INFN LNGS

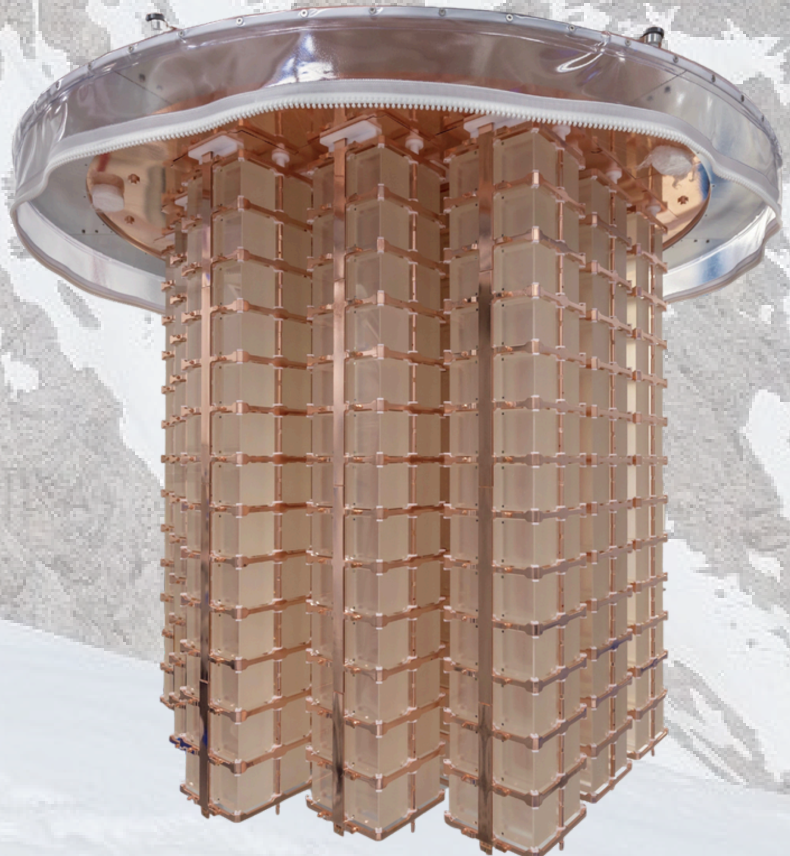
CUORE

GRAN SASSO SCIENCE INSTITUTE

Unlocking the CUORE keV Frontier: Axion and Rare-Event Searches

Anastasiia Shaikina (Gran Sasso Science Institute)
on behalf of the CUORE collaboration

Identification of Dark Matter, Zaragoza, 2 June 2026



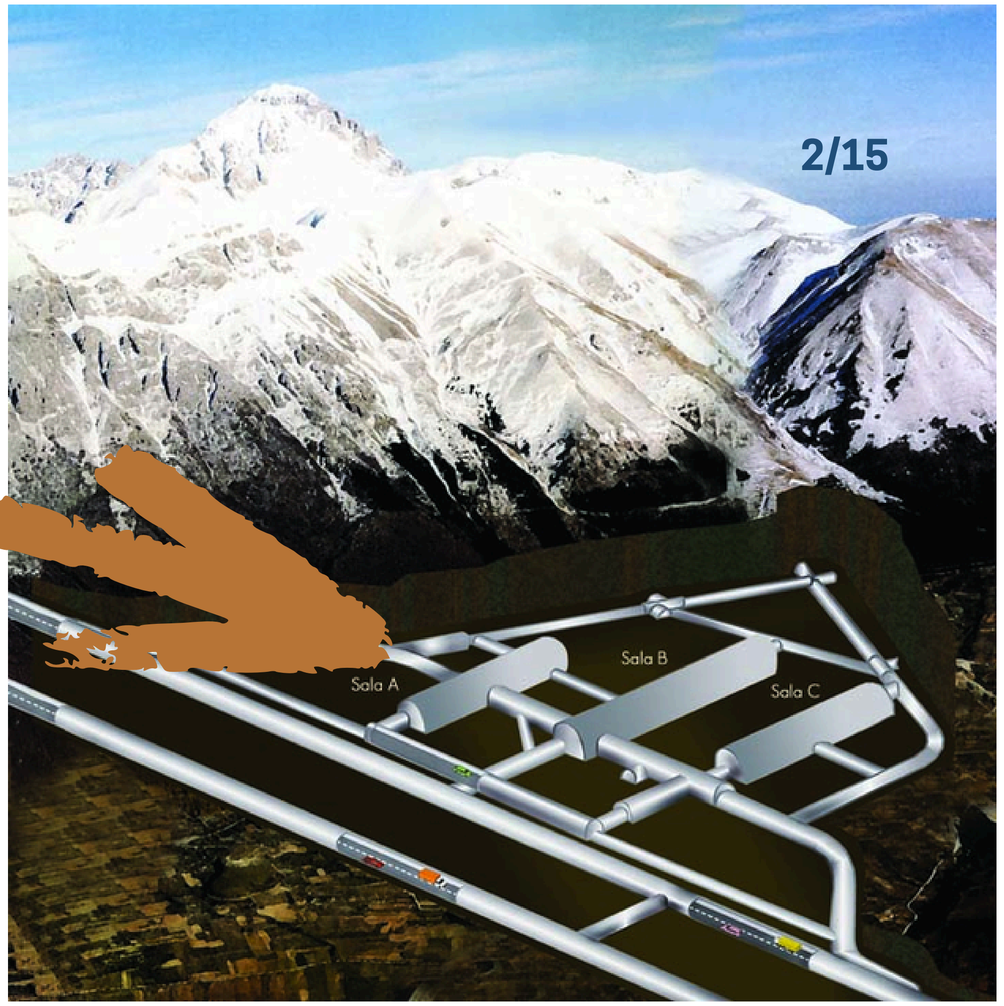
CUORE at a glance

Cryogenic Underground Observatory for Rare Events

Location

LNGS, Italy

Underground laboratory, ~3600 m.w.e.



Primary mission:

$0\nu\beta\beta$ search in ^{130}Te; low thresholds enable rare low-energy signals (e.g. **solar axions, cosmic axions, WIMPs**)

Detector

988 TeO_2 crystals arranged in 19 towers

Active mass

742 kg of TeO_2

Including 206 kg of ^{130}Te

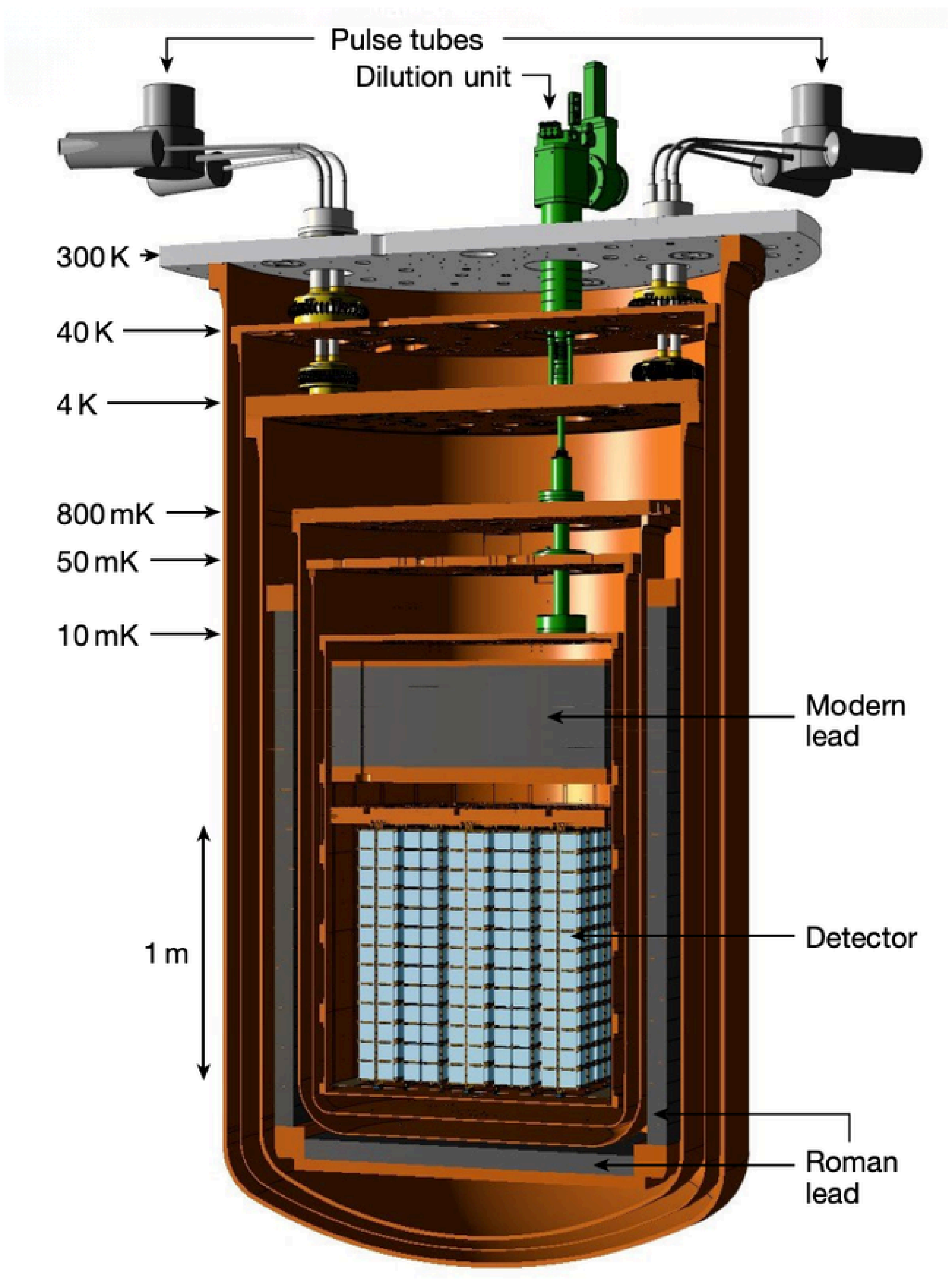
Operating conditions

Cryogenic calorimeters operated at ~10 mK

First tonne-scale cryogenic calorimeter array

Largest cryogenic calorimeter detector ever built

Operating a tonne-scale detector at ~10 mK



📖 Nature 604, 53–58 (2022)

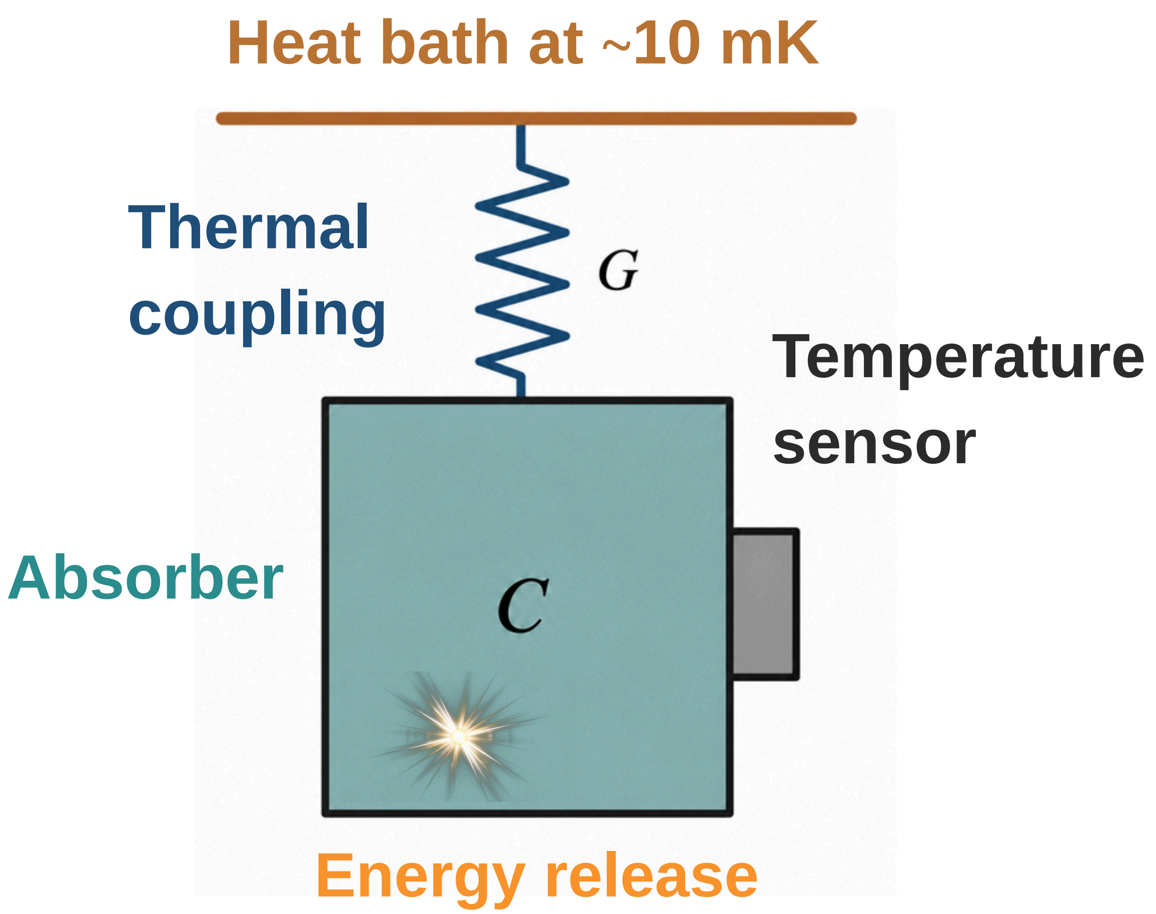
Cryogenics
- custom **cryogen-free dilution cryostat**
- stable operation at ~10 mK

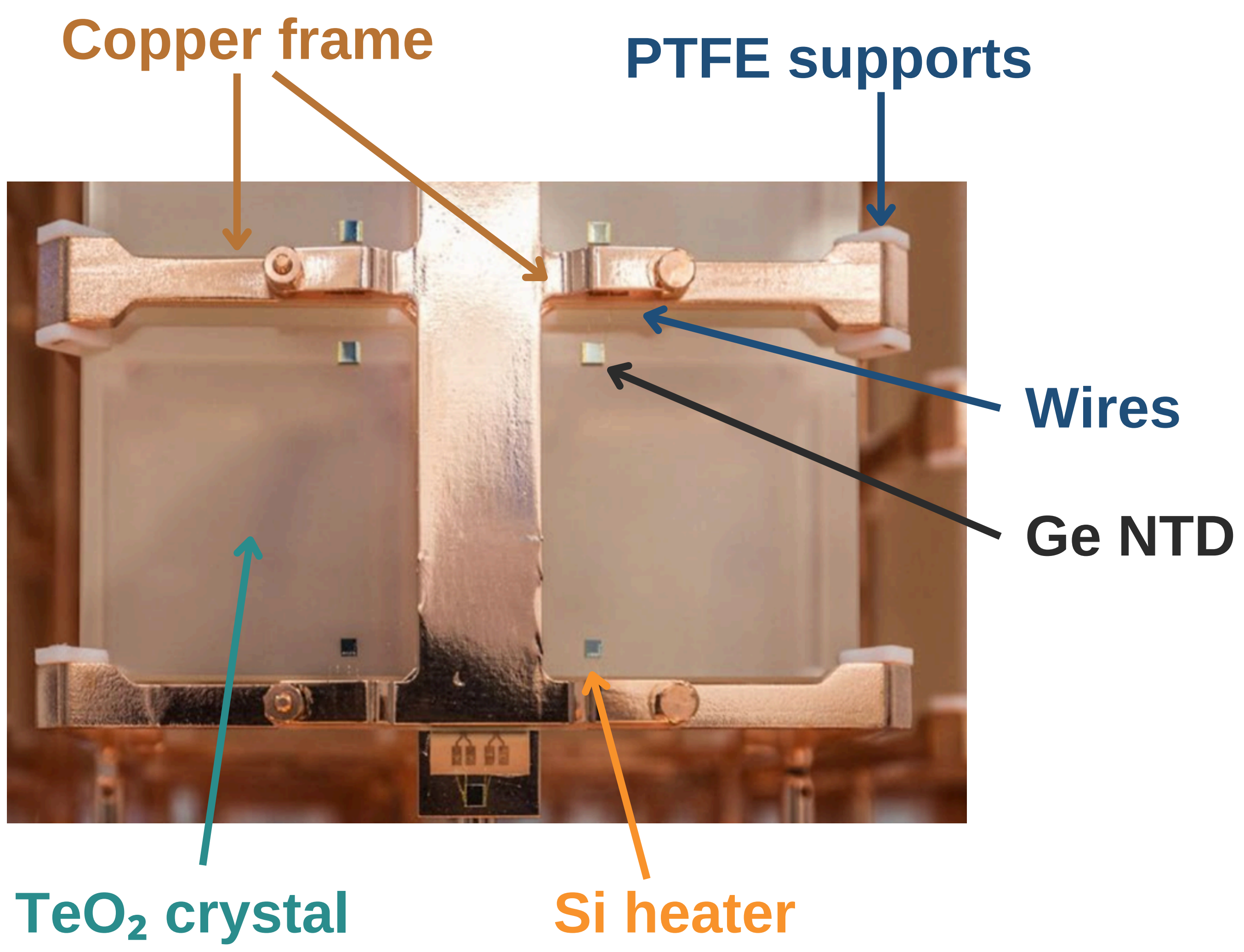
Noise and vibrations
- mechanical decoupling from the cryostat
- **passive isolation** and **active noise mitigation**

Low-background environment
- LNGS **underground location**
- radiopure materials and passive shields
- modern and ancient lead shielding

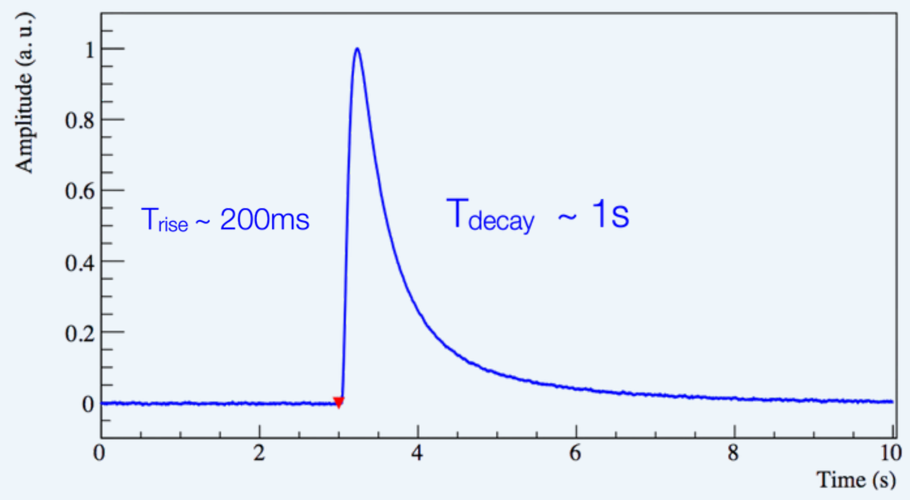
Principle of a CUORE bolometer

Energy deposit → phonons → ΔT → electrical pulse





The signal is a slow thermal pulse, well suited for rare event searches

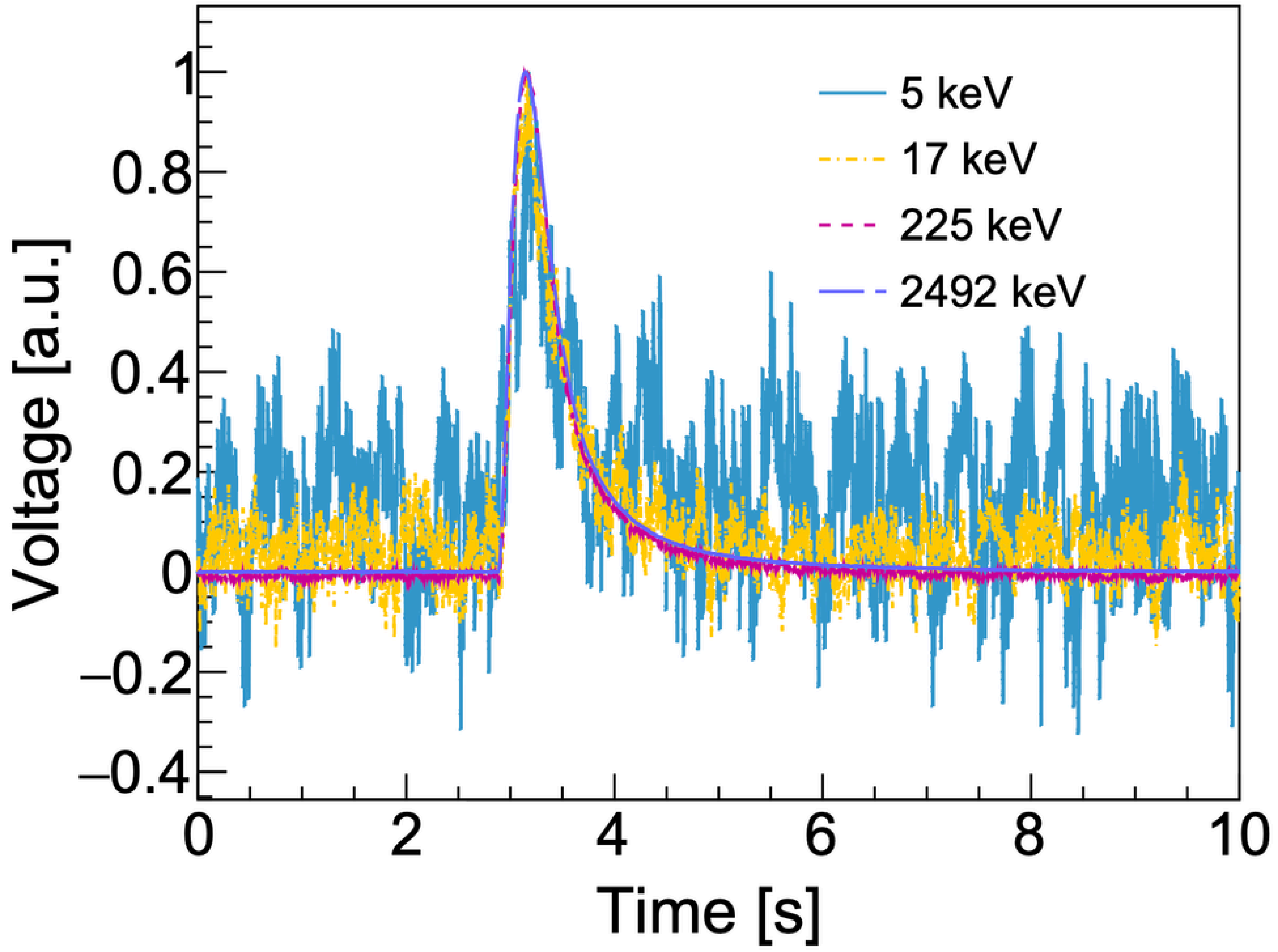


$\Delta T \propto \Delta E$

At ~10 mK, a **1 MeV** energy release produces **ΔT~100 μK**

A CUORE detector measures deposited energy as heat

Why keV-scale analysis is hard in CUORE



📖 Phys. Rev. D 113, 012012 (2026)

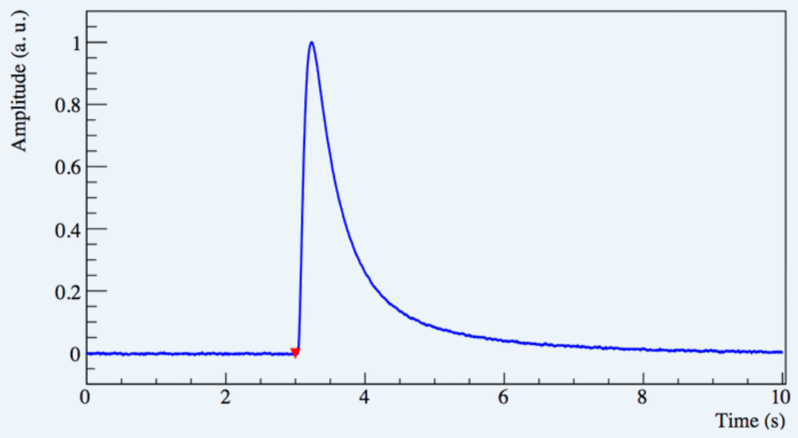
- **lower SNR** near threshold
- more **spurious pulses** from electronics and vibrations
- degraded **pulse-shape variables and efficiencies**
- selection must trade exposure for cleaner data

↓

We apply dedicated near-threshold techniques to recover true physical events.

Low-energy pipeline

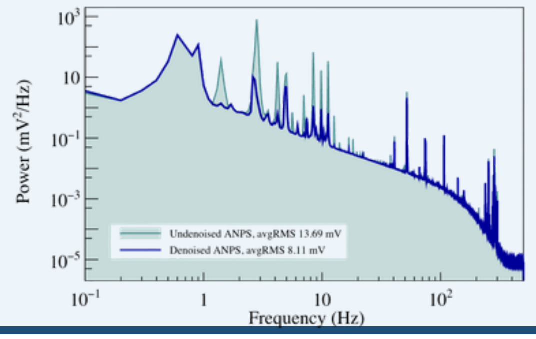
Raw waveforms



Denoising

Noise correlated with auxiliary devices is subtracted from the detector signals.

📖 Science 390, 1029–1032 (2025)



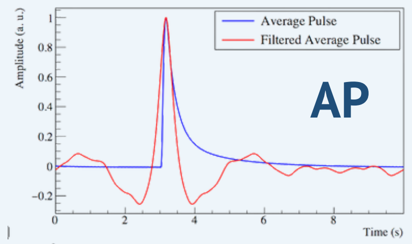
Optimum Trigger

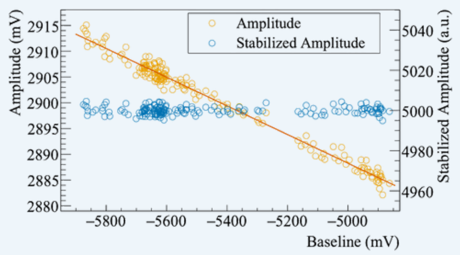
Offline re-triggering maximizes SNR.

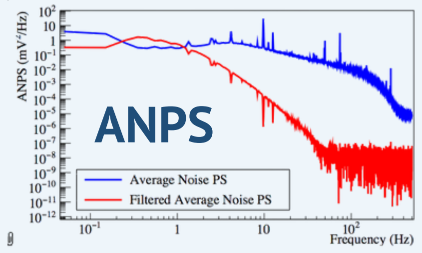
📖 JINST 6, P02007 (2011)

Energy Reconstruction

Optimum Filter + Thermal gain stabilization + Calibration







📖 arxiv:2510.25720

Pulsers

Pulser efficiencies:

- Trigger
- Base cuts
- Energy reconstruction

Te X-rays

PSD efficiency

Total efficiency

Low-energy selection

Event Selection

- M1
- Base cuts + pile up
- PSD

Detector Selection

- Channel
- Rate stability

📖 Phys. Rev. D 113, 012012 (2026)

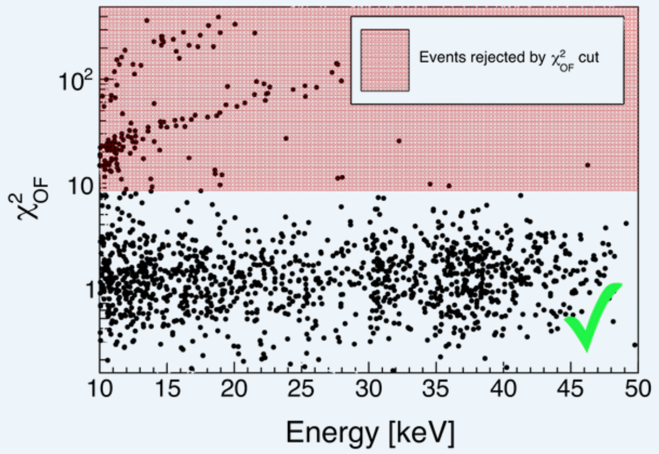
LE spectra

Event and detector selection

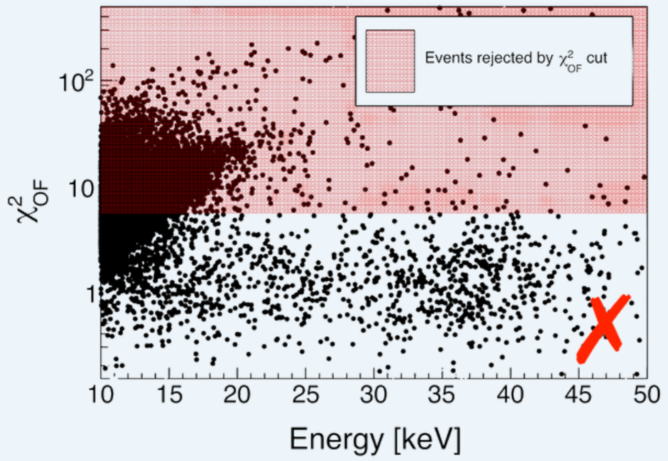
Event Level

For each detector:

χ^2 cut removes non-physical pulses



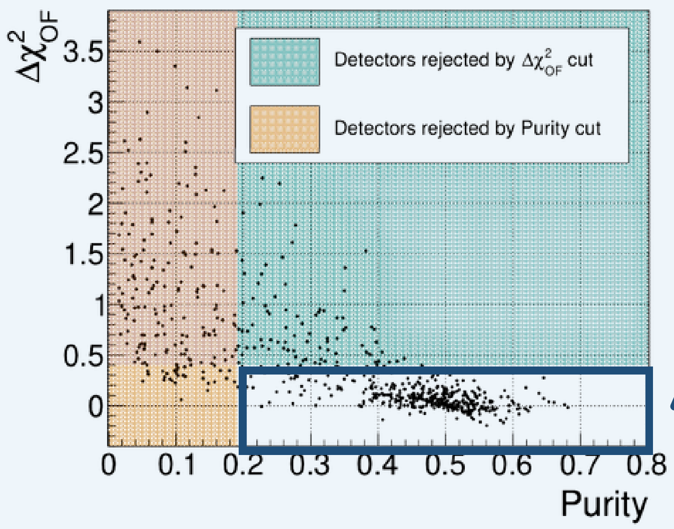
for some detectors there is no clear separation



📖 Phys. Rev. D 113, 012012 (2026)

Detector Level

For each detector:



📖 Phys. Rev. D 113, 012012 (2026)

- compute **purity P** (fraction passing the cut)
- compute **$\Delta\chi^2$** (median shift between the ROI and a high-E reference band)
- keep detectors with **high P** and **low $\Delta\chi^2$**.
- remove detectors with unstable rate

All cuts are optimized to maximize the significance:

$$S = \frac{\varepsilon \times M\Delta T}{\sqrt{B}}$$

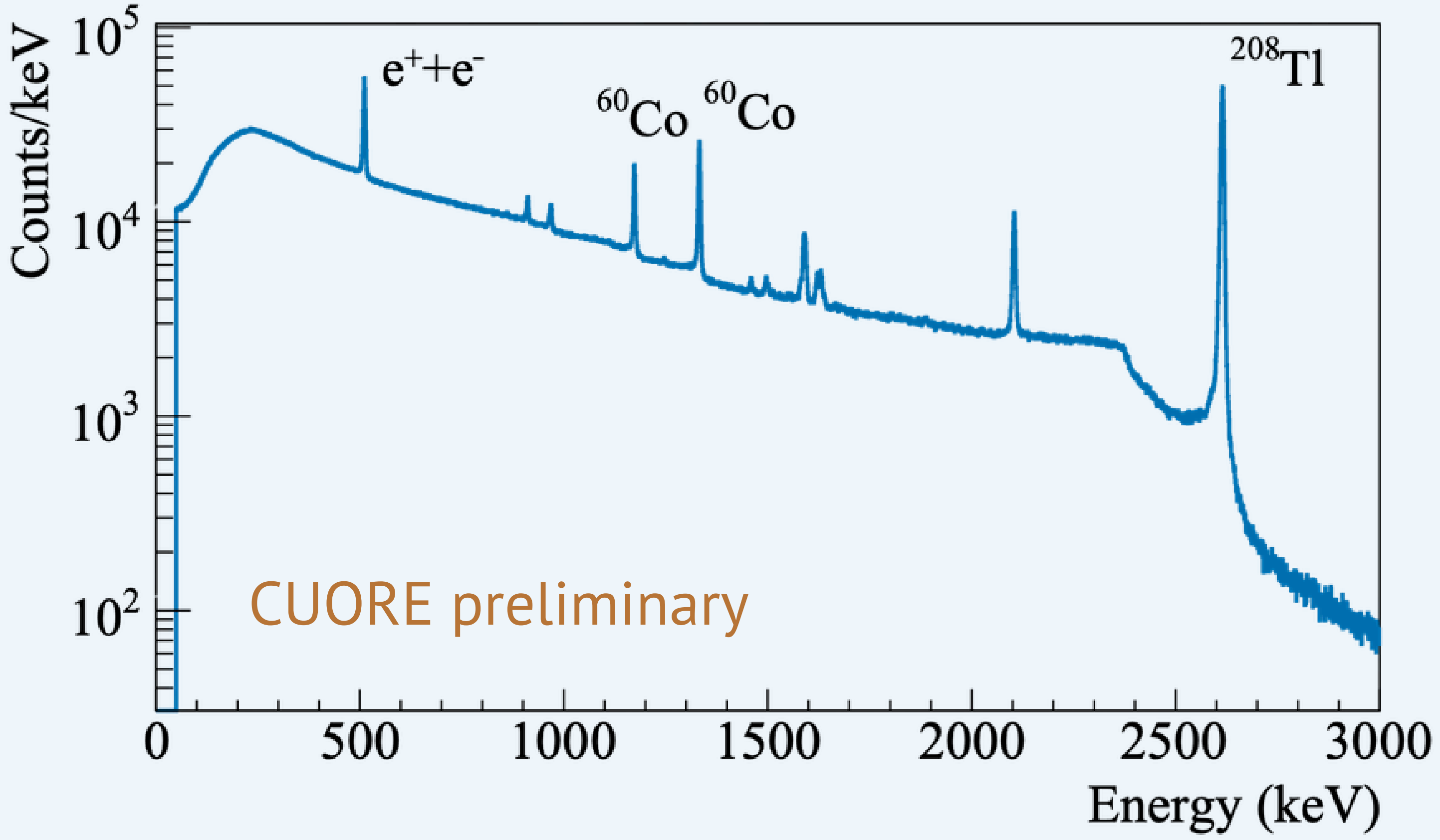
Total efficiency (ε)

Exposure ($M\Delta T$)

Background in ROI (B)

Low energy calibration

Calibration: use high-energy γ lines ($^{232}Th-^{60}Co$), then extrapolate to low energies



📖 arxiv:2510.25720

Validation: Te X-rays at 27 – 31 keV

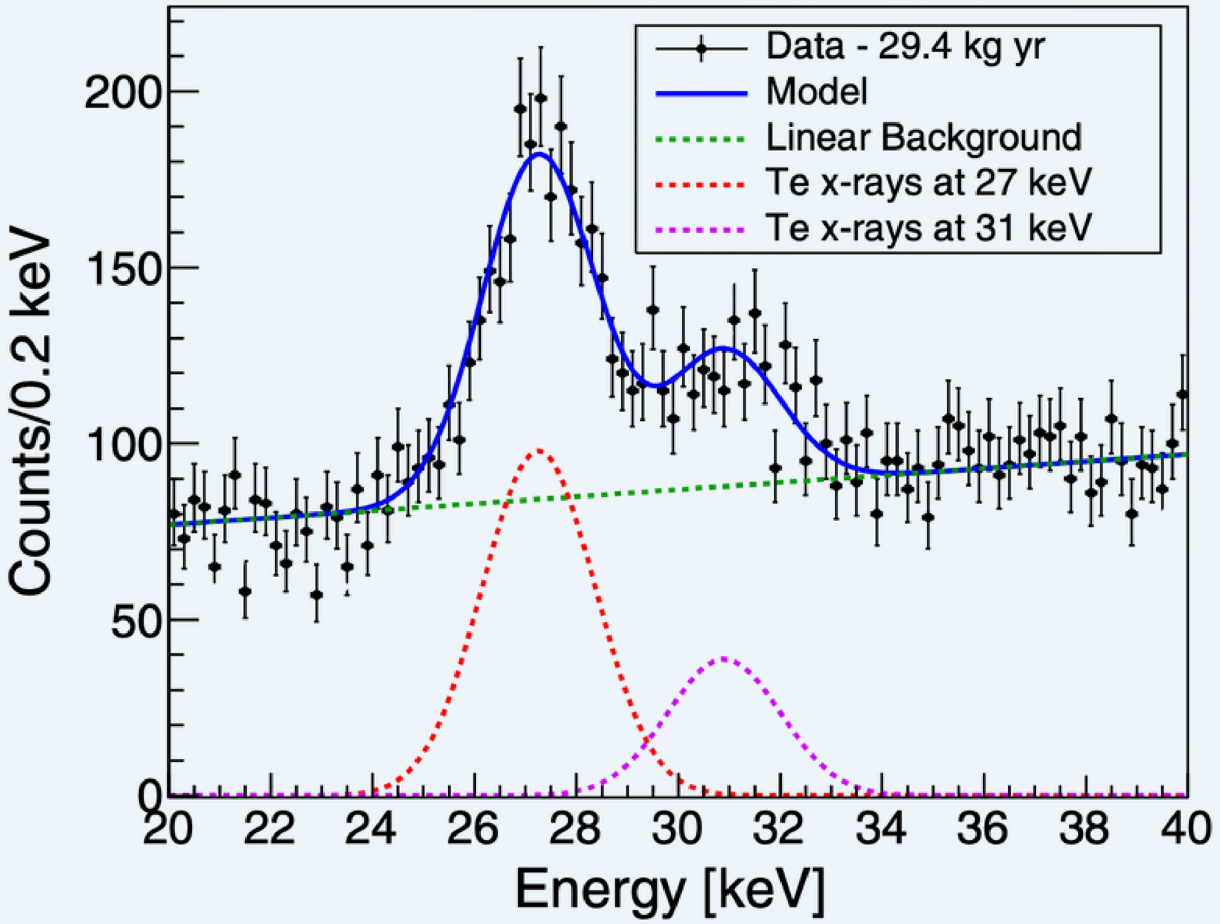
Topology: M2 (two-crystal coincidences) dominates due to surface interactions and escaping Te X-rays

Mean shifts are

+0.05 ± 0.02 keV (10 keV selection) and

+0.14 ± 0.06 keV (3 keV selection),

consistent with zero within energy resolution.



📖 Phys. Rev. D 113, 012012 (2026)

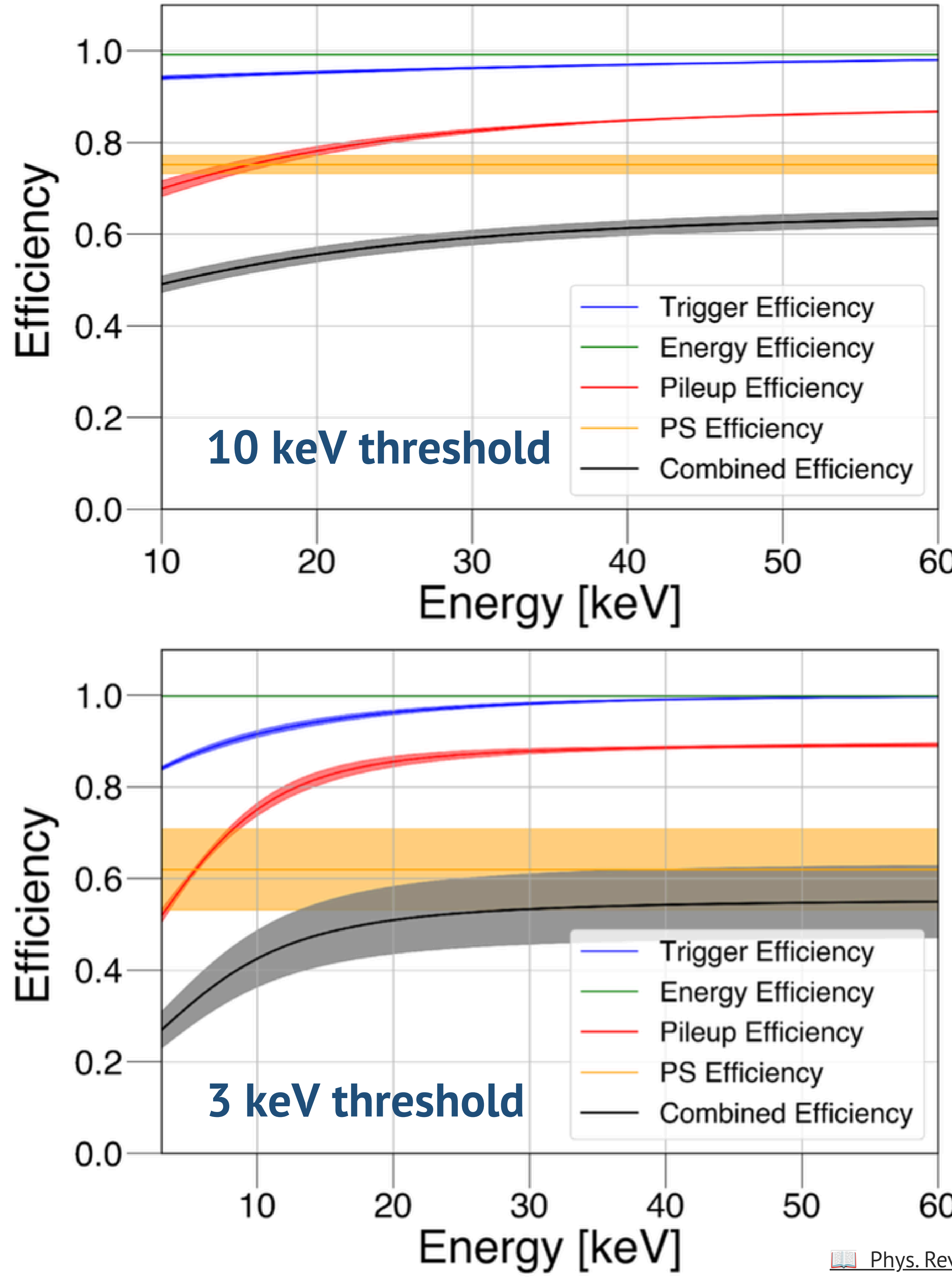
Efficiencies

Te X-ray peaks (27–31 keV)

- **Pulse-shape efficiency** = events after / before the χ^2 cut.

Injected thermal pulses at multiple amplitudes

- **Trigger:** probability that the Optimum Trigger fires within the signal window.
- **Energy:** probability that the reconstructed energy matches the injected value within tolerance.
- **Pileup:** probability that the pulse is isolated (no pile-up) and passes quality requirements.



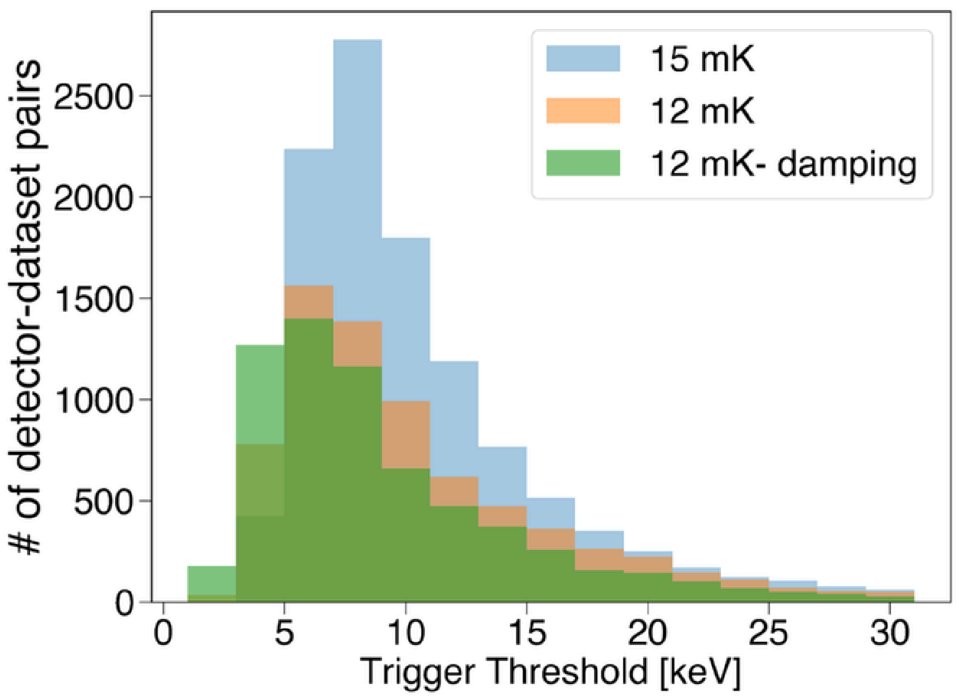
Phys. Rev. D 113, 012012 (2026)

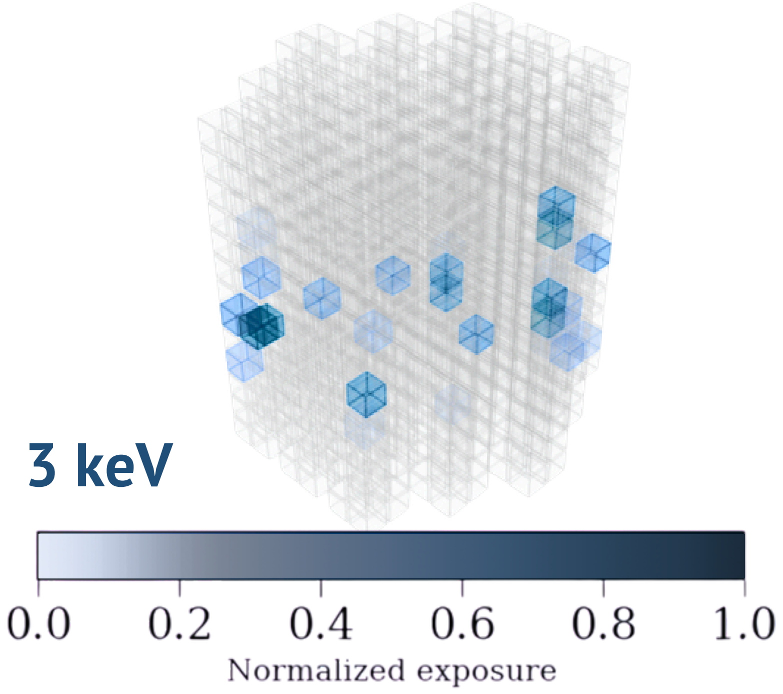
Selection results

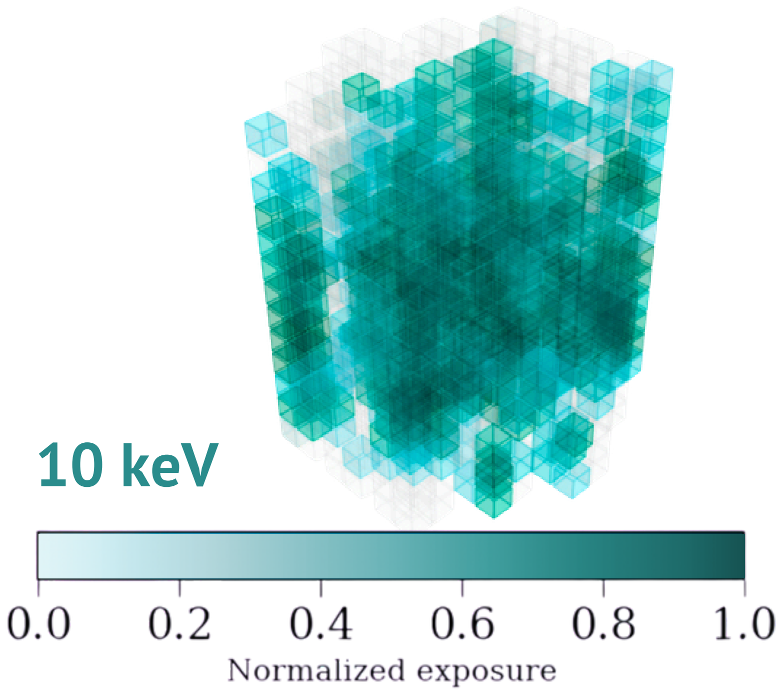
Same data, detectors selected with different thresholds

Threshold Selection	Role	Exposure	Strength	Baseline FWHM [keV]	Efficiency at the Threshold [%]
3 keV	rare nuclear decay, solar axions, cosmic axions	11 kg yr	clean near threshold	1.18	~26
10 keV	solar axions	691 kg yr	high statistics, low threshold	2.54	~50
20 keV	cosmic axions	1.43 ton yr	largest exposure	3.19	~76

📖 Phys. Rev. D 113, 012012 (2026)







Low energy physics program

Low-energy reconstruction down to 3 keV

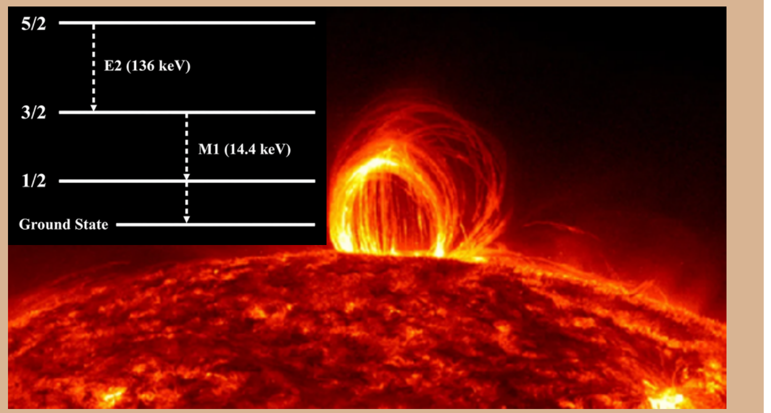
- denoising and optimum trigger lower the analysis threshold
- dedicated low-energy variables and event-level selections
- optimized for rare-event searches at the keV scale

📖 Phys. Rev. D 113, 012012 (2026)

New physics reach

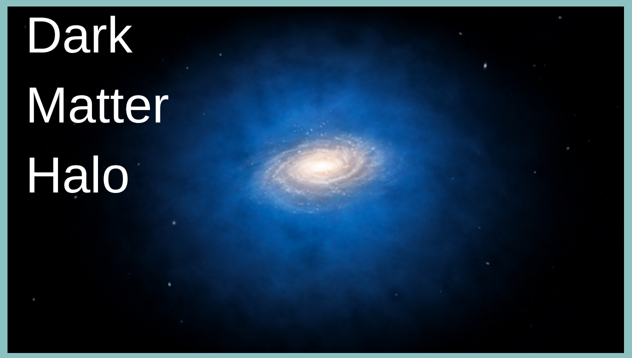
- dark matter searches (**solar** and **galactic** axions, **WIMPs**)
- **rare nuclear decays**

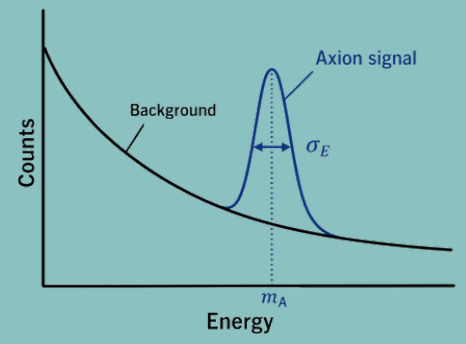
Solar Axions



- 14.4 keV solar axions from thermally excited ^{57}Fe nuclei
- 14.4 keV electron-like events in the detector

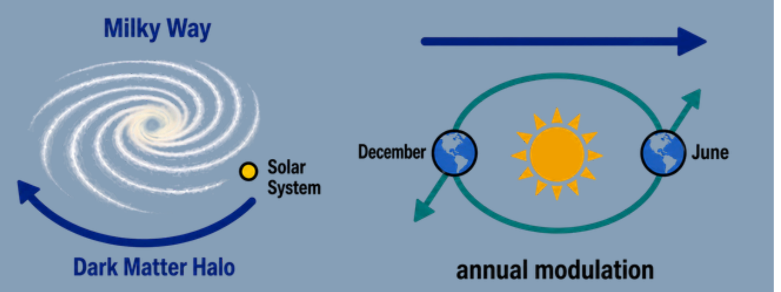
Galactic Axions





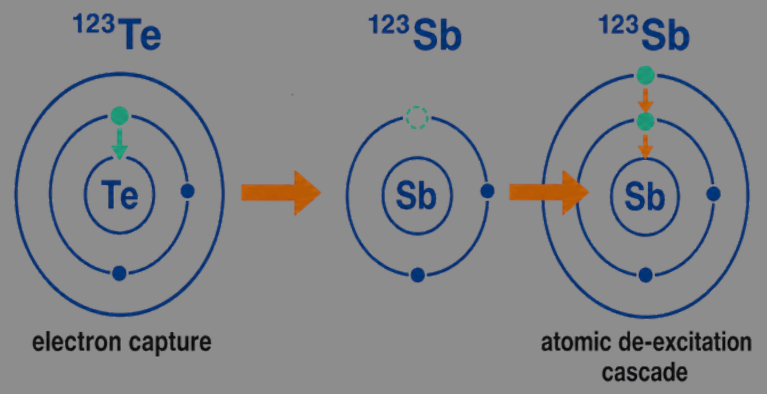
narrow peak at $E \simeq m_a$

WIMP annual modulation



- WIMP elastic scattering off nuclei in TeO_2
- Search for an annual modulation in the low-energy event rate

Forbidden ^{123}Te EC

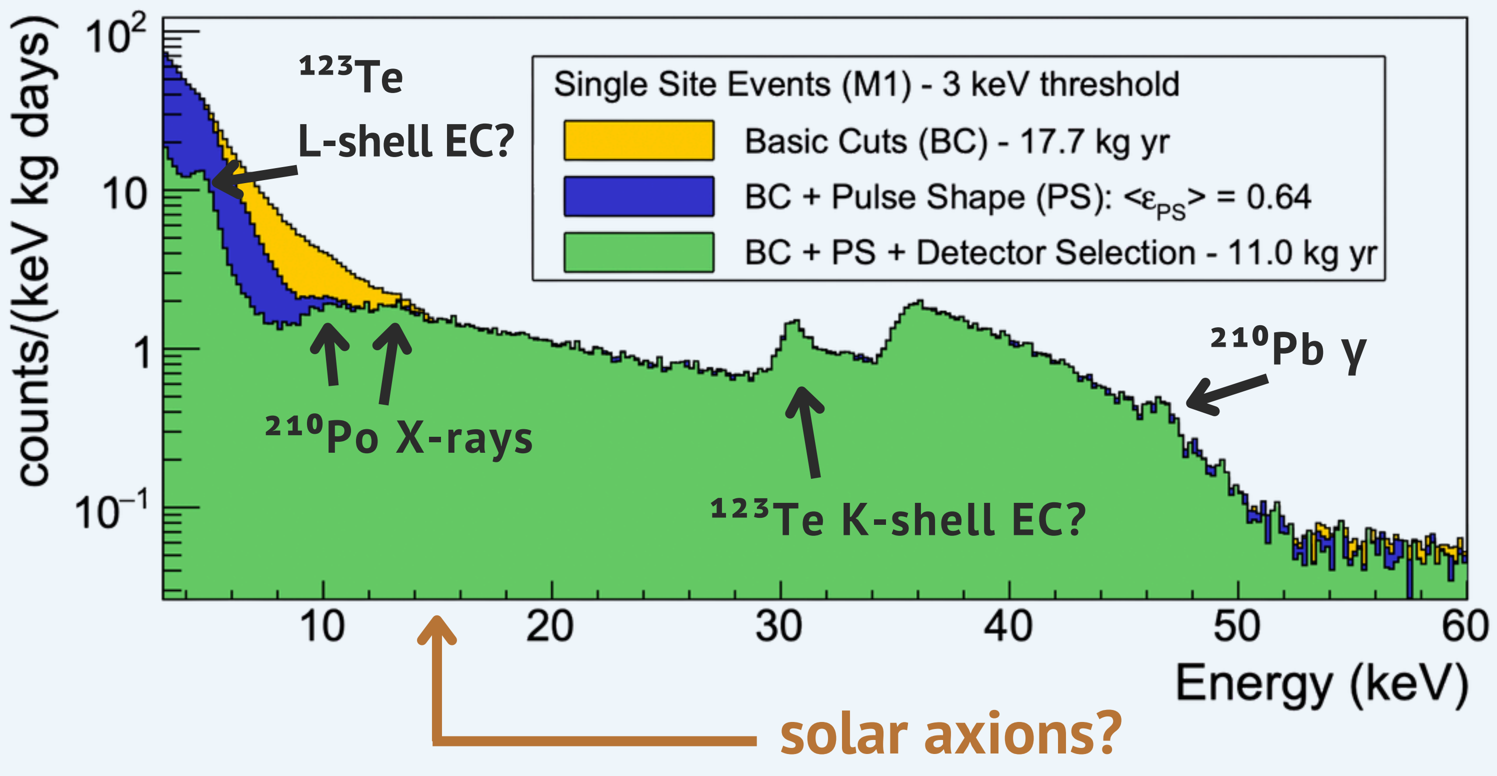


- Second-order forbidden electron capture in ^{123}Te
- Search for the atomic de-excitation signature

Low energy spectra

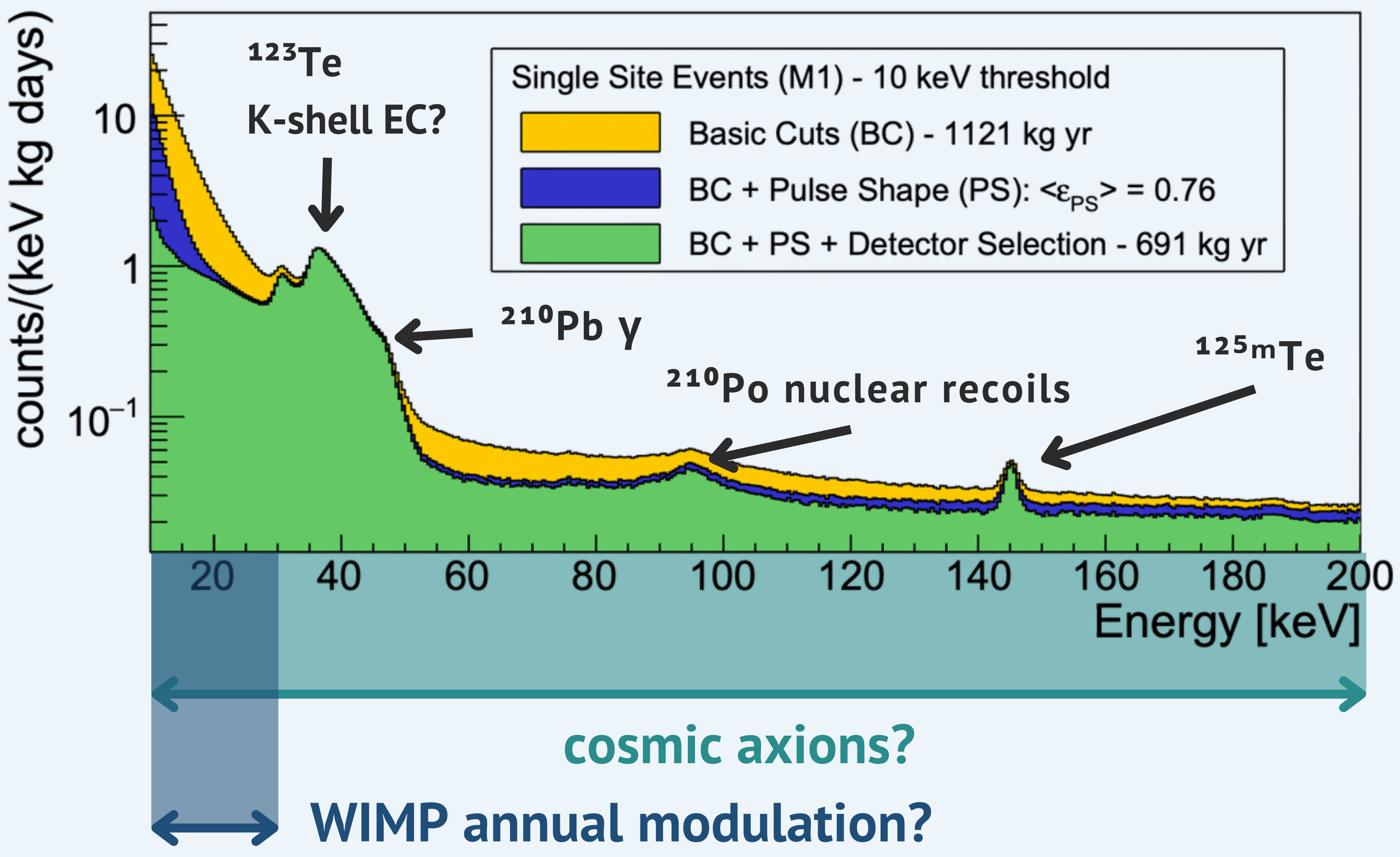
Detectors selected with 3 keV threshold:
1.2% of all detectors,
11 kg·yr of TeO_2 exposure,
1.18 keV FWHM

Phys. Rev. D 113, 012012 (2026)



Detectors selected with 10 keV threshold:
35% of all detectors,
691 kg·yr of TeO_2 exposure,
2.54 keV FWHM.

Phys. Rev. D 113, 012012 (2026)



Solar axions in CUORE

Signal

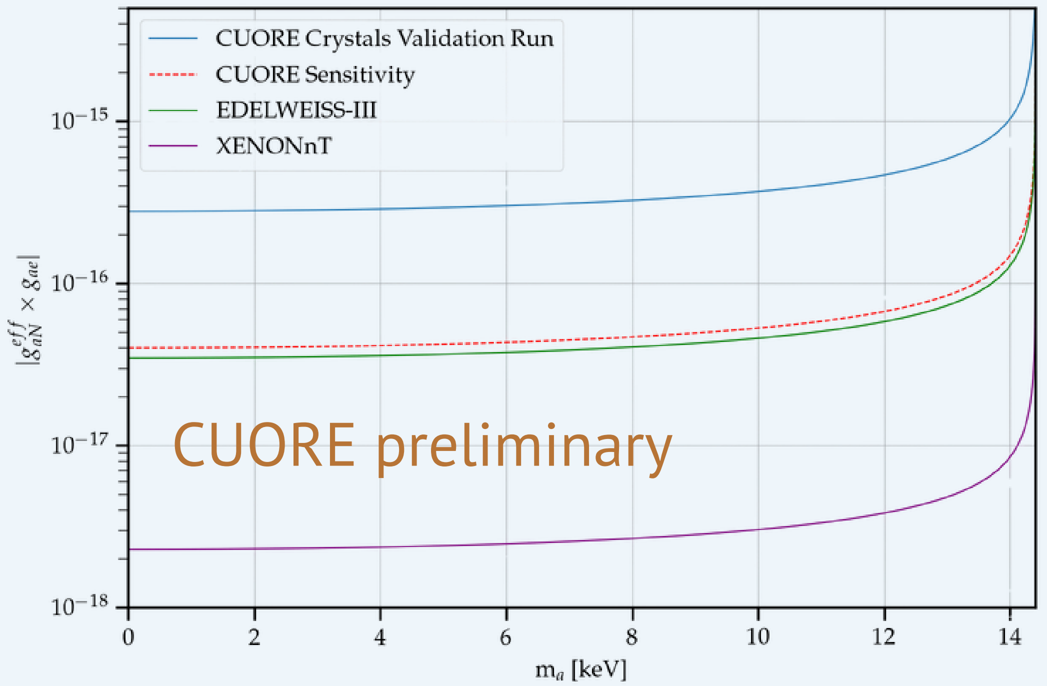
- ^{57}Fe solar axions
- 14.4 keV monoenergetic flux
- axio-electric absorption → narrow peak

Analysis

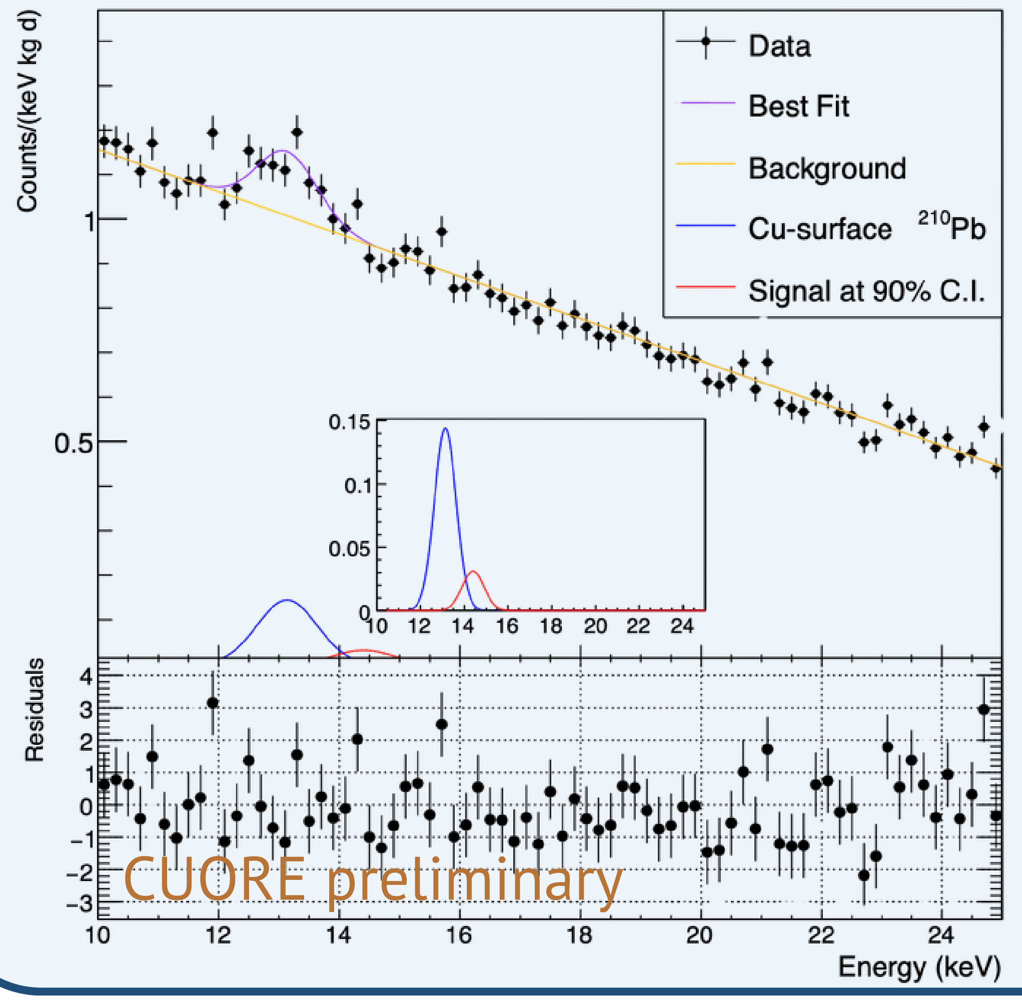
Local fit around the signal region:
smooth background + 13 keV ^{210}Pb excess + signal peak.

Sensitivity

Expected 90% CL sensitivity to $g_{ae} \times g_{an}$
Limited by the nearby 13 keV background structure



Background validation

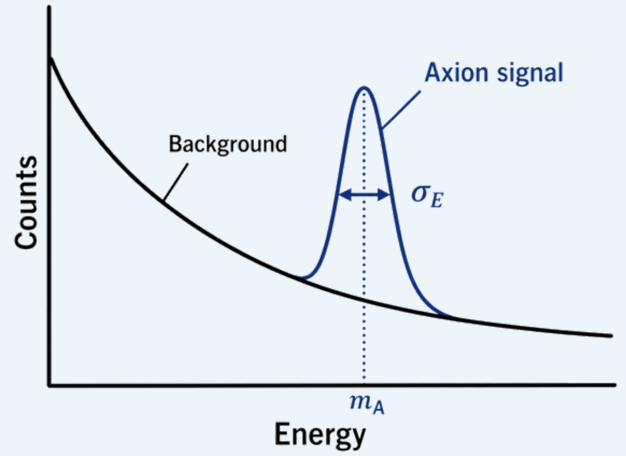


3 keV selection: best resolution near threshold.
The fitted signal is compatible with zero.

Cosmic axions in CUORE

Signal

- Galactic halo axions can be absorbed in TeO_2
- Axio-electric effect → full axion rest energy deposited
- Expected signature: narrow peak at $E \simeq m_a$



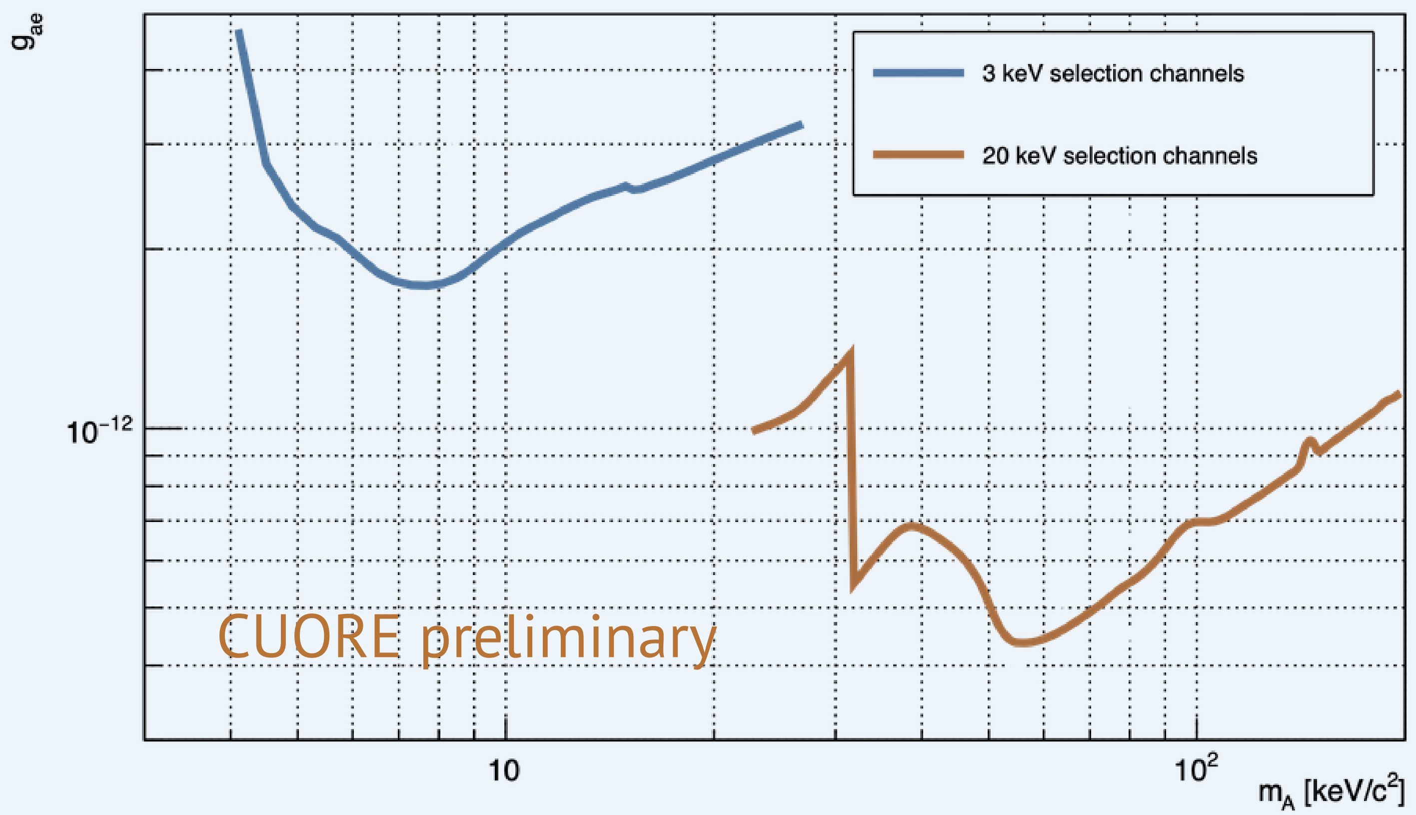
Search strategy

- Peak search over axion masses
- background-only exclusion sensitivity

Expected 90% CL sensitivity to g_{ae}

- First **tonne-scale cryogenic calorimeter** search for cosmic axions
- First search with a **tellurium**-based target
- Sensitivity close to current limits, demonstrating the potential of large mass cryogenic detectors at the keV scale
- Results provide a reusable framework for other dark matter interpretations, including bosonic and fermionic candidates

Sensitivity



Summary

- CUORE is not only a $0\nu\beta\beta$ experiment, but a **broad range rare event detector** spanning from the keV to the MeV scale.
- Dedicated denoising, optimum trigger, event selection and detector selection techniques enabled low energy reconstruction down to **3 keV**.
- This opened a low energy physics program including **solar axions**, **cosmic axions**, **WIMP** annual modulation and **rare nuclear decay** searches.
- CUORE demonstrates that tonne scale cryogenic calorimeters can perform keV scale rare event searches, with sensitivities approaching current limits in selected dark matter channels.

Status

Low energy techniques:
published in Phys. Rev. D 113, 012012 (2026)

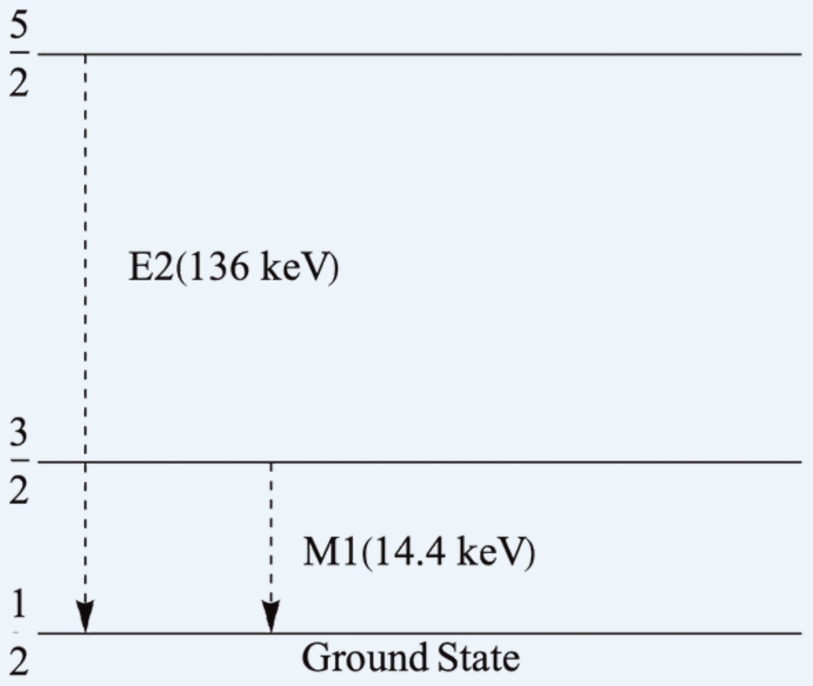
Physics searches:
solar axions, galactic axions and WIMPs under collaboration review

Backup

Solar Axions

Production

^{57}Fe M1 nuclear transition in the Sun



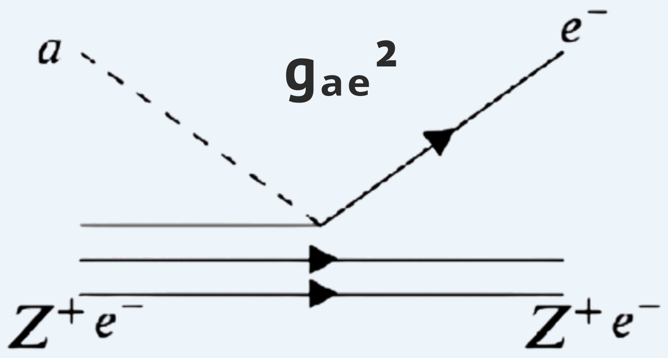
MAGIC and Fermi-LAT Collaborations, JCAP 02 (2016) 031

Signal

Gaussian centered at 14.4 keV

Detection

Axio-electric effect



$$N_a = \Phi_a^{Fe} \cdot \sigma_{ae} \cdot N_{TeO_2} \cdot \Delta T$$

Axio-electric effect cross section ∝ g_{ae}^2

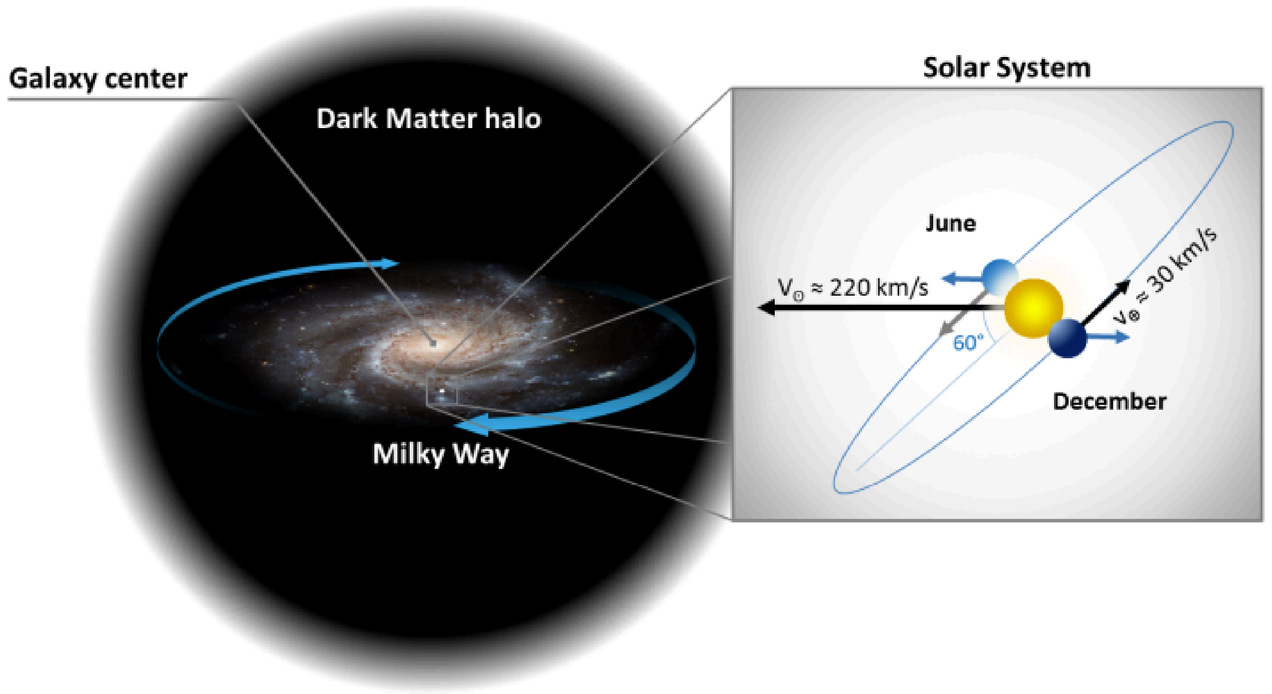
Axion flux from ^{57}Fe in the Sun ∝ g_{aN}^2

Annual Modulation of WIMP Dark Matter

- Search for scattering **interactions of WIMPs off Te and O** nuclei

  - Combination of light and heavy targets increases range of sensitivity
- **Annual Modulation**: seasonal variation in event rate caused by revolution of Earth about Sun

  - Unique signature that creates ability to search for WIMPs on top of background



📖 https://cuoreexperiment.com/sites/default/files/SimoneCopelloThesis.pdf

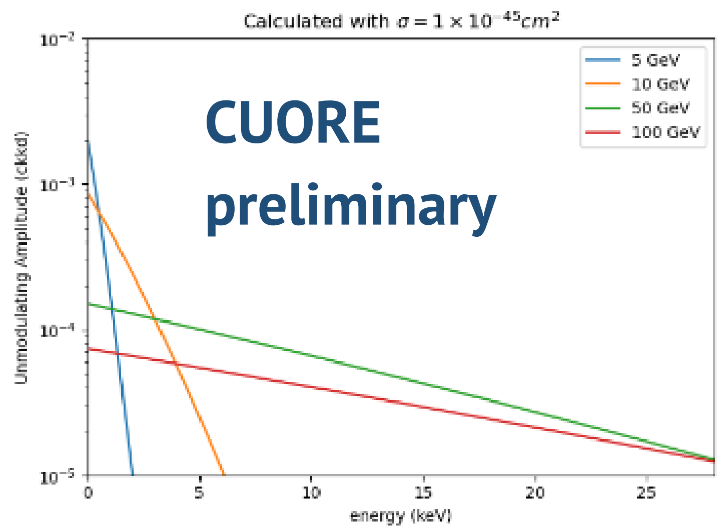
Expected WIMP Event Rate

Expected scattering differential event rate:

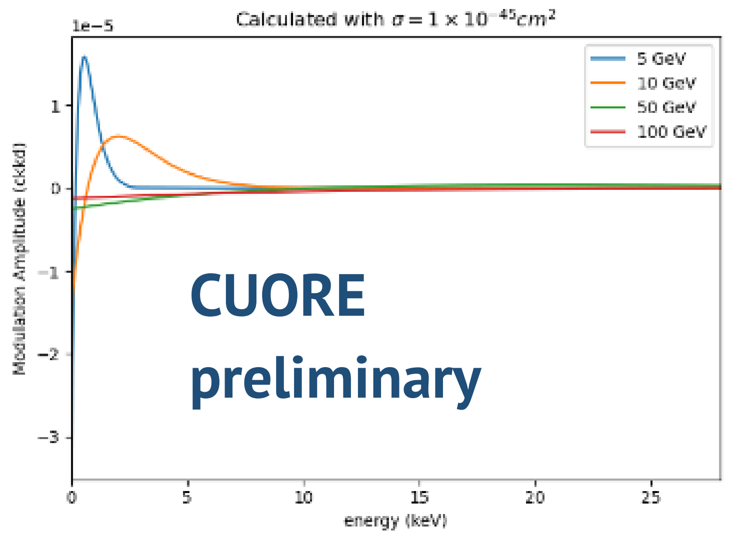
$$\frac{dR}{dE_R} \propto \frac{N_0}{A} \frac{\rho_\chi}{M_\chi} \sigma_0 \int_{v_{min}}^{v_{esc}} v f(v) dv$$

- N_0 = Avogadro's number
- A = atomic mass of target nucleus
- ϱ_χ = local dark matter density
- M_χ = WIMP mass
- σ_0 = WIMP scattering cross section
- f(v) = velocity distribution of dark matter

Unmodulated rate

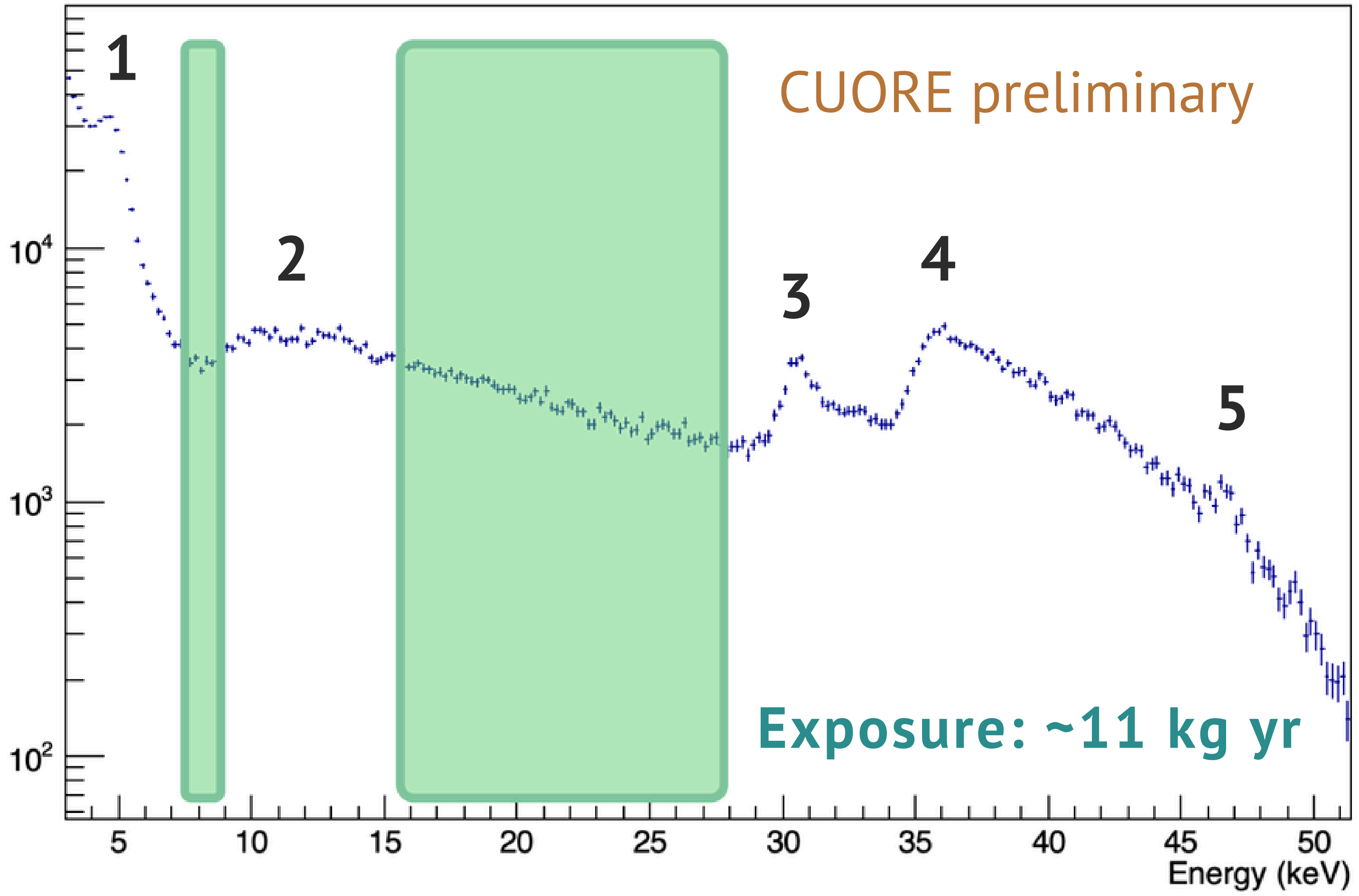


Annual-modulation amplitude

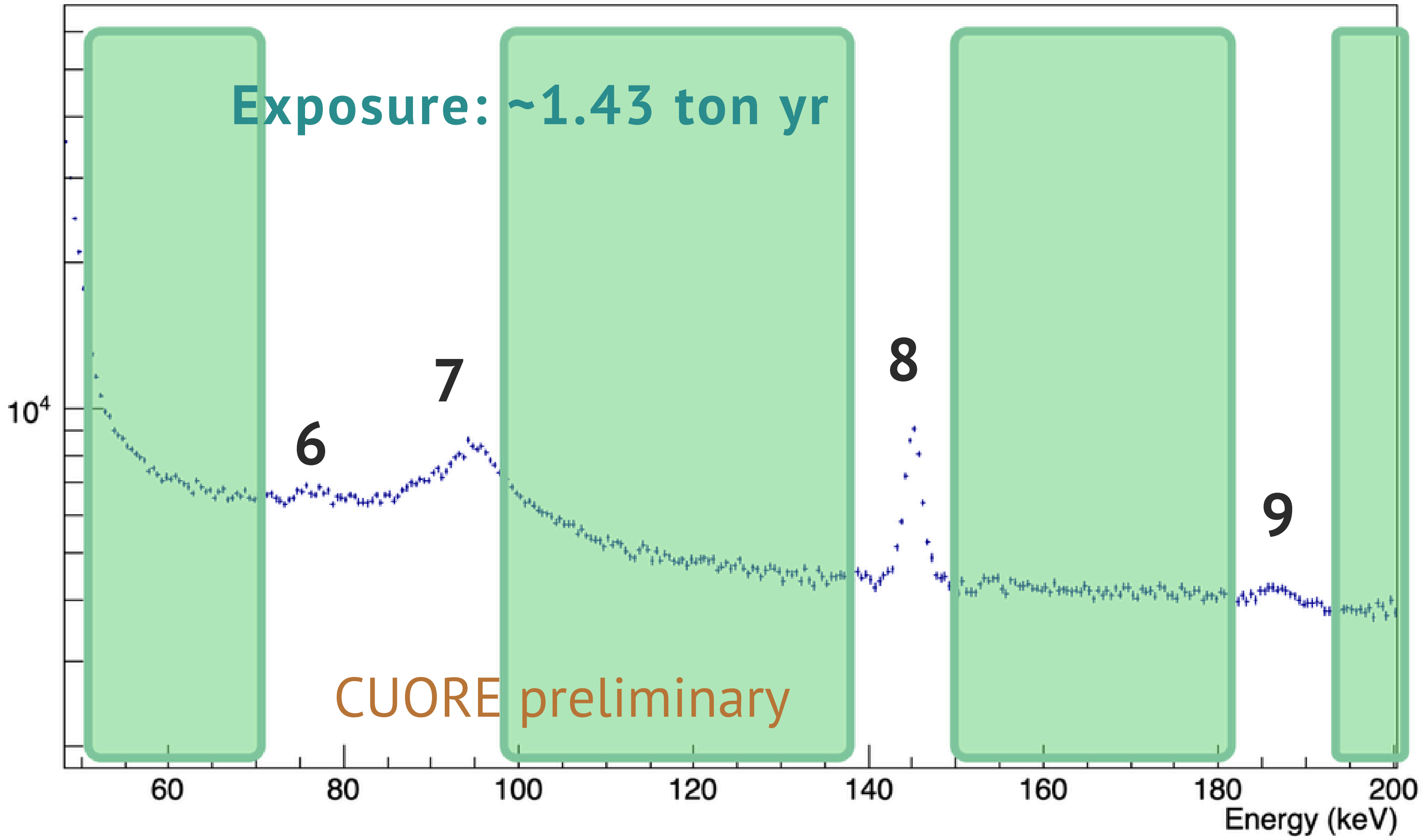


Analysis sample

3 keV selection fit region



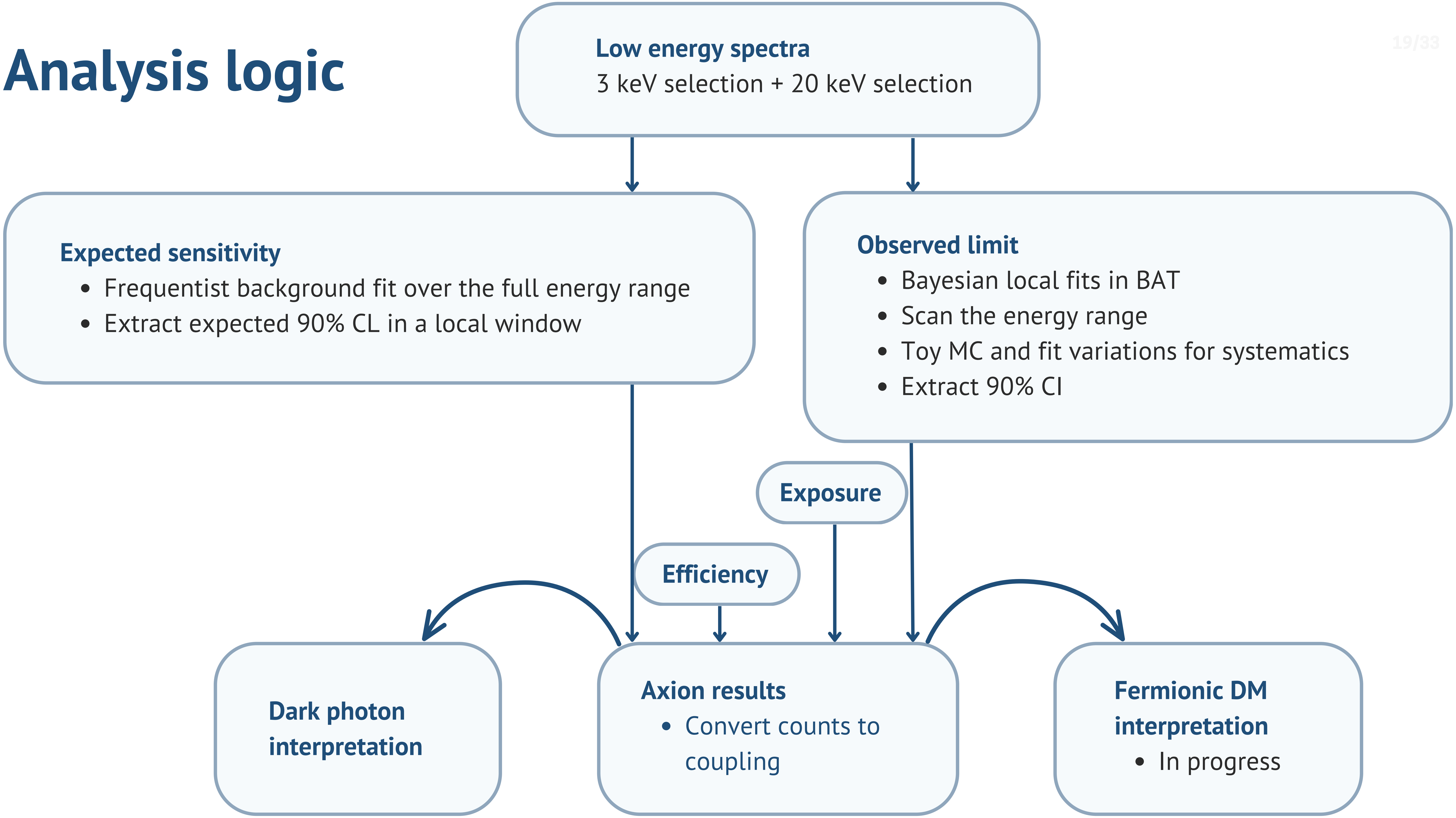
20 keV selection fit region



Spectral features excluded from the analysis:

1. ^{123}Te L-shell EC (4.7 keV)
2. ^{210}Pb X-rays (~10 and ~13 keV)
3. ^{123}Te K-shell EC (30.5 keV)
4. Unknown (36 keV)
5. ^{210}Pb gamma (~46.5 keV)
6. Likely Bi X-rays (~76 keV)
7. ^{210}Po nuclear recoils (~90 keV)
8. ^{125m}Te (145 keV)
9. Likely ^{226}Ra alpha + gamma (~187 keV)

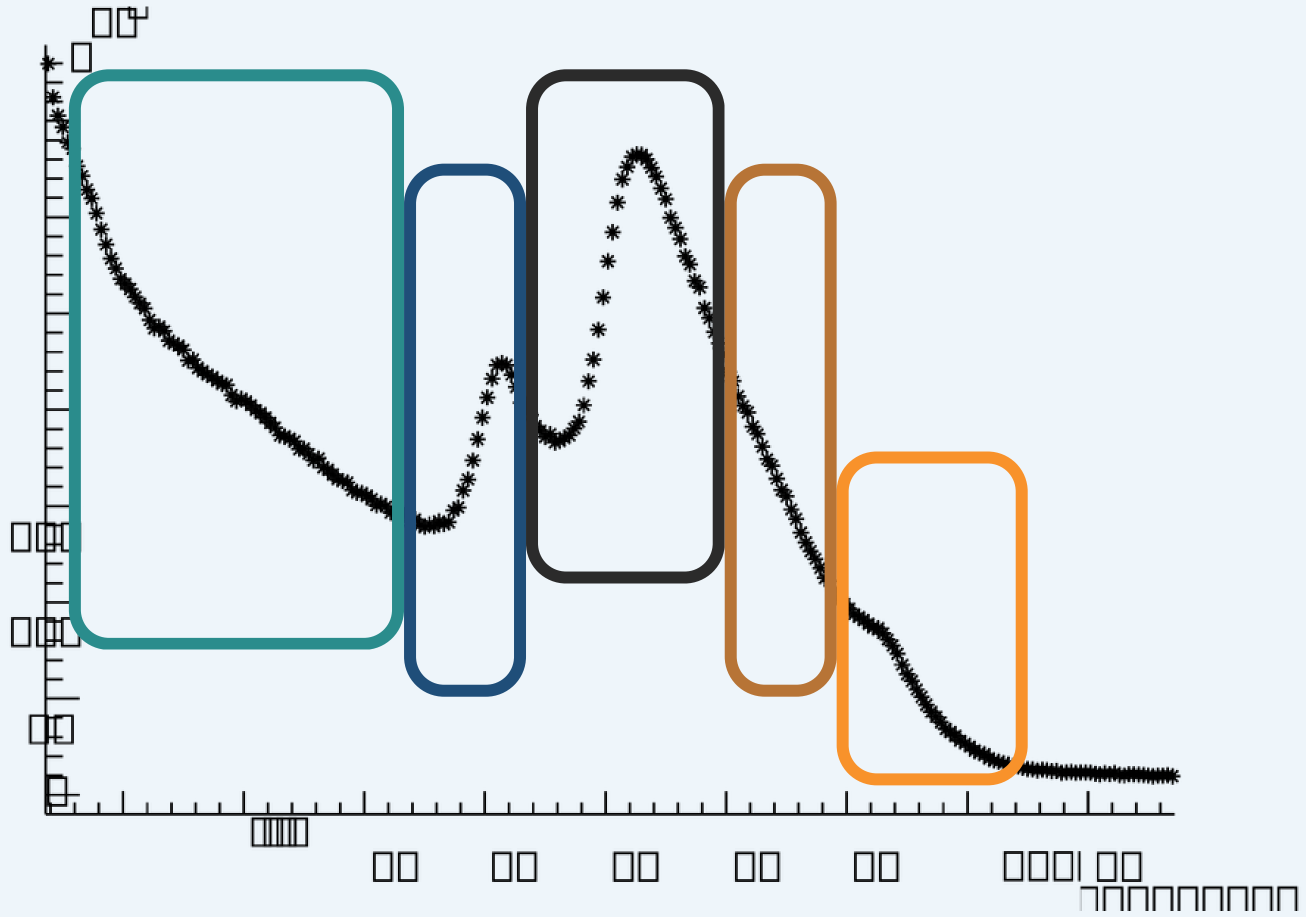
Analysis logic



Sensitivity: fit and upper limit

Fit

Spectrum segmented into energy chunks; binned likelihood fit in ROOT

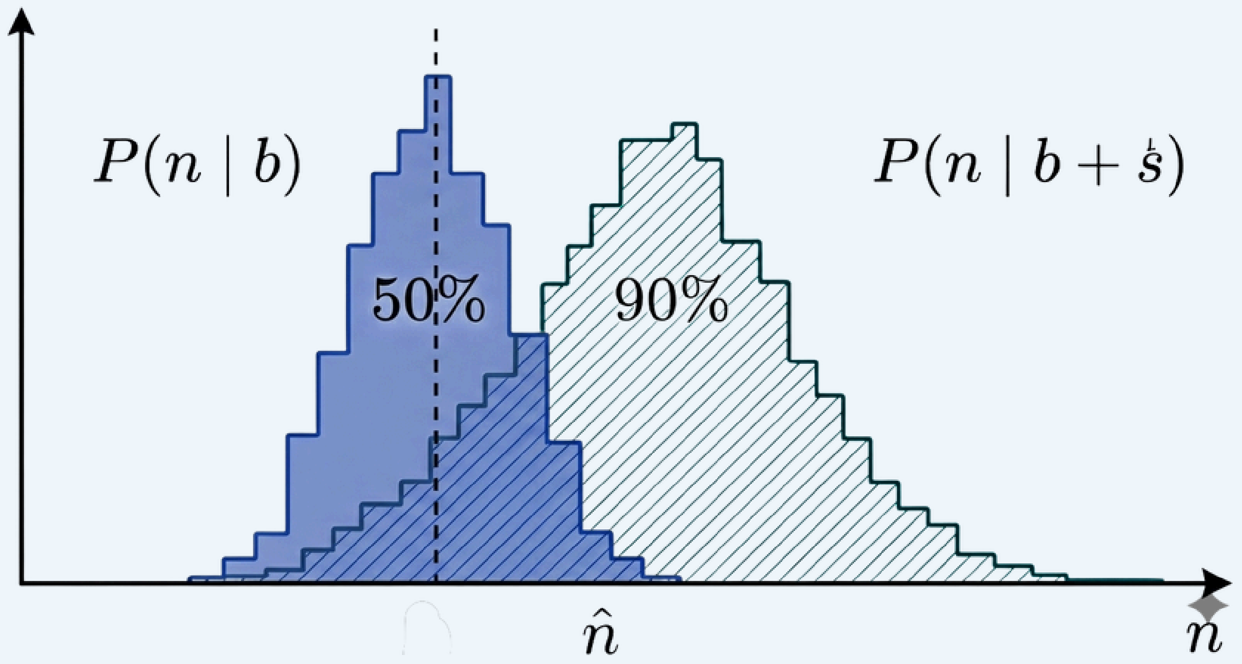


Upper Limit Estimation

- Scan over 3–200 keV with 0.4 keV steps and a 2σ window
- Poissonian statistics are assumed for both **background-only** and **signal + background** hypotheses

$$\hat{s}_{90} \sim 1.28\sqrt{b}$$

#background events in a window



From counts to coupling

Expected number of signal events

$$N_{\text{exp}} = \Phi_{\text{DM}}\, n_{\text{mol}}\, \sigma_{Ae}(m_A)\, MT$$

Galactic axion flux

$$\Phi_{\text{DM}} = \frac{9.0 \times 10^{15}}{m_A}\beta$$

3.77×10^{24} [molecules kg^{-1}]

20 keV selection: 1.43 ton·yr
3 keV selection: 11 kg·yr

Axio - electric cross section

$$\sigma_{Ae} = \sigma_{pe}(E)\, g_{Ae}^2 \frac{3E^2}{16\pi\alpha m_e^2} \frac{1-\beta^2/3}{\beta}$$

90% CL upper limit from the fit

total weighted efficiency

$$g_{Ae}^{90} = \sqrt{\frac{\mu_{90}/A}{N_{\text{exp}}(g_{Ae}=1)}}$$

Neutrinoless double-beta decay as a probe of lepton number violation

Allowed in the Standard Model

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

2νββ, ΔL=0

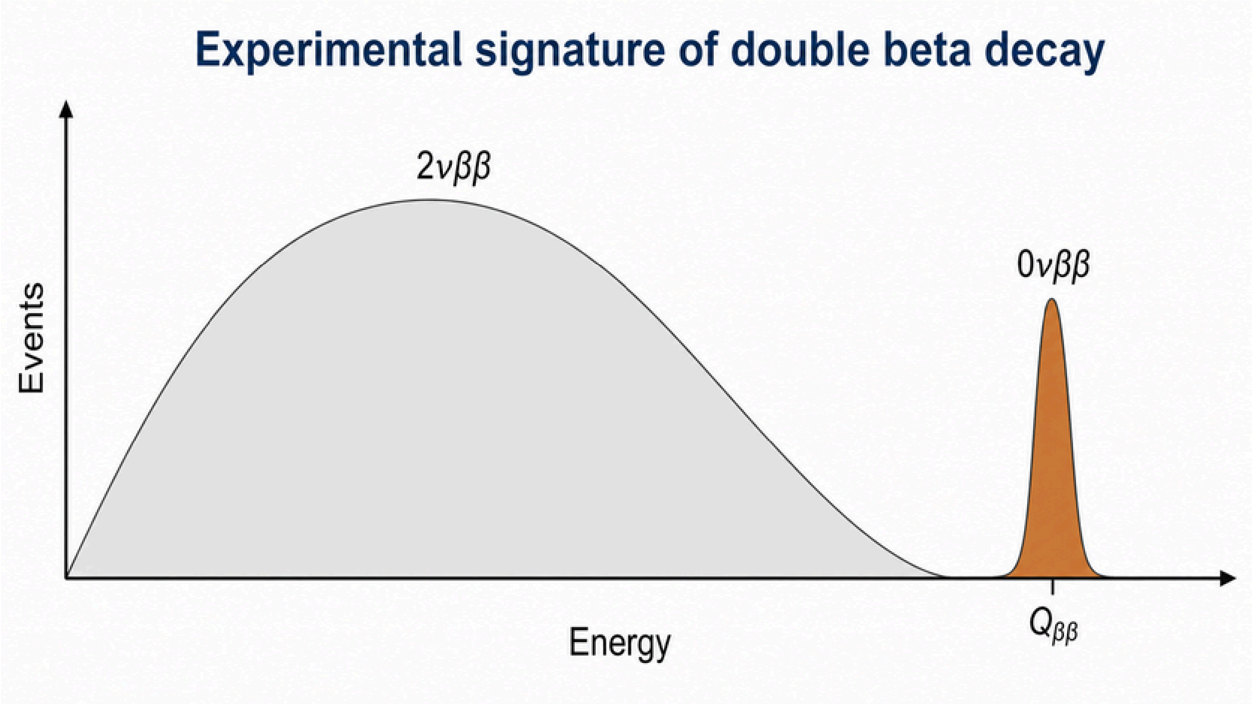
Beyond the Standard Model

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

0νββ, ΔL=2

Observation would imply:

- lepton number violation
- Majorana nature of neutrinos
- access to the absolute neutrino mass scale



Phase space factor

Effective Majorana mass

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,|m_{\beta\beta}|^2$$

Nuclear matrix element

For light Majorana neutrino exchange, the half-life limit constrains mββ.

Experimental sensitivity to 0νββ: what matters?

We need:

High efficiency
source embedded in detector

Low background
underground site + radiopure materials + passive shields

Good resolution
cryogenic calorimetry + vibration control

Large exposure
tonne-scale mass + stable long-term data taking

Isotopic abundance

$\eta(^{130}\mathrm{Te}) \simeq 34\%$

Natural tellurium, no enrichment required

Exposure

M·t=2039.0 kg yr TeO_2
(567.0 kg yr of ^{130}Te)

Sensitivity

$$S^{0\nu} \propto \eta \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

Background index

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

Low background in the ROI

Detection efficiency

$\varepsilon_{\mathrm{cuts}} = 93.4\%$

Source equals detector

Energy resolution

$\Delta E_{\mathrm{FWHM}} = 7.310 \pm 0.024$ keV at $Q_{\beta\beta}$ (~2528 keV)

$\Delta E/E \simeq 0.3\%$

📖 Science 390, 1029–1032 (2025)

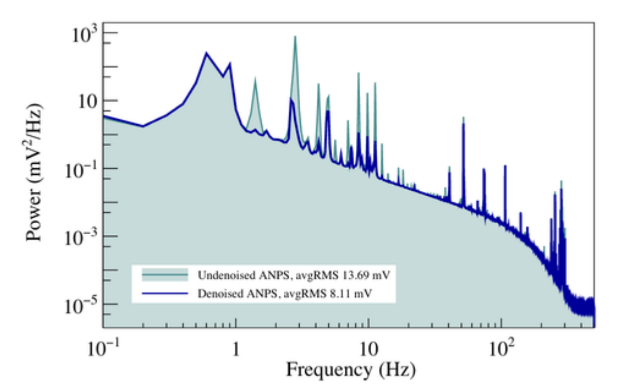
From bolometer pulses to a physics spectrum

Waveforms

Continuous detector data

Denoising

Noise correlated with auxiliary devices is subtracted from the detector signals.



📖 Science 390, 1029–1032 (2025)

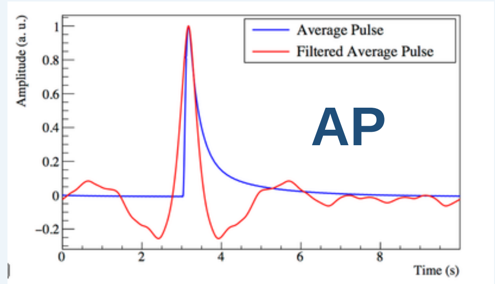
Optimum Trigger

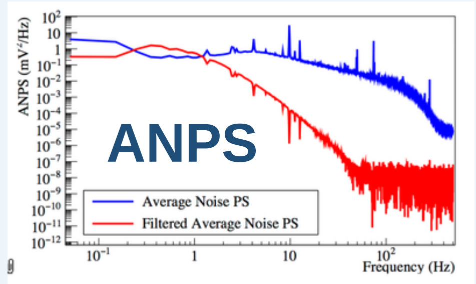
Offline re-triggering maximizes SNR using signal and noise spectra.

📖 JINST 6, P02007 (2011)

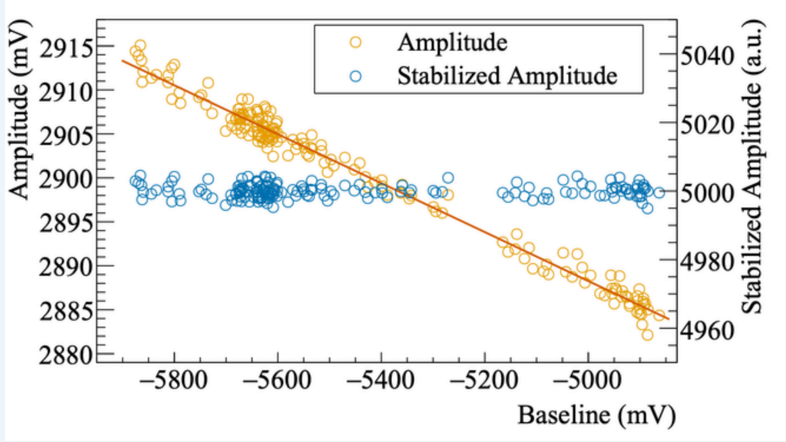
Optimum Filter

The signal is filtered using Average Pulse (AP) and Average Noise Power Spectrum (ANPS) to improve amplitude estimation.





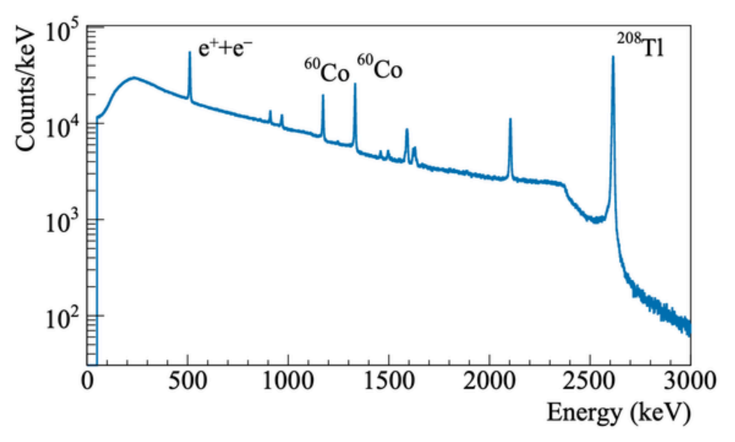
Thermal gain stabilization



📖 arxiv:2510.25720

Energy calibration

External ^{232}Th and ^{60}Co sources provide reference peaks for the energy scale.



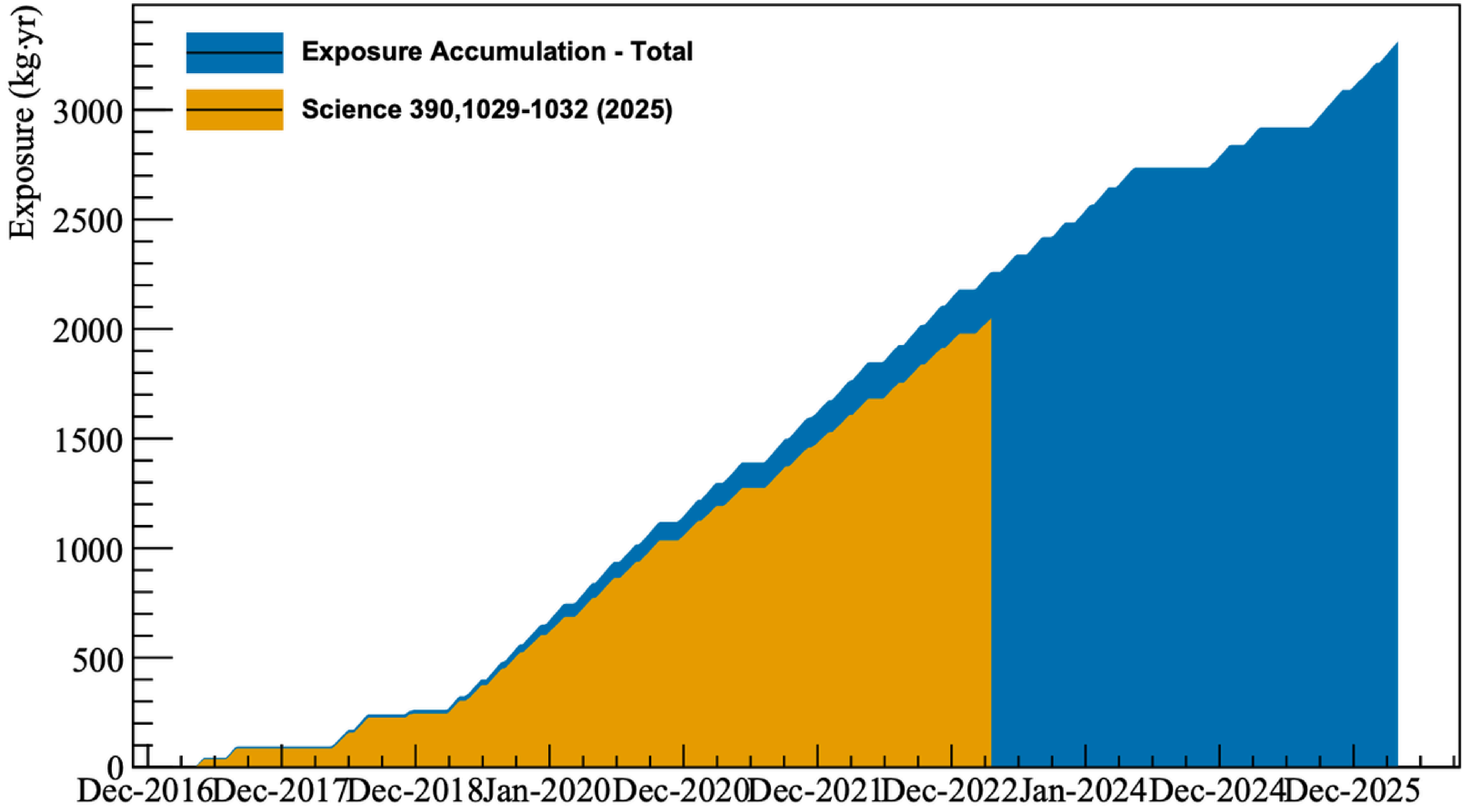
📖 arxiv:2510.25720

Event selection

- Anti-coincidence (AC): require energy deposition in one crystal only
- Pulse-shape discrimination (PSD)

Physics spectrum

Tonne-scale exposure from stable operation



📖 arxiv:2510.25720

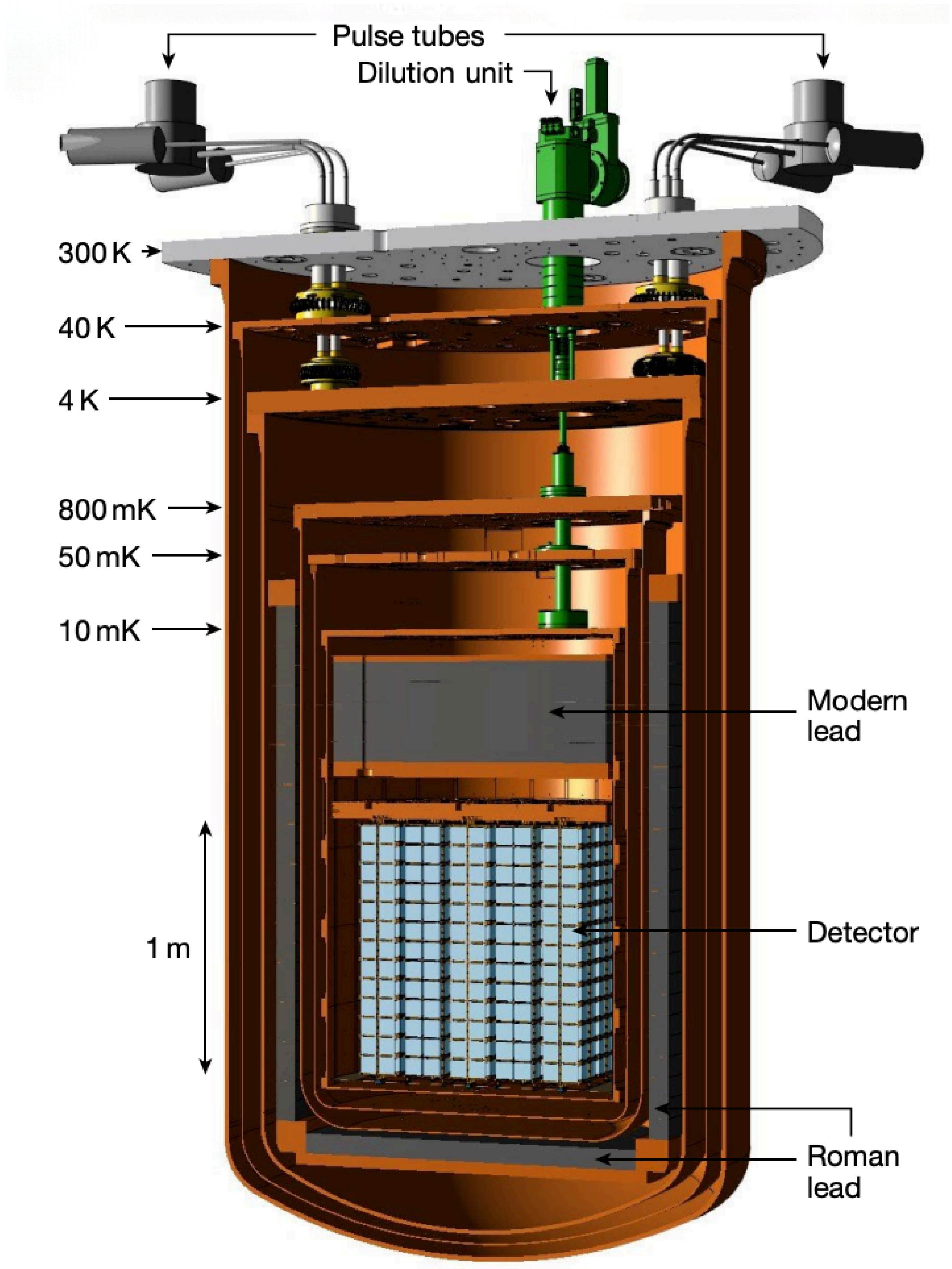
2039.0 kg yr TeO_2
analyzed exposure

567.0 kg yr ^{130}Te
for the 0νββ search

~3 tonne yr TeO_2
raw exposure accumulated

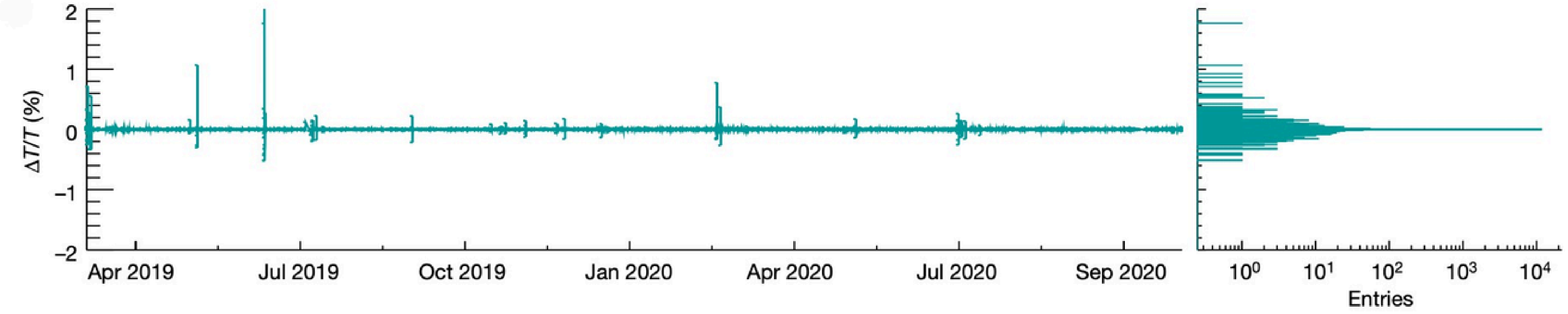
Data taking since 2017
stable long-term operation

CUORE cryogenic system



📖 Nature 604, 53–58 (2022)

- Custom-made dry, cryogen-free dilution cryostat
- **5 pulse-tube cryocoolers**, one spare
- **6 nested vessels** at decreasing temperature
- Base temperature Tmin≃**7 mK**
- Detector operated at ~**10 mK**
- Mass below 4 K: ~15 tons
- Mass at 50 mK: ~3 tons
- Stable operation: >5 years below 20 mK, >90% uptime since 2019



The 2 tonne-year 0νββ spectrum

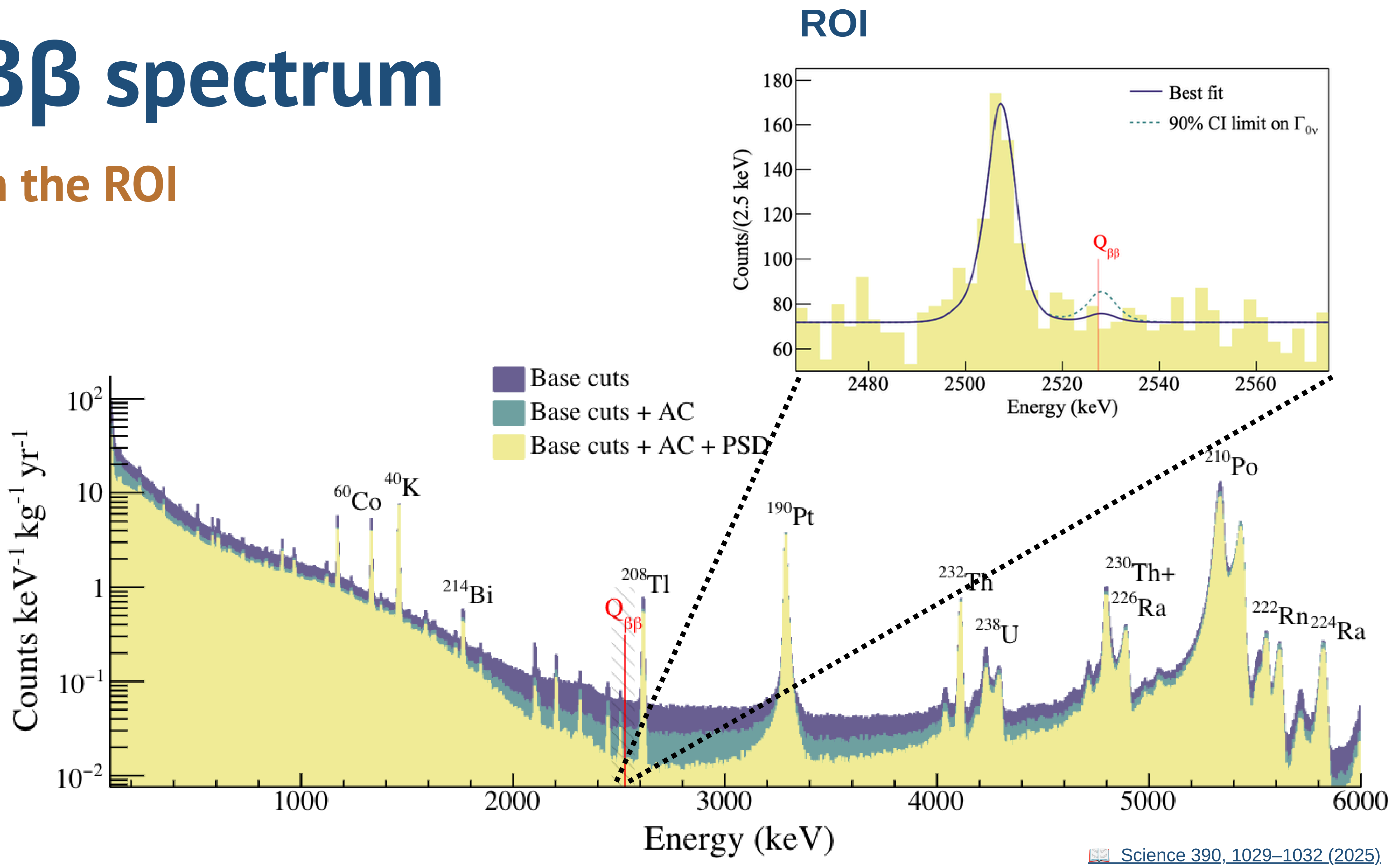
No evidence of a signal is observed in the ROI

2 tonne-year data release
2039.0 kg yr TeO_2
567.0 kg yr ^{130}Te

Selection:
Base cuts
trigger, energy reconstruction, pileup

Anti-coincidence
single-crystal events

Pulse-shape discrimination
signal-like pulses



Science 390, 1029–1032 (2025)

Total analysis efficiency: **93.4%**
Average ROI background index:
1.42×10^{-2} counts/(keV kg yr)

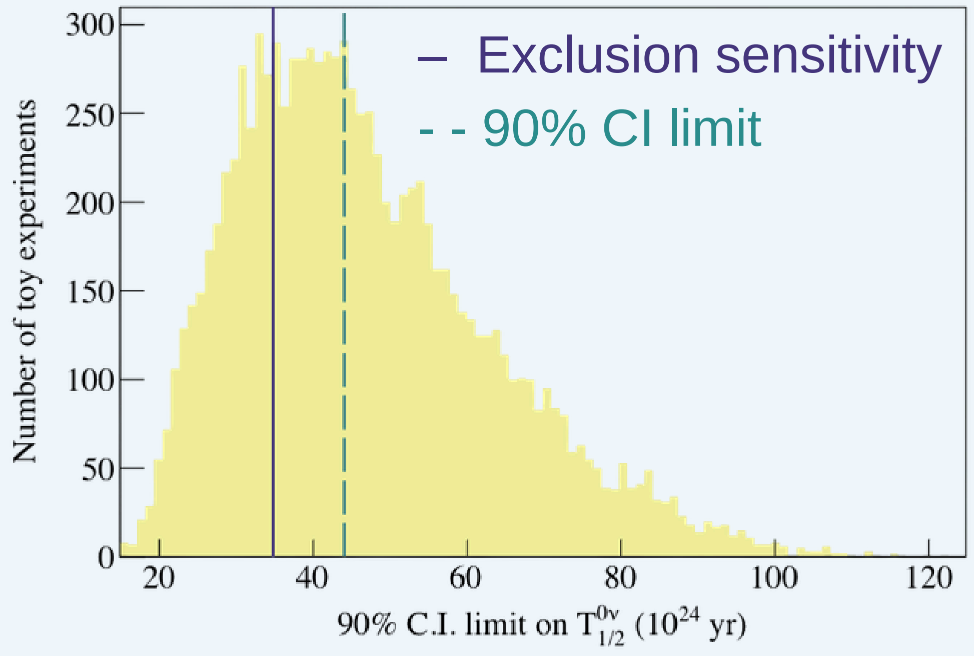
Latest ^{130}Te 0νββ result

Bayesian fit of the data in the ROI

$$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 3.5 \times 10^{25}\ \mathrm{yr}$$

90% C.I.

Exclusion sensitivity from toy MC

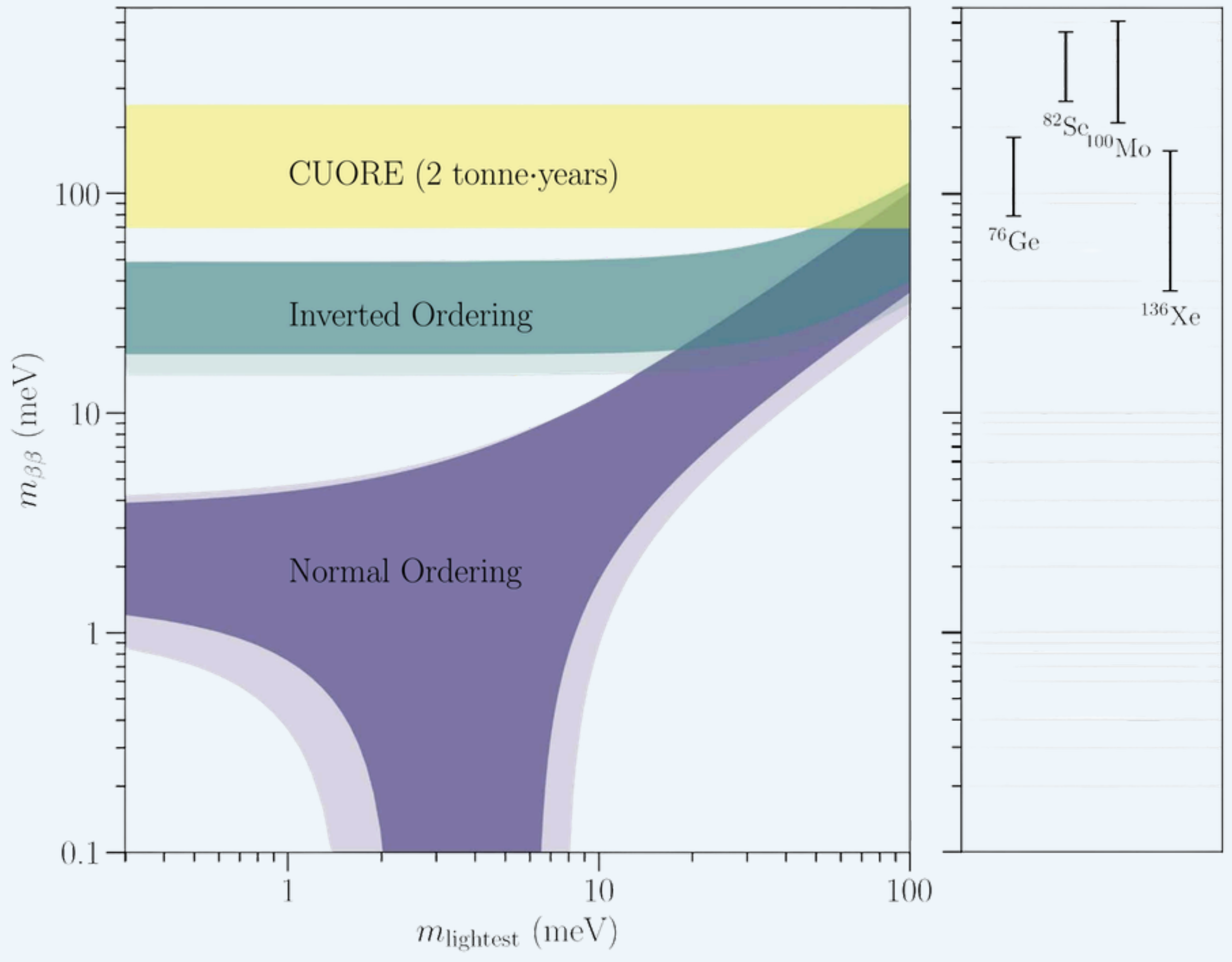


Frequentist cross-check

$$T^{0\nu}_{1/2} > 3.4 \times 10^{25}\ \mathrm{yr} \quad (90\%\ \mathrm{C.L.})$$

Limit on the effective neutrino mass

$$m_{\beta\beta} < 70 \text{ to } 250\ \mathrm{meV}$$



📖 Science 390, 1029–1032 (2025)

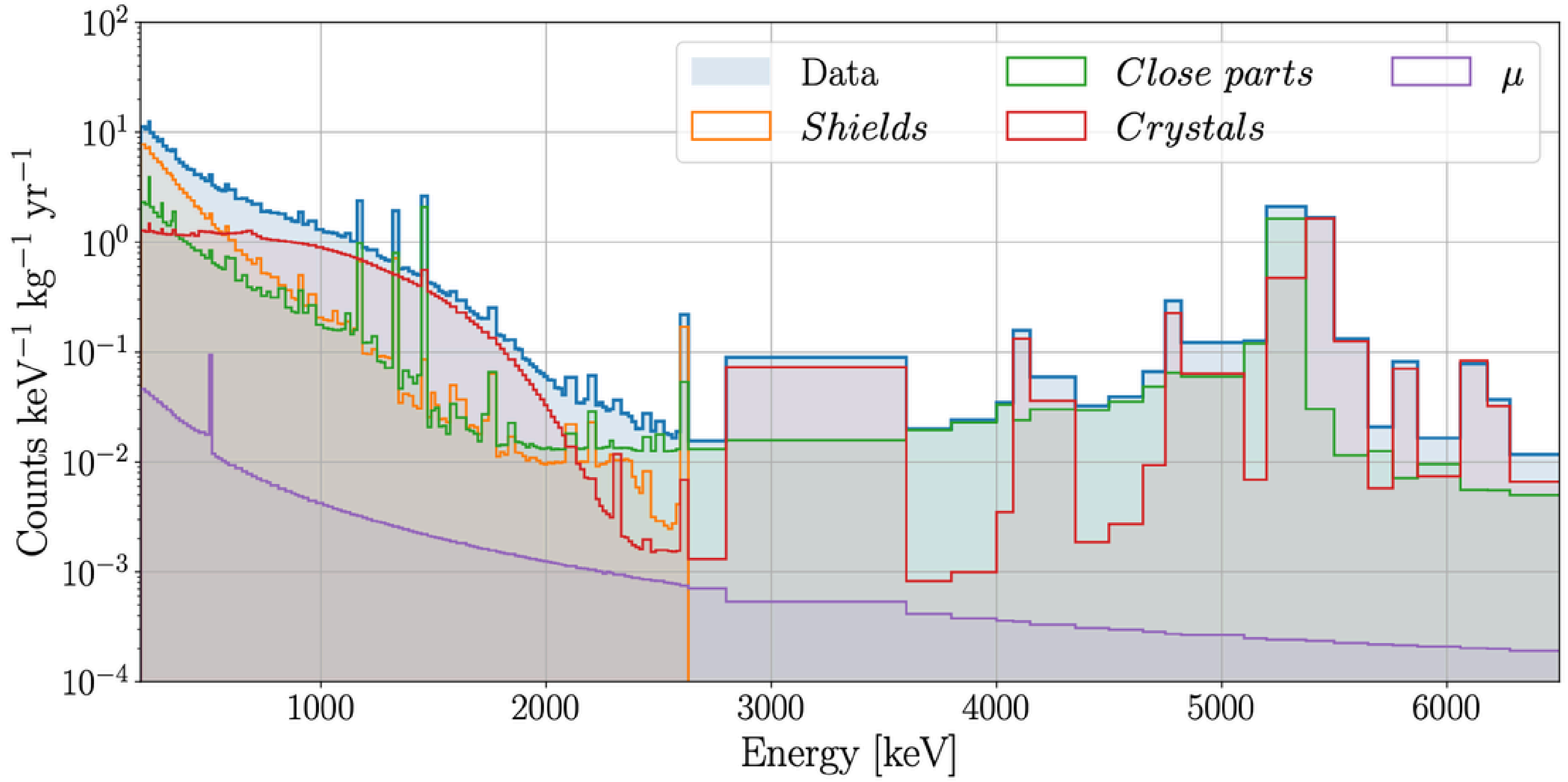
Data-driven background model

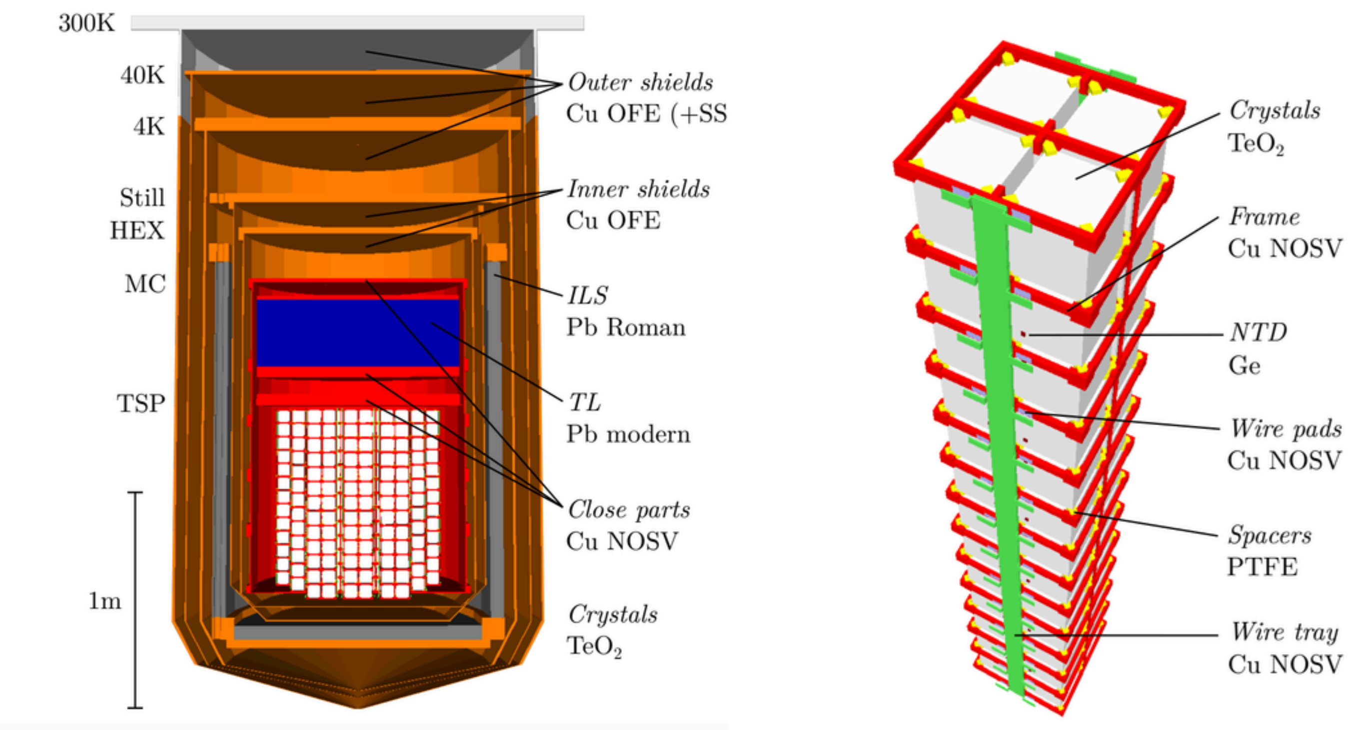
Background model

• **GEANT4** simulation + measured detector response
expected spectra for each background source
• **Coincidences + detector self-shielding**
constrain the source locations
• BM exposure: 1038.4 kg yr TeO_2
sensitivity down to **10 nBq/kg** and **0.1 nBq/cm²** for bulk and surface contamination

ROI background

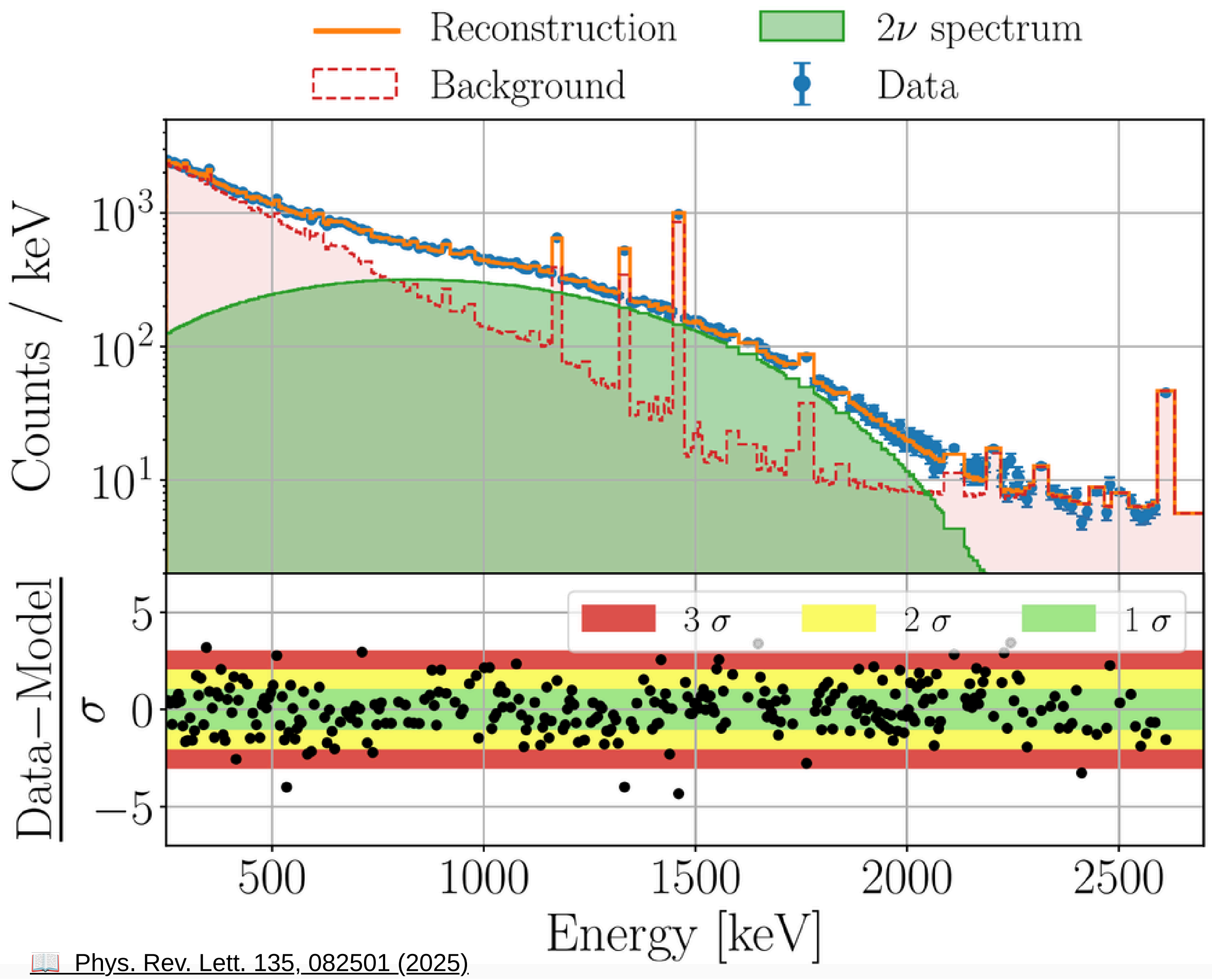
• Dominated by **degraded α particles**, about 90%
• Smaller contributions from multi-Compton γ events and cosmic muons





📖 Phys. Rev. D 110, 052003 (2024)

Precision measurement of ^{130}Te 2νββ



📖 Phys. Rev. Lett. 135, 082501 (2025)

Dominant spectral component

2νββ is the dominant single-site contribution between ~1 and 2 MeV

Half-life

$$T^{2\nu}_{1/2}(^{130}\mathrm{Te}) = \left[9.32^{+0.05}_{-0.04}(\mathrm{stat})^{+0.07}_{-0.07}(\mathrm{syst})\right] \times 10^{20}\ \mathrm{yr}$$

Spectral-shape fit

Improved 2νββ formalism used to test nuclear-model descriptions

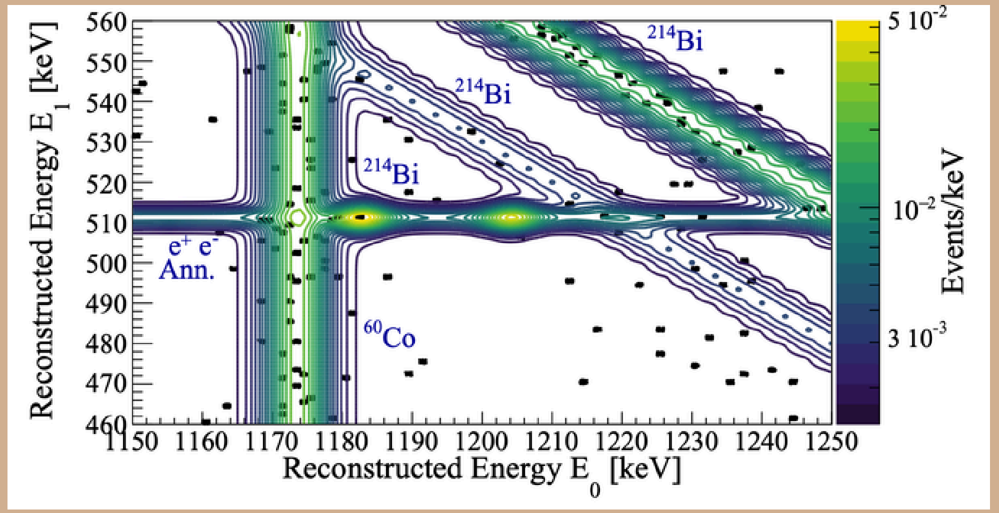
The large CUORE exposure turns an allowed rare decay into a precision measurement.

Other rare event searches with CUORE

Other tellurium channels

^{120}Te $0\nu\beta^+$EC

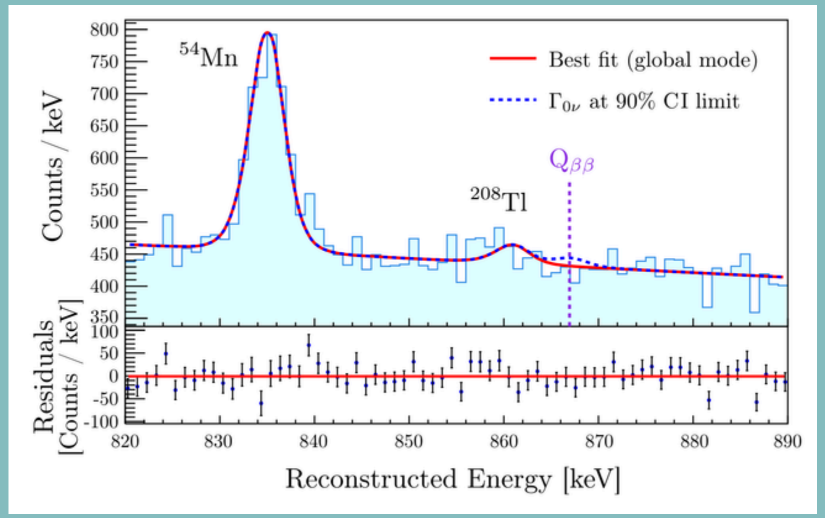
$$T^{0\nu}_{1/2} > 2.9 \times 10^{22} \text{ yr}$$



📖 Phys. Rev. C 105, 065504 (2022)

^{128}Te $0\nu\beta\beta$

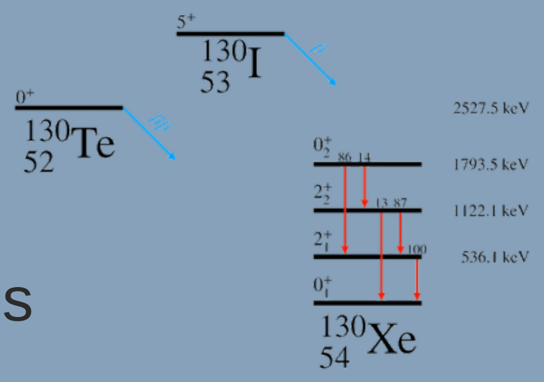
$$T^{0\nu}_{1/2} > 3.6 \times 10^{24} \text{ yr}$$



📖 Phys. Rev. Lett. 129, 222501 (2022)

^{130}Te $\rightarrow ^{130}$Xe*

excited-state searches



$$(T_{1/2})^{0\nu}_{0^+_2} > 5.9 \times 10^{24} \text{ yr (90\% C.L.)}$$

$$(T_{1/2})^{2\nu}_{0^+_2} > 1.3 \times 10^{24} \text{ yr (90\% C.L.)}$$

📖 Eur. Phys. J. C 81, 567 (2021)

Other physics

- Fractionally charged particles

📖 Phys. Rev. Lett. 133, 241801 (2024)

- Muon event reconstruction

📖 arXiv:2509.05528

- Environmental and vibrational studies

📖 Commun. Phys. 9, 121 (2026)

- Thermal modeling of CUORE calorimeters

📖 JINST 17, P11023 (2022)

- Multi-crystal track-like topologies
- Background-model related studies

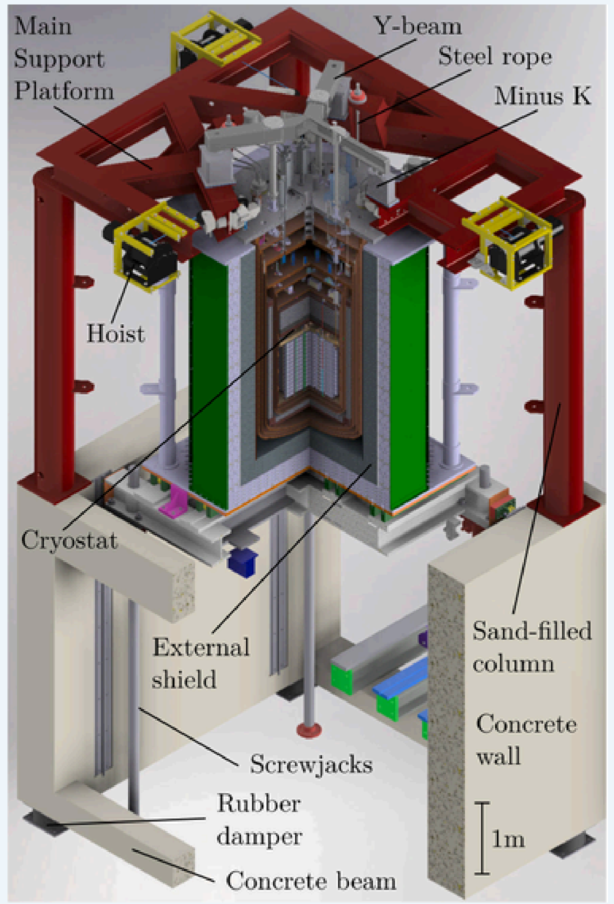
Low-background shielding and radiopurity

LNGS natural shielding

- underground location: ~**3600 m.w.e.**
- **~1400 m** rock overburden
- cosmic-ray flux reduced by ~6 orders of magnitude
- muon flux: **$\Phi_\mu \simeq 3 \times 10^{-8}\ \mathrm{cm^{-2}\ s^{-1}}$**
- neutron flux: **$\Phi_n \simeq 4 \times 10^{-6}\ \mathrm{cm^{-2}\ s^{-1}}$**

External shields

- γ shielding: **25 cm Pb layer**
- neutron shielding: **20 cm polyethylene**
- H_3BO_3 panels for neutron capture



📖 Cryogenics 102, 9–21 (2019)

Radiopurity strategy

- strict material selection and screening
- radiopure copper for cryostat plates and vessels
- minimized material close to the detector
- clean assembly procedures to limit surface contamination

Internal shields

- top shield: **30 cm modern Pb** at ~50 mK
- side and bottom shields: **6 cm ancient Roman Pb** at ~4 K
- ancient Pb activity: ^{210}Po < 4 mBq/kg

📖 Nucl. Instrum. Methods B 142, 163–172 (1998)

Blinding and fit model in the 0νββ ROI

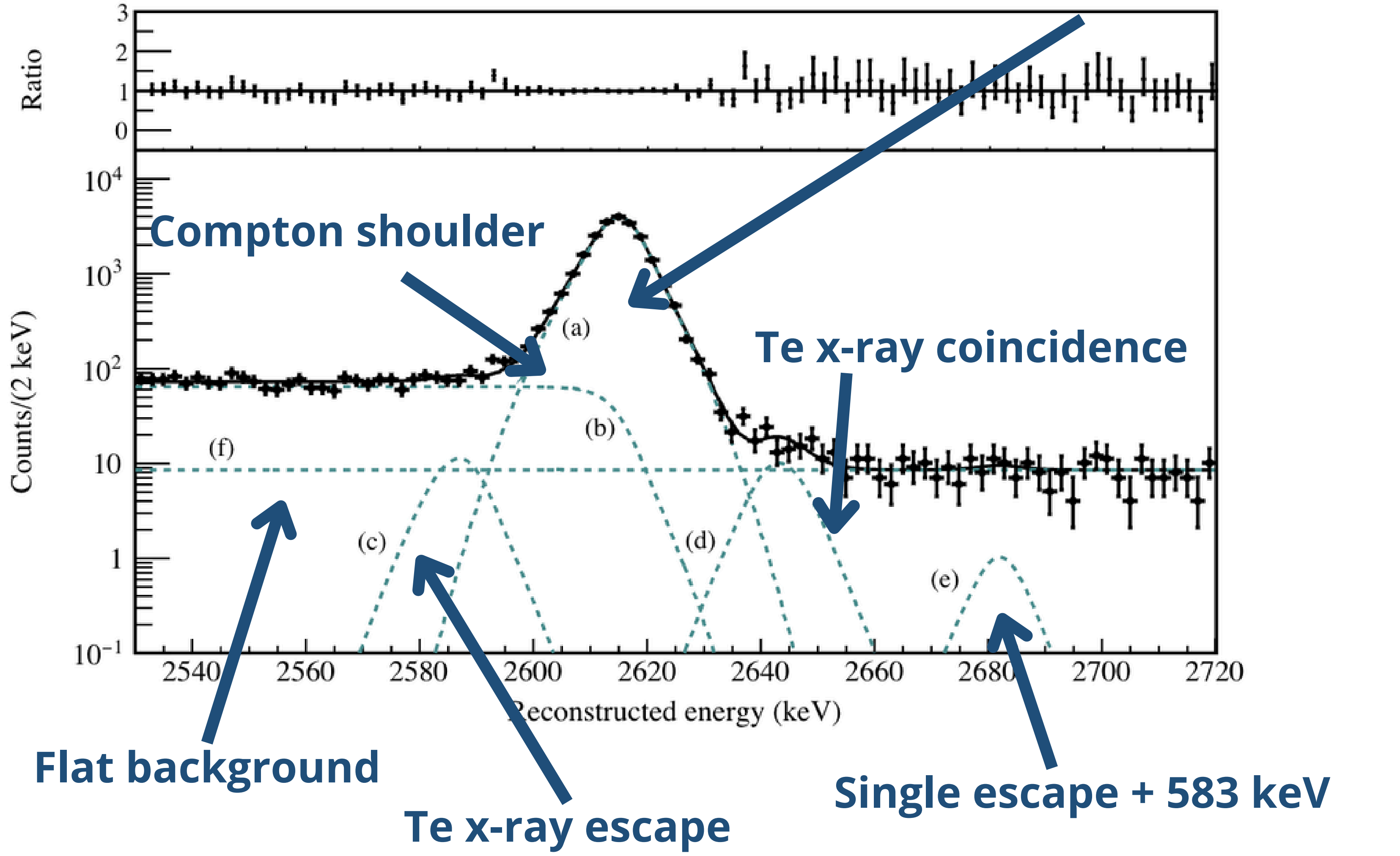
Blinding strategy

- Analysis developed on **blinded data**
- Salting: a small fraction of events around the 2615 keV ^{208}**Tl peak** and around **Qββ** were exchanged
- This creates an artificial peak near Qββ during analysis development
- Unblinding performed only after freezing the analysis procedure

ROI fit model

- Fit performed in the region around **Qββ = 2527.5 keV**
- Components:
  - possible 0νββ signal peak at Qββ
  - ^{60}Co summation peak at 2505.7 keV
  - smooth continuum background
- Peak shapes described by the detector response function
- The fit parameter of interest is the 0νββ signal rate

Detector response model



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

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

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

📖 Science 390, 1029–1032 (2025)