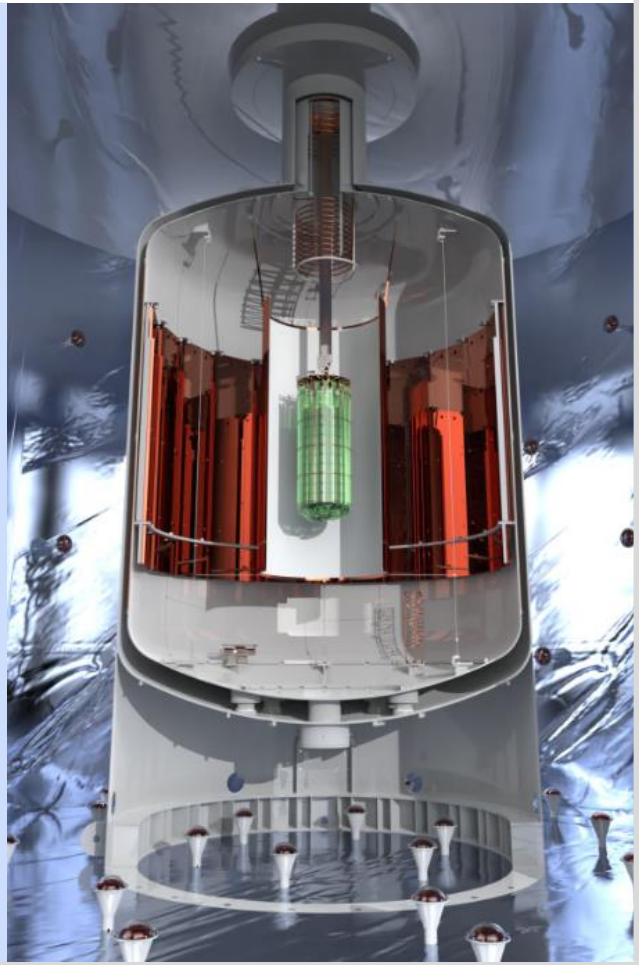
First Results from the LEGEND Experiment

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



Erin Engelhardt

On behalf of the LEGEND collaboration

August 29th, 2024

ICNFP 2024

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

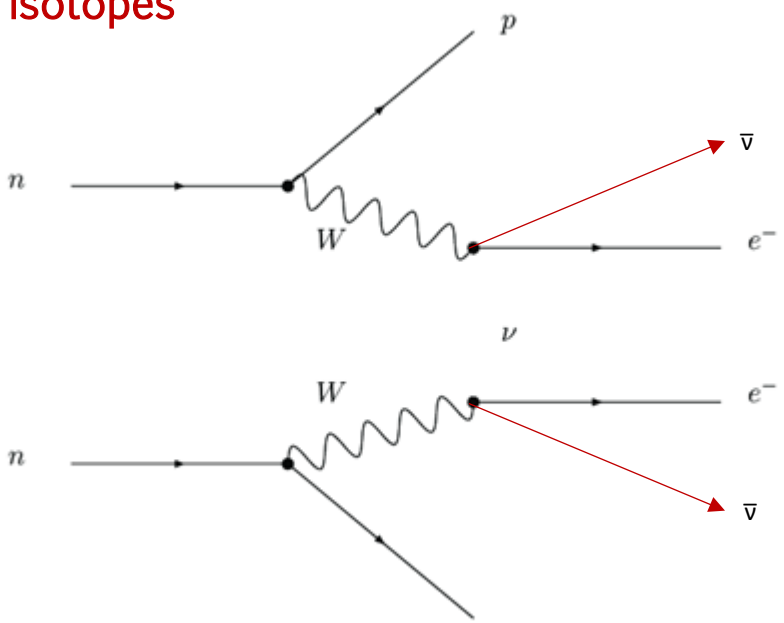
TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

Neutrinoless Double Beta Decay

Double Beta Decay

Measured in 14 isotopes

$T_{1/2} \sim 10^{19} - 10^{21}$ yr



$2n \rightarrow 2p + 2e^- + [2\bar{\nu}_e]$

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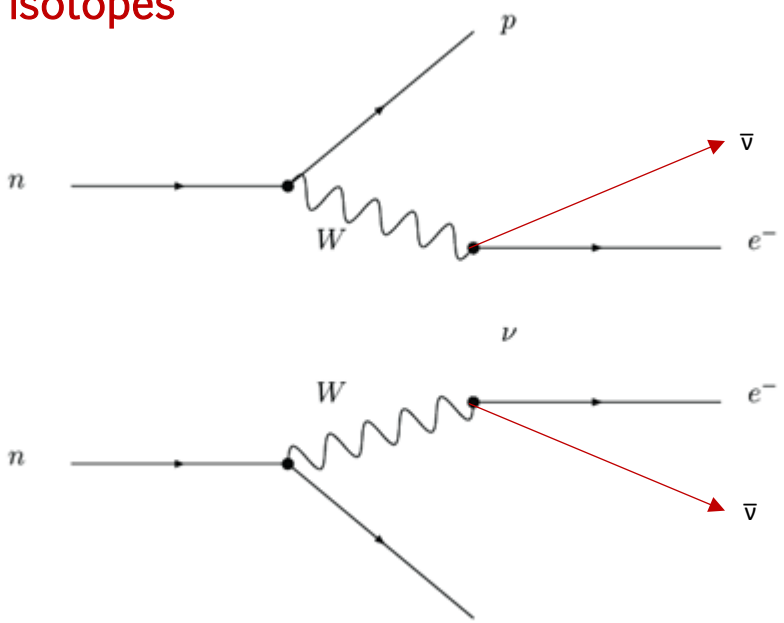
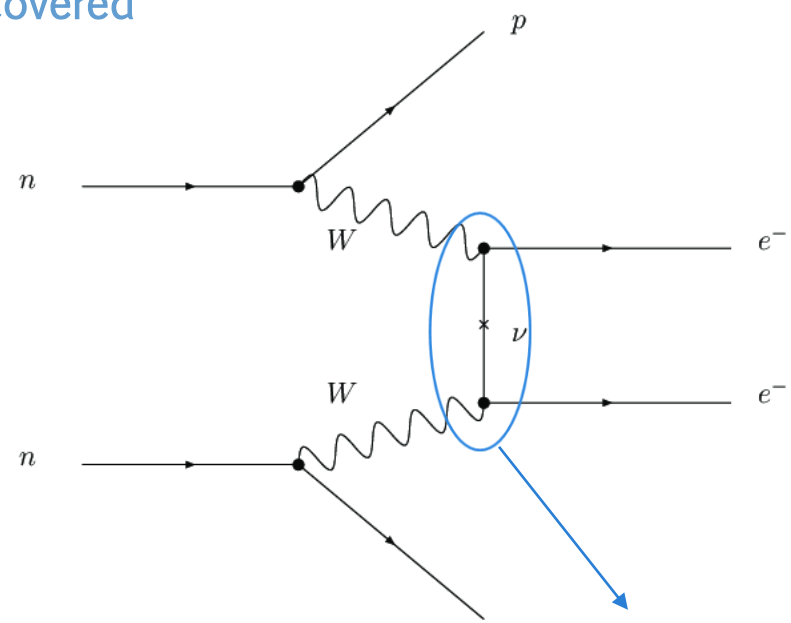


$2n \rightarrow 2p + 2e^- + [2\bar{\nu}_e]$

Neutrinoless Double Beta Decay

Has yet to be discovered

$T_{1/2} > 10^{26}$ yr



New Physics!

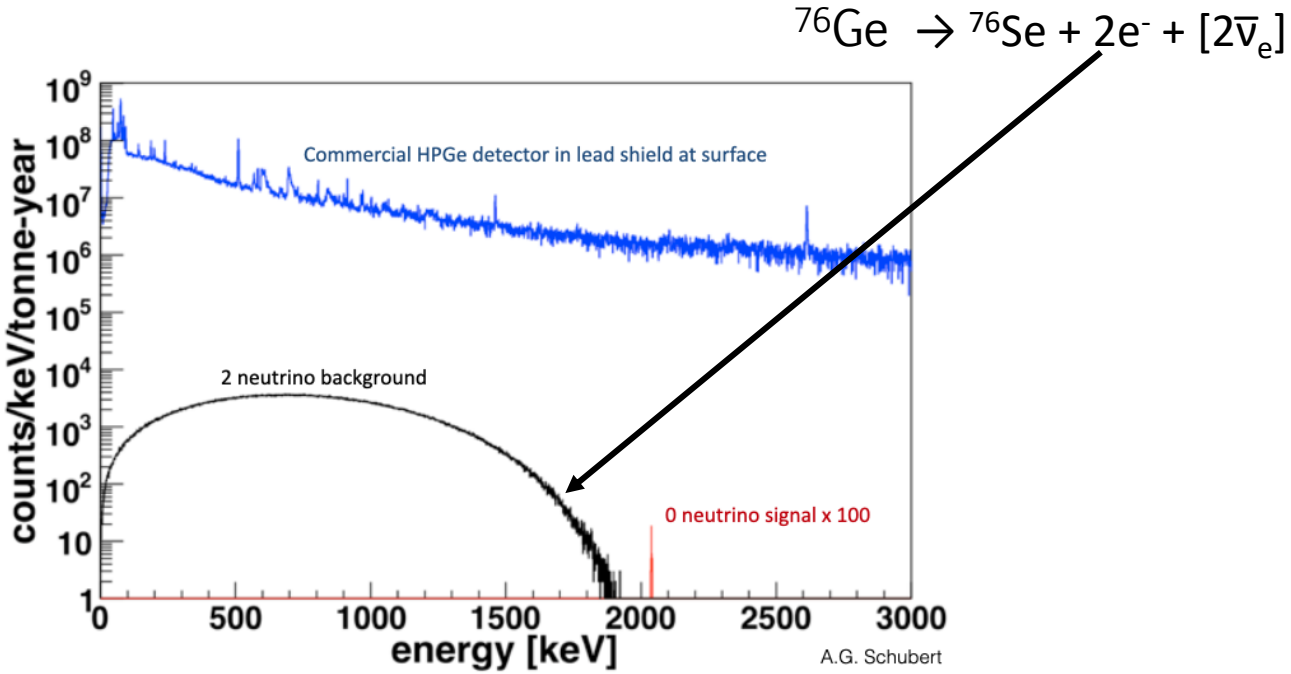
Neutrinoless Double Beta Decay would be exciting new physics

- Neutrino is its own antiparticle
- Hints at the neutrino mass scale and mass hierarchy
- Lepton number violating process → new path towards matter-antimatter asymmetry

Searching for Neutrinoles Double Beta Decay

Measure energies of the electrons,
look for peak at $Q_{\beta\beta}$

- High efficiency, large exposure
- Low Backgrounds
- Good energy resolution



Searching for Neutrinoles Double Beta Decay

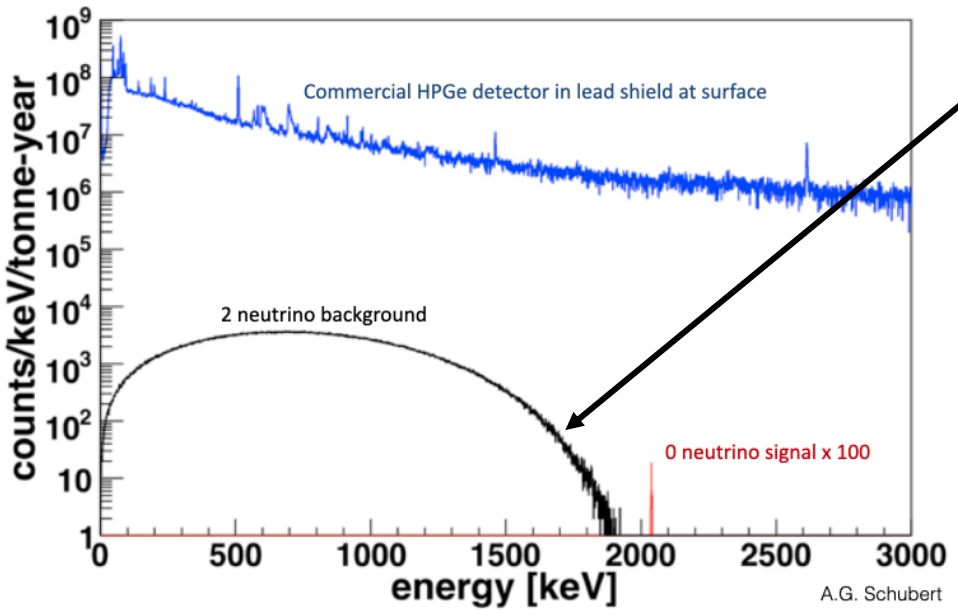
Measure energies of the electrons, look for peak at $Q_{\beta\beta}$

- High efficiency, large exposure
- Low Backgrounds
- Good energy resolution

Germanium is excellent for 0νββ searches

- Source = Detector → High efficiency
- High Purity Germanium → Low intrinsic background
- ~0.1% Energy resolution at $Q_{\beta\beta}$

$^{76}Ge \rightarrow {}^{76}Se + 2e^- + [2\bar{\nu}_e]$

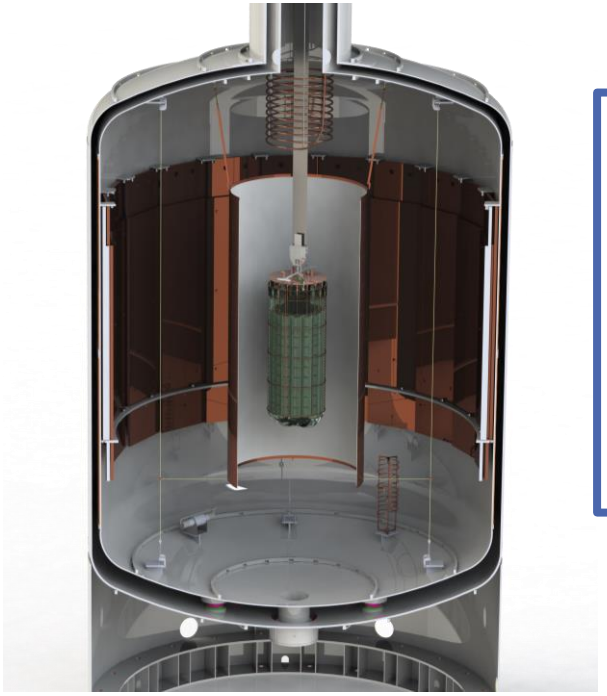


Limits from GERDA and MAJORANA are among the most stringent

GERDA: $T_{1/2} > 1.8 \times 10^{26}$ yr [Phys. Rev. Lett. 125, 252502]

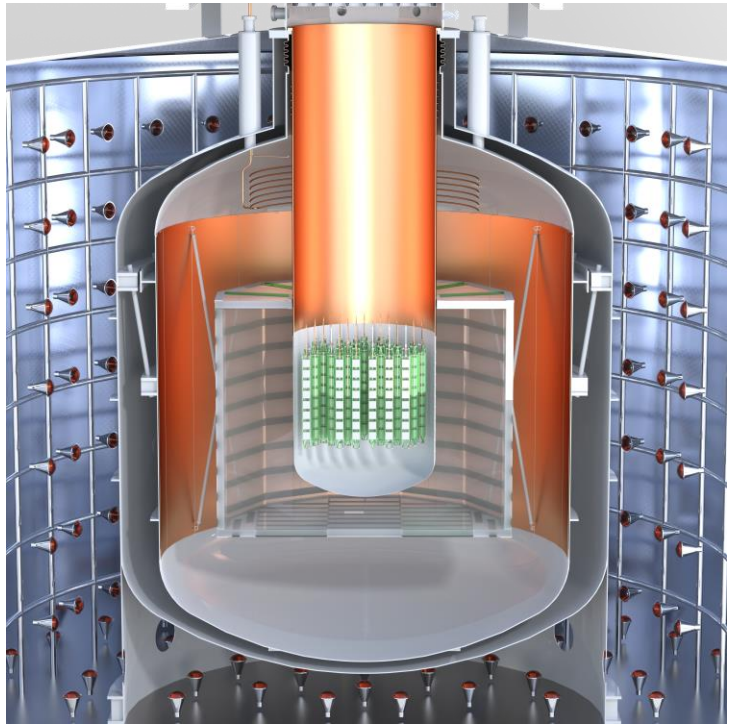
MAJORANA: $T_{1/2} > 8.3 \times 10^{25}$ yr [Phys. Rev. Lett. 130, 062501]

The LEGEND Experiment



"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**."

Located at Laboratori Nazionali del Gran Sasso (LNGS)



LEGEND-200 (Now) ← This talk

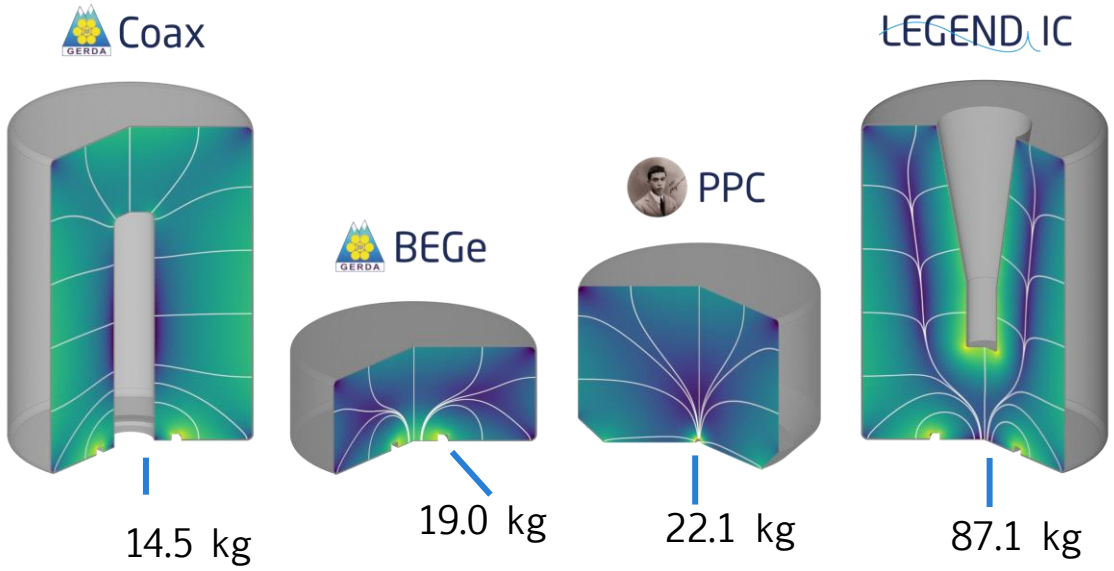
- 200 kg of enriched Ge, 5 yr of data taking
- BI ~ 2×10^{-4} cts/(keV kg yr) → $T_{1/2} > 10^{27}$ yr
- Started physics data-taking in March 2023 with 142 kg of enriched Ge

LEGEND-1000 (Future)

- 1 ton of enriched Ge, 10 yr of data taking
- BI $< 10^{-5}$ cts/(keV kg yr) → $T_{1/2} > 10^{28}$ yr
- Probe the entire inverted ordering region
- Start data taking in 2030 (depending on funding timeline)

LEGEND-200 Detectors

- Enriched in >92% ^{76}Ge
- Excellent energy resolution at $Q_{\beta\beta}$ (~2.5 keV)
- Point-contact geometry
  - BEGe, PPC, and ICPC
  - Low capacitance
  - Topological discrimination of events



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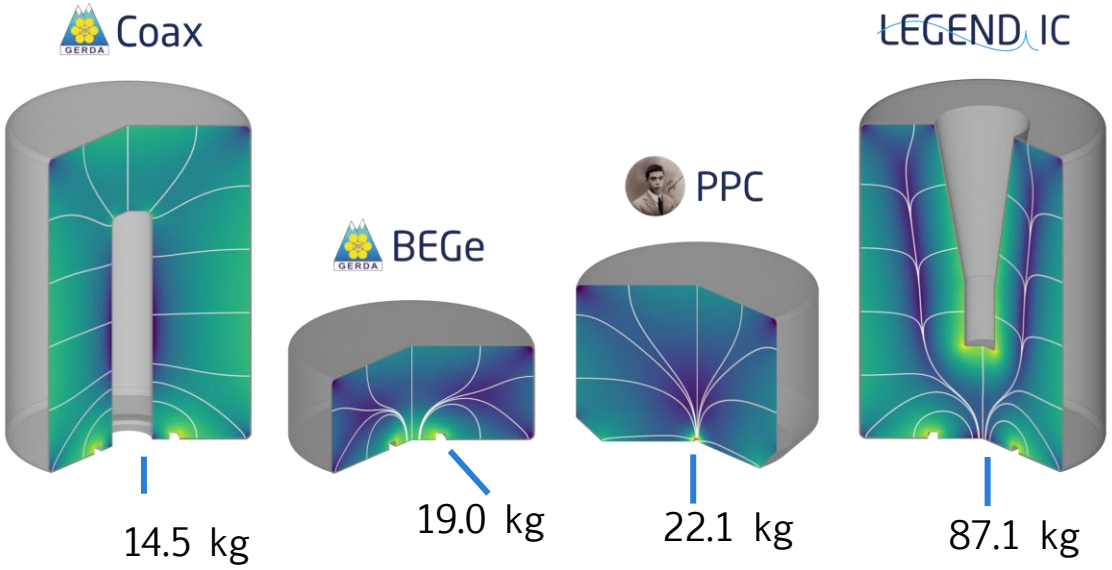
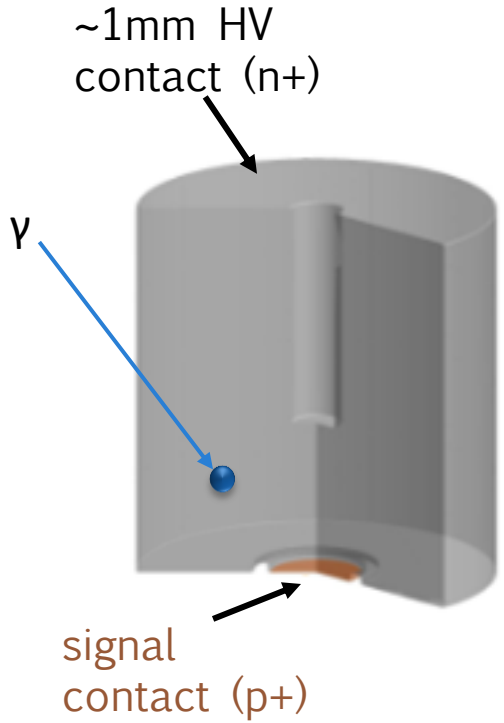


- Radiation hits detector, creates charge cloud



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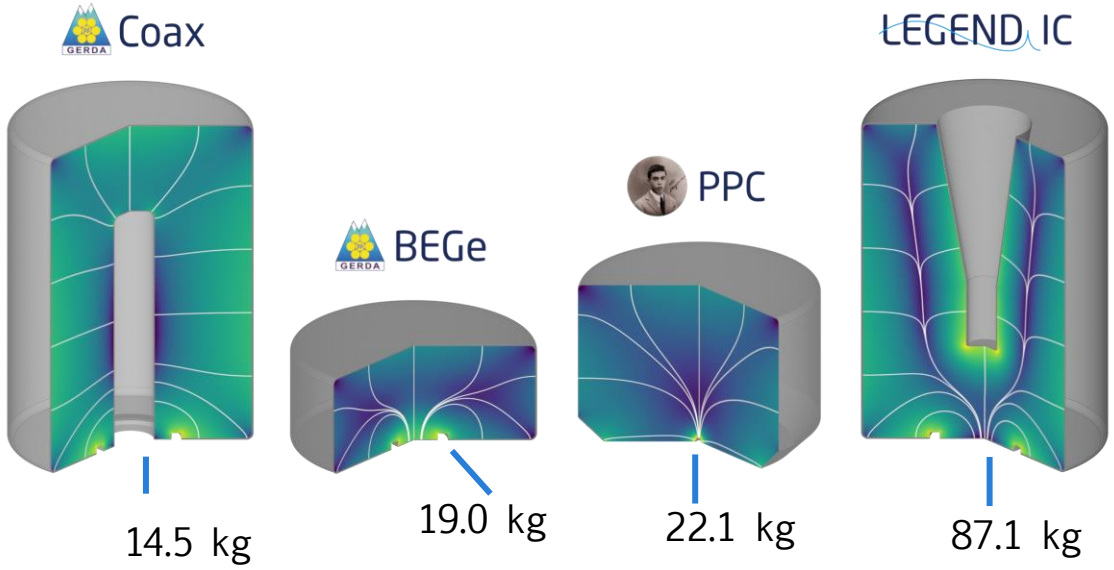
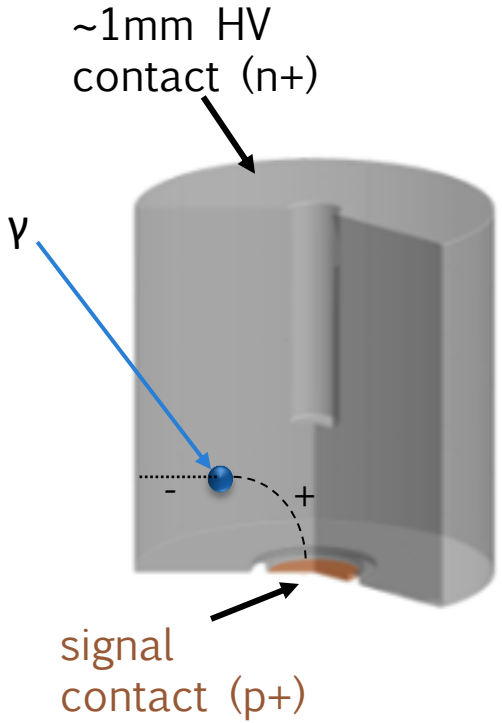


- Radiation hits detector, creates charge cloud
- Holes drift towards p+, electrons towards n+ along E-field lines



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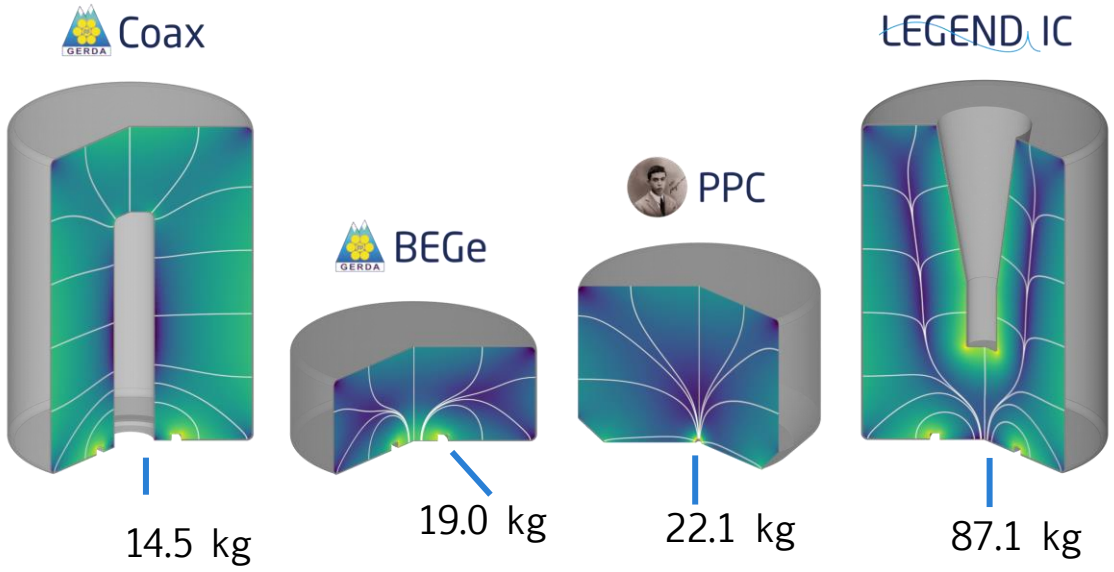
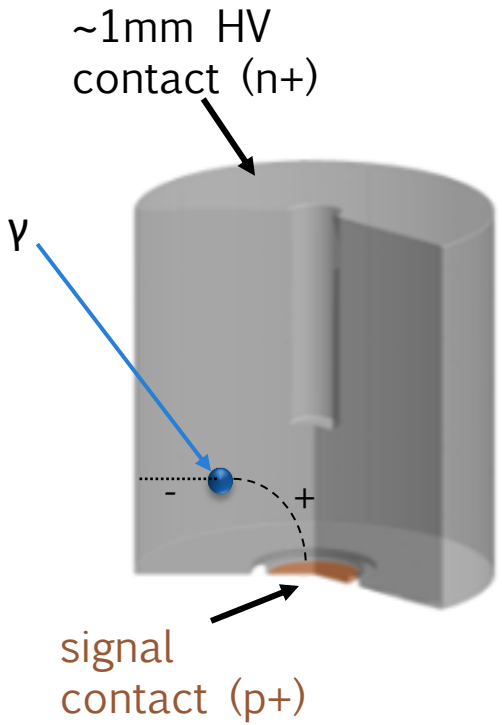
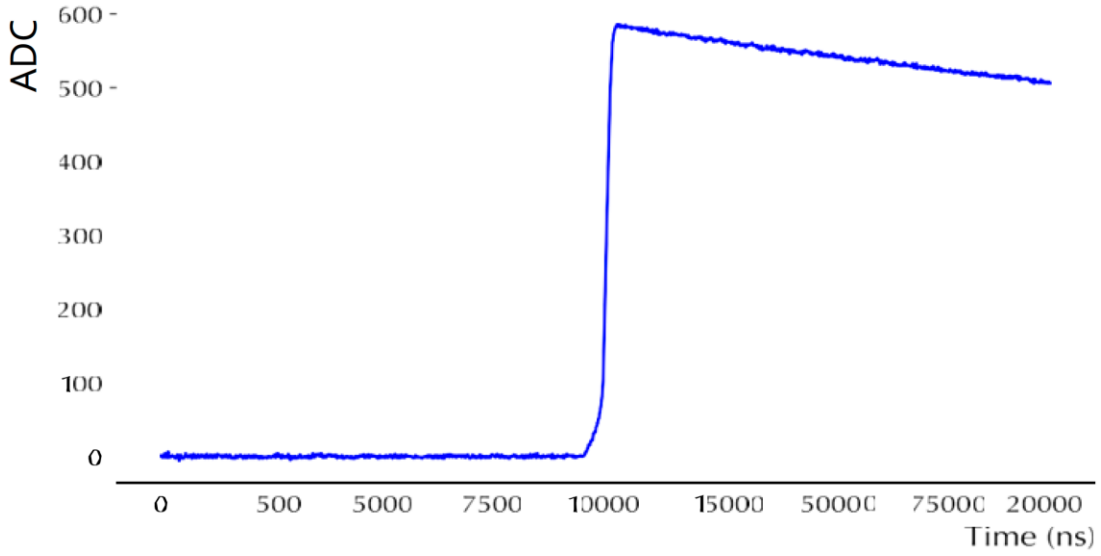
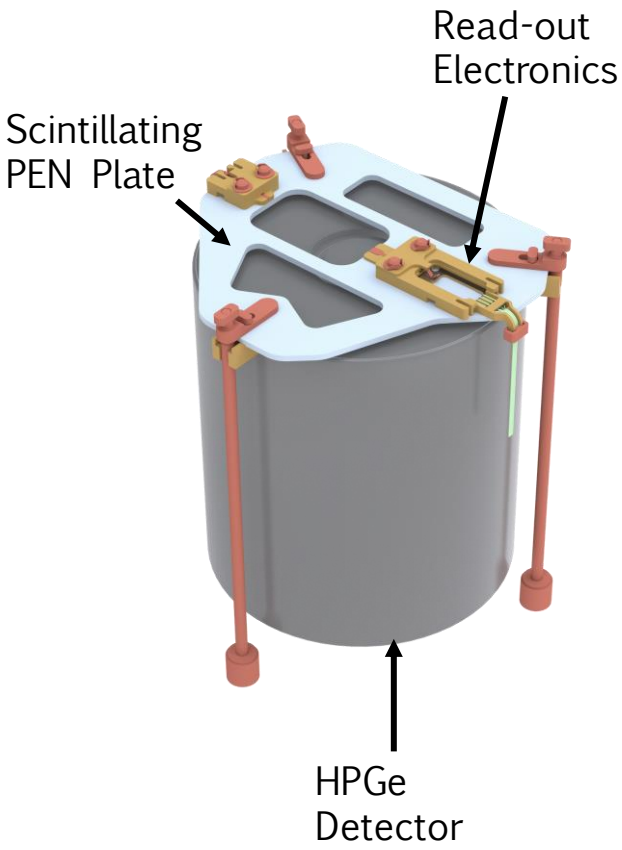


- Radiation hits detector, creates charge cloud
- Holes drift towards p+, electrons towards n+ along E-field lines
- Movement of charge through E-field induces current on p+ contact

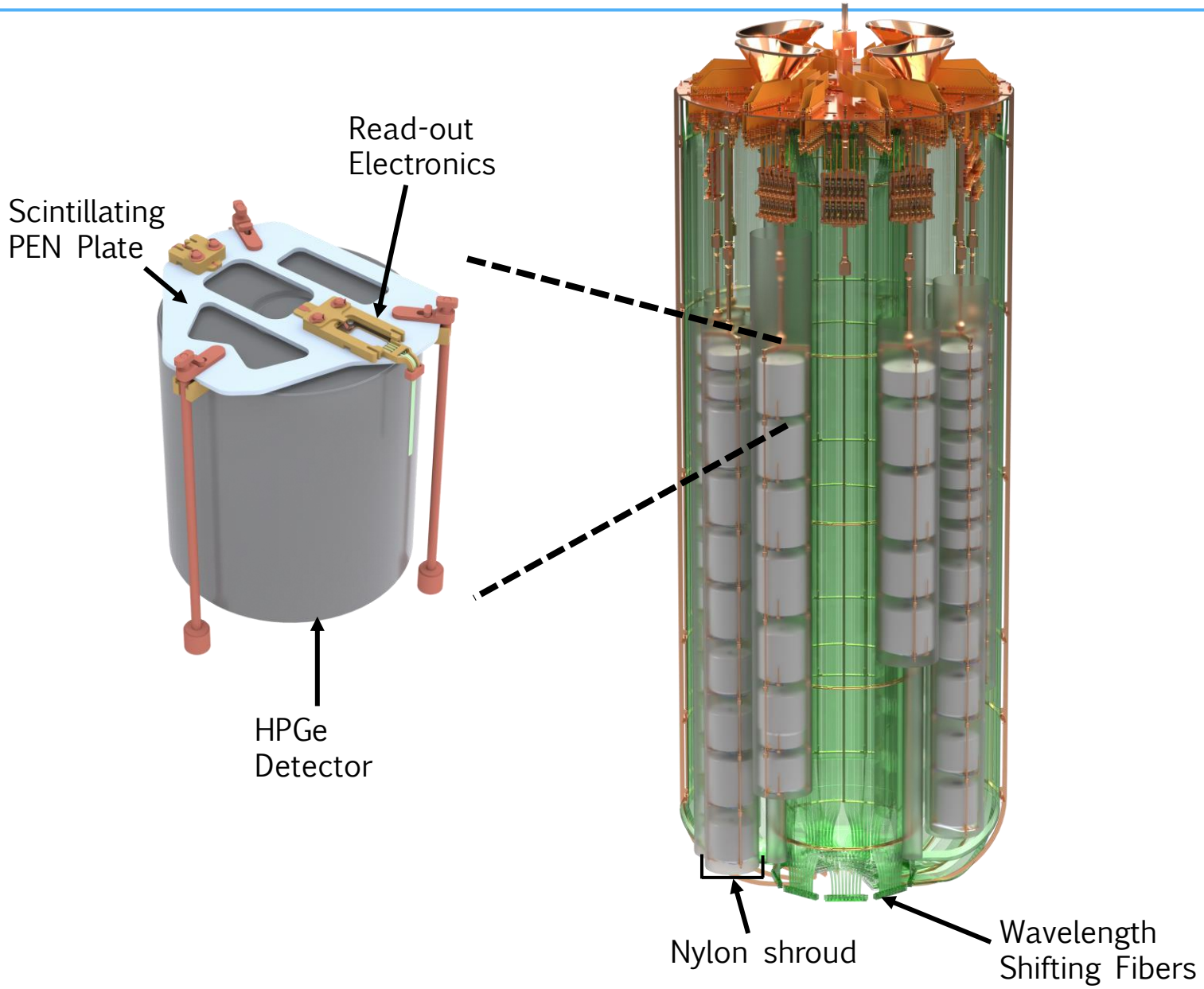




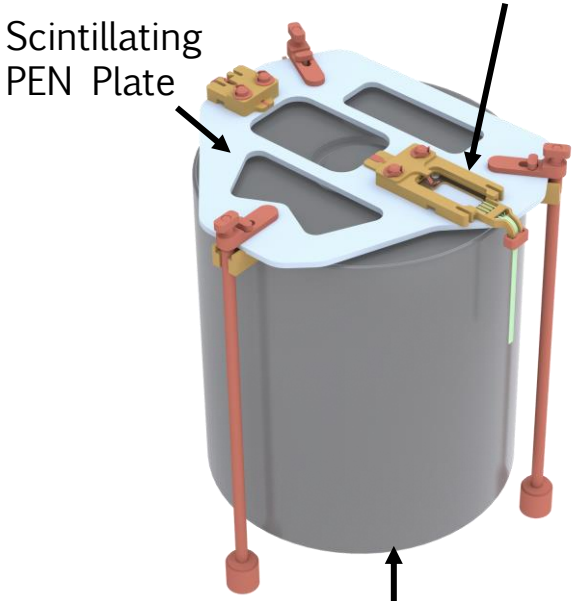
The LEGEND Strategy

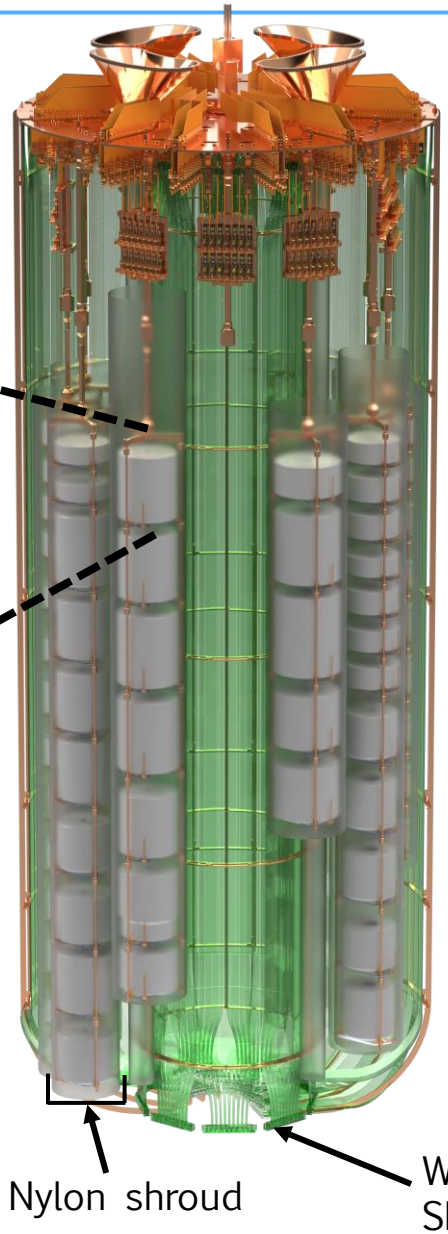


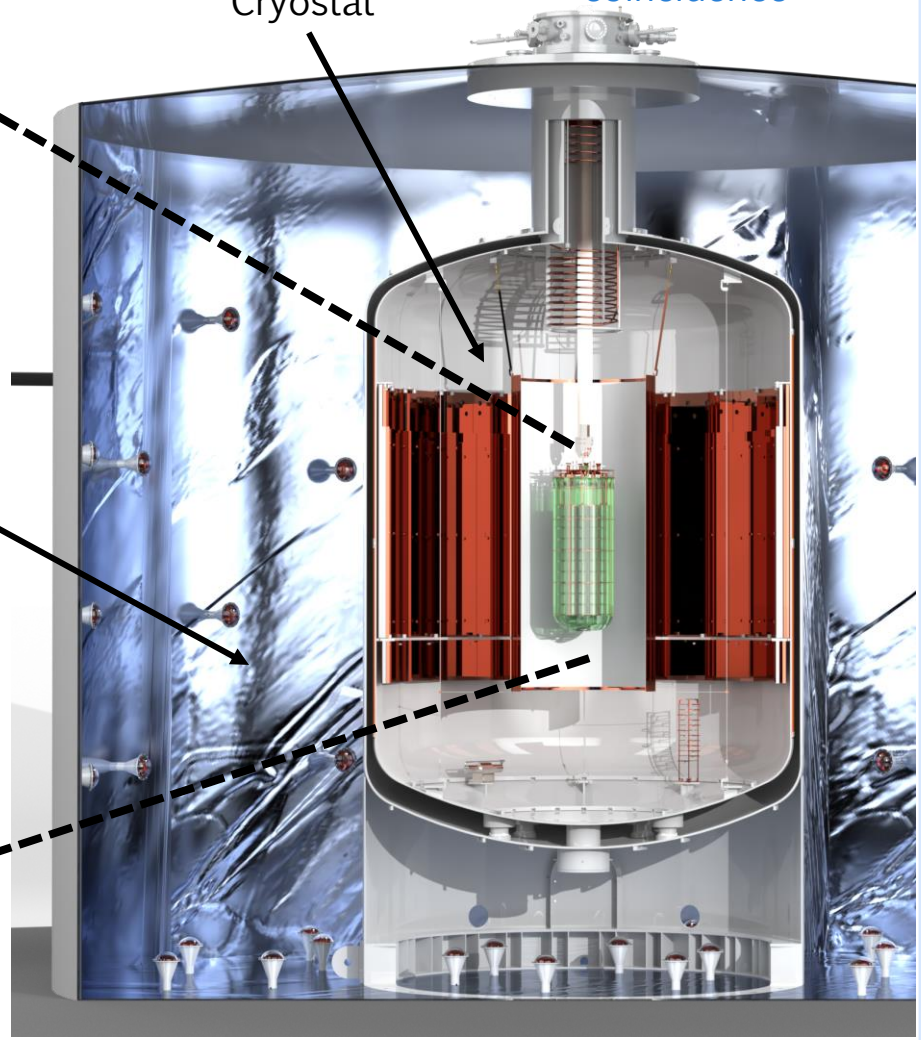
The LEGEND Strategy



The LEGEND Strategy



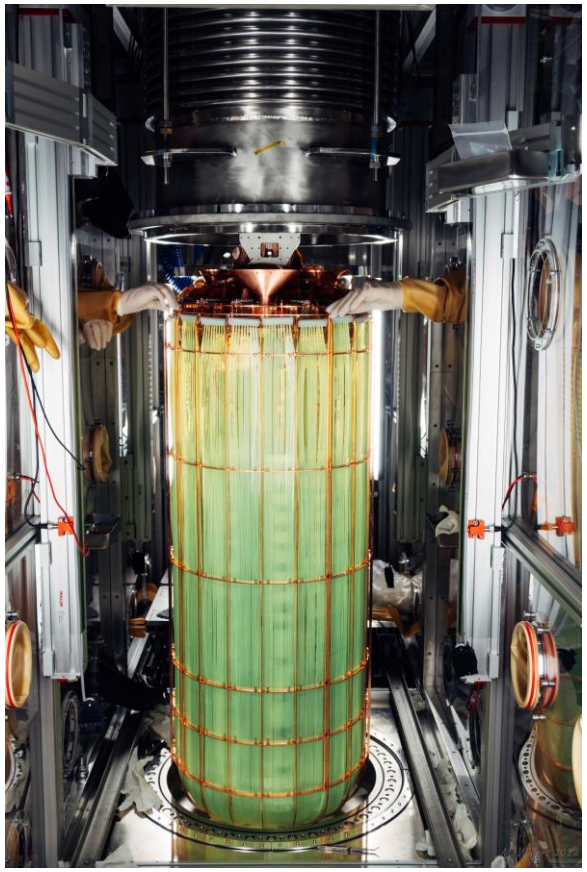




Designed to maximize background rejection

- Detector array for Ge anti-coincidence
- Liquid Argon anti-coincidence
- Water Cherenkov muon veto

LEGEND-200



Photos: Michael Willers / LEGEND Collaboration

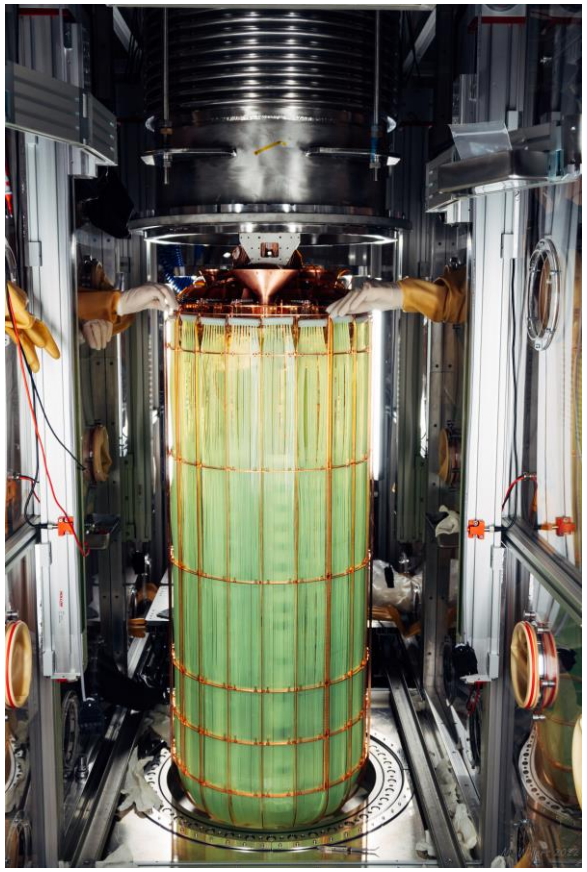
Installation and commissioning

Physics data taking

2023

2024

LEGEND-200



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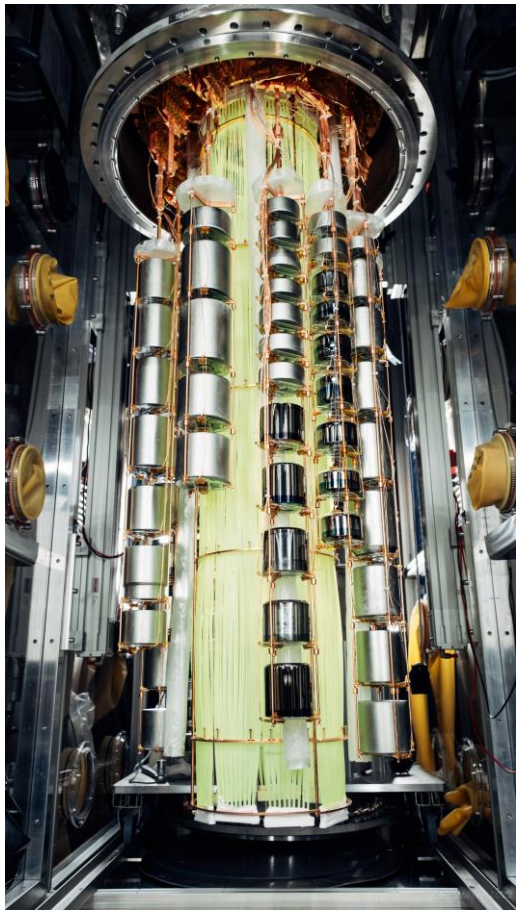


Special datasets without outer barrel and nylon shrouds

Installation and commissioning

Physics data taking

Background characterization runs

Assay campaign and maintenance

Resume data taking

2023

2024

Present Day

First Year of Data Taking

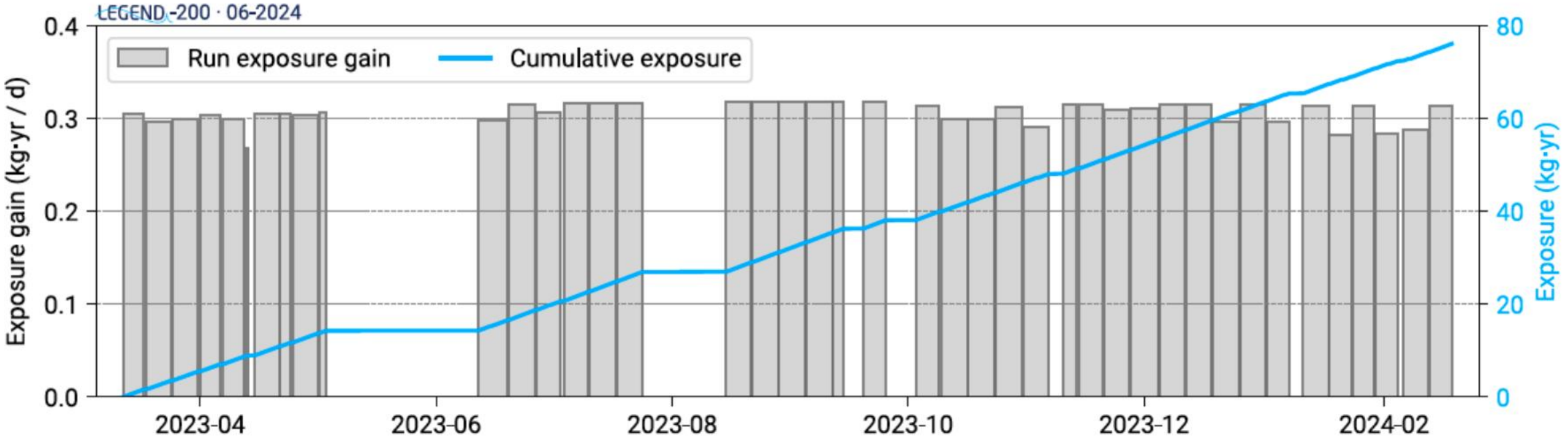
Physics data taking from March 2023 – February 2024

Silver Dataset

- 76.2 kg yr
- Low background and performance characterization data

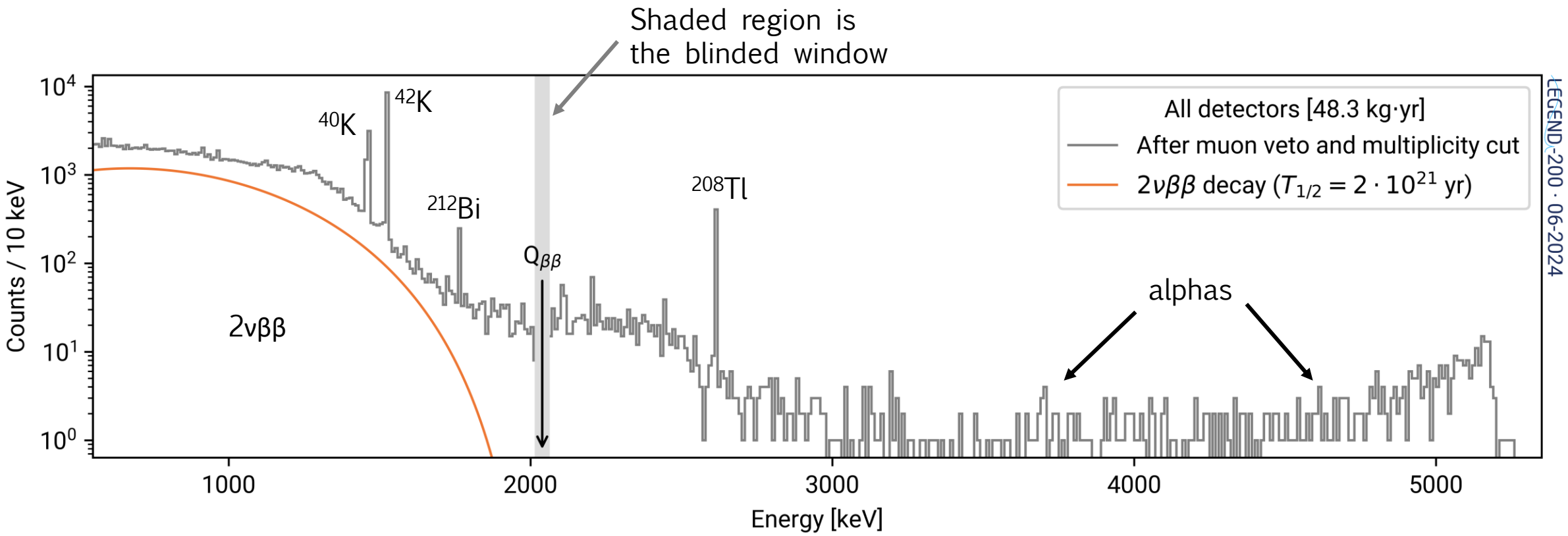
Golden Dataset

- 48.3 kg yr
- Low background data with fully vetted analysis



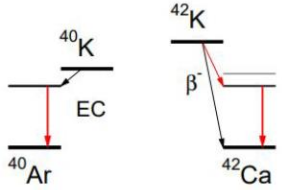
Dataset after Muon and Multiplicity Cuts

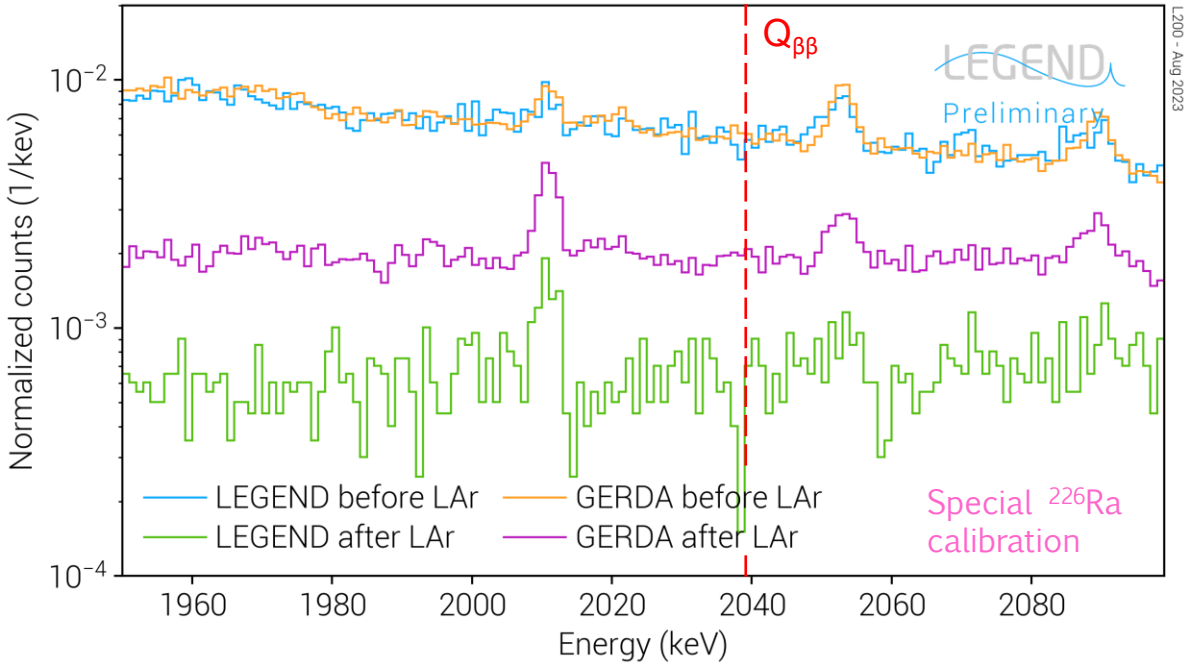
- Blinding applied to 50 keV window around Q_{BB}
- >95% physics events survive after data cleaning

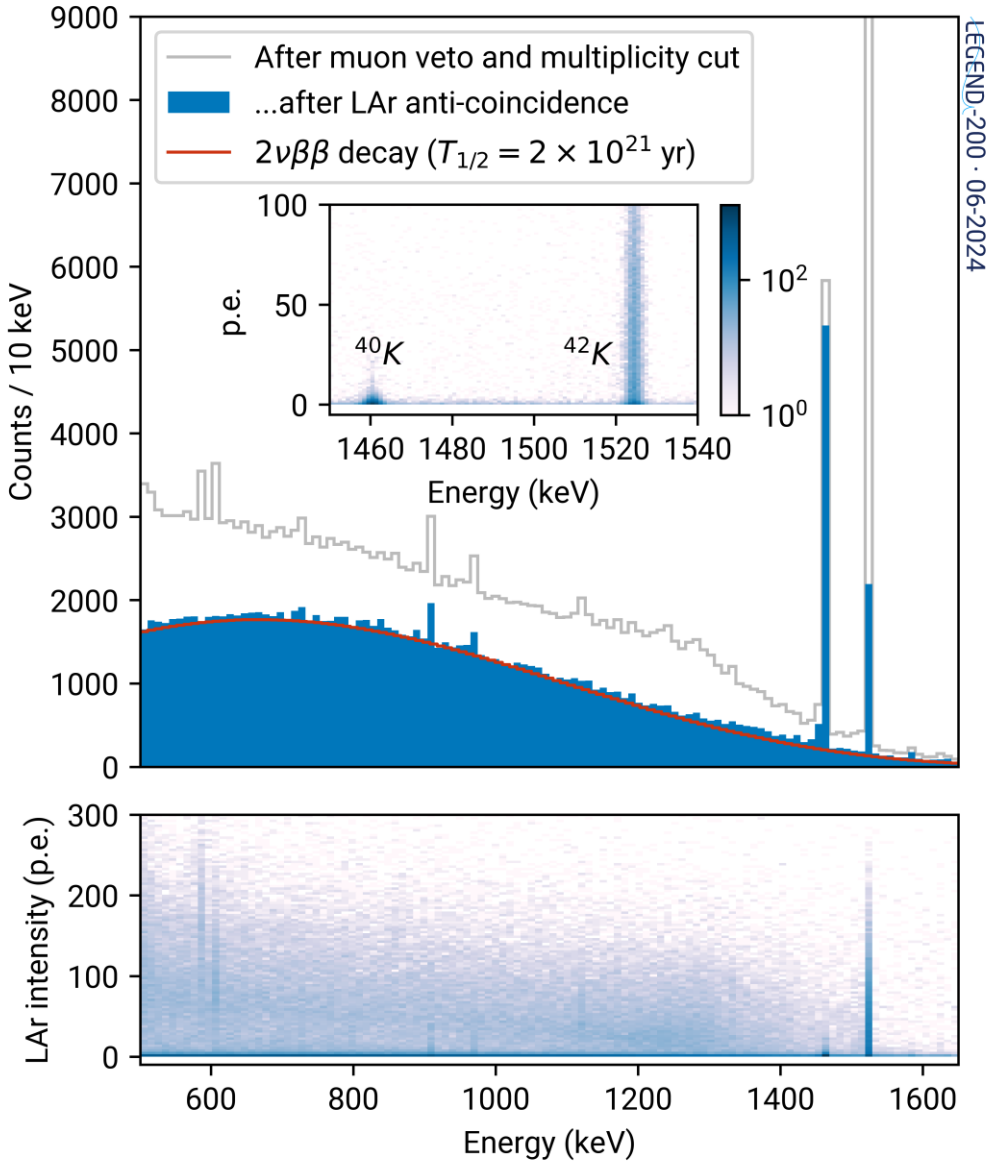


Liquid Argon (LAr) Instrumentation

- Reject events coincident with LAr Instrumentation
  - Improved background rejection in ROI compared to GERDA
  - Higher light yield due to more fibers, less shadowing, and higher purity LAr
- Suppression depends on event topology
  - Strong rejection of ^{42}K, minimal rejection of ^{40}K

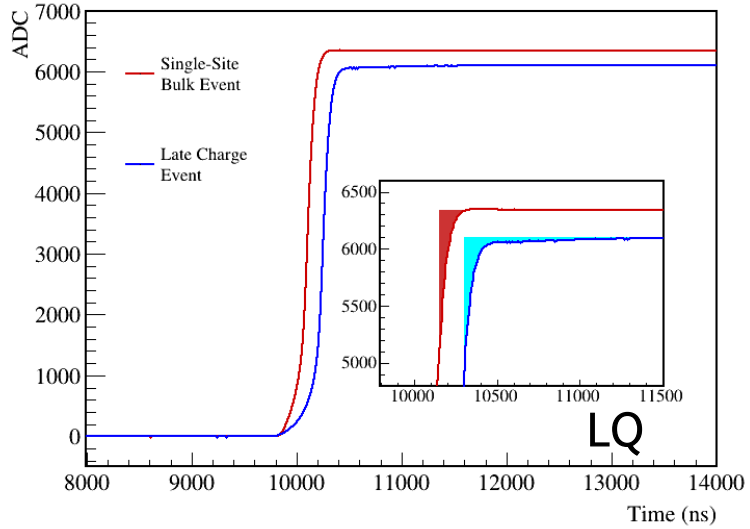


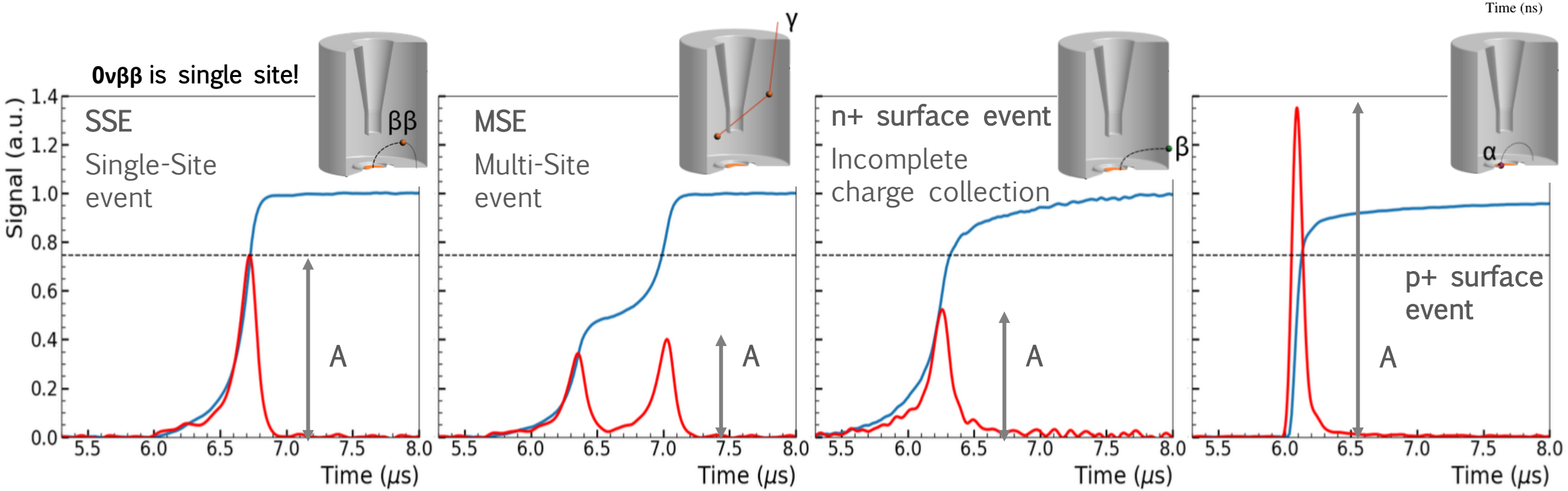




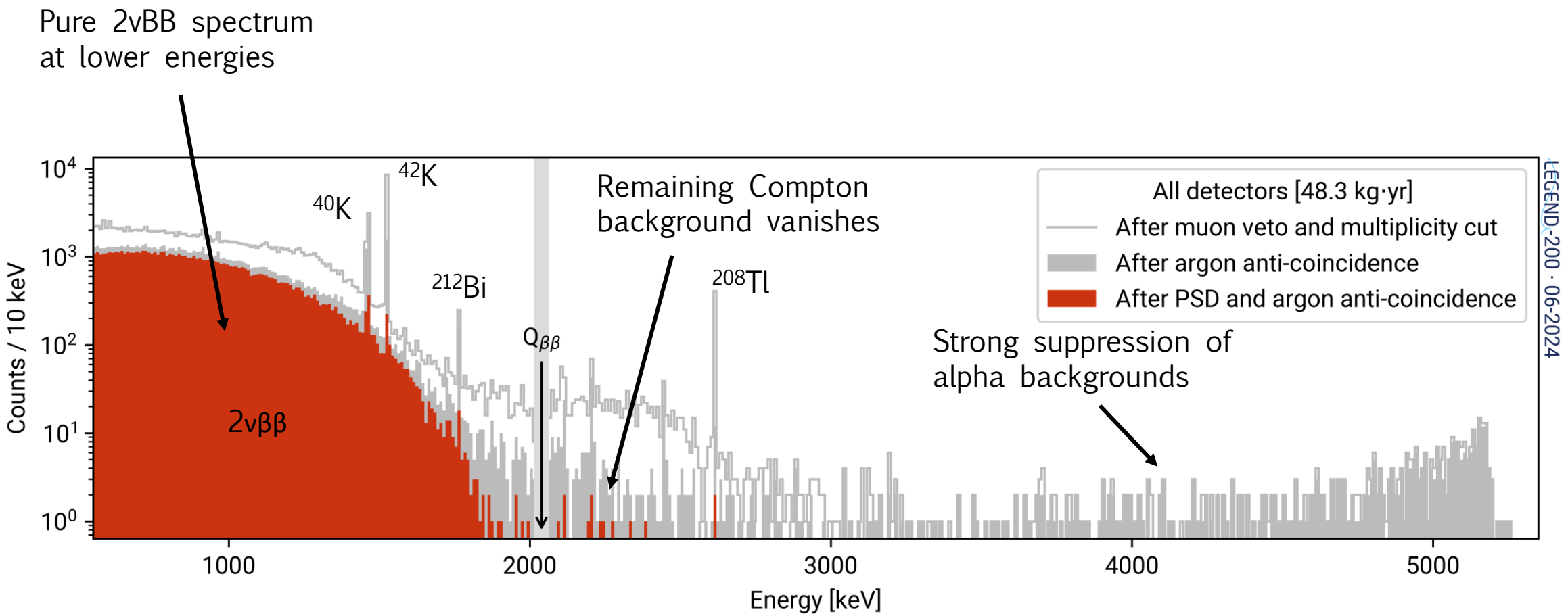
Pulse Shape Discrimination (PSD)

- A/E classifier = max(current)/energy
  - Low A/E → Multi-site & n+ events
  - High A/E → p+ events (alphas)
- Late Charge (LQ)
  - High LQ → n+ & p+ events
  - Replaces High A/E for detectors with large passivated surfaces





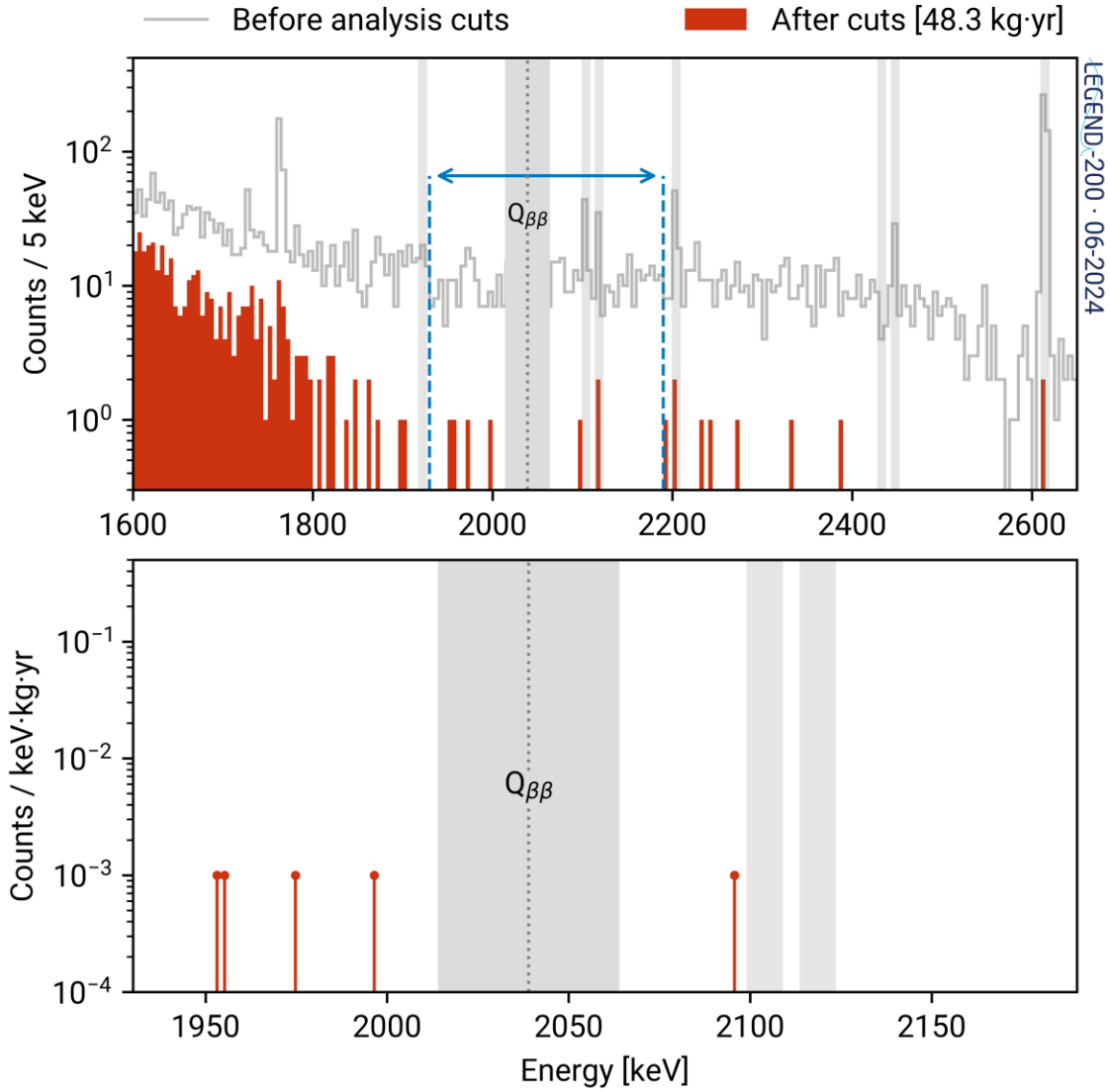
Dataset after PSD



Background Index (BI) Window

Before Unblinding

- 5 events in BI window after all analysis cuts



First Results from LEGEND

After Unblinding

Unblinded on June 13th, 2024

- 7 events surviving in BI window

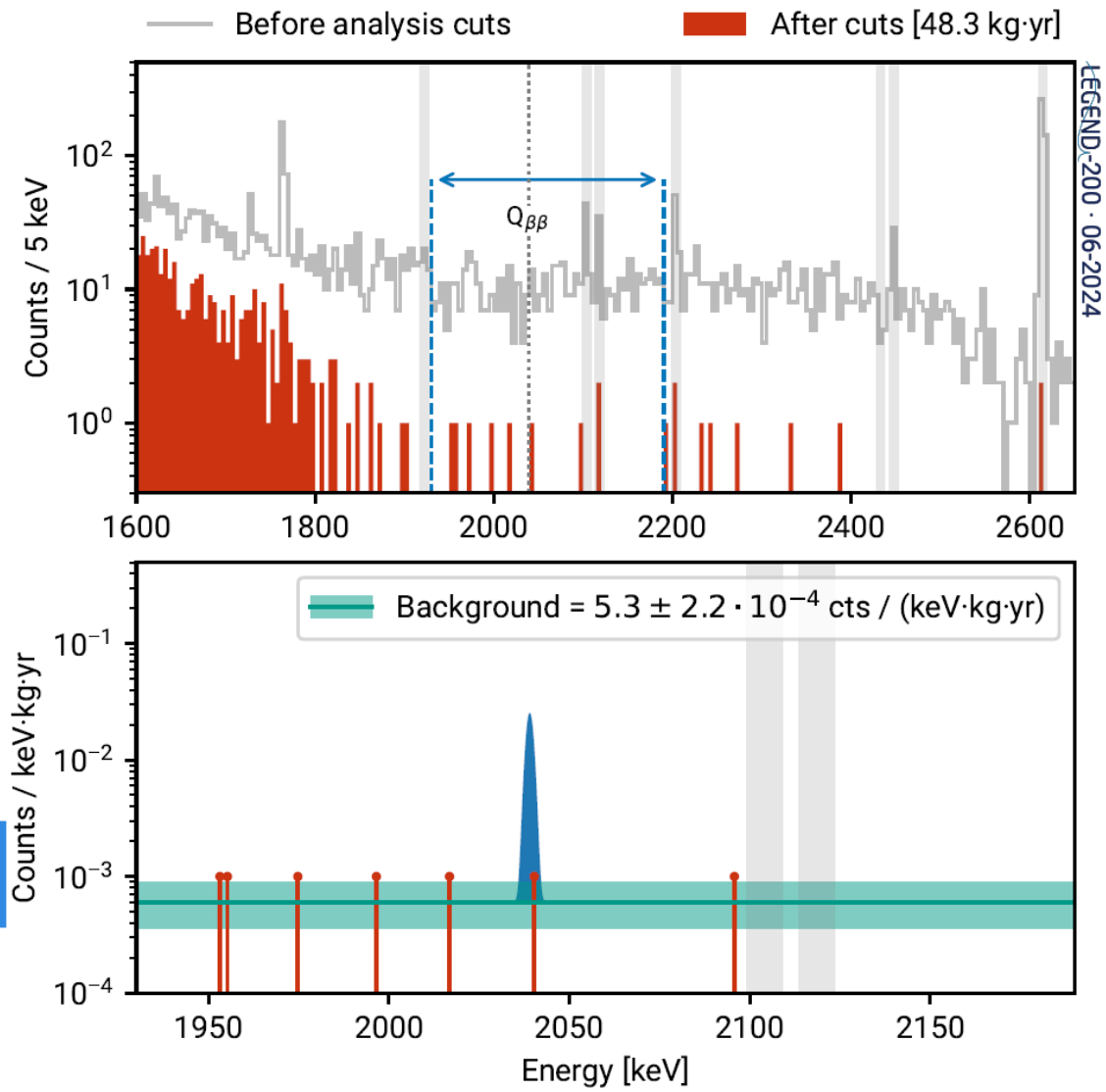
  BI = (5.3 ± 2.2) x 10^{-4} cts/(keV kg yr)

  [World-leading among 0νββ experiments]

- Combined fit from GERDA, MAJORANA and LEGEND:

  $T_{1/2}$ (0νββ) > 1.9 x 10^{26} yr (90% frequentist C.L.)

  Combined limit weakened by event 1.4σ from $Q_{\beta\beta}$



Full report at Neutrino 2024

Next Steps for LEGEND

- Currently in a maintenance period
  - Undergoing assay campaign to understand backgrounds
  - Moving to 150 kg configuration in Fall 2024
- Further development of analysis routines
  - Further optimization of existing PSD routines
  - Development of new PSD techniques
  - Implement machine learning routines
- Publication of first result is in progress
- Restart physics data taking in Fall 2024

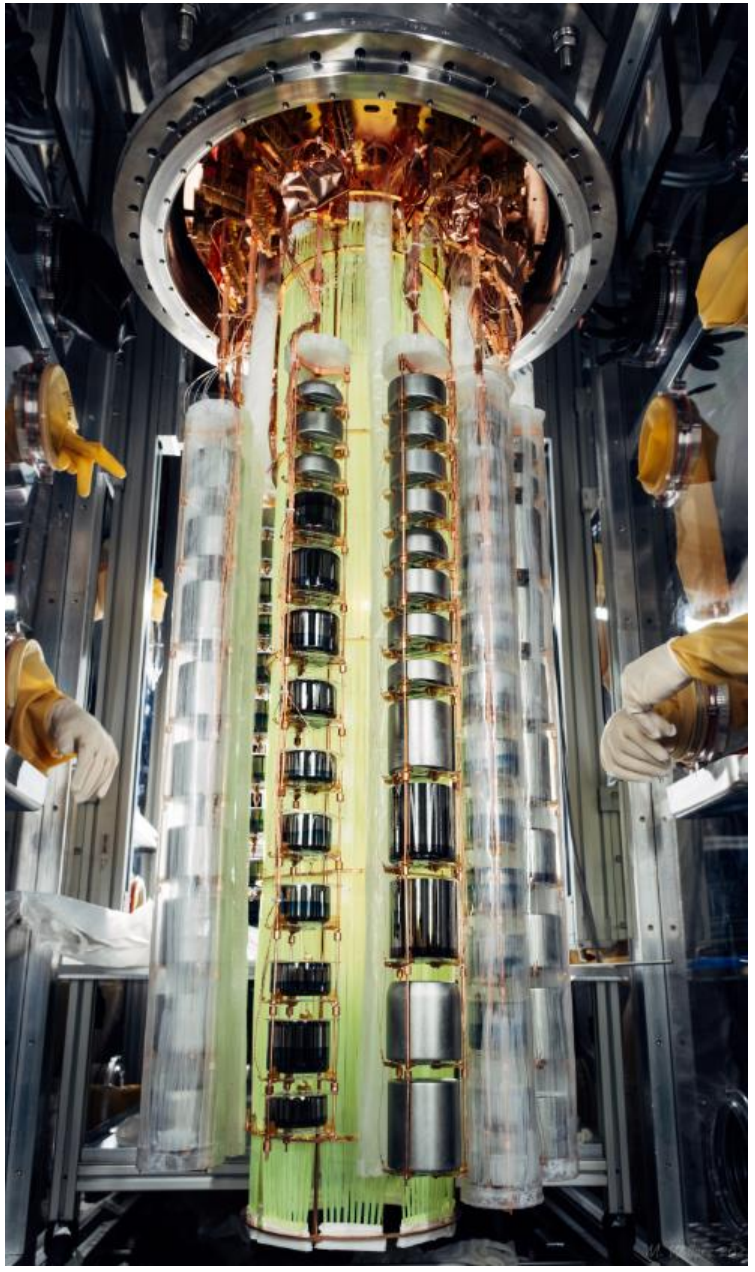


Photo: Michael Willers / LEGEND Collaboration

The LEGEND Collaboration

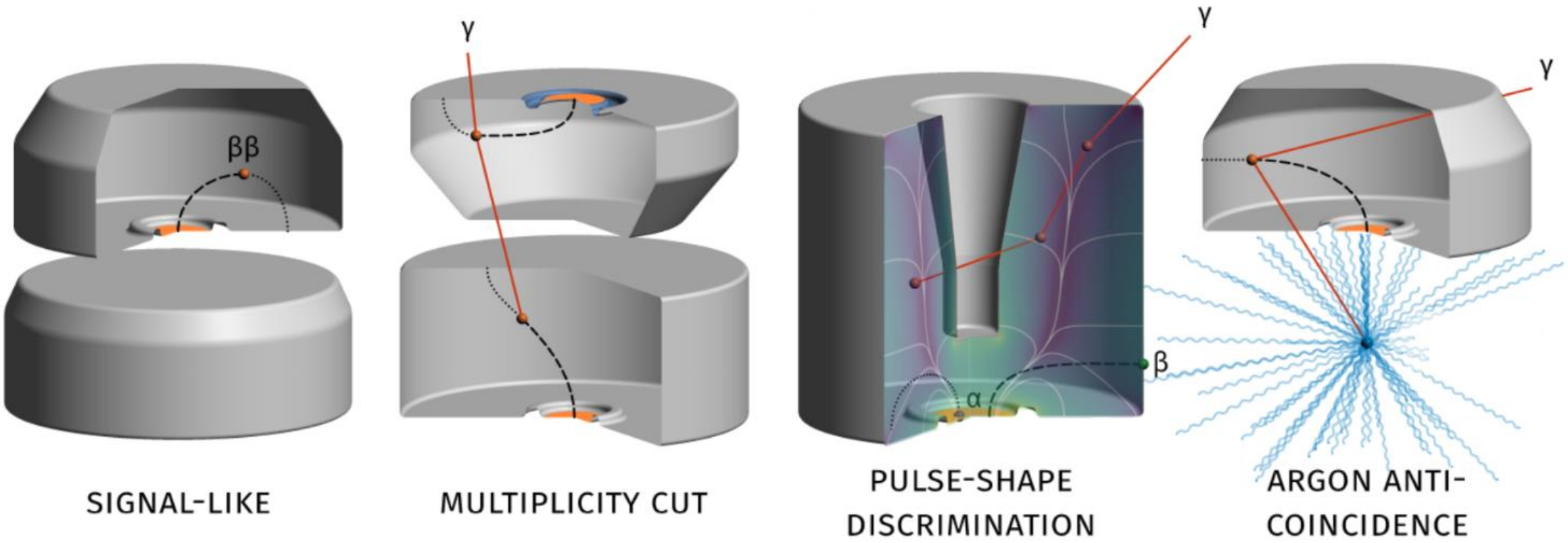
Comenius Univ.
Czech Tech. Univ. Prague and IEAP
Daresbury Lab.
Duke Univ. and TUNL
Gran Sasso Science Inst.
Indiana Univ. Bloomington
Inst. for Nucl. Res. Rus. Acad. Sci.
Jagiellonian Univ.
Joint Inst. for Nucl. Res.
Joint Res. Centre Geel
Lab. Naz. Gran Sasso
Lancaster Univ.
Leibniz Inst. for Crystal Growth
Leibniz Inst. for Polymer Research
Los Alamos Natl. Lab.
Max Planck Inst. for Nucl. Phy.
Max Planck Inst. for Physics
Natl. Res. Center Kurchatov Inst.
Natl. Res. Nucl. Univ. MEPhI
North Carolina State Univ.
Oak Ridge Natl. Lab.
Polytech. Univ. of Milan
Queen's Univ.
Roma Tre Univ. and INFN
Simon Fraser Univ.
SNOLAB
South Dakota Mines
Tech. Univ. Dresden
Tech. Univ. Munich
Tennessee Tech. Univ.
Univ. of California and LBNL
Univ. College London
Univ. of L'Aquila and INFN
Univ. of Liverpool
Univ. of Milan and INFN
Univ. of Milano Bicocca and INFN
Univ. of New Mexico
Univ. of North Carolina at Chapel Hill
Univ. of Padova and INFN
Univ. of Regina
Univ. of South Carolina
Univ. of South Dakota
Univ. of Tennessee Knoxville
Univ. of Texas at Austin
Univ. of Tuebingen
Univ. of Warwick
Univ. of Washington and CENPA
Univ. of Zuerich
Williams College

Summary

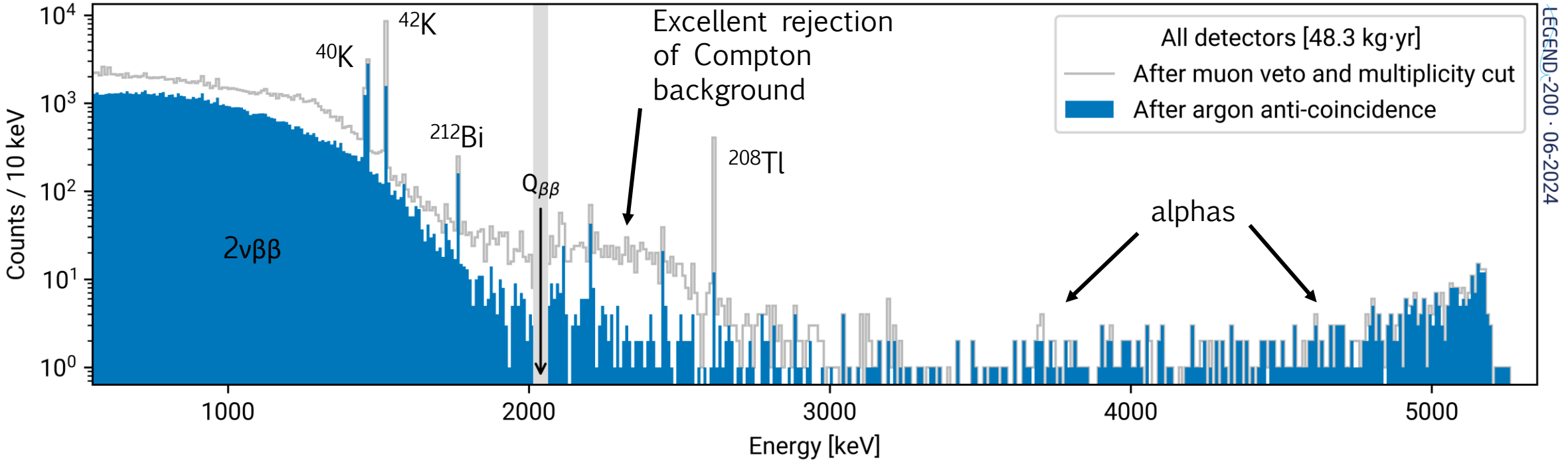
- Germanium is a leading isotope for 0νββ searches
- LEGEND-200 has taken a year of data and has completed its first 0νββ unblinding
- Achieved a background level comparable with GERDA, world-leading among 0νββ experiments
- Currently undergoing an assay campaign to understand backgrounds, resume data taking in Fall 2024
- Publication of first result in progress

Backups

Background Discrimination with Germanium



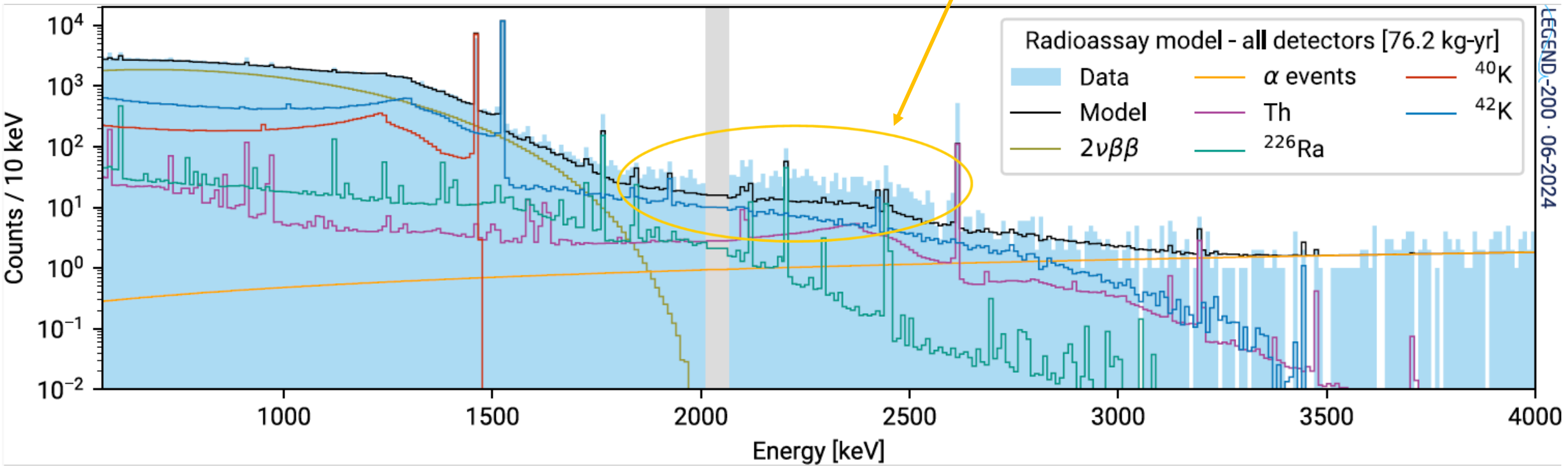
Dataset after LAr Anti-Coincidence



Assay-Based Background Model

Simulations using material assay values as inputs

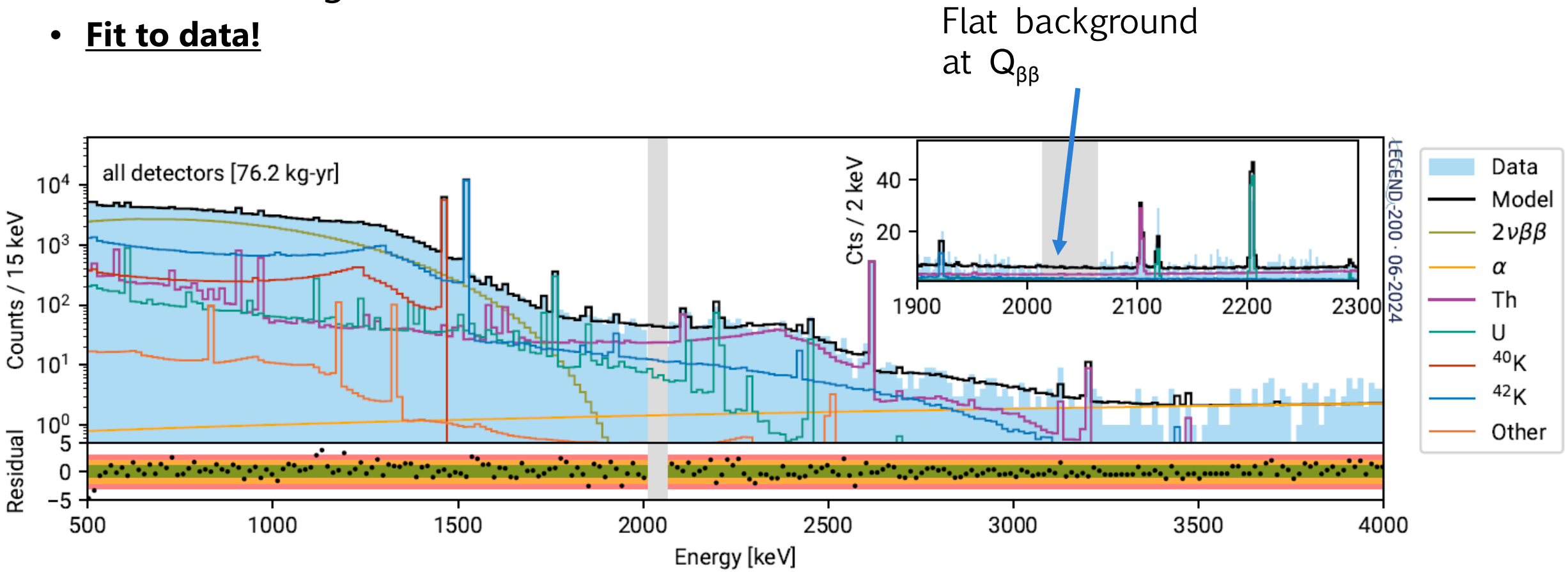
- **Not a fit to data!**



Background Model Fit

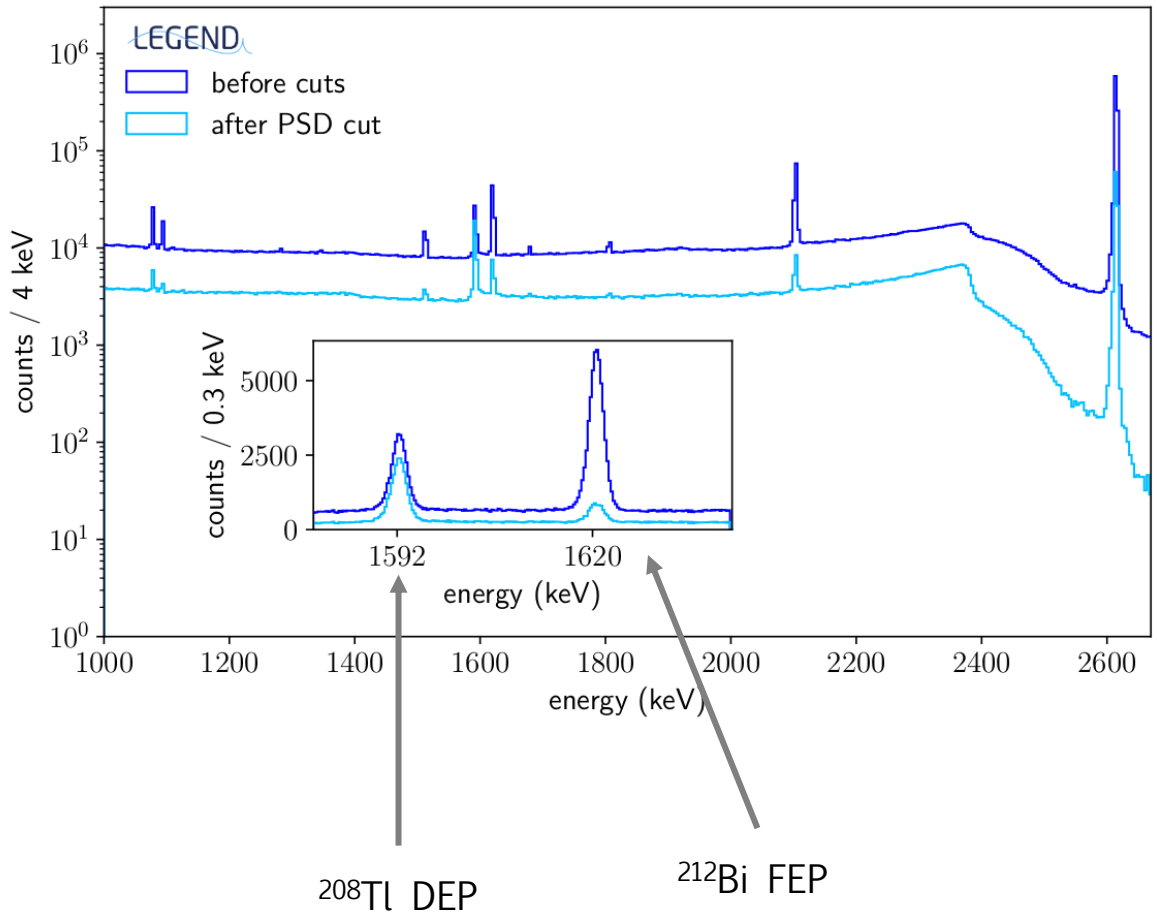
Simulated background model

- **Fit to data!**



PSD Calibration

- Correct for A/E energy and rise-time dependences
- Tune A/E cut on gamma peaks in calibration data
  - ^{208}Tl double escape peak (DEP) is a single-site proxy
  - ^{212}Bi full energy peak (FEP) is a background proxy
- Set A/E cut such that DEP acceptance is 90%

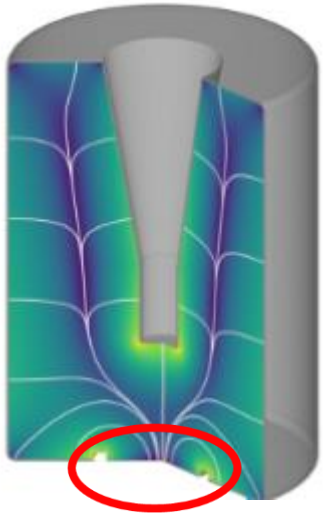


Passivated Surface Events

Passivated surface separating n+ and p+ contacts can significantly degrade energy of alpha events

Mirion Detectors

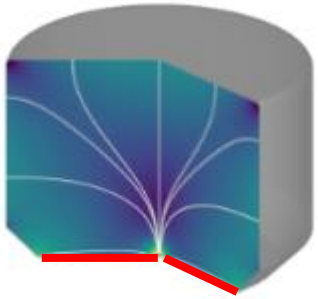
- Large p+ contact, small passivated ditch
- Events on ditch and p+ contact have high current → High A/E
- Use A/E classifier to reject events



High A/E region

Ortec Detectors

- Large, thin passivation layer
- Events on passivated surface have slow charge collection component → High LQ
- Use LQ to reject events



High LQ region

Event at 2040 keV

- Low drift time → Near p+ contact
- Event was in an ORTEC detector
  - ORTEC detectors have large passivated surface → More susceptible to surface events
- Event is outside of A/E acceptance region if used
  - Statistical study showed A/E was not necessary for ORTEC detectors
- Need more statistics to study events with this signature
  - Recent background characterization runs can aid in this