Final Results from the MAJORANA DEMONSTRATOR

Vincente Guiseppe, ORNL
on behalf of the MAJORANA Collaboration

Dec. 2, 2023
DBD23 Hawaii

Sanford Underground Research Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

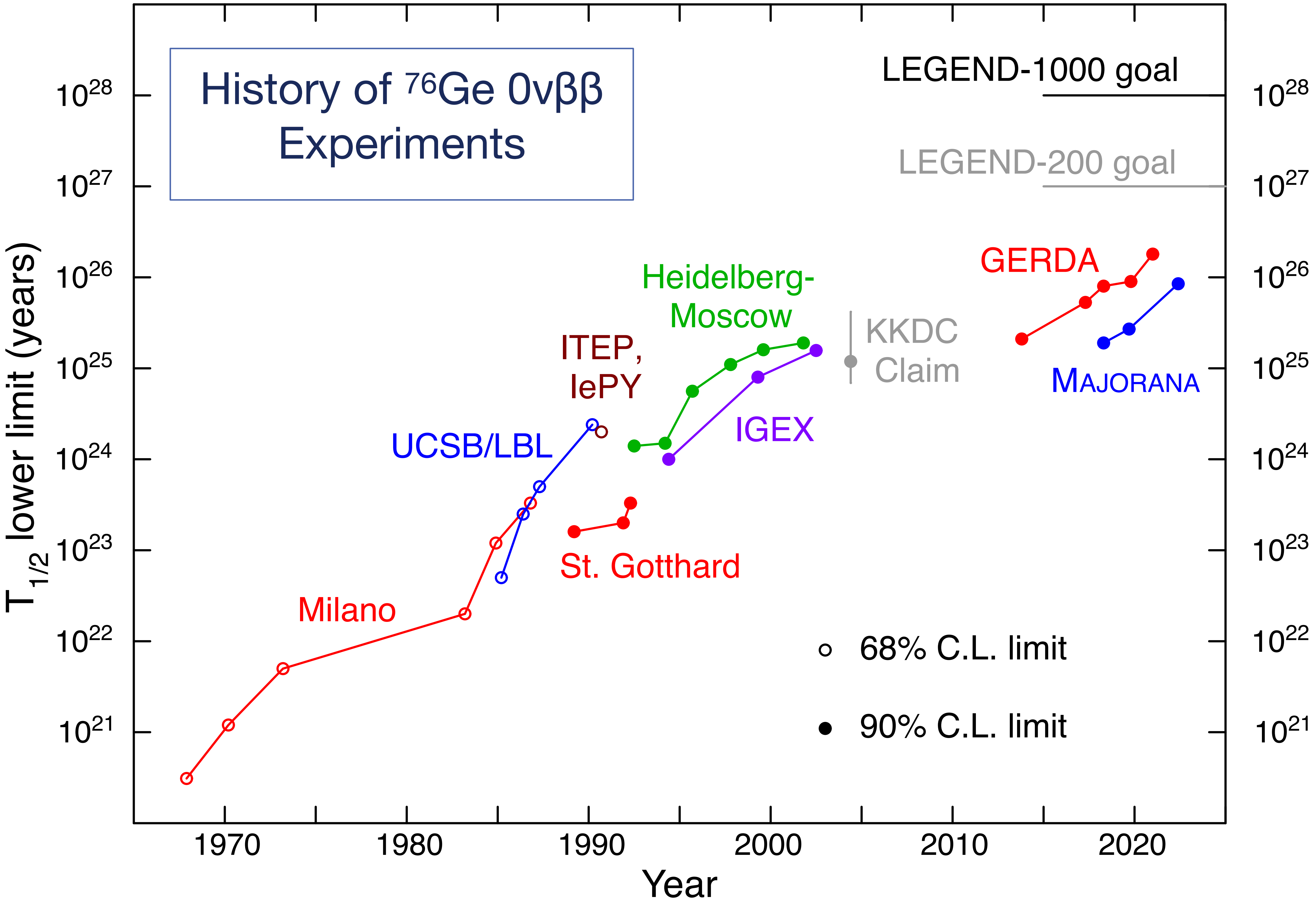
Searching for 0νββ in ^{76}Ge

Current limits on the 0νββ half-life in ^{76}Ge are around 10^{26} yrs

- Achieved with quasi-background-free measurements ~100 kg-yrs of exposure

High purity germanium detectors have many advantages in this search:

- Well understood detector technology
- High detection efficiency
- Low intrinsic backgrounds
- Excellent energy resolution
- Background rejection techniques through pulse-shape-based event topology
- Long history of 0νββ searches



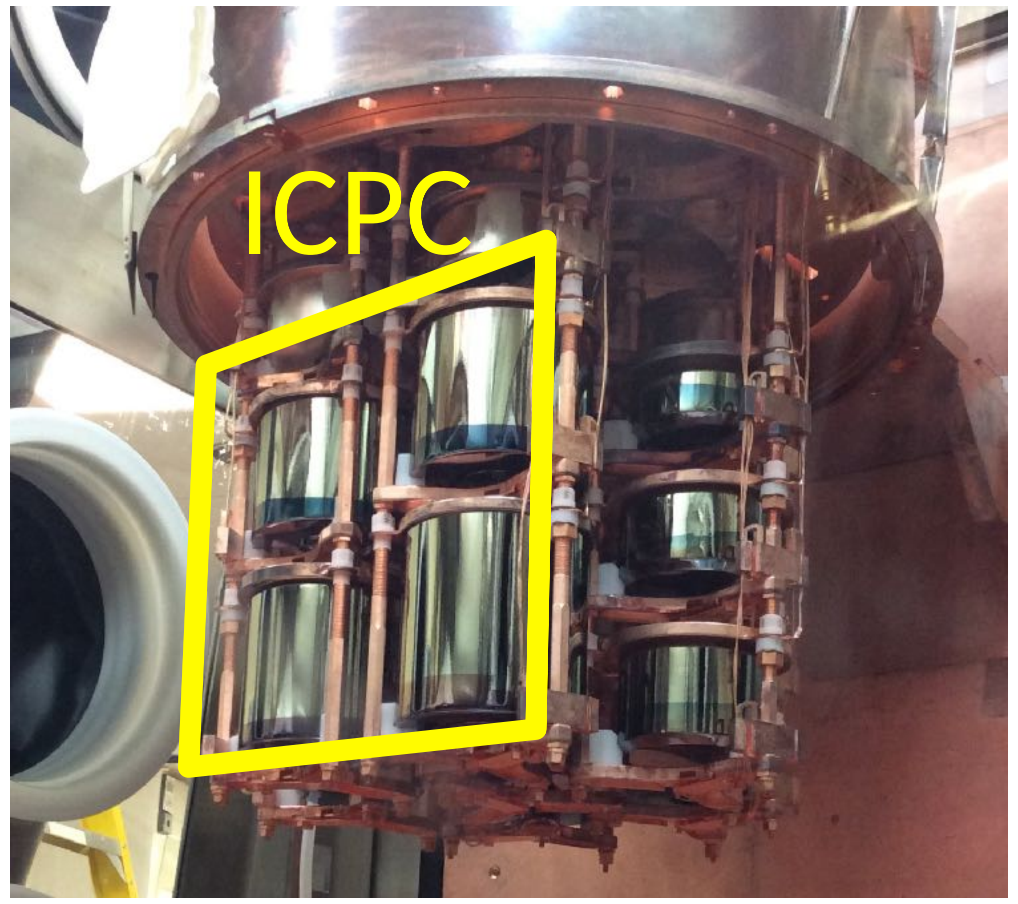
Status and Prospects of the LEGEND Experiment
Ann-Kathrin Schuetz
Friday @ DBD23

Final result of the GERDA experiment
Grzegorz Zuzel
Today @ DBD23

MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

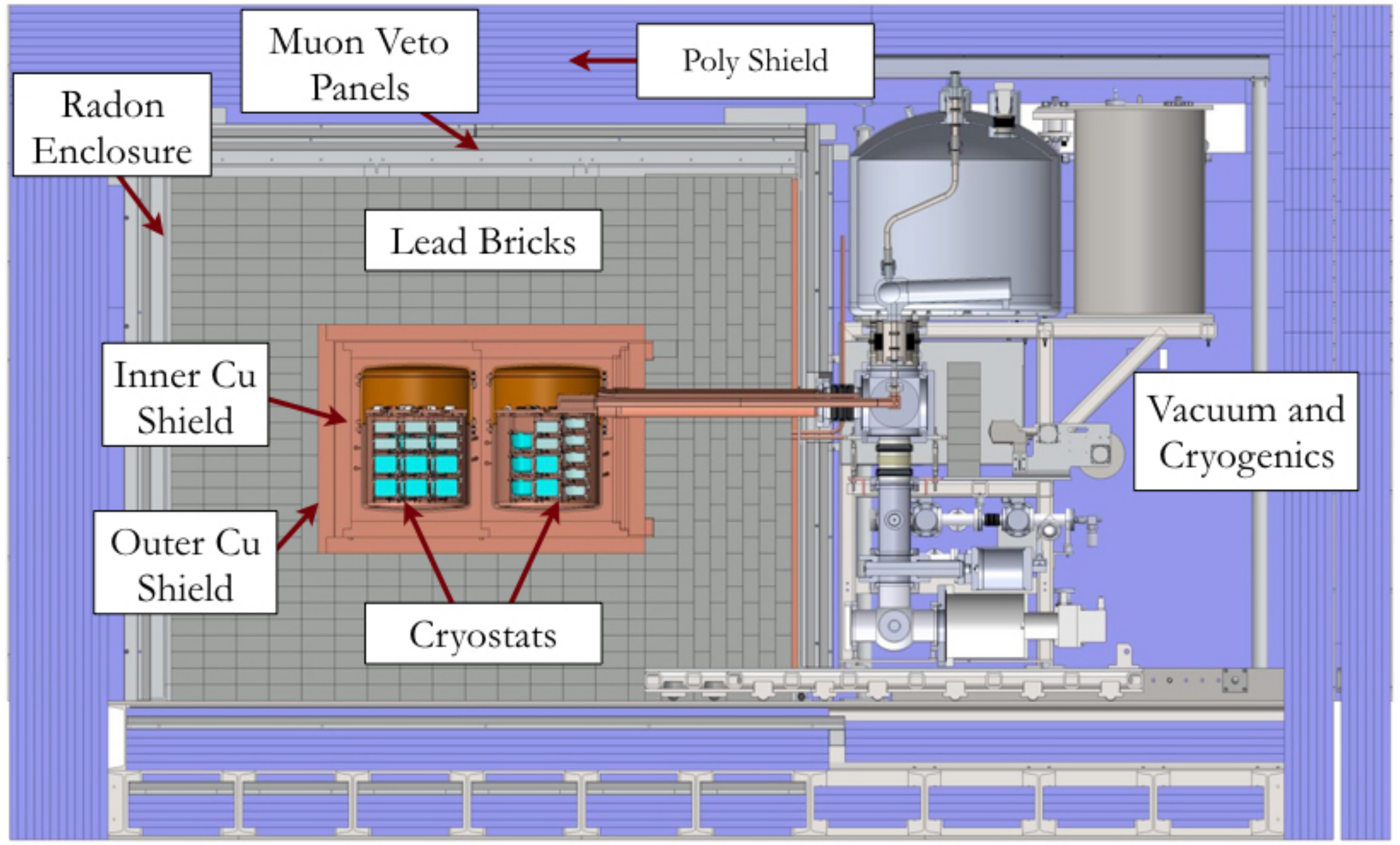
Source & Detector: Array of p-type, point contact detectors
30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals
Included 6.7 kg of ^{76}Ge **inverted coaxial, point contact (ICPC) detectors** in final run



Excellent Energy Resolution: 2.5 keV FWHM @ 2039 keV
and **Analysis Threshold:** 1 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS



Continuing to operate at the Sanford Underground Research Facility with natural detectors for a ^{180m}Ta decay search

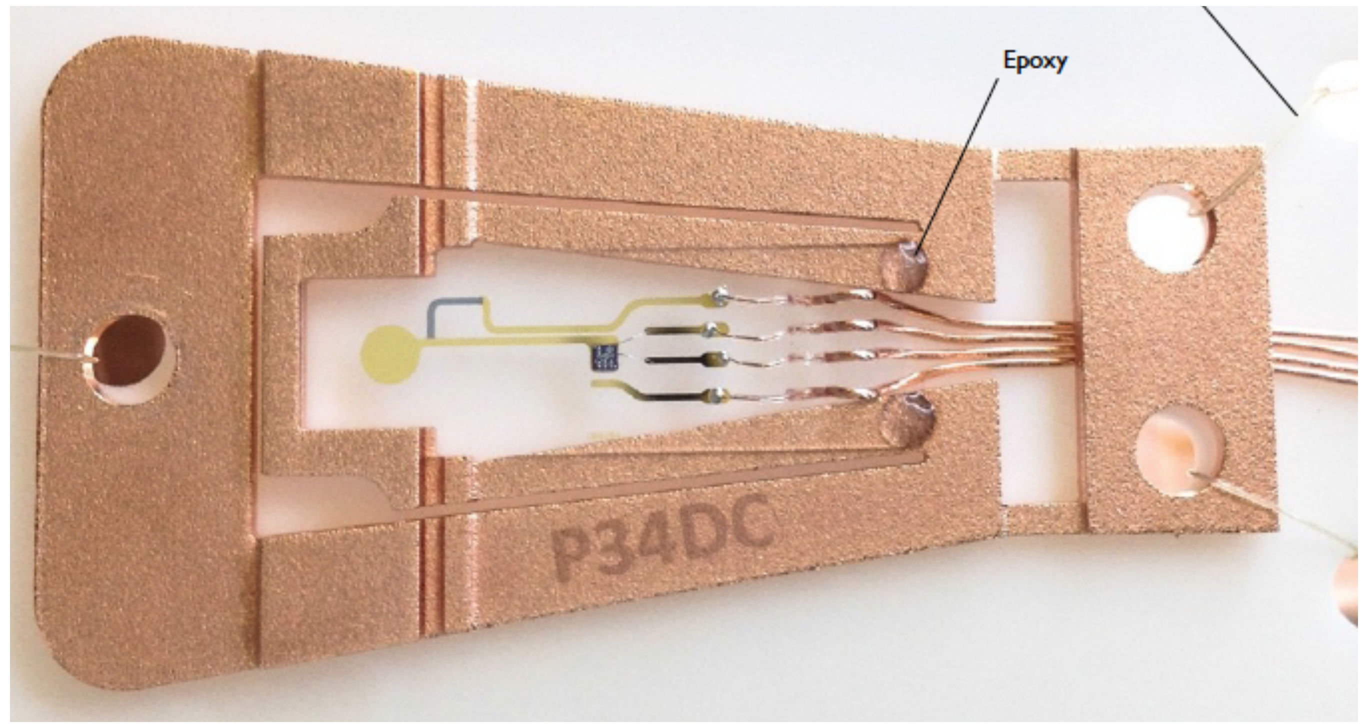
MAJORANA Run Configuration & Timeline

The MAJORANA Approach to Backgrounds

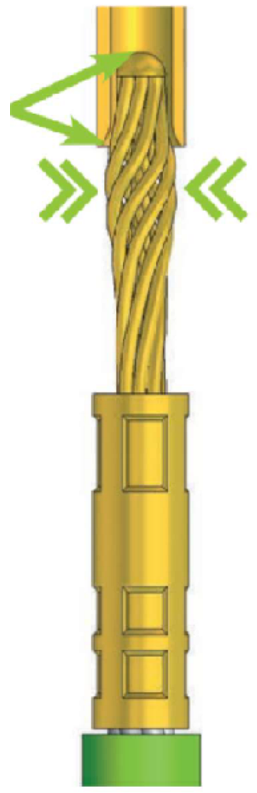
Ultra-pure Materials

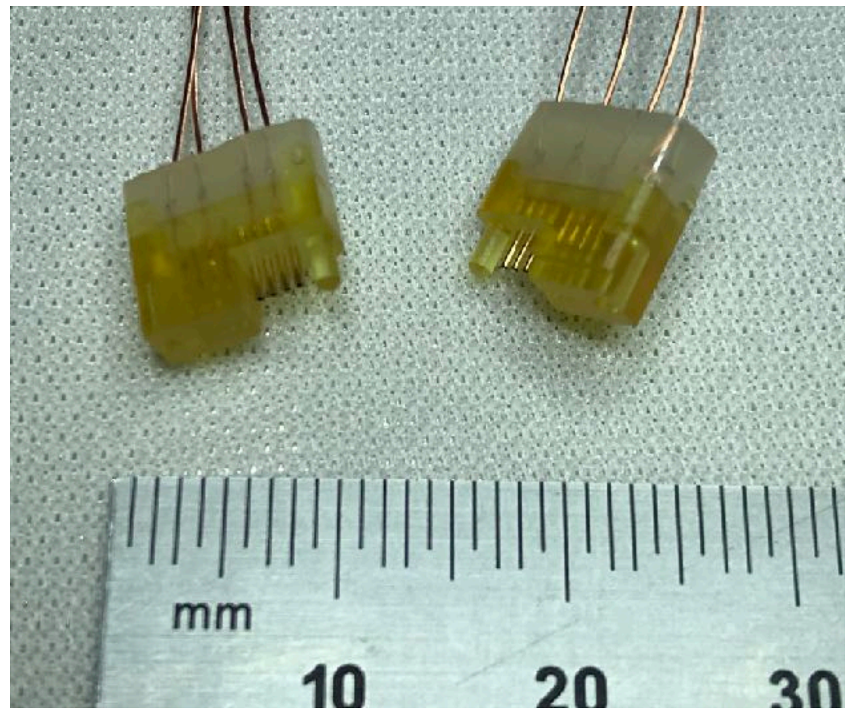
In-house production of underground electroformed Cu

Custom Electronics and Components

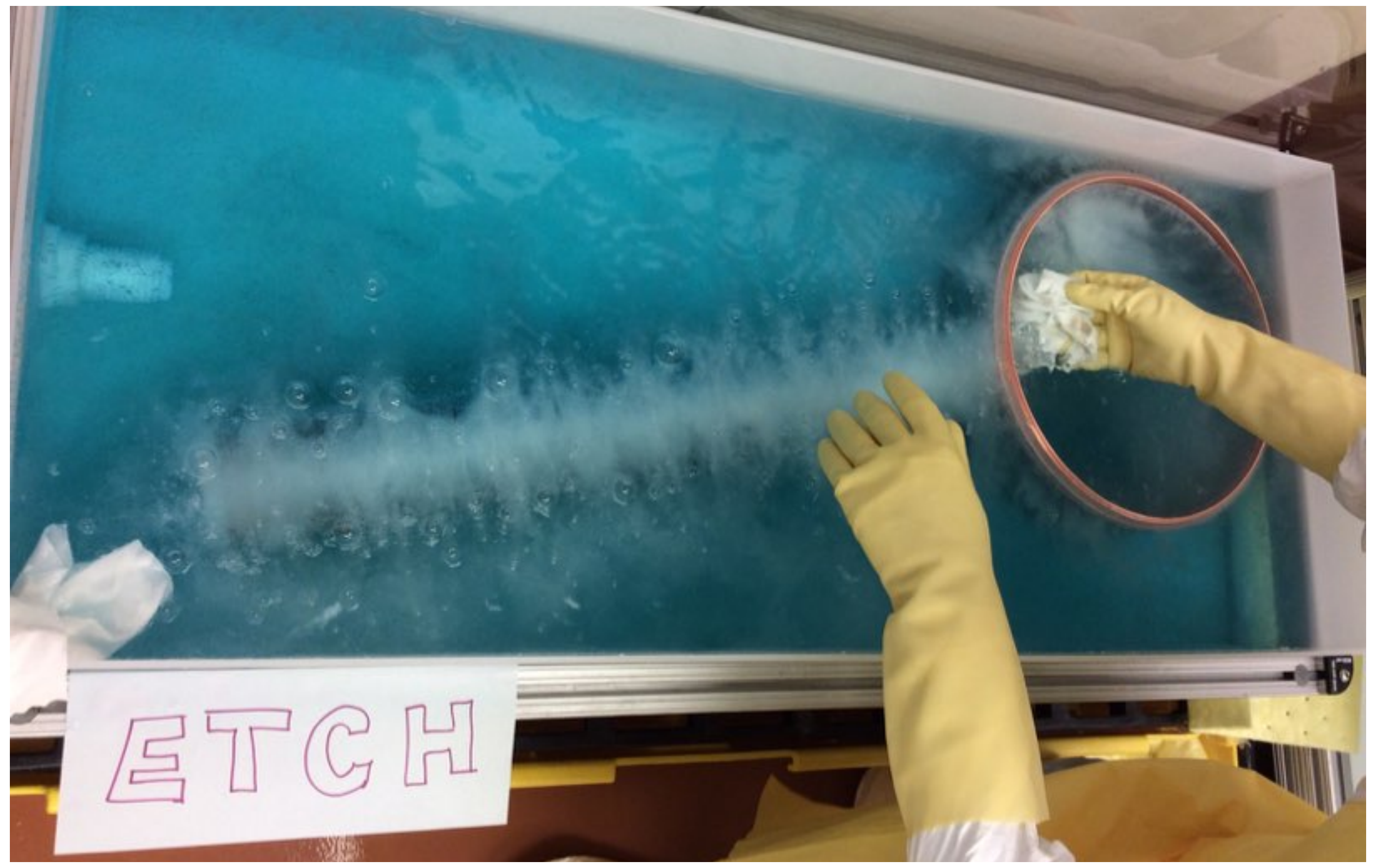


Custom front-end boards that use fine coaxial cable with clean connectors

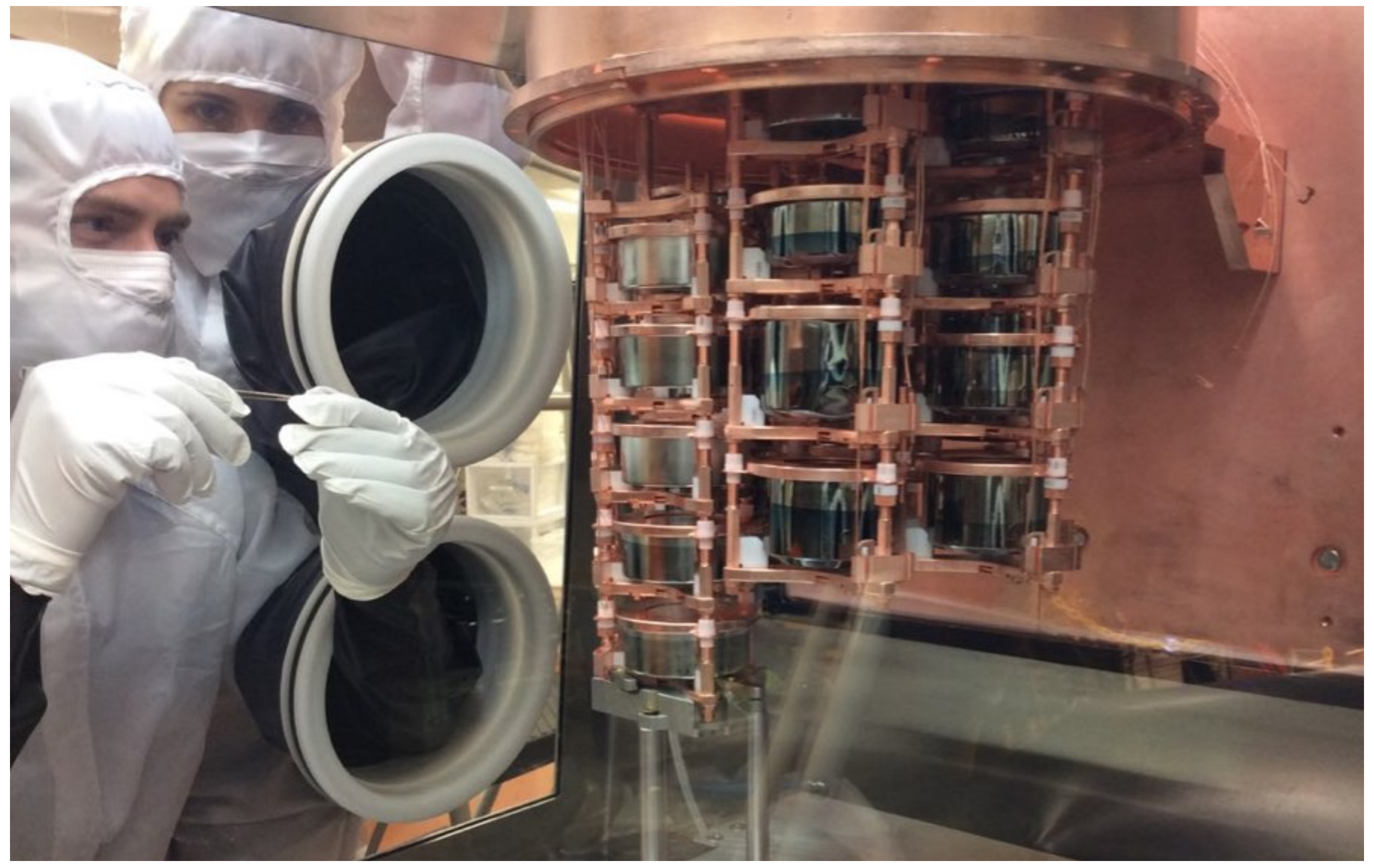




Controlled Handling



Validated cleaning procedures
N_2-purged assembly and storage of parts



Excellent Energy Resolution

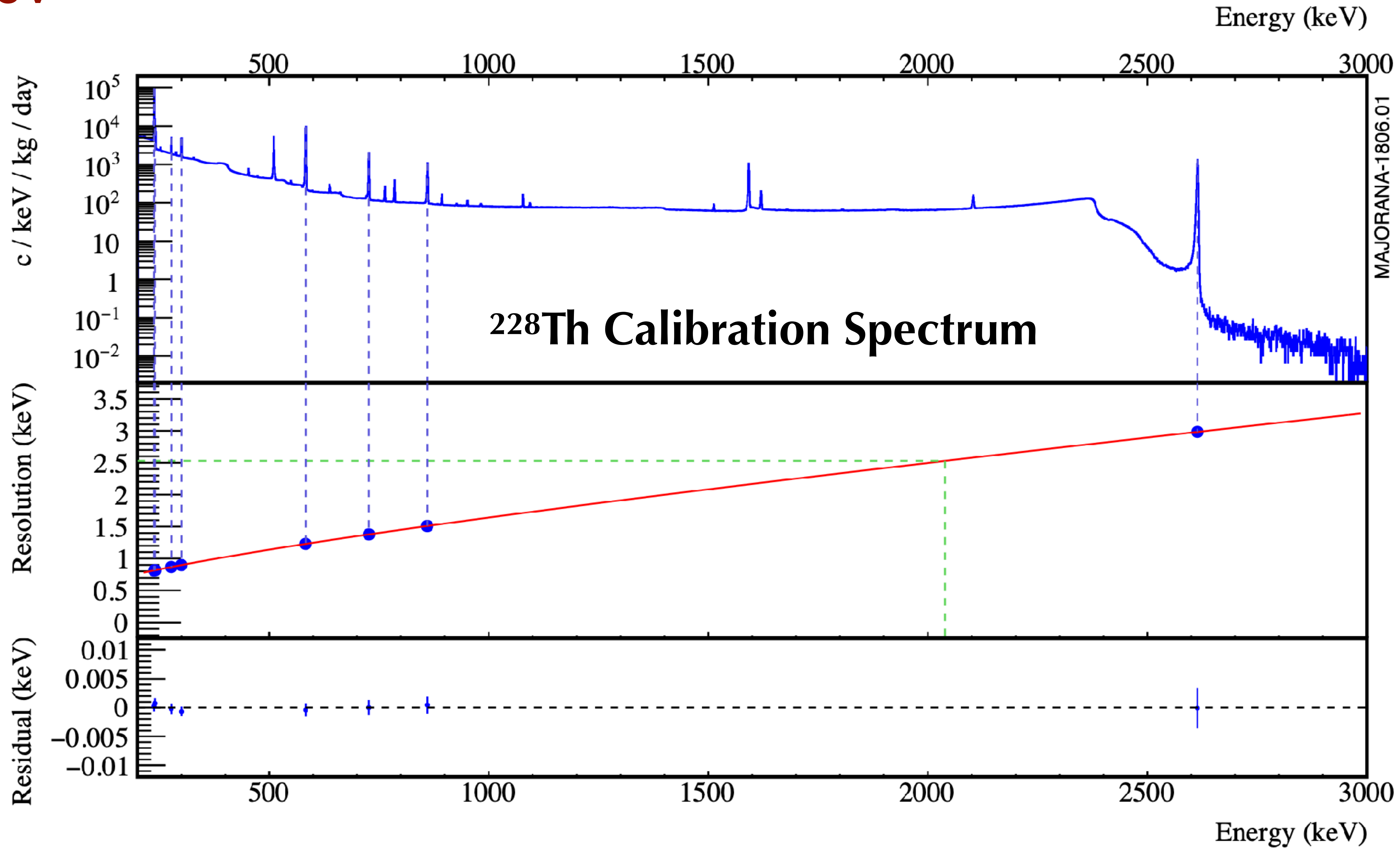
Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected traces with charge-trapping correction

FWHM of 2.5 keV at $Q_{\beta\beta}$ of 2039 keV (0.12%) is a record for $0\nu\beta\beta$ searches

Charge trapping correction improves FWHM at 2039 keV from 4 keV to 2.5 keV

Calibrated on weekly ^{228}Th calibration data

^{228}Th line source deployed during calibration



FWHM of combined enriched detectors in the MAJORANA DEMONSTRATOR, measured using ^{228}Th calibration data

IEEE Trans. Nucl. Sci. **68** 359 (2021)

PRC 872 045503 (2023)

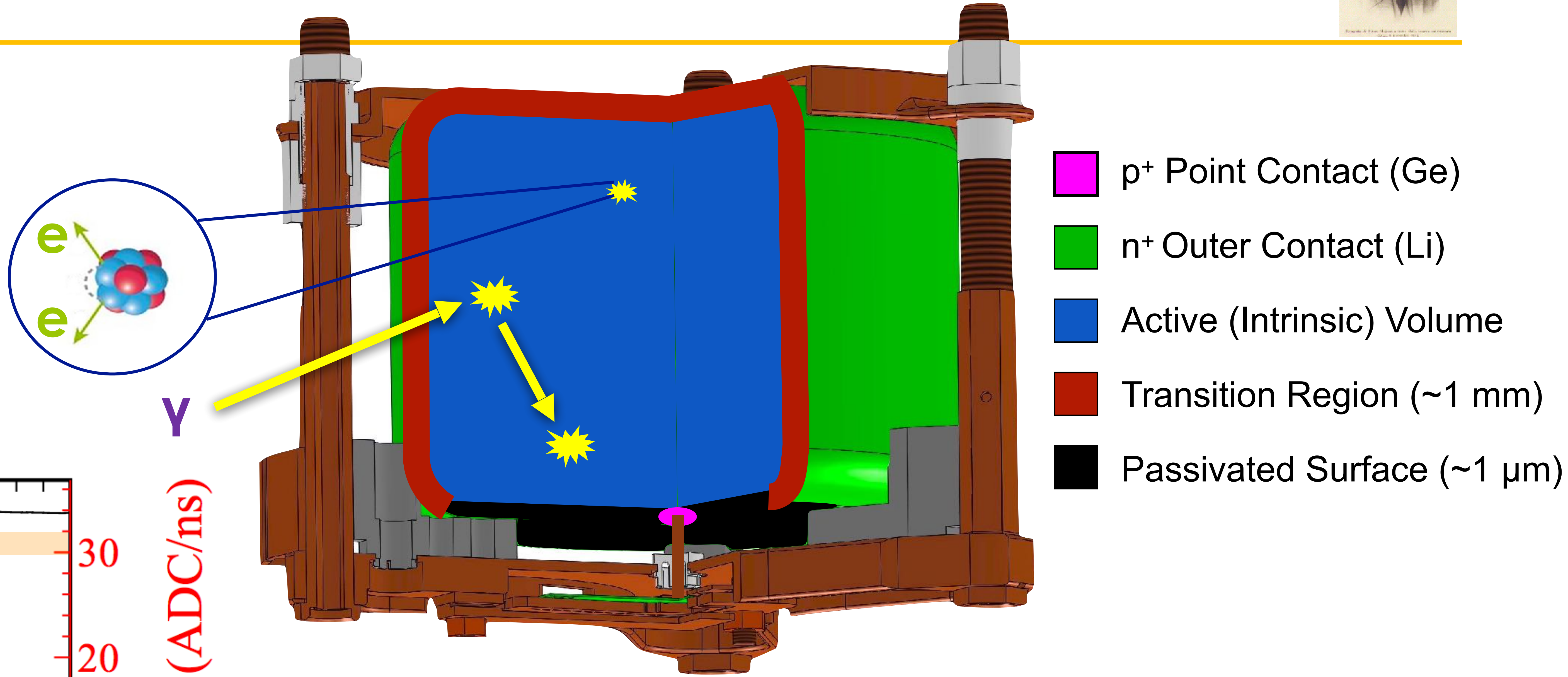
NIMA 872 16 (2017)

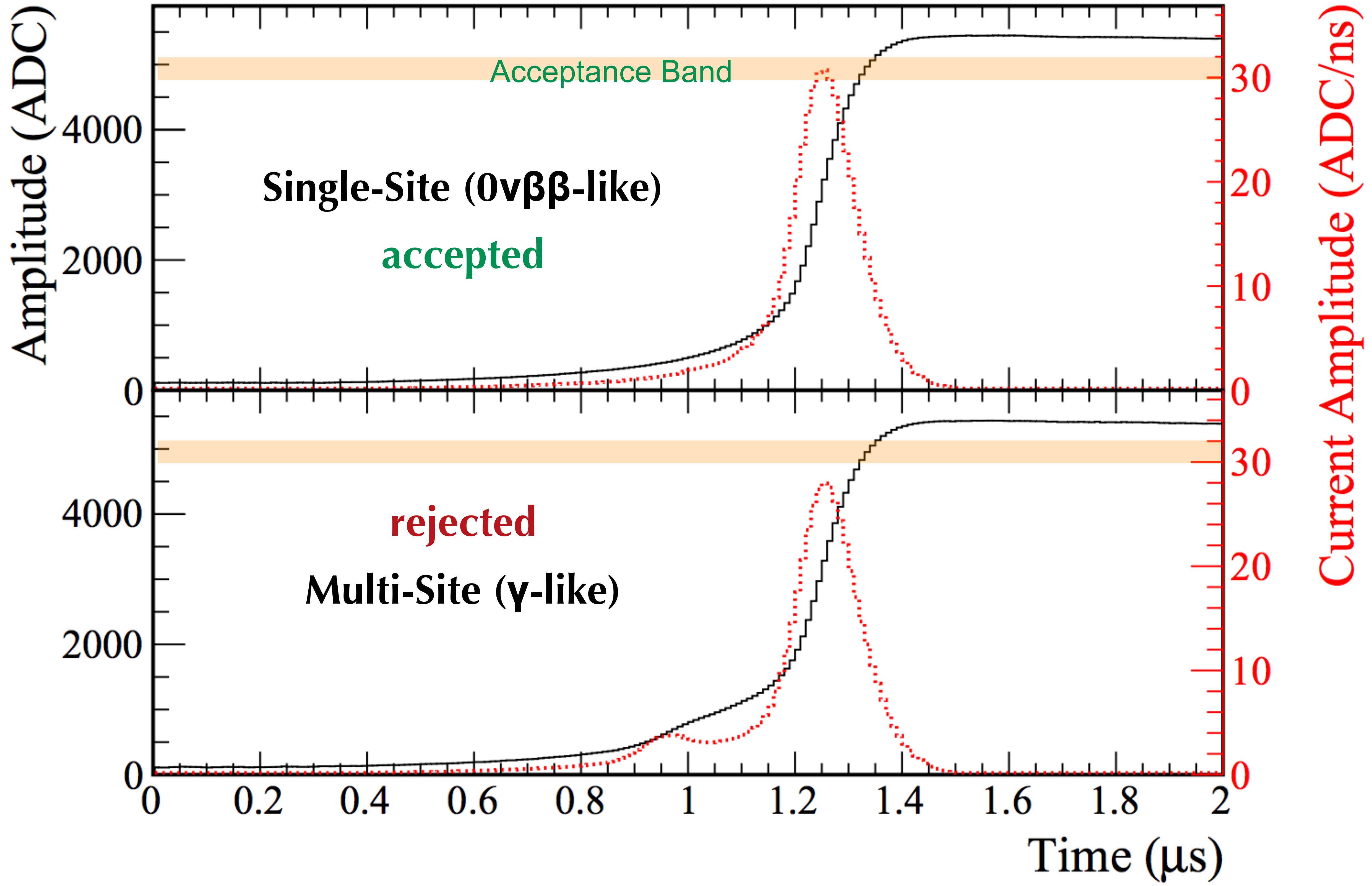
JINST 18 P09023 (2023)

Pulse Shape Discrimination: Multisite Events

Detector waveform is examined to determine topology of an event

- 0vbb signal is single-site (localized to 1 mm)
- Many backgrounds are multi-site





Reject multi-site events in active volume with an **AvsE cut**

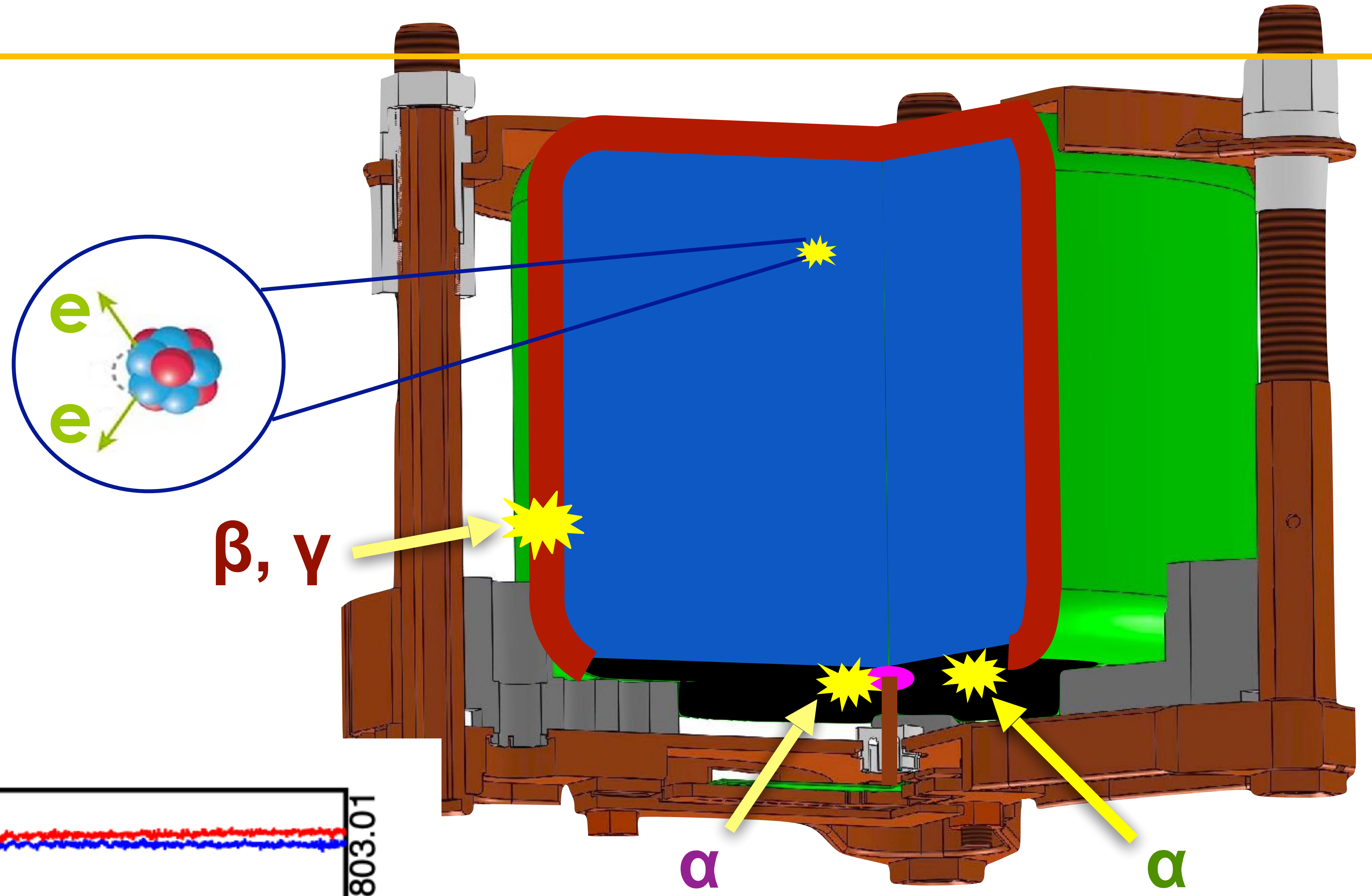
Amplitude of current pulse is suppressed for a multi-site event compared to a single-site event of the same event **E**nergy: (AvsE)

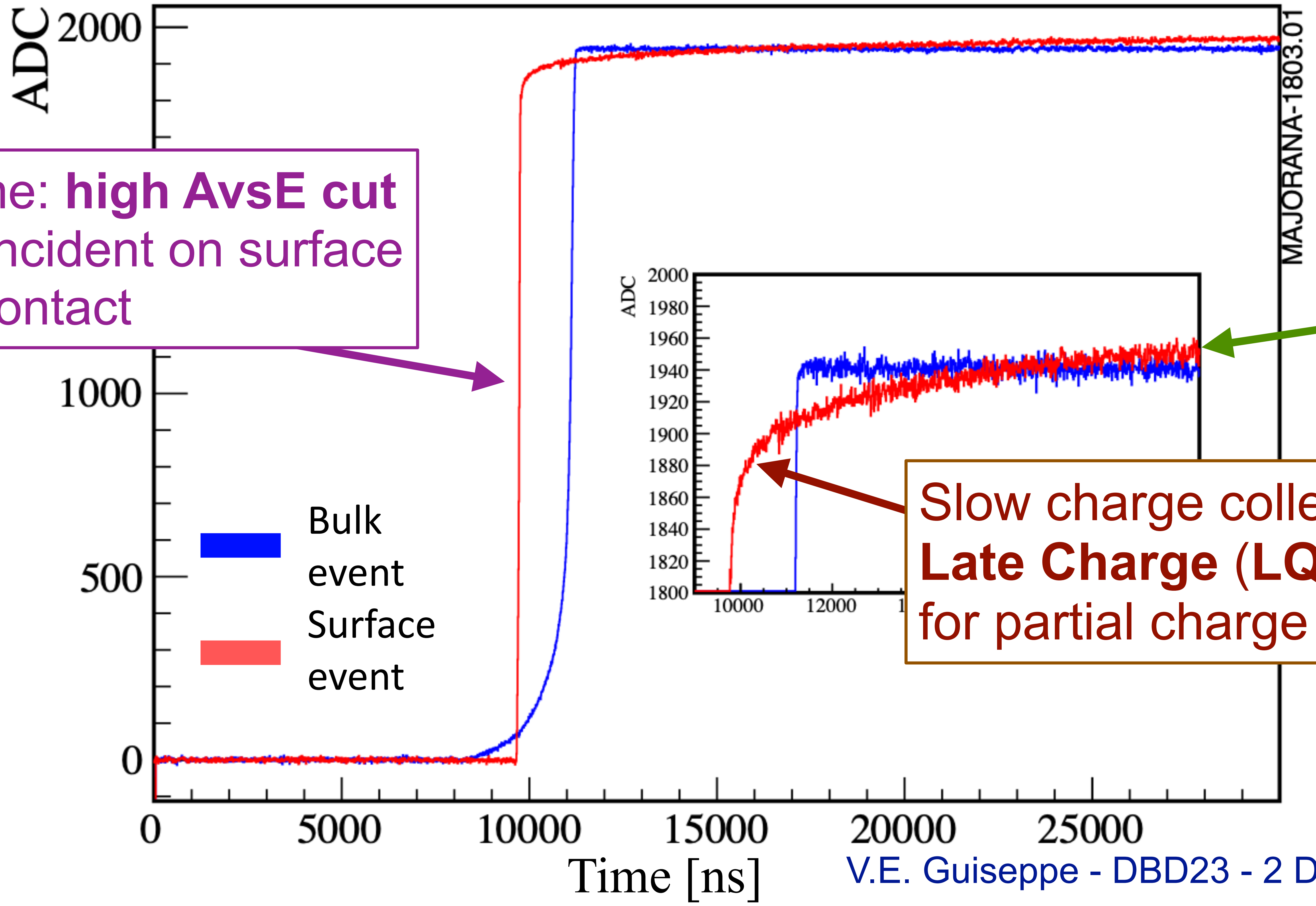
PRC **99** 065501 (2019)

Pulse Shape Discrimination: Surface Events

Detector waveform is examined to determine topology of an event

- 0vbb signal is single-site (localized to 1 mm)
- Many backgrounds are located near detector surfaces.





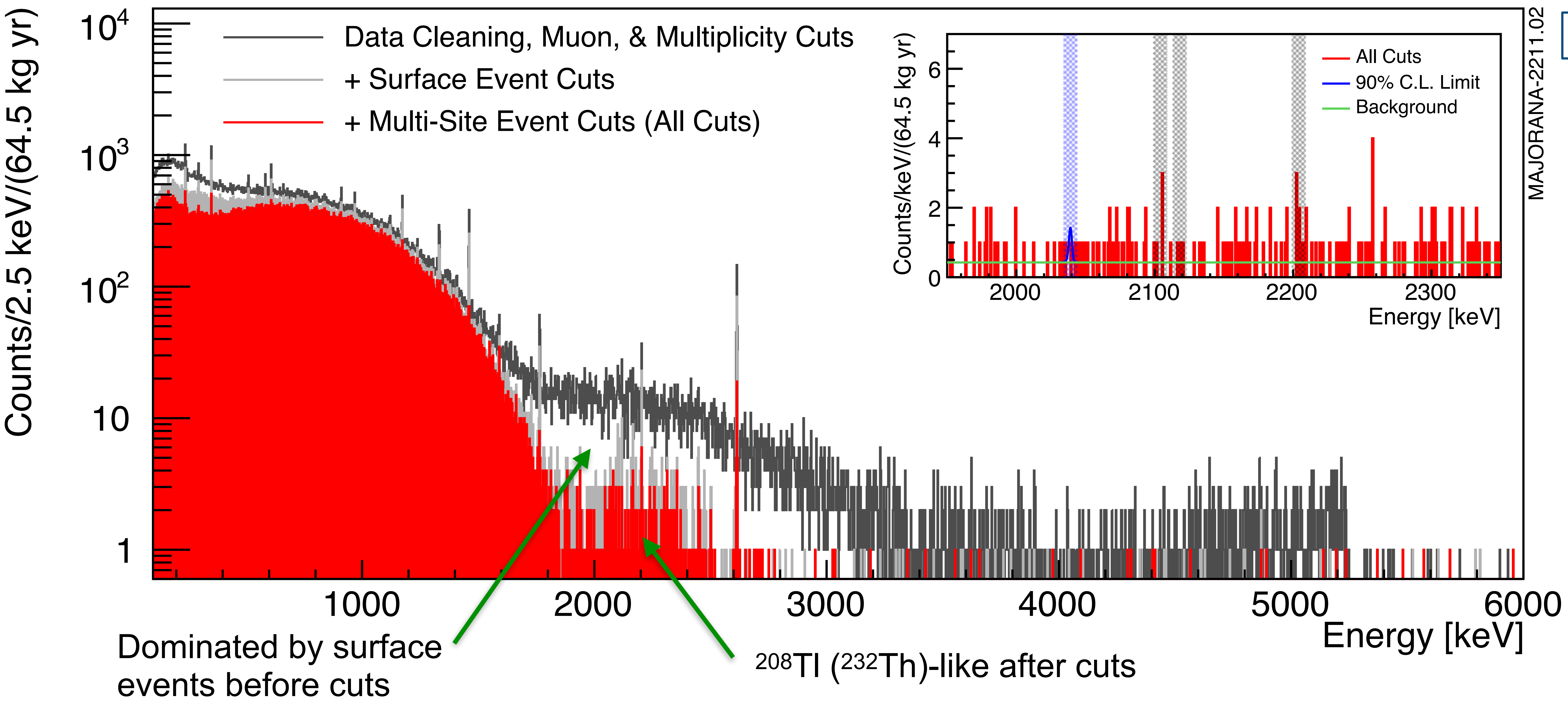
Fast drift time: **high AvsE cut** for particle incident on surface near point contact

Slow charge collection (~10 μs): **Delayed Charge Recovery (DCR) discriminator** for particle incident on passivated surface:

EPJC **82** (2022) 226

Slow charge collection (~1 μs): **Late Charge (LQ) discriminator** for partial charge deposition in transition dead layer

Final Neutrinoless Double-Beta Decay Result



PRL **130** 062501 (2023)

Final enriched detector active exposure:

64.5 ± 0.9 kg-yr

Frequentist Limit:

65 kg-yr Exposure Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I.)

Median T1/2 Sensitivity: 8.1×10^{25} yr (90% C.I.)

$m_{\beta\beta} < 113 - 269$ meV

Using $M_{0\nu} = 2.66 - 6.34$

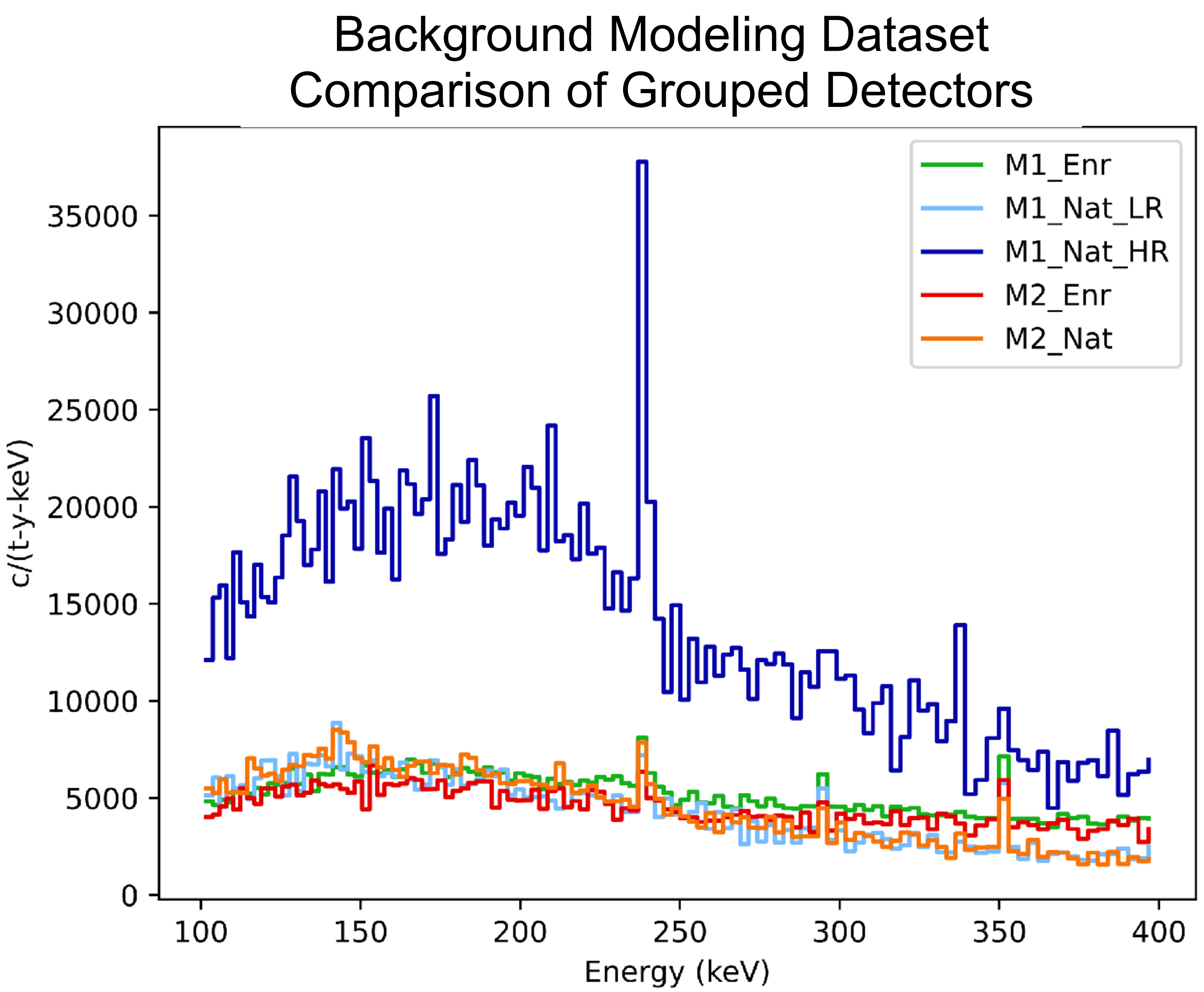
Background Index: $(6.23 \pm 0.55) \times 10^{-3}$ cts/(keV kg yr) in lowest background configuration

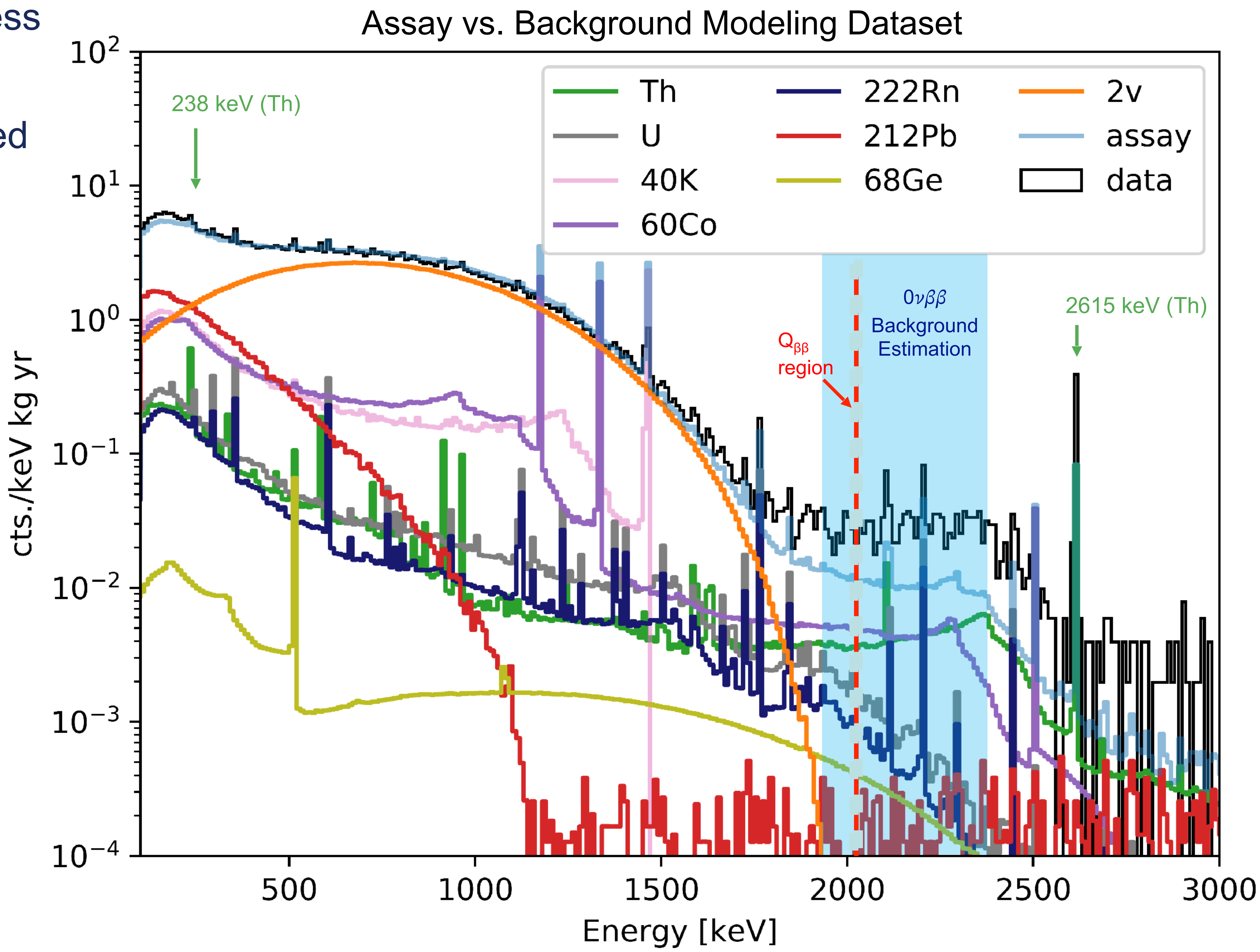
Module 1: $(7.38 \pm 0.71) \times 10^{-3}$ cts/(keV kg yr)

Module 2: $3.33^{+0.75}_{-0.67} \times 10^{-3}$ cts/(keV kg yr)

MAJORANA DEMONSTRATOR Background

- Background at 0νββ Q value is flat and featureless
  - Background model not needed for 0νββ limit
- Measured 0νββ background higher than expected
  - <1.16 x 10^{-3} cts/(keV kg yr): radioassay prediction
  - (6.23 ± 0.55) x 10^{-3} cts/(keV kg yr): in lowest background configuration



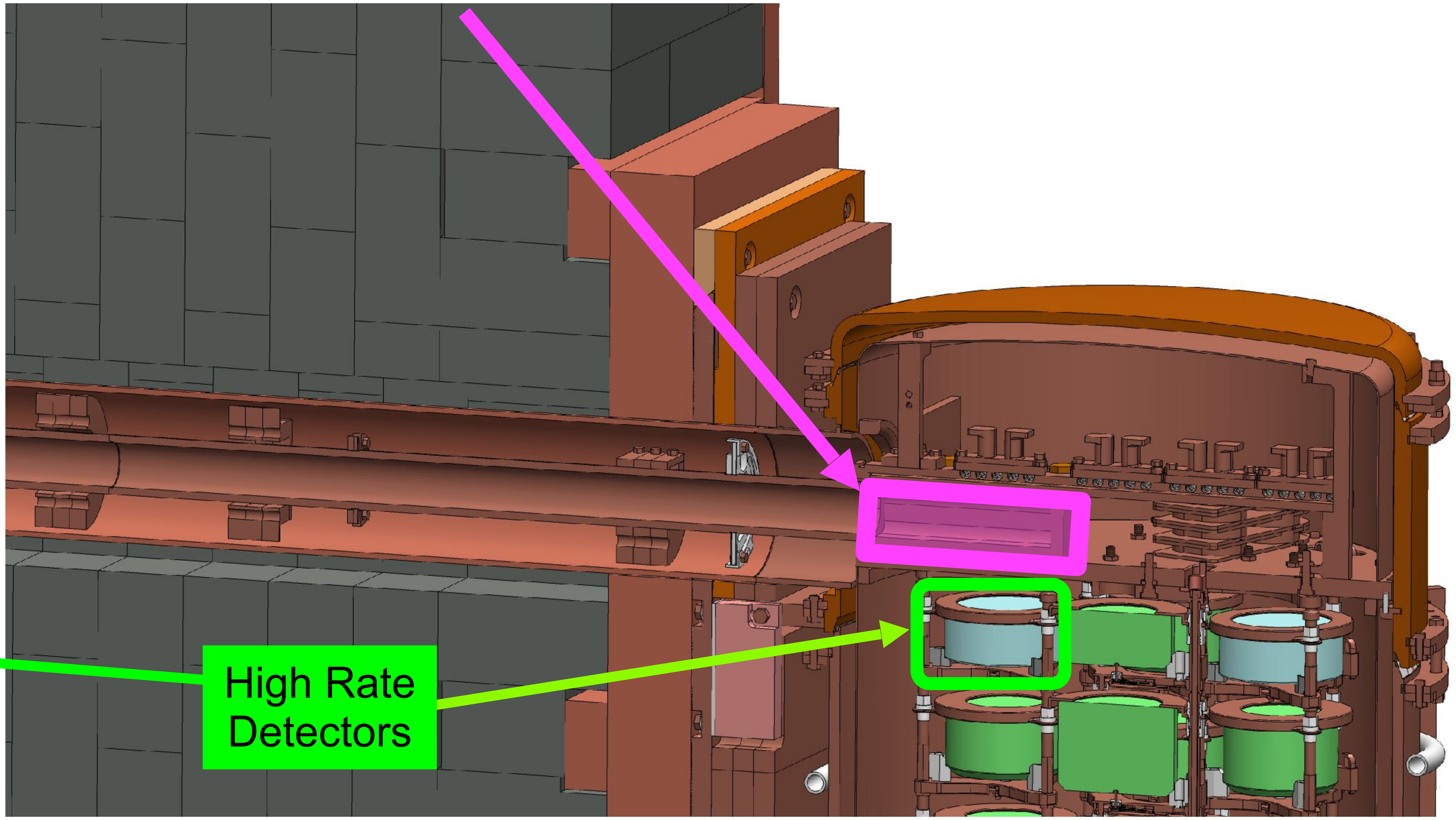


MAJORANA DEMONSTRATOR Background Excess

Characteristics of background excess:

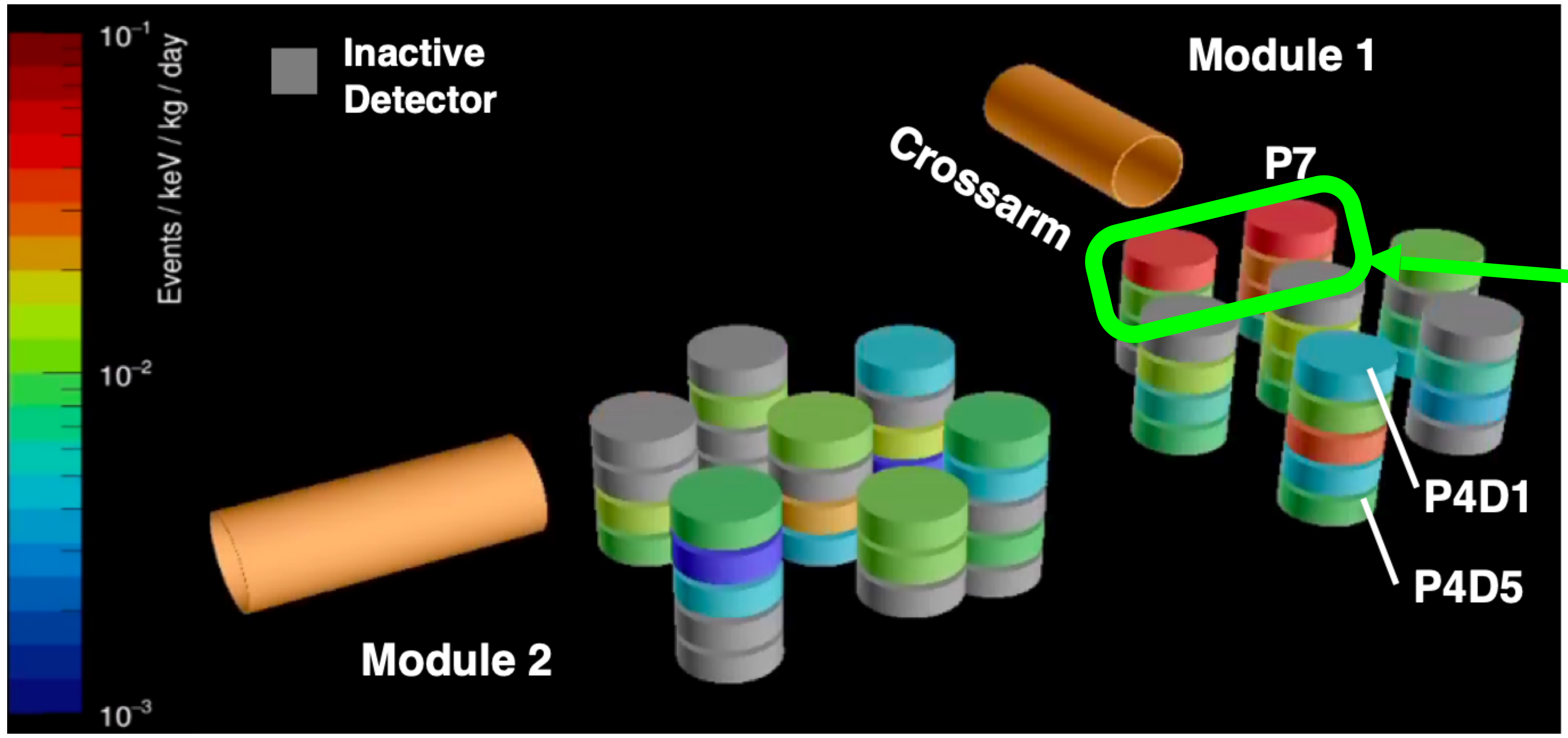
- Dominated by ^{232}Th decay chain — excess apparent at ^{208}Tl, especially 238 keV and 2615 keV
- Strong evidence excess is located near Module 1 feedthrough interface
- Does not indicate a source within the Ge detector array (front end electronics, detector holders, etc.)
- Not from a uniform bulk activity in any component groups, but from a localized region

Systematic fitting campaign localized the major source of the excess to a component above the array

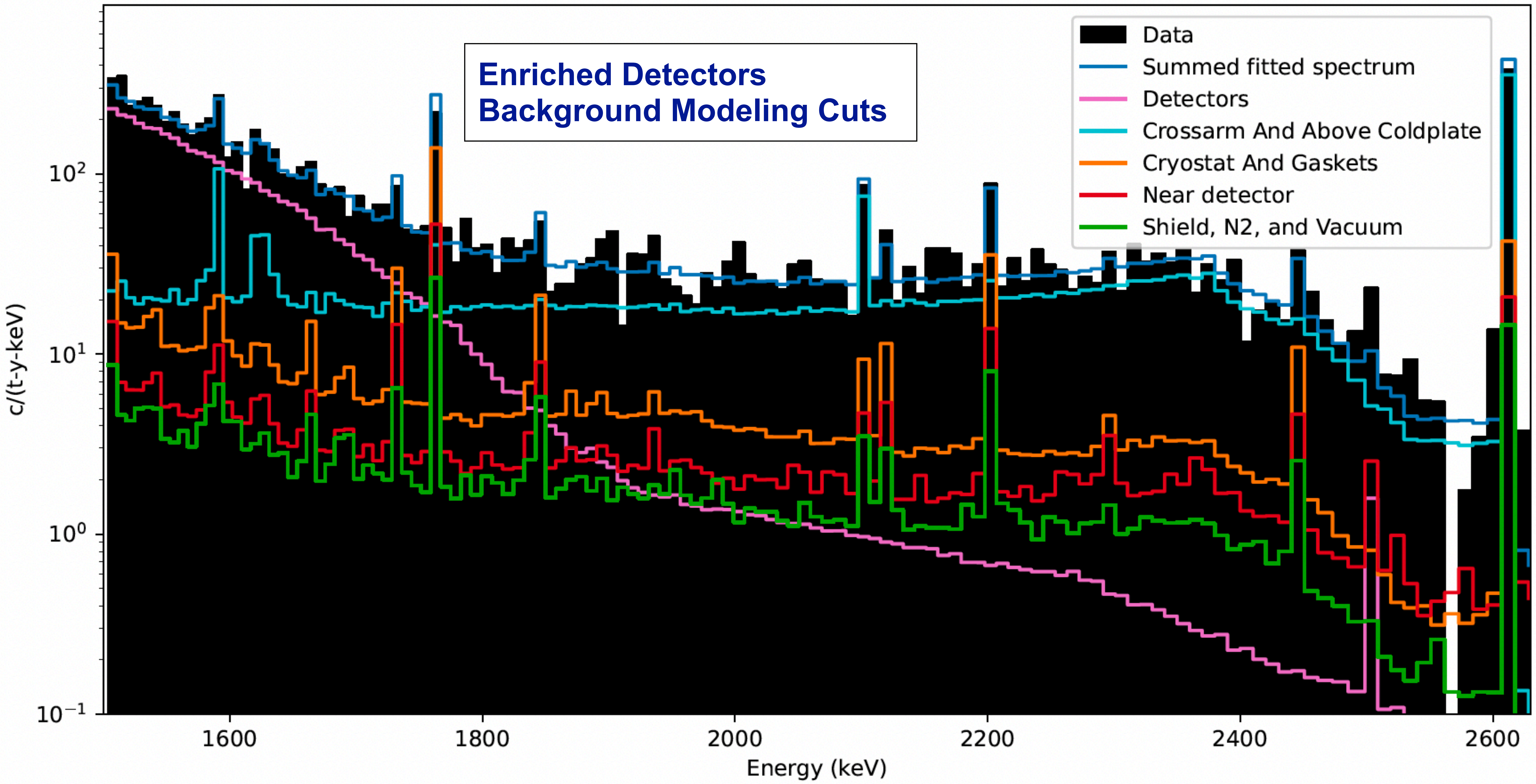


Recent assay of the component is not consistent with presence of excess now — Likely not present in the bulk
Excess could have been present earlier during operation

2615 keV rate in Background Modeling Dataset



Major Background Sources



The dominant backgrounds in the Demonstrator are not from a near-detector region that would pose problems for LEGEND

Recent Progress in the MAJORANA DEMONSTRATOR Background Model
Ethan Blalock @ Hawaii2023

A Study of MAJORANA DEMONSTRATOR Backgrounds with Bayesian Statistical Modeling
Christopher R. Haufe, UNC-CH - PhD Dissertation - 2023

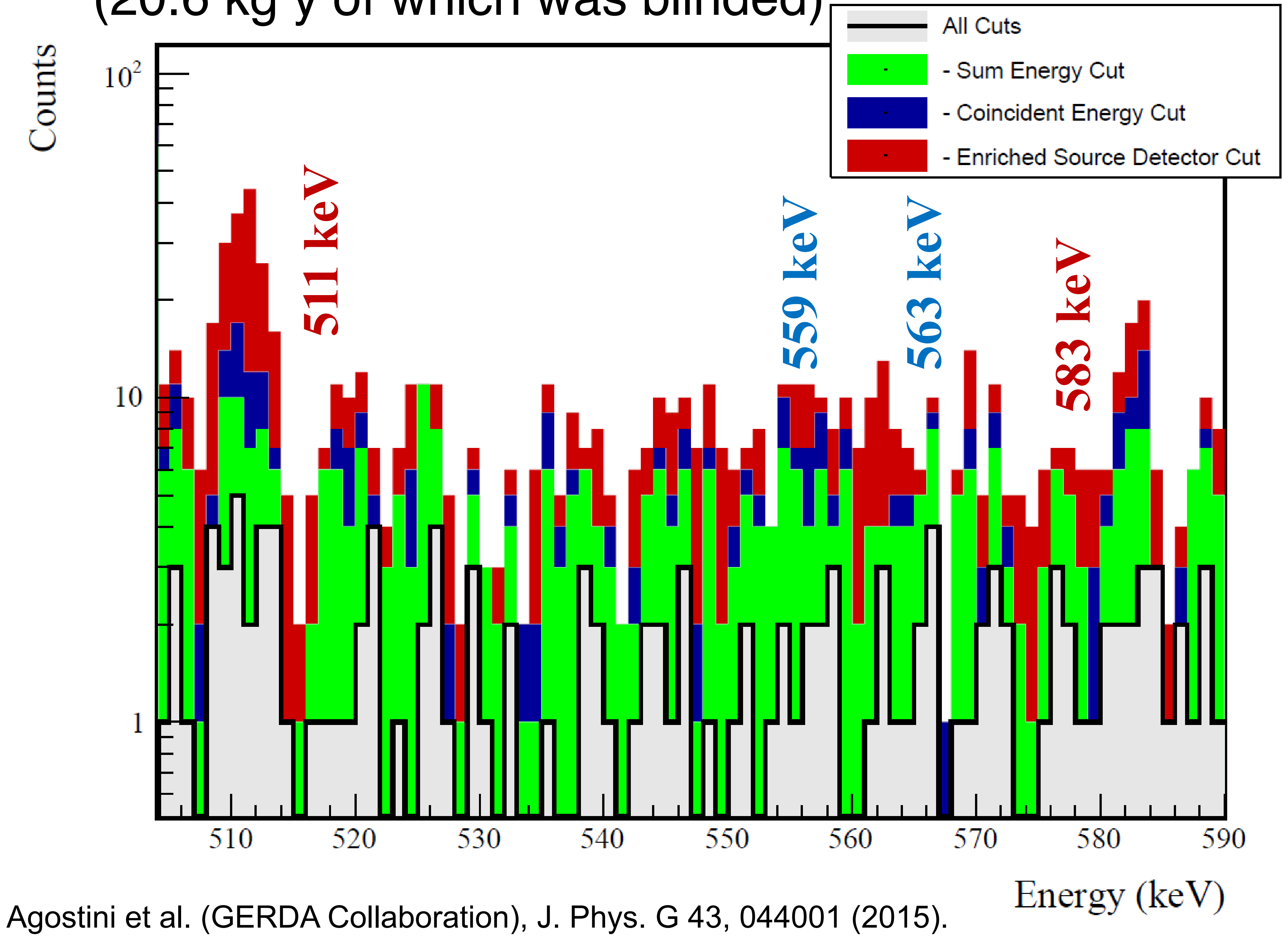
An Improved Background Model and Two-Neutrino Double-Deta Measurement for the MAJORANA DEMONSTRATOR
AnnaL. Reine, UNC-CH. - PhD Dissertation - 2023

Double Beta Decay to Excited States

An inherently multi-site signal topology:

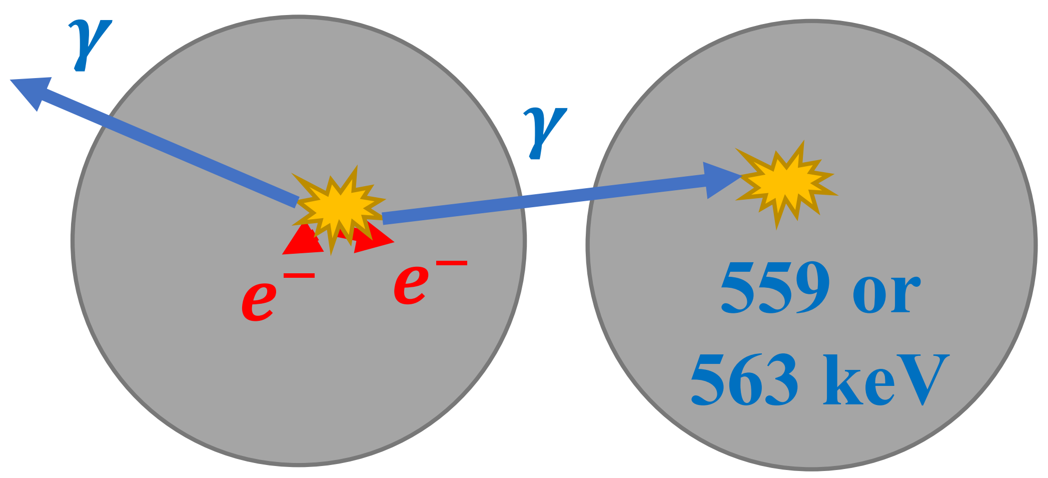
- A "source" detector will have a broad energy spectrum from ββ
- The "gamma" detector will measure energy peaked at the γ energies

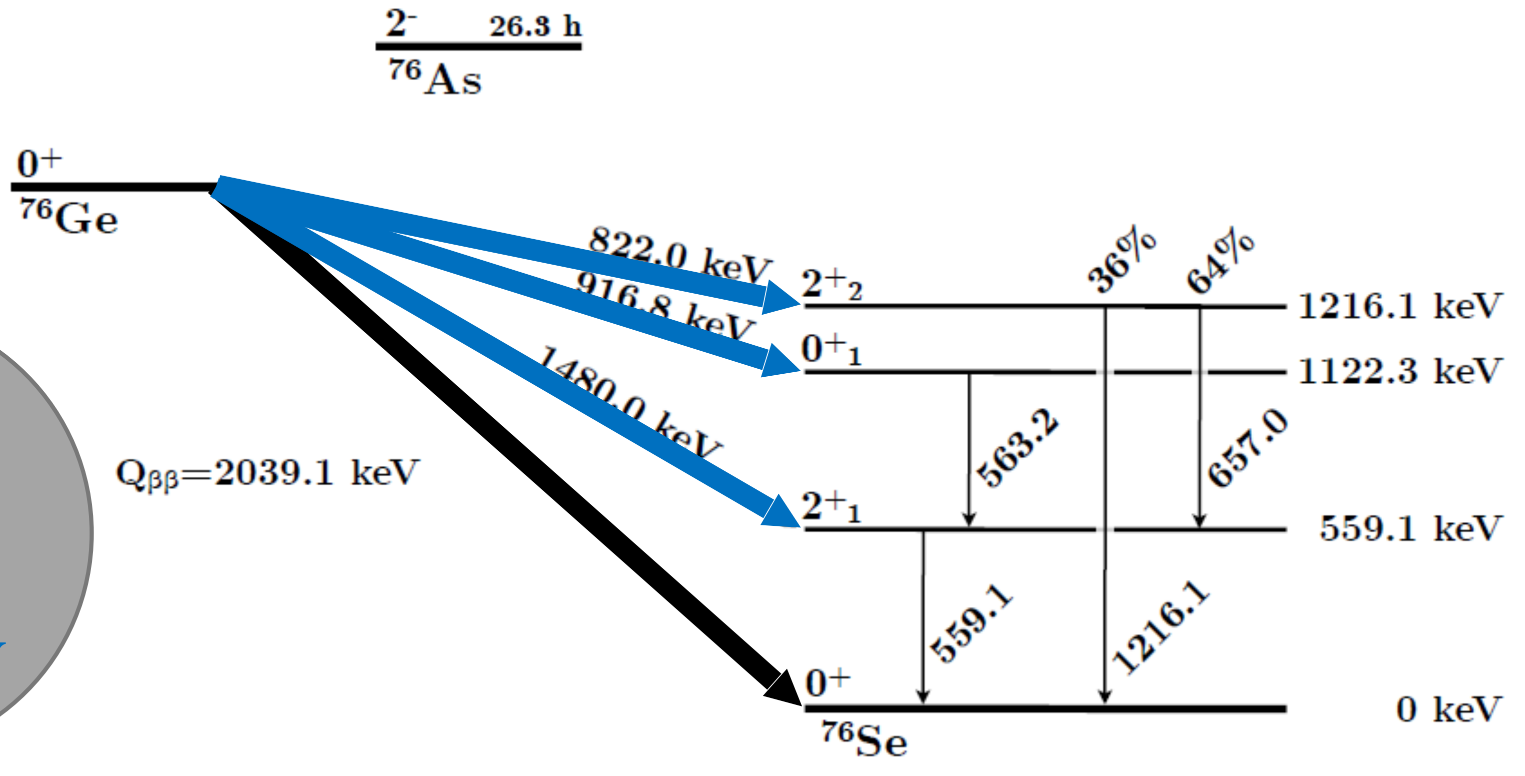
41.9 kg y of isotopic exposure
(20.6 kg y of which was blinded)



[1] M. Agostini et al. (GERDA Collaboration), J. Phys. G 43, 044001 (2015).
[2] A. Morales, et al., Nuovo Cim. A 100, 525 (2008).
[3] B. Maier (Heidelberg Moscow Collaboration), Nucl. Phys. B – Proc. Suppl. 35, 358 (1994).
[4] A. S. Barabash, A. V. Derbin, L. A. Popeko, and V. I. Umatov, Z. Phys. A 352, 231 (1995).

PRC **103** 015501 (2021)





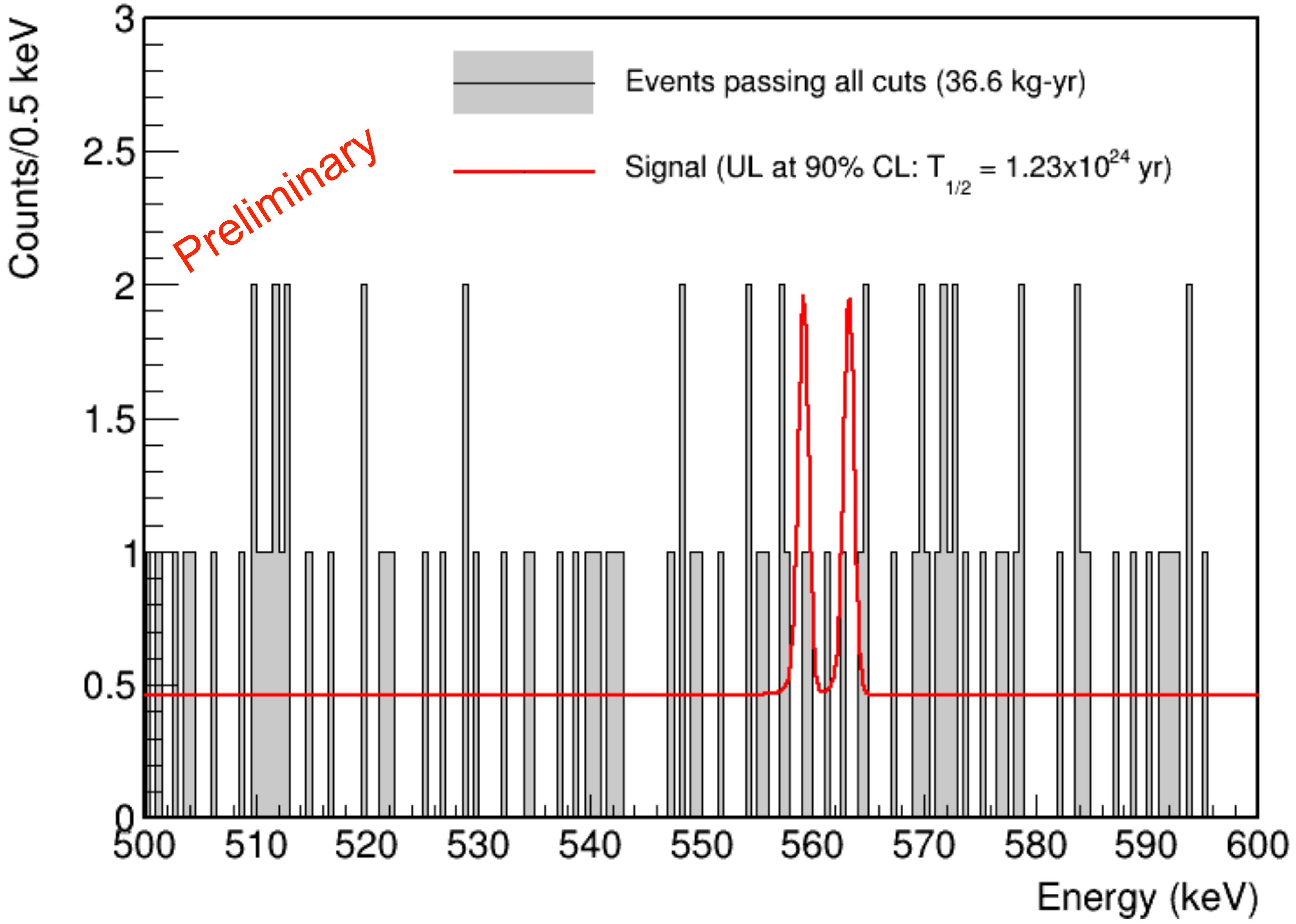
Decay Mode	Det. efficiency (M1, M2)	$T_{1/2}$ prev. limit (90% CI)	$T_{1/2}$ new limit (90% CI)	$T_{1/2}$ sensitivity (90% CI)
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$	2.4%, 1.0%	$> 3.7 \cdot 10^{23} y$ [1]	$> \mathbf{7.5 \cdot 10^{23} y}$	$> \mathbf{10.5 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_1$	1.4%, 0.6%	$> 1.6 \cdot 10^{23} y$ [1]	$> \mathbf{7.7 \cdot 10^{23} y}$	$> \mathbf{10.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_2$	2.2%, 0.8%	$> 2.3 \cdot 10^{23} y$ [1]	$> \mathbf{12.8 \cdot 10^{23} y}$	$> \mathbf{8.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 0^+_1$	3.0%, 1.2%	$> 1.3 \cdot 10^{22} y$ [2]	$> \mathbf{39.9 \cdot 10^{23} y}$	$> \mathbf{39.9 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_1$	1.6%, 0.7%	$> 1.3 \cdot 10^{23} y$ [3]	$> \mathbf{21.2 \cdot 10^{23} y}$	$> \mathbf{21.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_2$	2.3%, 1.0%	$> 1.4 \cdot 10^{21} y$ [4]	$> \mathbf{9.7 \cdot 10^{23} y}$	$> \mathbf{18.6 \cdot 10^{23} y}$

Using date collected **up to 2019**, set the **most stringent limits** to date for ββ to each excited state of ^{76}Se due to:

- Operating an array in vacuum: high detection efficiency
- Exquisite energy resolution for identifying peaks
- Low environmental backgrounds & analysis cuts

New: Double Beta Decay to Excited States

Background after cuts with signal at 90% CL upper limit



Preliminary result for $2\nu\beta\beta$ of ^{76}Ge to 0_1^+ excited state of ^{76}Se

Isotopic Exposure: 36.6 kg-y

Detection Efficiency: 2.7% (M1), 1.4% (M2)

Background Index (after cuts): 0.025 cts/keV-kg-y

Compared to previous analysis, upgrades have improved detection efficiency, with similar background reduction

90% Sensitivity: $T_{1/2} > 1.1 \times 10^{24}$ yr

90% Limit: $T_{1/2} > 1.2 \times 10^{24}$ yr

Using the full dataset of the experiment (97.4 kg-y isotopic exposure), MAJORANA will produce an improved limit

A projected half-life sensitivity of 2.2 x 10^{24} yr

Rich and Broad Physics Programs

Tests of Fundamental Symmetries and Conservations
- Lepton number violation via neutrinoless double beta decay
- Baryon number violation
- Pauli Exclusion Principle violation

PRL **130** 062501 (2023)

PRD **99** 072004 (2019)

arXiv:2203.02033 (2023) Accepted by Nature Phys

Standard Model Physics

BSM Physics

Standard Model Physics, Backgrounds
- $2\nu\beta\beta$ to excited states
- In situ cosmogenics
- (alpha, n) reactions
- ^{180m}Ta decay

PRC **103** 015501 (2021)

PRC **105** 014617 (2022)

PRC **105** 064610 (2022)

PRL **131** 152501 (2023)

MAJORANA DEMONSTRATOR

Excellent energy performance &

Low backgrounds

across broad energy regions

Low-mass dark matter signatures
- Pseudoscalar dark matter
- Vector dark matter
- Fermionic dark matter
- Sterile neutrino
- Primakoff solar axion
- 14.4-keV solar axion

PRL **118** 161801 (2017)

PRL **129** 081803 (2022)

arXiv:2206.10638 (2023) Accepted by PRL

Exotic Physics
- Quantum Wavefunction collapse
- Lightly ionization particle

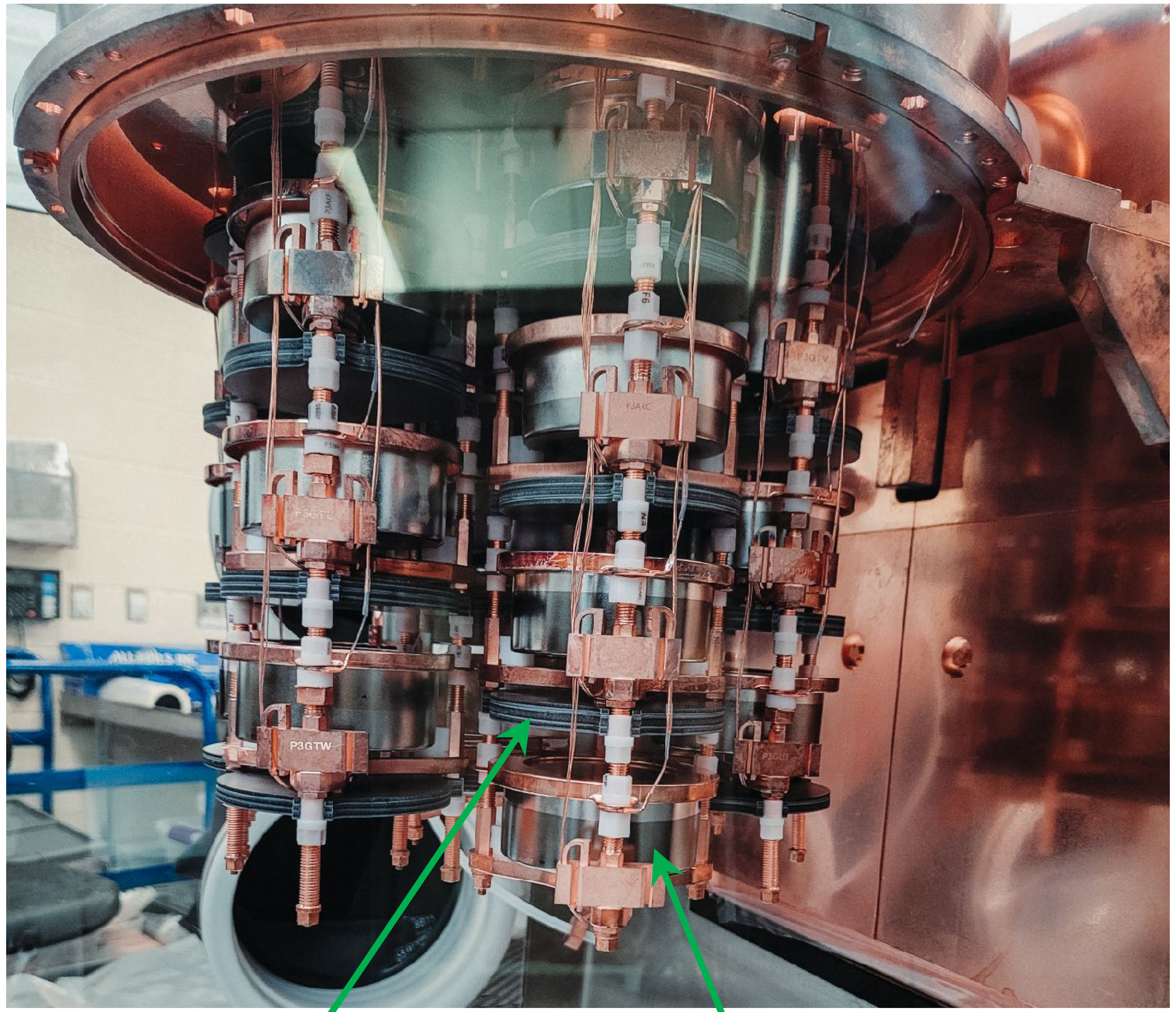
PRL **129** 080401 (2022)

PRL **120** 211804 (2018)

Tantalum: The Next DEMONSTRATOR Chapter

MAJORANA DEMONSTRATOR has been reconfigured with single module of natural detectors

Searching for decay of ^{180m}Ta, nature's longest lived metastable isotope



17 kg tantalum disks
2 g ^{180m}Ta

23 ^{nat}Ge BEGe detectors

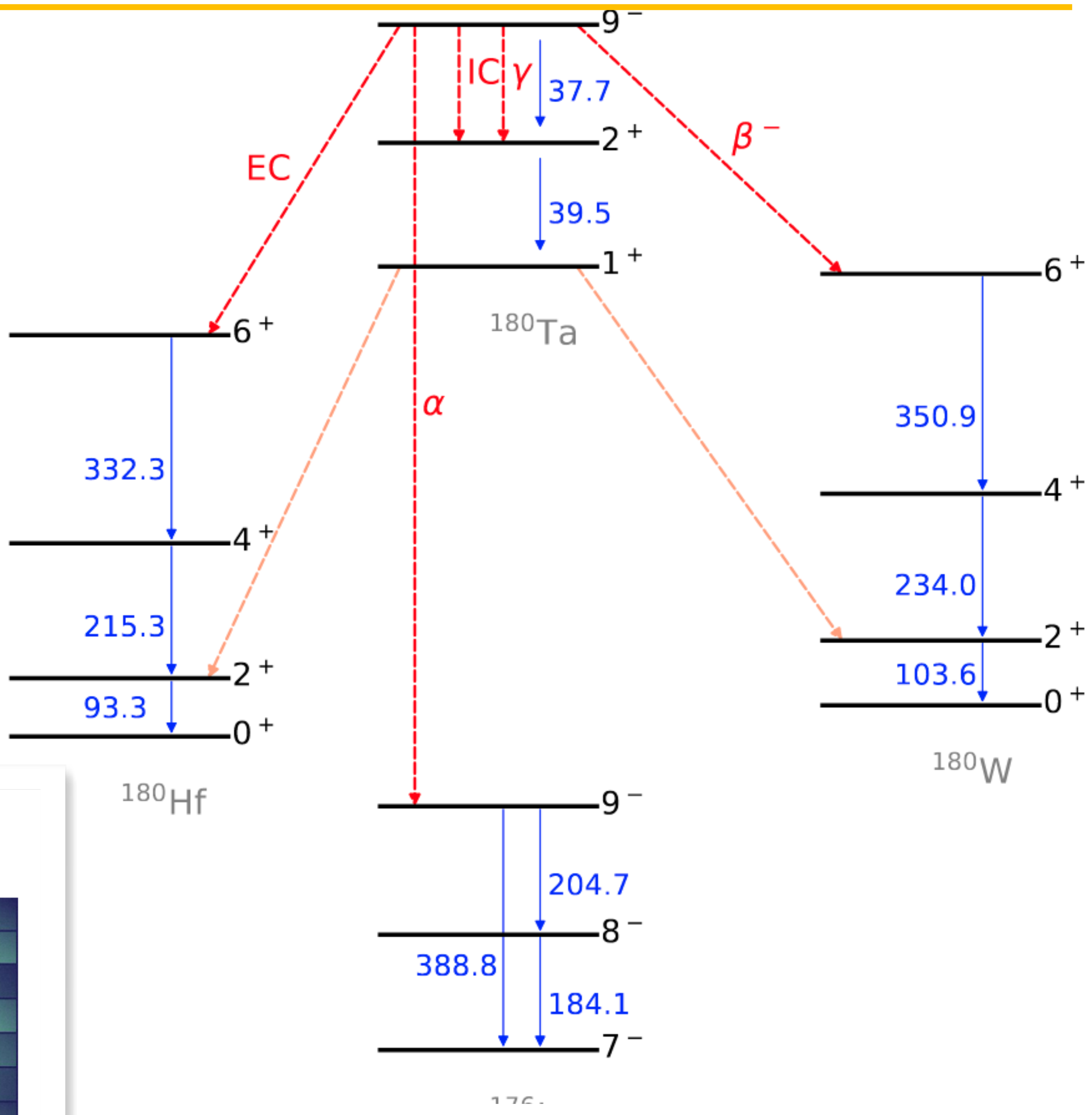
symmetry
dimensions of particle physics

Illustration by Sandbox Studio, Chicago with Kimberly Boustead

Majorana Demonstrator finds 'tantalizing' new purpose

09/06/22 | By Erin Lorraine Broberg

Scientists are using a detector originally designed to study neutrinos to pin down an elusive nuclear physics measurement.



Decay scheme of ^{180m}Ta with possible decay channels (red) and detection signatures (blue)

Constraints on the decay of ^{180m}Ta
Steve Elliott @ Hawaii2023

Lower limits on the decay half-life of ^{180m}Ta

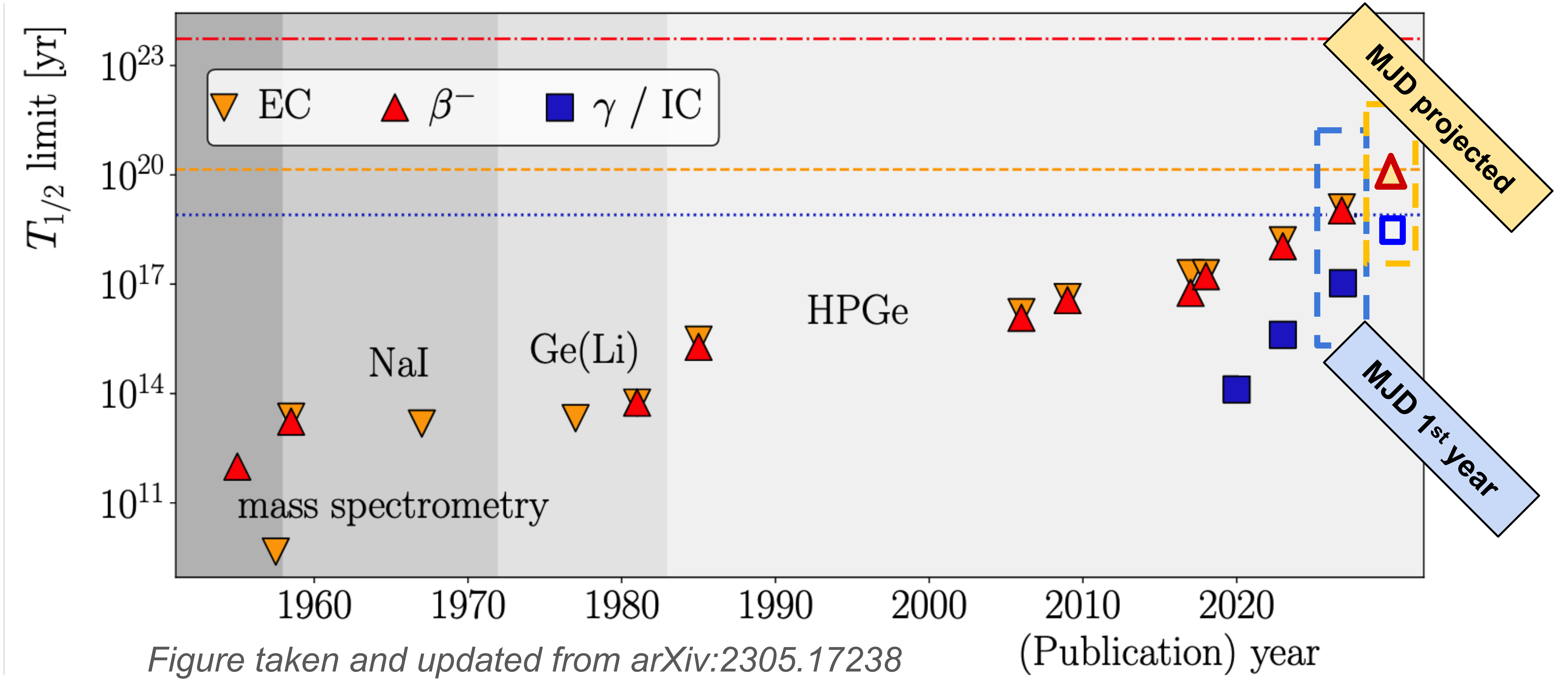


Figure taken and updated from arXiv:2305.17238

Most sensitive search for half-life measurements in isomers world-wide

First data improved previous half-life limits by 1-2 orders of magnitude

> **Constraints on the Decay of ^{180m}Ta**
> I. J. Arnquist *et al.* (MAJORANA COLLABORATION)
> Phys. Rev. Lett. **131**, 152501 (2023) – Published 11 October 2023

MAJORANA DEMONSTRATOR Summary and Outlook

- Started taking data with first module in 2015 and has completed enriched Ge data-taking in 2021
  - Excellent energy resolution of 2.5 keV FWHM @ 2039 keV, best of all 0νββ experiments
  - **Latest limit on 0νββ of $T_{1/2}$ > 8.3 × 10^{25} yr (90% C.I.) from 64.5 kg-yr exposure**
- Leading limits in the search for double-beta decay of ^{76}Ge to excited states
  - Set a new upper limit on 2νββ of ^{76}Ge to 0^+_1 excited state of ^{76}Se using 36.6 kg-y of open data from the full dataset
  - An unblinded analysis with 97.4 kg-y of data will have a projected half-life sensitivity of 2.2 x 10^{24}y
- Working towards the publication of a background model including fits over the full exposure and evaluations of systematic uncertainties
  - Including a measurement of 2νββ half-life with evaluated uncertainties
- Low background + energy resolution + multiple years of high-quality data allows for broad physics program, yielding many new results
  - BSM physics results extracted in wide energy range with various analysis techniques
- Continuing operation with natural detectors for other physics (e.g. decay of ^{180m}Ta)

This material is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, the Particle Astrophysics and Nuclear Physics Programs of the National Science Foundation, and the Sanford Underground Research Facility.

The MAJORANA Collaboration

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain:
Clara Cuesta

Duke University, Durham, NC, and TUNL:
Matthew Busch

Indiana University, Bloomington, IN:
Walter Pettus

Joint Institute for Nuclear Research, Dubna, Russia:
Sergey Vasilyev

Lawrence Berkeley National Laboratory, Berkeley, CA:
Yuen-Dat Chan, Alan Poon

Los Alamos National Laboratory, Los Alamos, NM:
Pinghan Chu, Steven Elliott, In Wook Kim, Ralph Massarczyk, Samuel J. Meijer, Keith Rielage, Danielle Schaper, Sam Watkins, Brian Zhu

National Research Center '*Kurchatov Institute' Institute of Theoretical and Experimental Physics, Moscow, Russia:*
Alexander Barabash

North Carolina State University, Raleigh, NC and TUNL:
Matthew P. Green, Ethan Blalock, Rushabh Gala

Oak Ridge National Laboratory, Oak Ridge, TN:
Vincente Guiseppe, José Mariano Lopez-Castaño, David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan:
Hiroyasu Ejiri

Pacific Northwest National Laboratory, Richland, WA:
Isaac Arnquist, Maria-Laura di Vacri, Eric Hoppe, Richard T. Kouzes

South Dakota Mines, Rapid City, SD:
Cabot-Ann Christofferson, Sam Schleich, Ana Carolina Sousa Ribeiro, Jared Thompson

University of North Carolina, Chapel Hill, NC, and TUNL:
Kevin Bhimani, Brady Bos, Thomas Caldwell, Morgan Clark, Julieta Gruszko, Ian Guinn, Chris Haufe, Reyco Henning, David Hervas, Aobo Li, Eric Martin, Anna Reine, John F. Wilkerson

University of South Carolina, Columbia, SC:
Franklin Adams, Frank Avignone, Thomas Lannen, David Tedeschi

University of South Dakota, Vermillion, SD:
C.J. Barton, Laxman Paudel, Tupendra Oli, Wenqin Xu

University of Tennessee, Knoxville, TN:
Yuri Efremenko

University of Washington, Seattle, WA:
Micah Buuck, Jason Detwiler, Alexandru Hostiuc, Nick Ruof, Clint Wiseman

Williams College, Williamstown, MA:
Graham K. Giovanetti

*students