

Latest results from CUORE and path towards CUPID

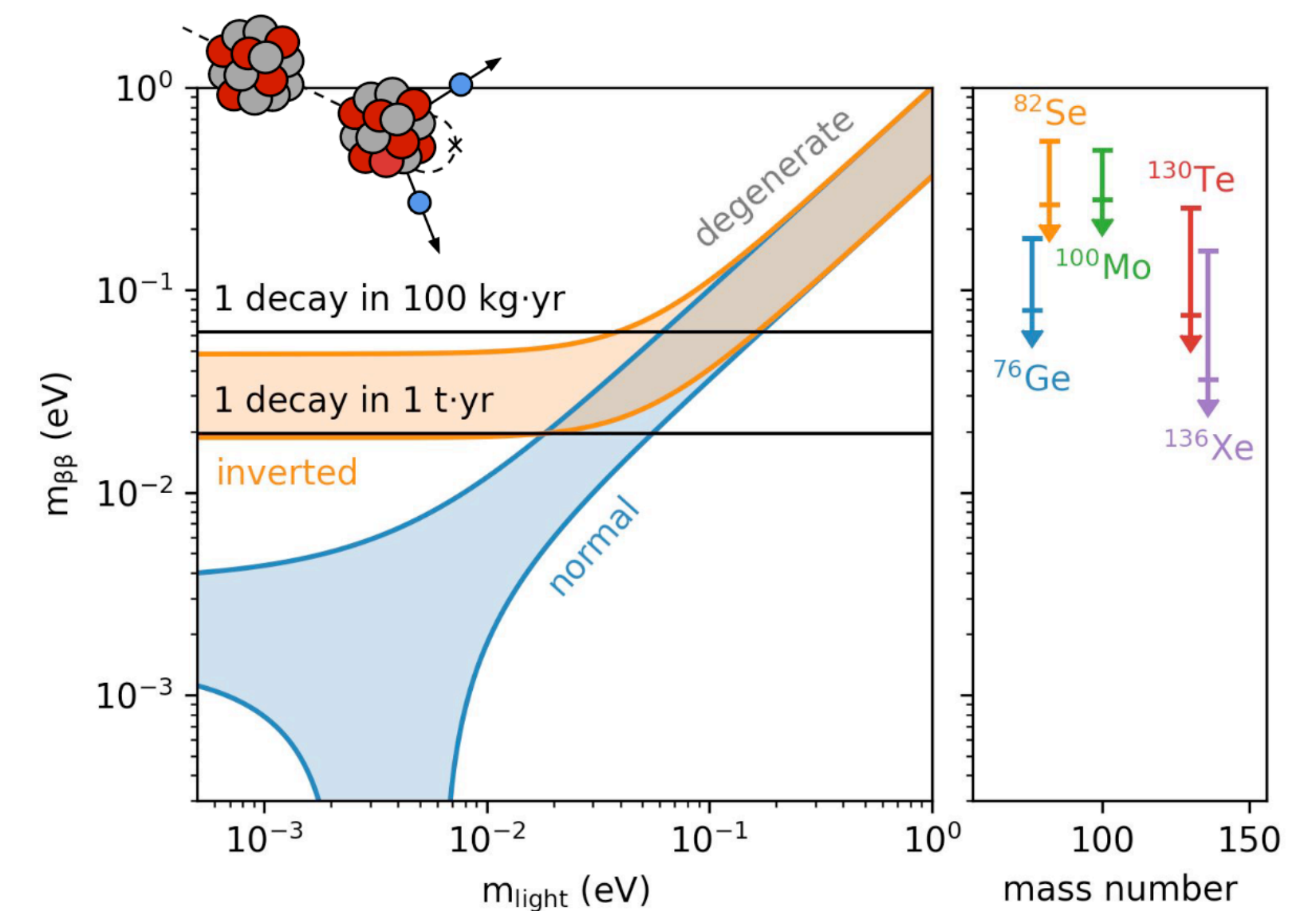
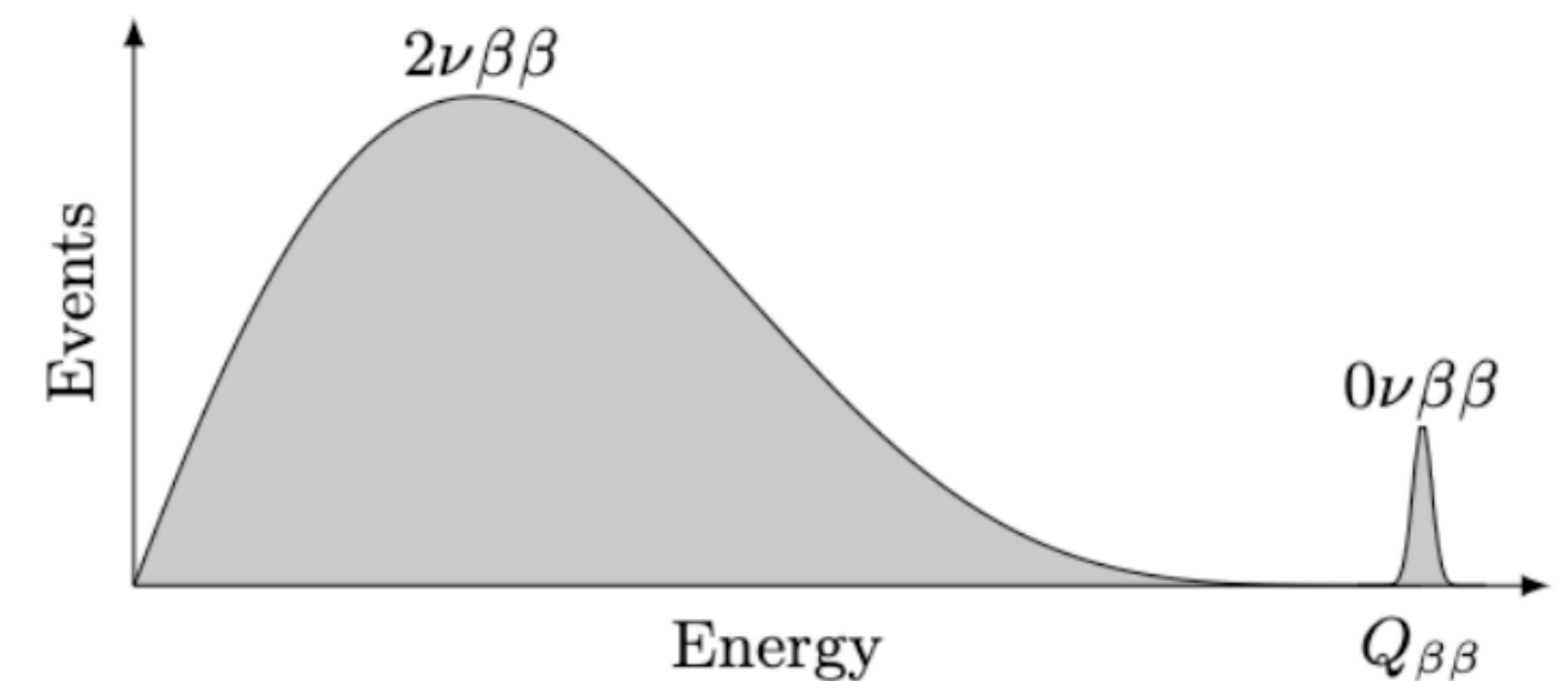
Dounia Helis on behalf of CUORE and CUPID collaborations

TeV Particle Astrophysics Conference, 3-7 Novembre 2025

Physics case: What are we looking for ?

Neutrinoless double-beta decay

- $2\nu\beta\beta$, observed for 11 nuclei with $T_{1/2} \sim 10^{18}-10^{24}$ yr
- $0\nu\beta\beta$, violates L and B-L number, possible if neutrino are Majorana
- $0\nu\beta\beta$ to probe neutrino mass and nature
- Experimentally challenging
- $0\nu\beta\beta$ candidates: only 9 are relevant experimentally
 ^{48}Ca , ^{76}Ge , ^{82}Se , ^{96}Zr , ^{100}Mo , ^{116}Cd , ^{130}Te , ^{136}Xe

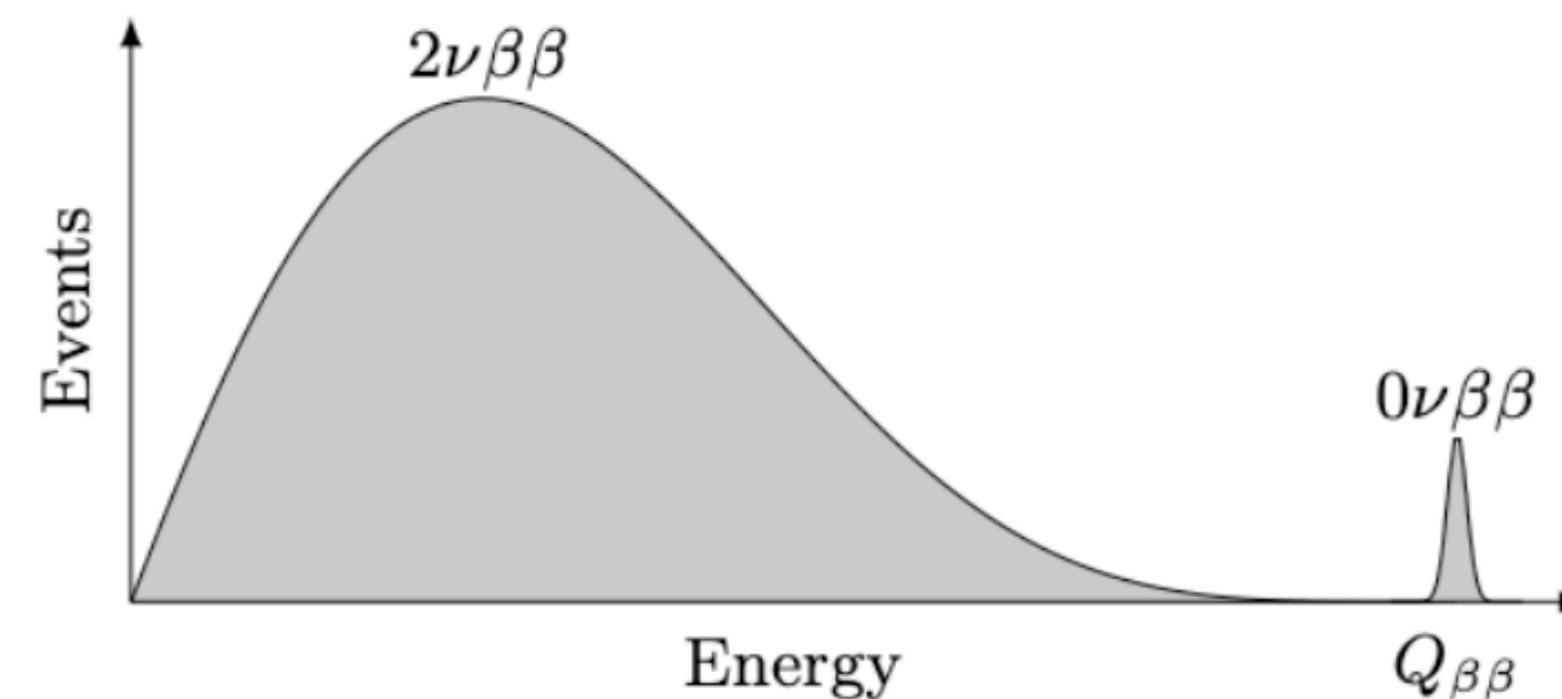


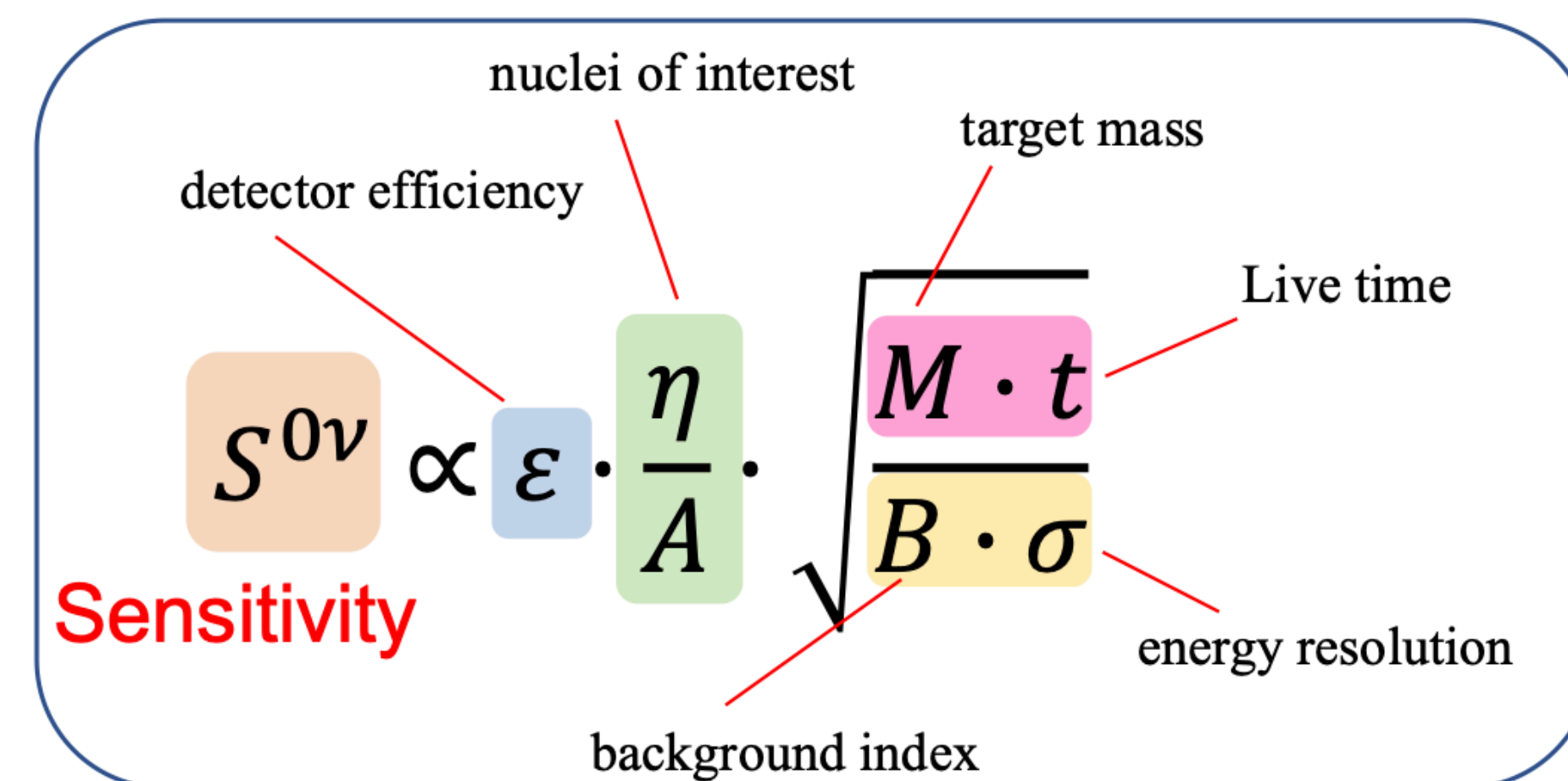
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q, Z) |M_{0\nu}|^2 \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}$$

Neutrinoless double beta decay searches

The challenges

- Experimental signature : **a peak over a flat background**
- We need
 - **High efficiency detectors** => source embedded in detector
 - Good energy resolution
 - Low background in the ROI
 - **Underground experiments**
 - **Active and passive shields**
 - Long and stable data collection





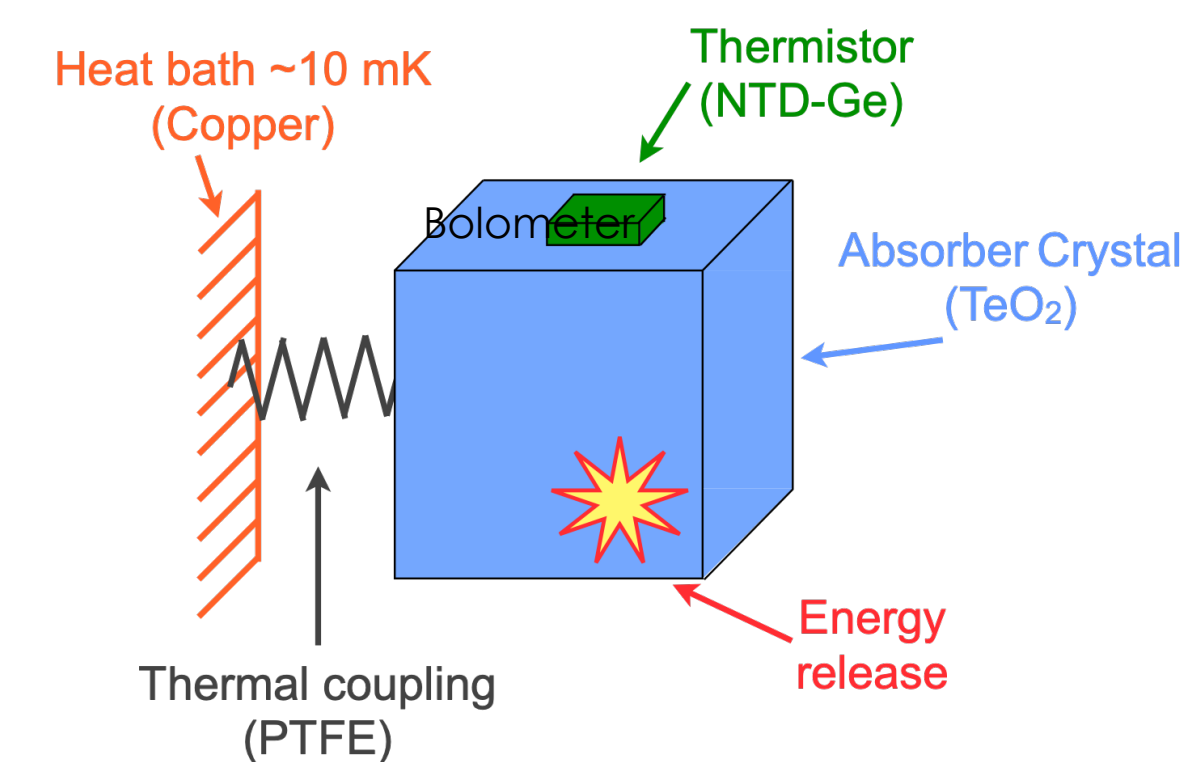
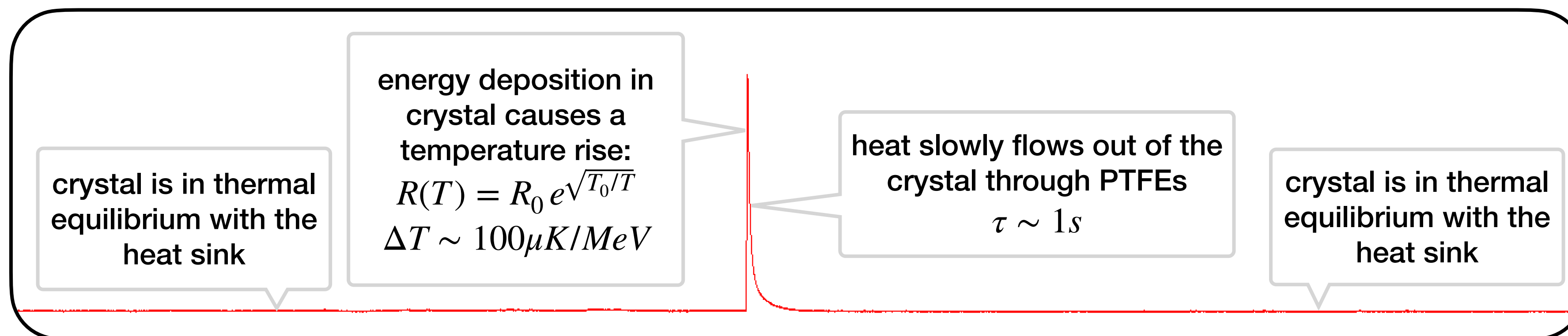
The diagram illustrates the formula for sensitivity $S^{0\nu}$ with the following components labeled:

- Sensitivity**: $S^{0\nu}$ (orange box)
- detector efficiency**: ϵ (blue box)
- nuclei of interest**: $\frac{\eta}{A}$ (green box)
- target mass**: $M \cdot t$ (pink box)
- Live time**: t (part of the pink box)
- background index**: $B \cdot \sigma$ (yellow box)
- energy resolution**: σ (part of the yellow box)

The formula is:
$$S^{0\nu} \propto \epsilon \cdot \frac{\eta}{A} \cdot \sqrt{\frac{M \cdot t}{B \cdot \sigma}}$$

... and how do we do it ?

Cryogenic Calorimeters



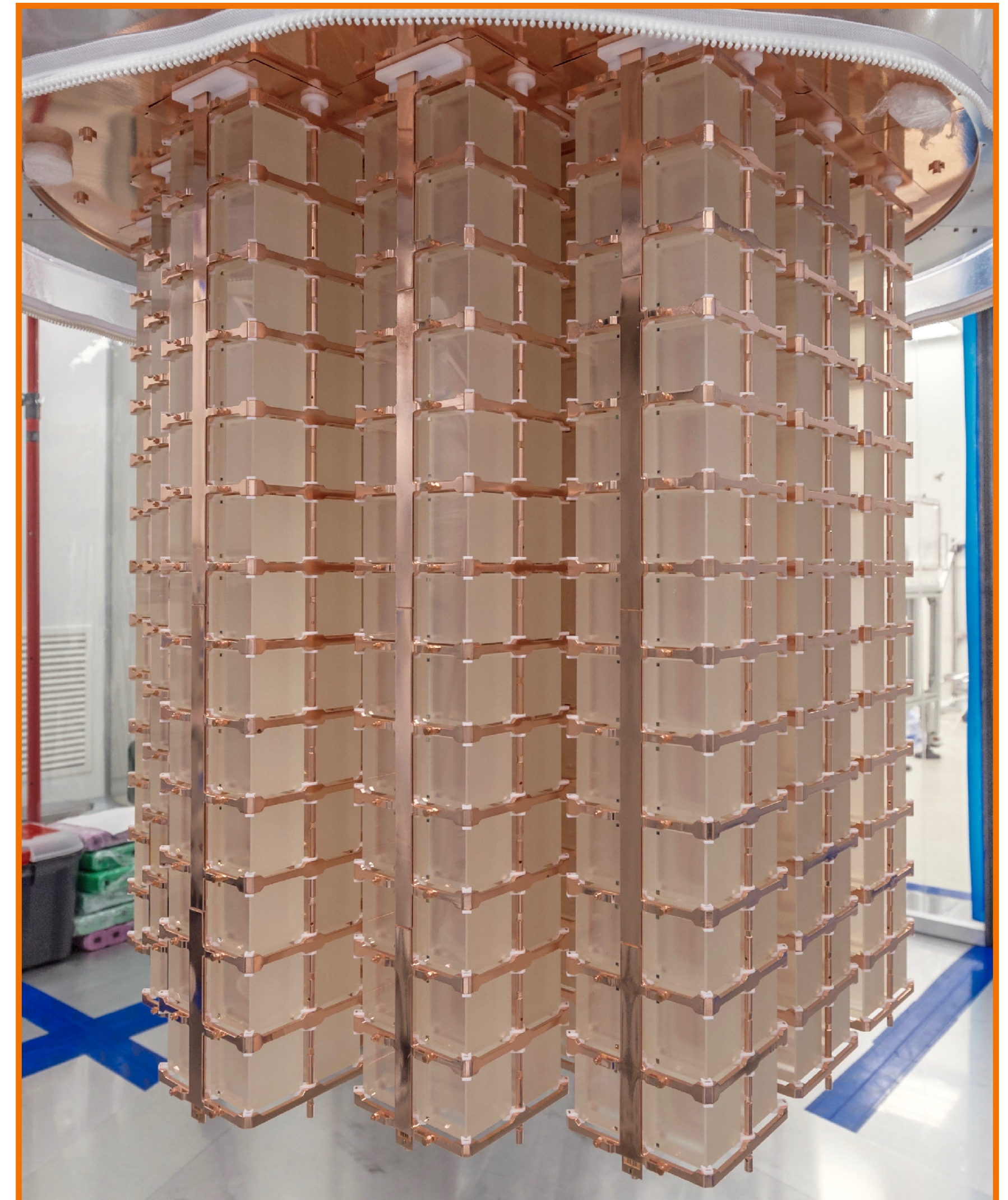
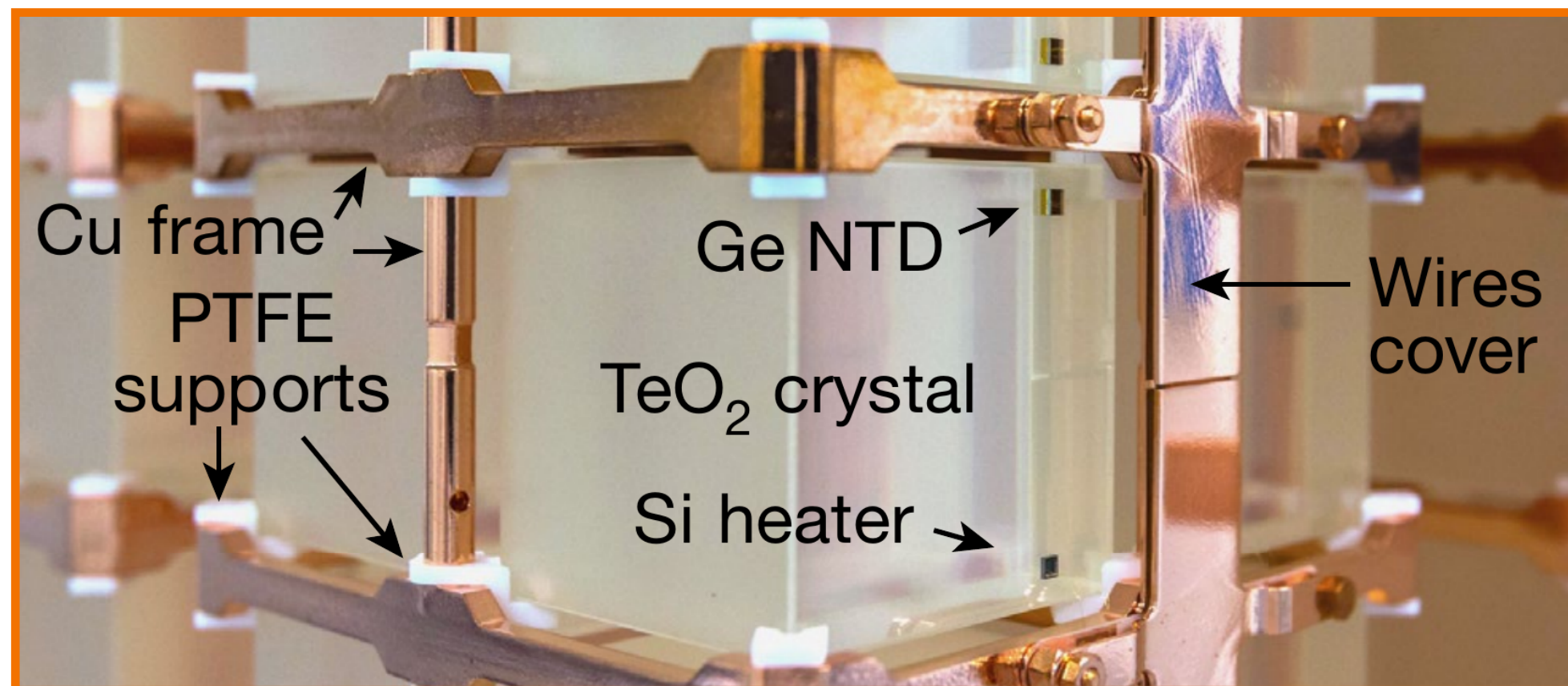
- Energy deposition measured as a rise of temperature => phonons mediated signal
- Working at T ~10-20 mK
- Variety of thermal sensors: NTD, TES, MMC
- Variety of material for the absorber => probing several $0\nu\beta\beta$ candidates
- Good energy resolution ~ 5 keV at 2.6 MeV
- Particle identification using two bolometers to detect phonons and light (spoiler!)

$$\Delta T = \frac{\Delta E}{C(T)}$$

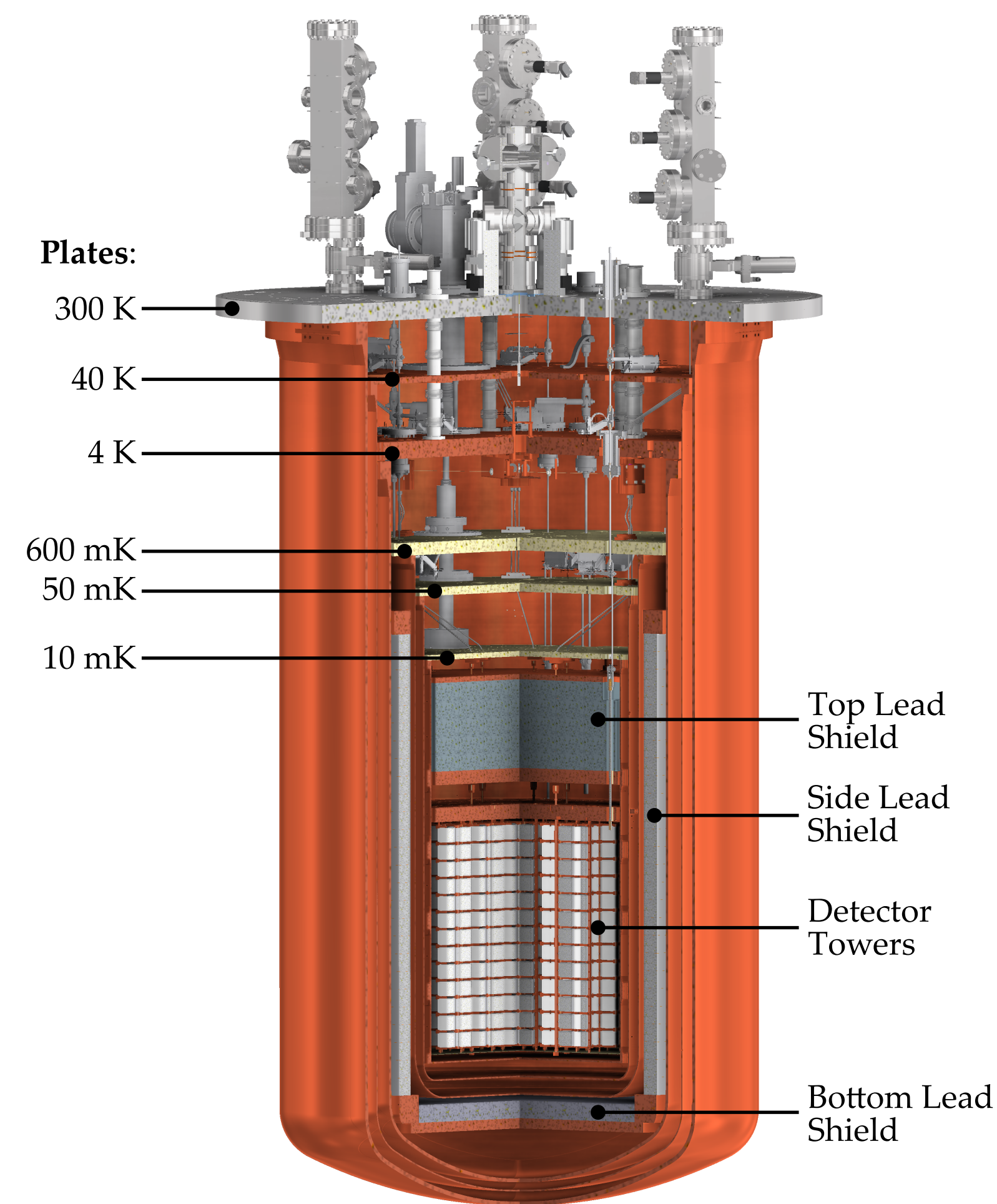
$$C(T) \propto T^3$$

Cryogenic Underground Observatory for Rare Events

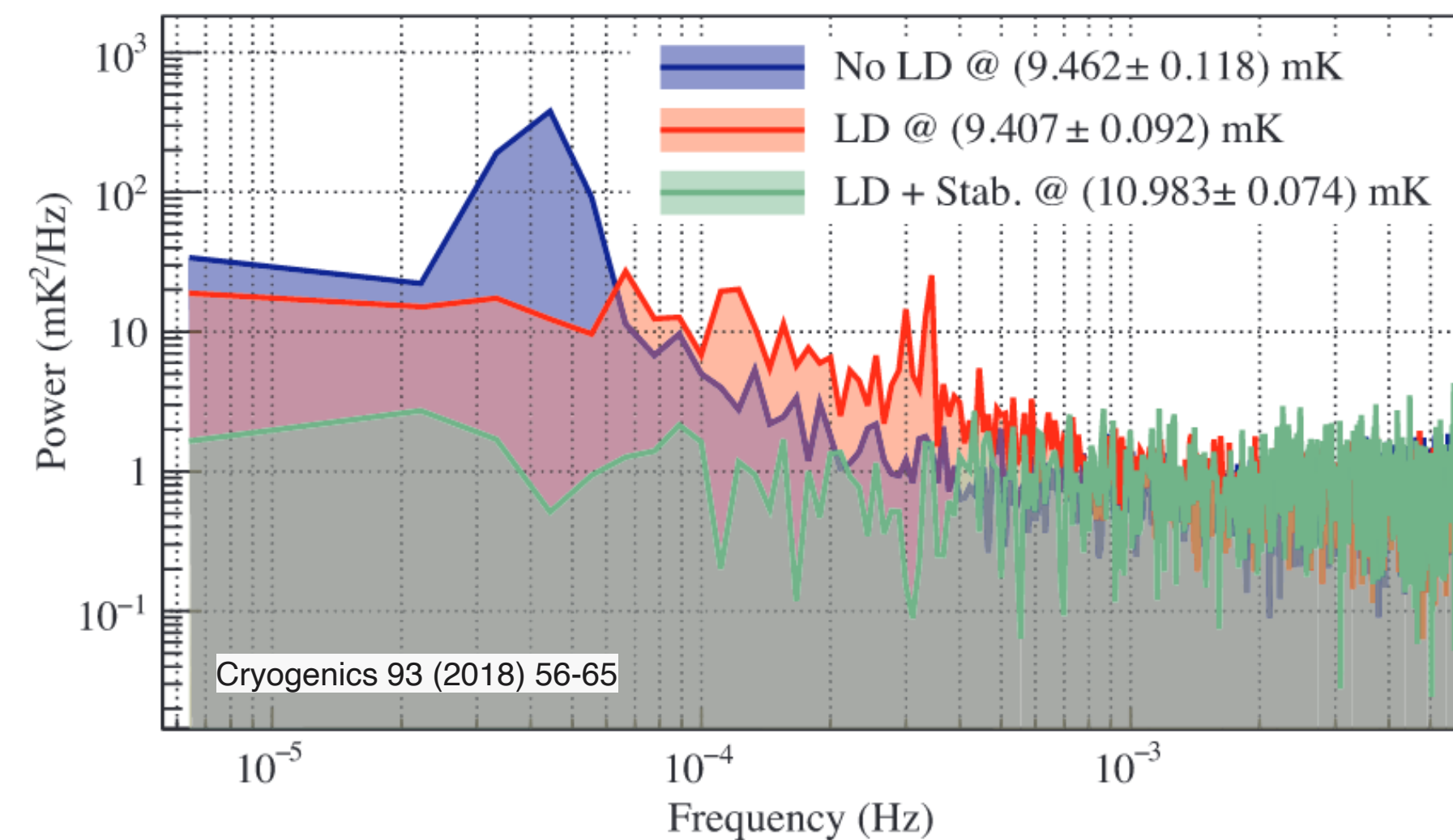
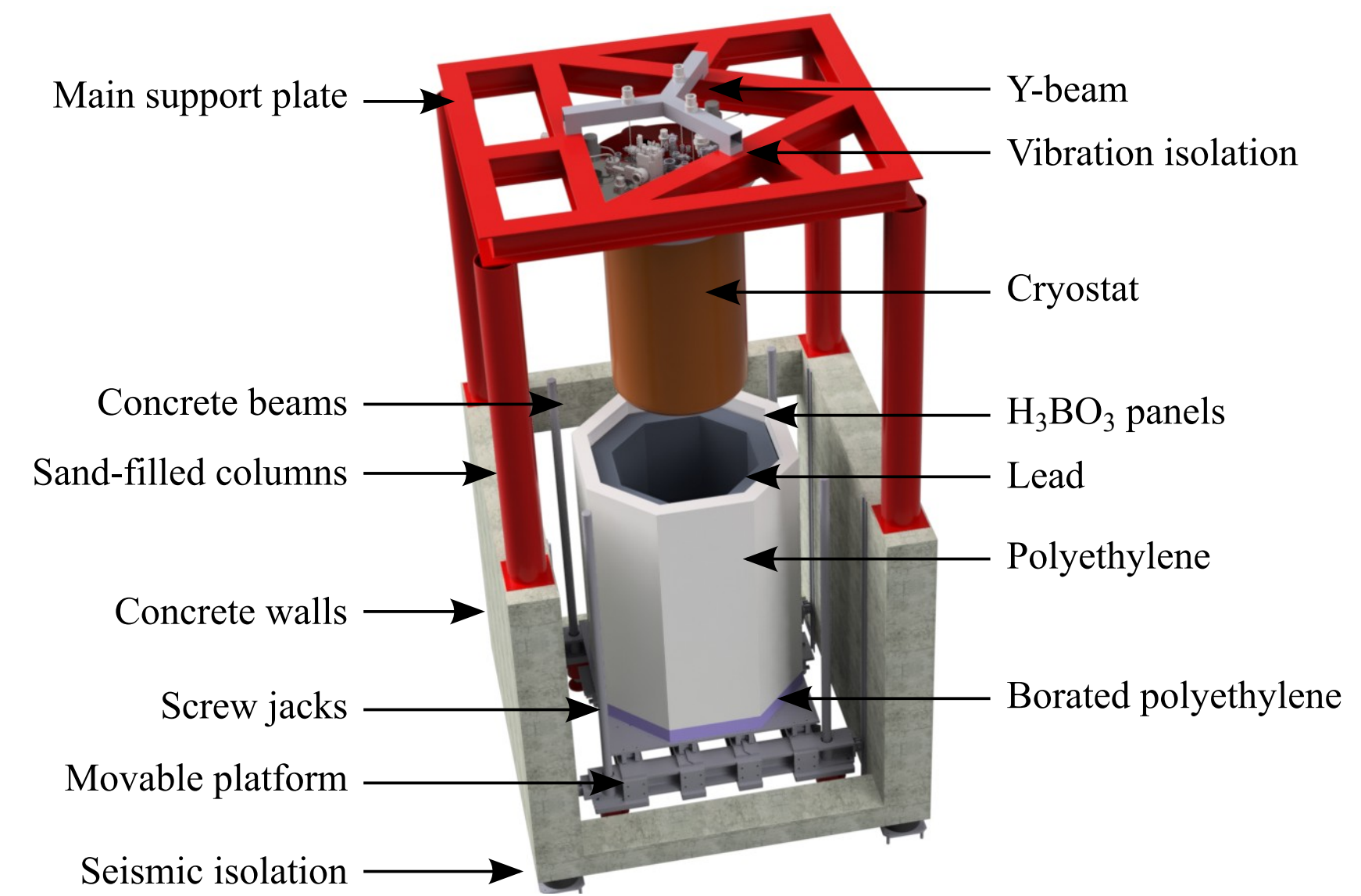
- Located at LNGS under ~ 3600 m.w.e
- Search for $0\nu\beta\beta$ of ^{130}Te
- 988 TeO_2 crystals arranged in 19 towers
- 742 kg of TeO_2 (206 kg ^{130}Te) with natural isotopic abundance ($\sim 34\%$)
- Cryogenic detectors cooled down to ~ 10 mK



The CUORE infrastructure



- Cryogen-free cryostat
- Five PT cryocoolers
- Dilution refrigerator with 4 μW of cooling power at 10 mK
- Low radioactivity materials
- External decoupling system to mitigate vibration
- Pulse tubes noise active cancellation system and linear drives
- Passive shielding



CUORE data taking

And what do we do with all this data?

- Stable data taking since 2019 after two years of cryostat and detector optimization
- Latest data release in Science [10.1126/science.adp6474](https://doi.org/10.1126/science.adp6474)
- Improved limit on the $0\nu\beta\beta$ decay of ^{130}Te

Half-life limit: $T_{1/2}^{0\nu} > 3.5 \times 10^{25} \text{ yr}$ (90% C.I.)

- And many other rare events searches and physics

[arXiv:2503.24137](https://arxiv.org/abs/2503.24137)

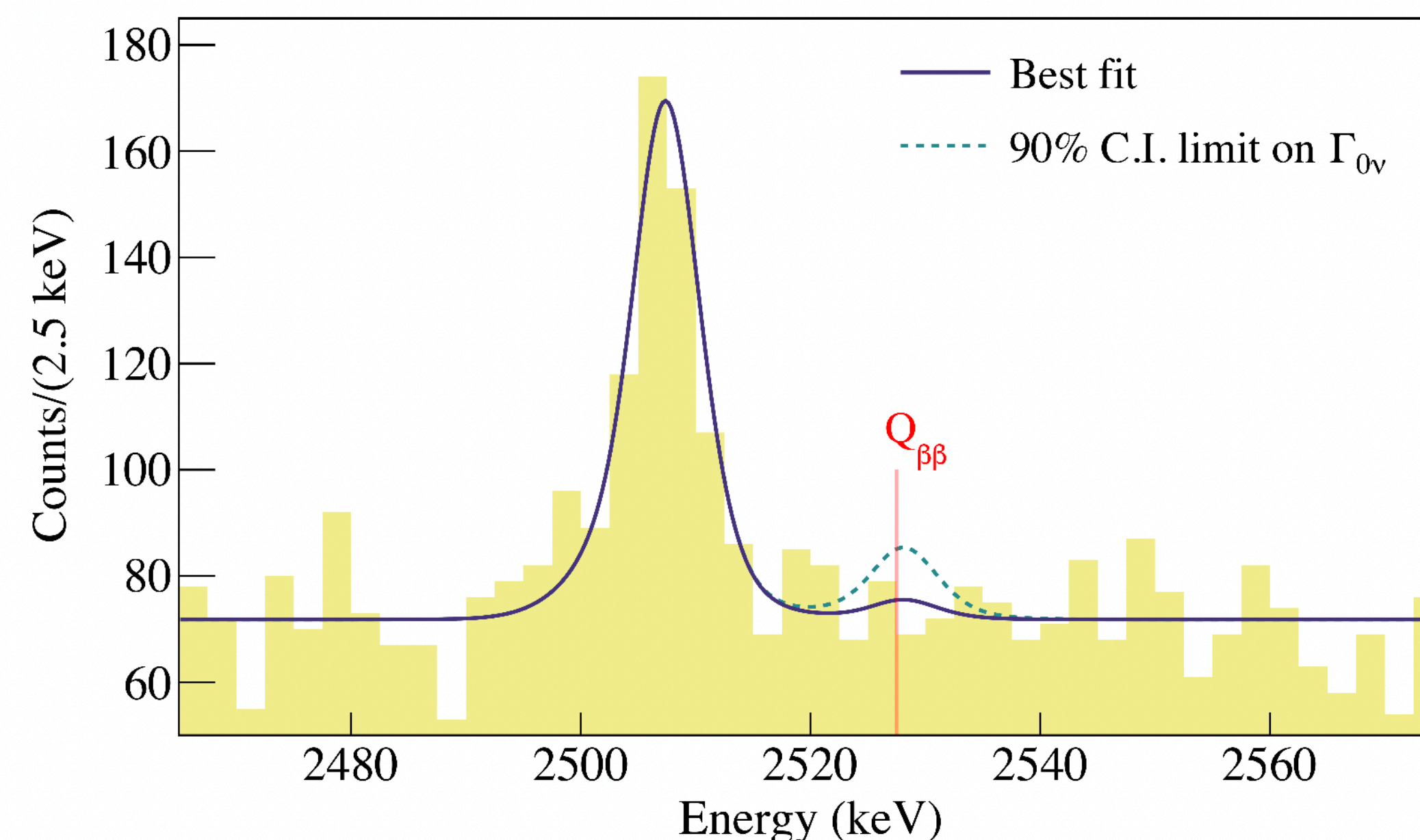
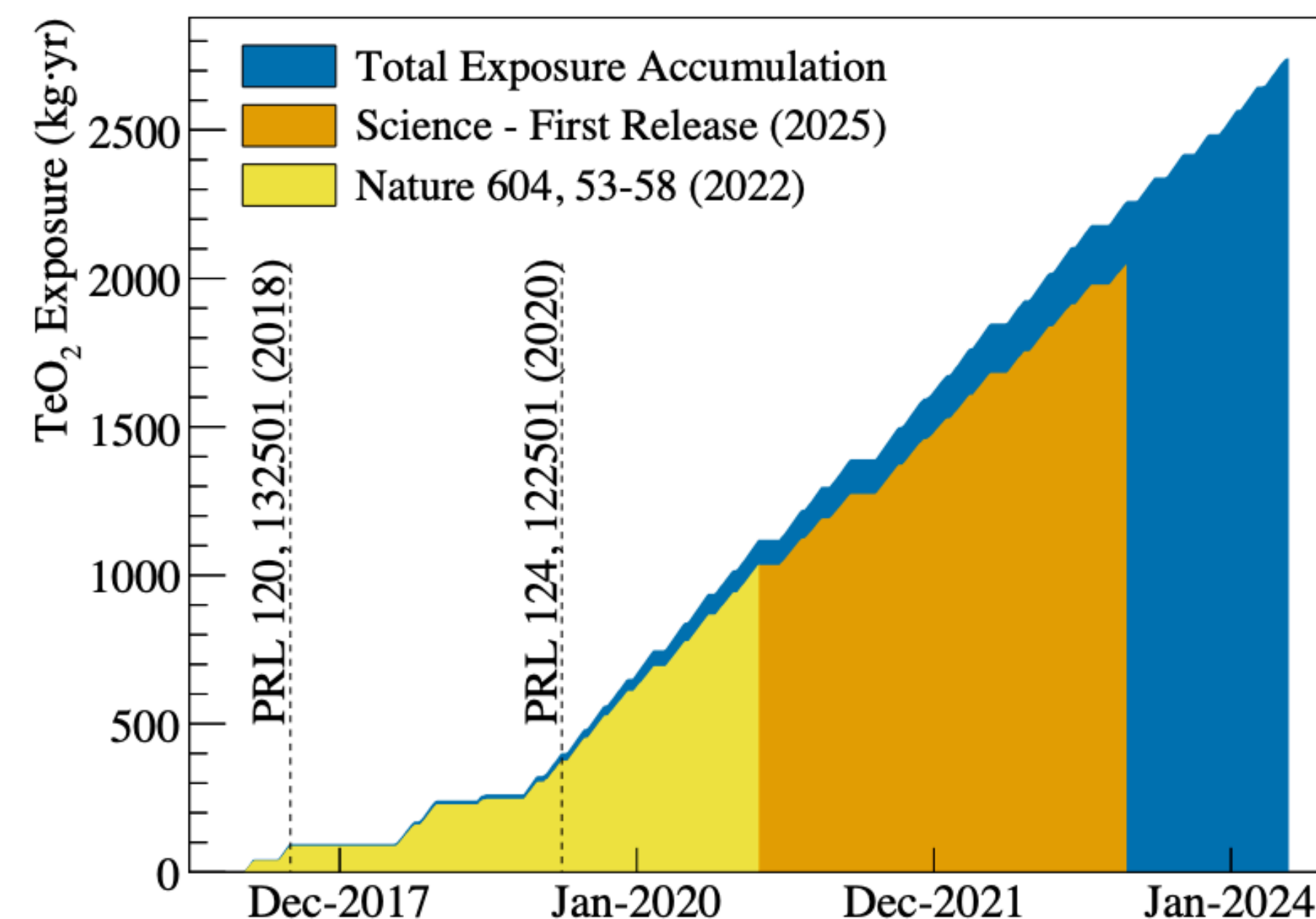
[Eur. Phys. J. C 81, 567 \(2021\)](https://doi.org/10.1146/annurev-nucl-010921-015000)

[Phys. Rev. C 105, 065504 \(2022\)](https://doi.org/10.1103/PhysRevC.105.065504)

[Phys. Rev. Lett. 133, 241801 \(2024\)](https://doi.org/10.1103/PhysRevLett.133.241801)

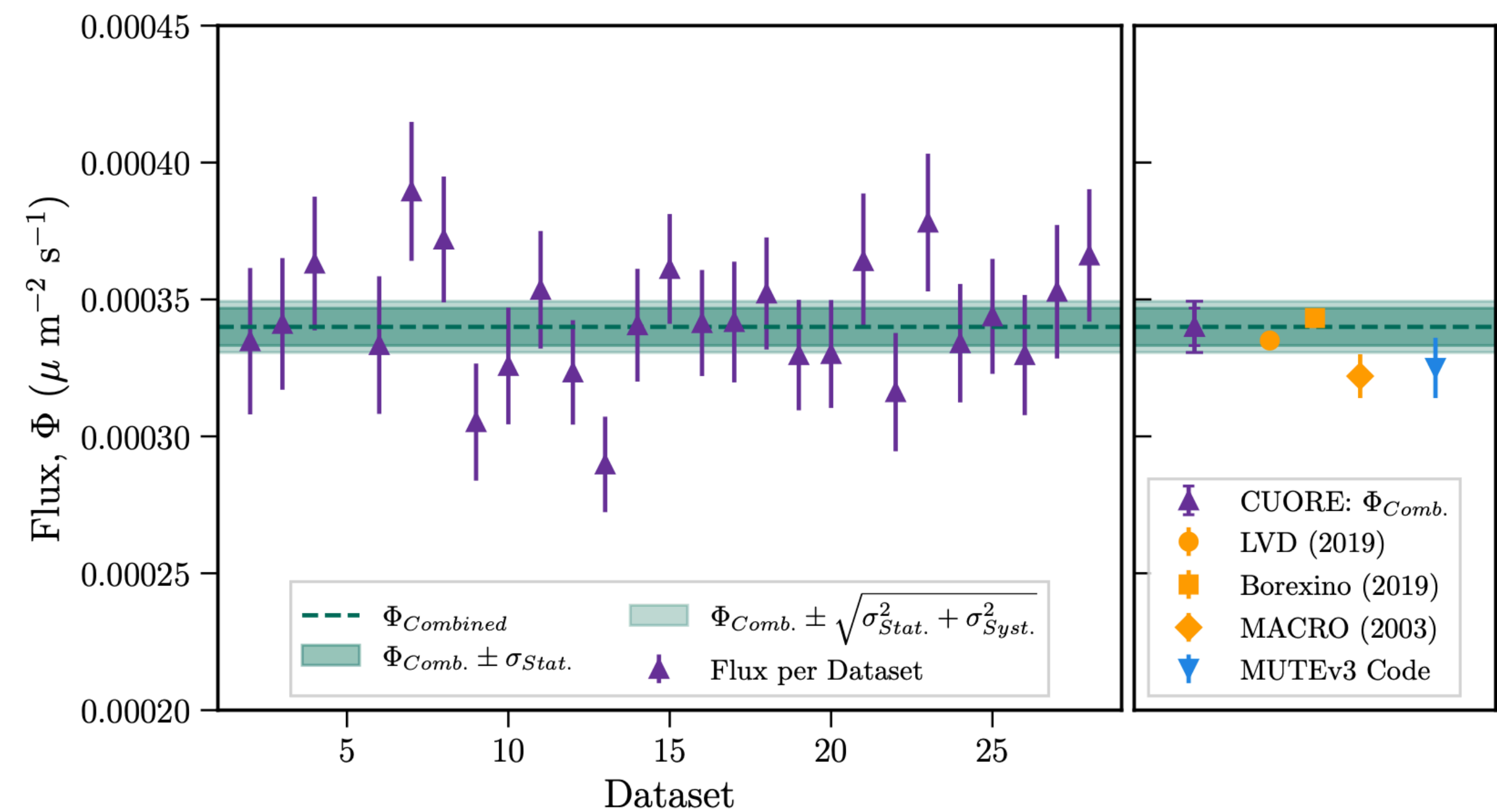
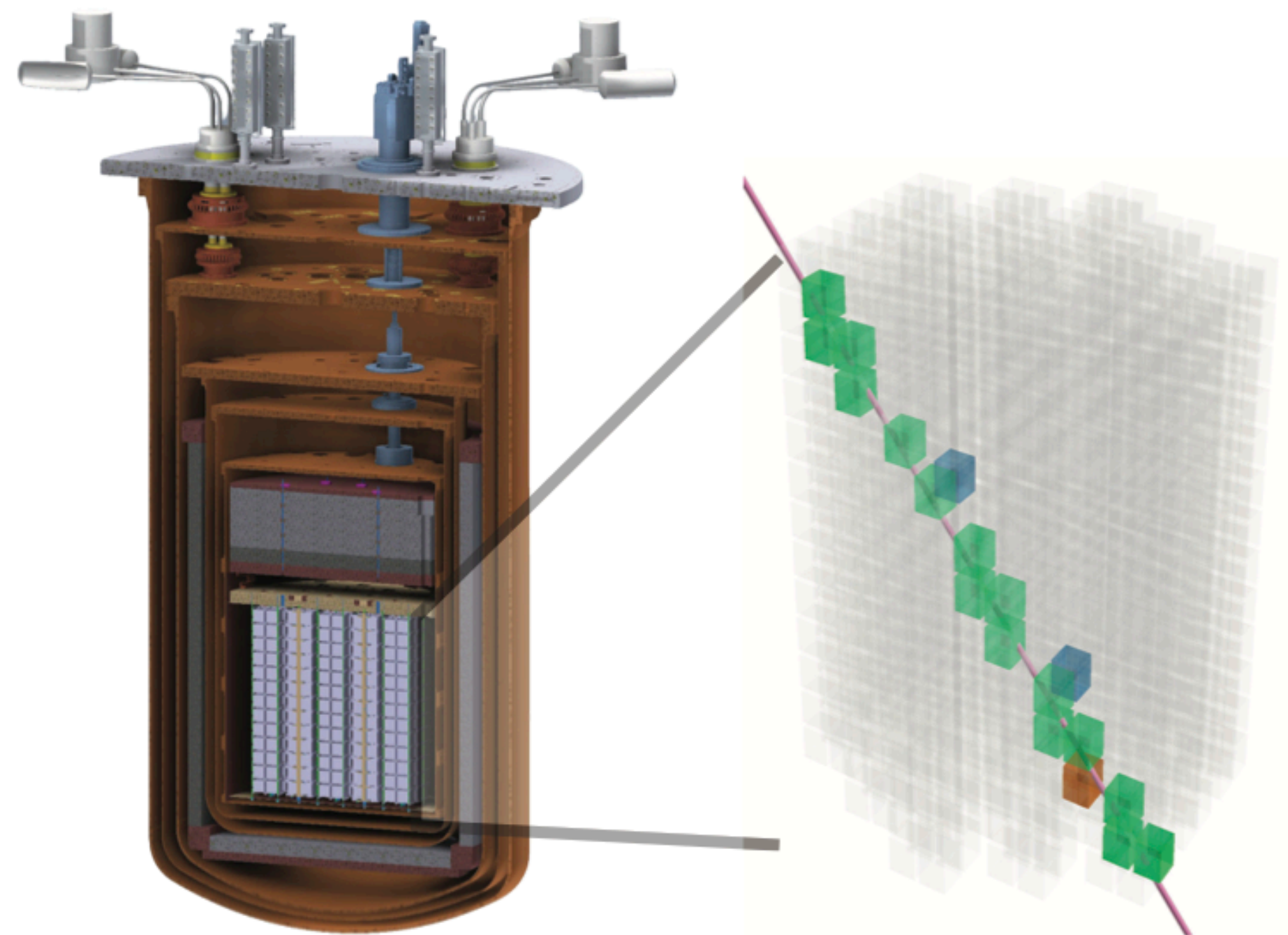
[Eur. Phys. J. C 84, 728 \(2024\)](https://doi.org/10.1146/annurev-nucl-010921-015000)

[arXiv:2505.09652](https://arxiv.org/abs/2505.09652) (CUORE Collaboration)



Cosmic rays with CUORE

Among other things



Muon analysis through tracks reconstruction

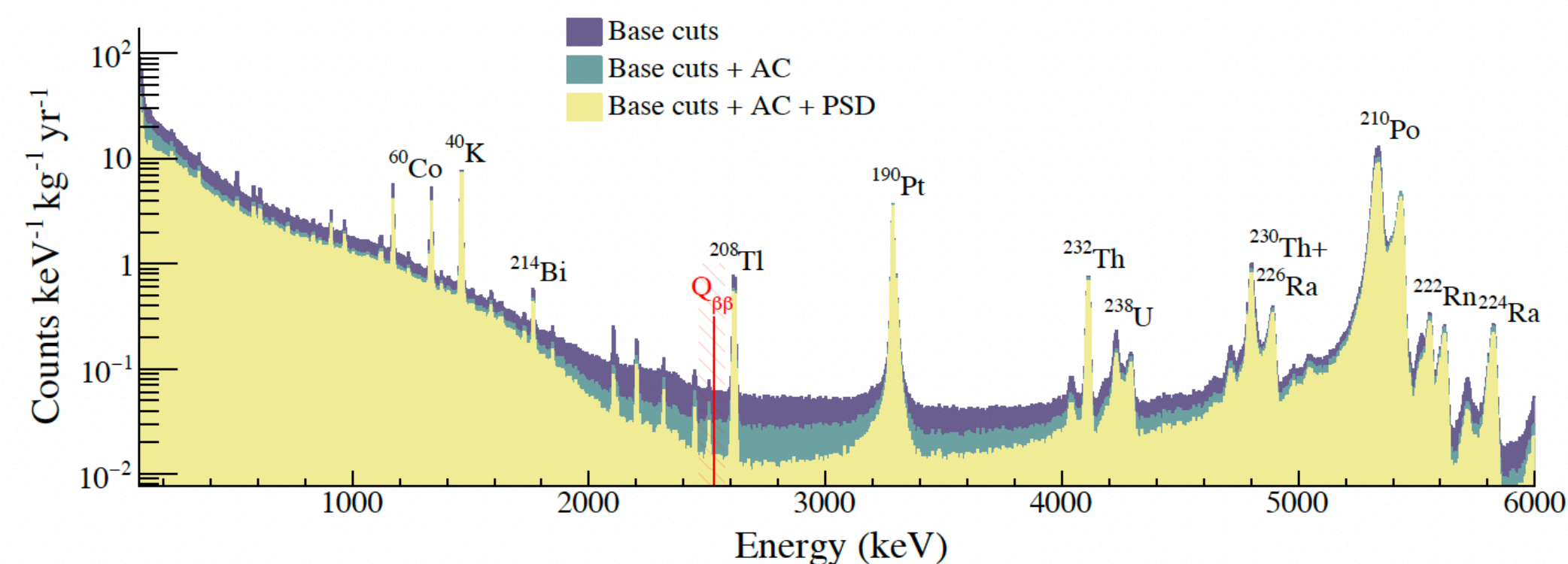
What is next?

From CUORE to CUPID

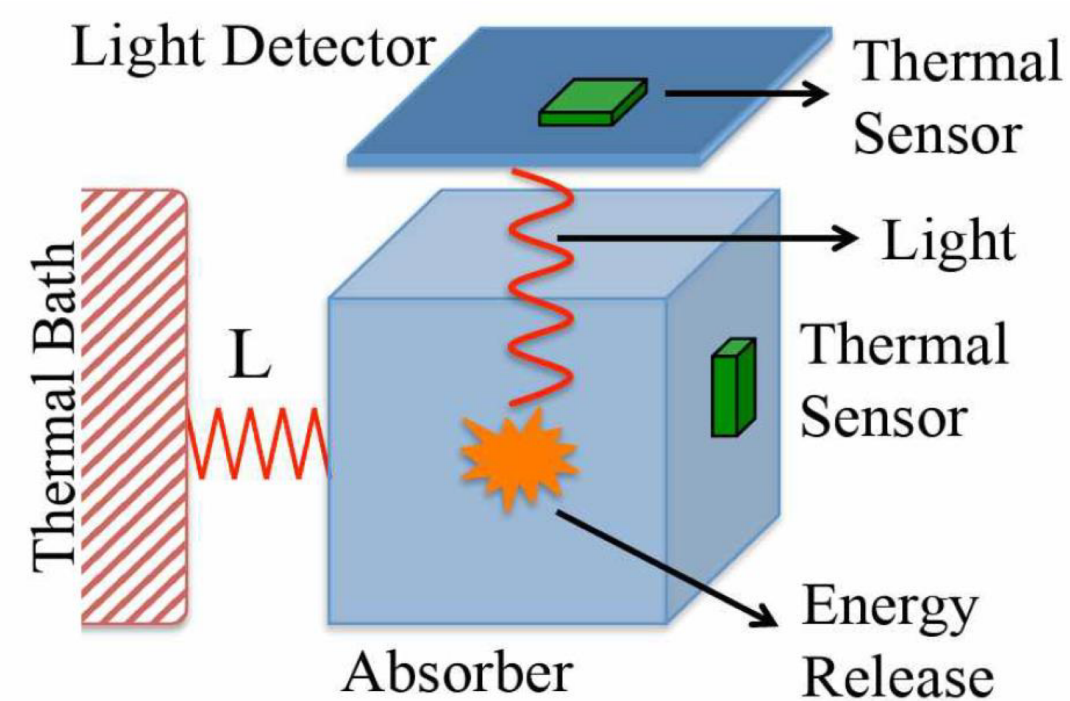
- CUORE will complete its data taking reaching 3 ton.yr of exposure (mid-2026)
- Background dominated by degraded alphas

$$BI = (1.42^{+0.03}_{-0.02}) \times 10^{-2} \text{ counts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$$

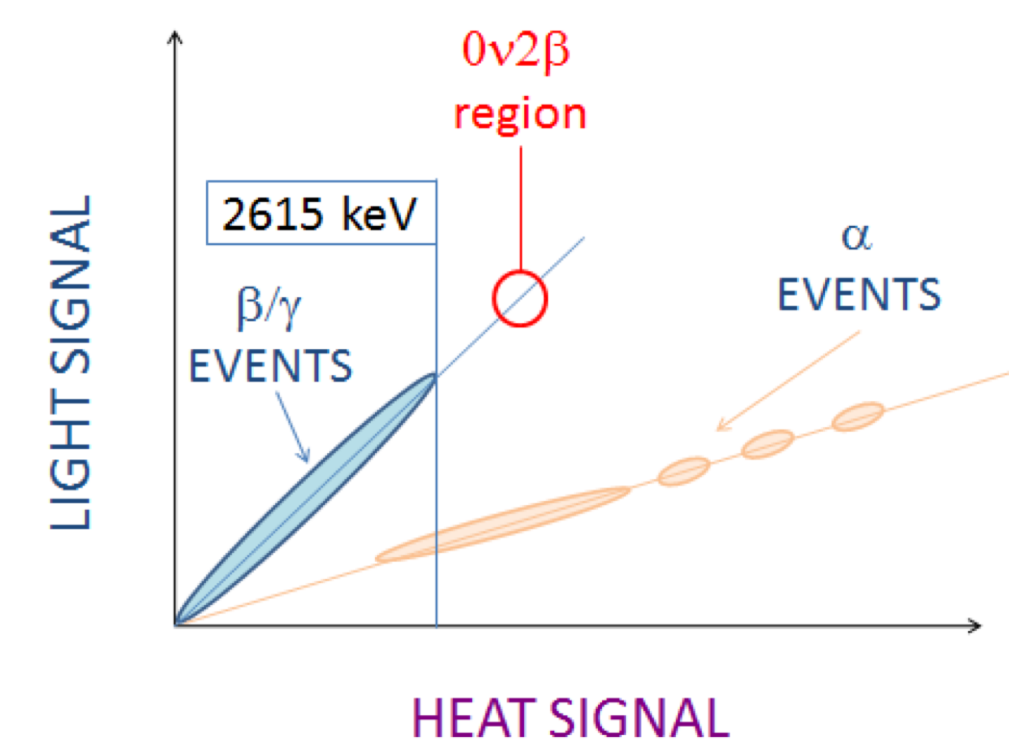
- Need to upgrade to CUORE phase-II [2505.23955 \[hep-ex\]](#)
 - Cryostat updates: mitigation of vibrational noise to lower the energy threshold (CUORE is sensitive to very low frequency noise)
 - Prepare the cryostat to host CUPID
- Why CUPID ?
 - Another Isotope to probe with $Q > 2.6$ MeV
 - Scintillating cryogenic calorimeters for PID
 - $BI \sim 10^{-4}$ counts / (keV·kg·yr)



Scintillating Bolometer



Particle Identification



CUPID ok, but how ?

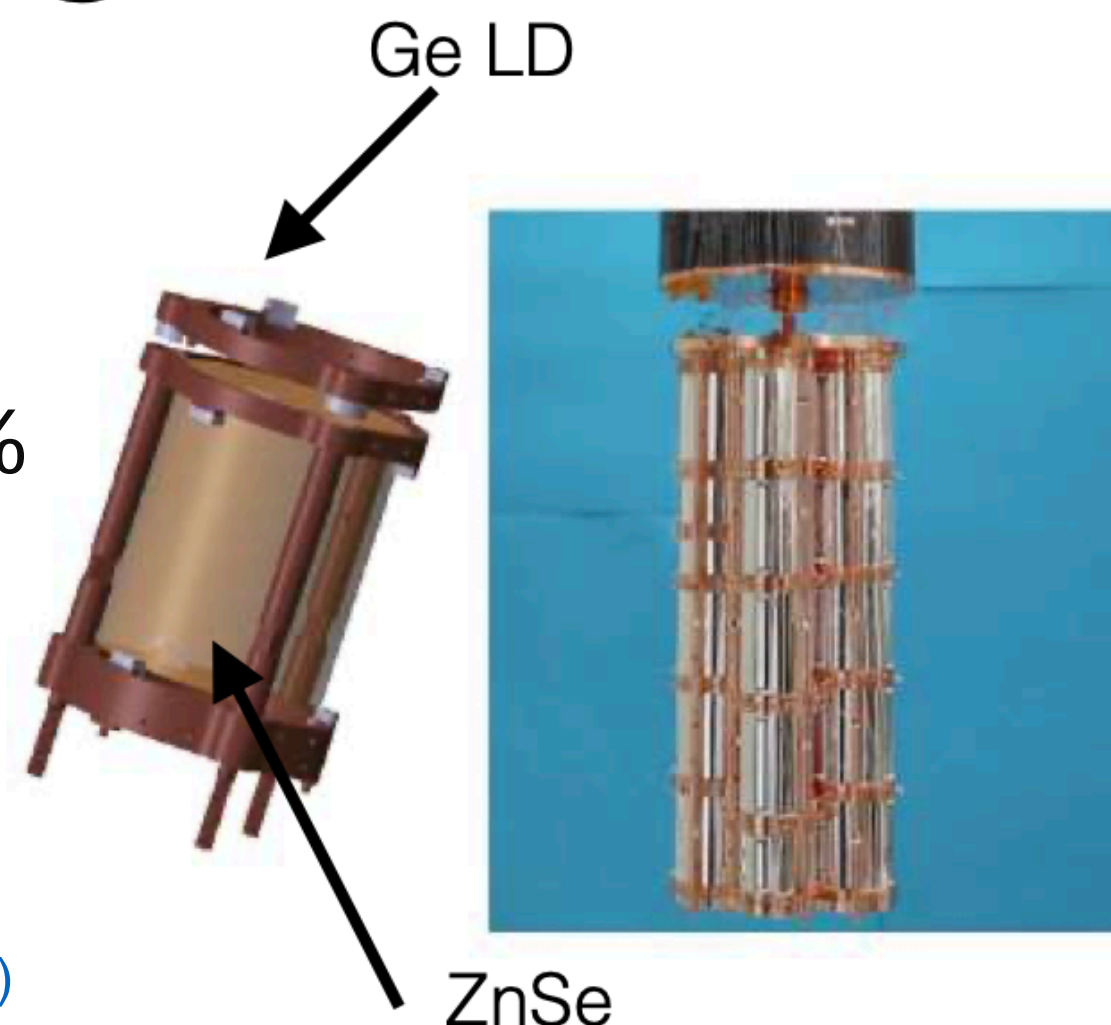
Our demonstrators



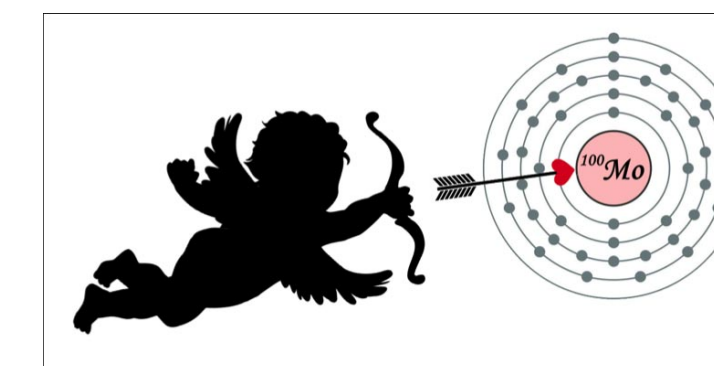
**CUPID-0 (2017-2020)
@LNGS**

- ZnSe crystals, 95% ^{82}Se enrichment
- (5.17 kg ^{82}Se) at LNGS (Italy)
- α -rejection efficiency $> 99.9\%$
- Background index: 3.5×10^{-3} c/kky
- $\Delta E = 21.8$ keV @ 3 MeV

CUPID-0: Phys. Rev. Lett. 129, 111801 (2022)



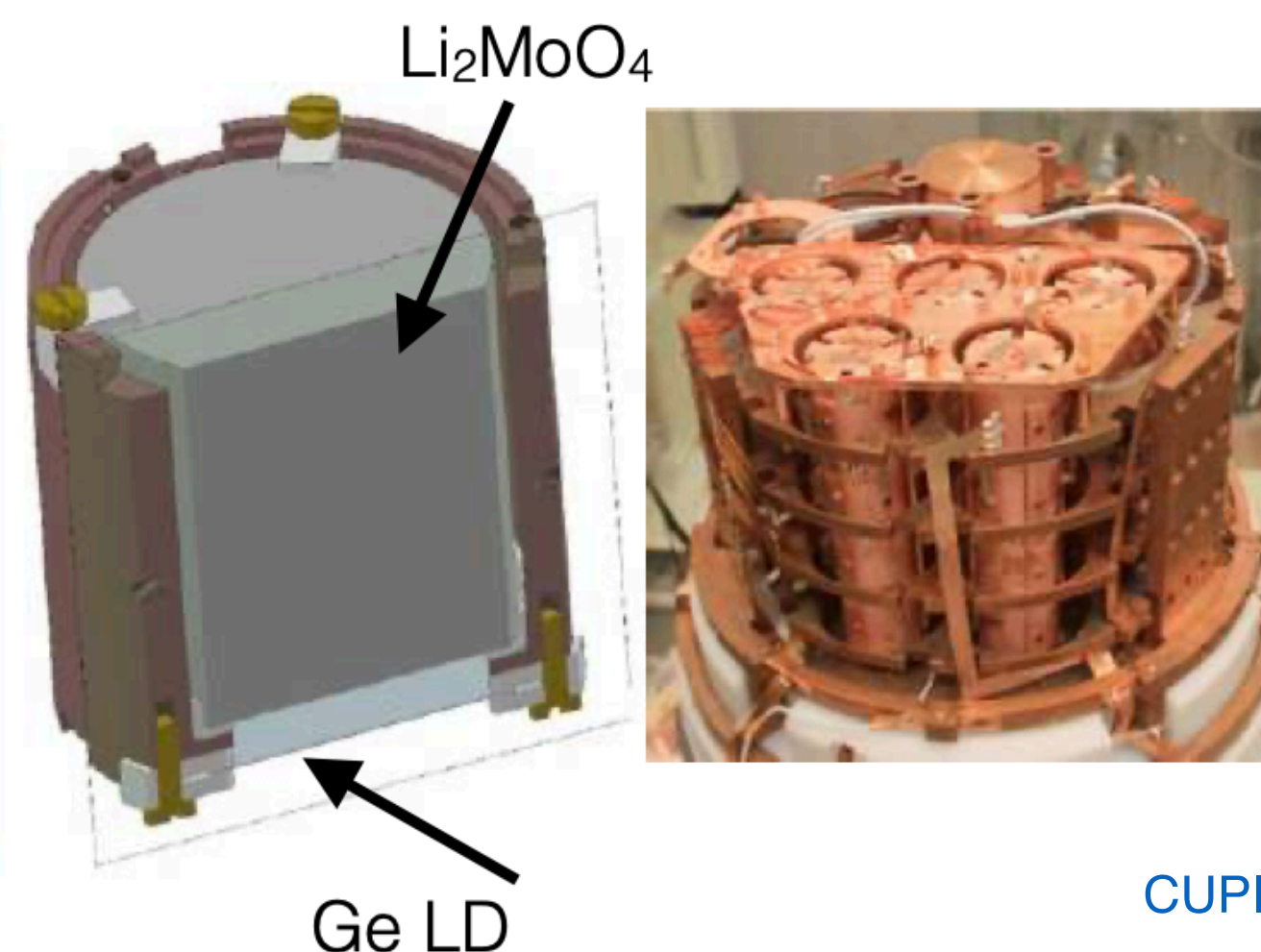
**CUPID-Mo (2019-2021)
@Modane**



Li₂MoO₄ crystals, 97% ^{100}Mo enrichment

- (2.26 kg ^{100}Mo) at Modane (France)
- α -rejection efficiency $> 99.9\%$
- Background index: 2.7×10^{-3} c/kky
- $\Delta E = 7.4$ keV @ 3 MeV

CUPID-Mo: Eur. Phys. J. C 82, 1033 (2022)



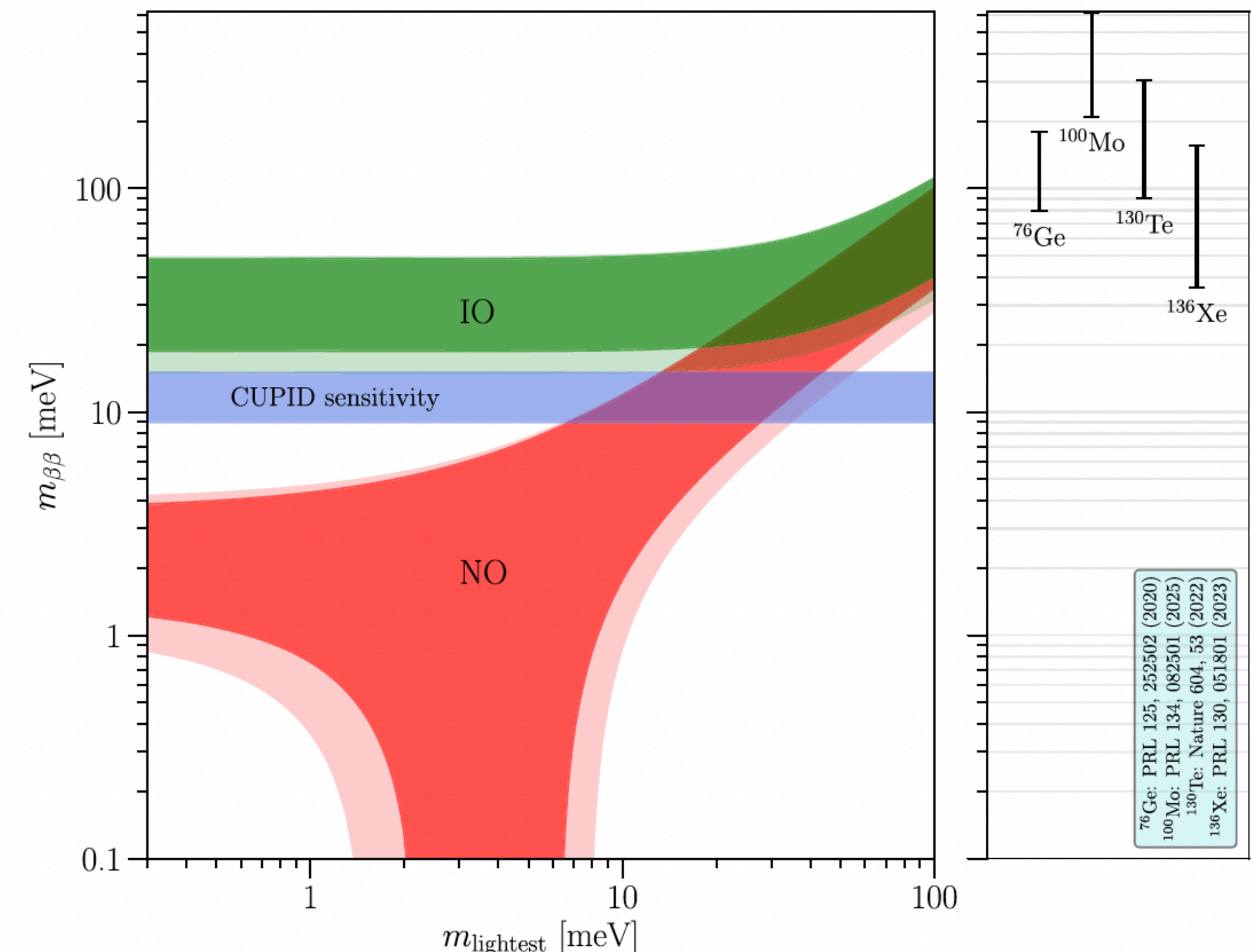
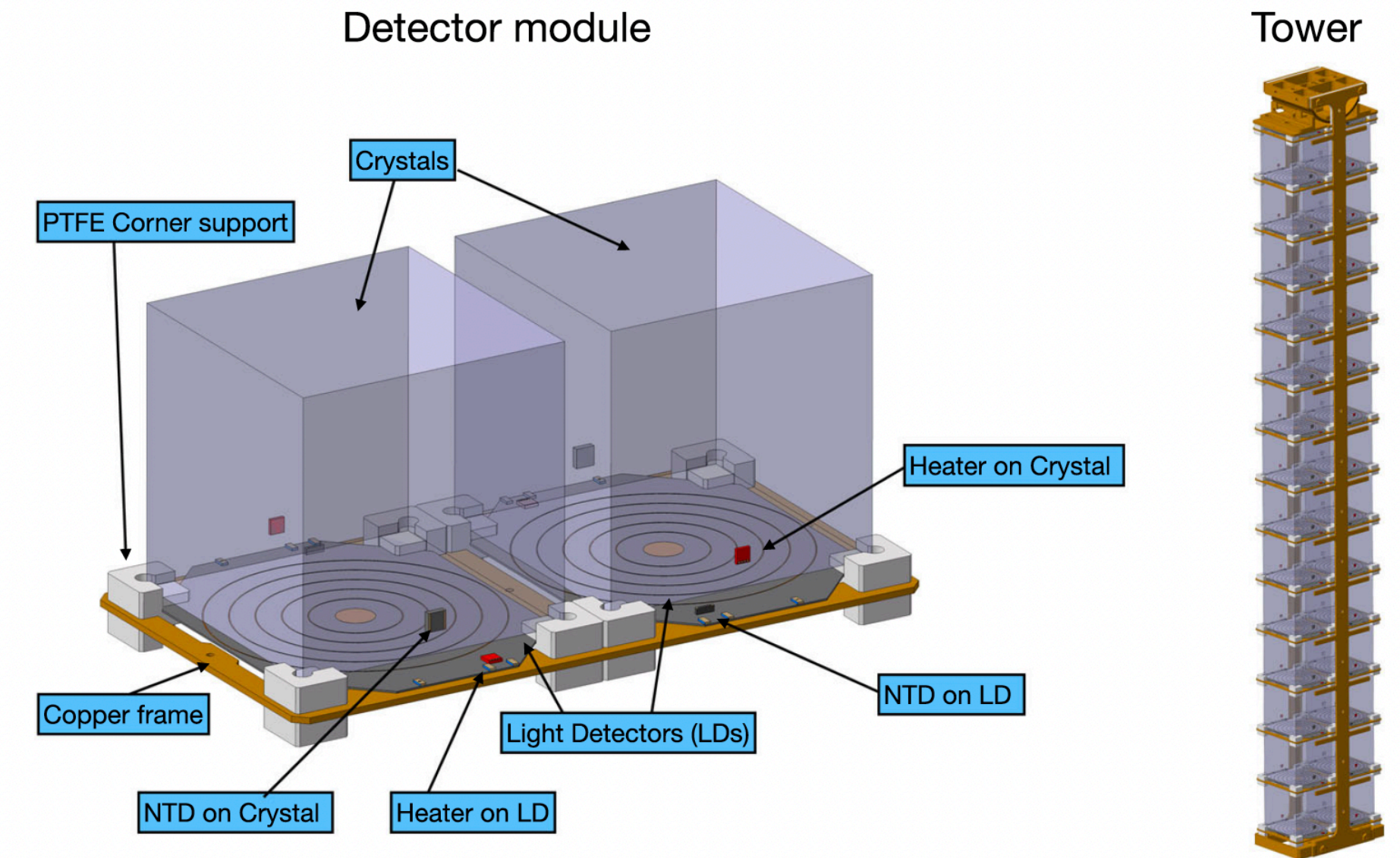
Two midscale experiments running almost in parallel demonstrated that the **cryogenic scintillating calorimeter technology** is mature and can be scaled up

The CUPID experiment

What is it ?

- New detector array
 - 1586 Li_2MoO_4 scintillating crystals (280 g each)
 - 1700 light detectors $\rightarrow$ scintillation signal read-out
- Probe fully the IH region for $m_{\beta\beta}$
- Livetime 10 years
- Energy resolution 5 keV
- Sensitivity goal:
 - $T_{0\nu 1/2} = 1 \times 10^{27}$ yr
 - $m_{\beta\beta} = 12\text{-}20$ meV

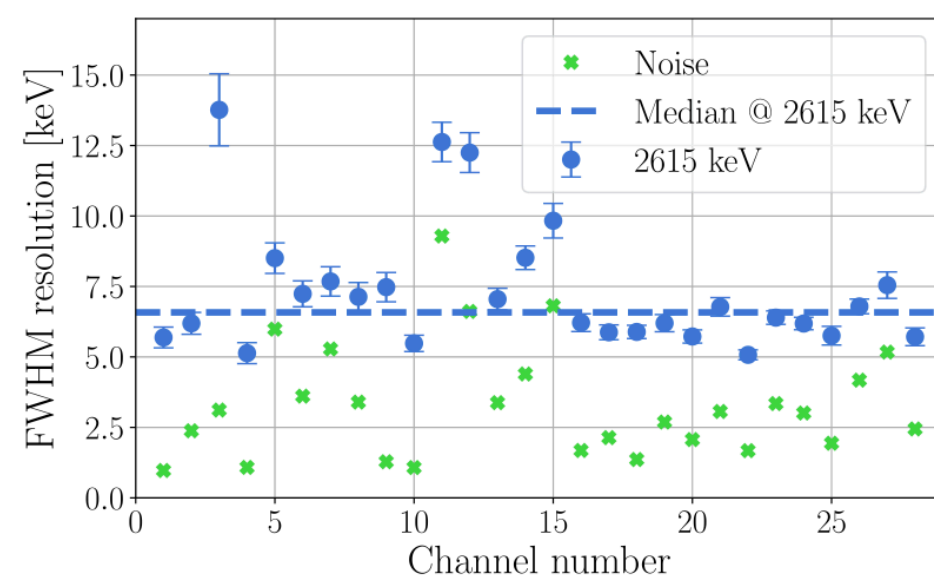
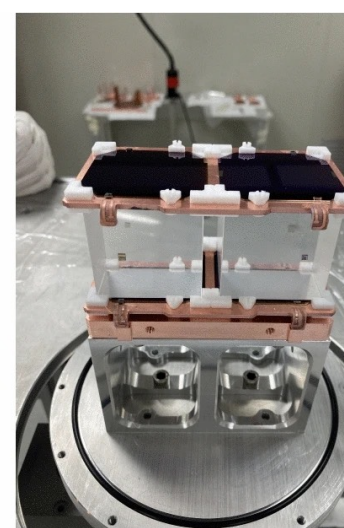
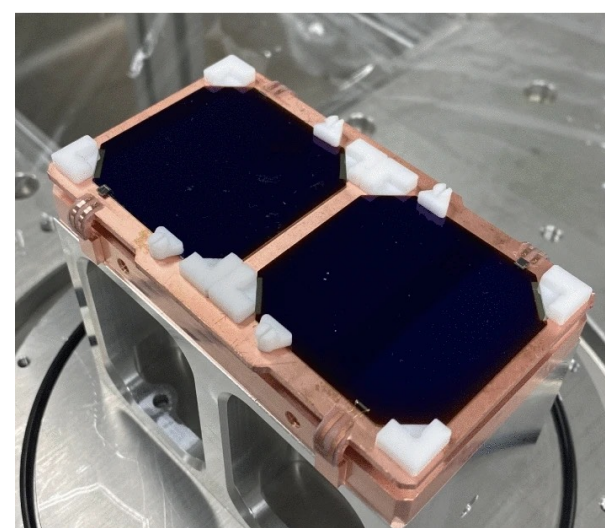
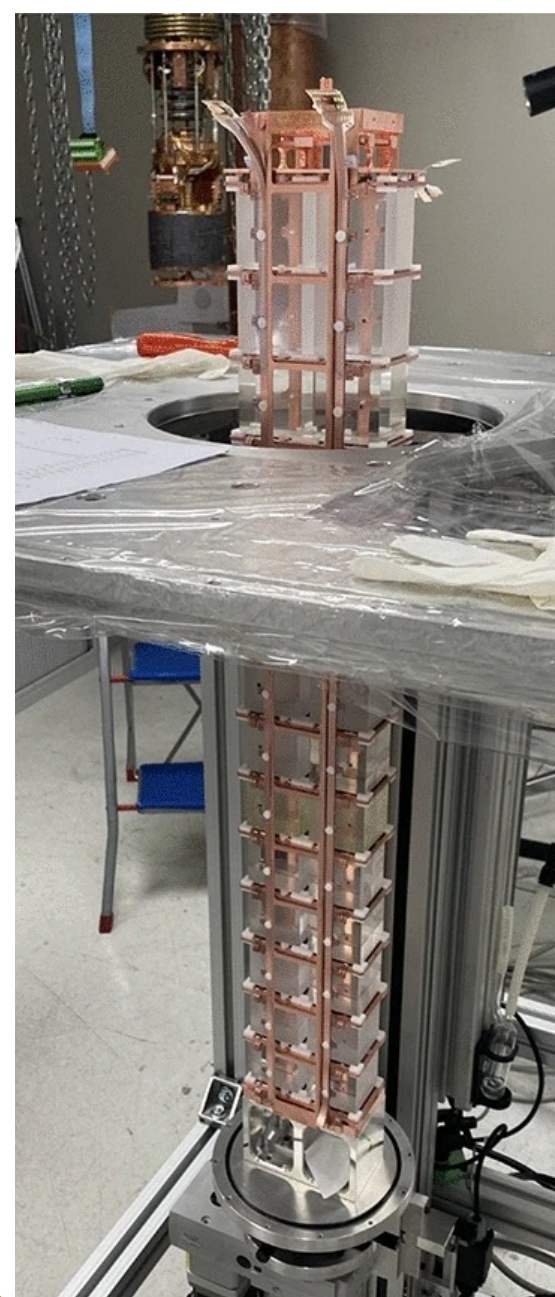
[10.1140/epjc/s10052-025-14352-1](https://arxiv.org/abs/10.1140/epjc/s10052-025-14352-1)



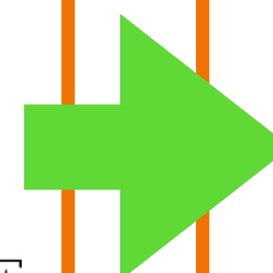
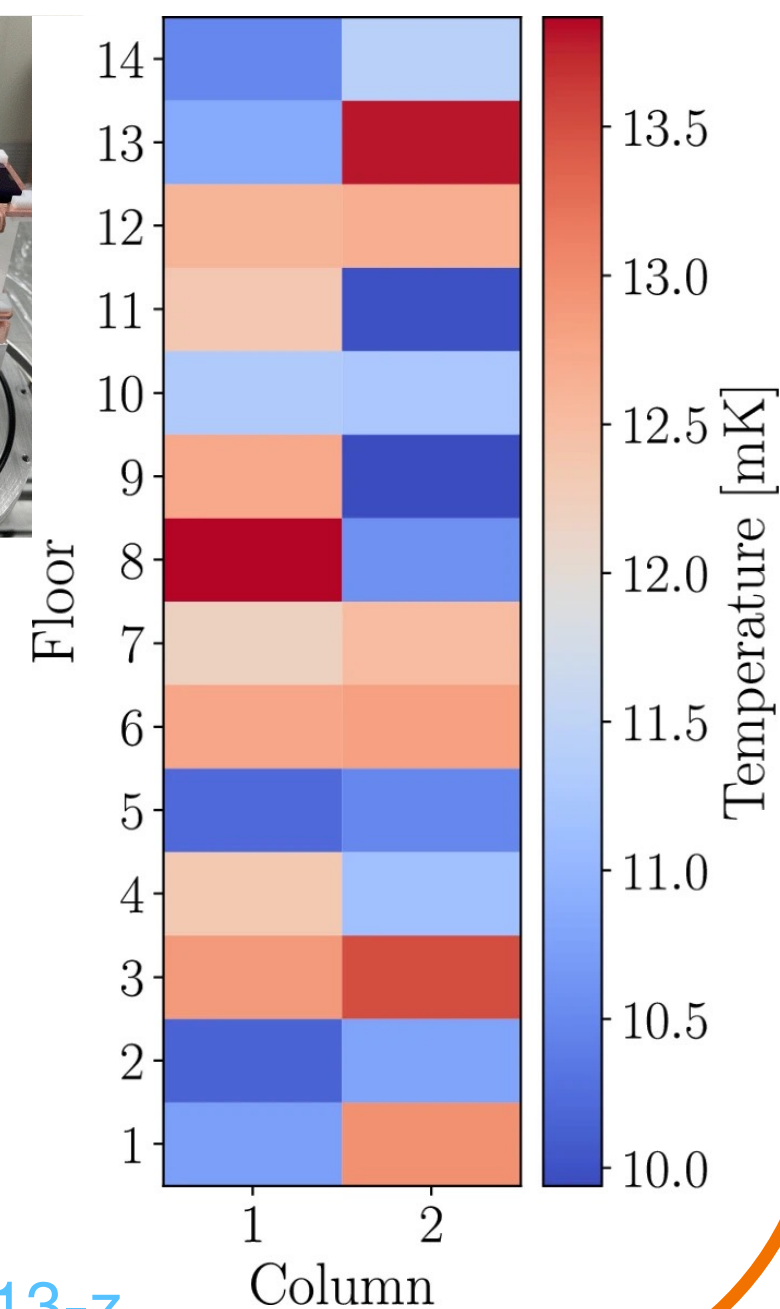
Towards CUPID: our prototypes

GDPT (Gravity Detector Prototype Tower)

- Innovative gravity assisted design validate with smaller scale test
- Conceptual test in 2022 @LNGS
- Goal of the test thermal properties assessment and detector performances
- Light detectors experienced low SNR and correlated noise

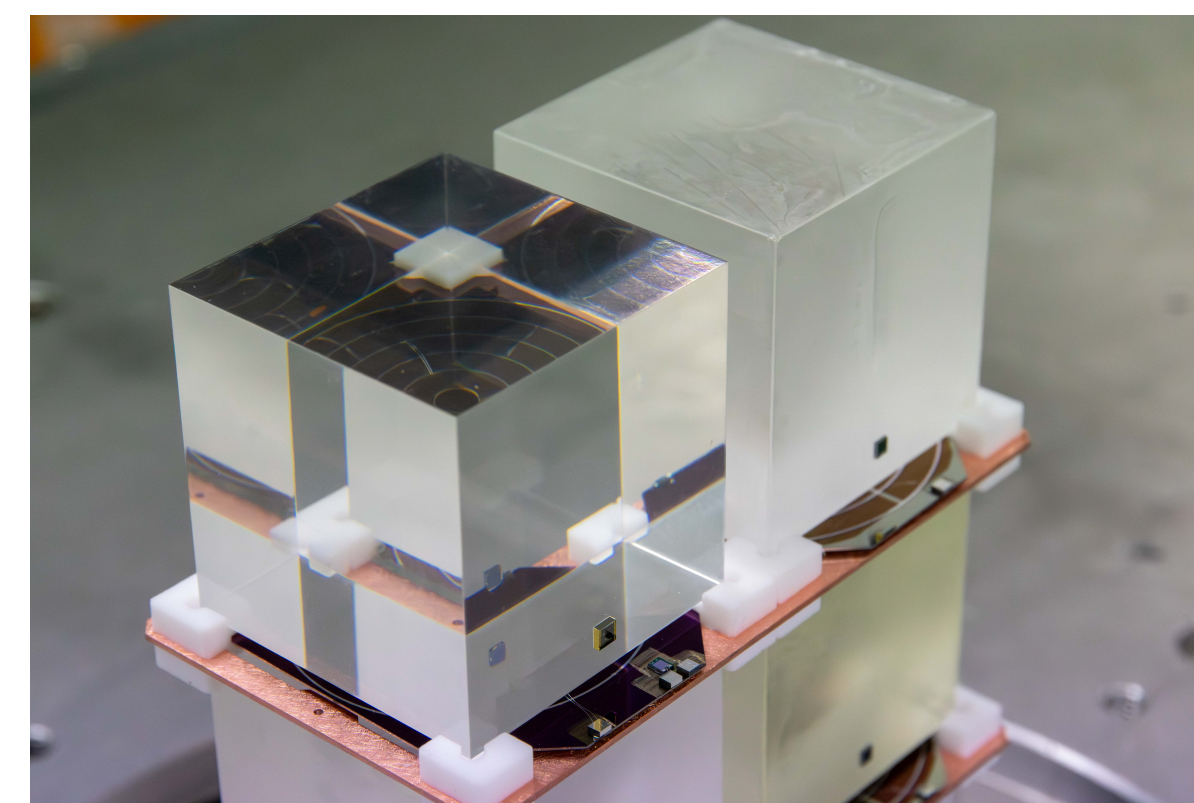


[10.1140/epjc/s10052-025-14613-z](https://arxiv.org/abs/10.1140/epjc/s10052-025-14613-z)



VSTT (Vertically Sliced Test Tower)

- Upgrades on the design and assembly line testing
- NTL light detectors
- Optical fibers for LD calibration
- New DAQ and electronics
- **Currently taking data!**

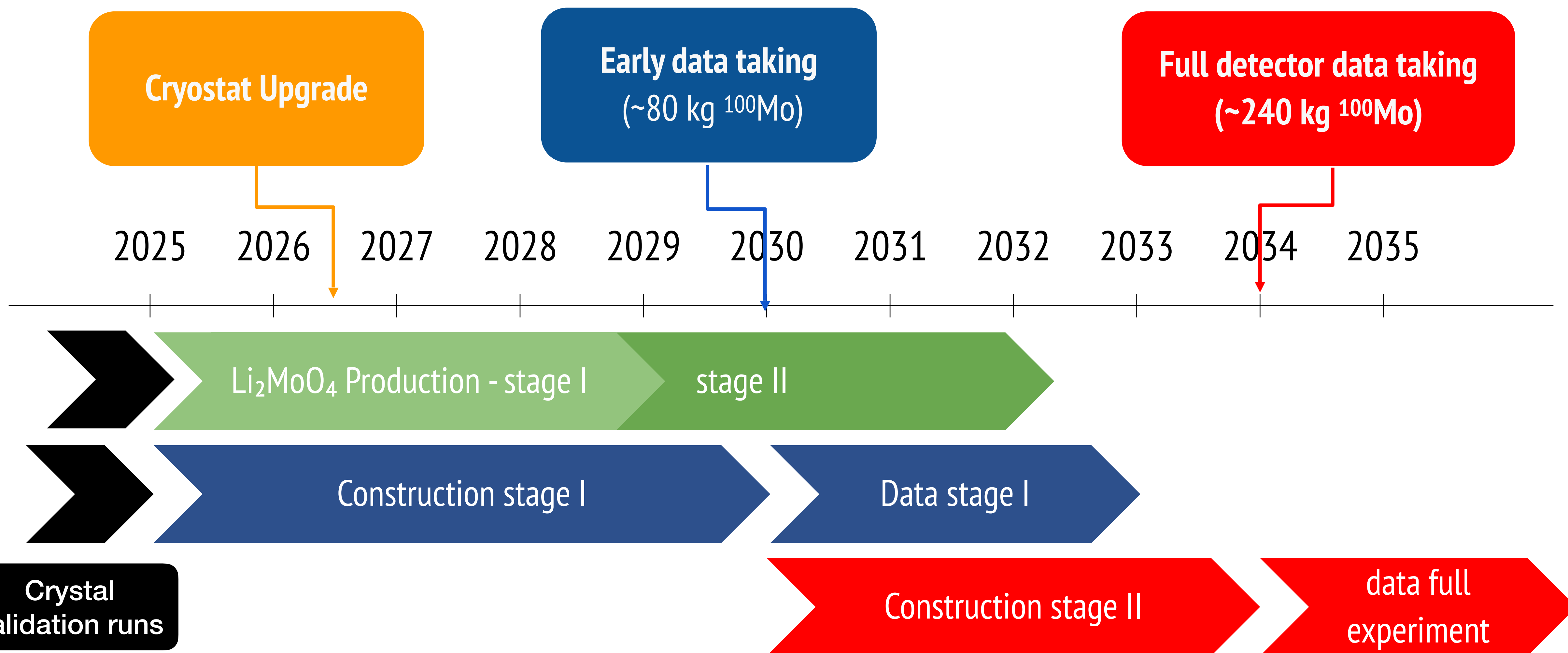


WORK IN PROGRESS



CUPID timeline

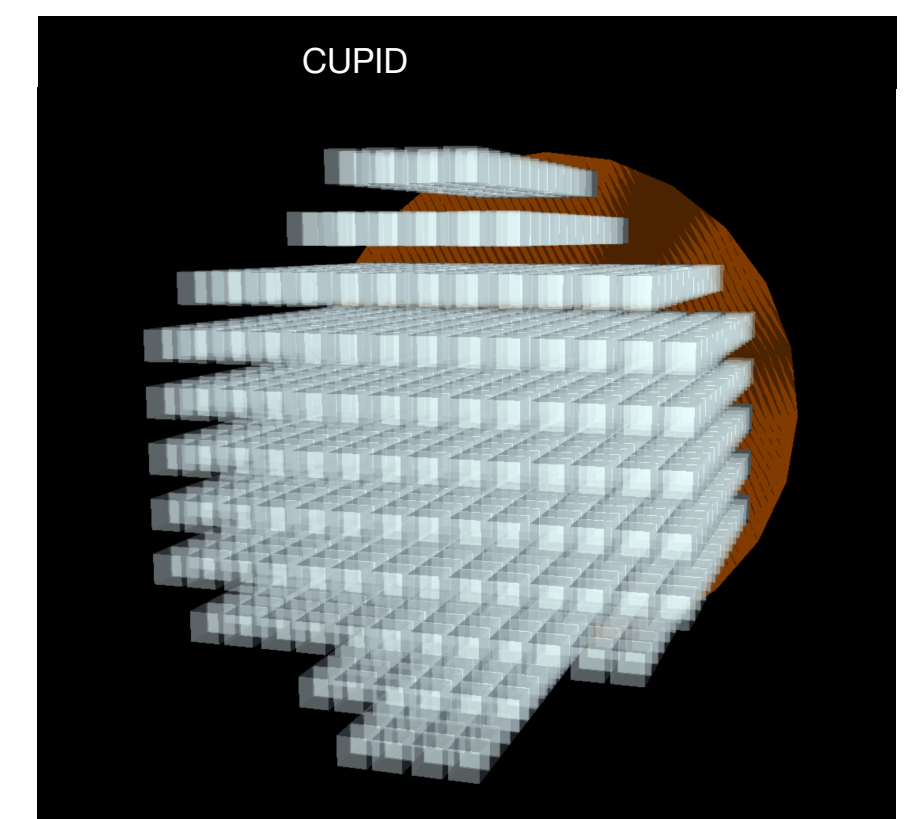
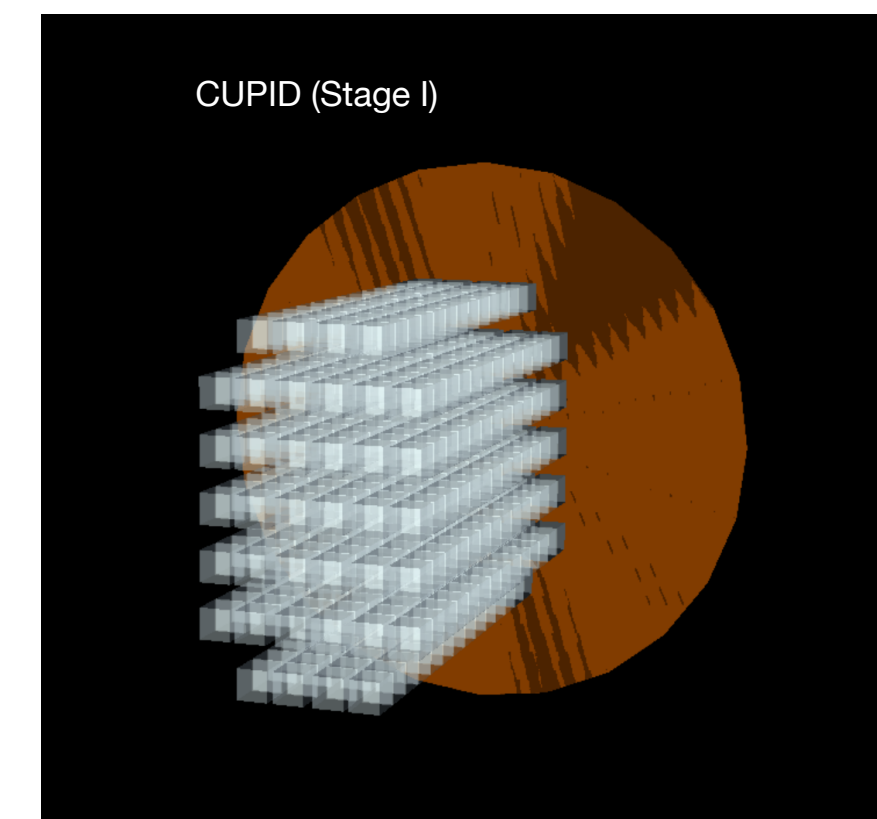
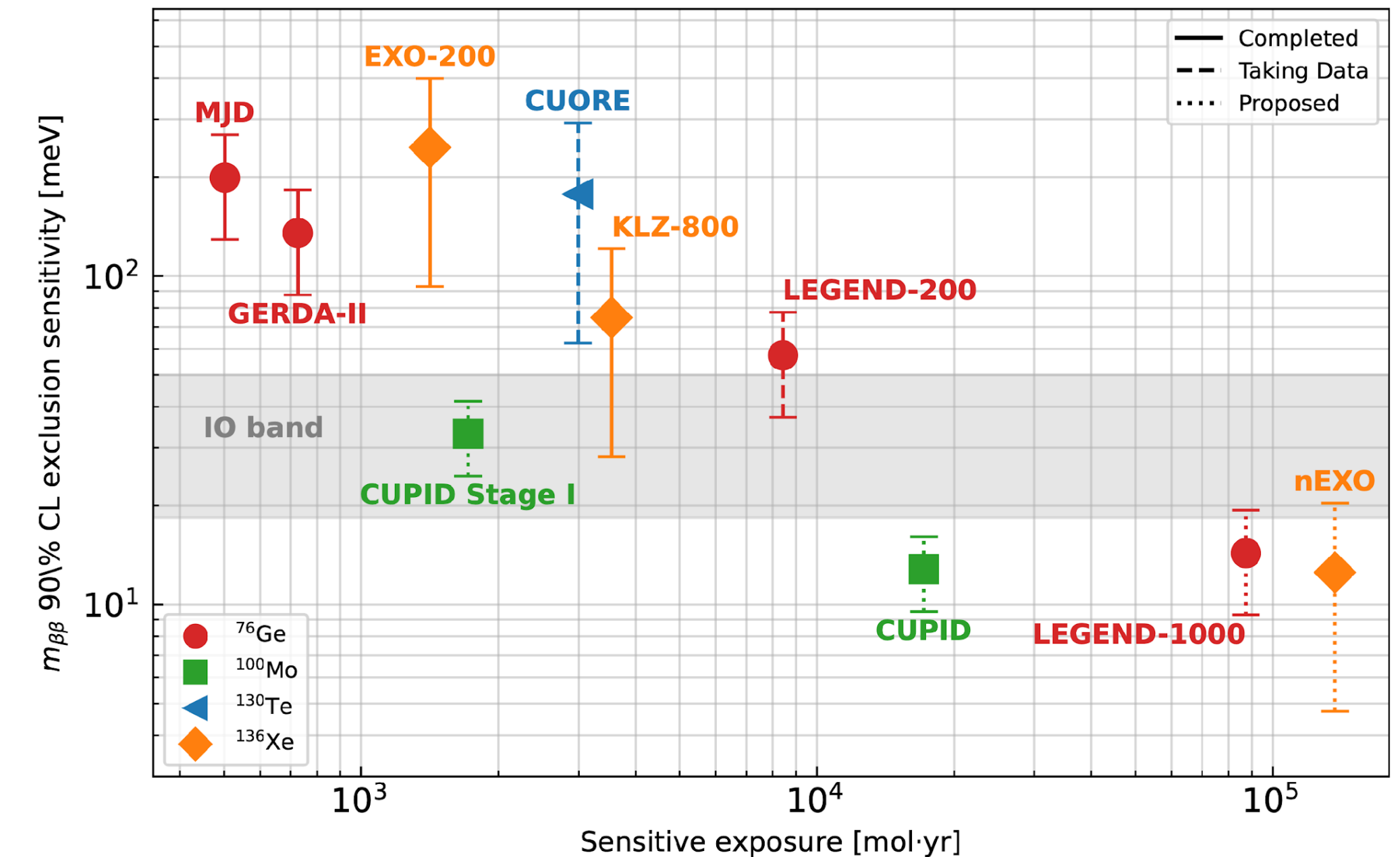
And what can we do meanwhile

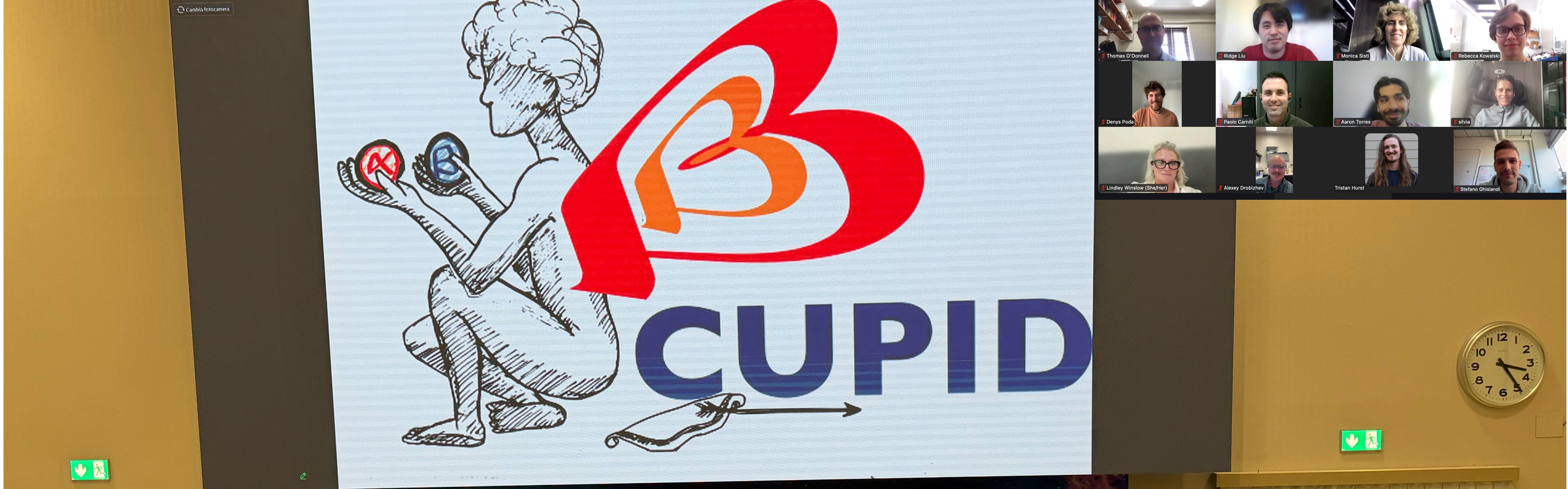


Conclusions

... and perspectives

- CUORE demonstrated the feasibility of an array of ~ 1000 cryogenic calorimeter
- CUORE raw exposure reached 3 ton. yr
- Latest data release in Science with an improved limit on $0\nu\beta\beta$ of ^{130}Te
- The path towards CUPID has started with full tower prototypes and crystal validation runs
- CUPID will play a central role in the $0\nu\beta\beta$ search and discovery program at LNGS in the next years

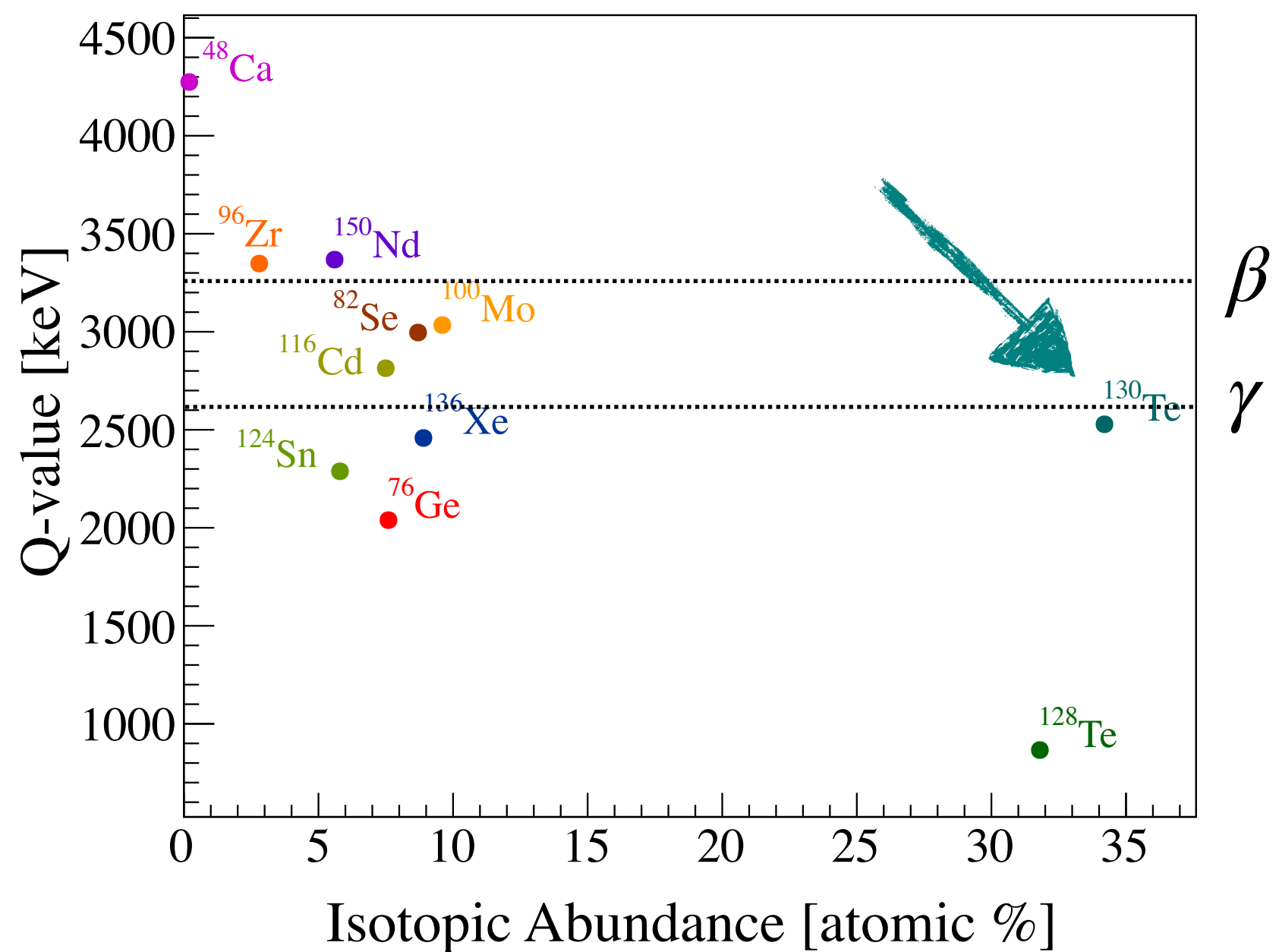




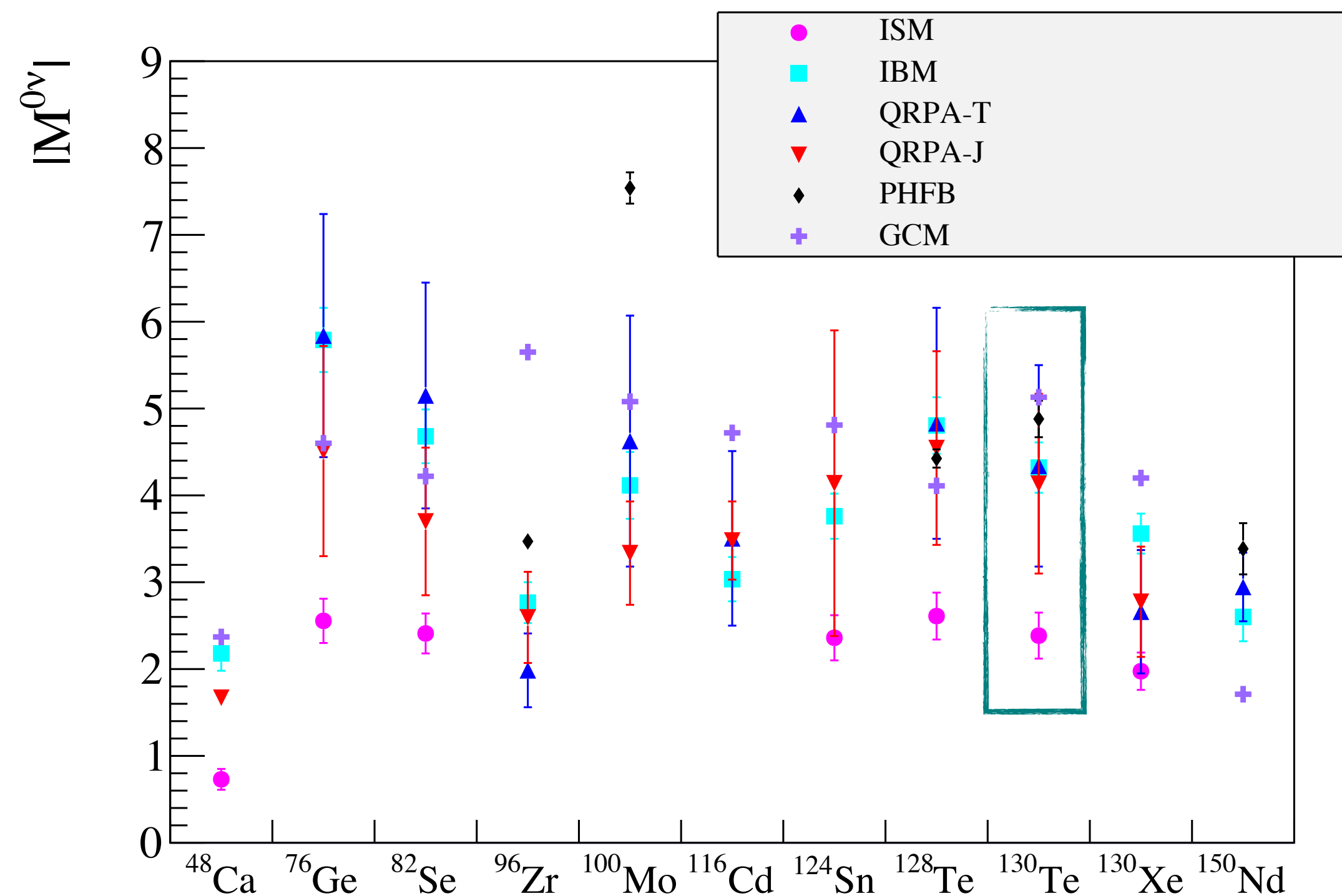
The CUPID Collaboration thanks the directors and staff of the Laboratori Nazionali del Gran Sasso and the technical staff of our laboratories. This work was supported by the Istituto Nazionale di Fisica Nucleare, the Italian Ministry of University and Research (Italy), the European Research Council and European Commission, the US Department of Energy (DOE) Office of Science, the DOE Office of Science, Office of Nuclear Physics, the National Science Foundation (USA), the Russian Science Foundation (Russia), and the National Research Foundation (Ukraine). This research used resources of the National Energy Research Scientific Computing Center (NERSC). This work makes use of both the DIANA data analysis and APOLLO data acquisition software packages, which were developed by the CUORICINO, CUORE, LUCIFER and CUPID-0 Collaborations.

BACKUP SLIDES

Isotope choice / NME



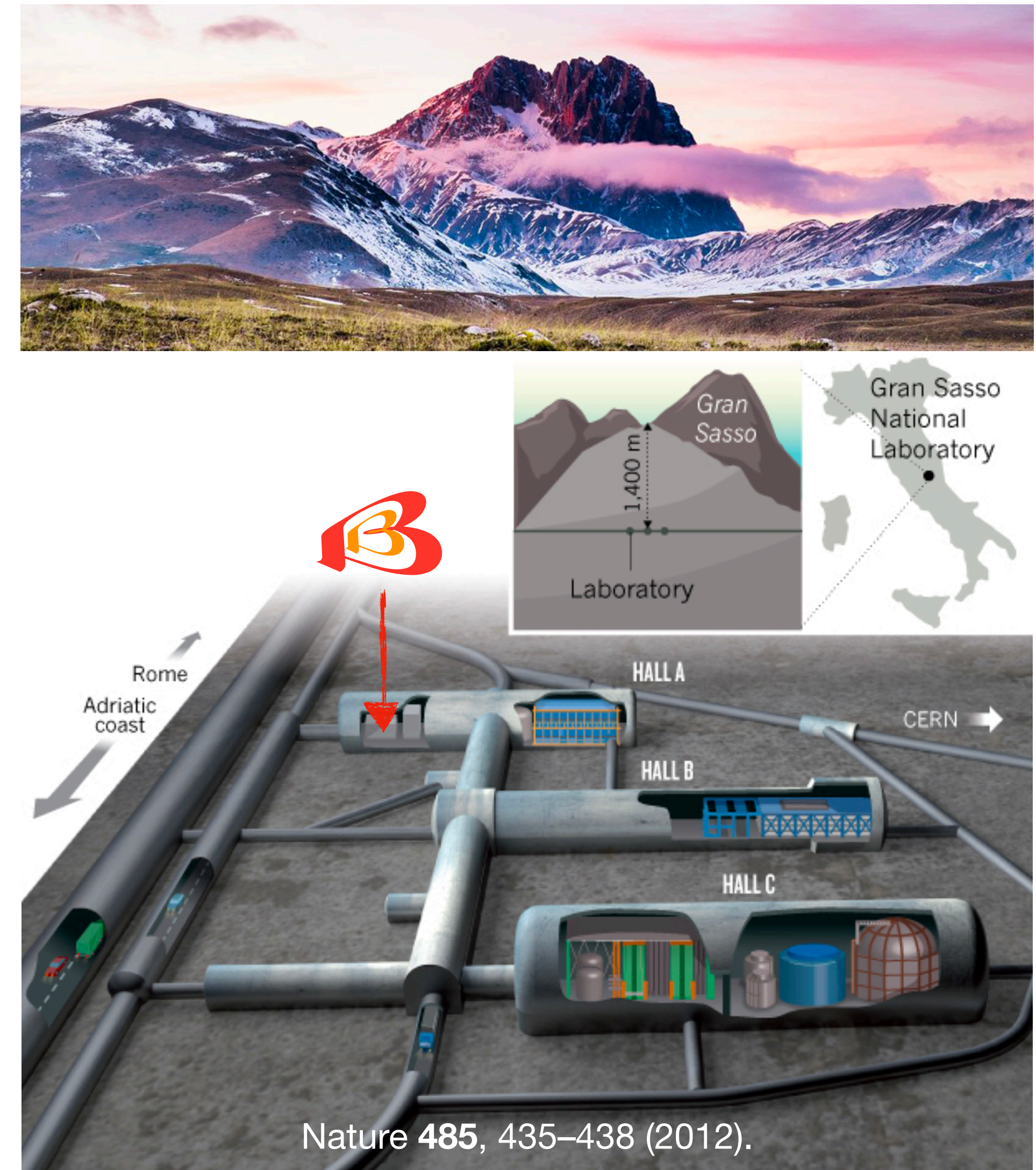
- High natural isotopic abundance
- Relatively low β/γ background
- Reproducible growth of high quality crystals



$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q, Z) |M_{0\nu}|^2 \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}$$

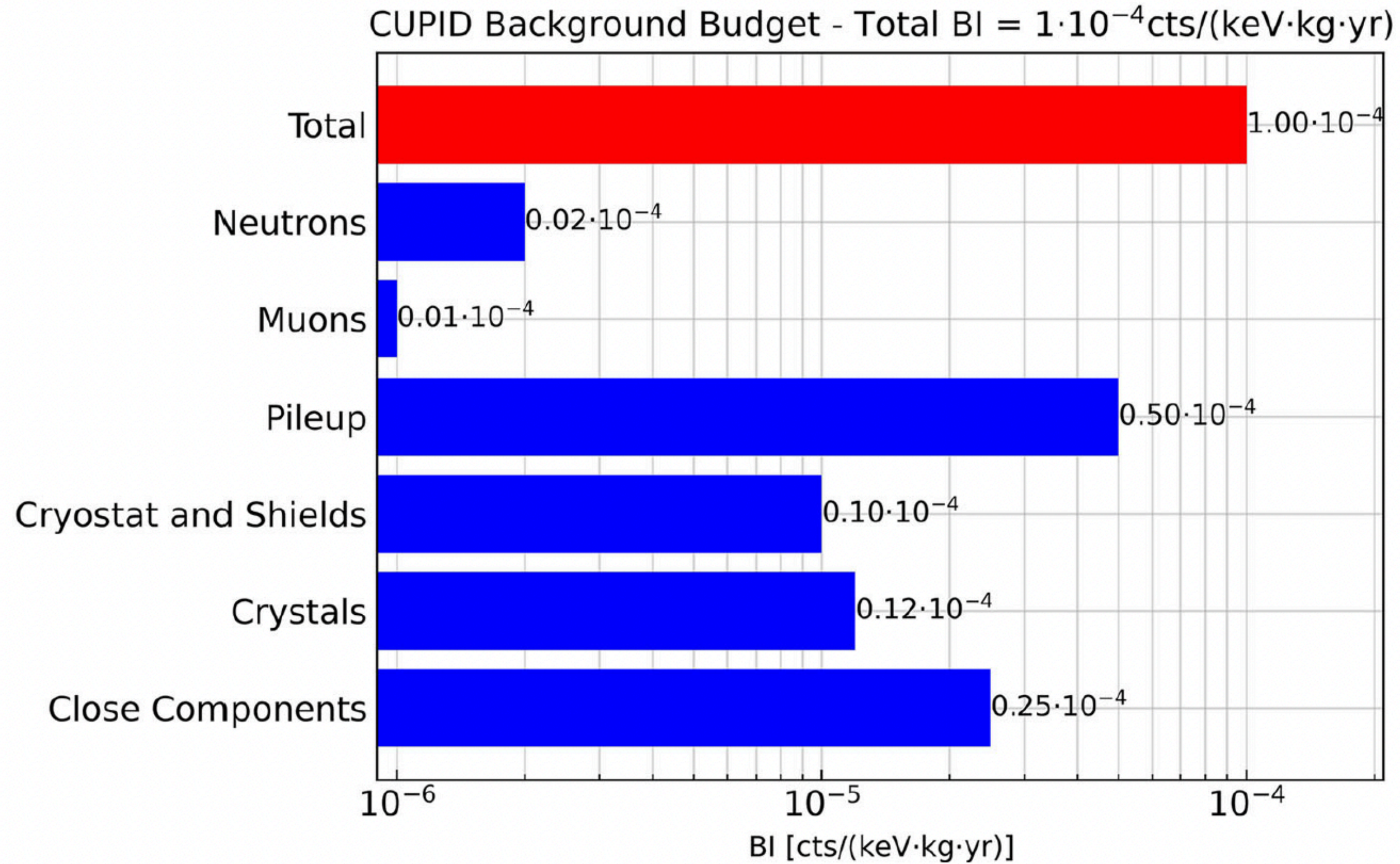
LNGS

- Gran Sasso National Laboratory
 - ~ 3600 m.w.e. deep
 - ~ 3×10^{-8} muons / (s cm²)
 - ~ 0.73 gammas / (s cm²)
 - ~ 4×10^{-6} neutrons / (s cm²) below 10 MeV



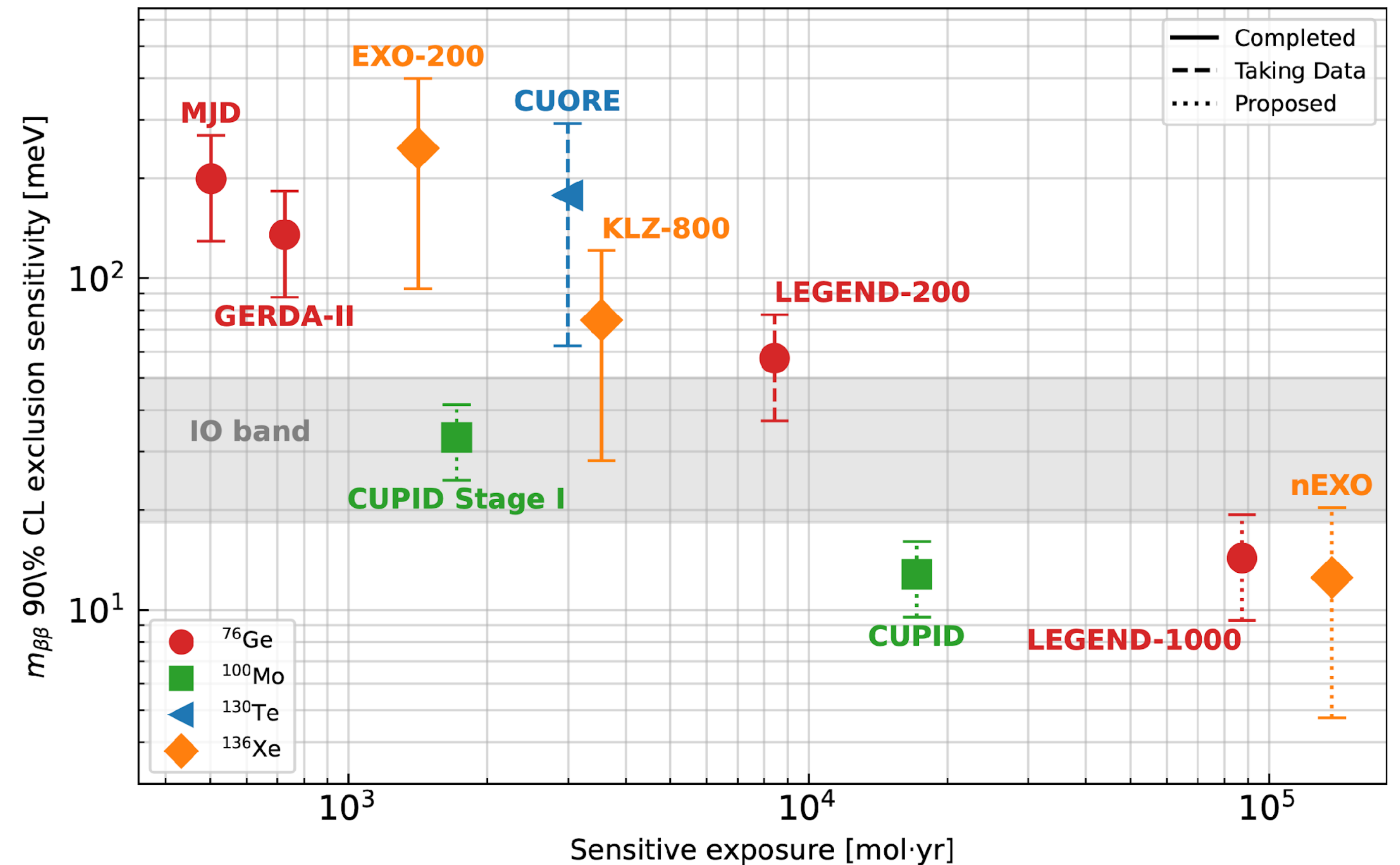
Nature 485, 435–438 (2012).

The CUPID background



CUPID sensitivity

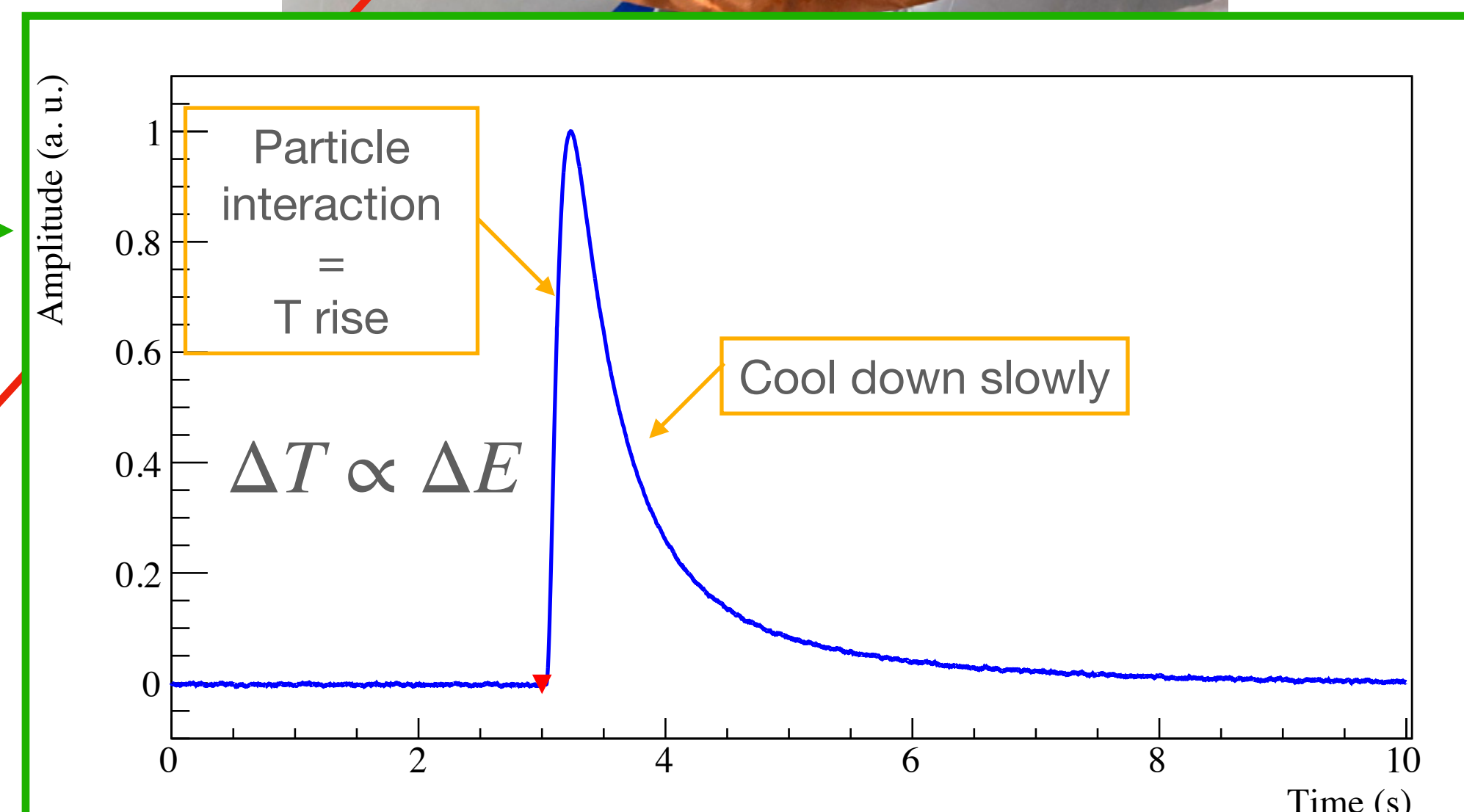
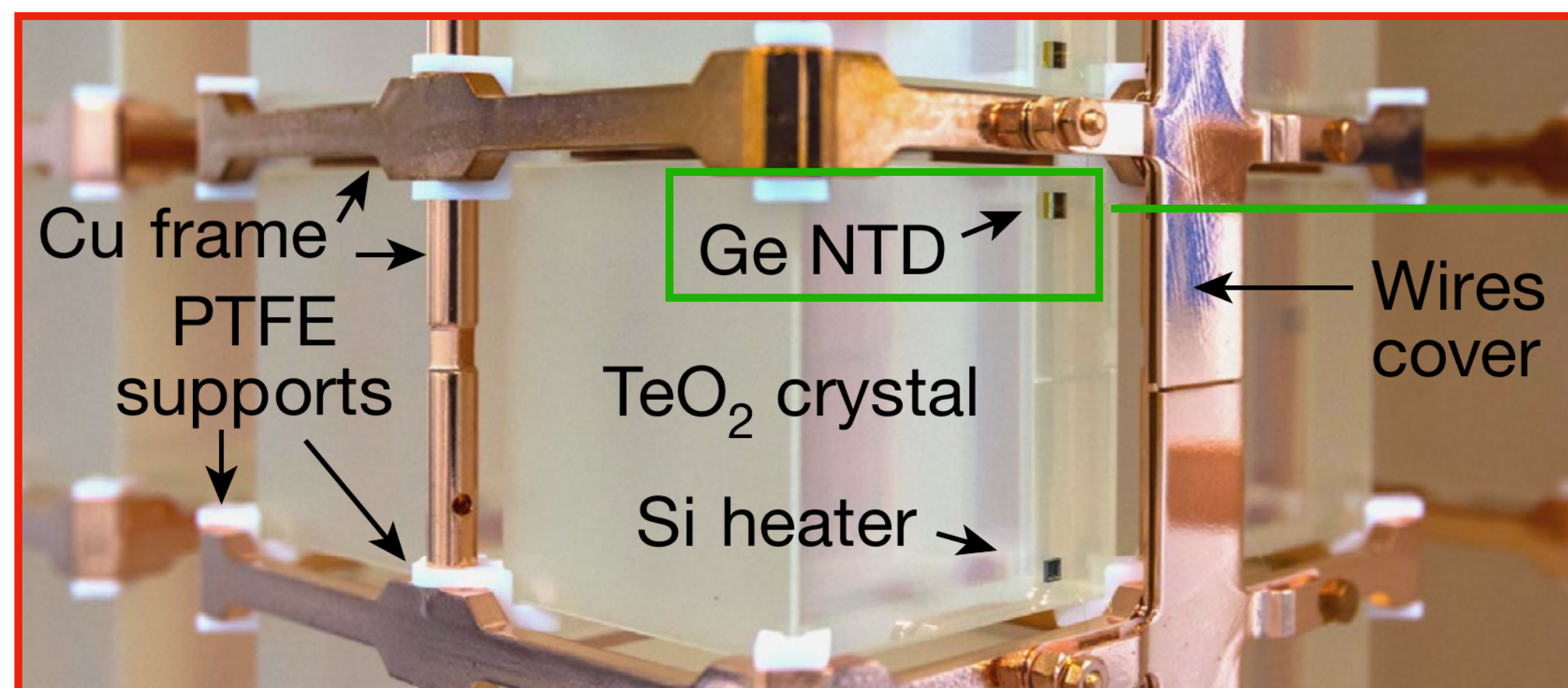
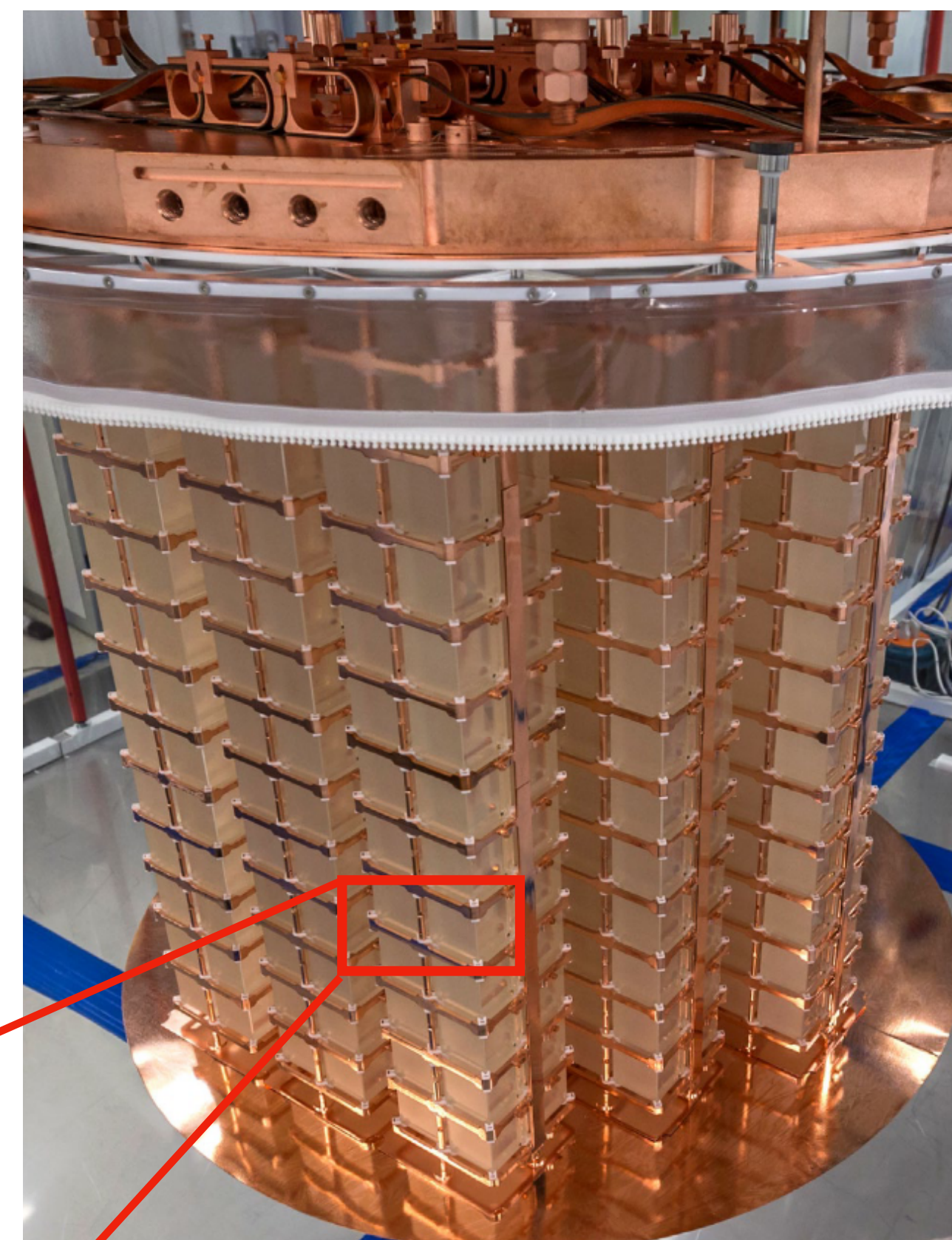
CUORE, arXiv:2404.04453 (2024)
 CUPID-0, PRL 129,111801 (2022), <https://doi.org/10.1103/PhysRevLett.129.111801>
 CUPID-Mo, EPJC 82,1033 (2022), <https://link.springer.com/article/10.1140/epjc/s10052-022-10942-5>
 MJD, <https://arxiv.org/abs/2207.07638>
 GERDA-II, PRL 125,252502 (2020), <https://arxiv.org/abs/2009.06079>
 LEGEND-200, Proc. Neutrino2024, https://agenda.infn.it/event/37867/contributions/233912/attachments/121891/177847/202406-Neutrino24_edited.pdf
 EXO-200, PRL 123,161802 (2019), <https://arxiv.org/abs/1906.02723>
 KLZ-800, arXiv:2406.11438 (2024), <https://arxiv.org/pdf/2406.11438>
 LEGEND-1000, arXiv:2107.11462 (2021), 90% CL exclusion sensitivity: <https://arxiv.org/pdf/2107.11462>
 NEXT-HD, arXiv:2005.06467 (2021), 90% exclusion sensitivity. <https://arxiv.org/pdf/2005.06467>
 nEXO, JPG: Nucl.Part.Phys. 49,015104 (2022), 90% CL exclusion sensitivity: <https://arxiv.org/pdf/2106.16243>



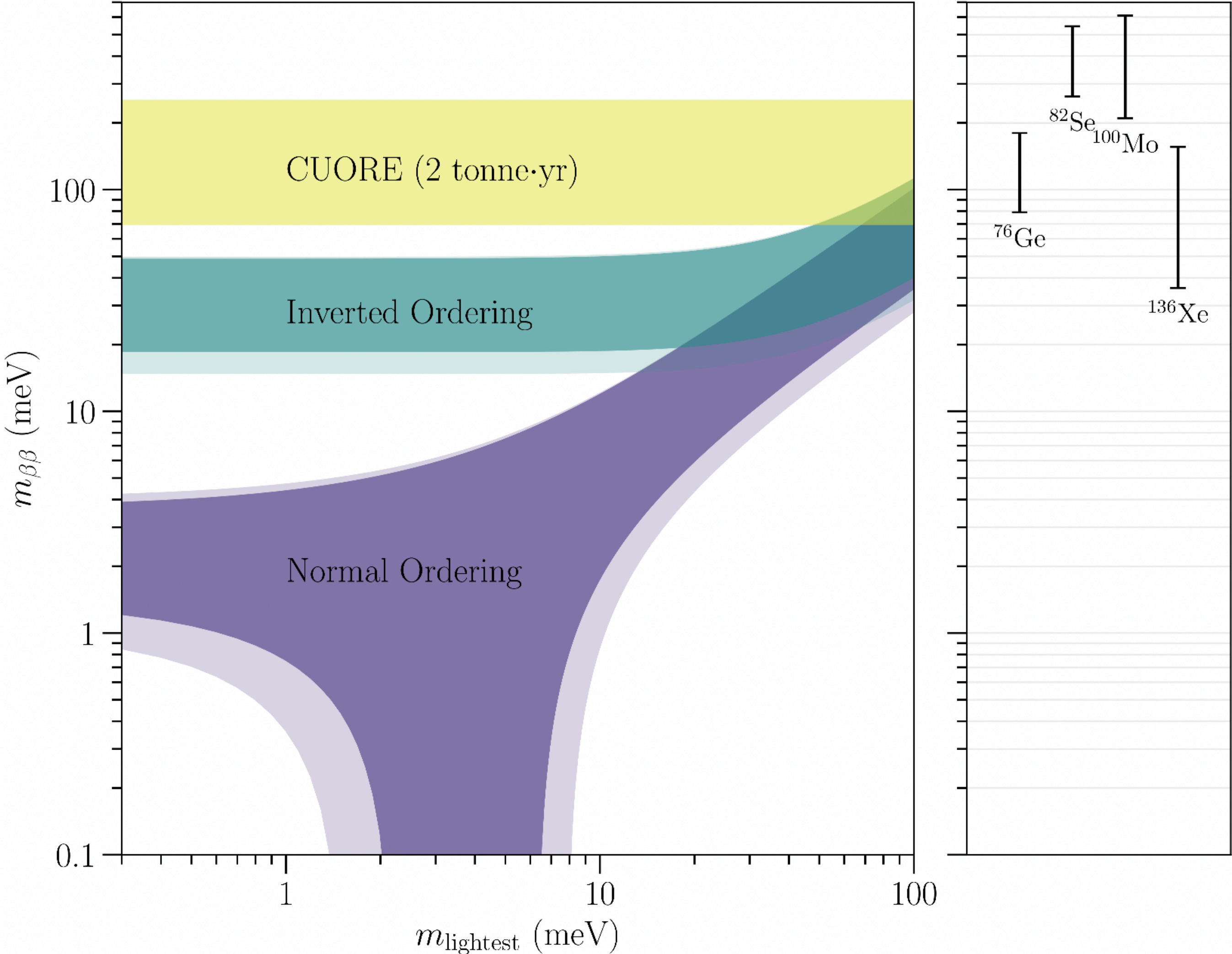
CUORE analysis chain

The 988 CUORE detectors

- 988 identical **bolometers**
- Excellent energy resolution $\sim 0.3\%$ FWHM at 2527.5 keV ($Q_{\beta\beta}$)
- Each crystal is equipped with thermal sensor (NTD) to register particle interaction and Si resistor to perform thermal gain correction
- Mounted in towers => possibility of looking for coincidences
- Signal => thermal pulse, slow response



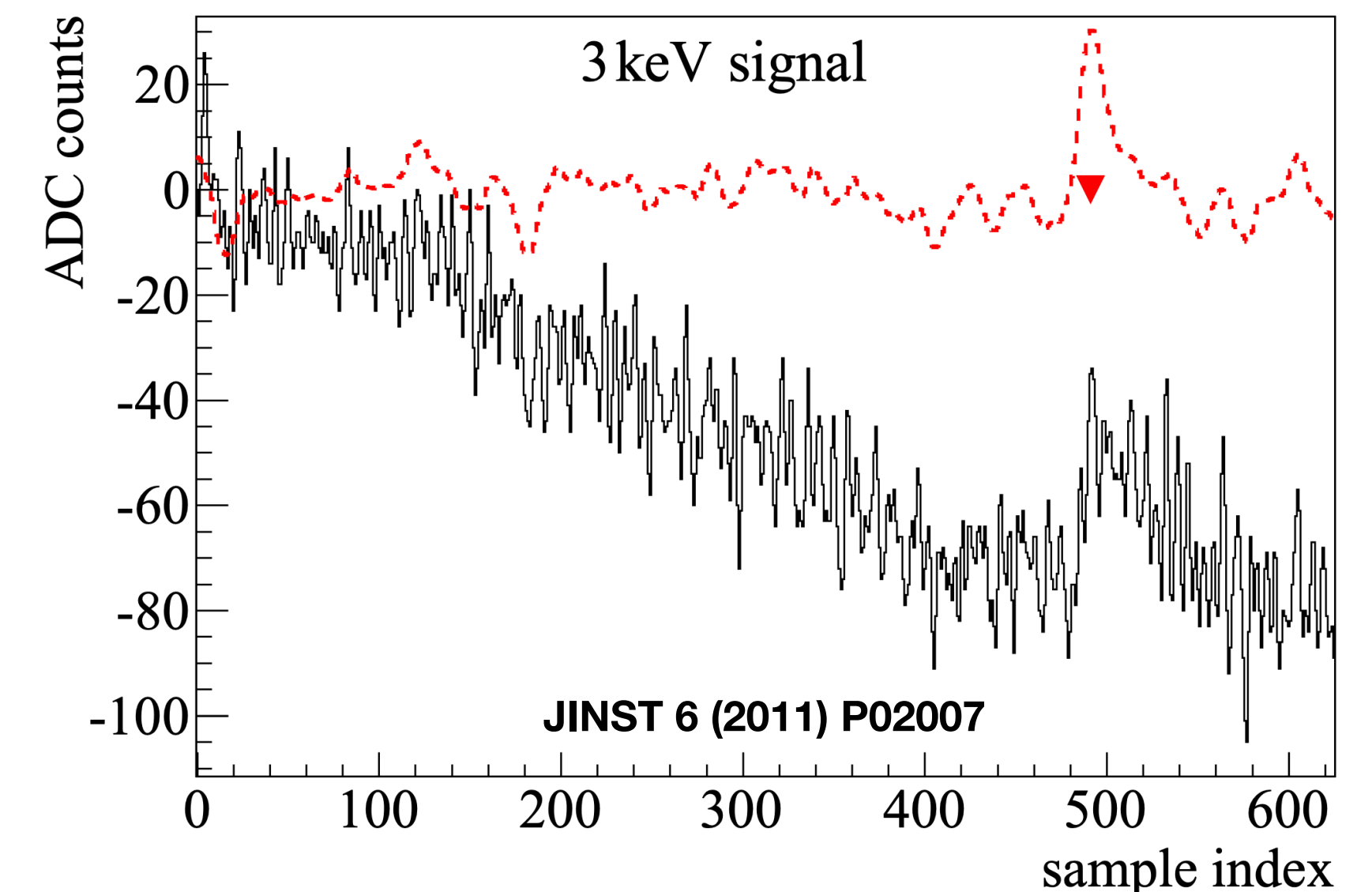
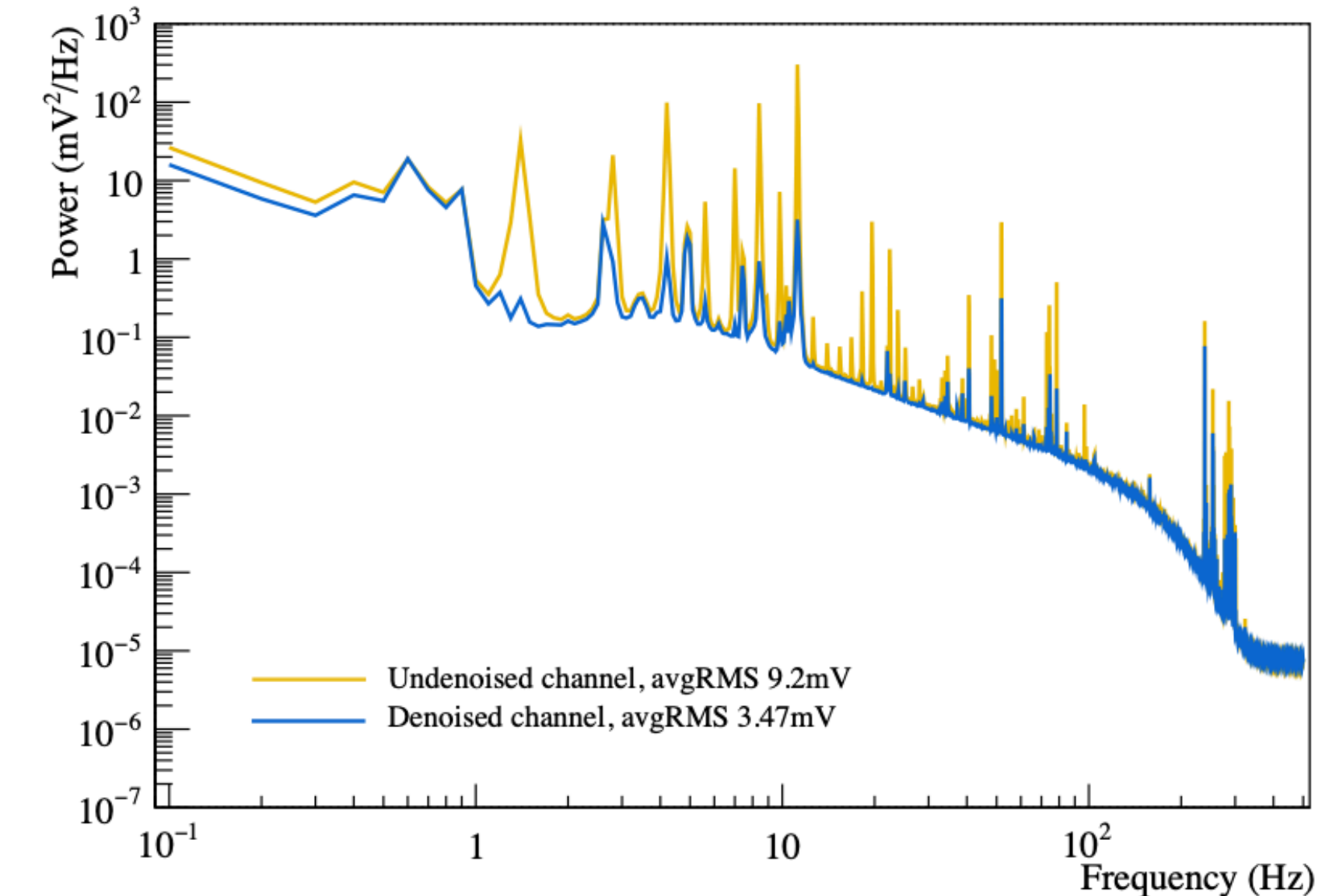
CUORE



Signal processing (offline)

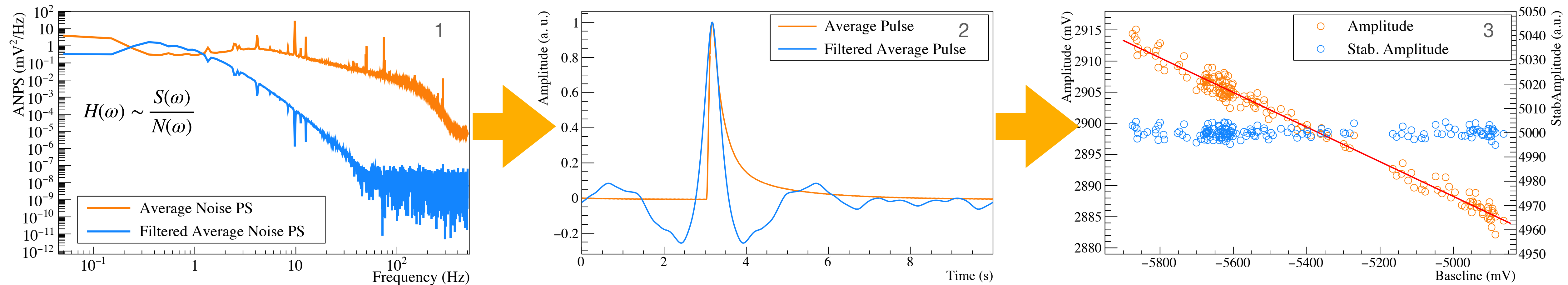
From stream data to trigger data

- **Denoising algorithm** (newly implemented!)
 - Measure the vibrational and electrical noise with auxiliary devices: seismometers, accelerometers, microphones and antennas
 - Noise reduction with decorrelation algorithms using the measured noise with the auxiliary devices
- **Optimum trigger**
 - Filters the data using the ideal pulse and noise
 - Filtered data with amplitude higher than a certain value is flagged as an event
 - Allows to trigger low energy events



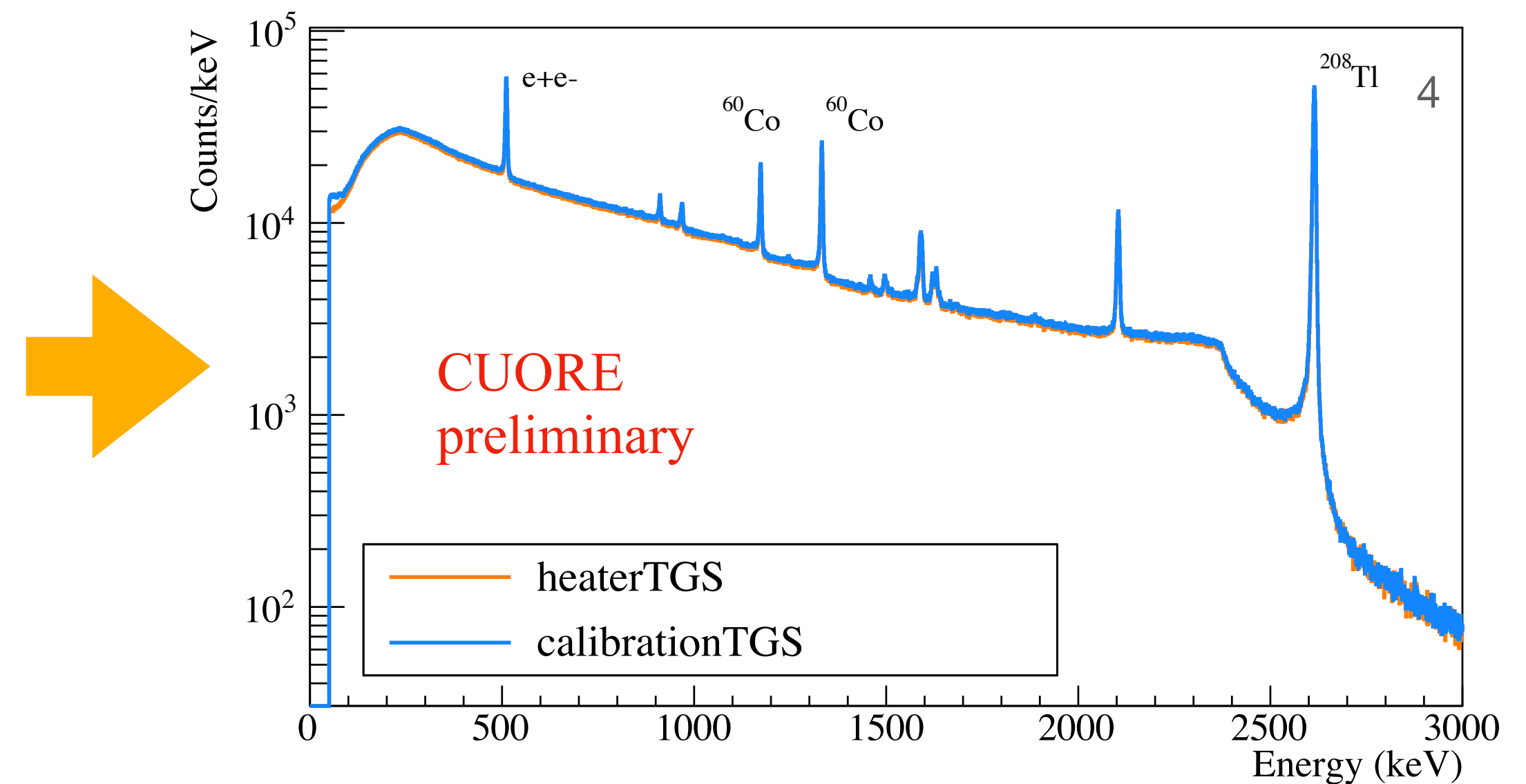
Energy reconstruction

From triggered data to energy spectrum



Energy reconstruction steps

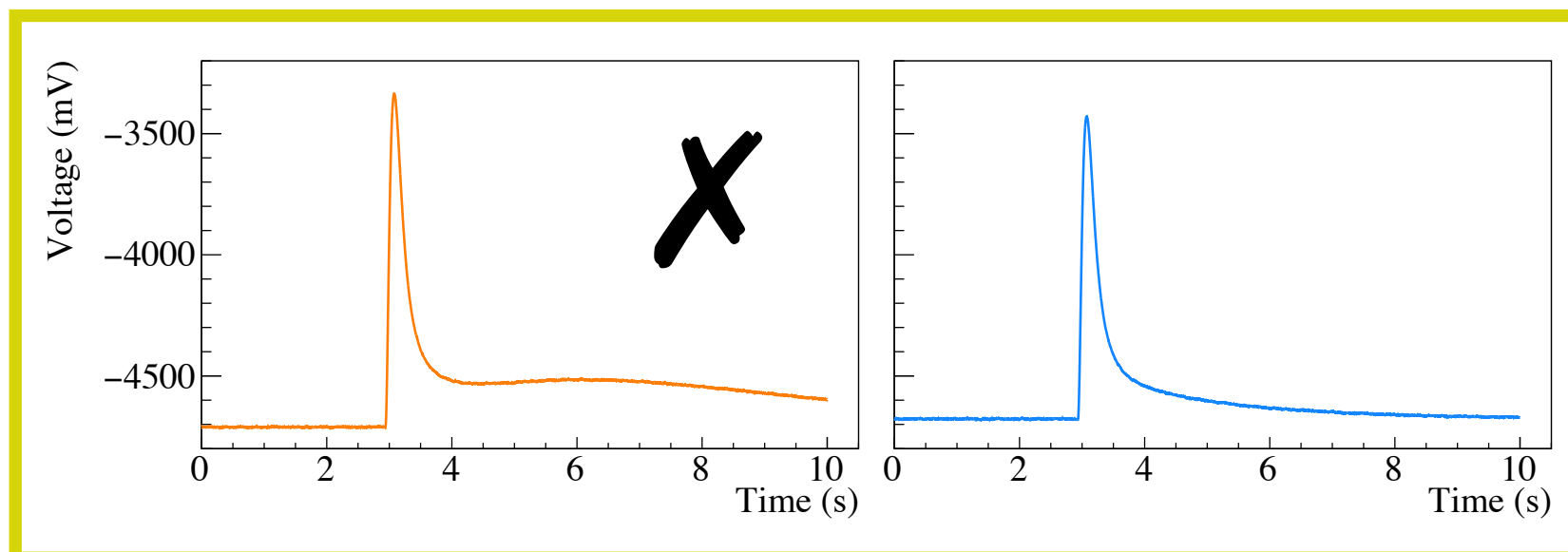
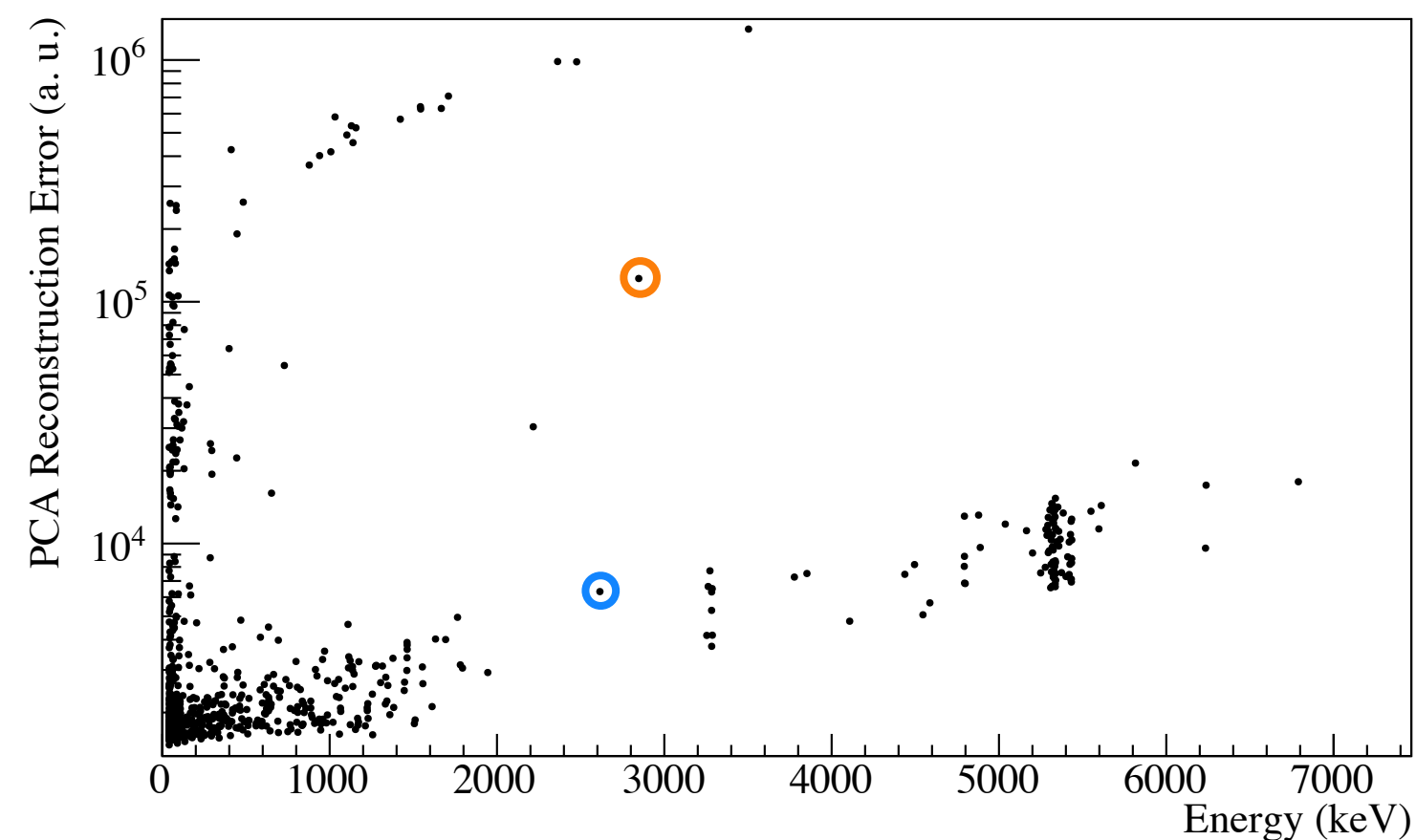
1. Optimum filter to maximise the SNR
2. Amplitude evaluation from the filtered pulses
3. Thermal gain stabilisation using a fixed energy source
4. Energy calibration using energy peaks from Th-232 and Co-60 from calibration sources deployed during the data taking



Event selection

Pulse shape discrimination (PSD)

- Based on principle component analysis
- The average pulse is used as a template for the principal component that models the physical pulse
- Reconstruction error is used to select physical events and reject non physical events (noise, pileup, ...)



Anti-coincidences (AC)

- Select events that occur only in one crystal => use of an anti-coincidence cut to keep only single site events (M1)
- Most of the double-beta decay events deposit energy occurs in a single crystal
- Coincidence = deposit of $E > 40$ keV in multiple crystal within 5 ms

