Results on neutrinoless double beta decay of ^{130}Te from CUORICINO

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on behalf of the CUORICINO Collaboration

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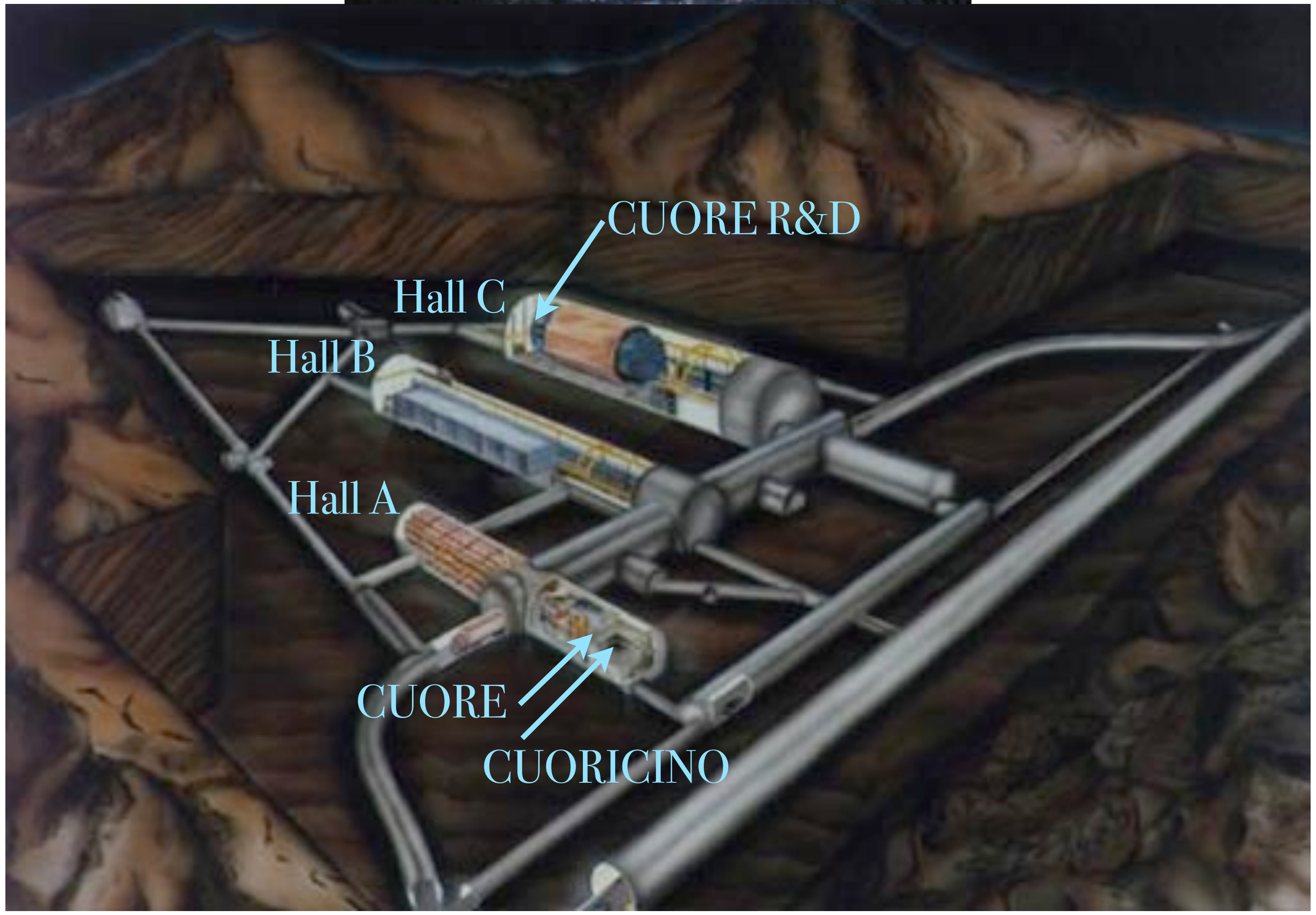
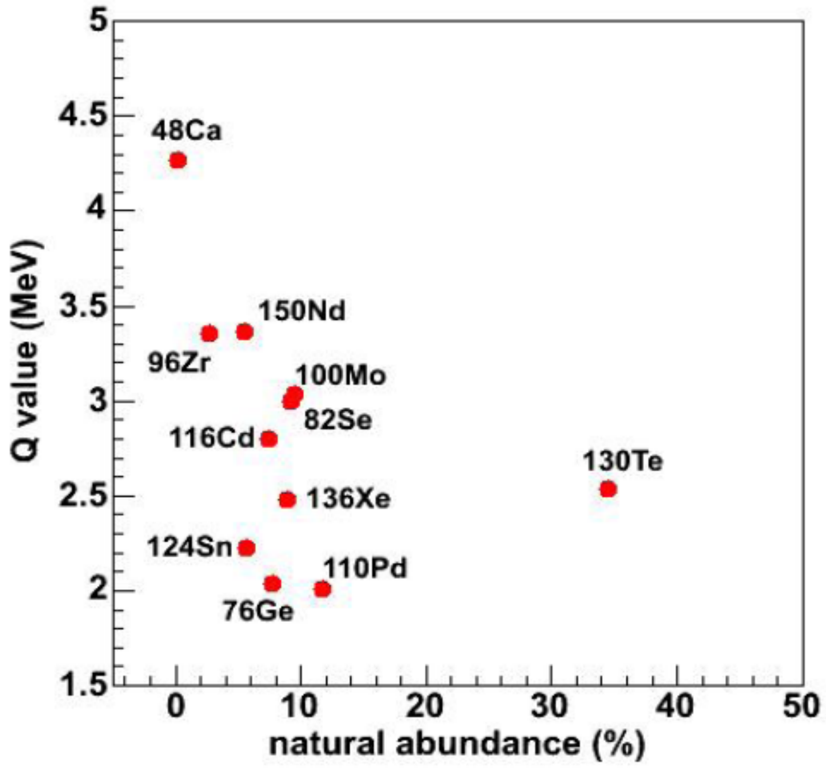
Gran Sasso National Lab

- National laboratory of the Istituto Nazionale di Fisica Nucleare (INFN) of Italy
- Built adjacent to a highway tunnel through the Gran Sasso mountain range
- 1400 m of rock overburden
  (about 3500 meters water equivalent)
- Cosmic ray muon flux attenuated by about 10^6 to about 0.7 muons / m^2 / h



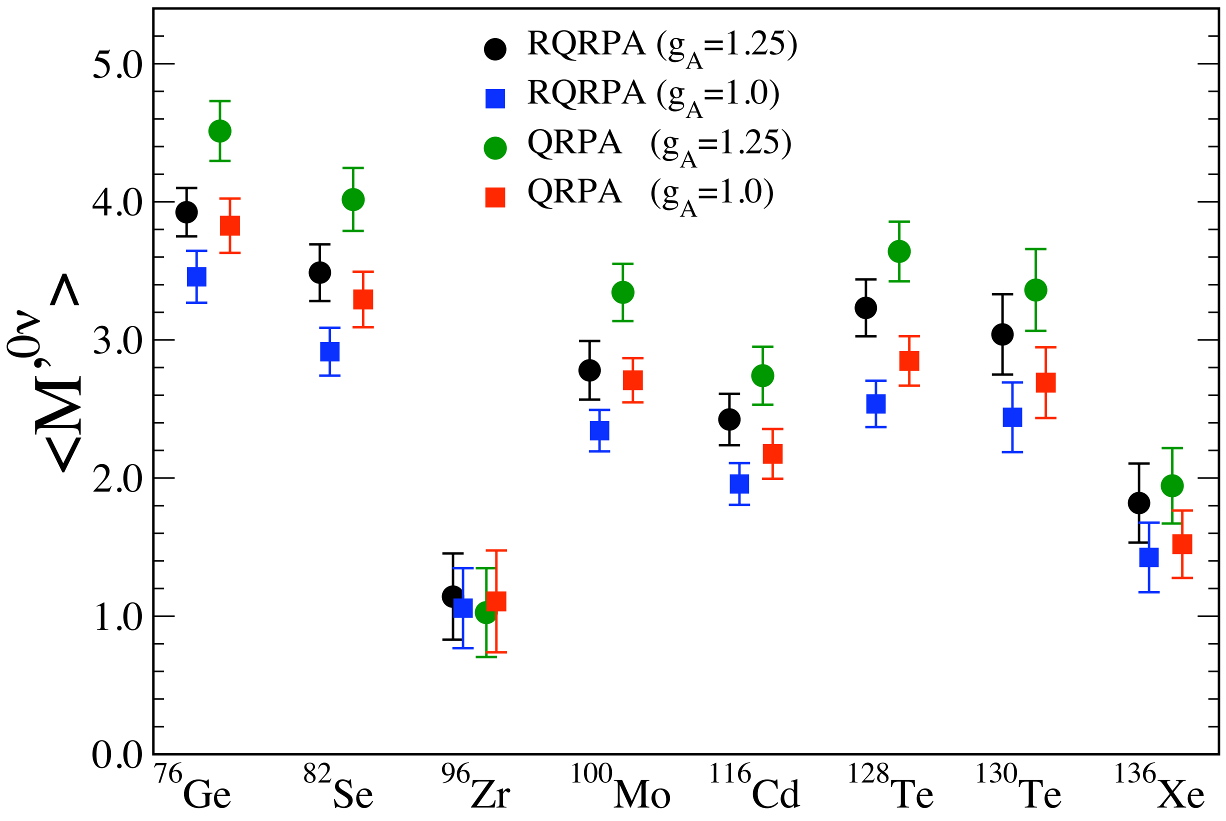
^{130}Te as a 0νββ decay candidate



Natural isotopic abundance of 33.80%
-no enrichment

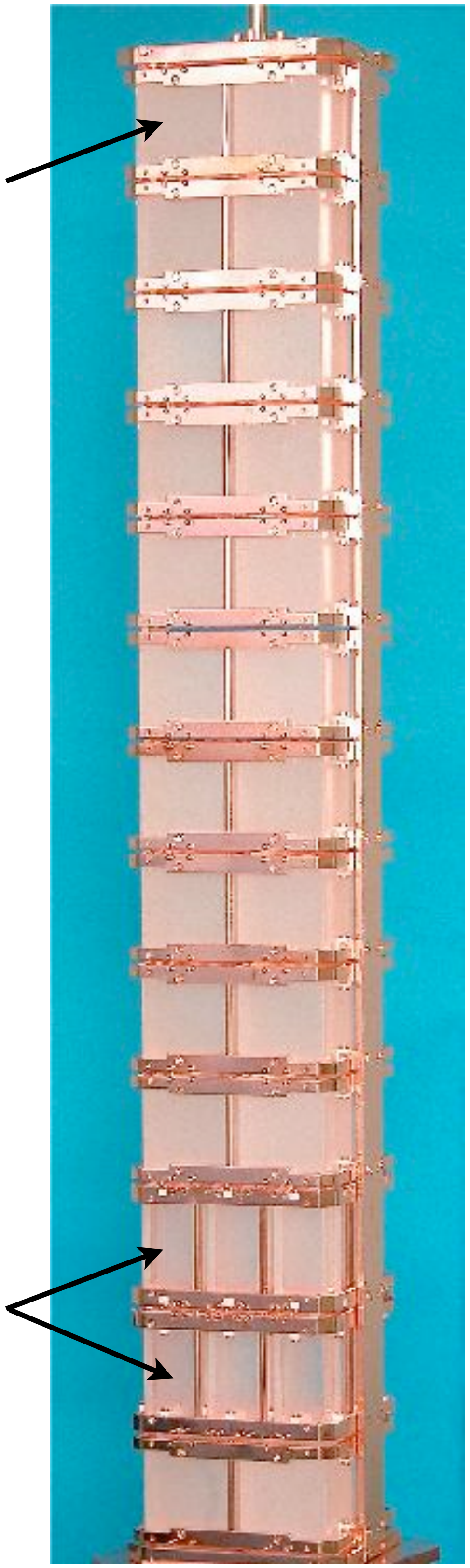
Q-value of 2530 keV
-favorable phase space
-above most naturally occurring γ-rays

Nuclear Matrix Elements



Rodin et al., arXiv:0706.4304v1

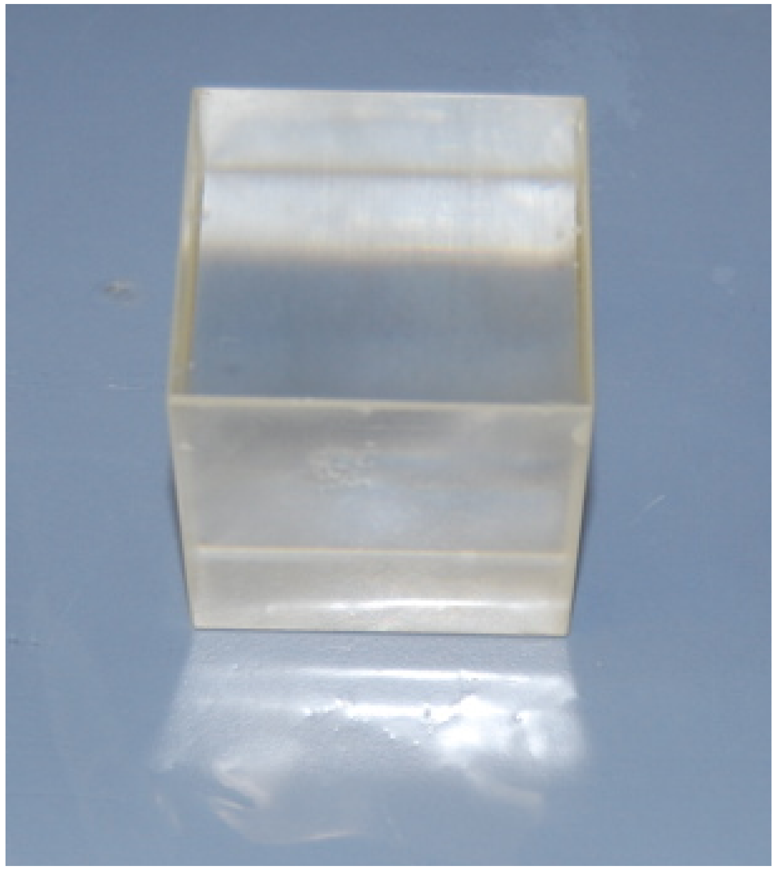
The CUORICINO detector



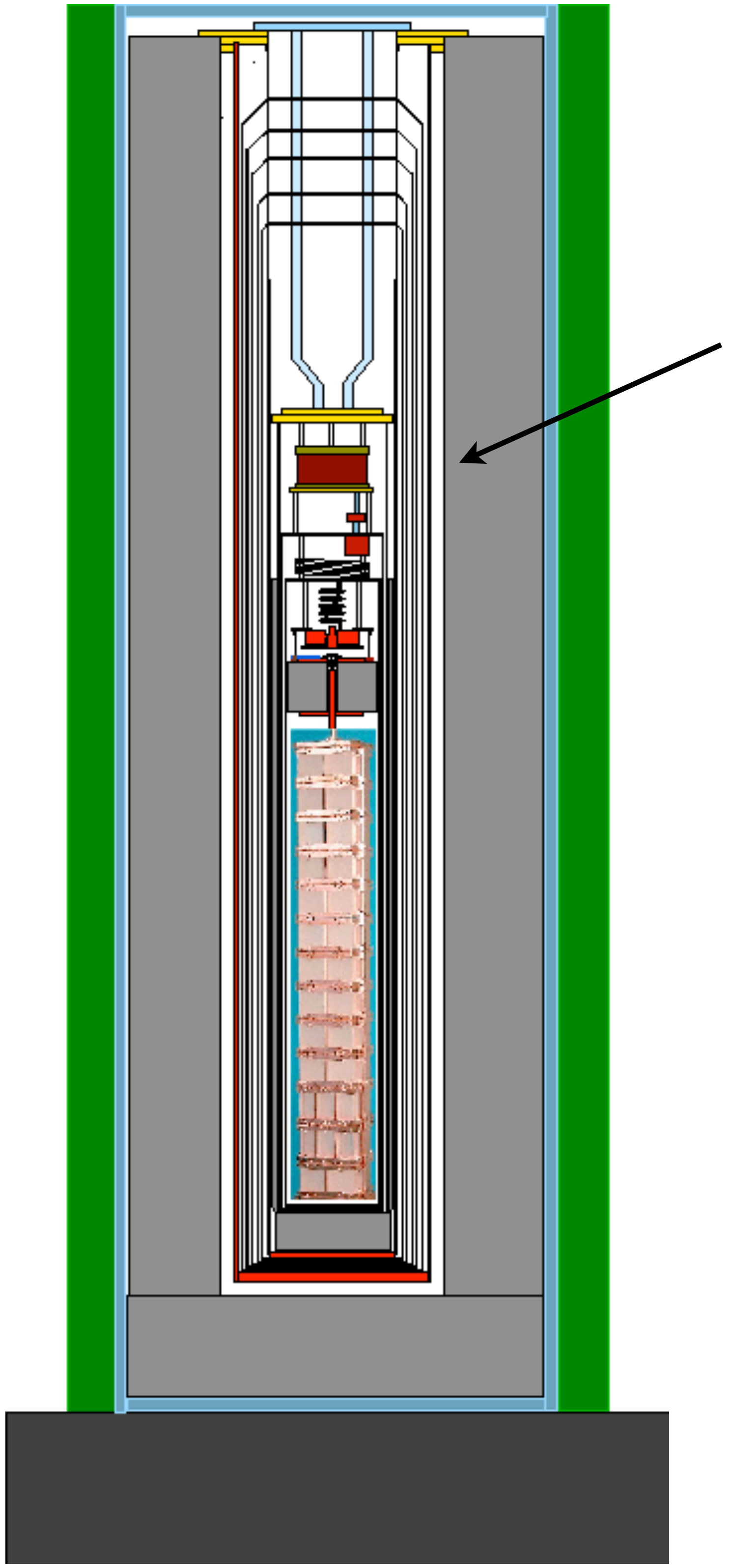
$5 \times 5 \times 5\ \text{cm}^3$
790 g

$3 \times 3 \times 6\ \text{cm}^3$
330 g

- Predecessor to CUORE
- 62 TeO_2 crystals serve as source and detector
- 40.7 kg of TeO_2
- 2 small crystals were enriched to 75% in ^{130}Te
- 2 small crystals were enriched to 82.3% in ^{128}Te
- 11.6 kg of ^{130}Te
- Operated 2003–2008 at Gran Sasso National Laboratory (LNGS) in Italy



Bolometric technique



Dilution refrigerator cools crystals to about 8 mK.

Heat capacity of dielectric and diamagnetic crystals follows the Debye law at low temperatures:

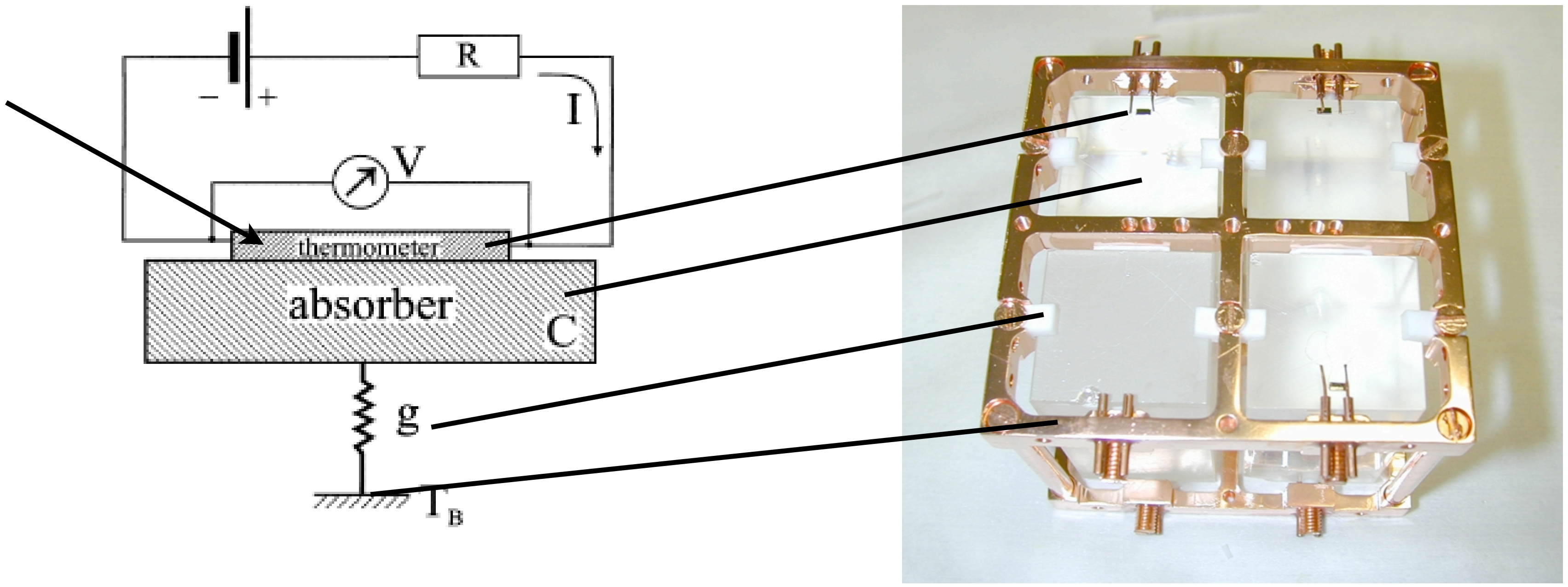
$$C = \beta \left(\frac{T}{T_d} \right)^3$$

$$C \approx 1 \text{ MeV}/0.1 \text{ mK}$$

The energy deposited by a single particle results in a measurable temperature rise.

NTD thermistors

Neutron-transmutation-doped (NTD) Ge thermistors function as sensitive thermometers to measure the small temperature change, $\Delta T = E/C$.



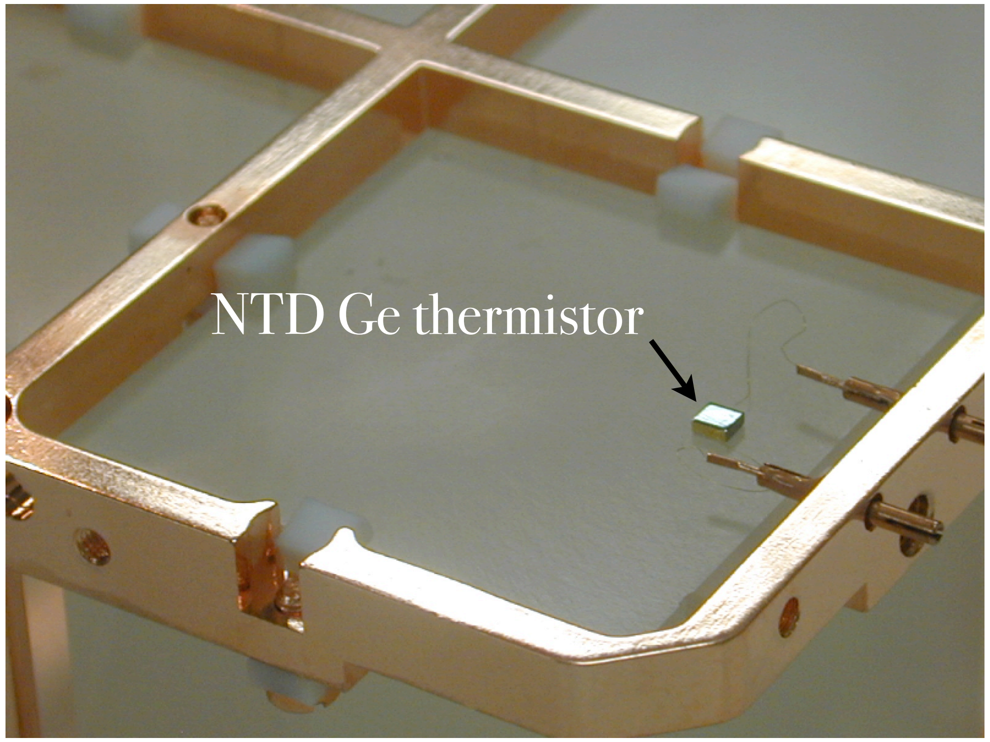
NTD thermistor resistance:

$$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$$

Nuclear processes creating dopants

$$\begin{array}{rcll}
{}^{70}Ge\ (21\%) + n & \rightarrow & {}^{71}Ge\ (\sigma_T = 3.43 \pm 0.17\ \text{b},\ \sigma_R = 1.5\ \text{b}) & \\
{}^{71}Ge & \rightarrow & {}^{71}Ga\ (t_{1/2} = 11.4\ \text{day}) & \text{Acceptor} \\
 & & & \\
{}^{74}\text{Ge}\ (36\%) + n & \rightarrow & {}^{75}\text{Ge}\ (\sigma_T = 0.51 \pm 0.08\ \text{b},\ \sigma_R = 1.0 \pm 0.2\ \text{b}) & \\
{}^{75}\text{Ge} & \rightarrow & {}^{75}\text{As}\ (t_{1/2} = 83\ \text{min}) & \text{Donor} \\
 & & & \\
{}^{76}\text{Ge}\ (7.4\%) + n & \rightarrow & {}^{77}\text{Ge}\ (\sigma_T = 0.16 \pm 0.014\ \text{b},\ \sigma_R = 2.0 \pm 0.35\ \text{b}) & \\
{}^{77}\text{Ge} & \rightarrow & {}^{77}\text{Se}\ (t_{1/2} = 38.8\ \text{hr}) & \text{Double Donor}
\end{array}$$

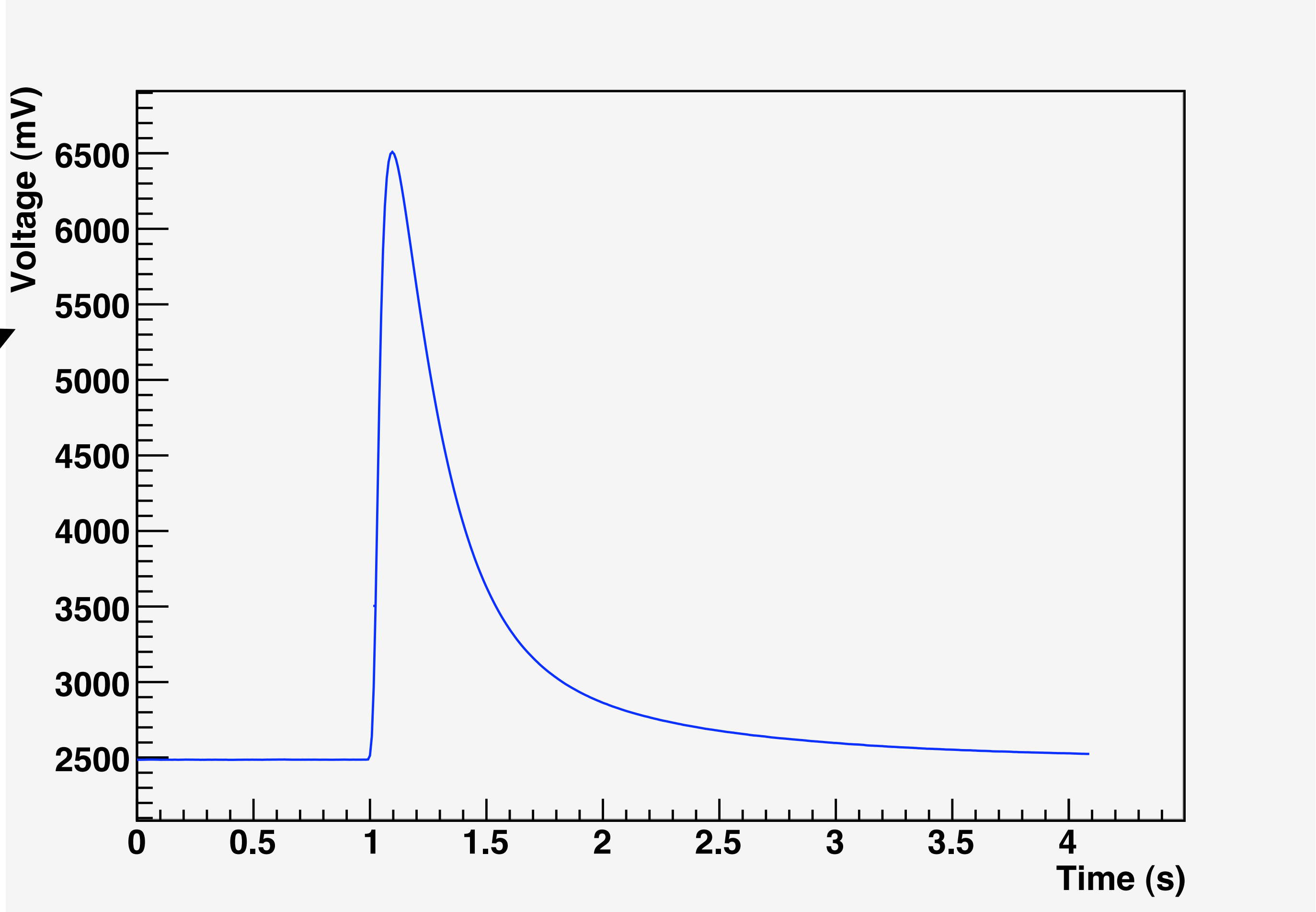
Temperature pulses



Excellent energy resolution:
average resolution of CUORICINO big crystals was about 7 keV FWHM at 2615 keV ≈ 0.27%
(CUORE goal is 5 keV FWHM at 2615 keV ≈ 0.19%).

However, no other information such as event location within crystal or particle identification

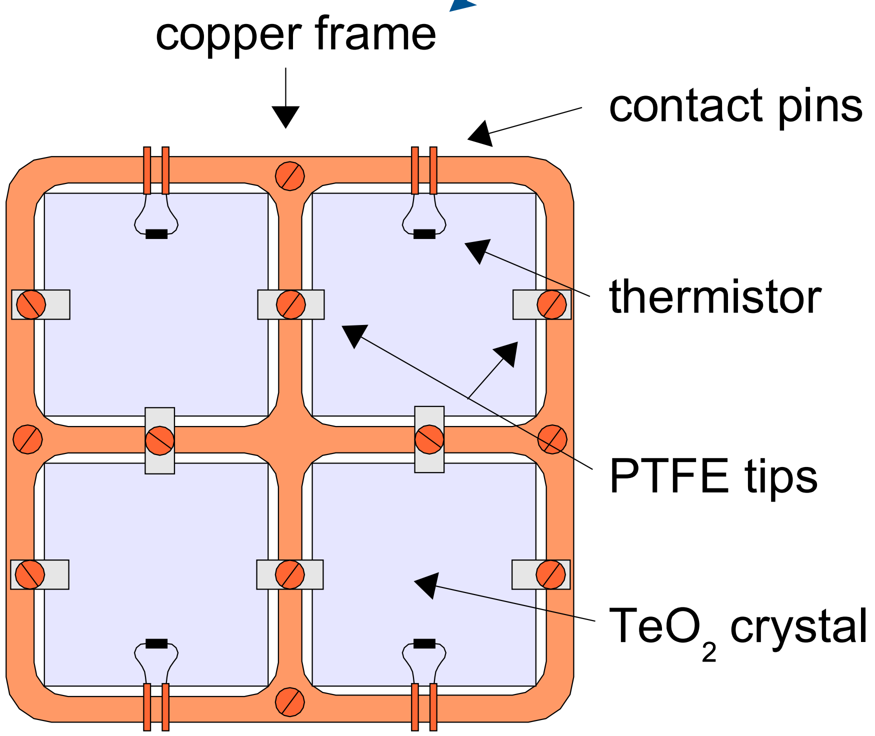
Thermistor voltage, after amplification

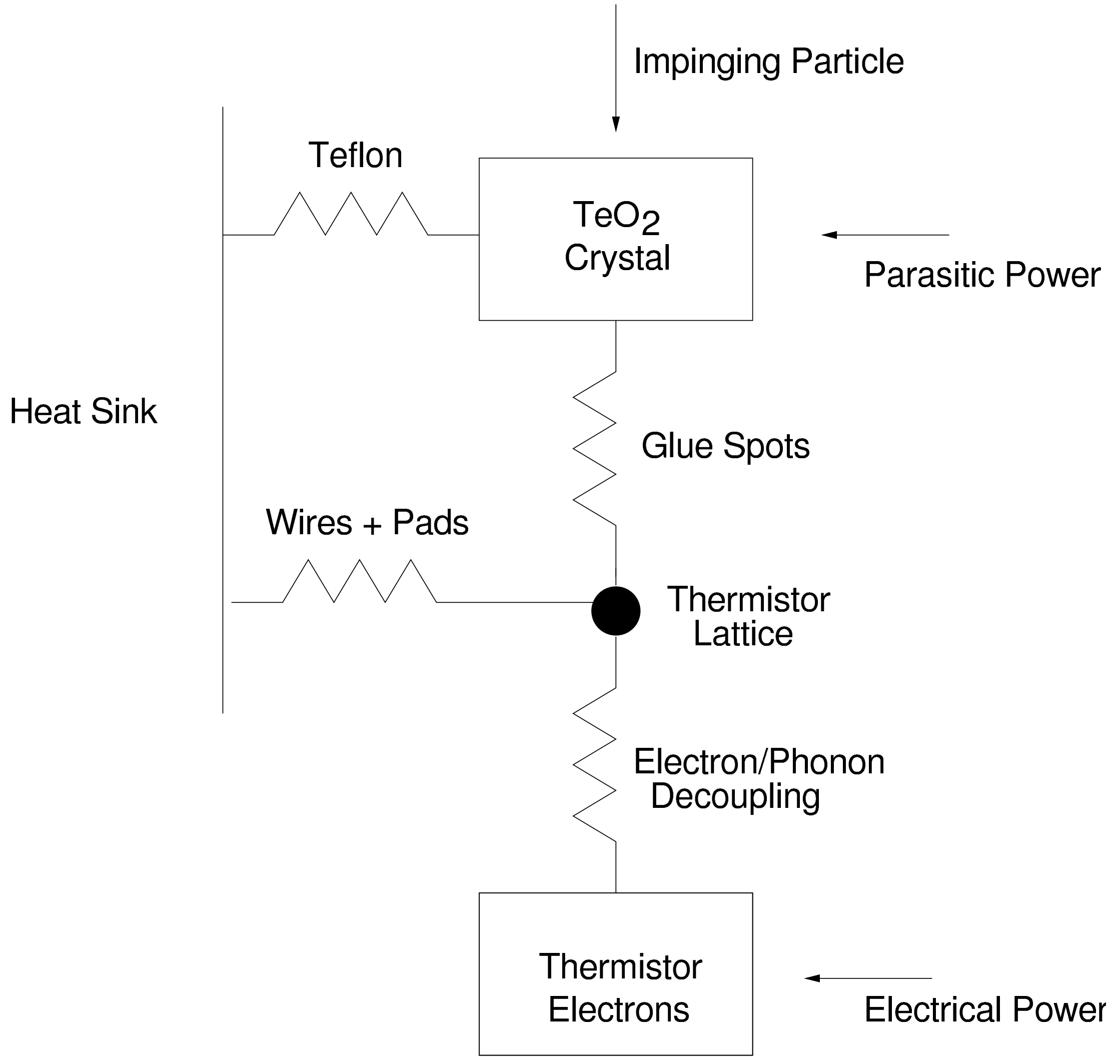


Slow signals, ok for a low background experiment

Resolution of CUORICINO bolometers

connected to mixing chamber of dilution refrigerator (heat sink)





Thermodynamic limit on energy resolution:

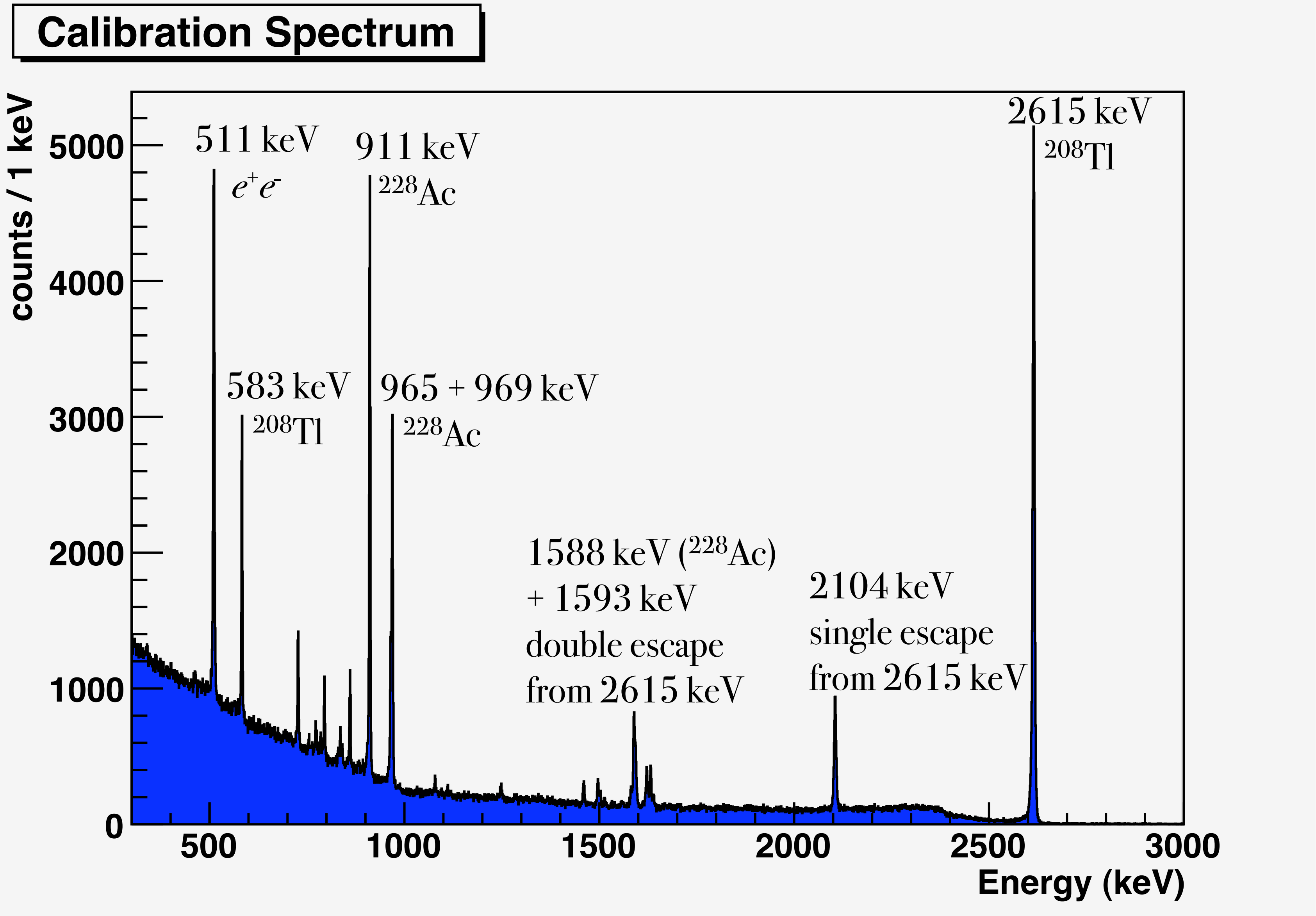
$\Delta E = \xi \sqrt{k_B C T^2}$ (independent of energy)

due to exchange of phonons with heat sink

$\Delta E \sim$ tens of eV for kg size crystals

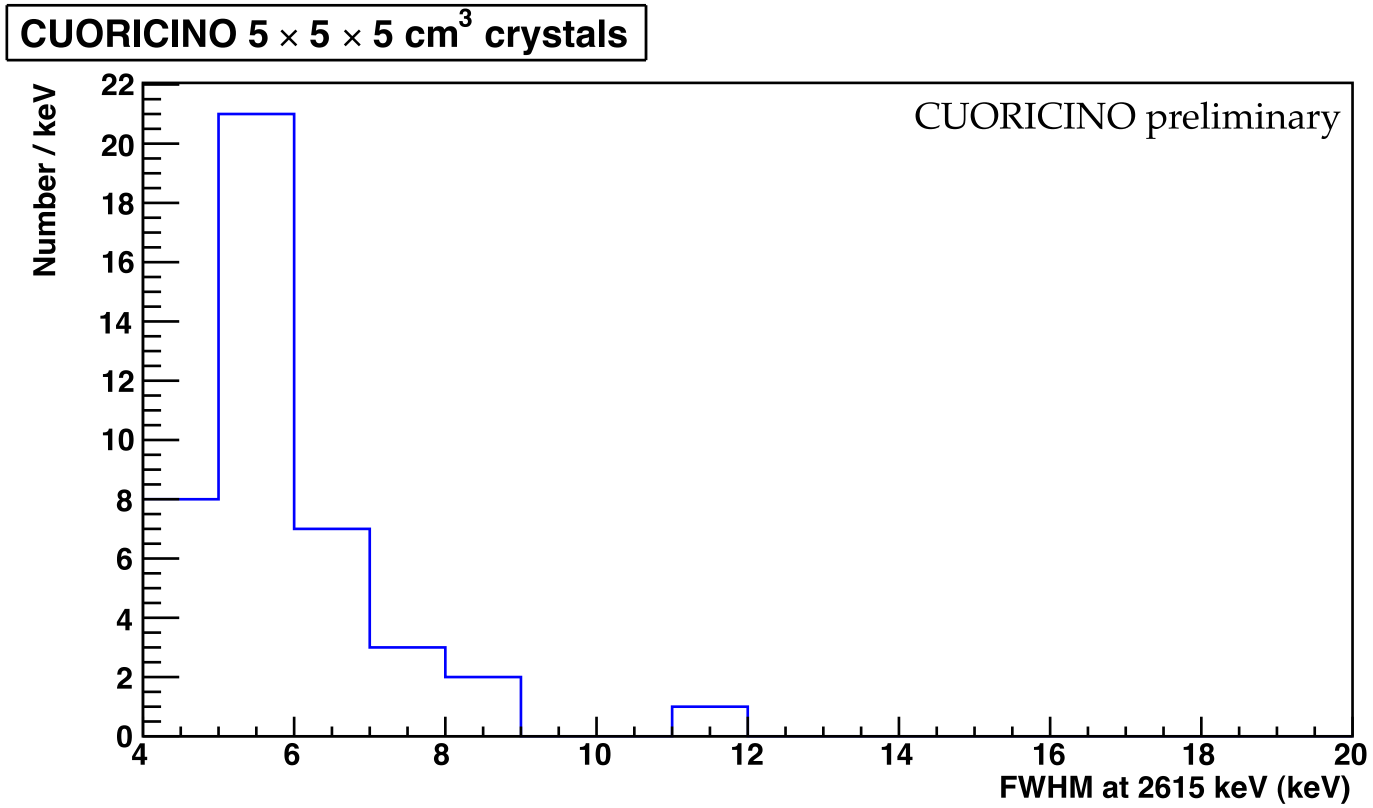
Extrinsic noise sources, mainly mechanical vibrations, determine observed resolutions.

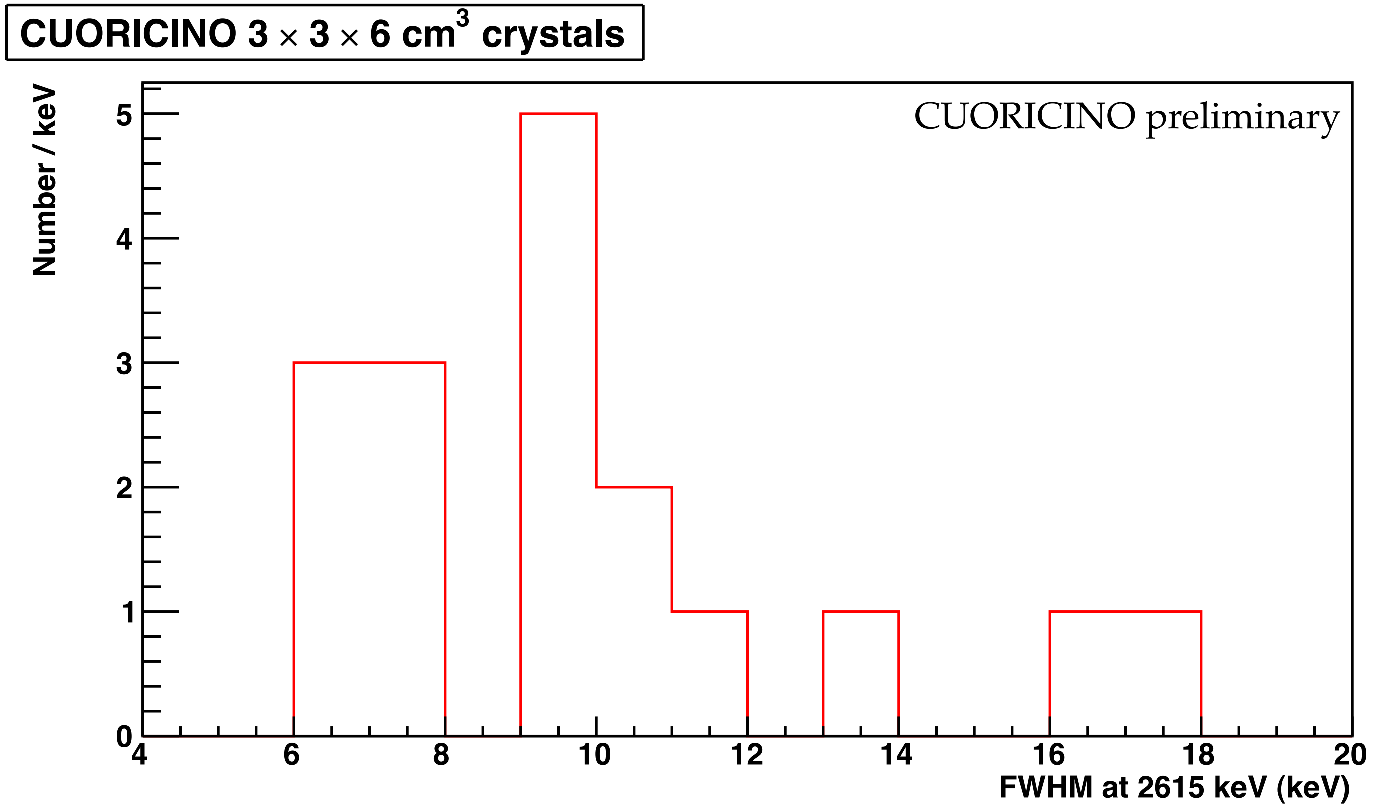
Calibration of CUORICINO



- Th source calibration every 1–2 months lasting 2–3 days
- Calibration data used to derive relationship between pulse amplitudes and energies and for obtaining resolutions at 2615 keV

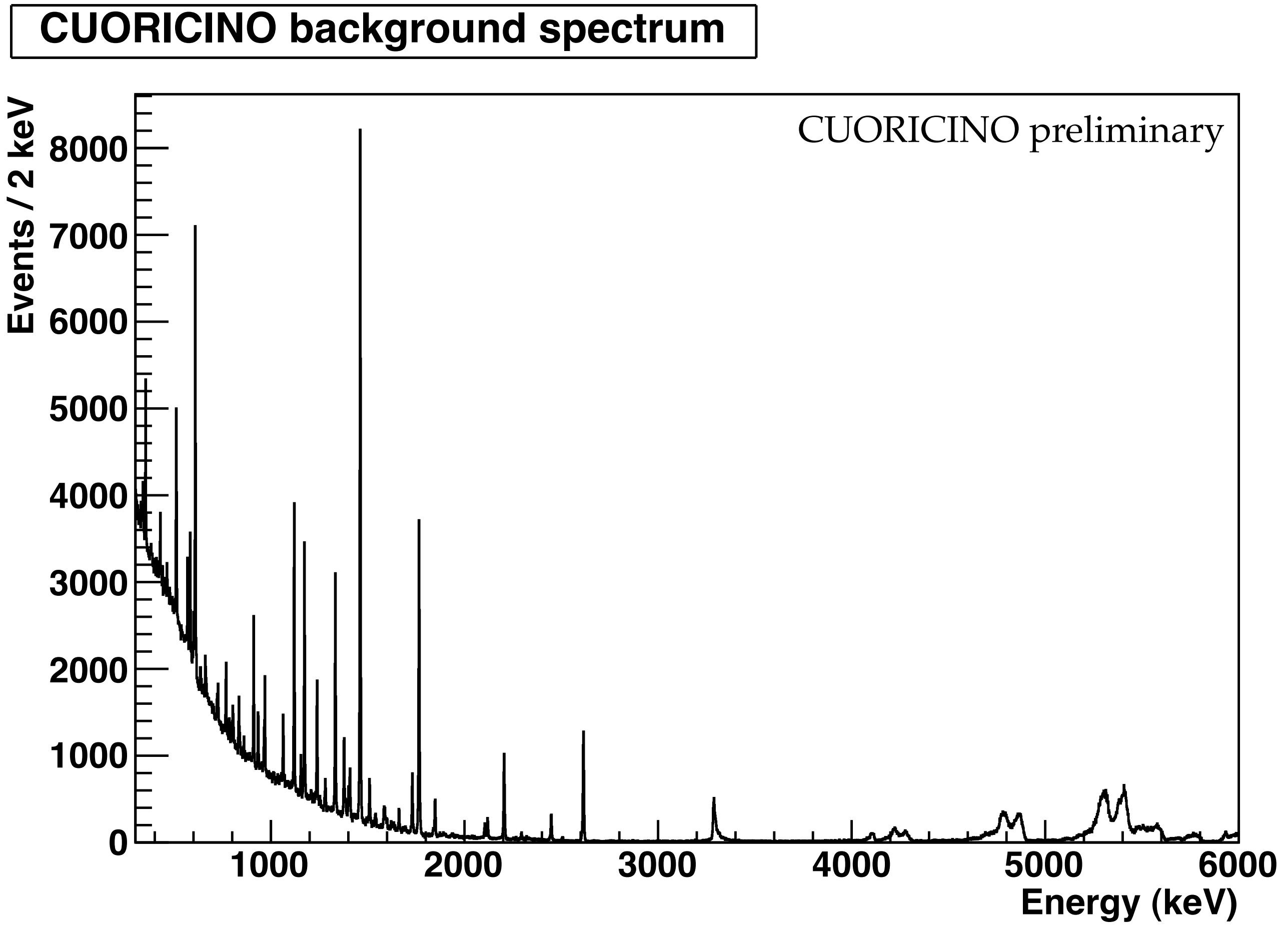
Resolutions at 2615 keV

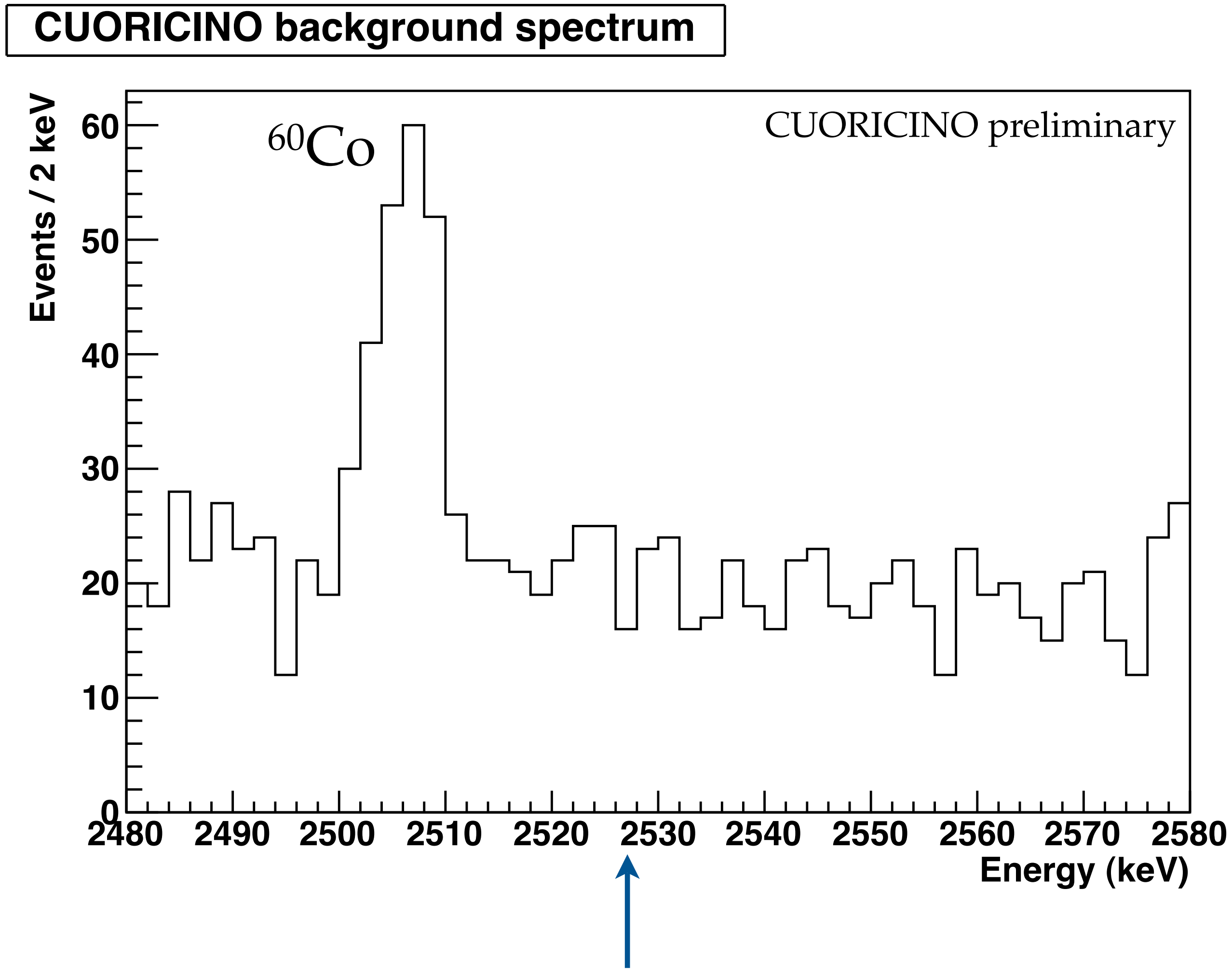




CUORICINO background spectrum

anti-coincidence cut applied

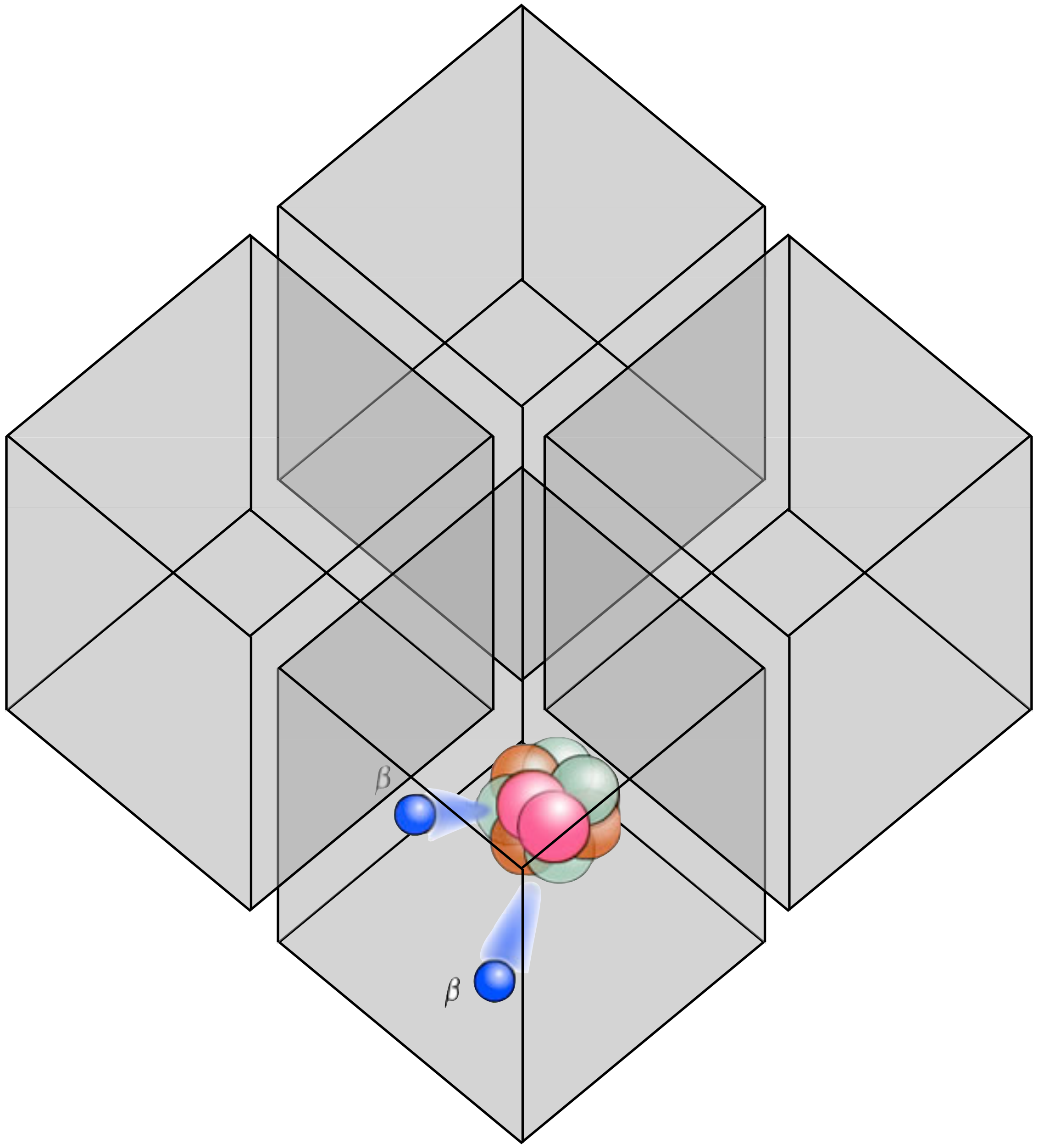




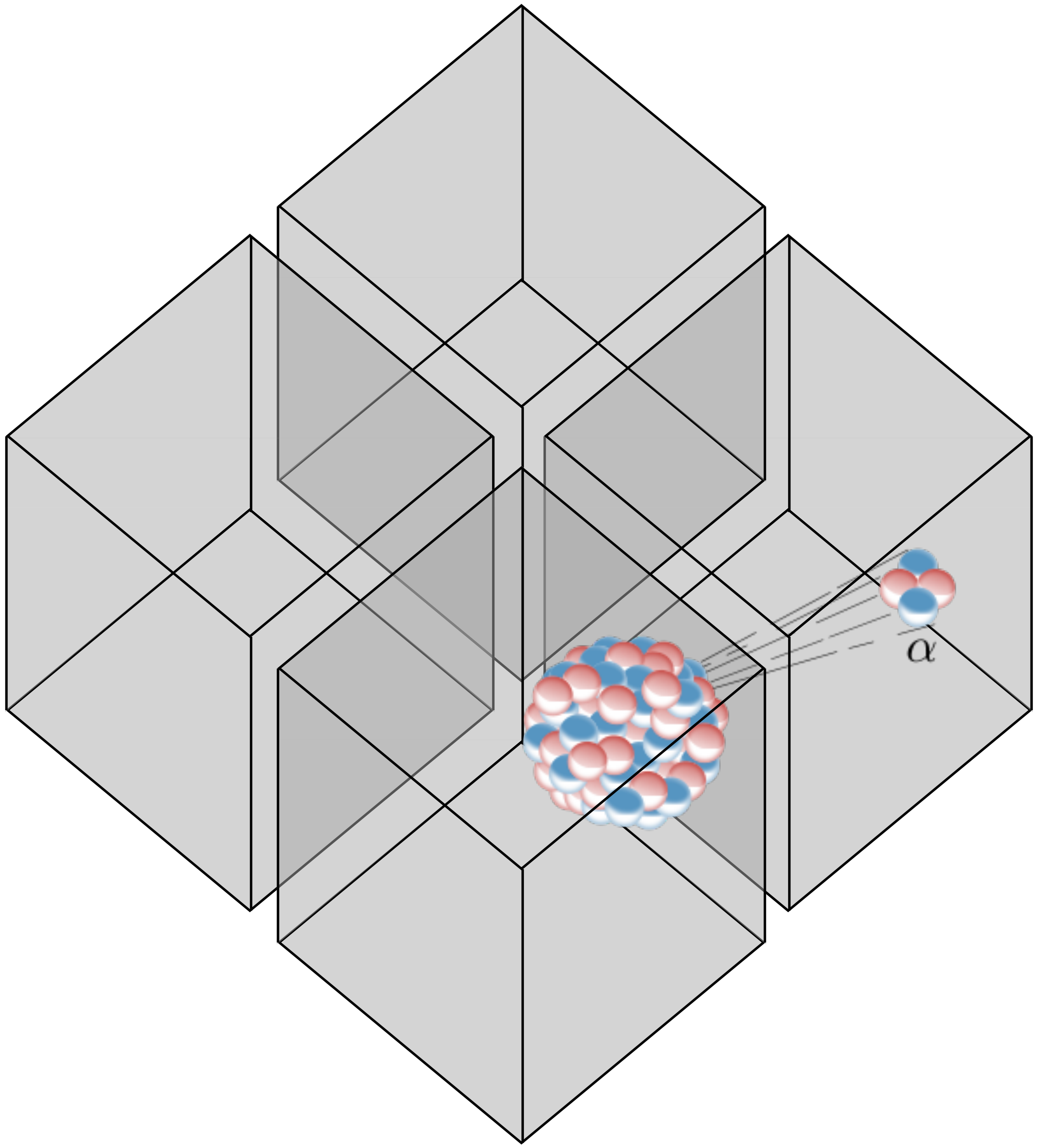
^{130}Te Q-value

Crystal type	background counts / (keV · kg · yr)
$5 \times 5 \times 5$ cm^3	0.18 ± 0.01
$3 \times 3 \times 6$ cm^3	0.20 ± 0.04

Anti–coincidence



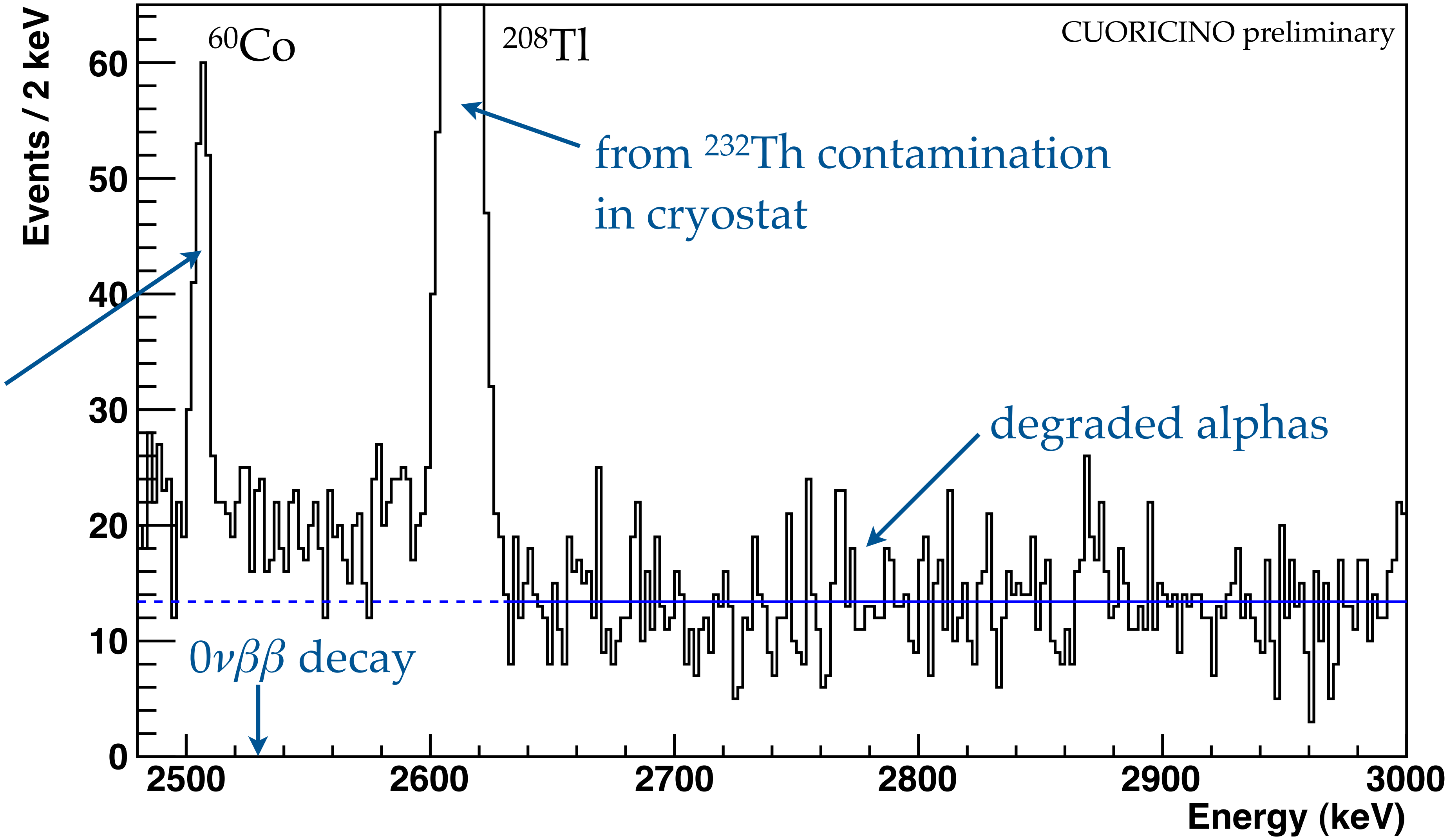
The electrons from a $0\nu\beta\beta$-decay event stop in one crystal 86.3% of the time (84.5% for the small crystals).



Many backgrounds, such as muons, alpha decays near crystal surfaces, and Compton-scattered gammas, deposit energy in multiple crystals in coincidence.

Background sources

CUORICINO background spectrum



Sum of 1173 keV and 1333 keV gamma-ray cascade in beta decay of ^{60}Co. Most likely due to cosmic ray activation of copper.

from ^{232}Th contamination in cryostat

degraded alphas

$0\nu\beta\beta$ decay

Contribution	Source
$(50 \pm 20)\%$	degraded alpha particles from ^{238}U and ^{232}Th contaminations on copper surfaces
$(10 \pm 5)\%$	degraded alpha particles from ^{238}U and ^{232}Th contaminations on crystal surfaces
$(40 \pm 10)\%$	multiple Compton events from 2615 keV gamma of ^{208}Tl

New ^{130}Te Q-value measurements

Two new measurements of the $\beta\beta$ decay Q-value of ^{130}Te were published in 2009.

Q-value (keV)	**Reference**
2530.3(2.0)	2003 Atomic Mass Evaluation recommended value G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003)
2527.01(32)	N. D. Scielzo *et al.*, Phys. Rev. C 80, 025501 (2009)
2527.518(13)	M. Redshaw *et al.*, Phys. Rev. Lett. 102, 212502 (2009)

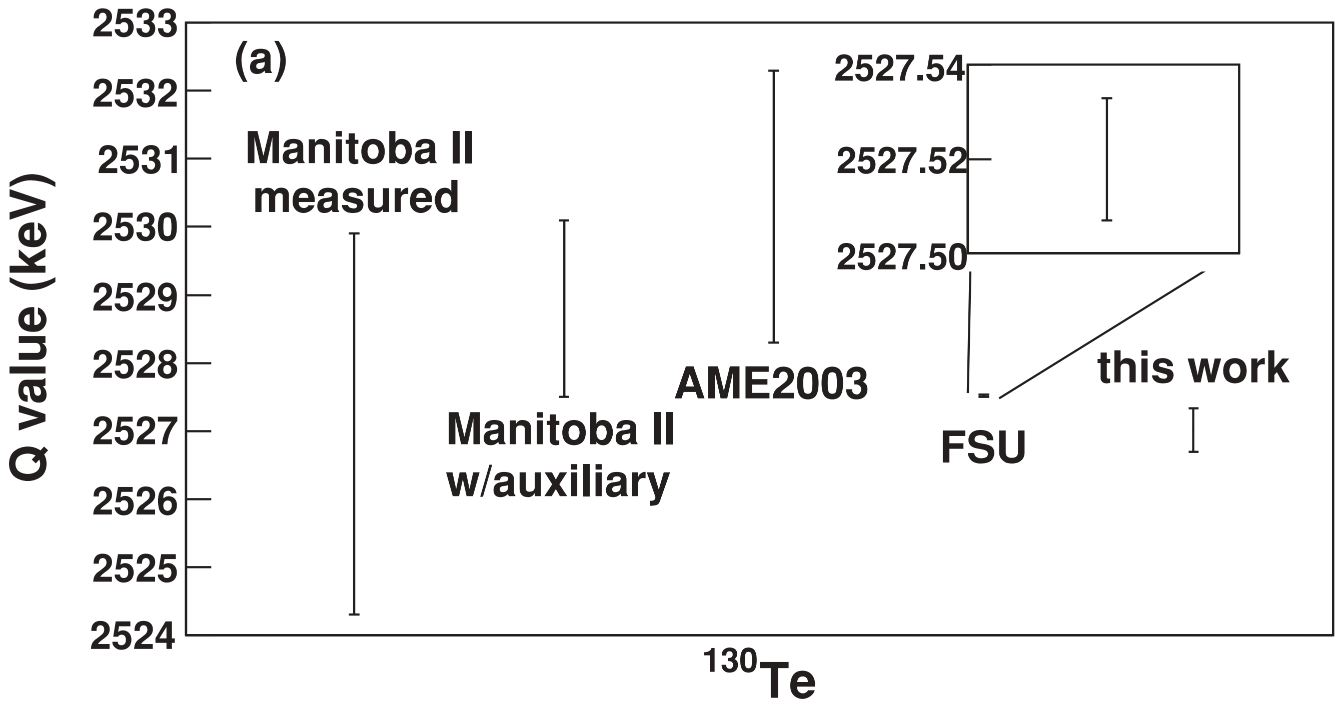
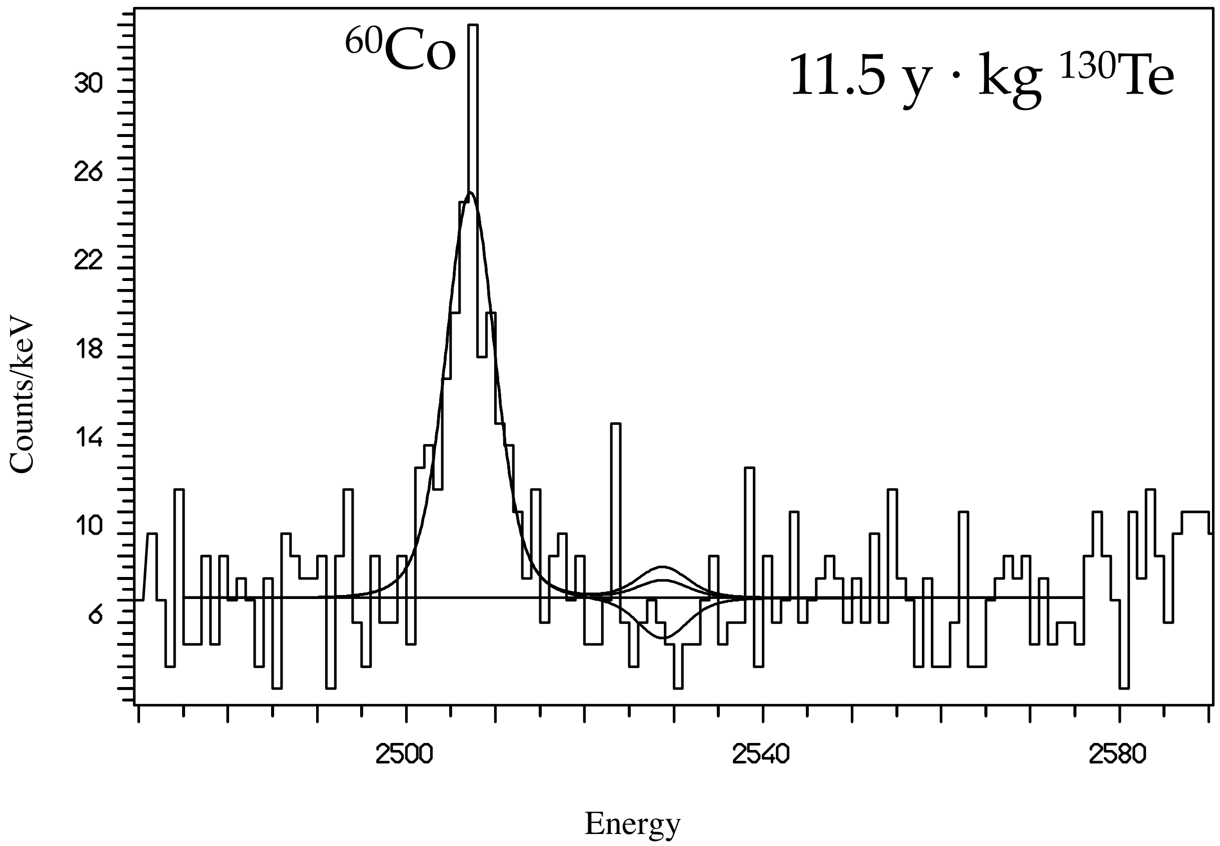
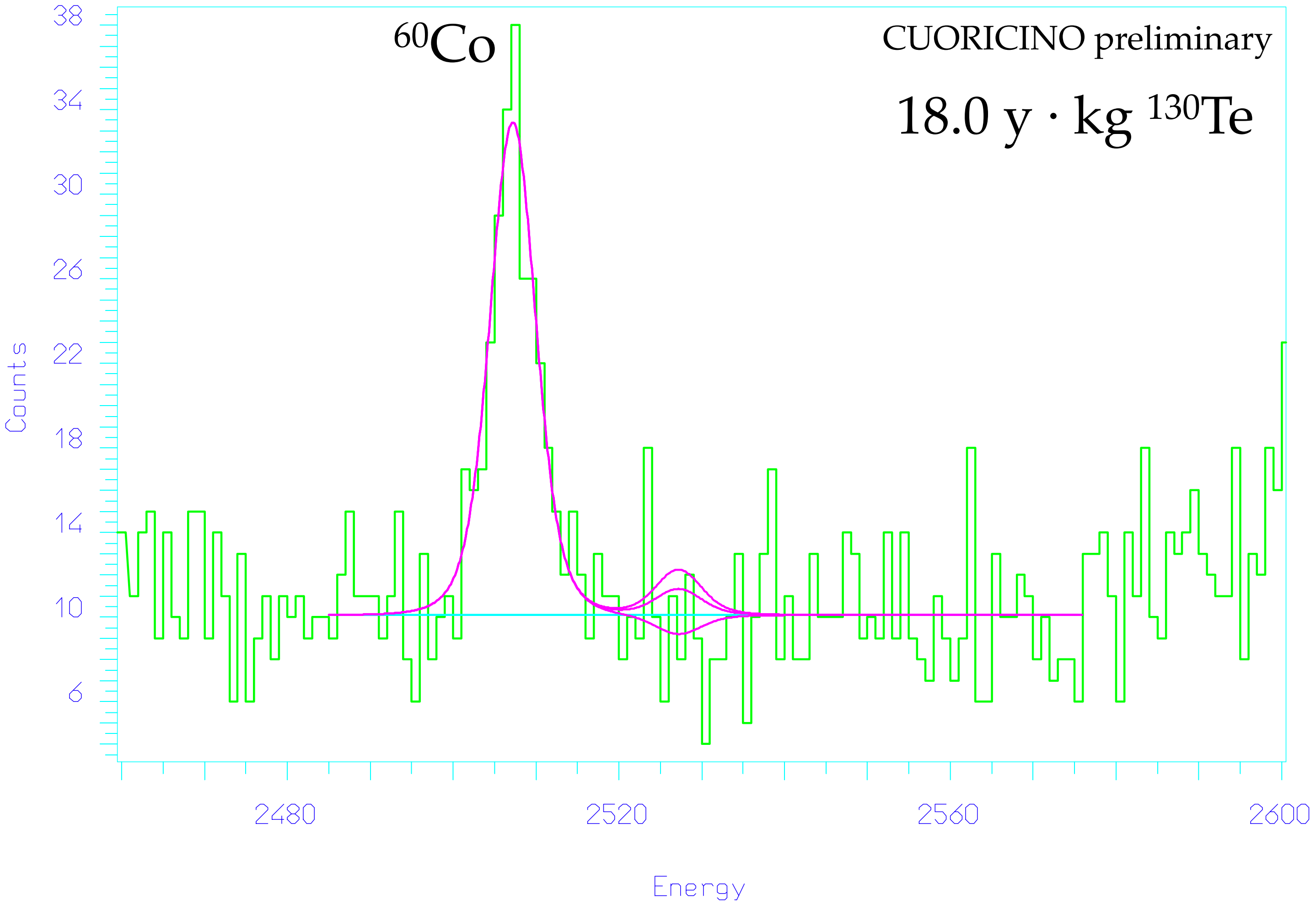


Figure from N. D. Scielzo *et al.*, Phys. Rev. C 80, 025501 (2009)

Results from CUORICINO





Q-value = 2530.3 keV

Phys. Rev. C 78, 035502 (2008)

$$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 3.0 \times 10^{24}\ \mathrm{y}\ (90\%\ \mathrm{C.L.})$$

$$\langle m_{\beta\beta} \rangle < 0.19 - 0.68\ \mathrm{eV}$$

Limit aided by downward fluctuation of background in signal region

Q-value = 2527.5 keV

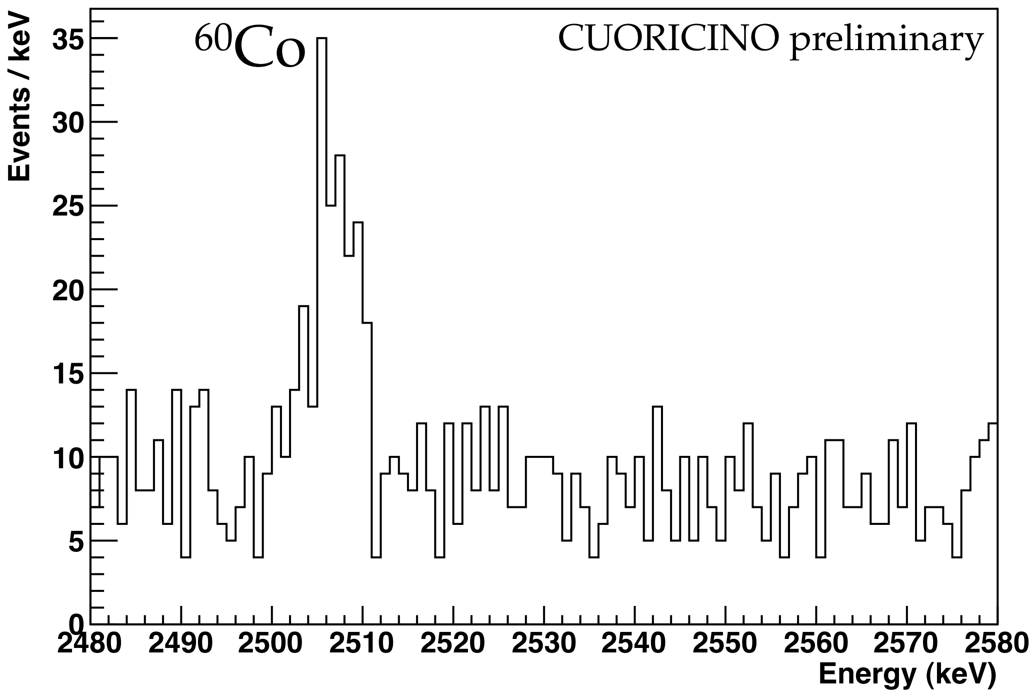
(preliminary)

$$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 2.9 \times 10^{24}\ \mathrm{y}\ (90\%\ \mathrm{C.L.})$$

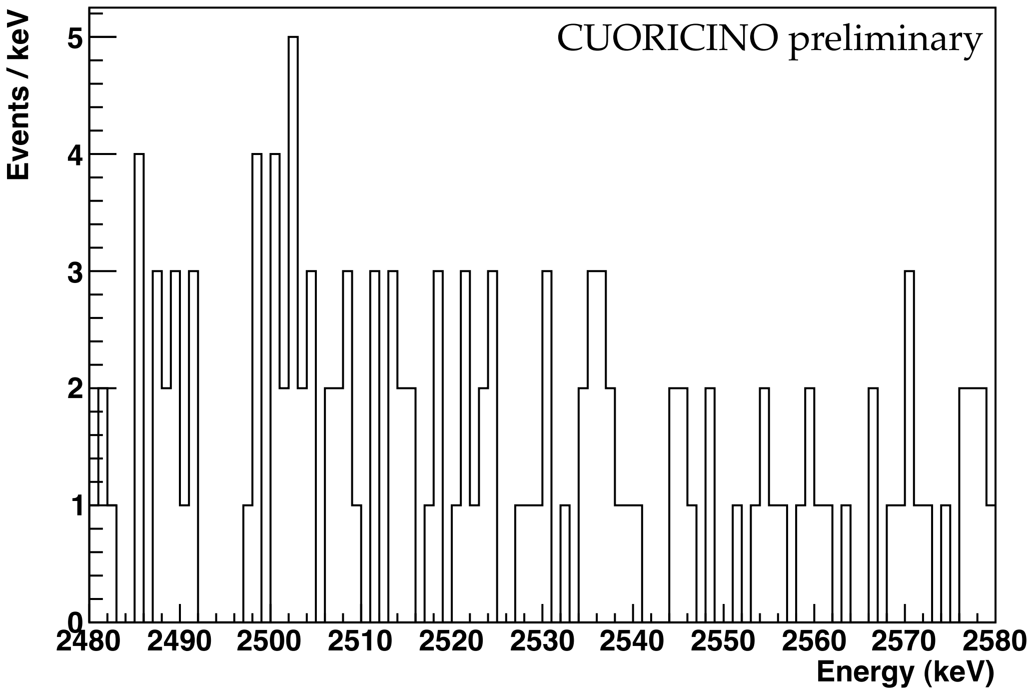
$$\langle m_{\beta\beta} \rangle < 0.20 - 0.69\ \mathrm{eV}$$

Fitting technique

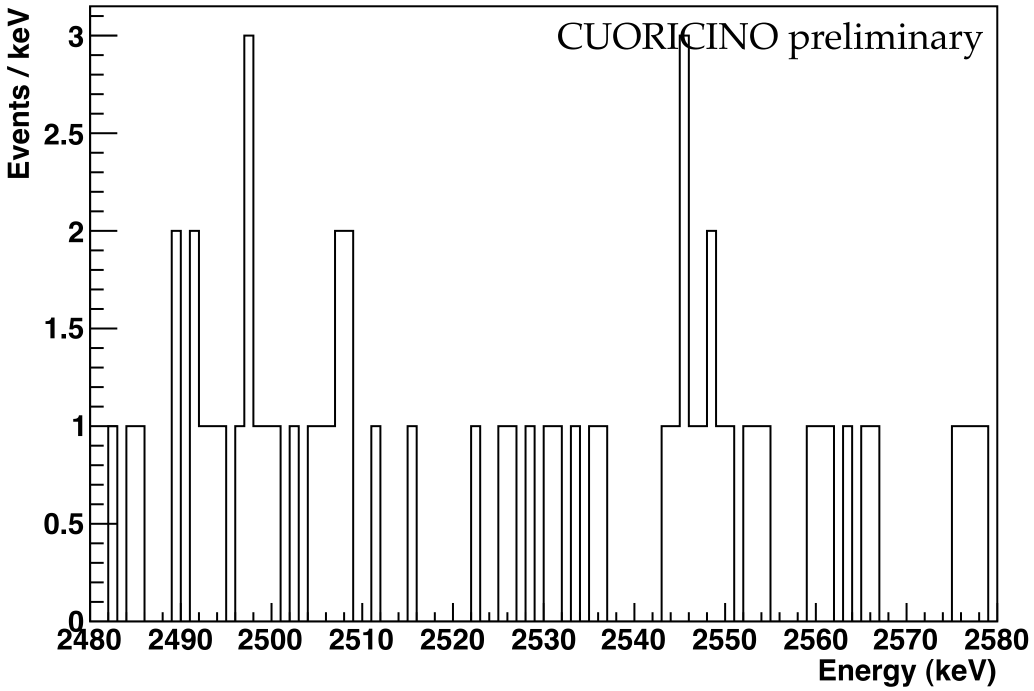
CUORICINO big crystals



CUORICINO small natural crystals



CUORICINO small enriched crystals



Simultaneous fit to three spectra

$$\text{response function} = \sum_{i=1}^{N} \text{gaus}(Q, \sigma_i) \times \text{exposure}(i)$$

Background includes a flat component and a Gaussian component for ^{60}Co.

Likelihood function is used to obtain the 90% C.L. limit, following the Bayesian method with a flat prior in the physical region.

Finalizing the analysis

- Analysis of complete CUORICINO data set is being performed with new software developed for CUORE – opportunity to debug, improve, and validate new software with existing data.
- Thorough checks of data quality are in the final stages.
- Potential improvements being tested: treating each detector separately in the analysis and doing a simultaneous fit to all independent detectors, each with its own resolution. We are also trying taking into account variation in the resolution over time.

Conclusions

- CUORICINO has set the strongest limit on the $0\nu\beta\beta$ decay rate of ^{130}Te:

$$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 2.9 \times 10^{24}\ \mathrm{y}\ (90\%\ \mathrm{C.L.}) \quad \text{(preliminary)}$$

- CUORICINO has set one of the most stringent limits on the effective neutrino mass:

$$\langle m_{\beta\beta} \rangle < 0.20 - 0.69\ \mathrm{eV} \quad \text{(preliminary)}$$

- The analysis of the complete CUORICINO data set is being finalized.
- CUORICINO demonstrated the technology for CUORE in a large scale bolometric experiment that operated for several years with good energy resolution and low background.