
# The Status of the MAJORANA DEMONSTRATOR

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on behalf of the MAJORANA Collaboration
CoS@SURF — May 12th, 2022

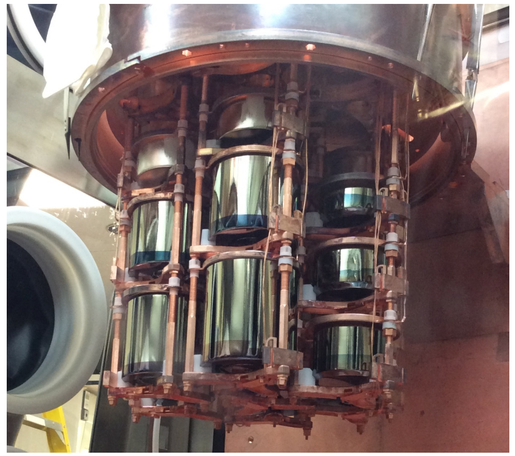
# MAJORANA DEMONSTRATOR

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

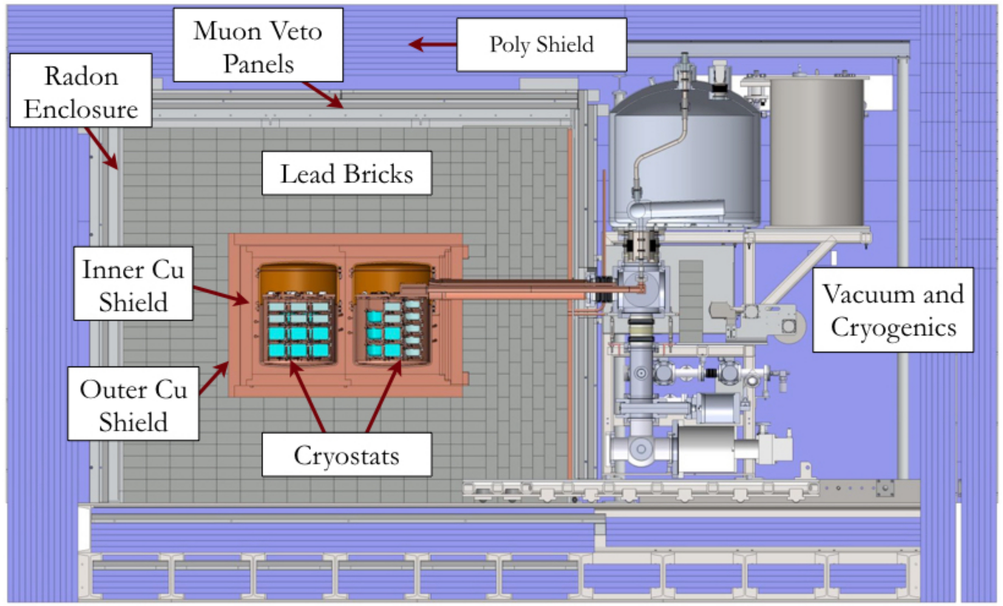


**Reached an exposure of ~65 kg-yr** before removal of the enriched detectors for the LEGEND-200 experiment at LNGS

Leading limits in the search for double-beta decay of $^{76}$Ge to excited states — PRC **103** 015501 (2021)

Limit from 26 kg-yr of exposure:
$T_{1/2} > 2.7 \times 10^{25}$ yr (90% CL) — Final result in preparation

Low background, low threshold, & excellent energy resolution allows for broad physics program — New beyond the standard model results in preparation

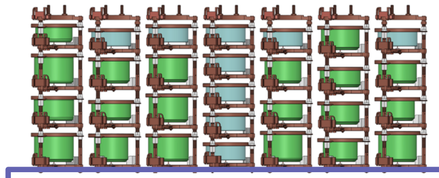



Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

# MAJORANA Run Configuration & Timeline

## Module 1

16.8 kg (20) $^{enr}$Ge
5.6 kg (9) $^{nat}$Ge



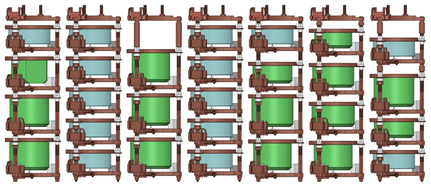
Deploy Module 1 in shield

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

| 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|

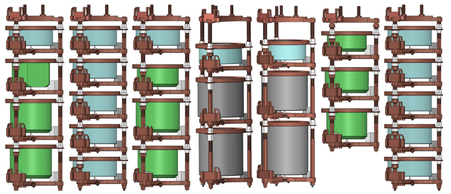
## Module 2

12.9 kg (15) $^{enr}$Ge
8.8 kg (14) $^{nat}$Ge



Deploy Module 2 in shield

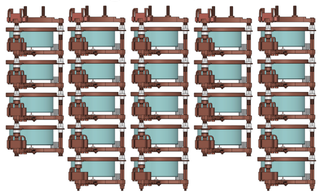
14.1 kg (13) $^{enr}$Ge
8.8 kg (14) $^{nat}$Ge



6.7 kg (4) as ICPC

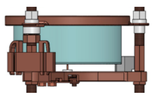
Cable/Connector Upgrade of Module 2
Removed 5 PPC detectors for LEGEND Testing
Installed 4 LEGEND ICPC Detectors

14.3 kg (23) $^{nat}$Ge

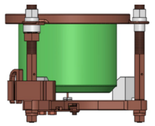


Continuing operation of Module 2 only with natural Ge detectors

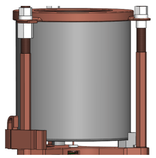
Mirion/Canberra BEGe $^{nat}$Ge



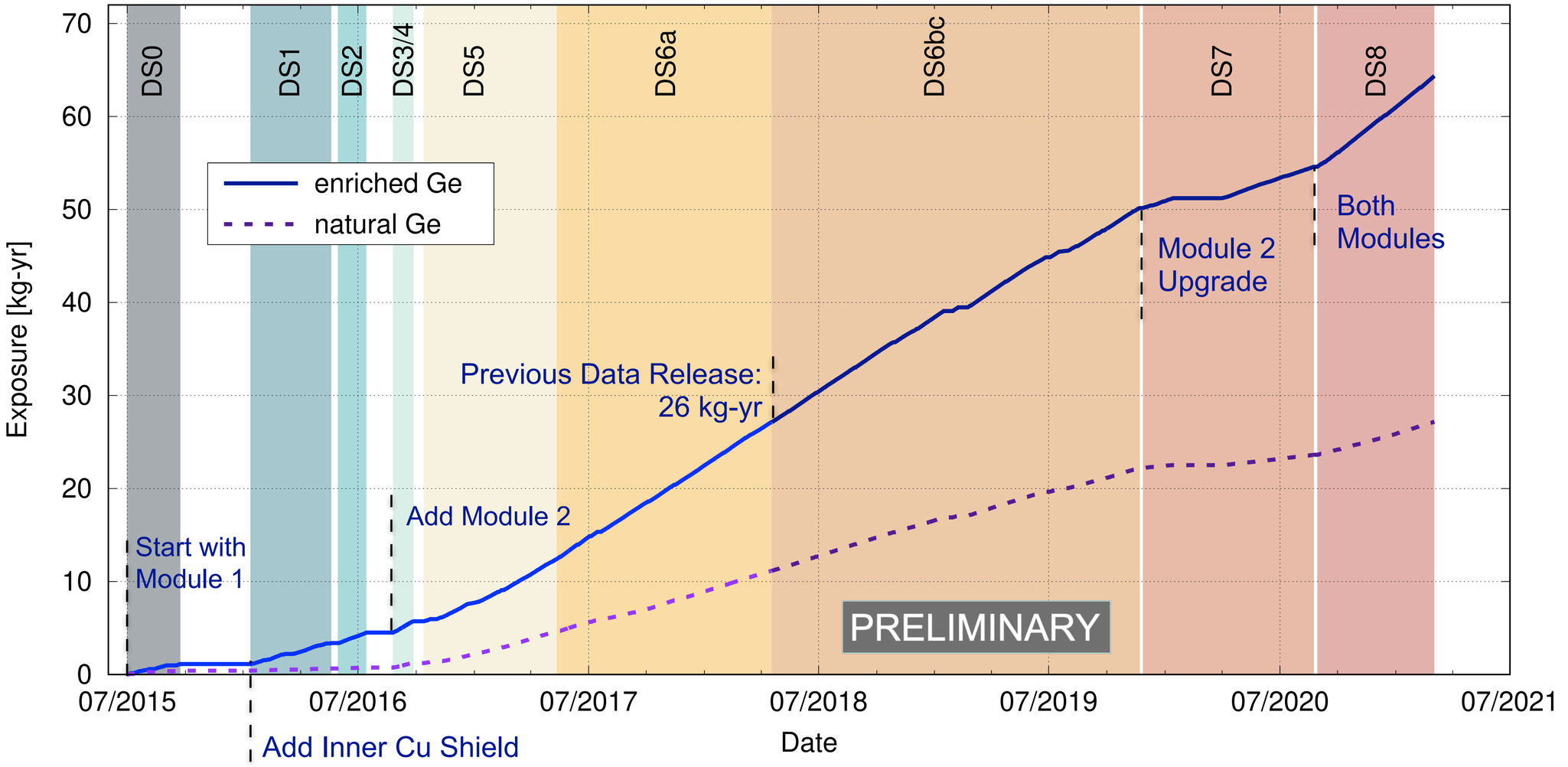
Ortec PPC $^{enr}$Ge



Ortec ICPC $^{enr}$Ge



# MAJORANA Total Exposure



# MAJORANA Approach to Backgrounds

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

PRC **100** 025501 (2019)

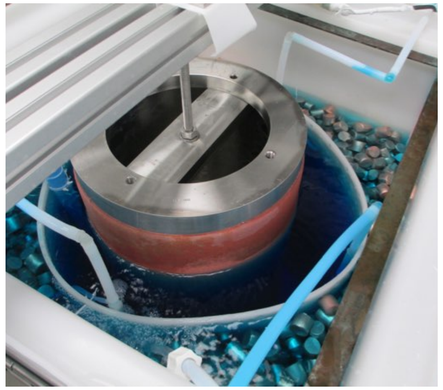
- Ge enrichment, zone-refining and crystal pulling processes enhance purity

NIM A **877** 314 (2018)

- 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 A **828** 22 (2016)



Rejection of backgrounds

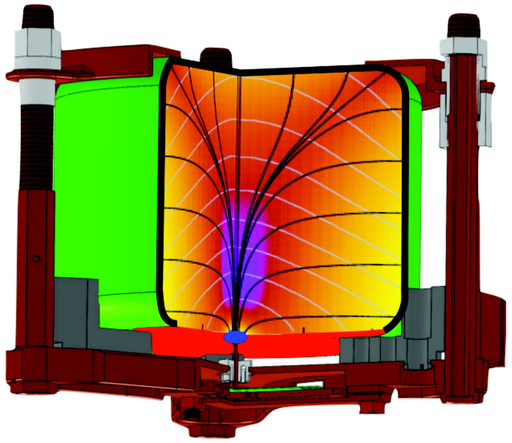
- Muon Veto: reject events coincident with muons

Astropart. Phys. **93** 70 (2017)

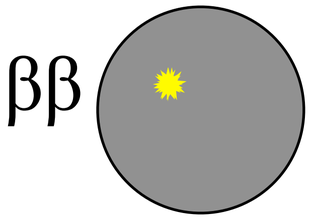
- Granularity: multiple detectors hit
- Pulse shape discrimination: no multiple hits, reject surface events

PRC **99** 065501 (2019)

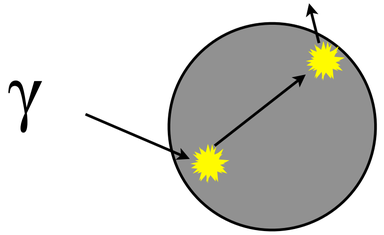
Eur. Phys. J. C **82,** 226 (2022)

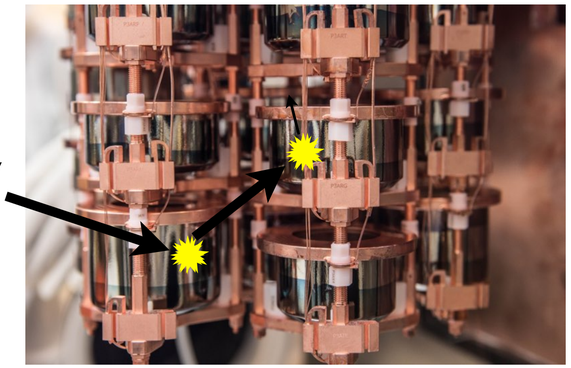


Single-site event

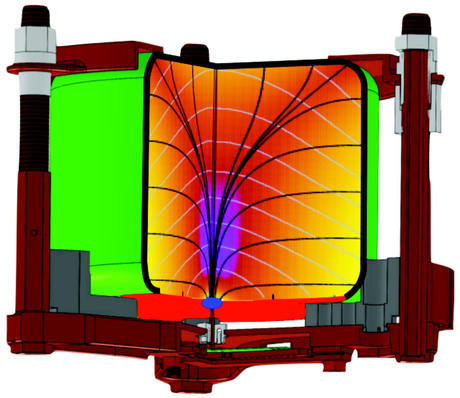



Multi-site event



# Background Rejection



p+ Point Contact (Ge)
n+ Outer Contact (Li)
Active (Intrinsic) Volume
Passivated Surface
Transition Layer (~1mm)
e-/h+ drift path
Isochrons (Δ100 ns)

ββ events are intrinsically single-site and occur in the bulk of the detector

γ backgrounds often Compton scatter as multi-site events

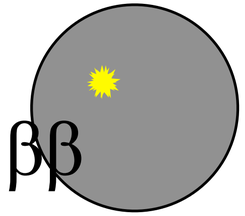
Compare max current amplitude to full charge collection (AvsE)

PRC **99** 065501 (2019)

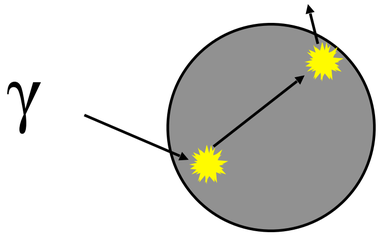
α-particles incident on the passivated surface will have degraded energy

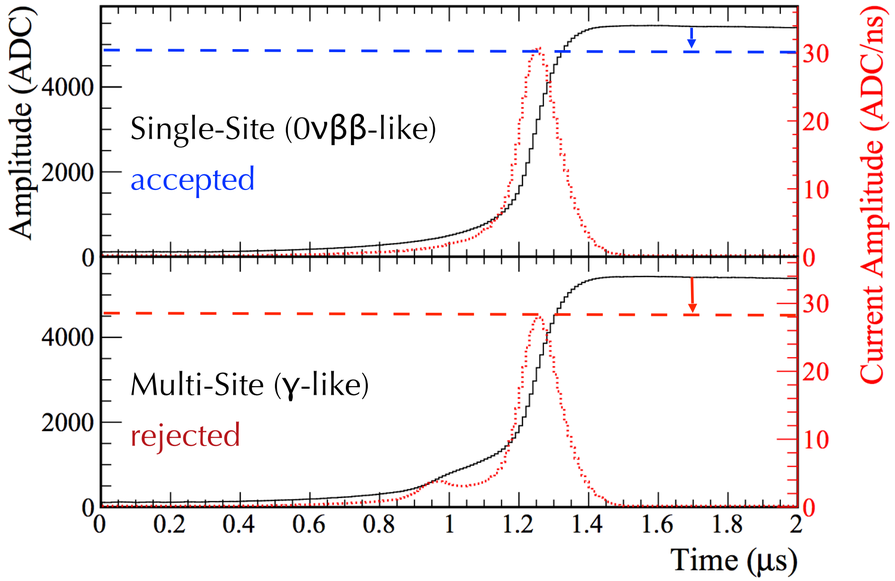
Detect delayed charge recovery (DCR) Eur. Phys. J. C **82,** 226 (2022)

## Single-site event

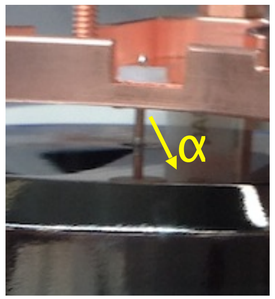


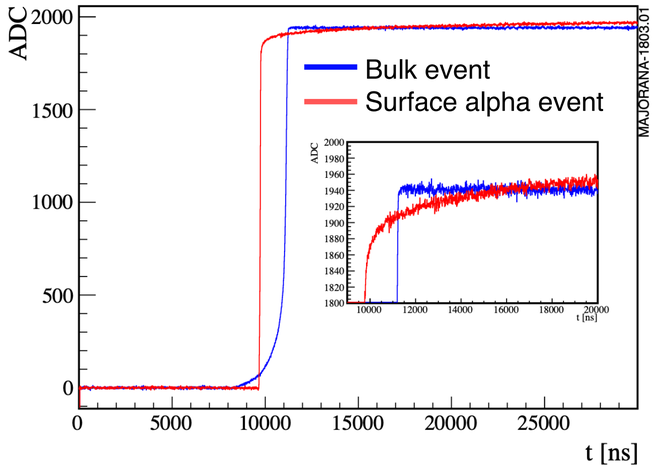

## Multi-site event




## Passivated surface event



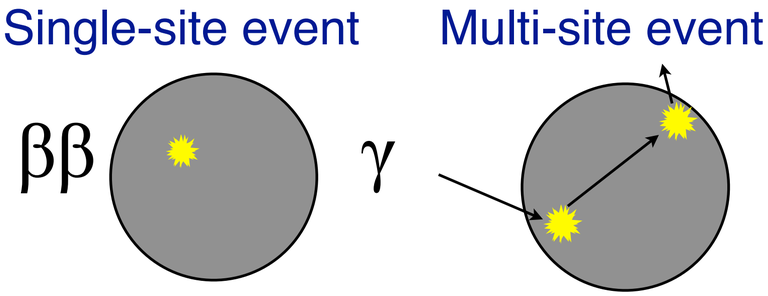



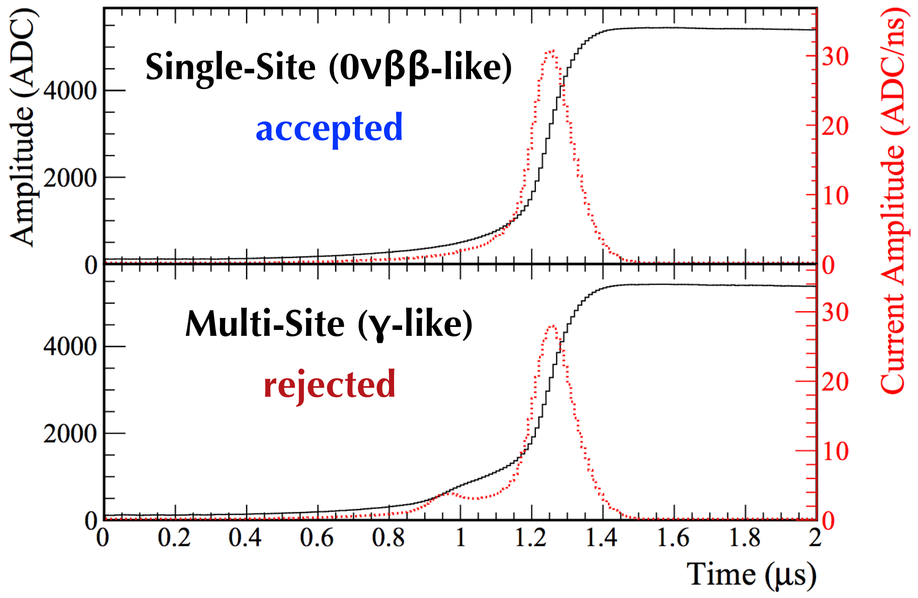
# Backgrounds: Multi-Site Event Rejection

Benefit of P-type Point-Contact (PPC) style detectors for background rejection:

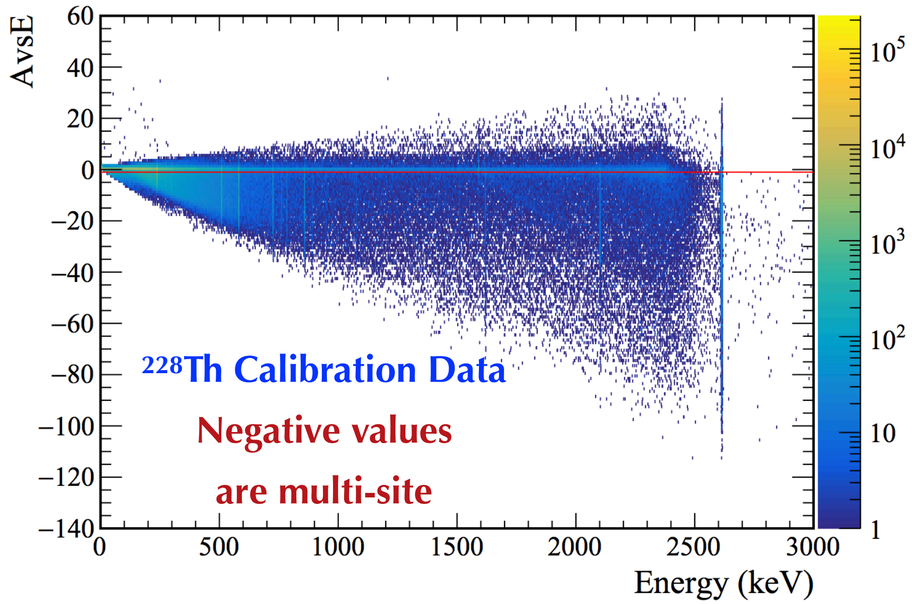
- Slow drift time of the ionization charge cloud
- Localized weighting potential gives excellent multi-site rejection

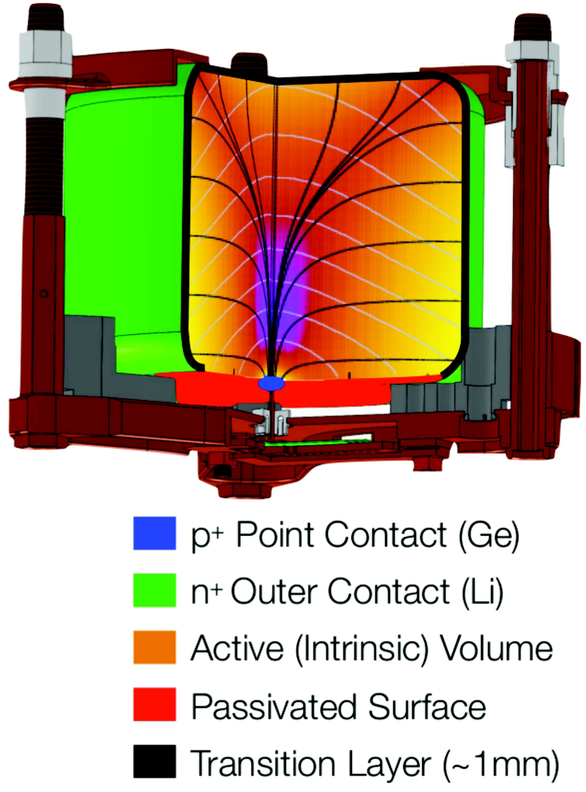
Amplitude of current pulse is suppressed for a multi-site event compared to a single-site event of the same event Energy (AvsE)




Tuned to accept 90% of single-site events

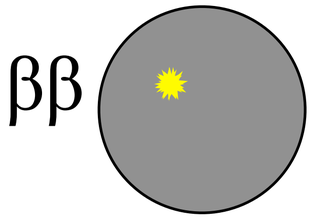


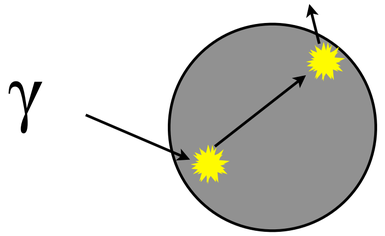

PRC **99** 065501 (2019)

# Improved Multi-Site Event Rejection

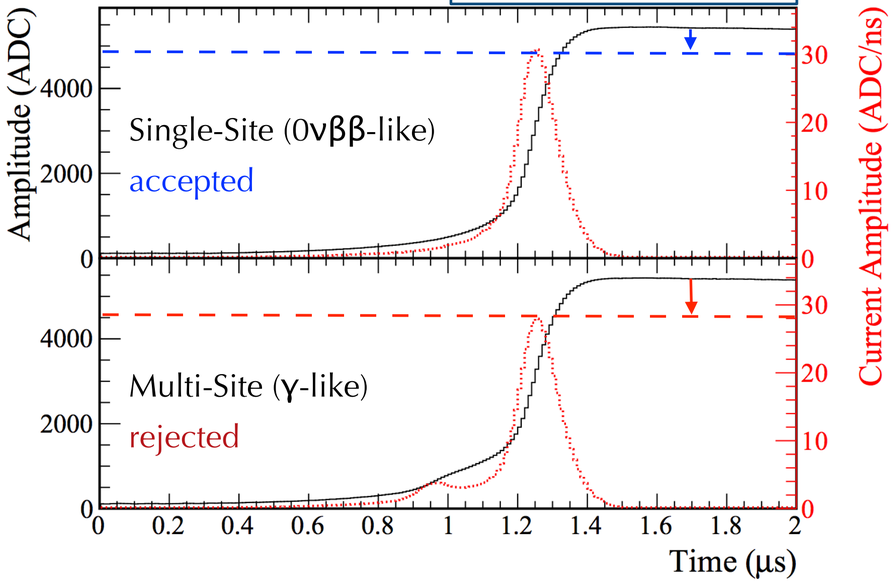
## Single-site event




## Multi-site event




PRC **99** 065501 (2019)



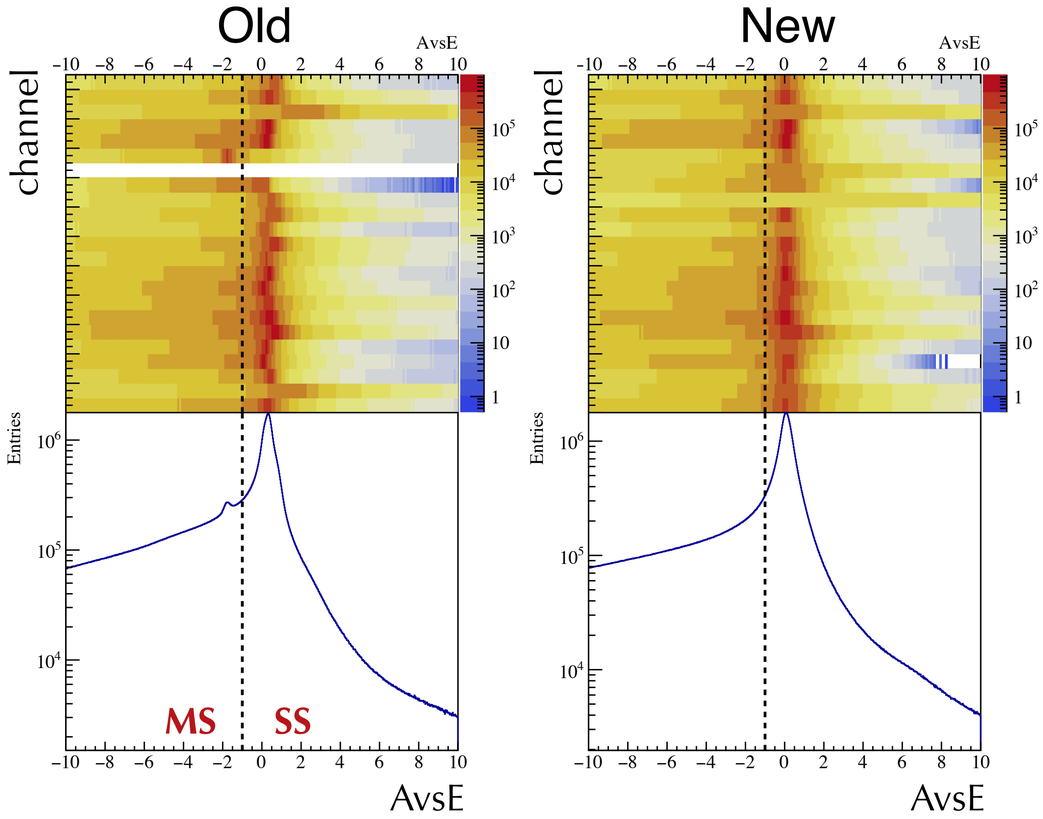

Amplitude of current pulse is suppressed for a multi-site event compared to a single-site event of the same event Energy (AvsE)

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

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




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

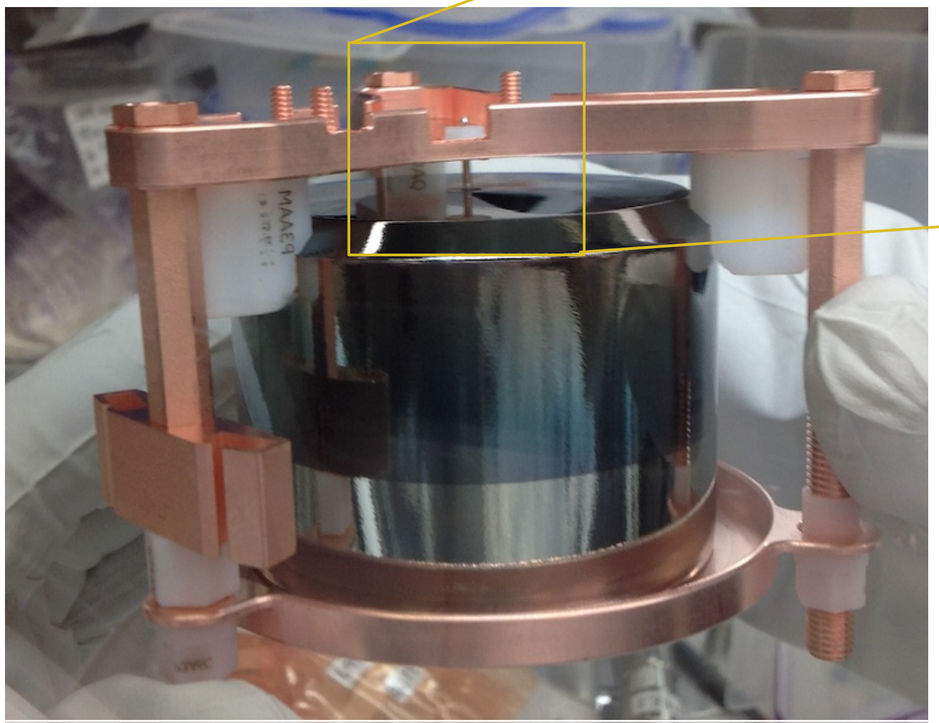
# Backgrounds: Surface Alpha Rejection

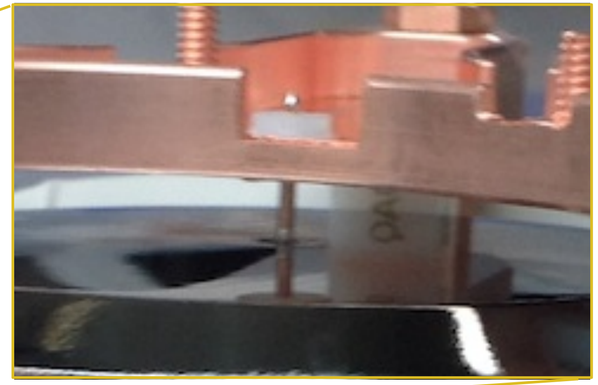
Alpha background with degraded energies observed; charge trapped at passivated surface, slowly released into bulk: *delayed charge recovery* (DCR)

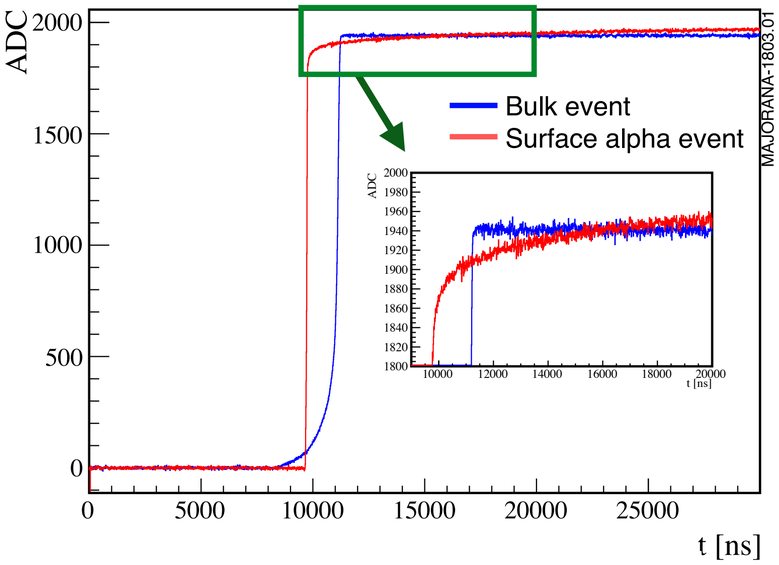
- Cut with a parameter related to slope of tail after the rising edge
- Retains 99% of the $\beta/\gamma$ events, evaluated based on $^{228}$Th data

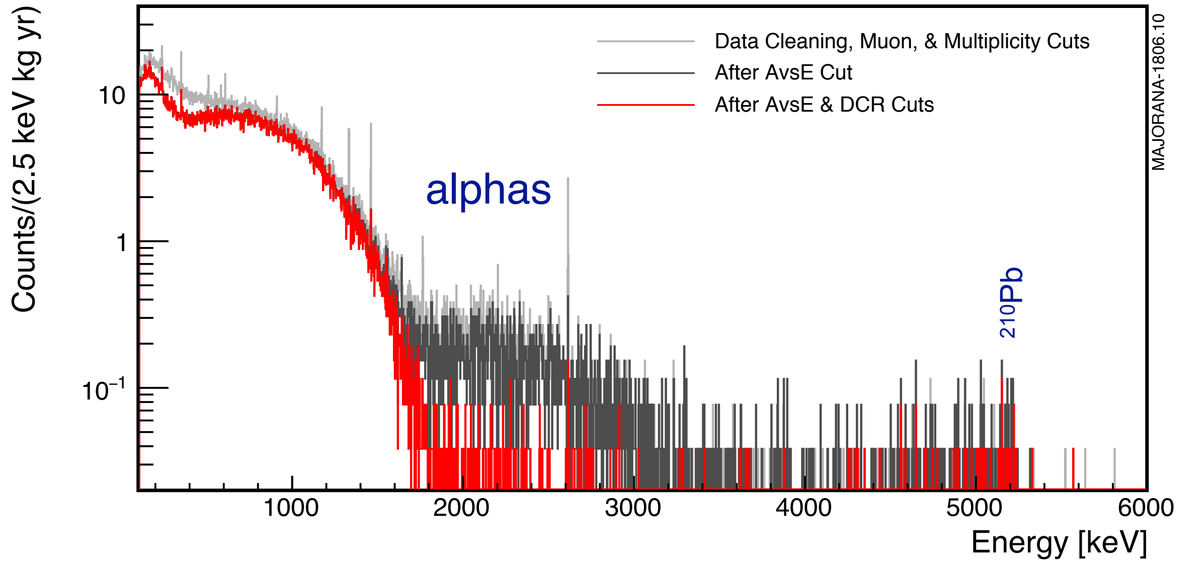
Eur. Phys. J. C **82,** 226 (2022)

Suspect α contamination near point contact
$^{210}$Po from $^{222}$Rn exposure

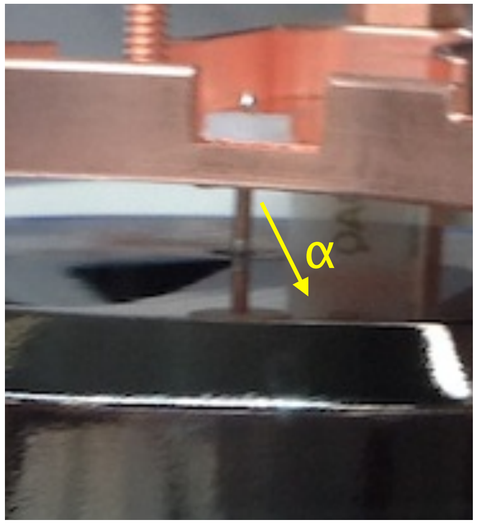


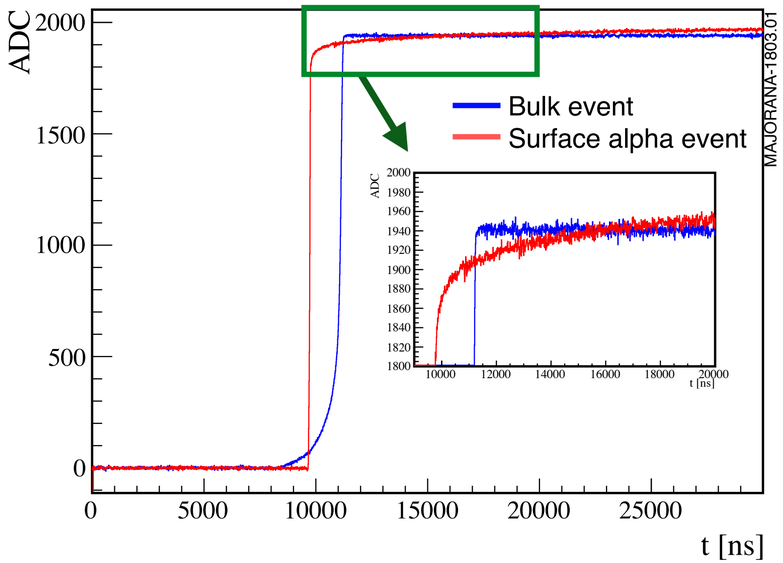




# Improved Surface Alpha Rejection




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

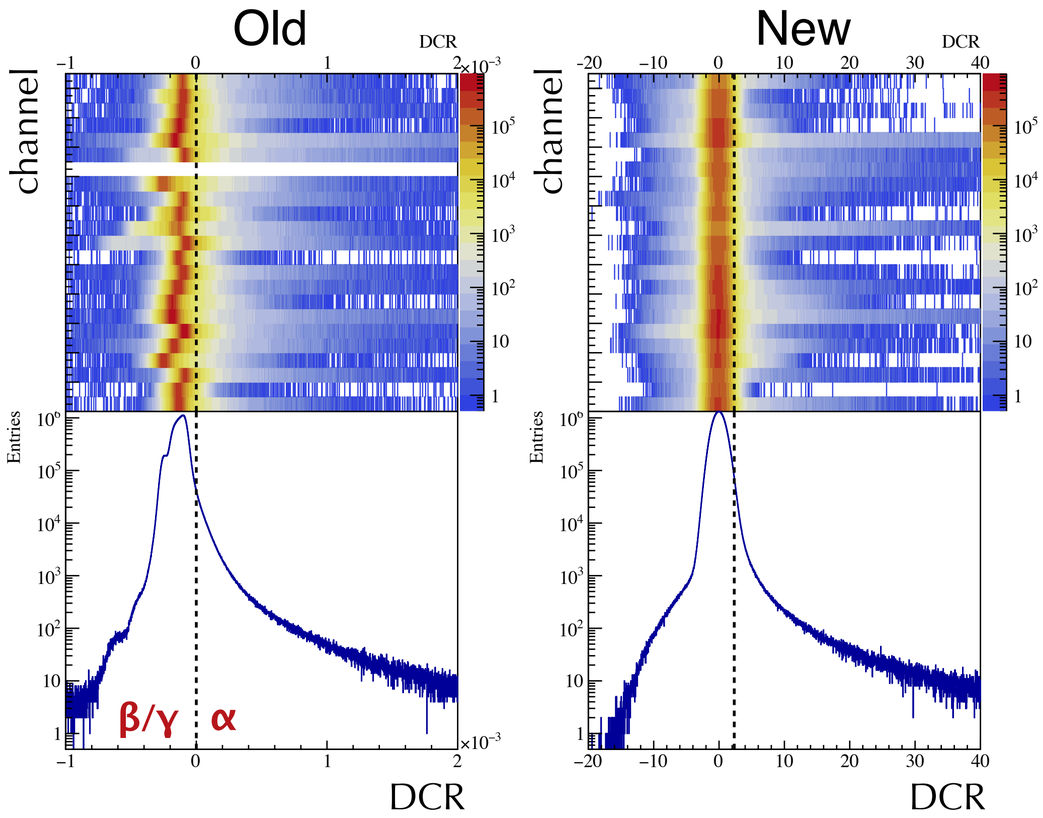
Eur. Phys. J. C **82,** 226 (2022)

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
- 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.

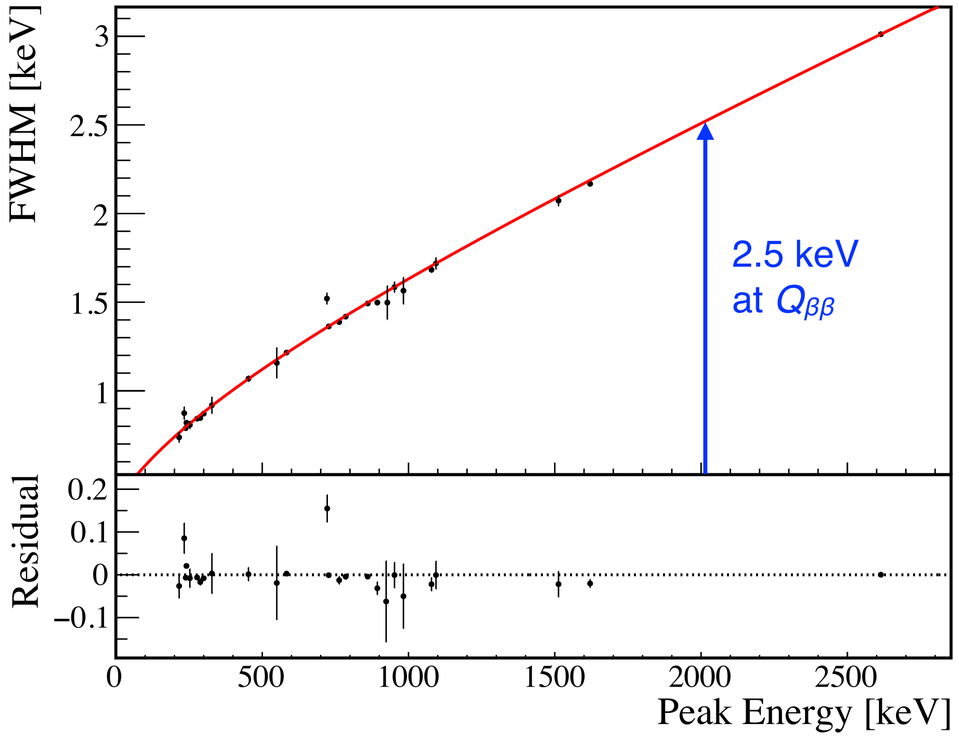
# Improved Energy Estimation

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

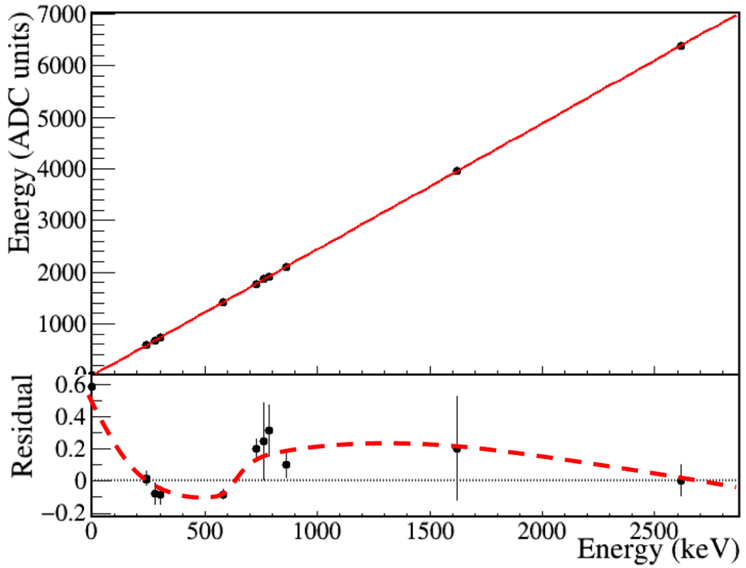
Calibrated on weekly $^{228}$Th calibration data, retuned on full data set

Recent improvements: correction for $t_0$ estimate bias, quadratic correction for charge recombination

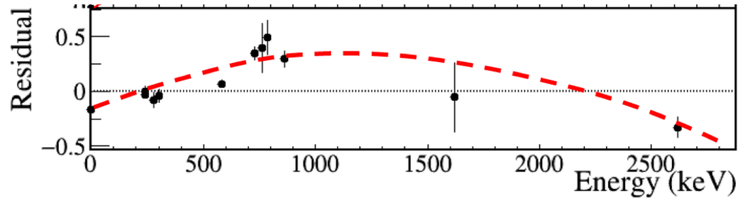
FWHM (2.5 keV) and linearity (<0.2 keV up to 3 MeV) a record for neutrinoless double-beta decay searches



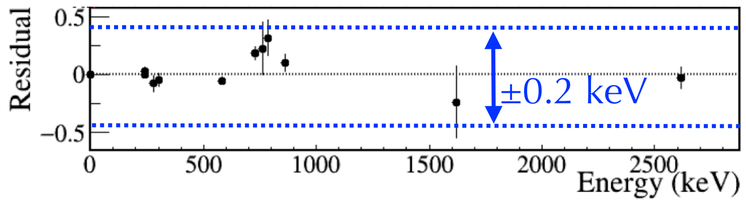

$E$ calibration with no $t_0$ correction




Linear $E$ calibration with $t_0$ correction



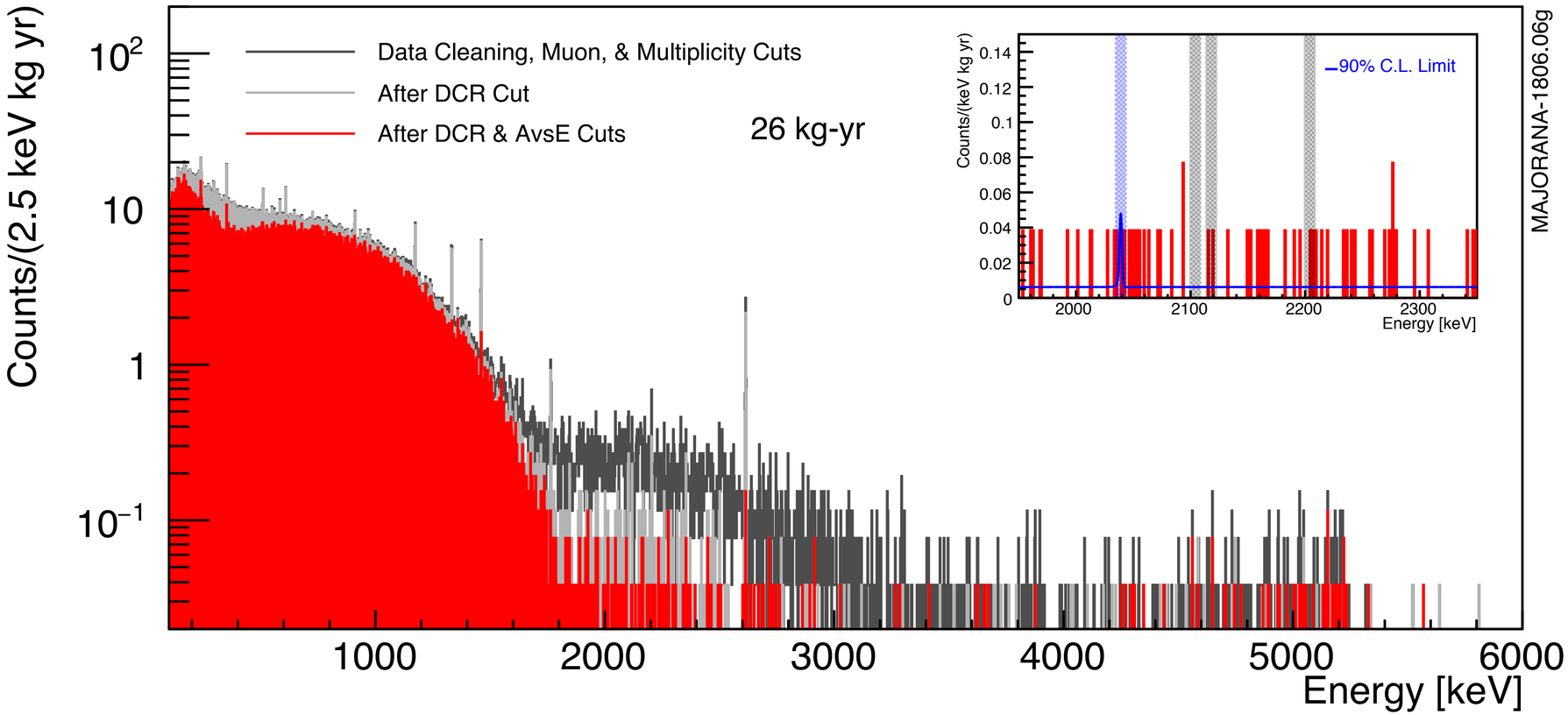

Quadratic $E$ calibration with $t_0$ correction




* IEEE Trans. on Nuc Sci
10.1109/TNS.2020.3043671

# MAJORANA DEMONSTRATOR 2019 0νββ Result

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:**

$4.8 \times 10^{25}$ 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 ~65 kg-yr from the complete data set and analysis improvements, is being prepared for release

# Rich and Broad Physics Programs

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

PRC **100** 025501 (2019)
PRC **103** 015501 (2021)
PRD **99** 072004 (2019)
arXiv:2203.02033 (2022)

Standard Model Physics

BSM Physics

Standard Model Physics, particular backgrounds
- In situ cosmogenics
- (alpha, n) reactions

PRC **105** 014617 (2022)
arXiv:2203.14228 (2022)

MAJORANA DEMONSTRATOR
Excellent energy performance
Low backgrounds
in broad energy regions

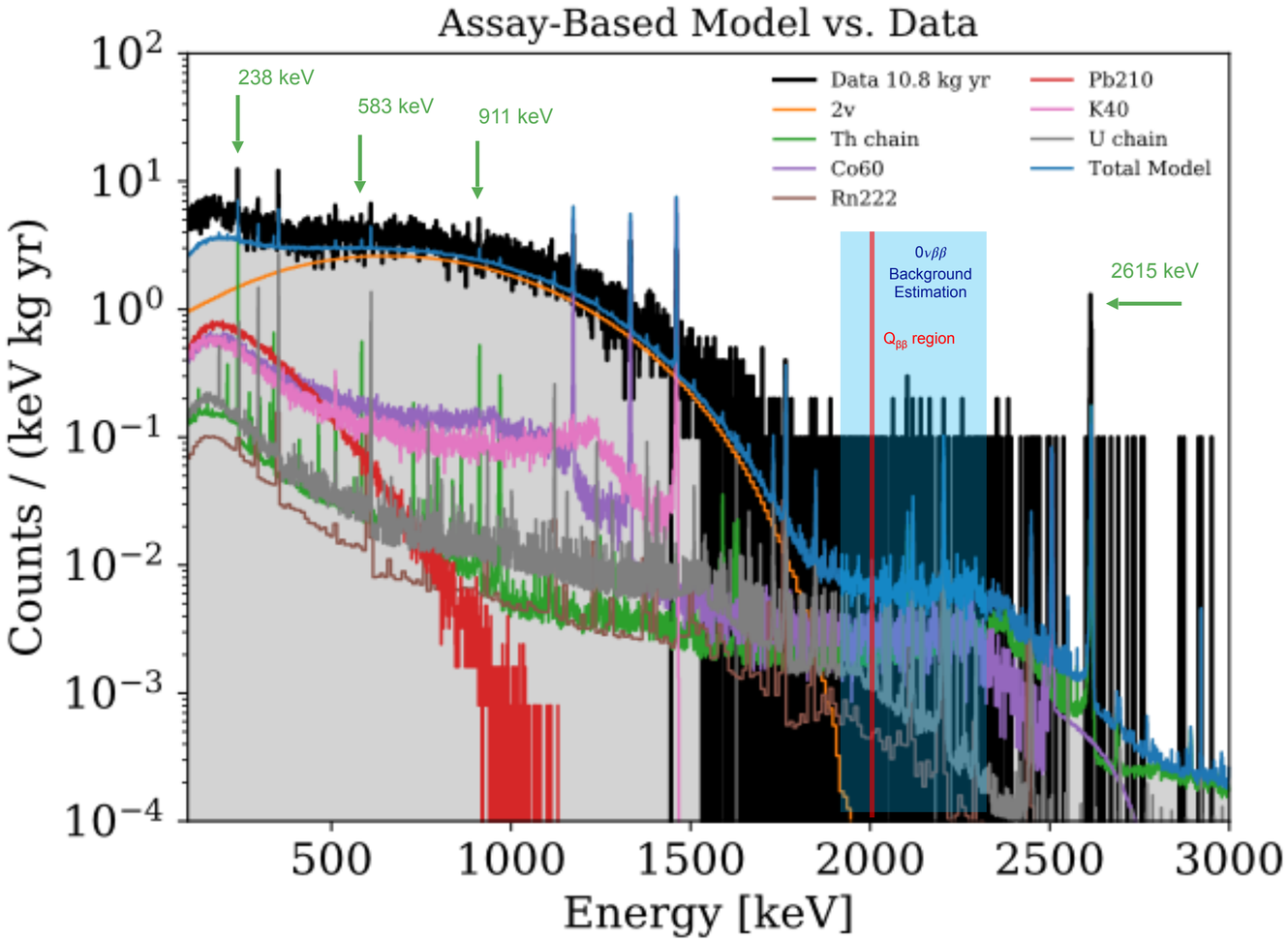
Low-mass dark matter signatures
- Pseudoscalar dark matter
- Vector dark matter
- Fermionic dark matter
- Sterile neutrino
- Primakoff solar axion
- 14.4-keV solar axion

PRL **118** 161801 (2017)
arXiv:220x.xxxxx (2022) **x3**

Exotic Physics
- Quantum Wavefunction collapse
- Lightly ionization particle

arXiv:2202.01343 (2022)
PRL **120** 211804 (2018)

# Background Modeling and Investigation




Investigating observed background near $Q_{\beta\beta}$

Assay-based prediction: 2.9 ± 0.14 cts/(FWHM t y) at $Q_{\beta\beta}$

Measured Background: 11.9 ± 2.0 cts/(FWHM t y)

PRC **100** 025501 (2019)

Characteristics of background excess:

- Dominated by $^{232}$Th decay chain
- Higher in Module 1 than Module 2
- Some evidence that Module 1 has higher rates at top of array compared to bottom
- The observed $^{232}$Th excess is not consistent with either a point or uniformly distributed source in the near-detector components --- This is an important finding for LEGEND-200 which uses similar materials for near-detector components

# 2020 Module 2 Upgrade

Installed new cables & connectors to improve overall robustness

Improved cable bundling and increased cross-arm shielding

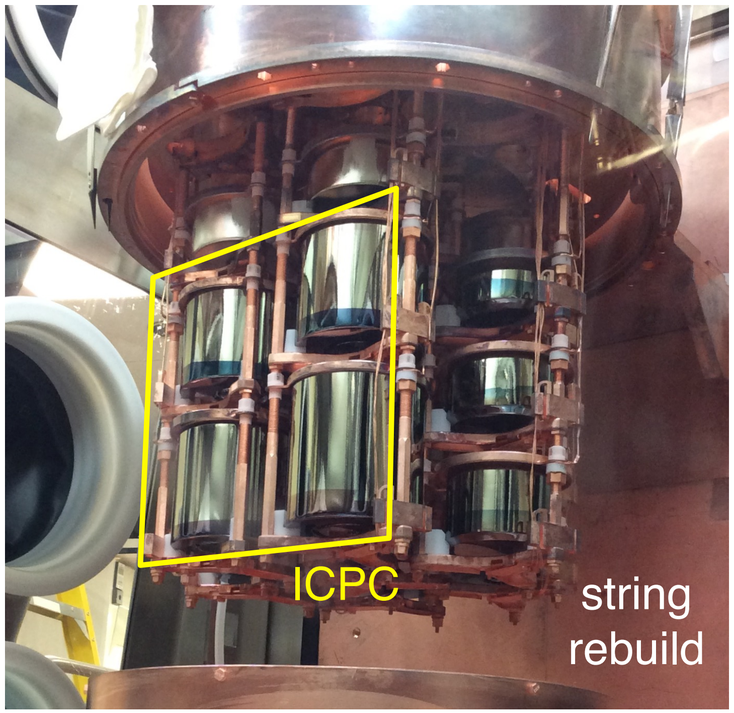
Removed 5 p-type point contact (PPC) $^{enr}$Ge detectors

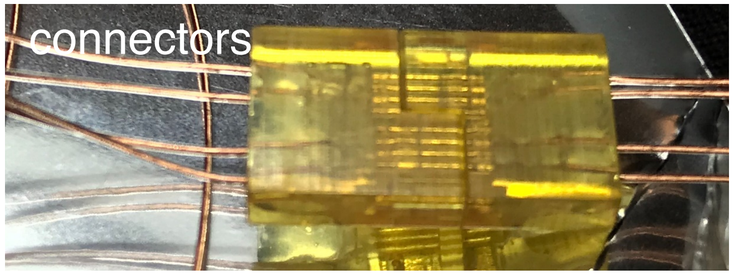
- Early LEGEND-200 tests in LAr at LNGS

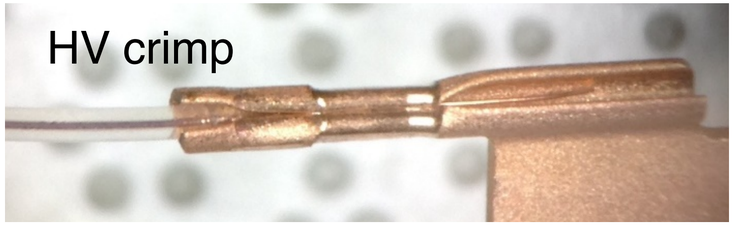
Operated with 4 ORTEC inverted-coaxial point-contact (ICPC) $^{enr}$Ge detectors

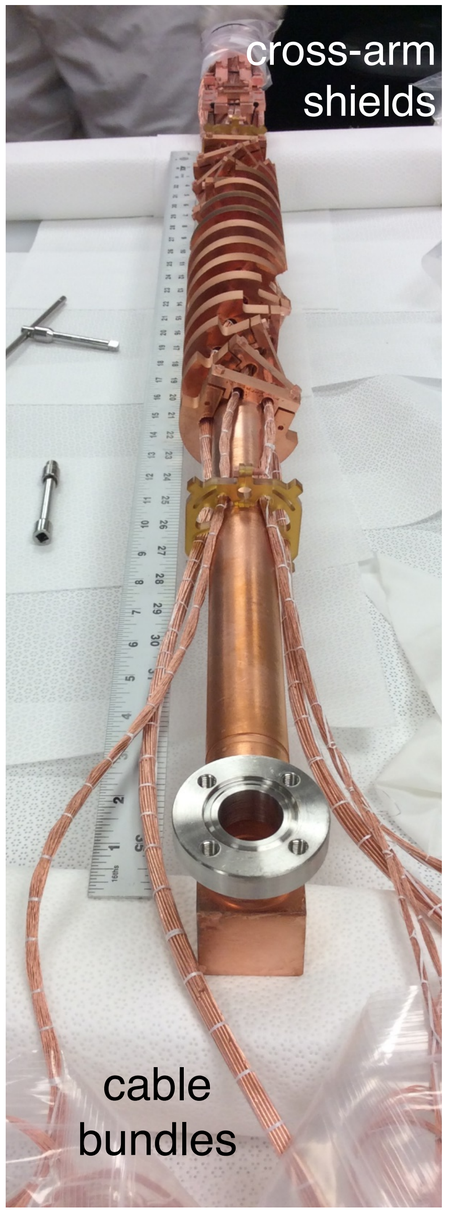
- Low background vacuum testing in advance of LEGEND-200

| | 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%)*<br>*Used for final analysis | 27/27 (100%)**<br>**Final selection not yet made |



# Current Operations

- $^{enr}$Ge detector operation completed in March 2021
  - Ultimate integrated exposure: ~65 kg y ($^{enr}$Ge)
  - Removed all $^{enr}$Ge detectors and packaged for shipment
  - $^{enr}$Ge detectors shipped to LNGS for installation in LEGEND-200

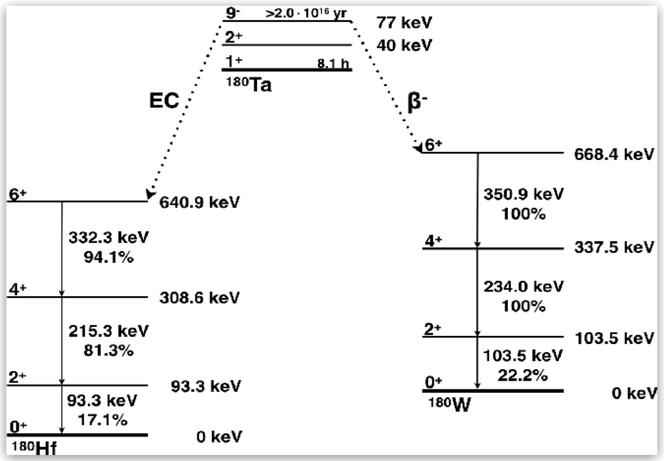


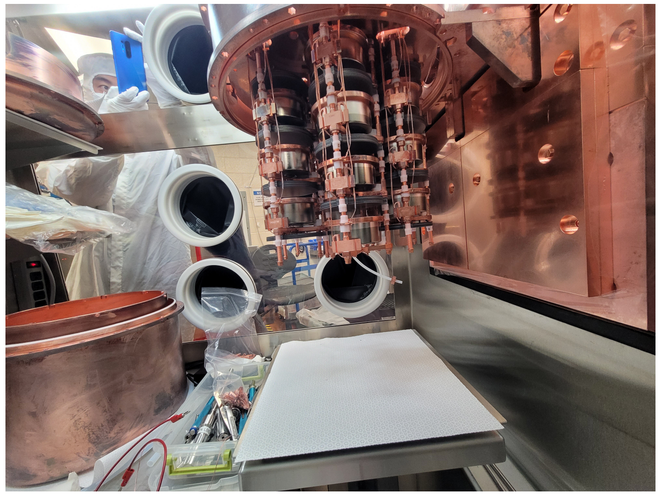
- Continuing operation with natural detectors
  - All remaining natural Ge detectors consolidated into Module 2
  - 23 BEGe detectors filling 5 of the 7 string positions
  - Background studies to refine background model
  - Additional physics studies:
    - A dedicated search for the decay of $^{180m}$Ta

# The Decay of Nature's Rarest Isotope

- 1 - 2 ppm of Earth's crust is Ta, and 99.98% is $^{181}$Ta
- $^{180}$Ta is the only long-lived nucleus that occurs in an isomeric state with an unobserved decay
- Best measurement used ~1kg of $^{nat}$Ta (~0.2 g of $^{180m}$Ta)
- MAJORANA and LANL LDRD project (2022-2023) :
  - Rearrangement of $^{nat}$Ge detectors
  - Installation of 17.9 kg ultra-pure $^{nat}$Ta
  - Making use of the excellent background conditions and energy resolution
  - Sensitivity ~ $10^{19}$ years (with an expected half-life of $10^{17}$-$10^{18}$ years)

LDRD
LABORATORY DIRECTED
RESEARCH & DEVELOPMENT



slide courtesy of Ralph Massarczyk

# Final Spectrum after the 1st Phase Unblinding

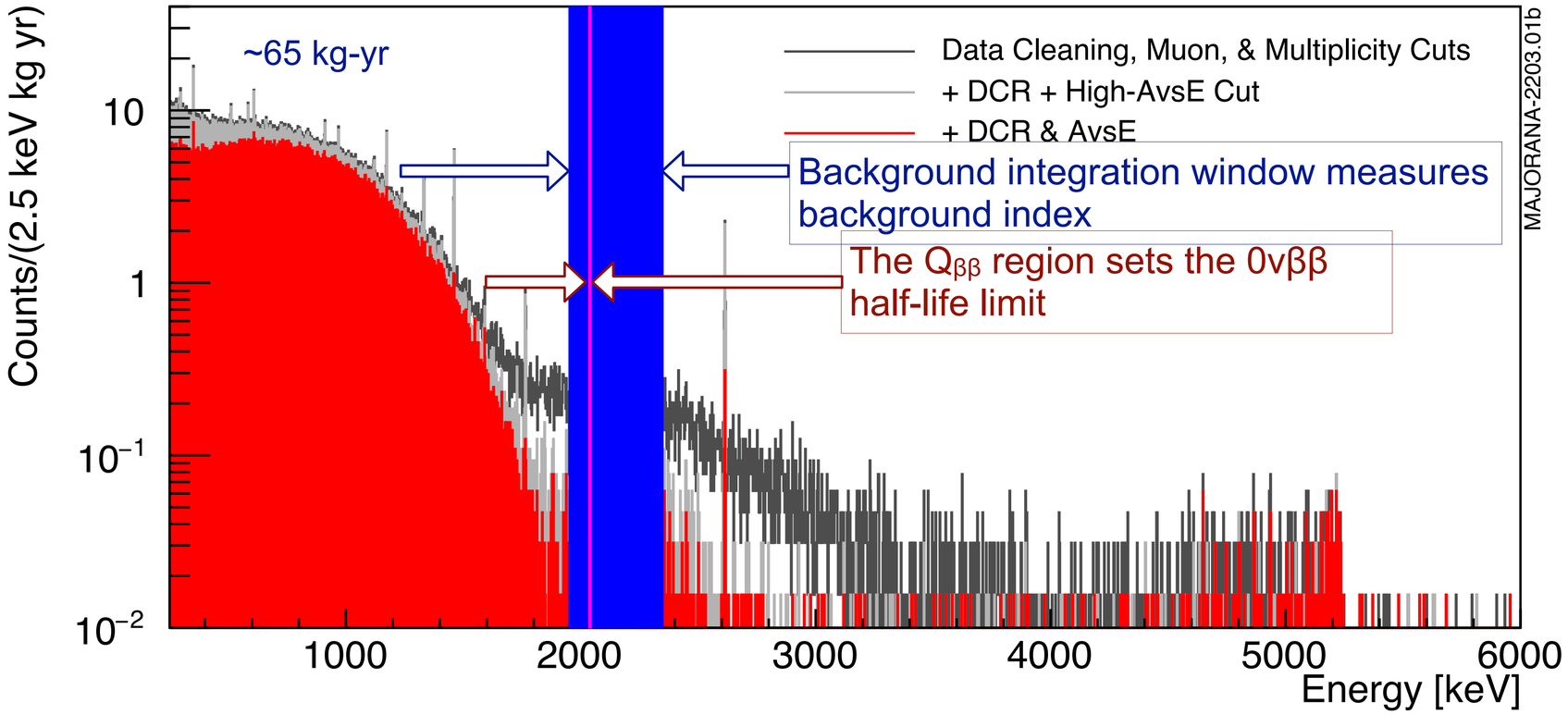
Data is split for statistical blindness, analysis cuts developed on open data

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

Phase 1: Opened up outside the 1950-2350 keV background integration region

The next phases of unblinding are underway now




Previous Release:

26 kg-yr exposure

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

PRC **100** 025501 (2019)

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

PRC **103** 015501 (2021)

Upcoming Release:

~65 kg-yr final exposure results to be released after unblinding

# MAJORANA DEMONSTRATOR Summary and Outlook

Started taking data with first module in 2015 and has completed enriched Ge data-taking in 2021

- Optimization of analysis cuts has been finalized to improve background rejection
- Excellent energy resolution of 2.5 keV FWHM @ 2039 keV, best of all 0νββ experiments
- **Latest limit on 0νββ coming soon from ~65 kg-yr exposure**
- Preliminary sensitivity ~ 8 x $10^{25}$ yr (90% C.L.)
- Leading limits in the search for double-beta decay of 76Ge 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 is important to understand these backgrounds

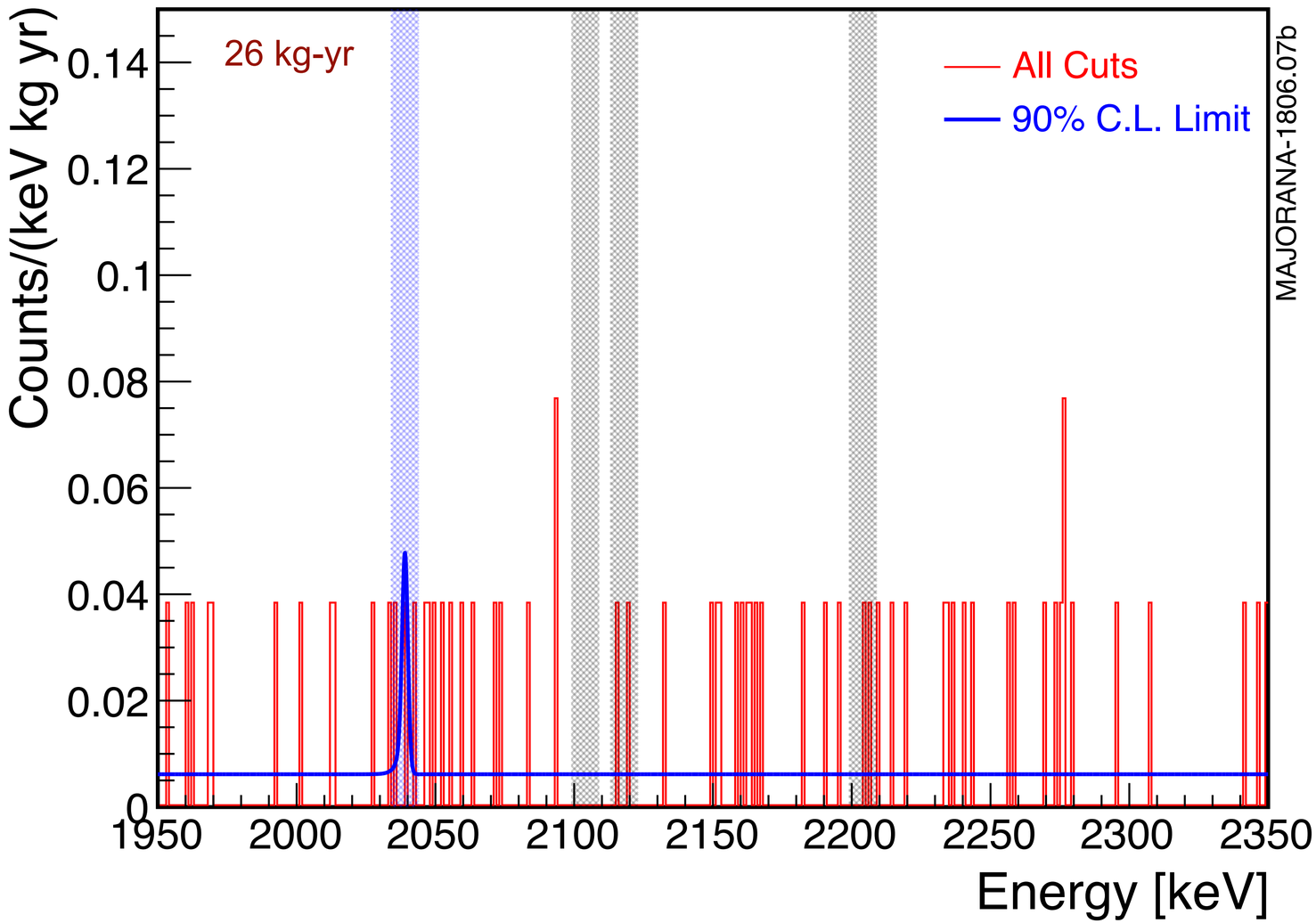
Continuing operation with natural detectors for background studies and other physics (e.g. Decay of $^{180m}$Ta)

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

# BACK-UP SLIDES

# MAJORANA DEMONSTRATOR 2019 0νββ Result

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:

$4.8 \times 10^{25}$ 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)

# Beyond the Standard Model Searches

Excellent energy resolution: ~0.4 keV FWHM at 10.4 keV

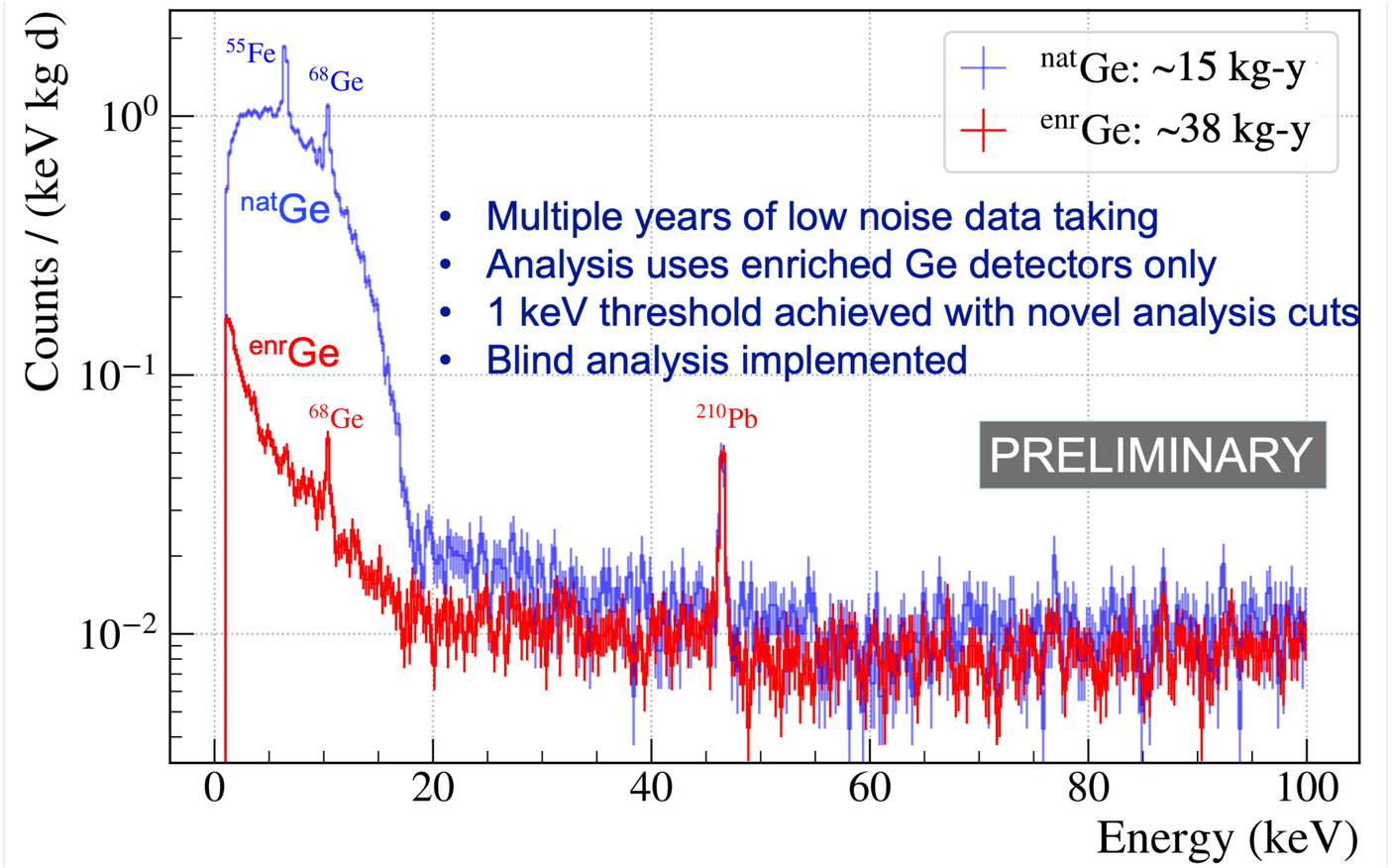
Progress towards a low-E background model

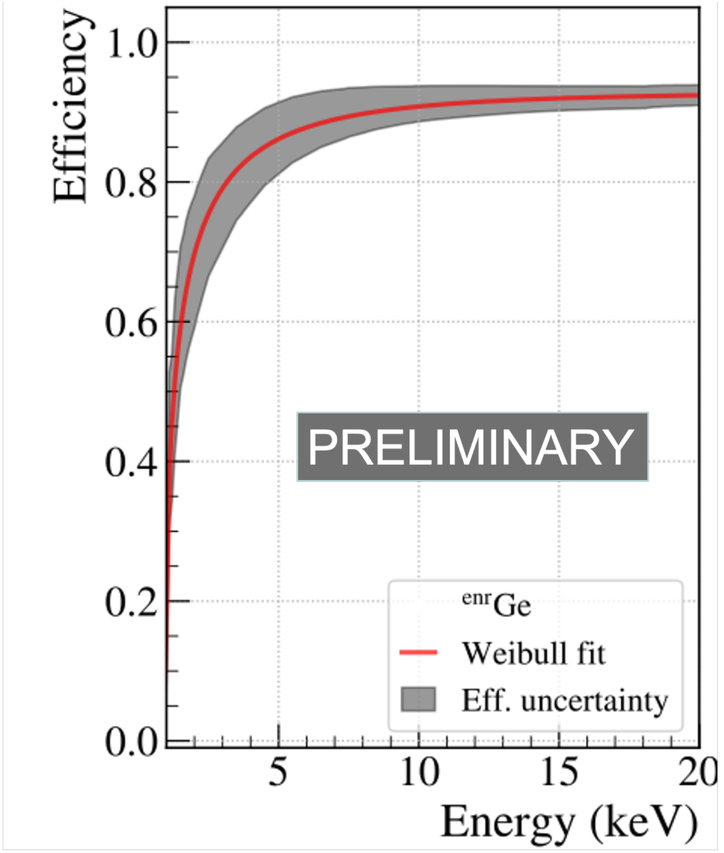
The low backgrounds, low threshold, high resolution spectra allows additional physics searches

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



# 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)

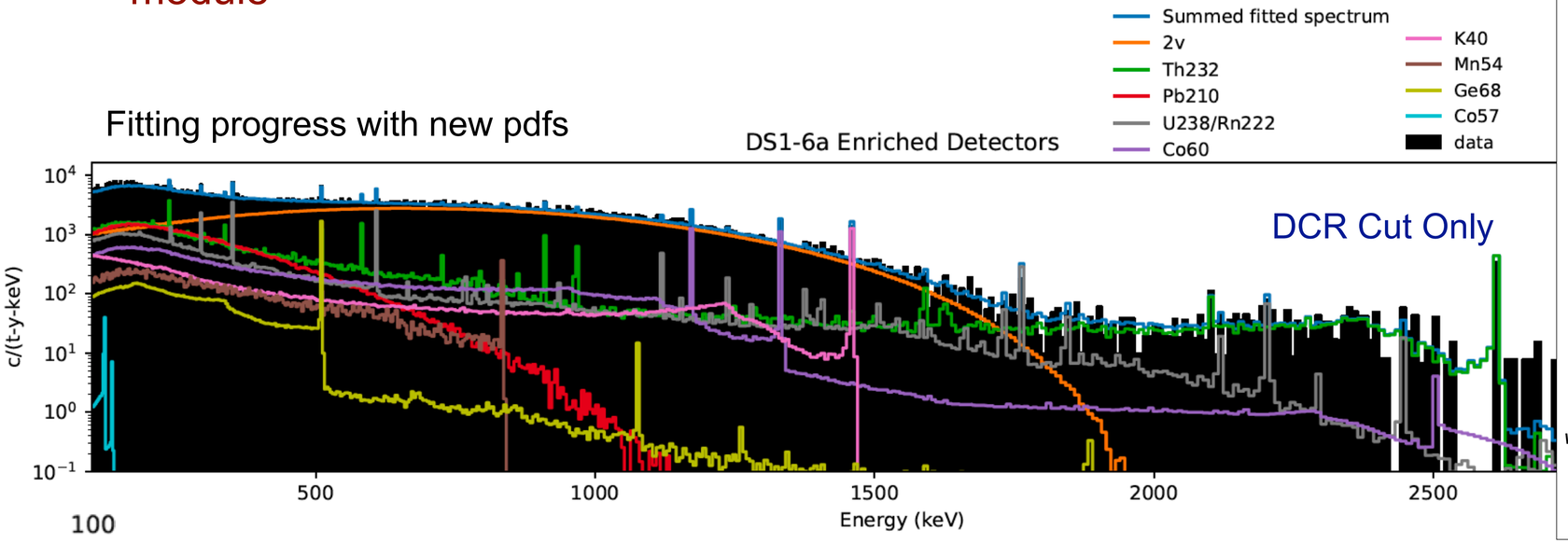
New techniques have been used to quantify uncertainties in our assay-based background model

New high statistic simulations allow for modeling of regions with low efficiency

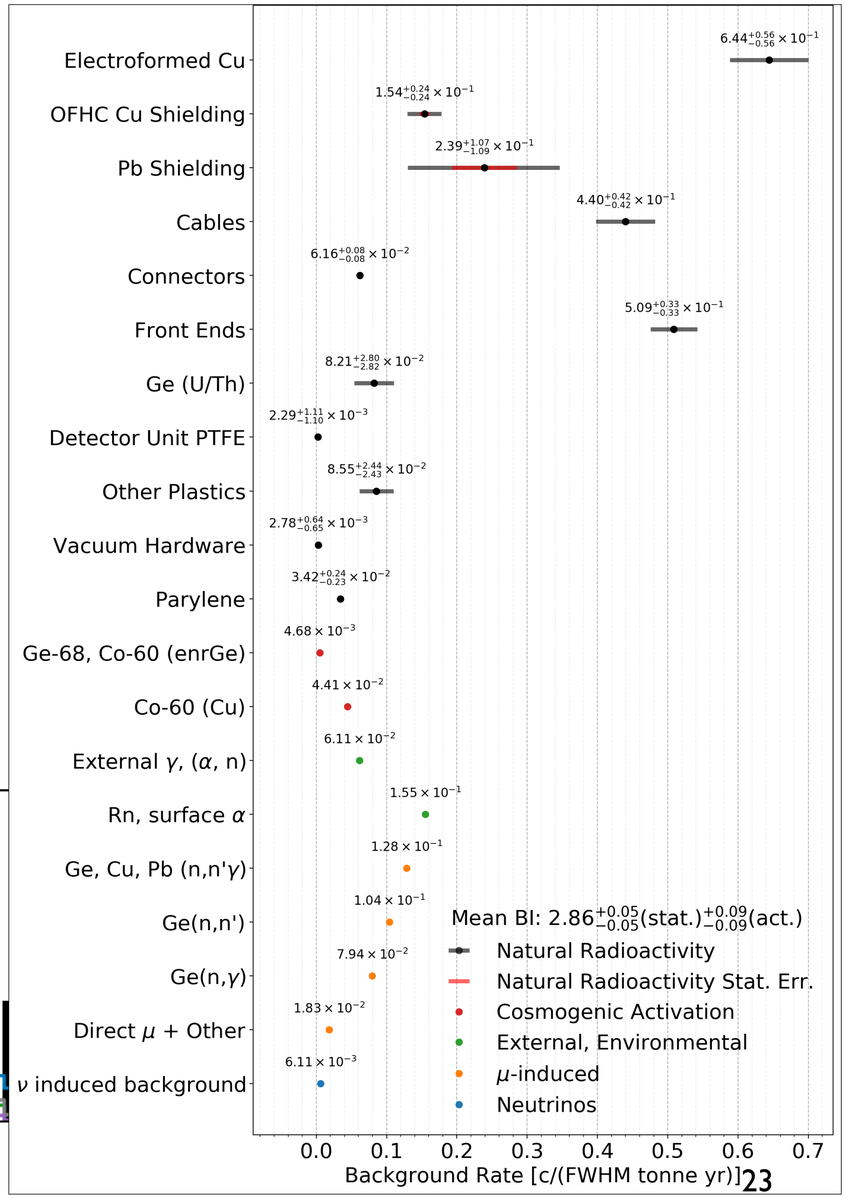
Improved Frequentist and Bayesian fitting efforts underway in order to more precisely locate source of excess Th background

- Components grouped by location (e.g. “far vs. near”) and separated by module

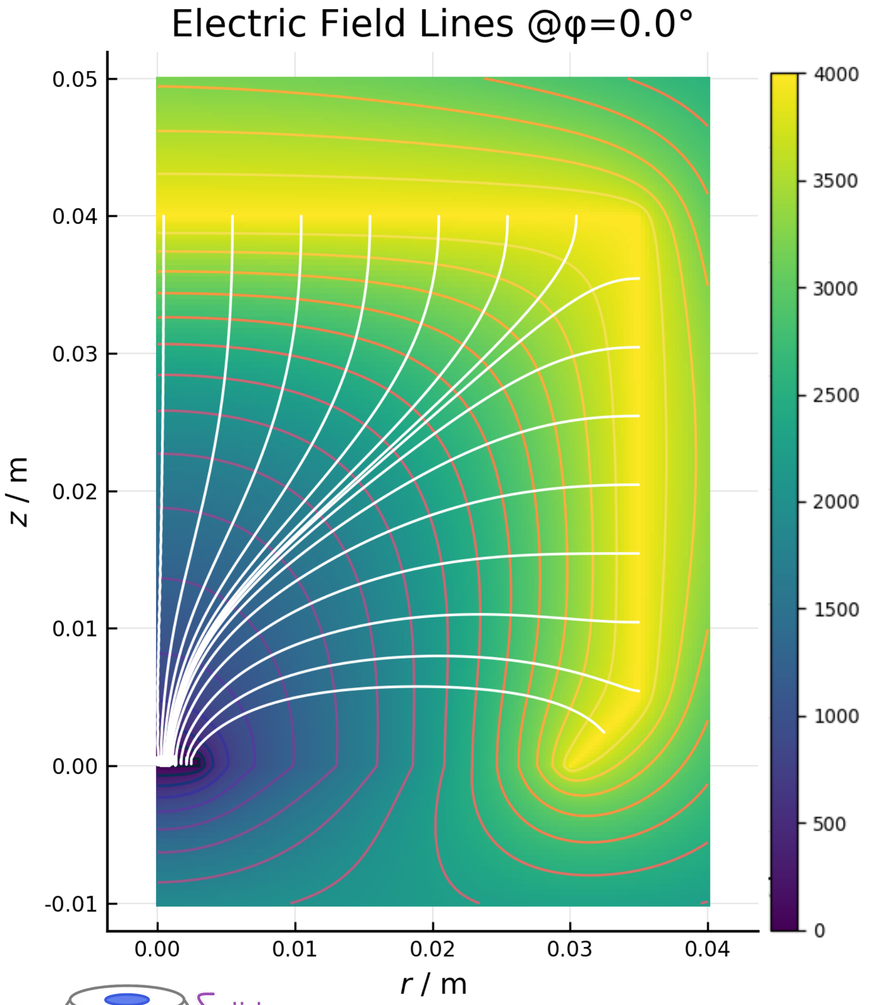
Fitting progress with new pdfs




As-Built Assay-Based Background Model



# Background Rejection: Multi-Site Events





PRC **99** 065501 (2019)