Status and Recent Results of the MAJORANA DEMONSTRATOR

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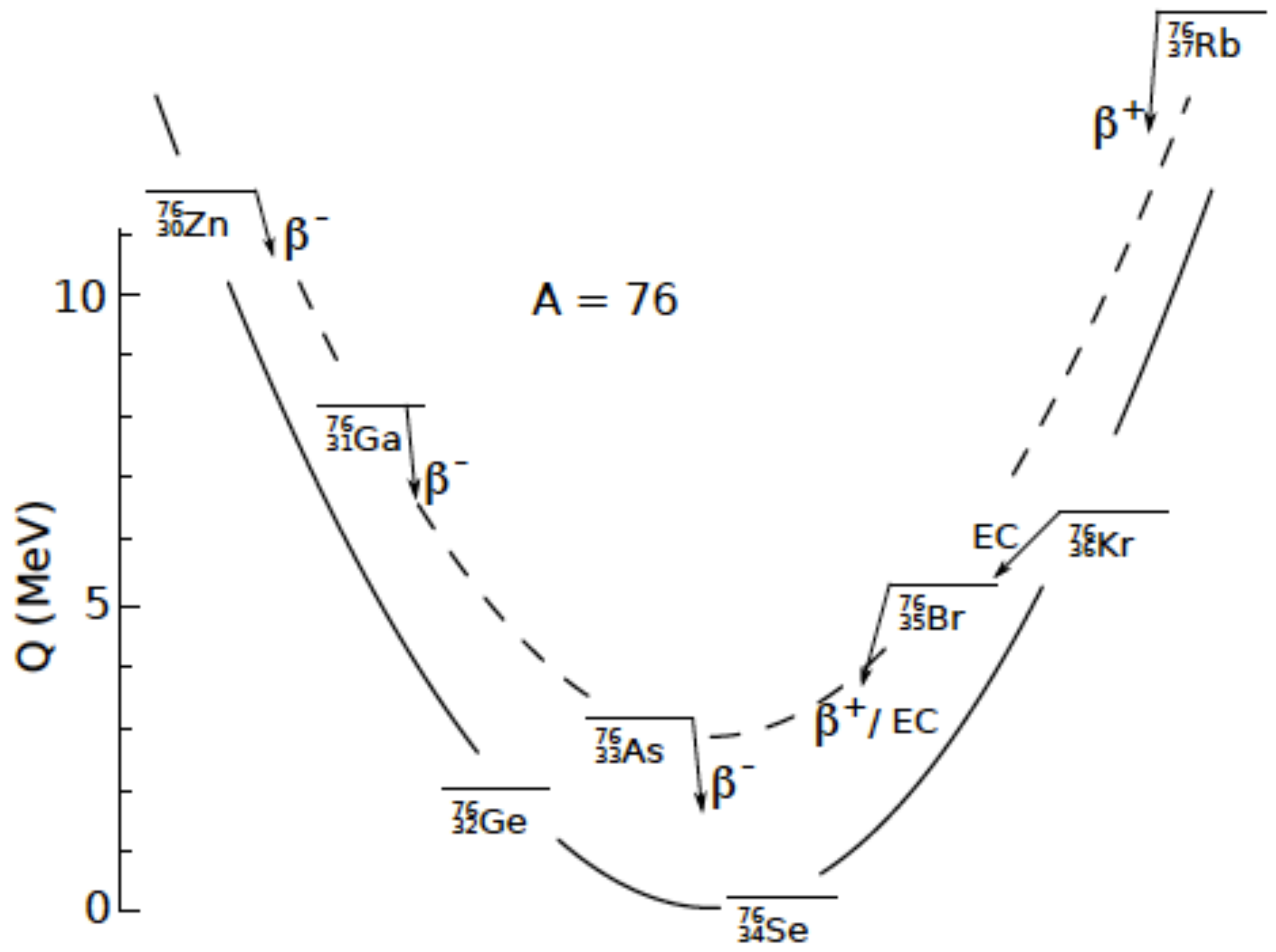
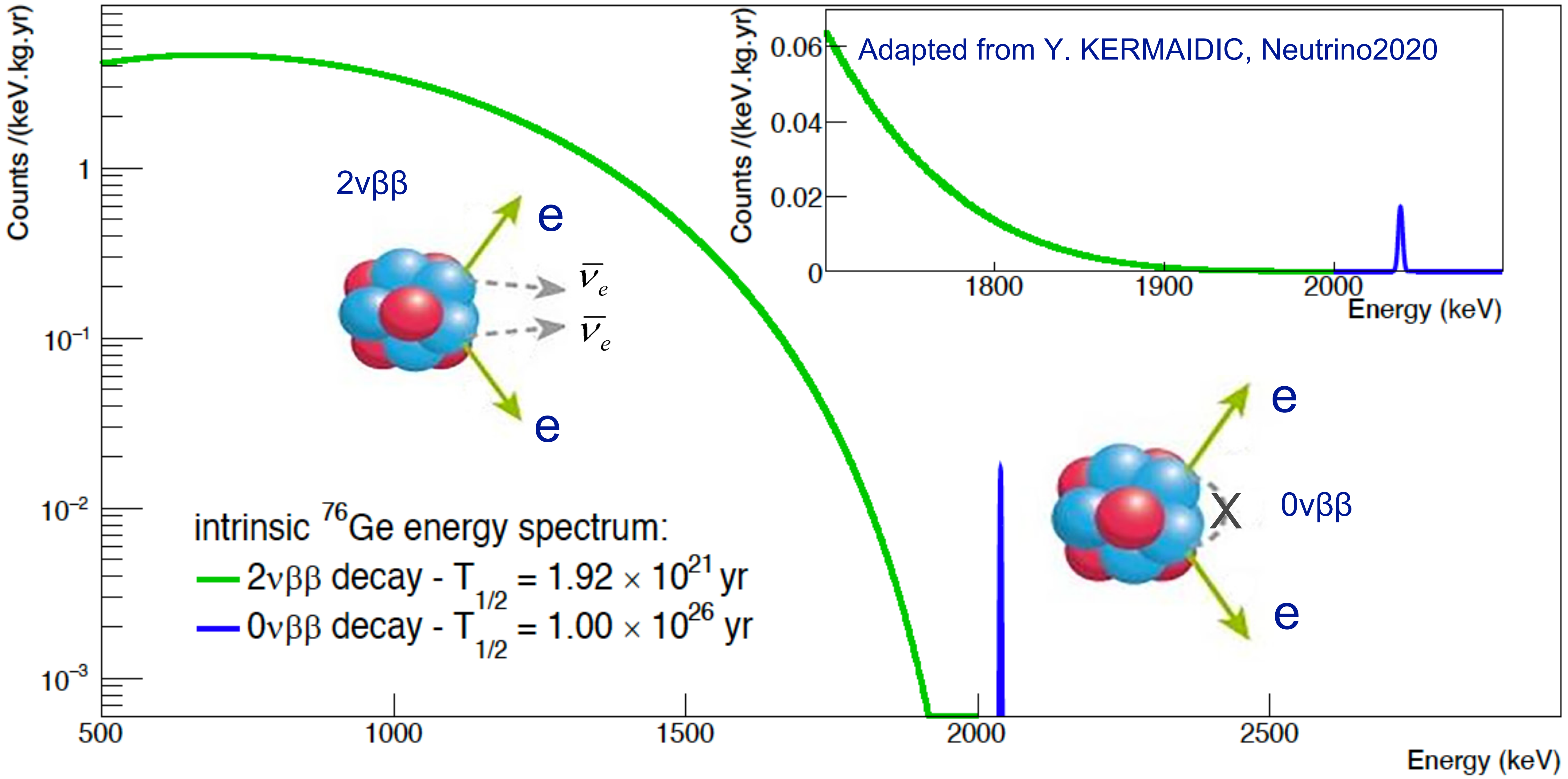
for the MAJORANA Collaboration

2020-07-29

Neutrinoless Double Beta Decay





Double-beta decay is possible when energetically favored

Neutrinoless double-beta decay (0νββ) searches

- test total lepton number conservation
  - -- 0νββ violates total lepton number by 2 units ($\Delta L = 2$)
- probe the Majorana or Dirac nature of massive neutrinos
  - -- observation of 0νββ would imply neutrinos are Majorana fermions
- if observed, shed light on the absolute scale of neutrino mass

Nuclear Matrix Element — Effective Neutrino Mass

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\,|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

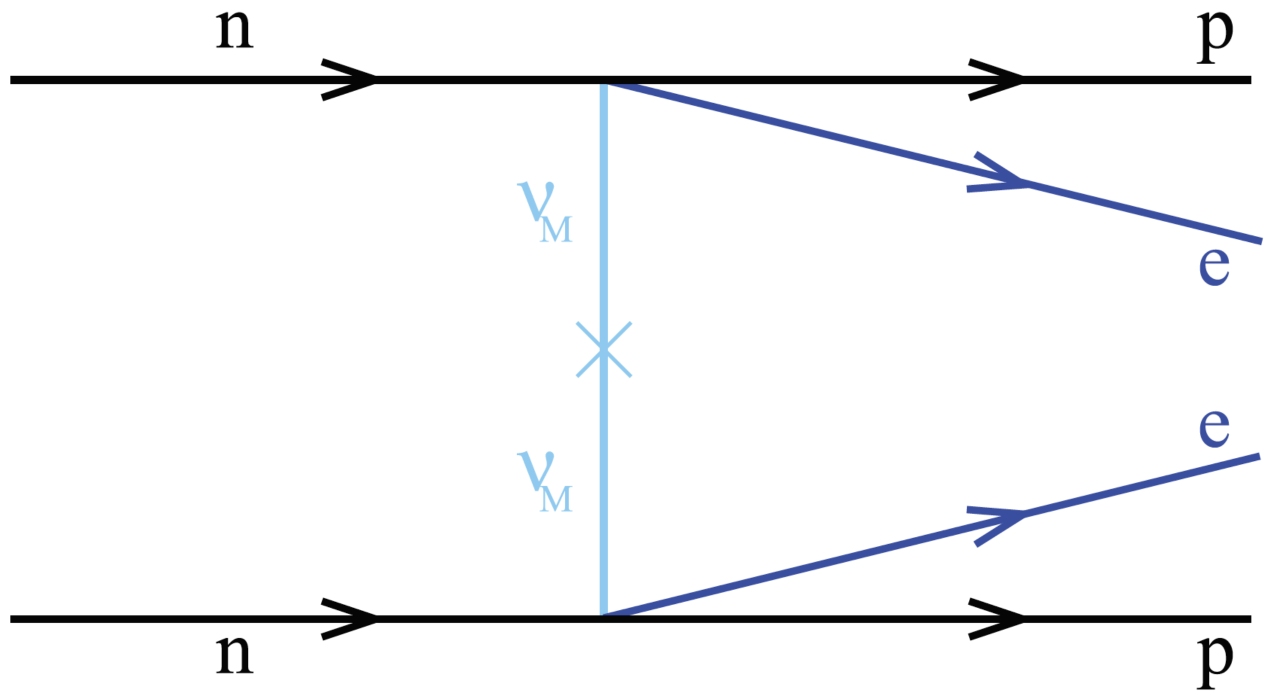
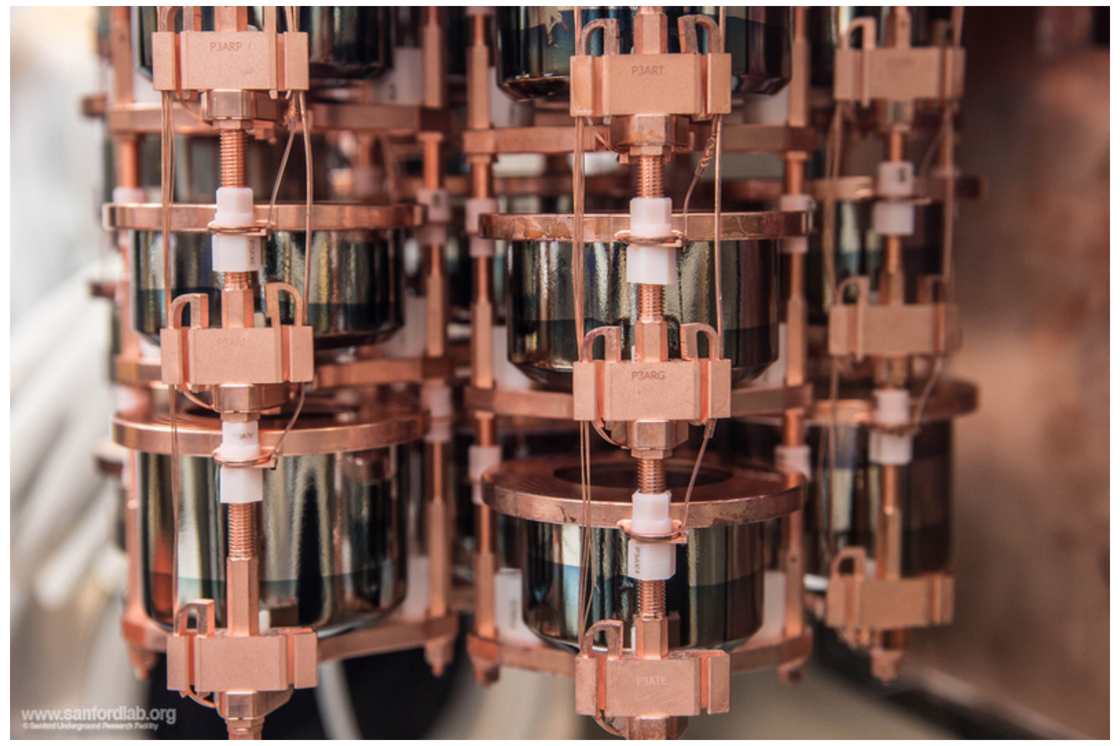


Diagram for Light neutrino exchange

J. Engel and J. Menéndez, Rep. Prog. Phys. 80 (2017) 046301

MAJORANA DEMONSTRATOR

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

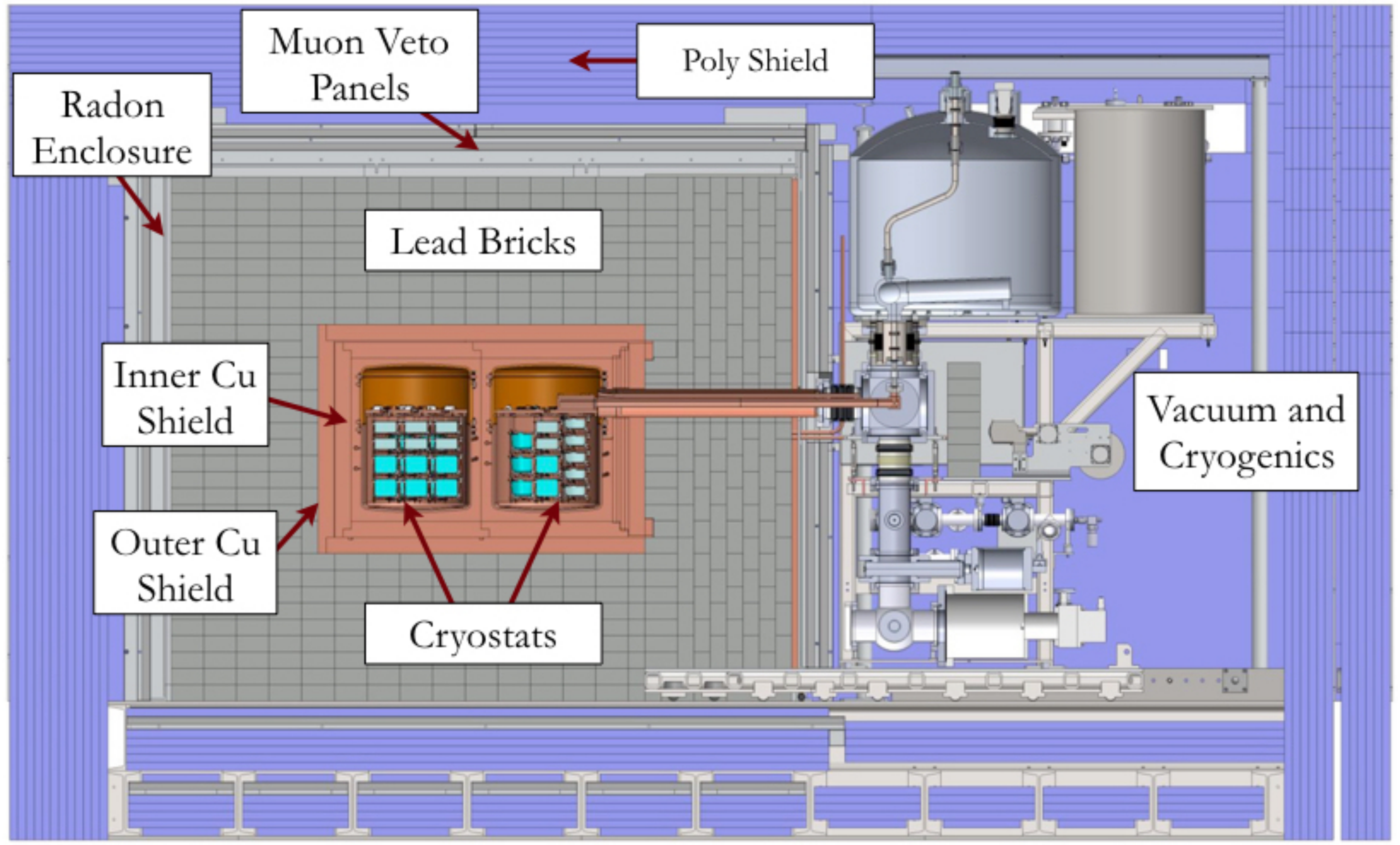


Source & Detector: Array of p-type, point contact detectors
29.7 kg of 88% enriched ^{76}Ge crystals

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 intrinsic backgrounds, energy resolution, background suppression

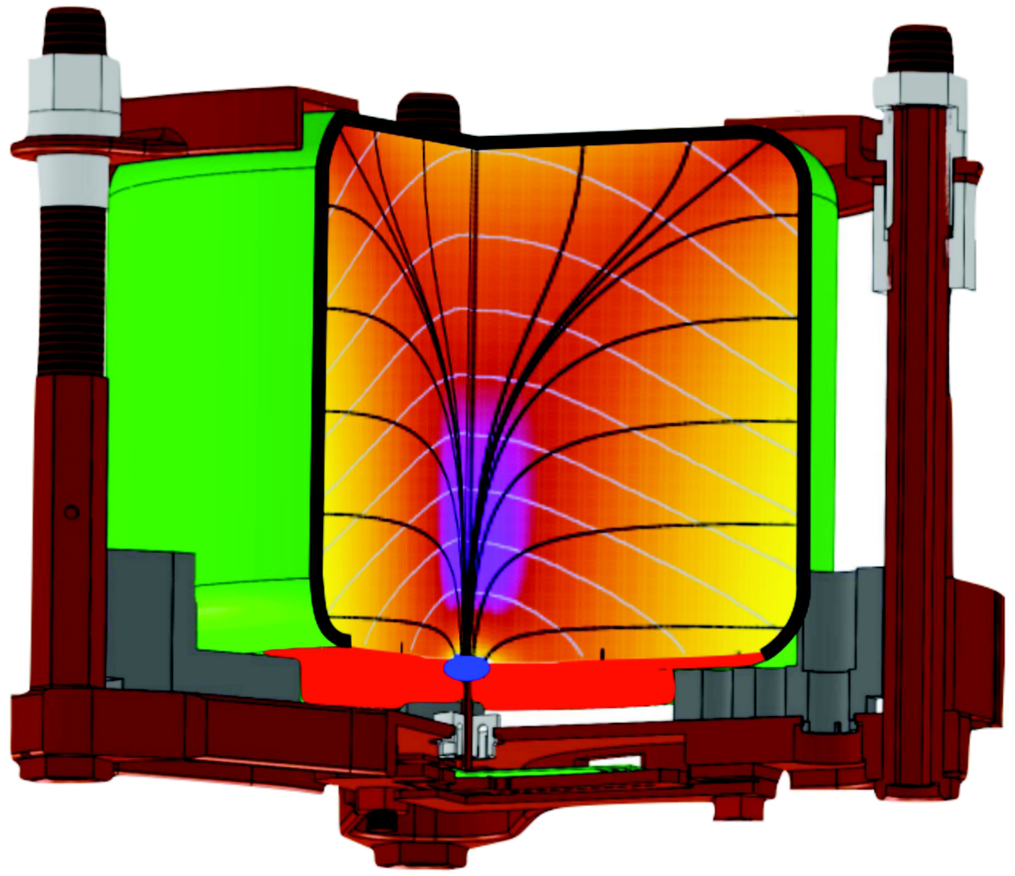
- Ge enrichment, zone-refining and crystal pulling processes enhance purity
- Limit above-ground exposure to prevent cosmic activation.
- Slow drift of ionization charge carriers allows separation of multiple interactions inside a detector.

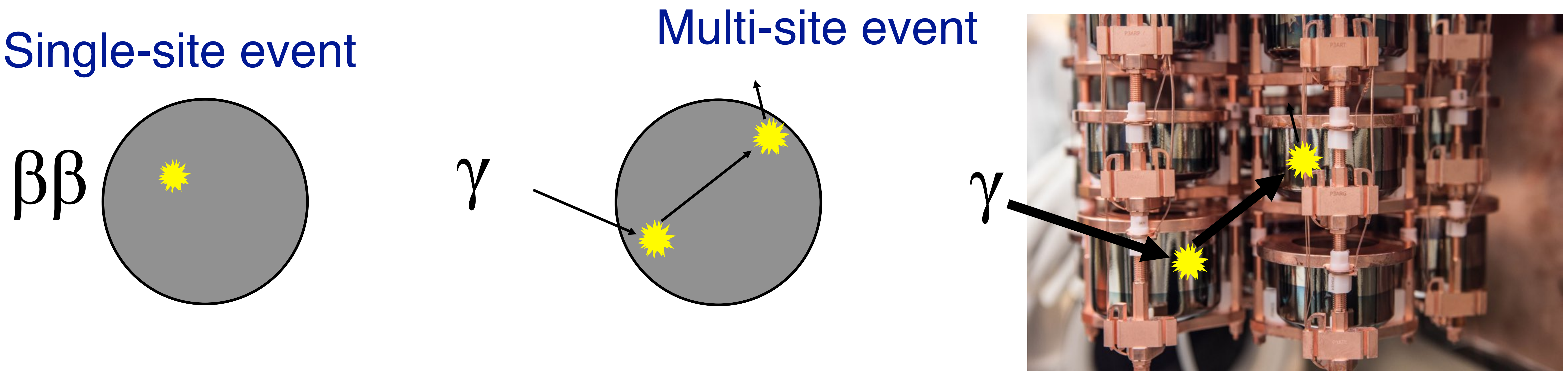
Array components and passive shielding fabricated from ultra-pure materials with extremely low radio-isotope content

[NIM **A828** (2016) 22–36]

Rejection of backgrounds

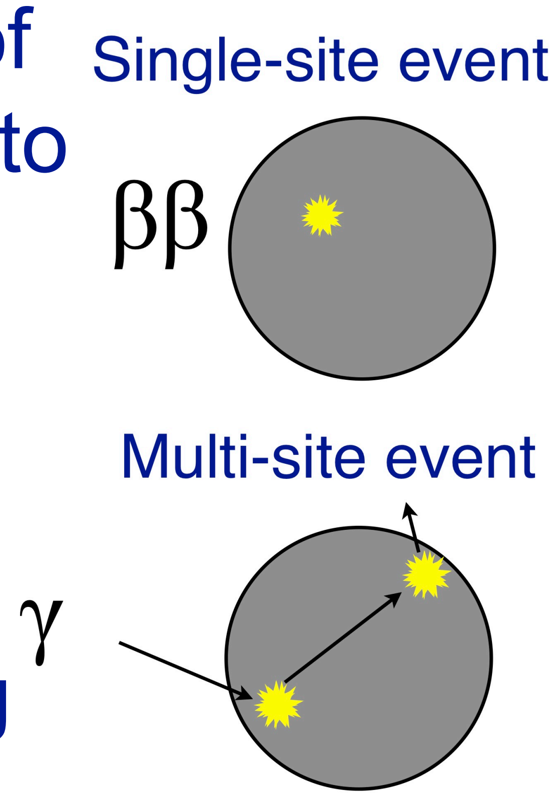
- Muon Veto: reject events coincident with muons
- Granularity: multiple detectors hit
- Pulse shape discrimination: no multi-site event, reject surface events

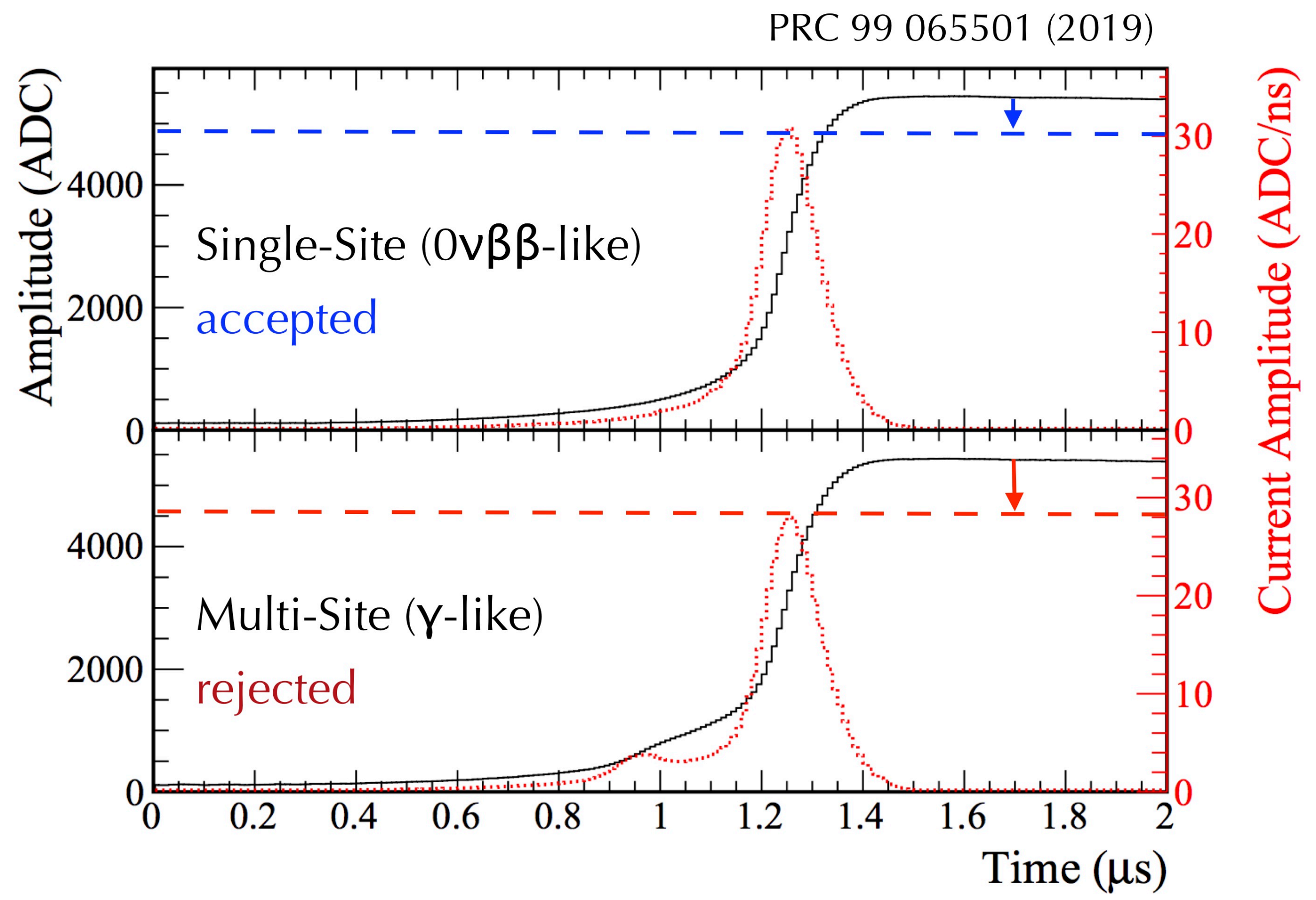




Improved Multi-Site Event Rejection

- A pulse shape analysis cut that compares the maximum amplitude of the current pulse (A) with the energy (E), named **AvsE**, and is used to identify multi-site background
- It is applied to keep 90% of known single-site event populations based on ^{228}Th calibration data
- 50% reduction of Compton continuum background
- Results in a factor of three suppression in the background averaging window

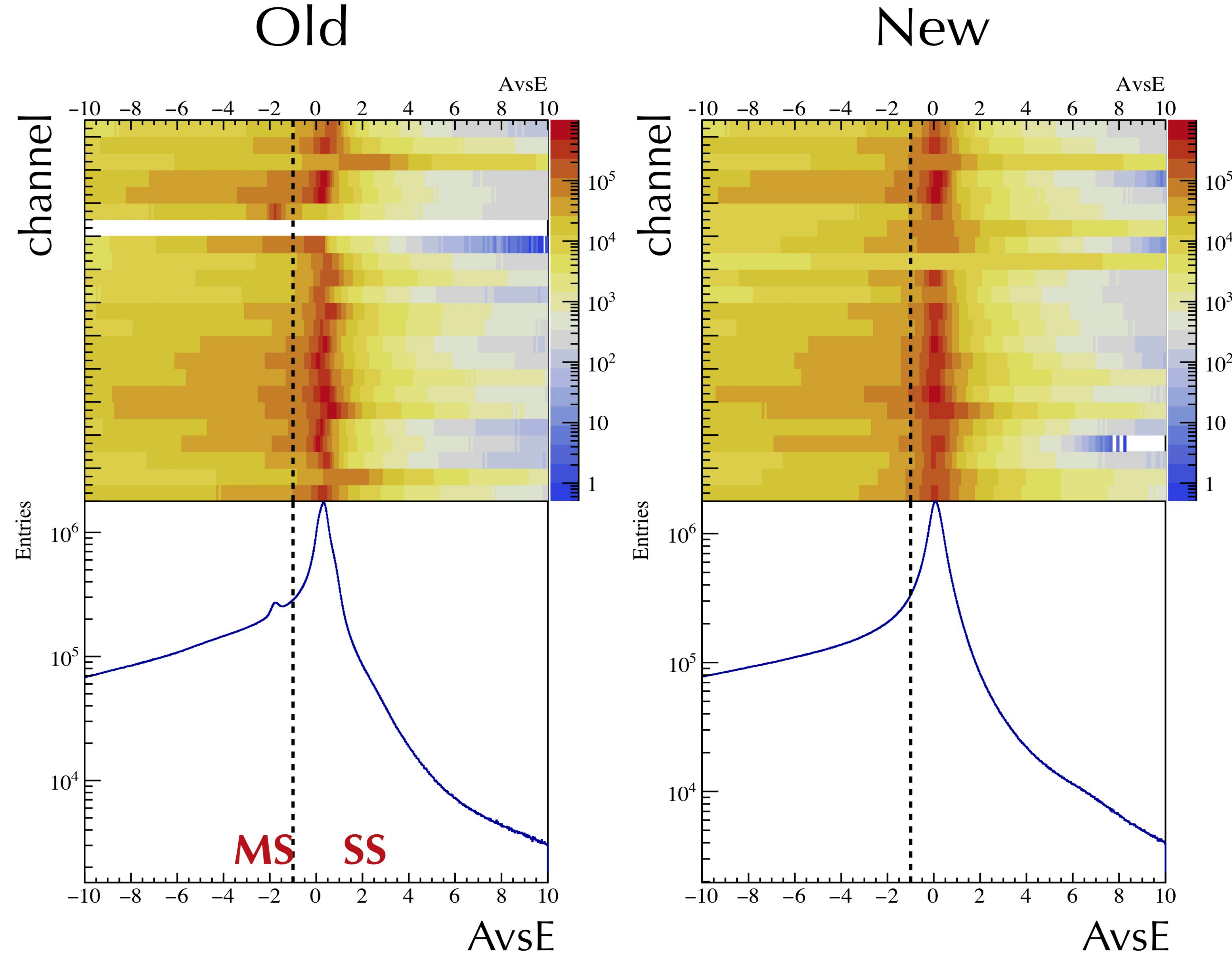




Improvements to AvsE

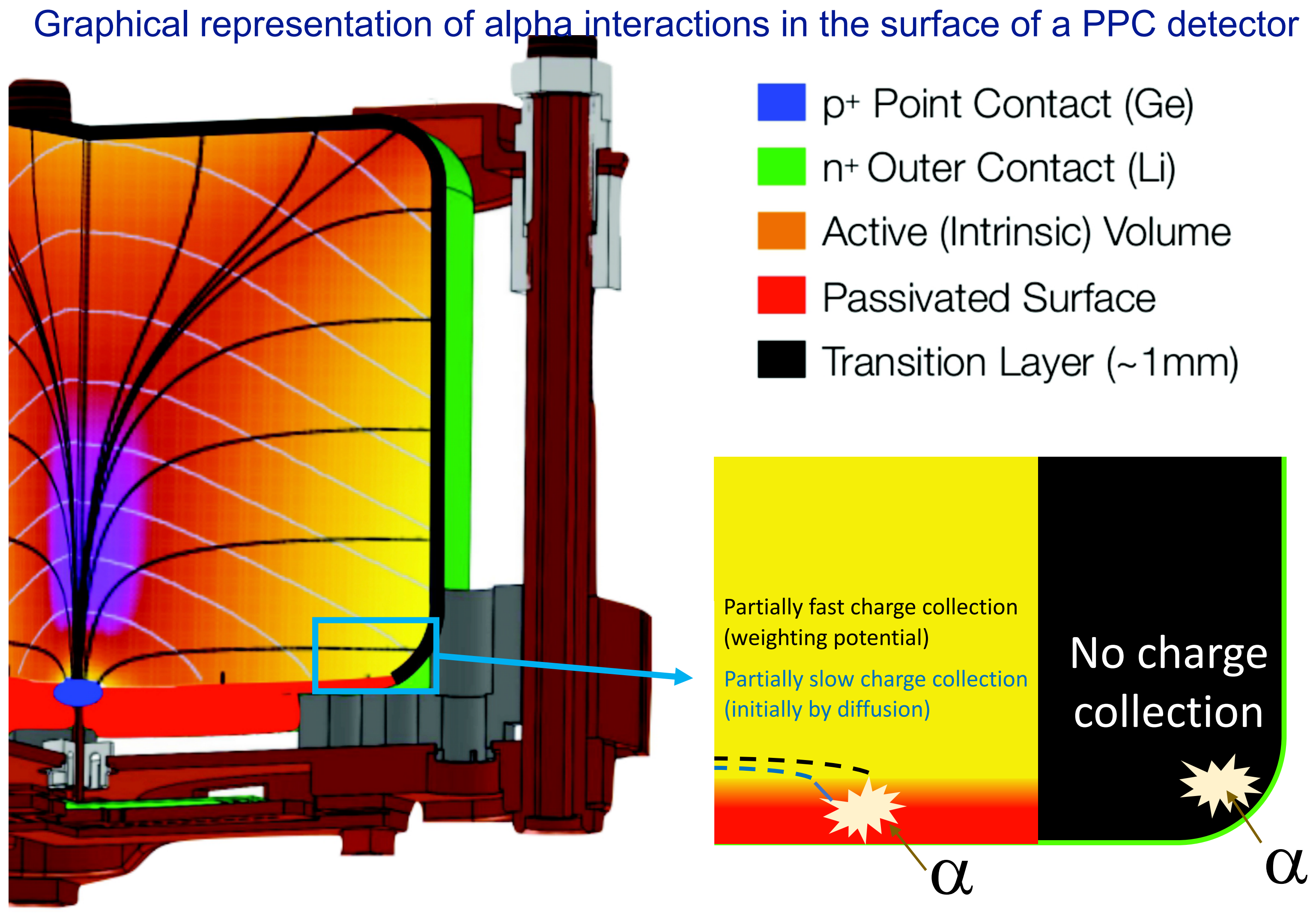
1. Refined alignment of the distribution center to produce a more precise cut
2. Introduced a width-energy dependence correction that improves the single-site acceptance at higher energies
3. Adjusted for correlations with event drift-time

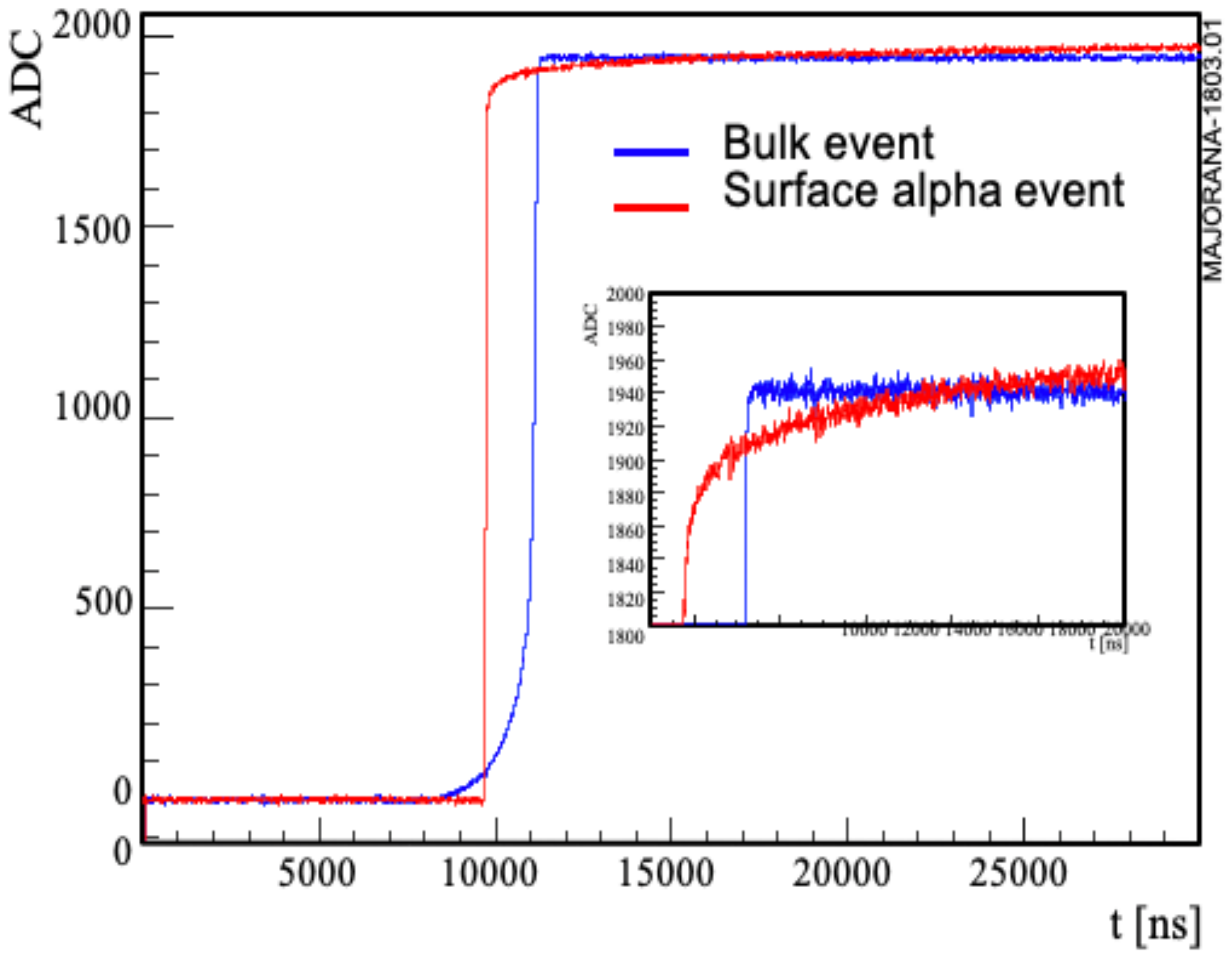
> The new AvsE parameter offers better stability and uniformity across all detectors, while accounting for acceptance degradation at higher energies. The result is a better multi-site discriminating parameter



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

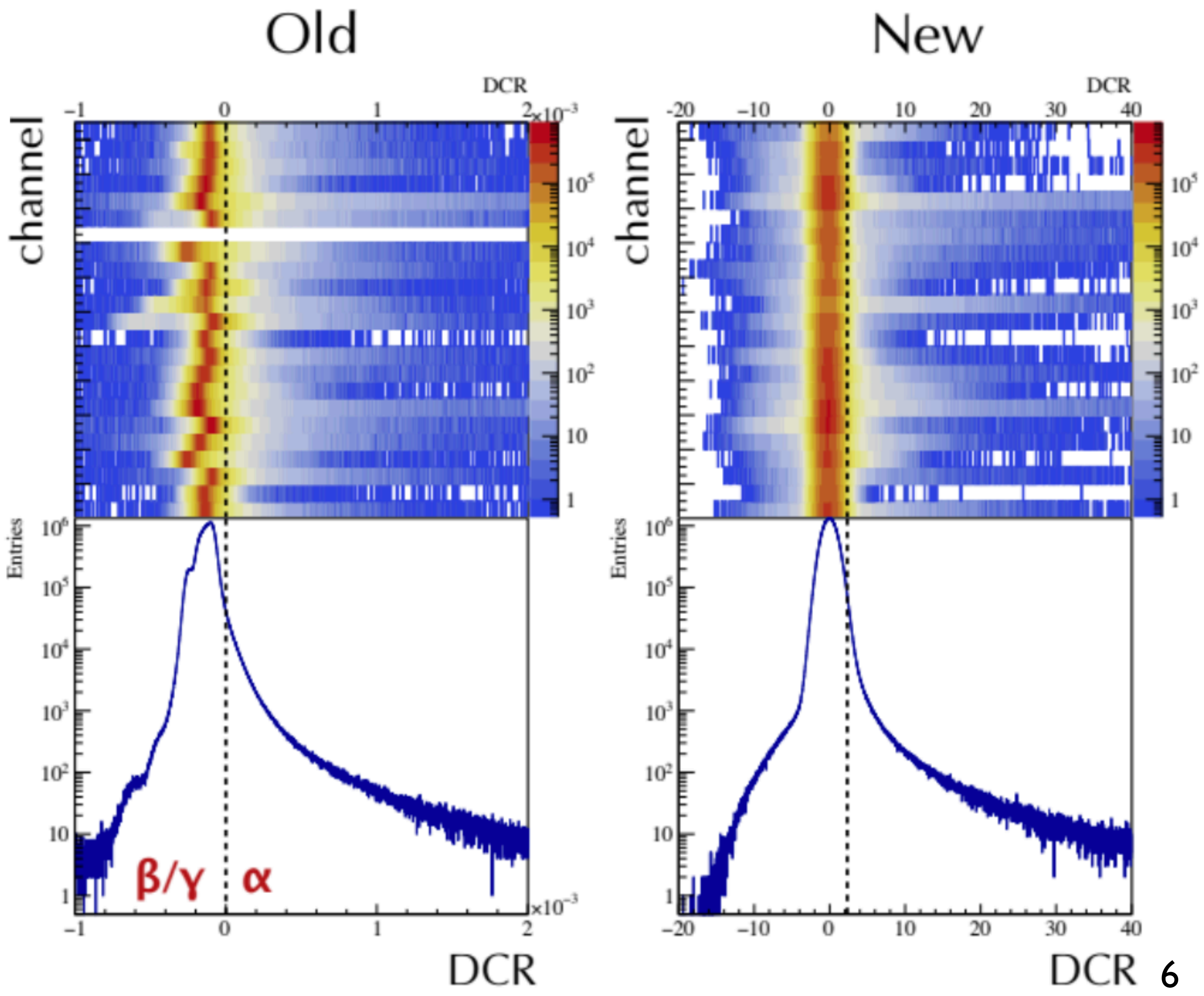
Improved Surface Alpha Rejection





Delayed charge recovery (DCR)

- Estimates the slope of the waveforms after the rising edge to identify α-like events with a delayed charge collection component
- Retains 99% of the β/γ events, evaluated based on ^{228}Th data
- arXiv:2006.13179



Improvements to DCR

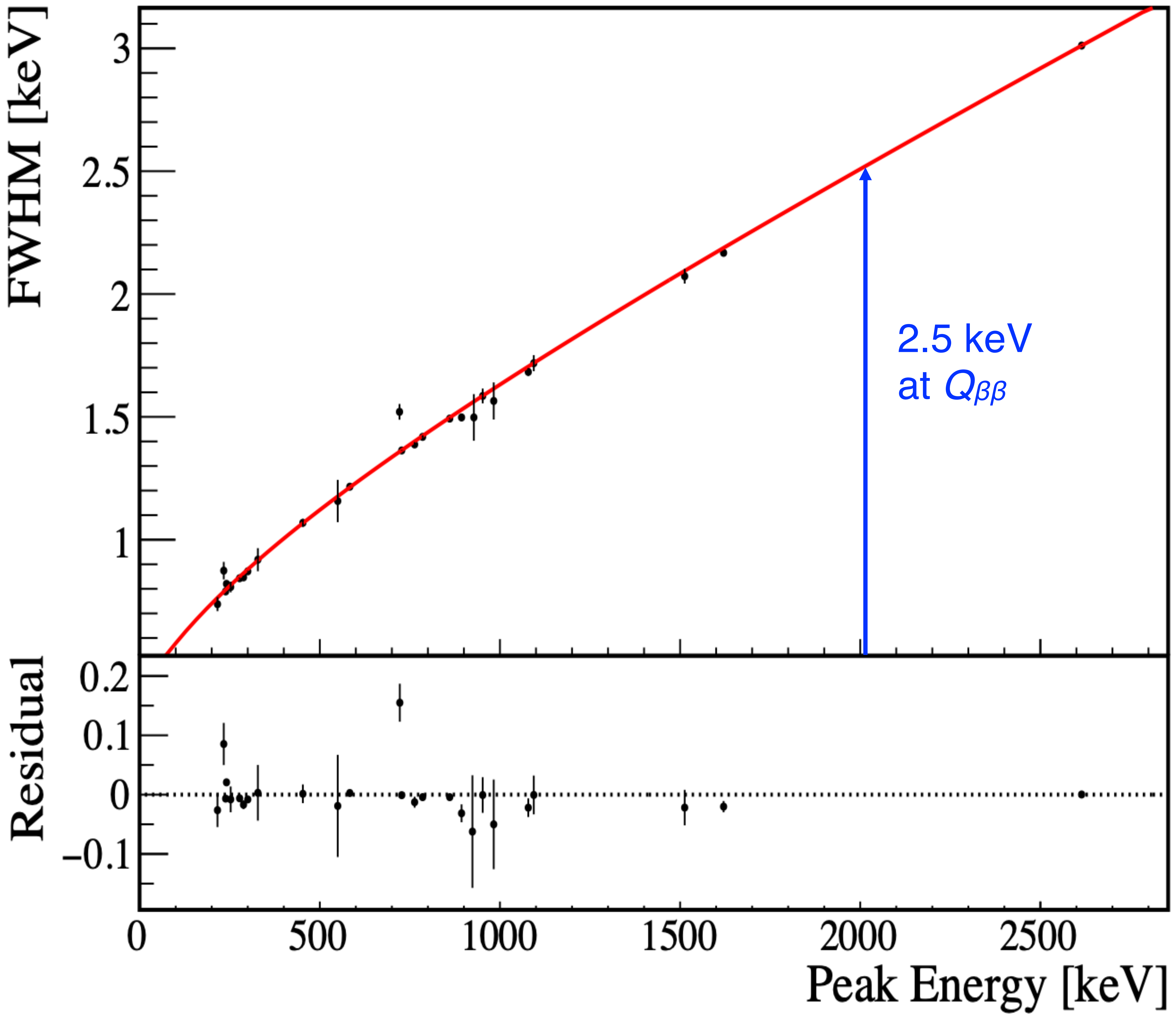
1. Electronics' transfer function deconvolved waveforms
2. Parameters converting the slope of the waveform into DCR, whose distribution is designed to have a mean of 0 and a standard deviation of 1
3. Charge trapping, or drift time, correction

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.

Improved Energy Estimation

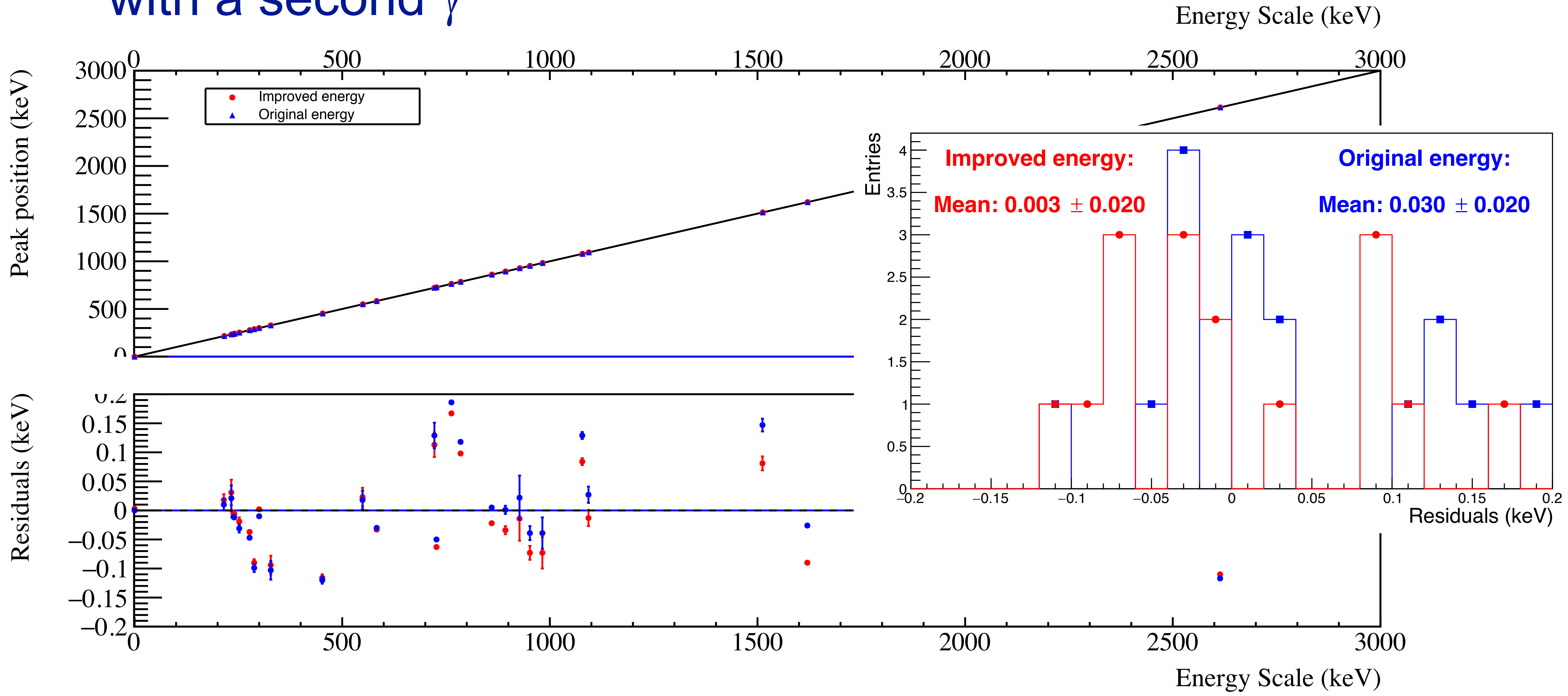
FWHM (2.5 keV at Q-value, approaching 0.1%) and linearity (<0.2 keV up to 3 MeV) a record for $0\nu\beta\beta$ searches

Dedicated non-linearity correction, arXiv:2003.04128 [physics.ins-det]



Improvements to energy estimator

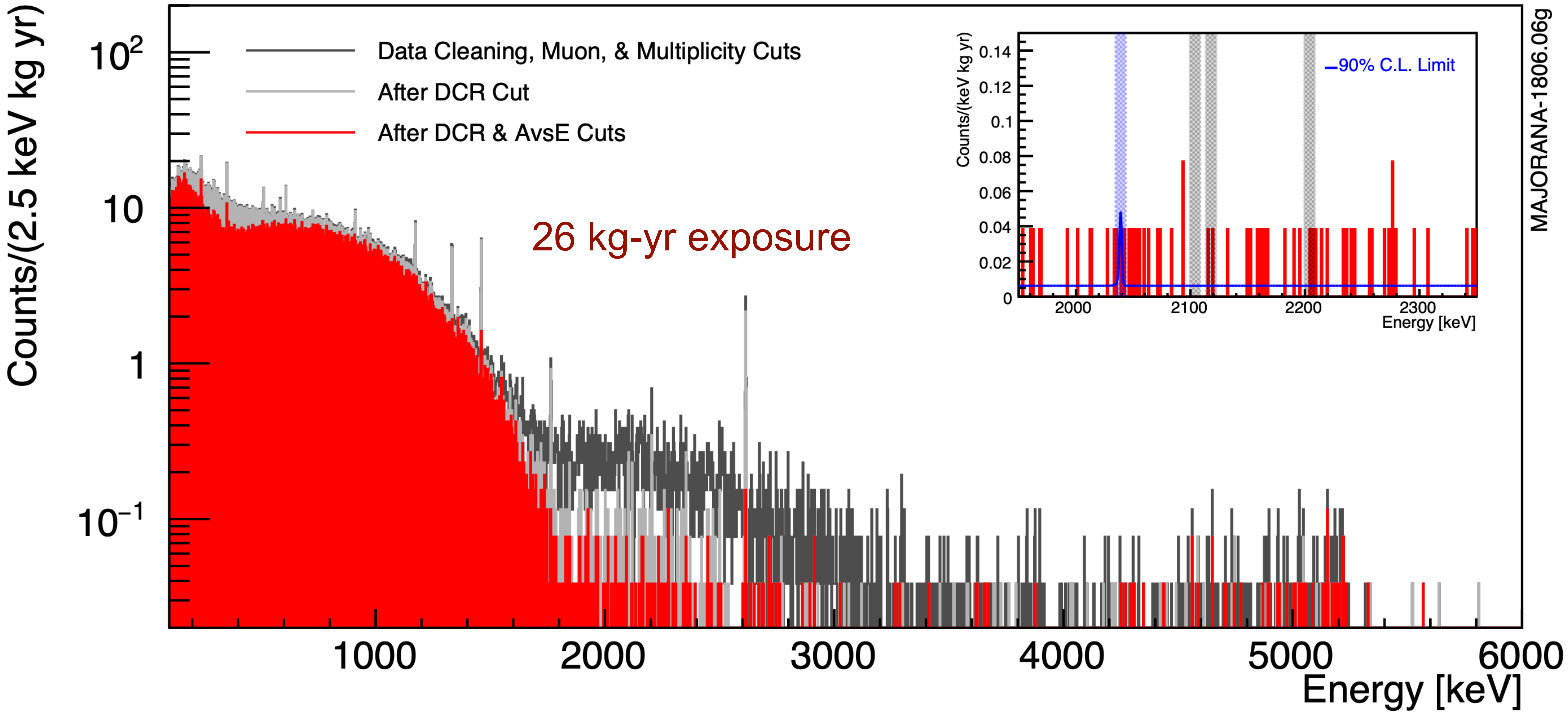
- a correction applied to the waveform start time, obtained from ^{228}Th calibration data through coincidences between 583 keV γ with a second γ



The waveform start time correction reduces the non-linearity in the energy scale, which improves the energy parameter, especially at low energies but also at high energies, where the $0\nu\beta\beta$ peak is expected

MAJORANA DEMONSTRATOR 0νββ Results

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



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)

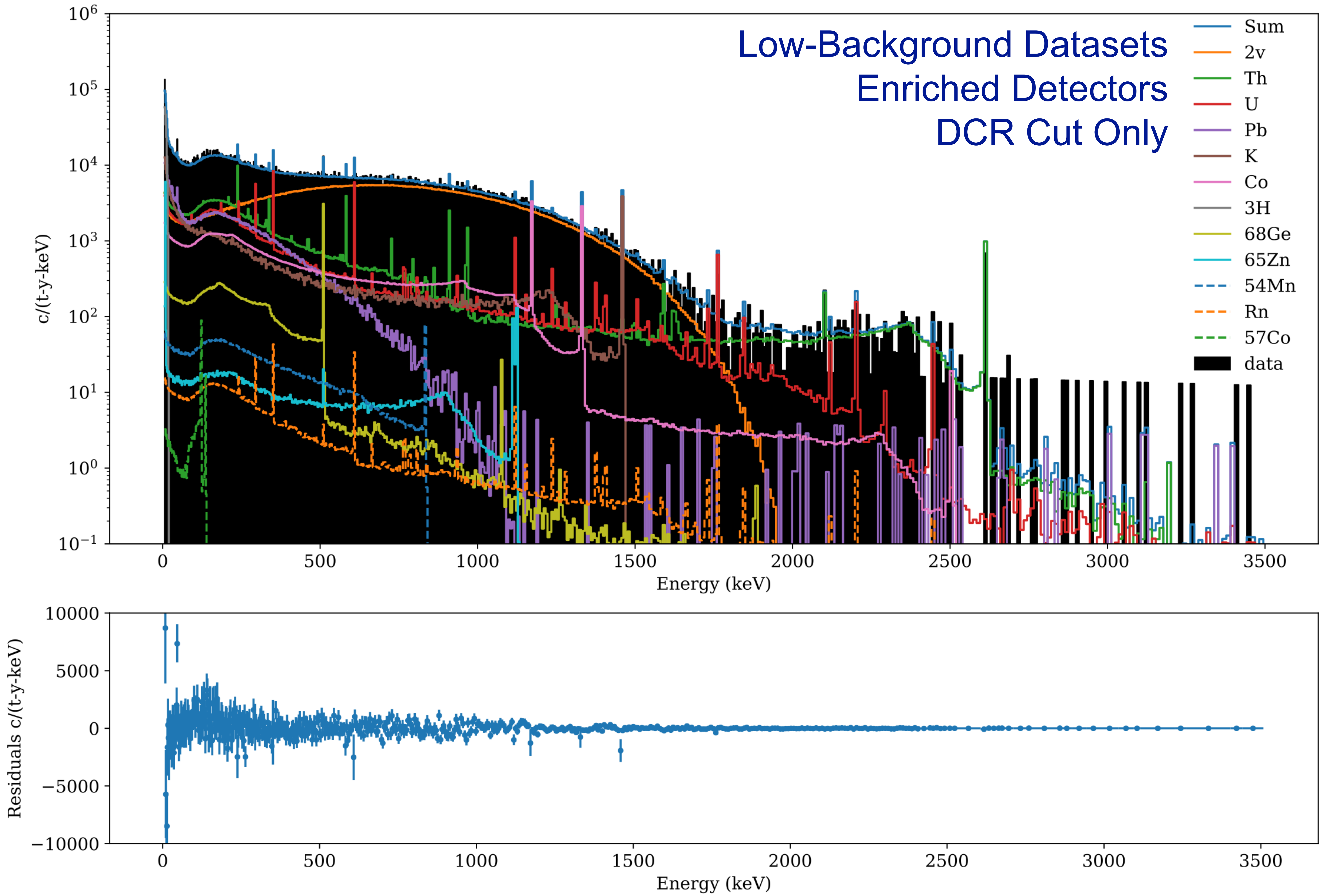
Background Index at 2039 keV in lowest background config:

11.9 ± 2.0 cts/(FWHM t yr)

A new result, with a combined total of ~50 kg-yr and analysis improvements, is to be released this Fall

Background Modeling

- Investigating observed background near $Q_{\beta\beta}$
  - 11.9 c/(FWHM t y) measured after all cuts
  - Newer assays and updated simulations to revise our background index prediction
- Preliminary background model fits to data perform well
- Background at $Q_{\beta\beta}$ clearly due primarily to ^{232}Th chain contamination
  - Fits indicate a preference for the source of excess ^{232}Th from distant components
  - Supporting evidence for distant Th contribution from peak intensity and coincidence studies
- Extensive simulation campaign underway with higher statistics to complete the model
  - Improved component groupings
  - Adding a higher fidelity modeling of distant components



M. Buuck, UW, PhD Dissertation 2019

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) ^{enr}Ge 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:

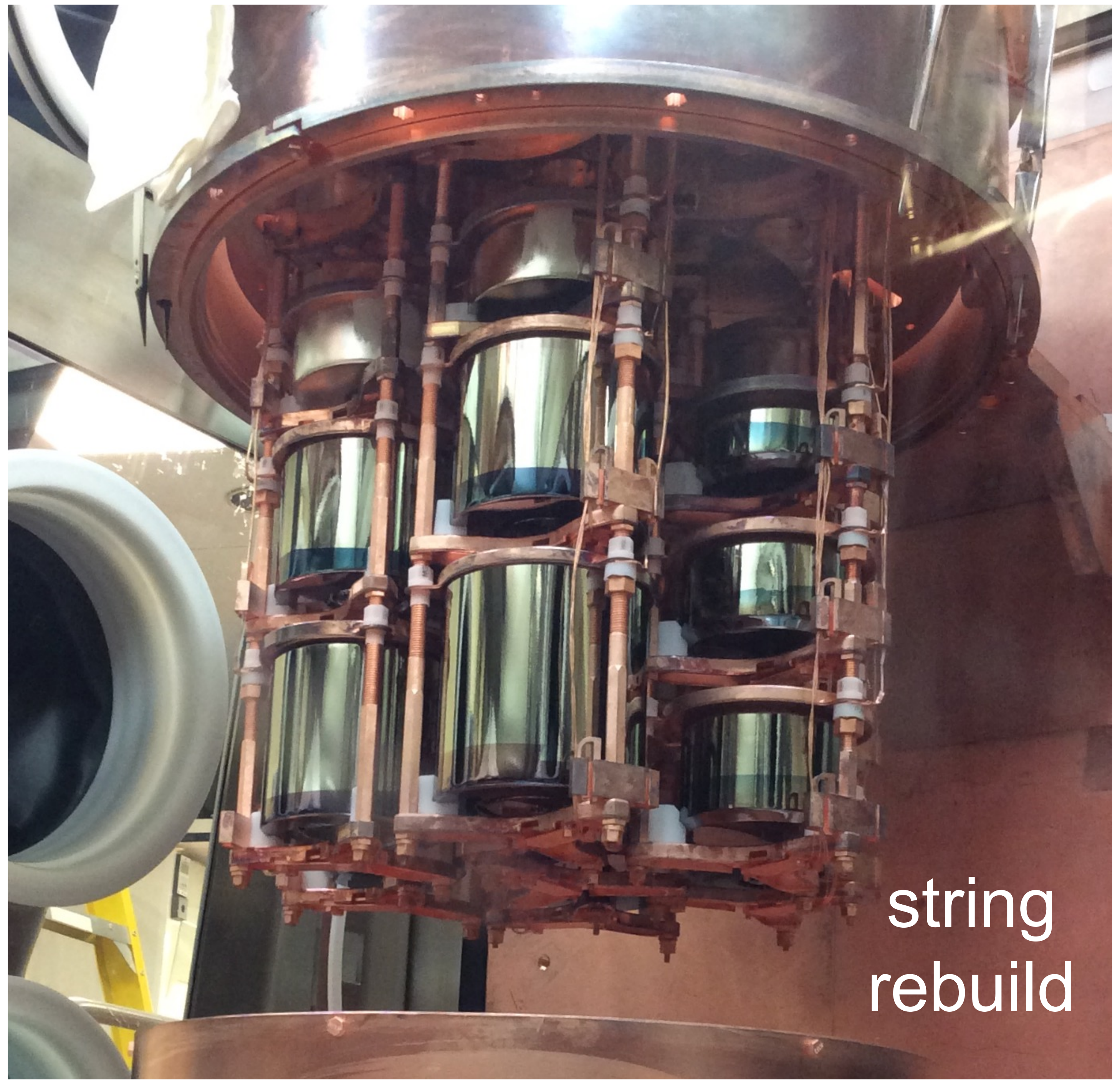
Run for ~6+ months to measure performance, including Th background.

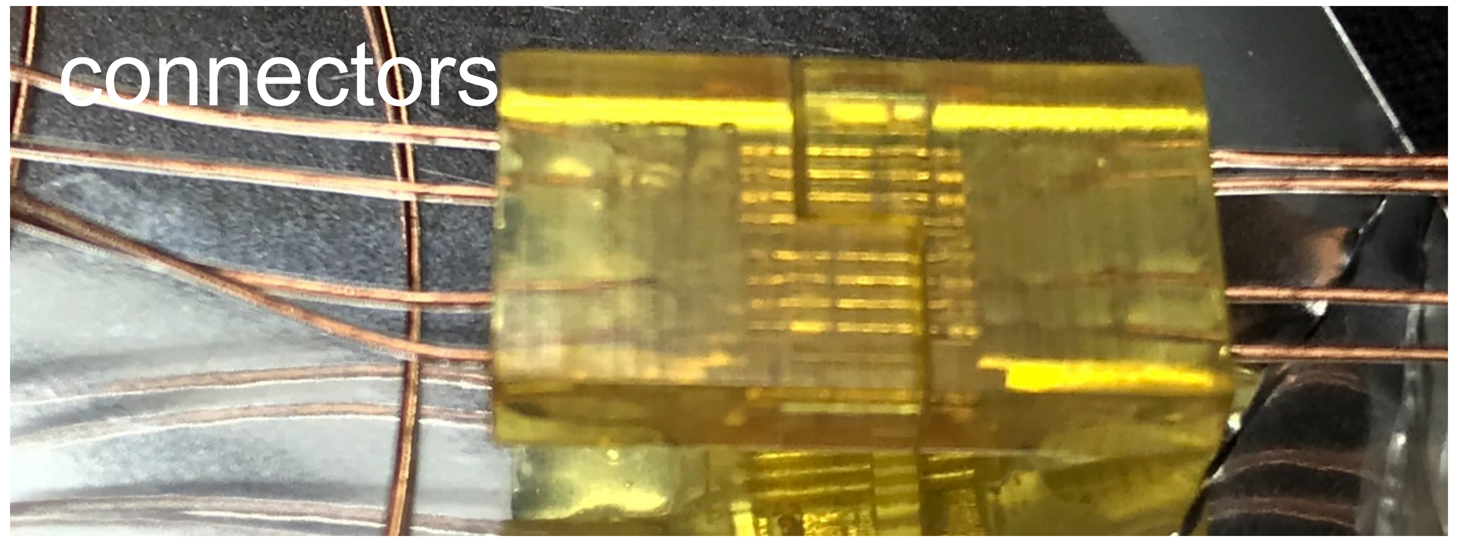
Ultimate integrated exposure: ~65 kg y

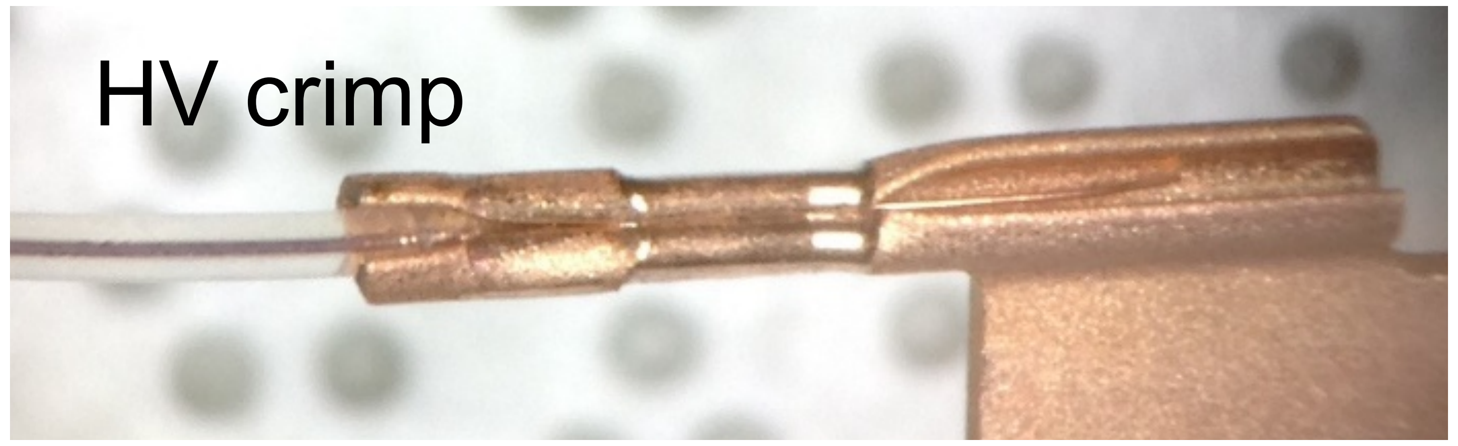
ICPC performance will inform LEGEND-200

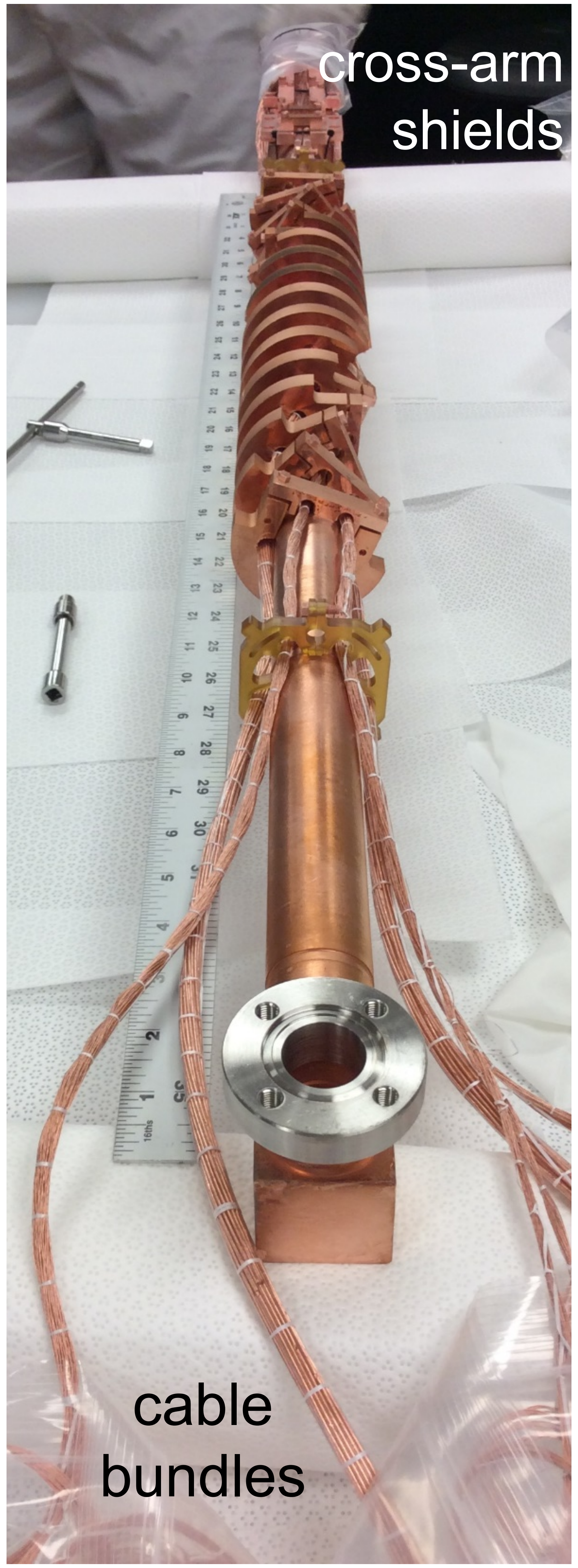
Stop as-late-as-possible to ship enriched detectors to LNGS for installation in LEGEND-200

Continue background studies with natural detectors









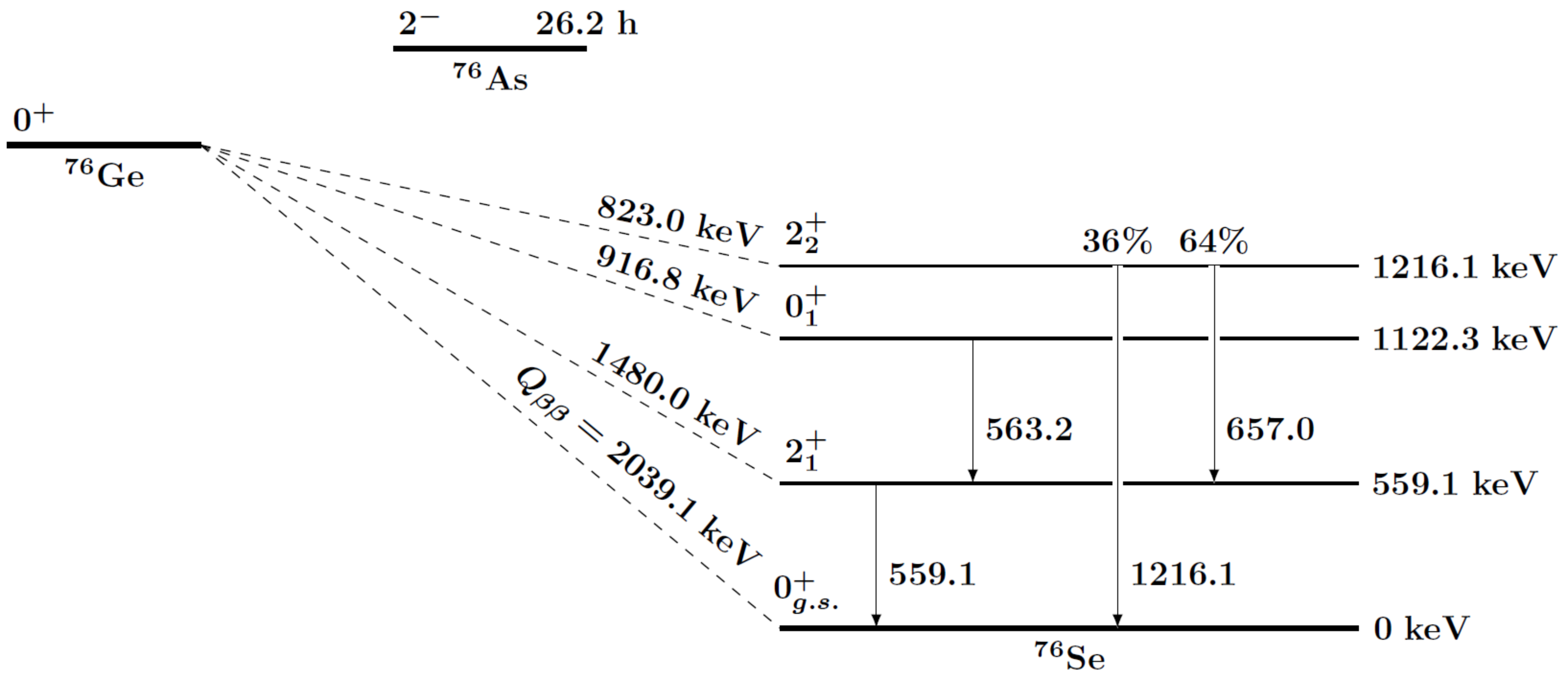
New Result: Double Beta Decay to Excited States

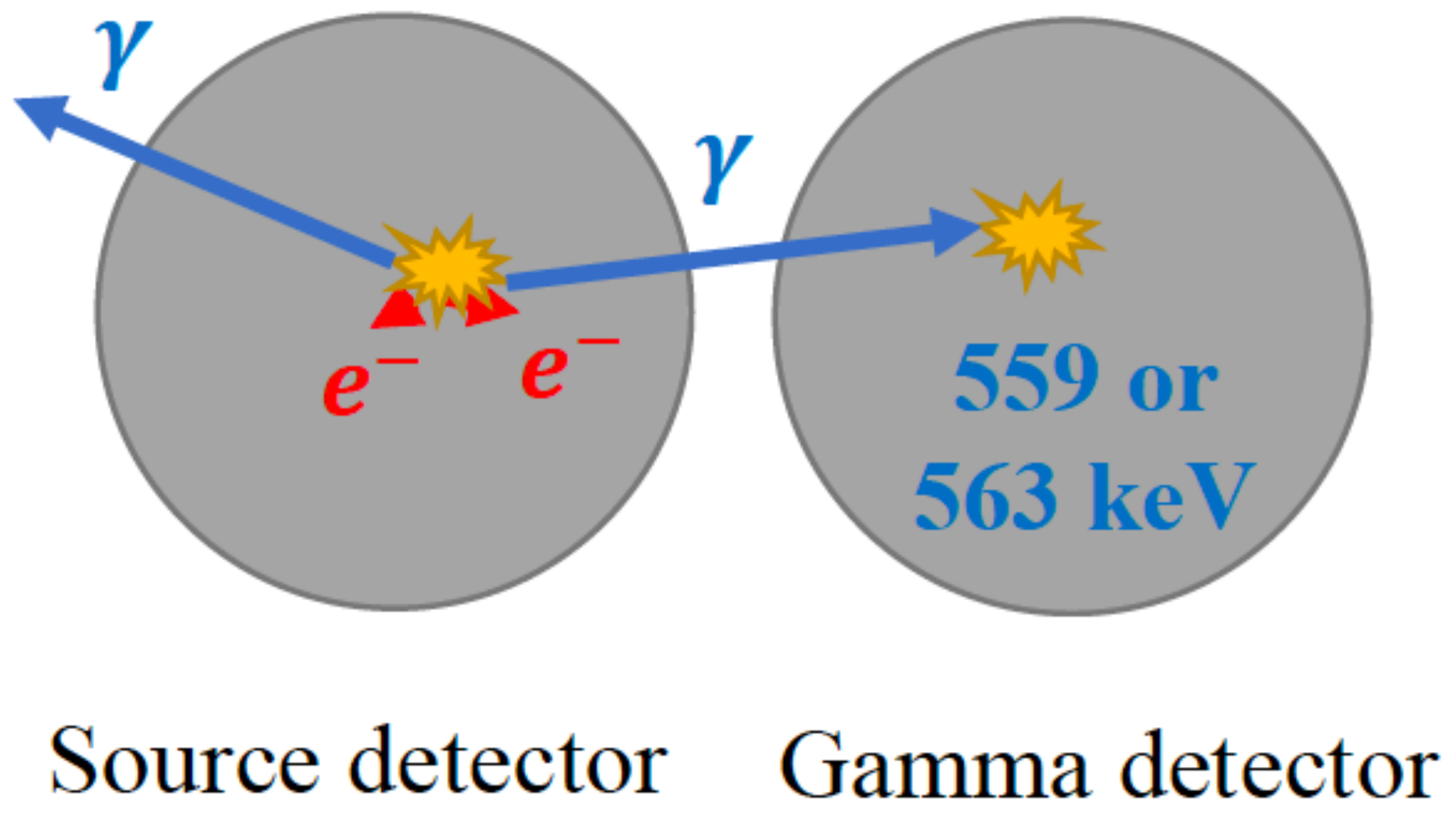
- A half-life measurement would offer **a test for the nuclear matrix element calculations** used to obtain the effective ν mass, $m_{\beta\beta}$, from a 0νββ measurements

- **Sensitive to neutrino properties**: e.g. if the neutrino has a bosonic component, the ββ half-life to the 2_1^+ state would be sensitive

- ββ to Excited States is inherently multi-site. Look for **events with multiple detectors**:
  - The “source” detector will have a broad energy spectrum from the ββ-site
  - The “gamma” detector will measure energy peaked at the γ energies

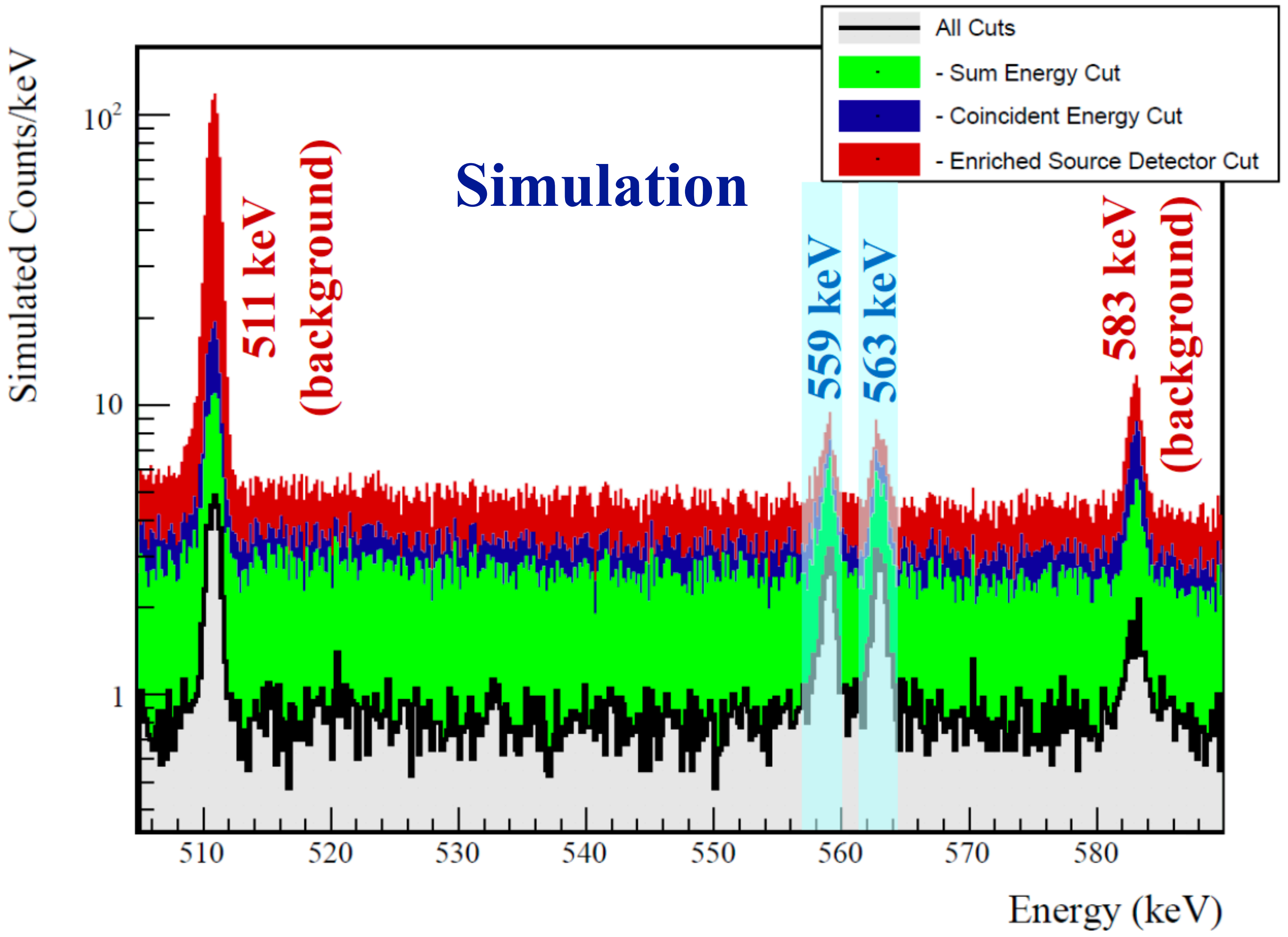
- **Perform a peak search**, utilizing information from the source detector to reduce backgrounds and improve sensitivity





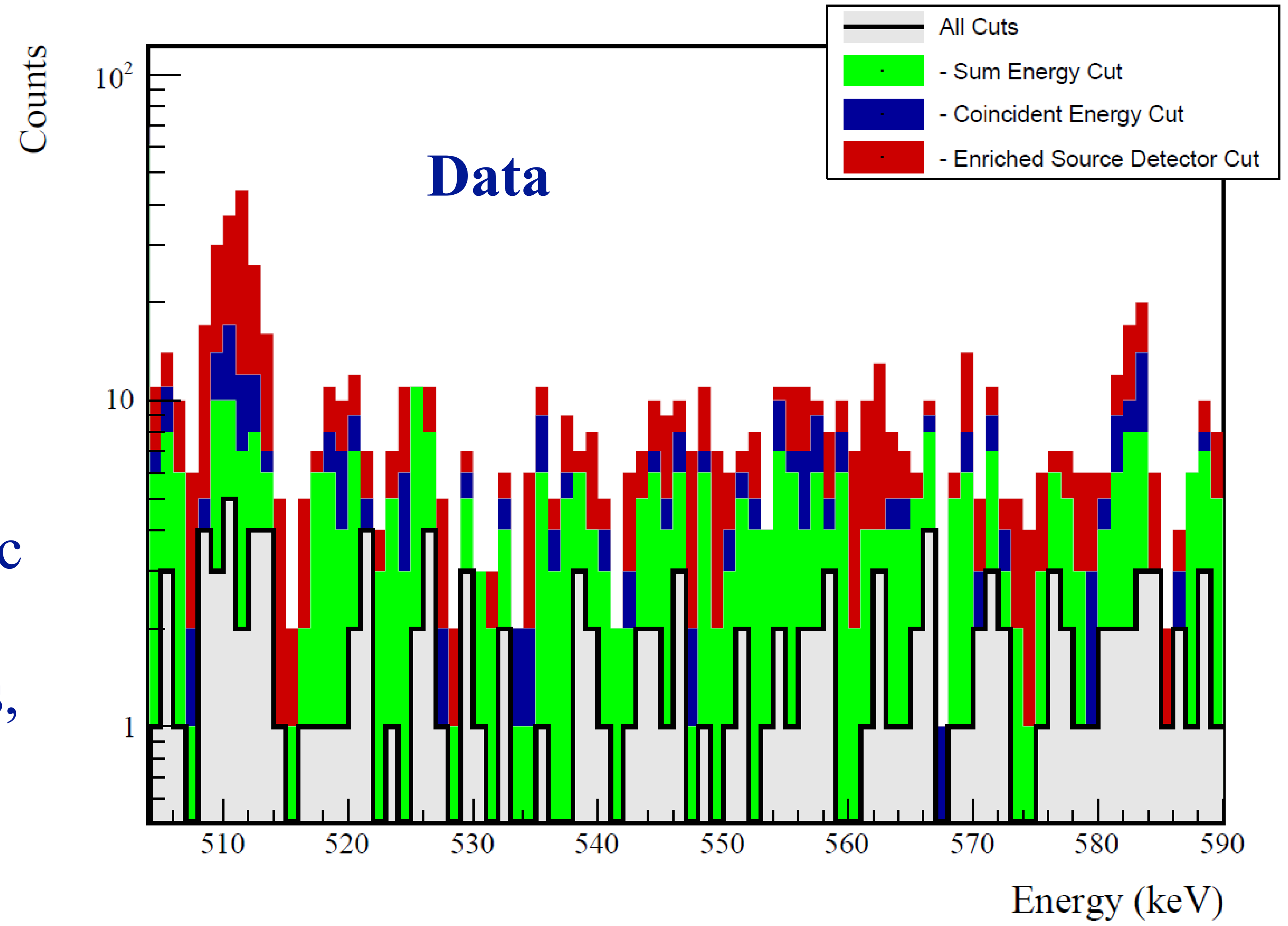
Example of 2νββ to the 0_1^+ state

New Result: Double Beta Decay to Excited States



⇦ **Left**: **Simulation** with MJD backgrounds included; assume a half-life of 10^{24} y with 42 kg y of isotopic exposure.

Right: Data of detector hits in multi-detector events near the region of interest for ββ to the 0_1^+ state, with cuts applied. 41.9 kg y of isotopic exposure (20.6 kg y of which was blinded)
For 2νββ to the 0_1^+ state: 5 counts in peak ROIs, with 4.2 counts expected from backgrounds ⇨



The MAJORANA DEMONSTRATOR has set the most stringent limits to date for ββ to each excited state of ^{76}Se, thanks to:

- Operating an array in vacuum, resulting in (relatively) **high detection efficiency** (>2× better efficiency in Module 1 than previous searches)
- **Exquisite energy resolution** for identifying peaks
- **Low environmental backgrounds**, and the ability to mitigate them in analysis

New Half-Life Limits Set

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

1) M. Agostini et al. (GERDA Collaboration), J. Phys. G 43, 044001 (2015).
2) A. Morales, J. Morales, R. Núñez-Lagos, J. Puimedón, J. Villar, and A. Larrea, 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

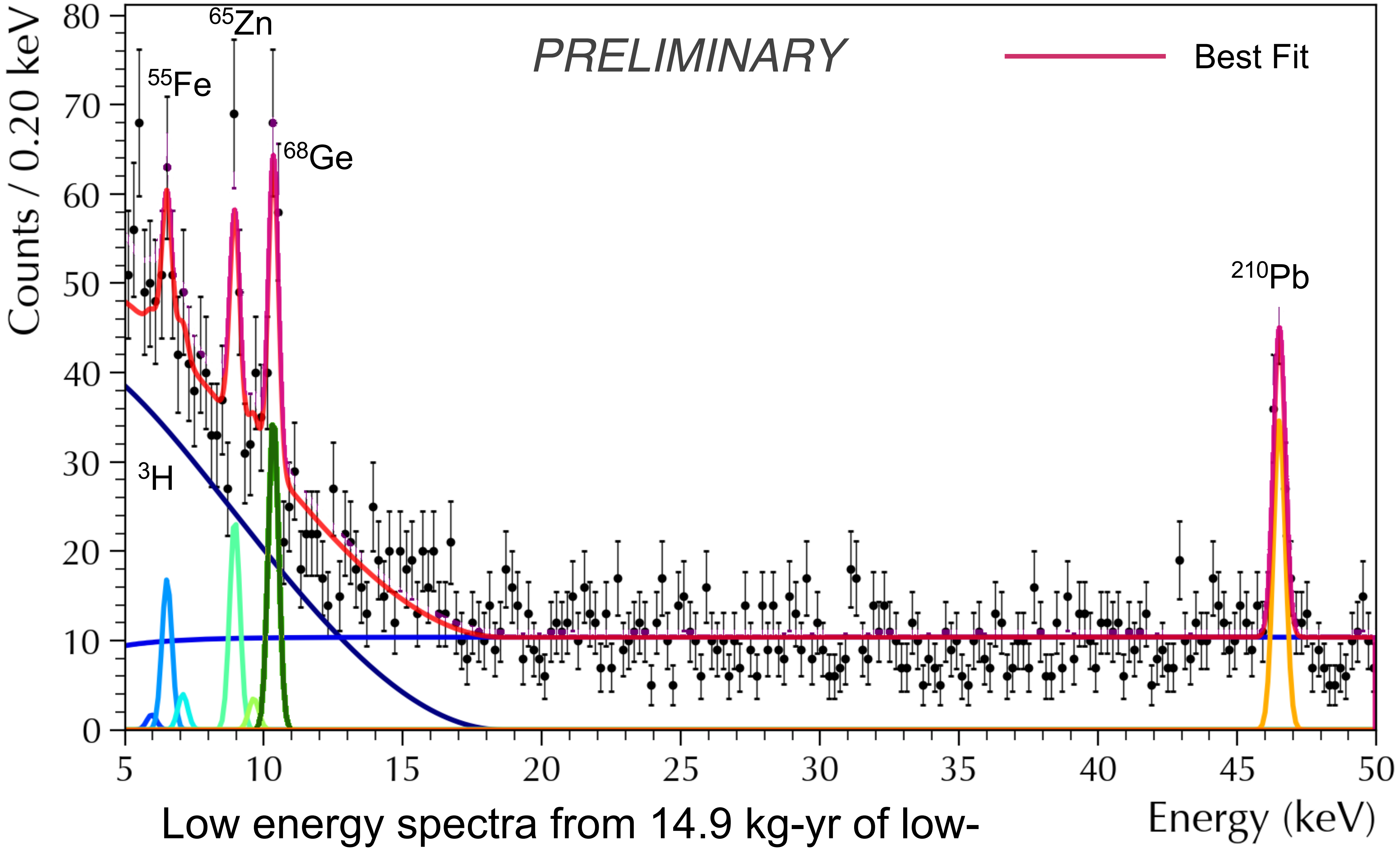
The low backgrounds, low threshold, high resolution spectra allows additional searches

Controlled surface exposure of enriched material to minimize cosmogenics

Upcoming updates to beyond the standard model searches

Excellent energy resolution: 0.4 keV FWHM at 10.4 keV

Progress towards a low-E background model



Low energy spectra from 14.9 kg-yr of low-background open physics running (DS1-6a)

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

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

Search for tri-nuclean decay

A test of baryon number violation

PRD **99** 072004 (2019)

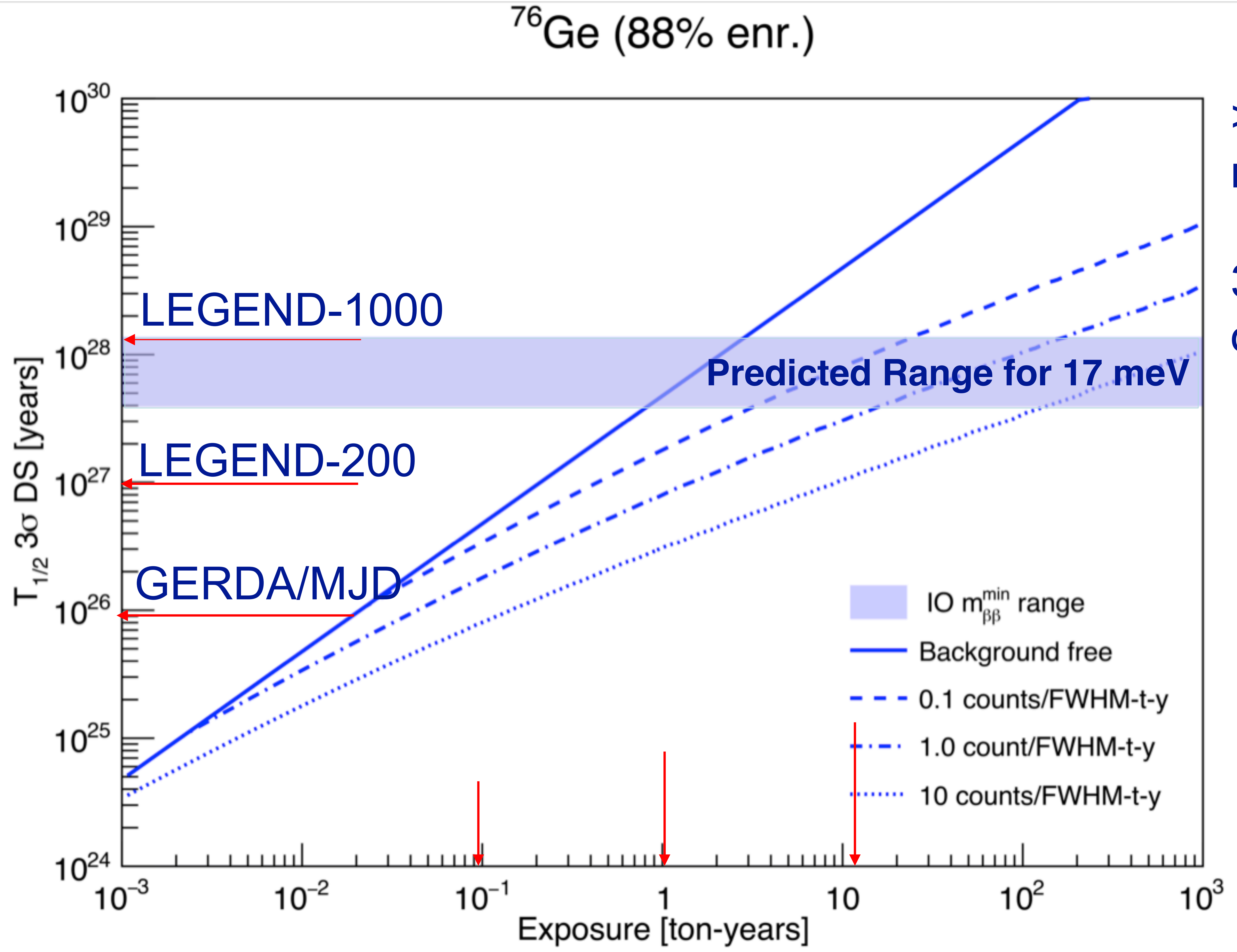
Lightly ionizing particles

First limit for charge as low as e/1000

PRL **120** 211804 (2018)

Going forward to LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND)



>10^{28} yr or $m_{\beta\beta}$=17 meV for worst case matrix element of 3.5 and unquenched g_A.

3-σ discovery level to cover inverted ordering, given matrix element uncertainty.

LEGEND-related presentations at this meeting

- **"Neutron Background Simulations for LEGEND-1000 in a Geant4-based Framework",** Clay Barton for the LEGEND collaboration, Abstract #745, July 31.
- **"Usage of PEN as self-vetoing structural material in low background experiments",** Luis Manzanillas for the PEN working group, Abstract #664, July 30.
- **"Results of the GERDA Phase II experiment",** Konstantin Gusev for the GERDA collaboration, Abstract #752, July 30.

LEGEND (arXiv:1709.01980)

Mission: “The collaboration aims to develop a phased, **Ge-76 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**.”

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

MAJORANA
- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves PSD
- Low energy threshold (helps reject cosmogenic background)

GERDA
- LAr veto
- Low-A shield, no Pb

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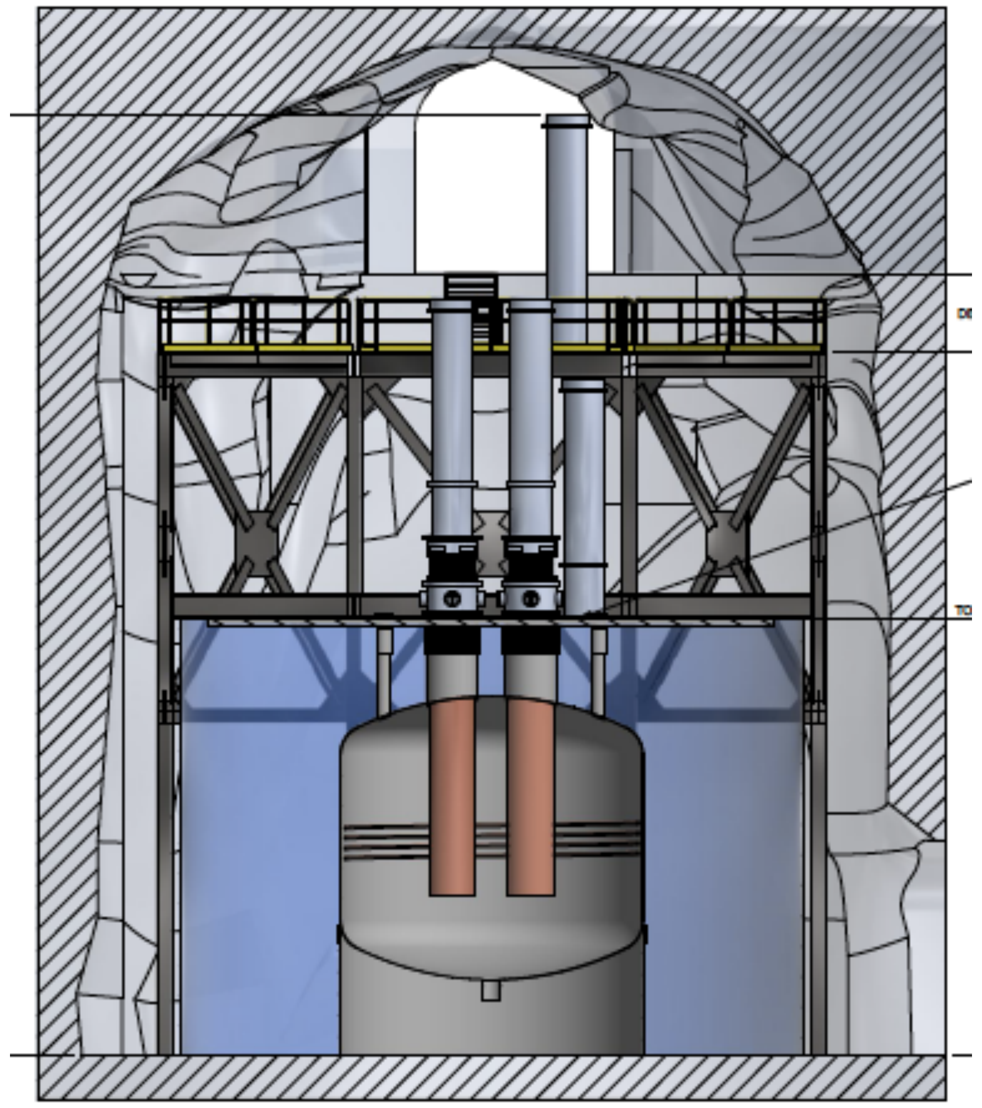
Both
- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution 0νββ experiments

LEGEND

First phase:
- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- BG goal: <0.6 c /(FWMH t y)
- Discovery sensitivity at a half-life of 10^{27} years
- Data start ~2021



Subsequent stages:
- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal <0.03 cts/(FWHM t yr)
- Location to be selected

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, including Dark Matter searches

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

- Completing 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.

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*students

Backup

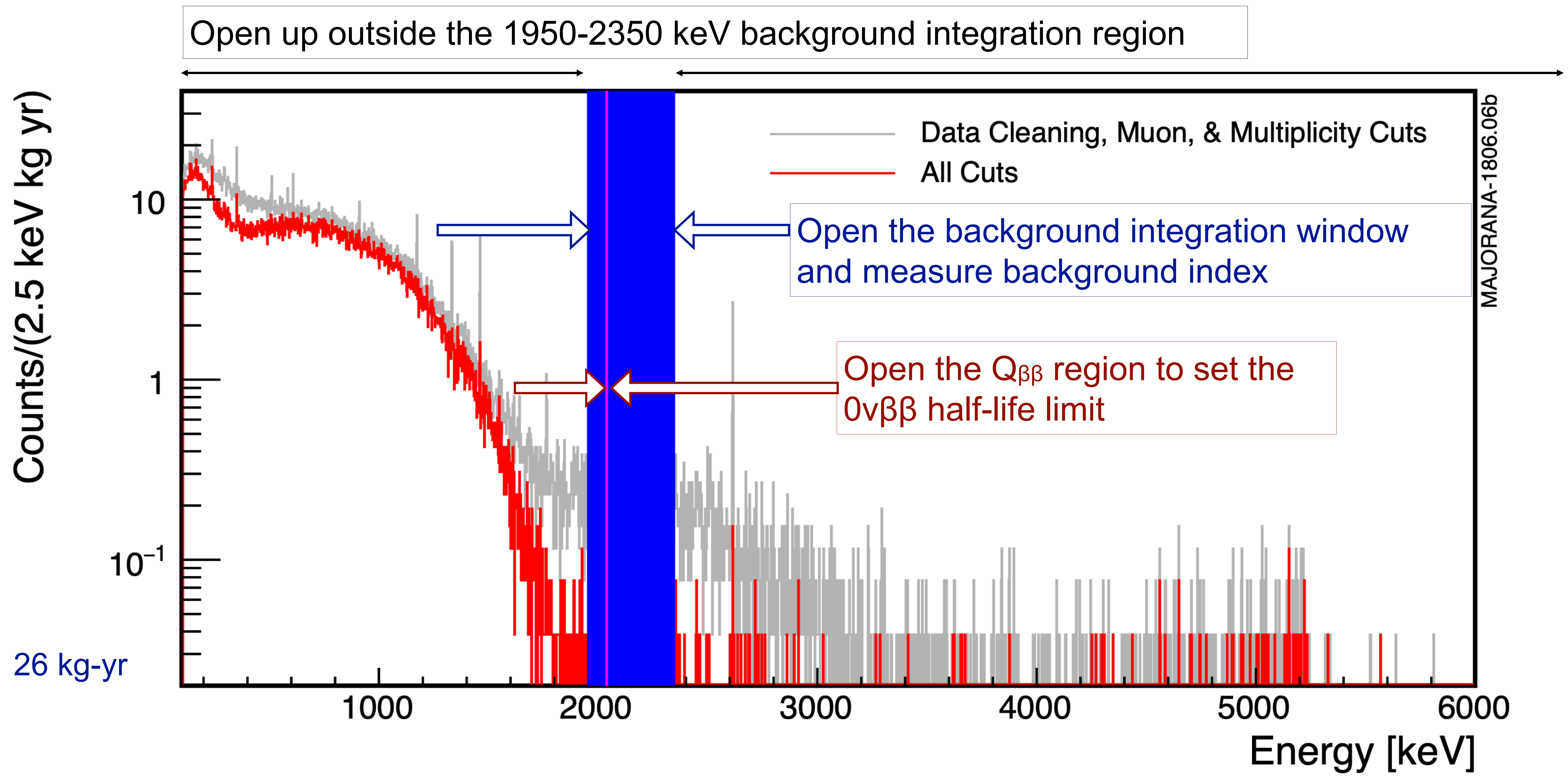
Blindness Implementation

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)



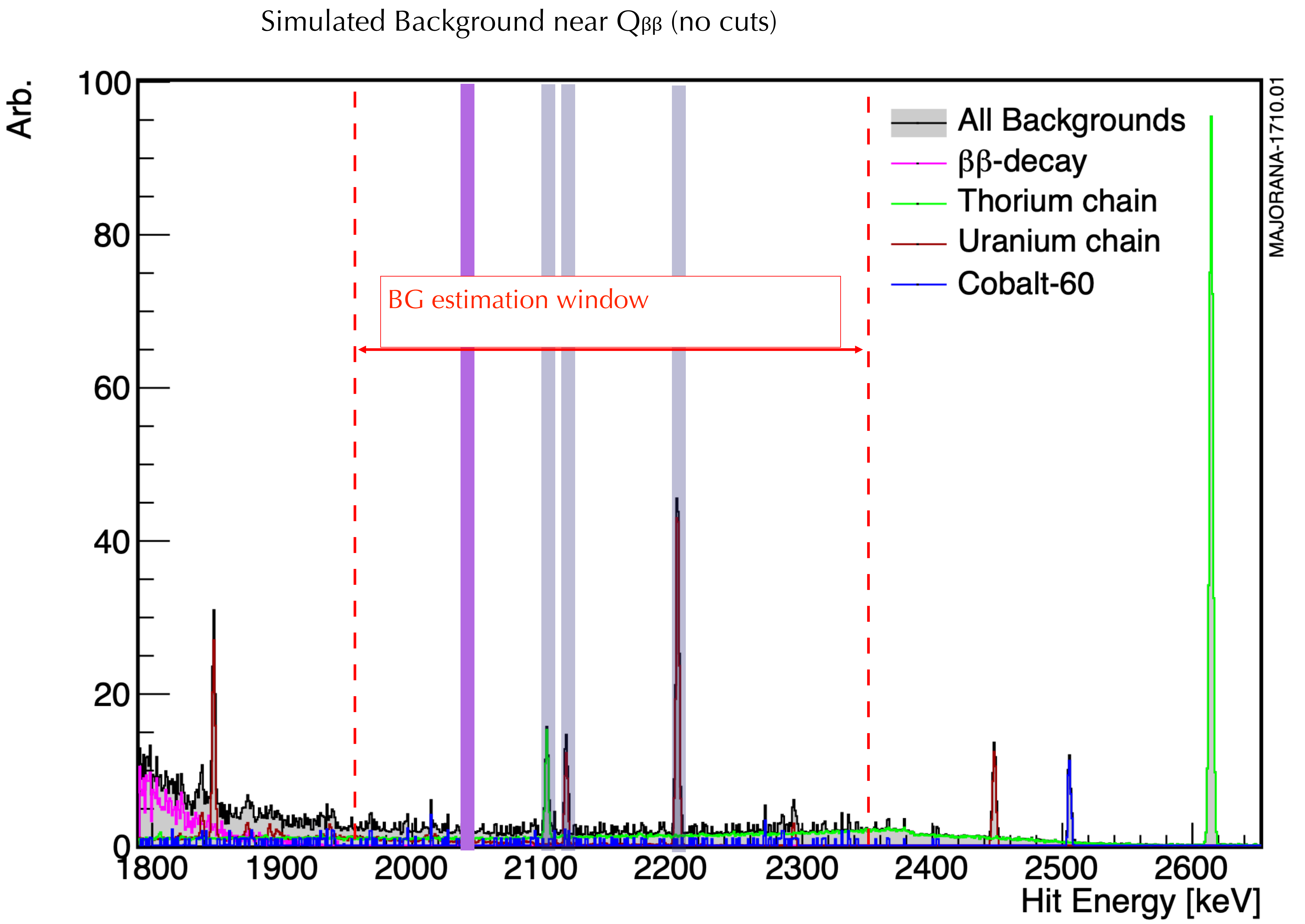
360 keV Background Integration Window

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 $Q_{\beta\beta}$



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

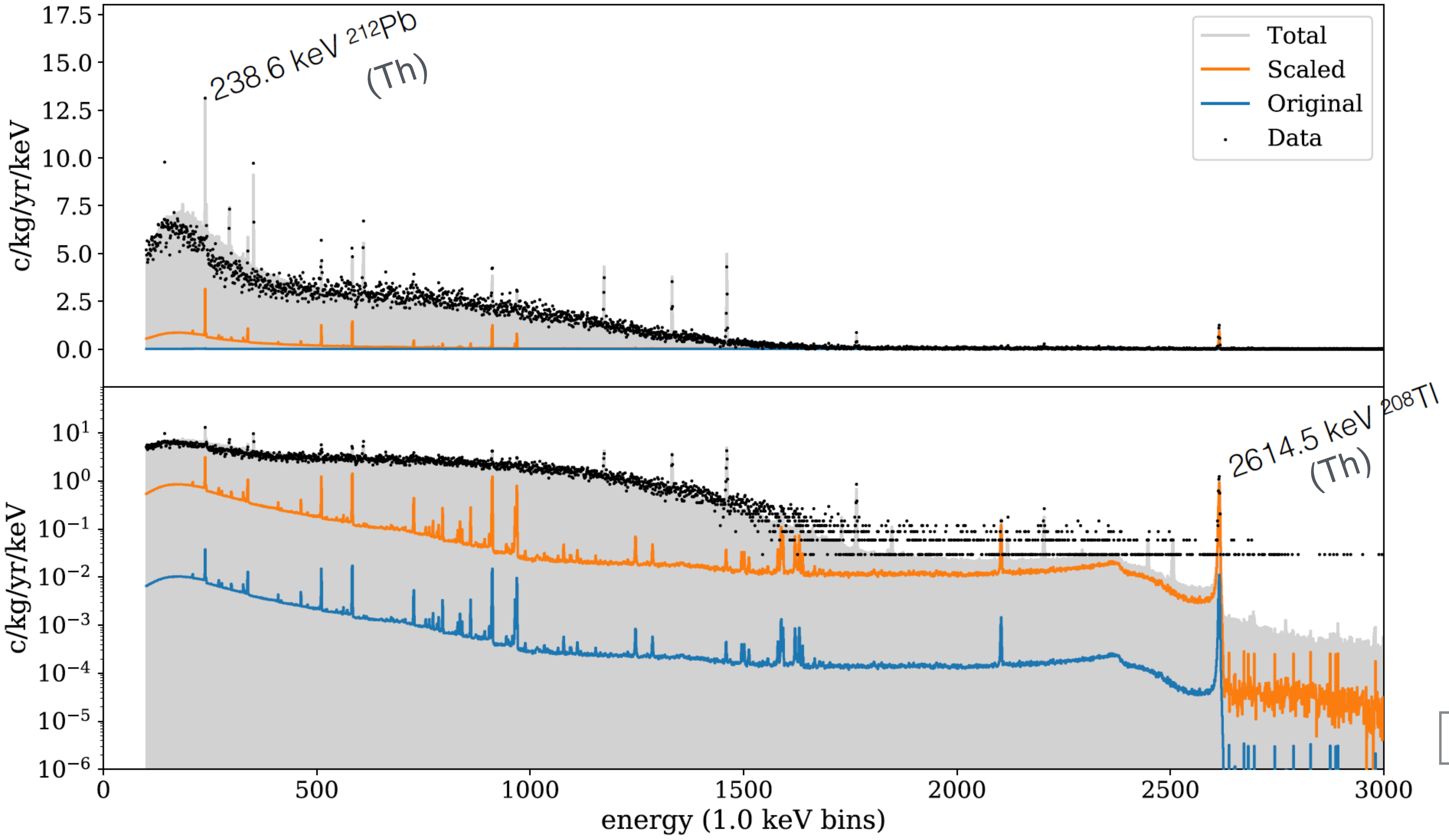
2034 - 2044 keV
$Q_{\beta\beta}$ = 2039 keV

Background Model Development: An example

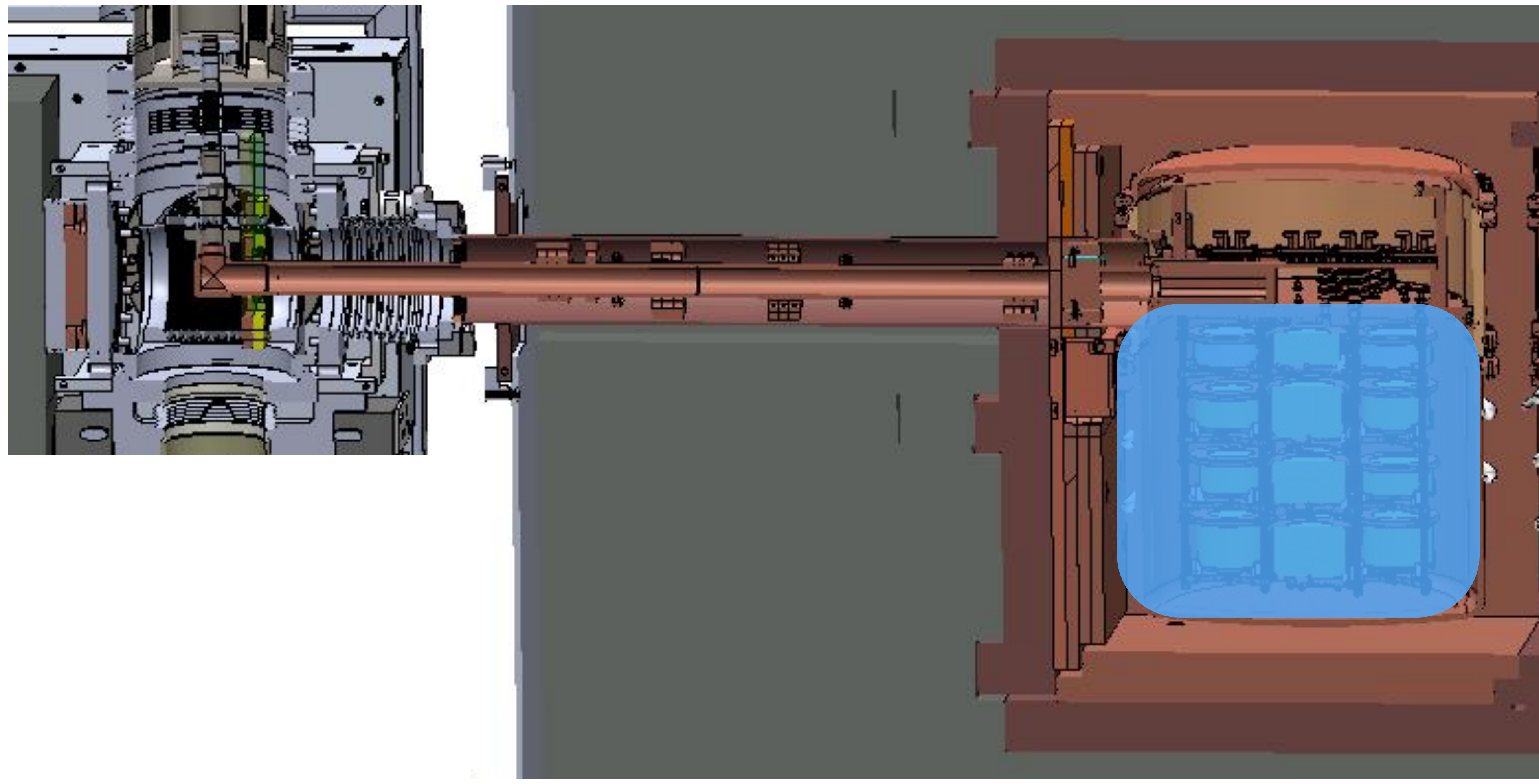
Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components

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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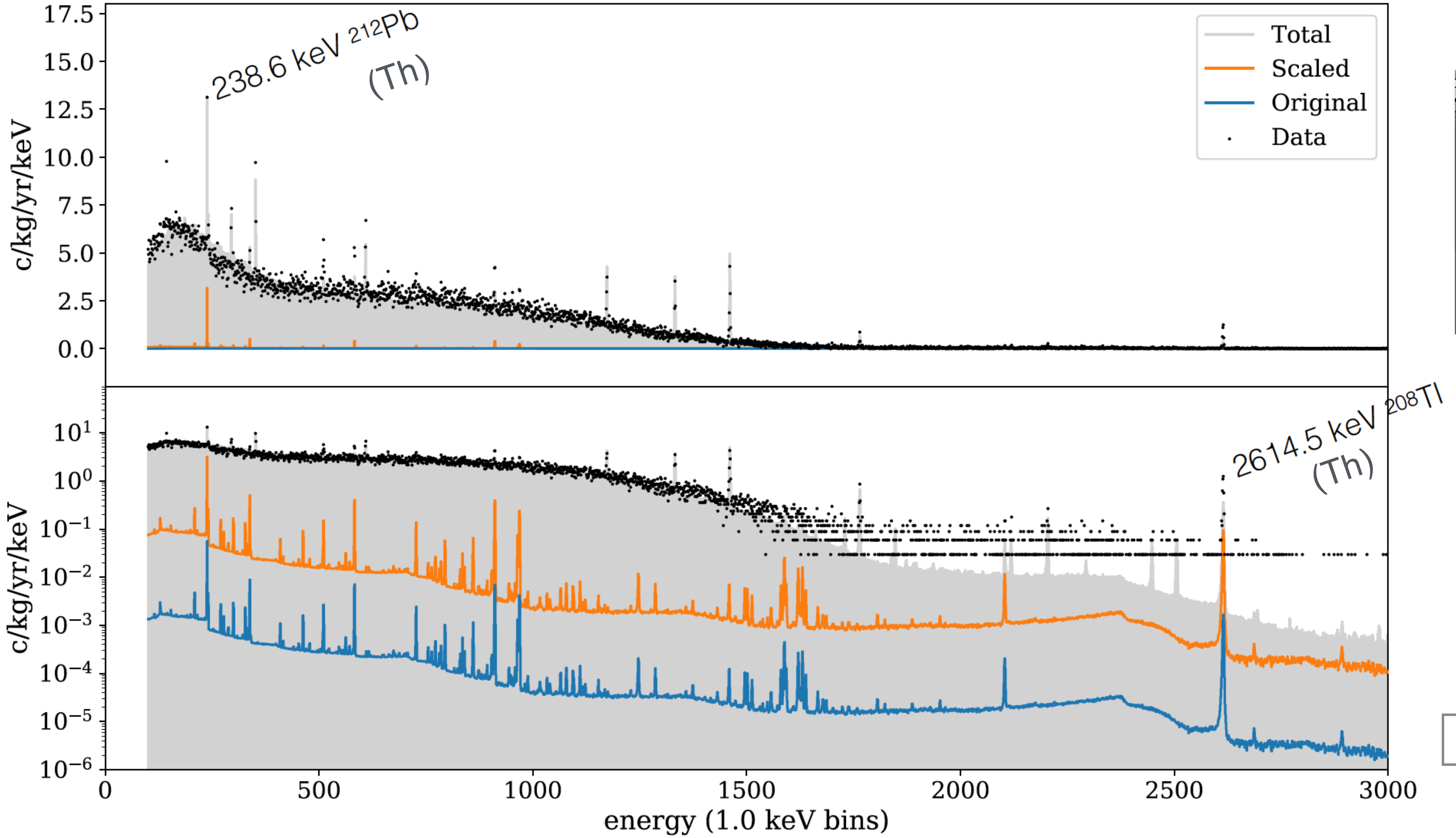
Background Model Development: An example

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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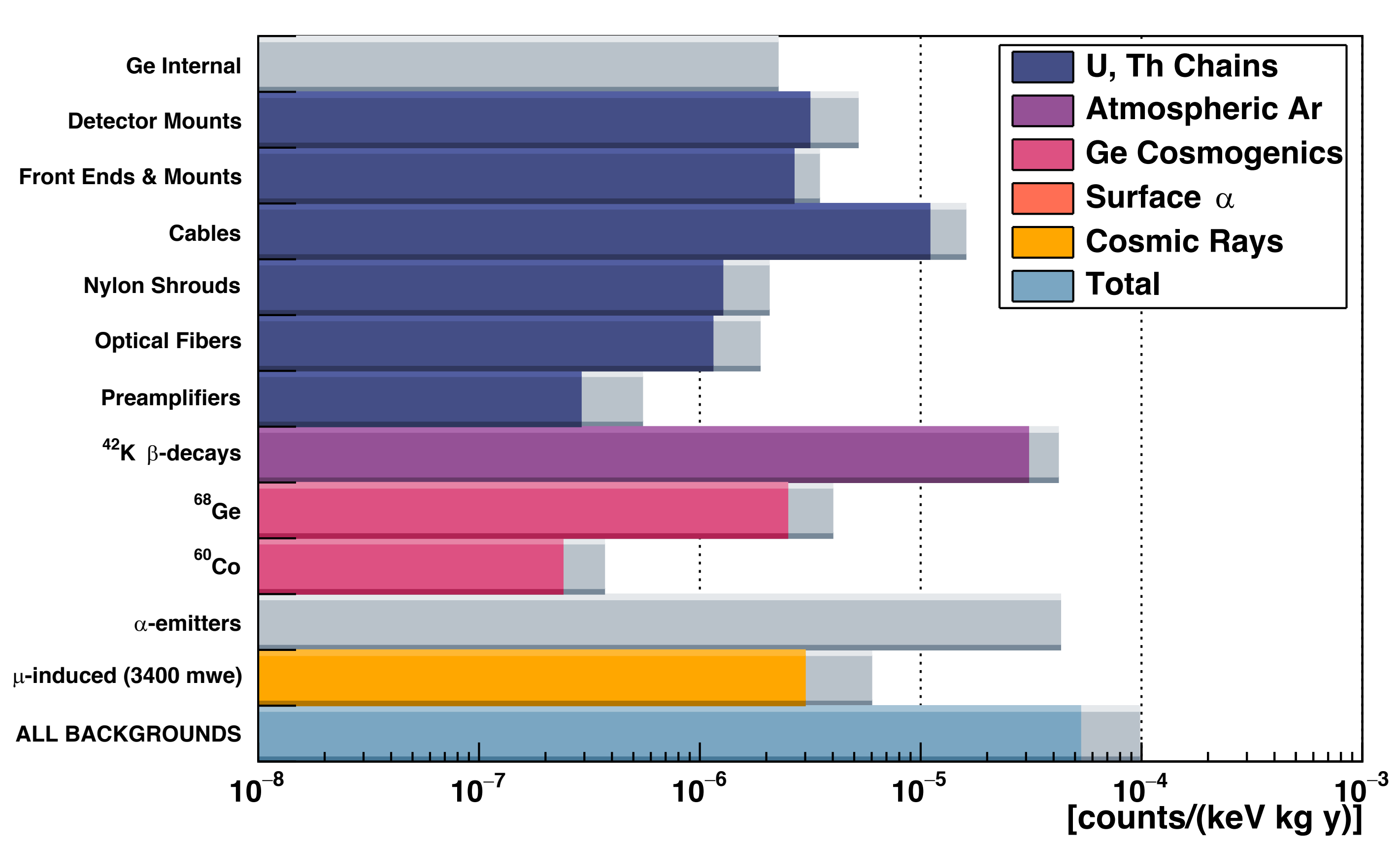

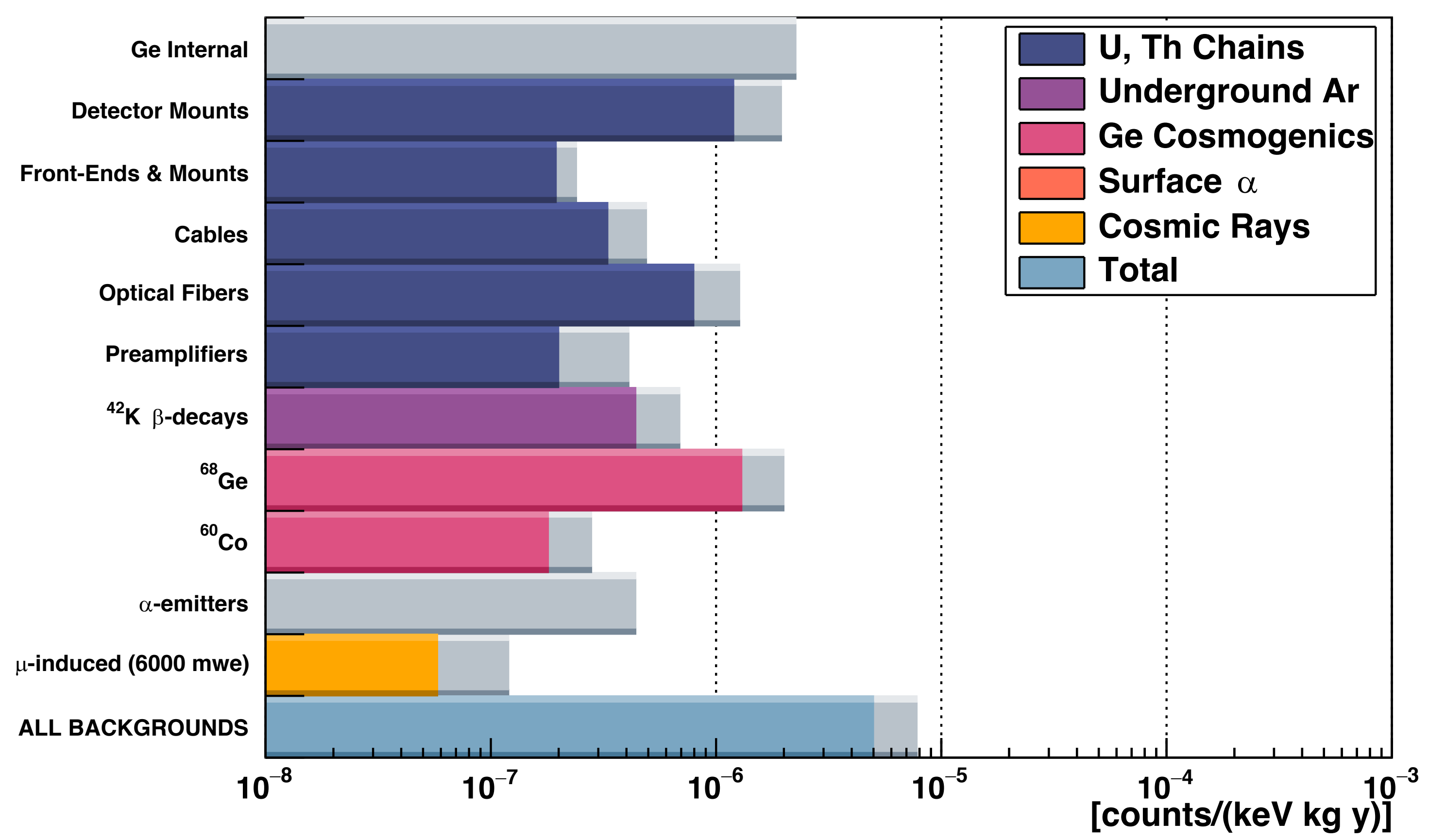

- LEGEND-200 has already informed the LEGEND-1000 background estimate.
- LEGEND-200 background anticipates roughly equal contributions of U/Th, ^{42}Ar, surface α before analysis cuts.

–Because background is so low after cuts, the model has uncertainties.

- LEGEND-1000 needs a background lower by about x20 than LEGEND-200.
- To reach this:

–U/Th can be reduced by optimizing array spacing, minimizing opaque materials, larger detectors, better light collection, cleaner materials, improved active suppression.

–^{42}Ar can be eliminated by using underground sourced Ar.

–Surface α can be reduced by improved process control.

- Hypothesis is Rn in air at detector fabrication facility.

- LEGEND-1000 will have a higher total response and efficiency.

–Larger detectors have a better surface to volume ratio.

–Higher isotope fraction is now cost effective.