Results from the MAJORANA DEMONSTRATOR ^{76}Ge detector array

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on behalf of the MAJORANA Collaboration

COSMS INSTITUTE

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

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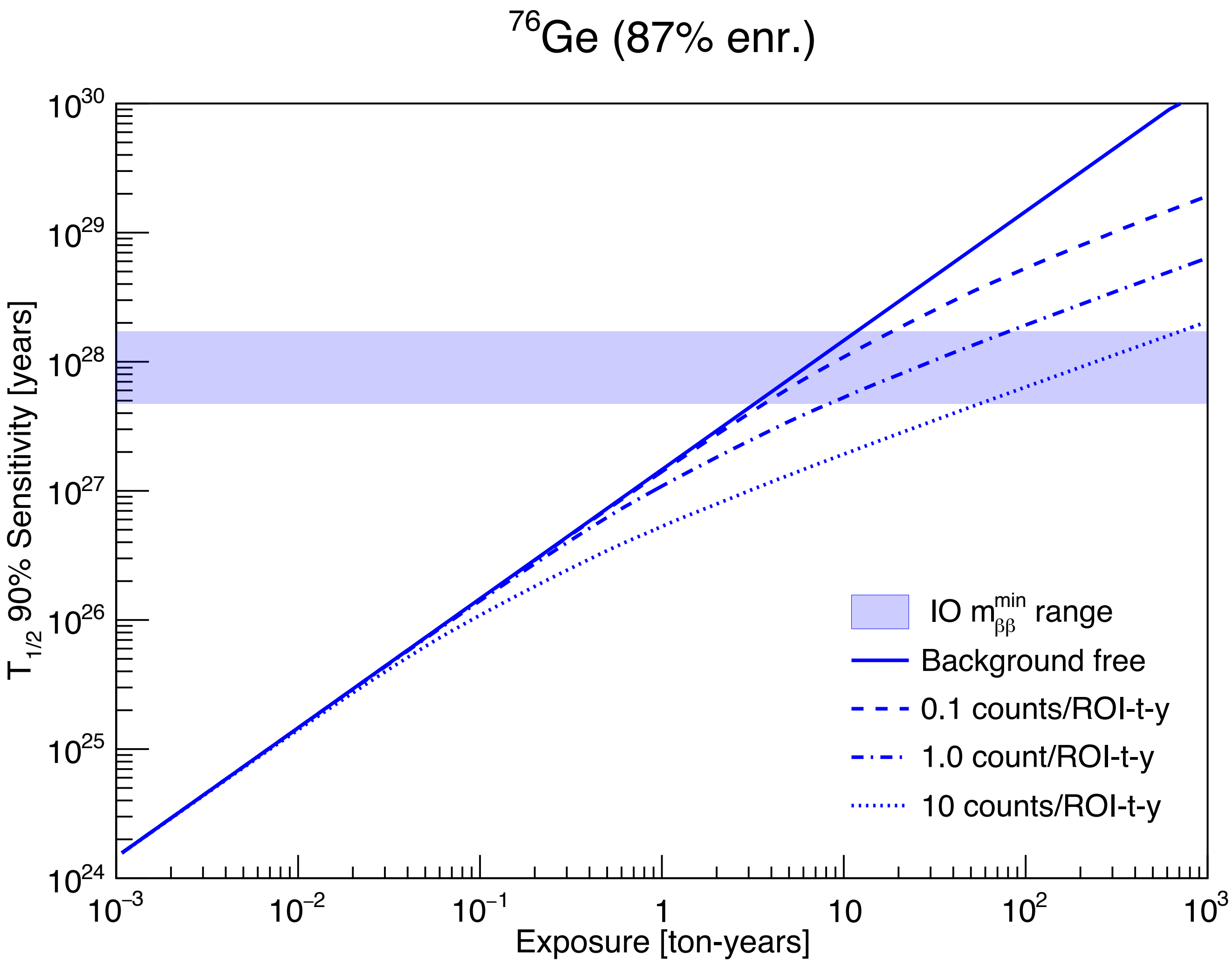
Sensitivity vs. Exposure vs. Signal

Half life (years)	~Signal (cnts/ton-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
5×10^{28}	0.1
$>10^{29}$	0.05



J. Detwiler

Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure

MAJORANA and GERDA —> LEGEND

Advantages of Ge

- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution: approaching 0.1% at 2039 keV (~3 keV ROI)
- Demonstrated ability to enrich from 7.44% to ≥87%
- Powerful background rejection: multiplicity, timing, pulse-shape discrimination

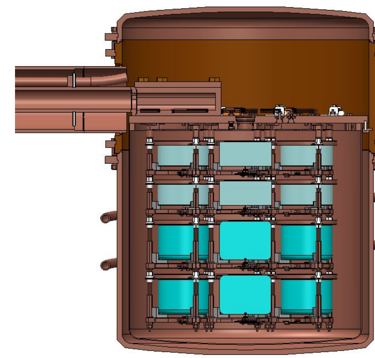
MAJORANA
Compact configuration: Vacuum cryostats in a passive graded shield with ultra-clean materials

GERDA
Direct immersion in active LAr shield

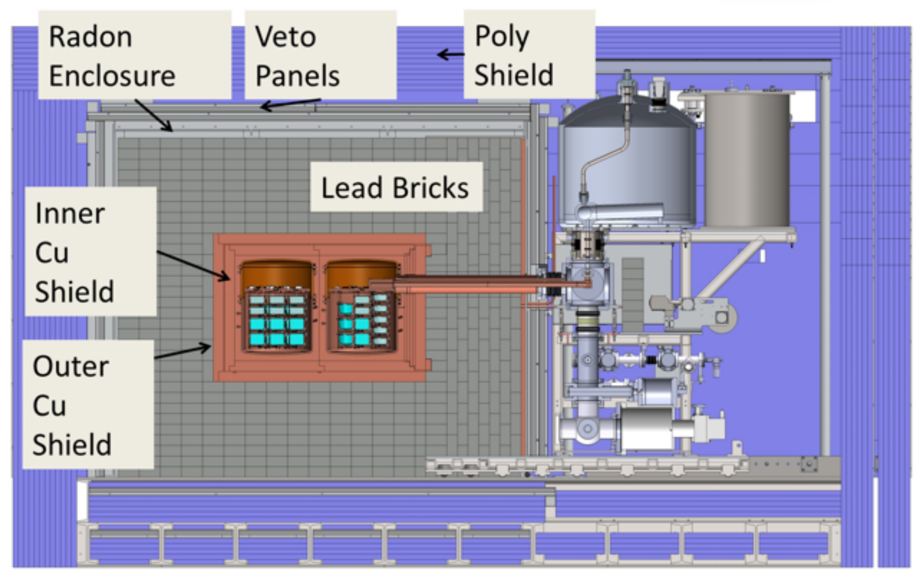
The MAJORANA DEMONSTRATOR

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
- 44.1-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

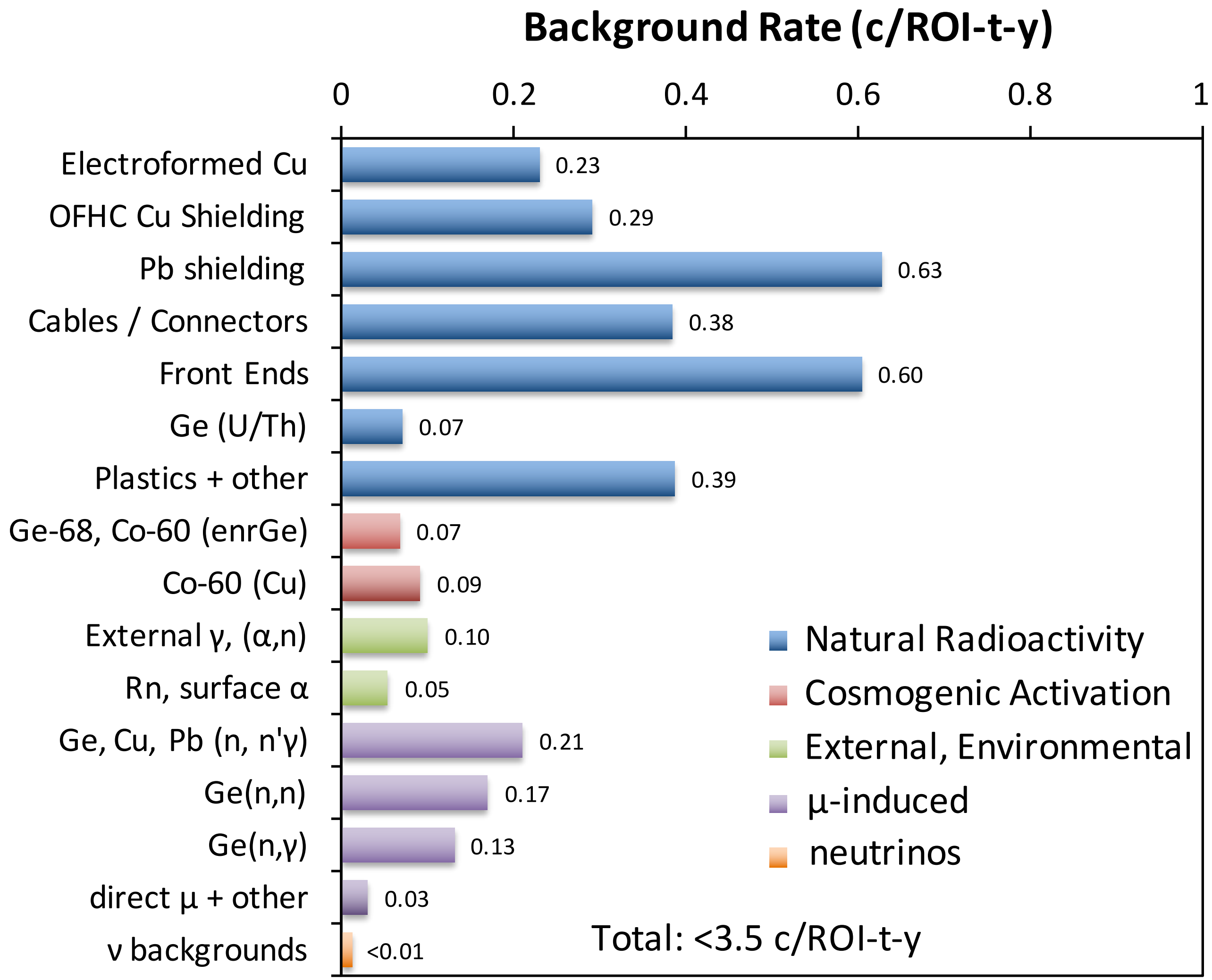


N. Abgrall *et al.*, Adv. High Ener. Phys. **2014**, 365432 (2013) arXiv:1308.1633

DEMONSTRATOR Background Budget

Based on assays of materials; When upper limit, use upper limit value as contribution

(NIMA **828** (2016) 22)



Majorana Electroformed Copper

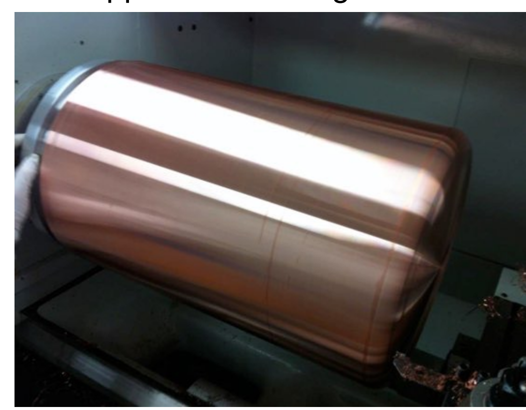
- Majorana operated 10 baths at the 4850′ level of Sanford Underground Research Facility (SURF) and 6 baths at a shallow UG site at PNNL. All copper was machined at the SURF Davis campus.
- The electroforming of copper completed in May 2015.
  - 2474 kg of electroformed copper on the mandrels,
  - 2104 kg after initial machining,
  - 1196 kg that will be installed in the Demonstrator.

Electroforming Baths in TCR

Inspection of EF copper on mandrels

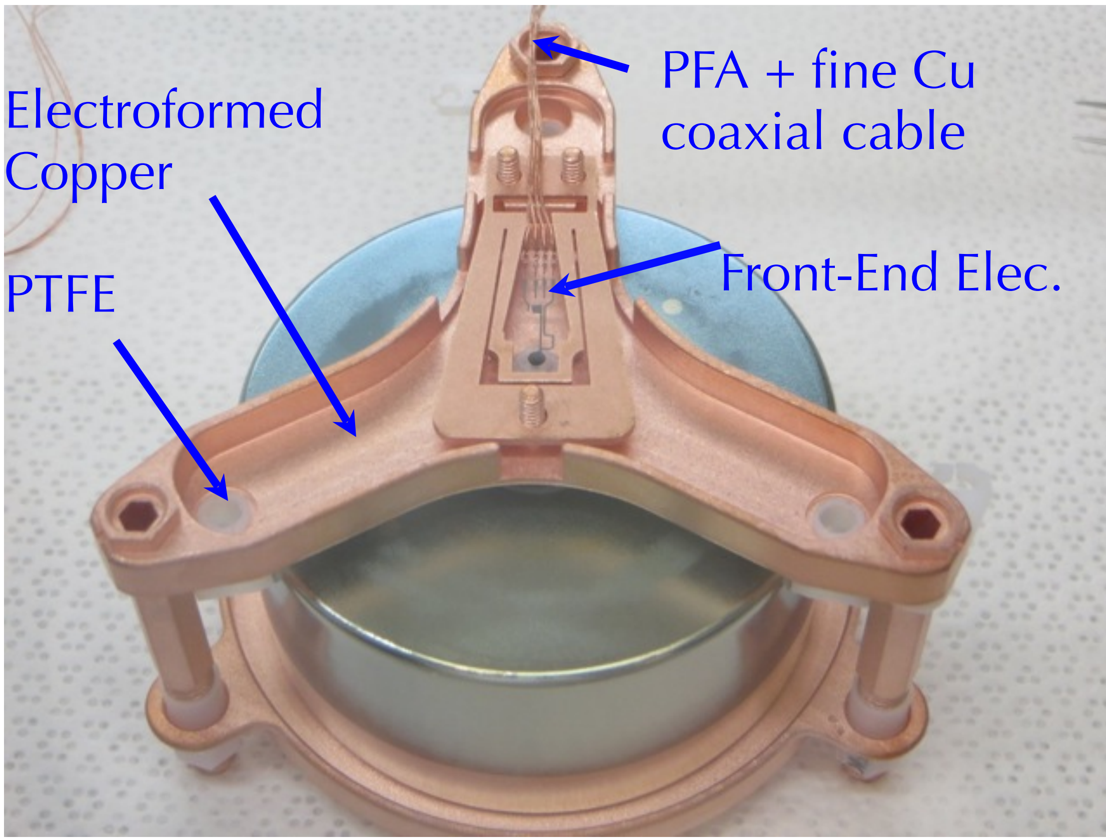
- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg

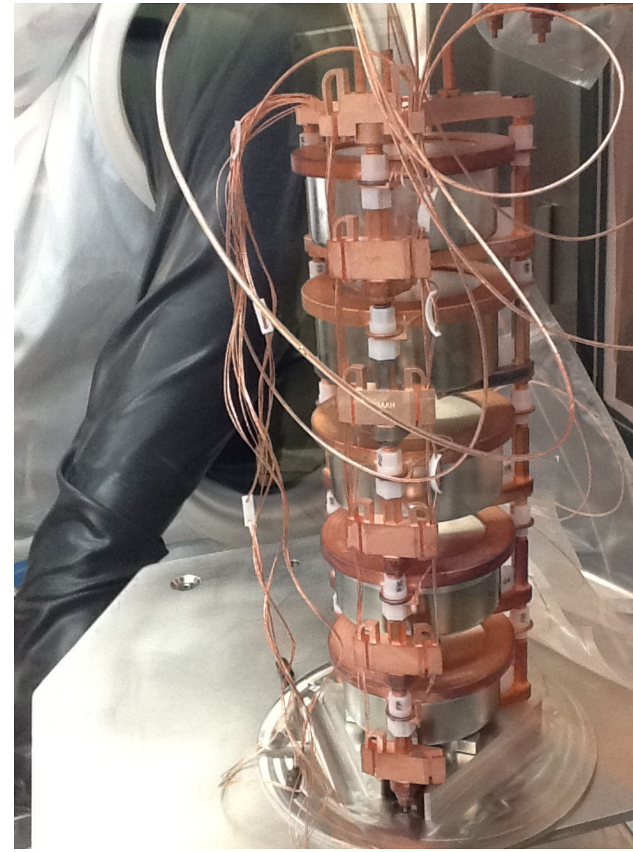
EF copper after turning on lathe



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).



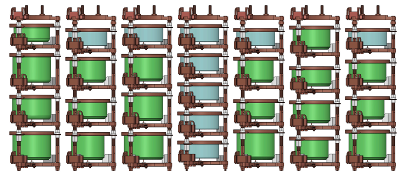


All detector assembly performed in N_2 purged gloveboxes.
All detectors' dimensions recorded by optical reader.

MAJORANA DEMONSTRATOR Implementation

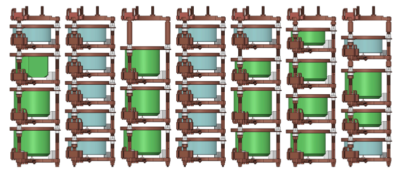
In-shield Running

Module 1: 16.9 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge

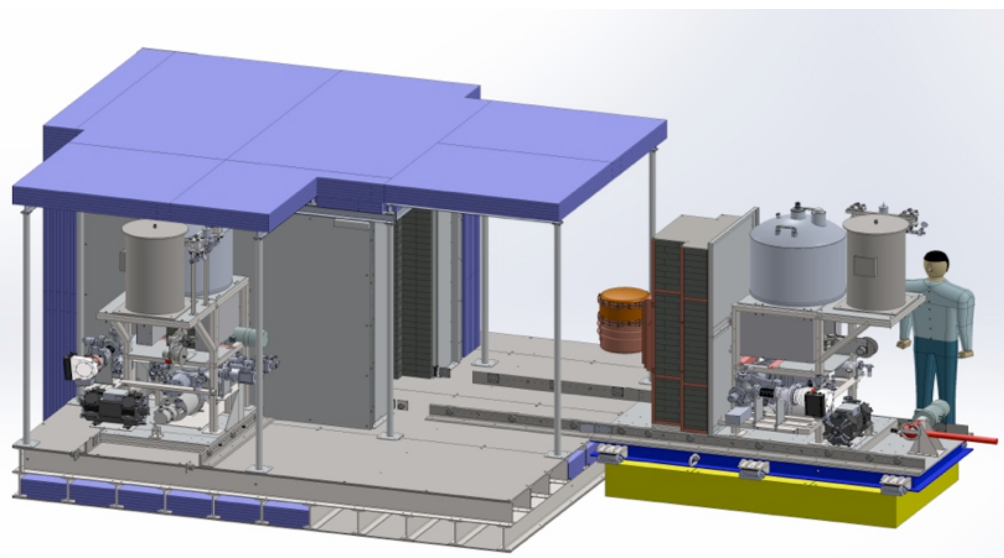


05/2015 – 10/2015
Module Improvements
01/2016 – ongoing

Module 2: 12.9 kg (14) ^{enr}Ge
8.8 kg (15) ^{nat}Ge

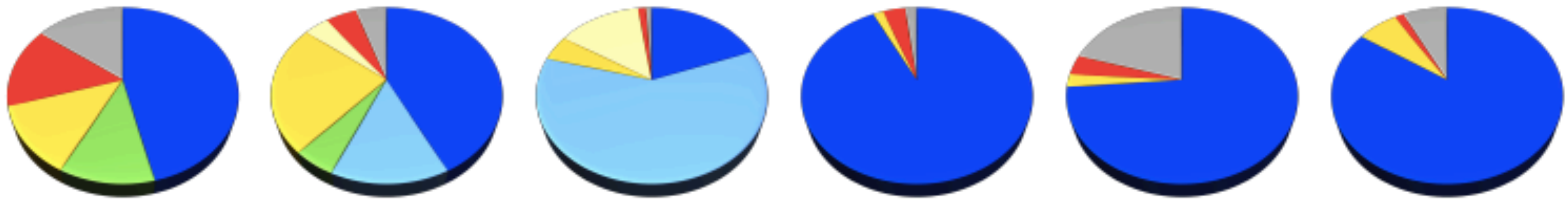


07/2016 – ongoing



Data Sets and Duty Cycles

DS-0	DS-1	DS-2	DS-3	DS-4	DS-5



M1 Commissioning No inner shield	*M1 inner shield*	*M1 Multi-sampling*	*Modules 1 and 2 Together in-shield*	*Module 1 & 2 Integrated DAQ*

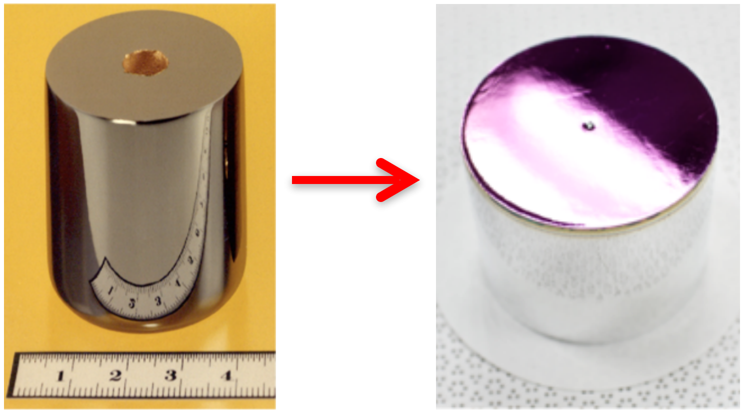
	DS-0 Module 1 June 26 - Oct. 7, 2015	DS-1 Module 1 Dec. 31, 2015 - May 24, 2016	DS-2 Module 1 May 24 - July 14, 2016	DS-3 Module 1 Aug. 25 - Sep. 27, 2016	DS-4 Module 2 Aug. 25 - Sep. 27, 2016	DS-5 Module 1 & 2 Oct. 13, 2016 - ***ongoing*** *
Total (days)	103.15	144.50	50.97	32.37	32.36	97.7
Total acquired	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

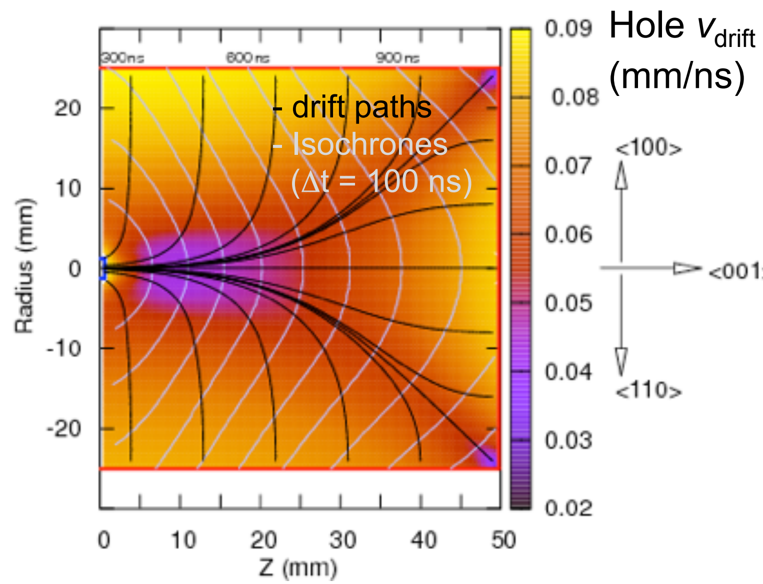
~93% live (phys+cal)

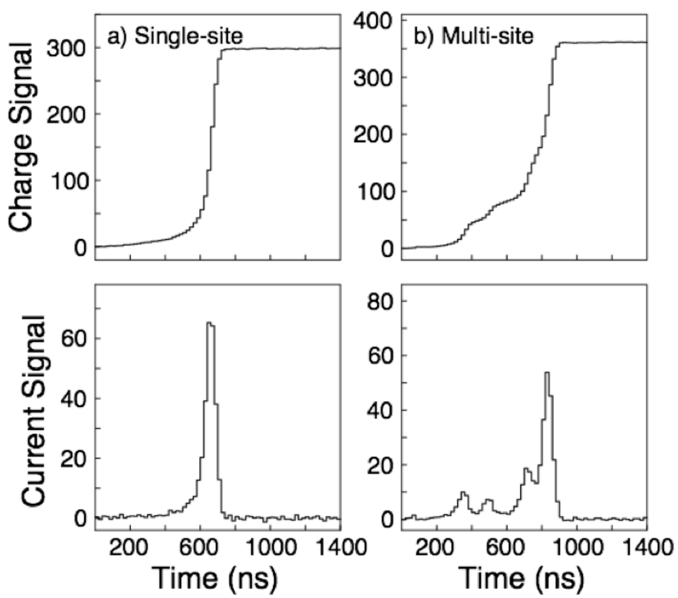
*Blind data

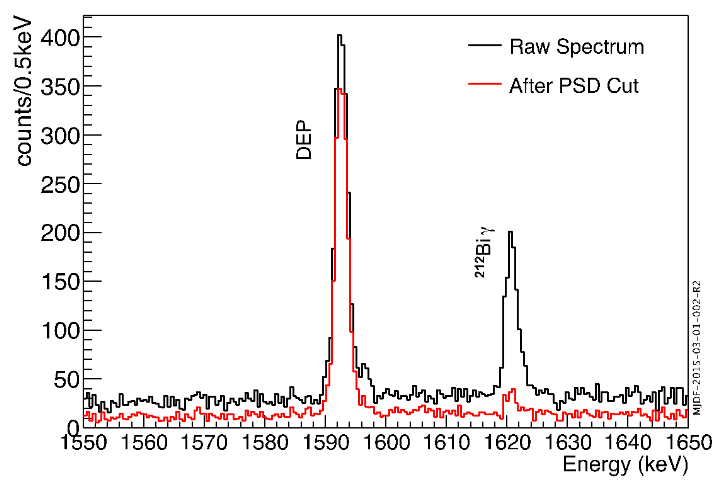
*Values up to Jan. 19, 2017

0νββ with Point Contact Detectors





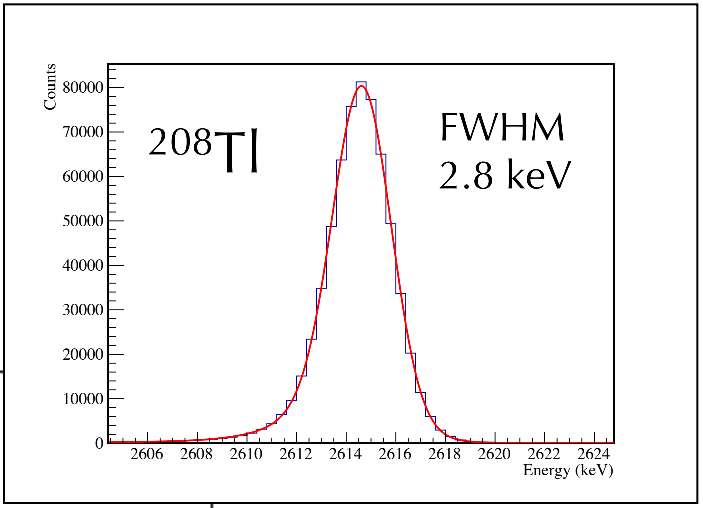


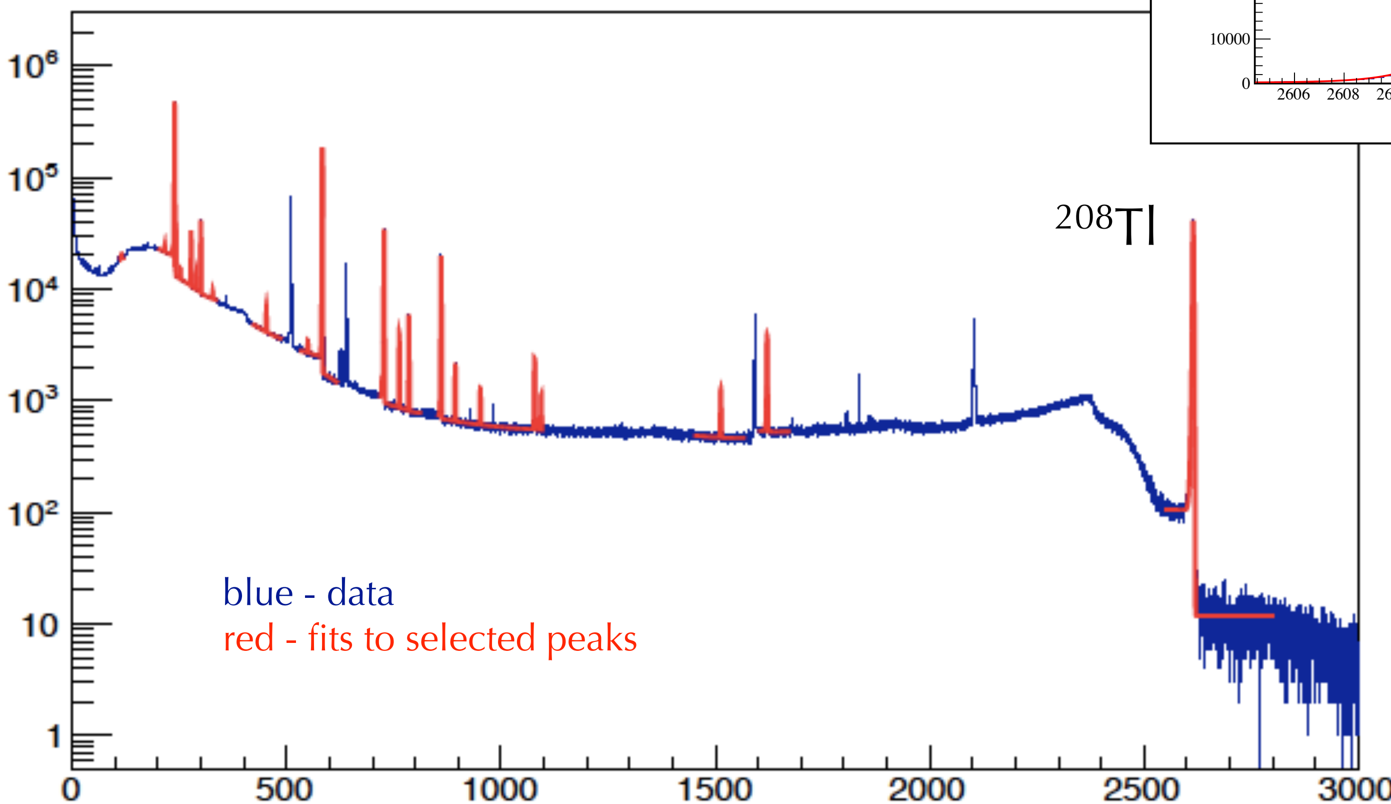


Luke et al., IEEE trans. Nucl. Sci. 36 , 926 (1989)
Barbeau, Collar, and Tench, J. Cosm. Astro. Phys. 0709 (2007).

Summed ^{228}Th Calibration Spectrum (DS3&DS4)

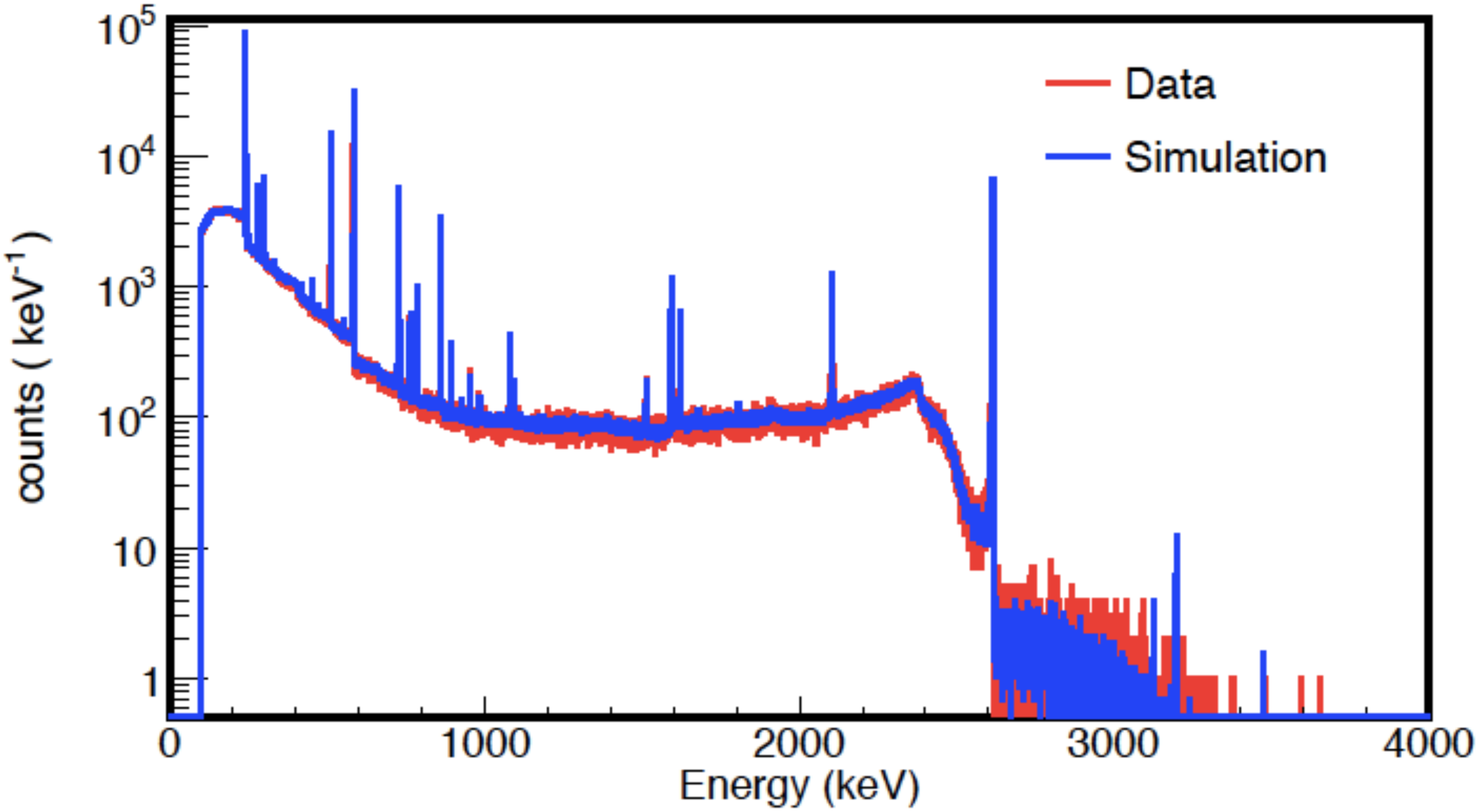
- Enriched detectors in Modules 1 and 2
- ^{228}Th calibration source
- FWHM = 2.4 keV at $Q_{\beta\beta}$ (2039 keV)





Calibration paper
arXiv:1702.02466

Summed ^{228}Th Calibration (DS1) & Simulation

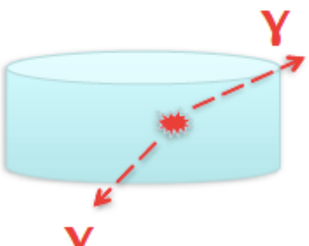


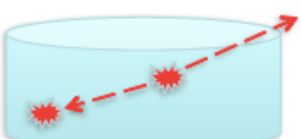
Calibration paper
arXiv:1702.02466

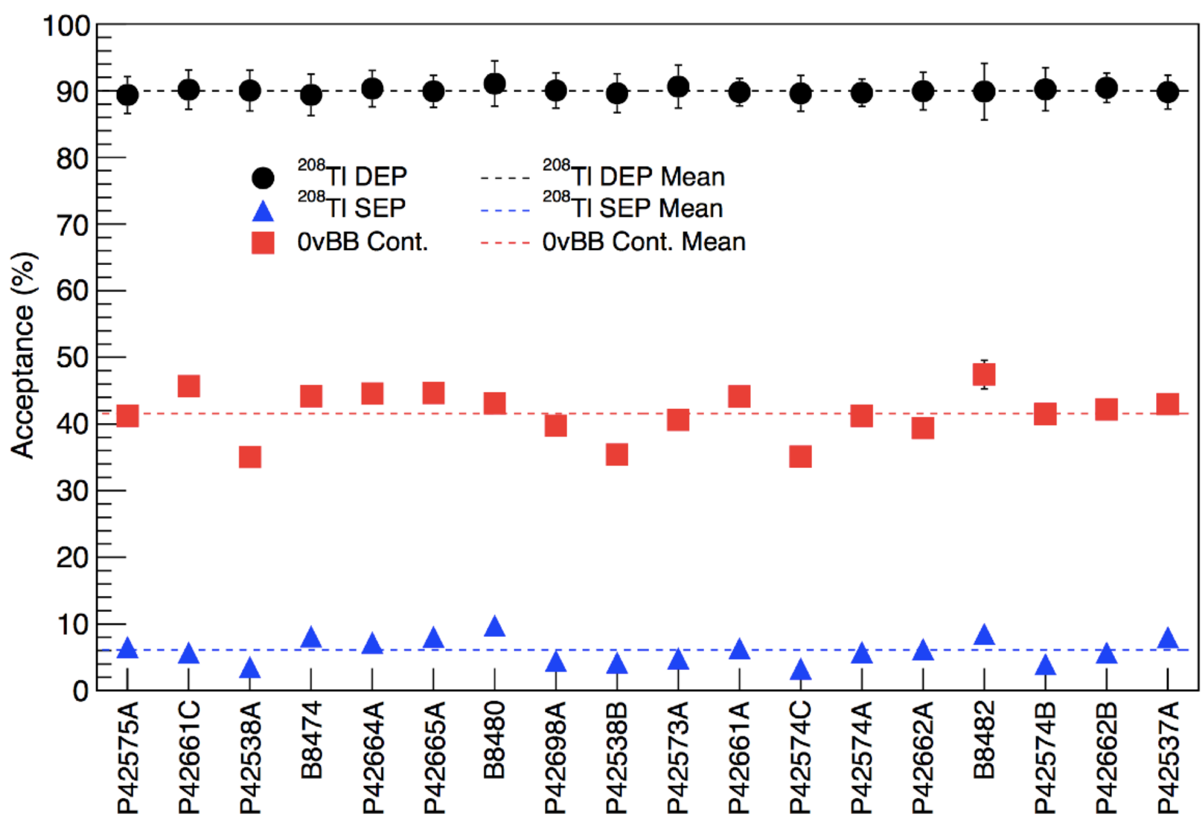
Ge Detector PSD Performance in Module 1 (DS1)

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

- $0\nu\beta\beta$ is a single site event
- ^{208}Tl 2614 keV γ can pair produce with annihilation γ's escaping detection







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

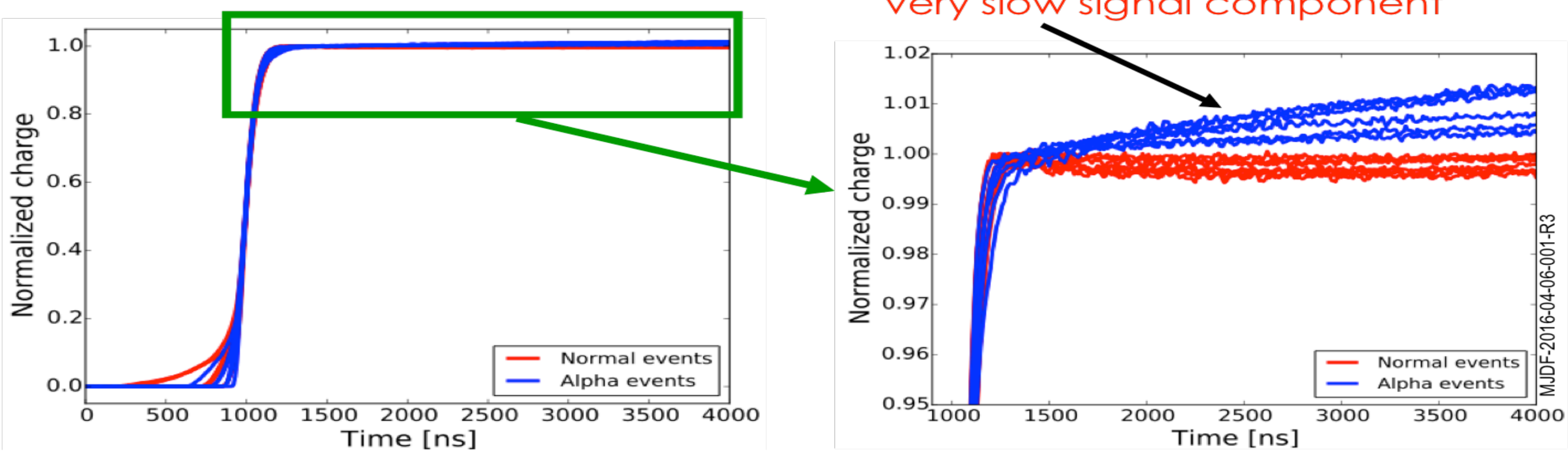
^{208}Tl SEP (Multiple site events) reduced to 6%

Cut for α's, Delayed Charge Recovery

- Alpha background with degraded energies observed in DS0
- Charge of these events drifts along the detector surface, not bulk
- Produces a distinctive waveform allowing a high efficiency cut

Example pole-zero corrected waveforms

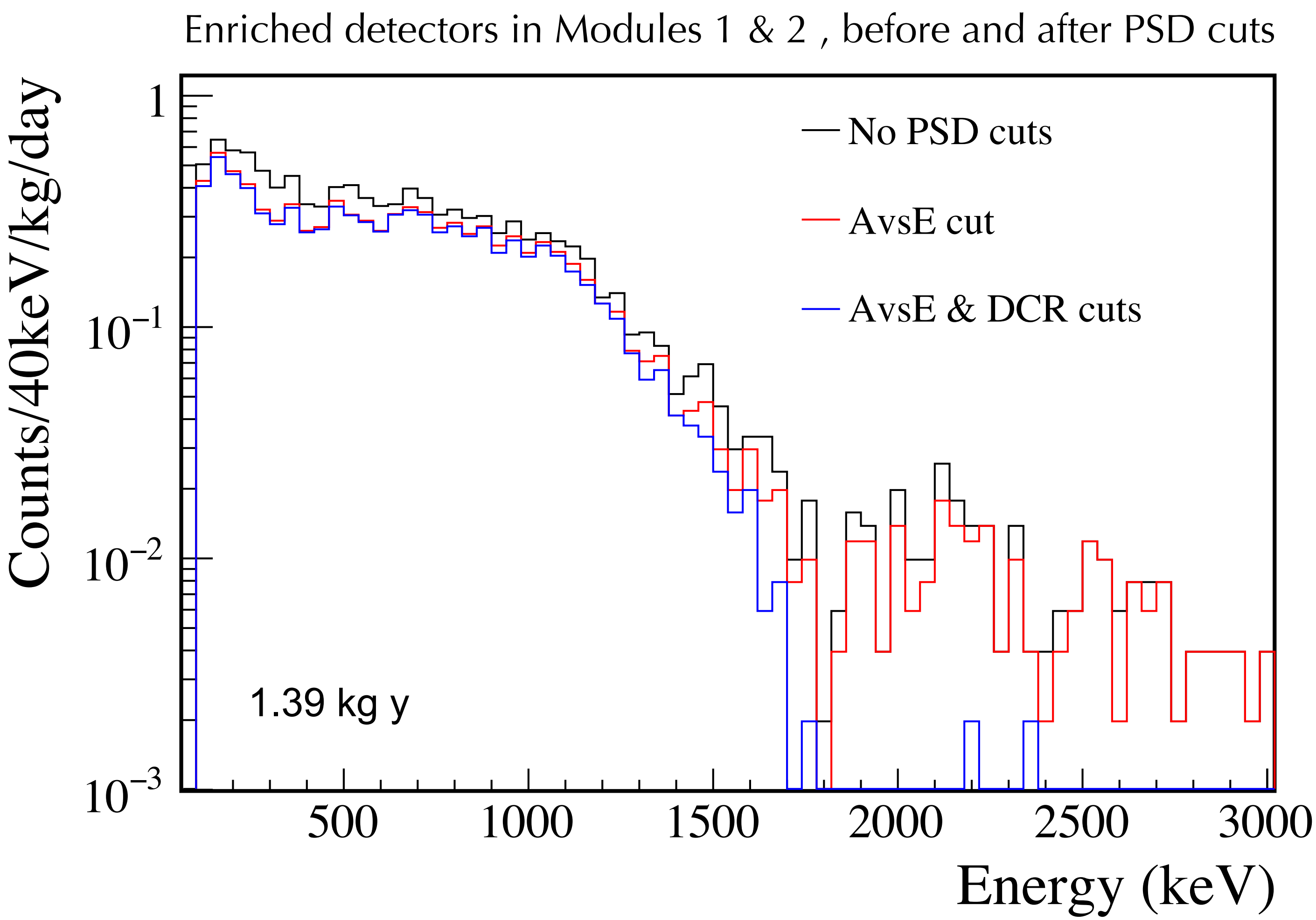
Slow drift of charges along passivated surface results in very slow signal component



Background Spectrum (DS3 & DS4)

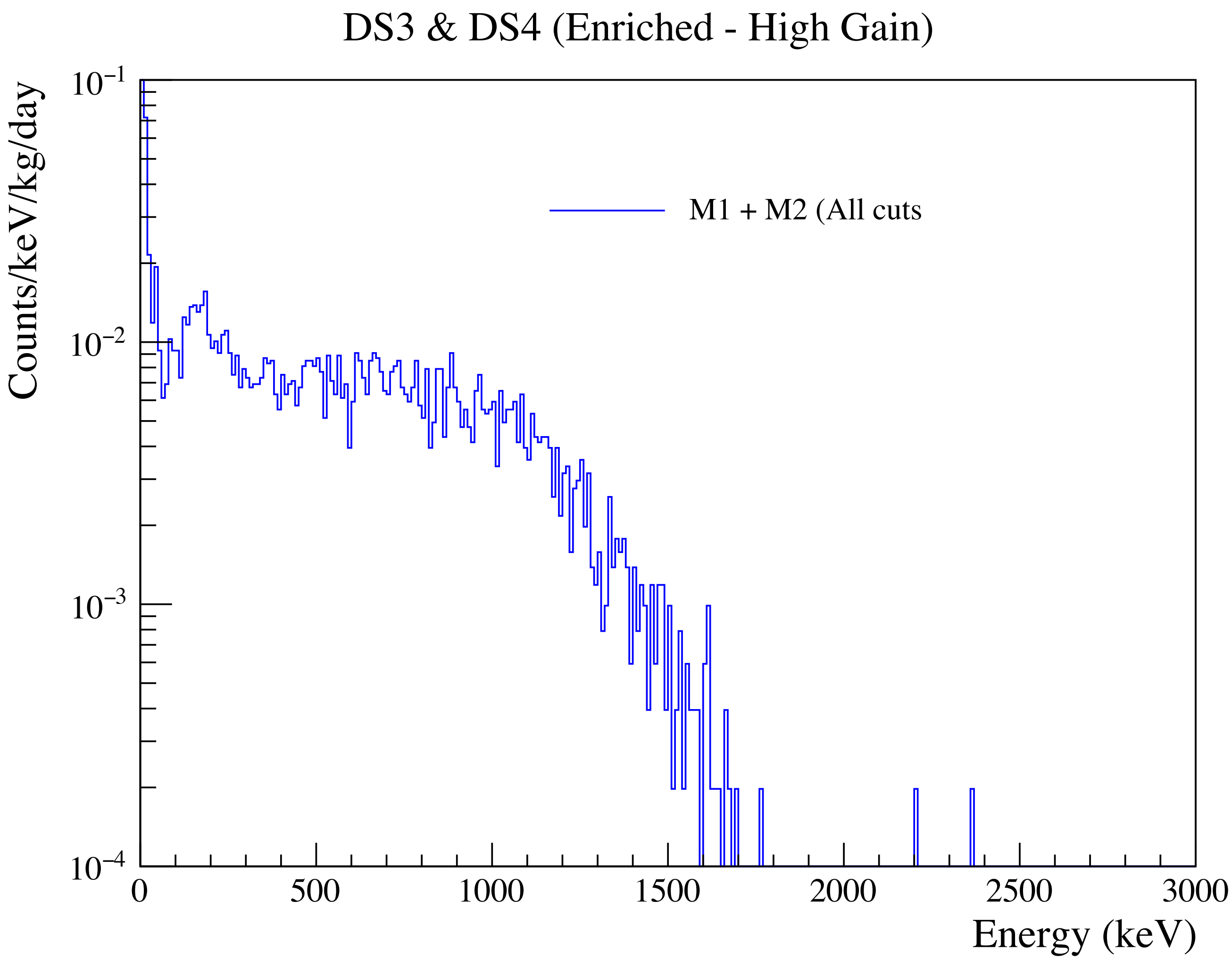
Lowest background configuration, with both modules in shield.

(Previous data presented at Neutrino 16 was from Module 1, DS 0/1)



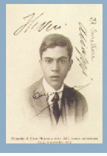
Spectrum is dominated by $2\nu\beta\beta$

Estimated 0νββ-decay ROI background (DS3 & DS4)



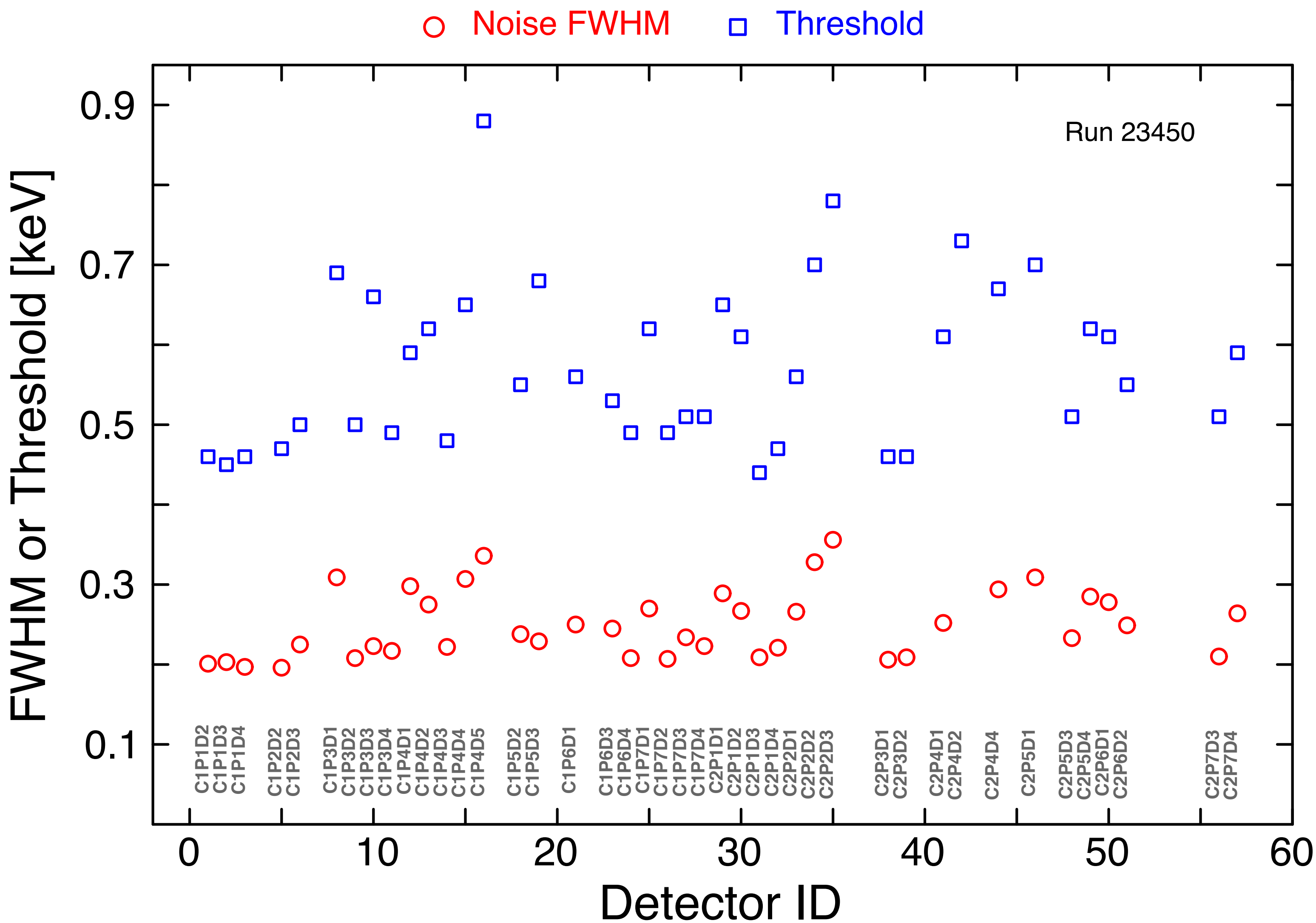
- Exposure: 1.39 kg y
- After cuts, 1 count in 400 keV window centered at 2039 keV (0νββ peak)
- Projected background rate is $5.1^{+8.9}_{-3.2}$ c /(ROI t y) for a 2.9 (M1- DS3) & 2.6 keV (M2 - DS4) keV ROI, (68% CL).
- Background index of 1.8×10^{-3} c/(keV kg y)
- Analysis cuts are still being optimized.

Detector Low-energy Thresholds and Noise (DS5)



$FWHM_{Avg} \lesssim 250$ eV

$Threshold_{Avg} \lesssim 700$ eV



DS0: Low-energy spectrum

arXiv 1612.00886v1

Controlled surface exposure of enriched material.

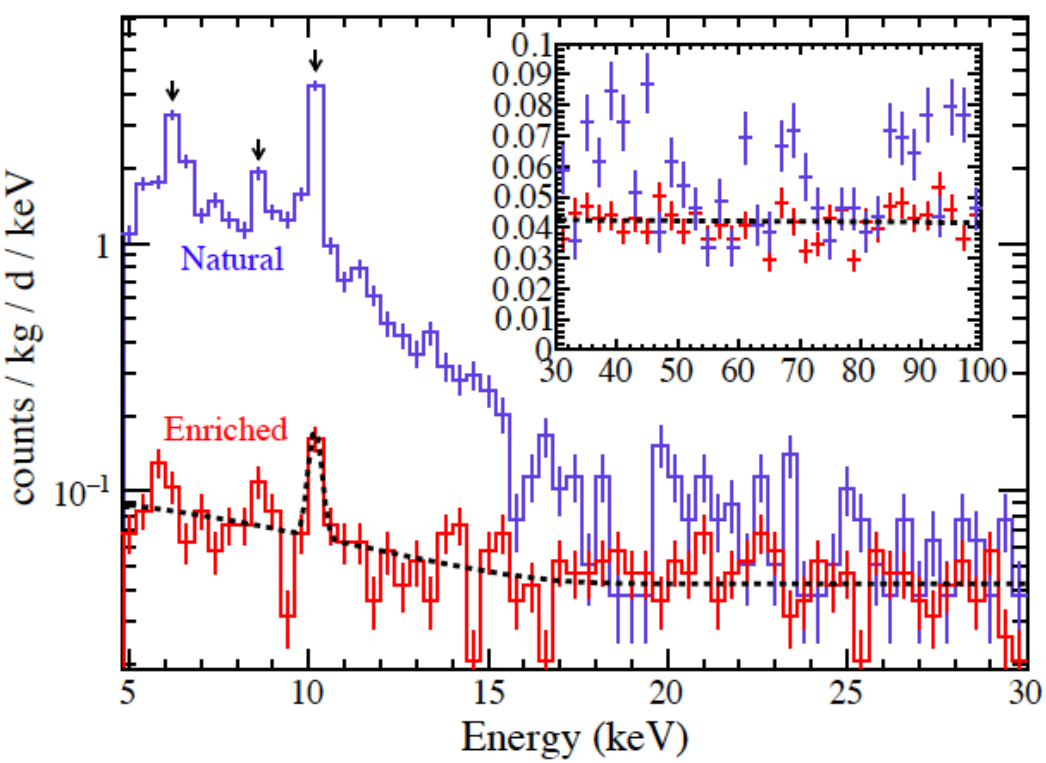
For the DEMONSTRATOR, the enriched detector ^{68}Ge rate is low enough that an X-ray delayed coincidence cut will not be necessary.

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.

DS0 Natural 4.1 kg Enriched 10.06 kg



Low-Energy Searches for Physics Beyond SM

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

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arXiv 1612.00886v1

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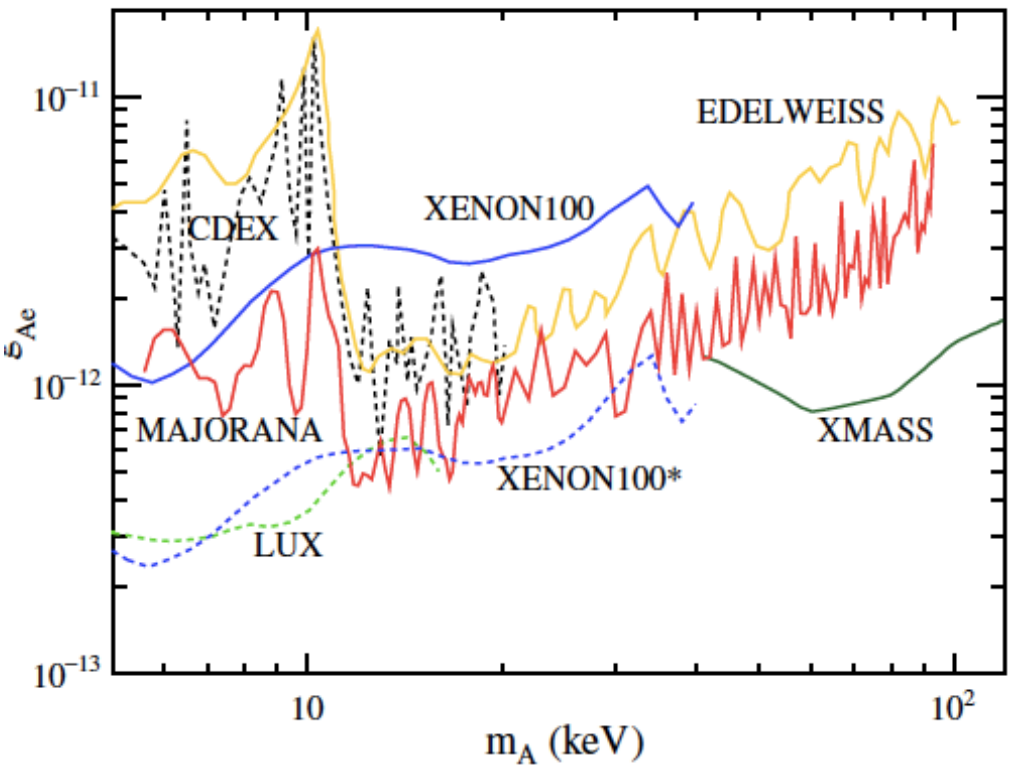


pseudoscalar axion-like particle dark mater coupling

Low-Energy Searches for Physics Beyond SM

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

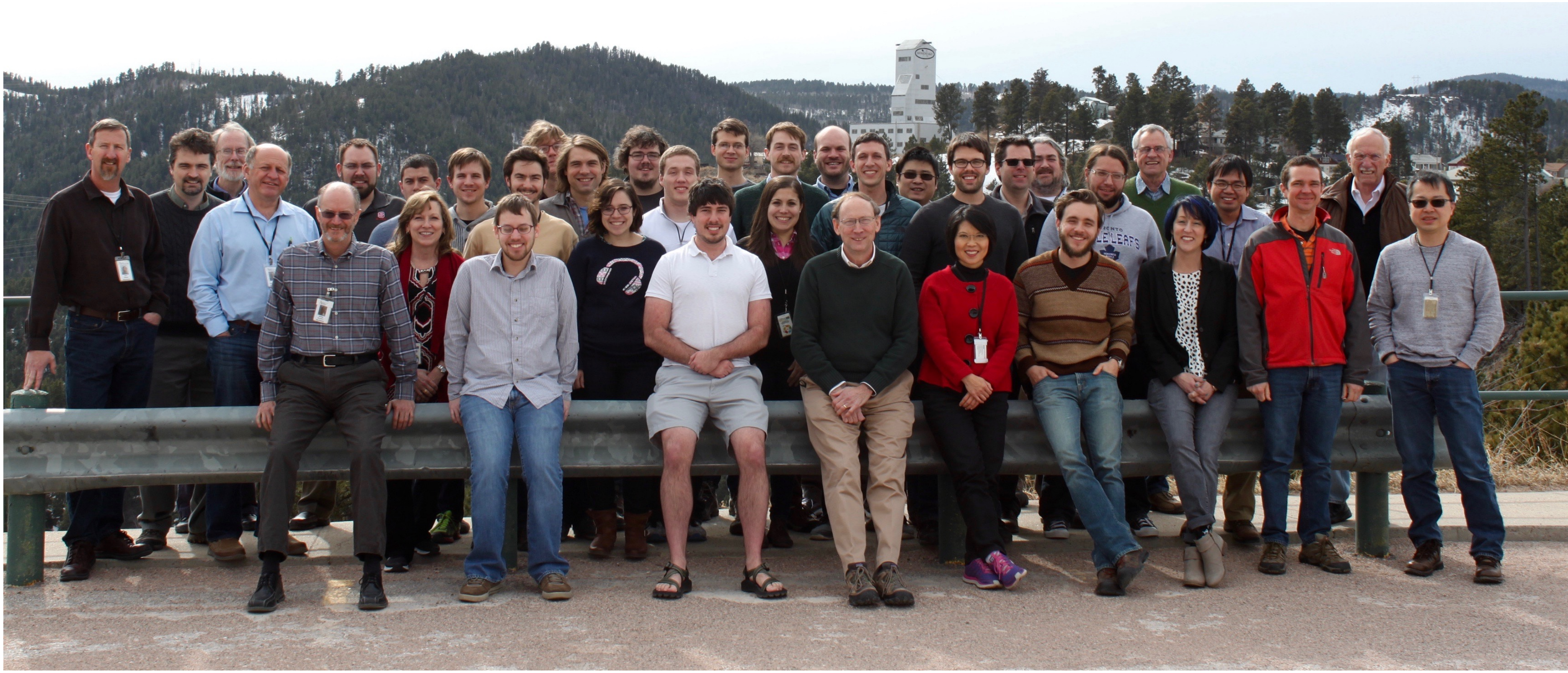
MAJORANA DEMONSTRATOR Summary

- The ^{76}Ge enriched point contact detectors developed by MAJORANA
  - have attained the best energy resolution (2.4 keV FWHM at 2039 keV) of any ββ-decay experiment.
  - provide excellent pulse shape discrimination reduction of backgrounds.
  - at low energies have sub-keV energy thresholds and excellent resolution allowing the DEMONSTRATOR to perform sensitive test in this region for physics beyond the standard model.

- The DEMONSTRATOR's initial backgrounds are amongst the lowest backgrounds in the ROI achieved to date (approaching to GERDA's recent best value). Attained by development and selection of ultra-low activity materials and low mass designs.

- Combining the strengths of GERDA and the MAJORANA DEMONSTRATOR, the LEGEND Collaboration is moving forward with a ton-scale ^{76}Ge based experiment. Based on the successes to date, LEGEND should be able to reach the backgrounds (~0.1 c /(ROI t y) and energy resolution necessary for discovery level sensitivities in the inverted ordering region.

The MAJORANA COLLABORATION



Black Hills State University
ITEP
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Research Institute for Nuclear Joint
Duke University
The University of North Carolina at Chapel Hill
Oak Ridge National Laboratory
Los Alamos National Laboratory EST 1943
South Dakota School of Mines & Technology
Tennessee Tech
University of South Carolina
The University of Tennessee Knoxville
TUNL
NC State University
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大阪大学 Osaka University
Pacific Northwest National Laboratory
Proudly Operated by Battelle Since 1965
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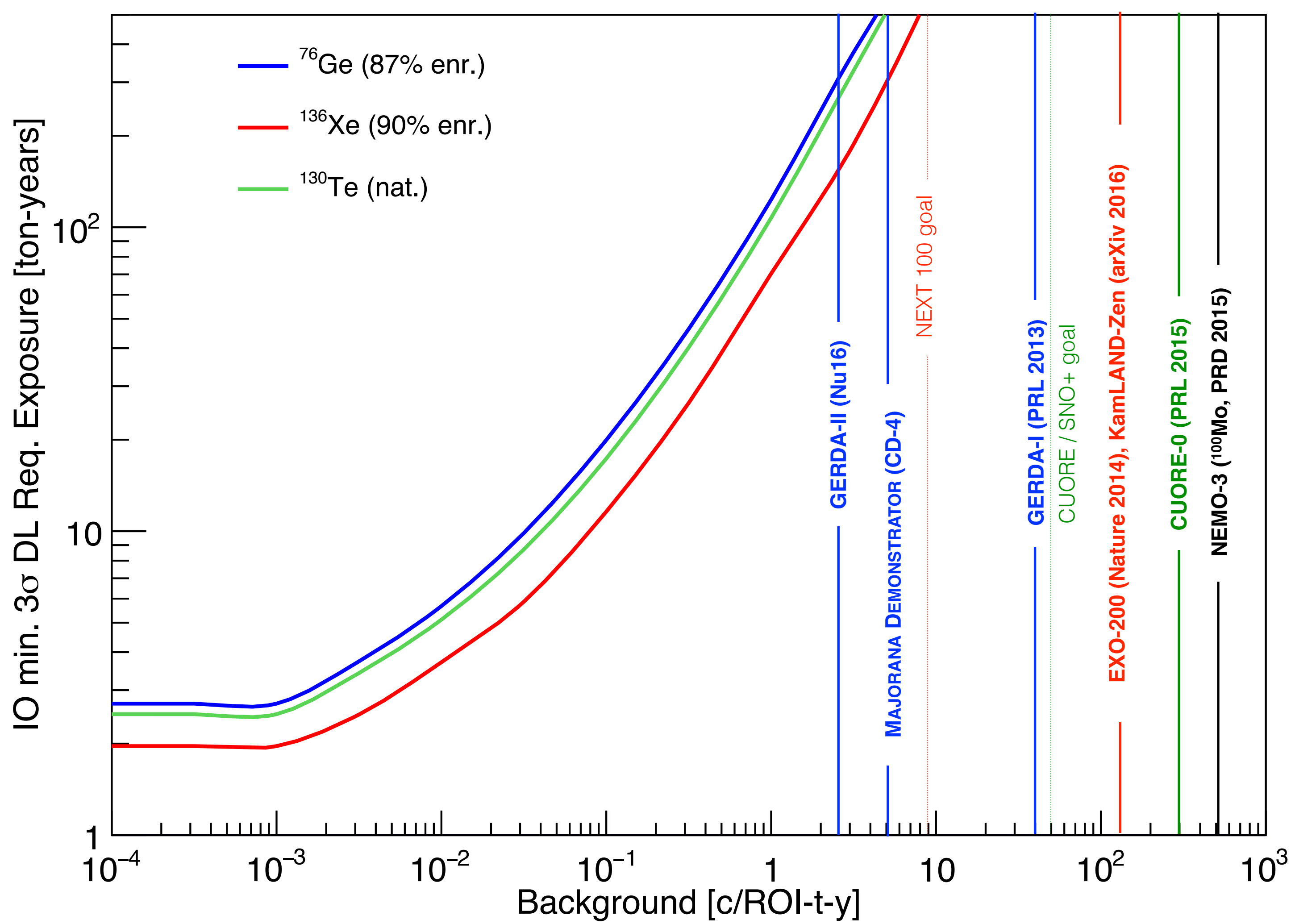
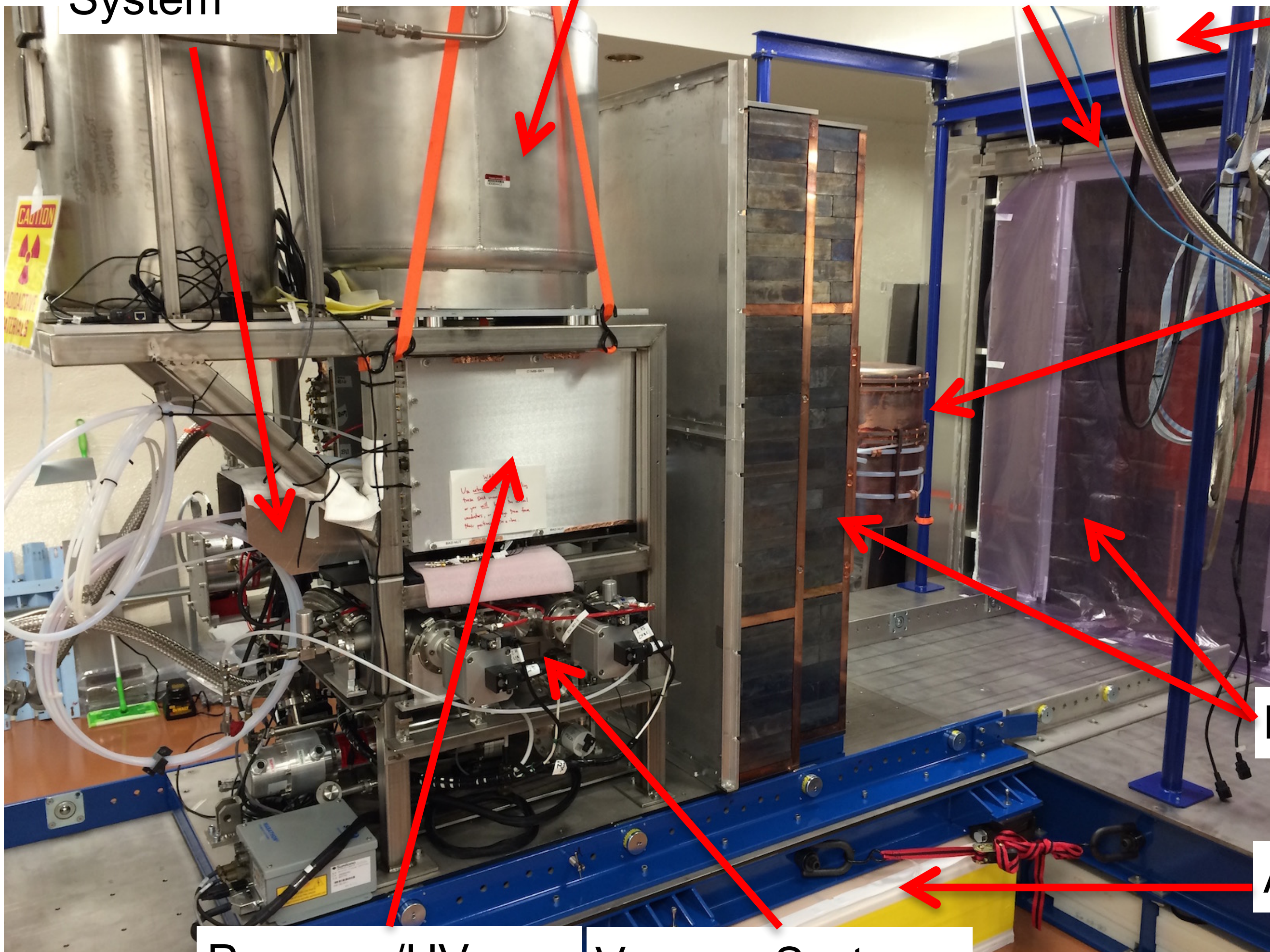
3σ Discovery : Exposure vs. Background



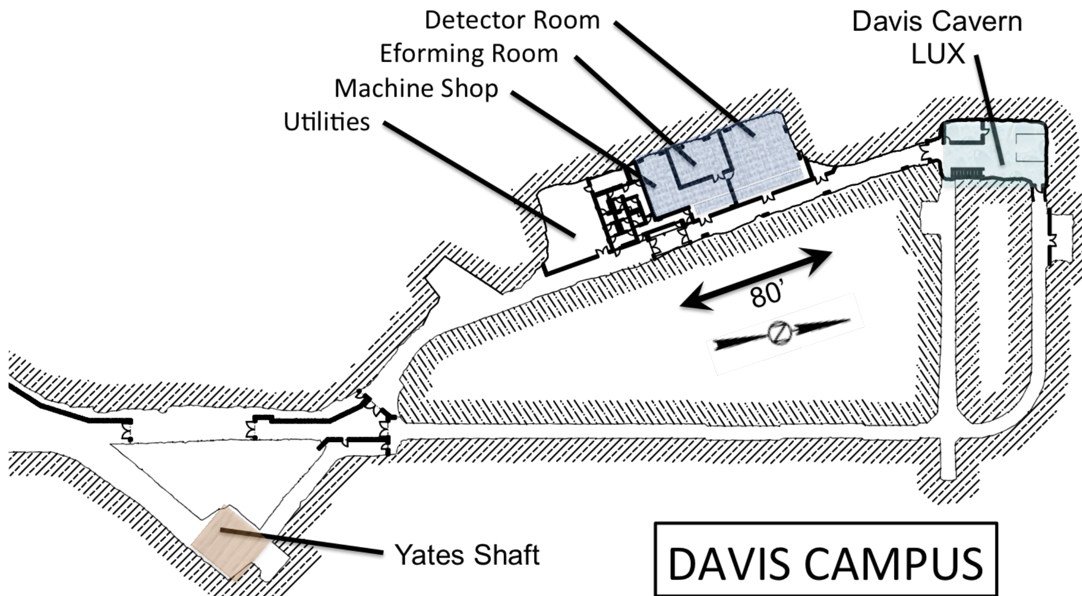
J. Detwiler

Module and Shield Details



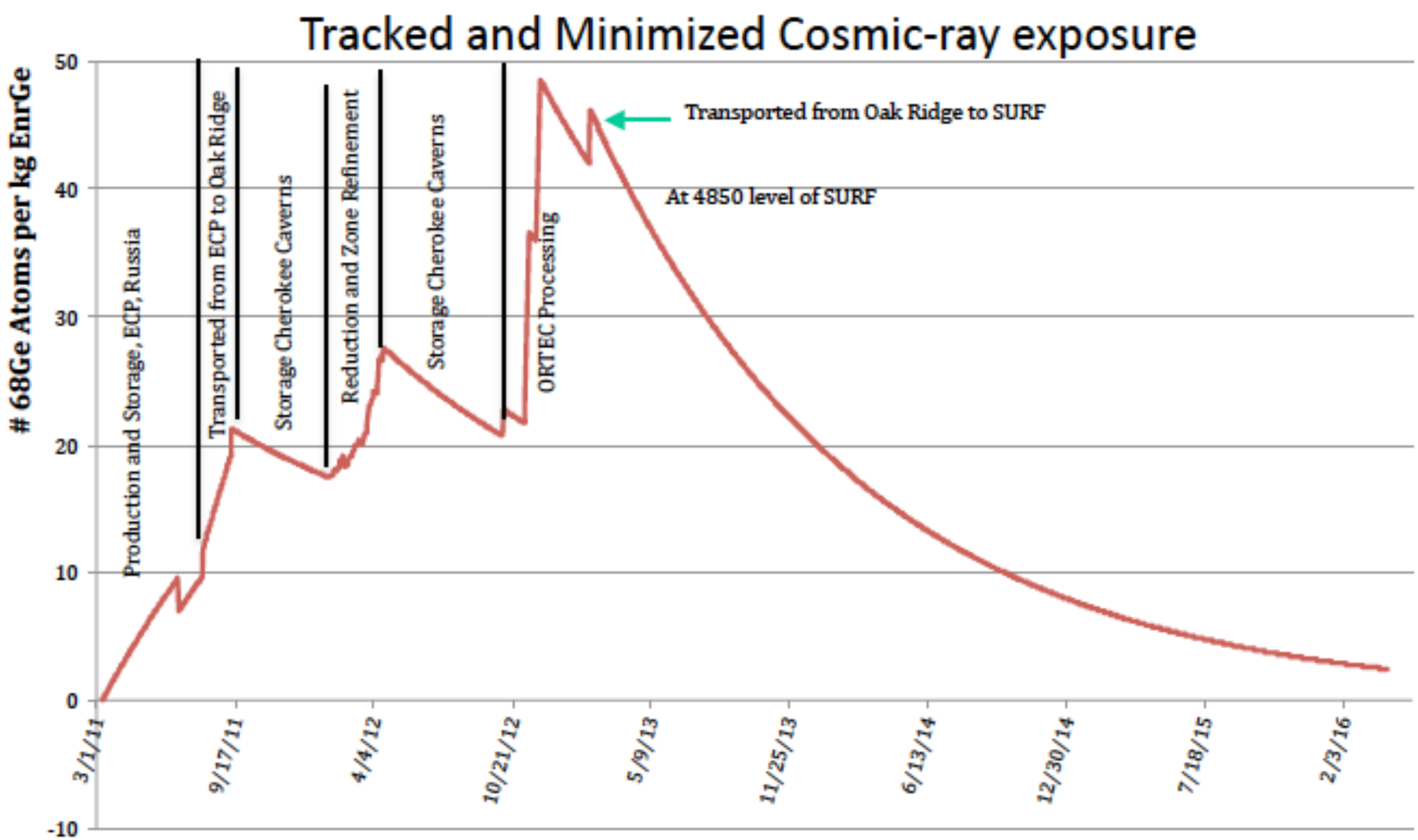
MAJORANA Underground Laboratory

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



^{68}Ge Production in Detector P42537A

Cosmic ray exposure minimized throughout all processes
Typical sea-level equivalent exposure is about 35 d for the enriched detectors.



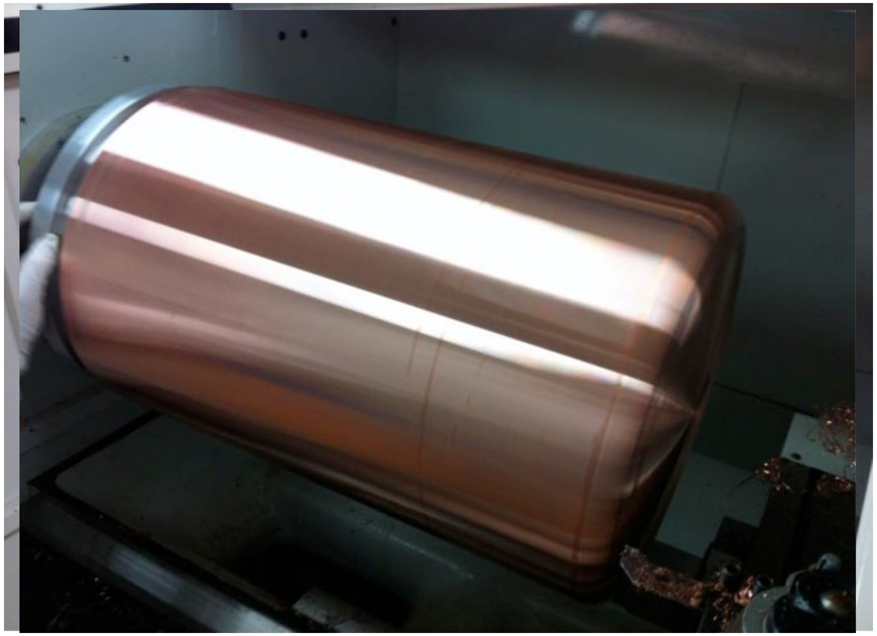
DEMONSTRATOR Electroforming Cu

Insertion of mandel into EF bath

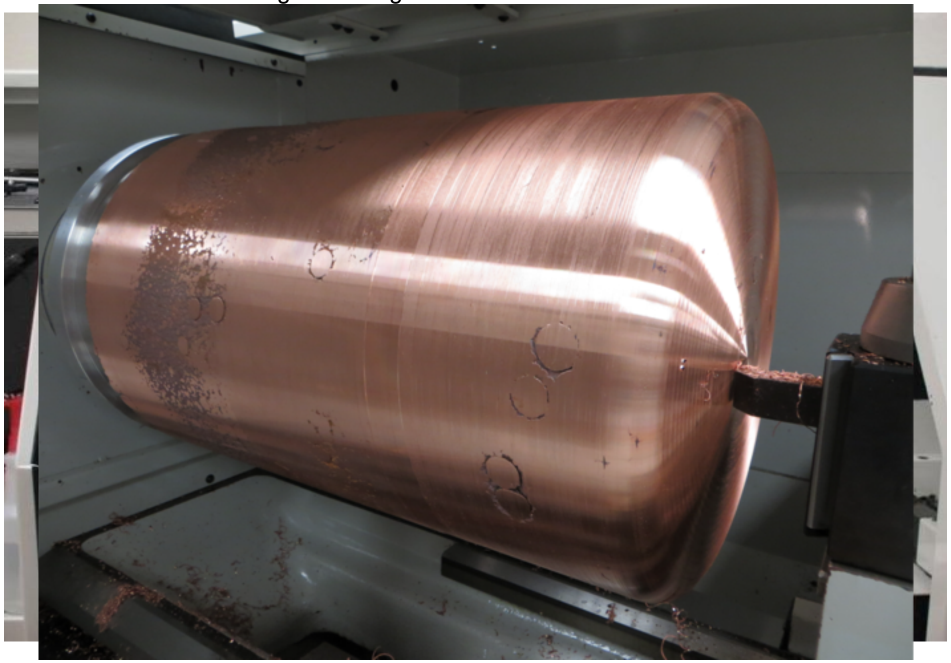
Electroforming Baths in TCR

Inspection of EF copper on mandrels

“Good” Mandrel



“Poor” Mandrel with large nodule growth



DEMONSTRATOR Cables and Connectors

	Total			Biased			Analysis		
DS3+DS4	Det(kg)	Active (kg)	#	Det (kg)	Active (kg)	#	Det (kg)	Active (kg)	#
Total	44.1	40.3 ± 0.7	58	33.8	30.9 ± 0.5	44	29.0	24.8 ± 0.4	35
Enriched	29.7	27.4 ± 0.4	35	23.2	21.4 ± 0.3	27	19.6	18.1 ± 0.3	23
Natural	14.4	12.9 ± 0.3	23	10.7	9.5 ± 0.2	17	9.4	6.7 ± 0.2	12

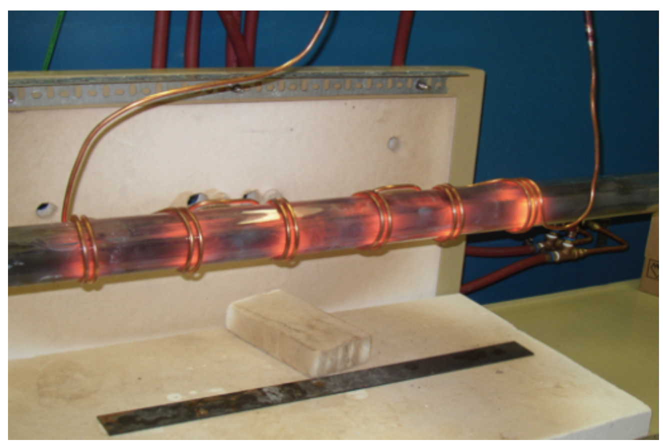
- 44 of the 58 installed detectors are operating
- Problems with non-operating detectors
  - 7 associated with the signal connectors that are located on the cryostat cold plate or with damaged low mass front end boards.
  - 7 detectors cannot be biased either because of problems with the HV cables, connections, or in one instance a likely detector problem.
- Upgrade underway
  - “Fuzz buttons” for signal connectors.
  - HV cable study in progress

Ge Processing and Recovery

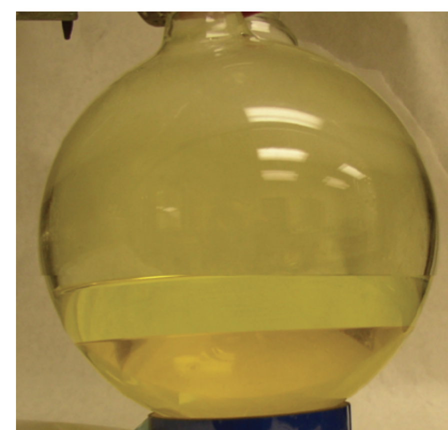
- **Reduction & Zone refining**: 98.7% yield of > 47 Ohm-cm Ge from 42.5 kg of ^{enr}Ge (61.7 kg of GeO_2)
- **ORTEC manufactured**: 30 ^{enr}Ge detectors, 25.3 kg of mass.
  - 64.4% yield of detectors, 3.22 kg of > 47 Ohm-cm Ge material not used,
- **Recovered Ge:** from processing det. manufacturing waste (NSF suppl. funding)
  - Reprocessed 8.4-kg of "scrap"
    - effluent, kurf, and 2.87 kg of metal from detector manufacturer reject.
  - Recovered 5.87 kg of Ge with >47 Ohm-cm.
- The 5.87 kg was combined with 3.22 kg of Ge material to provide 9.1 kg of Ge > 47 Ohm-cm. ORTEC manufactured 5 additional detectors with 4.4 kg mass.
- **Final yield of detectors:** 74.5%
  - unused ^{enr}Ge inventory: 1.49 kg (crystal) and 1.15 kg (zone refined).

Ge reduced in Chlorine gas

Zone refining of Ge metal



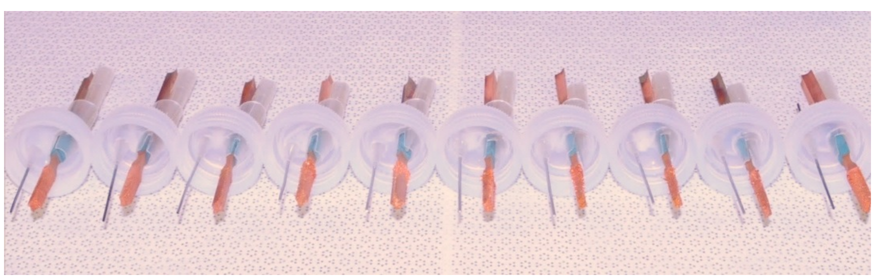
$GeCl_4$ with cover liquid



MJD Materials Assay

- Assay of samples from all materials used in the DEMONSTRATOR.
  - Radiometric, NAA, & ICP-MS techniques.
- By necessity have developed world's most sensitive ICP-MS based assay techniques for U and Th in Cu (Original MJD Goal: <0.3 μBq/kg for U & Th)
  - Current MDL (method detection limits) with iridium anode improvements
    - U decay chain 0.1 μBq ^{238}U/kg
    - Th decay chain 0.1 μBq ^{232}Th/kg
  - Sensitivities with ion exchange copper sample preparation (MDL study)
    - U decay chain <0.13 μBq ^{238}U/kg
    - Th decay chain <0.034 μBq ^{232}Th/kg

Evaluation of iridium electrodes following copper sample preparation



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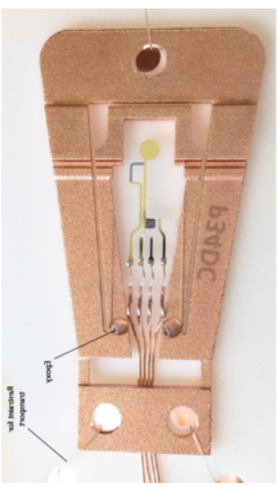
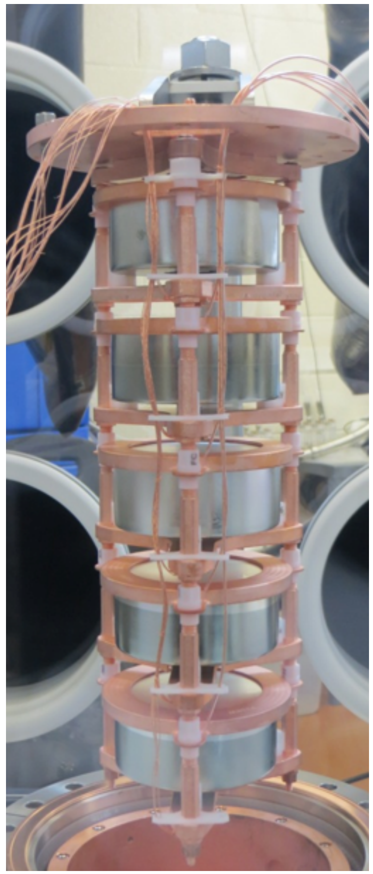
DEMONSTRATOR Detector Strings

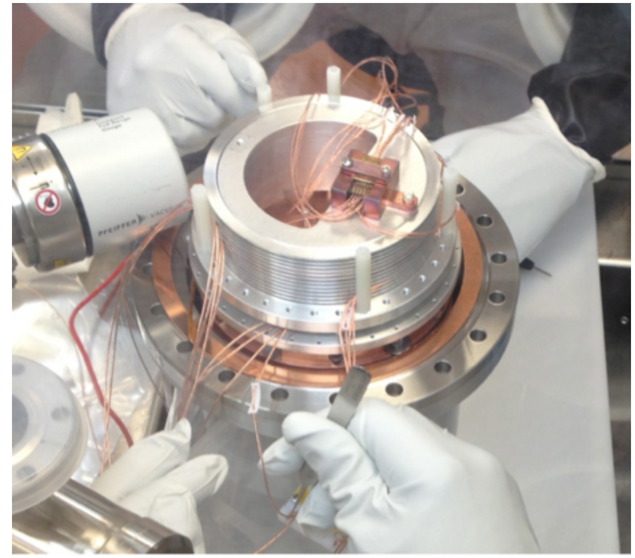
^{Nat}Ge BEGe PPC detector in MJD mount



String with 5 ^{Nat}Ge BEGe PPC detectors



Cable Management System



Loading string into string test cryostat in Glove Box