Searching for Neutrinoless Double-Beta Decay with the MAJORANA DEMONSTRATOR

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on behalf of the MAJORANA collaboration

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Sanford Underground Research Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

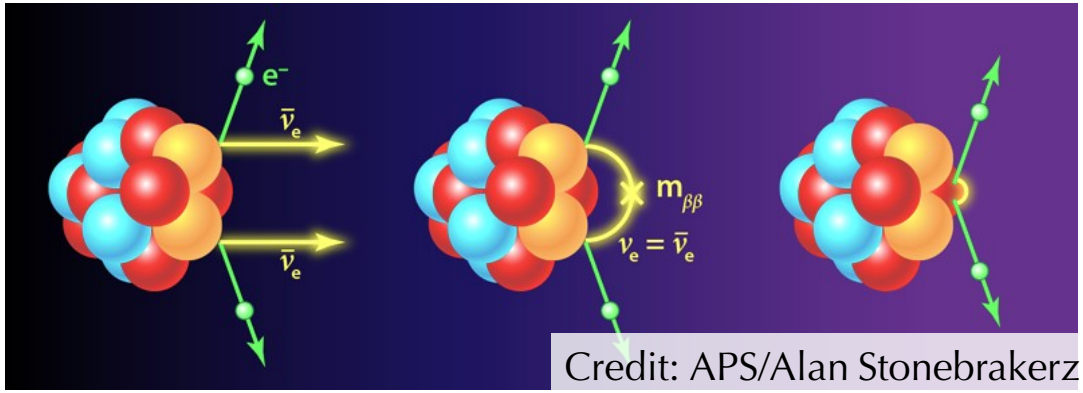
Outline

- Introduction to neutrinoless double beta in ^{76}Ge
- Experimental setup of the MAJORANA DEMONSTRATOR
- Background Modeling
- Implications for LEGEND
- Beyond the Standard Model searches

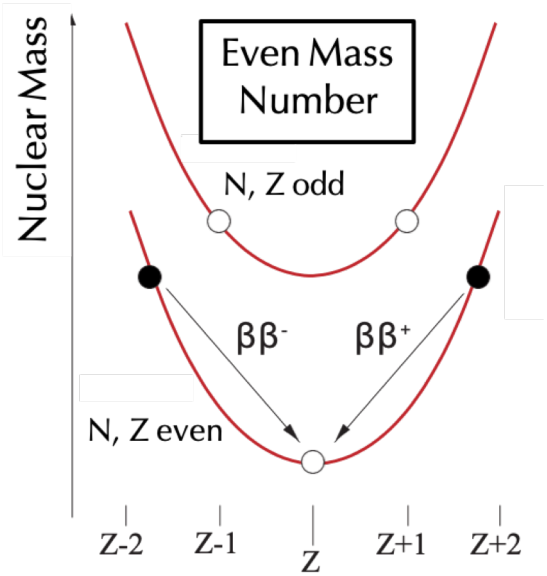
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

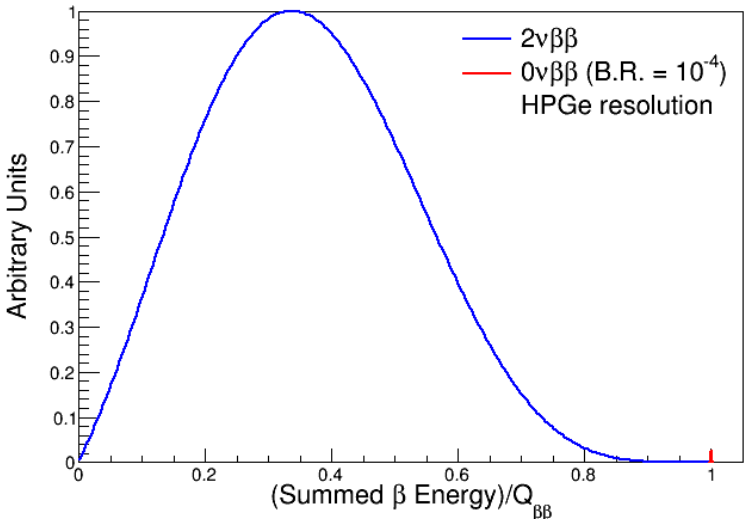
The signature of $0\nu\beta\beta$ is a model-independent probe of physics beyond the Standard Model

Majorana neutrinos violate lepton conservation



Credit: APS/Alan Stonebrakerz



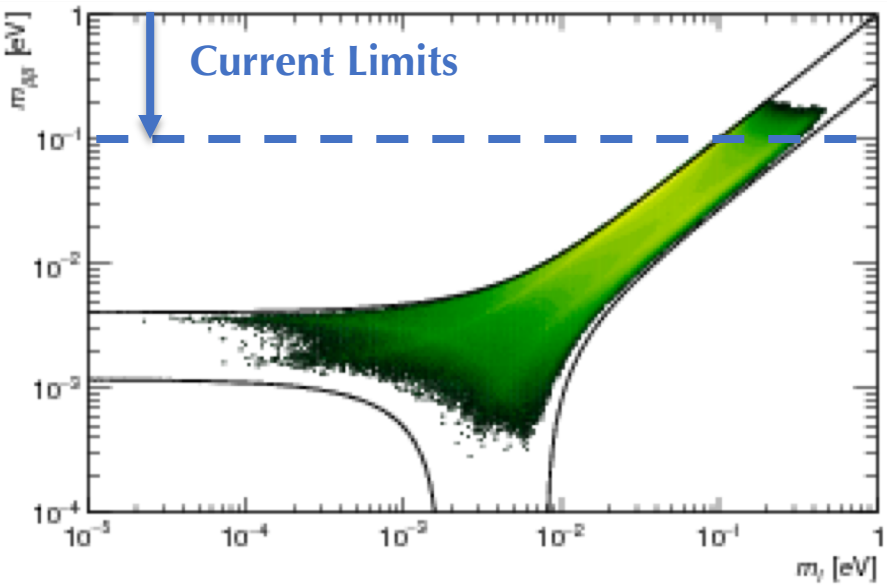


$0\nu\beta\beta$ Current Status and Future Prospects

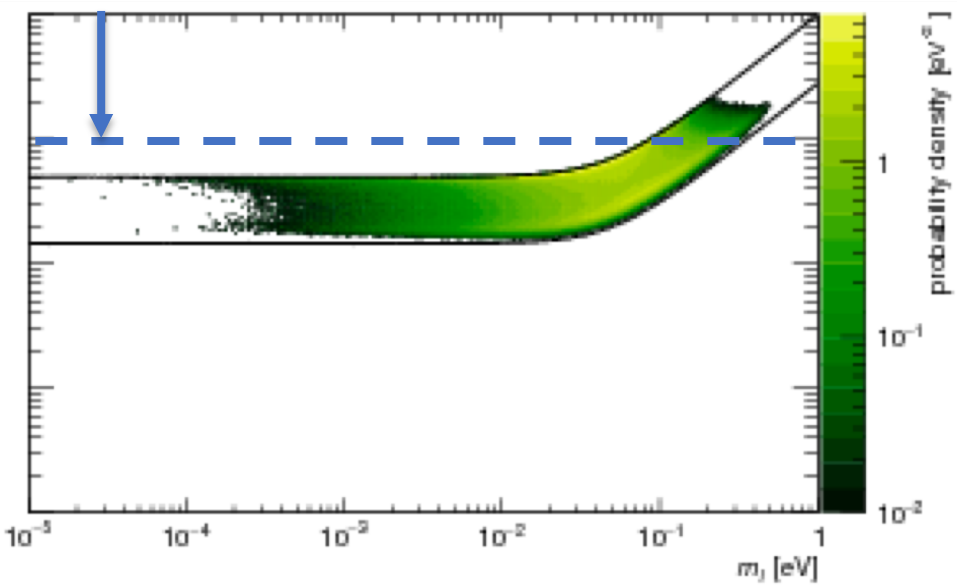
Assuming $0\nu\beta\beta$ occurs via light neutrino exchange, the decay half life depends on the neutrino mass scale:

$$[T^{0\nu}_{1/2}]^{-1} \propto m^2_{\beta\beta} \qquad \langle m_{\beta\beta} \rangle = \left| \sum_k m_k U^2_{ek} \right|$$

Normal Ordering



Inverted Ordering



Bayesian posterior distributions of $0\nu\beta\beta$ parameter space (assuming absence of mechanisms driving $m_{\beta\beta}$ or m_l to 0)

[Agostini, Benato, Detweiler (2017) arXiv:1705.02996v3

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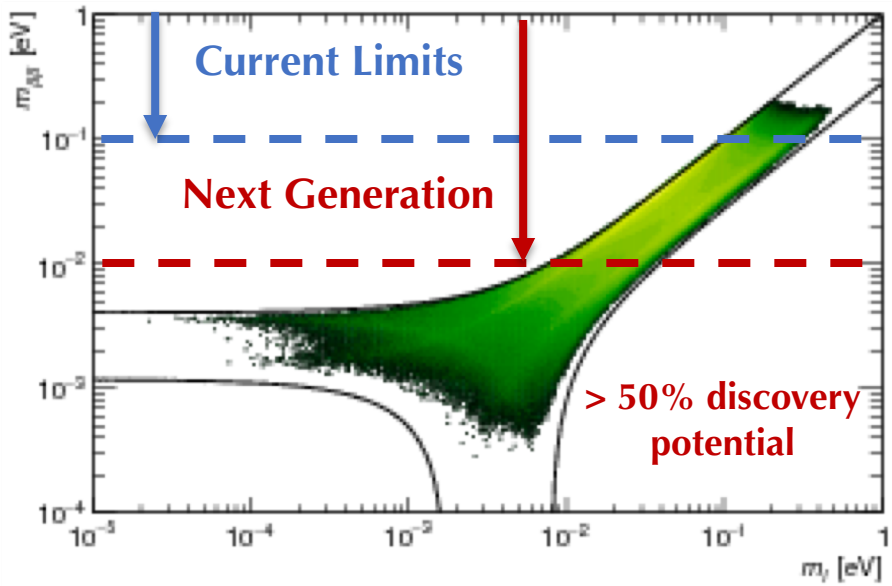

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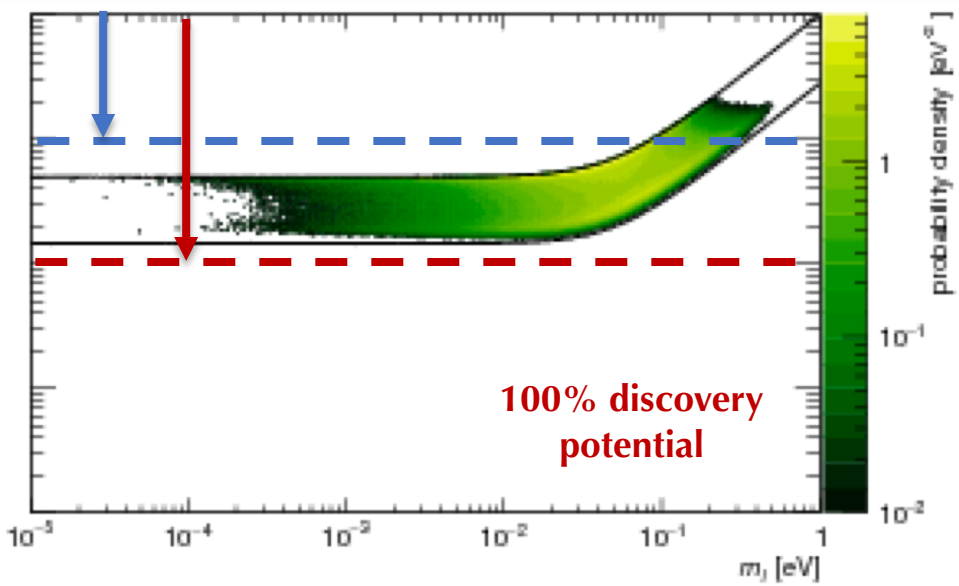
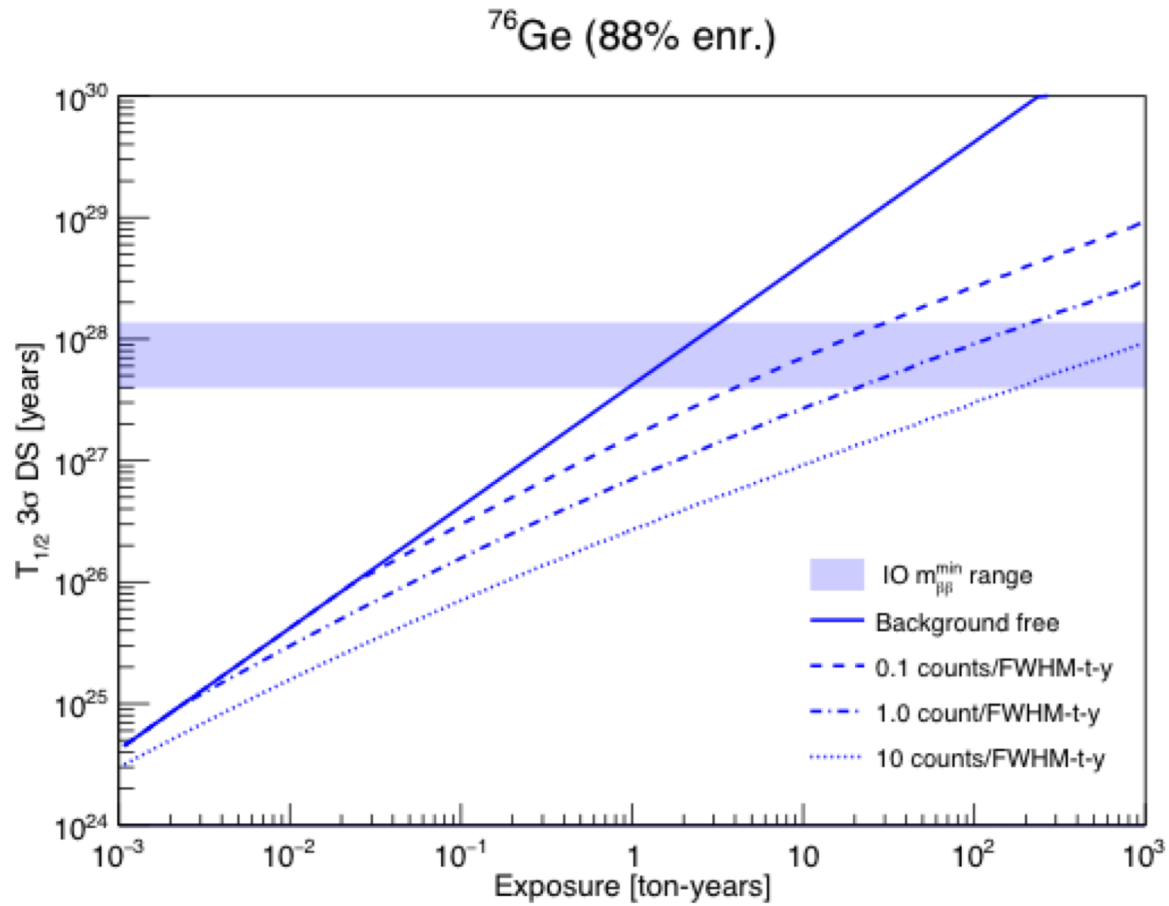


Bayesian posterior distributions of $0\nu\beta\beta$ parameter space (assuming absence of mechanisms driving $m_{\beta\beta}$ or m_l to 0)

[Agostini, Benato, Detweiler (2017) arXiv:1705.02996v3

$0\nu\beta\beta$ with Germanium Detectors

- Intrinsic high-purity Ge as both the **source and detector**
- Demonstrated **ability to enrich** from 7.4% ^{76}Ge to 88% (and beyond)
- Best **energy resolution** at the Q-value of all $0\nu\beta\beta$ experiments)
- Powerful background rejection, leading to lowest achieved **background index** in the ROI of all $0\nu\beta\beta$ isotopes



If not background free,

$$T_{1/2}^{0\nu} \propto \varepsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

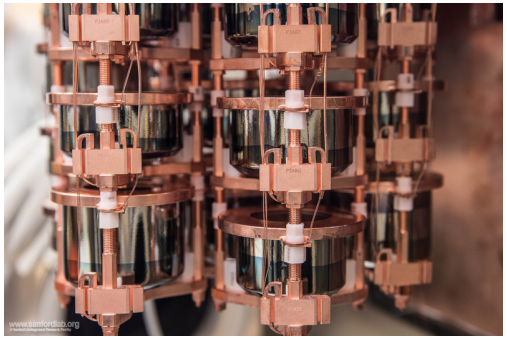
MAJORANA DEMONSTRATOR

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

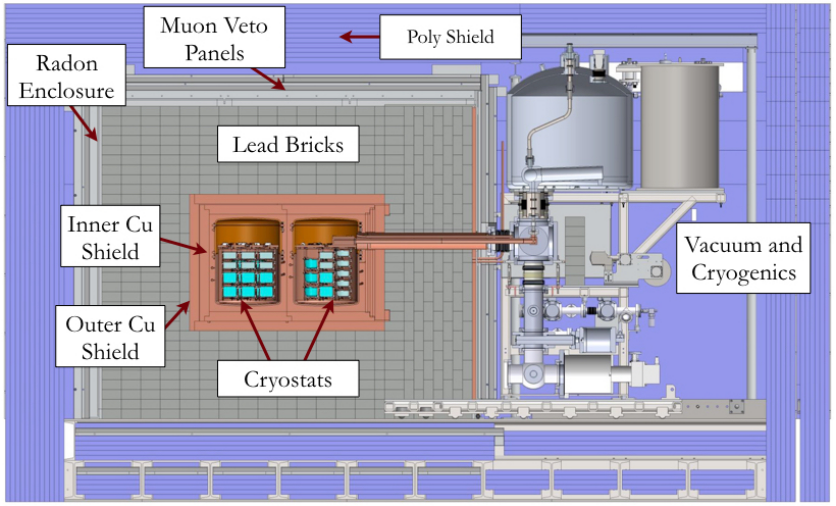
Source & Detector: Array of p-type, point contact detectors 29.7 kg of 88% enriched ^{76}Ge crystals, and 14.4 kg of 7.8% (natural) ^{76}Ge crystals.

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



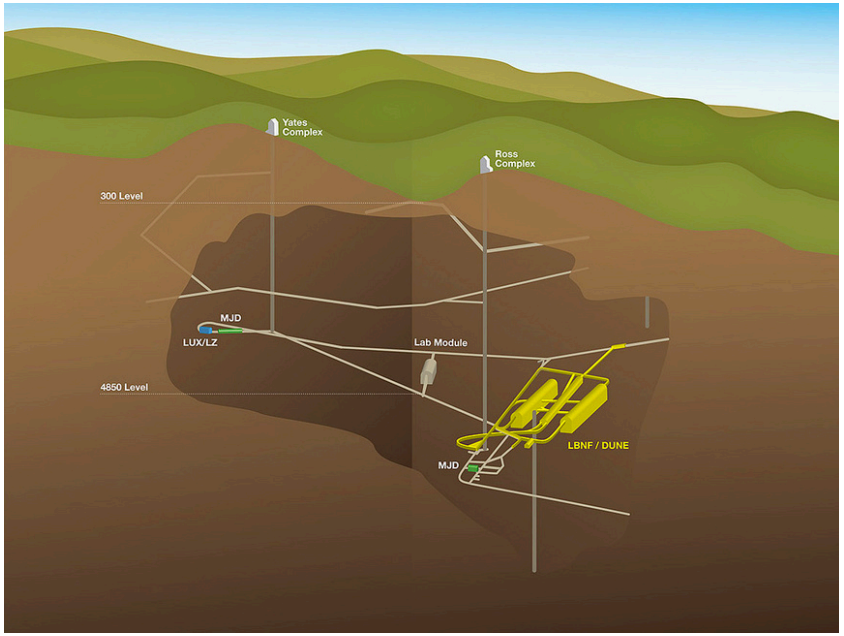
Mitigating Backgrounds

Potential sources of background include:

- Long-lived cosmogenics
- Naturally occurring radiation (alphas and gammas from ^{238}U and ^{232}Th decay chains)
- Neutrons
- $2\nu\beta\beta$

MAJORANA Background Reduction Techniques

- Underground lab space
- Passive shielding and active muon veto
- Radiopure near-detector components
- Analysis cuts due to PPC detector properties

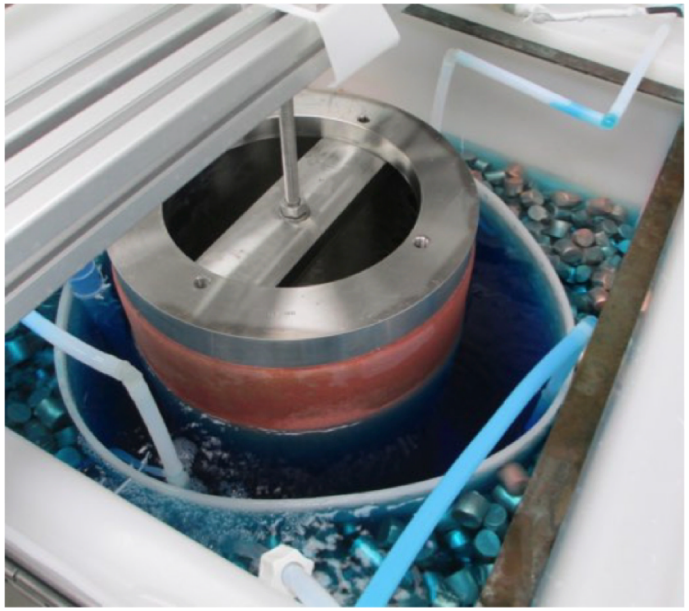


From https://www.flickr.com/photos/134273042@N07/19700139489

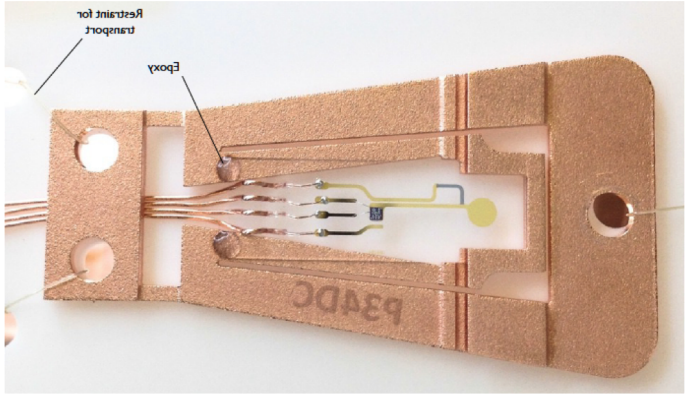
Detector Modules and Shield

- 2 modules with independent electronics and cryogenics
- Active muon veto
- N_2 purged radon exclusion box
- Compact, graded shield
  - 30 cm polyethylene
  - 45 cm high-purity Pb
  - 5 cm commercial Cu
  - 5 cm underground electroformed copper (UGEFCu)

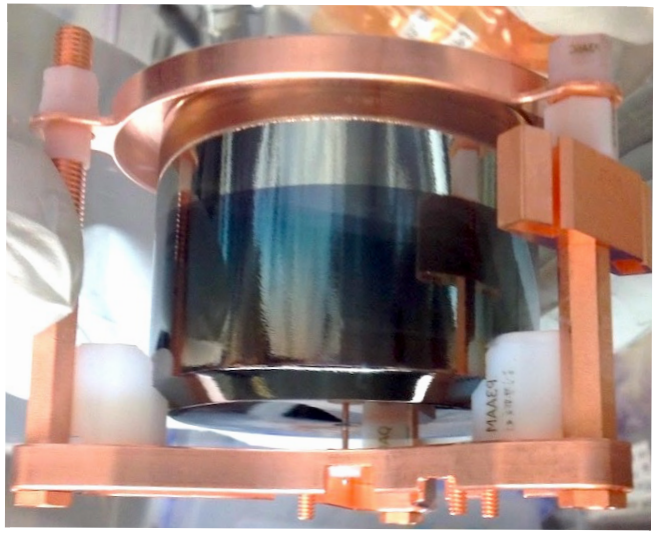
Radiopure Components



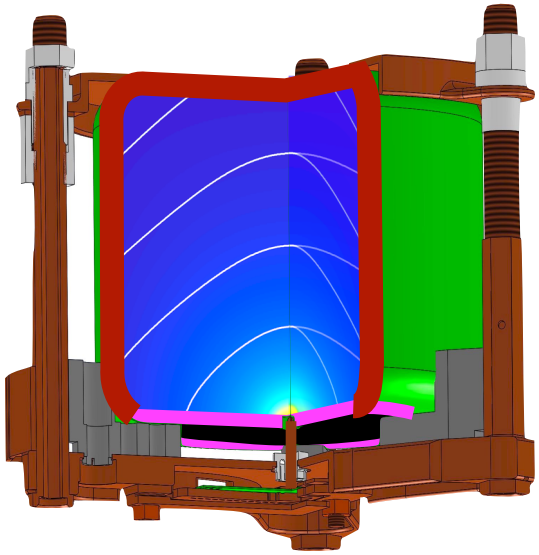
- Ultra-pure materials
  - Low mass design
  - Underground electroformed Cu
    - Th decay chain ≤ 0.1 μBq/kg
    - U decay chain ≤ 0.1 μBq/kg
  - Custom connectors and front-end electronics
  - Carefully selected plastics and pico-Coax cables
- Machining and cleaning in underground clean room
- Assembly and parts storage in N_2 purged environment

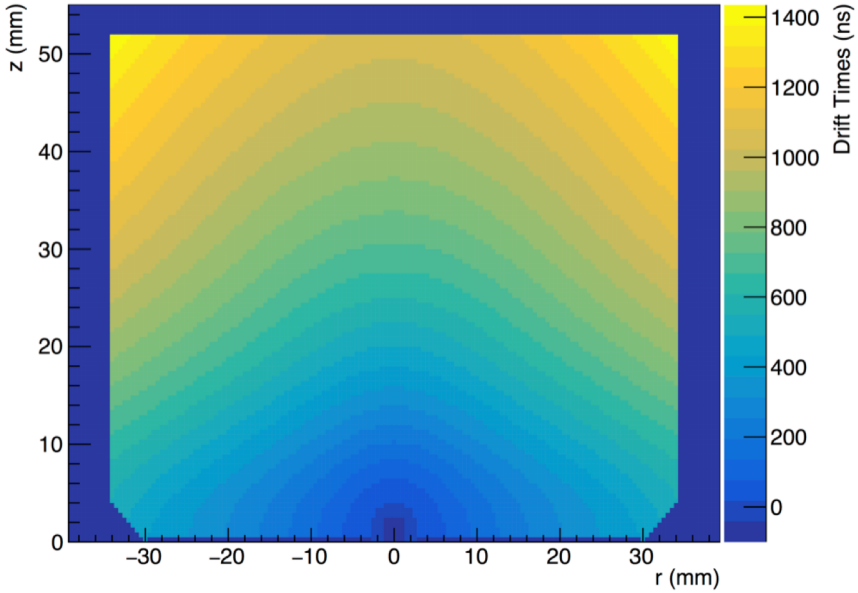


P-type Point Contact (PPC) Detectors



- p^+ Point Contact (Ge)
- n^+ Outer Contact (Li)
- Active (Intrinsic) Volume
- Transition Region (~1 mm)
- Passivated Surface (~1 μm)
- Passivation Boundary



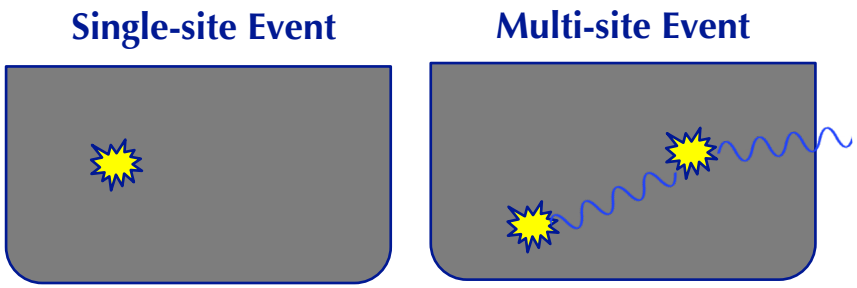


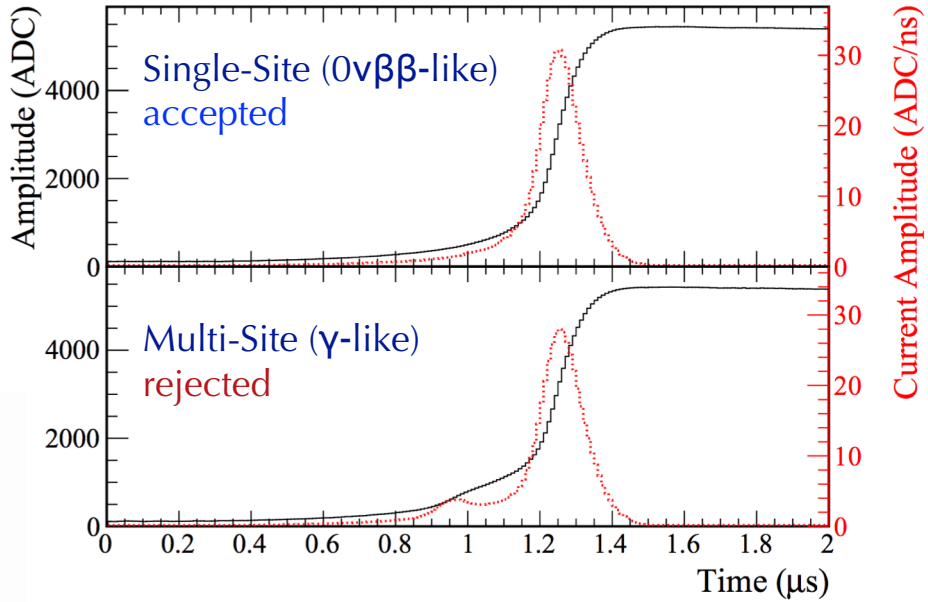
Benefit of PPCs for background rejection:

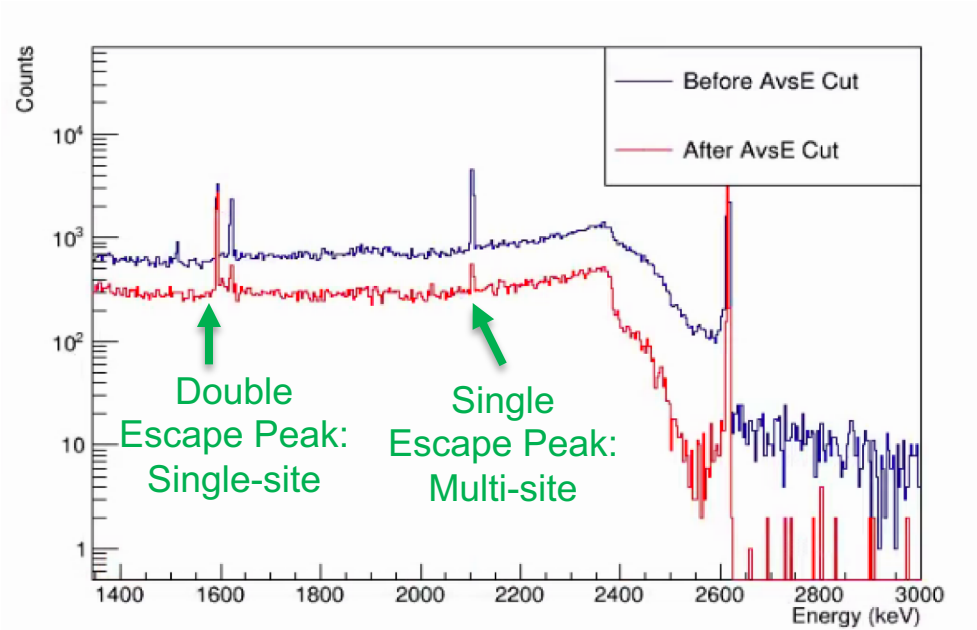
Pulse shape is highly **dependent on position** of energy deposit due to:

- **Slow drift time** of the ionization charge cloud
- Localized weighting potential—**most of signal induced** when charge carriers are very **close to p^+ contact**

Multi-site Event Rejection







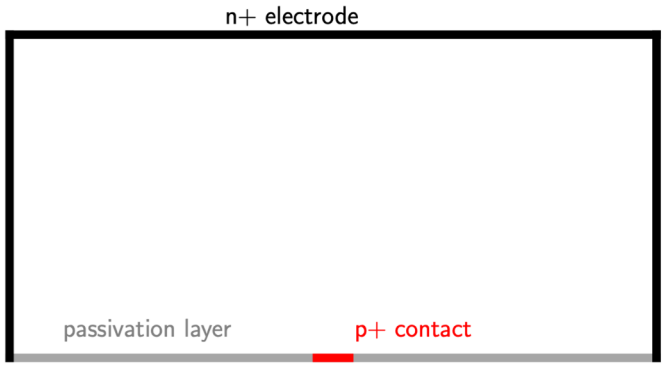
AvsE Cut: Amplitude of current pulse (A) is reduced for a multi-site event compared to a single-site event of the same event Energy (E)

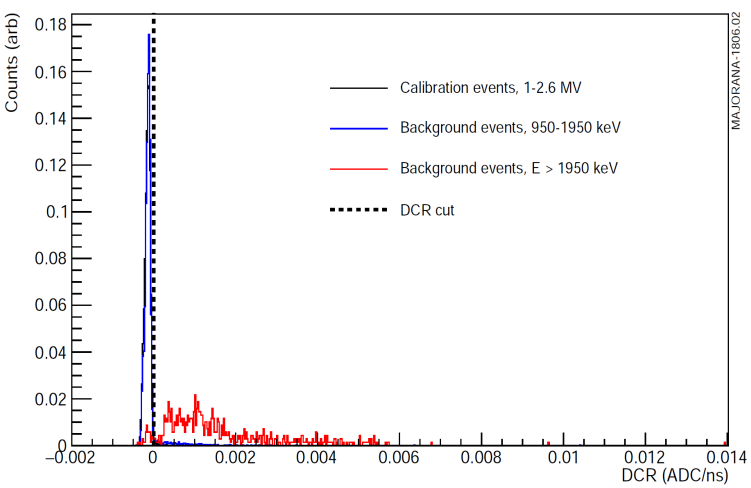
PRC **99** 065501 (2019)

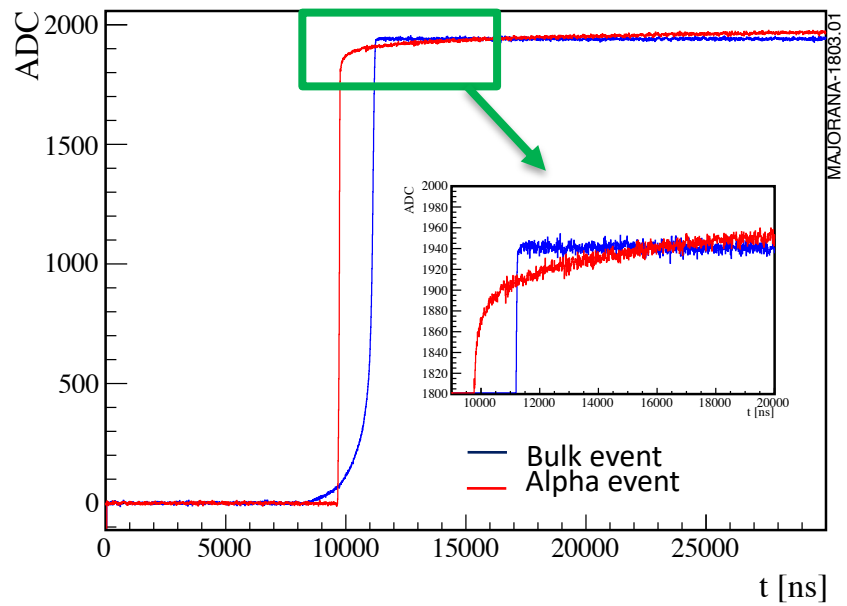
^{228}Th calibration data is used to tune AvsE cut and evaluate its efficiency

Surface Alpha Rejection

Alpha background with degraded energies observed; charge trapped at passivated surface, slowly released into bulk





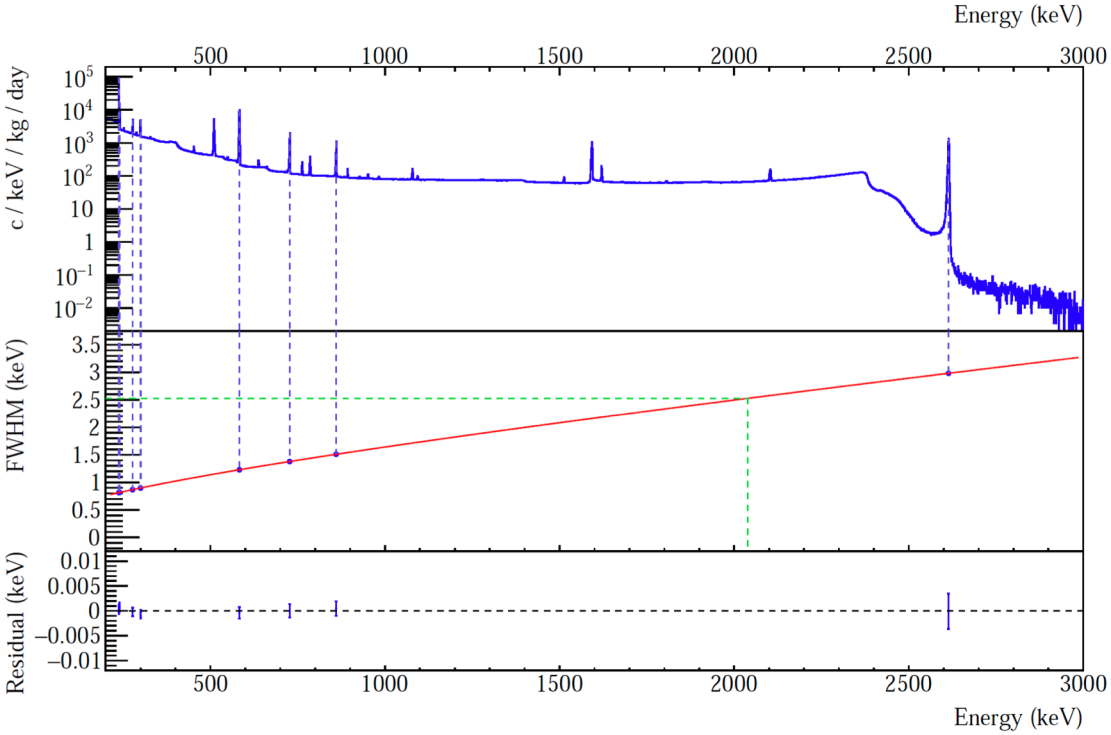


Implemented delayed charge recovery (DCR) cut based on slope of waveform tail

Energy Resolution

- 2.53 keV FWHM at $0\nu\beta\beta$ Q-value—best of any $0\nu\beta\beta$ experiment
  - PPC design and location of first stage electronics near readout contact
  - Charge trapping and adc-nonlinearity corrections applied to filtered, pole-zero corrected waveforms

- Weekly calibrations using ^{228}Th line source

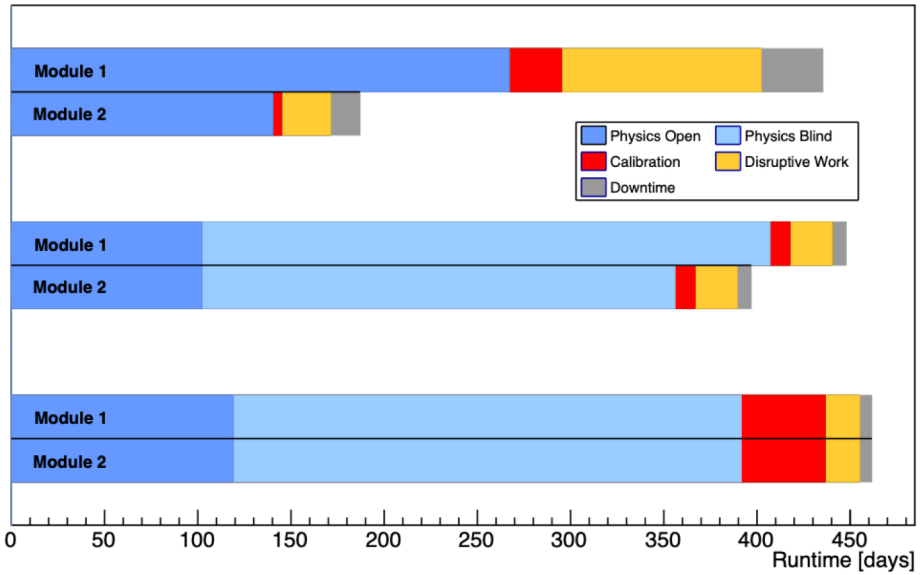


Runtime and Exposure

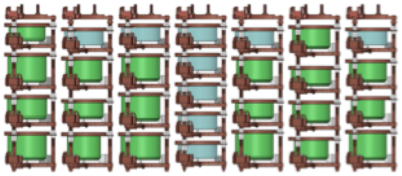
Open data: Jun. 2015 - Mar. 2017
9.95 kg-yr

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

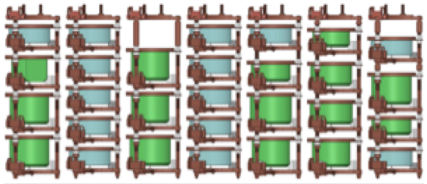
April 2018 - Present*



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

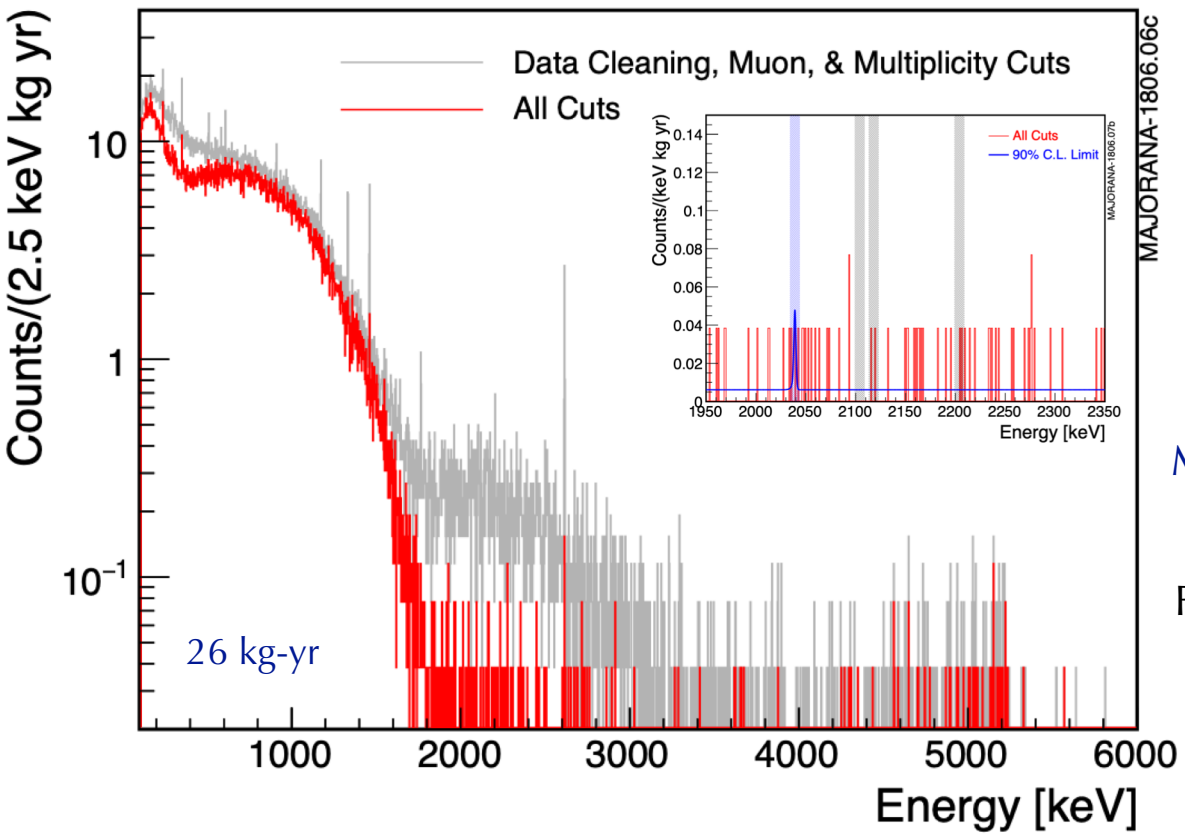


2017 Release	**2018 Release**
9.95 kg-yr open data	26 kg-yr open+blind
PRL **120** 132502 (2018)	PRC **100** 025501(2019)

*As of July 24, 2019

2018 0νββ Result

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



Initial Release:

PRL 120 132502 (2018)

Latest Release:

First unblinding of data
26 kg-yr of exposure

PRC **100** 025501(2019)

Median half-life sensitivity:

$$4.8 \times 10^{25}\ \mathrm{yr}$$

Full Exposure Limit:

$$T^{0\nu}_{1/2} > 2.7 \times 10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{CL})$$

Background index at 2039 keV in the lowest background configuration:

$$11.9 \pm 2.0\ \mathrm{cts/(FWHM\ t\ yr)}$$

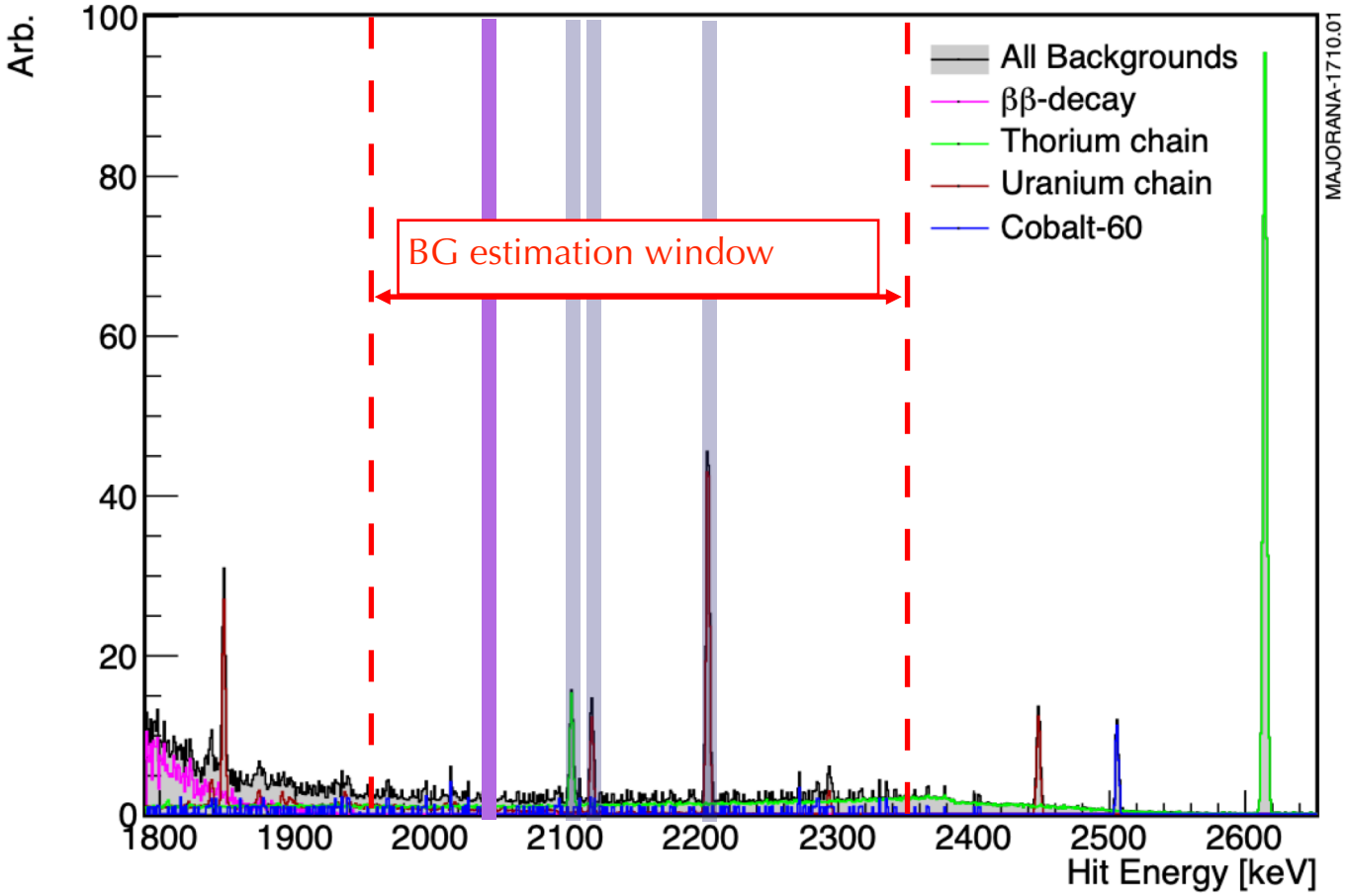
360 keV Background Integration Window

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

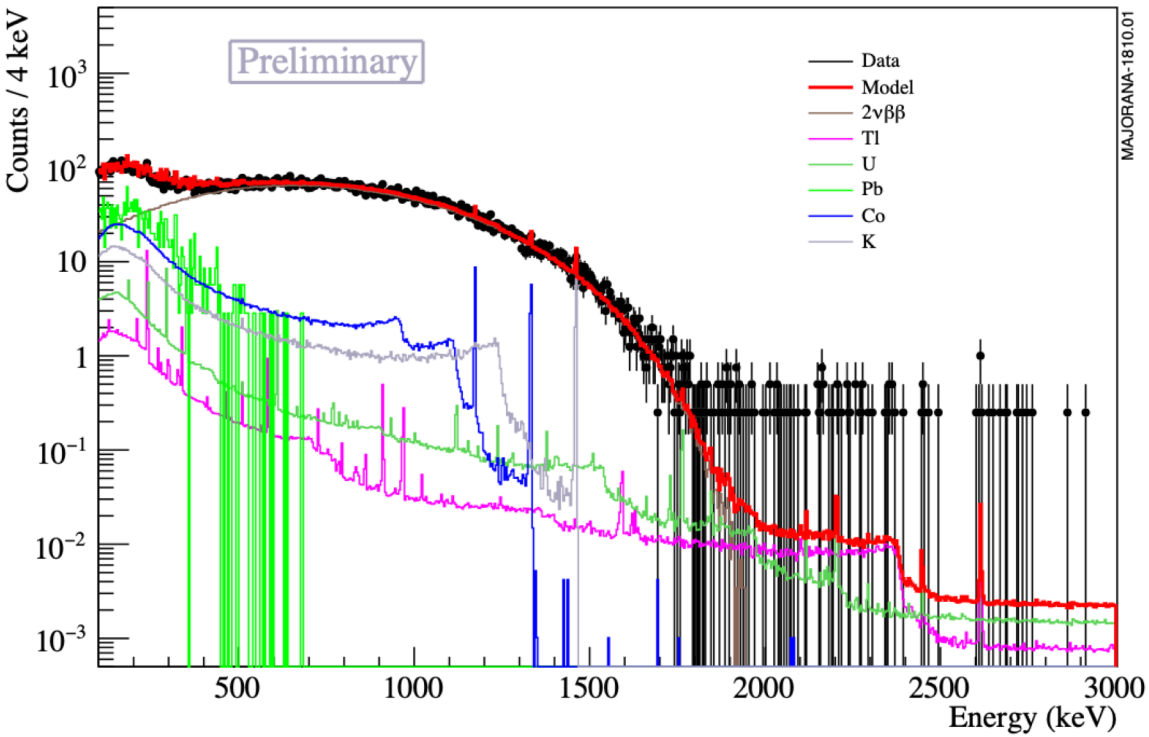
Background Model Development

Observed background of 11.9 +/- 2.0 c/(FWHM t y) based on the 1950-2350 keV window

Initial assay measurements with early simulations predicted <2.2 c/(FWHM t y) at $Q_{\beta\beta}$

Reviewing available assay information and updating the assay-based model with as-built simulations, detector configurations, and updated physics lists

All cuts, components fixed to assay estimate



Developing a background model to fit the observed energy spectra

- MaGe/Geant4 simulations with the as-built geometry of experiment
- ~4000 parts, ~70 unique designs
- ~40 component groups of related parts

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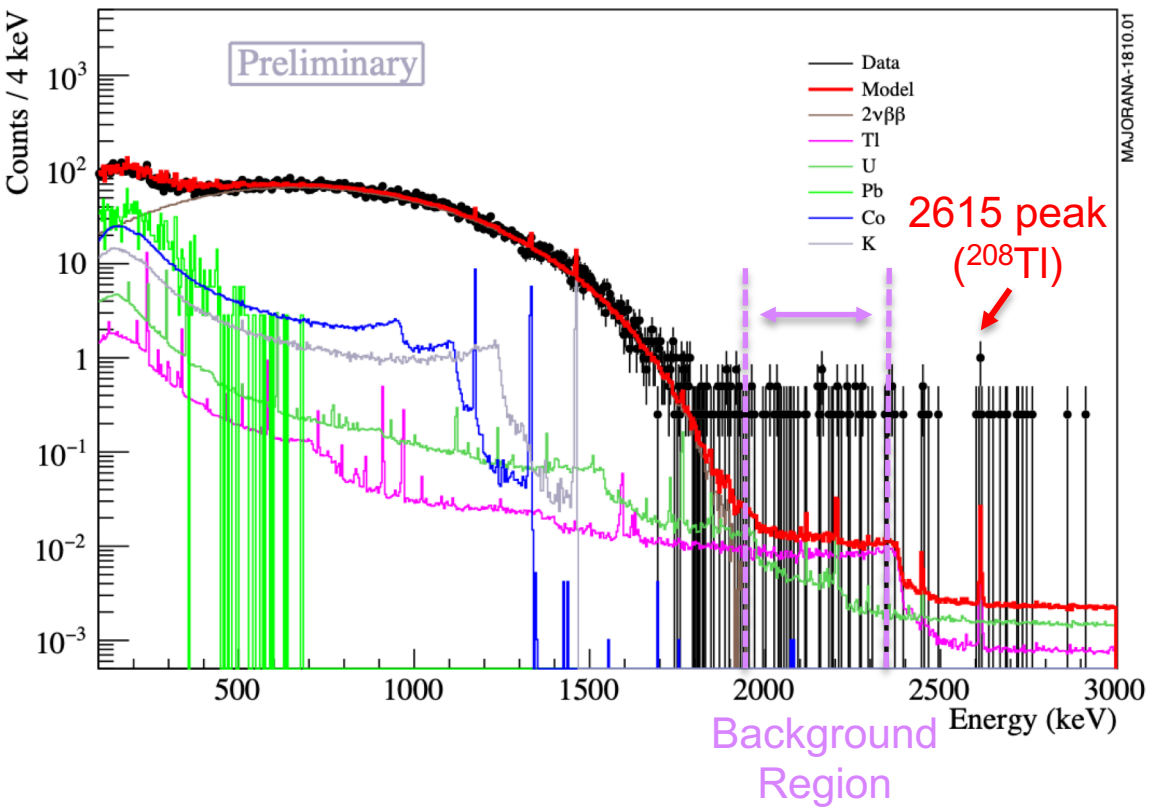

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Background Model Development

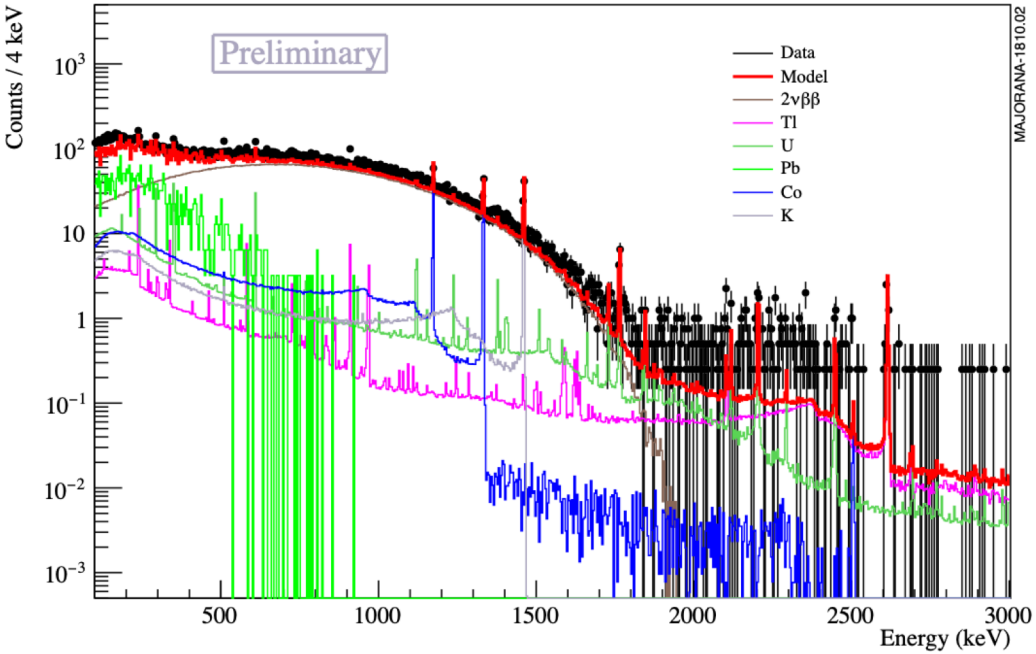
Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components

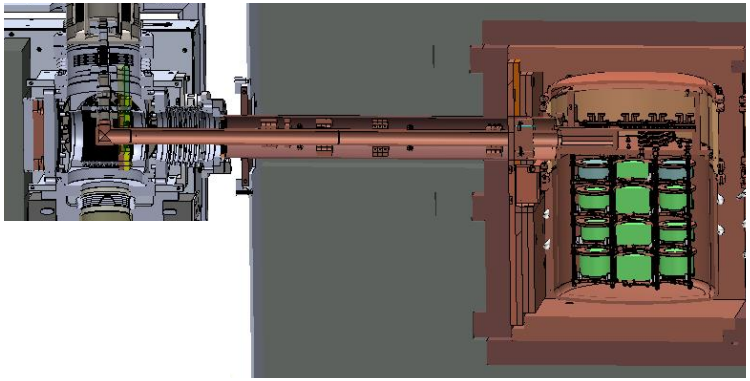
- Based on the energy dependence of the peak intensities
- Also consistent with the low rate of detector coincidences observed
  - One observed coincidence between 583 and 2615 keV ^{208}Tl-decay gammas.
  - Factor of 5-10 more expected for sources near detectors

Identifying missing spectral components

Using coincidence studies to constrain spectral fits

No multisite cut, activities fit to background spectrum





Initial spectral fits missing strength at high energies

Significance for LEGEND

Next Generation ^{76}Ge: LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay
(52 institutions, ~250 members)

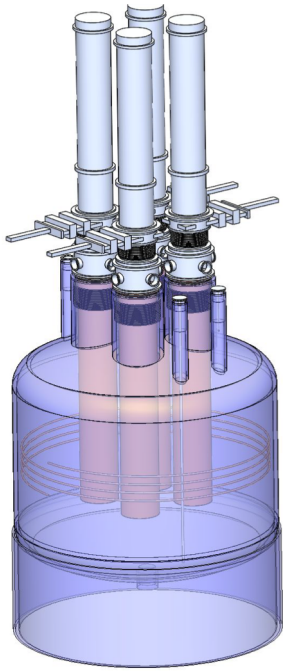
The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with **discovery potential at a half-life beyond 10^{28} years**.

First phase:

- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x5 lower) 0.6 c /(FWHM t y)
- start by 2021

Subsequent stages:

- 1000 kg (staged)
- BG: goal (x30 lower) <0.1 c /(FWHM t y)
- Location and start date: TBD



Select best technologies from existing experiments, such as MAJORANA and GERDA

GERDA	LEGEND	MAJORANA
Liquid argon veto	Clean fabrication techniques	Radiopure components
Water shield (no Pb)	Controlled surface exposure	Low noise electronics
Existing infrastructure	Development of new detectors	Low energy thresholds

Beyond the Standard Model Searches

The DEMONSTRATOR's **low backgrounds and high resolution** enable competitive BSM searches. For processes that require coincident events, backgrounds are even lower.

In addition, the **low thresholds** and **controlled surface exposure** of enriched Ge material to minimize cosmogenic backgrounds make a low energy program possible.

Publications

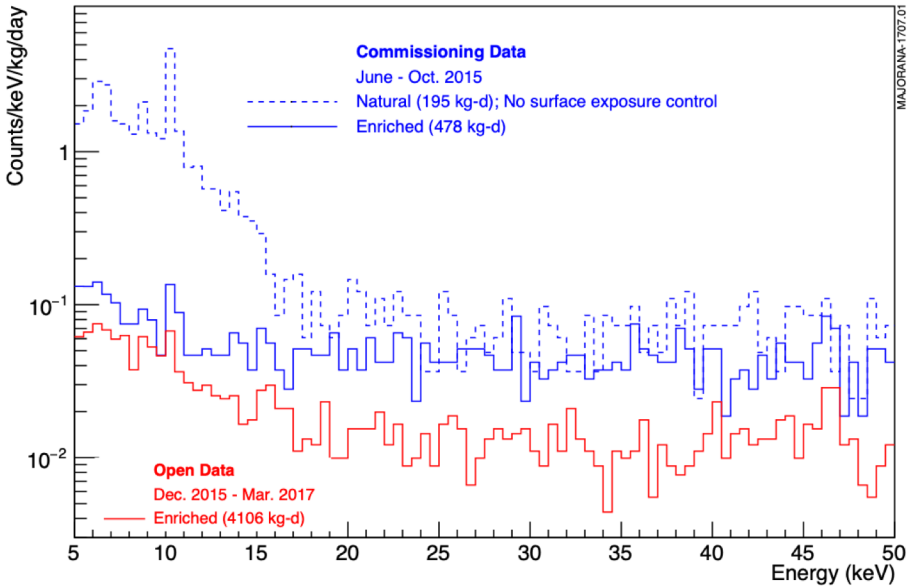
Bosonic dark matter and other keV-scale exotic physics	PRL **118** 161801 (2017)
Lightly Ionizing Particles	PRL **120** 211804 (2018)
Tri-Nucleon Decay	PRD **99** 072004 (2019)

Low Energy BSM Physics

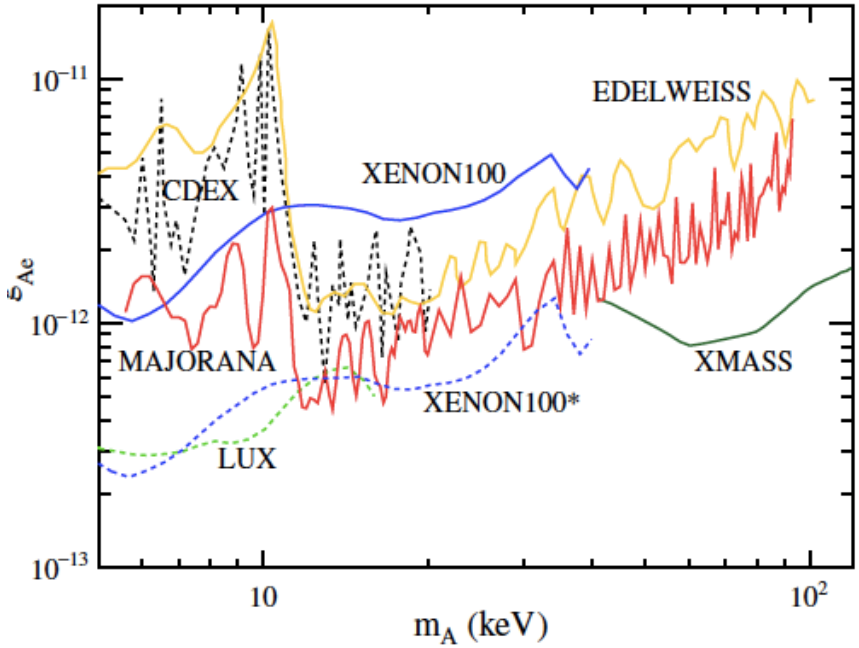
Search for anomalous peaks in the low energy spectrum allows limits to be set for keV-scale BSM physical processes, including

- pseudoscalar and vector dark matter couplings
- 14.4-keV solar axion coupling
- Pauli exclusion principle violating decay ($e^- \rightarrow 3\nu$)

PRL **118** 161801 (2017)



Low energy spectra during commissioning (blue) and first low-background physics running (red)



The 90% UL on the pseudoscalar axionlike particle dark mater coupling

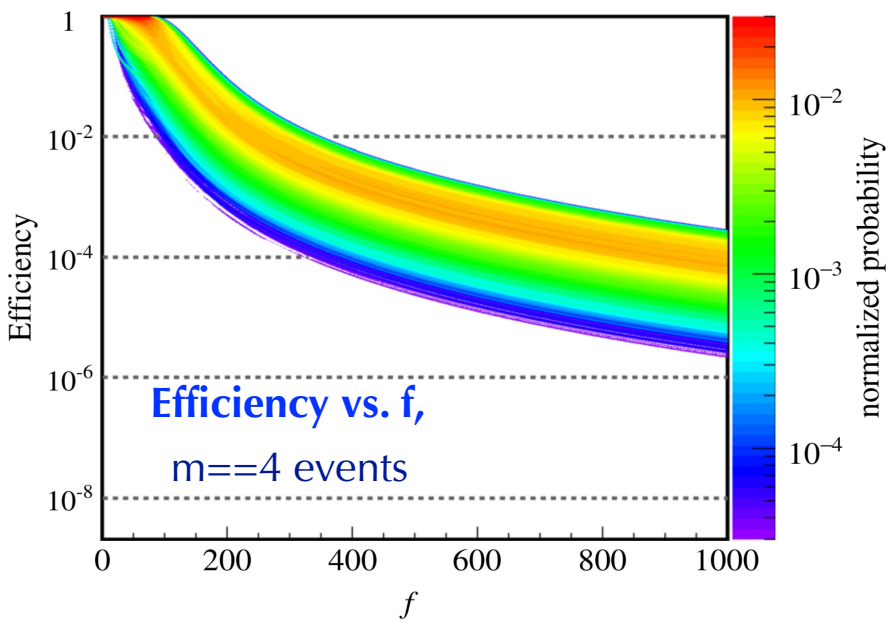
Lightly Ionizing Particles (LIPs)

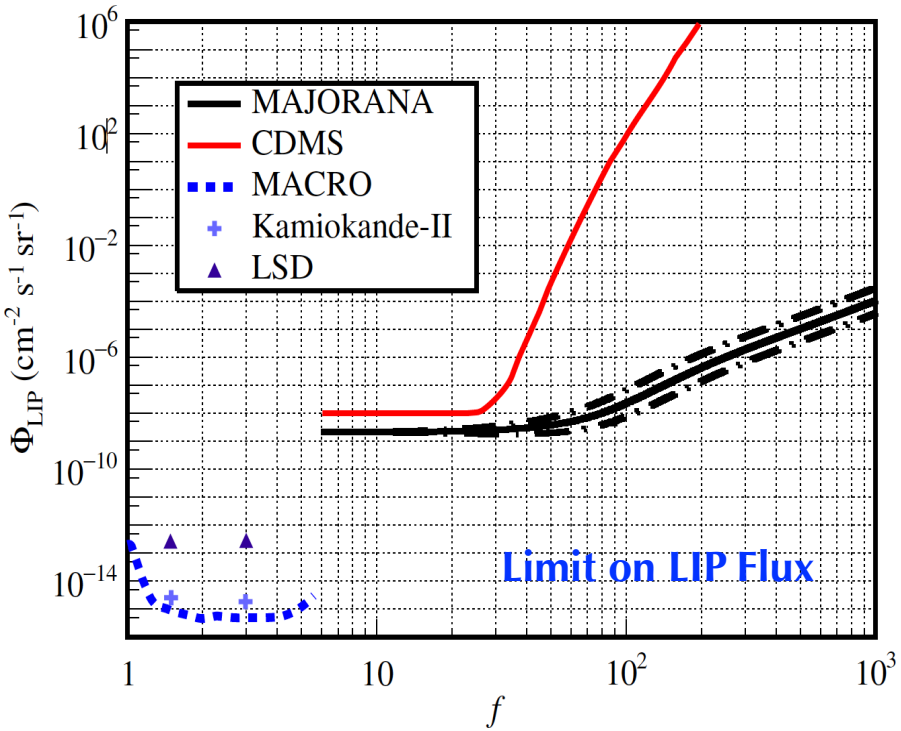
Candidate LIPs include noninteger-charged bound quarks, unbound quarks, and/or new leptons.

Charge reduction factor: $f = \frac{e}{q}$

Event Signature:

a high multiplicity, non-muon event, background-free with a good muon veto





Sensitivity to e/1000 achieved via **long path length** through detectors and **low thresholds**.

PRL **120** 211804 (2018)

Tri-Nucleon Decay

Observation of three-nucleon decays in ^{76}Ge **would be evidence of baryon number violation**

Event Signature:

Time-delayed, single-detector events

Energy and time-coincidence cuts reduce the DEMONSTRATOR's already low backgrounds

Multiple decay modes considered, including:

^{76}**Ge(ppn)** $\rightarrow$ ^{73}**Zn e+ π+**

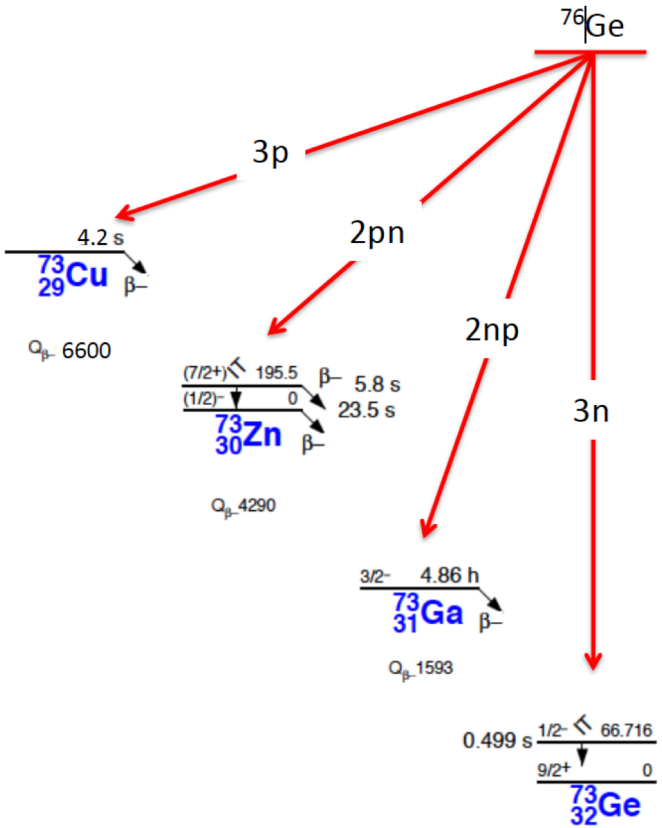
$T_{1/2} > 4.9 \times 10^{25}$ yr (90% UL)

^{76}**Ge(ppp)** $\rightarrow$ ^{73}**Cu e+ π+ π+**

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

"Invisible" ^{76}**Ge(ppp)**

$T_{1/2} > 7.5 \times 10^{24}$ yr



PRD **99** 072004 (2019)

Summary and Outlook

MAJORANA DEMONSTRATOR began 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

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 underway to improve background rejection

- Improved analysis and additional data will yield new results

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

PRL **118** 161801 (2017) | PRL **120** 211804 (2018) | PRD **99** 07200 (2019)

Planning an upgrade to cables and connectors as a part of LEGEND R&D

Expect to reach ~65 kg-yr exposure with sensitivity in the range of 10^{26} yr half-life before a shutdown for LEGEND-200 in late 2020

- Next Generation ^{76}Ge: LEGEND is selecting the best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR

The MAJORANA Collaboration

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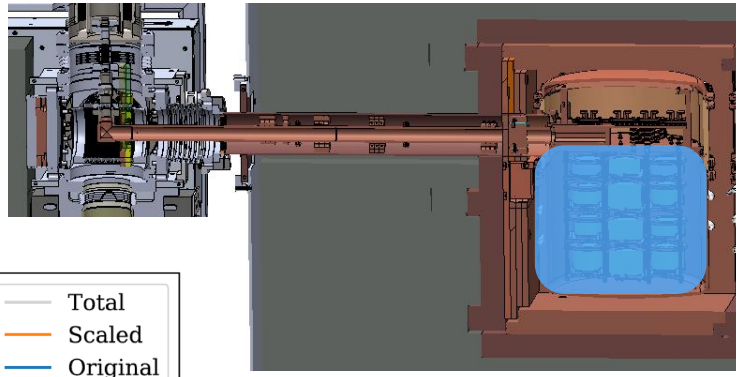
Massachusetts Institute of Technology
NC State University
Oak Ridge National Laboratory
大阪大学 Osaka University
Pacific Northwest National Laboratory — Proudly Operated by Battelle Since 1965
Princeton University
Queen's University
South Dakota School of Mines & Technology
Technische Universität München
Tennessee Tech
TUNL
The University of North Carolina at Chapel Hill
University of South Carolina
University of South Dakota
The University of Tennessee Knoxville

Backup Slides

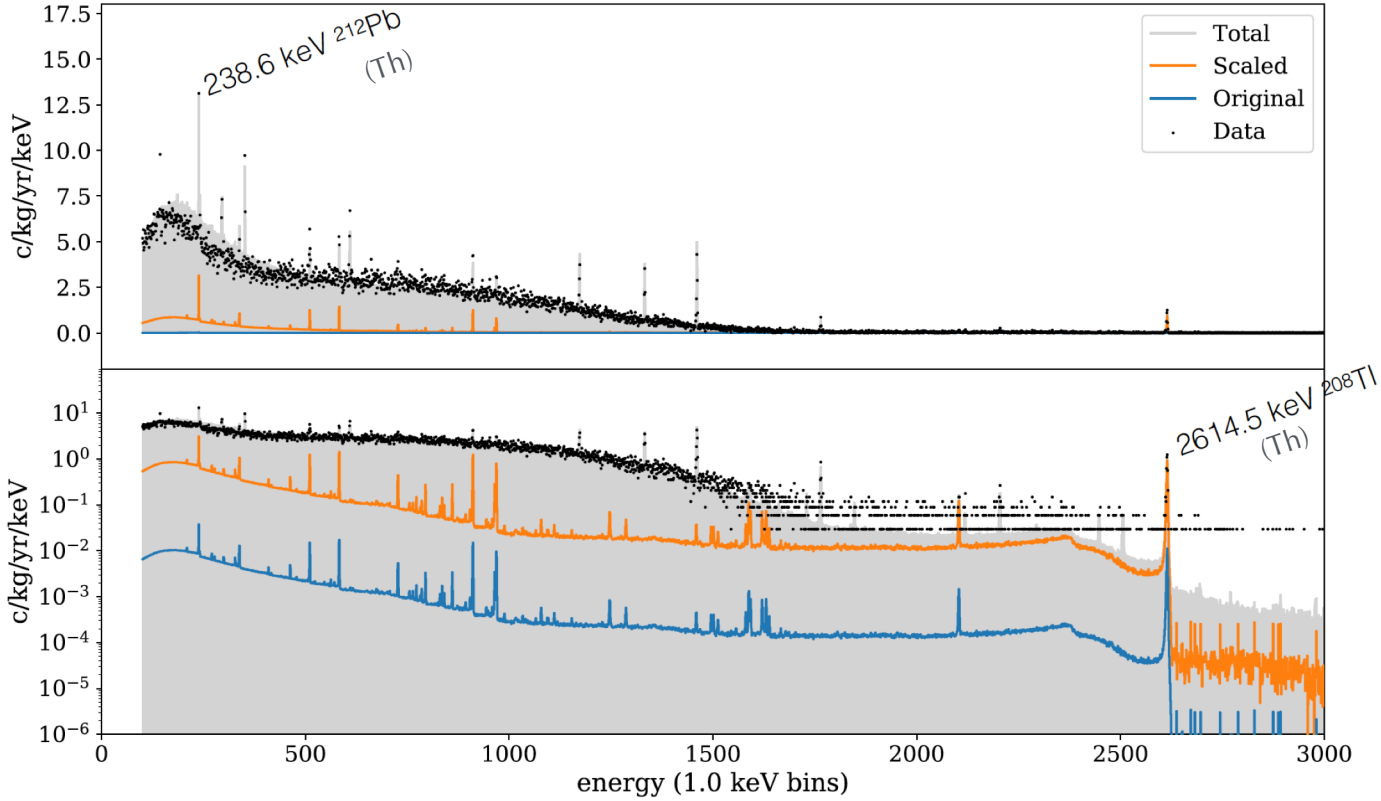
Background Model Development: An example

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 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

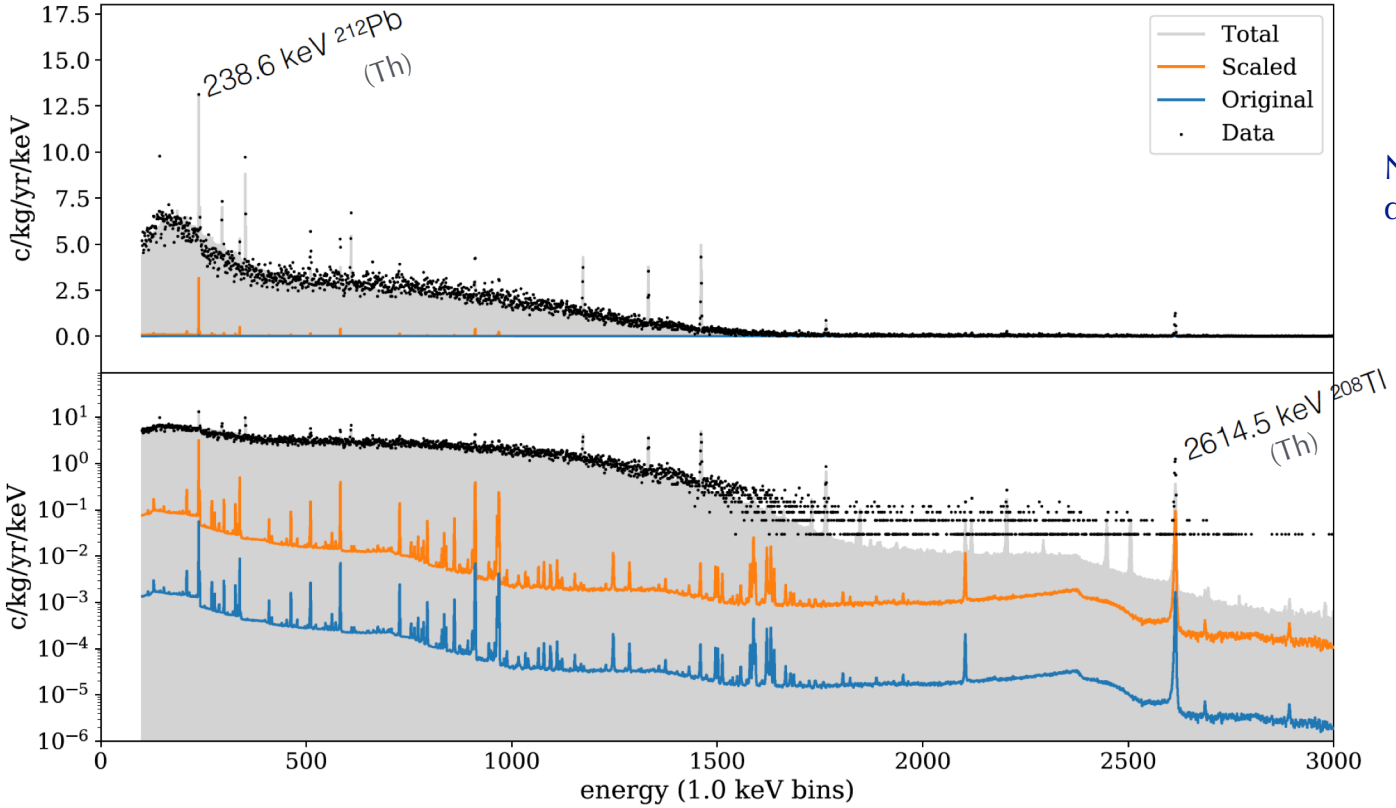
T.F. Gilliss, UNC, PhD Dissertation 2019

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 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

T.F. Gilliss, UNC, PhD Dissertation 2019

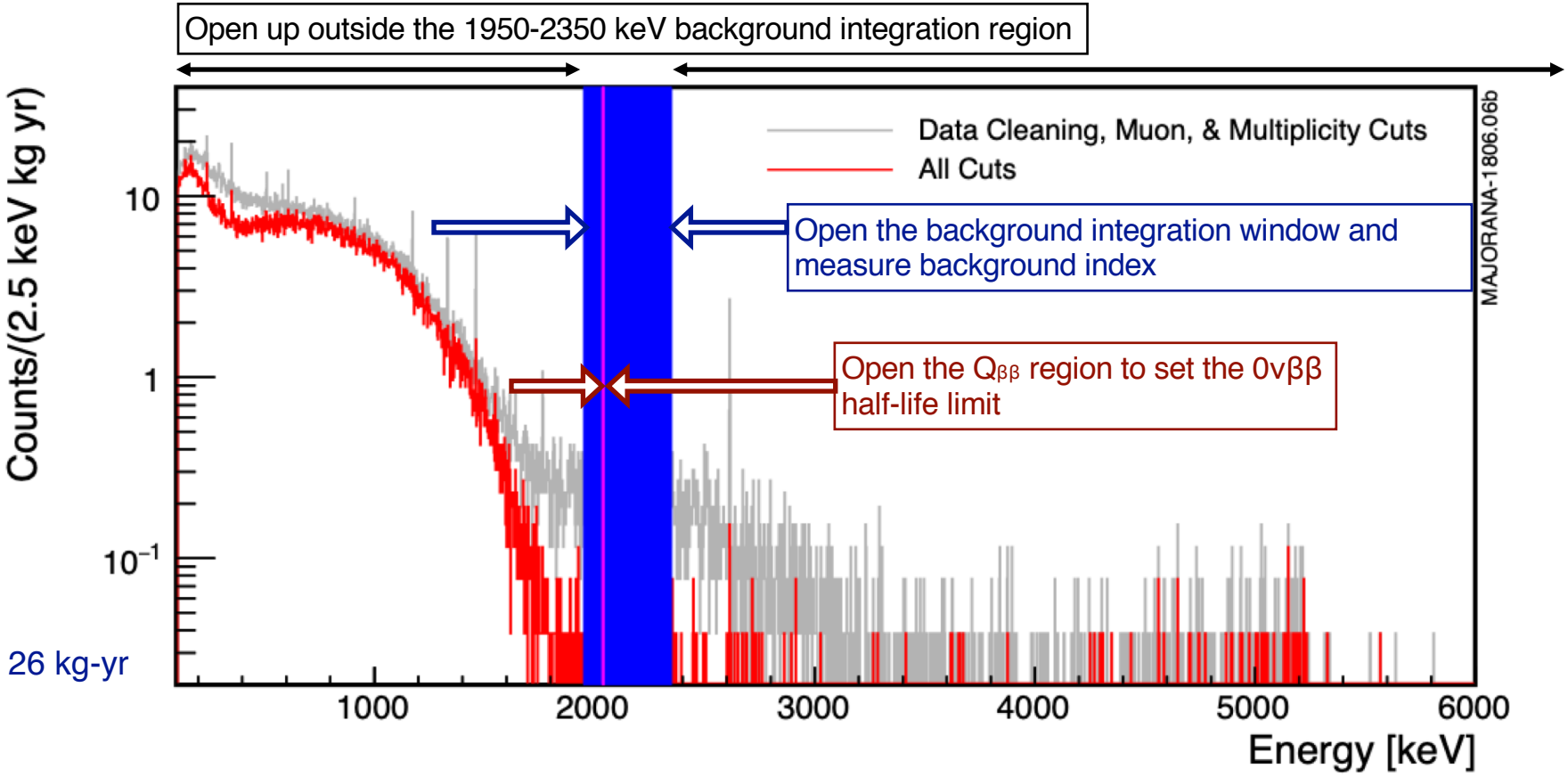
Blindness Implementation

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

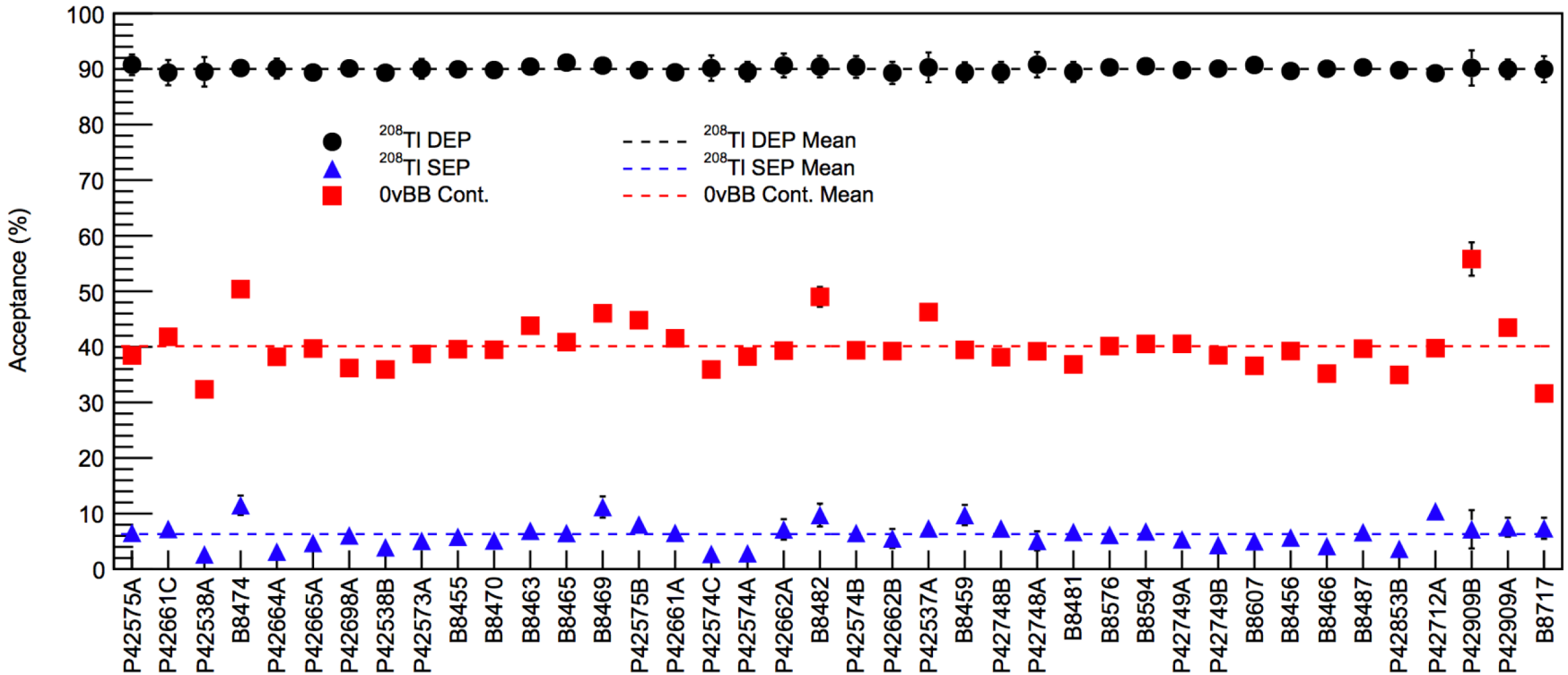
Unblinding in phases to perform data quality and consistency checks

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



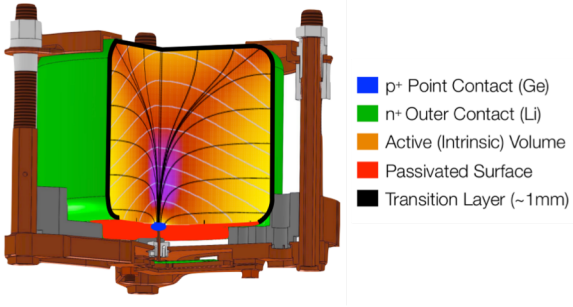
26 kg-yr

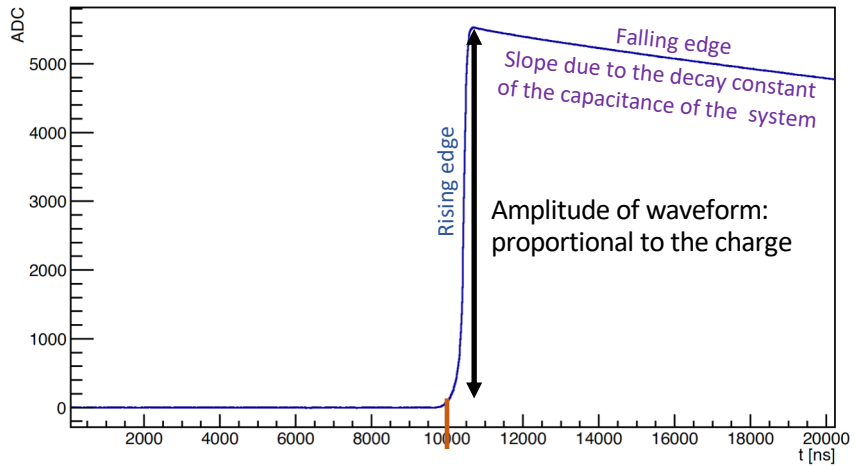
AvsE Acceptance



Germanium Detector Waveforms

An interacting particle produces an energy deposition, generating a cloud of charge which is collected in the point of contact





ELECTRONIC NON-LINEARITY

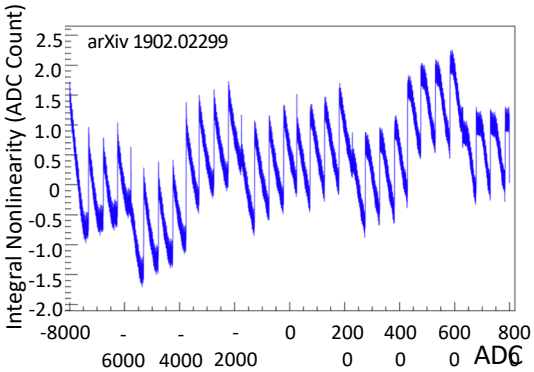
A non-linearity associated with this process appears

14 bit 100 MS/s digitizers

Low gain channel (amplif: ~ 3 times)

High gain channel (amplif: ~ 10 times)

- The **ADC non-linearity** associated to the electronics can modify the energy value
- They have to be corrected sample by sample
- An external pulser is used to determine this correction



Energy Estimation

DECAY CONSTANT DETERMINATION

The energy is determined from the waveform using a trapezoidal filter

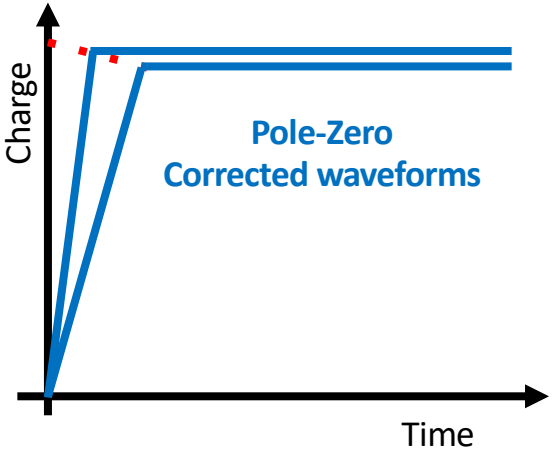
$$\frac{1}{\tau} = \frac{1}{\tau_{PZ}} + \frac{1}{\tau_{CT}}$$

- PZ (Pole Zero): Intrinsic correction due to the pre-amp (70 μs)
- CT (Charge Trapping): The detector impurities capture part of the charge before it is collected
- τ is varied to find the value which minimizes the FWHM in calibration data

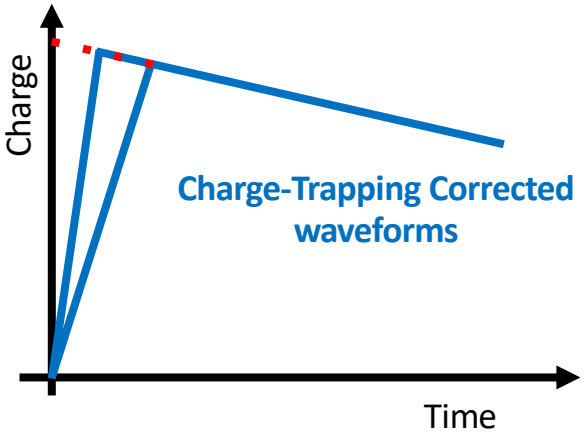
- t_0 determination
  - Small trapezoidal filter
    - 1 μs rise time
    - 1.5 μs flat time

- Decay constant determination
  - Pole zero correction
  - Charge trapping correction
- Baseline subtraction

- Filtered waveform
  - Trapezoidal filter
    - 4 μs rise time
    - 2.5 μs flat time
  - **<u>Energy (ADC counts)</u>**



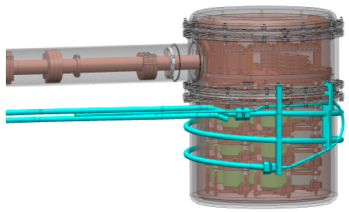
Schemes of the two events with the same energy and different rise times after pole-zero correction



Schemes of the two events with the same energy and different rise times after pole-zero correction and charge trapping correction

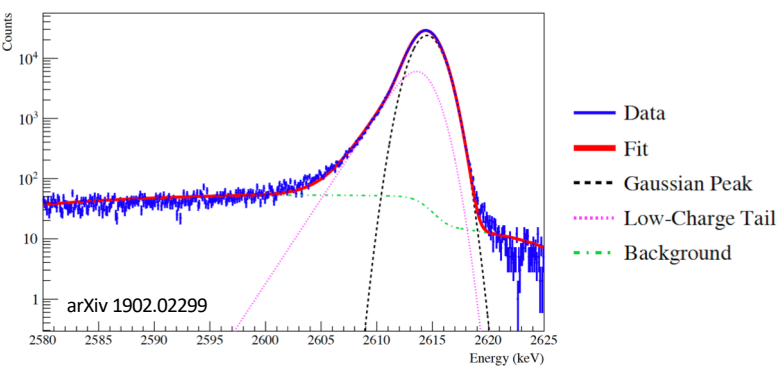
Energy Calibration

- Periodic energy calibrations (^{228}Th)



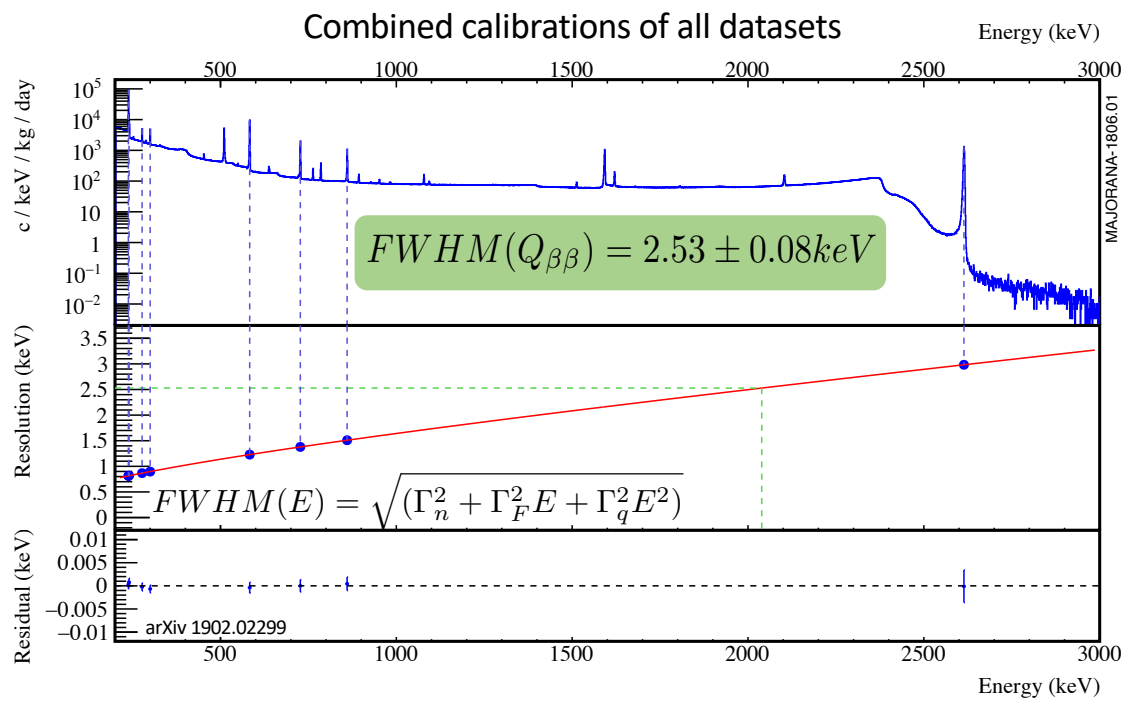
Nucl. Instrum. Meth. A 872 16

- Initial calibration: zero energy & 2614 keV



Flat background + Peak (gaussian, tail and step function)

- Second step: simultaneous fit and combined statistics (by dataset)



Simultaneous fit to eight peaks in the calibration spectrum peaks (keV)							
238.6	241.0	277.4	300.1	583.2	727.3	860.6	2614

Background Rejection

After data cleaning (>99.9% eff.), multiplicity cut and muon veto