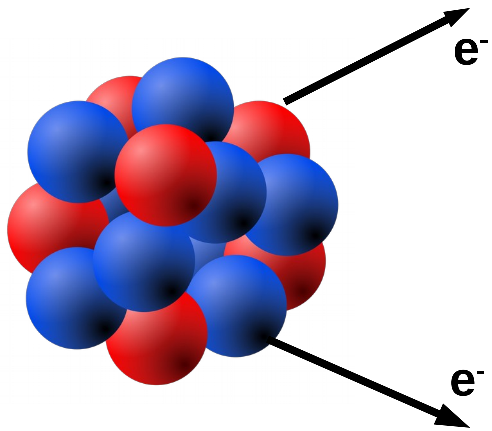
New results from the CUORE experiment

S. Di Domizio
Genova University and INFN
for the CUORE collaboration

ICPPA 2020 – Oct 9 2020

Neutrinoless double-beta decay



Decay: allowed on even-even nuclei

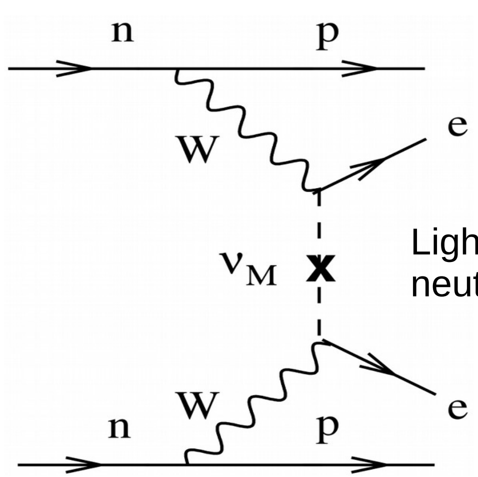
Signature: 2 electrons with fixed sum energy

Implications: ΔL=2, Majorana neutrinos

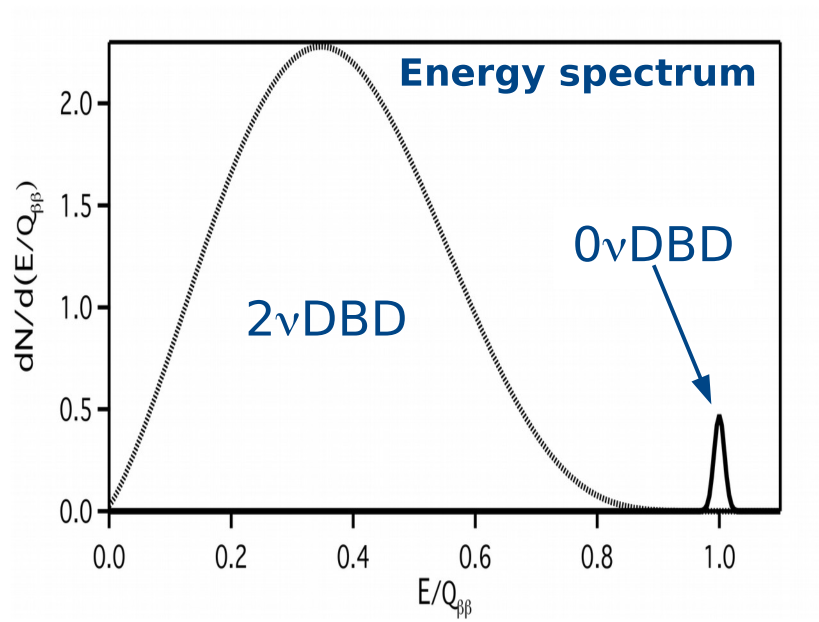
Half-life limits: $10^{25} - 10^{26}$ y

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

Make assumptions on decay mechanism
→ measure the effective neutrino mass



Light Majorana neutrino exchange



$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu} \; |M^{0\nu}|^2 \; \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

sensitivity: $\propto \; \varepsilon \sqrt{\frac{M\cdot t}{b\cdot\Delta E}}$

CUORE

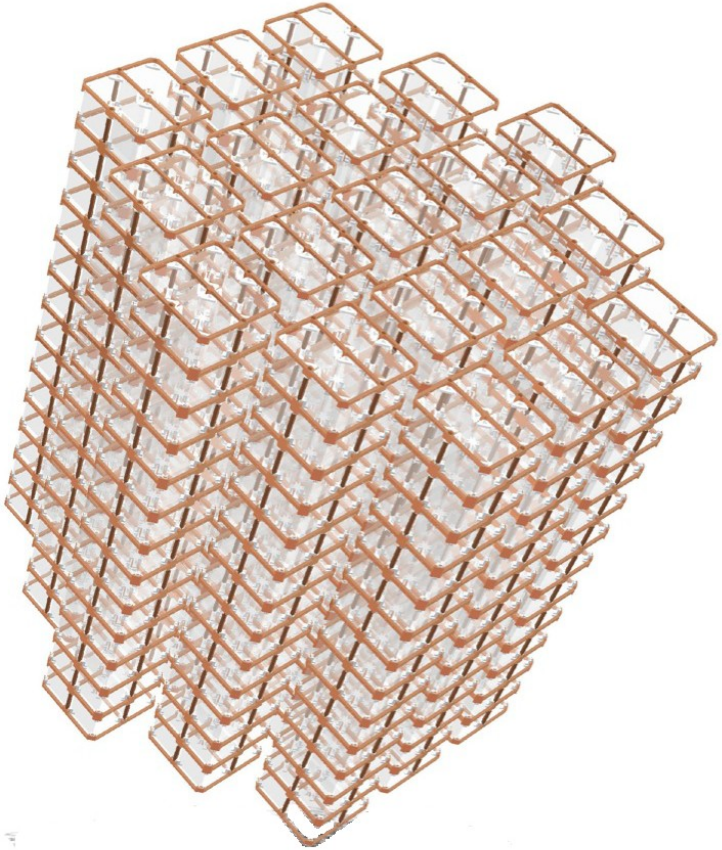
Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

- Search for $0\nu\beta\beta$ decay in ^{130}Te (Q = 2527.5 keV)
- 988 TeO_2 bolometers operated at 10 mK
- Arranged in 19 towers
- 742 kg of TeO_2 (206 kg of ^{130}Te)
- Background aim: 0.01 counts/(keV·kg·y)
- Energy resolution aim: 5 keV FWHM

half-life sensitivity in 5 y

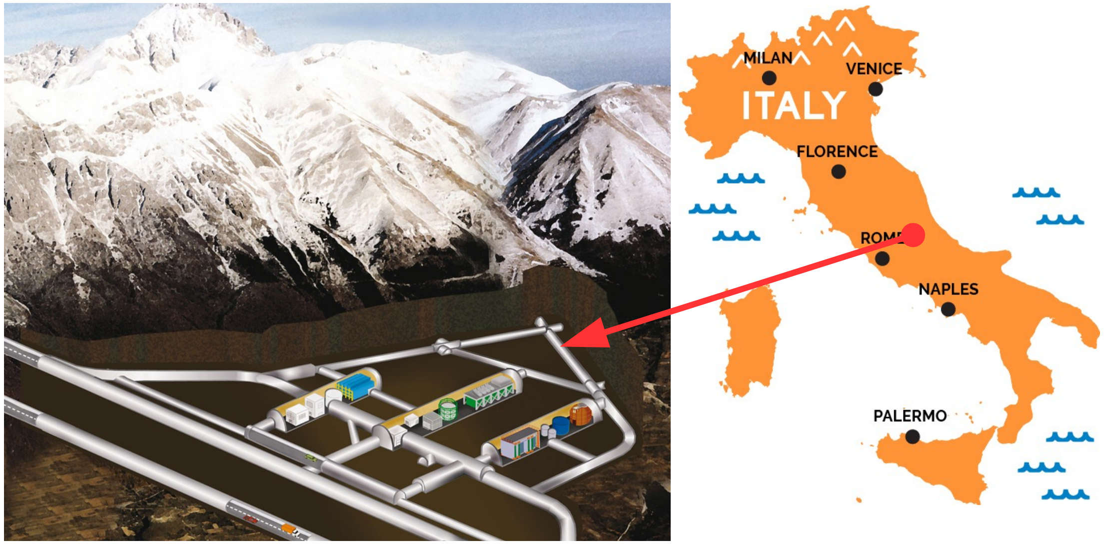
$S^{0\nu}(^{130}Te) = 9 \times 10^{25}$ y (90% CL)

Eur. Phys. J. C77 (2017), 532



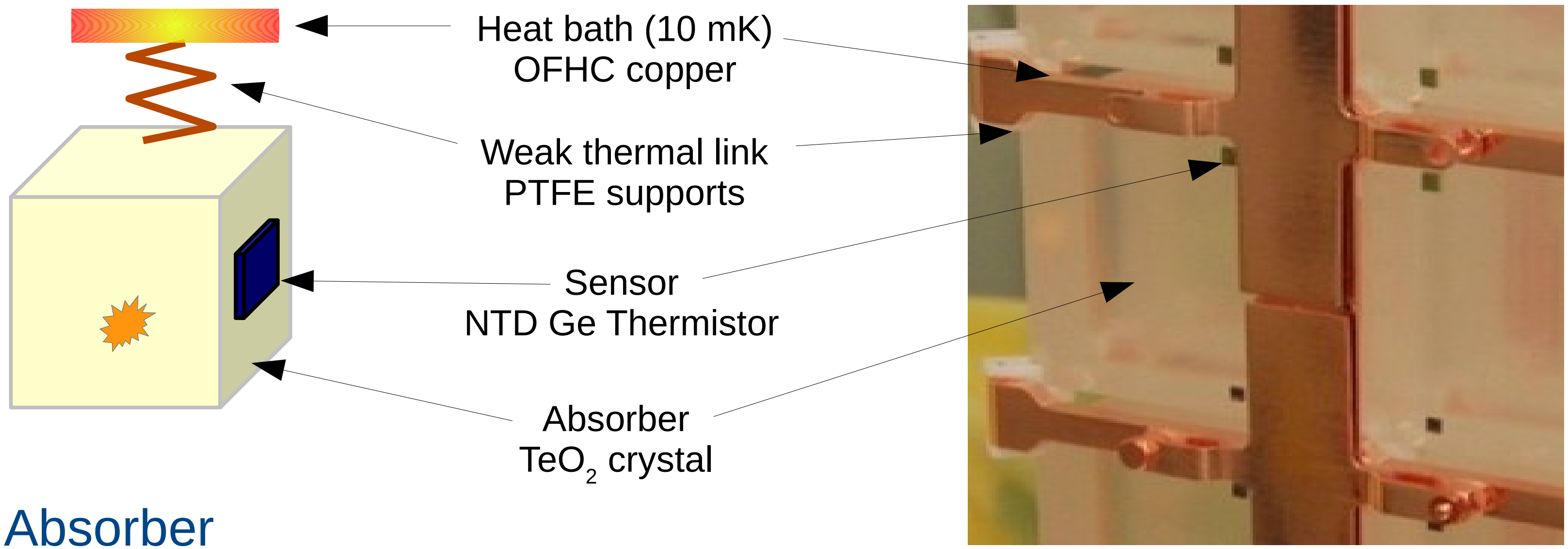
Adv. in High En. Phys. 2015 (2015), 879871

Located underground at the Laboratori Nazionali del Gran Sasso of INFN



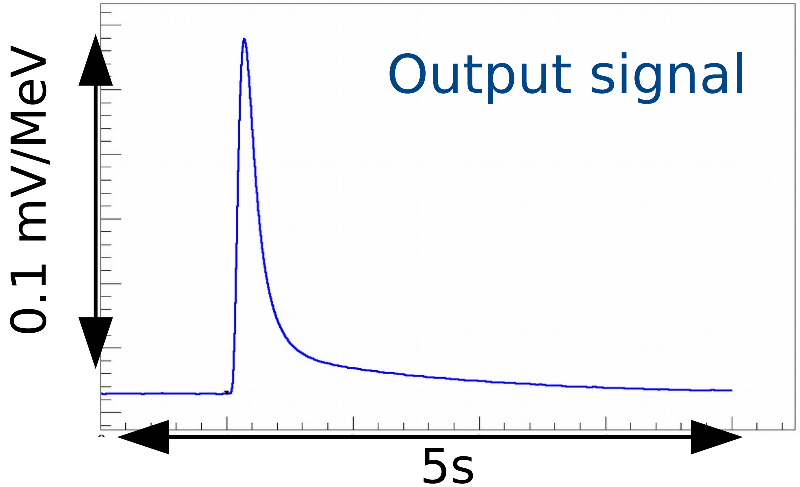
Experimental technique

Measure the temperature rise of the absorber crystal: $\Delta T = \frac{E}{C}$



Absorber

- Dimension: 5x5x5 cm^3
- Mass: 0.75 kg
- Heat capacity: $2x10^{-9}$ J/K
- $\Delta T/\Delta E$ ~ 10 – 20 μK/MeV



Sensor

- $R = R0 \exp[(T_0/T)^{1/2}]$
- R ~ 100 MΩ
- $\Delta R/\Delta E$ ~ 3 MΩ/MeV

Towers construction

Tower construction completed in 2014

Towers stored nitrogen atmosphere before installation

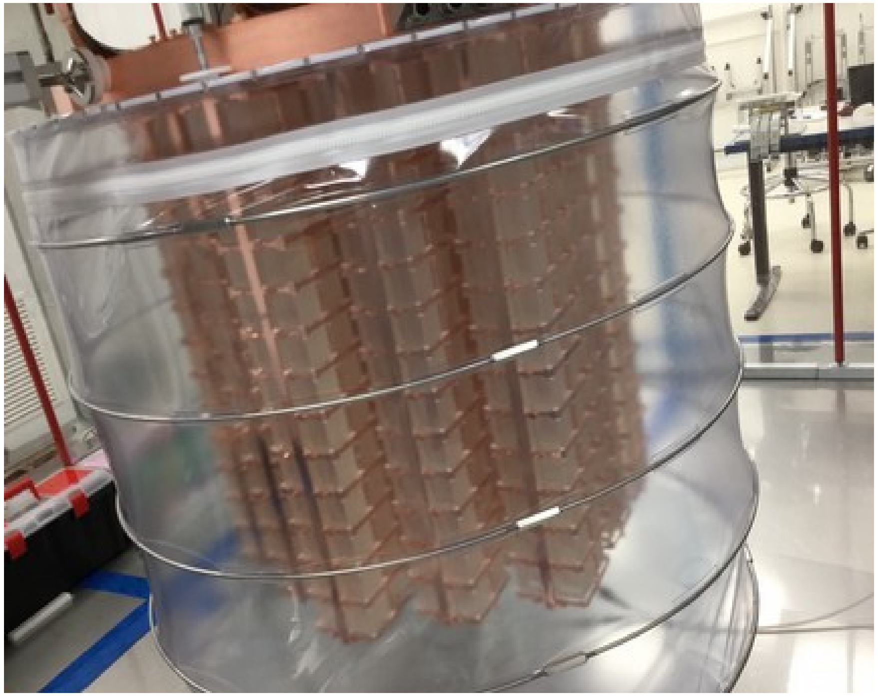
Towers installation

Installation in summer 2016

Performed in Rn-free air (< 1Bq/m^3)

Towers enclosed in nitrogen-flushed protective bag over night

First and only time when the towers were exposed to air



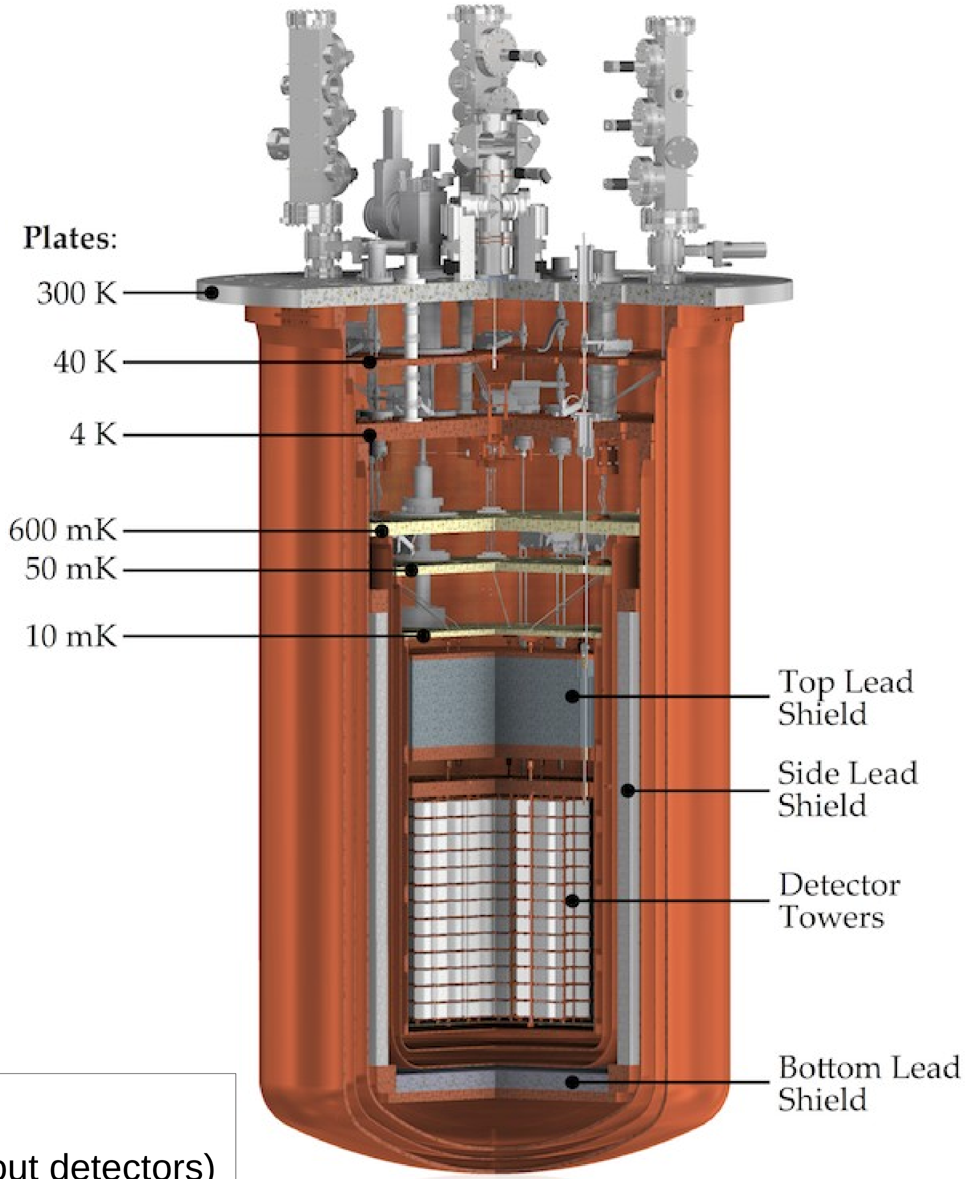
Cryostat

Cool a ton-scale detector at 10 mK in a radiopure, low noise environment

- Total cryostat mass: 30 t
- Mass below 4K: 15 t
- Mass below 50 mK: 3 t

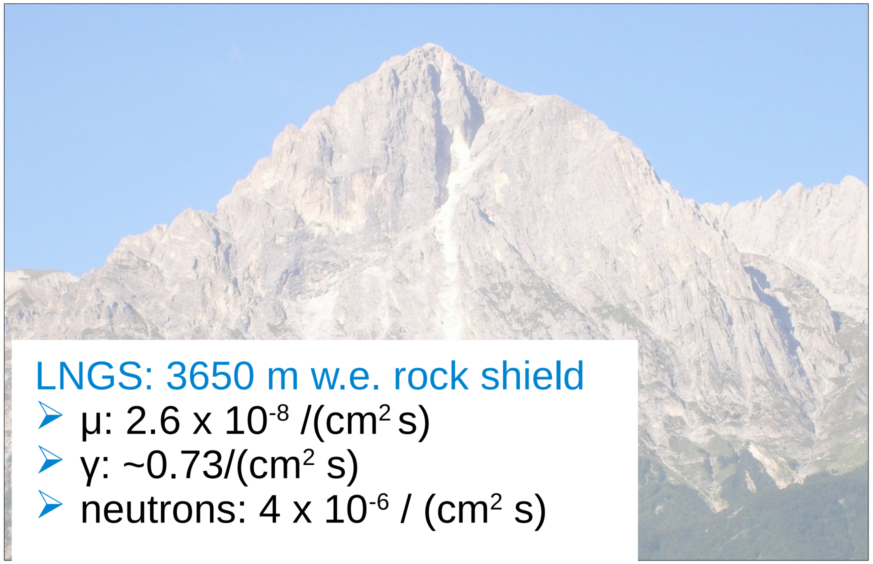
Nominal cooling power: 3μW at 10 mK

- Cryogen-free apparatus
- Fast cooling system: gas exchange down to 50K
- 5 pulse tubes down to 4K
- Dilution unit: down to ~10mK
- Suspension system: detectors are mechanically isolated from the cryostat vibrations



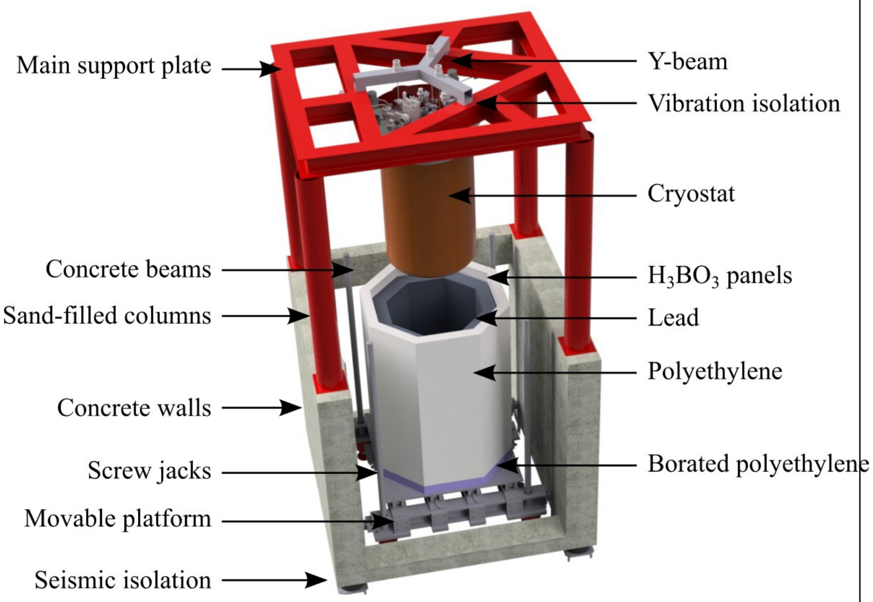
Cryostat commissioning completed in 2016
Reached a stable base temperature < 6 mK (without detectors)

Radiation shields



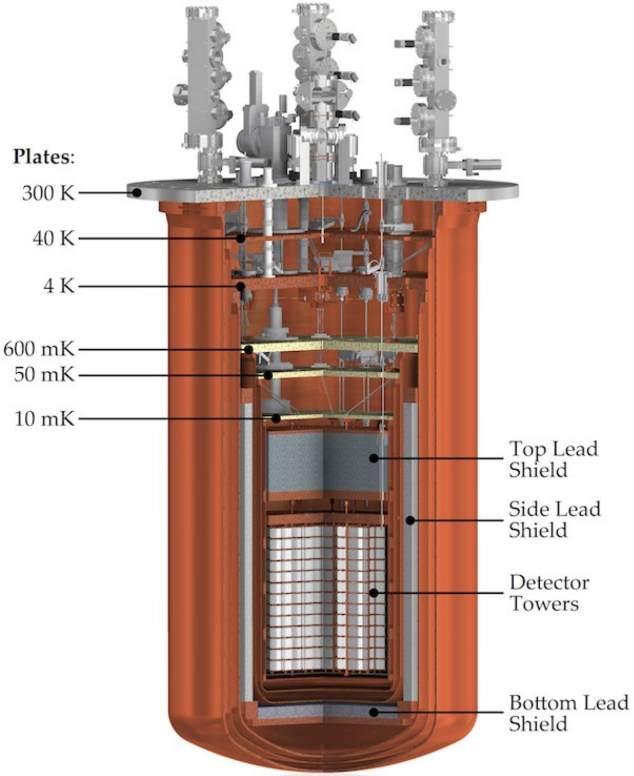
LNGS: 3650 m w.e. rock shield
- μ: 2.6 x 10^{-8} /(cm^2 s)
- γ: ~0.73/(cm^2 s)
- neutrons: 4 x 10^{-6} / (cm^2 s)

External shields: H_3BO_3 and lead

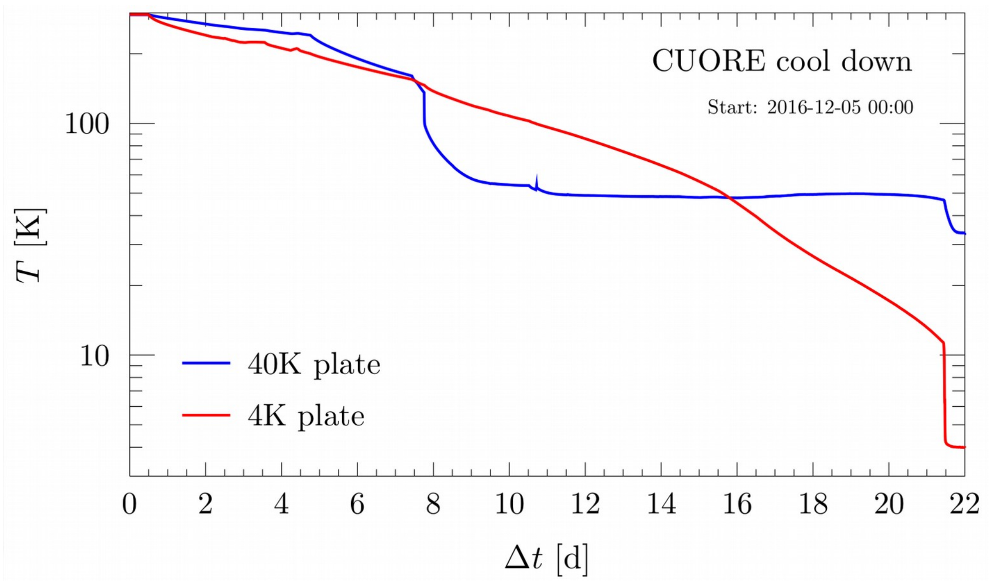


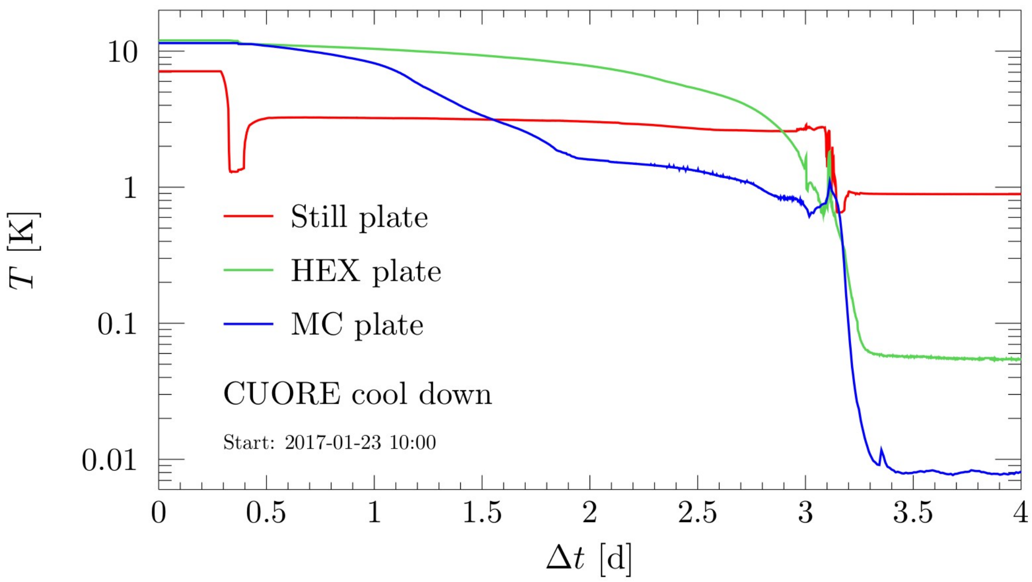
Inner (cold) shields

- Top: low ^{210}Pb activity lead
- Side and bottom: ancient roman lead

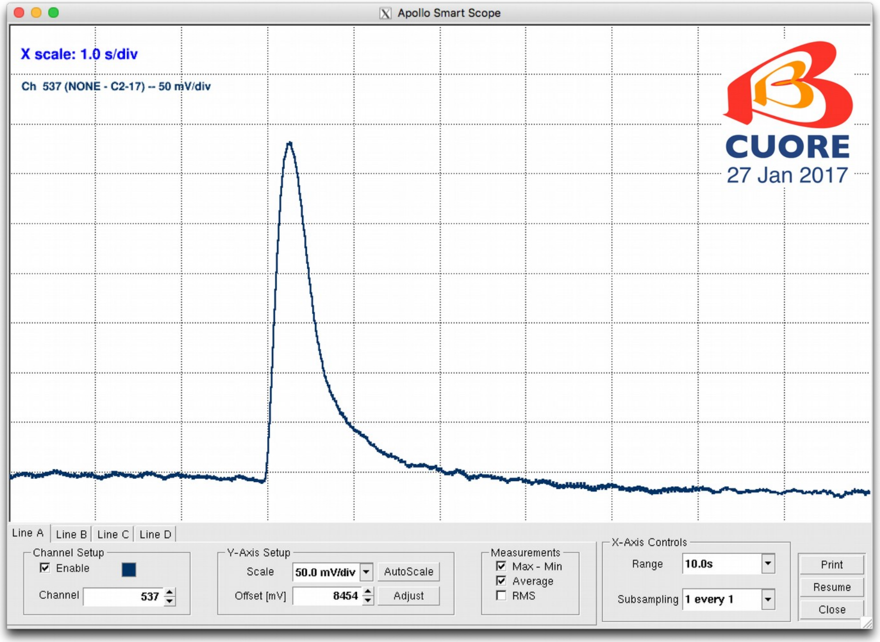


Cool down



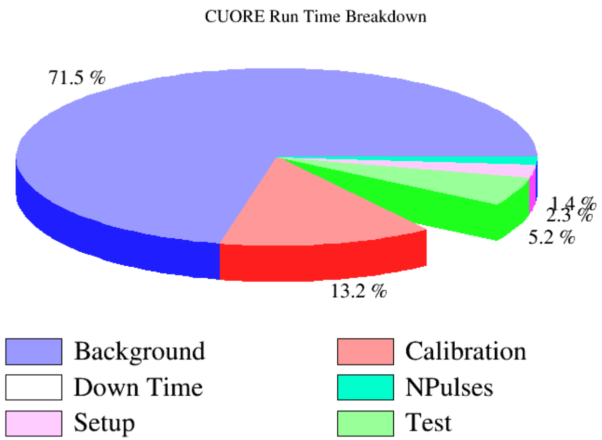


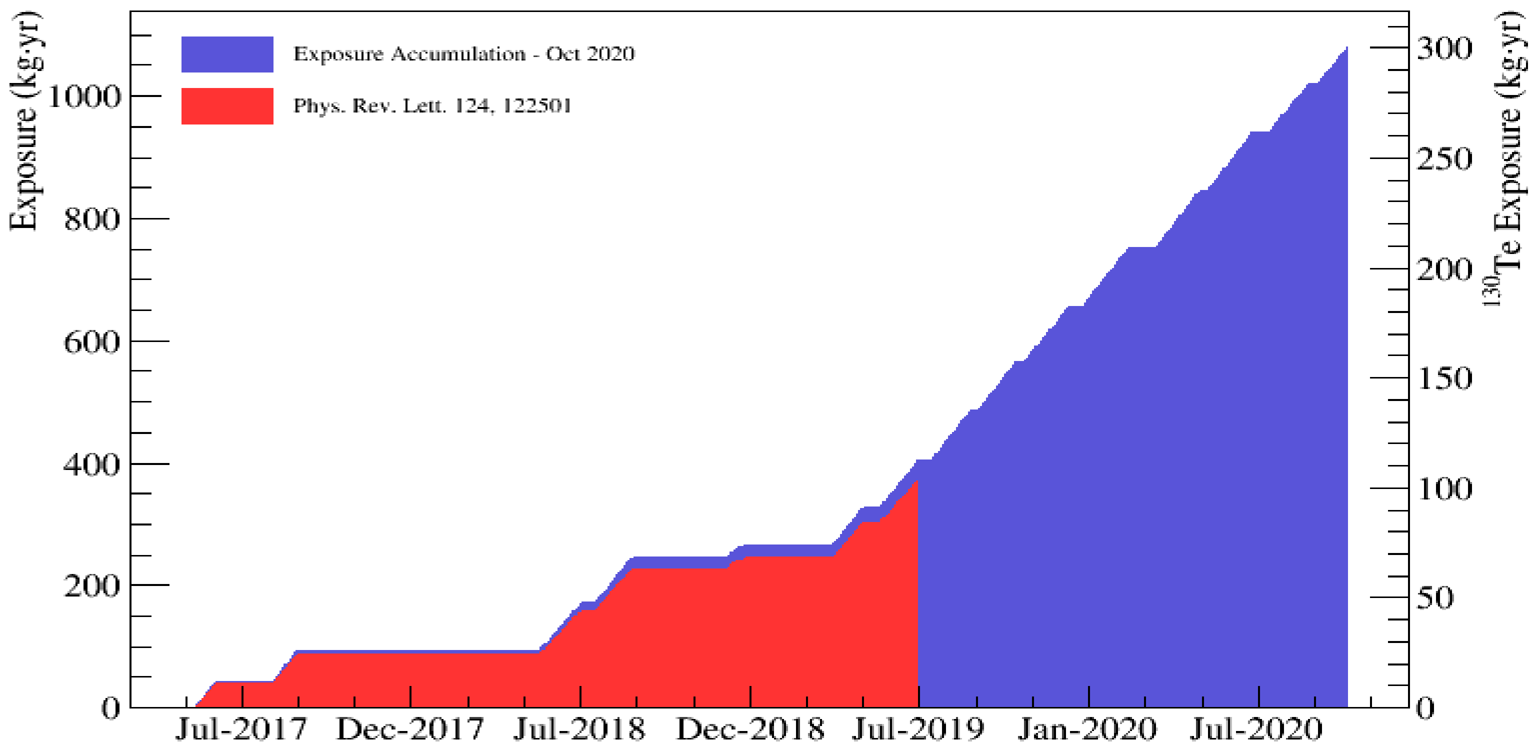
- CUORE cool down started in December 2016
- 4K reached in 22 days
- Base temperature reached in 3.5 days
- First pulse observed the same day



Data taking and performance

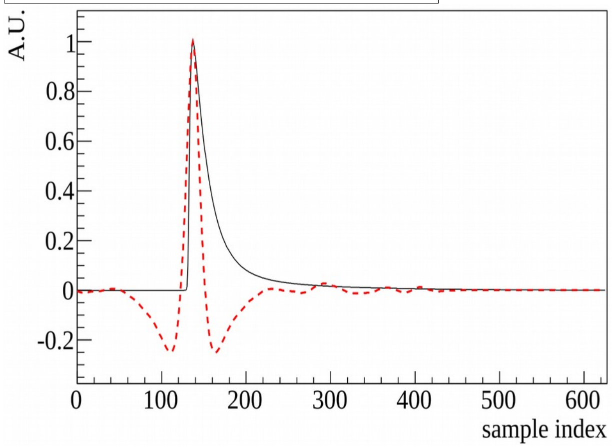
- 984 out of 988 working detectors
- 2 stops to understand and solve cryogenic problems
- Excellent stability and high duty cycle since Apr 2019
- Data taking continued smoothly during recent lockdowns



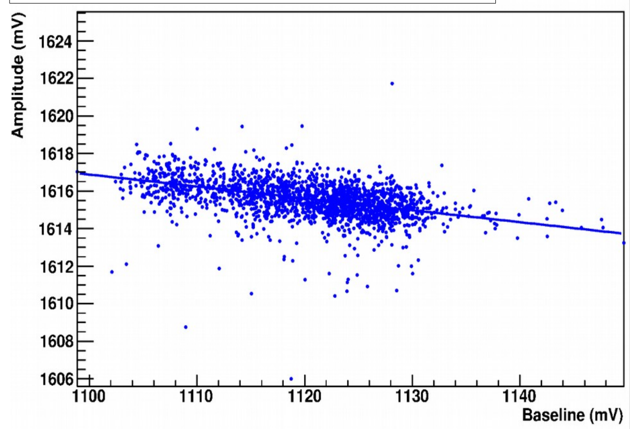


Analysis chain

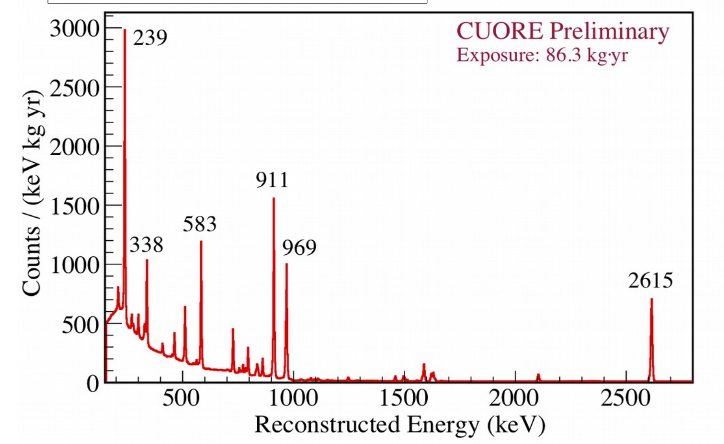
Amplitude estimation



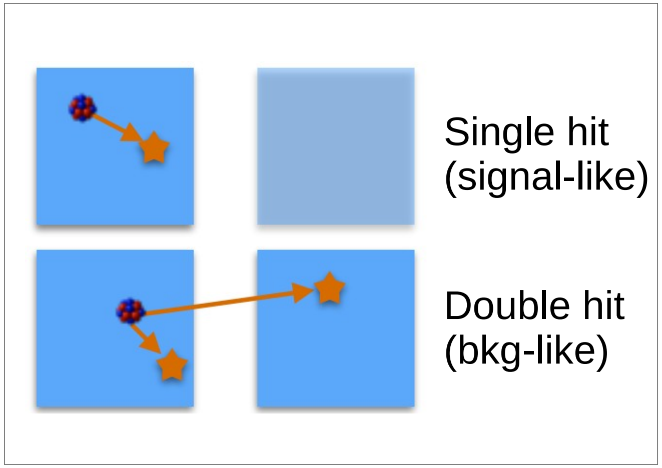
Thermal gain correction



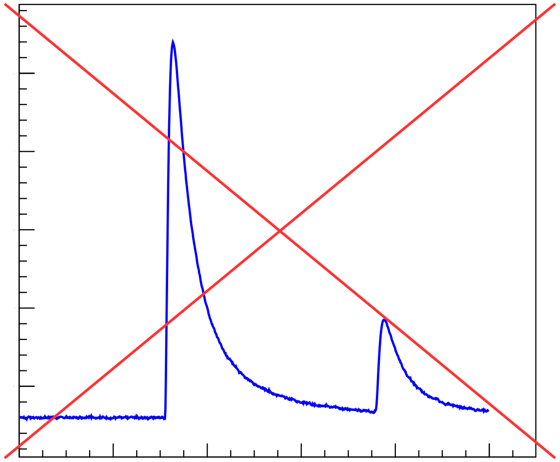
Energy calibration



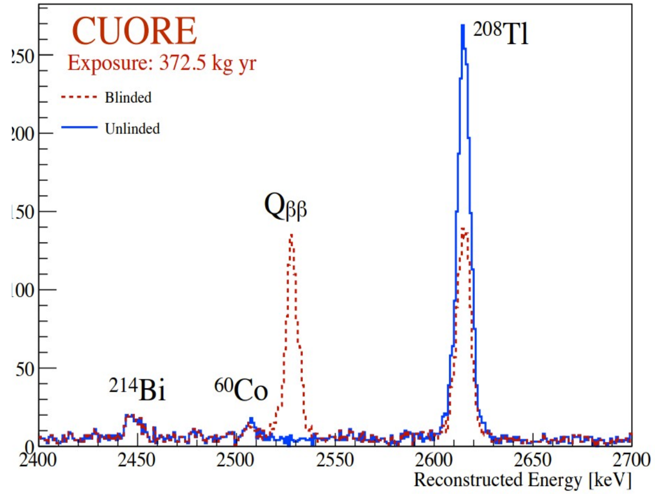
Event multiplicity



Pulse shape

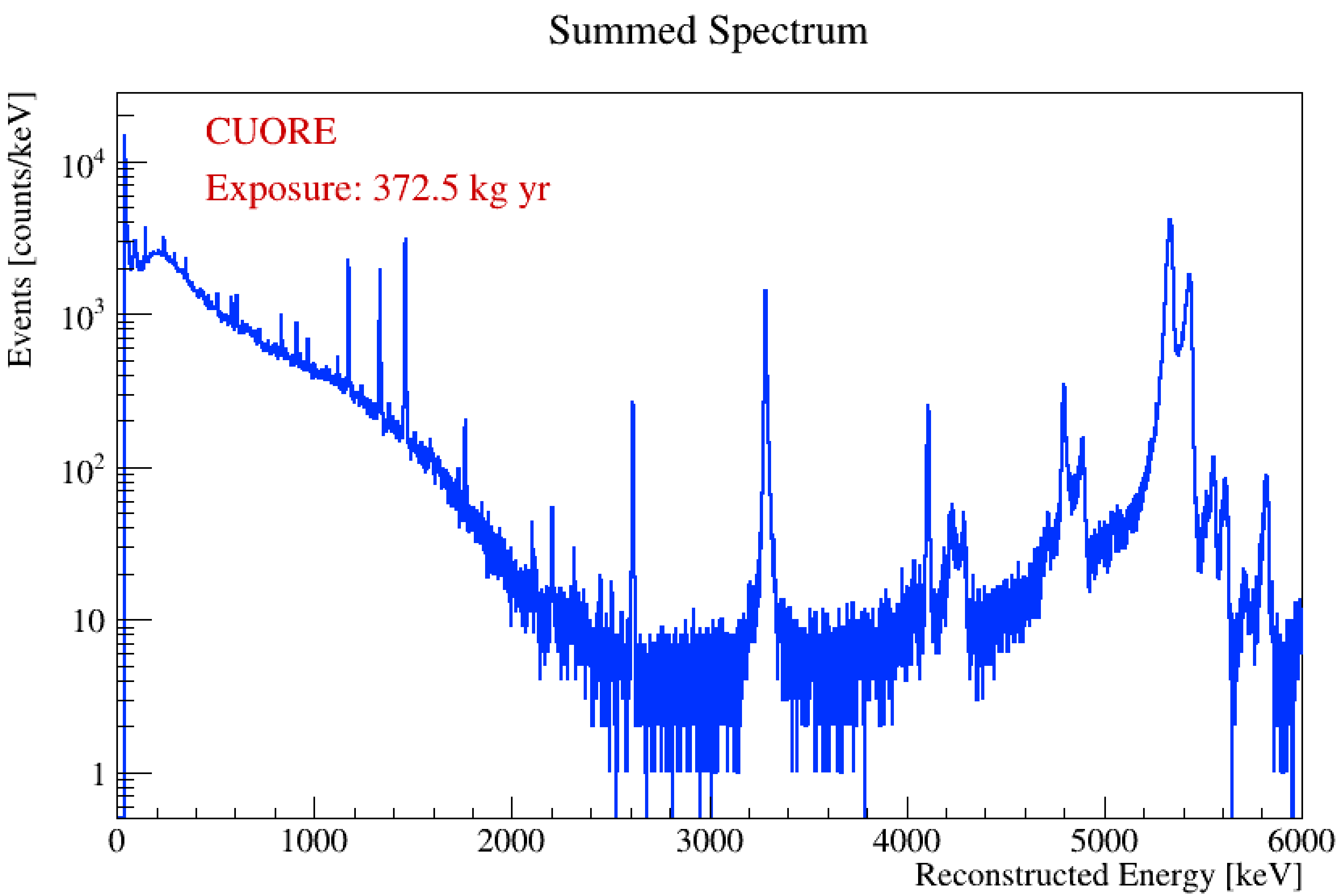


Blinding



Most of the analysis is explained in Phys. Rev. C 93, 045503 (2016)

Energy spectrum

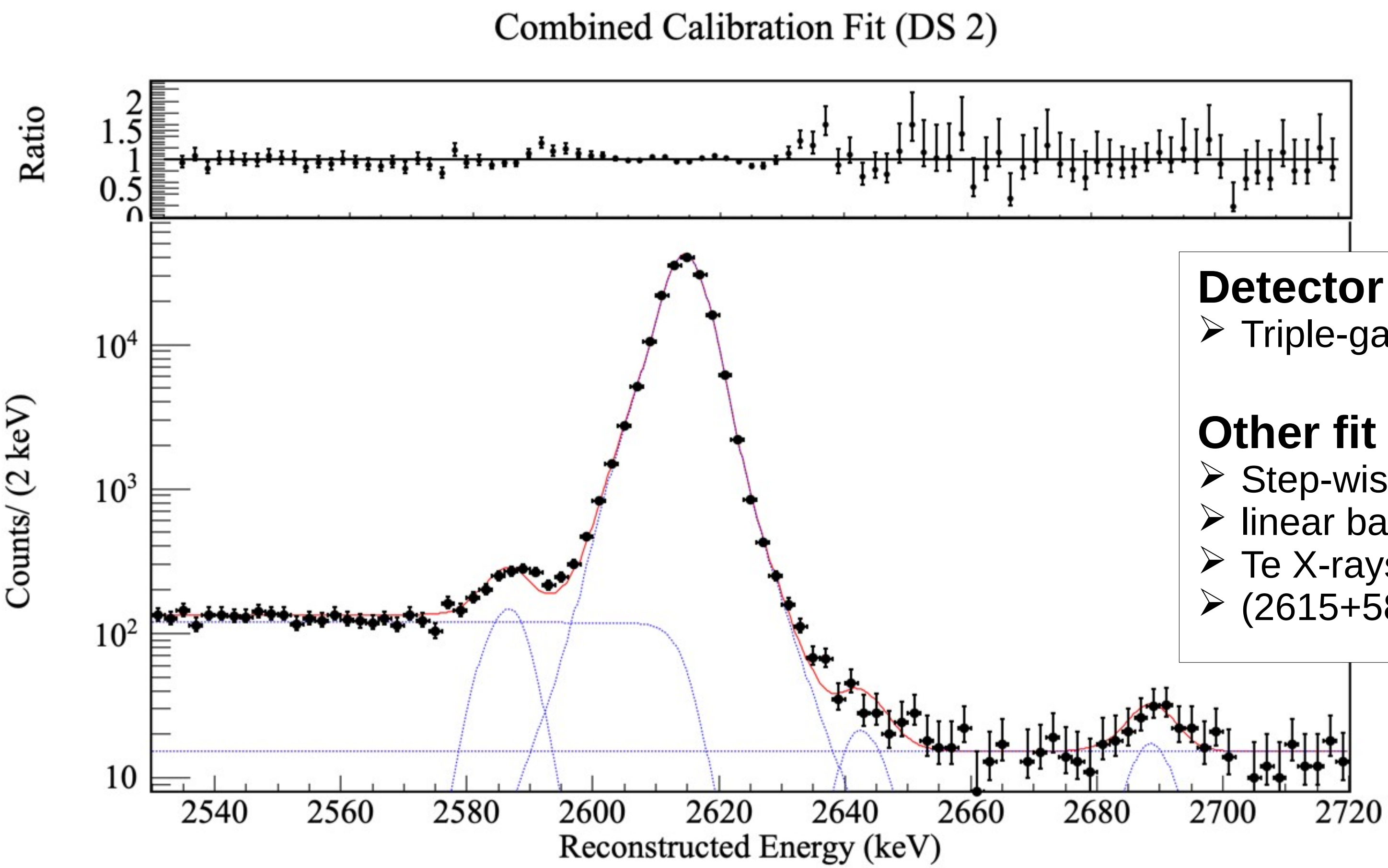


Line shape and energy resolution

Detector response function evaluated on the high statistics Tl-208 peak in calib runs

Scaling factor applied to obtain the energy resolution at $Q_{\beta\beta}$ in physics runs

Characteristic energy resolution at $Q_{\beta\beta}$: 7.0 ± 0.4 keV FWHM



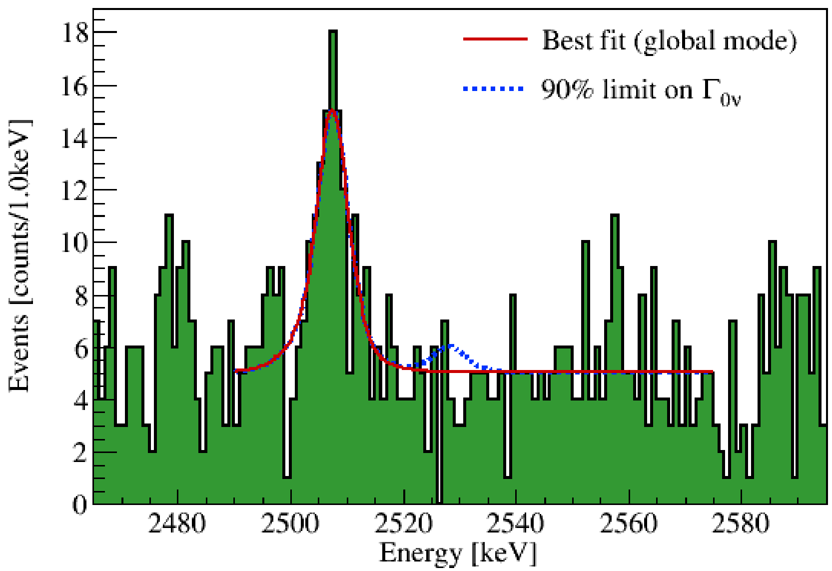
Detector response function

- Triple-gaussian shape

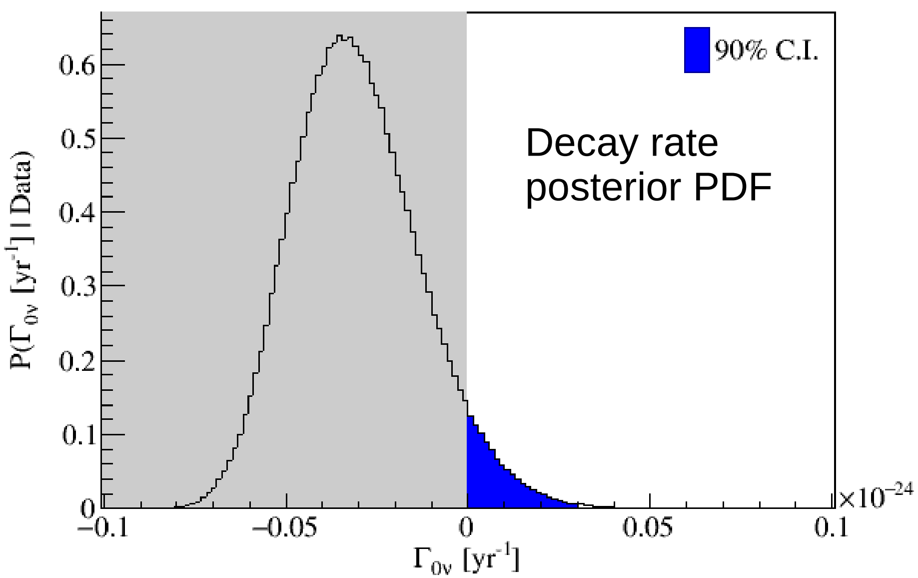
Other fit components

- Step-wise multi-compton background
- linear background
- Te X-rays escape peak
- (2615+583-511) keV peak

0νDBD limit



- TeO_2 exposure: 372.5 kg·y
- Bayesian fit based on BAT
  - flat continuum
  - posited peak for 0νDBD (rate)
  - Posited peak for ^{60}Co (position and rate)
- Unbinned fit in the physical range
  - Non-negative rates
  - Uniform prior on 0νDBD rate



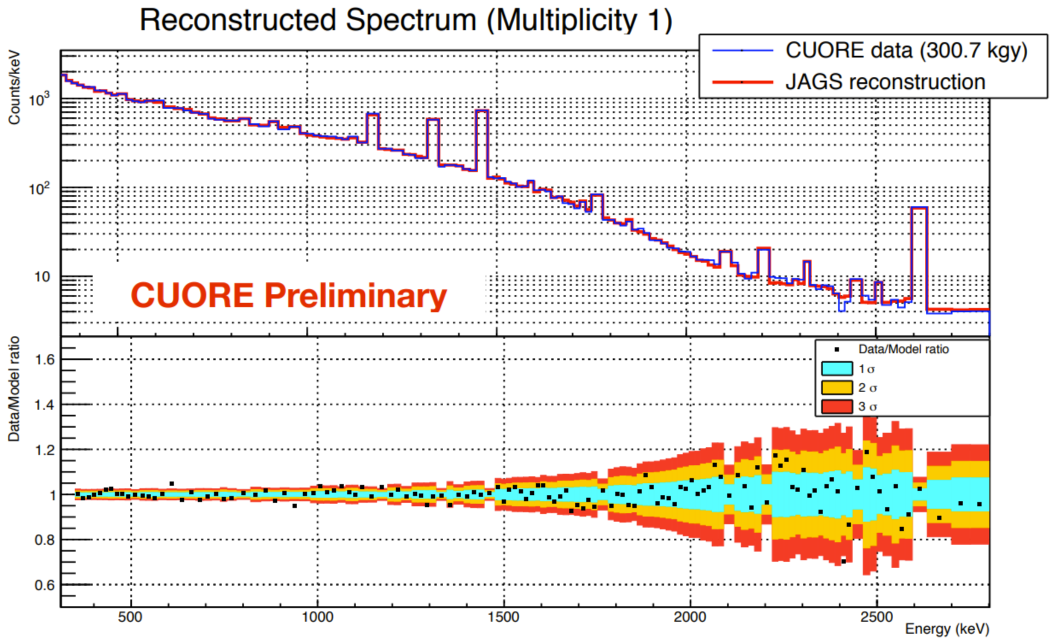
Half-life limit: $T_{1/2} > 3.2 \times 10^{25}$ y (90% CI)

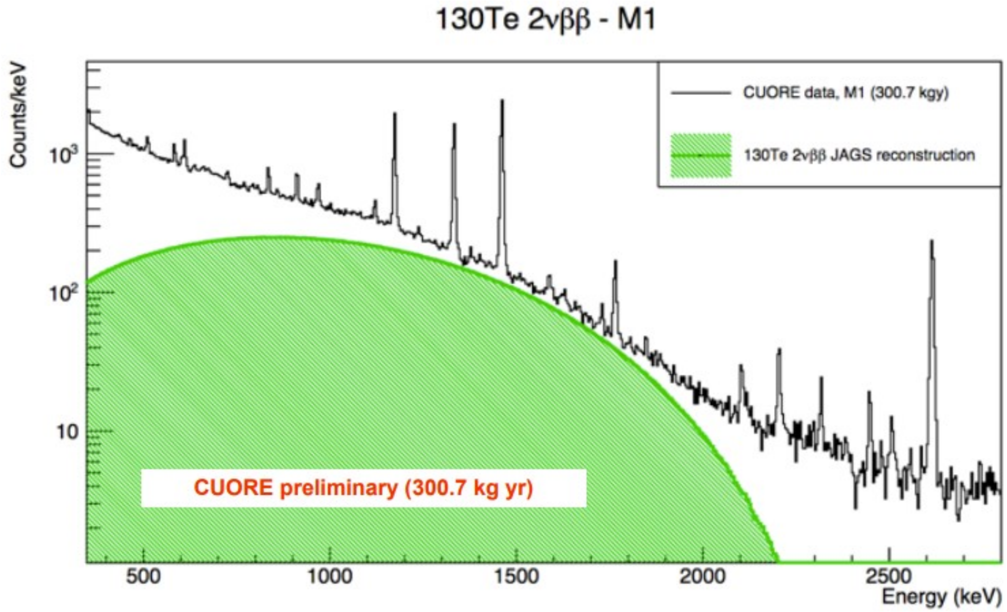
Bkg index: $(1.38 \pm 0.07) \cdot 10^{-2}$ counts/(keV·kg·y)

Effective Majorana mass: $m_{\beta\beta} < 75 – 350$ meV

PRL 124 (2020), 122501

2νDBD measurement





- Energy spectrum reconstruction using Monte Carlo simulations (based on Geant 4)
- 62 radioactive sources taken into account
- Bayesian fit with flat priors
- Exploit modular detector and self shielding to constrain the sources

Preliminary

$$T_{1/2} = (7.71^{+0.08}_{-0.06}\ (\text{stat})\ ^{+0.17}_{-0.15}\ (\text{syst}))\ 10^{20}\ \text{y}$$

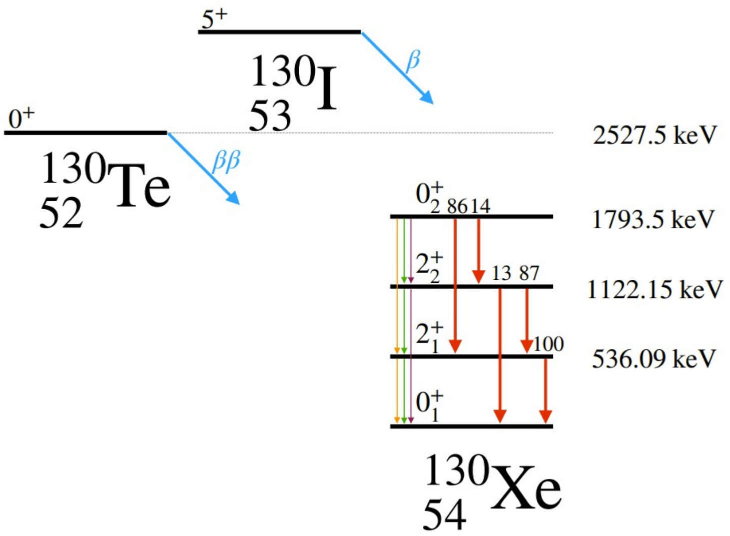
- Result based on 300.7 kg·y
- 2νDBD dominant component 1-2 MeV region

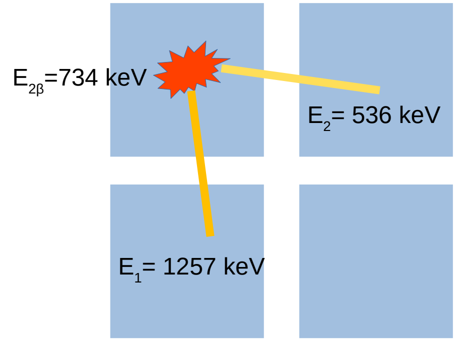
Systematics

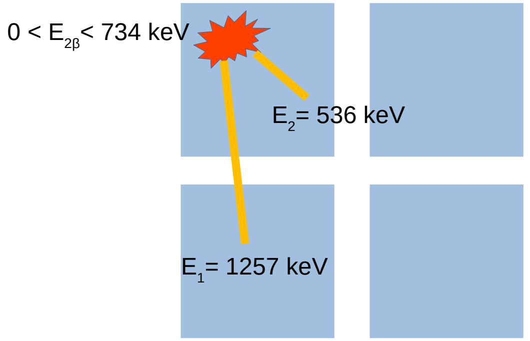
- Analysis-related: geometric and temporal splitting of detectors, fit range
- 2νDBD spectrum: HSD vs SSD
- Unconstrained fallout products (Sr-90)

Paper in preparation

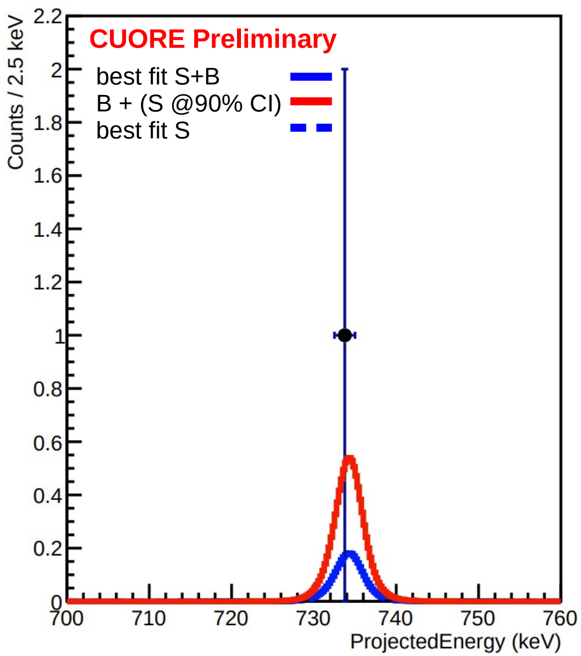
Te-130 decay to excited states

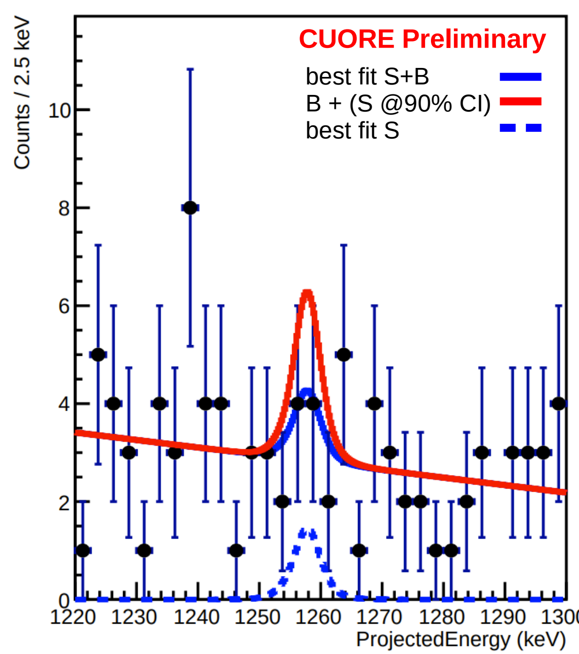






- Search for 0νDBD and 2νDBD to the first 0+ excited state of Xe-130
- Decay accompanied by de-excitation γs
- Events can involve multiple crystals: clear signature and low background
- Several event topologies considered, some examples are reported here





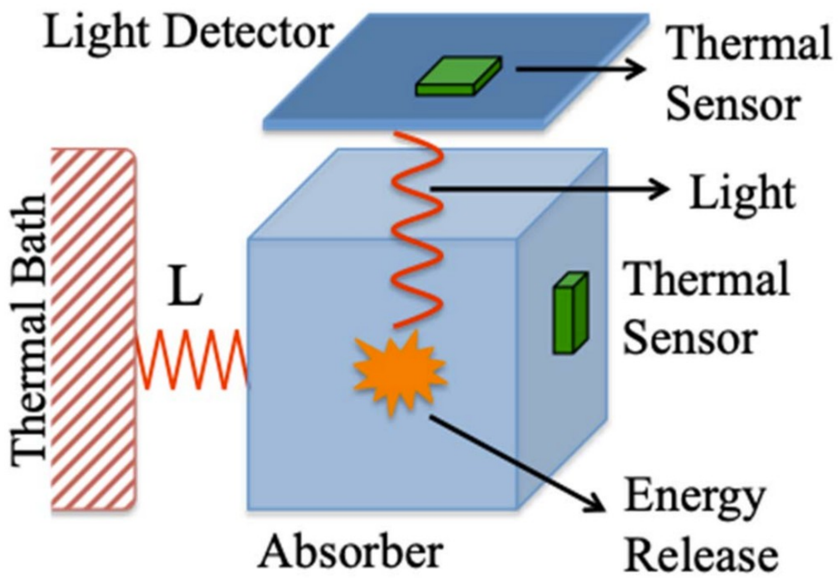
Paper in preparation

$0_2^+ (T_{1/2}^{0\nu}) > 5.9 \cdot 10^{24}$ y (90% CI)
Preliminary

$0_2^+ (T_{1/2}^{2\nu}) > 1.3 \cdot 10^{24}$ y (90% CI)
Preliminary

CUPID: Cuore Upgrade with Particle IDentification

- A next-generation DBD experiment, based on Mo-100
- Aiming at a full exploration of the IH region
- Scintillating Li_2MoO_4 crystals with Mo-100 enrichment (>95%)
- $Q_{\beta\beta}$ (Mo-100) = 3034 keV, much lower β/ɣ background than Te-130
- α vs β/ɣ discrimination: dual readout of light and thermal signals
- Will exploit the CUORE cryogenic infrastructure at LNGS
- Add external muon veto
- CUPID design based on many R&Ds



CUPID pre-CDR: arXiv:1907.09376

Parameter	Baseline
Crystal	Li_2MoO_4
Crystal size	⌀50 mm× h50 mm
Crystal mass (g)	308
Number of crystals	1534
Number of light detectors	1652
Detector mass (kg)	472
^{100}Mo mass (kg)	253
Energy resolution FWHM (keV)	5
Background index (counts/(keV·kg·yr))	10^{-4}
Containment efficiency	79%
Selection efficiency	90%
Livetime	10 years
Half-life limit sensitivity (90%) C.L.	1.5×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y
$m_{\beta\beta}$ limit sensitivity (90%) C.L.	10 – 17 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12 – 20 meV

Conclusion

- CUORE is taking data at LNGS since 2017
- 2 stops for detector debug and optimization
- Data taking stable and with high duty cycle since Apr 2019
- Te-130 0νDBD analysis based on 372.5 kg·y published in 2020
- Next 0νDBD data release when 1 ton·y will be reached (soon)
- Te-130 2νDBD measurement released, paper in preparation
- Limits on Te-130 decay to excited states released, paper in preparation
- CUPID will surpass CUORE sensistivity using scintillating detectors based on Mo-100