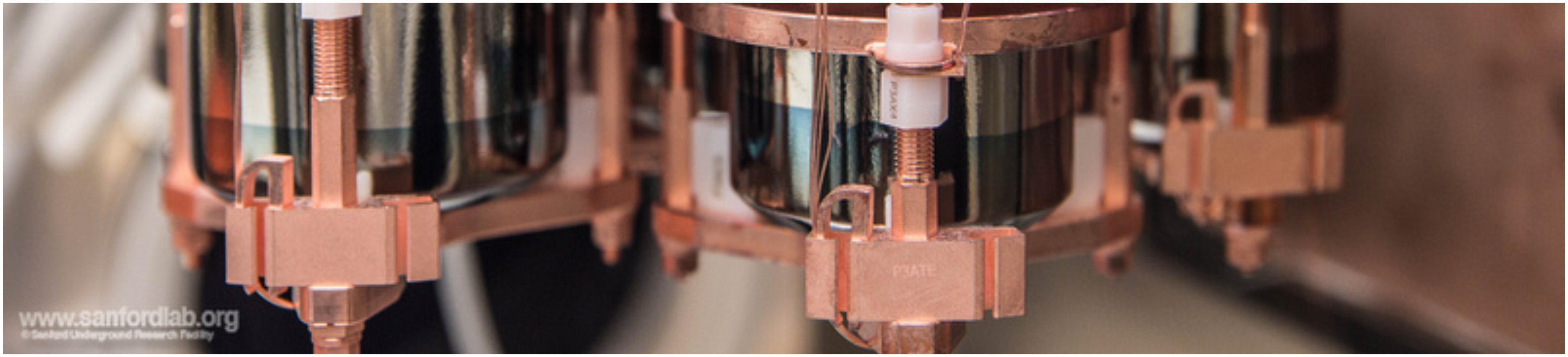
Initial Results from the MAJORANA DEMONSTRATOR

Tom Caldwell for the MAJORANA Collaboration
University of North Carolina
Triangle Universities Nuclear Laboratory

TAUP 2017
Sudbury, ON
July 24, 2017



The MAJORANA Collaboration

Black Hills State University, Spearfish, SD
Kara Keeter

Duke University, Durham, North Carolina, and TUNL
Matthew Busch

Joint Institute for Nuclear Research, Dubna, Russia
Viktor Brudanin, M. Shirchenko, Sergey Vasilyev, E. Yakushev, I. Zhitnikov

Lawrence Berkeley National Laboratory, Berkeley, California and the University of California - Berkeley
Nicolas Abgrall, Yuen-Dat Chan, Lukas Hehn, Jordan Myslik, Alan Poon, Kai Vetter

Los Alamos National Laboratory, Los Alamos, New Mexico
Pinghan Chu, Steven Elliott, Ralph Massarczyk, Keith Rielage, Larry Rodriguez, Harry Salazar, Brandon White, Brian Zhu

National Research Center '*Kurchatov Institute' Institute of Theoretical and Experimental Physics*, Moscow, Russia
Alexander Barabash, Sergey Konovalov, Vladimir Yumatov

North Carolina State University, and TUNL
Matthew P. Green

Oak Ridge National Laboratory
Fred Bertrand, Charlie Havener, Monty Middlebrook, David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan
Hiroyasu Ejiri

Pacific Northwest National Laboratory, Richland, Washington
Isaac Arnquist, Eric Hoppe, Richard T. Kouzes

Princeton University, Princeton, New Jersey
Graham K. Giovanetti

Queen's University, Kingston, Canada
Ryan Martin

South Dakota School of Mines and Technology, Rapid City, South Dakota
Colter Dunagan, Cabot-Ann Christofferson, Anne-Marie Suriano, Jared Thompson

Tennessee Tech University, Cookeville, Tennessee
Mary Kidd

Technische Universität München, and Max Planck Institute, Munich, Germany
Tobias Bode, Susanne Mertens

University of North Carolina, Chapel Hill, North Carolina, and TUNL
Thomas Caldwell, Thomas Gilliss, Chris Haufe, Reyco Henning, Mark Howe, Samuel J. Meijer, Christopher O'Shaughnessy, Gulden Othman, Jamin Rager, Anna Reine, Benjamin Shanks, Kris Vorren, John F. Wilkerson

University of South Carolina, Columbia, South Carolina
Frank Avignone, Vince Guiseppe, David Tedeschi, Clint Wiseman

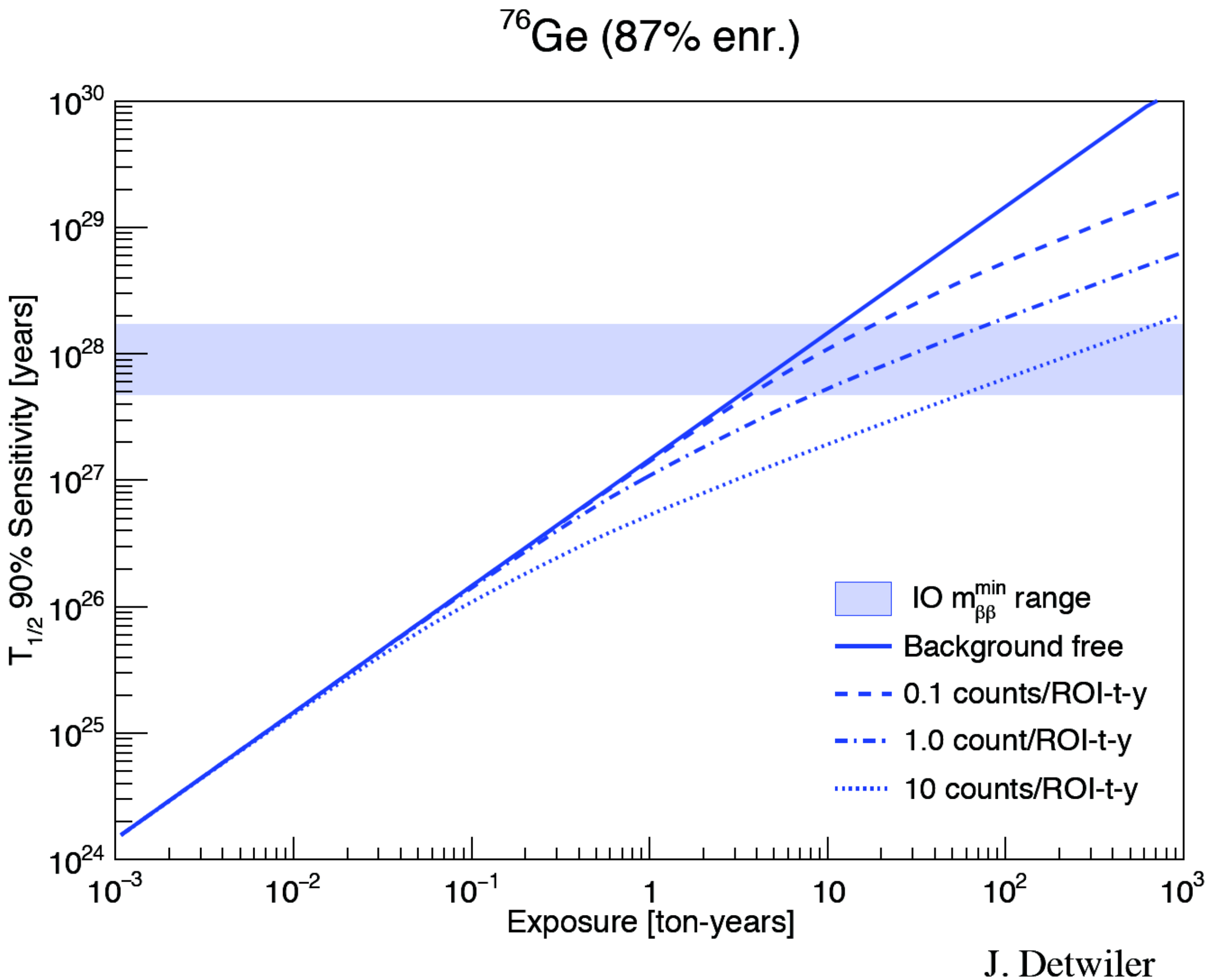
University of South Dakota, Vermillion, South Dakota
Wenqin Xu

University of Tennessee, Knoxville, Tennessee
Yuri Efremenko, Andrew Lopez

University of Washington, Seattle, Washington
Sebastian Alvis, Tom Burritt, Micah Buuck, Clara Cuesta, Jason Detwiler, Julieta Gruszko, Ian Guinn, David Peterson, R. G. Hamish Robertson, Tim Van Wechel

0νββ with Germanium Detector Arrays

- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution, approaching 0.1% at 2039 keV
- Demonstrated ability to enrich from 7.4% ^{76}Ge to ≥87%
- Powerful background rejection: multiplicity, timing, pulse-shape analysis



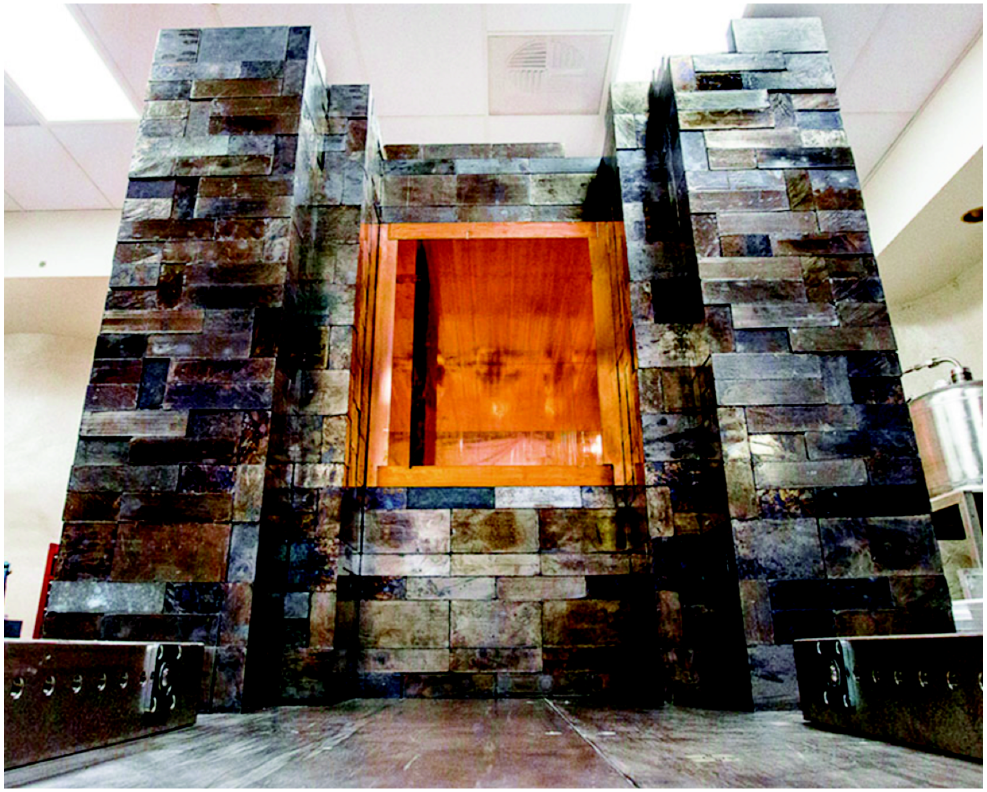
Assumes 75% efficiency based on GERDA Phase I.
Enrichment level is accounted for in the exposure

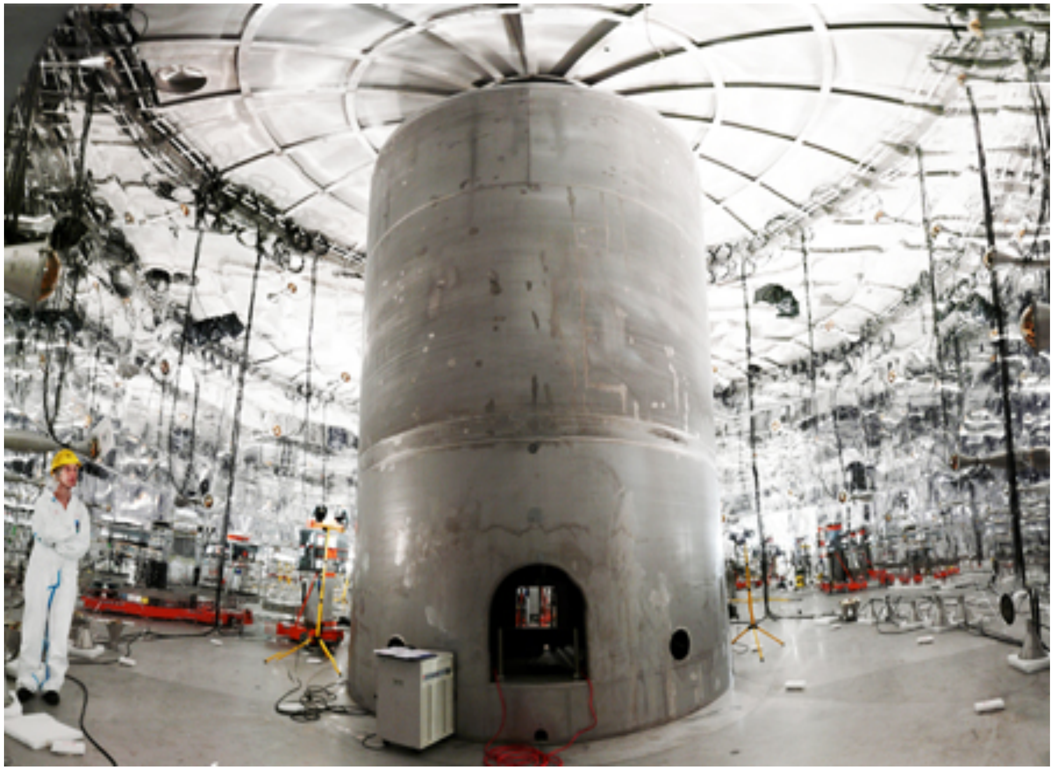
MAJORANA and GERDA

- To reach the ton-scale (and the necessary backgrounds), LEGEND will combine the strengths of both GERDA and the MAJORANA DEMONSTRATOR
- See Wilkerson – Neutrino Parallel Session 3

MAJORANA:
Ge detectors in a compact configuration: vacuum cryostats in graded passive shield with ultra-clean materials

GERDA:
Ge detectors directly immersed in an active liquid argon shield



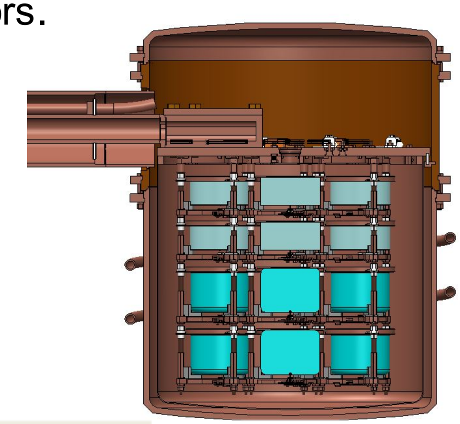


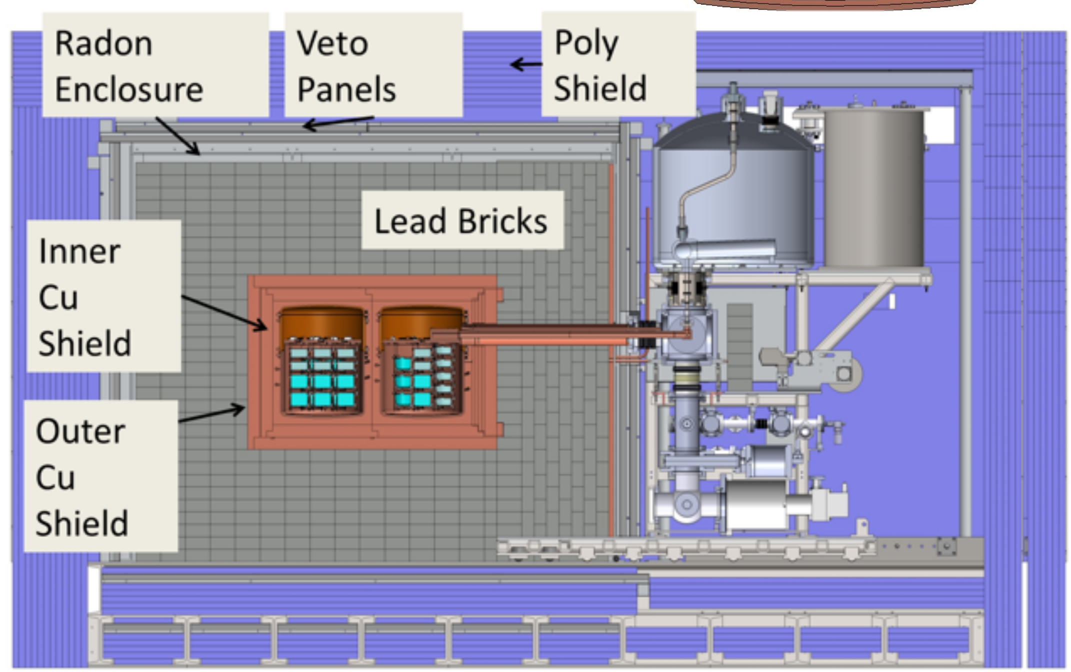
The MAJORANA DEMONSTRATOR

Operating underground at 4850' Sanford Underground Research Facility with the best energy resolution (2.4 keV FWHM @ 2039 keV) of any ββ-decay experiment.

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.

- Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)
  - 3 counts/ROI/t/y (after analysis cuts) Assay U.L. Currently ≤ 3.5
- 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



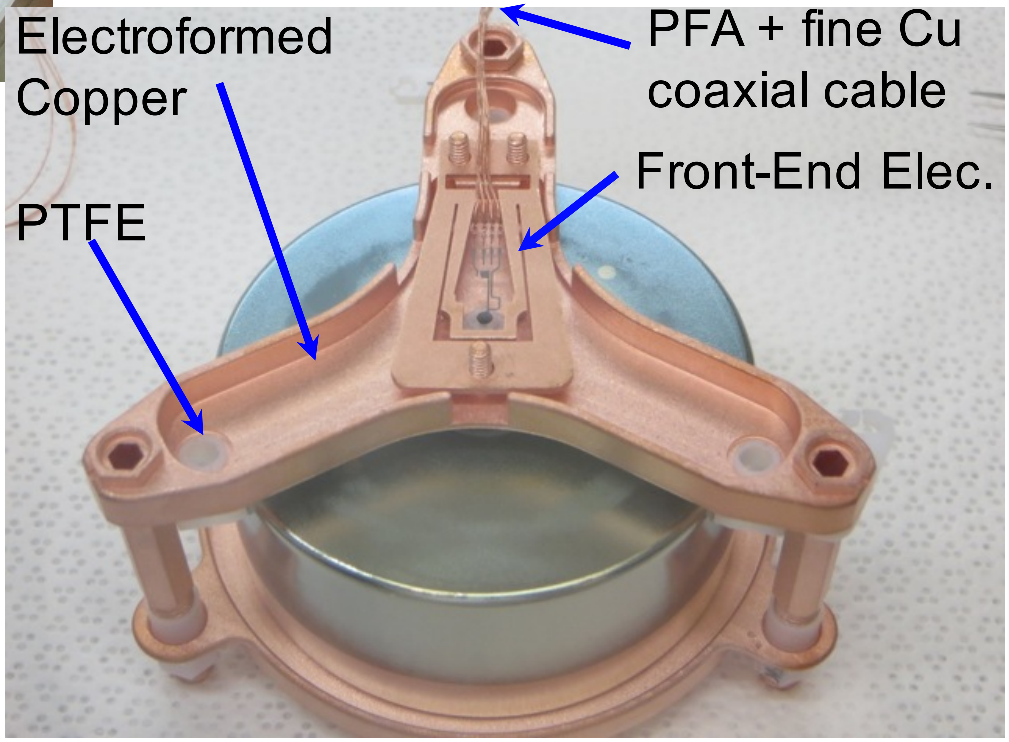


N. Abgrall *et al.*, Adv. High Ener. Phys. **2014**, 365432 (2013) arXiv:1308.1633

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

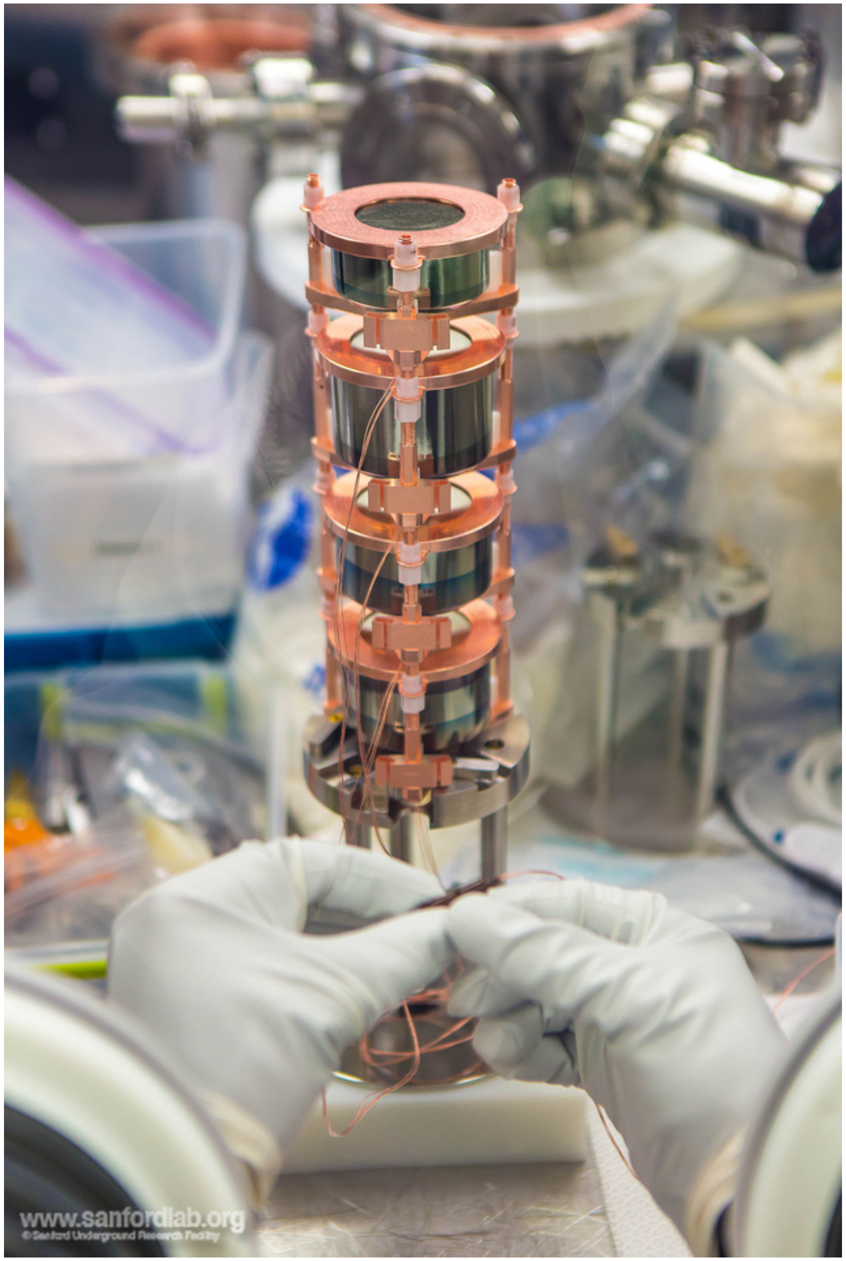
Electroformed Cu and Enriched Ge

- Electroformed undergroud
- Average Th decay chain ≤ 0.1 μBq/kg
- Average U decay chain ≤ 0.1 μBq/kg
- ~1.1 tons used in the DEMONSTRATOR
  - String components
  - Cryostats/thermosyphon
  - Inner layers of shielding



- AMTEK (ORTEC) fabricated enriched detectors
- 35 enriched point contact detectors (29.7 kg), 88% ^{76}Ge
- 33 Canberra modified natural BEGe detectors (20 kg)
- Tracked and minimized surface exposure of enriched material to determine cosmogenic activation

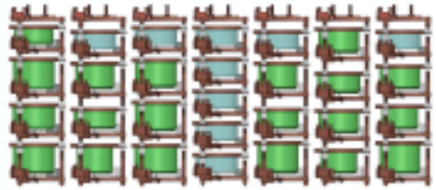
Electroformed Cu and Enriched Ge



DEMONSTRATOR Implementation

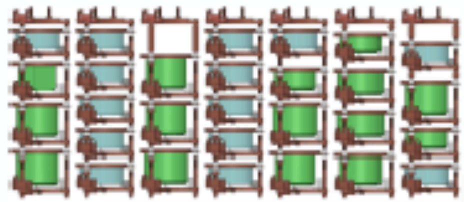
In shield Operation

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

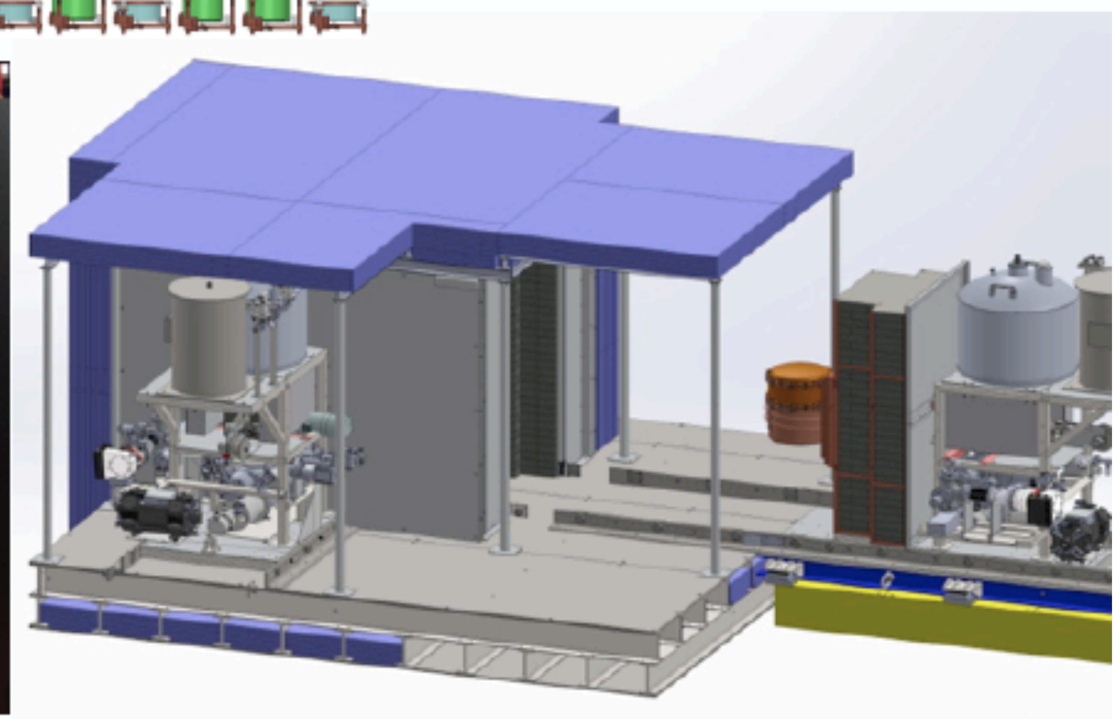


May – Oct. 2015, Final Installation, Dec. 2015 — ongoing

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



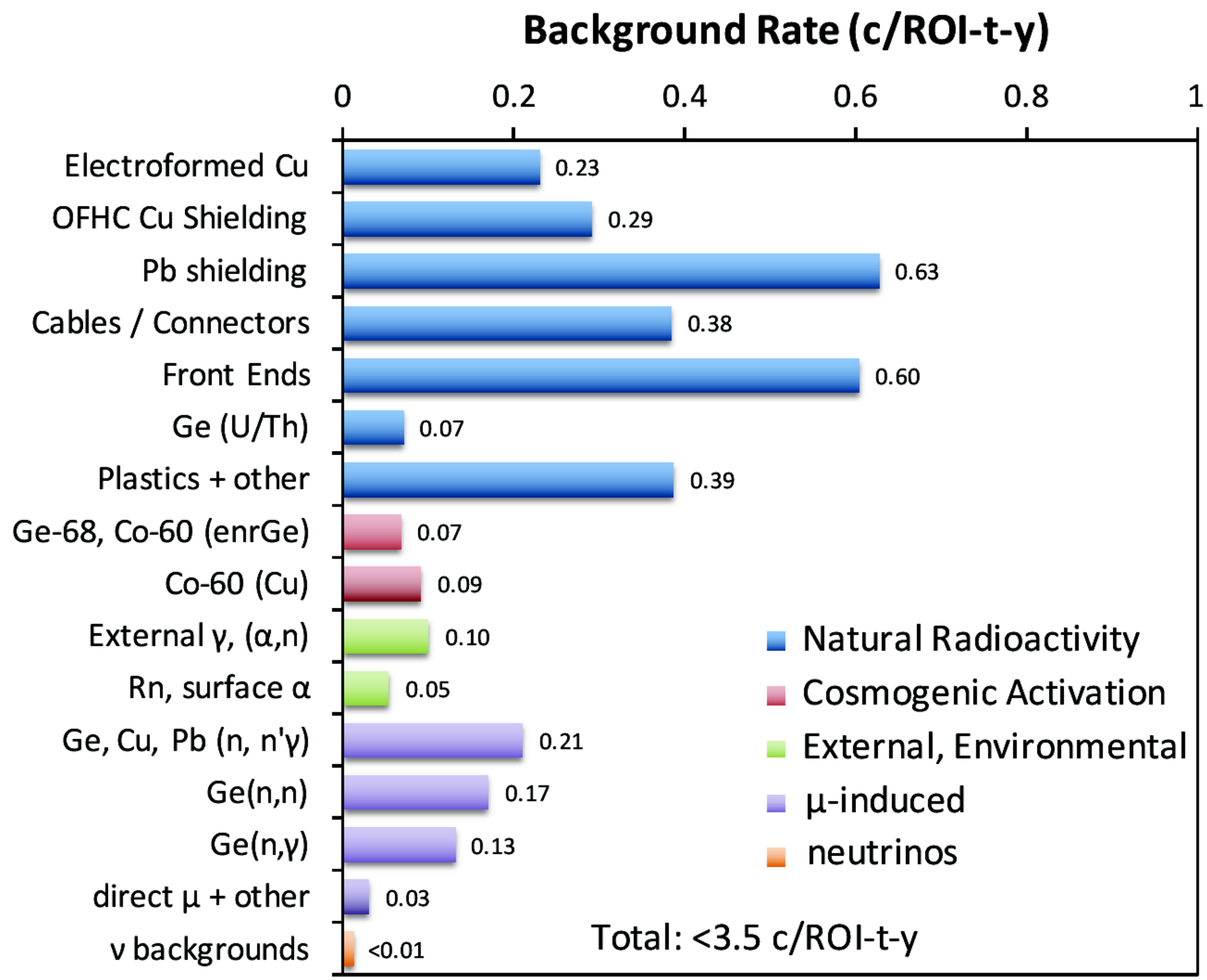
July 2016 — ongoing



DEMONSTRATOR Backgrounds

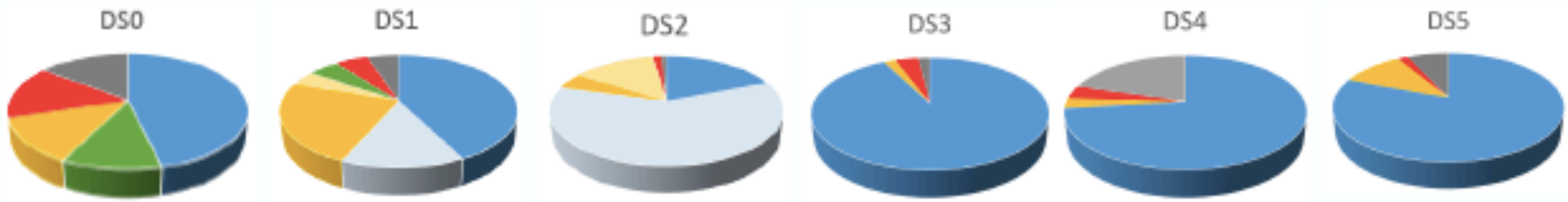
Based on assays of materials; When upper limit, use upper limit value as contribution

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



Data Sets and Duty Cycles

Currently taking blind data in DS-6 with multi-sampling

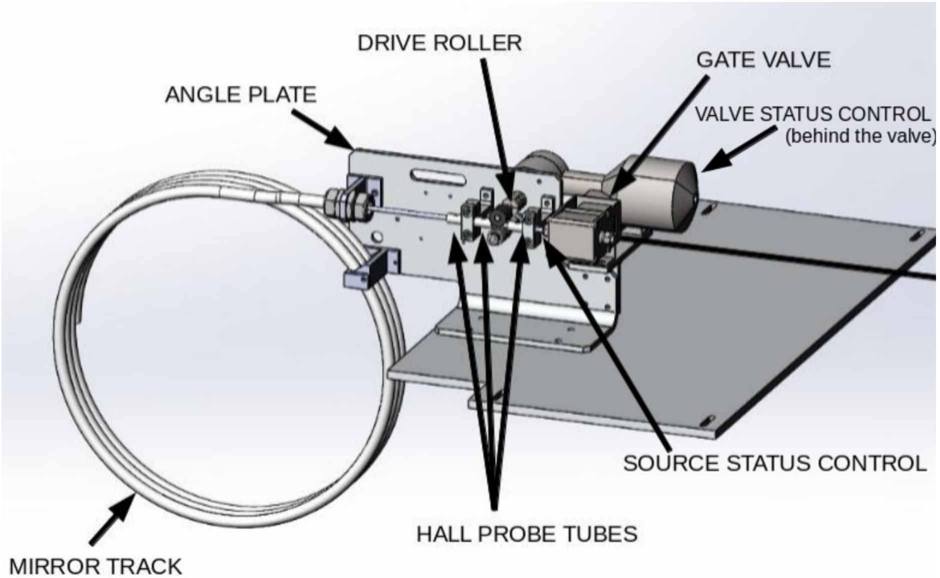


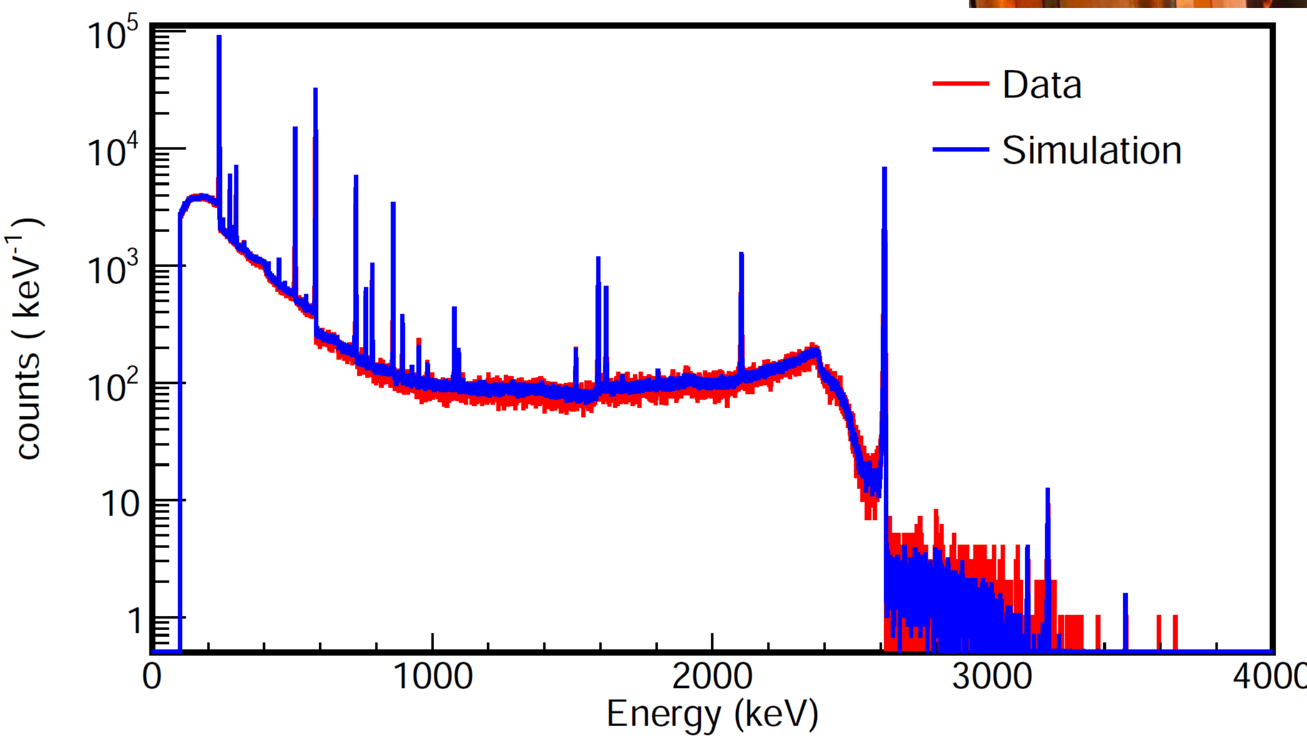
M1 Commissioning, no inner shield | *M1 inner shield* | *M1 Multi-sampling* | *Modules 1 and 2 Together in-shield* | *Module 1 & 2 Integrated DAQ*

		DS0 (days) **Module 1** June 26, – Oct. 7, 2015	**DS1 (days)** **Module 1** Dec. 31, 2015 – May 24, 2016	**DS2 (days)** **Module 1** May 24 – July 14, 2016	**DS3 (days)** **Module 1** Aug. 25, – Sept. 27, 2016	**DS4 (days)** **Module 2** Aug. 25, – Sept. 27, 2016	**DS5 (days)** **Module 1 & 2** Oct. 13, 2016 – May 11, 2017*
Total		103.15	144.50	50.97	32.37	32.36	147.68
Total acquired		87.93	136.98	50.47	31.73	25.80	137.42
Physics	■ *	47.70	61.34 + 20.41*	9.82 + 30.56*	29.91	23.69	119.38
High radon	■	11.76	7.32	-	-	-	-
Disruptive Activities	■ *	13.10	34.43+ 5.92*	2.41 + 7.03*	0.63	0.93	15.68
Calibration	■	15.44	7.32	0.65	1.18	1.17	2.36
Down time	■	15.21	7.51	0.50	0.64	6.56	10.25

*Values thru 03/10/17

Energy Calibration

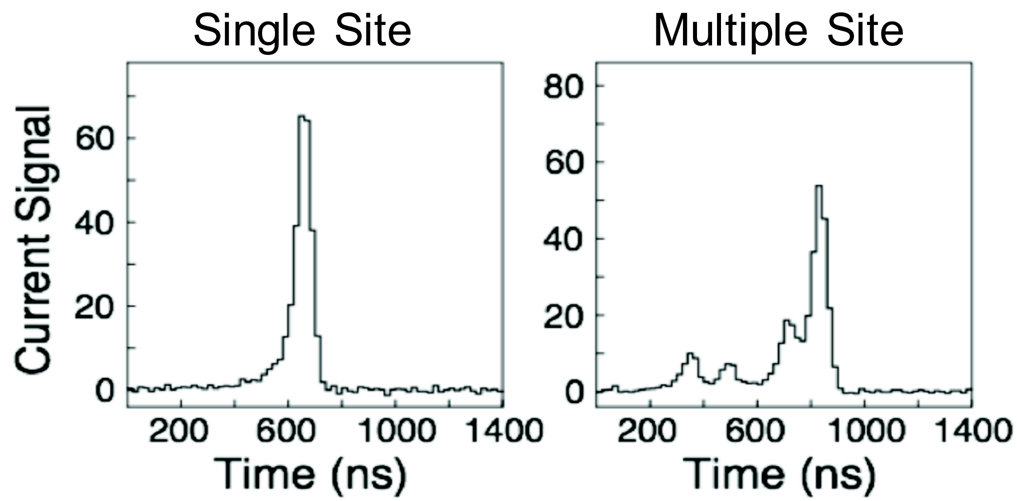


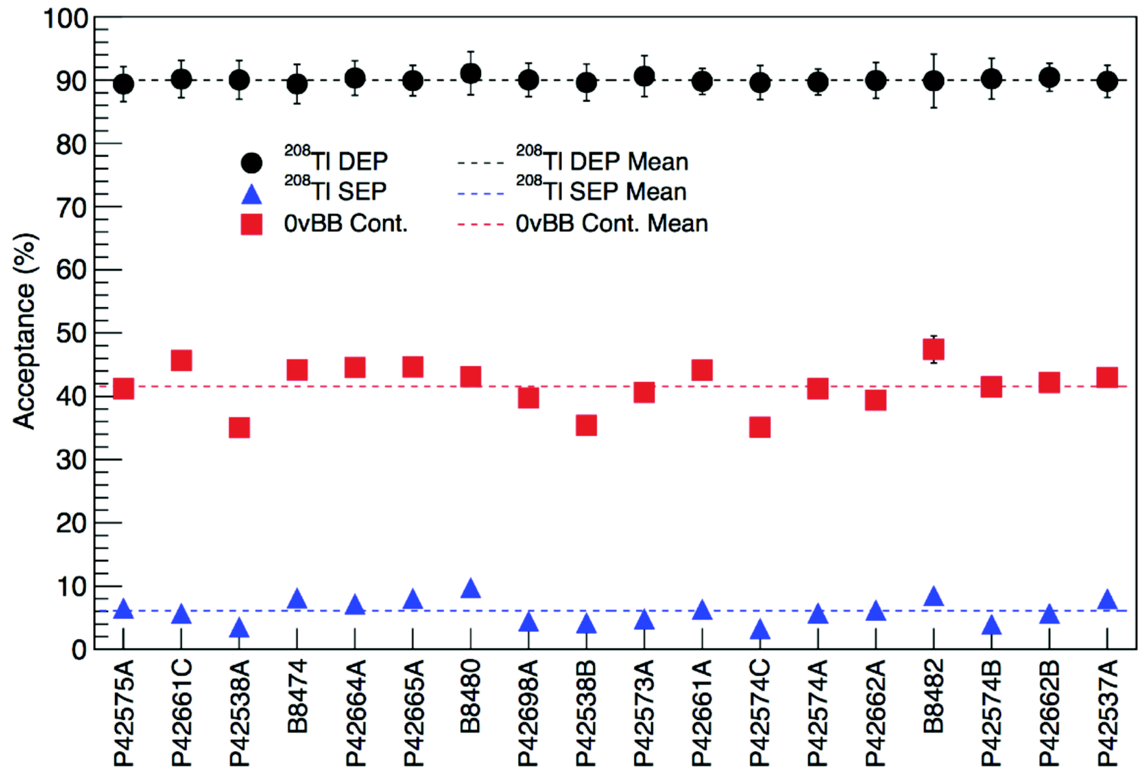


Calibration System Paper:
arXiv:1702.02466

Multiple Site Event Rejection

- $0\nu\beta\beta$ decays occur at a single site in the Ge crystal
- Point-contact detectors have sufficient differences in drift times throughout the bulk to identify multiple site interactions
- Tune current amplitude-to-energy ratio (AvsE) to ^{208}Tl calibrations to accept 90% of single site double escape events





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

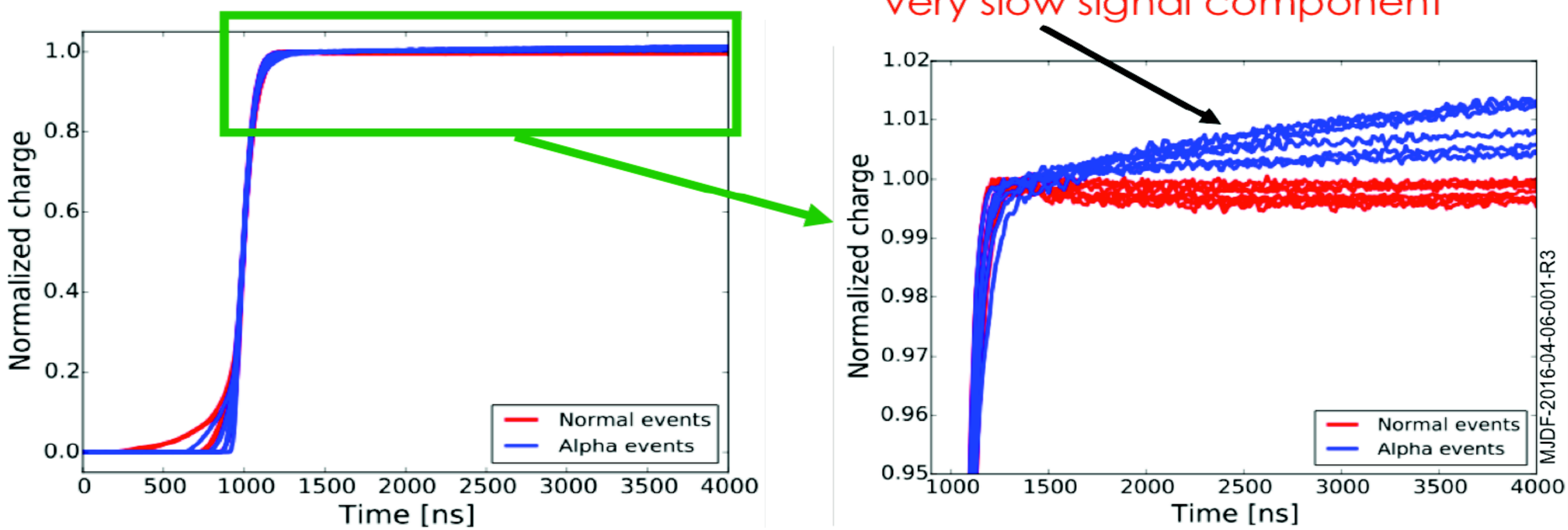
^{208}Tl SEP (Multiple site events) reduced to 6%

Alpha Backgrounds

- Energy degraded alpha background observed in early data sets
- Charge from these events drifts along the surface rather than through the bulk
- Results in a distinctive delayed charge recovery (DCR) signal which is used to efficiently cut alpha events based on the slope past the rising edge
- Measurements taken and being analyzed from a DEMONSTRATOR detector in the TUBE alpha scanner at Technical University of Munich to better understand the source and response of surface alphas

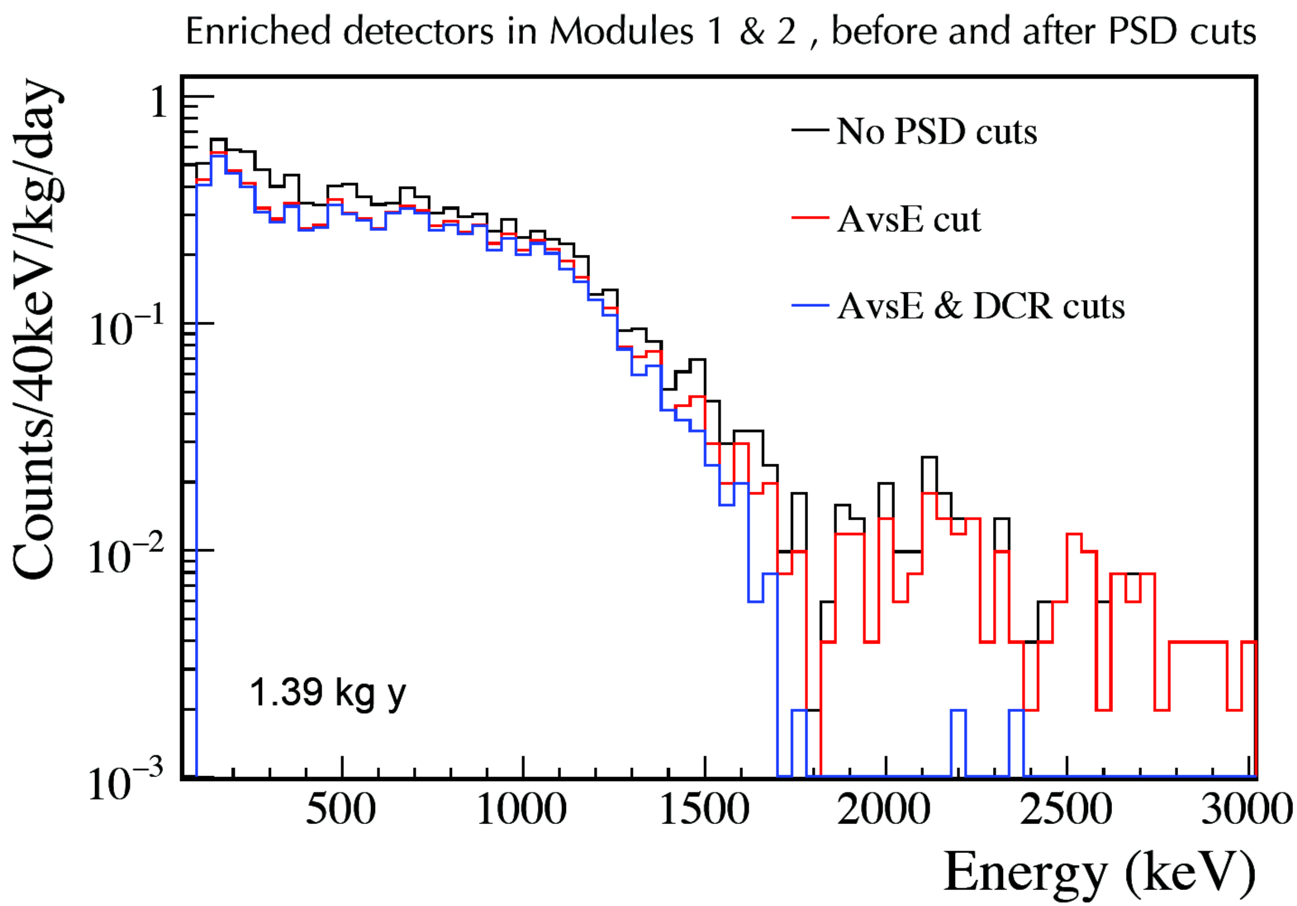
Example pole-zero corrected waveforms

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



Background in DS3 and DS4

- 1.39 kg-yr exposure of enriched detectors
- One count after cuts in a 400 keV region around the Q-value of 2039 keV
- Projected background in 2.8 keV wide ROI of $5.1^{+8.9}_{-3.2}$ c/(ROI-t-y)
- Background index of 1.8×10^{-3} c/(keV-kg-y)
- See Hehn – Neutrino Parallel Session 3



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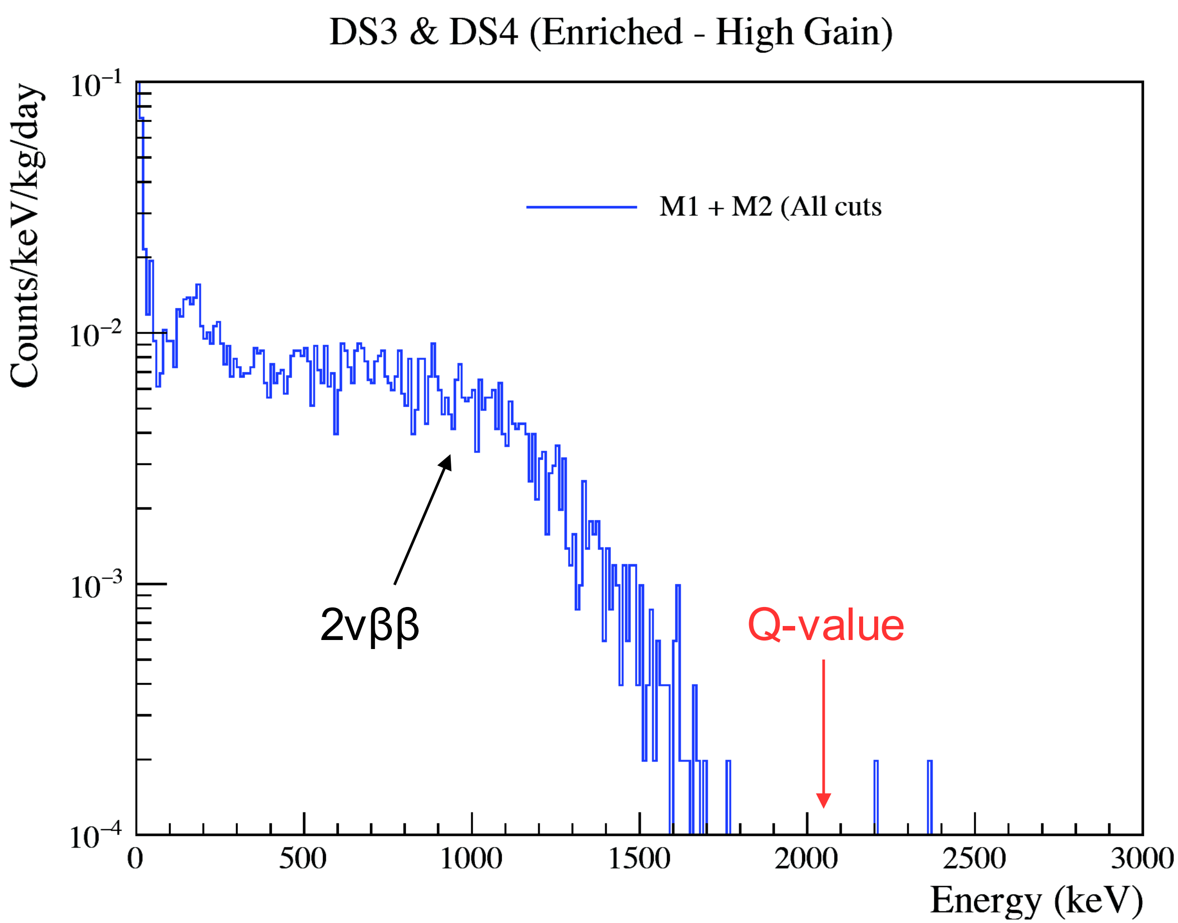
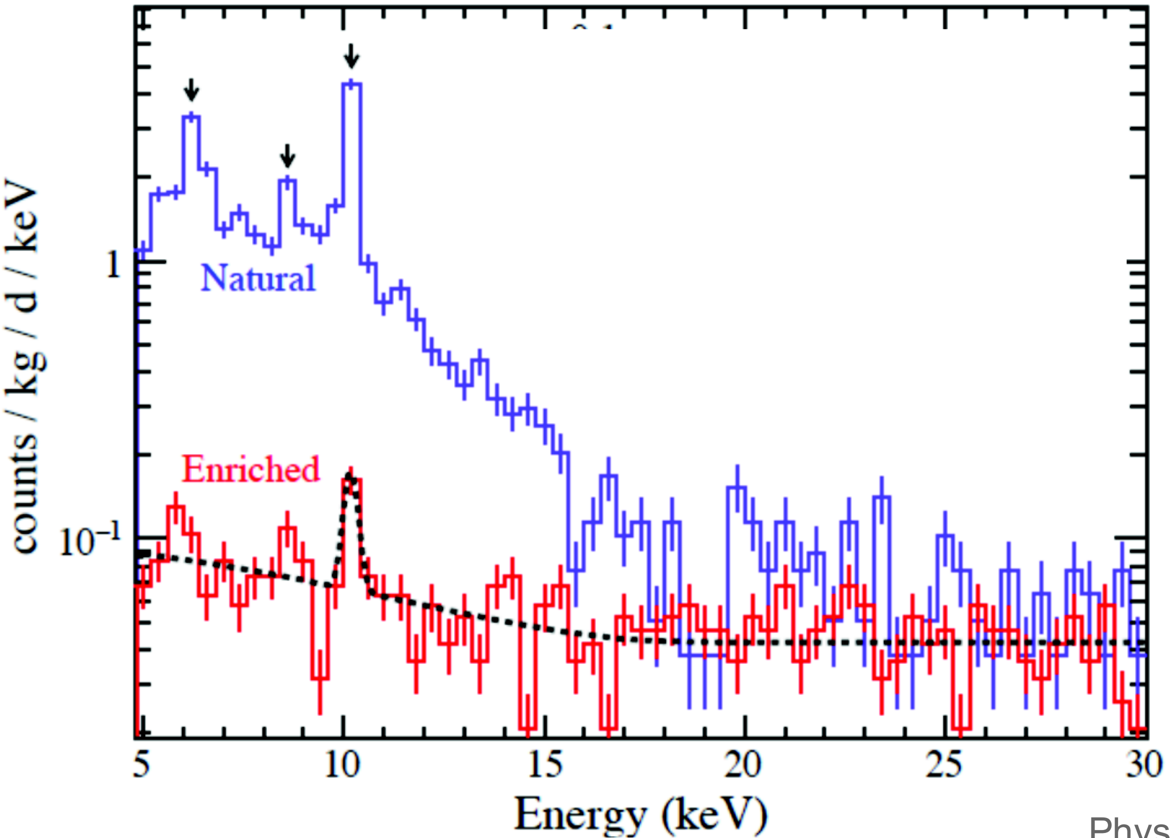


Low-Energy Physics Searches

- Limited exposure of enriched material to cosmic rays
  For the DEMONSTRATOR, the enriched detector ^{68}Ge rate is low enough that an X-ray delayed coincidence cut is not necessary
- Tritium is obvious and dominates in natural detectors below 20 keV
- Hardware thresholds below 1 keV, analysis below 5 keV is ongoing
- DS0 commissioning background below (without full electroformed Cu shield)
- Factor of several reduction in low-energy background in later datasets
- See Othman – Neutrino Parallel Session 3



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 violation

Phys. Rev. Lett. 118, 161801 (arXiv:1612.00886)

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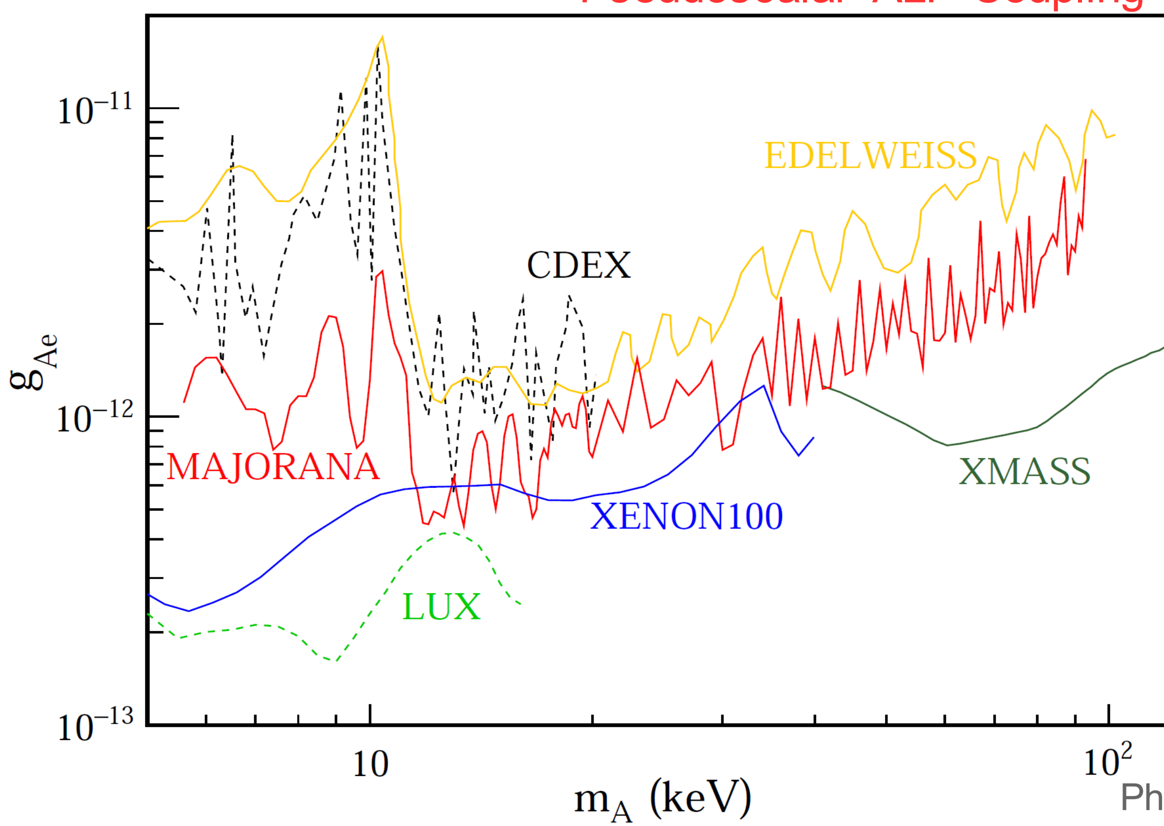
Pseudoscalar ALP Coupling



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Summary

- The ^{76}Ge enriched PPC 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 for reduction of backgrounds.
  - have sub-keV thresholds and excellent energy resolution at low-energy allowing the DEMONSTRATOR to perform sensitive tests in this region for physics beyond the standard model.

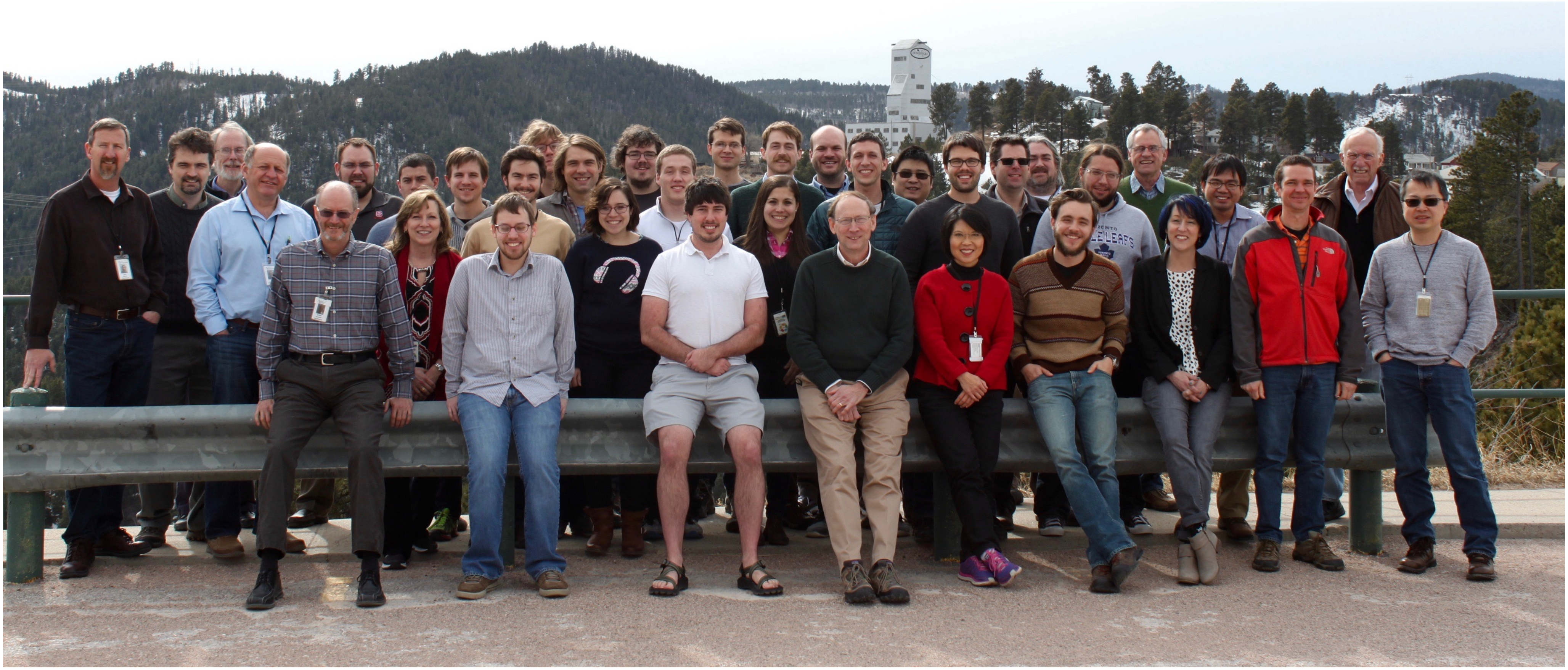
- The DEMONSTRATOR's initial backgrounds are amongst the lowest in the ROI achieved to date (approaching GERDA's recent best value) by development and selection of ultra-low activity materials and low-mass designs.

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

MAJORANA DEMONSTRATOR Posters and Talks

Gillis – Progress towards a two-neutrino double-beta decay measurement from the MAJORANA DEMONSTRATOR
Meijer – High precision modeling of germanium detector waveforms using MCMC and machine learning
Myslik – Data quality assurance for the MAJORANA DEMONSTRATOR
Reine & Haufe - Design Improvements to Cables and Connectors in the MAJORANA DEMONSTRATOR
Hehn (Neutrino 3) Spectral analysis for the MAJORANA DEMONSTRATOR experiment
Othman (Neutrino 3) Rare Low-Energy Event Searches with the MAJORANA DEMONSTRATOR

The MAJORANA Collaboration



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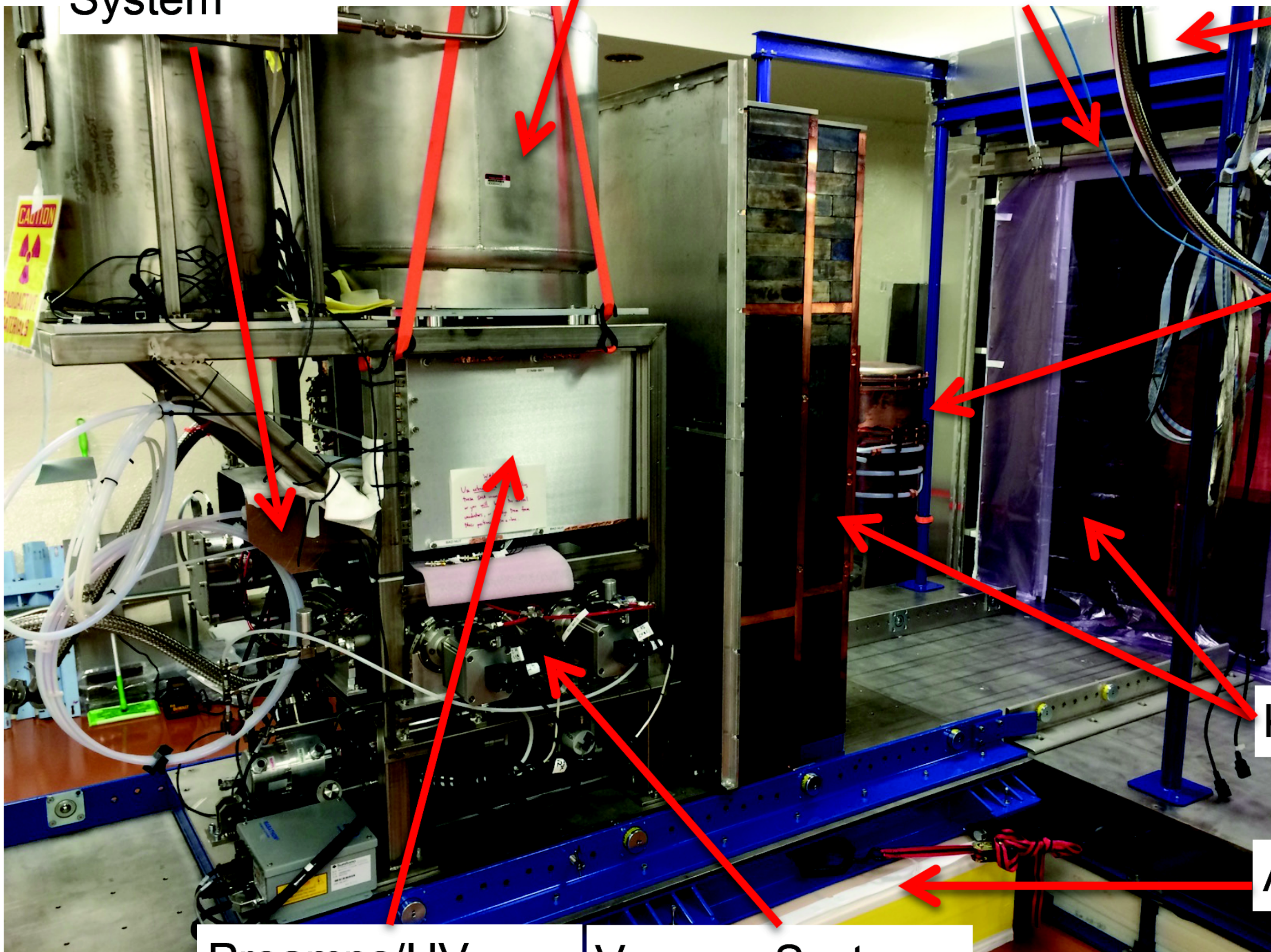
Module and Shield Details



MAJORANA Electroformed Cu

- 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.

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