Final Results from the MAJORANA DEMONSTRATOR

INDIANA UNIVERSITY

Walter C. Pettus
On behalf of the MAJORANA collaboration

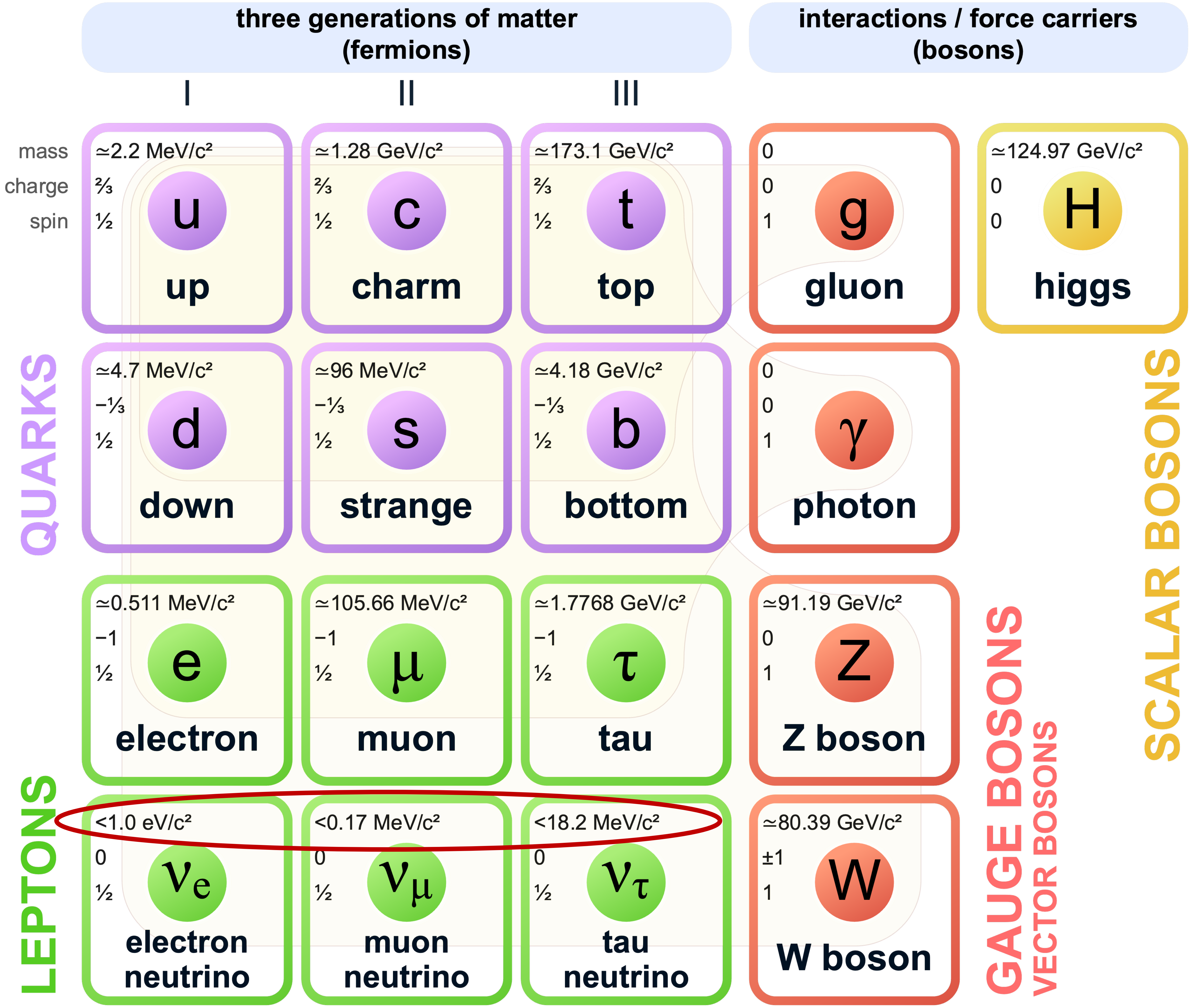
CIPANP 2022
3 September 2022

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Sanford Underground Research Facility

Neutrino Mass ~~Problem~~ Opportunity



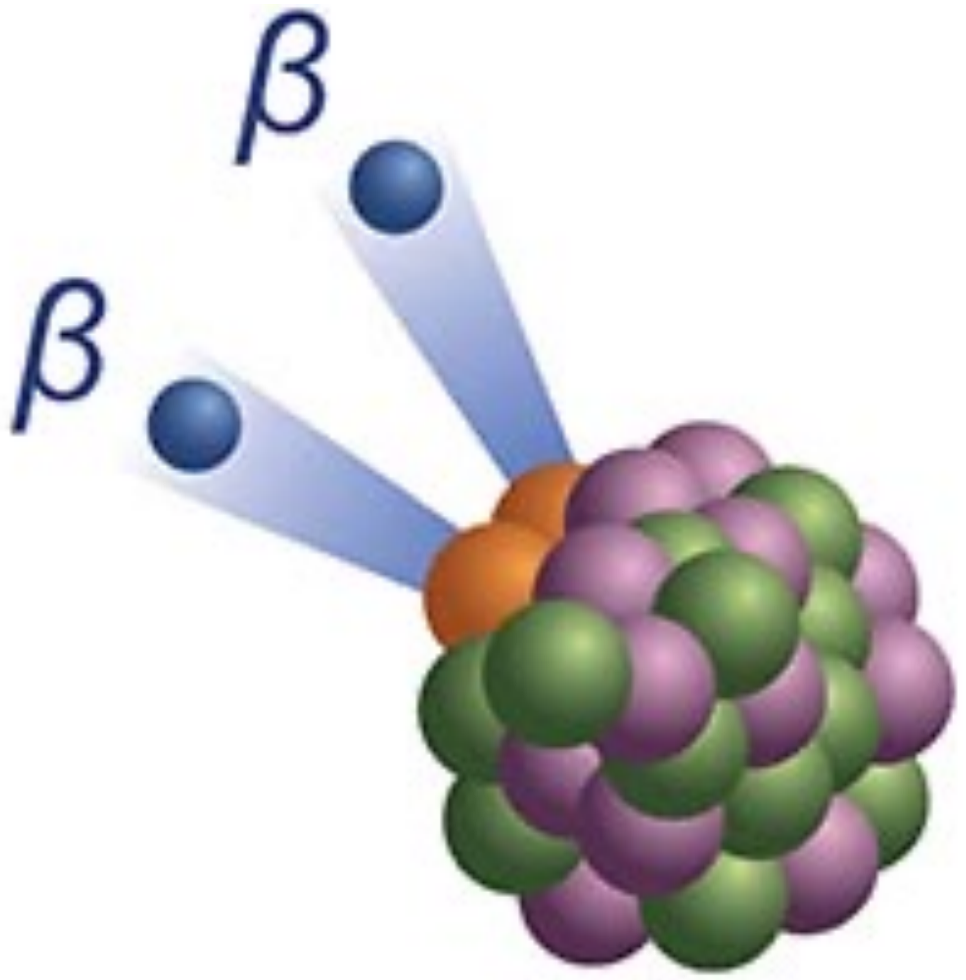
Neutrino mass is missing number for completing Standard Model checklist of properties

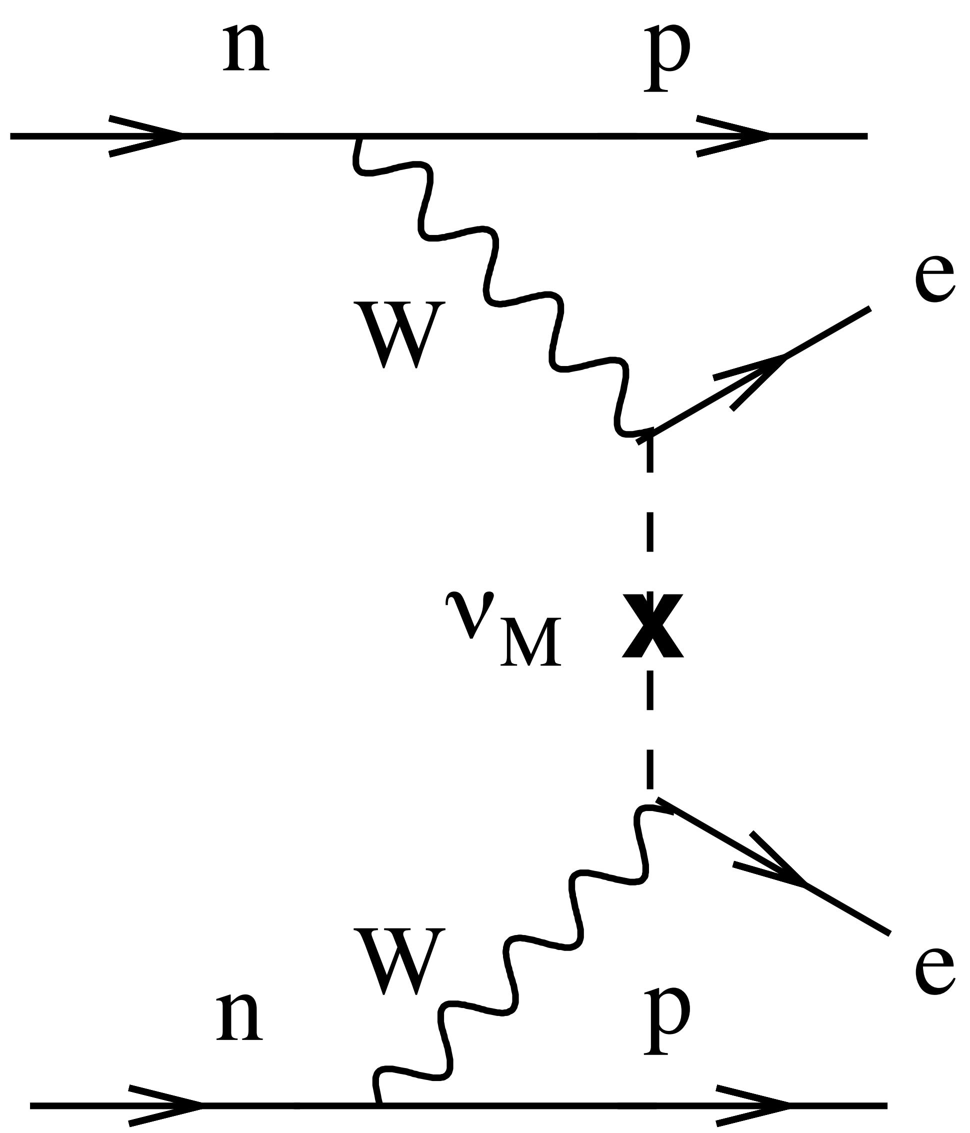
Neutrino mass at a widely disparate scale from other fermions

At a conference on "Intersections," neutrino mass appears in nuclear, particle, astrophysics, cosmology…

Connected to big open questions across these fields

Neutrinoless Double Beta Decay (0νββ)





Searching for theoretical process:

$$\mathbf{(A, Z) \rightarrow (A, Z+2) + 2e^-}$$

Contrast with observed 2νββ : $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

0νββ necessarily requires new physics

Lepton number is not conserved

Fundamental Majorana particles exist

0νββ related to other exciting physics

Majorana neutrinos help explain small observed neutrino masses via see-saw mechanism

Leptogenesis as ingredient for explaining matter-antimatter asymmetry

$0\nu\beta\beta$ Detection

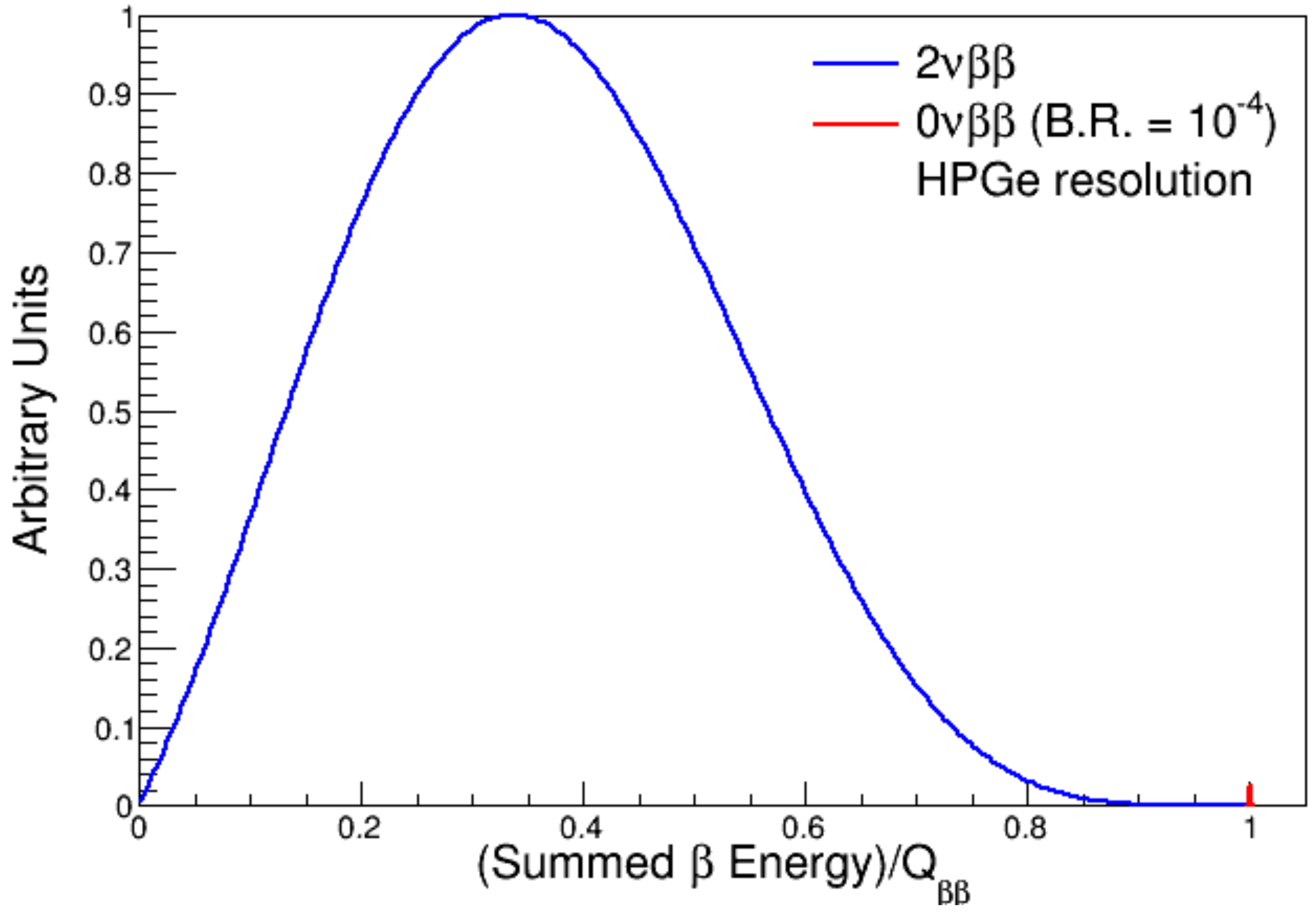
Signature of $0\nu\beta\beta$ is monoenergetic peak at Q-value

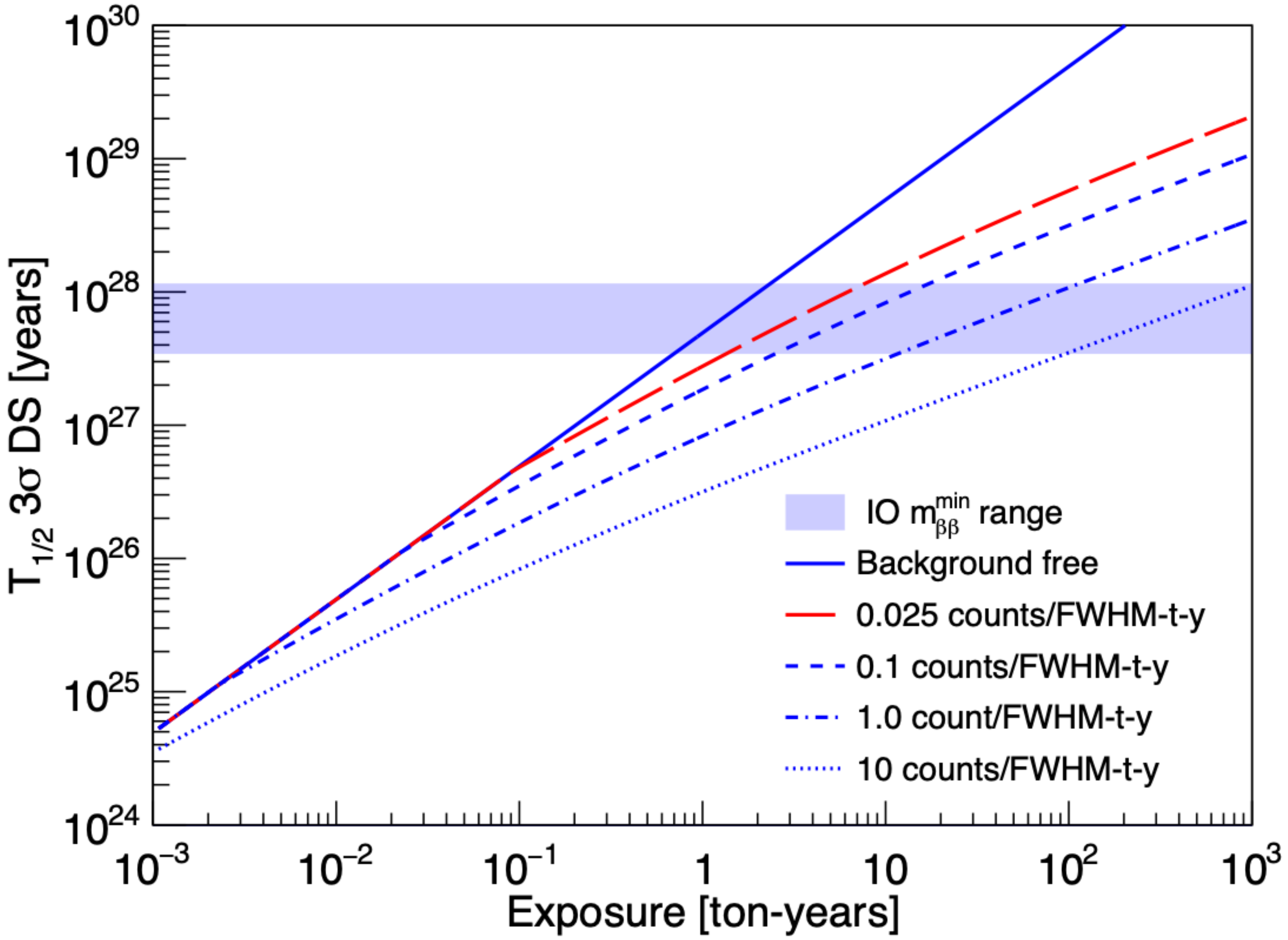
- Half-life greater than 1.8x10^{26} yr (^{76}Ge) [1]

Intrinsic background from continuous $2\nu\beta\beta$ spectrum at lower energy

- Half-life of 1.9x10^{21} yr (^{76}Ge) [2]

[1] M. Agostini et al. (GERDA Collaboration), PRL **125**, 252502 (2020)
[2] M. Agostini et al. (GERDA Collaboration), EPJC **75**, 416 (2015)





Experimental Challenges

More Exposure

Mass scaling

Detection Efficiency

Less Background

Material Cleanliness

Background Rejection

Energy Resolution

Also … unambiguous signal detection

The MAJORANA Collaboration

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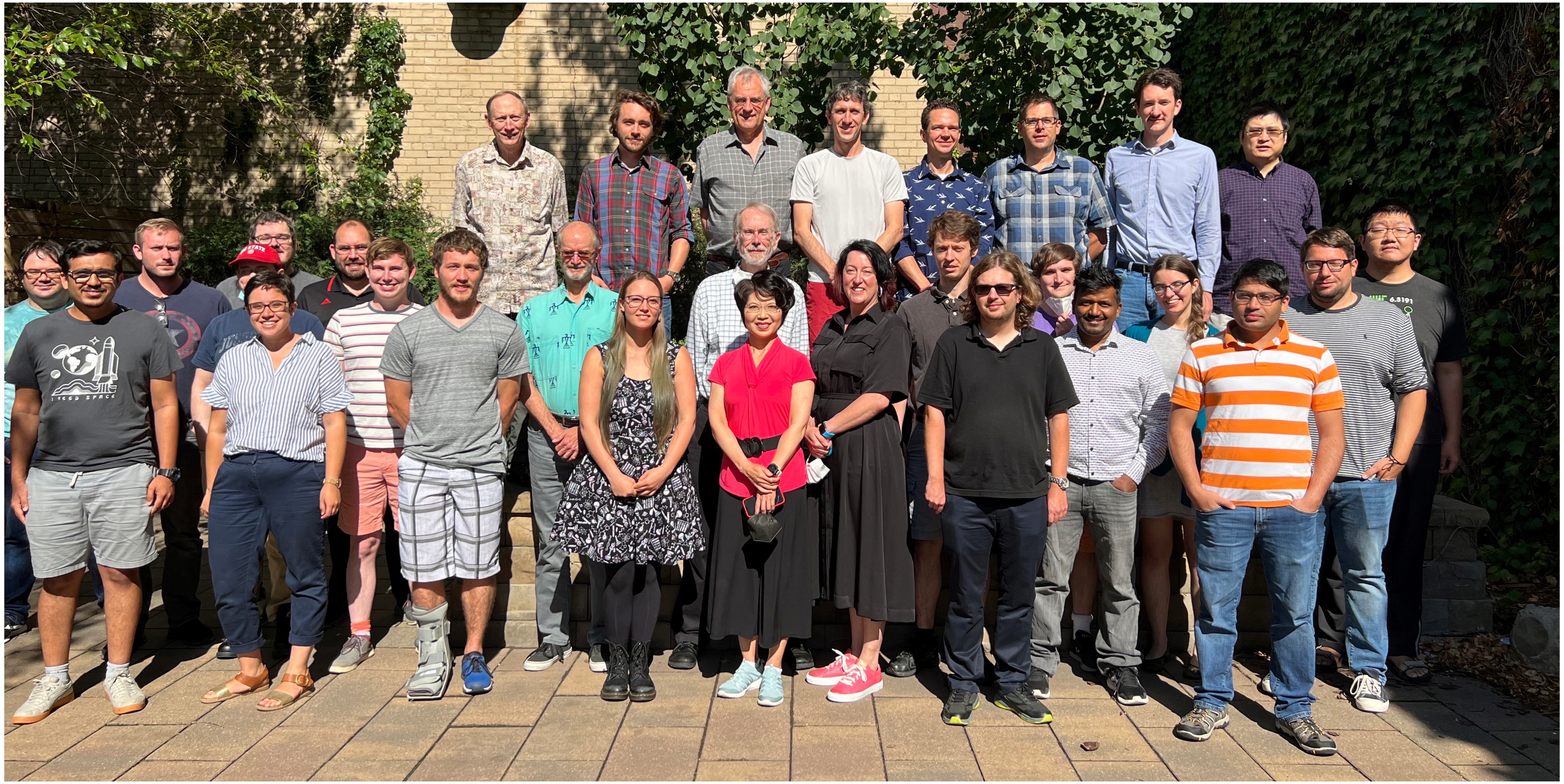

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Williams

MAJORANA DEMONSTRATOR

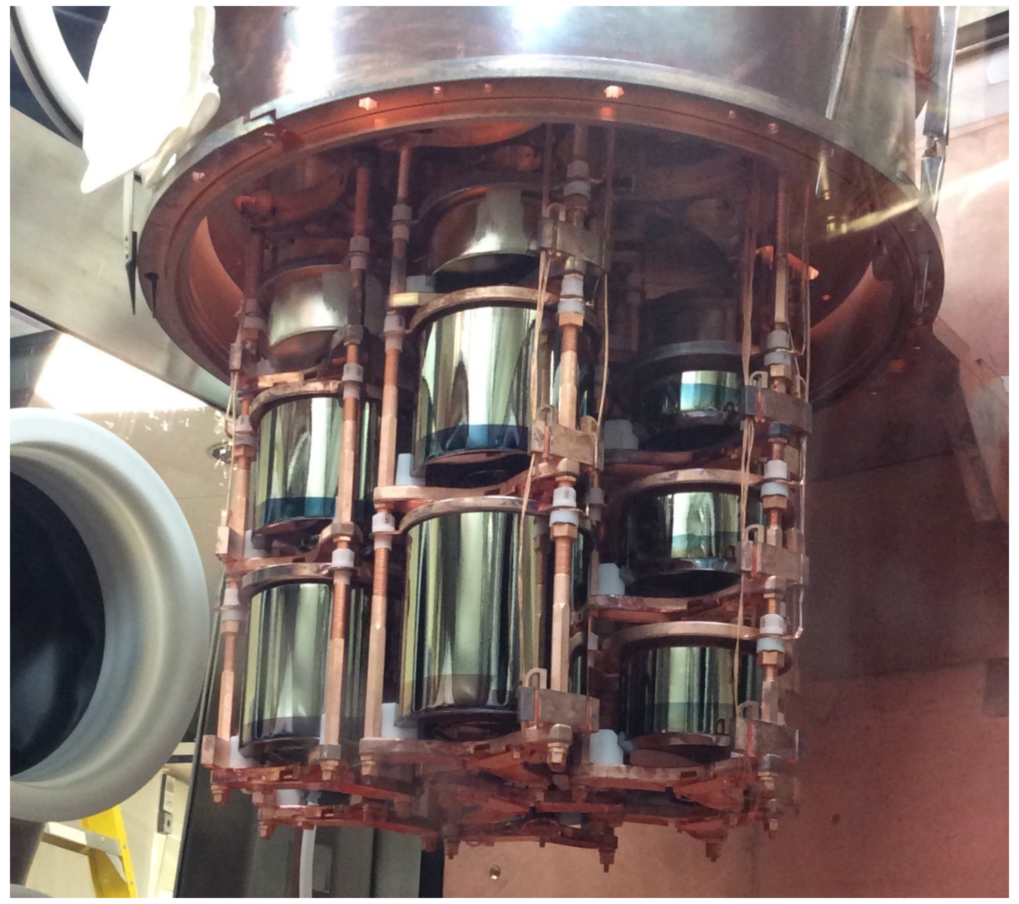
Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

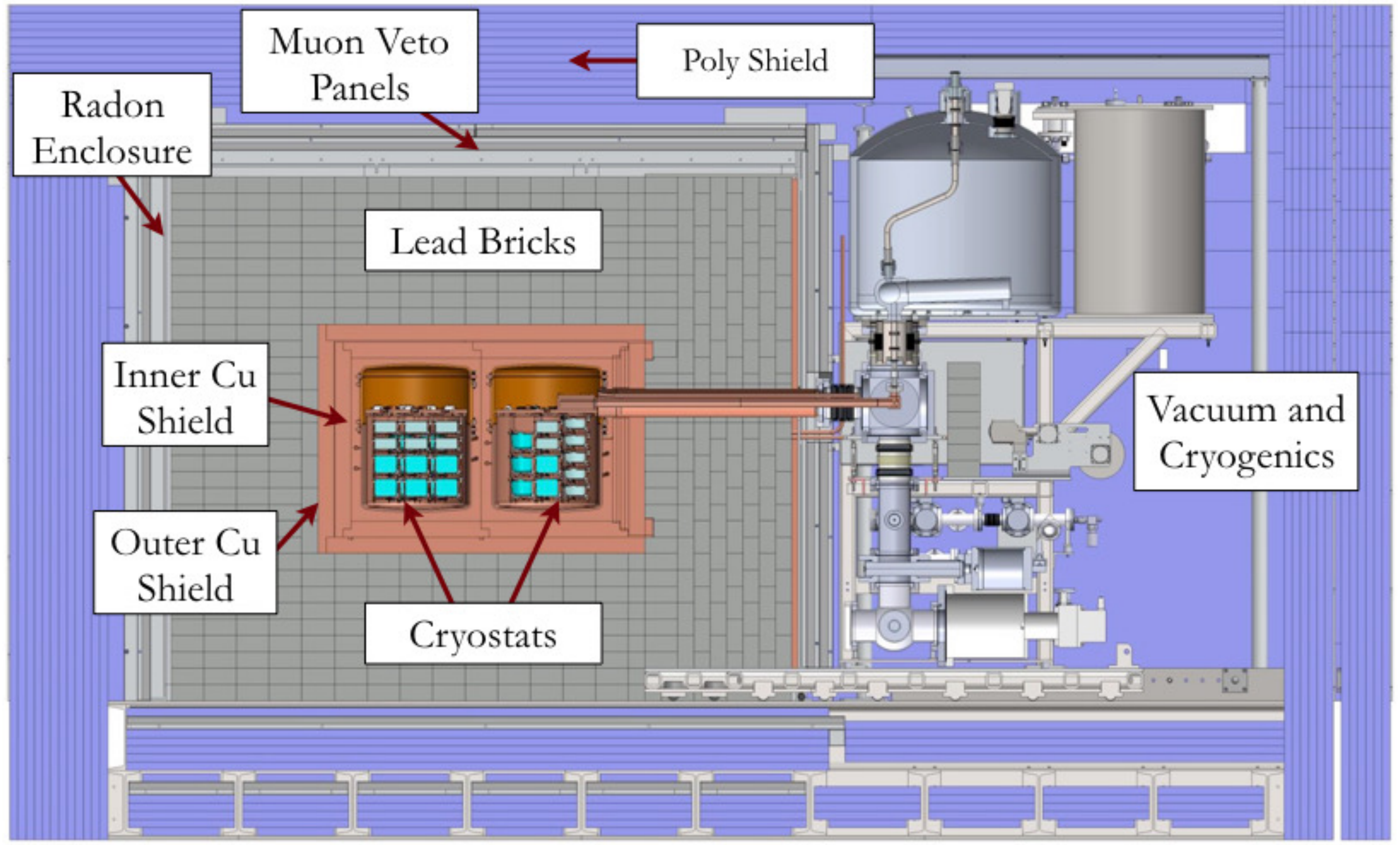
Source & Detector: Array of p-type, point contact detectors
- 30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals
- Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run

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

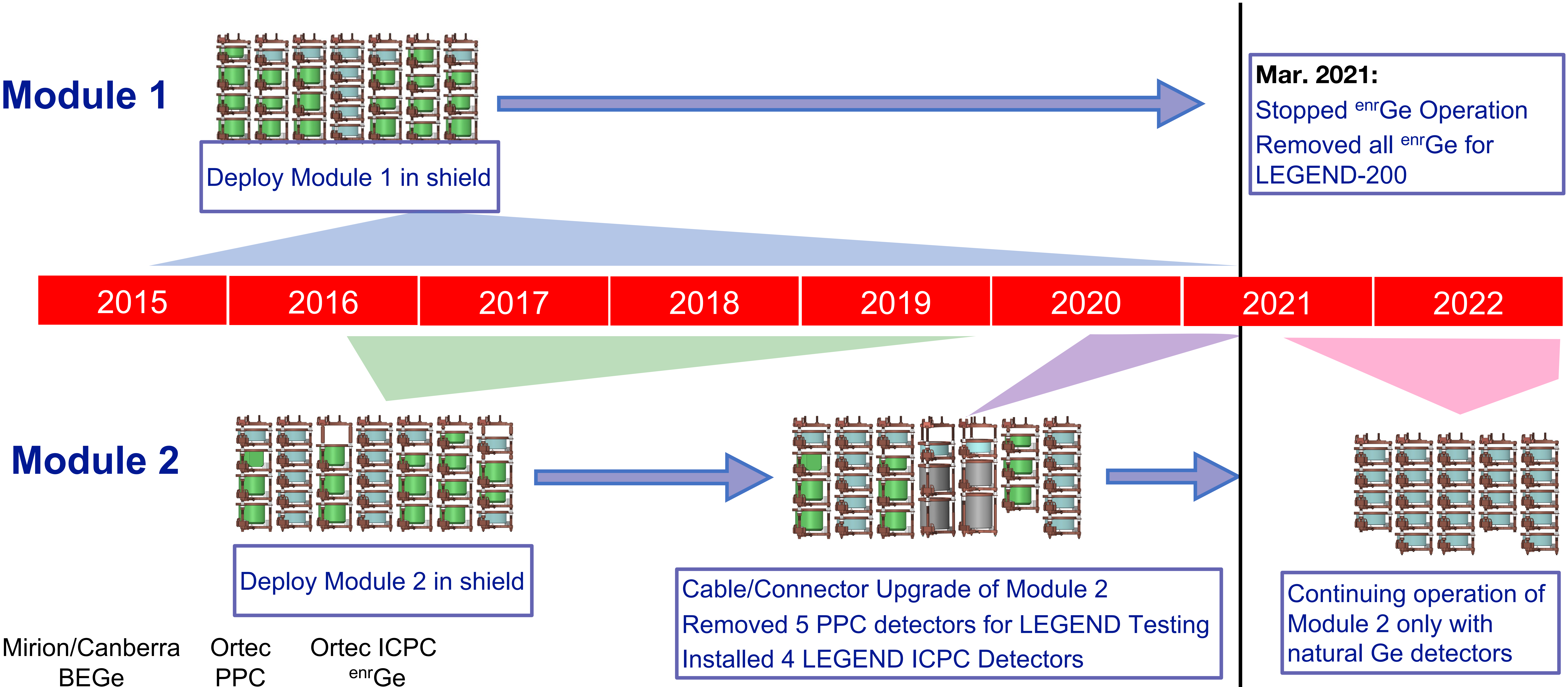
Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS





Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

MAJORANA Run Configuration & Timeline



Module 1

Deploy Module 1 in shield

Mar. 2021:
Stopped ^{enr}Ge Operation
Removed all ^{enr}Ge for LEGEND-200

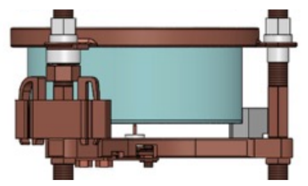
Module 2

Deploy Module 2 in shield

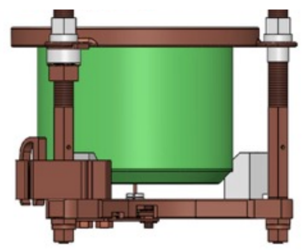
Cable/Connector Upgrade of Module 2
Removed 5 PPC detectors for LEGEND Testing
Installed 4 LEGEND ICPC Detectors

Continuing operation of Module 2 only with natural Ge detectors

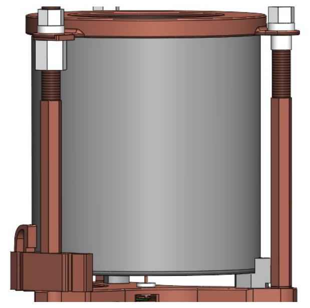
Mirion/Canberra BEGe ^{nat}Ge



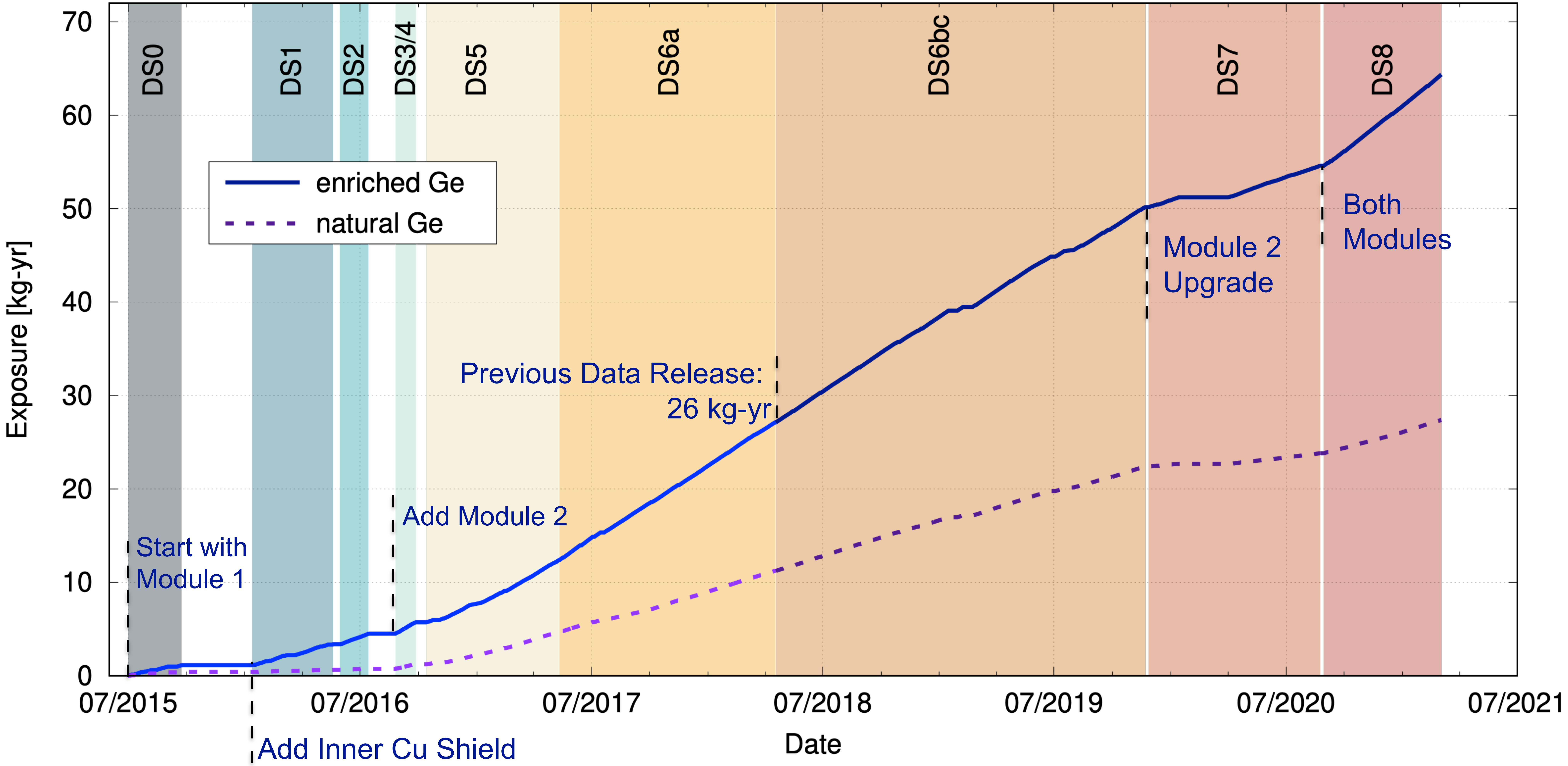
Ortec PPC ^{enr}Ge



Ortec ICPC ^{enr}Ge



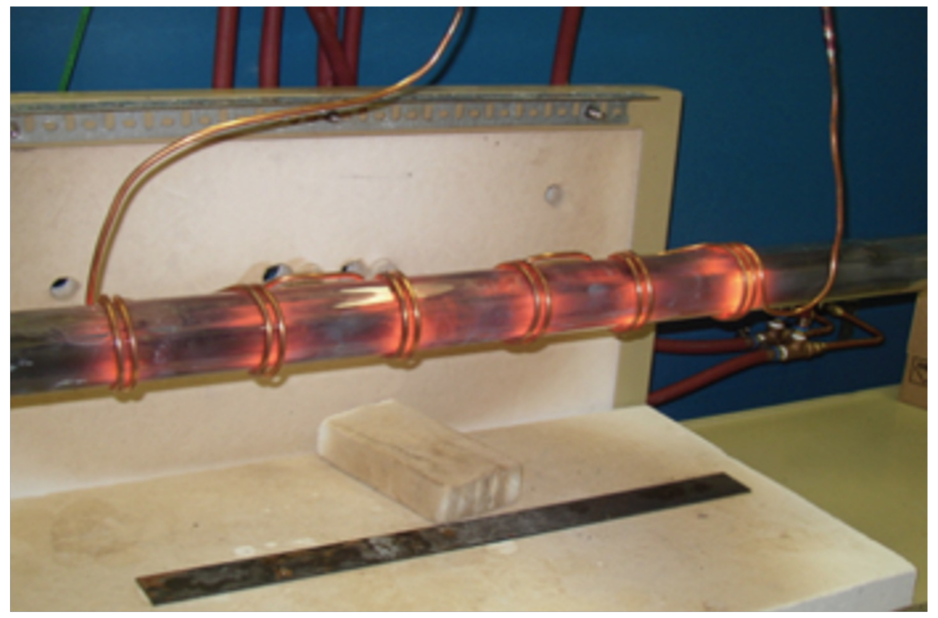
MAJORANA Active Exposure



Material Selection and Cleanliness

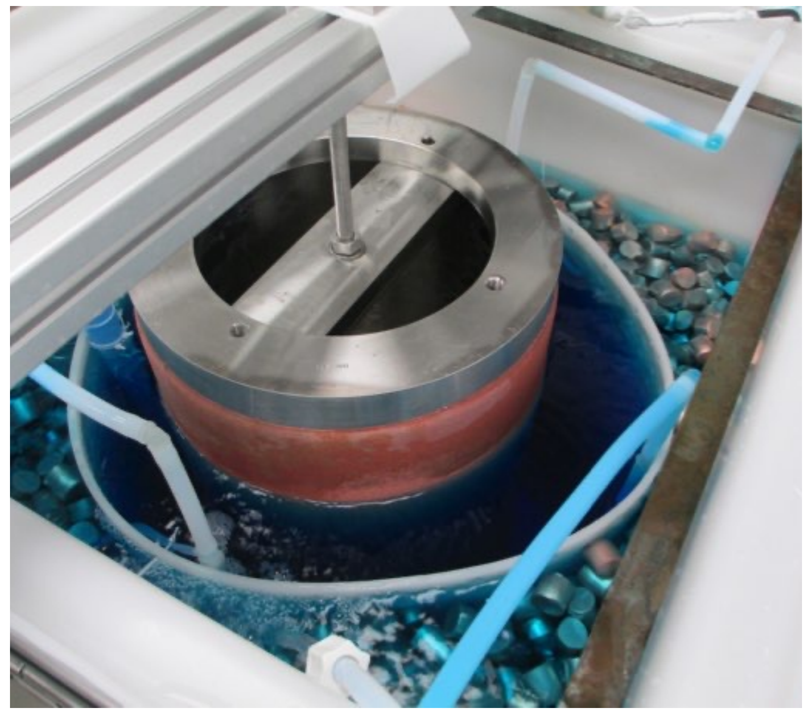
- Germanium detector material is enriched, zone-refined, and pulled into crystals
  - Enrichment to 88% in ^{76}Ge ββ isotope of interest
  - Removal of impurities to HPGe level
  - Limit above-ground exposure to prevent cosmic activation

NIM A **877** 314 (2018)

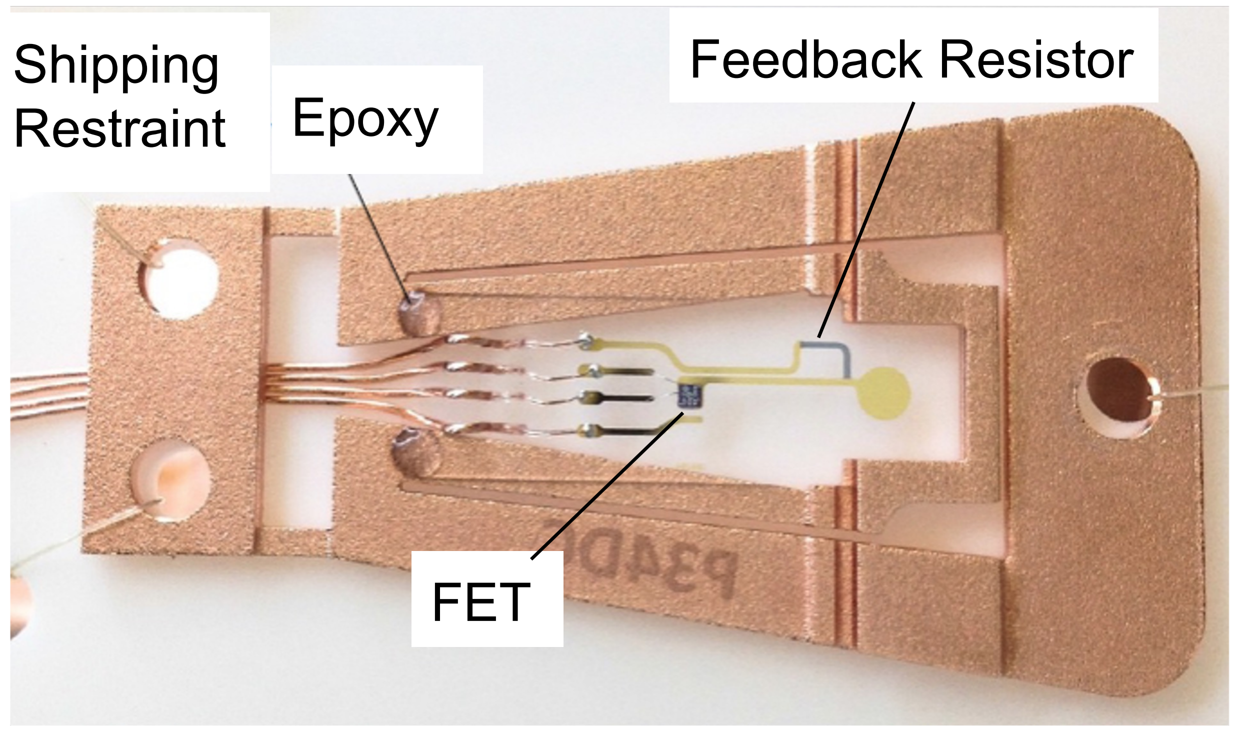


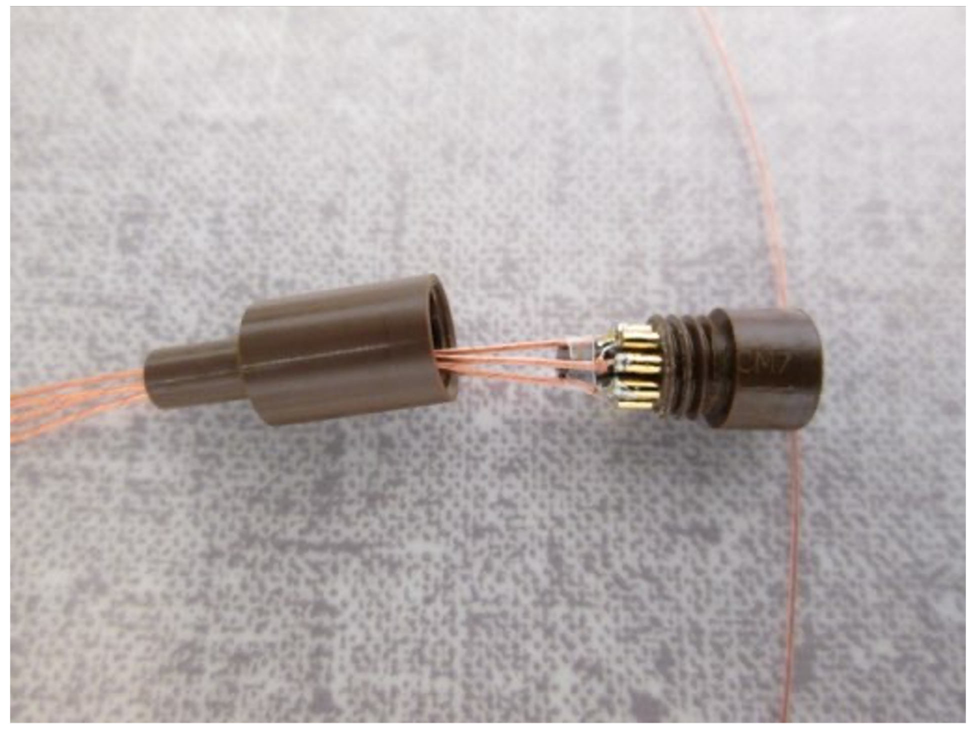
- Structural components and shielding produced from ultra-pure underground electroformed copper
  - No above-ground exposure to prevent cosmic activation

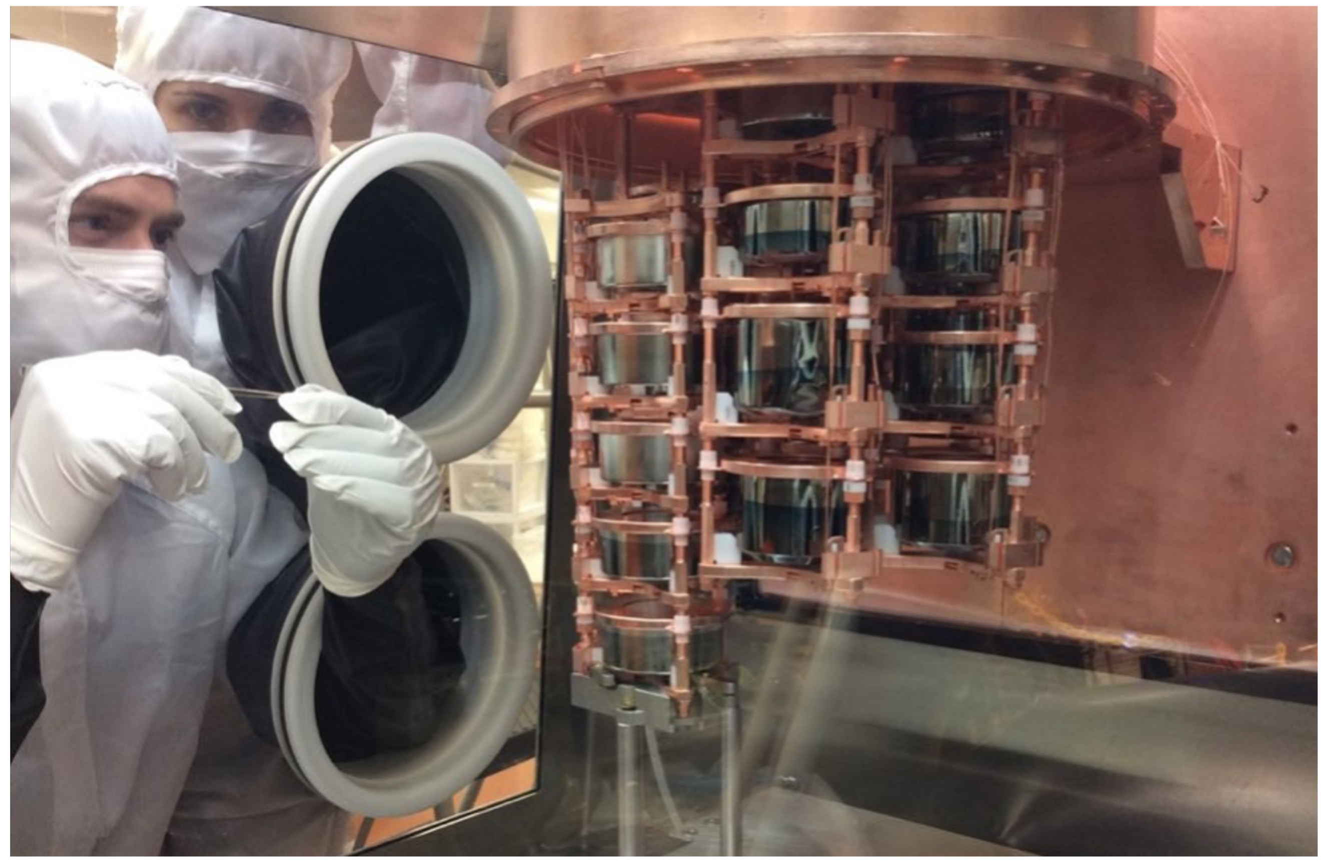
NIM A **828** 22 (2016)



- Nearby components low mass and selected for material cleanliness







Best-in-Class Energy Performance

Energy resolution (2.5 keV FWHM) and linearity (<0.2 keV up to 3 MeV) a record for neutrinoless double-beta decay searches

Less than 0.1 keV energy scale offset at low energy 1 keV~10keV

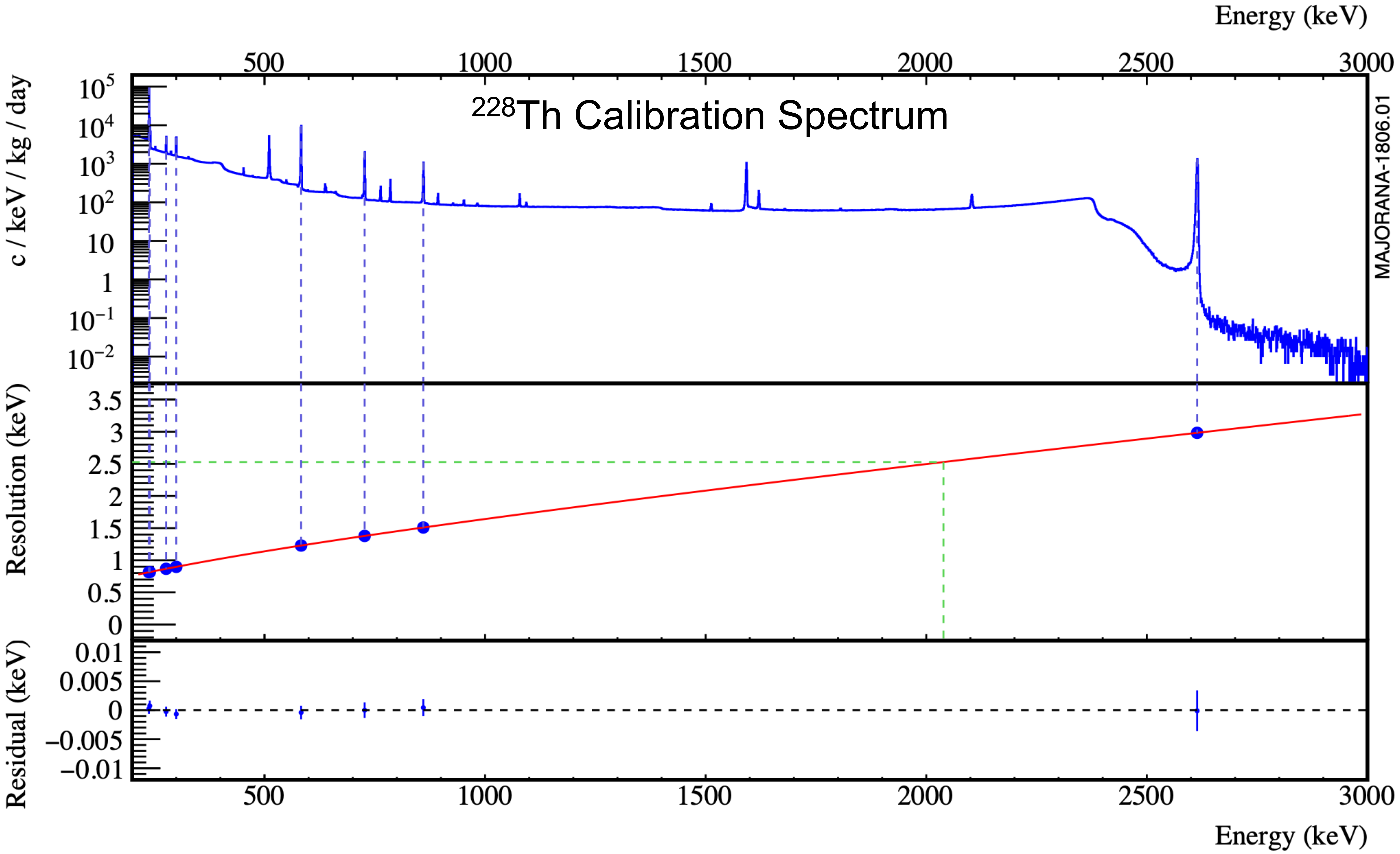
First-stage JFET amplification located ~1 cm from detector

JINST 17 (2022) 05, T05003

Calibrated on weekly ^{228}Th calibration data, retuned on full data set

NIM A **872**,16 (2017)

Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected* traces with charge-trapping correction# and fixed-time pickoff from "t_0"



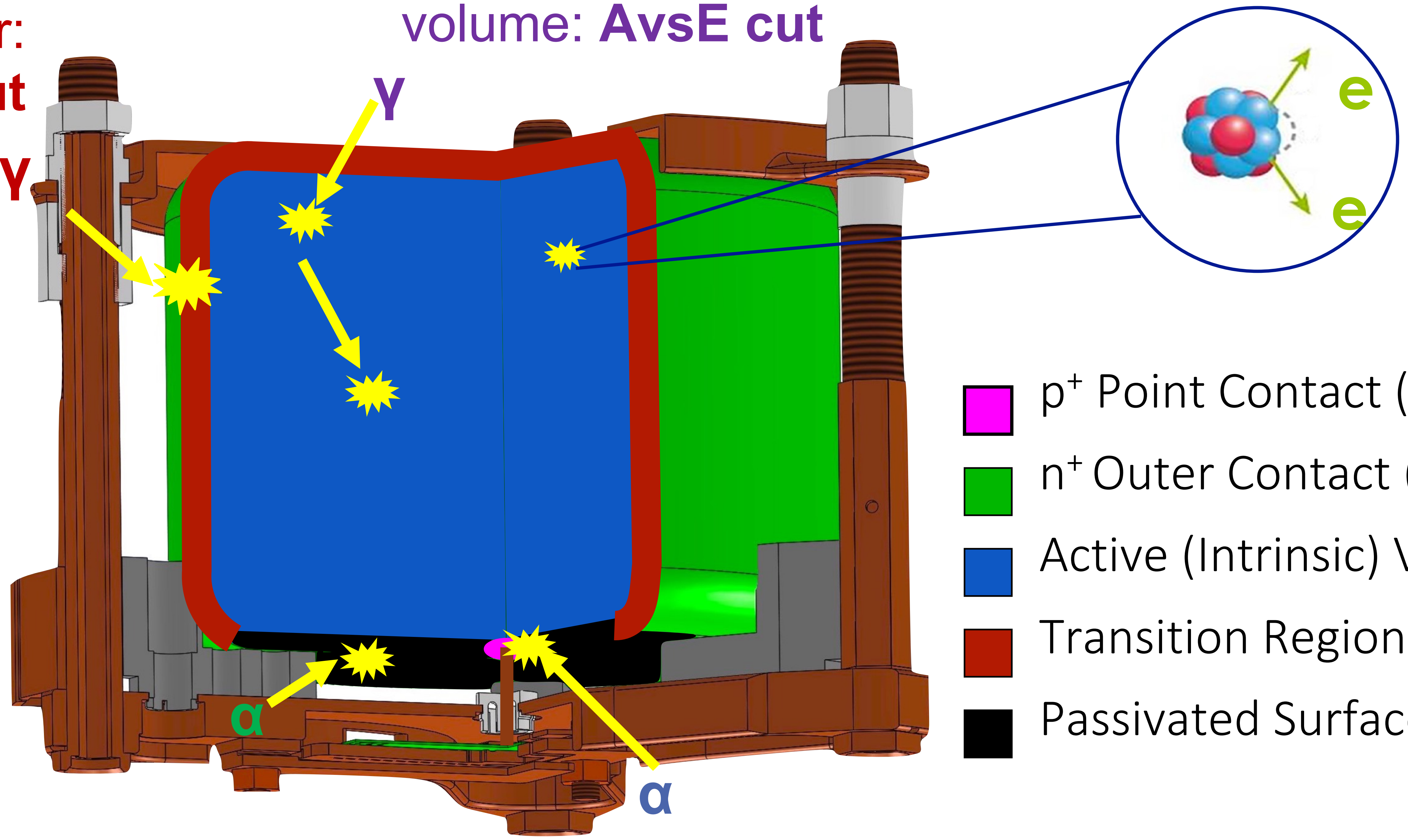
* IEEE Trans. Nucl. Sci. **68** 359 (2021)

\# arXiv:2208.03424

Analysis Techniques for Reducing Backgrounds

0νββ is dominantly single-site and located in the bulk of the detector.

Many backgrounds are multi-site or located near detector surfaces.
Pulse-shape discrimination is used to distinguish between these event topologies.



Detector surface: for partial charge deposition in transition dead layer:
LQ cut

Multi-site events in active volume: **AvsE cut**

PRC **99** 065501 (2019)

🟪 p^+ Point Contact (Ge)
🟩 n^+ Outer Contact (Li)
🟦 Active (Intrinsic) Volume
🟥 Transition Region (~1 mm)
⬛ Passivated Surface (~1 μm)

Detector surface - for particle incident on passivated surface:
DCR cut

EPJC 82 (2022) 226

Detector surface - for particle incident on surface near point contact:
high AvsE cut

Background Rejection: Multi-Site Events

Signal strongly localized in time to charge drift near point contact

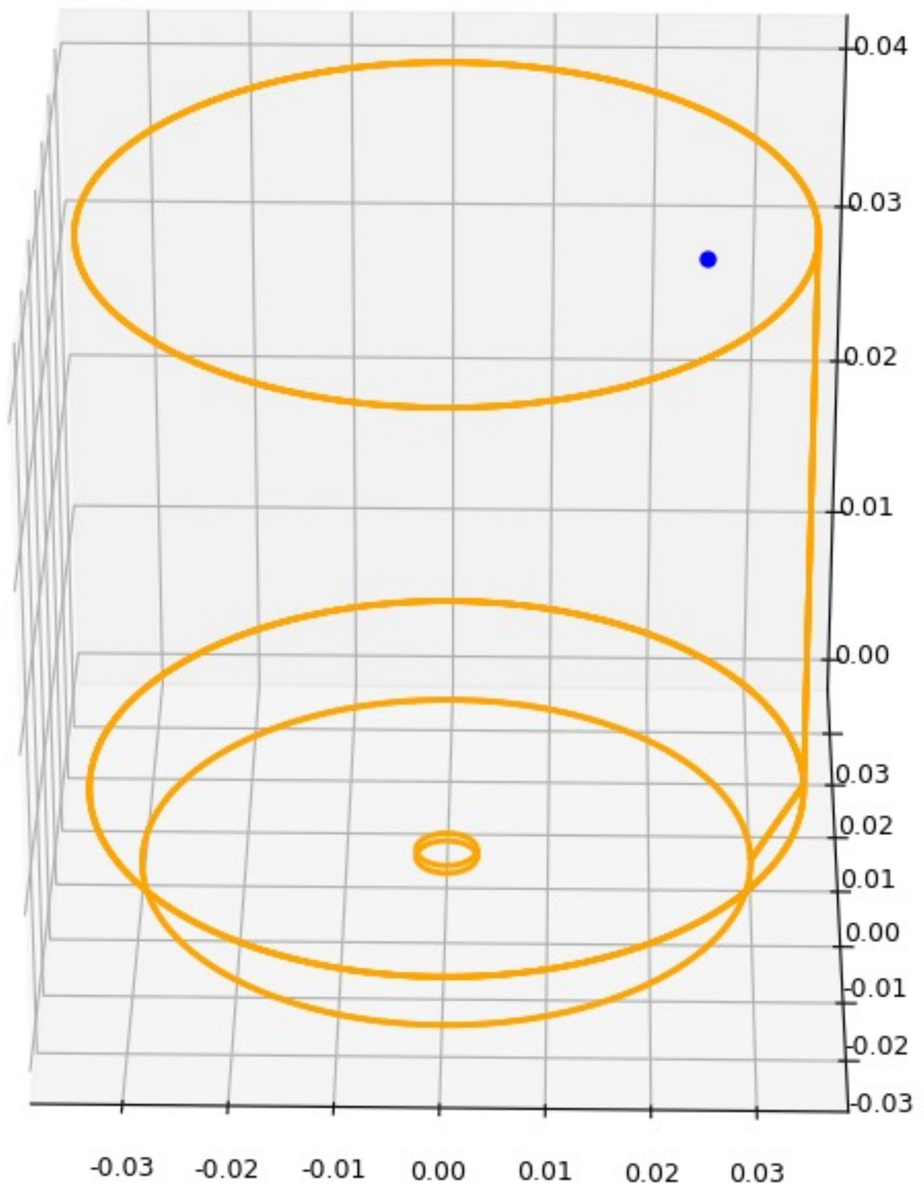
- Provides excellent discrimination of single-site (electron-like) from multi-site (gamma-like) events

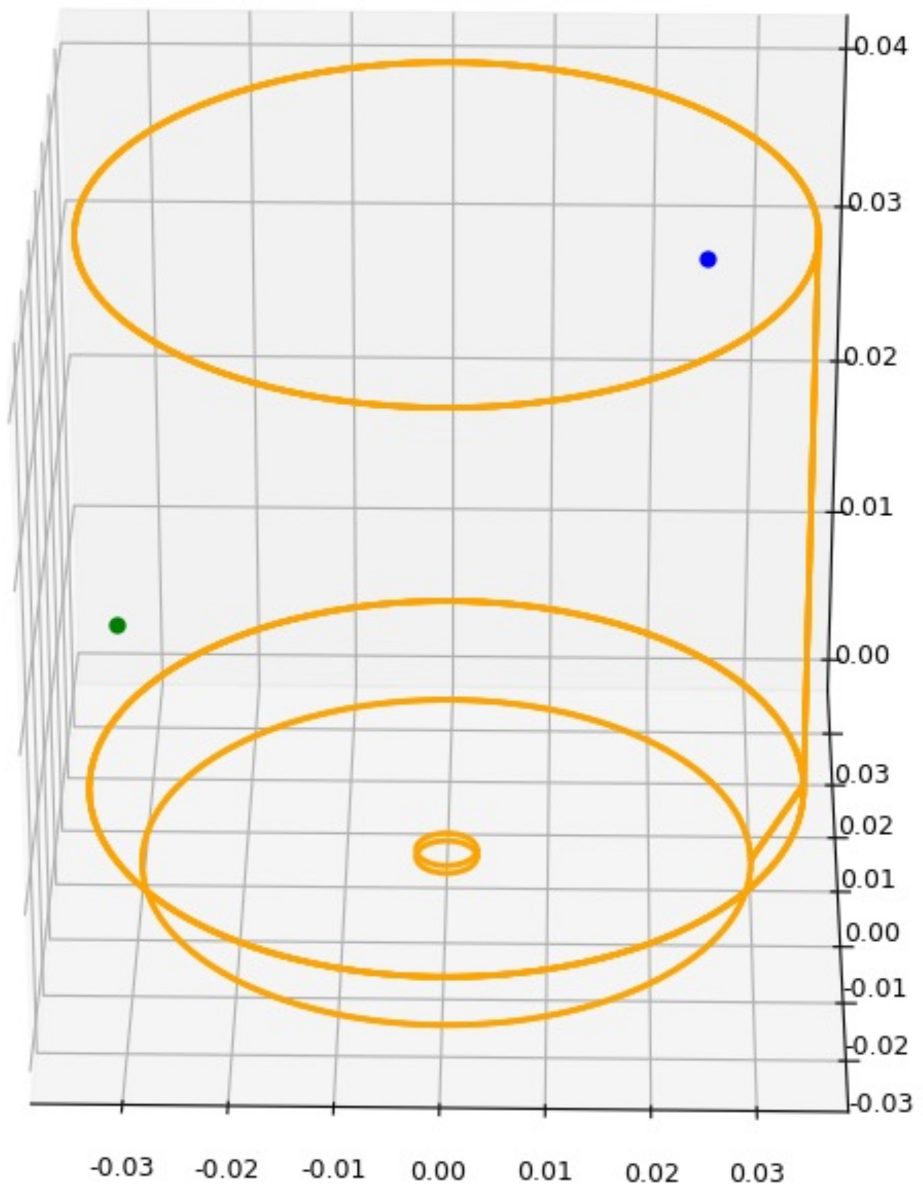
Cut maintains 90% signal efficiency

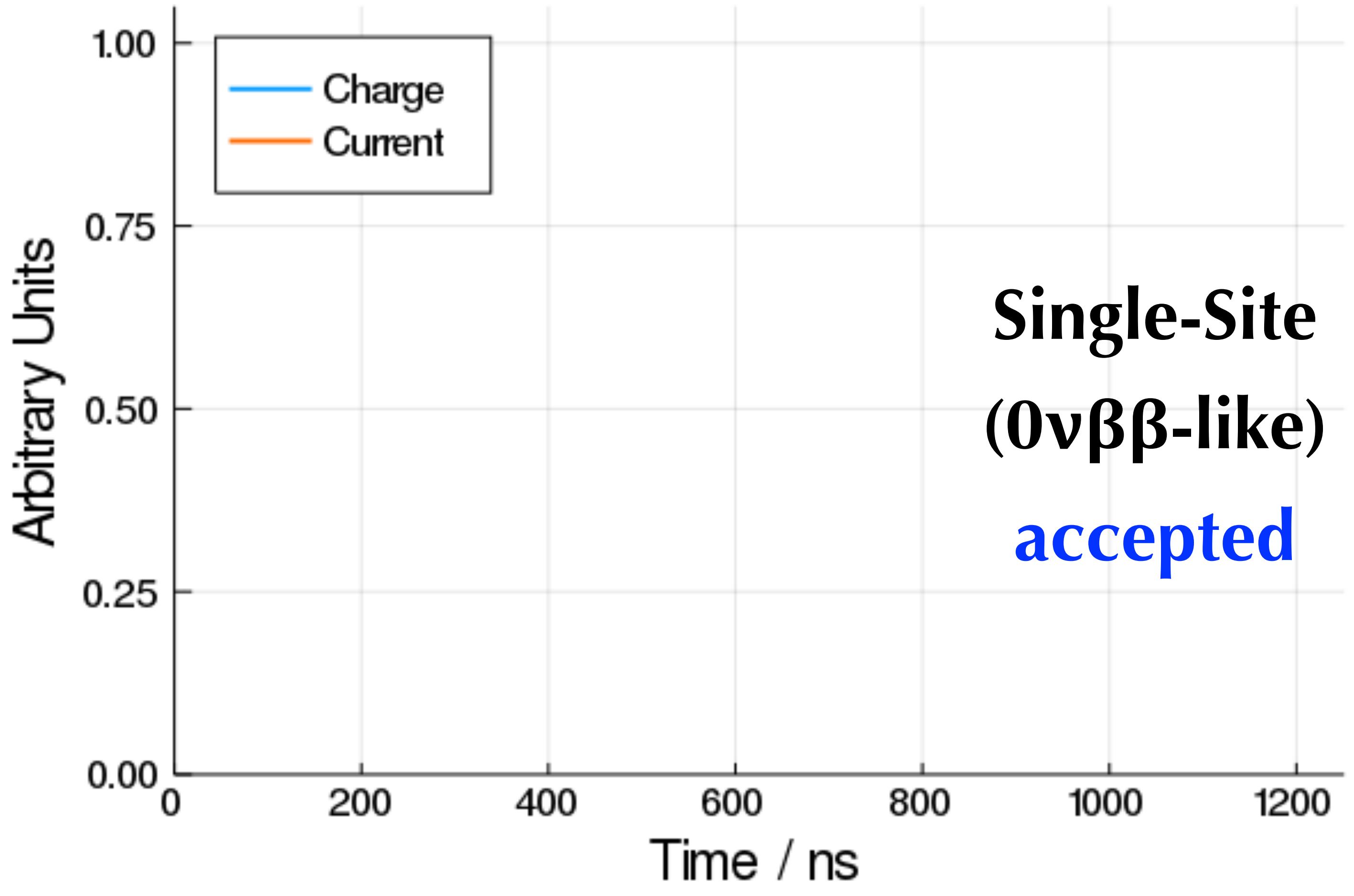
- Removes >90% of true multi-site
- Cleans >50% of ROI Compton background

Recent upgrades ensure energy-independent performance, improve stability and consistency

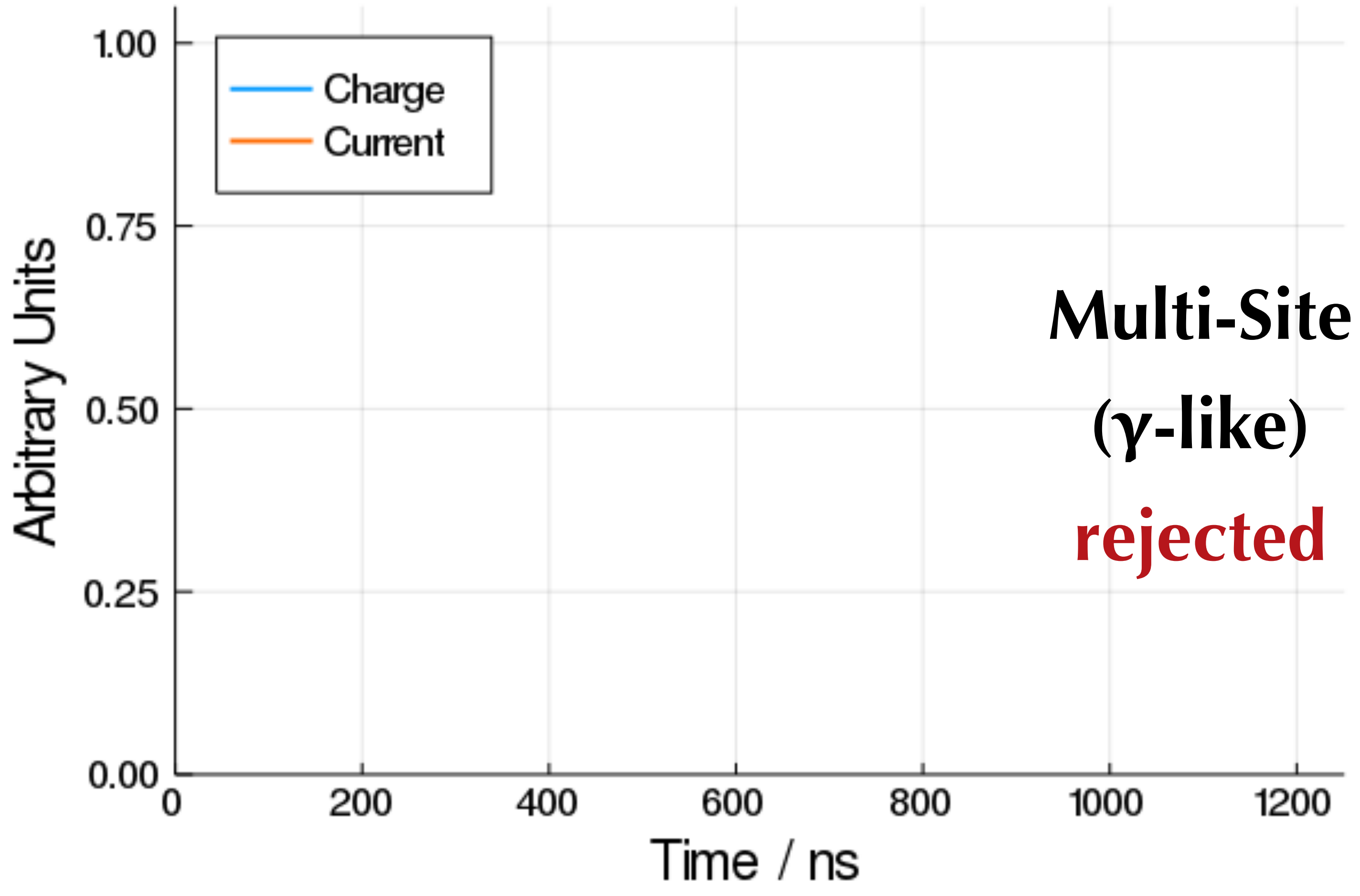
PRC **99** 065501 (2019)







Single-Site
(0νββ-like)
accepted



Multi-Site
(γ-like)
rejected

Background Rejection: Surface Events

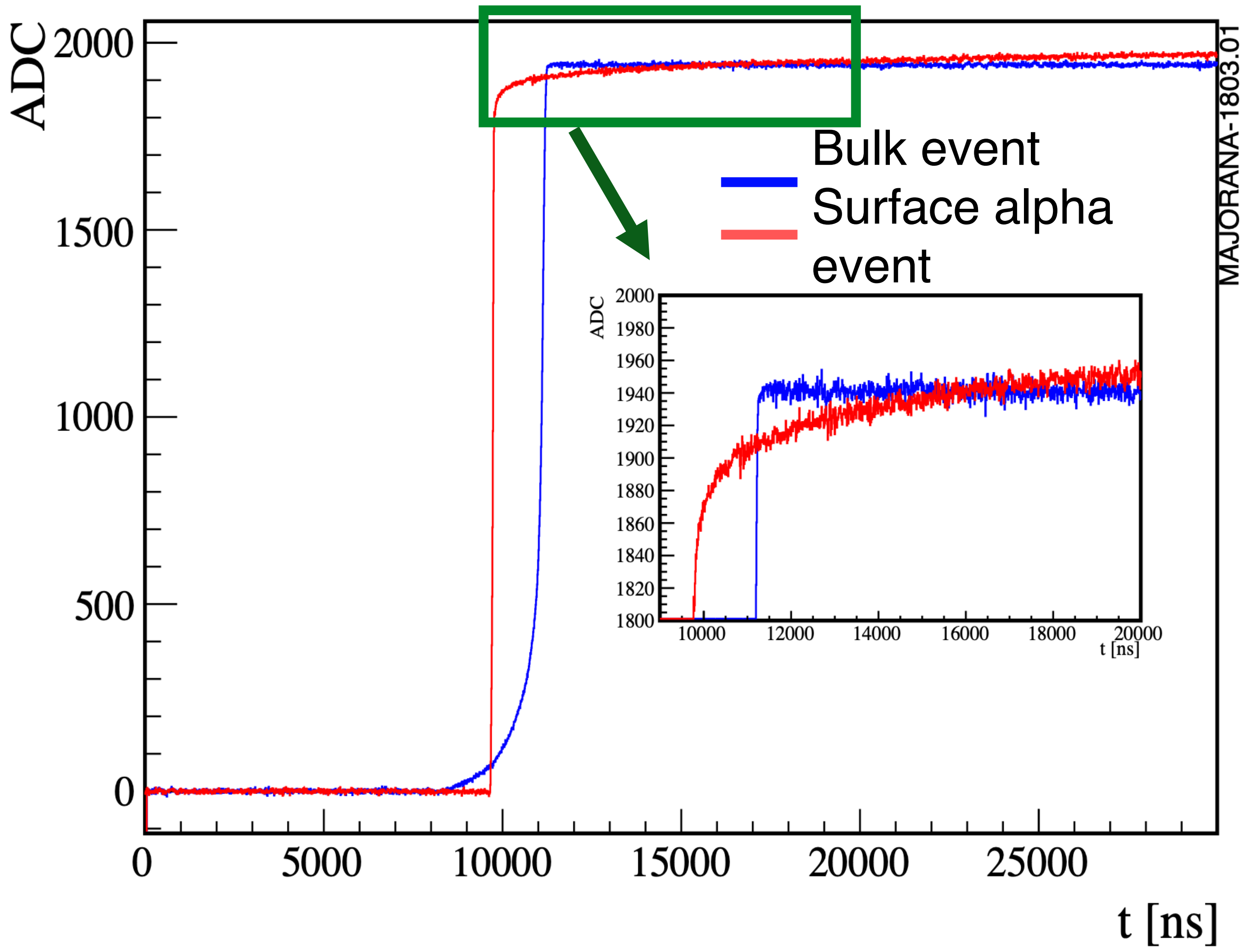
- Surface energy depositions have characteristic features enabling discrimination
  - ~98-99% signal acceptance with minimal background remaining
  - Strongly overlapping event selections

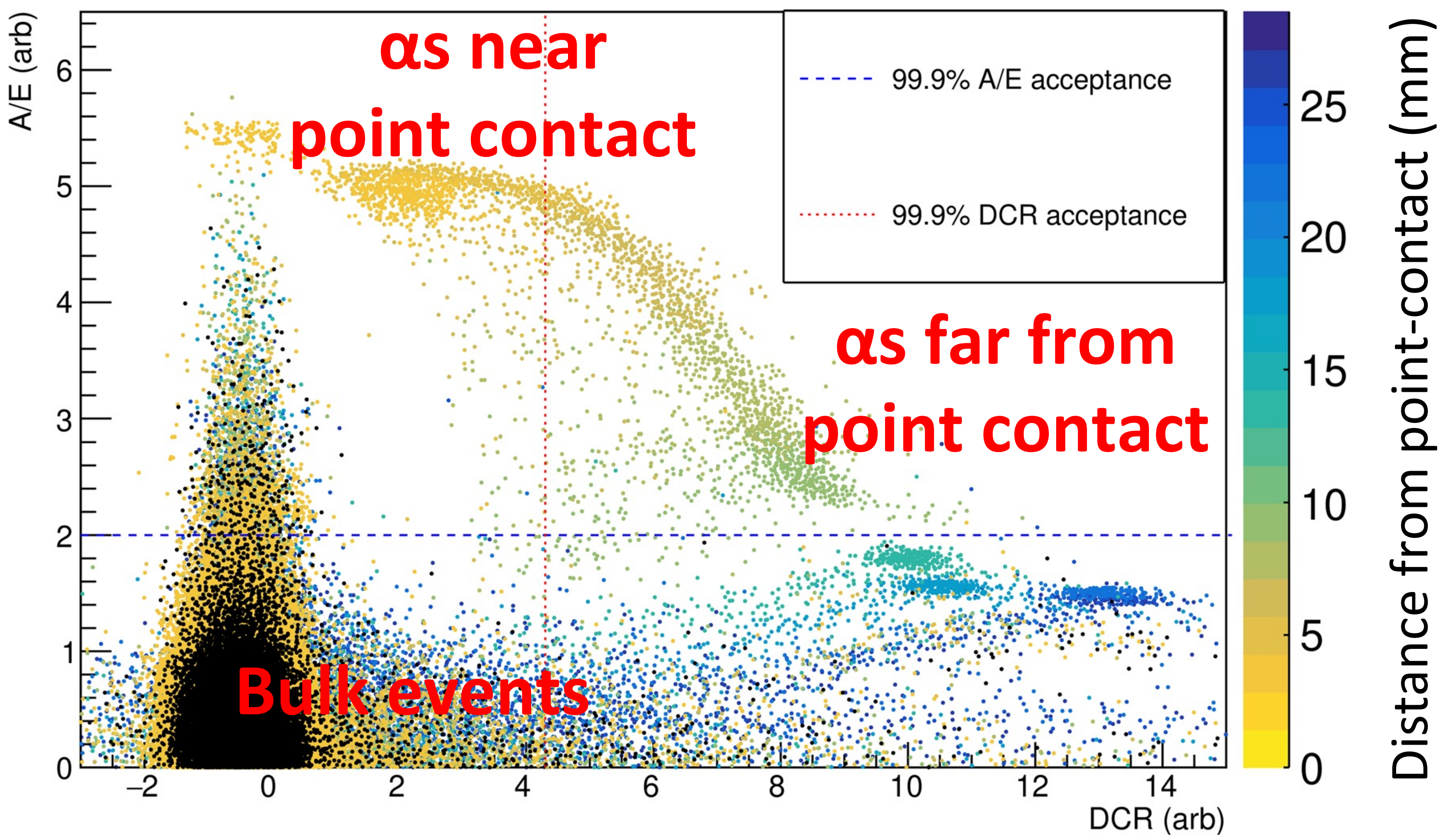
arXiv:2207.07638

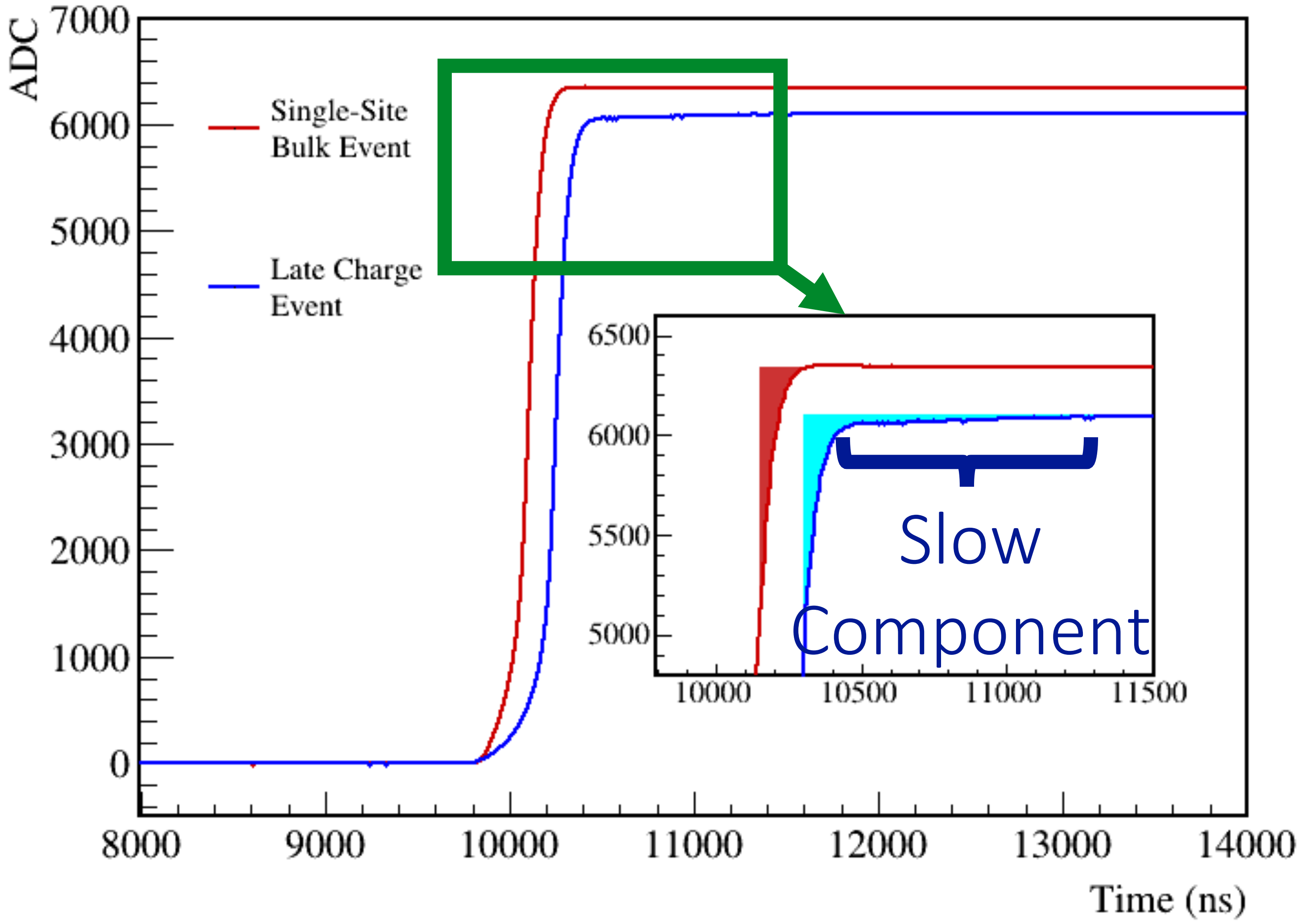
- Three distinct topologies identified
  - Passivated surface alphas have slow charge trapping and re-release (~10s of μs) component
  - Near point-contact surface events have anomalously fast rising edge
  - Transition dead layer events have charge trapping with moderate re-release component (~1-2 μs)

EPJC 82 (2022) 226

- Charge trapping leads to degraded energy estimation, critical to identify and reject







"God made the bulk, the surface was invented by the devil." – Pauli

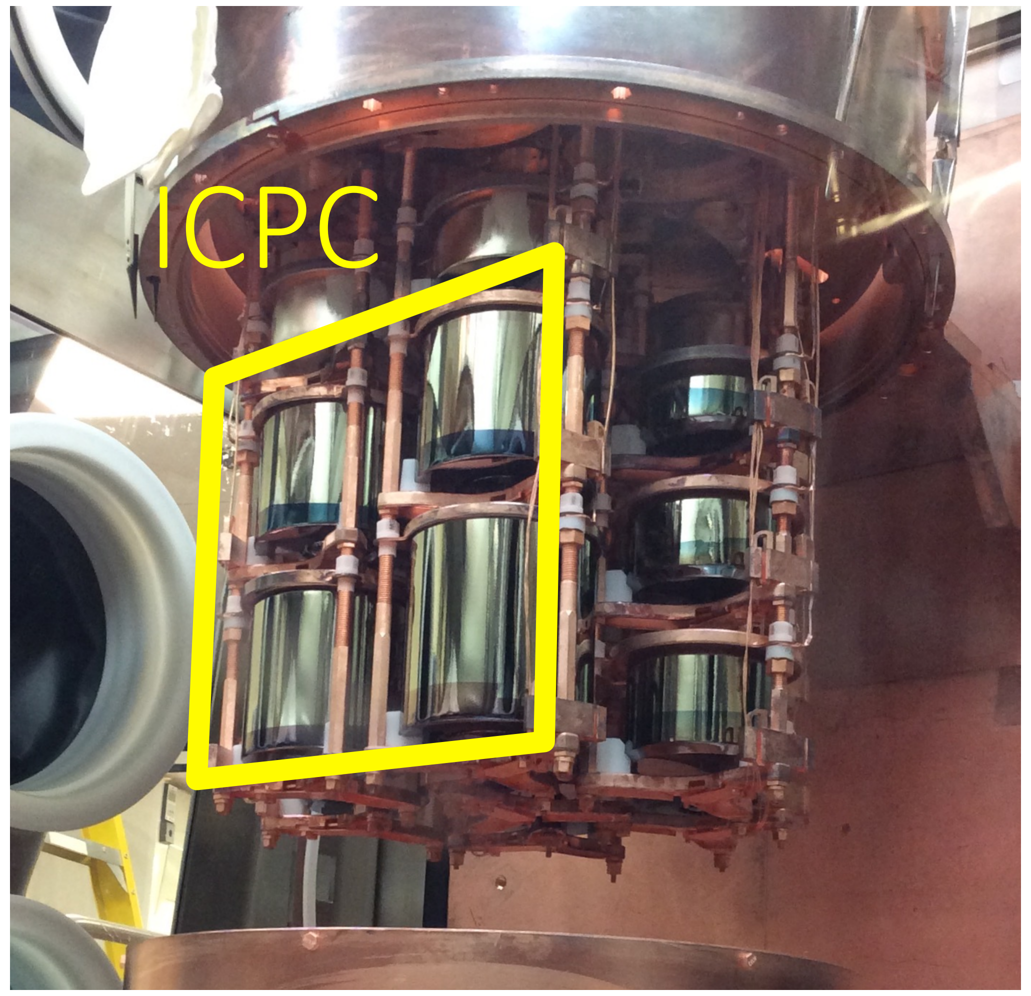
Inverted Coaxial Point Contact Detectors

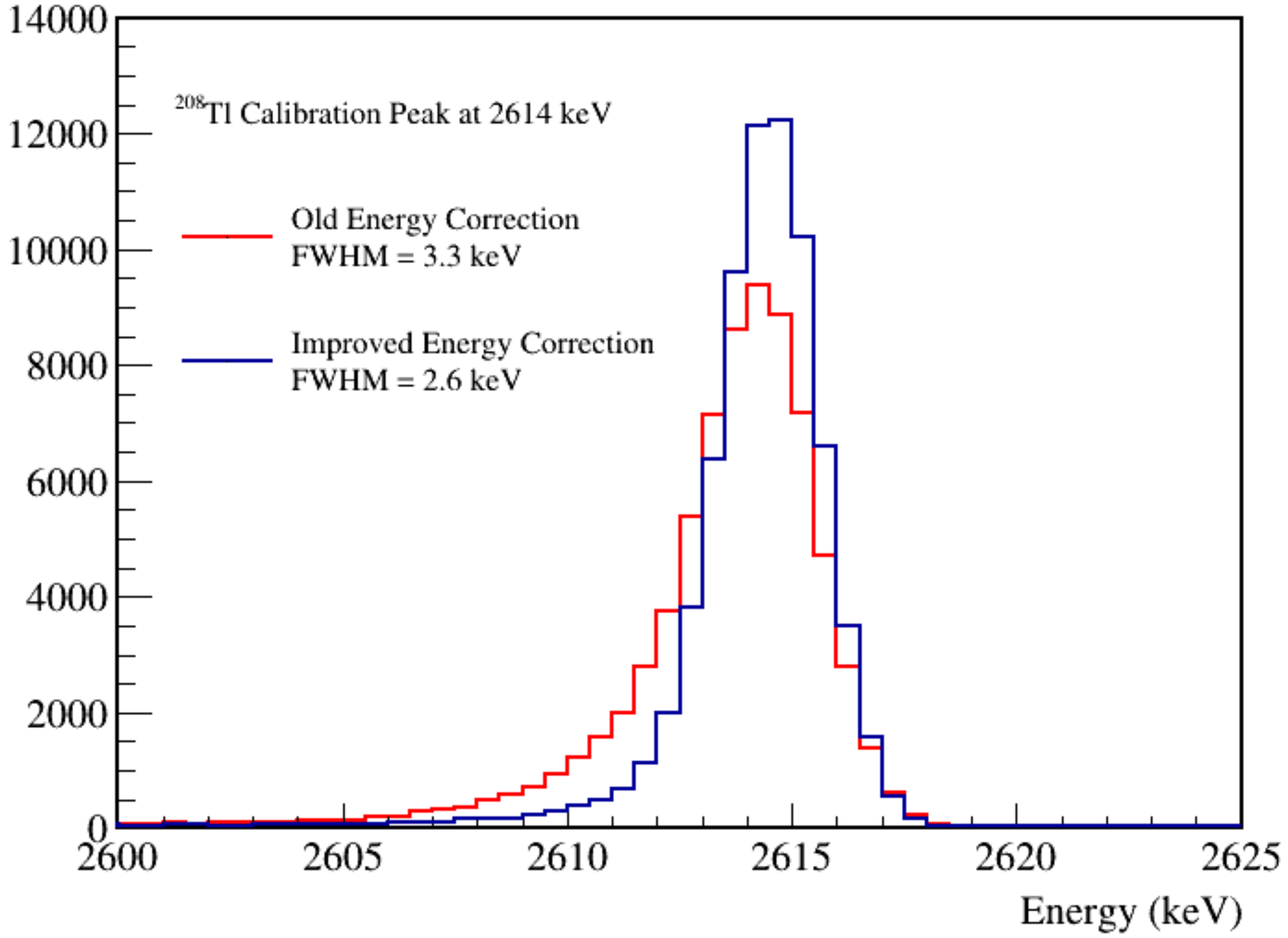
Inverted coaxial point contact (ICPC) detectors are larger (>3 kg) than PPC detectors (up to 1.2 kg). MAJORANA operated 4 ICPCs from Aug. 2020 to Mar 2021

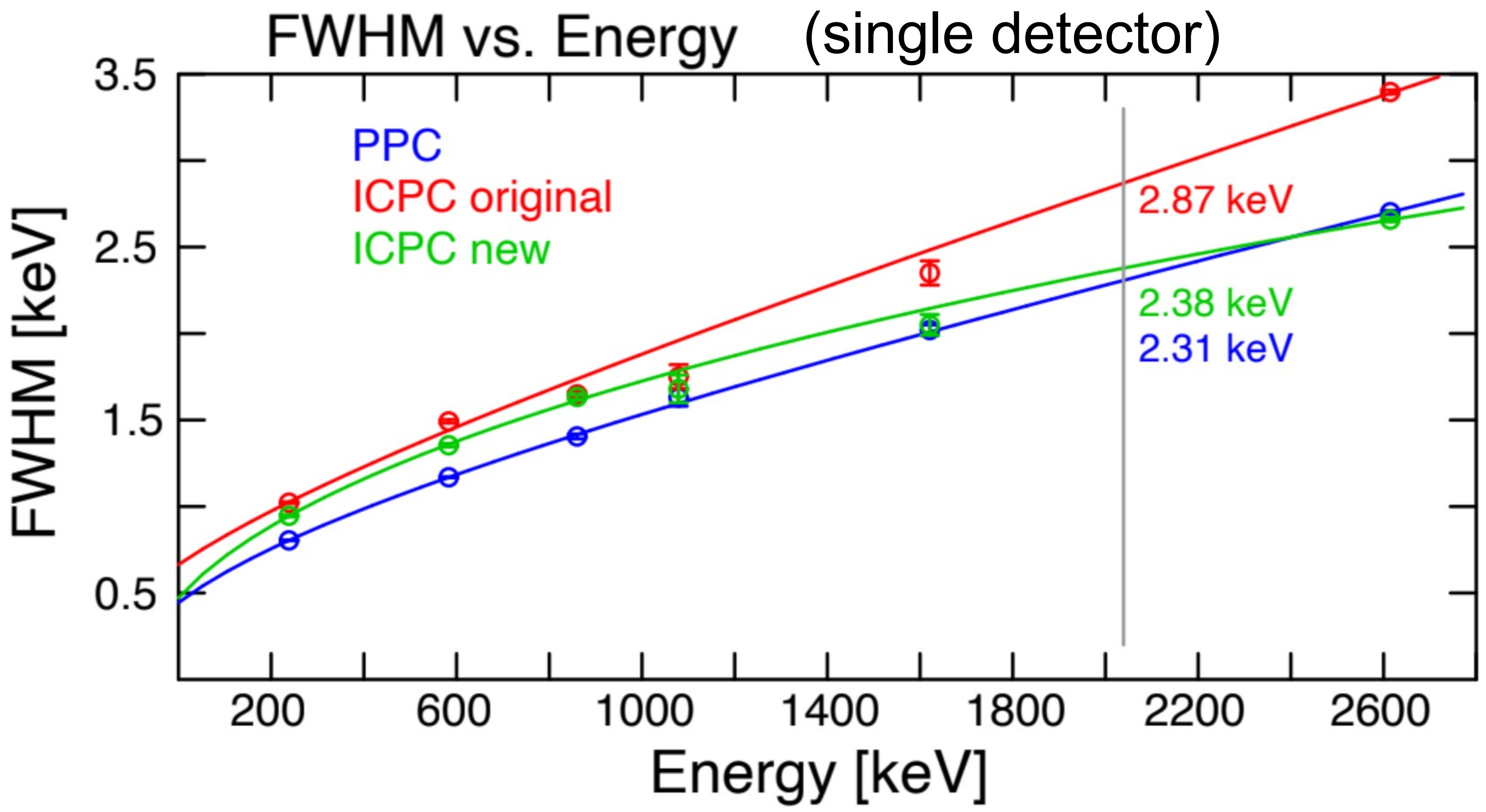
Beneficial for background reduction in LEGEND

Larger range of drift times requires more refined analysis techniques

MAJORANA has demonstrated comparable performance with ICPCs and PPCs. Best energy resolution for ICPCs to date!



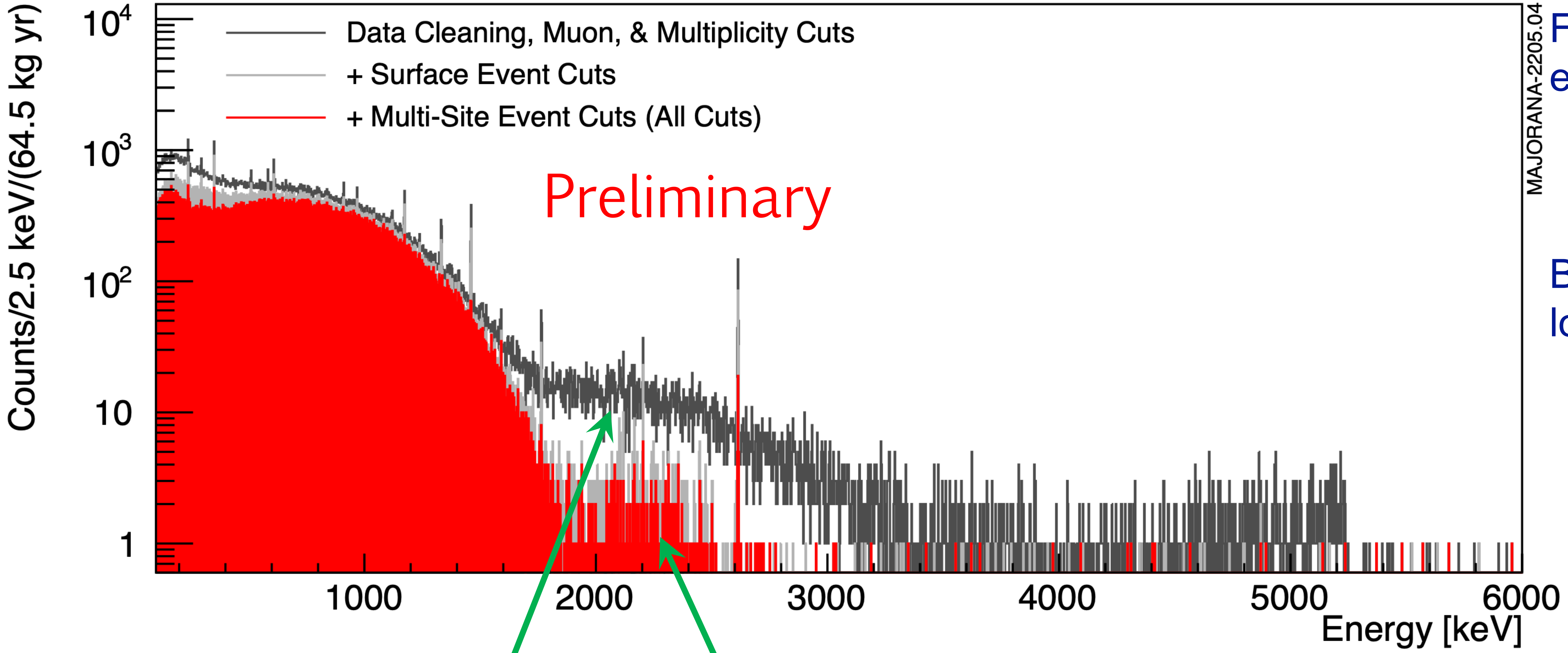




New analysis techniques improve combined energy resolution of ICPCs to 2.55 keV FWHM at $Q_{\beta\beta}$
Comparable to PPC performance

MAJORANA DEMONSTRATOR 2022 0νββ Result

Operating in a low background regime and benefiting from excellent energy resolution



arXiv:2207.07638 (2022)

Dominated by surface alphas before cuts

^{208}Tl (^{232}Th)-like after cuts

Final enriched detector active exposure:

64.5 ± 0.9 kg-yr

Background index at 2039 keV in low-background configuration

15.7 ± 1.4 cts/(FWHM t yr)

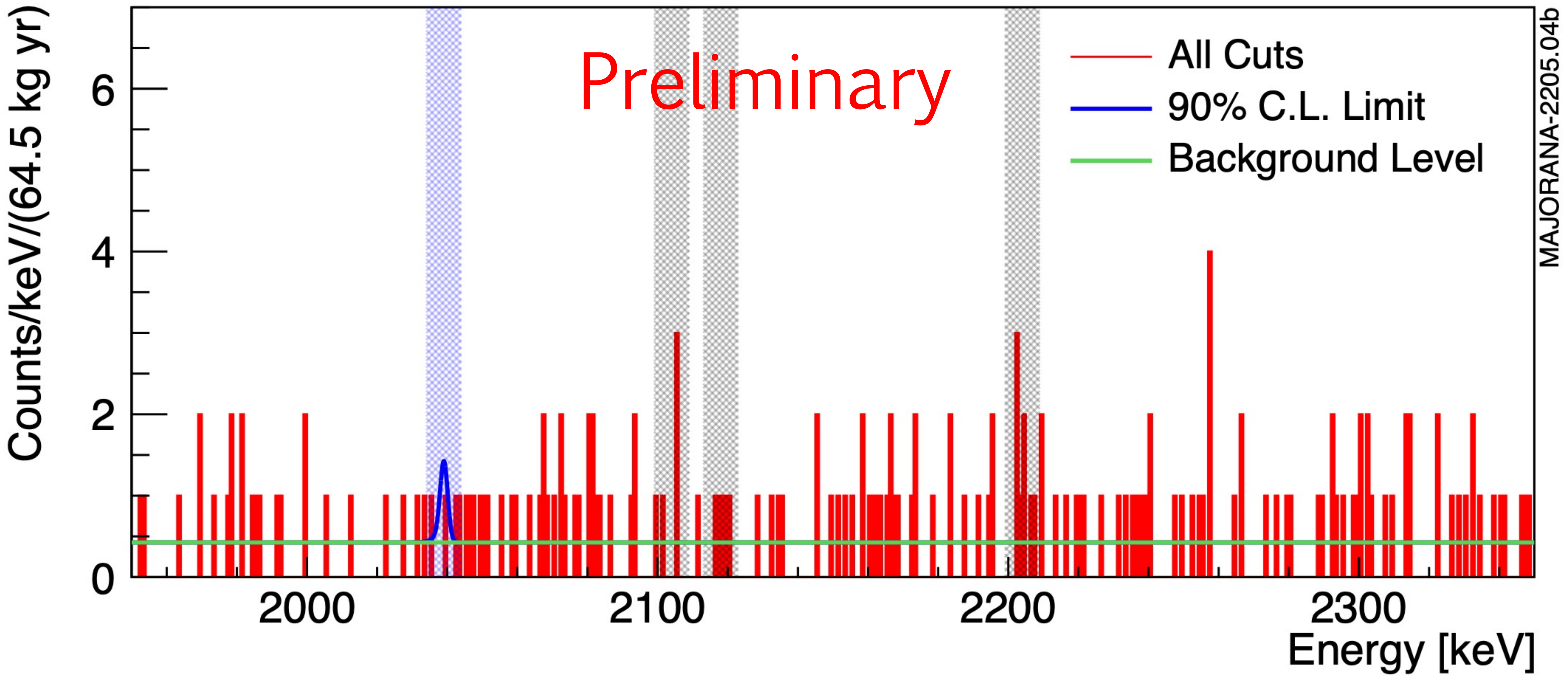
Background index in Module 1

18.6 ± 1.8 cts/(FWHM t yr)

Background index in Module 2

$8.4^{+1.9}_{-1.7}$ cts/(FWHM t yr)

MAJORANA DEMONSTRATOR 2022 0νββ Result



arXiv:2207.07638 (2022)

Background Index:

$(6.2 \pm 0.6) \times 10^{-3}$ cts/(keV kg yr)

Energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$

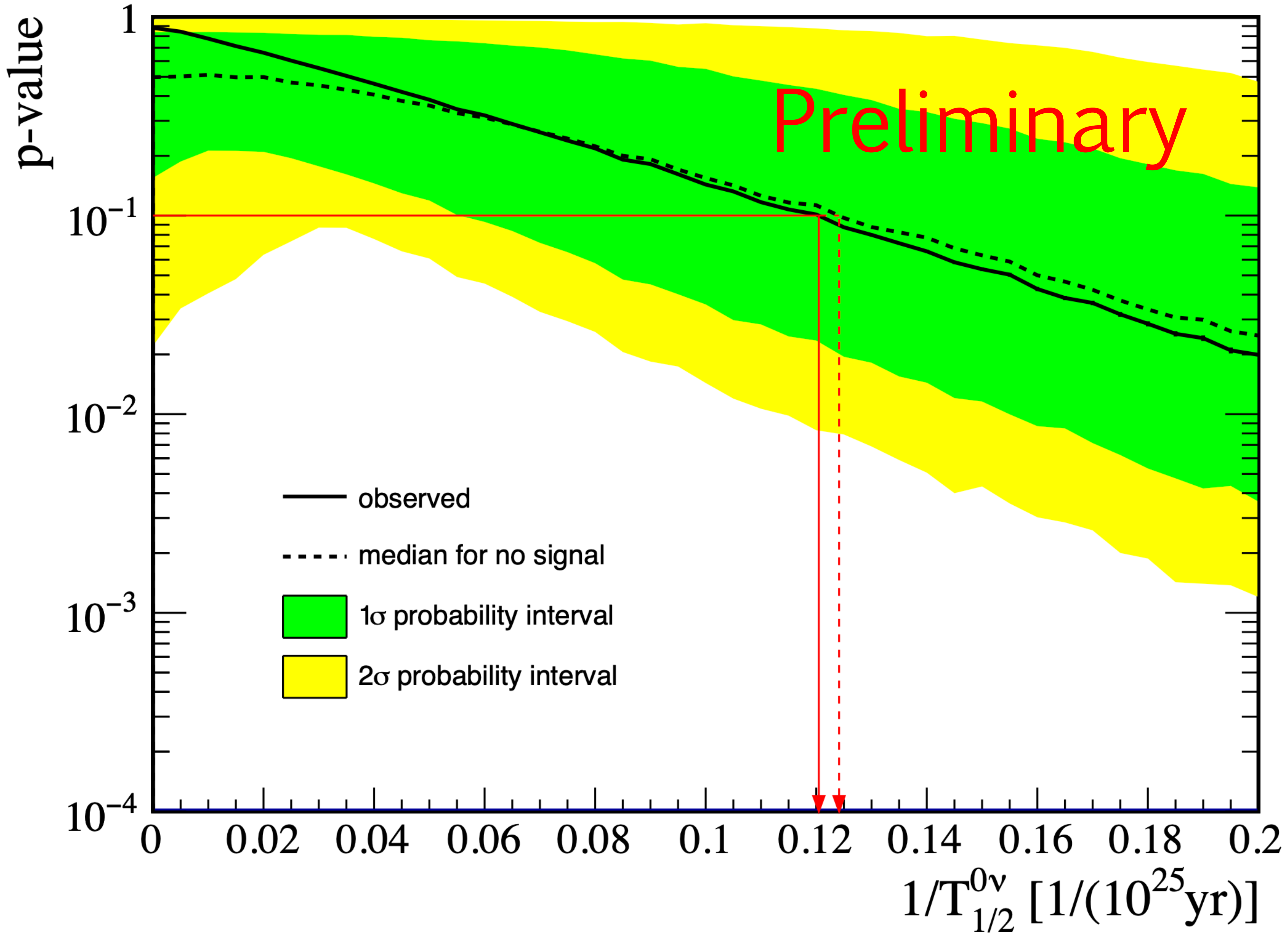
Frequentist Limit:

Median $T_{1/2}$ Sensitivity: 8.1×10^{25} yr (90% C.I.)

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

Bayesian Limit: (flat prior on rate)

65 kg-yr Exposure Limit: $T_{1/2} > 7.0 \times 10^{25}$ yr (90% C.I.)



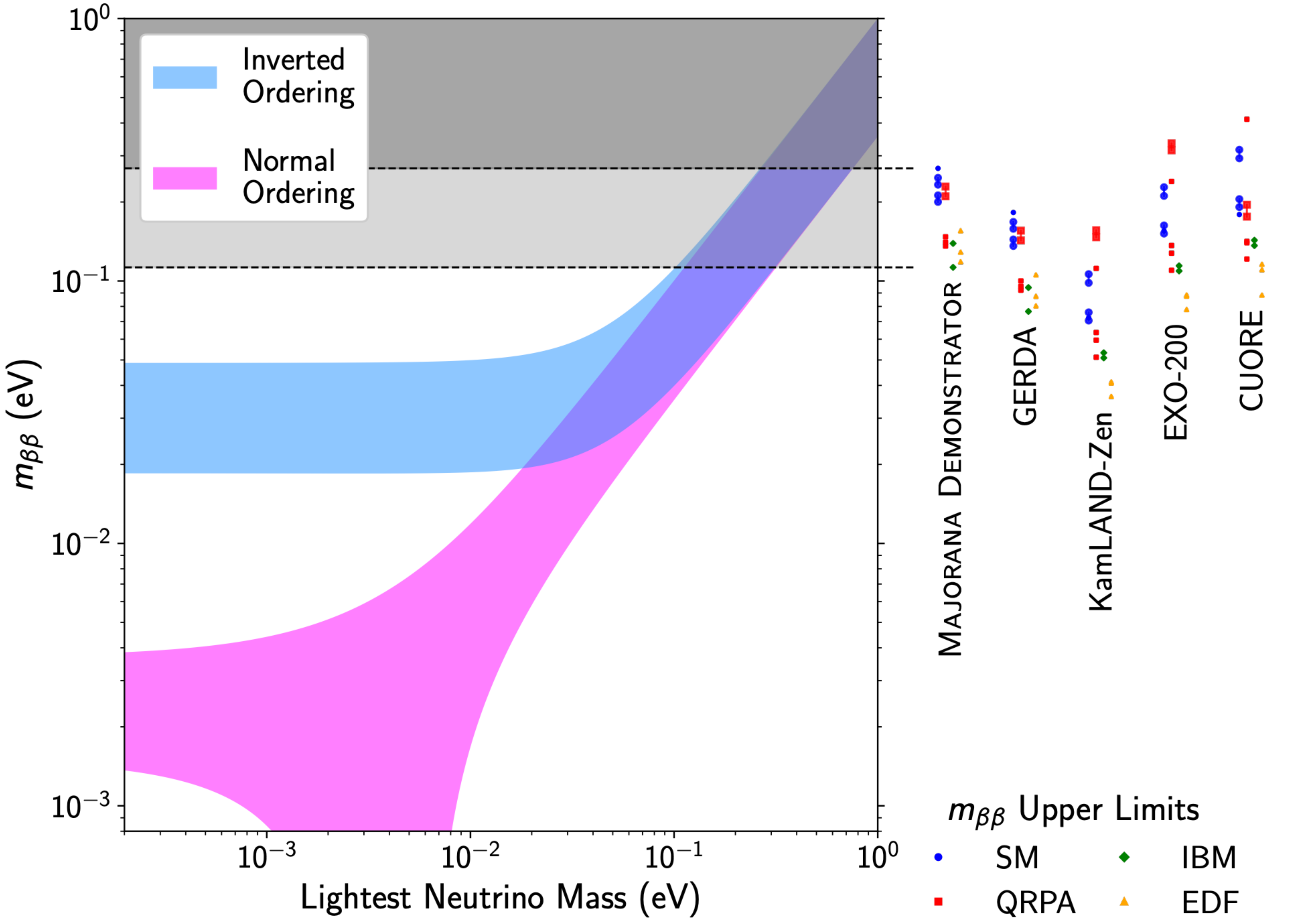
$m_{\beta\beta} < 113 - 269$ meV

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

MAJORANA DEMONSTRATOR 2022 0νββ Result

With significantly lower exposure, germanium experiments set competitive limits on 0νββ

Both GERDA and MAJORANA DEMONSTRATOR are nearly background free, so half-life limits add ~linearly



Experiment	Half-Life Limit (yr)	Exposure (kg*yr)
MAJORANA DEMONSTRATOR	8.3e25	65
GERDA [1]	1.8e26	127
KamLAND-Zen800 [2]	2.3e26	970
EXO-200 [3]	3.5e25	234
CUORE [4]	3.2e25	373

[1] M. Agostini et al. (GERDA Collaboration), PRL **125**, 252502 (2020)
[2] S. Abe et al (KamLAND-Zen Collaboration), arXiv:2203.02139
[3] G. Anton et al. (EXO-200 Collaboration), PRL **123**, 161802 (2019)
[4] D. Q. Adams et al. (CUORE Collaboration) PRL **124**, 122501 (2019)

Best-fit values of neutrino oscillation parameters from 2022 PDG [PTEP **2022** 083C01 (2022)]

MAJORANA DEMONSTRATOR 2022 0νββ Result

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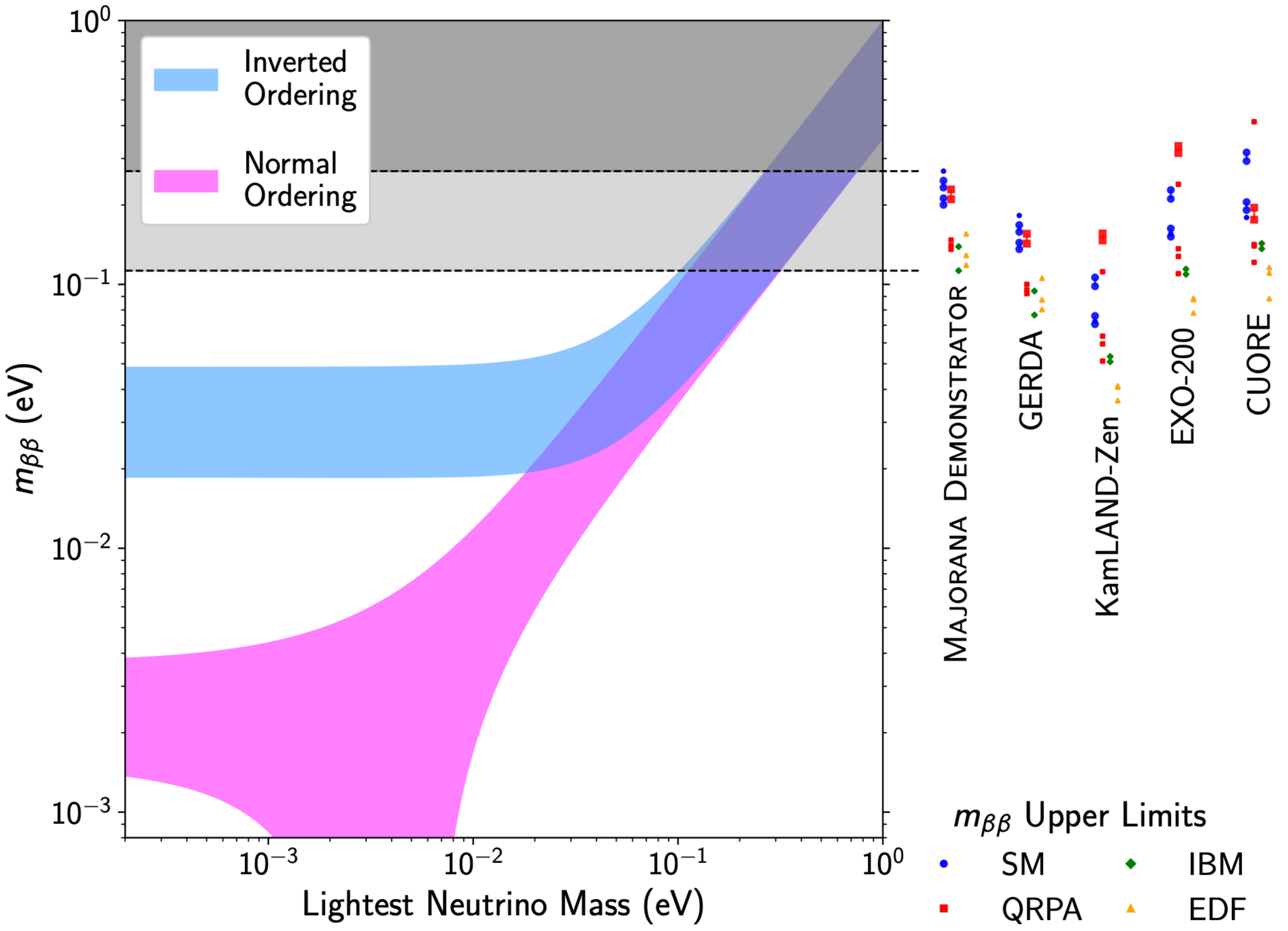
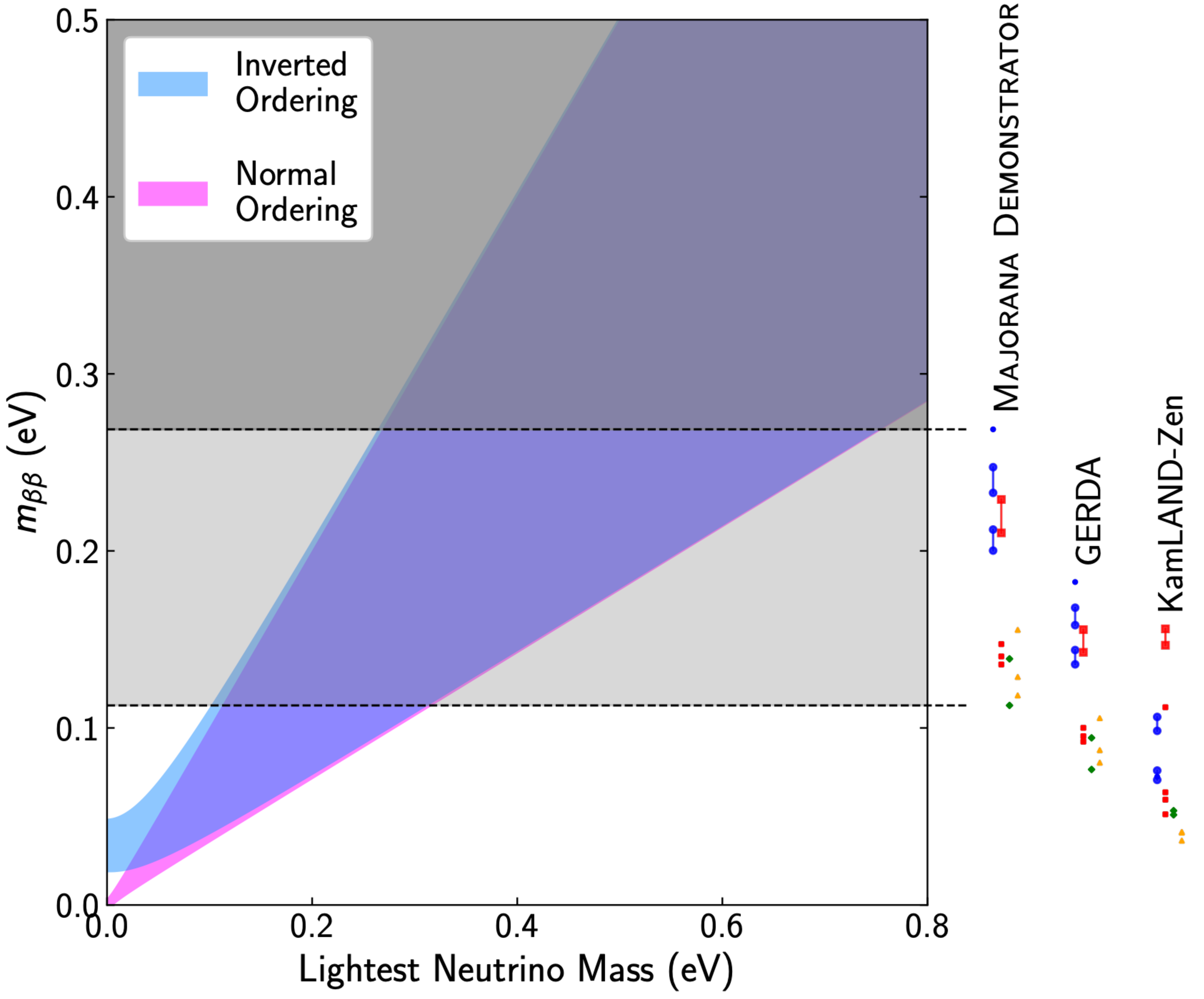




Best-fit values of neutrino oscillation parameters from 2022 PDG [PTEP **2022** 083C01 (2022)]

Rich and Broad Physics Programs

Tests of Fundamental Symmetries and Conservations

- Lepton number violation via $0\nu\beta\beta$
- Baryon number violation
- Pauli Exclusion Principle violation

arXiv:2208.03424 (2022)

PRC **100** 025501 (2019)

PRD **99** 072004 (2019)

arXiv:2203.02033 (2022)

Standard Model Physics

Standard Model Physics, particular backgrounds

- $2\nu\beta\beta$ to excited states
- In situ cosmogenics
- (alpha, n) reactions

PRC **103** 015501 (2021)

PRC **105** 014617 (2022)

PRC **105** 064610 (2022)

MAJORANA DEMONSTRATOR
Excellent energy performance &
low backgrounds
across broad energy regions

BSM Physics

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 (2022)

Exotic Physics

- Quantum wavefunction collapse
- Lightly ionization particle

PRL **129** 080401 (2022)

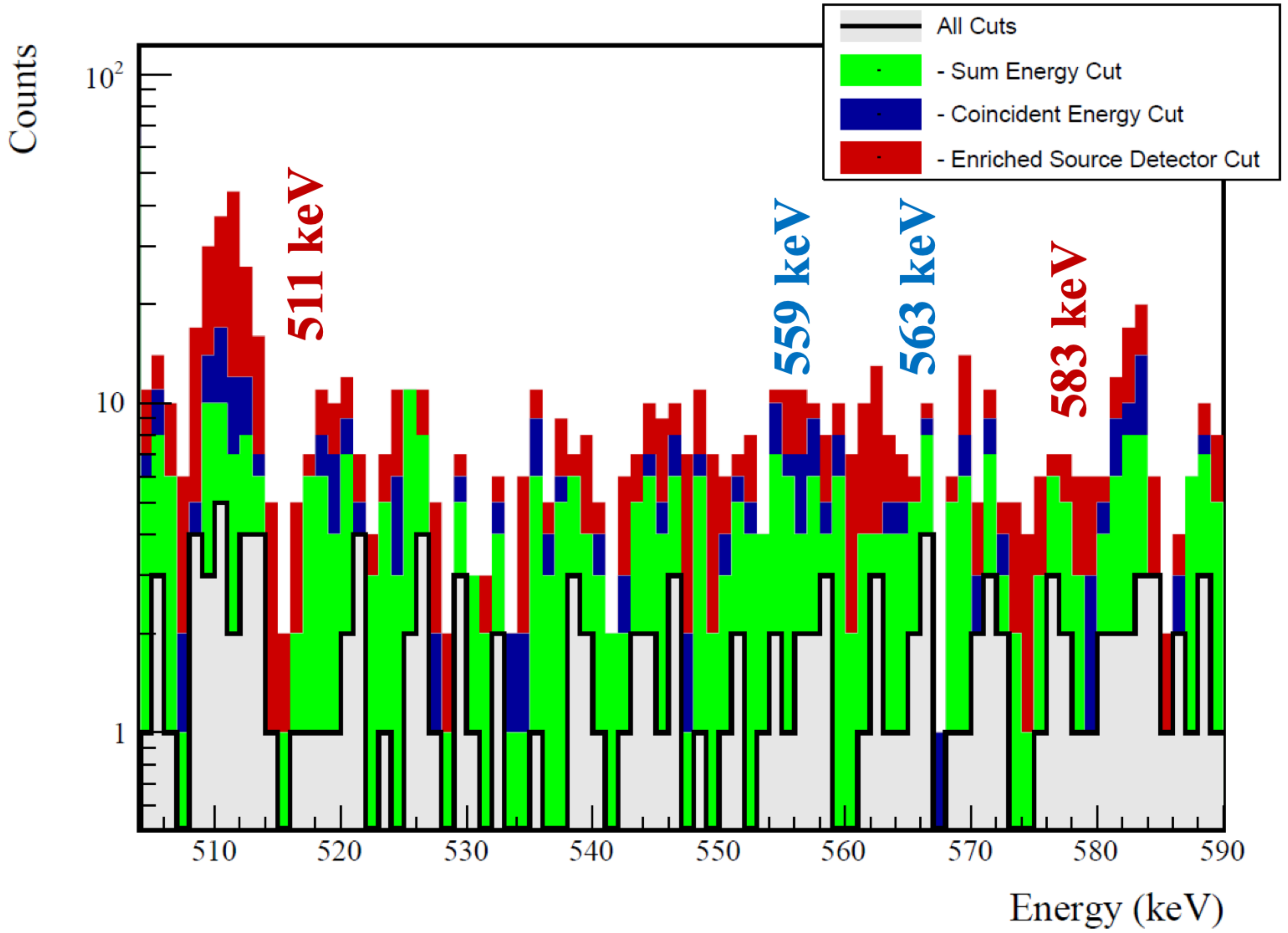
PRL **120** 211804 (2018)

Double Beta Decay to Excited States

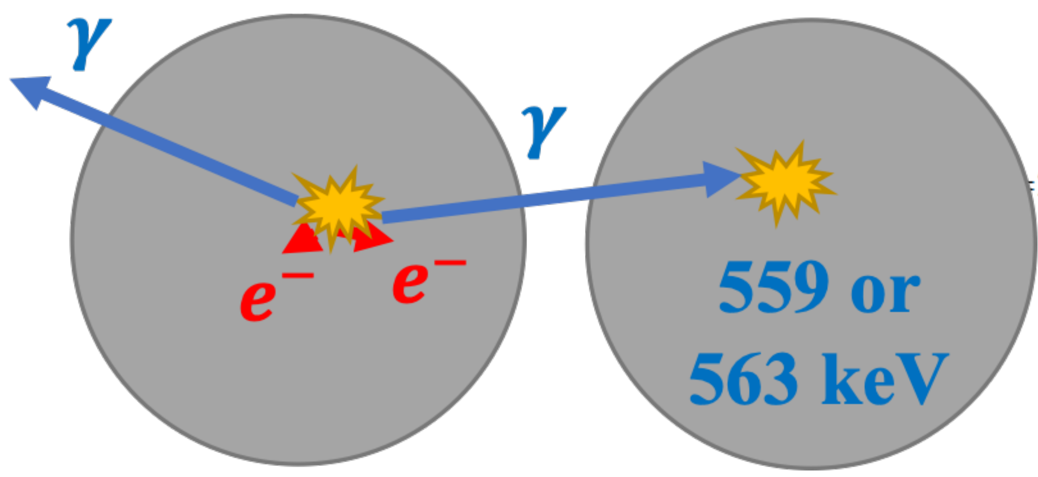
An inherently multi-site signal topology:

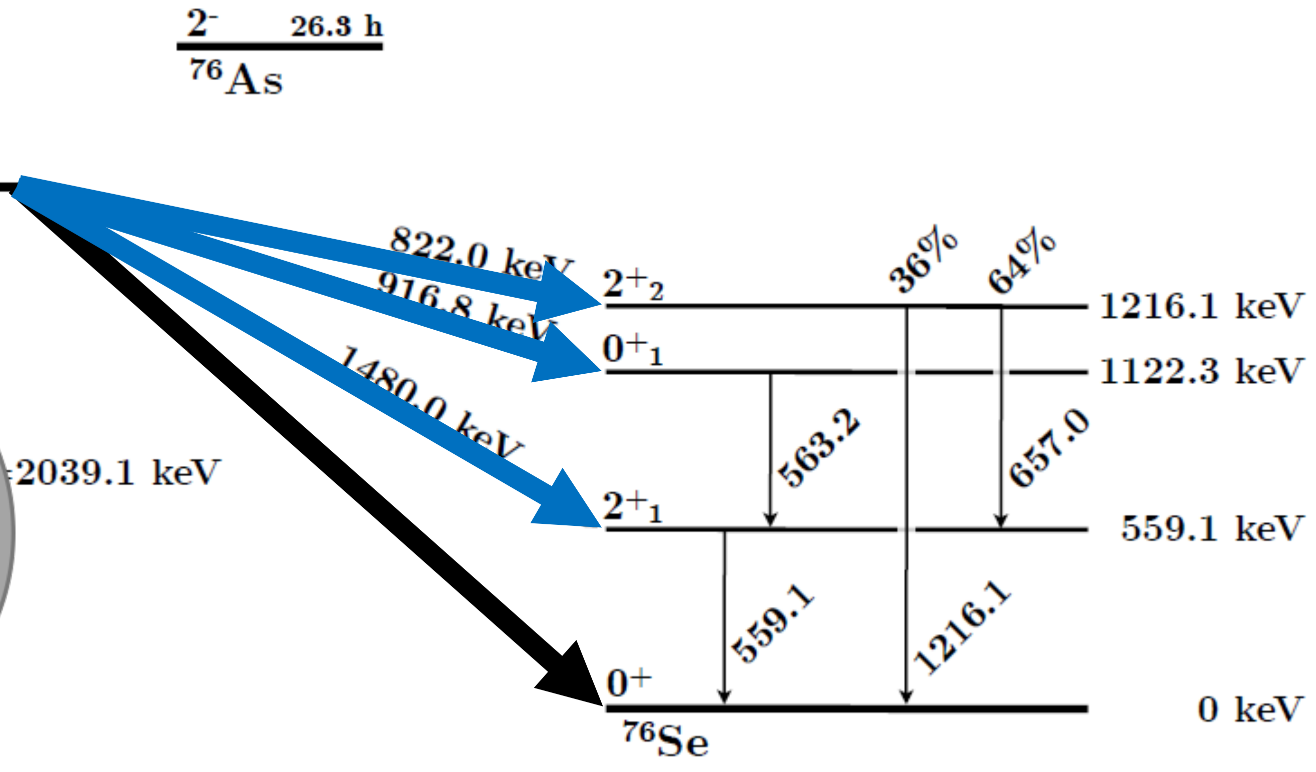
- A “source” detector will have a broad energy spectrum from ββ
- The “gamma” detector will measure energy peaked at the γ energies

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



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]	$> \mathbf{9.7 \cdot 10^{23} y}$	$> \mathbf{18.6 \cdot 10^{23} y}$

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

[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).

Beyond the Standard Model Searches

Excellent energy resolution: ~0.4 keV FWHM at 10.4 keV

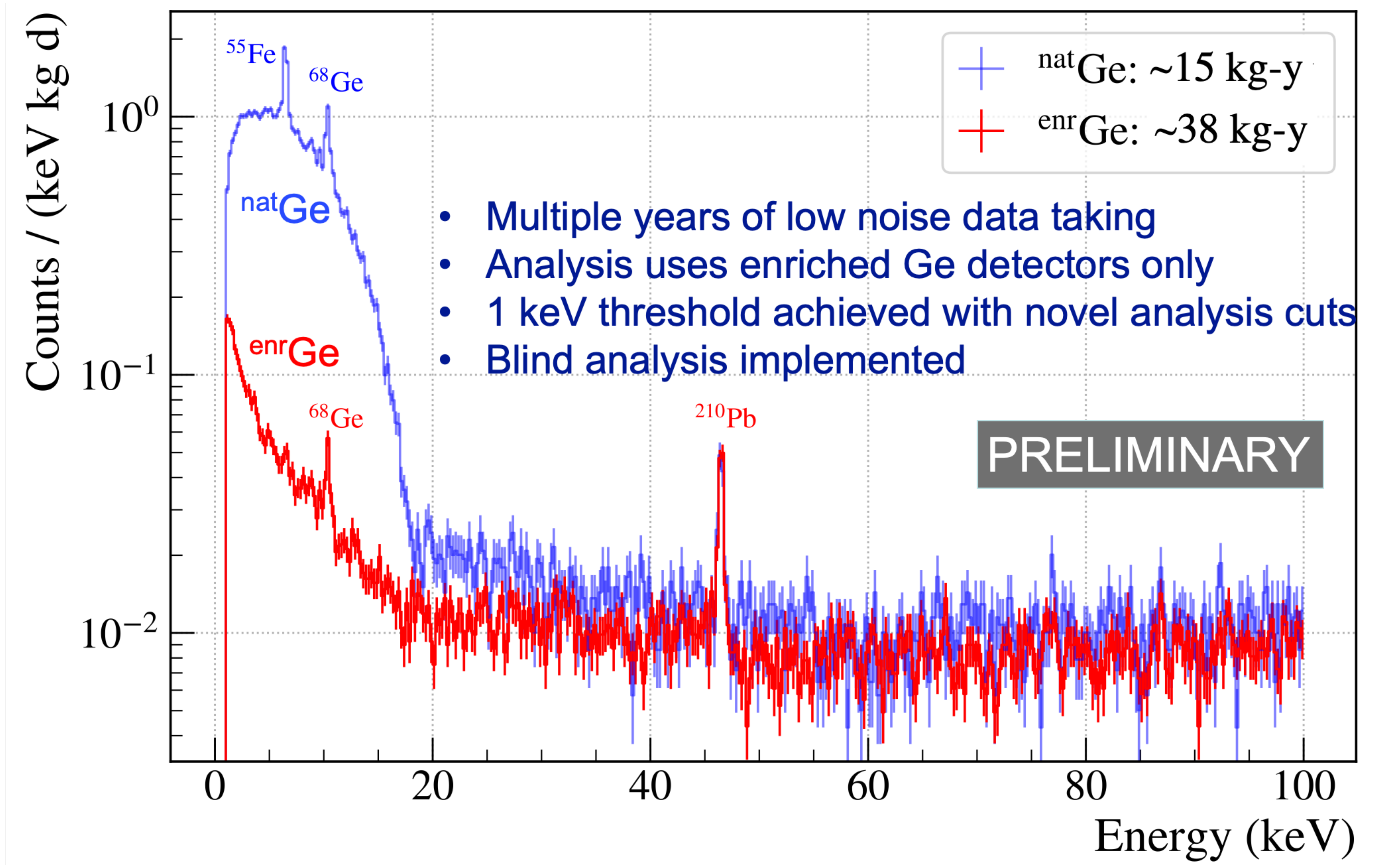
Progress towards a low-E background model

The low backgrounds, low threshold, high resolution spectra allows additional physics searches

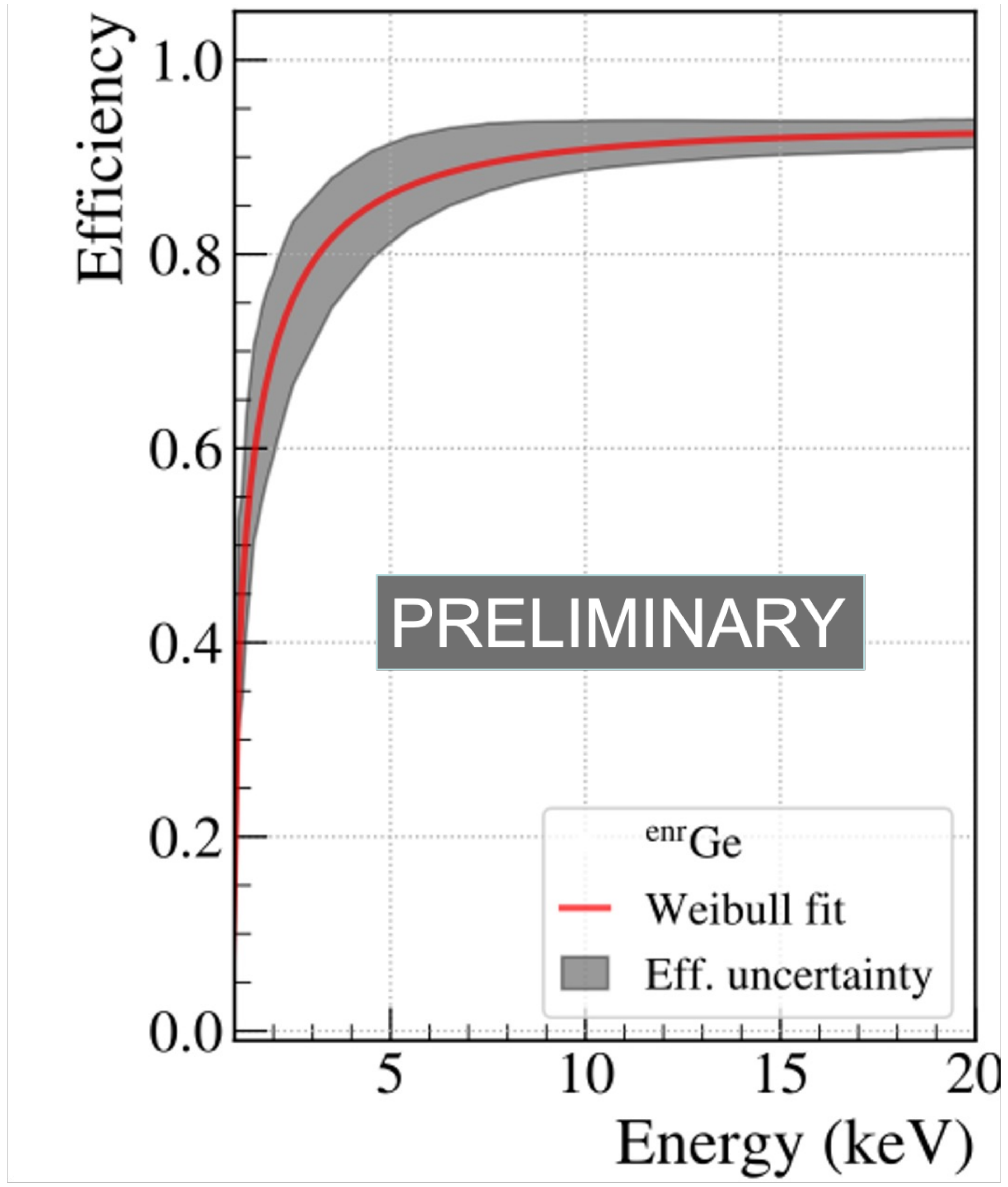
Controlled surface exposure of enriched material to minimize cosmogenics

Low Energy Physics is enabled by low-capacitance of PPC detectors and low-noise electronics

JINST 17 (2022) 05, T05003



- Multiple years of low noise data taking
- Analysis uses enriched Ge detectors only
- 1 keV threshold achieved with novel analysis cuts
- Blind analysis implemented



See Clint Wiseman's talk
Tuesday afternoon

Rich and Broad Physics Program

On the Cover

Axion signatures from coherent Primakoff-Bragg scattering over a 24-hour period.

From the article:

Search for Solar Axions via Axion-Photon Coupling with the MAJORANA DEMONSTRATOR

I.J. Arnquist *et al.* (MAJORANA Collaboration)

Phys. Rev. Lett. **129**, 081803 (2022)

129

PHYSICAL
REVIEW
LETTERS

Published week ending 19 AUGUST 2022

PRL 129 (8), 080401–089901, 19 August 2022 (224 total pages)

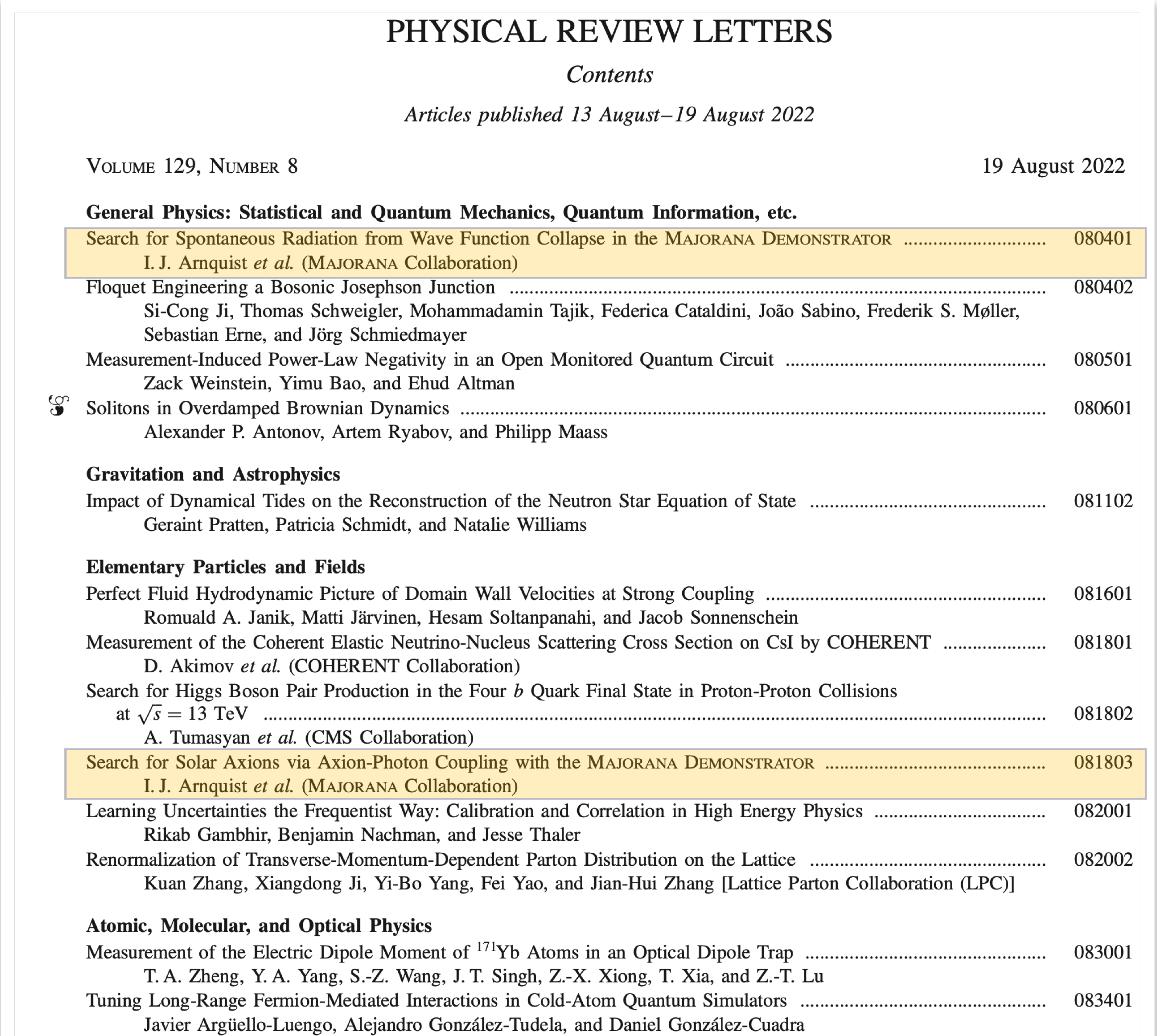
8

Published by
American Physical Society

APS physics

Volume 129, Number 8

https://journals.aps.org/prl/issues/129/8



PHYSICAL REVIEW LETTERS

Contents

Articles published 13 August–19 August 2022

VOLUME 129, NUMBER 8 19 August 2022

General Physics: Statistical and Quantum Mechanics, Quantum Information, etc.

Gravitation and Astrophysics

Elementary Particles and Fields

Atomic, Molecular, and Optical Physics

Solar Axion

On the Cover

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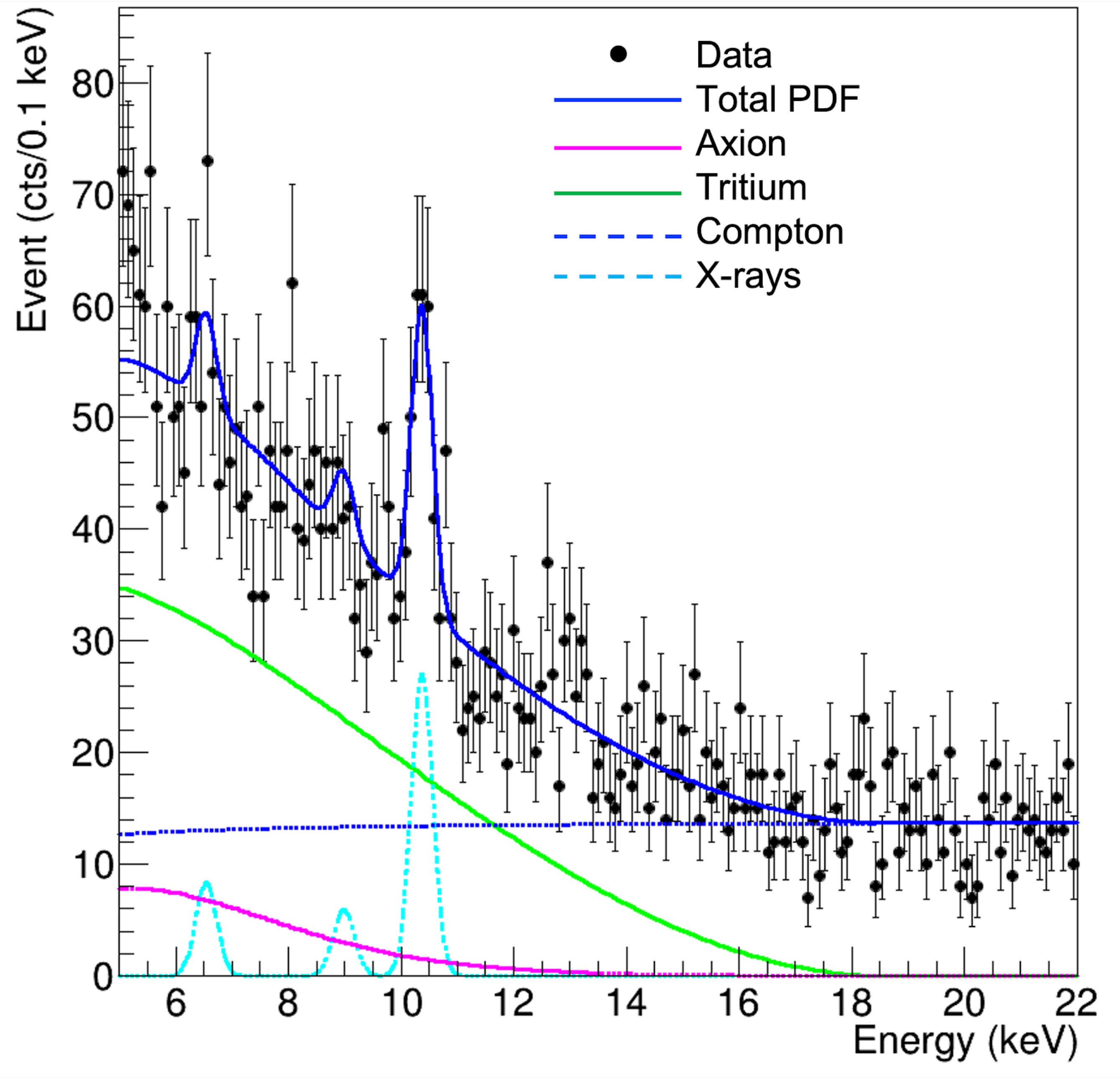


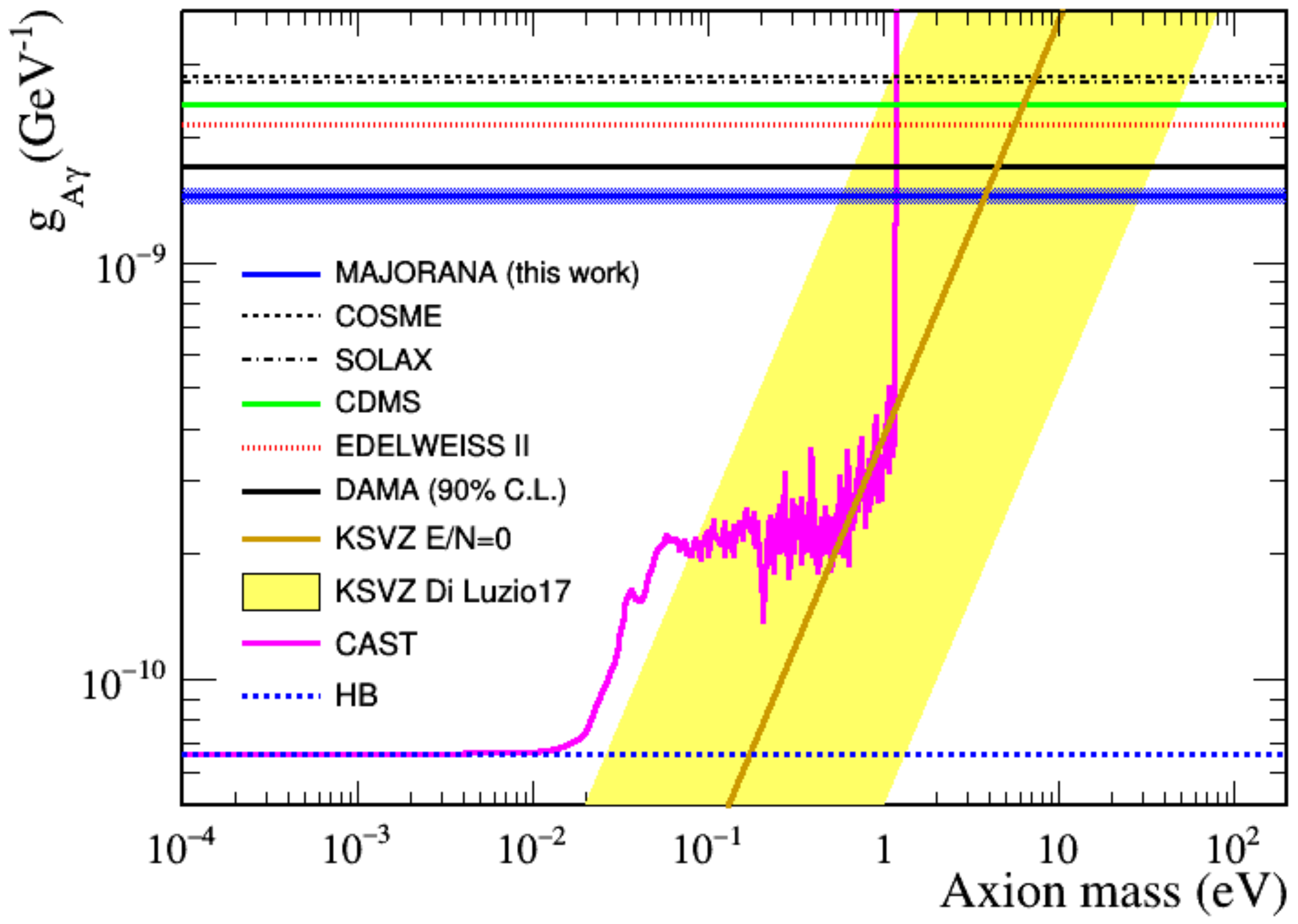
Axions produced by reverse-Primakoff effect in Sun

Perform 2-D search in time and energy for signature

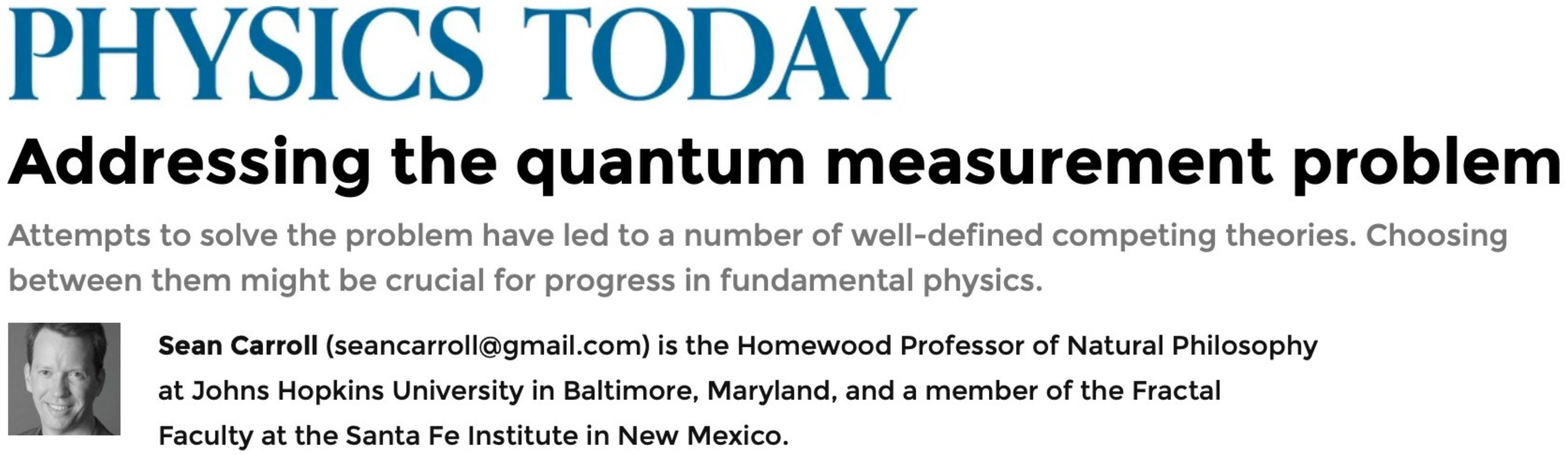
- 5 min bins over 3 year dataset

Best lab-based limit for m_A = 1.2 ~ 100 eV

Improves on 21-year old DAMA limit



Wavefunction Collapse



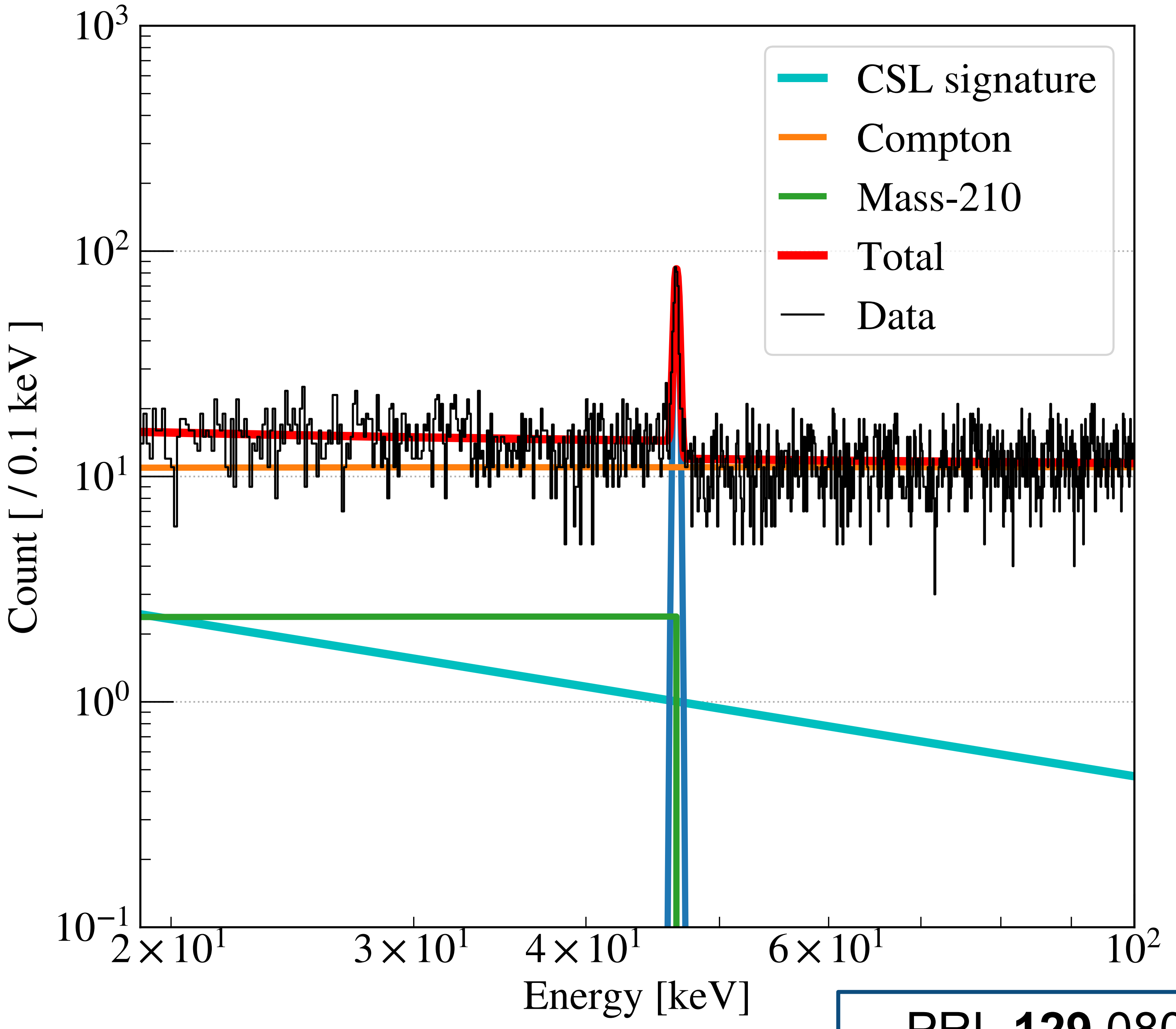
PHYSICS TODAY

Addressing the quantum measurement problem

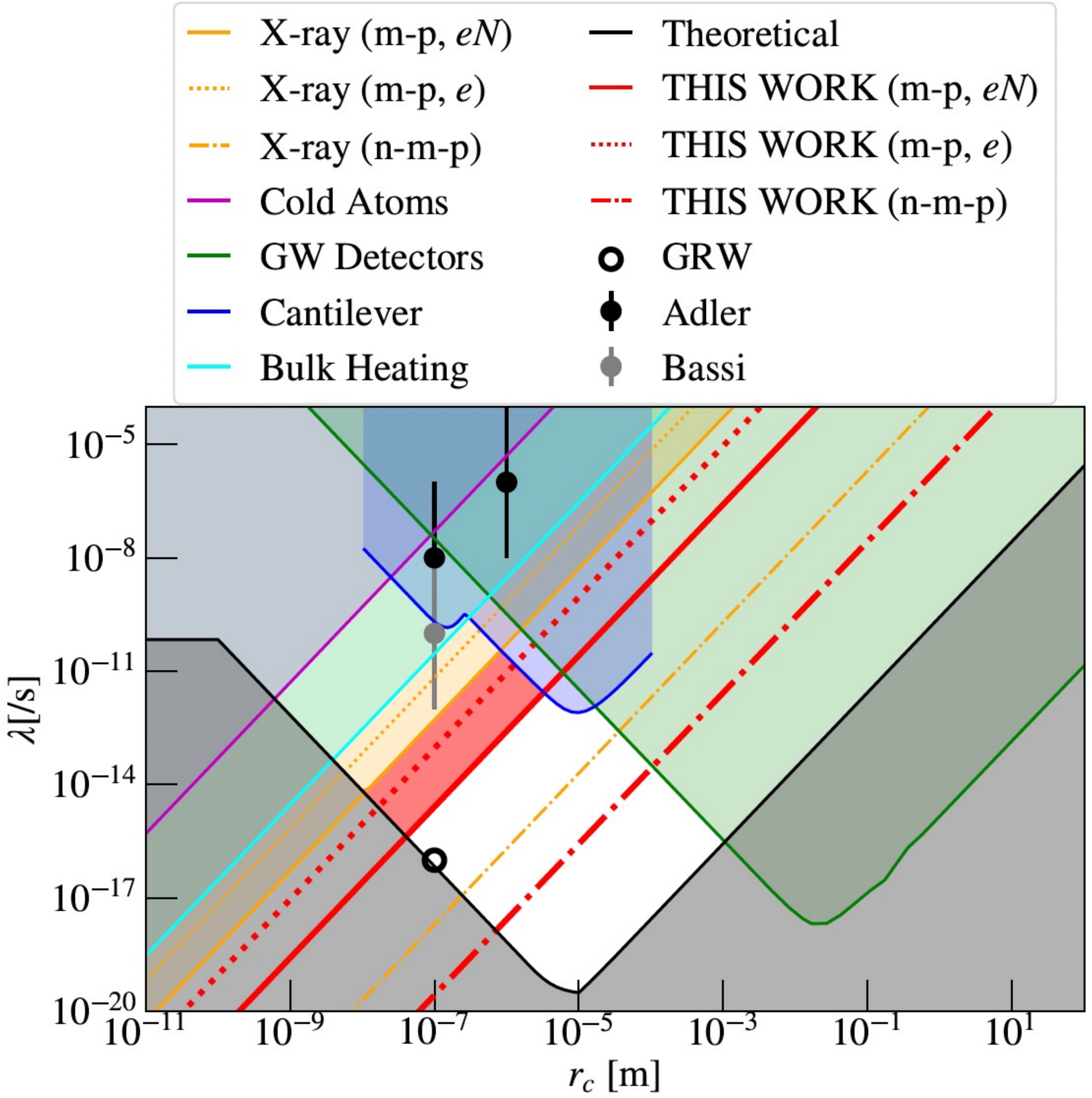
Attempts to solve the problem have led to a number of well-defined competing theories. Choosing between them might be crucial for progress in fundamental physics.

Sean Carroll (seancarroll@gmail.com) is the Homewood Professor of Natural Philosophy at Johns Hopkins University in Baltimore, Maryland, and a member of the Fractal Faculty at the Santa Fe Institute in New Mexico.

Theory of quantum wavefunction collapse yields 1/E prediction for spectral signature



PRL **129** 080401 (2022)



Low-background low-energy spectrum of MAJORANA leads to significant improvement in sensitivity to process

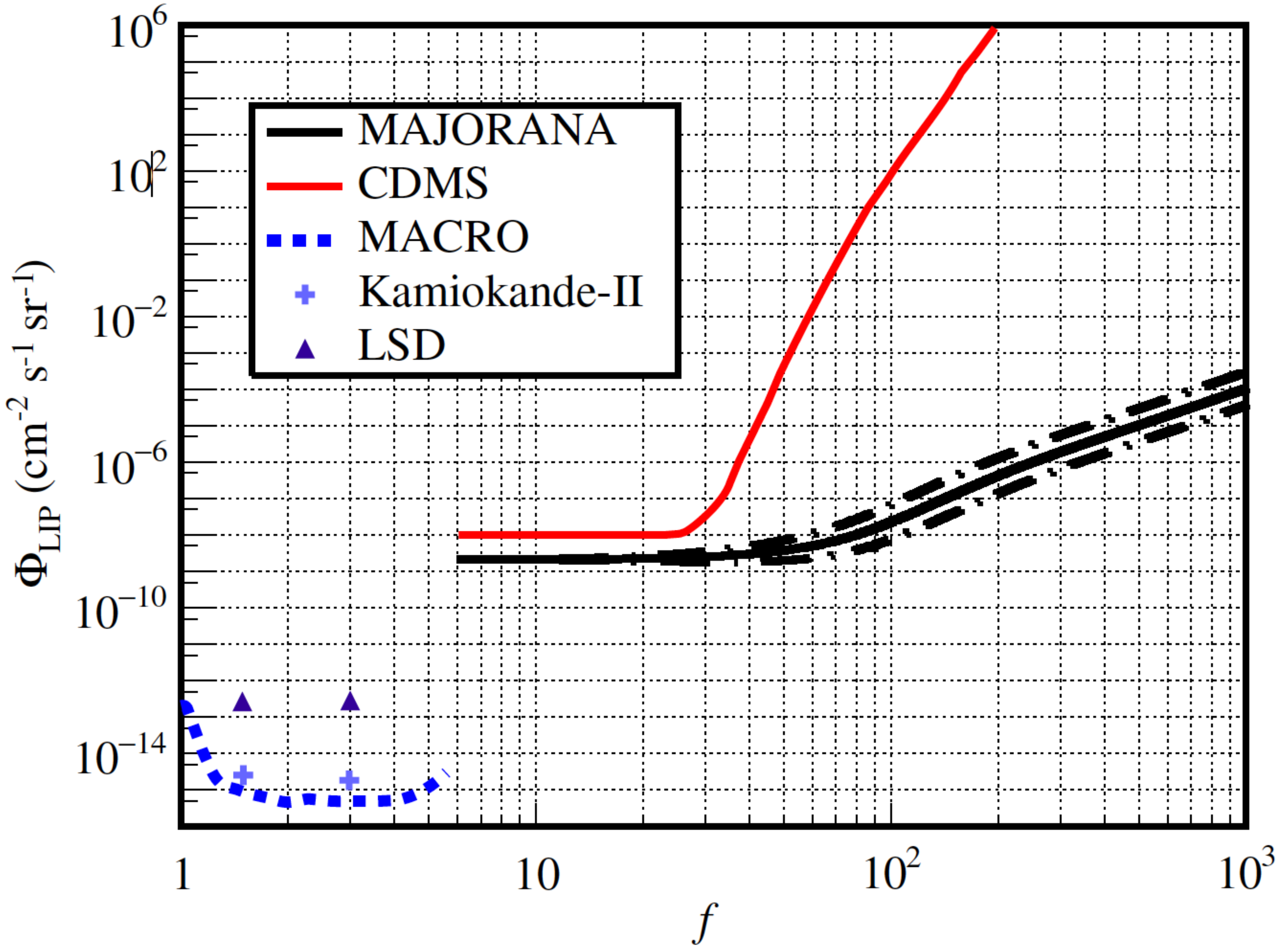
This and much more, see Clint Wiseman's talk Tuesday afternoon

Beyond the Standard Model Searches

The low backgrounds, low threshold, high-resolution spectra allows additional searches

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

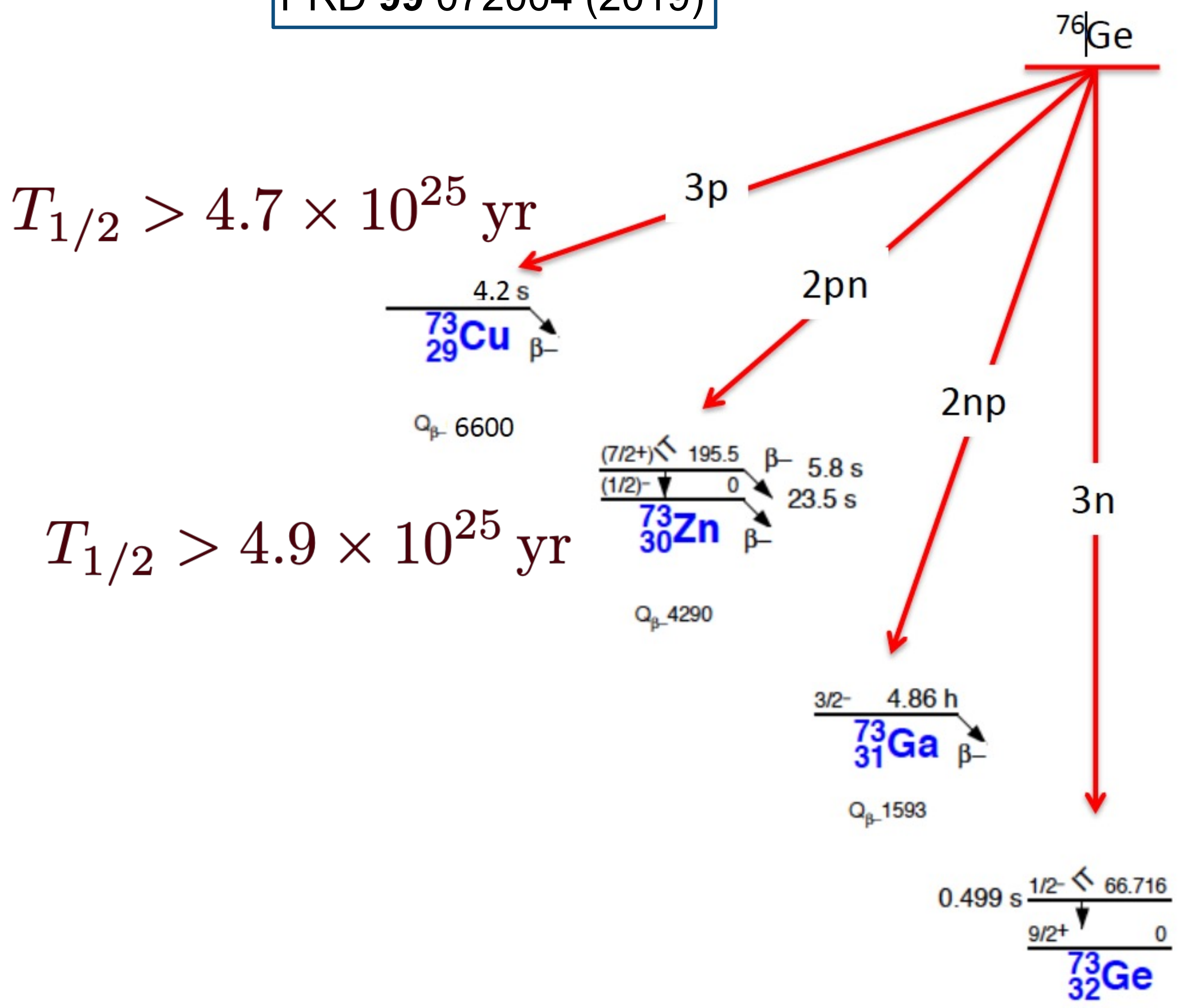
PRL **120** 211804 (2018)



The 90% UL on the Lightly Ionizing Particle flux with 1σ uncertainty bands

Search for Tri-Nucleon Decay: A test of baryon number violation

PRD **99** 072004 (2019)

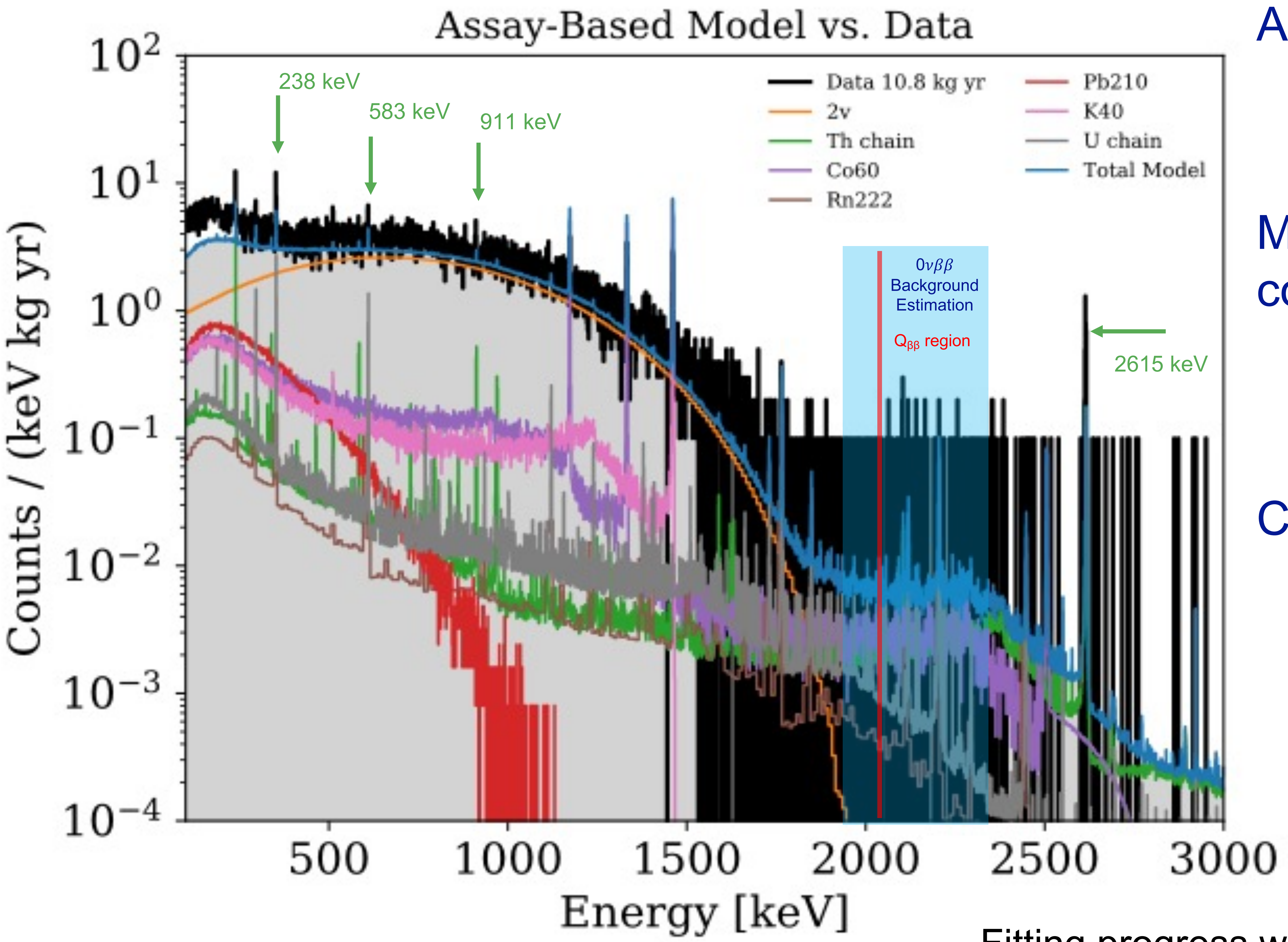


$T_{1/2} > 4.7 \times 10^{25}$ yr

$T_{1/2} > 4.9 \times 10^{25}$ yr

The 90% UL for two tri-nucleon decay-specific modes

Background Modeling and Investigation



Assay-based prediction: 2.9 ± 0.14 cts/ (FWHM t y)

- Updated to match as-built geometry, new assay information, and more refined uncertainties

Measured Background in lowest background configuration: 15.7 ± 1.4 cts/(FWHM t y) [PRELIMINARY]

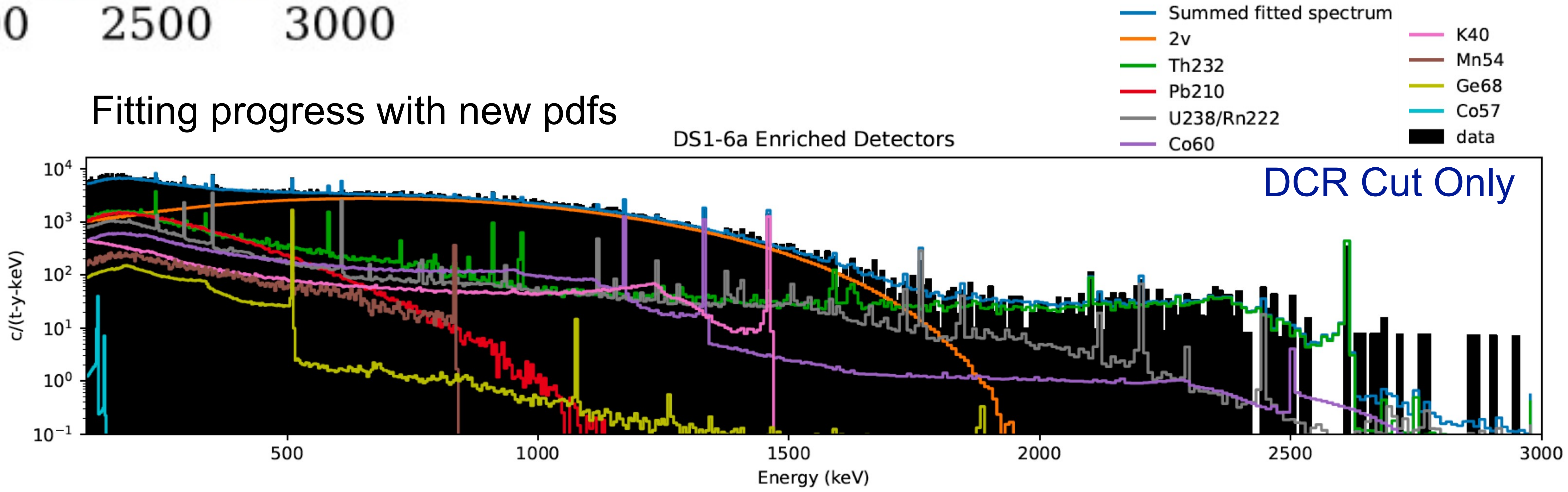
- Module 1: 18.6 ± 1.8 cts/(FWHM t yr)
- Module 2: $8.4\,^{+1.9}_{-1.7}$ cts/(FWHM t yr)

Characteristics of background excess:

- Dominated by ^{232}Th decay chain — excess apparent at ^{208}Tl, especially 238 keV and 2615 keV
- Does not indicate a source within the Ge detector array (front end electronics, detector holders, etc.).

Improved Frequentist and Bayesian fitting efforts underway in order to more precisely locate source of excess ^{232}Th background and complete the background model

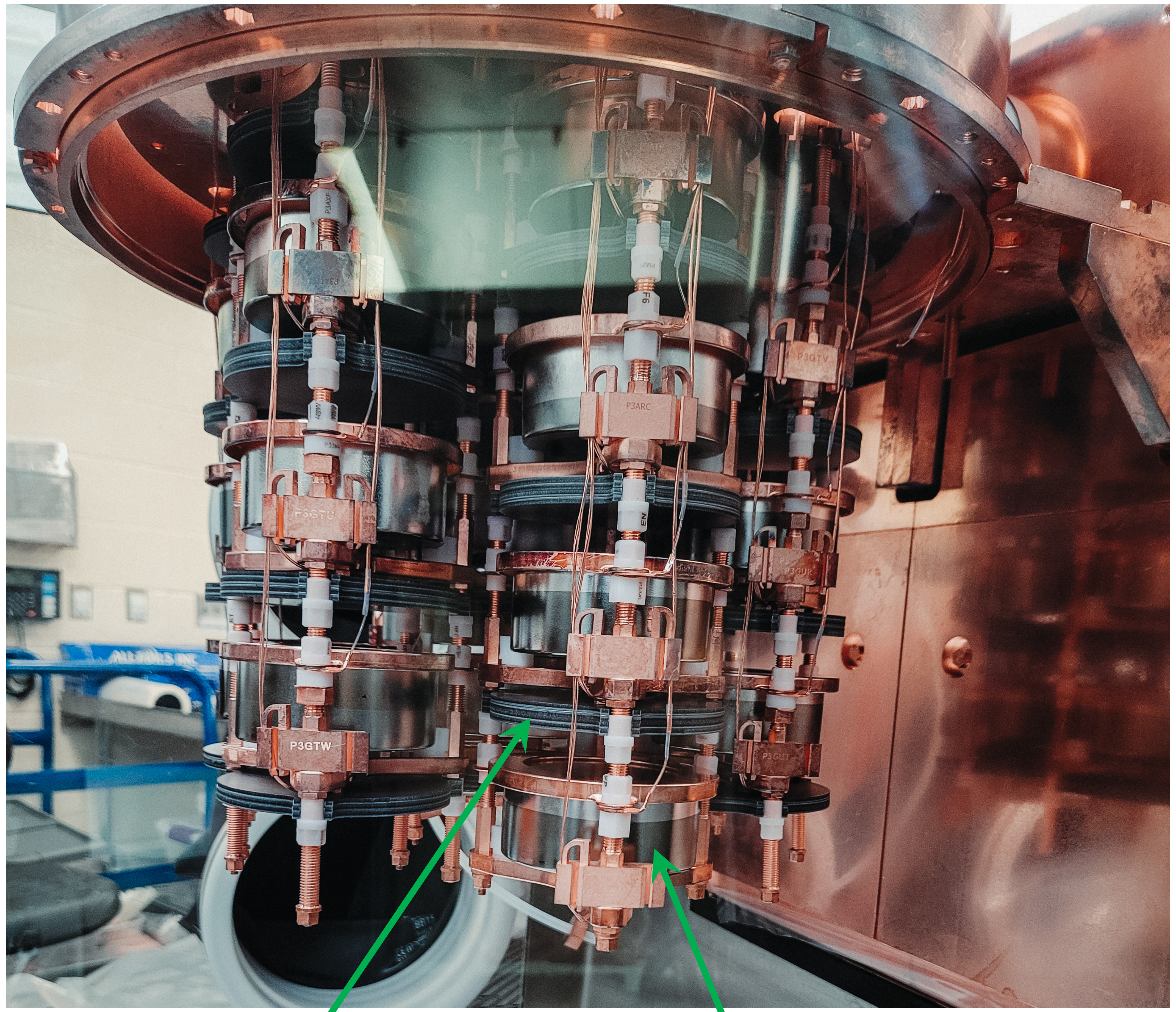
Fitting progress with new pdfs



Tantalum: The Next DEMONSTRATOR Chapter

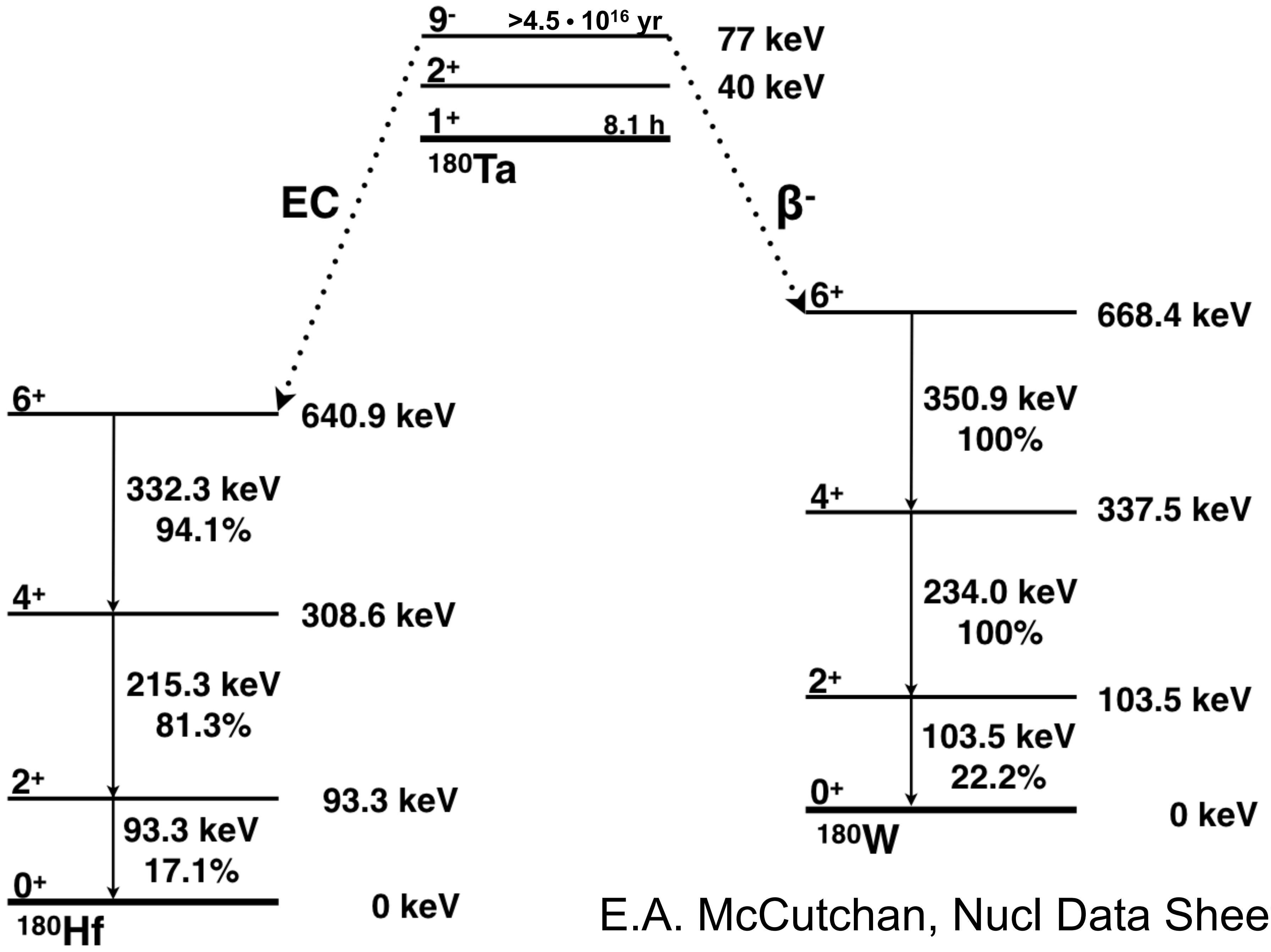
MAJORANA DEMONSTRATOR has been reconfigured with single module of natural detectors only

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



E.A. McCutchan, Nucl Data Sheets (2015)
B. Lehnert *et al.* Phys. Rev. C (2017)

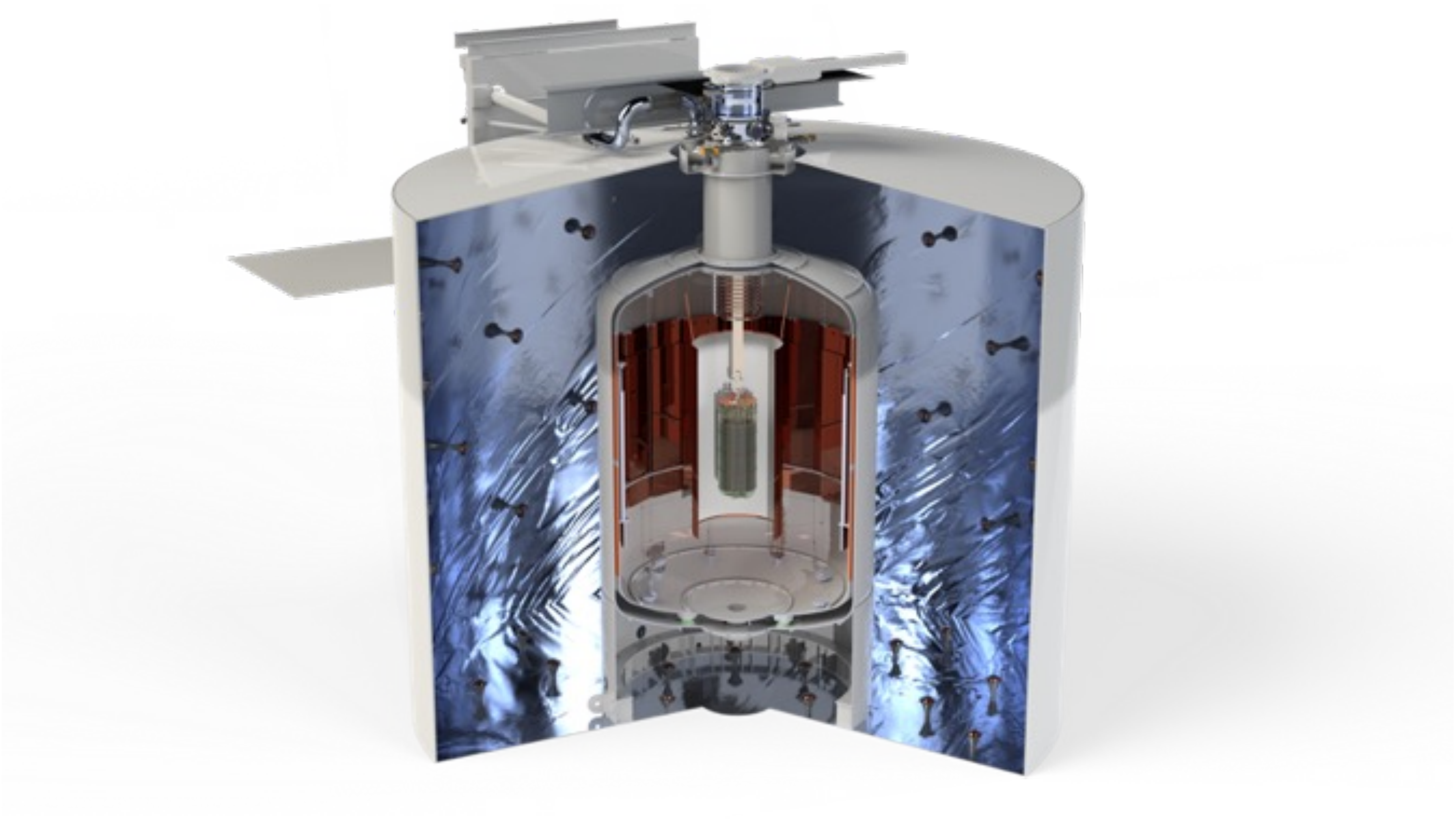
MAJORANA search will be sensitive to theory-favored half-lives of 10^{17}–10^{18} yr

- Order of magnitude more ^{180m}Ta than previous searches
- Many more detectors for coincidence gammas
- Ultra-low background DEMONSTRATOR environment
- Two orders of magnitude improvement in sensitivity

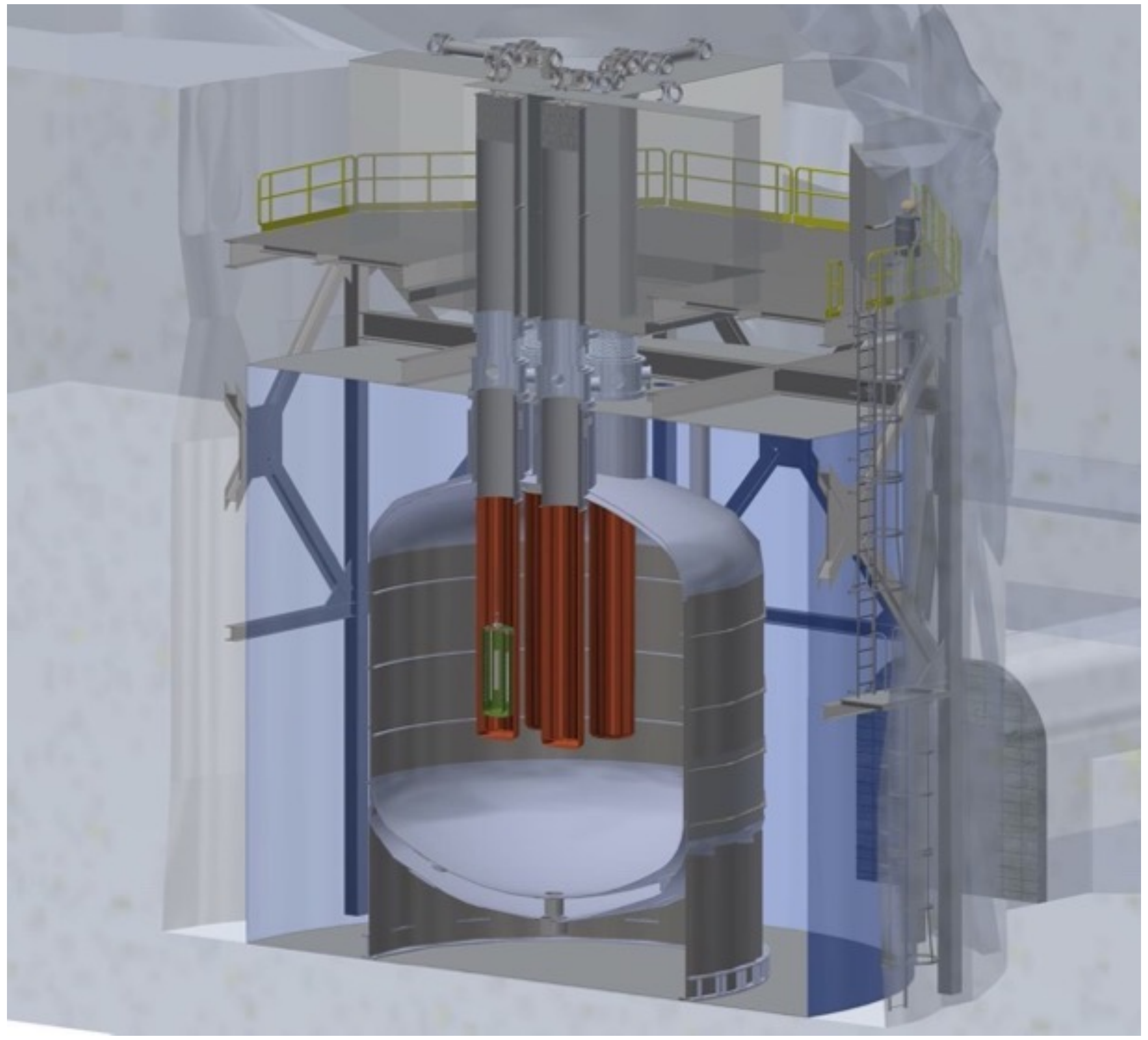
LEGEND: The Future of ^{76}Ge $0\nu\beta\beta$

Germanium-based $0\nu\beta\beta$ efforts from both sides of the Atlantic (MAJORANA and GERDA) have come together to form one collaboration, LEGEND with the mission:

The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results.



LEGEND-200: Commissioning Now!



LEGEND-1000: Pursuing CD-1

See Wenqin Xu parallel talk this afternoon

Several postdoctoral opportunities on MAJORANA and LEGEND open now, see https://legend-exp.org

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
- Background model being investigated and refined
  - Initial background fits are informing possible distribution of background sources
- 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
  - Search for neutron and cosmogenic signatures at high energy
- Continuing operation with natural detectors for background studies, tantalum decay, and other physics
- The technologies, analysis techniques, and people involved in MAJORANA will continue to play a major role in searching for 0νββ with LEGEND

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