Recent Results from the MAJORANA DEMONSTRATOR

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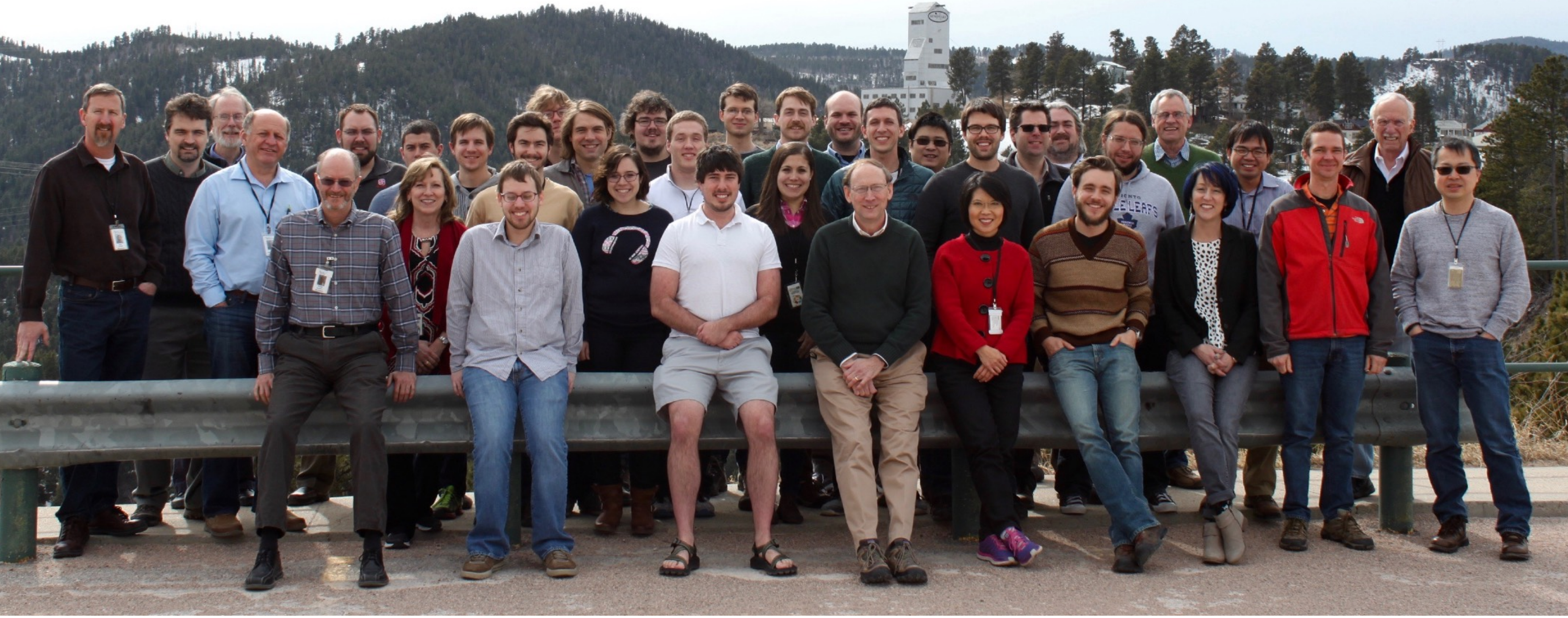
On behalf of the MAJORANA Collaboration

This material is based upon work supported by: The U.S. Department of Energy, Office of Science, Office of Nuclear Physics, the Particle Astrophysics and Nuclear Physics Programs of the National Science Foundation, and the Sanford Underground Research Facility.

The MAJORANA Collaboration



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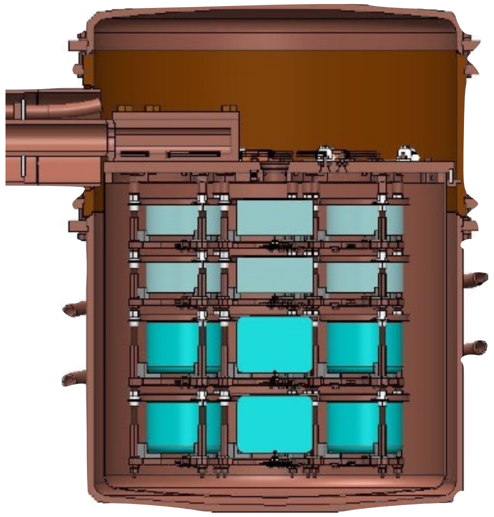
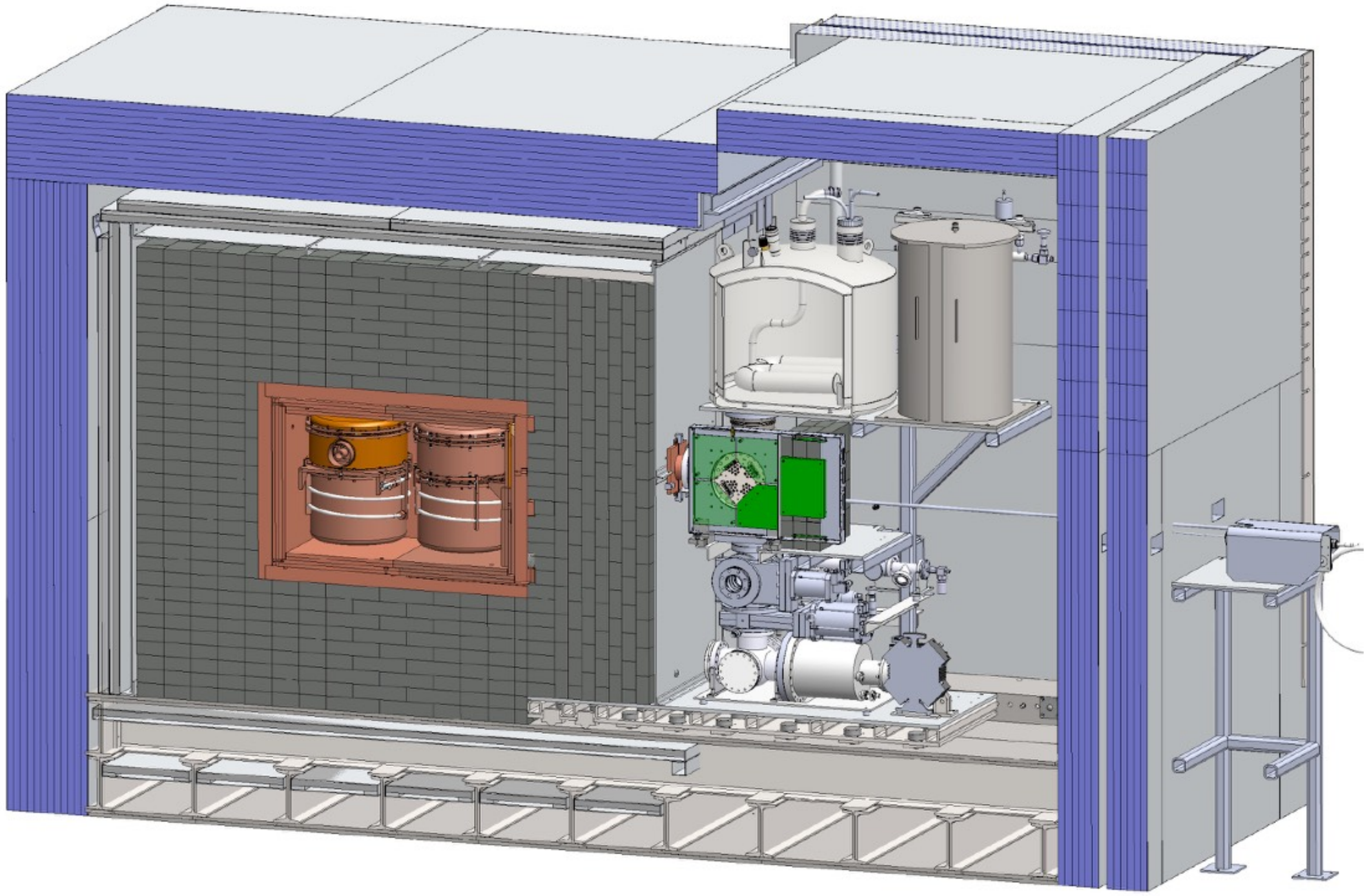
The MAJORANA DEMONSTRATOR

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

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.



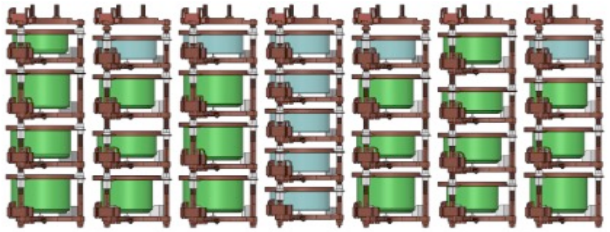
- **Located underground** at 4850′ level of Sanford Underground Research Facility
- **Background Goal** in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV) :
  - **3 counts/ROI/t/y** (after analysis cuts). Assay UL currently ≤ 3.5
  - Scales to 1 count/ROI/t/y for a tonne-scale experiment
- **44.1 kg of Ge detectors**
  - 29.7 kg of 87% 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
  - Active muon veto



Module Implementation

Module 1: 16.9 kg (20) $^{\mathrm{enr}}$Ge

5.6 kg (9) $^{\mathrm{nat}}$Ge



9/2014 : Module commissioning

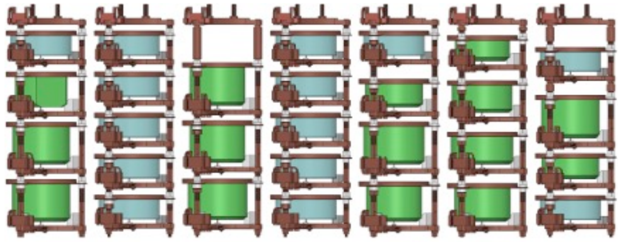
5/2015 - 10/2015 : In-shield running

10/2015 - 1/2016 : Offline, upgrades

1/2016 - Present : In-shield running

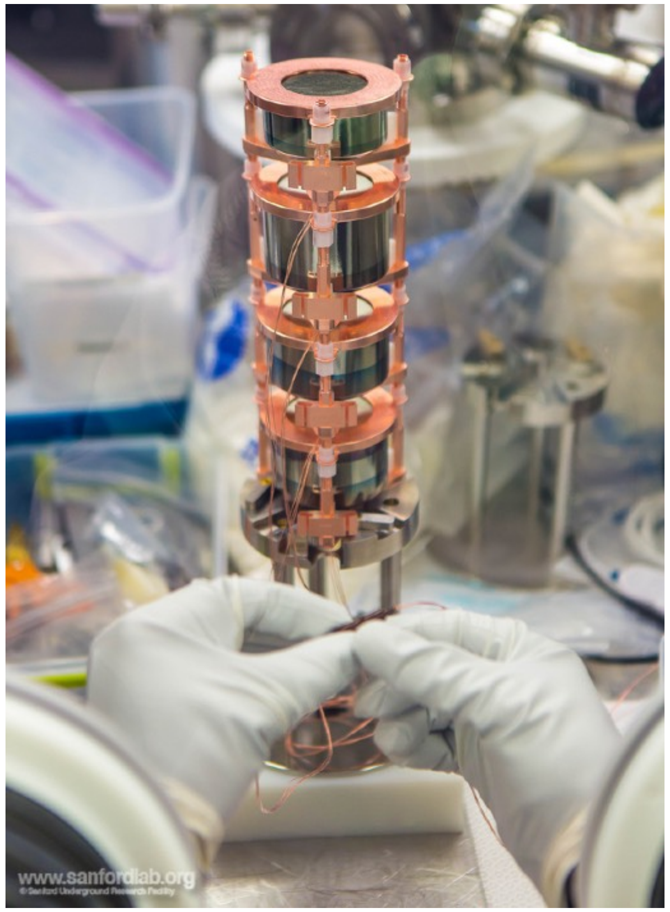
Module 2: 12.9 kg (14) $^{\mathrm{enr}}$Ge

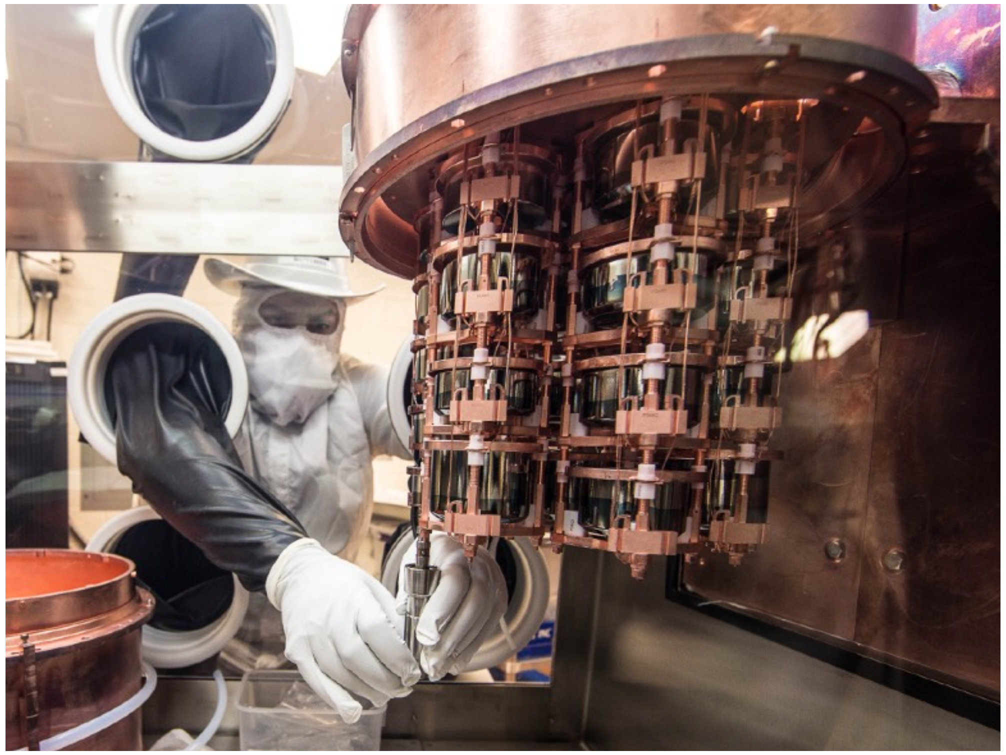
8.8 kg (15) $^{\mathrm{nat}}$Ge



4/2016 : Module commissioning

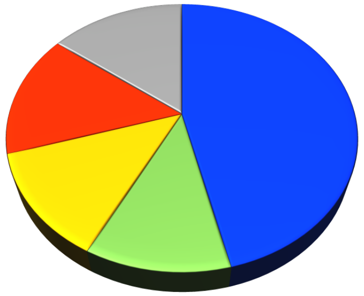
7/2016 - Present: In-shield running





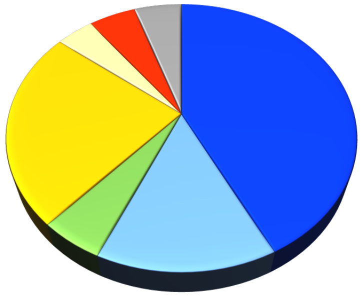
Duty Cycles & Data Sets

DS-0



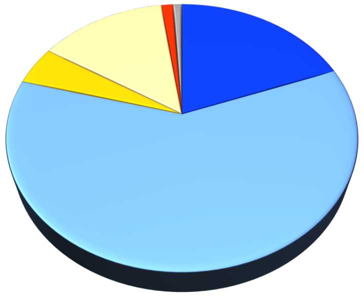
Commissioning, No inner shield

DS-1



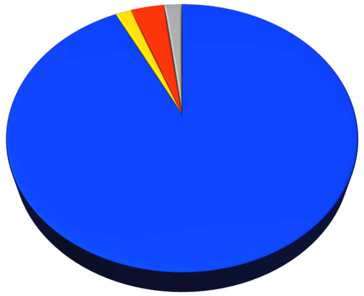
Inner EFCu shield installed

DS-2



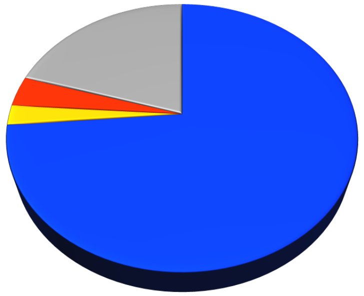
Inner shield & multi-sampling

DS-3



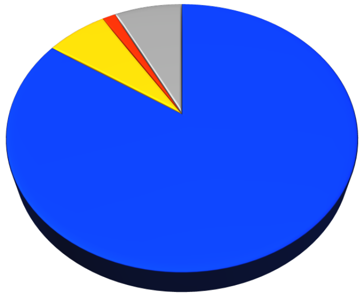
No multi-sampling

DS-4



First Module 2 data

DS-5



First combined M1+M2 dataset

	DS-0 **Module 1** June 26 – Oct. 7, 2015	**DS-1** **Module 1** Dec. 31, 2015 – May 24, 2016	**DS-2** **Module 1** May 24 – July 14, 2016	**DS-3** **Module 1** Aug. 25 – Sep. 27, 2016	**DS-4** **Module 2** Aug. 25 – Sep. 27, 2016	**DS-5** **Module 1 & 2** Oct. 13, 2016 – ***ongoing*** *
Total (days)	103.15	144.50	50.97	32.37	32.36	97.7
Total acquired	87.93	136.98	50.47	31.73	25.80	90.41
Physics 🟦 🟦*	47.70	61.34 + 20.41*	9.82 + 30.56*	29.97	23.84	82.52
High radon 🟩	11.76	7.32	-	-	-	-
Calibration 🟥	15.44	7.32	0.65	1.18	1.17	1.39
Down time ▨	15.21	7.51	0.50	0.64	6.56	7.29
Disruptive/ Commissioning 🟨 🟨*	13.10	34.43+ 5.92*	2.41 + 7.03*	0.57	0.78	6.51

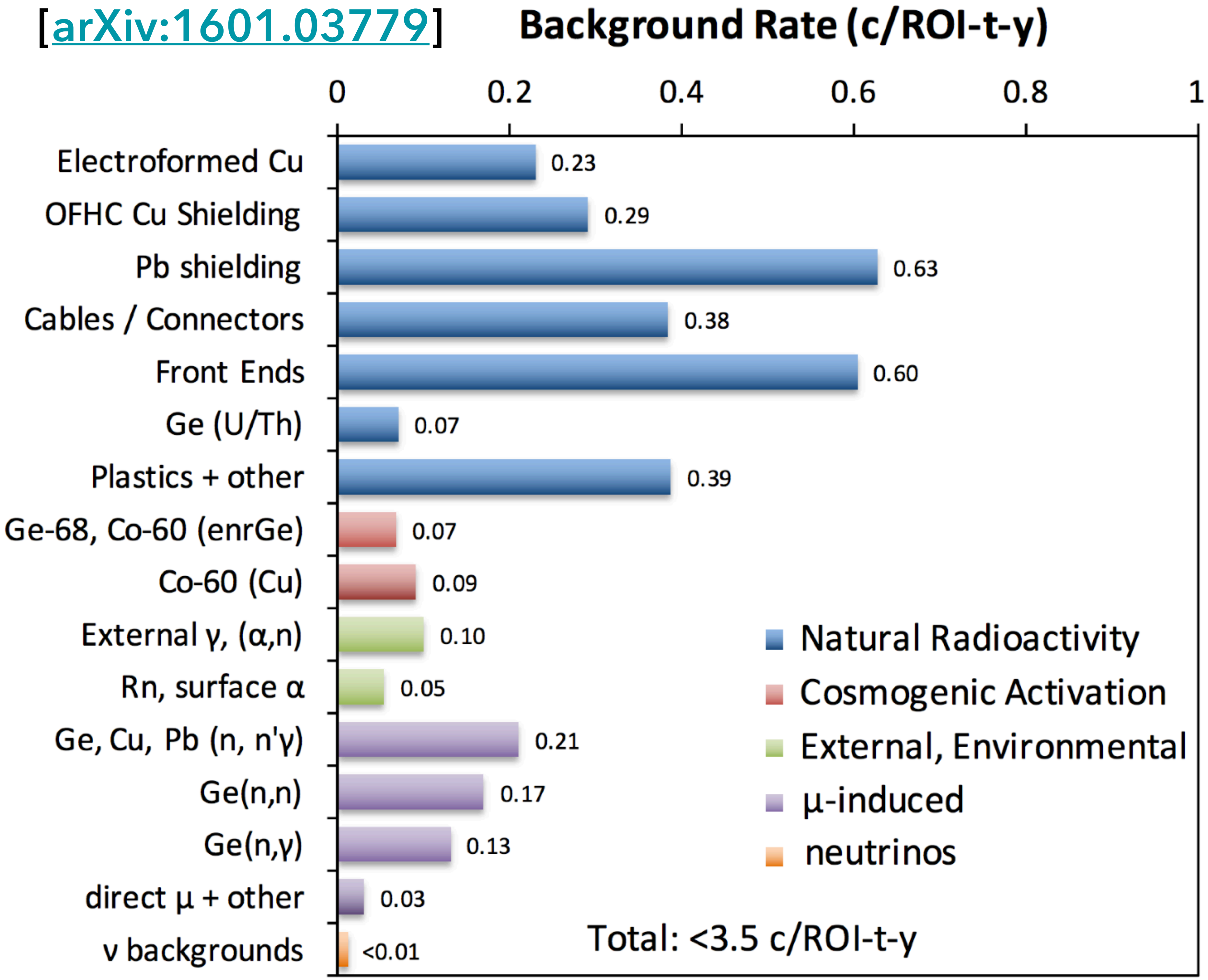
*Blind data

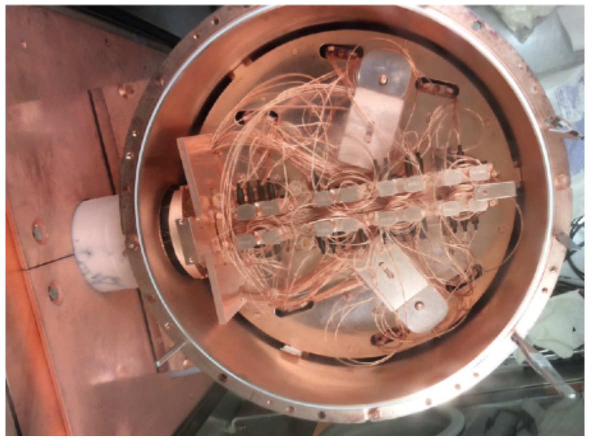
*Values up to Jan. 19, 2017

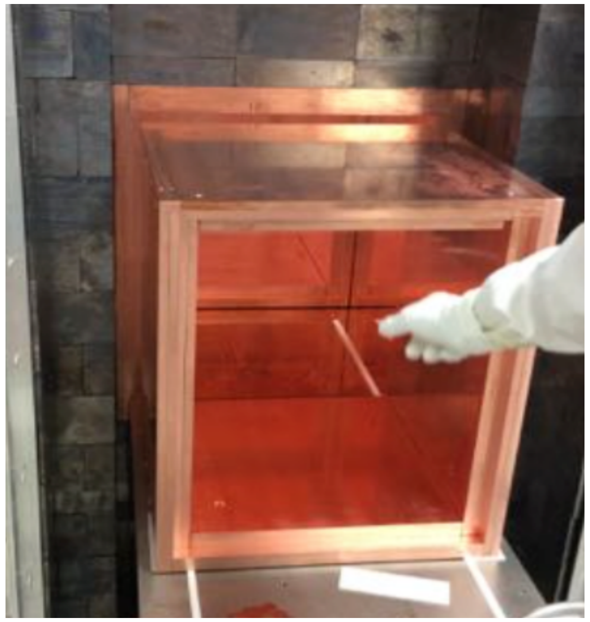
Background Model and Assay

Results from radioassay paper: NIMA 828 (2016) 22

[arXiv:1601.03779]







Muon Flux at the 4850

Muon veto system has run continuously since 2014: [arXiv:1602.07742]

- First opportunity for vertical μ-flux measurement using completed Pb shield
- Flux predicted for 4850 level (Hime & Mei, PRD 2006)

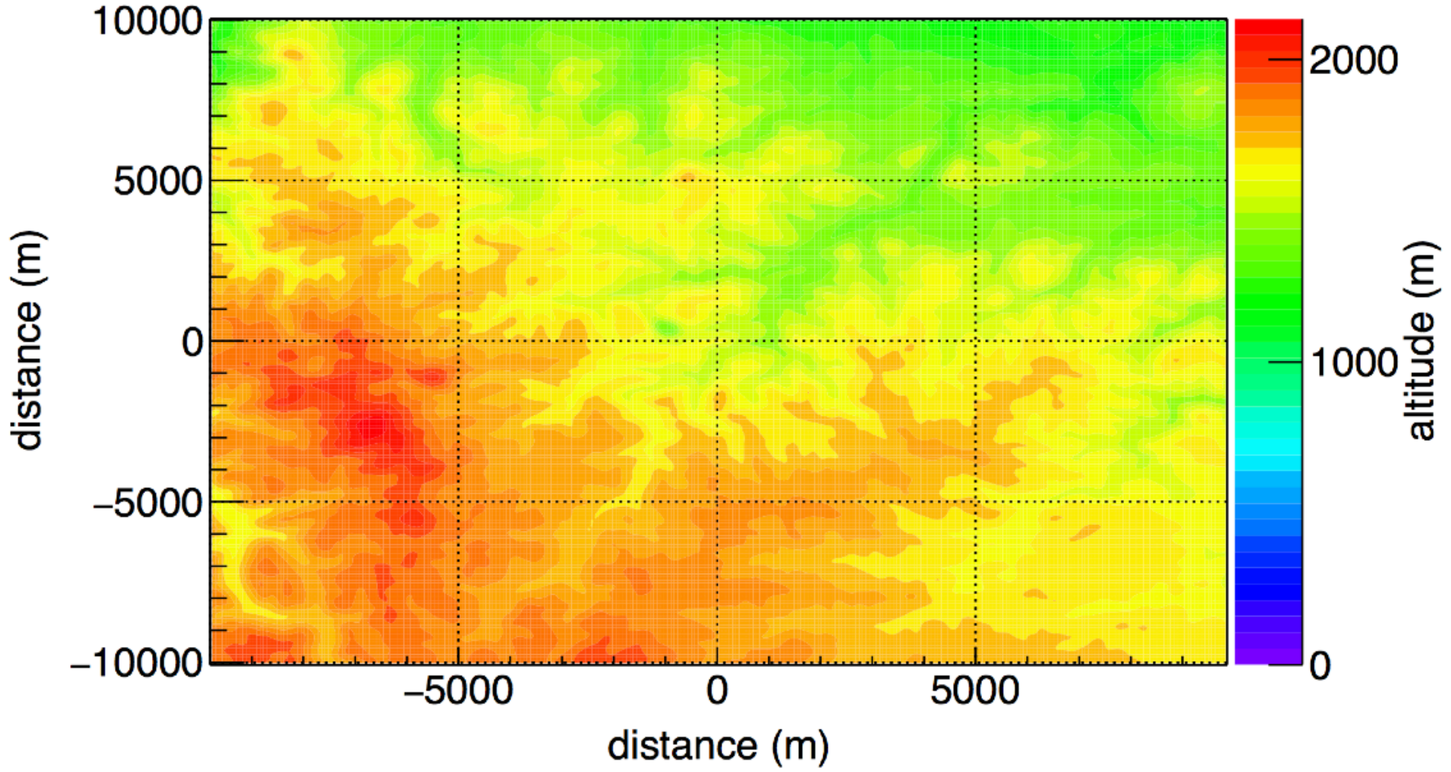
$$\Phi = (4.4 \pm 0.1) \times 10^{-9}\ \mu/s/\mathrm{cm}^2$$

- Our simulation (optimized for SURF):

$$\Phi = (5.3 \pm 0.4) \times 10^{-9}\ \mu/s/\mathrm{cm}^2$$

- Measured flux:

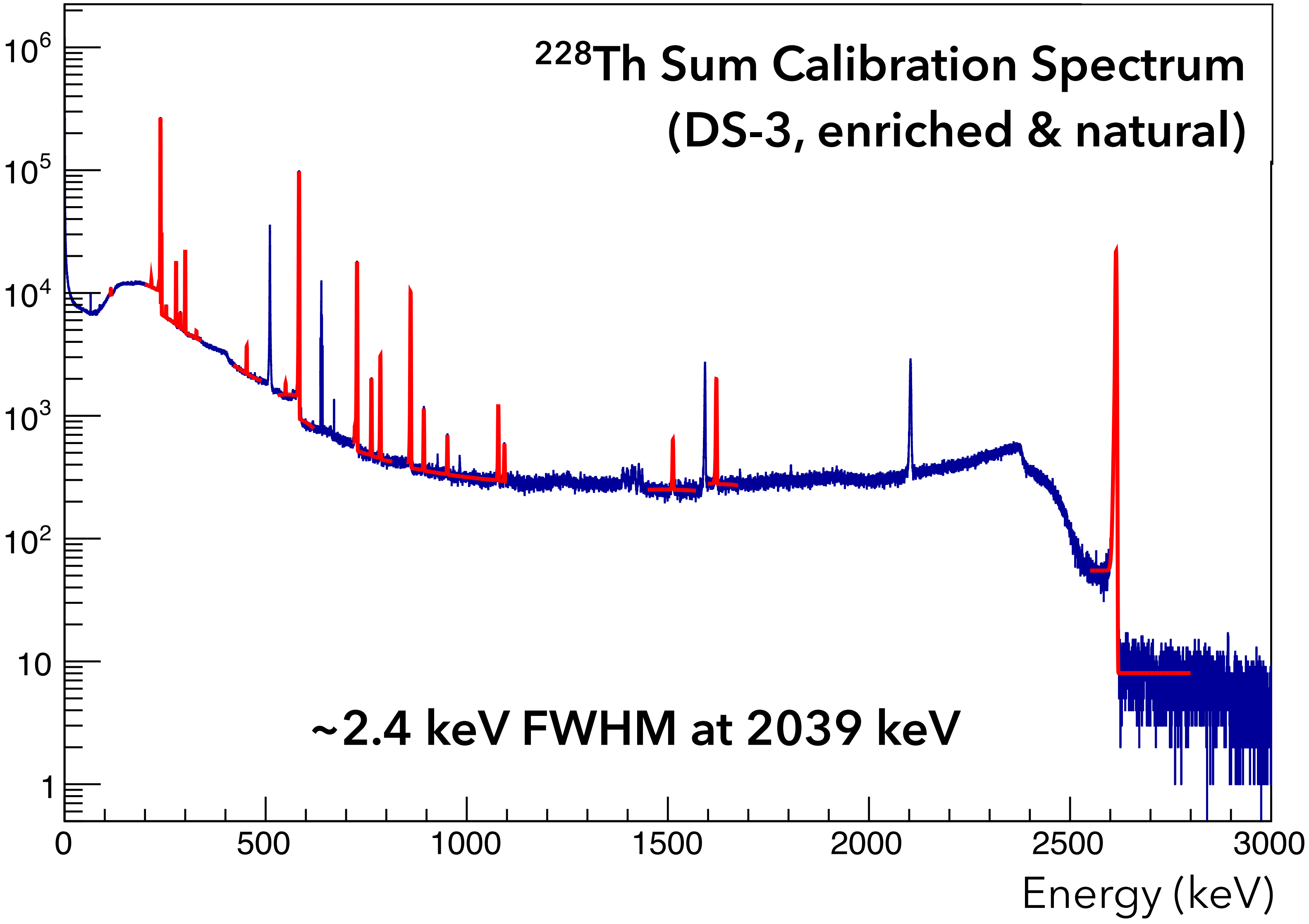
$$\Phi = (5.31 \pm 0.17) \times 10^{-9}\ \mu/s/\mathrm{cm}^2$$



Calibrating the DEMONSTRATOR

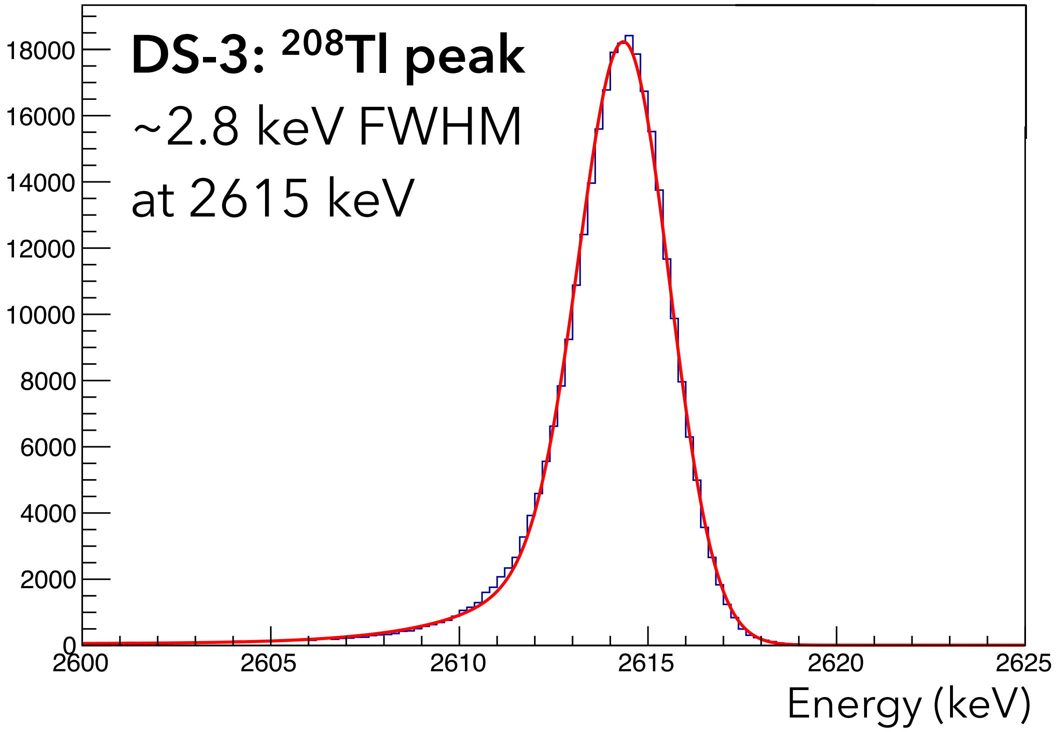
Using custom ^{228}Th line sources and routine remote calibration:

- Multi-peak fitter employed, online database stores results
- New calibration paper: [arXiv:1702.02466]



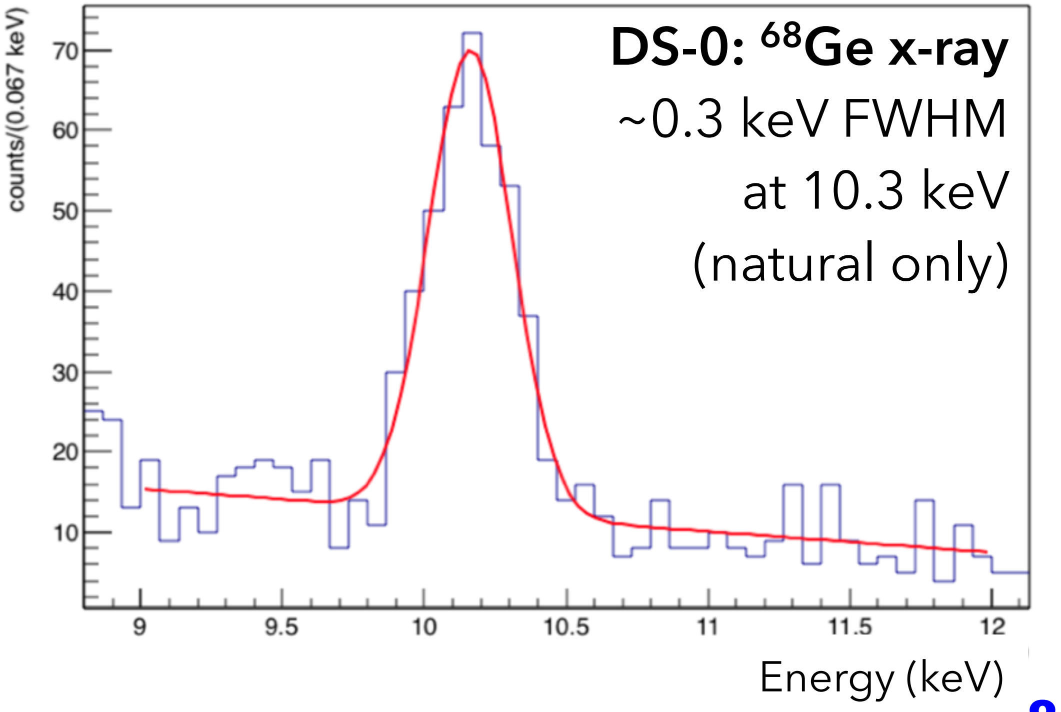
^{228}Th Sum Calibration Spectrum (DS-3, enriched & natural)

~2.4 keV FWHM at 2039 keV



DS-3: ^{208}Tl peak

~2.8 keV FWHM at 2615 keV



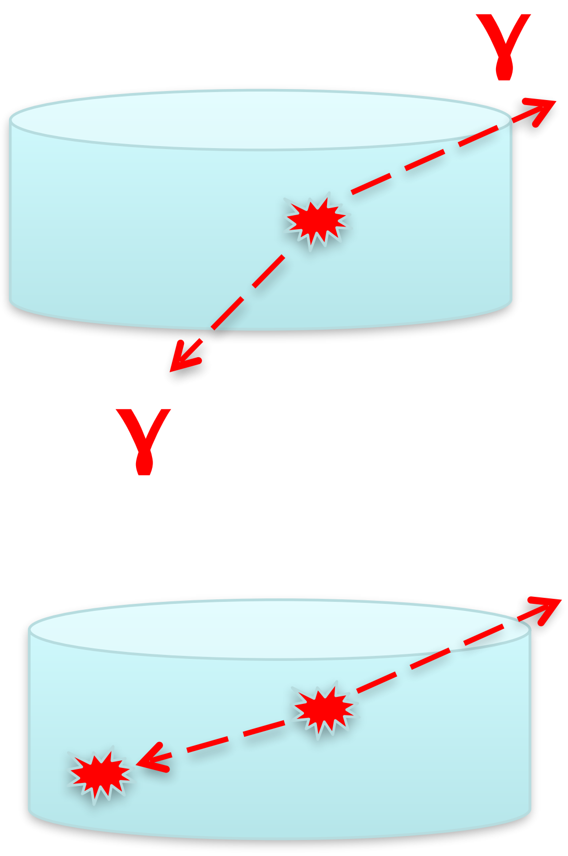
DS-0: ^{68}Ge x-ray

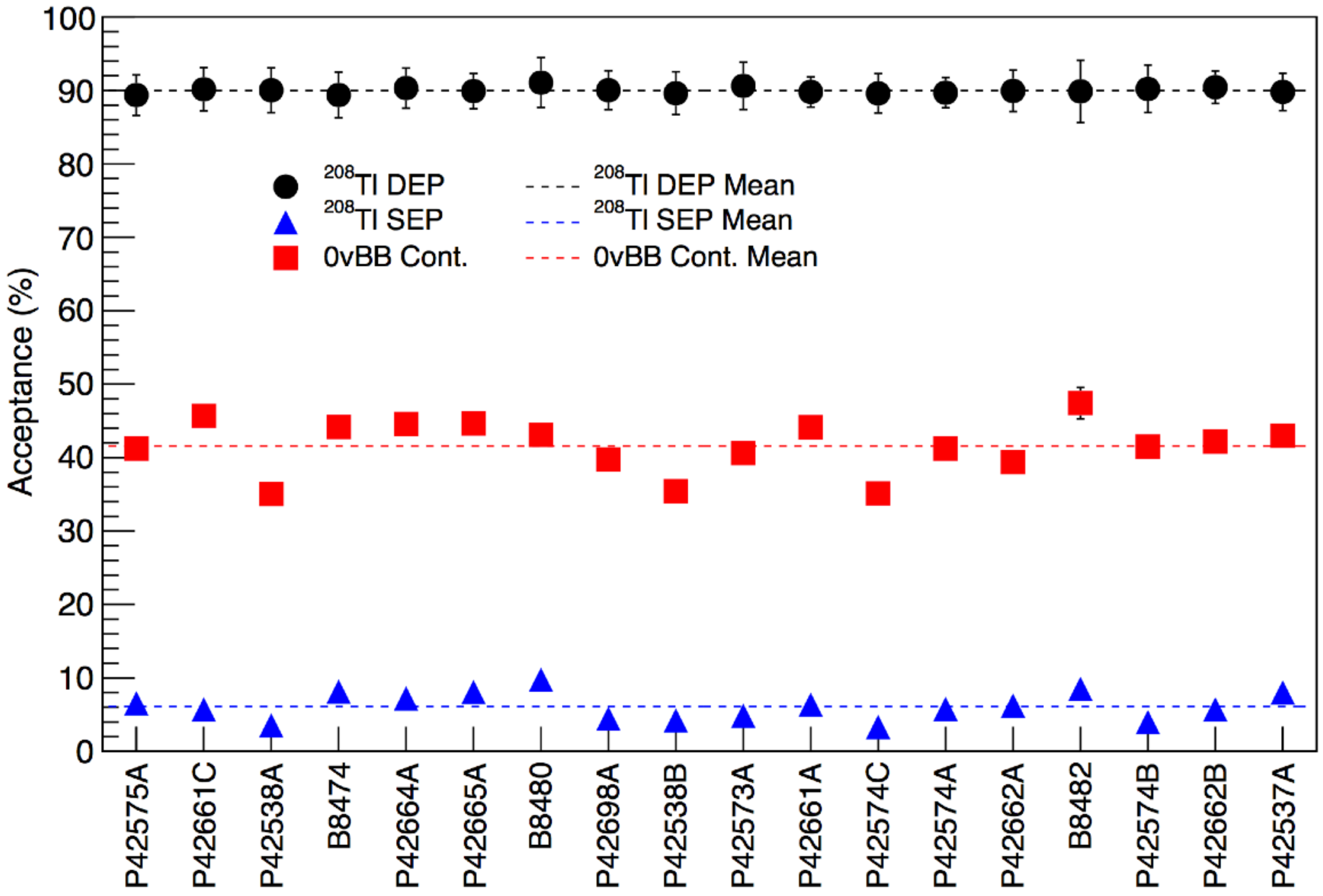
~0.3 keV FWHM at 10.3 keV (natural only)

Ge Detector PSD Performance

PSD cuts are optimized to keep 90% single-site and < 10% multi-site events

- 0νββ is a single site event
- ^{208}Tl 2614 keV γ can have pair production and emit 2γ
- Both γ's escape from detectors → double escape peak (DEP), single site
- One γ escapes from detectors → Single escape peak (SEP), multi-site





^{208}Tl DEP (single site events) fixed to 90%

^{208}Tl SEP (Multiple site events) reduced to 6%

Module 1 detectors

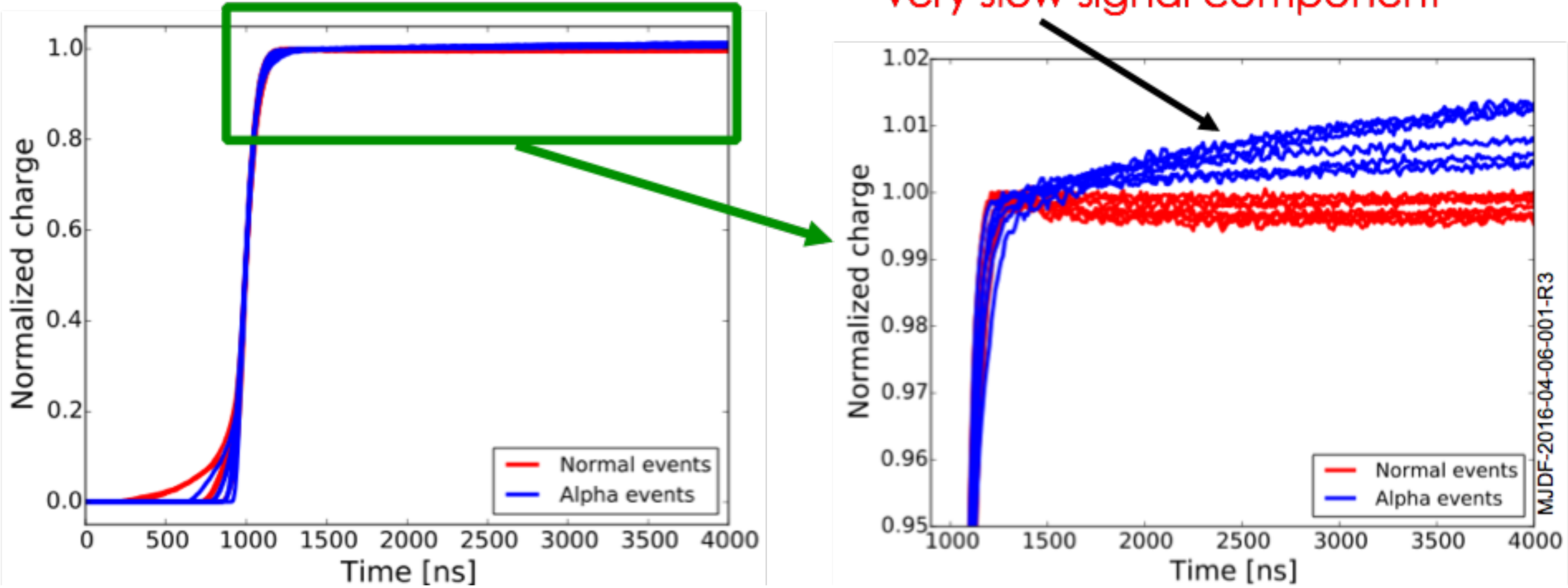
Delayed-Charge Recovery Cut for α's

Alpha BG observed in DS-0 has been identifed and cut with high efficiency

- Charge of these events drifts along the detector surface, not bulk
- Distinctive waveform allows a high-efficiency (90%) cut for events < 2 MeV

Example pole-zero corrected waveforms

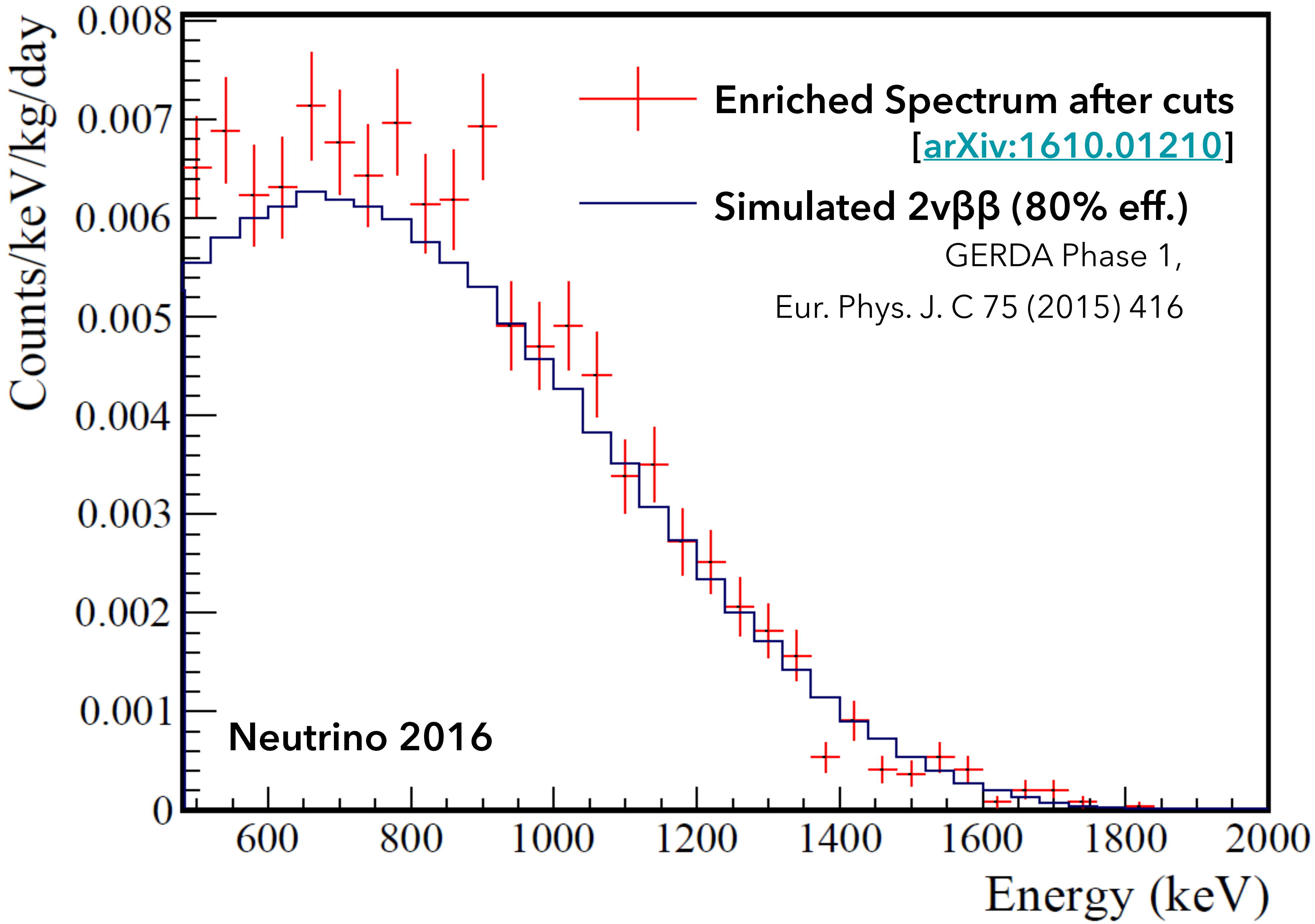
Slow drift of charges along passivated surface results in very slow signal component



Background Spectrum in DS-1

Spectrum in the enriched detectors is dominated by 2vββ (good news!)

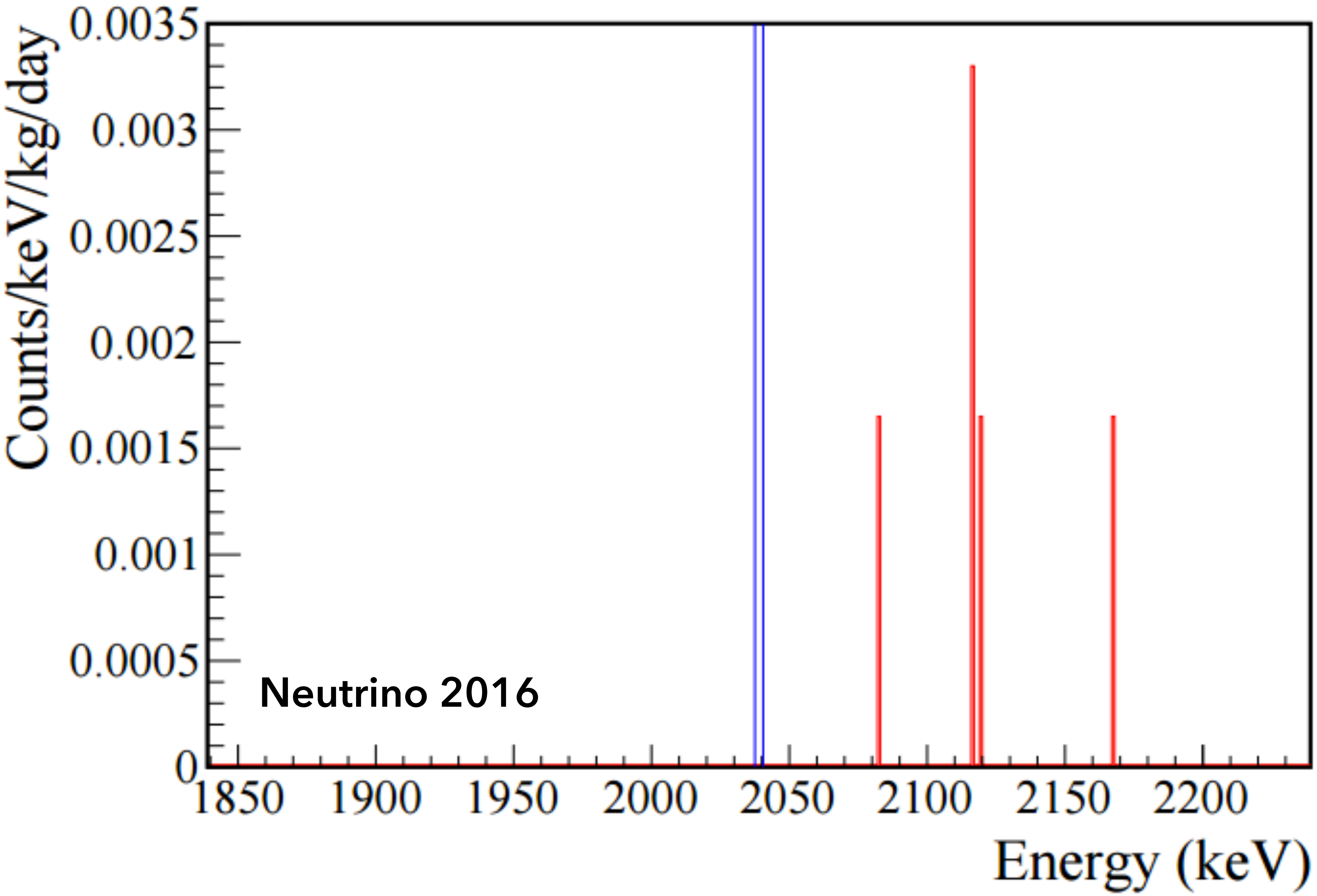
- Module 1 data with all cuts applied: 606.0 kg-days exposure
- Compare to simulated 2vββ spectrum with $T^{2\nu}_{1/2} = (1.926 \pm 0.095) \times 10^{21}\ \mathrm{yr}$



The 0νββ Region of Interest in DS-1

Enriched detectors in DS-1 are used to estimate the background:

- 5 events left after analysis cuts* in a 400 keV window around ROI.
- Background rate (3.1 keV ROI, 68%CL) : $23^{+13}_{-10}\ \mathrm{cts/(ROI\ t\ y)}$
- Background index (400 keV window) : $7.5^{+4.5}_{-3.4} \times 10^{-3}\ \mathrm{cts/(keV\ kg\ y)}$



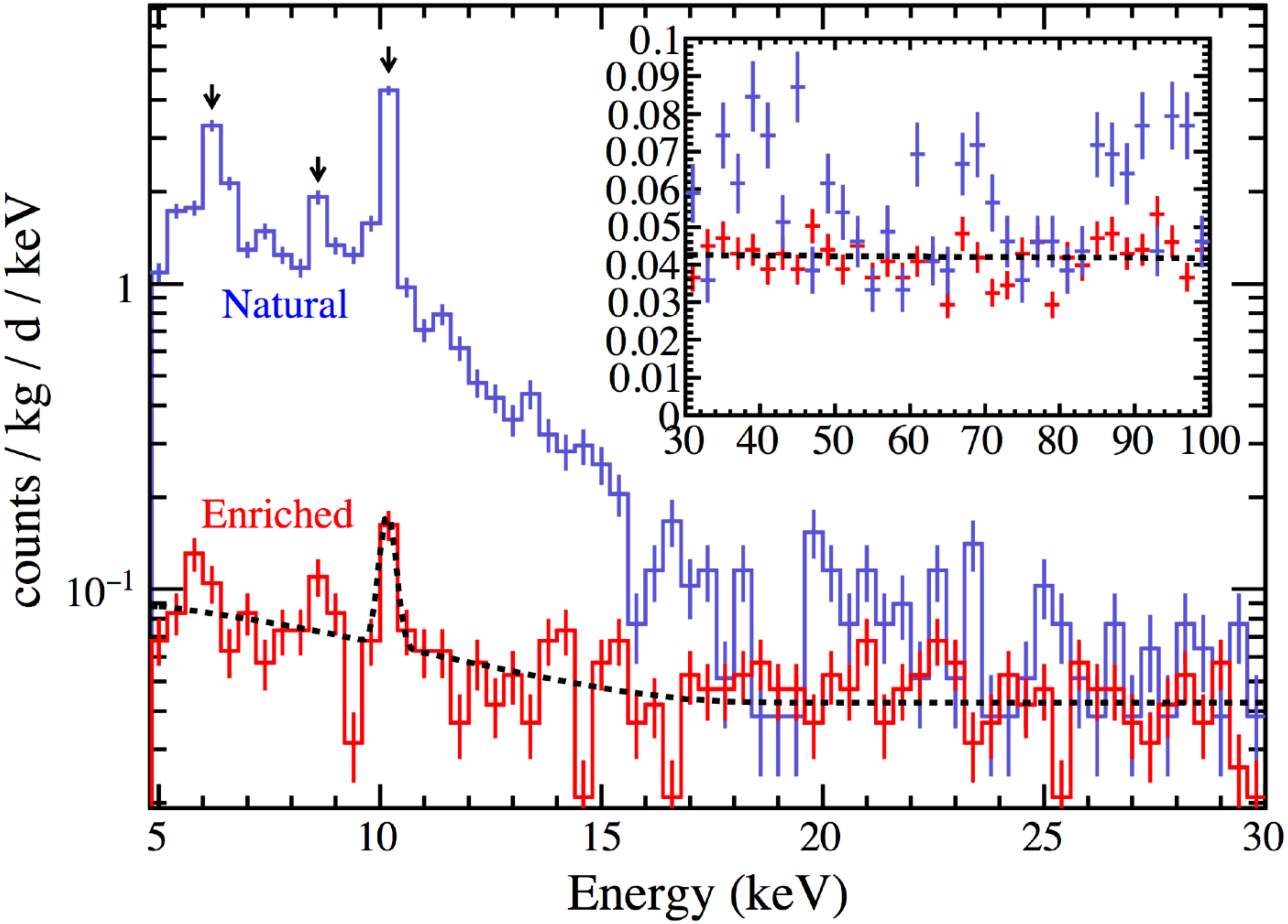
*All analysis cuts are still being optimized.

Low-Energy Spectrum in DS-0

Much lower background in enriched detectors, due to tight exposure control

- Exposure, enriched: 478 ± 6 kg-days, natural: ~195 kg-days
- From 20-40 keV: **~0.04** cts/kg-d-keV

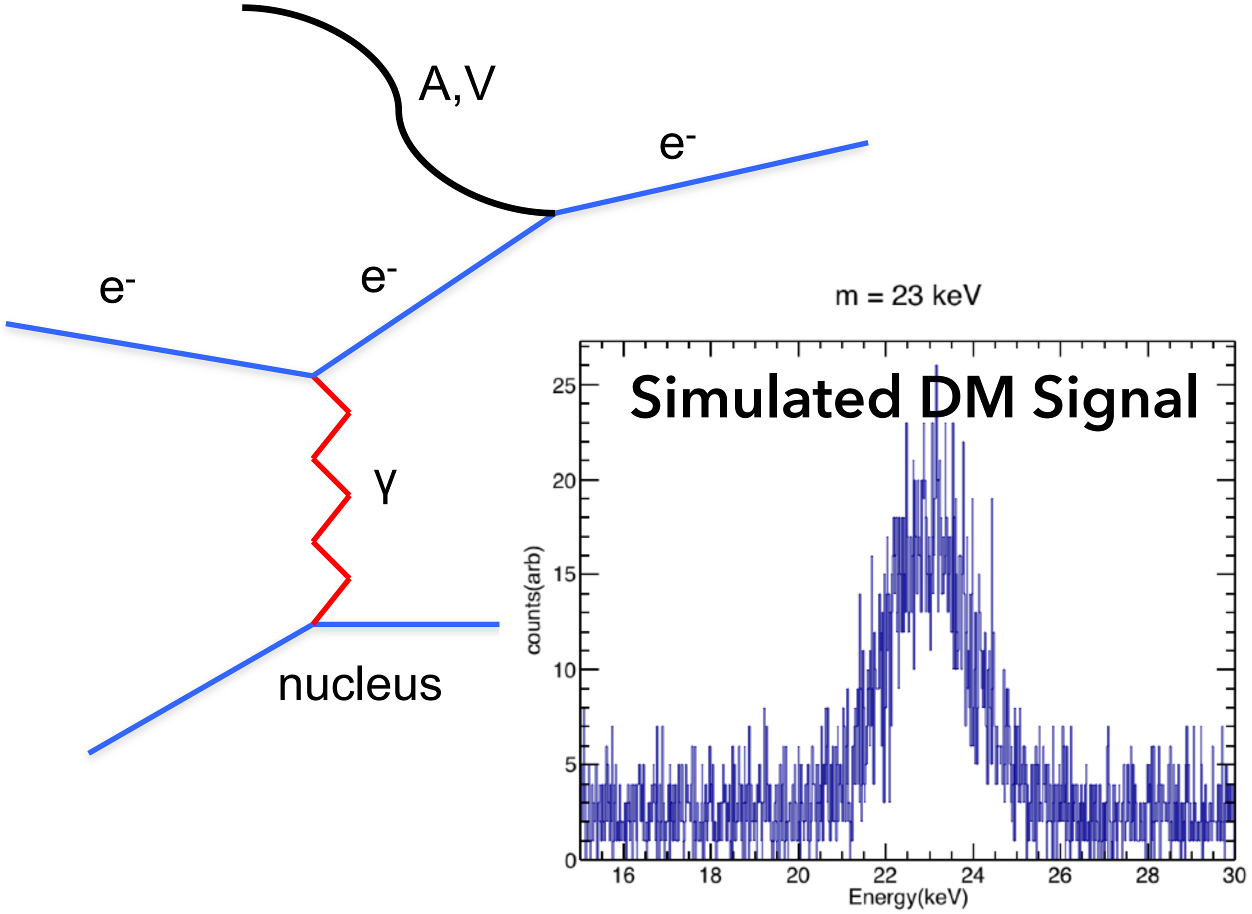
[arXiv:1612.00886]



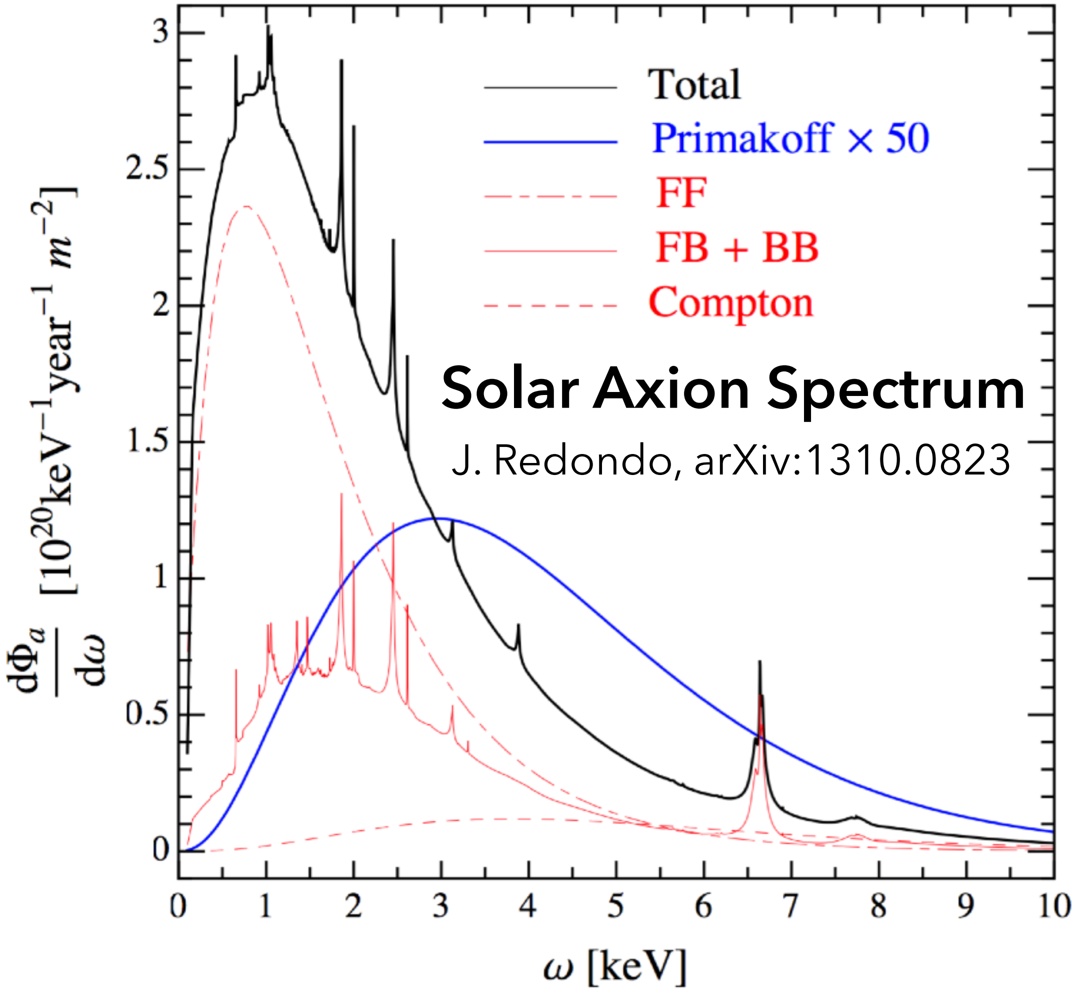
The MAJORANA Low-Energy Program

Low detector thresholds allow us to perform several low-energy searches:

Search:	**Expected Signal:**
Light (<10 GeV/c^2) WIMP searches	*Excess < 2-2.5 keV from nuclear recoils*
Bosonic Superweak Dark Matter	*Anomalous peak < 100 keV*
Pauli-Exclusion Principle Violation	*Ge x-ray peak at 10.6 keV*
Electron decay: $e^- \to \nu_e \bar{\nu}_e \nu_e$	*Ge x-ray peak at, 11.1 keV*
Solar Axions	*Excess in continuum or peaks < 15 keV*



Simulated DM Signal



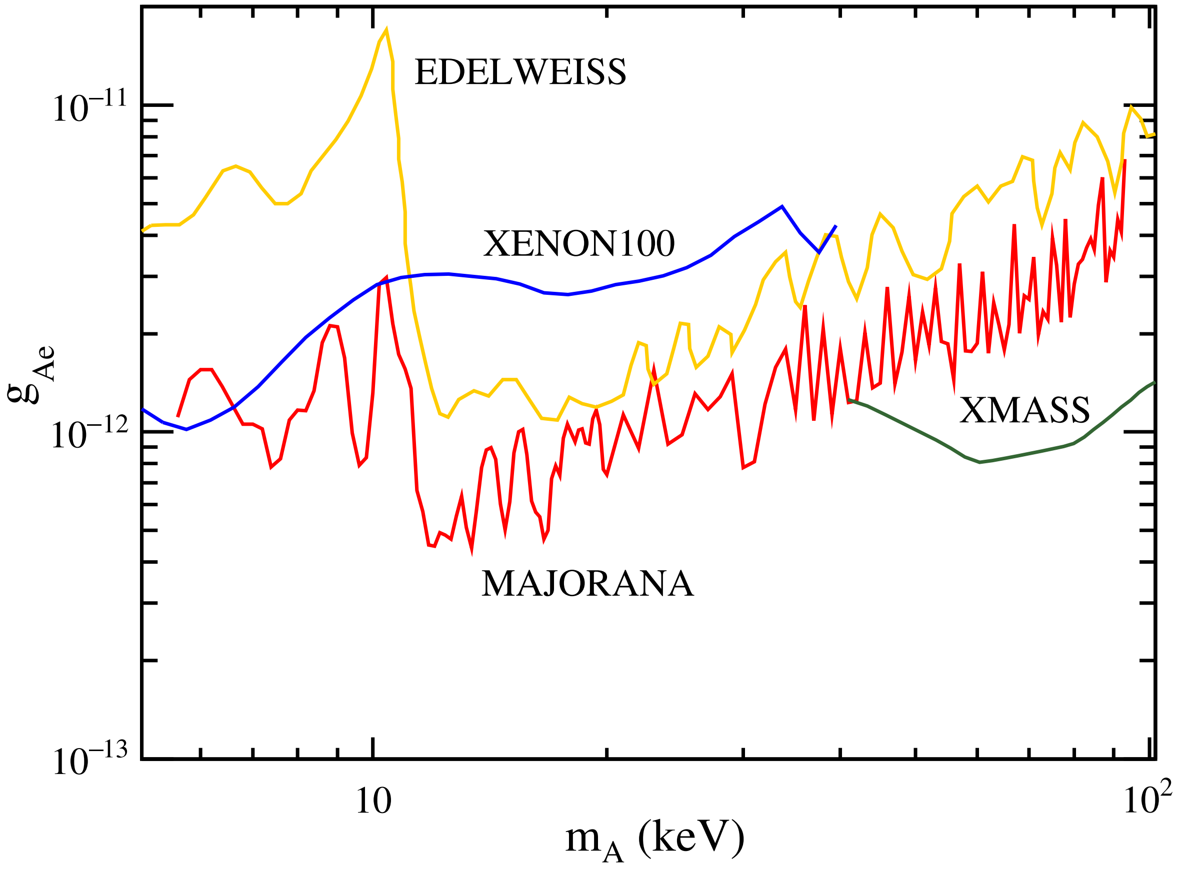
Solar Axion Spectrum

J. Redondo, arXiv:1310.0823

Dark Matter Coupling Results

For DS-0, 13 enriched detectors and a 478 kg-day exposure: [arXiv:1612.00886]

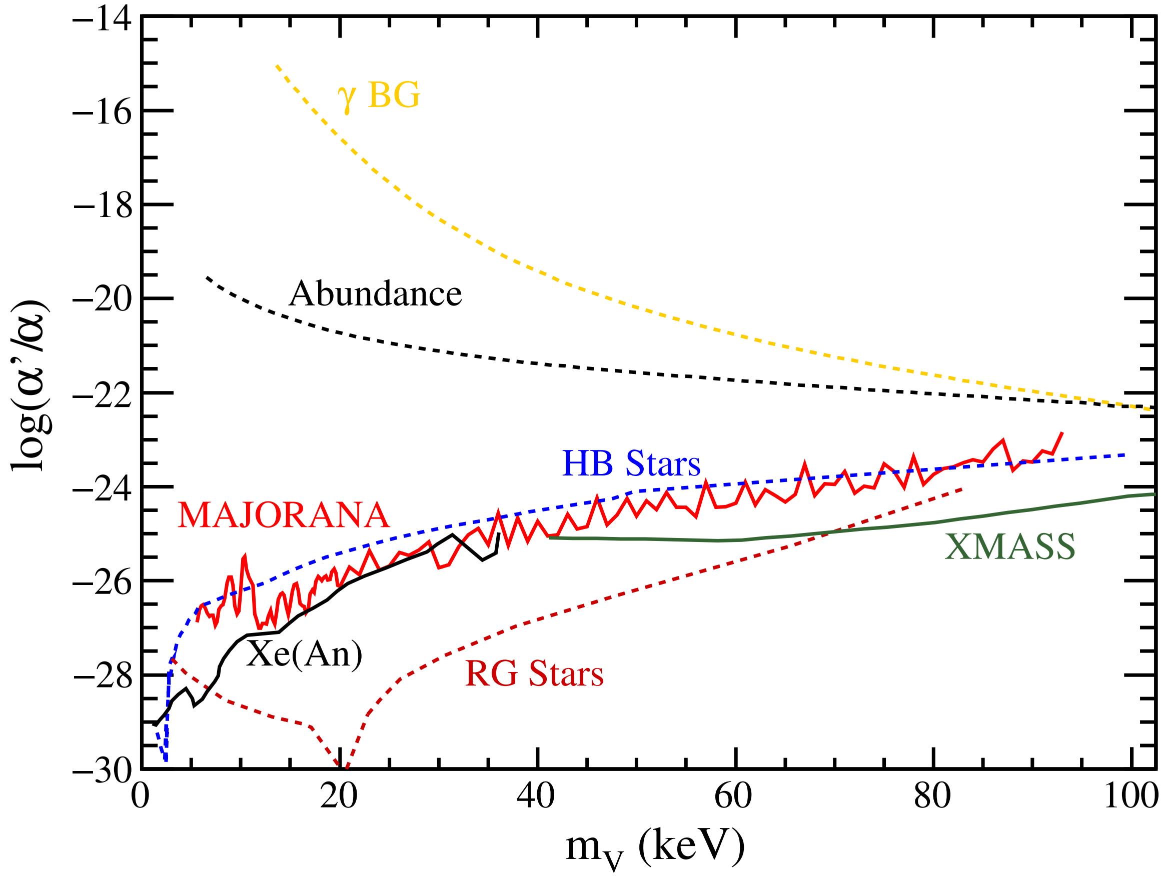
- Most stringent limit is for pseudoscalar axion-like particles (mass 11.8 keV)
- 90% upper limit for the coupling constants based on the expected event rate



Pseudoscalar ALP-like DM

$$g_{Ae} < 4.5 \times 10^{-13}$$

$$S(E) \approx g_{A_e}^2 \left(\frac{m_A}{\text{keV}}\right)\left(\frac{\sigma_{pe}}{\text{barn}}\right)\frac{1.2 \times 10^{-19}}{A}$$



Vector DM electron coupling α'

$$\left(\frac{\alpha'}{\alpha}\right) < 9.7 \times 10^{-28}$$

$$\Phi_{\text{DM}}(m_V)\sigma_{Ve}(m_V) = \frac{4 \times 10^{23}}{m_V}\left(\frac{\alpha'}{\alpha}\right)\frac{\sigma_{pe} m_V}{A}$$

Additional Low-Energy Results

Three additional limits obtained from DS-0: [arXiv:1612.00886]

- **Solar axion coupling** (14.4 keV ^{57}Fe M1)

  Low-mass limit. 90% UL.

  $$g_{AN}^{\text{eff}} \times g_{Ae} < 3.8 \times 10^{-17}$$

- **Non-Paulian transition** in Ge:

  $$a_i a_j^\dagger - q\; a_j^\dagger a_i = \delta_{ij}$$

  $$q = -1 + \beta^2$$

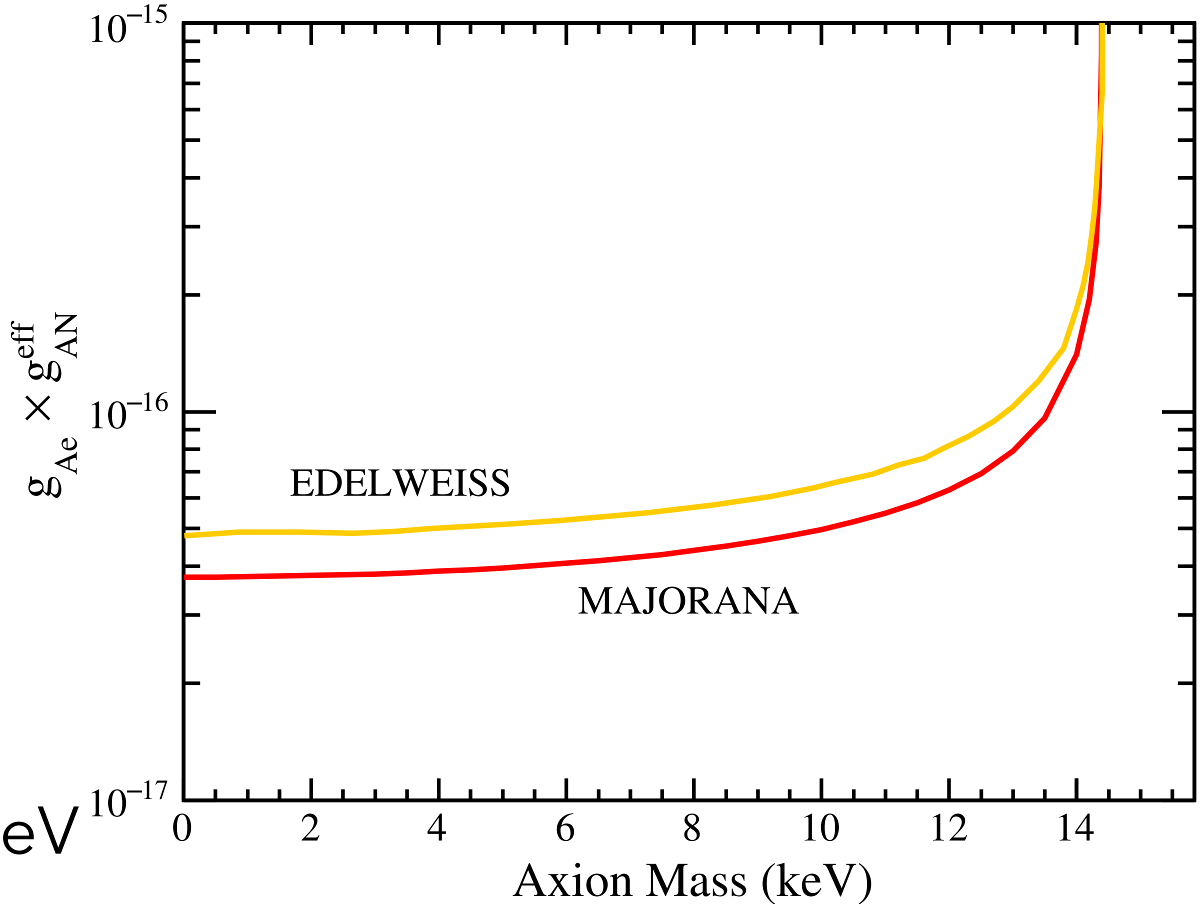
  Binned likelihood study for peak at 10.6 keV

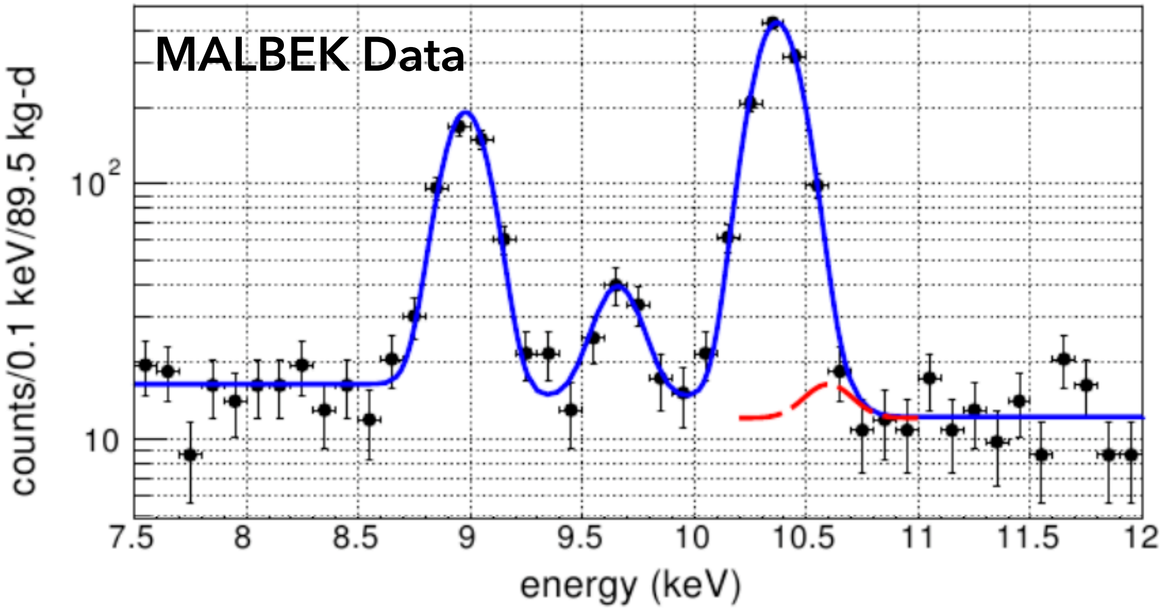
  $$1/2\ \beta^2 < 8.5 \times 10^{-48} \quad \text{(90\% CL UL)}$$

- **Electron decay** $e^- \to \nu\ \bar{\nu}\ \nu$

  Binned likelihood for peak at 11.1 keV

  $$\tau_e > 1.2 \times 10^{24}\ \text{yr} \quad \text{(90\% CL UL)}$$





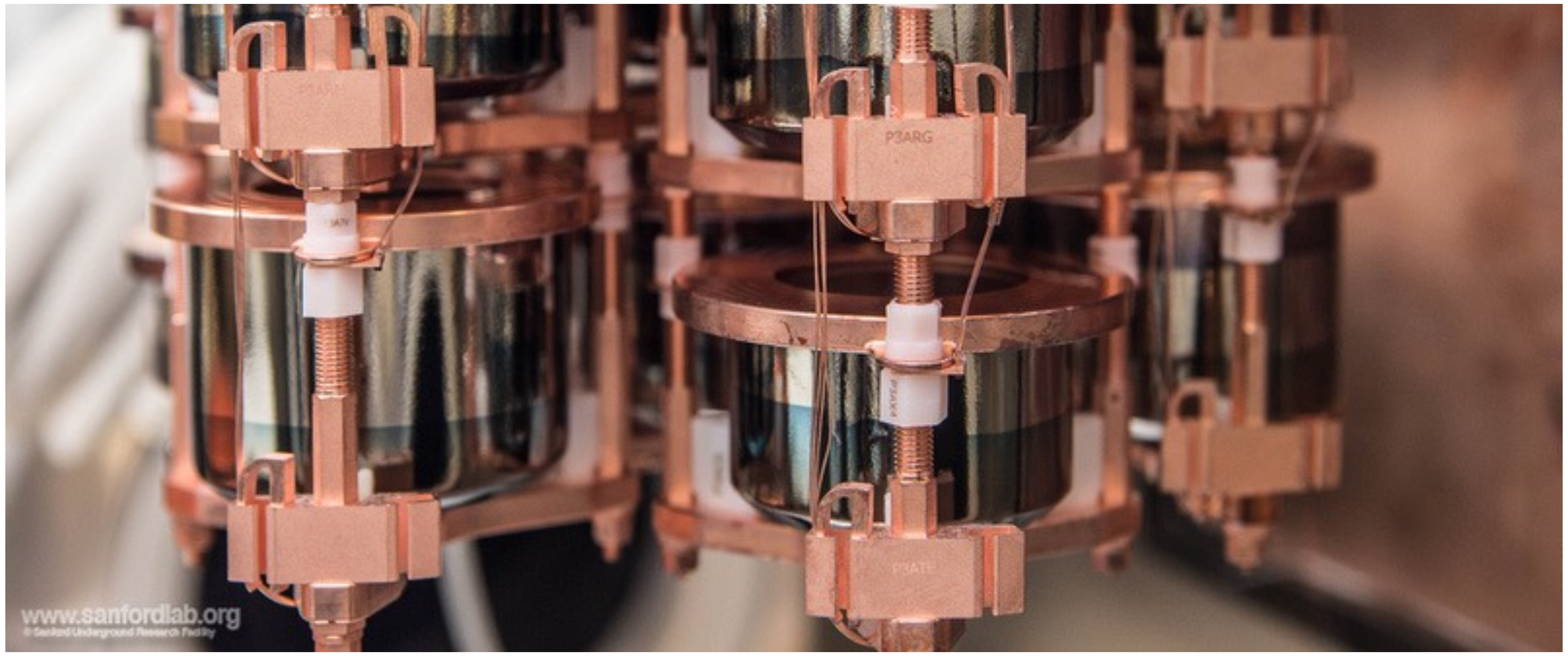
Ref. MALBEK, arxiv:1610.06141

Summary and Outlook

A few recent MAJORANA papers:

- Low-energy DS-0 Results: [arXiv:1612.00886]
- Muon Flux at SURF: [arXiv:1602.07742]
- Calibration System: [arXiv:1702.02466]
- Delayed Charge Recovery: [arXiv:1610.03054]
- Initial 0νββ Results: [arXiv:1610.01210]
- Background Model: [arXiv:1610.01146]

Final shield construction is nearly complete, with both modules online and taking data!



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Backup Slides

LEGEND

Large Enriched Germanium Experiment for Neutrinoless Decay

Working cooperatively with GERDA and other interested groups toward the establishment of a next-generation 76Ge 0vBB decay experimental collaboration, to build an experiment to explore the inverted ordering region of the effective mass.

37 institutions in 14 countries: North America, Europe, and Asia

DS-1 DCR Cut and Bulk-Event Response

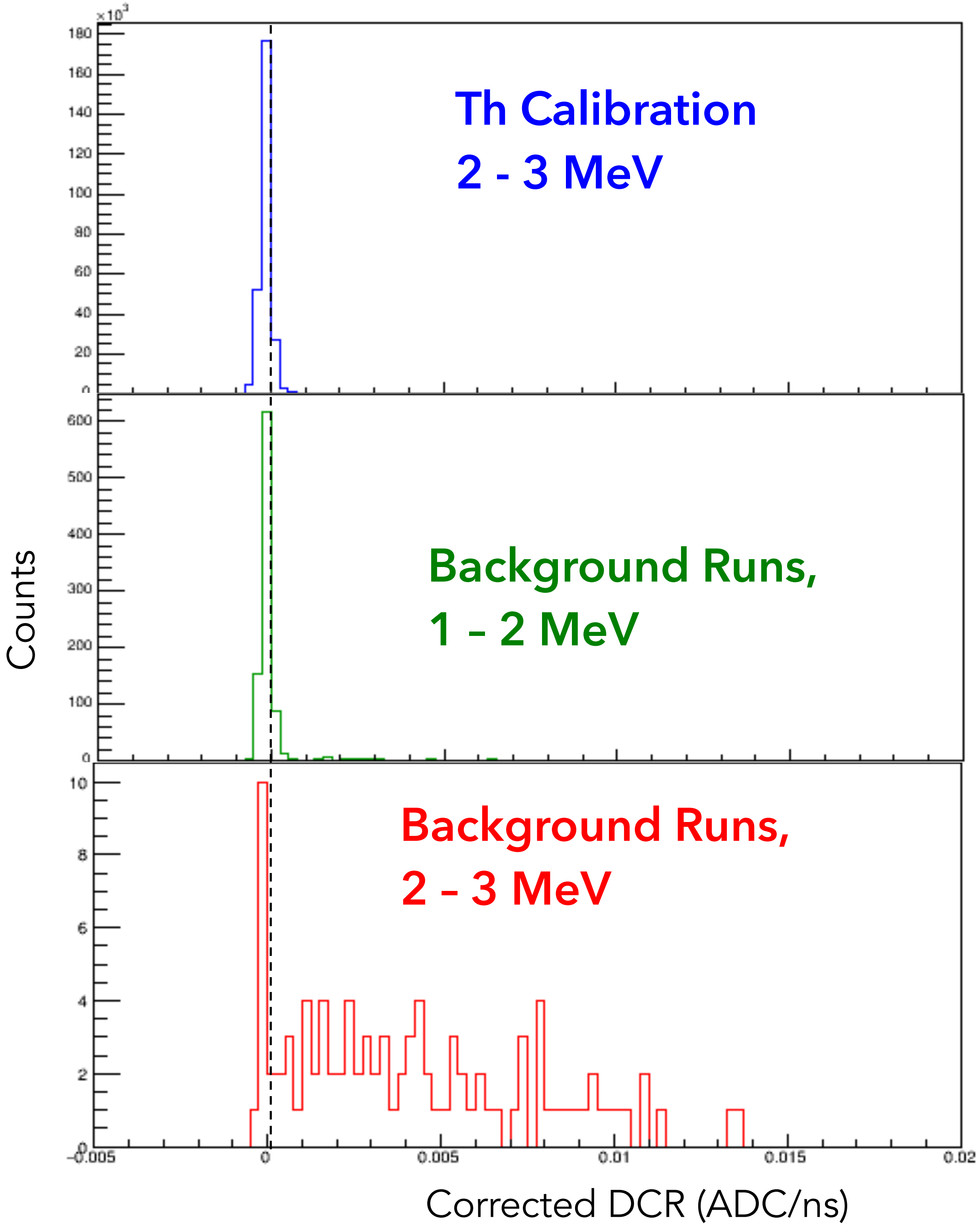
Removes most events above 2 MeV in the background spectrum, which are α candidates. Cut is 90% efficient for retaining events within detector bulk. Only ~5% of α's survive cut.

During calibration runs γ events survive cut.

During background runs ββ(2ν) events survive cut.

Candidate α events from background runs are removed.

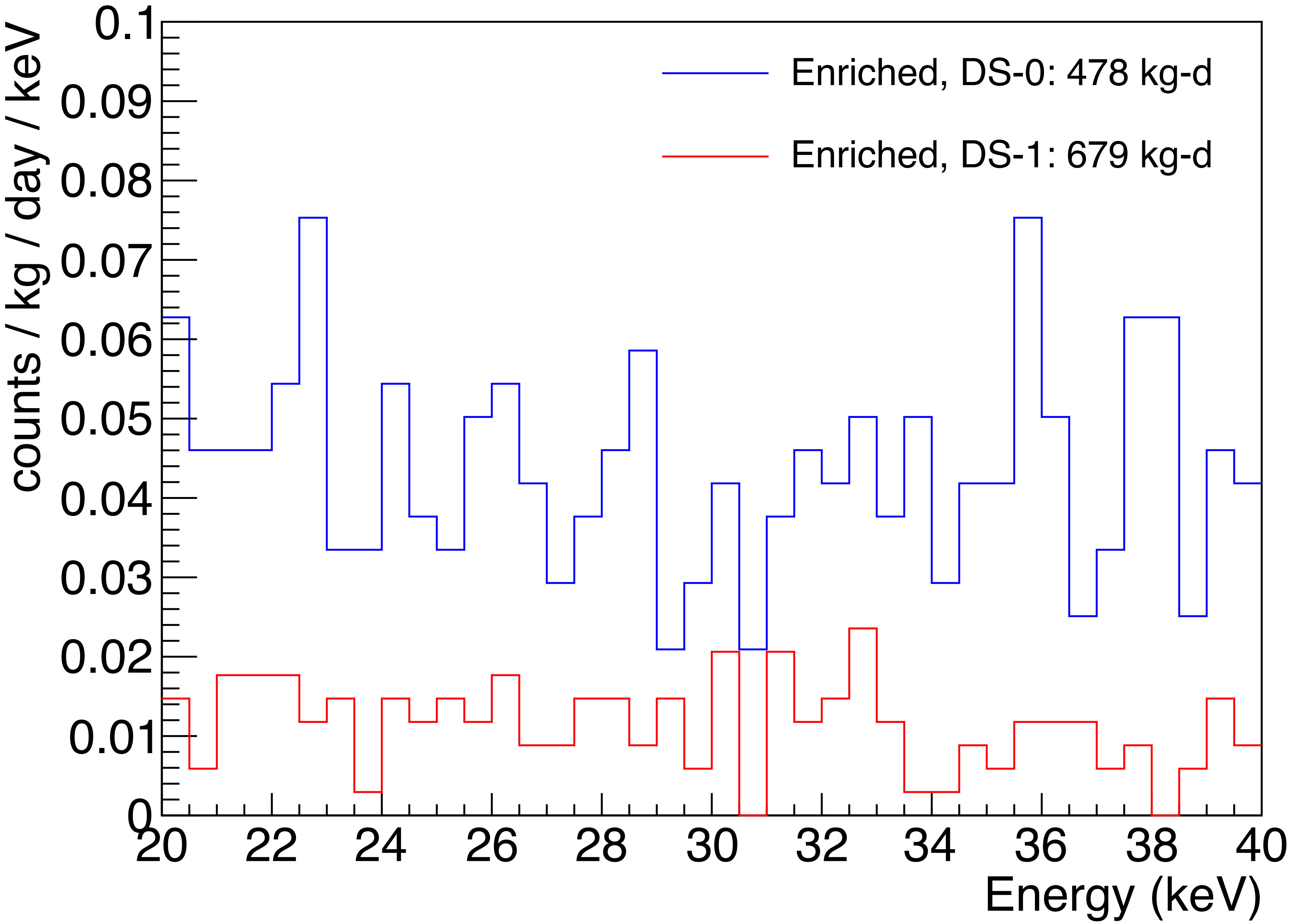
DS1, Enriched Detectors



Enriched Spectra in DS-0 vs. DS-1

Low-energy backgrounds in DS-1 are reduced by a factor of ~ 4 !

- From 20-40 keV: **DS-0 ~0.04** cts/ka-d-keV. **DS-1 ~0.01** cts/ka-d-keV



The MJD Shield

0νββ: Half-Life and Neutrino Mass

$$\boxed{[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2}$$

$T^{0\nu}_{1/2}$ 0νββ half-life. Best current result: > 3.0 x 10^{25} years [5]

$G^{0\nu}(Q_{\beta\beta}, Z)$ phase space factor: kinematics of emission of two electrons

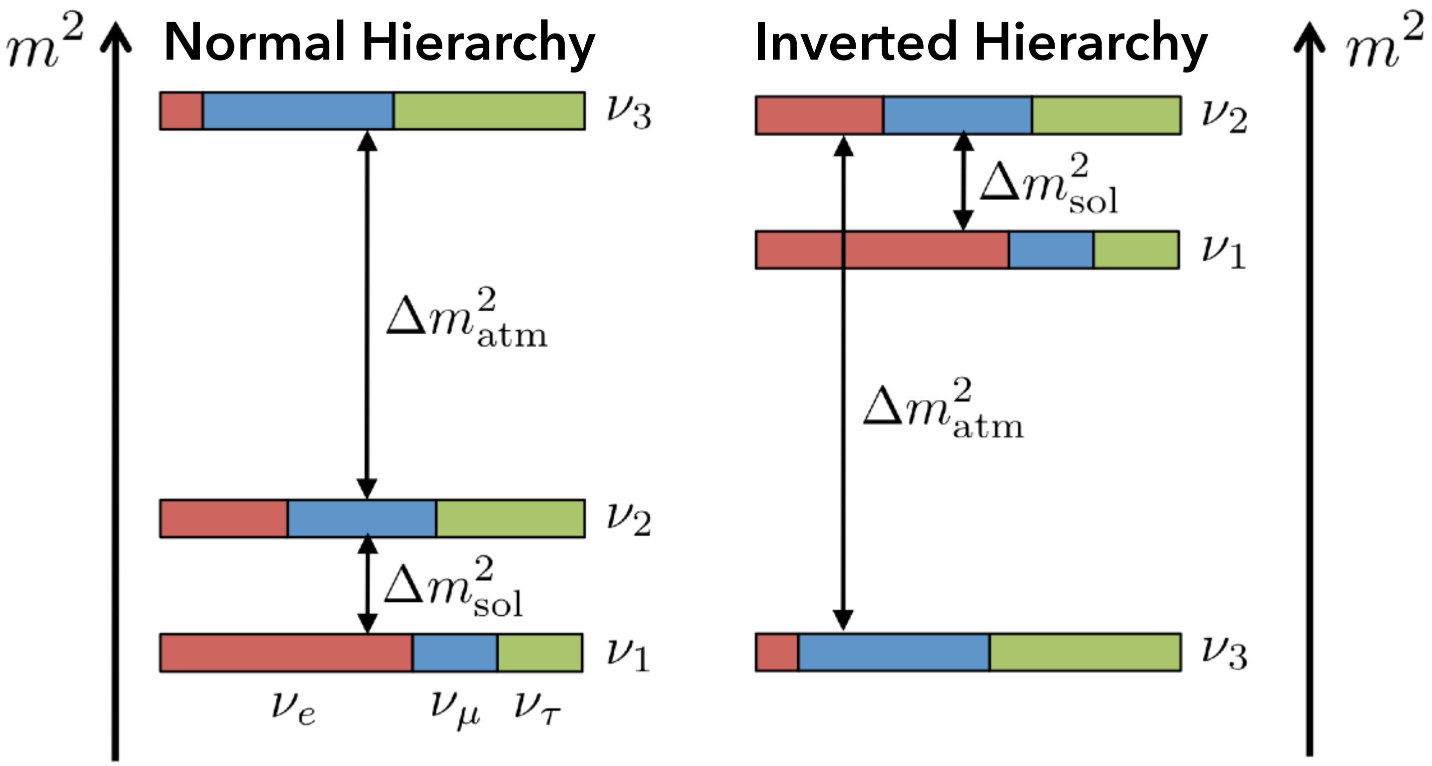
$M_{0\nu}$ nuclear matrix elements: govern transition probabilities

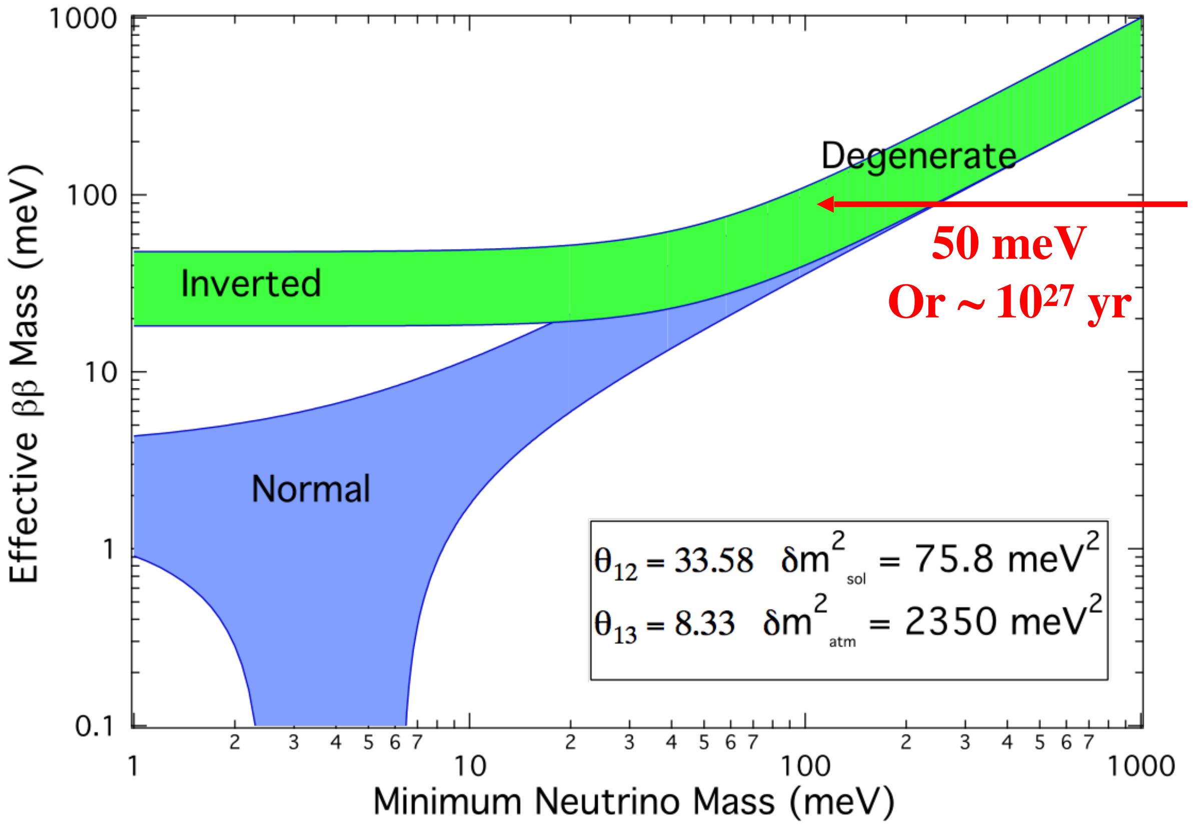
$$\boxed{\langle m_{\beta\beta}\rangle \equiv \left|\sum_k m_k U^2_{ek}\right|}$$

Effective Majorana mass of electron neutrino

Contributions from electron terms in mixing matrix U

Measurements constrain the minimum mass eigenstate

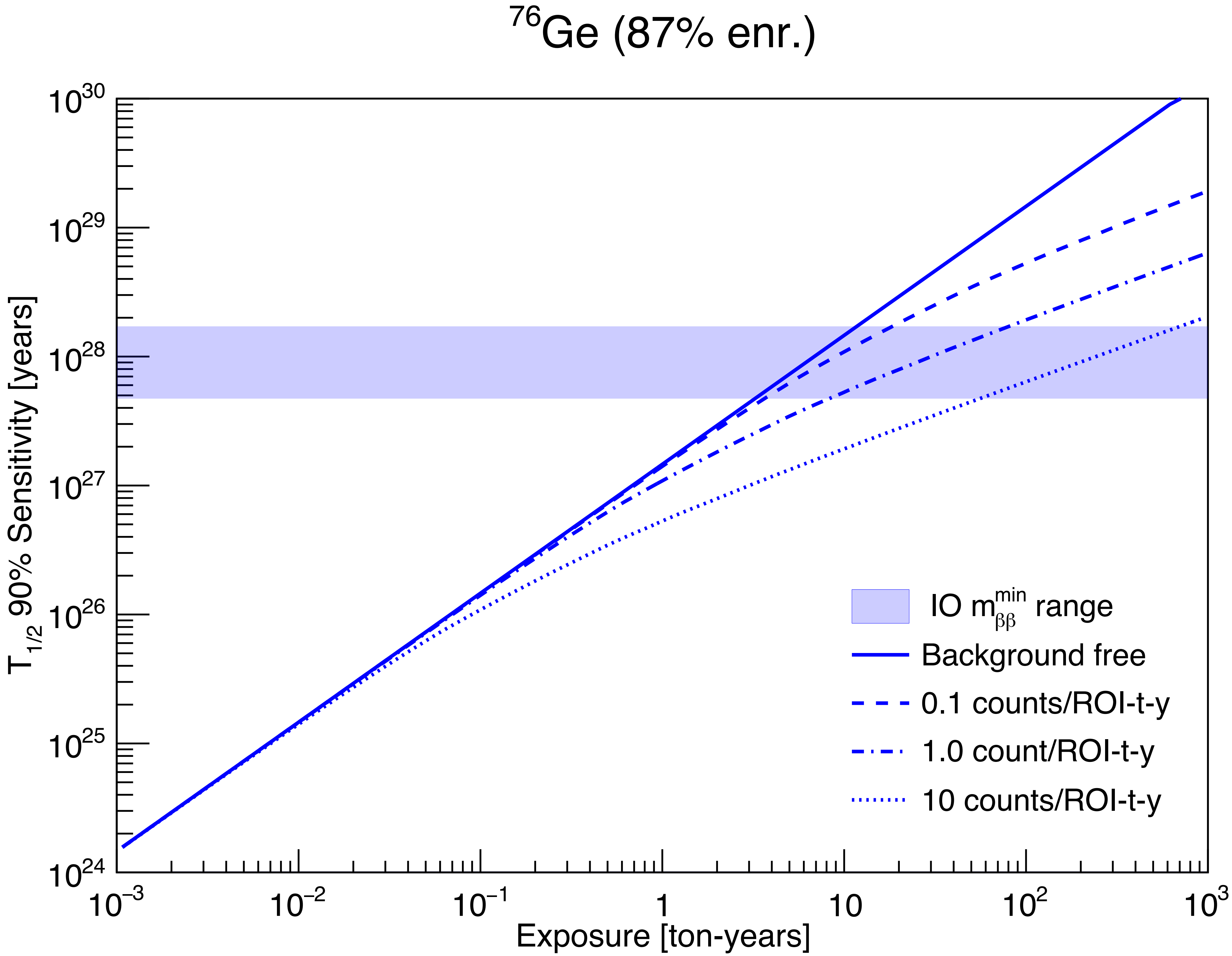




SR Elliott et al. [4]

Sensitivity vs. Exposure

(Slide courtesy J. Detwiler)



Inverted Ordering (IO)

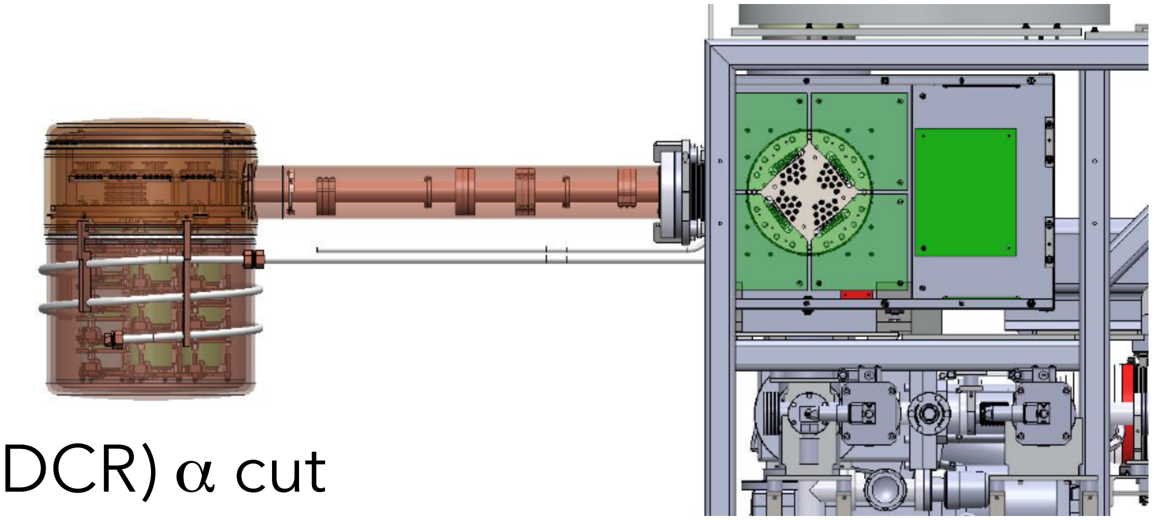
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

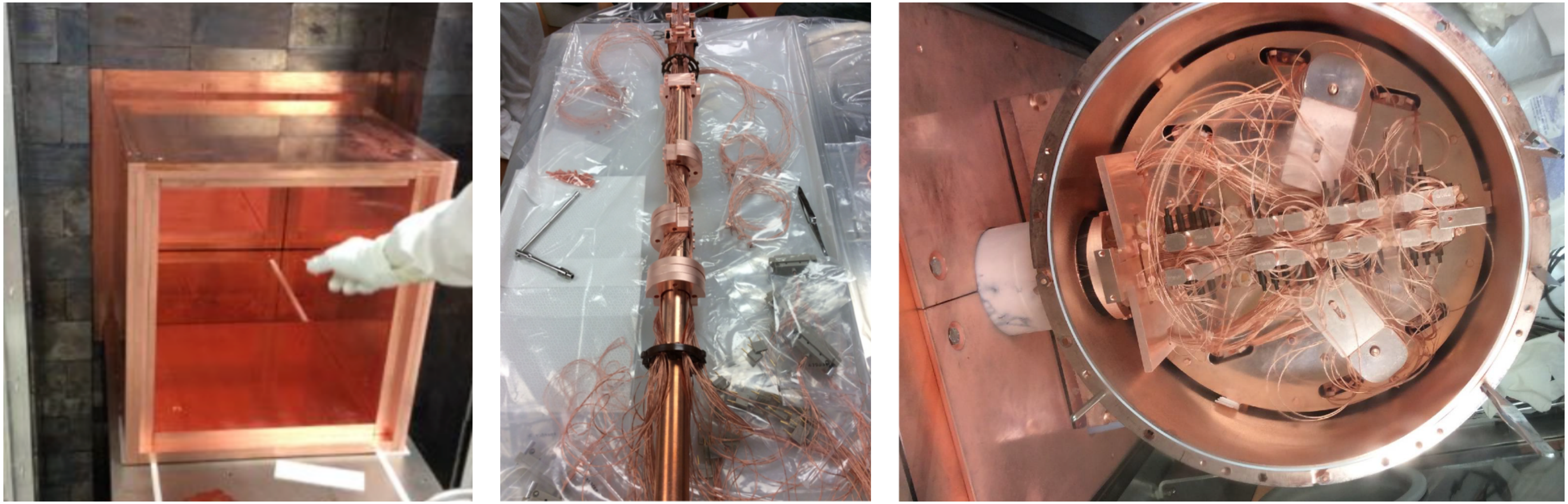
Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

DS-1 Hardware & Analysis Upgrades

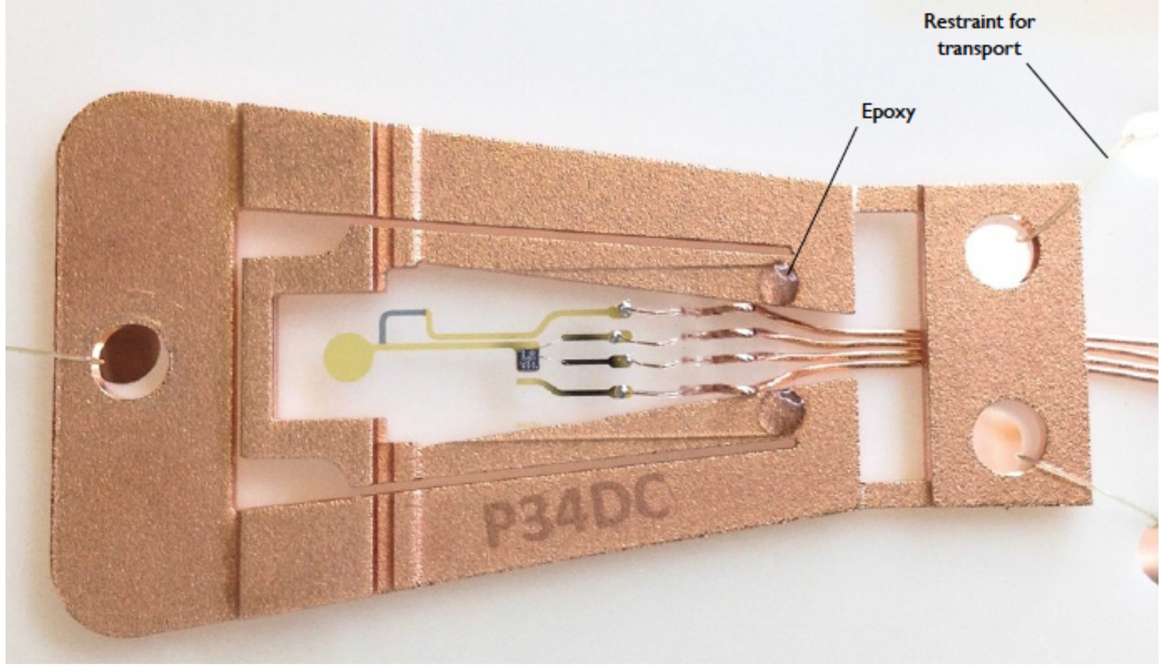
Prior to DS-1 (Dec. 31, 2015 - May 24, 2016)

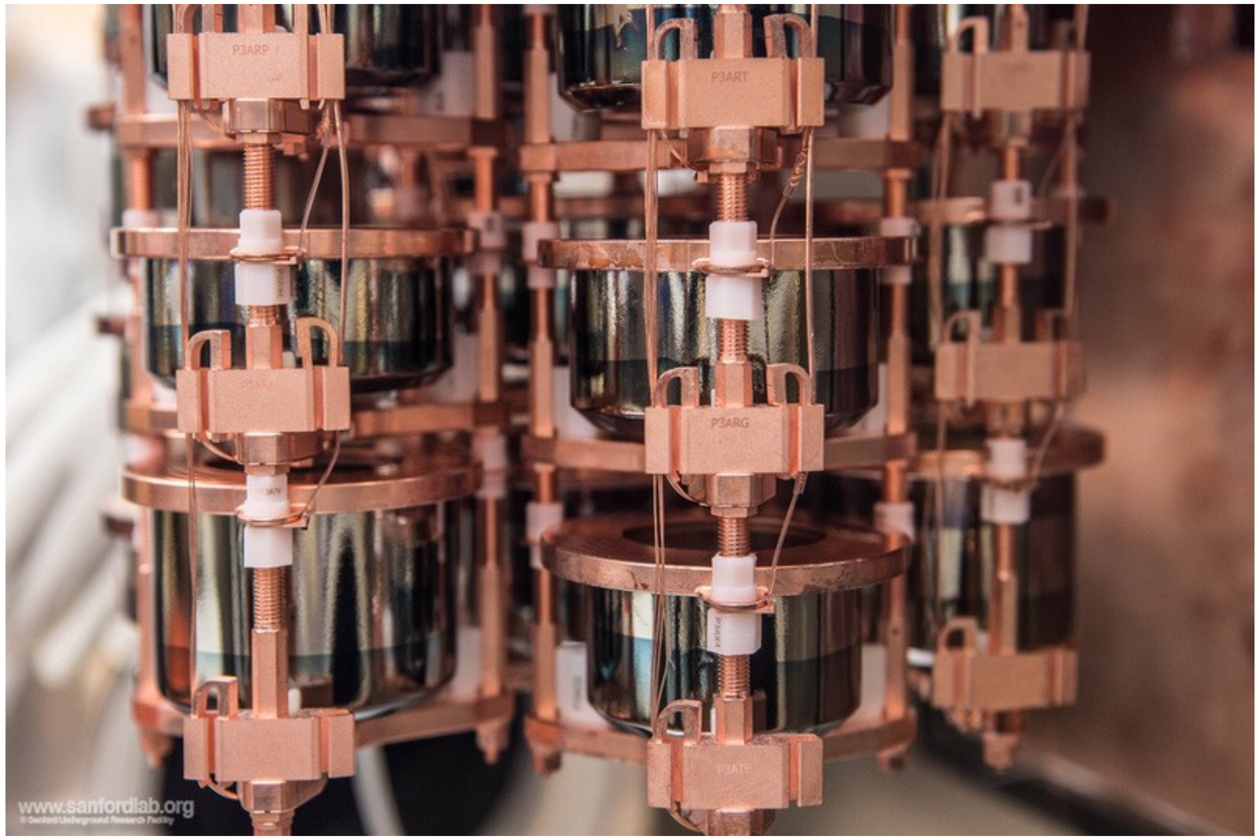
- Installed electroformed inner Cu shield
- Added shielding in cryostat cross arm
- Replaced cryostat seal with PTFE gasket
- Implemented delayed-charge recovery (DCR) α cut
- Implemented muon veto and microphonics cuts





Radiopure Components





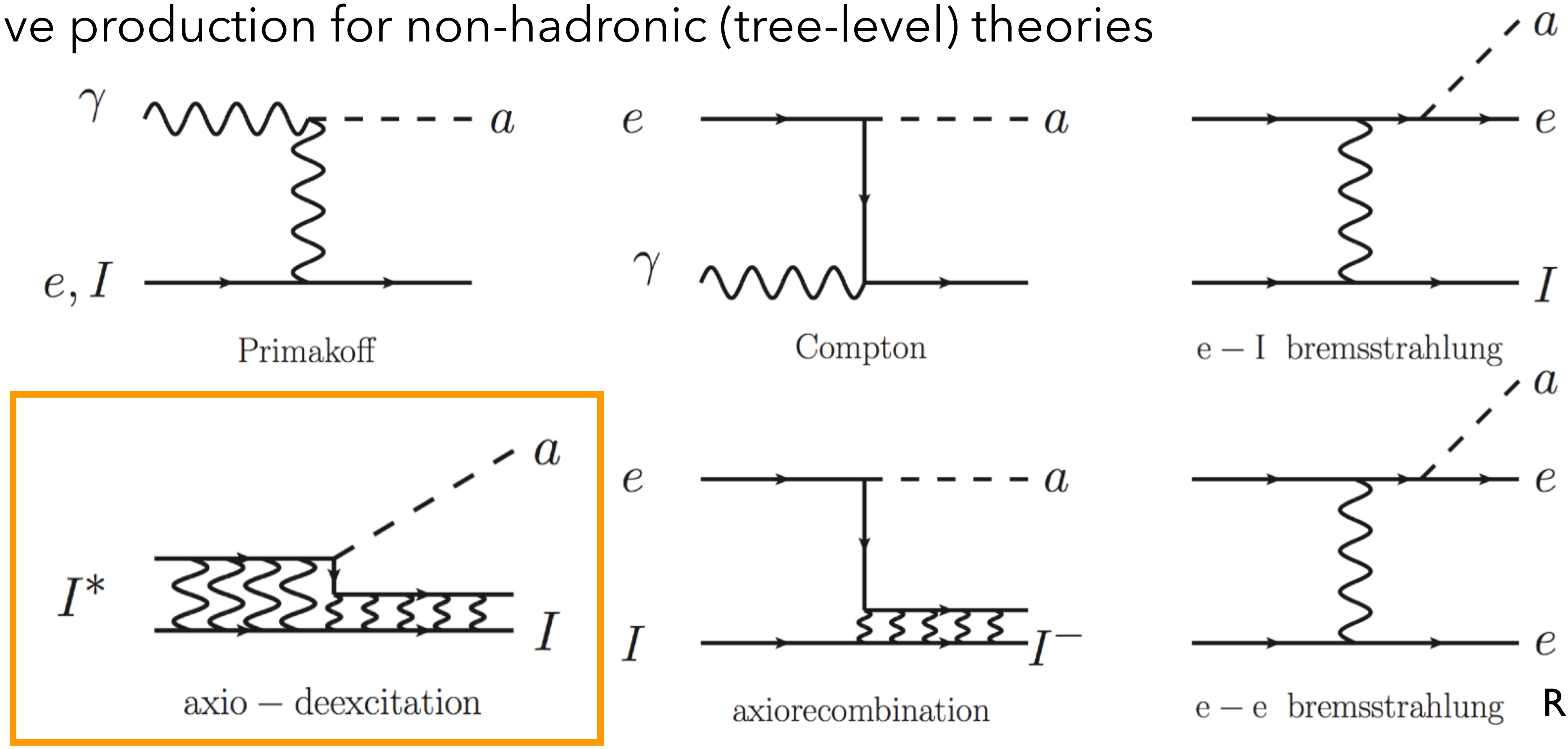
Solar Axions: A Brief Overview

The "strong-CP" problem: The neutron electric dipole moment is too small!

- Value predicted by QCD: $10^{-18} e \cdot cm$ Best experimental bound: $< 2.9 \times 10^{-26} e \cdot cm$
- Peccei and Quinn added a U(1) symmetry term to the Standard Model which is broken at high energy scales and *results in CP violation at low energy scales*
- Creates a Goldstone boson: neutral, spin-zero pseudoscalar particle, dubbed **"axion"**

"Solar Axions" would be produced in the sun in large quantities

- The "ABC" reactions: **A**xion deexcitation & recombination, **B**remmstrahlung, **C**ompton drive production for non-hadronic (tree-level) theories



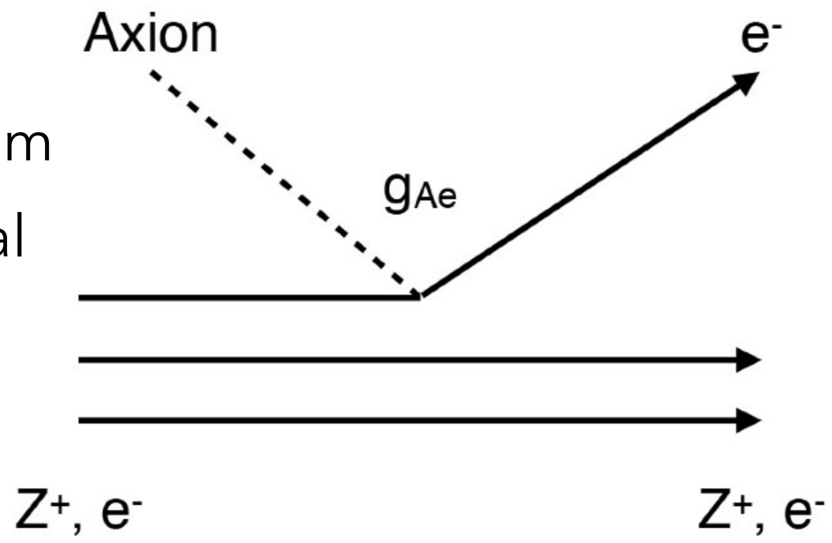
Ref: J. Redondo, [16]

***CP-symmetry**: We observe the same physics when we replace a particle with its antiparticle (C) and invert its spatial coordinates (P)

Observing Axions in HPGe Detectors

The axio-electric effect:

The axion "takes the place" of a photon and ionizes a germanium nucleus. The released electron is given an energy (nearly) equal to the incident axion.



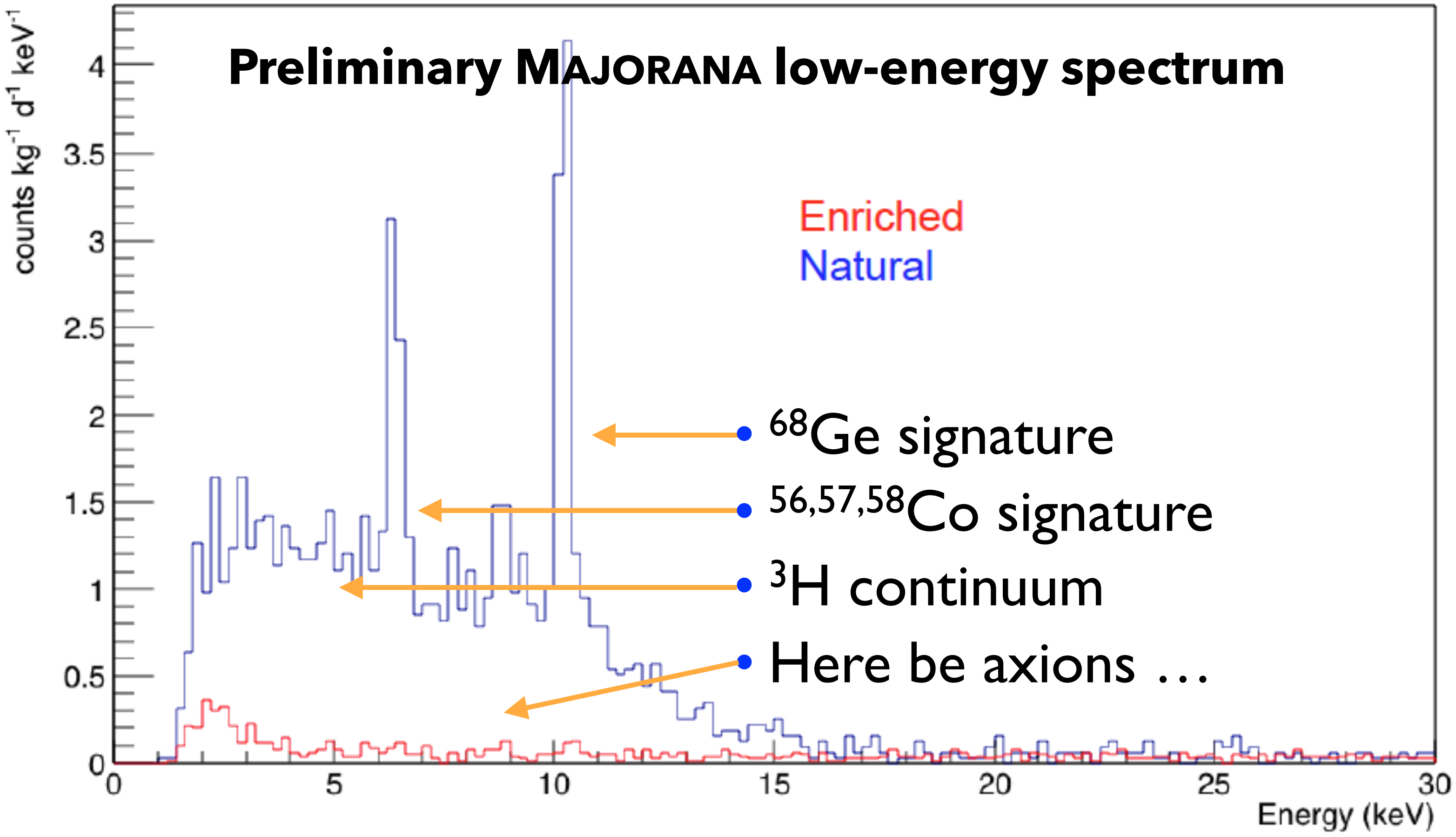
$$\sigma_{ae}(E_a) = g_{ae}^2\ (2.088 \times 10^{-5}) E_a^2\ \sigma_{pe}(E_\gamma)$$

HPGe detector advantages:

- **Sub-keV energy thresholds** possible
- Excellent energy resolution
- Enriched detectors have reduced cosmogenic activation

Proposed research:

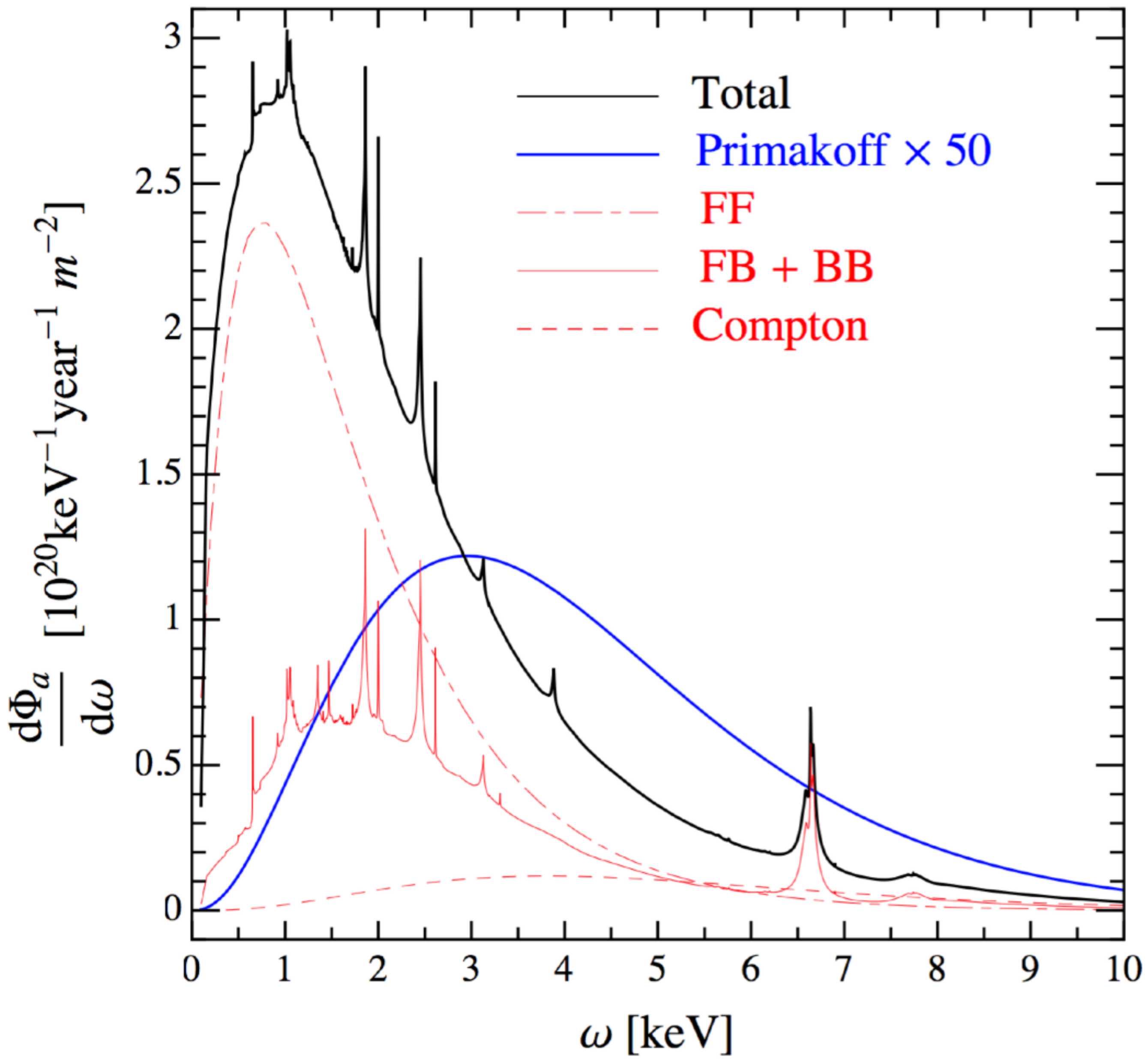
- Search the low-energy region for the peaks predicted by Redondo. If no peaks are found, set a competitive upper limit on the coupling term g_{ae}
- Contribute to the ongoing effort to characterize the low-energy region of the Ge detectors.

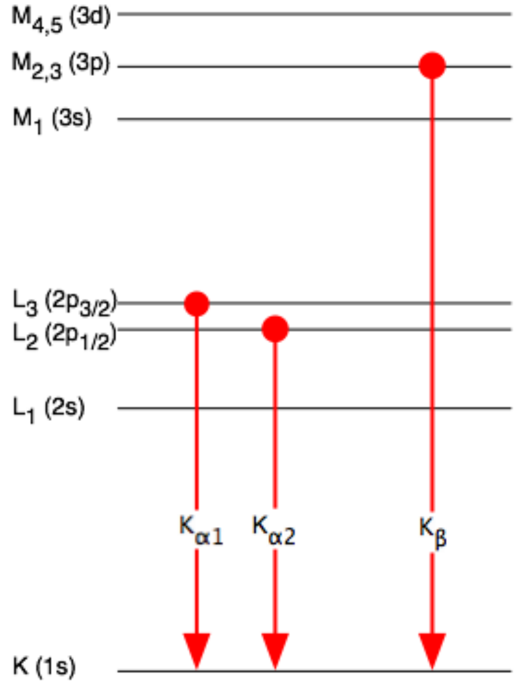


Preliminary MAJORANA low-energy spectrum

- ^{68}Ge signature
- ^{56,57,58}Co signature
- ^{3}H continuum
- Here be axions …

Solar Axions from Nuclear Transitions





Source	Energy (keV)	Predicted Flux cts/(cm^2 day)
Si($K_{\alpha1,\alpha2}$)	1.739	4.95×10^{38}
Si($K_{\beta1}$)	1.836	4.06×10^{38}
S($K_{\alpha1,\alpha2}$)	2.307	4.00×10^{38}
S($K_{\beta1}$)	2.464	2.57×10^{38}
Fe($K_{\alpha1,\alpha2}$)	6.4	4.06×10^{38}

Monoenergetic transitions in the Sun: The axion can "take the place" of a photon by axio-deexcitation and recombination, and be emitted with (nearly) the same energy

Experiments can set bounds on **axion coupling terms**: g_{ae} $\quad g_{a\gamma\gamma}$

Example: $\Phi^{\text{a}}_{Fe}(6.4\ \text{keV}) = g^2_{ae}\ (4.7\times10^{33}\text{cm}^{-2}\ \text{s}^{-1})$

J Redondo, private communication to F.T. Avignone