Initial Results and Status of the MAJORANA DEMONSTRATOR

@ The 26th International Workshop on Weak Interactions and Neutrinos

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On behalf of the MAJORANA Collaboration

UNIVERSITY OF SOUTH DAKOTA

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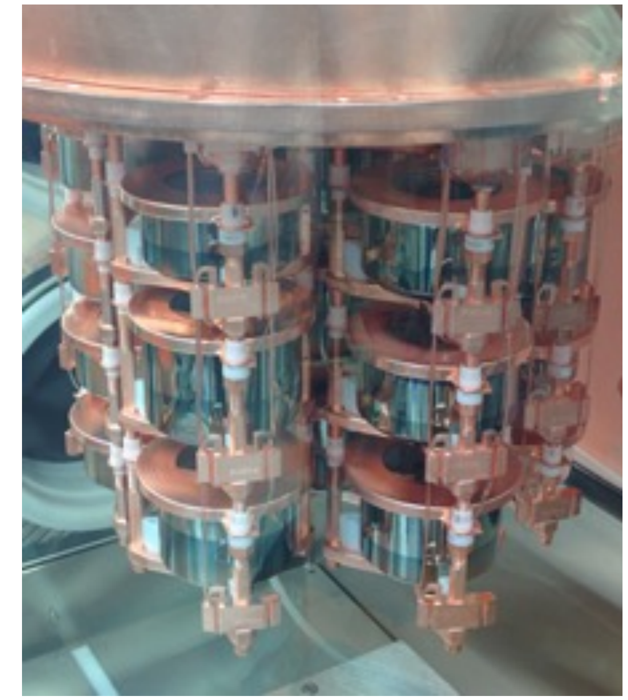
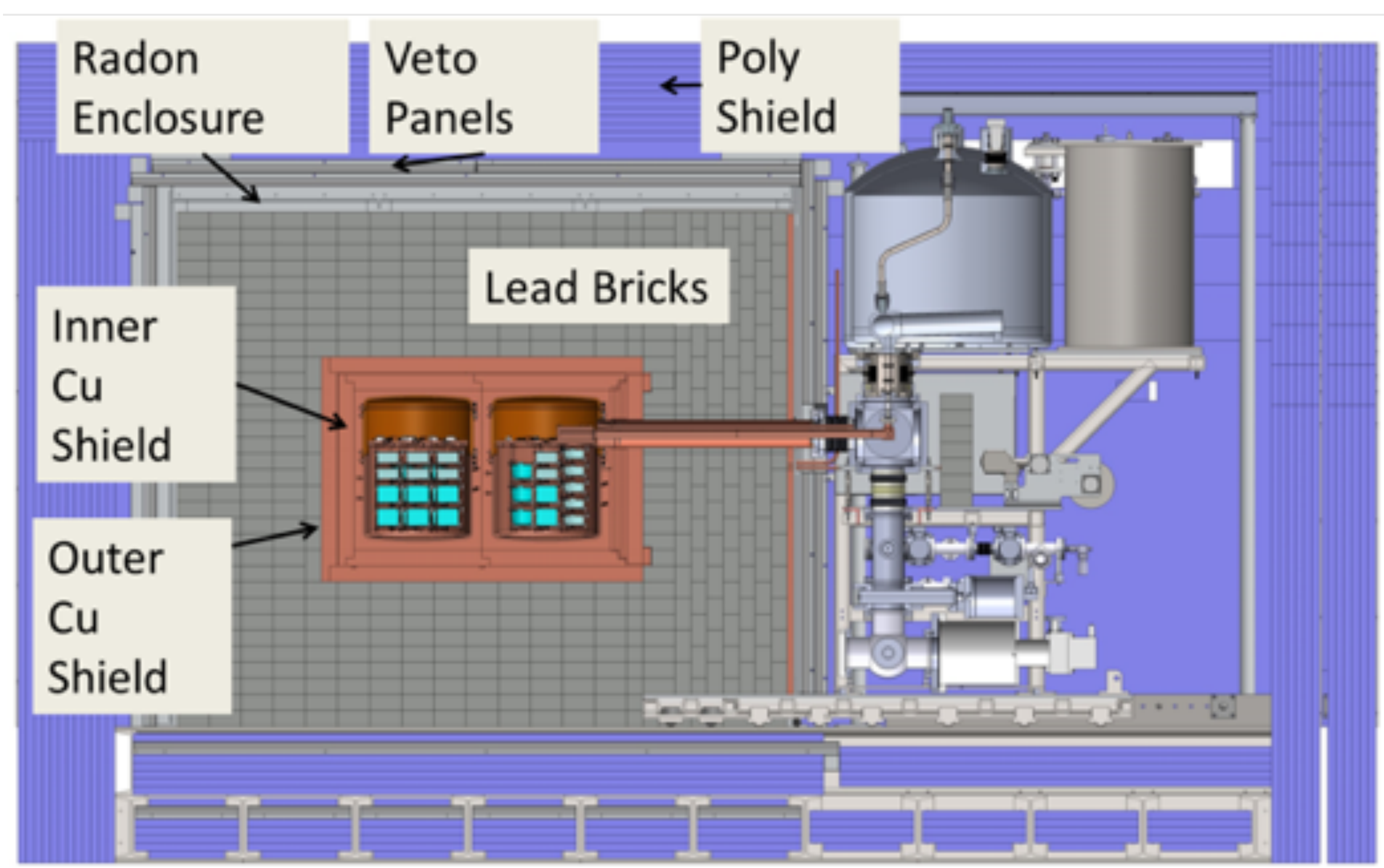
The MAJORANA DEMONSTRATOR

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 expt.**
— Establish feasibility to construct & field modular arrays of Ge detectors.
— Search for additional physics beyond the standard model.

- **Operating underground** at 4850′ level of 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 UL currently ≤ 3.5
- **44.1 kg of Ge detectors**
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detectors: P-type, point-contact (PPC)
- **2 independent cryostats**
  - Ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - Naturally scalable
- **Ultra low-activity components and construction**
- **Compact Shield**
  - Low-background passive Cu and Pb shield with active muon veto

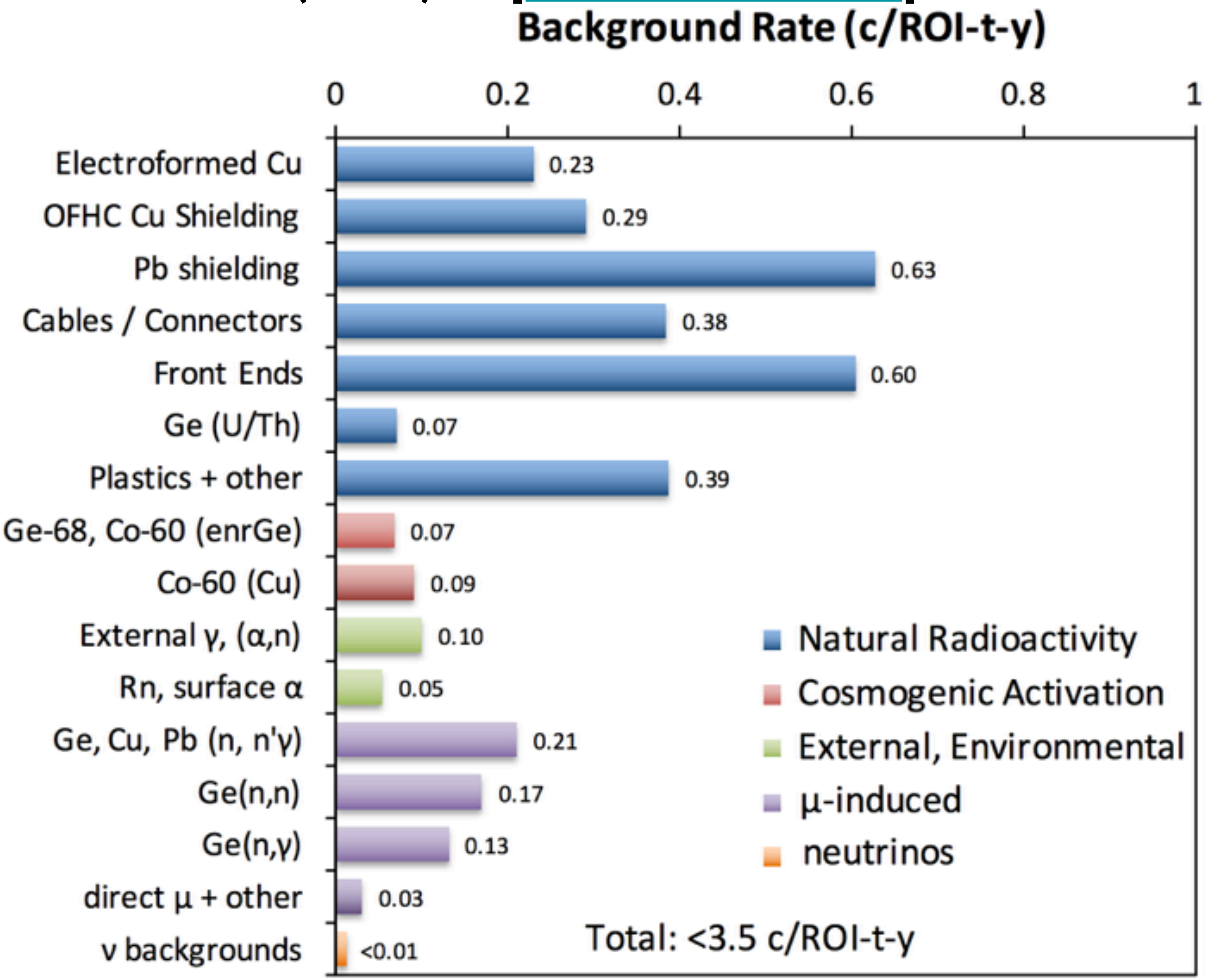


N. Abgrall *et al.*, Adv. High Ener. Phys. **2014**, 365432 (2013); arXiv:1308.1633

Background Model and Assay

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

NIMA 828 (2016) 22 [arXiv:1601.03779]

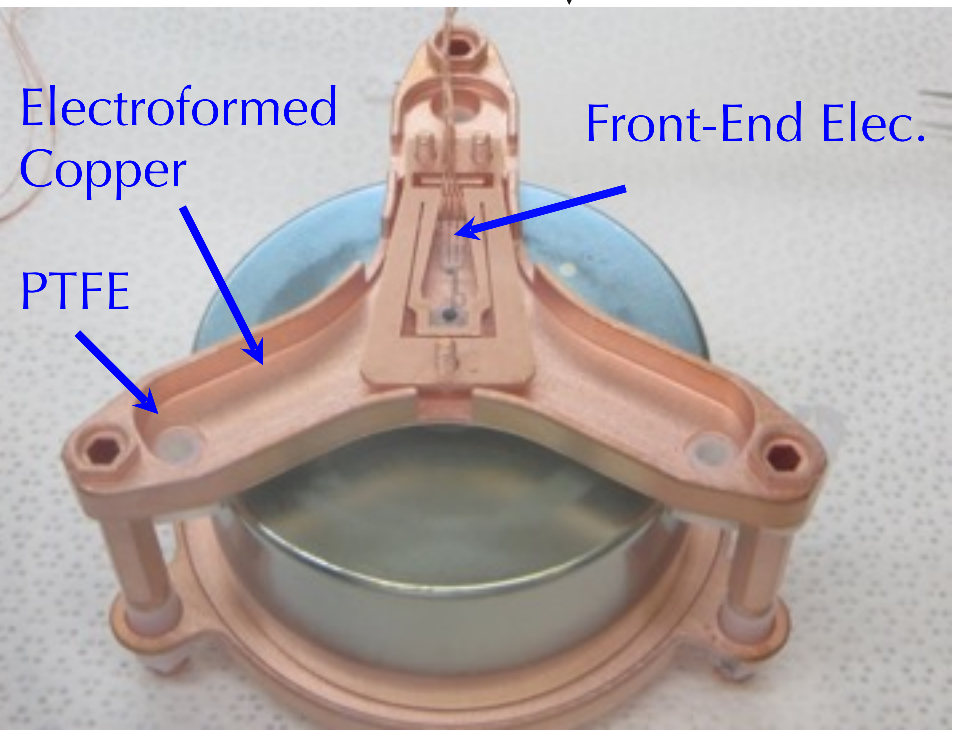


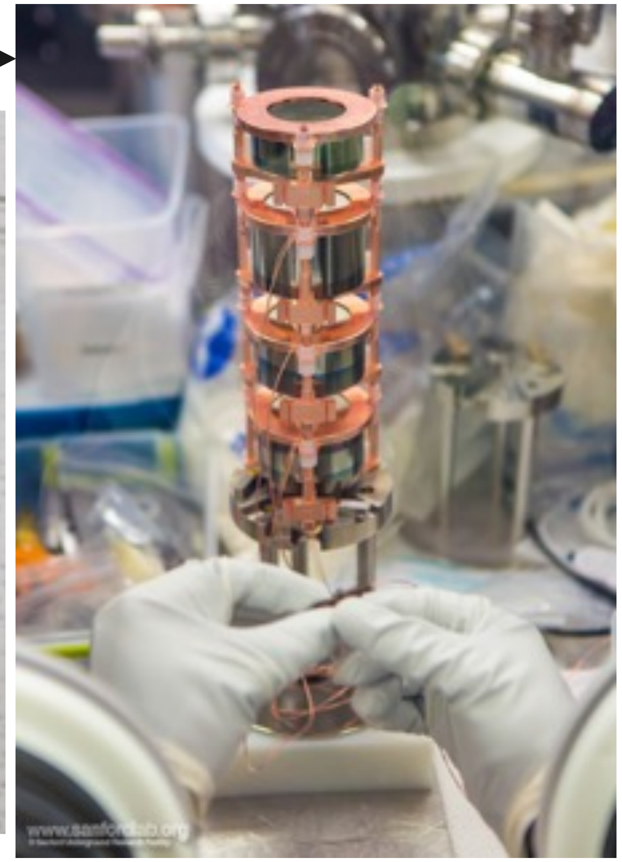
- MAJORANA operated multiple baths to electroform copper in underground labs.
- All copper was machined at the SURF Davis campus.
- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg

Electroforming Baths at SURF

Module Construction

Detector unit ↓ String →

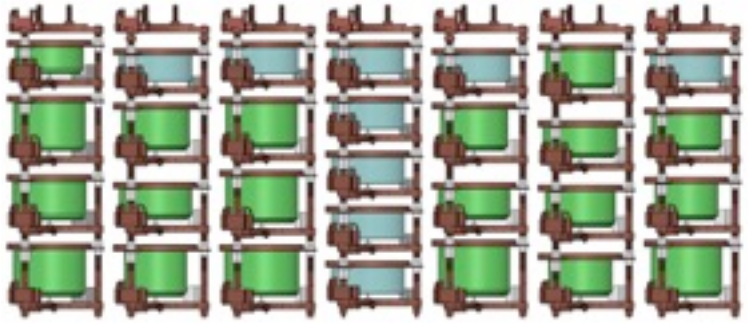




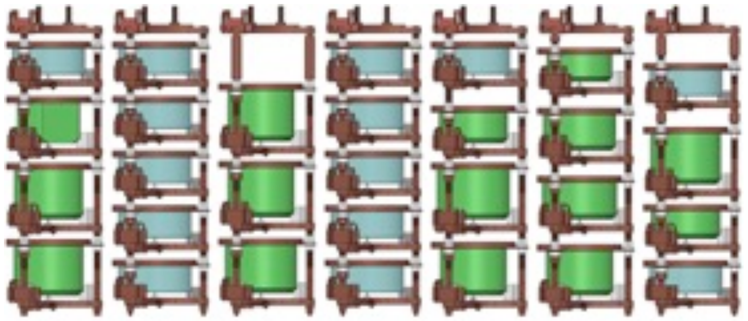
↑ open Module in glove box

← closed Module in shield

The DEMONSTRATOR Implementation



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

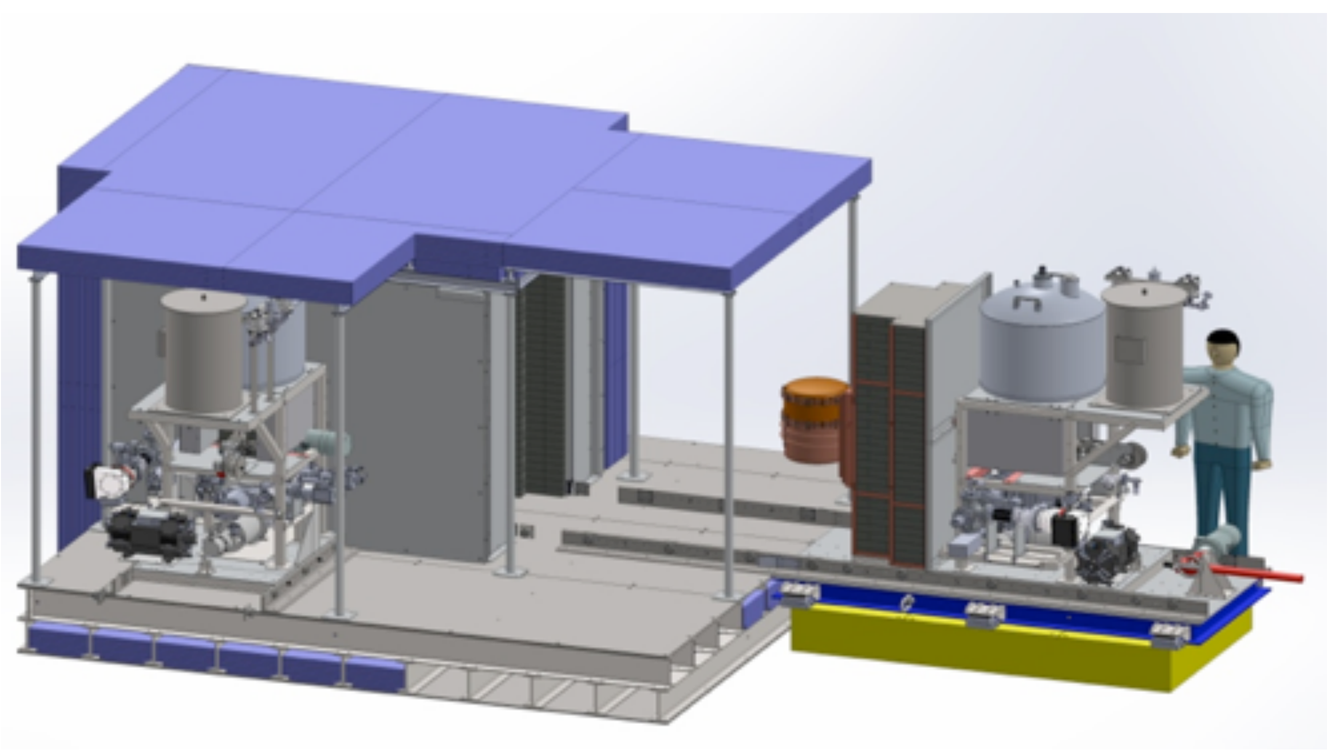


Module 2: 12.9 kg (15) ^{enr}Ge
8.8 kg (14) ^{nat}Ge

In-shield Running

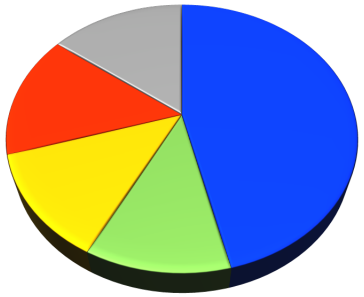
05/2015 – 10/2015
Module Improvements
01/2016 – ongoing

07/2016 – ongoing



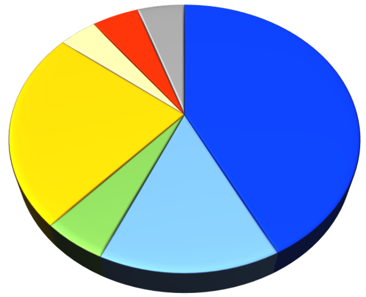
MAJORANA Data Sets

DS-0



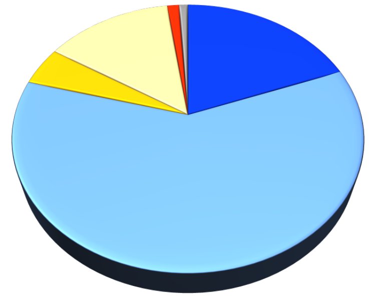
M1 Commissioning, no inner shield

DS-1



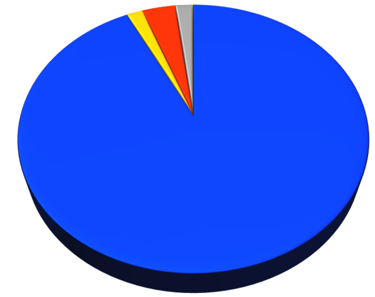
M1 inner shield

DS-2

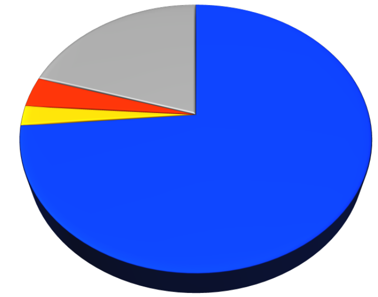


M1 multi-sampling

DS-3

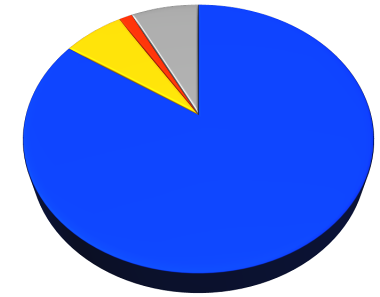


DS-4



Modules 1 and 2 Together in-shield

DS-5



Modules 1 and 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

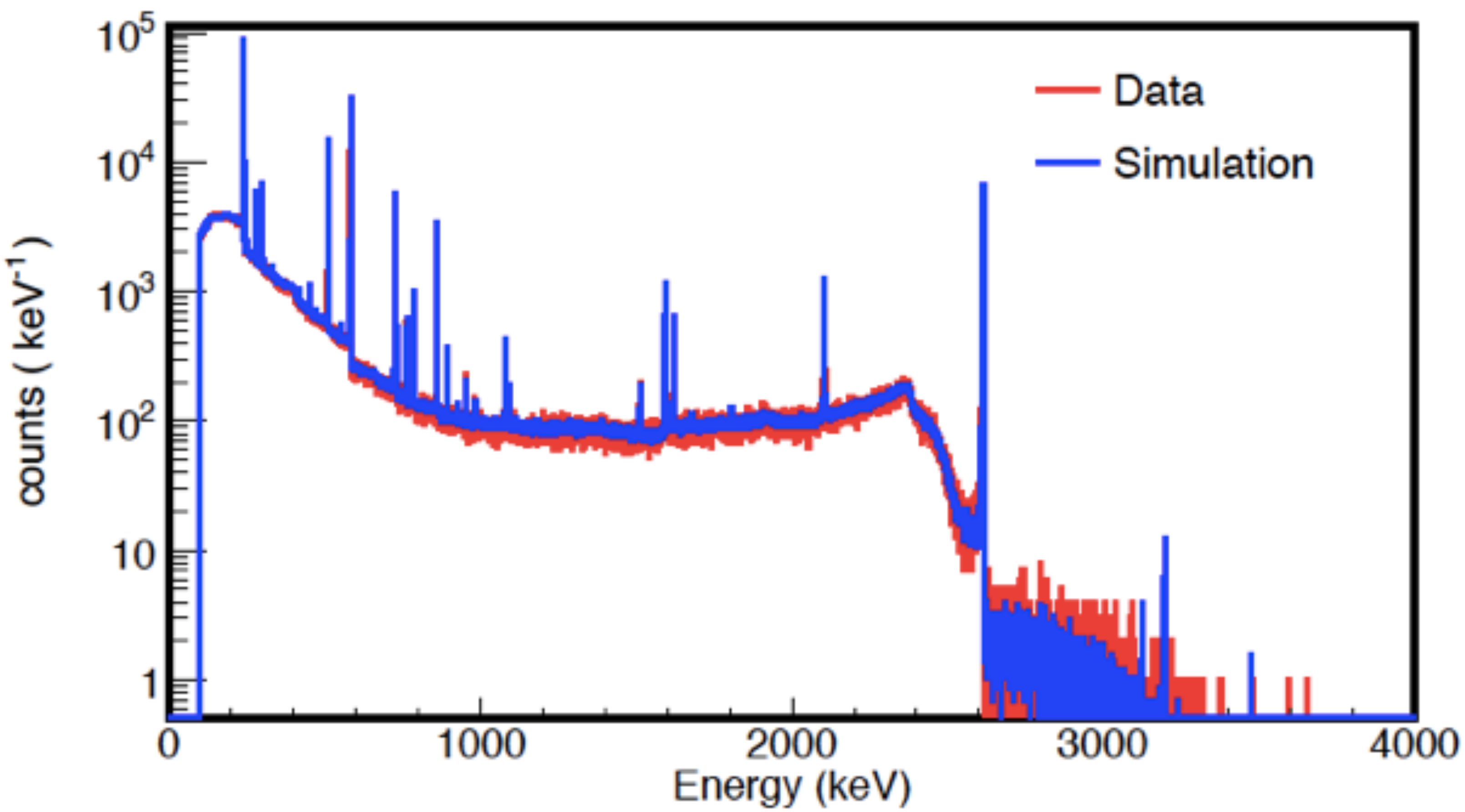
DS6 has started with multisampling and blindness

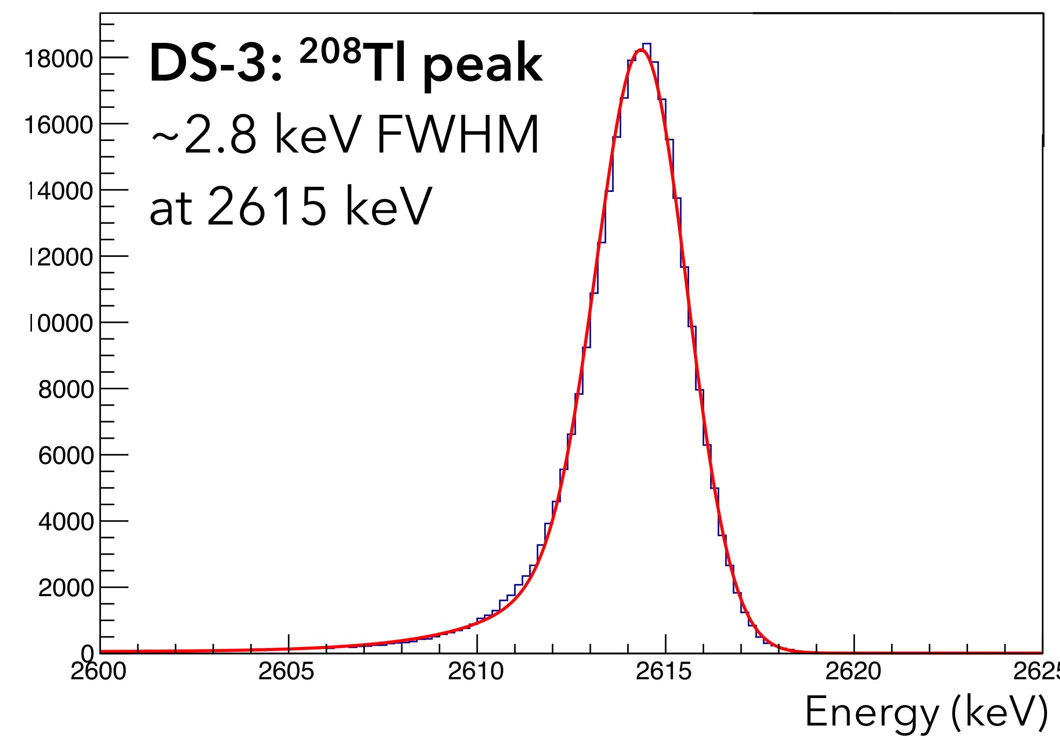
*Values up to Jan. 19, 2017

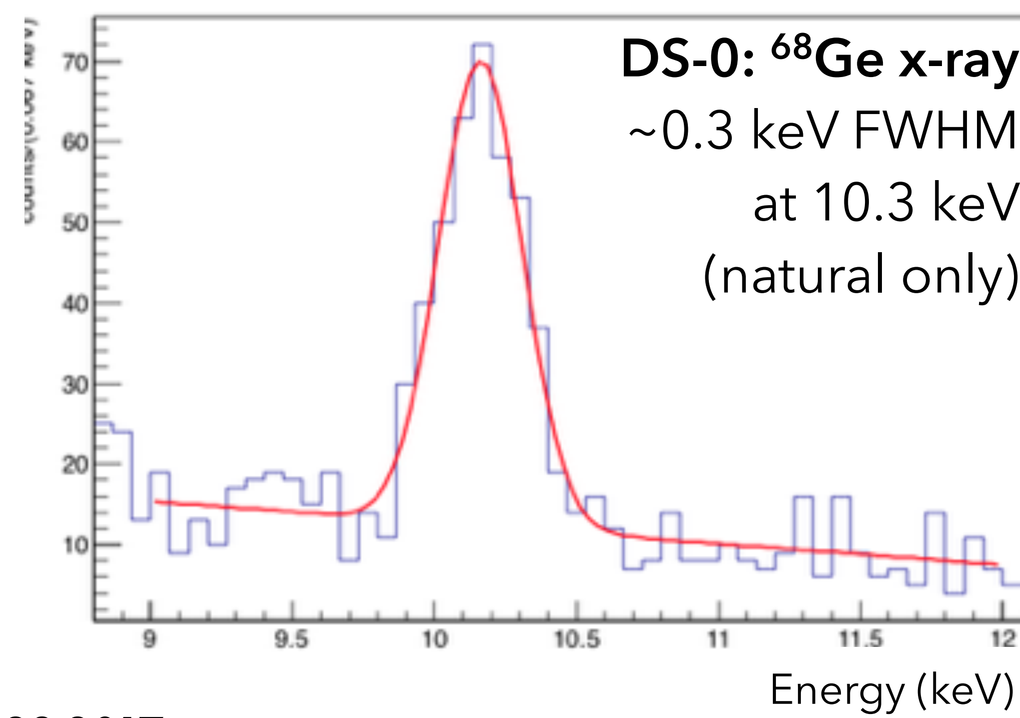
Calibrating the DEMONSTRATOR

Using custom ^{228}Th line sources and routine remote calibration:

- Multi-peak fitter employed, online database stores results
- Calibration paper: [arXiv:1702.02466]

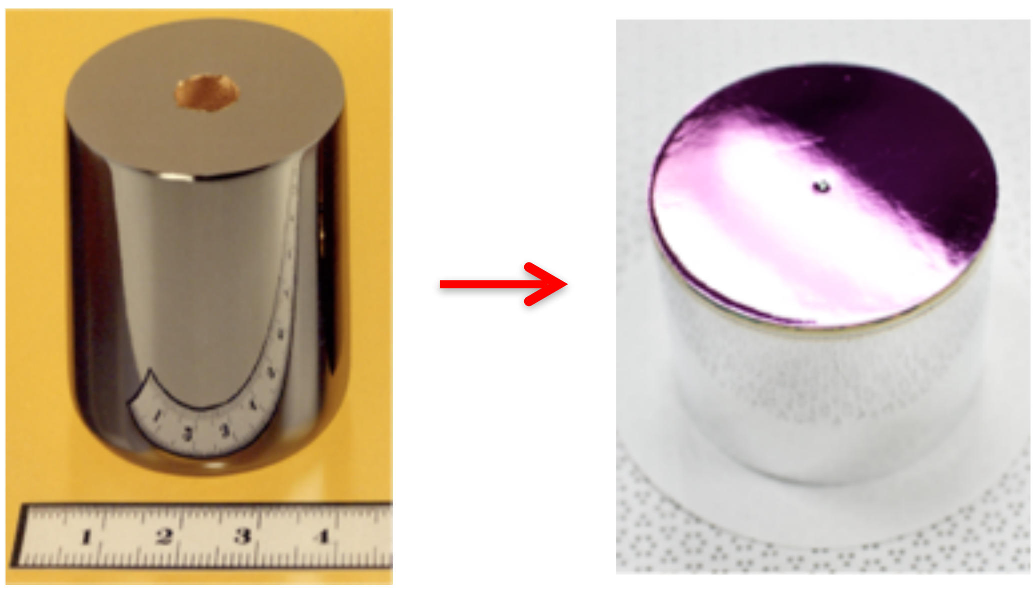


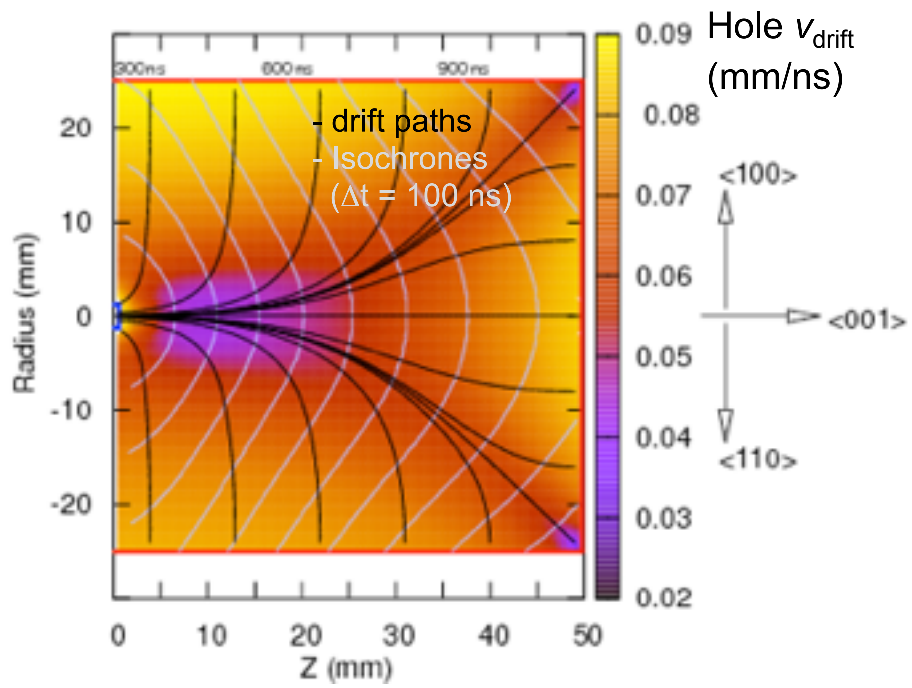


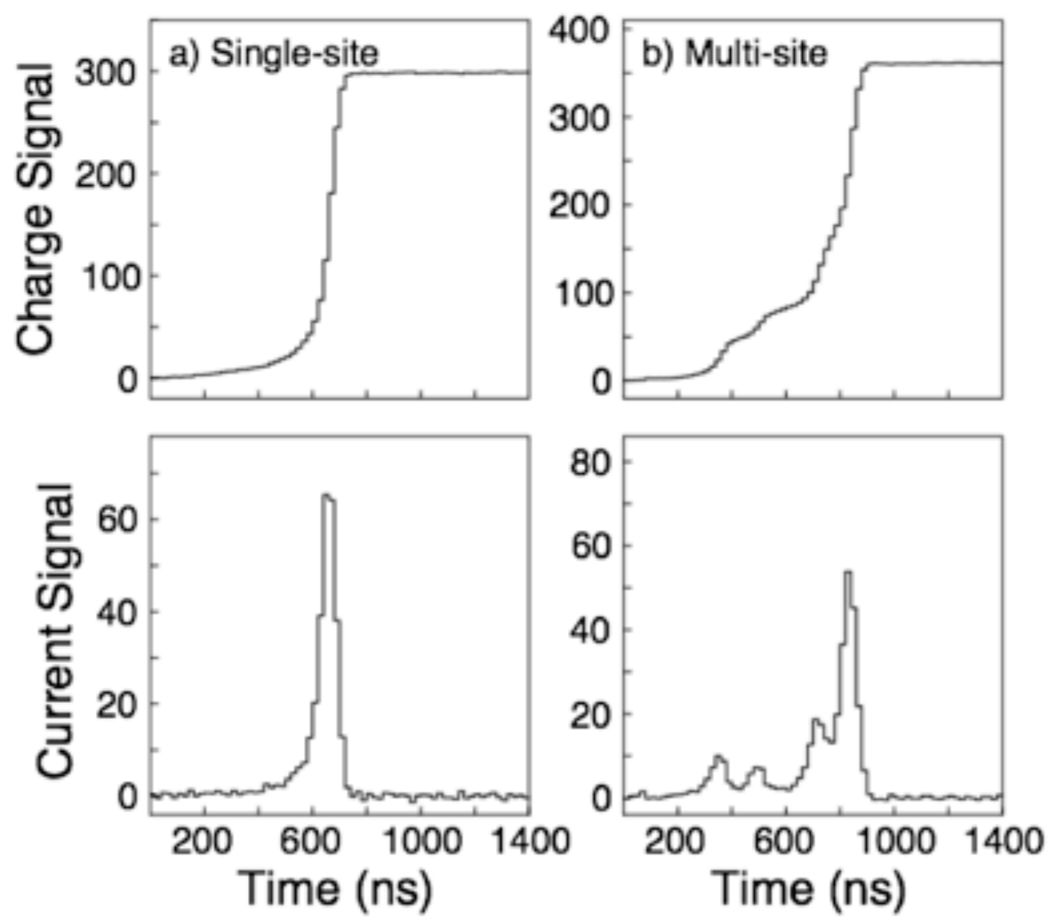


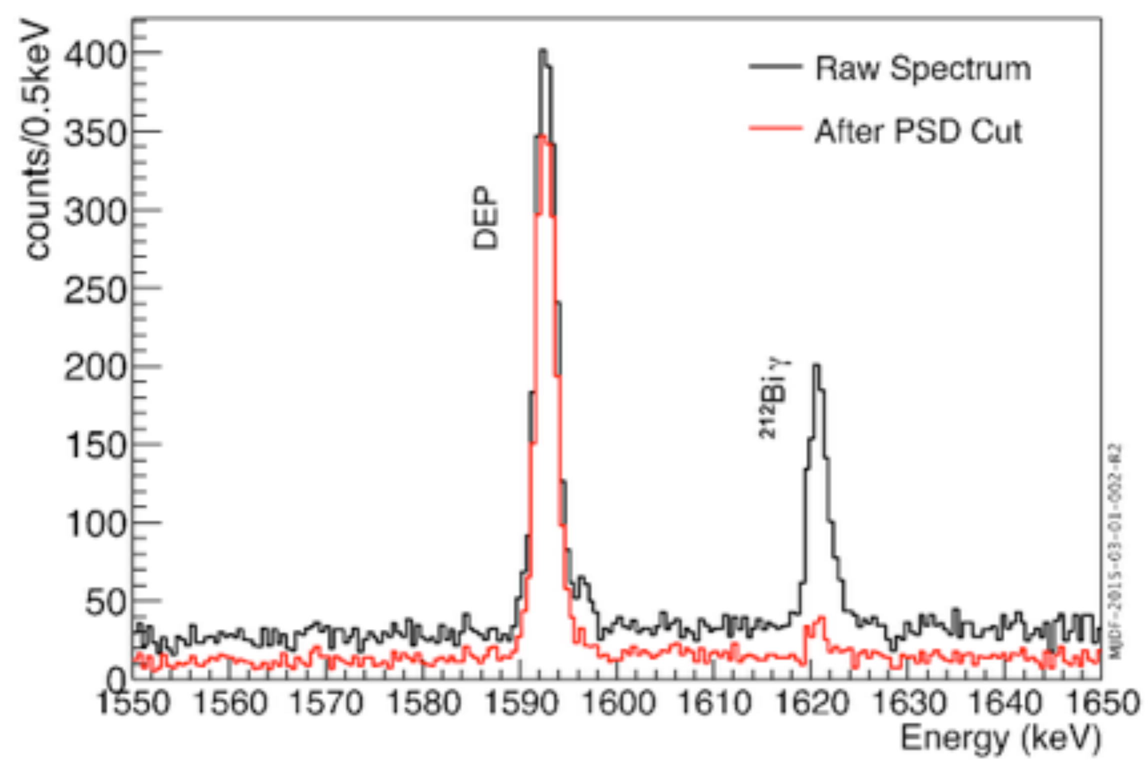
PPC Detector PSD Performance

Pulse Shape Discrimination (PSD) cuts have better performance in PPC detectors







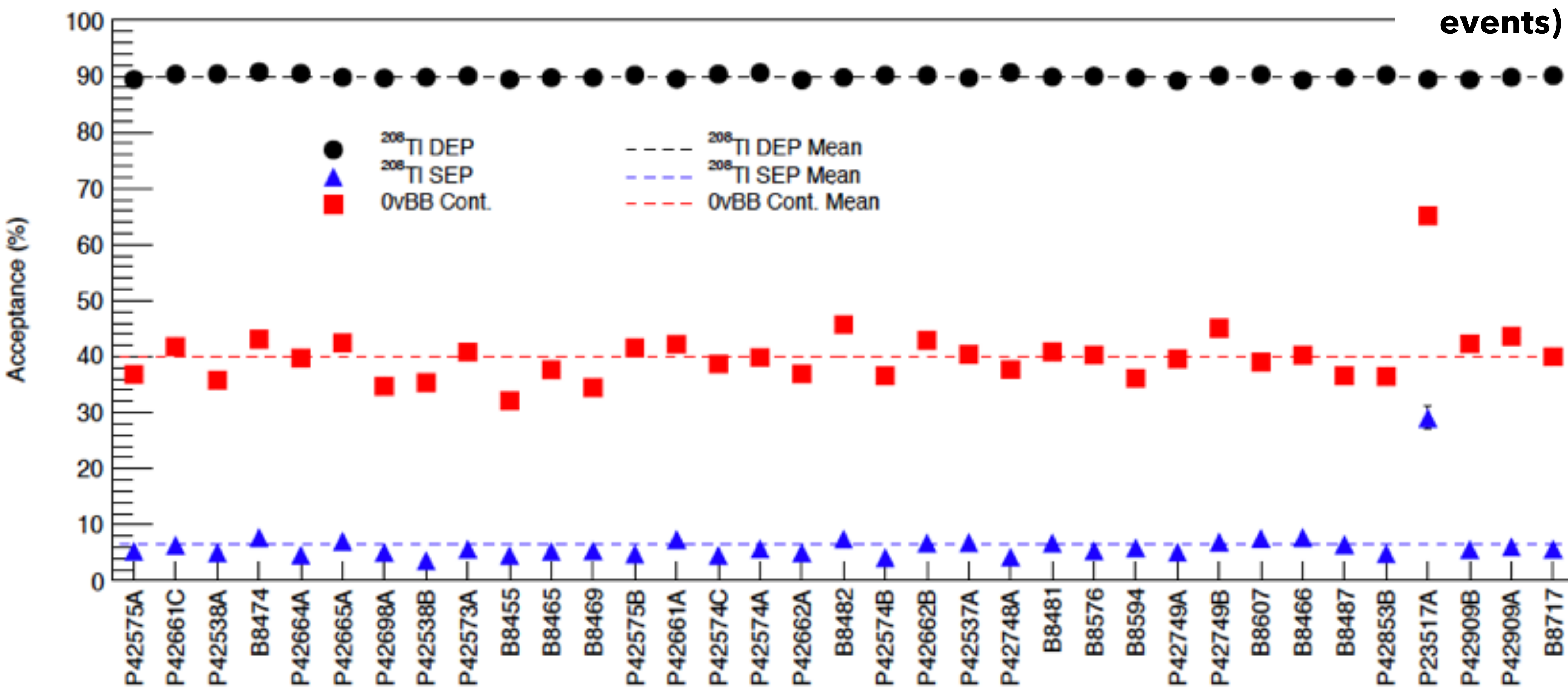


Luke et al., IEEE trans. Nucl. Sci. 36 , 926 (1989)
Barbeau, Collar, and Tench, J. Cosm. Astro. Phys. 0709 (2007).

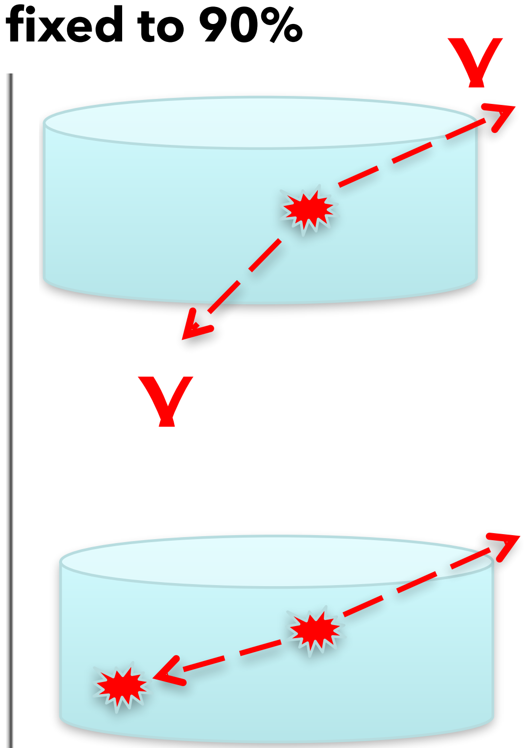
Ge Detector PSD Performance

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 have pair production and with annihilation γ's escaping
- Both γ's escape from detectors → double escape peak (DEP), single site
- One γ escapes from detectors → Single escape peak (SEP), multi-site



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



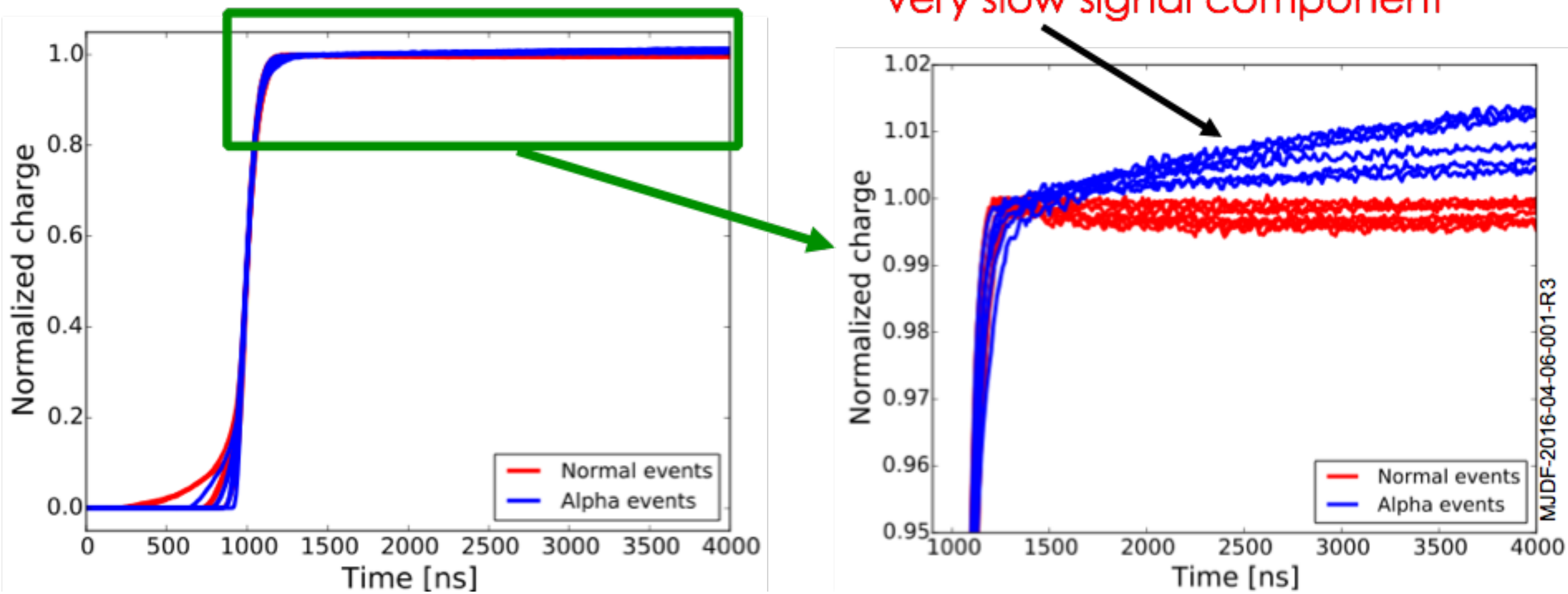
^{208}Tl SEP (multiple site events) reduced to 6%

Delayed-Charge Recovery Cut for α's

- Alpha background with degraded energies observed in DS-0
- 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

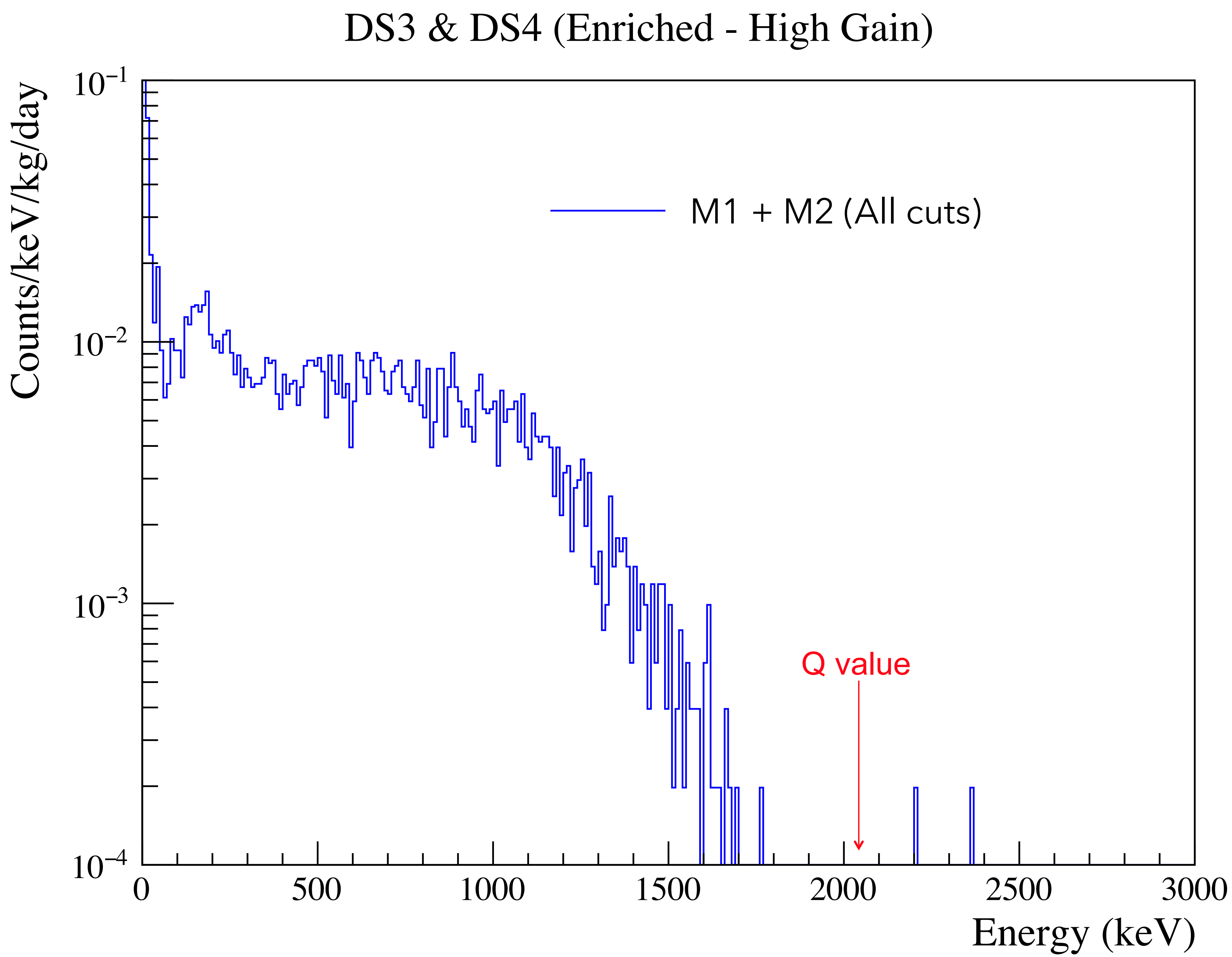
Slow drift of charges along passivated surface results in very slow signal component



Estimated 0νββ-decay ROI background, DS-3&4

Lowest background configuration, with both modules in shield.

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

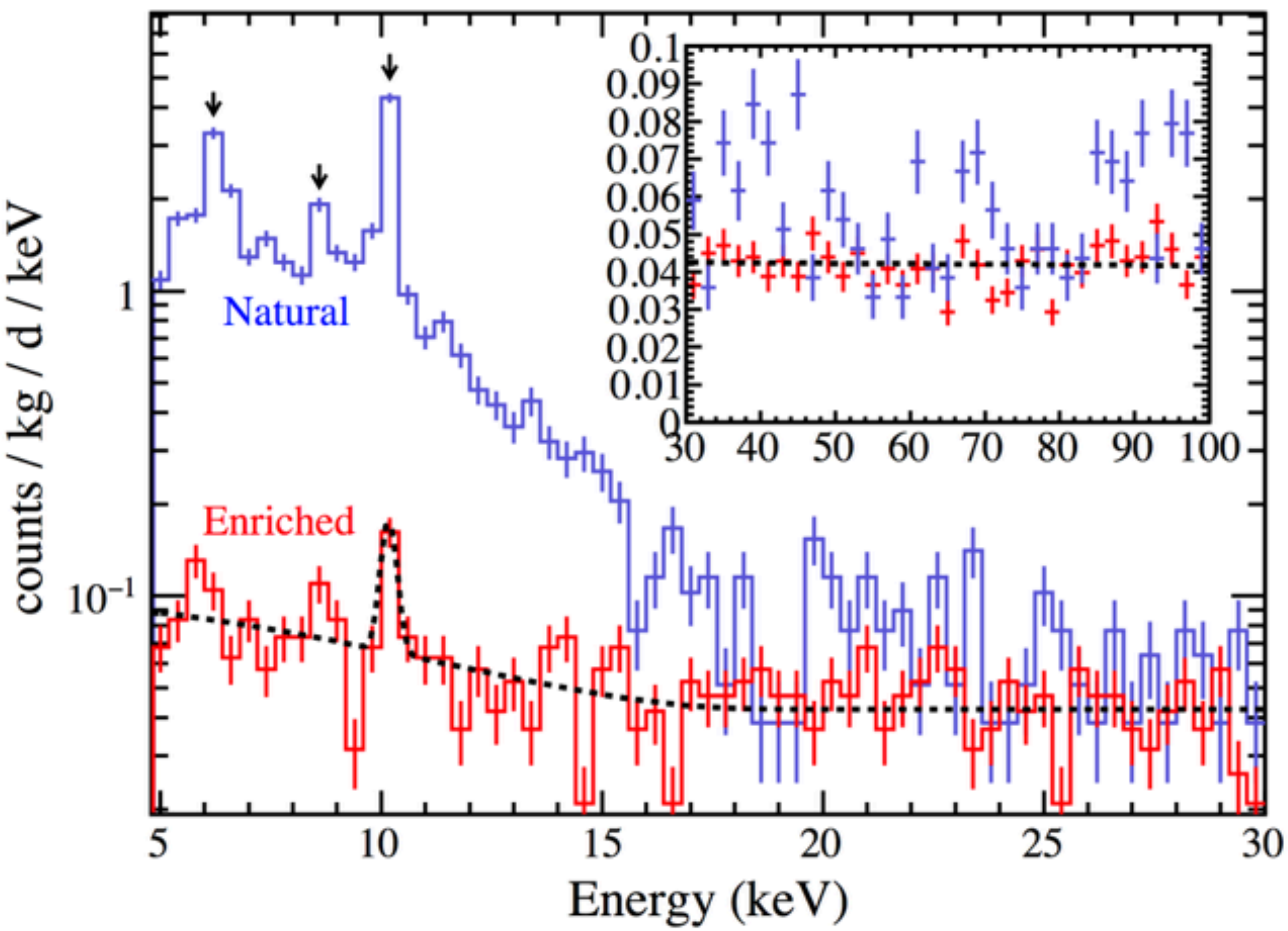


- Exposure: 1.39 kg y
- After cuts, 1 count in 400 keV window centered at 2039 keV (0νββ peak)
- Projected background rate is 5.1 $^{+8.9}_{-3.2}$ c /(ROI t y) for a 2.9 (Module1-DS3) & 2.6 (Module2 - DS4) keV ROI, (68% CL).
- Background index of 1.8×10^{-3} c/(keV kg y)
- Analysis cuts are still being optimized.
- Through mid-May, have 10x more exposure in hand. Analysis is in progress.

Low-Energy Spectrum in DS-0

- Significant reduction of the cosmogenics in the low-energy region in enriched detectors, due to tight surface exposure control.
- Tritium is obvious and dominates in natural detectors below 20 keV.

DS-0 (commissioning data): Natural 4.1 kg (~195kg d) Enriched 10.06 kg (~478 kg d)



PRL 118, 161801 (2017)

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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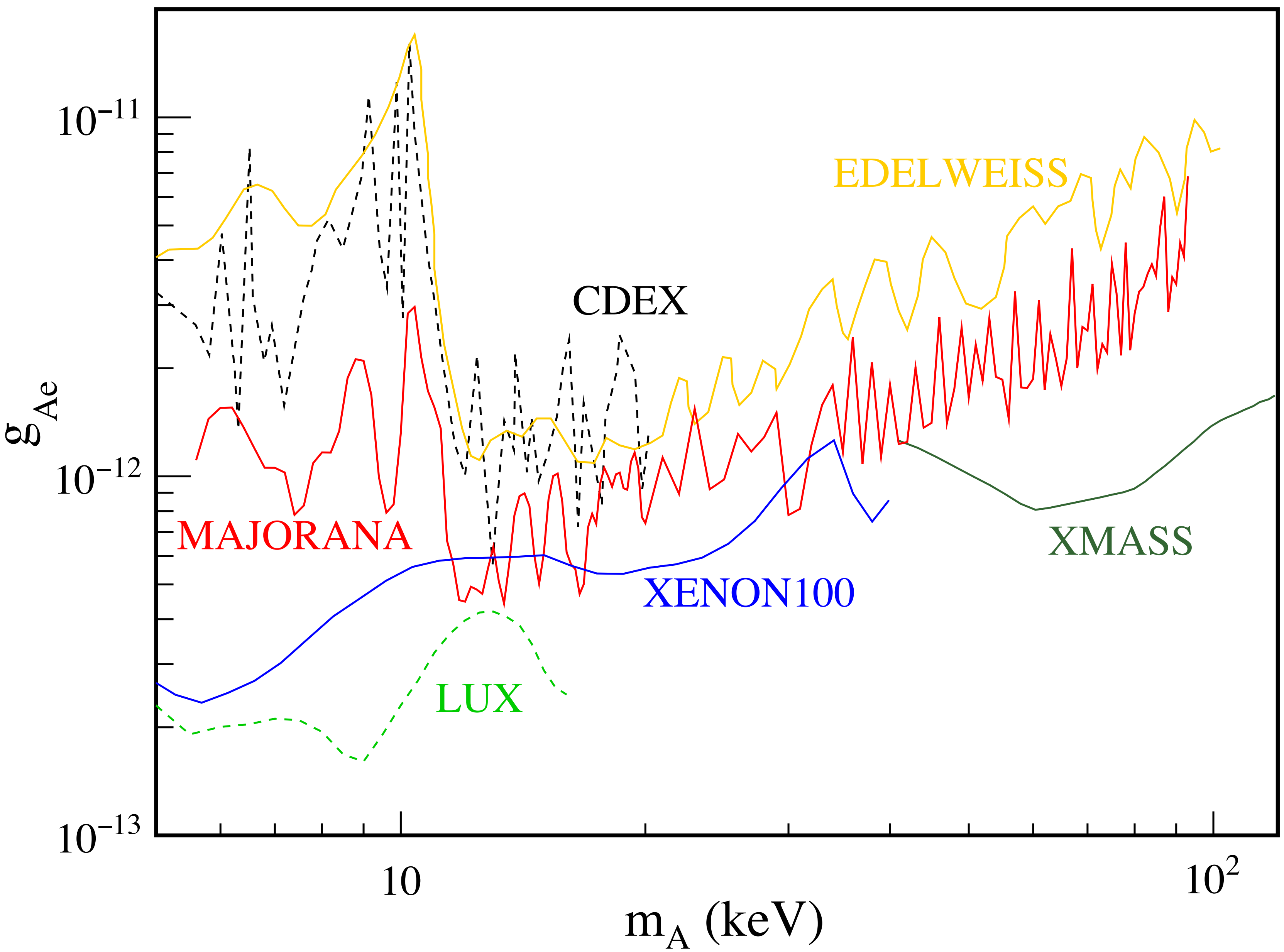

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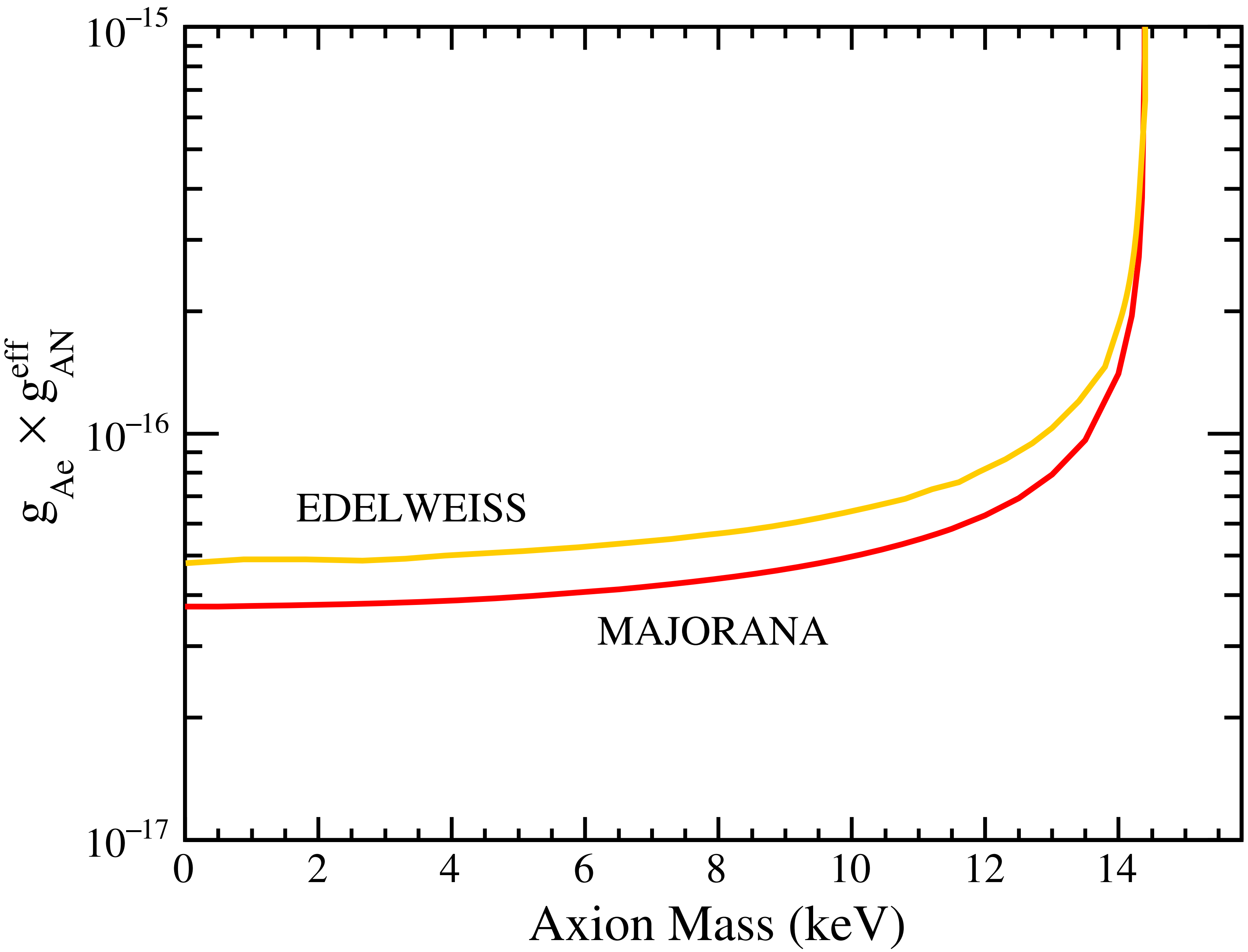

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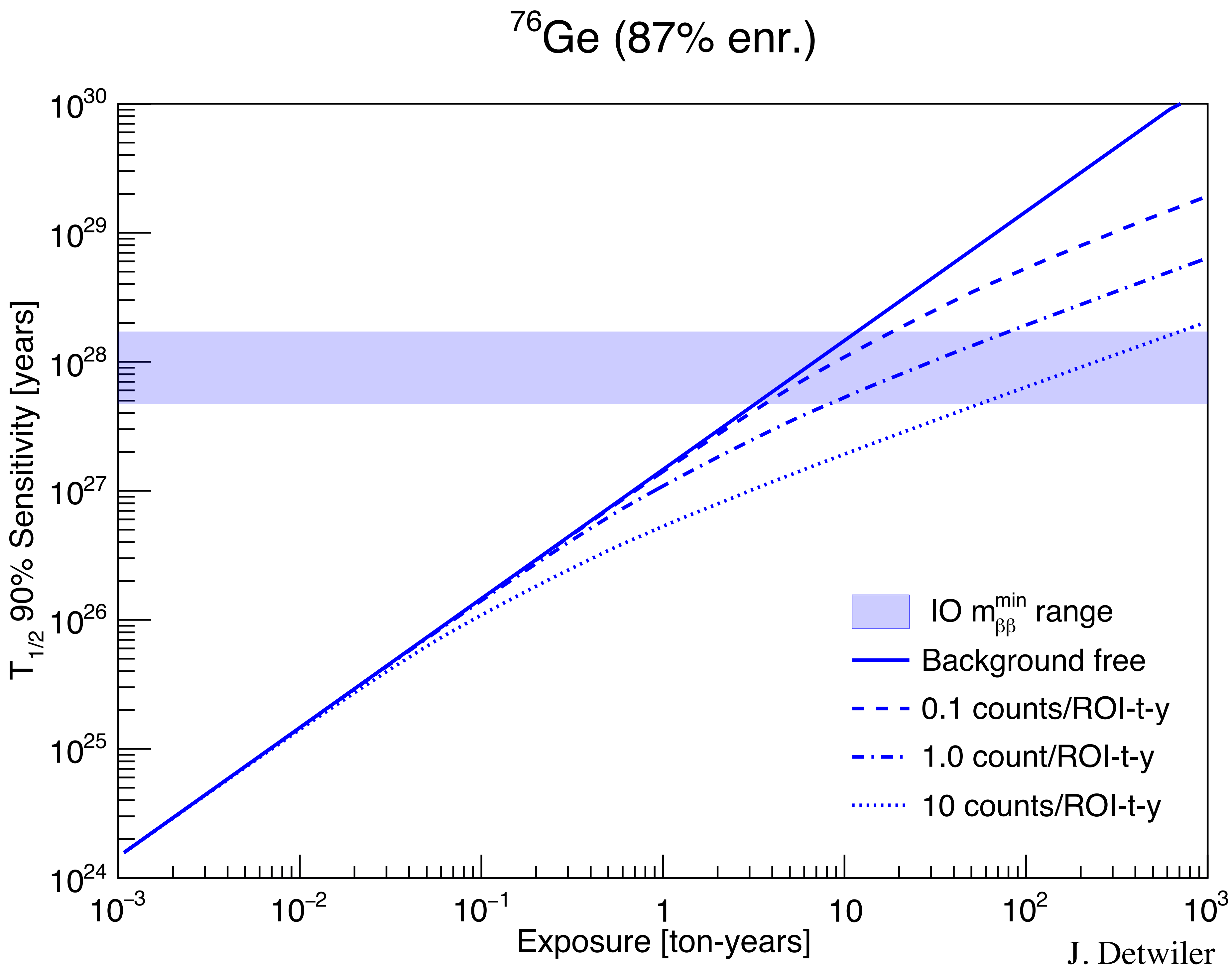
Sensitivity of 0νββ Decay v.s. Exposure

Ge-based experiments

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



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

LEGEND

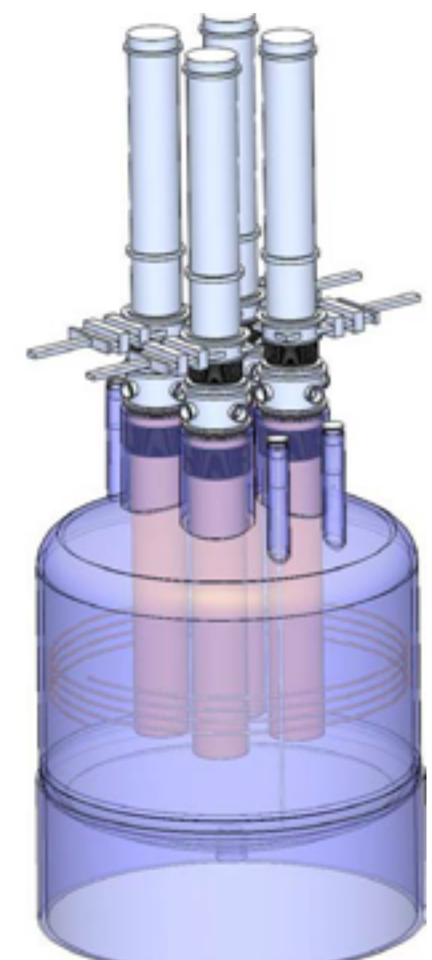
Large Enriched Germanium Experiment for Neutrinoless ββ Decay (47 institutions, 219 scientists)

Mission: “The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results.”

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First phase:
- up to 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal 0.6 c /(FWMH t y)
- start by 2021

Subsequent stages
- staged 1000 kg
- timeline connected to U.S. DOE down select process
- BG: goal 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (Ge-77m) under investigation



Summary and 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 $\beta\beta$-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 tests in this region for physics beyond the standard model (PRL **118**, 161801 (2017)).

- The DEMONSTRATOR's initial backgrounds and the GERDA Phase II backgrounds are by over an order of magnitude the lowest backgrounds in the region of interest (ROI) achieved to date of all current or previous $0\nu\beta\beta$ experiments.

- 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 /(FWHM t y) and energy resolution necessary for discovery level sensitivities in the inverted ordering region.

The MAJORANA Collaboration

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BERKELEY LAB
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
Technische Universität München
Sanford Underground Research Facility
UNIVERSITY OF SOUTH CAROLINA
THE UNIVERSITY of TENNESSEE UT KNOXVILLE
NC STATE UNIVERSITY
大阪大学 OSAKA UNIVERSITY
UNIVERSITY OF SOUTH DAKOTA
Pacific Northwest NATIONAL LABORATORY Proudly Operated by Battelle Since 1965
PRINCETON UNIVERSITY
Queen's UNIVERSITY

Backup Slides

LEGEND

Large Enriched Germanium Experiment for Neutrinoless Decay

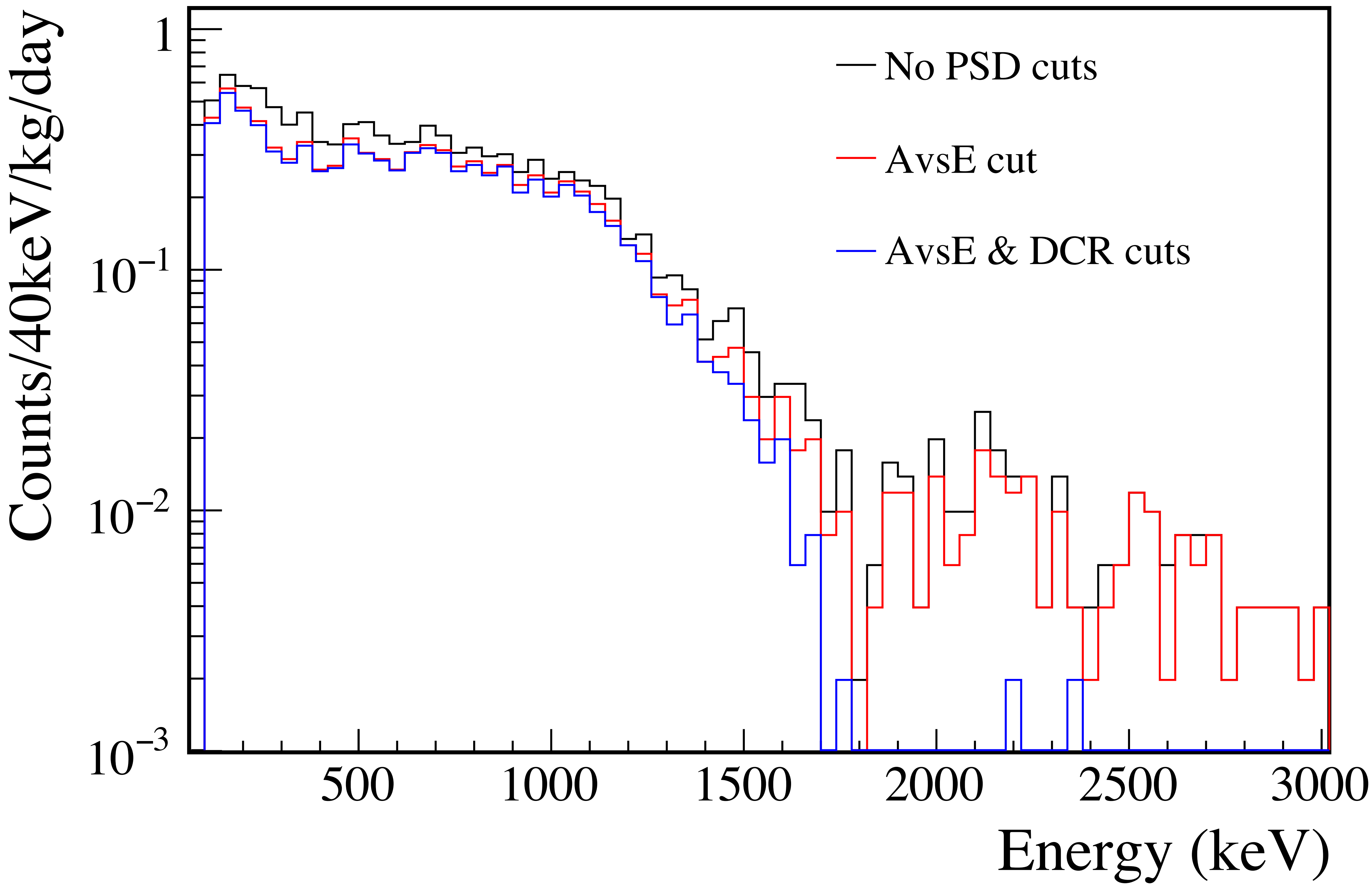
Working cooperatively with GERDA and other interested groups toward the establishment of a next-generation 76Ge 0vBB decay experimental collaboration, to build an experiment to explore the inverted ordering region of the effective mass.

Background Spectrum in DS-3 & DS-4

Lowest background configuration, with both modules in shield.

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

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



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

Muon Flux at the 4850' and Muon Veto

Muon veto system has run continuously since 2014:

- First opportunity for vertical μ-flux measurement using completed Pb shield
- Flux predicted for 4850 level (Hime & Mei, PRD 2006)

$$\Phi = (4.4 \pm 0.1) \times 10^{-9}\ \mu/s/\mathrm{cm}^2$$

- Our simulation (optimized for SURF):

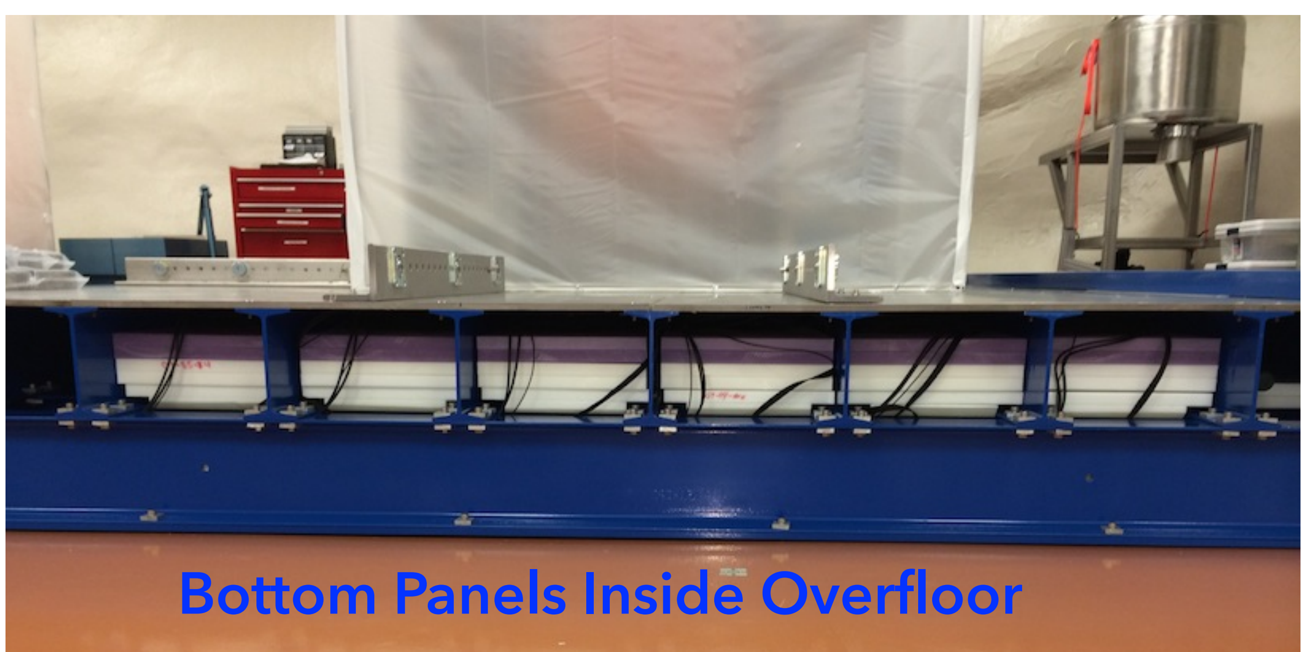
$$\Phi = (5.3 \pm 0.4) \times 10^{-9}\ \mu/s/\mathrm{cm}^2$$

- Measured flux:

$$\Phi = (5.31 \pm 0.17) \times 10^{-9}\ \mu/s/\mathrm{cm}^2$$

Astroparticle Physics in press

[arXiv:1602.07742]



Bottom Panels Inside Overfloor

Top Muon Veto Panels

0νββ: Half-Life and Neutrino Mass

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$T^{0\nu}_{1/2}$ 0νββ half-life. Best current result: > 3.0 x 10^{25} years [5]

$G^{0\nu}(Q_{\beta\beta}, Z)$ phase space factor: kinematics of emission of two electrons

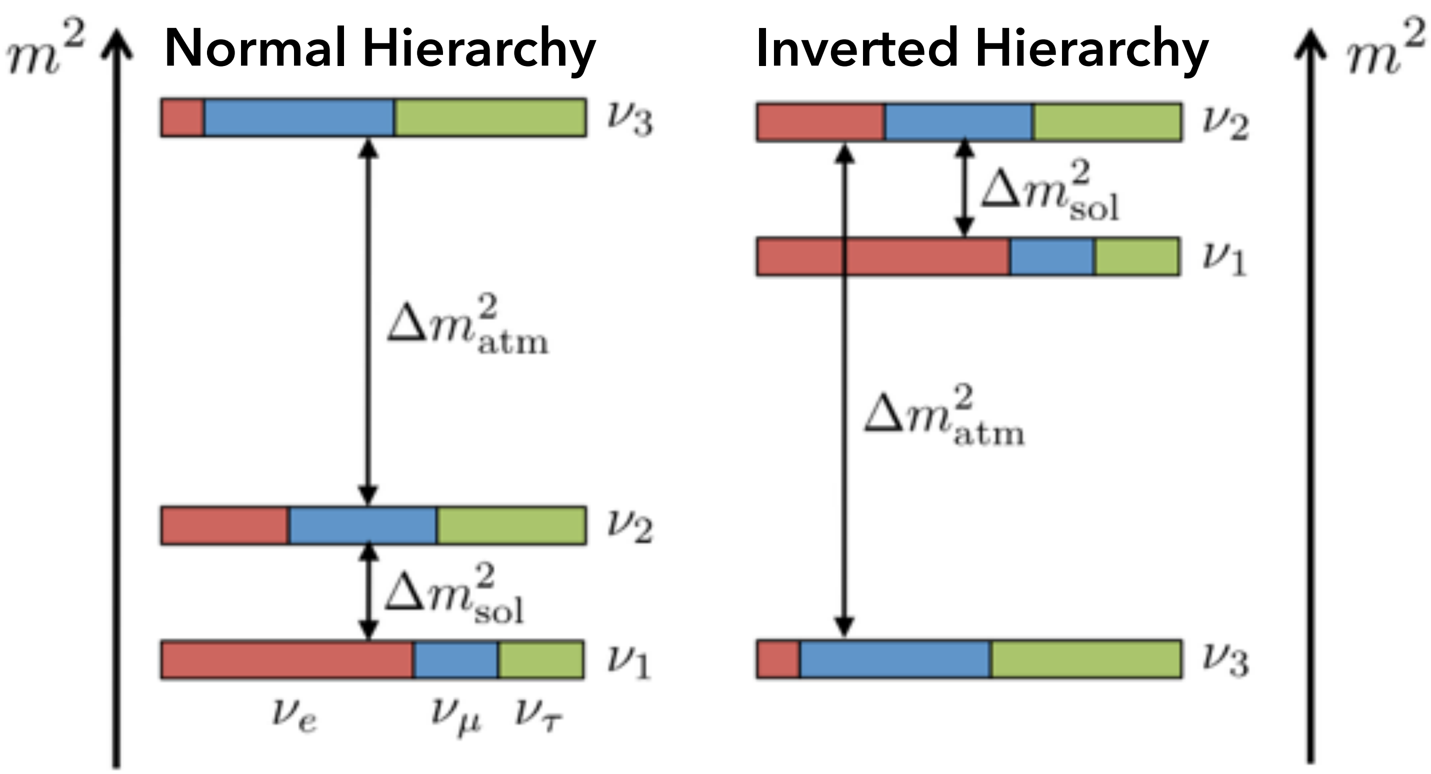
$M_{0\nu}$ nuclear matrix elements: govern transition probabilities

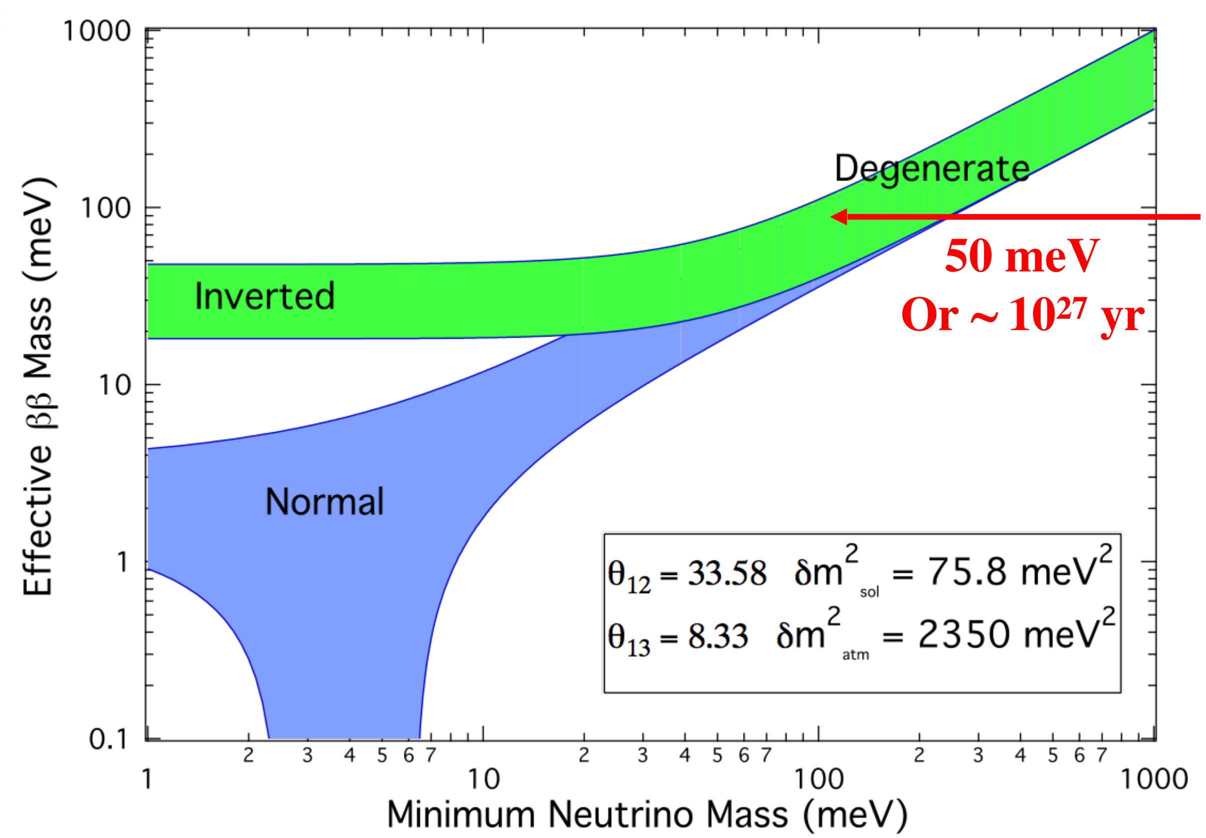
$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_k m_k U_{ek}^2\right|$$

Effective Majorana mass of electron neutrino

Contributions from electron terms in mixing matrix U

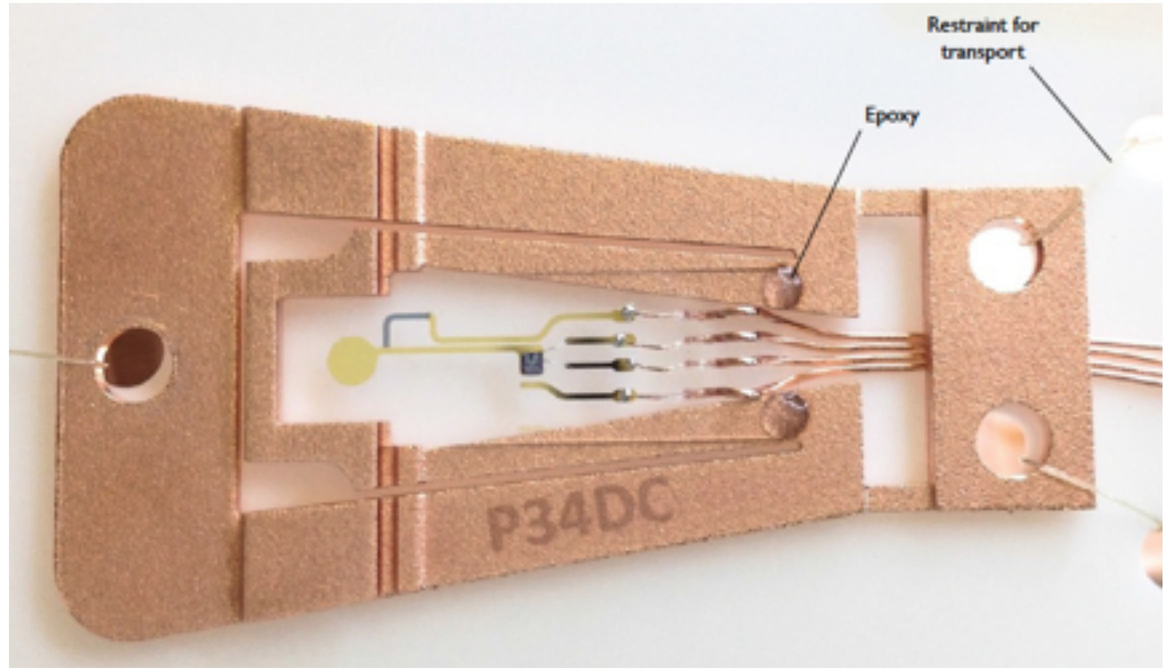
Measurements constrain the minimum mass eigenstate

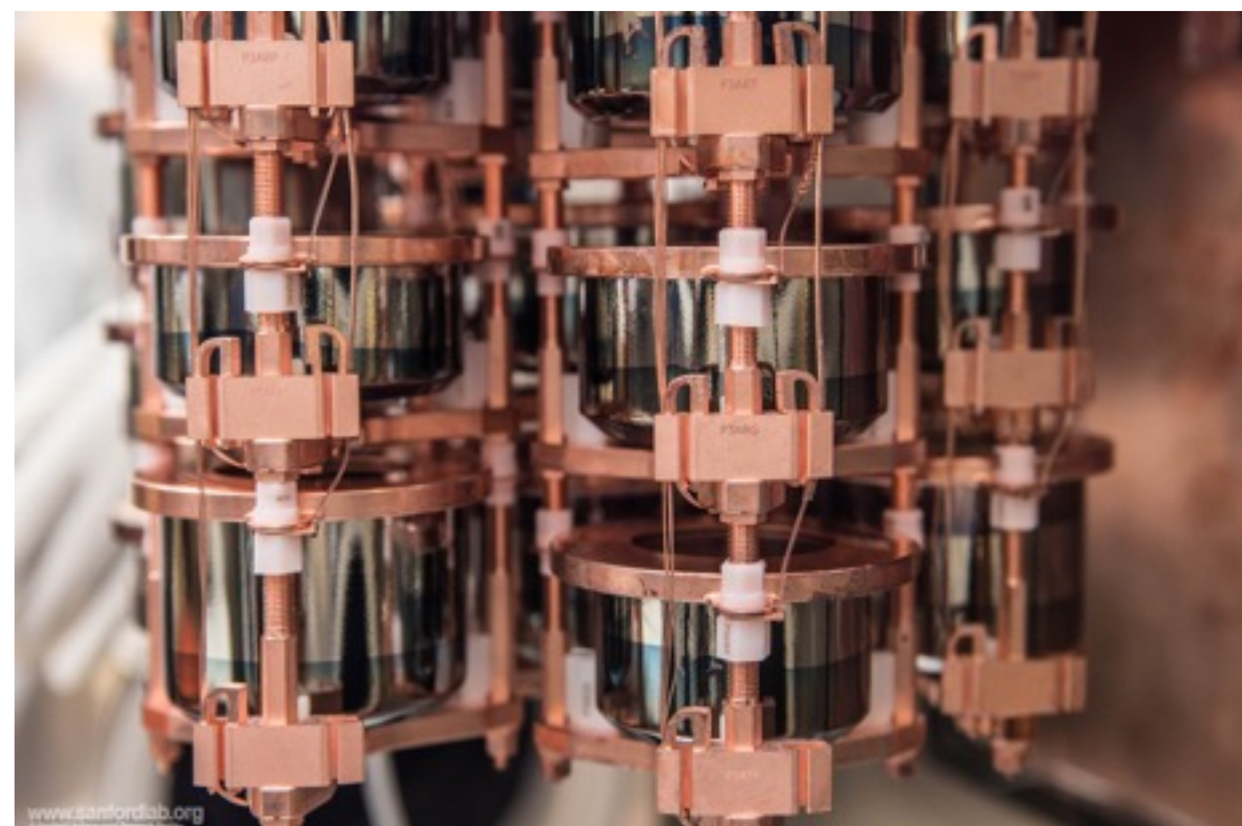




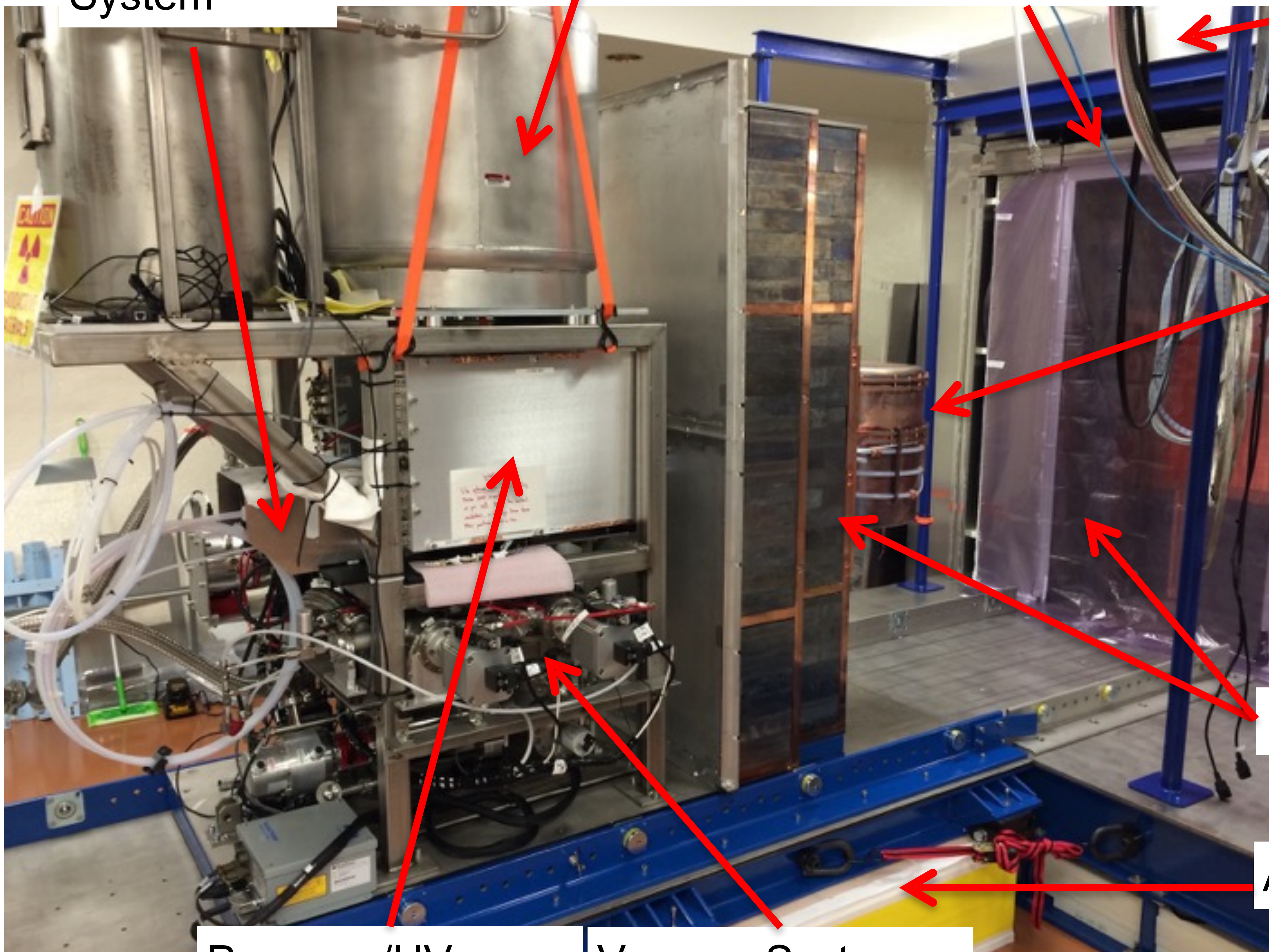
SR Elliott et al. [4]

Radiopure Components



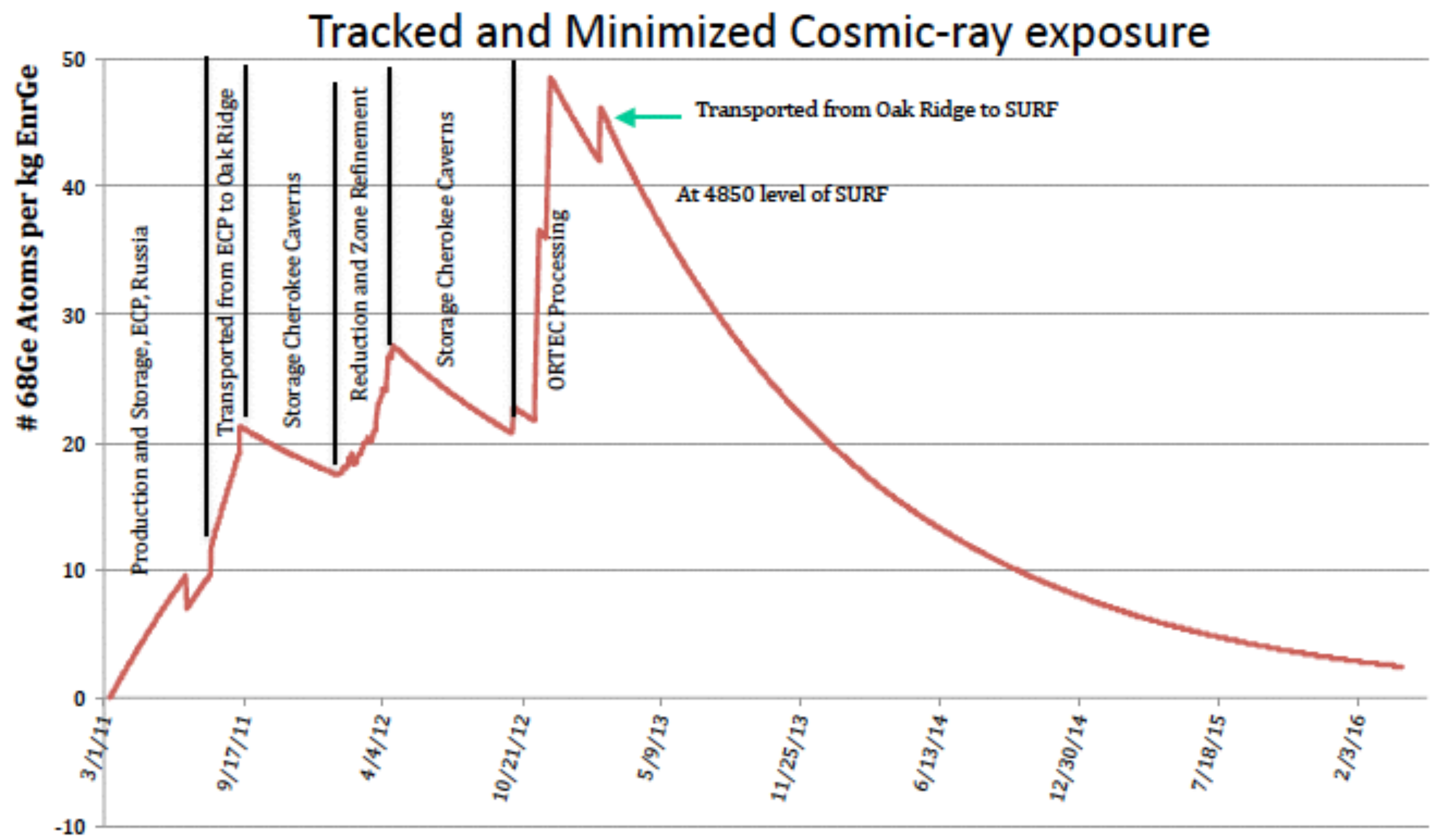


Module and Shield Details

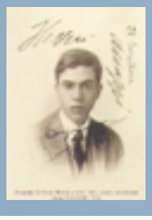


^{68}Ge Production in Detector P42537A

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



DEMONSTRATOR Electroforming Cu

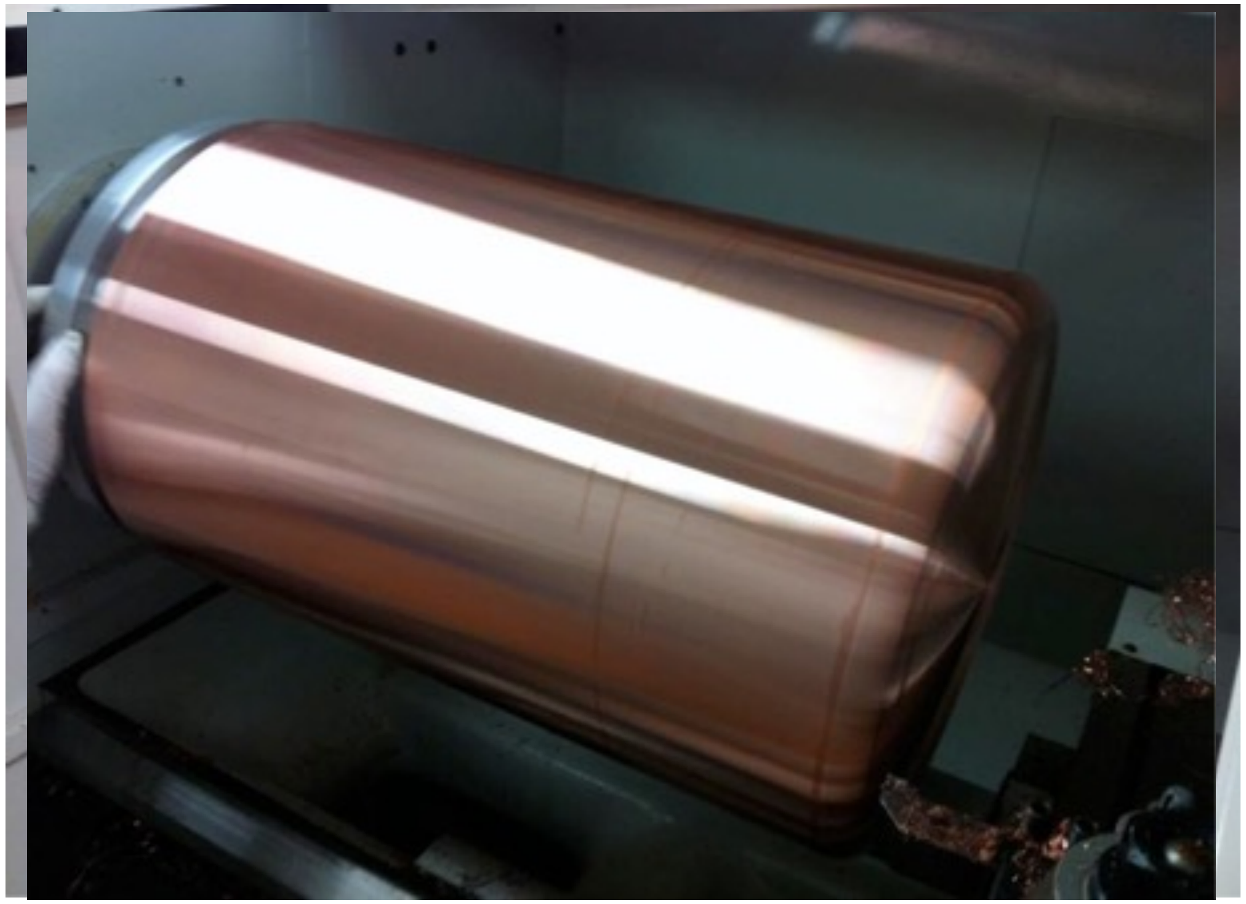


Insertion of mandel into EF bath

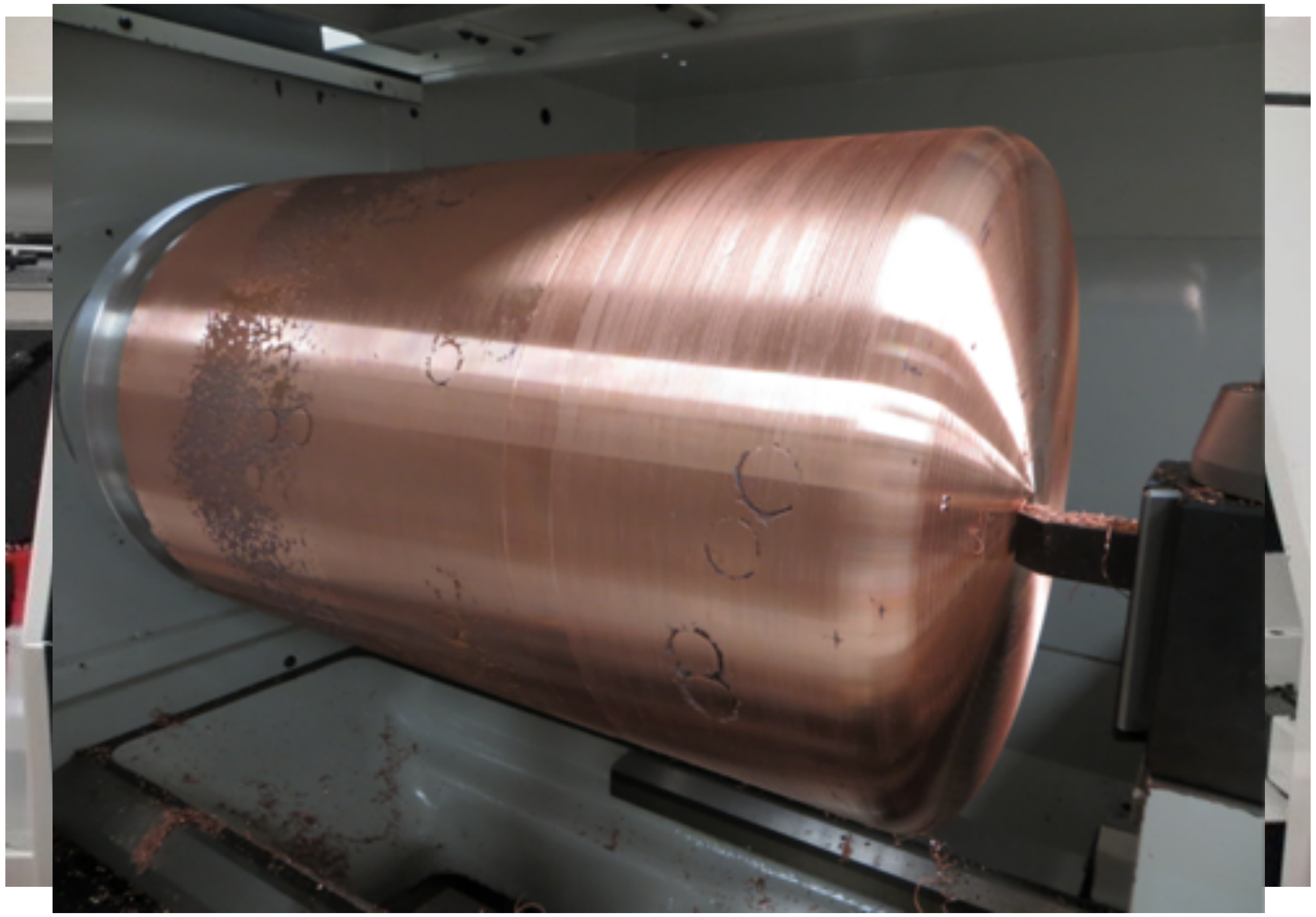
Electroforming Baths in TCR

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

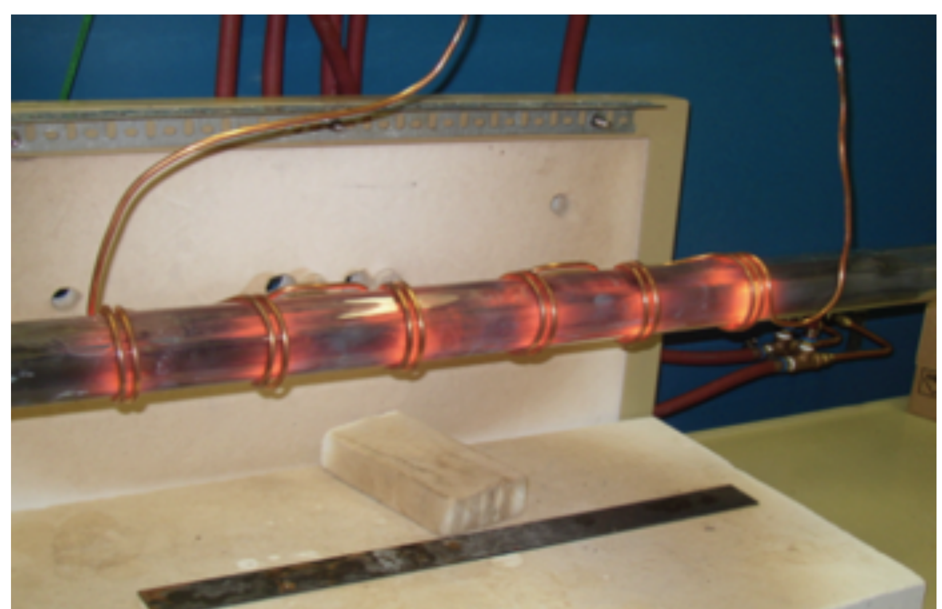
- 44 of the 58 installed detectors are operating
- Problems with non-operating detectors
  - 7 associated with the signal connectors that are located on the cryostat cold plate or with damaged low mass front end boards.
  - 7 detectors cannot be biased either because of problems with the HV cables, connections,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

Ge Processing and Recovery

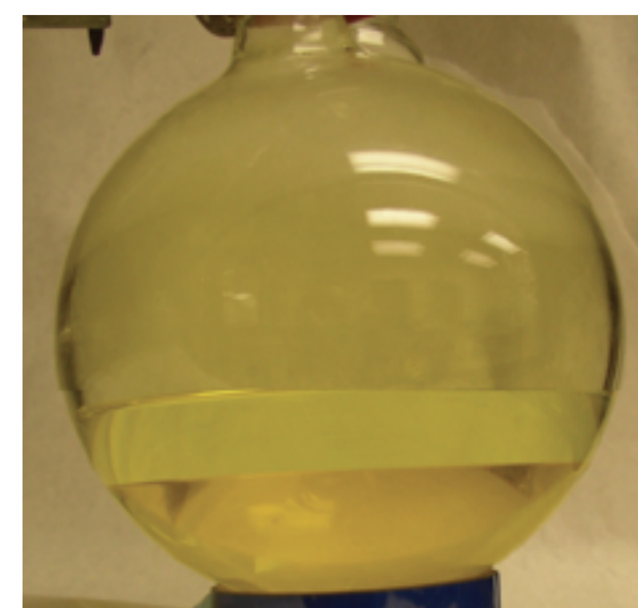
- **Reduction & Zone refining**: 98.7% yield of > 47 Ohm-cm Ge from 42.5 kg of ^{enr}Ge (61.7 kg of GeO_2)
- **ORTEC manufactured**: 30 ^{enr}Ge detectors, 25.3 kg of mass.
  - 64.4% yield of detectors, 3.22 kg of > 47 Ohm-cm Ge material not used,
- **Recovered Ge:** from processing det. manufacturing 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



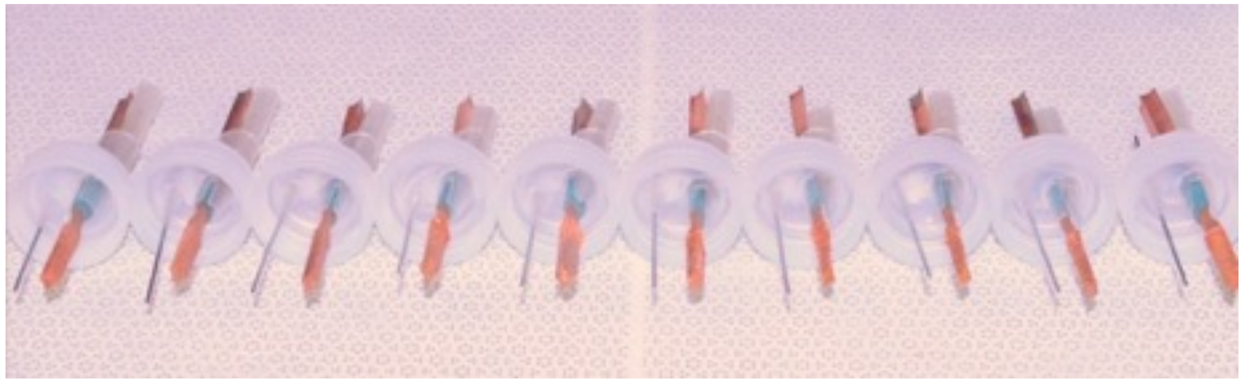
$GeCl_4$ with cover liquid



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

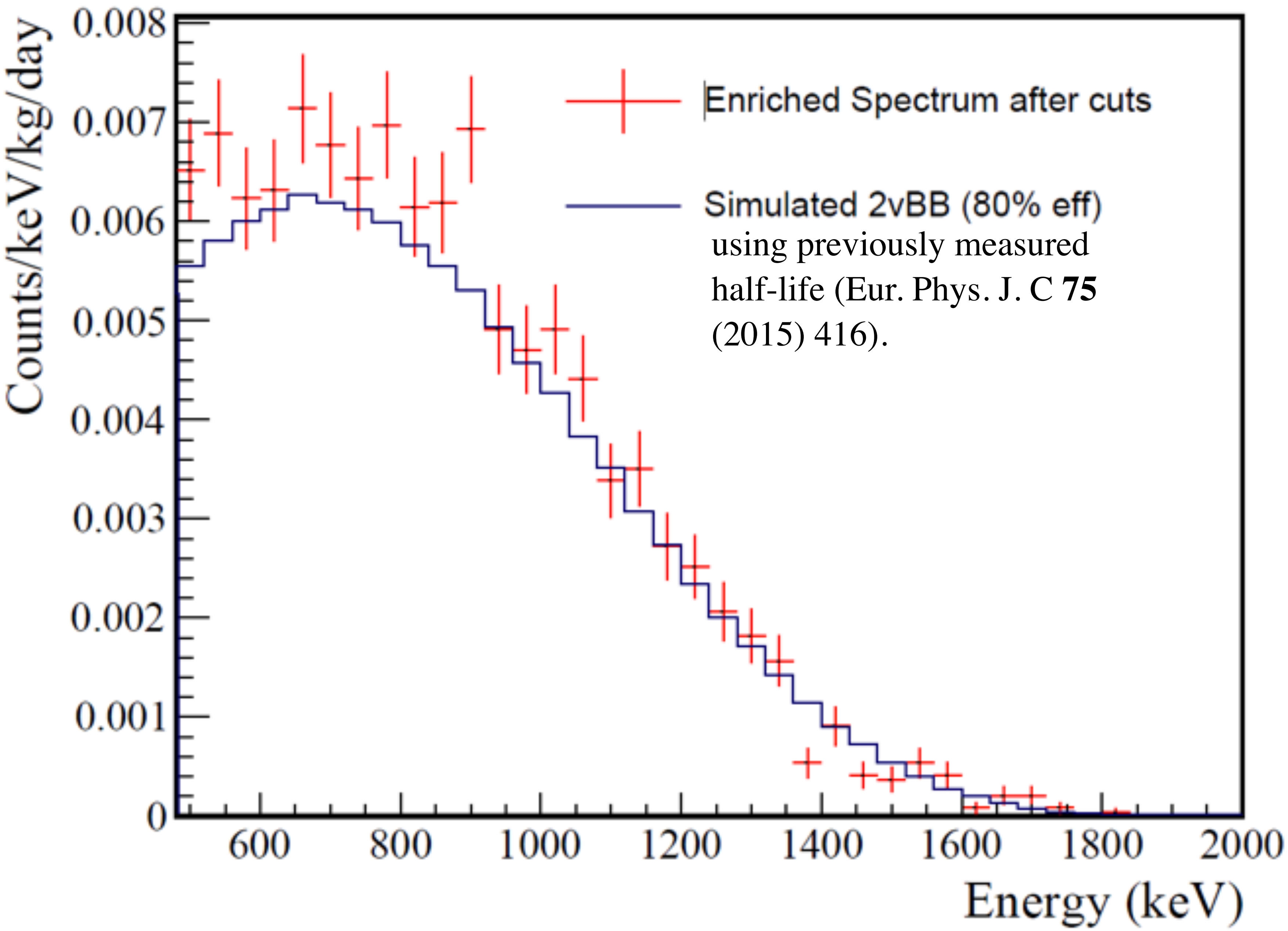


NIM A 775 (2015) 93-98

Background Spectrum (DS1)

Enriched detectors in Module 1 after all cuts (Exposure: 1.66 kg y)

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



Background rate

23^{+13}_{-10} counts/(ROI t y)

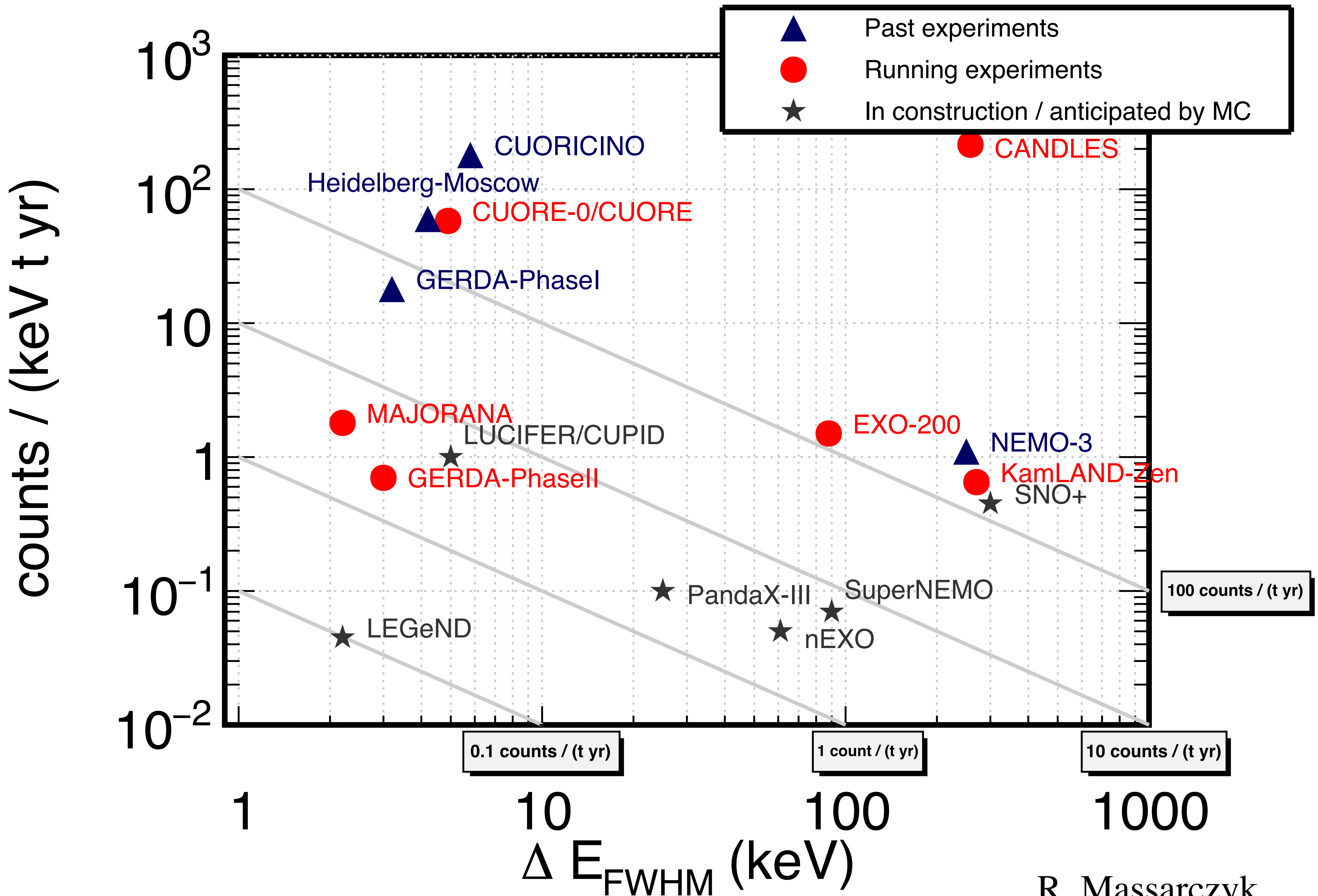
(3.1 keV ROI, (68% CL))

Background index

$(7.5^{+4.5}_{-3.4}) \times 10^{-3}$

counts/(keV kg y).

Backgrounds, Resolution, Discovery

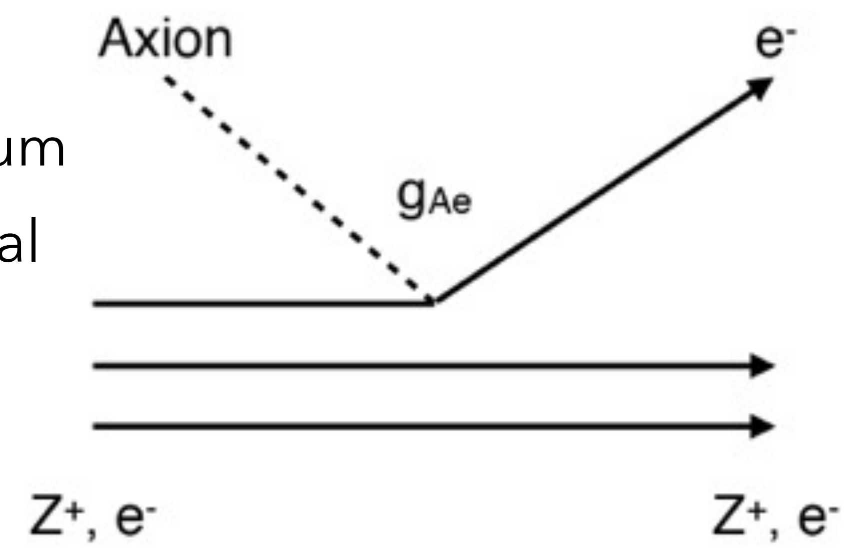


R. Massarczyk

Observing Axions in HPGe Detectors

The axio-electric effect:

The axion "takes the place" of a photon and ionizes a germanium nucleus. The released electron is given an energy (nearly) equal to the incident axion.



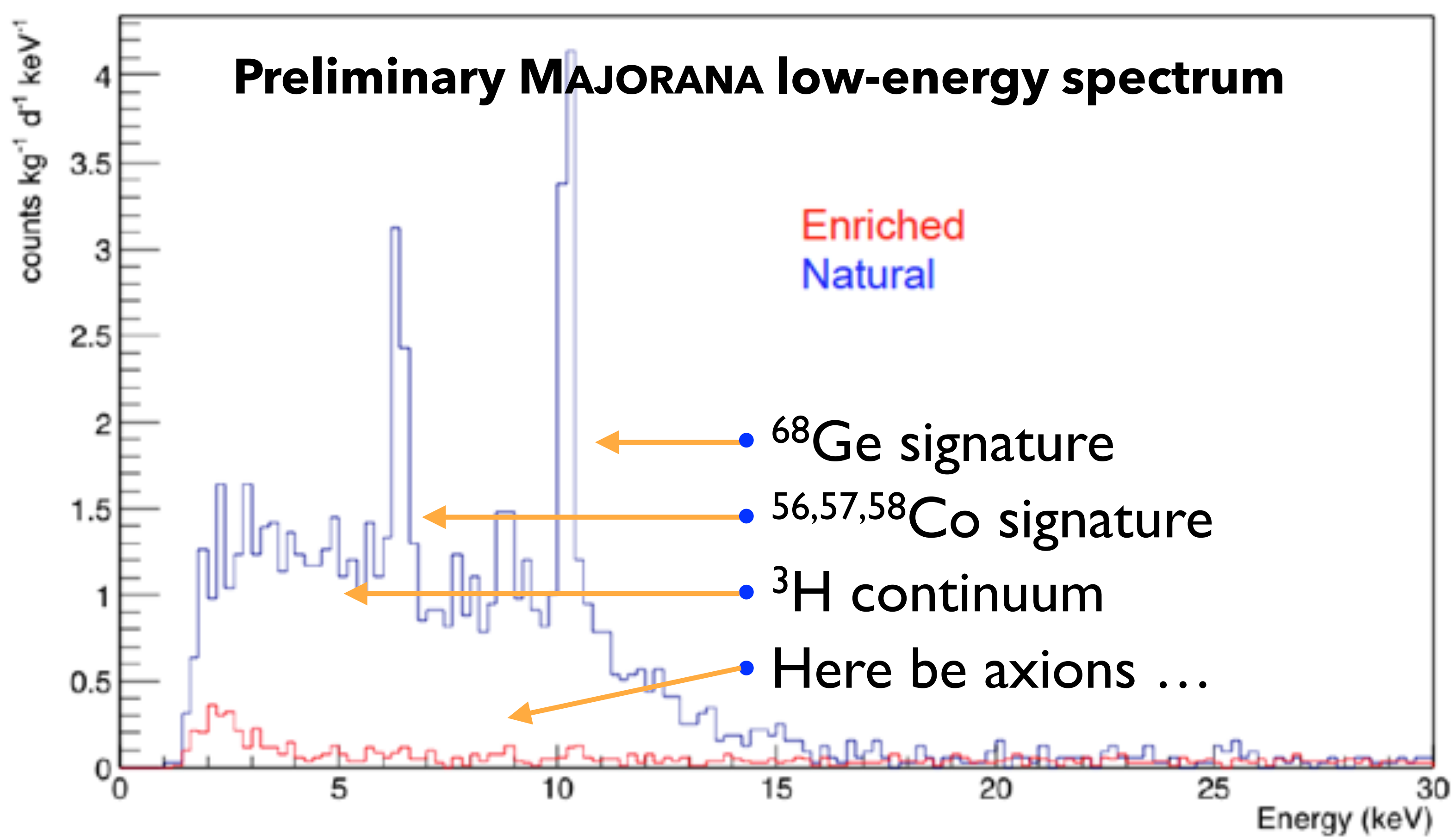
HPGe detector advantages:

- **Sub-keV energy thresholds** possible
- Excellent energy resolution
- Enriched detectors have reduced cosmogenic activation

$$\sigma_{ae}(E_a) = g_{ae}^2 \ (2.088 \times 10^{-5}) E_a^2 \ \sigma_{pe}(E_\gamma)$$

Proposed research:

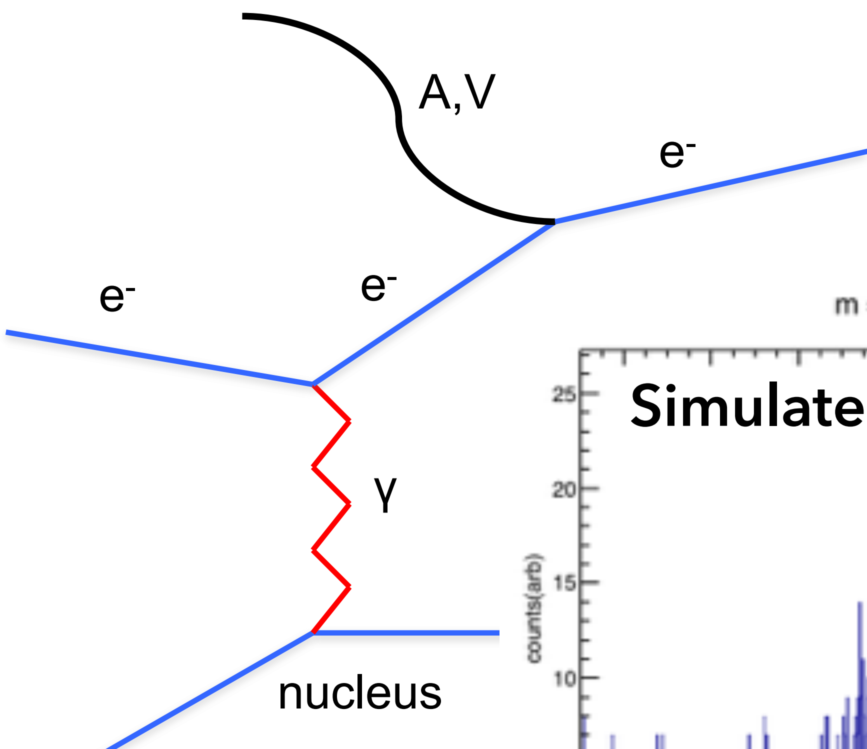
- Search the low-energy region for the peaks predicted by Redondo. If no peaks are found, set a competitive upper limit on the coupling term g_{ae}
- Contribute to the ongoing effort to characterize the low-energy region of the Ge detectors.

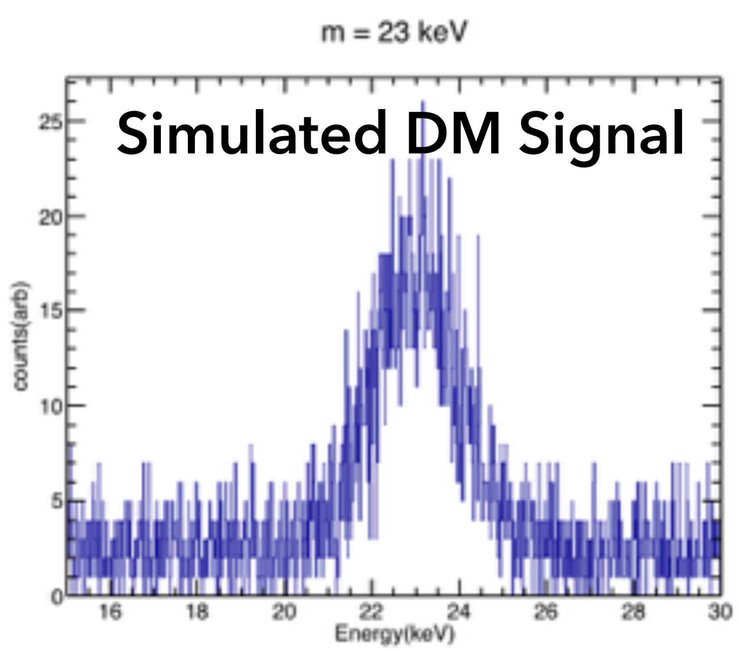


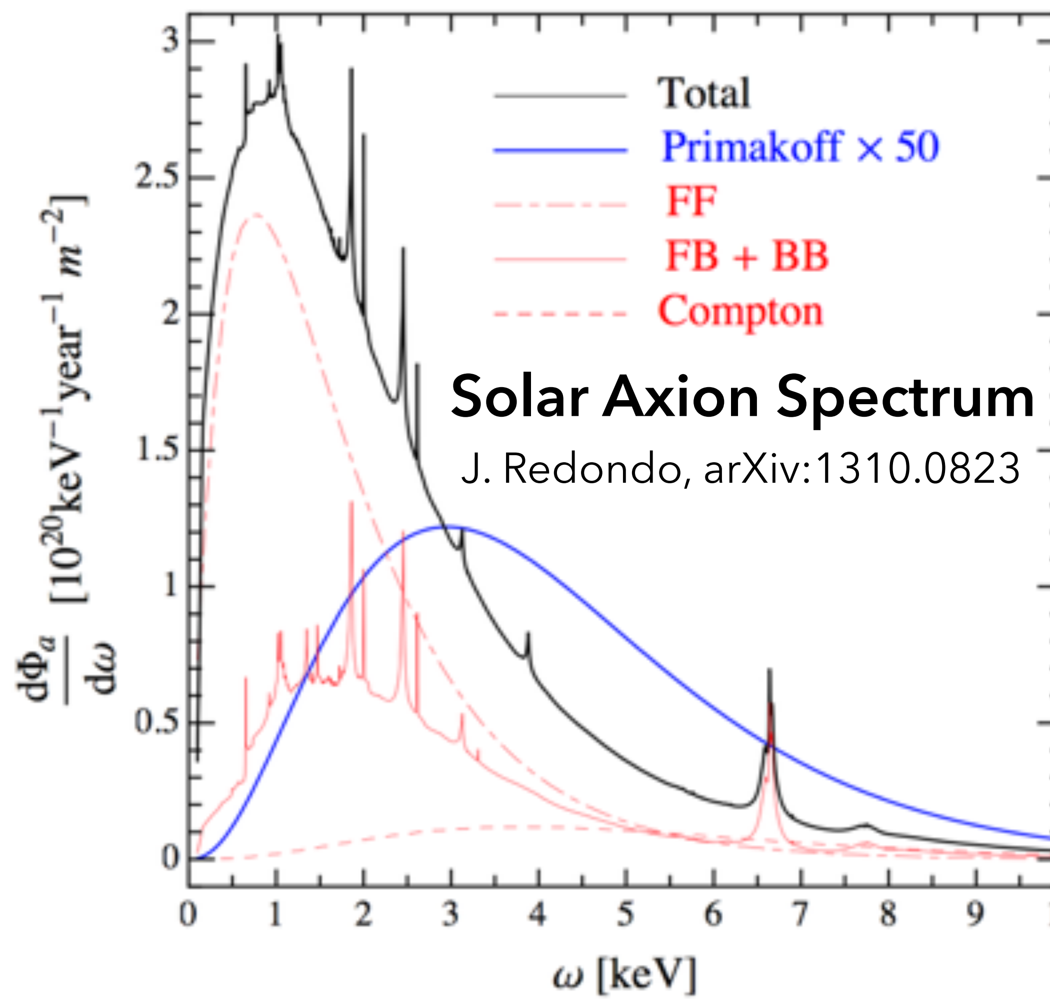
The MAJORANA Low-Energy Program

Low detector thresholds allow us to perform several low-energy searches:

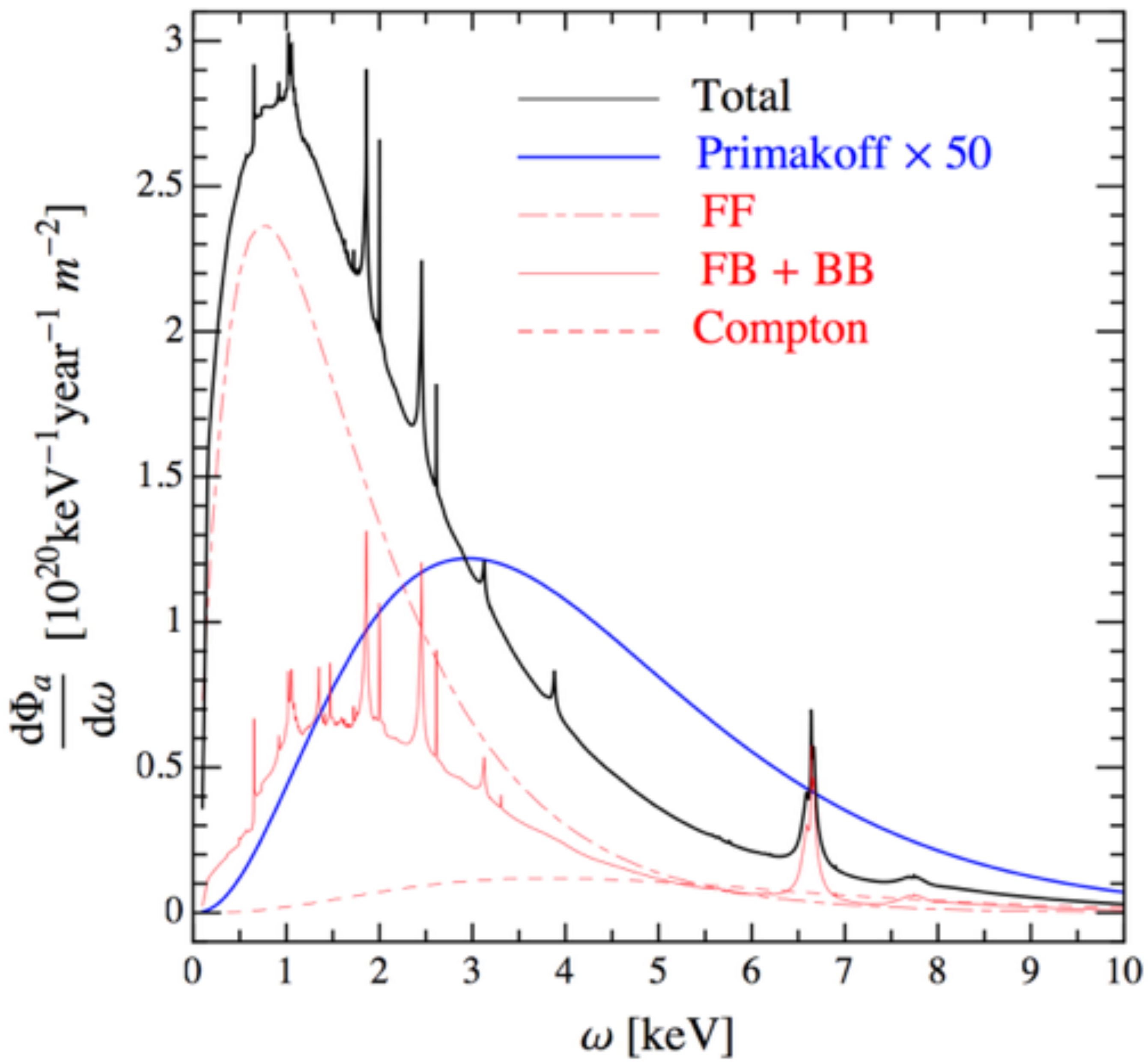
Search:	Expected Signal:
• Light (<10 GeV/c^2) WIMP searches	*Excess < 2-2.5 keV from nuclear recoils*
• Bosonic Superweak Dark Matter	*Anomalous peak < 100 keV*
• Pauli-Exclusion Principle Violation	*Ge x-ray peak at 10.6 keV*
• Electron decay: $e^- \to \nu_e \bar{\nu}_e \nu_e$	*Ge x-ray peak at, 11.1 keV*
• Solar Axions	*Excess in continuum or peaks < 15 keV*

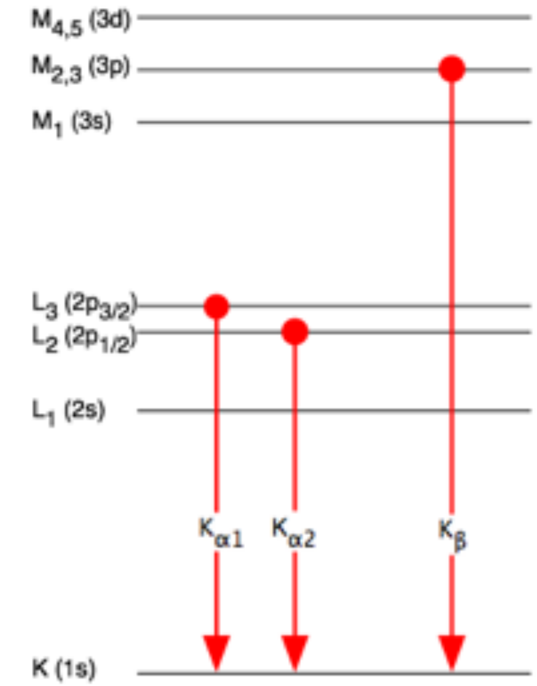






Solar Axions from Nuclear Transitions





Source	Energy (keV)	Predicted Flux cts/(cm^2 day)
Si($K_{\alpha1,\alpha2}$)	1.739	4.95×10^{38}
Si($K_{\beta1}$)	1.836	4.06×10^{38}
S($K_{\alpha1,\alpha2}$)	2.307	4.00×10^{38}
S($K_{\beta1}$)	2.464	2.57×10^{38}
Fe($K_{\alpha1,\alpha2}$)	6.4	4.06×10^{38}

Monoenergetic transitions in the Sun: The axion can "take the place" of a photon by axio-deexcitation and recombination, and be emitted with (nearly) the same energy

Experiments can set bounds on **axion coupling terms**: g_{ae} $g_{a\gamma\gamma}$

Example: $\Phi^{\mathrm{a}}_{Fe}(6.4\ \mathrm{keV}) = g^2_{ae}\ (4.7 \times 10^{33}\mathrm{cm}^{-2}\ \mathrm{s}^{-1})$

J Redondo, private communication to F.T. Avignone

GERDA results

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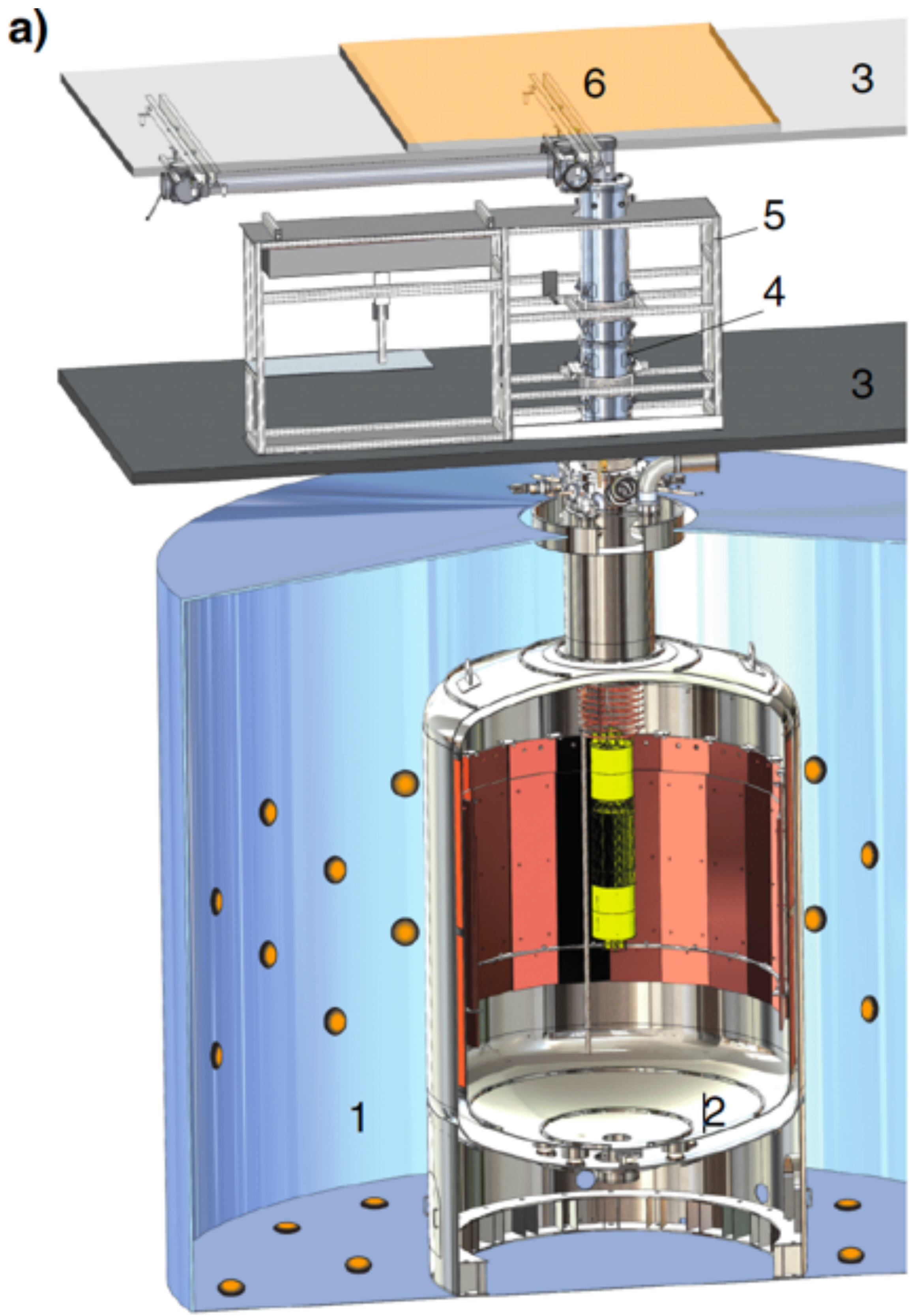

Table 1 | Parameters of data sets

Data set	$\mathcal{E}$ (kg yr)	FWHM (keV)	ϵ	BI (10^{-3} counts keV^{-1} kg^{-1} yr^{-1})
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI silver	1.3	4.3(1)	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}
PIIa coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PIIa BEGe	5.8	3.0(2)	0.60(2)	$0.7^{+1.1}_{-0.5}$

List of data sets, exposures $\mathcal{E}$ (for total mass), energy resolutions in FWHM, efficiencies ϵ (including enrichment, active mass, selection efficiencies and dead times) and background indices (BI) in the analysis window excluding $Q_{\beta\beta} \pm 5$ keV. The numbers in parenthesis give the uncertainty of the respective values in the least significant digit.

in 34.4 kg yr total exposure

$$T^{0\nu}_{1/2} > 5.3 \times 10^{25}\ \text{yr}$$