Status and Preliminary Results from the MAJORANA DEMONSTRATOR

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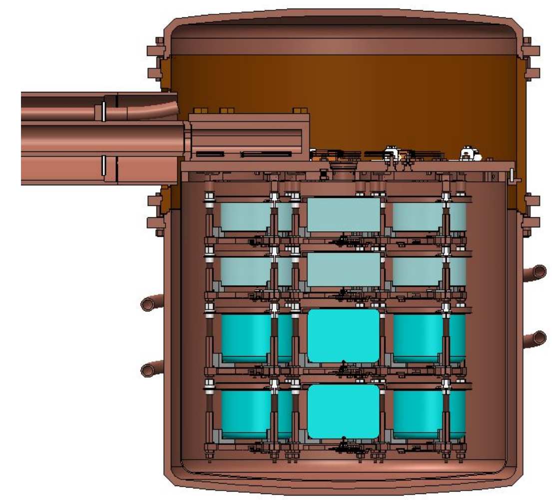
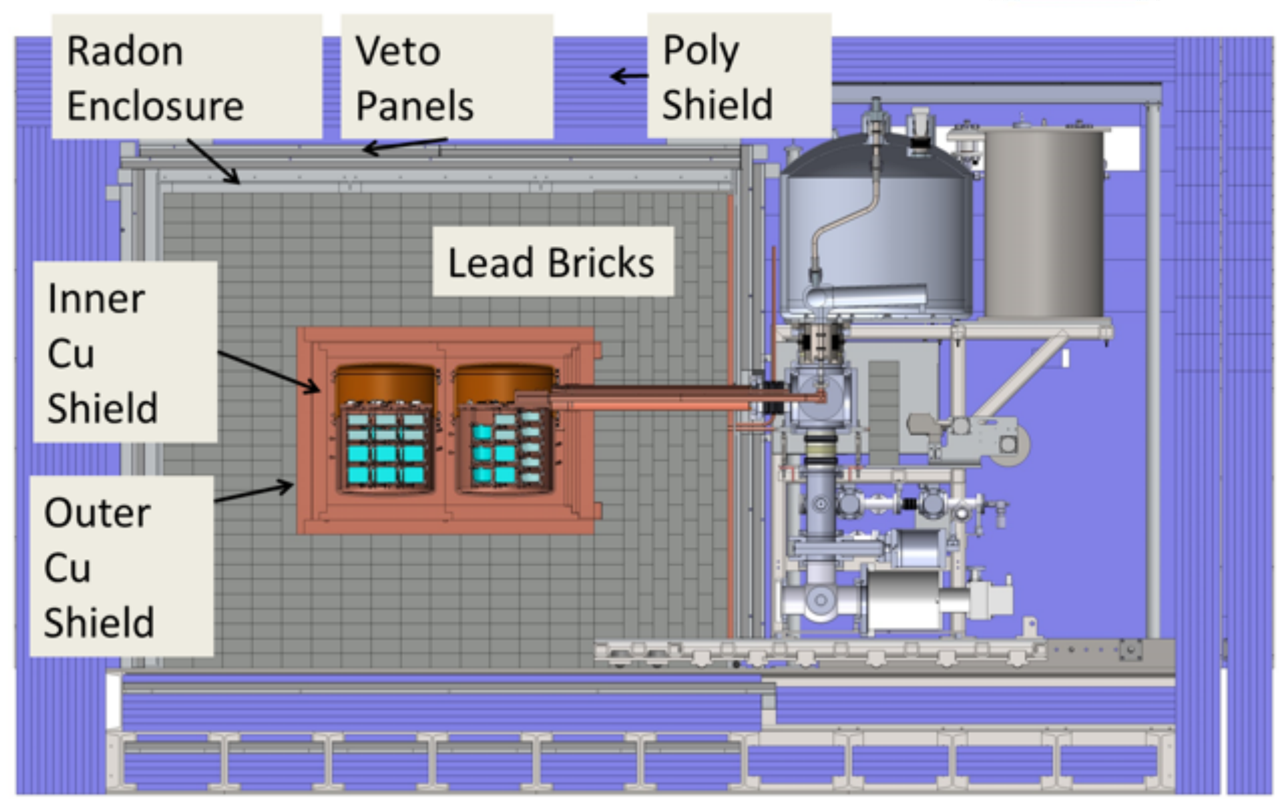
MAJORANA DEMONSTRATOR Overview

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.
- Searches for additional physics beyond the standard model.

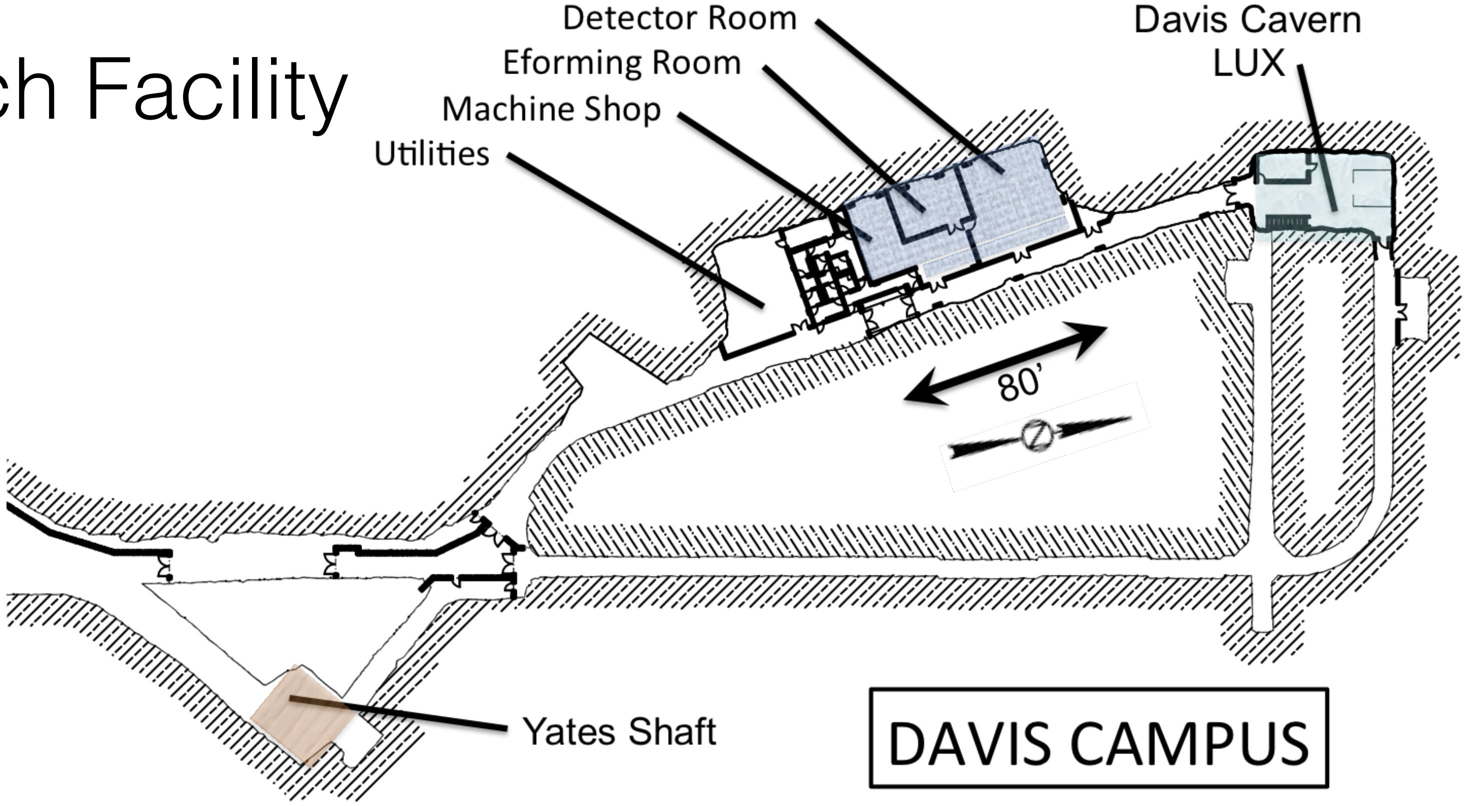


- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5
  scales to 1 count/ROI/t/y for a tonne experiment
- 44.1-kg of Ge detectors
  – 29.7 kg of 88% enriched ^{76}Ge crystals
  – 14.4 kg of ^{nat}Ge
  – Detector Technology: P-type, point-contact.
- 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



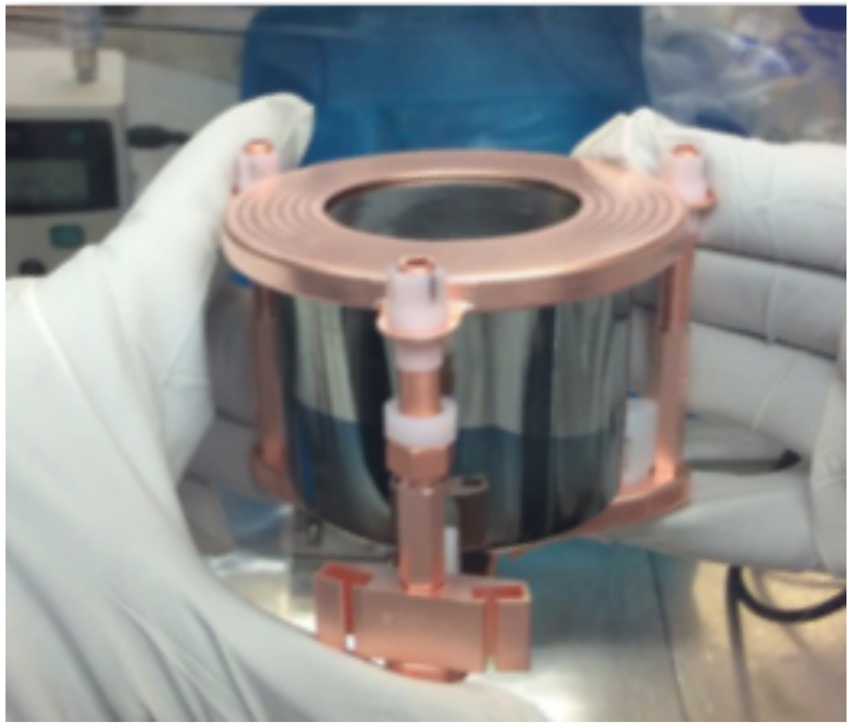
MAJORANA Underground Laboratory

Sanford Underground Research Facility
4850ft level
Lead, SD
Clean room conditions
Muon flux: 5×10^{-9} μ/cm^2/sec
(arXiv: 1602.07742)



MAJORANA Ge Detectors

- **P-Type Point Contact HPGe**
  - Simple, cost-effective
  - Localized weighting potential enables multi-site event rejection
  - Low noise allows for excellent resolution at low energy
- **Enriched Detectors:**
  - AMETEK/ORTEC
  - ~900g each
  - All production in Oak Ridge, TN, USA
- **Natural Detectors:**
  - Canberra modified BeGes
  - ~650g each



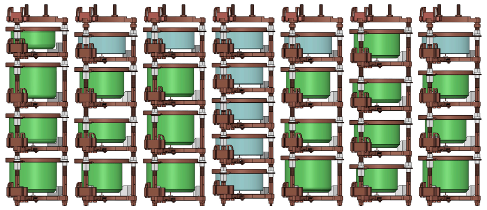
^{enr}Ge PPC

^{nat}Ge BeGe

MAJORANA DEMONSTRATOR Implementation

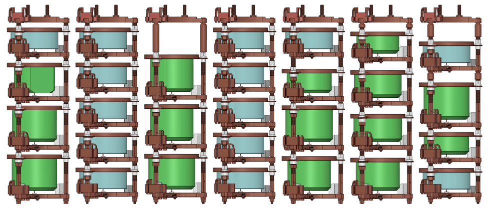
Module 1

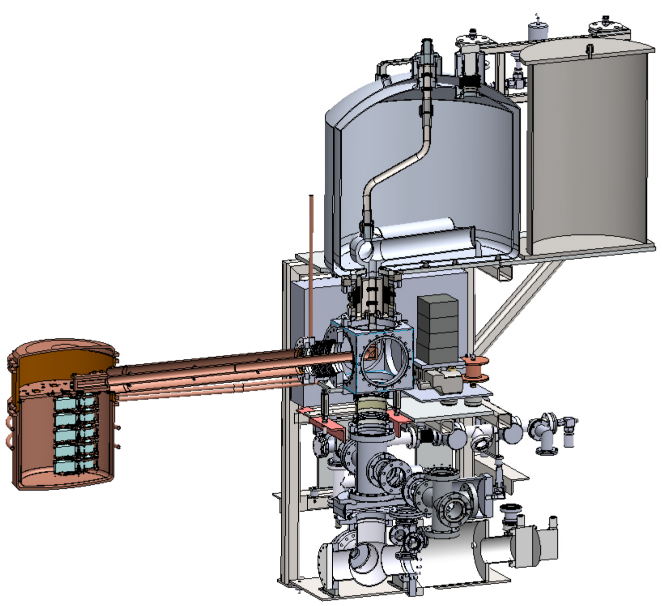
16.9 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge

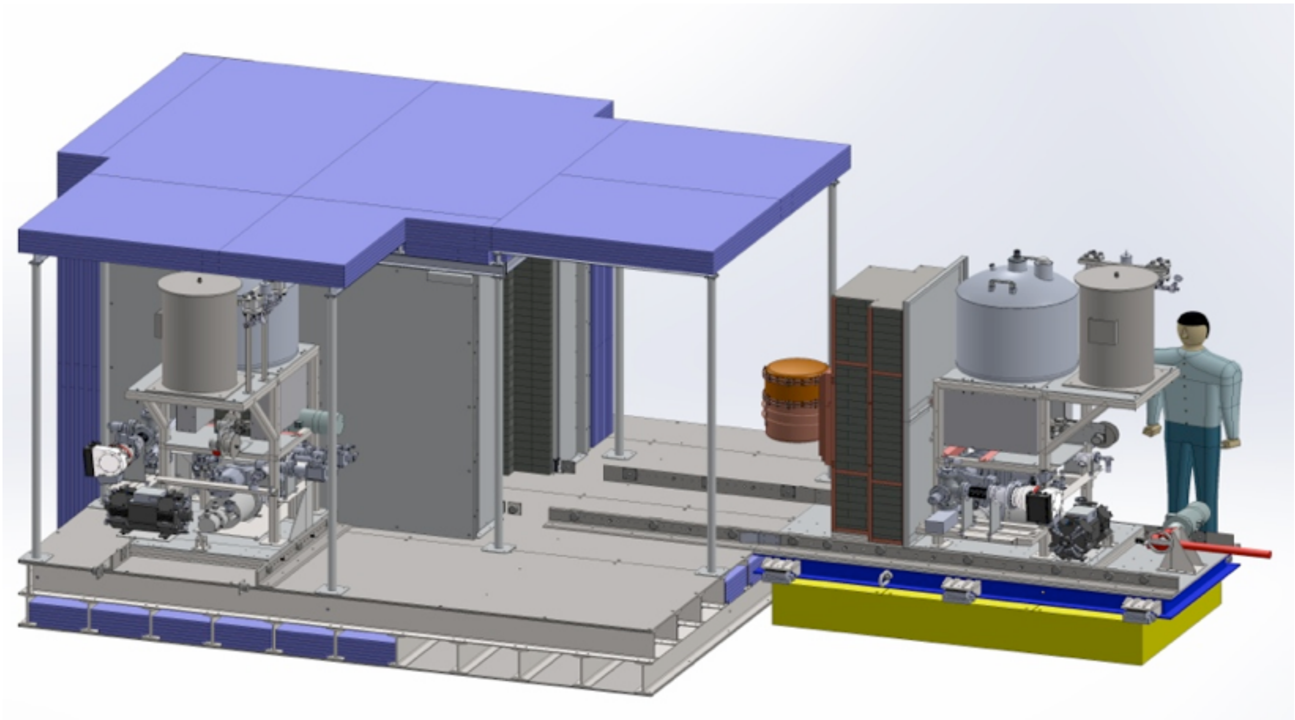


Module 2

12.9 kg (14) ^{enr}Ge
8.8 kg (15) ^{nat}Ge





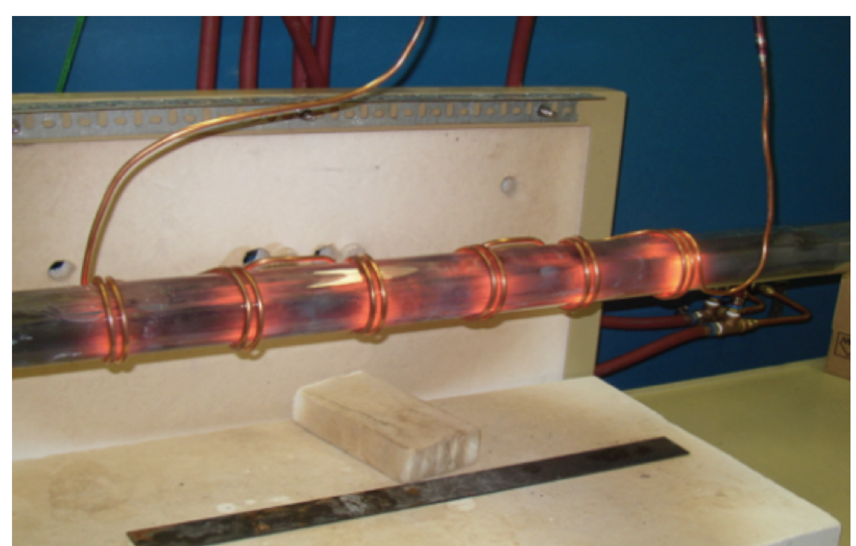


Ge Processing and Recovery

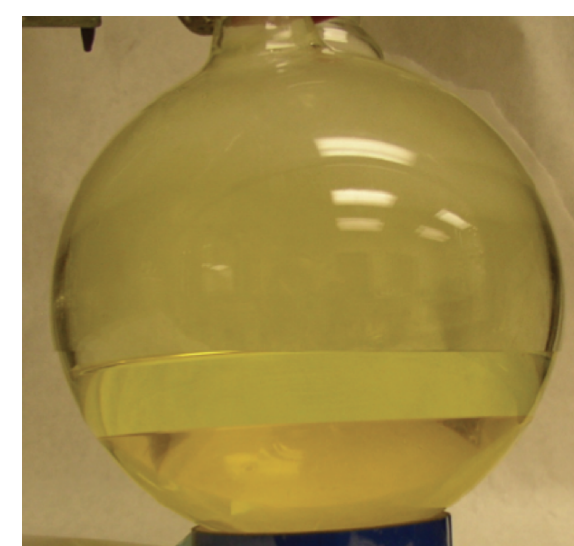
- Better than 98% yield from original 42.5-kg of ^{enr}Ge (61.7 kg of GeO_2)
- Recovered Ge from processing detector manufacturing waste
  - 8.4 kg of “scrap” reprocessed
    - 2.87 kg of metal from detector manufacturer reject
    - 5.87kg of Ge with >47 Ω-cm recovered from the manufacturing effluent and kerf
  - Mixed with 3.22 kg of remaining Ge material to yield 9.1 kg of Ge >47 Ω-cm
- Resulted in 74% yield of operating detectors; best to date for Ge experiments

Ge reduced in Cl gas

Zone refining of Ge metal

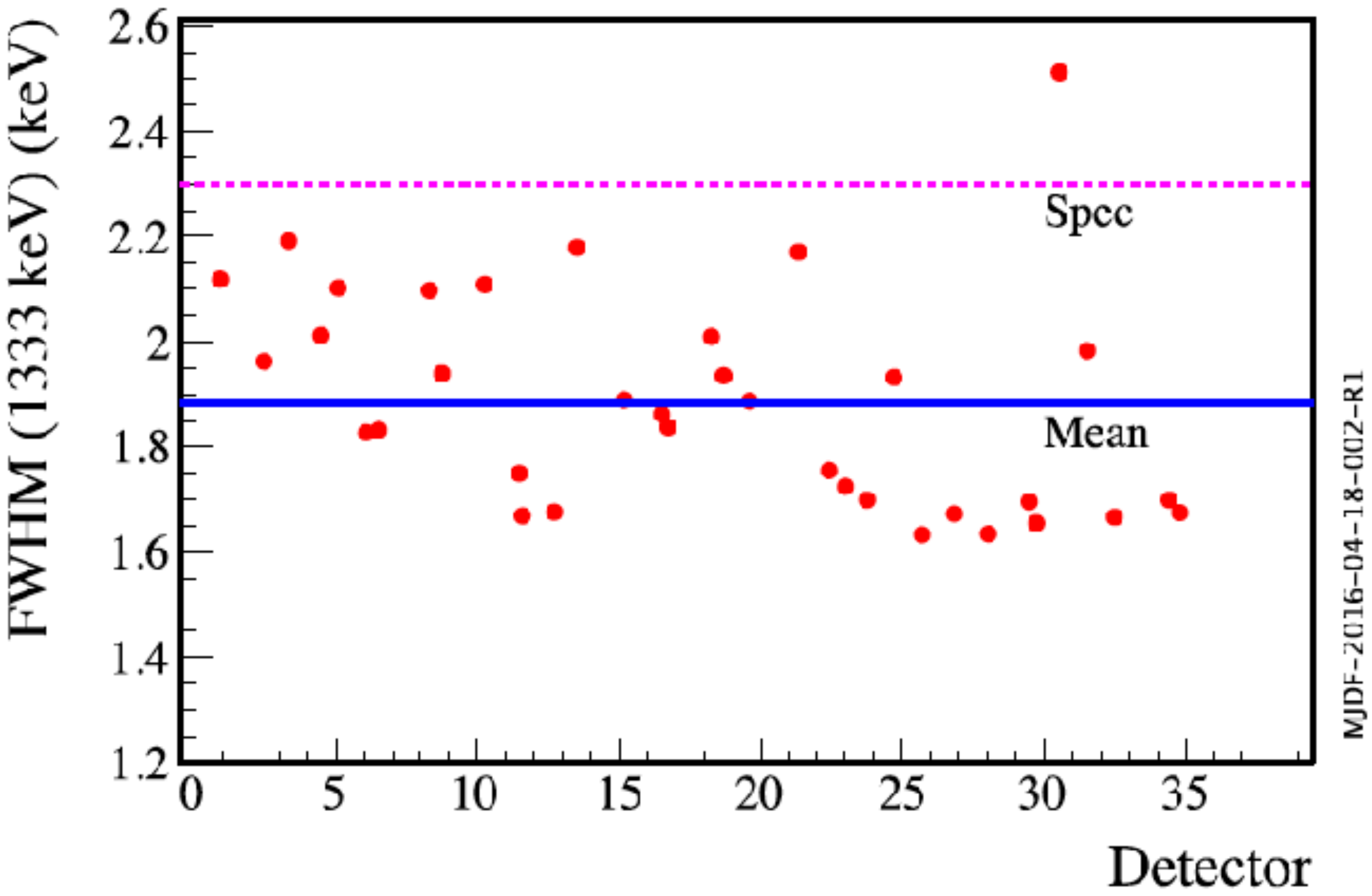


GeCl with cover liquid



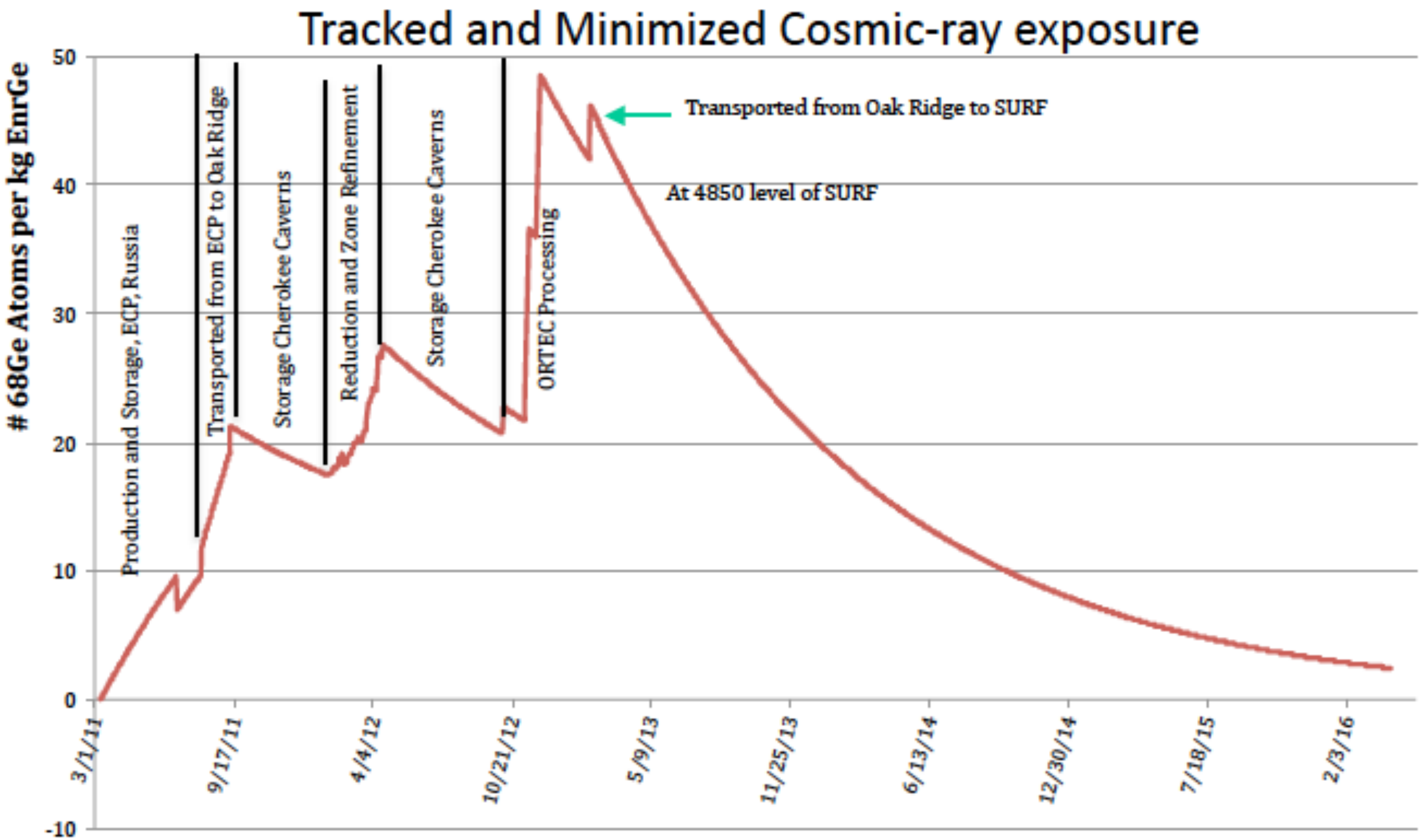
Total Delivered Detectors

Vendor: AMETEK/ORTEC
Enriched detector production completed in June 2015
Total enriched detector mass = 29.683 kg / 35 detectors
Mean FWHM at 1333 keV = 1.88 keV



^{68}Ge Production in Detector P42537A

- Cosmic ray exposure minimized throughout all processes
- Typical sea-level equivalent exposure is ~35days for enriched detectors



Low-Background Materials

- Low-mass component design
- Electroformed production of radio-pure copper
- Careful selection of low-background plastics
- Deep underground cleanroom production, fabrication, assembly facilities
- Glovebox assembly
- Extensive materials assay campaign
  - See: **NIM A 828 23-36 2016**

MAJORANA Electroformed Copper

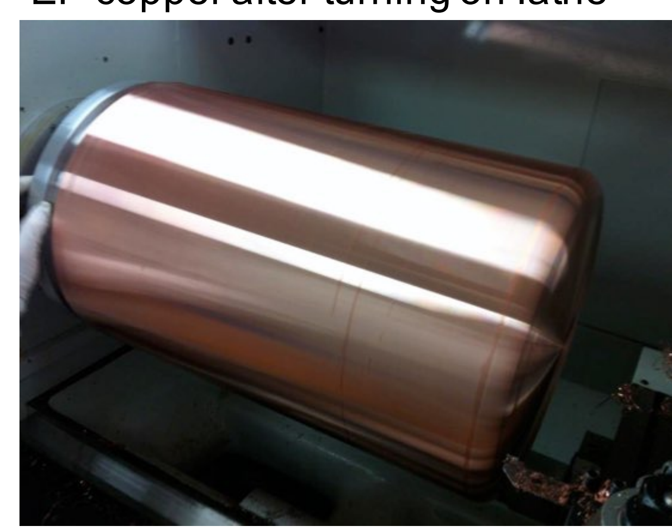
- Majorana operated 10 baths at the Temporary Clean Room (TCR) facility at the 4850' level and 6 baths at a shallow UG site at PNNL. All copper was machined at the Davis campus.
- The electroforming of copper for the DEMONSTRATOR successfully completed in May 2015.
  - 2474 kg of electroformed copper on the mandrels,
  - 2104 kg after initial machining,
  - 1196 kg installed in the DEMONSTRATOR.
- Underground machining completed April 2016. (Machinist still available as needed.)
- TCR decommissioning is underway.

Electroforming Baths in TCR

Inspection of EF copper on mandrels

- **Th decay chain (avg) ≤ 0.1 μBq/kg**
- **U decay chain (avg) ≤ 0.1 μBq/kg**

EF copper after turning on lathe

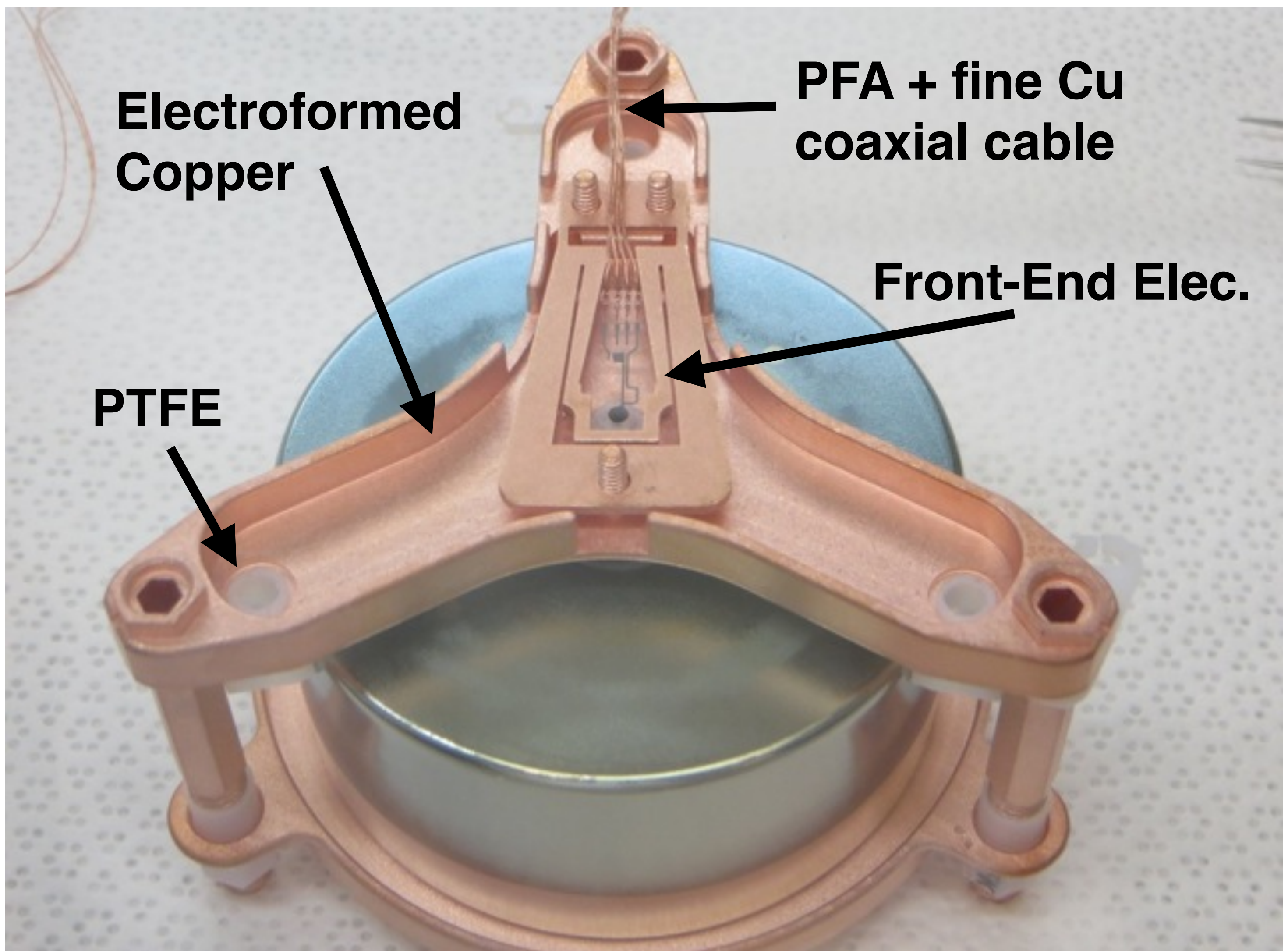


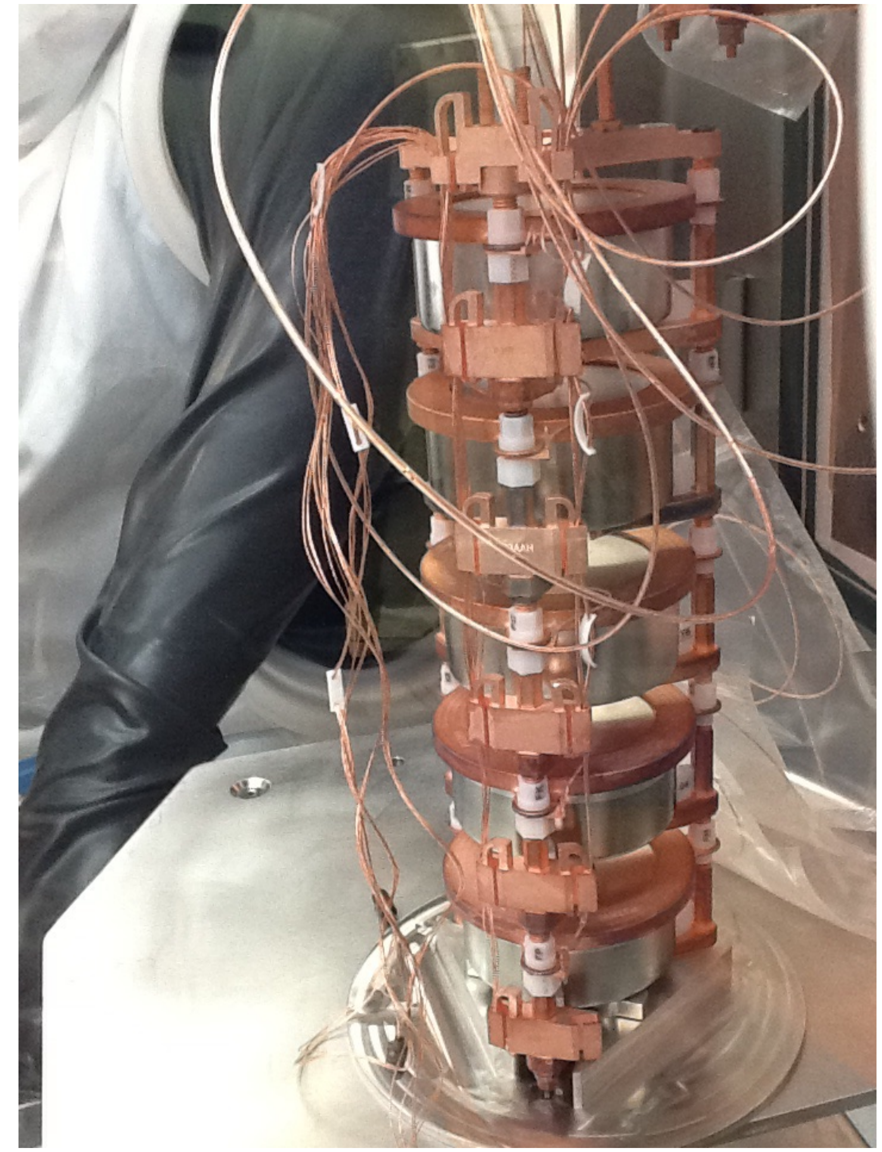
Detector Units and Strings

AMETEK (ORTEC) fabricated enriched detectors.

35 Enriched detectors at SURF 29.7 kg, 88% ^{76}Ge.

20 kg of modified natural-Ge BEGe (Canberra) detectors in hand (33 detectors UG).

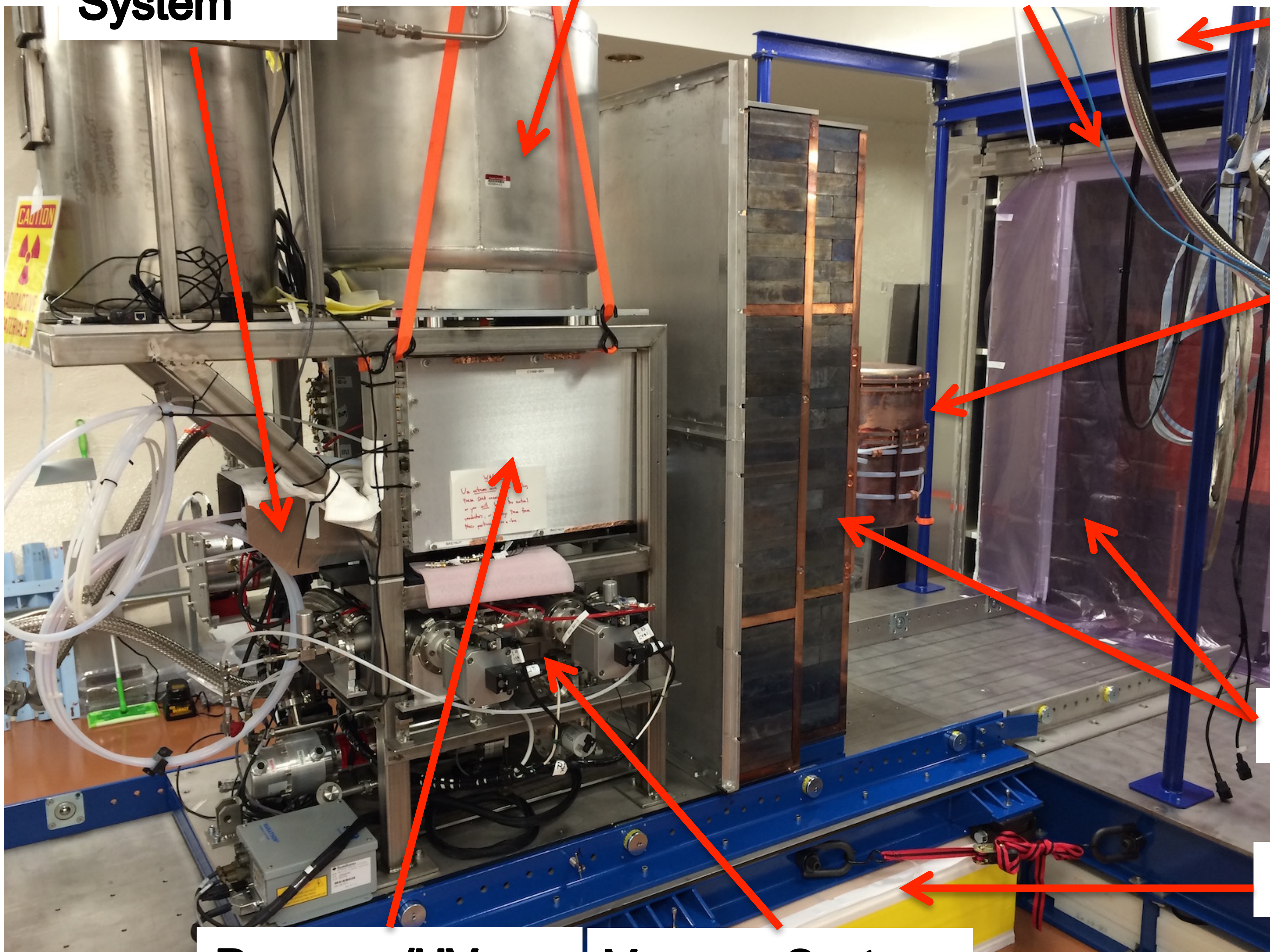




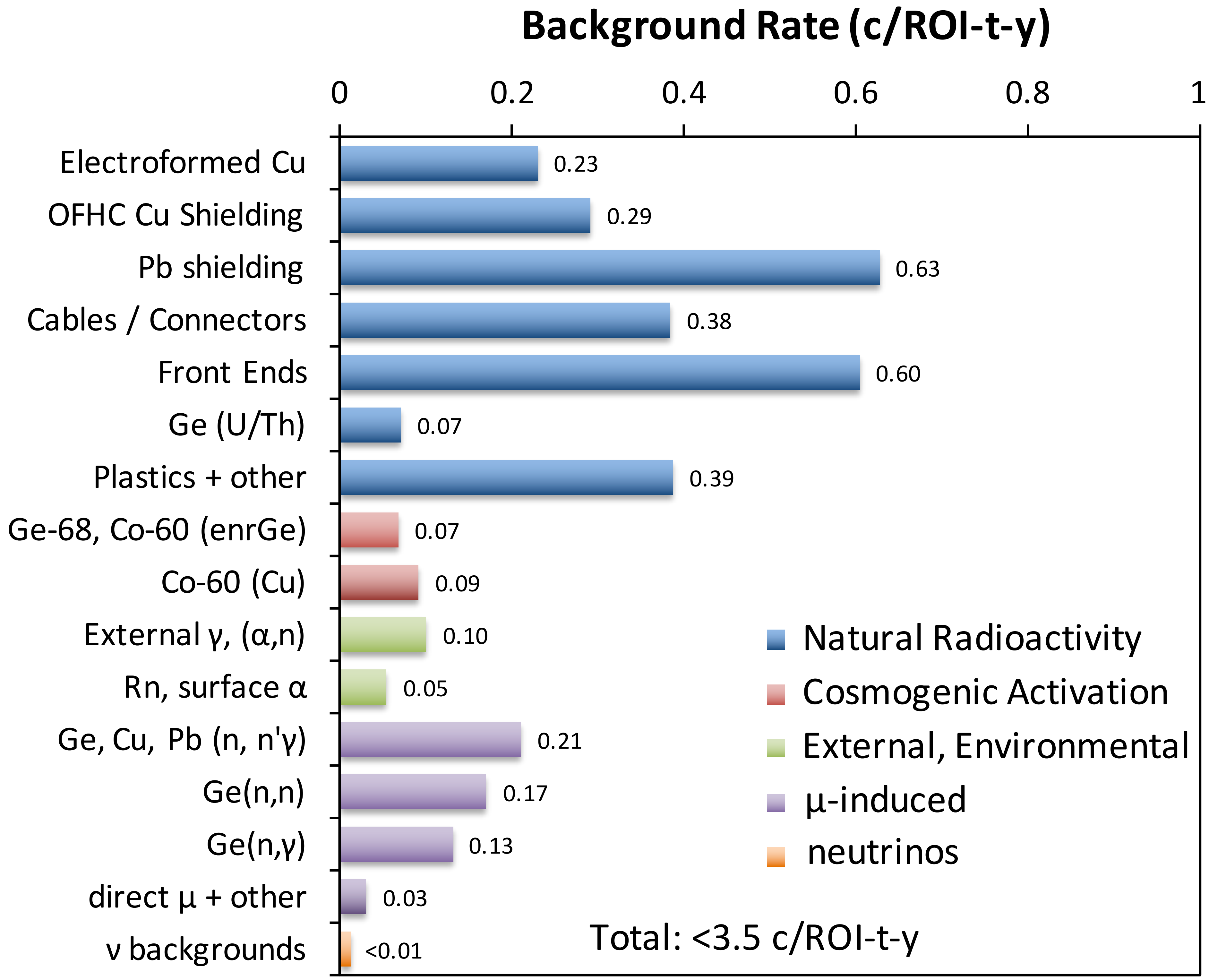
All detector assembly performed in N_2-purged gloveboxes.

All detectors' dimensions recorded by optical reader.

Module and Shield



DEMONSTRATOR Background Model



MAJORANA DEMONSTRATOR Implementation

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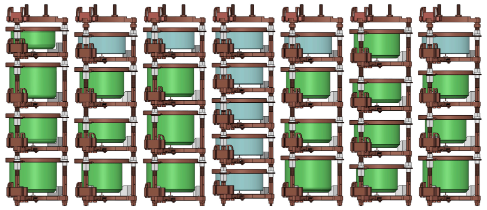
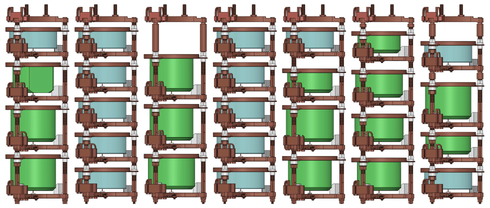


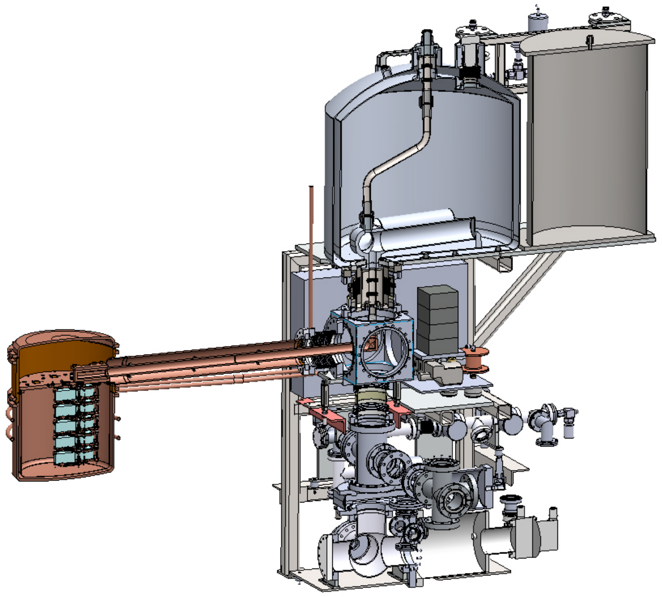
May 2015 - Oct 2015
Final Installations
Dec. 2015 - June 2016

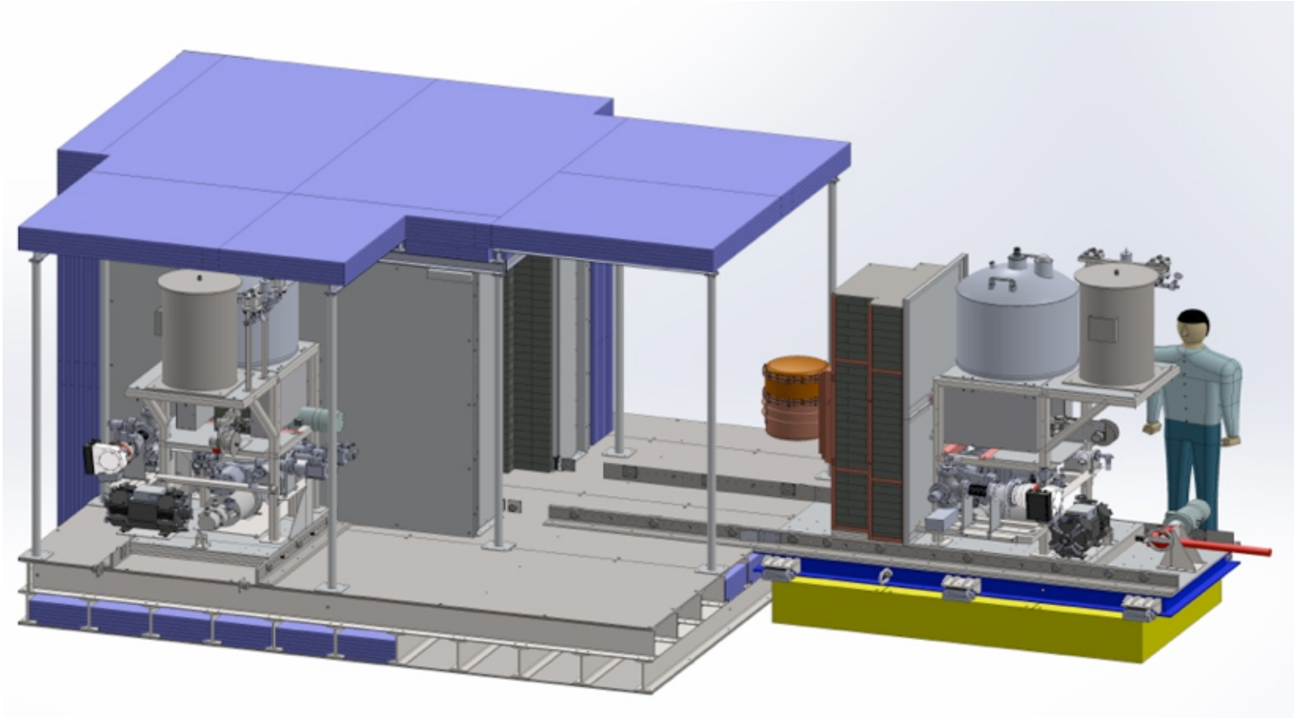
Module 2

12.9 kg (14) ^{enr}Ge
8.8 kg (15) ^{nat}Ge



Aug. 2016 with M1
Oct. 2016- combined DAQ

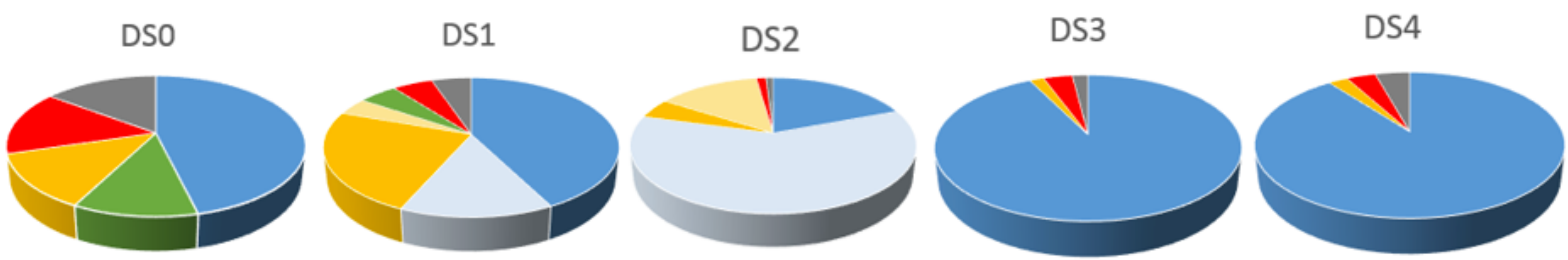




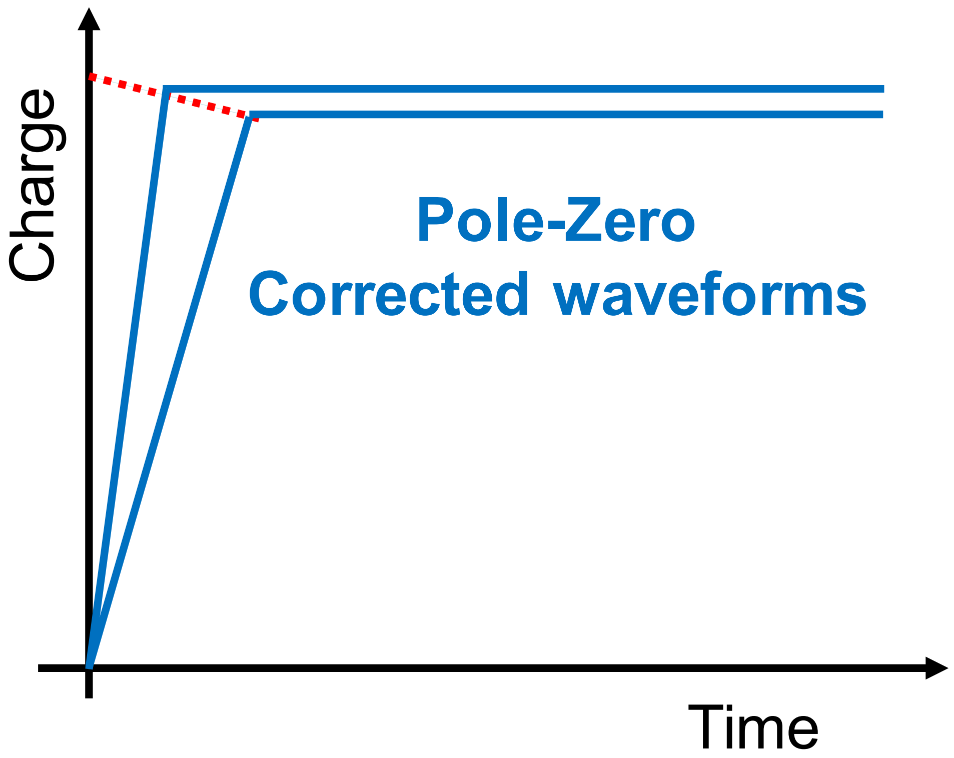
Data Set Duty Cycles

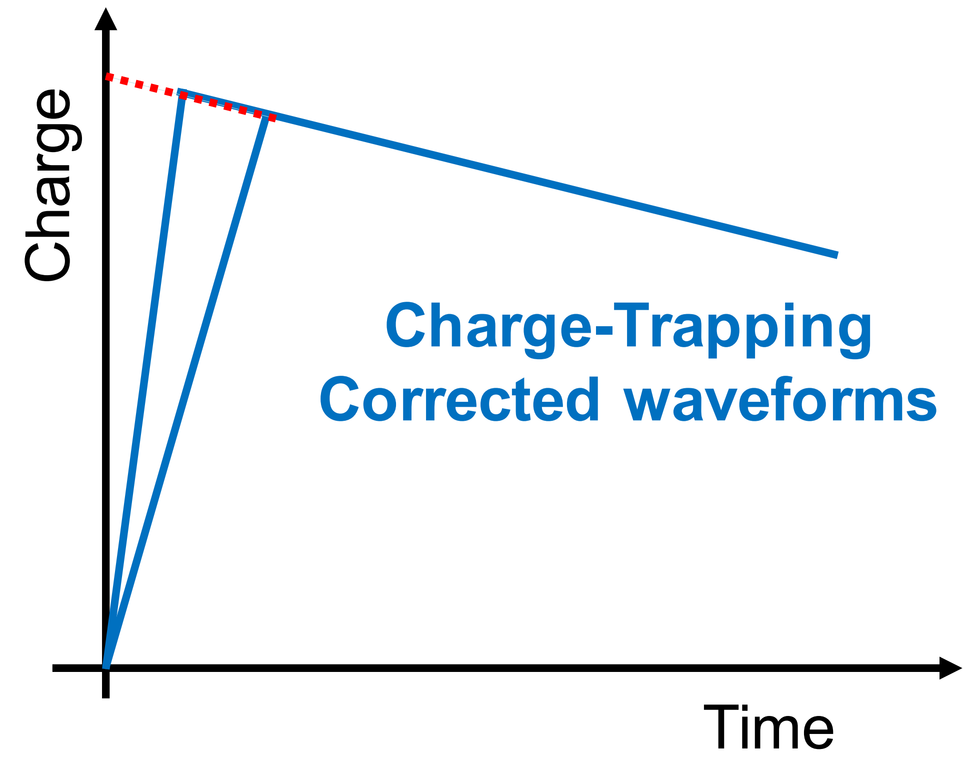
		DS0 (days) Module1 No inner shield June 26, – Oct. 7, 2015	DS1 (days) Module 1 with inner shield Dec. 31, 2015 – May 24, 2016	DS2 (days) Module 1 with inner shield and multi-sampling May 24 – July 14, 2016	DS3 (days) Module 1 with inner shield Aug. 25, – Sept. 27, 2016	DS4 (days) Module 2 with inner shield Aug. 25, – Sept. 27, 2016
Total		103.15	144.50	50.97	32.37	32.36
Total acquired		87.93	136.98	50.47	31.73	30.97
Physics	*	47.70	61.34 + 20.41*	9.82 + 30.56*	29.97	29.01
High radon		11.76	7.32	-	-	
Disruptive Commissioning tests	*	13.10	34.43+ 5.92*	2.41 + 7.03*	0.57	0.78
Calibration		15.44	7.32	0.65	1.18	1.17
Down time		15.21	7.51	0.50	0.64	1.39

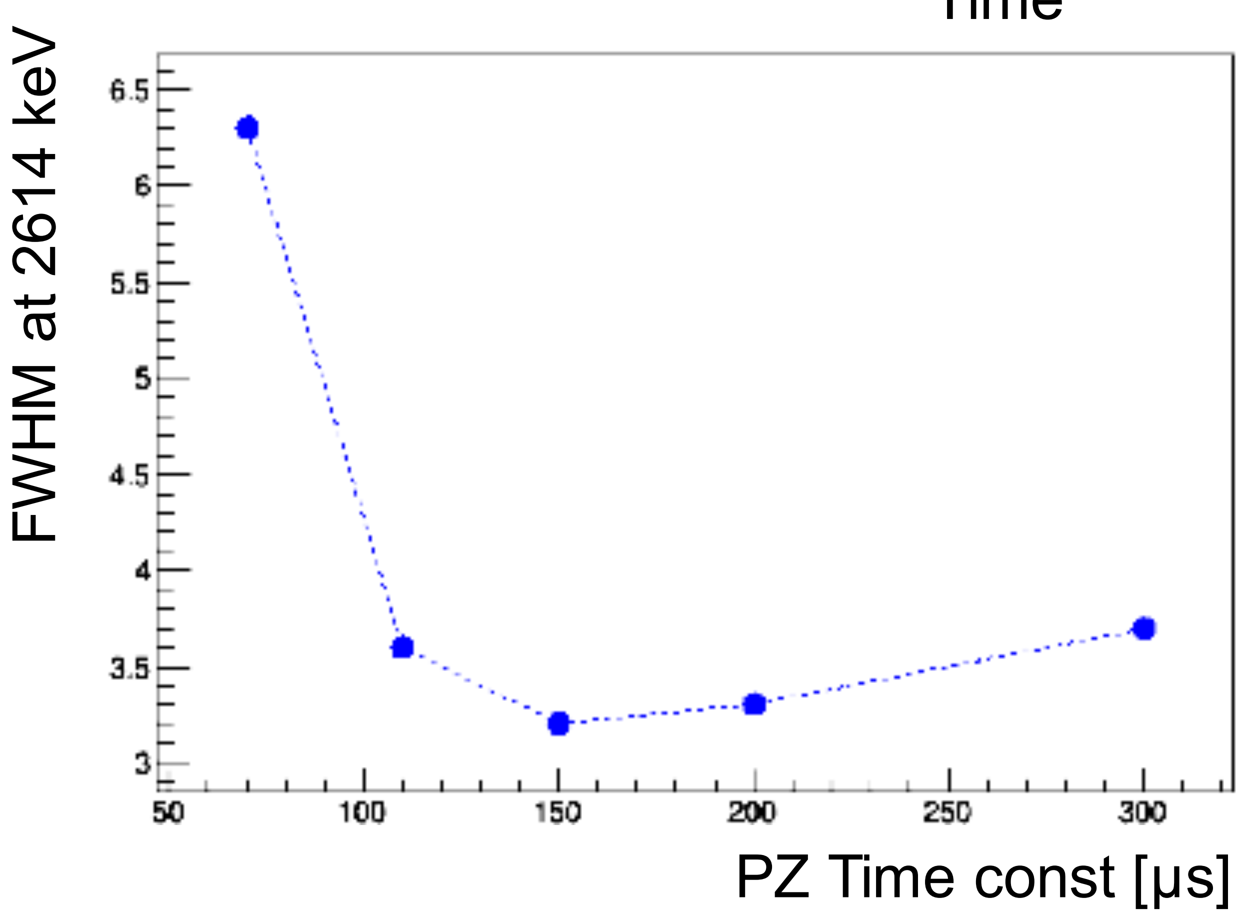
* Blind data

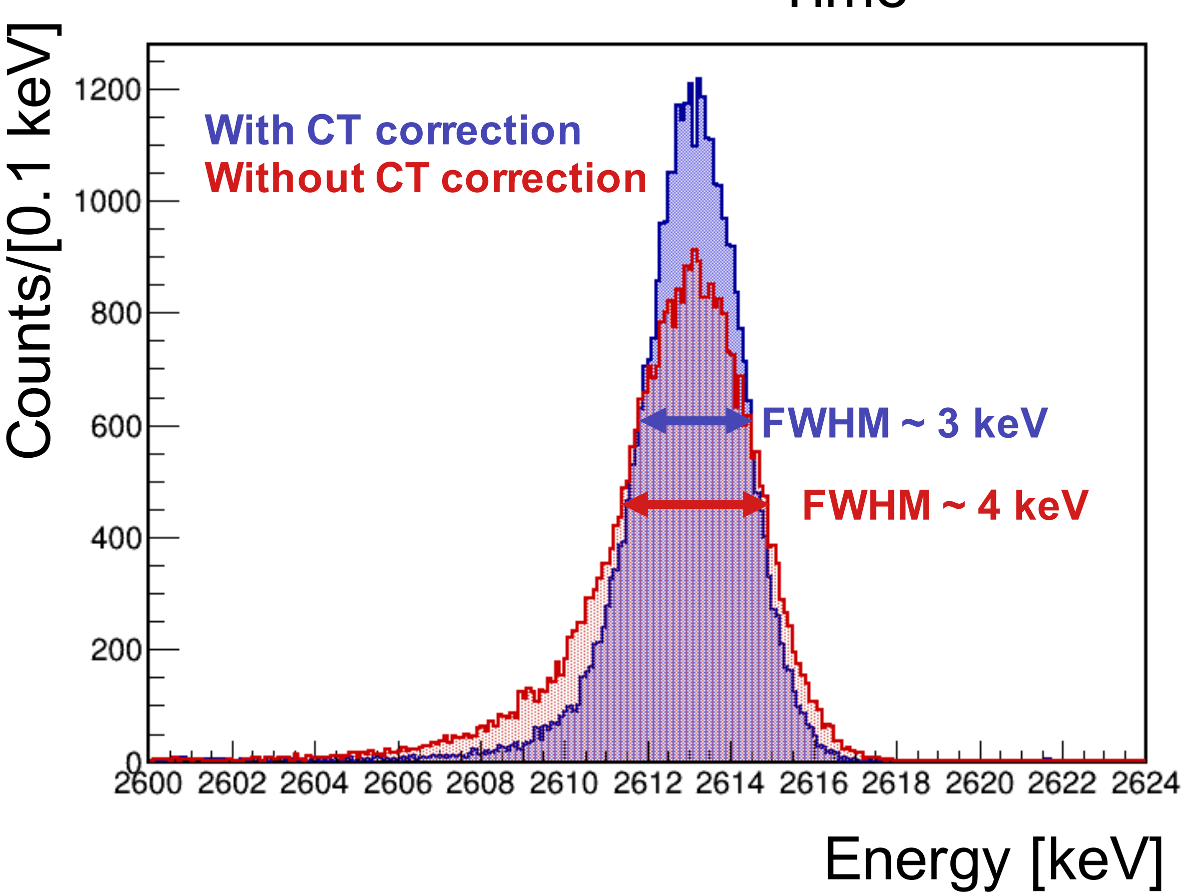


Ge Detector Energy Resolution

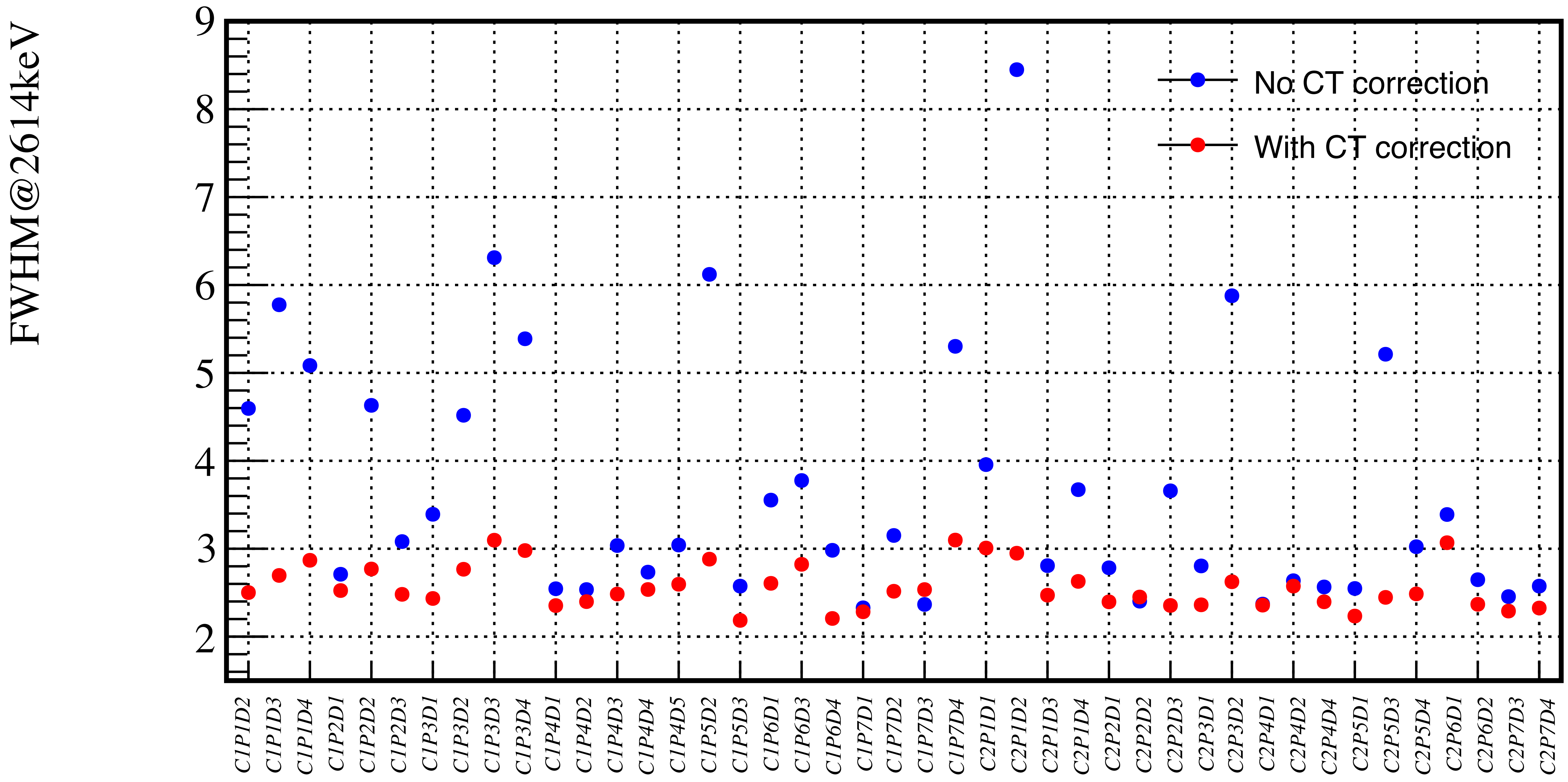








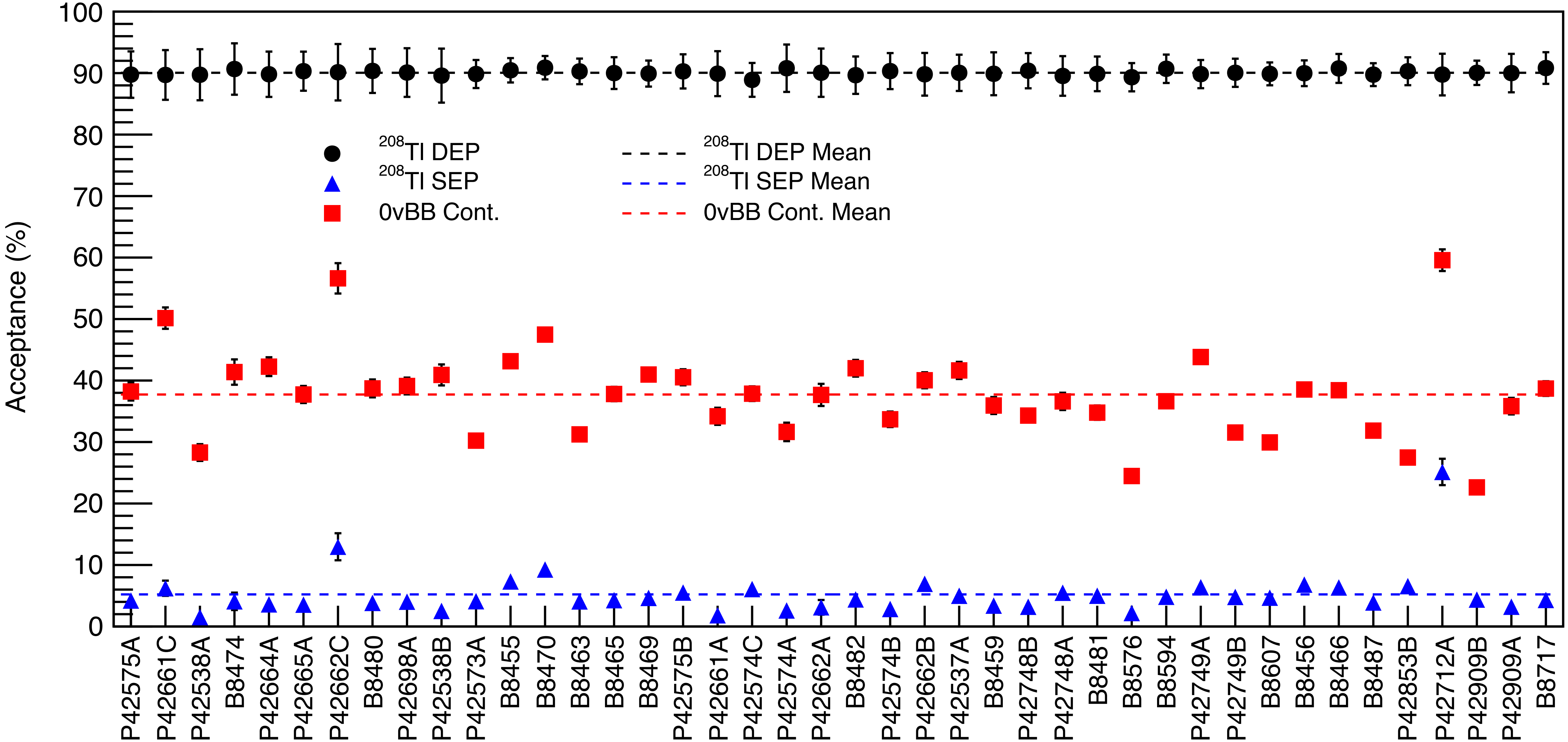
Ge Detector Resolution



Resolution at ROI: 2.6keV FWHM

0νββ ROI: 3.1keV

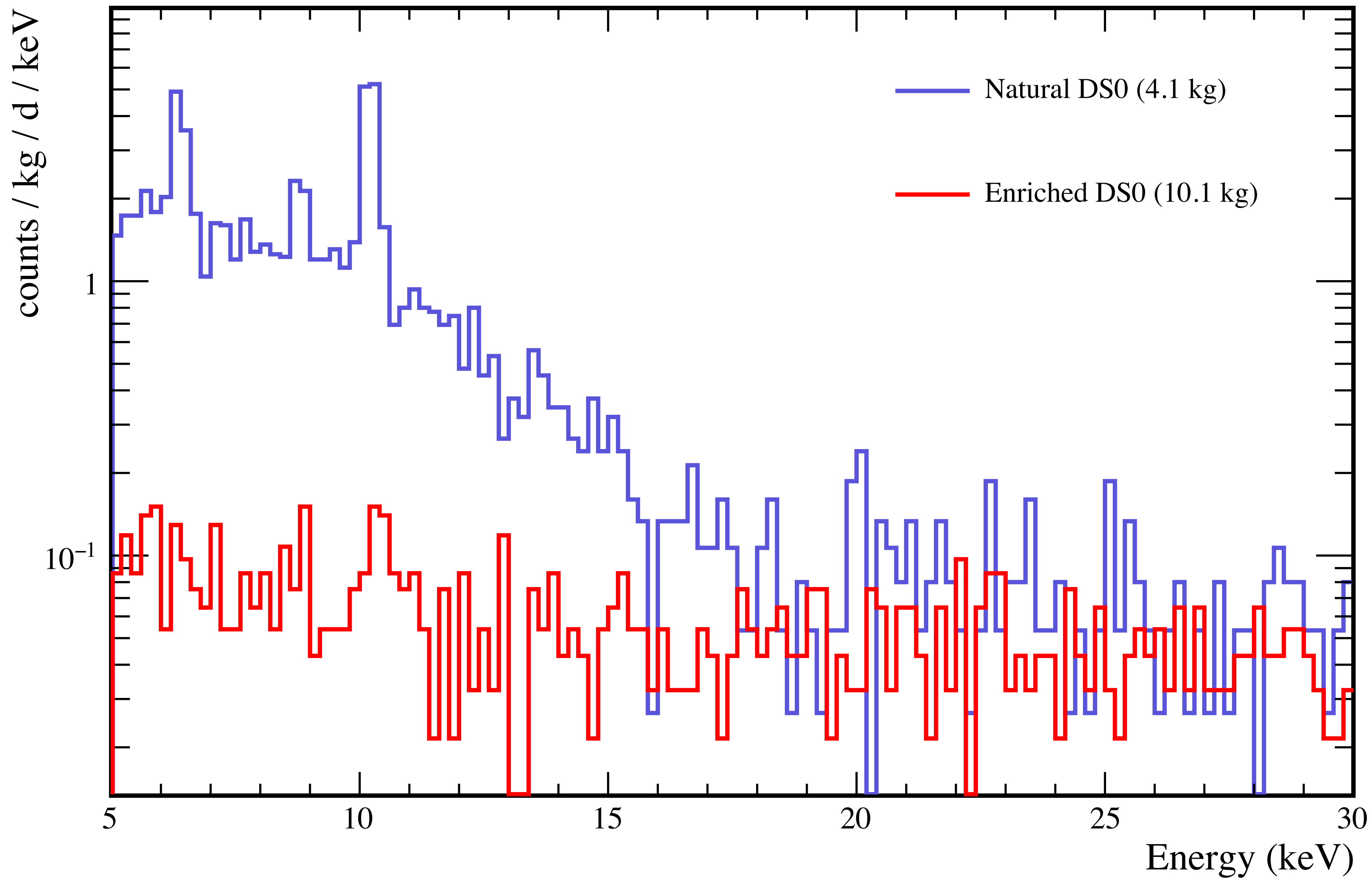
Ge Detector PSD Performance



- **^{208}Tl Double-Escape Peak (single-site): Fixed to 90%**
- **^{208}Tl Single-Escape Peak (multi-site): Reduced to 6%**
- **Compton Continuum at 0νββ ROI: Reduced to ~40%**

Tritium / Cosmogenic X-rays

- Controlled cosmic ray exposure of enriched material
- Significant reduction of cosmogonics in low-energy region. Factor of a few better in DS1.
- The ^{68}Ge rate is low enough that an **SSTC cut will not be necessary.**
- Tritium is obvious and dominated in natural detectors below 20 keV
- Efficiency below 5 keV is still being studied.

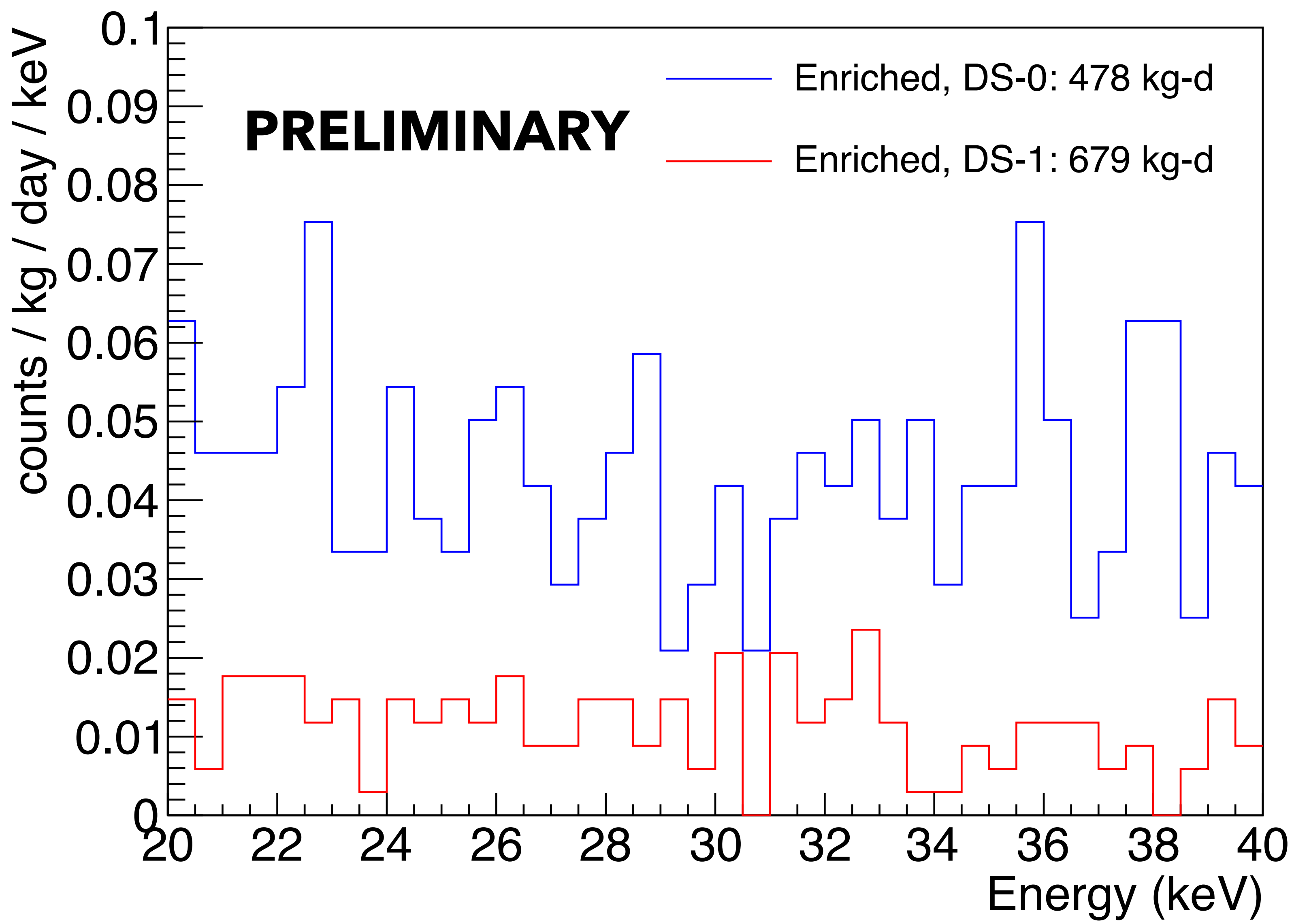


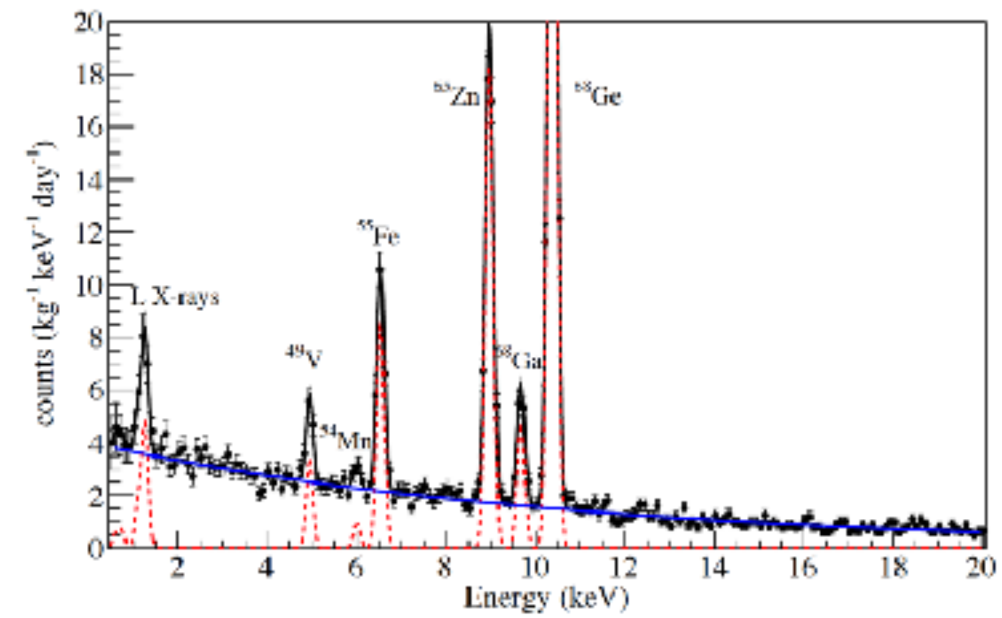
Low-Energy Background — DS0 & DS1

20-40 keV:

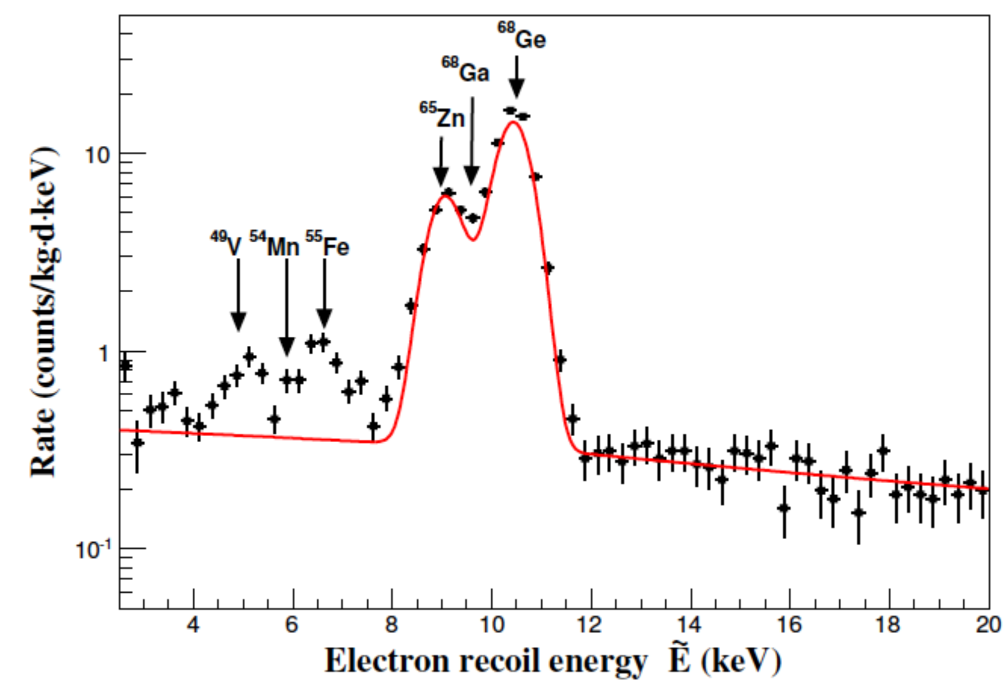
DS-0 ~0.04 cts/kg-d-keV

DS-1 ~0.01 cts/kg-d-keV





CDEX: arXiv:1610.07521

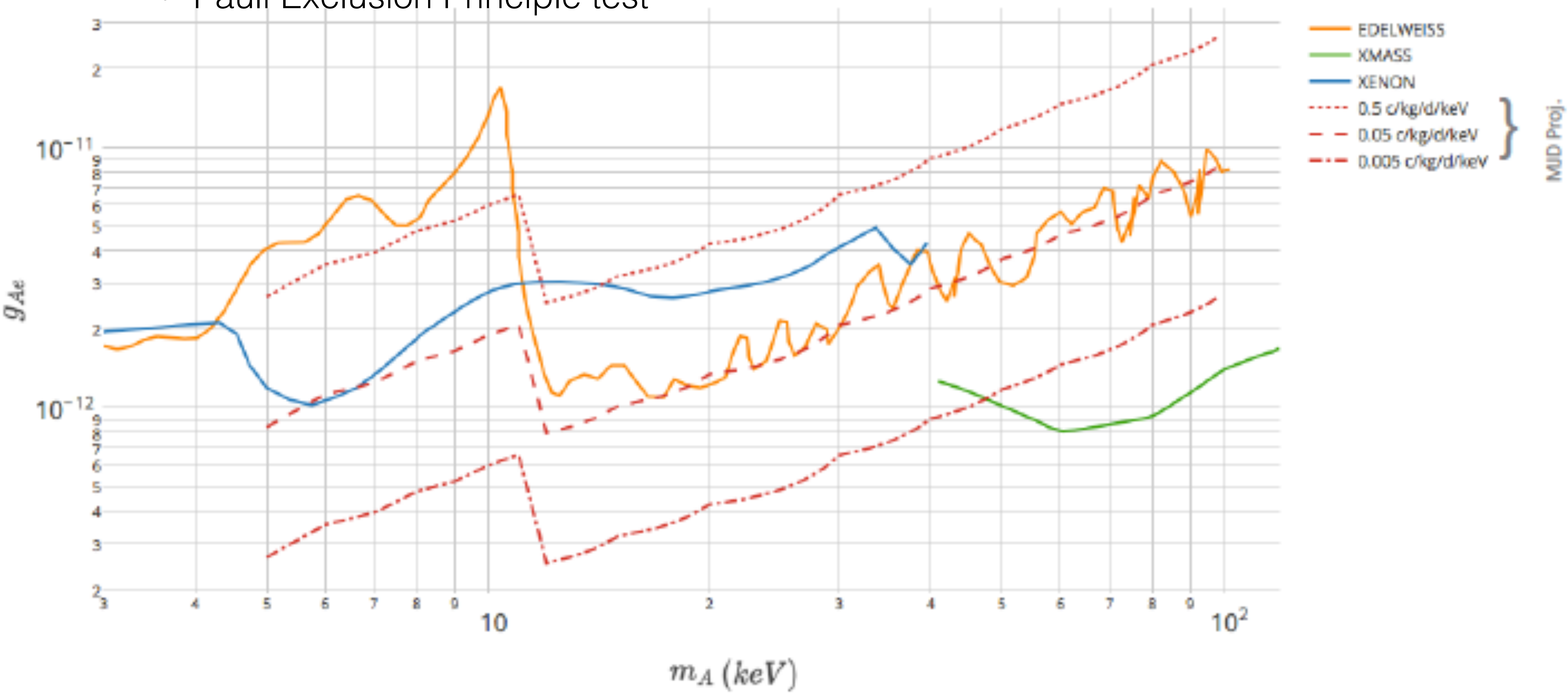


EDELWEISS II: JCAP 11 (2013)067

Bosonic Dark Matter Analysis — DS0

Other Low-Energy Physics presenting as mono-energetic peaks:

- Pseudoscalar dark matter coupling: g_{Ae}
- Vector dark matter coupling: α'/α
- 14.4-keV solar axion: g_{AN} x g_{Ae}
- $e^{-} \rightarrow 3\nu$
- Pauli Exclusion Principle test

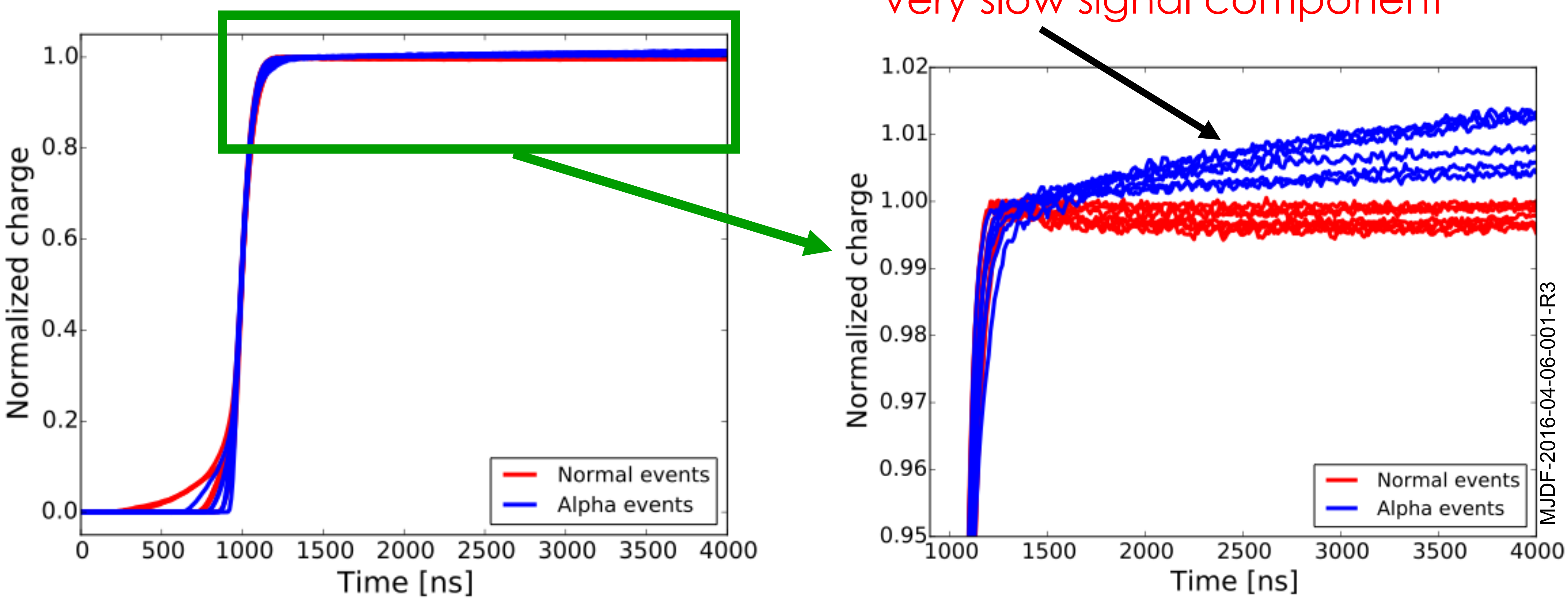


Delayed Charge Recovery Cut for Alphas

- Alpha background response observed in Module 1 commissioning (DS0).
- Identified as arising from α particles impinging on passivated surface.
- Results in prompt collection of some energy, plus very slow collection of remainder.
- Produces a distinctive waveform allowing a high-efficiency cut.
- See detailed description: **arXiv:1610.03054**

Example pole-zero corrected waveforms

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



DS1 DCR Cut and Bulk-Event Response

Removes most events from above 2MeV in the background spectrum, which are α candidates.

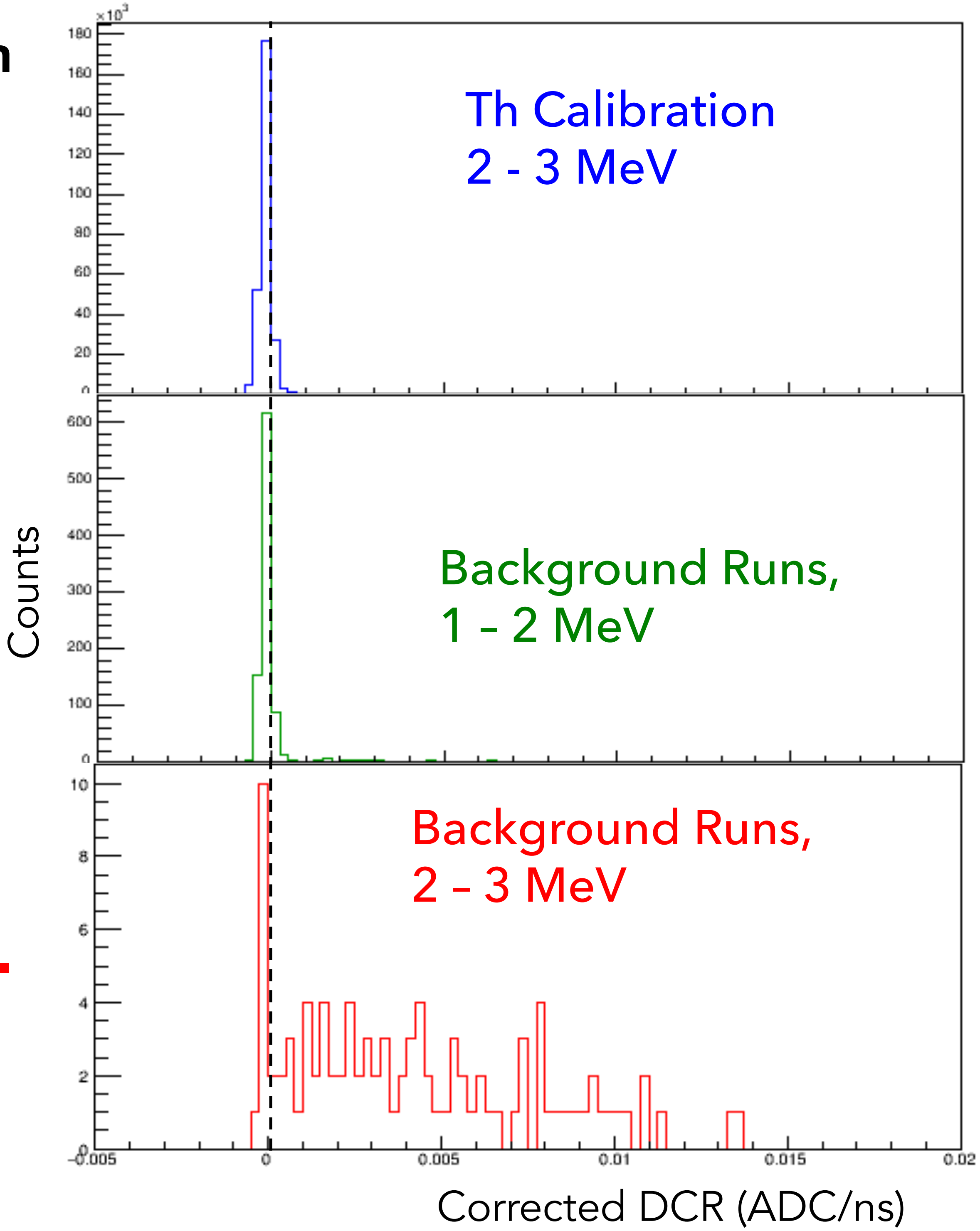
Cut is 90% efficient for retaining events within detector bulk. Only 5% of α survive cut.

During calibration runs, γ events survive cut.

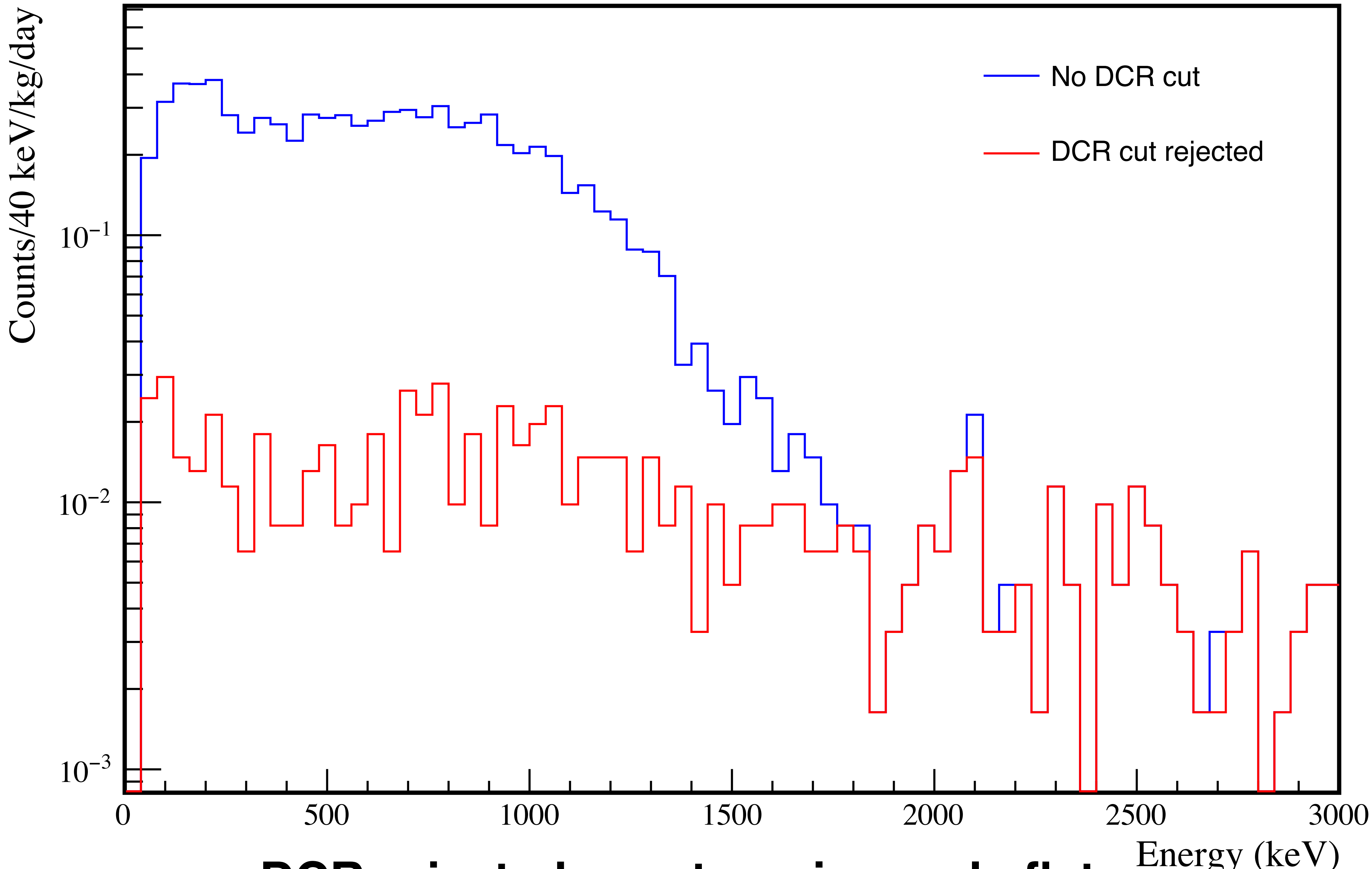
During background runs, 2νββ events survive cut.

Candidate α events from background runs are removed.

DS1, Enriched Detectors



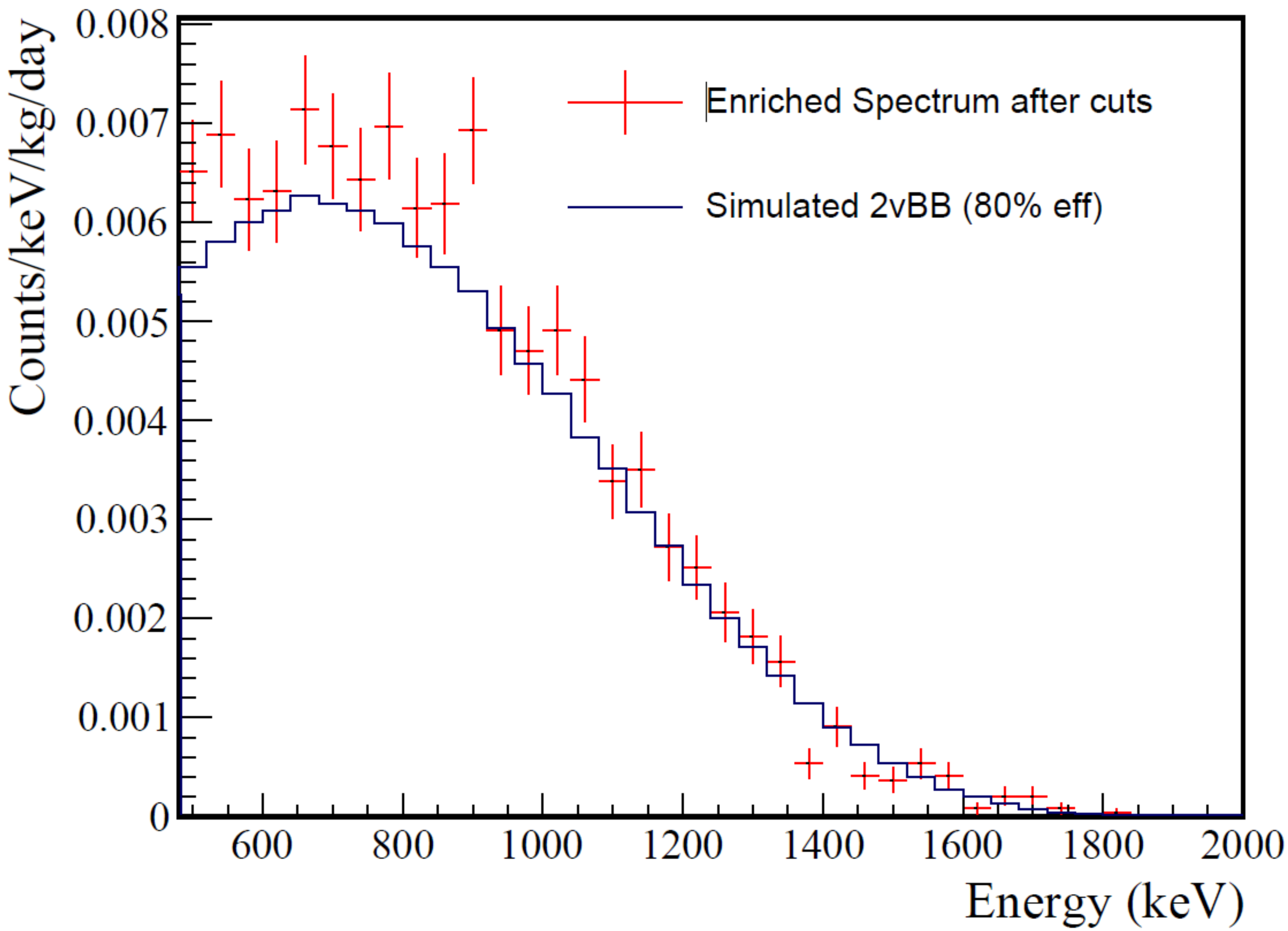
The DCR-cut Spectrum — DS1



DCR-rejected spectrum is nearly flat.
Removes a large fraction of events over ~1800 keV

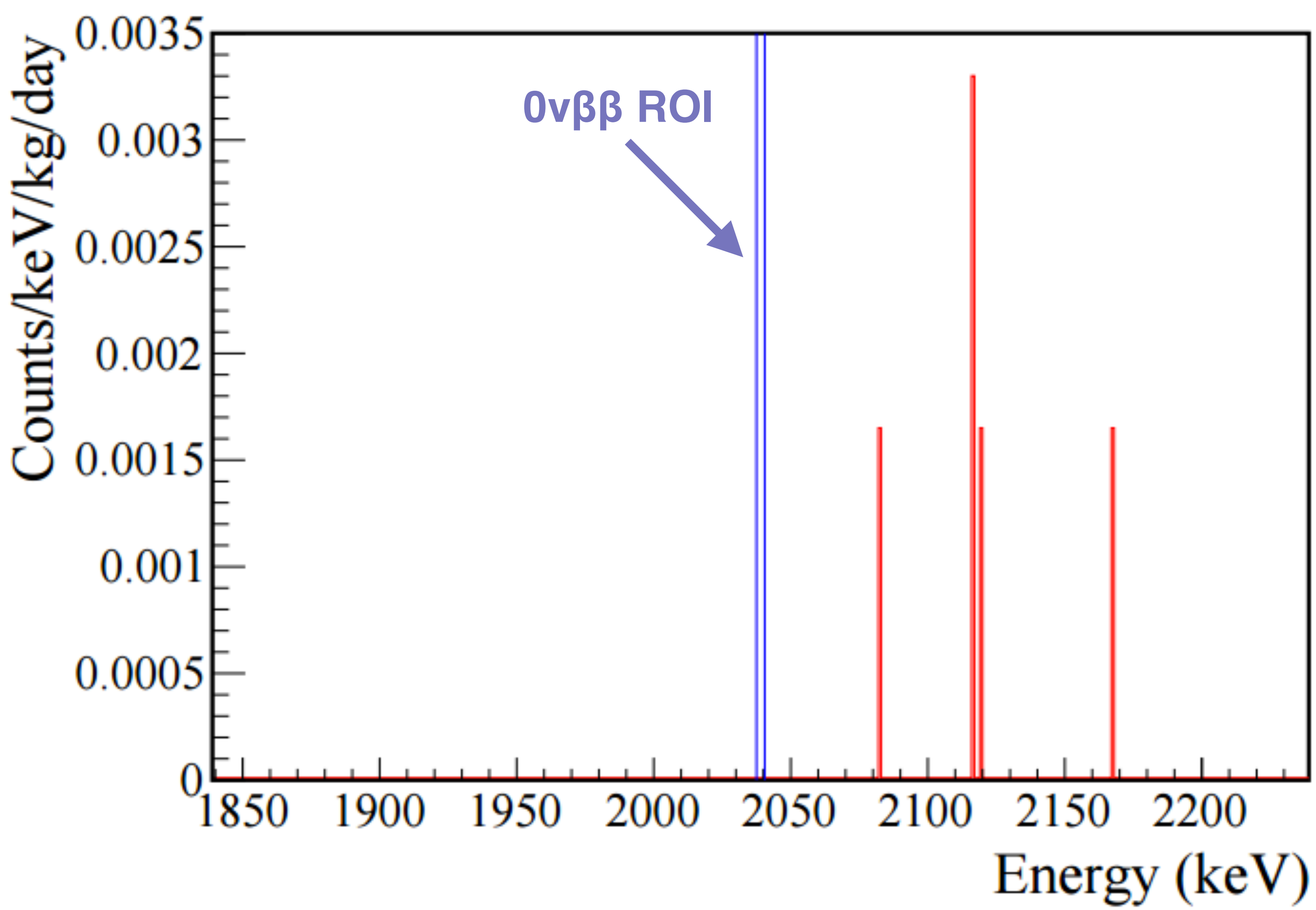
DS1:500-2000keV — 2νββ

- Data Set 1 Spectrum after all analysis cuts.
- Above 500keV the spectrum is dominated by 2νββ
- Simulated rate using previously-measured half-life (**Eur. Phys. J. C 75 (2015) 416**)



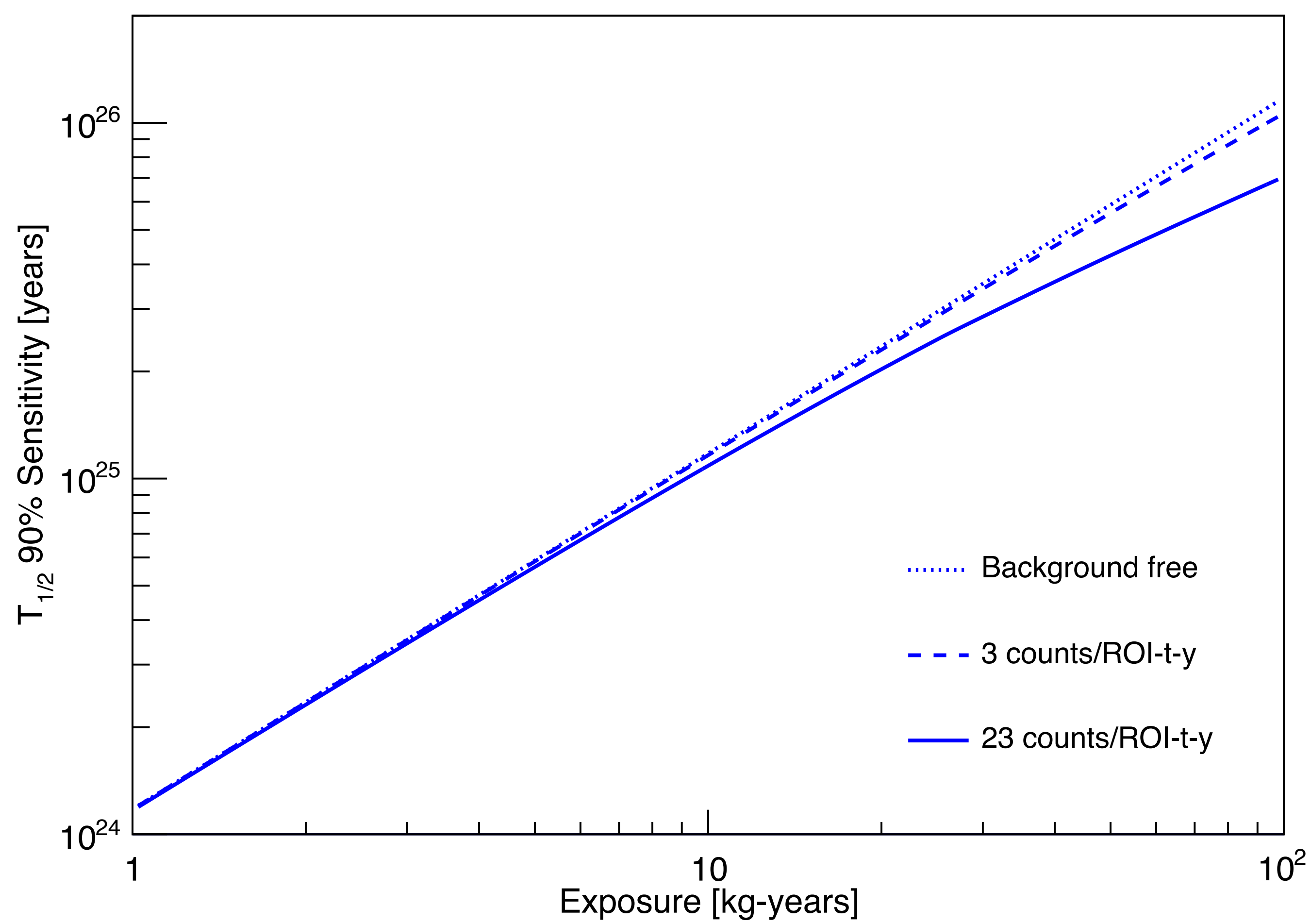
The ROI and DCR in DS1

- The enriched detectors in Data Set 1 are used to estimate the background.
- Most events near ROI are removed by the DCR cut. Only 5 survive in 400keV window.
- Background rate is 23^{+13}_{-10} counts/(ROI t y) for a 3.1-keV ROI (68% CL).
- Background index is $7.5^{+4.5}_{-3.4}$ x10^{-3} counts/(keV kg d).
- All analysis cuts are still being optimized.



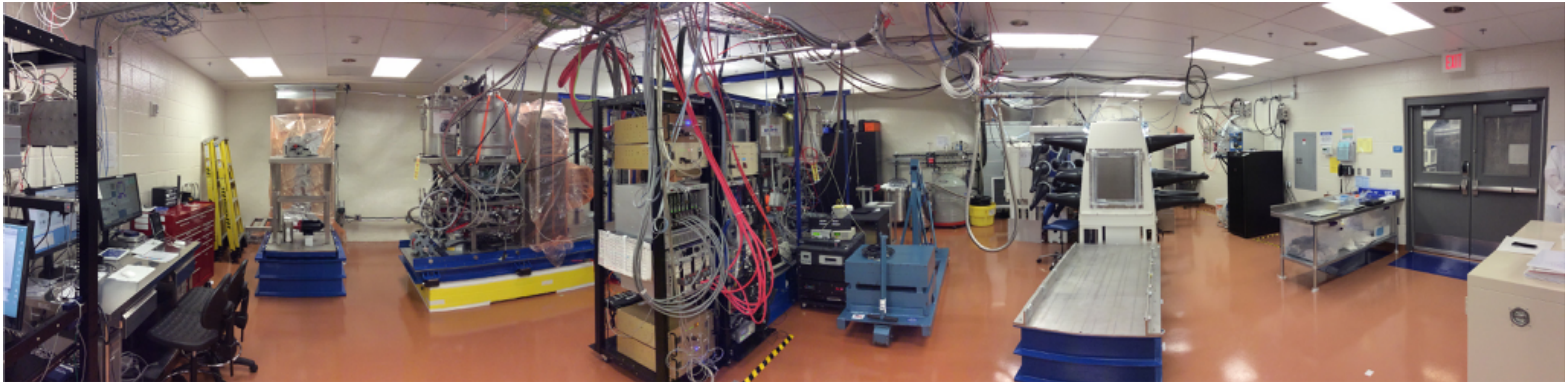
DEMONSTRATOR 0νββ Sensitivity

- DS0 & DS1: No ROI events. Total exposure: 3.03 kg y
- DS0 1.37 kg-y, DS1 1.66 kg y
- Efficiency for 0νββ is 0.61±0.04
  0.61 = (0.84)(0.9)(0.9)(0.9)
  = (Resol.)(Full Energy)(A/E)(DCR)
- $T_{1/2} > 3.7\times10^{24}$ y (90% CL)
- Background is very low. Sensitivity almost linear with exposure.
- This analysis is on open data. Blind data taking began on April 14. Data taking with Module 2 began in August

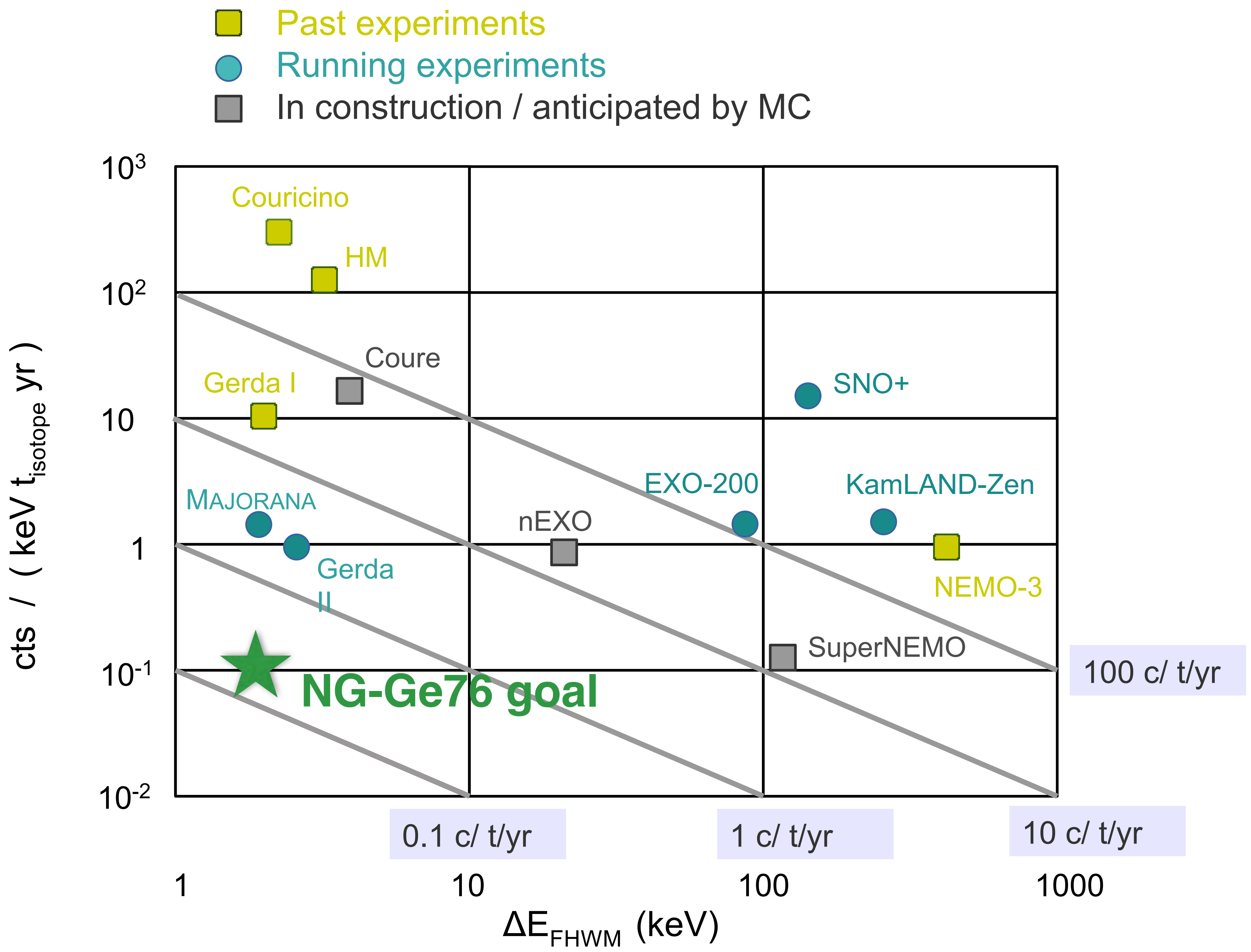


MAJORANA Summary

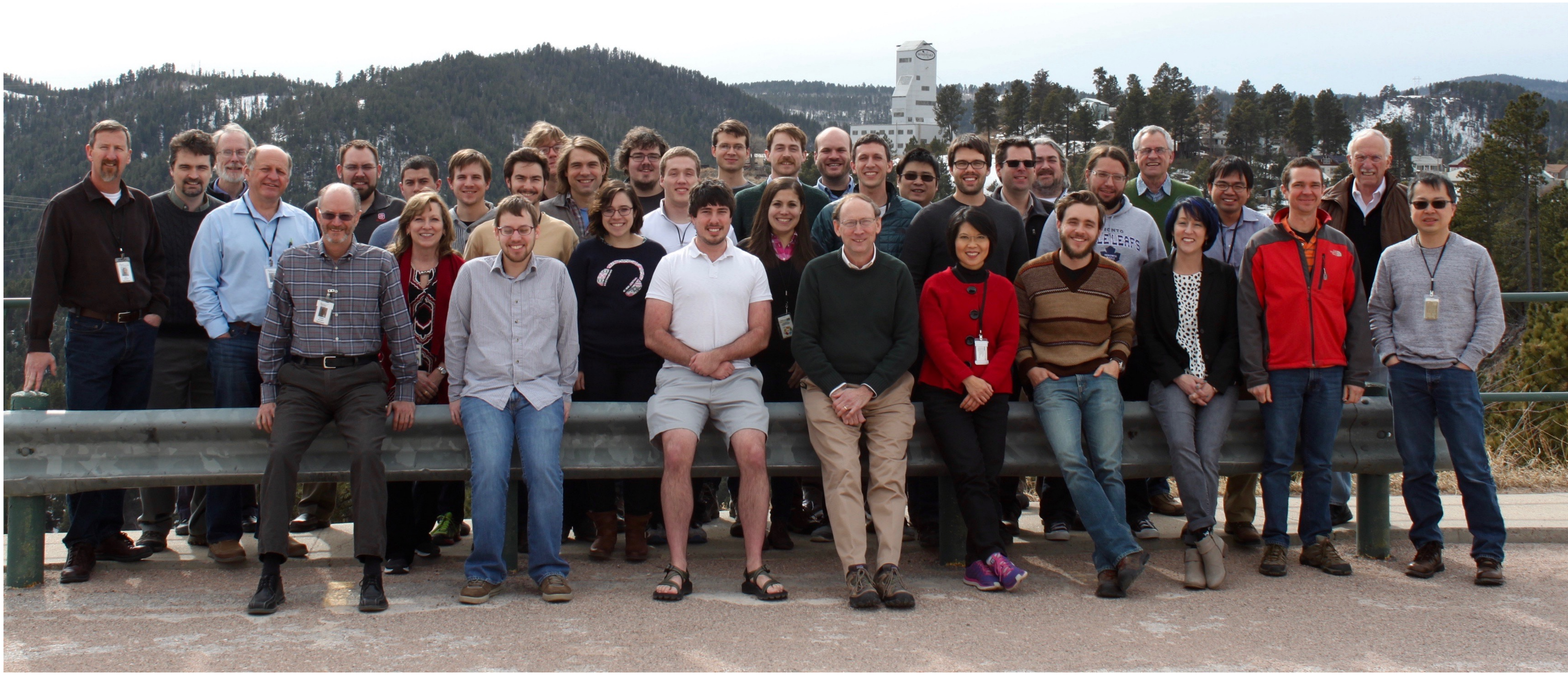
- Comprehensive paper on DEMONSTRATOR materials & assays : NIM A 828 23-36 2016.
- Produced and machined underground over 2100 kg of ultra clean electroformed Cu.
- Produced 35 (29.66 kg) of 88% enriched ^{76}Ge p-type point contact detectors.
- Installation of neutron shielding to be completed by Jan. 2017.
- New analysis techniques developed to improve energy resolution, reduce alphas.
- Collected 3.03 kg yr of exposure from DS0 & DS1 before going blind. $T_{1/2} > 3.7\times10^{24}$ y
- Modules 1&2 operating concurrently in-shield; analysis of DS3/4 data in progress.
- 41 of 58 detectors used in physics analysis (24 of 35 ^{enr}Ge); investigating recabling options to bring more detectors online.



Towards the Ton-Scale



The MAJORANA Collaboration



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NC State University
The University of Tennessee
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The MAJORANA Collaboration

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The Potential for the DCR Background was Anticipated.

- Due to the uncertainty in passivated surface fields, surface alphas were our most poorly constrained potential background at the time of the design.
- In our studies of surface alphas at that time, we estimated a surface activity limit of 500 nBq/cm2. This assumed negligible contribution from the passivated surface, i.e. that contributions from the PC itself would dominate. Our justification was that for the passivated surface one of the following three possibilities would occur:
    1. The “effective” dead region at the passivated surface is so thick (>10 mm) that alphas cannot penetrate
    2. The “effective” dead region at the passivated surface is so thin (<1 mm) that alpha energy depositions will lie well above Qbb
    3. In the unlucky case that the “effective” dead region is intermediate between these two, the fact that the near-surface fields so strongly affect charge collection should imply that these events would be characterized by special pulse shapes that can be identified and rejected.
- In our enriched detectors, it appears that slow e- mobility on the passivated surface distorts the waveform, resulting in a diminished energy measurement and increasing the probability that an alpha particle populates the ROI (case 3).
- As anticipated, these signals are indeed accompanied by a feature indicating slow recovery of the missing charge. Our “Delayed Charge Recovery” (DCR) pulse-shape cut removes them effectively.
- We are only sensitive to alphas on the PC and the passivated surface, which extends to about 3 cm radius from the point contact. This is a surface area of ~28 cm2. If we assume all the DCR cut events are alphas on 15 enrGe detectors, we have an alpha rate of approximately <110 nBq/cm2.
  The surface activity is below our goal stated in the design report.
- We are working on improvements in this surface alpha rejection:
    - Longer digitization time to improve sensitivity to the delayed charge recovery.
    - Fast rise time cut to enhance rejection of alphas that occur directly on the point contact (c.f. GERDA)
    - Detector scan of a PPC detector to provide a pure sample for R&D / systematics studies.

DS3 / DS4 Active Detectors

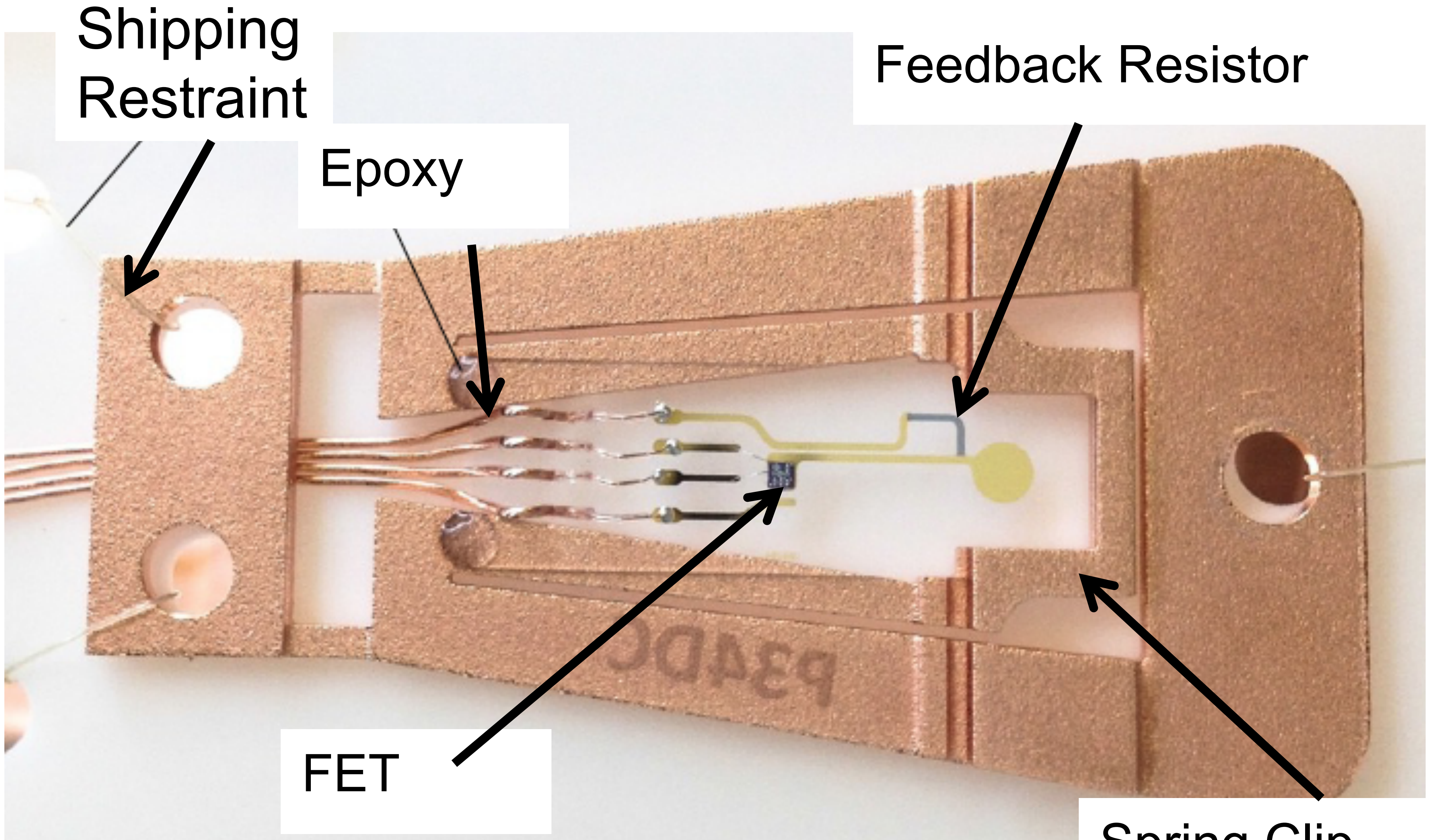
DS3

	Total			Biased			Physics		
	Detector	Active	# det	Detector	Active	# det	Detector	Active	# det
Total	22.41	20.50 ± 0.35 kg	29	18.67	17.09 ± 0.29 kg	24	18.67	17.09 ± 0.29 kg	24
^{enr}Ge	16.82	15.49 ± 0.23 kg	20	13.69	12.63 ± 0.19 kg	16	13.69	12.63 ± 0.19 kg	16
^{nat}Ge	5.60	5.02 ± 0.12 kg	9	4.98	4.46 ± 0.10 kg	8	4.98	4.46 ± 0.10 kg	8

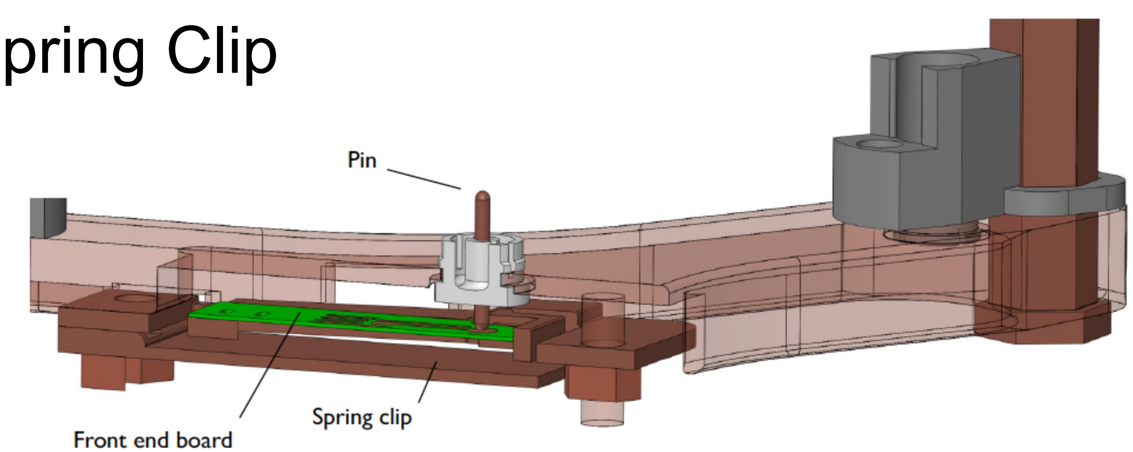
DS4

	Total			Biased			Physics		
	Detector	Active	# det	Detector	Active	# det	Detector	Active	# det
Total	21.72	19.80 ± 0.35 kg	29	15.14	13.81 ± 0.24 kg	20	13.46	12.26 ± 0.22 kg	17
^{enr}Ge	12.89	11.91 ± 0.17 kg	15	9.47	8.72 ± 0.12 kg	11	7.79	7.18 ± 0.10 kg	8
^{nat}Ge	8.83	7.89 ± 0.18 kg	14	5.67	5.09 ± 0.12 kg	9	5.67	5.09 ± 0.12 kg	9

Front-End Board

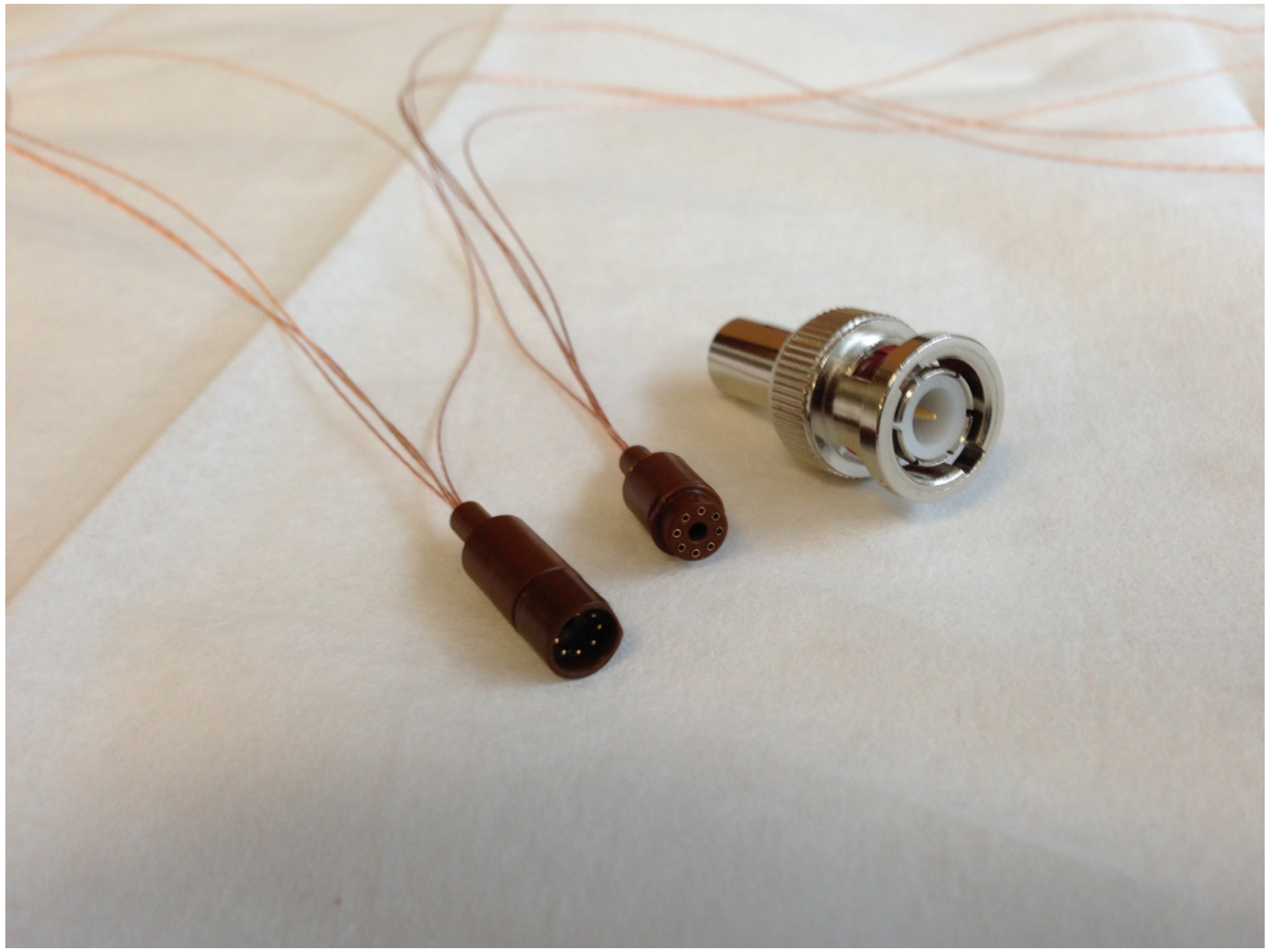


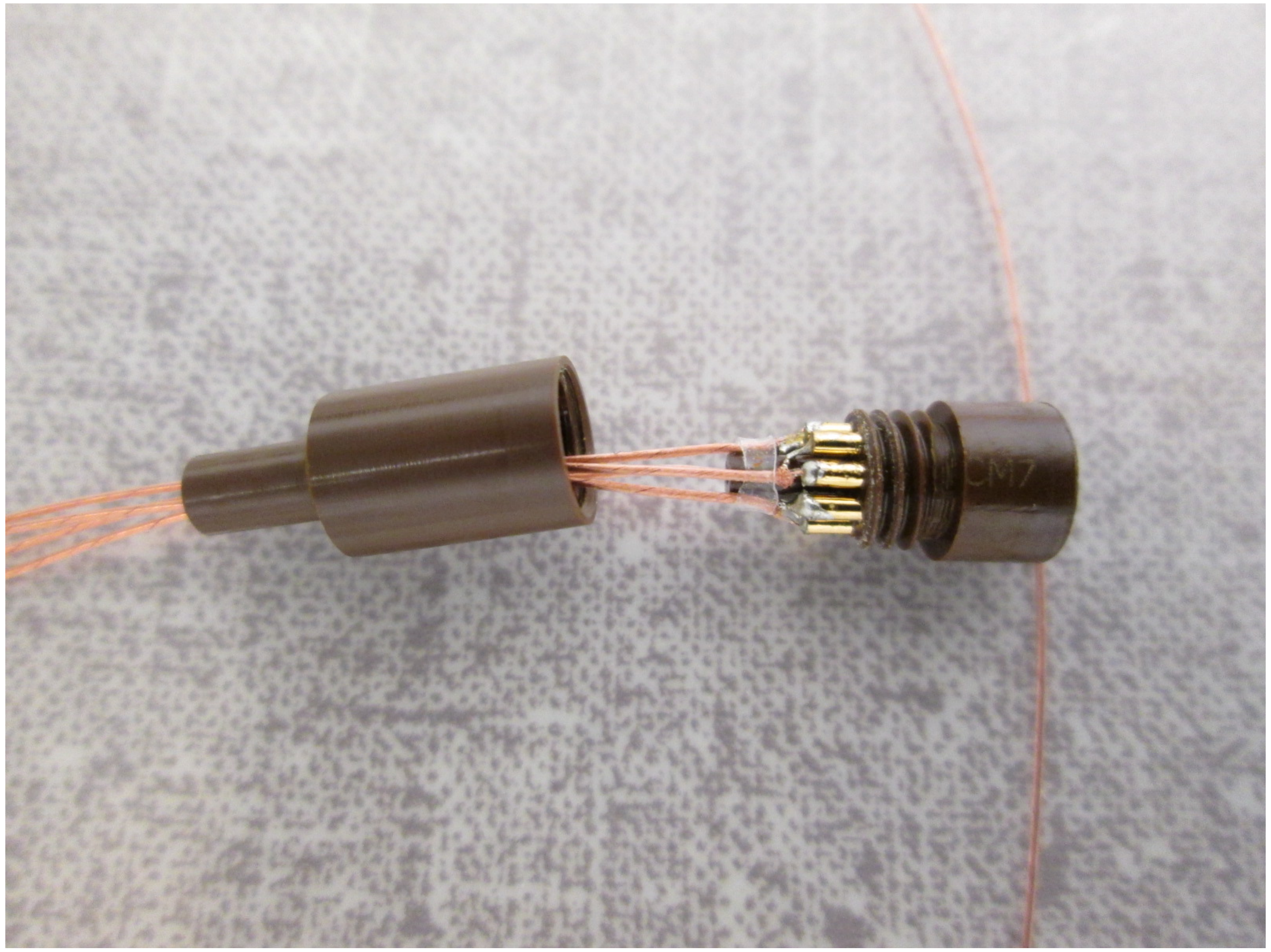
- **Clean Au + Ti traces on fused silica**
- **Amorphous Ge resistor**
- **FET mounted with silver epoxy**
- **EFCu + low-BG Sn-coated Cu contact pin**



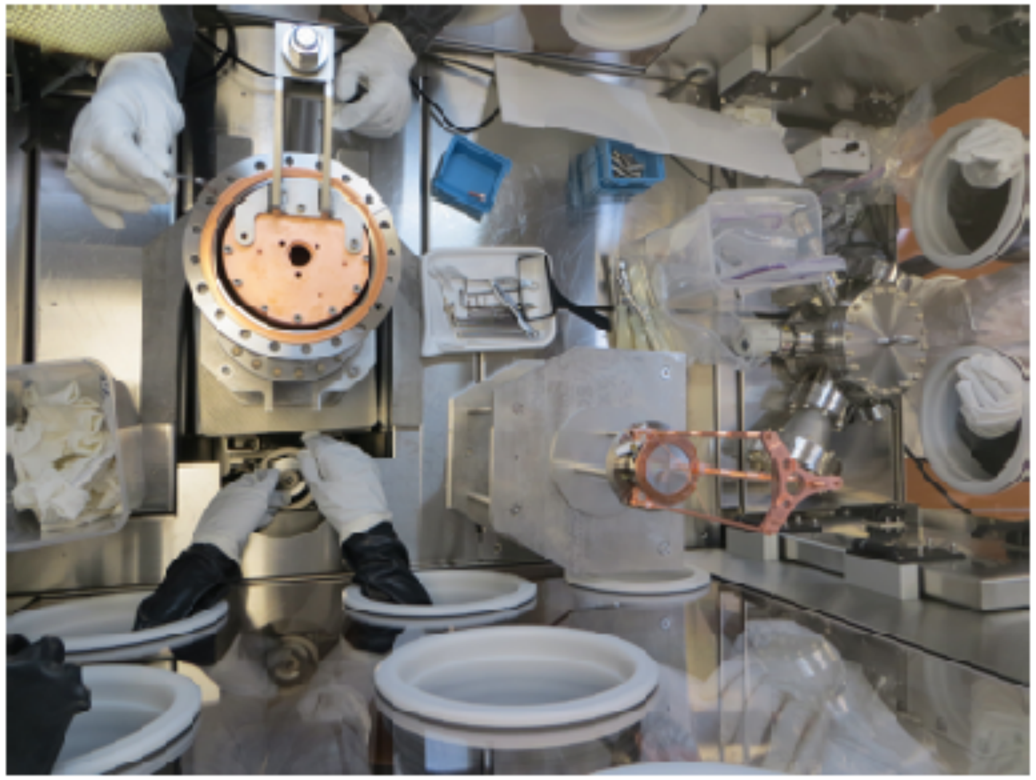
Signal Connectors

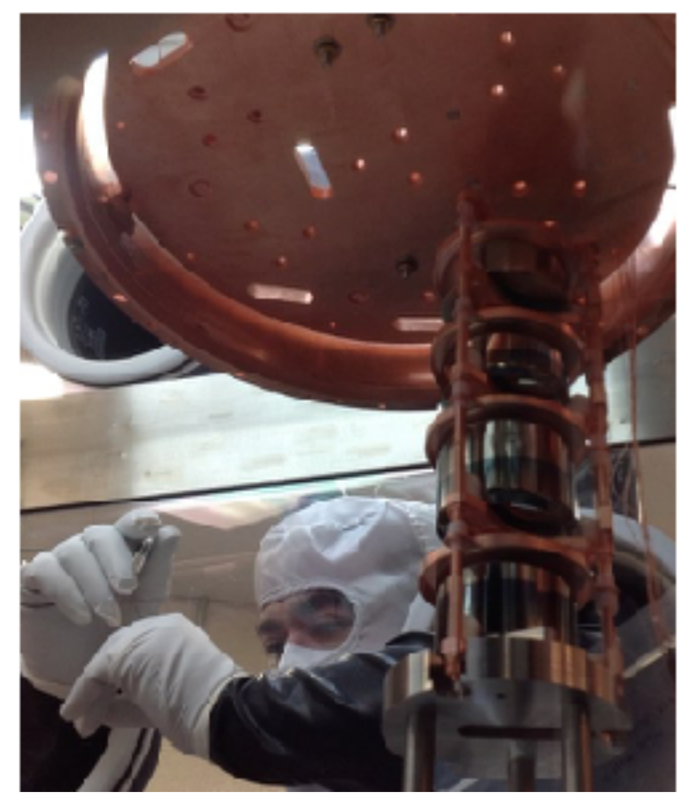
- Connectors reside on top of cold plate
- In-house machined from Vespel SP-1.
- Low-background solder and flux.
- Axon' Picocoax HV and signal cables
- All HV cables and connectors tested (NIM A823 (2016) 83)



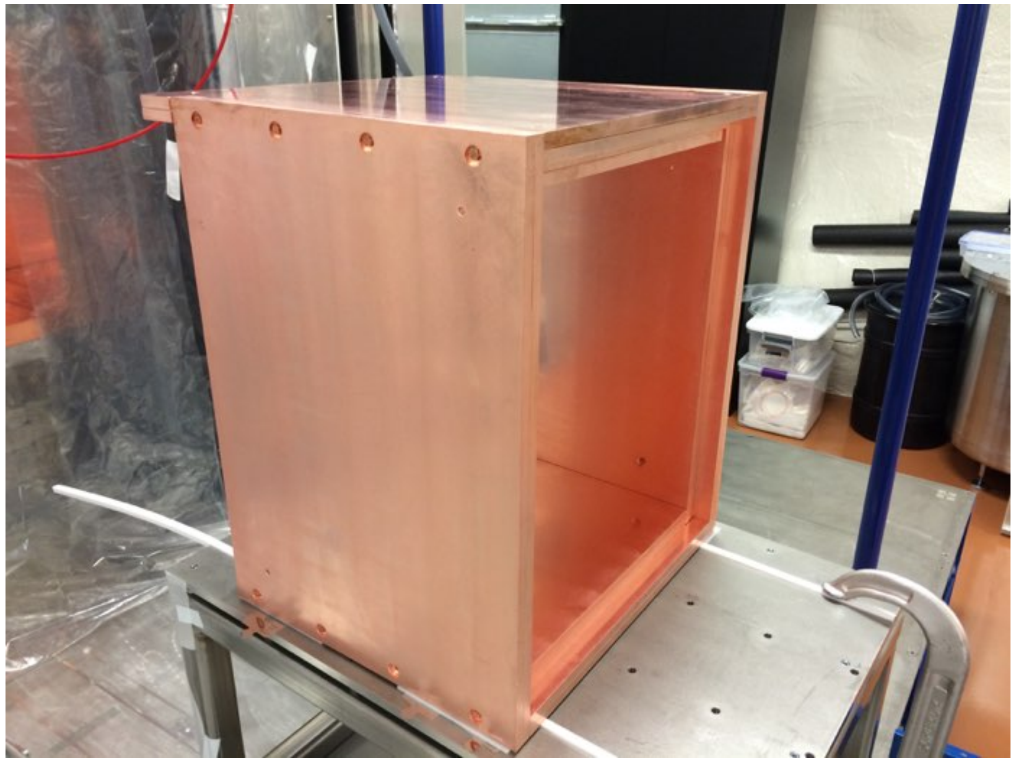


Glovebox Assembly

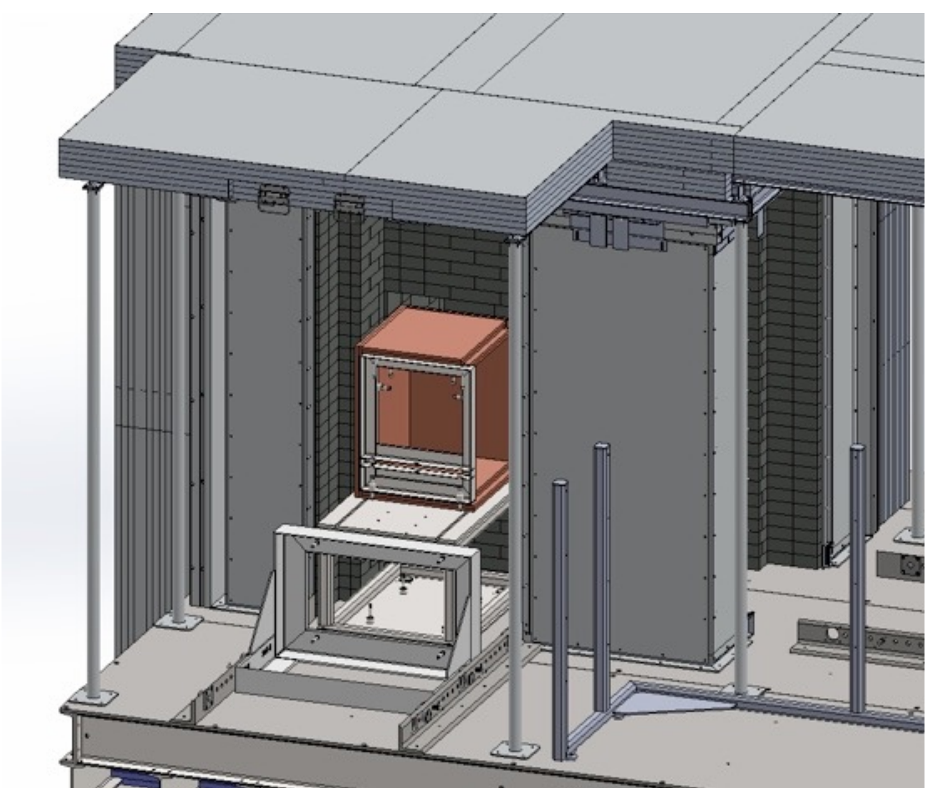


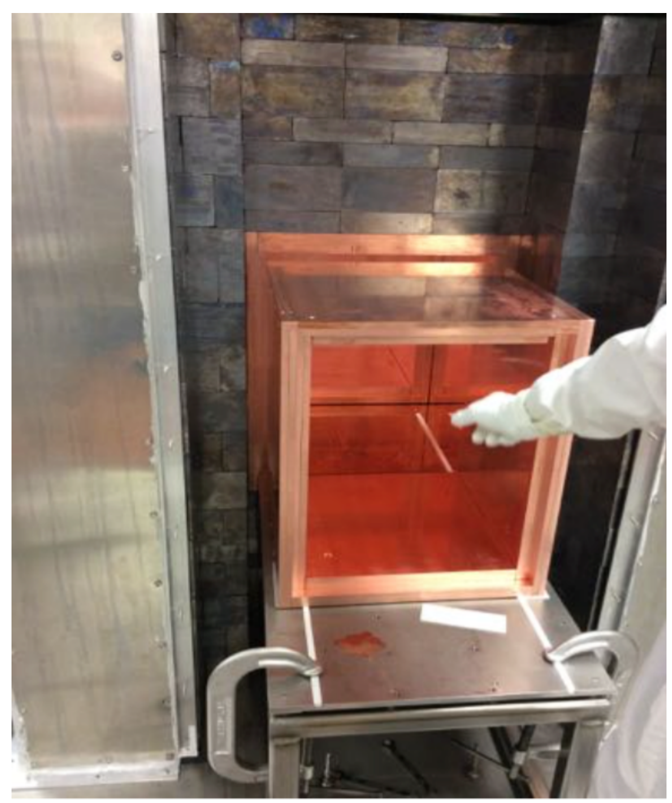


Inner Copper Shield Installation



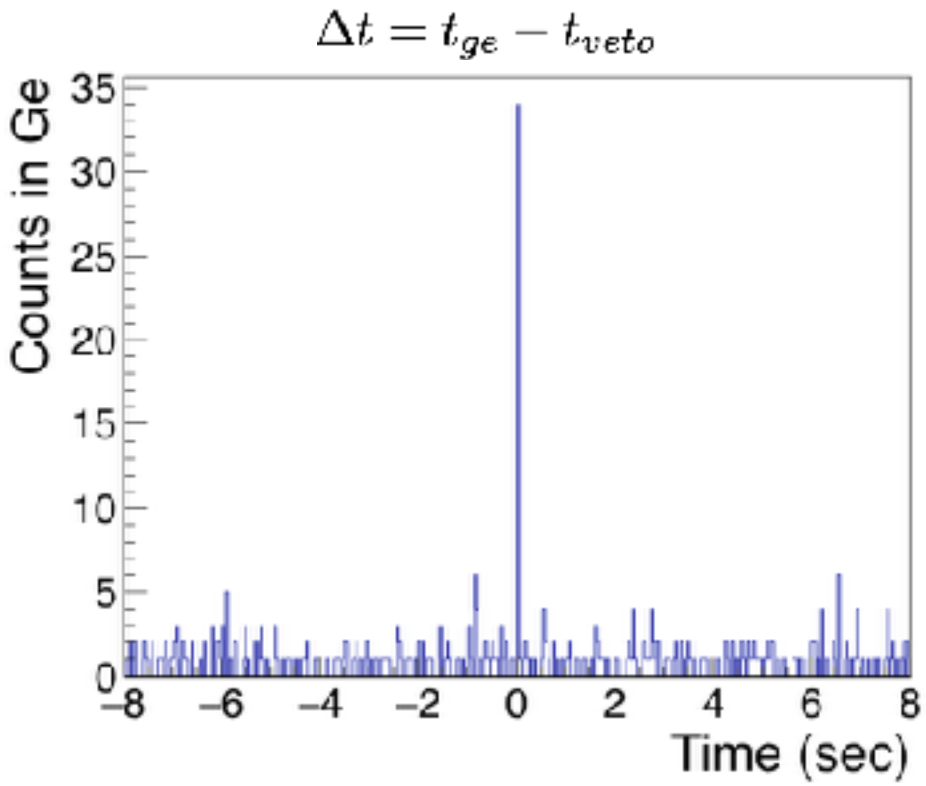
- Schedule driven by electroforming.
- String parts higher priority for machining.
- Installed after shield constructed.
- Expect x10 reduction in background from other shield materials.



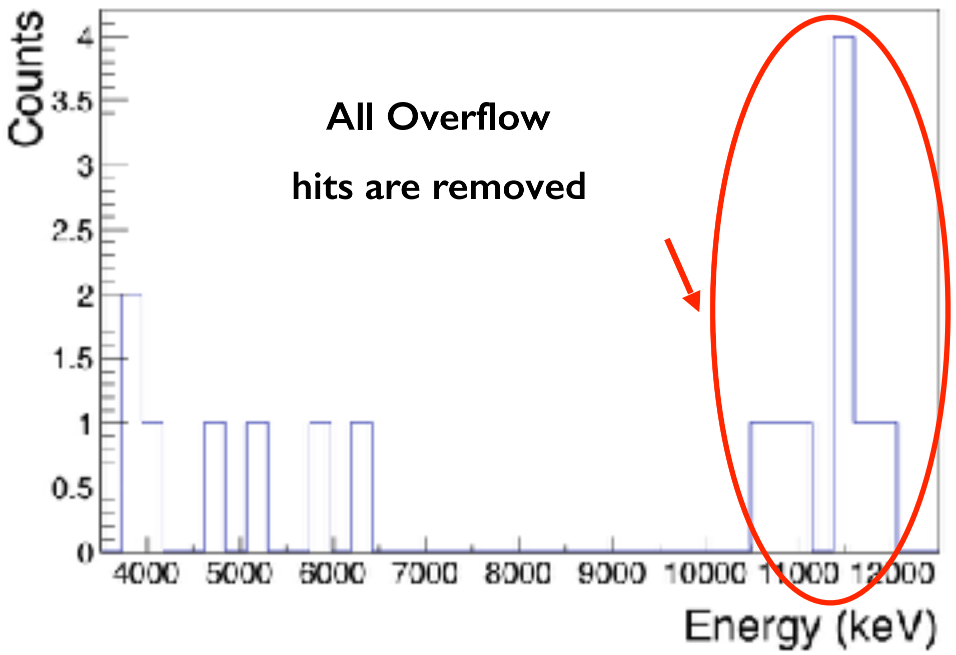


Muon Veto

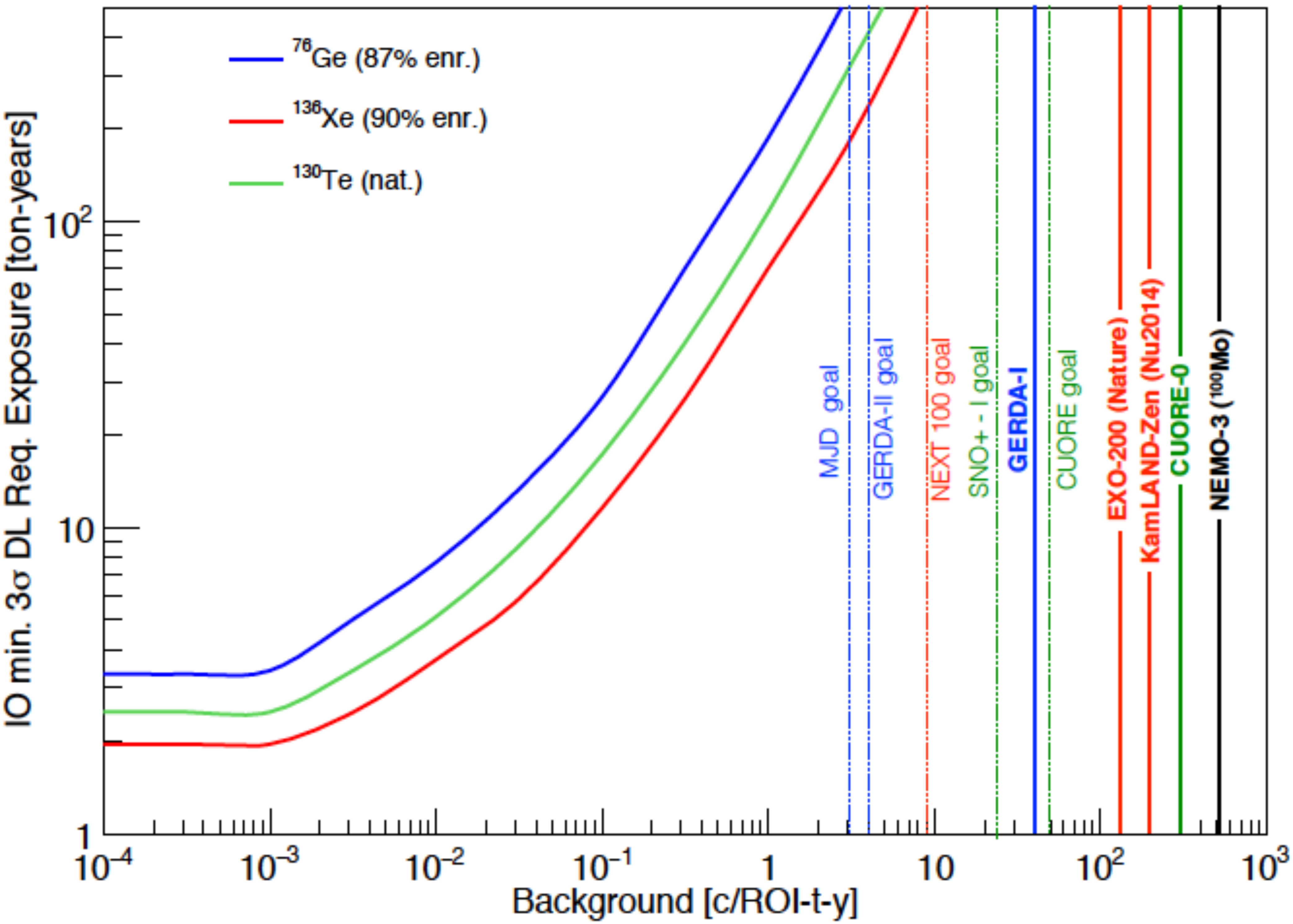
- Veto and Ge DAQ systems share a common 100 MHz clock.
- Prompt coincidences stand out in Δt distribution.
- Many high-energy Ge events (>3.5 MeV) coincident with muons
- Commissioning runs have demonstrated the veto system's ability to tag direct muons in Ge data by accounting for all overflow events.
- Flux measured by Majorana at Davis Campus:
  $(5.31 \pm 0.17) \times 10^{-9}$ $\mu/s/cm^2$ (arXiv:1602.07742)



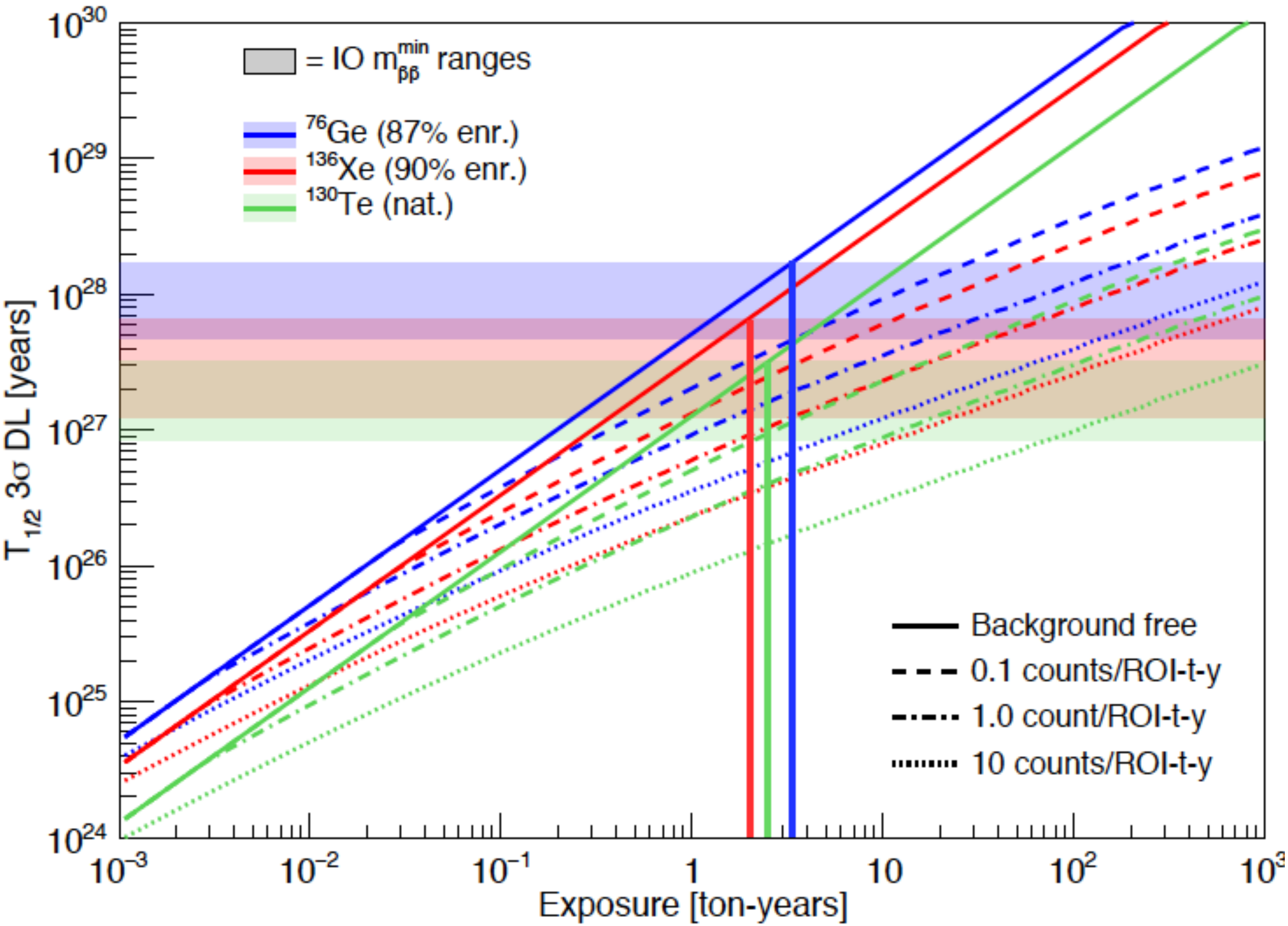
DS0: Ge Hits Coincident with μ Veto



Discovery Potential



Discovery Potential



$T_{1/2}$ Sensitivity