# Latest results from the CUORE experiment

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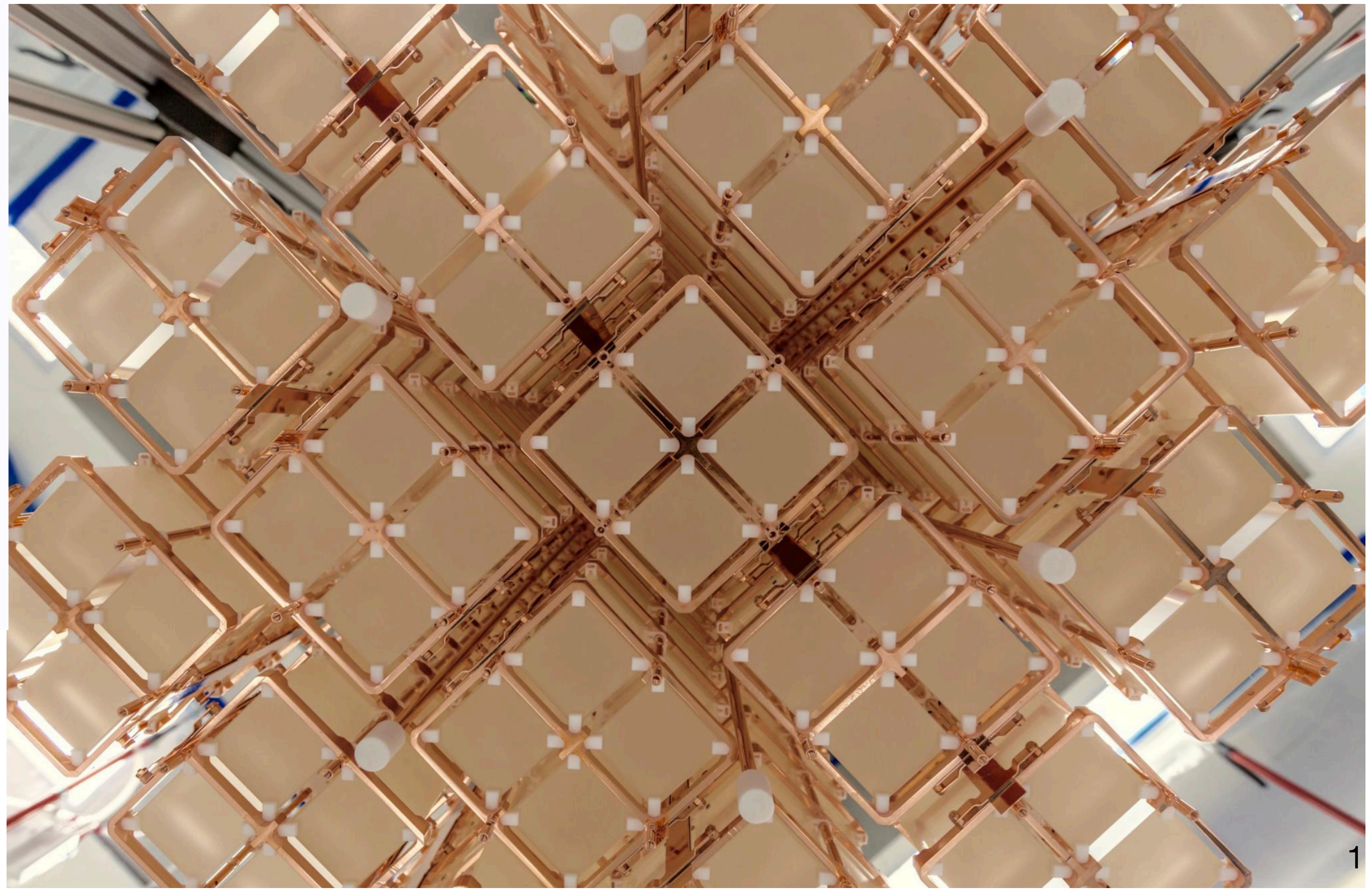
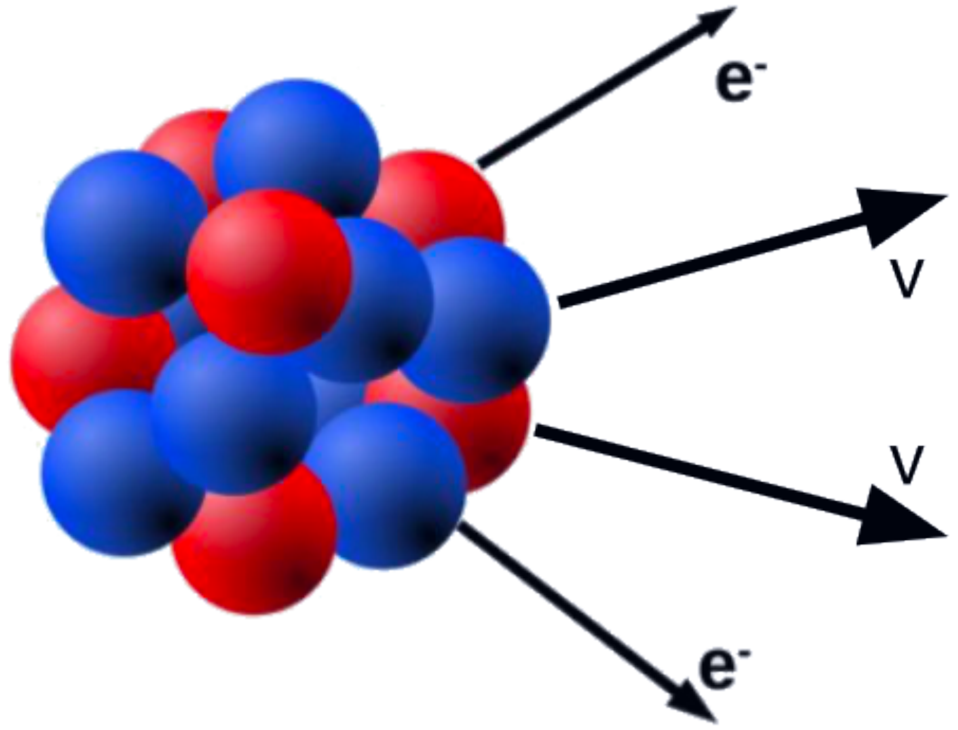


La Thuile 2021 - Les reconcontres de Physique de la Vallée d'Aoste

# Double beta decay

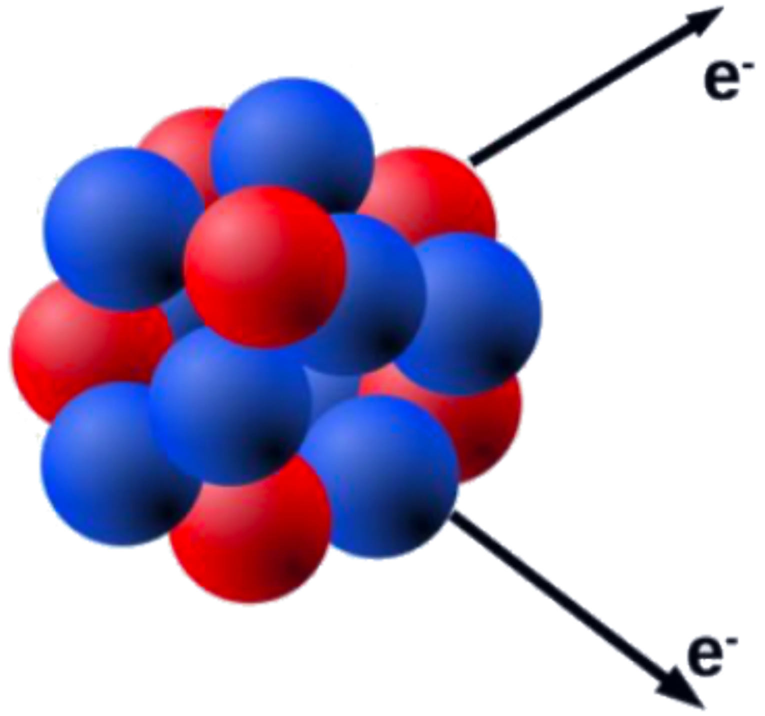
Rare 2nd order nuclear decay: $(A, Z) \rightarrow (A, Z+2) + 2e^- + (2\bar{\nu}_e)$

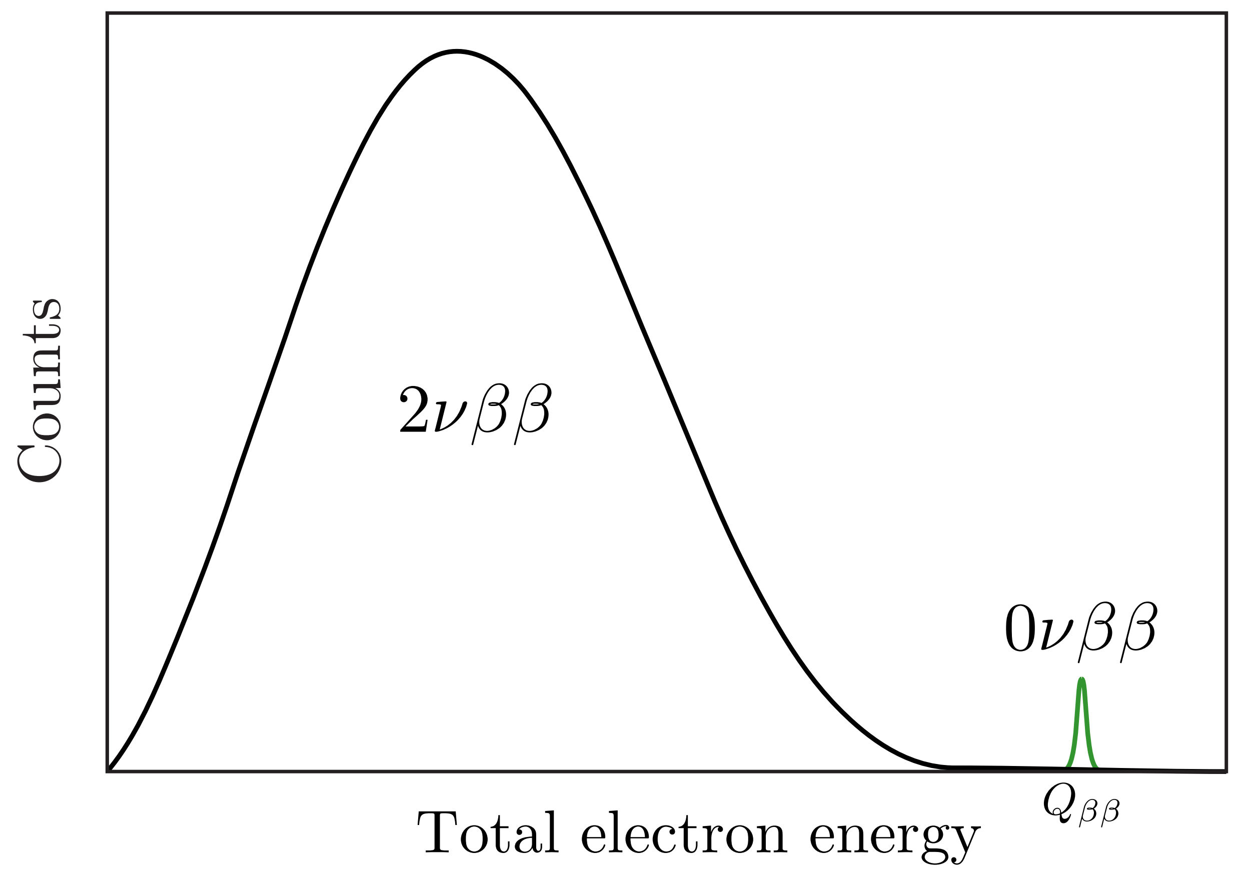
$2\nu\beta\beta$




- Allowed in SM for even-even nuclei ($\Delta L = 0$)
- Observed in several nuclei: $T^{1/2}_{2\nu\beta\beta} \sim 10^{18} - 10^{24}$ y

$0\nu\beta\beta$




- Beyond SM: $\Delta L = 2$, Majorana neutrinos
- Hint on origin of matter antimatter asymmetry
- Half-life limits: $T^{1/2}_{0\nu\beta\beta} > 10^{25} - 10^{26}$ y
- Signature: peak at $Q_{\beta\beta}$ in $K_{ee}$

- Decay rate [light Majorana neutrino]

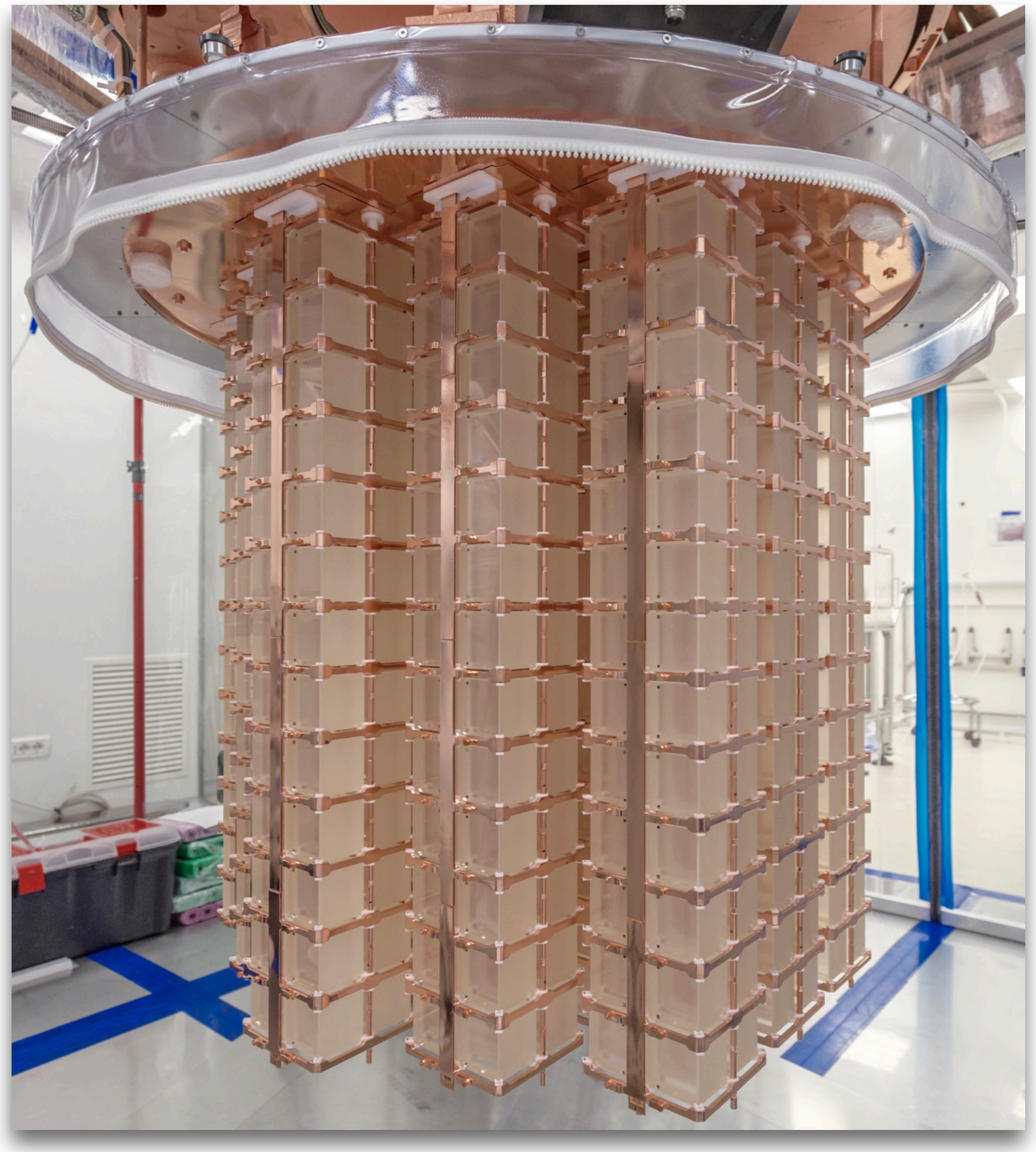
$$\Gamma_{0\nu\beta\beta} = G_{0\nu}(Q, Z)\left|M_{0\nu}\right|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

- Constraints on neutrino mass and hierarchy

# The CUORE experiment

***C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents*

- Scientific goal: search for 0νββ decay of $^{130}Te$
  (isotopic fraction ~34%, $Q_{\beta\beta}$~2527 keV, only $^{208}Tl$ γ line above)
- Tonne-scale detector: 988 $^{(nat)}TeO_2$ crystals operated at ~10 mK
  $TeO_2$ mass is 742 kg (206 kg of $^{130}Te$)
- Underground experiment at LNGS



Effective FWHM at $Q_{\beta\beta}$
7.0(4) keV
Background index in the ROI
$1.38(7)\cdot10^{-2}$ counts/keV/kg/yr

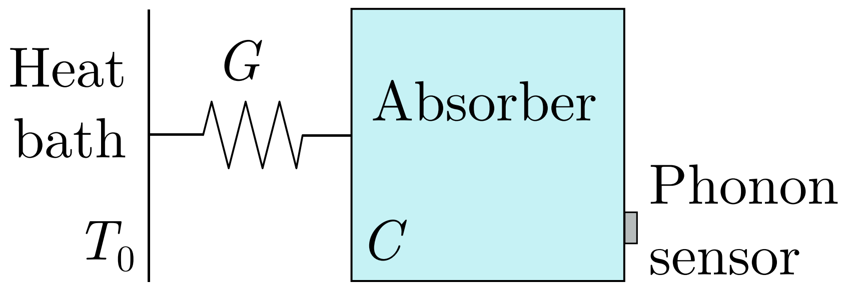
Adv. in High En. Phys. 2015, 879871
Eur. Phys. J. C77 (2017), 532

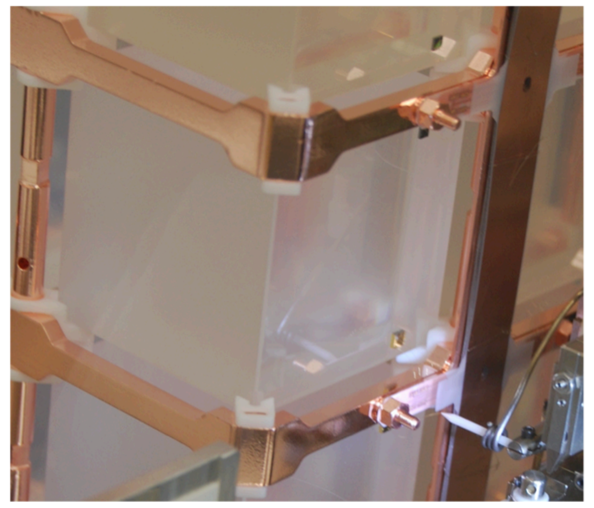
Projected sensitivity
(5 years)

$$T^{1/2}_{0\nu\beta\beta} = 9 \cdot 10^{25}\ \text{yr}$$

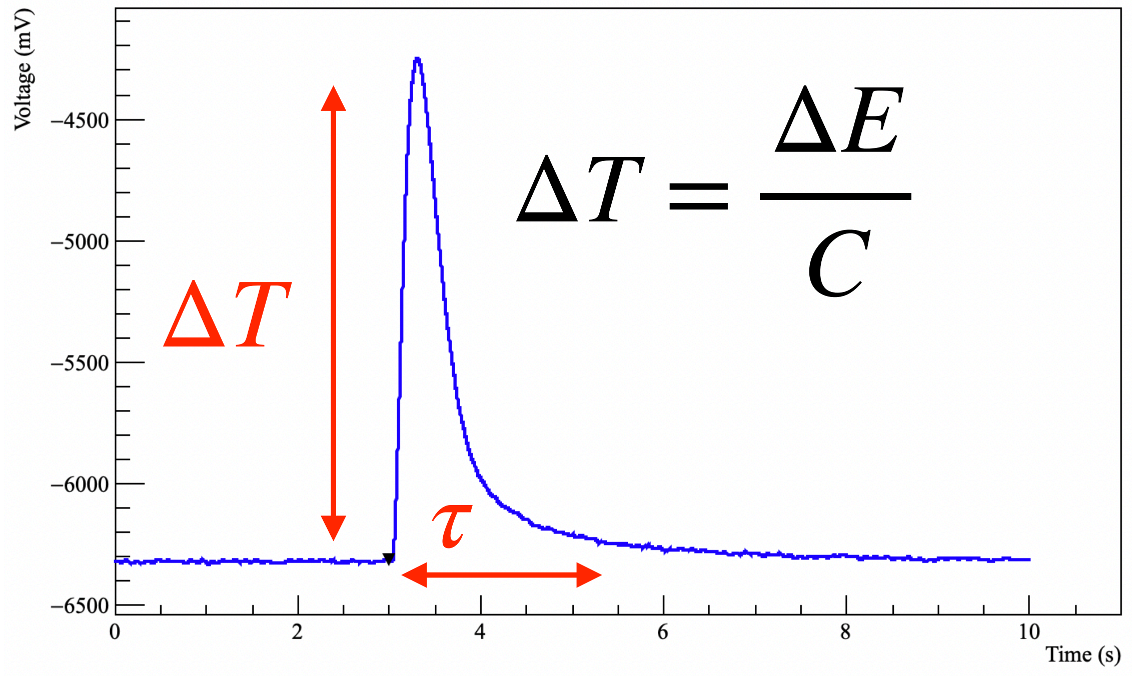
# The CUORE challenge

## Bolometric technique



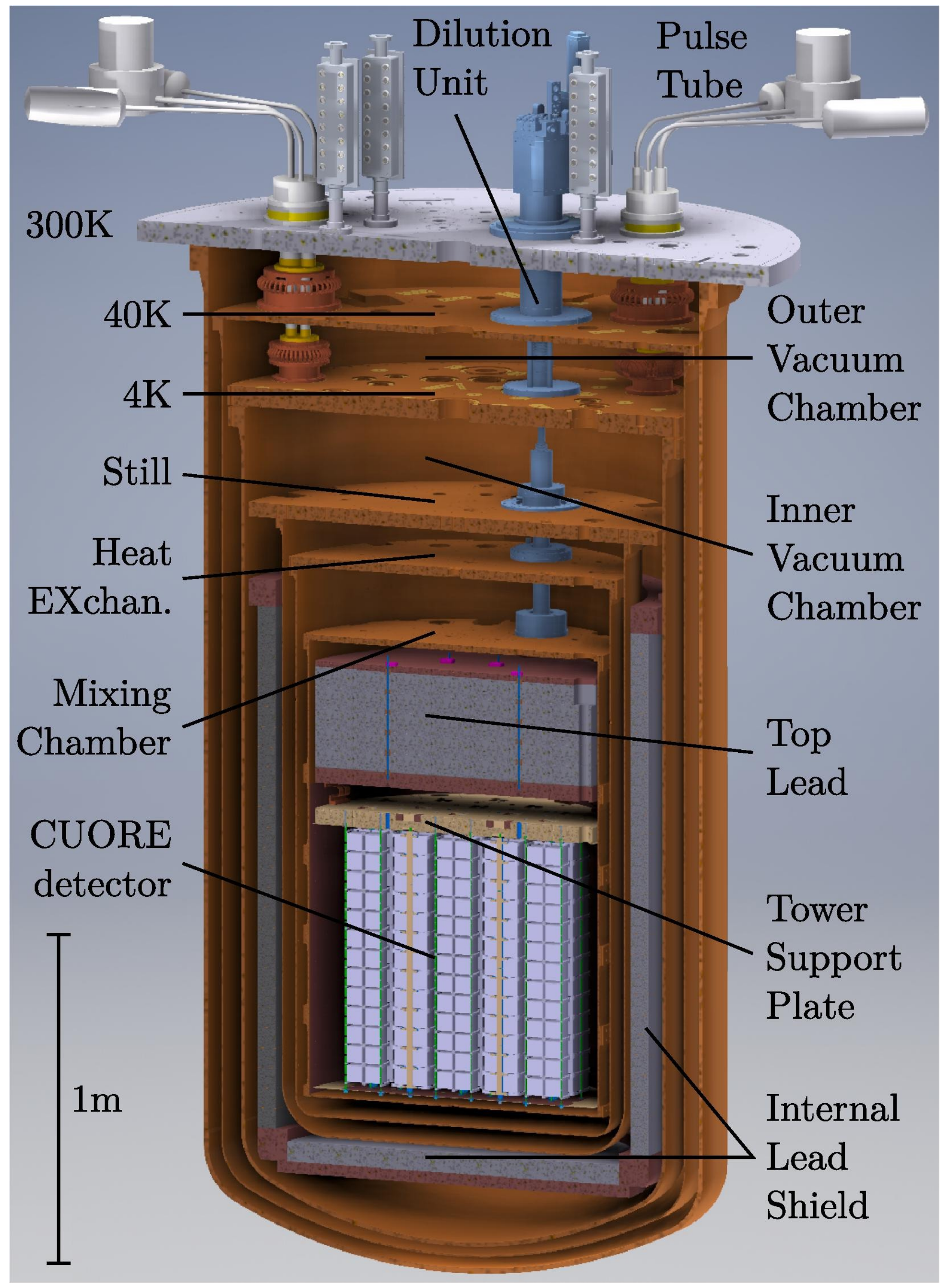



Particle energy release measured via crystal temperature increase




Pulse amplitude ∝ ΔT ∝ ΔE
(1 MeV ΔT~100 μK)
NTD Ge thermistors:
ΔR~3MΩ/MeV

## Custom cryogen free cryostat




- 5 pulse tubes to reach 4K
- Dilution unit to maintain ~10 mK
- Strict constraints in terms of temperature and mechanical stability, materials radiopurity

## Radiation shielding

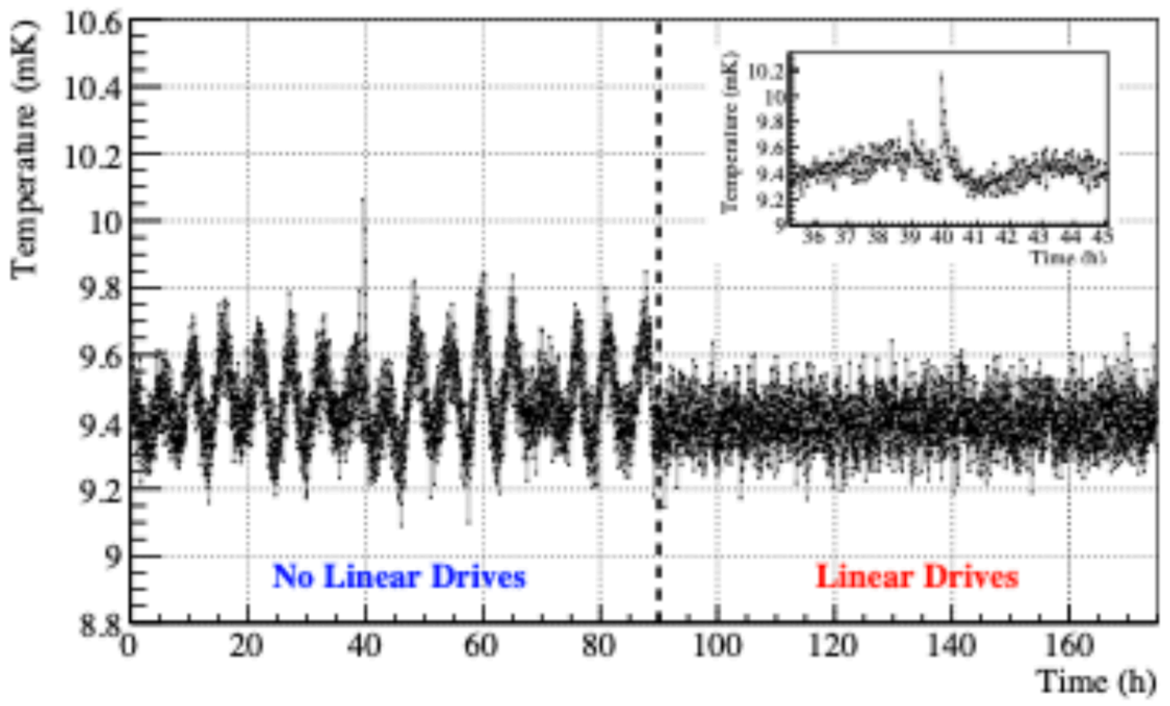
- Underground (LNGS): cosmic rays flux $10^{-6}$ relative to surface

- Internal shields:
  *top*: 30-cm Pb shield
  *side and bottom*: 6-cm ancient roman Pb shield ($^{210}$Po<4 mBq/kg)
- External shield from γs: 25-cm Pb layer
- External shield from neutrons: 20-cm layer in polyethylene $H_3BO_3$ panels

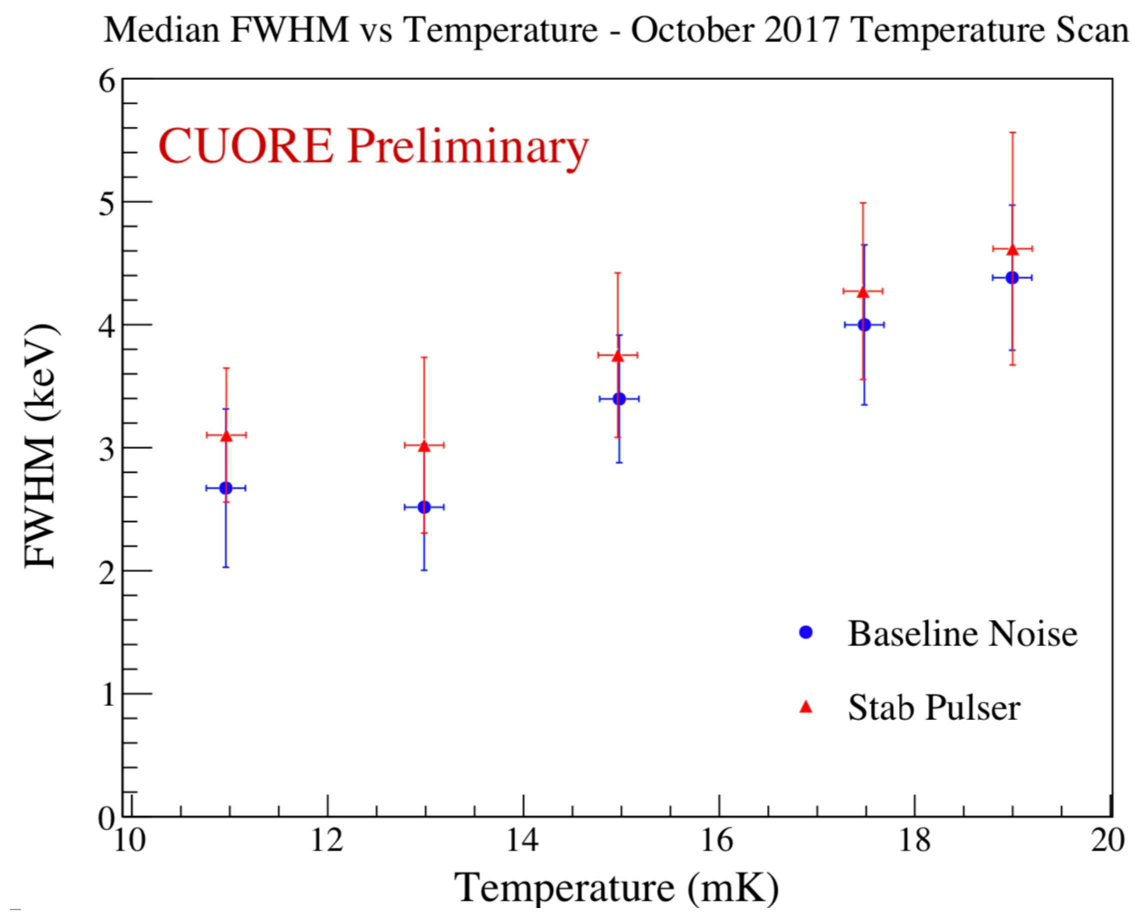
# The CUORE commissioning and detector optimization

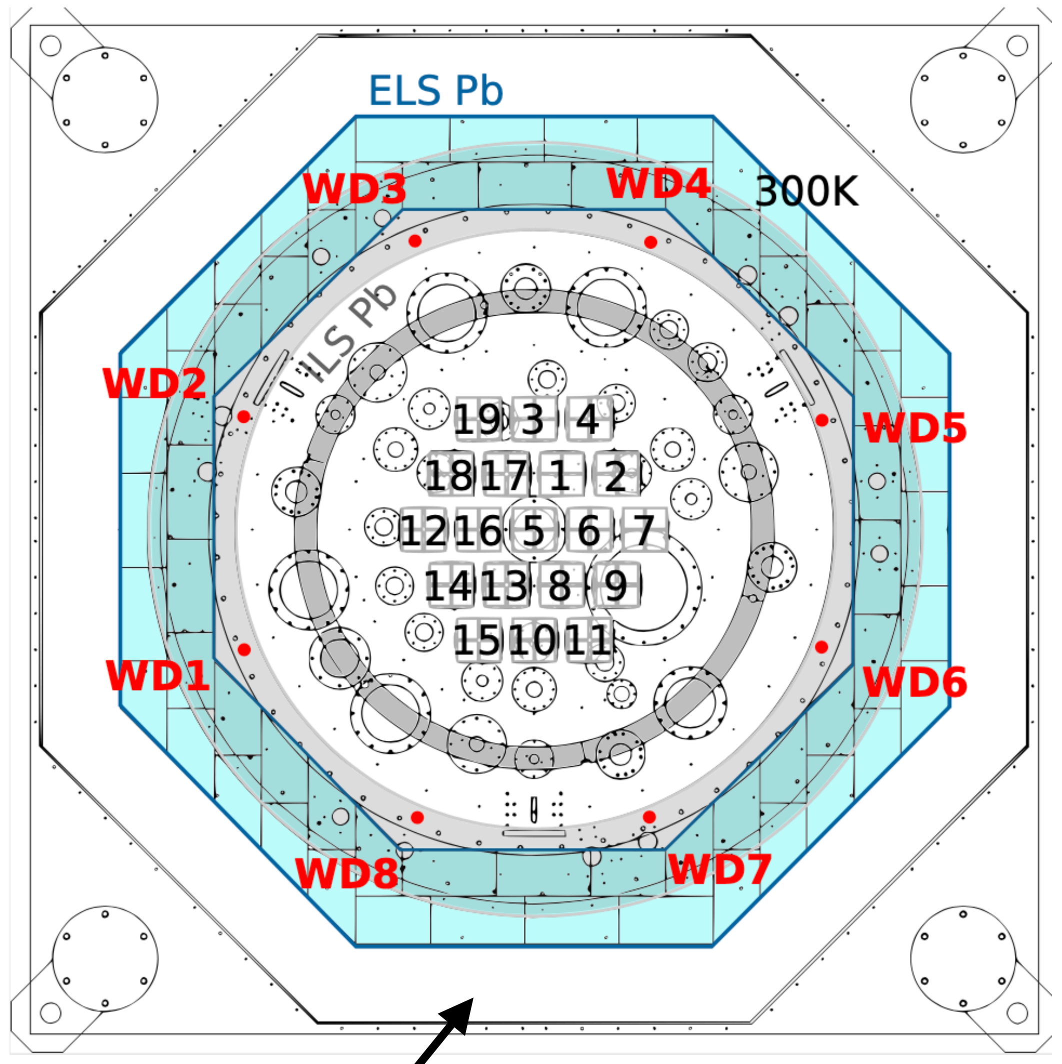
- Detector assembly in 2012 - first cooldown in 2016 - data taking started in 2017

- Linear drives and active noise cancellation to minimize vibrations induced by the pulse tubes




Cryogenics 93, 55-56 (2018)



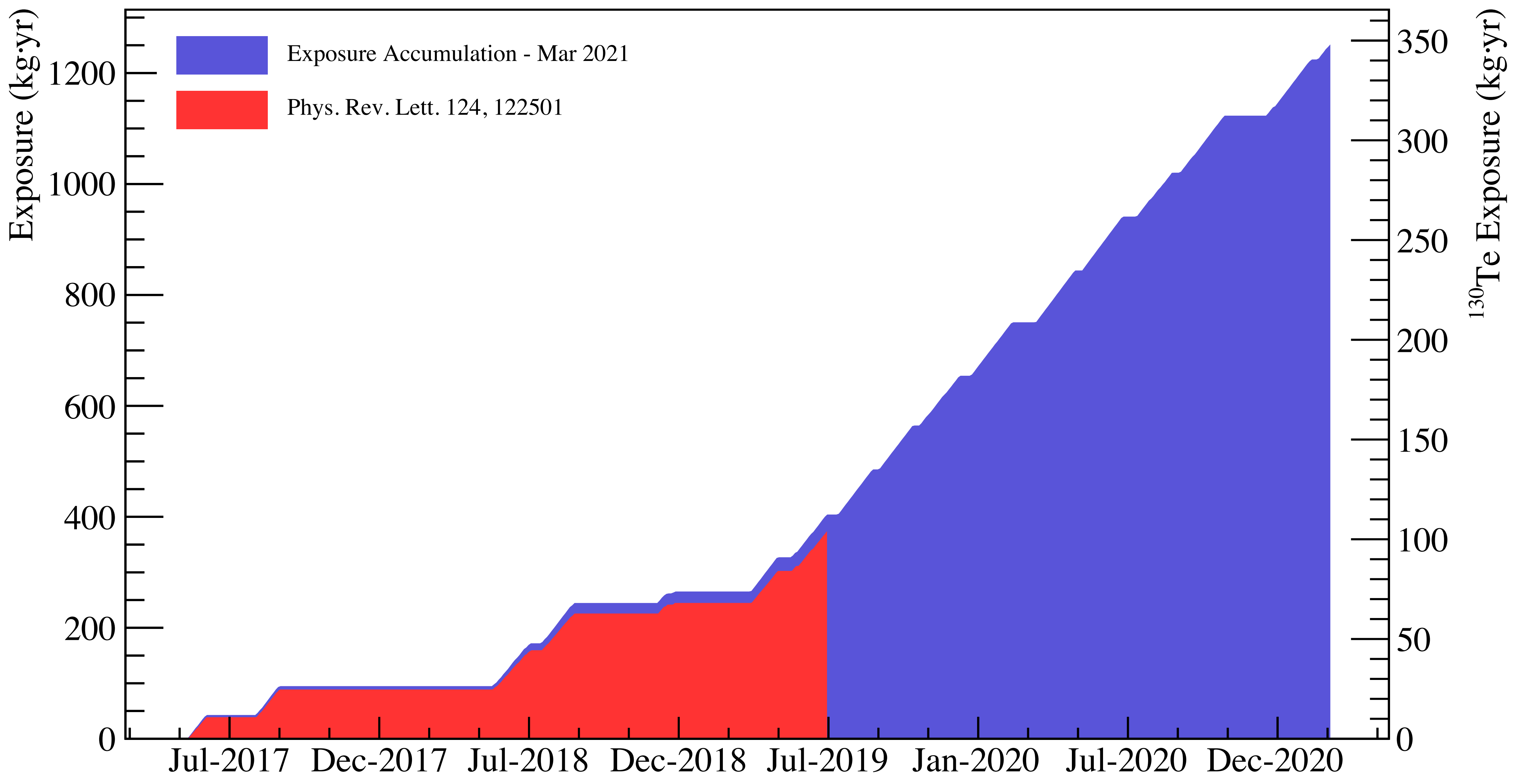




- Temperature scan to identify the optimal temperature (currently at 11.8 mK)

- Upgrade of our detector calibration system in 2018 - less invasive external setup

- Maintenance of the cryogenic system in 2019 - stable data taking since then

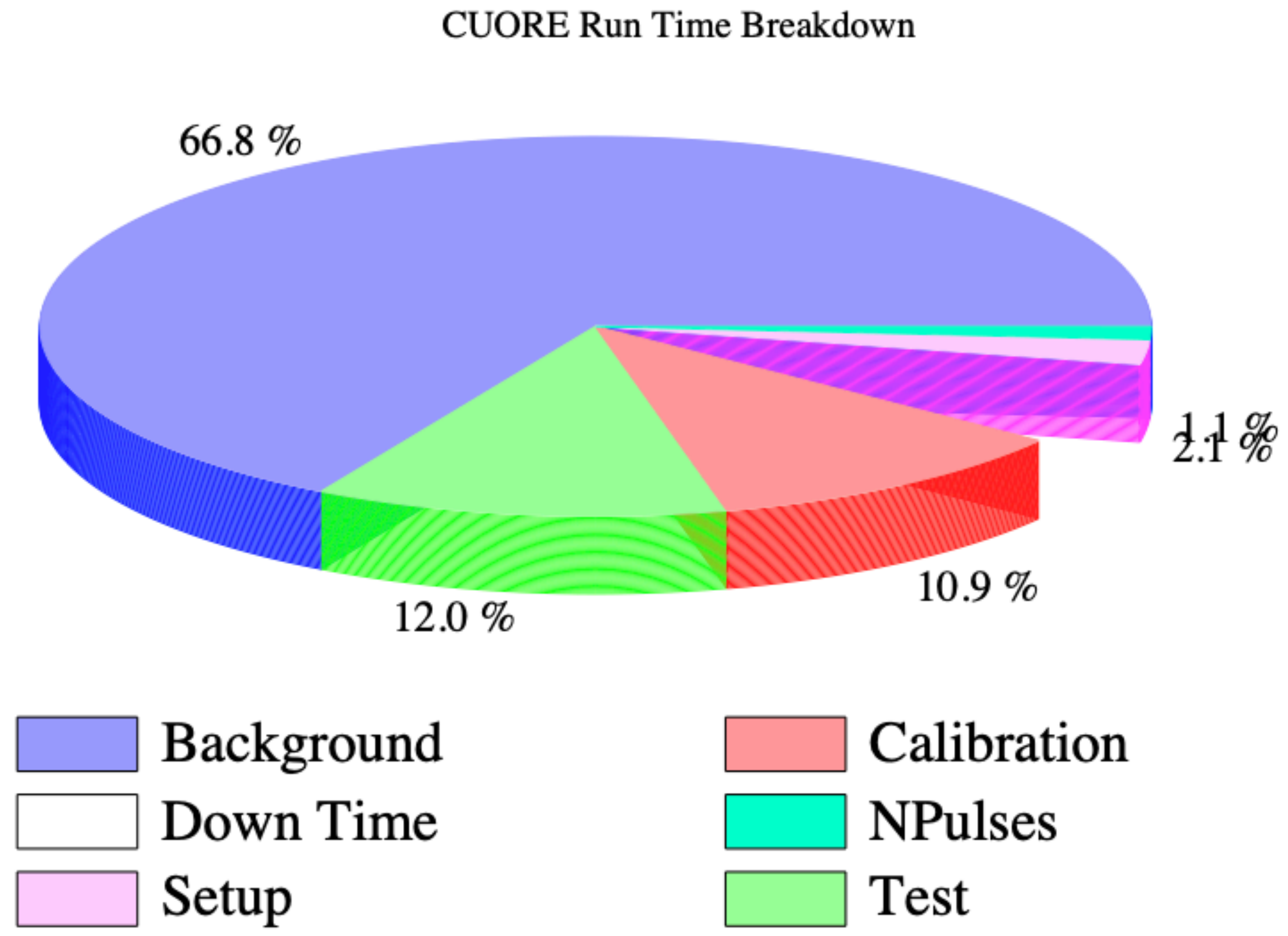
# The CUORE data taking




Since march 2019 stable data taking

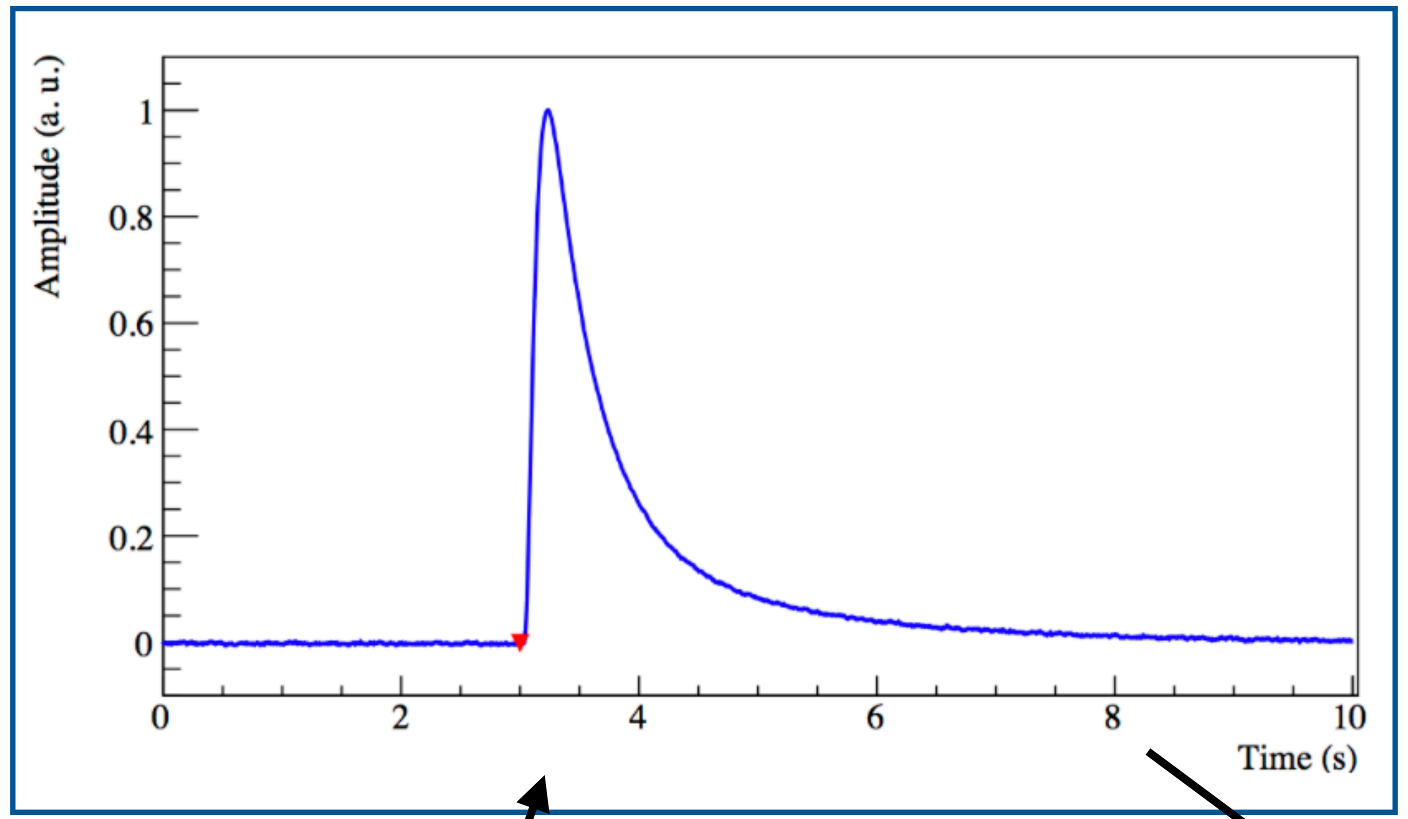
- >90% uptime
- Reached 1 tonne·yr exposure
- Average rate ~50 kg·yr/month

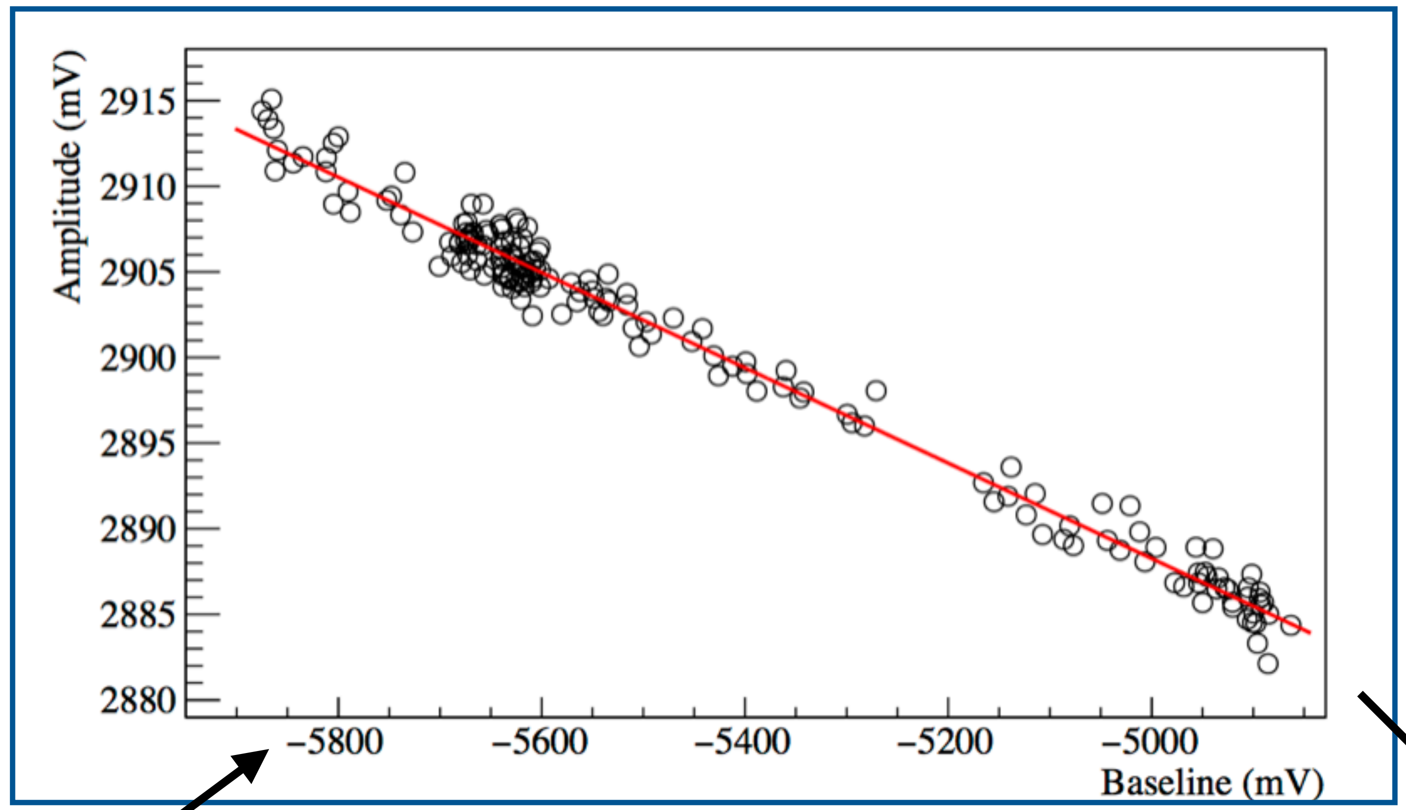
- Data split in "datasets": 1/2 months of physics data bookended by calibration periods

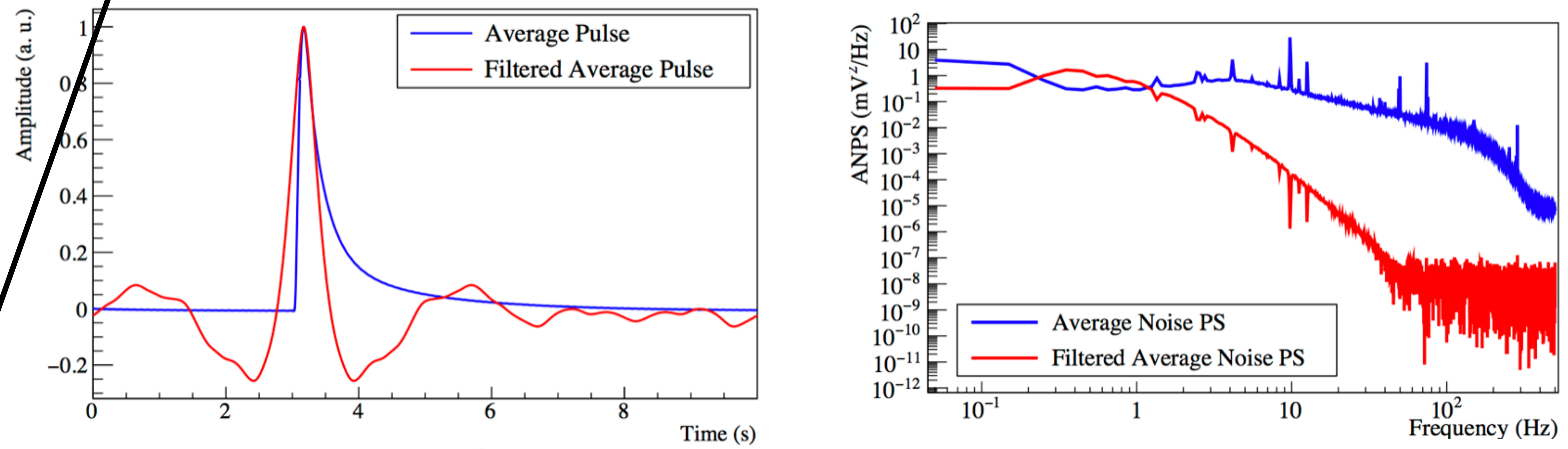



- Voltage across NTD Ge thermistors continuously sampled at 1kHz
- Events triggered with software offline

# The CUORE data analysis

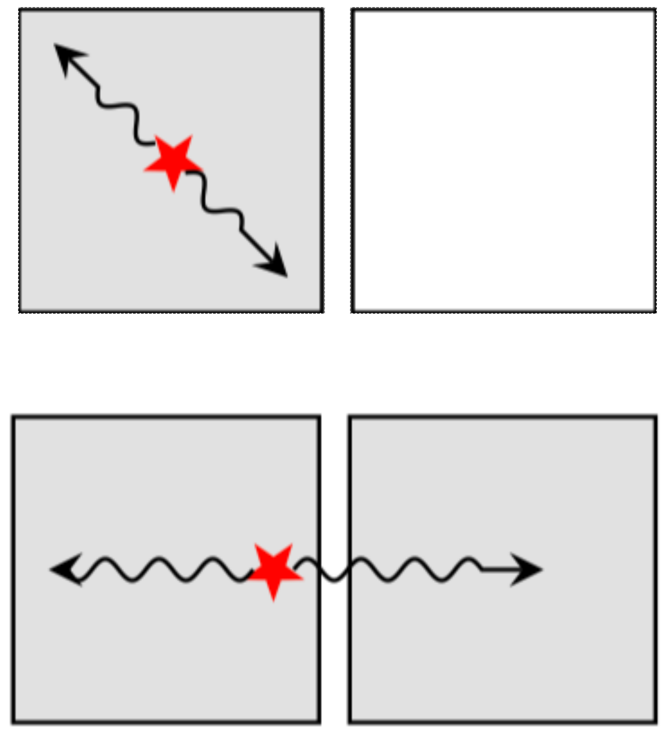



Optimum filter technique

- $^{232}$Th + $^{60}$Co strings deployed
- pol2 fit to extract calibration coefficients



Identify simultaneous events on multiple crystals

Trigger events

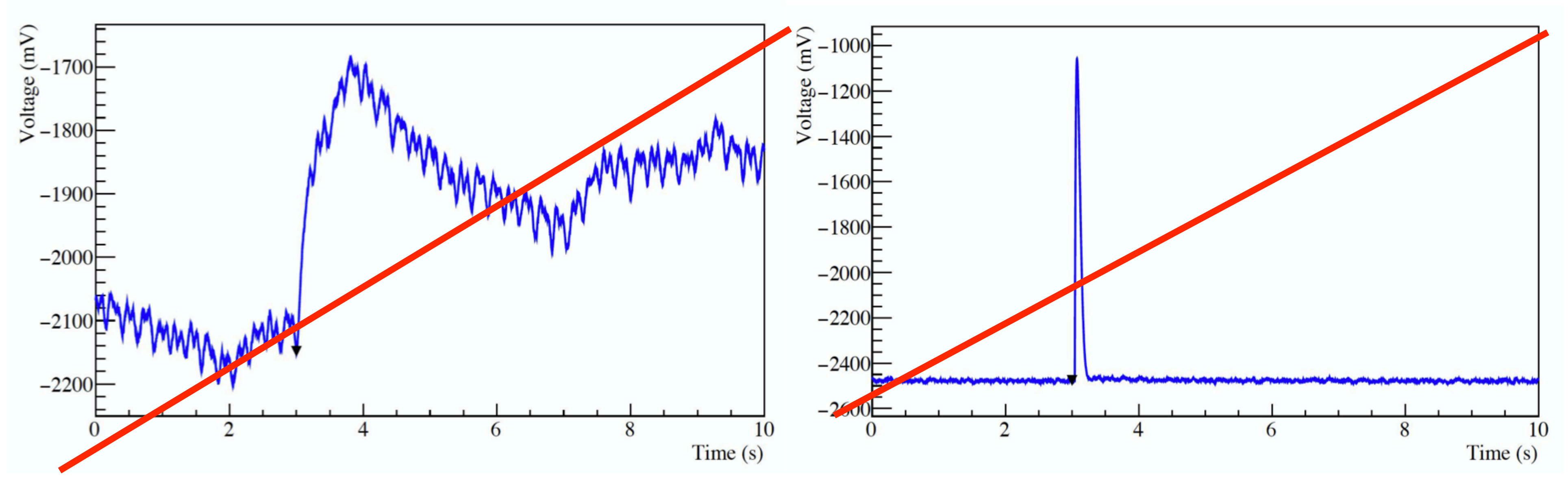
Amplitude evaluation

Thermal gain correction

Calibration

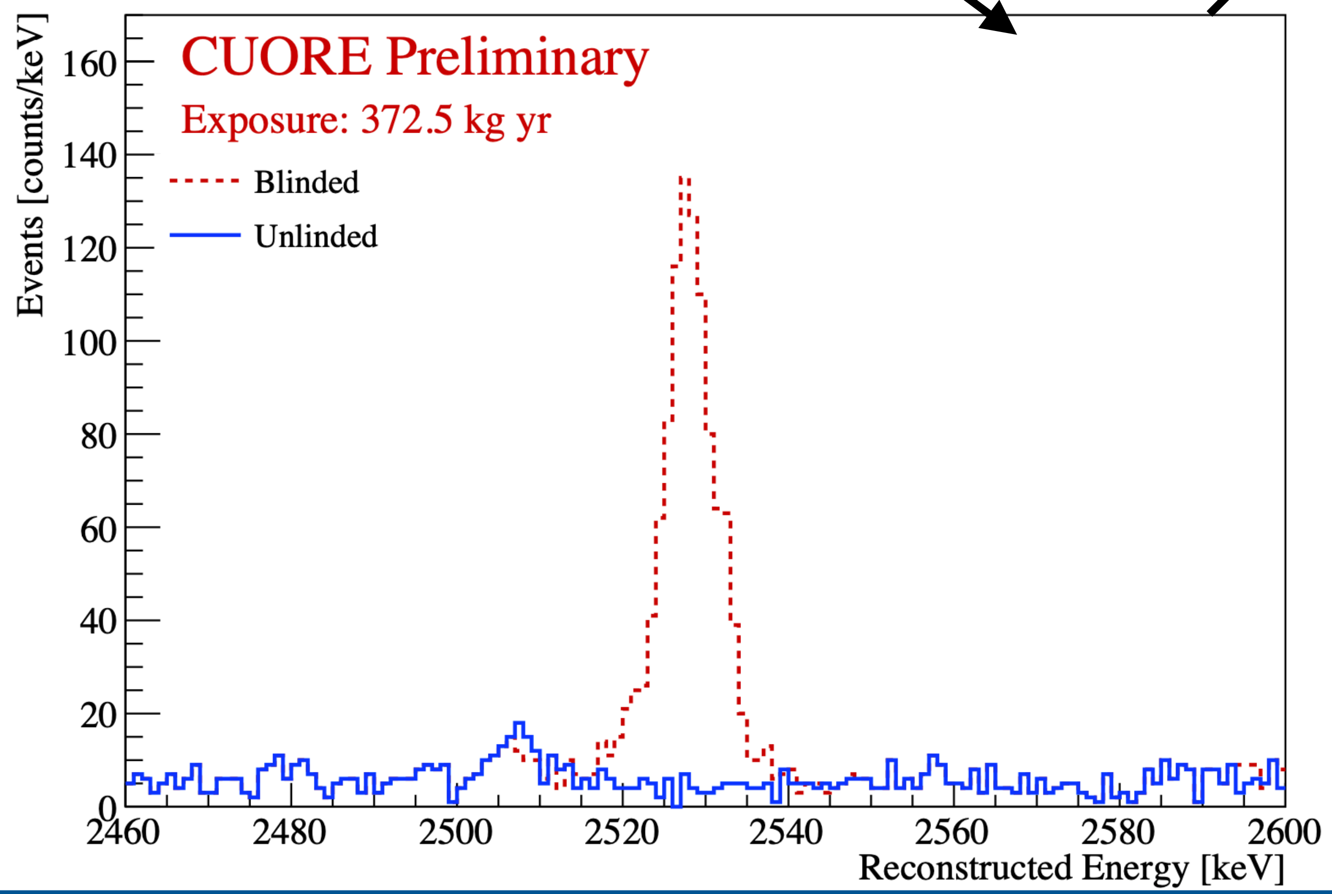
Coincidences

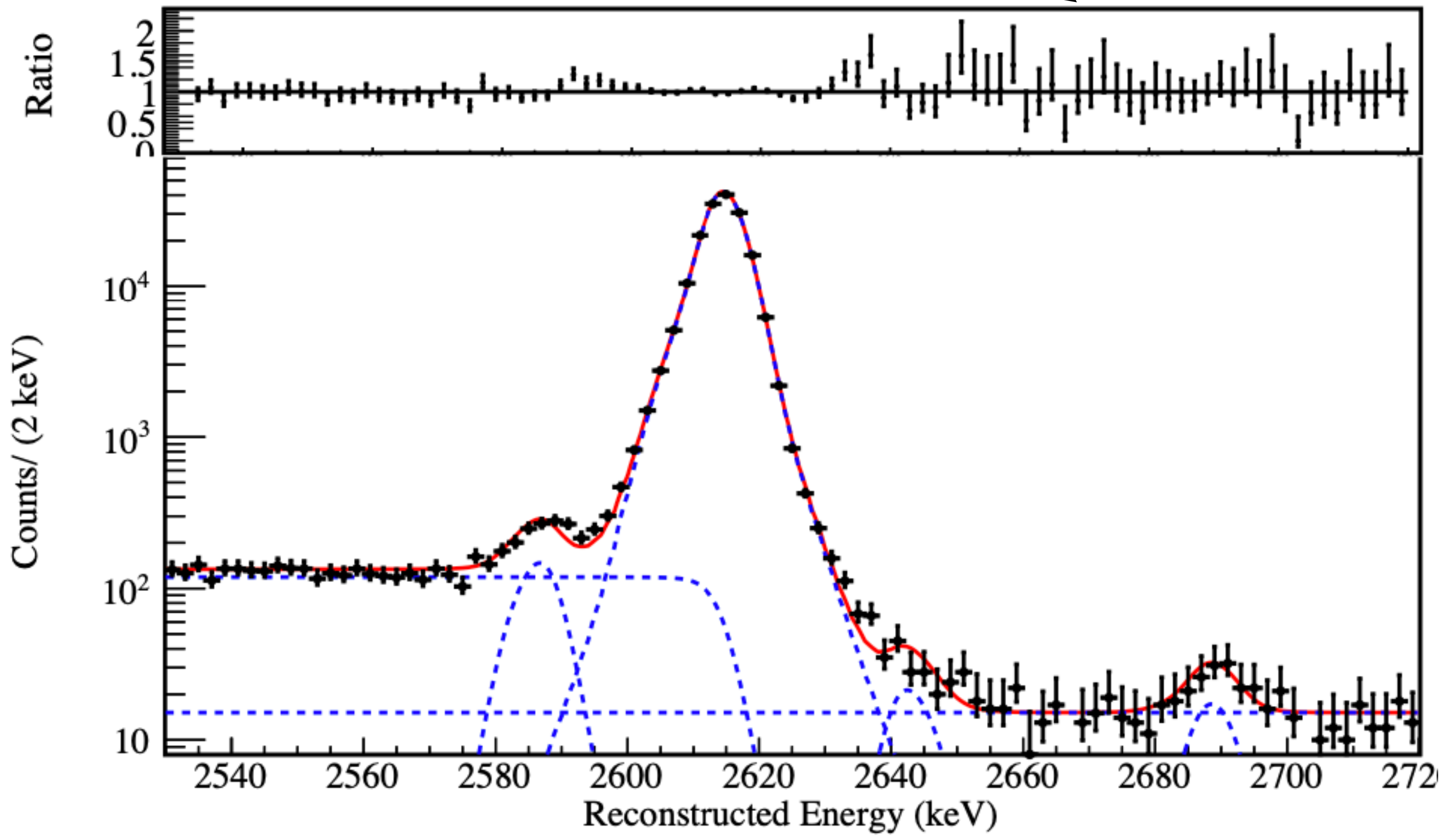
# The CUORE data analysis




Reject spurious events

| | |
|---|---|
| Reconstruction efficiency | 95.802(3)% |
| Anticoincidence efficiency | 98.7(1)% |
| PSA efficiency | 92.6(1)% |
| Total analysis efficiency | 87.5(2)% |
| Containment efficiency | 88.35(9)% |




Model detector response on calibration data, extrapolate FWHM resolution and bias in physics

Pulse shape Analysis

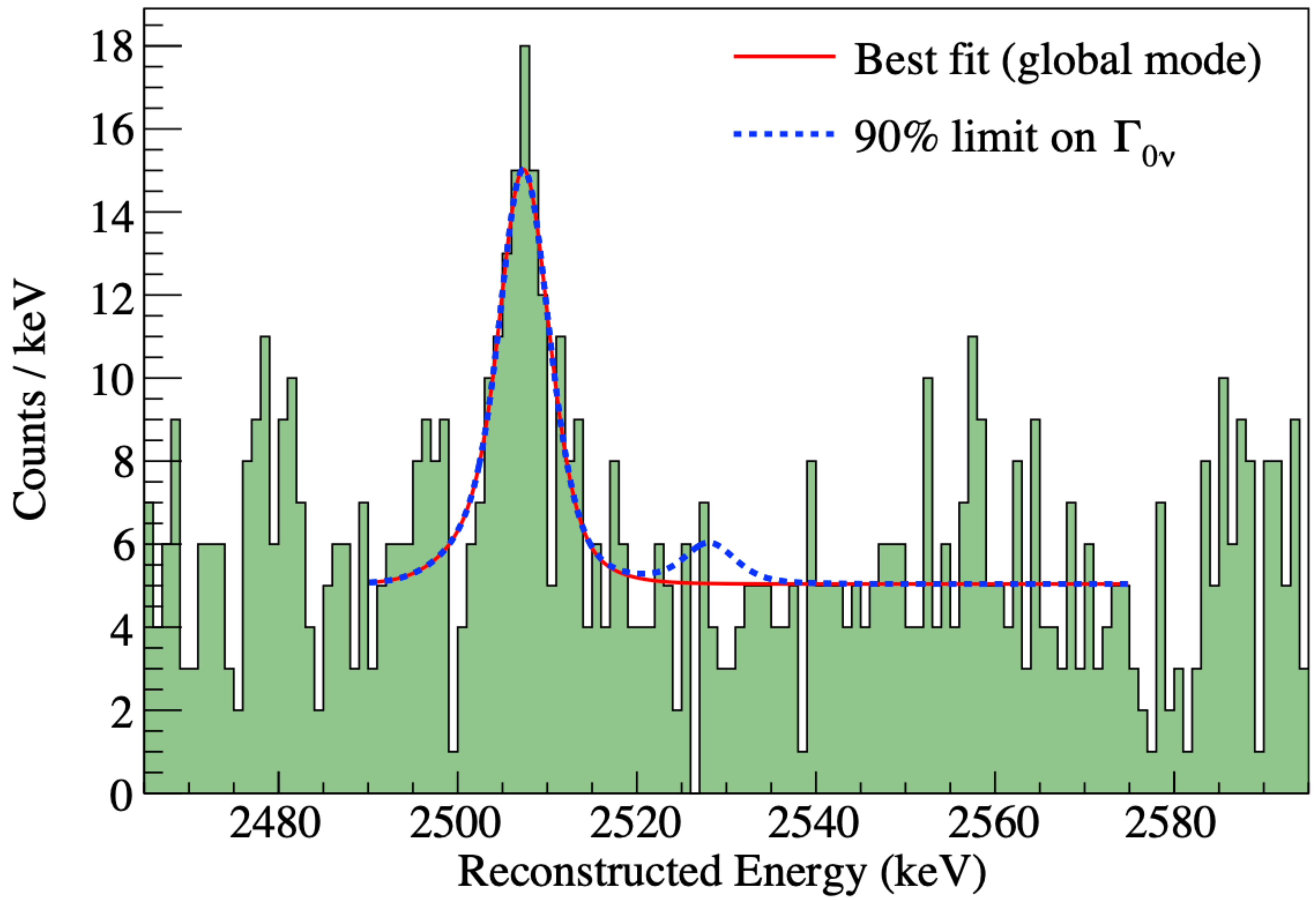
ROI blinding

Efficiency evaluation

Detector response

ROI model Fit strategy

# Results on the 0νßß decay of $^{130}$Te to the ground state




Assuming 0νßß decay is mediated by light Majorana neutrino exchange:

$$m_{\beta\beta} < 75 - 350 \text{ meV}$$

- $TeO_2$ exposure included is 372 kg·yr
- Bayesian unbinned fit to the maximum posterior probability: flat priors, $\Gamma_{0\nu\beta\beta} > 0$

We model the ROI (2490, 2575) keV with:

- Flat continuum
- $^{60}$Co sum peak (rate + position)
- Posited peak for 0νßß (rate)

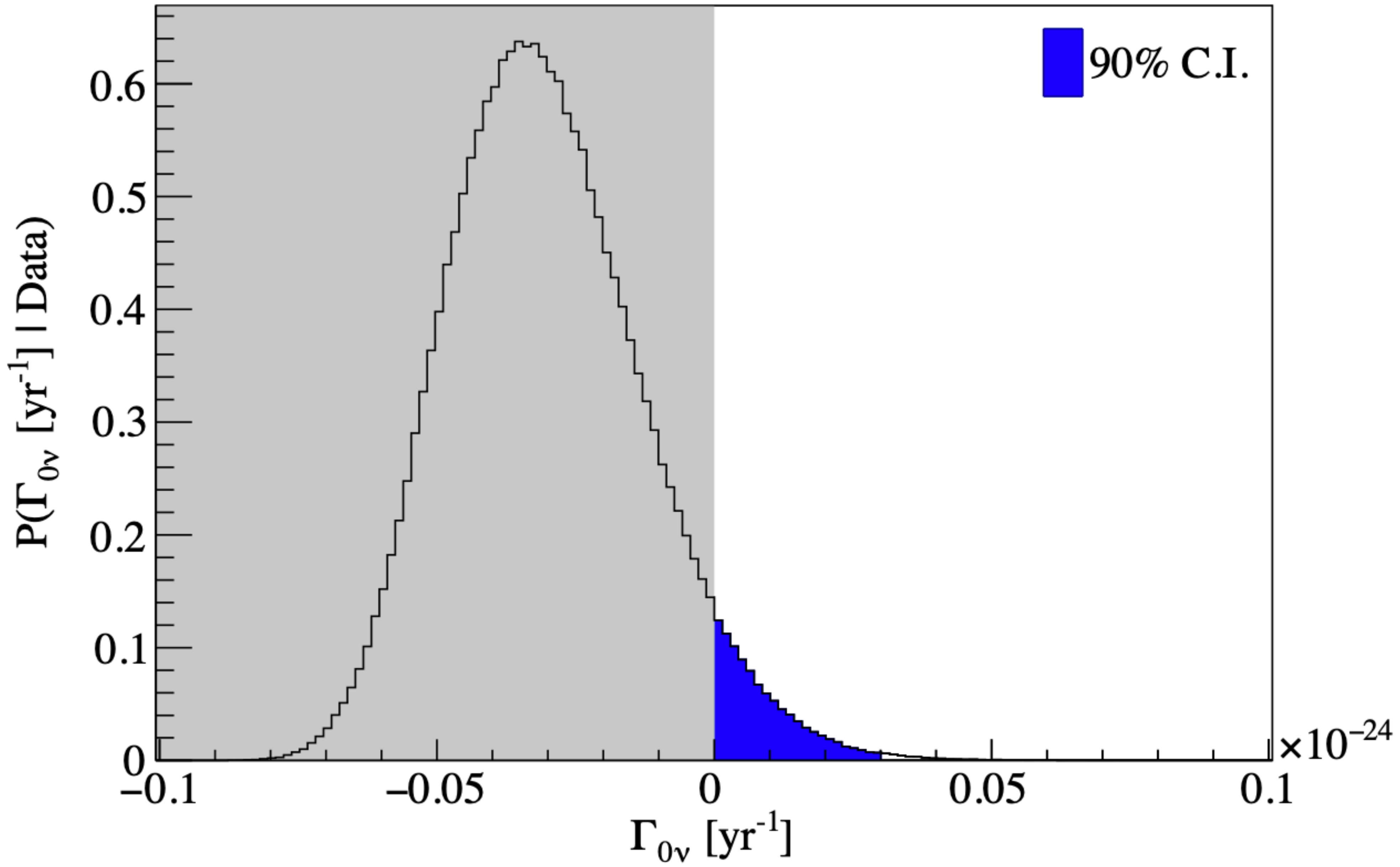
No evidence of 0νßß decay

$$T^{1/2}_{0\nu\beta\beta} > 3.2 \cdot 10^{25} \text{ yr } (90\,\%\,\text{C.I.})$$

Phys. Rev. Lett. 124, 122501 (2020)

# Results on the 0νßß decay of $^{130}$Te to the ground state

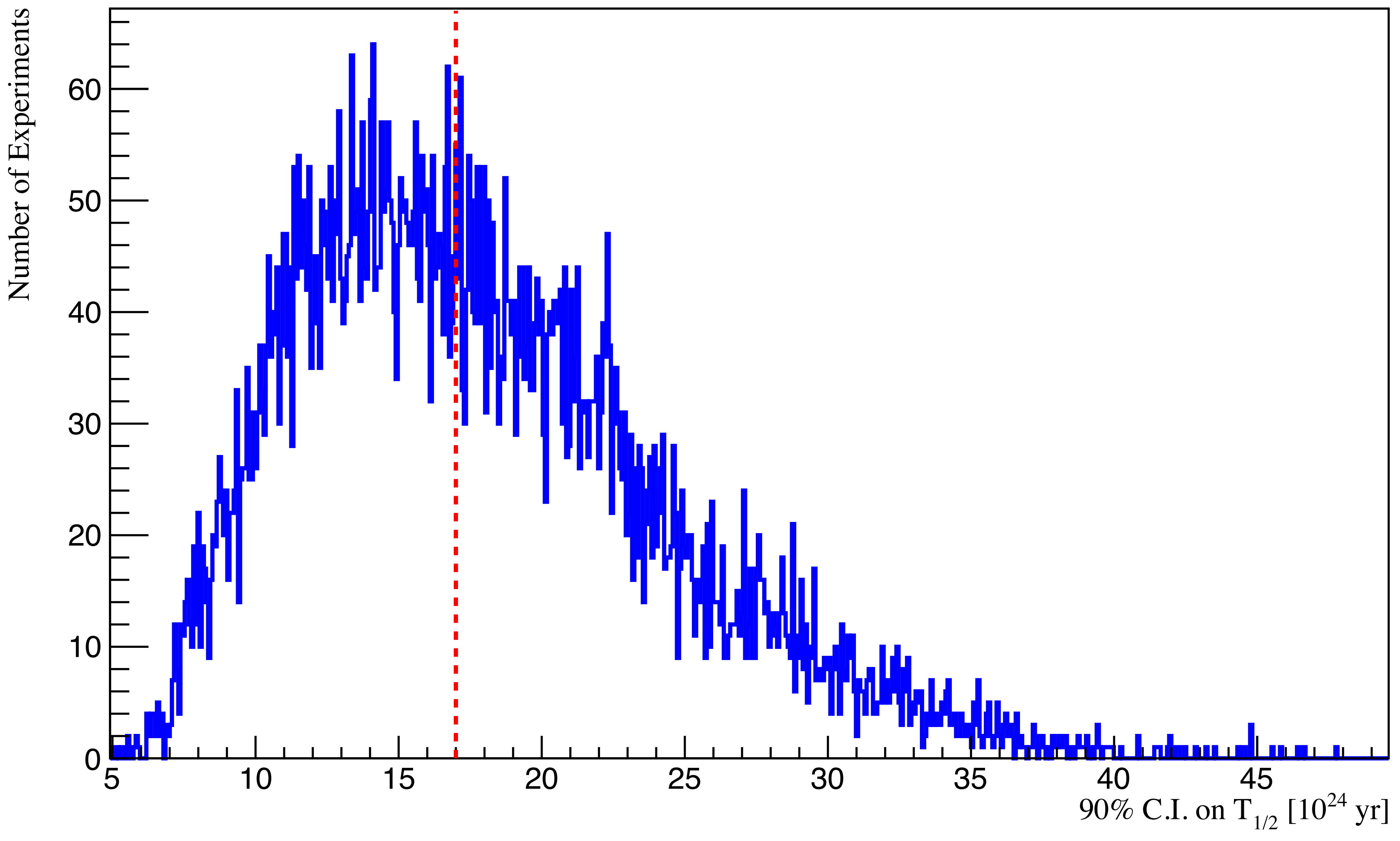
Posterior for $\Gamma_{0\nu\beta\beta}$




We artificially release the physical constraint $\Gamma_{0\nu\beta\beta} > 0$ to evaluate how the systematics (nuisance parameters) affect our best fit [<0.04%]

The impact on the half-life limit is <0.4%

Exclusion sensitivity




Median 90% C.I. limit setting sensitivity

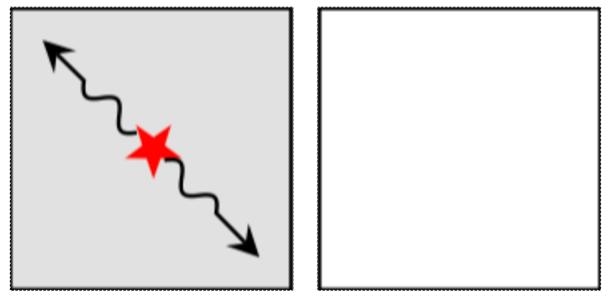
$$T^{1/2}_{0\nu\beta\beta} = 1.7 \cdot 10^{25}\ \mathrm{yr}$$

The probability to obtain a stronger limit than $3.2 \cdot 10^{25}$ yr is **~3%**

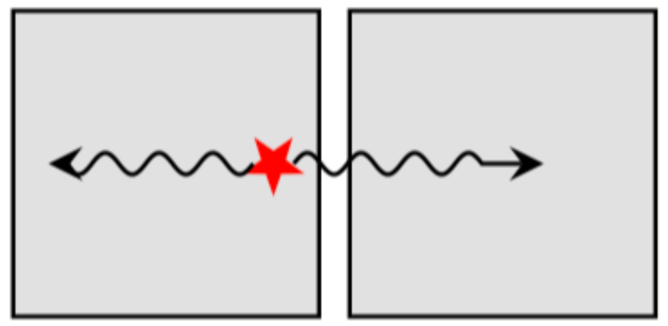
# The CUORE background model

- Based on CUORE-0 + CUORE budget Eur.Phys.J.C 77 (2017) 8, 543
- 9 geometric elements included: crystals, towers copper structure, copper vessel, cryostat thermal shields, lead shields, lead suspension system
- 60 ß/γ contaminants + muons + $^{130}$Te 2νßß decay
- GEANT4 + detector response to simulate CUORE events
- 3 energy spectra considered:
  - ★ single bolometer energy deposition ($M_1$) [~90% ßß events]
  - ★ energies simultaneously deposited in two crystals ($M_2$)
  - ★ sum energy of $M_2$ events ($\Sigma_2$)

→ [$\gamma$ scatters, $\alpha$ decays]

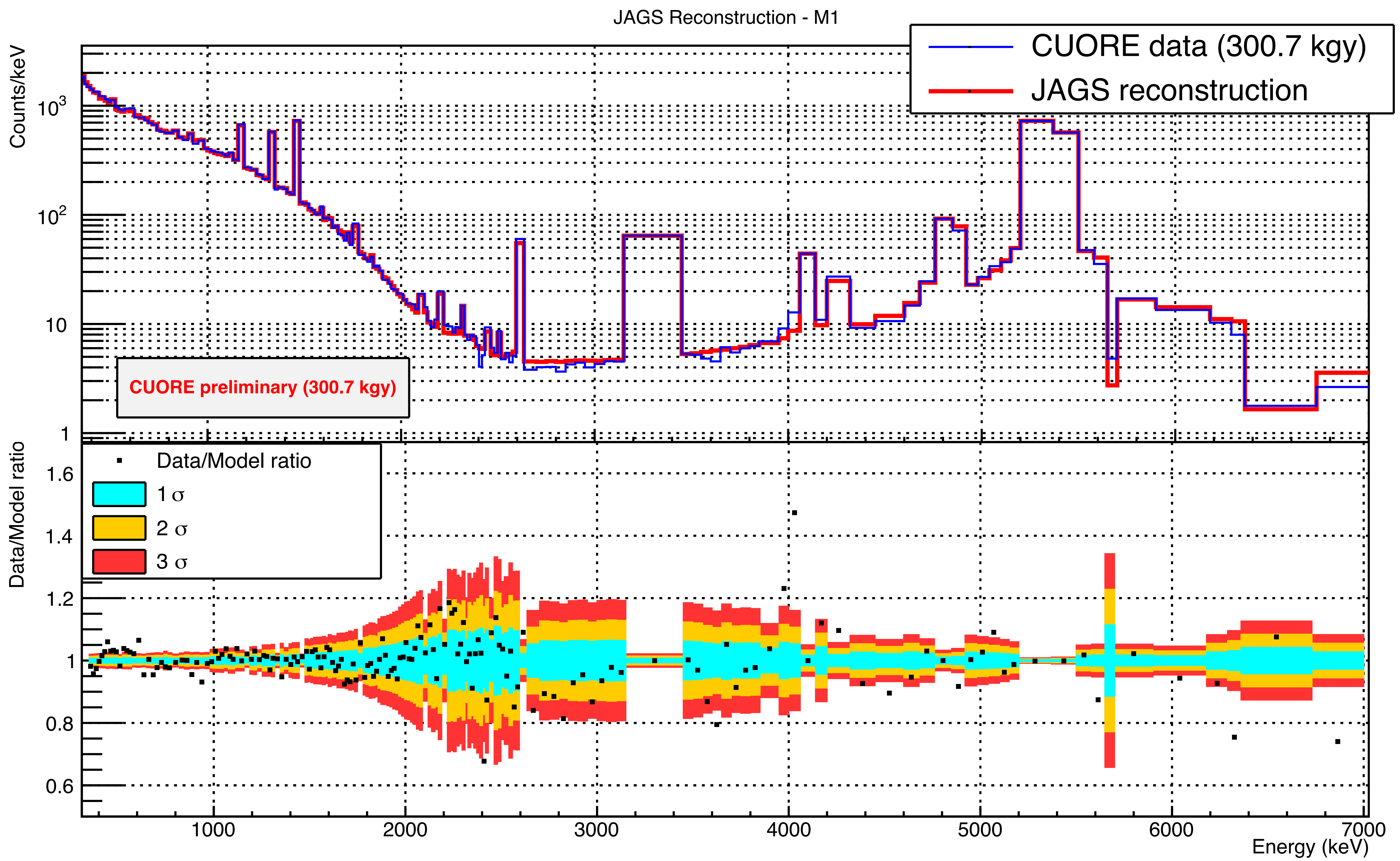


$M_1$ events



$M_2$ events

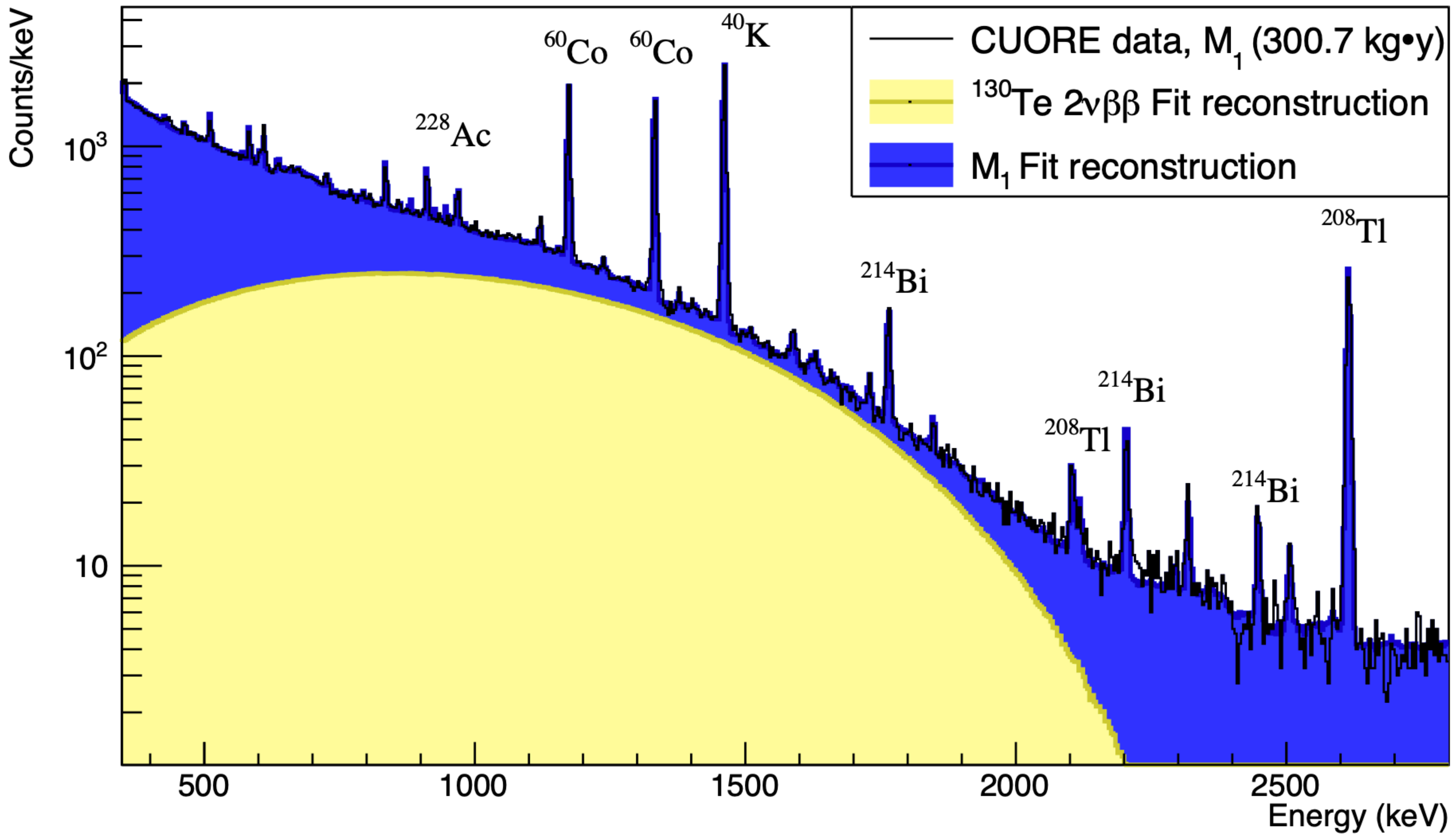
# The CUORE background model




- MCMC binned Bayesian fit of simulations to real data with JAGS
- Flat prior for all the sources except muons (Gaussian pdf)

arXiv:2012.11749

# New measurement of $^{130}$Te 2νββ decay half-life




Systematic effects:

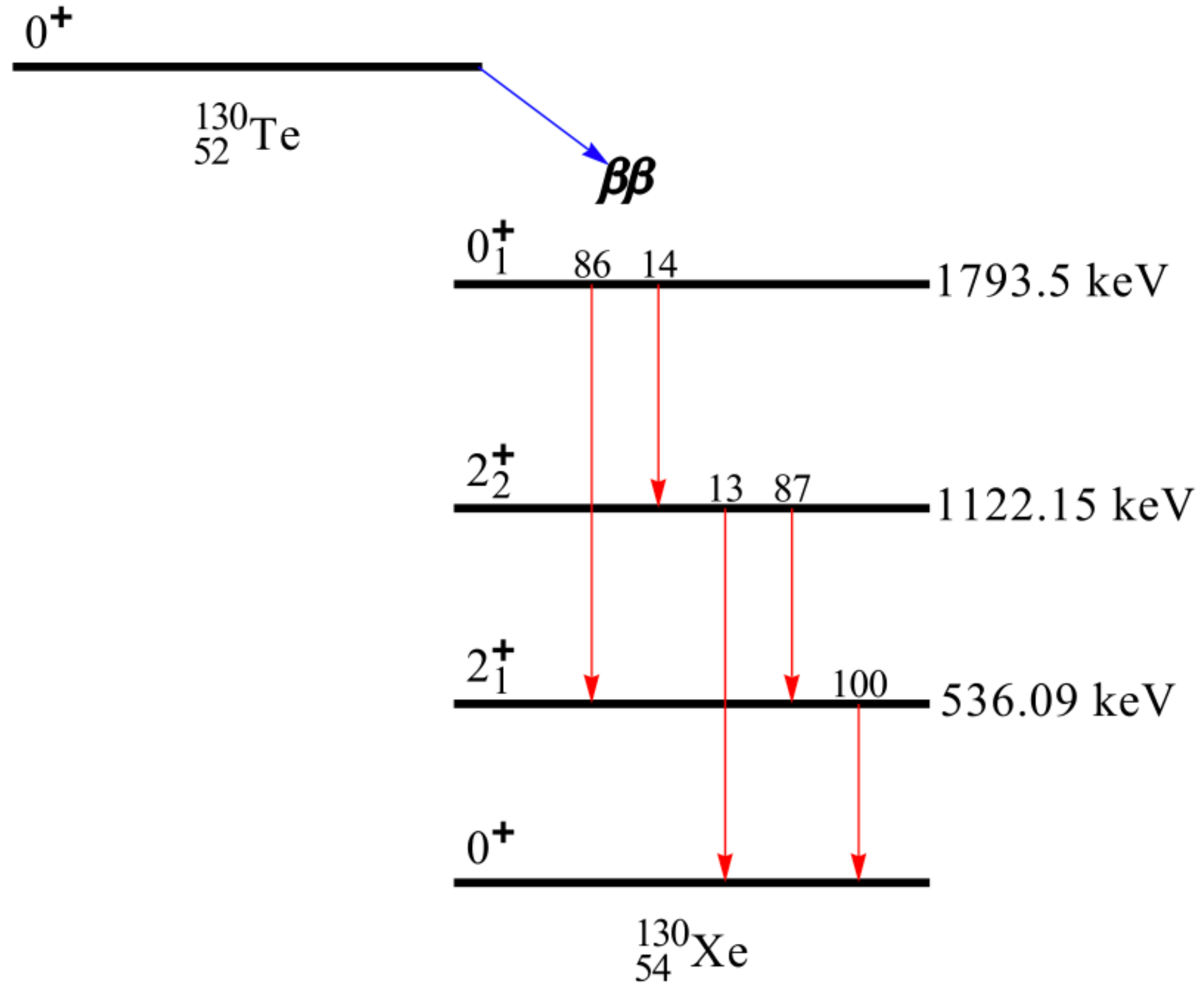
- 2νββ spectral shape (SSD/HSD) [±1.3%]
- Energy threshold (300,800) keV [±0.4%]
- Different detector splitting [±0.8%]
- Single dataset fits [+0.3%,-1.1%]
- $^{90}$Sr removal/only 25 sources [±0.3%]

$$T^{1/2}_{2\nu\beta\beta} = \left[7.71^{+0.08}_{-0.06}(\text{stat.})^{+0.12}_{-0.15}(\text{syst.})\right] 10^{20}\ \text{yr}$$

arXiv:2012.11749

# Other analyses with CUORE

## $^{130}$Te double beta decay to excited states




- Fully contained events from the most significant signatures (multiple crystals)

$$T^{0\nu}_{1/2} > 5.9 \times 10^{24}\ \text{yr}\ (90\,\%\ \text{C.I.})$$

$$T^{2\nu}_{1/2} > 1.3 \times 10^{24}\ \text{yr}\ (90\,\%\ \text{C.I.})$$

arXiv:2101.10702

## $^{120}$Te positron emitting electron capture (0νβEC) decay

$$^{120}\text{Te} + e_b^- \rightarrow {}^{120}\text{Sn} + \beta^+ + X$$
$$\rightarrow {}^{120}\text{Sn} + 2\gamma_{511} + X$$

- $Q_{\beta\beta}$ = 1714.8 keV
- Several decay signatures based on where the positron/511-keV γs release energy
- Bayesian fit algorithm tested on blinded data
- Median 90% CI exclusion sensitivity (toy MC)

$$T^{1/2}_{0\nu\beta EC} = 3.3 \cdot 10^{22}\ \text{yr}$$

# Conclusion and perspectives

- CUORE proved the scalability of the bolometric technique and paved the way to rare processes bolometric searches

- Data taking is proceeding smoothly to collect 5 years of run time

- More than 1 tonne · yr exposure collected up to now

- Updated results on $^{130}$Te $0\nu\beta\beta$ and other rare decay searches will be released soon

- Important feedback for the future CUPID project arXiv:1504.03599

# Thank you on behalf of the CUORE collaboration