Status of the MAJORANA DEMONSTRATOR

A search for $0\nu\beta\beta$ in 76Ge and other physics beyond the standard model

Ian Guinn, on behalf of the MAJORANA Collaboration

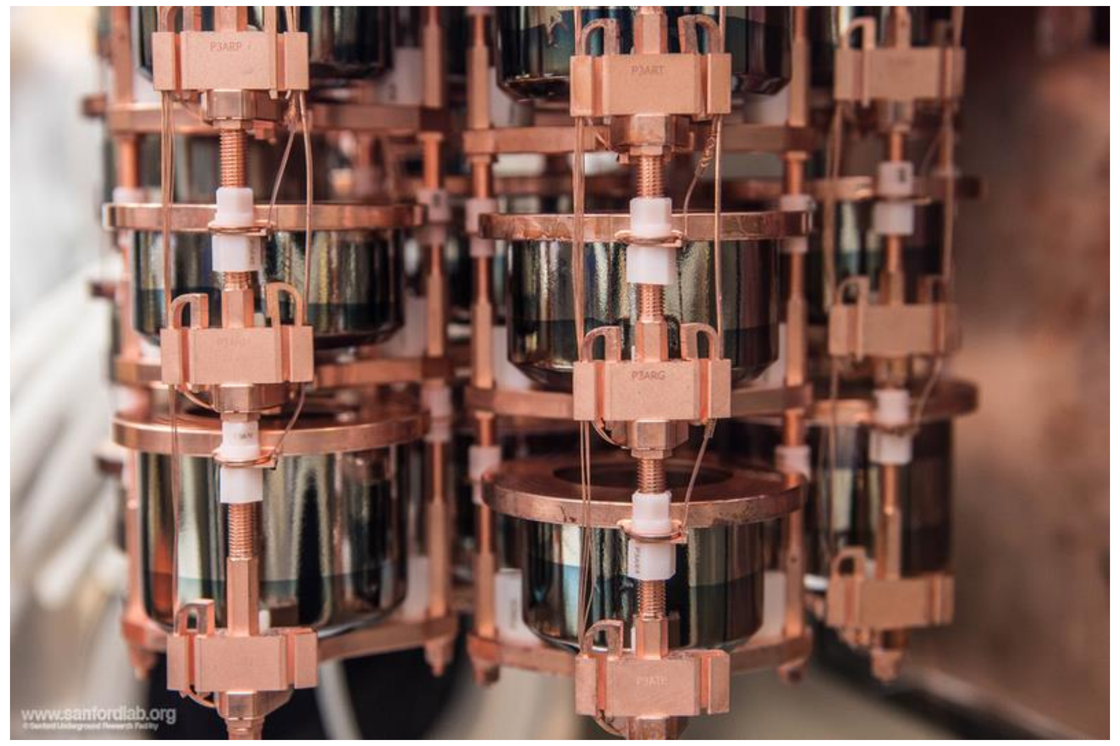
February 23, 2021

XIX International Workshop on Neutrino Telescopes

MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors and additional physics beyond the standard model

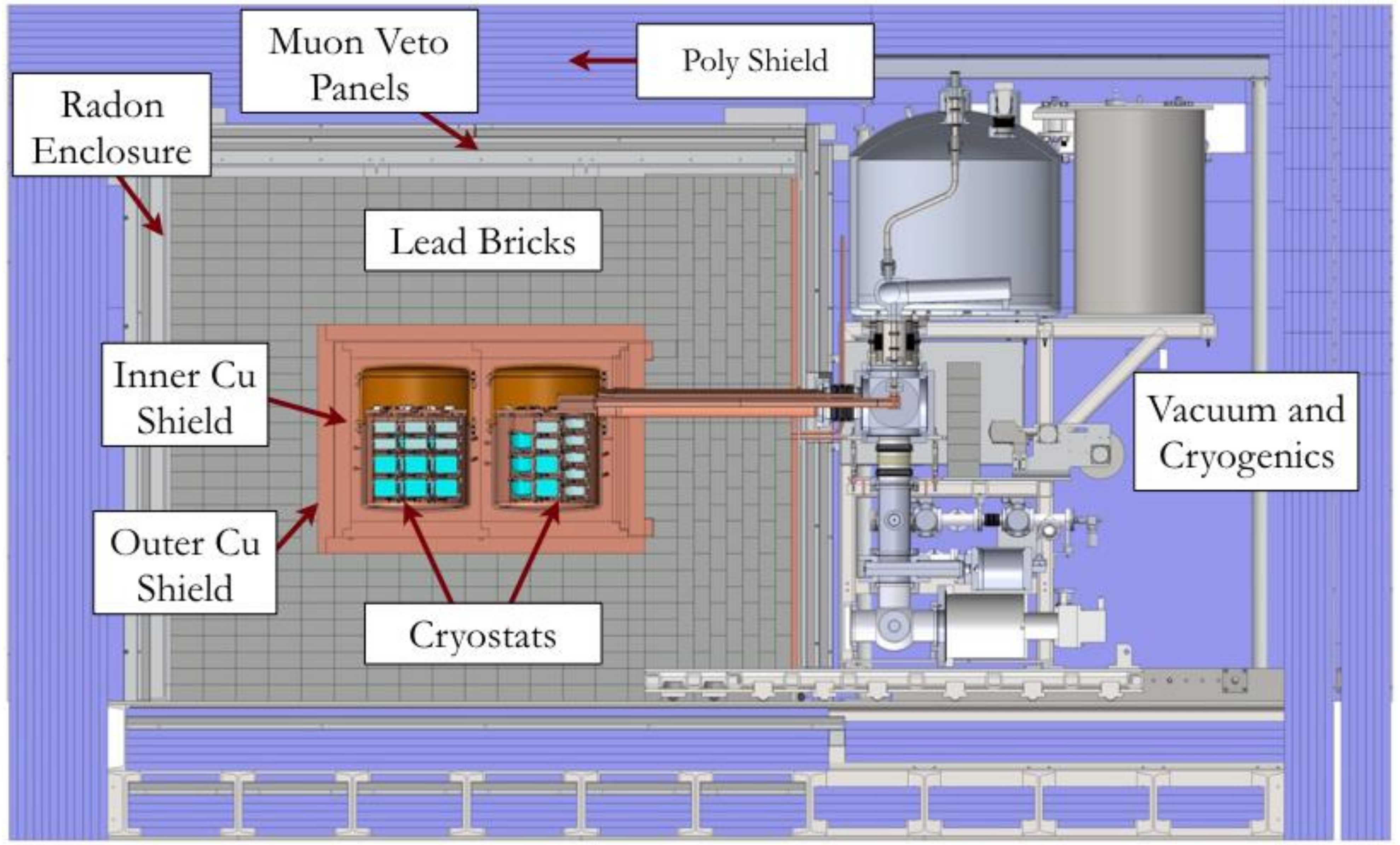
Source & Detector: Array of p-type, point contact detectors
29.7 kg of 88% enriched ^{76}Ge crystals



Excellent Energy resolution: 2.5 keV FWHM @ 2039 keV

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

Operating underground at the 4850' level of the Sanford Underground Research Facility since 2015



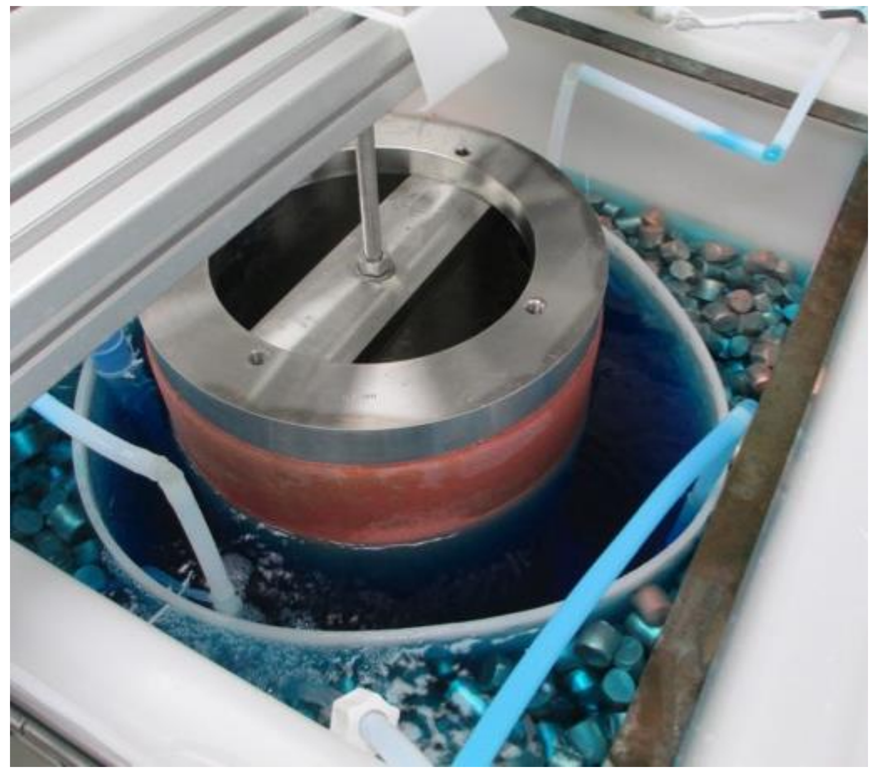
MAJORANA Approach to Backgrounds

P-type point contact detectors for low intrinsic backgrounds, excellent energy resolution, pulse-shape based background suppression

- Ge enrichment, zone-refining and crystal pulling processes enhance purity
- Limit above-ground exposure to prevent cosmic activation.
- Slow drift of ionization charge carriers allows separation of multiple interactions inside a detector.

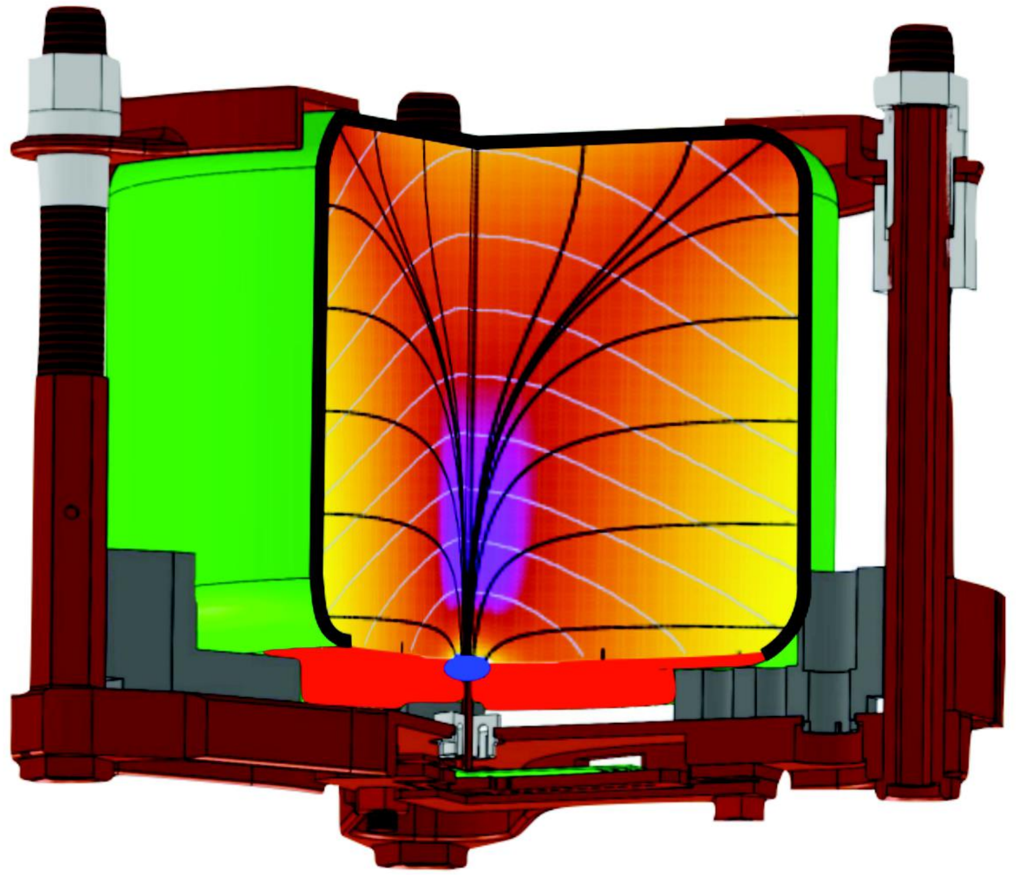
Array components and passive shielding fabricated from ultra-pure materials with extremely low radio-isotope content

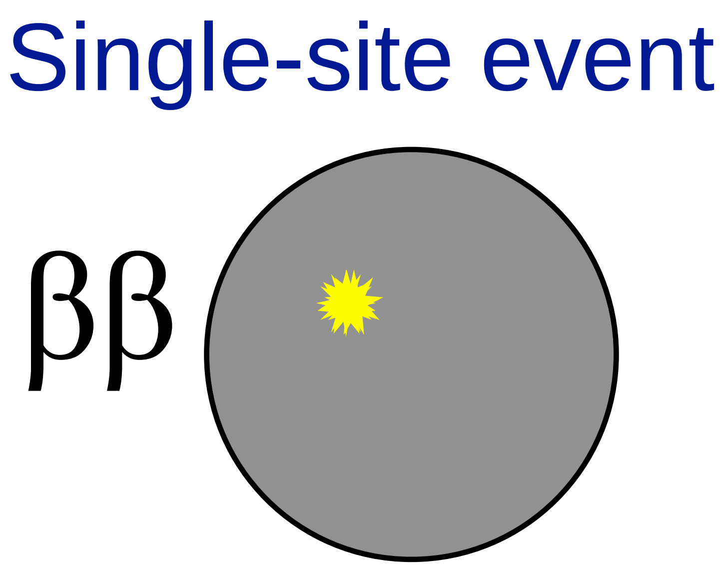
- [NIM A828 (2016) 22–36]

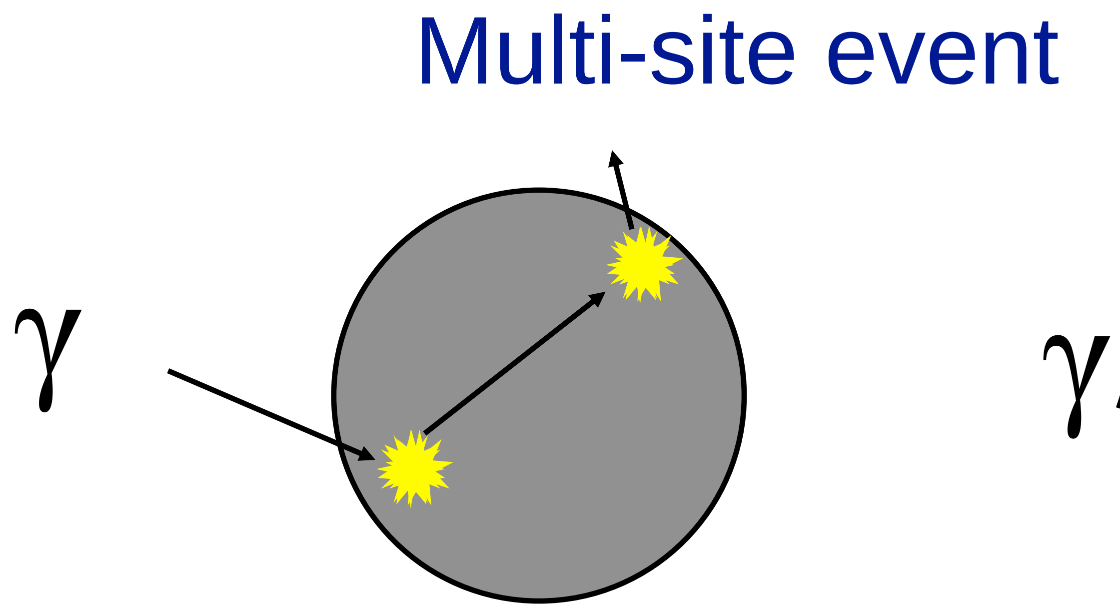


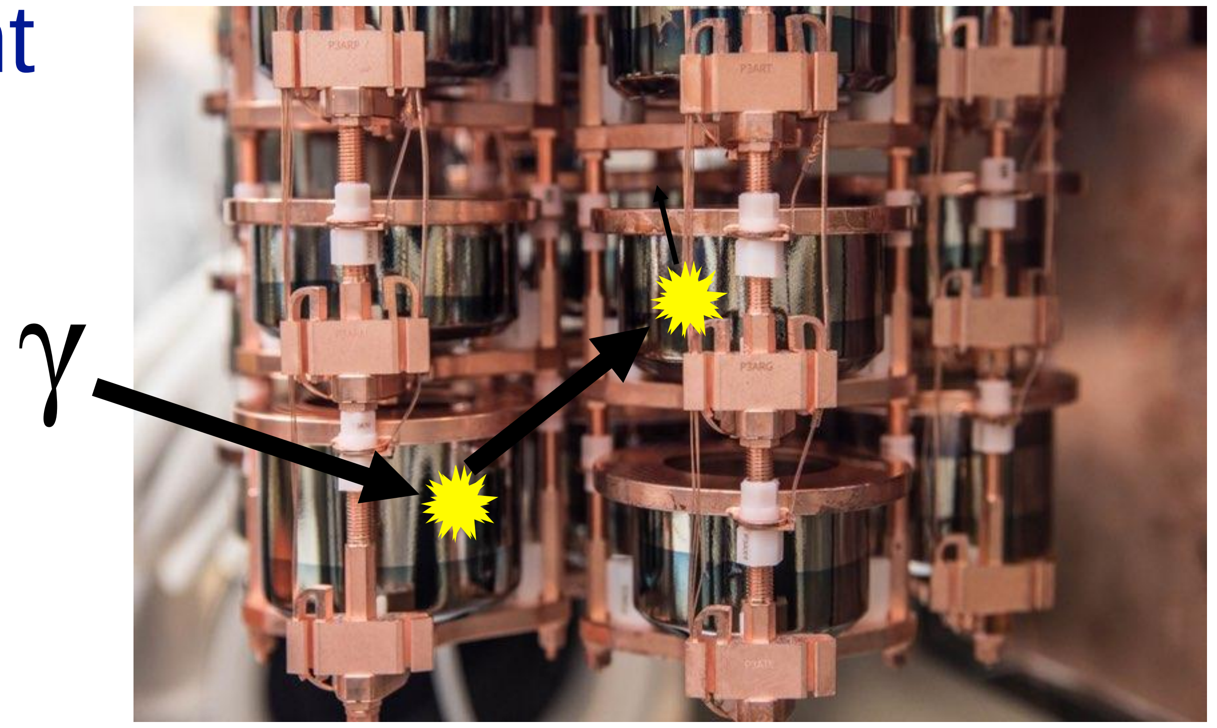
Rejection of backgrounds

- Muon Veto: reject events coincident with muons
- Granularity: multiple detectors hit
- Pulse shape discrimination: no multiple hits, reject surface events

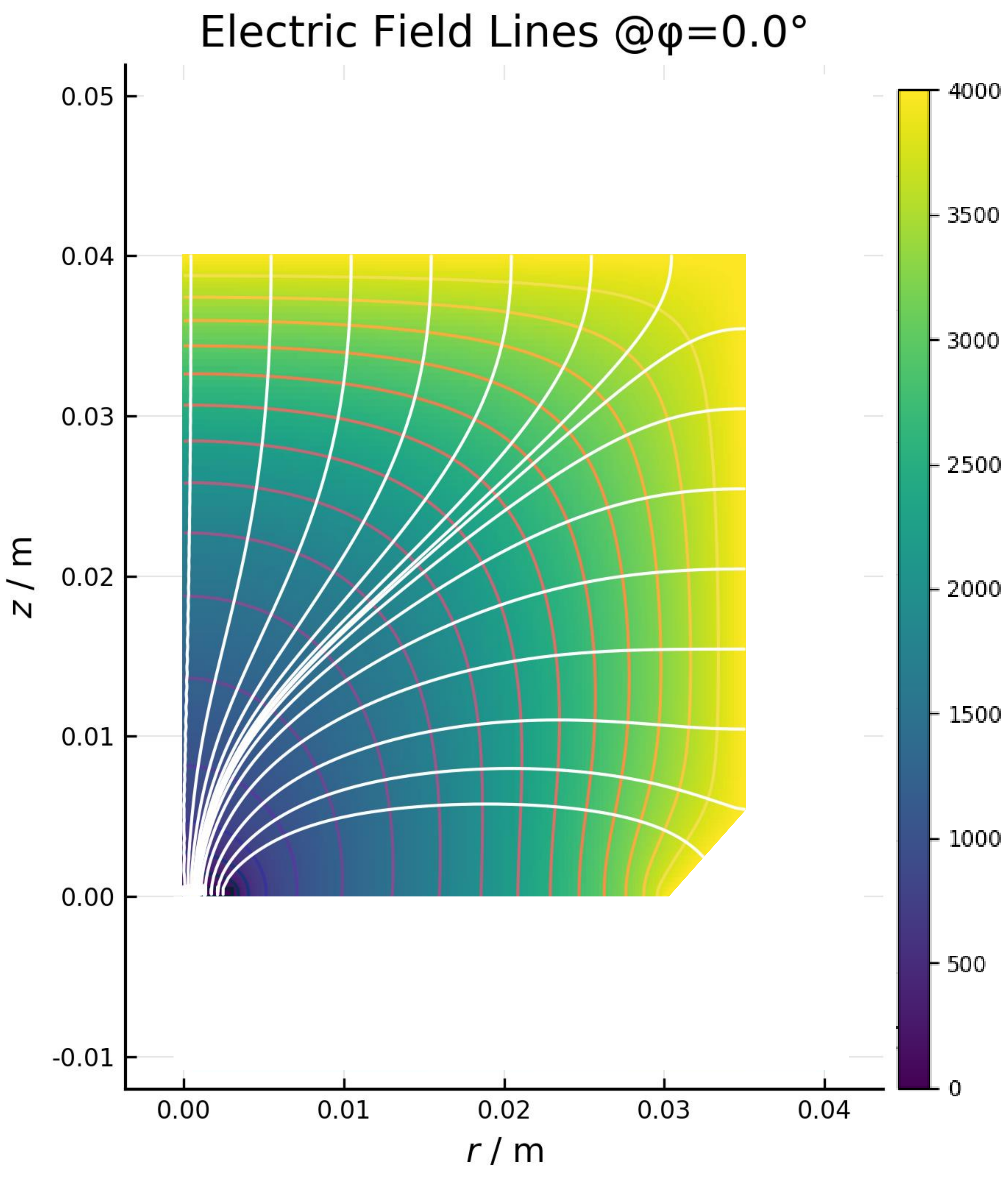


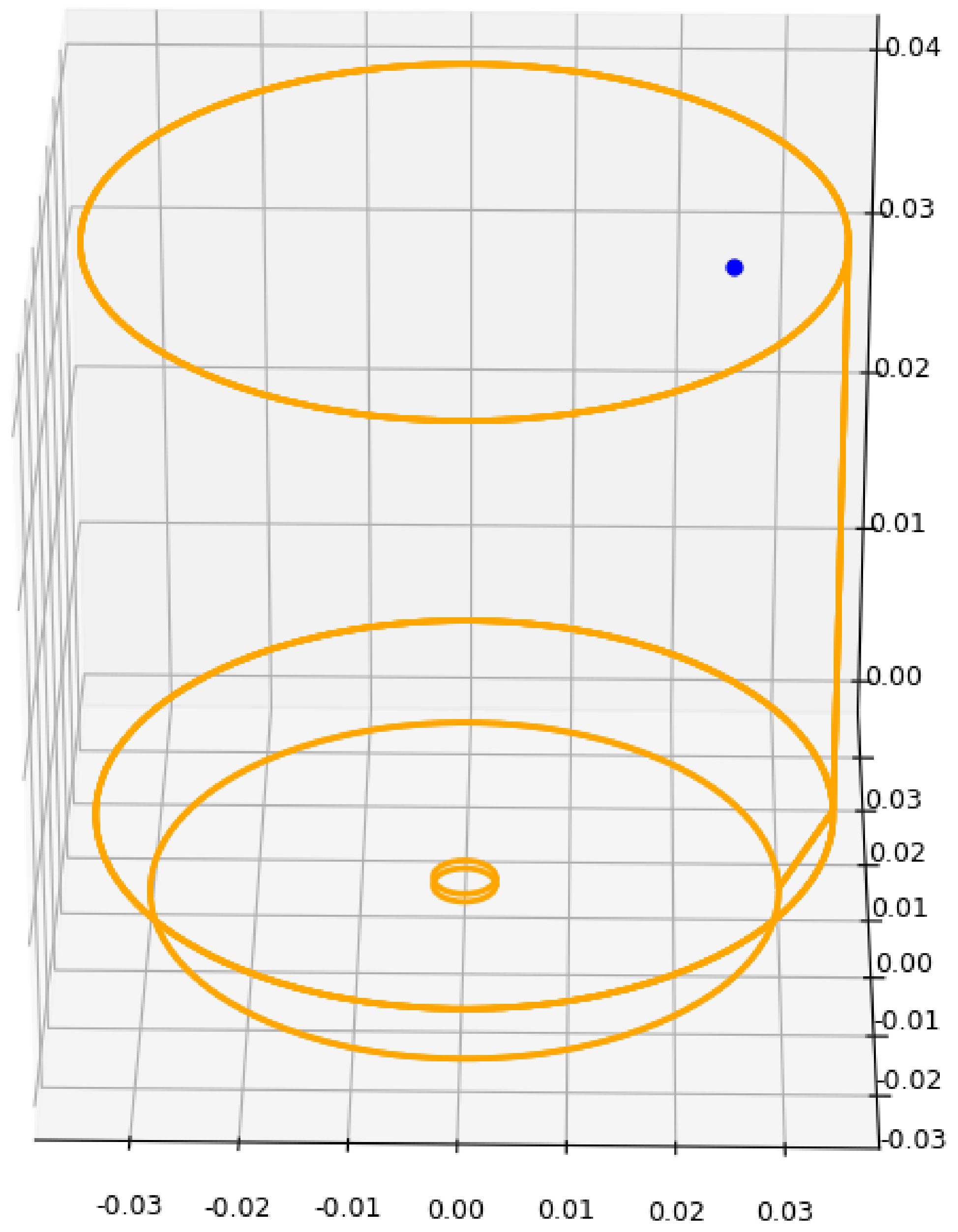


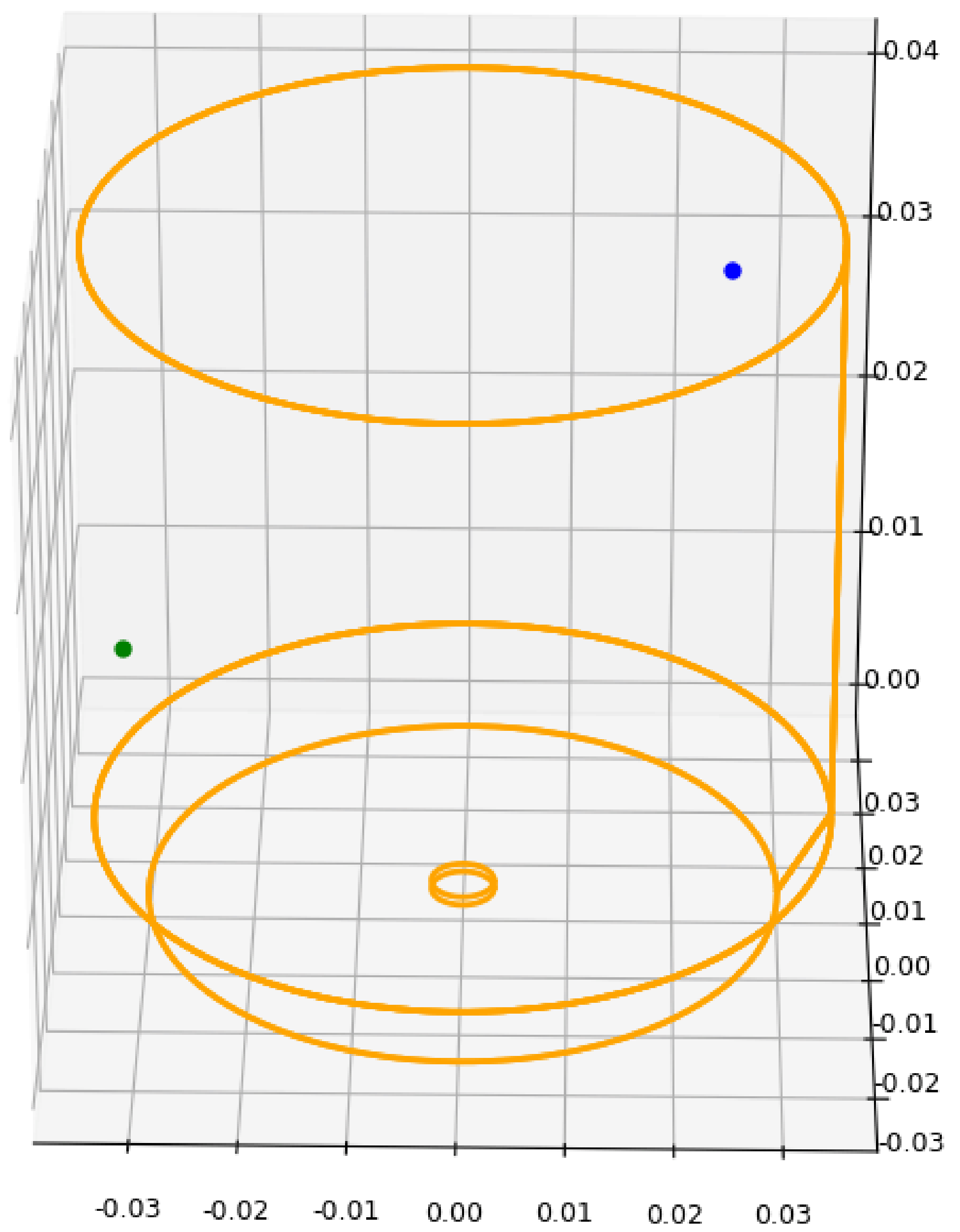


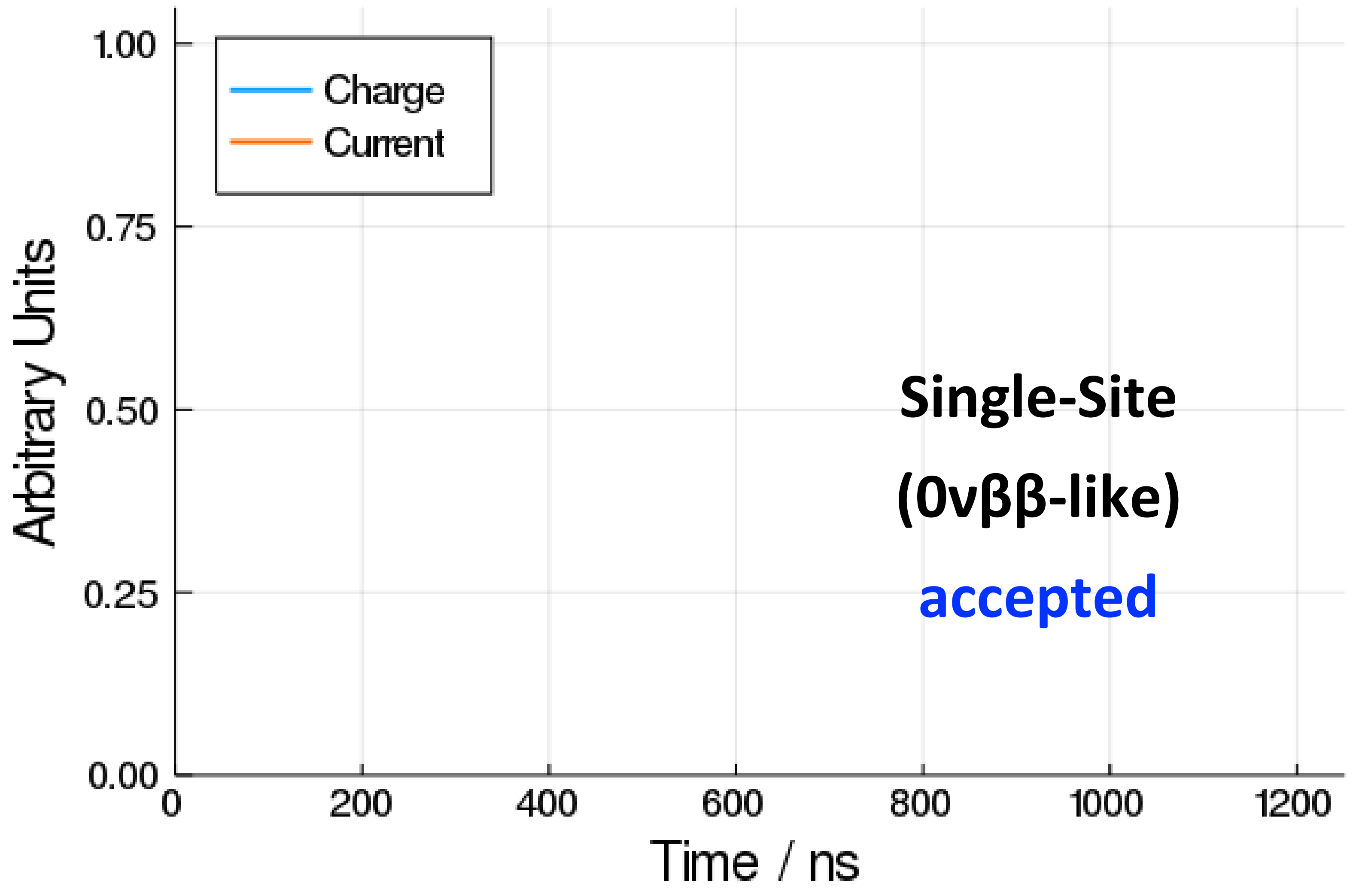


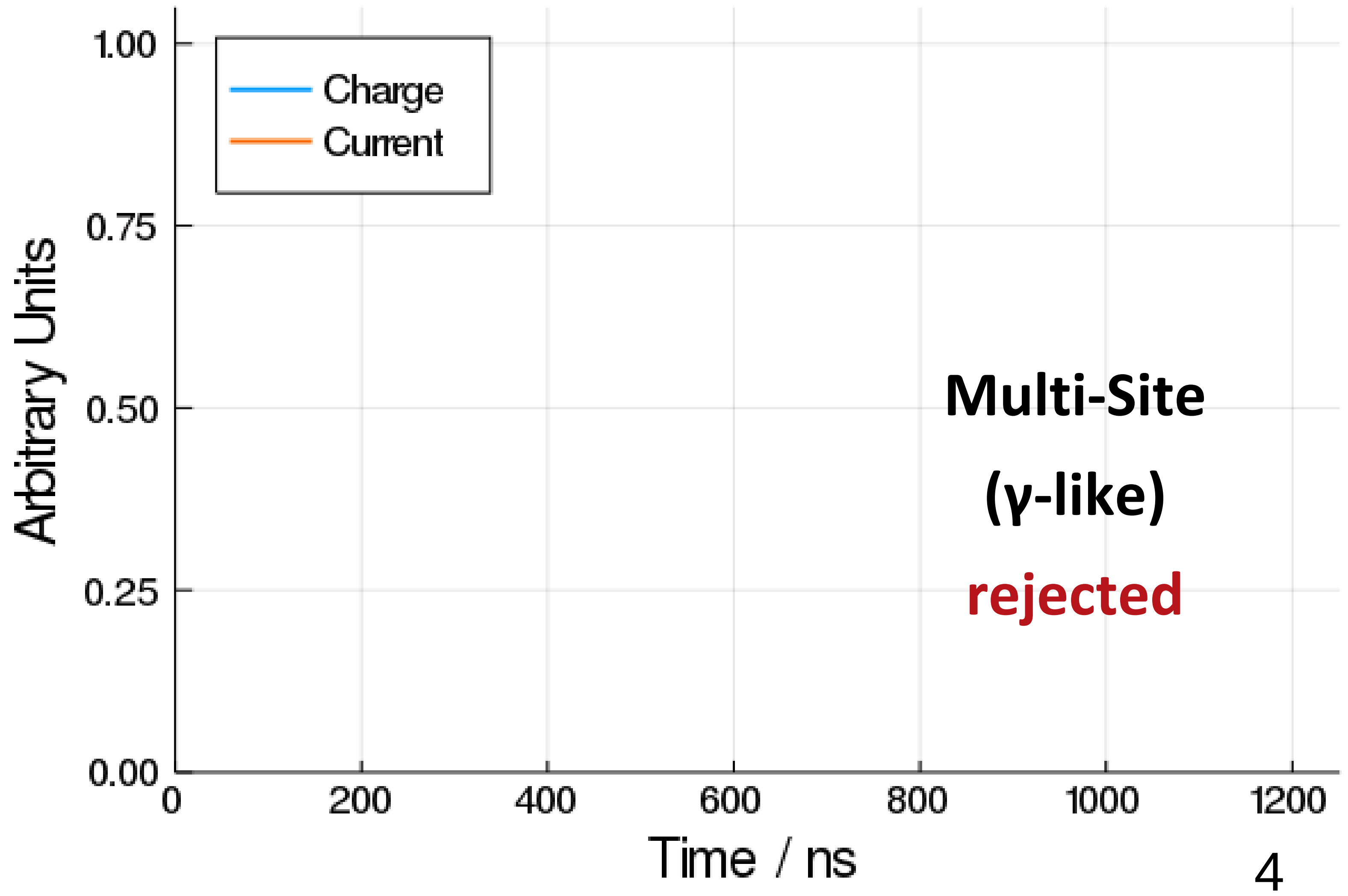
Background Rejection: Multi-Site Events

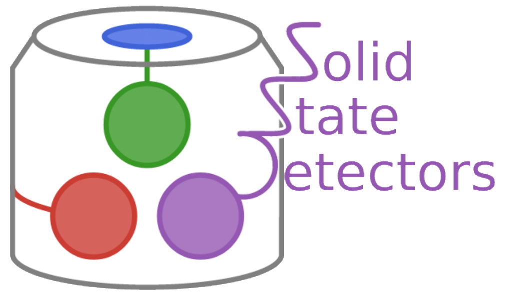








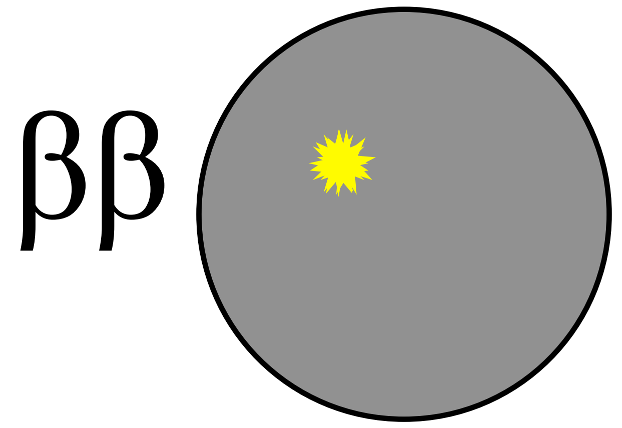




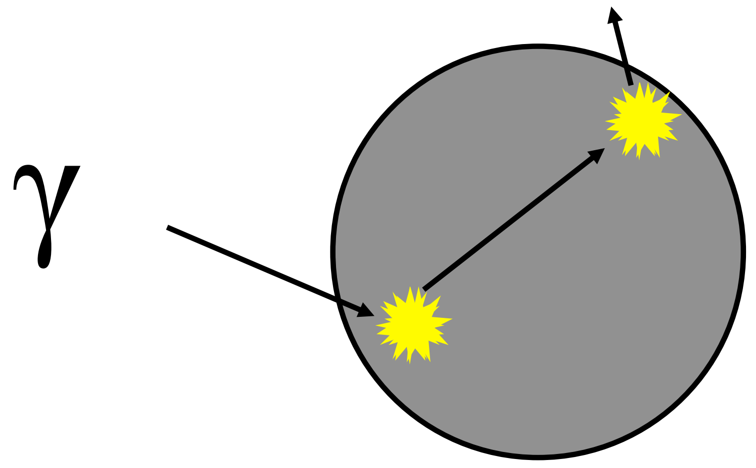
PRC **99** 065501 (2019)

Improved Multi-Site Event Rejection

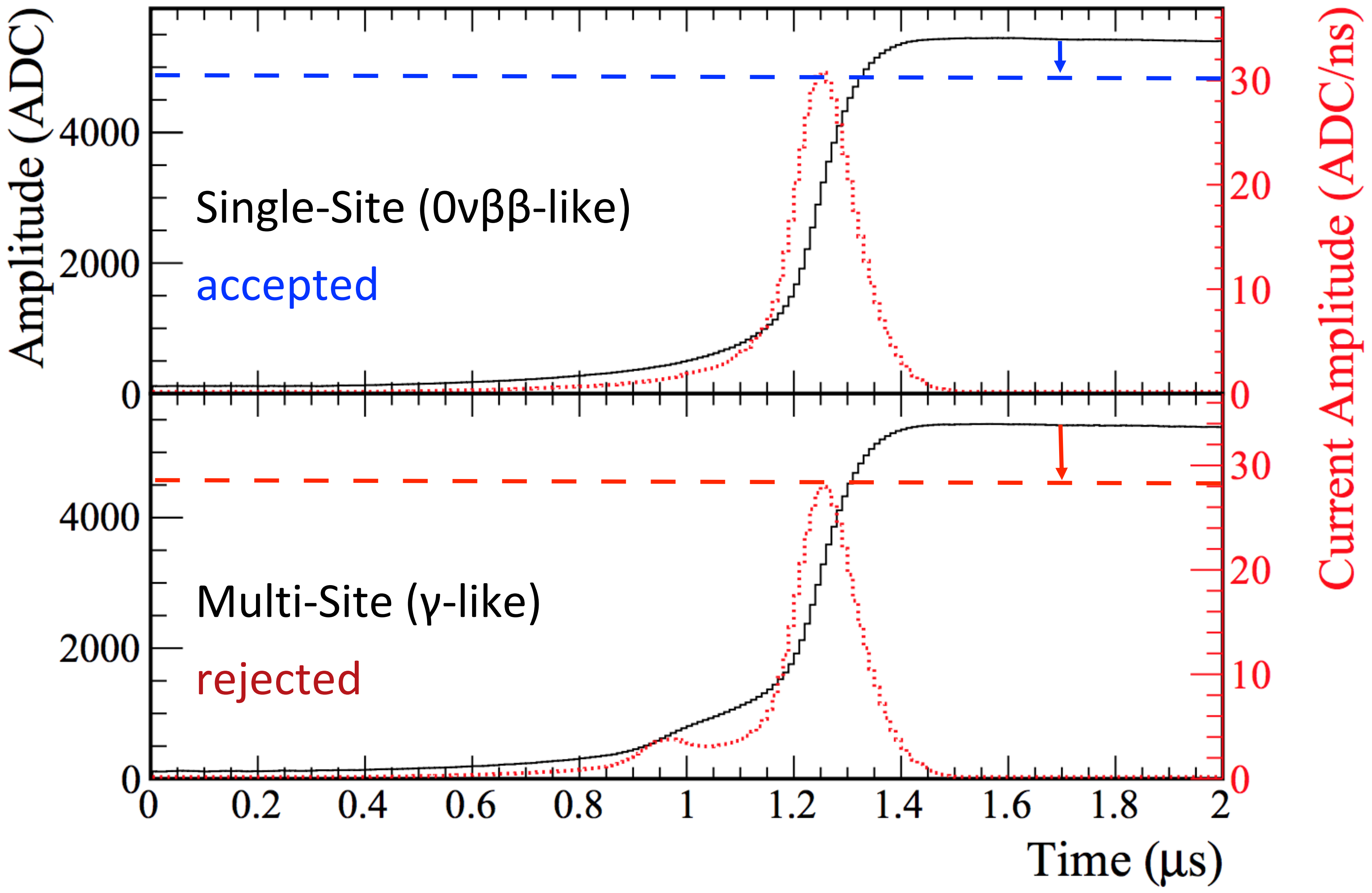
Single-site event



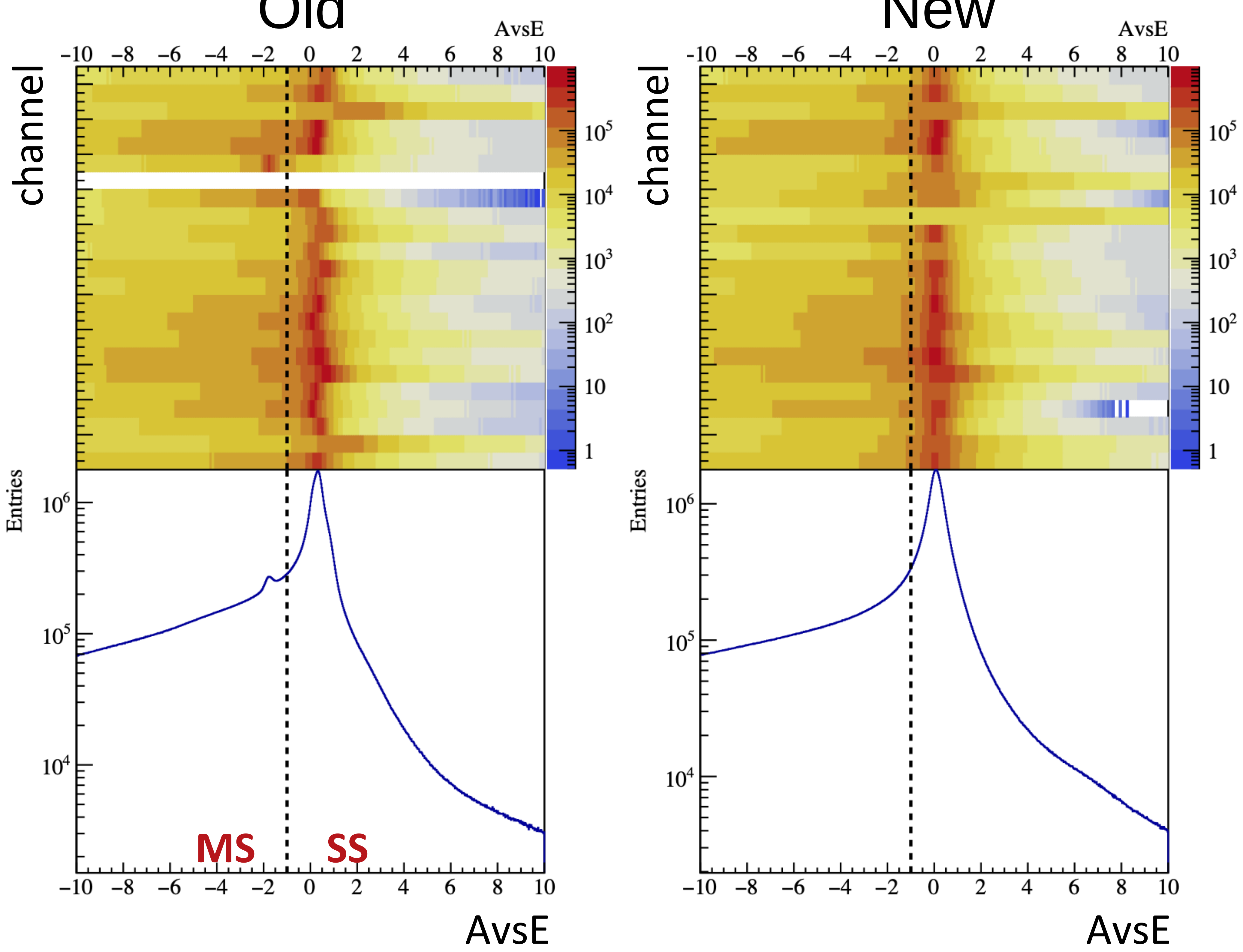
Multi-site event



PRC **99** 065501 (2019)



Measurements of the AvsE parameter, before and after analysis improvements, on calibration data



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

Tuned on ^{228}Th calibration data to accept 90% of single-site DEP events. Rejects >50% of the Compton continuum near $Q_{\beta\beta}$

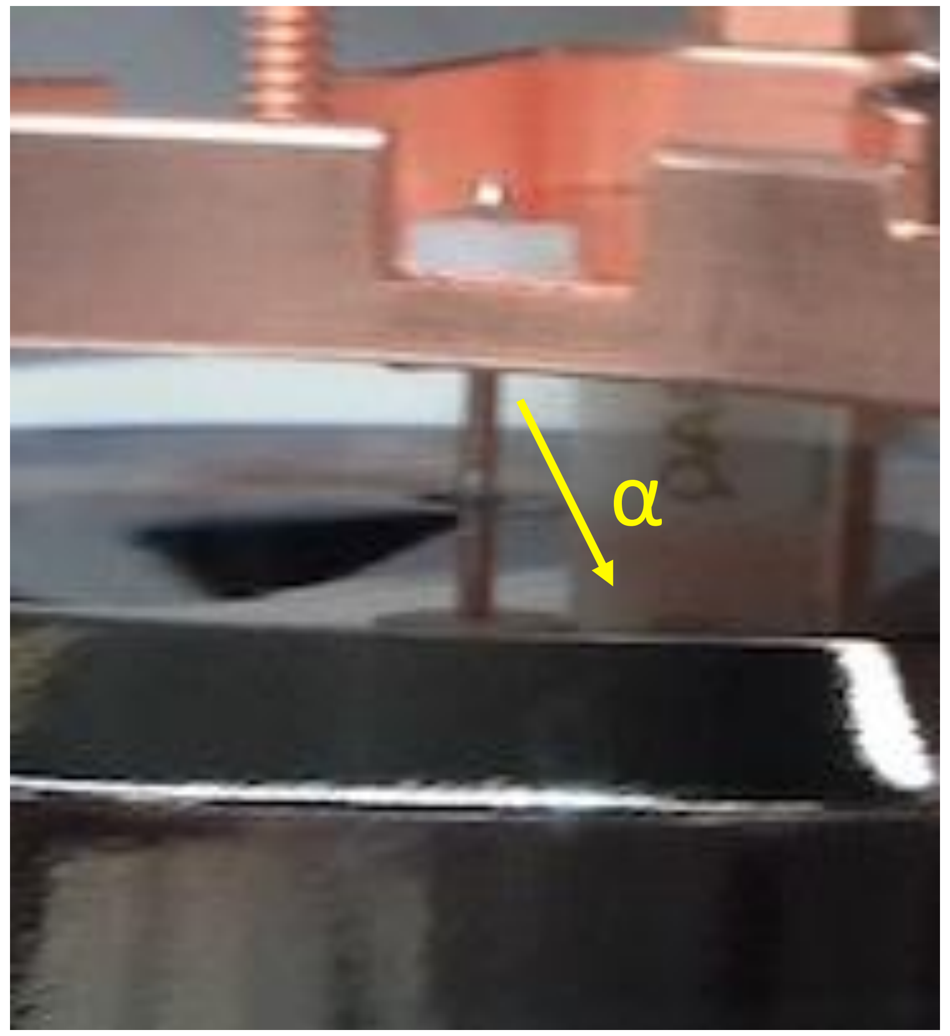
Recent improvements:

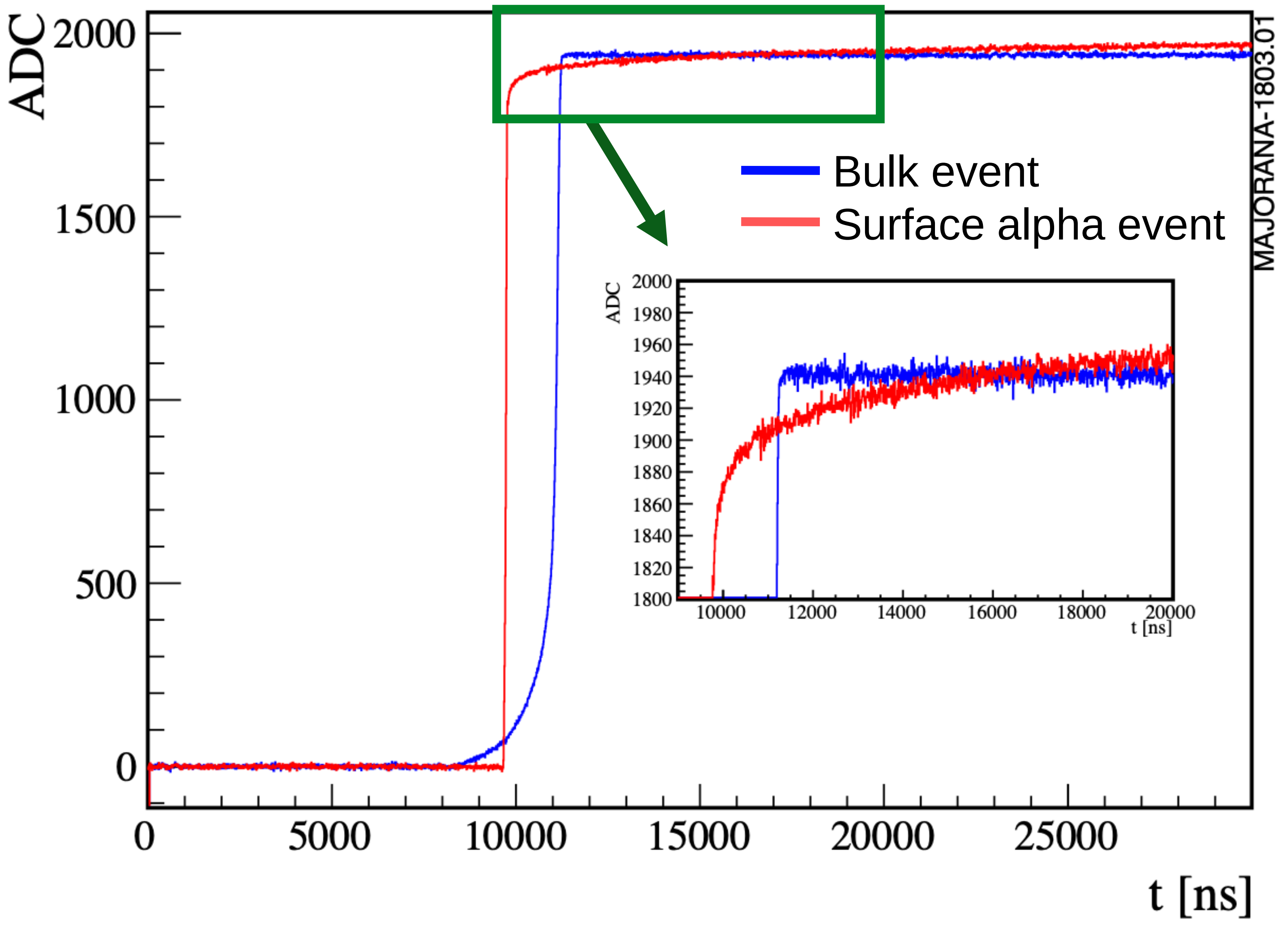
- Refined alignment of the AvsE distribution center
- Introduced a width-energy dependence correction that improves the single-site acceptance at higher energies
- Adjusted for correlations with event drift-time

The new AvsE parameter offers better stability and uniformity across all detectors, while accounting for acceptance degradation at higher energies. The result is a better multi-site discriminating parameter

Improved Surface Alpha Rejection

arXiv:2006.13179





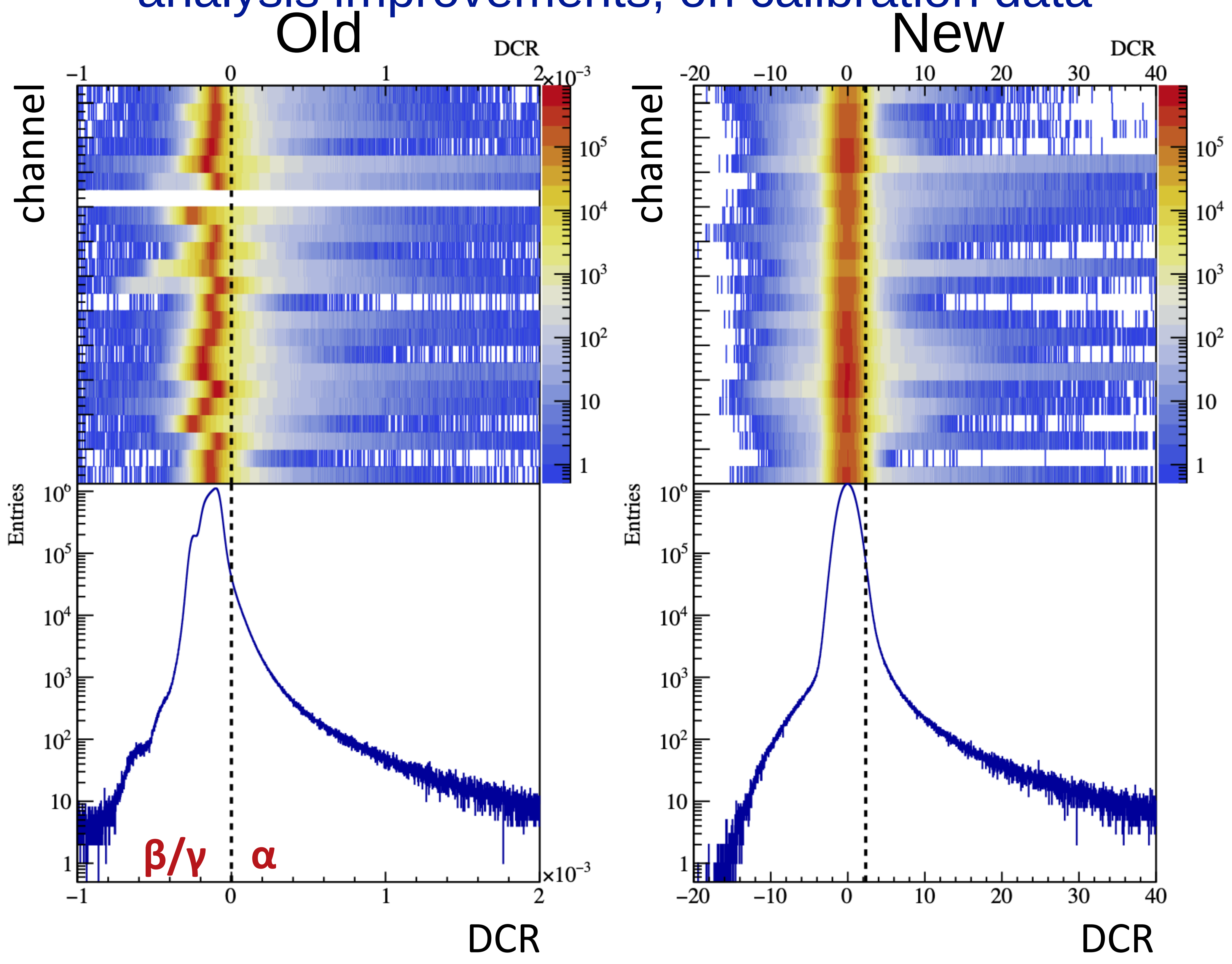
Alpha penetrating passivated surface result in trapped charge that is slowly released into bulk: delayed charge recovery (DCR) measured via slope of flat-top

Tuned on ^{228}Th calibration data to accept 99% of bulk γ events.

Recent Improvements:

- Electronics' transfer function deconvolved waveforms
- Improved alignment of mean and unit σ between channels
- Added charge trapping, or drift time, correction

Measurements of the DCR parameter, before and after analysis improvements, on calibration data



The new DCR parameter provides better stability across time and across detectors as well as increased exposure.
Better discrimination between normal bulk events and alphas is expected.

Energy Estimation

Energy resolution of 2.5 keV at 2039 keV (0.12%) is current record for 0νββ

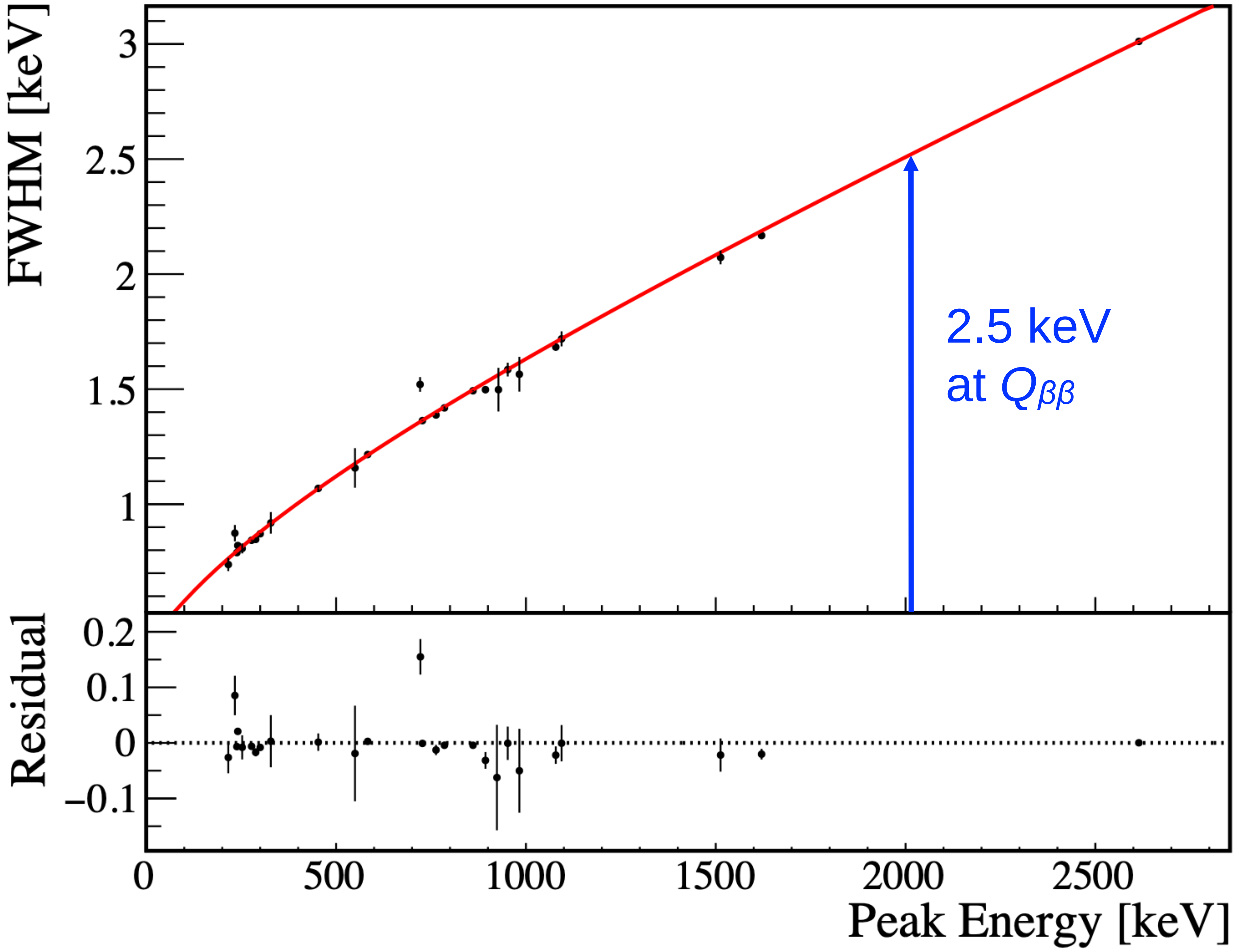
- Correct for degradation due to charge trapping by measuring drift time of charges and applying correction to the trapezoidal filter
- Correct waveform traces for ADC nonlinearity*

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

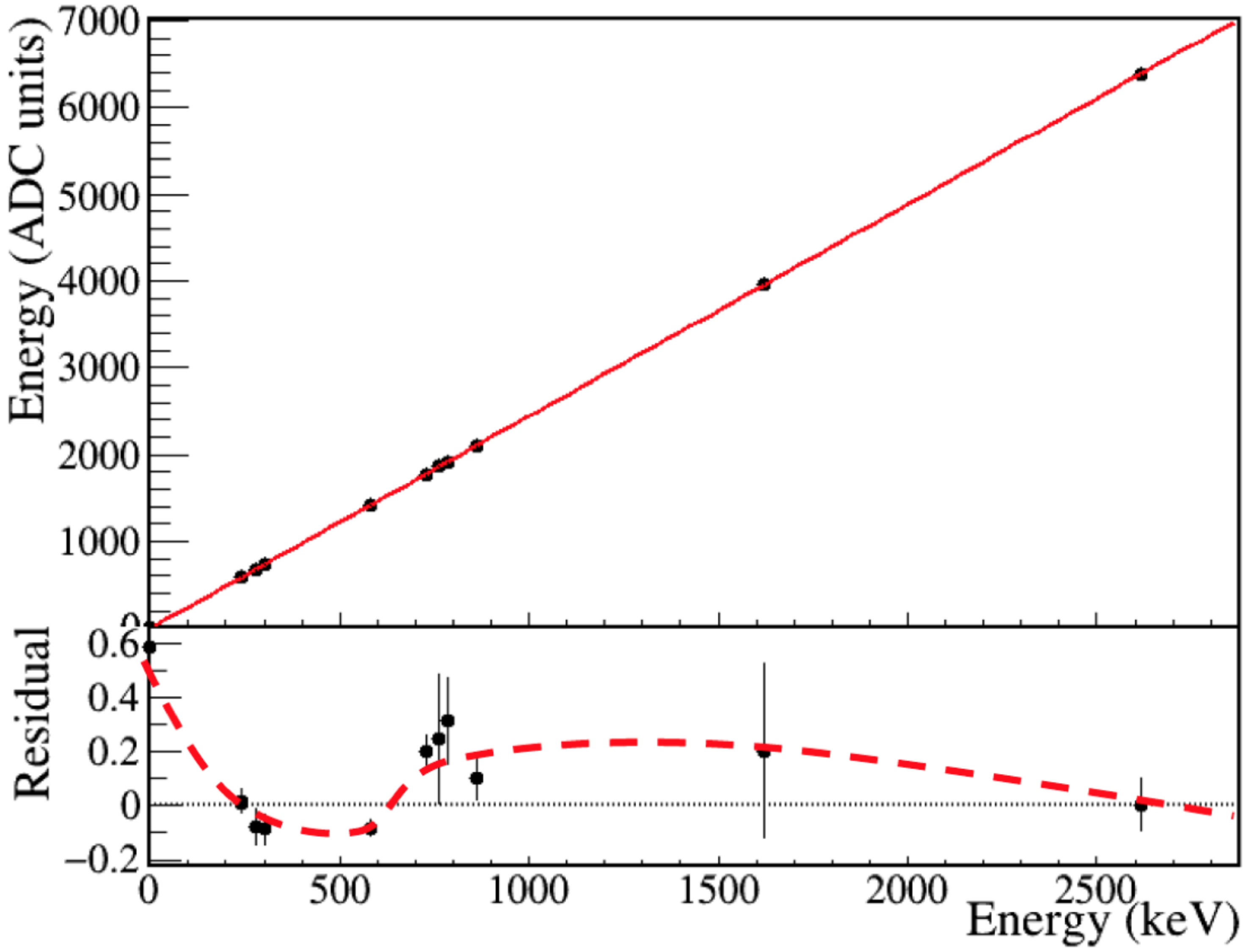
Recent improvements:

- Correct energy dependence of drift time measurement to achieve linearity for full energy spectrum

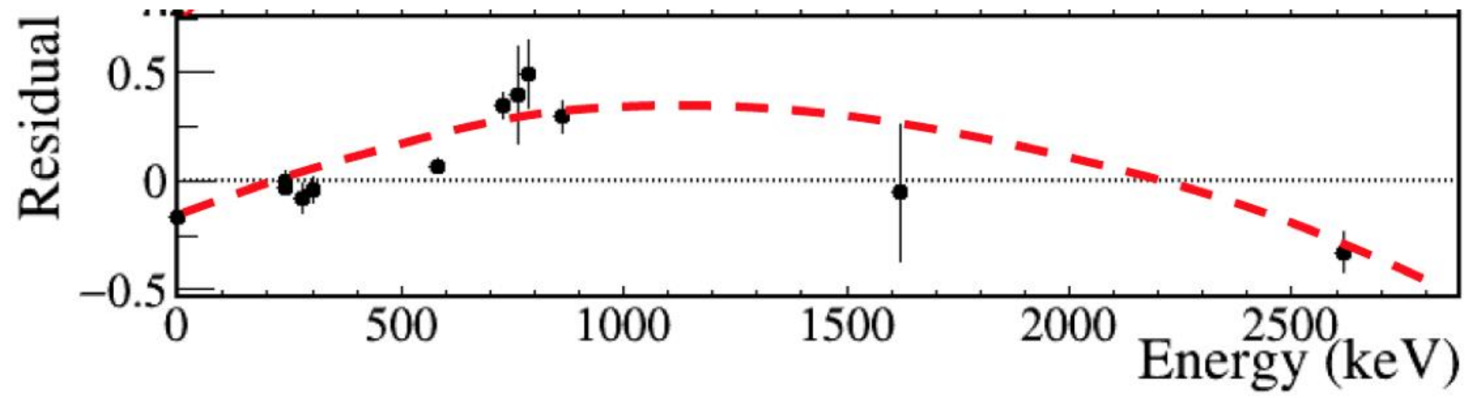
^{228}Th calibration line source is placed in tubing surrounding cryostat



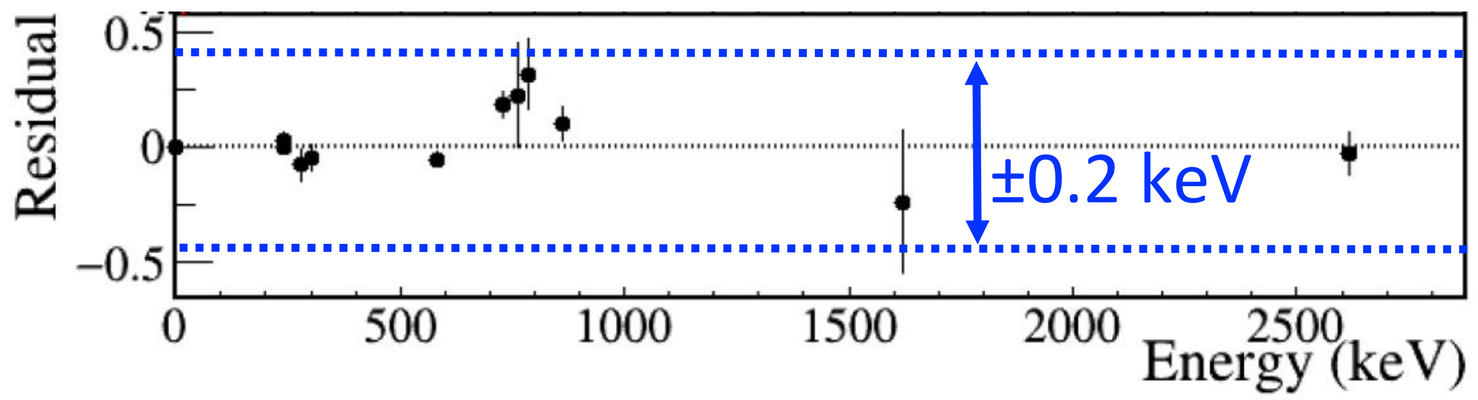
E calibration with no t_0 correction



Linear E calibration with t_0 correction



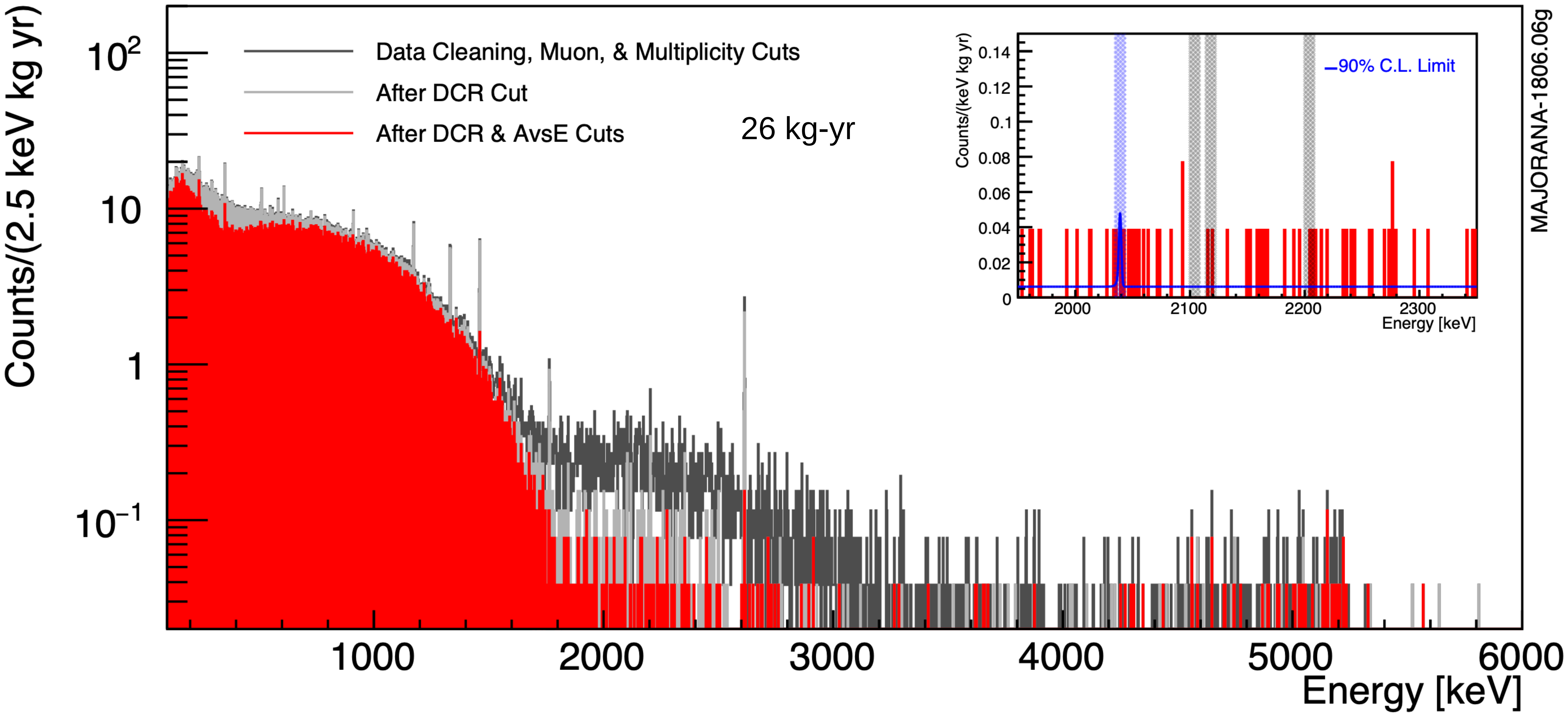
Quadratic E calibration with t_0 correction



* IEEE Trans. Nucl. Sci. (2020)
doi: 10.1109/TNS.2020.3043671

MAJORANA DEMONSTRATOR 2019 0νββ Result

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



A new result, with a combined total of ~50 kg-yr and analysis improvements, is in preparation

Initial Release:

9.95 kg-yr open data

PRL **120** 132502 (2018)

Latest Release:

First unblinding of data

26 kg-yr exposure

PRC **100** 025501 (2019)

Median $T_{1/2}$ Sensitivity:

4.8×10^{25} yr

Full Exposure Limit:

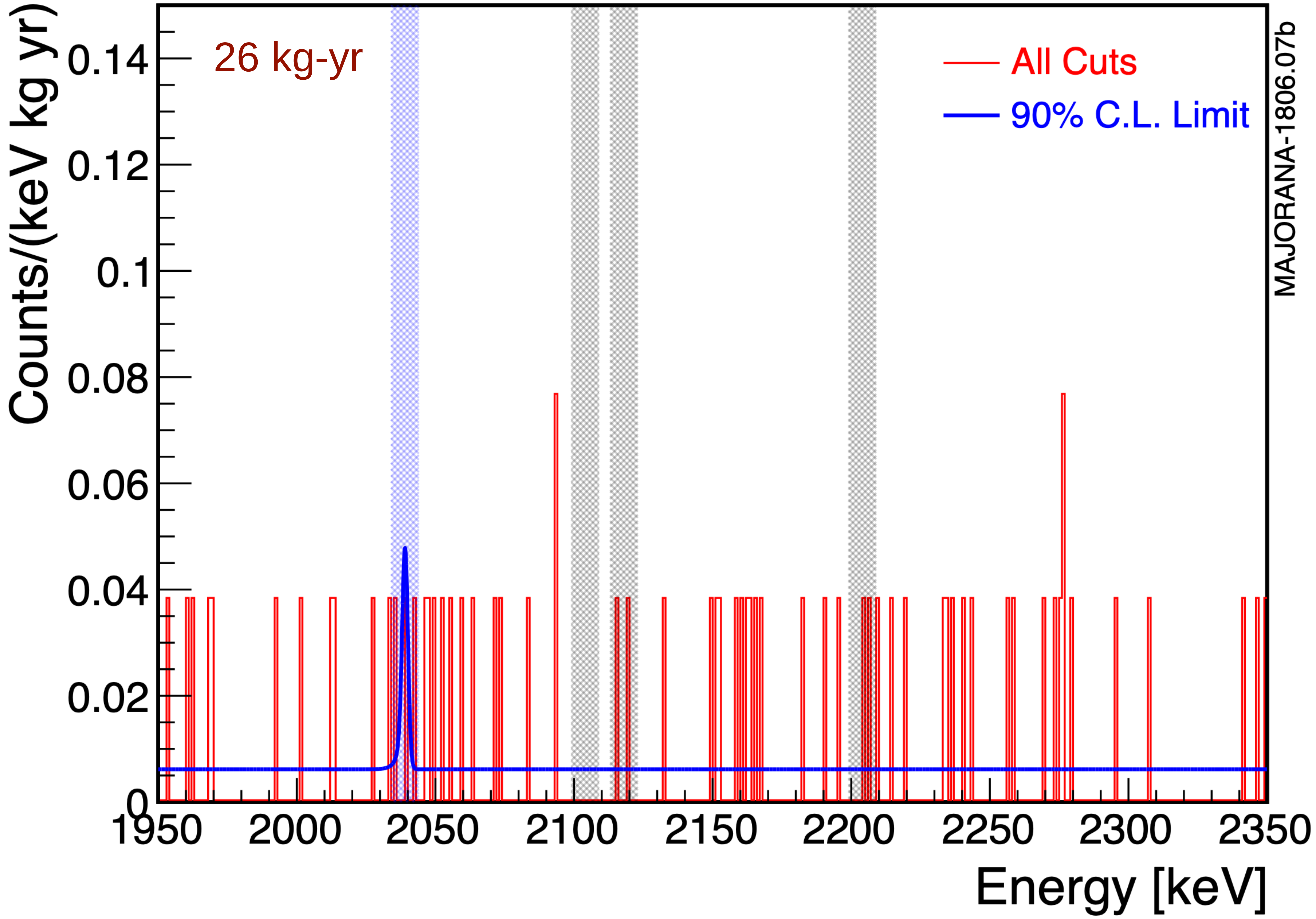
$T_{1/2} > 2.7 \times 10^{25}$ yr (90% CL)

Background Index at 2039 keV in lowest background config:

11.9 ± 2.0 cts/(FWHM t yr)

MAJORANA DEMONSTRATOR 2019 $0\nu\beta\beta$ Result

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



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Background Index at 2039 keV in lowest background config:

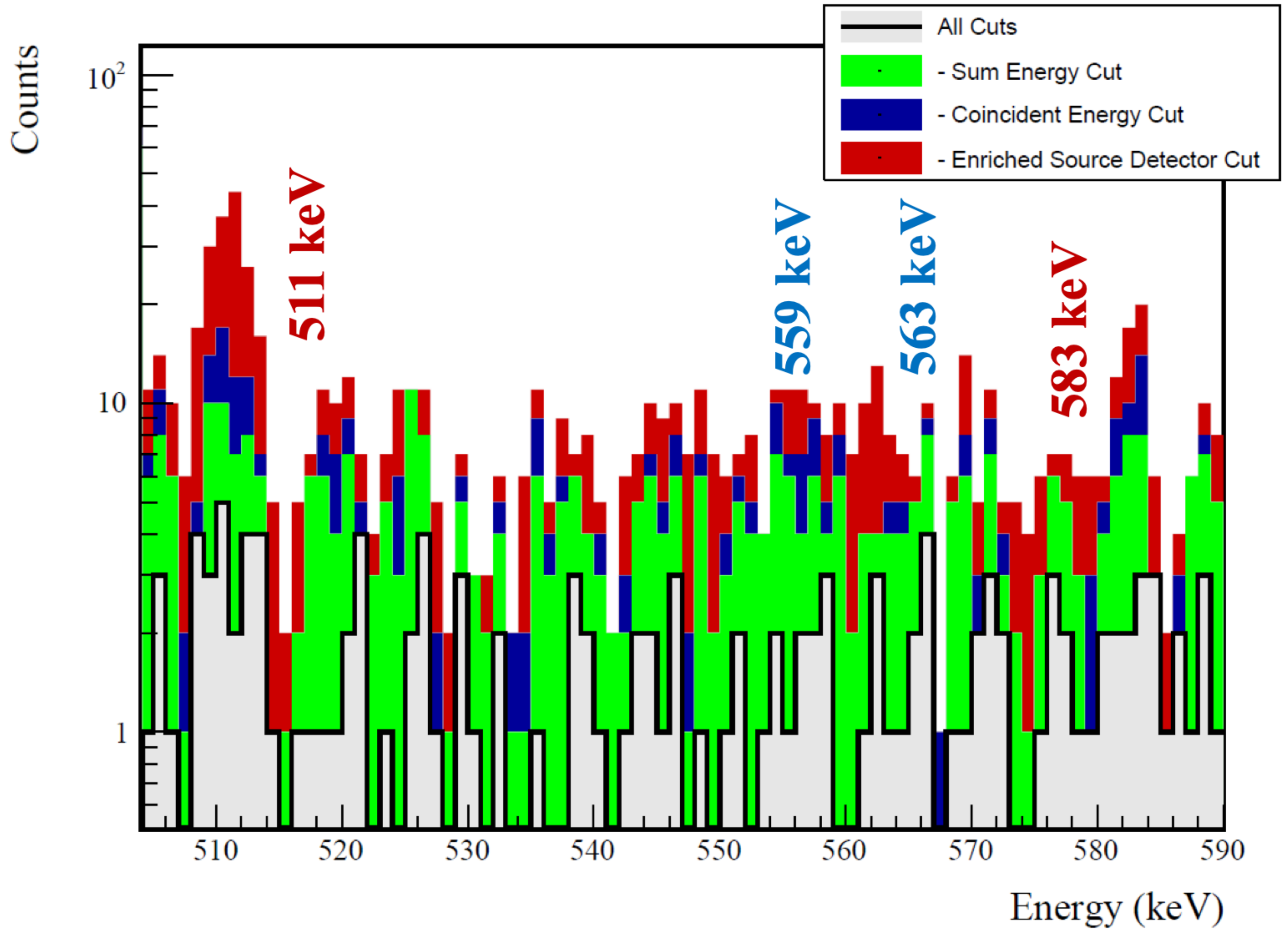
11.9 ± 2.0 cts/(FWHM t yr)

New Result: Double Beta Decay to Excited States

An inherently multi-site signal topology:

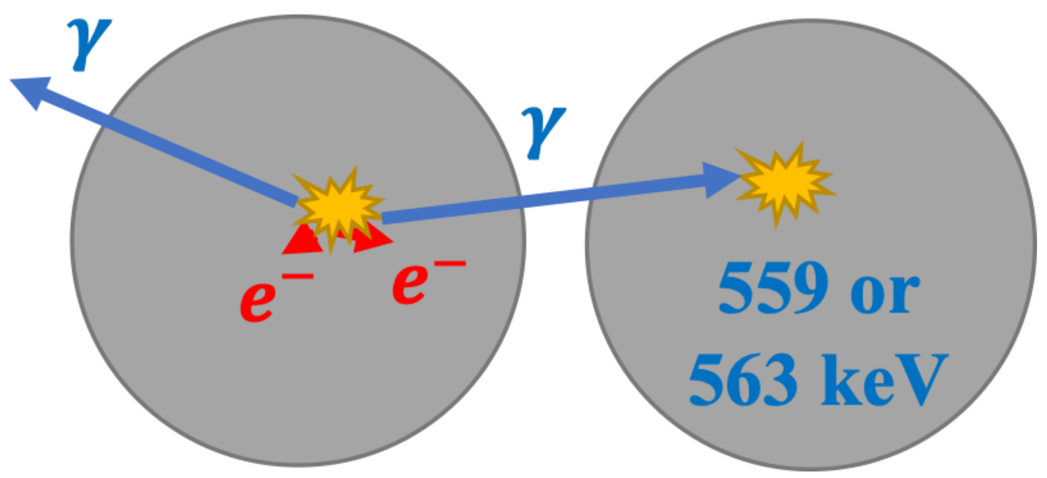
- A “source” detector will have a broad energy spectrum from ββ
- The “gamma” detector will measure energy peaked at the γ energies

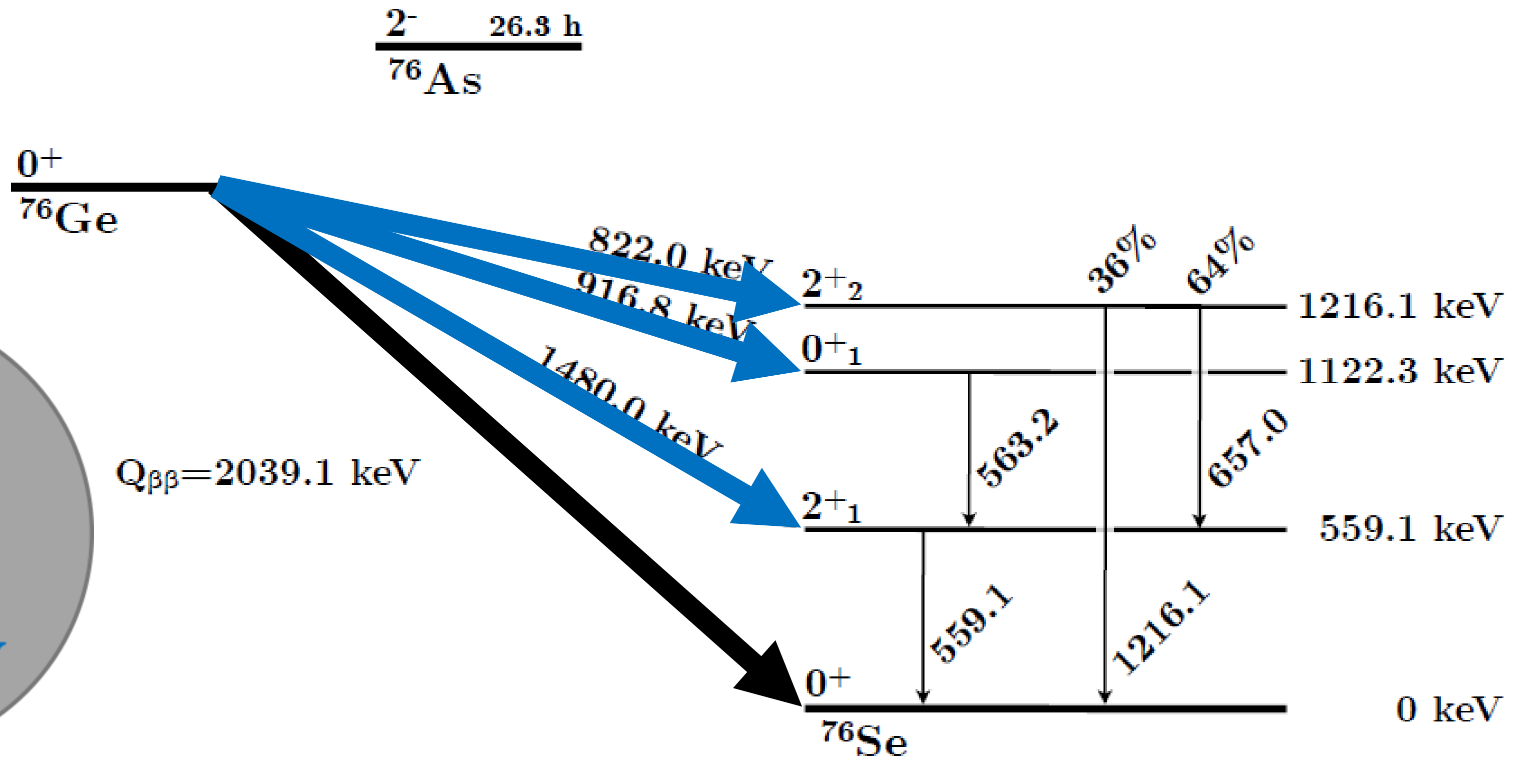
41.9 kg y of isotopic exposure
(20.6 kg y of which was blinded)



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

The most stringent limits to date for ββ to each excited state of ^{76}Se

For 2νββ to the 0^+_1 state, half-life predictions from several nuclear models have been ruled out. With additional exposure and analysis improvements, we can test more models

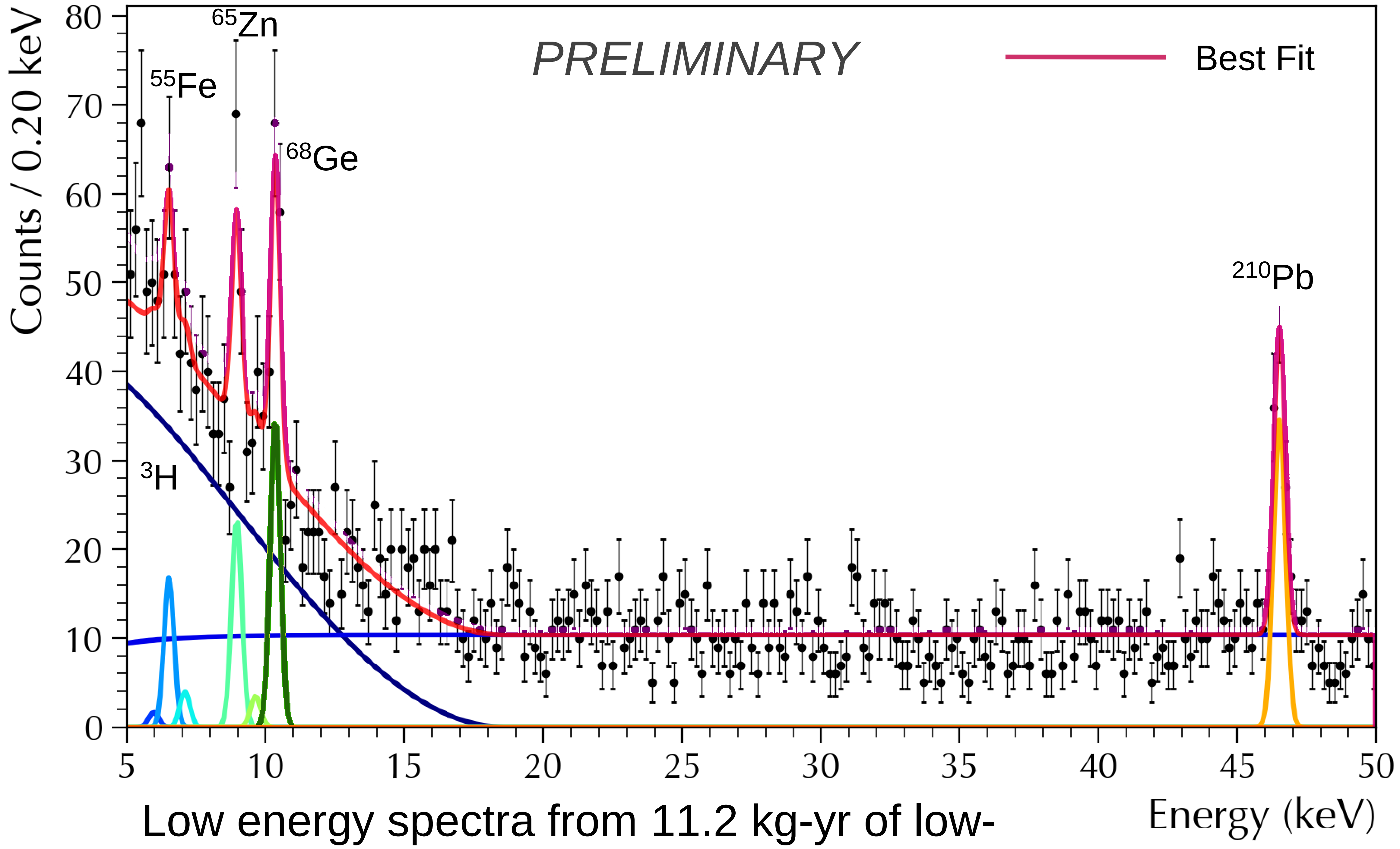
Beyond the Standard Model Searches

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

- Controlled surface exposure of enriched material to minimize cosmogenics

Excellent energy resolution: ~0.4 keV FWHM at 10.4 keV

- Progress towards a low-E background model
- Applying a dynamic threshold calculation to lower the analysis threshold to 1 keV



Low energy spectra from 11.2 kg-yr of low-background open physics running (DS1-6a)

Upcoming updates to beyond the standard model searches

Low-energy physics searches

- pseudoscalar dark matter
- vector dark matter,
- 14.4-keV solar axion

PRL **118** 161801 (2017)

Updated limits to be released after unblinding

J. Phys. Conf. Ser. 1468, 012040 (2020)

Search for tri-nuclean decay

- A test of baryon number violation

PRD **99** 072004 (2019)

Lightly ionizing particles

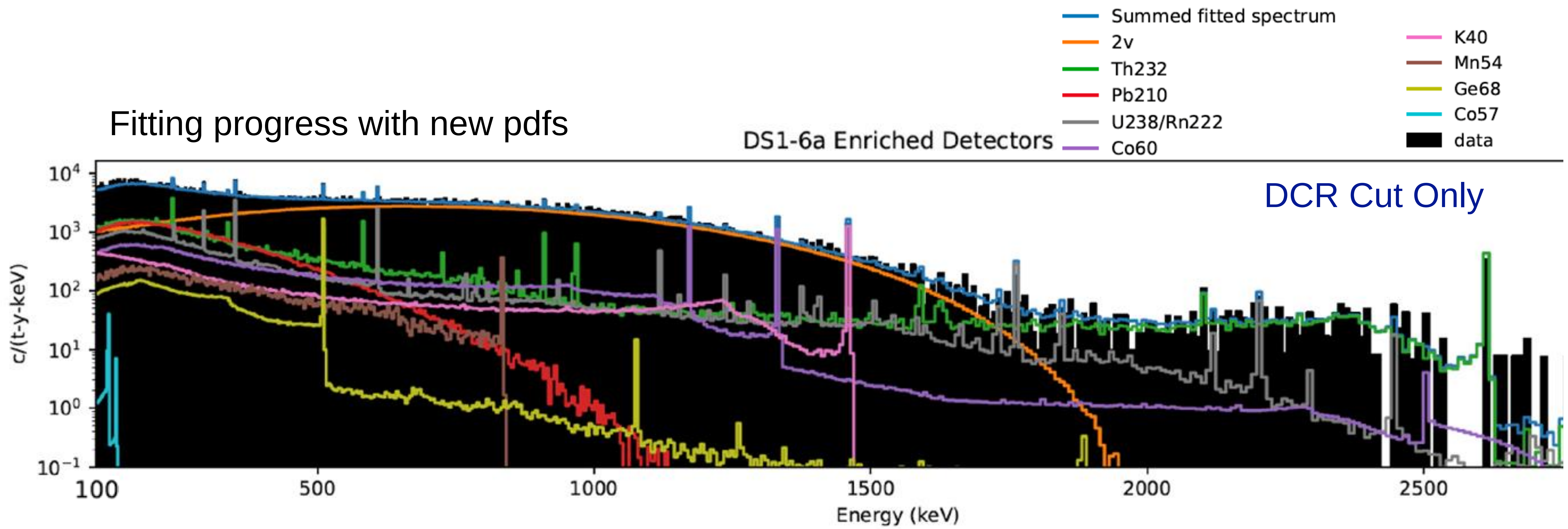
- First limit for charge as low as *e*/1000

PRL **120** 211804 (2018)

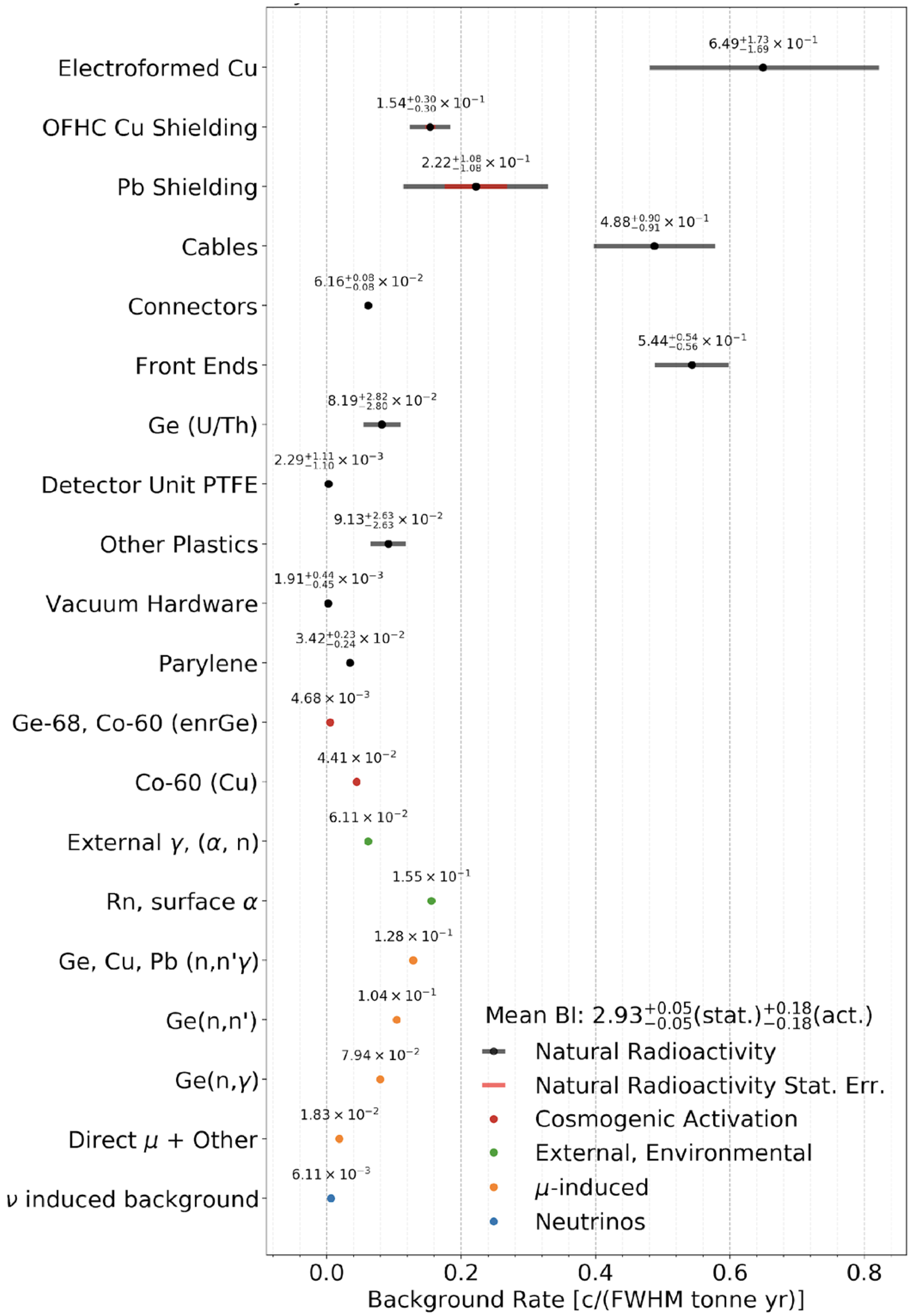
Improvements to Background Modeling

- Reviewing new assay information, as-built geometry and simulations, detector configurations, and updated physics lists
  - Projected Background Index increased from 2.2 to 2.9 cts/FWHM-t-y but continues to under-predict observed background 11.9 cts/(FWHM t yr)
- New techniques have been used to quantify uncertainties in our assay-based background model
- New high statistic simulations allow for modeling of regions with low efficiency
- Improved Frequentist and Bayesian fitting efforts underway in order to more precisely locate source of excess Th background
  - Components grouped by location (e.g. “far vs. near”) and separated by module

Fitting progress with new pdfs



As-Built Assay-Based Background Model



Detector Upgrade and Future Plans

Installed new cables & connectors to improve overall robustness

Improved cable bundling and increased cross-arm shielding

Removed 5 p-type point contact (PPC) ^{enr}Ge detectors for early LEGEND-200 tests in LAr at LNGS

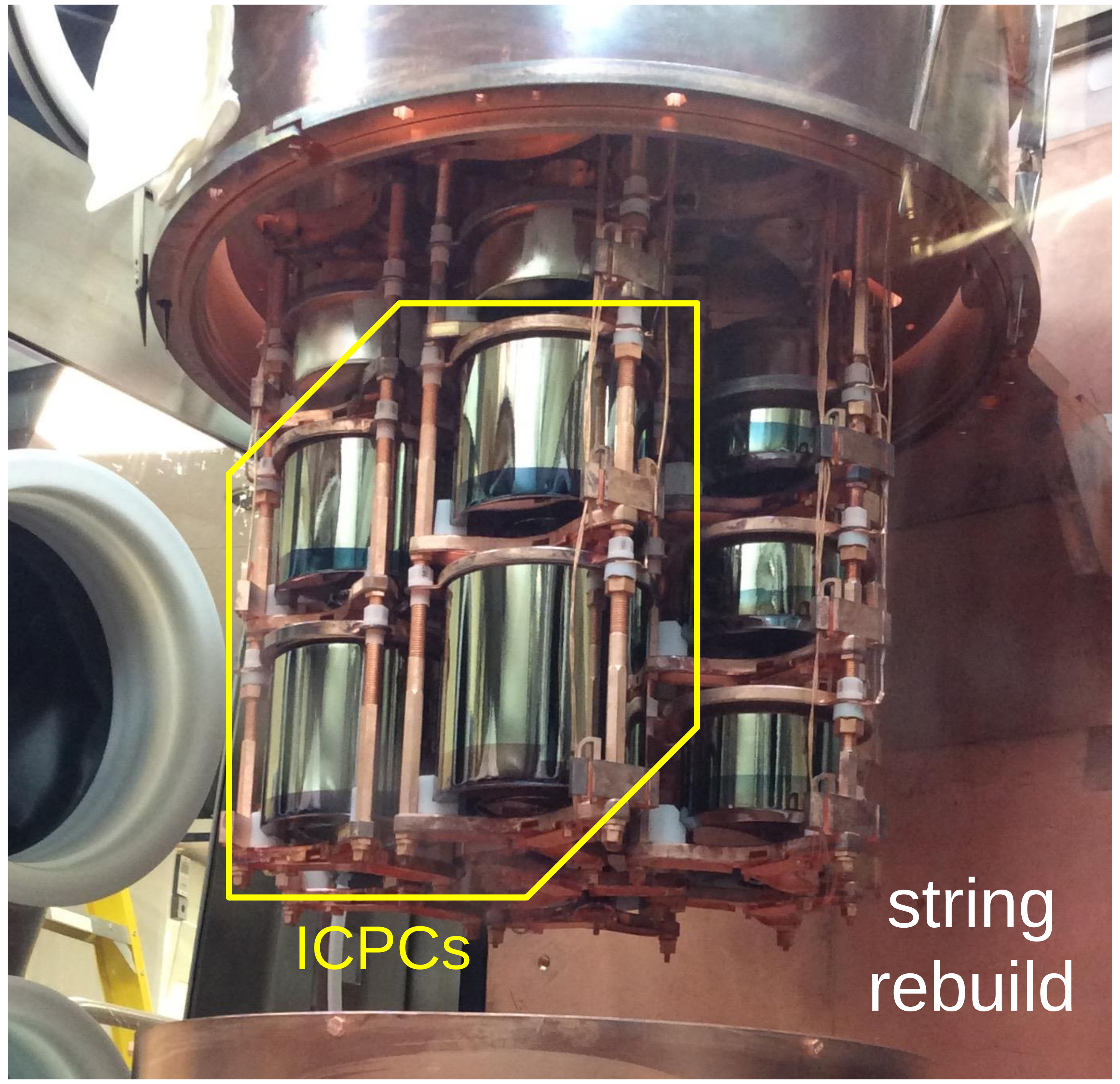
Installed 4 ORTEC inverted-coaxial point-contact (ICPC) ^{enr}Ge detectors for low background vacuum testing in advance of LEGEND-200

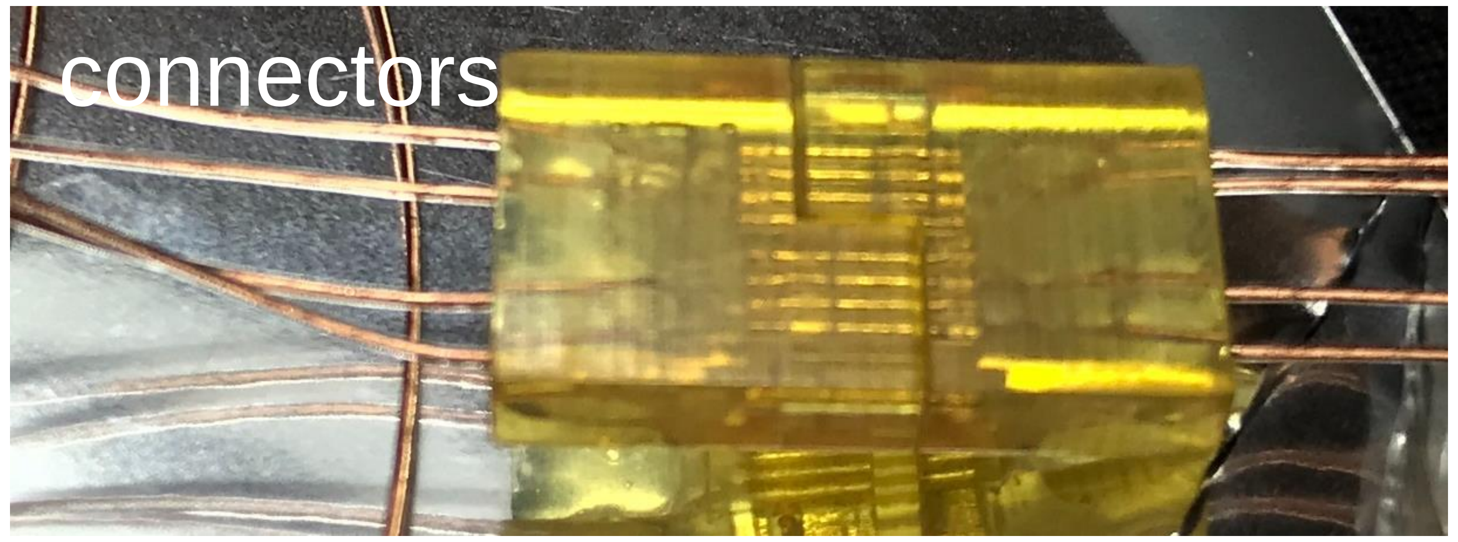
	Before Upgrade	After Upgrade
Working signal conn.	24/29 (82%)	27/27 (100%)
Reliable HV conn.	19/24 (79%)	27/27 (100%)
Operational	18/29 (62%)* *Used for final analysis	27/27 (100%)** **Final selection not yet made

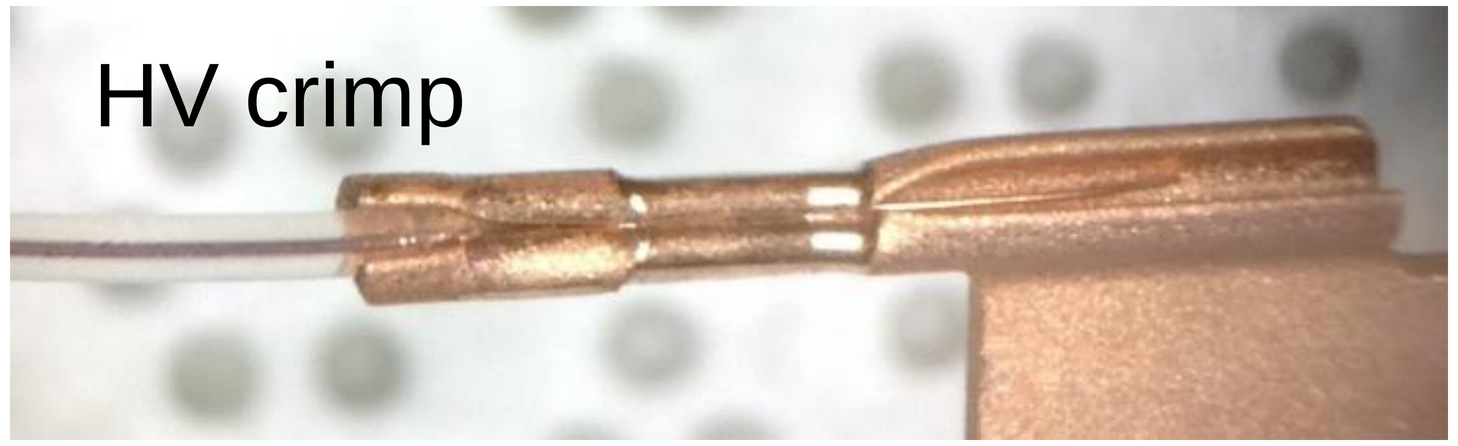
Run through Feb. 2021 to measure performance; ship all enriched detectors to LNGS for installation in LEGEND-200

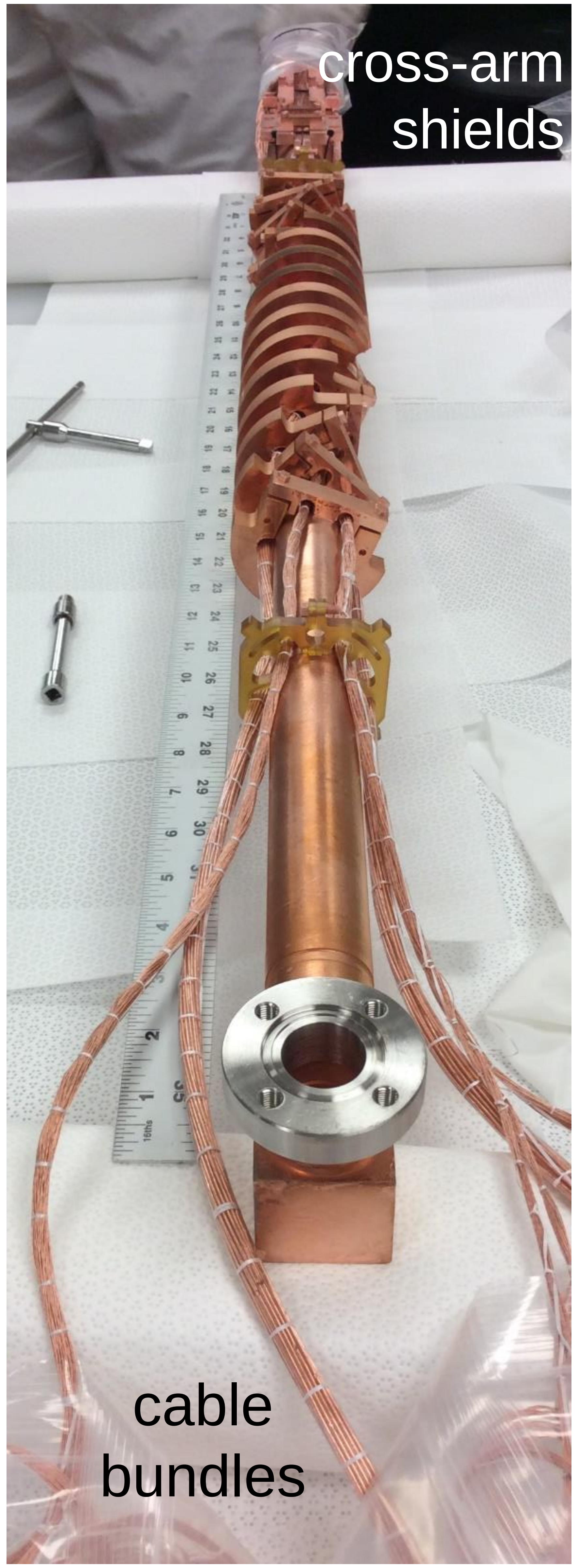
Ultimate integrated exposure: >65 kg y (^{enr}Ge)

Continue background studies with natural detectors









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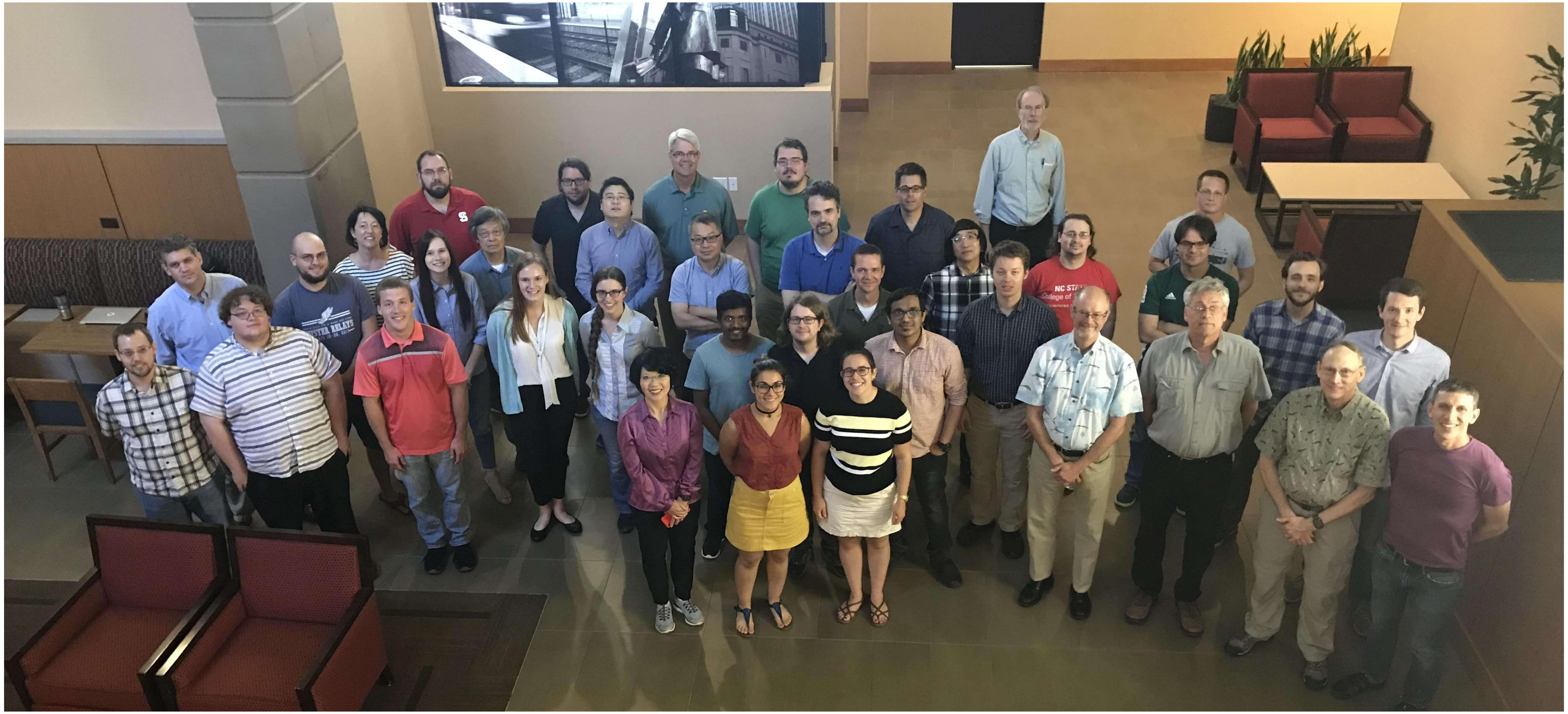
The MAJORANA Collaboration



Duke University · IU · Institute for Nuclear Research · Berkeley Lab · Los Alamos National Laboratory · Max-Planck-Gesellschaft · ITEP · NC State University · Oak Ridge National Laboratory · Osaka University · Pacific Northwest National Laboratory · Queen's University

South Dakota Mines · Technische Universität München · Tennessee Tech · TUNL · The University of North Carolina at Chapel Hill · University of South Carolina · University of South Dakota · The University of Tennessee Knoxville · W · Williams

MAJORANA DEMONSTRATOR Summary and Outlook

Started taking data with first module in 2015 and has been operating with both modules since 2016

- Latest limit from 26 kg-yr exposure: >2.7 x 10^{25} yr (90% C.L.); sensitivity 4.8 x 10^{25} yr (90% C.L.)
- Excellent energy resolution of 2.5 keV FWHM @ 2039 keV, best of all $0\nu\beta\beta$ experiments

PRC **100** 025501 (2019)

Background model being investigated and refined

- Initial background fits are informing possible distribution of background sources
- Goal of a full background model consistent with the data - inform design of next generation experiments

Optimization of analysis cuts is being finalized to improve background rejection

- New results to be released this Fall with ~ 50 kg-yr exposure

Low background + low threshold + energy resolution allows for broad physics program

PRL **118** 161801 (2017) | PRL **120** 211804 (2018) | PRD **99** 072004 (2019)

Completed an upgrade to cables and connectors, including deployment of new ICPC detectors, as part of LEGEND R&D

Expect to reach ~65 kg-yr exposure with sensitivity in the range of 10^{26} yr half-life before removal of enriched detectors for redeployment in LEGEND-200

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.

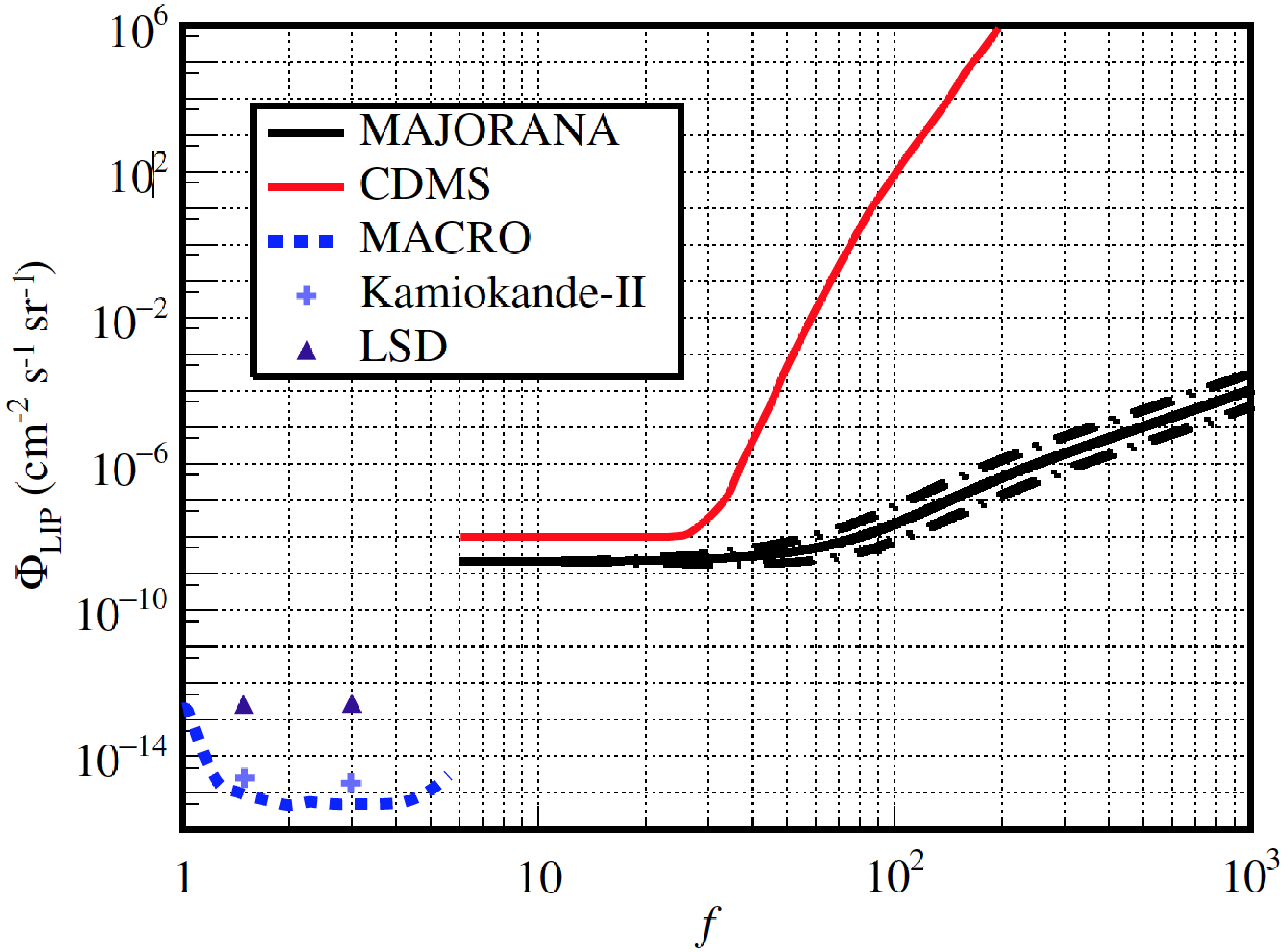
Backup Slides

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

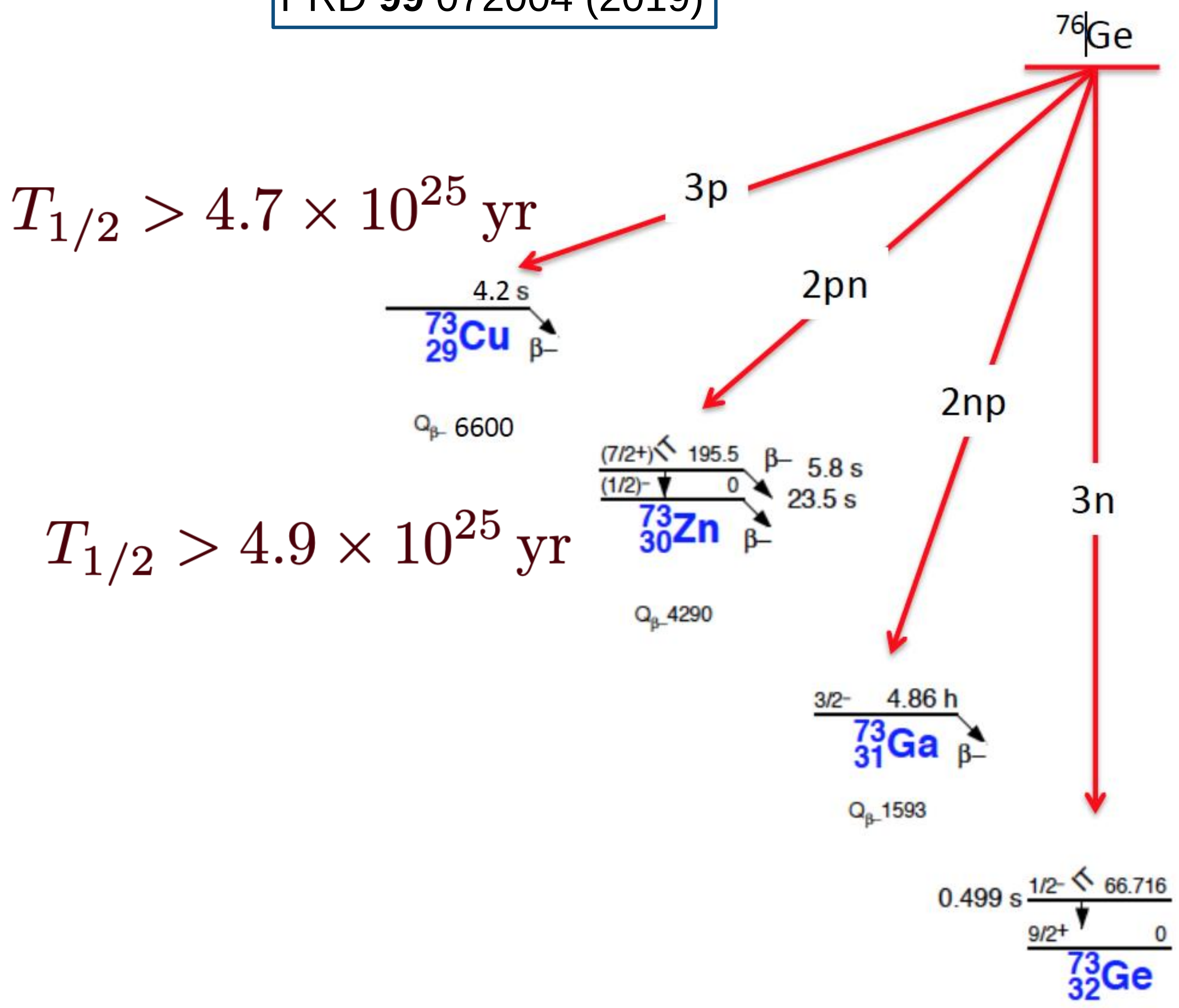
PRL **120** 211804 (2018)



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)



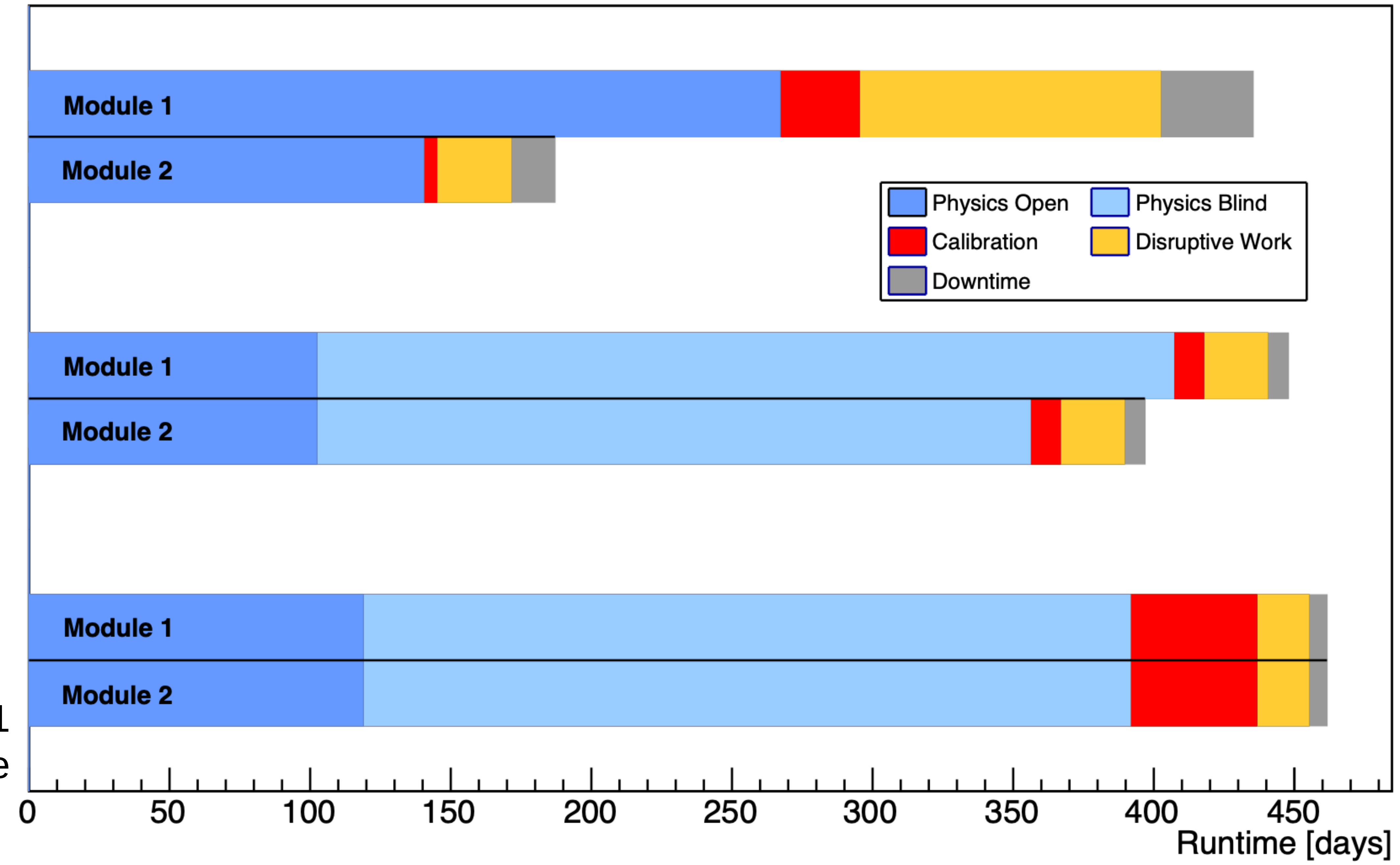
The 90% UL for two tri-nucleon decay-specific modes

Runtime and Exposure

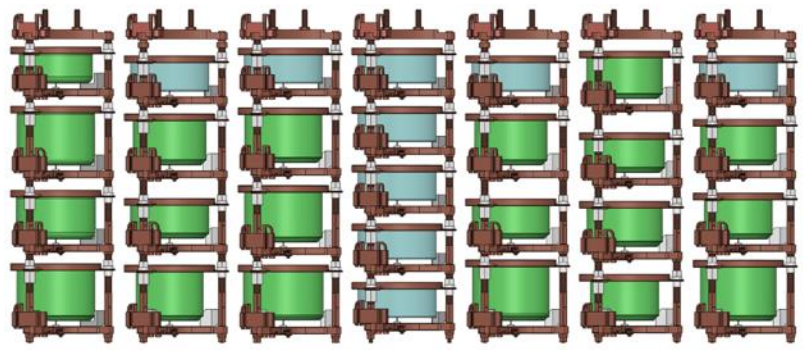
Open data: Jun. 2015 - Mar. 2017
9.95 kg-yr

All blind data: Jan. 2016 - Apr. 2018
New Open Data: Mar. 2017 - Apr. 2018
+16.1 kg-yr

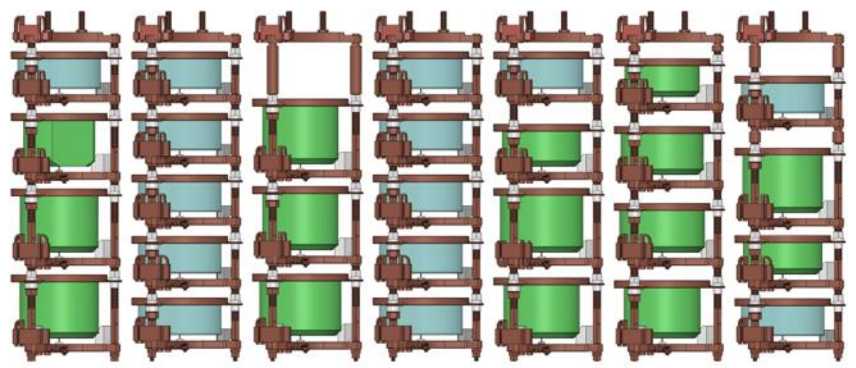
New Data: April 2018 - Nov. 2019*
*Continuing to operate Module 1 during Module 2 upgrade



Jun. 2015 - Module 1: 16.9 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge



Aug. 2016 - Module 2: 12.9 kg (15) ^{enr}Ge
8.8 kg (14) ^{nat}Ge



2017 Release

9.95 kg-yr open data

PRL **120** 132502 (2018)

2018 Release

26 kg-yr open+blind

PRC **100** 025501 (2019)

Runtime and Exposure

Open data: Jun. 2015 - Mar. 2017

PRL **120** 132502 (2018)

9.95 kg-yr

All blind data: Jan. 2016 - Apr. 2018

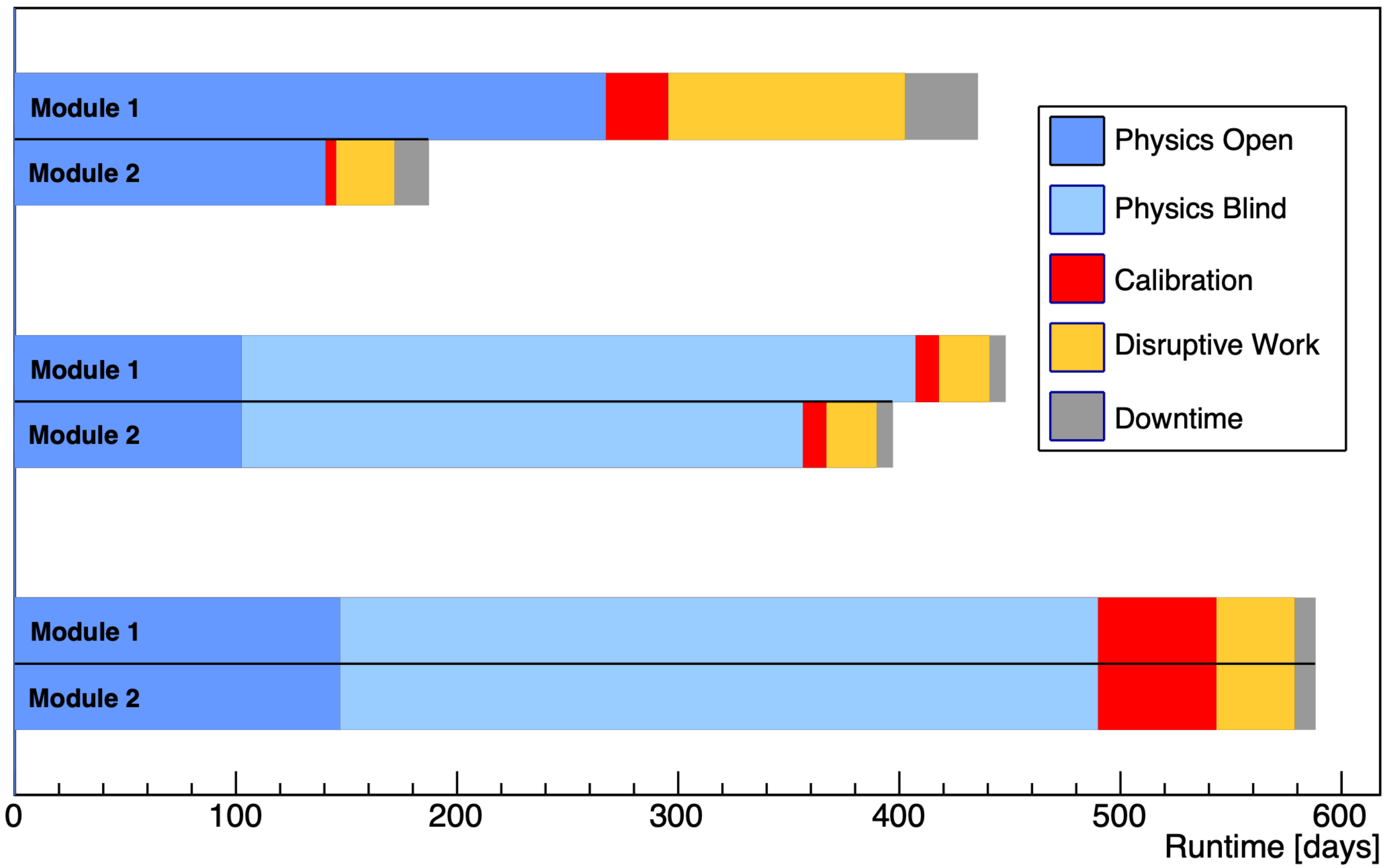
New Open Data: Mar. 2017 - Apr. 2018

PRC **100** 025501 (2019)

+16.1 kg-yr

New Data: April 2018 - Nov. 2019*

*Continuing to operate Module 1 during Module 2 upgrade



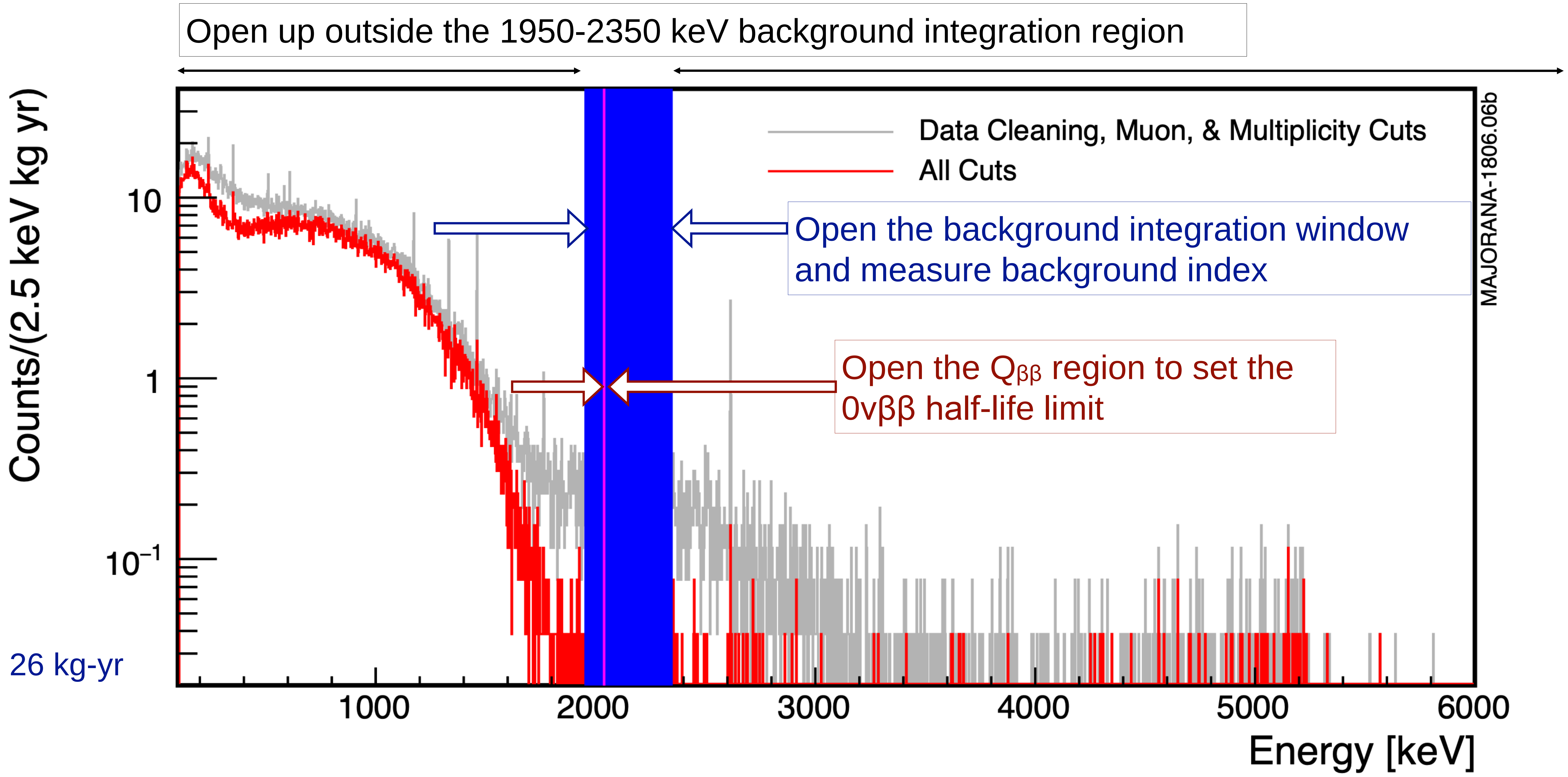
Blindness Implementation

Data is split for statistical blindness, analysis cuts developed on open data

- Each 31 hours of open data is followed by 93 hours of completely blind data

Unblinding in phases to perform data quality and consistency checks

(<100 keV and multiple-detector events remain blind for other studies)



360 keV Background Integration Window

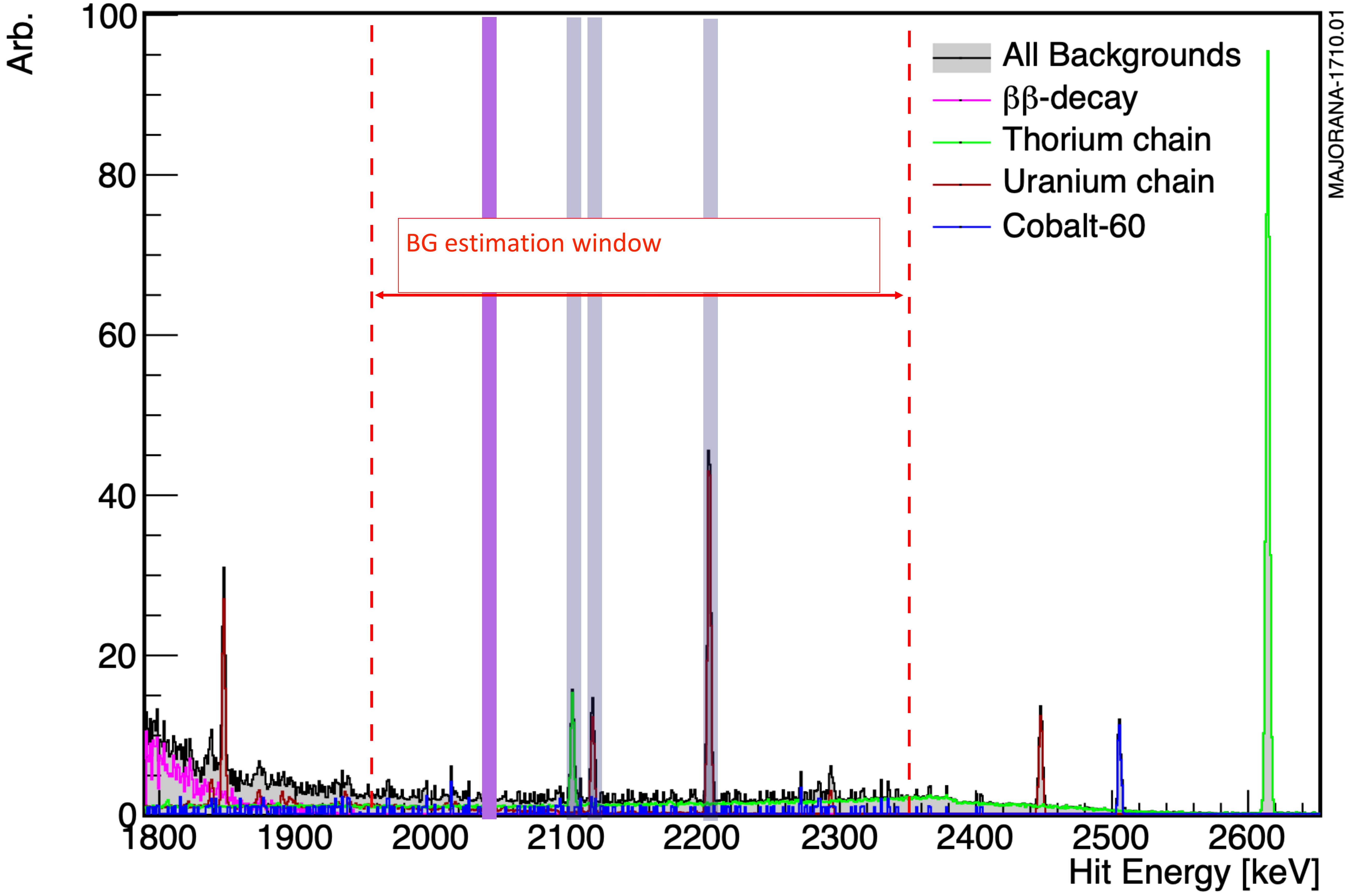
Simulated background PDFs, relative scaling based on assay results

Flat between 1950 keV and 2350 keV

- Remove ±5 keV around $Q_{\beta\beta}$ and prominent γ lines

Use counts in this window to estimate background level at Qββ

Simulated Background near $Q_{\beta\beta}$ (no cuts)



Exclude:
2099 - 2109 keV
2113 - 2123 keV
2199 - 2209 keV

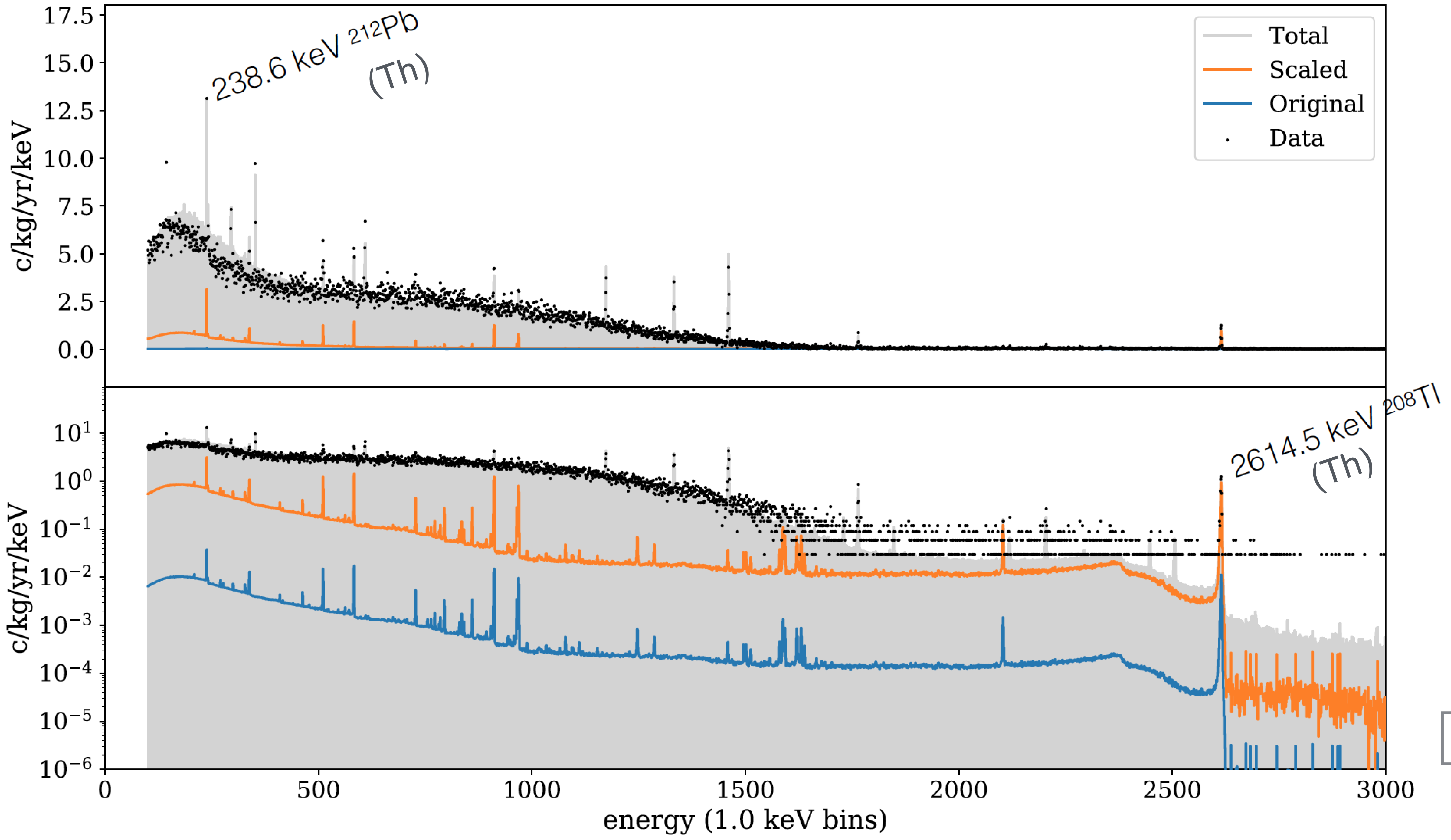
2034 - 2044 keV
$Q_{\beta\beta}$ = 2039 keV

Background Model Development: An example

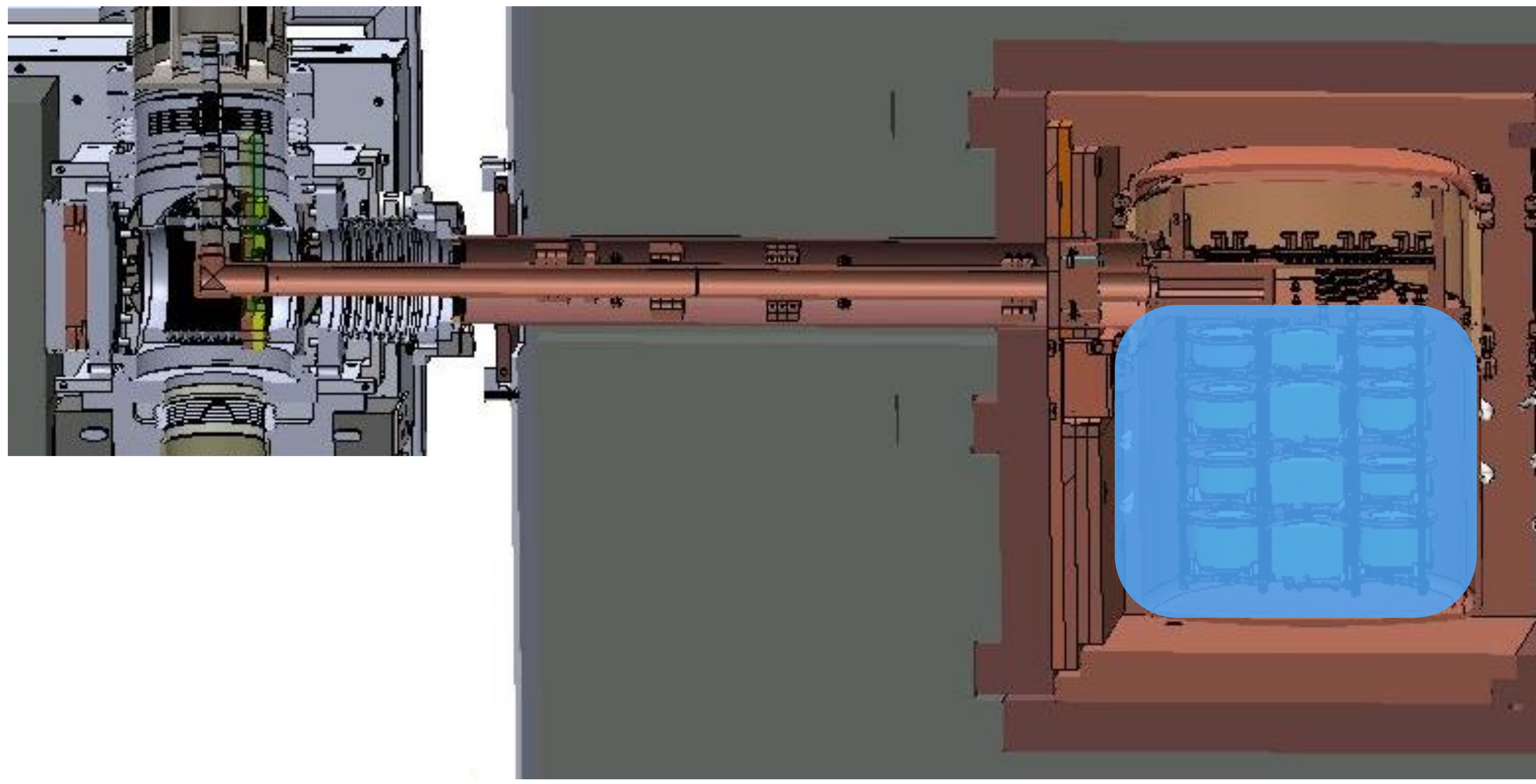
Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components

Based on the energy dependence of the relative peak intensities

A scaling of a distant component matches both the 239-keV and 2615-keV peak intensities from the ^{232}Th chain



Distant ≈ Outside of the Ge-detector array



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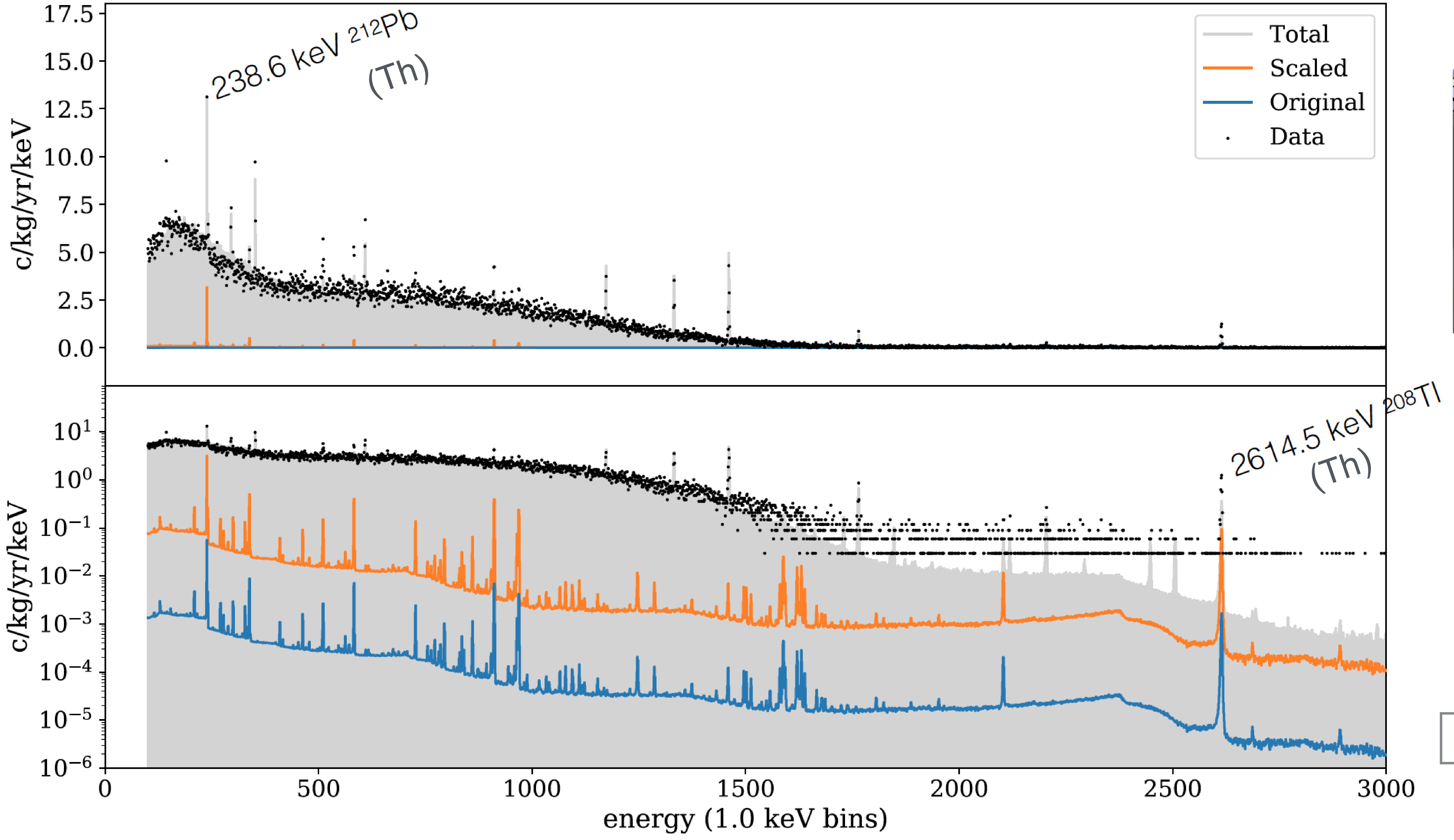
Background Model Development: An example

Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components

Based on the energy dependence of the relative peak intensities

A scaling of a nearby component scaled to the 239-keV peak underestimates the 2615-keV peak intensity from the ^{232}Th chain



Nearby ≈ Within of the Ge-detector array

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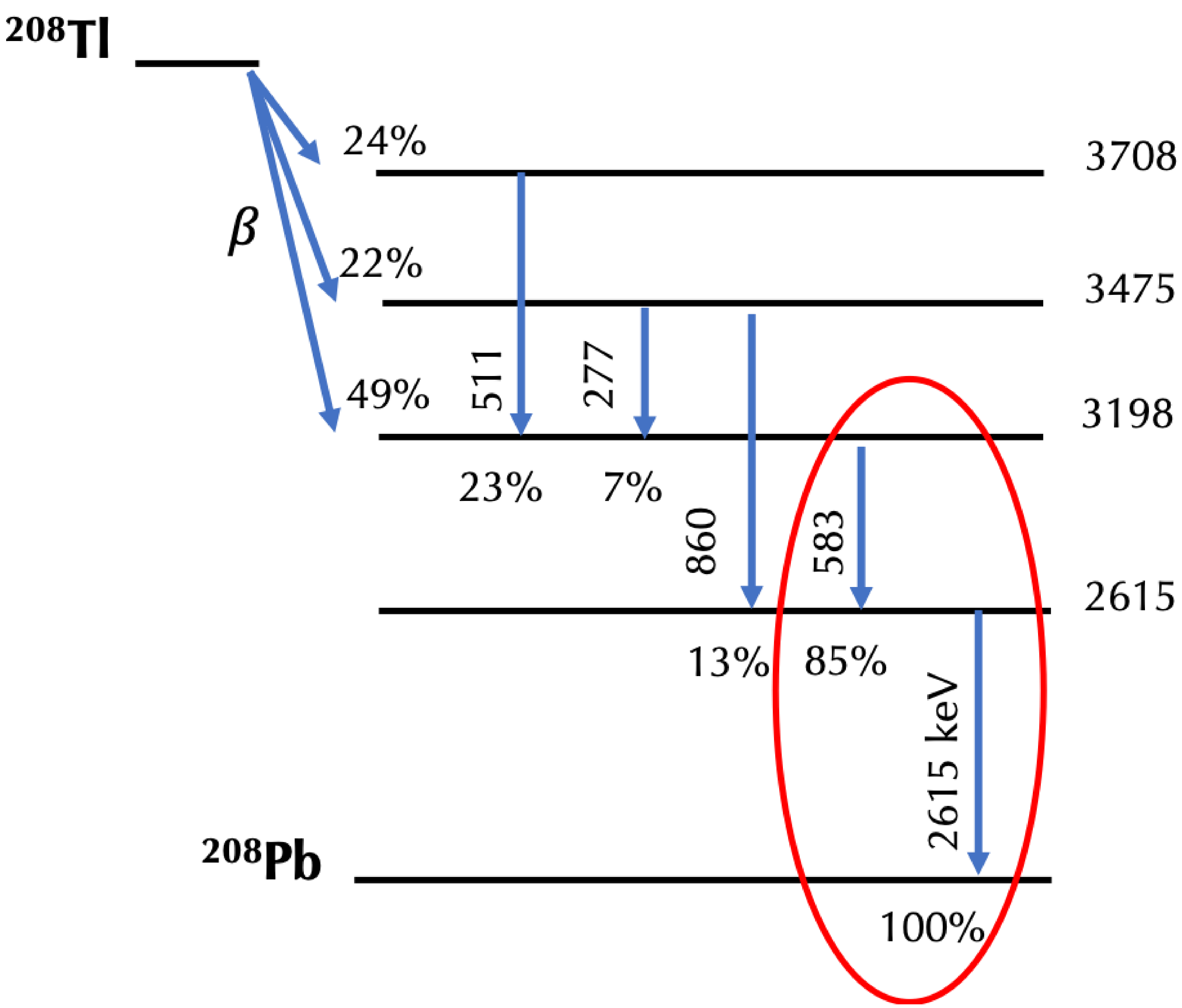
Coincident Event Studies



Search for events with energy deposits in two detectors with a combined energy of 3198 keV

Rate depends on distance between ^{208}Tl source and detectors

- Energy-dependent gamma attenuation in materials
- Solid angle subtended by detector array

1 event found in almost 20 kg-yr (Enr+Nat) open data

- Event came from commissioning period

Ratio of 3198 keV sum events to 2615 sum events compared between data and background model simulation

- Data: 0.03
- Simulations with ^{208}Tl excess in near components (e.g. LMFE, copper components): ~0.1 to 1
- Simulations with excess in far components (e.g. Pb): ~0.01

Coincident gamma detection rate more consistent with ^{208}Tl source located outside Ge detector array

Detector Upgrade and Future Plans

2020 Upgrade of Module 2

- Before the upgrade
  - Working connectors : 24/29 (82%)
  - HV good : 19/24 (79%)
  - Operational and used for analysis : 18/29 (62%)
- Upgrade
  - 5 p-type point contact (PPC) enrGe detectors removed and shipped to LNGS for LEGEND-200 tests in LAr
  - Installed signal cables with new ultra-clean, low mass connectors
  - Installed HV cables with improved end connectors
  - Careful bundling of cables (NASA specs)
  - Installed extra cross-arm shielding
  - Installed 4 ORTEC inverted coaxial point contact (ICPC) ^{enr}Ge detectors for LEGEND-200 for low background vacuum testing in Module 2
- Post upgrade
  - Working connectors : 27/27 (100%)
  - HV good : 27/27 (100%)
  - Operational : 27/27 (100%)

Status and Next Steps:

- Run for ~6+ months to measure performance, including Th background.
- Ultimate integrated exposure: ~65 kg y
- ICPC performance will inform LEGEND-200
- Stop as-late-as-possible to ship enriched detectors to LNGS for installation in LEGEND-200
- Continue background studies with natural detectors