The latest results from the MAJORANA DEMONSTRATOR

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on behalf of the MAJORANA Collaboration

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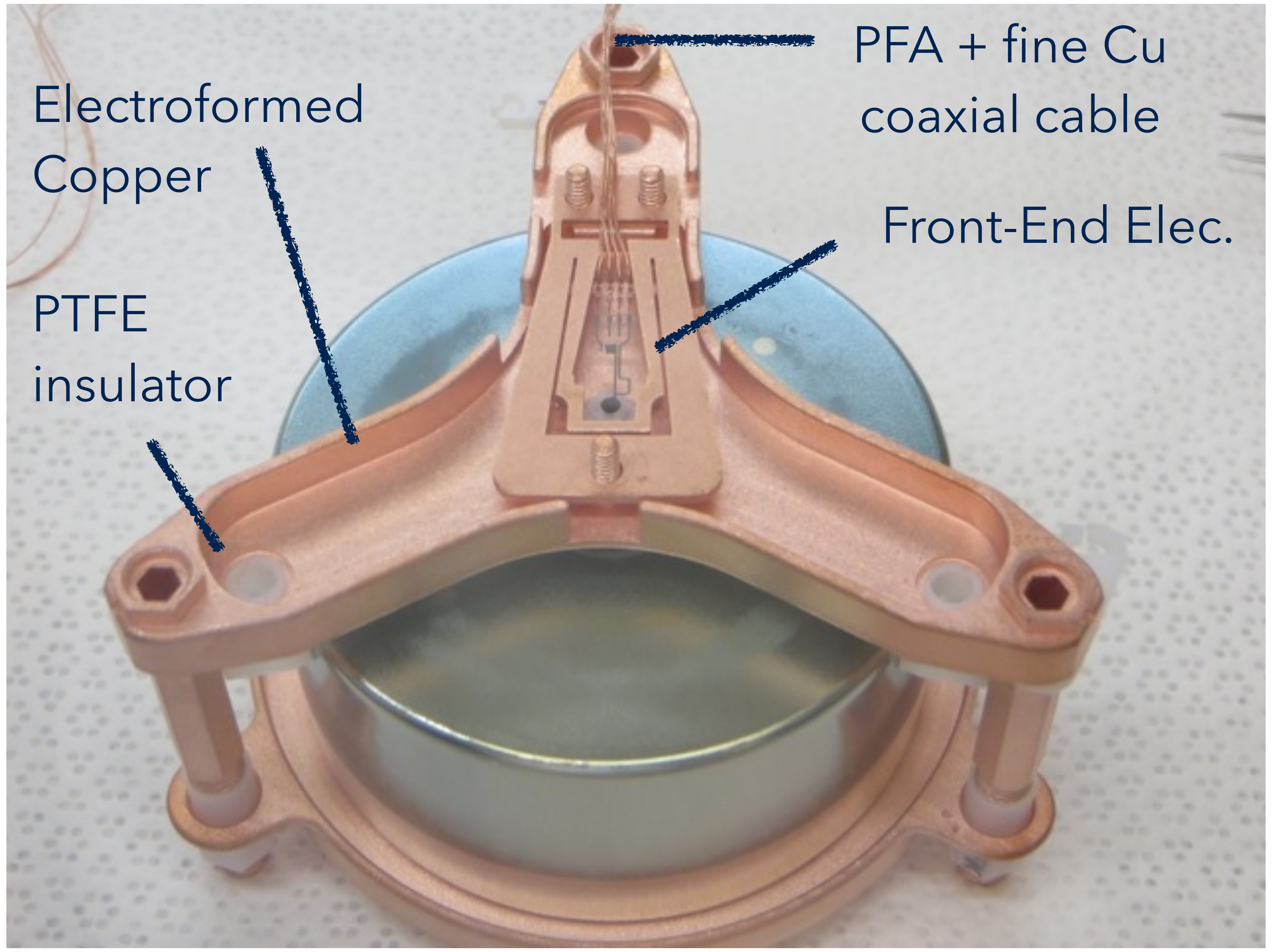
U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Why use ^{76}Ge?

- HPGe diodes have excellent energy resolution and are intrinsically very pure
- Demonstrated ability to enrich from 7.44% to 88%
- Powerful pulse shape rejection techniques to further decrease backgrounds

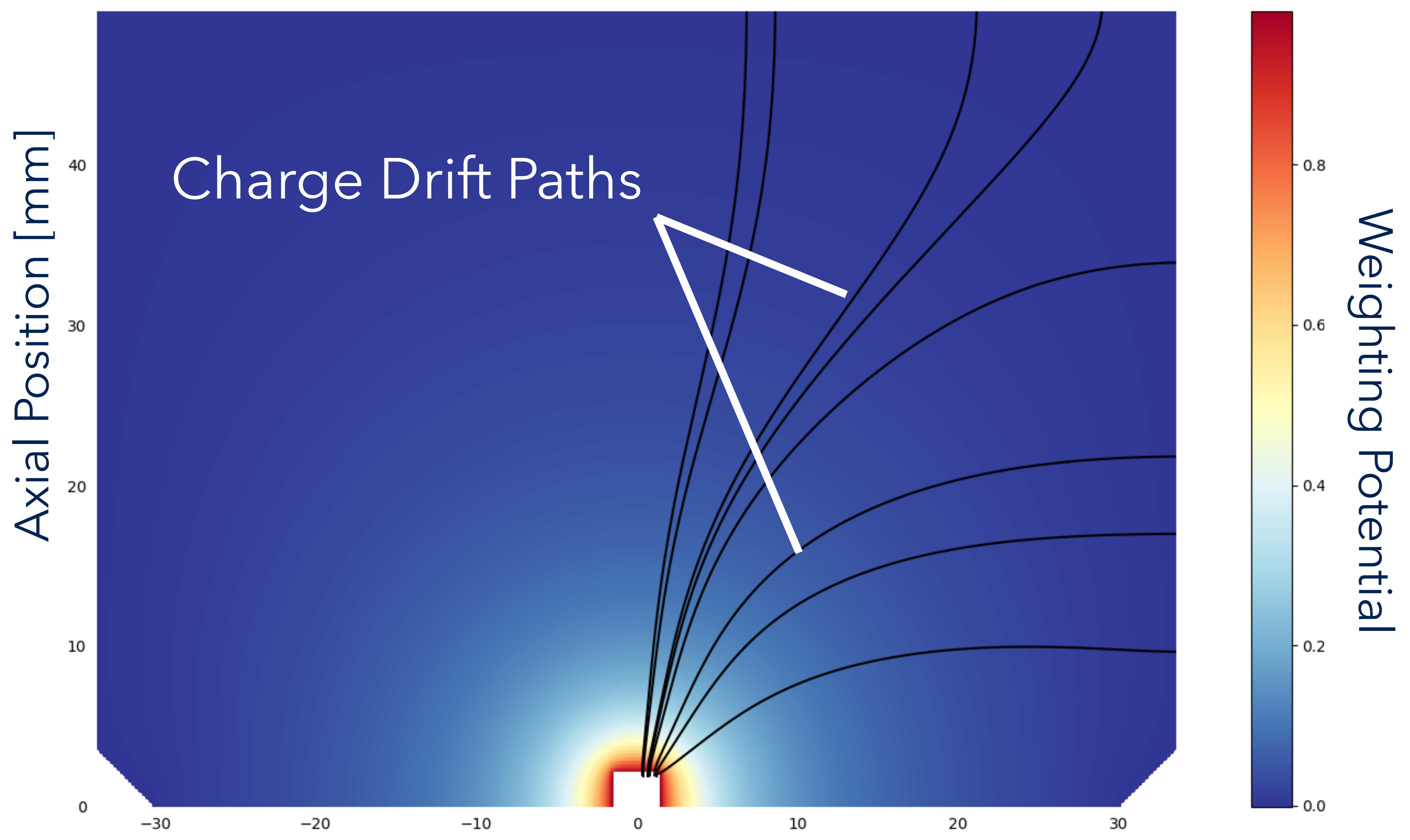
^{nat}Ge detector

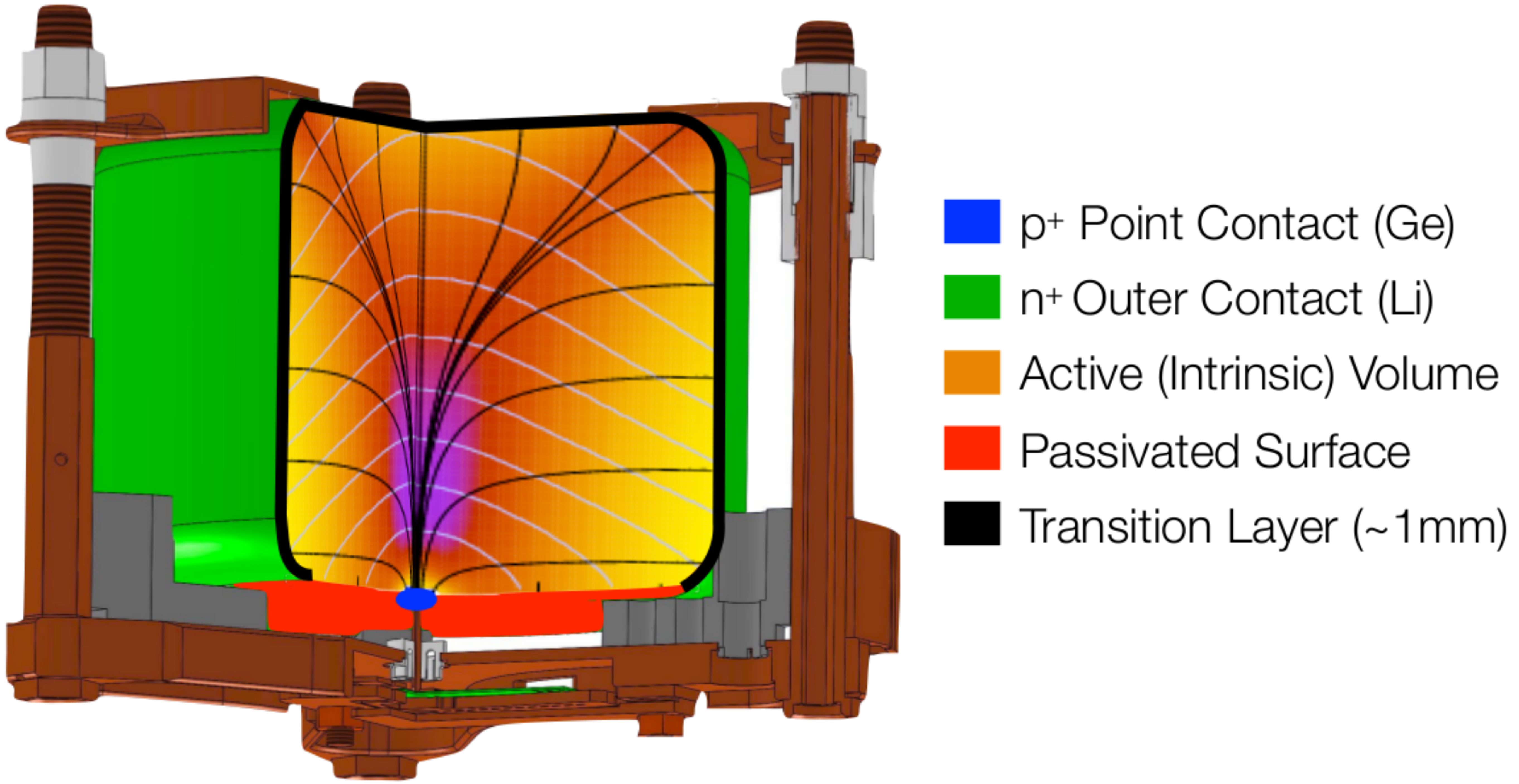


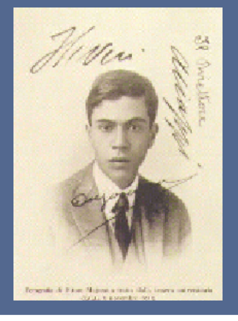
P-type Point Contact (PPC) Detectors

- Detector geometry allows for powerful pulse shape rejection
  - Slow drift time of ionization charge cloud
  - **Localized weighting potential** gives excellent multi-site event rejection

Sample Detector Weighting Potential



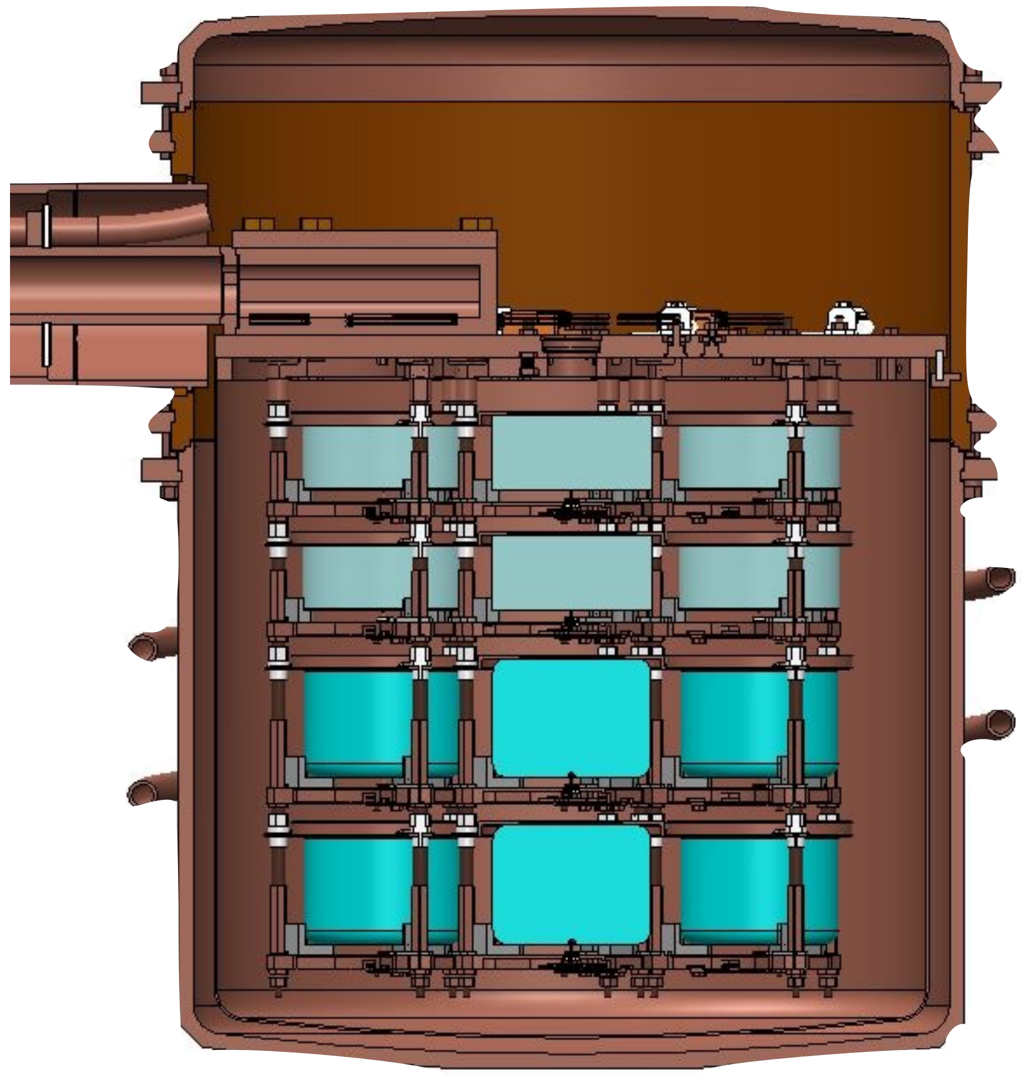




The MAJORANA DEMONSTRATOR

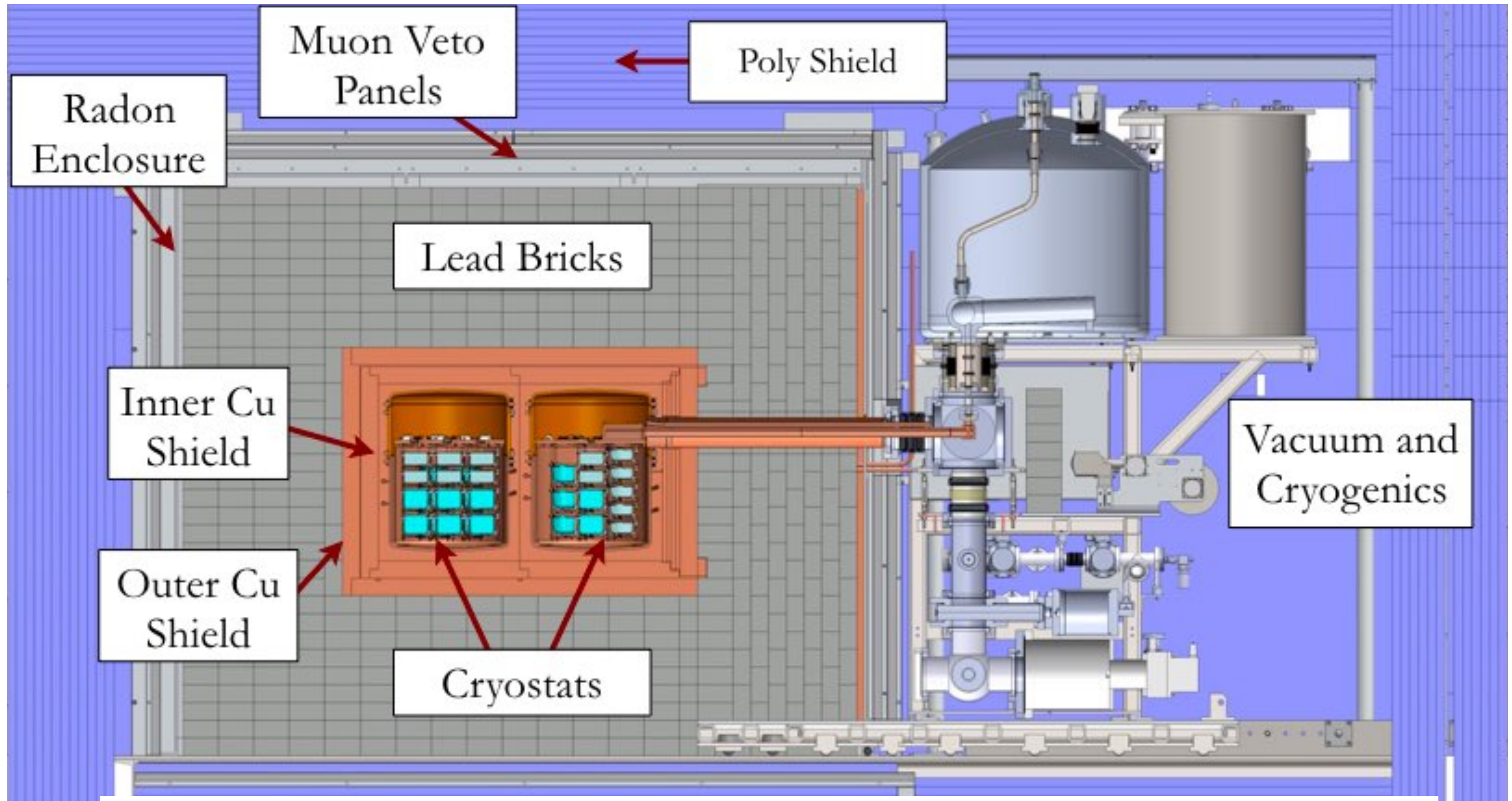
Operating underground at 4850′ level of Sanford Underground Research Facility

Goals: – Demonstrate backgrounds low enough to justify building a tonne-scale experiment.
– Establish feasibility to construct & field modular arrays of Ge detectors.
– Search for additional physics beyond the standard model.



Energy resolution of 2.5 keV FWHM @ 2039 keV is the best of any 0νββ experiment

- **Background Goal in the 0νββ peak region of interest after analysis cuts**
  - With the achieved resolution: 2.5 counts/FWHM/t/yr
  - Projected backgrounds based on assay results ≤ 2.2 counts/FWHM/t/yr
- **44.1 kg of Ge detectors**
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detectors: P-type, point-contact (PPC)
- **2 independent cryostats**
  - Ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - Naturally scalable
- **Compact Shield**
  - Low-background passive Cu and Pb shield with active muon veto

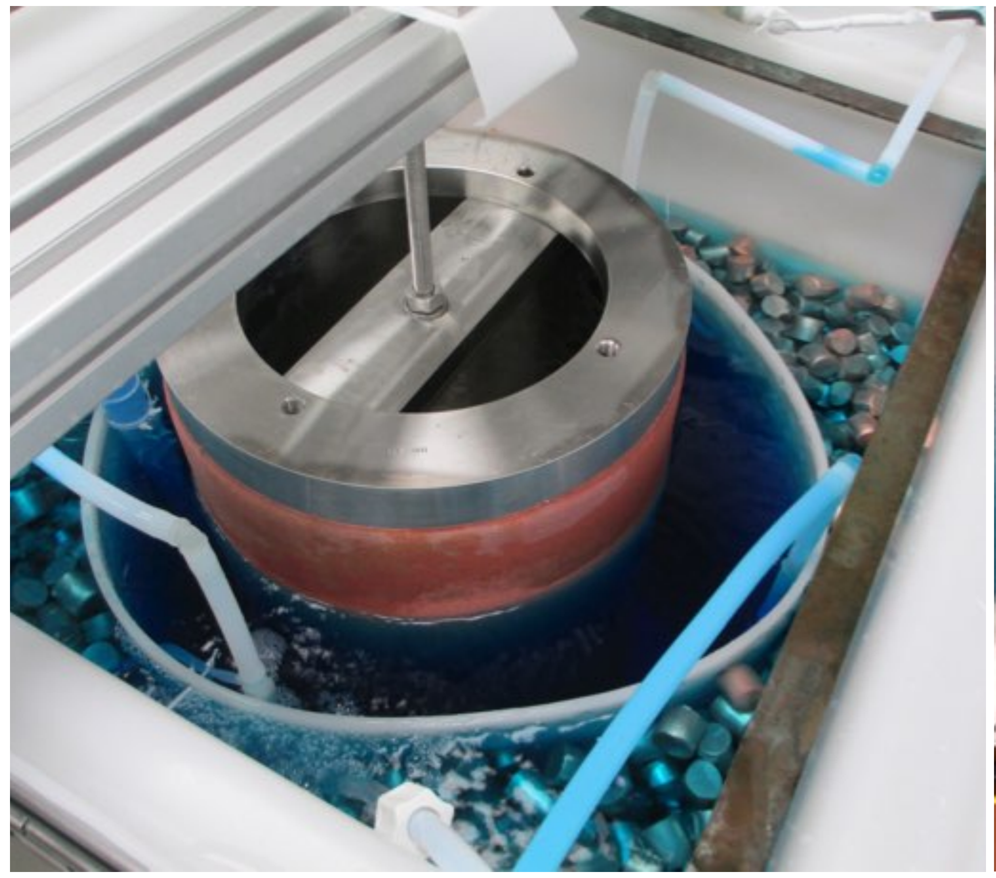


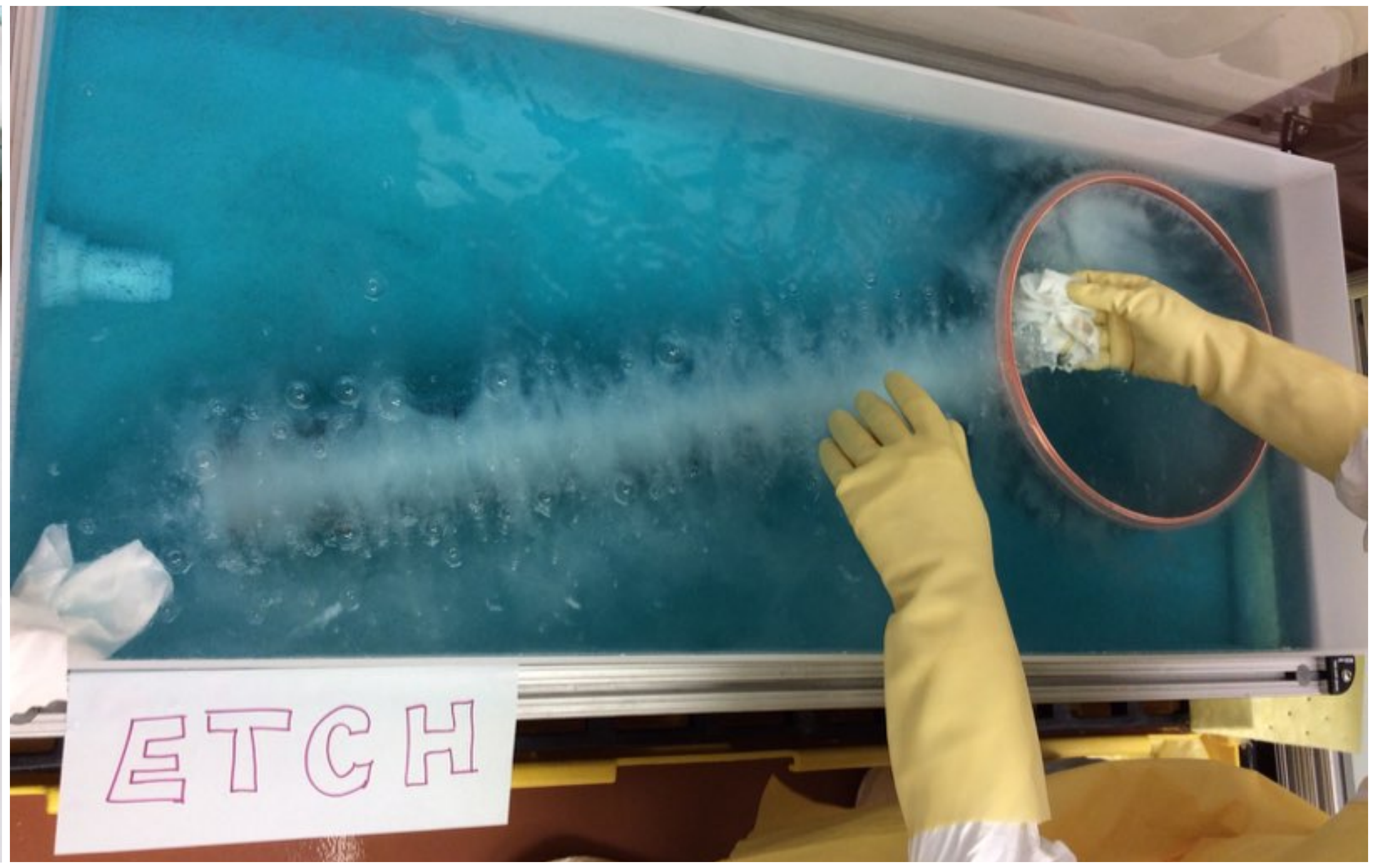
N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics with additional contributions from international collaborators.

Background Control and Module Implementation

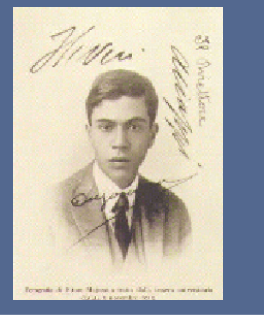
- Backgrounds controlled through ultra-pure material selection and assembly procedures
  - Underground electroformed copper
  - Custom cable connectors and front-end boards
  - Machining and cleaning of Cu in underground clean room





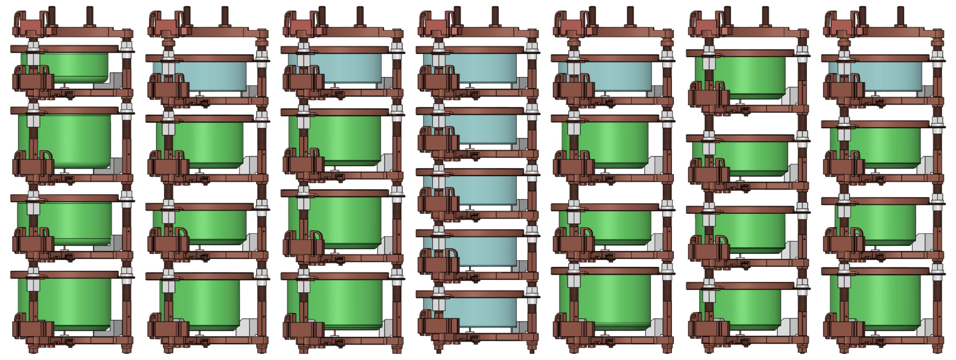
- Two independent detector modules
  - Self-contained vacuum and cryogenic vessel housing the detector cryostat
  - Modular design allows for independent operation

Dataset Designation



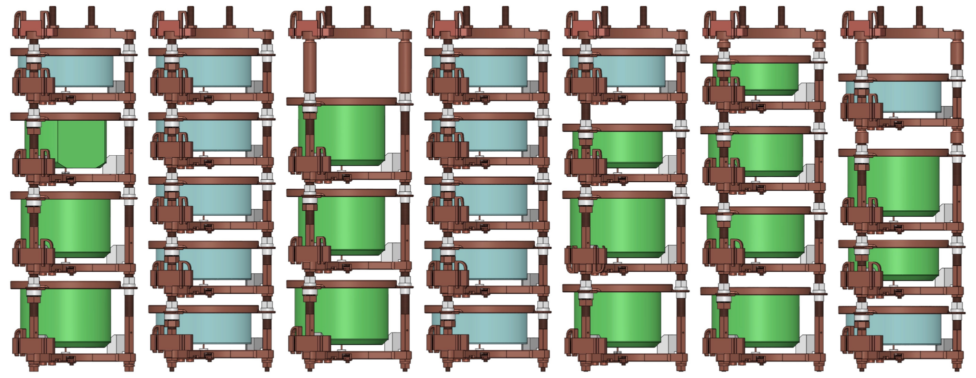
Module 1: 16.8 kg (20) ^{enr}Ge

5.6 kg (9) ^{nat}Ge



Module 2: 12.9 kg (15) ^{enr}Ge

8.8 kg (14) ^{nat}Ge



Dataset	Start	Configuration	^{enr}Ge Exposure (kg-yr)	
			Blind	Open
DS0	June 2015	Module 1, No Inner Shield	-	1.26
DS1	Dec 2015	Module 1, Inner Shield	0.51	1.81
DS2	May 2016	Multisampling	0.93	0.29
DS3 & DS4	Aug 2016	Module 1 & 2, Separate DAQ	-	1.29
DS5a	Oct 2016	Combined DAQ	-	3.45
DS5b	Jan 2017	Construction Complete	-	1.85
DS5c	March 2017	Blindness Implemented	1.49	0.48
DS6a	May 2017	Multisampling	8.93	3.74

First Result: 9.95 kg-yr

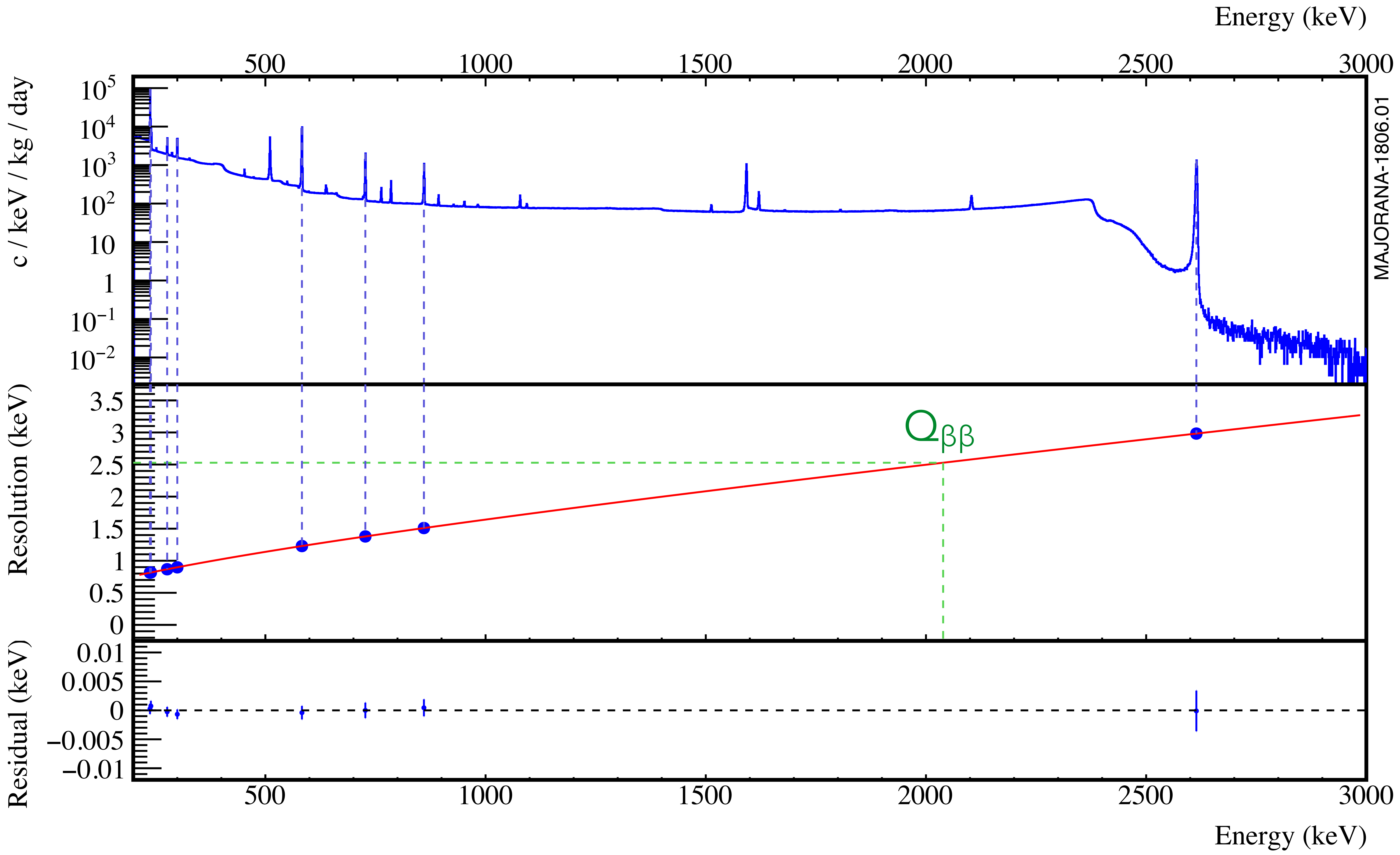
Full Result*: 26 kg-yr

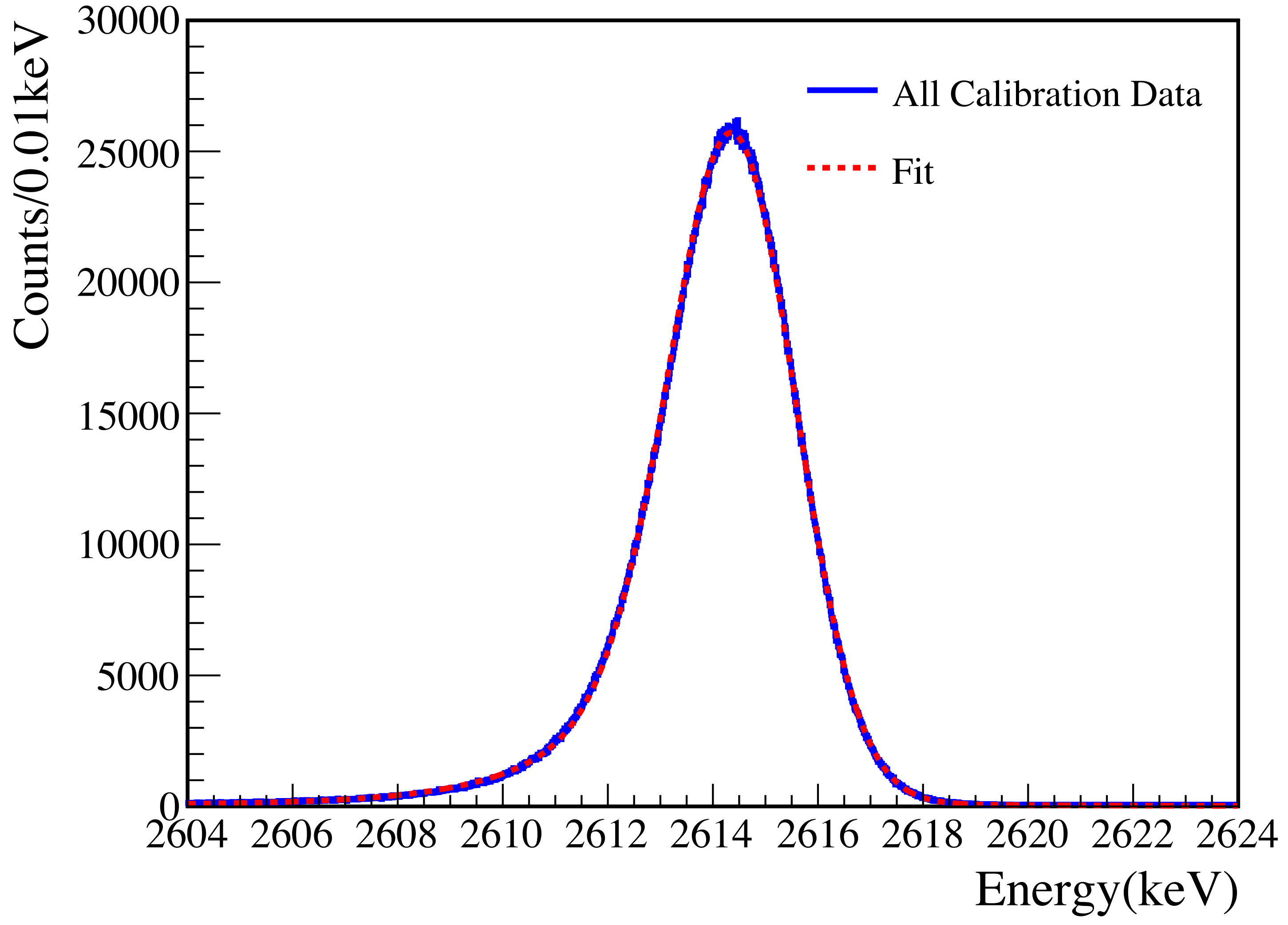
*Exposure until April 15, 2018

- Initial hardware/DAQ configuration changes resulted in multiple datasets
  - Operating in a stable, final detector configuration since Spring 2017
- Background in DS0 (no inner shield) and DS5a (high electronic noise resulting in degraded PSA performance) higher than other datasets

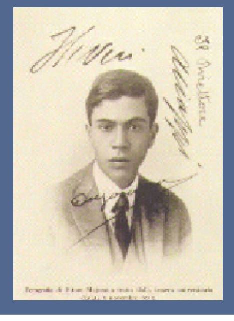
Detector Performance: Calibration

- Custom ^{228}Th line sources are deployed from outside the shielding into tubes that wrap around each cryostat
- **Best resolution** achieved for 0νββ searches (2.5 keV FWHM at $Q_{\beta\beta}$, 3.0 keV FWHM at 2615 keV)

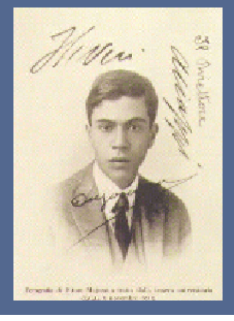




NIMA **872**,16 (2017) [arXiv:1702.02466]

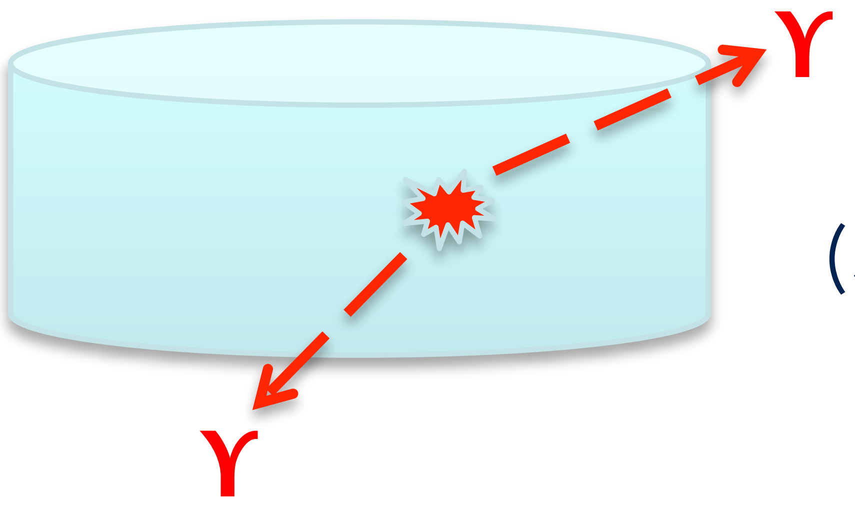


Multi-site Event Discrimination: AvsE



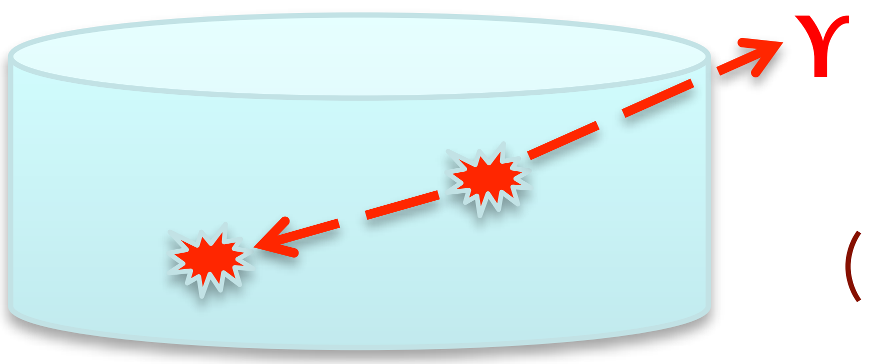
- **Max current to charge comparison (AvsE)** provides discrimination between single and multi-site events
- $0\nu\beta\beta$ is a single site event, use pair production events from ^{208}Tl γ (2615 keV) as a proxy for both single and multi-site events
  - Both γ's escape = double escape peak (DEP), single site
  - One γ escapes = single escape peak (SEP), multi-site

Kept at 90% efficiency

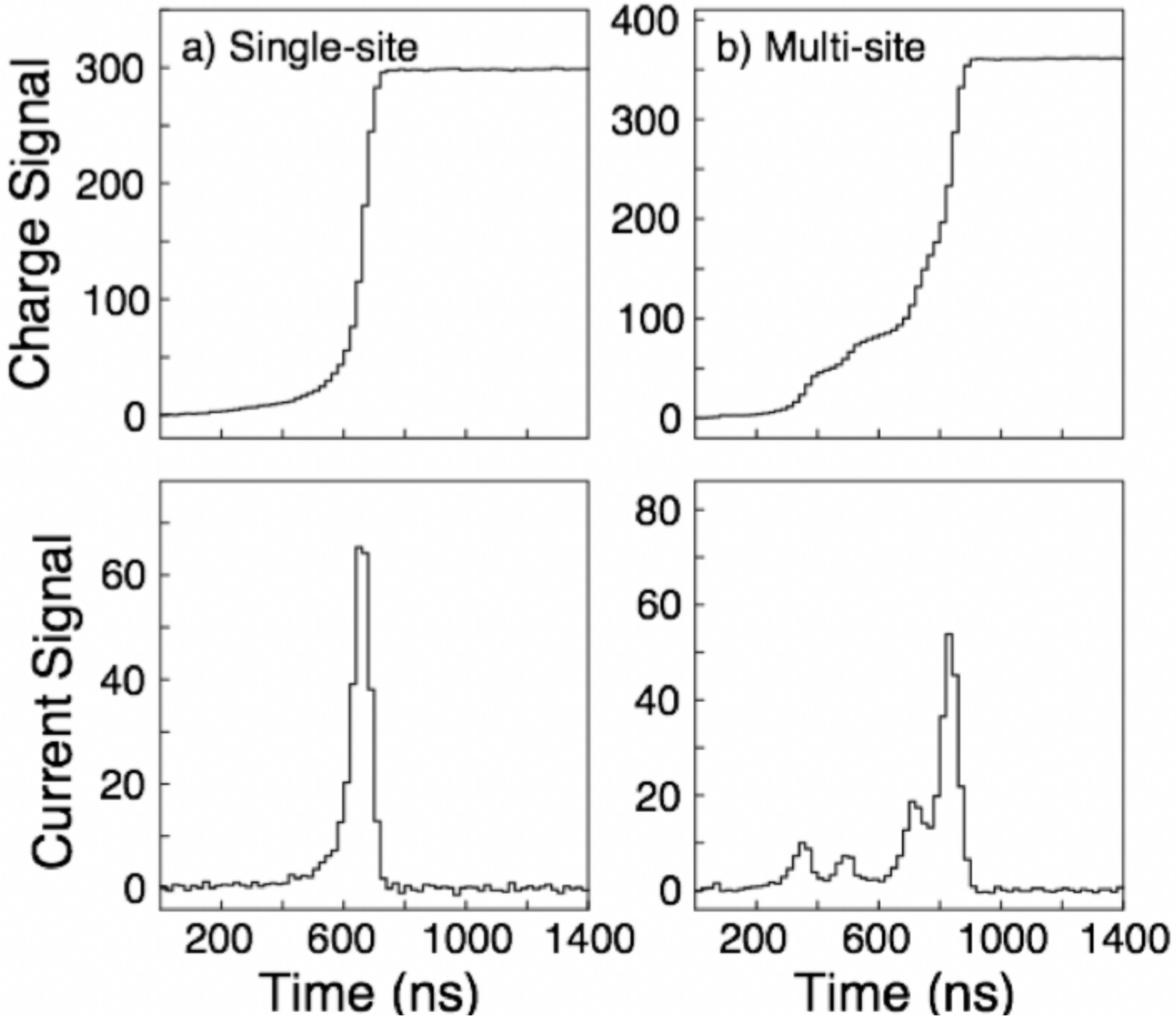


^{208}Tl DEP
(single site event)

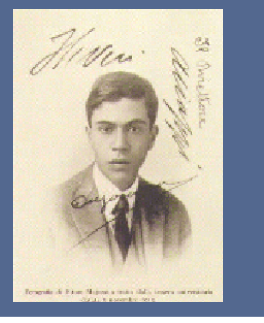
Reduced to ~6%

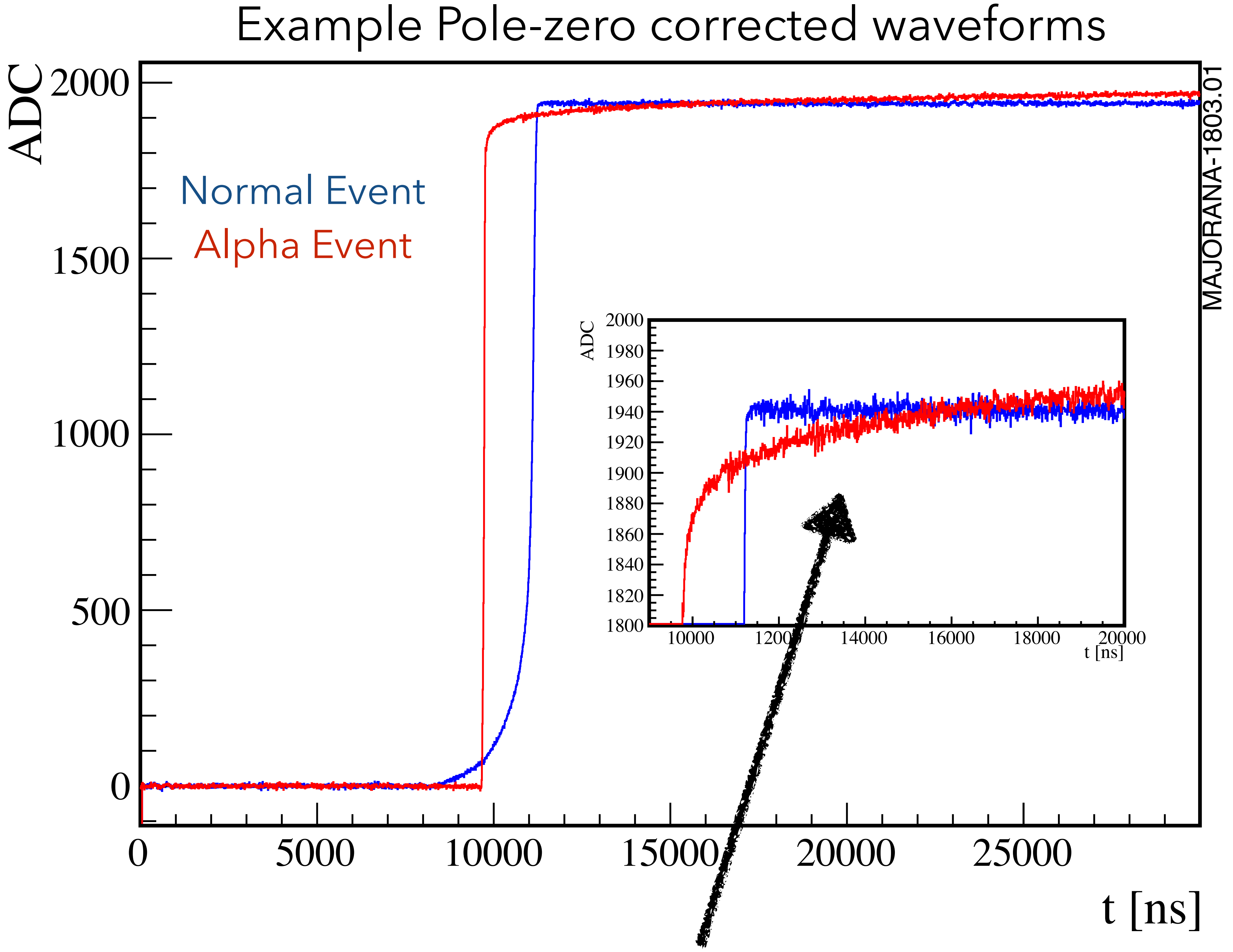


^{208}Tl SEP
(multi-site event)



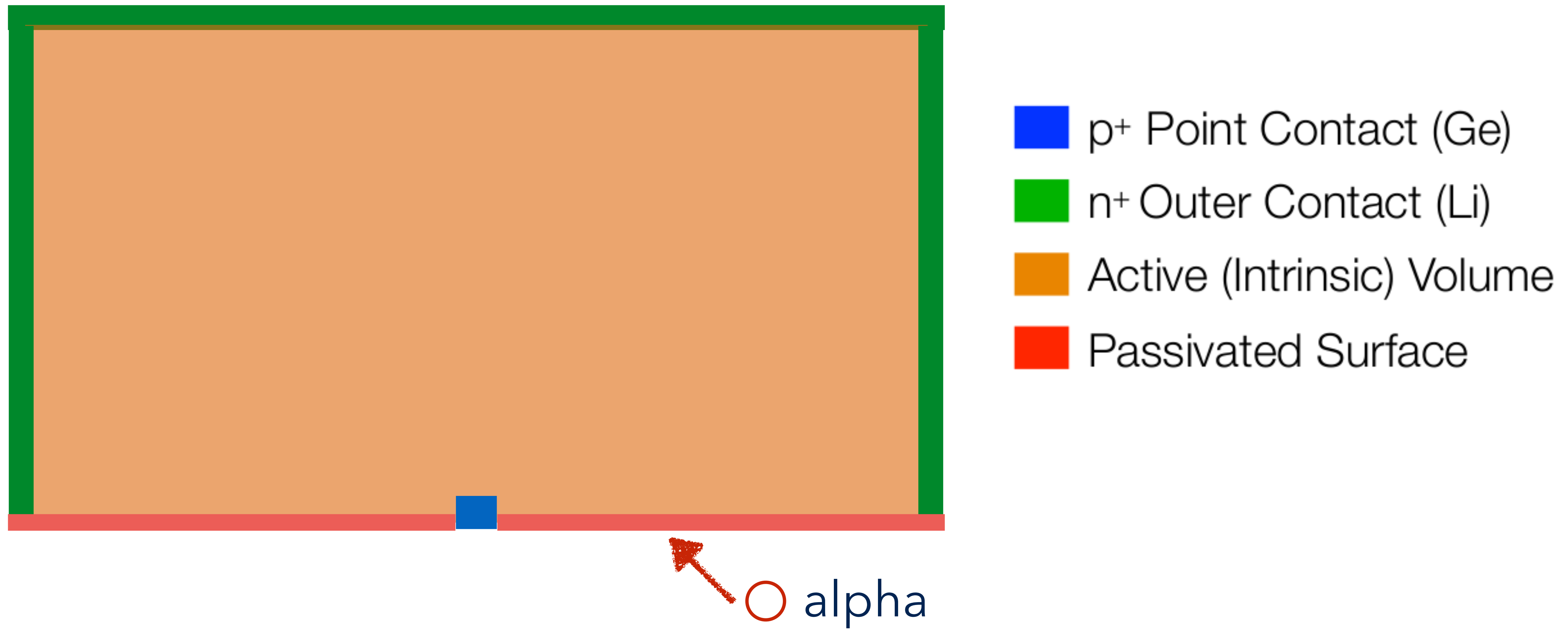
Surface Alpha Event Rejection: DCR



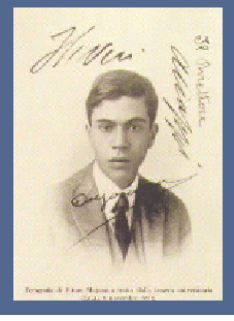


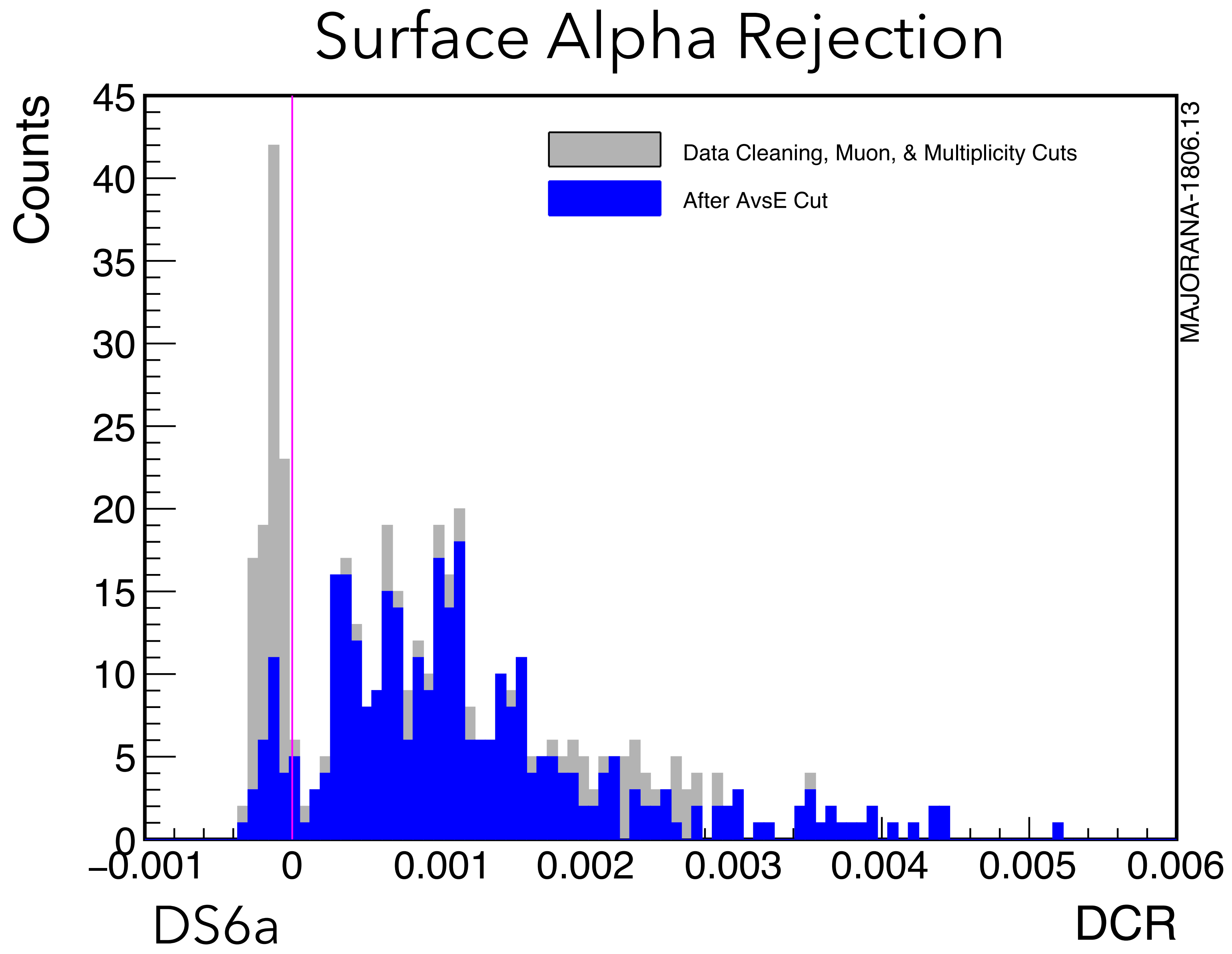
DCR Alphas have a **positive slope** after the rising edge

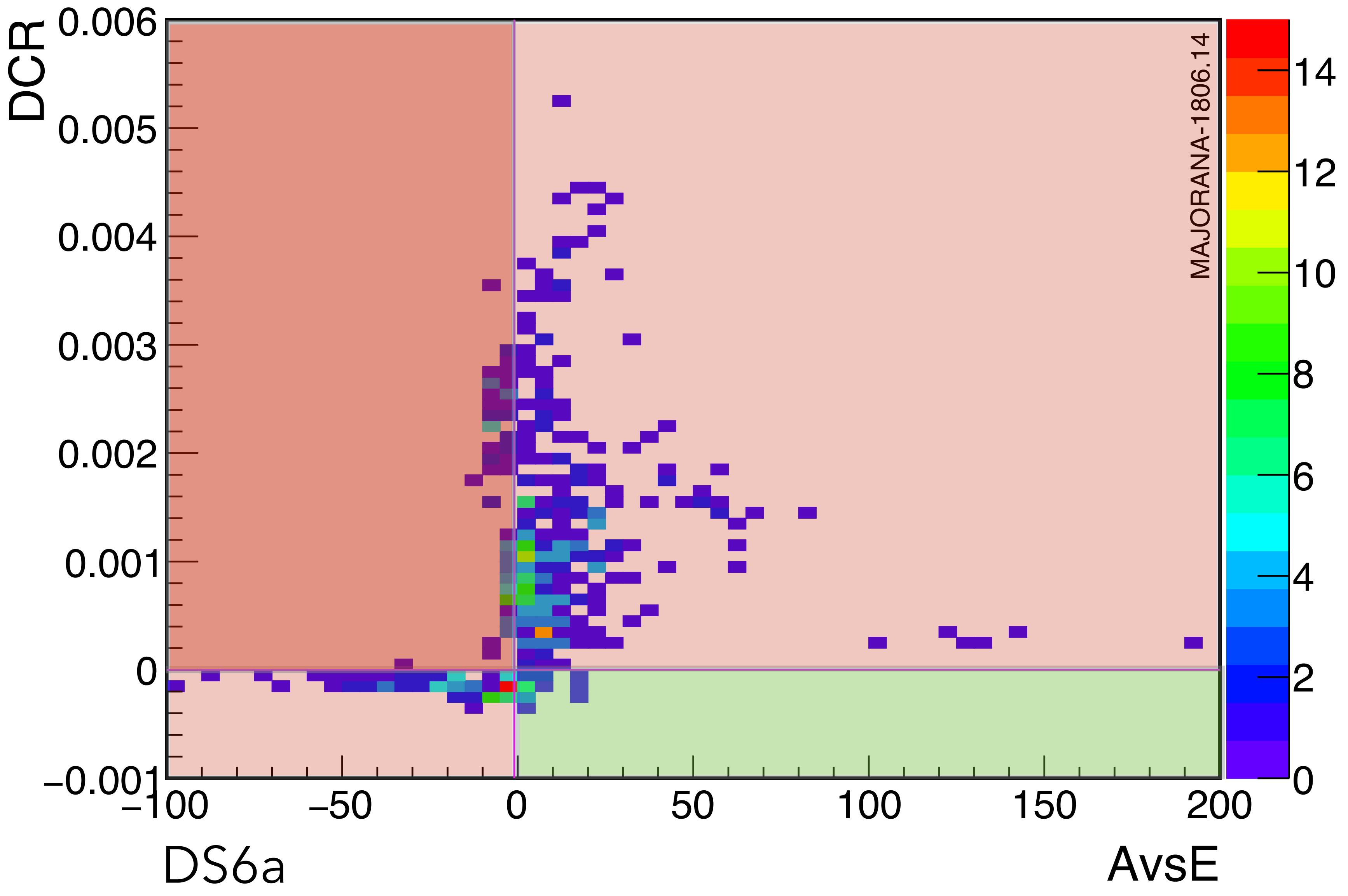
- Alpha background with **degraded energy** observed
  - Theorized to be alpha particles (^{210}Po) impinging on passivated surface, studied phenomenon in an auxiliary experiment
- Charges trapped at passivated surface are slowly released into bulk producing a distinctive waveform
  - "Delayed Charged Recovery" **(DCR)** parameter related to slope of waveform tail after rising edge

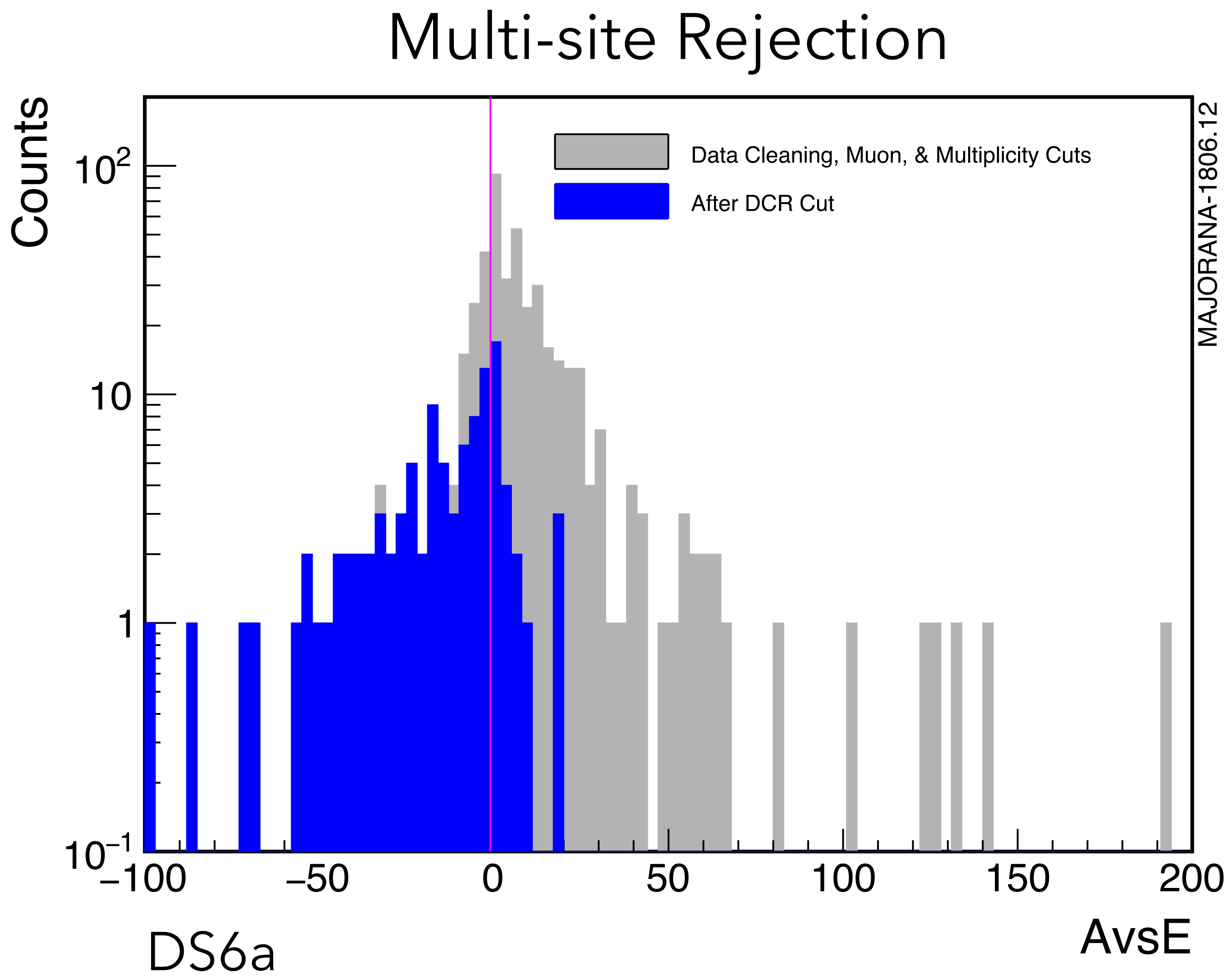


PSA Performance









- DCR and AvsE exhibit **complementary performance**

Background Estimation Window

- Counts in estimation window used to evaluate background index
- Simulated background PDFs with relative component scaling based on assay results
- **Background flat** between 1950 and 2350 keV
  - Remove ±5 keV around $Q_{\beta\beta}$ and prominent γ lines
- Excluded Regions:

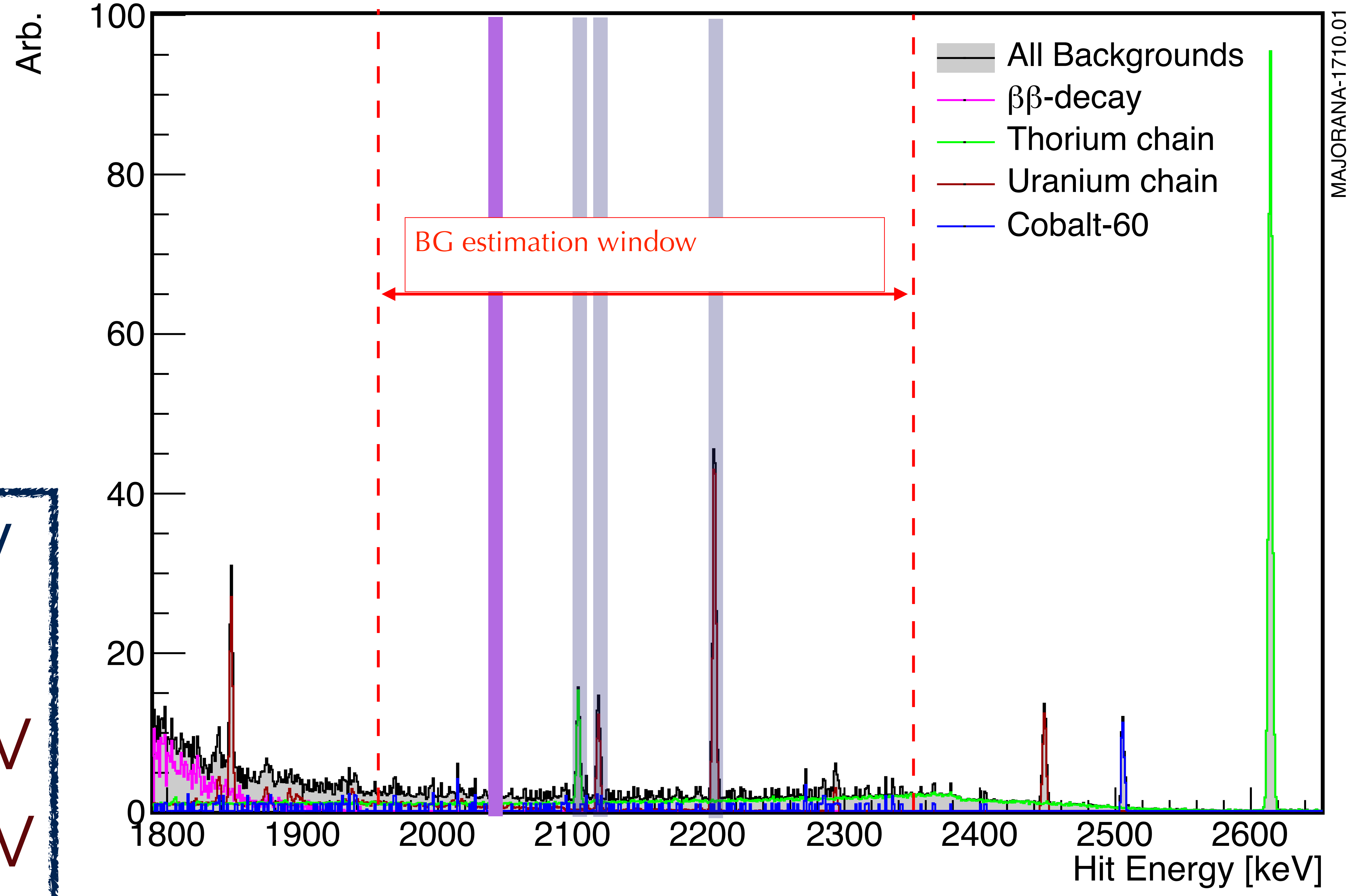
$Q_{\beta\beta}$: 2034 - 2044 keV

^{208}Tl: 2099 - 2109 keV

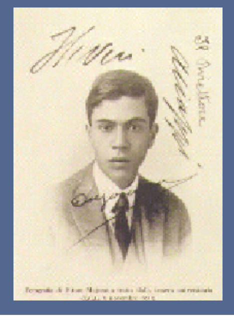
^{214}Bi: 2113 - 2123 keV

^{214}Bi: 2199 - 2209 keV

Simulated Background near $Q_{\beta\beta}$ (no cuts)

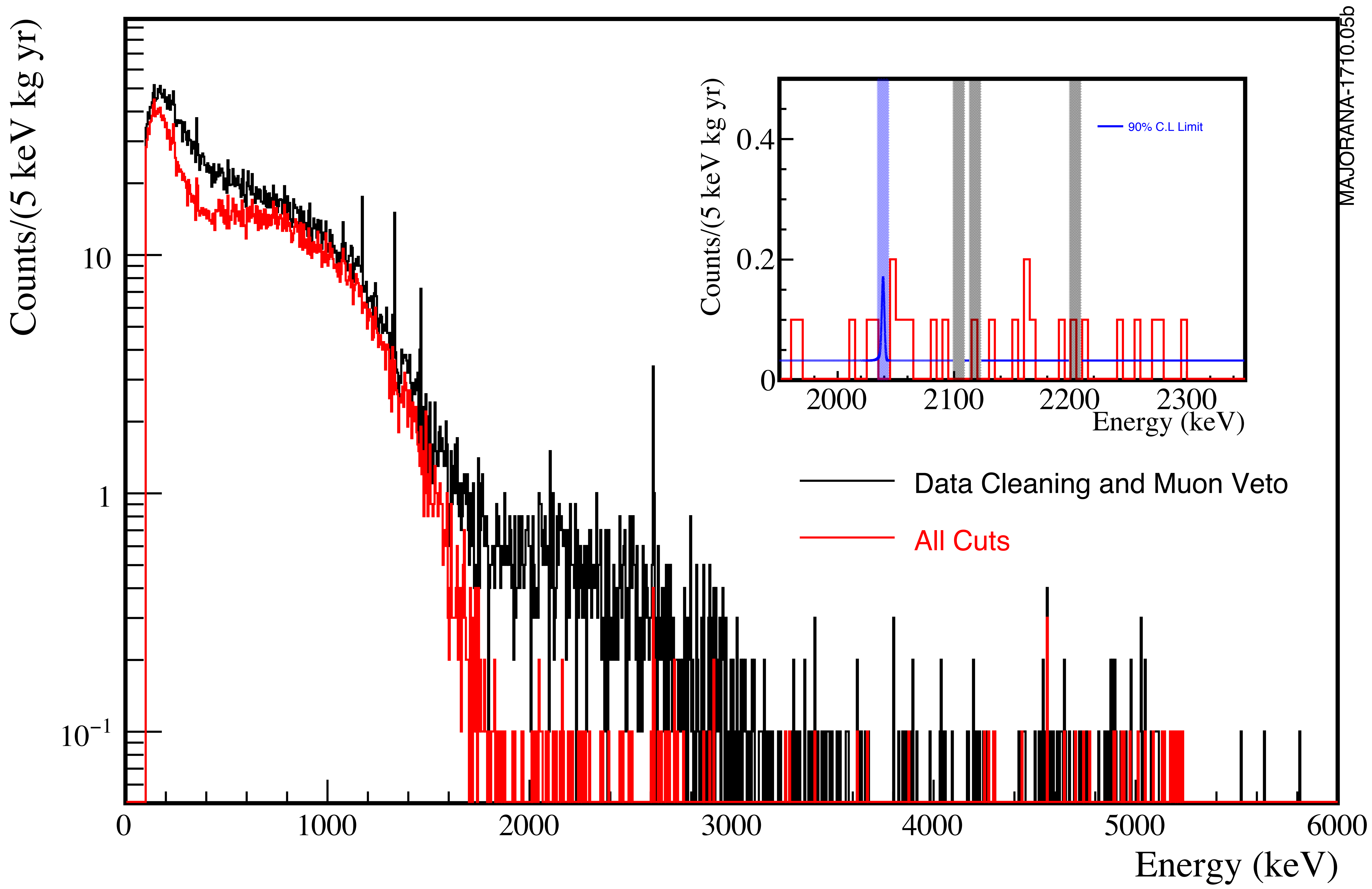


First 0νββ Result

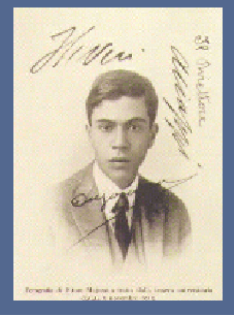


- First result released in Oct. 2017
  - Only using open data (9.95 kg-yr ^{enr}Ge)
- Full Exposure Background:
  17.8 ± 3.6 c/(FWHM t yr)
- **Limit: 1.9 x 10²⁵ yr (90% C.L.)**
  - Sensitivity: 2.1 x 10²⁵ yr (90% C.L.)
- Lowest background configuration:
  $4.0^{+3.1}_{-2.5}$ c/(FWHM t yr)

PRL **120** 132502 (2018) [arXiv:1710.11608]

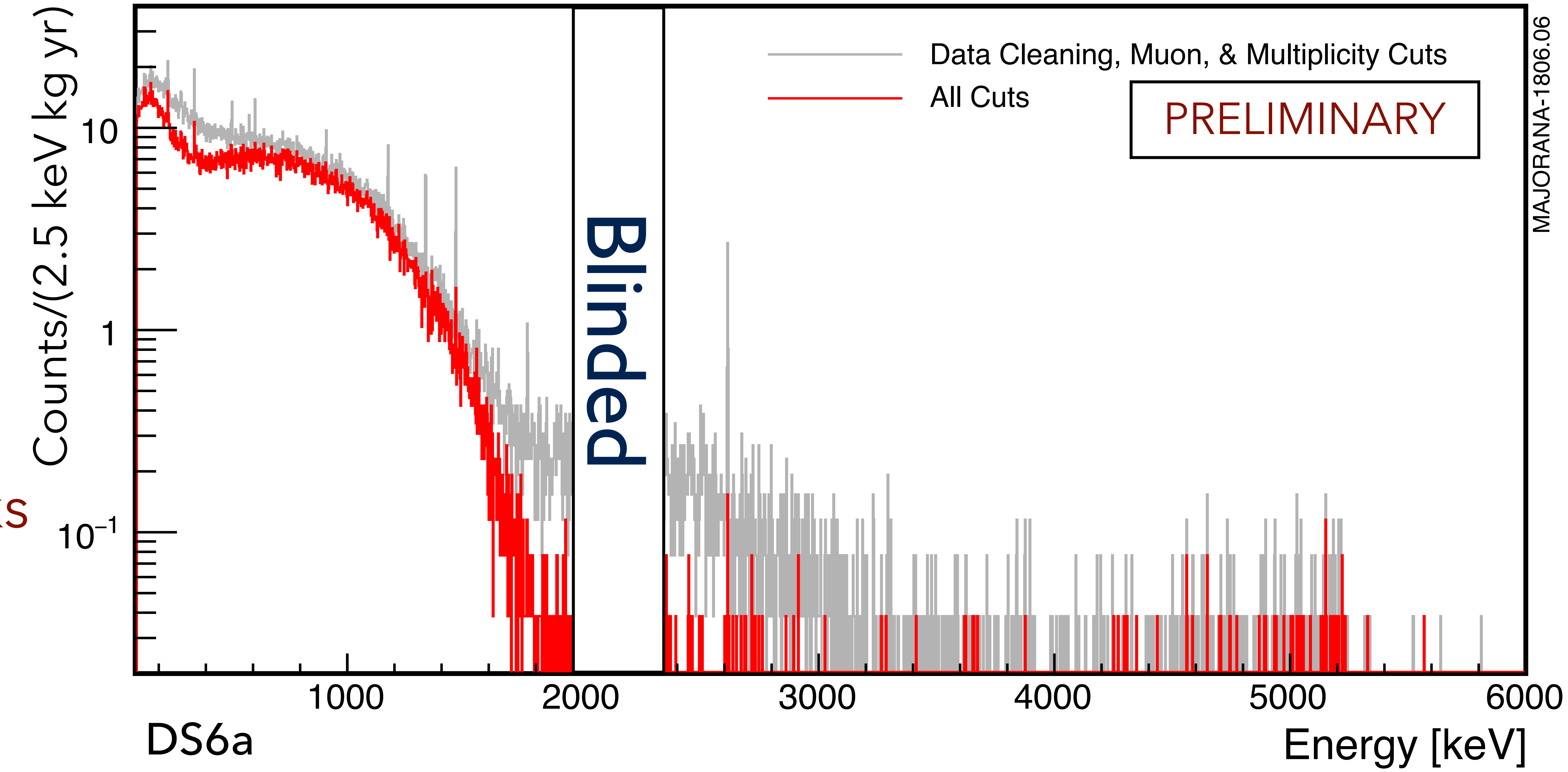


Blindness Implementation



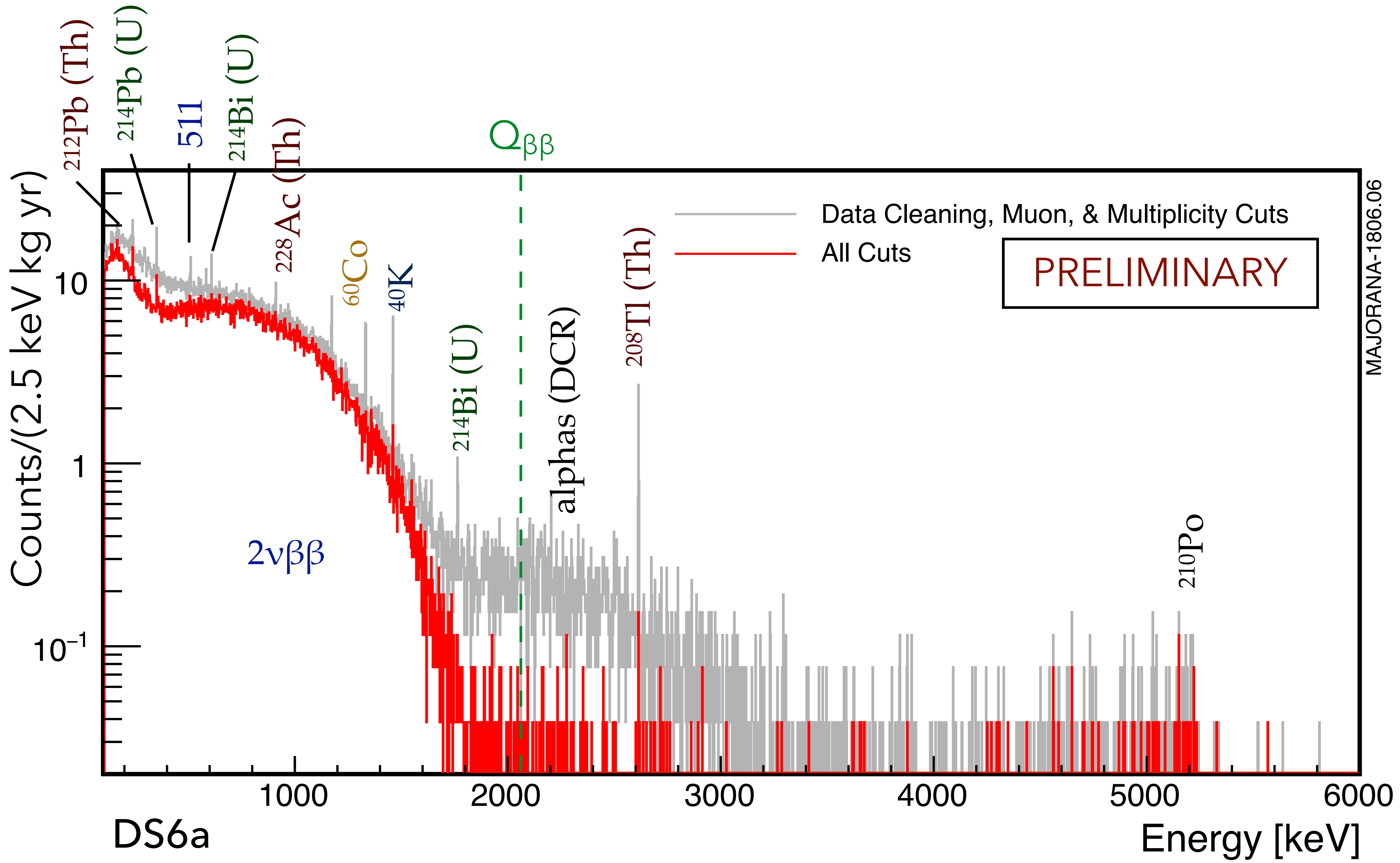
- Blindness implemented using a 25%/75% Open/Blind ratio
- Data below 100 keV and multi-detector events kept blind for other analyses
- Unblinding performed in 3 stages:
  - **Stage 1:** Open data around background estimation window for data quality checks
  - **Stage 2:** Open background estimation window to evaluate background index
  - **Stage 3:** Open Q-value region for limit analysis

All data (open and previously blinded) up until April 15, 2018

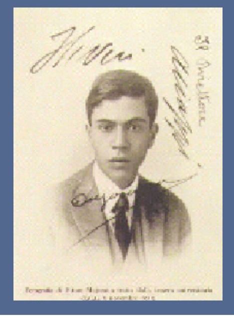


Backgrounds Identified

- Primary remaining spectral components are $2\nu\beta\beta$, ^{208}Tl, and ^{210}Po alphas
- **Increased statistics** gathered after unblinding will aid in the full background model, focus of future release



New Result: Background Index



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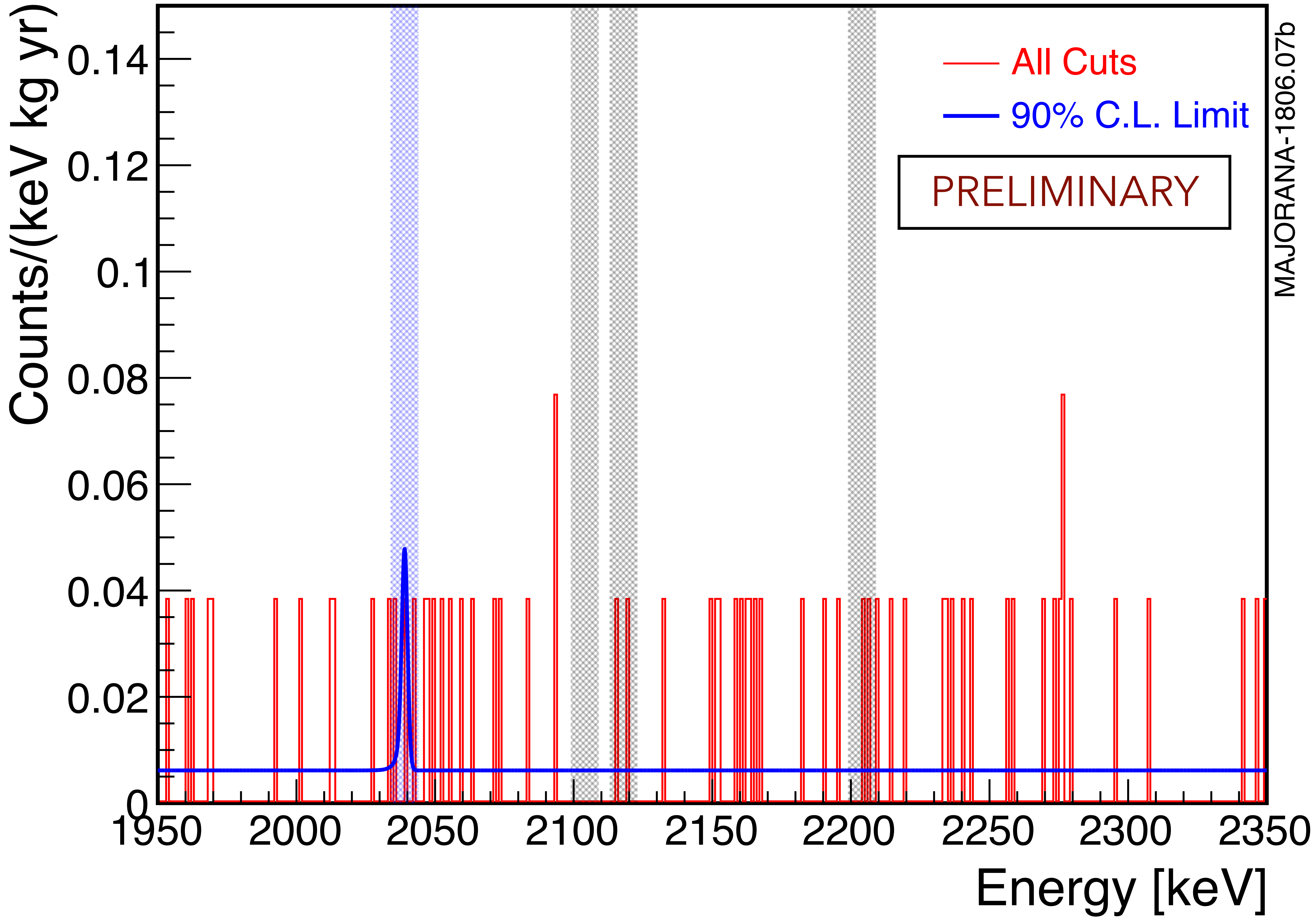
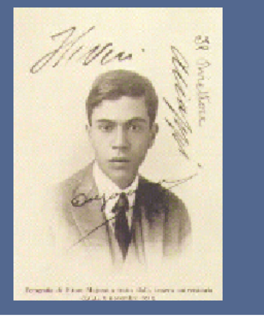


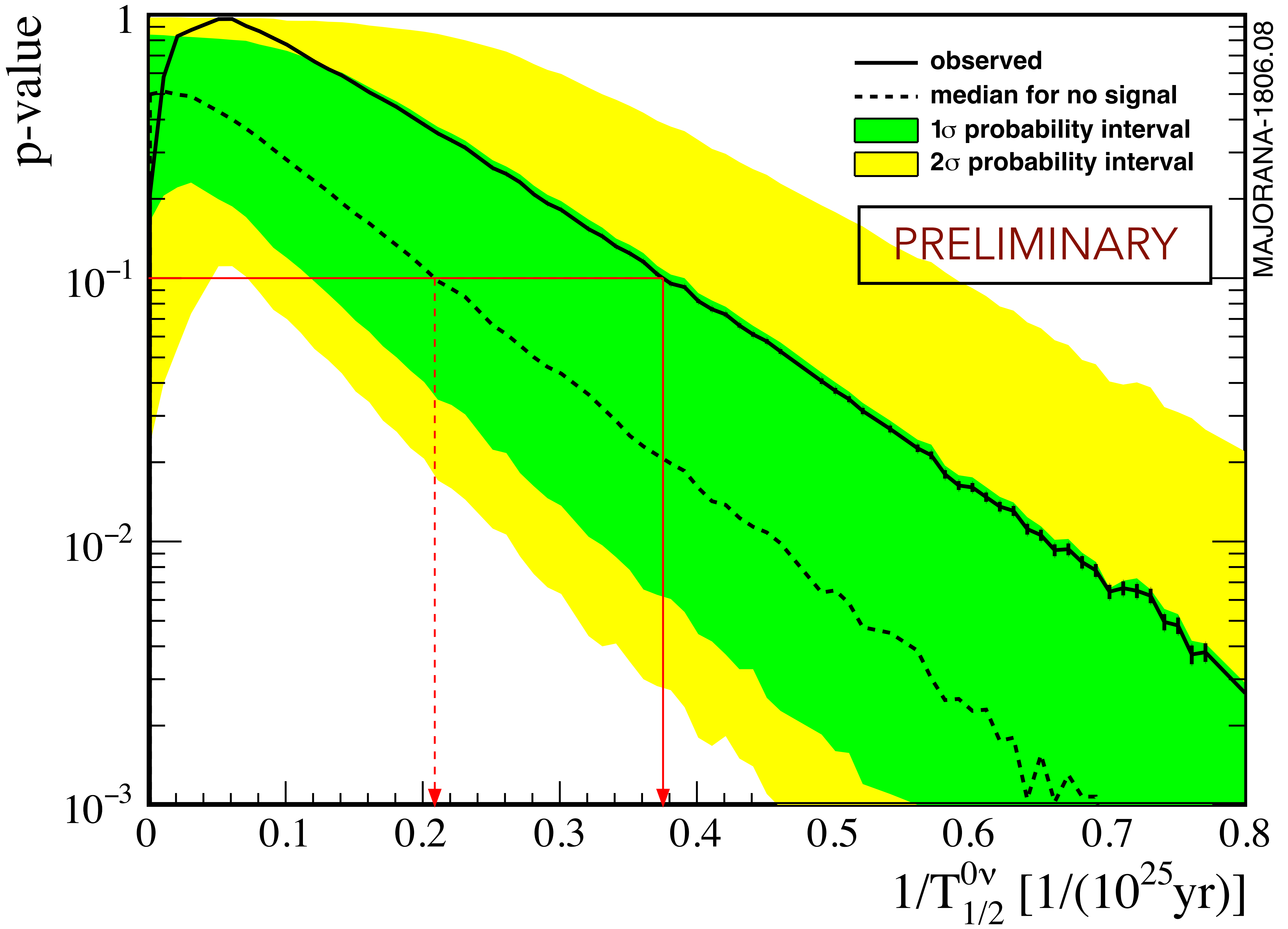
Full Exposure (26 kg-yr)
Background: 15.4 ± 2.0 c/(FWHM t yr)

- Lowest Background Configuration:
  11.9 ± 2.0 c/(FWHM t yr)
  Active Exposure: 21.3 kg-yr (^{enr}Ge)
- After final unblinding, 1 event at 2040 keV
  - Expected 0.66 counts in optimal ROI (4.13 keV)

New Result: Half-Life Limit



Limit and sensitivity verified using
various statistical methods



Median Sensitivity (90% C.L.):
4.8×10^{25} yr

Statistical Method	Exclusion Limit
Nominal Profile Likelihood	**2.7×10^{25} yr**
Feldman-Cousins	2.5×10^{25} yr
Modified Profile Likelihood (CLS)	2.5×10^{25} yr
Bayesian (flat prior on decay rate)	2.5×10^{25} yr

Limit Implies:
$m_{\beta\beta}$ < (200 – 433) meV

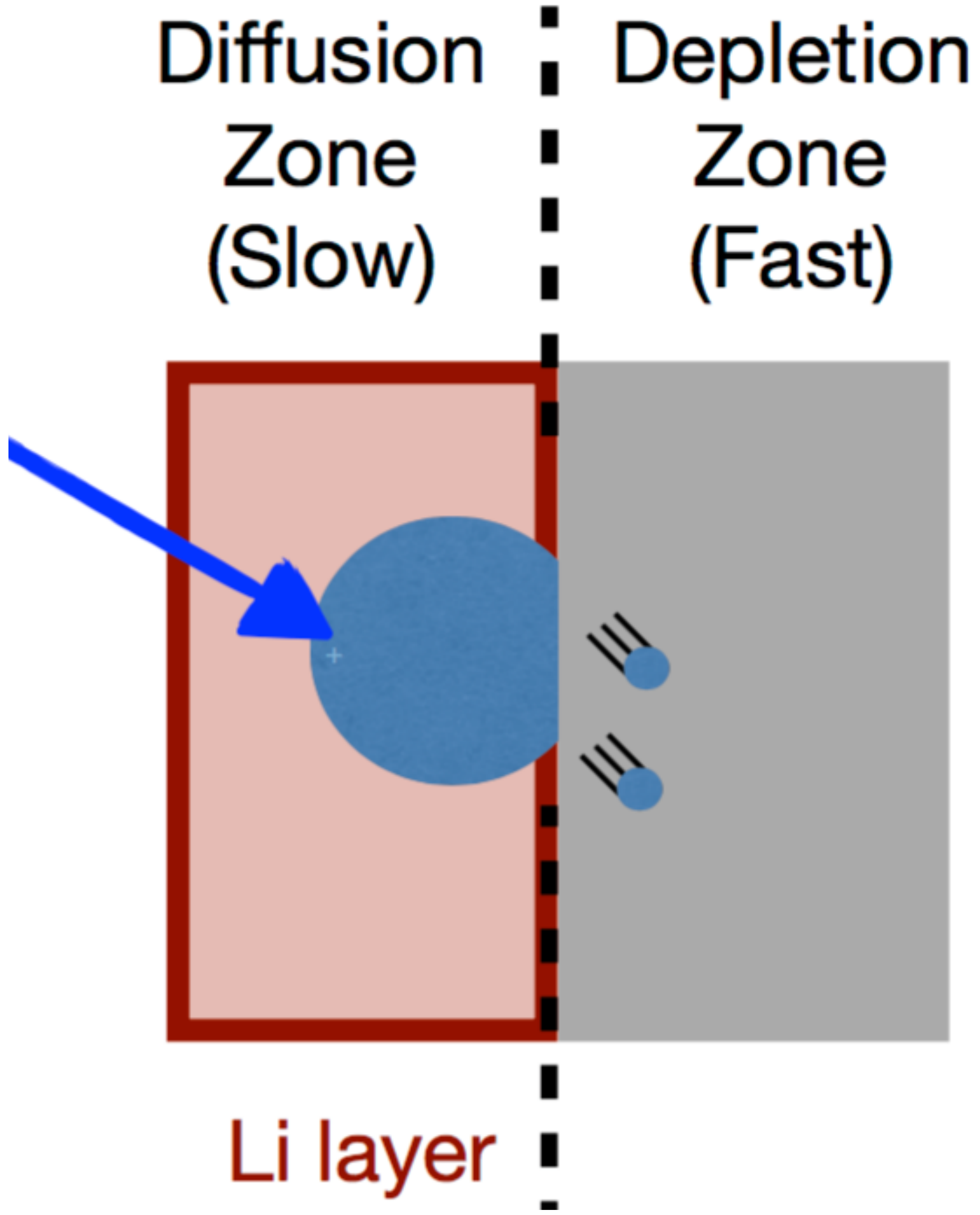
Using: $M_{0\nu} = 2.81 - 6.13$

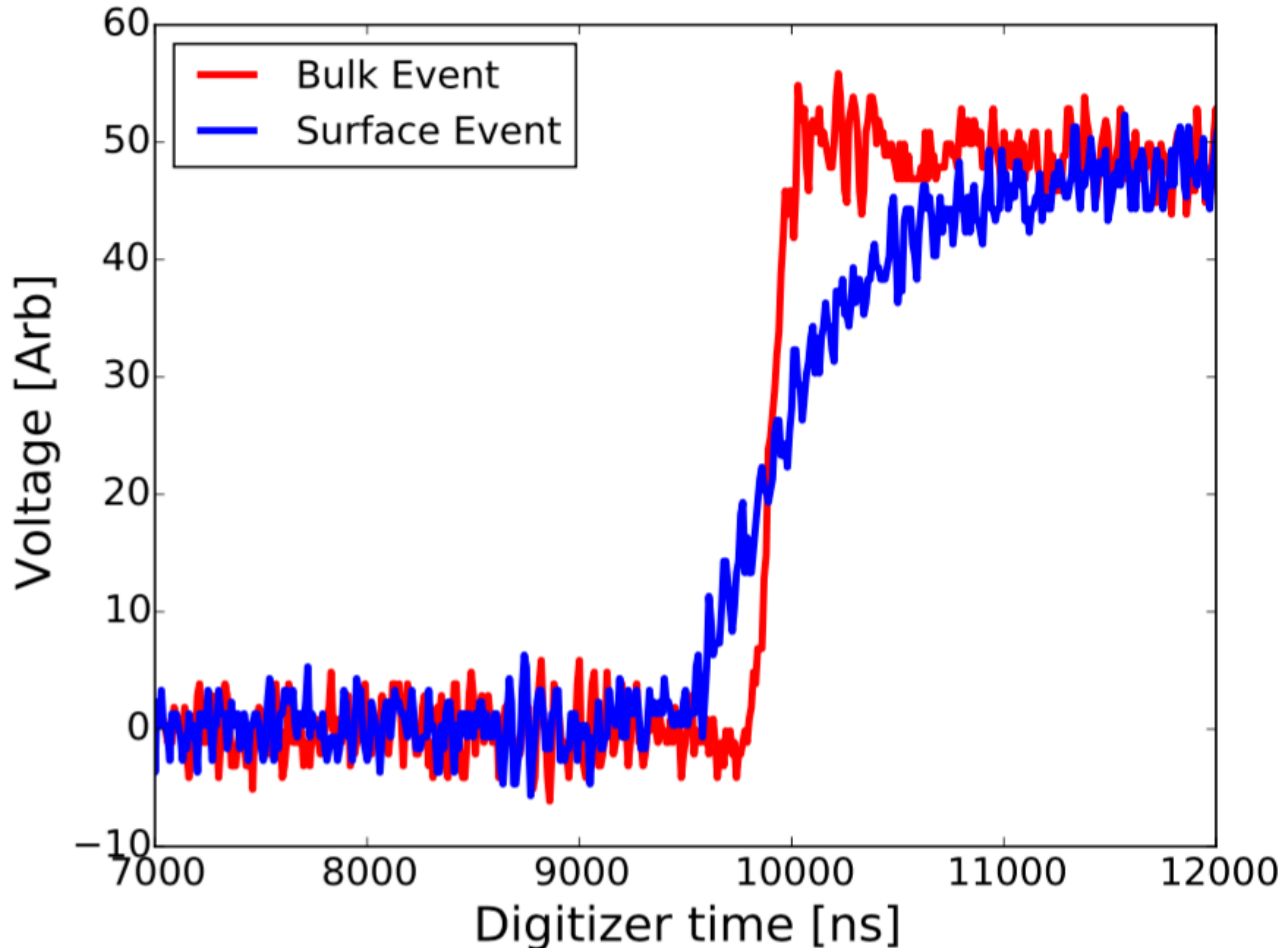
$G_{0\nu} = (2.36 - 2.37) \times 10^{-15}\,\mathrm{yr}^{-1}$

$g_A = 1.27$

The MAJORANA Low Energy Program

- Along with with searching for $0\nu\beta\beta$, the low backgrounds and thresholds of PPC detectors allow a **diverse** low energy program
- **Degraded energy** from slow pulses arising from energy deposition in the diffusion zone
  - Slow rise time is a handle to distinguish from bulk events

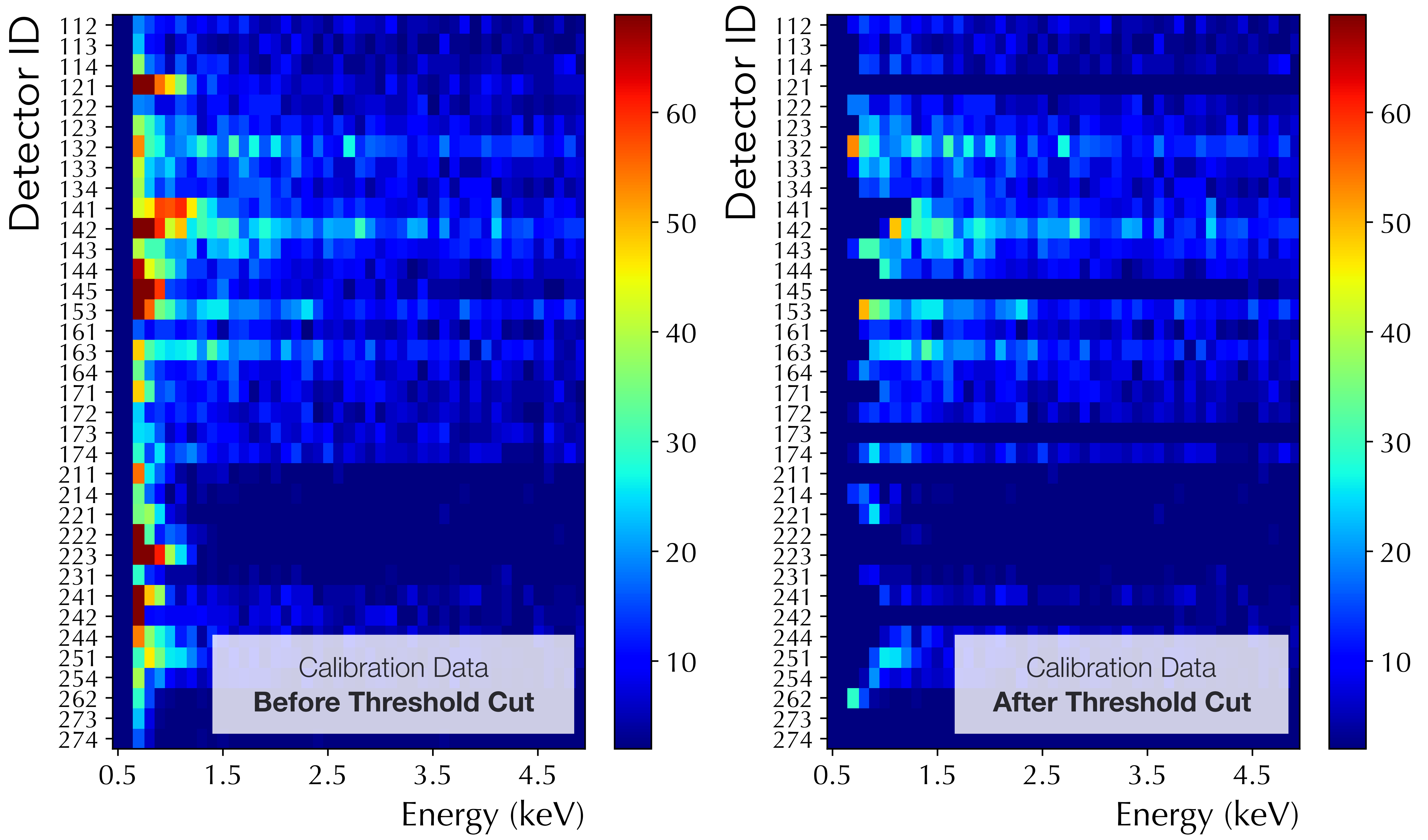




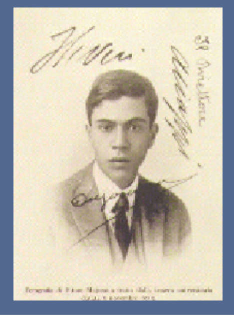
Threshold Noise Removal

Physics at keV-scale is possible, however additional pulse shape analyses to remove **transient noise** are necessary

- Gaussian noise produces an excess of triggers when a detector is too close to its threshold
  - Keep hits above 99% of trigger efficiency to reduce noise

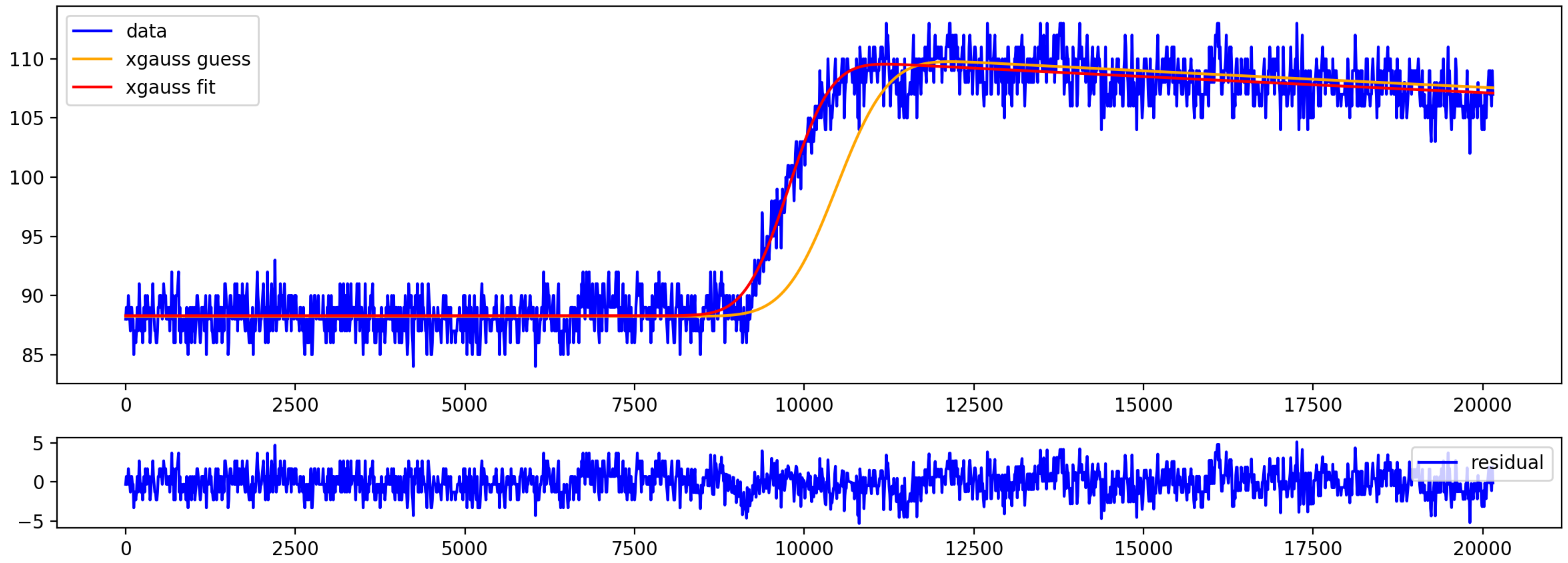


Slow Waveform Rejection



- Every waveform fit using an **exponentially modified Gaussian**
  - Low Signal/Noise makes xG a suitable heuristic over more accurate signal models
- Effective at rejecting both **transition layer events** and **transient noise**

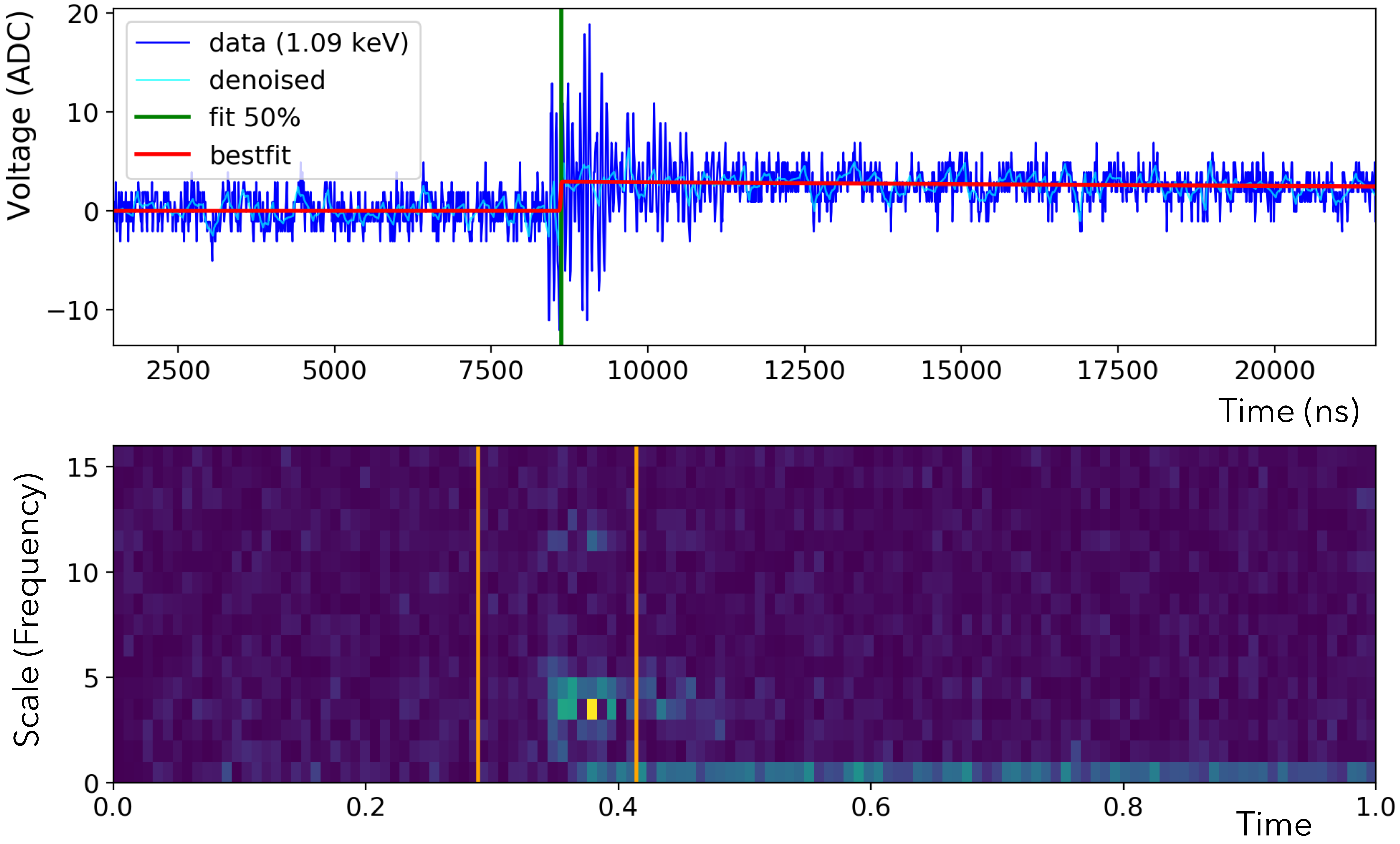
Sample Waveform Fit

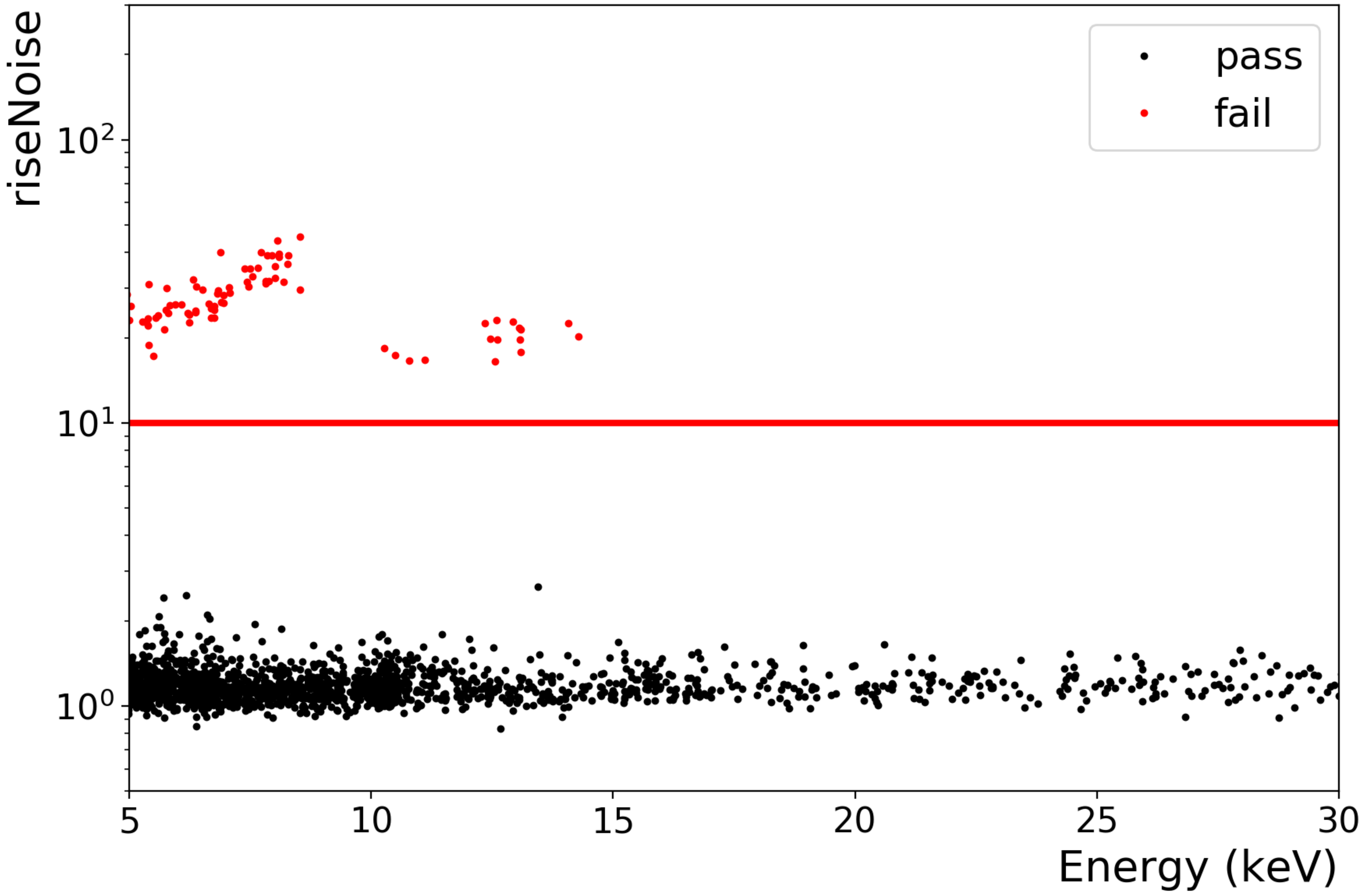


$$\mathrm{xG} = \frac{1}{2\tau}\,\exp\left(\frac{x-\mu}{\tau} + \frac{1}{2}\left(\frac{\sigma}{\tau}\right)^2\right)\,\mathrm{erfc}\left(\frac{1}{\sqrt{2}}\left(\frac{\sigma}{\tau} - \frac{x-\mu}{\sigma}\right)\right)$$

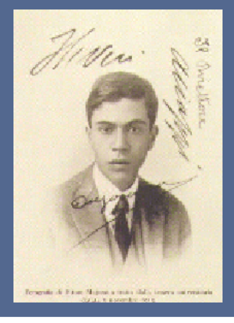
High Frequency Noise

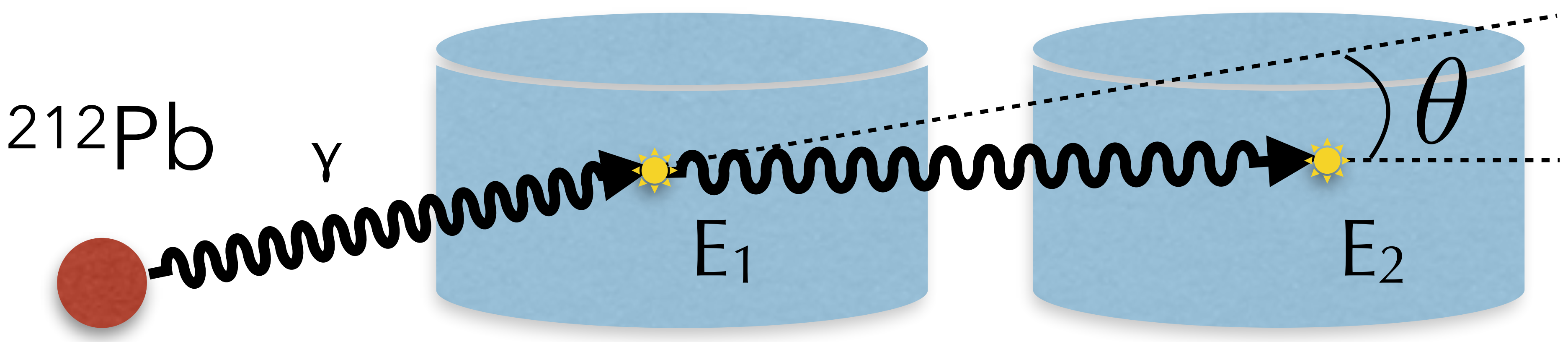
- **Localized noise bursts** on the rising edge of a waveform can impact amplitude evaluation
- Utilize waveform fitting in combination with wavelet packet transform (WPT) to reject localized noise bursts





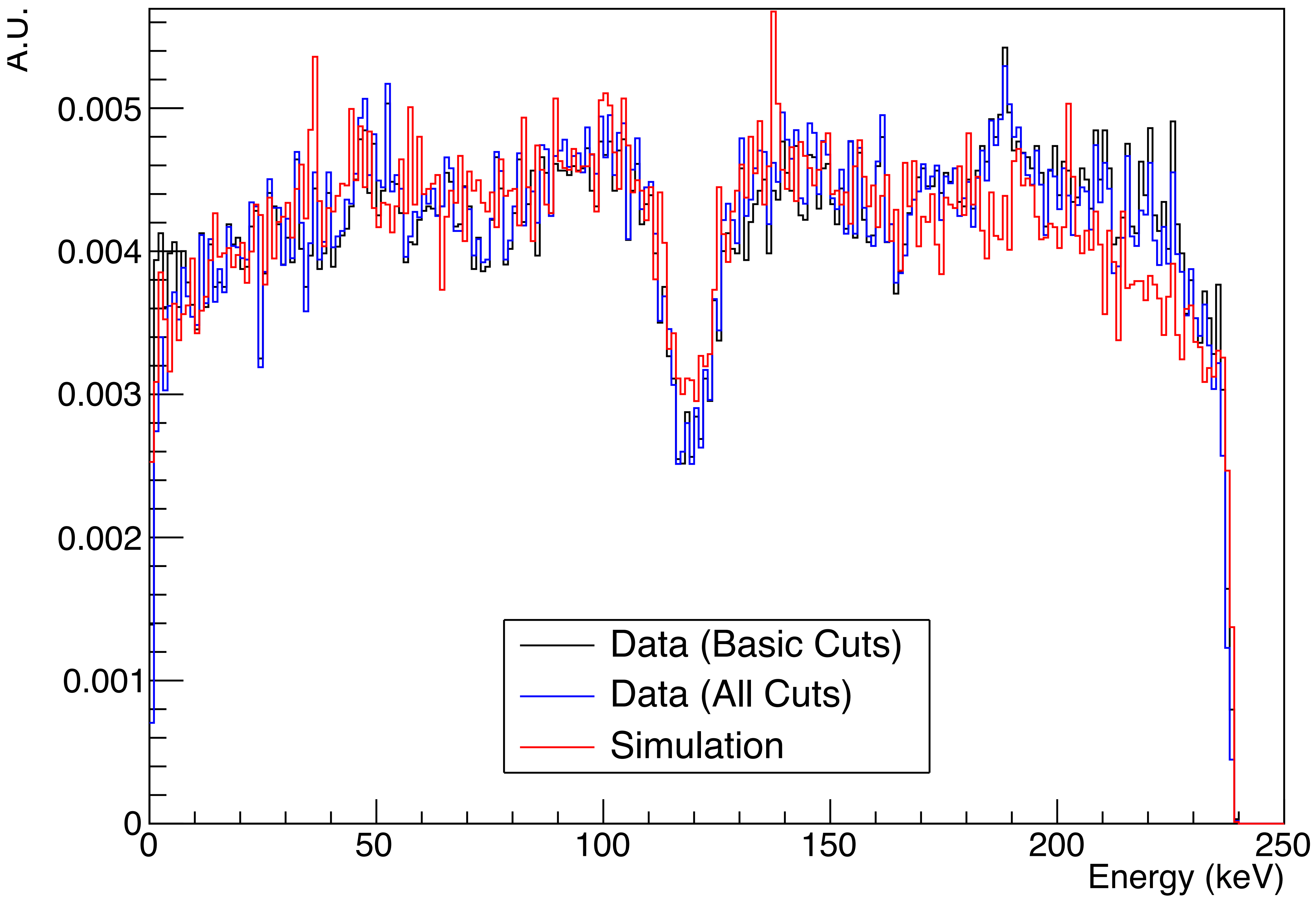
Efficiency Evaluation





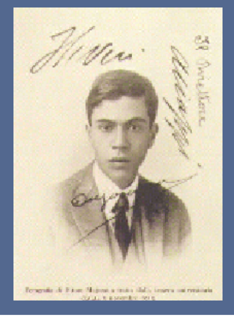
$$E' = \frac{E}{(1 - \frac{E}{mc^2})(1 - cos(\theta))}$$

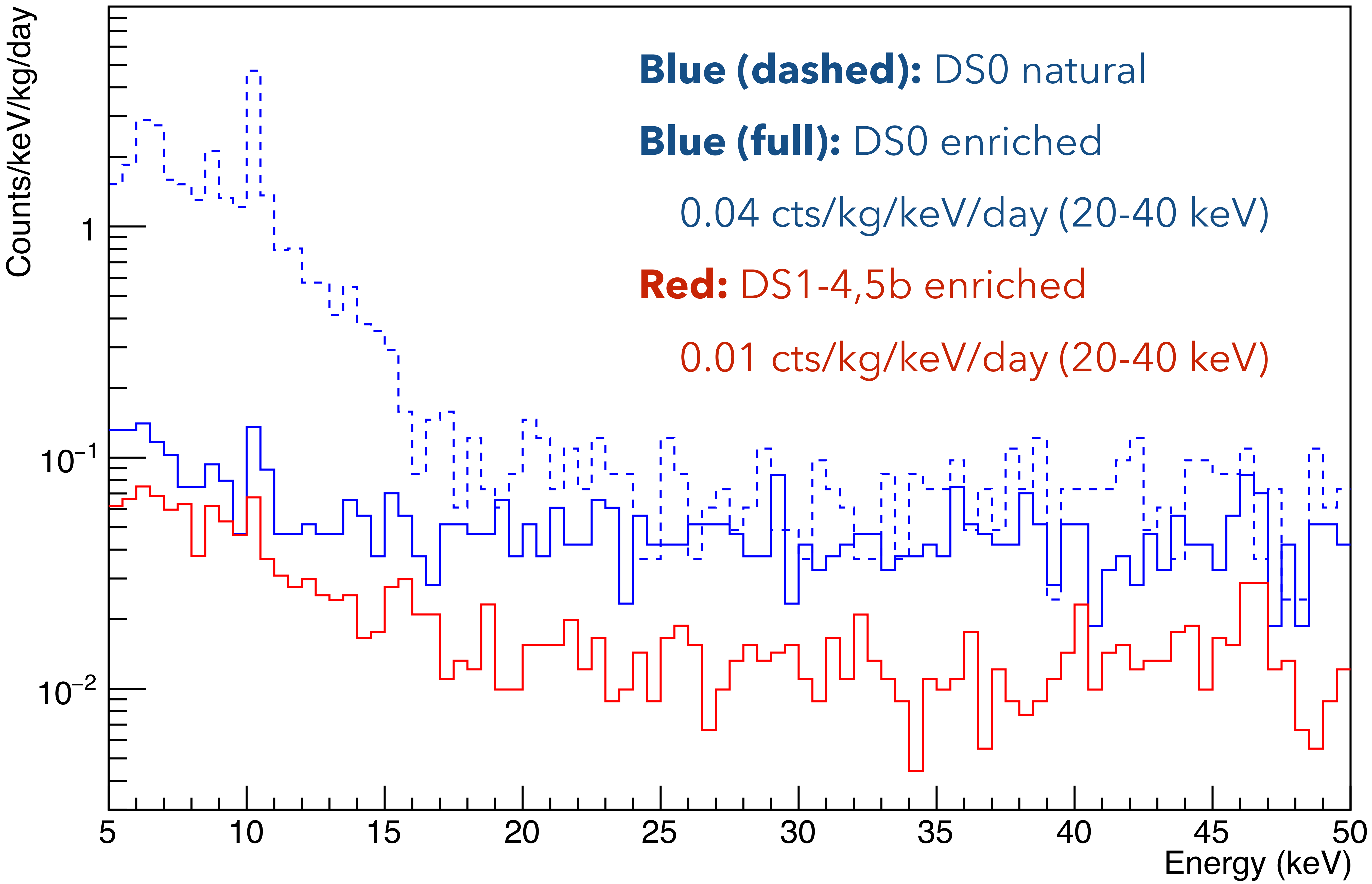
Multiplicity 2, Summed 238 keV peak



- Characterization of cut performance challenging due to low backgrounds and no low energy calibration source
- Utilize **forward scattered Compton events** from calibration (Multiplicity 2; Summed 238 keV peak) as a sample of low energy physics events
  - Comparison with simulations suggest small surface event contribution

Low Energy Spectrum

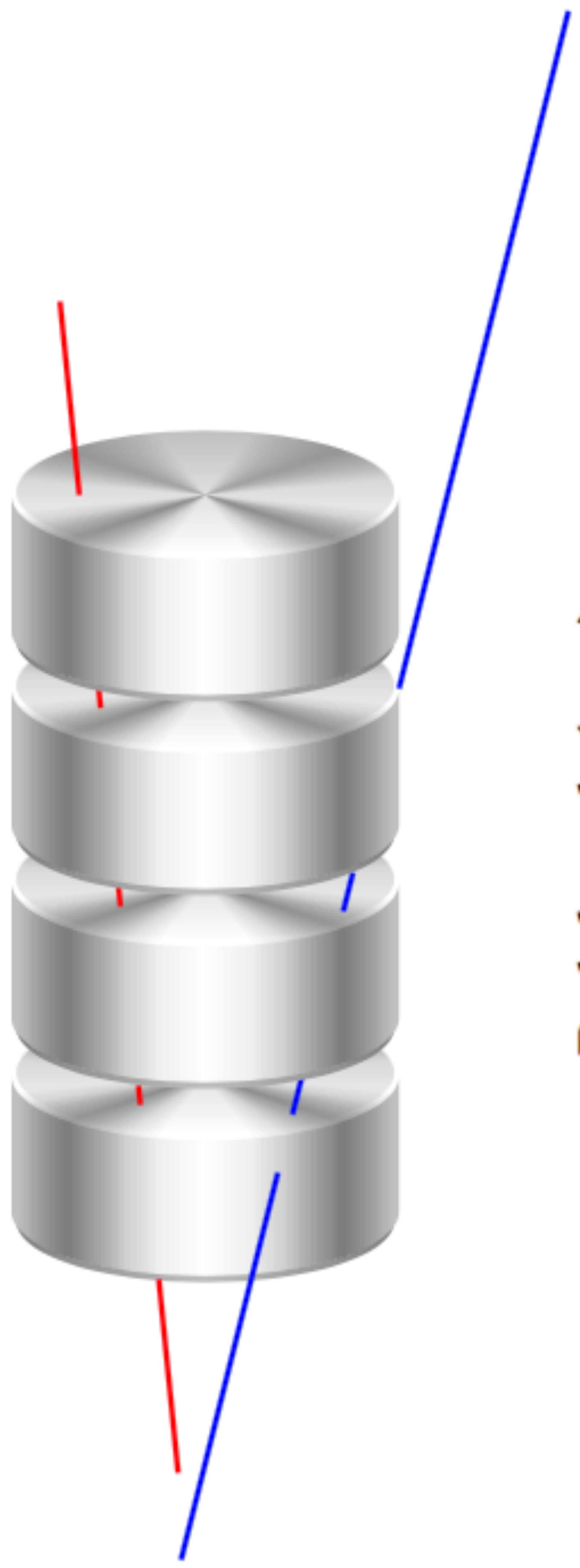




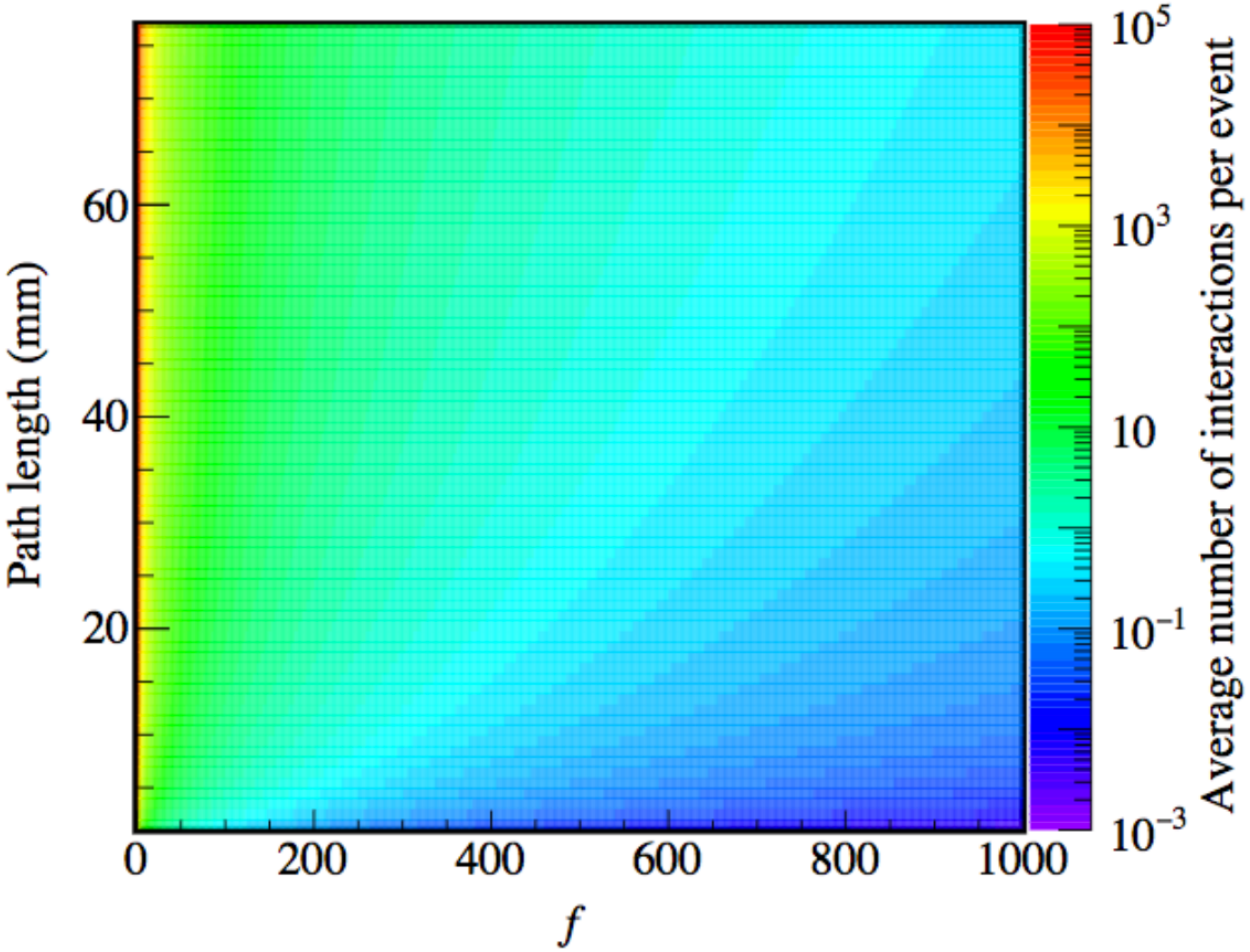
- Cosmogenic backgrounds dominate low energy region for natural detectors
- Enriched detectors have **reduced background** due to isotopic enrichment and control of exposure to cosmic rays on the surface
- Various physics analyses underway

Fractional Charged Particles (LIPs)

- Fractional free particles are possible in many extensions of the Standard Model
  - Particle with charge q = e/f
  - Energy loss described by PAI model (Ann. Rev. Nucl. Part. 30, 253 (1980))
- Thicker detectors compared to previous searches allow for **greater sensitivity to higher f values**



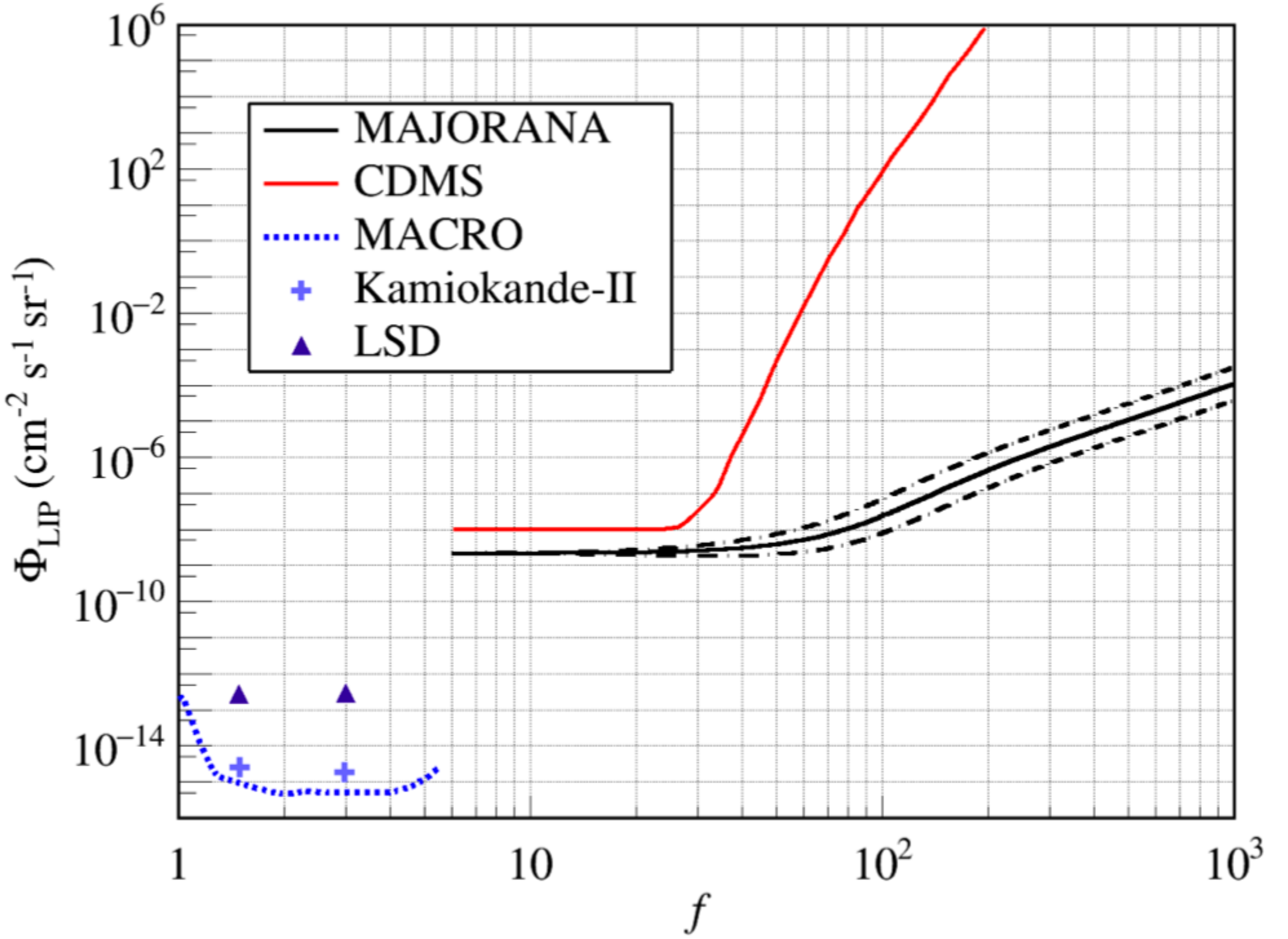
Phys. Rev. Lett. **120** 211804 (2018) [arXiv:1801.10145]



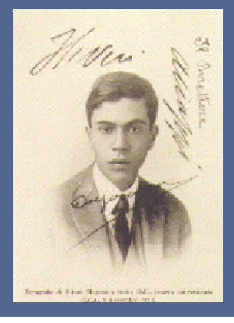
Fractional Charged Particles (LIPs)

- Search for coincident detector responses similar to a muon (4 to 6 multiplicity)
  - Nearly background free search as f > 6 shows negligible showering
  - Tracking algorithm rejects remaining backgrounds from cross-talk
- **No candidate** event found

Phys. Rev. Lett. **120** 211804 (2018) [arXiv:1801.10145]

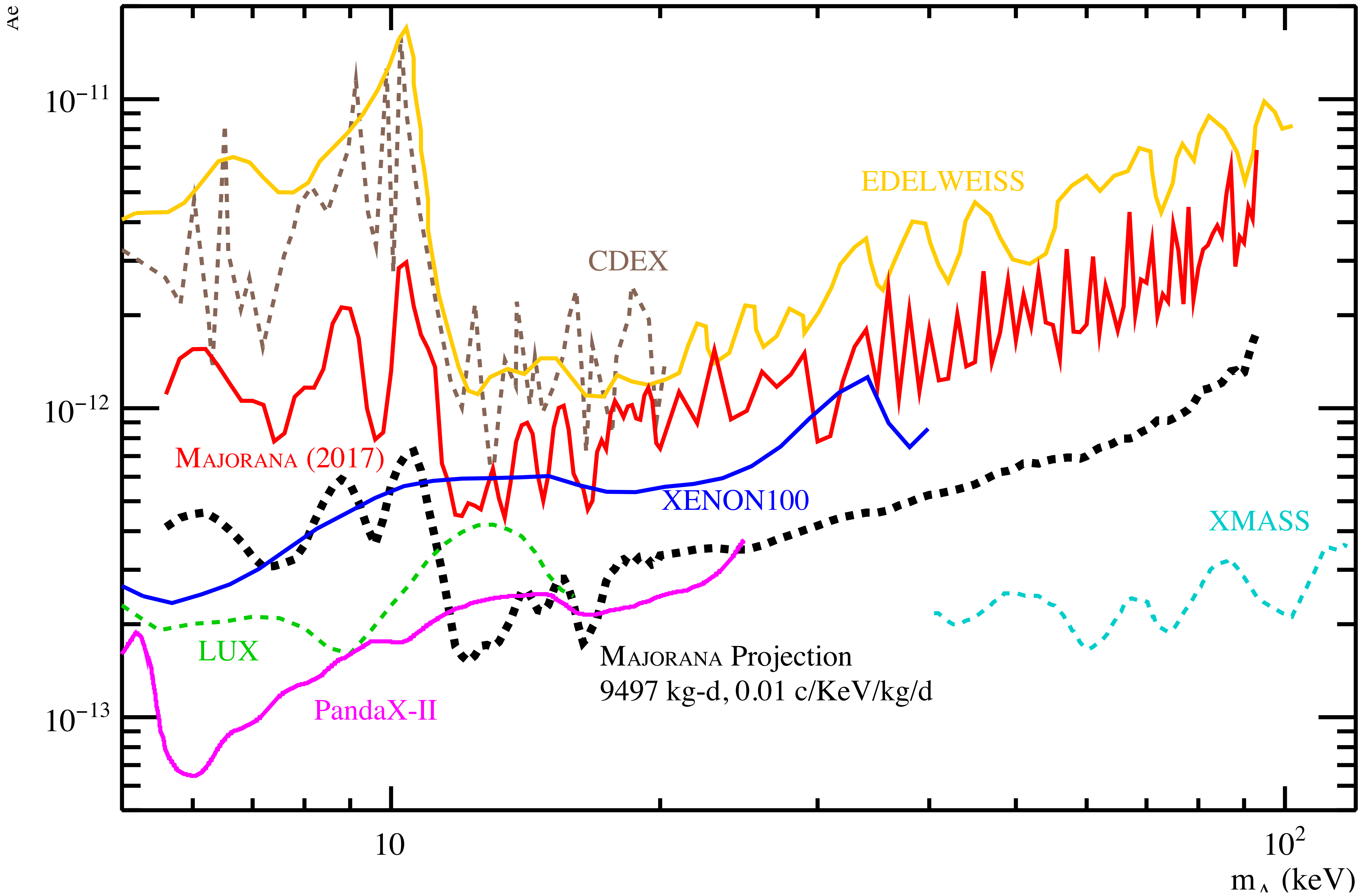


Dark Matter

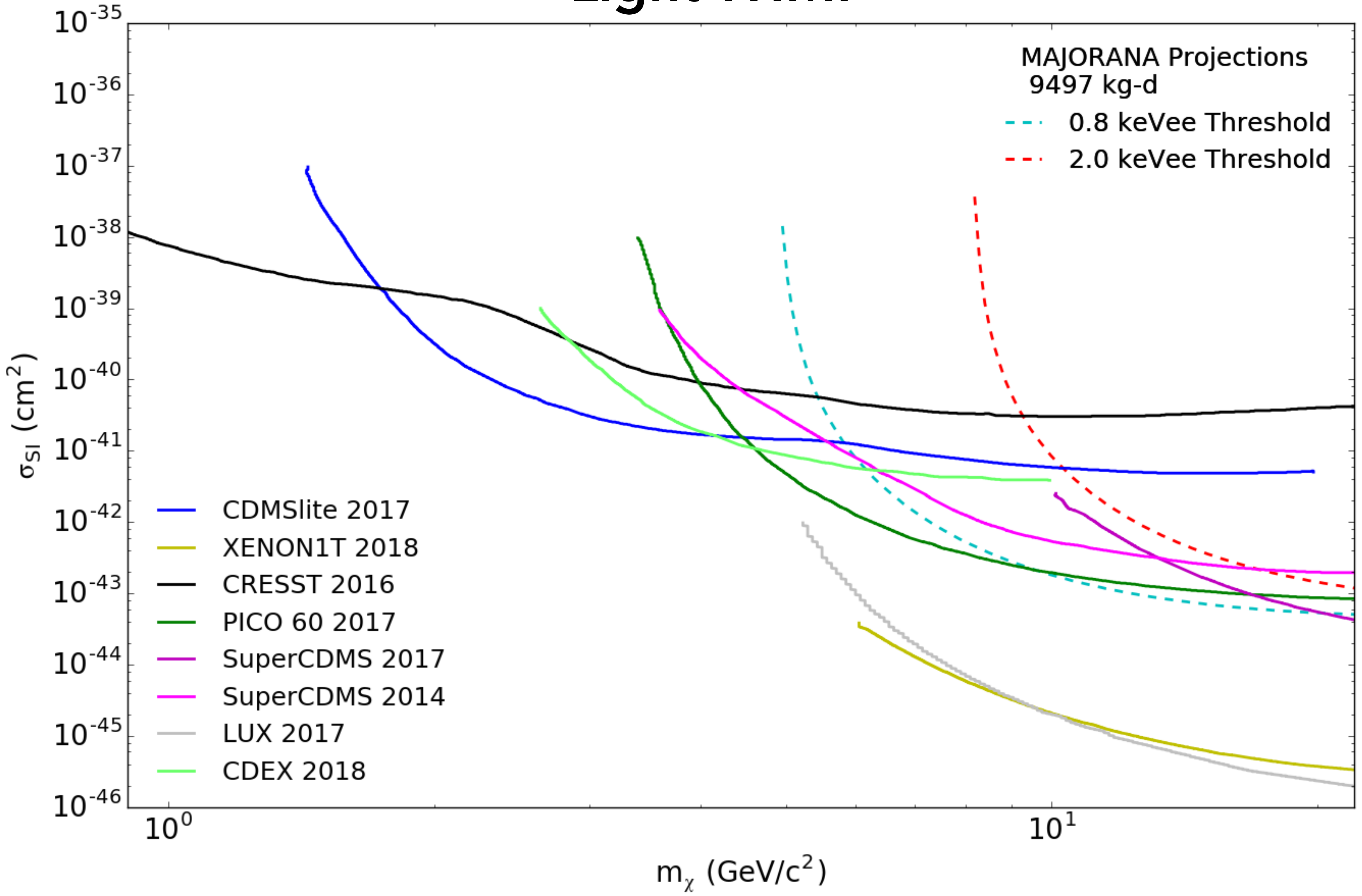


Previous Result: PRL **118**,161801 (2017) [arXiv:1612.00886]

Pseudoscalar ALP-like DM

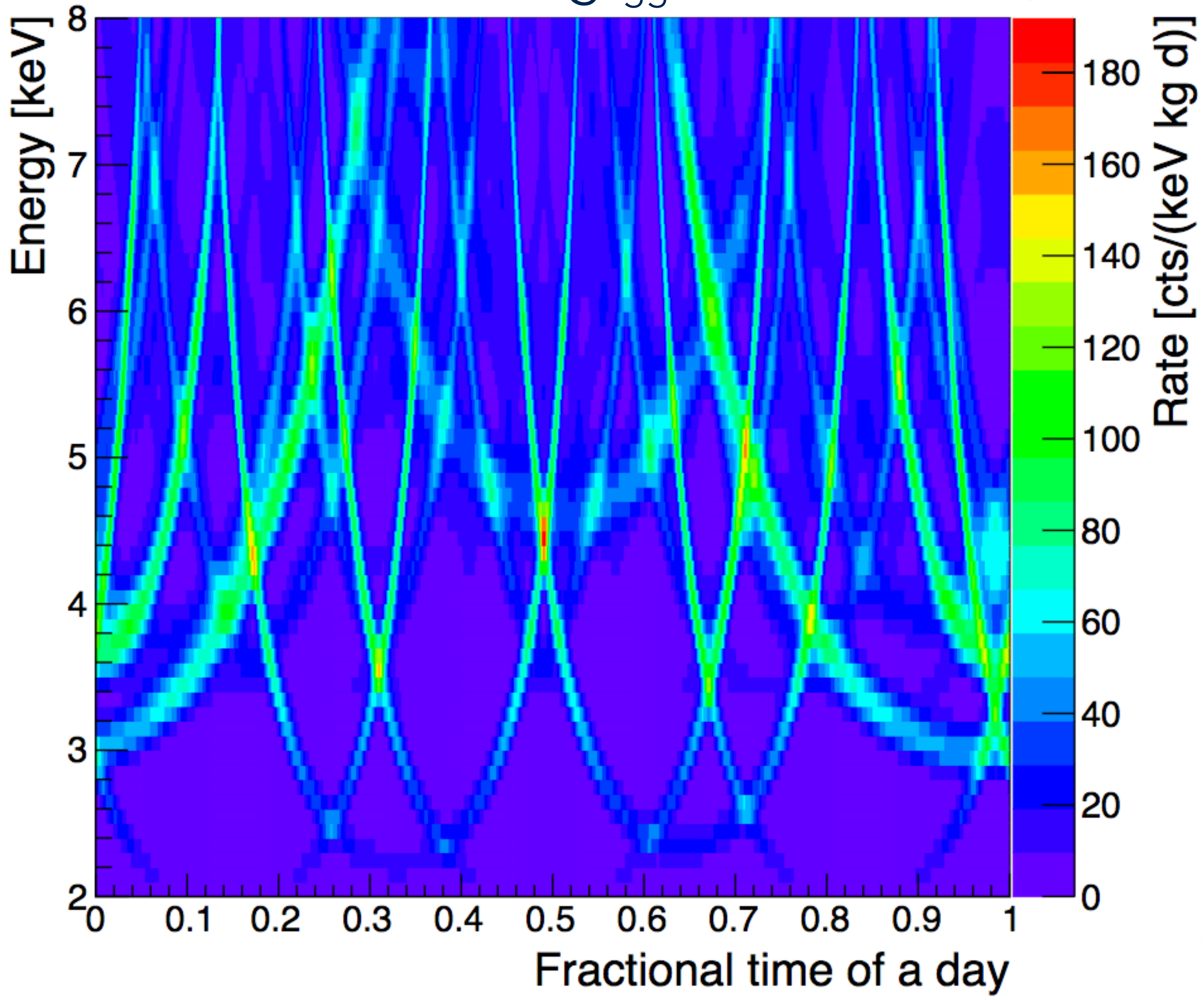


Light WIMP



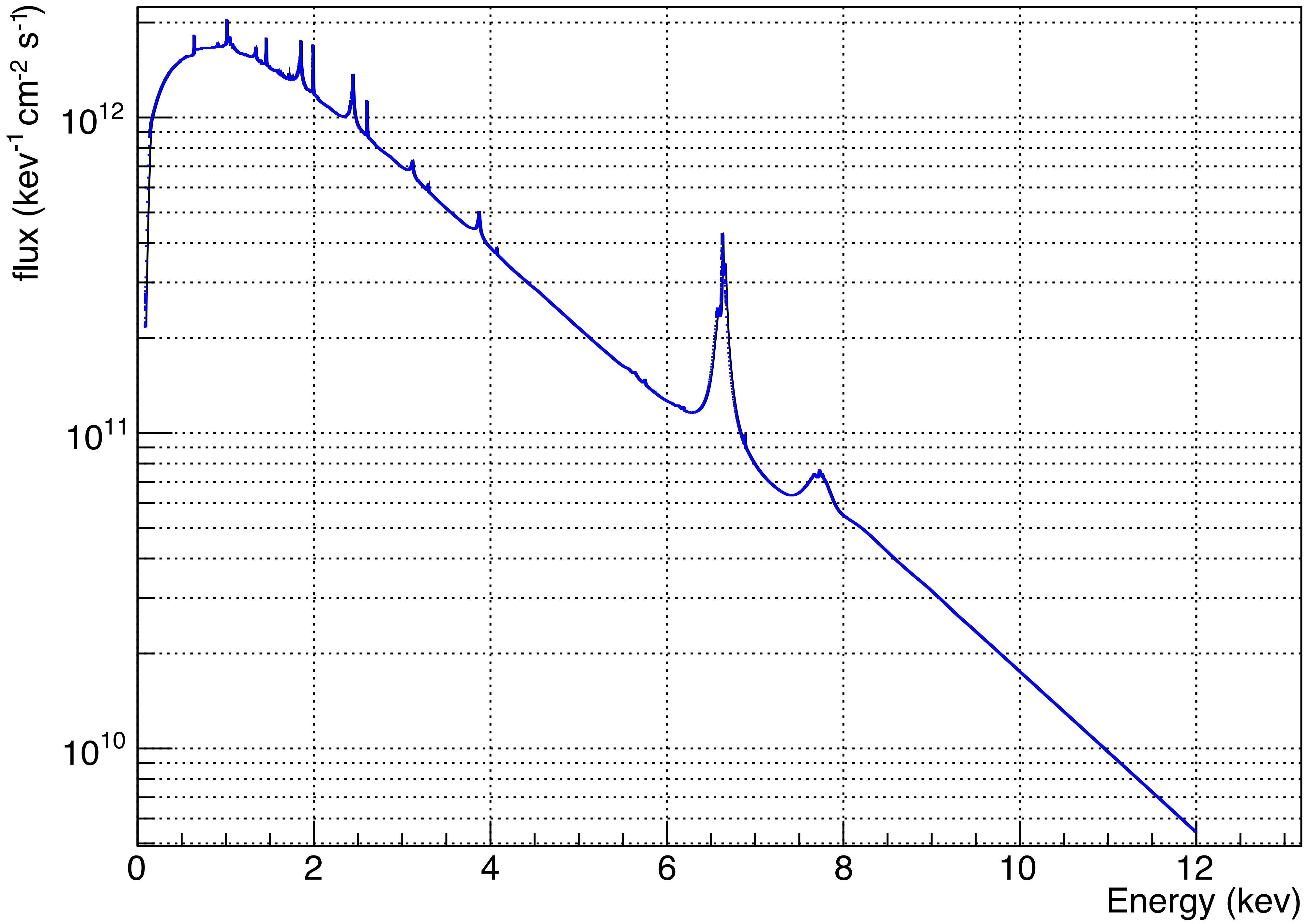
- Sensitivity to both Bosonic Dark Matter with mass scale of 1-100 keV and low mass WIMPs
- Ongoing efforts to improve WIMP sensitivity by reducing analysis thresholds

Solar Axions



Solar axion flux for $g_{agg} = 10^{-8}$ at Lead, SD

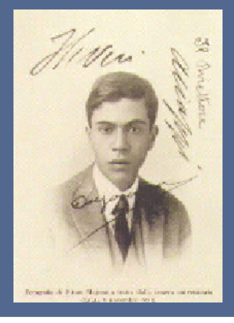
Astroparticle Physics 89 (2017) 39-5 [arXiv:1610.03886]



Solar axion flux for $g_{ae} = 10^{-12}$

- Searches for solar axions through both the axio-electric effect (g_{ae}) and coherent Bragg-Primakoff conversion (g_{agg})
- Averaged angle method provides sensitivity to g_{agg} without knowledge of crystal axes

Summary and Outlook



- The MAJORANA DEMONSTRATOR has finished construction and has been continuously taking data in its final configuration since Spring 2017
  - **Sensitivity (from 26 kg-yr exposure): 4.8 x 10^{25} yr (90% C.L.)**
  - **Limit: 2.7 x 10^{25} yr (90% C.L)**
- Low backgrounds, energy resolutions, and thresholds allow for a broad physics program
- Planning upgrade to improve channel reliability and reduce background
- Expect to reach 50-70 kg-yr exposure with sensitivity in the range of 10^{26} yr half-life
- Next Generation ^{76}Ge: the LEGEND collaboration is selecting the best technologies from the MAJORANA DEMONSTRATOR and GERDA (**see talk on Wednesday by S. Schonert**)

MAJORANA Collaboration