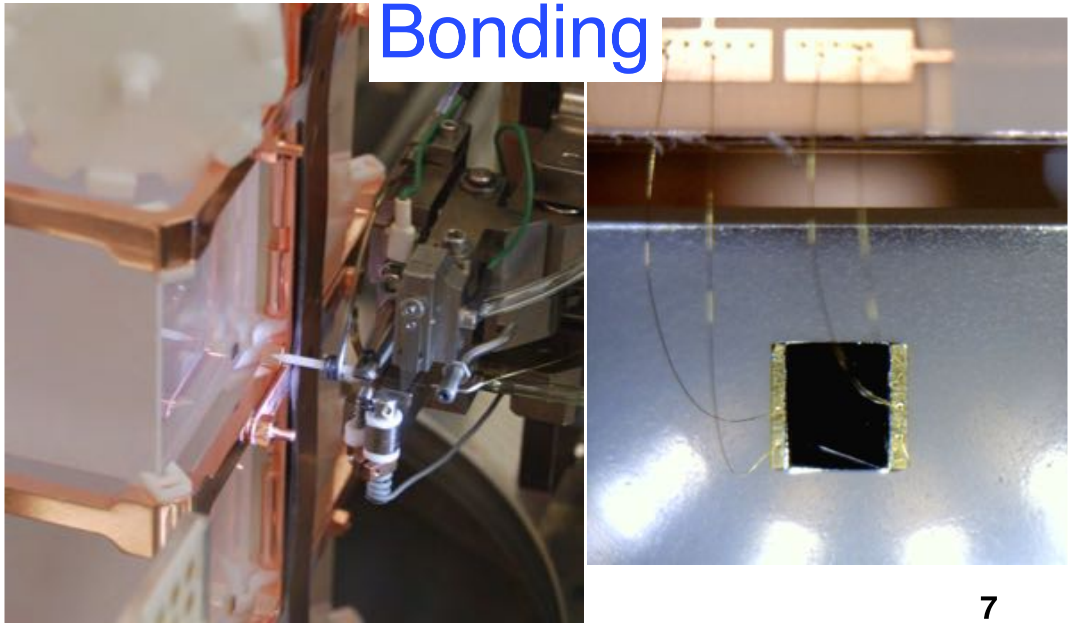
Assembly



Cabling



Bonding



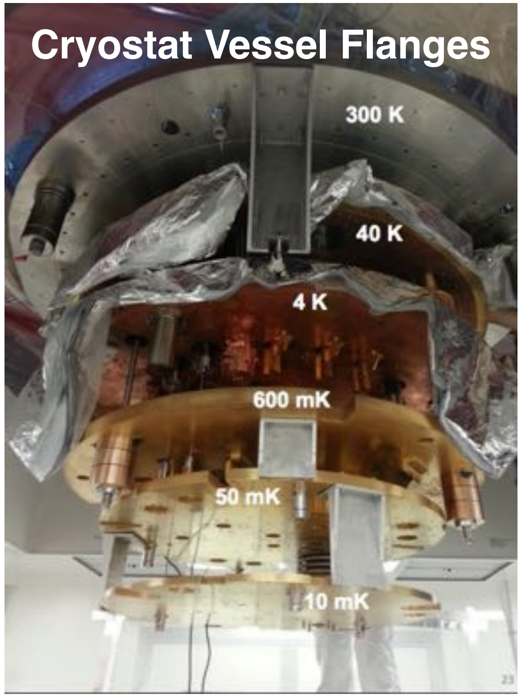
Status of CUORE: assembly

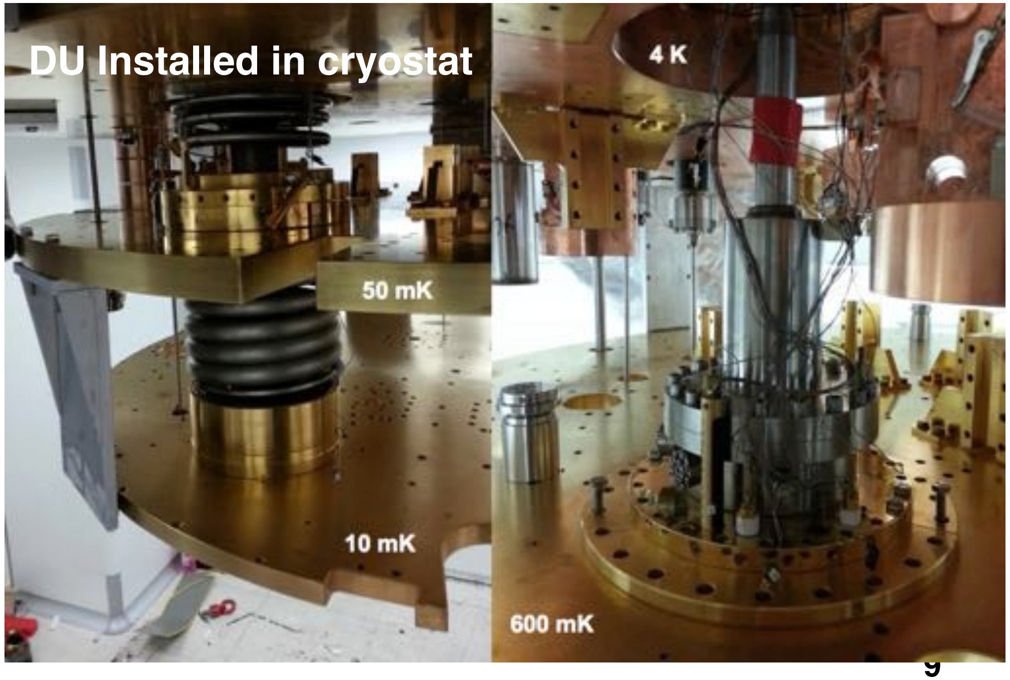
All 19 towers are complete!

Expect to deploy the array in the cryostat this year

Status of CUORE: cryogenic system

- Cryostat assembled, passed 4 K commissioning test
- Dilution unit able to maintain ~5 mK in standalone commissioning test
- 2 out of 3 planned integration runs already reached ~6 mK base T
- Final integration run (everything expect detectors) is ongoing





CUORE-0

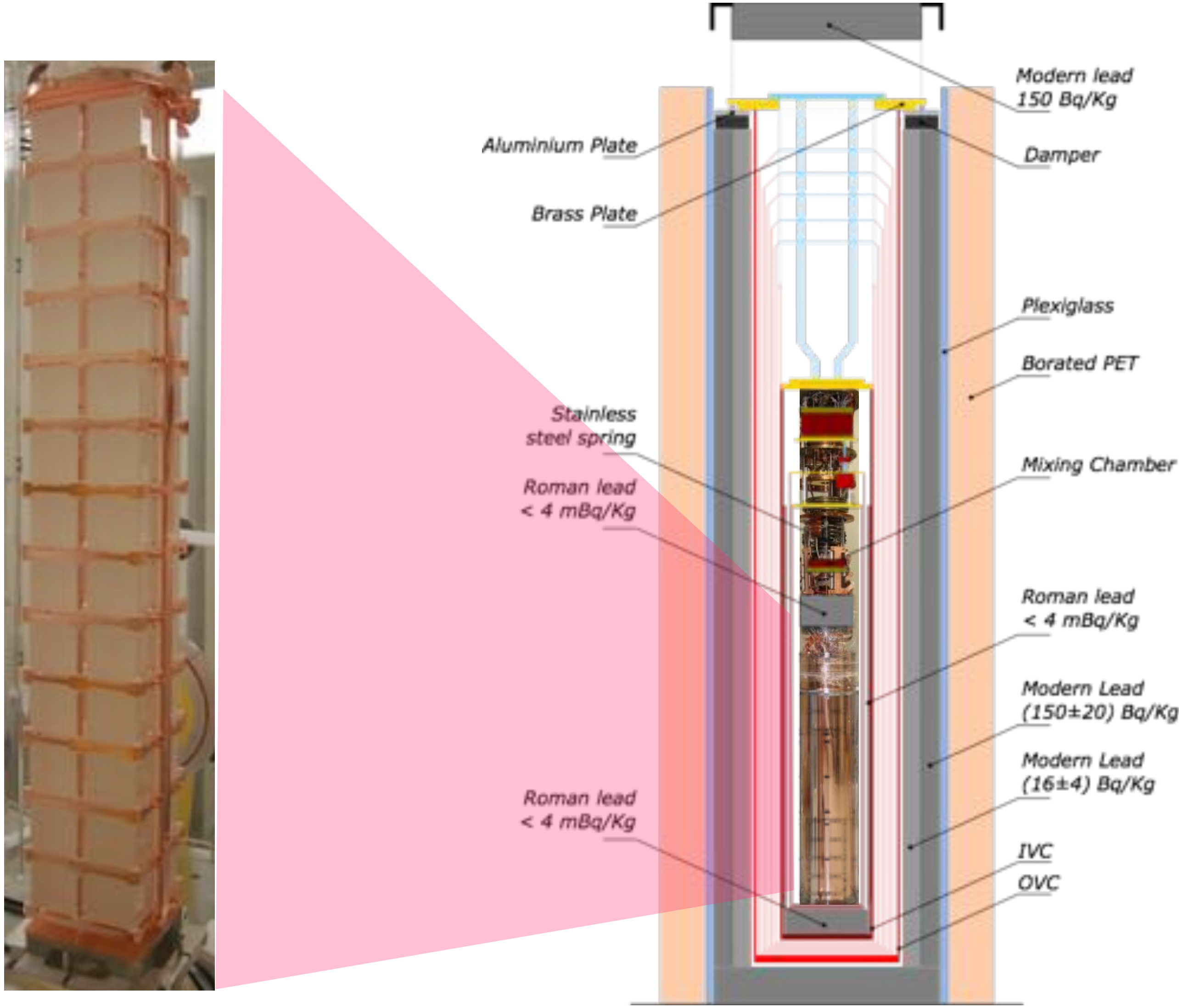
A single CUORE-like tower to test cleaning & assembly

Size similar to CUORICINO:

- 52x750g crystals
- 13 floor of
  4 crystals each

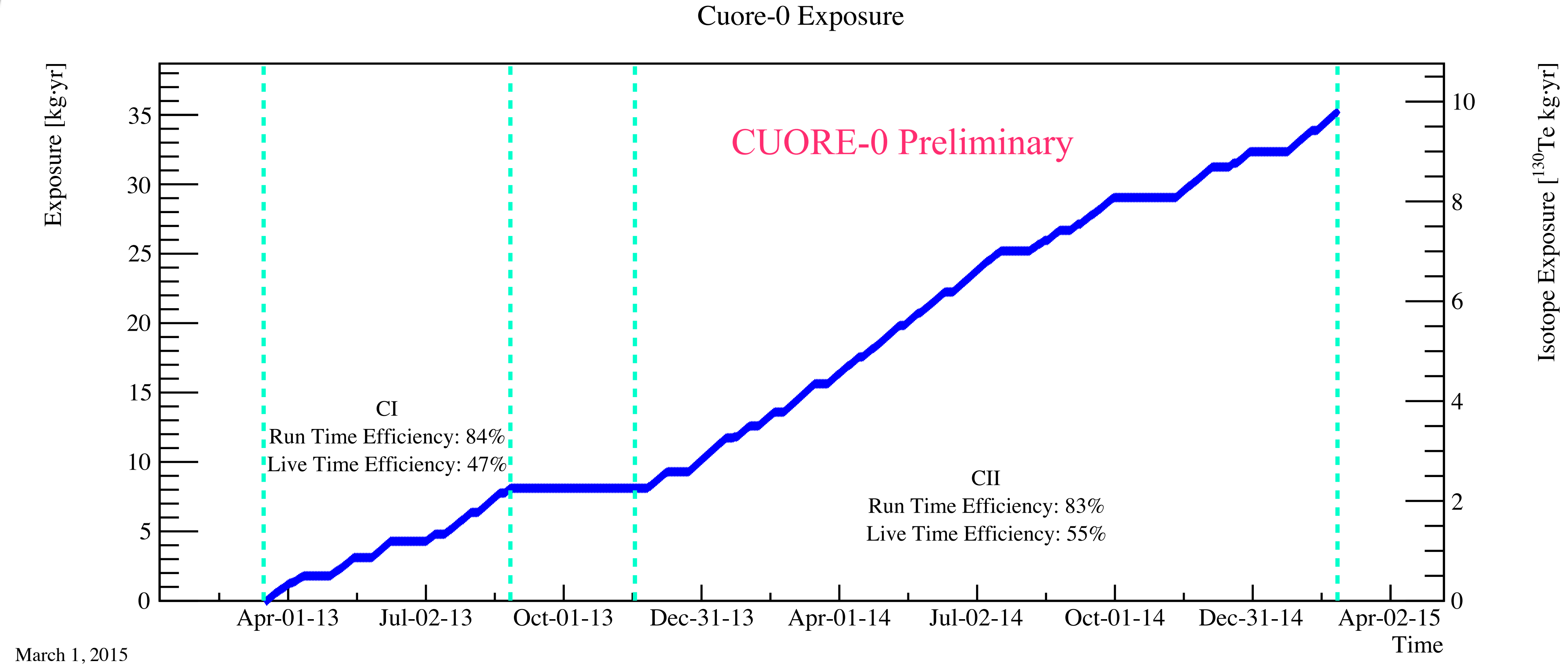
Active mass:

- TeO_2: 39 kg
- ^{130}Te: ~11 kg
  ($5 \cdot 10^{25}$ nuclei)

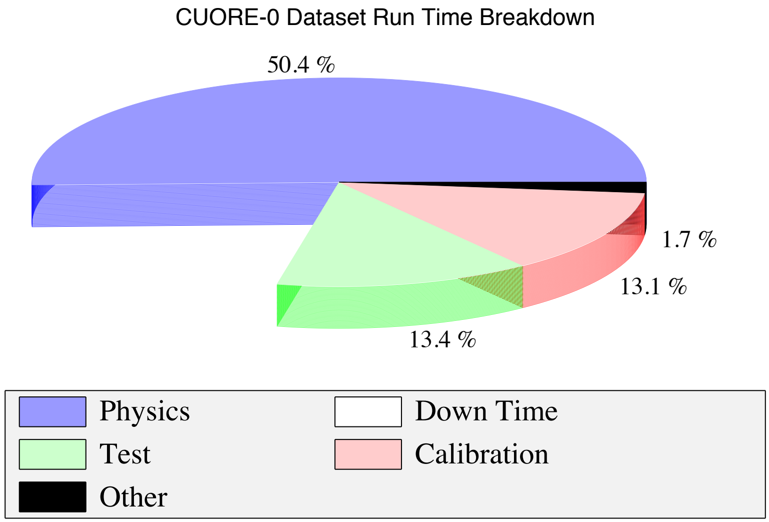


Same cryostat as CUORICINO:
γ background (^{232}Th) not expected to change ⇒ test the α background

Data Taking

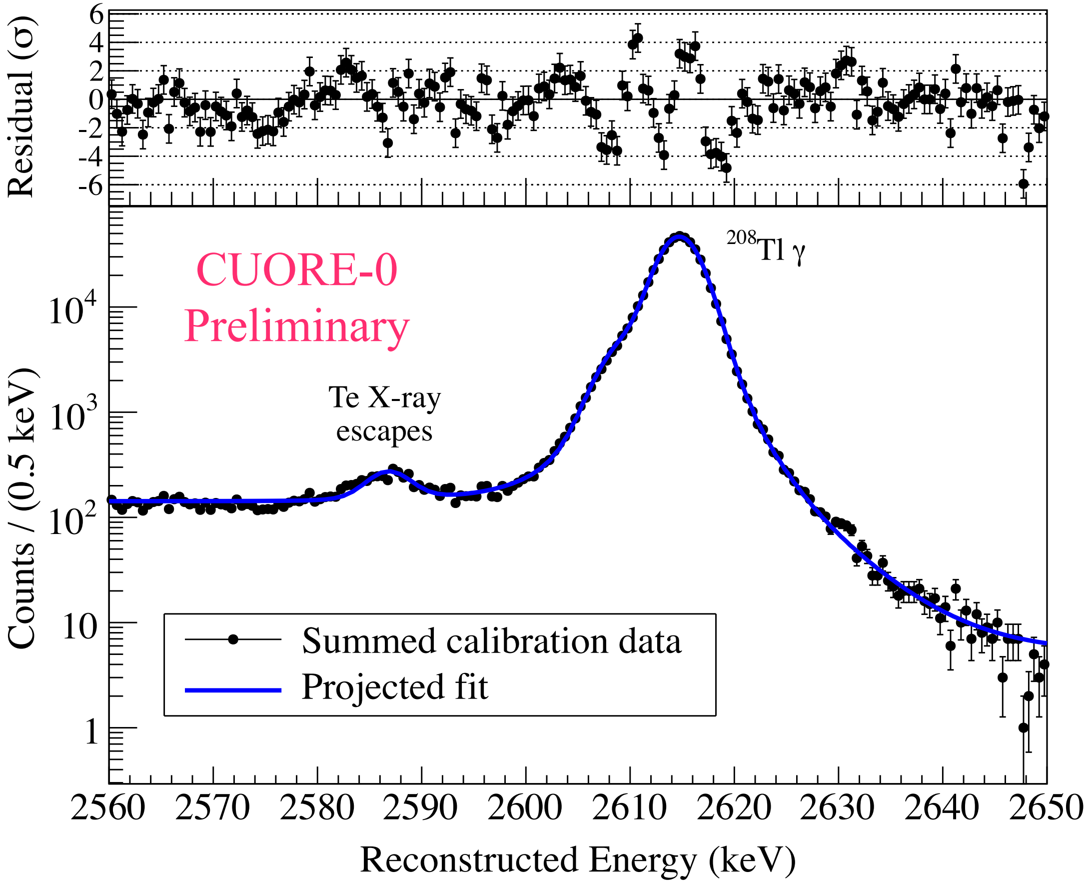


- 2 campaigns, divided by major cryostat maintenance
- ~1-month datasets, with 2-3 days of shared calibration at beginning & end
- Total exposure: 35.2 kg · yr of TeO_2 (9.8 kg · yr of ^{130}Te)



Calibration energy resolution

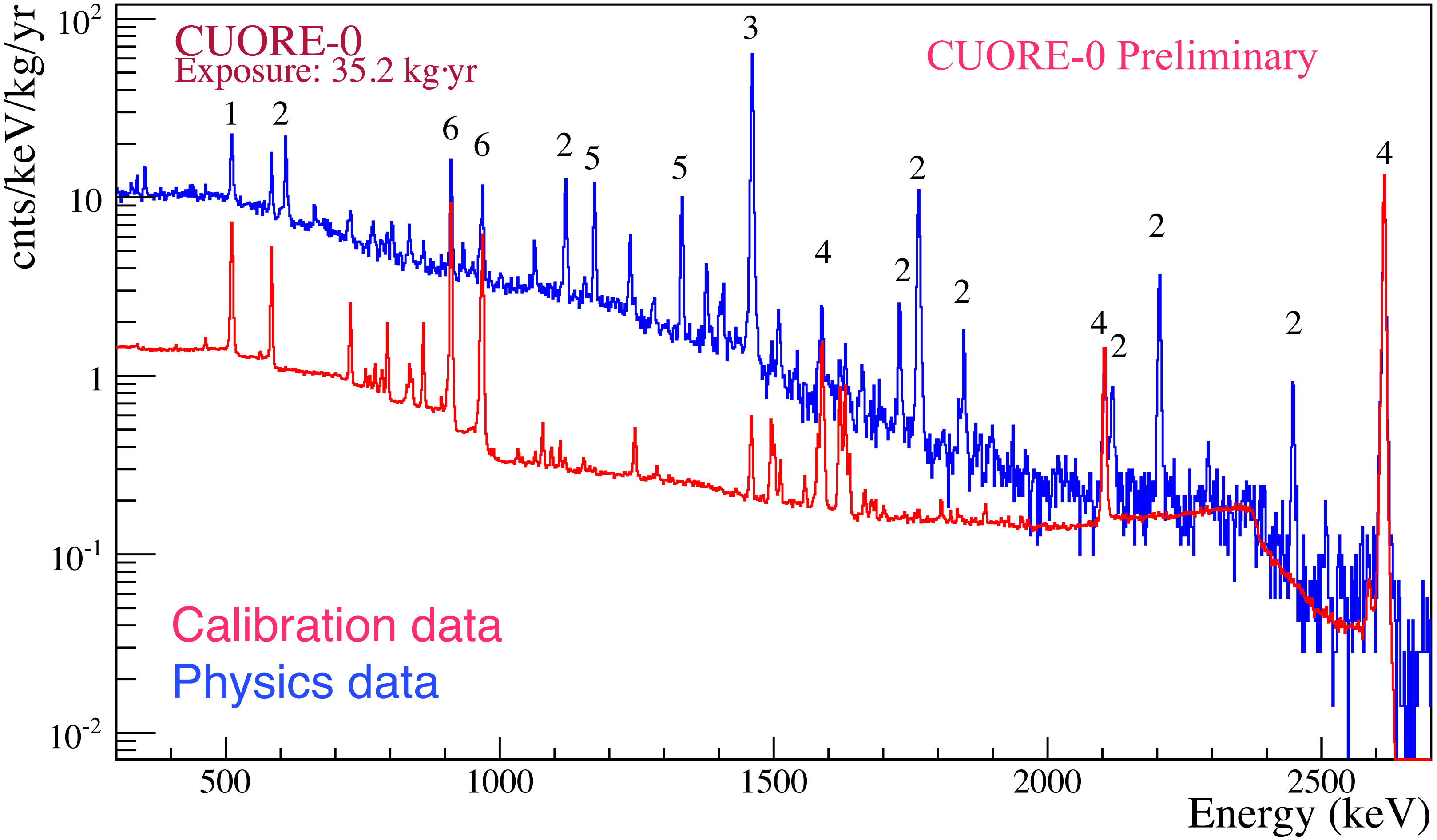
- Exposure weighted sum of the line-shapes of each bolometer-dataset overlaid ^{208}Tl-2615 keV calibration data
- Exposure weighted harmonic mean FWHM: 4.9 ± 2.9 keV



CUORE goal of 5 keV reached

CUORE-0 full spectrum

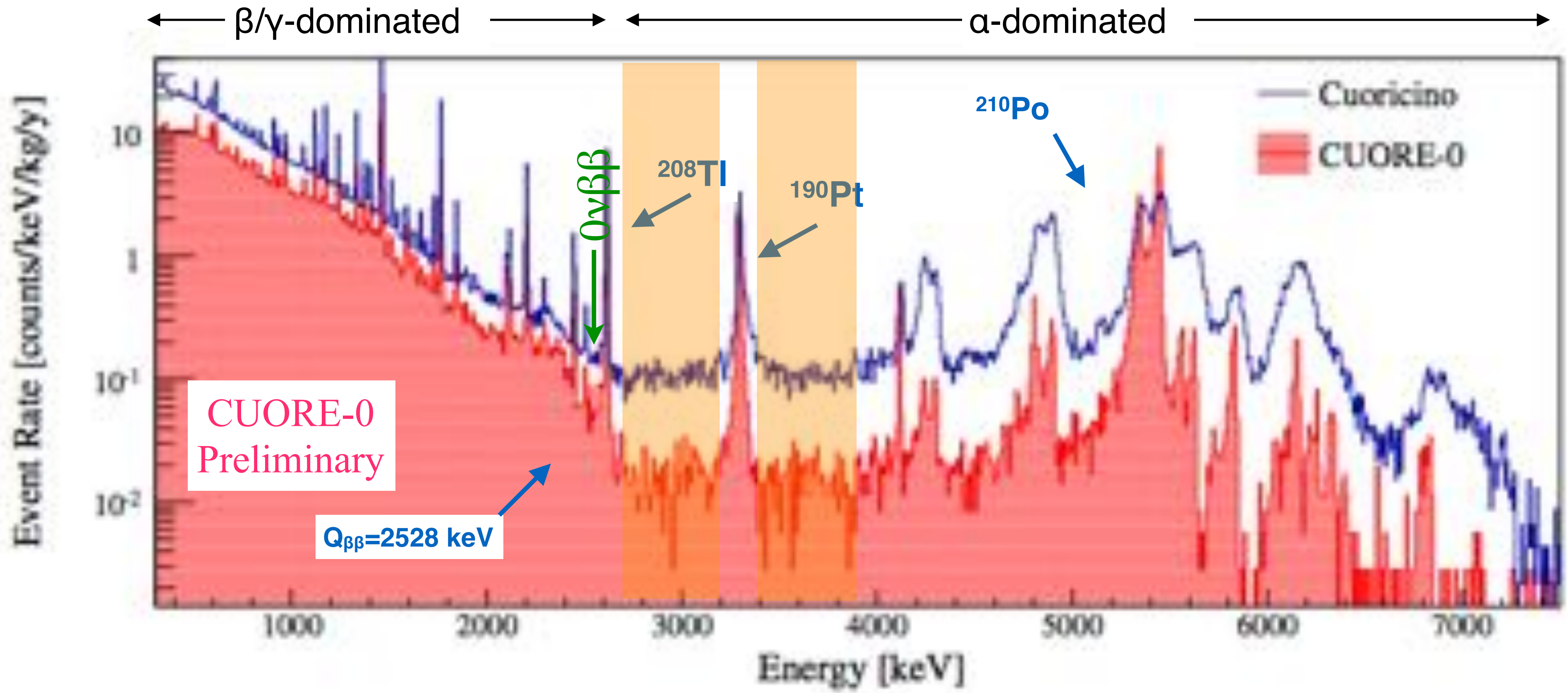
Calibration spectrum from Th source normalised to ^{208}Tl peak in physics data



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

Use prominent peaks in the physics data to check compatibility of calibration line-shapes

CUORE-0 background



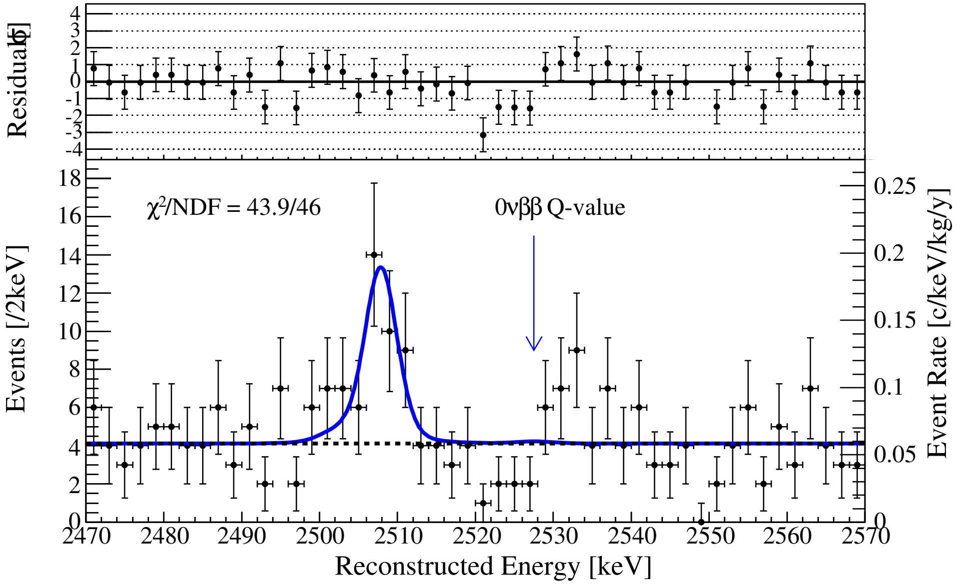
	Avg. flat bkg. [c/(keV · kg · yr)]	
	$0\nu\beta\beta$ region	2700-3900 keV
CUORICINO ε = 83%	0.169 ± 0.006	0.110 ± 0.001
CUORE-0 ε = 81%	0.058 ± 0.04	0.016 ± 0.001

- ^{238}U γ lines reduced by ~2 (better radon control)
- ^{232}Th γ lines not reduced (originate from the cryostat)
- ^{238}U/^{232}Th α lines reduced (detector surface treatment)

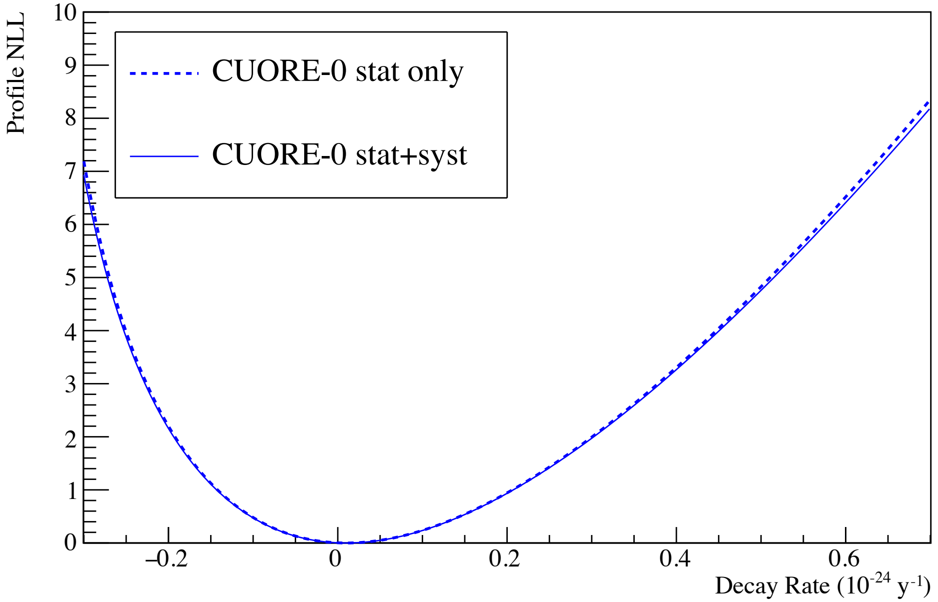
CUORE-0: 0νββ search

- Simultaneous UEML fit to 233 events in ROI [2470-2570 keV].

CUORE-0 Preliminary



CUORE-0 Preliminary



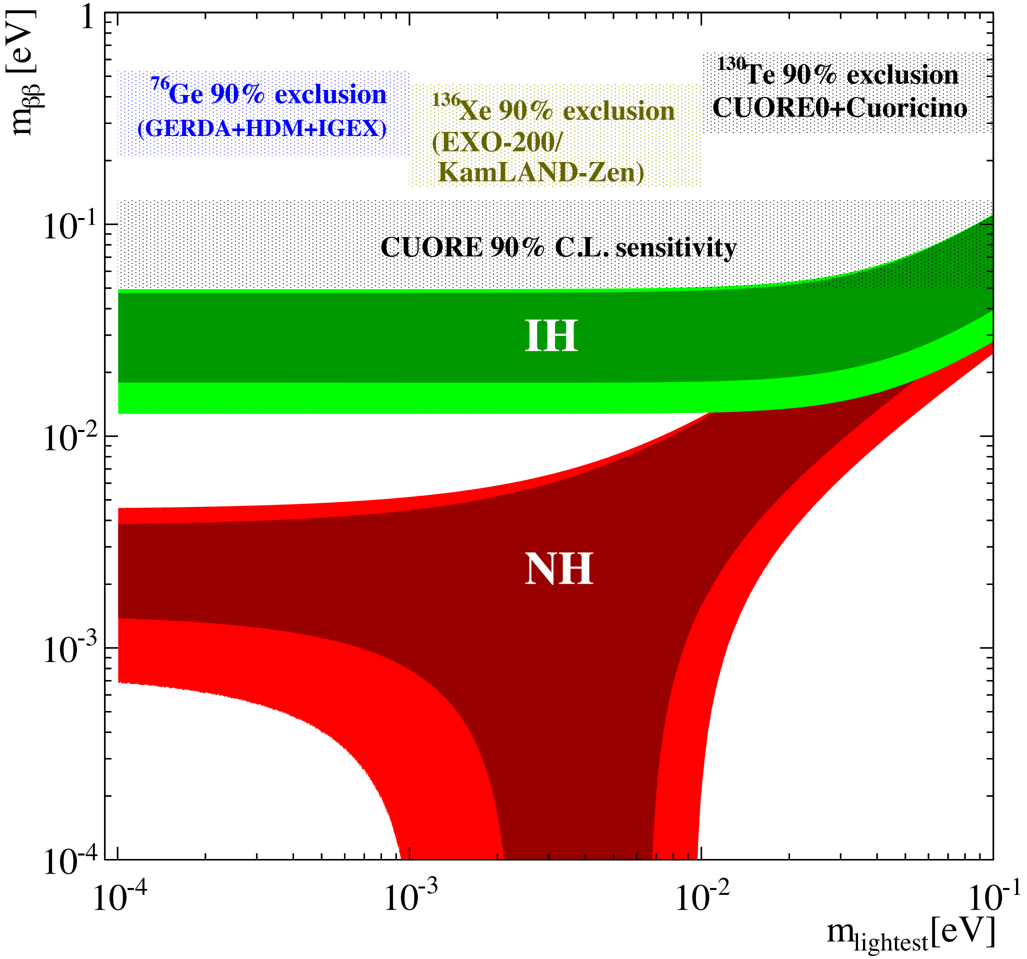
- Best fit $\Gamma_{0\nu}$: $\Gamma_{0\nu} = 0.01 \pm 0.12\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \times 10^{-24}\text{yr}$
- Best fit Γ_{bkg}: $0.058 \pm 0.004\,(\text{stat.}) \pm 0.002\,(\text{syst.})\ \text{c/keV/kg/yr}$
- 90%CL bayesian lower limit: $T^{0\nu}_{1/2} > 2.7 \cdot 10^{24}$ yr
- Median 90% C.L. lower limit sensitivity: $T^{0\nu}_{1/2} > 2.9 \cdot 10^{24}$ yr,

^{130}Te global limit

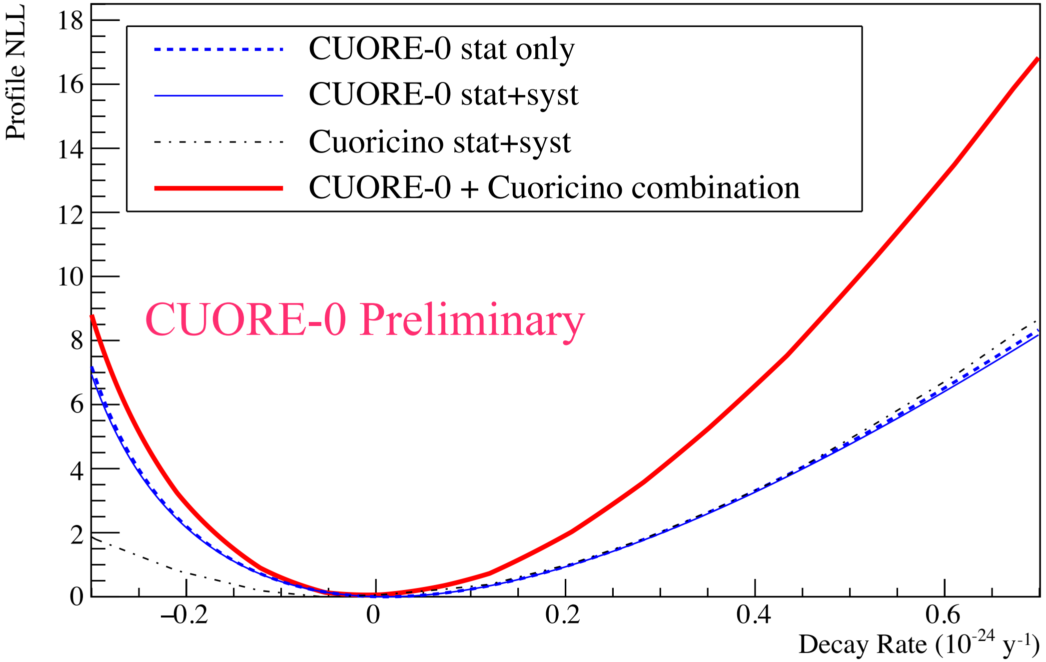
- Combine CUORE-0 and CUORICINO limit

$T^{0\nu}_{1/2} > 4.0 \cdot 10^{24}$ yr @ 90%CL

IBM-2 Phys. Rev. C 91, 034304 (2015)
QRPA-TU Phys. Rev. C 87, 045501 (2013)
pnQRPA Phys. Rev. C 91, 024613 (2015)
ISM Nucl. Phys. A 818, 139 (2009)
EDF Phys. Rev. Lett. 105, 252503 (2010)



$m_{\beta\beta} < (270\text{-}650)$ meV



Conclusions

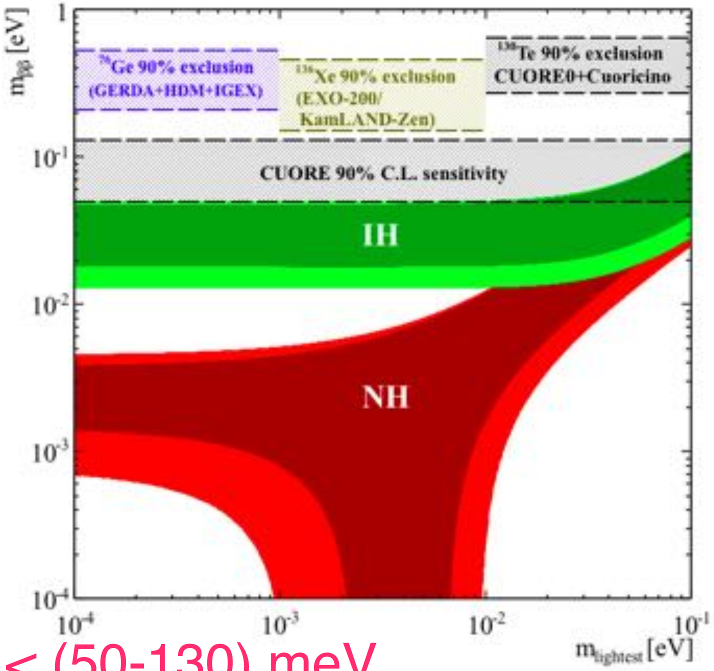
CUORE-0

- CUORE assembly and cleaning technique validated
- Energy resolution and background goals achieved
- Combined with CUORICINO: most stringent limit on 0νββ decay of ^{130}Te

arXiv:1504.02454 $T^{0\nu}_{1/2} > 4.0 \cdot 10^{24}$ yr @ 90%CL $m_{\beta\beta} <$ (270-650) meV

CUORE

- Towers assembly complete
- Commissioning of the cryogenic system in advanced phase
- Start operation by end of 2015
- 5 yr sensitivity
  bkg: 0.01 c/(keV · kg · yr), ΔE_{FWHM} : 5 keV

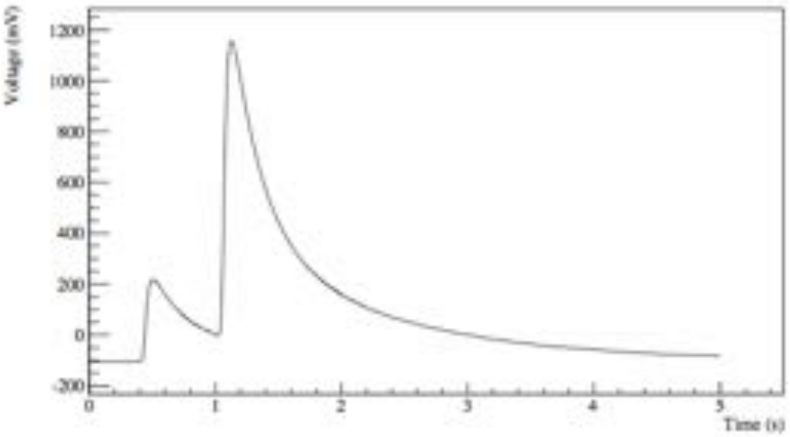


$T^{0\nu}_{1/2} = 9.5 \cdot 10^{25}$ yr @ 90%CL $m_{\beta\beta} <$ (50-130) meV

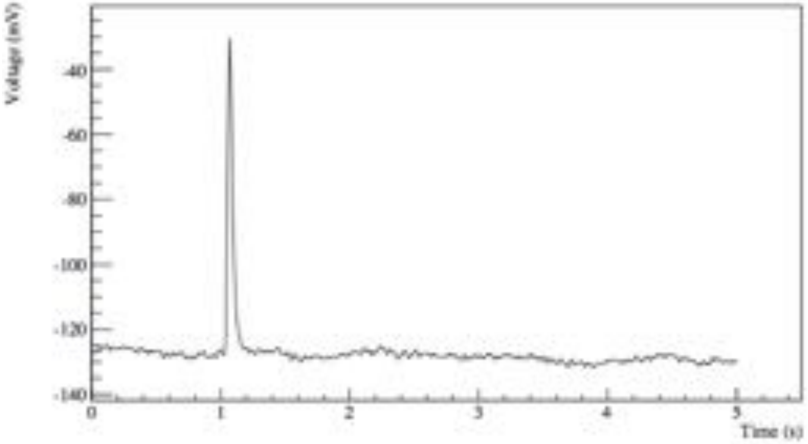
BACKUP SLIDES

Event Selection

Pile-up: discard multiple events in the same acquisition window

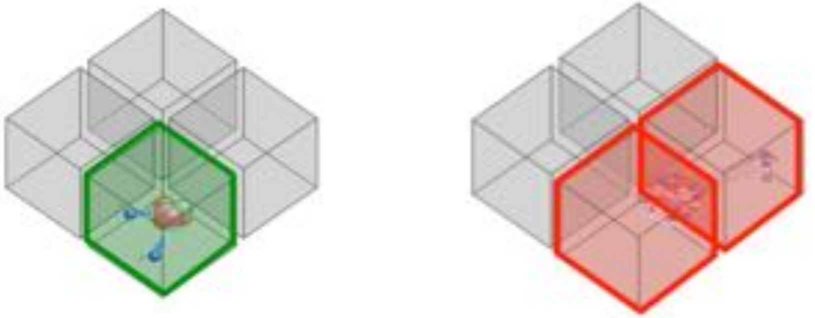


Pulse shape discrimination: discard events with unexpected shapes



Selection	Efficiency (%)
Trigger & reconstruction	98.529 ± 0.004
Pileup & Pulse shape	93.7 ± 0.7
Anticoincidence ($0\nu\beta\beta$ containment)	88.4 ± 0.09
Anticoincidence (survive accidental)	99.6 ± 0.1
Total	81.3 ± 0.6

Anti-coincidence: select single crystal energy deposition



Detector Response

- Use calibration ^{208}Tl line @ 2615 keV
- Find a small low energy tail, well described by double gaussian:

$$\rho(\mu, \sigma, \delta, \eta, E) = \frac{1}{\sqrt{2\pi}\sigma}\left[(1-\eta)\cdot e^{-\frac{(E-\mu)^2}{2\sigma^2}} + \eta \cdot e^{-\frac{(E-\delta\cdot\mu)^2}{2\sigma^2}}\right]$$

Primary gaussian ~ 95% of intensity

Common width σ for both

Secondary gaussian:
Intensity (η) ~ 5% of total intensity
Mean (μ’) ~ 0.3% lower than μ, δ=μ’/μ

- Simultaneous UML fit to each bolometer-dataset calibration data to determine the line shape parameters

$$\rho_{b,d} = \rho(\mu_{b,d}, \sigma_{b,d}, \delta_{b,d}, \eta_{b,d})$$

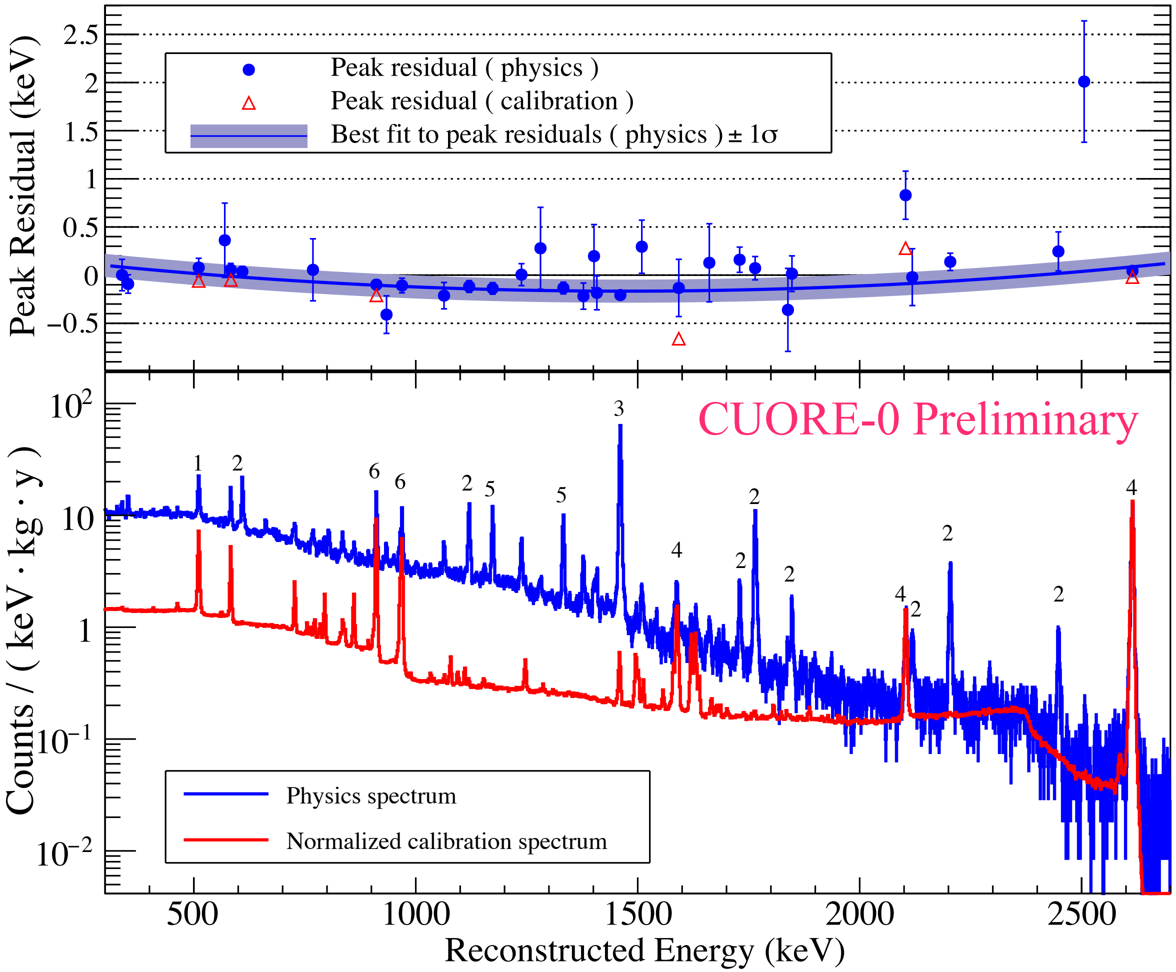
$$b = \{1, 2, \cdots, 51\}$$

$$d = \{1, 2, \cdots, 20\}$$

- Fit includes bolometer-dataset independent parameters to model Compton continuum and background
- Line shape used for calibration uncertainty study & for ROI peaks in the fit

Calibration uncertainty

Projection of calibration line-shape to physics data



μ (b,d) is allowed to vary around the expected calibrated energy via a global free parameter Δμ(E)

σ (b,d) are varied relative to the ones calculated from calibration data via a global scaling parameter α(E)

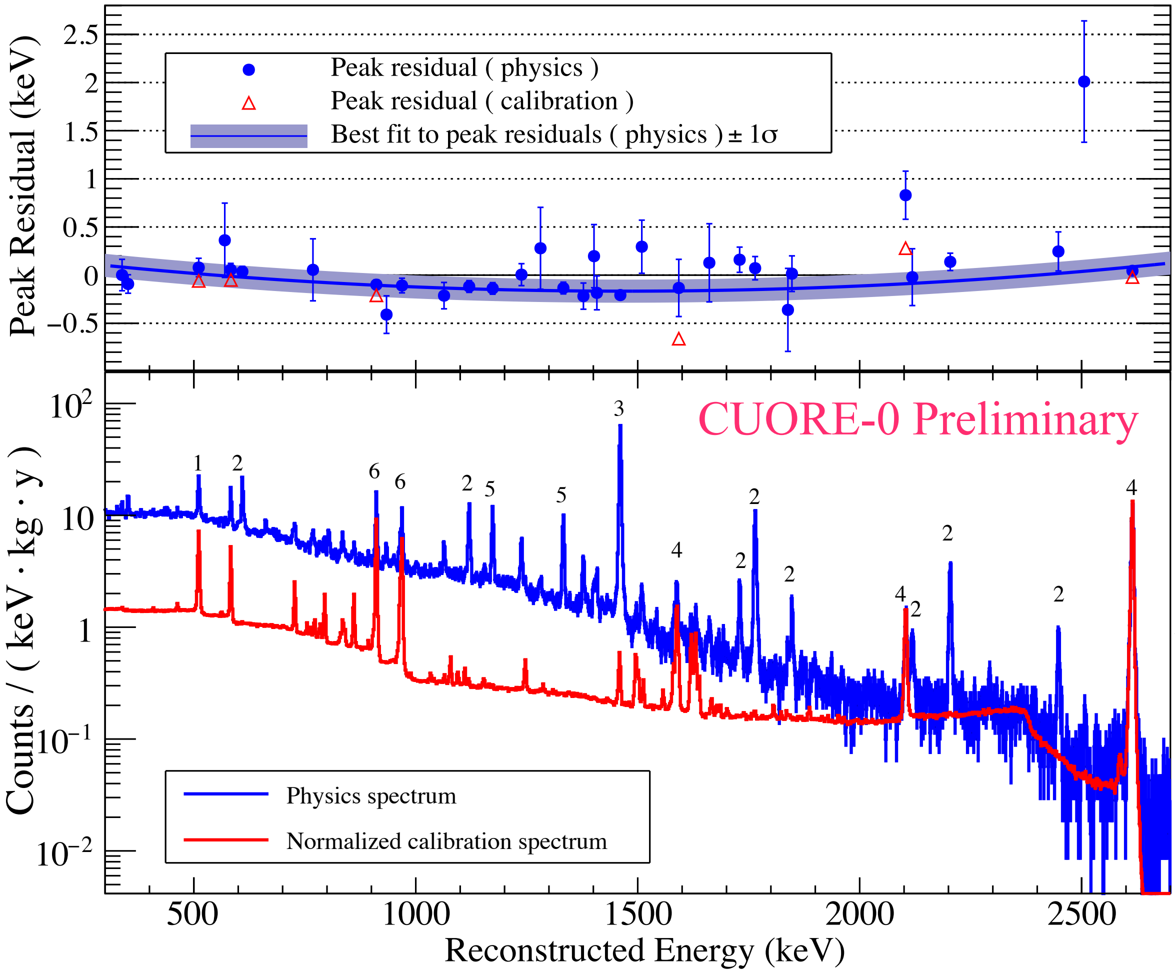
δ (b,d) are varied relative to the ones calculated from calibration data by the ratio of E to 2615 keV

η (b,d) are fixed relative to the ones calculated from calibration data

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

Calibration uncertainty

Projection of calibration line-shape to physics data



- Fit a quadratic function to the physics peak residuals
- Use the resulting best-fit function to estimate the offset at $Q_{\beta\beta}$
- Use the standard deviation of the peak residuals about the best-fit to estimate the systematic uncertainty on $\Delta\mu(Q_{\beta\beta})$

$$\Delta\mu(Q_{\beta\beta}) = 0.05 \pm 0.05(\text{stat.}) \pm 0.12(\text{syst.})\ \text{keV}$$

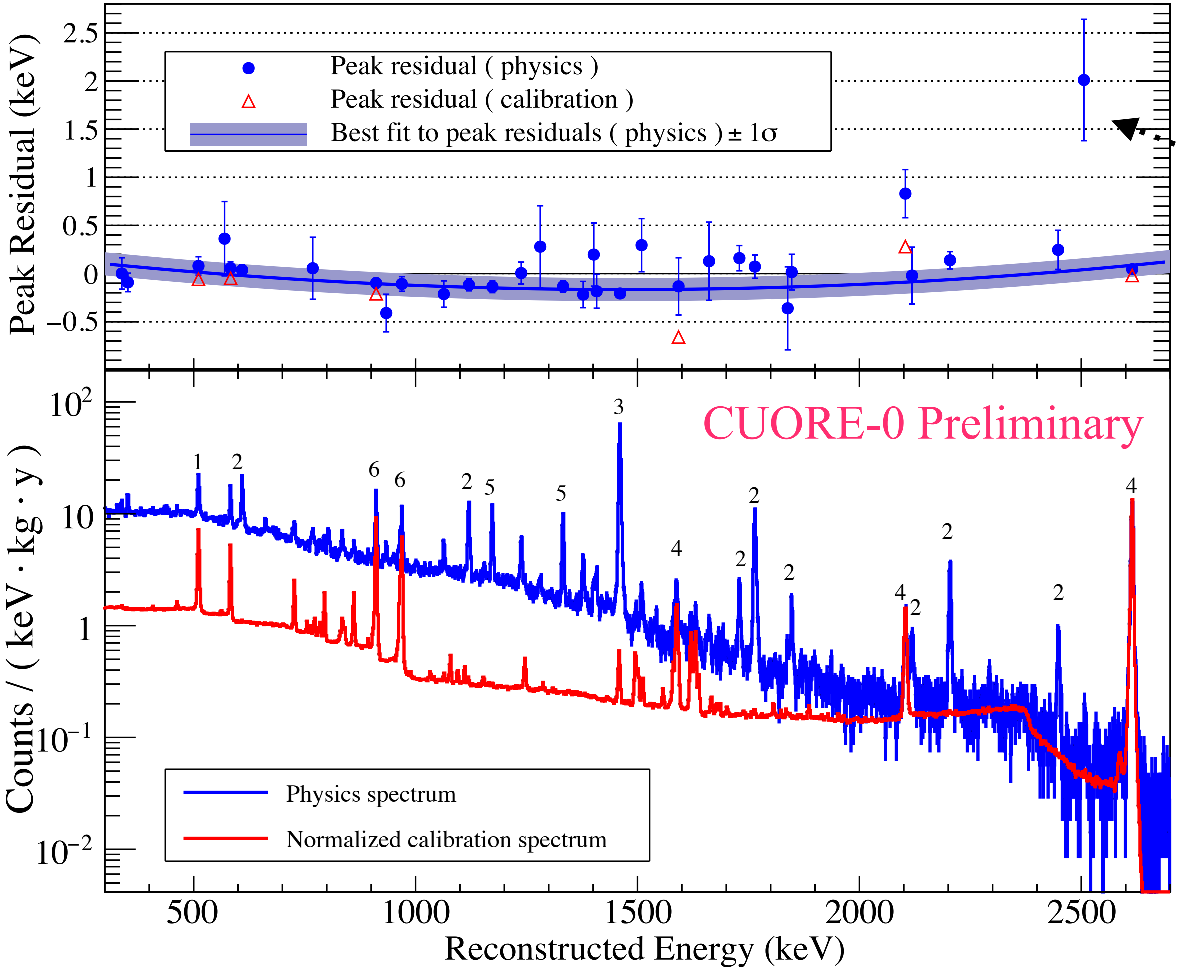
- We estimate the resolution scaling at $Q_{\beta\beta}$ from a fit to the collection of peak resolution scaling parameters

$$\alpha(Q_{\beta\beta}) = 1.05 \pm 0.05\ (\text{stat.} + \text{syst.})$$

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

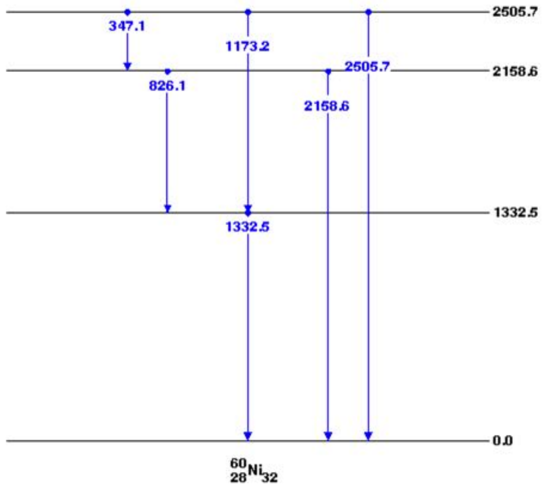
Calibration uncertainty

- Prominent outlier from ^{60}Co double gamma events
    - ~2507 keV reconstructed vs. ~2505 keV expected



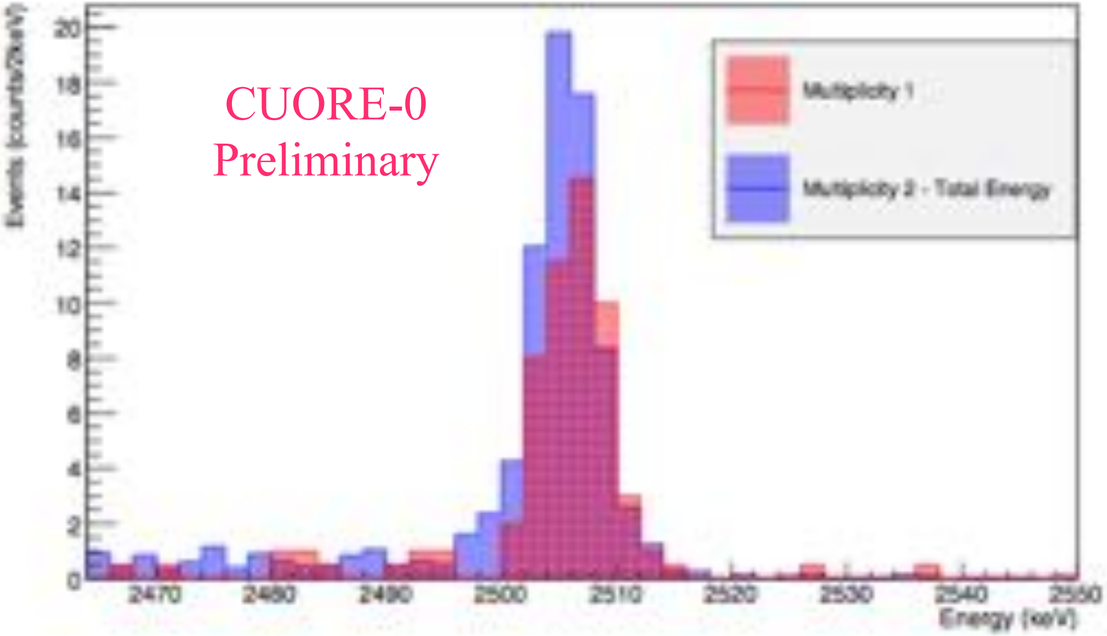
^{60}Co ⟶ ^{60}Ni*

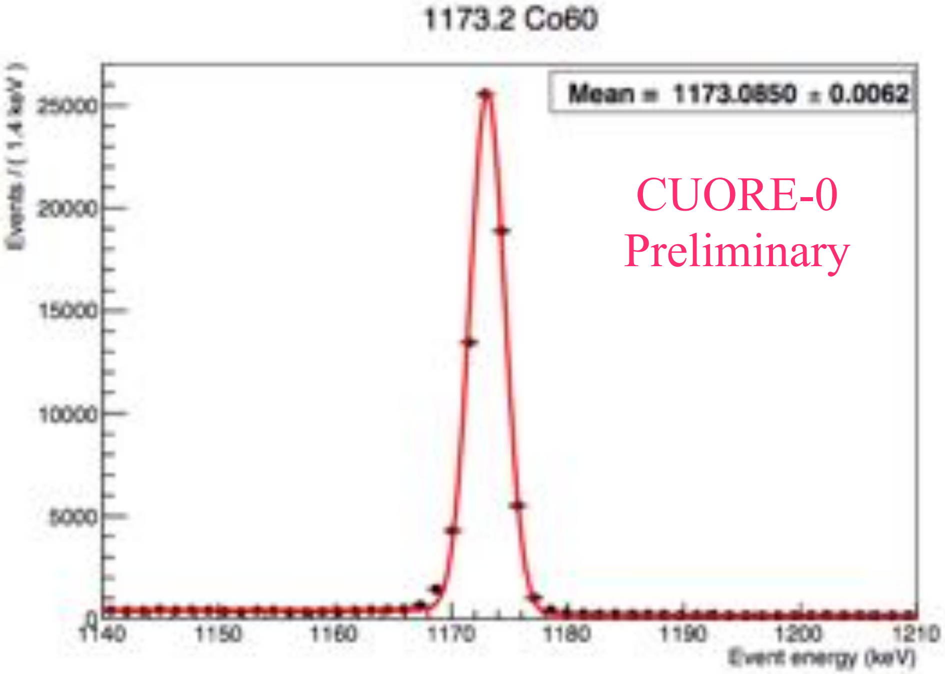
^{60}Ni* ⟶ γ(1173.2keV) + γ(1332.5 keV)

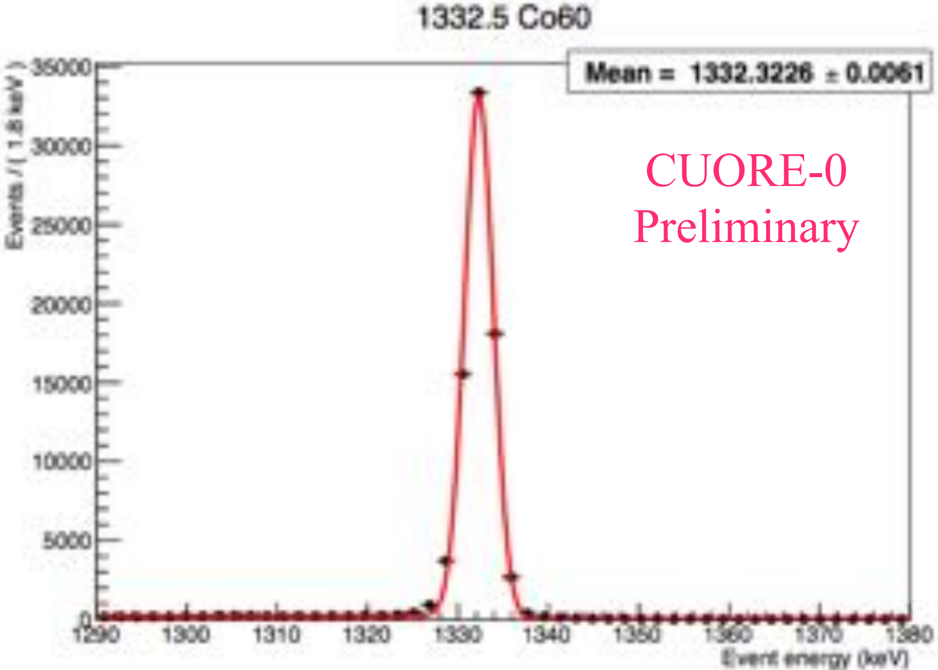


- In a dedicated ^{60}Co calibration run, the double gamma events reconstruct at ~2507 keV in agreement with our physics data

^{60}Co calibration





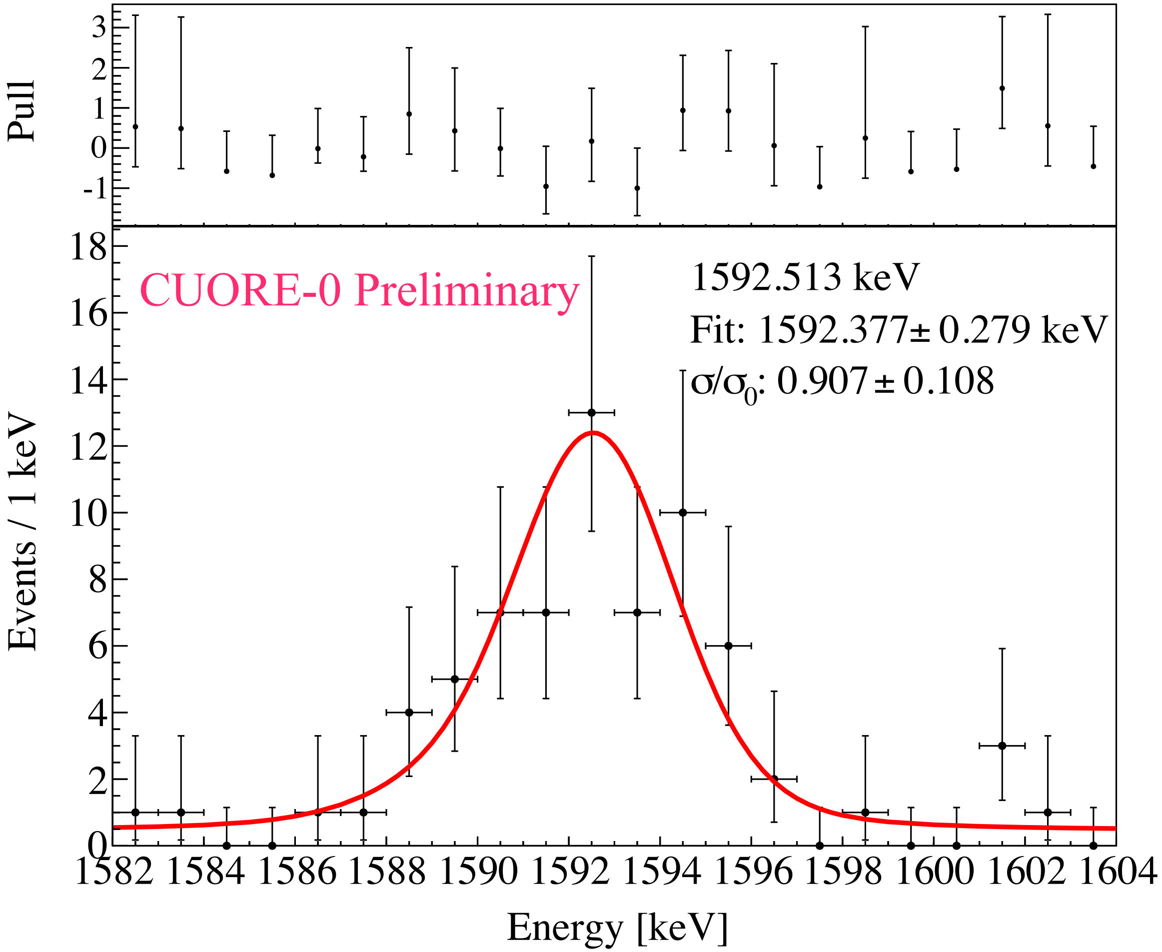


^{60}Co double-gamma events reconstruct at 2507.6 ± 0.7 keV,

1.9 ± 0.7 keV higher than the established value at 2505.6 keV

2615 double escape peak

- Same topology of neutrino-less double beta decay (2 electrons)
- Reconstructs at the correct energy



Fit in the ROI

- We determined the yield of 0vDBD events by performing a simultaneous UEML fit in the energy region 2470-2570 keV

- The fit has 3 components:
  - a posited peak at the Q-value of ^{130}Te
  - a peak at 2507 keV, attributed to the double gamma events from ^{60}Co in the nearby copper and constrained to follow ^{60}Co half life
  - a smooth continuum background, attributed to multi scattered Compton events from ^{208}Tl and surface α events

both peaks are modelled using the established line shape

use flat background but also consider first- and second-order polynomials

- The fit has 4 global free paramters:
  - $\Gamma_{0\nu\beta\beta}, N60_{Co}, \Delta\mu(60_{Co}), \Gamma_B$

$\Delta\mu\ (Q_{\beta\beta}) = 0.05 \pm 0.05$ (stat.) $\pm\ 0.12$ (syst.)

used to shift μ(b,d) from calibration data

$\alpha_\sigma\ (Q_{\beta\beta}) = 1.05 \pm 0.05$

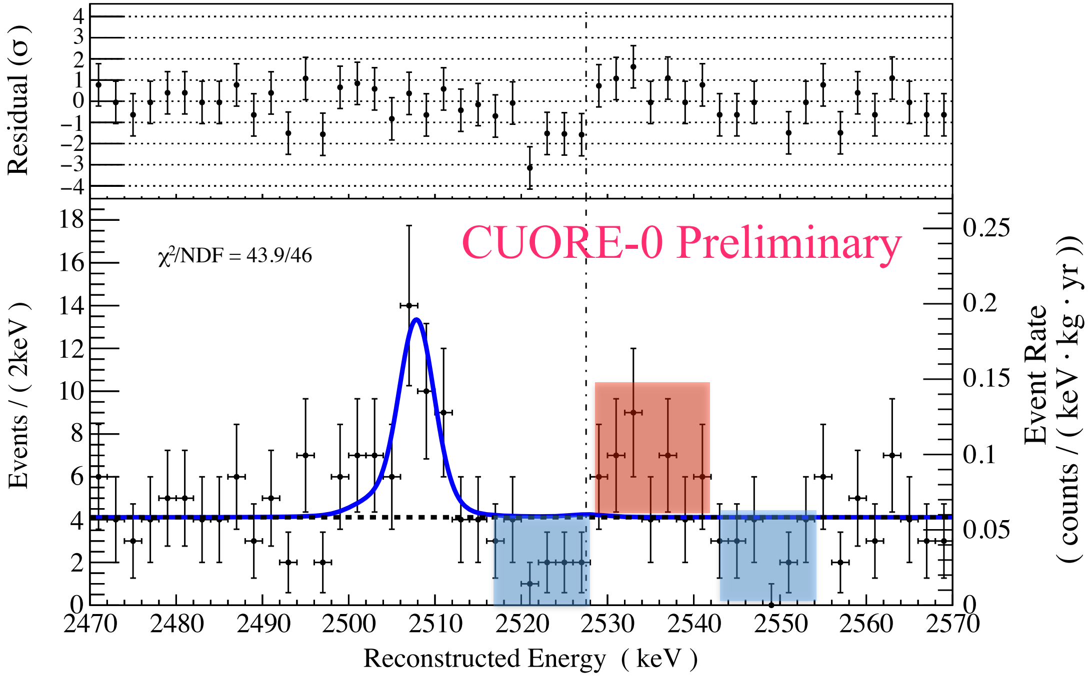
used to scale σ (b,d) from calibration data

Systematics

- For each systematic, we run toy Monte Carlo to evaluate bias on fitted 0νββ decay rate
- Bias is parametrised as $p_0 + p_1 \times \Gamma$, where p_0=“additive” and p_1=“scaling”
    - Signal line-shape: use single and triple gaussian alternatives
    - Energy resolution: vary resolution scaling parameter $\alpha(Q_{\beta\beta})$ within its uncertainty(5%)
    - Energy scale: vary energy offset $\Delta\mu(Q_{\beta\beta})$ within its uncertainty(0.12 keV)
    - Fit bias: Find fit procedure is not biased
    - Bkg function: use 1st, 2nd-order polynomial alternatives

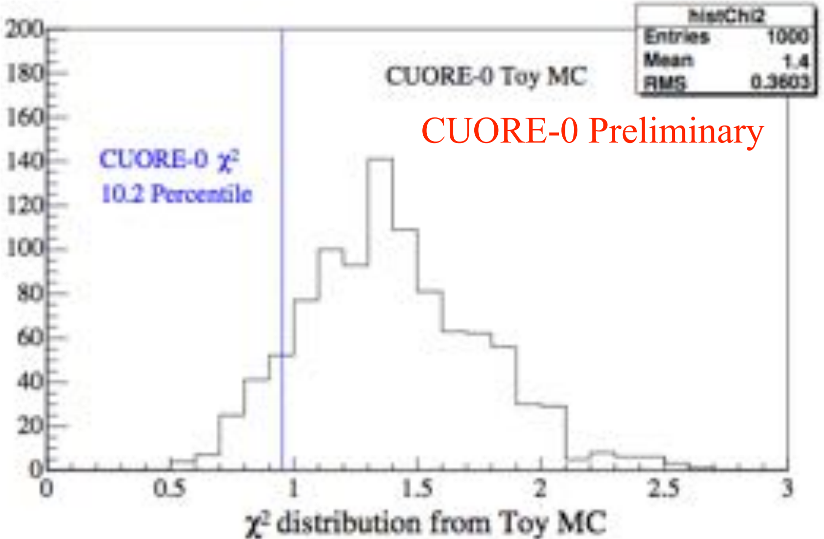
	Signal line shape	Energy resolution	Fit bias	Energy scale	Background function	Efficiency correction
p_0 (additive)	0.007	0.006	0.006	0.005	0.004	
p_1 (percentage bias)	1.3%	2.3%	0.15%	0.4%	0.8%	0.7%

Statistical checks

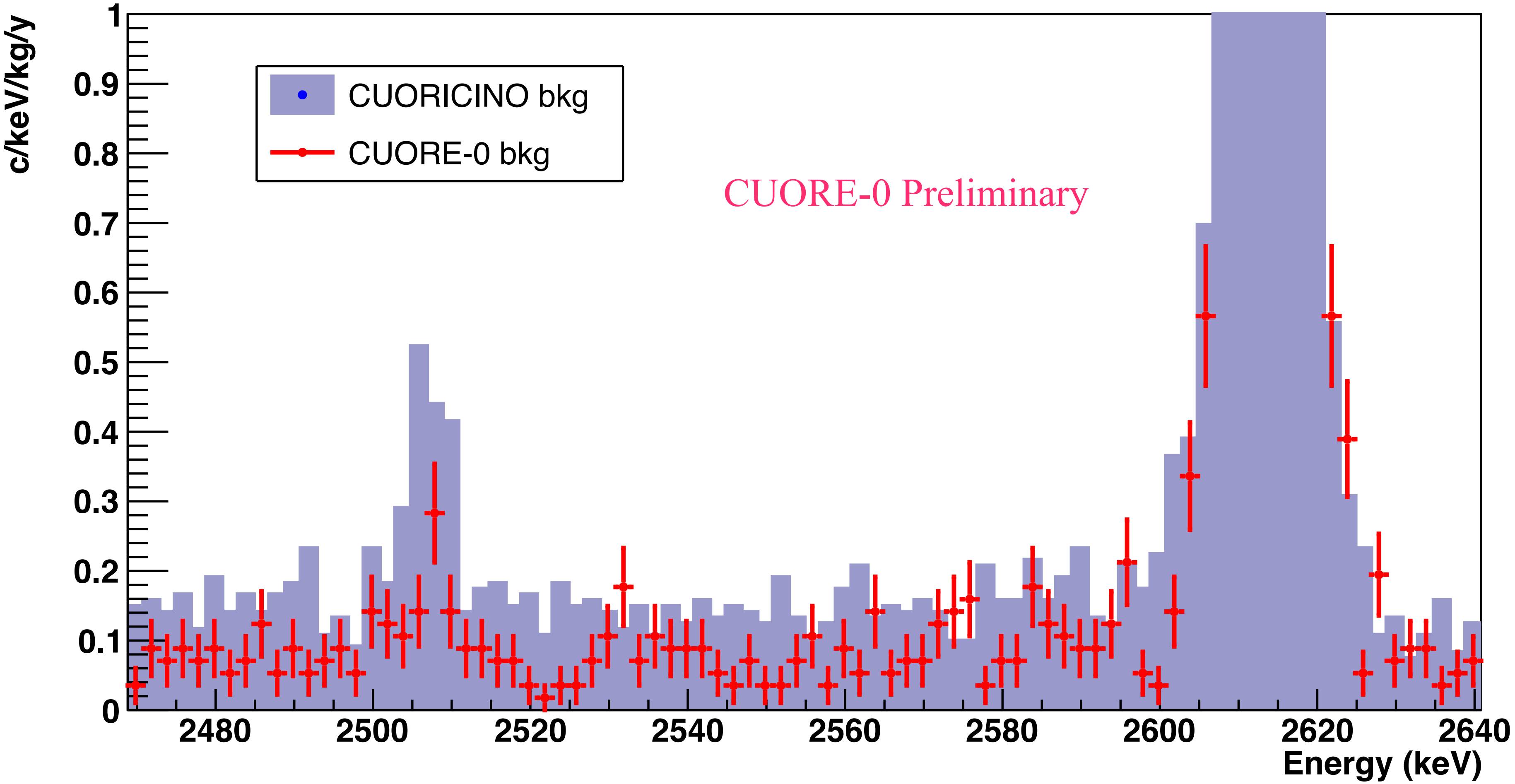


- Estimate the significance of fluctuations from a likelihood ratio test
- Compare hypotheses modelling fluctuations with a peak to our best-fit model
- None of the fluctuations has a significance >3σ C.L.
- Probability to observe the largest fluctuation somewhere in the 100 keV ROI is ~10%

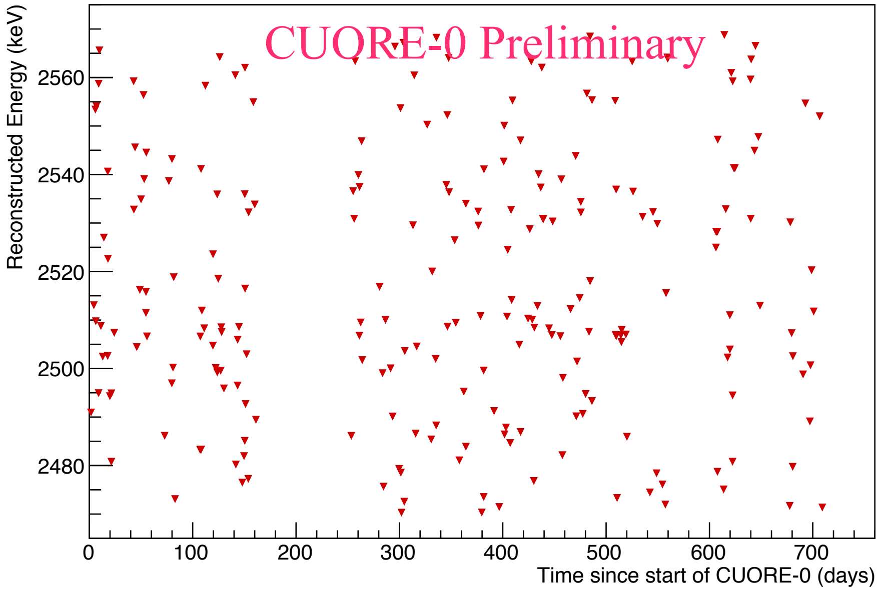
- We compared the value of the binned χ^2 with the distribution from a large set of Toy MC.
- The 90% of such experiments return a value of χ^2>43.9

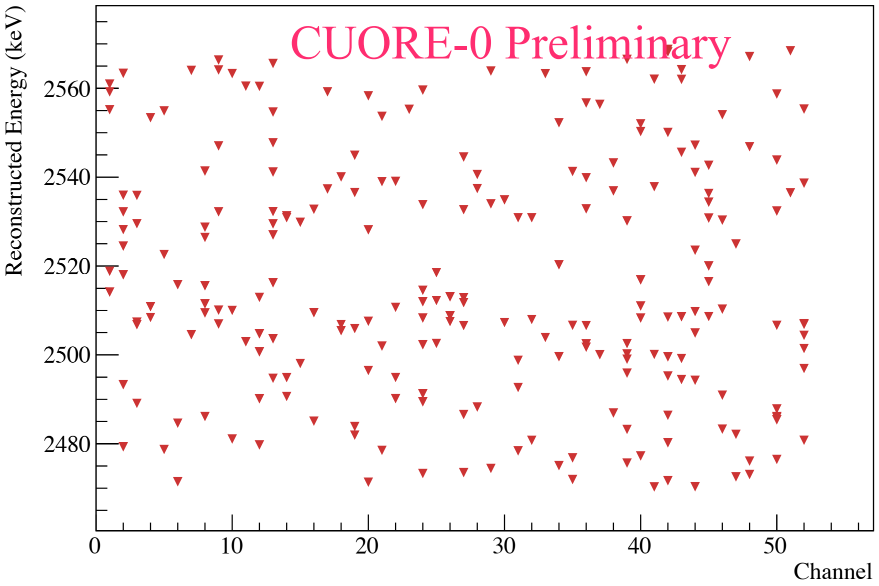


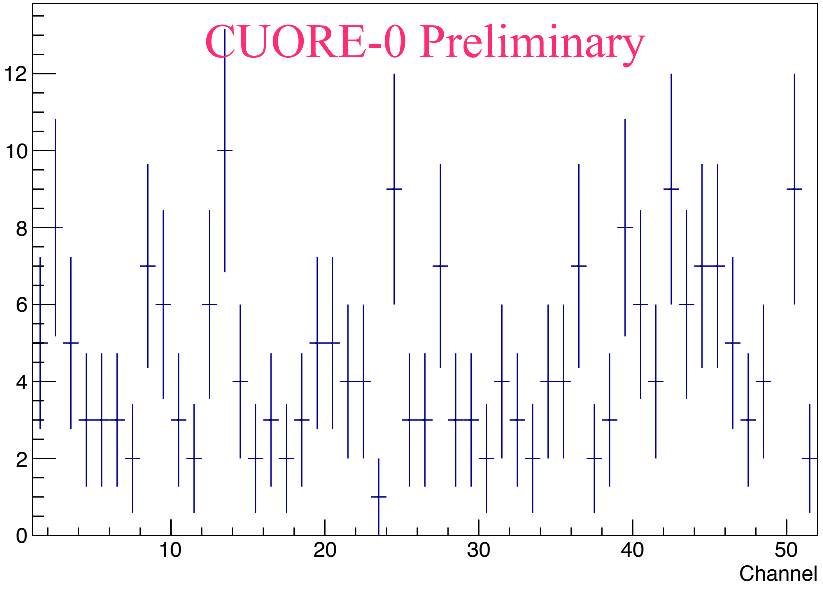
ROI:CUORE-0 vs CUORICINO



ROI events distribution per ch,time

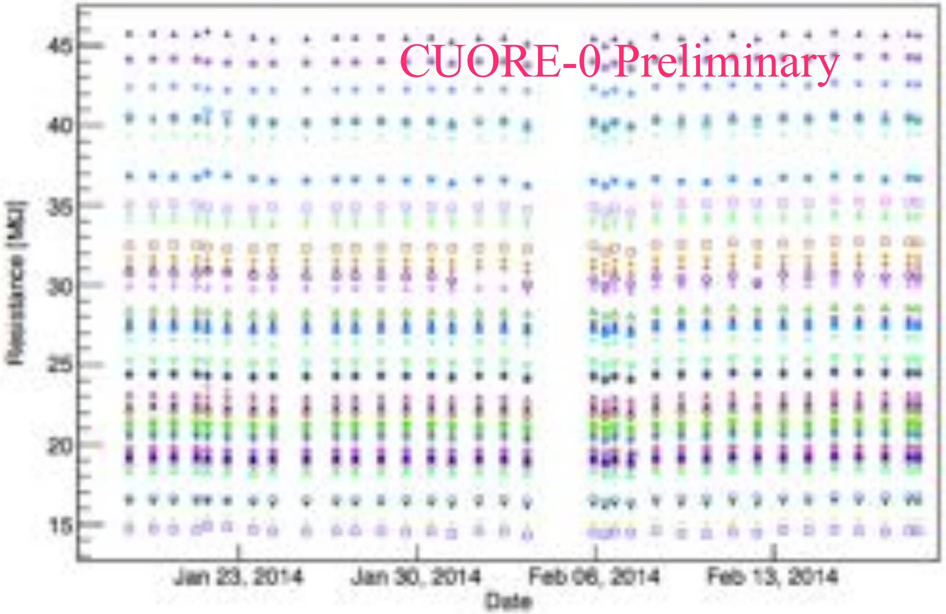


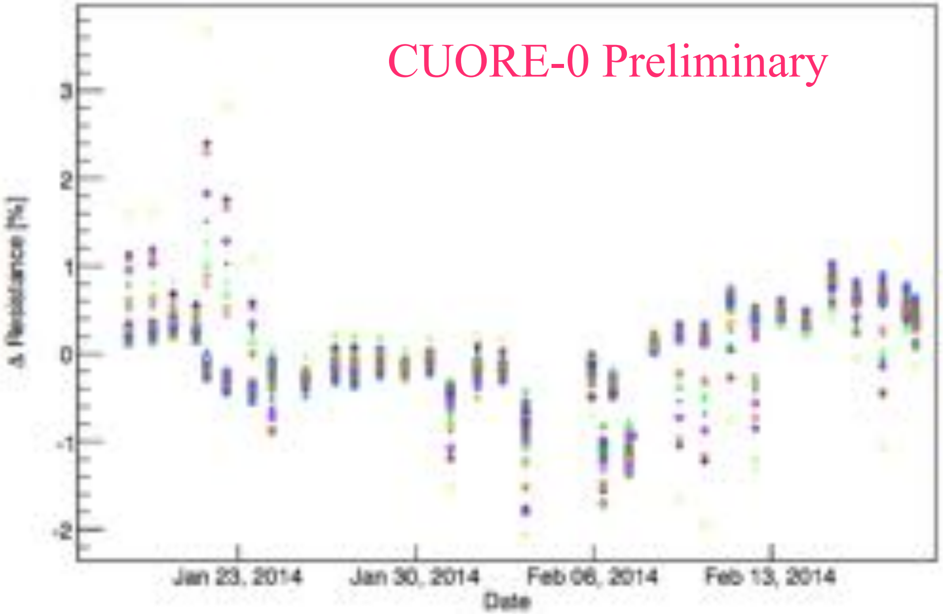




Detector stability

- Routinely measure NTD resistances to monitor detector stability



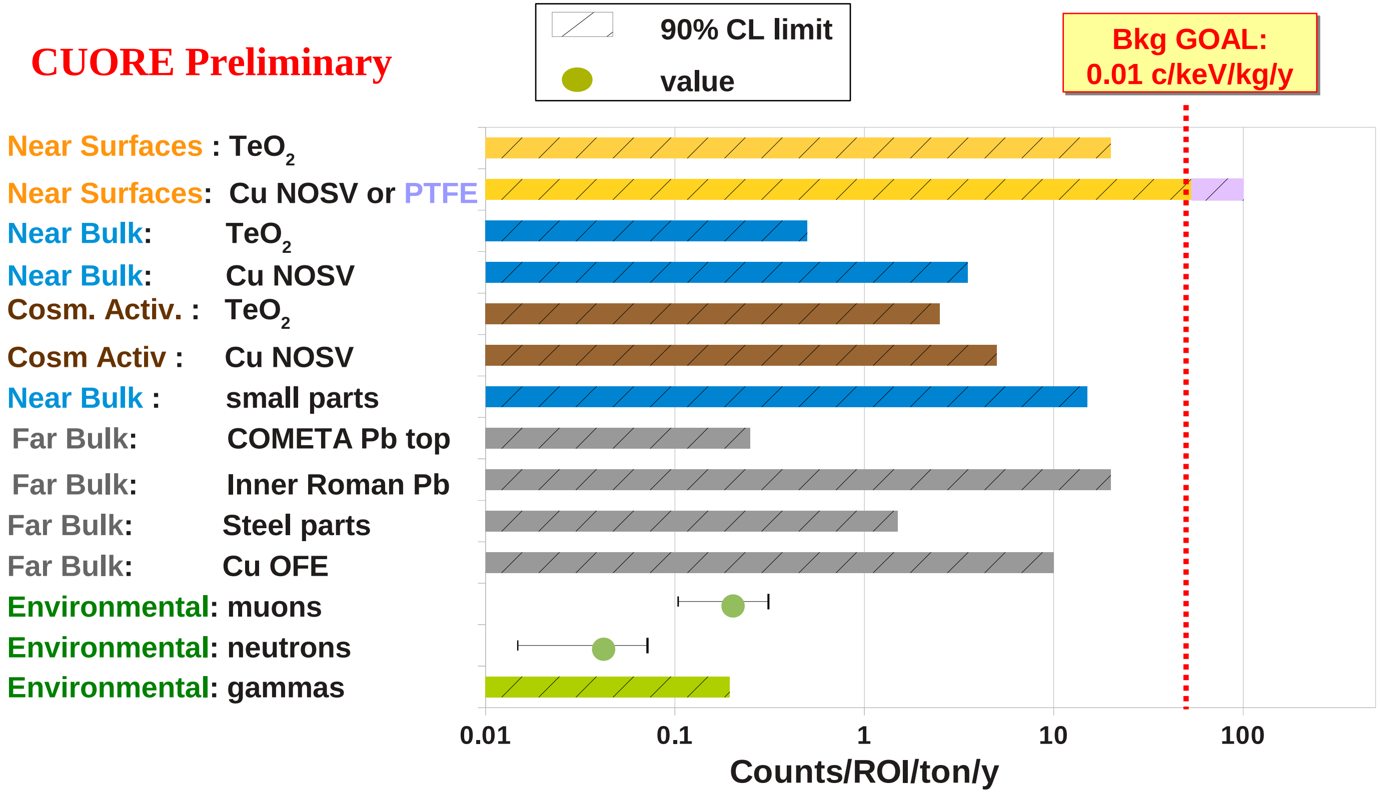


- Spread of NTD resistances across detector within factor of 3
- Resistance of individual NTDs stable to within 3% over a month-long dataset

- It is possible to operate a large bolometer array stably!

CUORE Background Projection

- New cryostat with radio-pure materials: γ contribution negligible
- Less copper facing the crystals: α from Cu surface reduced
- Enhanced granularity: negligible α bkg from crystals surface



Conservative upper limits

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

Crystals

- Radio-purity control protocol to limit bulk & surface contaminations in crystal production

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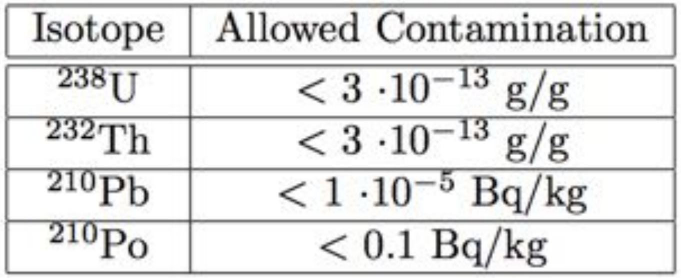
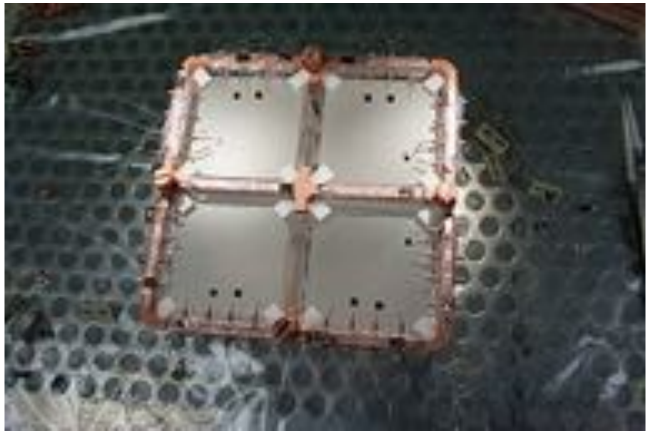


Isotope	Allowed Contamination
^{238}U	$< 3 \cdot 10^{-13}$ g/g
^{232}Th	$< 3 \cdot 10^{-13}$ g/g
^{210}Pb	$< 1 \cdot 10^{-5}$ Bq/kg
^{210}Po	< 0.1 Bq/kg

- Benchmarked in dedicated runs at LNGS



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	Bulk(90% C.L. U.L.)	Surface(90% C.L.U.L)
^{238}U	$5 \cdot 10^{-14}$ g/g	$1 \cdot 10^{-9}$ Bq/cm^2
^{232}Th	$2 \cdot 10^{-13}$ g/g	$2 \cdot 10^{-9}$ Bq/cm^2
^{210}Pb	$3.3 \cdot 10^{-6}$ Bq/kg	$9.8 \cdot 10^{-7}$ Bq/cm^2
^{210}Po	0.05 Bq/kg	

- CUORE: bkgd $<1.1 \cdot 10^{-4}$ ($4.2 \cdot 10^{-3}$) counts/keV/kg/y from bulk (surface)