UNIVERSITY OF
SOUTH DAKOTA

Status and Initial Results of the MAJORANA DEMONSTRATOR

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University of South Dakota

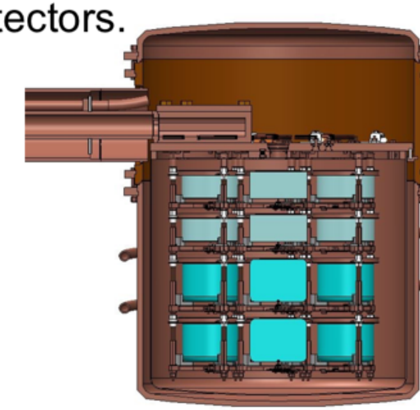
CIPANP 2018

Palm Springs, CA, May 29, 2018

The Majorana Demonstrator

Operating underground at the 4850' Sanford Underground Research Facility

Goals:
- Demonstrating backgrounds low enough to justify building a tonne scale experiment.
- Establishing feasibility to construct & field modular arrays of Ge detectors.
- Searching for additional physics beyond the standard model.



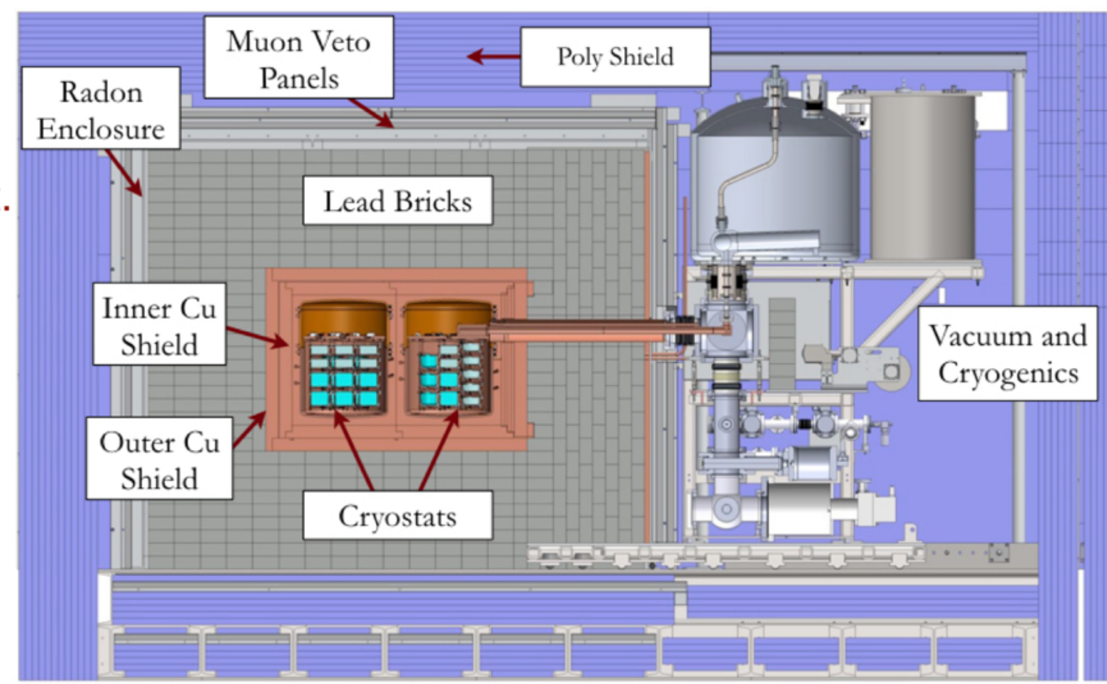
Energy resolution of 2.5 keV FWHM @ 2039 keV is the best of any ββ-decay experiment

Background Goal in the 0νββ peak after analysis cuts with the achieved resolution: 2.5 counts/(FWHM t yr)
- Projected backgrounds based on assay results ≤ 2.2 counts/(FWHM t yr)

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



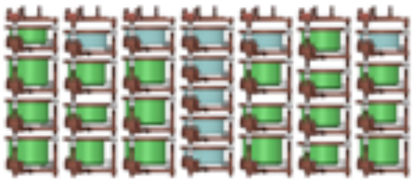
[N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)]

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

DEMONSTRATOR Implementation

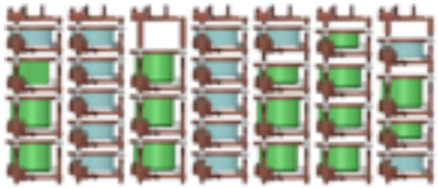
In shield Operation

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

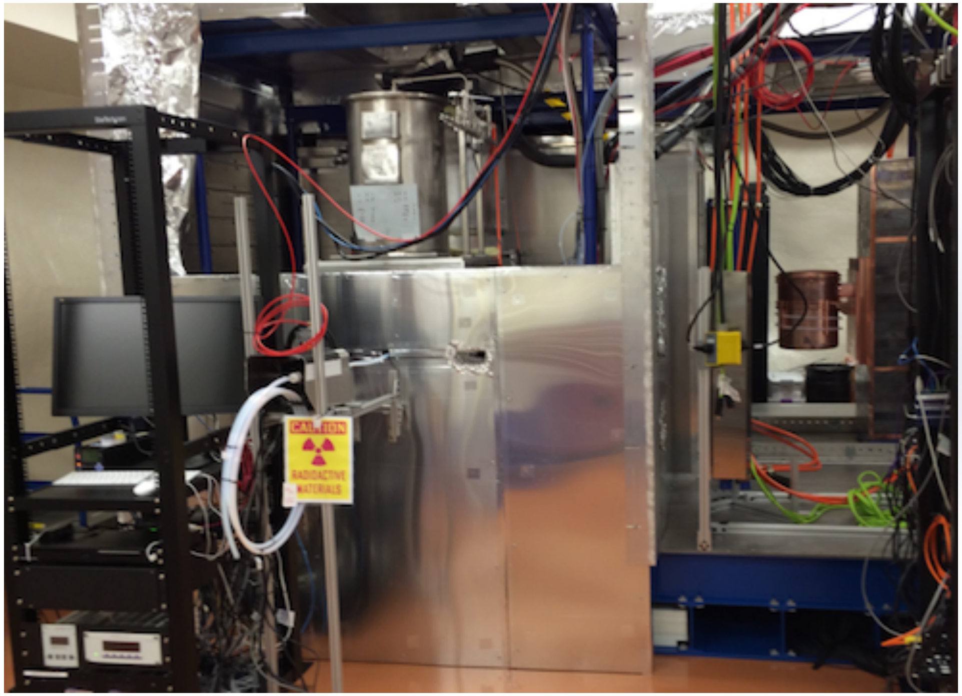


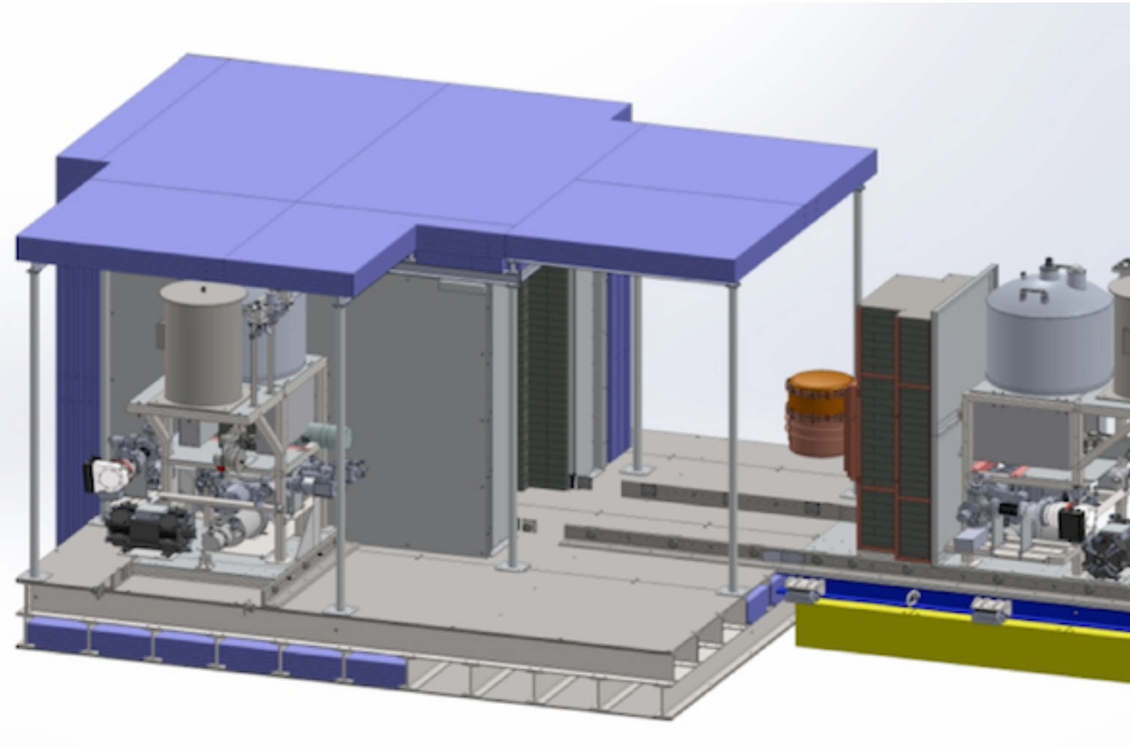
May – Oct. 2015,
Final Installation,
Dec. 2015 — ongoing

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

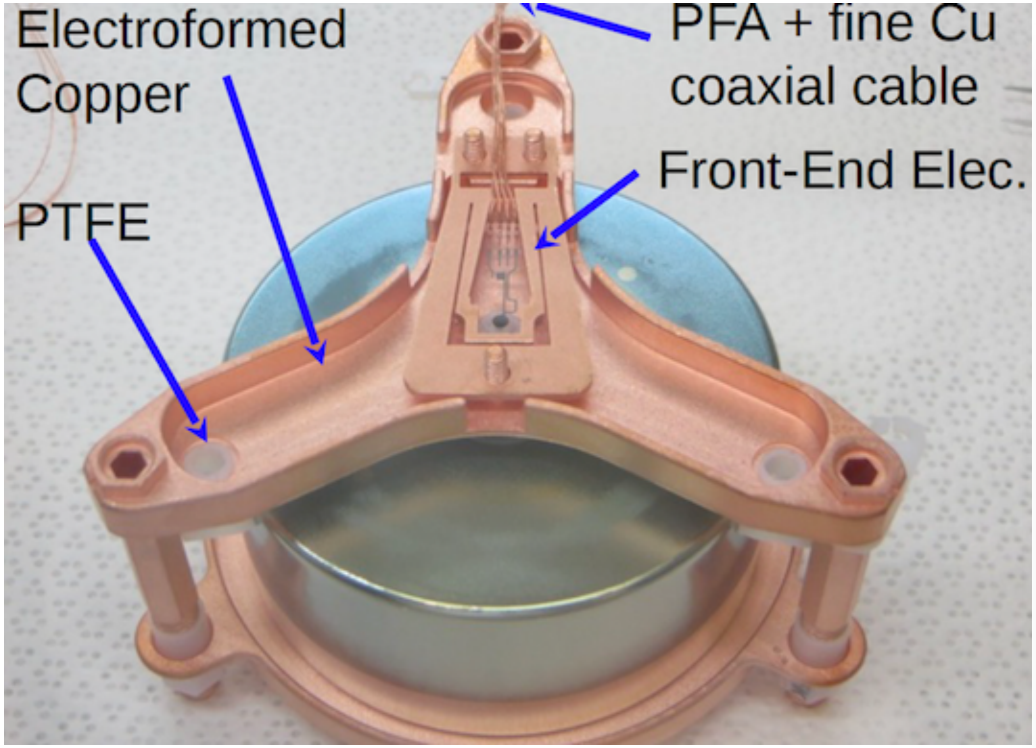


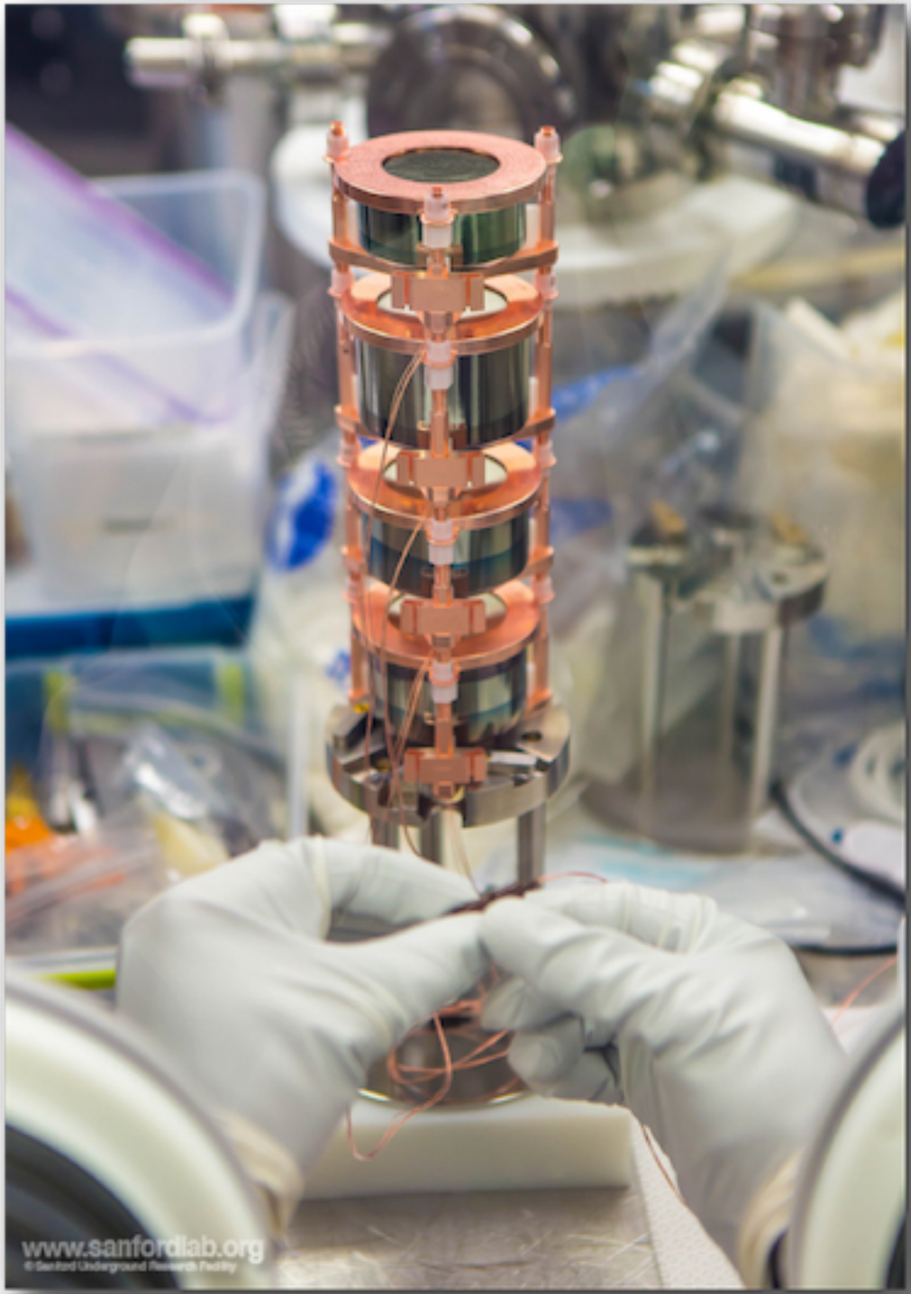
July 2016 — ongoing





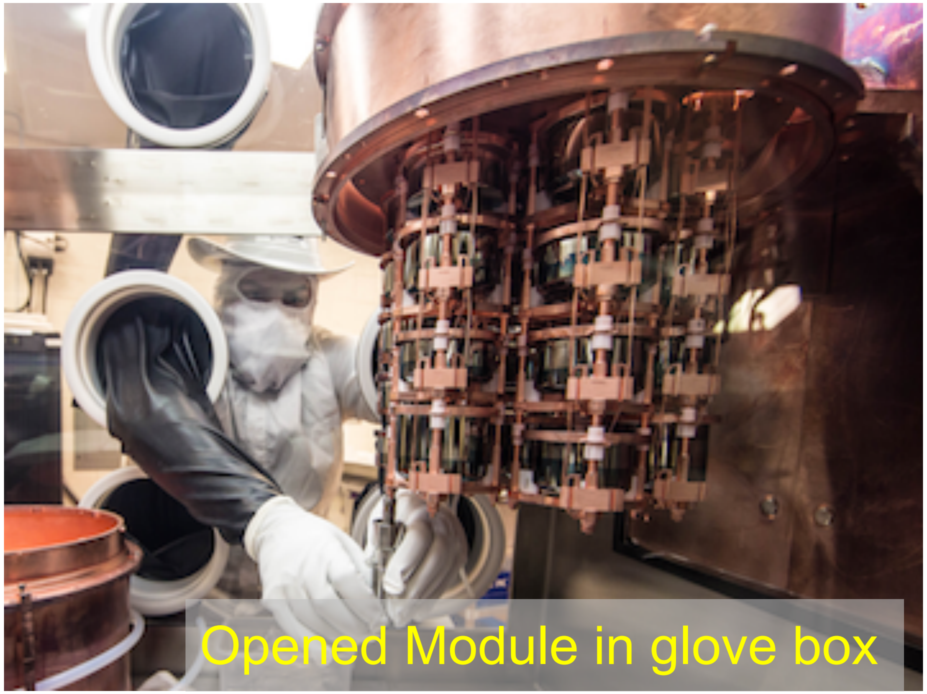
The DEMONSTRATOR Detectors & Strings



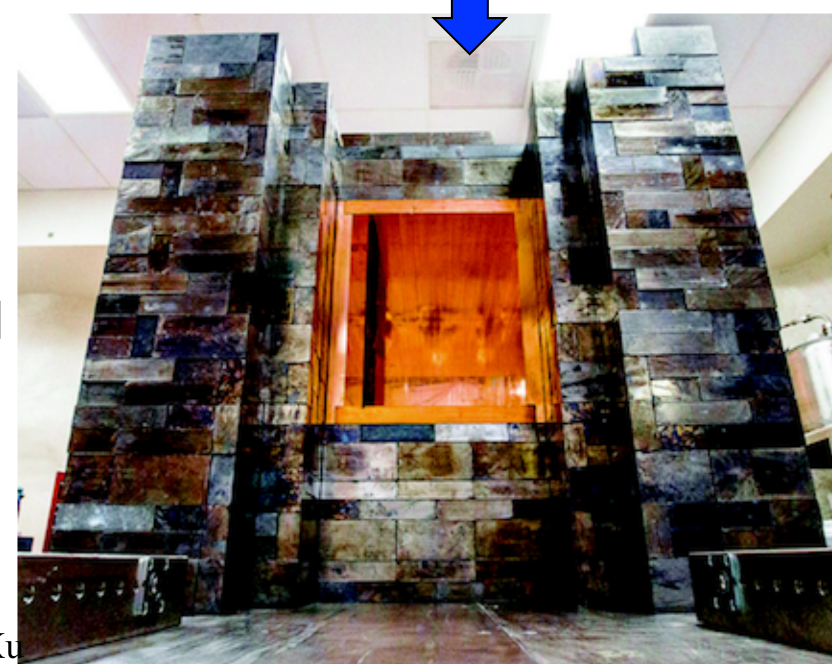


- AMTEK (ORTEC) fabricated enriched detectors
- 35 enriched point contact detectors (29.7 kg), 88% ^{76}Ge
- 33 Canberra modified natural BEGe detectors (20 kg)
- Tracked and minimized surface exposure of enriched material to determine cosmogenic activation

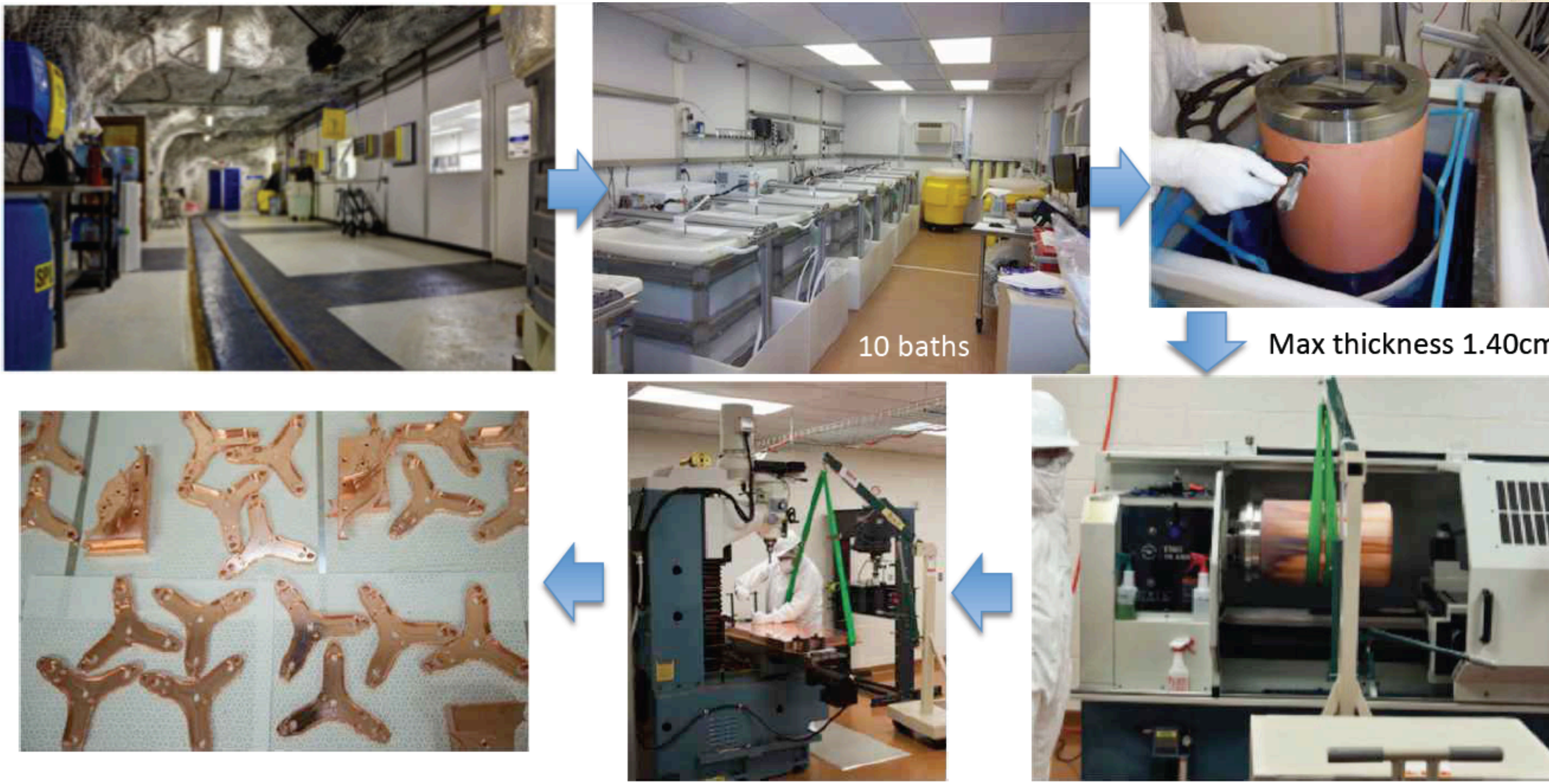
The DEMONSTRATOR Strings & Modules



Transporting a closed module from the glove box into shield



Electroformed Cu

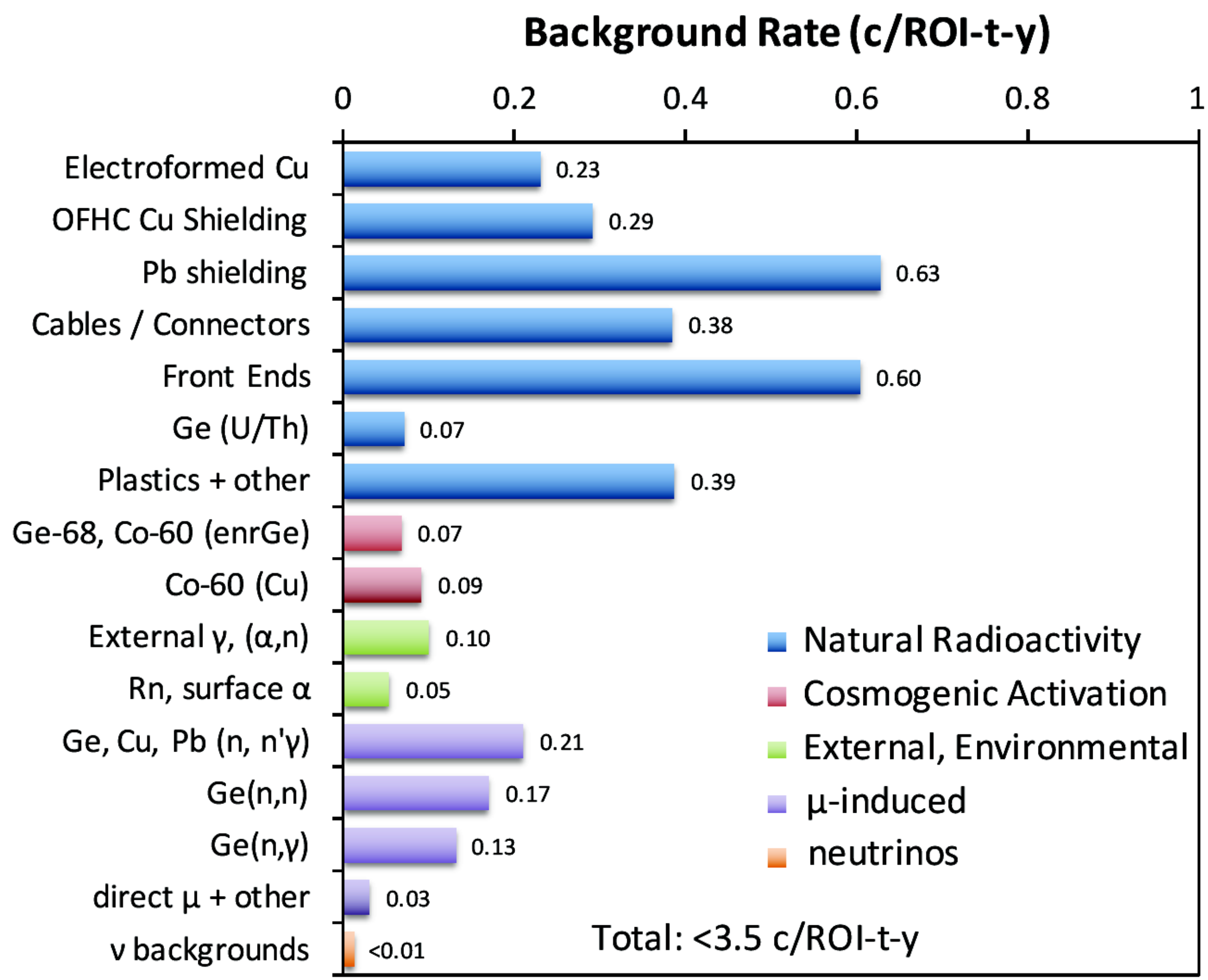


- Electroformed underground
- Average Th decay chain ≤ 0.1 μBq/kg, Average U decay chain ≤ 0.1 μBq/kg
- ~1.1 tons used in the Demonstrator
  - String components
  - Cryostats/thermosyphon
  - Inner layers of shielding

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

M1 Commissioning (No Inner Shield)
June 27 - Oct. 7, 2015

M1 (With Inner Shield)
Dec. 31, 2015 – May 24, 2016

M1 (DAQ Multisampling)
May 24 – July 14, 2016

Module 1 (M1 & M2 in-shield)
Aug. 25 – Sept. 27, 2016

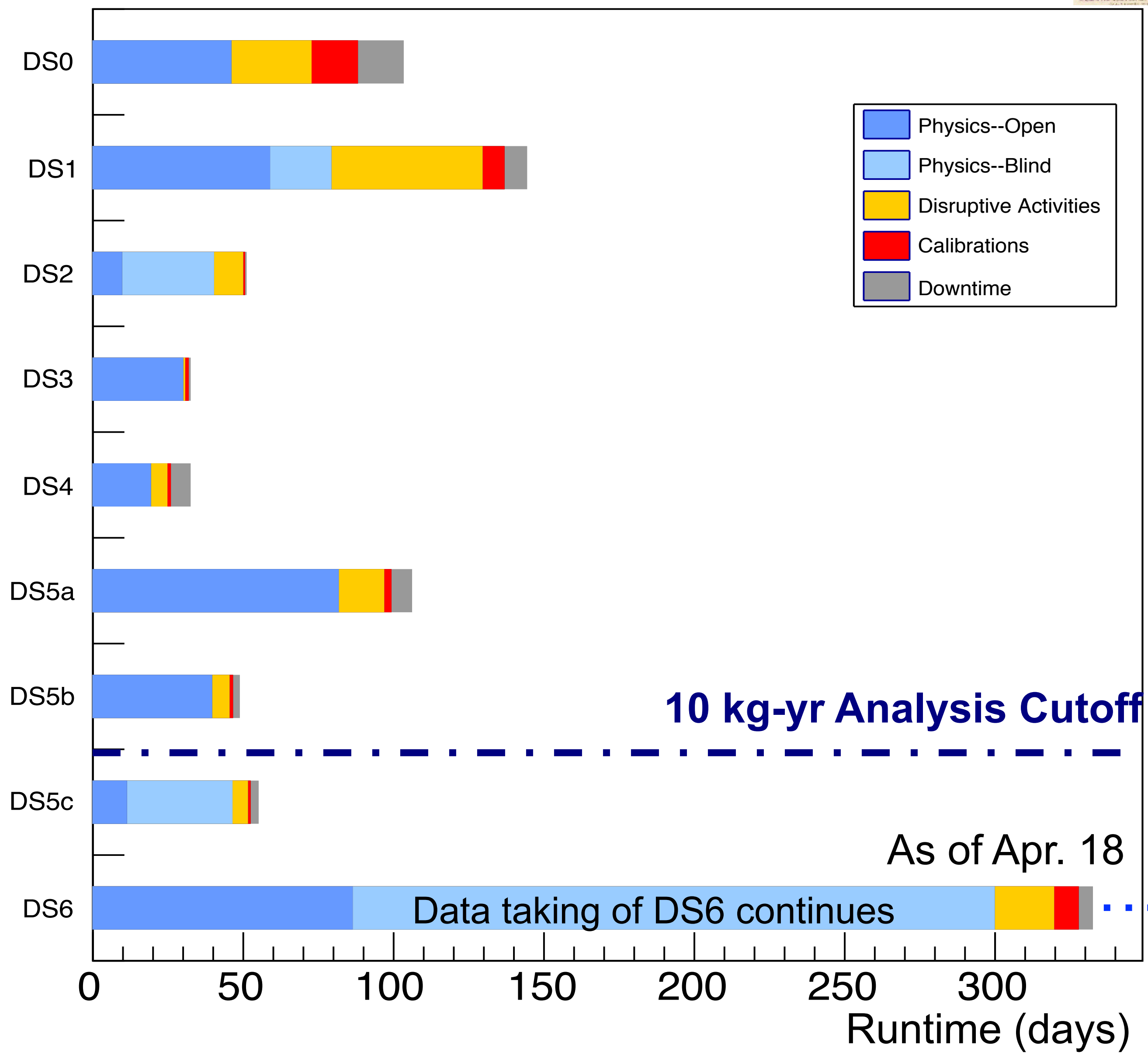
Module 2 (M1 & M2 in-shield)
Aug. 25 – Sept. 27, 2016

M1 & M2 (Integrate DAQ; high noise)
Oct. 13, 2016 – Jan. 27, 2017

M1 & M2 (Optimized Grounding)
Jan. 27 – Mar. 17, 2017

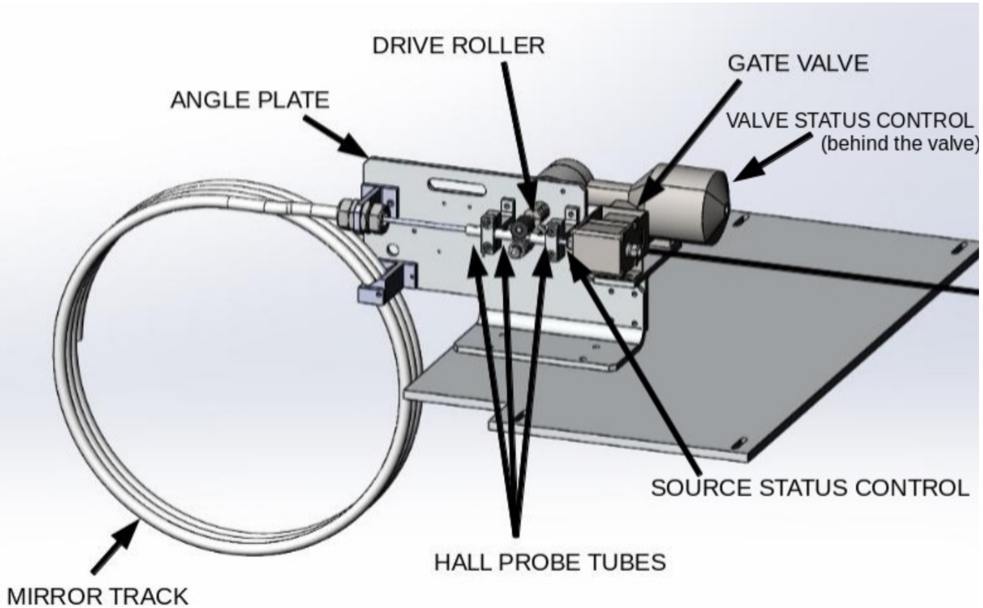
M1 & M2 (Blindness Implemented)
Mar. 17 – May 11, 2017

M1 & M2 (DAQ Multisampling)
May 11, 2017 - Present



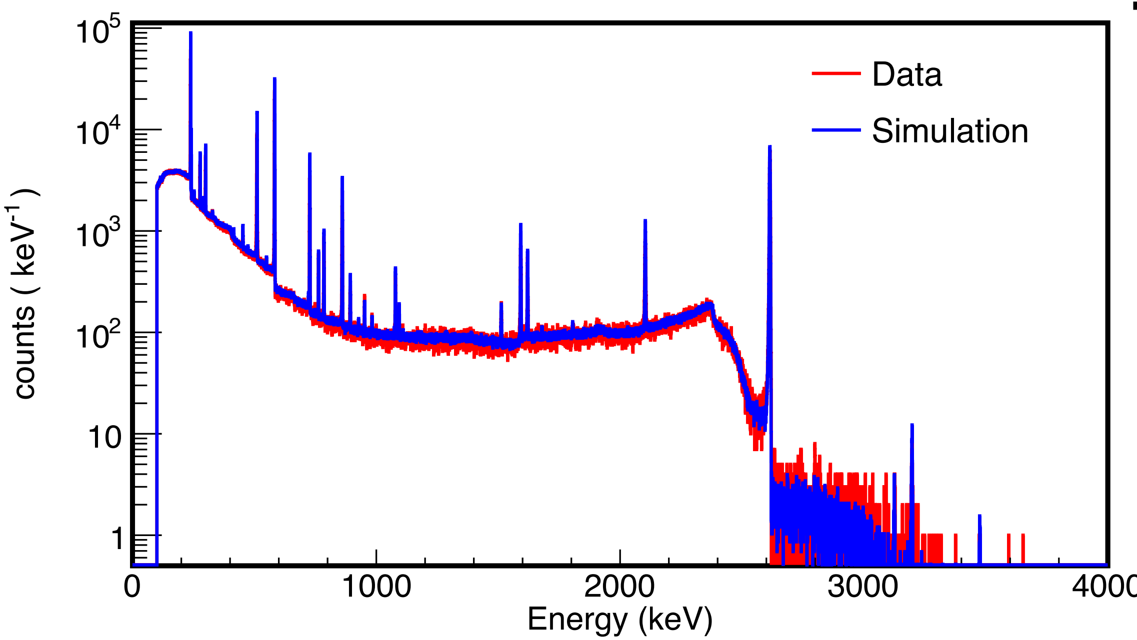
New results based on all data up to Apr 15th 2018 under preparation and to be released soon.
Total blind + open physics data ~ 26 kg-yr

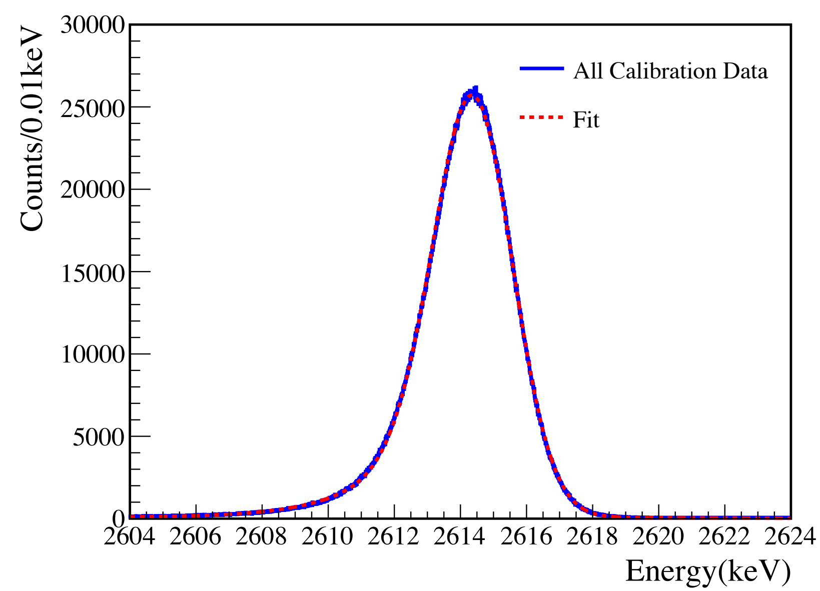
Energy Calibration



Calibration System Paper NIMA, 16-22. **872**. 2017.

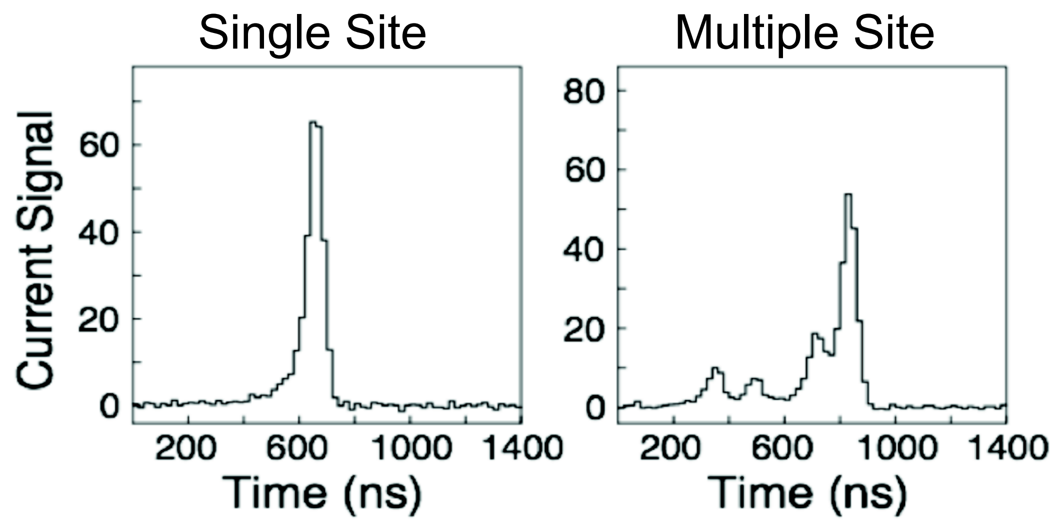
~3 keV FWHM at 2614 keV, approaching 0.1%
➔ 2.5 keV FWHM at Q-value

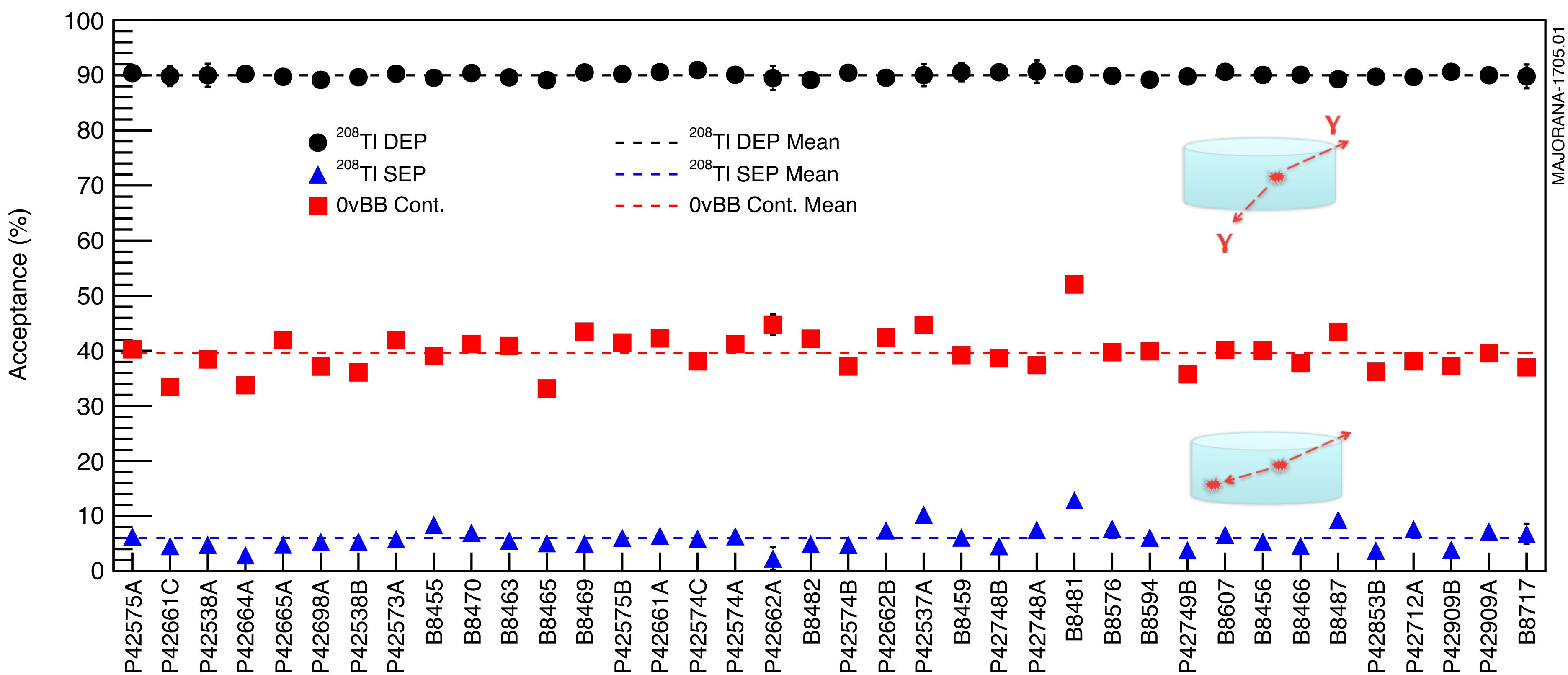




Multiple Site Event Rejection

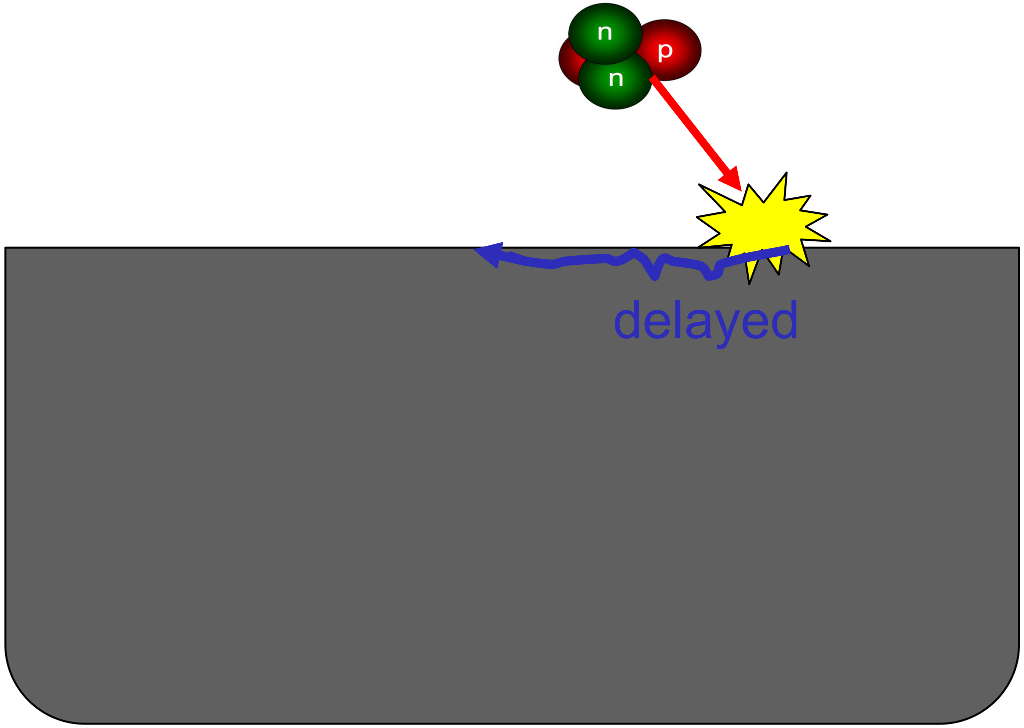
- $0\nu\beta\beta$ decays occur at a single site in the Ge crystal
- Point-contact detectors have sufficient differences in drift times throughout the bulk to identify multiple site interactions
- Tune max current amplitude-to-energy ratio (AvsE) to ^{208}Tl calibrations to accept 90% of single site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





Alpha Backgrounds

- Energy degraded alpha background observed
- Charge from these events drifts along the surface rather than through the bulk



Alpha Backgrounds

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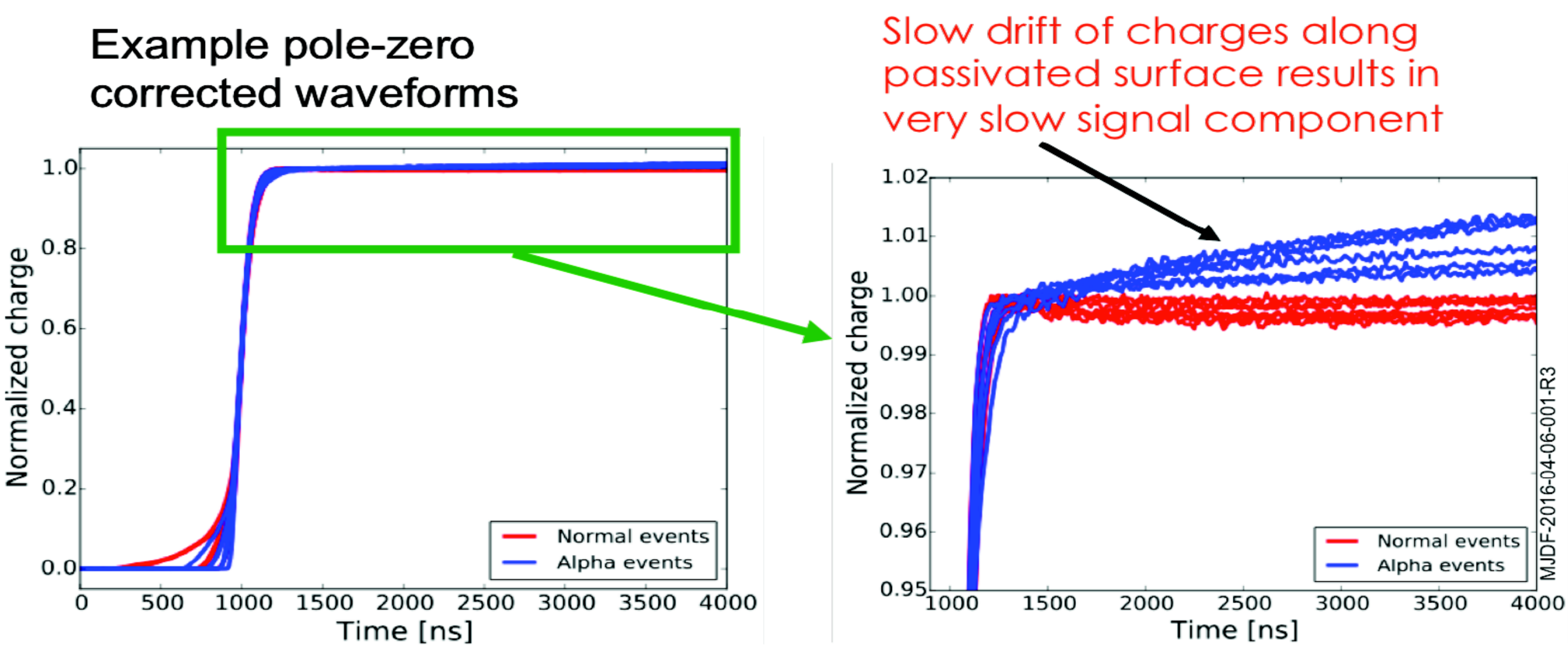
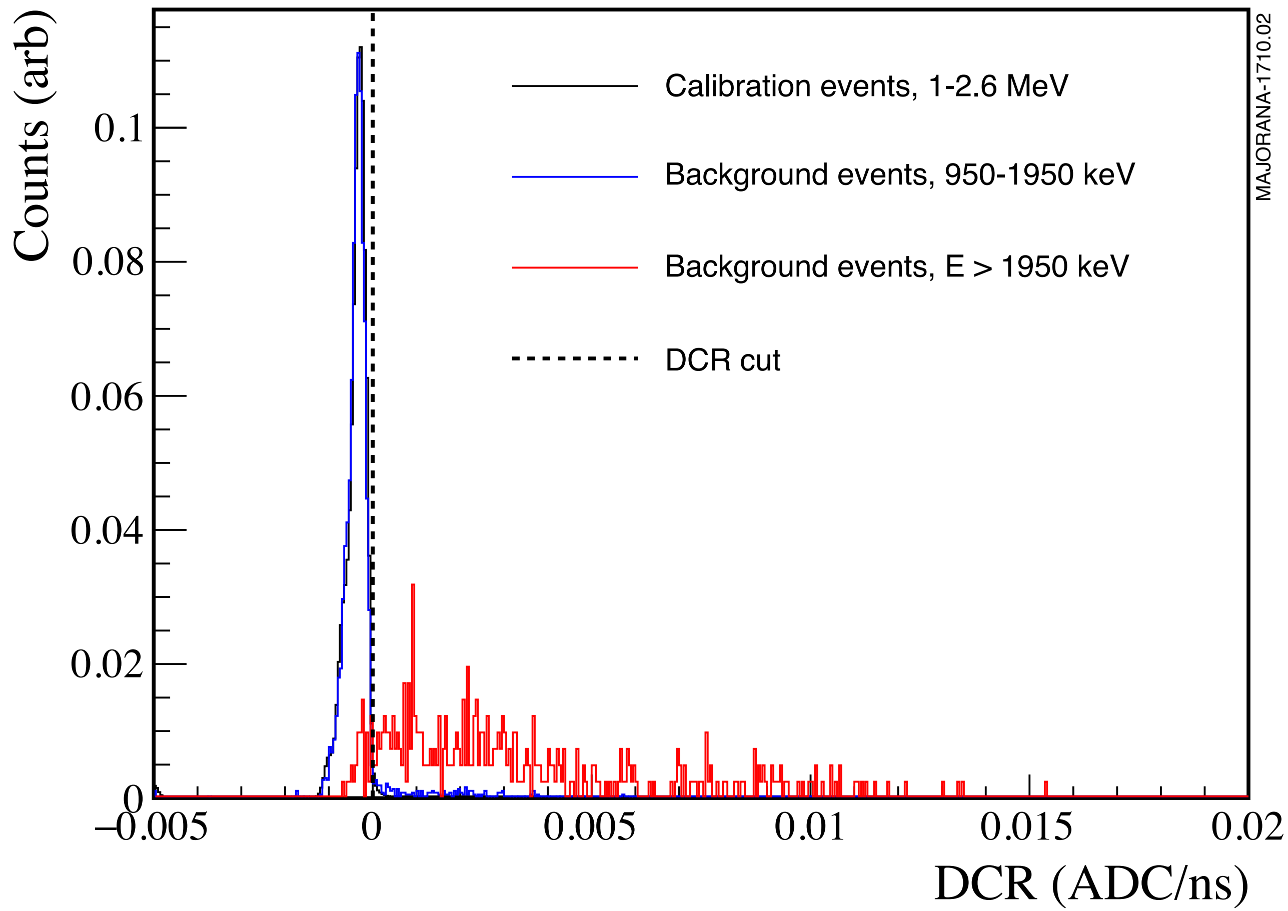
- Charge from these events drifts along the surface rather than through the bulk
- Results in a distinctive delayed charge recovery (DCR) signal which is used to efficiently cut alpha events based on the slope past the rising edge



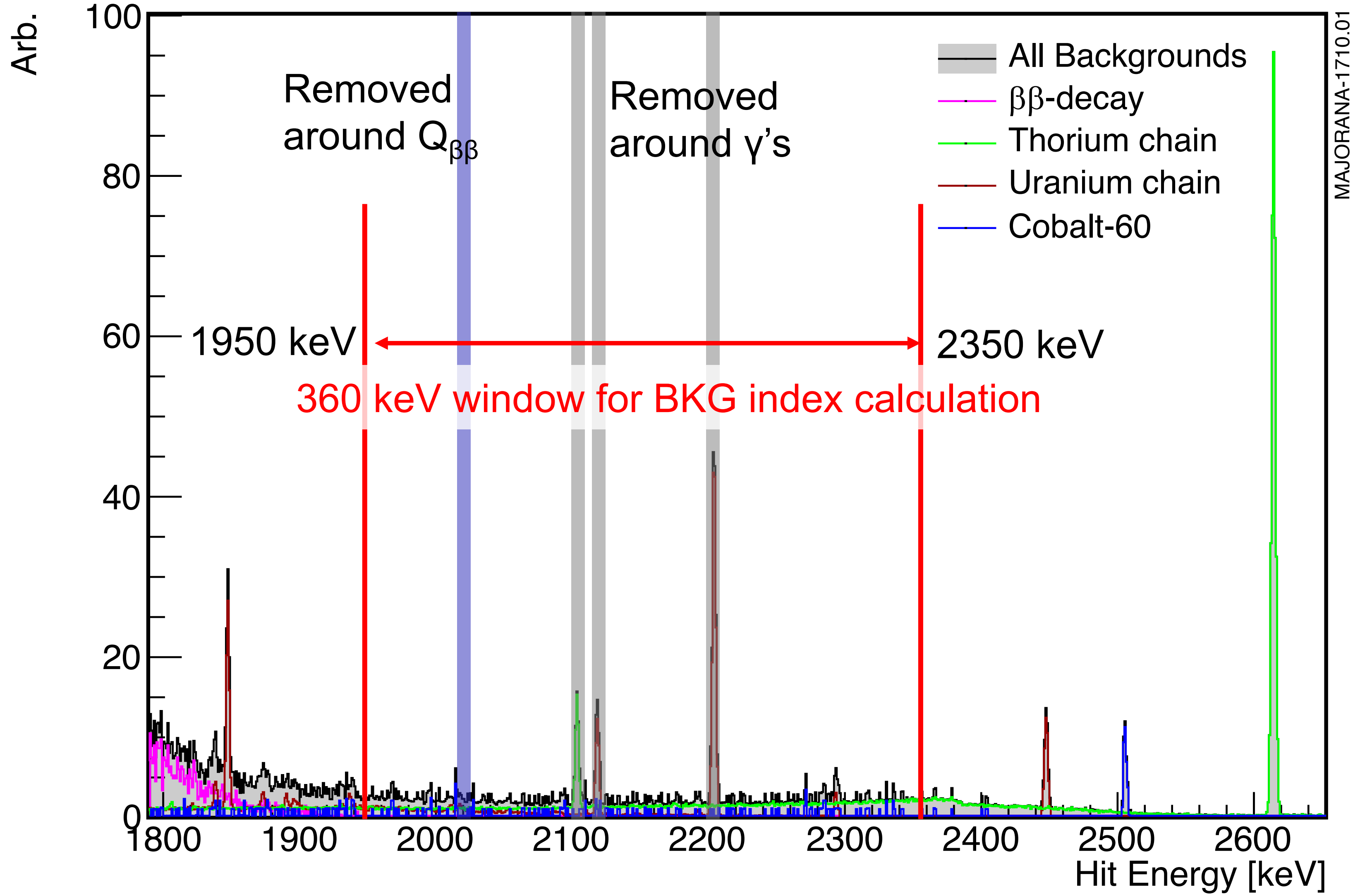
Alpha Backgrounds

- Energy degraded alpha background observed
- 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.
- DCR cut tuned to keep 99% of the photons in calibration
- Surface alpha response has been characterized using a MAJORANA detector in the TUBE alpha scanner at Technical University of Munich



Background Index Calculation

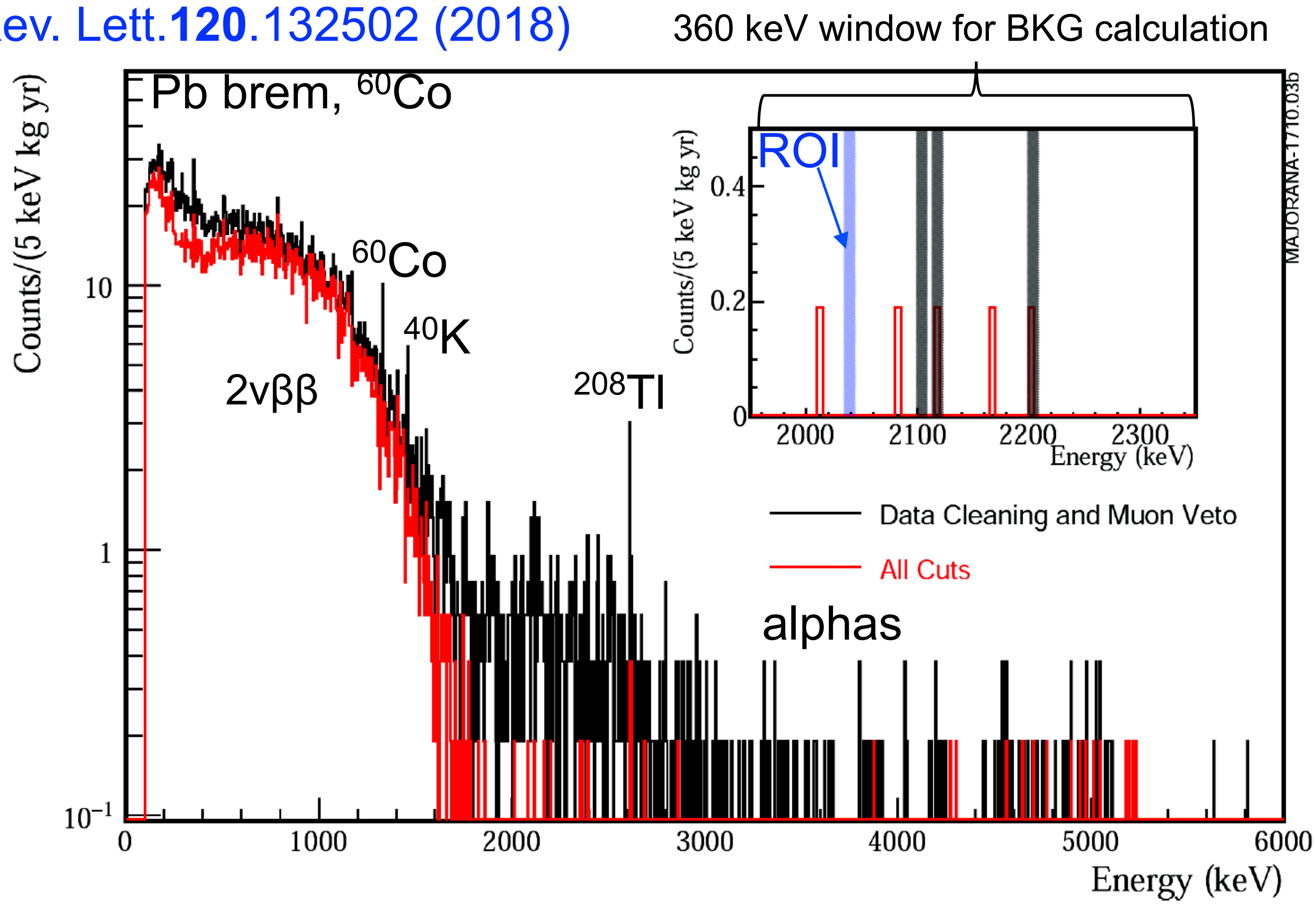
- Simulated background PDFs, relative scaling based on assay results
- Flat between 1950 keV and 2350 keV
- Remove ±5 keV around $Q_{\beta\beta}$ and 3 prominent γ lines
- The remaining 360 keV window is used for background index calculation



Background Spectrum

- Active exposure: 5.24 kg-y (^{enr}Ge) w/. configurations allowing lowest background
- Background after cuts: 3 counts in 360 keV window
- Background rate: $4.0^{+3.1}_{-2.5}$ c/FWHM/t/y; $1.6^{+1.2}_{-1.0} \times 10^{-3}$ c/keV/kg/y

Phys. Rev. Lett.**120**.132502 (2018)



Background Spectrum

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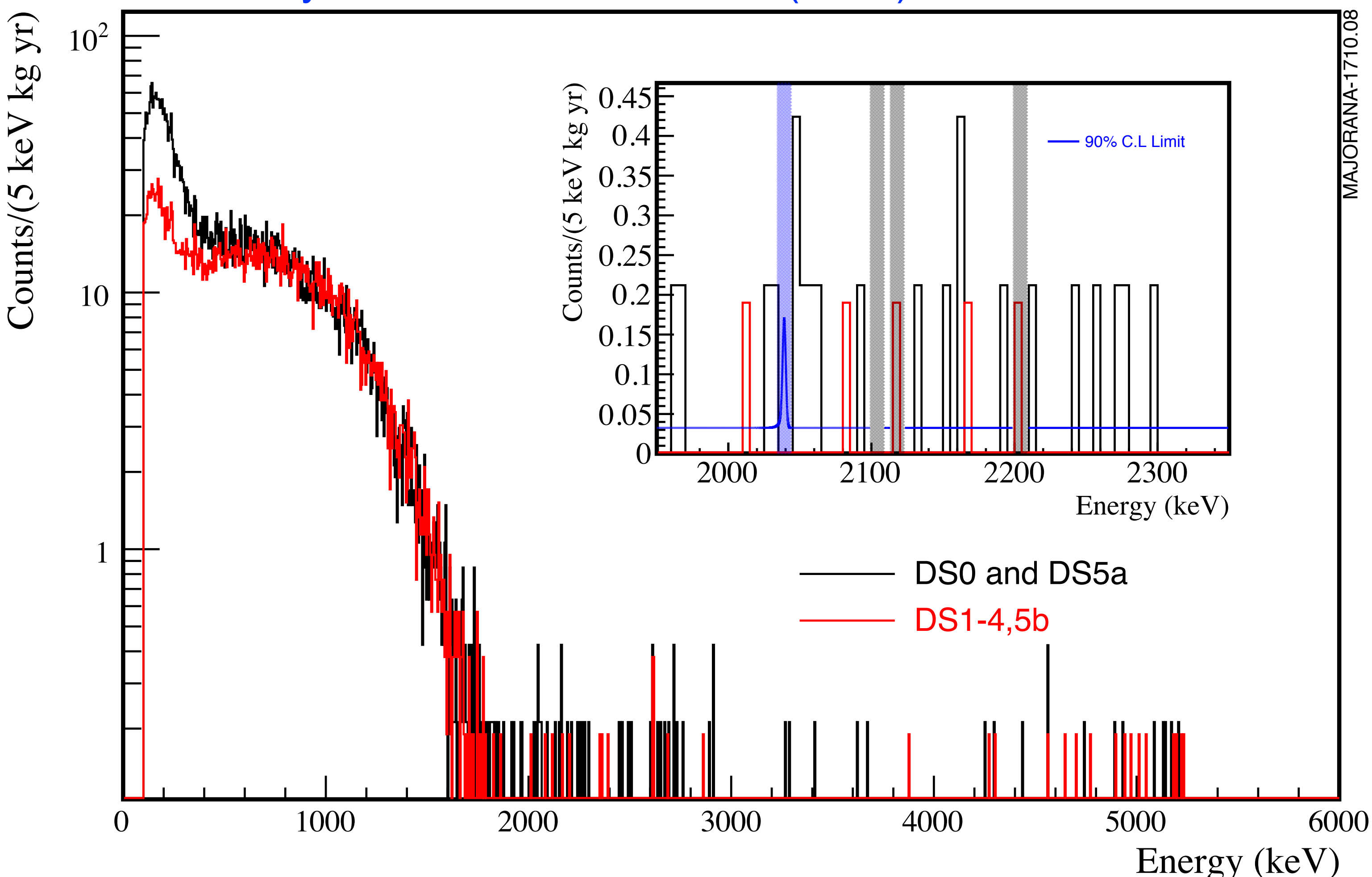
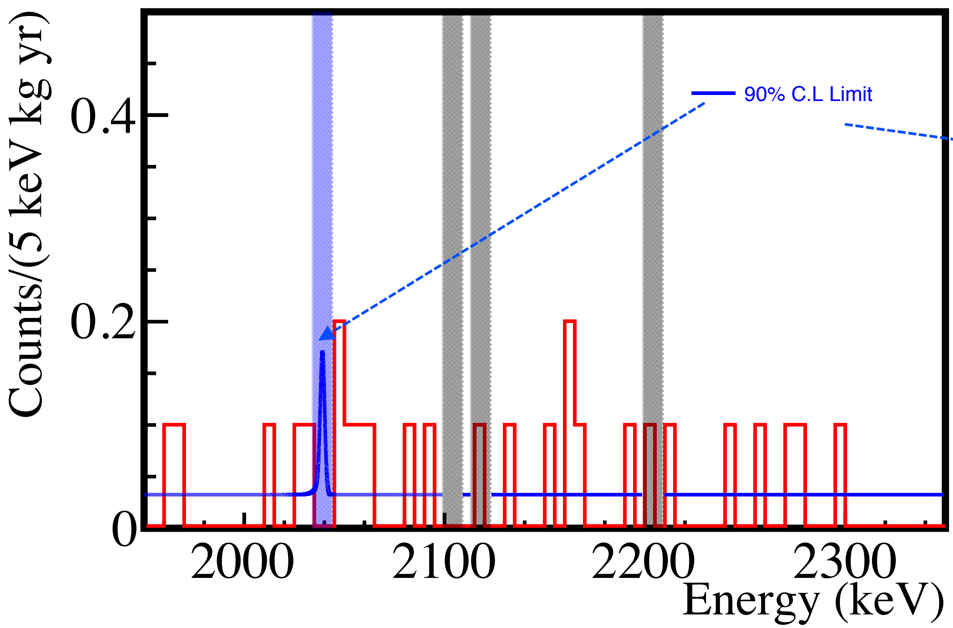


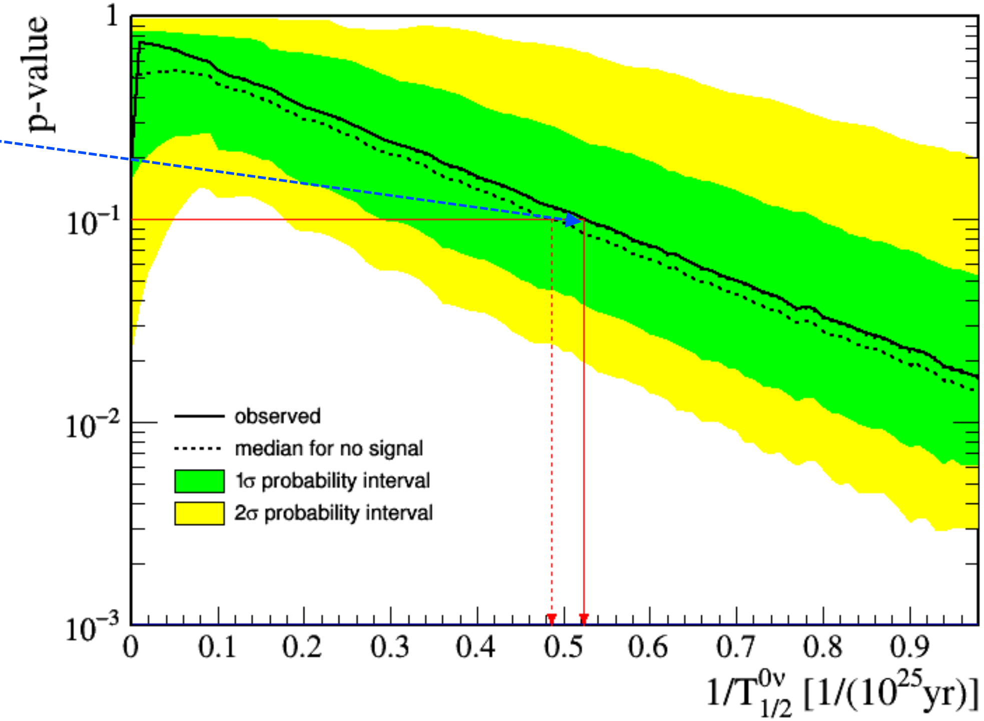
- DS0 and DS5a
  - not lowest background configurations due to incomplete shield and high noise during shield construction.
  - still can be included in decay half limit calculation.
- Total exposure is 9.95 kg-yr of enriched Ge.

Half Life Limits

total exposure: 9.95 kg-yr



unbinned, extended profile likelihood



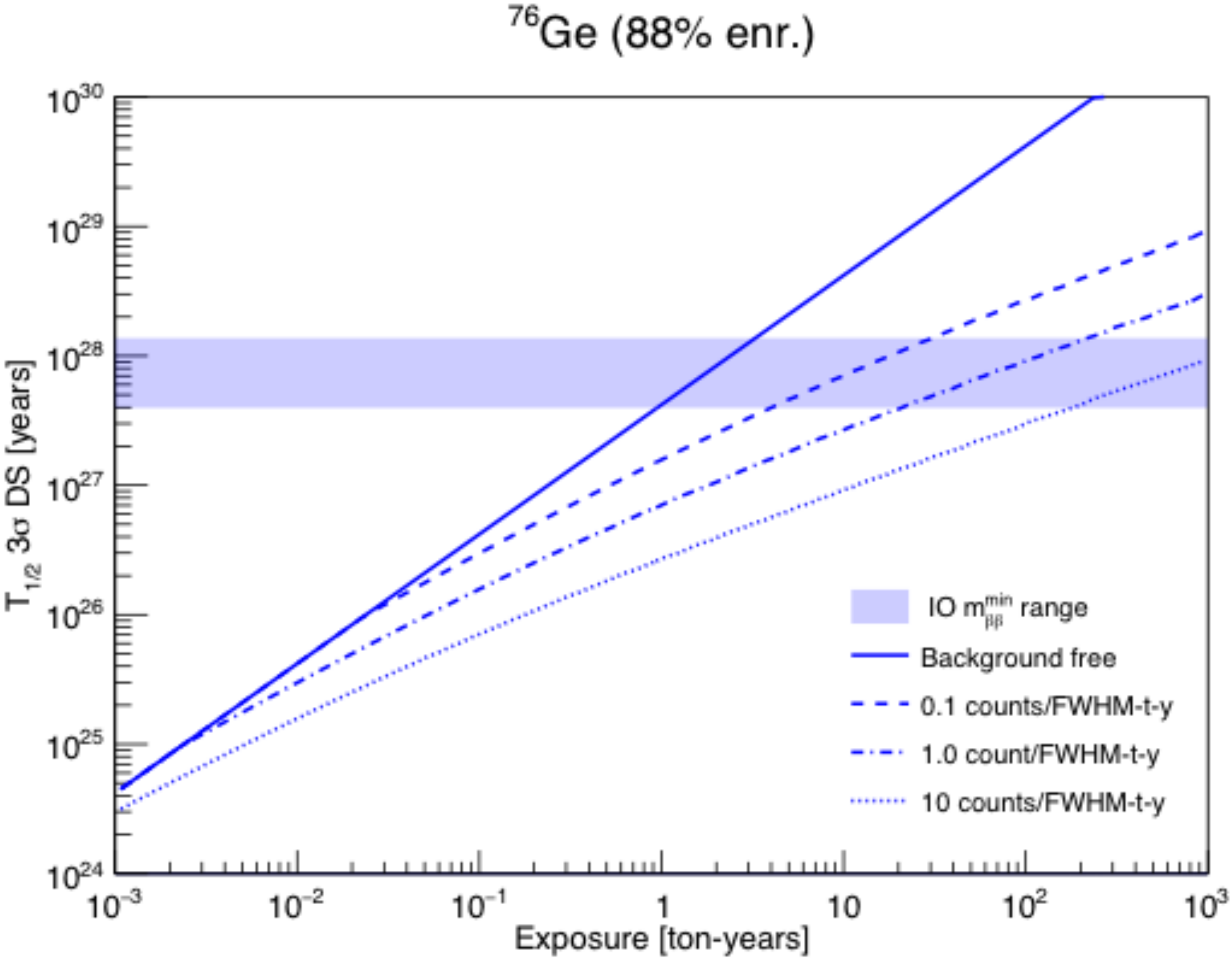
Phys. Rev. Lett.**120**.132502 (2018)
Also reports limits from Feldman-Cousins, CLs, and Bayesian methods: 1.5 -1.6 x 10^{25}yr.
Improved limits with ~26 kg-yr exposure will be released soon.
Projected sensitivity is ~ 5 x 10^{25} yr.

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{CL})$$

Median sensitivity (90% CL)

$$T_{1/2}^{0\nu} > 2.1 \times 10^{25}\ \mathrm{yr}$$

Discovery, Background and Exposure



GERDA & MAJORANA DEMONSTRATOR

Advantages of Ge

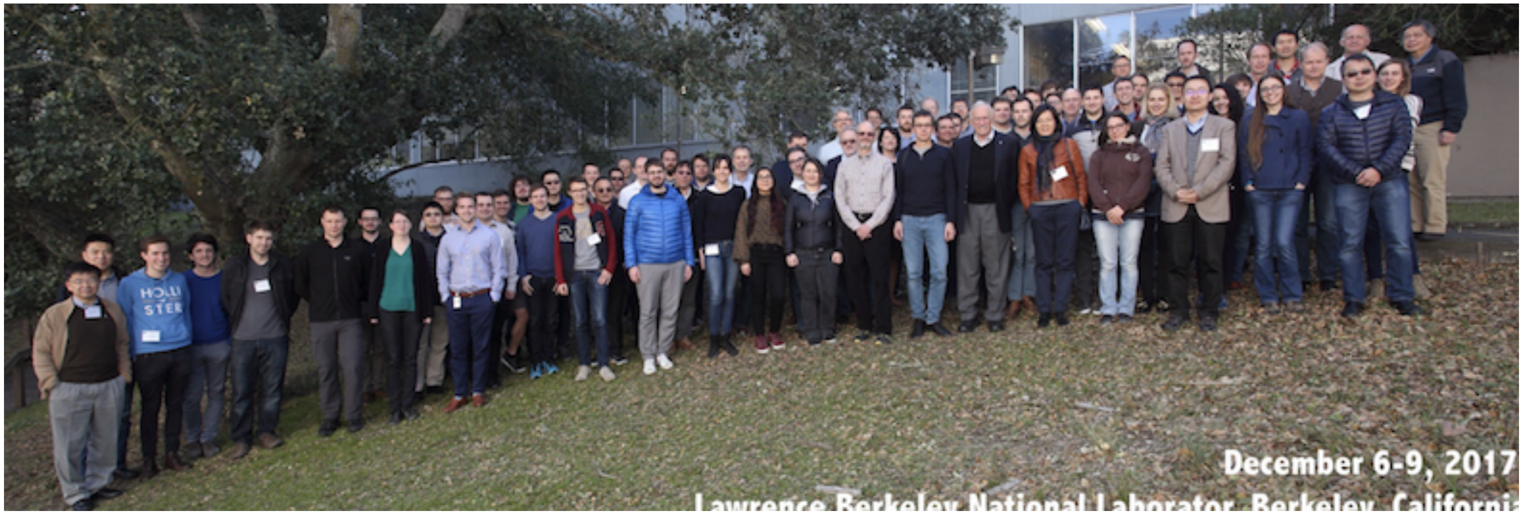
- Best energy resolution: FWHM 0.12% at Q-value 2039 keV
- Demonstrated ability to enrich from 7.44% to ≥87%
- Powerful background rejection: multiplicity, timing, pulse-shape discrimination
- Intrinsic high-purity Ge detectors = source

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

GERDA
Direct immersion in active LAr shield

- Both experiments are presently operating “background free” and benefiting from excellent energy resolution.
- Excellent limits with modest exposure.
- Combine the best of Majorana & GERDA !

Large Enriched Germanium Experiment for Neutrinoless ββ Decay



47 institutions, 237 Scientists

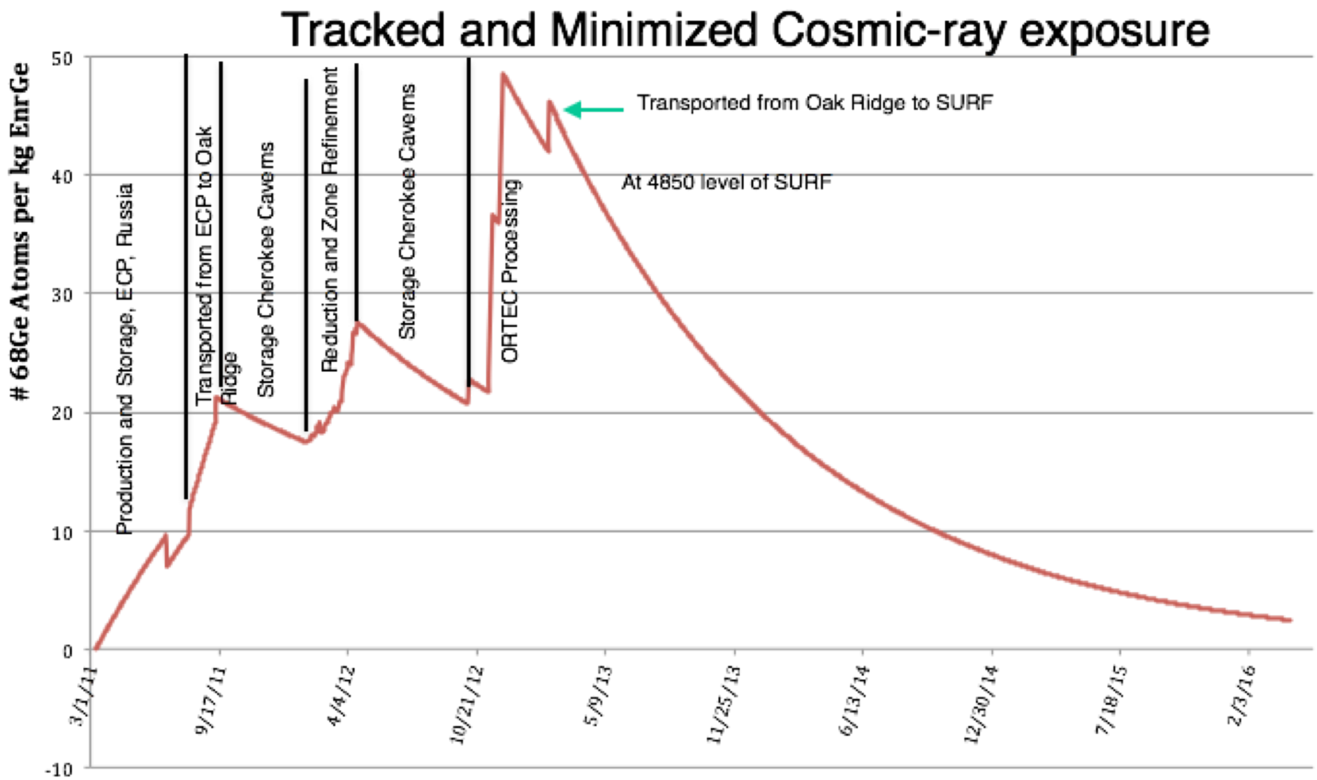
International collaboration

arXiv:1709.01980. Also see the next talk by Jordan Myslik on LEGEND 17:10 - 17:30

More Physics with the DEMONSTRATOR

Iron shielding during transportation of the enriched ^{76}Ge from Russia

Underground cave storage during detector manufacture at vendor

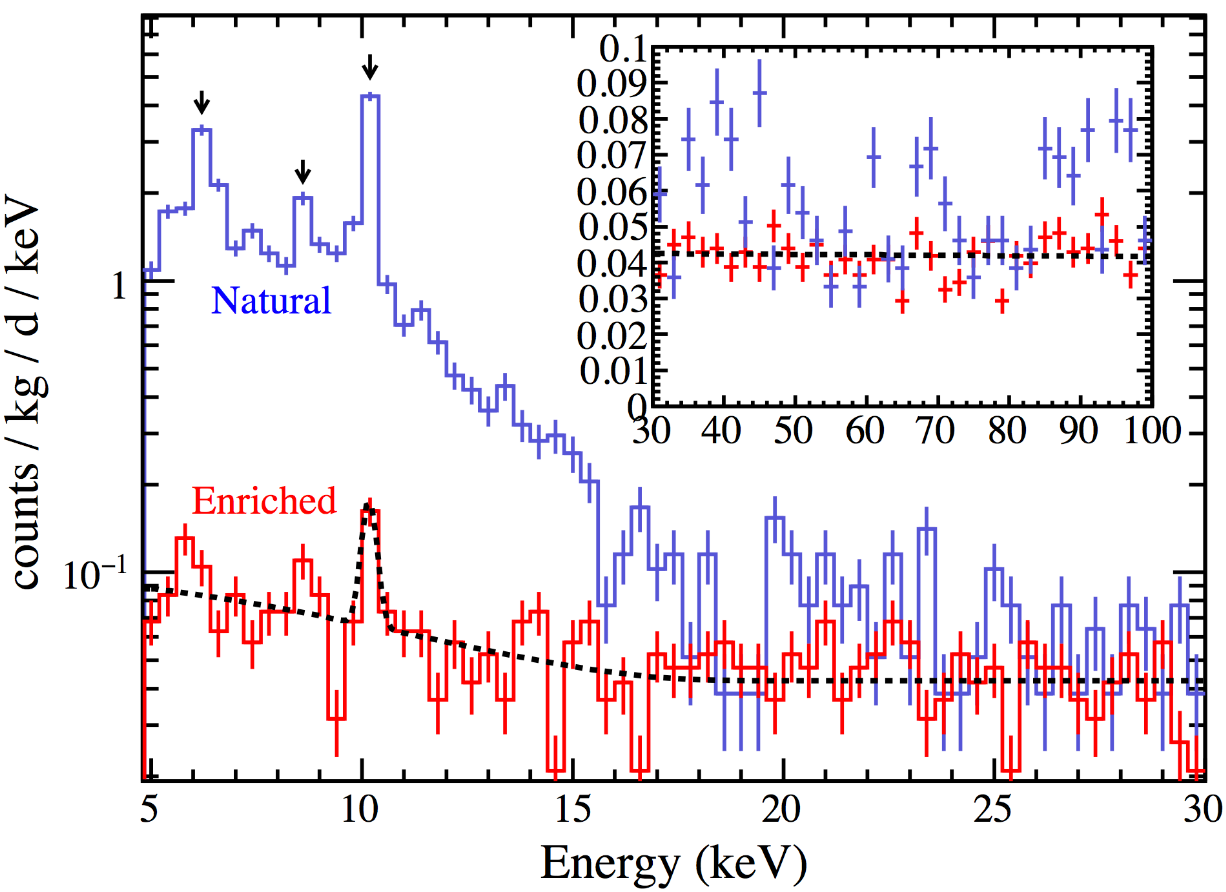


Limited exposure of enriched material to cosmic rays to ~31 days of total sea-level equivalent

Sophisticated parts-tracking database **NIMA 779(2015)52–62**

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
- Commissioning data below. Factor of several reduction in low-energy background in later datasets.
- Updated results and new searches are coming soon.



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

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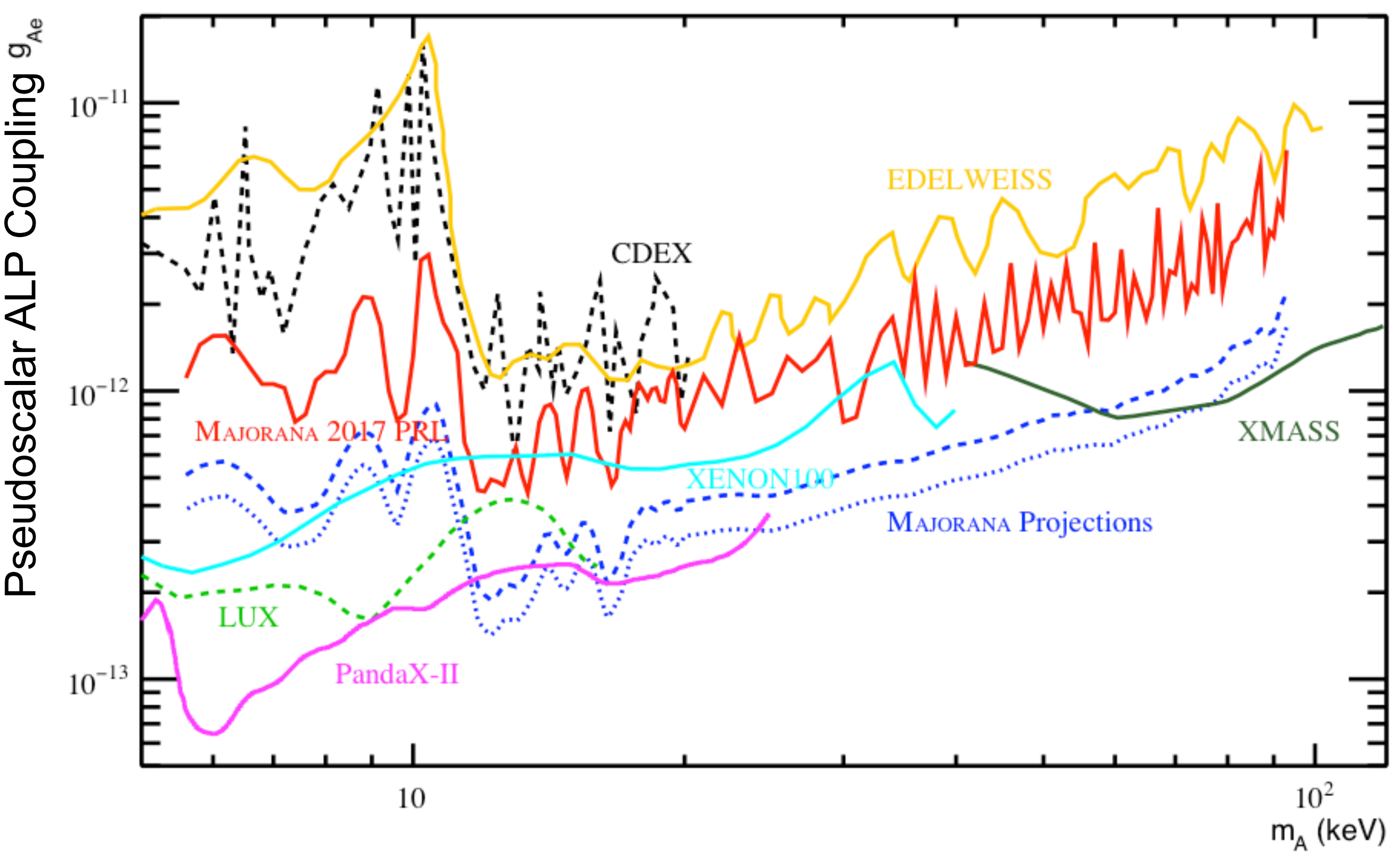

Low-Energy Searches for Physics Beyond SM

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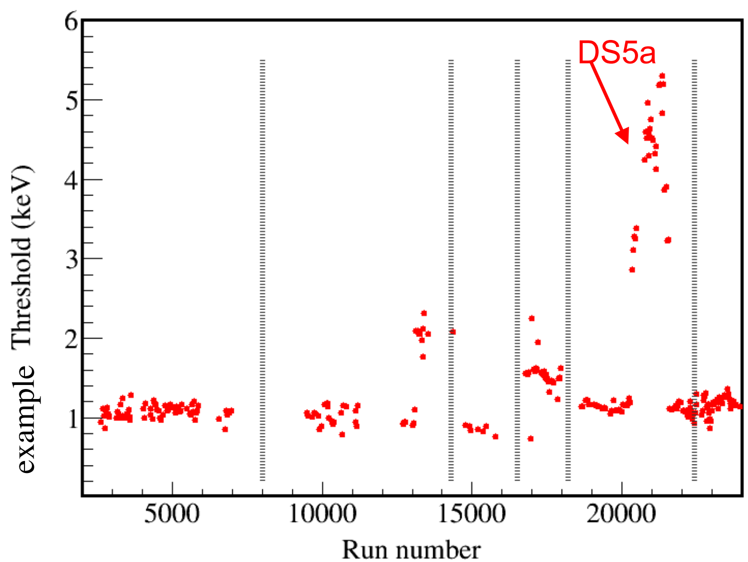
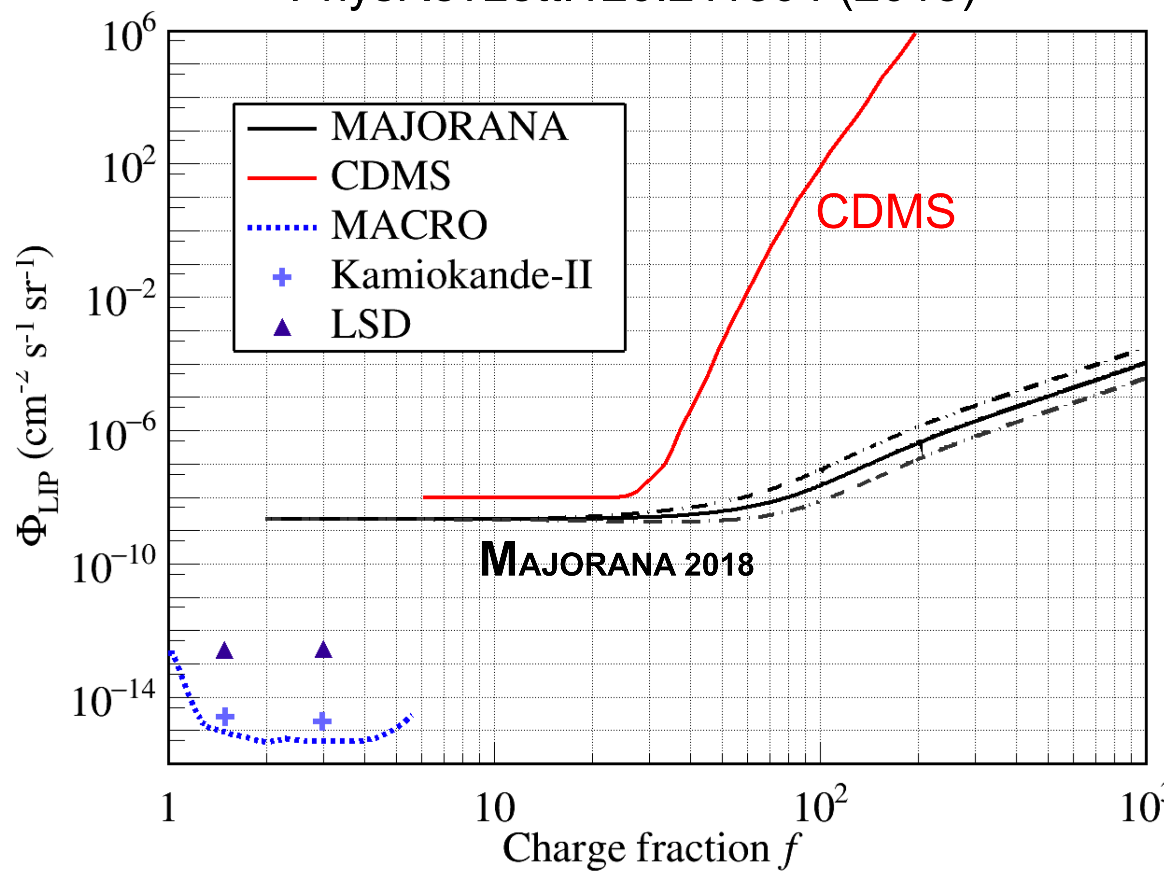
Phys. Rev. Lett. 118, 161801

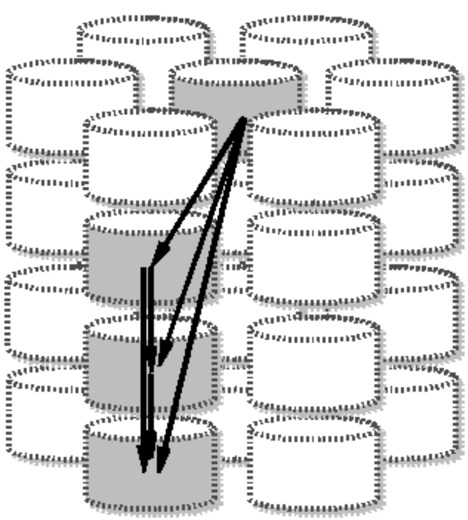
Low-Energy Physics Searches

First Limit on the Direct Detection of Lightly Ionizing Particles for Electric Charge as Low as *e*/1000



PhysRevLett.120.211804 (2018)





- Thanks to low backgrounds and low energy thresholds
- First results for a non-accelerator based experiment on the natural flux of lightly ionizing particles with charges less then e /200
- Improvement of the existing limits between e /6 and e /200.

Summary

- Using ^{76}Ge enriched PPC detectors, MAJORANA have
    - ultra-low activity materials and low-mass designs
    - the best energy resolution (2.5 keV FWHM at 2039 keV) of any 0νββ-decay experiment
    - excellent pulse shape discrimination for reduction of backgrounds.
- The observed background index of the DEMONSTRATOR in the lowest background configuration is $4.0^{+3.1}_{-2.5}$ cts/(FWHM t yr). Phys. Rev. Lett.**120**.132502 (2018)
- Established 0νββ-decay half life > 1.9 x 10^{29} yr at 90% CL based on ~10 kg-yr of exposure.
- Unblind in Summer 2018 with a total exposure of ~26 kg-yr and a projected sensitivity of ~ 5 x 10^{25} yr.
- Combining the strengths of GERDA and the MAJORANA DEMONSTRATOR, the LEGEND collaboration is moving forward towards a ton-scale ^{76}Ge based experiment
- Low energy thresholds, excellent energy resolution and reduced cosmology activations in enriched detectors allowing the DEMONSTRATOR to perform sensitive tests at low-energy for rich physics beyond the standard model.

The MAJORANA Collaboration

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U.S. DEPARTMENT OF ENERGY | Office of Science

The Majorana Collaboration

NSF

Sanford Underground Research Facility

Black Hills State University

Duke University

ITEP

Joint Institute for Nuclear Research

BERKELEY LAB

Los Alamos National Laboratory EST. 1943

MAX-PLANCK-GESELLSCHAFT

Massachusetts Institute of Technology

NC STATE UNIVERSITY

Oak Ridge National Laboratory

大阪大学 OSAKA UNIVERSITY

Pacific Northwest National Laboratory
Proudly Operated by Battelle Since 1965

PRINCETON UNIVERSITY

Queen's University

South Dakota School of Mines & Technology

TUM Technische Universität München

Tennessee Tech

TUNL

The University of North Carolina at Chapel Hill

University of South Carolina

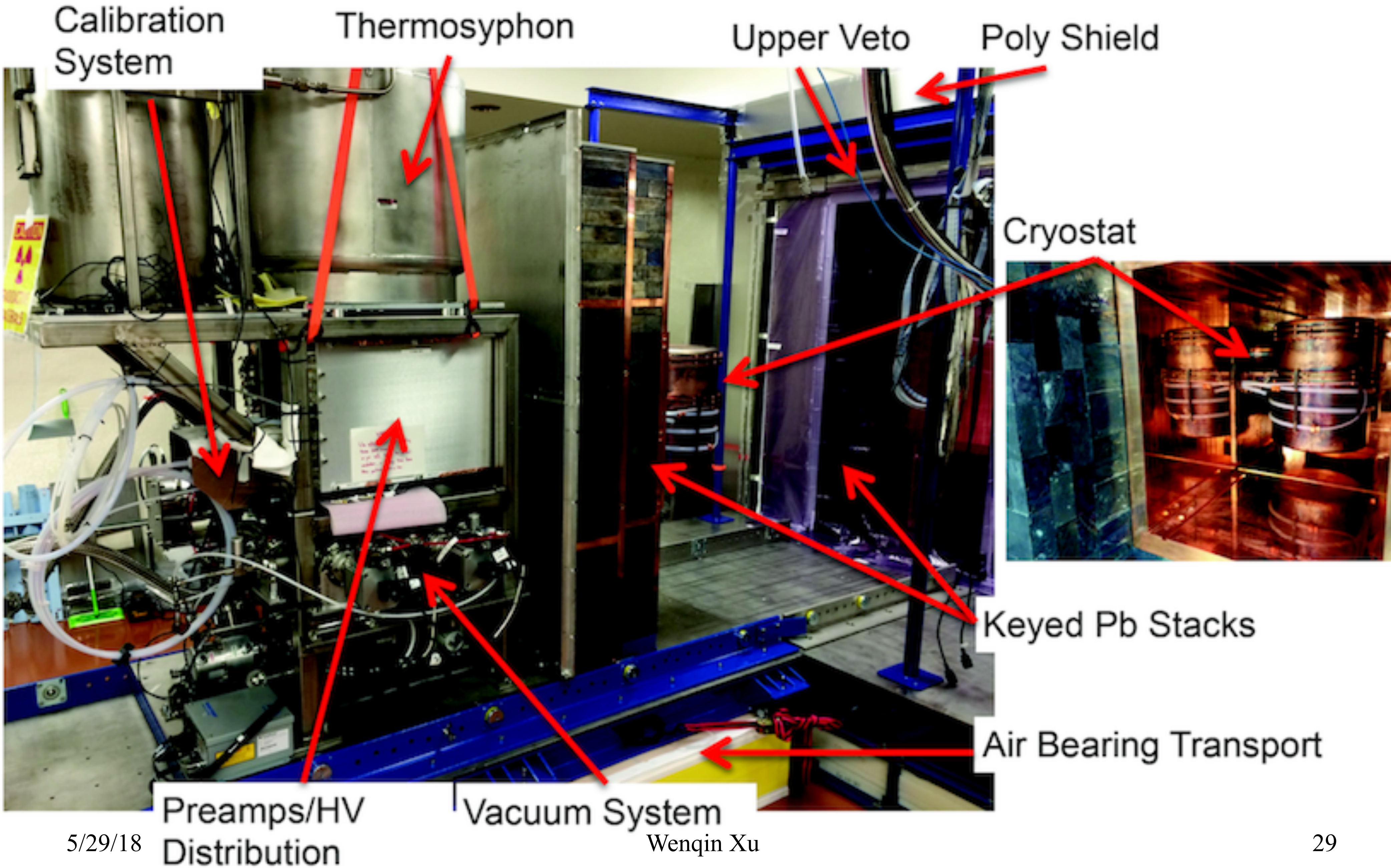
University of South Dakota

The University of Tennessee Knoxville

W

Backup

Module and Shield Details

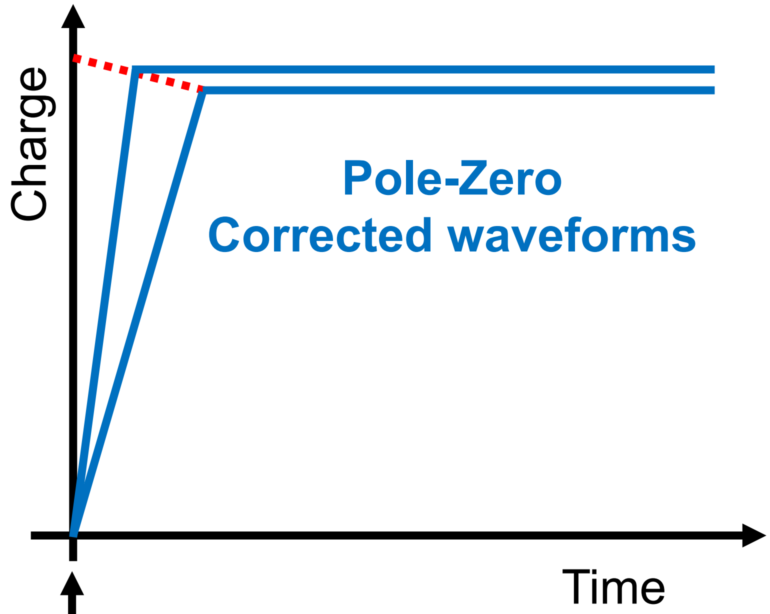


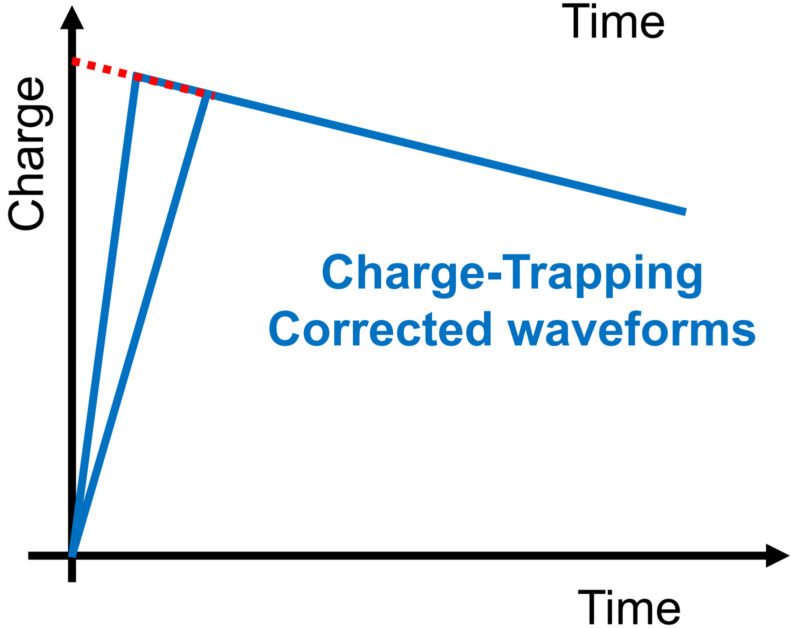
MAJORANA Electroformed Cu

- 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.

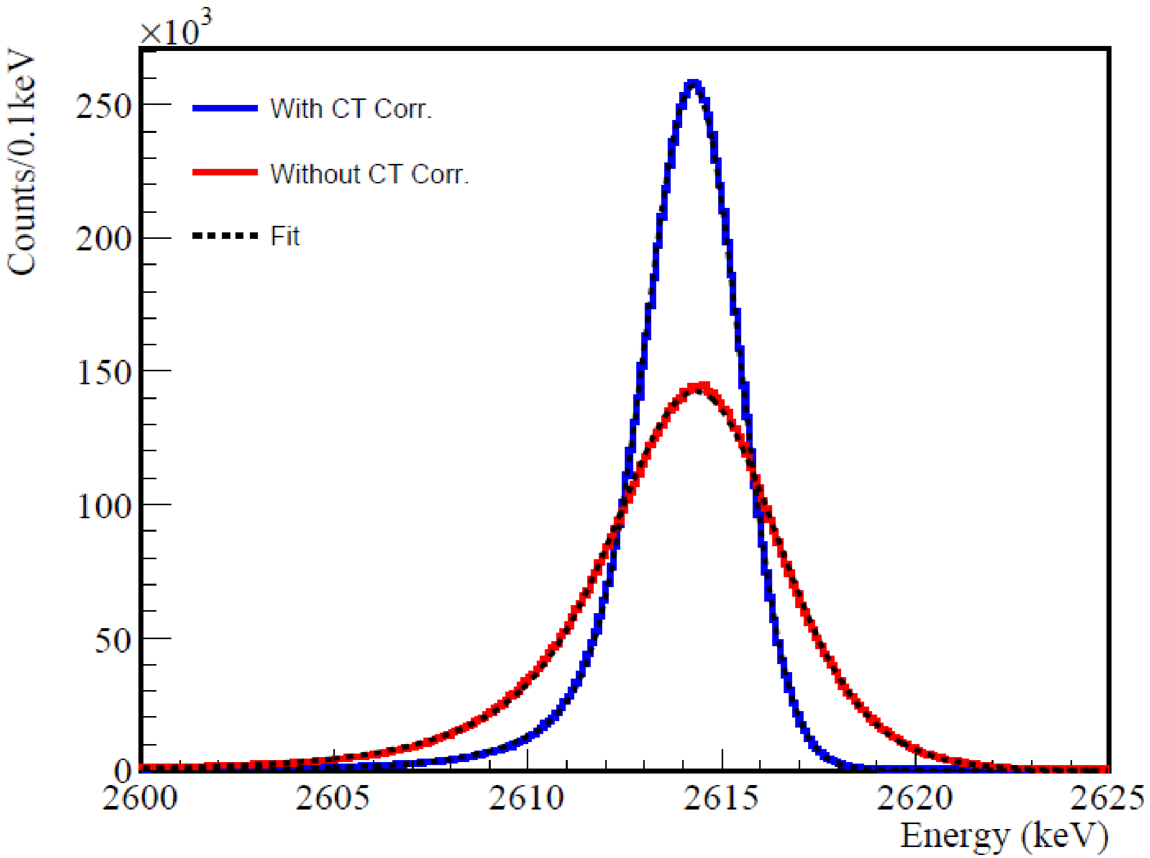
  - Th decay chain (ave) ≤ 0.1 μBq/kg
  - U decay chain (ave) ≤ 0.1 μBq/kg

Charge Trapping Correction



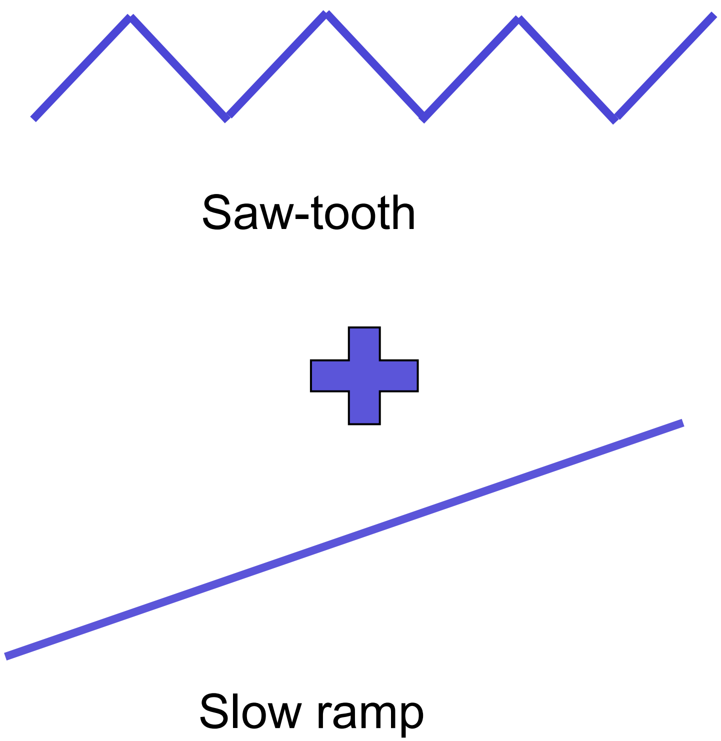


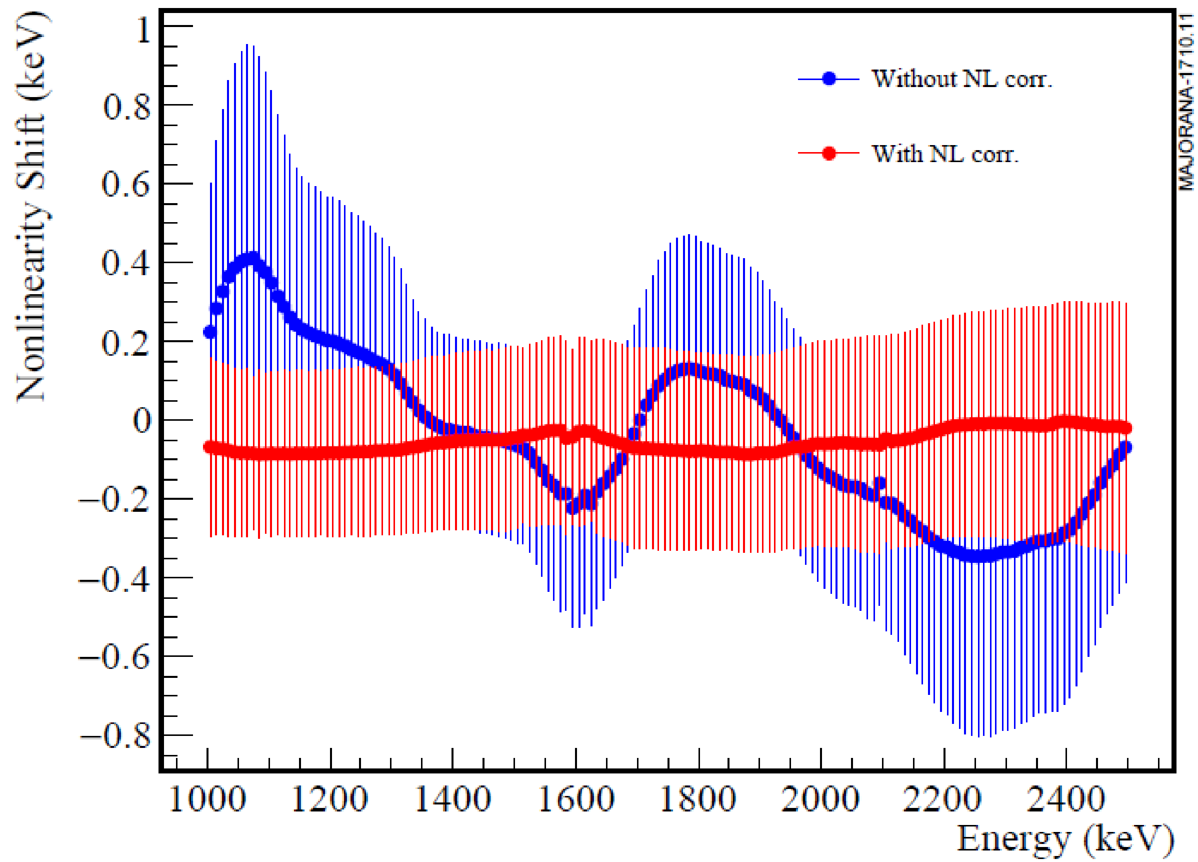
Total charge collected depends on rise time of current pulse



Adjust Pole-Zero correction so that decay time of waveforms matches charge trapping time constant. Provides ~25% improvement in energy resolution

Energy Nonlinearity Correction





Use saw tooth + slow ramp input voltage to measure ΔV of each ADC bin.
Use this to correct ADC nonlinearity