The Status and Initial Results of the MAJORANA DEMONSTRATOR Experiment

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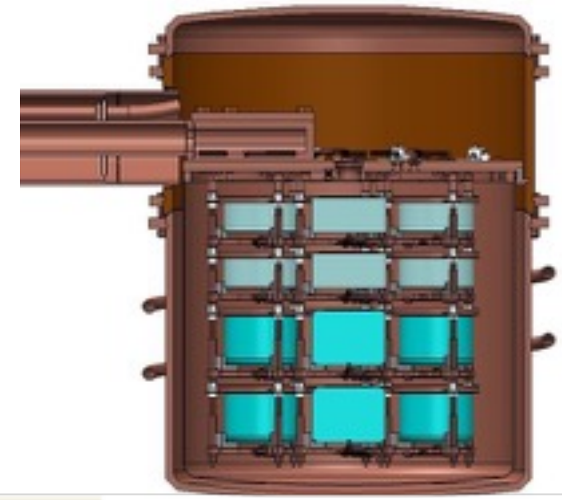
The MAJORANA DEMONSTRATOR

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 0νββ 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

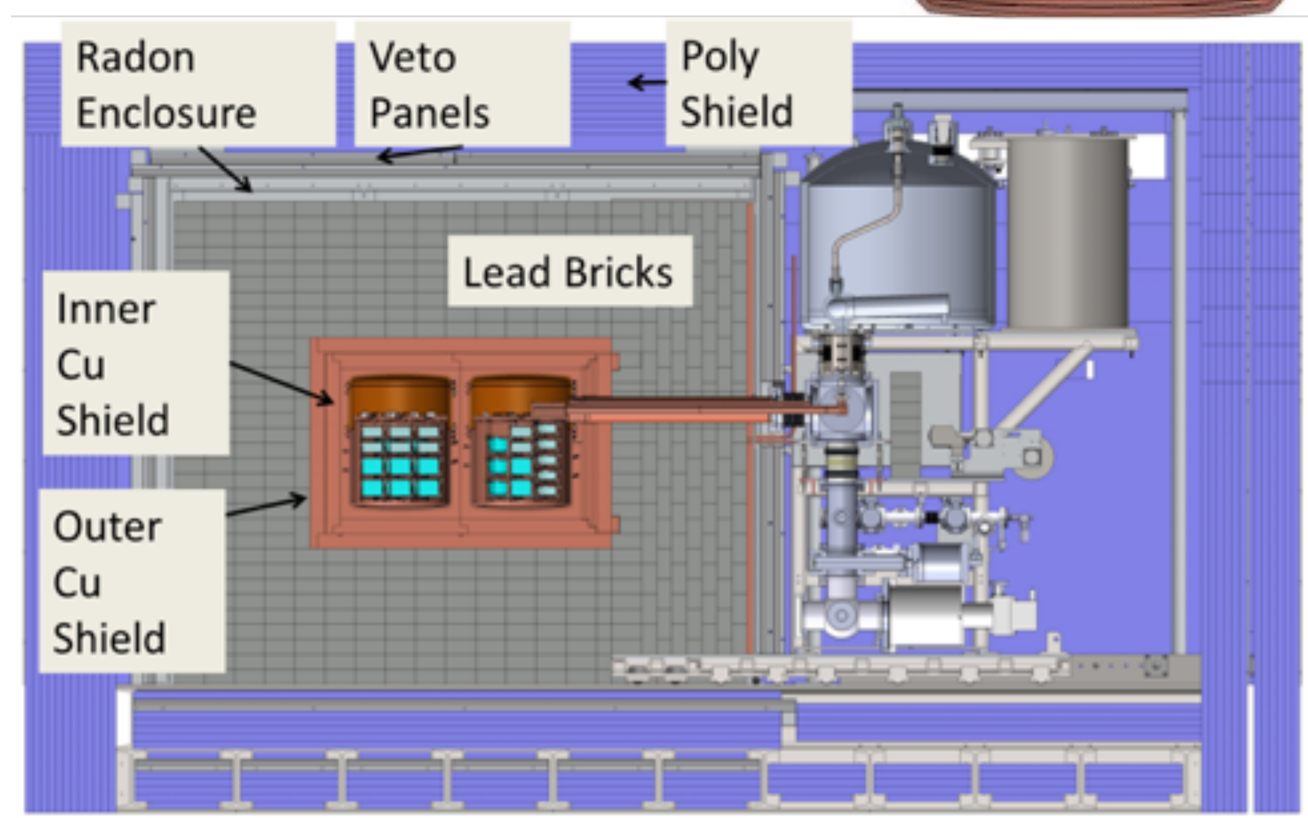
- 29.7 kg of 88% enriched ^{76}Ge crystals
- 14.4 kg of ^{nat}Ge
- Detector Technology: P-type, point-contact.

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

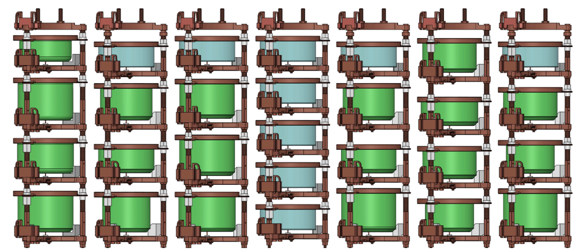


N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)

MAJORANA DEMONSTRATOR Implementation

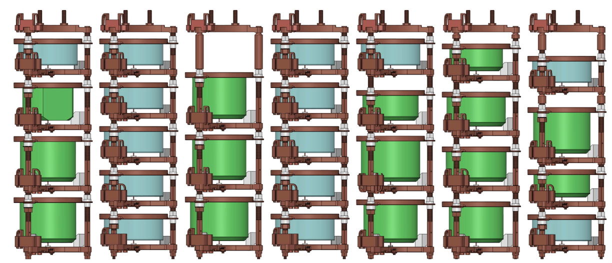
In shield Operation

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

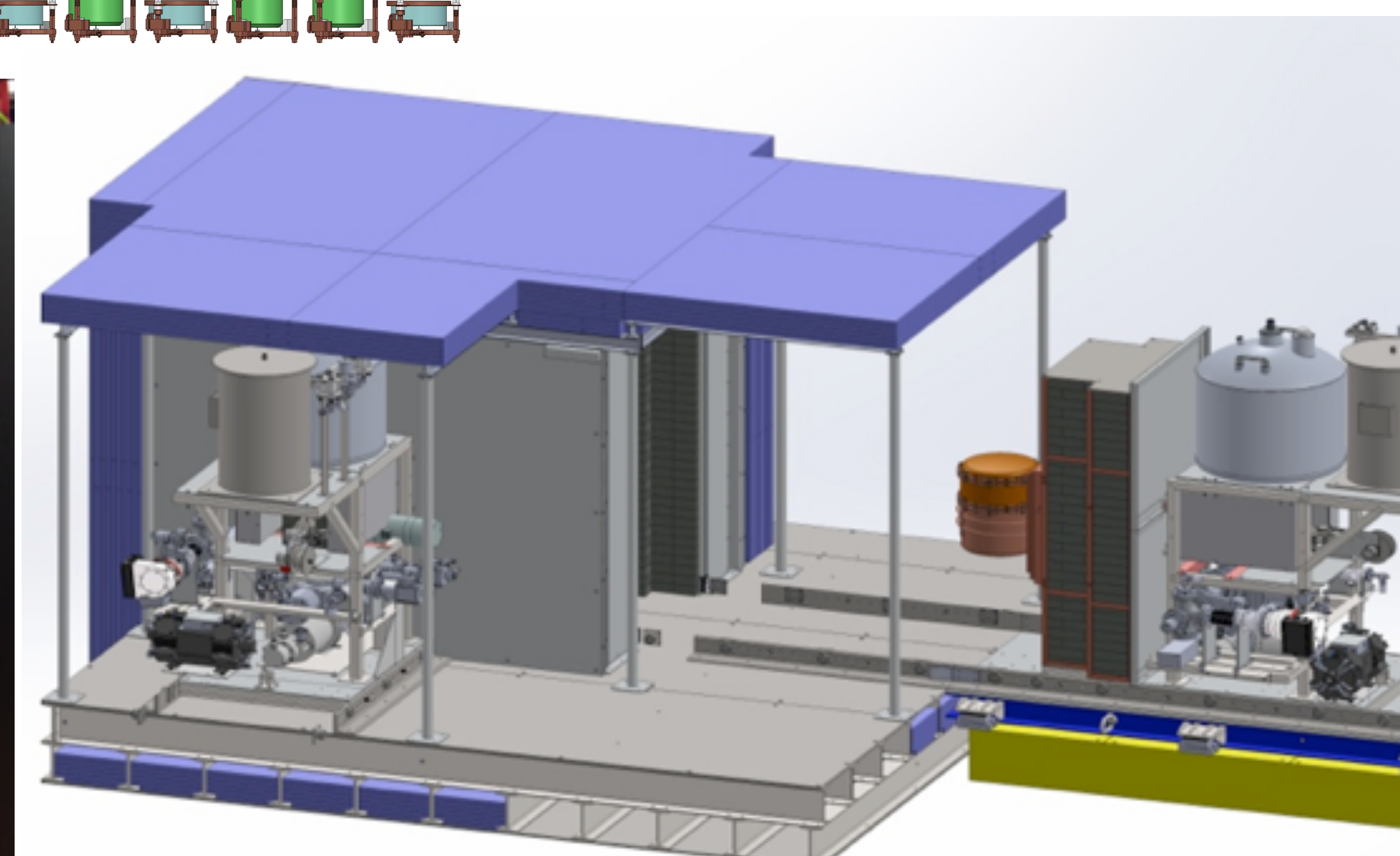


May – Oct. 2015,
Final Installation,
Dec. 2015 — ongoing

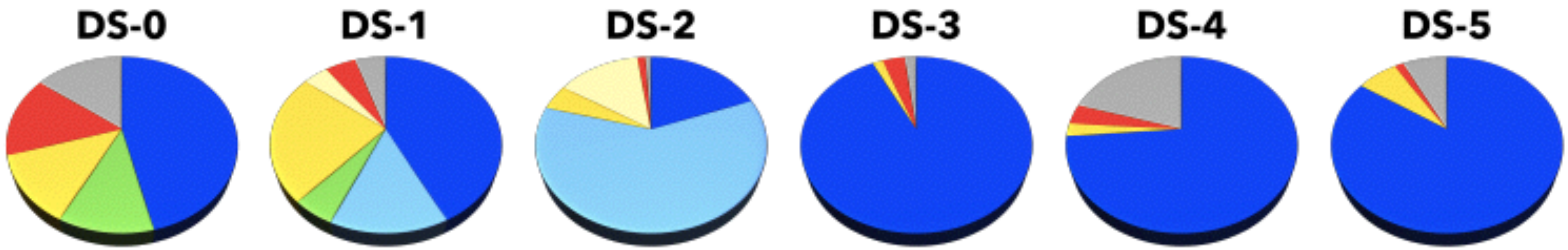
Module 2: 12.9 kg (15) ^{enr}Ge, 8.8 kg (14) ^{nat}Ge



July 2016 — ongoing



MAJORANA Data Sets



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

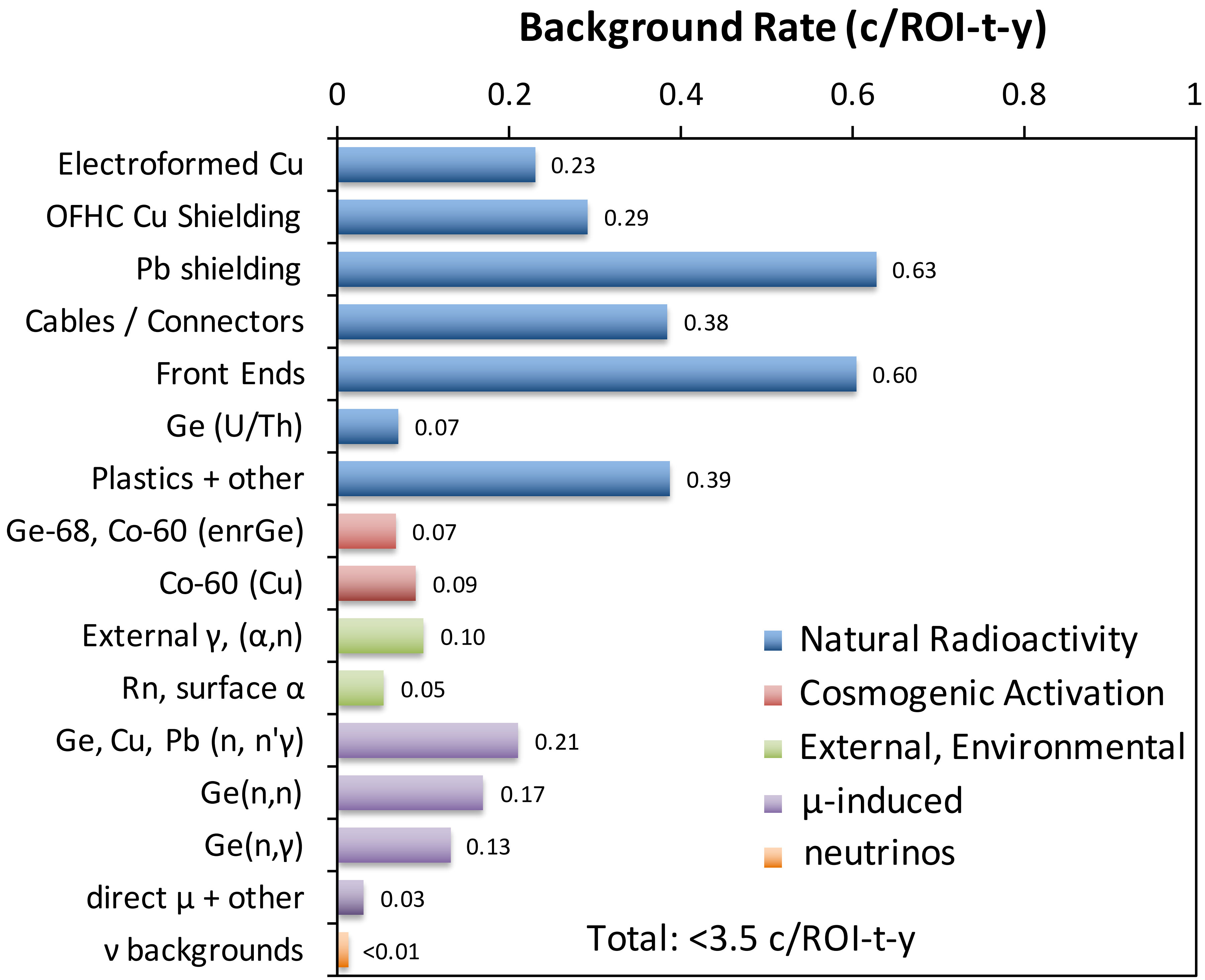
	DS-0 Module 1 June 26 - Oct. 7, 2015	DS-1 Module 1 Dec. 31, 2015 - May 24, 2016	DS-2 Module 1 May 24 - July 14, 2016	DS-3 Module 1 Aug. 25 - Sep. 27, 2016	DS-4 Module 2 Aug. 25 - Sep. 27, 2016	DS-5 Module 1 & 2 Oct. 13, 2016 - ***May. 11 2017****
Total (days)	103.15	144.50	50.97	32.37	32.36	97.7
Total 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

*Blind data

*Values up to Jan. 19, 2017

DS6 has started with multisampling and blindness

DEMONSTRATOR Background Model



Background based on assay of materials.

Where an upper limit exists, use upper limit as contribution

NIMA **828** (2016) 22–36 arXiv:1601.03779 [physics.ins-det]

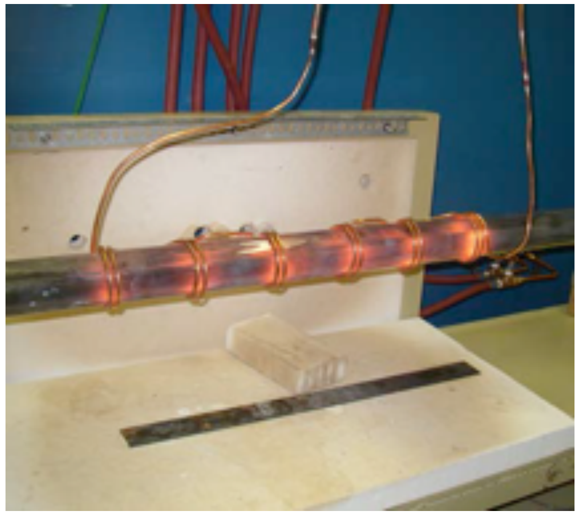
MAJORANA Approach to Backgrounds

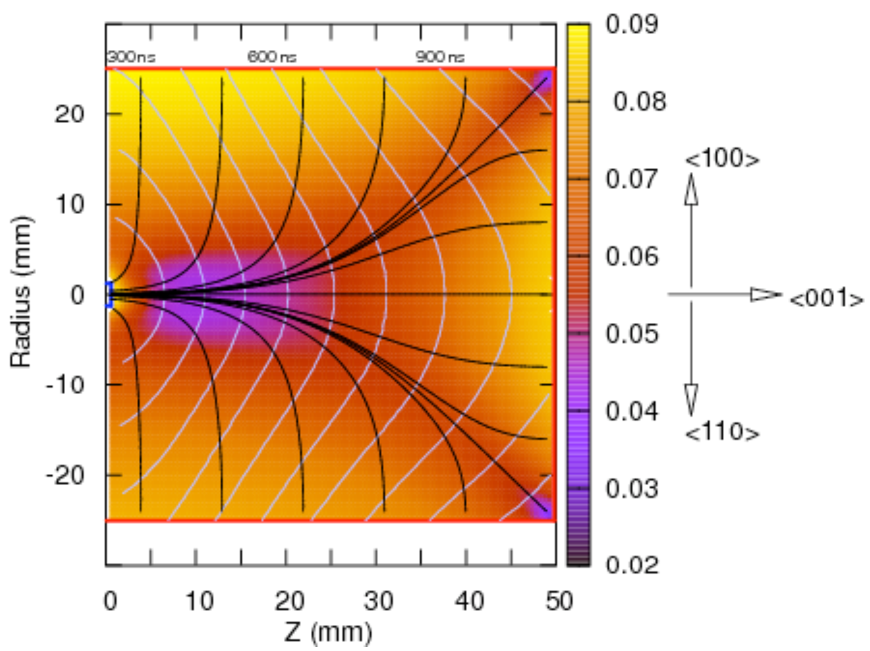
The detector: P-type point contact

- ^{enr}Ge metal zone refined and pulled into a crystal that provides purification
- Limit above-ground exposure to prevent cosmic activation
- Slow drift velocity and localized weighting potential: separation of multi-site events

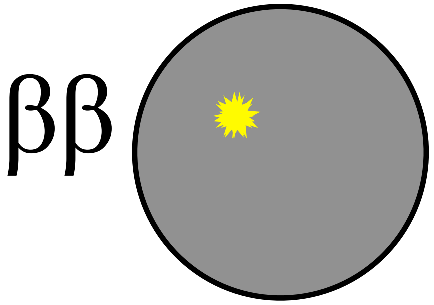
Rejection of backgrounds

- Granularity: multiple detectors hit
- Pulse shape discrimination: multiple hits in a detector
- Alpha events near surface: based on response

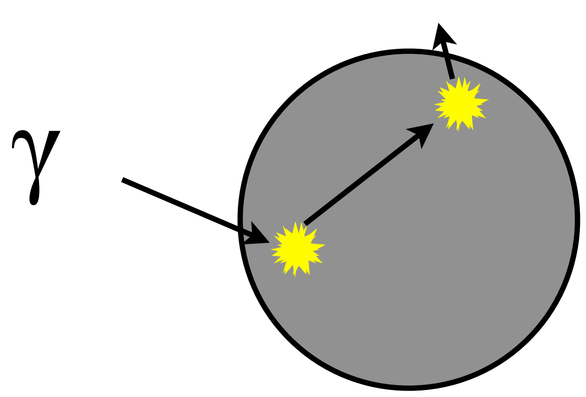


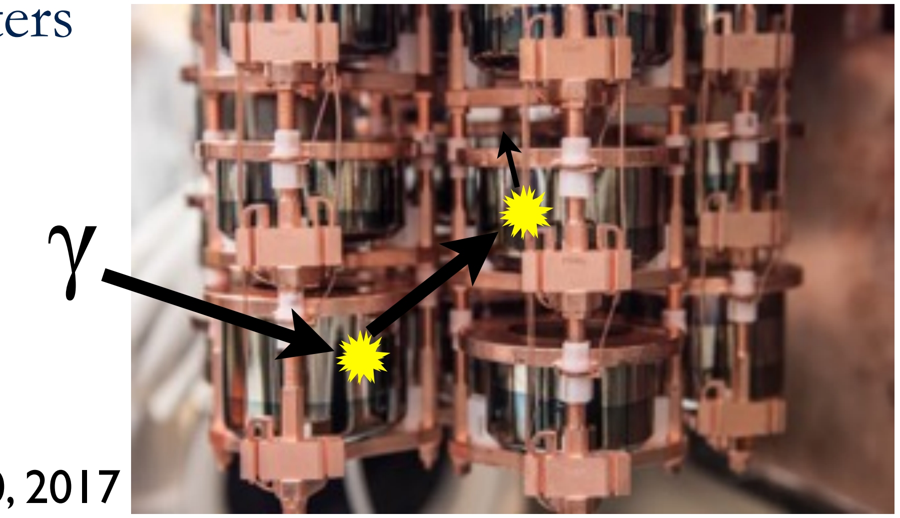


Single-site event



Multiple scatters





Majorana Approach to Backgrounds

Ultra-pure materials

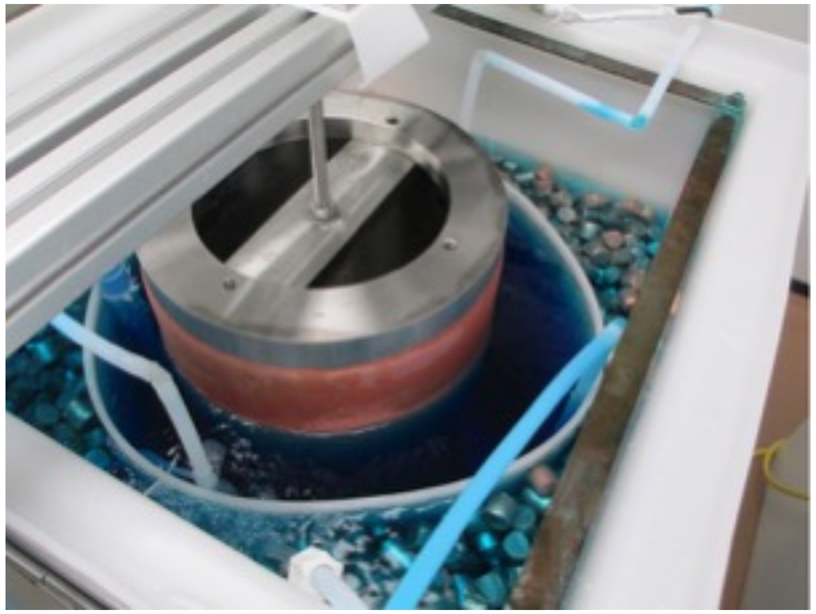
- Low mass design
- Custom cable connectors and front-end boards
- Carefully selected plastics & fine Cu coax cables
- **Underground Electro-formed Cu**

  10 baths at SURF, 6 baths at PNNL

  2474 kg of electroformed copper produced.

  Th decay chain (ave) ≤ 0.1 μBq/kg

  U decay chain (ave) ≤ 0.1 μBq/kg

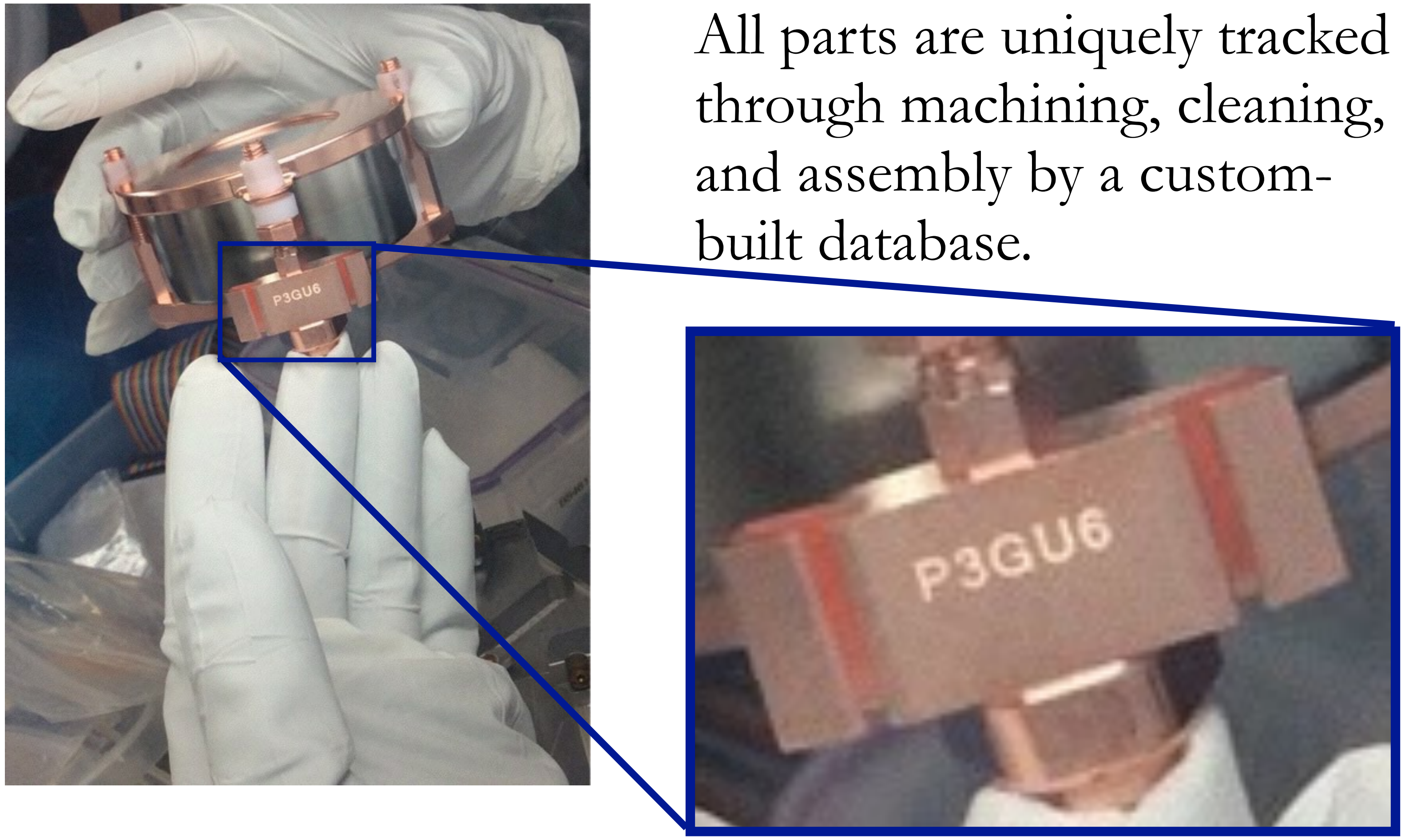


Machining and Cleaning

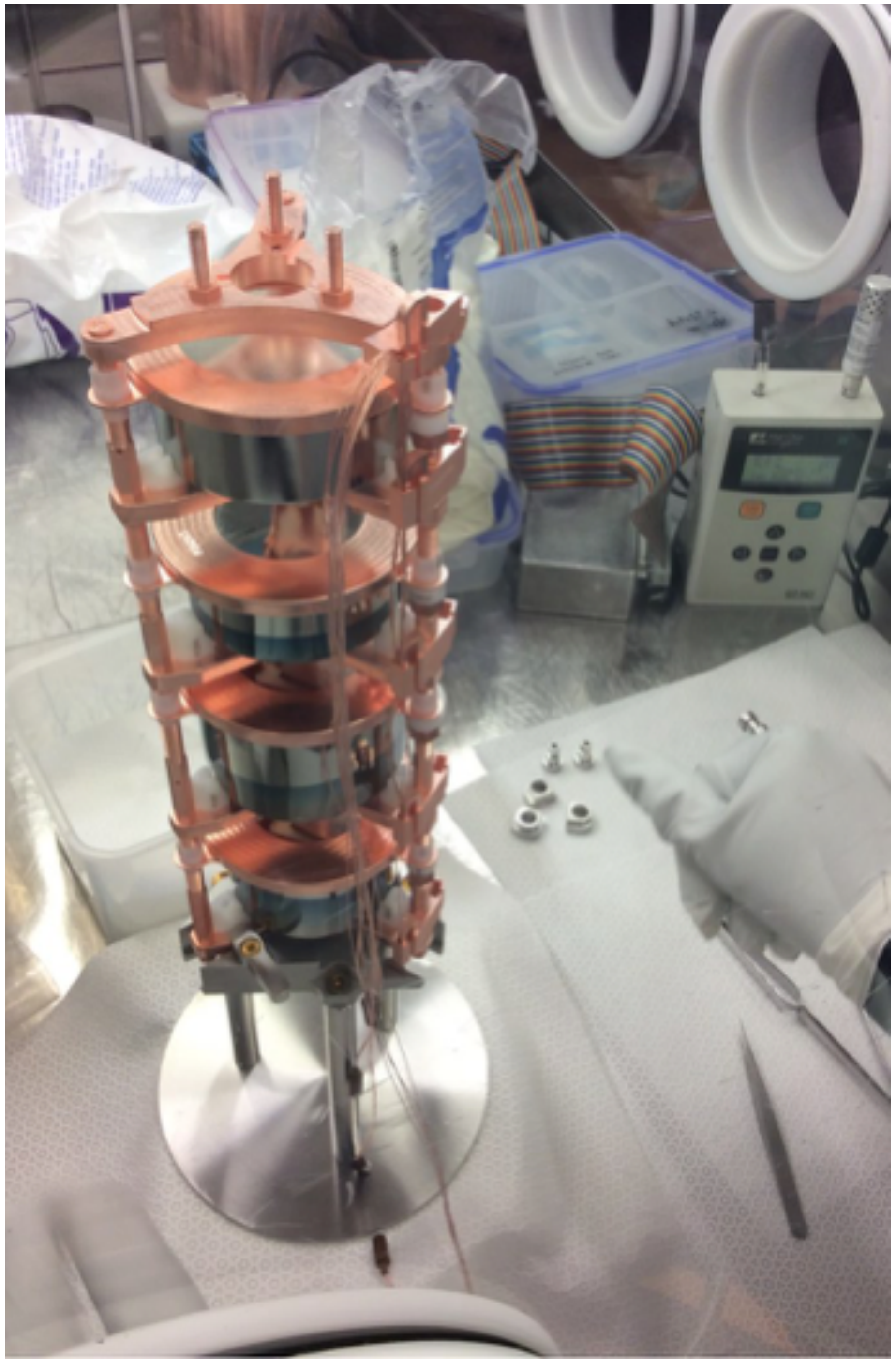
- Cu machining in an underground clean room
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts

Detector Units and Strings

Detector parts stored and assembled inside radon-reduced, dry N_2 environment storage and glove boxes.



All parts are uniquely tracked through machining, cleaning, and assembly by a custom-built database.

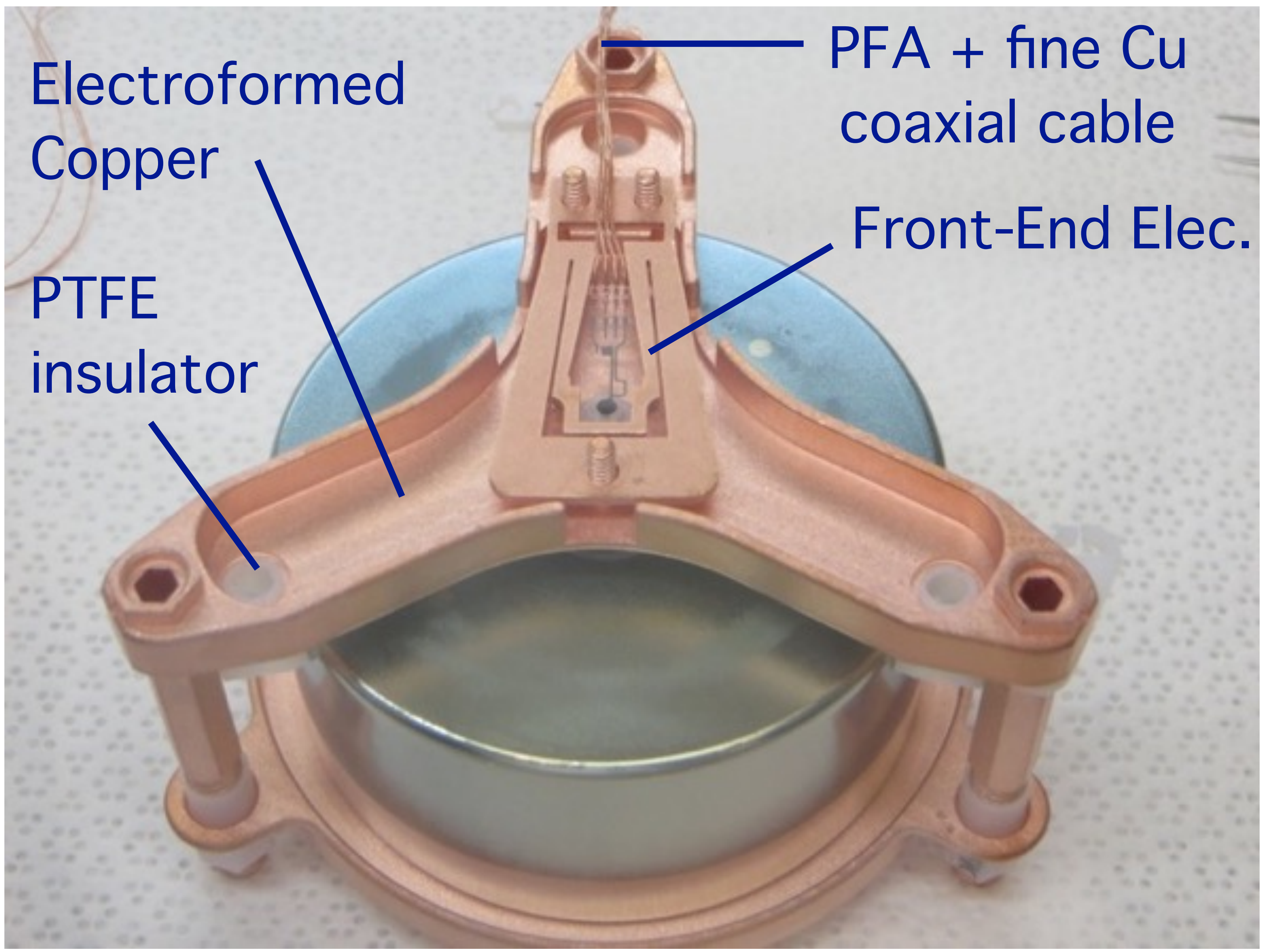


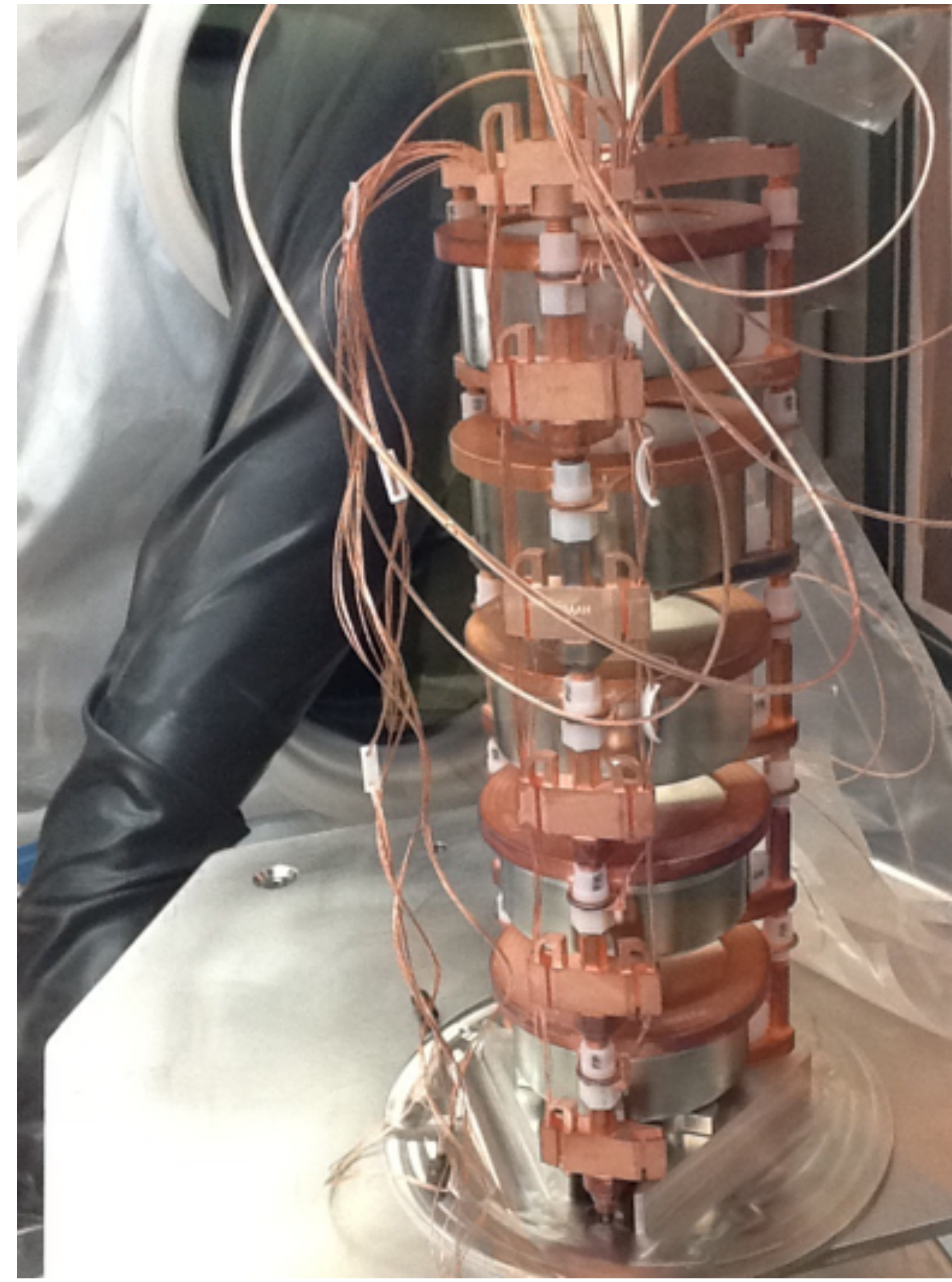
Assembled Detector Unit and String

AMETEK (ORTEC) fabricated enriched-Ge PPC detectors

- 35 enriched detectors: 29.7 kg, 88% ^{76}Ge.

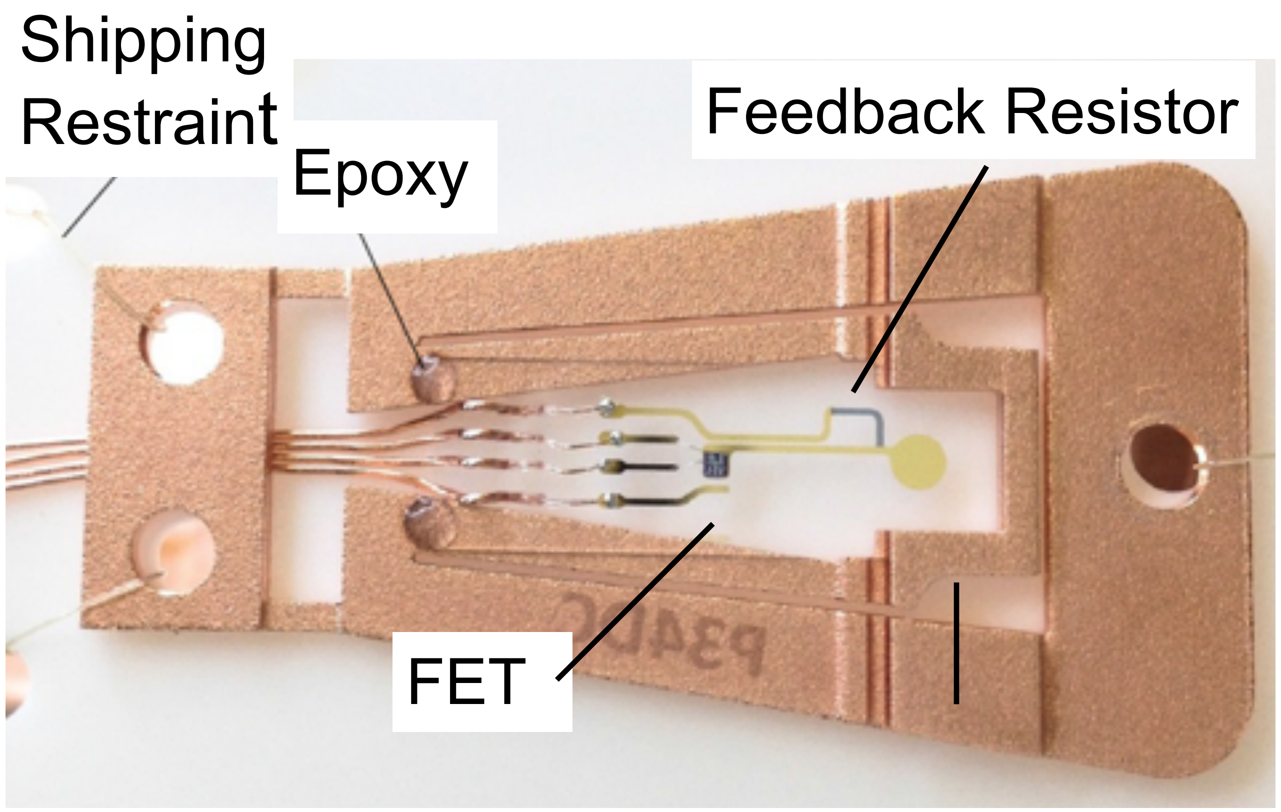
Canberra fabricated natural-Ge BEGe detectors





String Assembly

Detector Readout Components



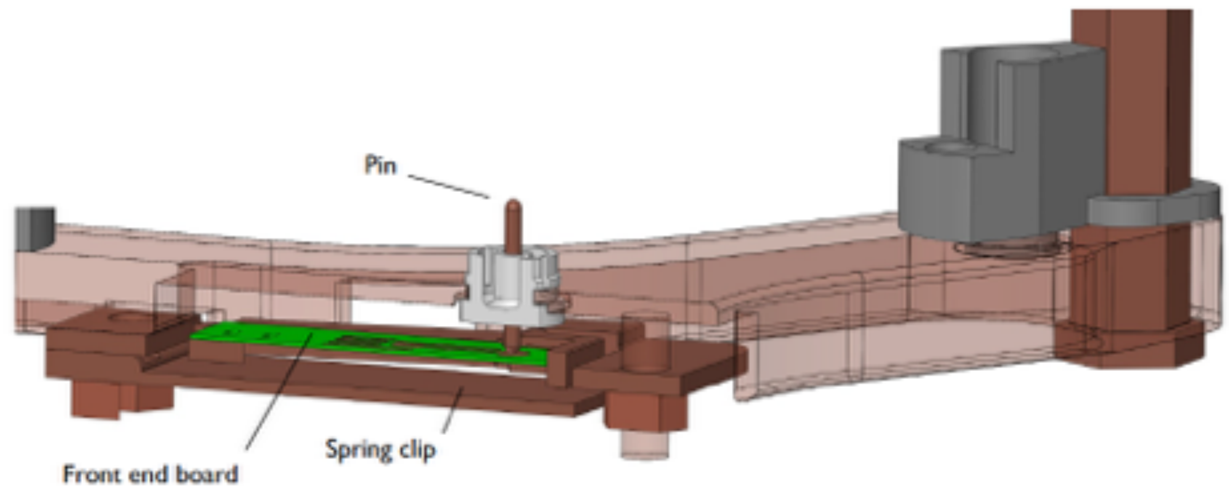
Custom low mass front-end boards

Clean Au+Ti traces on fused silica

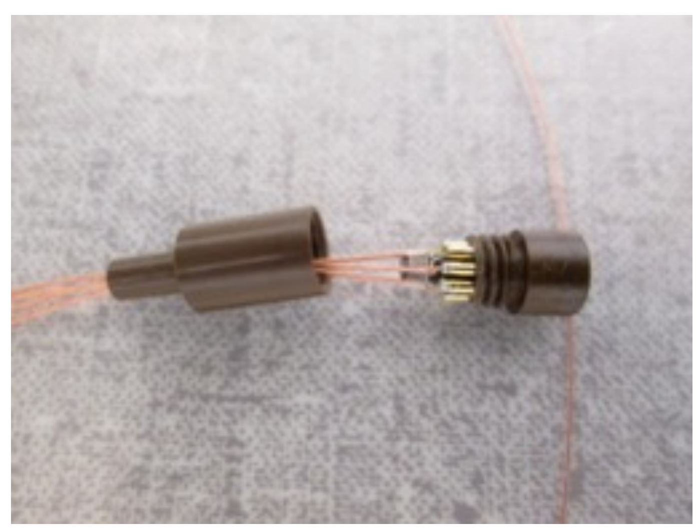
Amorphous Ge resistor

FET mounted with silver epoxy

EFCu + low-BG Sn contact pin



Fine Cu coaxial cable and clean connectors



Connectors reside on top of cold plate.

In-house machined from Vespel.

Axon' pico co-ax cable.

Low background solder and flux.

Detector Module

- A self contained vacuum and cryogenic vessel
- Contains a portion of the shielding
- Can be transported for assembly and deployment

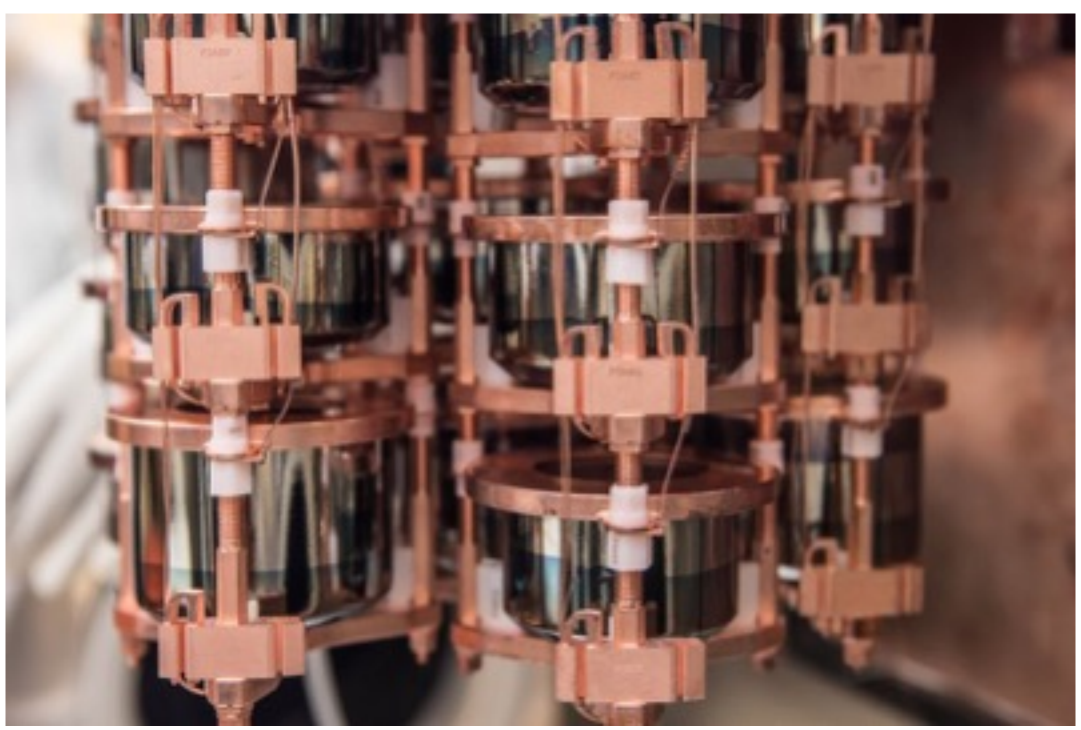
Module moving to/from transporter

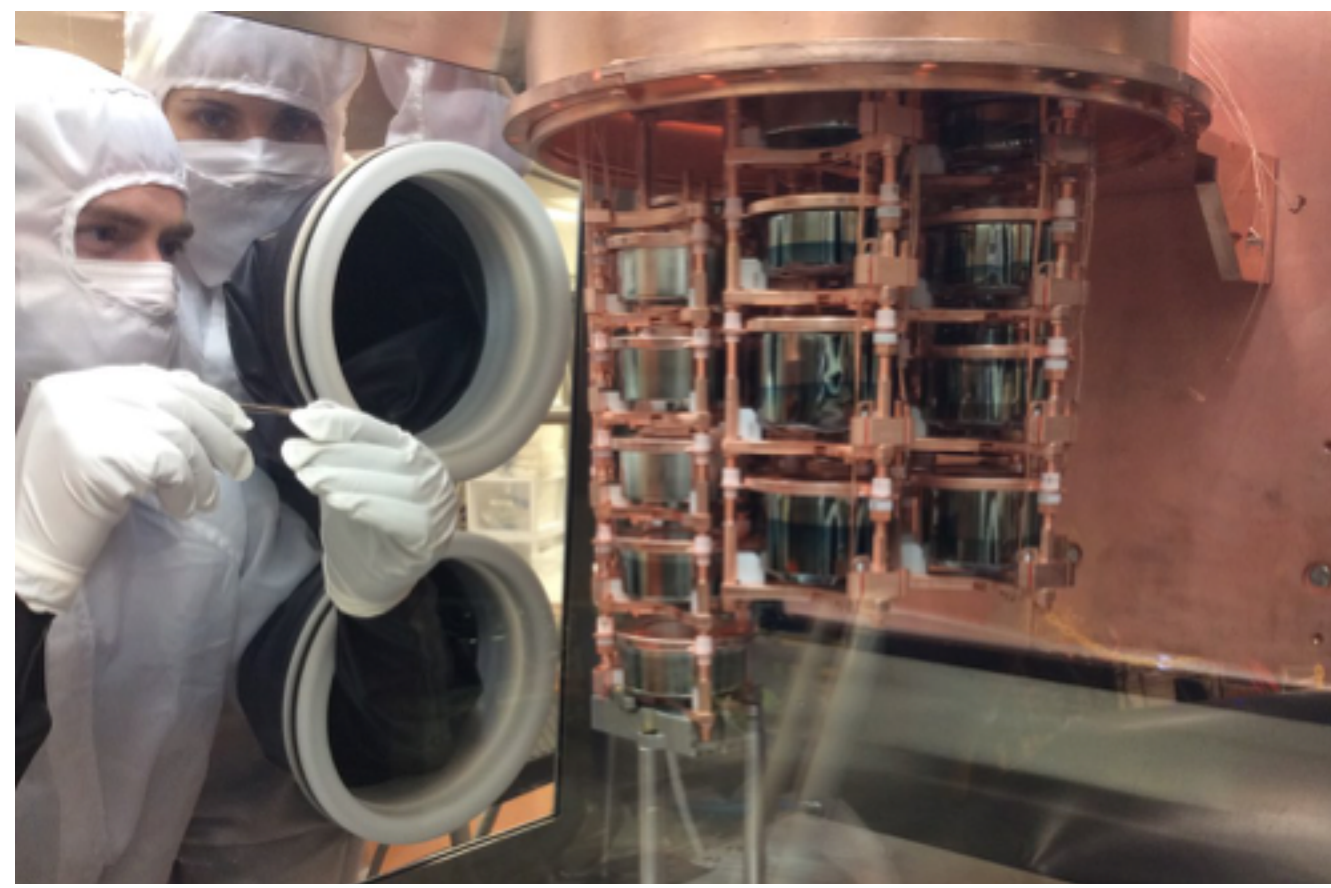
Module mated to the glovebox for string installation

Detector Module

Loading of ^{enr}Ge in Cryostat 2

Loading of ^{enr}Ge in Cryostat 1

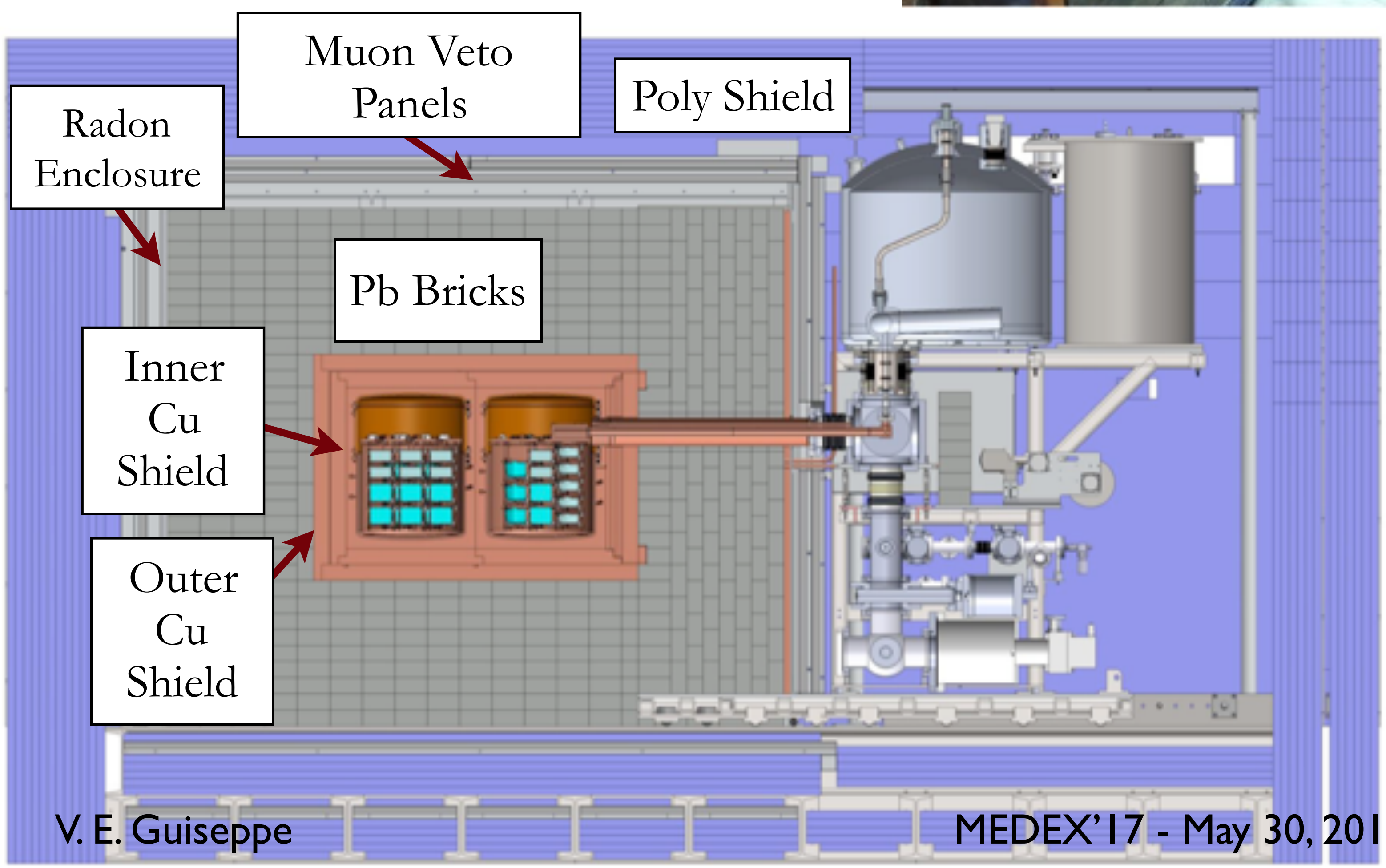




Passive Shielding and Muon Veto

Pb and outer Cu shield

Module deployment



Muon panels

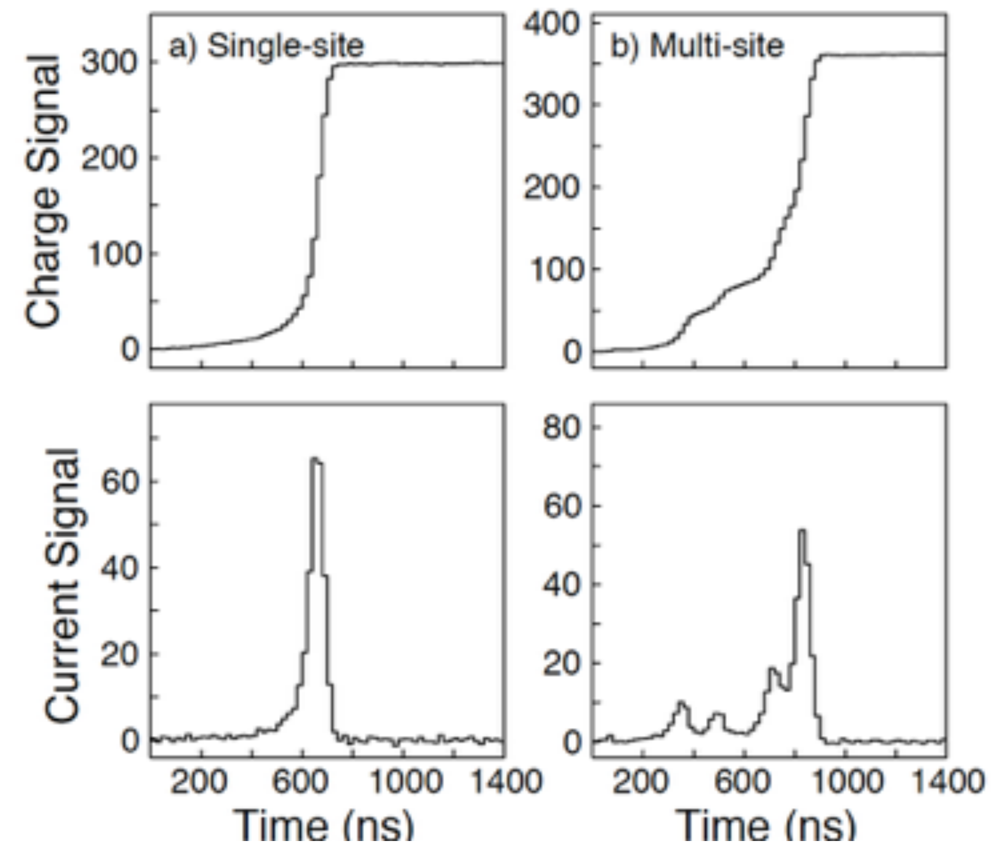
Pulse Shape Analysis

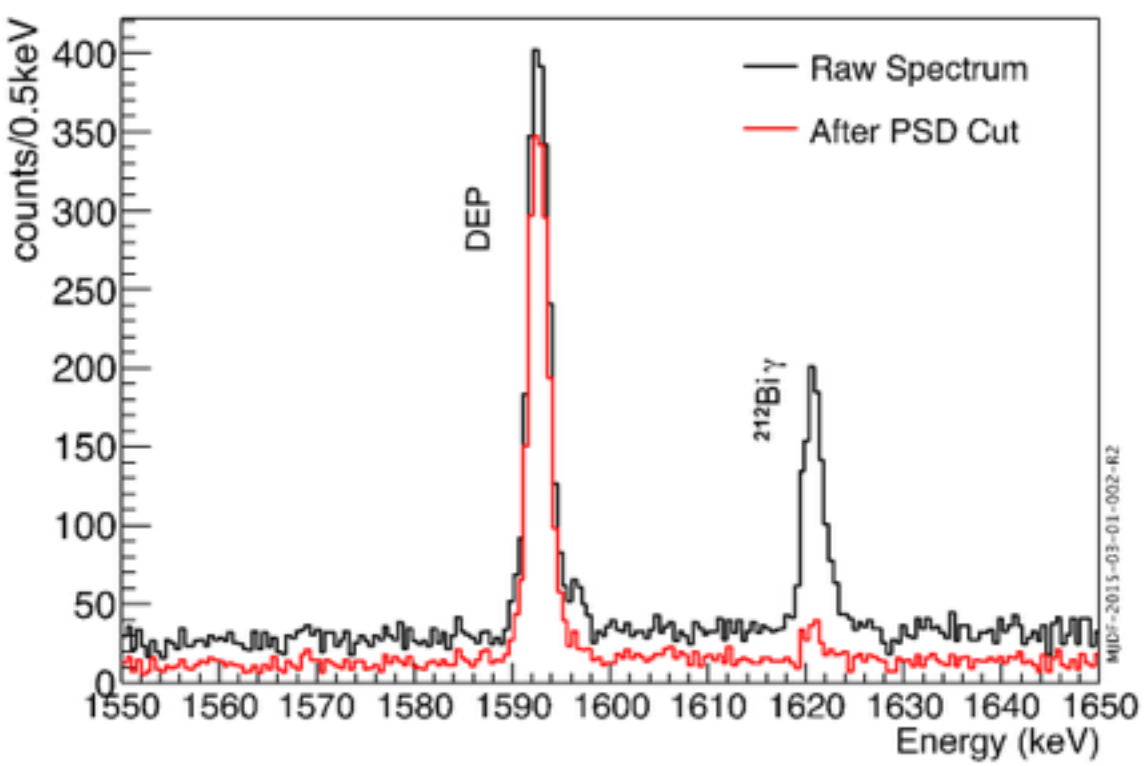
Use a pulse shape analysis (PSA) rejection of multi-site gamma events

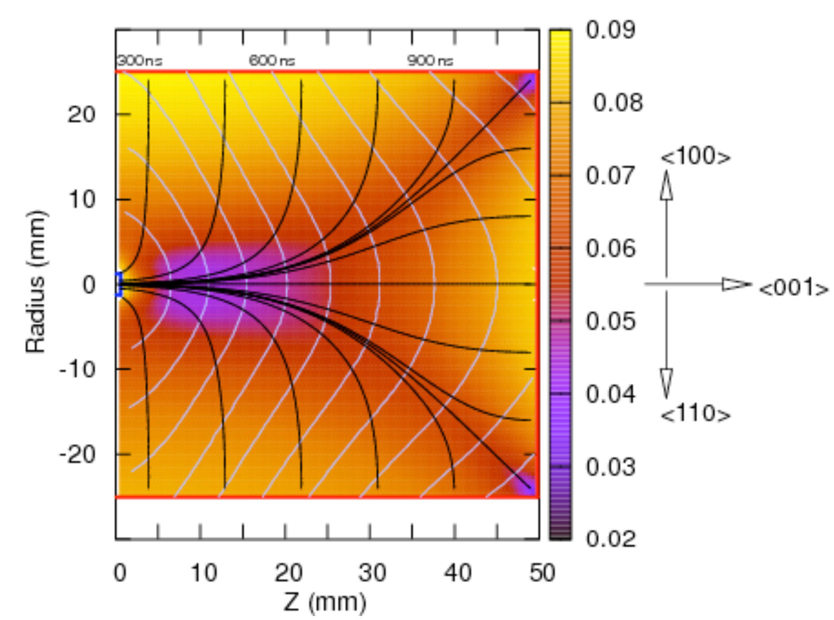
Benefit of P-type Point-Contact (PPC) detectors for background rejection:

- Slow drift time of the ionization charge cloud
- Localized weighting potential gives excellent multi-site rejection

Rising edge "stretched" in time ⇒ improved PSA







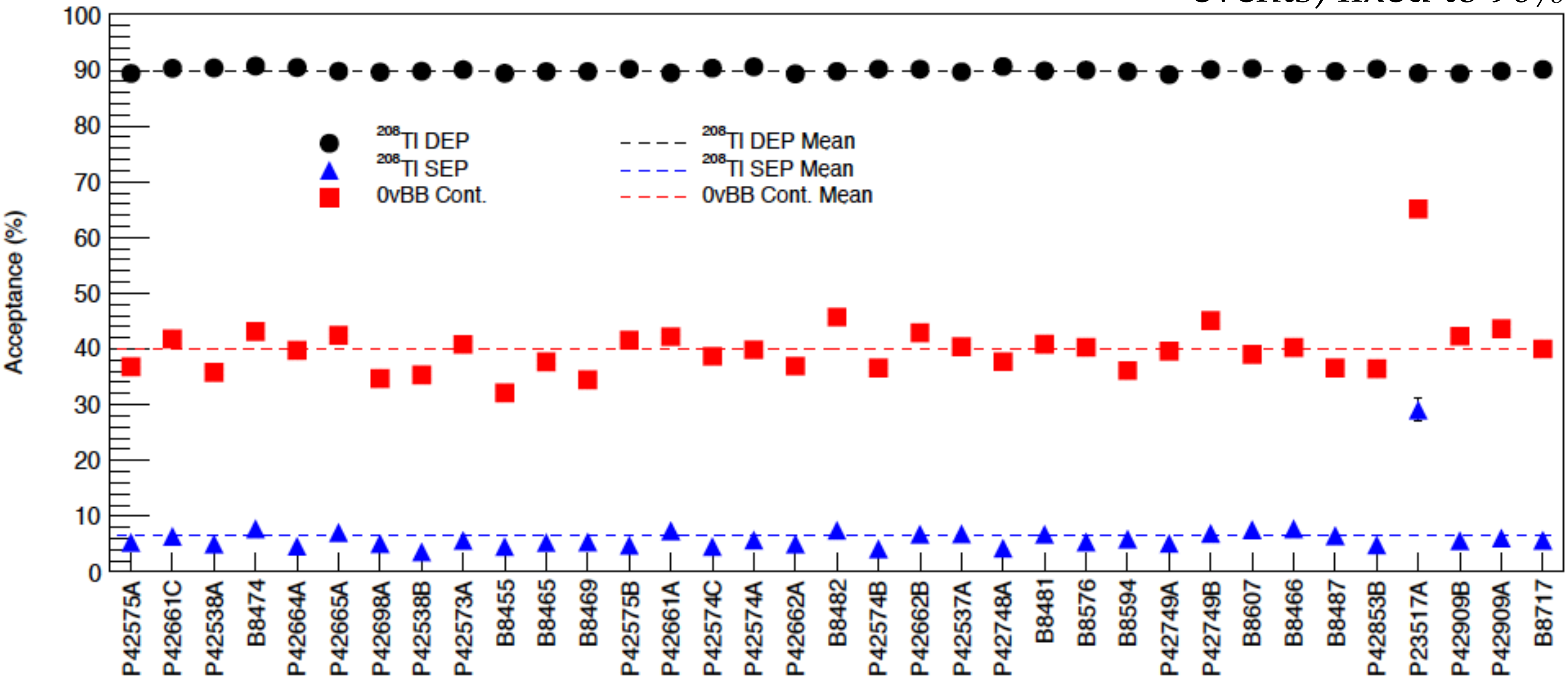
Hole v_{drift} [mm/ns] with paths and isochrones

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

Ge Detector PSD Performance (DS3 & DS4)

^{228}Th calibration data provides data to tune multi-site event rejection

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



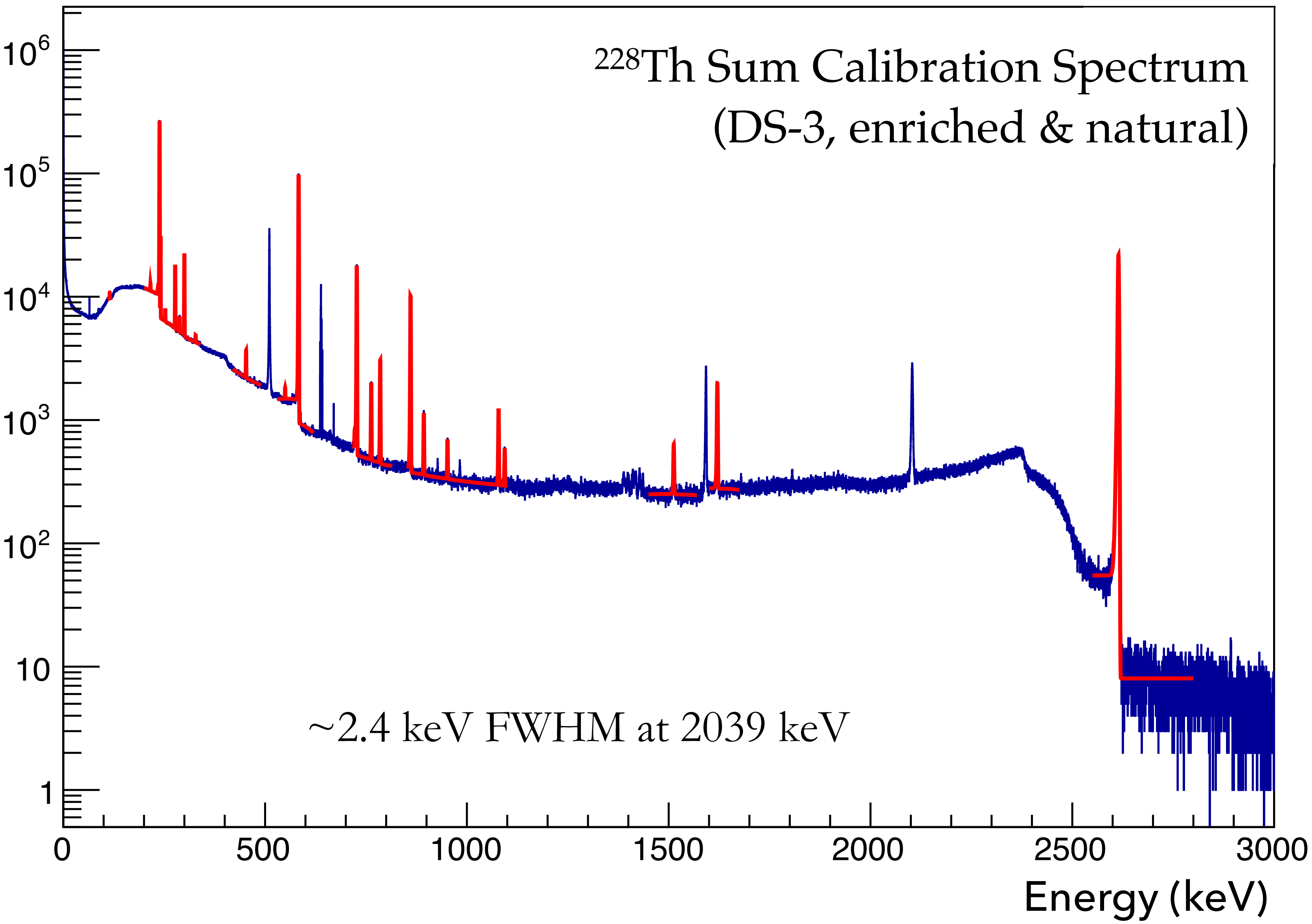
^{208}Tl SEP (multiple site events) reduced to 6%

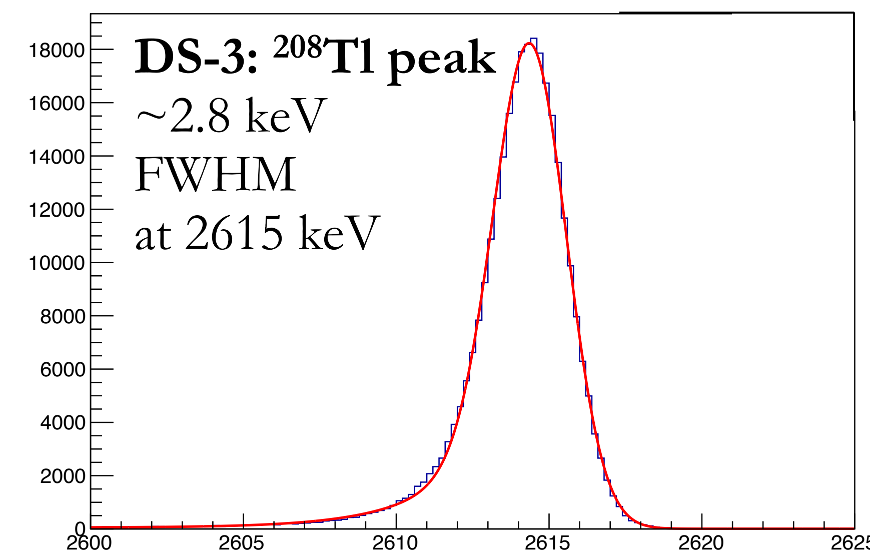
Calibration

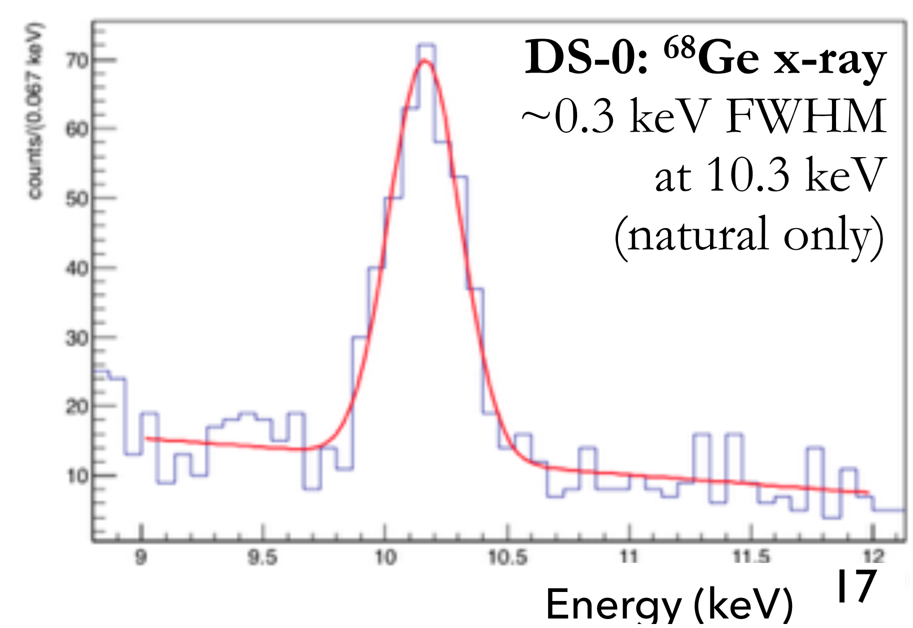
Calibration of the detector array with a ^{228}Th line source

- Source is inserted and retracted for scheduled calibrations

Calibration system: arXiv:1702.02466







Delayed Charge Recovery and Alphas

Alpha background response observed in Module 1 commissioning (DS0)

- Identified as arising from alpha particles impinging on passivated surface

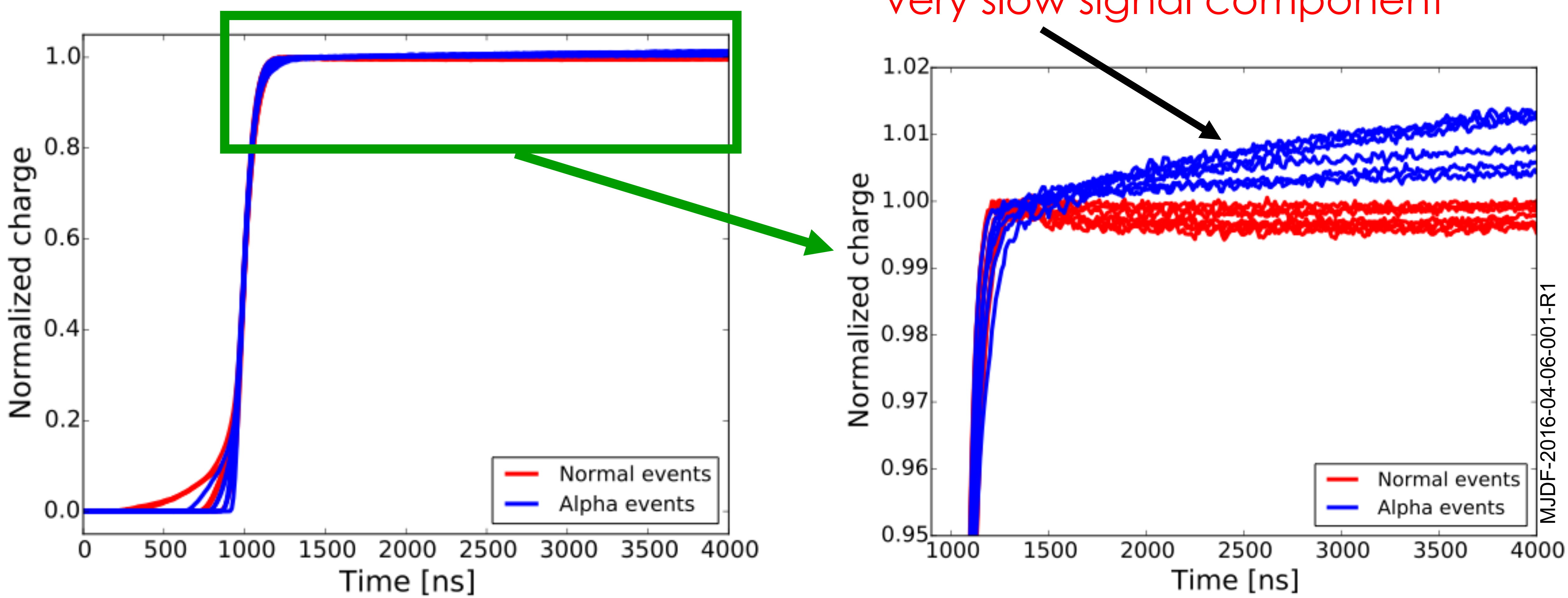
Results in prompt collection of some energy, plus very slow collection of remainder

Produces a distinctive waveform allowing a high efficiency cut

- "Delayed Charge Recovery" (DCR) parameter related to slope of tail

Example pole-zero corrected waveforms

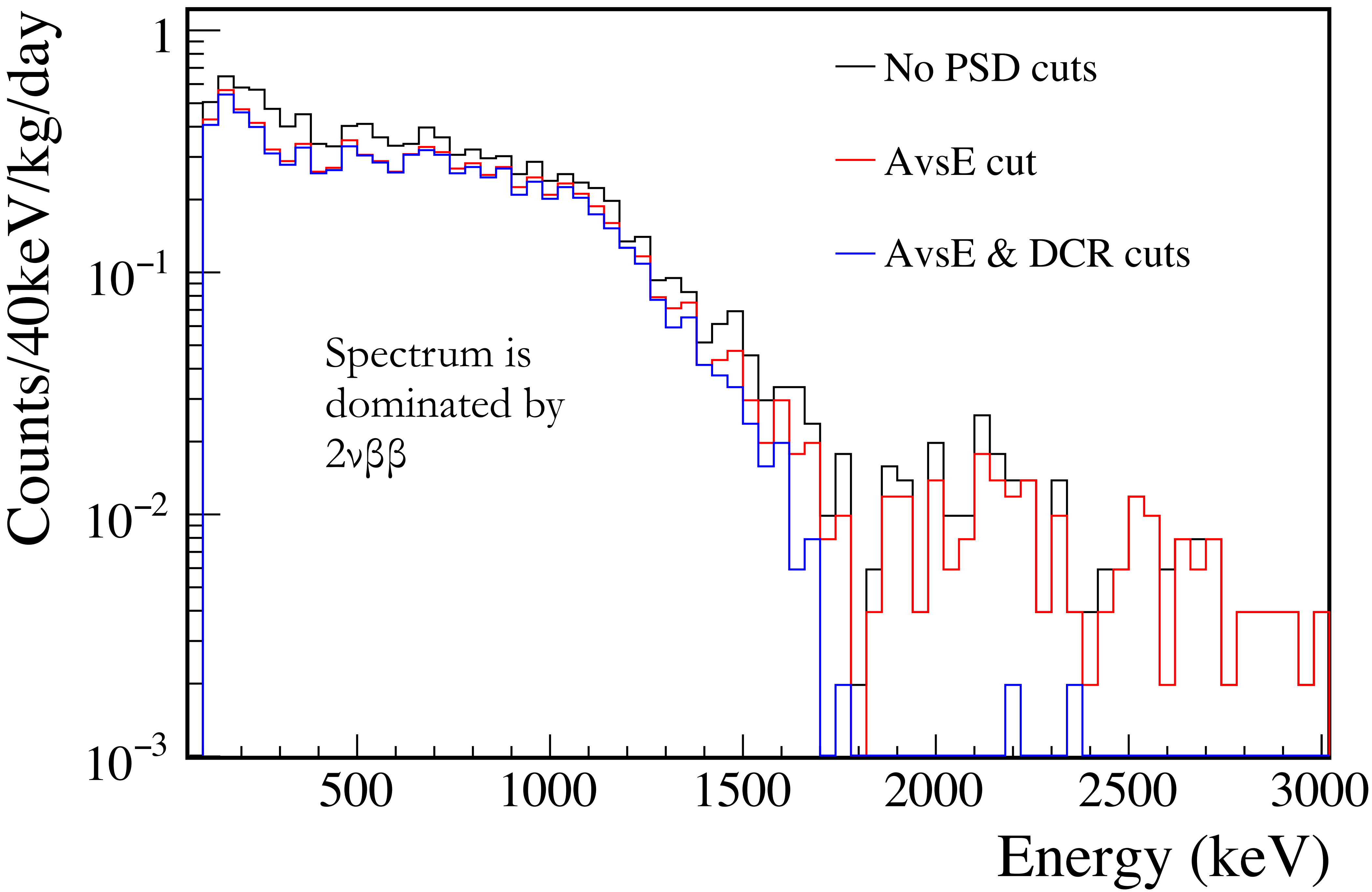
Slow drift of charges along passivated surface results in very slow signal component



Background Spectrum (DS3 & DS4)

Lowest background configuration with both modules in shield.

Enriched detectors in Modules 1 & 2 , before and after PSD cuts



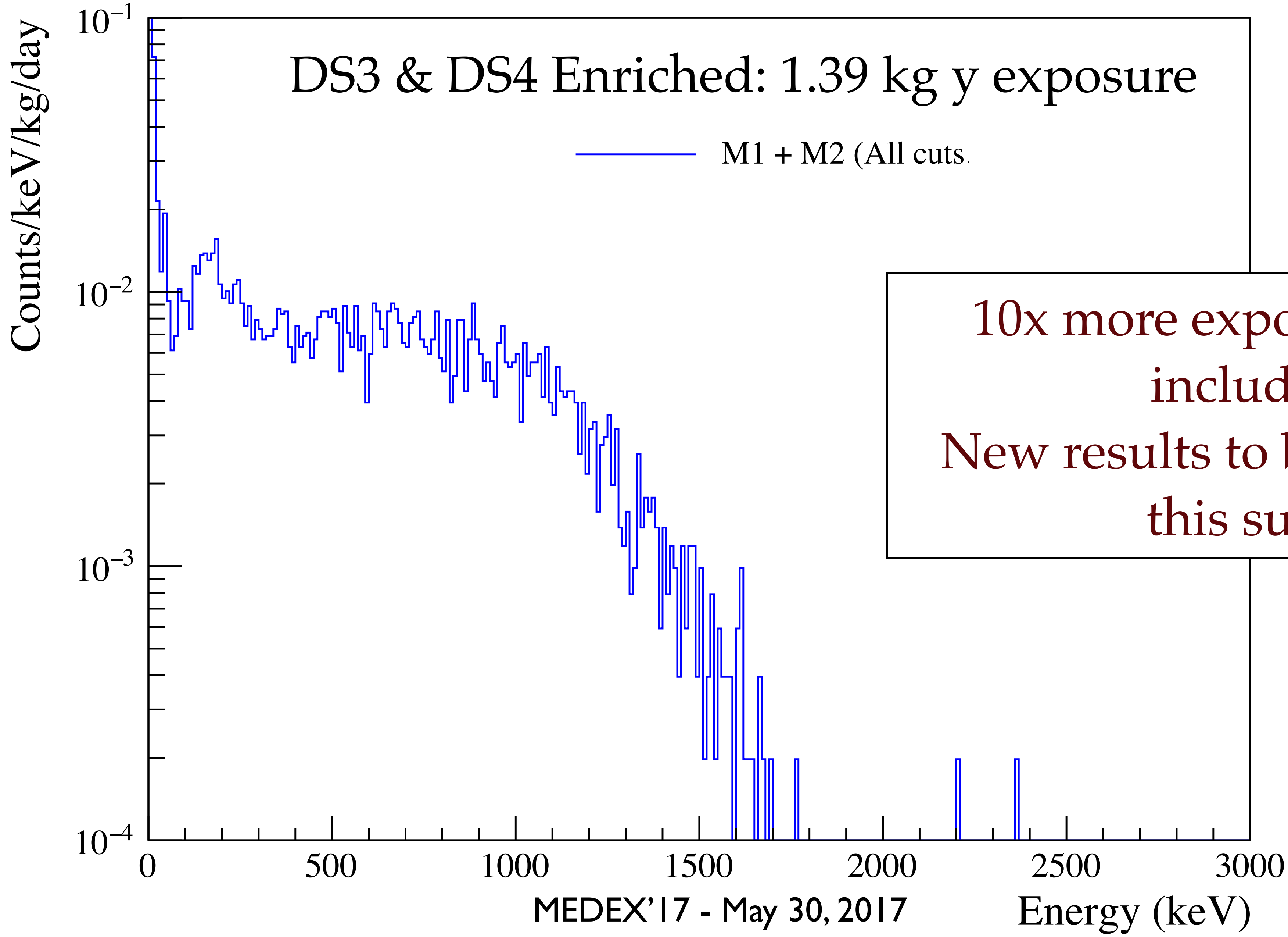
Background Spectrum (DS3 & DS4)

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)

  using a 2.9 (M1- DS3) & 2.6 keV (M2 - DS4) keV ROI (68% CL).
- Background index of 1.8 x 10^{-3} c/(keV kg y)

Analysis cuts are still being optimized.

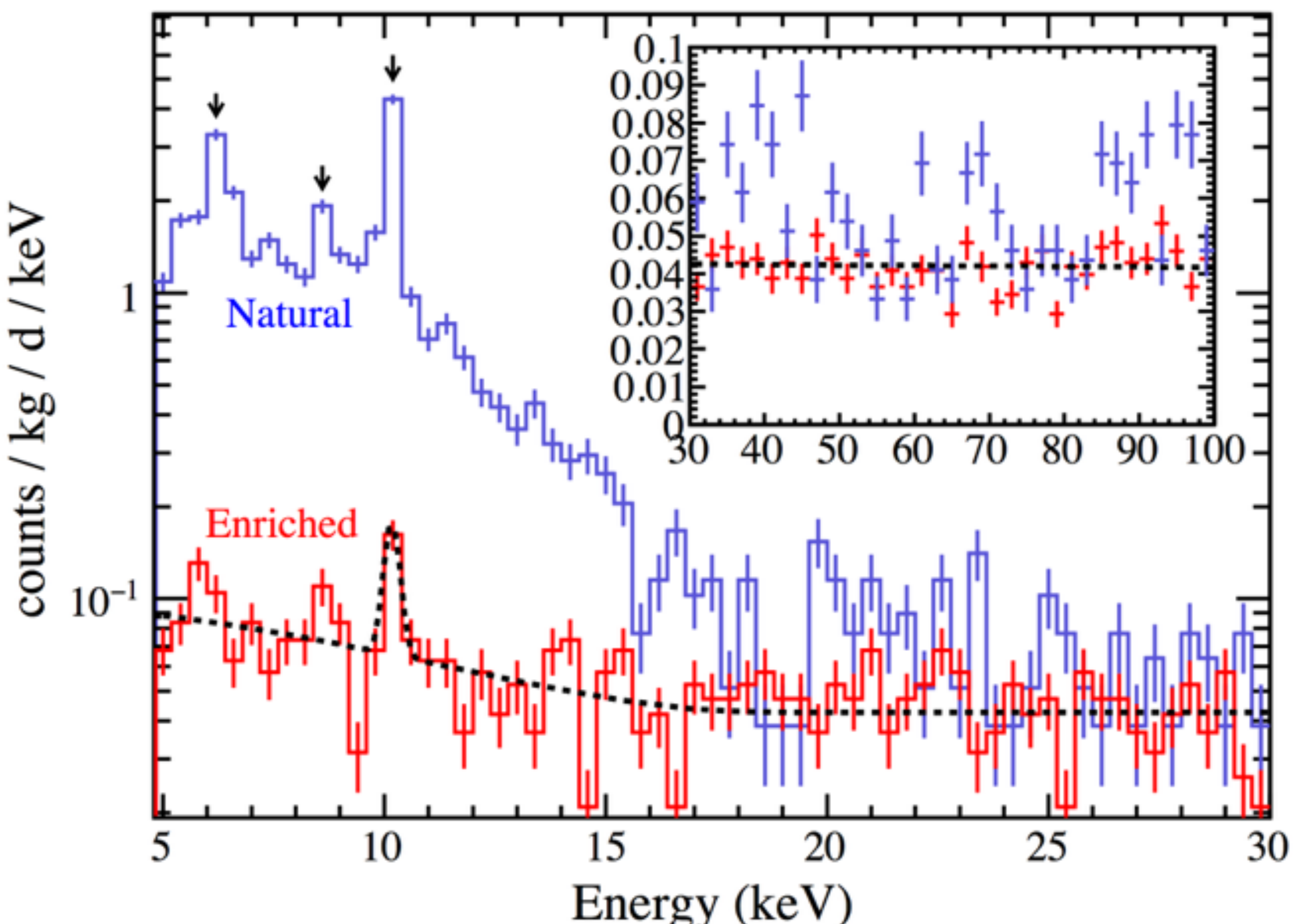


10x more exposure when we include DS5.
New results to be released later this summer.

Low Energy Spectrum in DS0

Controlled surface exposure of enriched material to minimize cosmogenics
Significant reduction of cosmogenics in the low-energy region.
- Low-energy rate is improved in subsequent data sets

Enriched Detectors: ~0.04 cts/(kg-keV-d) near 20 keV
Efficiency below 5 keV is under study.



Phys. Rev. Lett. 118, 161801 (2017).

Permits Low-Energy physics
- Pseudoscalar dark matter
- Vector dark matter
- 14.4-keV solar axion
- $e^- \Rightarrow 3\nu$
- Pauli Exclusion Principle

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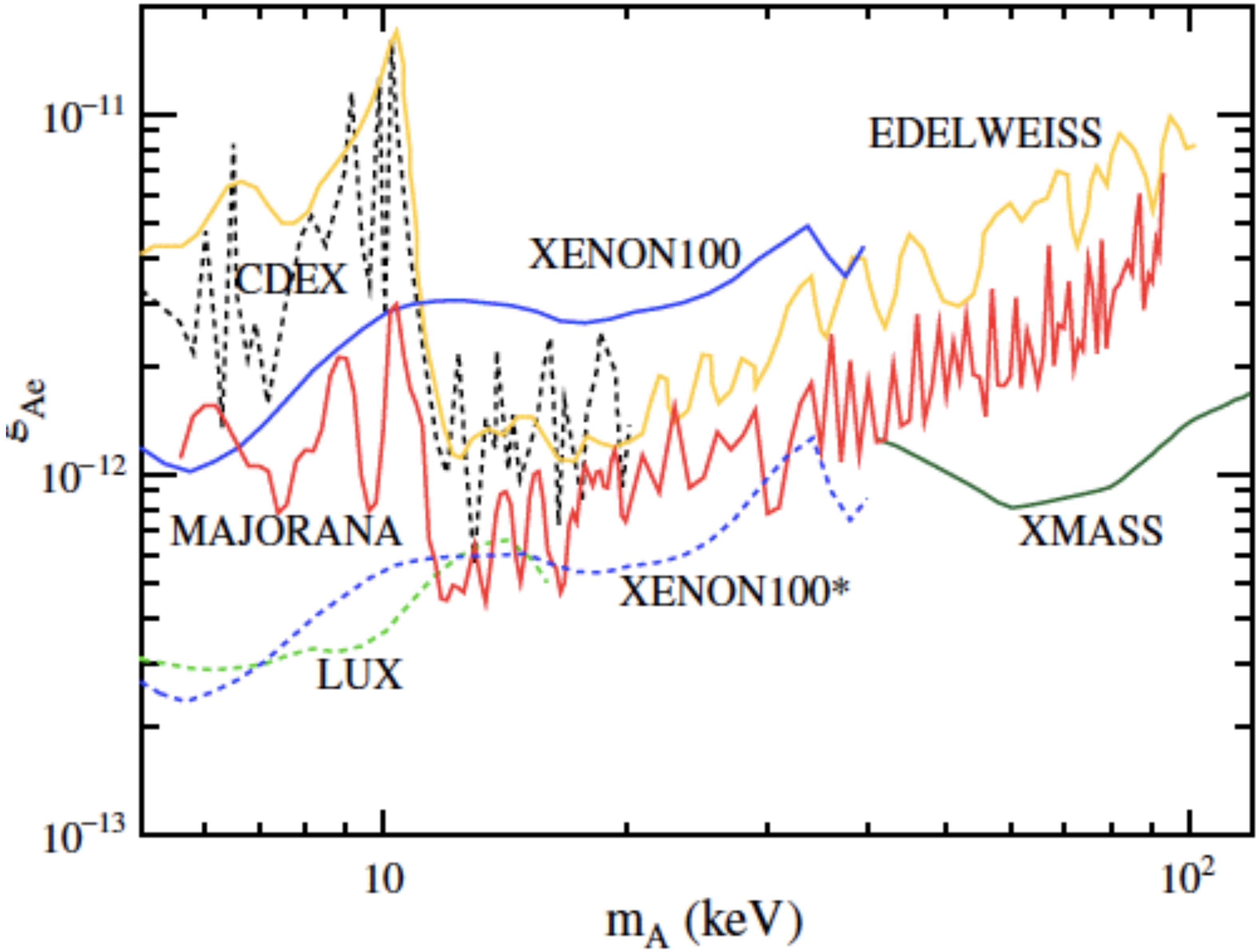
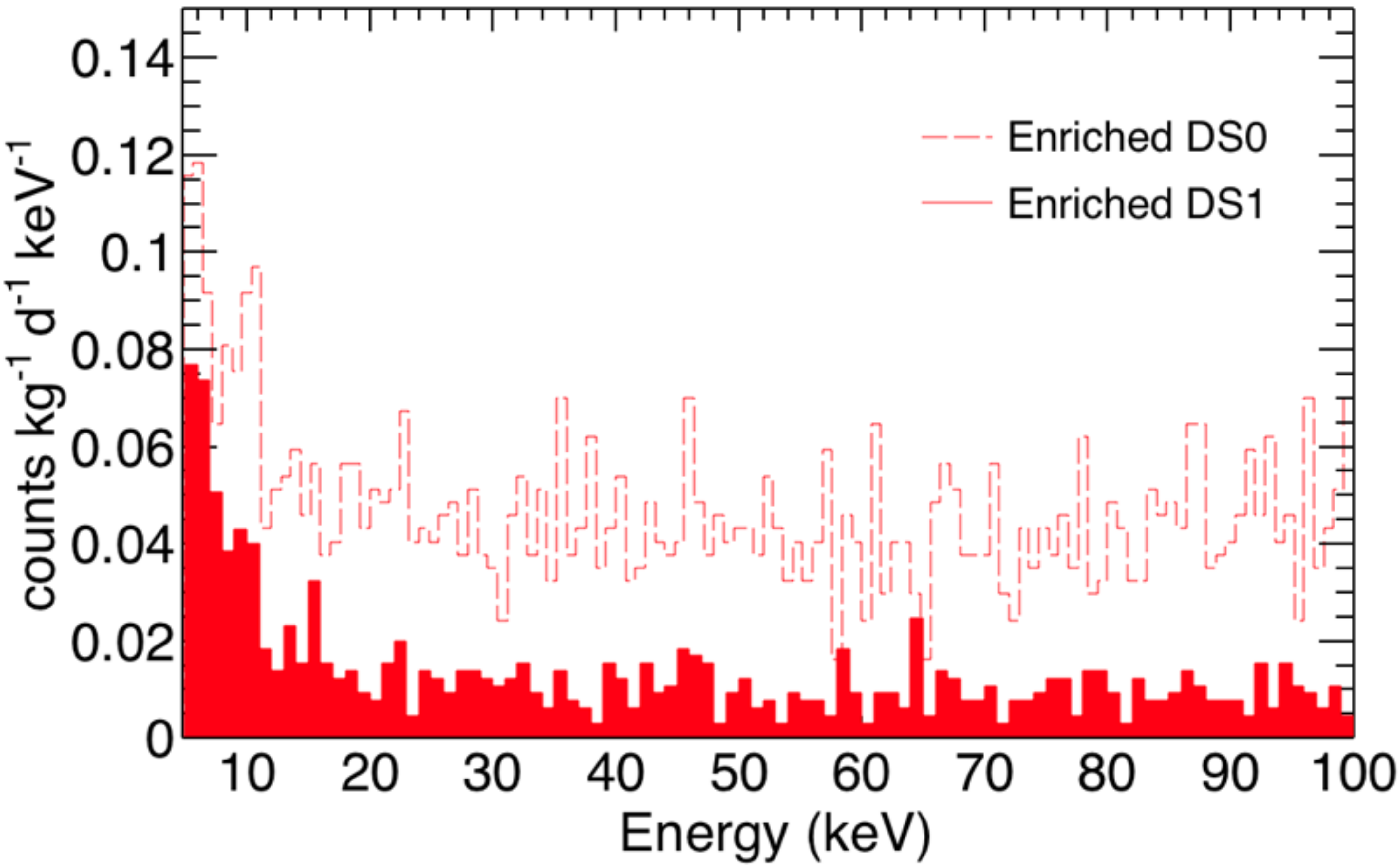


Phys. Rev. Lett. 118, 161801 (2017).

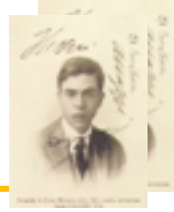
Permits Low-Energy physics
- Pseudoscalar dark matter
- Vector dark matter
- 14.4-keV solar axion
- $e^- \Rightarrow 3\nu$
- Pauli Exclusion Principle

Low Energy Spectrum in DS0 & DS1

Controlled surface exposure of enriched material to minimize cosmogenics
Significant reduction of cosmogenics in the low-energy region.
- **Low-energy rate is improved in subsequent data sets**



MAJORANA DEMONSTRATOR Outlook

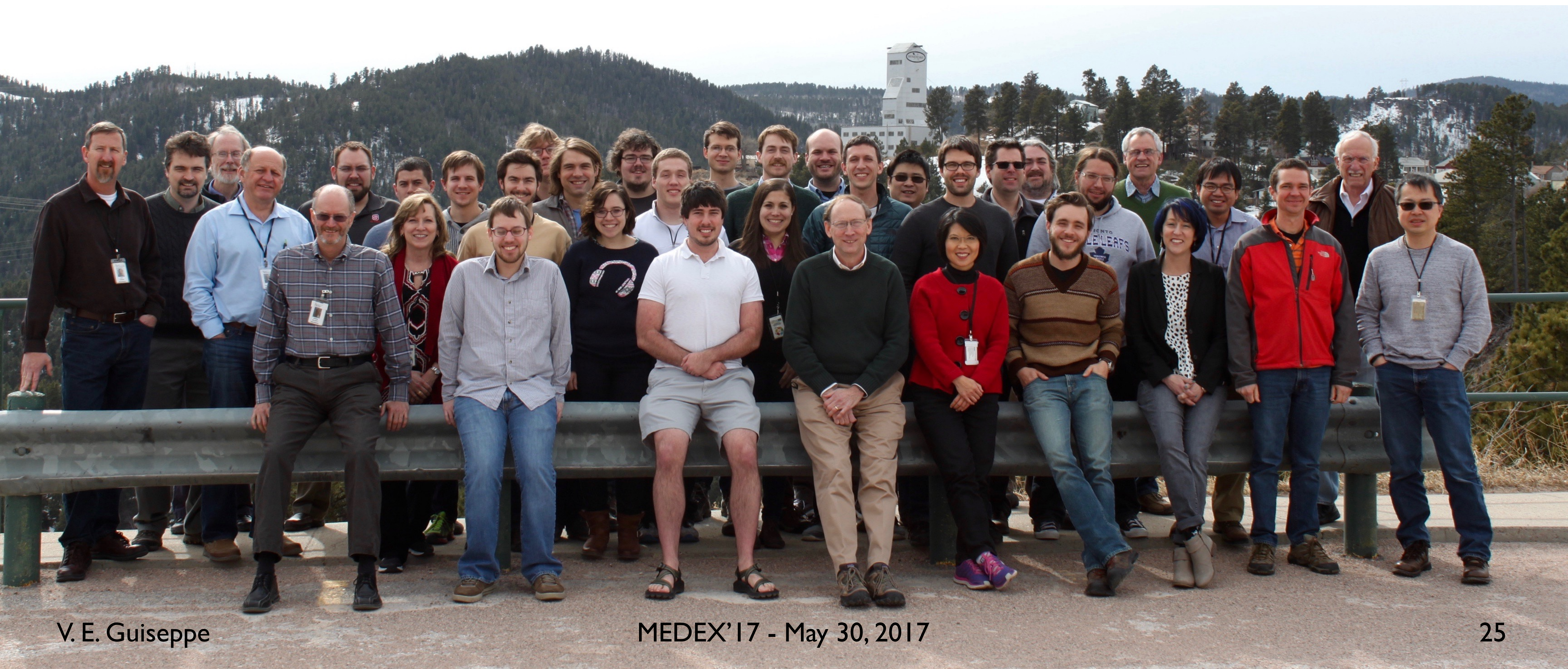


The ^{76}Ge enriched point contact detectors developed by MAJORANA
- have attained the best energy resolution (2.4 keV FWHM at 2039 keV) of any ββ-decay experiment.
- provide excellent pulse shape discrimination reduction of backgrounds.
- at low energies have sub-keV energy thresholds and excellent 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.

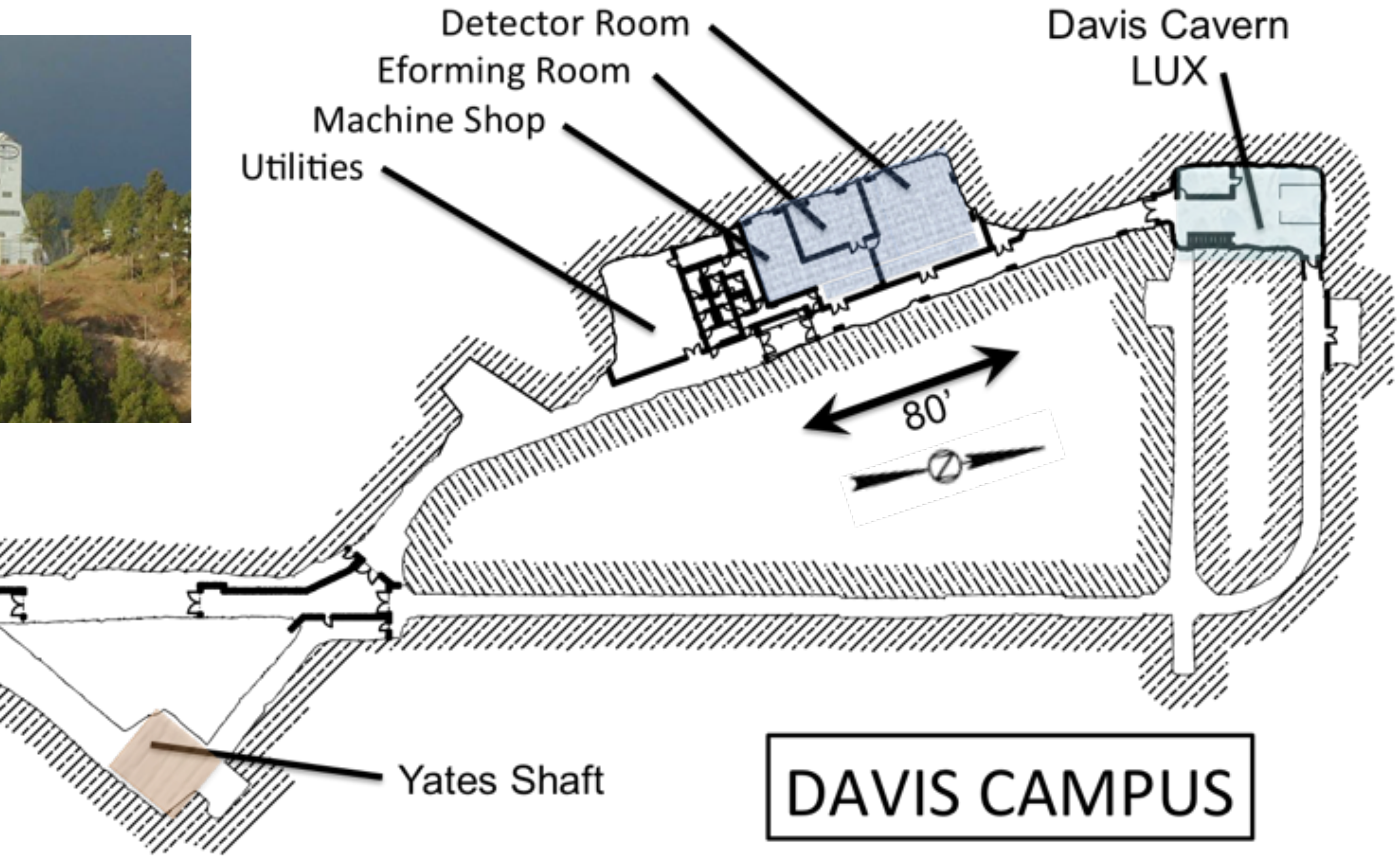
Combining the strengths of GERDA and the MAJORANA DEMONSTRATOR, the LEGEND Collaboration is moving forward with a ton-scale ^{76}Ge based experiment. Based on the successes to date, LEGEND should be able to reach the backgrounds ~0.1 c / (ROI t y) and energy resolution necessary for discovery level sensitivities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

The MAJORANA Collaboration



Backup Slides

MAJORANA Underground Laboratory



MAJORANA Detector Choice

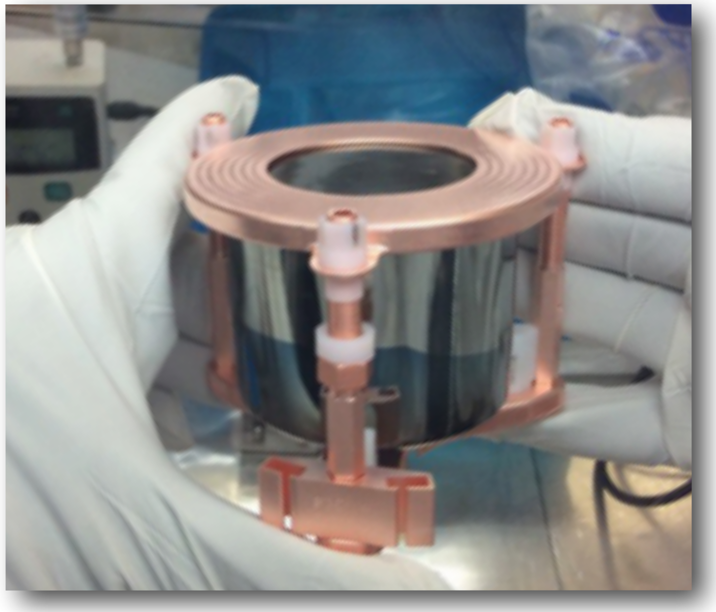
MAJORANA DEMONSTRATOR

Natural Detectors

- CANBERRA modified BEGe
- ~ 70 mm x 30 mm
- ~ 650 g each
- Made in Meriden, CT, USA; different from the Olen-type used in GERDA

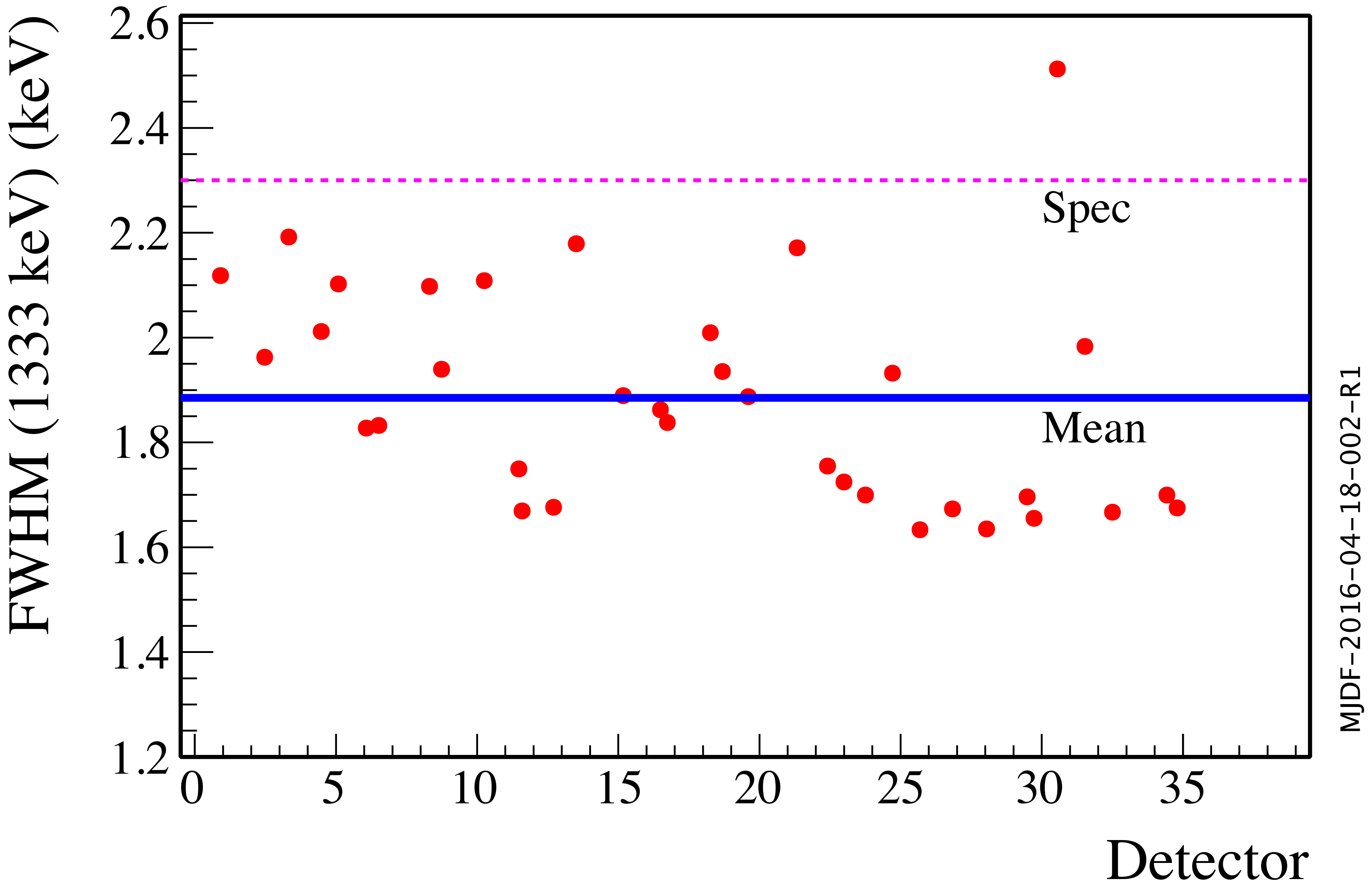
Enriched Detectors

- ORTEC PPC
- ~ 70 mm x 50 mm
- ~ 900 g each
- All production (zone refinement, crystal pull and diode production) in Oak Ridge, TN, USA
- Production began in Nov. 2012



Delivered ^{enr}Ge Detectors

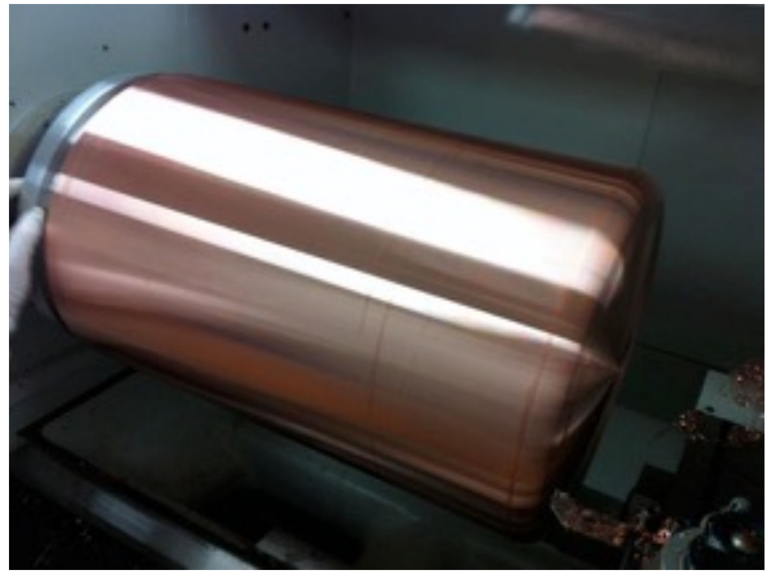
Vendor: AMETEK/ORTEC
Enriched detector production completed in June 2015
Total enriched detector mass = 29.683 kg / 35 detectors
Mean FWHM at 1333 keV = 1.88 keV



Cu Production and Machining

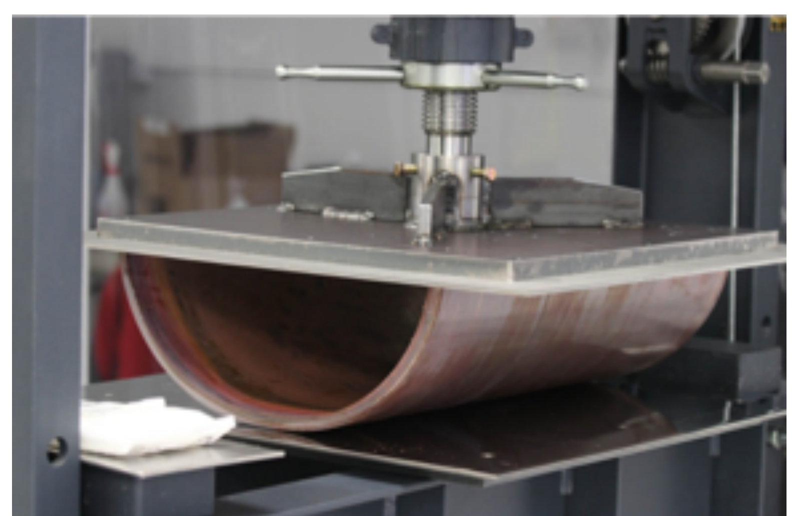
Underground Cu electro-forming laboratory produces all of the ultra-pure inner Cu

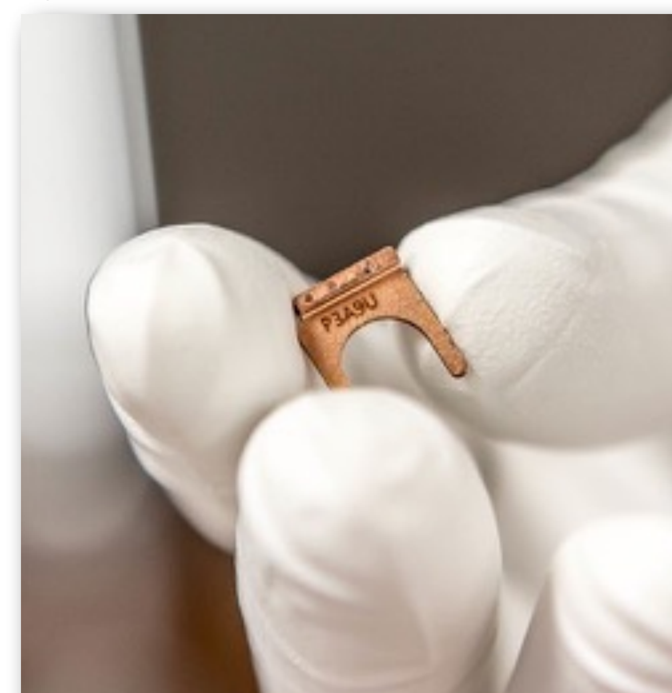
Cu Production and Machining



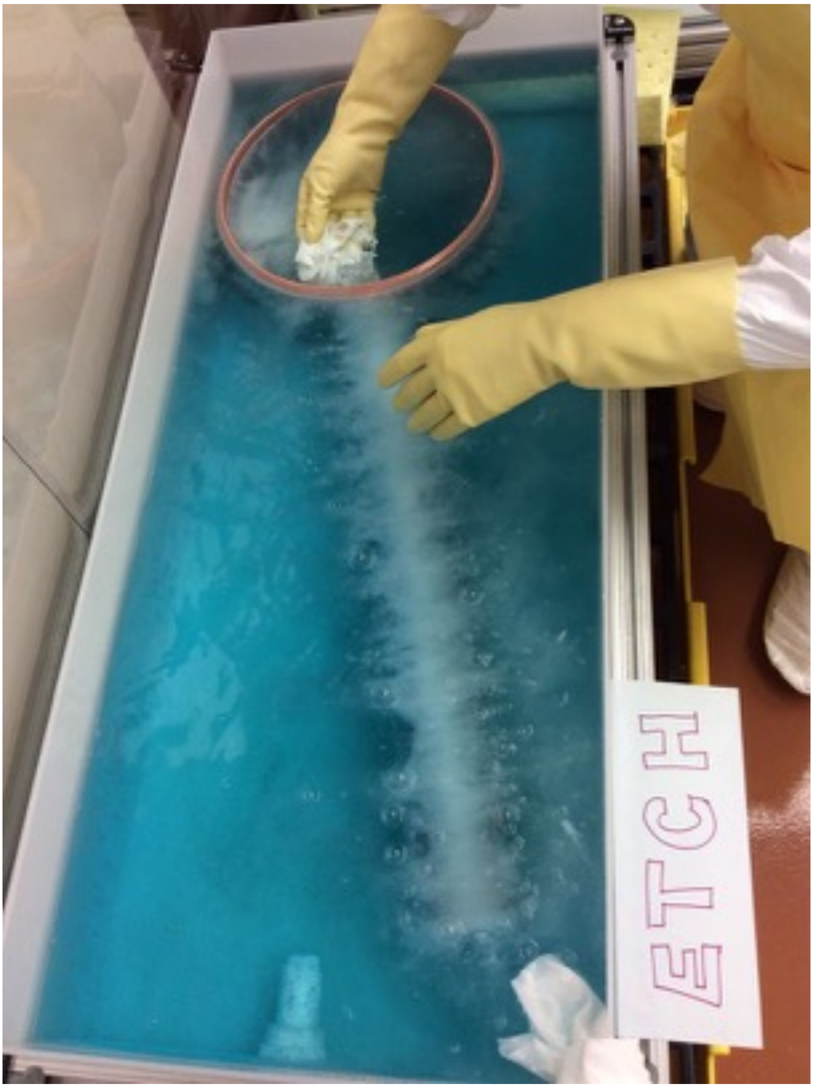
Cu machining in an underground clean room machine shop complete April 2016

All parts are uniquely tracked through machining, cleaning, and assembly by a custom-built database.





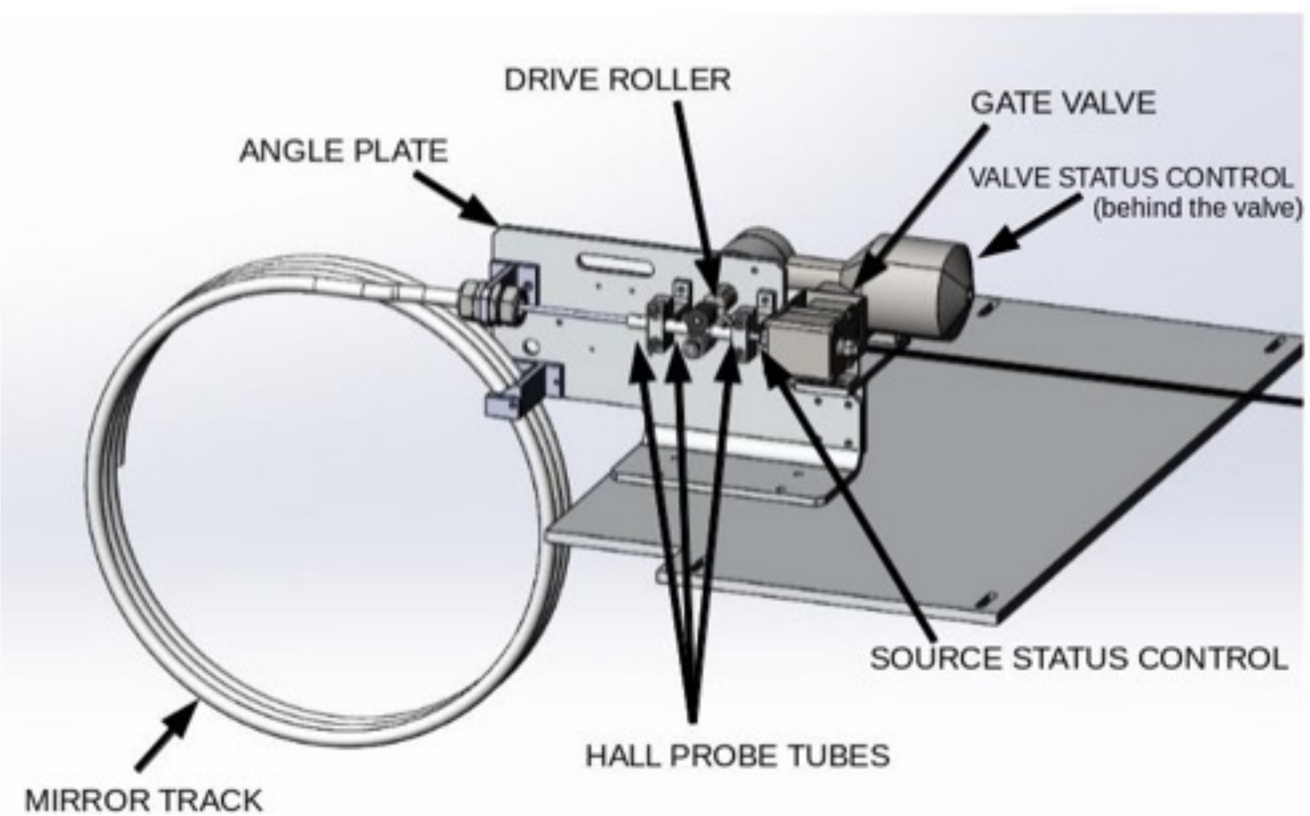
Cu Part Cleaning



Cleaning of Cu parts by acid etching and passivation

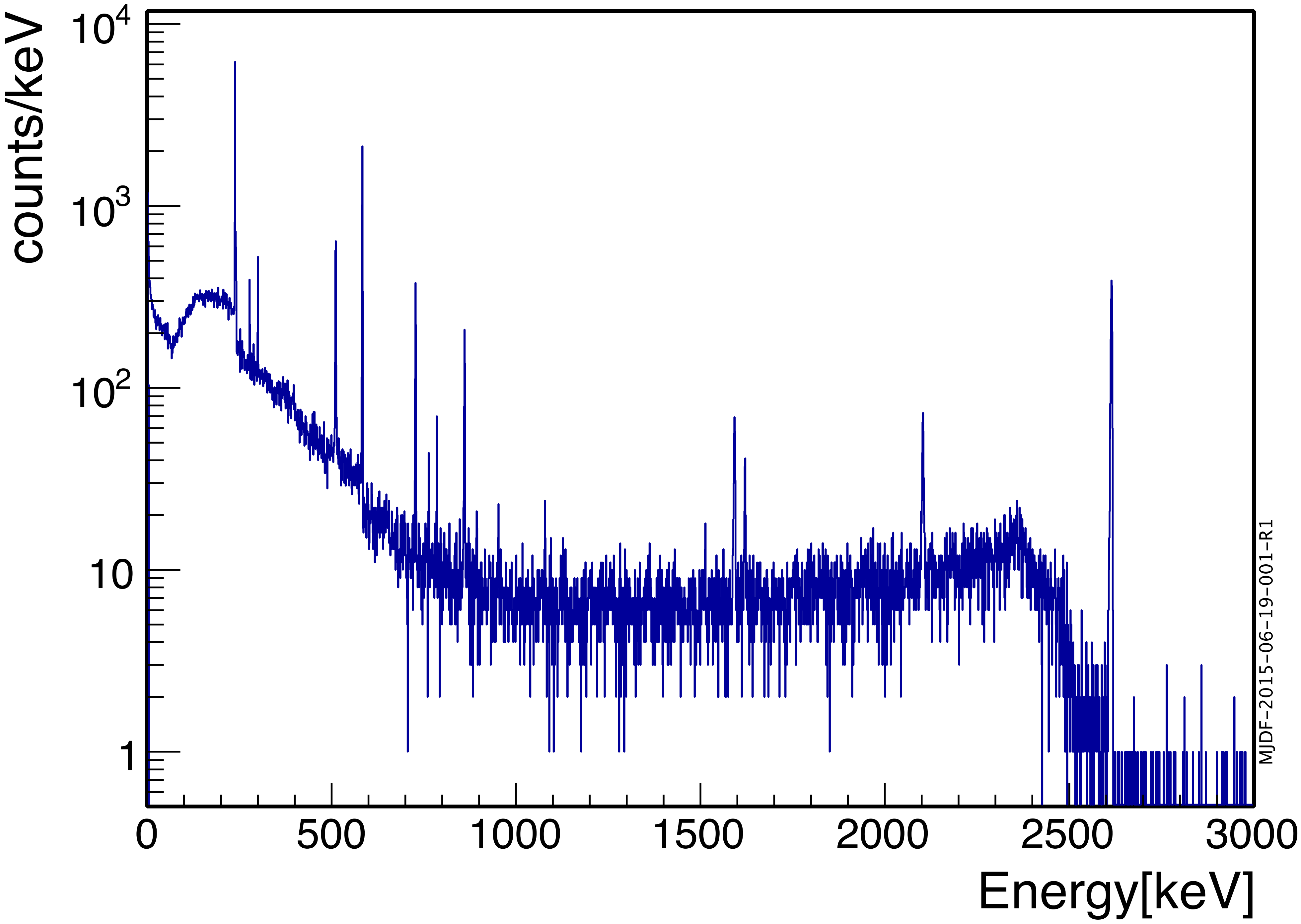
The MAJORANA Calibration system

- Line sources are deployed from outside the shielding within a tube that surrounds each cryostat.
- ^{228}Th (11.6 kBq) and ^{60}Co (6.3kBq) sources available.
- Calibration tube is externally purged during calibration.
- Several sensors monitor the position of the source and the status of the system.



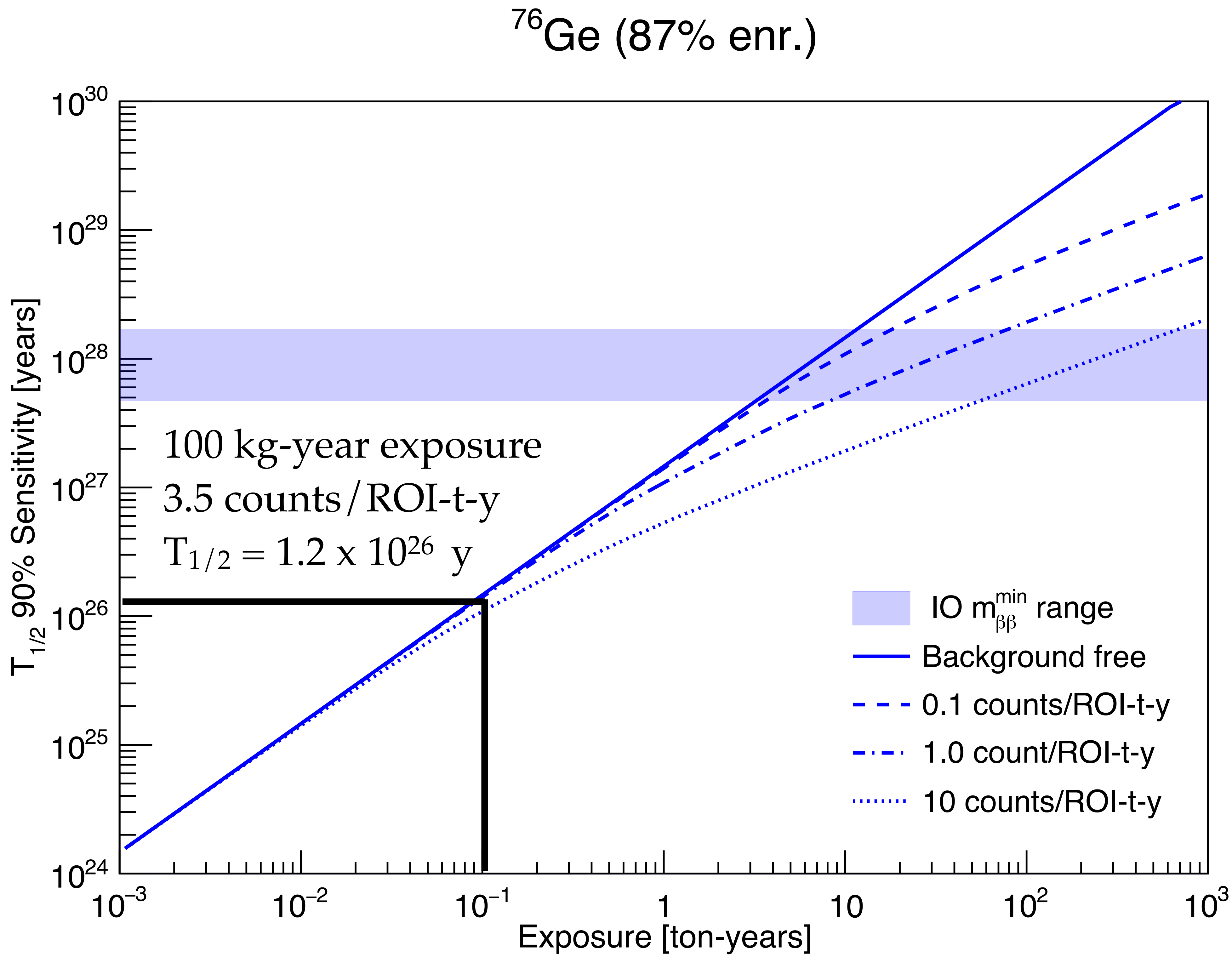
^{228}Th Calibration Spectrum in Module 1 (DS0)

One enriched detector spectrum within a string mounted in Module 1 and inside shield. FWHM 3.6 keV at 2.6 MeV



Sensitivity vs. Exposure ^{76}Ge

J. Detwiler



Inverted Ordering (IO)

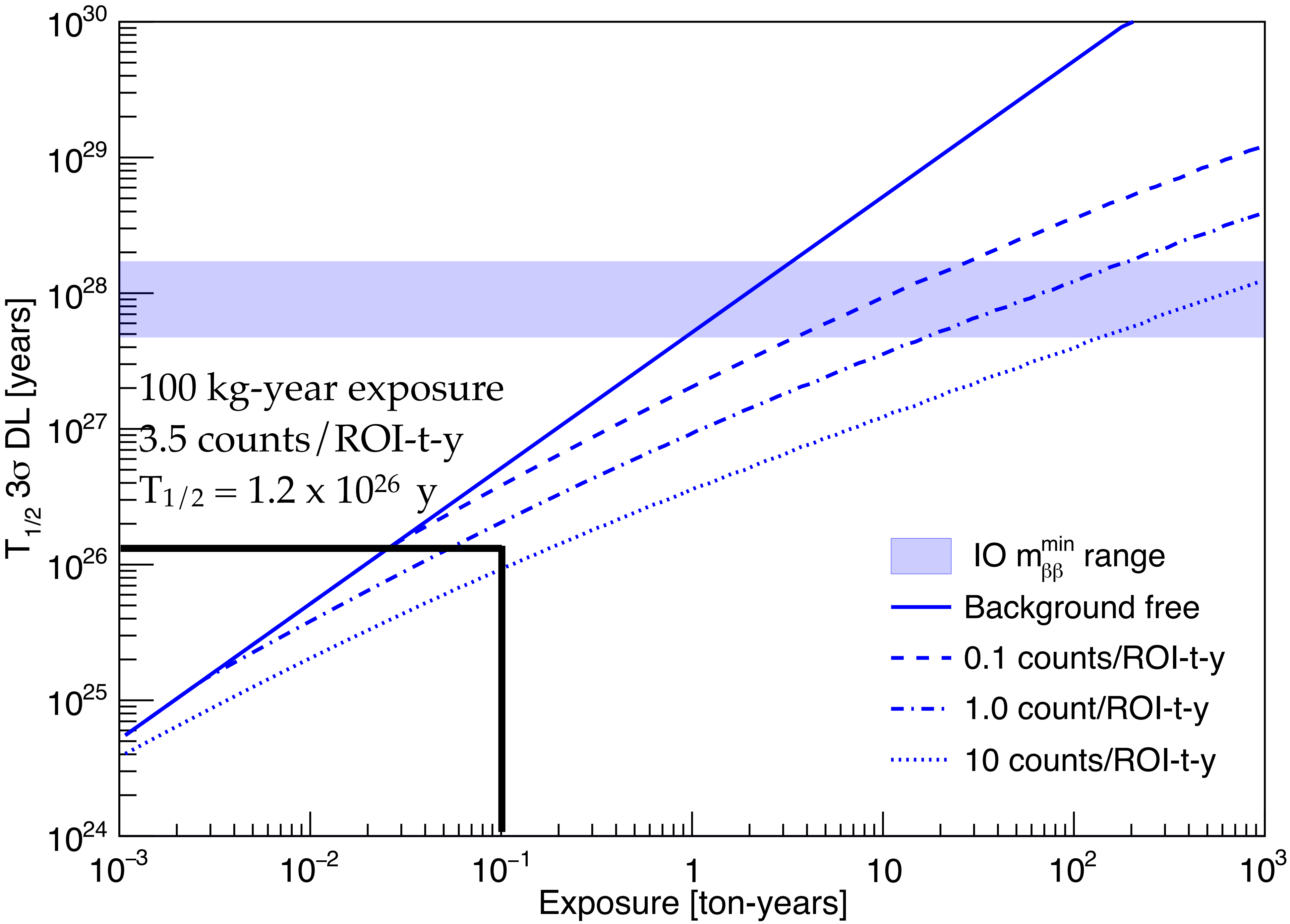
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

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

3σ Discovery vs. Exposure for ^{76}Ge

J. Detwiler



Inverted Ordering (IO)

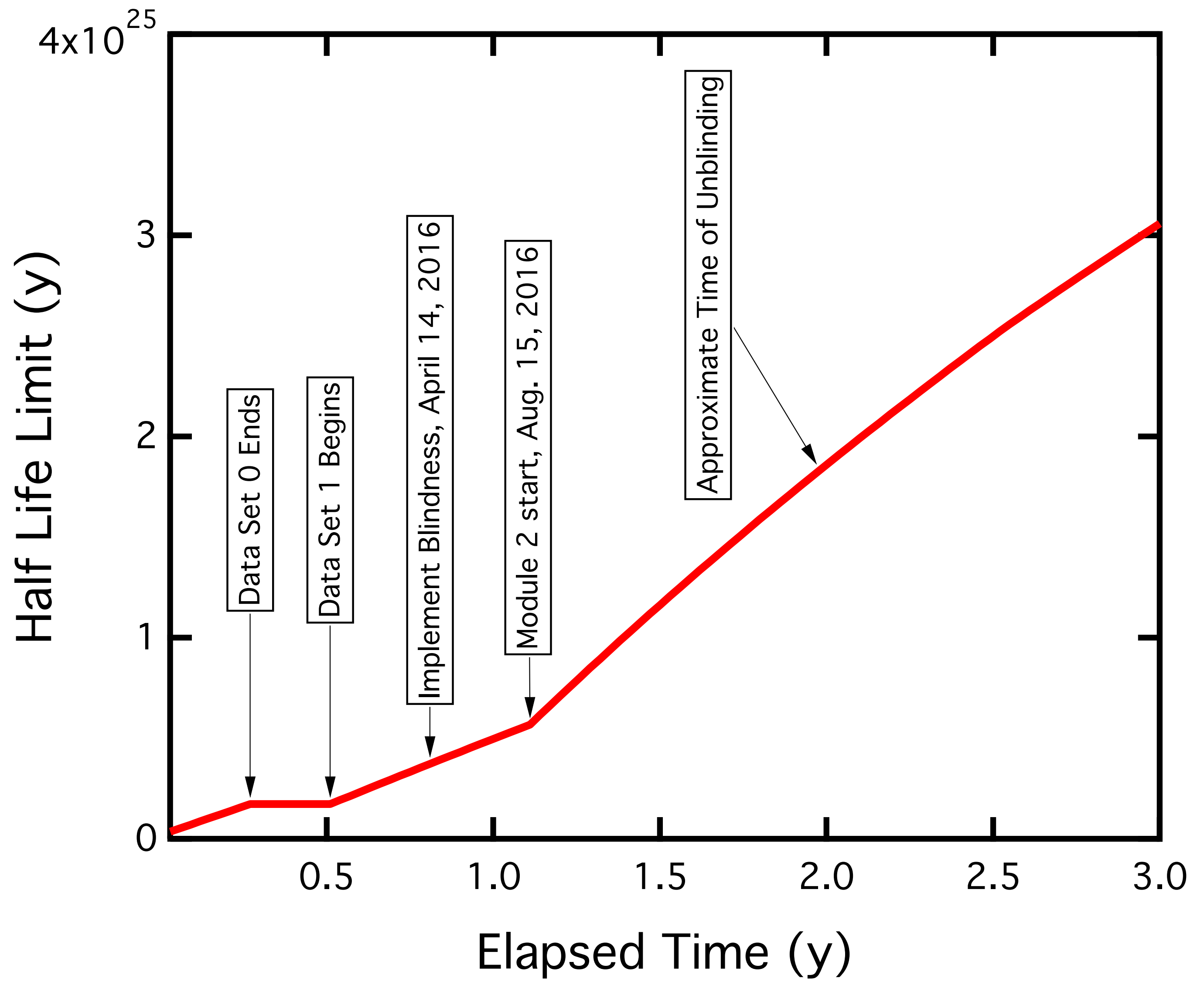
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

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

DS0 +DS1: 0ν Sensitivity

- No ROI events in either data set.
- T1/2 > 3.7x1024 y (90% CL).
- DS0 & DS1 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)
- 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%



Module 1 Improvements – Fall 2015

Operated in-shield June 2015 - Oct. 2015
- Partial shielding and some high-background components

During Oct.- Dec. 2015 performed planned improvements to Module 1.
- Installed inner Cu shield: Decrease background contribution from outer Cu shield and Pb by factor of about 10.
- Replaced Kalrez O-rings in cryostat: These o-rings contributed to our background. Replaced with PTFE.
  - Kalrez: Th ~ 2000-4000 ppt. Expect about 80 c/ROI t y.
  - PTFE sheet: significant reduction in BG compared to Kalrez.

Crossarm Shielding: Added to decrease background contributions from electronics-breakout box region.

Repaired non-operating detectors and upgrade cables:
- Repairing non-operating detectors (cable connection, HV connection, LMFE replacement, …)

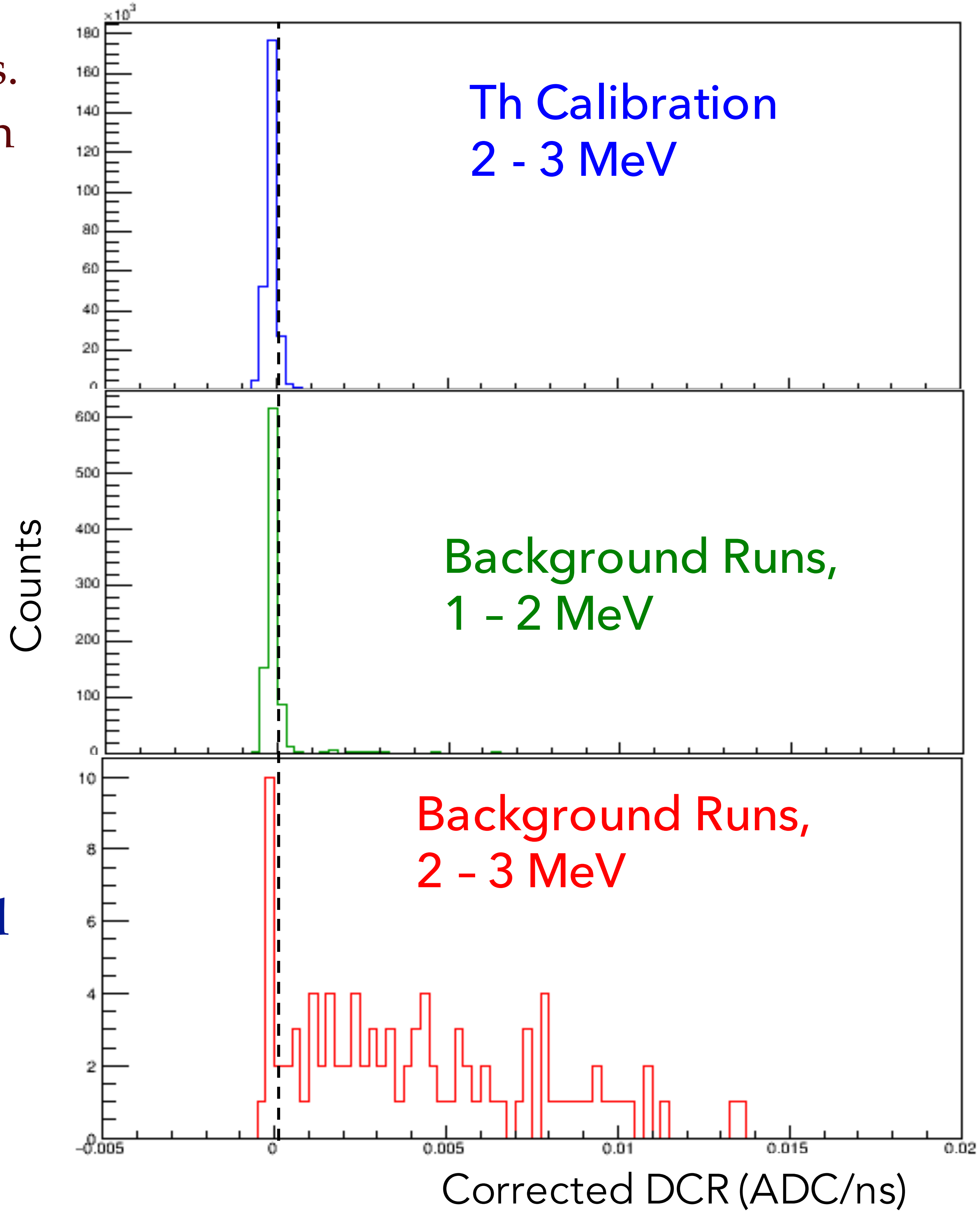
DS1 DCR Cut and Bulk-Event Response

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.