CUORE Low-Energy Spectrum Sensitivity to Cosmic Axions

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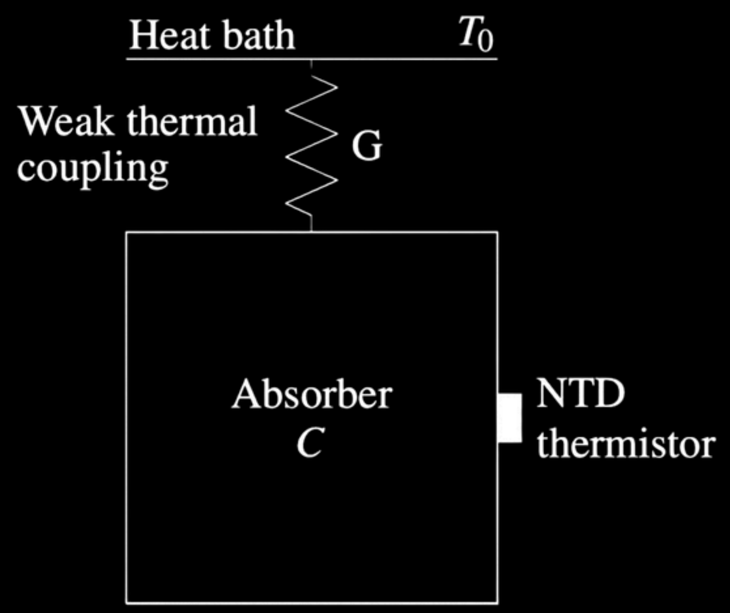
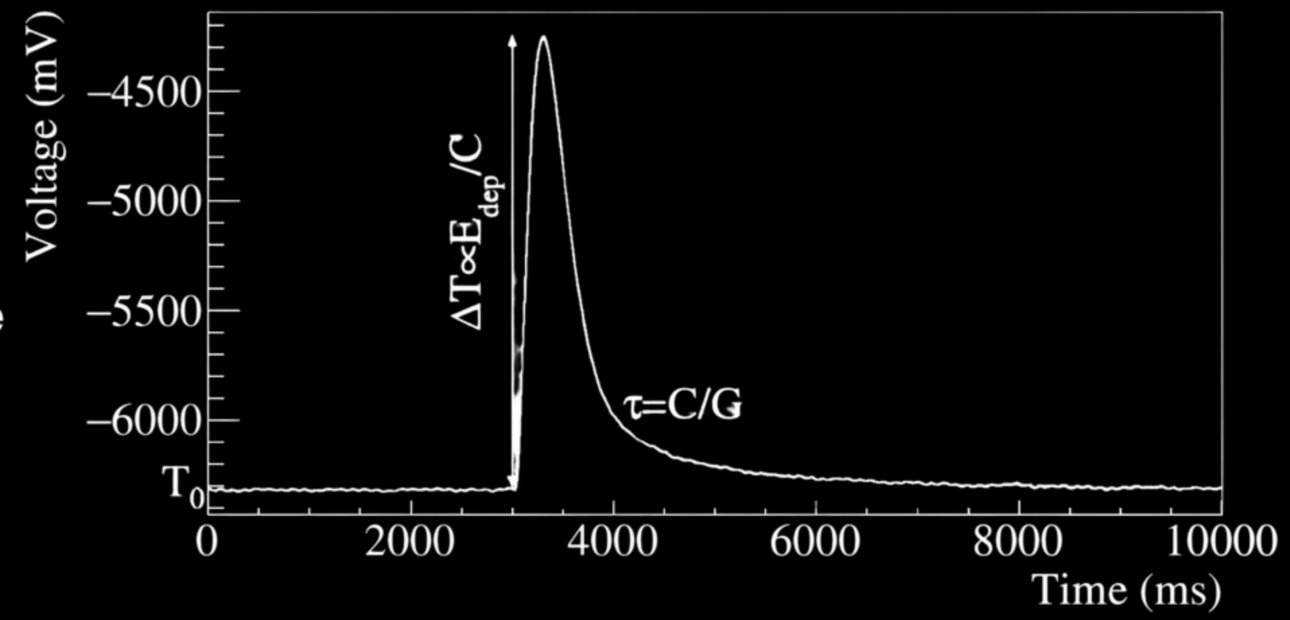
CUORE DETECTOR





- Highly sensitive calorimeter operated at cryogenic temperature. Energy measured as temperature variation of the absorber:

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

- 988 TeO_2 bolometers in 19 towers (total 741 kg, 206 kg ^{130}Te)
- Operated at 10 – 15 mK in the underground LNGS laboratory (≈1400 m rock overburden)
- Background index ~ 10^{-2} cts / keV / kg / yr achieved with ultra-clean materials & shielding
- 2 t · yr of exposure already collected
- Primary mission: 0νββ search in ^{130}Te; low thresholds enable rare low-energy signals (e.g. **axions**, WIMPs)

LOW ENERGY TECHNIQUES

OPTIMUM TRIGGER

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

Signal template

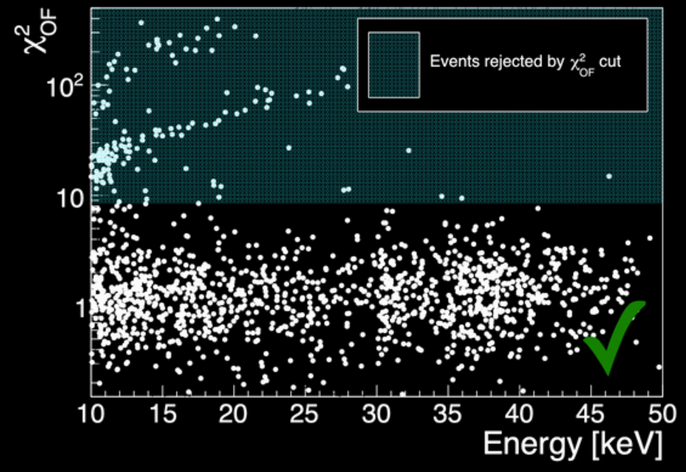
Noise power spectrum

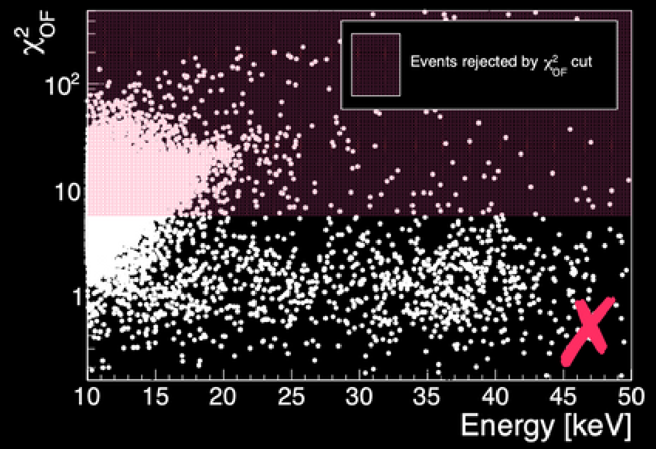
Trigger threshold is set at ε = 90%

Detectors with 3 keV and 10 keV threshold were selected

SPURIOUS EVENTS DISCRIMINATION

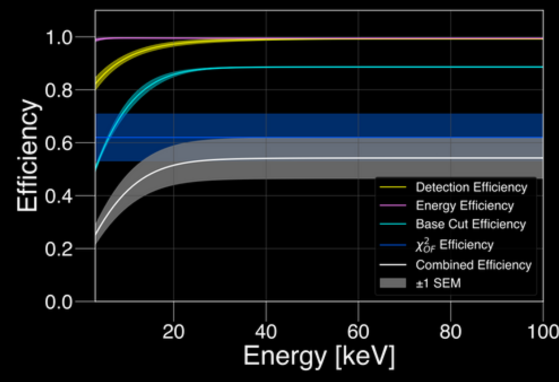
The reduced χ2 as an optimal pulse shape parameter was used



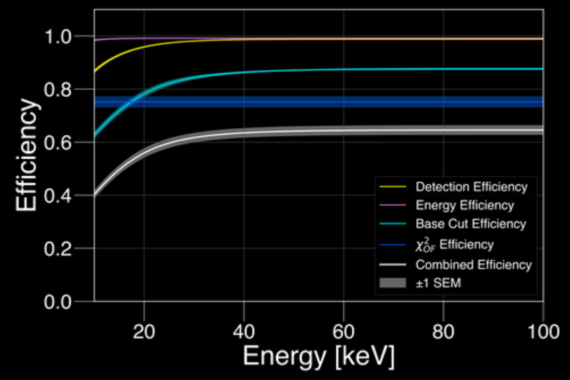


TOTAL EFFICIENCY

= pulser efficiency (trigger detection, energy reconstruction, and pile-up rejection efficiencies) + pulse-shape discrimination efficiency

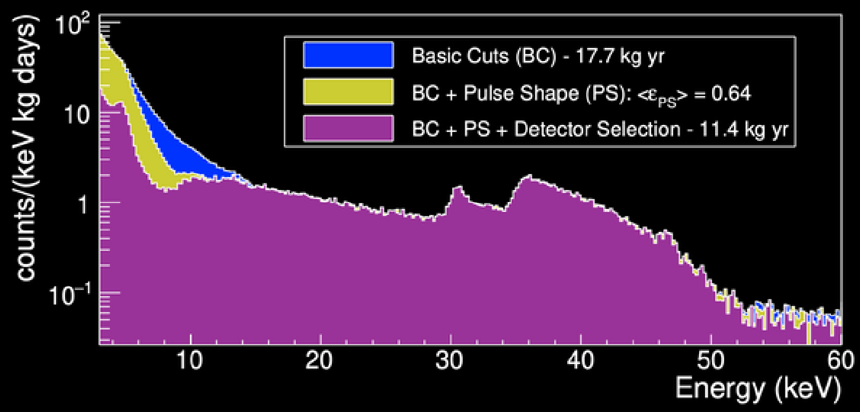


3 keV selection

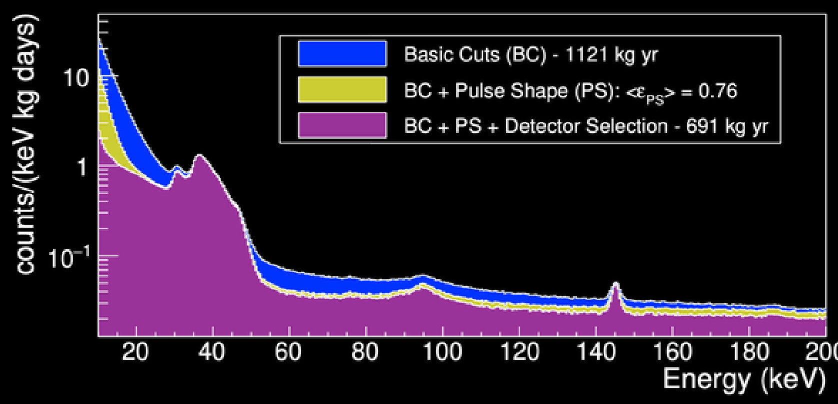


10 keV selection

M1 LOW_ENERGY SPECTRA

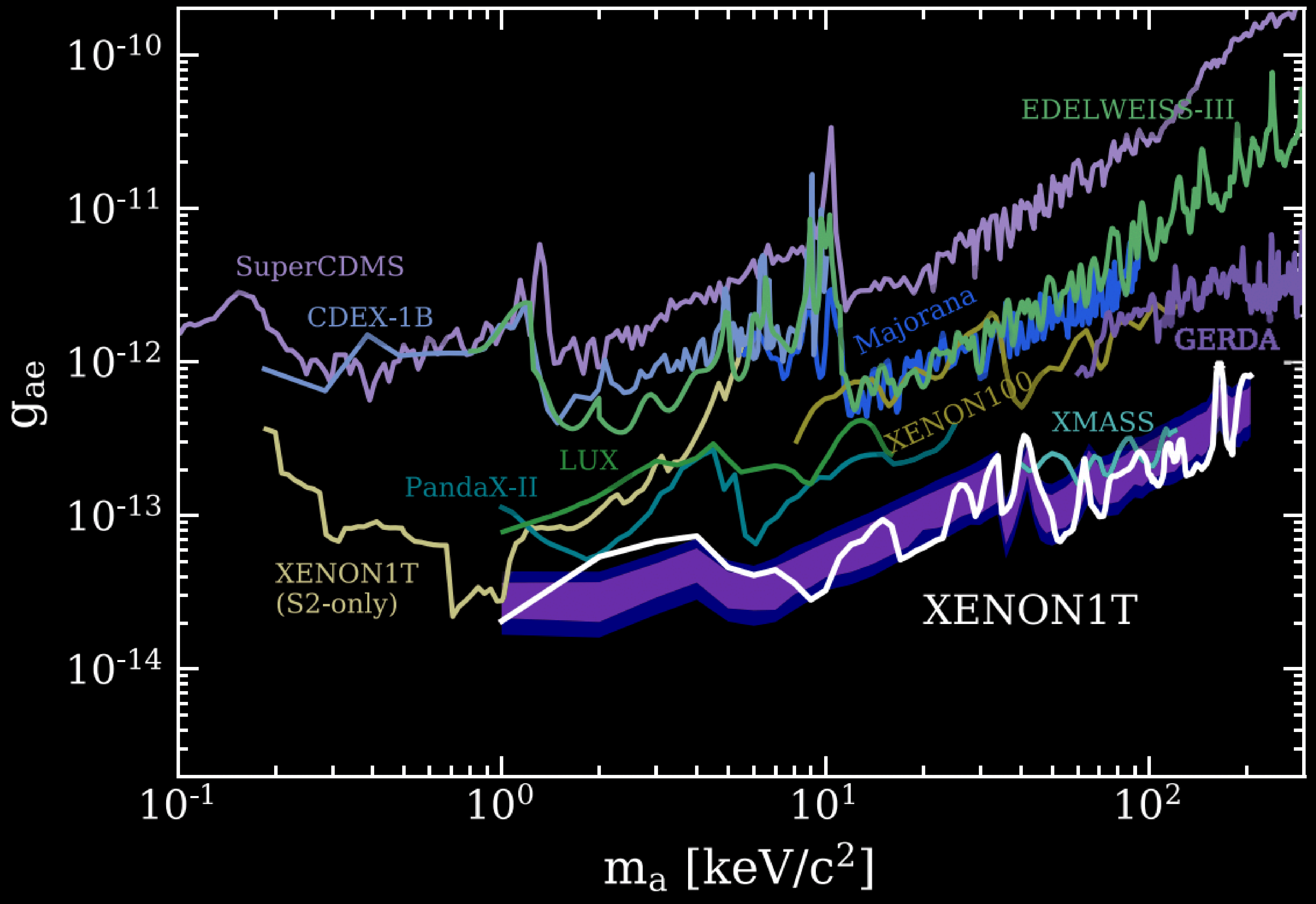


3 keV selection



10 keV selection

COSMIC AXIONS SENSITIVITY – MOTIVATION



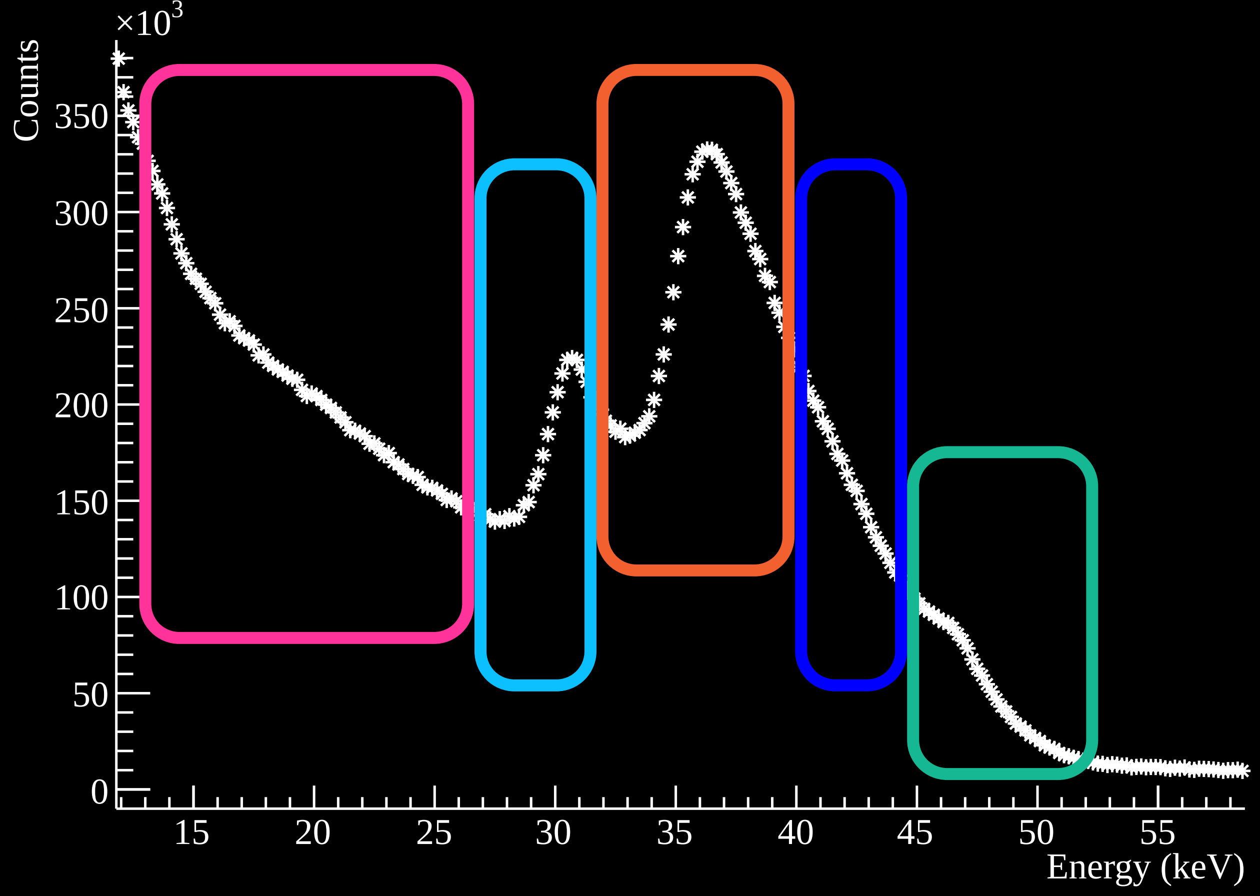
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.102.072004

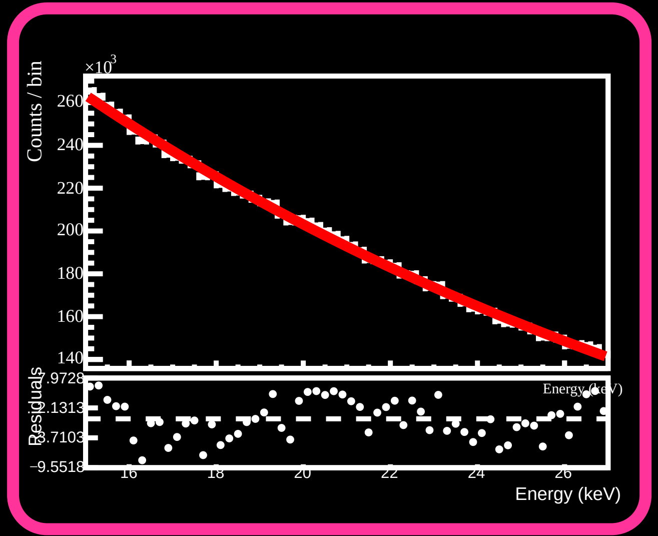
- We can consider axions as dark matter particles forming **the halo of our galaxy**
- Non-relativistic DM axions -> **monoenergetic electron recoils** at E = m_a
- Interaction via **the axio-electric effect**
- CUORE's low-energy data allows a search in the 3–10 keV range with 3 keV selection, and above with 10 keV selection channels
- **Goal**: **to set limits on the axio-electric coupling constant**

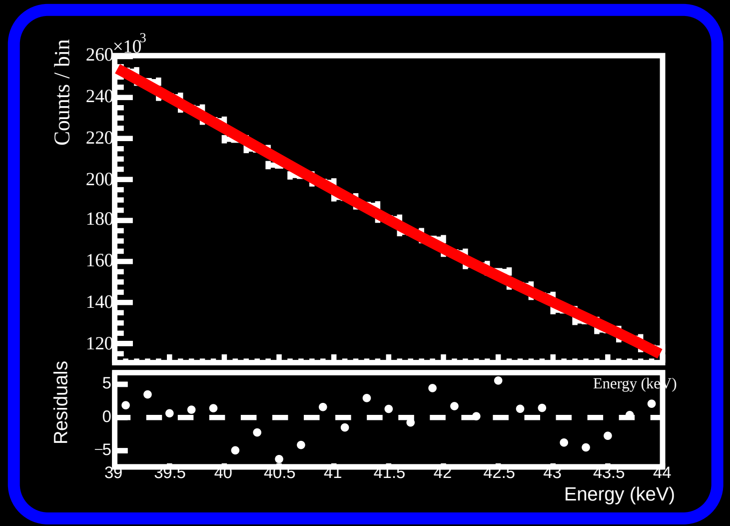
COSMIC AXIONS SENSITIVITY – FIT

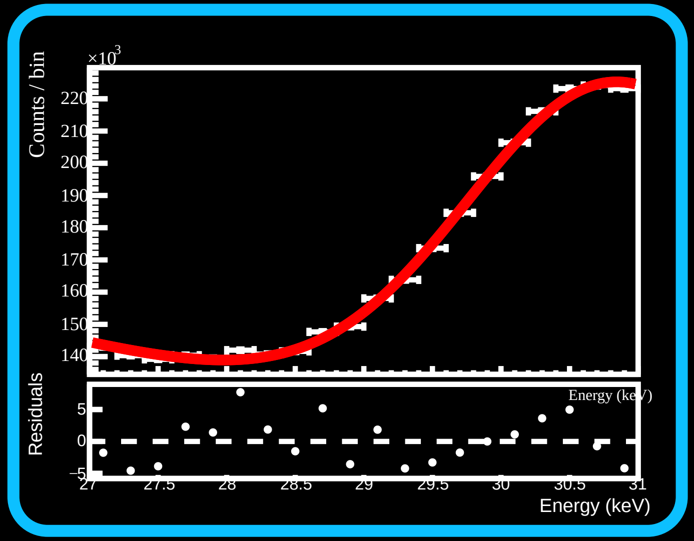
- Standard ROOT fit performed chunk-by-chunk
- **3 keV selection**: used up to ~12 keV
- **10 keV selection**: used above 12 keV

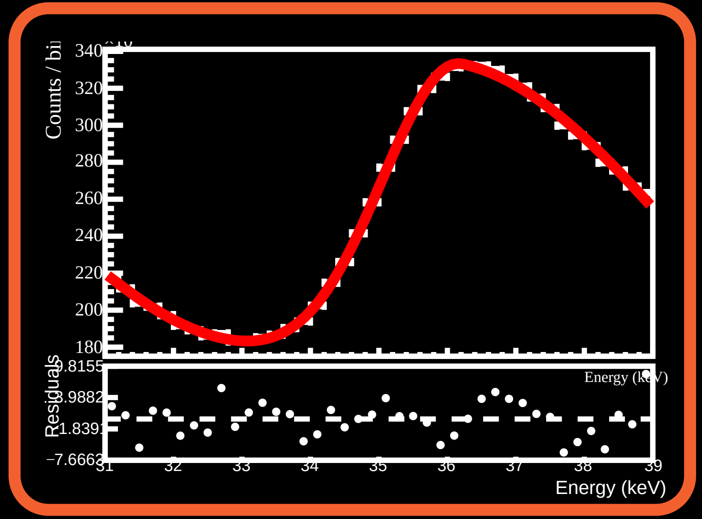
Combined raw spectrum

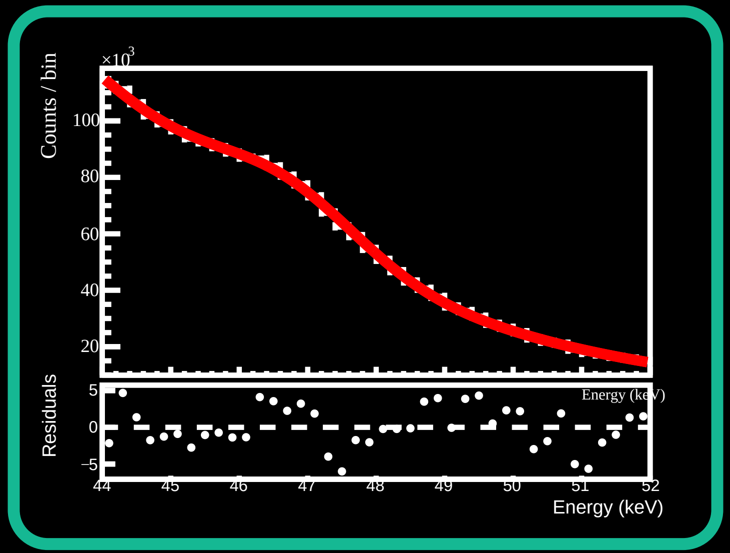












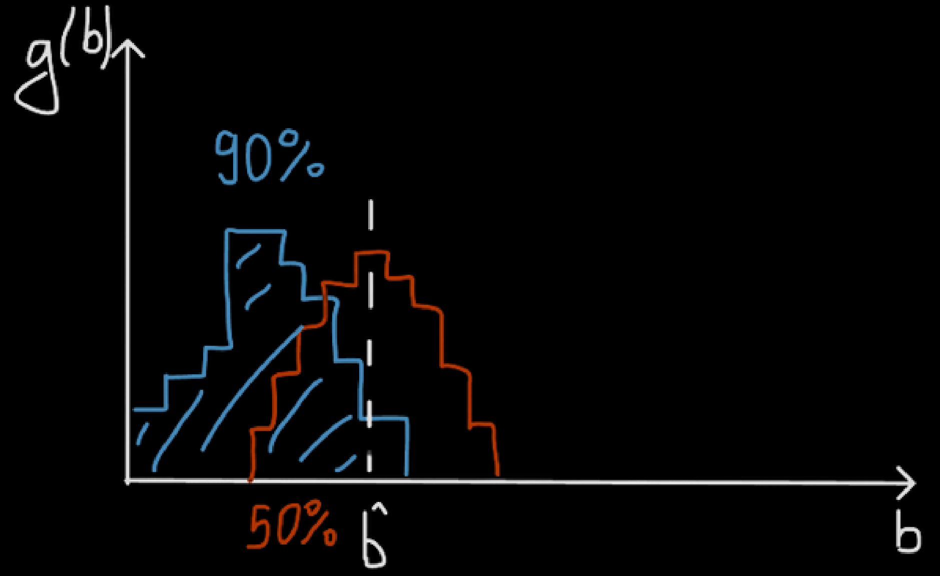
COSMIC AXIONS SENSITIVITY – UPPER LIMIT

- A scan over the [3 - 200] keV energy region with a 0.4 keV step
- For each point, a 2σ window is opened
- 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

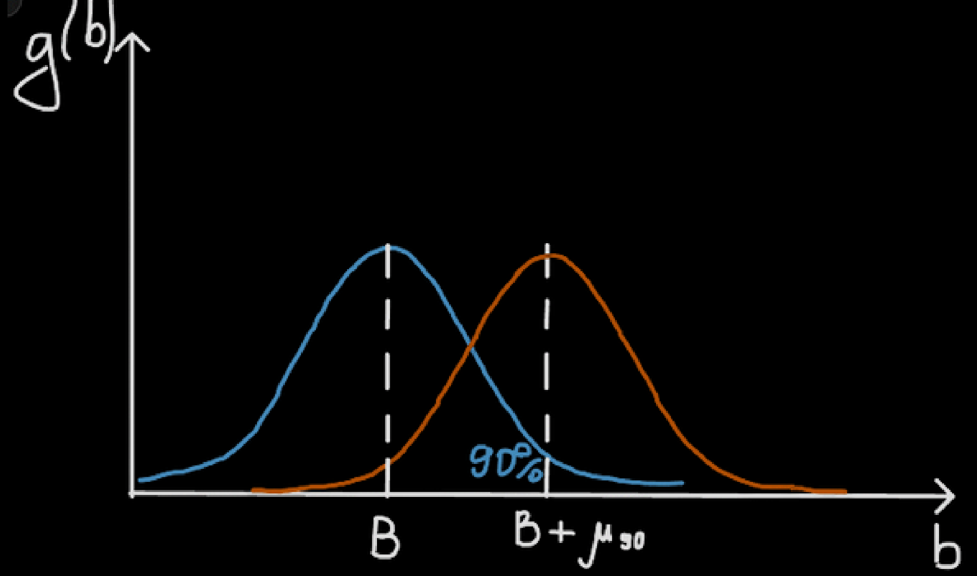


$$z = 1.28155 \quad (P(Z<z) = 0.9)$$

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

90% CL Upper Limit

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



COSMIC AXIONS SENSITIVITY – CALCULATIONS

Cosmic axion flux

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

Axio - electric cross section

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

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

The photoelectric cross section is extracted for each energy point for Te and O from https://physics.nist.gov/

$$\sigma[\mathrm{cm}^2/\mathrm{g}] = \frac{M_{\mathrm{Te}}\,\sigma_{\mathrm{Te}} + 2M_{\mathrm{O}}\,\sigma_{\mathrm{O}}}{M_{\mathrm{Te}} + 2M_{\mathrm{O}}}$$

$M_{\mathrm{Te}} = 127.6$ g/mol, $M_{\mathrm{O}} = 16.0$ g/mol

$$\sigma[\mathrm{cm}^2/\mathrm{molecule}] = \sigma[\mathrm{cm}^2/\mathrm{g}]\frac{M_{\mathrm{TeO_2}}}{N_A}$$

$M_{\mathrm{TeO_2}} = 159.6$ g/mol

$$n_{\mathrm{mol}} = \frac{1000}{M_{\mathrm{TeO_2}}} N_A = 3.77\times 10^{24}\ [\mathrm{molecules\ kg}^{-1}]$$

10 keV selection: 690.75 kg years
3 keV selection: 11.4 kg years

Expected number of signal events

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

90 CL from the fit

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

total efficiency

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

fraction of signal in the bin

COSMIC AXIONS SENSITIVITY – RESULTS

- Axion masses with 0.4 keV step in

[4.1 - 12.5] keV **for 3 keV selection**

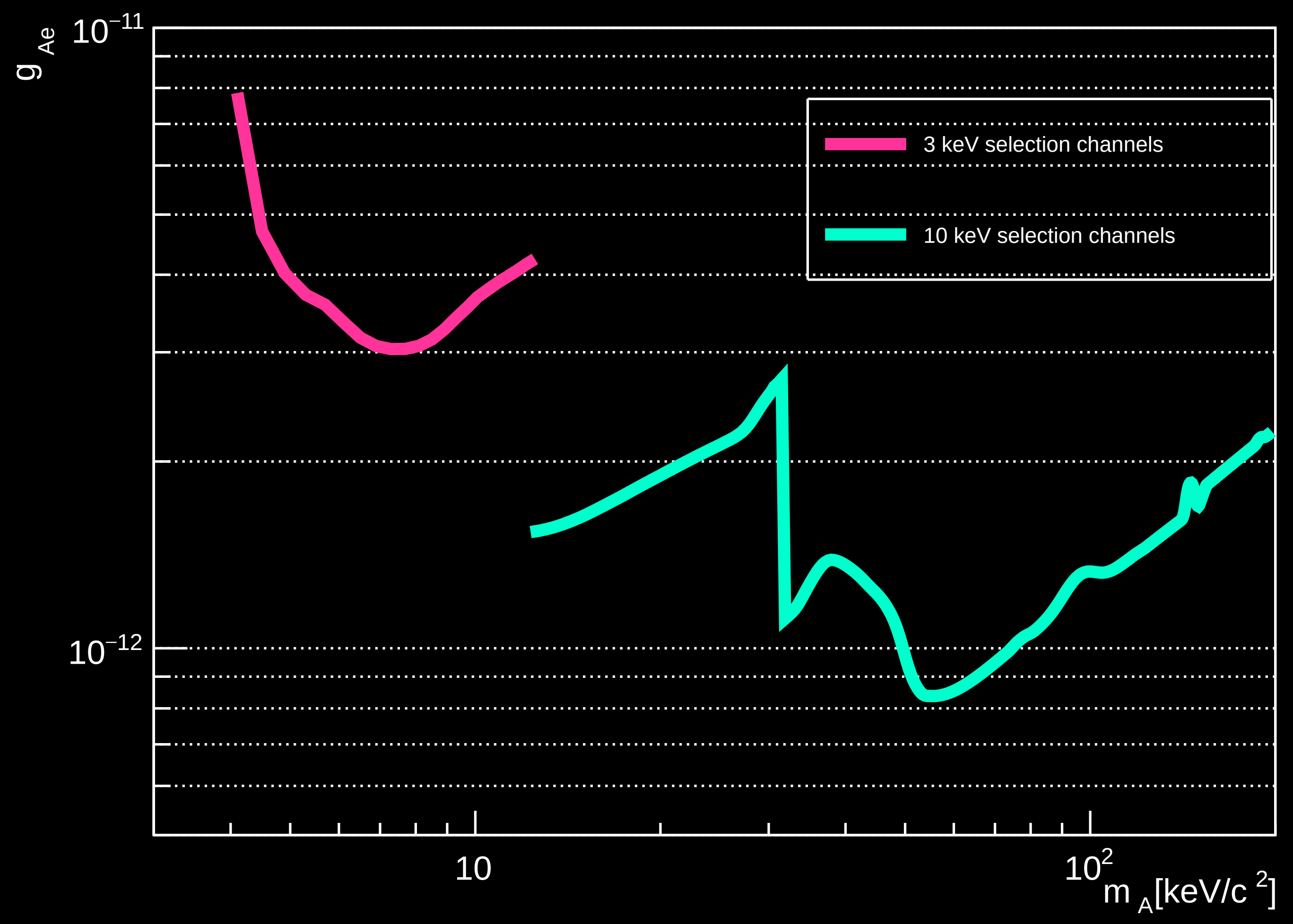
[12.3 - 197.5] keV **for 10 keV selection**

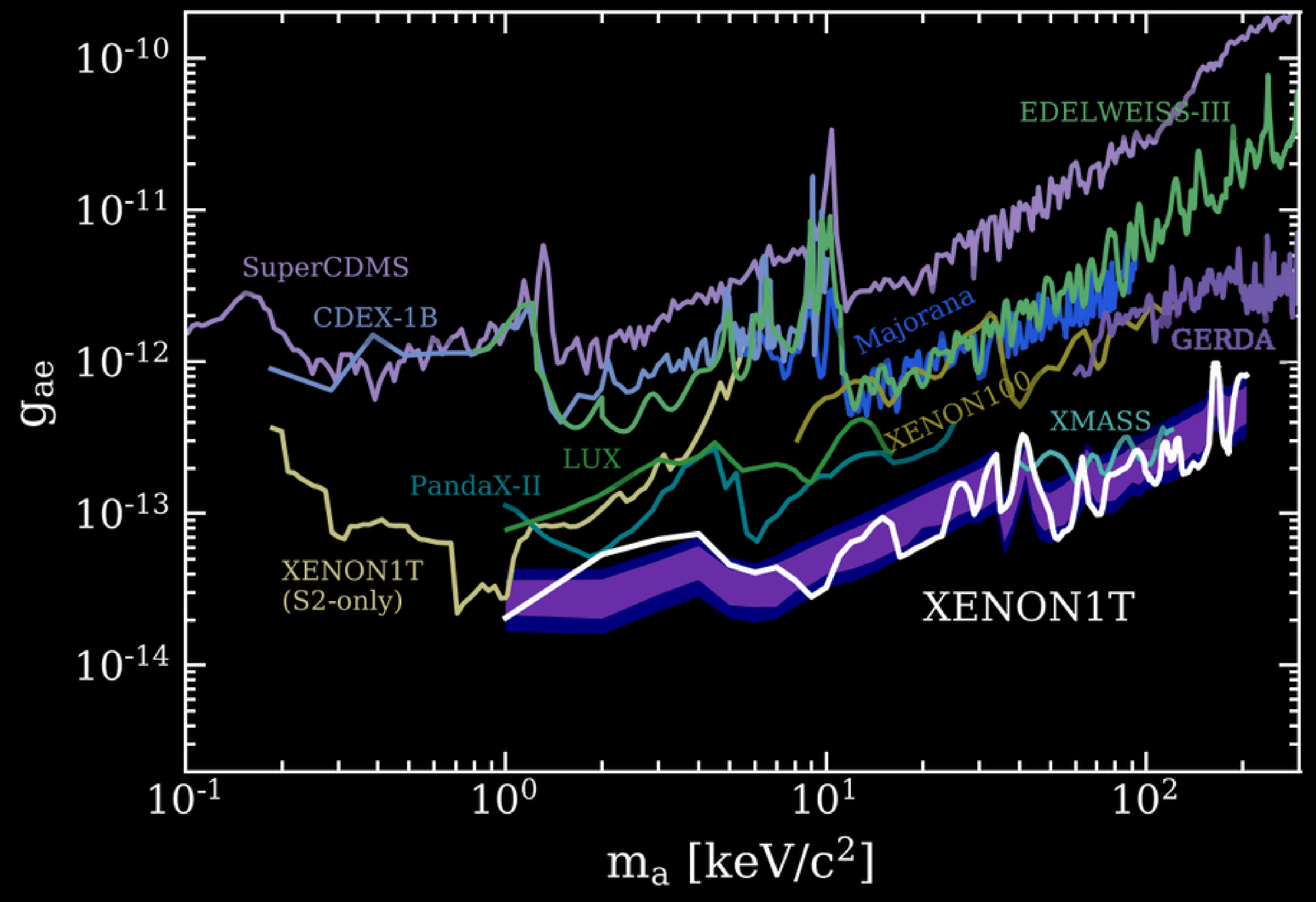
- 2σ window for the Gaussian axion signal

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

Combined 90% CL upper limits





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

BACKUP

CHANNEL SELECTION DISCREPANCY

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

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

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

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

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