Initial Results from the MAJORANA DEMONSTRATOR

Steve Elliott for the MAJORANA Collaboration
Los Alamos National Laboratory

Overview

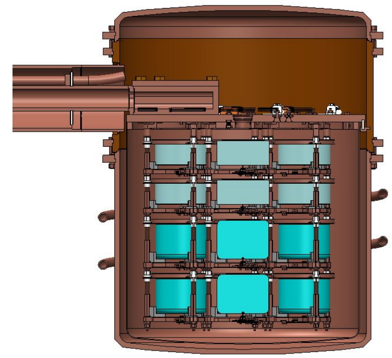
- The DEMONSTRATOR
- The Data Sets
- The Background at the $0\nu\beta\beta$ ROI
- The Low-Energy Program

Poster P4.060 Matt Green

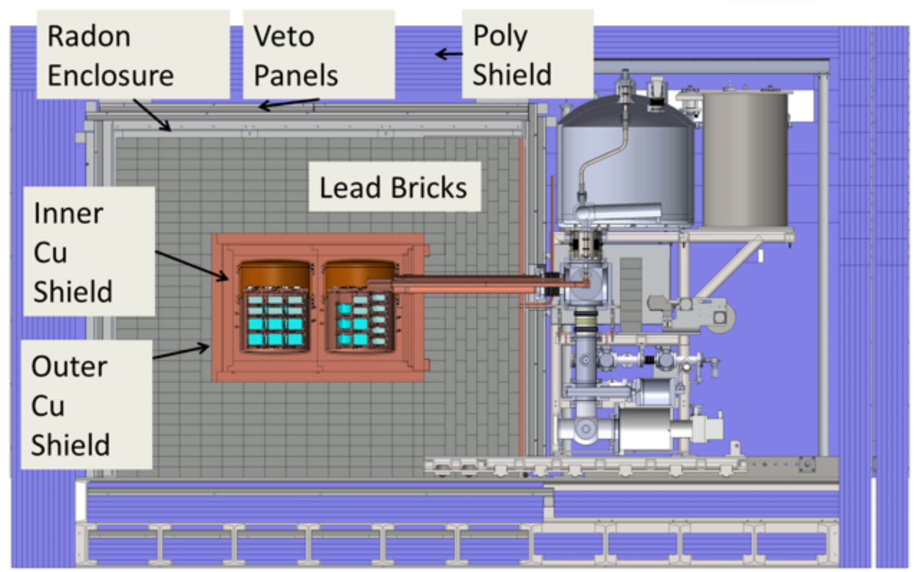
The MAJORANA DEMONSTRATOR

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.
- Searches for additional physics beyond the standard model.

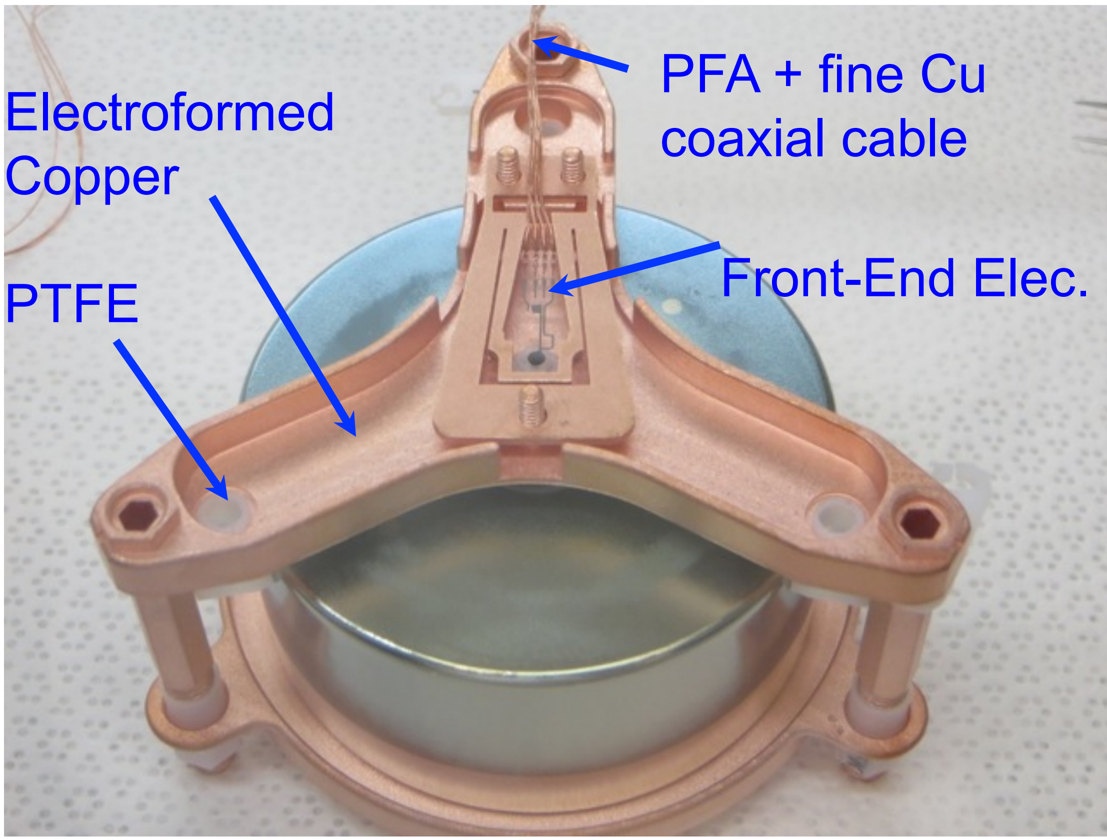


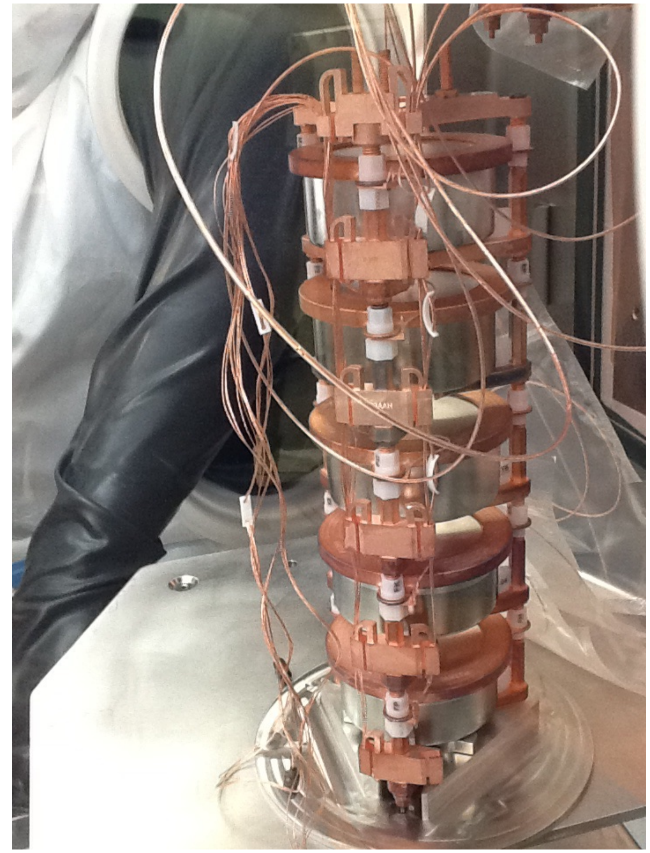
- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5
  scales to 1 count/ROI/t/y for a tonne experiment
- 44.8-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 15.1 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



Assembled Detector Unit and String

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).

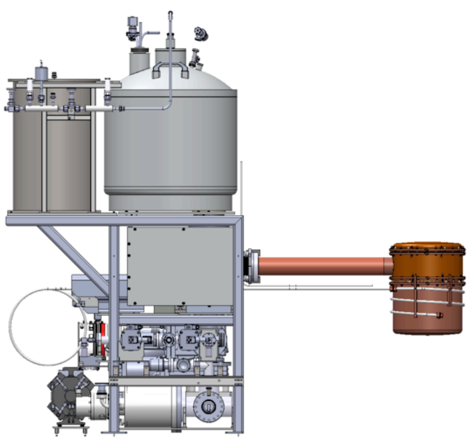




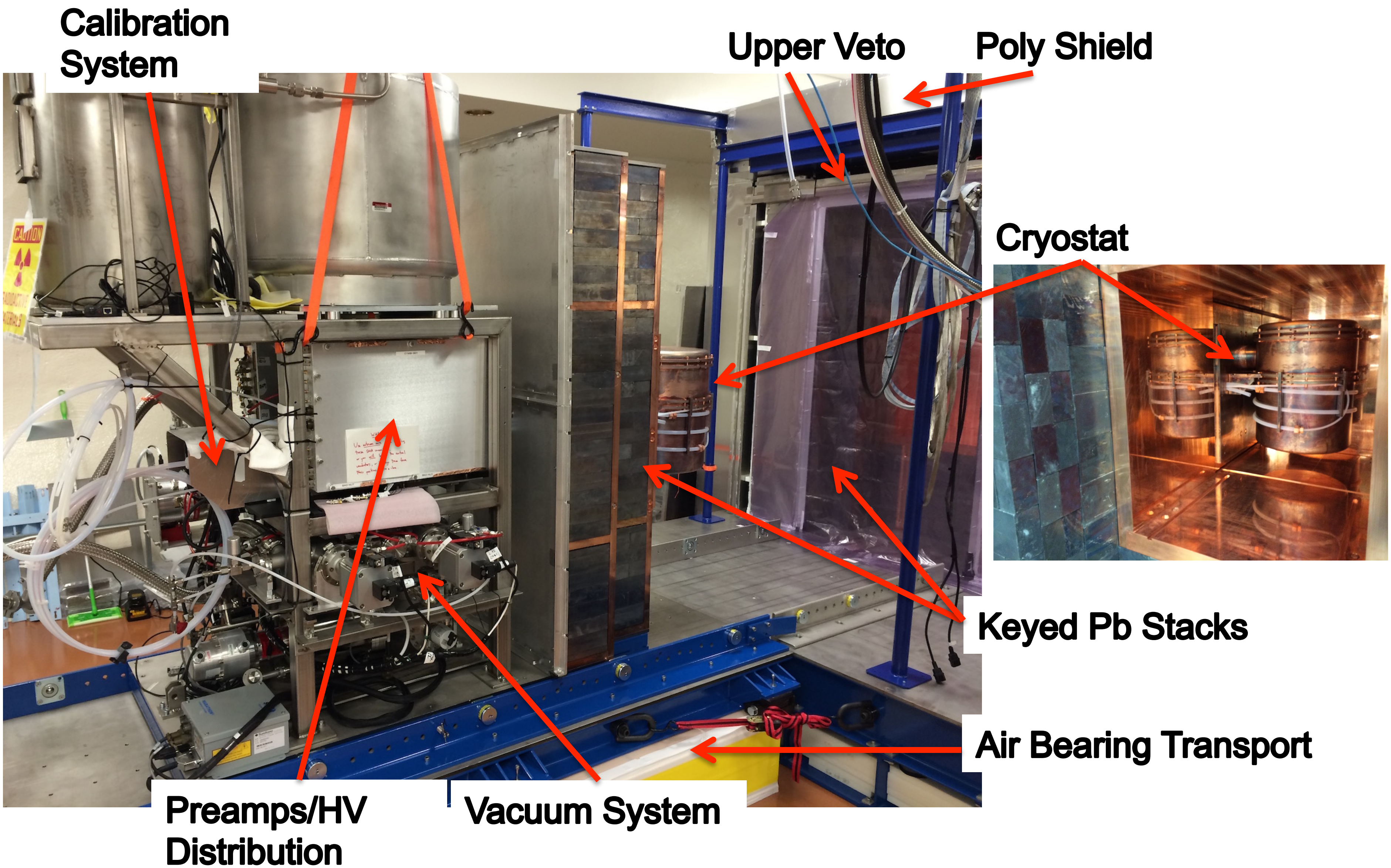
All detector assembly performed in N_2 purged gloveboxes.
All detectors' dimensions recorded by optical reader.

Modules

A Module is:
- **Cryostat**
- **Calibration sys.**
- **Thermosyphon**
- **Vacuum**
- **Shield Section**
- **All resting on a movable bearing table**

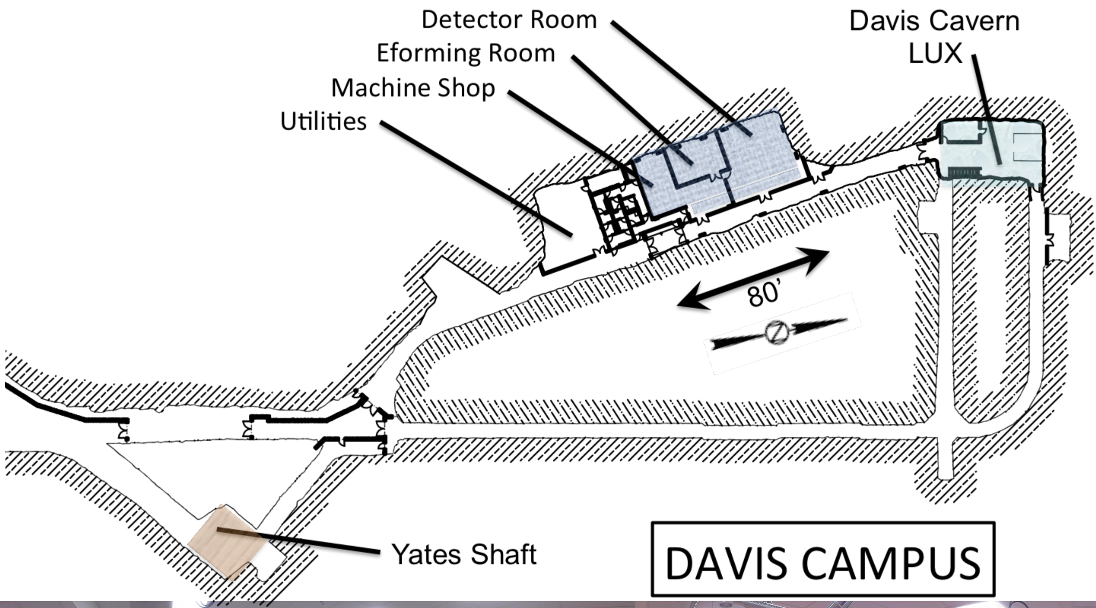


Module and Shield Details



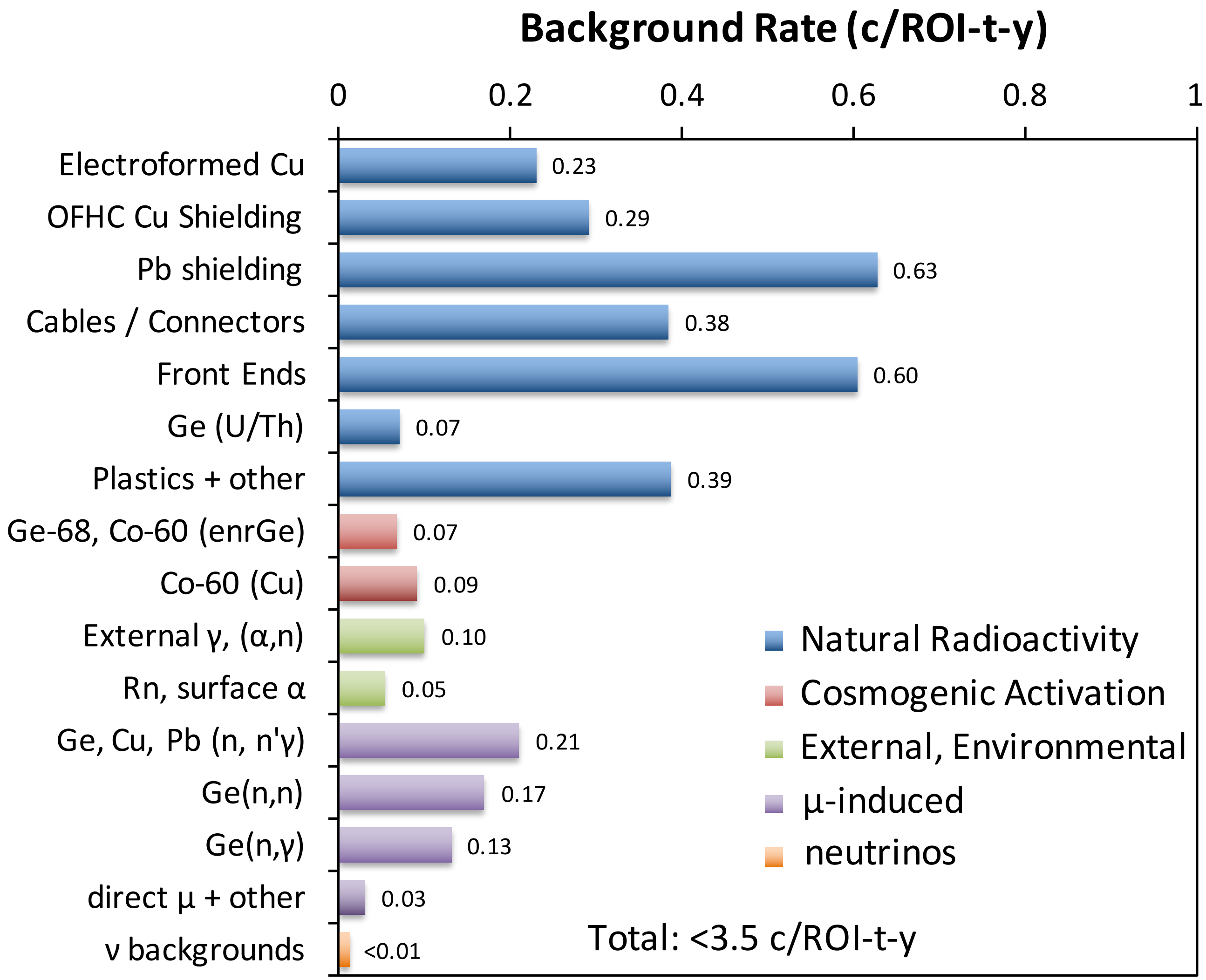
MAJORANA Underground Laboratory

4850’ level, SURF, Lead SD
Clean room conditions
Muon flux: 5 x 10^{-9} μ/cm^2 s
(arXiv:1602.07742)



DEMONSTRATOR Background Model

Background based on Assay Program (NIM A828 (2016) 22)
Poster P4.059 Clara Cuesta

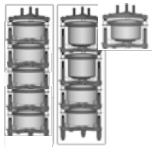


MAJORANA DEMONSTRATOR Implementation

Three Steps

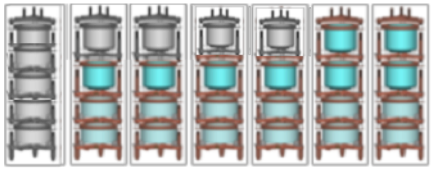
Prototype cryostat: 7.0 kg (10) ^{nat}Ge

Same design as Modules 1 and 2, but fabricated using commercial Cu Components



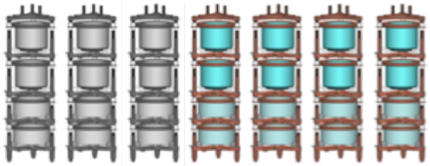
June 2014-June 2015

Module 1: 16.8 kg (20) ^{enr}Ge
5.7 kg (9) ^{nat}Ge

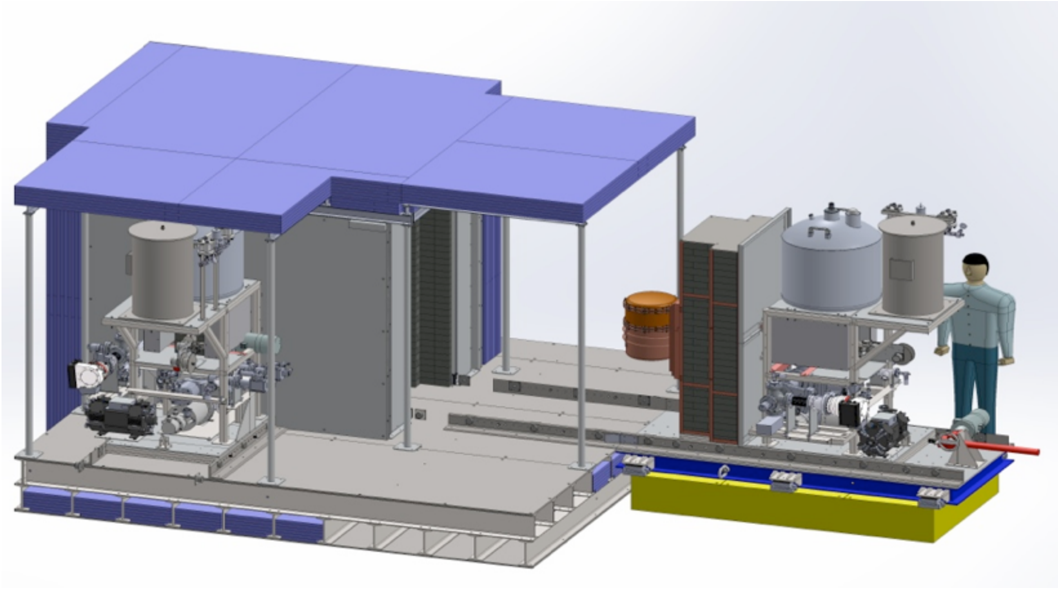


May–Oct. 2015,
Final Installations,
Dec. 2015 ongoing

Module 2: 12.8 kg (14) ^{enr}Ge
9.4 kg (15) ^{nat}Ge



Mid 2016

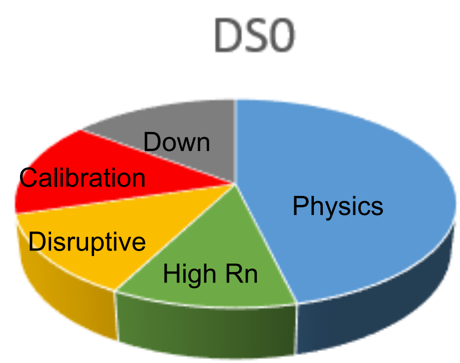


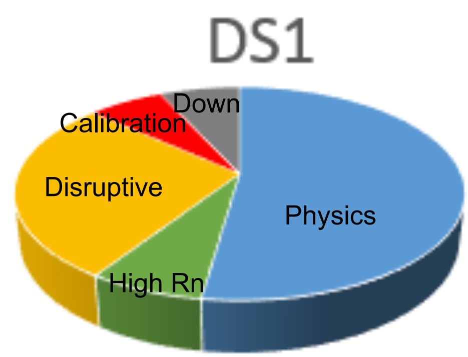
Module 1 Data Set Duty Cycles

The inner Cu shield, and cross-arm shielding was added between DS0 & DS1. Also a temporary non low-background cryostat seal was replaced.

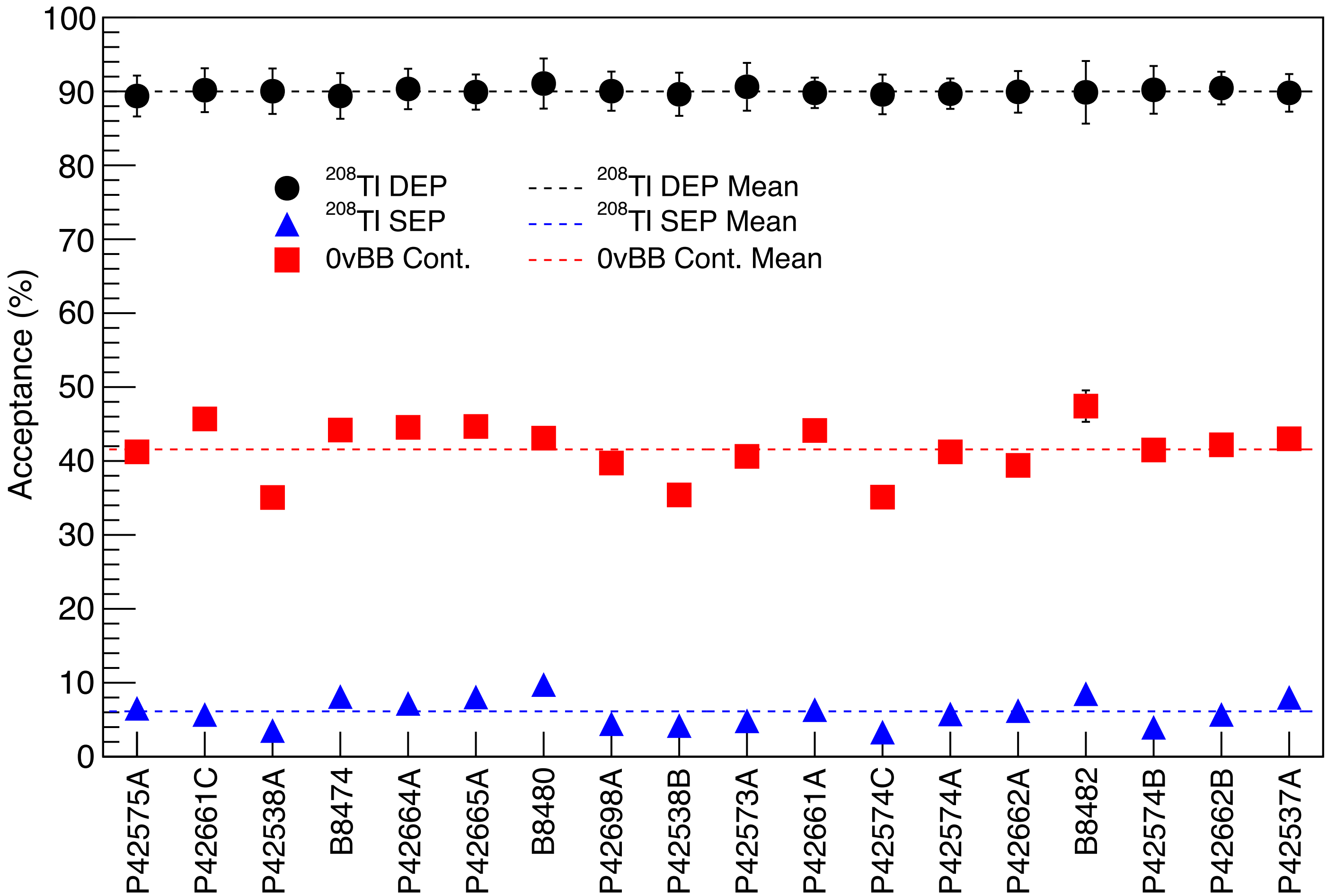
		DS0 (days) No inner shield June 26, – Oct. 7, 2015	DS1 (days) with inner shield Dec. 31, 2015 – Apr. 14, 2016*
Total		103.15	104.68
Total acquired		87.93	97.52
Physics	(blue)	47.70	54.73
High radon	(green)	11.76	7.32
Disruptive Commissioning tests	(yellow)	13.10	28.61
Calibration	(red)	15.44	6.86
Down time	(gray)	15.21	7.16

*Data taking ongoing





Ge Detector PSD Performance in Module 1 (DS1)



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

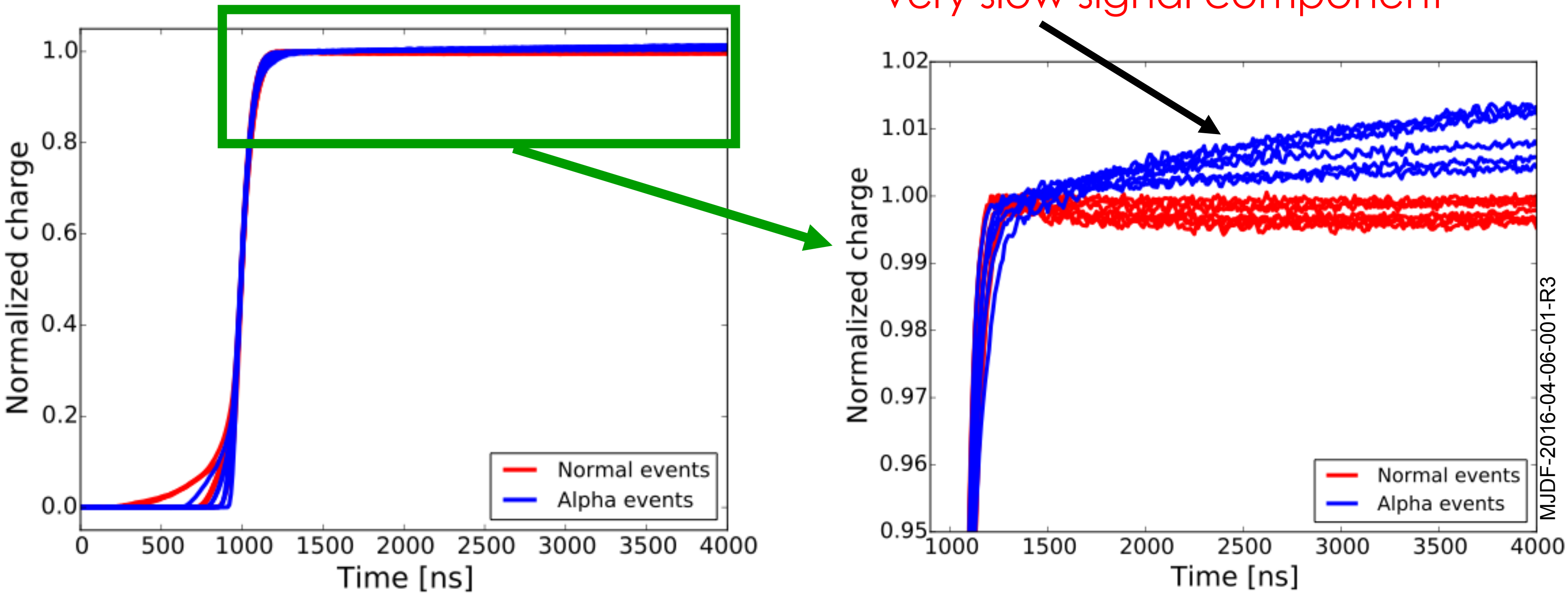
^{208}Tl SEP (Multiple site events) reduced to 6%

The Delayed Charge Recovery Cut for α's

- Alpha background response observed in Module 1 commissioning (DS0)
- Identified as arising from alpha 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.

Example pole-zero corrected waveforms

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



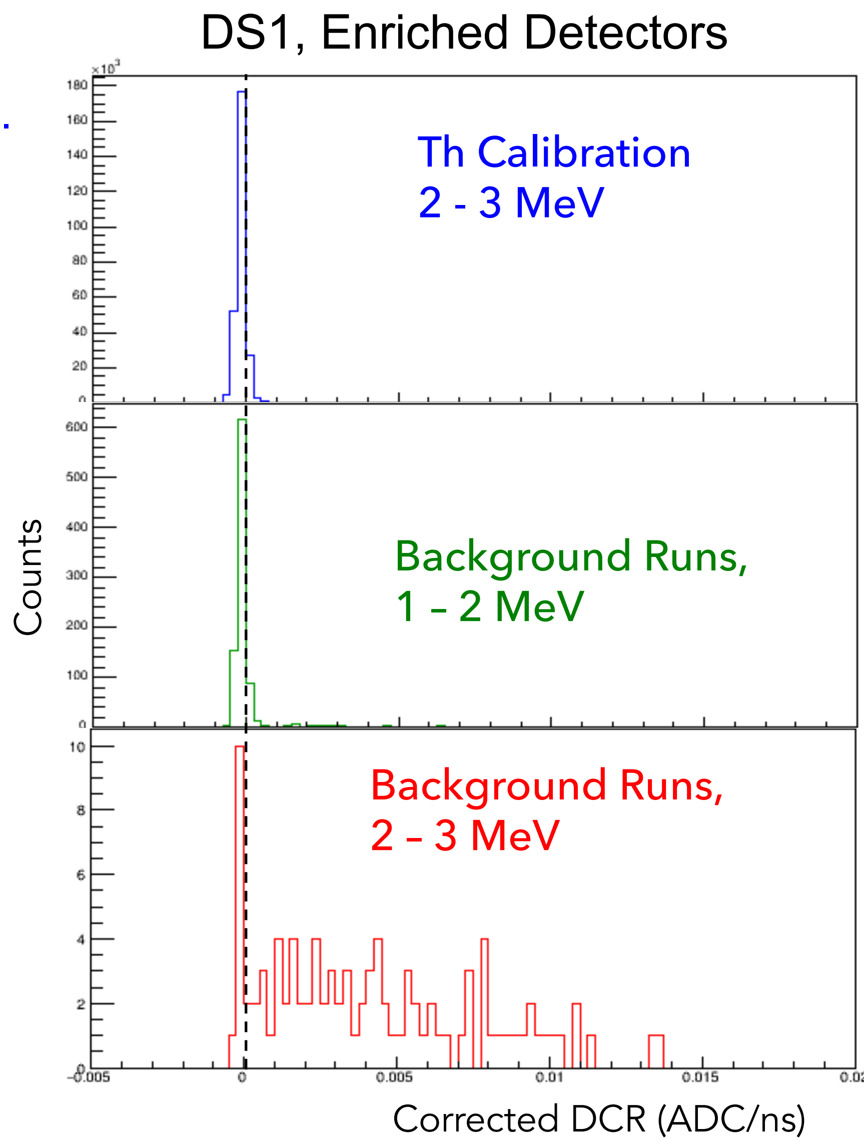
DS1 DCR Cut and Bulk-Event Response

Poster P4.094 Julieta Gruszko
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, $\beta\beta(2\nu)$ events survive cut.

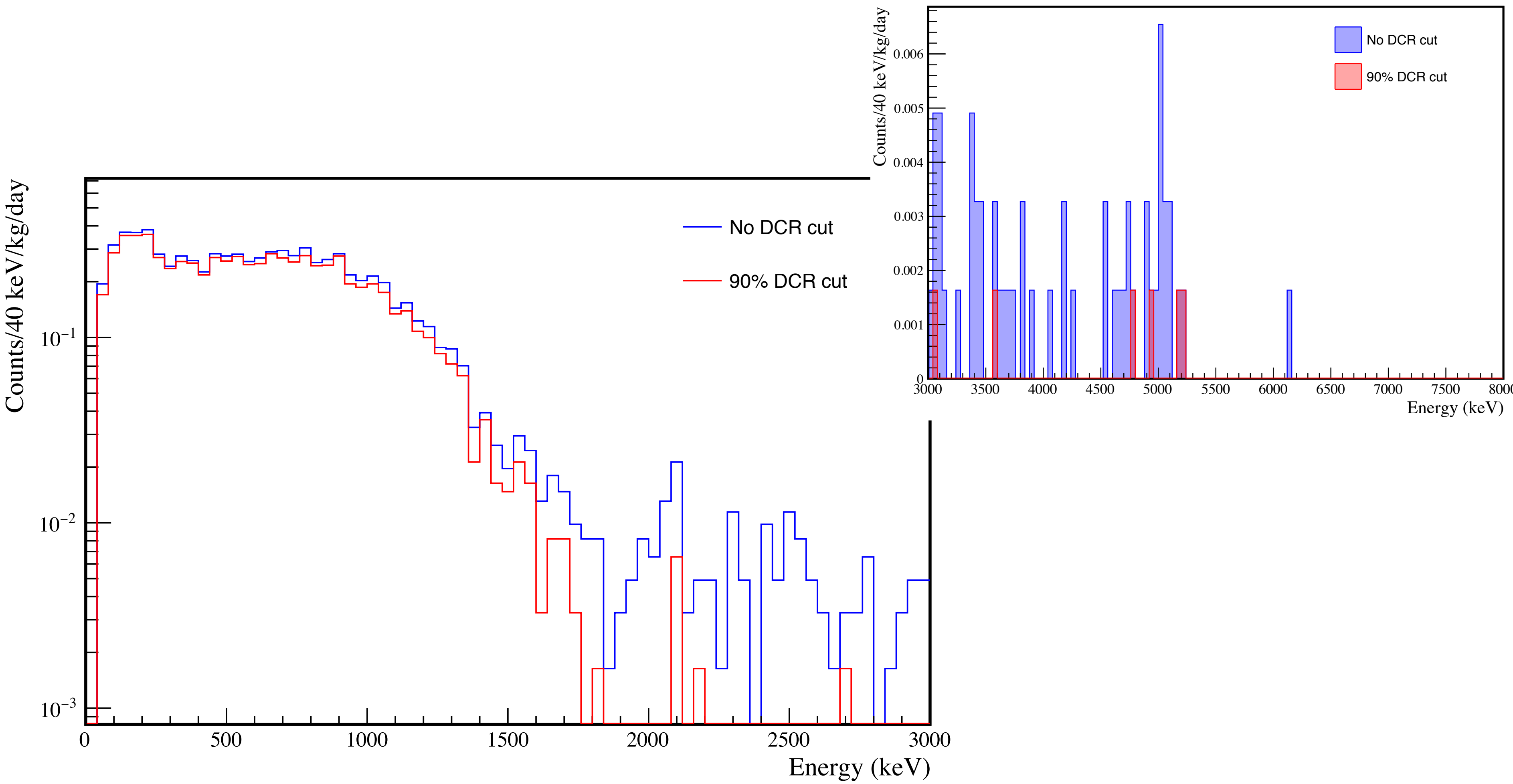
Candidate α events from background runs are removed.



DS1 Spectrum with DCR Cut

We perform some data cleaning cuts, granularity and PSD cuts to remove multiple site energy deposits, and the DCR cut to remove surface alphas.

DCR cut events stop at about 5.3 MeV. Circumstantial evidence that its Po.

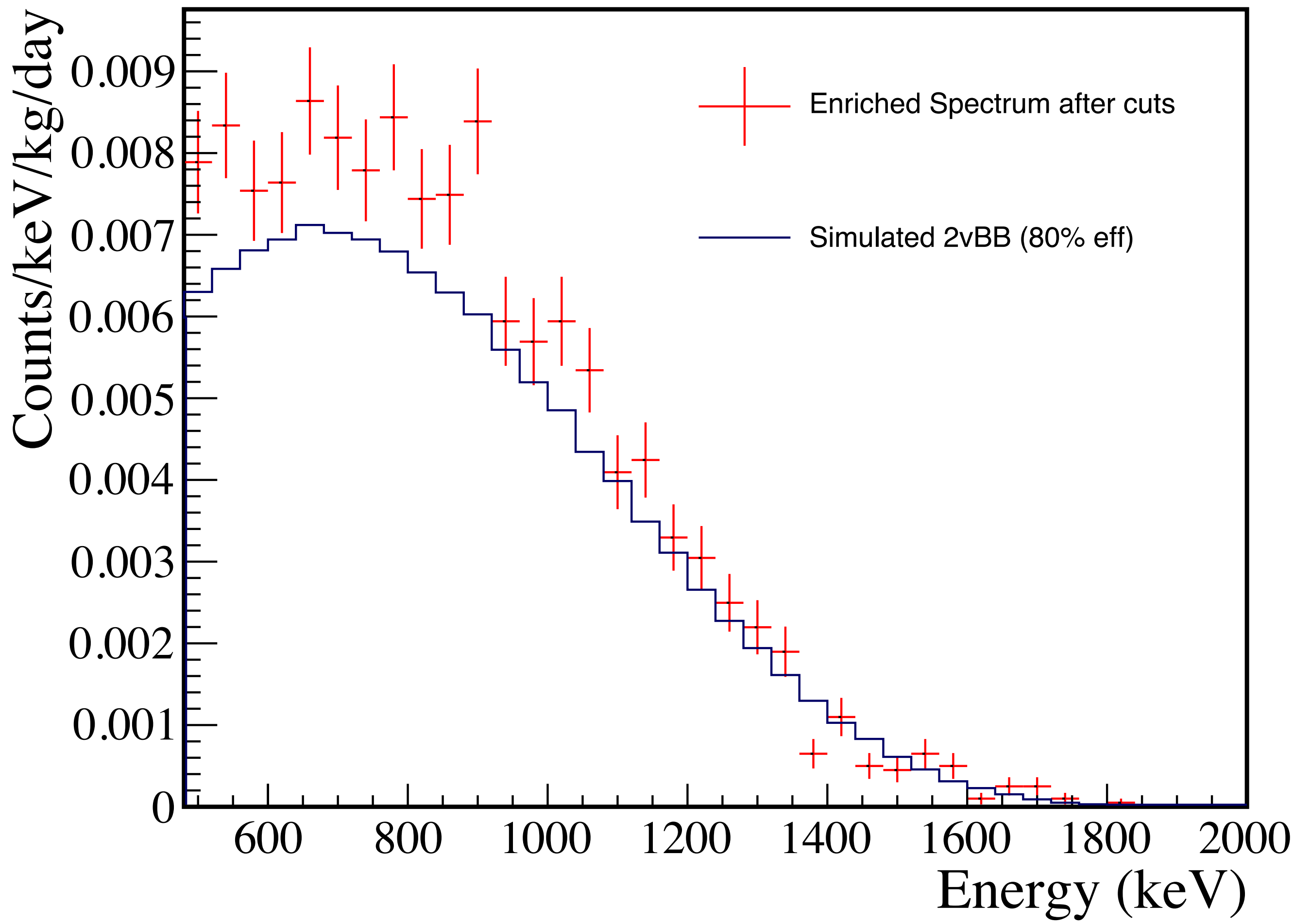


DS1: 500-2000 keV, ββ(2ν)

Data Set 1 spectrum after all cuts.

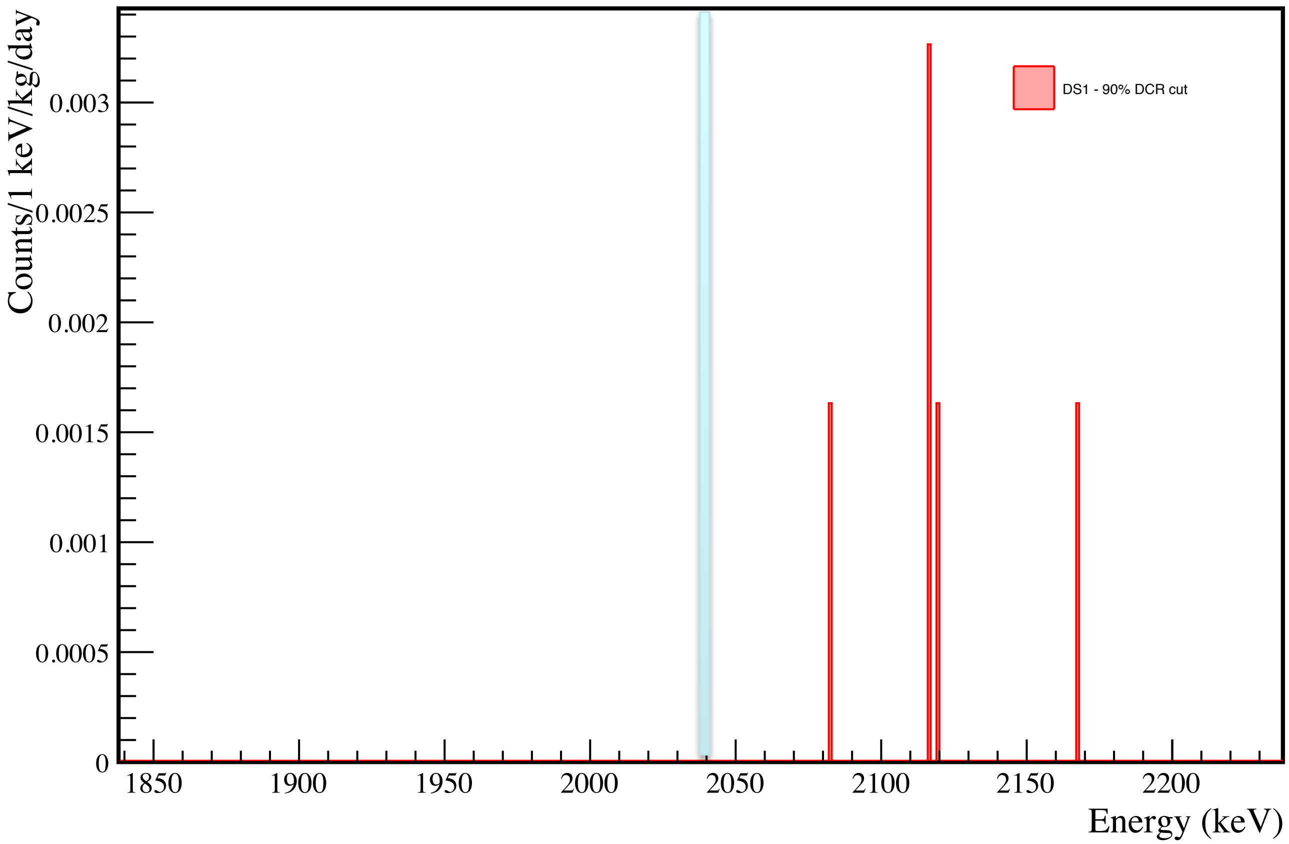
Above ~1200 keV the spectrum is dominated by ββ(2ν).

Simulated rate using previously measured half-life (Eur. Phys. J. C 75 (2015) 416).



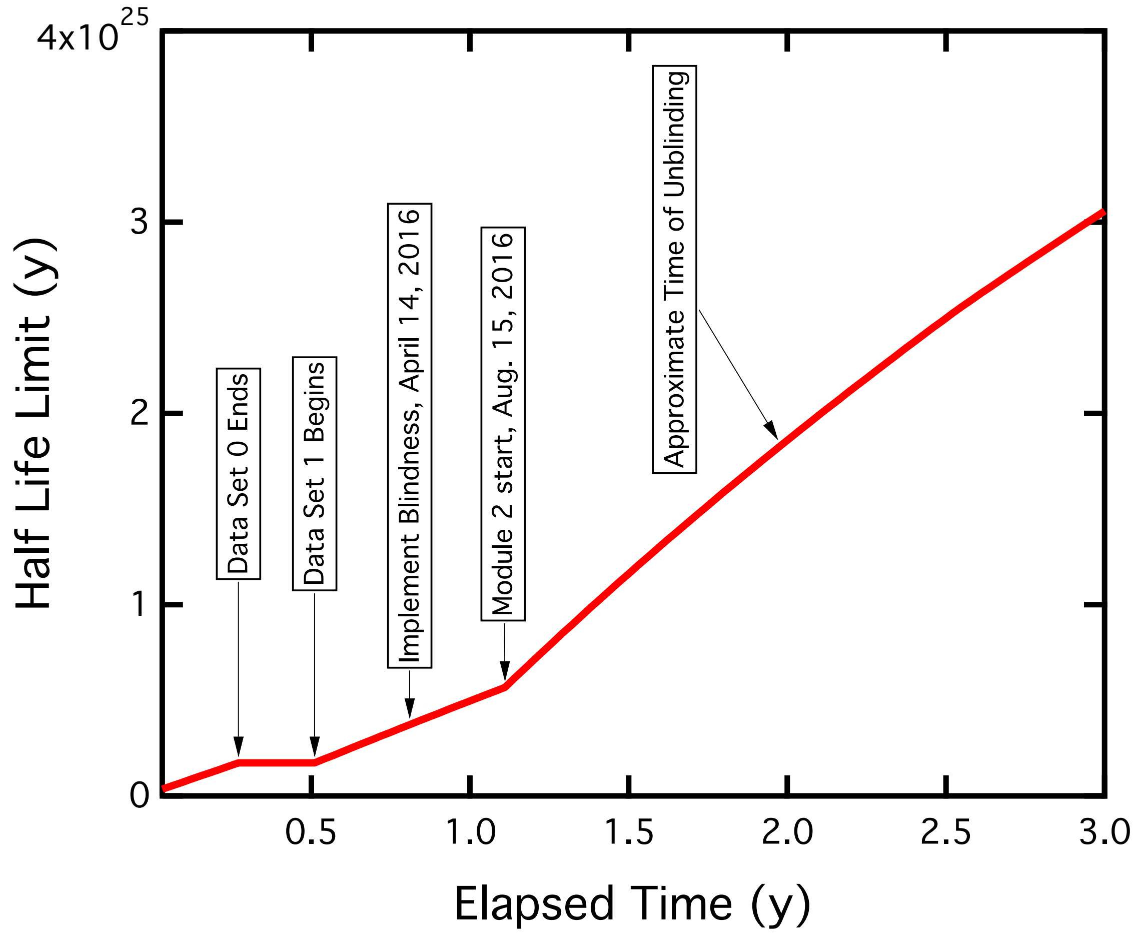
The ROI and DCR in DS1

The enriched detectors in Data Set 1 are used to estimate the background.
The lowest-background configuration. $Q_{\beta\beta}$ = 2039 keV.
Most events near ROI are removed by the DCR cut. Only 5 survive in 400 keV window.
Background rate is 23^{+13}_{-10} counts/(ROI t y) for a 3.1 keV ROI, (68% CL).
Background index is $(7.5^{+4.5}_{-3.4})\times10^{-3}$ counts/(keV kg y).
All analysis cuts are still being optimized.



DS0 +DS1: 0ν Sensitivity

- No ROI events in either data set.
- $T_{1/2} > 3.7 \times 10^{24}$ y (90% CL).
- DS0 & DS1 total exposure: 3.03 kg y.
  - DS0 1.37 kg-y, DS1 1.66 kg y
- Efficiency for $0\nu\beta\beta$ is 0.61±0.04.
  - 0.61 = (0.84)(0.9)(0.9)(0.9)
  - = (Resol.)(Full Energy)(A/E)(DCR)
- Background very low. Sensitivity almost linear with exposure.
- We are exploring additional techniques for reducing background.
  - –Fast rise-time cut.
- This analysis is on open data.
- Blind data taking began on April 14.
- We are studying the possibility of repairing cables/connectors. Could increase mass by 50%



DS0: Tritium with Cosmogenic X rays

Poster P4.012 Reyco Henning

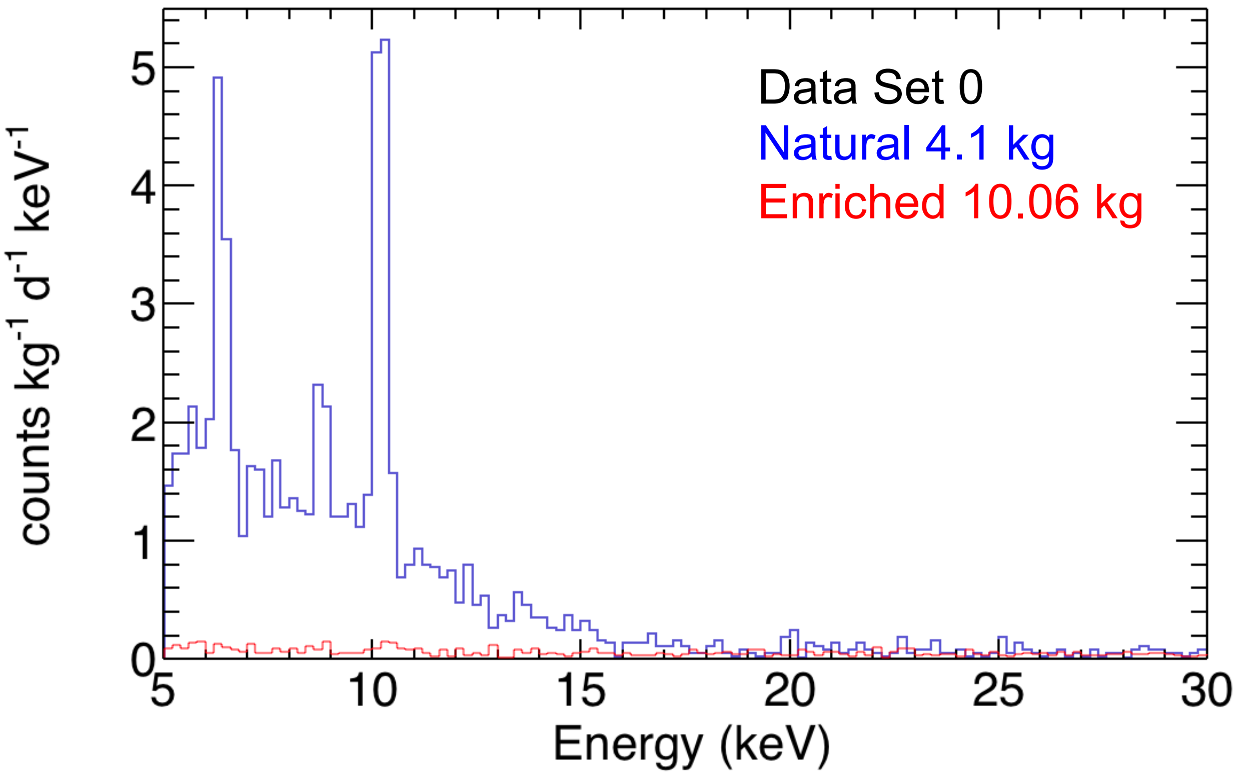
Controlled surface exposure of enriched material.

- The enriched detector ^{68}Ge rate is low enough that an X-ray delayed coincidence cut will not be necessary.

Significant reduction of cosmogenics in the low-energy region. Factor of a few better in DS1.

Tritium is obvious and dominates in natural detectors below 20 keV.

Efficiency below 5 keV is under study.



<u>Permits Low-Energy physics</u>

Pseudoscalar dark matter
Vector dark matter
14.4-keV solar axion
$e^- \rightarrow 3\nu$
Pauli Exclusion Principle

Next Generation ^{76}Ge Experiment

Working cooperatively with GERDA and other interested groups toward the establishment of a next-generation ^{76}Ge $0\nu\beta\beta$-decay experimental collaboration to build an experiment to explore the inverted ordering region of the effective mass.
Poster P4.075 SRE

Joint MAJORANA-GERDA Meeting
Nov. 2015 Kitty Hawk

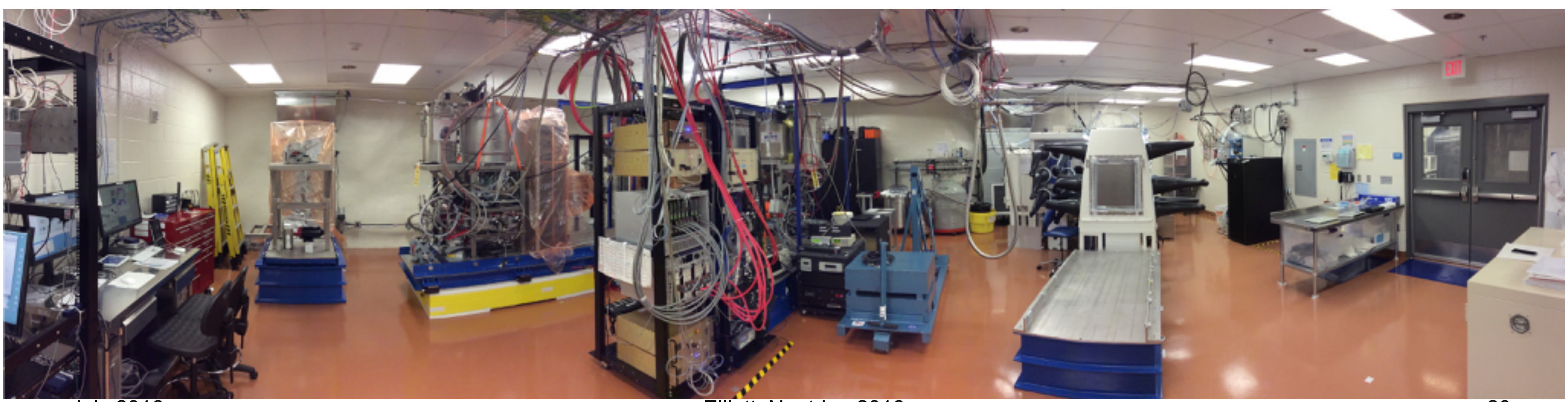
Meeting of Interested Parties
April 2016 Munich

Next Meeting
End Oct. East Coast US

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.
- Attained highest yield to date (74.5%) of enriched ^{76}Ge detectors from initial material.
- Module 1 in operation with improved shielding since January 2016, blind data collection mode since April 2016.
- Module 2 undergoing commissioning. Aim for in-shield background measurements by August.
- Final additions (neutron shielding) to main shield will be installed once Module 2 is in shield.
- Independent work continues to improve cables and connectivity in terms of an optimized next generation ton scale ^{76}Ge $0\nu\beta\beta$ experiment.
- Collected 3.03 kg yr of exposure from DS0 & DS1 before going blind. $T_{1/2} > 3.7\times10^{24}$ y
- Measured background level in DS1 at ROI is 23^{+13}_{-10} counts/(ROI t y). The ROI is 3.1 keV.
- The low energy spectrum in DS0 is producing physics results.

- Posters on MAJORANA: P4.094 DCR cut; P4.012 Low-E spectrum; P4.059 Background; P4.060 Overview; P4.075 Future Experiment



The MAJORANA Collaboration

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EXTRAS

The Data Sets

*Data set continuing after implementation of blindness.
These describe data sets that are open.
Blindness began on April 15.

Data Set	Prototype Module	Module 1 no inner shield	Module 1 with inner shield
mnemonic	DS-PM	DS0	DS1
Operation Dates	9/18/14 – 4/17/15	6/26/15 – 10/7/15	12/31/15 – 4/14/16*
Run Time	211 d	103.15 d	104.68 d
Live Time	138.22 d	46.9 d	53.6 d
Fraction Live	0.65	0.45	0.51
Enriched Ge Exposure	0 kg d	501.4 kg d	606.0 kg d
Natural Ge Exposure	701.7 kg d	183.3 kg d	54.7 kg d

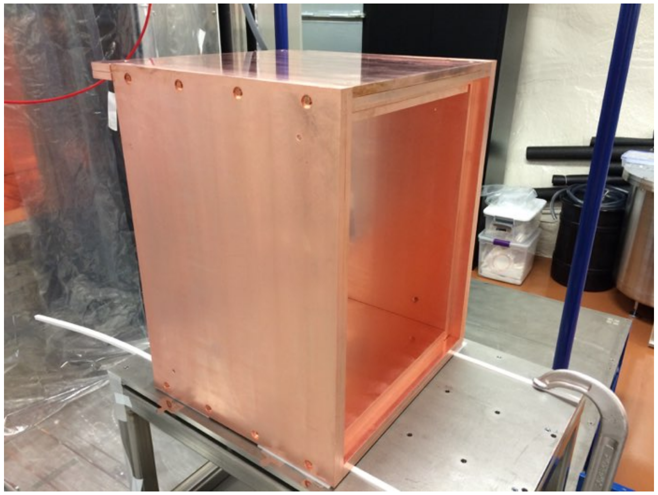
Final Installations in Module 1

- After early commissioning runs (DS0) of Fall 2015, we implemented planned improvements.
  - –Installed the inner copper shield. This part of the copper shield was last to be machined.
  - –Added additional shielding within the vacuum of the cross arm.
  - –Replaced the cryostat Kalrez seal with PTFE. Much better radiopurity and much lower mass. x2000 reduction in ROI contribution.
  - –Repaired non-operating channels.
- These changes define the difference between DS0 and DS1.
- Hence DS1 is the data set that is being used to determine the background.

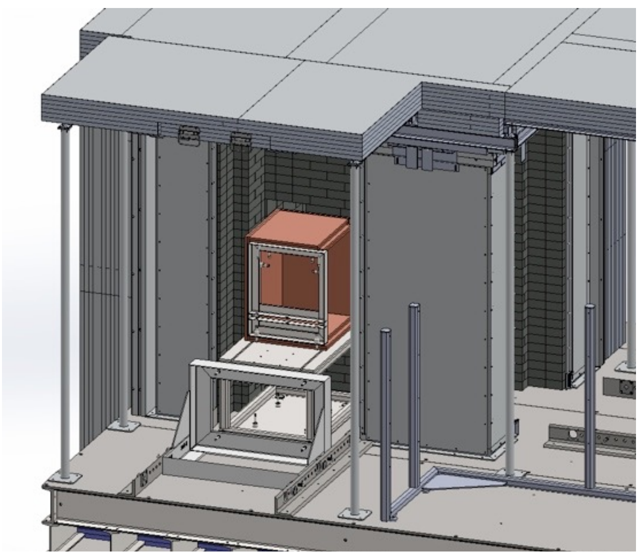
Seal Replacement

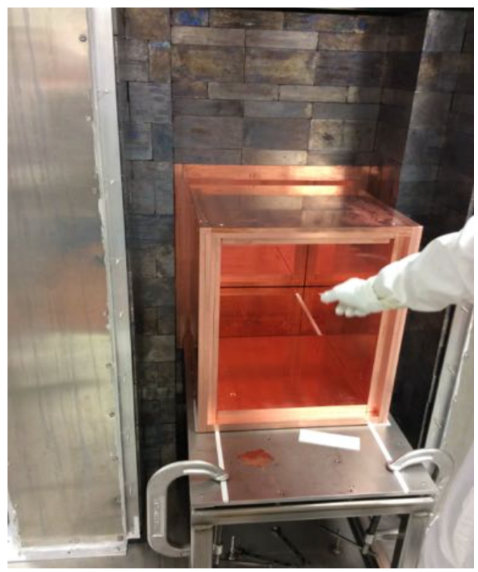
- Replaced reusable Kalrez gasket with low activity, low mass single-use 0.002” PTFE gasket.
- Determined one of the gaskets has a small vacuum leak. Vacuum is acceptable at ~2-3 x 10^{-7} Torr

The Inner Copper Shield

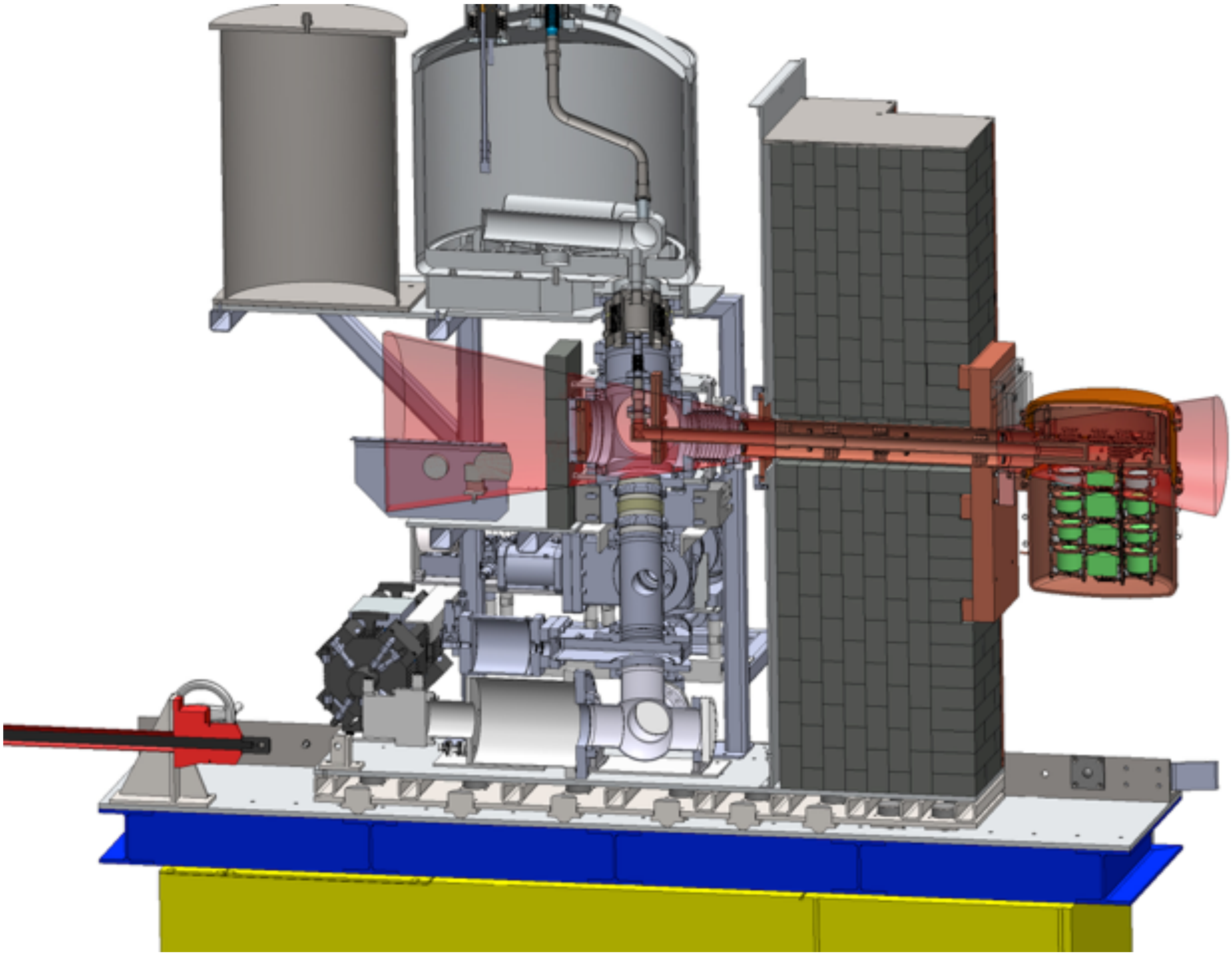


- Schedule driven by electroforming.
- String parts higher priority for machining.
- Installed after shield constructed.
- Expect x10 reduction in background from other shield materials.

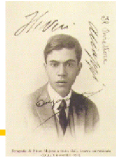




Shine Path through Cross arm



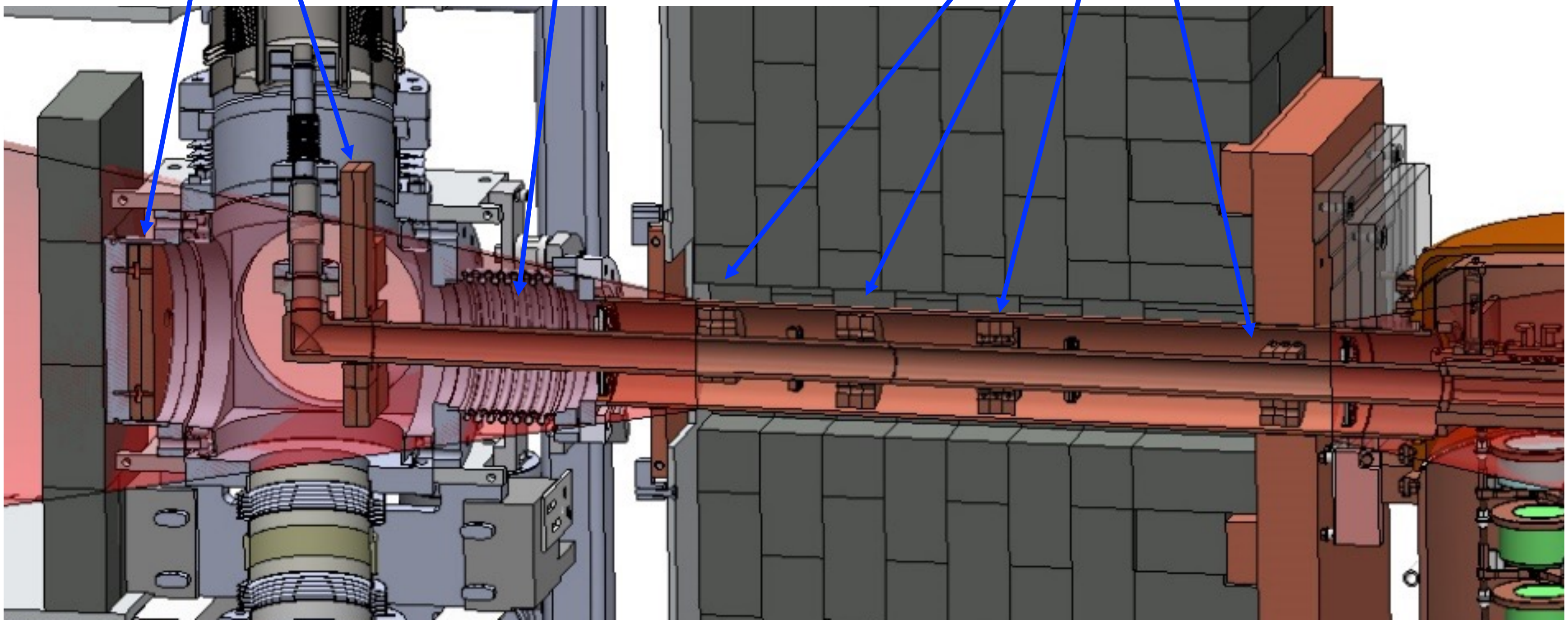
New in-vacuum shielding for M1 and M2



4 ea Cu plates ½ inch thick

Replacement Bellows with lower Th content

12 ea Cu plates ½ inch thick



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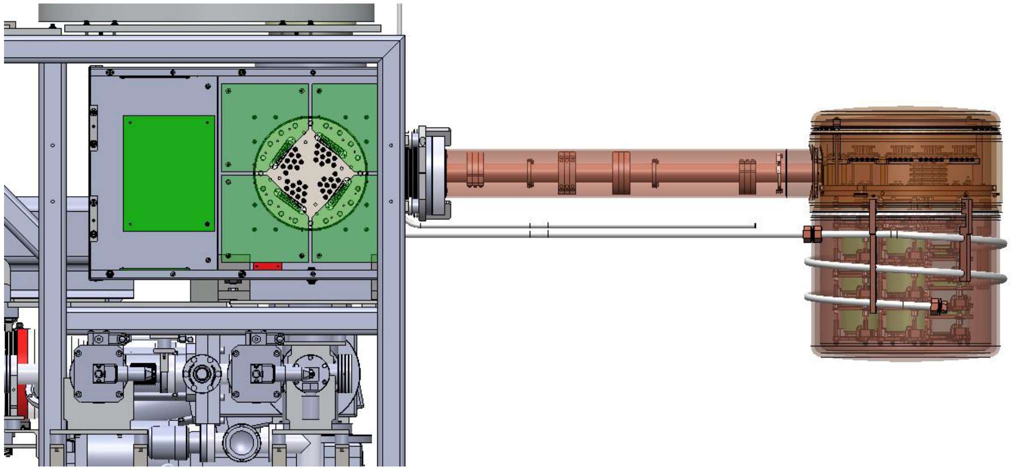
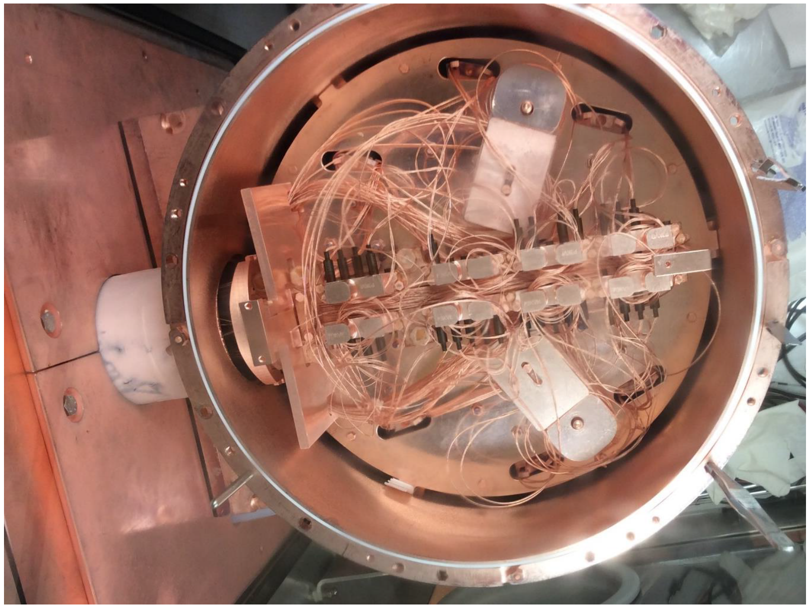


Module 2 thermosyphon with crossarm cables loaded, ready for installation into crossarm tube: Feb. 2, 2016.



MAJORANA Electroformed Copper

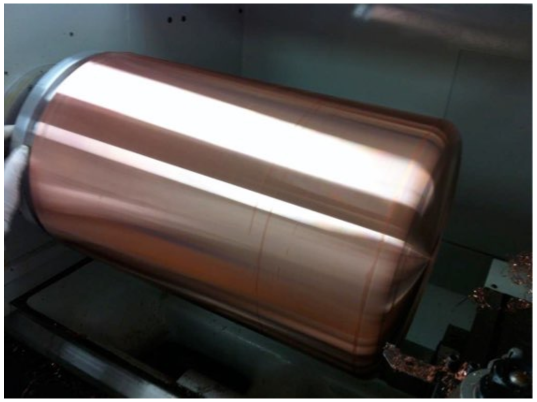
- MAJORANA operated 10 baths at the Temporary Clean Room (TCR) facility at the 4850' level and 6 baths at a shallow UG site at PNNL. All copper was machined at the Davis campus.
- The electroforming of copper for the DEMONSTRATOR successfully completed in May 2015.
  - 2474 kg of electroformed copper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

Electroforming Baths in TCR

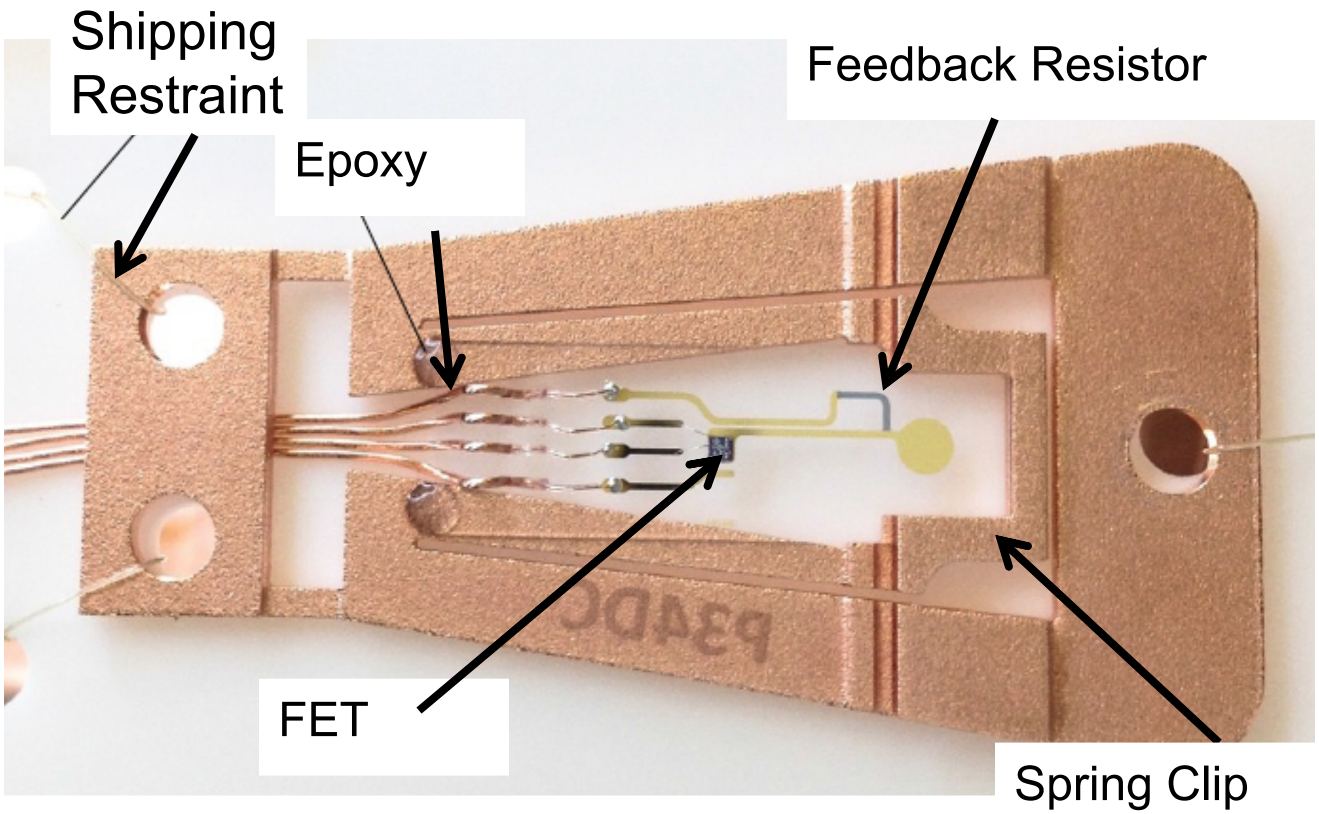
Inspection of EF copper on mandrels

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

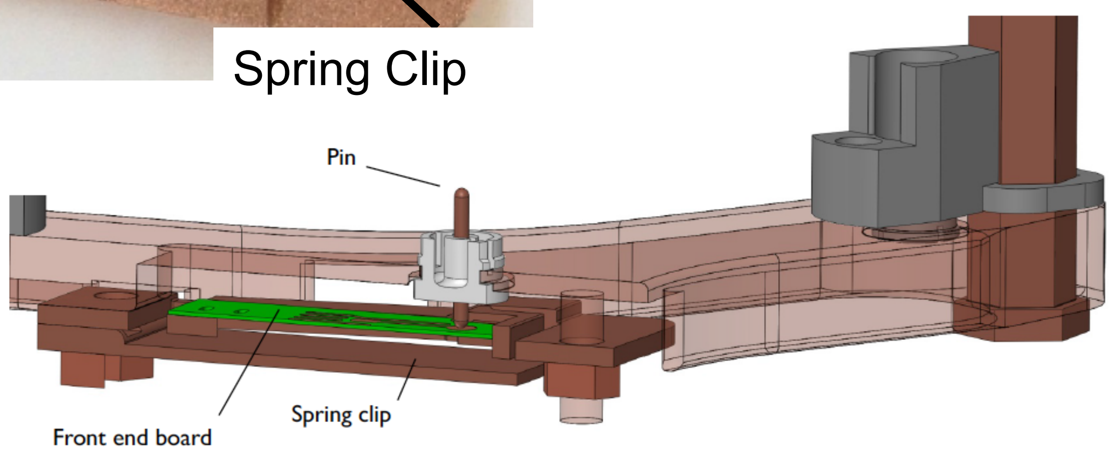
EF copper after turning on lathe



Front-End Board

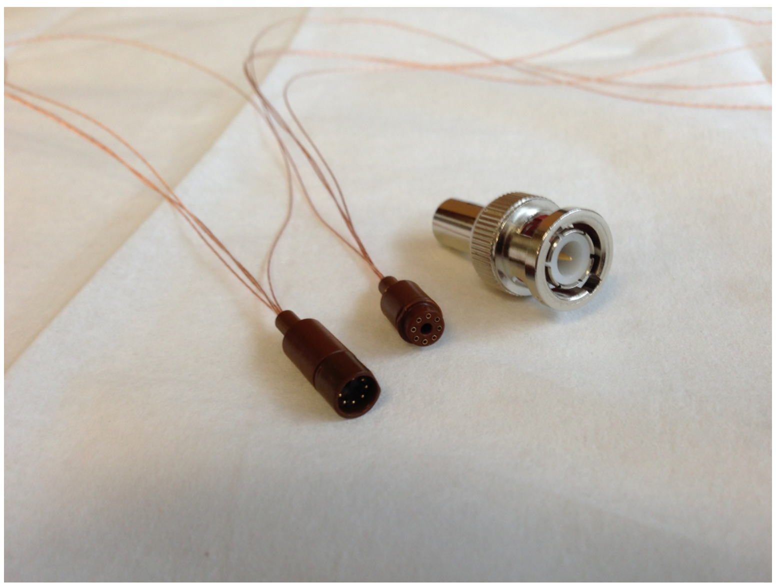


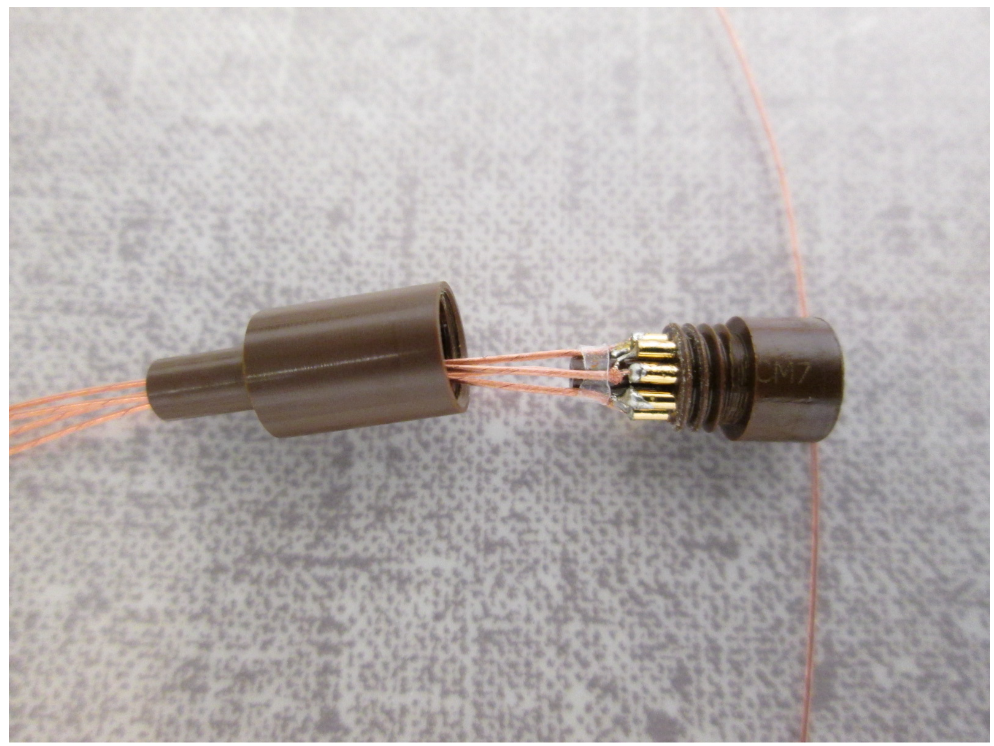
Clean Au+Ti traces on fused silica, amorphous Ge resistor, FET mounted with silver epoxy, EFCu + low-BG Sn-coated-Cu contact pin



Signal Connectors

Connectors reside on top of cold plate.
In-house machined from vespel. Axon' pico co-ax cable.
Low background solder and flux.
Axon' Picoax HV and signal cables.
All cables and connectors were HV tested (NIM A823 (2016) 83)



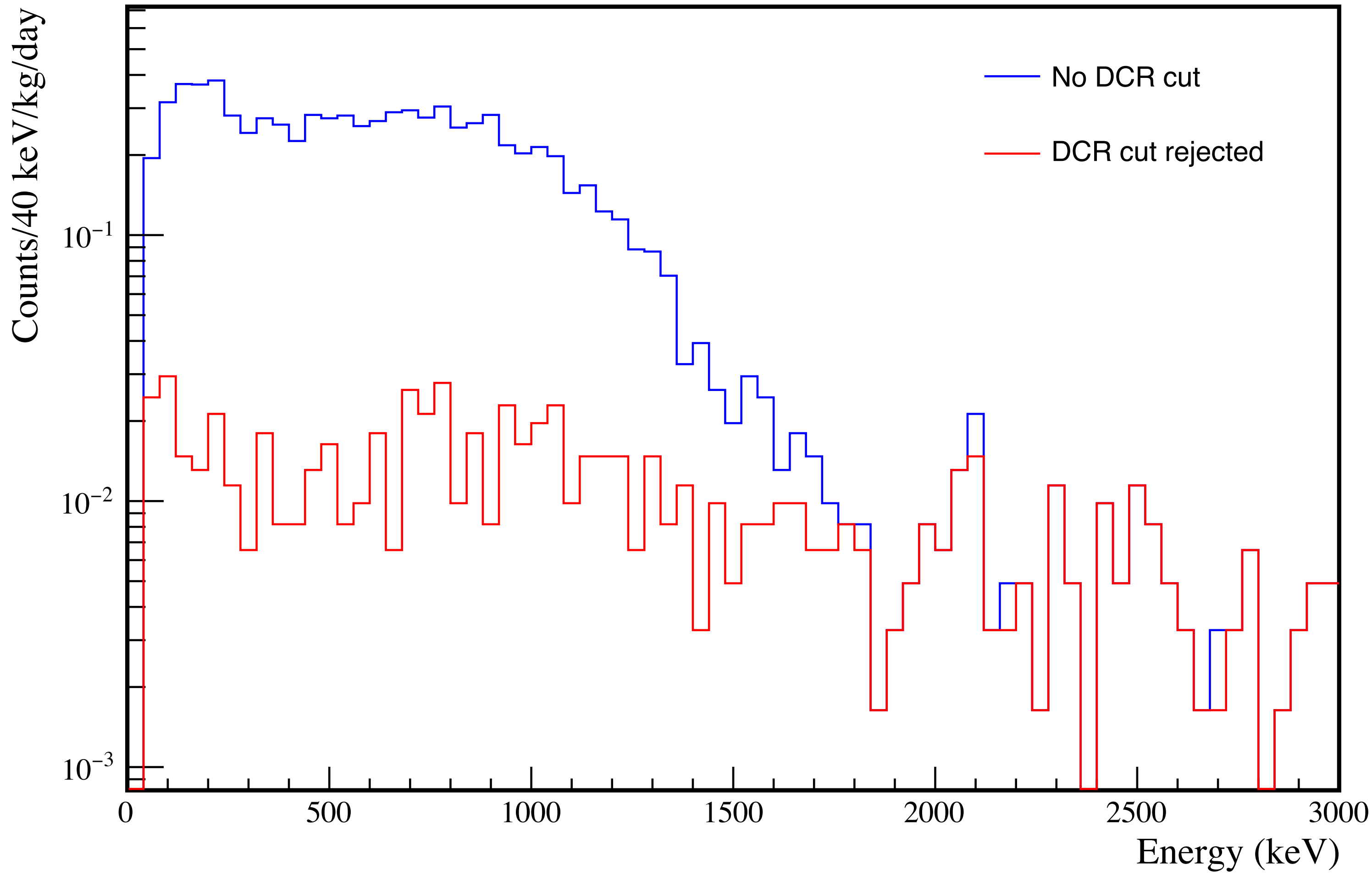


The Potential for the DCR Background was Anticipated

- 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/cm^2. 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 Q_{bb}
    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 cm^2. If we assume <u>all</u> the DCR cut events are alphas on 15 ^{enr}Ge detectors, we have an alpha rate of approximately <110 nBq/cm^2.
  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.

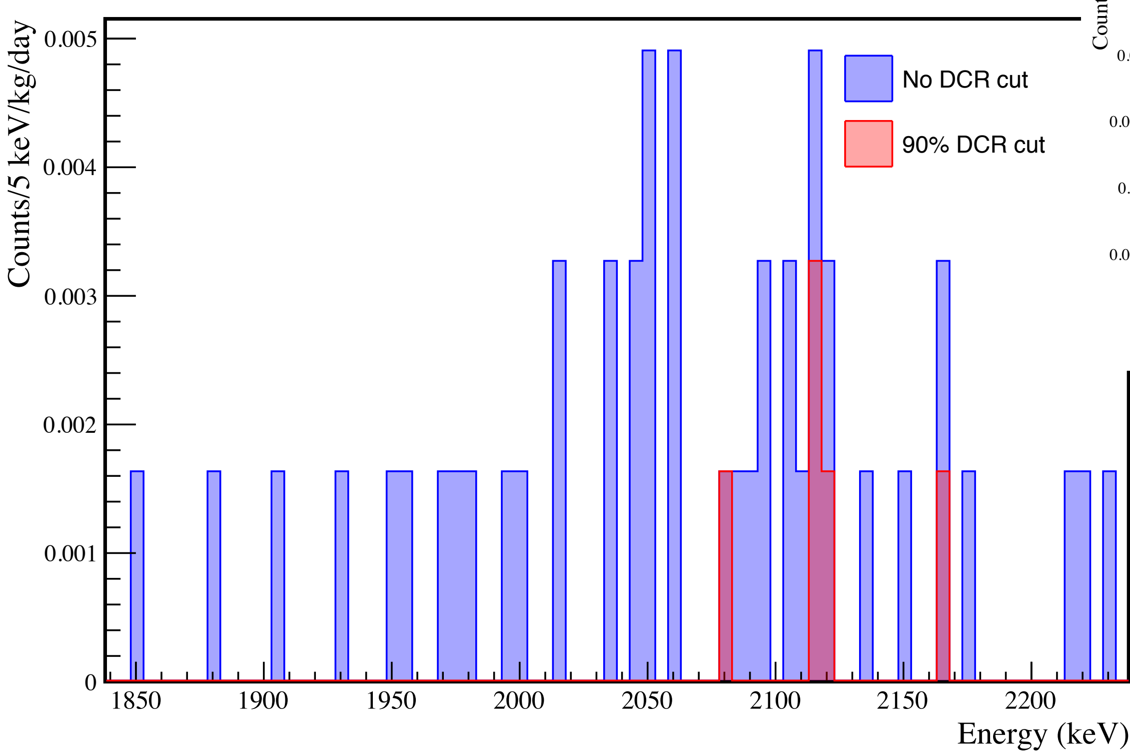
The DCR-cut Spectrum – DS1

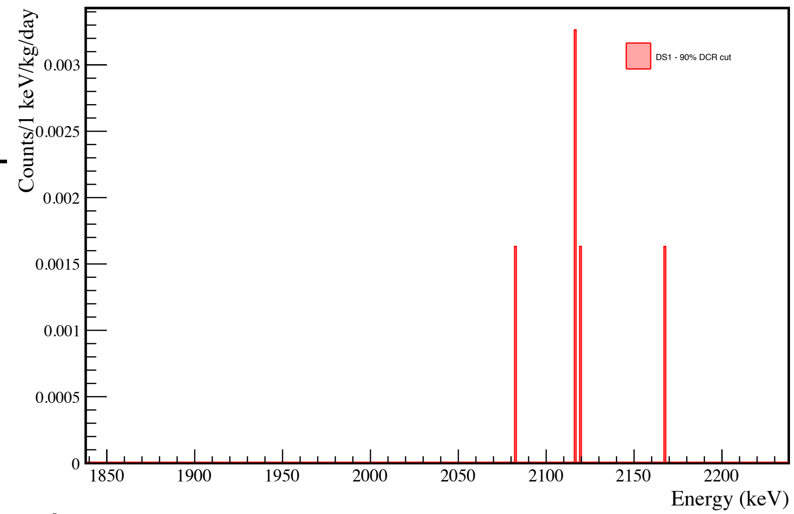
DCR rejected spectrum is nearly flat. Removes a large fraction of events over about 1800 keV.
High gain spectrum stops at 3 MeV.



The ROI and DCR in DS1

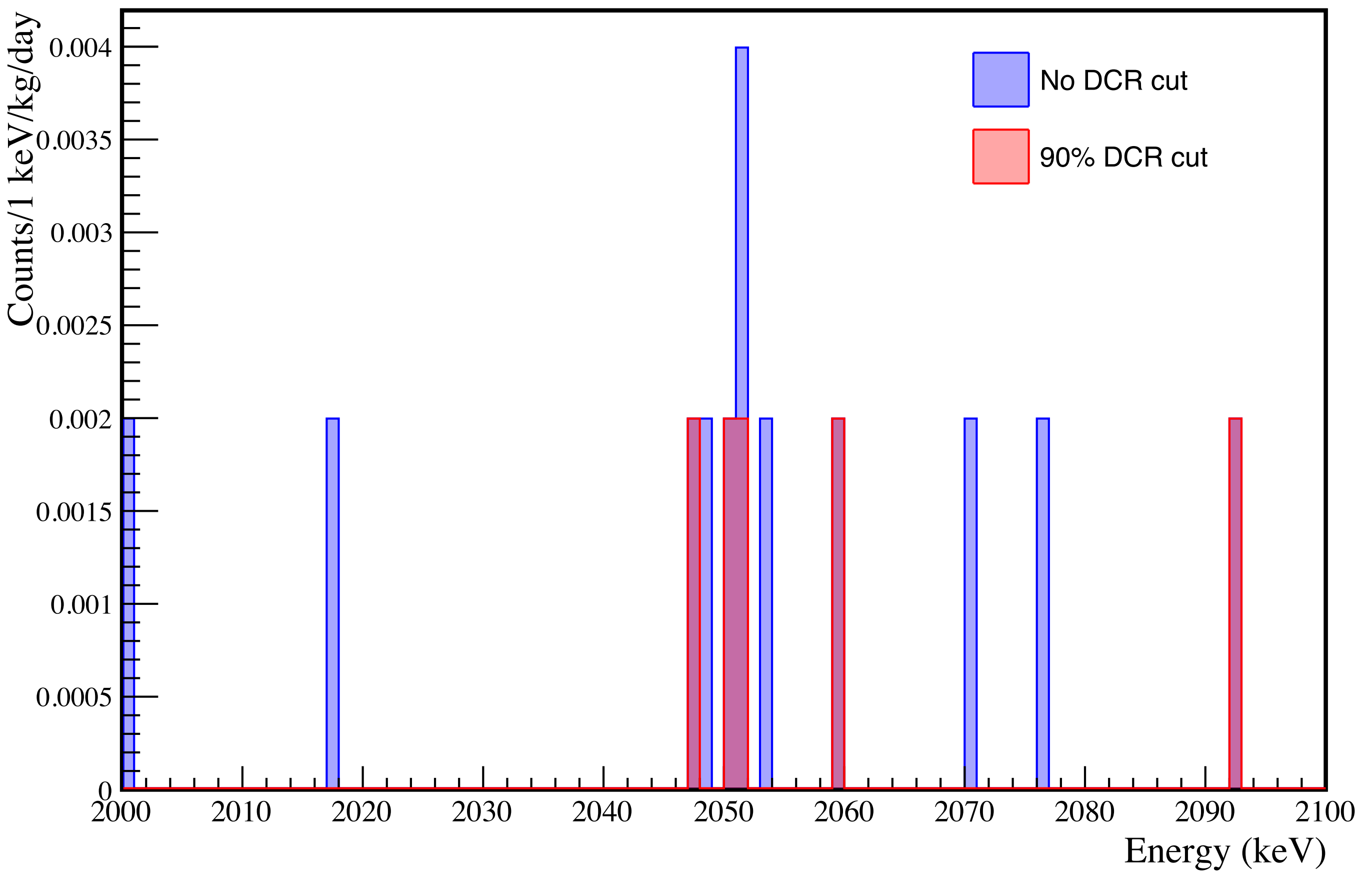
The enriched detectors in Data Set 1 are used to estimate the background.
The lowest-background configuration.
Most events near ROI are removed by the DCR cut. Only 5 survive in 400 keV window.
Background rate is 23^{+13}_{-10} counts/(ROI t y) for a 3.1 keV ROI.
Background index is 0.0075 counts/(keV kg y).





The ROI and DCR in DS0

DS0, Enriched Detectors
Most events near ROI are removed by the DCR cut.



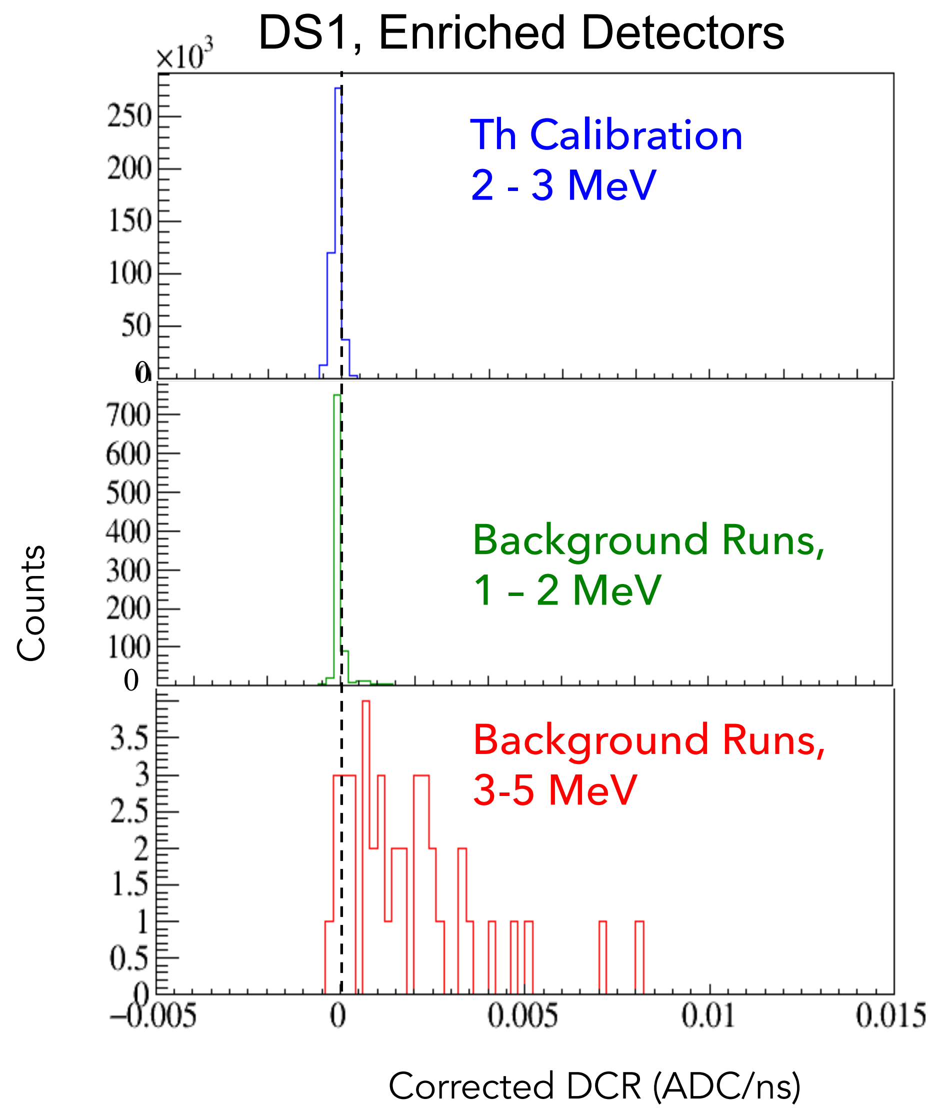
DCR Cut and Bulk-Event Response

90% efficient
Removes most events above 2 MeV

During calibration runs, γ events survive cut.

During Background runs, $\beta\beta(2\nu)$ events survive cut.

Candidate α events from background runs are removed.



Tritium with Cosmogenic X rays

Poster P4.012 Reyco Henning

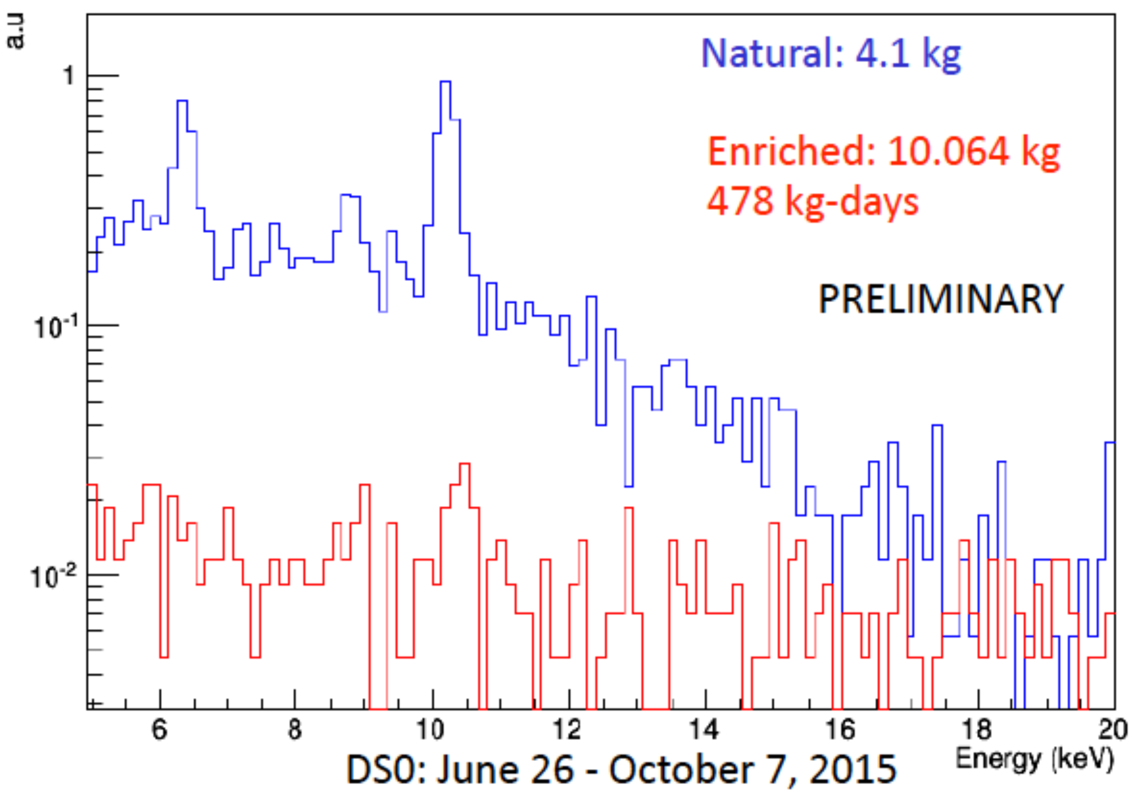
Controlled surface exposure of enriched material.

- The enriched detector ^{68}Ge rate is low enough that an SSTC cut will not be necessary.

Significant reduction of cosmogenics in the low-energy region. Factor of a few better in DS1.

Tritium is obvious and dominates in natural detectors below 20 keV.

Efficiency below 5 keV is still being studied.

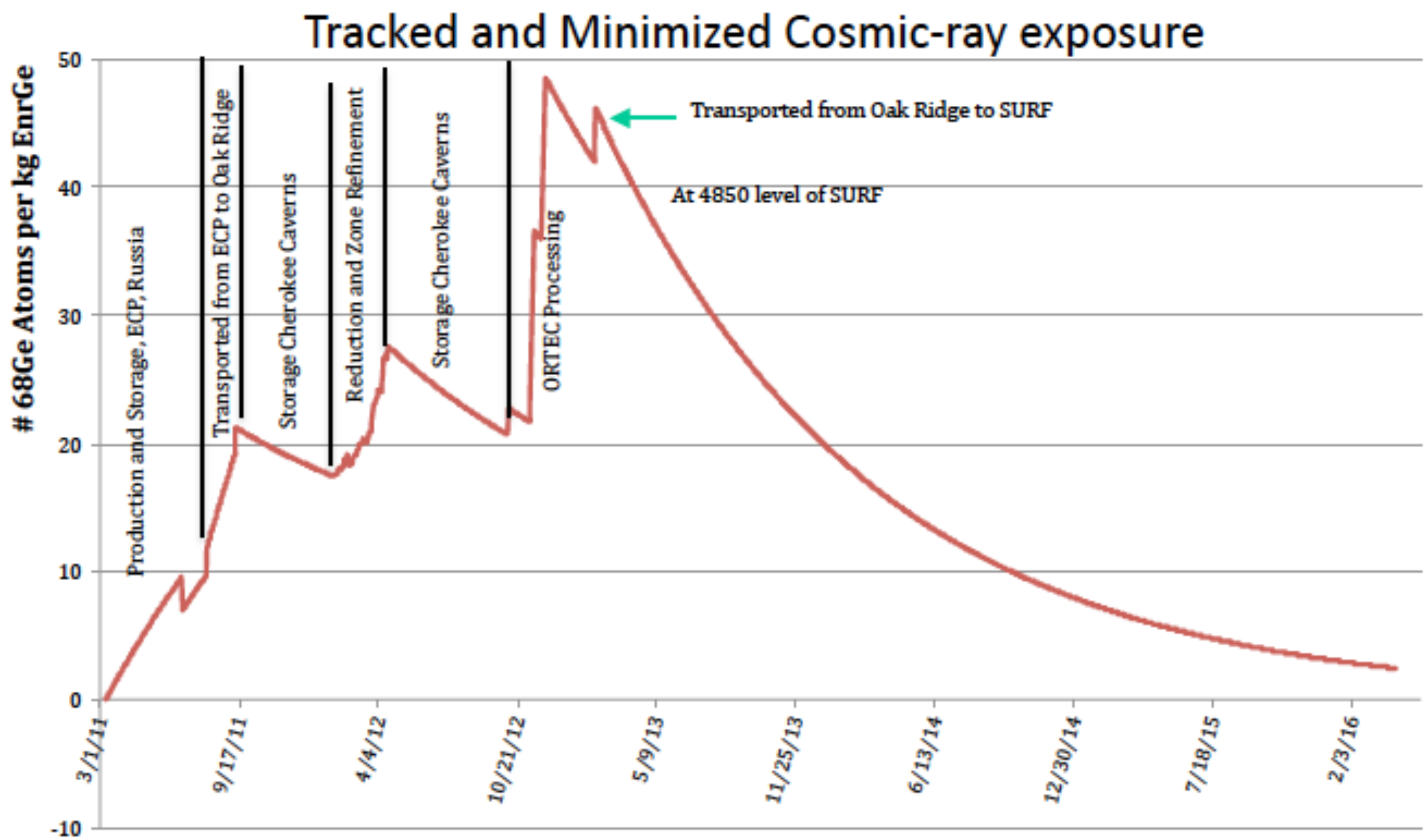


<u>Permits Low-Energy physics</u>

Pseudoscalar dark matter
Vector dark matter
14.4-keV solar axion
$e^- \rightarrow 3\nu$
Pauli Exclusion Principle

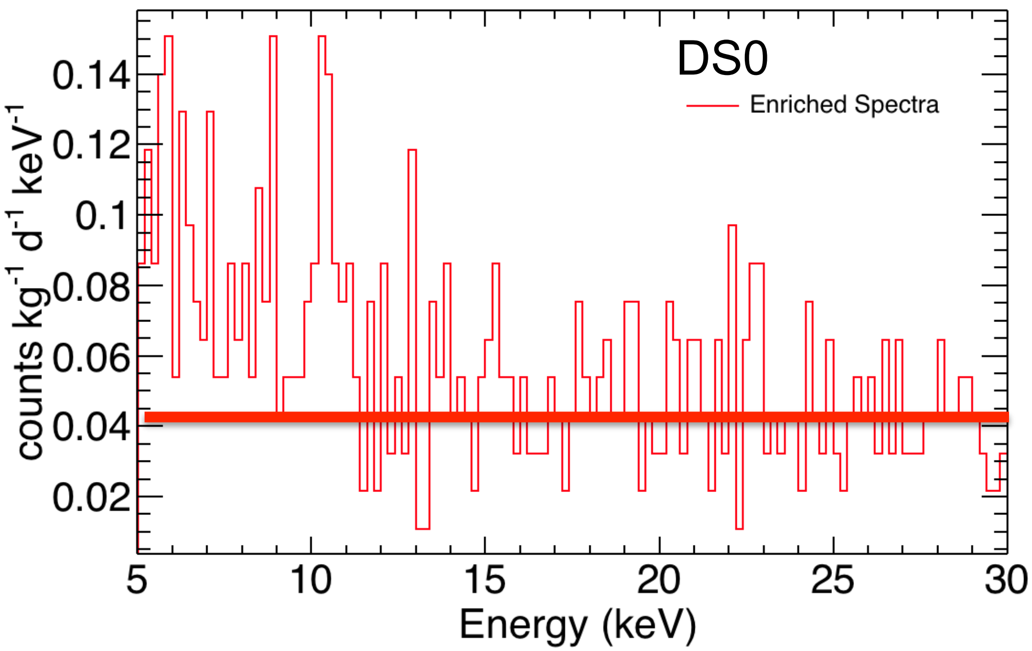
^{68}Ge Production in Detector P42537A

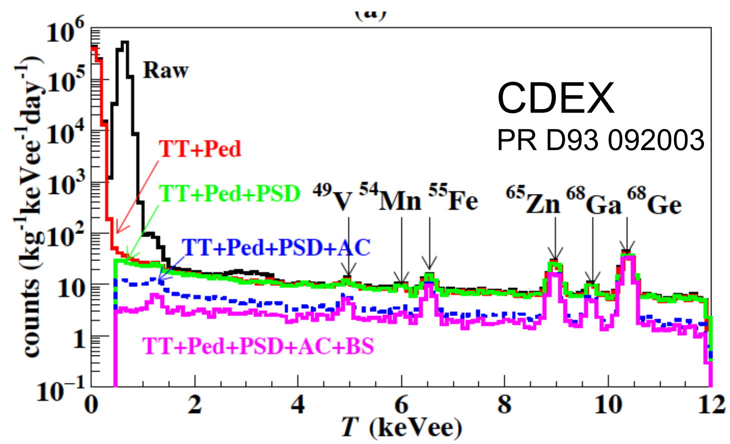
Typical sea-level equivalent exposure is about 35 d for the enriched detectors.

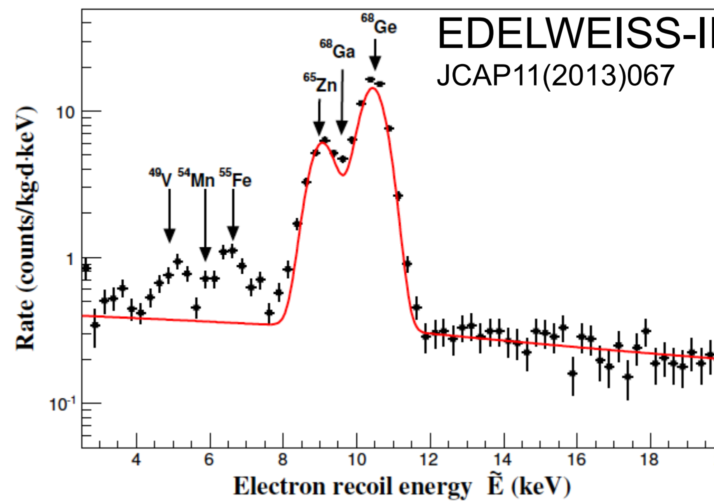


Very Low Background – DS0

The BG in DS0 at 20 keV: ~0.04 cnts/(kg keV d).







Bosonic Dark Matter Analysis – DS0

Other Low-Energy physics

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