Spectral Studies and Cosmic Axion Search in CUORE

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Passage of the Year
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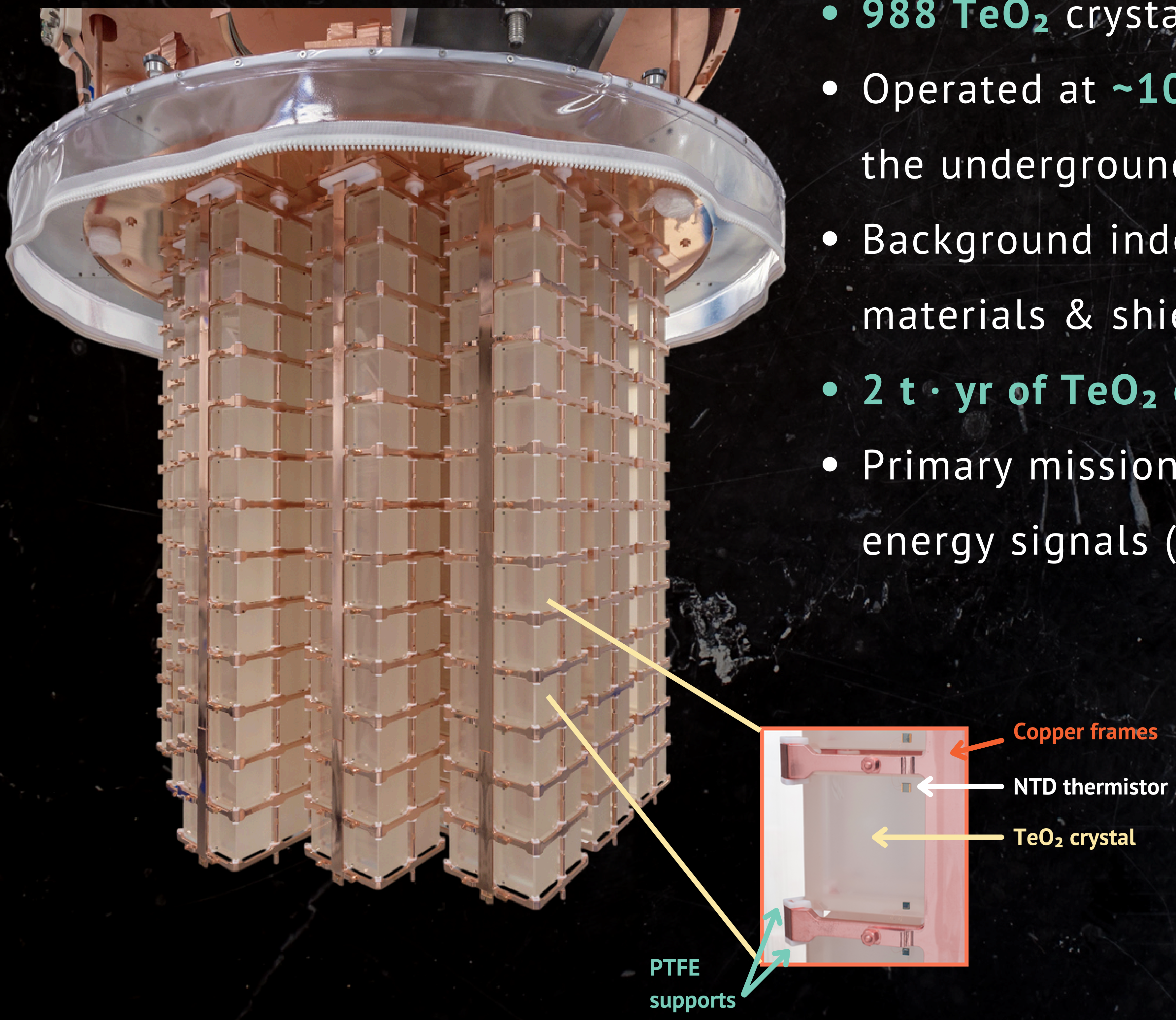
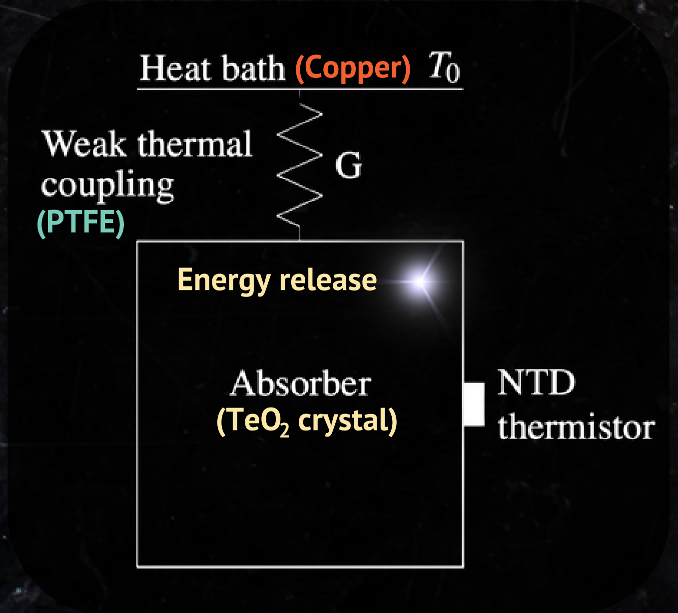
Outline

- CUORE low energy event selection and efficiencies
- Understanding the low energy spectrum components
- Cosmic axion search

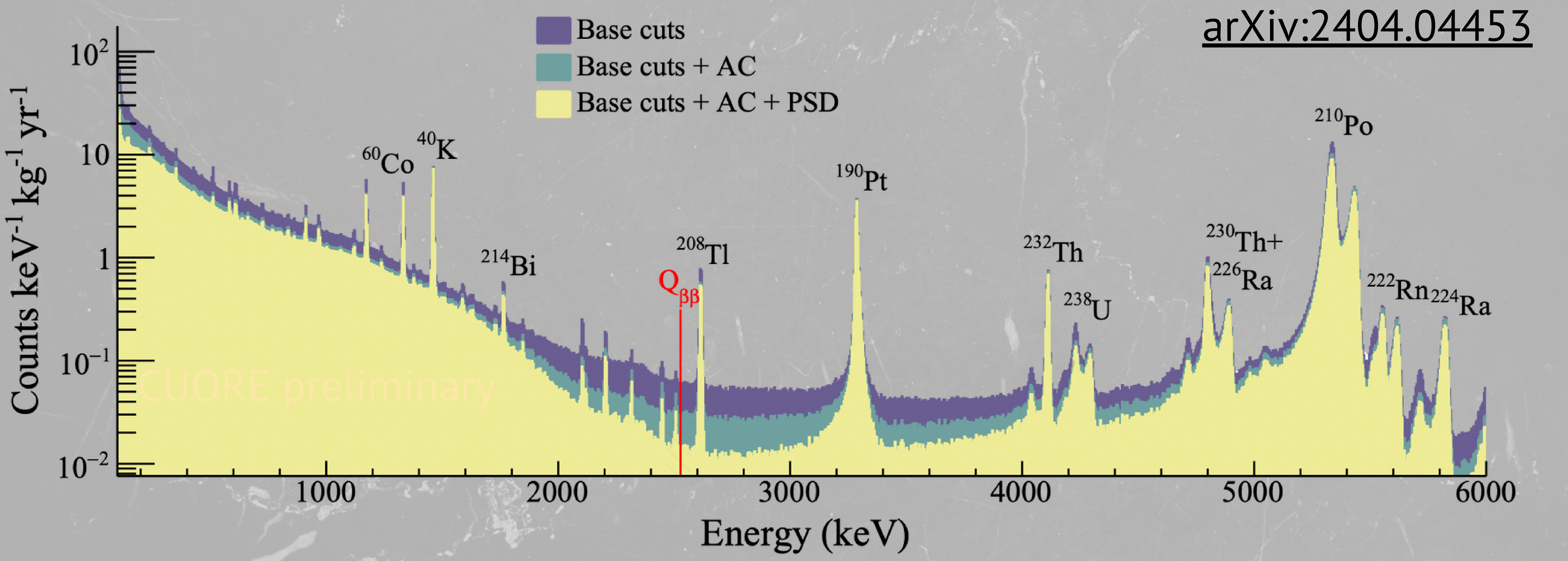
CUORE: Cryogenic Underground Observatory for Rare Events

- **988 TeO_2** crystals in 19 towers (total 742 kg, 206 kg ^{130}Te)
- Operated at **~10 mK** as cryogenic calorimeters inside a dilution cryostat in the underground LNGS laboratory (~3600 m.w.e. rock overburden)
- Background index: **1.42×10^{-2} counts/(keV·kg·yr)** achieved with ultra-clean materials & shielding @ ^{130}Te 0νββ Q-value (arXiv:2404.04453)
- **2 t · yr of TeO_2 exposure** already collected and analyzed
- Primary mission: 0νββ search in ^{130}Te; low thresholds enable rare low-energy signals (e.g. solar axions, **cosmic axions**, WIMPs)





CUORE Energy Spectrum

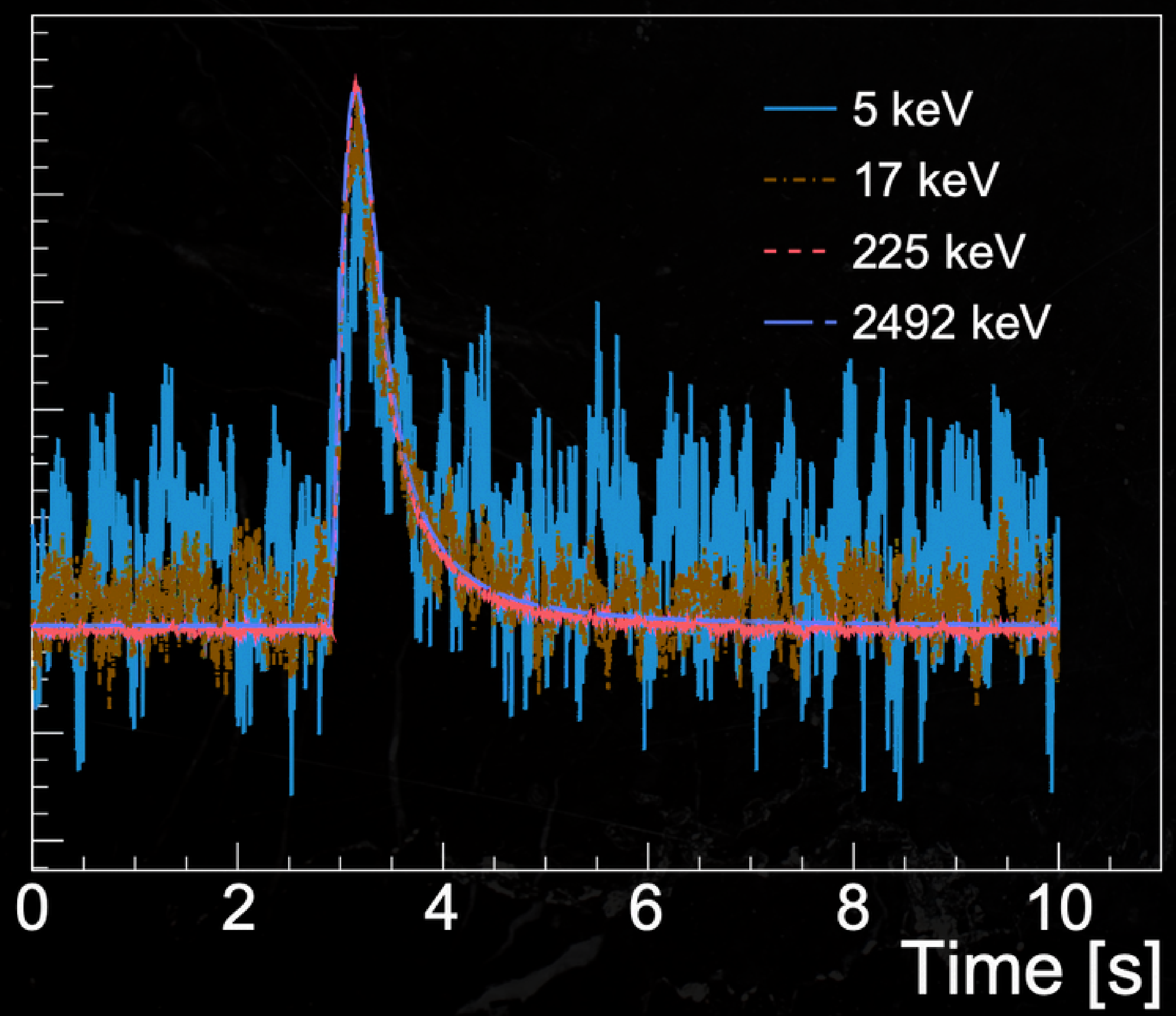


β and γ region

α region

← new physics? (e.g. axions, WIMPs)

Moving to Lower Energies



arXiv:2505.23955

- At lower energies we enter the near-threshold regime.
- **Noise grows**; SNR drops.
- **Spurious pulses** increase (electronics, vibrations).
- Pulse-shape estimations and efficiencies degrade.

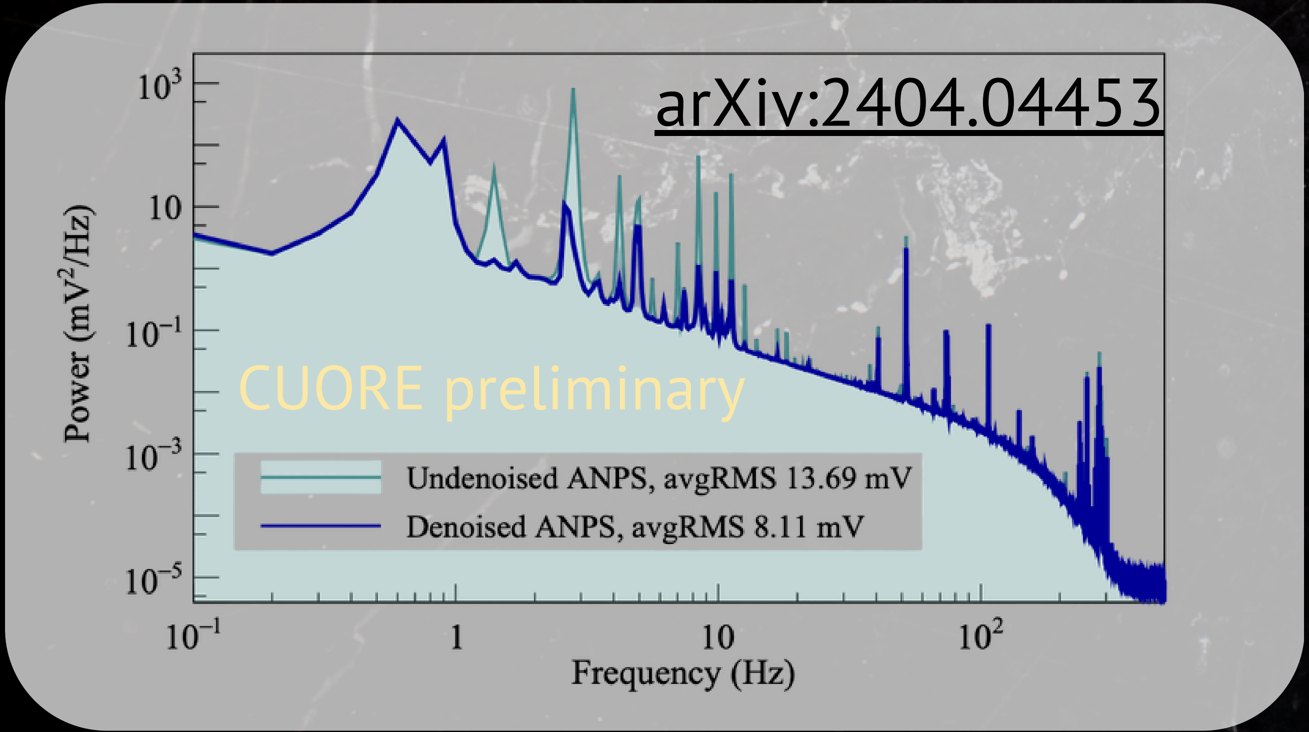
↓

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

CUORE Low Energy Techniques

Denoising

- **Method:** use microphones, accelerometers, a seismometer, and noise-only traces to infer the vibration transfer function and subtract it.
- **Result:** denoised waveforms → lower thresholds & better resolution near threshold



Optimum Trigger

- **Method:** apply a matched optimal filter (signal template + noise PSD) and trigger on the filtered peak; inject template pulses into noise-only data to map ε(E); set Ethr at 90% per detector.
- **Result:** lower thresholds

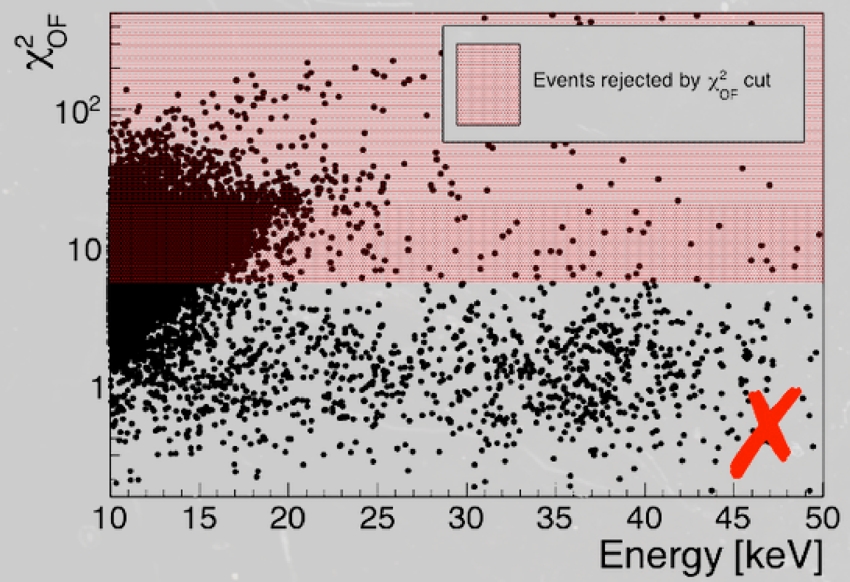
$$H(\omega) = k\frac{S^*(\omega)}{N(\omega)}e^{i\omega t_{peak}}$$

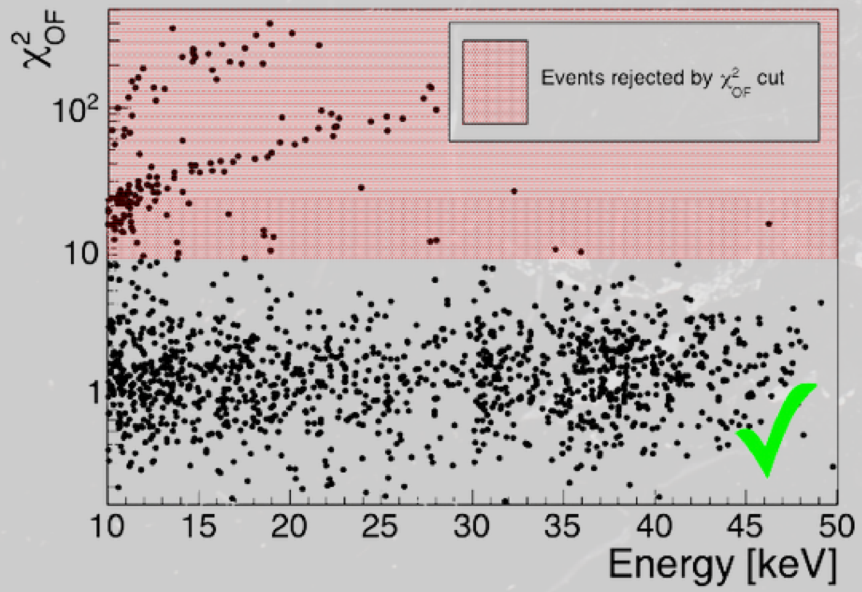
Signal template

Noise power spectrum

https://doi.org/10.1088/1748-0221/6/02/P02007

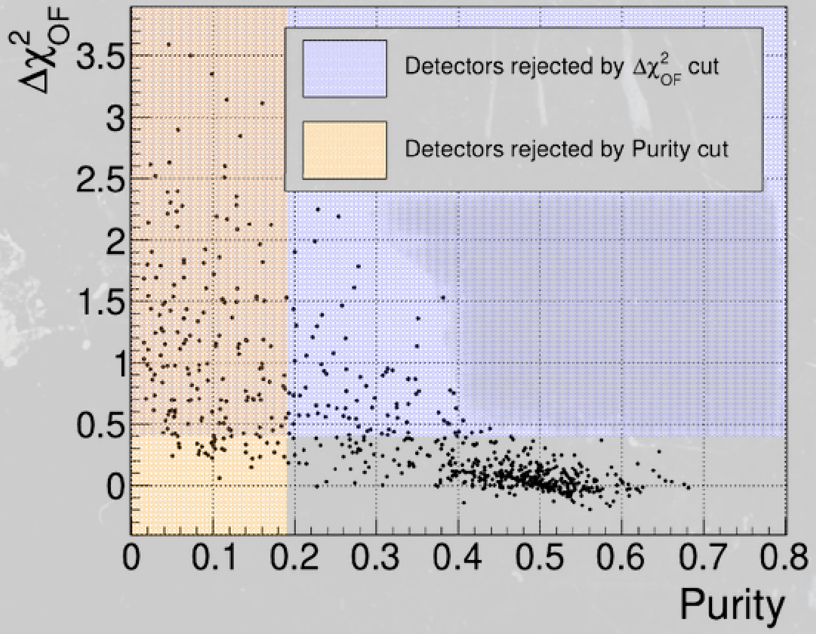
Low Energy Event Selection





arXiv:2505.23955

1. For each detector, compute the **pulse-shape metric χ^2**.
2. Toward threshold, noise increases and some detectors **lose separation at low E**.
3. **Event selection per detector**: Set a χ^2 threshold to keep one clean physics band and remove events with larger χ



4. Detector selection in the ROI:

- 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 $\Delta\chi^2$.

Event Selection Results

Detectors selected with 3 keV threshold

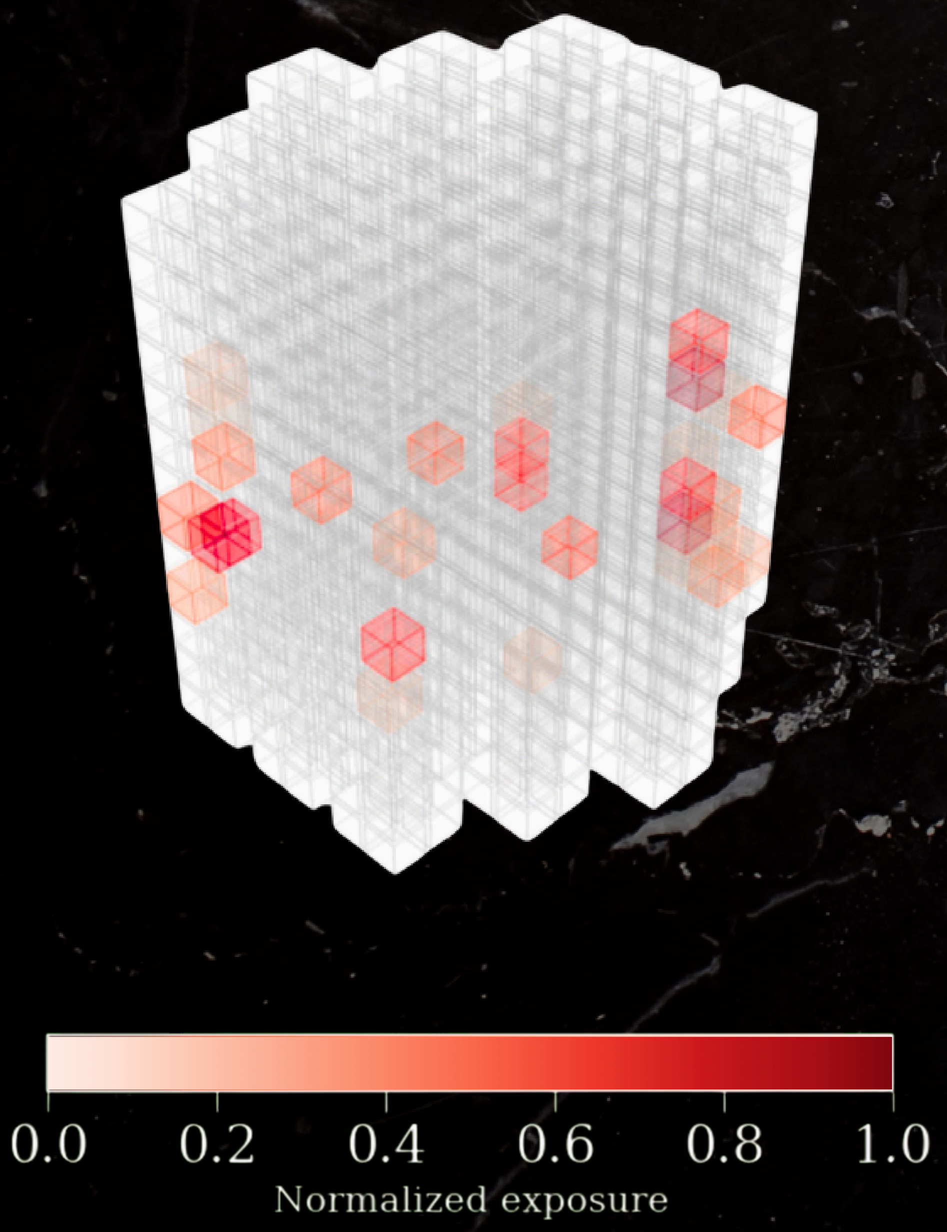
lowest achievable, high energy resolution

^{123}Te EC search

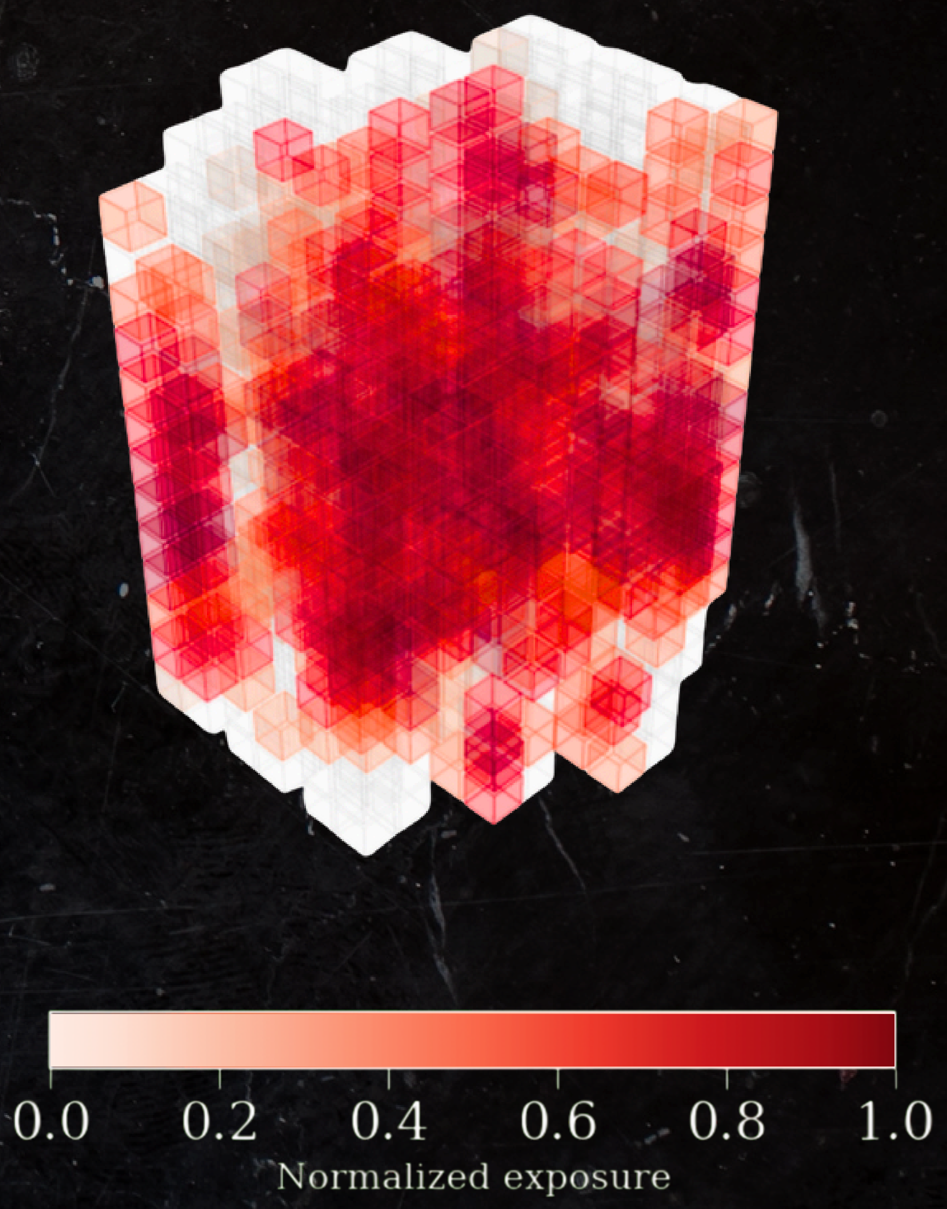
Detectors selected with 10 keV threshold

high exposure

new physics searches: axions, WIMPs



TeO₂ exposure [kg·yr]	
11	691
Selected detectors	
1.2%	35%
FWHM [keV]	
1.18	2.54
Background [cts/(keV·kg·day)]	
16	2.06
Total Efficiency	
26%	50%



arXiv:2505.23955

Efficiencies

To determine efficiencies we use:

- Te X-ray peaks (27 – 31 keV):

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

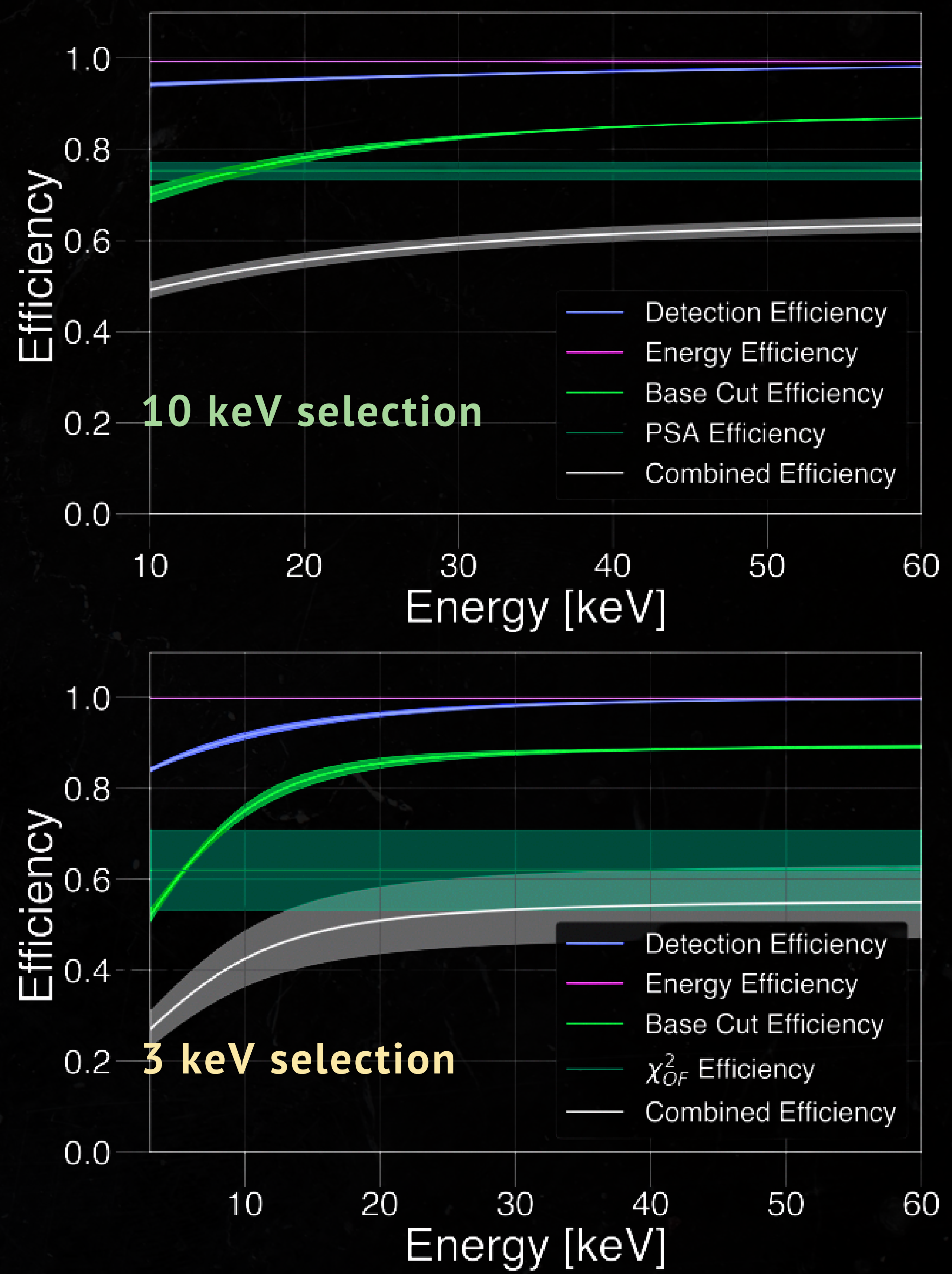
- Injected thermal pulses at multiple amplitudes:

  Detection: probability that the Optimum Trigger fires within the signal window.

  Energy: probability that the reconstructed energy matches the injected value within tolerance.

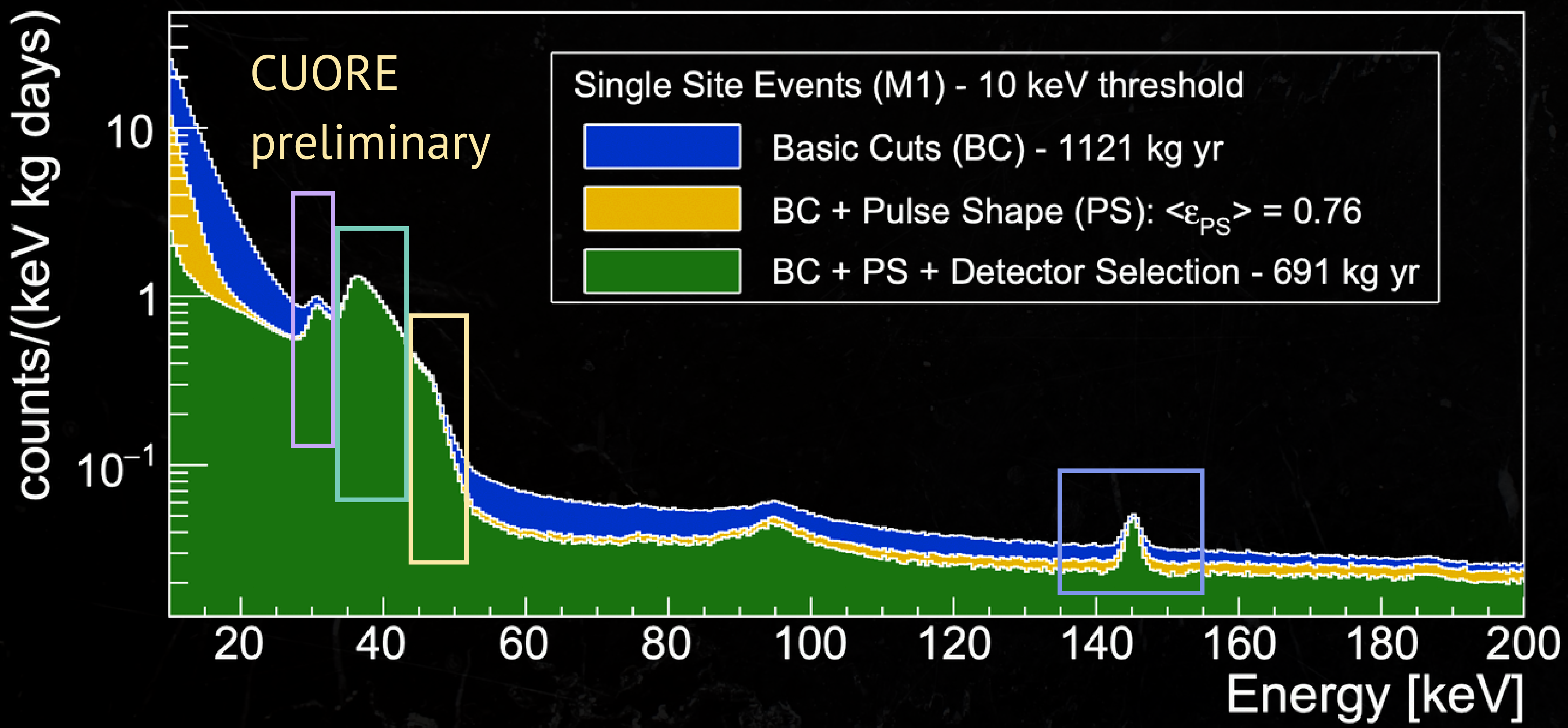
  Base Cut: probability that the pulse is isolated (no pile-up) and passes quality requirements.

Currently developing an upgraded **pulse-shape efficiency** based on injected pulses to account for its energy dependence.



arXiv:2505.23955

Low Energy Spectrum: 10 keV selection



cosmic axions?

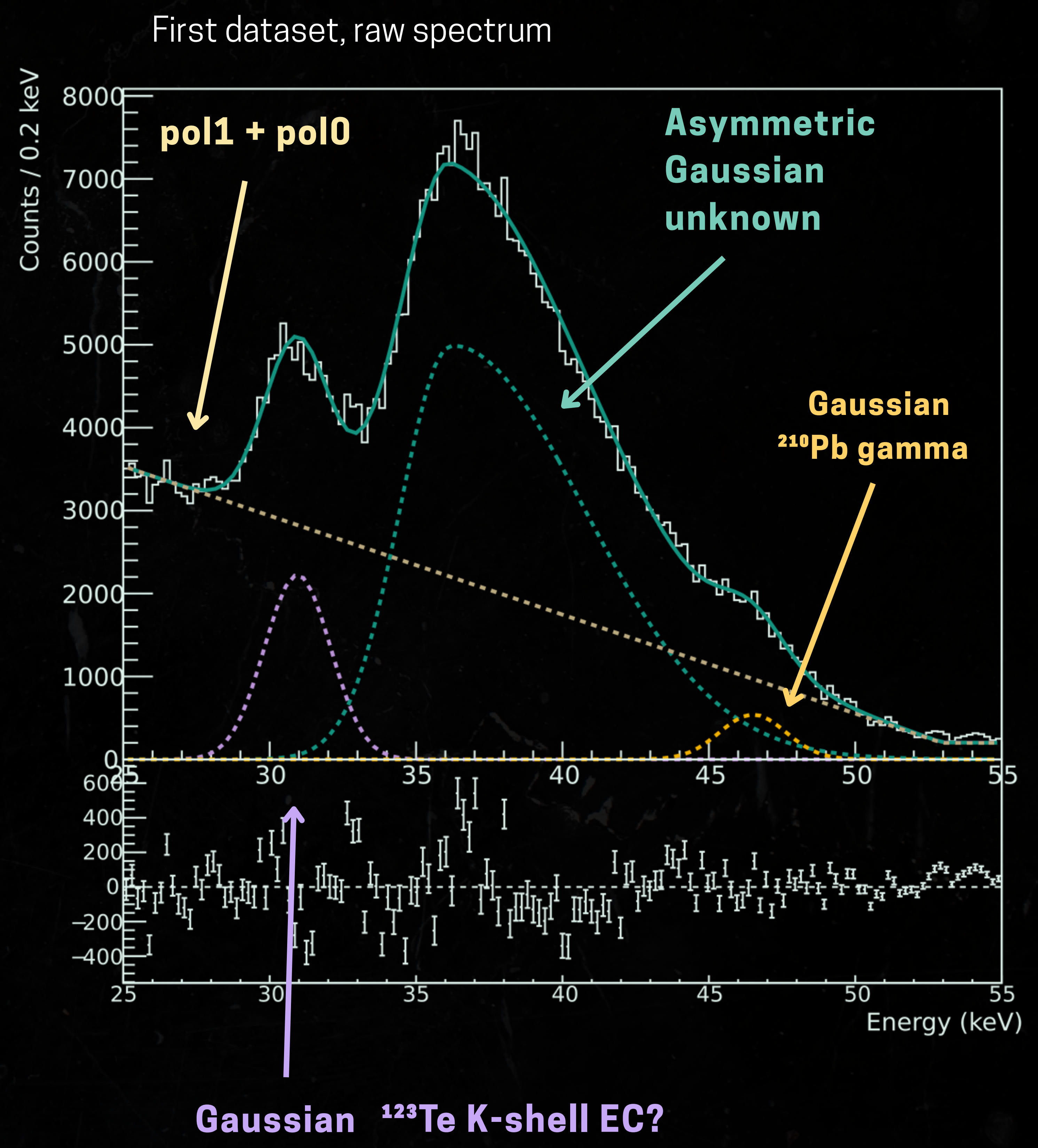
Energy [keV]	Hypothesis	Status
4.7	^{123}Te L-shell EC	Under investigation
~10	^{210}Pb X-rays	Under investigation
~13	^{210}Pb X-rays	Likely
30.5	^{123}Te K-shell EC	Under investigation (this work)
36	Unknown	Under investigation (this work)
46.5	^{210}Pb gamma	Likely (this work)
90	^{210}Po nuclear recoils	Verified
145	^{125}mTe	Well-established (this work)

Combined Fit

- The **36 keV structure** motivated a joint fit [25 - 55 keV]
- Fit performed on **10 keV** selection channels, **25** datasets, dataset-by-dataset
- **BAT** in frequentist approach was used
- Previously used **RooFit** yielded less stable background and small peak reconstruction

Peak models

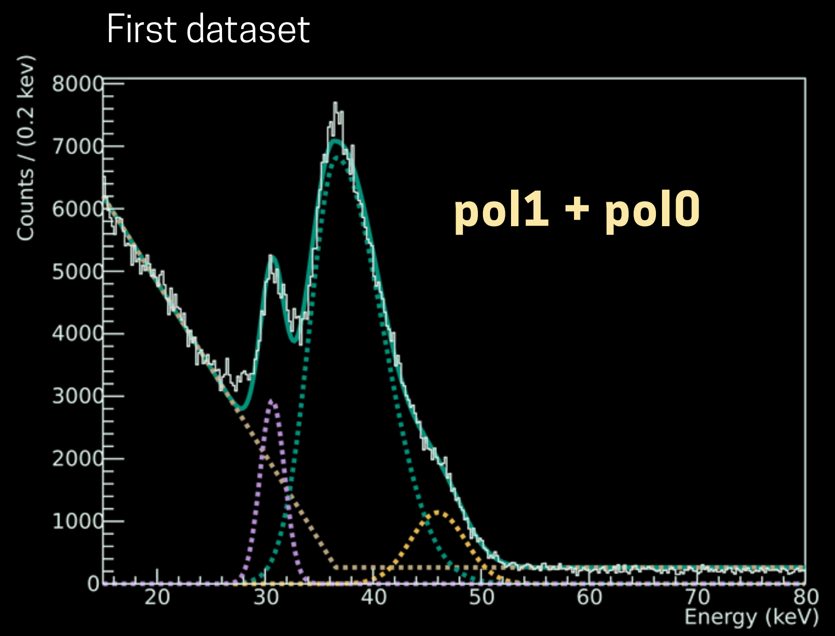
- **30.5** and **46.5 keV**: Gaussian, width fixed to baseline resolution, the 46.5 keV peak position is fixed as well. All the other parameters are **free**
- **36 keV**: Asymmetric Gaussian. Alternative fits (two Gaussians or Gaussian with β-like tails) gave similar χ^2 but added complexity

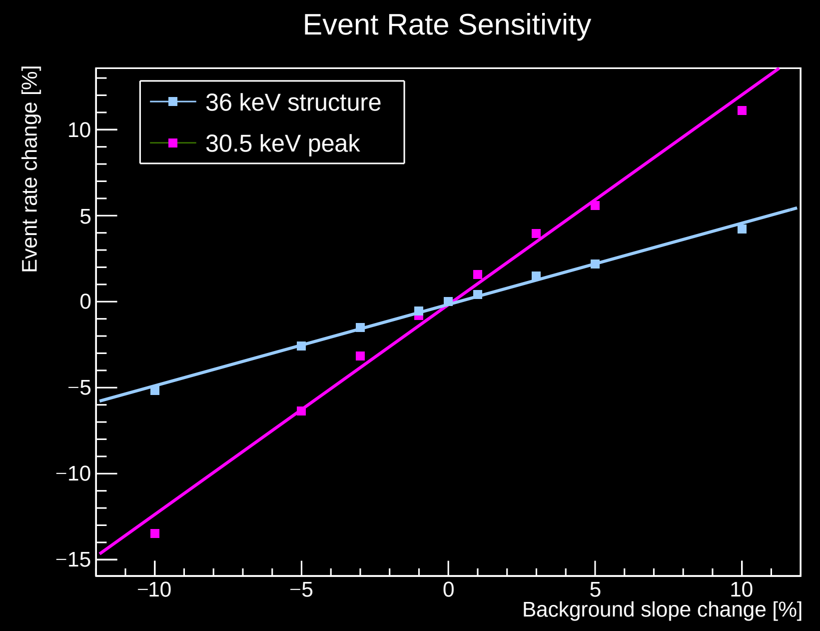


Background Model

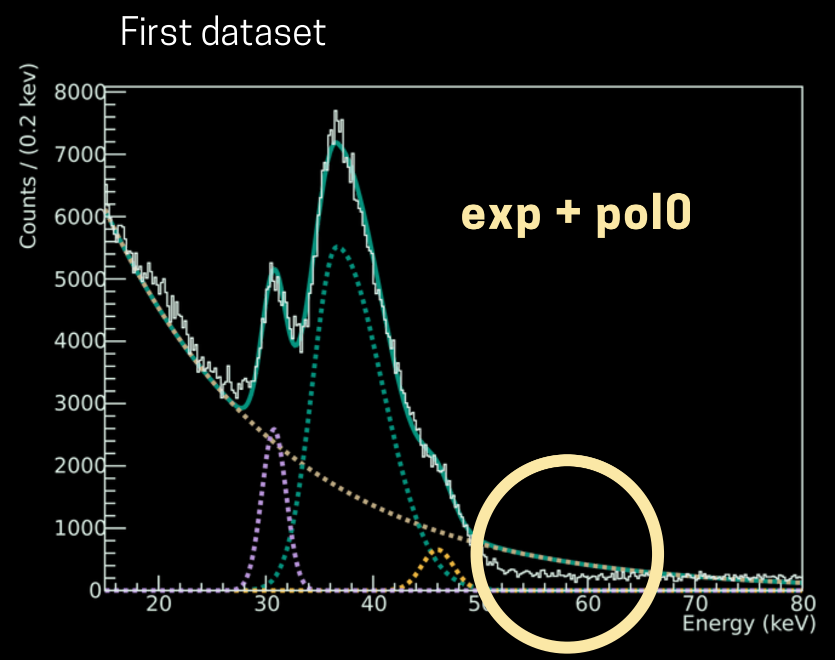
Background models tested:

- Exponential + constant
- Linear + constant (pol1 + pol0), used in this analysis
- 2 Exponential with different slopes

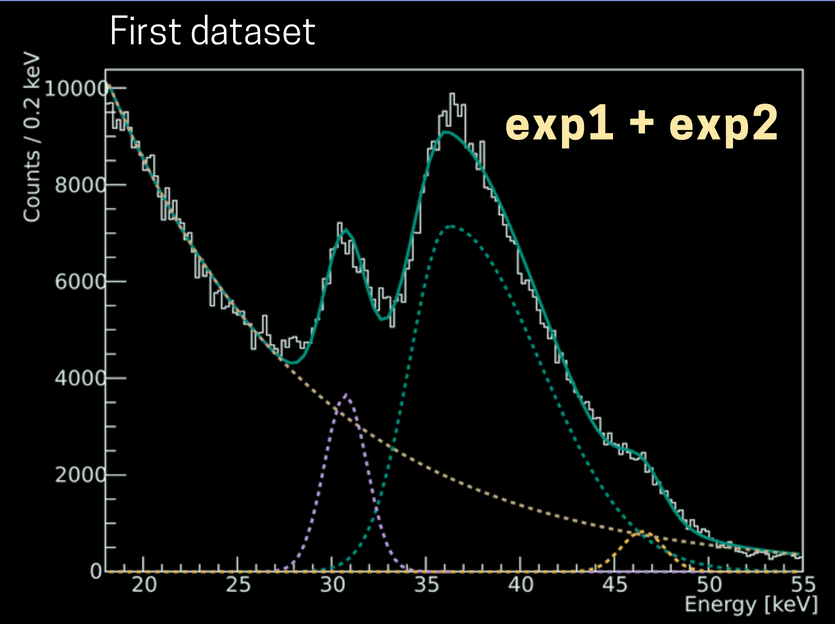




- Event rates are **highly sensitive to the background slope**.
- Reducing the ROI to 27 – 36 keV leads to **mis-reconstruction of the slope**, shifting the reconstructed rate of the 30.5 keV peak by ~30%.



Overestimates the background above 50 keV, leading to poorer fits



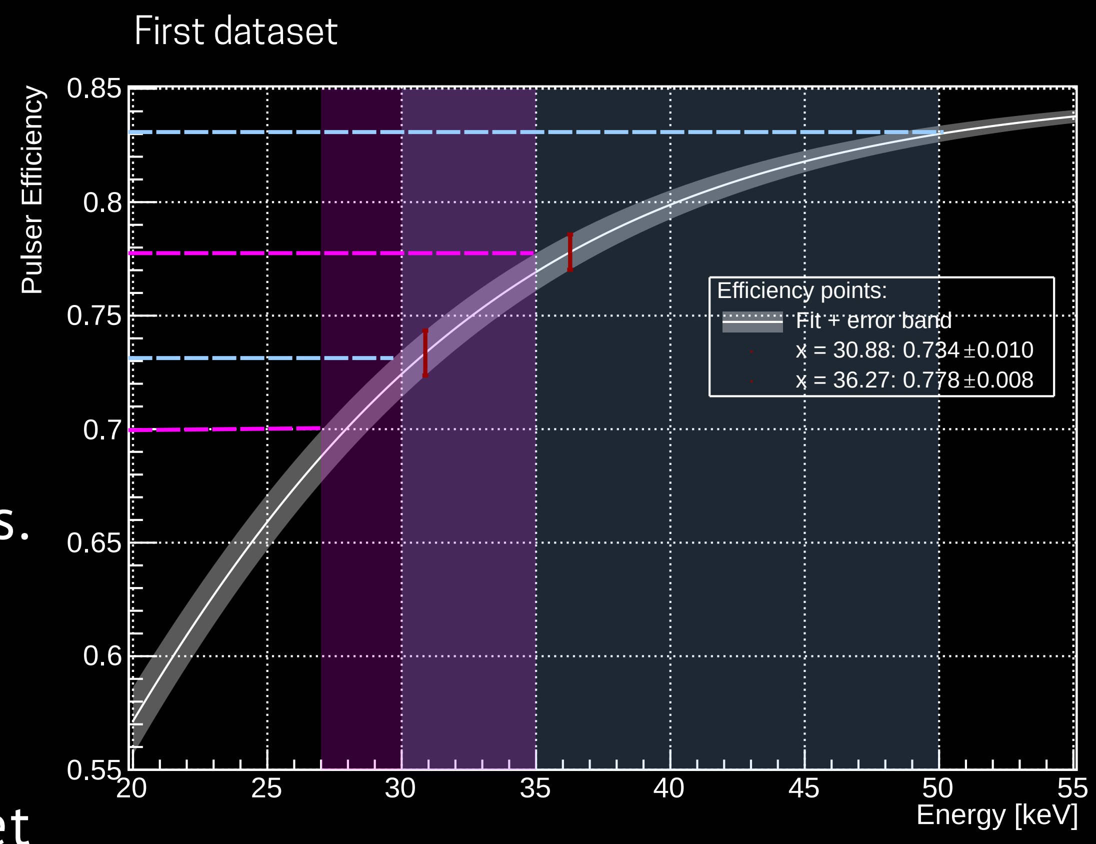
- Increases the 30.5 keV rate by 24% and the 36 keV structure rate by 32%
- Better reconstruction of the 30.5 keV peak position

Event Rates Calculation

Energy-dependent efficiency correction

Histogram counts are divided bin-by-bin by the pulser efficiency **before** the fit and weighted by the total exposure **after** the fit

$$\varepsilon_{\text{pulser}}(E) = \varepsilon_{\text{det}}(E)\,\varepsilon_{\text{cut}}(E)\,\varepsilon_{\text{energy}}$$



Two independent event rate calculations

- **RooFit** – take the fitted peak fraction and multiply by the total events in the histogram
- **BAT** – integrate the fitted peak PDF

For both the 30.5 keV and 36 keV structures, the two methods agree within statistical errors.

Uncertainty propagation

After fitting, the relative efficiency error is averaged over the fitted spectrum of each dataset

$$\delta_{\text{pulser}}(E) = \frac{\sigma_{\varepsilon_{\text{pulser}}}(E)}{\varepsilon_{\text{pulser}}(E)} = \sqrt{\left(\frac{\sigma_{\varepsilon_{\text{det}}}}{\varepsilon_{\text{det}}}\right)^2 + \left(\frac{\sigma_{\varepsilon_{\text{cut}}}}{\varepsilon_{\text{cut}}}\right)^2 + \left(\frac{\sigma_{\varepsilon_{\text{energy}}}}{\varepsilon_{\text{energy}}}\right)^2}$$

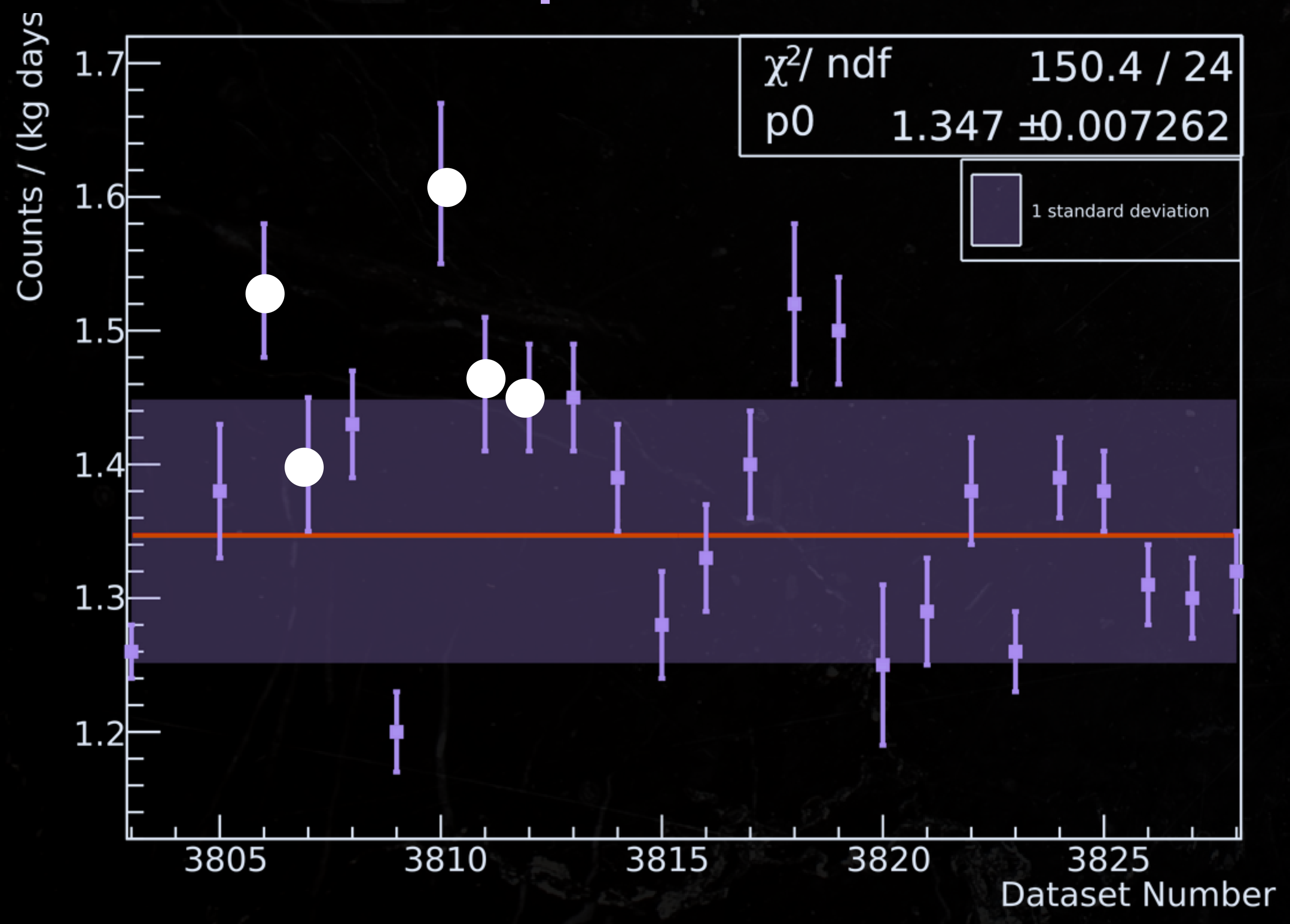
$$\delta_{\text{pulser}}^{(\text{weighted})} = \sqrt{\frac{\int f(E)\,[\delta_{\text{pulser}}(E)]^2\,dE}{\int f(E)\,dE}}$$

Total relative error on the event rate R

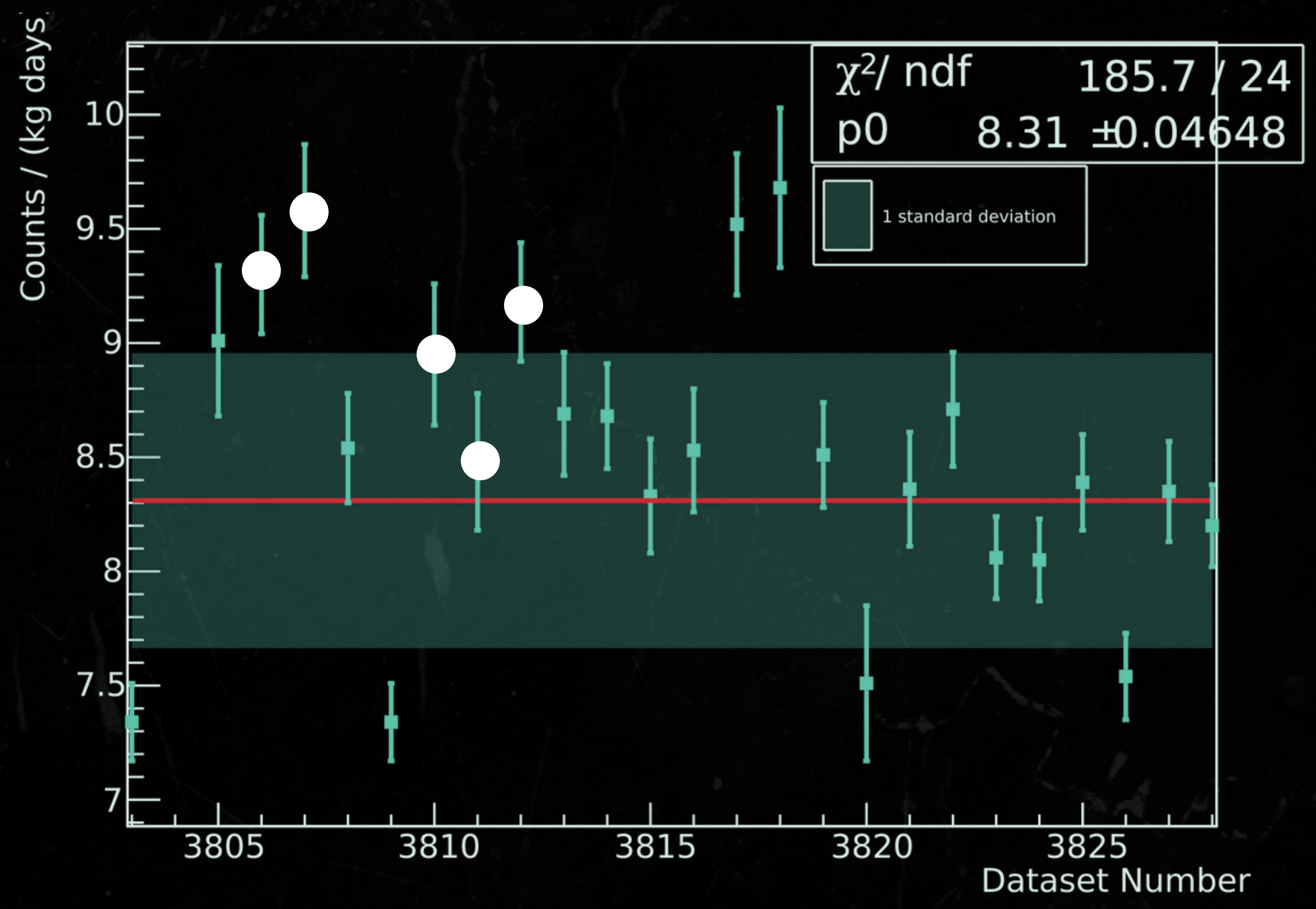
$$\frac{\sigma_R}{R} = \sqrt{\left(\frac{\sigma_{\text{stat}}}{R}\right)^2 + \left[\delta_{\text{pulser}}^{(\text{weighted})}\right]^2 + \left(\frac{\sigma_{\varepsilon_{\text{PS}}}}{\varepsilon_{\text{PS}}}\right)^2}$$

Event Rates: Results

30.5 keV peak event rate



36 keV structure event rate



- Datasets without pulser information

Event rates are computed as error-weighted averages over 25 datasets

No time dependence is observed → both peaks are **stable over the data-taking period**

Geometrical Dependencies

- Detector divided into:

inner / outer towers, bottom (1–4) / middle (5–8) / top (9-13) floors

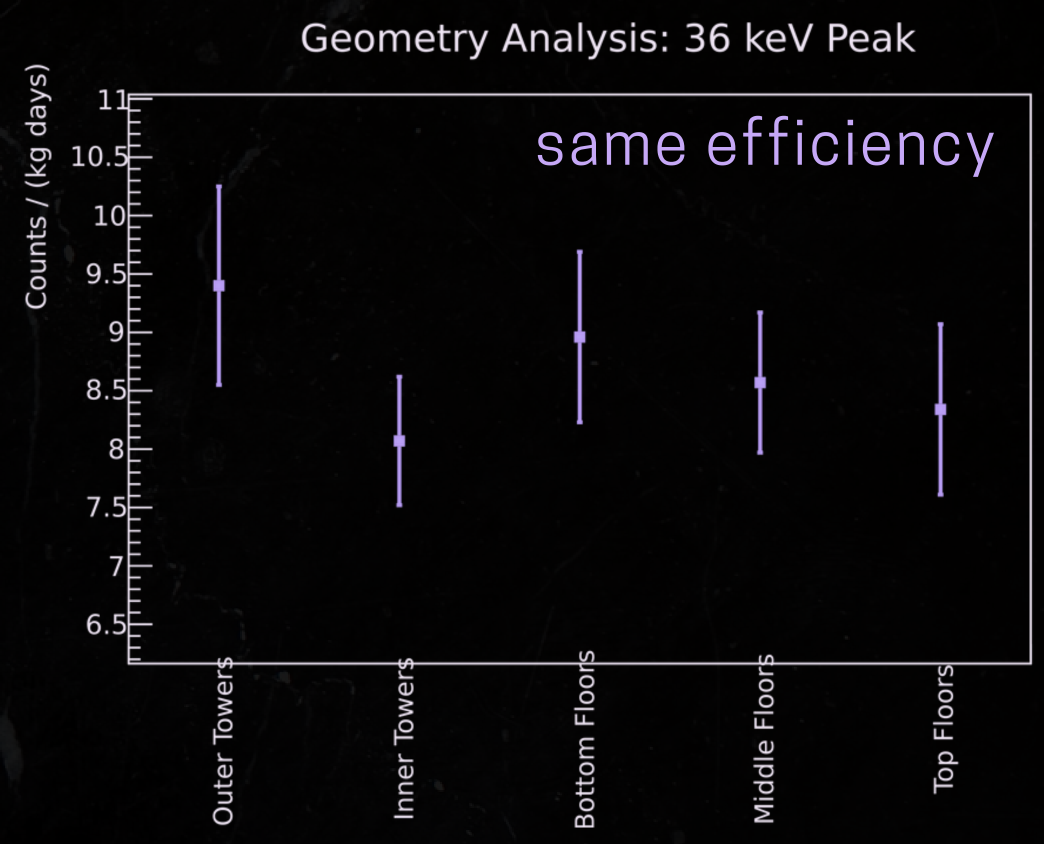
- Assumed the same efficiency across geometry — **now known to be incorrect**

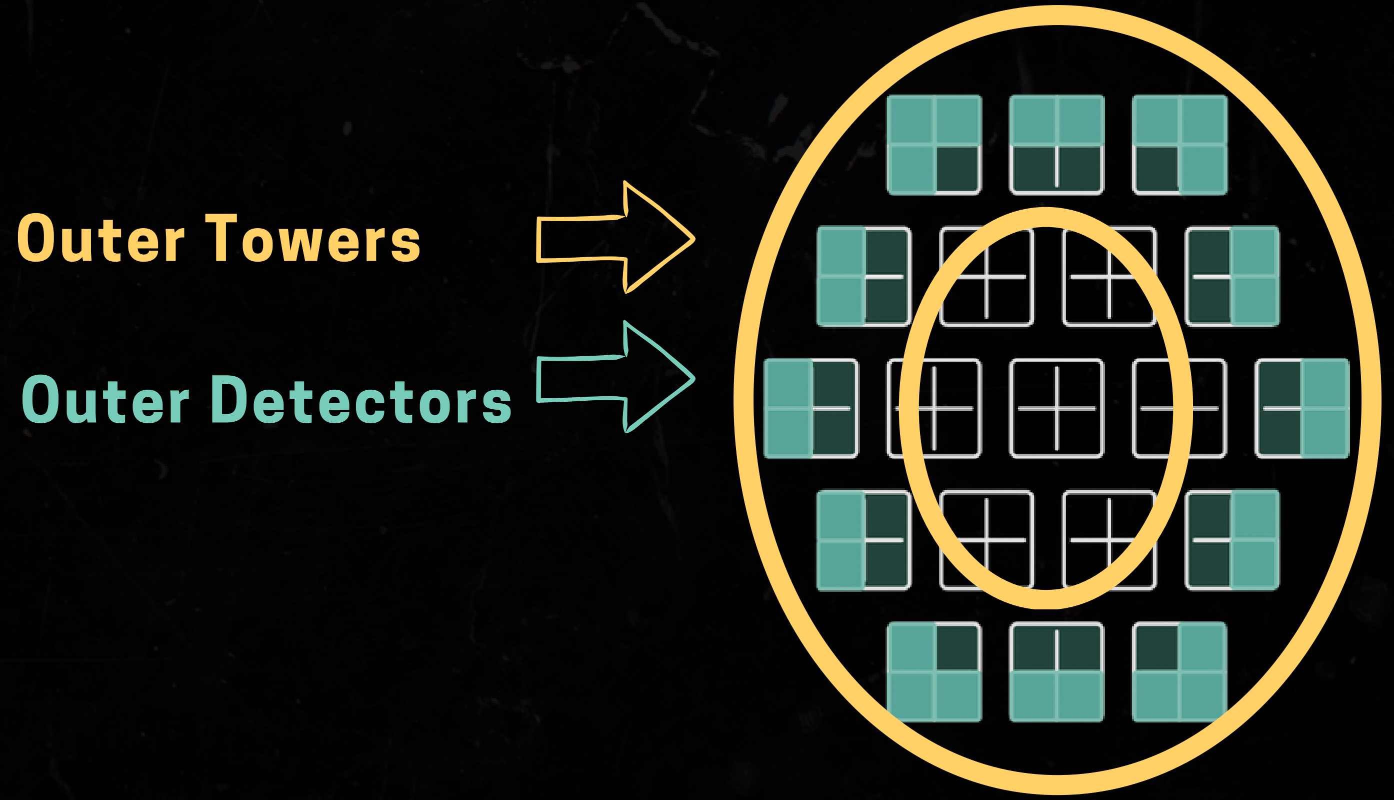
36 keV structure rates

- **Outer towers: 9.40 ± 0.85 counts / (kg·day)**
- Inner towers: 8.07 ± 0.55 counts / (kg·day)
- **1.31σ** preference for outer towers

Cross-check

- **Outer detectors: 9.35 ± 0.84 counts / (kg·day)**
- Same efficiency, but **no excess in outer detectors** → the structure likely originates **inside the detector**
- Will require **efficiency-dependent corrections** in final analysis





36 keV Structure Origin Mystery

- Observed in **all CUORE generations**
- No geometrical event rate dependence → **Internal origin**
- No time event rate dependence → **Stable for at least several years**

X-rays ❌

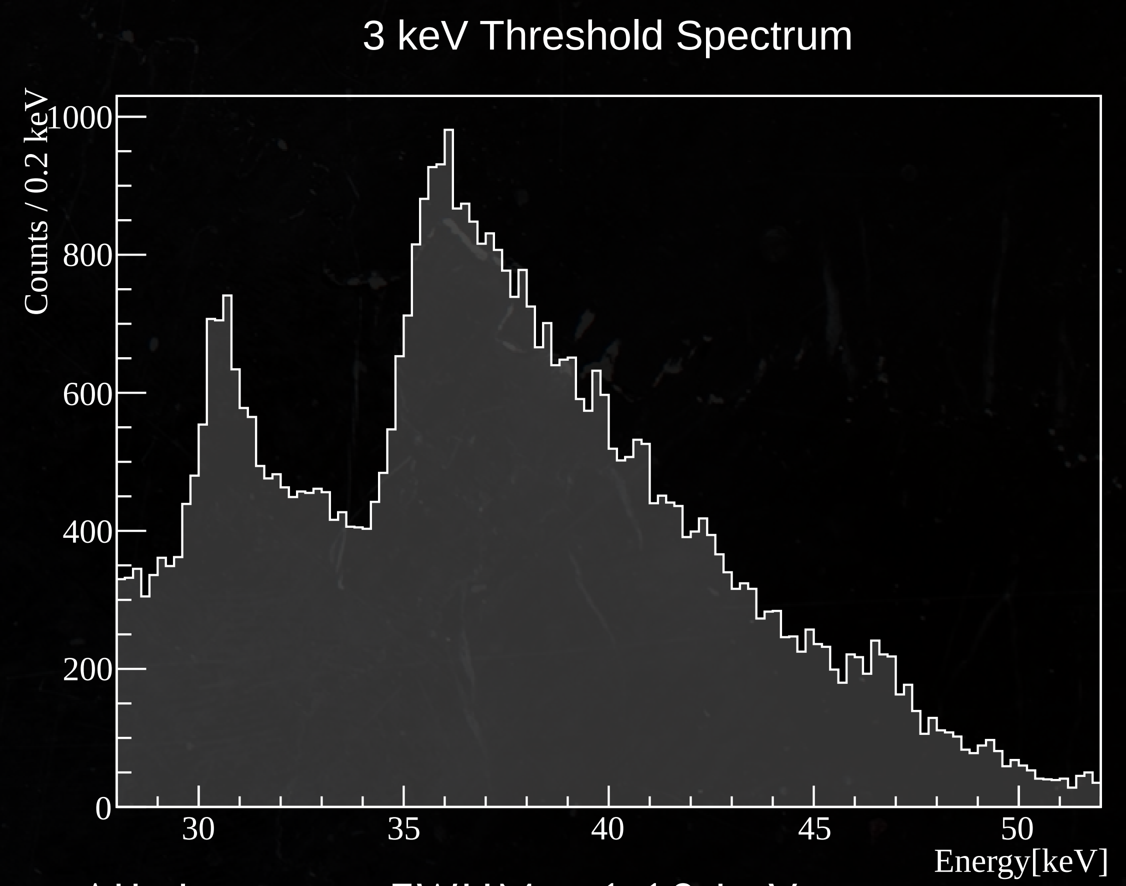
Element	Kα1	Kα2
Nd	36.03 keV	35.55 keV
Pr	37.36 keV	36.85 keV

Conversion Electrons ❌

- 25 candidates in the (35 - 38) keV
- **5 candidates** within 0.5 keV: Mo, I, Gd, Tb, W
- We should also see additional lines in the spectrum – but we don't

Shifted Beta ?

Only 1 peak + tail is observed even with **better resolution**



All datasets, FWHM = 1.18 keV

36 keV Structure Origin Mystery

All candidates in 0 - 65 keV Qβ region	Qβ, keV	Half-life	Shape	Gammas
Ru - 106	39.4	371.8 days	too long	no
Pd - 107	34.0	6.5 * 10^6 years	too long	no
Rh - 144	7.8	1.85 s	ok	> 300 keV
Re - 184	32.7	35.4 days	not tabulated	> 100 keV
Re - 187	2.5	4.33 * 10^10 year	ok	no
Pb - 210	63.5	22.2 years	ok	46.5 keV
At - 212	31.1	< 1 s	not tabulated	63 keV
Ac - 227	44.8	21.8 years	too long	9.3, 24.5, 37.9 keV
Ra - 228	45.5	5.75 year	ok	6.67, 33.07, 20.19, 6.28 keV

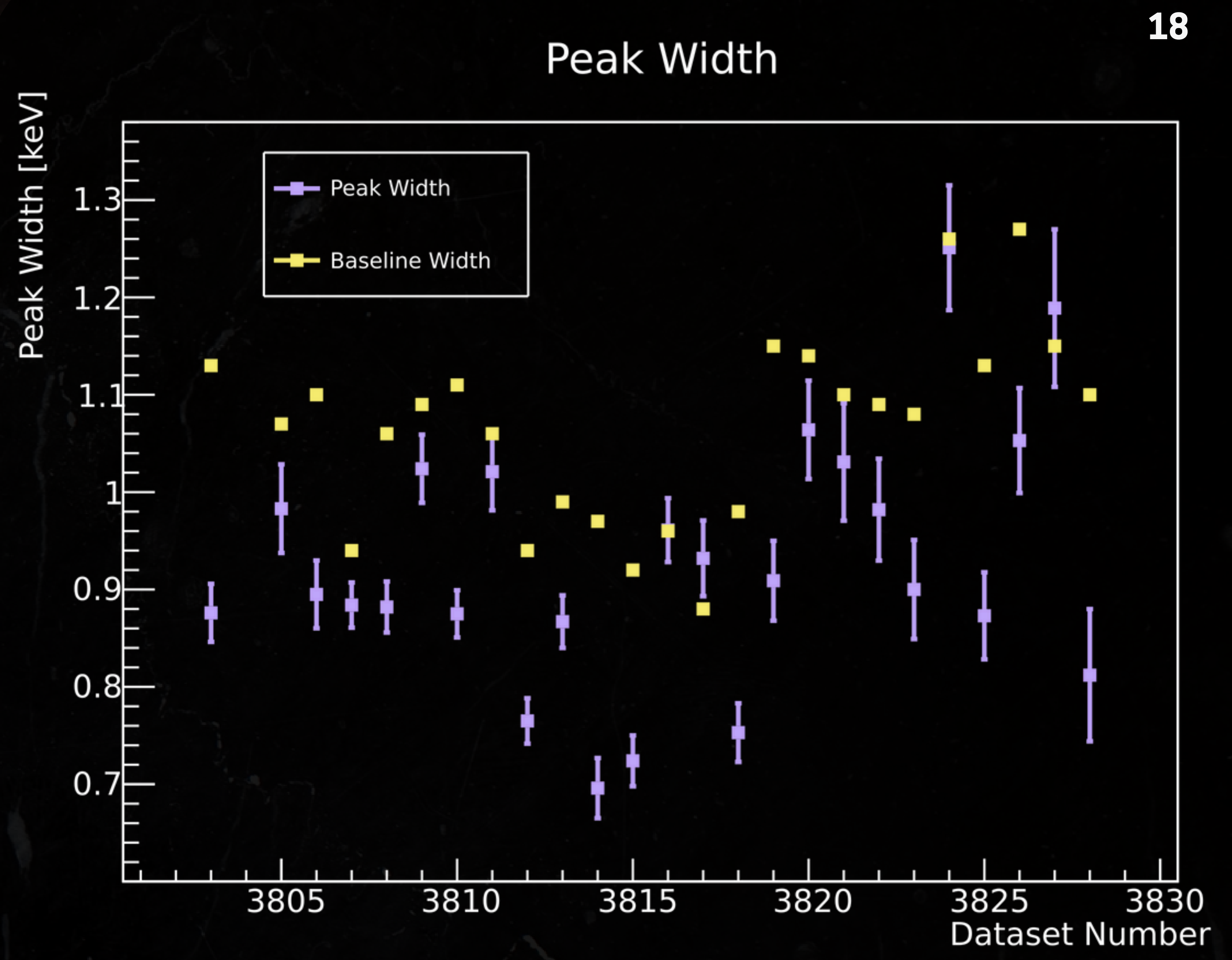
No suitable candidates found!

⇩

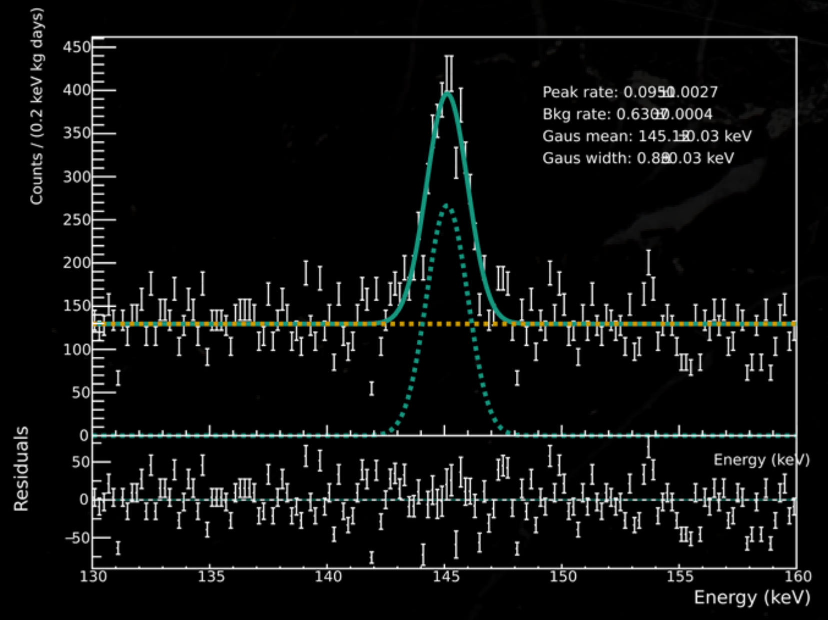
Shifted Beta ❌

145 keV Peak

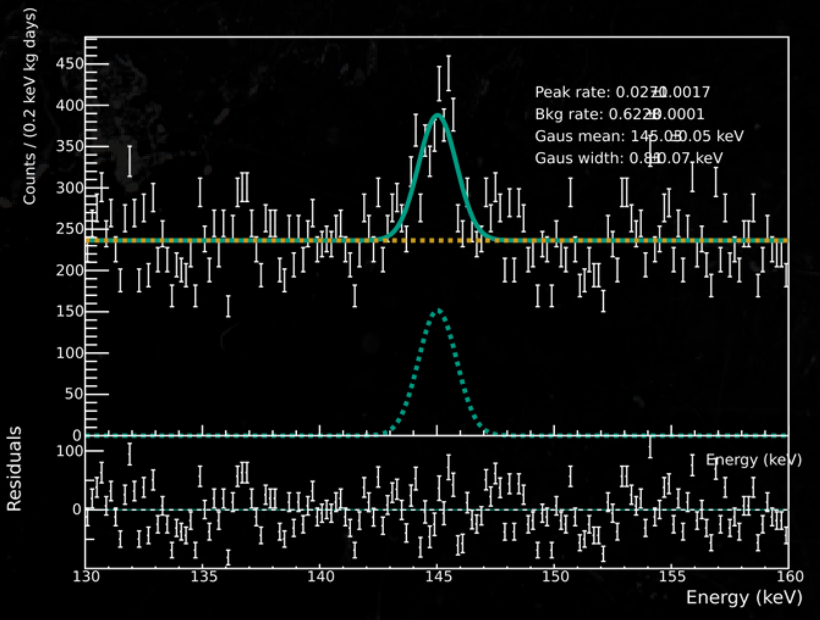
- A monochromatic structure at ~145 keV is observed
- Likely originates from **^{125m}Te decay**, metastable state of naturally abundant ^{125}Te (~7%)
- Fit performed in **RooFit (Gaussian peak + flat background)**
- **σ left free**, as it is reconstructed slightly better than baseline resolution
- Same procedure as for lower-energy peaks, applied in a higher ROI

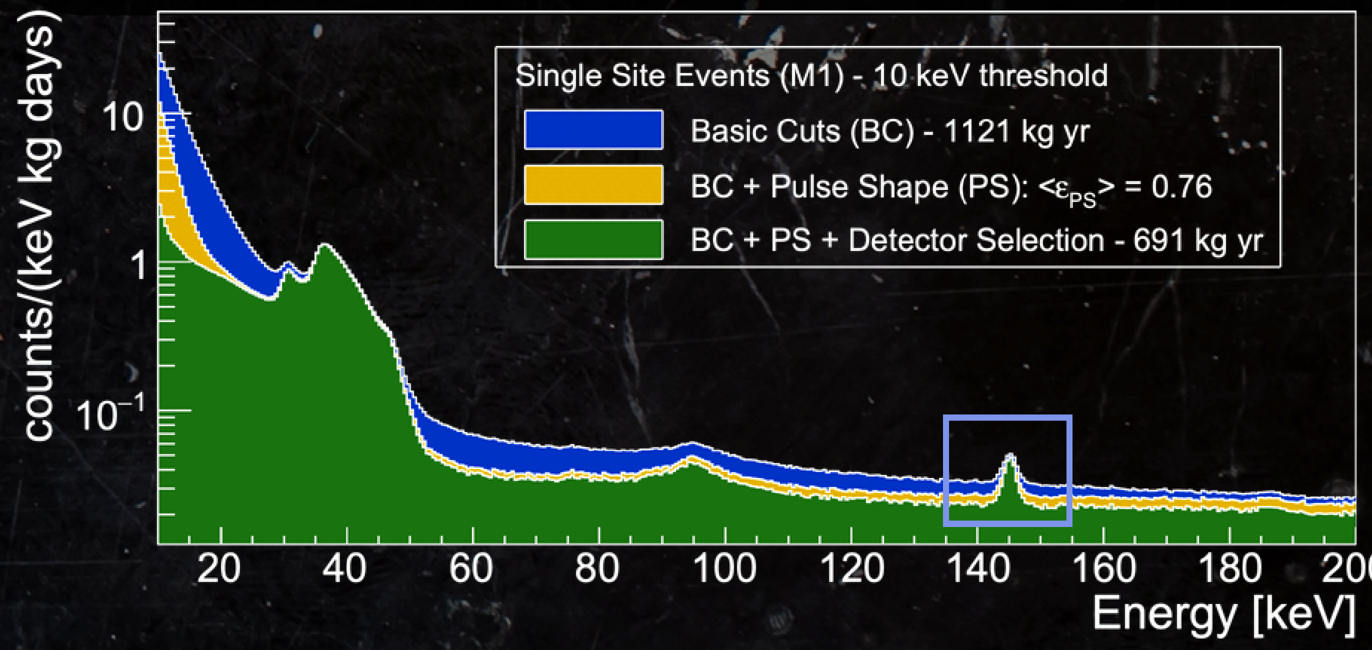


First dataset



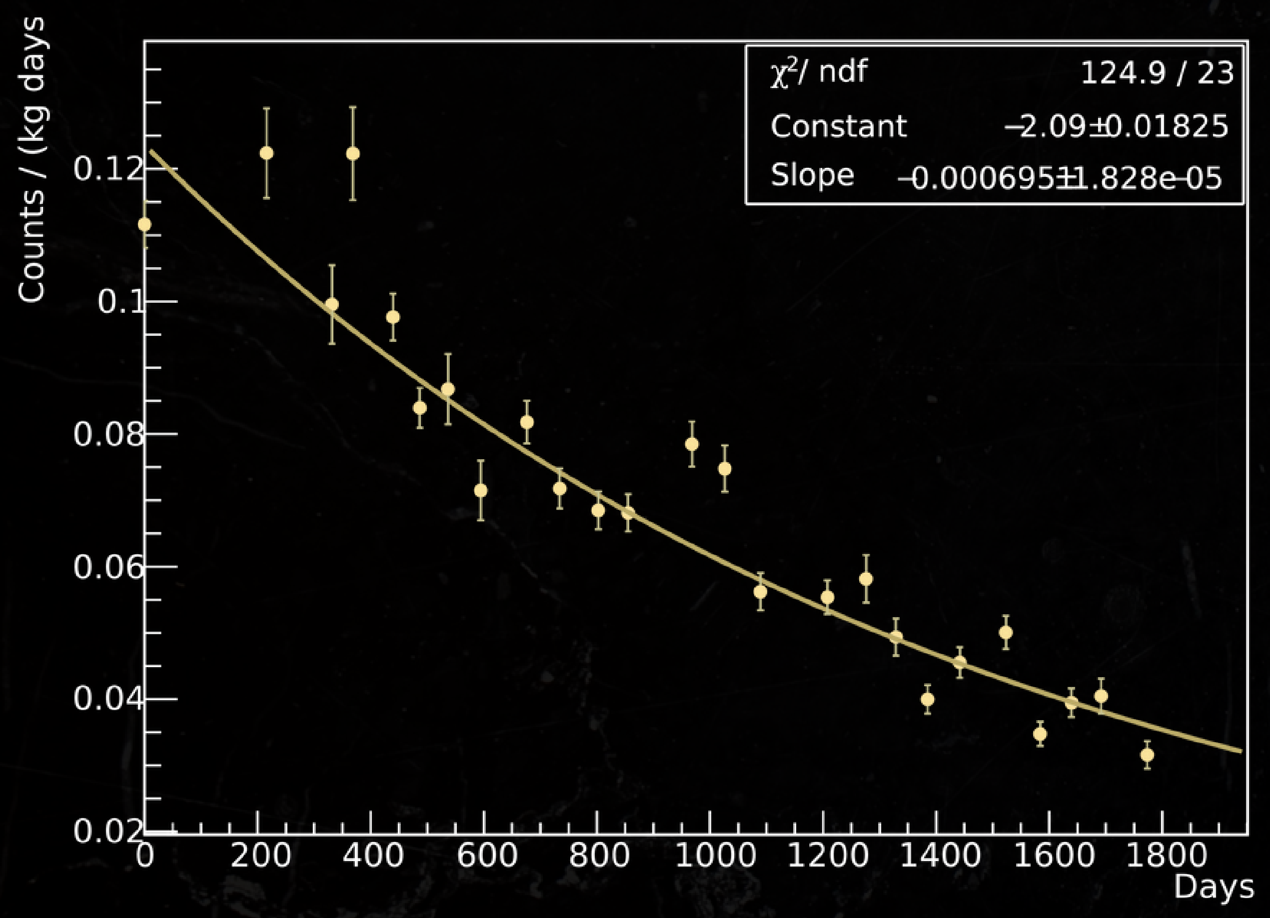
Last dataset



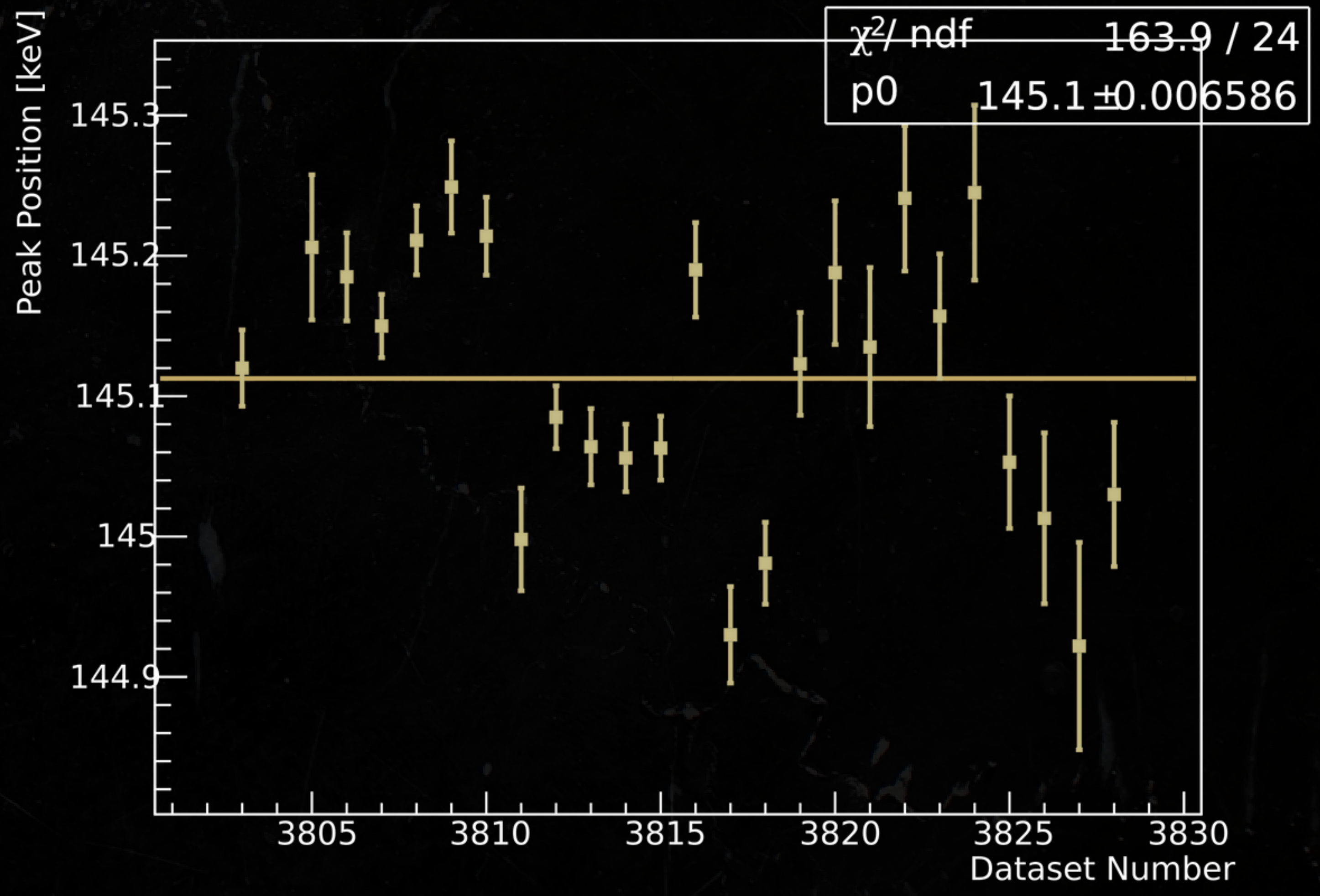


145 keV Peak: Fit Results

Event Rate



Peak Position



- **Half-life from the fit: 997 ± 14 days**
- **Tabulated half-life: 1007 days**

⇩

Consistent within statistical uncertainty

- **Observed peak position: 145.1 ± 0.1 keV**
- **Tabulated γ-energy: 144.8 keV**

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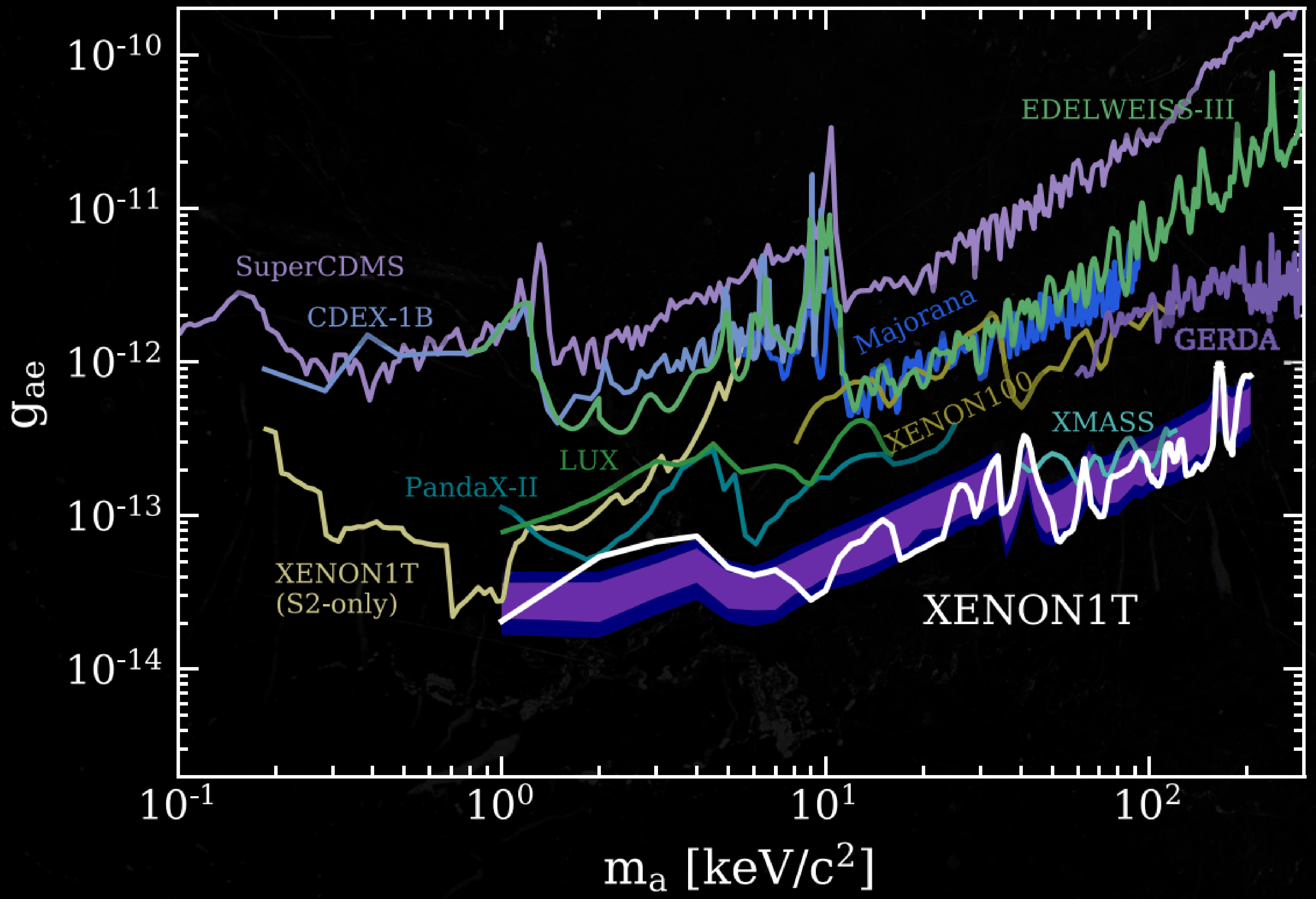
Offset of 0.3 keV, higher than expected from calibration

Cosmic Axions



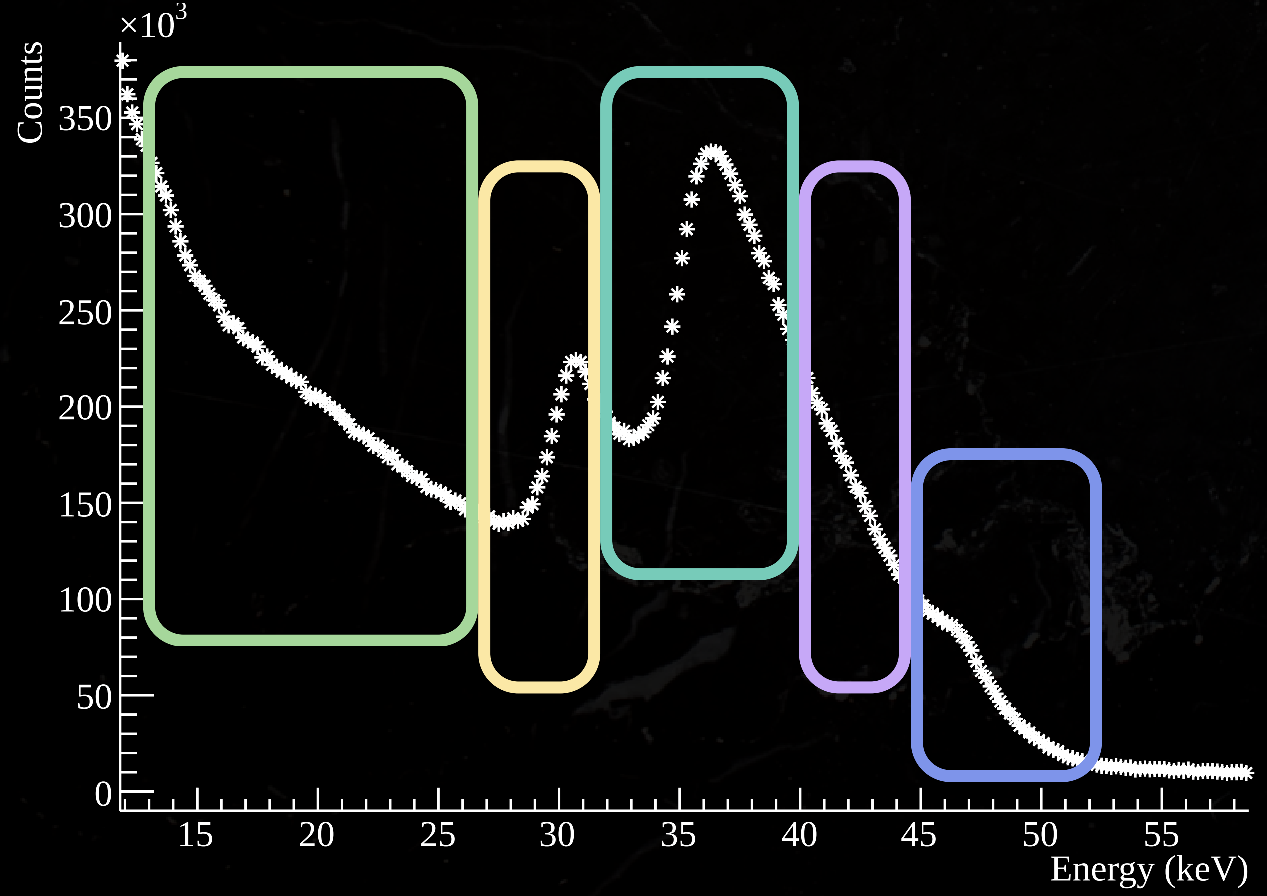
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.102.072004

- Assume axions/ALPs constitute the **Galactic dark-matter halo**.
- Non-relativistic axions produce **monoenergetic electron recoils** with E ≈ m_a (keV units).
- Interaction via **the axio-electric effect**
- CUORE’s low-energy data allow a search in the 3–10 keV range with 3 keV selection, and above with 10 keV selection
- **Goal**: **set limits on the axio-electric coupling constant**

Cosmic Axions: Fit & Upper Limit

Spectrum segmented into energy chunks; binned likelihood fit in ROOT.

- **3 keV selection**: used up to ~12 keV
- **10 keV selection**: used above ~12 keV



- 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.

$$\int_0^{\hat{b}} \frac{e^{-\lambda_b}\lambda_b^b}{b!}\, db = 0.90$$

$$\int_0^{\hat{b}} \frac{e^{-(\lambda_b+\lambda_s)}(\lambda_b+\lambda_s)^{b+s}}{(b+s)!}\, db = 0.50$$

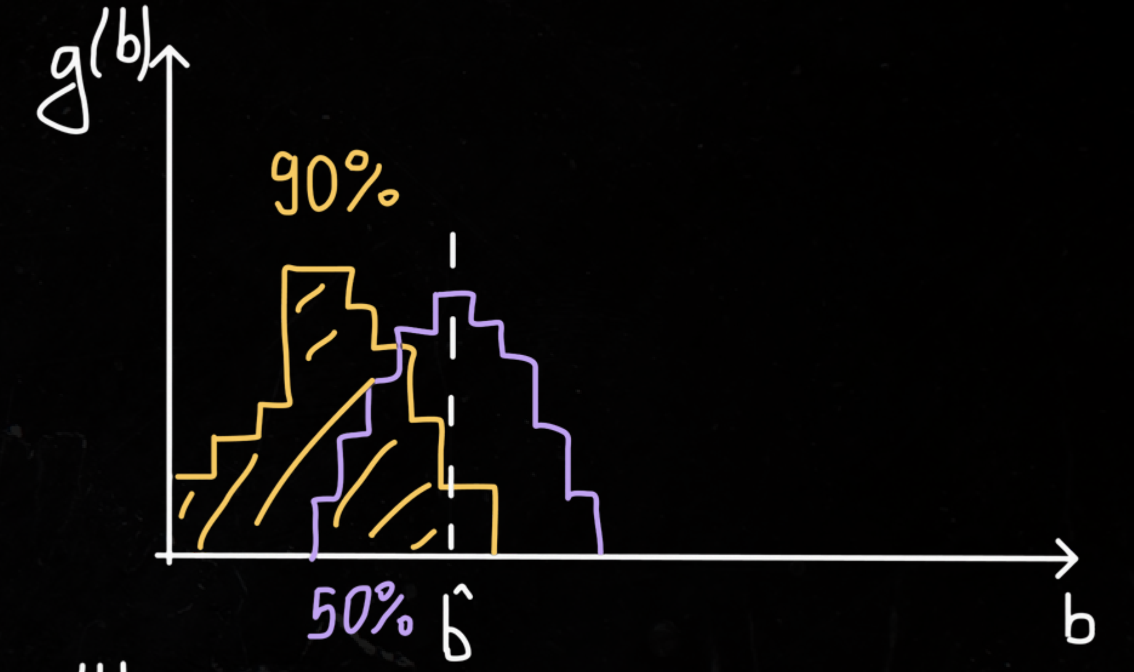
Gaussian approximation
for > 10^5 events in each window

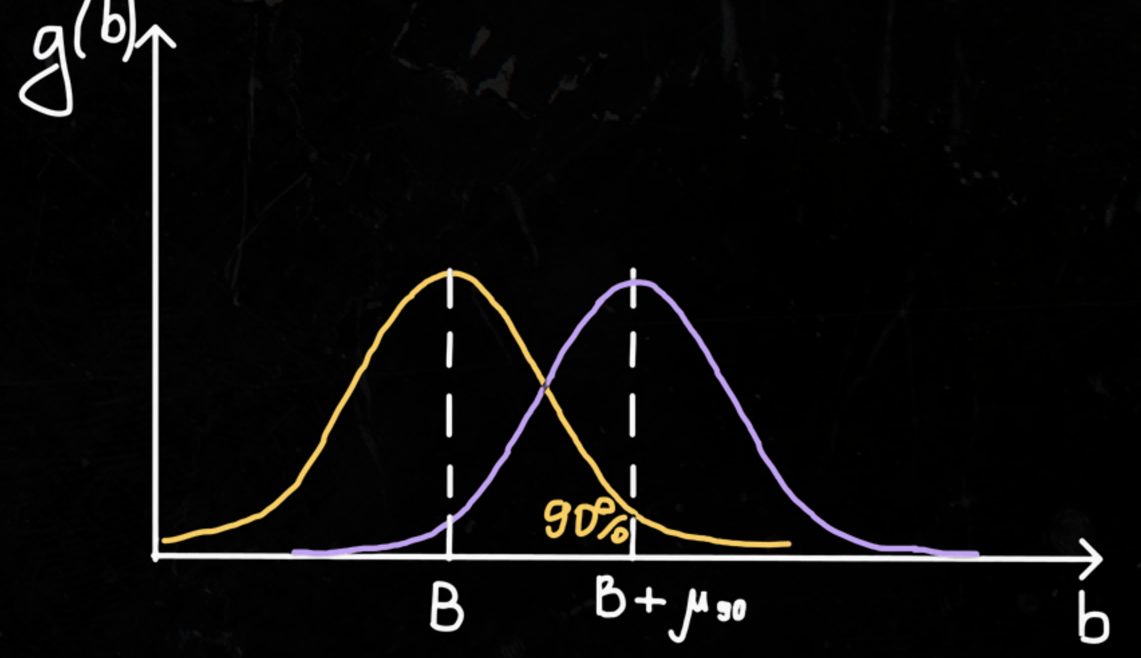
$$z = 1.28155 \quad (P(Z < z) = 0.9)$$

$$P(N < B + z\sigma_B \,|\, B + \mu_{90}) = 0.9$$

90% CL Upper Limit

$$\mu_{90} = z\sigma_B = z\sqrt{B}$$





Cosmic Axions Sensitivity

Cosmic axion flux

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

Axio - electric cross section

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

Photoelectric cross sections for Te and O are taken from NIST
https://physics.nist.gov/

https://iopscience.iop.org/article/10.1088/1475-7516/2013/11/067/pdf

10 keV selection: 691 kg·yr
3 keV selection: 11 kg·yr

Expected number of signal events

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

3.77×10^{24} [molecules kg^{-1}]

total efficiency

$$A(m_A) = \sum_i \varepsilon_i(E)\, w_i$$

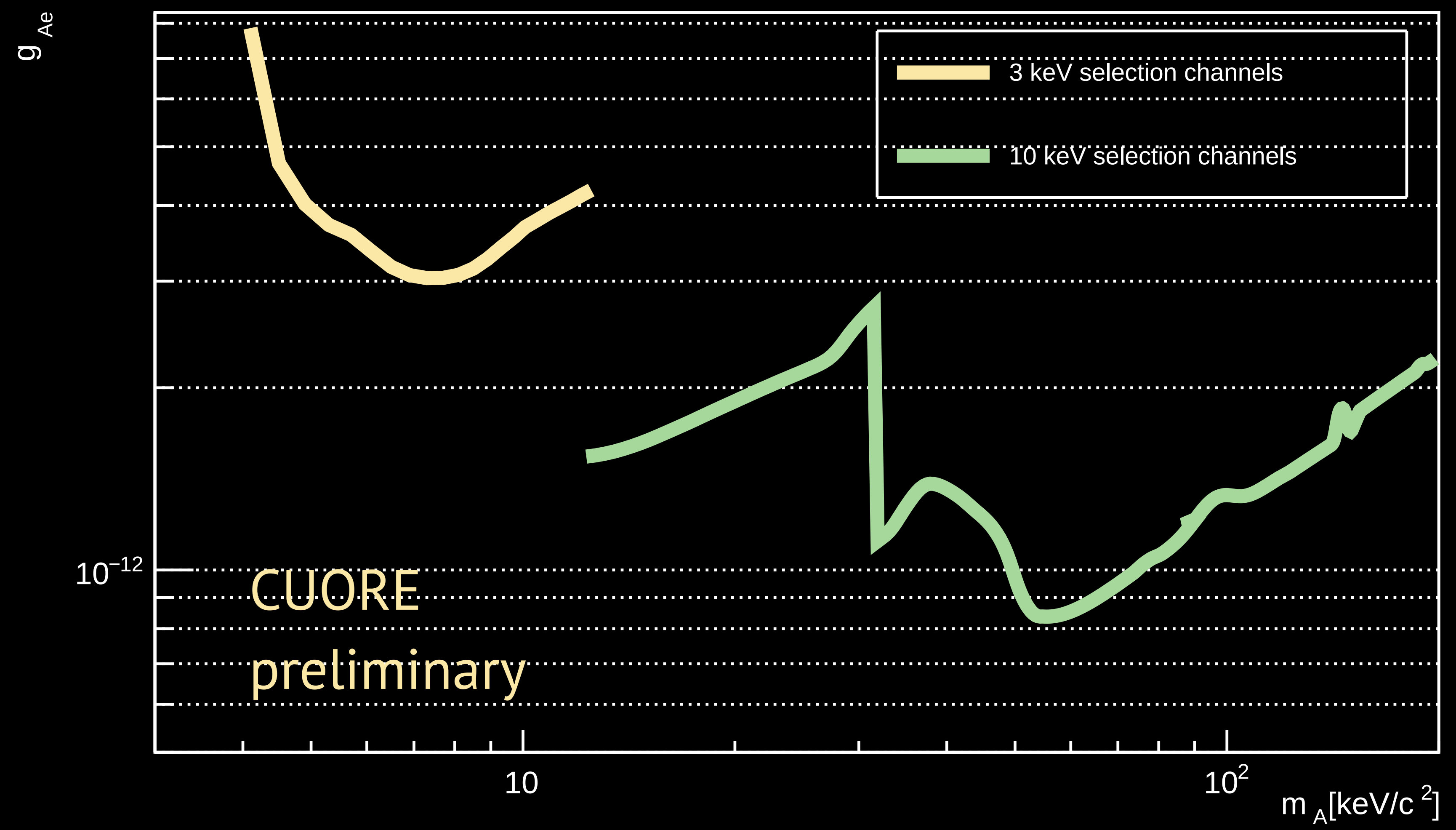
fraction of signal in the bin

90% CL upper limit from the fit

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

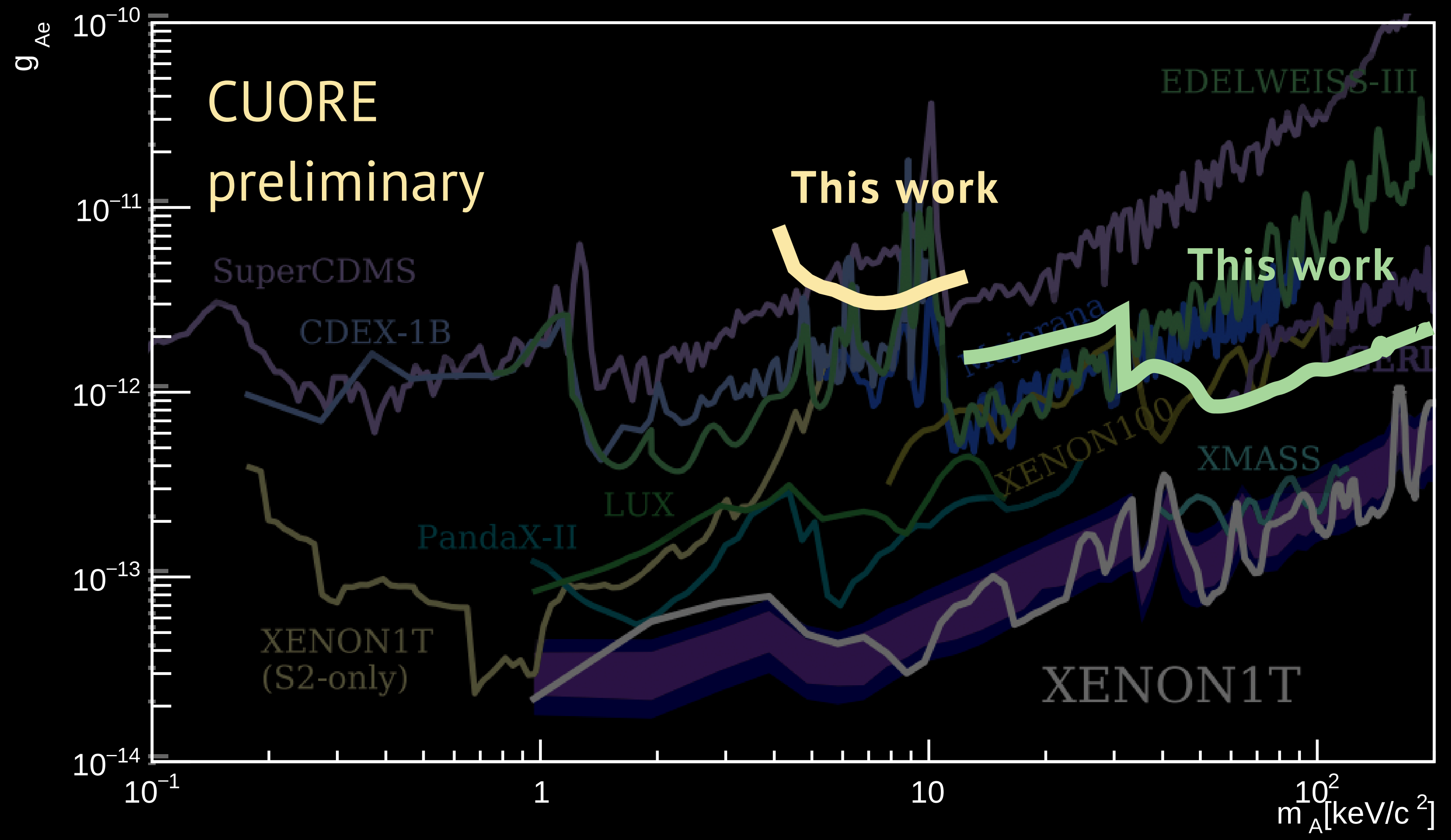
Cosmic Axions Sensitivity: Results

Combined 90% CL Upper Limits



CUORE sensitivity curves for **3 keV** and **10 keV** threshold channel selections.

Comparison with other experiments



Although CUORE sensitivity is not yet at the leading sensitivity, this study demonstrates for **the first time that a keV-scale cosmic axion search is feasible with a ton-scale cryogenic calorimeter.**

Status & Next Steps

Cosmic Axion Search

- ☑ Sensitivity
- ☑ Full Bayesian fit
- ☑ Systematics
- Loading... PS energy dependent efficiency evaluation
- ☐ Final coupling constant limit

Spectral Studies

- ☑ Full fit
- ☑ Event rate calculations
- Loading... Geometrical dependencies
- Loading... Systematics
- ? Origin of unknown peaks

Talks, Schools & Publications

Talks

- Exploring keV-scale physics with CUORE – Cosmology 2025, Elba
- SURFαCE: a cryogenic α detector for surface contamination – Lomonosov 2025, Moscow
- SURFαCE: a cryogenic α detector for surface contamination – LTD2025, Santa Fe
- Spectrum Studies and Cosmic Axions – CUORE Spring Meeting 2025, LNGS
- Development of a Silicon Bolometer for Rare Event Detection with LED Self-Calibration – CUPID Fall 2024, L'Aquila
- Development of a Silicon Bolometer for Rare Event Detection with LED Self-Calibration – LRT2024, Kraków
- Development of a Silicon Bolometer for Rare Event Detection with LED Self-Calibration – SIF 2024, Bologna
- Surface Screening with Si Detectors – CUORE/CUPID Spring 2024

Poster & Mini-Talk

- CUORE Low-Energy Spectrum Sensitivity to Cosmic Axions – MAYORANA School 2025, Modica

Publications (in preparation)

- SURFαCE – EPJ C (corresponding author)
- Exploring the keV-scale Physics Potential of CUORE – Physical Review D (resubmitted after minor review, DOI: 10.48550/arXiv.2505.23955, personal contribution)
- CUORE Low-Energy Spectrum Sensitivity to Cosmic Axions – Il Nuovo Cimento C (corresponding author)
- SURFαCE: A Cryogenic α-Detector for the Radioactive Contamination of Material Surfaces – IEEE TAS (corresponding author)
- The Cosmic Axion analysis is planned for publication as a CUORE collaboration paper after finalization

Schools & Workshops

- MAYORANA School & Workshop 2025, Modica
- 15th International Neutrino Summer School 2024, Bologna
- XX Seminar on Software for Nuclear, Subnuclear and Applied Physics 2023, Alghero

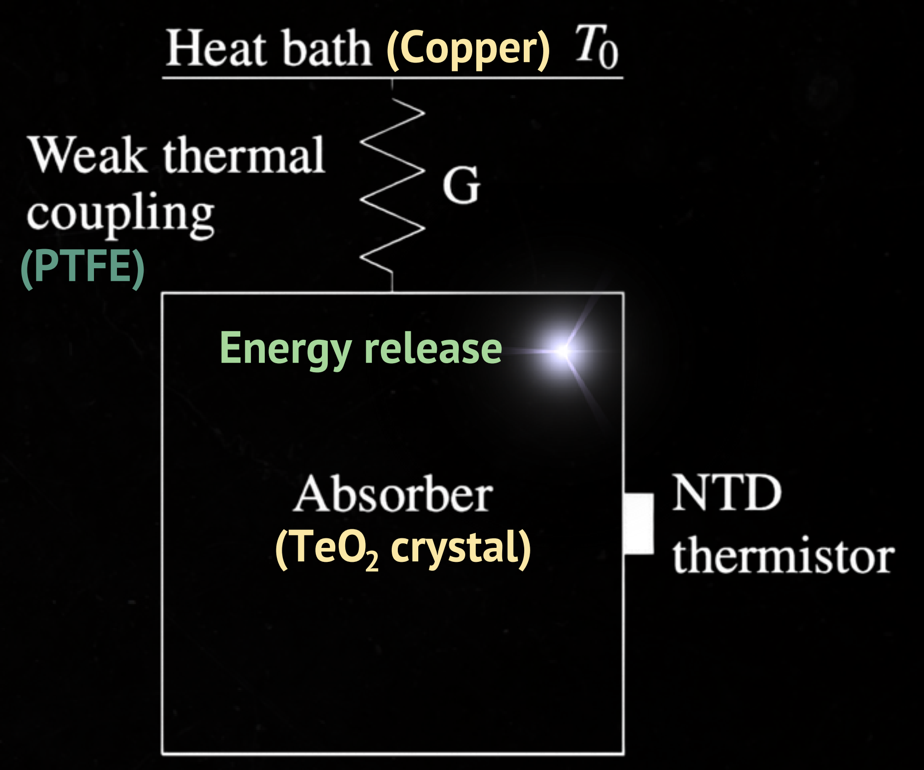
Backup

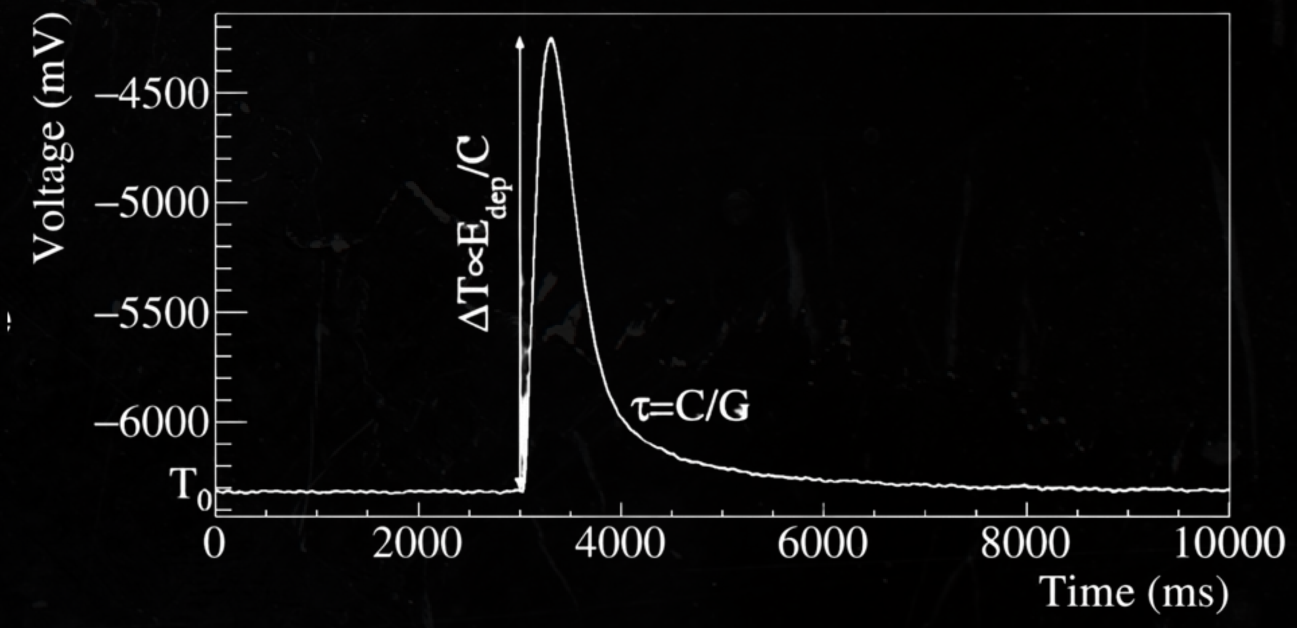
Cryogenic Calorimeters

Highly sensitive calorimeter operated at cryogenic temperature (~10 mK).
Energy is measured as temperature variation of the **absorber**:

$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau}\right) \qquad \tau = C/G$$

A temperature rise is measured by a thermistor and converted to an electric signal

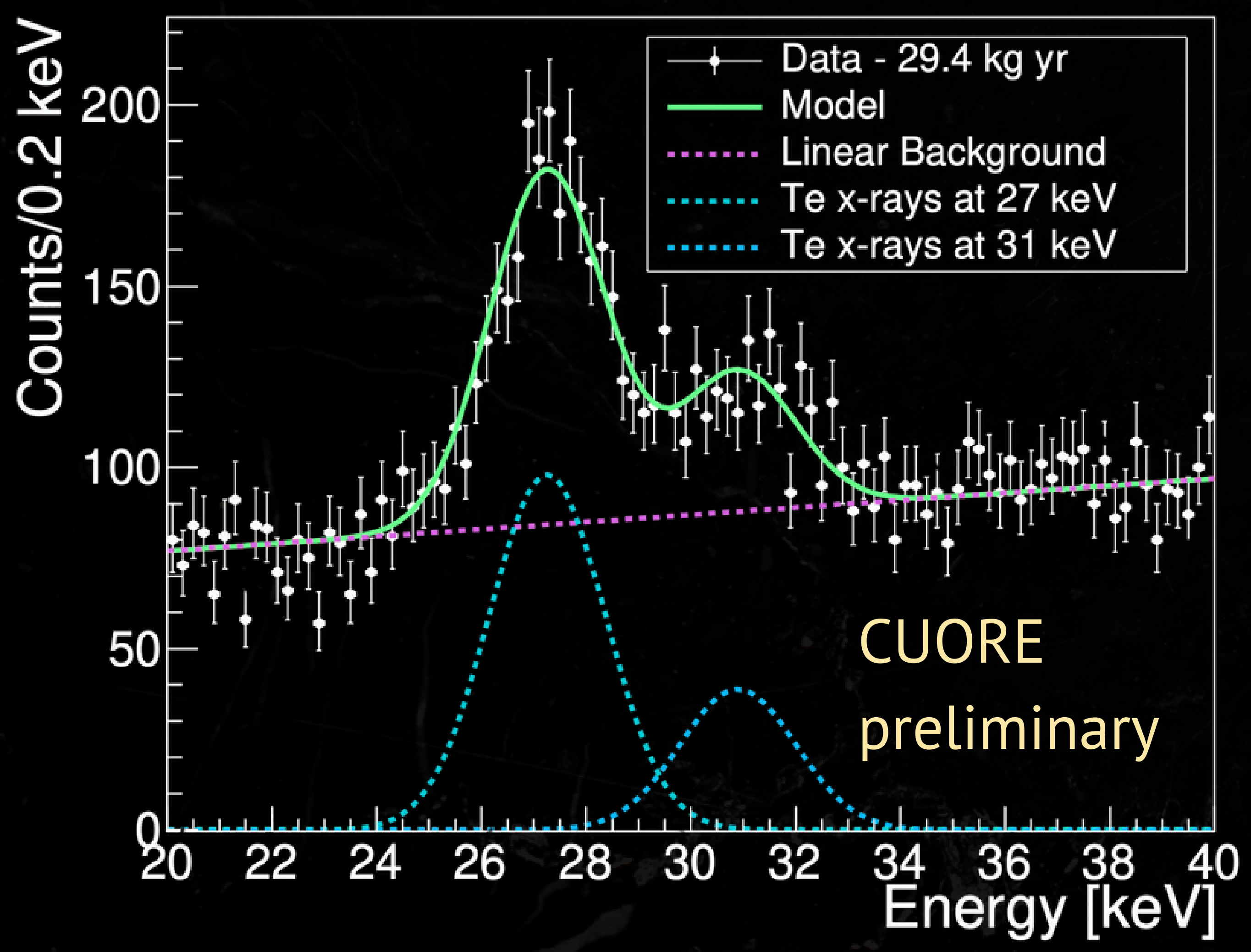




Main advantages

- Detector **modularity** → large exposure
- Stable **long-term** operation possible
- Great **dynamic range**, few keV to 10 MeV
- Excellent **energy resolution** (≲10 keV FWHM at ^{130}Te $0\nu\beta\beta$ Q-value)
- Possibility to use **different absorber crystals** and select the one with the lowest radioactive contamination

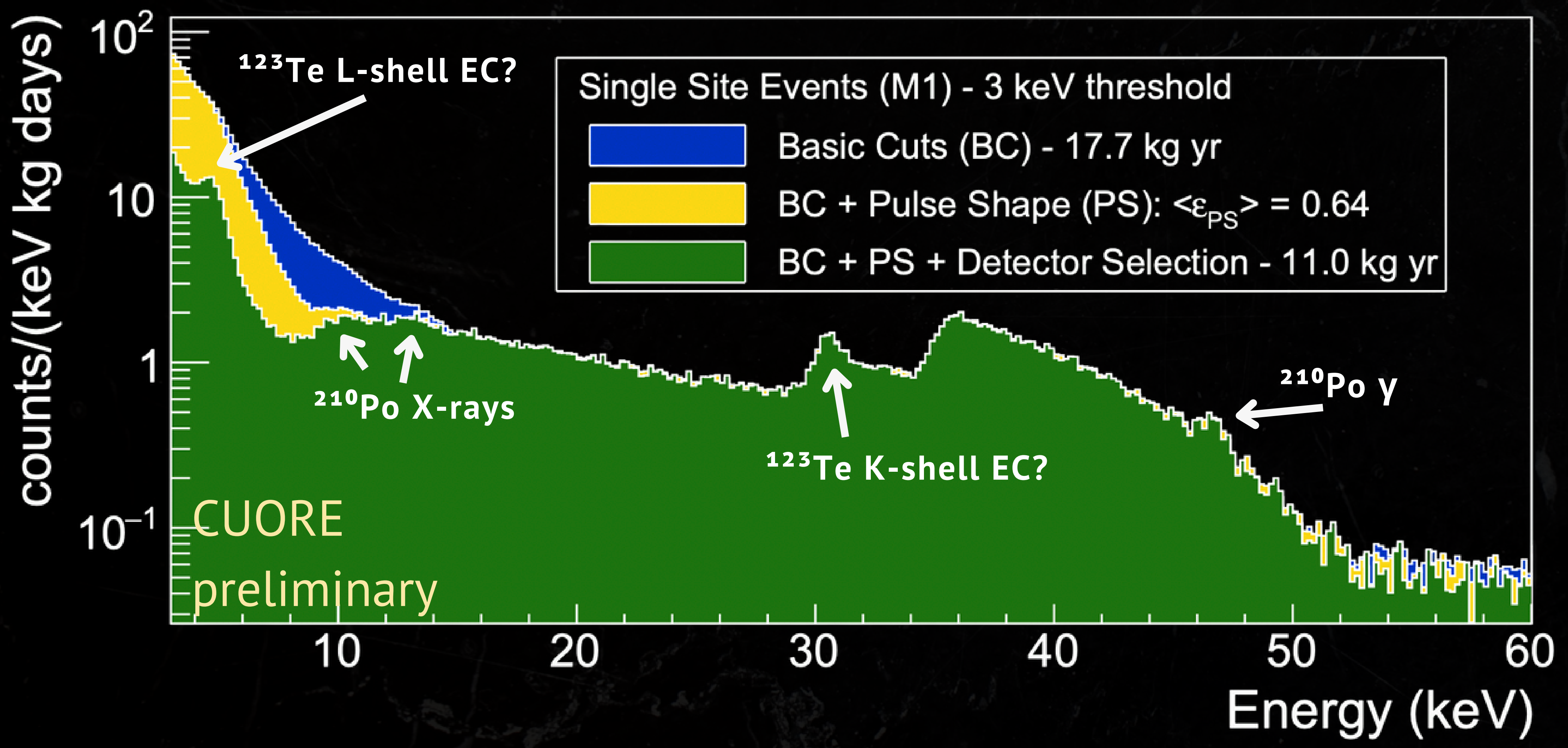
Low Energy Calibration



arXiv:2505.23955

- **Calibration:** use high-energy γ lines ($^{232}Th-^{60}Co$), then extrapolate to low energies
- **Validation:** Te X-rays at 27 – 31 keV
- **Topology:** M1 (single-site) and M2 (two-crystal coincidences); with external sources M2 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.

Low Energy Spectra: 3 keV selection



- Detectors with Optimum Trigger threshold < 3 keV
- Pulse shape cut
- Selected detectors

arXiv:2505.23955

Detectors selected with 3 keV threshold:

1.2% of all detectors,

11 kg·yr of TeO_2 exposure,

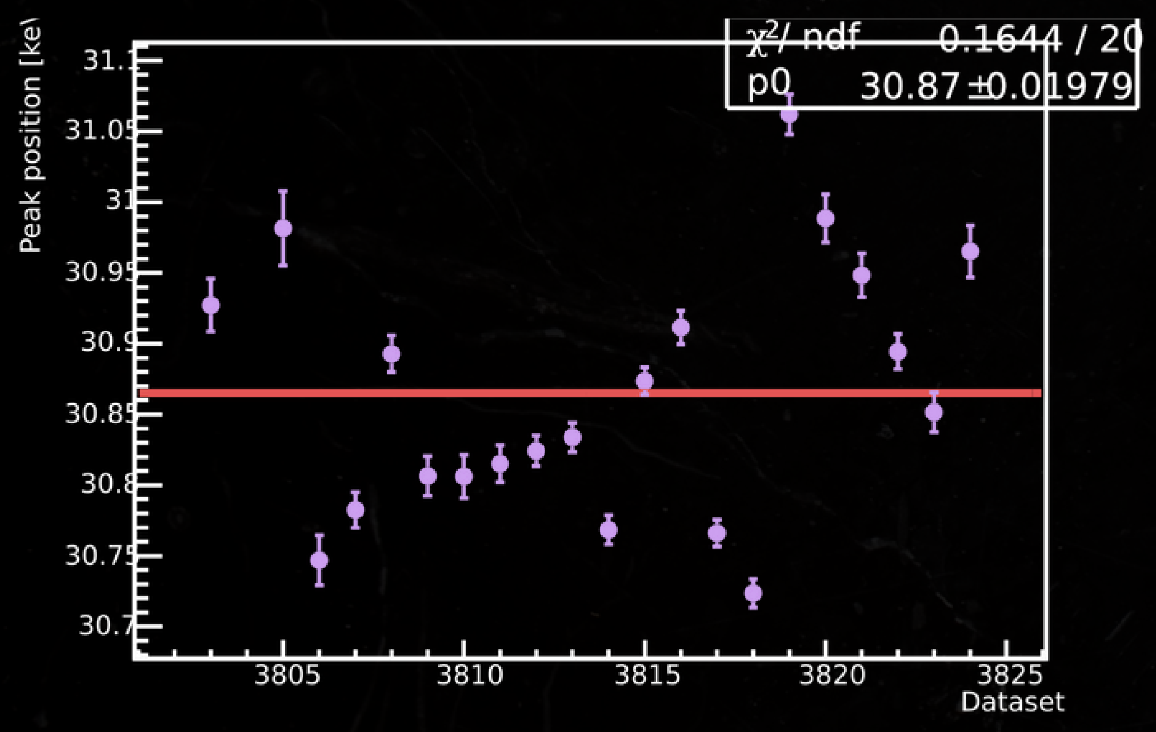
1.18 keV FWHM

Background model:

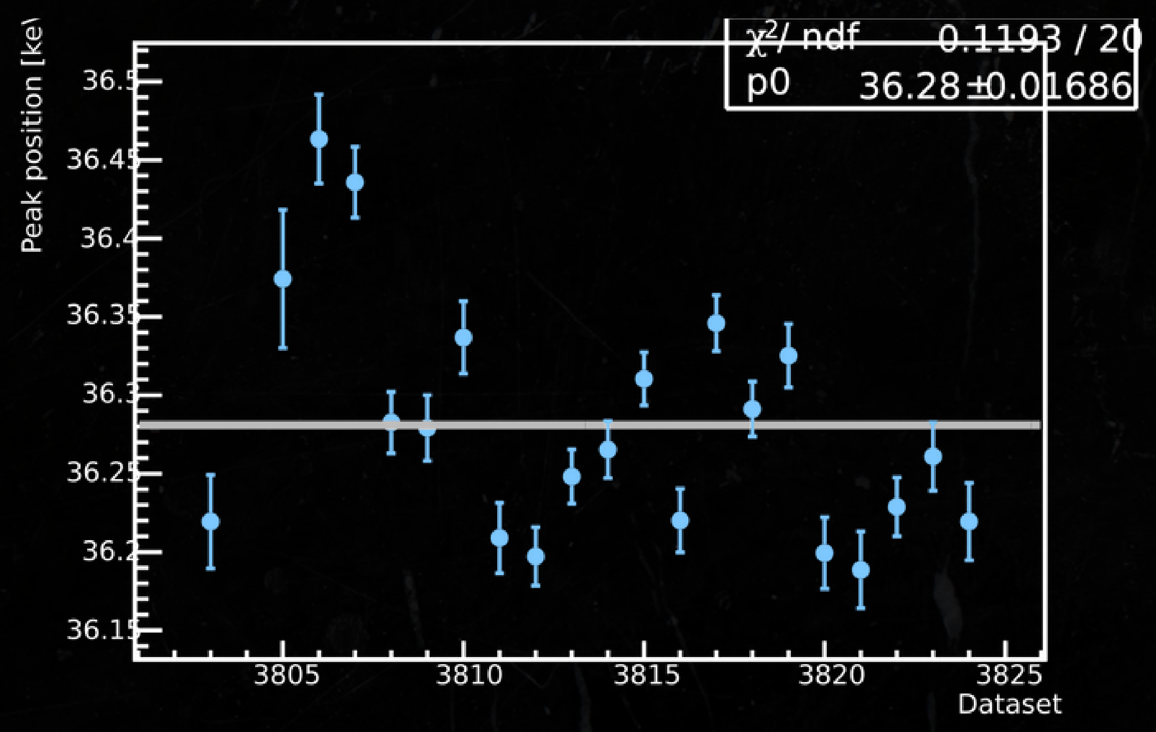
- **Several spectral features are still under investigation**
- **^{123}Te EC was never observed before!**

FIT RESULTS

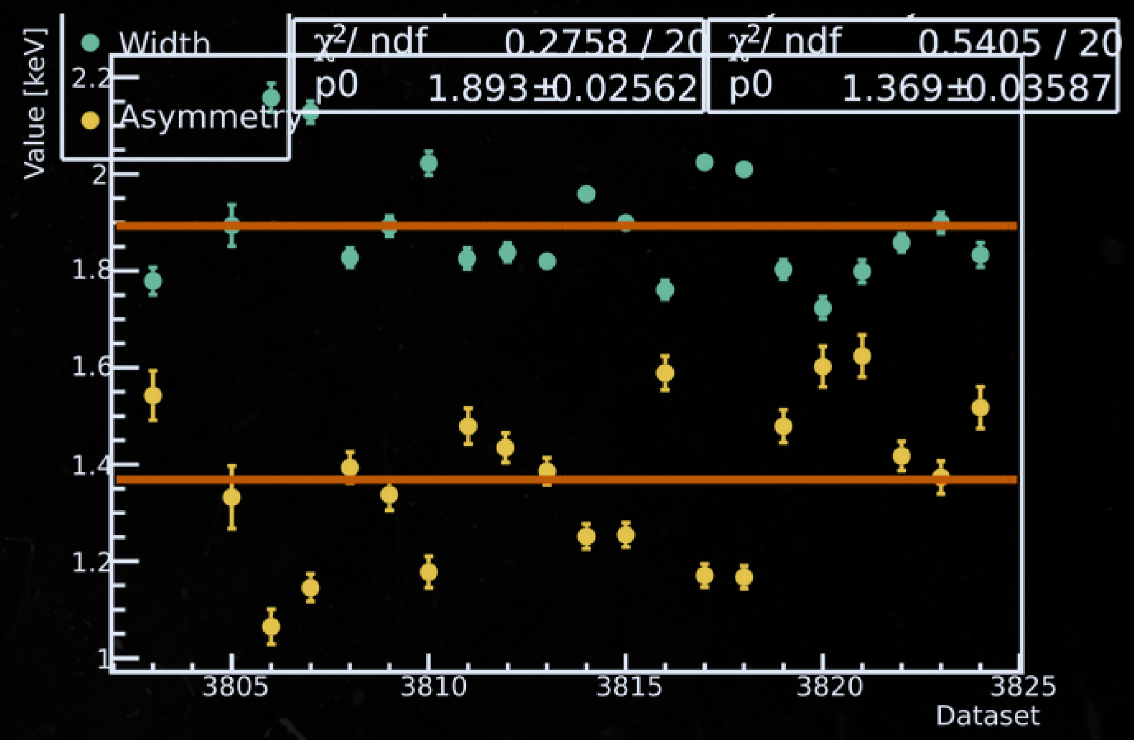
30.5 keV peak position



36 keV structure position



36 keV structure width and asymmetry



- The 30.5 keV peak is reconstructed at **30.88 keV** on average -> changes to **30.65 keV** with the 2 exponential background model
- The 36 keV peak is reconstructed at **36.28 keV** on average
- For the 36 keV peak higher width corresponds to lower asymmetry and vice versa: depends on whether the peak position is reconstructed slightly to the left or right

CHANNEL SELECTION DISCREPANCY

Tellurium electron binding energies [keV]

K 1s	$L_1 2s$	$L_2 2p_{1/2}$	$L_3 2p_{3/2}$	$M_1 3s$	$M_2 3p_{1/2}$	$M_3 3p_{3/2}$	$M_4 3d_{3/2}$	$M_5 3d_{5/2}$
31,814.	4,939.	4,612.	4,341.	1,006.	870.8	820.0	583.4	573.0

$$g_{Ae} \propto \sqrt{\frac{\mu_{90}}{\text{Exposure}\ \varepsilon}} \qquad \mu_{90} \approx 1.28\sqrt{N_{\text{bkg}}} \Longrightarrow \boxed{\mu_{90} \propto \sqrt{\text{Exposure}\ \sigma}}.$$

$$g_{Ae} \propto \sqrt{\frac{\sqrt{\text{Exposure}\ \sigma}}{\text{Exposure}\ \varepsilon}} = \frac{(\text{Exposure}\ \sigma)^{1/4}}{(\text{Exposure})^{1/2}\ \varepsilon^{1/2}} = \boxed{\sigma^{1/4}\ \text{Exposure}^{-1/4}\ \varepsilon^{-1/2}}$$

$$\frac{g_1}{g_2} = \left(\frac{\sigma_1}{\sigma_2}\right)^{1/4} \left(\frac{\text{Exposure}_2}{\text{Exposure}_1}\right)^{1/4} \sqrt{\frac{\varepsilon_2}{\varepsilon_1}}$$

$$\left(\frac{0.50}{1.08}\right)^{1/4} \approx 0.825,$$
$$\left(\frac{691}{11.4}\right)^{1/4} \approx 2.79,$$
$$\sqrt{\frac{0.40}{0.25}} \approx 1.265.$$

$$\longrightarrow \quad \frac{g_1}{g_2} \approx 0.825 \times 2.79 \times 1.265 \approx \boxed{2.9}.$$