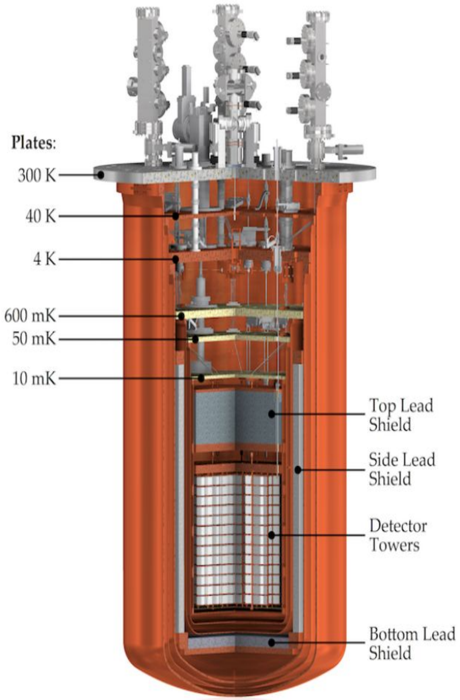
Investigating the keV Energy Fronter with CUORE: Axion and Rare-Event Searches

Rebecca Kowalski
on behalf of the CUORE Collaboration

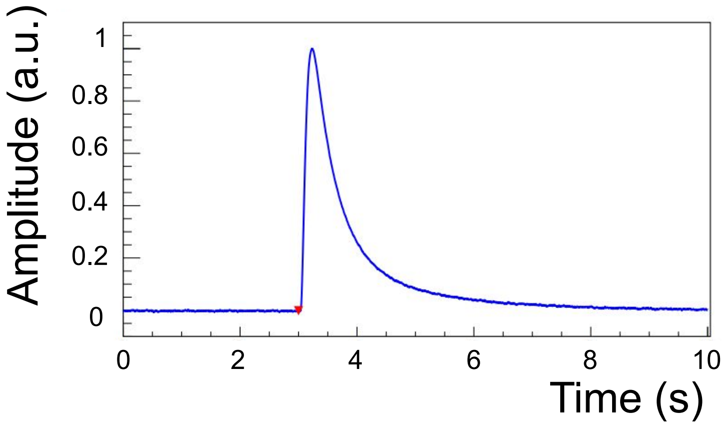
The CUORE Experiment

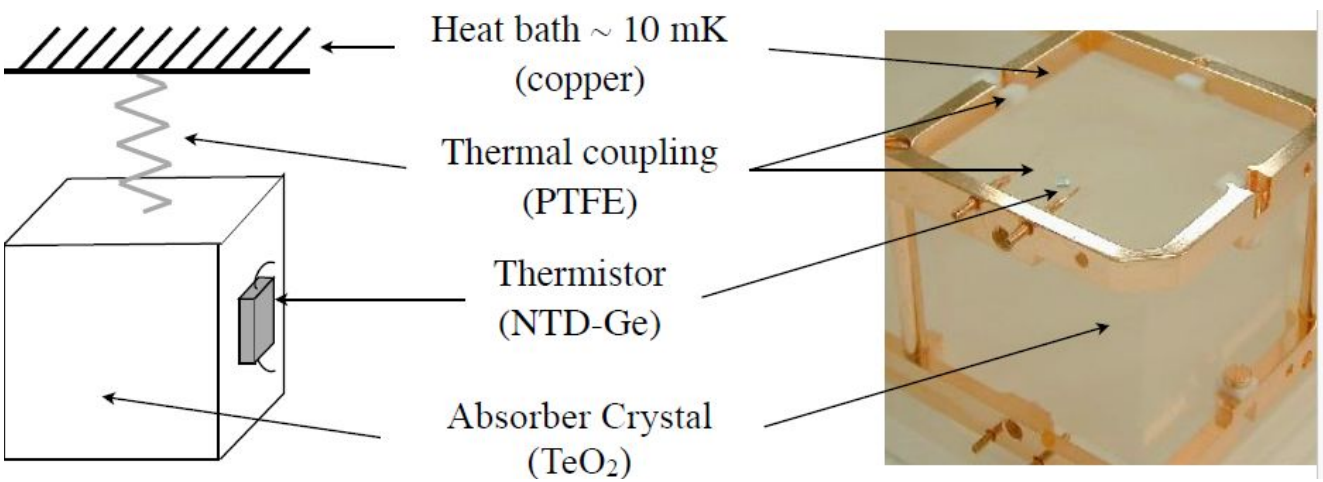
- The **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents located at Gran Sasso National Laboratories, Assergi, Italy
- Designed for a $0\nu\beta\beta$ decay search
  - Would be observed ~2527 keV for ^{130}Te
- High sensitivity, low noise, tonne scale experiment
  - 988 TeO_2 calorimeters ~ 742 kg
  - Goal resolution of ~5 keV
  - Cryogenic temperatures of ~10 mK
  - ~3600 w.m.e. overburden + inner and outer lead shielding
  - Near continuous data collection since 2017



Cryogenic Calorimetric Technique

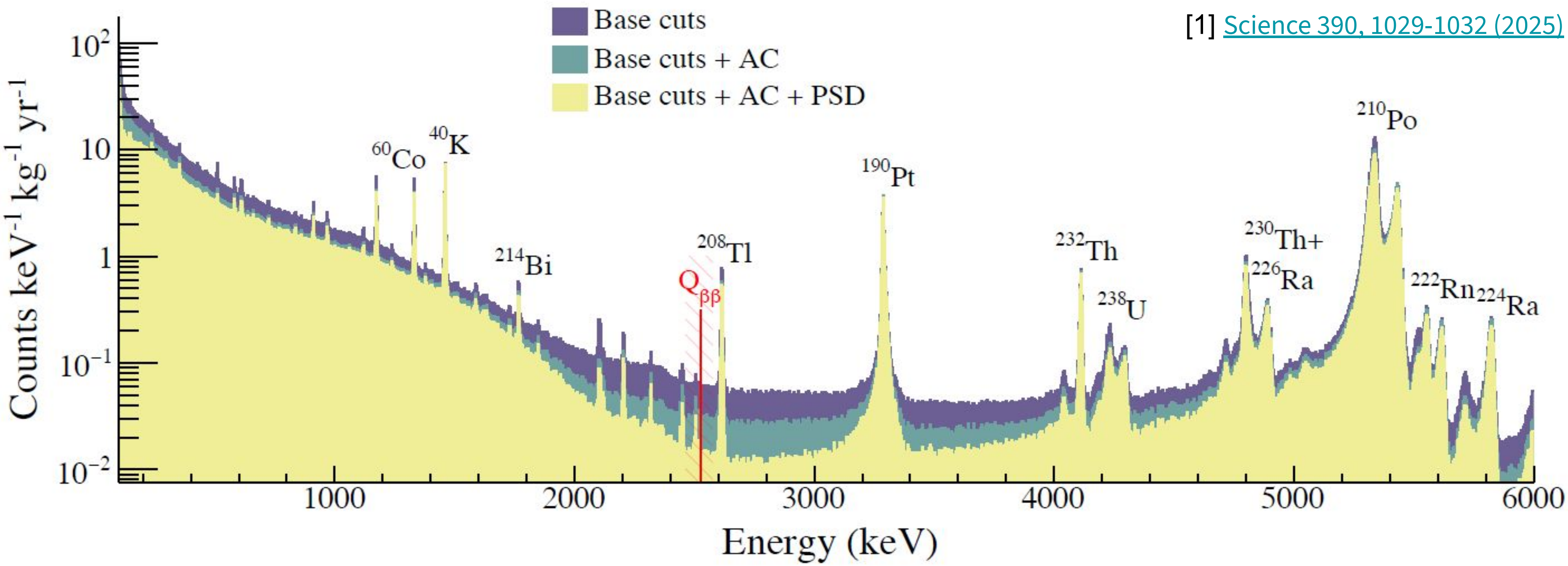
- Energetic interaction inside crystal
  - Temperature increase inside crystal
- Phonon propagation to NTD sensor from incident energy deposition
- Temperature detected in NTD proportional to the energetic reaction of the event
  - $\Delta T = \Delta E / C(T)$
  - $C(T) \propto T^3$





CUORE Energy Spectrum

[1] Science 390, 1029-1032 (2025)



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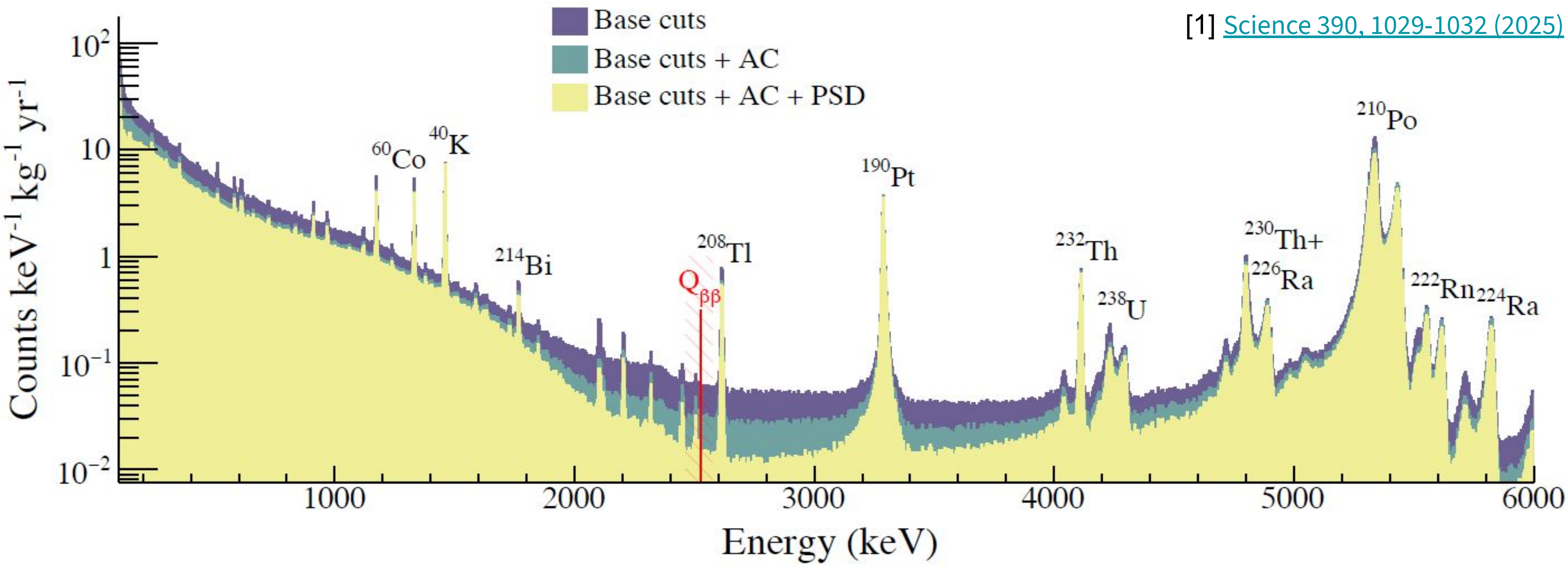

Example low energy process:

Interactions from dark matter candidates

- Axions
- Weakly Interacting Massive Particles

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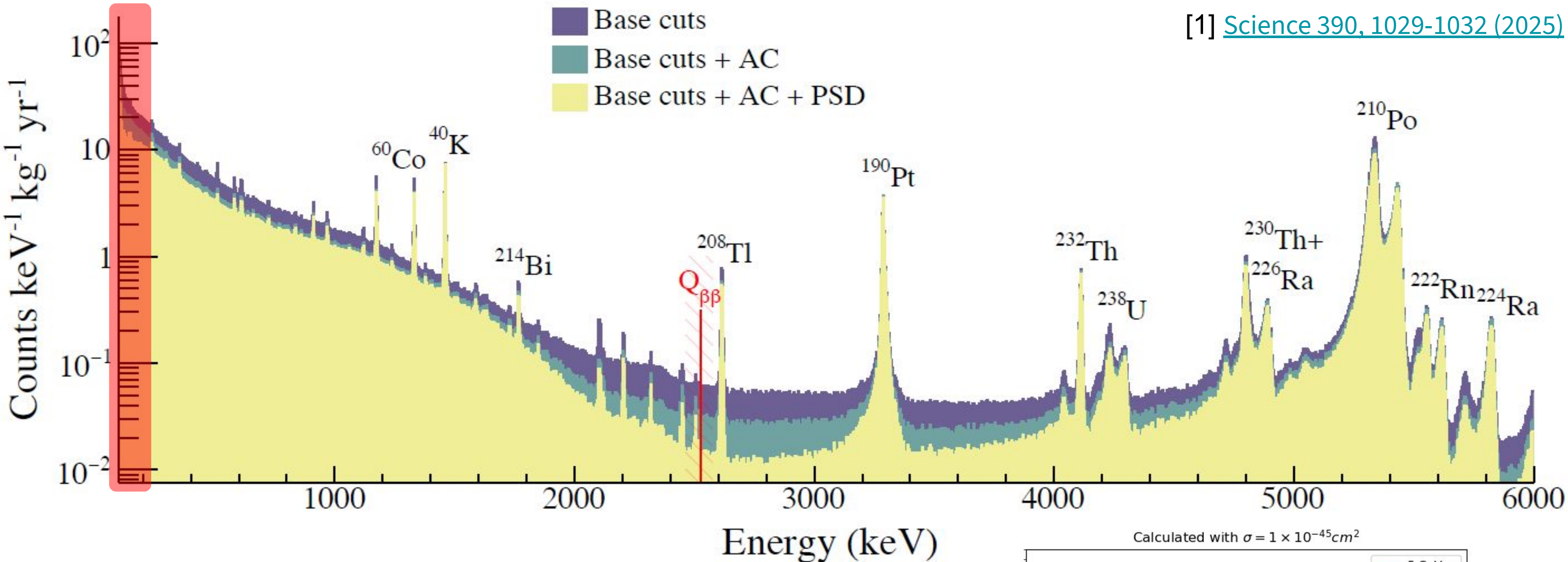
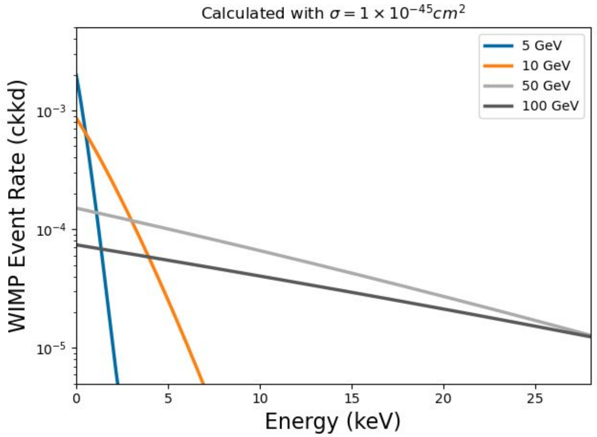




Example low energy process:

Interactions from dark matter candidates

- Axions
- Weakly Interacting Massive Particles

$0\nu\beta\beta$

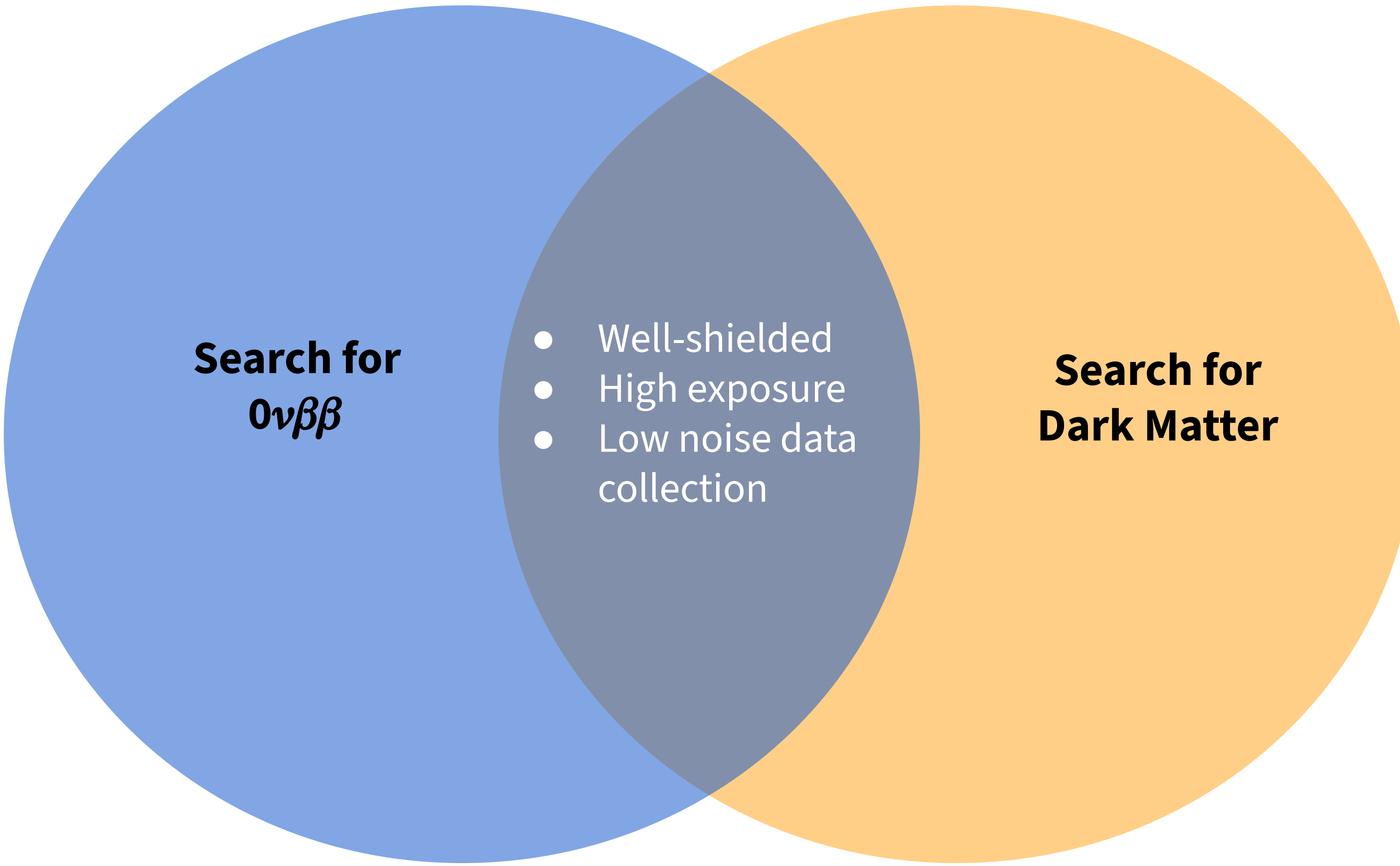
- Looking for: rare radioactive process
    - Small expected signal

- Build detector to:
    - Collect large amounts of data
    - Reduce noise sources

Dark Matter

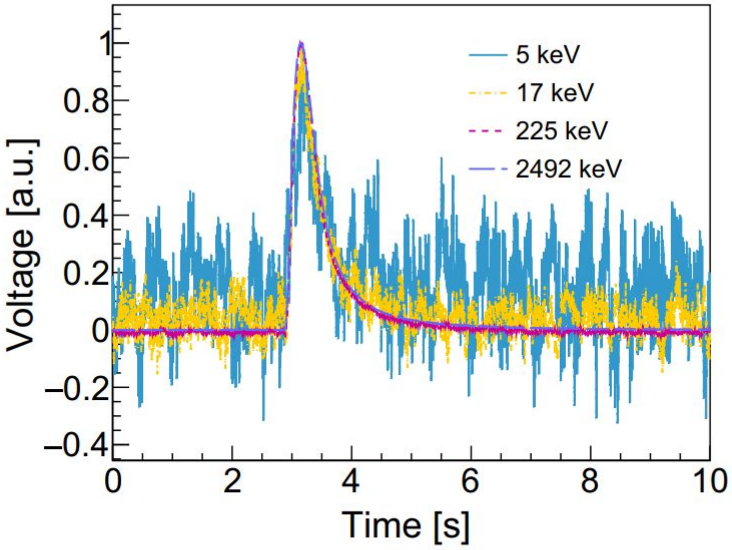
- Looking for: particles that minimally interact with SM
    - Small expected signal

- Build detector to:
    - Collect large amounts of data
    - Reduce noise sources


Search for
$0\nu\beta\beta$
Well-shielded
High exposure
Low noise data collection
Search for
Dark Matter

Accessing the low energy events of CUORE

- $0\nu\beta\beta$ analysis threshold is 40 keV
  - Axion and WIMP signatures around 10 keV
- Pulses near threshold have lower signal to noise ratio (SNR)
  - More vibration induced coincidental triggers
- Develop analysis techniques tailored to optimize selection of good quality low energy pulses



[2] Phys. Rev. D 113, 012012 (2026)

Data Processing

1. Denoising
2. Optimum Filtering
3. Offline retriggering
4. Energy Reconstruction
5. Quality Cuts

Data Processing

[3] Commun. Phys. 9, 121, (2026)

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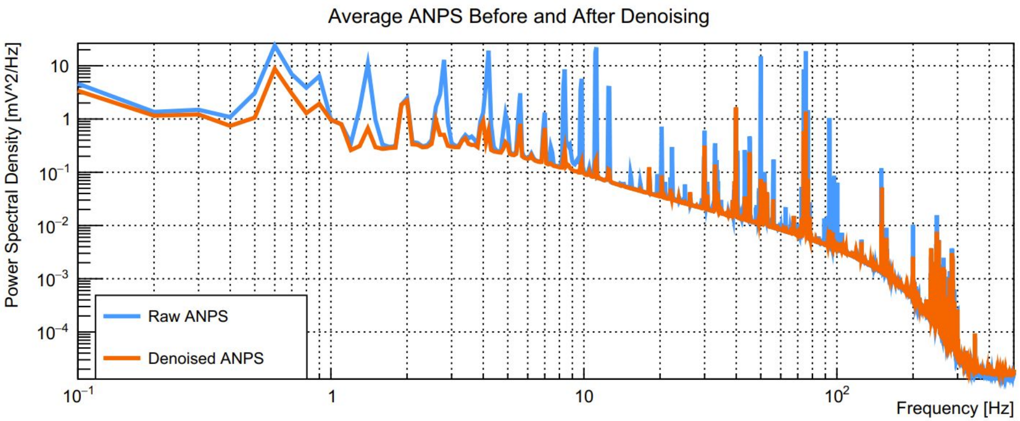

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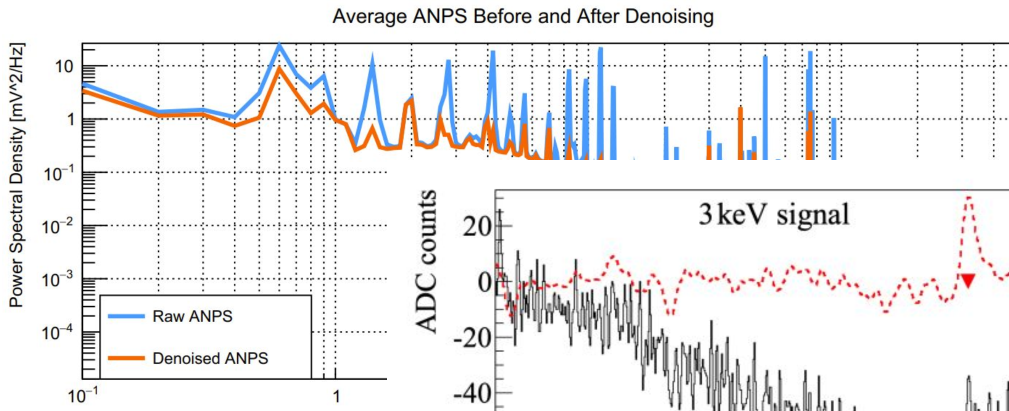

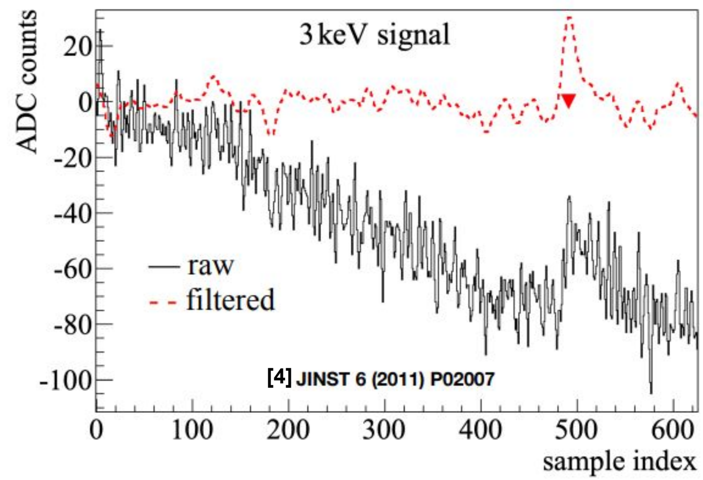

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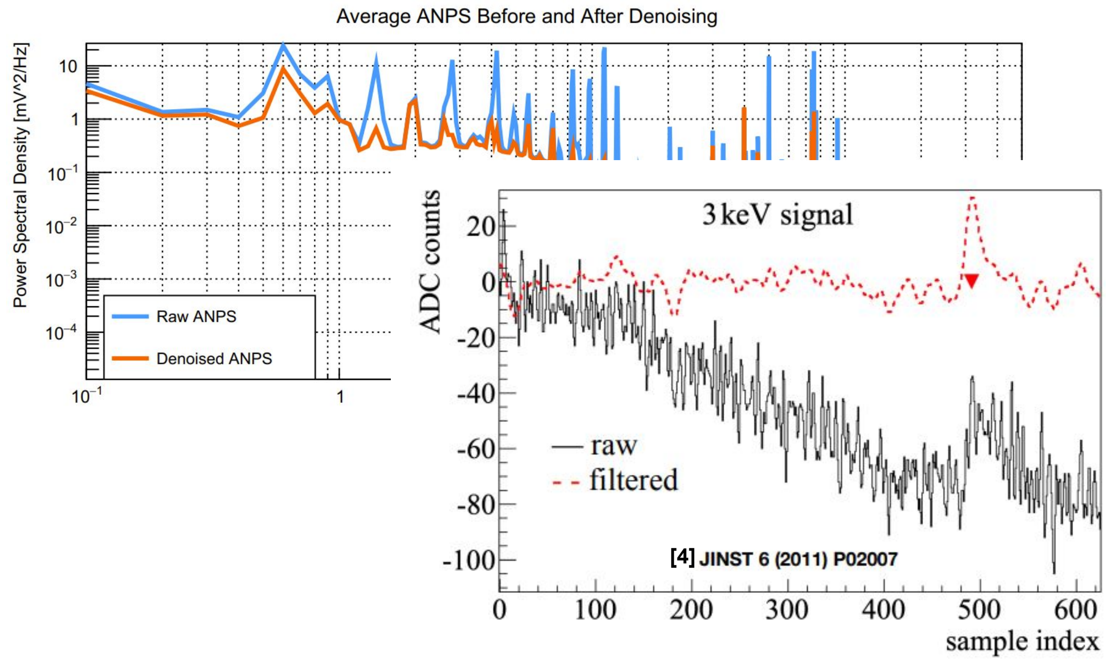
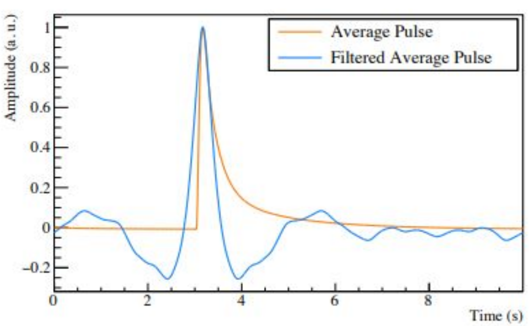
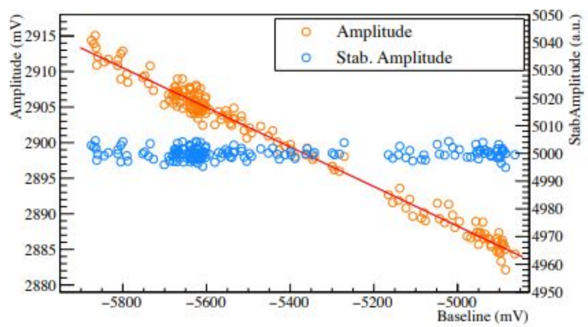


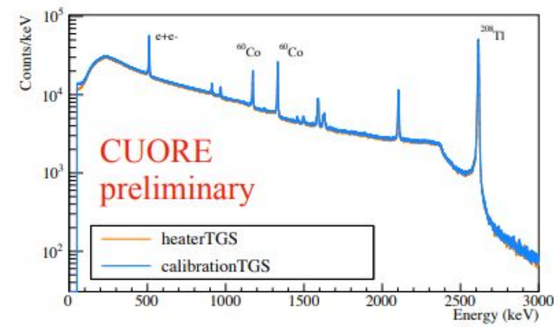
Amplitude evaluation



Thermal gain stabilization

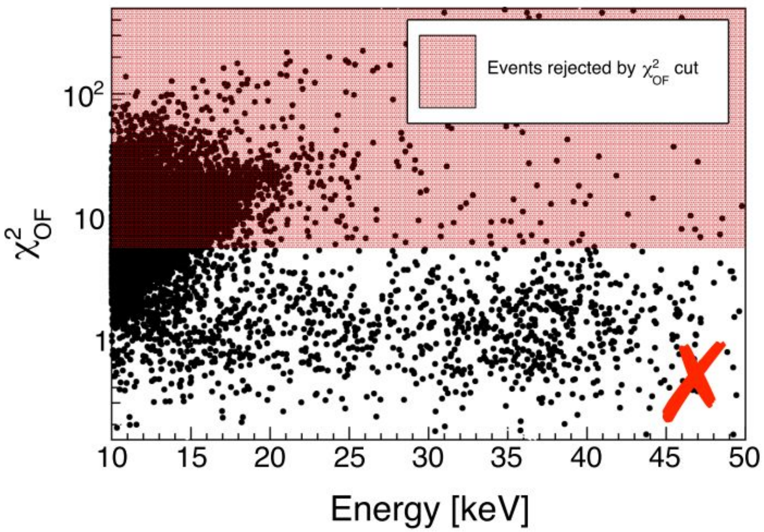


Energy calibration



Low Energy Quality Cuts - Event Level

- Use χ^2_{OF} as a Pulse Shape Discrimination (PSD) variable
    - Quantification of difference between an average pulse template and event pulse
- Determine a χ^2_{OF} threshold for each channel to remove un-physical events



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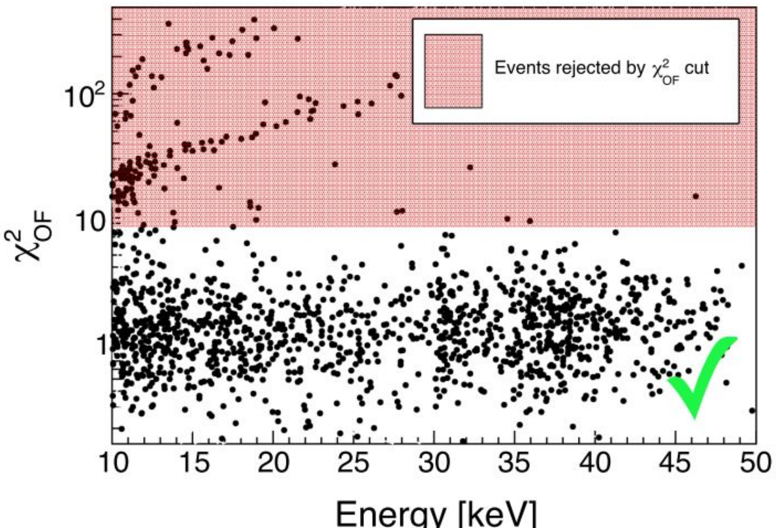

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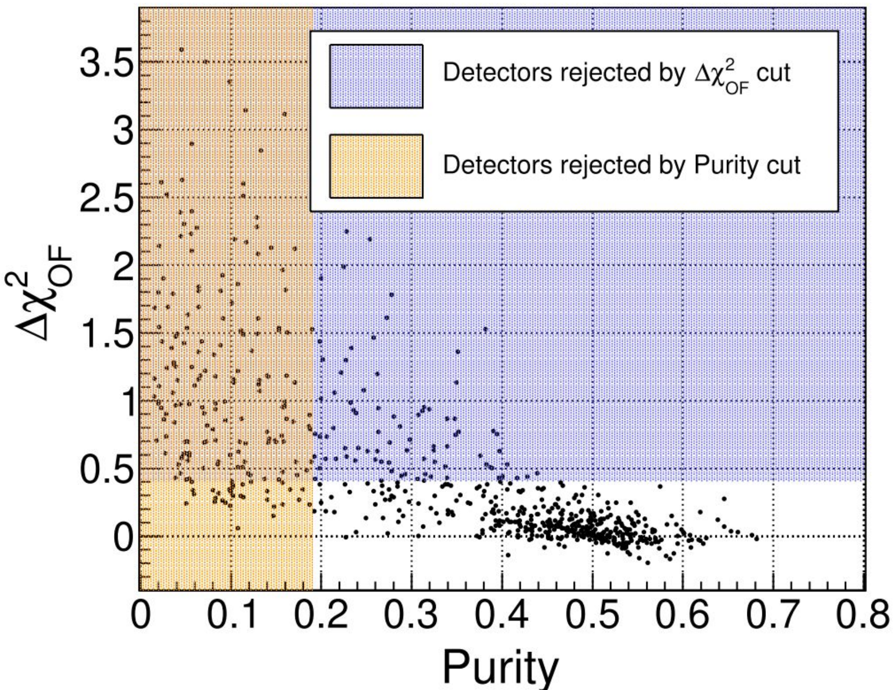
Low Energy Quality Cuts - Detector Level

- Select subset of channels of good signal quality for a given ROI
  - Purity - fraction of physical events relative to total events in ROI
  - $\Delta\chi^2_{OF}$ - difference between median χ^2_{OF} in low energy ROI and reference region
- Channels selected to maximize sensitivity to physics searches:

$$S = \frac{\epsilon_{PSA} MT}{\sqrt{N_{bkg,ROI}}}$$



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Low Energy Spectra

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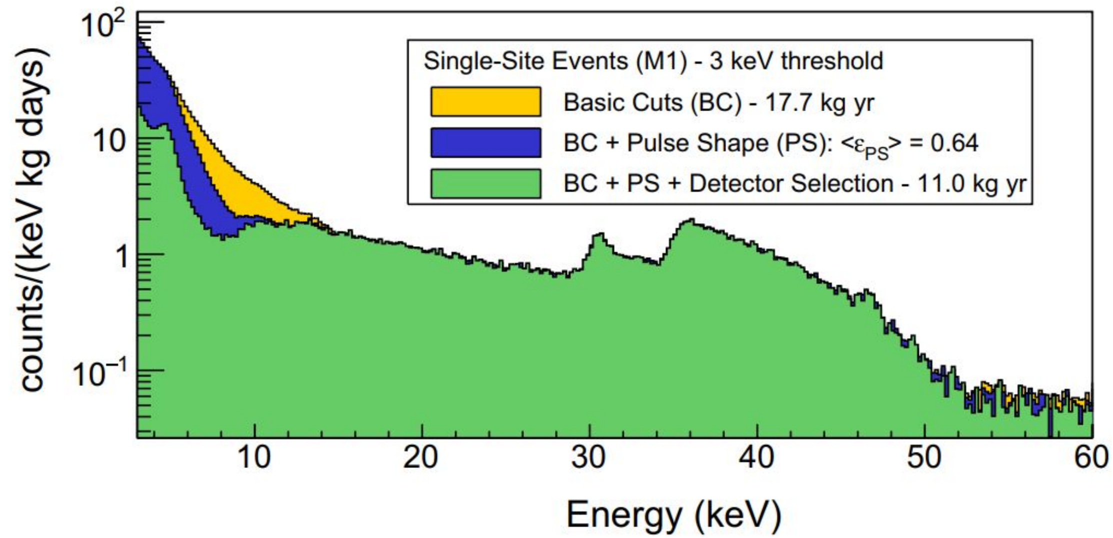
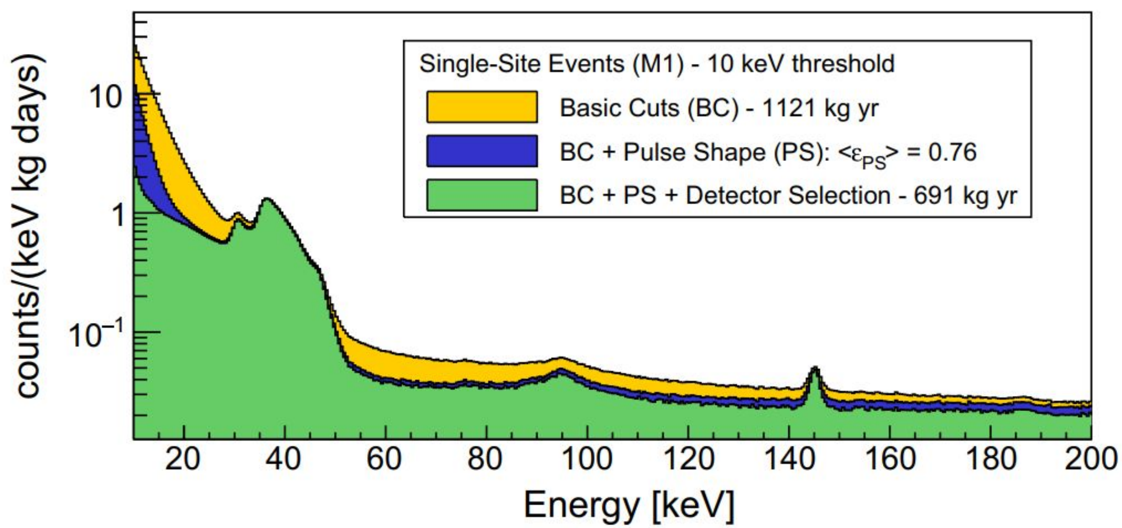
3-10 keV ROI



10-20 keV ROI



Low Energy Detector Response

- Energy Calibration
  - Determine shift of peaks in Te X-rays (27 - 31 keV)
  - Largest shift of 0.14 ± 0.06 keV for strictest 3-10 keV ROI
    - Shift is an order of magnitude lower than detector resolution
- Detector efficiencies
  - Evaluated with injected thermal pulses through Si heaters
  - Product of trigger, energy reconstruction, and pile-up efficiency

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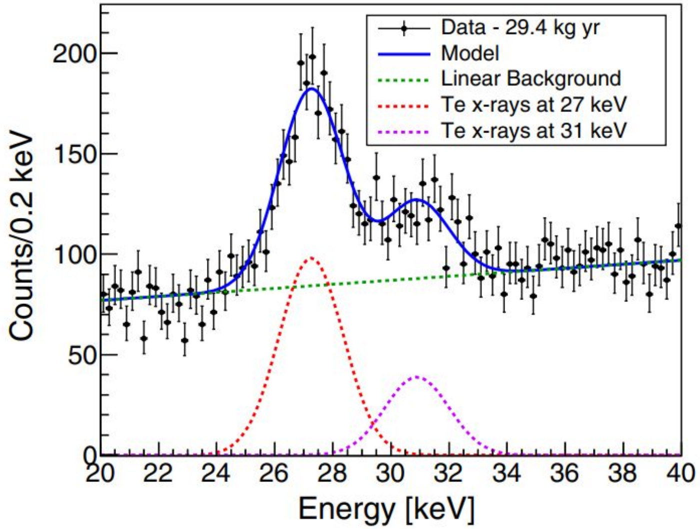

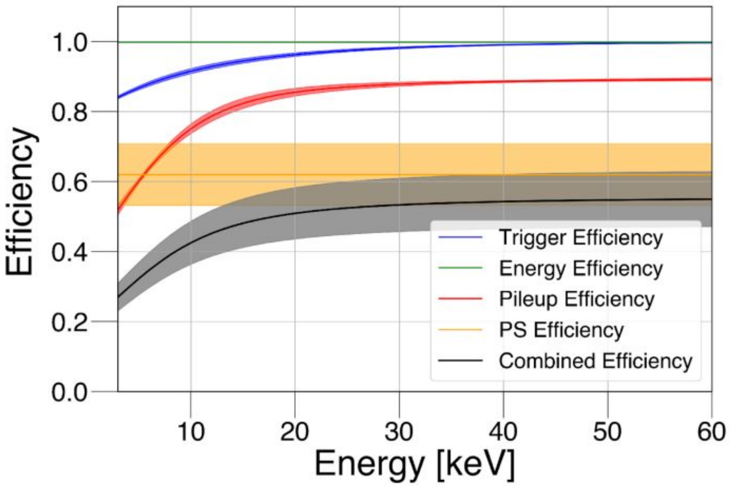

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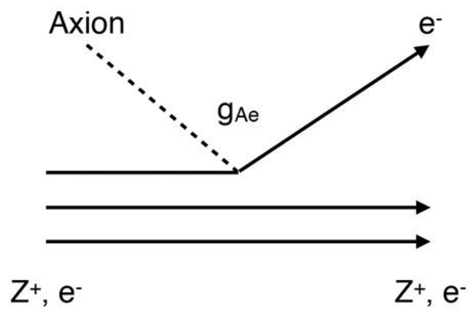
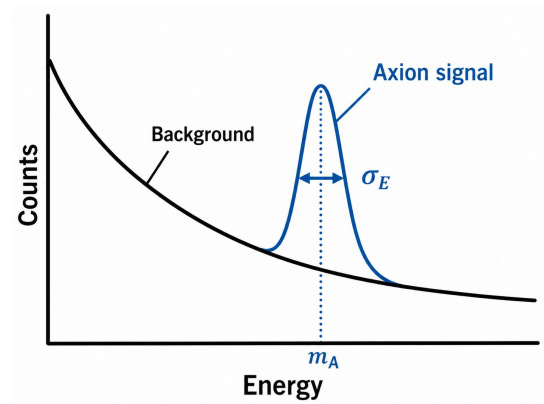
Rare Event Searches - Galactic Axions

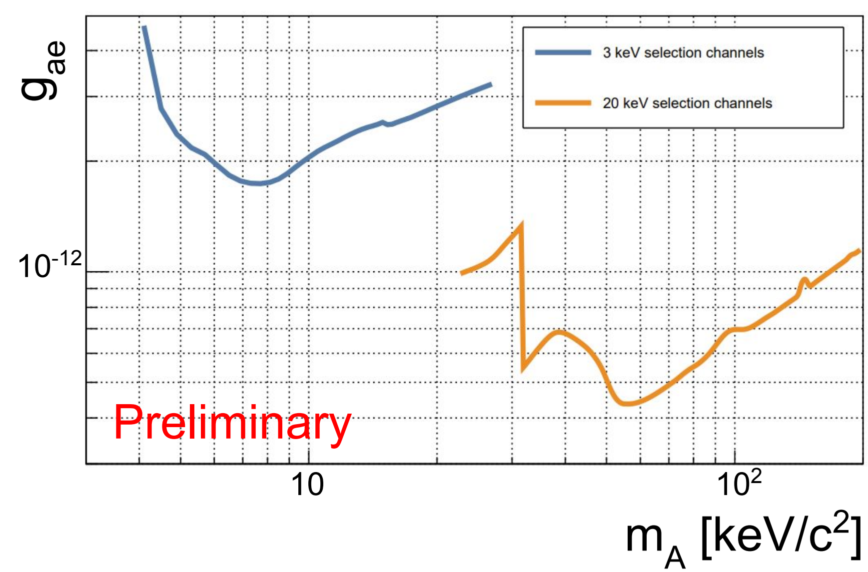
- Axion: particle associated with pseudo-scalar field to solve the strong CP problem
- Low energy spectrum of CUORE has sensitivity to axions that may make up galactic DM halo
    - Observe through axio-electric effect
    - $E \cong m_A$ due to non-relativistic speeds of axions
- Scan through available energy range to search for mono-energetic peak at axion mass



[5] N. Chott

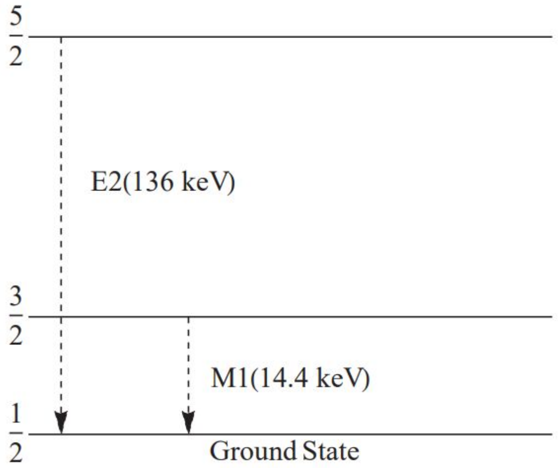


CUORE Sensitivity

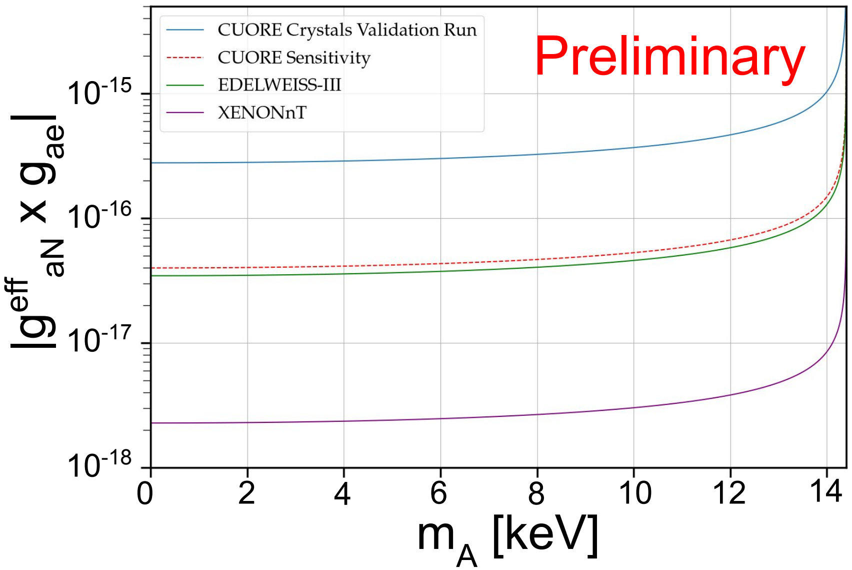


Rare Event Searches - Solar Axions

- Axions could be abundantly produced in the sun
    - Produced through nuclear de-excitation of ^{57}Fe with an energy of 14.4 keV
- Axion could interact with TeO_2 crystal through axio-electric effect
    - Would observe as a mono-energetic signature at 14.4 keV

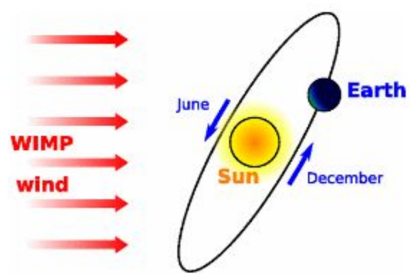


[4] D. Li et al

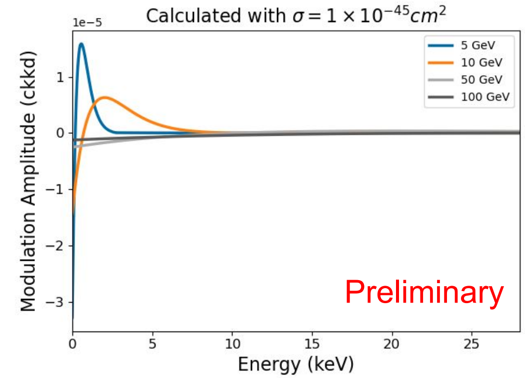


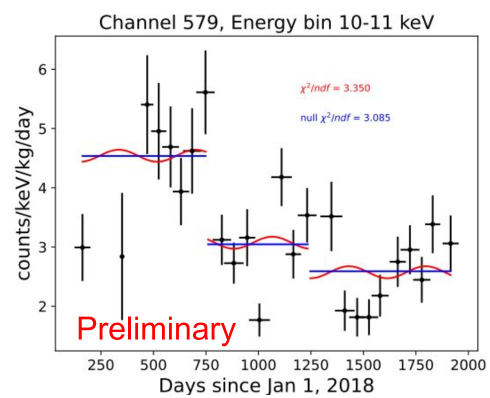
Rare Event Searches - WIMP Induced Annual Modulation

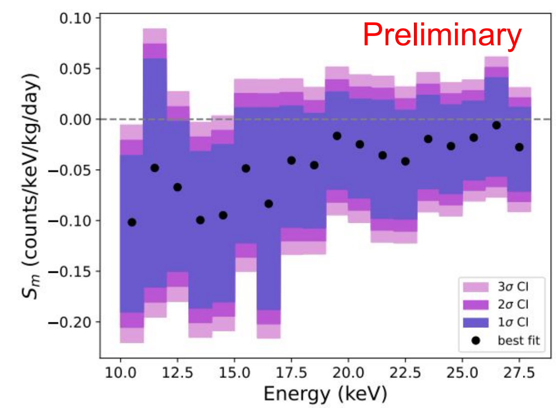
- DM halo could also be composed of WIMPs
- Nominal speed of solar system through halo ~ c^{-3}
  - Seasonal velocity variation as Earth revolves around Sun
  - Earth and Sun move in same direction (maximal additive velocity) ~ June 2nd with a period of 1 year
- Search for a WIMP induced annual modulation
  - Event rate vs time in ROI for low energy ROI
  - Powerful technique to search for WIMPs on top of non-negligible physical backgrounds



[6] K. Freese et al.







Summary

- CUORE has a broad physics campaign in addition to primary goal of searching for $0\nu\beta\beta$ of ^{130}Te
- Dedicated analysis methods have been developed for extending the accessible energy regime down to 3 keV
- Developed methods demonstrate the capability for a many-channel tonne-scale cryogenic calorimeter to have sensitivity to exotic low energy processes
    - Galactic Axions
    - Solar Axions
    - WIMP induced annual modulation
- Look out for related publications in near future!

Thank you!

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CUORE

References

[1] CUORE Collaboration. “Constraints on lepton number violation with the 2 tonne · year CUORE dataset”, *Science*, vol 390. DOI 10.1126/science.adp6474.

[2] CUORE Collaboration. “Exploring the keV-scale Physics Potential of CUORE.” *Physical Review D,* vol 113, p. 012012, APS Physics, doi.org/10.1103/fv25-bfgx.

[3] CUORE Collaboration. “The detection of marine microseismic activity with the CUORE tonne-scale cryogenic experiment”. *Communications Physics*, vol 9. DOI 10.1038/s42005-025-02484-5

[4] S Di Domizio, F Orio, and M Vignati. “Lowering the energy threshold of large-mass bolometric detectors.” *Journal of Instrumentation,* vol 6. DOI 10.1088/1748-0221/6/02/P02007.

[5] Chott, N. (2016). Rare event searches with CUORE style TeO_2 bolometers. [Doctoral Dissertation, University of South Carolina].

[6] K. Freese, M. Lisanti, and C. Savage. “Colloquium: Annual modulation of dark matter.” *Reviews of Modern Physics,*vol 85. doi.org/10.1103/RevModPhys.85.1561.

[7] D. Li *et al*. Sensitivity of the CUORE detector to 14.4 keV solar axions emitted by the M1 nuclear transition of ^{57}Fe. *Journal of Cosmology and Astroparticle Physics,* vol 2016. DOI 10.1088/1475-7516/2016/02/031

Backup

Optimum Filter

- A matched filter algorithm
  - Takes an expected signal shape and an expected noise shape
  - Fourier transforms time series to frequency space
  - Filter suppresses non signal shapes and maintains amplitude of signal (improved signal to noise ratio)

Expected Signal

$$H(\omega_k) = h\frac{s^*(\omega_k)}{N(\omega_k)}e^{-j\,\omega_k i_M}\,.$$

Expected Noise

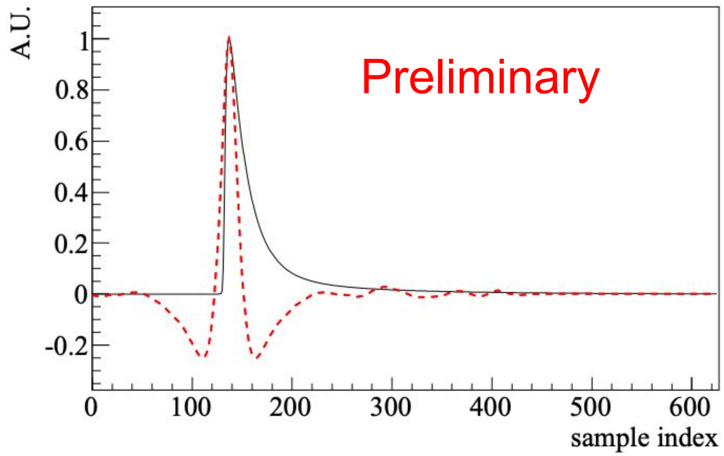
Filter Noise Power Spectrum

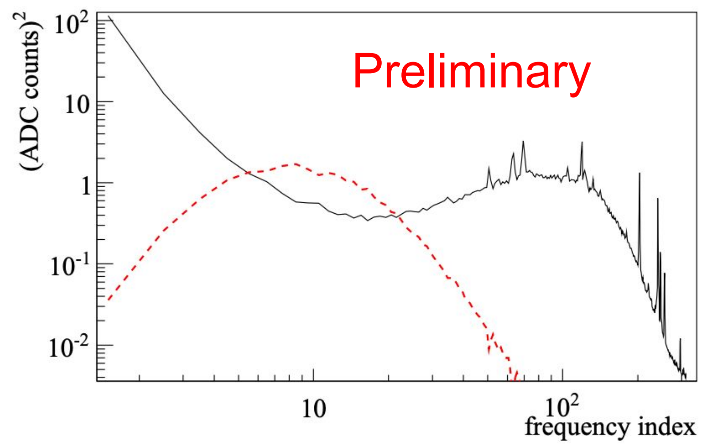
$$N_f(\omega_k) = h^2\frac{|s(\omega_k)|^2}{N(\omega_k)}$$

Filter Resolution

$$\sigma_f^2 = \sum_k N_f(\omega_k) = h\,.$$

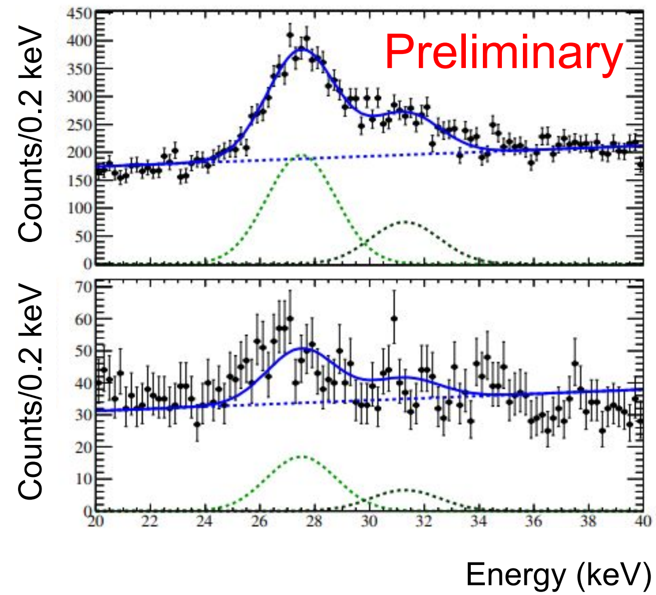
- Optimum Trigger: triggers when amplitude is $N\sigma_f$ over baseline

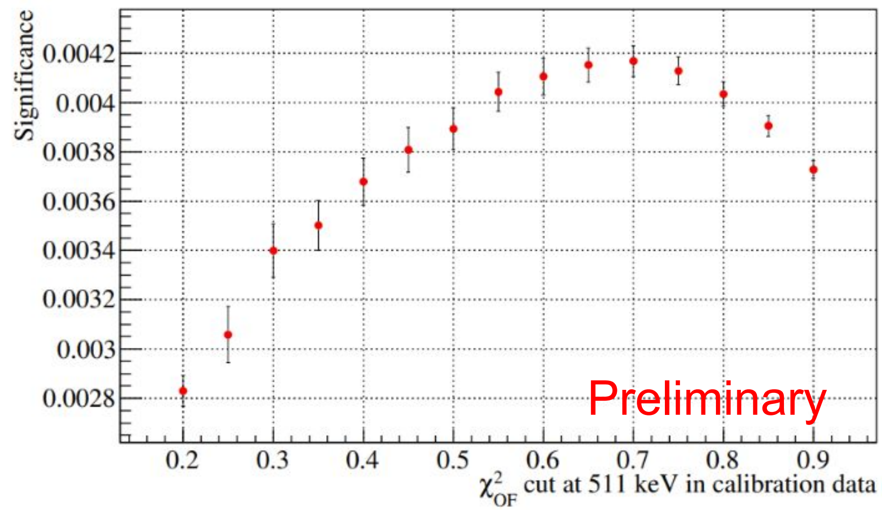




χ^2_{OF} Threshold evaluation

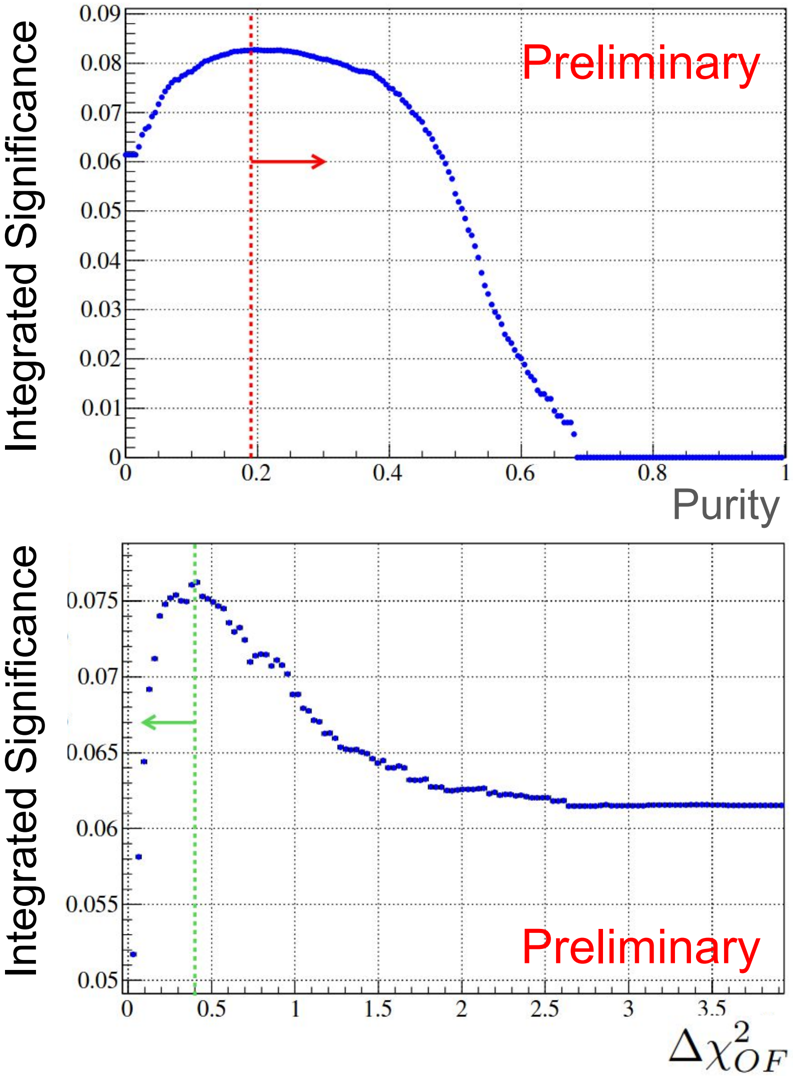
- Evaluated for each channel-dataset
  - Account for any change in detector response between different datasets
- Metric: $\mathcal{S} = \frac{\epsilon_{PSA} MT}{\sqrt{N_{bkg,ROI}}}$
  - Stricter χ^2_{OF} cut → lower ϵ_{PSA}
- Optimization:
  - Get quantile distribution of χ^2_{OF} for events in 511 keV γ line for each channel-dataset
  - χ^2_{OF} cut corresponding to 0.2 quantile
  - Calculate $\mathcal{S}$
    - ϵ_{PSA} evaluated on Te X-rays
  - Repeat for quantiles 0.2 - 0.9





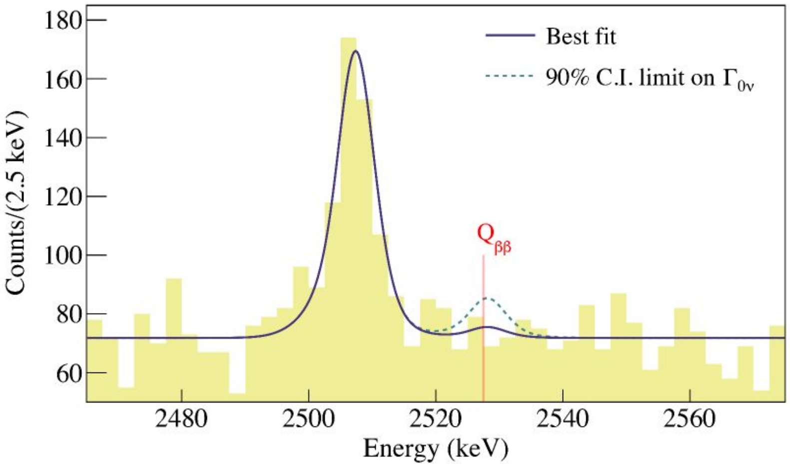
Optimization of Channel Selection

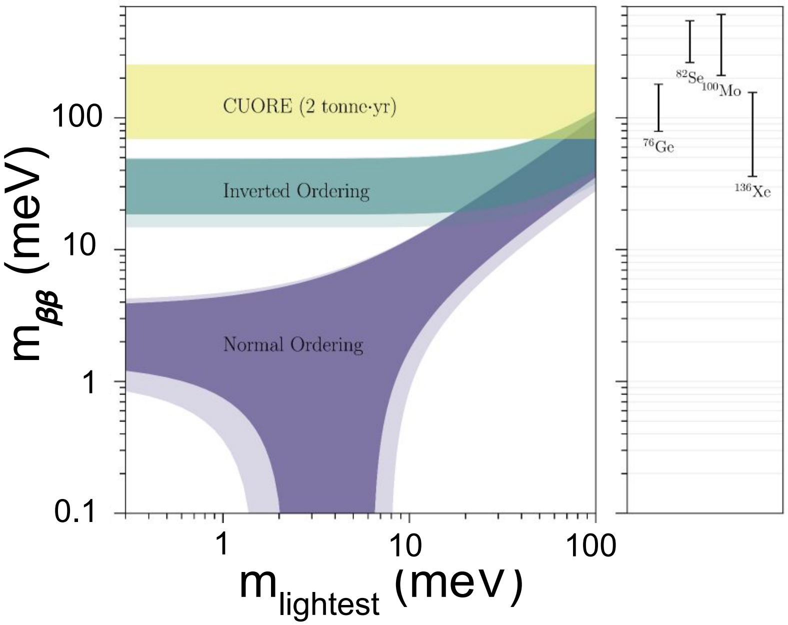
- Define low energy ROI for analysis (10-28 keV)
- Define relatively low energy REF that is not expected to have large noise population but has known physical population of events (30-50 keV)
- Metrics:
  - $\mathcal{P} = \frac{S}{S+N}$
  - $\Delta\chi^2_{OF} = \mathrm{Med}(\chi^2_{\mathrm{OF}})|_{\mathrm{ROI}} - \mathrm{Med}(\chi^2_{\mathrm{OF}})|_{\mathrm{REF}}$
- Optimization:
  - Calculate $\mathcal{P}$ and $\Delta\chi^2_{OF}$ for each channel dataset after event selection
  - Calculate $\mathcal{S}$ for all channels with $\mathcal{P}$ > .05, .1, …
  - Calculate $\mathcal{S}$ for all channels with $\Delta\chi^2_{OF}$ < .01, .02, …



Current Limits on 0$\nu\beta\beta$ of ^{130}Te

- Result on 2039 kg·yr of TeO_2 exposure
  - doi.org/10.1126/science.adp6474
- No evidence of 0$\nu\beta\beta$
- Limit on decay rate $\Gamma_{1/2} < 2.0 \times 10^{-26}$ yr^{-1} at 90% Credible Interval (CI)
  - $T_{1/2}^{0\nu} > 3.5 \times 10^{25}$ yr (90% CI)
- $|m_{\beta\beta}| = |U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3|$
  - Effective Majorana mass accounting for masses of all neutrinos and oscillations through the PMNS matrix





Axion Interaction [D. Li et al, 7]

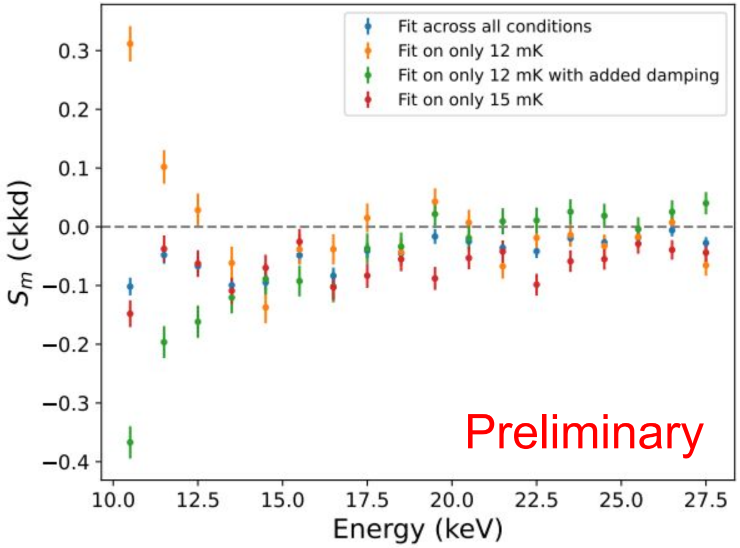
- Axio-Electric effect cross section: $\sigma_{Ae}(E) = \sigma_{pe}(E)\frac{g_{Ae}^2}{\beta}\frac{3E^2}{16\pi\alpha m_e^2}(1-\frac{\beta^{2/3}}{3})$
  - $\boldsymbol{\sigma}_{pe}$ = photoelectric cross section for Te and O
  - $\boldsymbol{\beta}$ ~ velocity of axion
  - Can determine coupling constant as a function of axion mass

WIMP Event Rate

- WIMP Interaction rate: $\frac{dR}{dE_R} = \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) dv$
  - ρ_0 = local dark matter density (0.3 GeV/cm^3)
  - m_N = nucleon mass
  - m_χ = dark matter mass
  - f(v) = maxwellian velocity distribution of dark matter
  - E_R = nuclear recoil energy
  - σ_χ = dark matter cross section
    - Coupling to nucleon, spin independent term is proportional to atomic mass squared
- Annual modulation: $v = v_S + v_E cos\phi cos(\omega(t - t_0))$
  - Amplitude = $\frac{1}{2}(\frac{dR}{dE_R}(t_{max}) - \frac{dR}{dE_R}(t_{min}))$

WIMP Systematics

- Investigated multiple sources of systematic uncertainty
  - Time dependence of low energy features
  - Possible modulation from muon flux
  - Possible modulation from seismically induced vibrations
  - Fitting different detector conditions separately
  - Leaving modulation phase fixed vs letting phase float



CUORE Upgrading to CUPID

- **C**UORE **U**pgrade with **P**article **ID**entification
- New Li_2MoO_4 towers to be installed after decommissioning of CUORE
  - Same cryostat used with upgraded pulse tubes
- Additional scintillating bolometer coupled to crystal
  - Light escapes crystal to induce a phonon signal in the light detector
- Allows for possibility to investigate particle discrimination in low energy searches to improve sensitivity