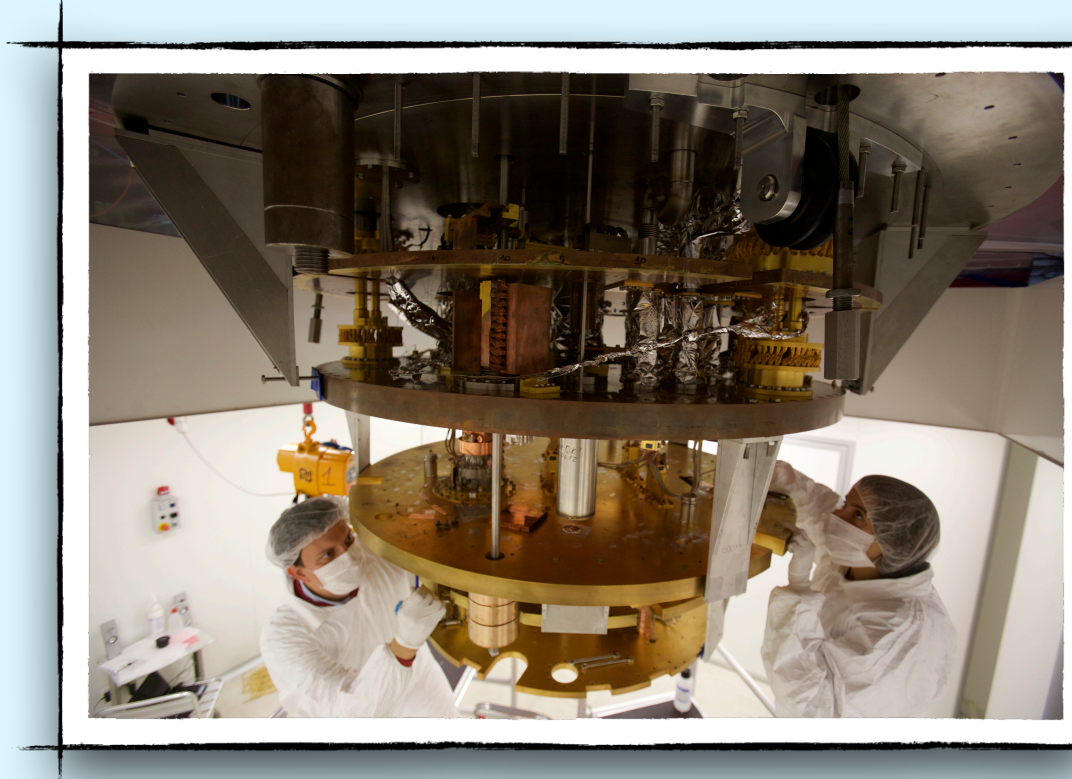
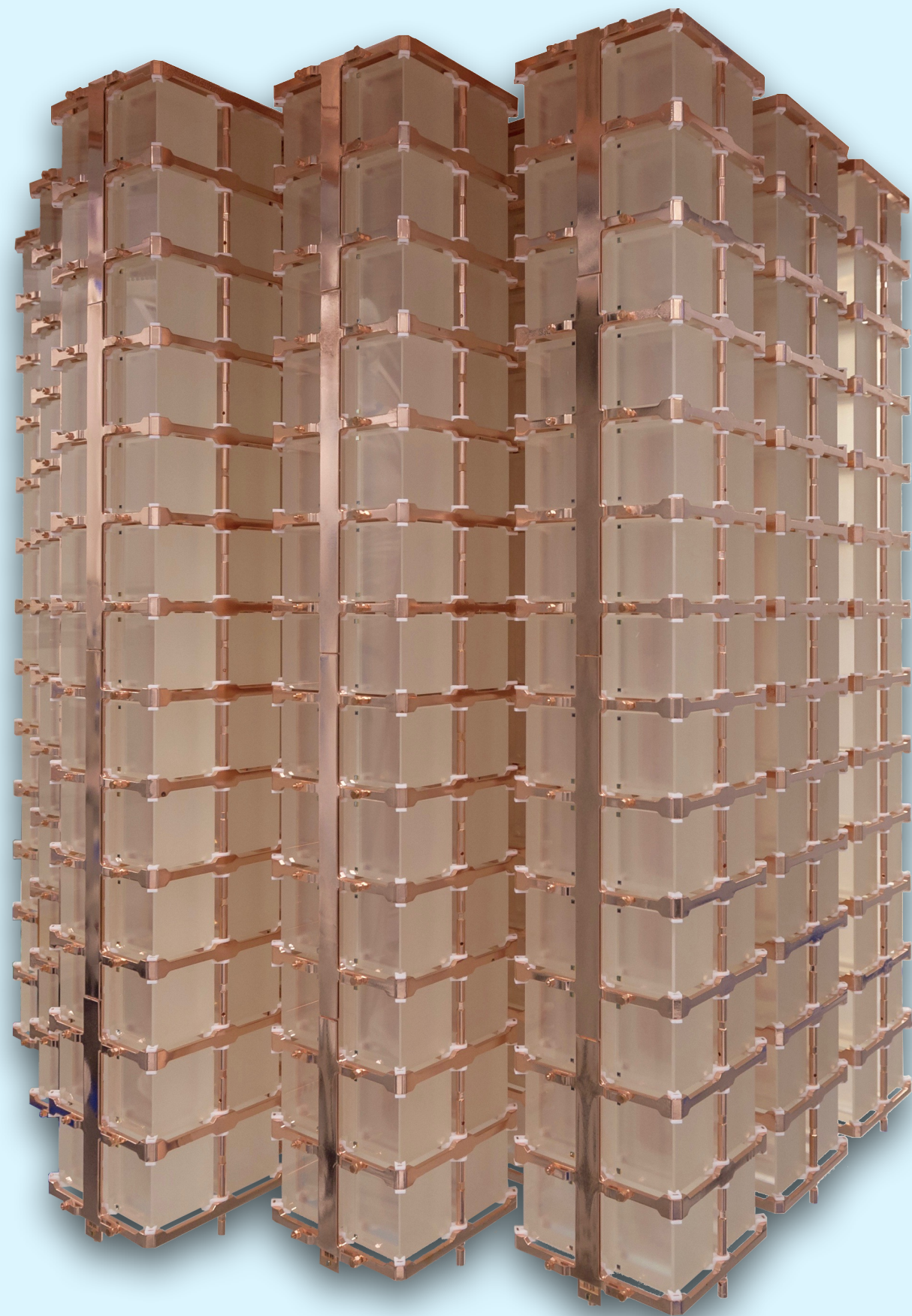


# Search for Majorana neutrinos with millikelvin technology in CUORE: current status and road ahead



Alice Campani

*on behalf of the CUORE collaboration*

Università degli studi di Genova - INFN Genova

Imperial College, London - 22 May 2026



Università  
di Genova



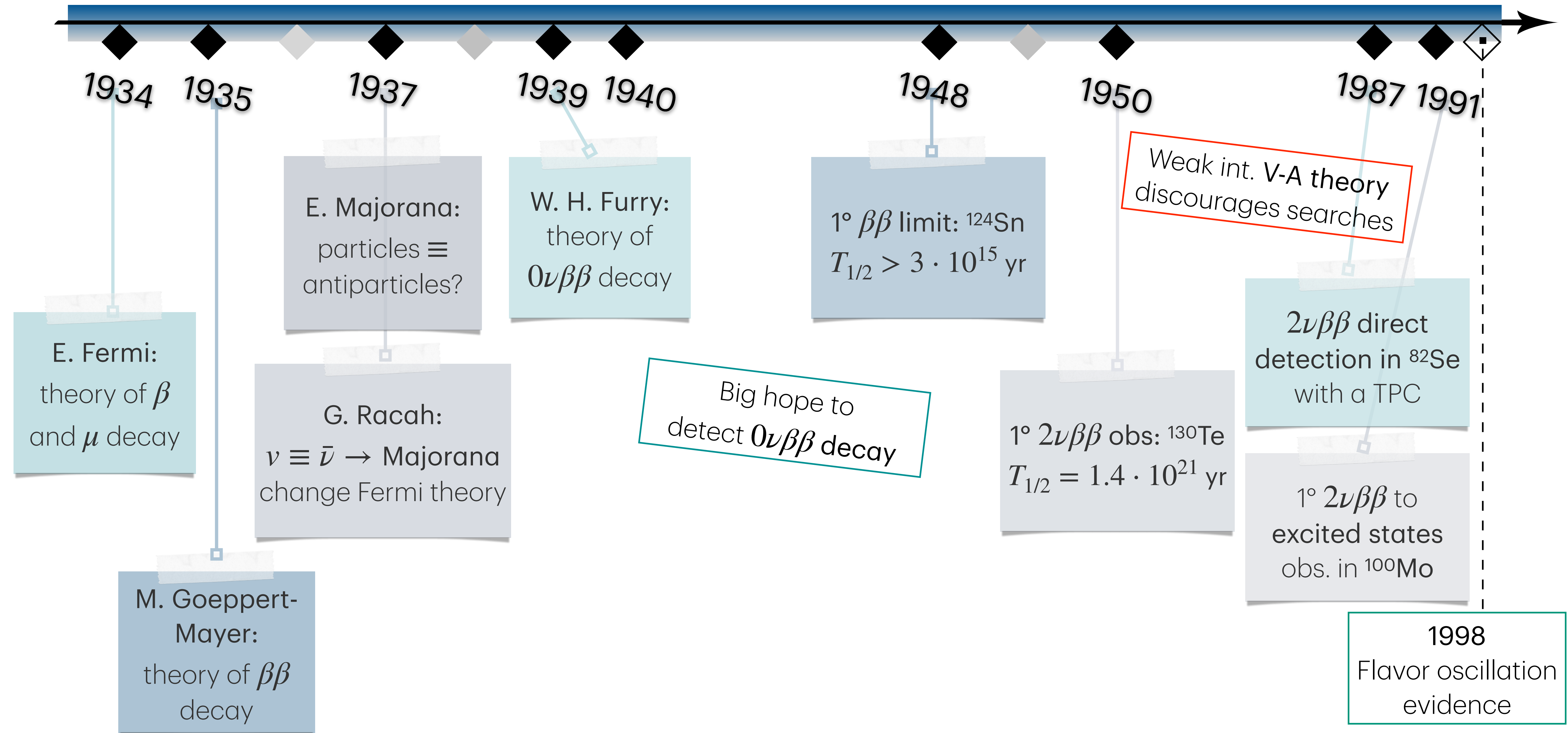
Istituto Nazionale di Fisica Nucleare

# Overview of this talk

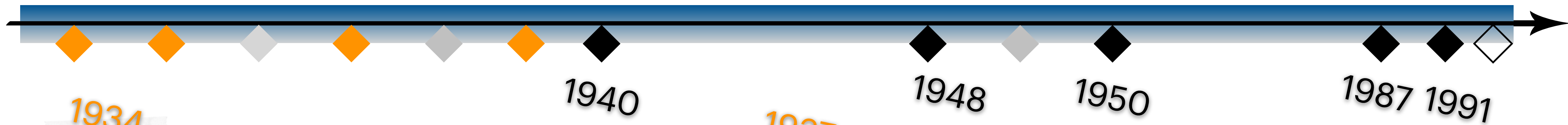
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- Introduction: neutrinoless double beta decay ( $0\nu\beta\beta$ ) in the context of neutrino physics
  - History and experimental program
- Search for  $0\nu\beta\beta$  decay with cryogenic calorimeters in CUORE
  - Challenges and solutions to reach high sensitivity
- Results on  $^{130}\text{Te}$   $0\nu\beta\beta$  decay with the largest statistics collected with CUORE
- Progress on a wide program of rare event searches
- Perspectives and next steps: CUPID and next-generation experiments

# Double beta decay: a long history



# Double beta decay: a long history

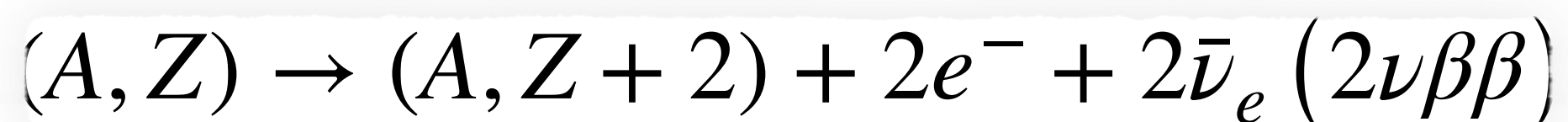


1934

E. Fermi formulates a convincing theory of  $\beta$  and  $\mu$  decay stimulating the search for neutrinos, new hypothesized particles

1935

M. Goeppert-Mayer shows the possibility that an even-even nucleus transforms into a stable nucleus simultaneously emitting two electrons



*“The process will appear as the simultaneous occurrence of two transitions, each of which does not fulfill the law of conservation of energy separately”*

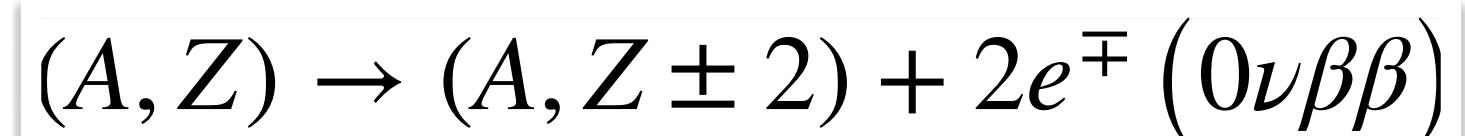
1940

1937

E. Majorana formulates an alternative to P. Dirac’s theory in which particles coincide with their own antiparticles

1937

G. Racah highlights that Fermi theory needs a change if a symmetry between particles and anti-particles exists



1948

1950

TEORIA SIMMETRICA DELL'ELETTRONE  
E DEL POSITRONE

Nota di ETTORE MAJORANA

*Sunto. - Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di DIRAC ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

1987 1991

1939

W. H. Furry combines Majorana & Goeppert-Mayer theories to hypothesize  $0\nu\beta\beta$  decay, with emission & absorption of virtual Majorana neutrinos motivating its search with geochemical experiments

# Double beta decay: a long history



**1940**

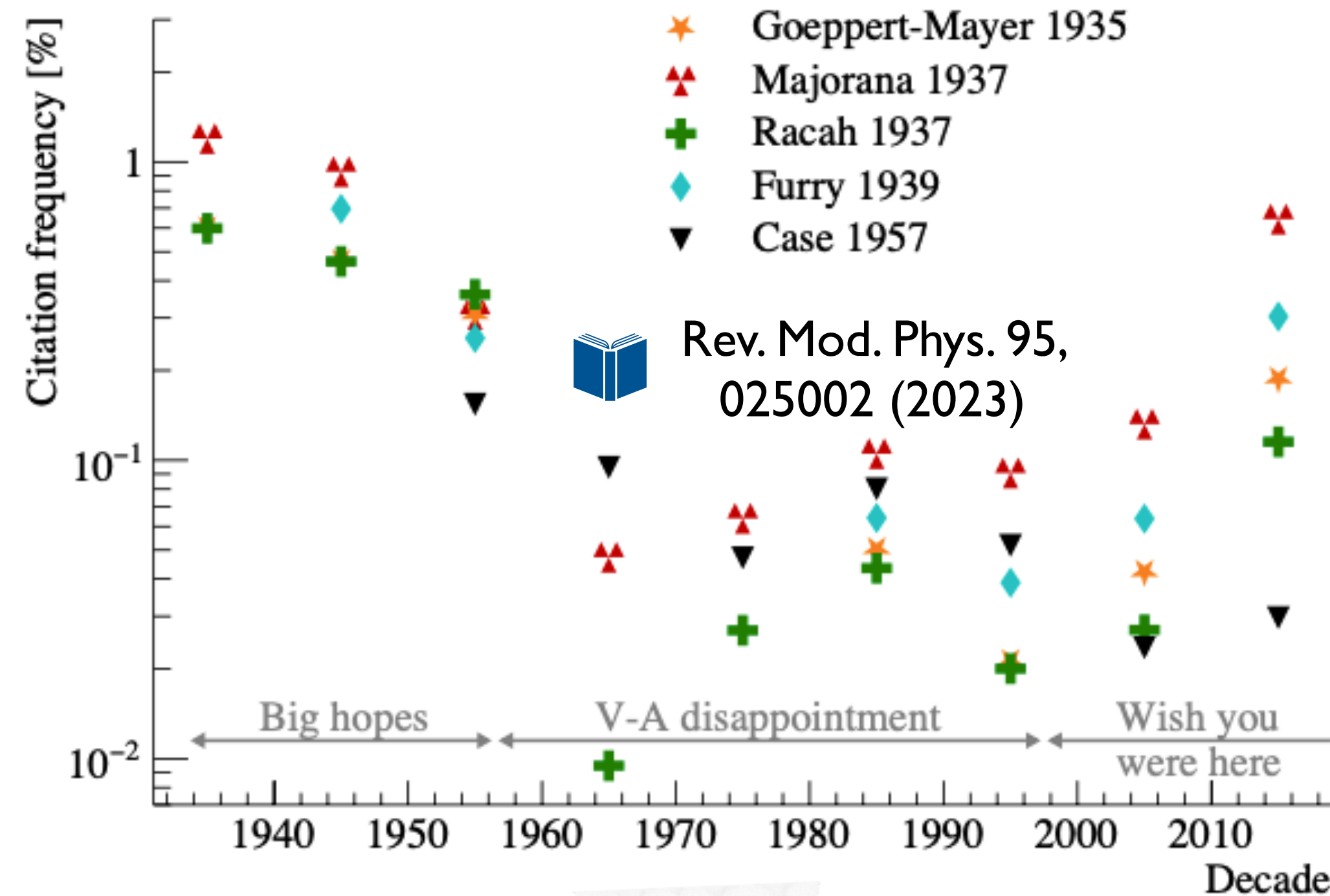
Search for  $\beta\beta$  decay in the two possible channels ( $2\nu$ ,  $0\nu$ ) begins

**1948**

First  $\beta\beta$  limit:  $^{124}\text{Sn}$   
 $T_{1/2} > 3 \cdot 10^{15}$  yr  
 with Geiger counters

**1950**

First  $2\nu\beta\beta$  observation:  
 $^{130}\text{Te}$   $T_{1/2} = 1.4 \cdot 10^{21}$  yr



1955 — 1987: a *Middle Age*  
 V-A nature of weak interactions implies  $0\nu\beta\beta$  is way **more rare** than anticipated

**1987**

First  $2\nu\beta\beta$  direct detection in  $^{82}\text{Se}$  with a TPC

**1991**

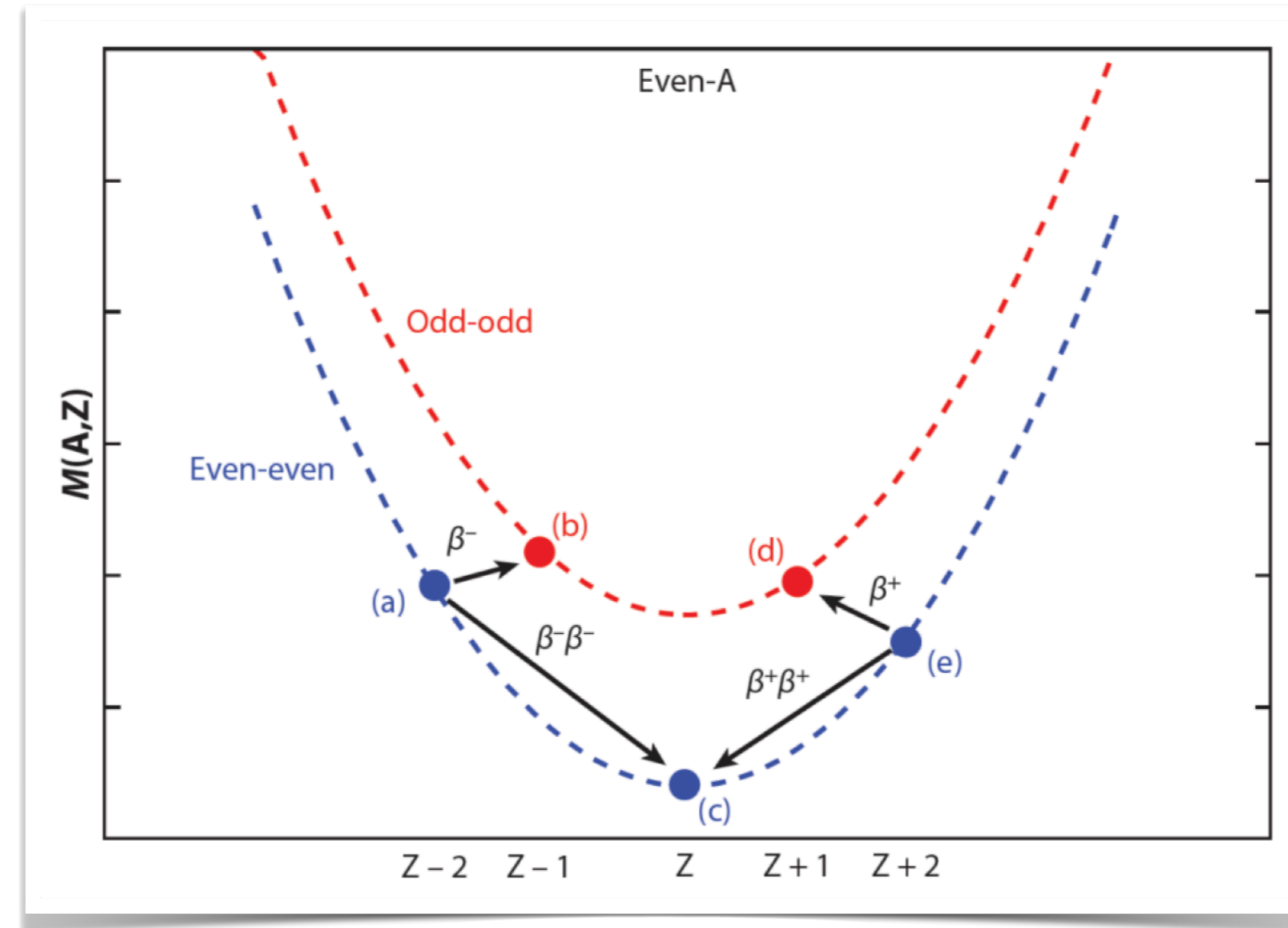
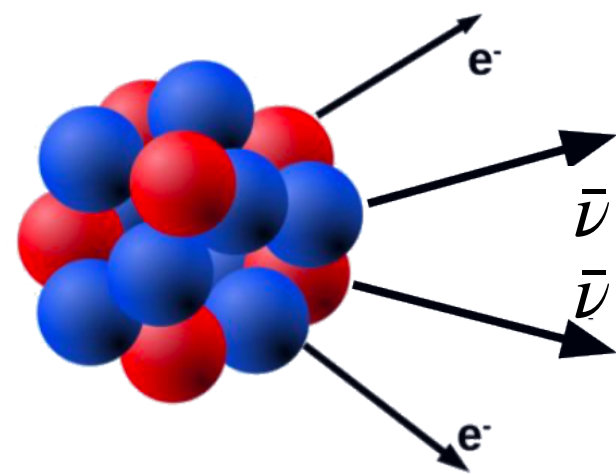
First detection of  $2\nu\beta\beta$  to excited states in  $^{100}\text{Mo}$

**1998**: neutrino flavor oscillation discovery motivates  $0\nu\beta\beta$  search

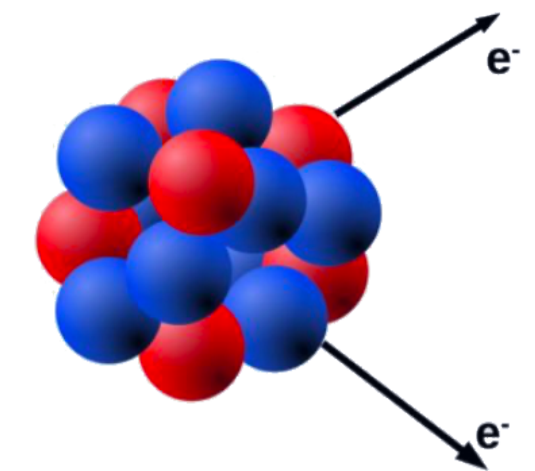
# Double beta decay: the nuclear process

Rare second-order nuclear decay between isobars:  $(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$   $(2\nu\beta\beta)$   $(0\nu\beta\beta)$

$2\nu\beta\beta$



$0\nu\beta\beta$

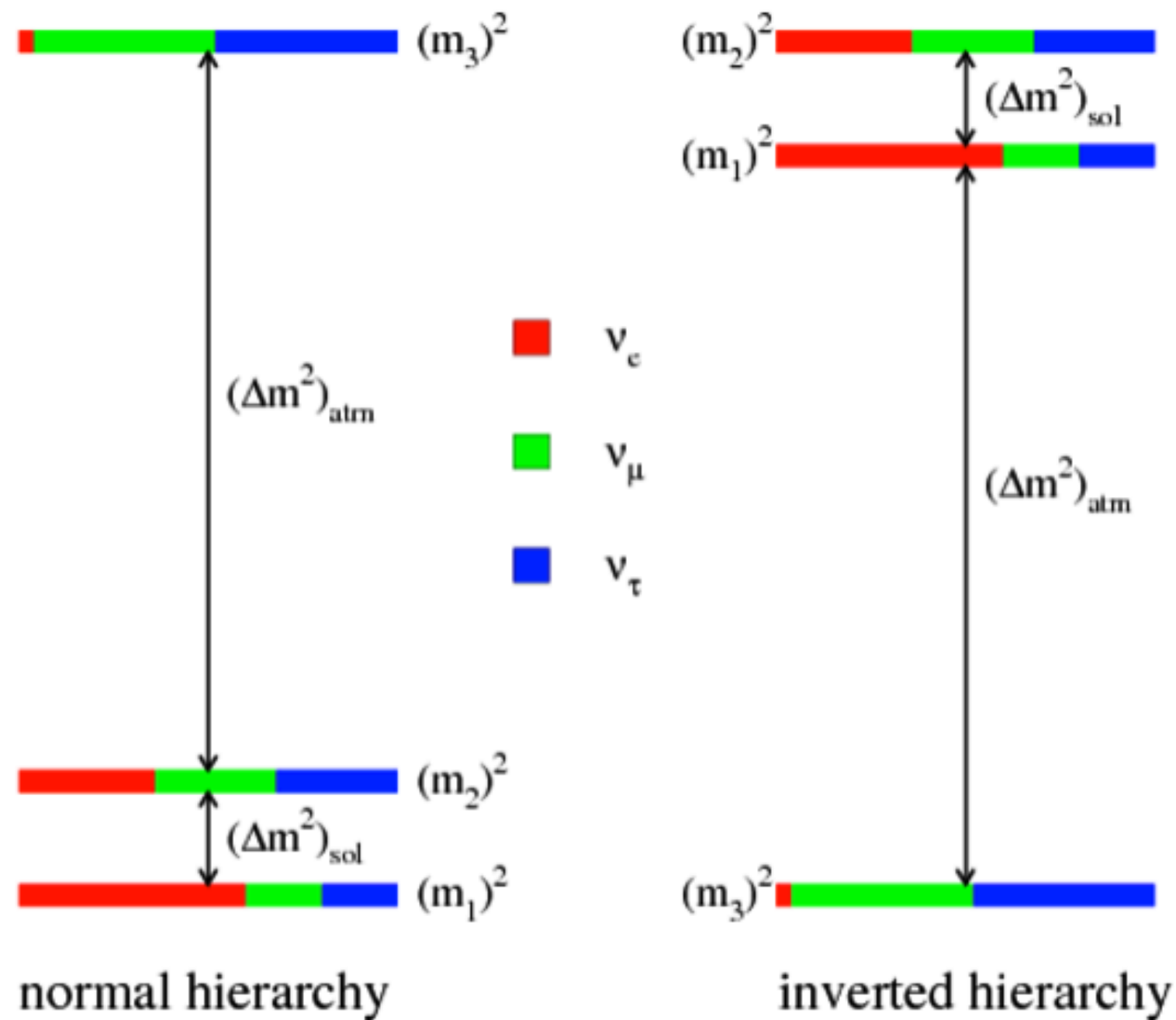


- Allowed in the Standard Model only for **even-even** nuclei ( $\Delta L = 0$ )
- Observed in several nuclei,  $^{76}\text{Ge}, ^{82}\text{Se}, ^{100}\text{Mo}, ^{136}\text{Xe}, \dots$
- Half-life  $T_{1/2}^{2\nu} \sim 10^{18} - 10^{22}$  yr

- Beyond the Standard Model: lepton number symmetry violation ( $\Delta L = 2$ )
- Simplest model: **Majorana  $\nu$**
- No evidence observed so far
- Half-life  $T_{1/2}^{0\nu} > 10^{24} - 10^{26}$  yr

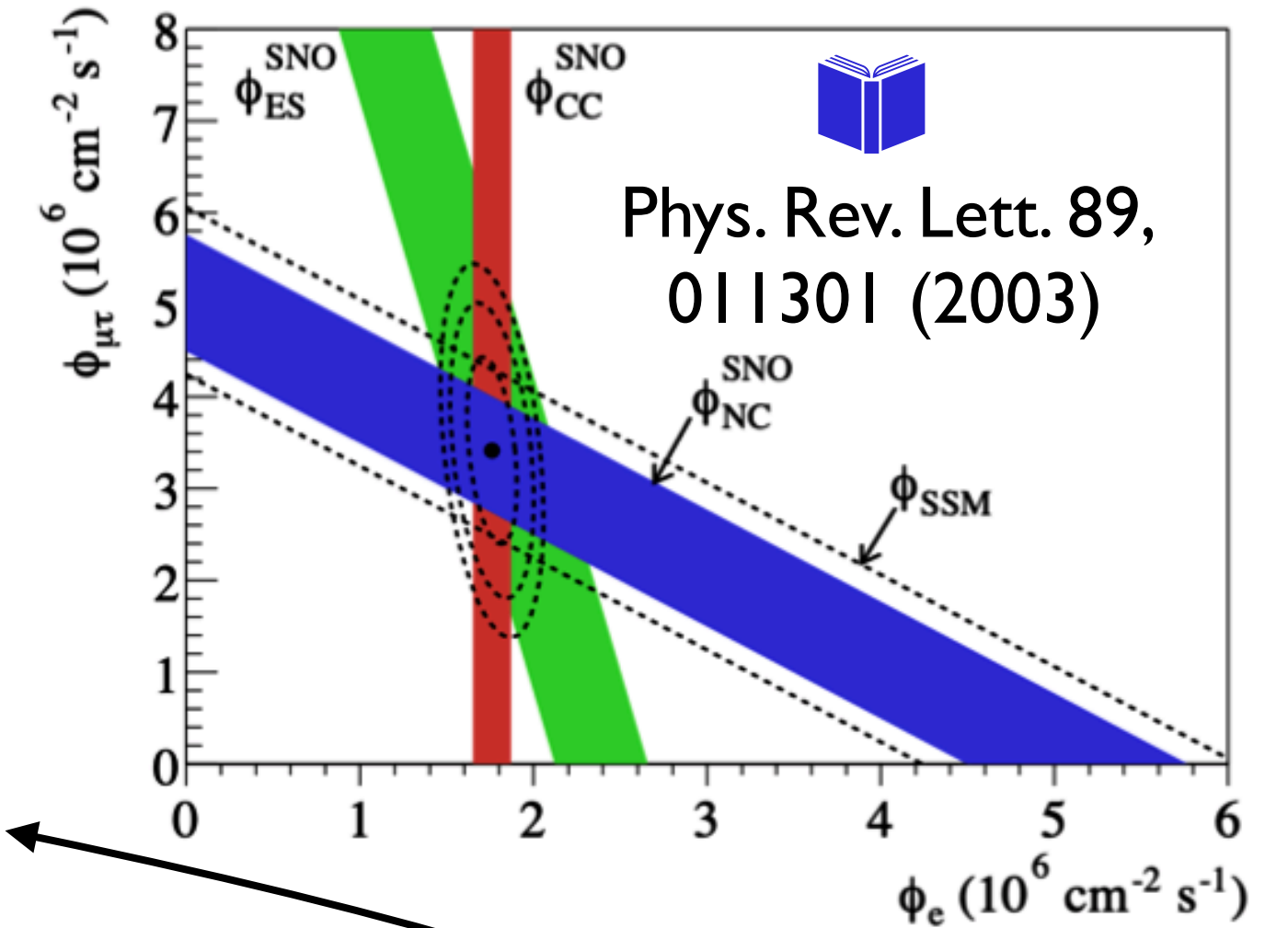
# $0\nu\beta\beta$ : interplay with neutrino physics and cosmology

- Neutrinos are the lightest known elementary fermions: no charge of any kind, only detected via weak interactions
- The existence of  $\nu$  flavour oscillations makes it necessary to extend the Minimal Standard Model to accommodate massive neutrinos



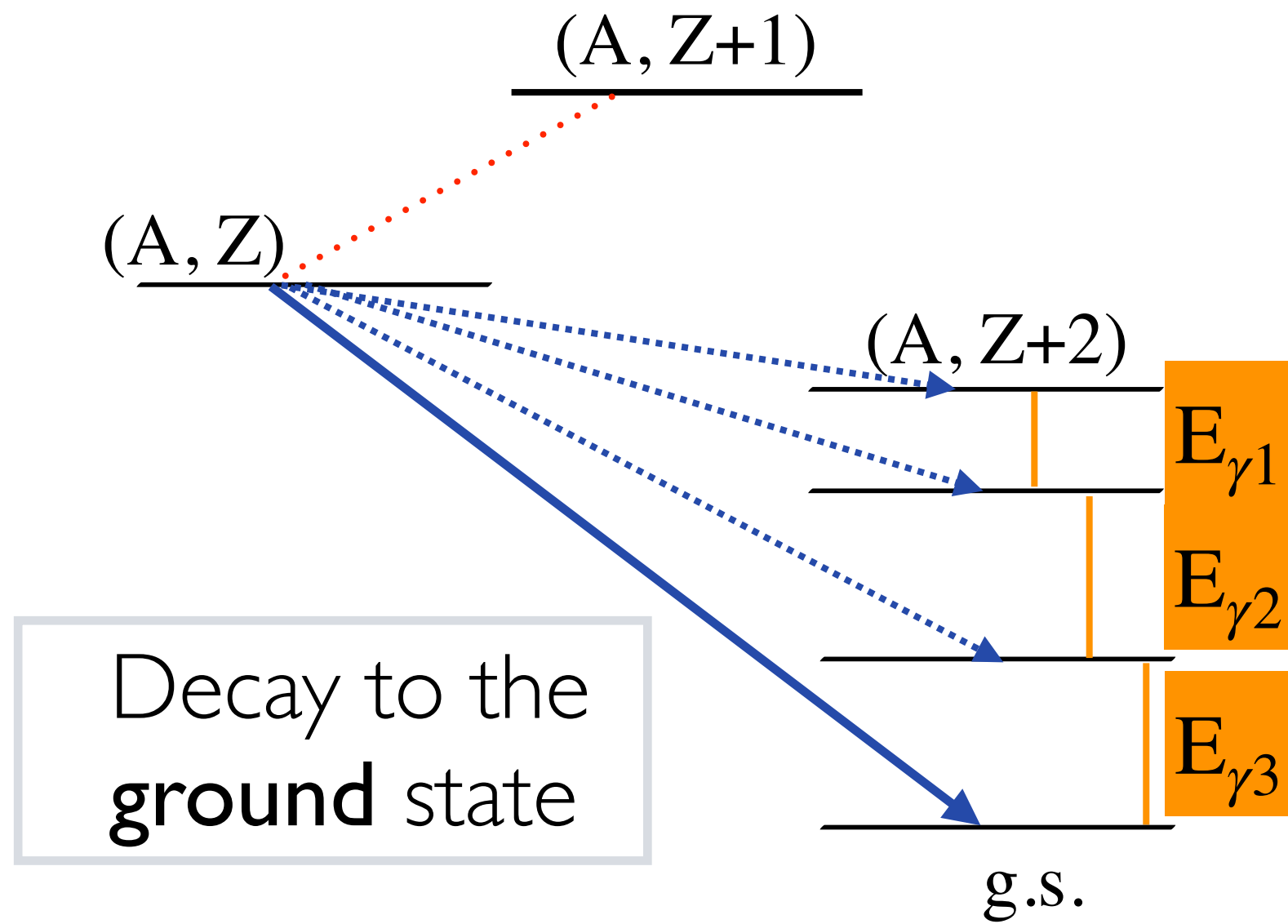
We don't know

- How mass eigenstates are ordered
  - Absolute values of neutrino masses
  - Why neutrino mass is  $\ll$  other SM particles
  - What is the nature of  $\nu$  mass
- $0\nu\beta\beta$  plays a role
- Stringent limits on the sum of neutrino masses from cosmology  
 $\sum m_\nu < 0.064 \text{ eV}$  [DESI+CMB] Phys. Rev. D 112, 083515 (2025)
  - Constraint on the electron neutrino mass from single  $\beta$  decay  
 $m_\beta < 0.45 \text{ eV}$  90 % C.L. [KATRIN] Science 388, 6743 (2025)

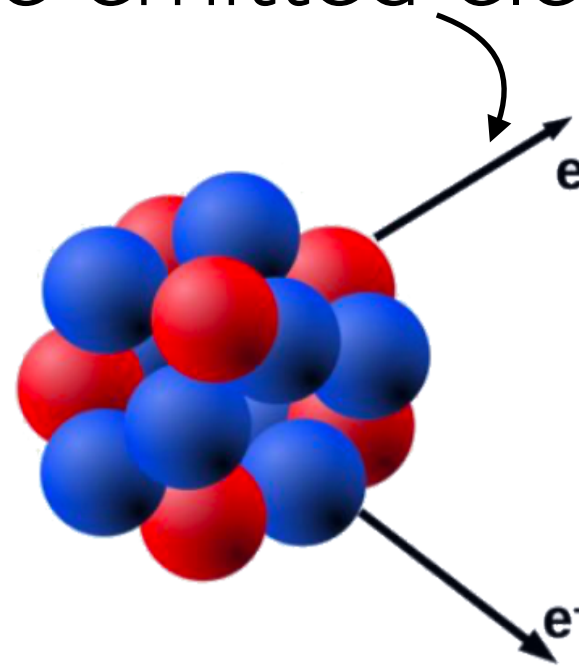


- **Lepton Number Violation** could play a role in the *matter-antimatter asymmetry* in the Universe

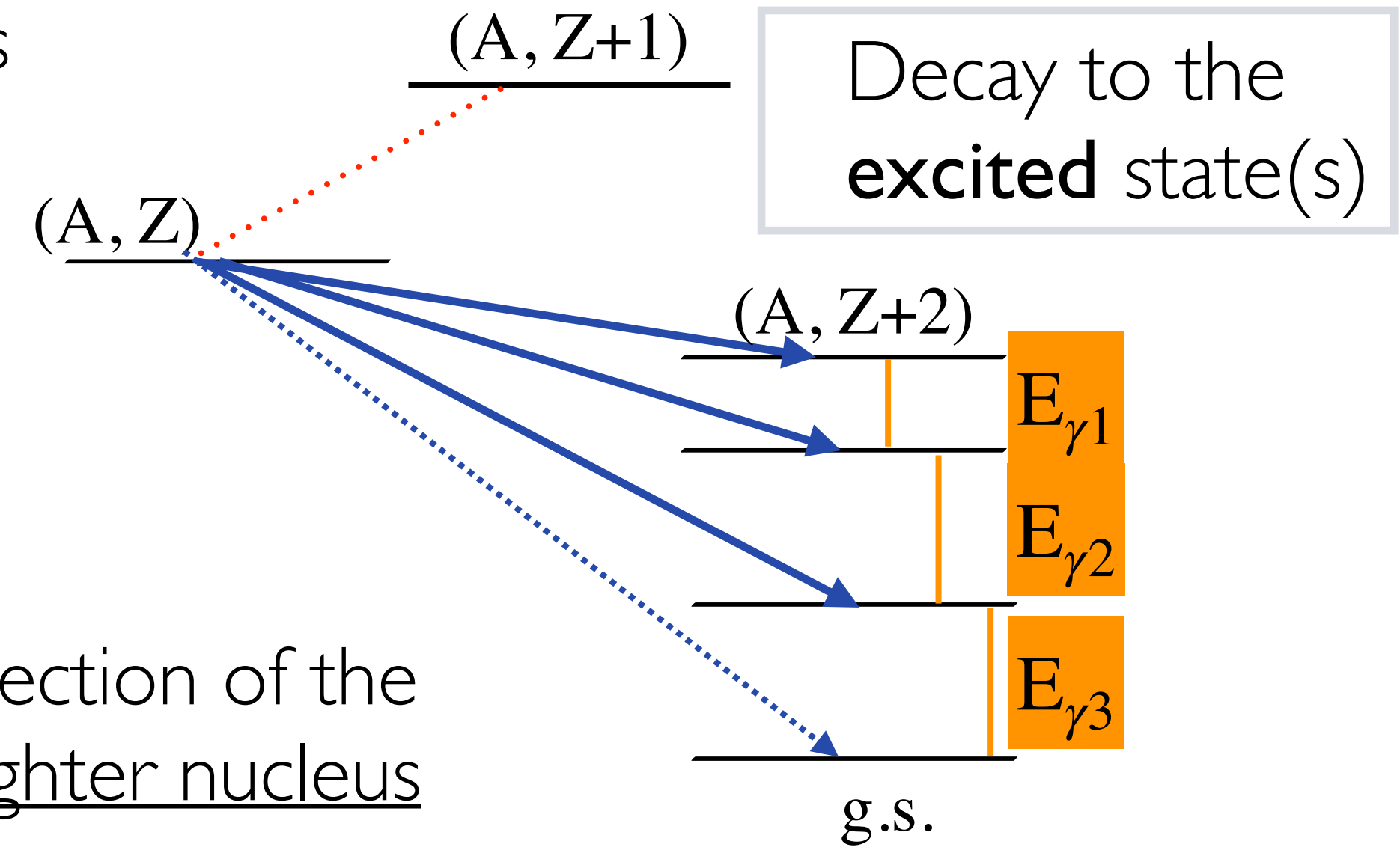
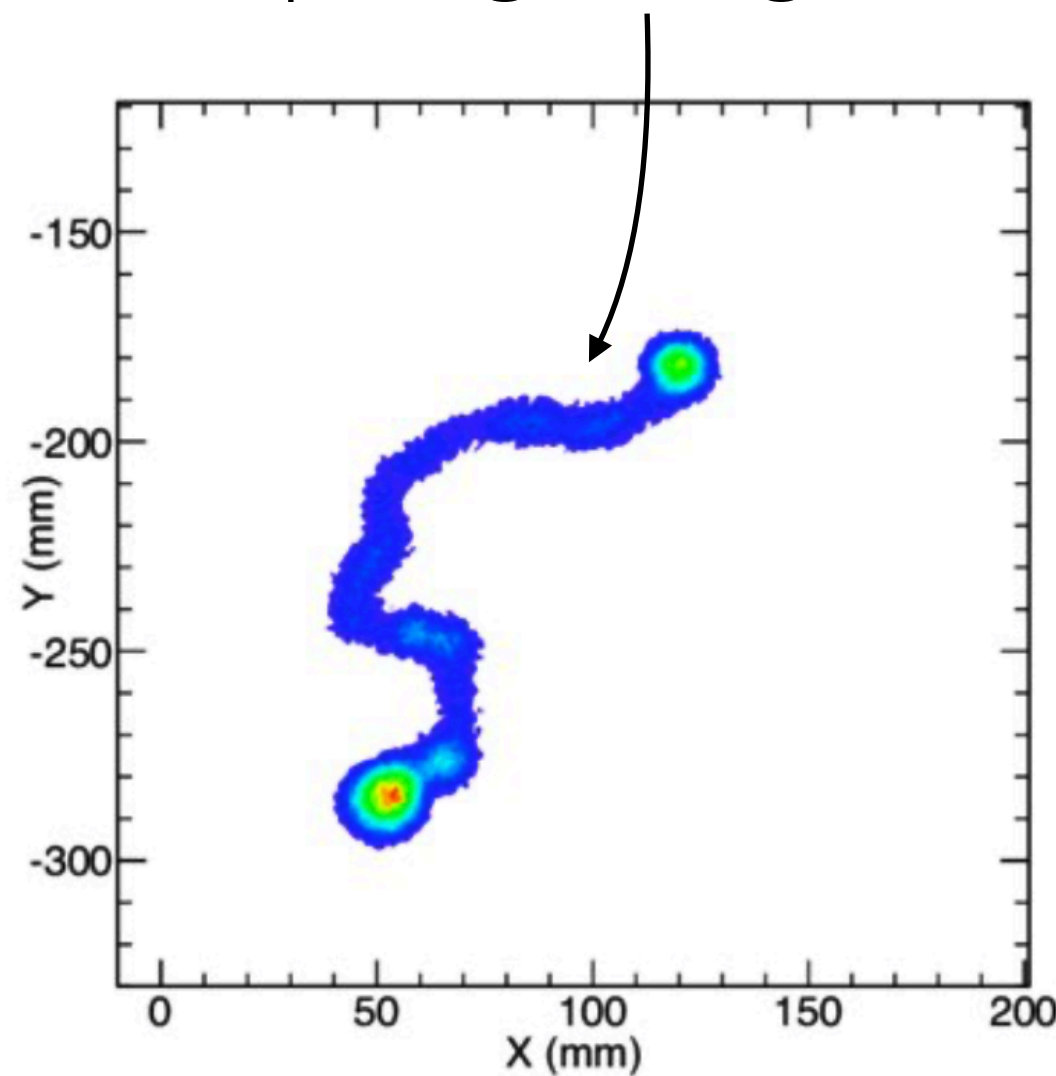
# $0\nu\beta\beta$ : experimental signatures



Kinematic of the emitted electrons



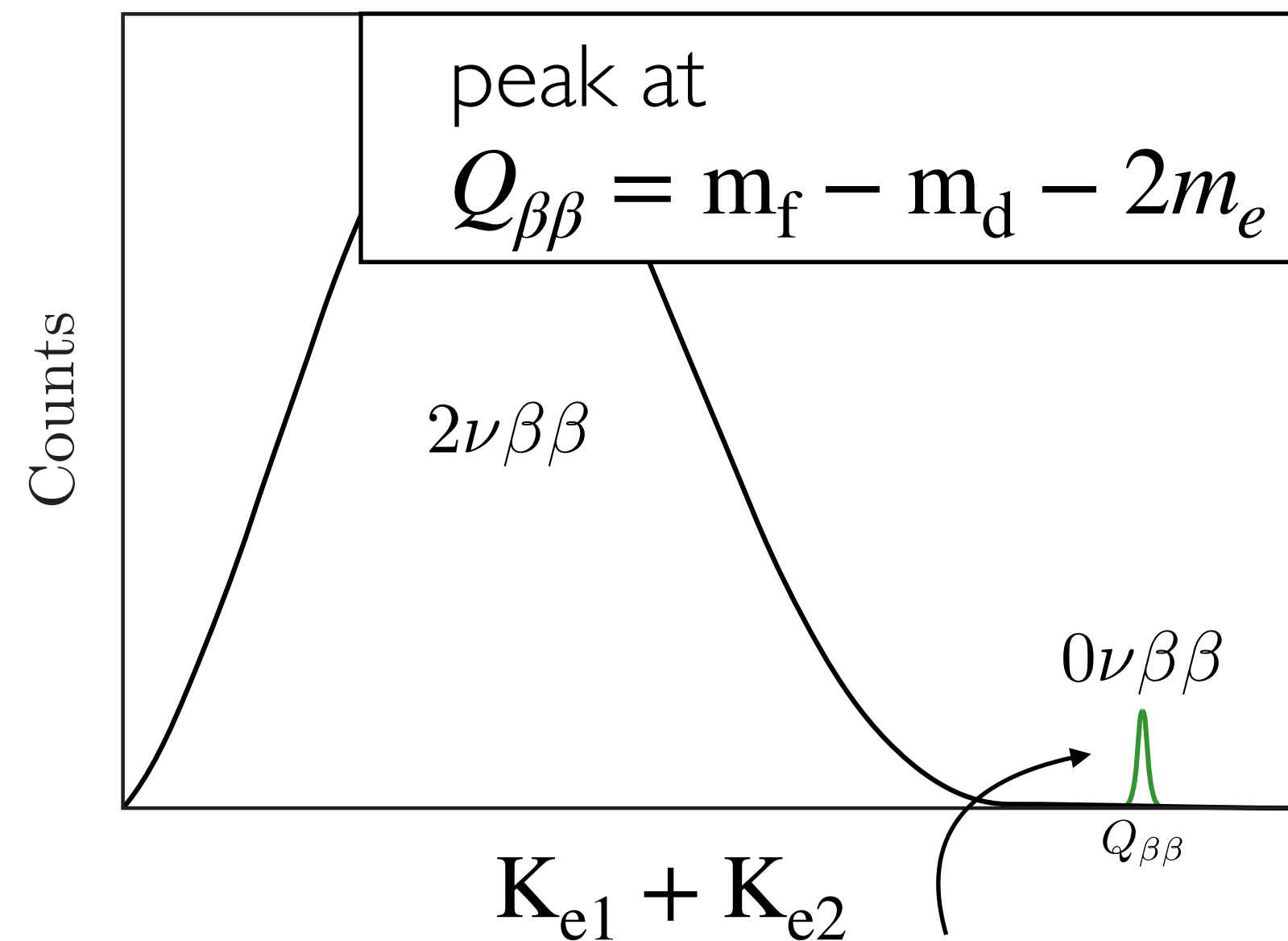
Two electrons topological signature



Nature 569, 203-7 (2019)

Detection of the emitted gamma-rays

Particles detected	Signal peak position (keV)
$\beta^+ + X + \gamma_{511}$	1203.8
$\beta^+ + X + 2\gamma_{511}$	1714.8
$(\beta^+ + X, \gamma_{511})$	(692.8, 511)
$(\beta^+ + X + \gamma_{511}, \gamma_{511})$	(1203.8, 511)
$(\beta^+ + X, \gamma_{511}, \gamma_{511})$	(692.8, 511, 511)



Summed kinetic energy of the two electrons

# $0\nu\beta\beta$ : signal rate and the effective Majorana mass

Assuming the exchange of a light Majorana neutrino  
the  $0\nu\beta\beta$  decay rate is

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

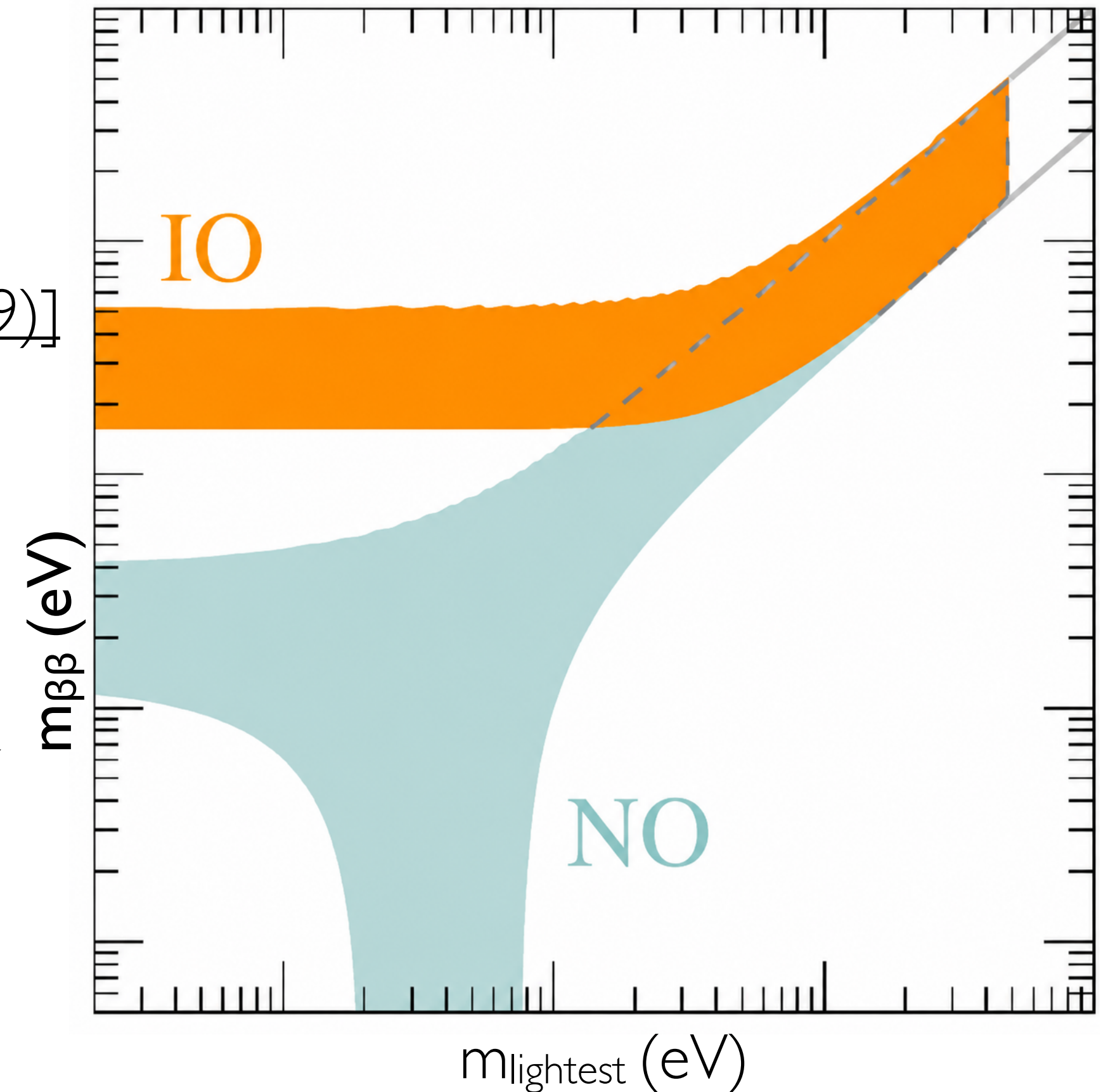
Phase space factor  
well known ( $\lesssim 7\%$ )

Nuclear matrix  
element  
significant  
theory  
uncertainty

Effective Majorana mass  
 $\langle m_{\beta\beta} \rangle = \left| \sum_{i=1,2,3} |U_{ei}|^2 e^{i\alpha_i} m_i \right|$   
coherent sum of mass eigenstates

Pictorial representation  
of the parameter space  
in the *lobster plot*  
[F.Vissani, JHEP06 022 (1999)]  
mixing  $\theta_{ij}$  fixed,  $\alpha_k$  free

Adapted from *nu-fit 6.1 (2025)*



- **Unique probe** of the **Majorana phases** that cannot be measured by oscillation experiments sensitive to squared mass differences only

# $0\nu\beta\beta$ : experimental sensitivity & critical parameters

Sensitivity to  $0\nu\beta\beta$  scales as<sup>†</sup>

$\beta\beta$  emitter isotopic fraction

detection efficiency

active mass

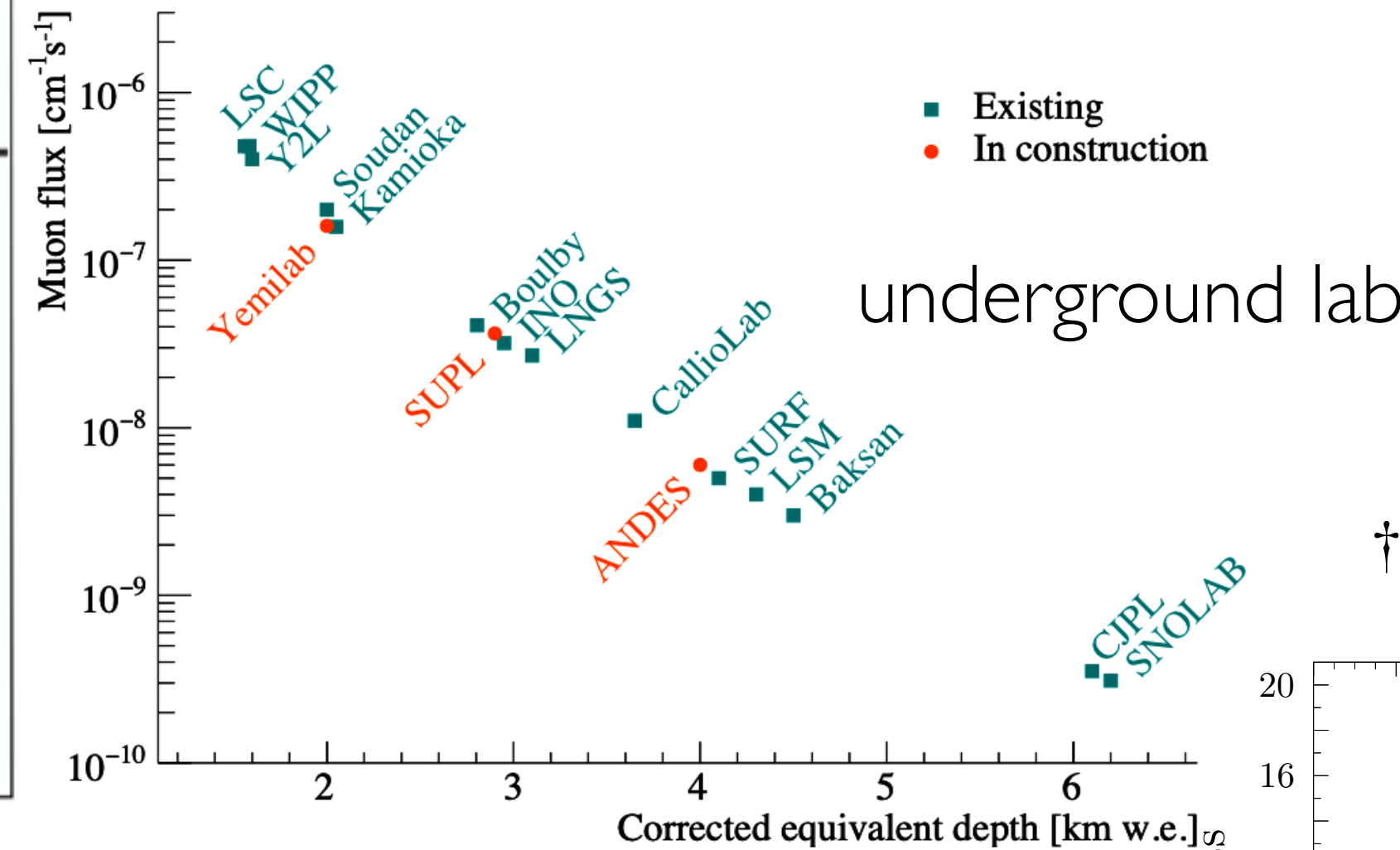
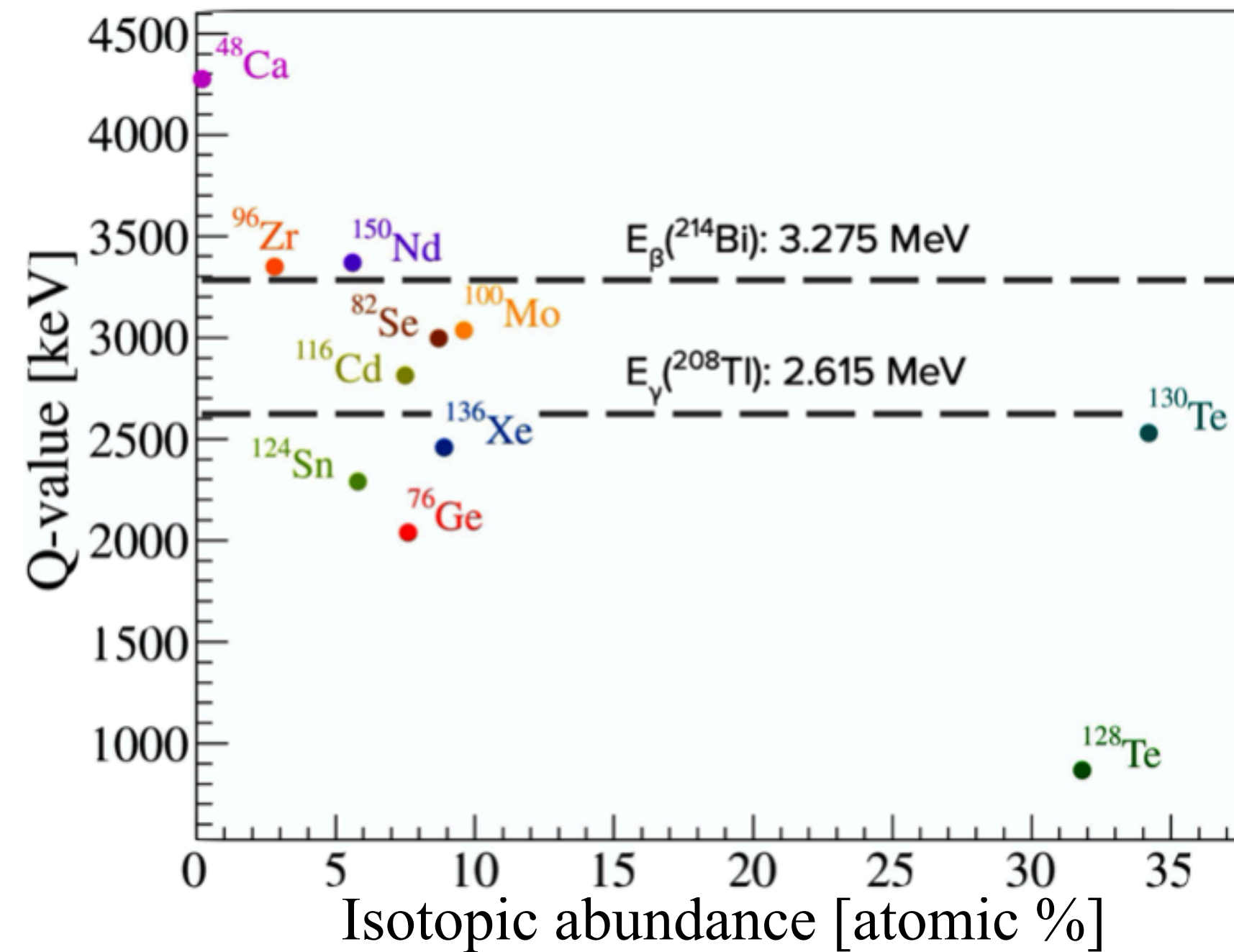
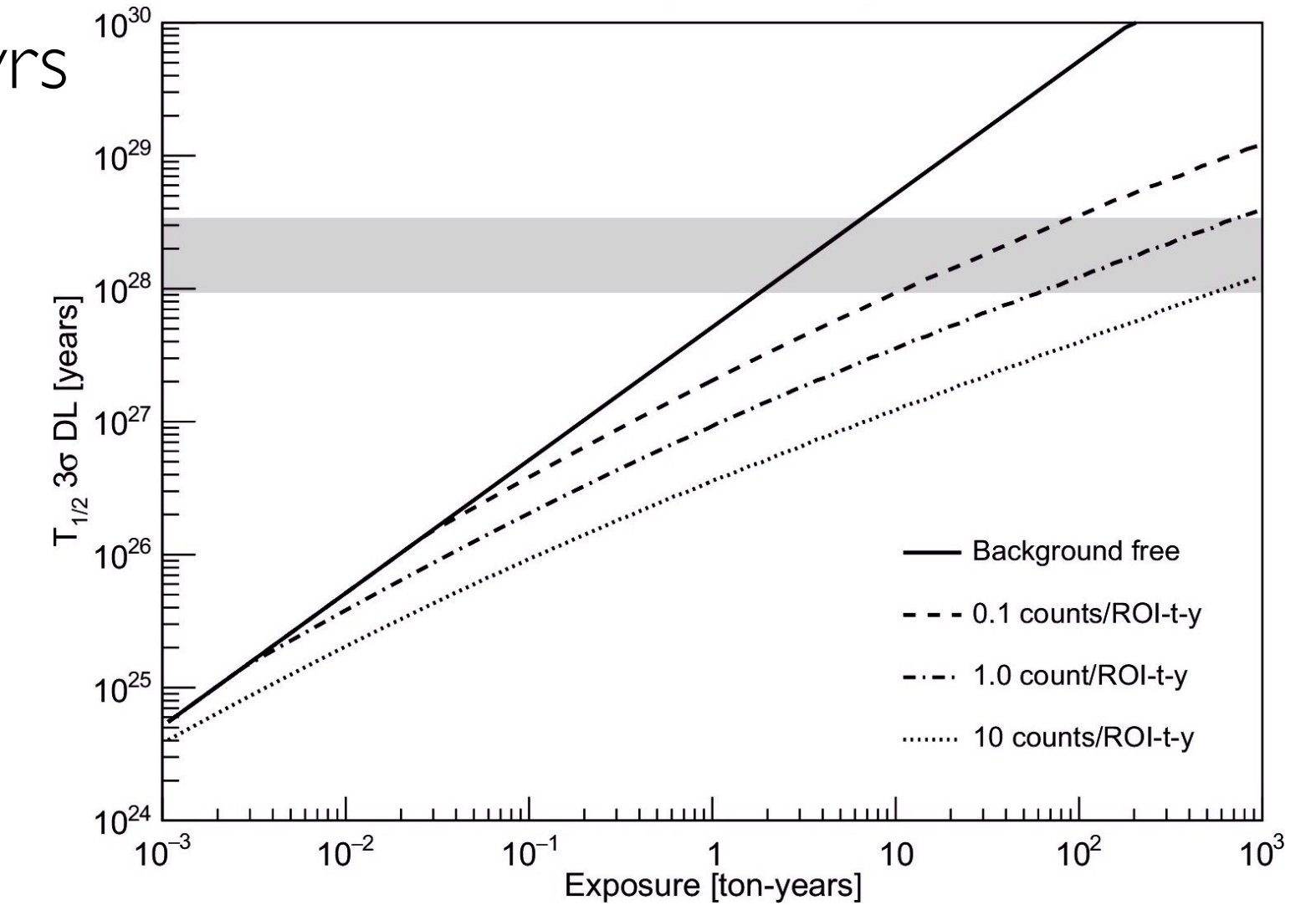
livetime

background in the ROI

$\gtrsim 90\%$

$$S_{0\nu} \propto \eta \cdot \varepsilon \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

ton-yr



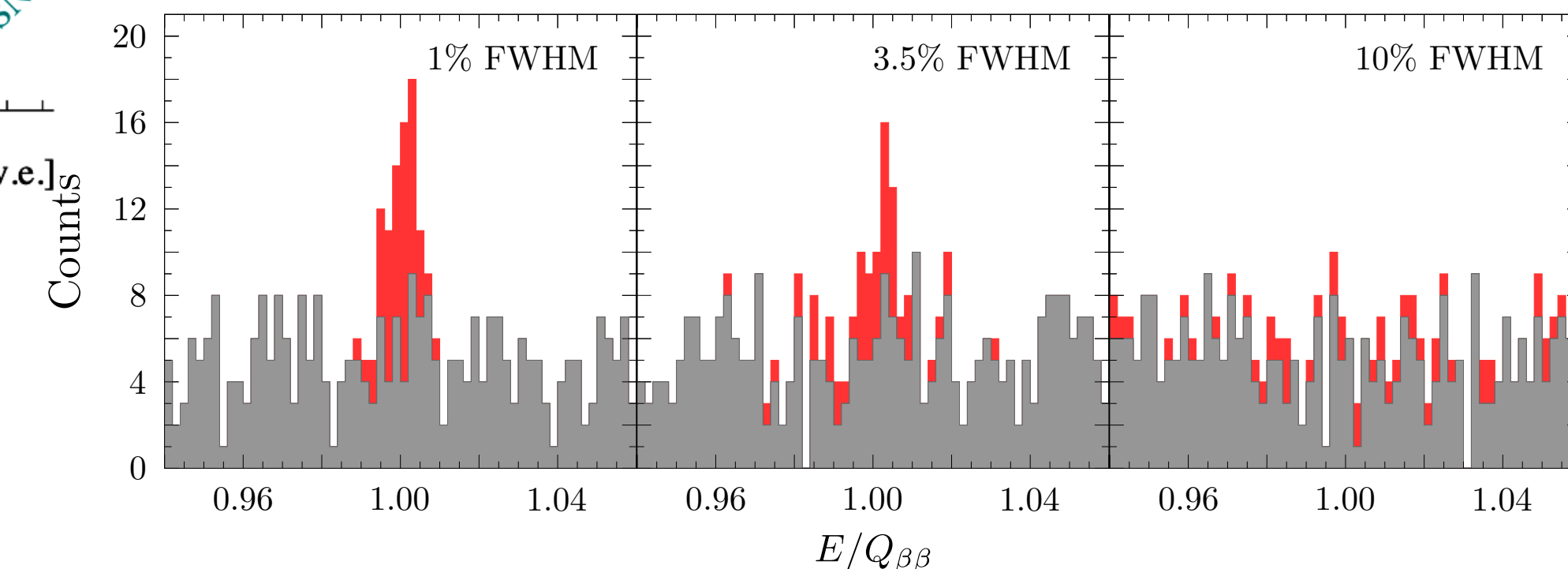
underground lab

<sup>†</sup> For zero-background cases  $S_{0\nu} \propto M \cdot T$

- Phase space  $G_{0\nu}(Q, Z) \propto Q^5$
- Fraction of events  $2\nu\beta\beta \propto 1/Q^5$
- Need of enrichment/costs

energy resolution ( $\Delta$ ) @  $Q_{\beta\beta}$

$$R_{0\nu/2\nu} \propto \left(\frac{Q_{\beta\beta}}{\Delta}\right)^6 \frac{t_{1/2}^{2\nu}}{t_{1/2}^{0\nu}}$$



$0\nu\beta\beta$  signal  
 background

# $0\nu\beta\beta$ : critical parameters - choices for CUORE

Sensitivity to  $0\nu\beta\beta$  scales as

## $\beta\beta$ emitter isotopic fraction

- natural  $^{130}\text{Te}$   $\sim 34\%$
- $\text{TeO}_2$  crystals with  $(\text{nat})\text{Te}$

## detection efficiency

- source  $\equiv$  detector
- total efficiency (all cuts)  $\sim 93\%$

## active mass

- tonne-scale detector:  
742 (206) kg  $\text{TeO}_2$  ( $^{130}\text{Te}$ )
- close-packed array - 988 crystals

## livetime

- 9 yr continuous operation
- $\sim 50$  kg  $\cdot$  yr/month

$$S_{0\nu} \propto \eta \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

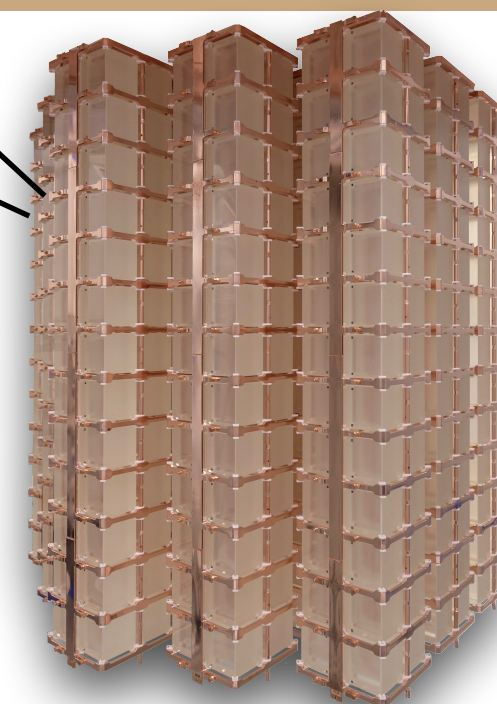
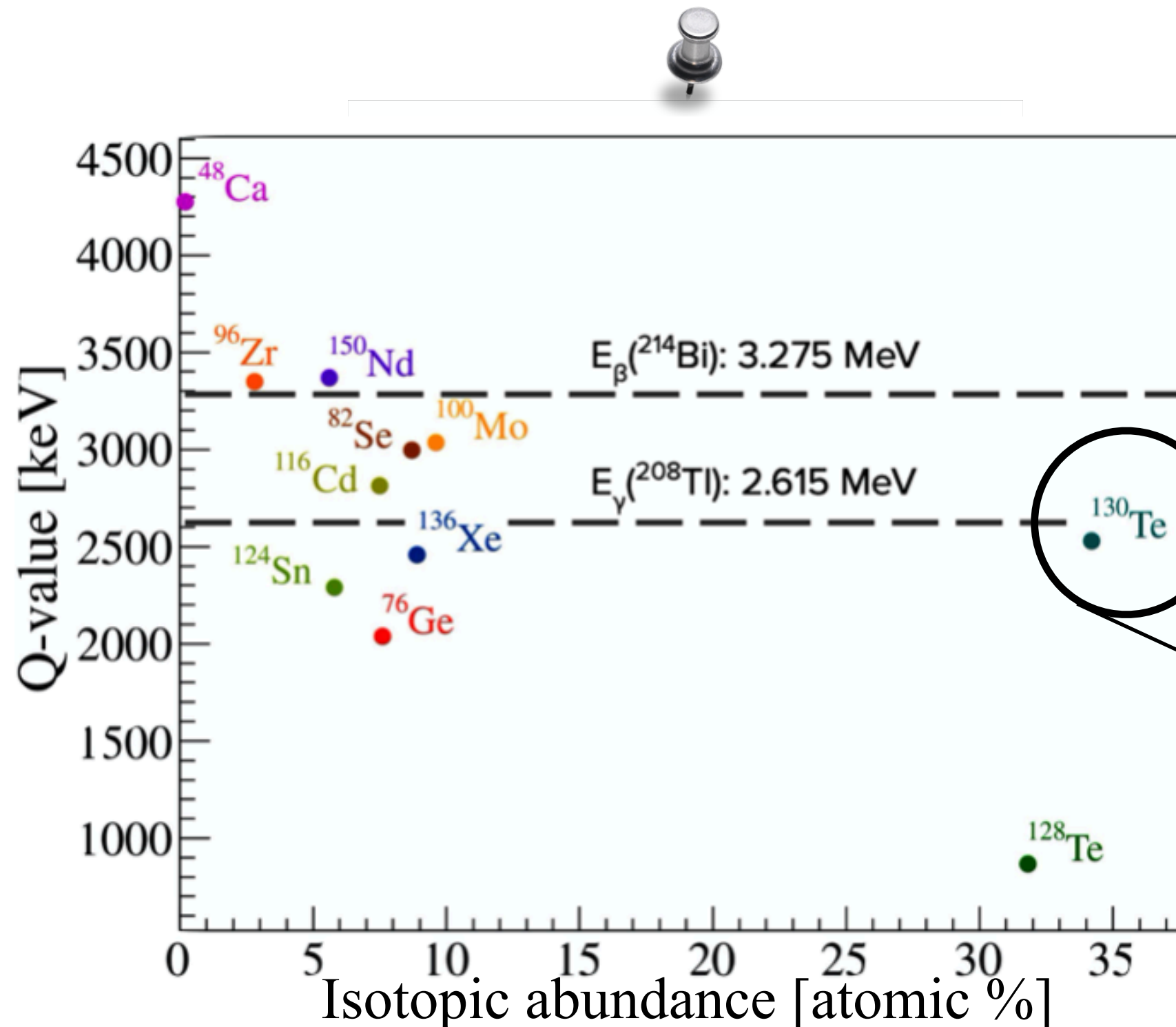
## background in the ROI

- $Q_{\beta\beta} \sim 2528$  keV only TI  $\gamma$  line above
- $(1.42^{+0.03}_{-0.02}) \cdot 10^{-2}$  counts/keV/kg/yr



## energy resolution @ $Q_{\beta\beta}$

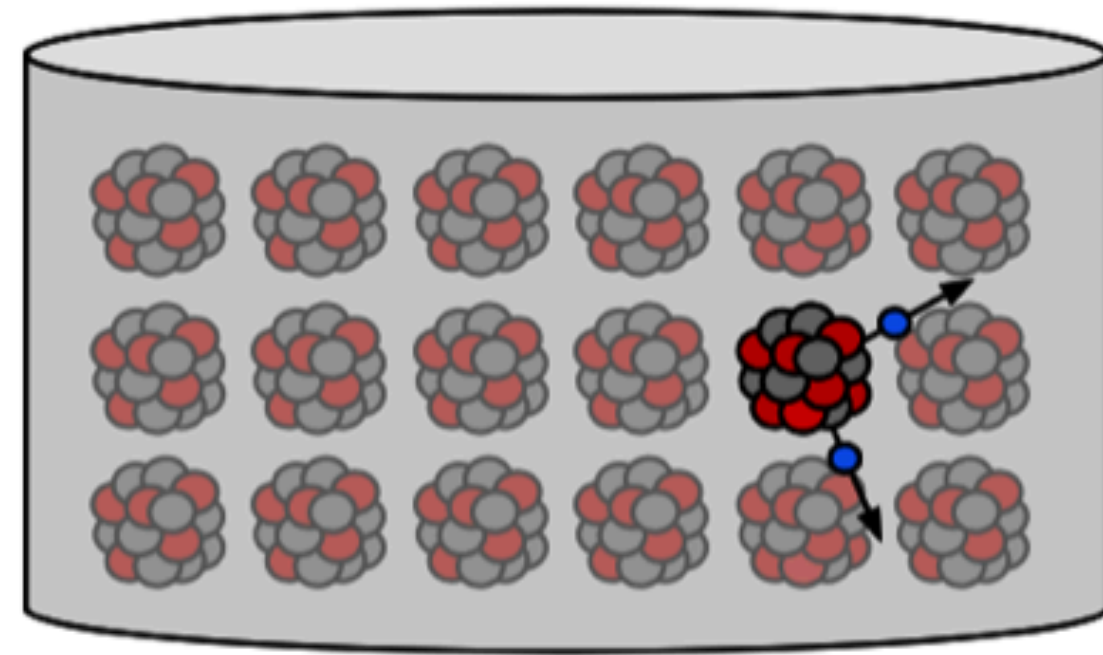
- $\Delta E$  (FWHM) =  $(7.310 \pm 0.024)$  keV
- $\Delta E/E \simeq 0.3\%$



Science 390, 1029-32 (2025)

# $0\nu\beta\beta$ : panorama of detector technologies and experiments

Source = detector concepts

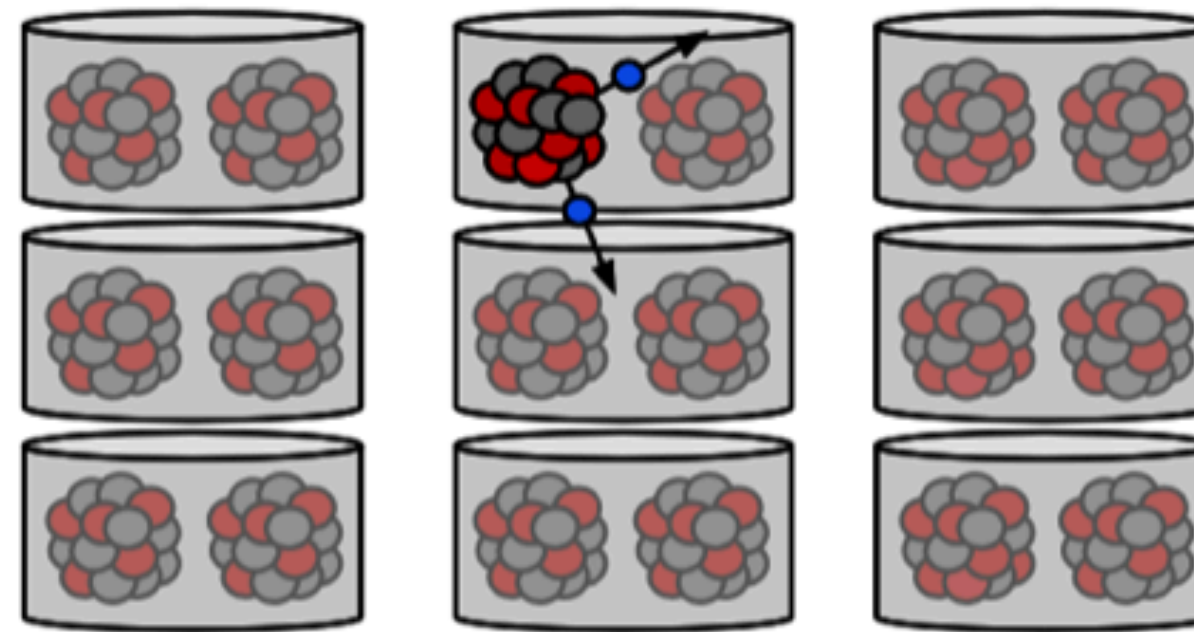


**Monolithic** scintillation /  
ionization detectors

AXEL, DARWIN, EXO, JUNO,  
**KamLAND-Zen**, LiquidO, LZ, **nEXO**,  
NEXT, NvDEX, R2D2, THEIA, Panda-X,  
**SNO+**, XENON, XLZD, ZICOS, ..

**Pros:** Self-shielding, scalability,  
Topology to lower bkg  
 $\epsilon \simeq 75 - 100 \% @ \text{MeV}$

**Cons:** Poor energy resolution



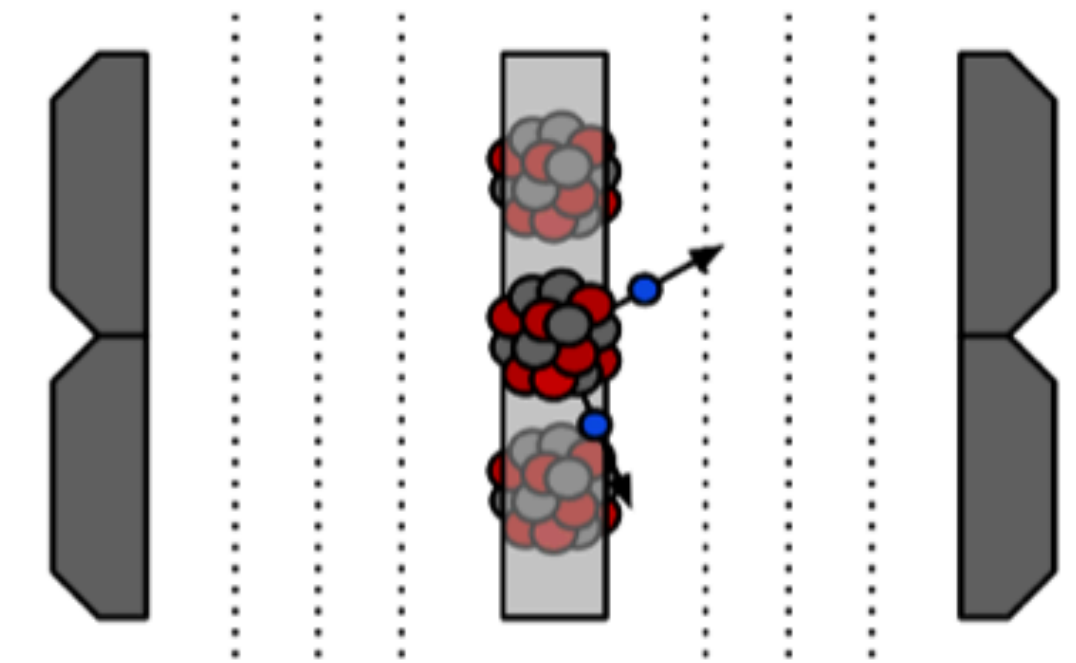
**Granular** semiconductor /  
cryogenic detectors

AMORE, BINGO, CANDLES, **CDEX**,  
COBRA, **CUORE**, **CUPID**, CROSS,  
GERDA, **LEGEND**, MAJORANA,  
SELENA, ..

**Pros:** Staging (semiconductors),  
Scalability (cryogenic d.),  
Energy resolution,  $\epsilon \simeq 70 - 95 \% @ \text{MeV}$

**Cons:** Scalability (semiconductors), Non-zero bkg (cryogenic d.)

TAUP XICHANG  
C. Weisinger talk @ TAUP 2025



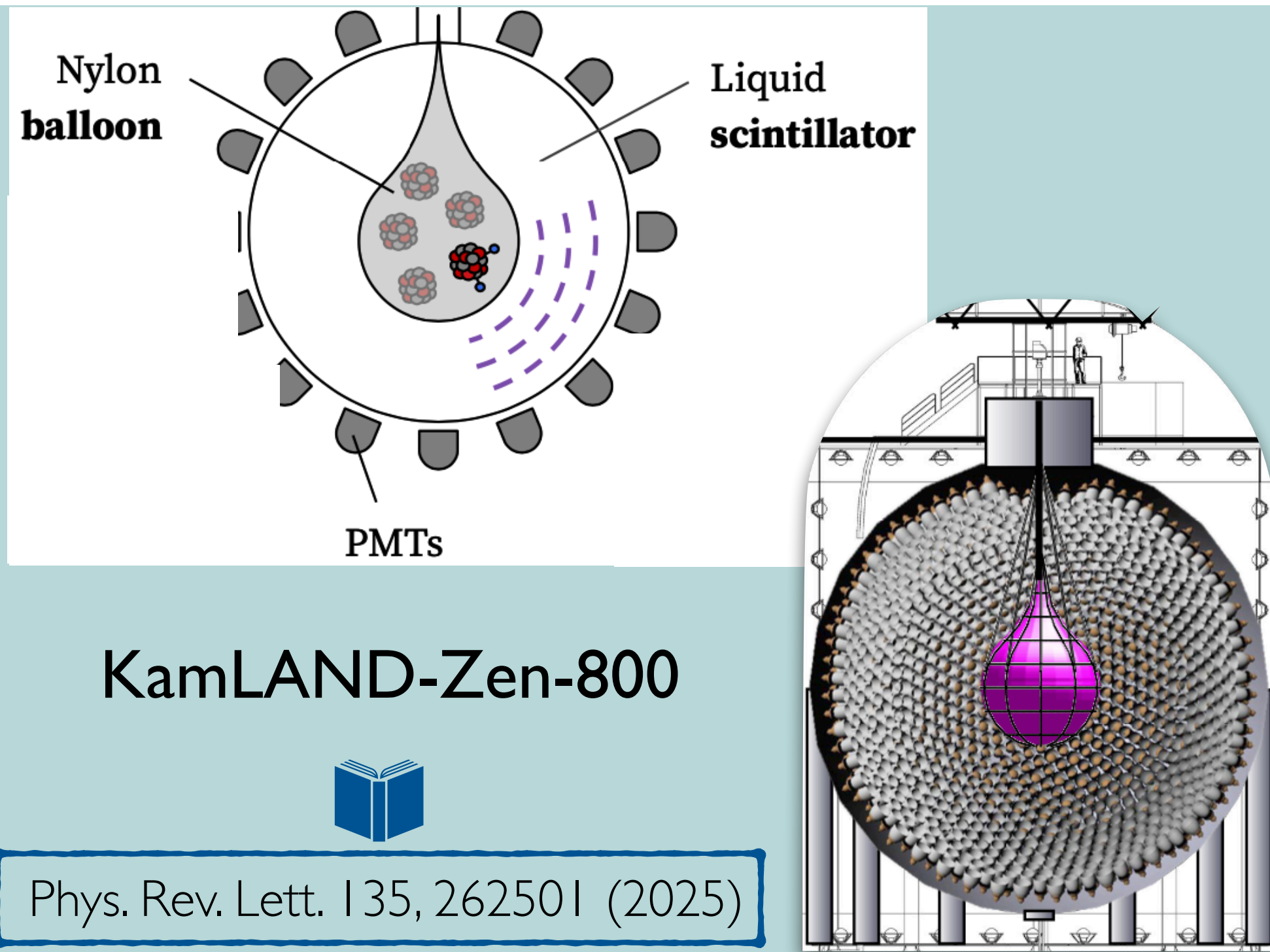
**Tracking**  
calorimeters

NEMO3, SuperNEMO, ..

**Pros:** Multiple isotopes at the same time  
Track reconstruction for single  $e^-$

**Cons:** Poor efficiency  $\epsilon \simeq 30 \%$   
Losses  $\downarrow$  Energy reconstruction

# $0\nu\beta\beta$ : searches with the highest sensitivity results



1000-t liquid scintillator, 750 kg of 91% enr.  $^{136}\text{Xe}$

$Q_{\beta\beta} \simeq 2458 \text{ keV}$ , resolution  $\sim 4\%$  @ 2.5 MeV

Final result & world-best constraint on  $0\nu\beta\beta$ :

$T_{0\nu\beta\beta}^{1/2} > 3.8 \cdot 10^{26} \text{ yr}$  (90 % C.L.)

$m_{\beta\beta} < 28 - 122 \text{ meV}$  (90 % C.L.)

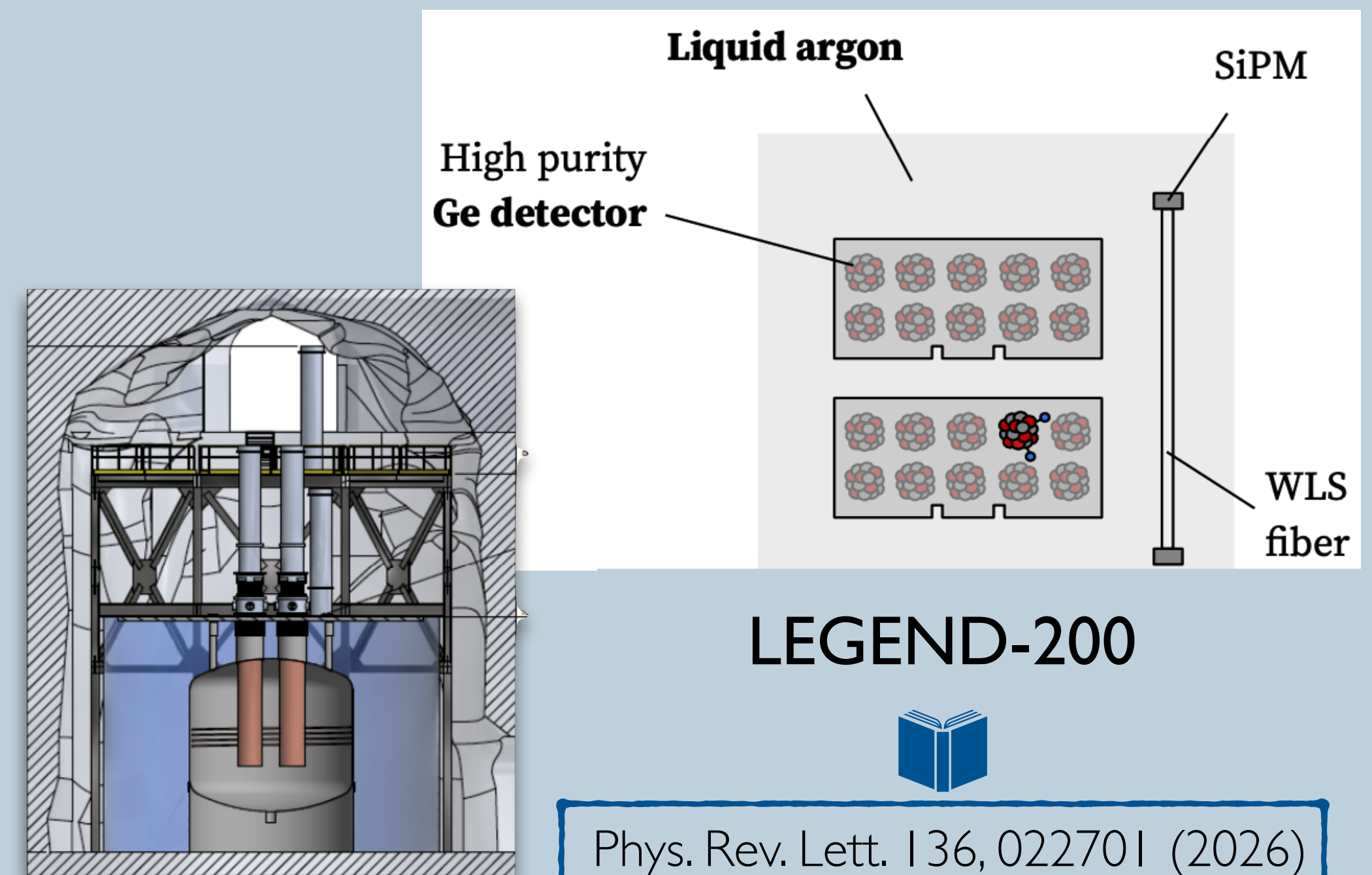
High purity enriched Ge detectors in an active liquid argon shield, 200 kg of 90% enr.  $^{76}\text{Ge}$

$Q_{\beta\beta} \simeq 2039 \text{ keV}$ , resolution  $\sim 0.12\%$  @ 2.0 MeV

First result (140 kg deployed):

$T_{0\nu\beta\beta}^{1/2} > 1.9 \cdot 10^{26} \text{ yr}$  (90 % C.L.)

$m_{\beta\beta} < 75 - 200 \text{ meV}$  (90 % C.L.)



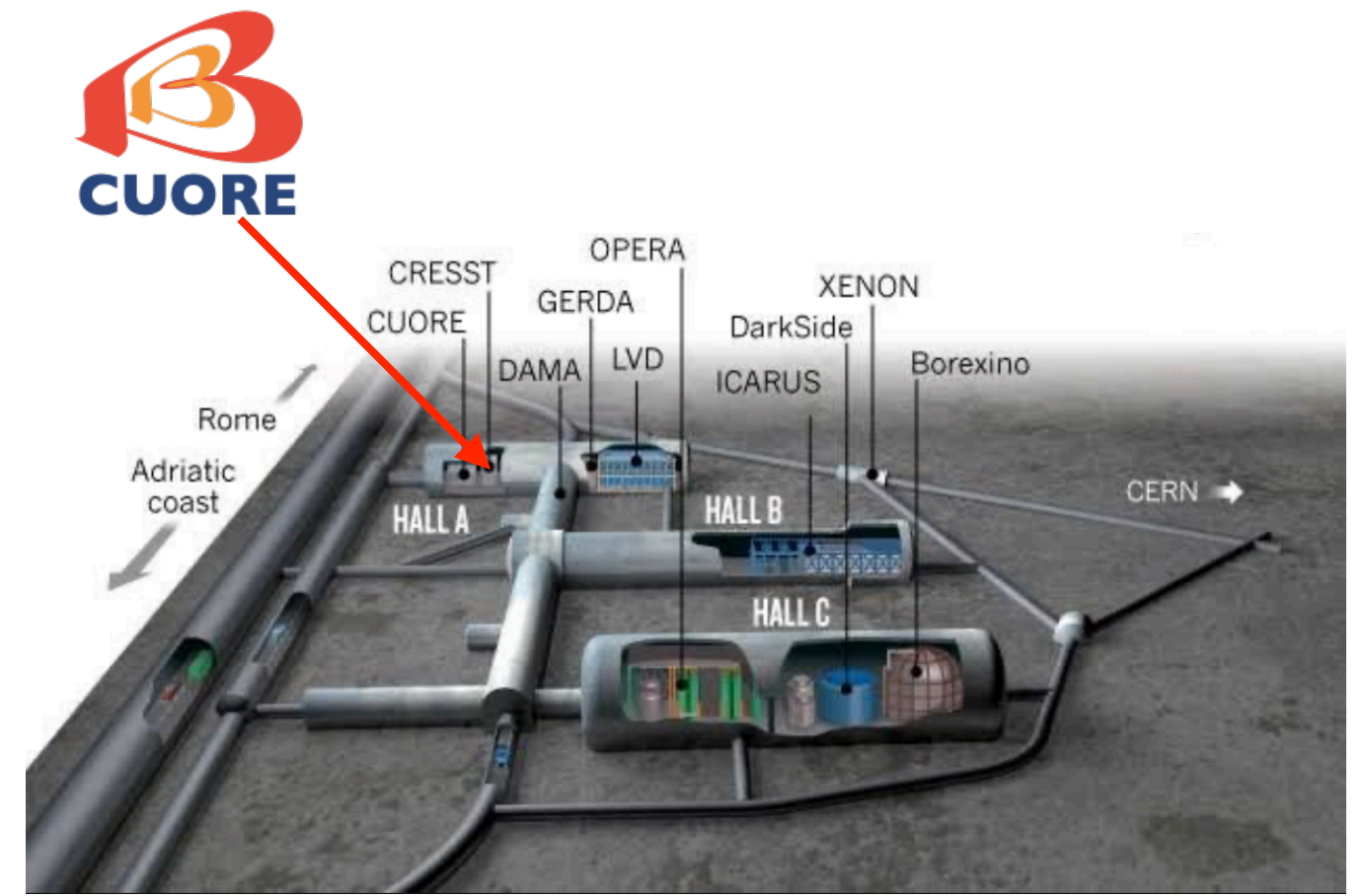
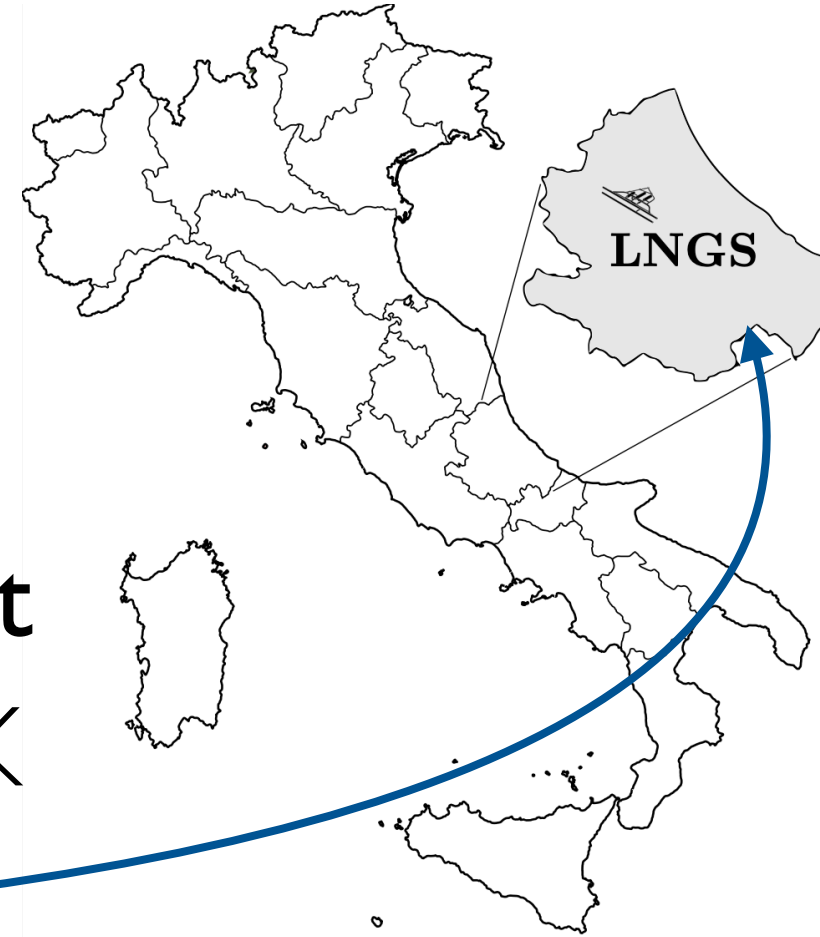
# The CUORE experiment in a nutshell

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

- Primary goal: search for  $0\nu\beta\beta$  decay of  $^{130}\text{Te}$

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

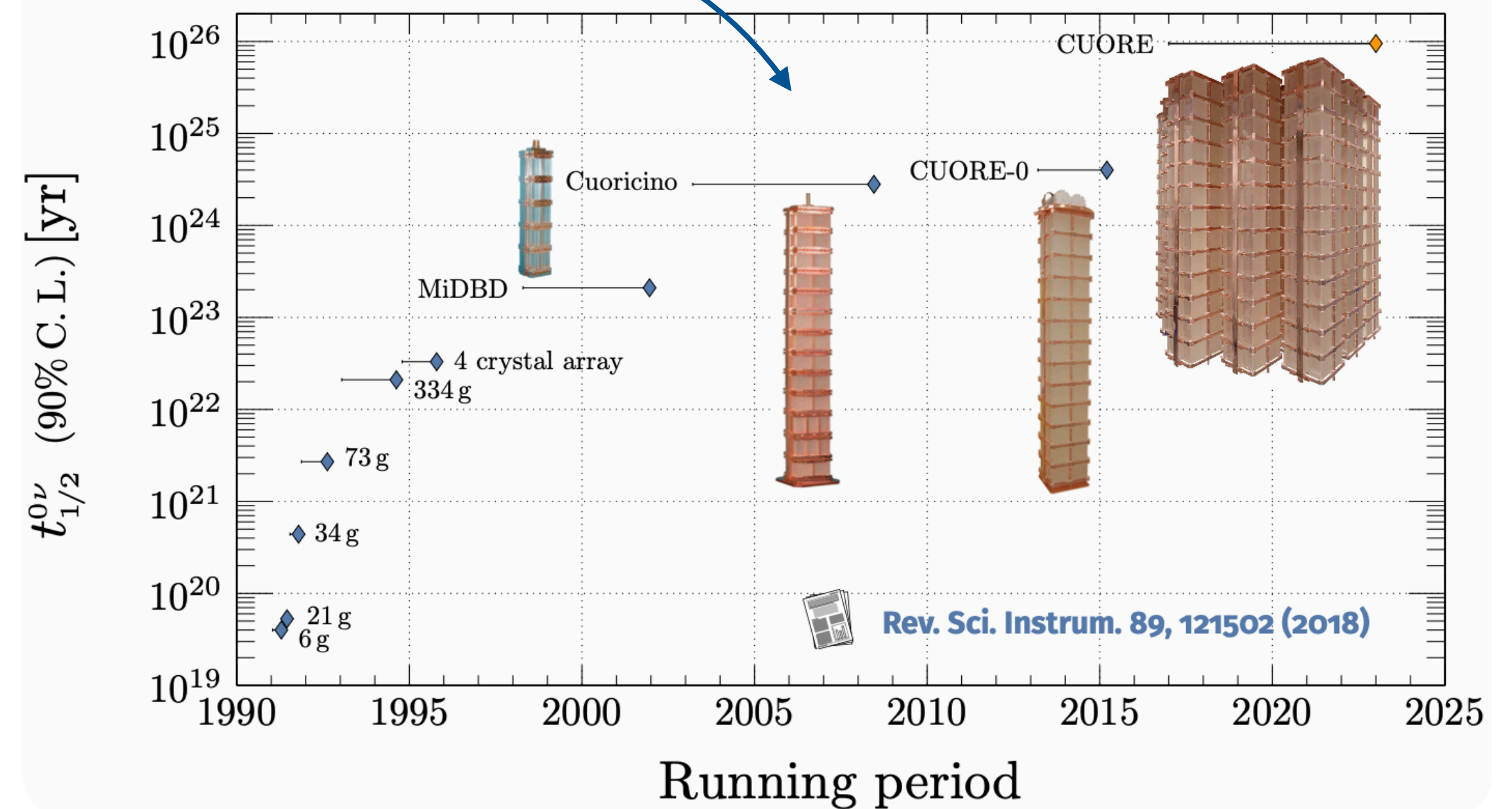
- Largest cryogenic-calorimeter detector ever built**  
19 towers of 13 floors of 4 crystals stably  $\lesssim 20$  mK
- Underground** at the **LNGS** (Abruzzo, Italy)



- Building on a 30-yr-long history of measurements



 Adv. in High En. Phys. 2015, 879871



# The CUORE collaboration

You can find all the relevant information on our new website <https://cuore.lngs.infn.it>

~150 scientists  
from 27 institutions  
of different countries

China, France,  
Italy, Ukraine,  
Russia, Spain  
United States

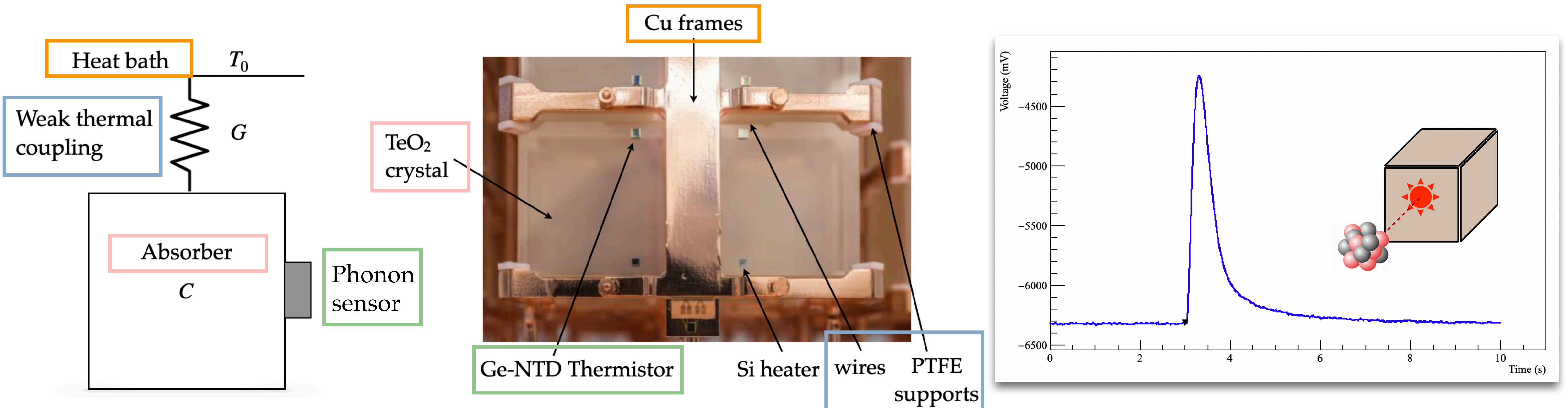
The image features a world map with countries colored in orange, red, and blue to represent the CUORE collaboration. The map is surrounded by logos of the 27 participating institutions. The logos are arranged as follows:

- North America:** Yale, Massachusetts Institute of Technology, Berkeley (University of California), Berkeley Lab, Cal Poly (San Luis Obispo), UCLA.
- South America:** Johns Hopkins University, University of Pittsburgh, University of South Carolina, Virginia Tech, University of South Carolina.
- Europe:** CSNSM, Università degli Studi di Genova, Sapienza Università di Roma, INFN (Istituto Nazionale di Fisica Nucleare), Università degli Studi di Padova, Università degli Studi di Milano Bicocca.
- Asia:** Fudan University, Tsinghua University, Jiao Tong University.
- Australia:** SINAP, GSI.
- Other:** Università Mater Studiorum, New Zealand.

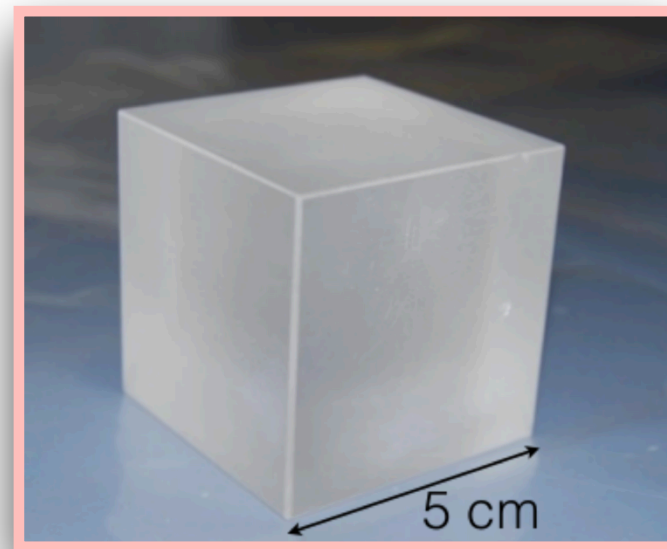
# Neutrinoless double beta decay with cryogenic calorimeters

The **energy** released in a particle interaction is measured via **thermal excitations** (*phonons*)

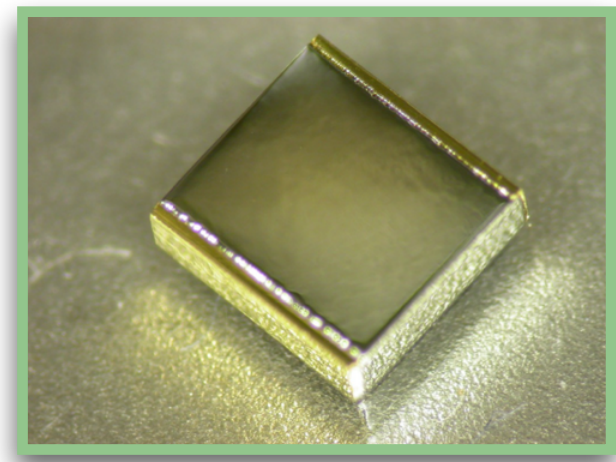
The **temperature increase** is converted into an **electrical signal** by a cryogenic sensor (e.g. a thermistor)



TeO<sub>2</sub> crystal  
 $C \propto T^3$  (Debye law)  
 $C \approx nJ/K$

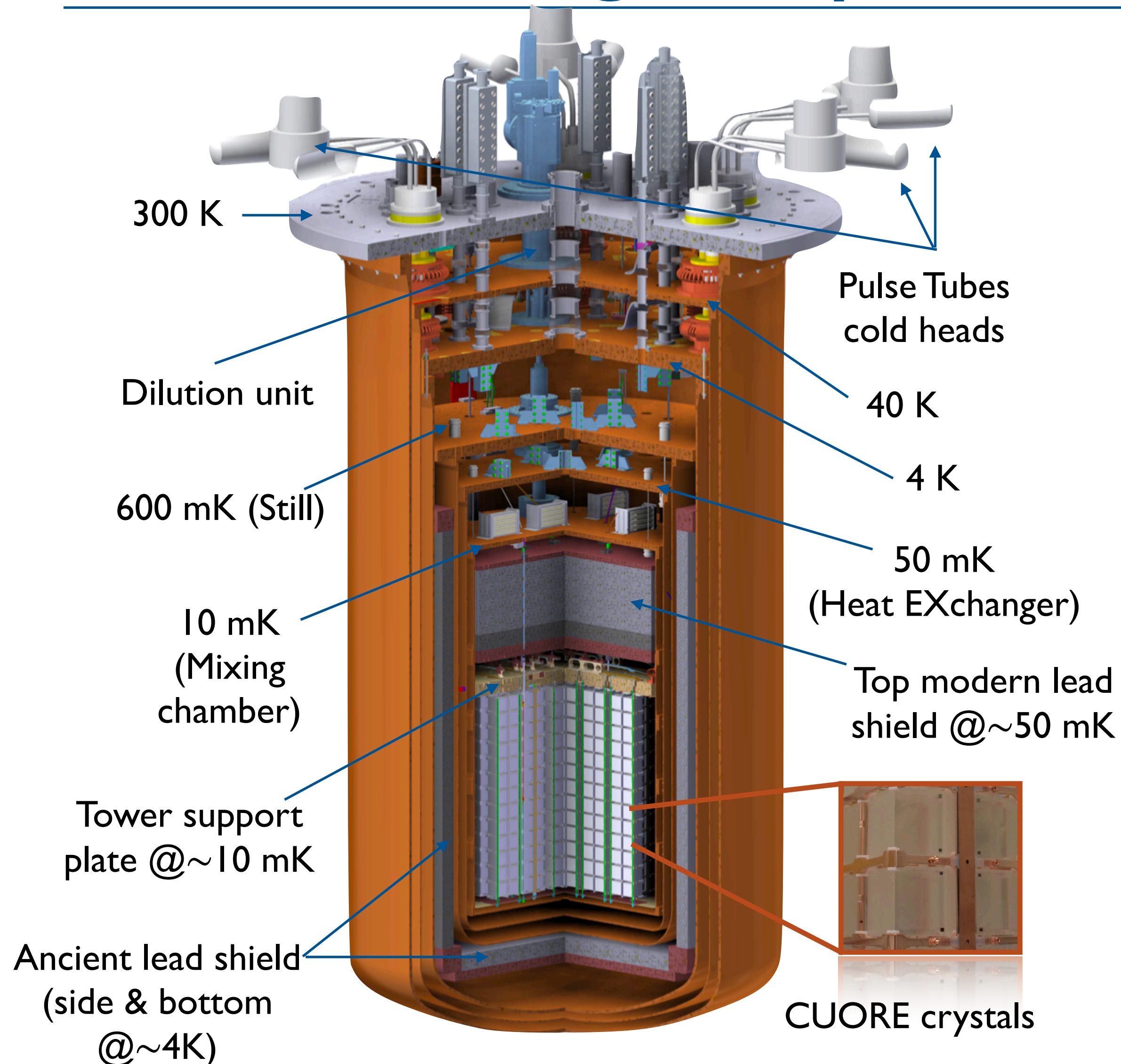


Ge-NTD thermistor  
 $R \propto e^{\sqrt{T_0/T}}$   
 $\Delta R \sim 3M\Omega/MeV$

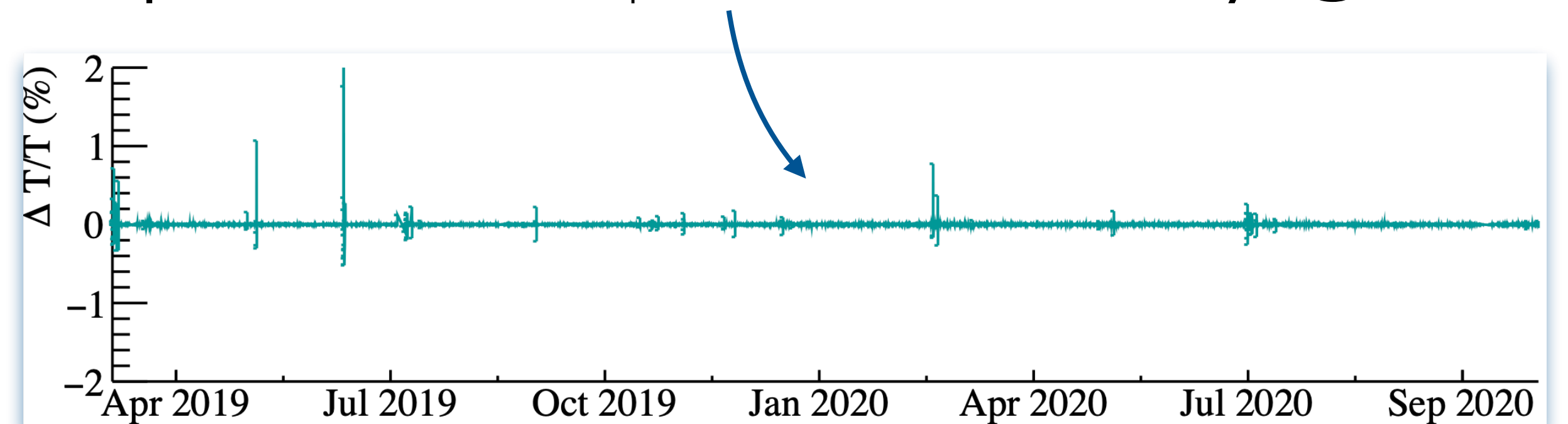


Operating at a temperature of  $\sim 10$  mK:  
**1 MeV** energy release causes  $\Delta T \sim 100$   $\mu K$   
 We use a **Si heater** to inject stable voltage pulses and do **thermal gain stabilization**

# The challenges - part I: cryogenic infrastructure



- Custom-made dry (cryogen-free) dilution cryostat
- Stringent constraints on **radiopurity** - only few materials acceptable (Cu OFE/NOSV for plates and vessels) - **mechanical reliability** and **response to seismic events**
- 5 **pulse-tube** cryocoolers (one spare)
- 6 **nested vessels** at decreasing temperature to reach base temperature ( $T_{\min} \simeq 7$  mK)
- Mass <4 K: 15 tons - mass @ ~50 mK: 3 tons
- Since 2019 the system has been operating with **>90% uptime** in stable temperature conditions: **>5 yr @ <20 mK**



# The challenges - part II: minimizing background

## LNGS *natural* shielding



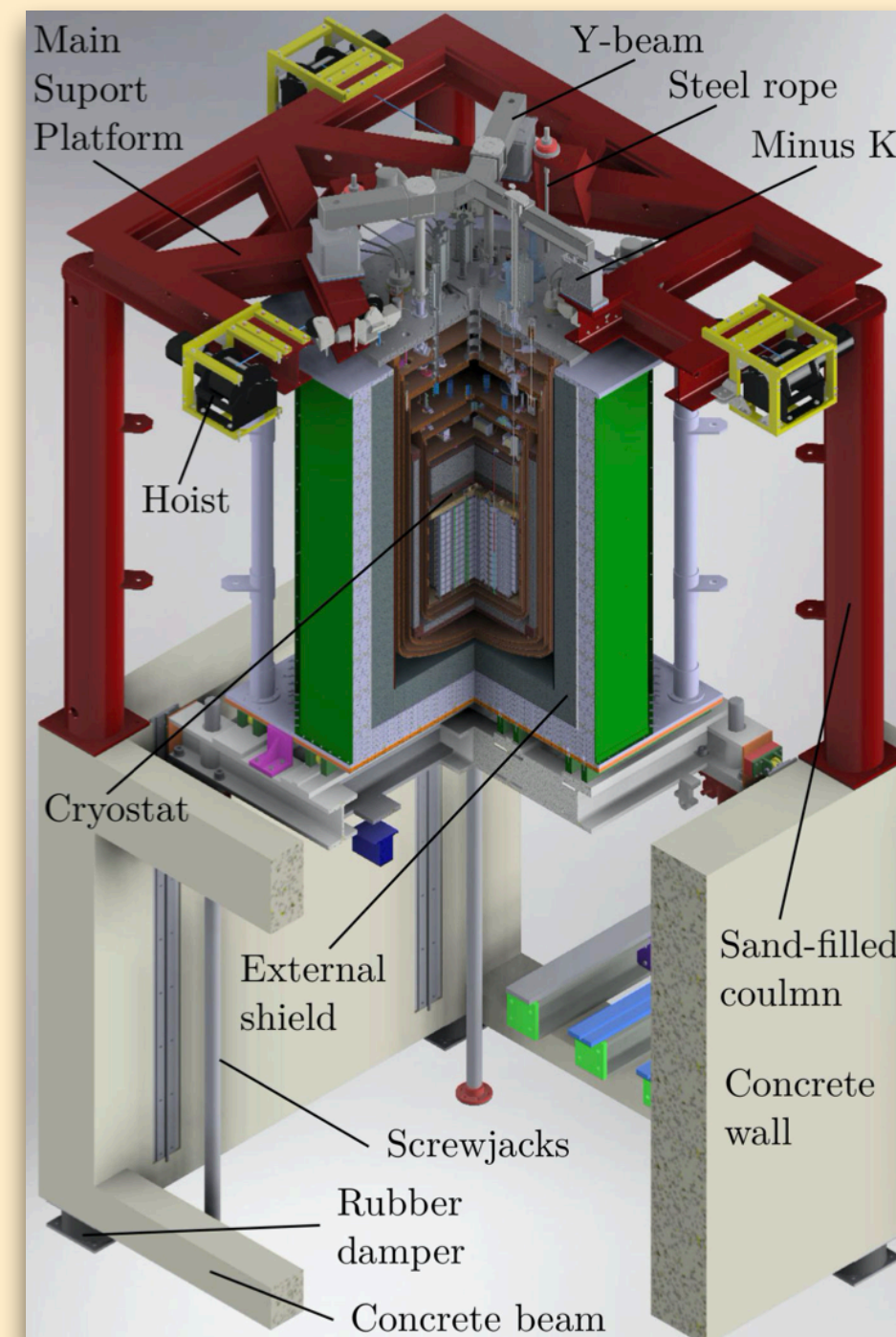
~3600 m water-equivalent rock overburden:  
cosmic rays flux reduced of six orders of magnitude compared to the surface


$$\Phi_{\mu} = 3 \cdot 10^{-8} \text{cm}^{-2} \text{s}^{-1}$$

 Astropart Phys. 34 (2010) 18-24

$$\Phi_n = 4 \cdot 10^{-6} \text{cm}^{-2} \text{s}^{-1}$$

## External shields



 Cryogenics 102 (2019) 9-21

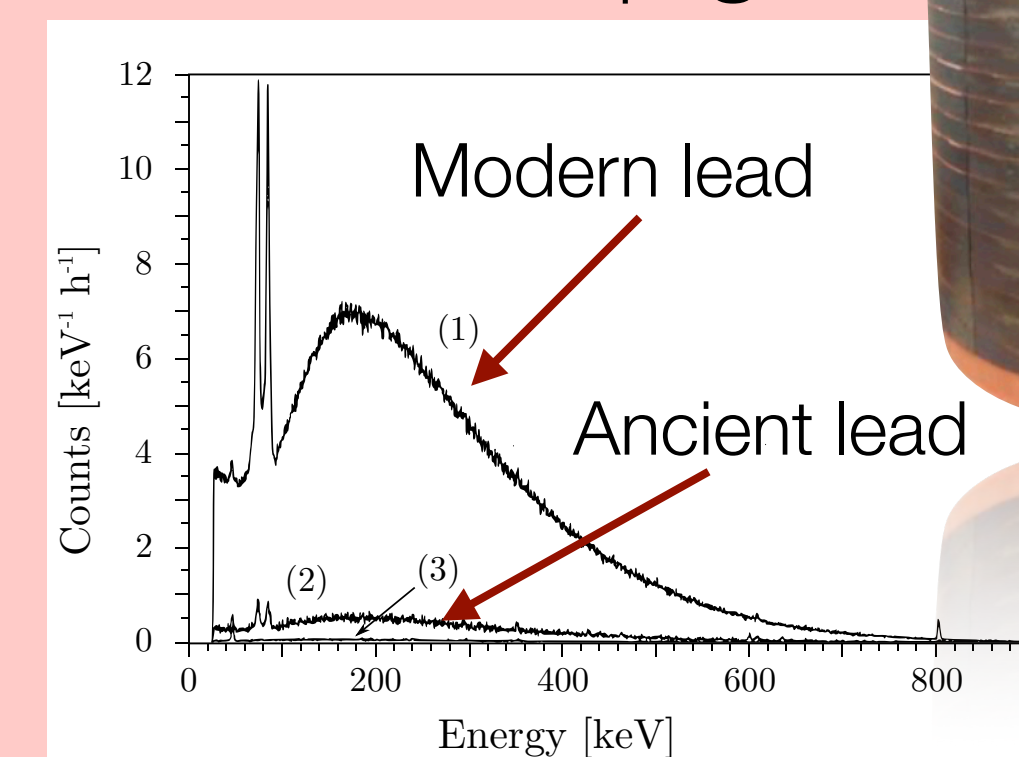
- ▶ From  $\gamma$ s: 25-cm thick Pb layer
- ▶ From neutrons: 20-cm layer in polyethylene +  $\text{H}_3\text{BO}_3$  panels

## Internal lead shields

**Top:** 30-cm modern lead



**Side & bottom:** 6-cm ancient roman lead from a shipwreck  
 $^{210}\text{Po} < 4 \text{ mBq/kg}$



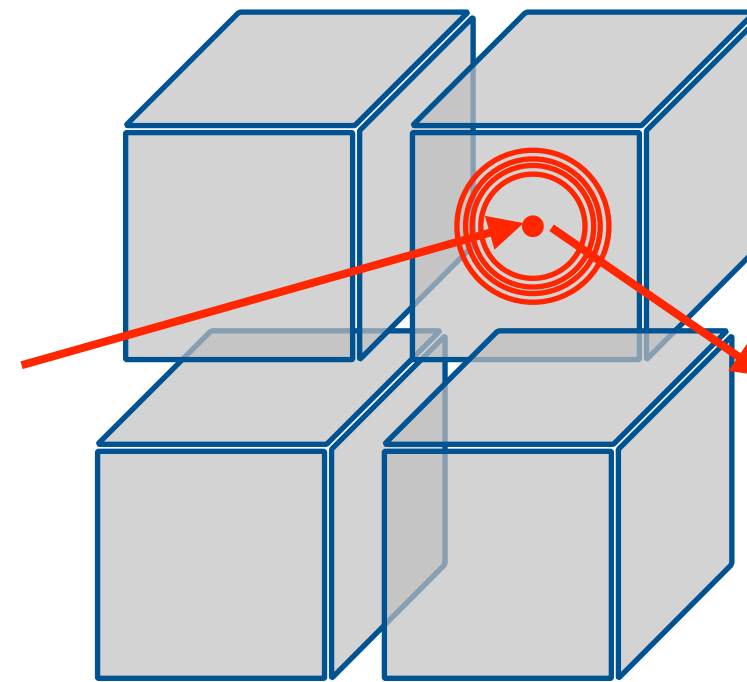
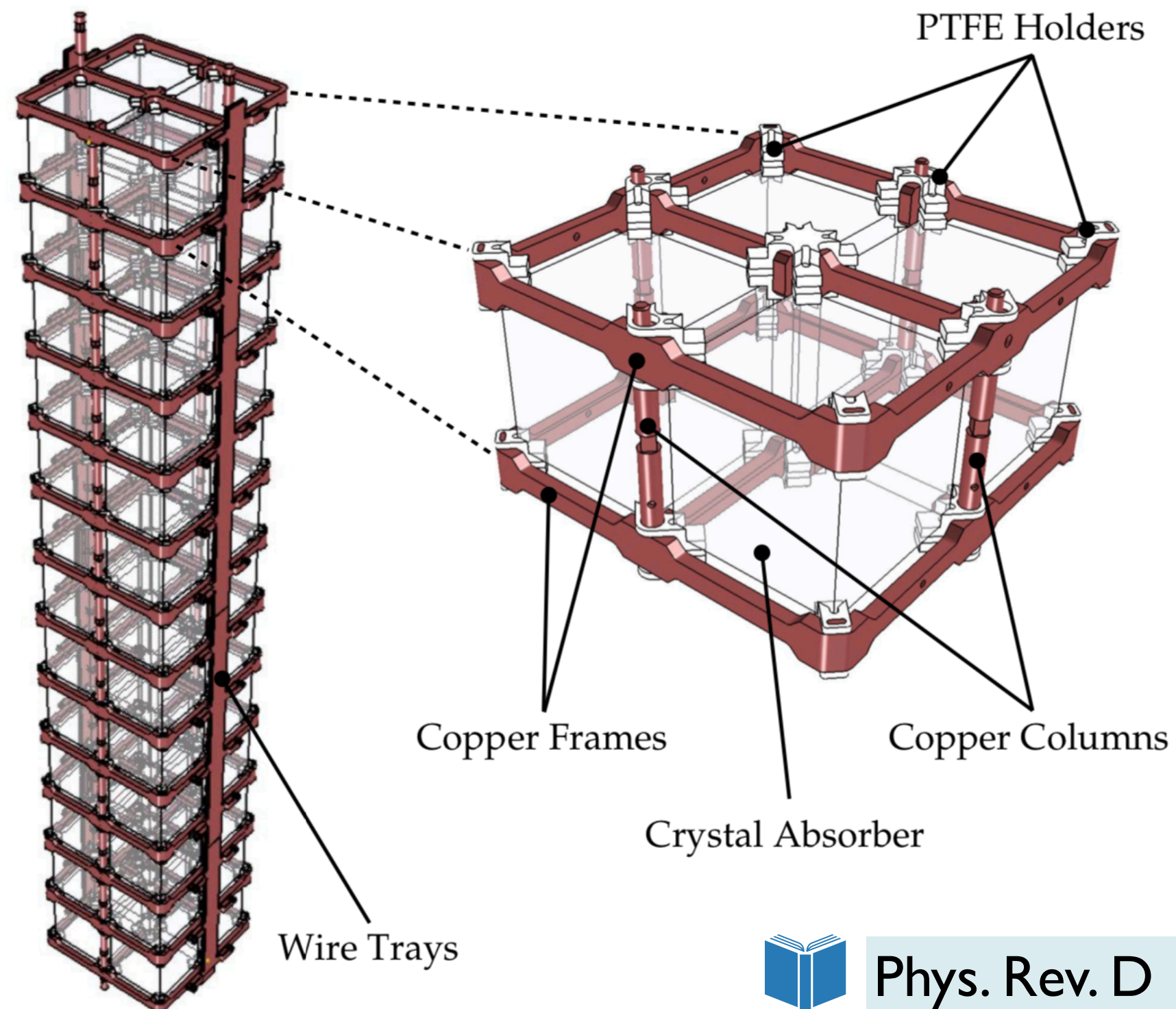
 Nucl. Instrum. Meth. B 142, 163 (1998)

# The challenges - part II: modeling (leftover) background

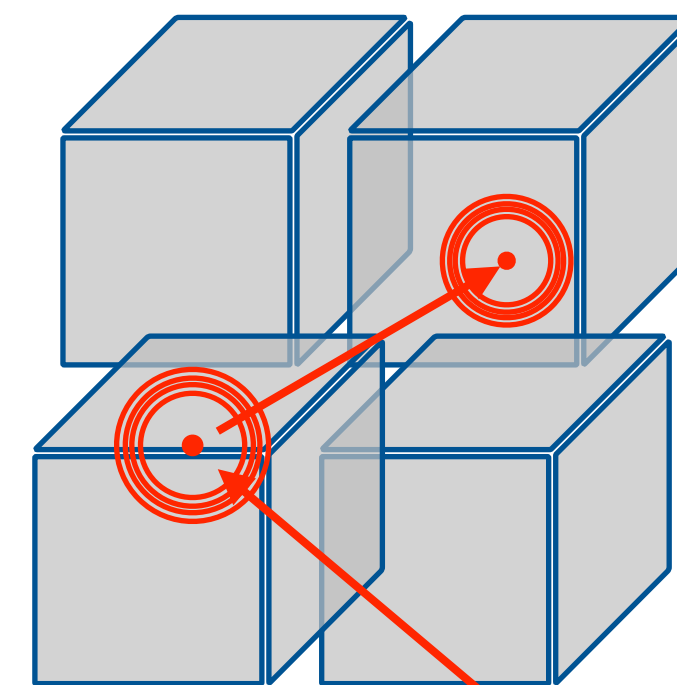
- Accurate **Geant-4** based background model with **80 background sources** simulated + measured detector response to generate the expected spectra, **Bayesian MCMC fit** to constrain source locations



Priors extracted from radioassays and past experiments

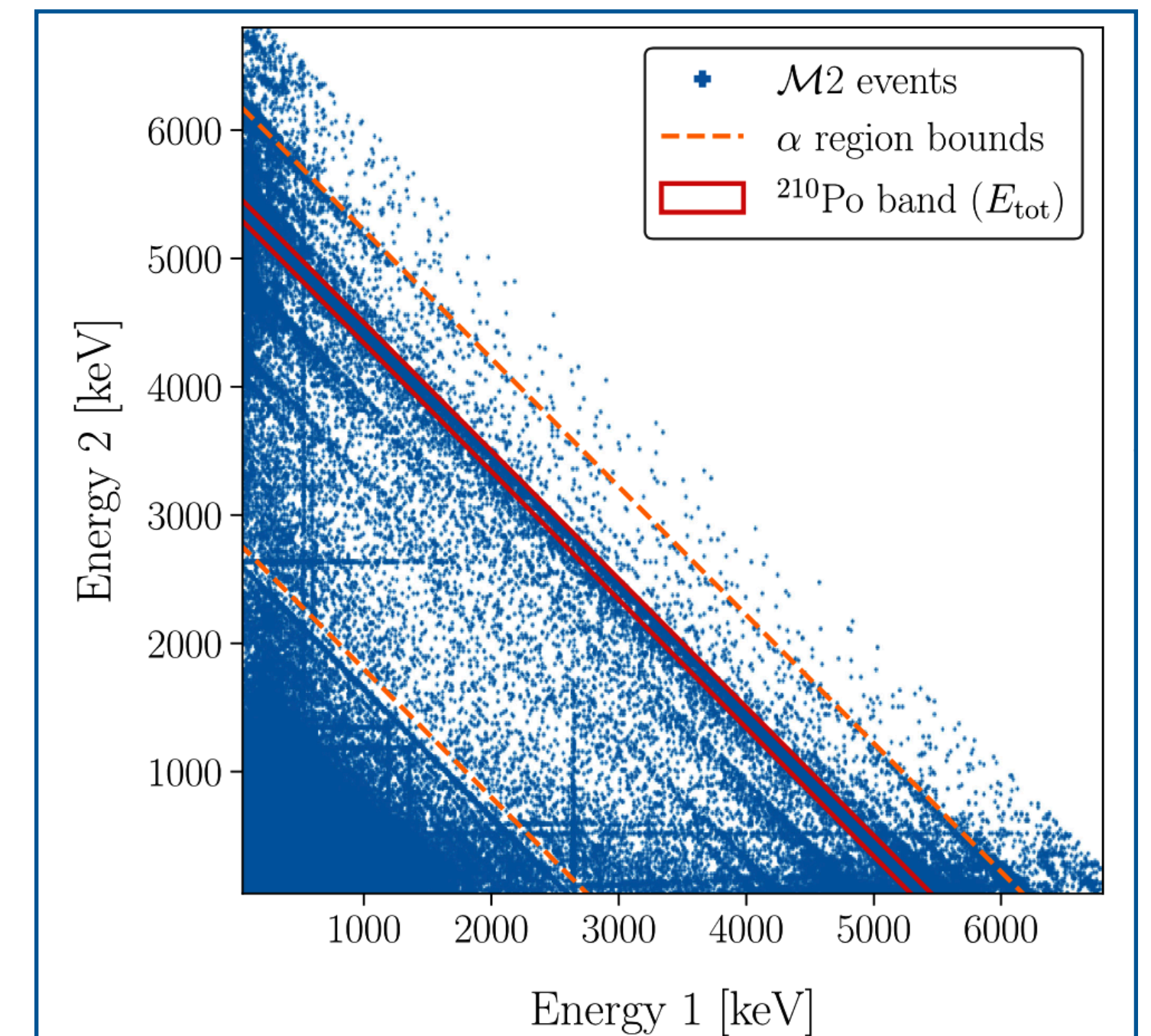


single-crystal

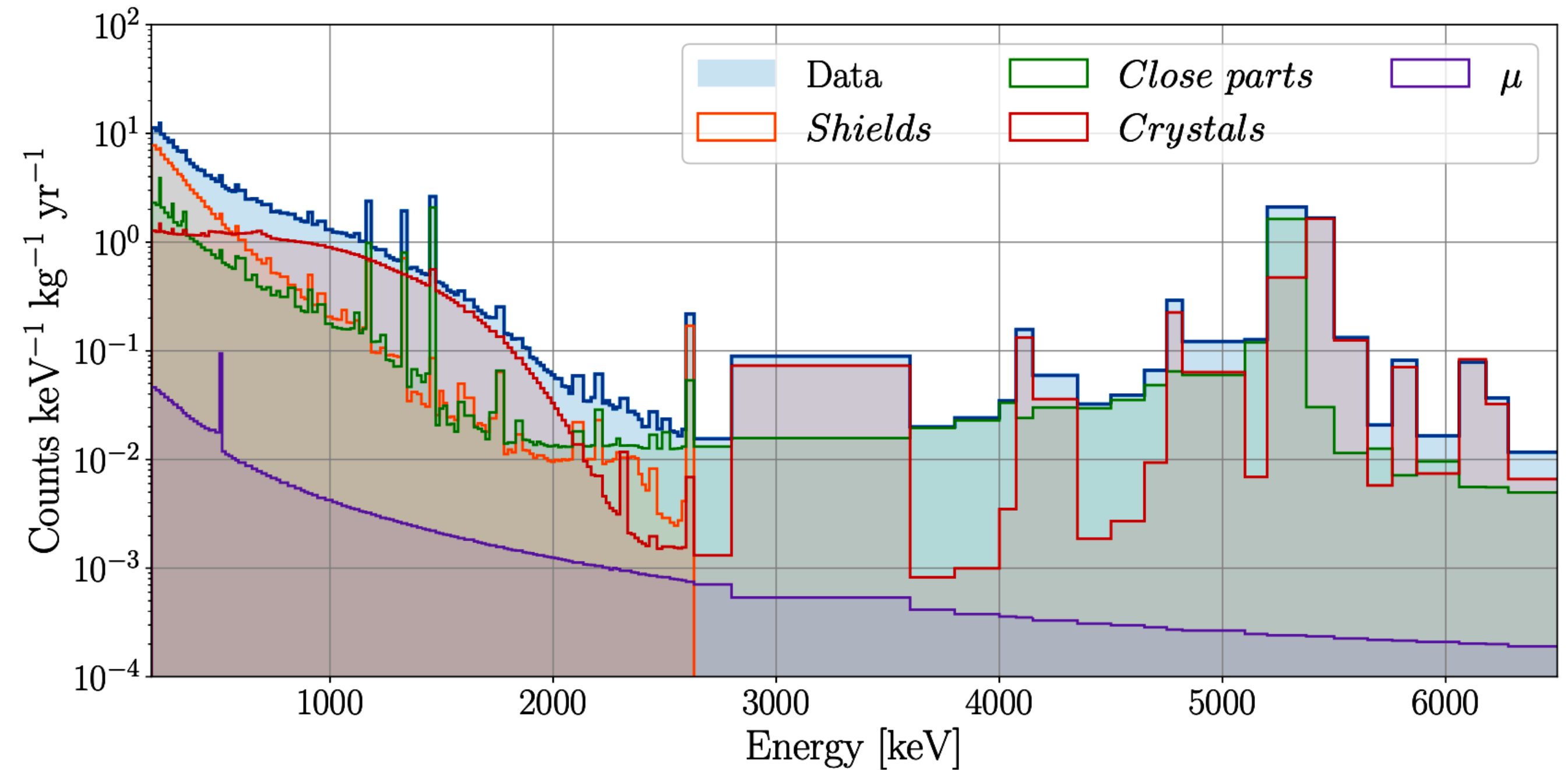
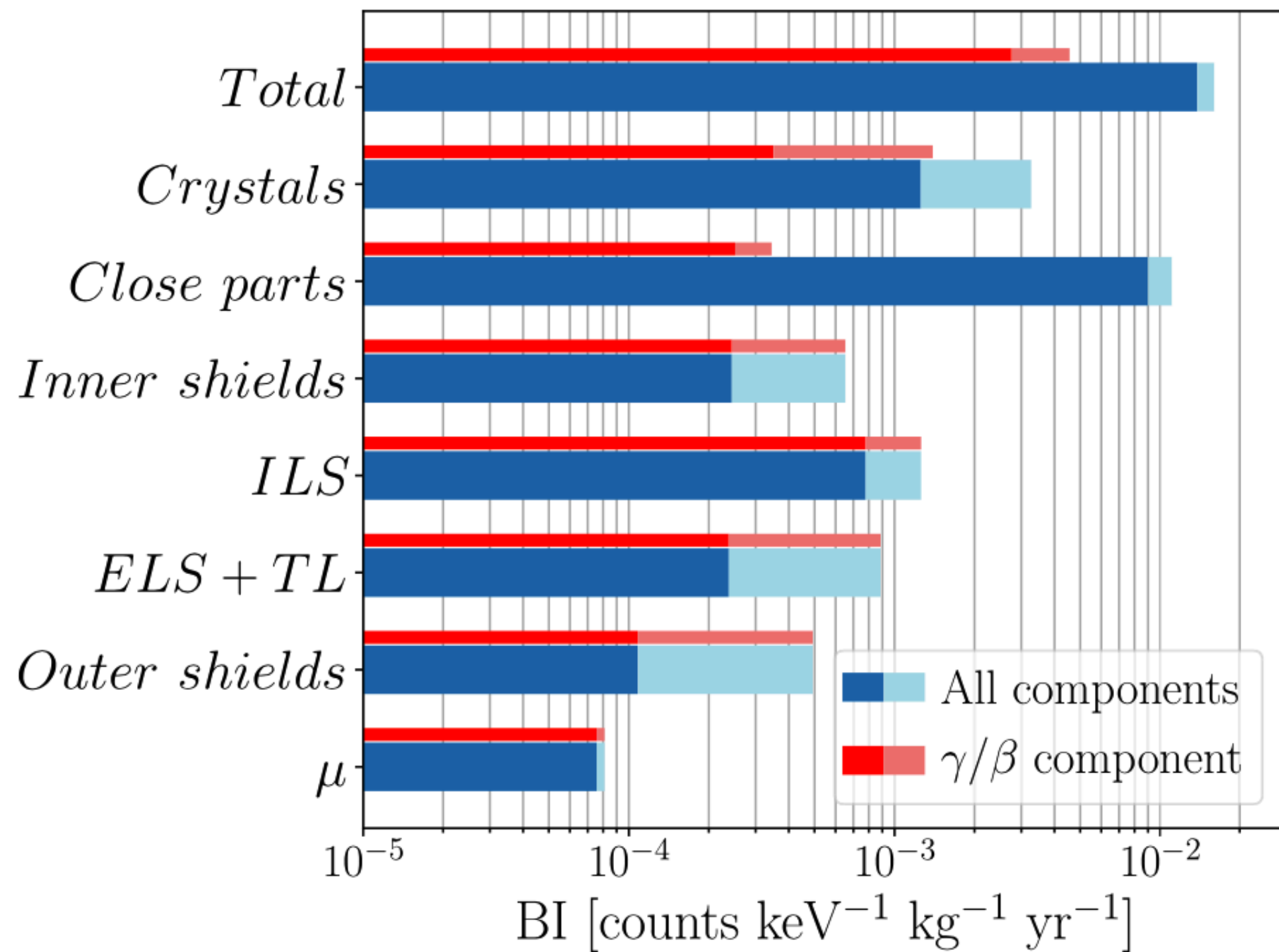


double-crystal

Bayesian fit of *single-crystal* & *double-crystal* events exploiting high detector granularity



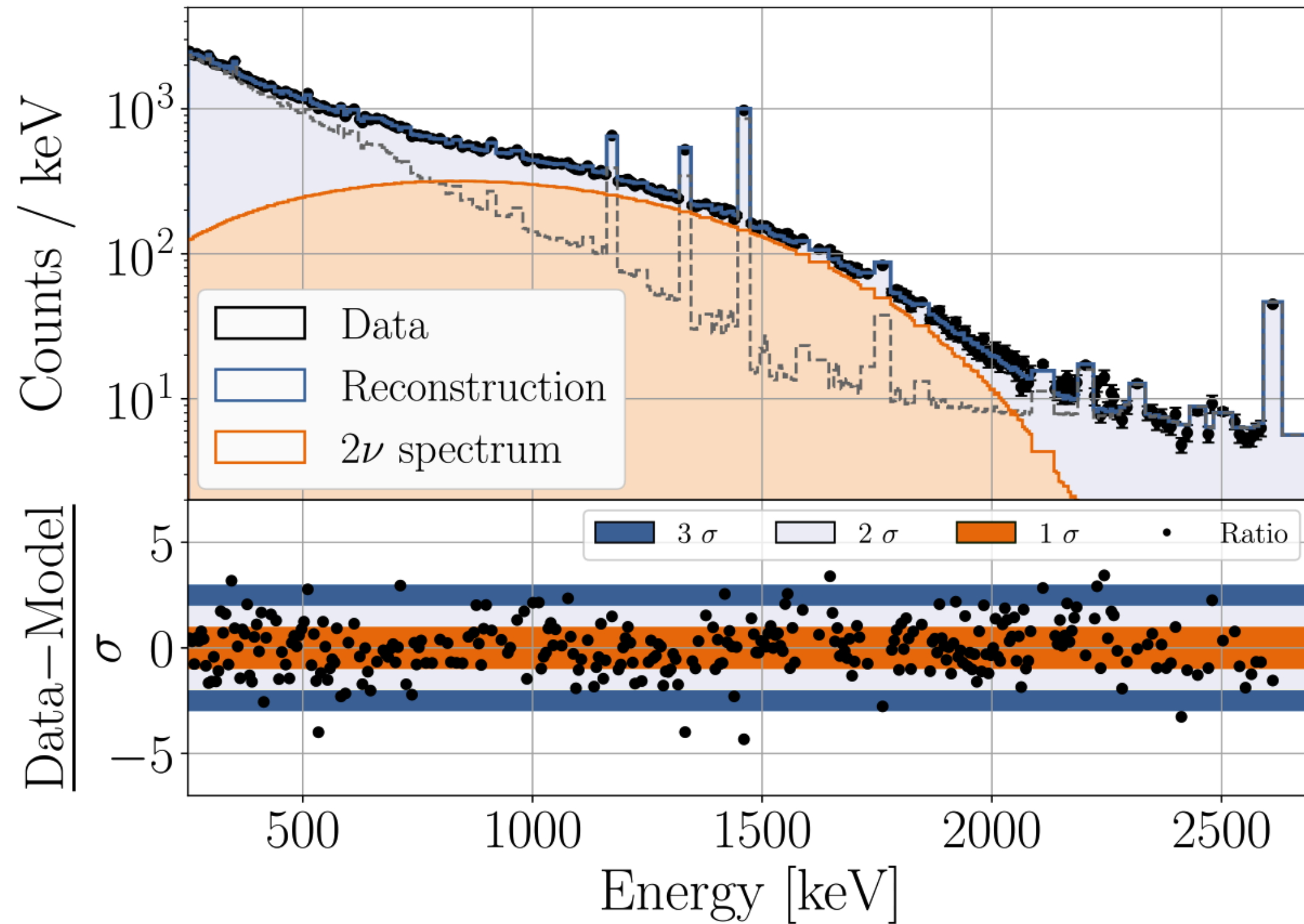
# The challenges - part II: modeling (leftover) background



Accurate background model relating **sources** and specific **spectral contributions**: important benchmark for **CUORE** physics analyses and in view of **CUPID**

Total  $\text{TeO}_2$  exposure for BM analysis: 1038.4 kg yr  
 Sensitivity levels down to **10 nBq kg<sup>-1</sup>** for **bulk** and **0.1 nBq cm<sup>-1</sup>** for **surface** contaminations  
 Main contributions to the  $0\nu\beta\beta$  ROI: degraded  $\alpha$  particles ( $\simeq 90\%$ ), multi-Compton of  $\gamma$ s and cosmic  $\mu$ s

# The outcome: most precise measurement of $^{130}\text{Te}$ $2\nu\beta\beta$ to date



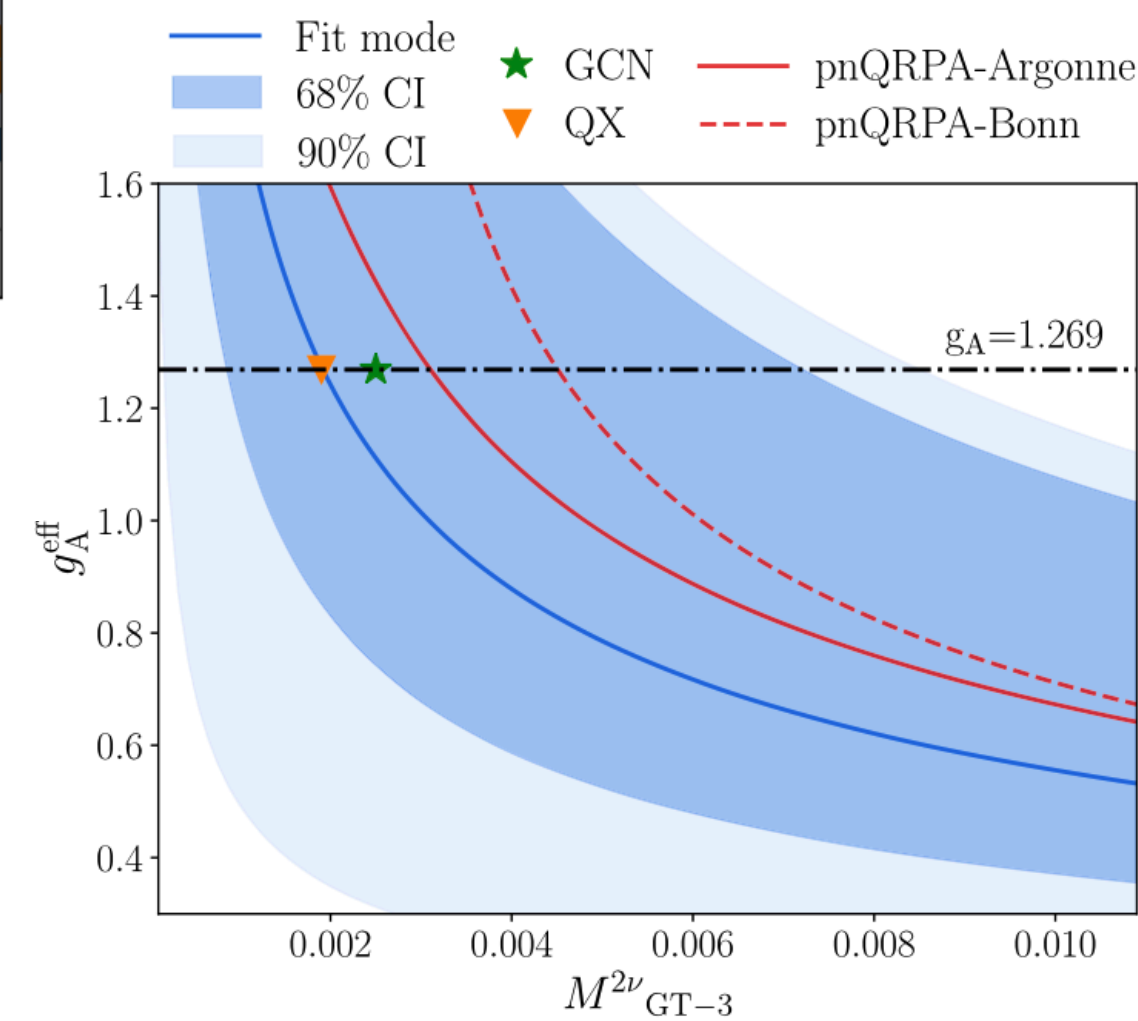
Twofold improvement on  $^{130}\text{Te}$   $2\nu\beta\beta$  half-life precision:

$$T_{1/2}^{2\nu} = \left[ 9.32^{+0.05}_{-0.04} \text{ (stat.) }^{+0.07}_{-0.07} \text{ (syst.)} \right] \cdot 10^{20} \text{ yr}$$

Stat. (Syst.) uncertainty  $\sim 0.5\%$  ( $< 1\%$ )

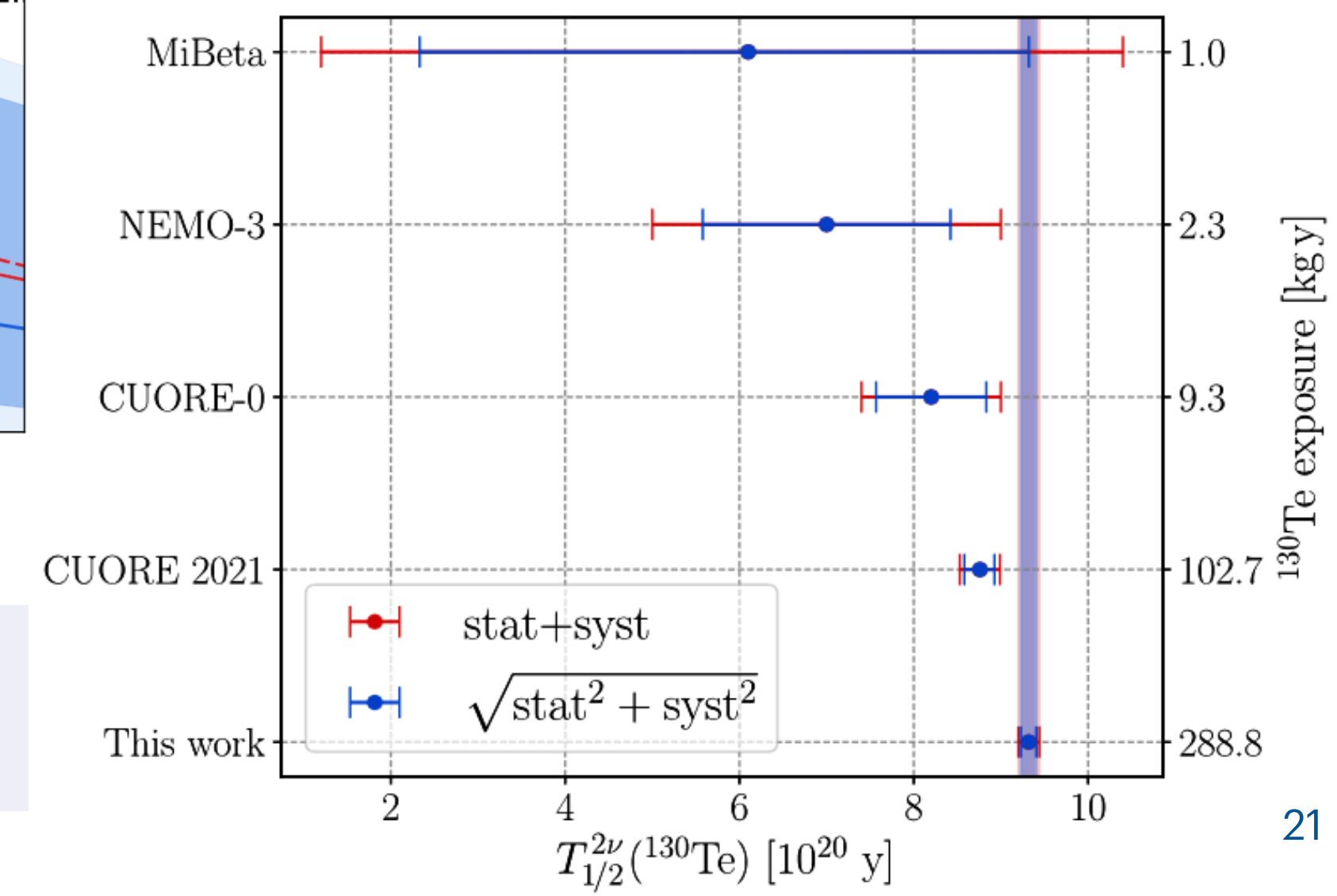
**Nuclear state model: *Single State Dominance (SSD)***

Phys. Rev. Lett. 135, 082501 (2025)



Quenching of  $g_A$  confirmed

Comparison with nuclear models shows results far from expectations  
Hp: incomplete description or BSM

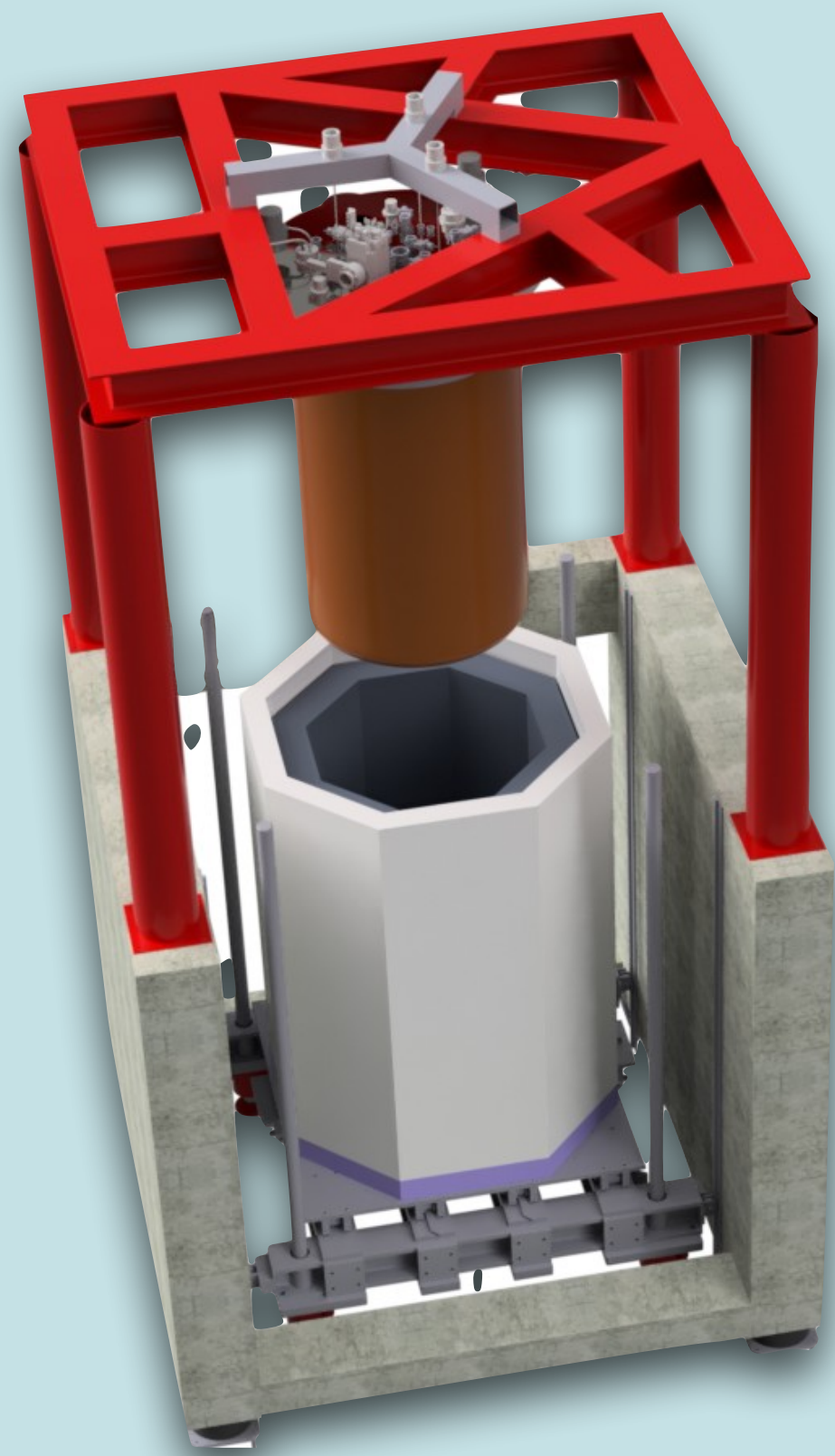


$^{130}\text{Te}$   $2\nu\beta\beta$  decay: dominant component of the single-site spectrum from  $\sim 1$  to 2 MeV  
 $\rightarrow$  Precise study of  $2\nu\beta\beta$  spectral shape with **improved formalism** to Taylor expand over lepton energies and **constraint  $g_A^{\text{eff}}$**  (1<sup>st</sup> time)

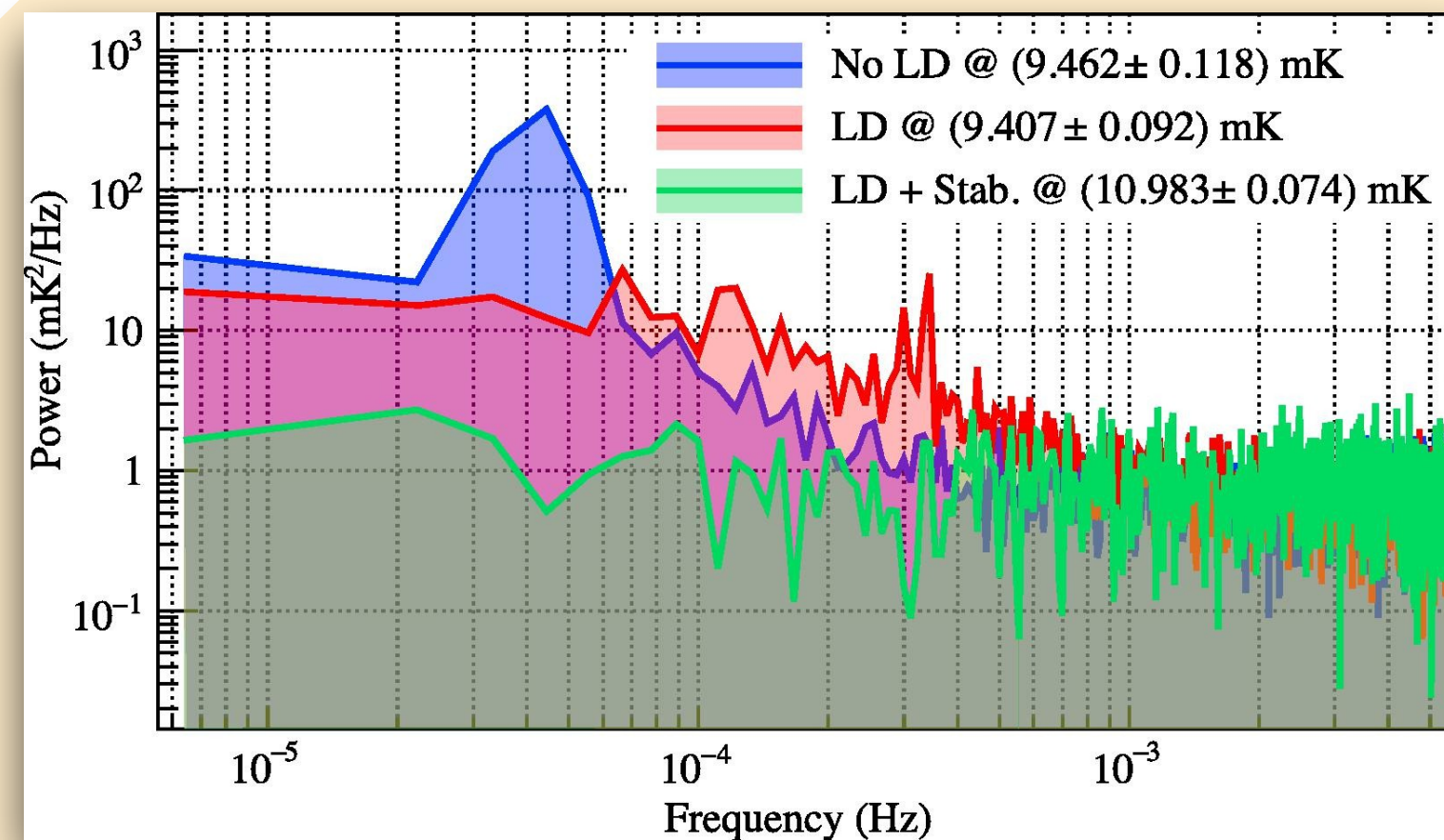
Phys. Rev. Lett. 135, 082501 (2025)

# The challenges - part III: suppressing noise sources

**External structure** to decouple the detector from the cryostat



Linear drives



Active noise cancellation to minimize vibrations induced by the **pulse tubes**

Cryogenics 93, 56-65 (2018)



Several **ancillary devices** installed in the CUORE hut to do data denoising and enhance the quality of our data



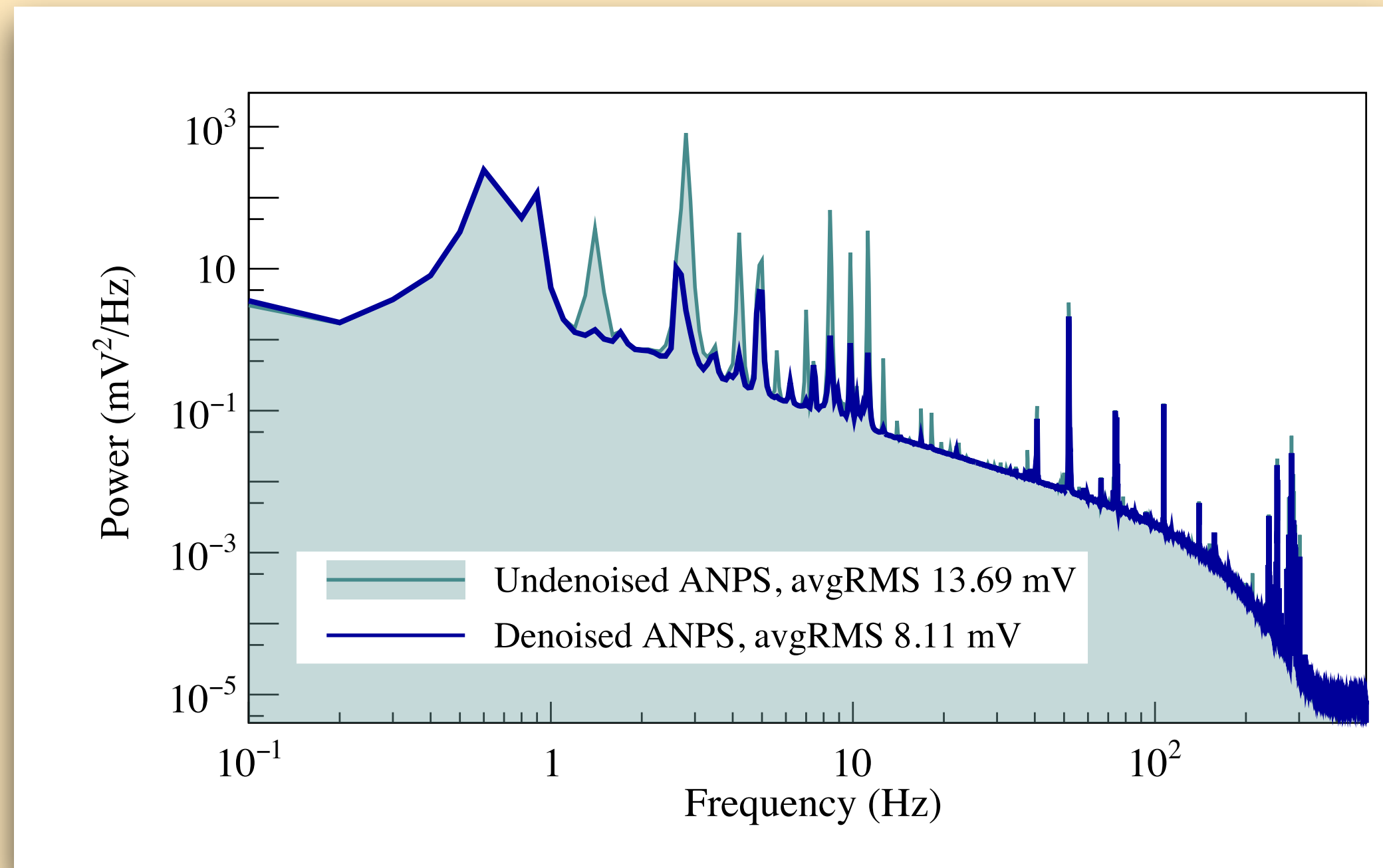
- seismometers, antennae, microphones and accelerometers



Eur. Phys. J. C 84, 243 (2024)

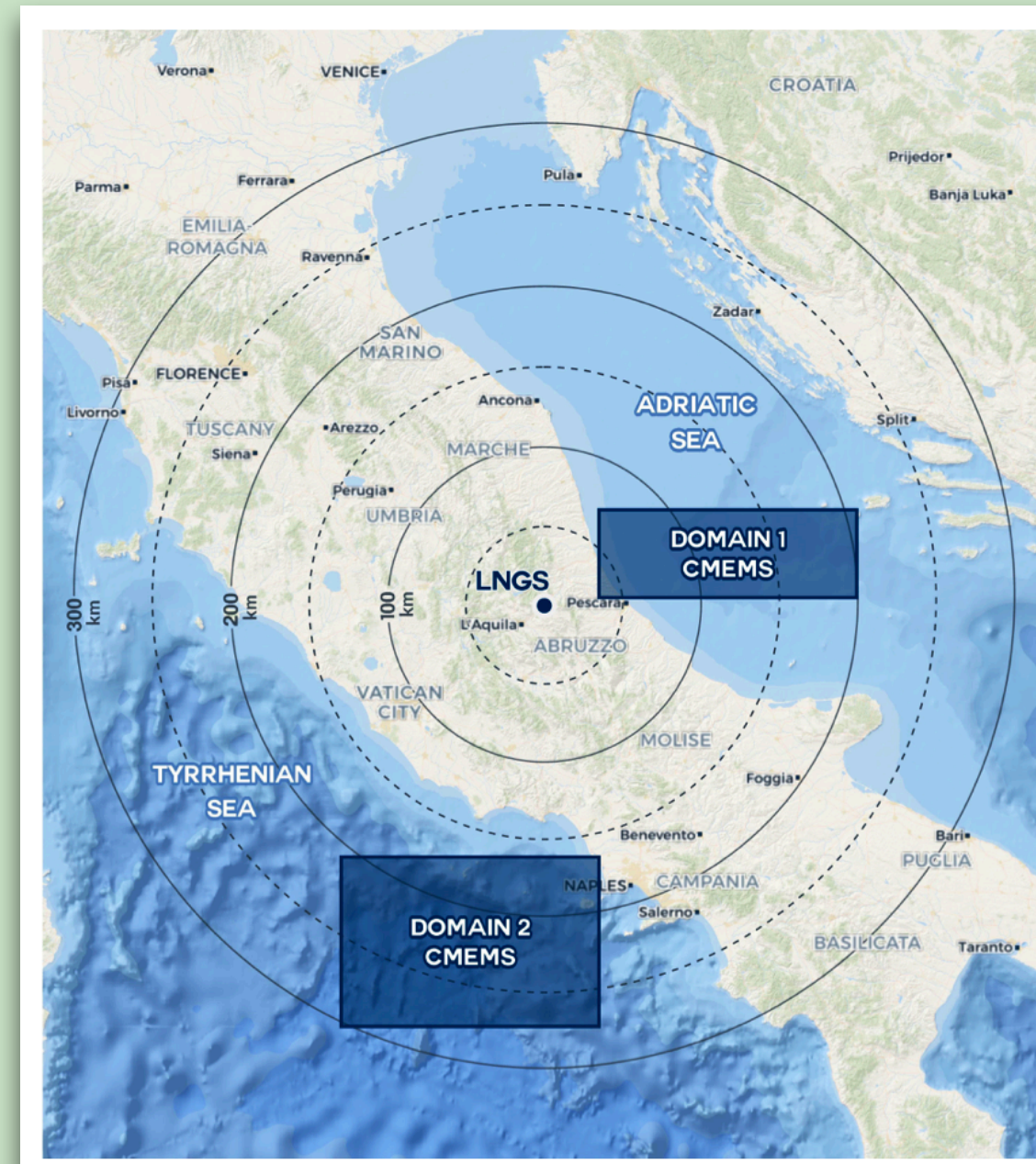
# The challenges - part III: modeling (leftover) noise

- **Noise decorrelation algorithms** rely on the correlation between noise power spectra of detector channels and all diagnostic devices installed in the experimental hut:




40% total raw-RMS reduction w/ denoising

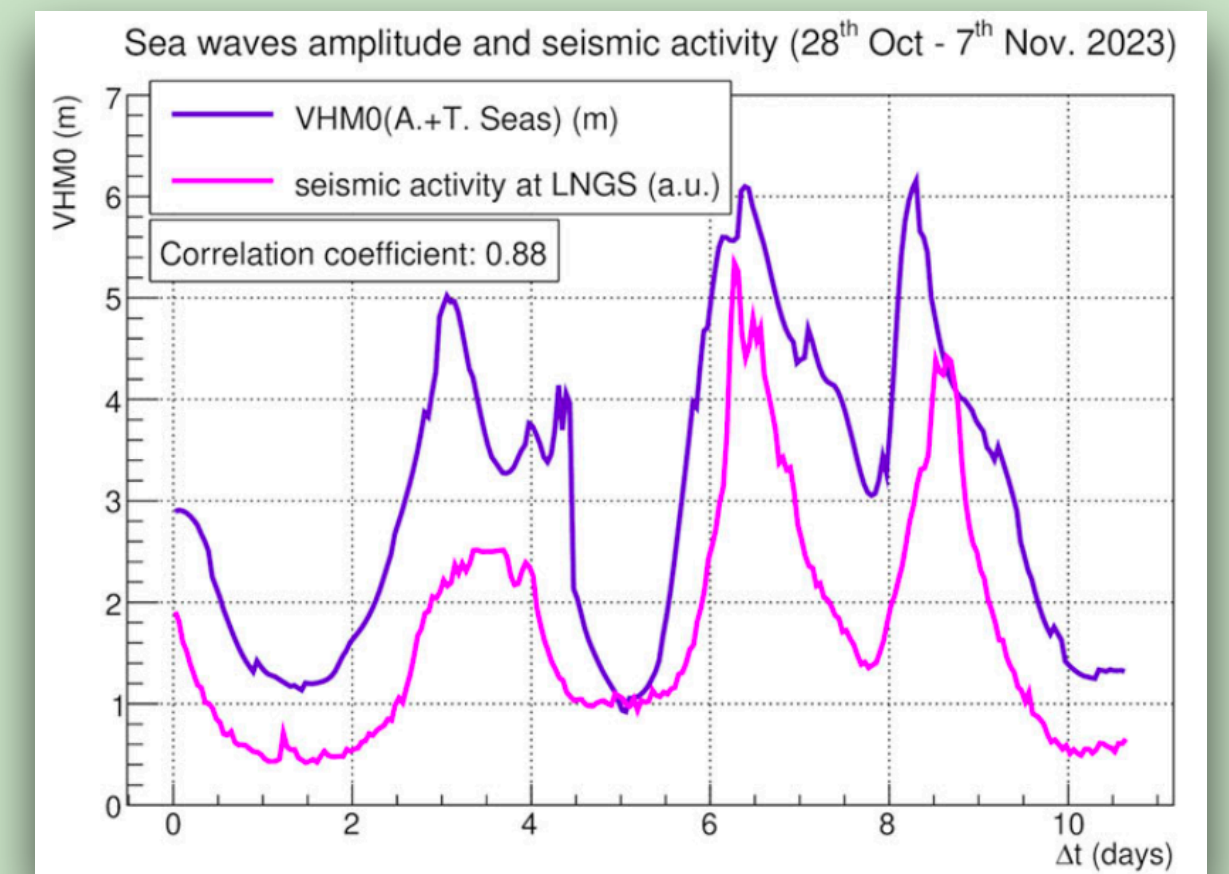
 Science 390, 1029-32 (2025)



- Multi-device analysis exploiting the Copernicus Earth Observation program
- Need solutions to improve cryostat decoupling

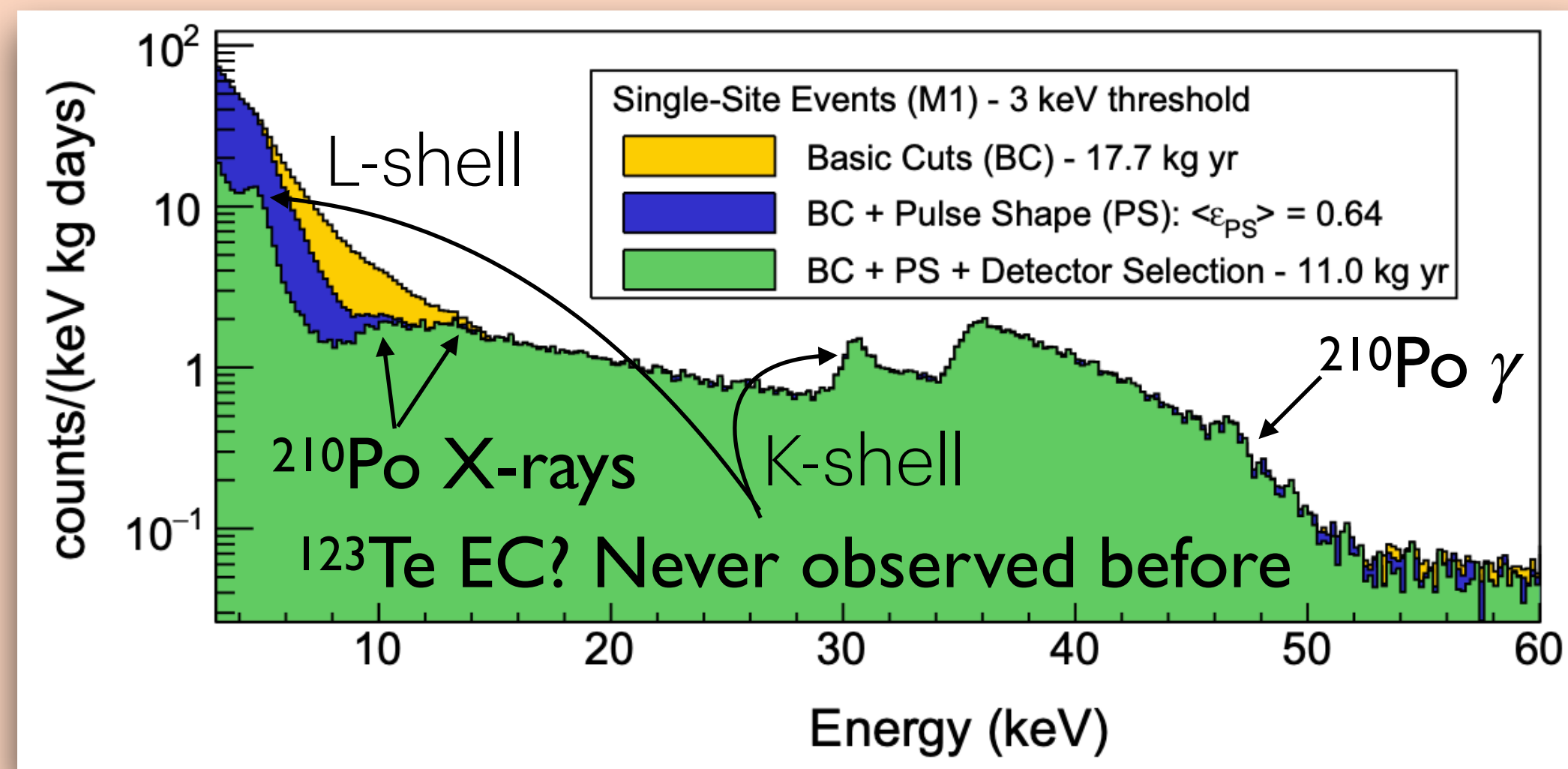
- Recent discovery: CUORE is sensitive to **microseismic activity** induced by the **sea waves** (0.2 - 0.3 Hz)
- Evident correlation **storms** ↔ low frequency noise

 Commun. Phys. 9, 121 (2026)

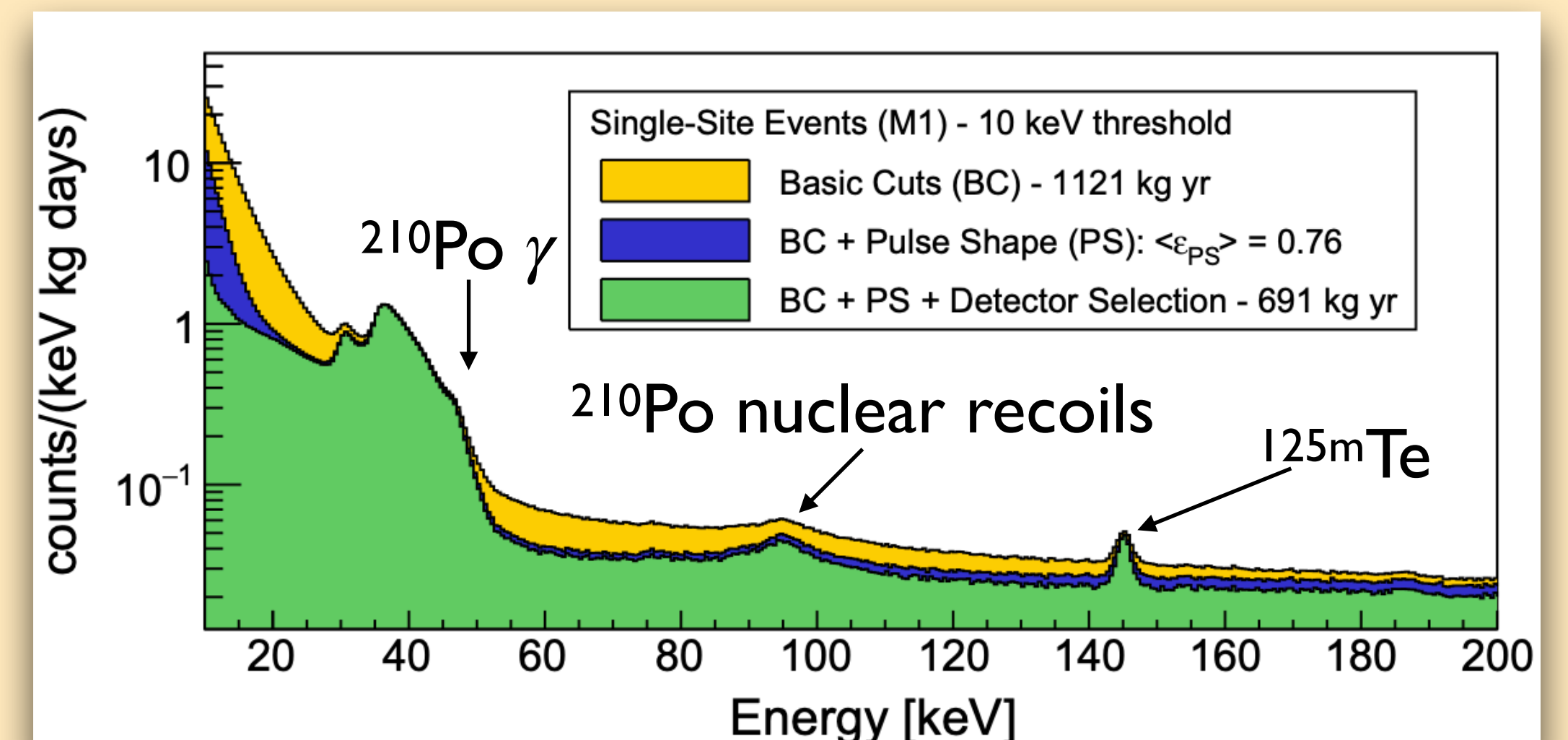


# The outcome: access to the low energy region for physics

- **Low energy studies:** specific event-level cuts to optimise sensitivity at keV-scale:
- spectral studies related to  $^{121}\text{Te}$ ,  $^{123}\text{Te}$ ,  $^{125\text{m}}\text{Te}$  decays and surface lead contaminations:  
**ROI of [3, 10] keV**,  $\sim 1.2$  keV FWHM, 11 kg  $\cdot$  yr / 2 tonne  $\cdot$  yr  $\rightarrow$  1.2% of crystals  
 16 cts/keV/kg/day bkg, efficiency  $\epsilon_{\text{tot}} \simeq 26\%$

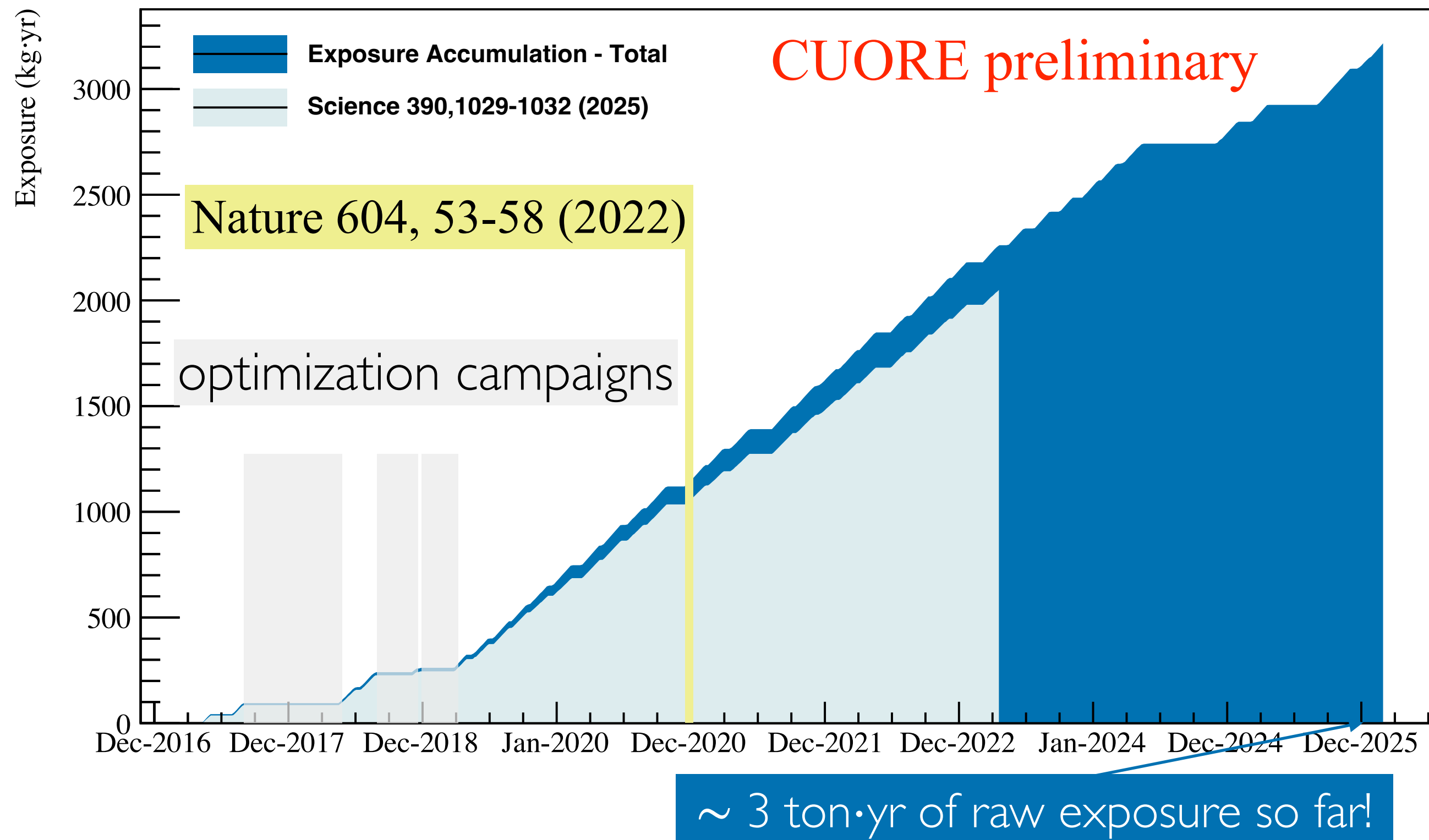


- Increased sensitivity for many phenomena predicted near CUORE threshold:
- **Cosmic and solar axions, WIMPs annual modulation: ROI of [10, 20] keV**,  $\sim 2.5$  keV FWHM, 691 kg  $\cdot$  yr / 2 tonne  $\cdot$  yr  $\rightarrow$  35% of crystals, 2 cts/keV/kg/day bkg,  $\epsilon_{\text{tot}} \simeq 50\%$

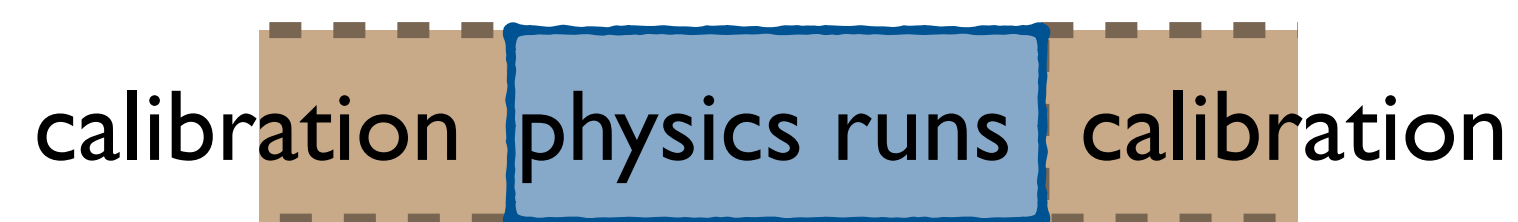


# The challenges - part IV: stable operation of 1000 detectors

- Data taking started in 2017

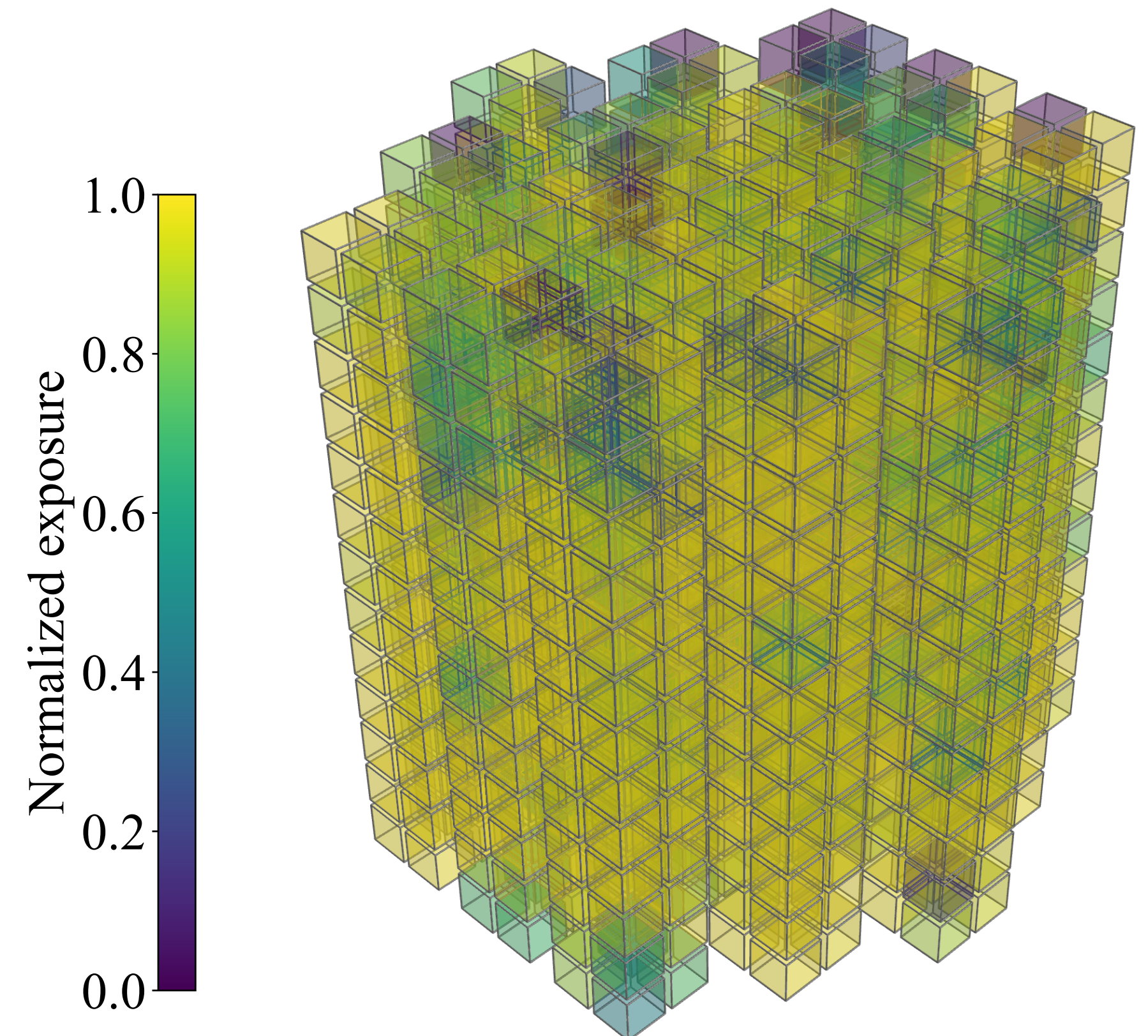


- Data split in *datasets*



- Trigger rate  $\sim 50$  mHz ( $\sim 6$  mHz) in calibration (physics) runs
- Voltage across NTD Ge thermistors sampled at 1kHz, a software trigger is applied offline

Analysed data (May 2017 - April 2023)



Science 390, 1029-32 (2025)

TeO<sub>2</sub> exposure: **2039.0 kg·yr**

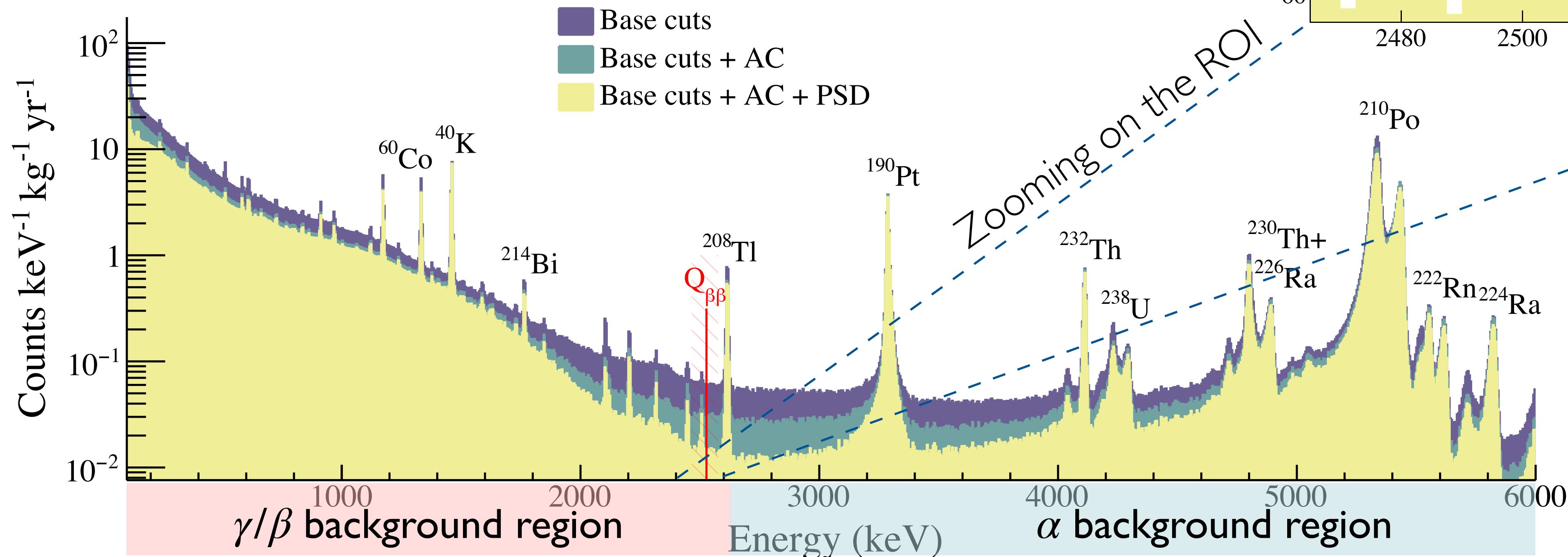
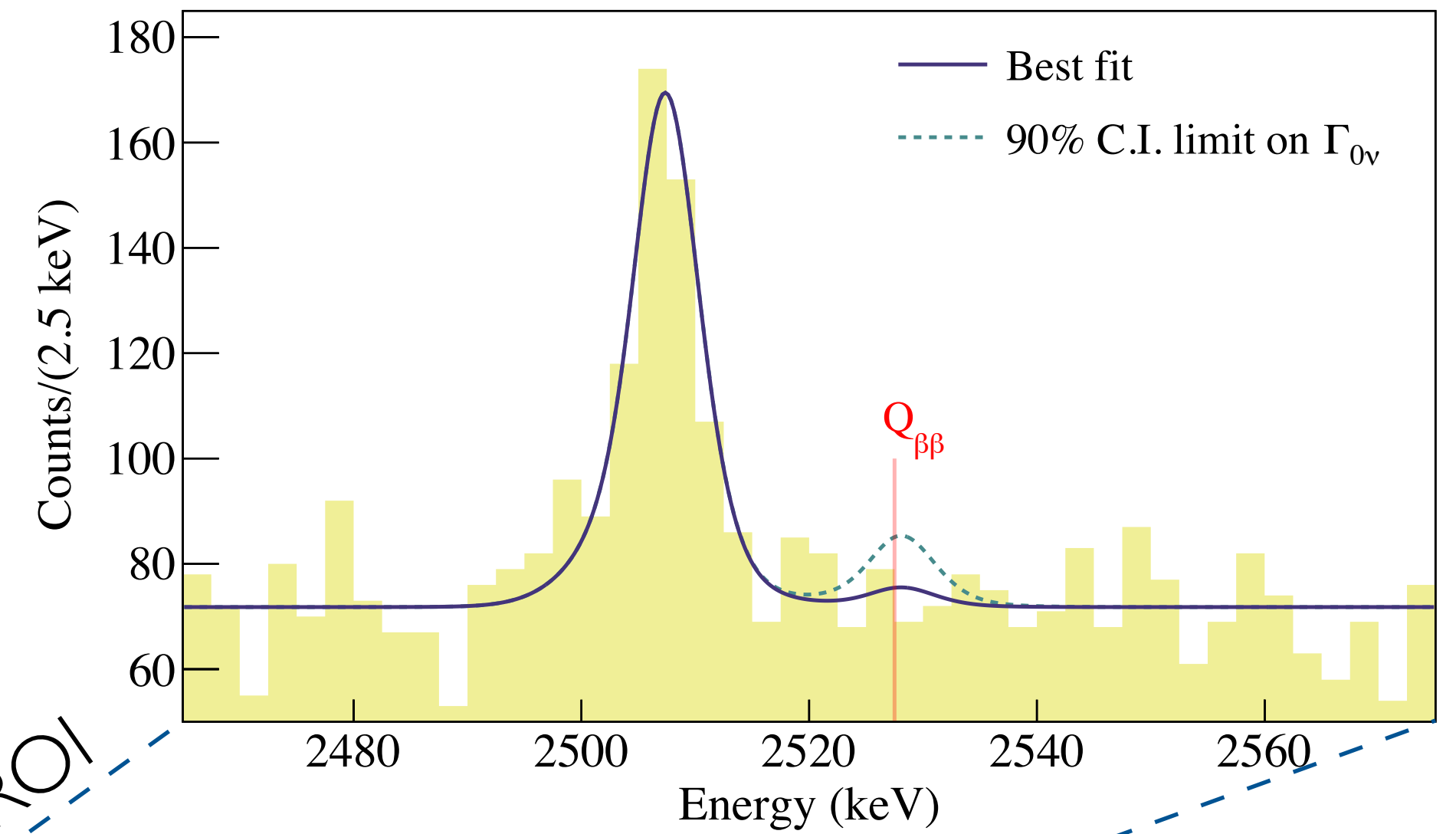
<sup>130</sup>Te exposure: **567.0 kg·yr**

**uniformly distributed** on the detector

# Unveiling the truth: the 2 tonne-yr data spectrum

- Several analysis cuts on top of each other:
  - **Base cuts** (trigger, energy reconstruction, pile-up)
  - **Anti-coincidence** (AC): only single-crystal events
  - **Pulse shape discrimination** (PSD): only signal-like events

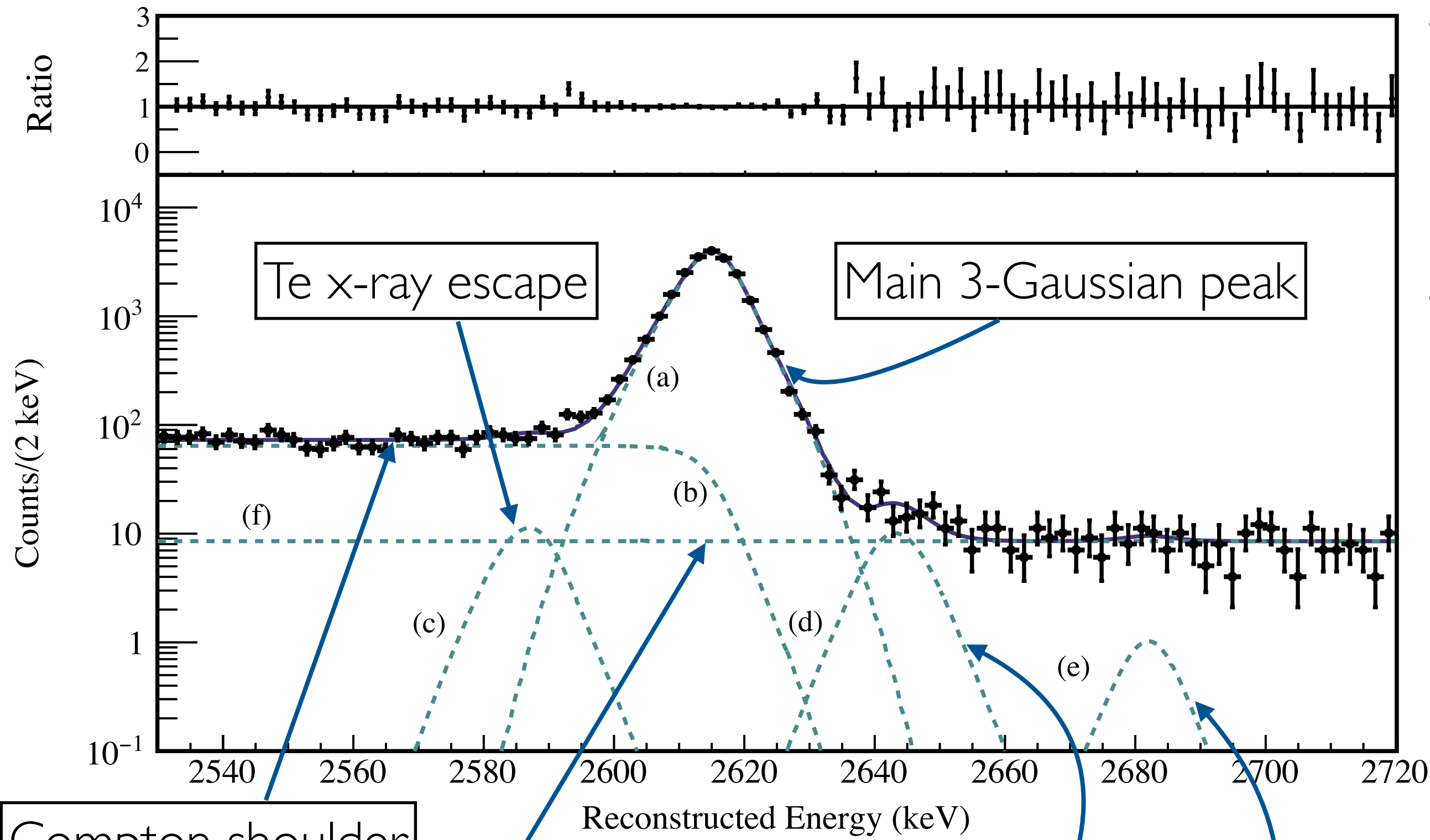
Total analysis cut efficiency **93.4(18) %**



Average background index in the ROI  
 $b = (1.42^{+0.03}_{-0.02}) \cdot 10^{-2}$   
 (counts/keV/kg/yr)

 Science 390, 1029-32 (2025)

# Unveiling the truth: modeling detector response



Compton shoulder

Flat background

Te x-ray coincidence

Single escape + 583 keV

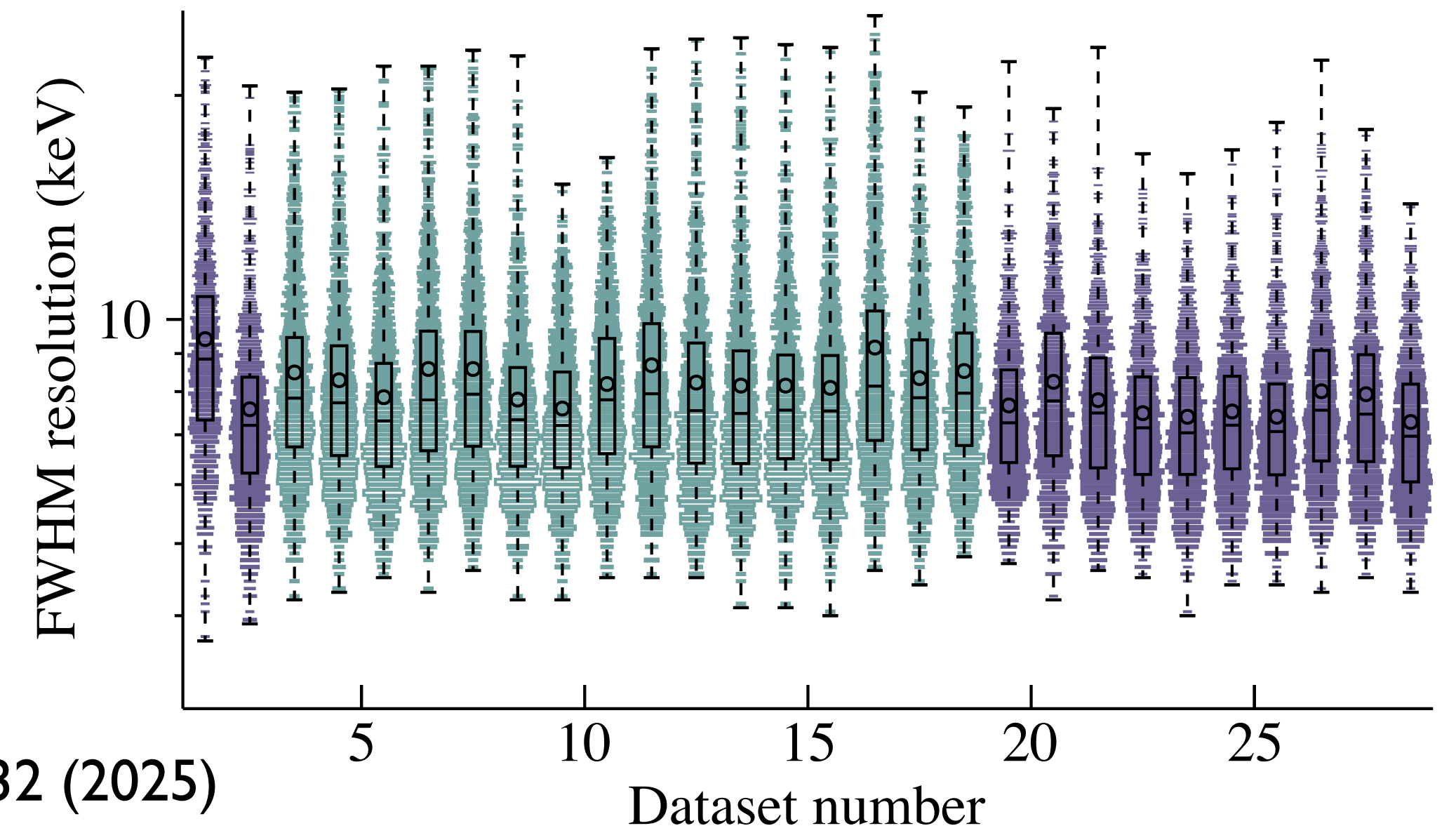
$$\text{FWHM} (^{208}\text{Tl}) = (7.540 \pm 0.024) \text{ keV}$$

$$\text{FWHM} (Q_{\beta\beta}) = (7.310 \pm 0.024) \text{ keV}$$

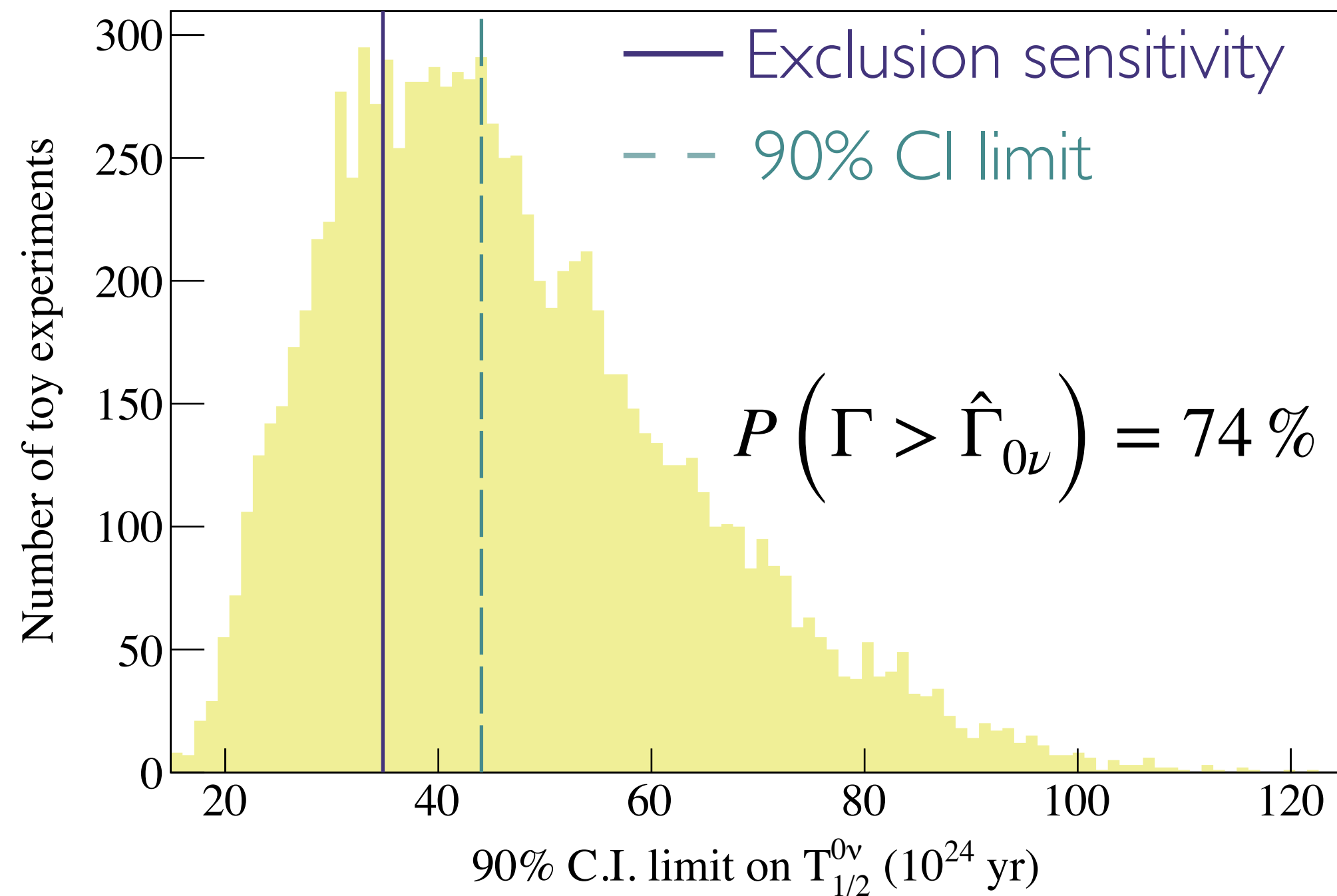
$$\Delta E (Q_{\beta\beta}) = (0.40^{+0.21}_{-0.44}) \text{ keV}$$

- Detector response extracted on events from the  $^{208}\text{Tl}$  line at 2615 keV in calibration data separately for each bolometer and dataset
- Fit of the most prominent  $\gamma$  lines in physics data to scale the energy resolution and calibration bias at  $Q_{\beta\beta}$

$T_{\text{base}} = 11 \text{ mK}$   
  $T_{\text{base}} = 15 \text{ mK}$



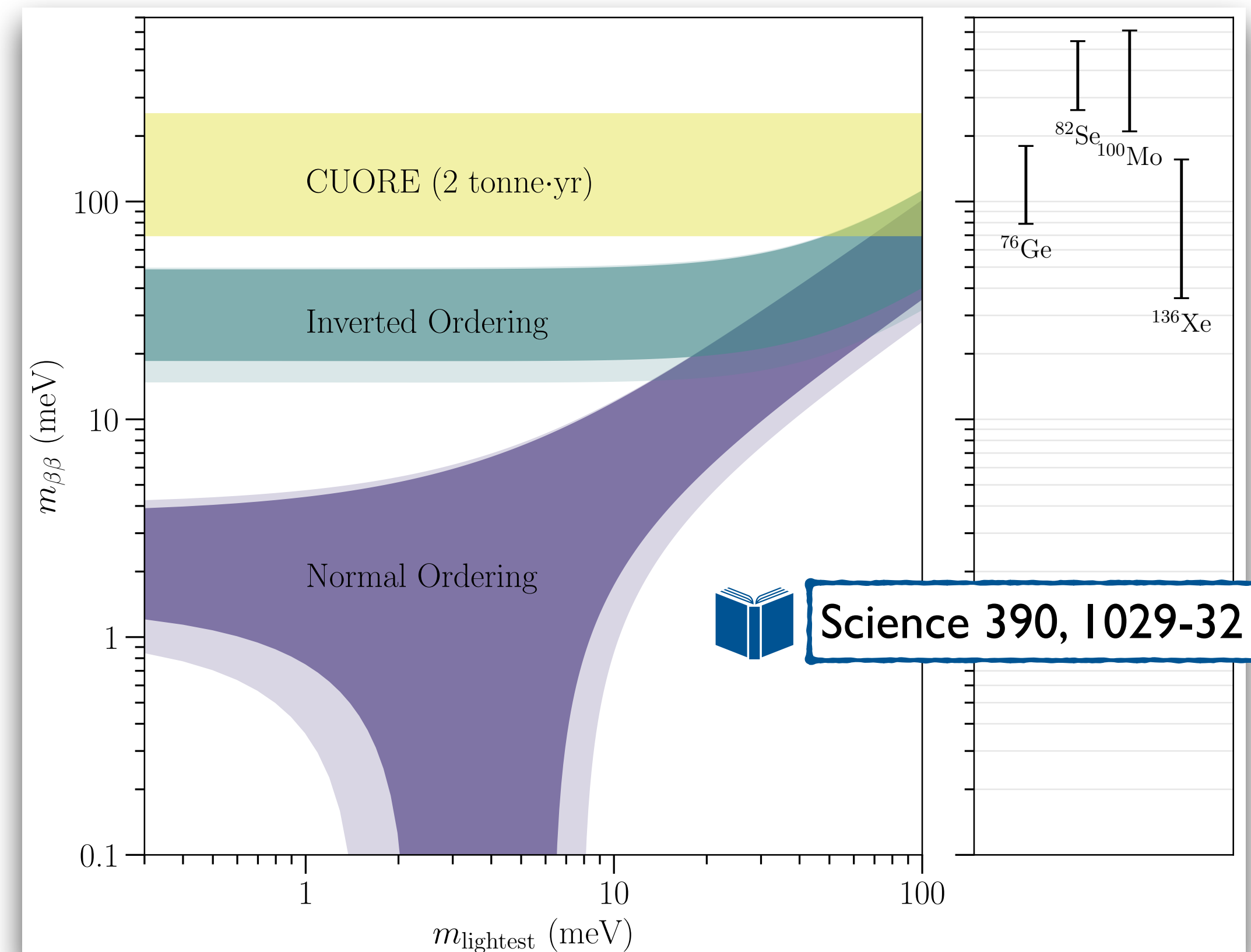
# Unveiling the truth: fitting our data to extract $\Gamma_{0\nu\beta\beta}$



Frequentist result  $T_{0\nu\beta\beta}^{1/2} > 3.4 \cdot 10^{25}$  yr (90% C.L.)

Assuming the exchange of a light Majorana neutrino  
the limit on the effective Majorana mass is

$$m_{\beta\beta} < 70 - 250 \text{ meV}$$



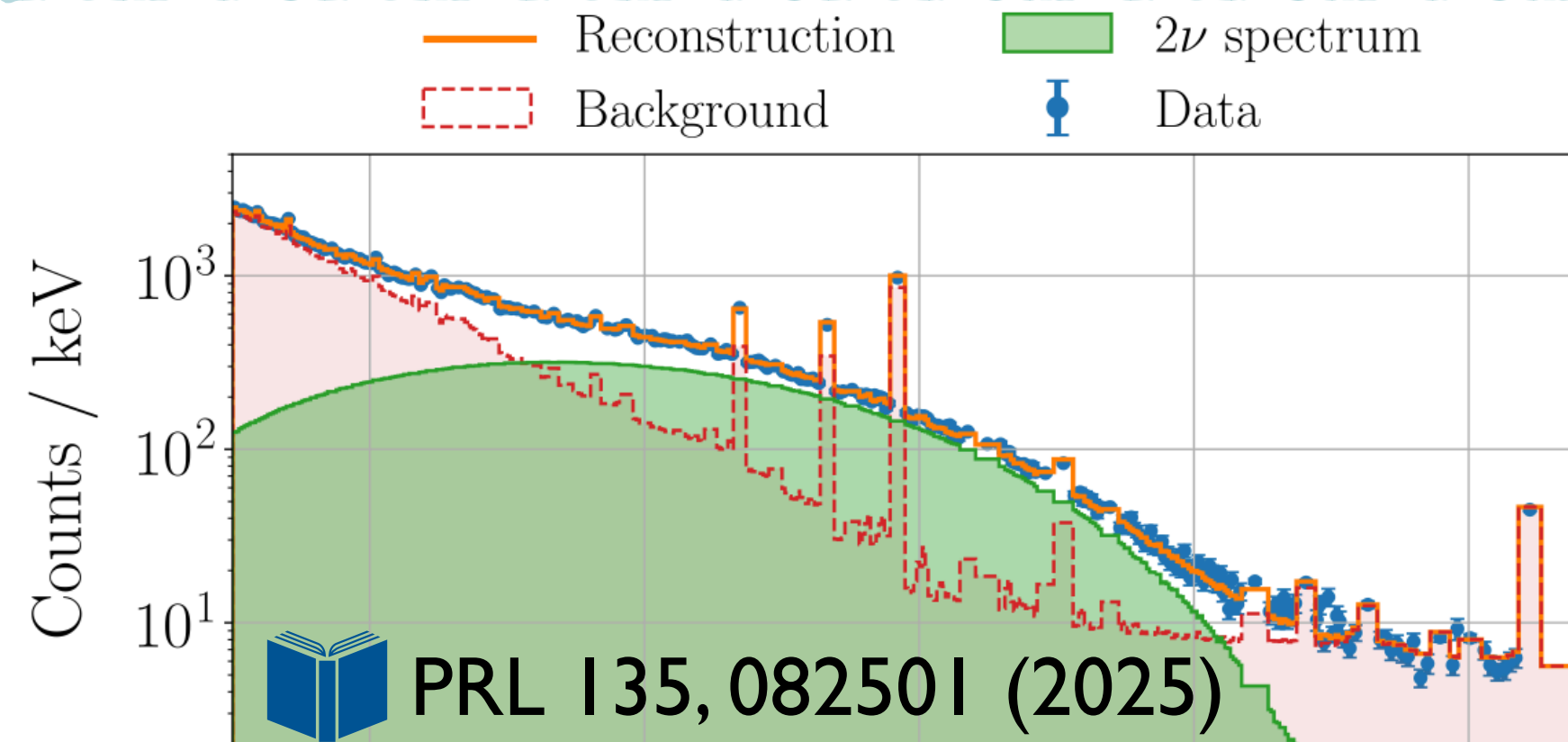
Science 390, 1029-32 (2025)

- Median exclusion sensitivity from toy MC experiments  $T_{0\nu\beta\beta}^{1/2} = 4.4 \cdot 10^{25}$  yr (90% C.I.)
- Unbinned Bayesian fit with  $\Gamma_{0\nu\beta\beta} > 0$
- No evidence of  $0\nu\beta\beta$  and new limit on  $^{130}\text{Te}$  half-life  $T_{0\nu\beta\beta}^{1/2} > 3.5 \cdot 10^{25}$  yr (90% C.I.)

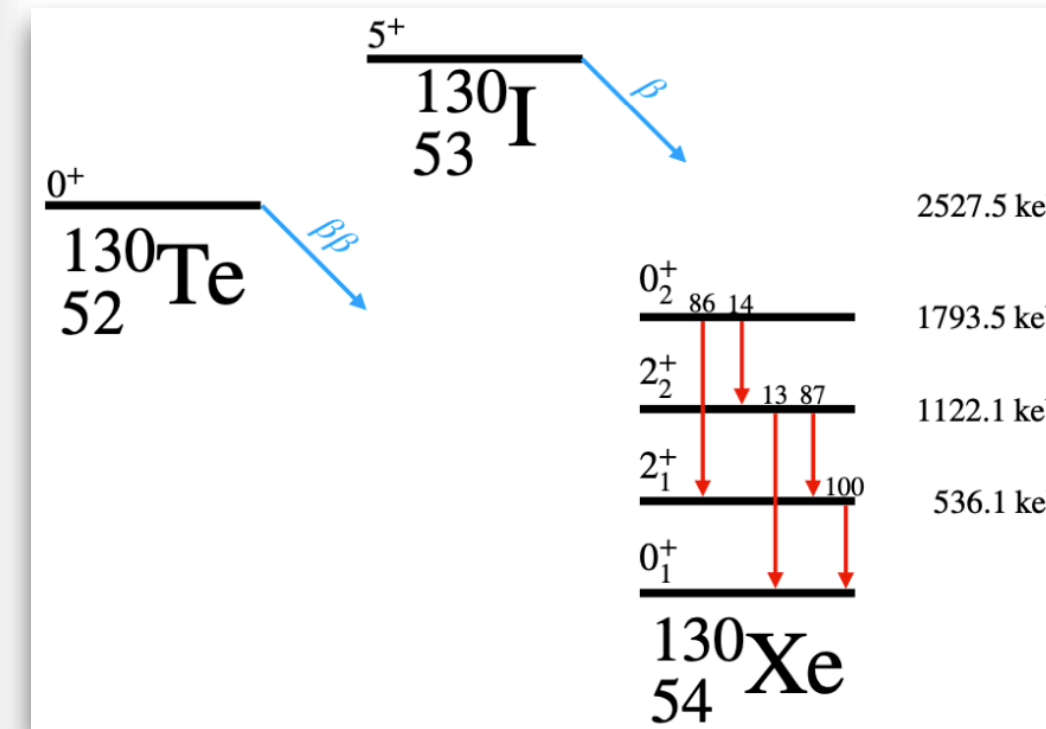
# Not only $^{130}\text{Te}$ $0\nu\beta\beta$ : other $\beta\beta$ searches

Analysis with 2 ton · yr in progress!

## $^{130}\text{Te}$ SM-allowed $2\nu\beta\beta$ decay



## $^{130}\text{Te}$ $\beta\beta$ decay to the 1<sup>st</sup> 0<sup>+</sup> excited state

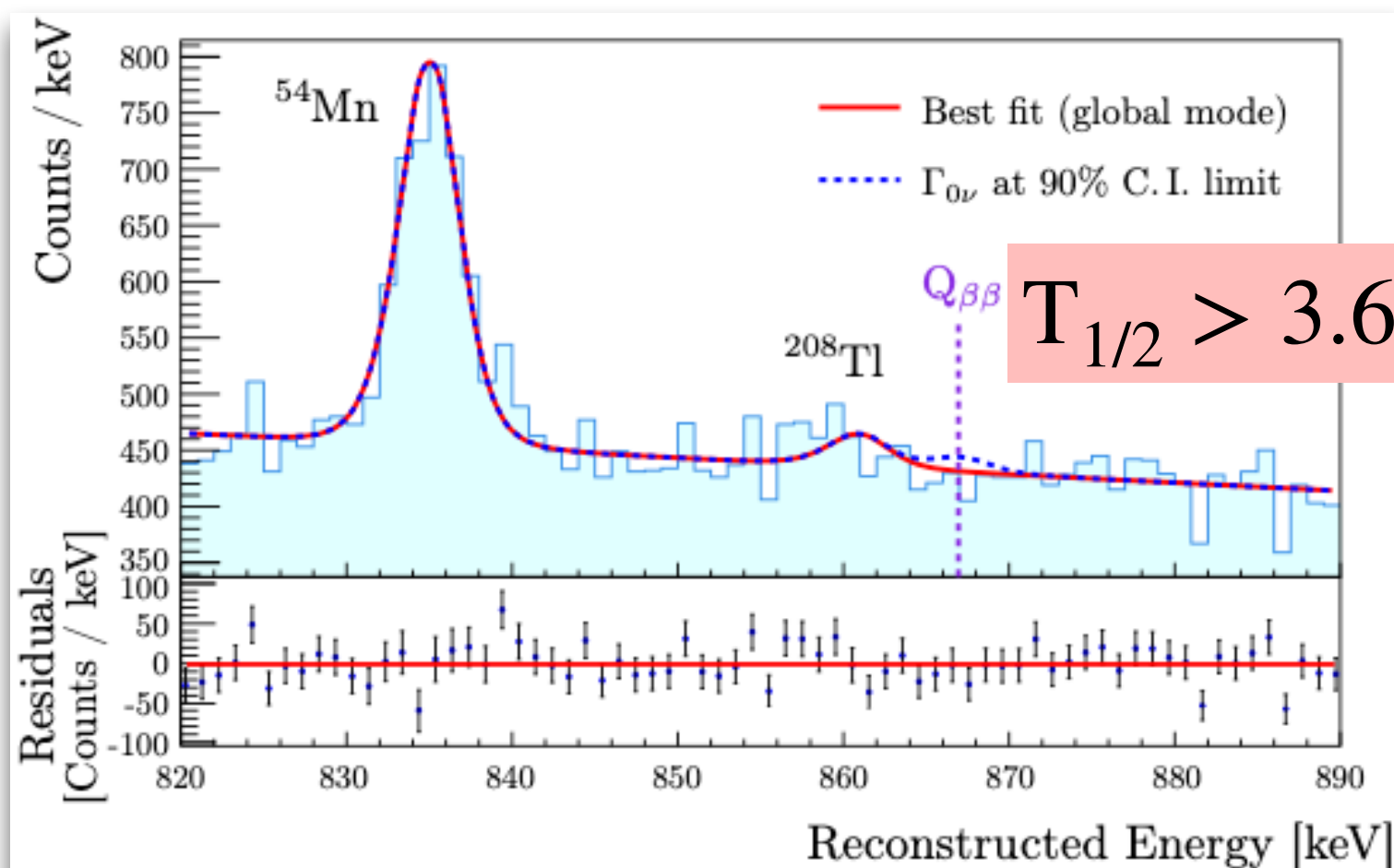


$$T_{0\nu}^{1/2} > 5.9 \cdot 10^{24} \text{ yr (90 \% C.I.)}$$

$$T_{2\nu}^{1/2} > 1.3 \cdot 10^{24} \text{ yr (90 \% C.I.)}$$

Eur. Phys. J. C 81, 567 (2021)

## $^{128}\text{Te}$ $0\nu\beta\beta$ decay to the ground state



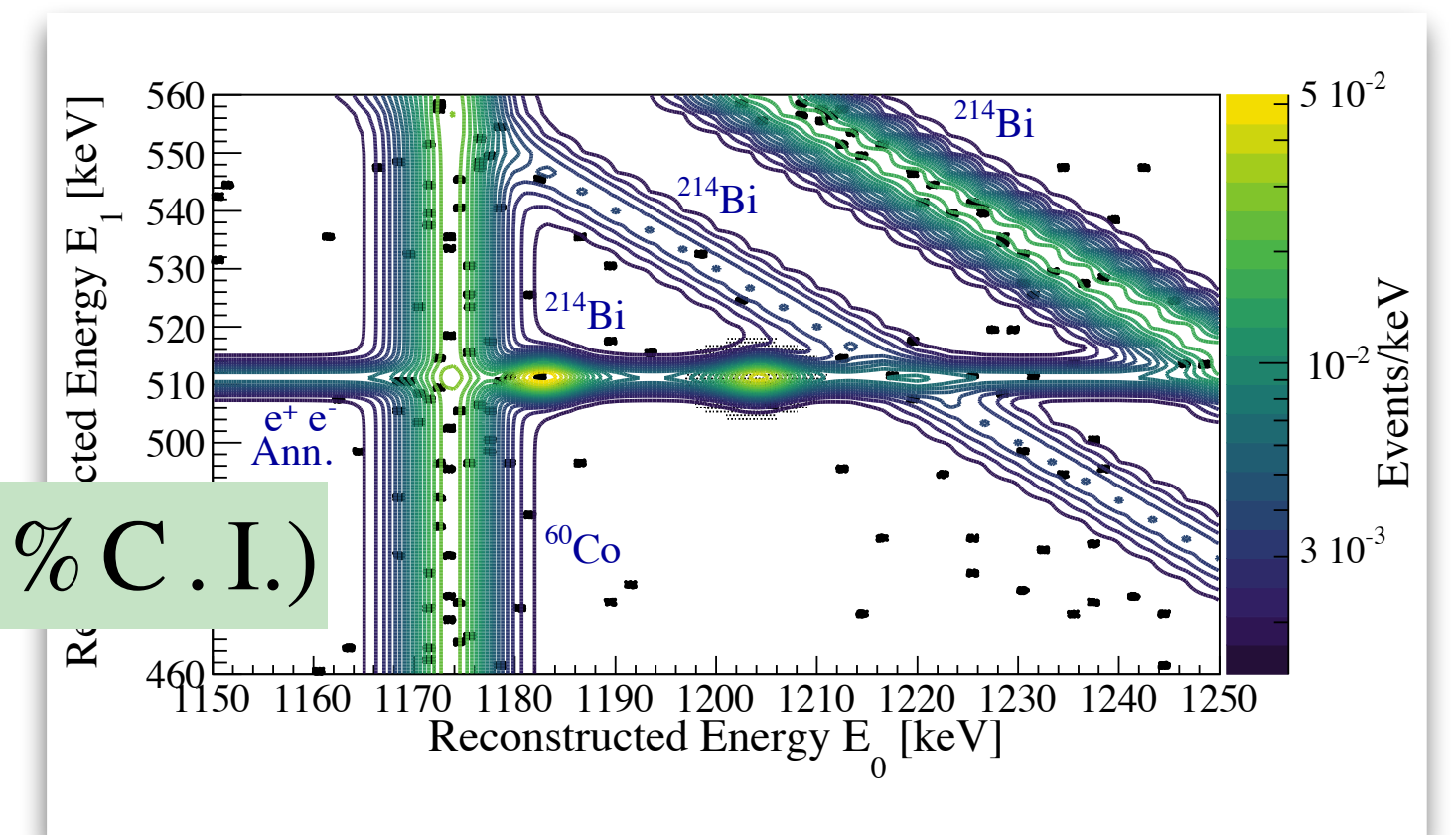
$$T_{1/2} > 3.6 \cdot 10^{24} \text{ yr (90 \% C.I.)}$$

PRL 129, 222501 (2022)

## $^{120}\text{Te}$ $0\nu\beta^+EC$ decay to the ground state

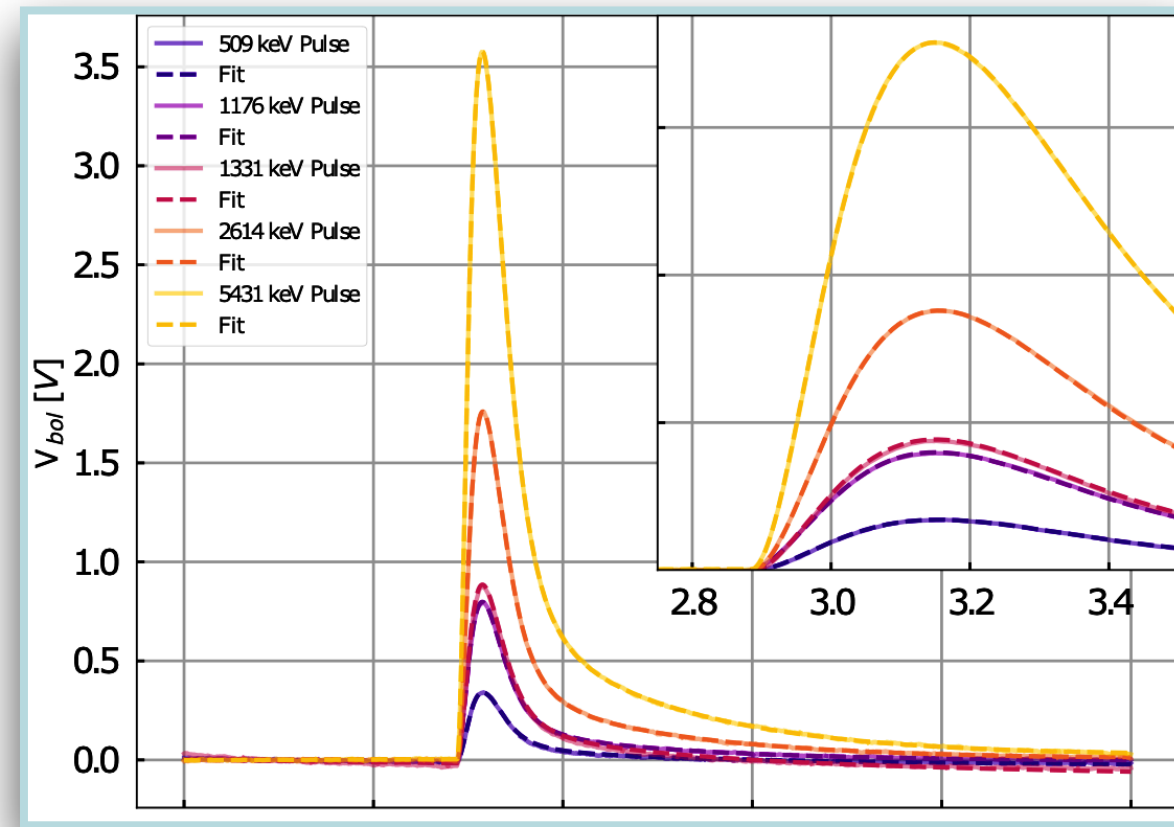
Phys. Rev. C, 105 065504 (2022)

$$T_{1/2} > 2.9 \cdot 10^{22} \text{ yr (90 \% C.I.)}$$



# Not only $^{130}\text{Te } 0\nu\beta\beta$ : other physics cases

## Thermal model of CUORE calorimeters

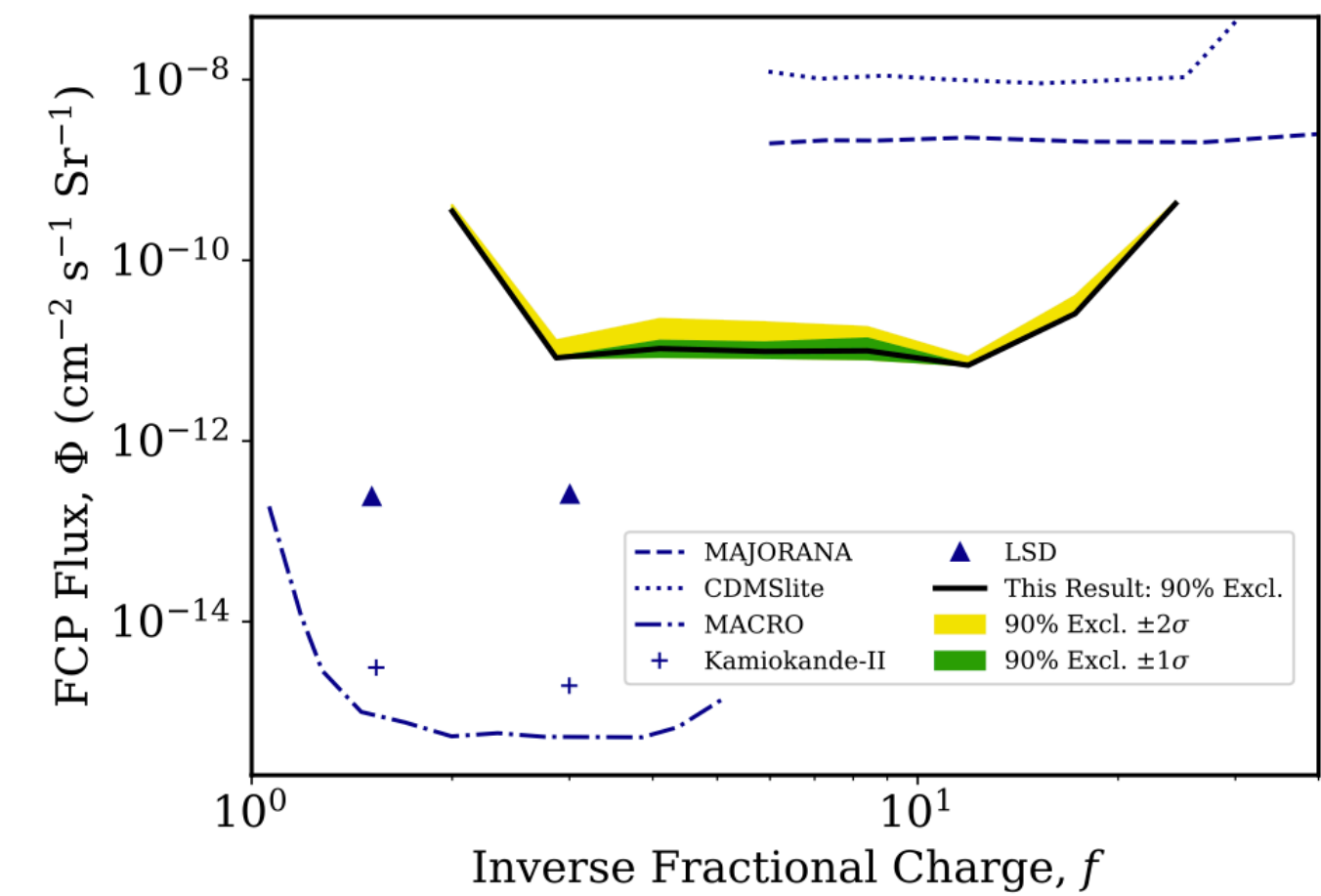


Dedicated study of environmental and antropic vibrational sources



JINST 17 (2022) 11, P11023

## Search for fractionally charged particles

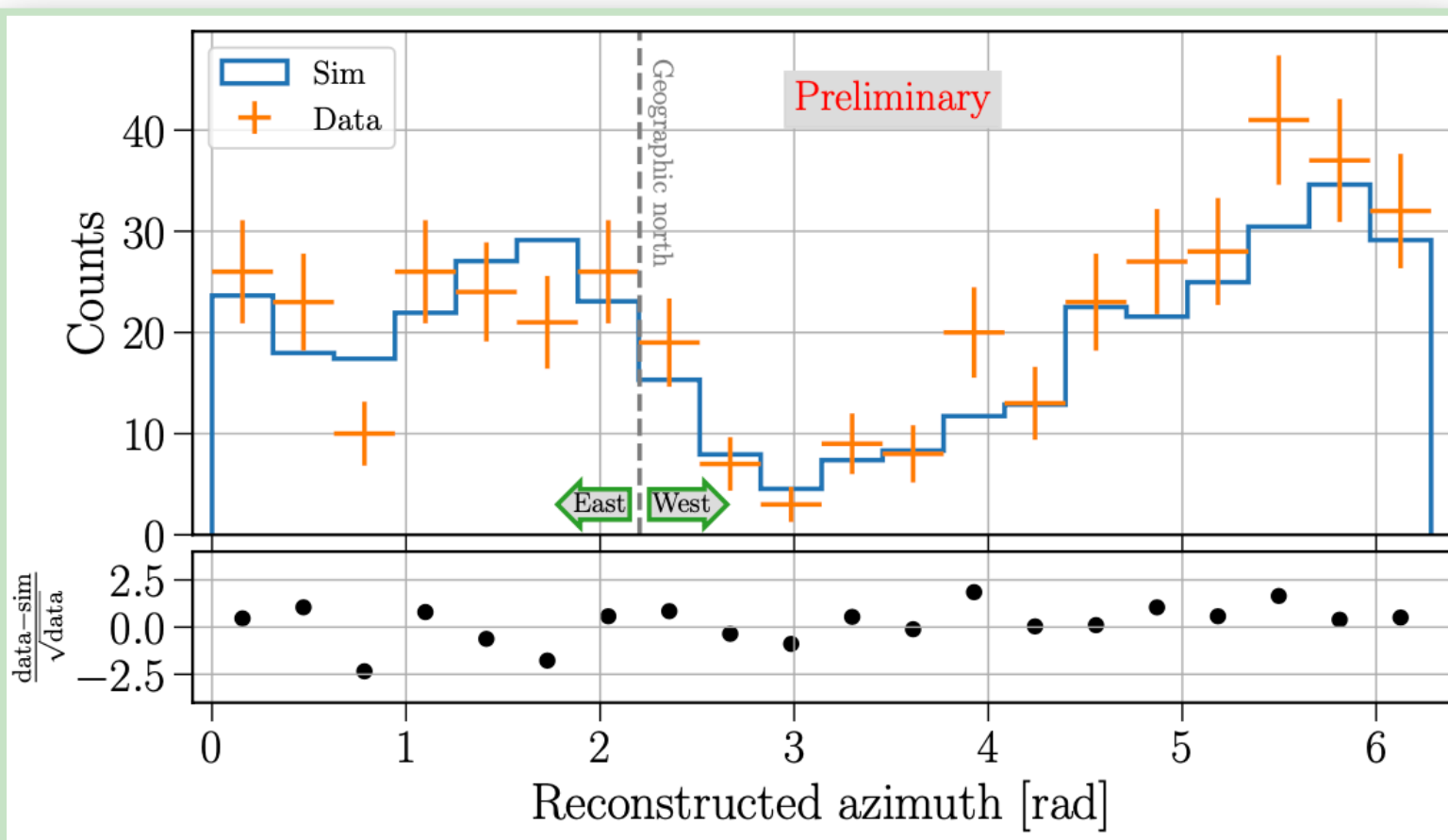


Multi-spectral search for rare events based on multi-crystal track-like topologies



Phys. Rev. Lett. 133, 241801

## Muon event reconstruction



Track-like events ( $N_{\text{crystals}} \geq 5$  &  $E_{\text{dep}} \geq 9$  MeV) to study  $\mu$ -induced background



arxiv:2509.05528

## Several additional analyses *in progress*

- Multi-spectral studies exploiting the high CUORE detector granularity to study detector response
- Low energy studies profiting of the improved analysis tools and energy thresholds
- Background model related studies
- Rare event searches with larger statistics

Paper accepted for publication on EPJC

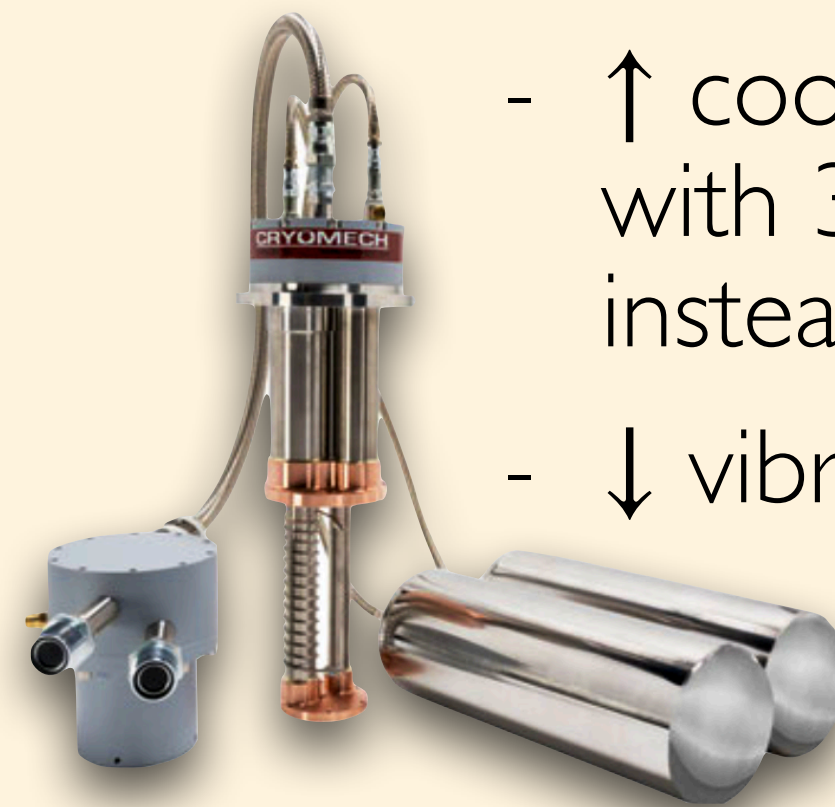
# CUORE: what's next? Our path towards CUPID

## CUORE (now)

- Continue data taking until meeting our goal:  
**3 tonne · yr  $\text{TeO}_2$  exposure**  
( $\sim 1$  tonne · yr of  $^{130}\text{Te}$ )
- Estimate: end up data taking by mid 2026
- Large statistics to perform high sensitivity searches in several channels ( $\beta\beta$  decay, dark matter, exotic phenomena, ...)

## CUORE-phase II

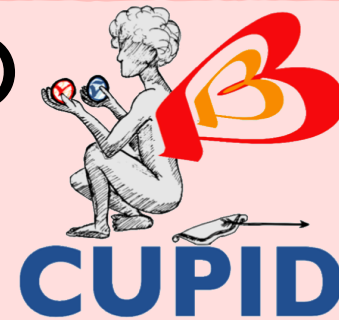
- Upgrade of the **cryogenic system** to improve **Pulse Tubes** performance and coupling to the cryostat



- $\uparrow$  cooling power with 3+1 setting instead of 4+1
- $\downarrow$  vibrations

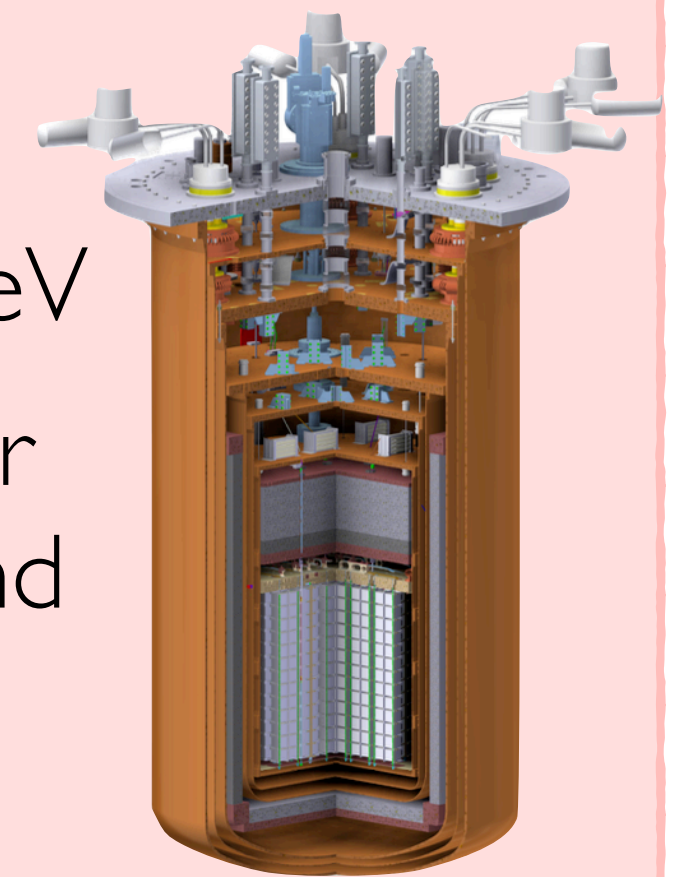
- Lower thresholds  $\rightarrow$  high sensitivity low energy studies (axions, WIMPS, ...)

## CUPID



*CUORE Upgrade with Particle IDentification*

- Scintillating cryogenic calorimeters to overcome CUORE-sensitivity-limiting  $\alpha$  background
- $^{130}\text{Te} \rightarrow ^{100}\text{Mo}$   
2528  $\rightarrow$  3034 keV
- $10^{-4}$  cts/keV/kg/yr target background
- Same cryogenic infrastructure



# The CUPID experiment

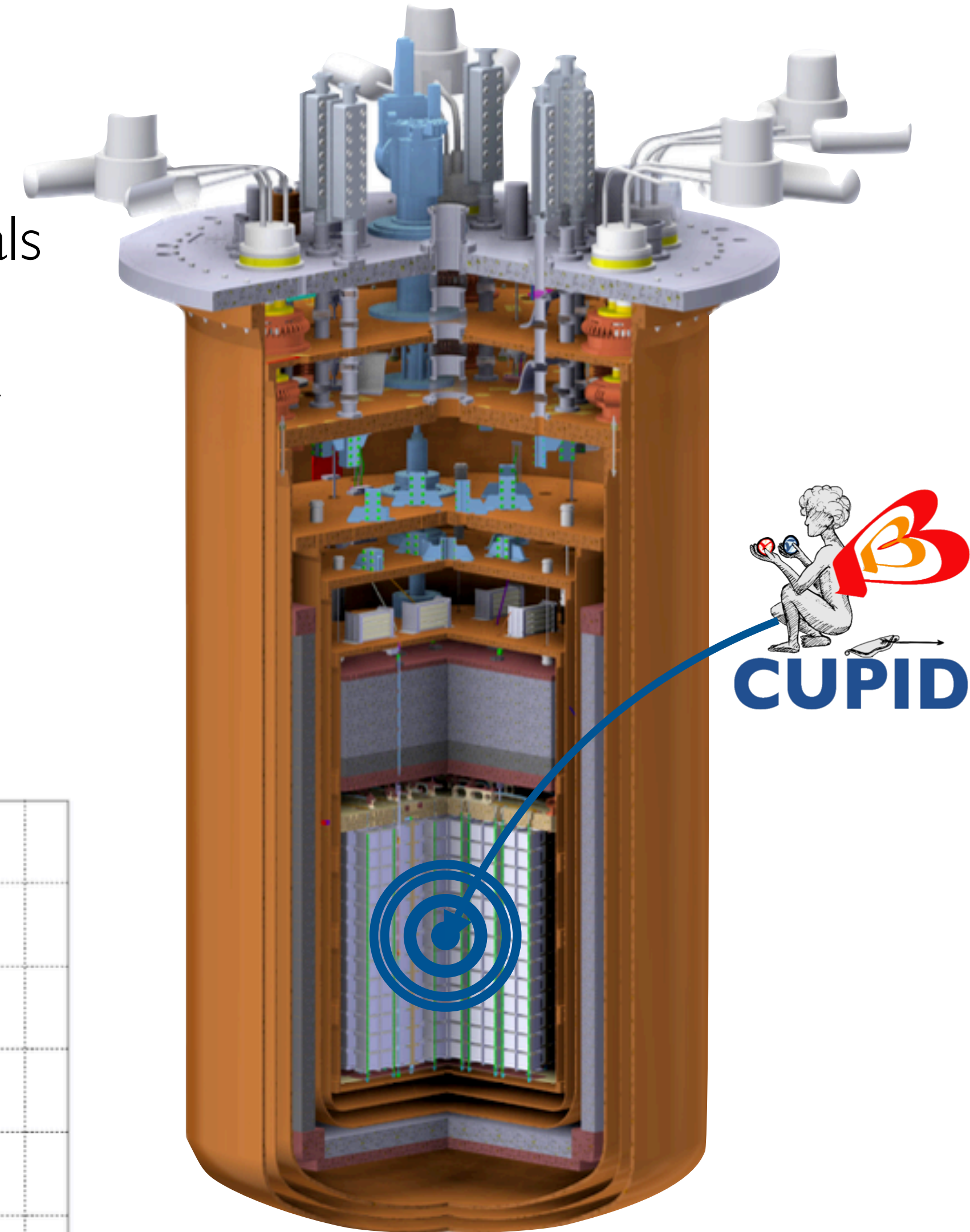
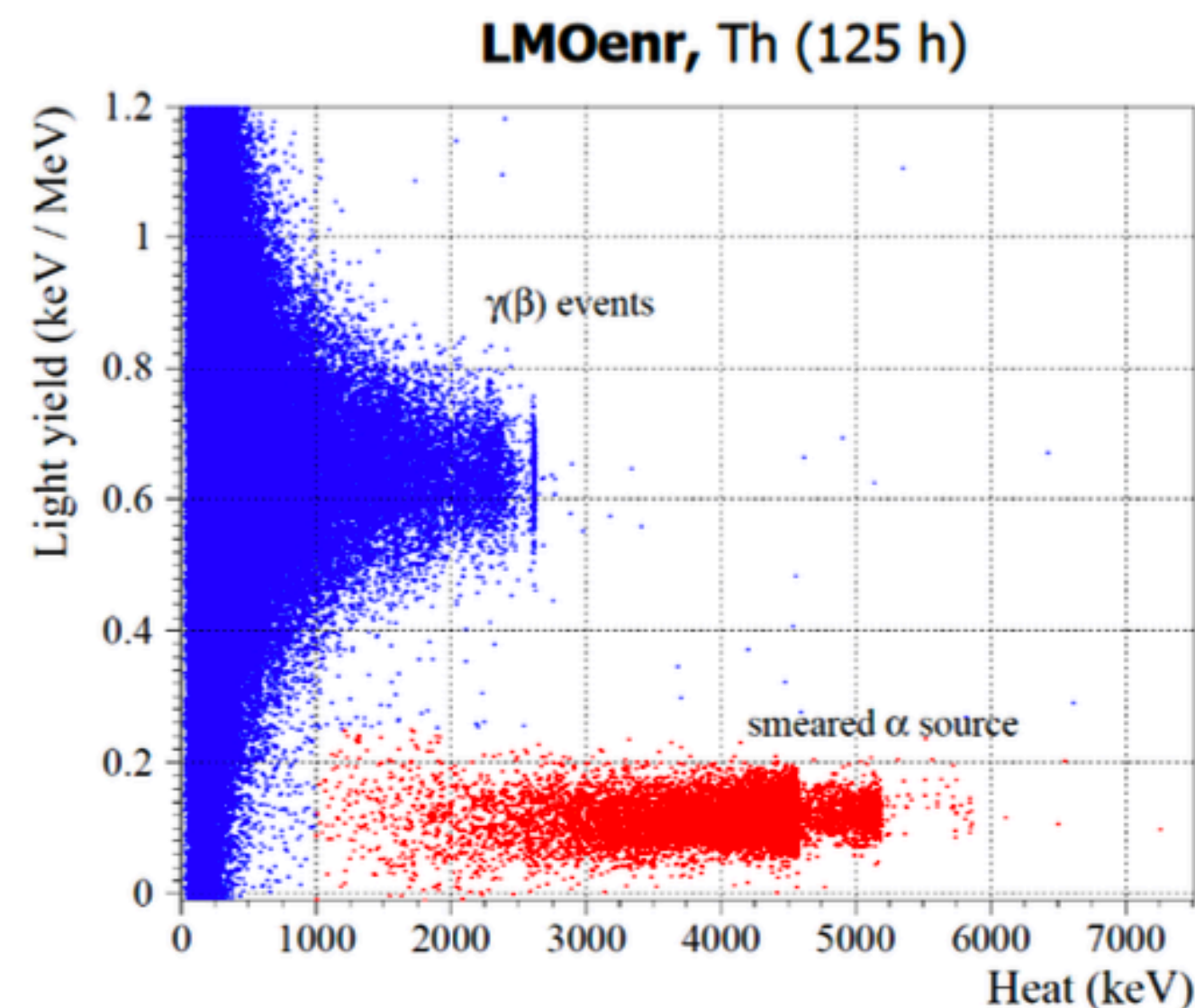
## CUPID: CUORE Upgrade with Particle IDentification

- Exploit  $^{100}\text{Mo}$  as a  $\beta\beta$  decay candidate  
→ replace CUORE  $\text{TeO}_2$  array with a matrix of  $\text{Li}_2^{\text{enr}}\text{MoO}_4$  crystals  
re-use th same (well-known & modeled) cryogenic infrastructure  
with a few upgrades to reduce vibrations/increase cooling power

- **Higher Q-value** (3034 against 2528 keV)  
→ larger phase space and NME compared to  $^{130}\text{Te}$   
→ most of  $\beta/\gamma$  bkg reduced

- $\text{Li}_2^{100}\text{MoO}_4$  **scintillating** crystals for **PID**  
→ high reduction of  $\alpha$  background  
the largest limiting factor for CUORE  
→  $\text{BI} = 10^{-4}$  counts/keV/kg/yr  
at  $Q_{\beta\beta}(^{100}\text{Mo})$

- 5 keV FWHM resolution at 3 MeV



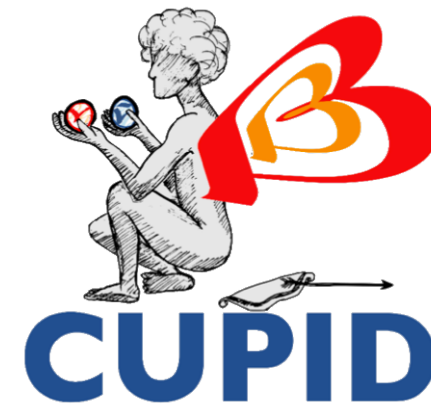
EPJ C 85,737 (2025)

# The CUPID experiment

## CUPID: CUORE Upgrade with Particle IDentification

 EPJC 85,737 (2025)

- **New detector array:**
  - Mo enriched to  $\gtrsim 95\%$  in  $^{100}\text{Mo}$  (240 kg  $^{100}\text{Mo}$  mass)
  - 1596  $\text{Li}_2^{100}\text{MoO}_4$  scintillating crystals (280 g each)
  - $\sim 1700$  light detectors for the scintillation readout
- Upgrades to the cryostat & shielding:
  - Need  $\sim 1600$  **double readout** array
  - Improve external neutron shield
  - Additional cosmic **muons veto**
- Discovery (exclusion) sensitivity  $T_{1/2}^{0\nu} = 1.0 (1.8) 10^{27} \text{yr}$ 
  - access to the inverted hierarchy region
  - $3\sigma$  discovery sensitivity  $m_{\beta\beta} = [12,21] \text{meV}$
  - exclusion sensitivity  $m_{\beta\beta} = [9,15] \text{meV}$

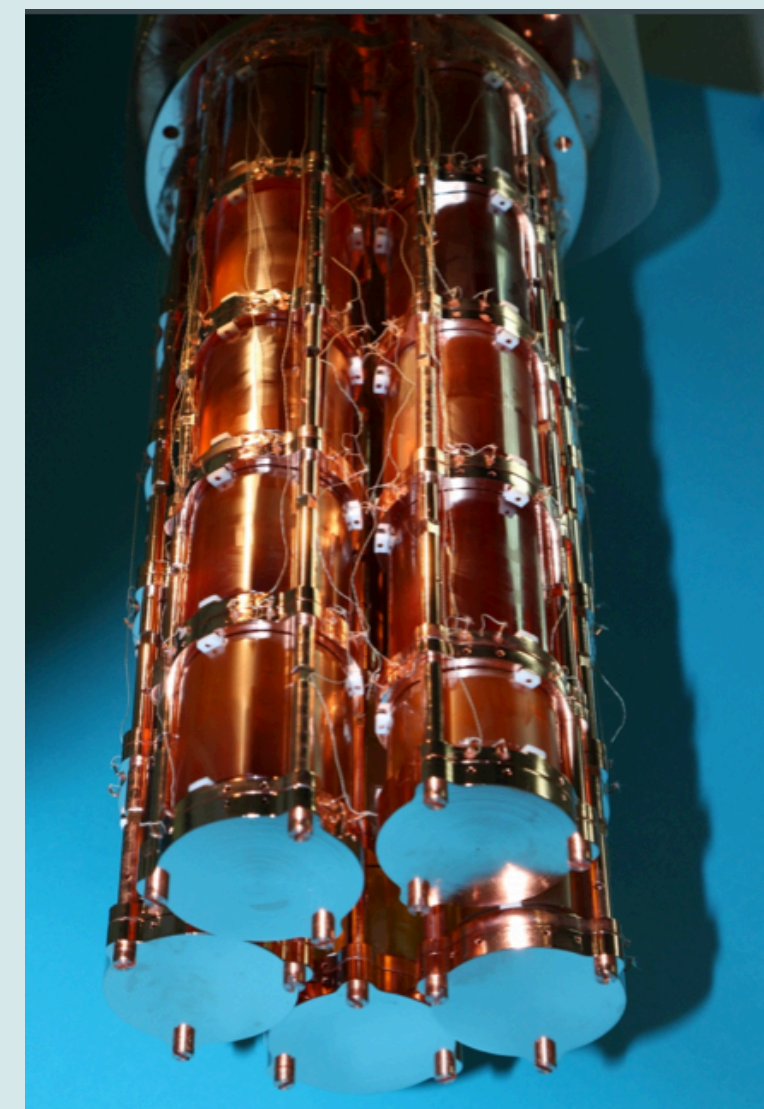


- Scintillating crystals after the **CUPID-0** ( $^{82}\text{Se}$ ) at LNGS and **CUPID-Mo** ( $^{100}\text{Mo}$ ) at LSM demonstrators showed the technology maturity to be implemented on a large scale detector



Phys. Rev. Lett. 123, 032501 (2019)

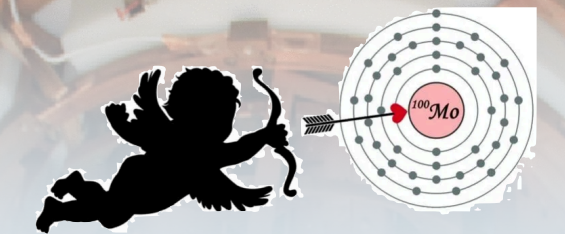
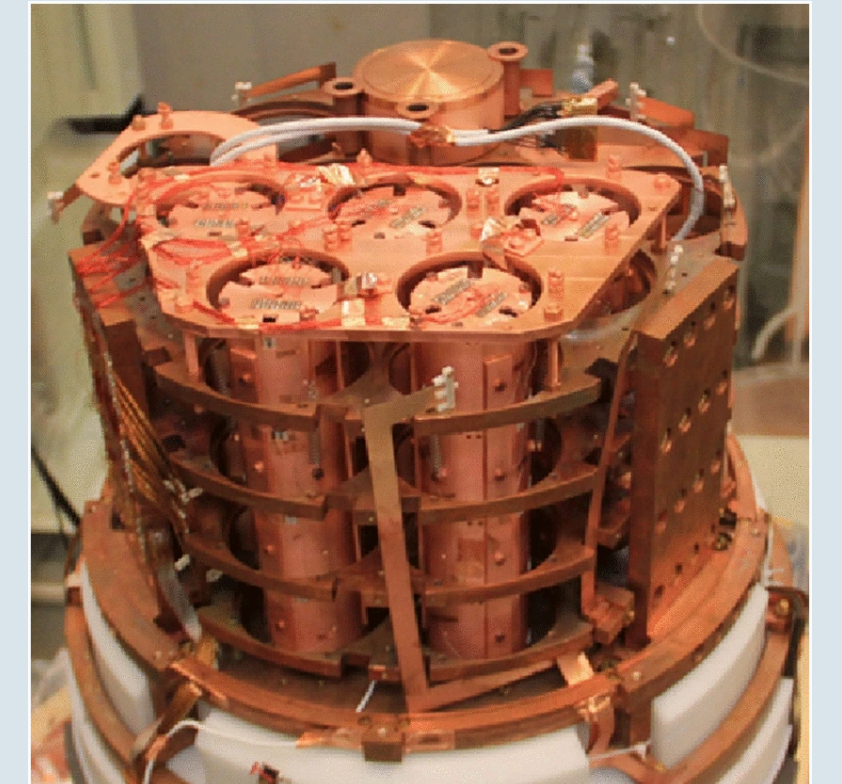
CUPID-0



$\text{Zn}^{\text{enr}}\text{Se}, m(^{82}\text{Se}) \sim 5 \text{ kg}$



CUPID-Mo

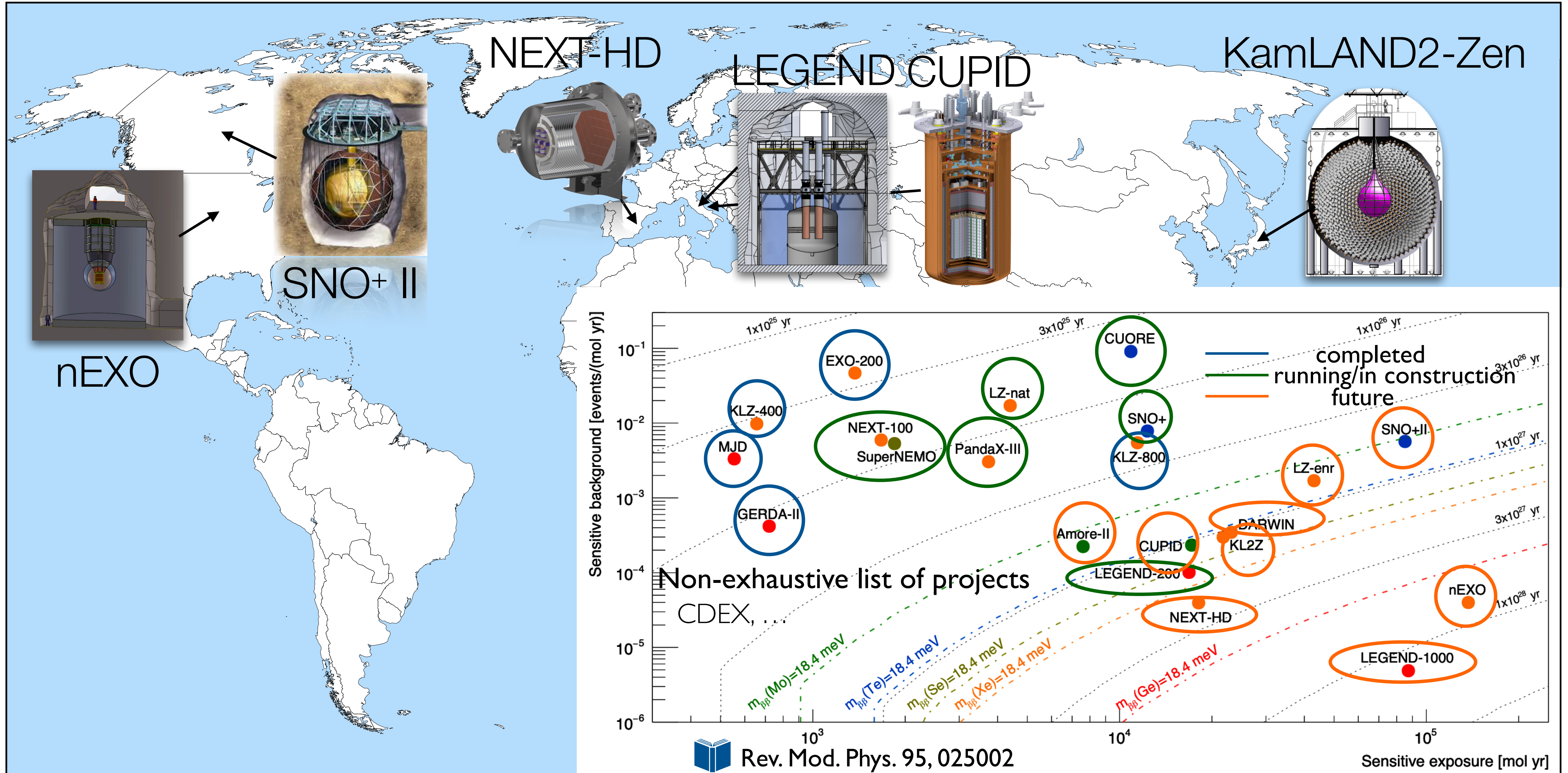


$\text{Li}_2^{\text{enr}}\text{MoO}_4$   
 $^{100}\text{Mo}$  (97%)  
 $m(^{100}\text{Mo}) \sim 2.26 \text{ kg}$



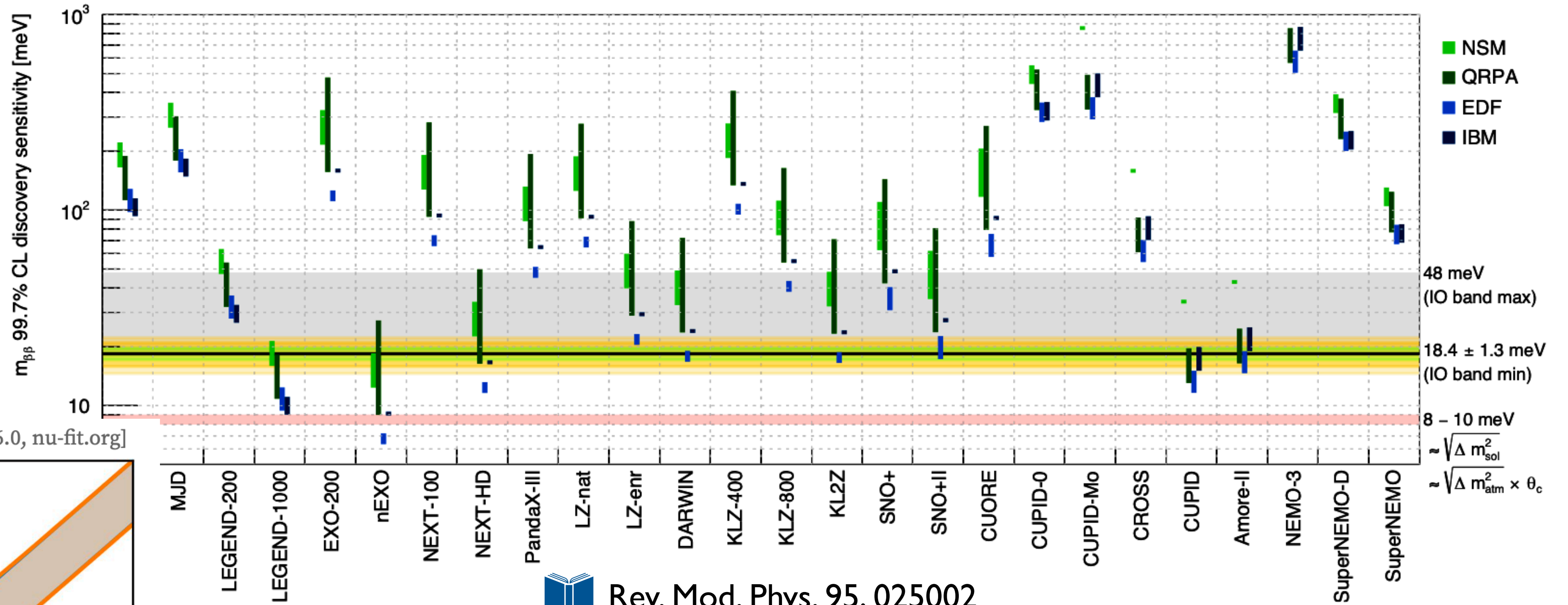
Phys. Rev. Lett. 126, 181802 (2021)

# Future perspectives of the search for neutrinoless double beta decay



# Future perspectives of the search for neutrinoless double beta decay

Discovery sensitivity of  $0\nu\beta\beta$  experiments for decay mediated by the light neutrino exchange



[NuFIT 6.0, nu-fit.org]

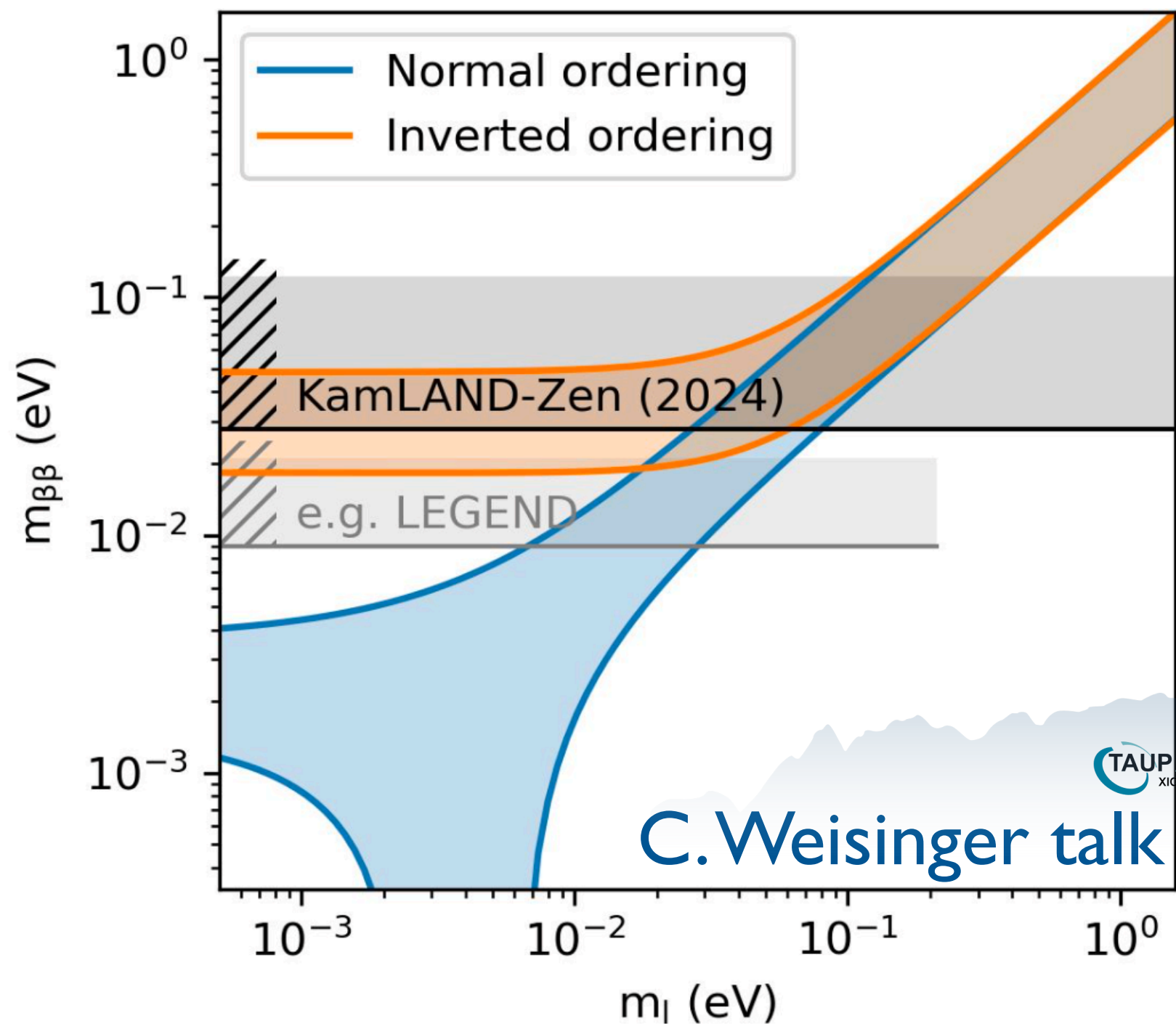
Rev. Mod. Phys. 95, 025002

Next generation tonne-scale projects will probe the **inverted ordering scenario**

$$m_{\beta\beta} = [9,21] \text{ meV } (3\sigma) \text{ LEGEND-1000}$$

$$m_{\beta\beta} = [12,21] \text{ meV } (3\sigma) \text{ CUPID}$$

similar numbers for Kam-LAND-2-Zen, nEXO...



C. Weisinger talk @ TAUP 2025

# Conclusions and perspectives

---

- ✓ CUORE proved the **scalability of the cryogenic calorimeters** technique to tonne-scale detectors thereby paving the way to **rare decay searches with cryogenic calorimeters**
- ✓ We exceeded 2 tonne · yr TeO<sub>2</sub> analyzed exposure and data collection is progressing towards our **goal** of a final **3 tonne · yr TeO<sub>2</sub> exposure** (corresponding to ~1 tonne · yr <sup>130</sup>Te)
- ✓ We found no evidence of  $0\nu\beta\beta$  decay with 2039.0 kg · yr TeO<sub>2</sub> exposure and set a new limit on the half life for such decay of  $T_{0\nu\beta\beta}^{1/2} > 3.5 \cdot 10^{25}$  yr (90 % C.I.)
- ✓ **Many interesting analyses ongoing** also beyond  $\beta\beta$  decay: background-related studies (e.g. muon reconstruction), multispectral (search for decays in multiple-crystal events) and low energy studies
- ✓ Important feedback for **CUPID**, both for the cryogenics and background budget
- ✓ After interventions on the cryogenics and before the CUPID detector installation, a CUORE phase II dedicated to **low energy studies** (dark matter searches, e.g. WIMPs, axions, ...) is planned

*Stay tuned*

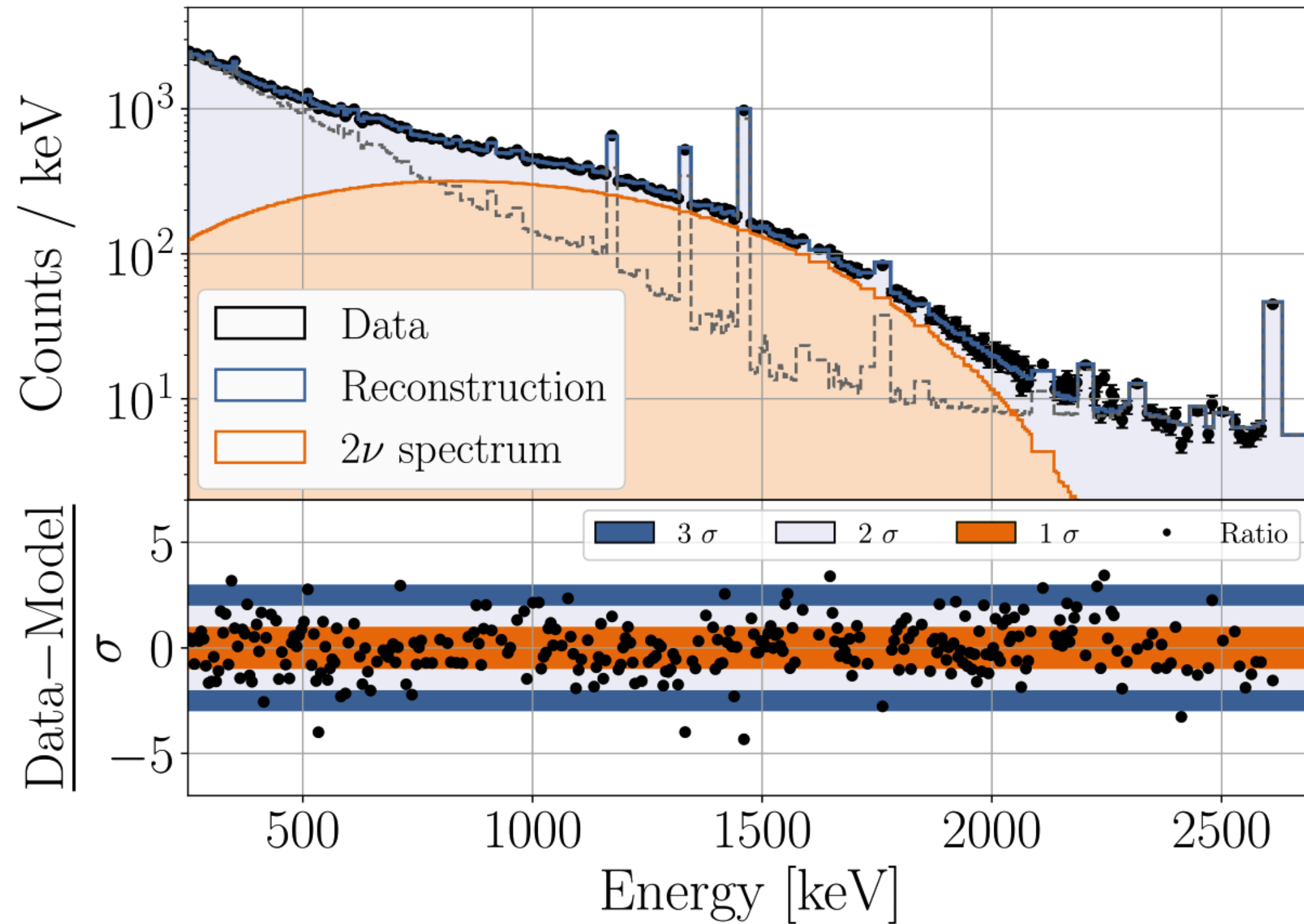
*Thank you for your attention*



*on behalf of CUORE collaboration*

# *Back -up slides*

# The outcome: most precise measurement of $^{130}\text{Te}$ $2\nu\beta\beta$ to date



$^{130}\text{Te}$   $2\nu\beta\beta$  decay: dominant component of the single-site spectrum from  $\sim 1$  to 2 MeV  
 → Precise study of  $2\nu\beta\beta$  spectral shape with **improved formalism** to Taylor expand over lepton energies and **constraint  $g_A^{\text{eff}}$**  (1<sup>st</sup> time)

Phys. Rev. Lett. 135, 082501 (2025)

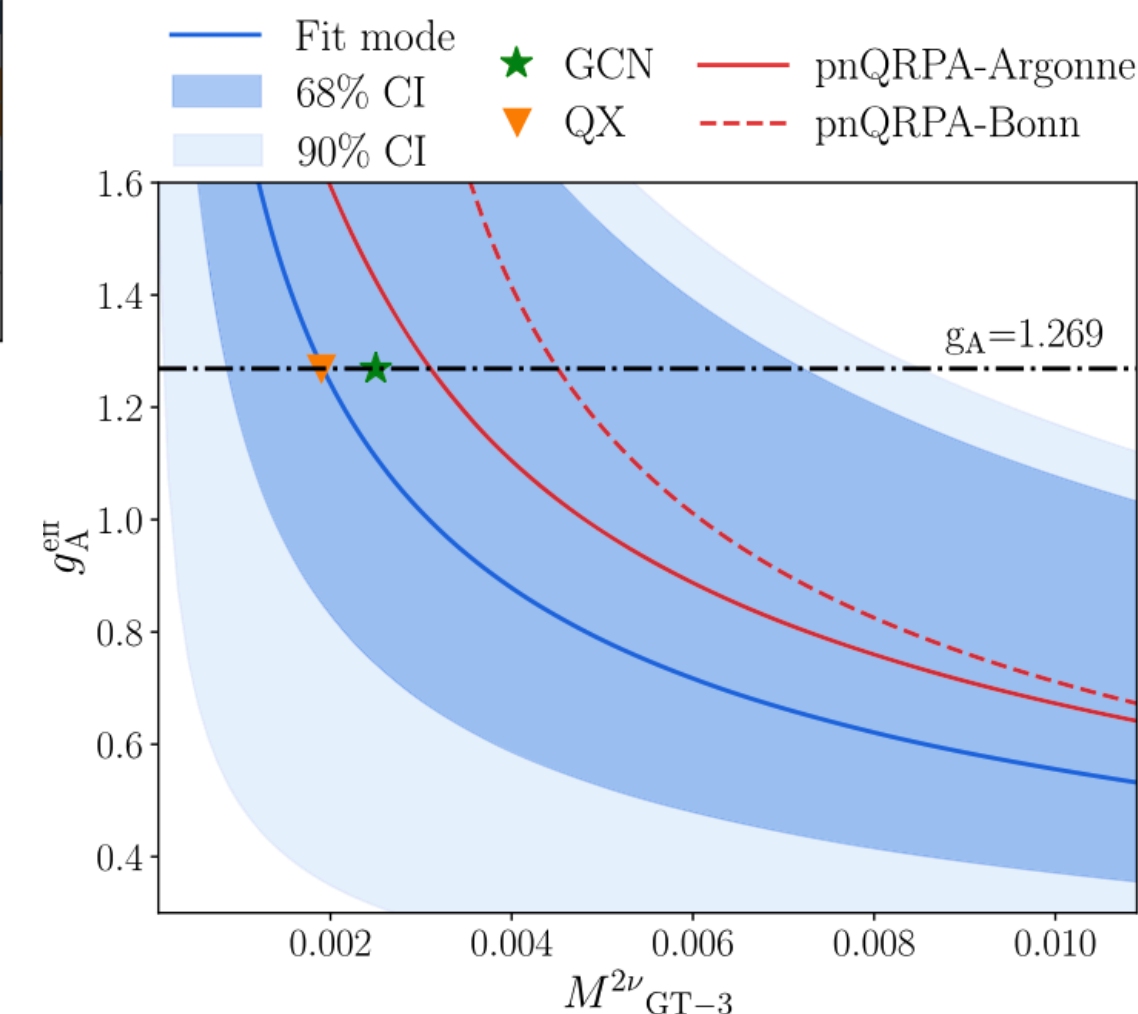
Twofold improvement on  $^{130}\text{Te}$   $2\nu\beta\beta$  half-life precision:

$$T_{1/2}^{2\nu} = \left[ 9.32 \begin{matrix} +0.05 \\ -0.04 \end{matrix} \text{ (stat.)} \begin{matrix} +0.07 \\ -0.07 \end{matrix} \text{ (syst.)} \right] \cdot 10^{20} \text{ yr}$$

Stat. (Syst.) uncertainty  $\sim 0.5\%$  ( $< 1\%$ )

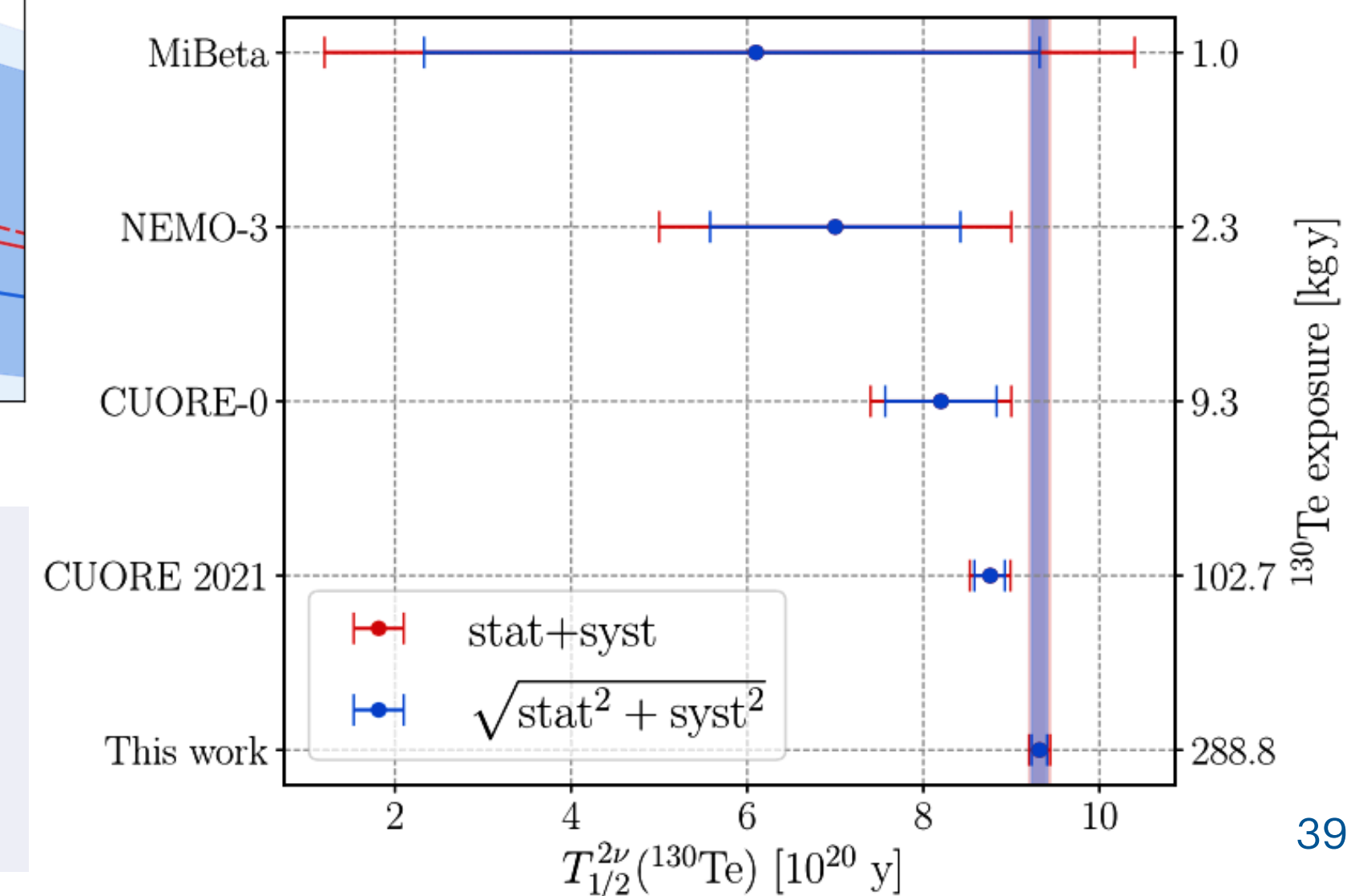
**Nuclear state model:** *Single State Dominance (SSD)* with leading contribution from  $1+$  state preferred

Phys. Rev. Lett. 135, 082501 (2025)



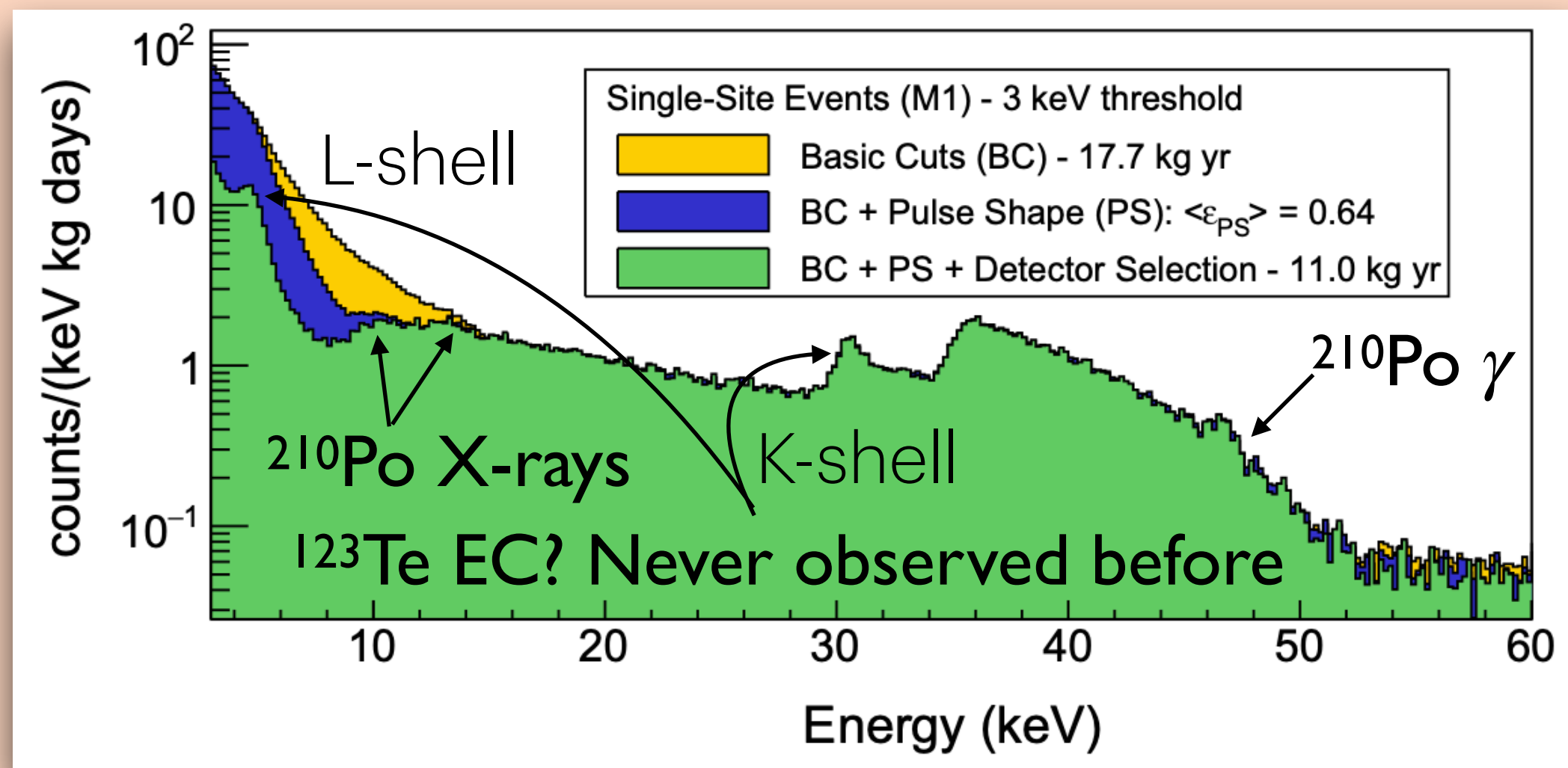
Quenching of  $g_A$  confirmed: match with theoretical models but high uncertainties

Comparison with nuclear models shows results far from expectations  
 Hp: incomplete description or BSM

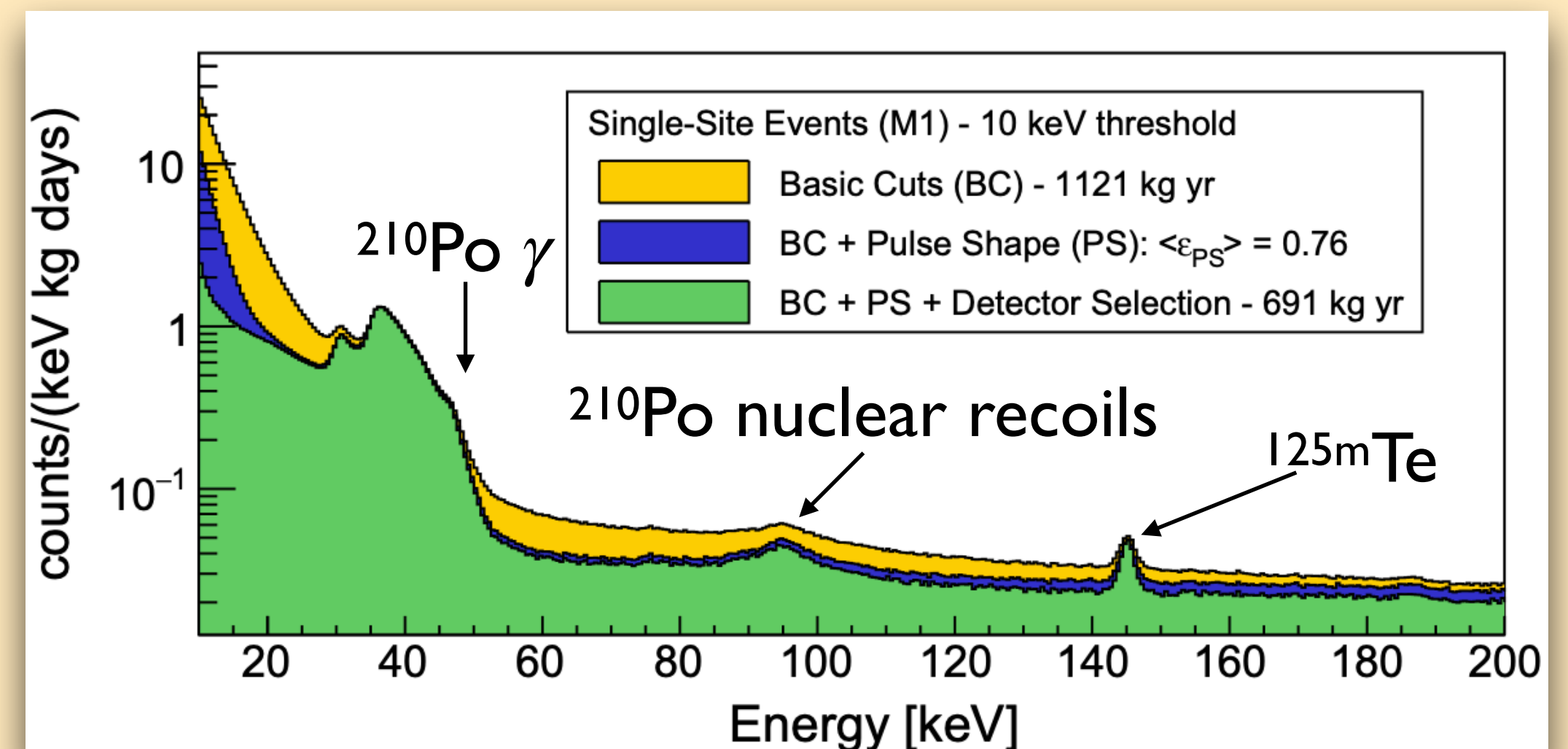


# The outcome: access to the low energy region for physics

- **Low energy studies:** specific low-energy variables and event-level cuts to optimise sensitivity at keV-scale targeting several searches:
- spectral studies related to  $^{121}\text{Te}$ ,  $^{123}\text{Te}$ ,  $^{125\text{m}}\text{Te}$  decays and surface lead contaminations ( $^{210}\text{TlPo}$ ): ROI of [3, 10] keV,  $\sim 1.2$  keV FWHM, 11 kg · yr / 2 tonne · yr  $\rightarrow$  1.2% of crystals  
16 cts/keV/kg/day bkg, efficiency  $\epsilon_{\text{tot}} \simeq 26\%$

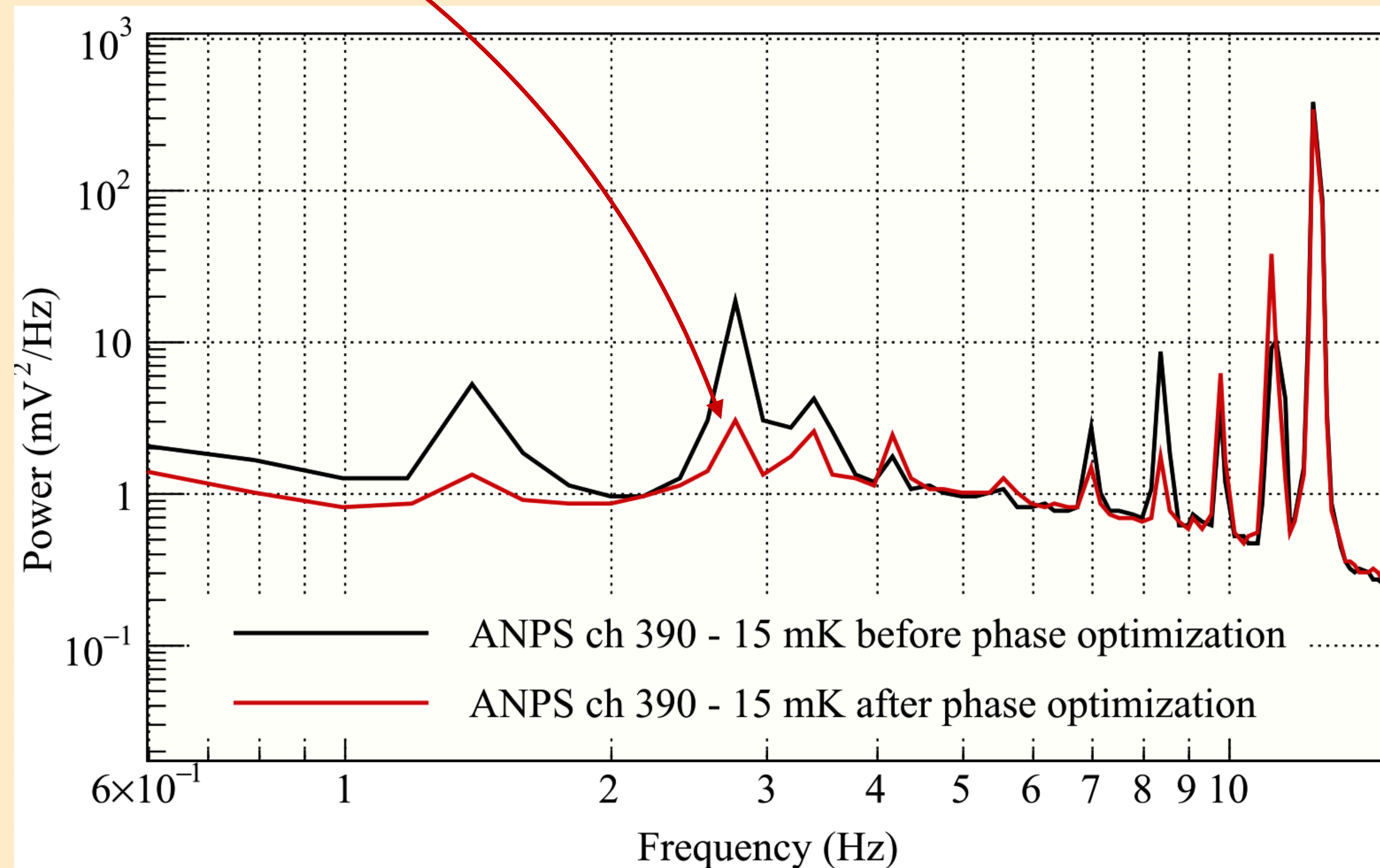



- Increased sensitivity for Beyond-SM searches - many phenomena predicted near CUORE threshold:
- **Cosmic** [3-200 keV from the Galactic Dark Matter Halo] and **solar** [14 keV line from  $^{57}\text{Fe}$  transition in the Sun] **axions, WIMPs annual modulation:** ROI of [10, 20] keV,  $\sim 2.5$  keV FWHM, 691 kg · yr / 2 tonne · yr  $\rightarrow$  35% of crystals, 2 cts/keV/kg/day bkg,  $\epsilon_{\text{tot}} \simeq 50\%$



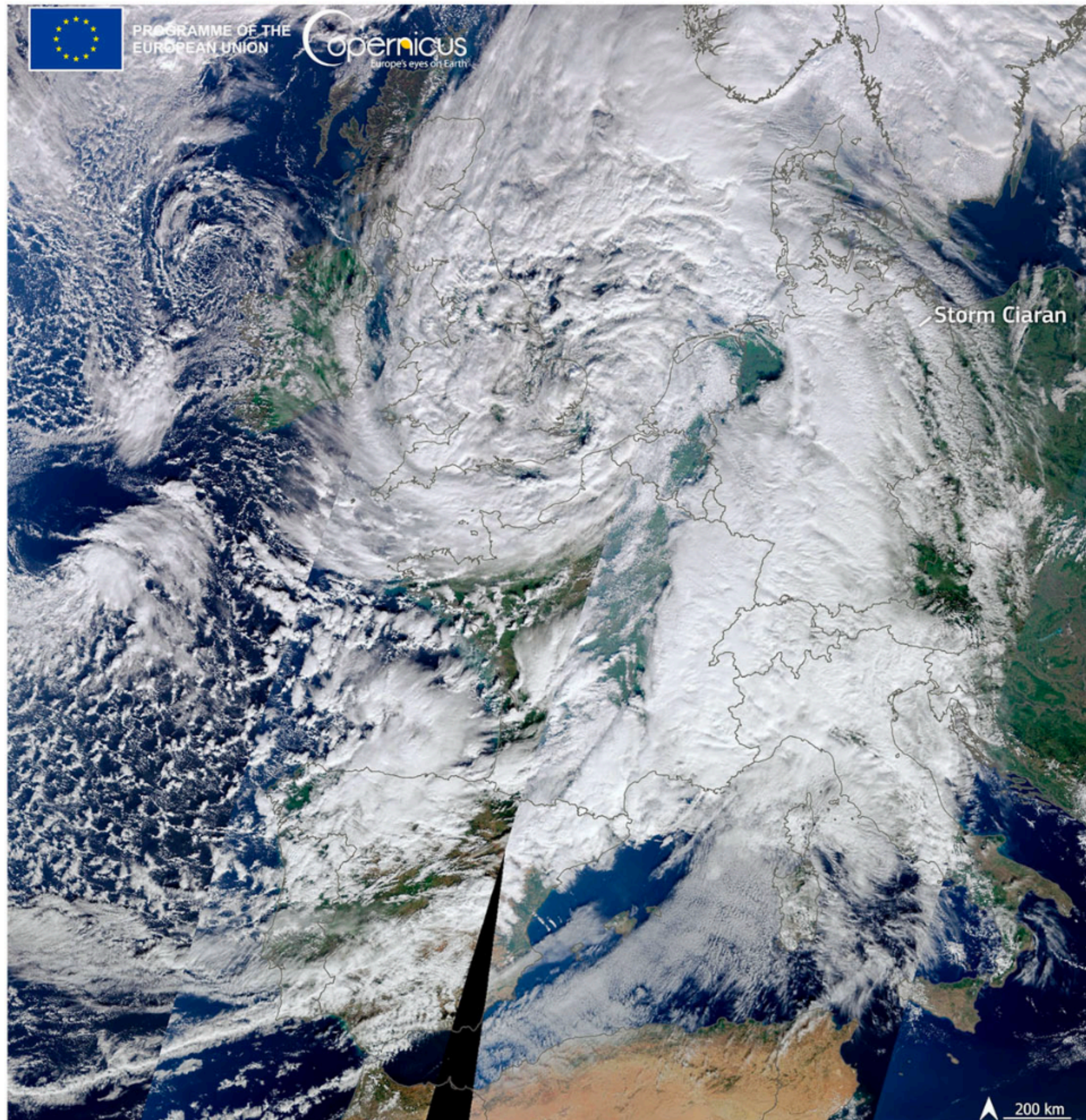
# The challenges - part II: suppressing noise sources

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

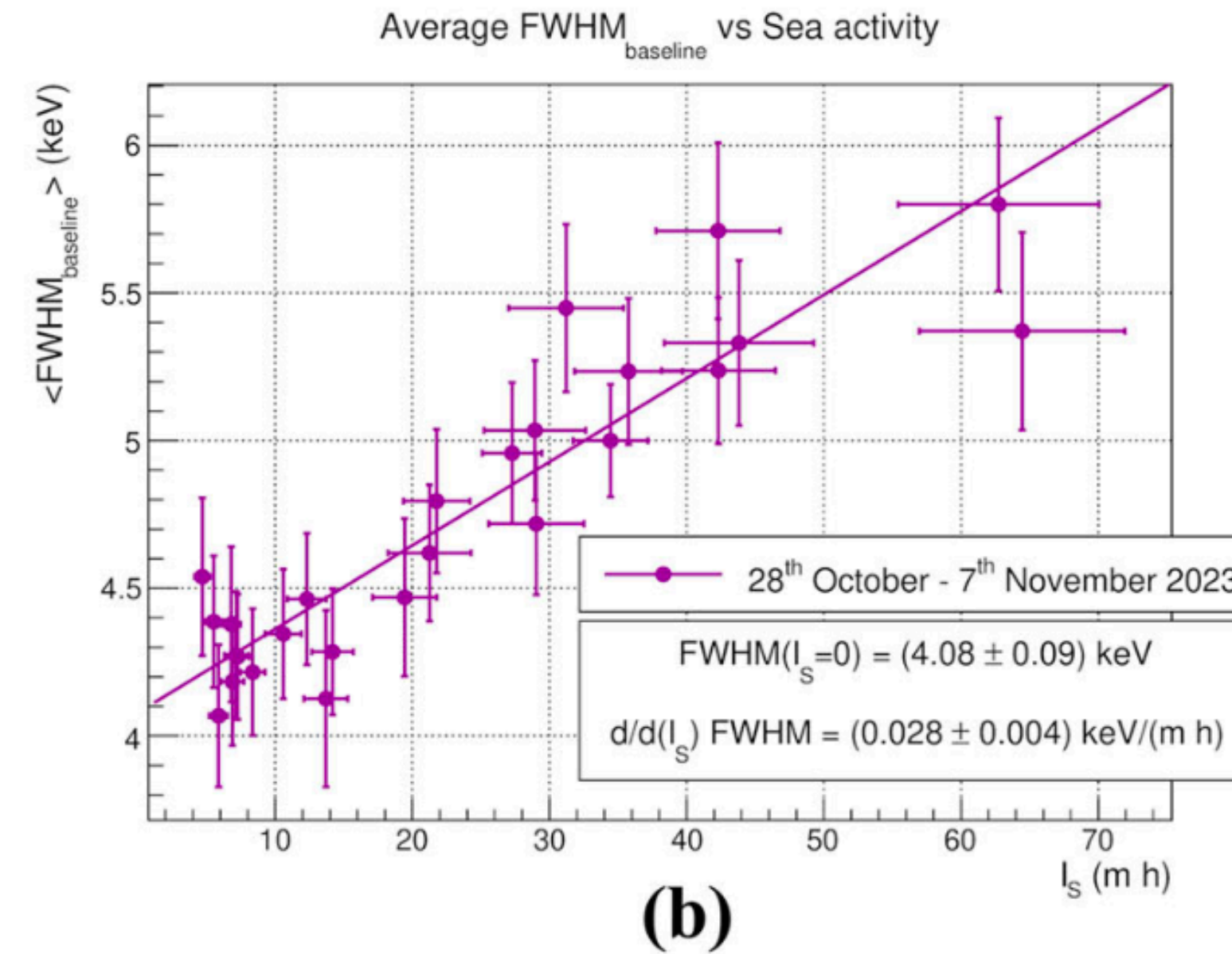


 Cryogenics 93, 56-65 (2018)

# The outcome: CUORE is sensitive to microseismic activity of the Mediterranean sea



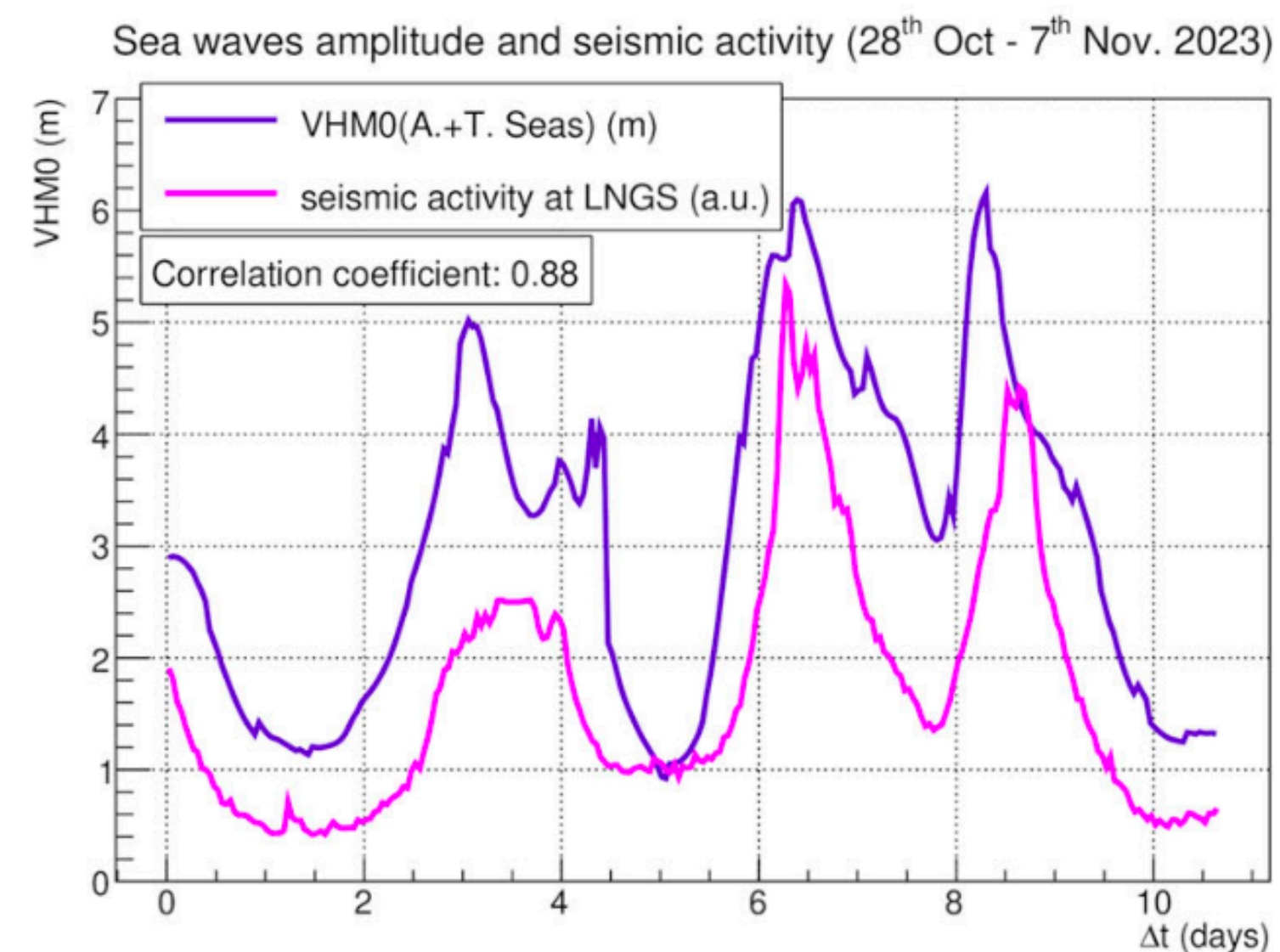
(a)



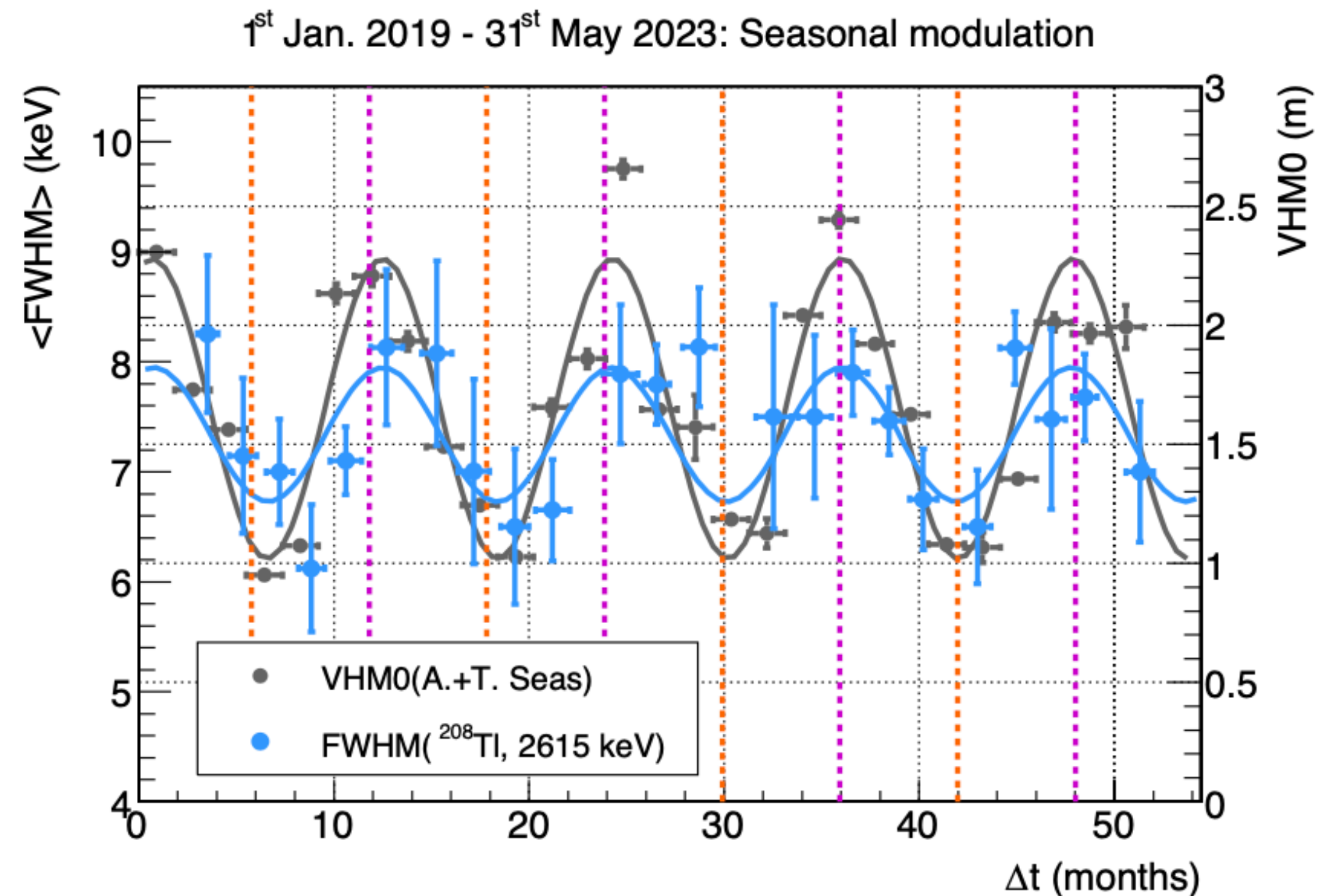
There is a correlation between sea activity and low frequency noise

subHz noise increases during Mediterranean storm outbreaks.

Maximum response at  $\nu \sim 0.6$  Hz: resonant mode of the CUORE infrastructure



# The outcome: CUORE is sensitive to microseismic activity of the Mediterranean sea



The seasonal modulation of CUORE baseline resolution:

CUORE FWHM baseline resolution is linearly correlated to Sea activity as reflected by its seasonal modulation (1 yr period)

# 2 tonne·yr data: analysis & $0\nu\beta\beta$ fit parameters

Table I: Relevant parameters for the 2 tonne yr  $0\nu\beta\beta$  analysis

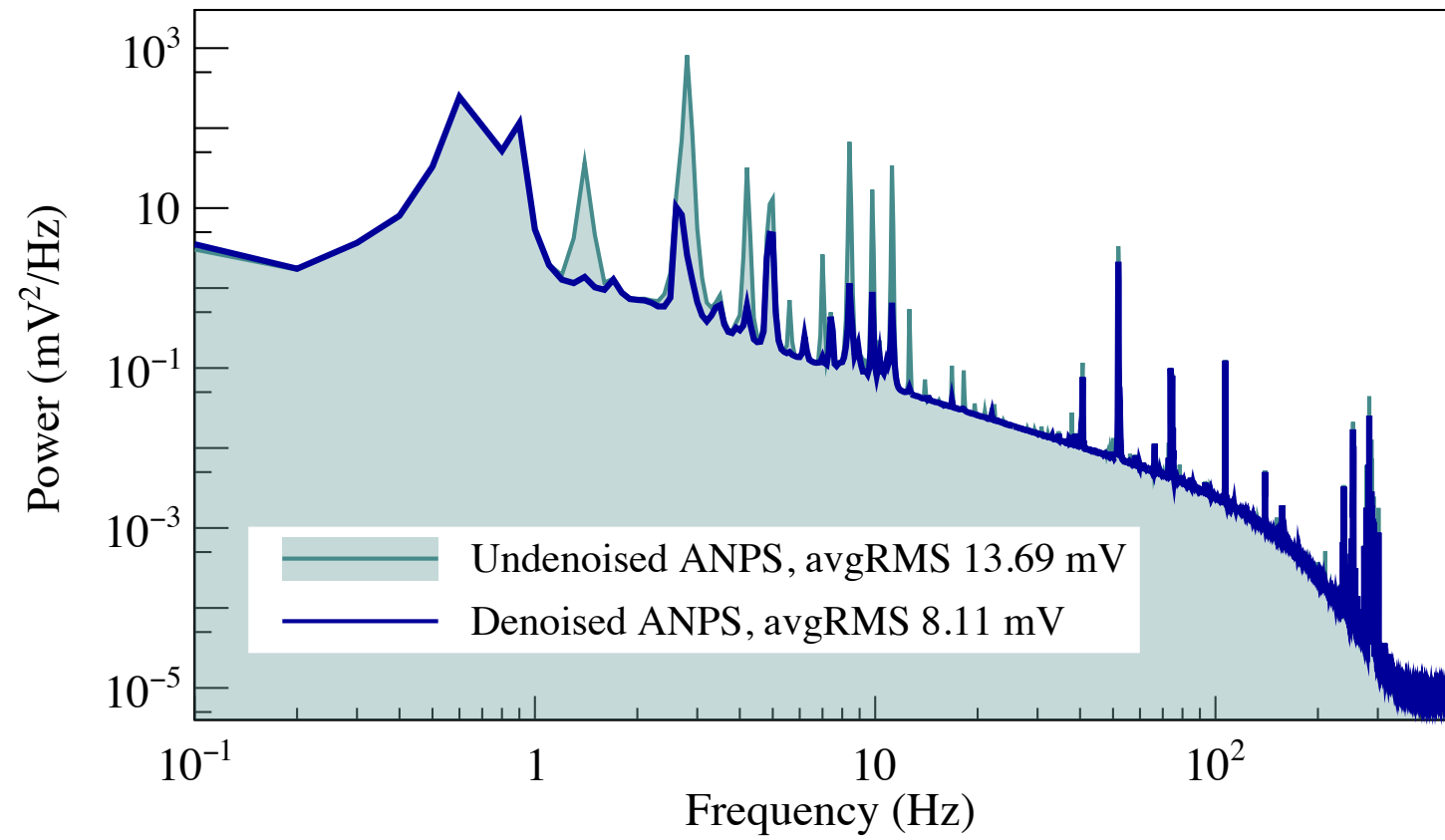
Operational detectors	Functioning detectors	984/988
	Active detectors (average)	914/988
Amount of data	# Datasets	28
	TeO <sub>2</sub> exposure	2039.0 kg yr
	<sup>130</sup> Te exposure	567.0 kg yr
Energy calibration	2615 keV ( <sup>208</sup> Tl) FWHM (calibration)	7.540(24) keV
	Q <sub>ββ</sub> (2528 keV) FWHM (physics)	7.310(24) keV
	Bias @ Q <sub>ββ</sub> (2528 keV) (physics)	0.40 <sup>+0.21</sup> <sub>-0.44</sub> keV
Data selection efficiency	Reconstruction (base cuts) efficiency	95.624(16)%
	Anti-coincidence (AC) efficiency	99.80(5)%
	Pulse Shape Discrimination (PSD) efficiency	97.9(18)%
	Total analysis efficiency	93.4(18)%
	Containment efficiency (Monte Carlo)	88.35(9)%

Table II:  $0\nu\beta\beta$  fit parameters of the 2 tonne yr data

<b>Limit setting sensitivity</b>	
90% C.I. limit on $T^{1/2}_{0\nu\beta\beta}$	4.4 10 <sup>25</sup> yr
<b>Bayesian fit</b>	
Best-fit $\Gamma_{0\nu\beta\beta}$	5.5 <sup>+7.3</sup> <sub>-5.5</sub> 10 <sup>-27</sup> yr <sup>-1</sup> (stat.+syst.)
90% C.I. limit on $\Gamma_{0\nu\beta\beta}$	2.0 10 <sup>-26</sup> yr <sup>-1</sup>
90% C.I. limit on $T^{1/2}_{0\nu\beta\beta}$	3.5 10 <sup>25</sup> yr
$P(T^{1/2} > T^{1/2}_{0\nu\beta\beta})$	74%
<b>Frequentist fit</b>	
90% C.L. limit on $\Gamma_{0\nu\beta\beta}$	2.0 10 <sup>-26</sup> yr <sup>-1</sup>
90% C.L. limit on $T^{1/2}_{0\nu\beta\beta}$	3.4 10 <sup>25</sup> yr
<b>Effective Majorana mass</b>	
$m_{\beta\beta}$	70 - 250 meV
<b>Residual background in the ROI</b>	
BI (counts/keV/kg/yr)	1.42 <sup>+0.03</sup> <sub>-0.02</sub> 10 <sup>-2</sup>

# Data processing chain to extract a spectrum of events

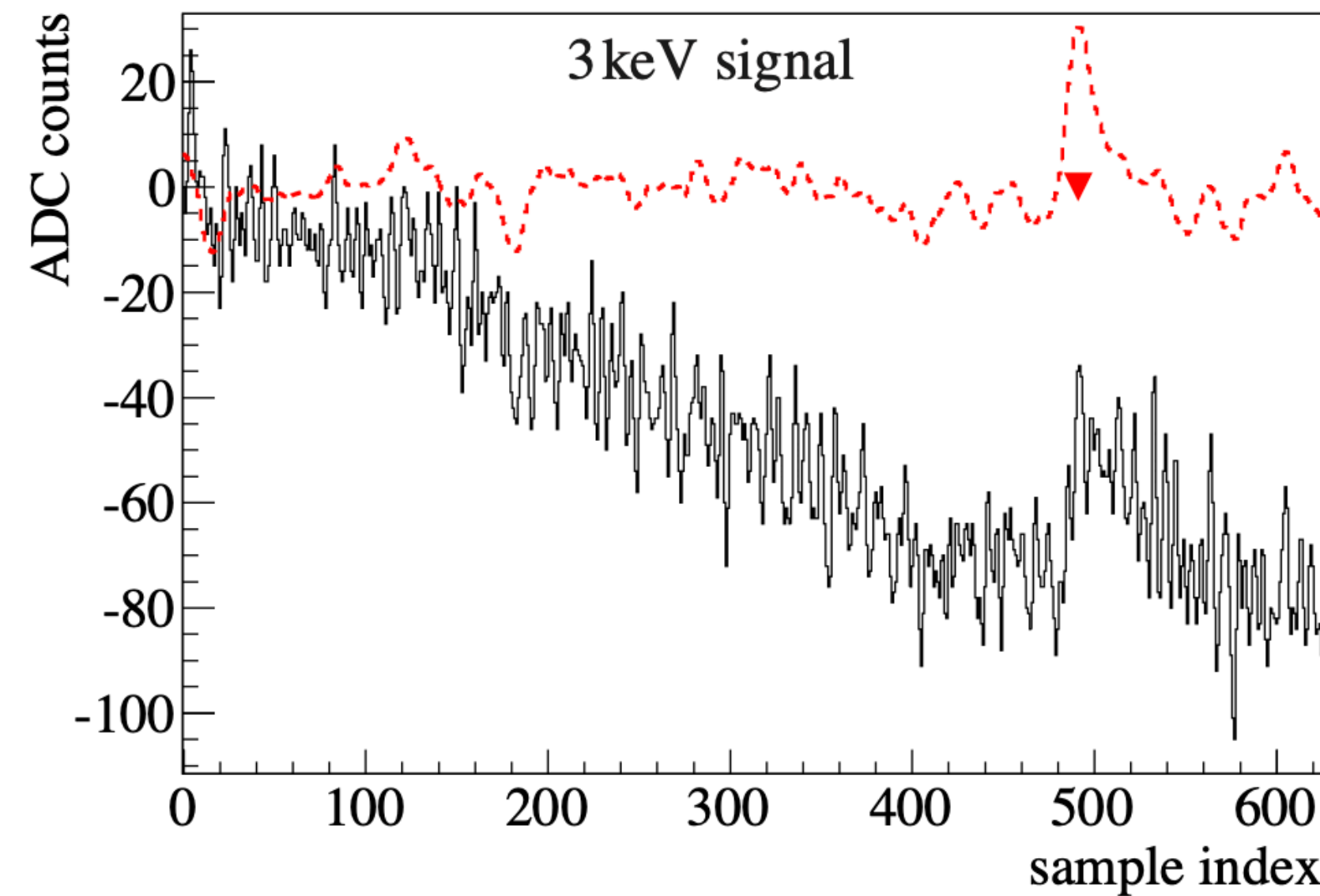
## Denoising (New!)



Noise is mitigated correlating vibrations with measurements obtained with *auxiliary devices*, i.e. microphones, accelerometers, seismometers

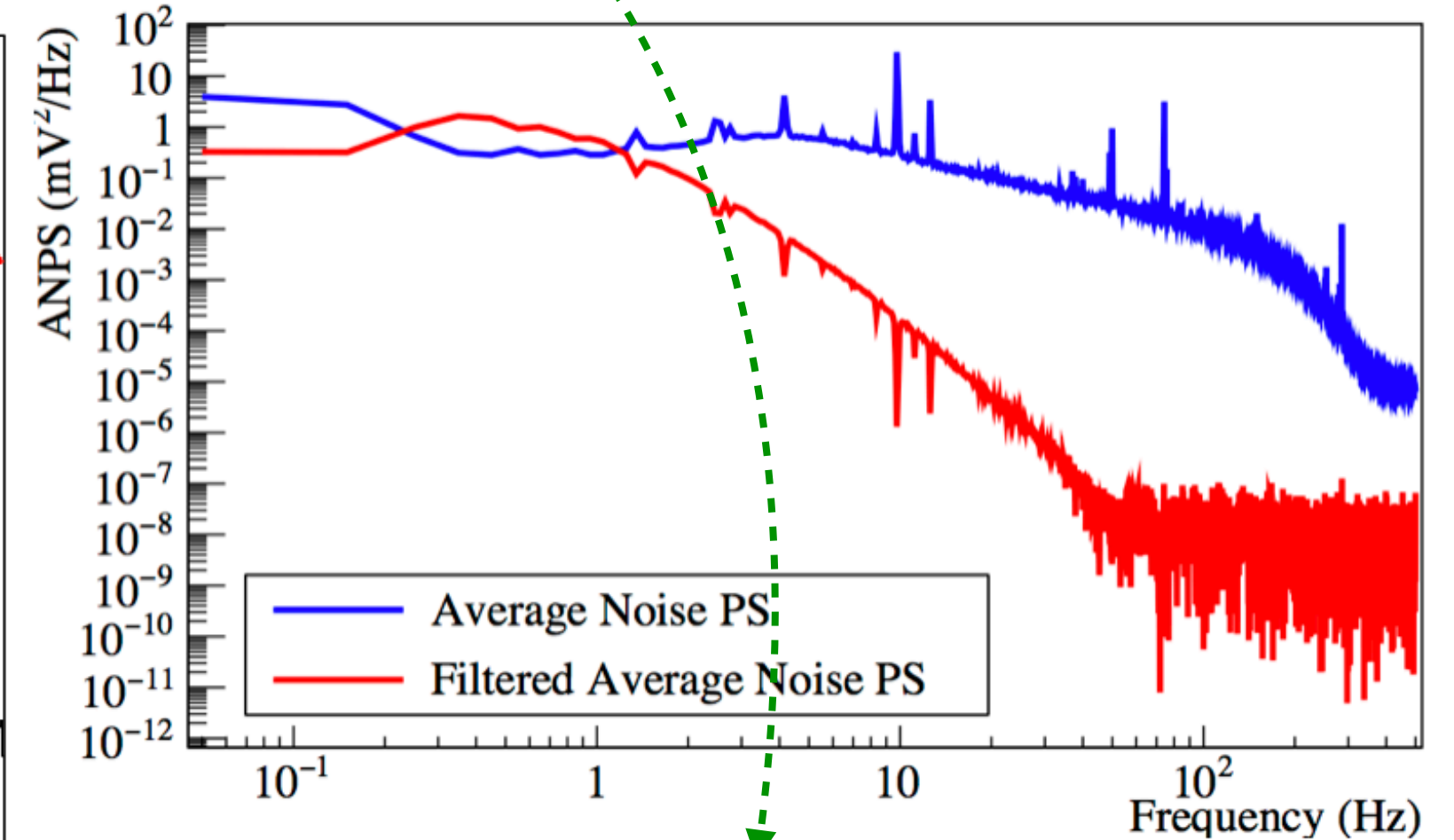
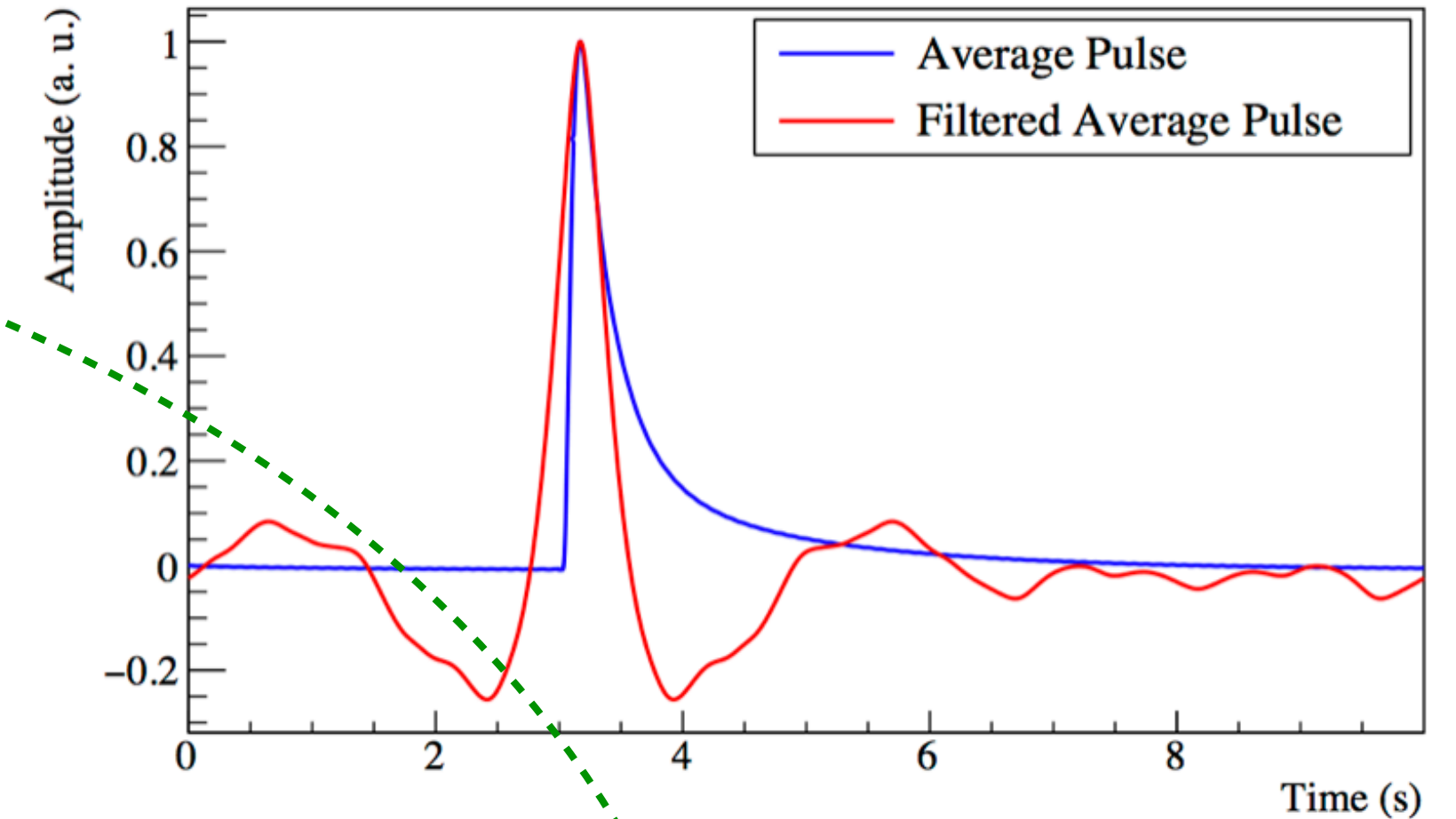
## Optimum trigger (OT)

Offline data retrigger with OT to maximize SNR exploiting the distinct power spectra of particle induced and noise waveforms.



JINST 6, P02007 (2011)

Science 390, 1029-32 (2025)

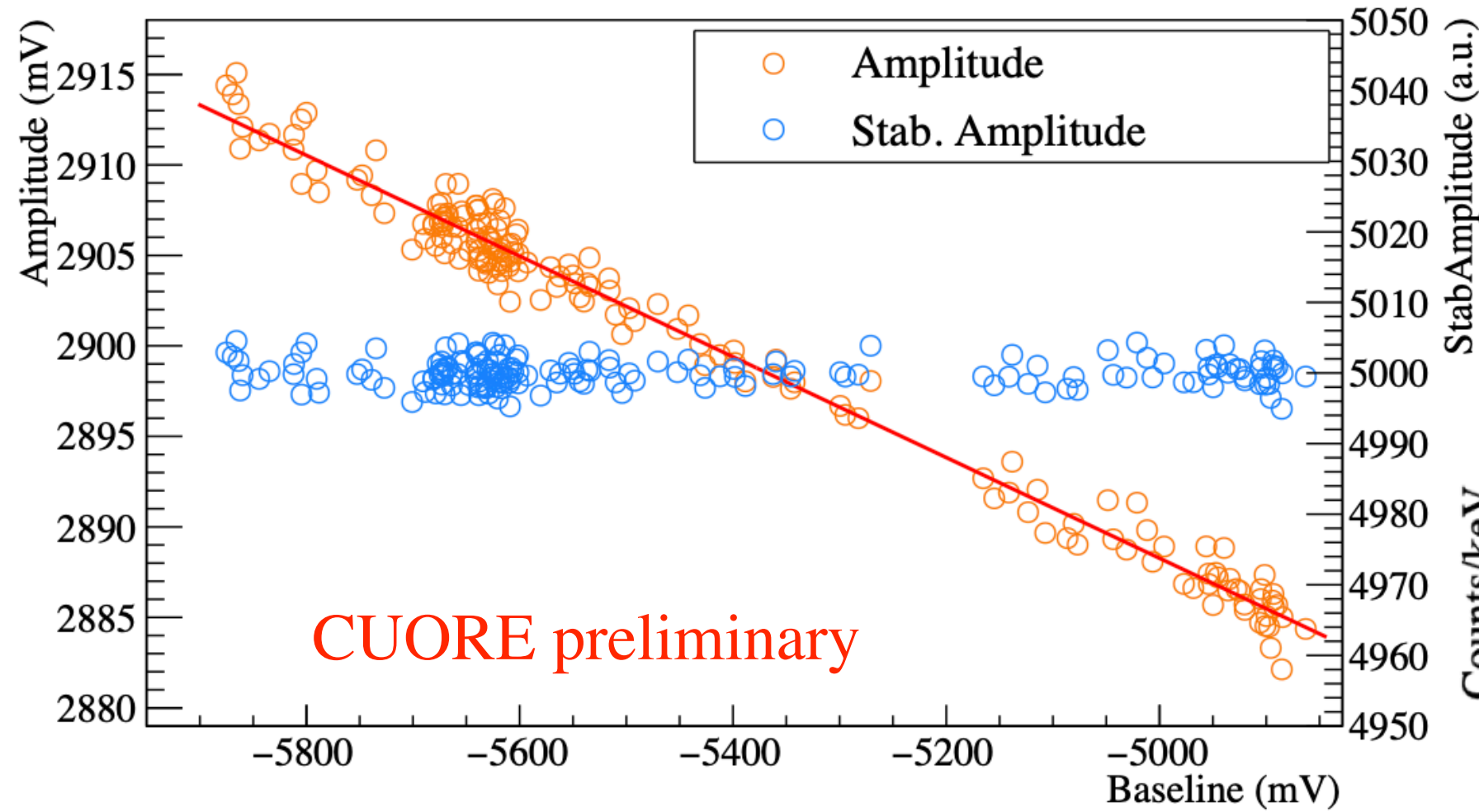


## Optimum Filter technique

We evaluate *filtered* signal amplitude

# Data processing chain to extract a spectrum of events

## Thermal gain stabilization (TGS)



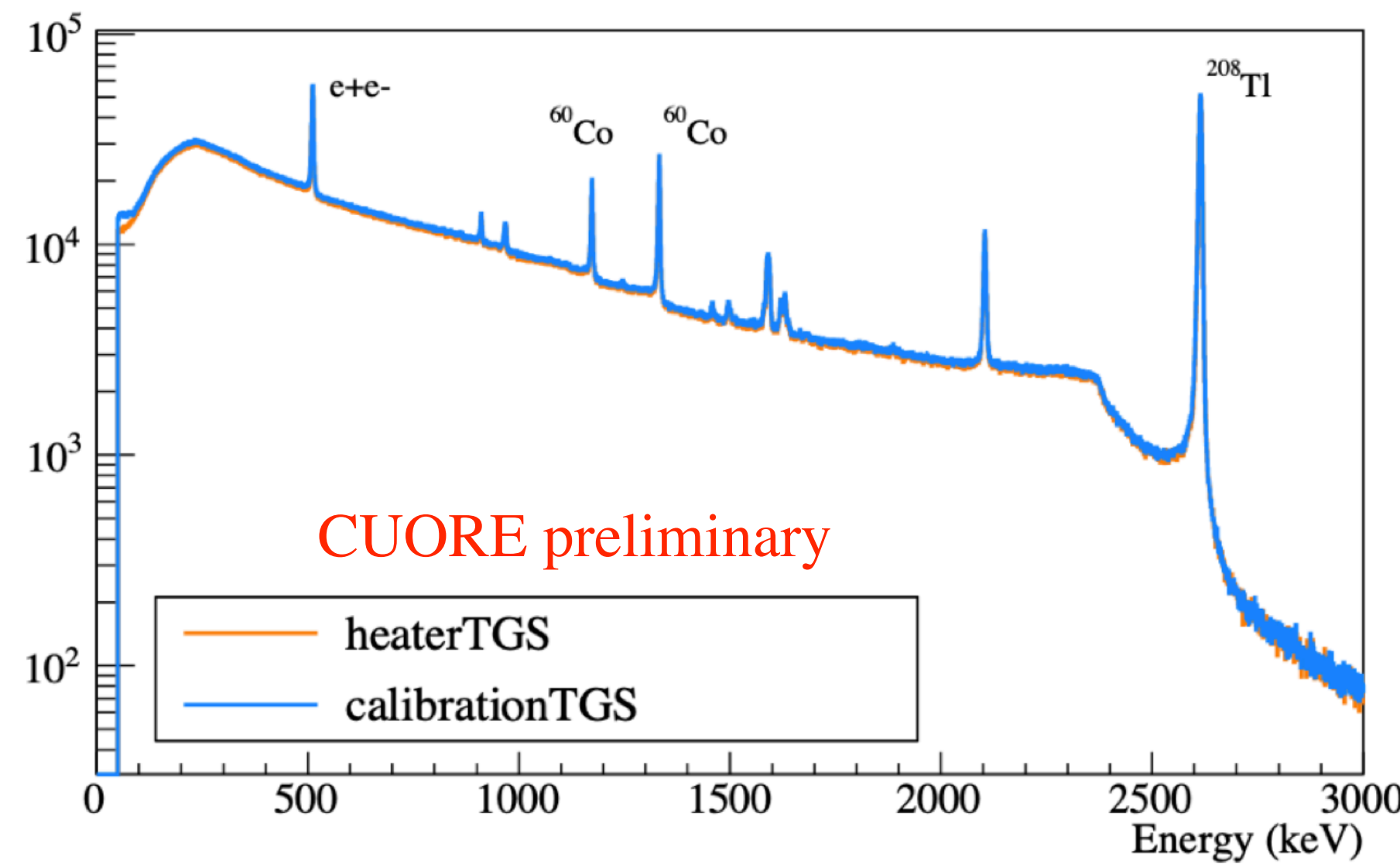
We employ fixed energy pulses to correct for drifts in the thermal gain



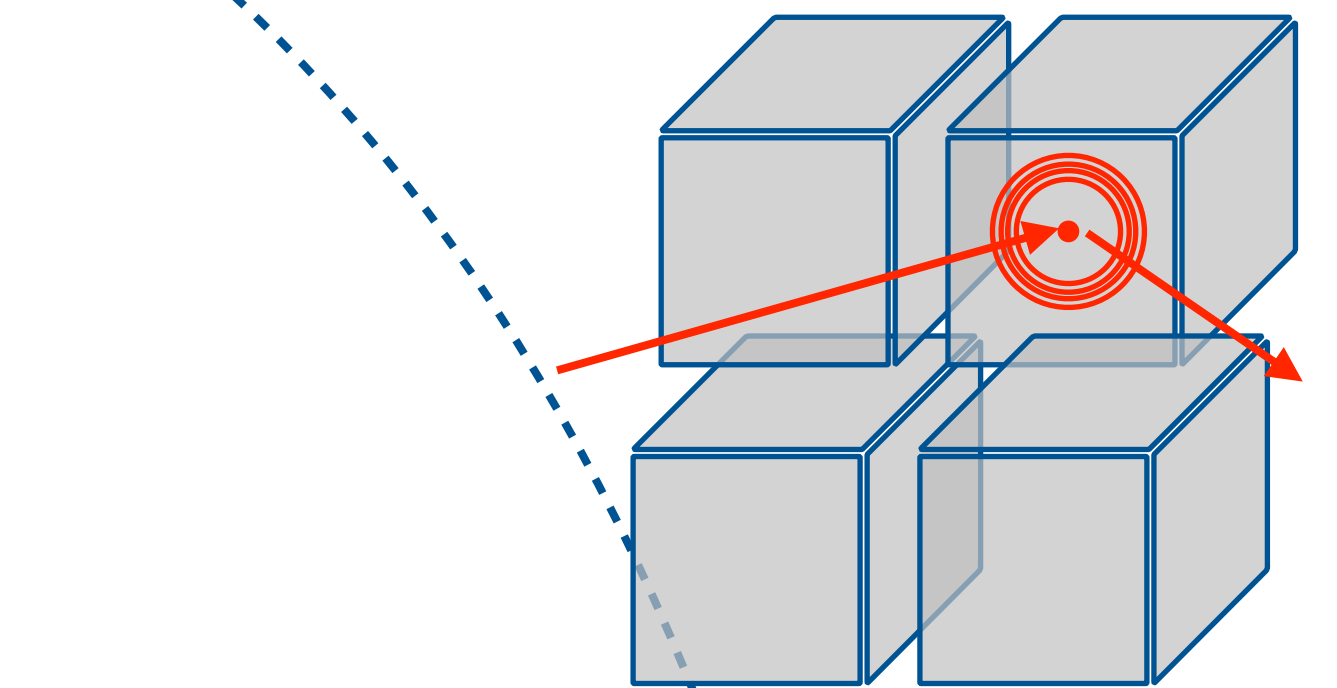
arxiv:2510.25720

## Energy calibration

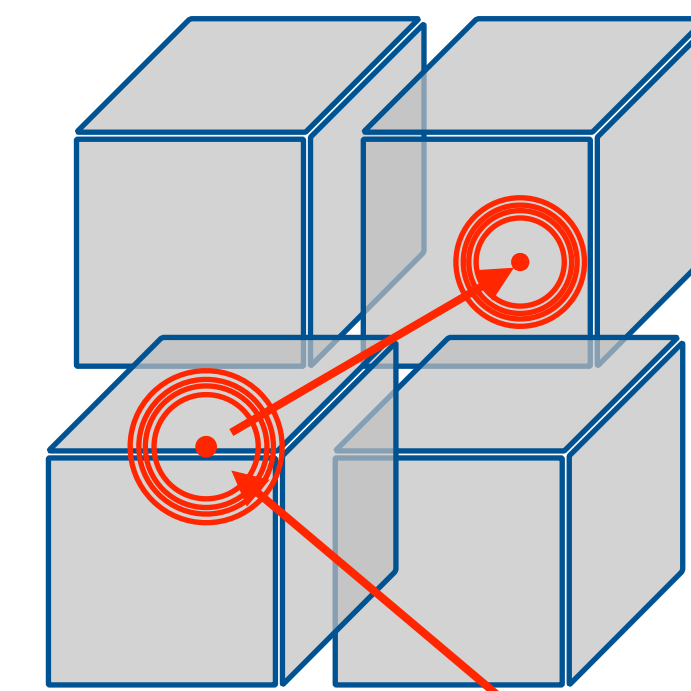
This is based on measurements with  $^{232}\text{Th}$  +  $^{60}\text{Co}$  external strings, periodically deployed in the detector  
We use a 2<sup>nd</sup> order polynomial fit to extract our calibration coefficients



We identify *simultaneous* ( $\pm 5$  ms) particle events on multiple crystals



single-crystal



multi-crystal

Coincidences

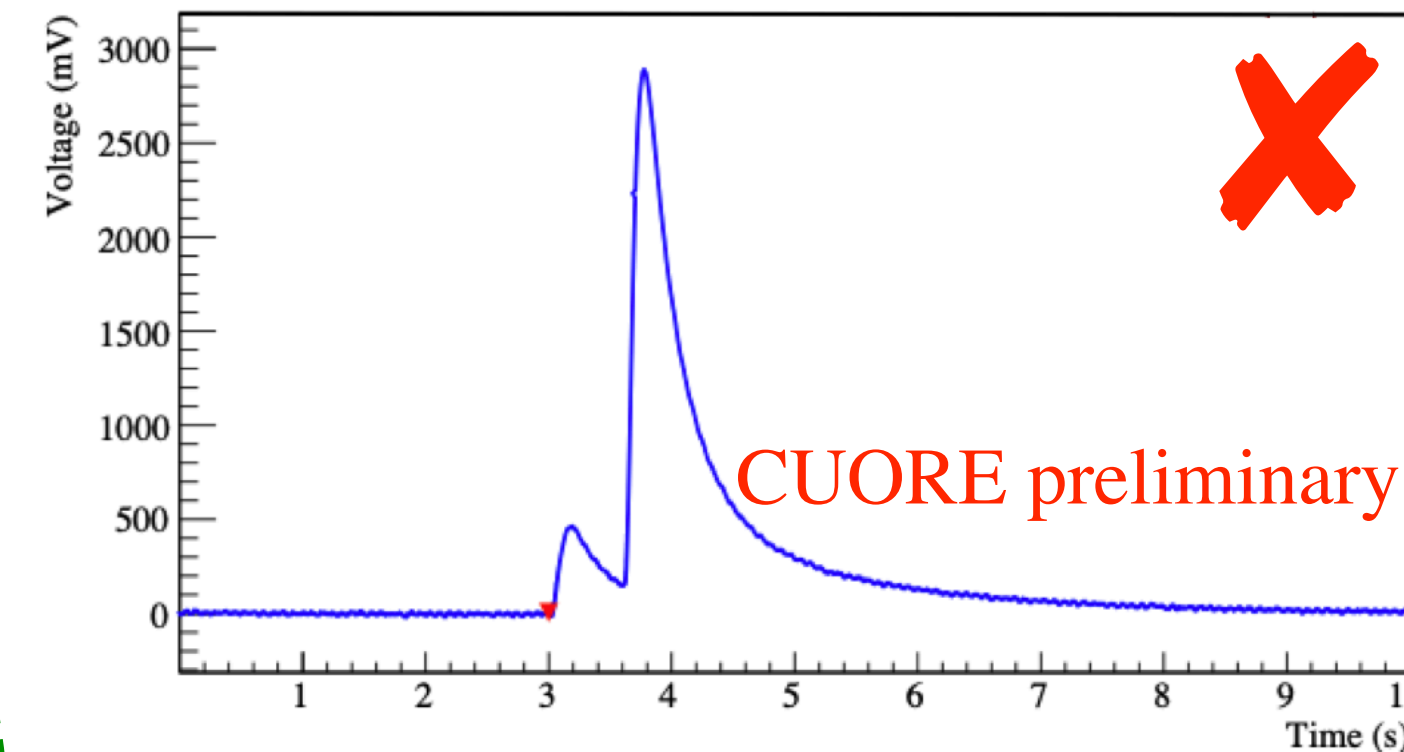
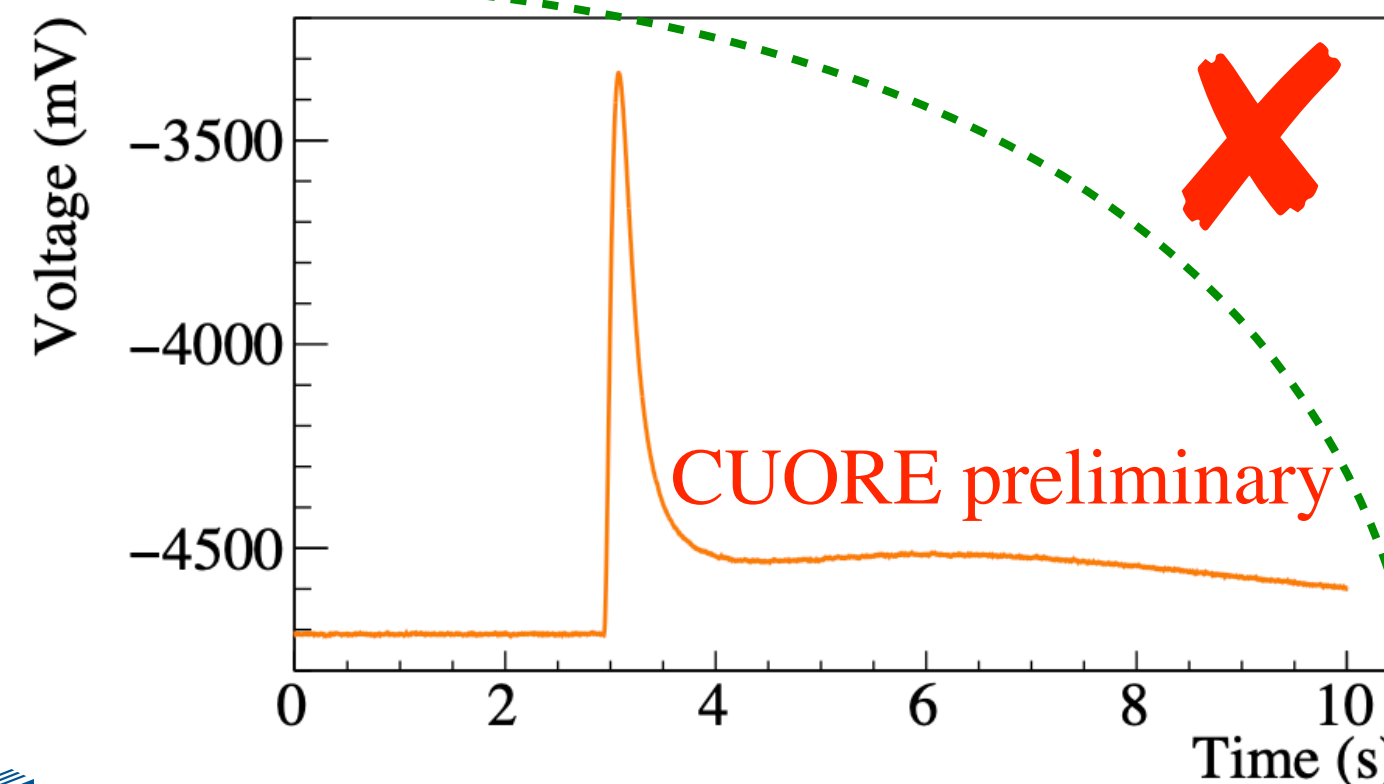
# Data selection to detect $0\nu\beta\beta$

## Anti-coincidence (AC) selection

From MC simulations, we expect  $\sim 88\%$  of  $0\nu\beta\beta$  events to release all the energy in the same crystal in which the decay occurred. Thus, we reject multi-site events, i.e. events with *Multiplicity*  $> 1$



arxiv:2510.25720



## Pulse shape discrimination (PSD)

We use Principal Component Analysis (PCA) to reject non-signal like and noisy events

## ROI blinding

To avoid biasing our result, we exchange events from  $^{208}\text{Tl}$  line at 2615 keV with events at the  $^{130}\text{Te}$   $0\nu\beta\beta$  Q-value

## Analysis efficiency evaluation

This is the strategy we adopted for the 2<sup>nd</sup> tonne · yr (**2<sup>nd</sup> TY**) data

## Detector response

## ROI model and blinded fit

## Data unblinding and fit