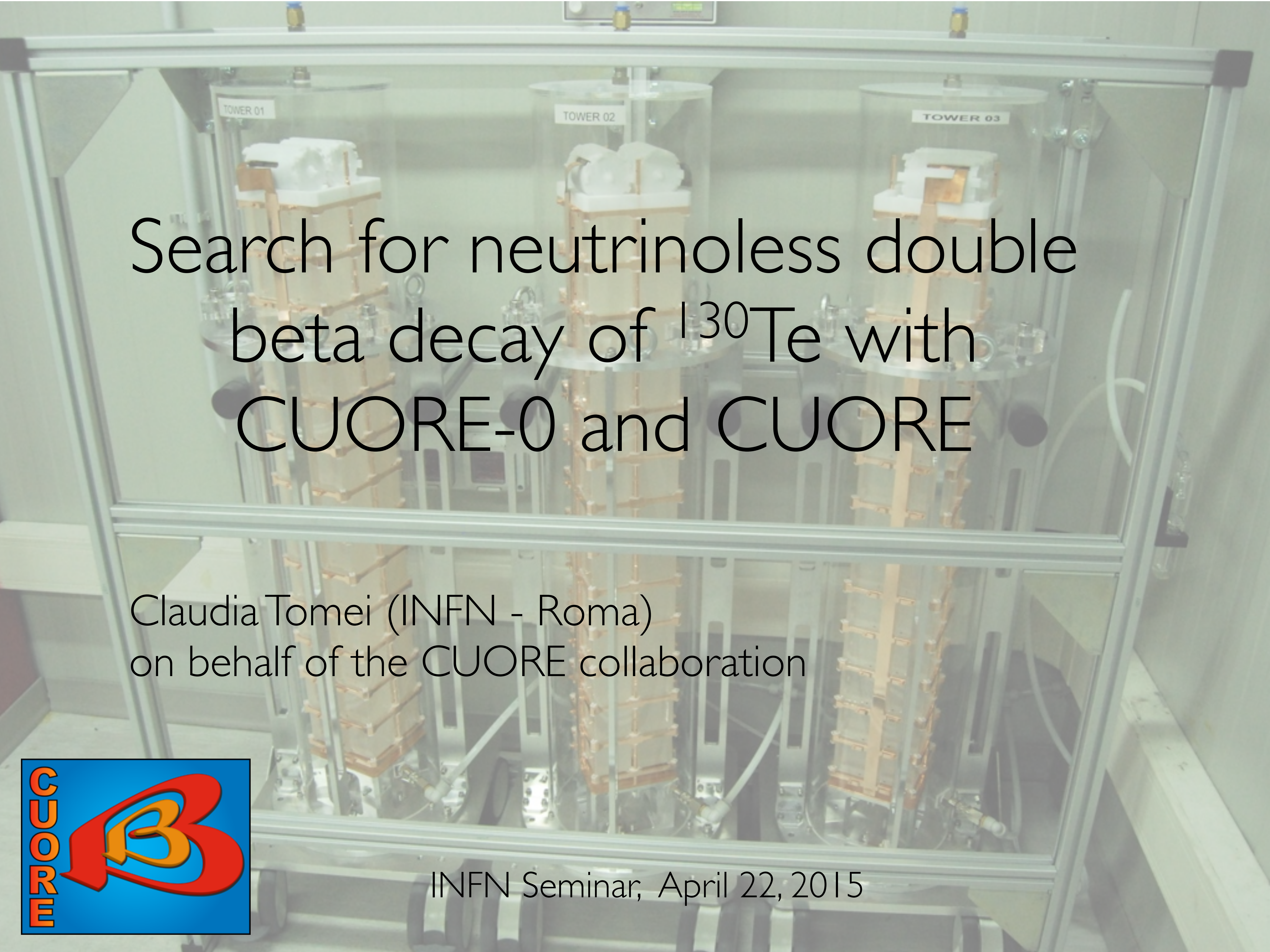
Search for neutrinoless double beta decay of ^{130}Te with CUORE-0 and CUORE

Claudia Tomei (INFN - Roma)
on behalf of the CUORE collaboration

INFN Seminar, April 22, 2015



The CUORE Collaboration

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Lawrence Livermore National Laboratory

Massachusetts Institute of Technology

UCLA

SAPIENZA UNIVERSITÀ DI ROMA

CSNSM

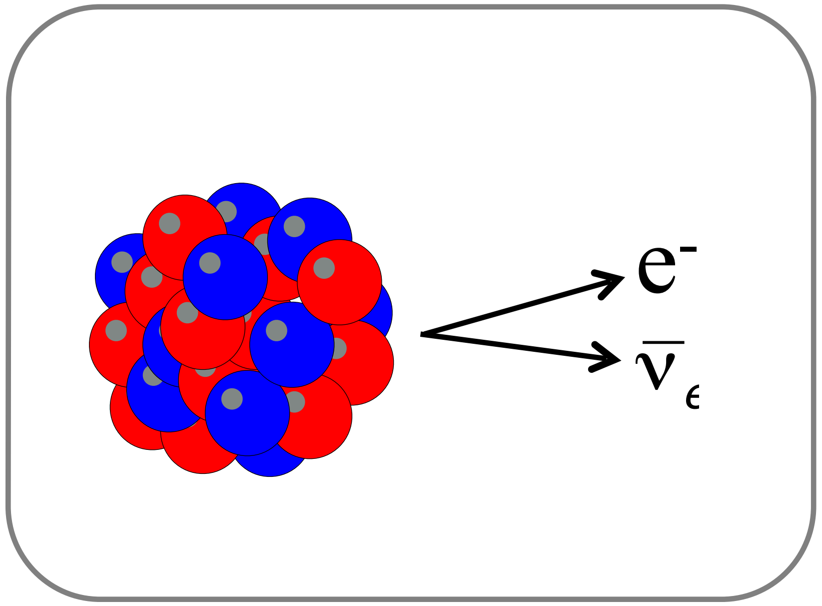
CUORE

BERKELEY LAB

UNIVERSITY OF SOUTH CAROLINA

- 157 collaborators
  - 120 researchers/authors
    - Italy: 71
    - USA: 38
    - Associated Institutions: 11

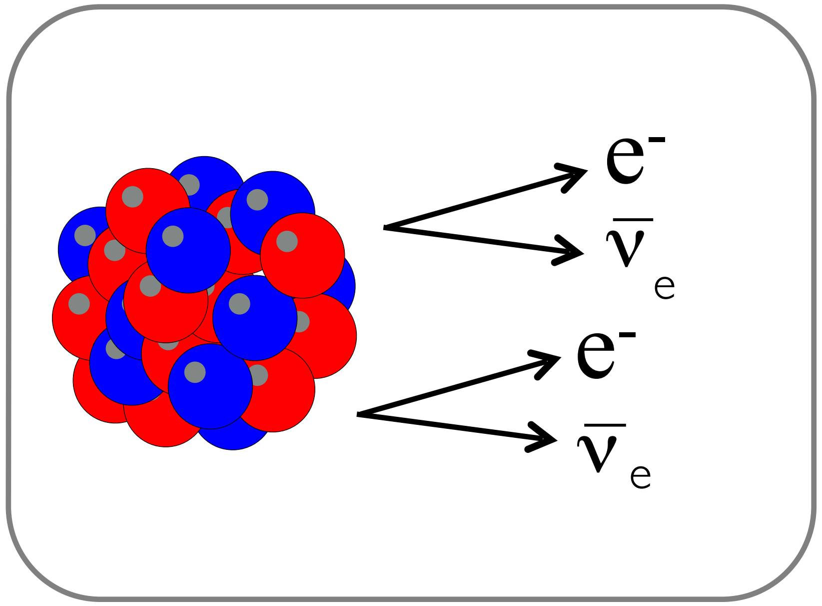
The double beta decay



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

β decay

Well known weak process



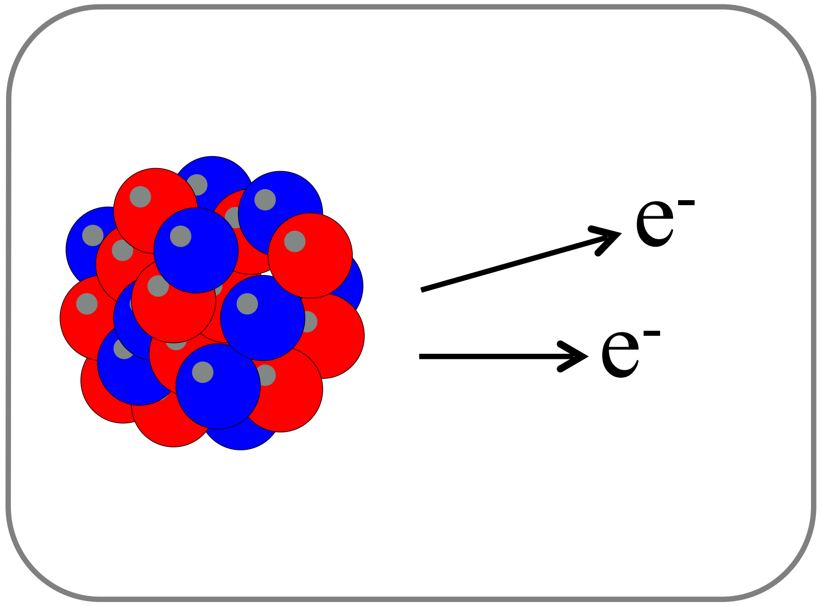
$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+2}\mathrm{X} + 2e^- + 2\bar{\nu}_e$$

2νββ

Observed, but rare

($T_{1/2} > 10^{19}$ yr)

Only visible in nuclei with forbidden single β



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

0νββ

Even rarer than 2νββ

(if it occurs at all)

Not observed so far

(one controversial claim of observation)

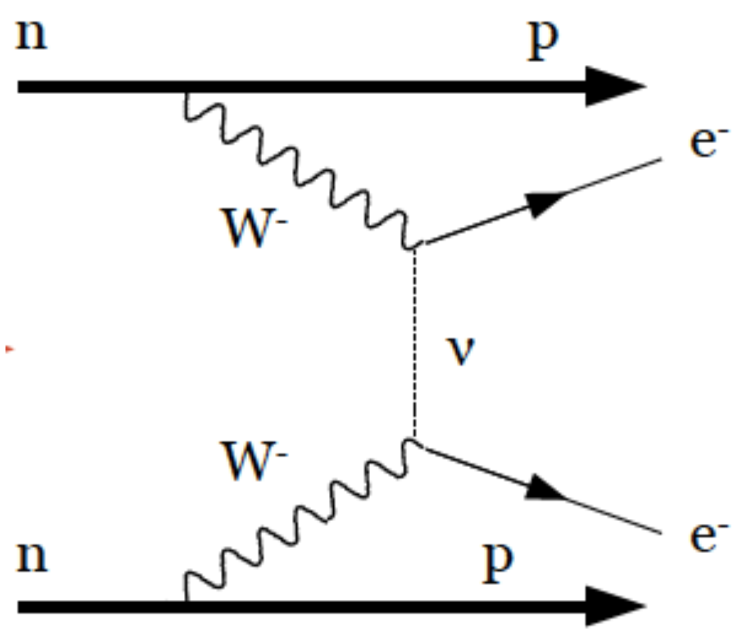
Neutrinoless double beta decay (0νββ)

Observation of 0νββ would:

Demonstrate that lepton number is not conserved

Establish neutrinos as Majorana particles

Set constraints on the effective Majorana mass $m_{\beta\beta}$ and provide info on absolute ν mass scale

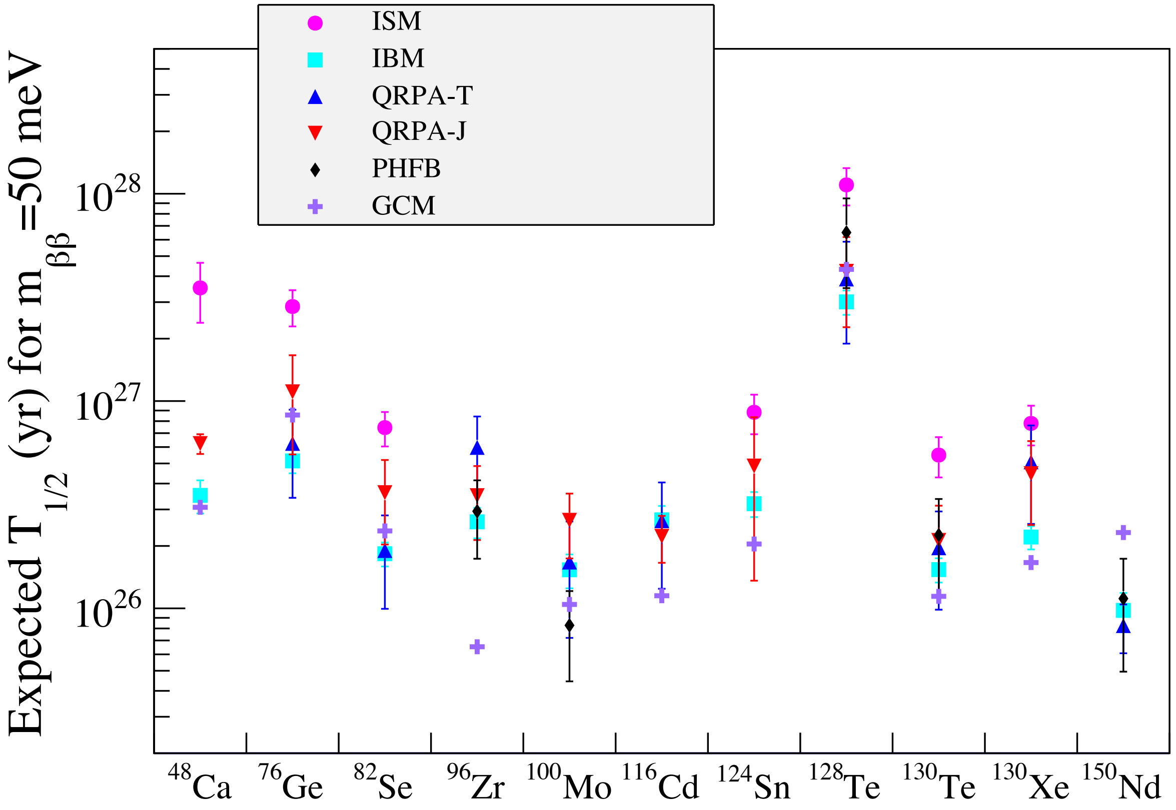


The observable is the half life:

$$T^{0\nu}_{1/2} = \frac{m_e^2}{G_{0\nu} \cdot M^2_{nucl} \cdot m^2_{\beta\beta}}$$

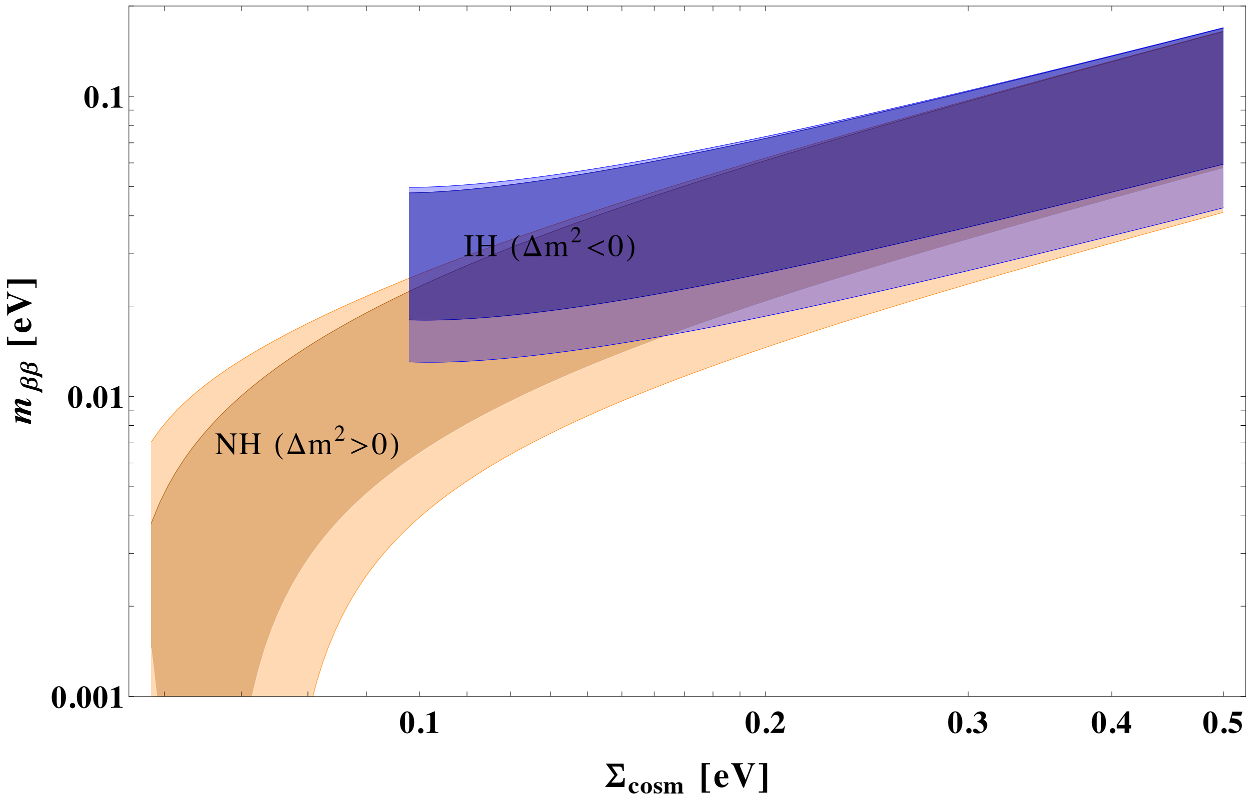
Phase space factor: known with good accuracy

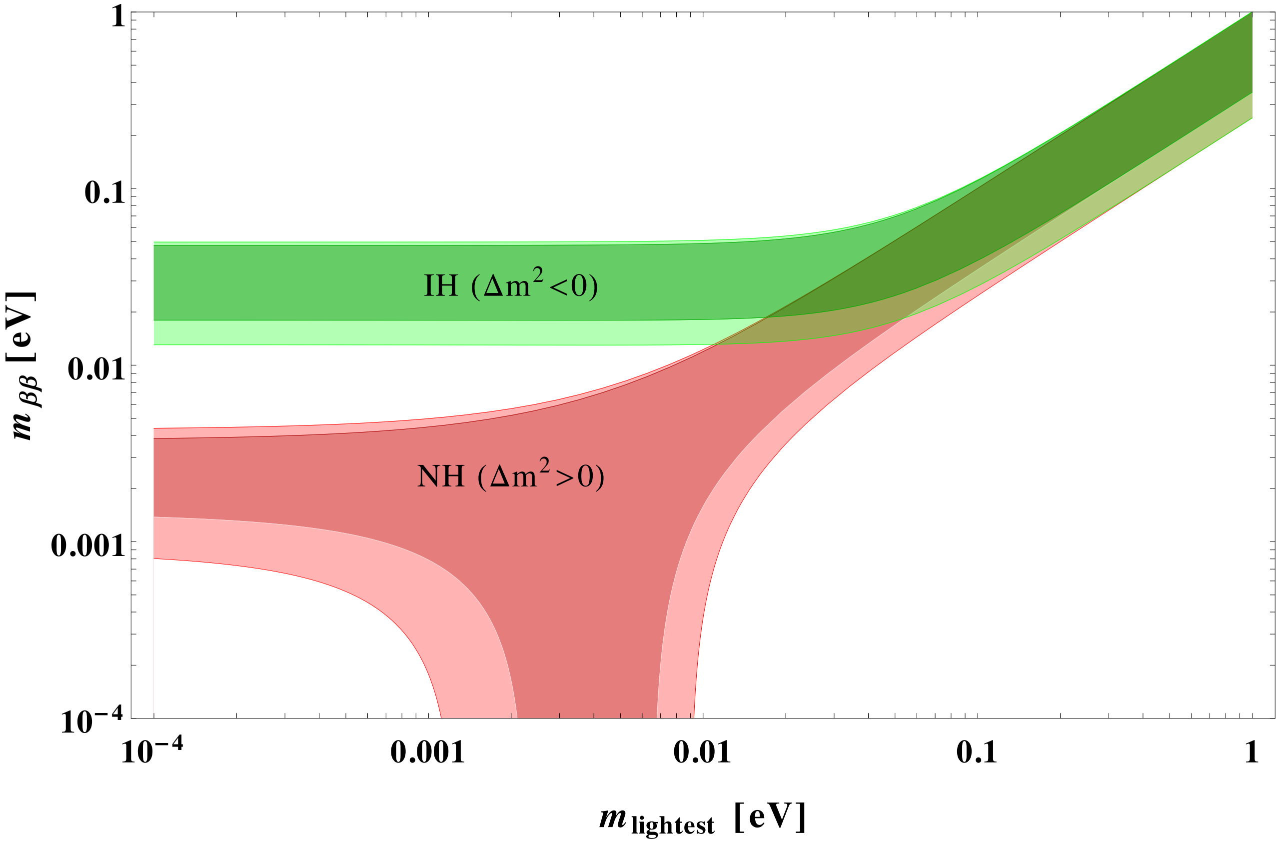
Nuclear matrix element



$0\nu\beta\beta$ and neutrino mass scale and hierarchy

$$m_{\beta\beta} = |\sum_i m_{\nu_i} U_{ei}^2|$$

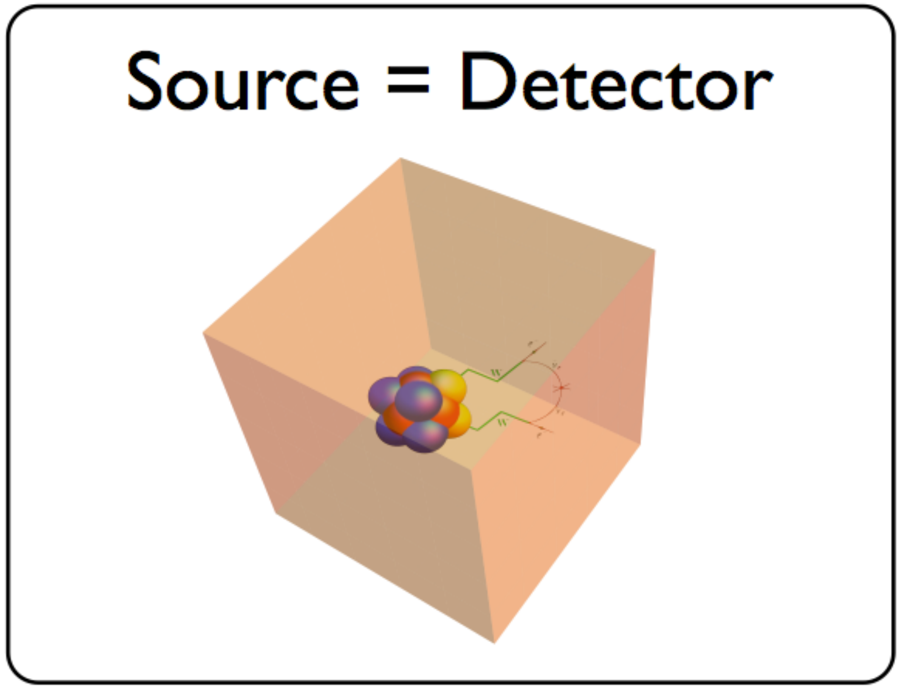


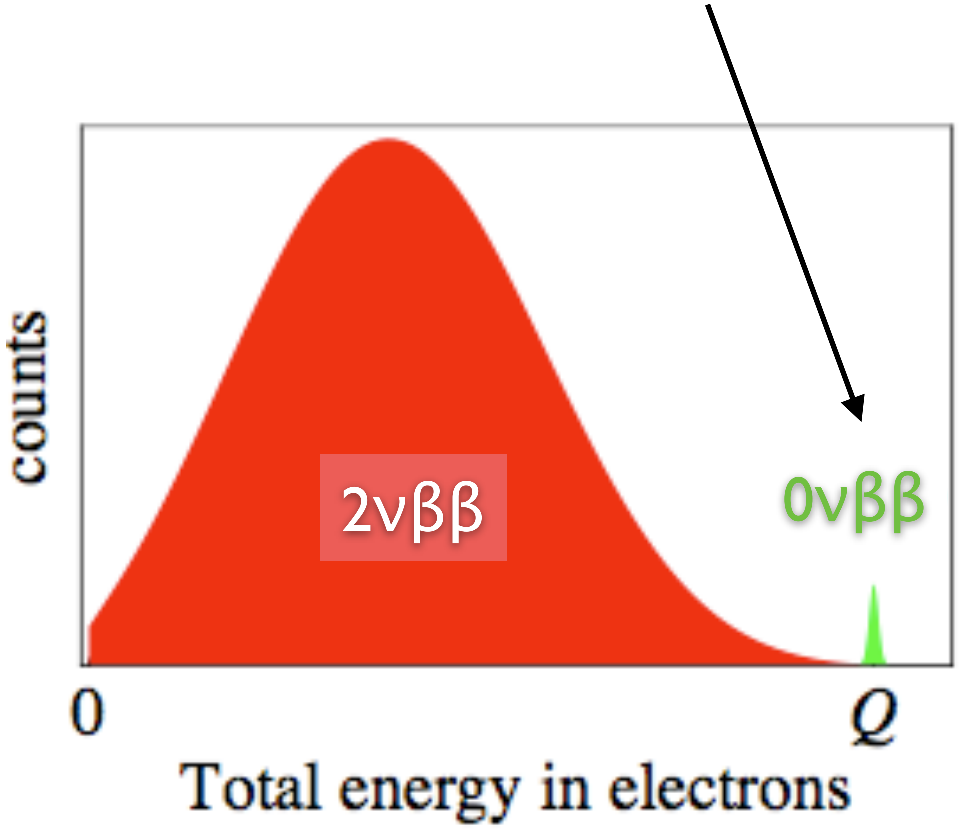


Stefano Dell'Oro, Simone Marcocci, Francesco Vissani
Phys. Rev. D 90, 033005 (2014)

Signature of neutrinoless double beta decay

In the general experimental approach of detecting the sum energy of the two final-state electrons, the signature of 0νββ decay is a peak at Q-value ($Q_{\beta\beta}$)

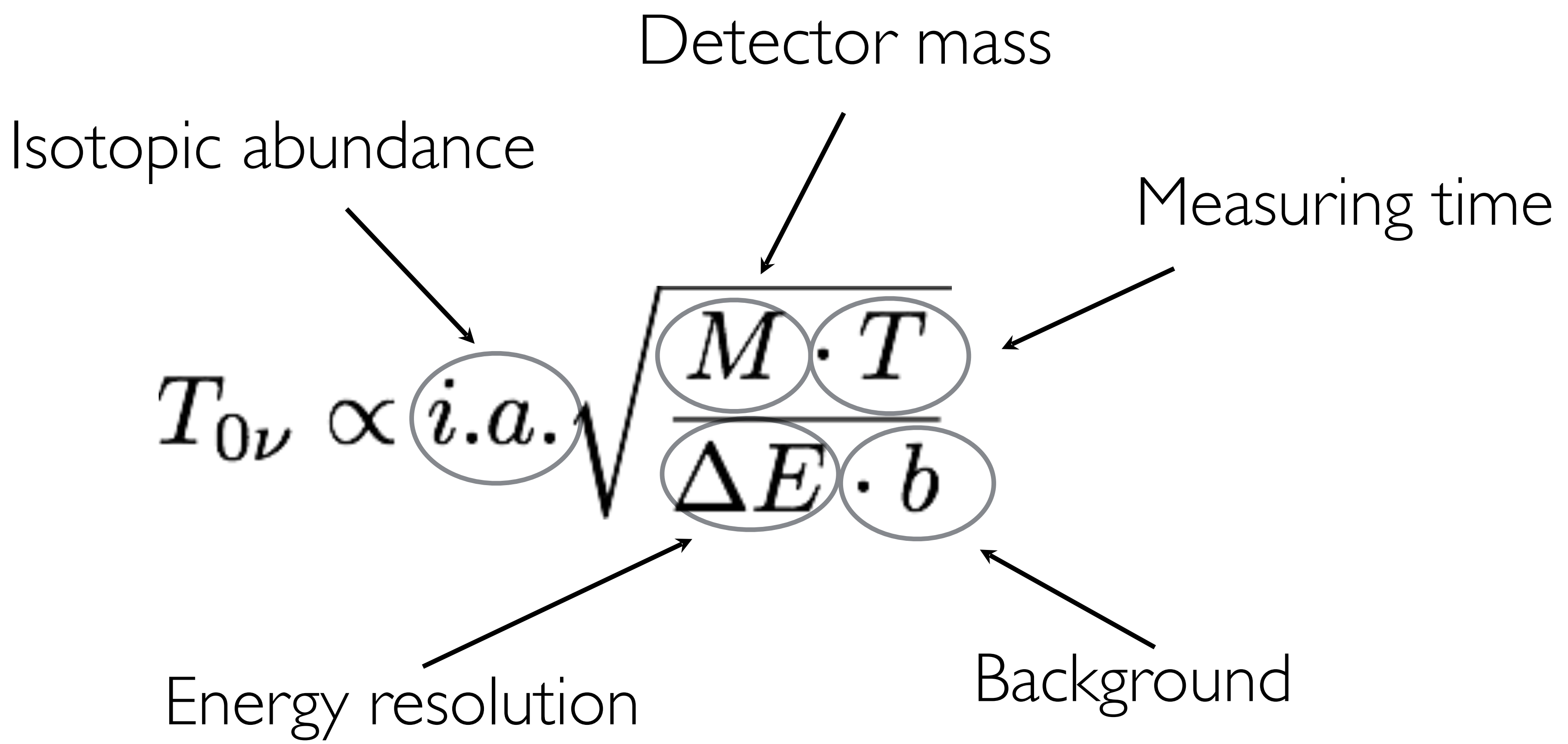




Reducing the background (if you can't discriminate against it) is the challenge

Experimental sensitivity to 0νββ

Half-life corresponding to the minimum number of detectable signal events above background at a given C.L.



$$T_{0\nu} \propto i.a. \sqrt{\frac{M \cdot T}{\Delta E \cdot b}}$$

Detector mass

Isotopic abundance

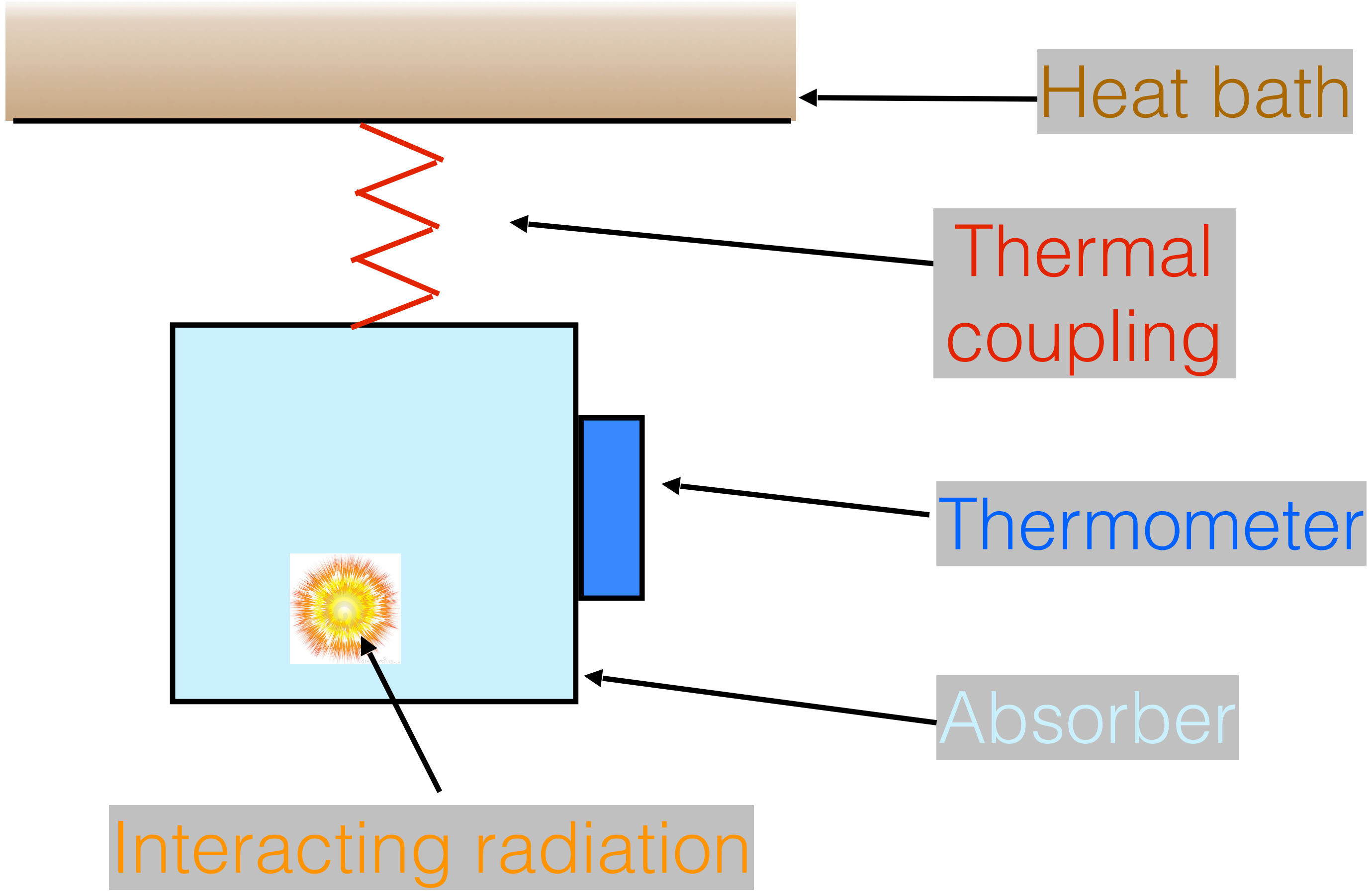
Measuring time

Energy resolution

Background

Thermal detectors

Ultracold crystals function as highly sensitive calorimeters



Heat bath

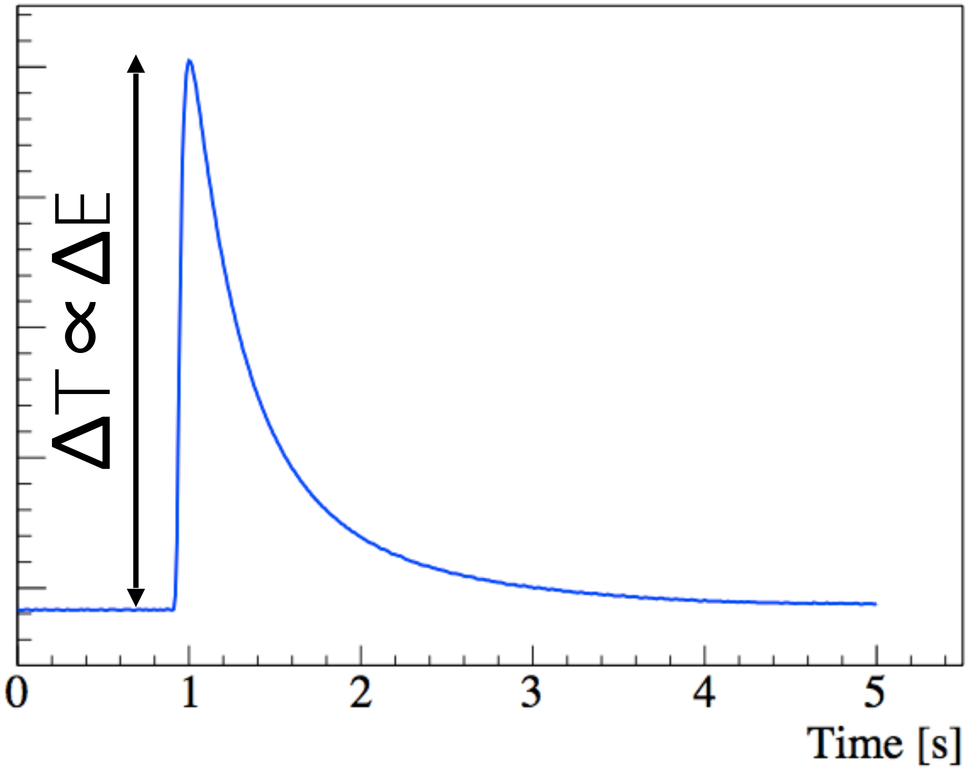
Thermal coupling

Thermometer

Absorber

Interacting radiation

The energy deposited by a particle interaction in the absorber is converted to a measurable temperature variation.



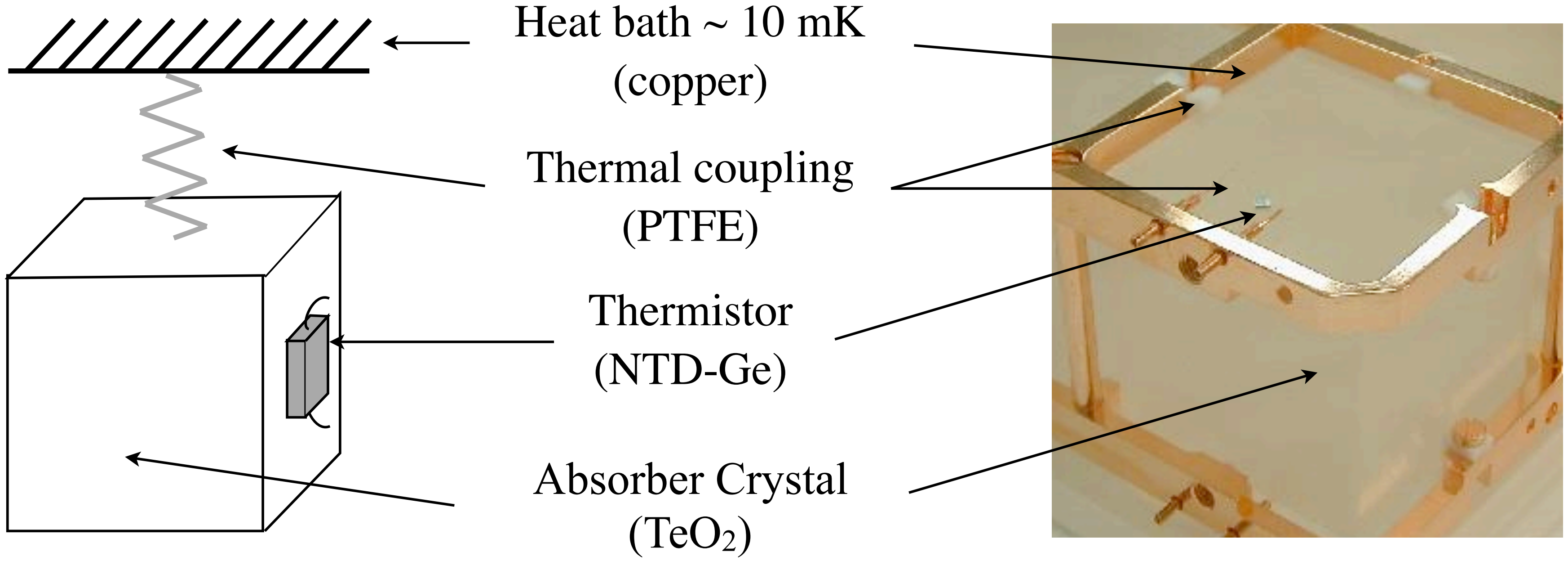
wide choice of detector materials

source embedded in the detector

excellent energy resolution

CUORE bolometers for double beta decay

CUORE searches for $0\nu\beta\beta$ of ^{130}Te with TeO_2 bolometers

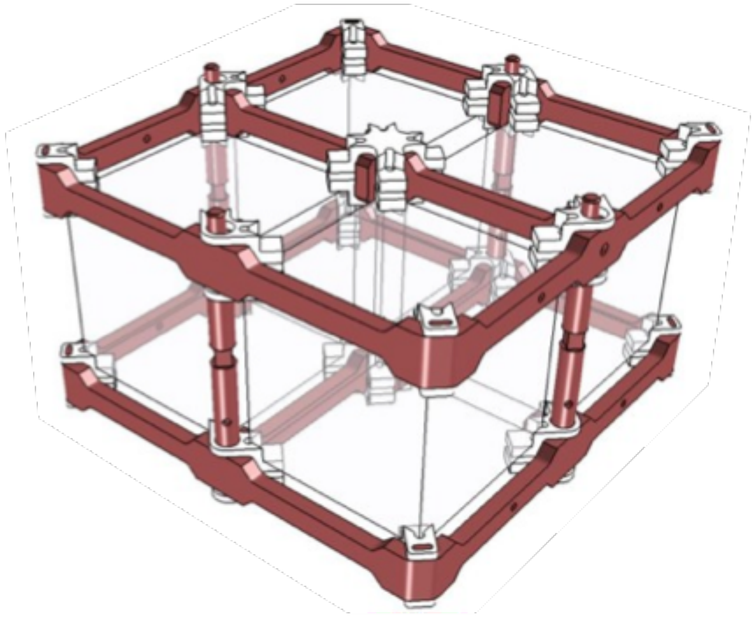


Heat bath ~ 10 mK
(copper)

Thermal coupling
(PTFE)

Thermistor
(NTD-Ge)

Absorber Crystal
(TeO_2)



Energy release → ΔT→ ΔR in the thermistor → ΔV

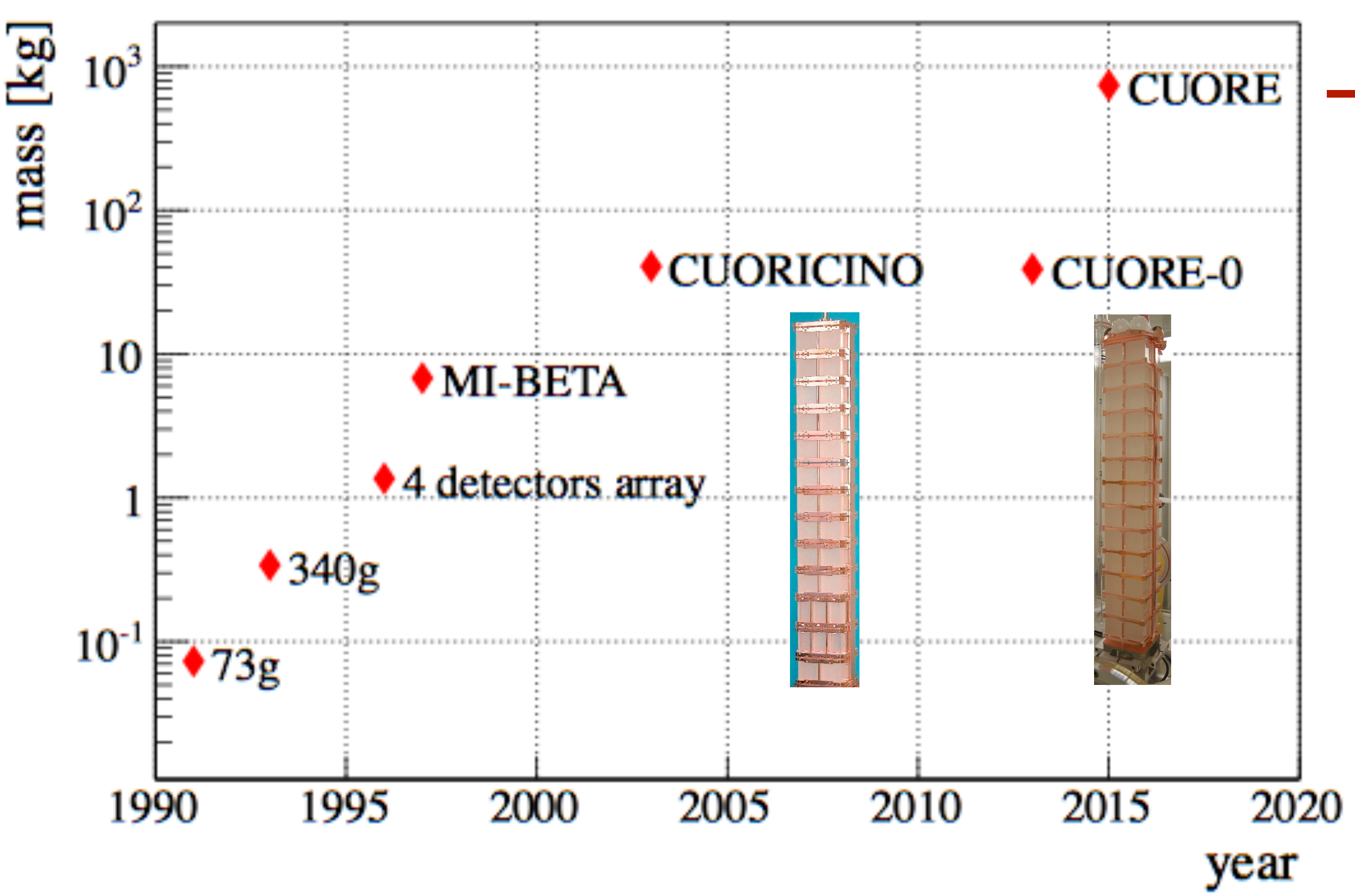
$\Delta T_{thermistor} \sim 0.03$ mK/MeV
$\Delta T_{crystal} \sim 0.1$ mK/MeV

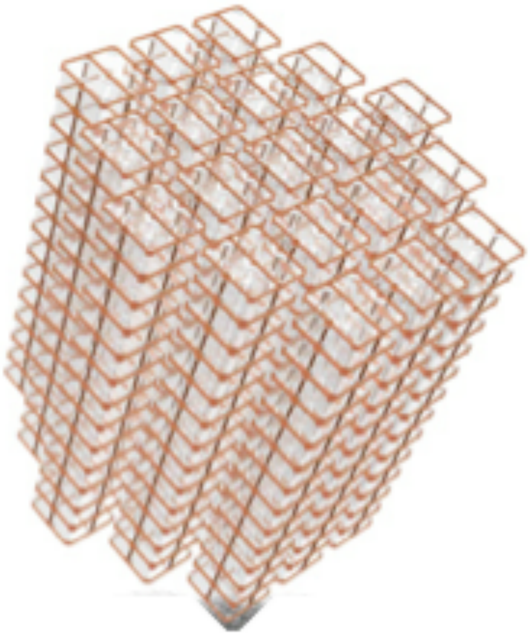
$\Delta V_{thermistor} \sim 0.3$ mV/MeV
$\Delta R_{thermistor} \sim 3$ MΩ/MeV

Arrays of TeO_2 bolometers

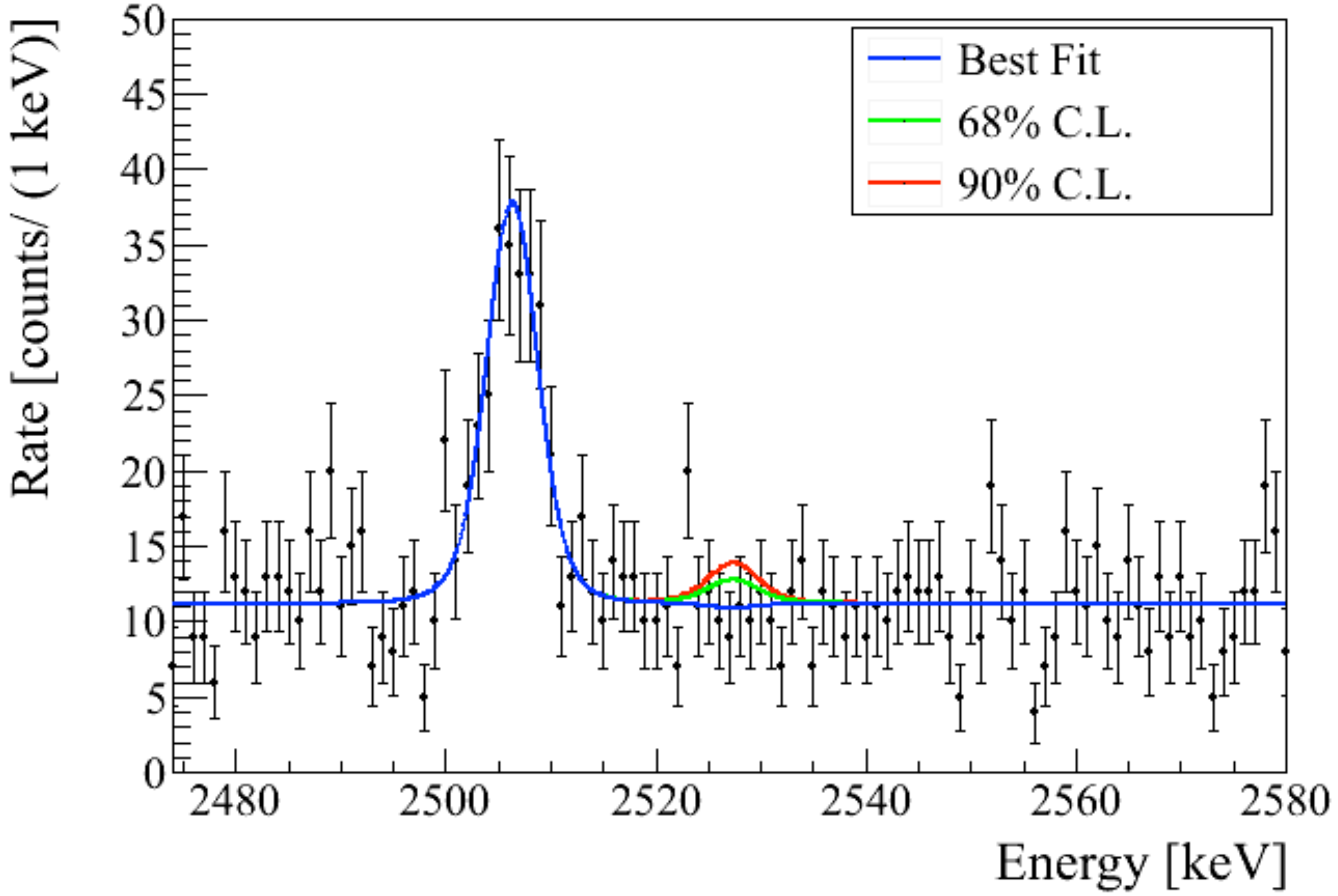
Advantages:

- high natural isotopic abundance (34.2%) of the ββ emitter (highest among the isotopes of interest)
- excellent energy resolution: 5 keV FWHM @ Q-value (2528 keV)





CUORICINO

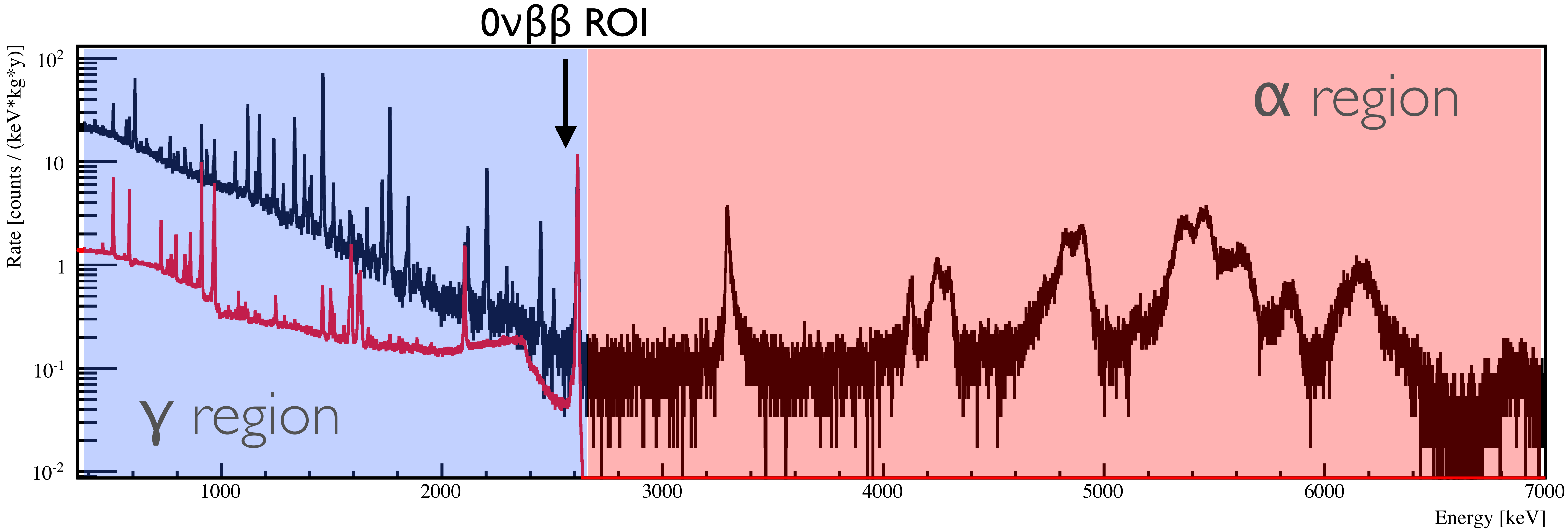


Operated between 2003 and 2008

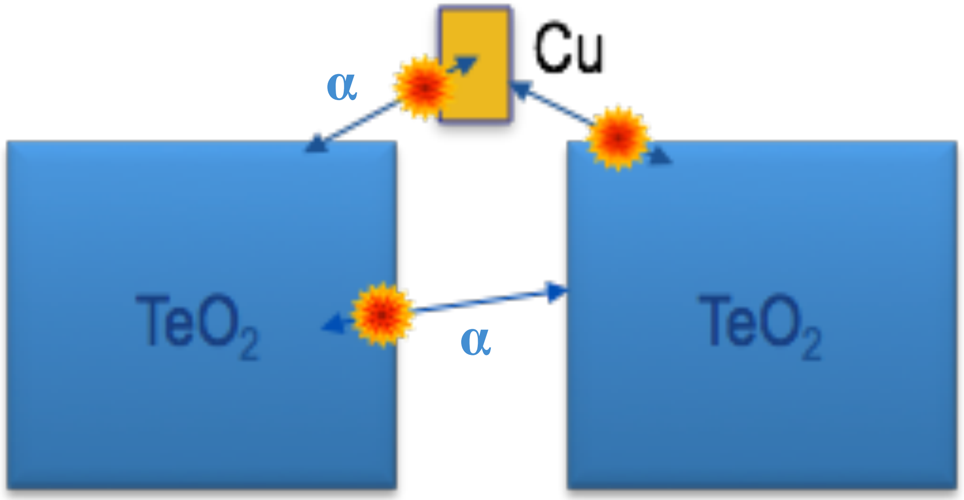
E. Andreotti et al. (CUORICINO Collaboration), Astropart. Phys. 34: 822–831 (2011) [arXiv:nucl-ex/1012.3266].

Exposure	19.75 kg y (^{130}Te)
Background	0.169 ± 0.006 counts/keV/kg/y (^{130}Te)
Lower limit, half-life:	$T_{1/2}(0\nu) \geq 2.8 \times 10^{24}$ y (90% C.L.)
Upper limit, Majorana ν mass:	$\langle m_{\beta\beta} \rangle < (300 - 710)$ meV

CUORICINO background



Main sources of background in the region around the Q value:



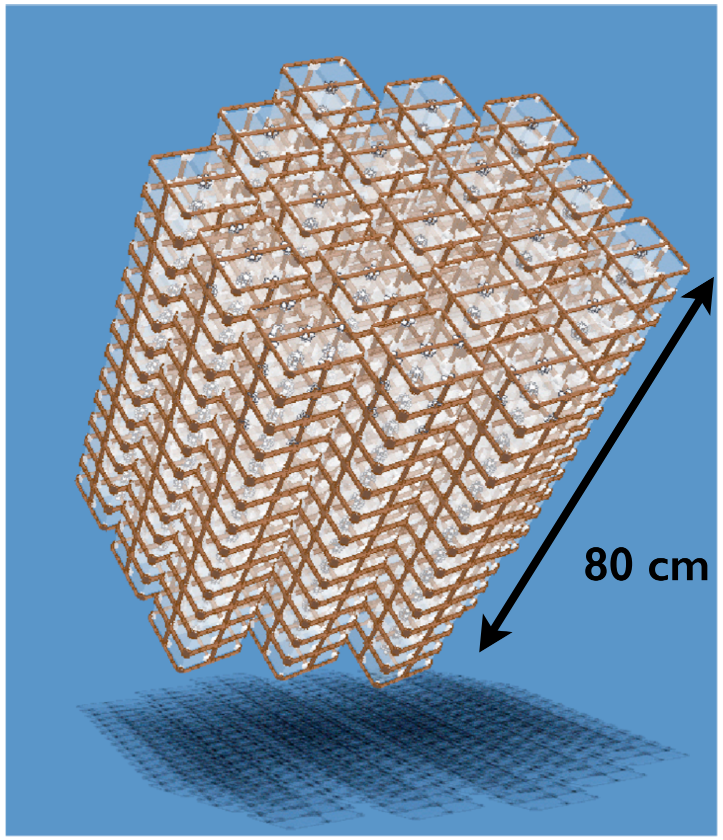
35% Compton from ^{208}Tl (^{232}Th chain) decays in cryostat (2615 keV line)

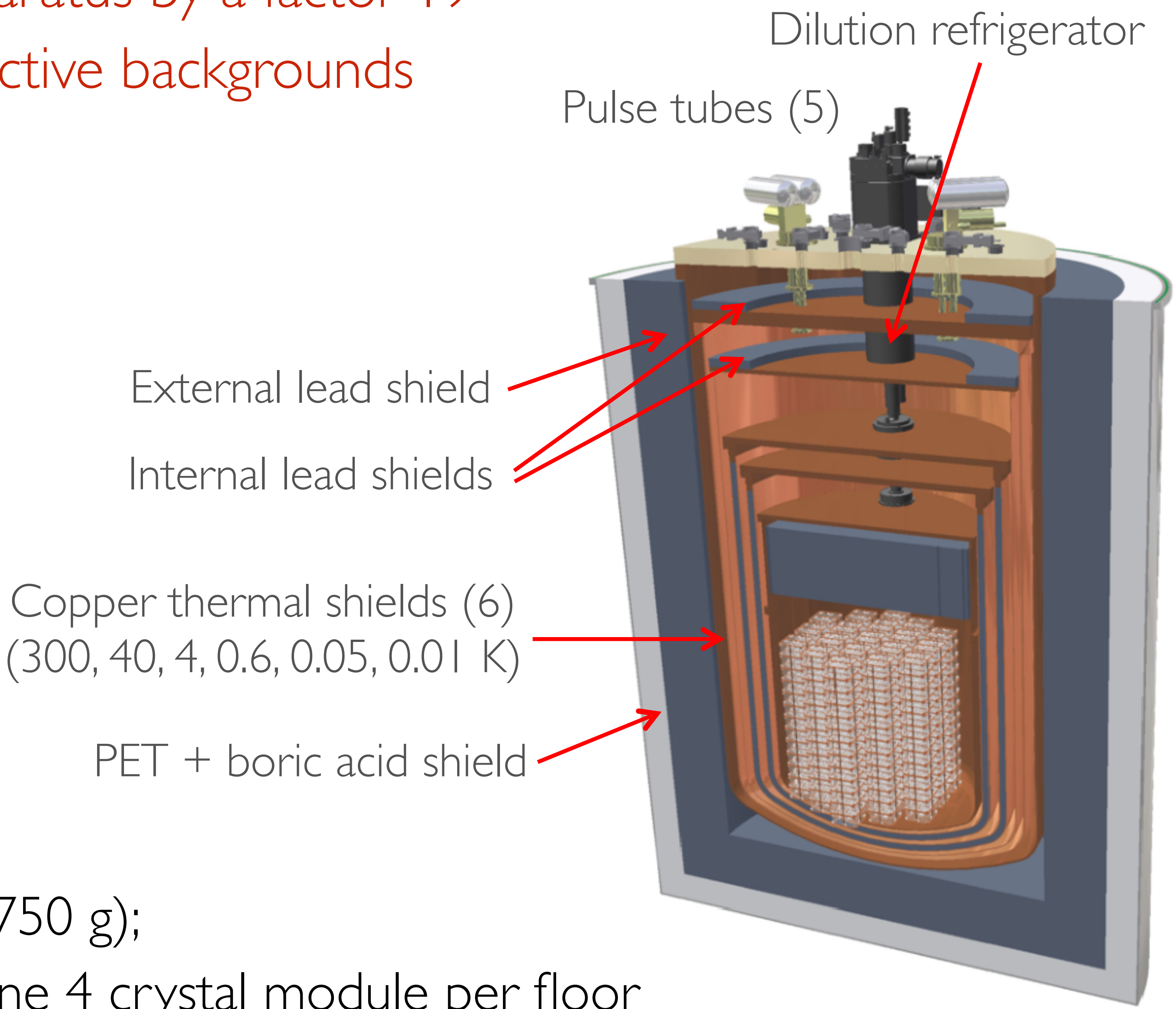
55% Degraded alphas from ^{238}U- and ^{232}Th-chain decays on copper surfaces

10% Degraded alphas from ^{238}U- and ^{232}Th-chain decays on crystal surfaces

CUORE (Cryogenic Underground Observatory for Rare Events)

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





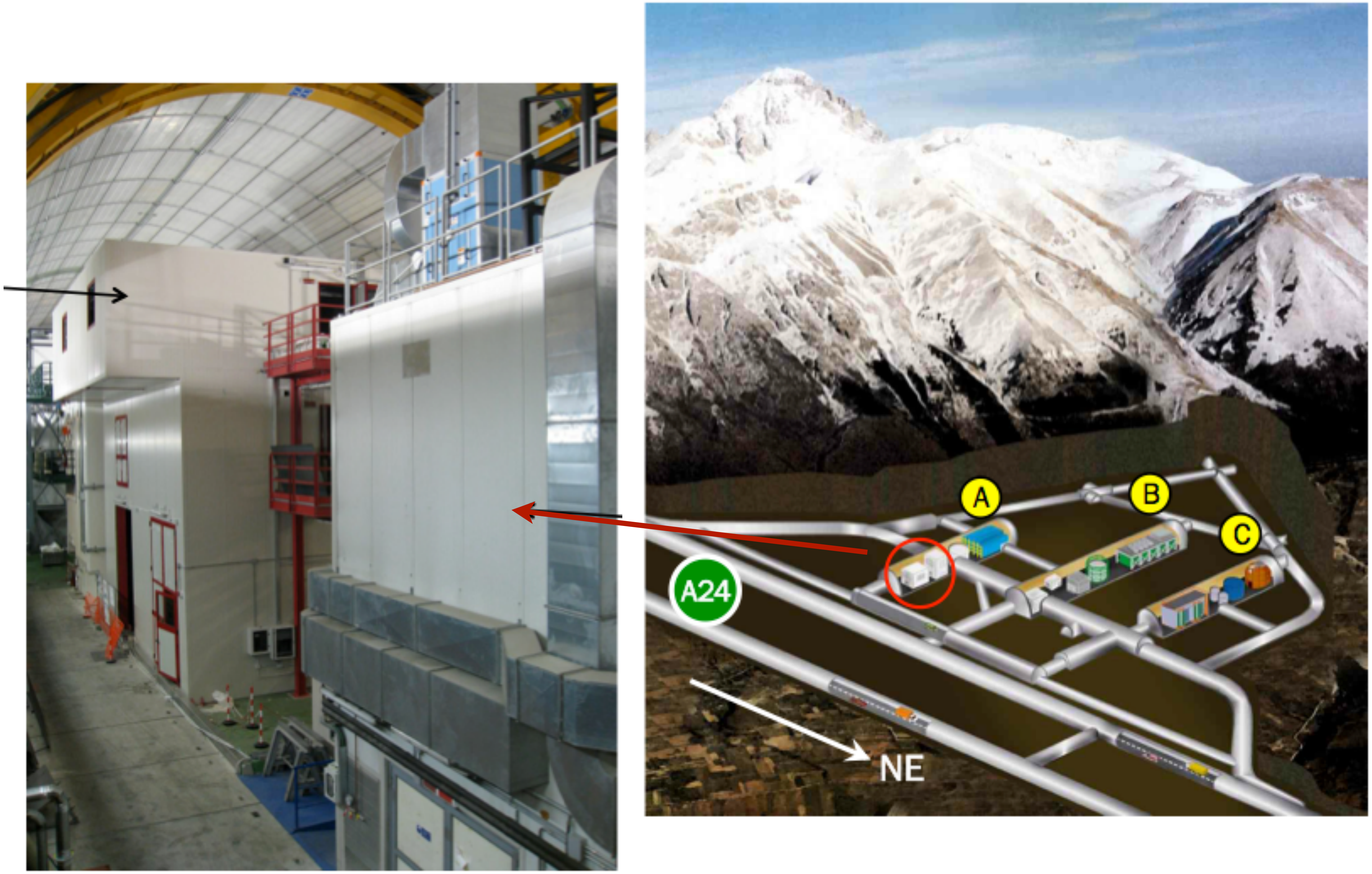
Array of 988 TeO_2 crystals:

- 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)

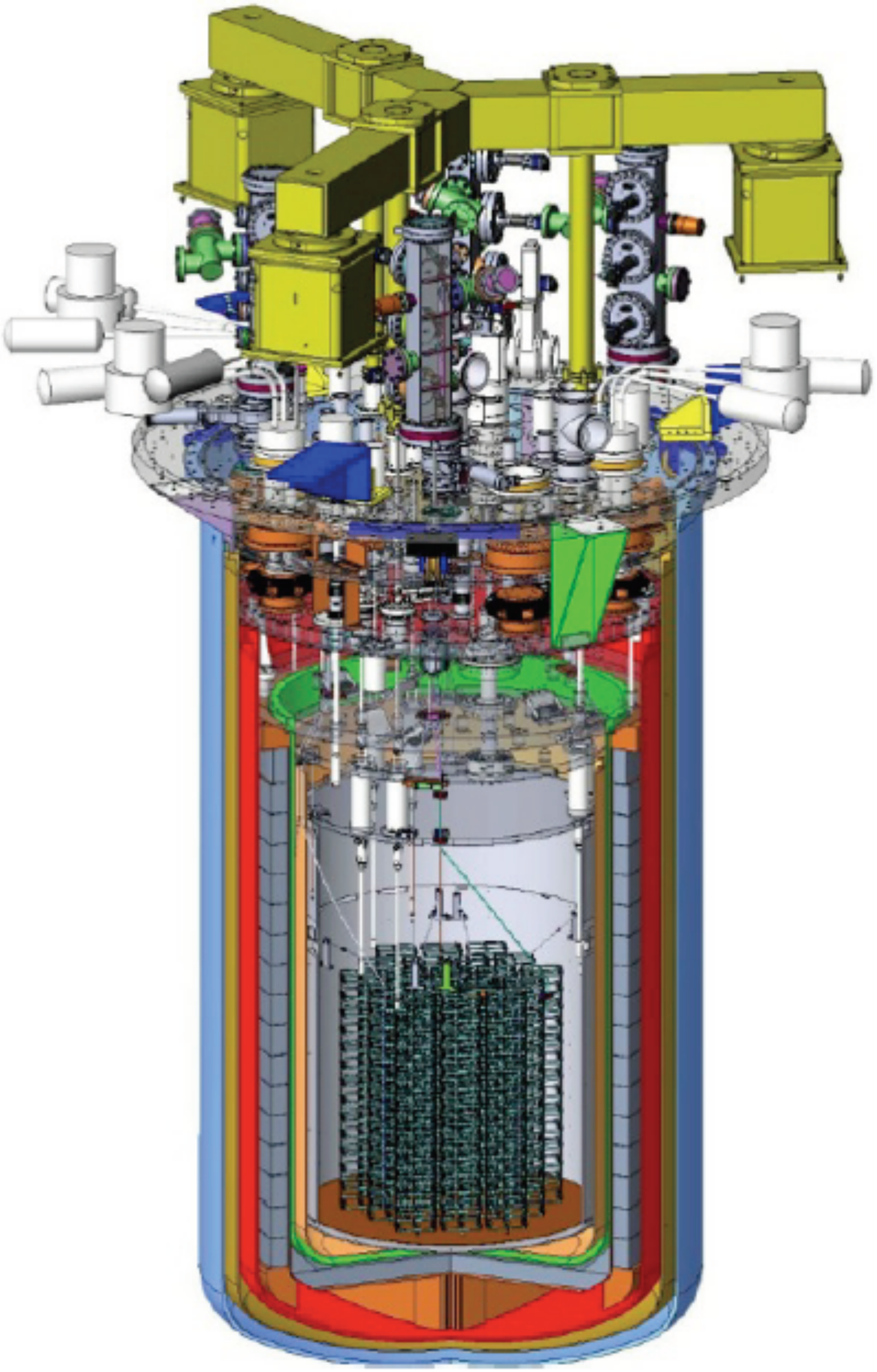
CUORE (Cryogenic Underground Observatory for Rare Events)

Located underground at LNGS

CUORE Hut



CUORE main challenges: cryostat



CUORE cryostat:

- Custom made pulse tube dilution refrigerator and cryostat. Technologically challenging: ~1 ton of detectors at 10 mK and several tons at various low temperature stages
- Radio-pure material and clean assembly to achieve low background at ROI
- Independent suspension of the detector array from the dilution unit: smaller vibrational noise.

CUORE main challenges: cleaning

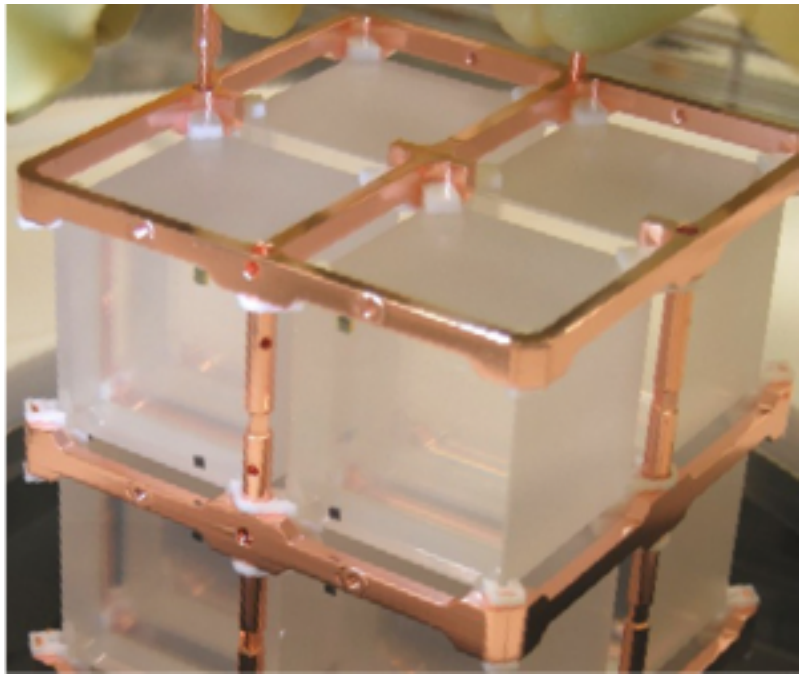
CUORE cleaning:

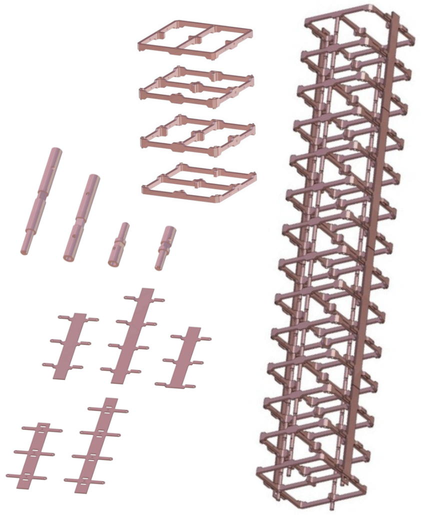
Crystals:

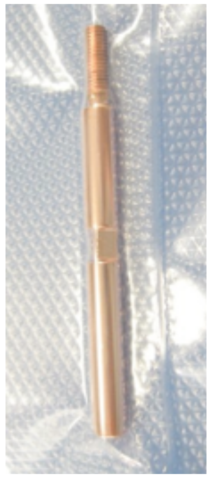
- strict radiopurity control protocol to limit bulk and surface contaminations in crystal production
- transportation at sea level to LNGS
- bolometric test to check performances and radiopurity (CCVR, Cuore Crystals Validation Run)

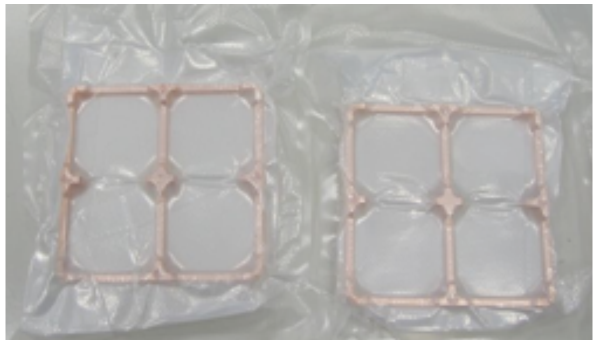
Copper:

- TECM (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) cleaning for copper surfaces
- Cleaner copper, and less of it per kg TeO_2
- Cleaner assembly environment









Goal and status of CUORE

Energy resolution @ ROI: 5 keV

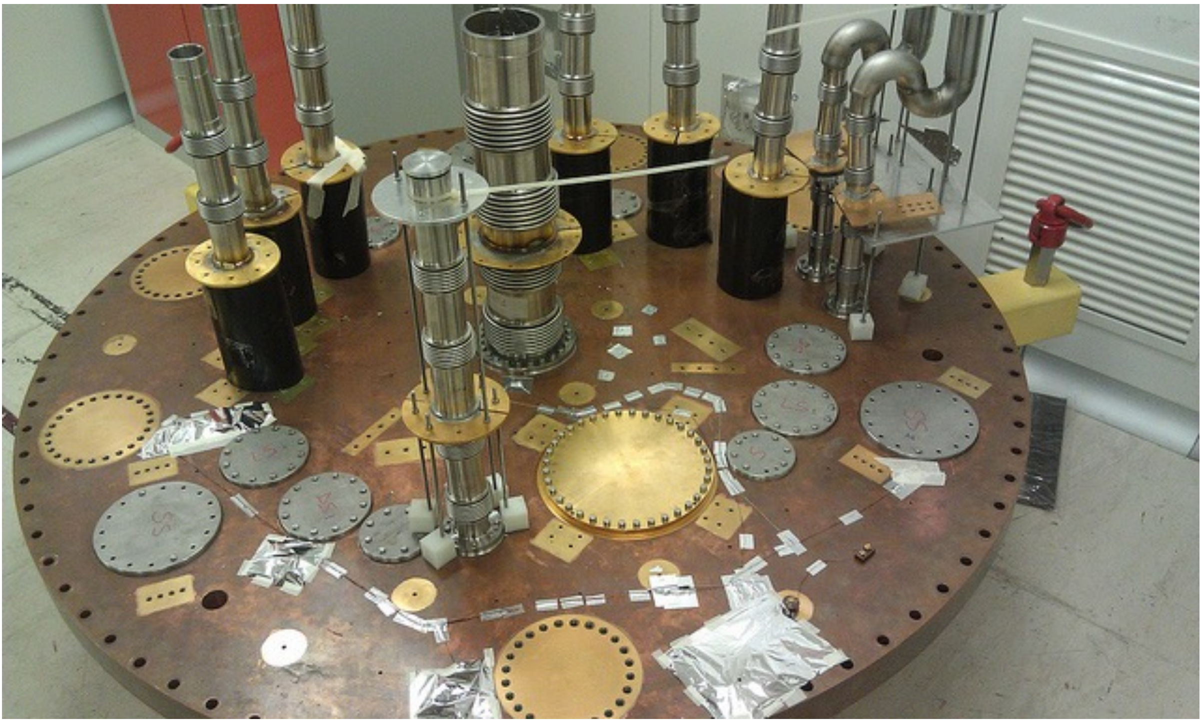
Background goal: 0.01 c/(keV kg y)

Sensitivity 90% C.L. (5 y):

$T_{1/2} = 9.5 \times 10^{25}$ y $m_{\beta\beta} = 50\text{-}130$ meV

Assembly of the 19 CUORE towers is complete.

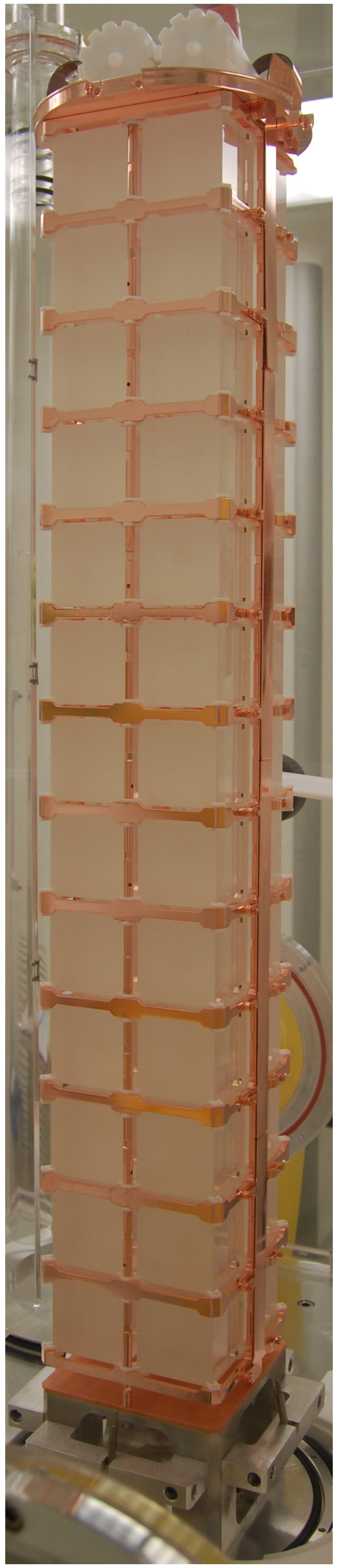
Commissioning of the cryogenic system and experimental infrastructure is in progress



Plan to start operations by end of 2015.

CUORE-0

CUORE-0: the 0-th CUORE-like tower



Single CUORE-like tower & technical prototype. Assembled from detector components manufactured, cleaned and stored following the same stringent protocols defined for CUORE.

First tower from the CUORE detector assembly line

52 TeO_2 crystals, total mass = 39 kg TeO_2 = 10.9 kg ^{130}Te

Purpose:

Commission assembly line

Run as standalone experiment while CUORE is being constructed, with aim of surpassing Cuoricino sensitivity

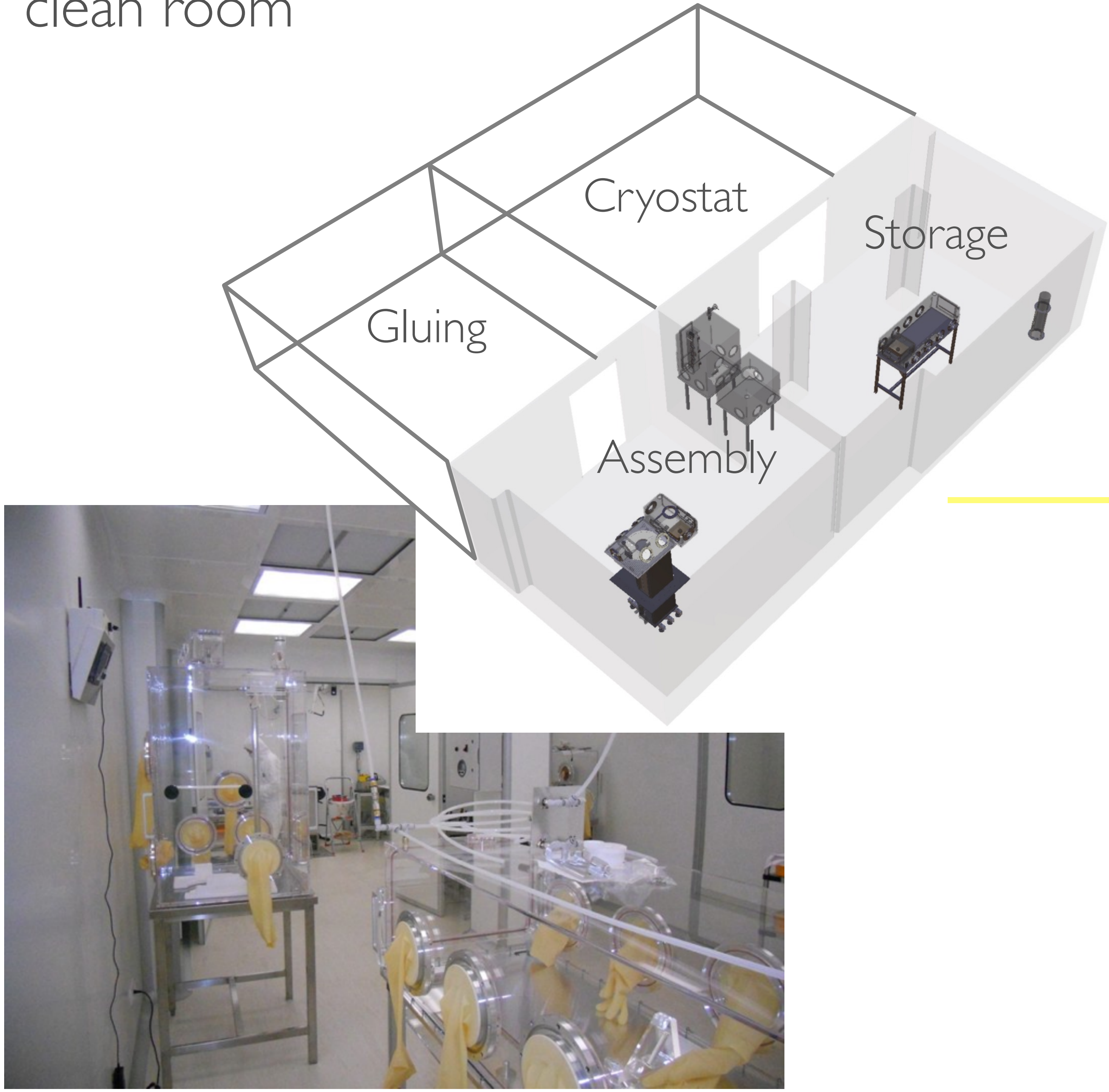
Validate CUORE detector design

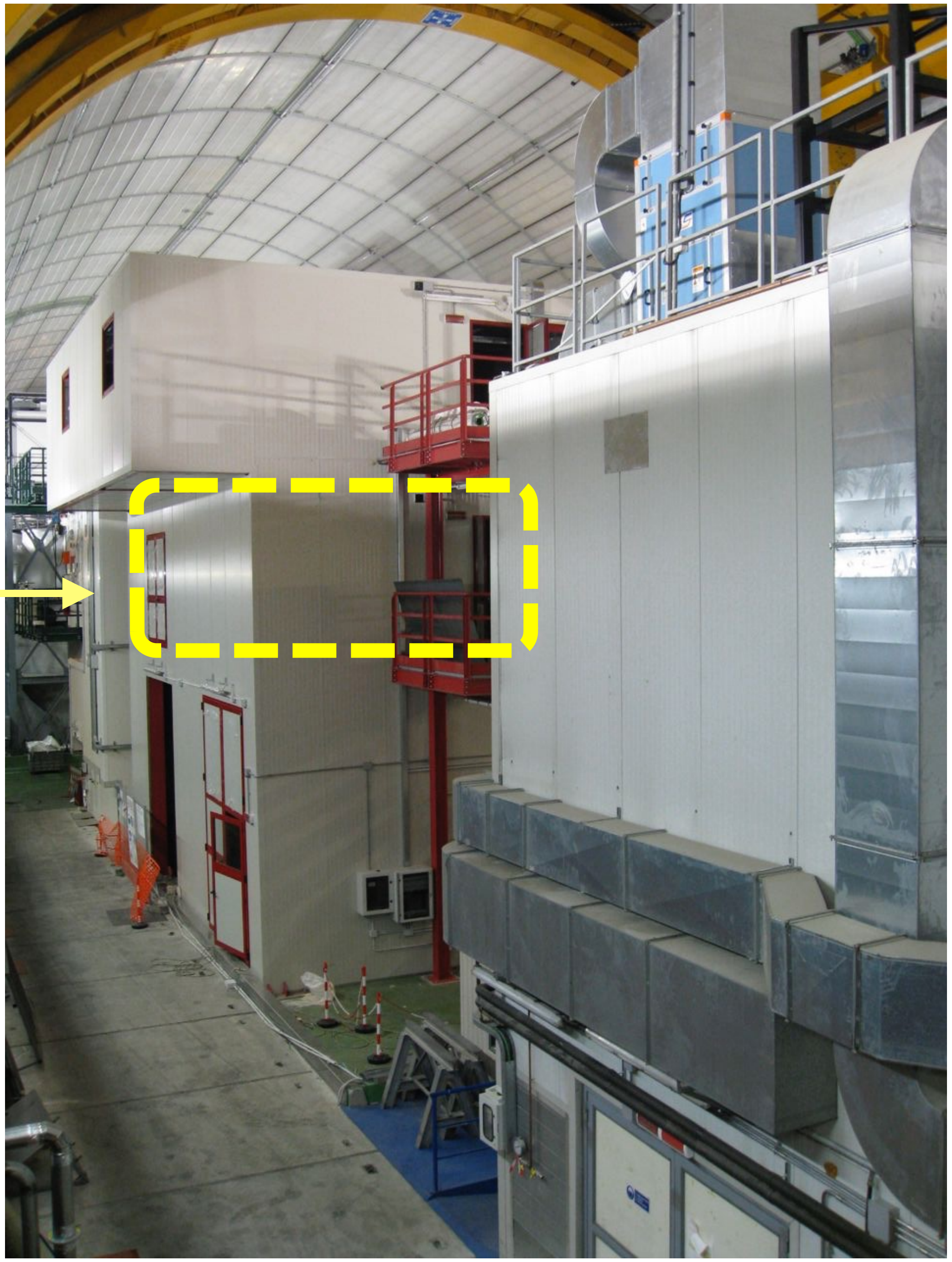
Provide test bed for developing DAQ & analysis framework

Operating in former Cuoricino cryostat since March 2013

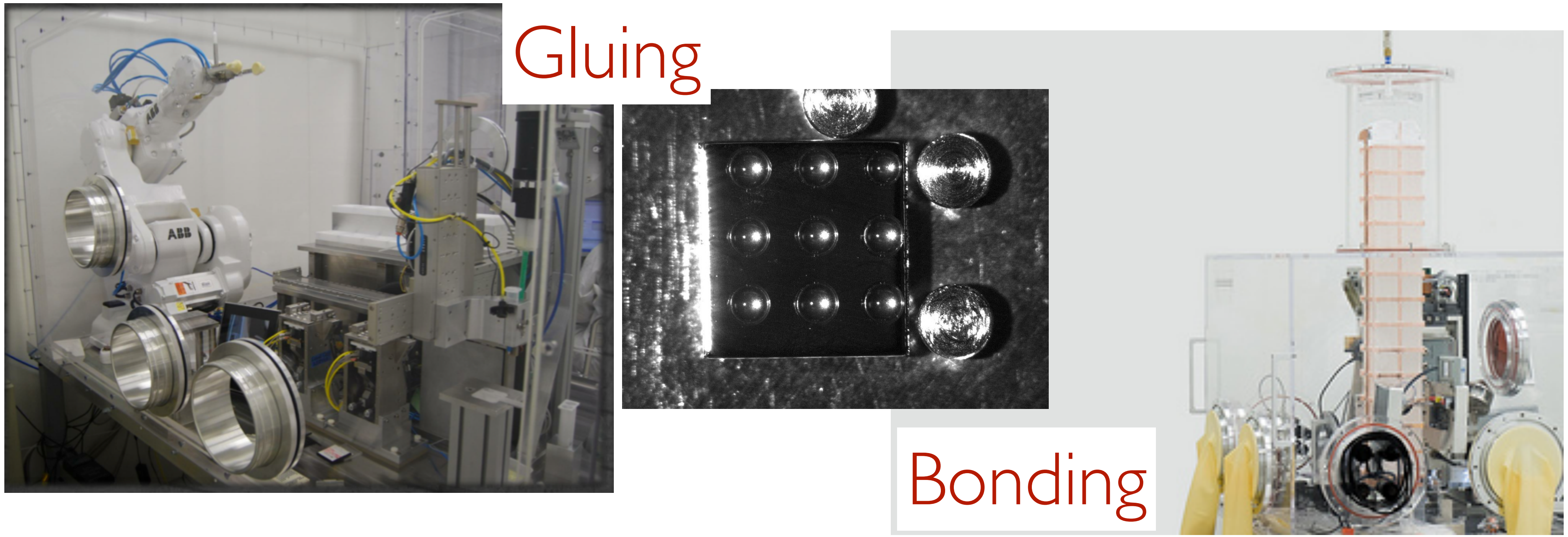
CUORE-0 assembly @ CTAL (Cuore Tower Assembly Line)

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



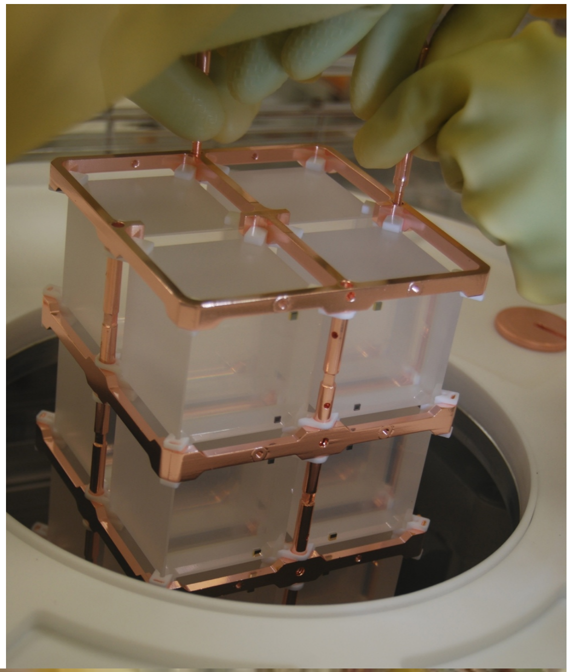


CUORE-0 assembly @ CTAL (Cuore Tower Assembly Line)

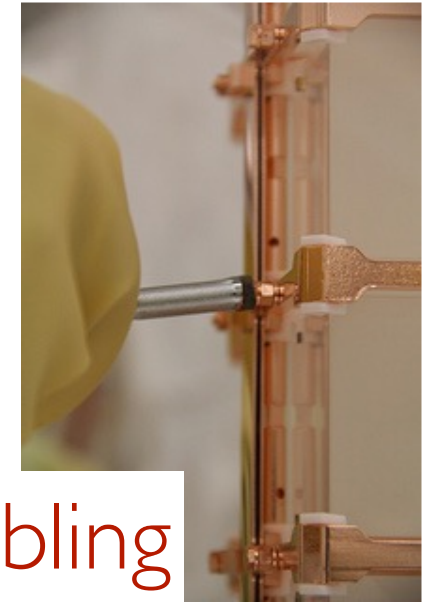


Gluing

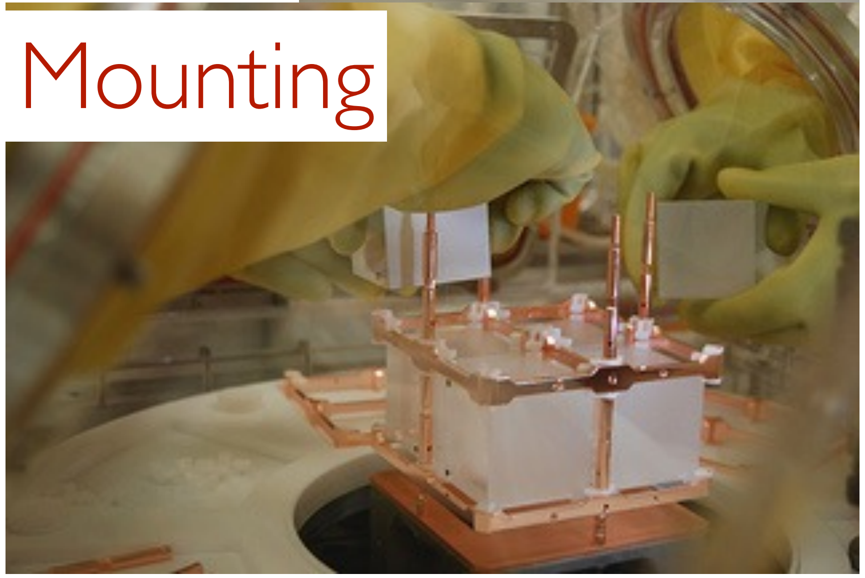
Bonding



Clean room



Cabling



Mounting

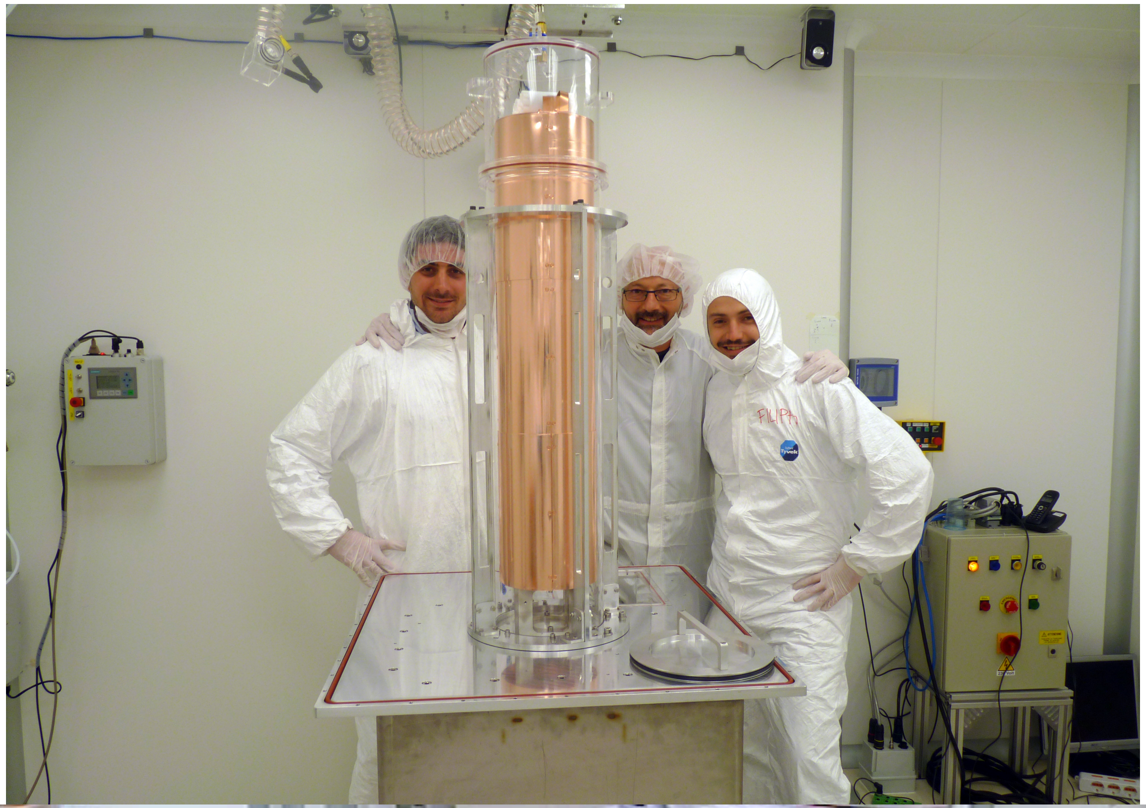
The successful operation of CUORE-0 demonstrated the validity of the CUORE tower assembly line and of the CUORE cleaning procedures.

Roma and CTAL

Silvio Morganti led the group responsible for the design, the installation and the commissioning of CTAL (Cuore Tower Assembly Line).

CUORE-0 was assembled by the CTAL group in 2012.

The 19 CUORE towers were assembled by TCS technicians lead by Marco Iannone.



CUORE-0

51/52 NTD connected

51/52 heaters connected

CUORE

988/988 NTD connected

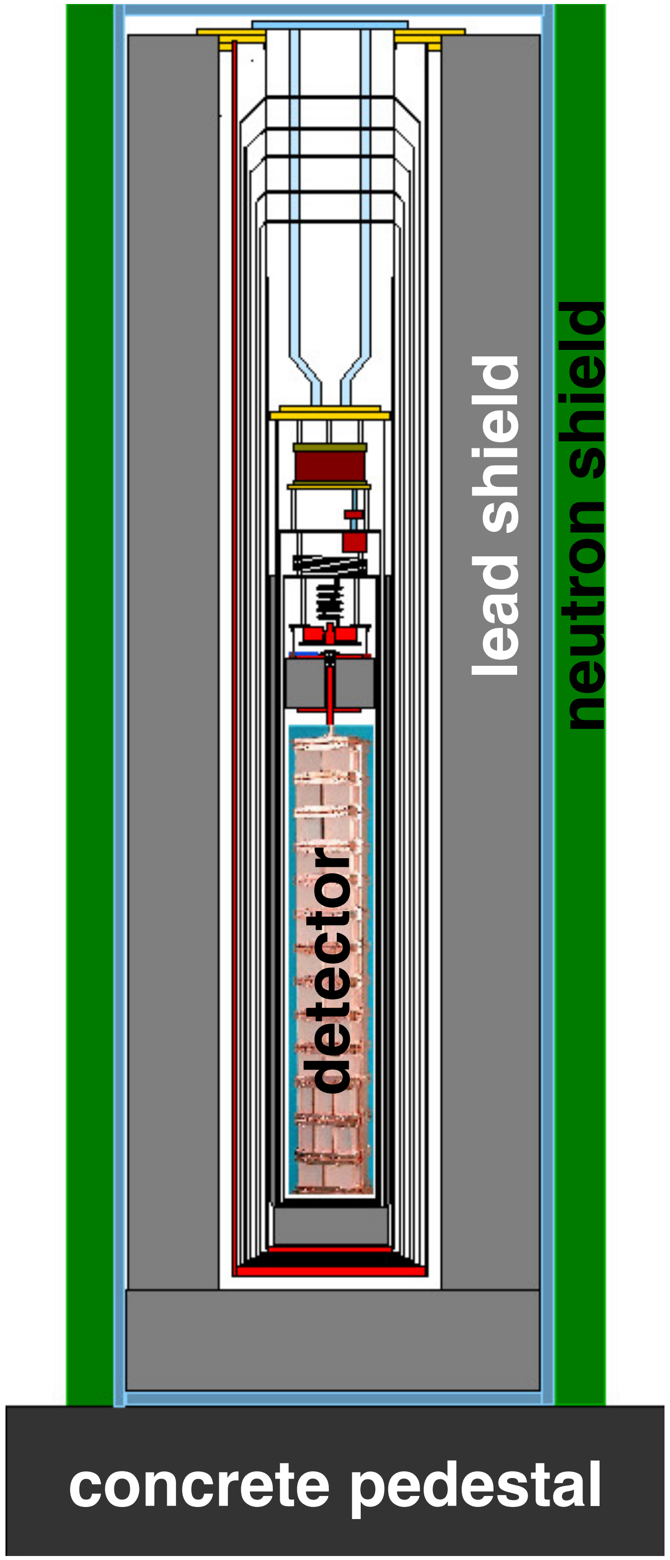
988/988 heaters connected

CUORE-0 shielding

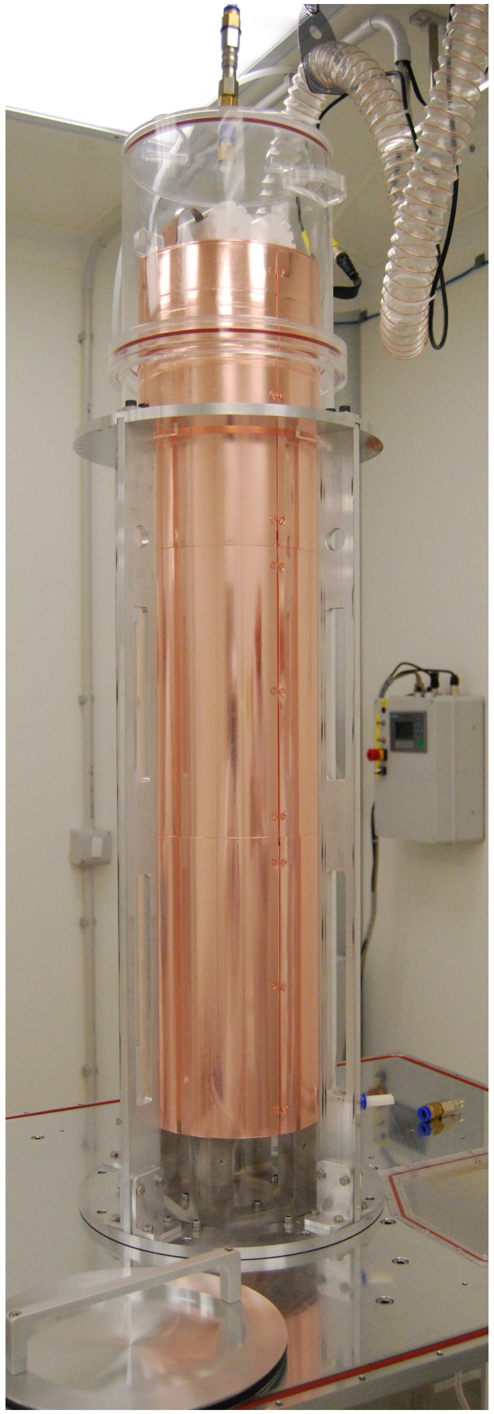
Same (old) cryostat as Cuoricino:

- 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

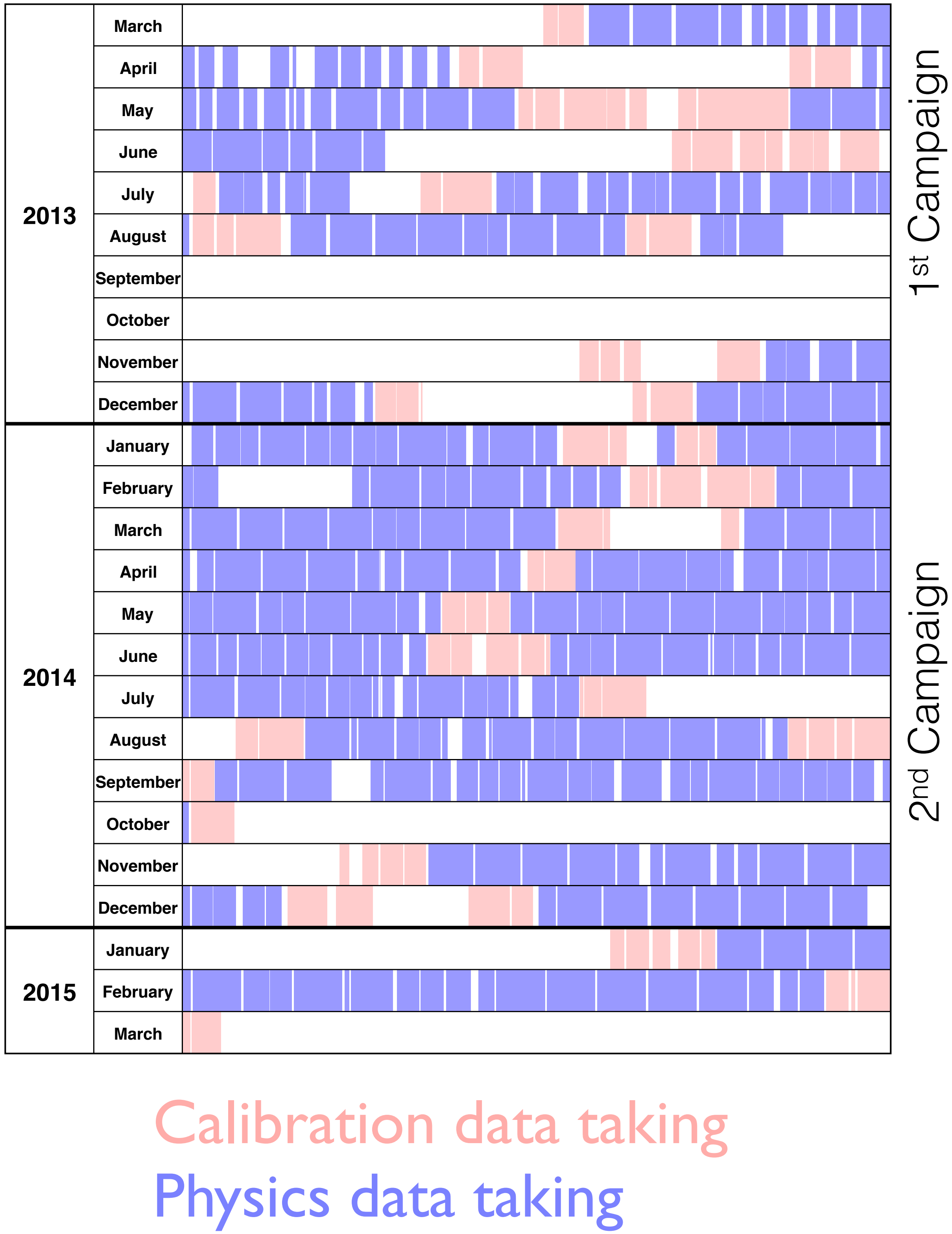
Gamma backgrounds not expected to change compared to Cuoricino, except for the improved radon control.



CUORE-0 installation



CUORE-0 data taking



Detector assembled in Spring 2012.

First successful cooldown in March 2013.

One heater connection lost during the cooldown

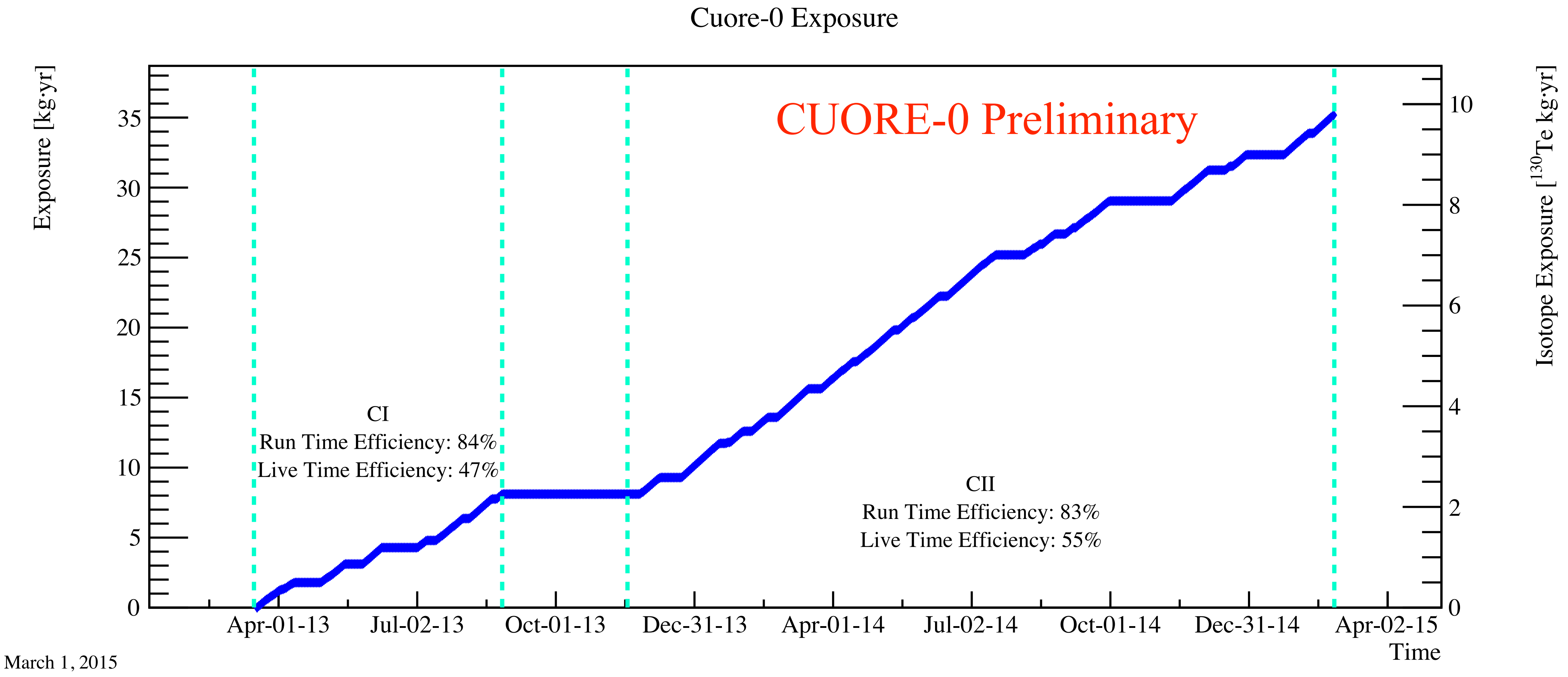
51/52 NTD connected

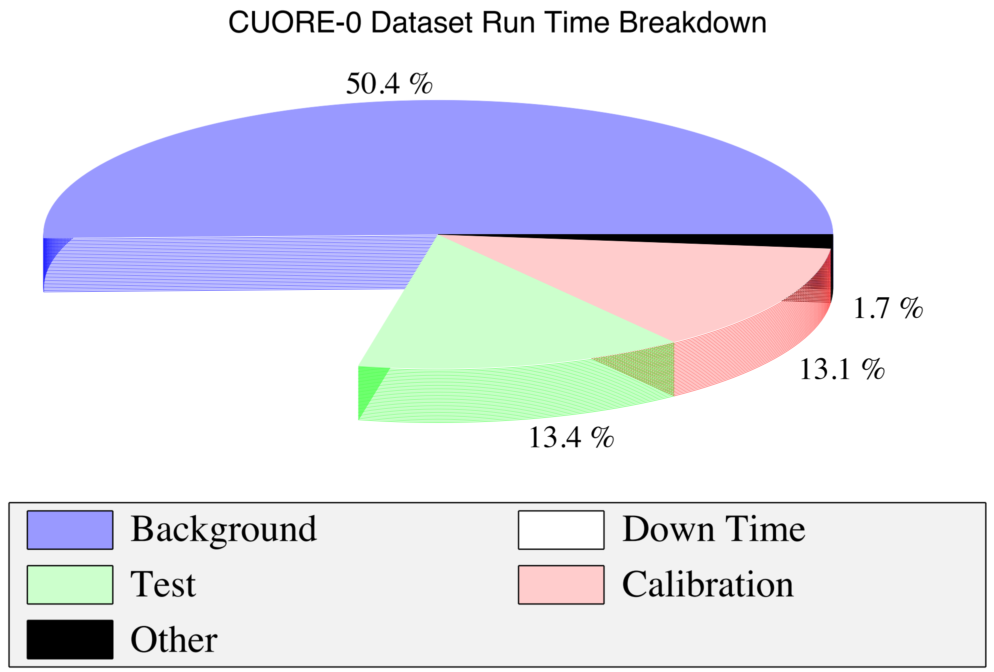
50/52 heater connected

2-3 days per months are devoted to ^{232}Th calibrations

Time between calibrations was devoted to physics data taking, and used for 0νDBD decay search

CUORE-0 exposure


Cuore-0 Exposure


CUORE-0 Dataset Run Time Breakdown

CUORE-0 analysis

Analysis chain: from raw pulses to final spectrum

- Acquisition of triggered pulses
- Preprocessing (baseline, rise and decay time estimation)
- Pulse Optimal Filtering (pulse amplitude estimation)
- Thermal Gain Stabilization (TGS)
  (correct for thermal gain instabilities)
- Energy calibration
- Event selection
- Energy spectrum
- Blinded energy spectrum

The Roma group was deeply involved in the CUORE-0 computing, software design and data analysis.

Marco Vignati, software coordinator (2008 -) and Physics Board member (2012 - 2014)

Fabio Bellini, responsible for the Cuore-0 computing cluster in Roma

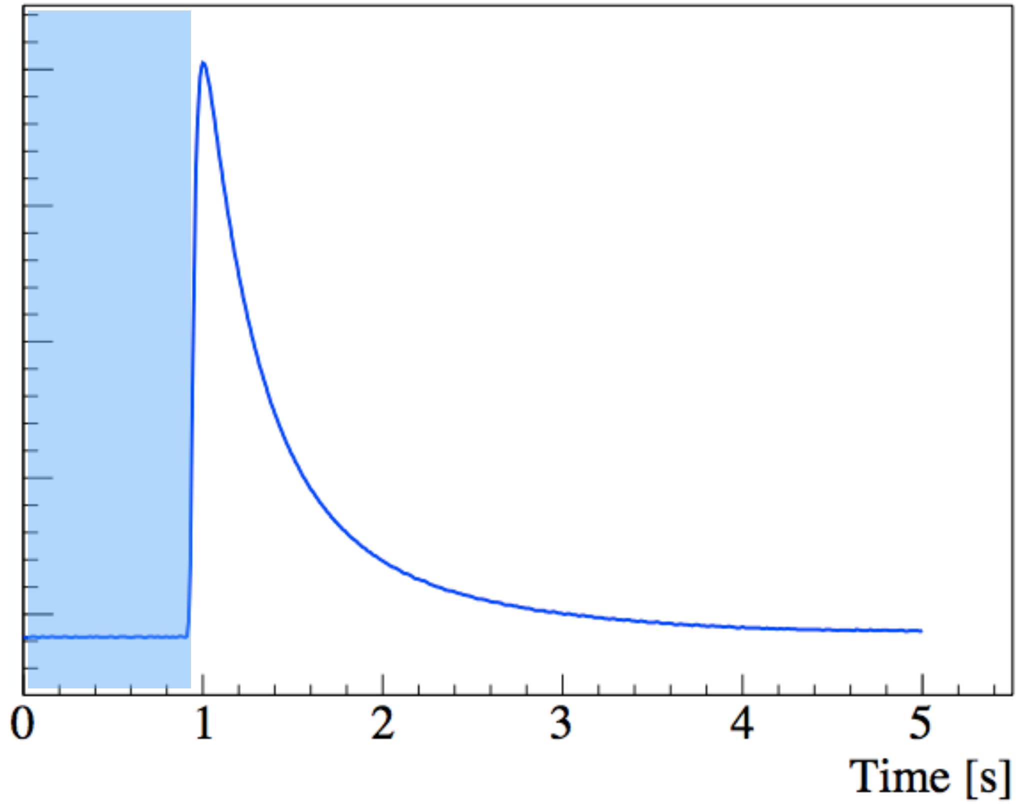
Claudia Tomei Physics Board member (2014 -)

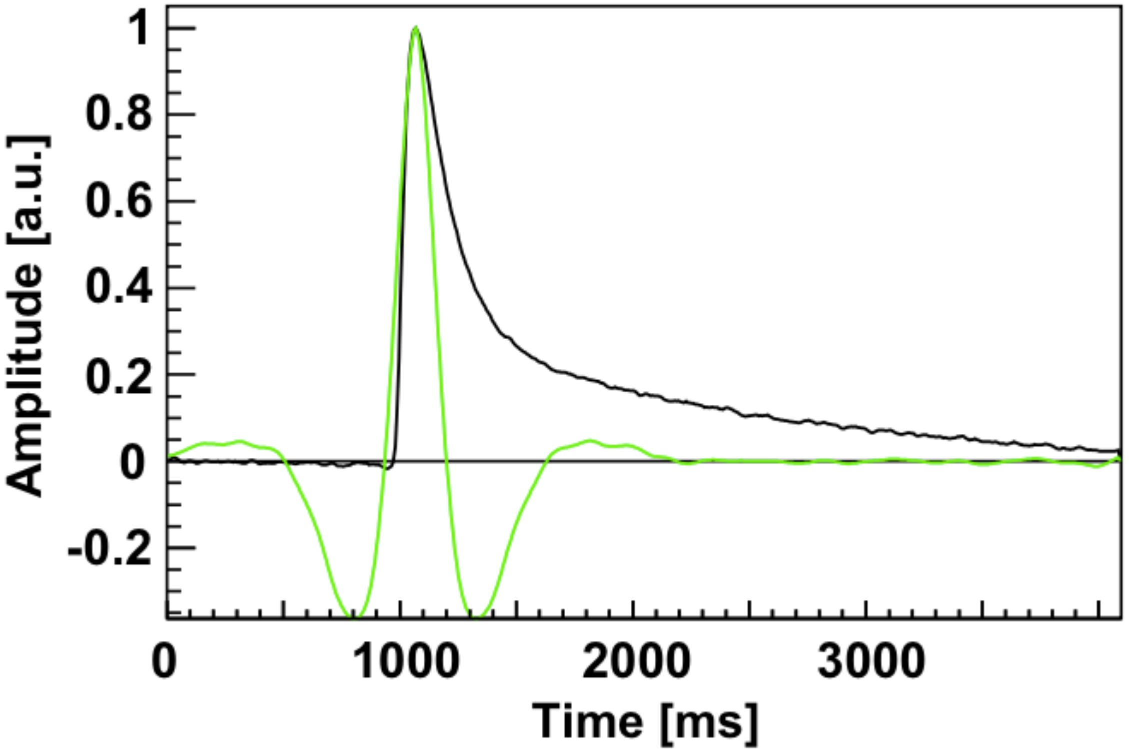
CUORE-0 analysis

Each thermistor voltage is continuously sampled at 125Hz.

A derivative trigger is used to acquire pulses above threshold. Once triggered, a 5 sec window is saved on disk.

The pre trigger voltage is a good proxy for the bolometer temperature before the event





Pulse amplitude estimation

Optimal Filter: we require that the waveform is consistent with an average reference waveform template. Optimises energy resolution by exploiting differences in the frequency characteristic of signal and noise events.

Decorrelated Optimal Filter: reduces the correlated noise between adjacent crystals in the array.

New technique developed for CUORE-0 analysis

CUORE-0 analysis

Thermal gain stabilisation (TGS)

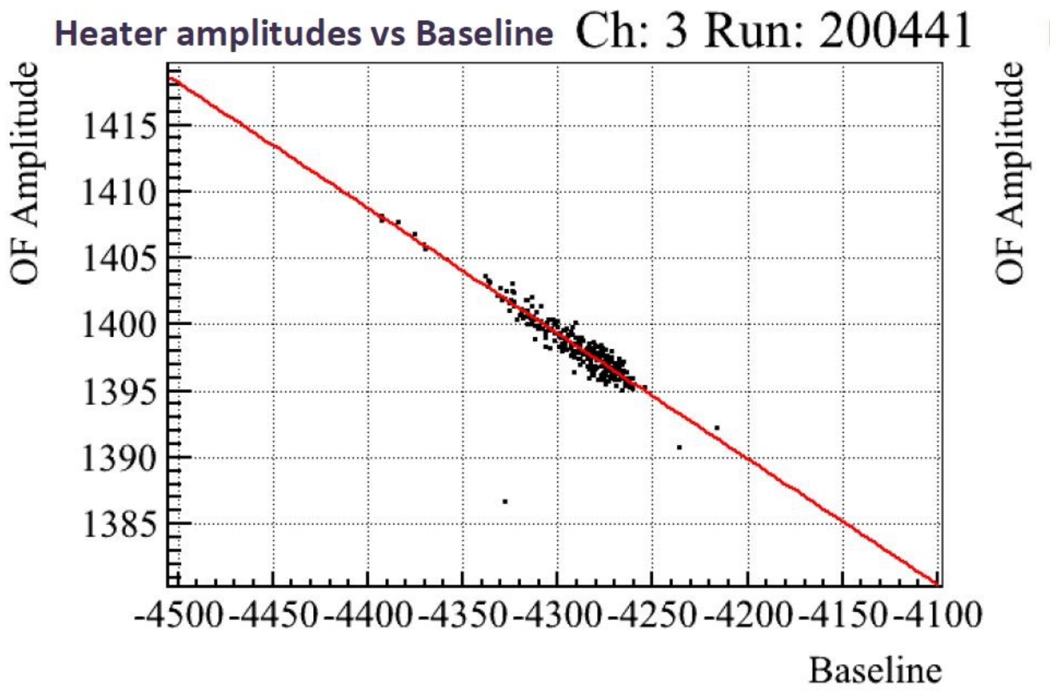
TGS is used to correct the filtered pulse amplitude for small changes in the energy-to-amplitude response of the bolometer:

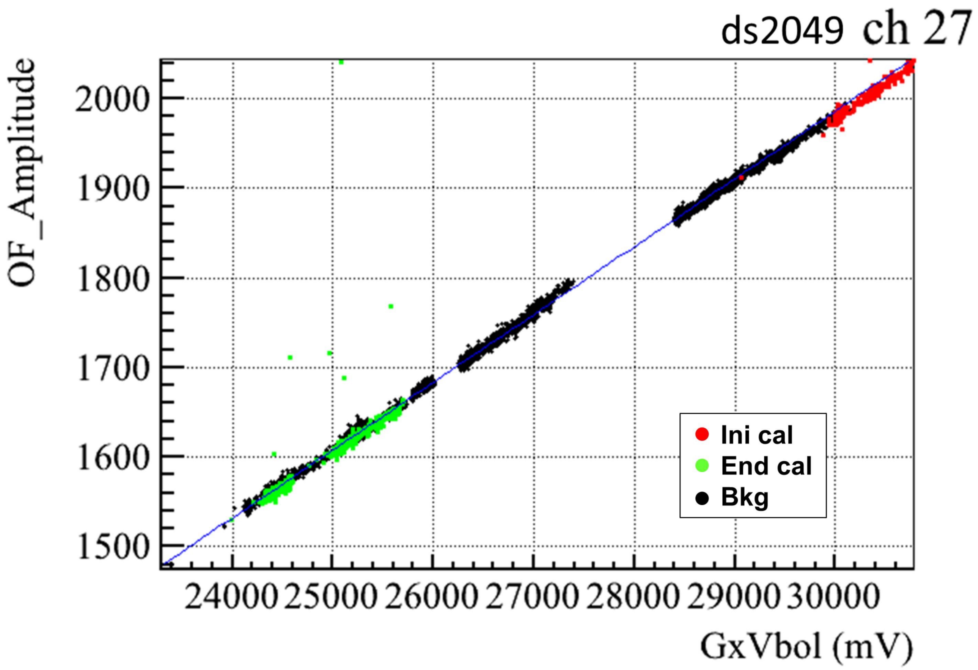
heater-TGS: uses as input the mono-energetic heater pulse

calibration-TGS: uses the 2.6 MeV line from calibration runs, to correct for the electronic parameters that can affect the bolometers response (drift in amplifier gain or DC offset).

New technique developed for CUORE-0 analysis.

We were able to recover the two channels without active heater.



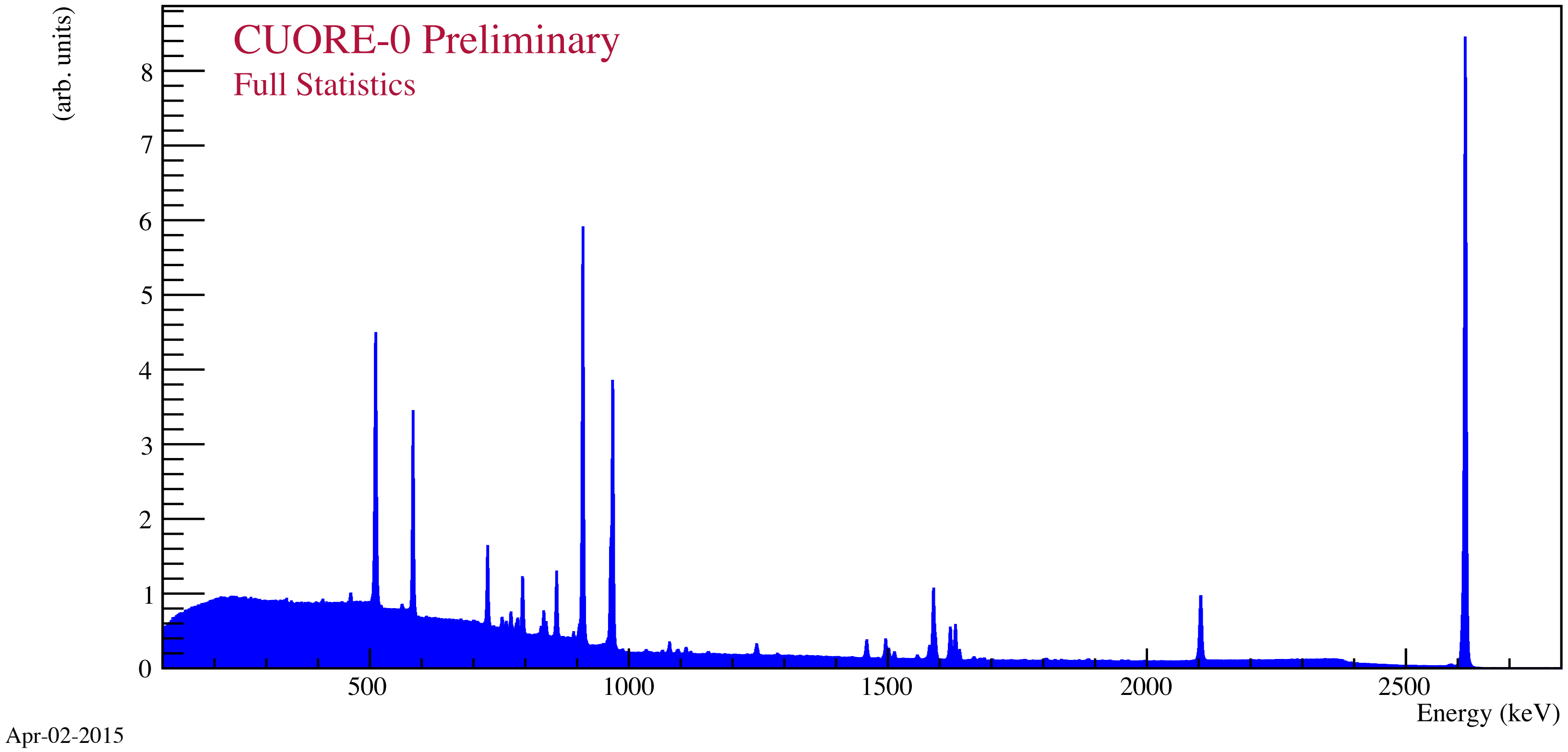


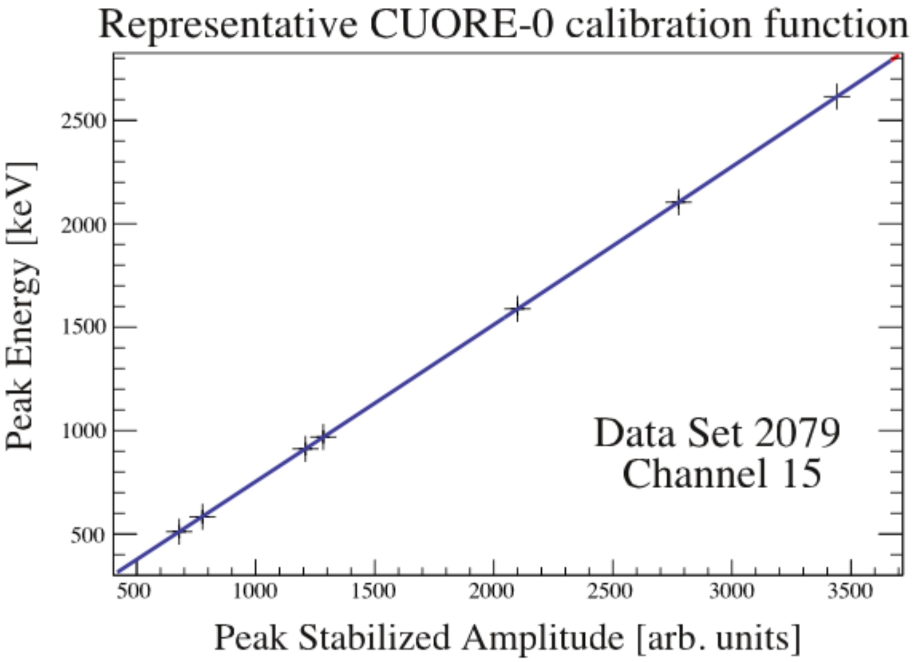
For each channel and dataset we can have up to 4 stabilised amplitudes

CUORE-0 analysis

Energy calibration

We calibrate the detector using two thoriated tungsten wires source placed in between the outermost cryostat shield and the external lead shield.





quadratic function with zero intercept

Coincidence calculation

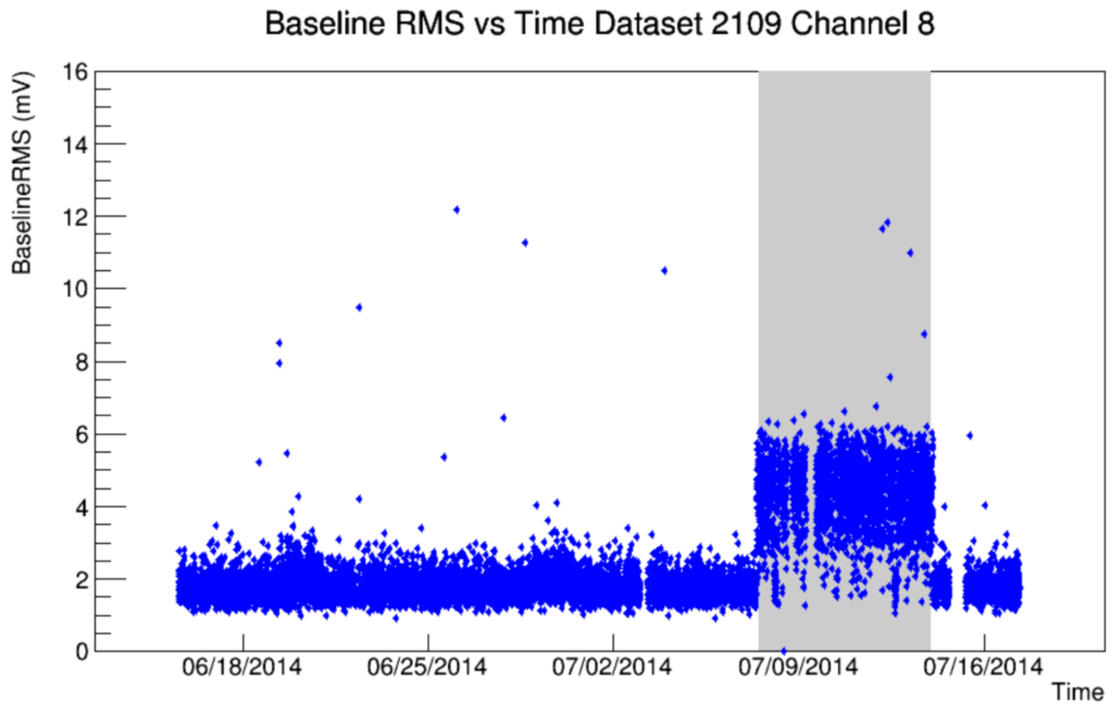
Search for coincident events in more than one crystal within ± 5 ms.

New method to synchronise the time response among different bolometers to reduce the coincidence window (100 ms).

CUORE-0 event selection

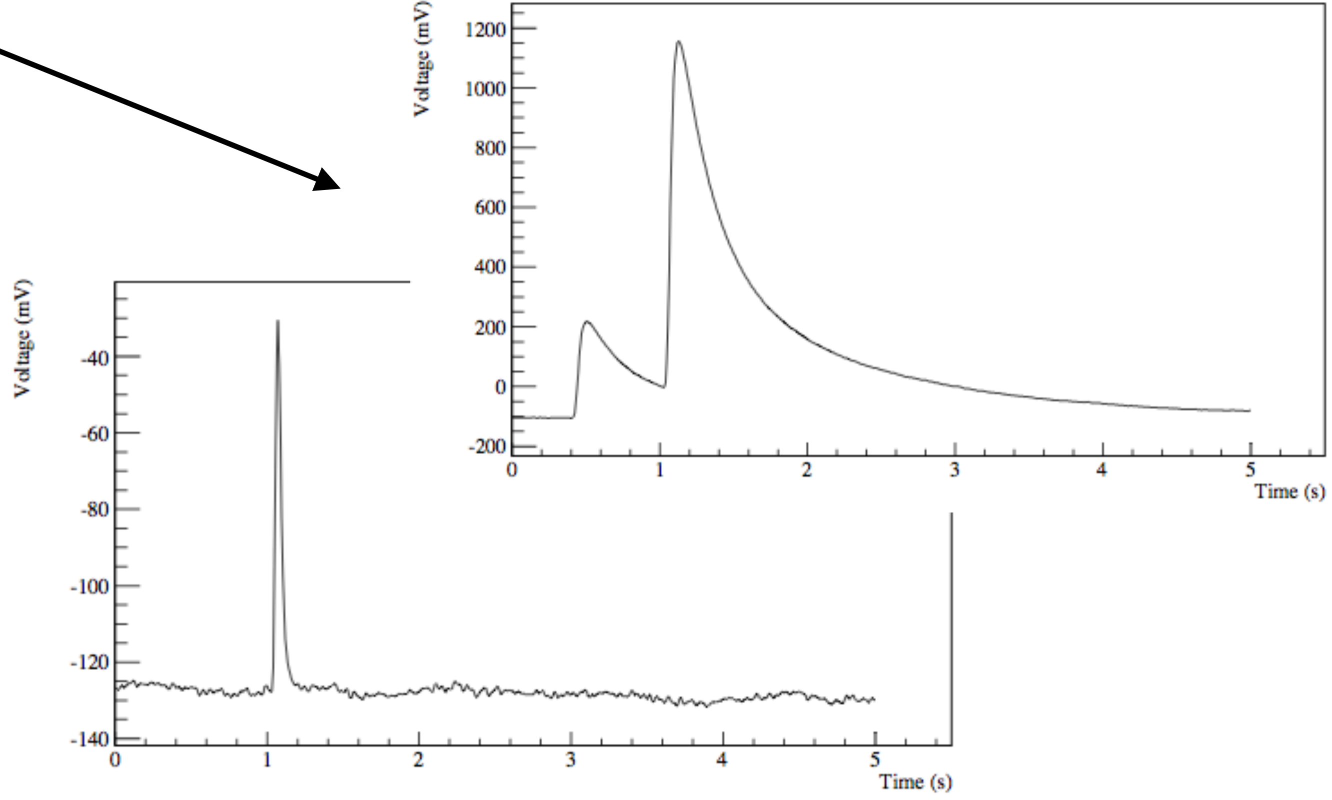
Data quality

Reject periods of low data quality (periods of cryostat instability or known equipment malfunction). Reduce total exposure of 7% .

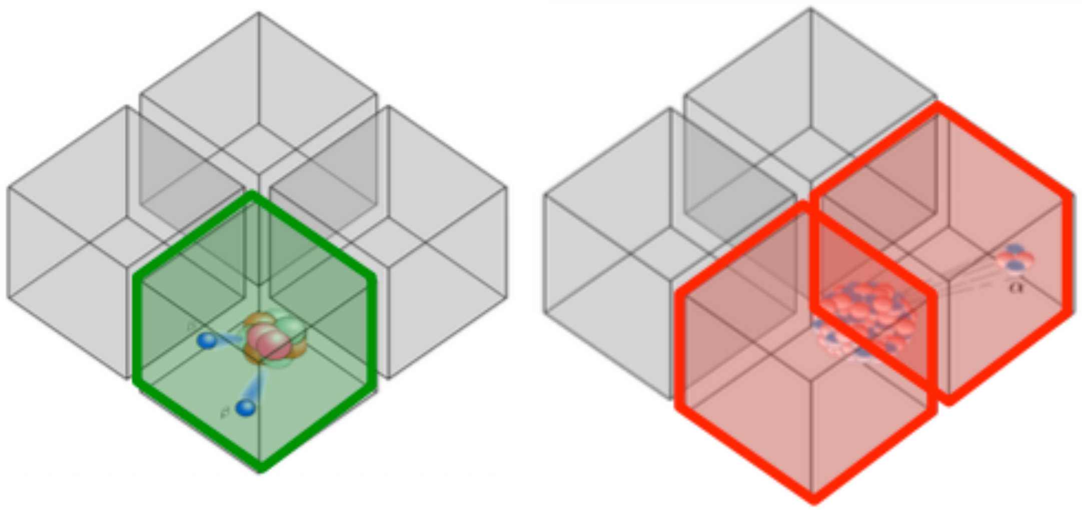


Pulse Shape parameters

Six pulse-shape parameters characterise the waveforms and the criteria for acceptance are tuned simultaneously on a set of prominent peaks in the physics data



Anticoincidence Exclude multi-site events



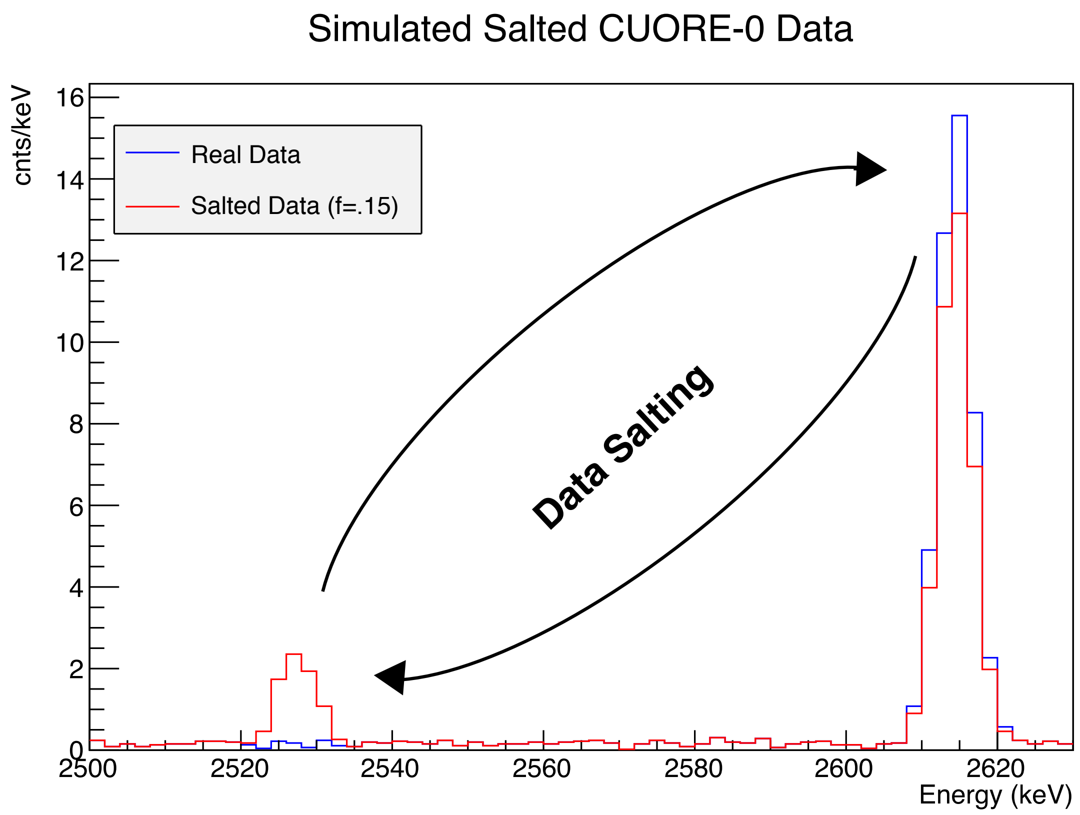
CUORE-0 global selection efficiency

	efficiency [%]	error [%]
Trigger	98.529	0.004
Pile-up and PSA	93.7	0.7
Event containment	88.4	0.09
Accidental coincidence	99.64	0.10

from GEANT4 simulations

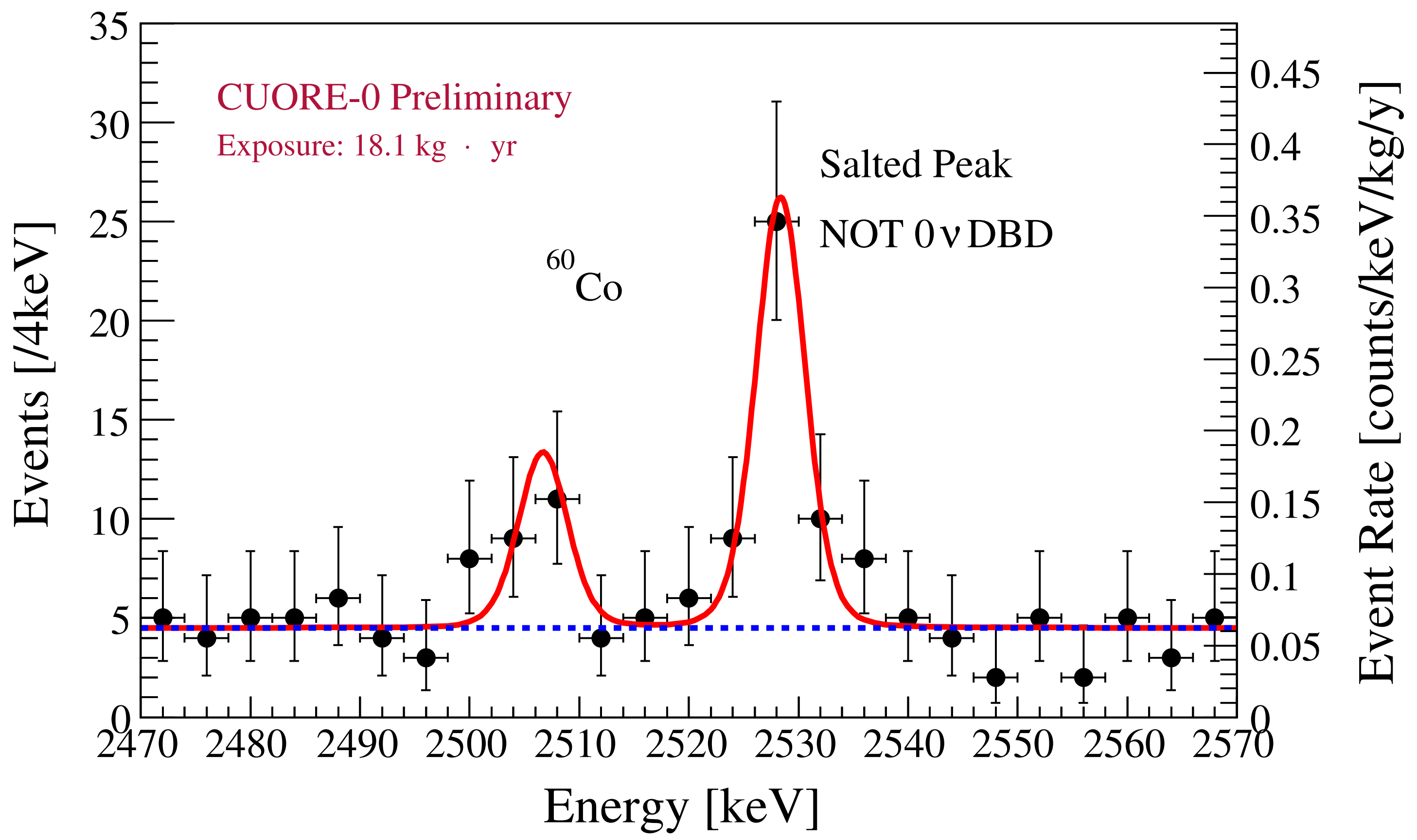
The total selection efficiency is: (81.3 ± 0.6)%

CUORE-0 blinding

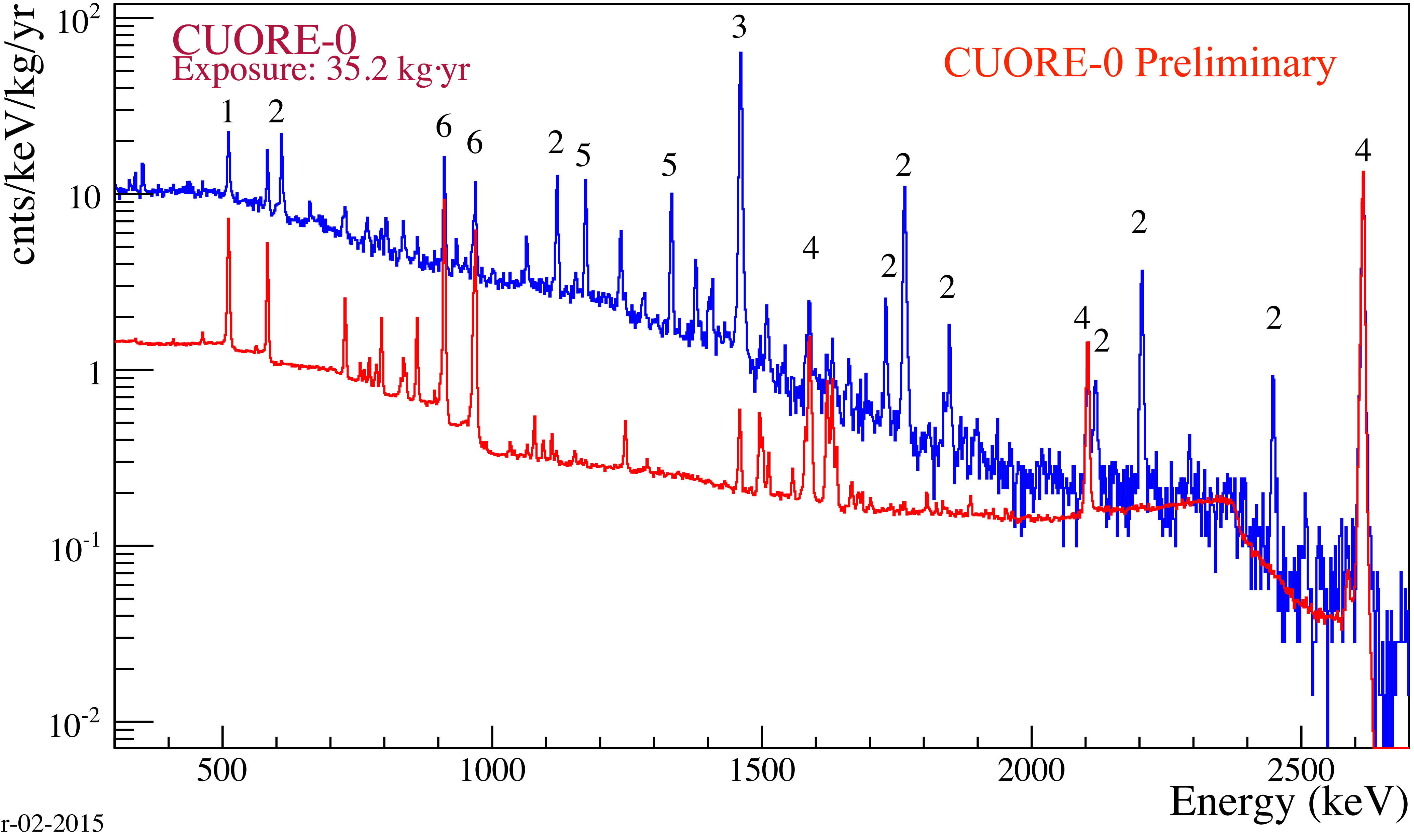


This methodology preserves the integrity of the possible 0νDBD events while maintaining the spectral characteristics with measured energy resolution and introducing no discontinuities in the spectrum.

To blind our data we randomly exchange a blinded fraction of events from the 2615 keV peak with events within ±10 keV of the 0νDBD Q-value, creating an artificial unlikely large peak around the 0νDBD Q-value that blinds the real rate.

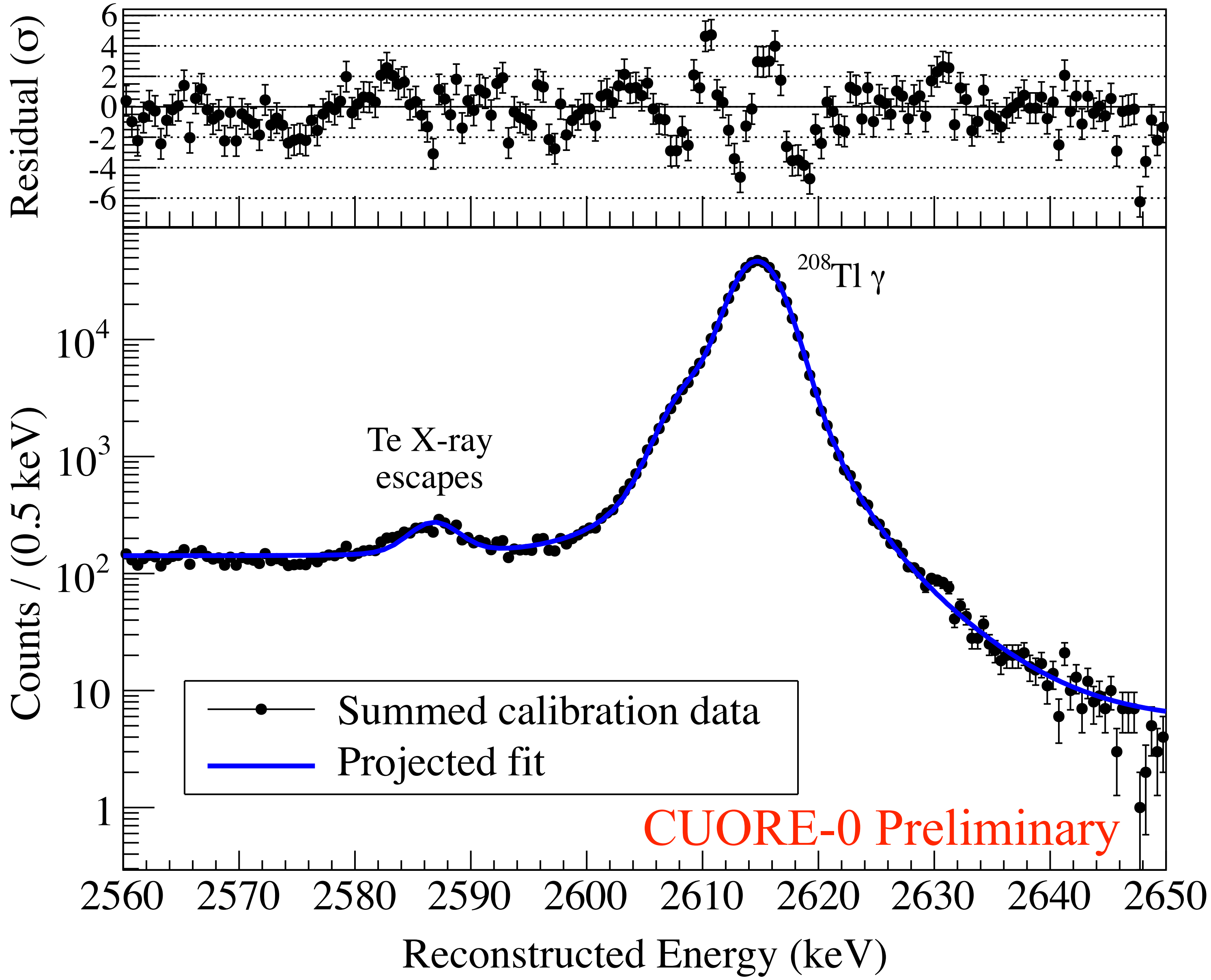


CUORE-0 full spectrum



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

CUORE-0 line shape study



Double gaussian lineshape for each bolometer and dataset (b,d)

common gaussian width of both peaks

ratio of the means of the secondary and primary peaks

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

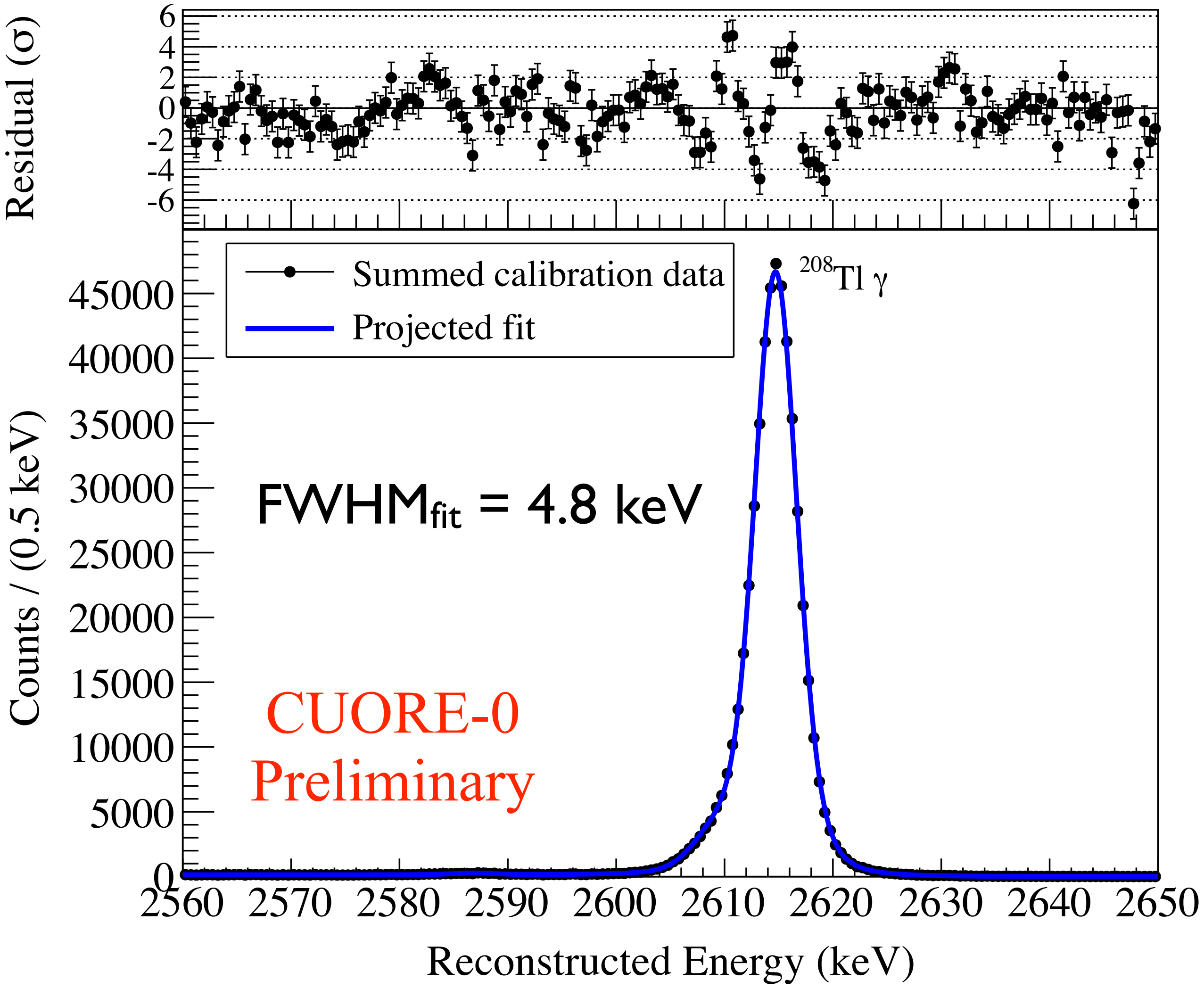
mean of the primary peak

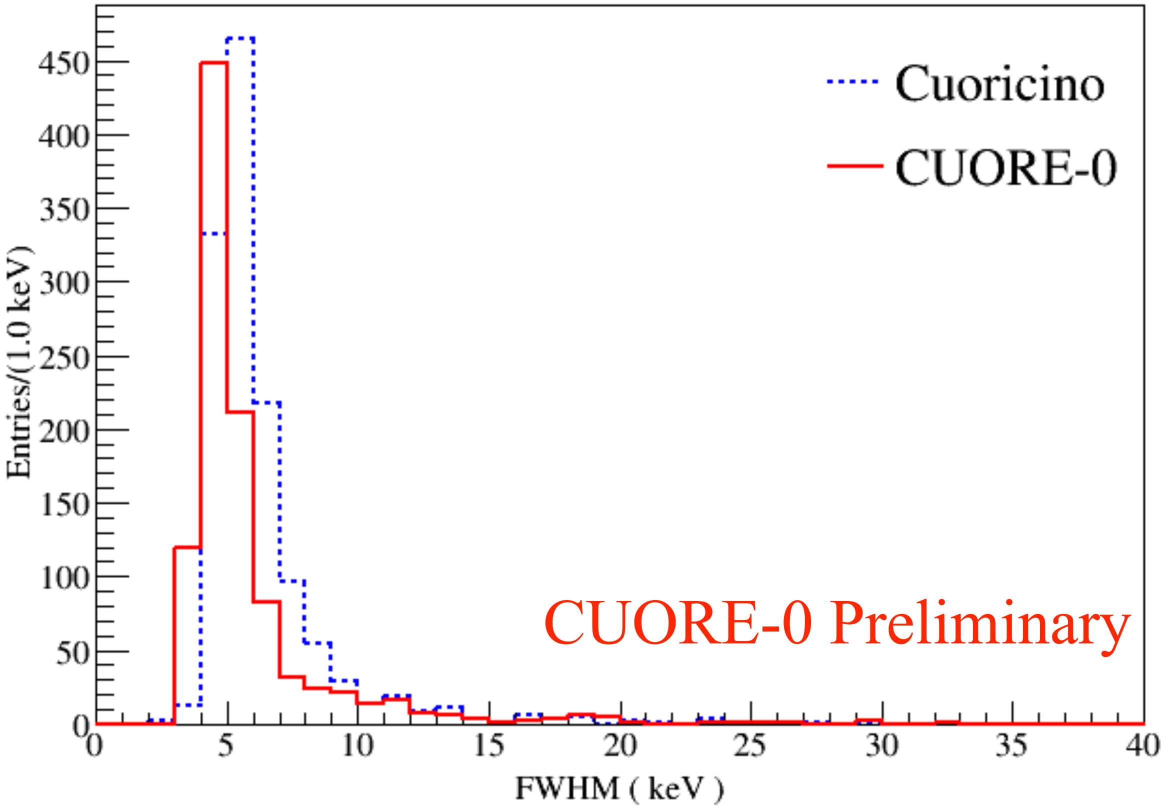
fractional intensity of the secondary peak

We estimate these parameter values with a simultaneous, unbinned extended maximum likelihood (UEML) fit to calibration data.

The same line shape has been used for the study of calibration uncertainty and for the ROI peaks in the fitting procedure.

CUORE-0 energy resolution



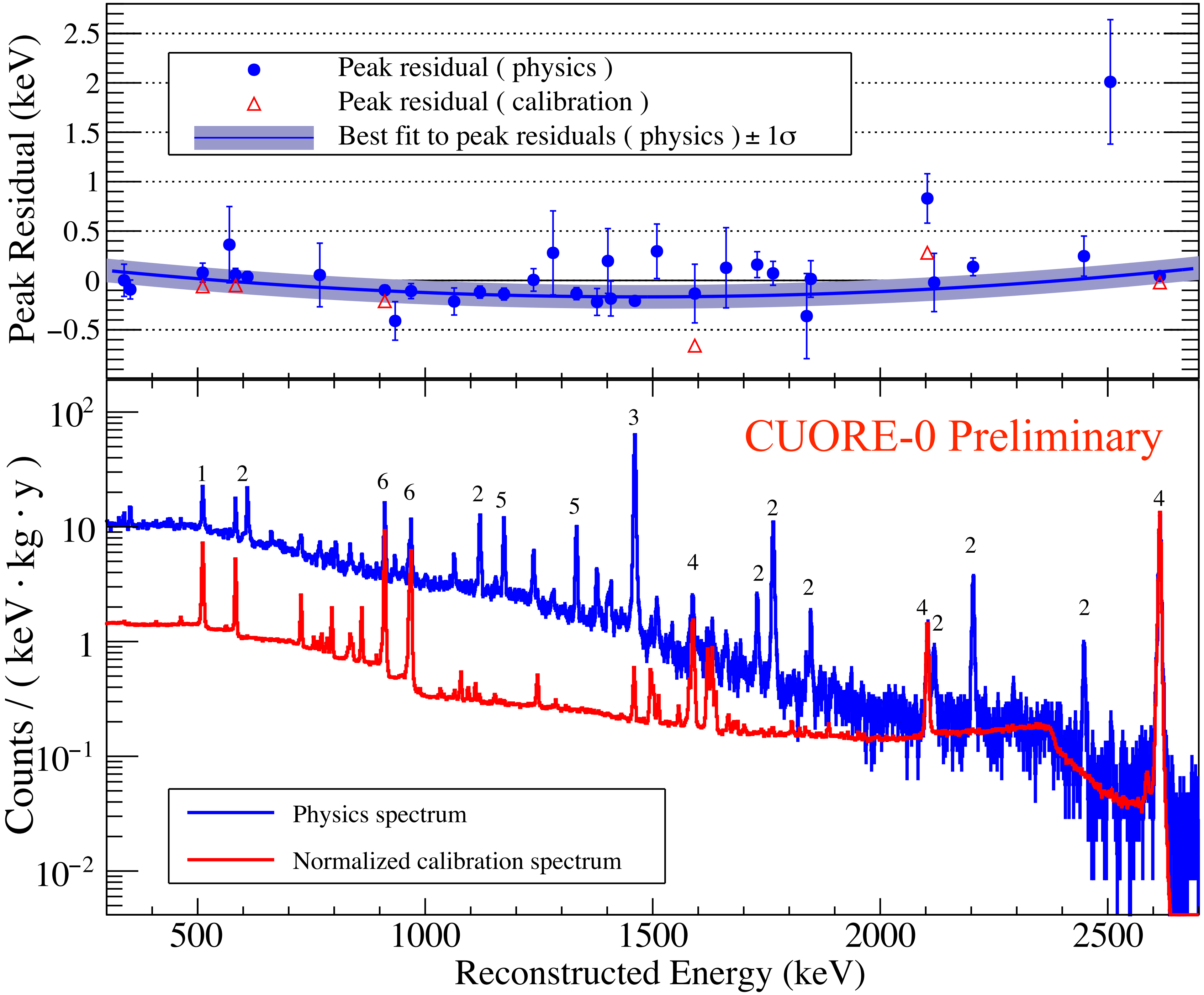


The 5 keV CUORE goal has been reached

Physics-exposure-weighted harmonic mean

	Average FWHM [keV]	RMS of FWHM [keV]
Cuoricino	5.8	2.1
CUORE-0	5.1	2.9

CUORE-0 calibration uncertainty and residuals



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)

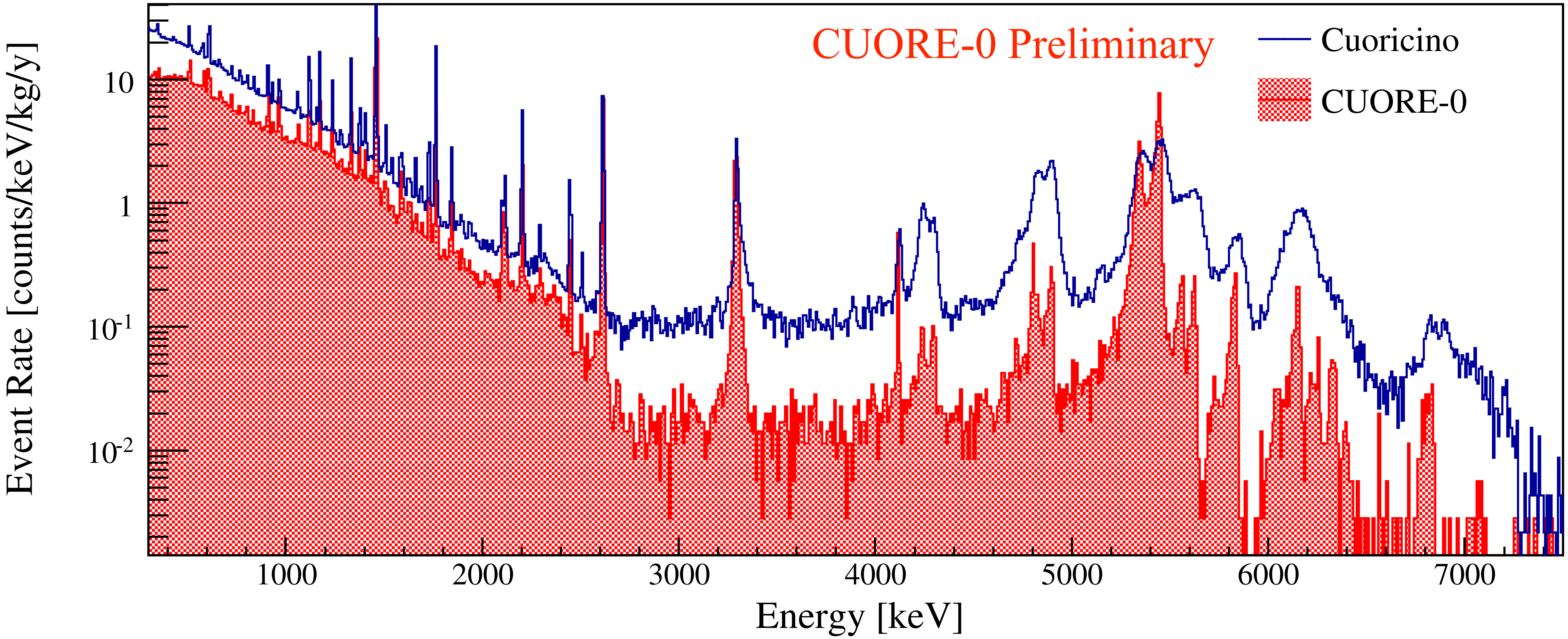
δ (b,d) are varied relative to the ones calculated from calibration data by the ratio of E to 2615 keV

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

CUORE-0 background

Background in ROI is due to degraded α particles from contamination on copper and crystal surfaces and compton-scattered γs from ^{208}Tl in cryostat and frames

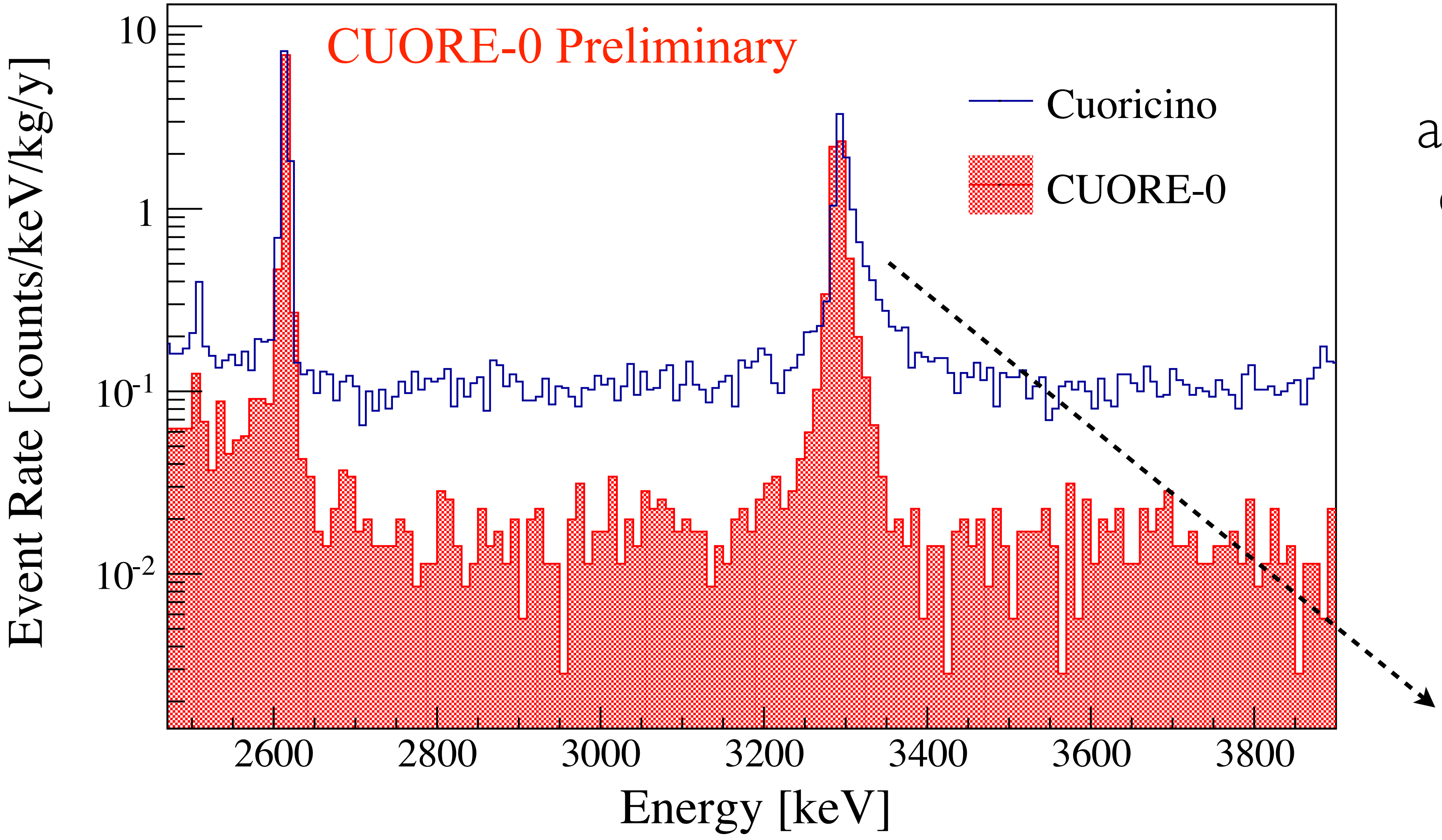


gamma lines from ^{238}U decay chain reduced by a factor 2 (better radon control)

gamma lines from ^{232}Th decay chain not reduced (same cryostat of CUORICINO)

alphas from ^{238}U/^{232}Th decay chain reduced (surface treatment)

CUORE-0 alpha background reduction



The background in the alpha-dominated region is evaluated in the interval (2700-3900) keV

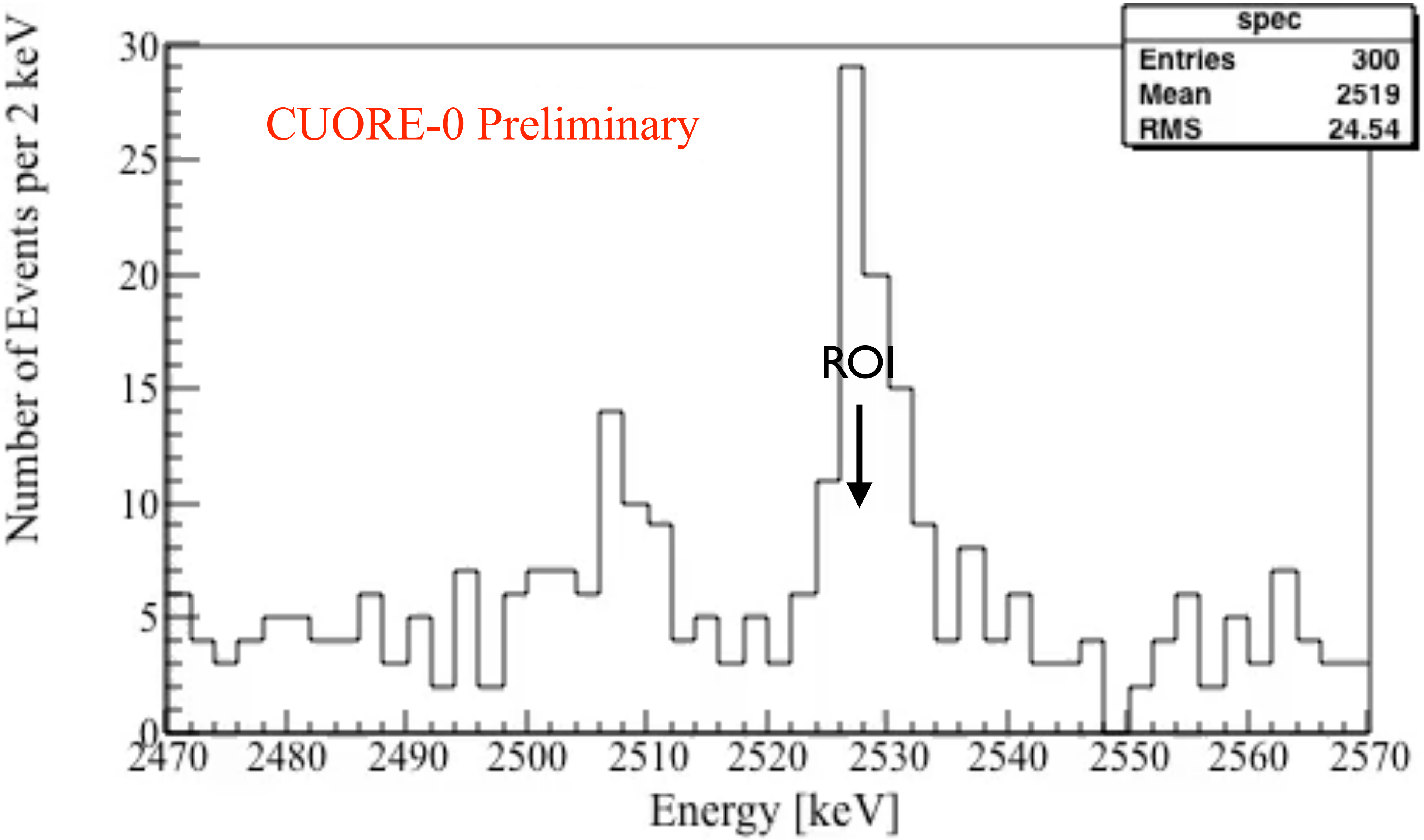
We obtain a factor 6 reduction in the alpha continuum region

^{190}Pt alpha peak, due to platinum inclusions from the crucible used to grow crystals

	2.7-3.9 MeV	eff [%]
CUORE-0	0.016 ± 0.001	81 ± 1
Cuoricino	0.110 ± 0.001	83 ± 1

CUORE-0 unblinding

We unblinded our data at the end of February 2015, once we surpassed the Cuoricino equivalent sensitivity.



Fit in the ROI

We determined the yield of 0νDBD 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

both peaks are modelled using the established line shape

- a smooth continuum background, attributed to multi scattered Compton events from ^{208}Tl and surface alpha events

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

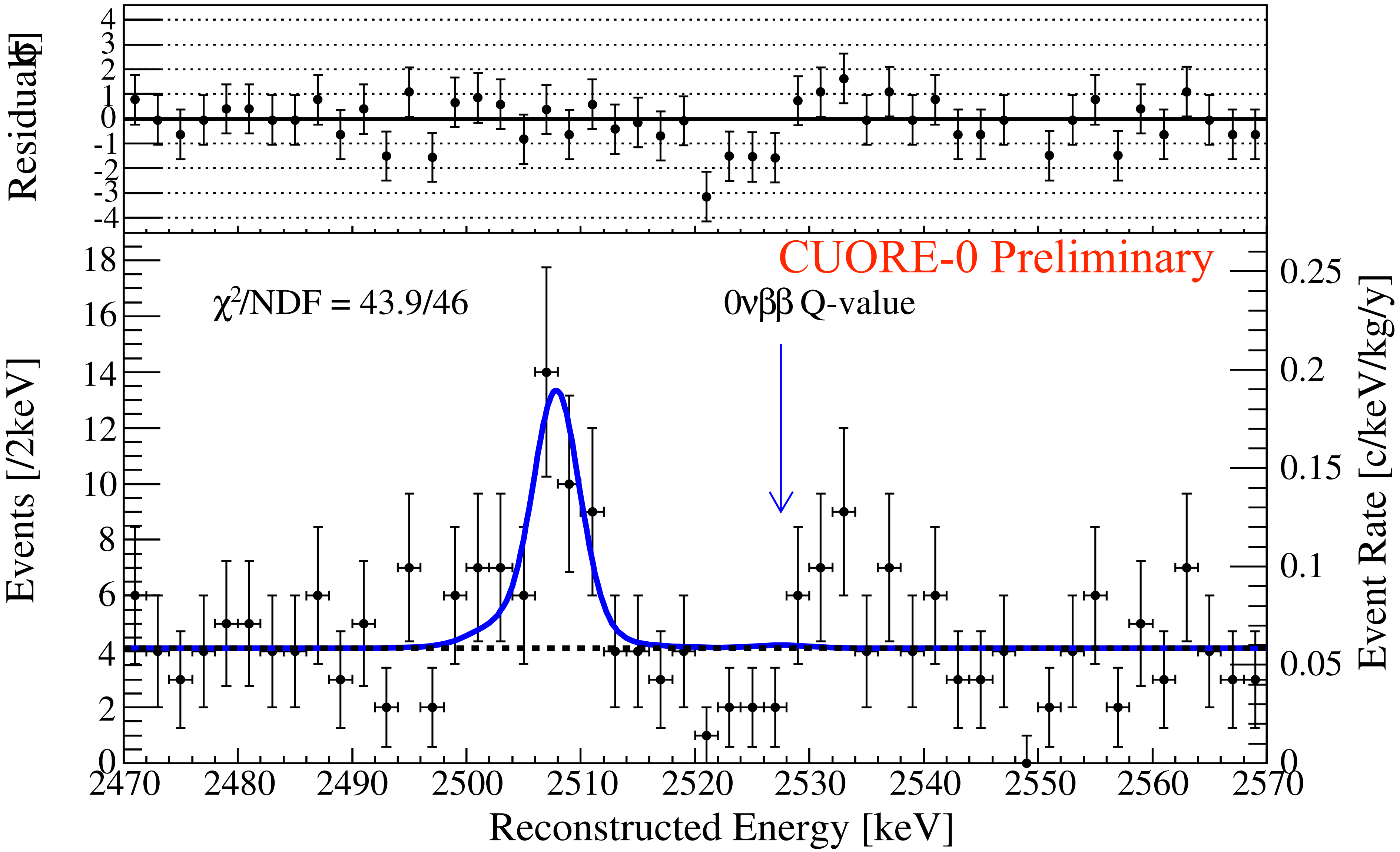
$\Delta\mu\ (Q_{\beta\beta})= 0.05\pm 0.05$ (stat) ± 0.12 (syst)

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

CUORE-0 limit



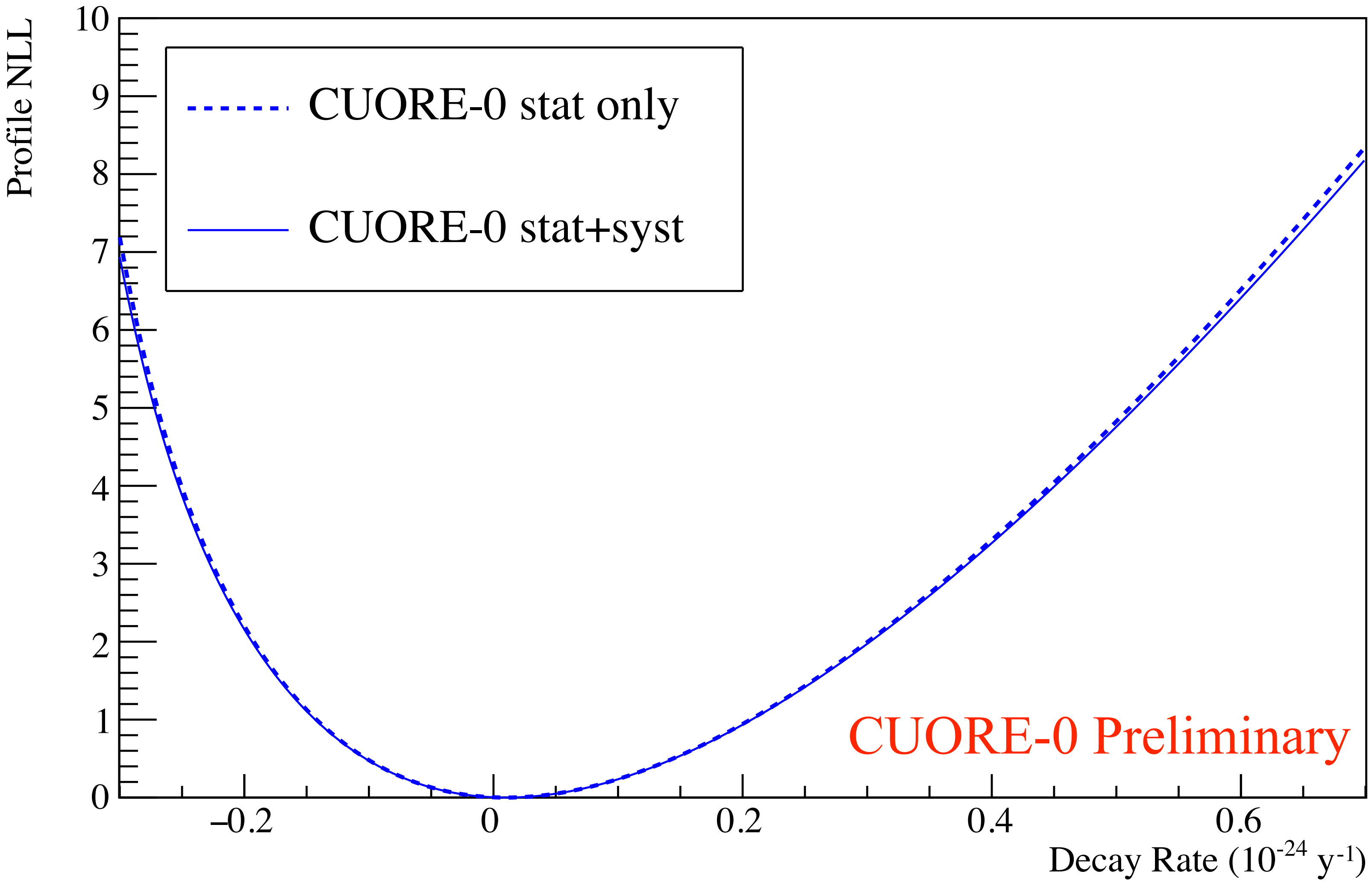
Best fit Γ $\Gamma_{0\nu} = 0.01 \pm 0.12\,(\mathrm{stat.}) \pm 0.01\,(\mathrm{syst.}) \times 10^{-24}\mathrm{yr}^{-1}$

Best fit ROI background index $0.058 \pm 0.004\,(\mathrm{stat.}) \pm 0.002\,(\mathrm{syst.})\ \mathrm{c/keV/kg/yr}$

CUORE-0 limit

We find no evidence for a signal and set 90% C.L. Bayesian lower limits:

$\Gamma^{0\nu} < 0.25 \times 10^{-24}$ yr $\quad T_{1/2}(0\nu) > 2.7 \times 10^{24}$ yr



The median 90% C.L. lower limit sensitivity is: 2.9×10^{24} yr

The probability of obtaining a more stringent limit is 54.7%

Systematics

For each systematic, we run toy Montecarlo to evaluate bias on fitted 0νββ decay rate

Bias is parameterized as $p_0 + p_1 \times \Gamma$, where p_0="additive" and p_1="scaling"

Signal lineshape: Used variety of different lineshapes to model signal

Energy resolution: Apply 5% uncertainty on the resolution scaling

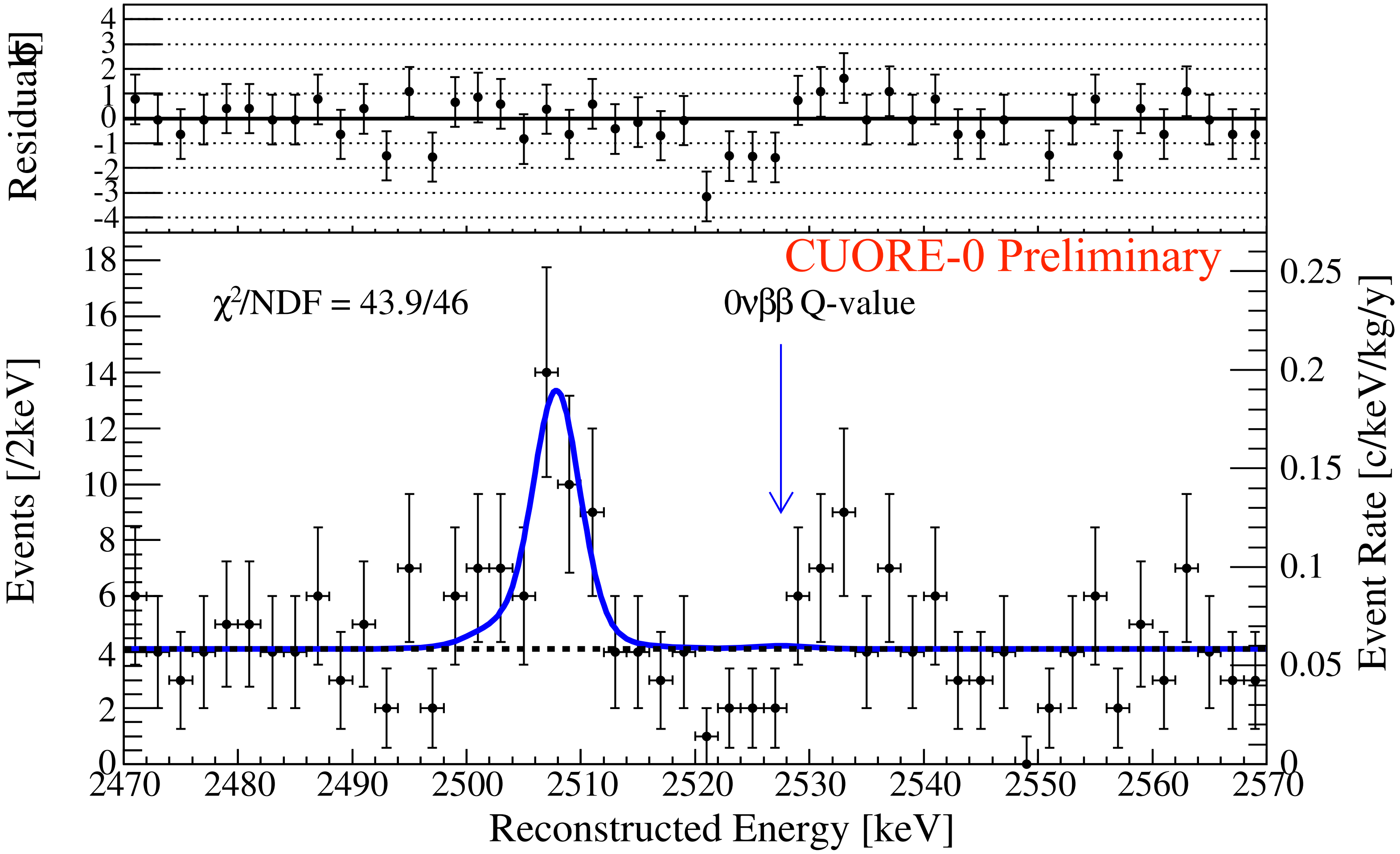
Fit bias: Effect of using unbinned extended ML fit to extract values

Energy scale: apply 0.12 keV calibration uncertainty

Bkg function: use 0-, 1-, 2-order polynomial

	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 analyses

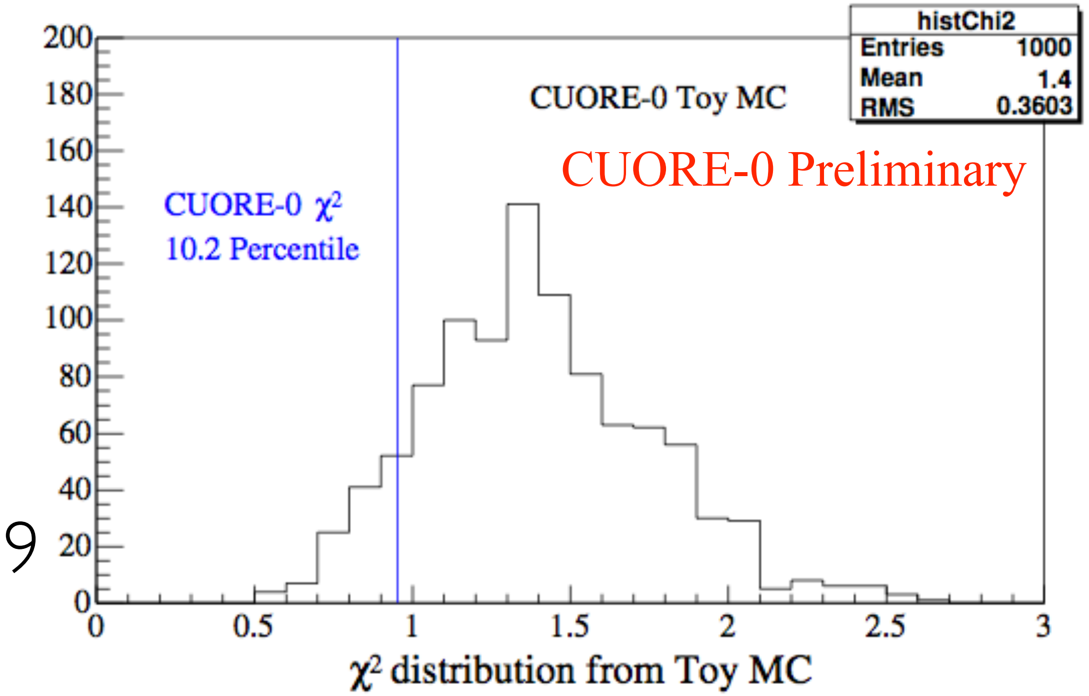


We evaluated the statistical significance of the event excess above the Q-value and the dips below and above the Q-value

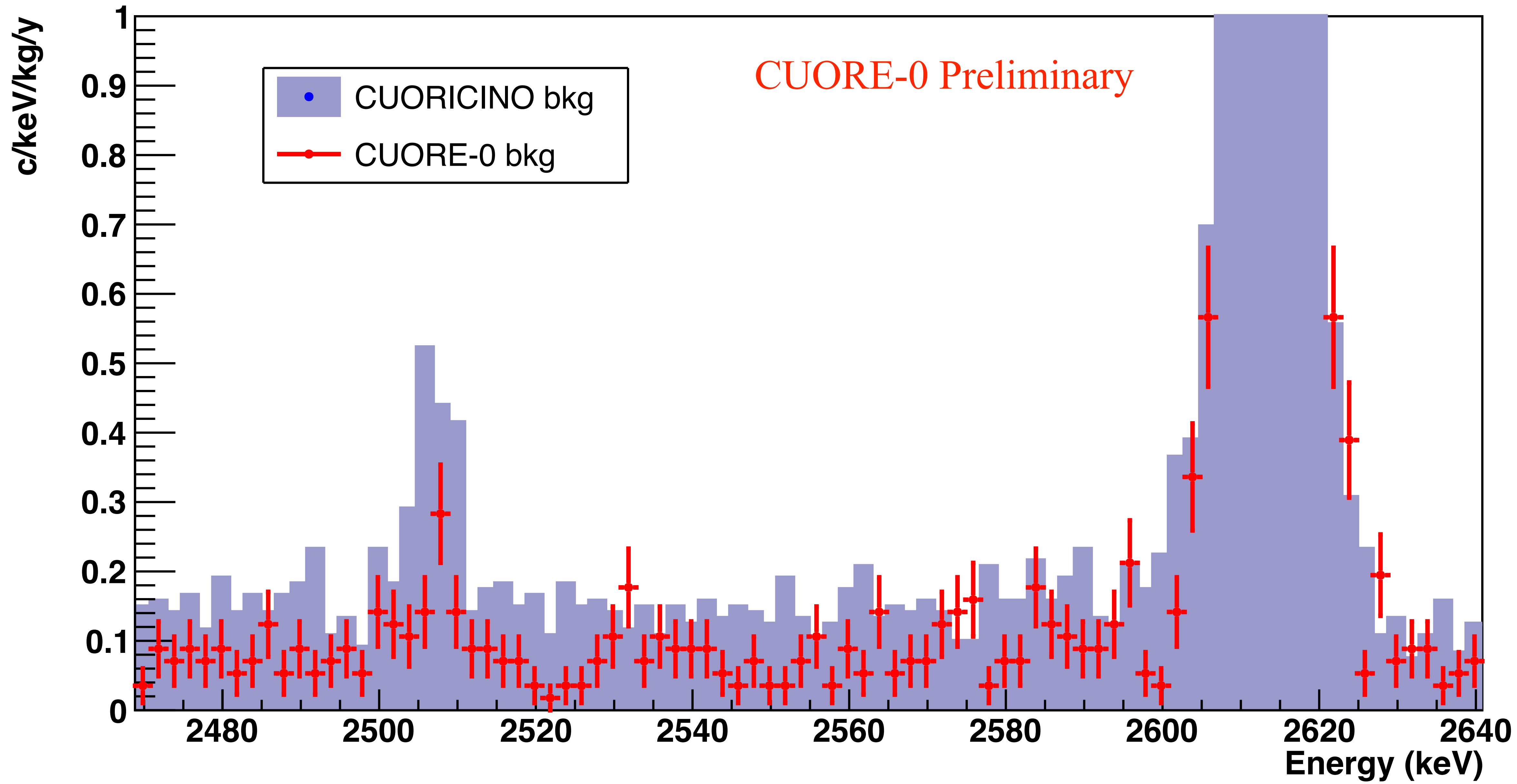
A Kolmogorov-Smirnov test shows the data is consistent with the null hypothesis (i.e., the best-fit model but with $\Gamma_{0\nu}$ fixed to zero).

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



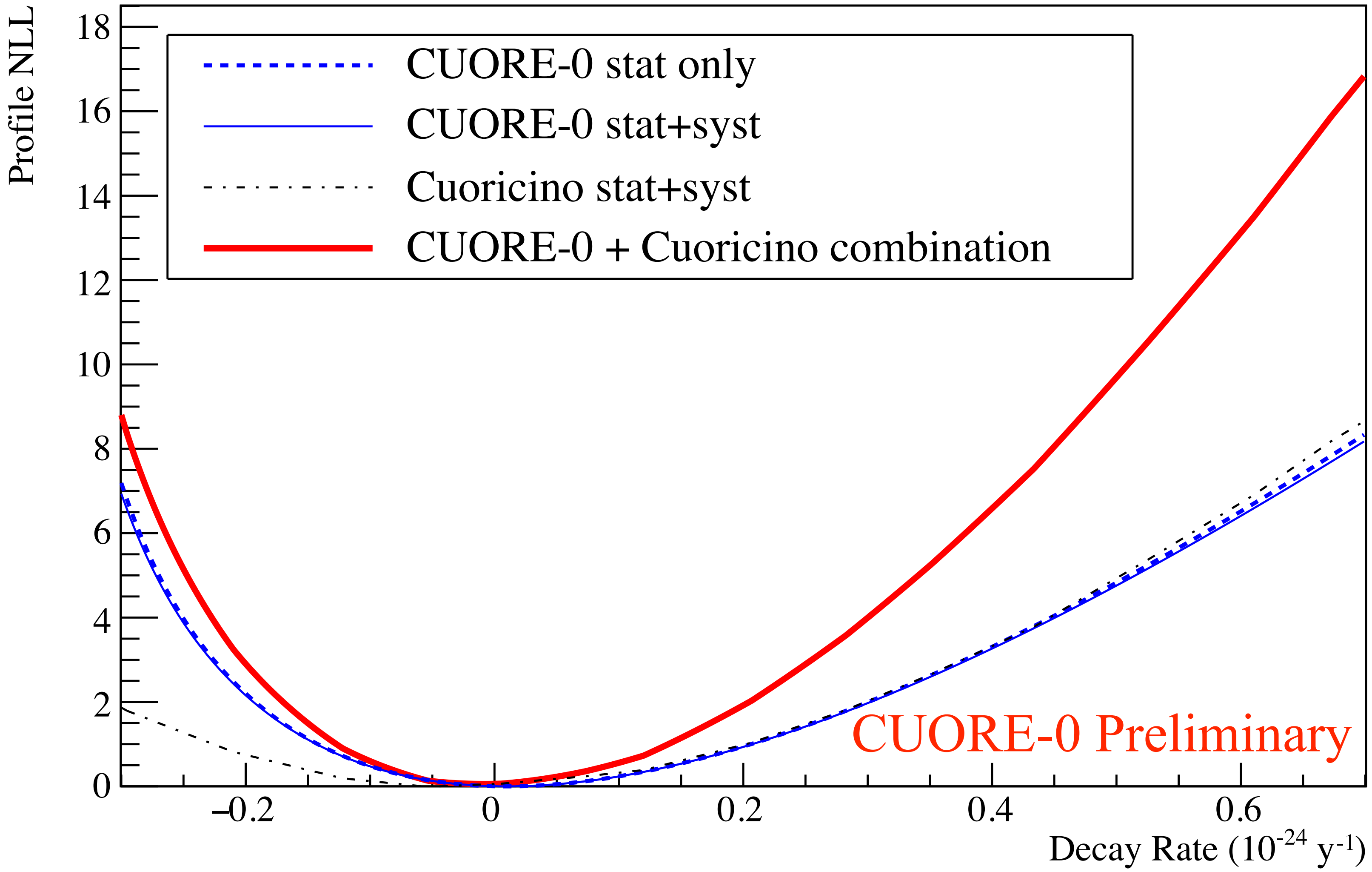
CUORE-0 vs CUORICINO comparison



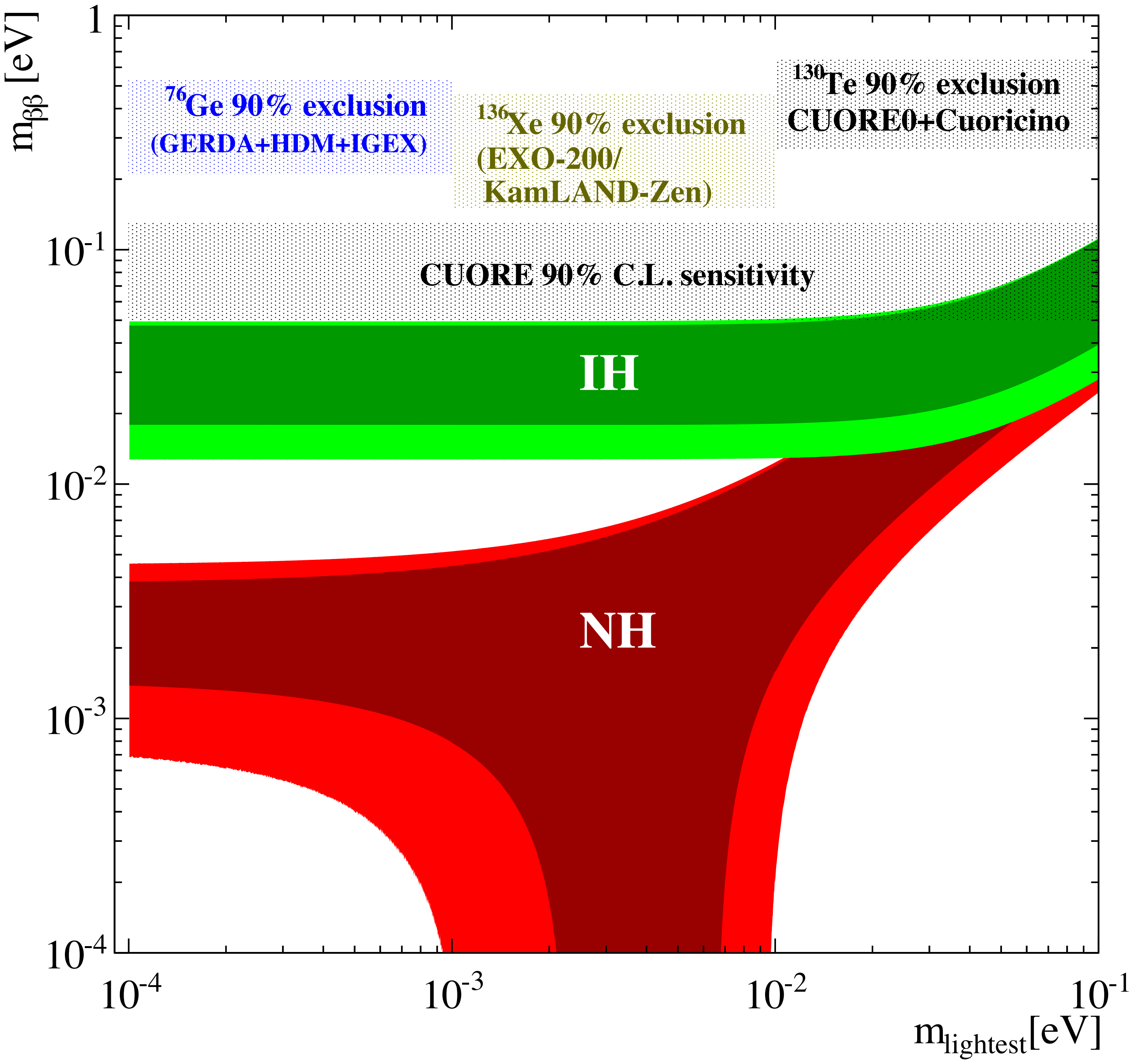
CUORICINO/CUORE-0 combined limit

We combine the CUORE-0 result with the existing 19.75 kg · yr of ^{130}Te exposure from Cuoricino

The combined 90% C.L. limit is $T_{0\nu} > 4.0 \times 10^{24}$ yr



Extrapolation to $m_{\beta\beta}$



We interpret our combined half-life result as a limit on the effective Majorana neutrino mass:

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

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)

Conclusions

TeO_2 bolometers offer a well-established, competitive technique in the search for 0νββ decay

CUORE-0

Achieved its energy resolution and background level goals, surpassing Cuoricino sensitivity in half the time.

Indicated CUORE sensitivity goal is within reach.

Did not find evidence of ^{130}Te 0νββ decay and after combination with CUORICINO data set the best limit to date on $T_{1/2}$ of the decay.

0νββ paper submitted to PRL. Two more papers in preparation (detector and background model).

CUORE:

Assembly of the 19 CUORE towers is complete.

Commissioning of the cryogenic system and experimental infrastructure is in progress

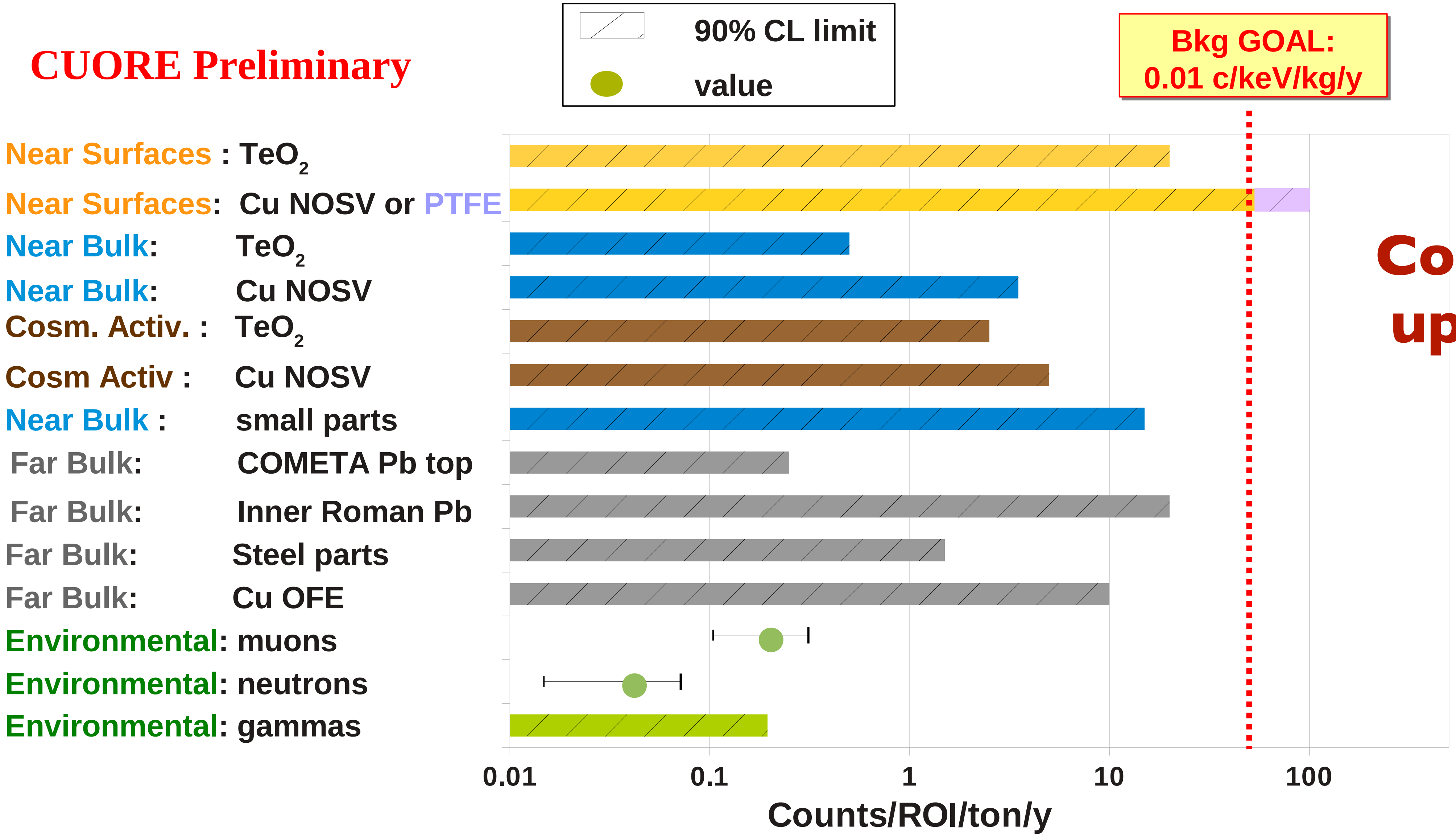
Plan to start operations by end of 2015.

Backup slides

CUORE Background Bugdet

CUORE strategies to reduce background

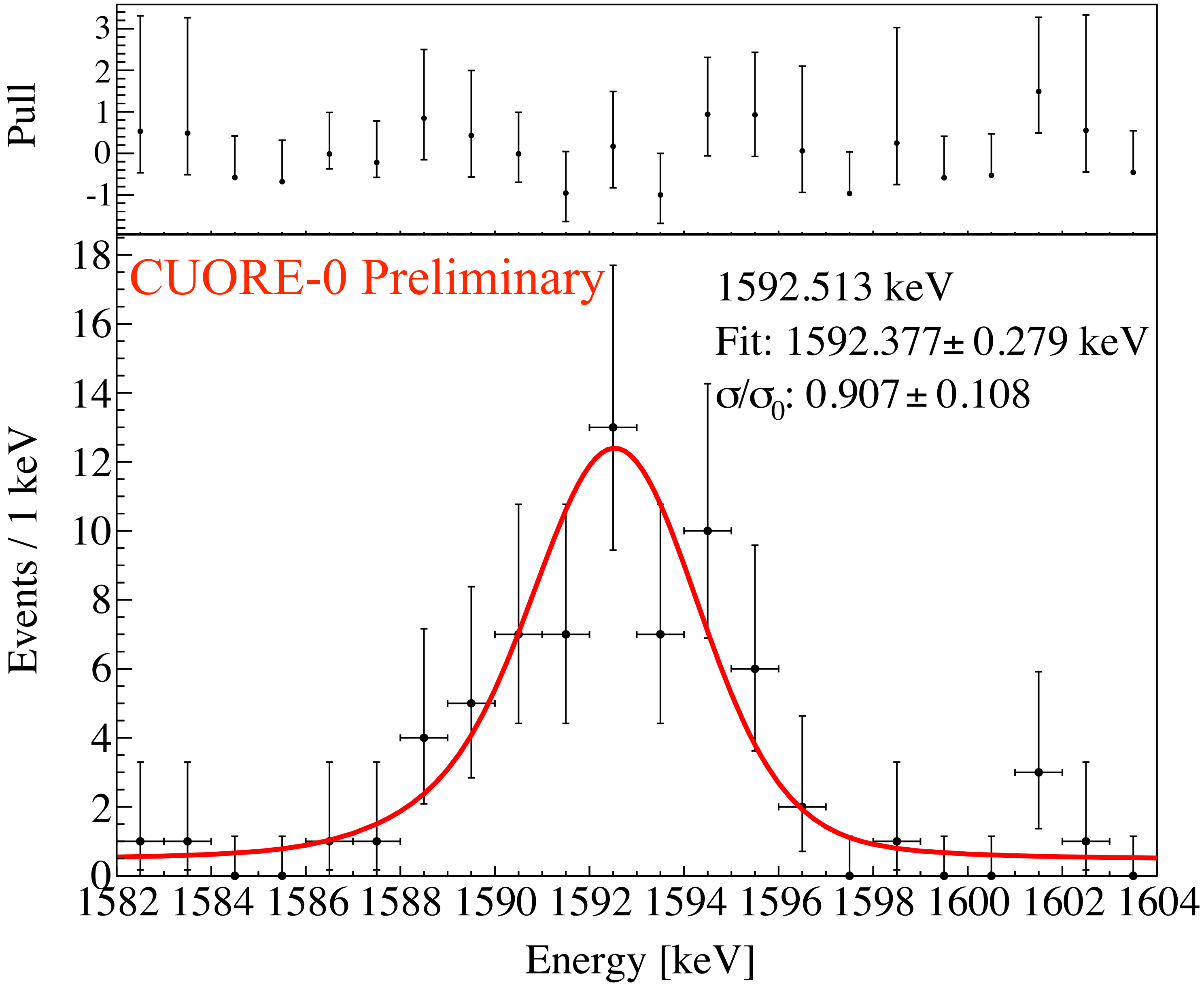
- undeground location
- external shielding
- radiopurity
- granularity
- self-shielding



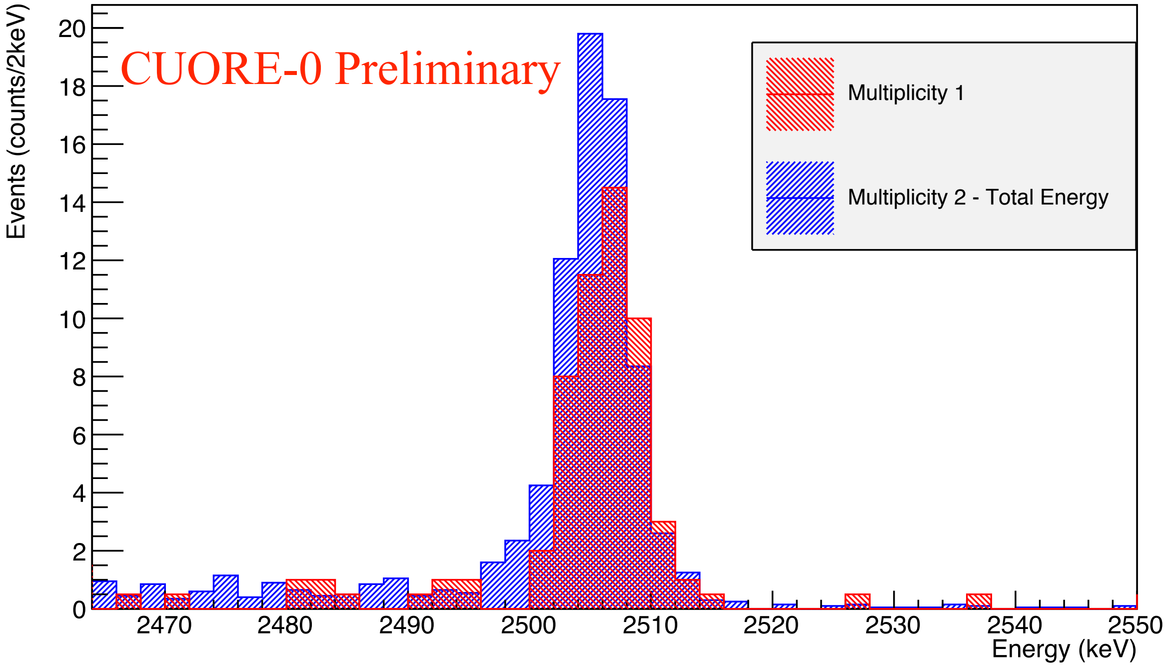
Conservative upper limits

2615 double escape peak

Same topology of neutrinoless double beta decay (2 electrons)
Reconstructs at the right energy

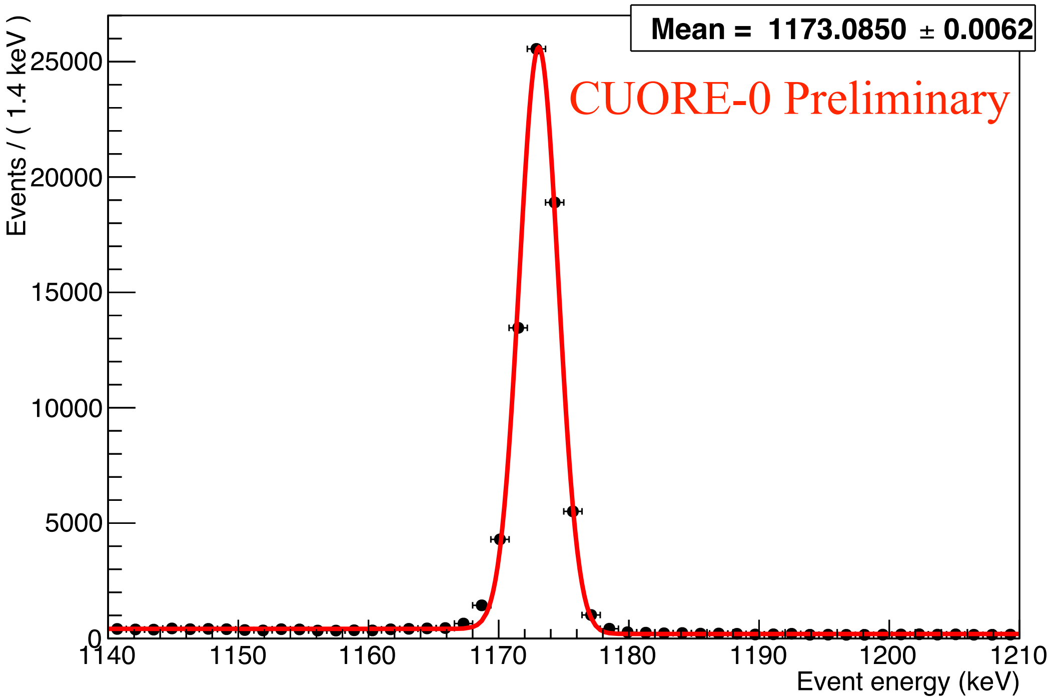


Cobalt calibration

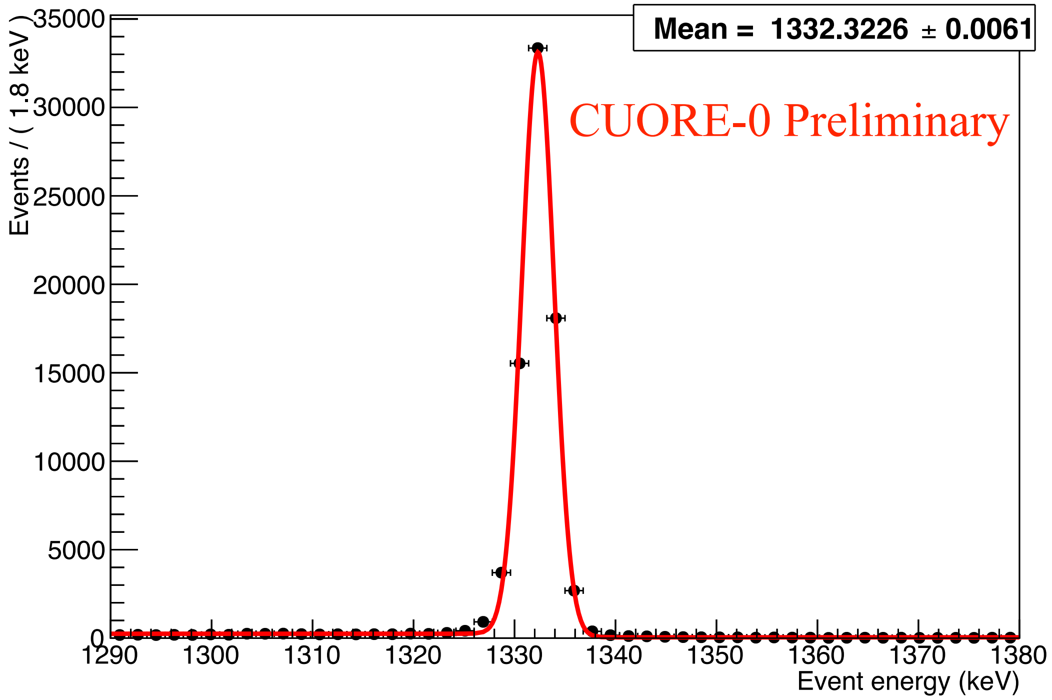


^{60}Co double-gamma events reconstruct at 2507.6 ± 0.7 keV, 1.9 ± 0.7 keV higher than the established value at 2505.6 keV

1173.2 Co60

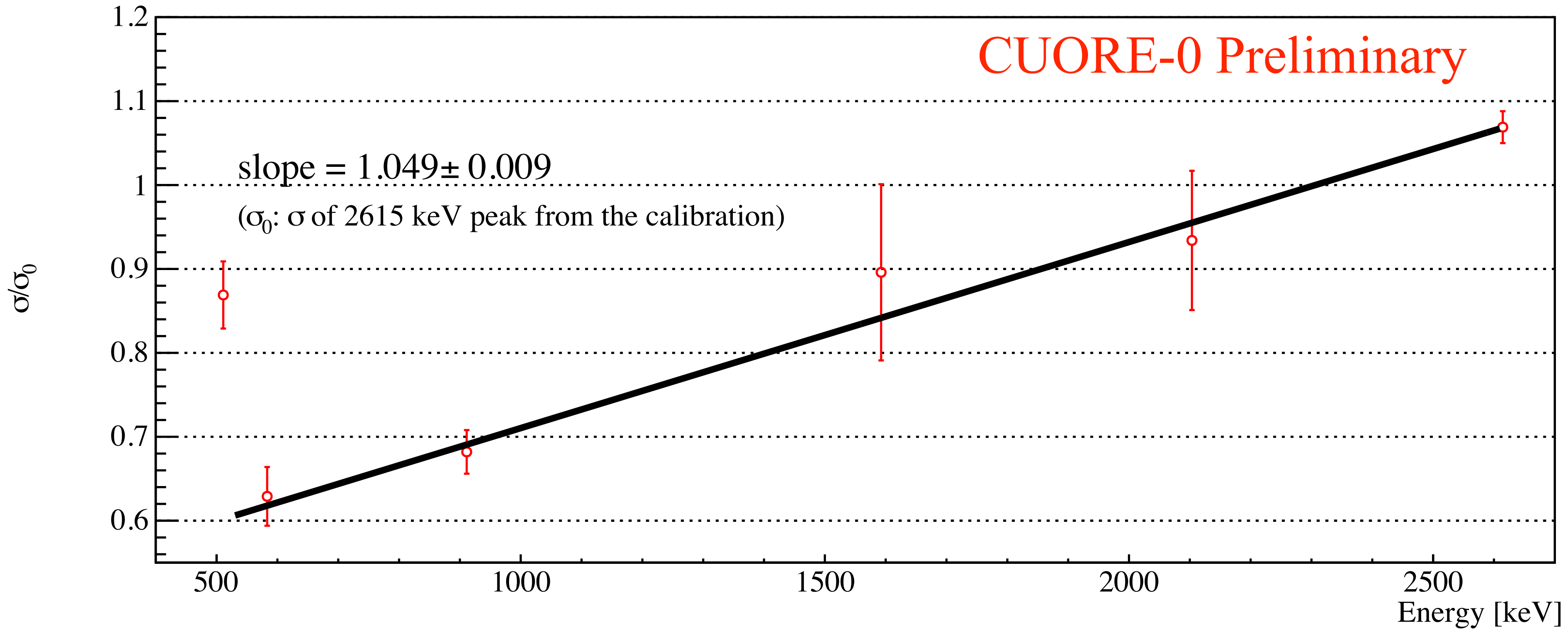


1332.5 Co60

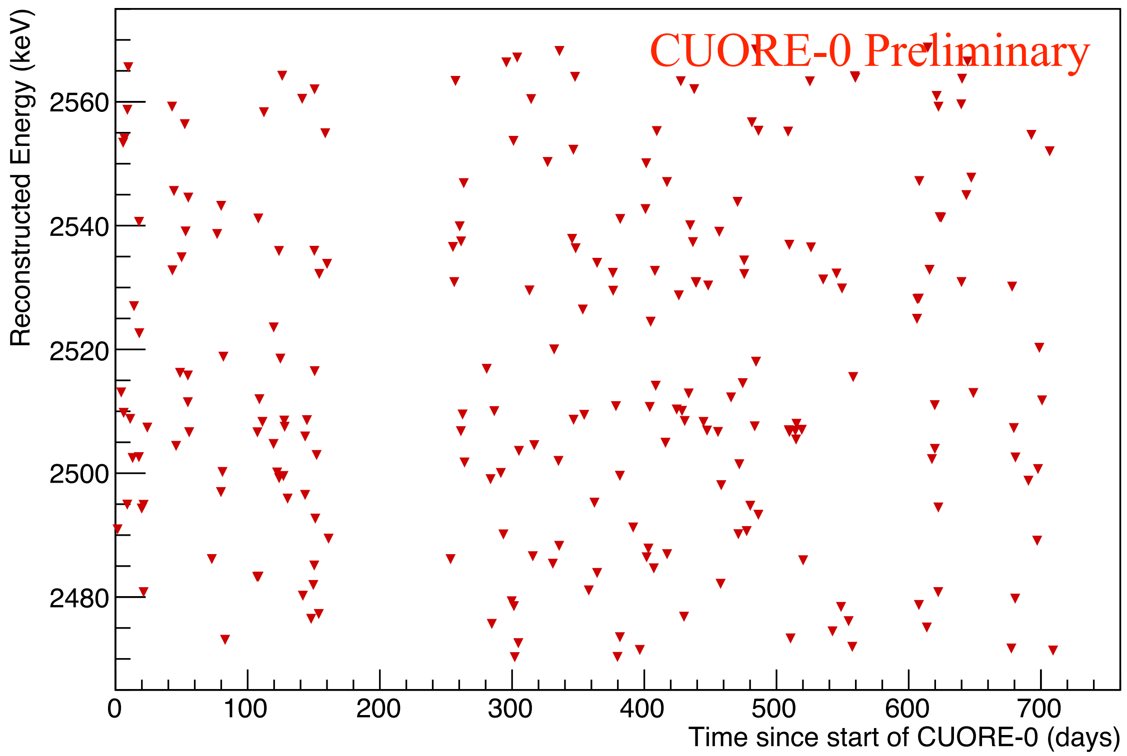


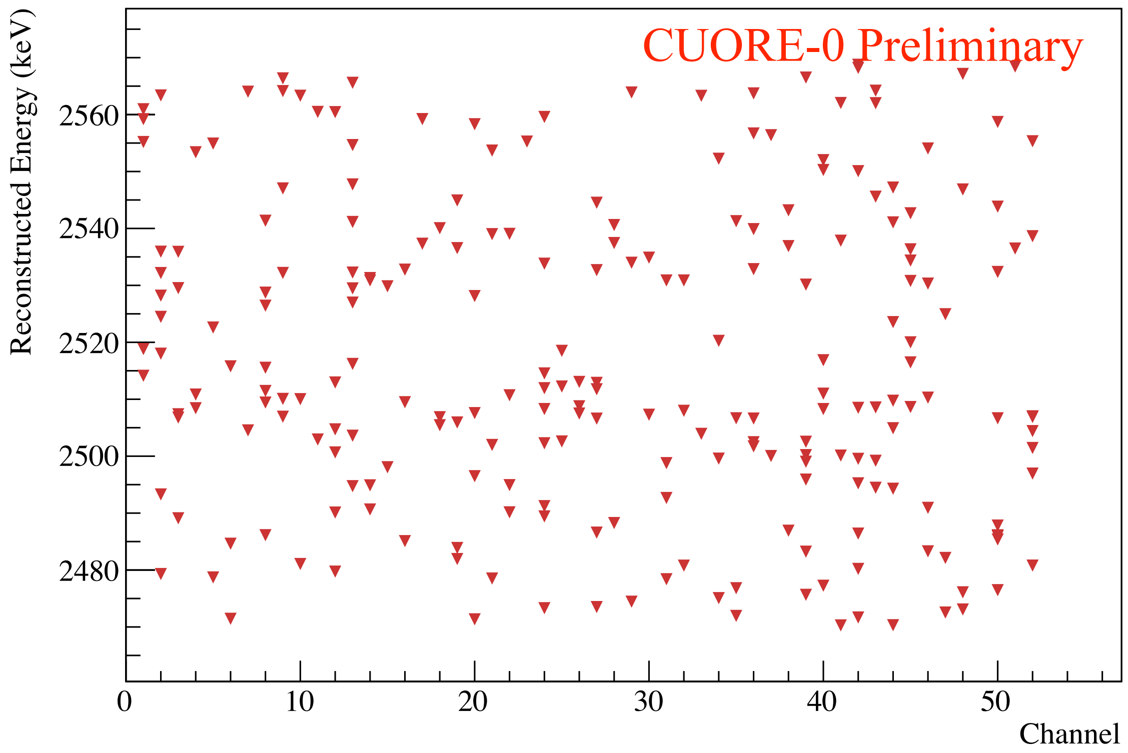
Background resolution scaling

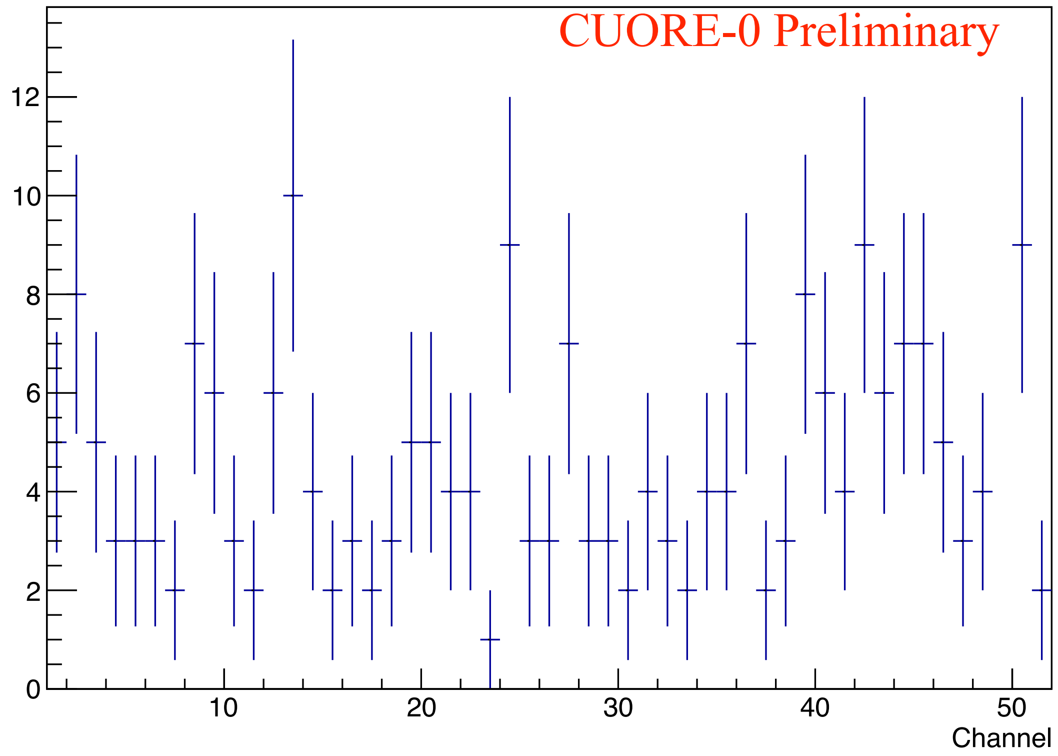
- Background resolution as a function of energy
- Uncertainty shown in the plot is only from the fit.



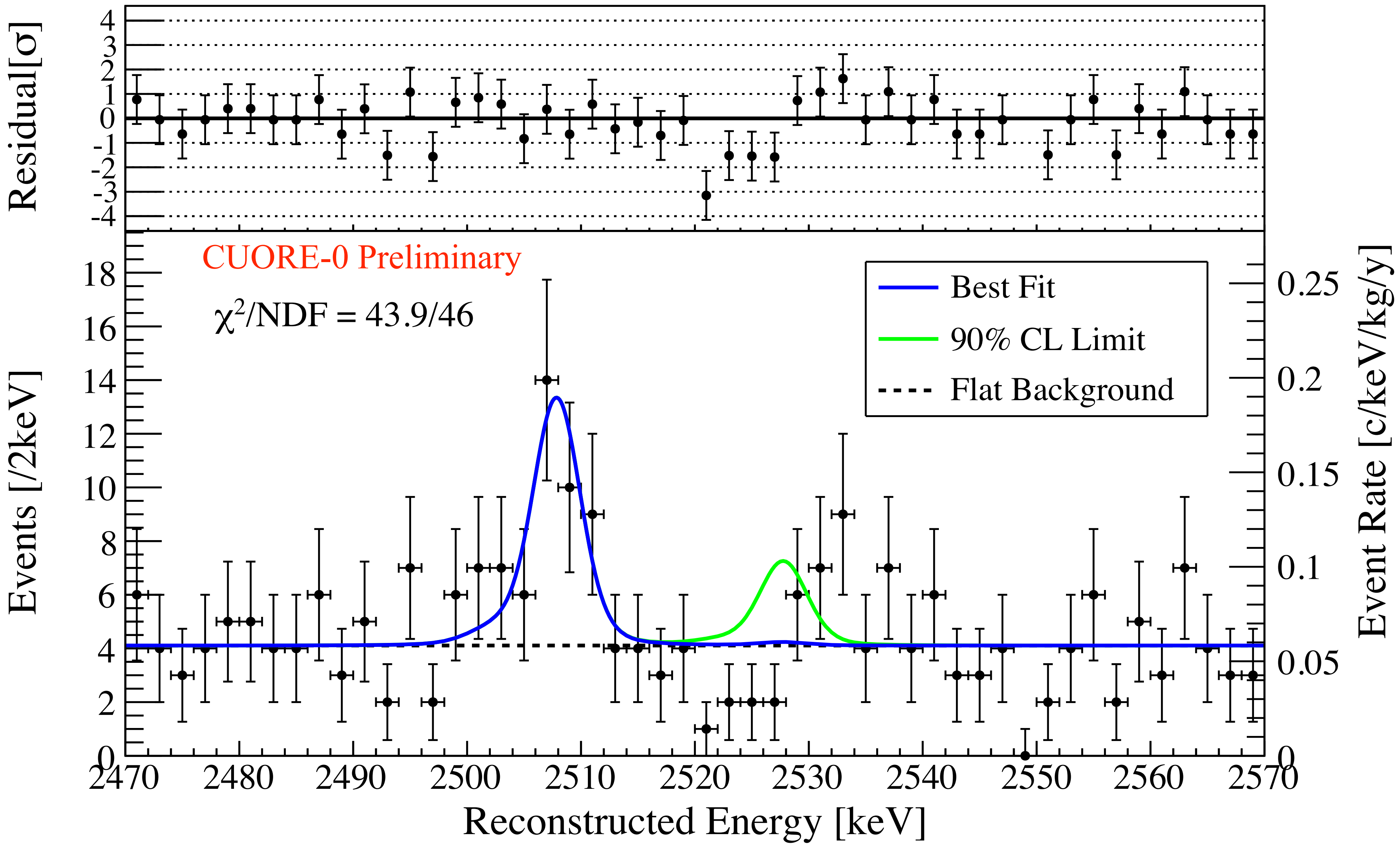
Distribution of ROI events per channel, time



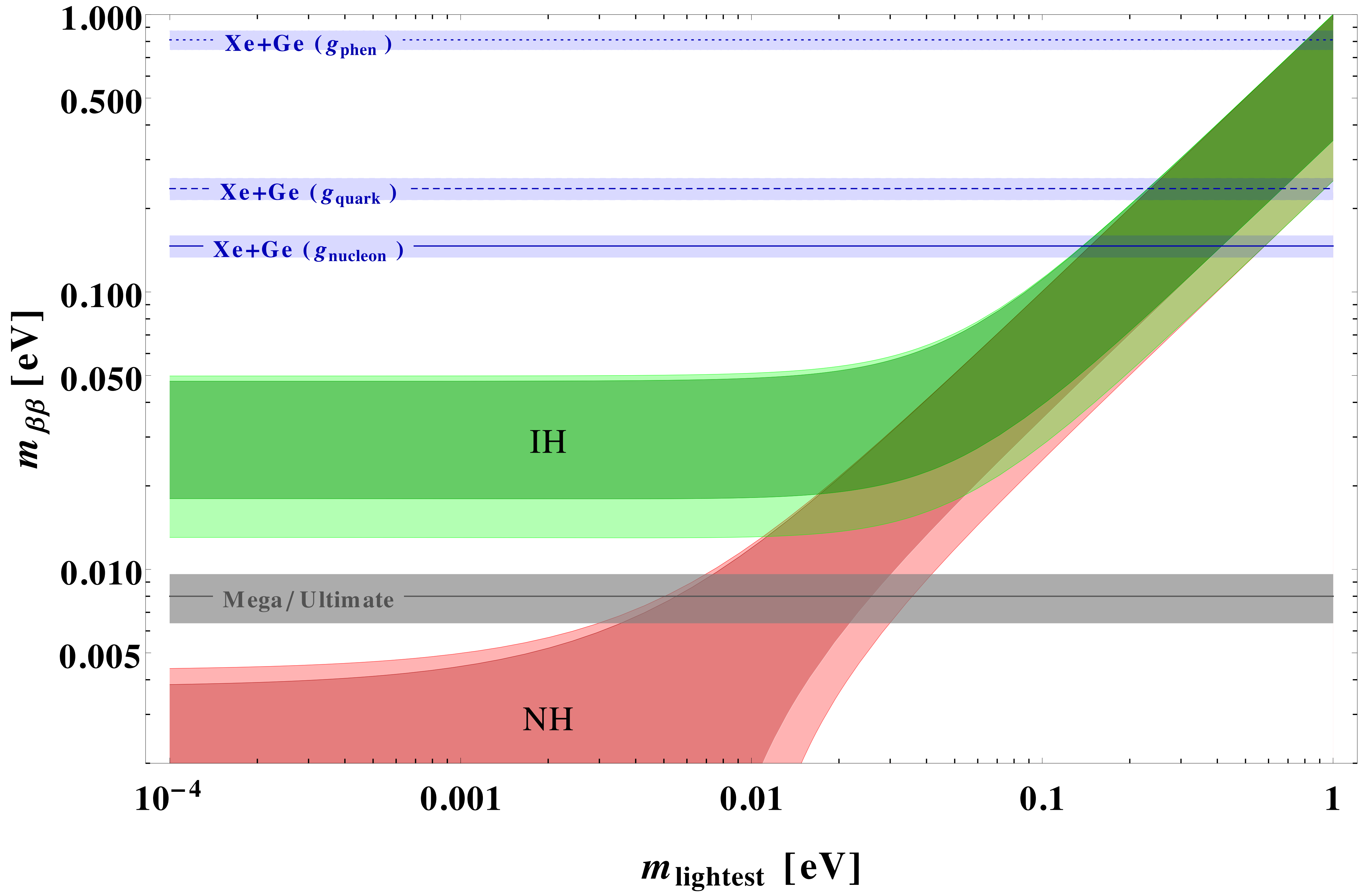




90% C.L. limit on number of events



effect of quenching of g_A



Systematics

For each source of the systematics, we run toy MC to evaluate its bias on fitted NDBD decay rate.

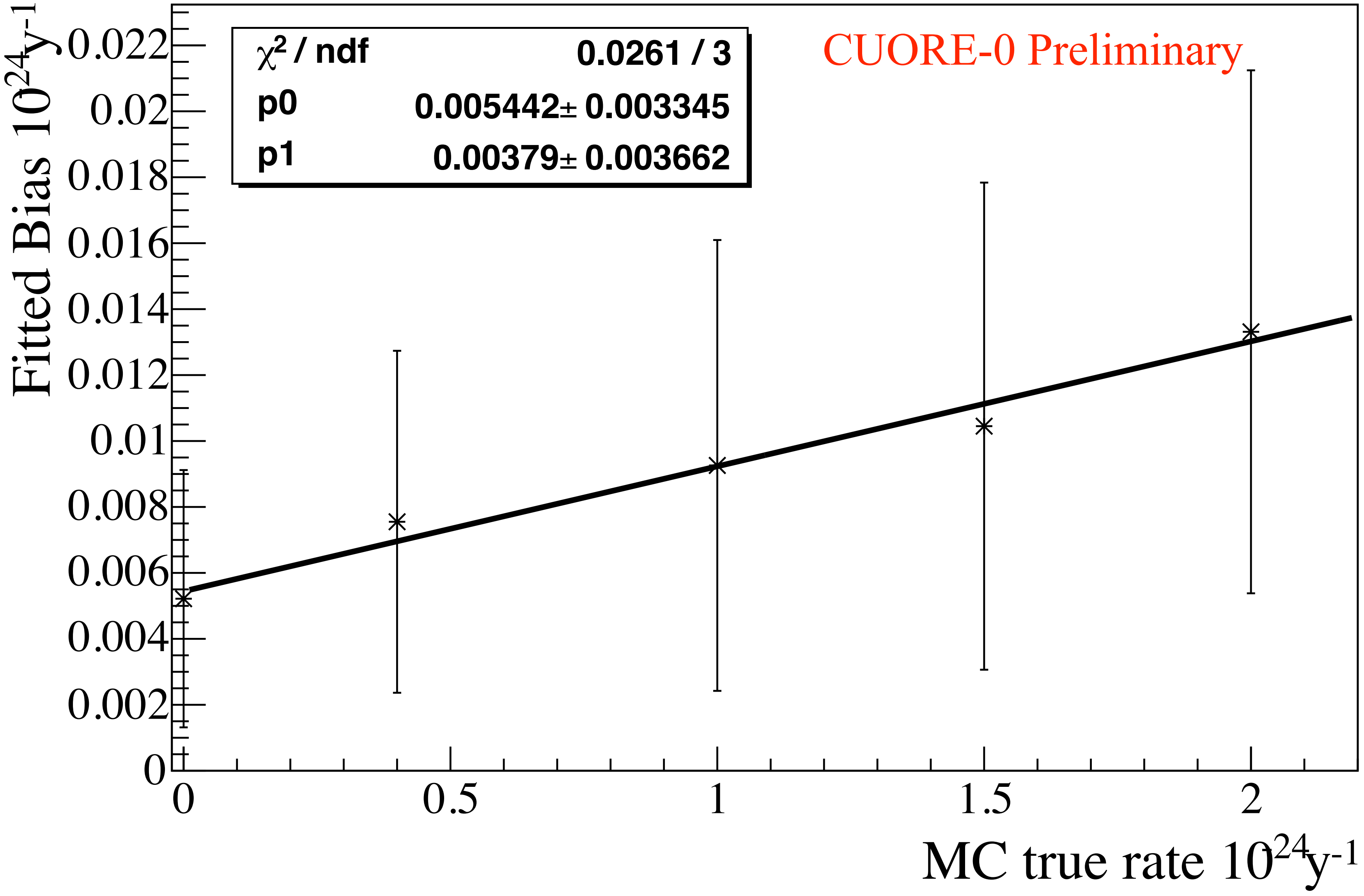
The bias may include a constant shift to the rate and linear part: bias = p0 + p1*Gamma

To get p0 and p1, we run a group of toy Montecarlo at each decay rate Gamma =g, where g ranges from 0 to 2 10^{-24} yr $^{-1}$ (as a reference, our fitted Gamma is close to zero: 0.01 10^{-24} yr $^{-1}$).

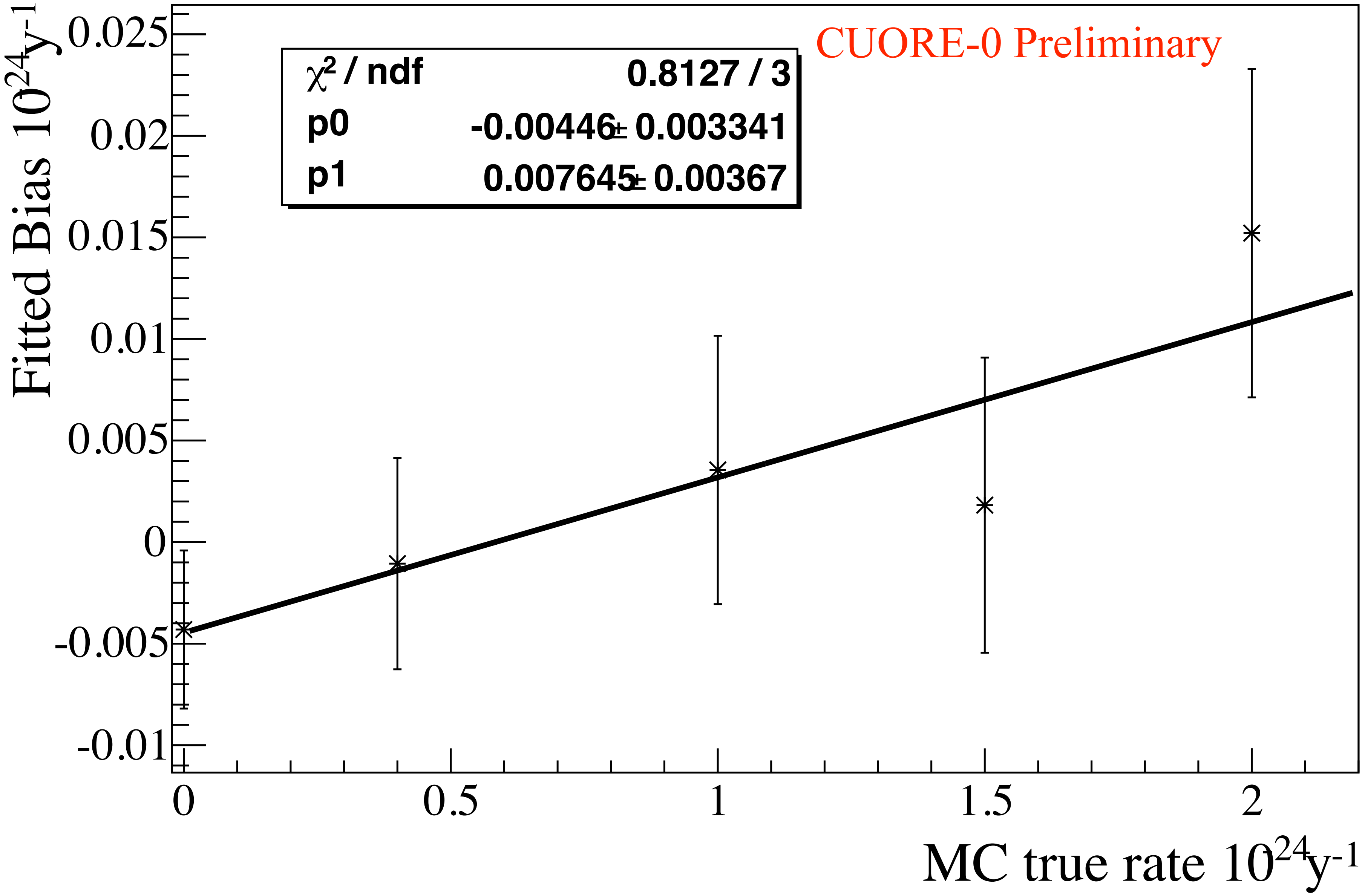
At each decay rate, we run N (N=1000 or 2000) pseudo-experiments in the following fashion:

- The ROI is fitted with a possible alternative form that may introduce bias, say linear background. The fitted function called f(Gamma).
- We set Gamma to a certain rate.
- We draw 233 events from the new f(g). Repeat N times.
- Fit each pseudo-experiment with the baseline fit function.
- Calculate average fitted gamma rate over the N experiments.
- Plot the fitted rate vs. MC true rate and get p0 and p1.

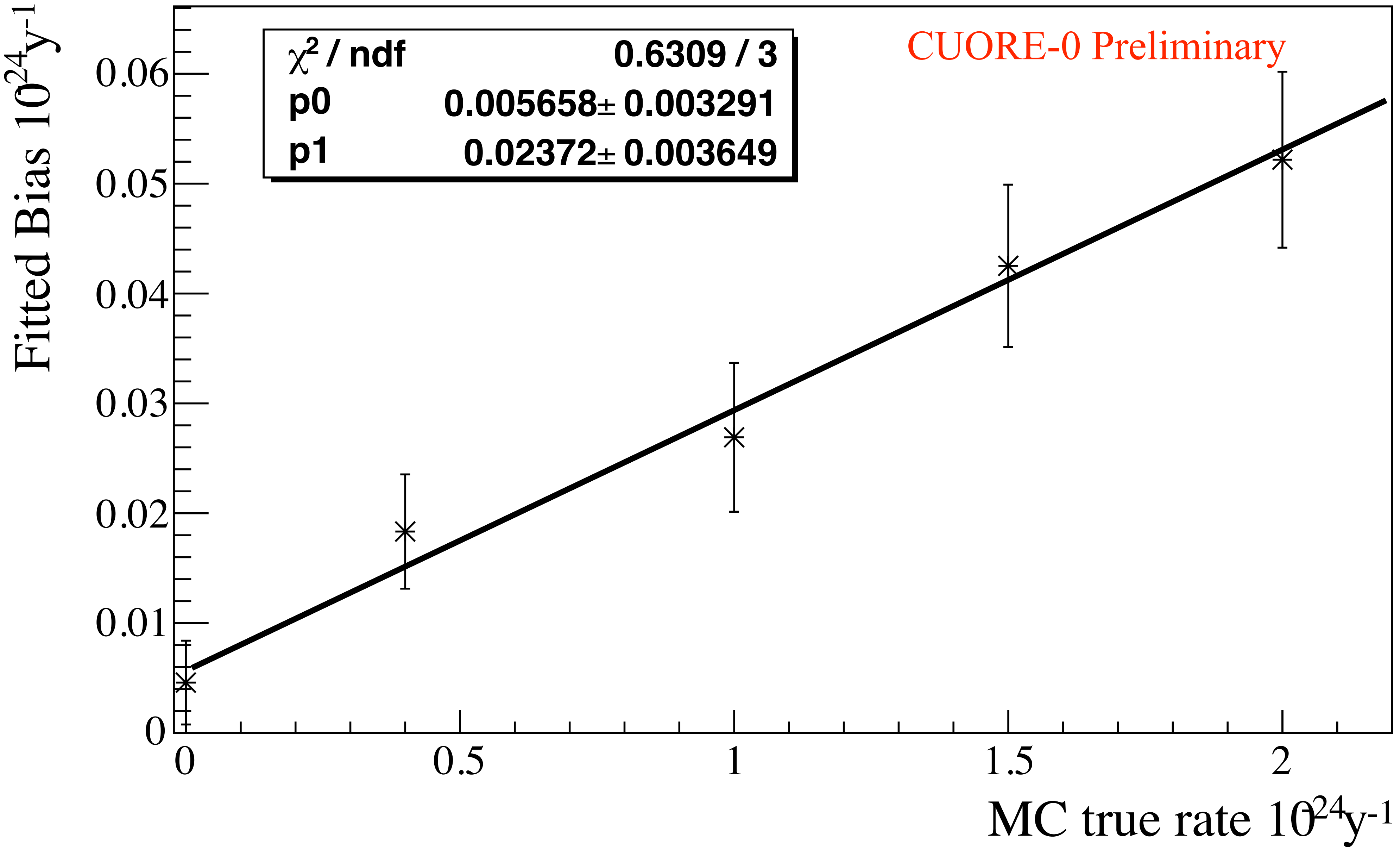
systematics from calibration uncertainty



systematics from background function

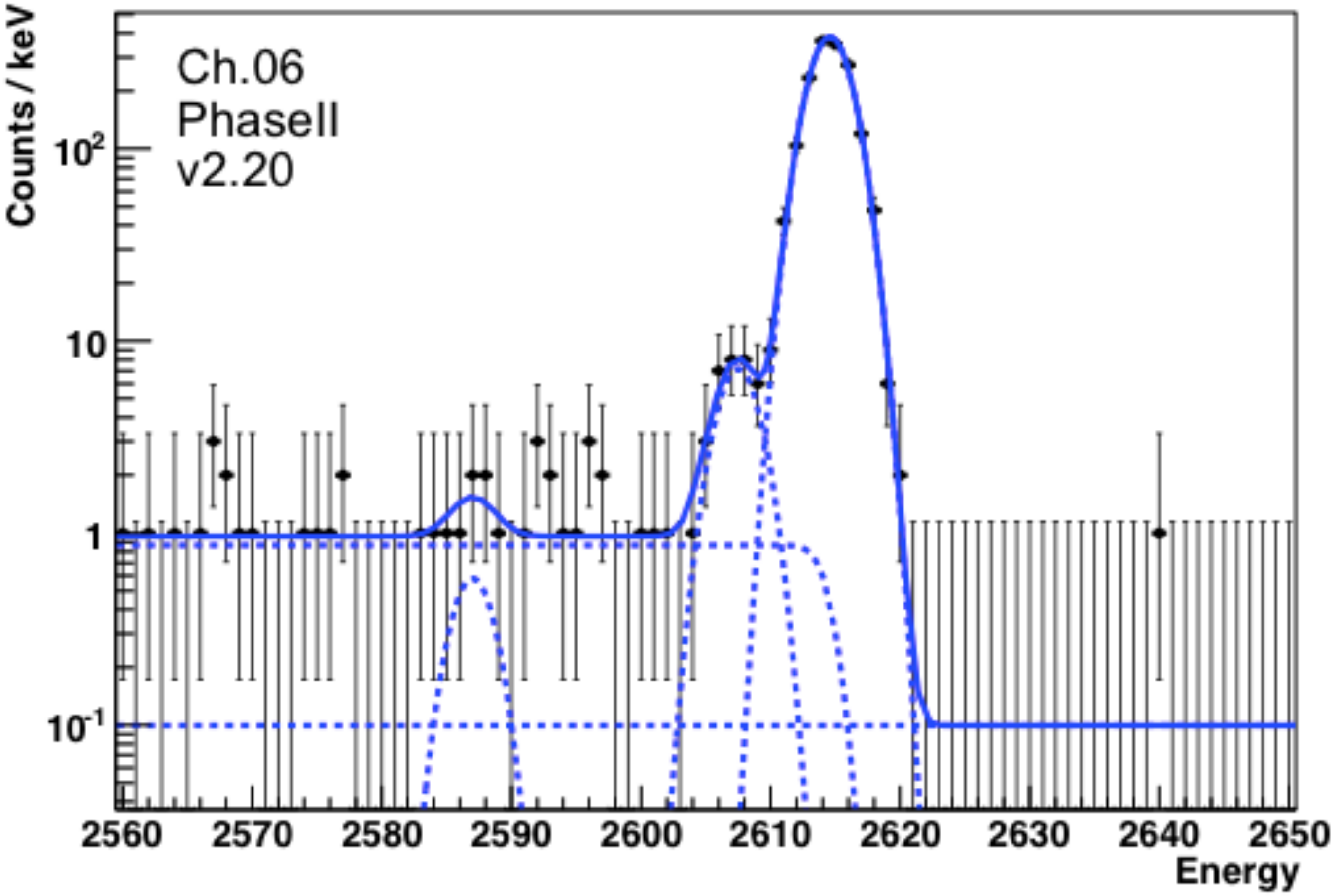


systematics from resolution scaling



CUORE-0 lineshape

$$
\begin{aligned}
f_{\mathrm{Cal}}(E) = {} & n_0 e^{-\frac{(E-E_0)^2}{2\sigma^2}} \\
& + n_1 e^{-\frac{(E-E_1)^2}{2\sigma^2}} \\
& + n_2 e^{-\frac{(E-E_2)^2}{2\sigma^2}} \\
& + n_3 \cdot \mathrm{erfc}\left[\frac{E-E_0}{\sigma}\right] \\
& + n_4 \ .
\end{aligned}
$$



Components: main photopeak, lower-energy subpeak, X-ray escape peak at ~30 keV below the photopeak, Compton multiscatter continuum, and flat background