The Quest for No Neutrinos:

Probing the Majorana Nature with LEGEND-200

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on behalf of the LEGEND collaboration

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Neutrinoless Double Beta Decay

Two-neutrino double beta decay 2νββ

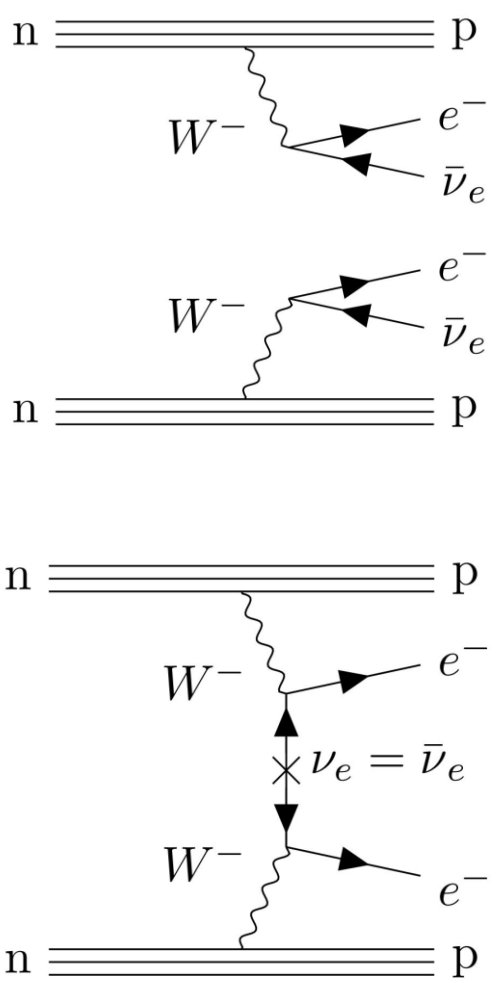
- allowed in SM
- 35 isotopes in nature

$$2n \longrightarrow 2p^+ + 2e^- + 2\bar{\nu}_e$$

Neutrinoless double beta decay 0νββ

- beyond SM process
- Lepton-number violating

$$2n \longrightarrow 2p^+ + 2e^-$$



Implications of observation of 0νββ

- Majorana nature of neutrinos
- Antimatter-matter-asymmetry

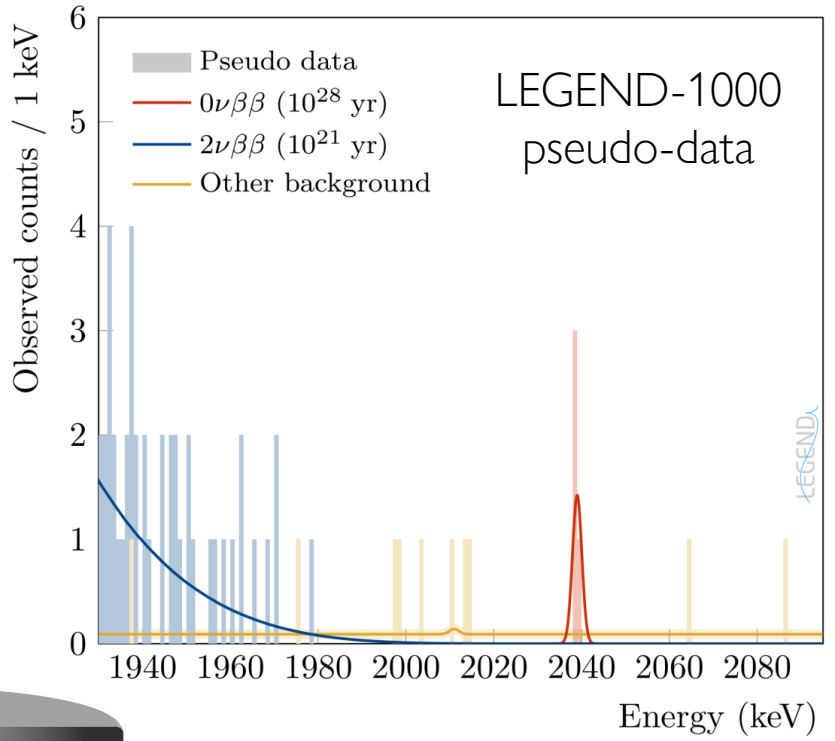
Searching for 0νββ in Germanium

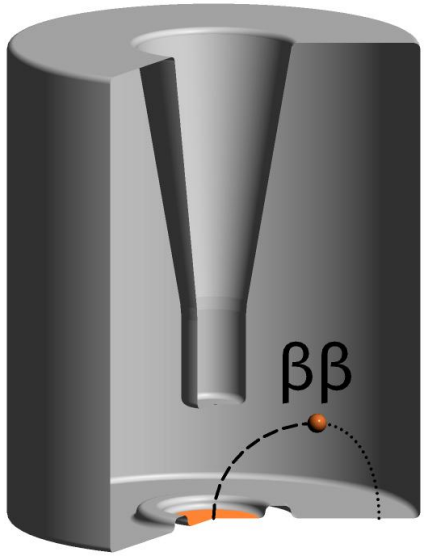
Double beta decay of ^{76}Ge

- $Q_{\beta\beta}$ = 2039 keV
- natural abundance: ~ 8%

High-purity, isotopically enriched Ge detectors (HPGe)

- source = detector ⟶ high efficiency
- enriched to ~ 90% ⟶ high 0νββ mass
- radiopure ⟶ low background
- Ge-crystal diode ⟶ excellent energy resolution
- signal topological ⟶ event discrimination





The LEGEND collaboration

The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} yr, using existing resources as appropriate to expedite physics results.

13 countries, 60 institutions, ~300 members

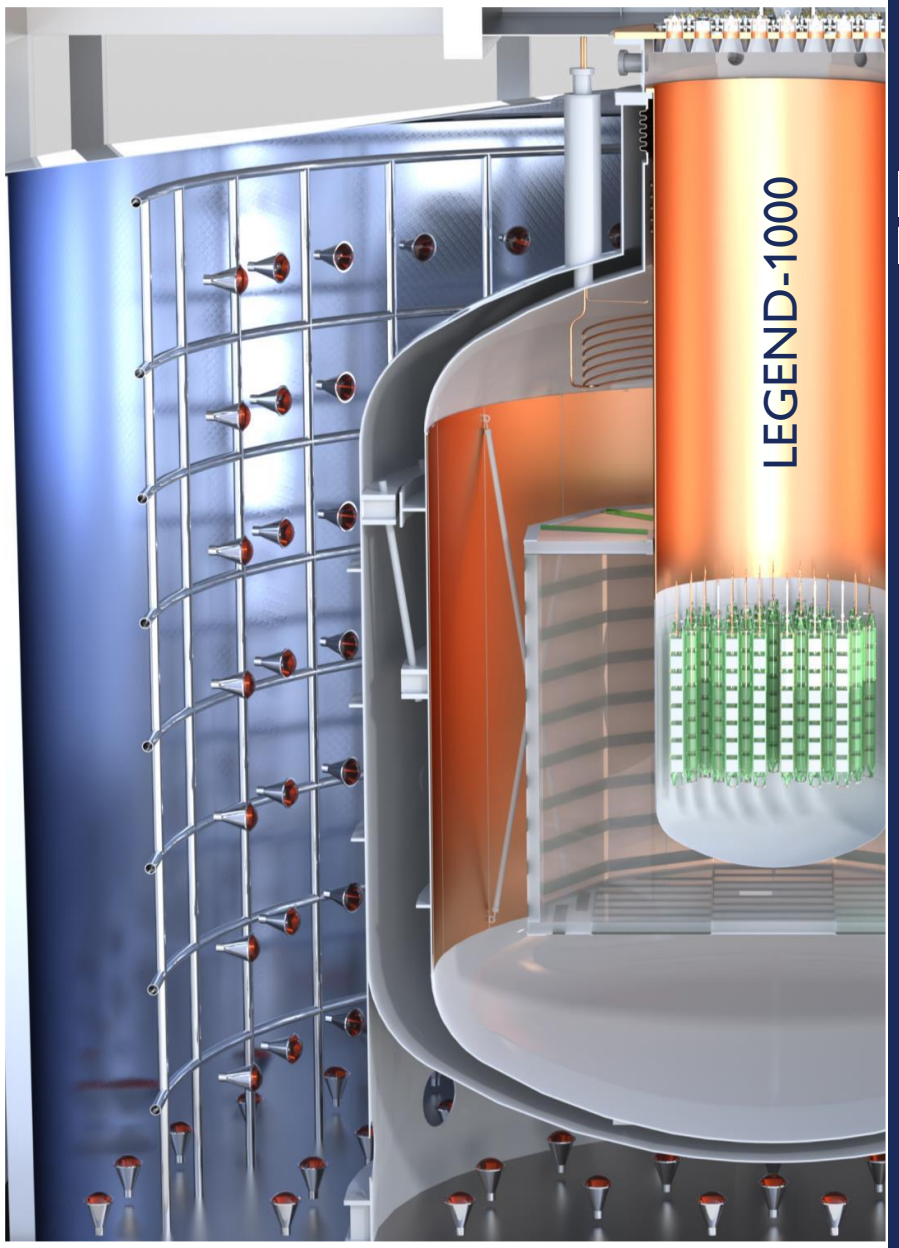
The LEGEND approach

LEGEND-200 [arXiv 2505.10440]

- taking data since 2023
- GERDA infrastructure at LNGS
- Up to 200 kg of HPGe detectors
- Goal: $T_{1/2}^{0\nu} > 10^{27}$yr after 1 ton-yr

LEGEND-1000 [arXiv 2107.11462]

- Seeking funding
- Reduced background (20x)
- Up to 1,000 kg of HPGe detectors
- Goal: $T_{1/2}^{0\nu} > 10^{28}$yr after 10 ton-yr



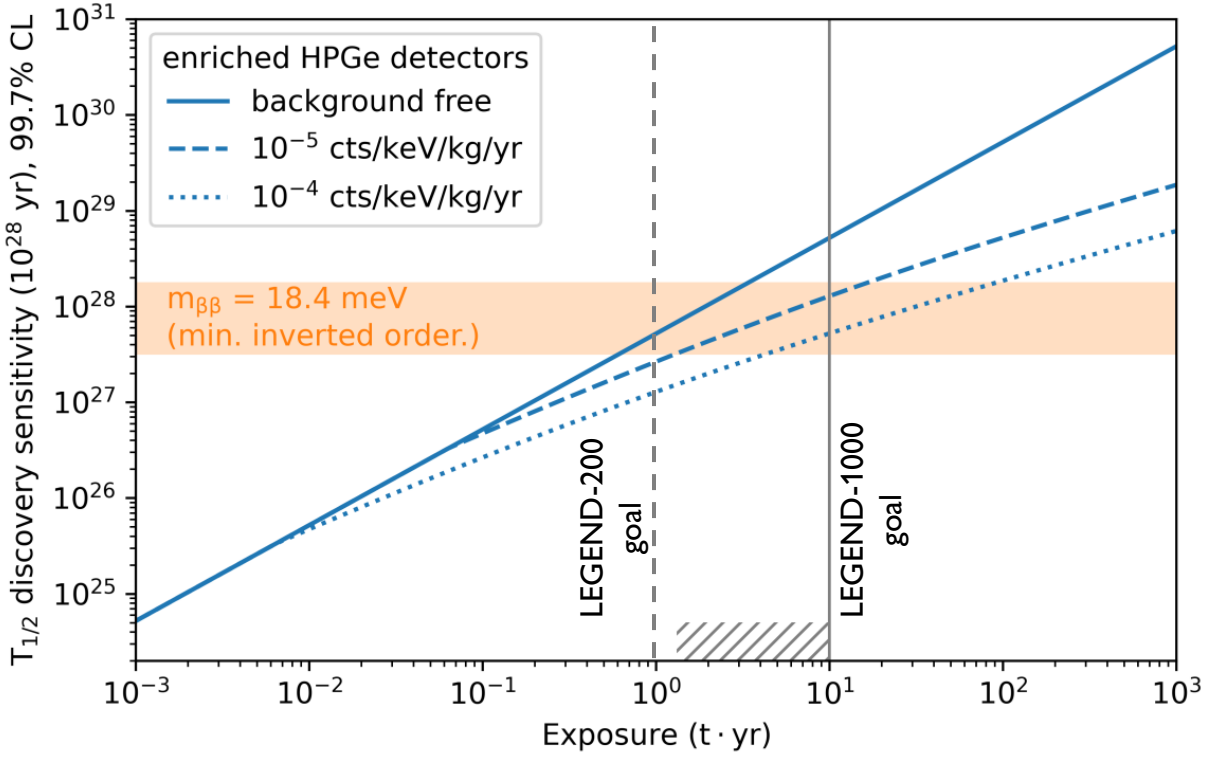
The scientific reach of LEGEND

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Half-life of 0νββ (observable)

effective majorana mass

$$T_{1/2}^{0\nu} \propto \begin{cases} M \cdot t & \text{background free} \\ \sqrt{\dfrac{M \cdot t}{B \cdot \sigma}} & \text{with background} \end{cases}$$



< 0.25 bkg events in $Q_{\beta\beta}$ peak (FWHM) after 10 ton-yr

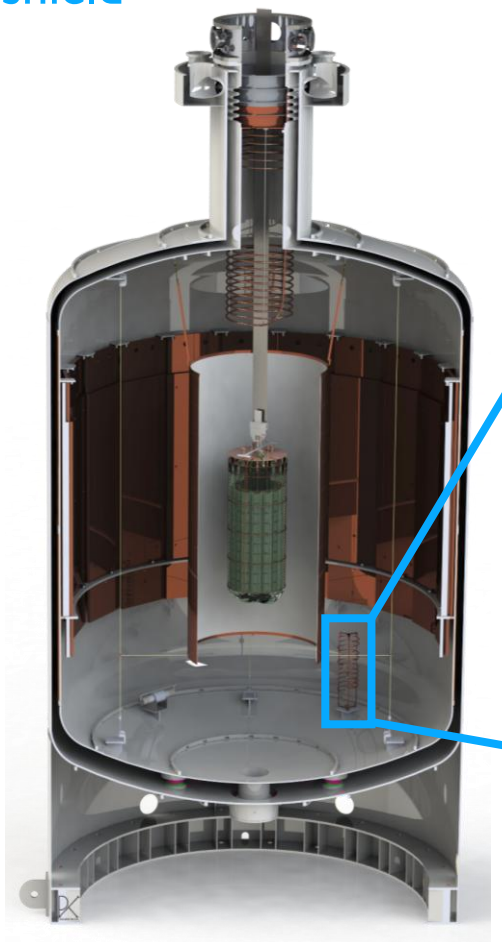
LEGEND-200 ⟶ BI: < 2 x 10^{-4} cts/keV/kg/yr

LEGEND-1000 ⟶ BI: < 10^{-5} cts/keV/kg/yr

LEGEND-200 design

Water tank
- 590 m^3
- 65 PMTs
- shield & muon veto

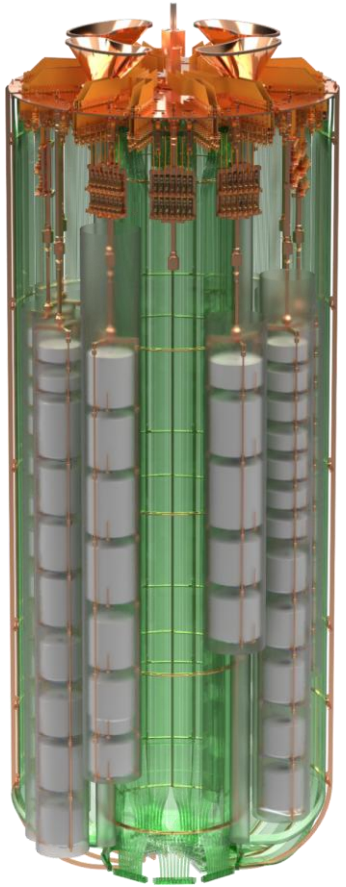
Cryostat
- 64 m^3 of liquid argon (LAr)
- cylindrical WLS reflector
- liquid argon monitoring with LLAMA
- active shield



LLAMA

[EPJ Web Conf. 253 (2021) 11014]

Detector assembly
- WLS fibers as light guides
- 58 SiPM channels for readout
- HPGe detectors in strings
- Nylon shrouds for ^{42}Ar mitigation



LEGEND-200 design

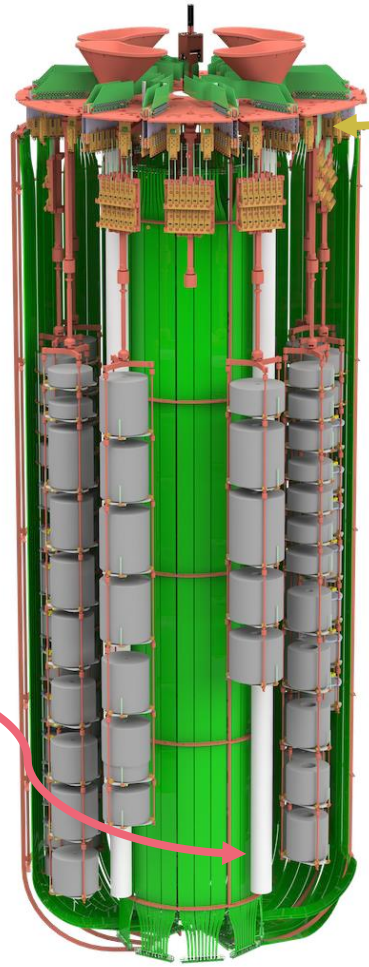
HPGe readout electronics

Optically active PEN holders

[2022 JINST 17 P01010]

Inner & Outer Barrel

- SiPM readout on top and bottom
- LAr event topologies



HPGe detectors

- four types
- up to 4 kg

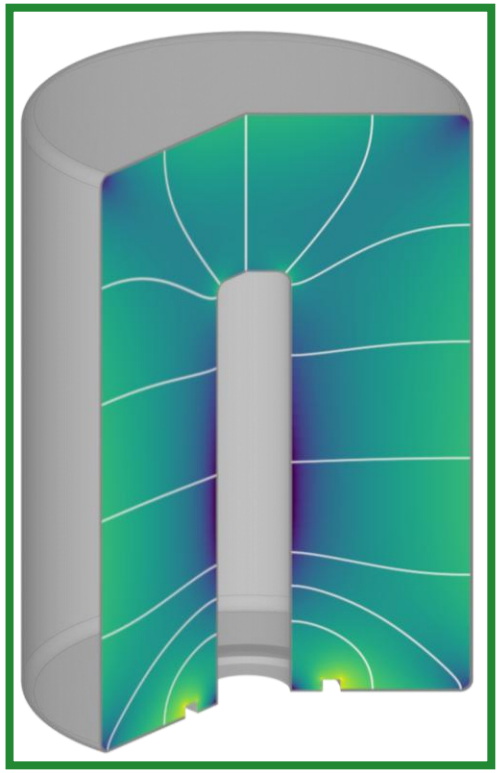
Source insertion system

- four WLS nylon tubes
- ^{228}Th calibration

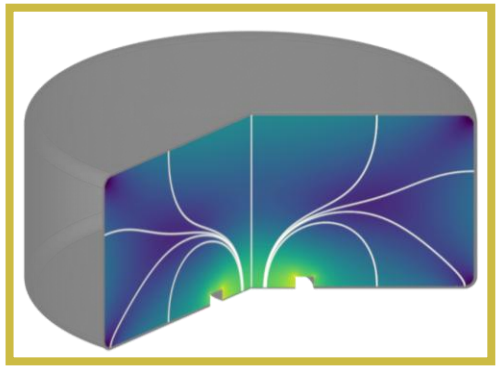
Underground electroformed copper supports

LEGEND-200: Detector geometries

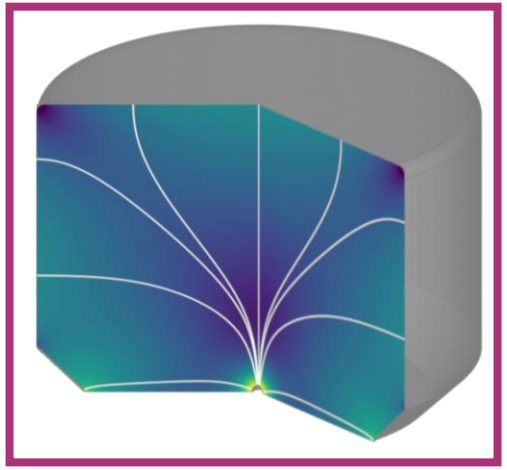
Coax



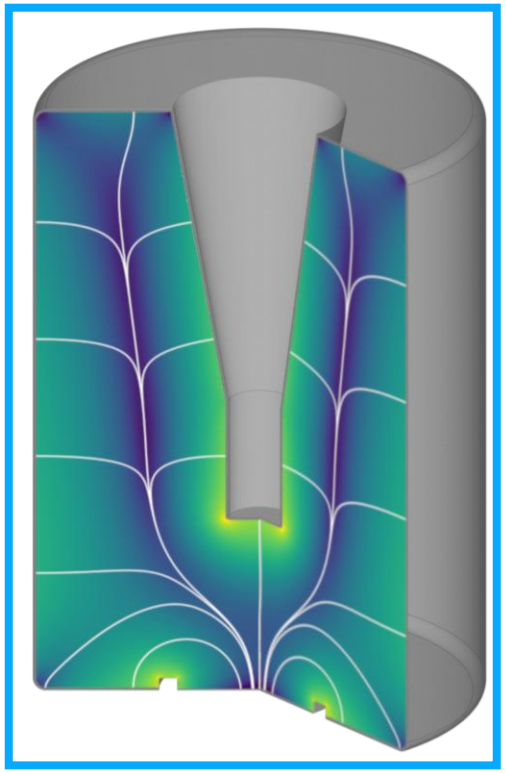
BEGe



PPC

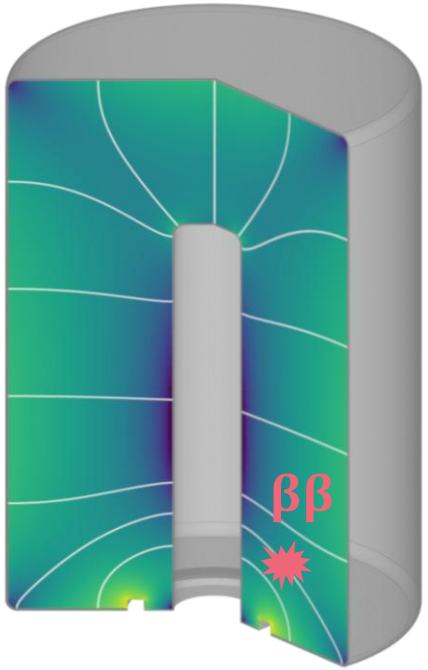


LEGEND IC

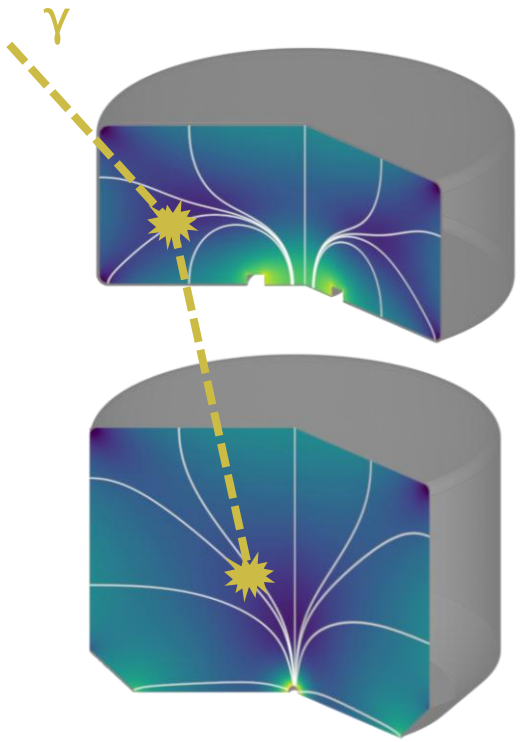


14.7 kg	19.0 kg	22.1 kg	86.7 kg

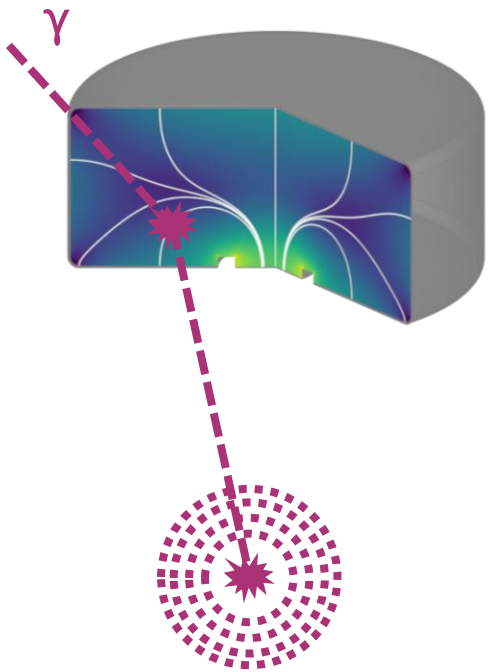
LEGEND-200: Event selection



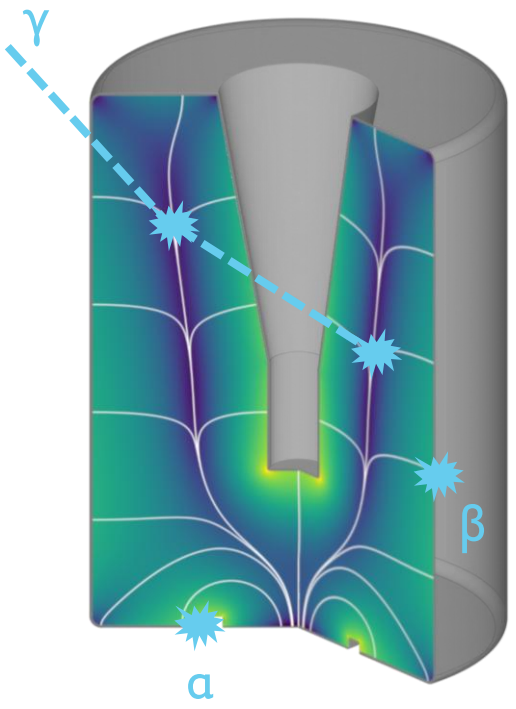
single-site event



multiplicity cut

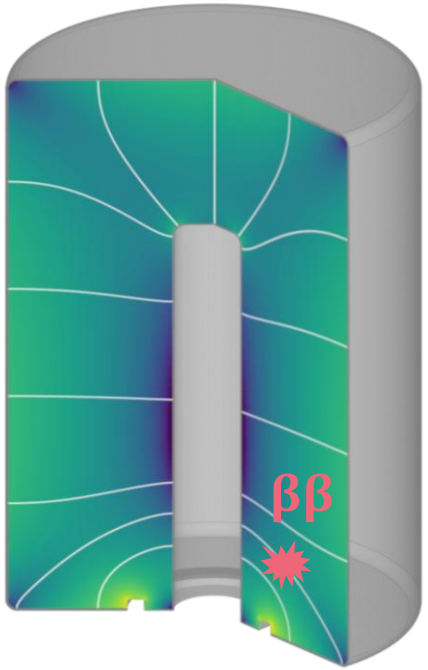


argon anti-coincidence

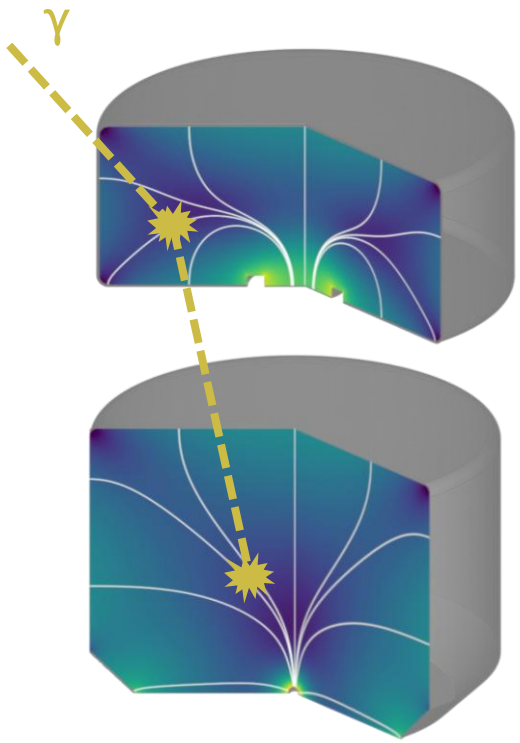


pulse shape discrimination

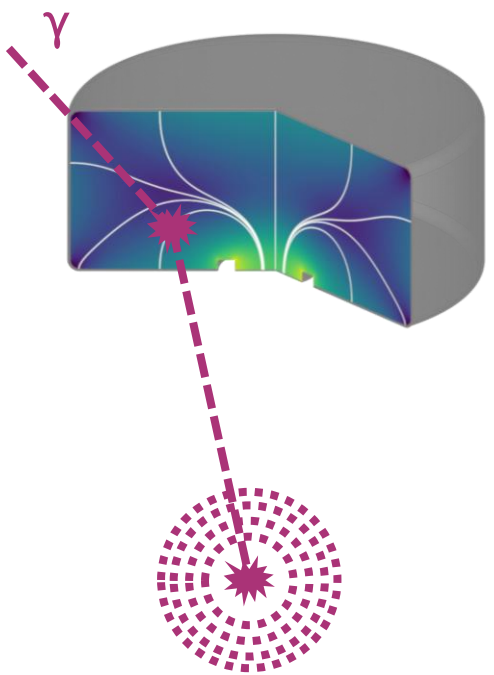
LEGEND-200: Event selection



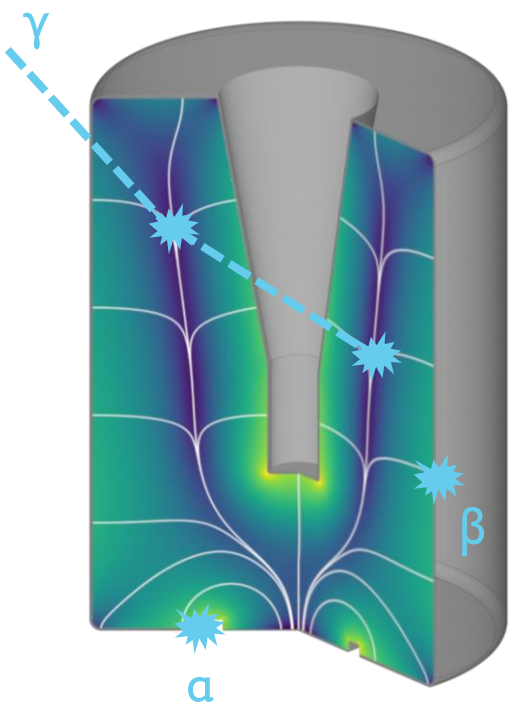
single-site event



multiplicity cut

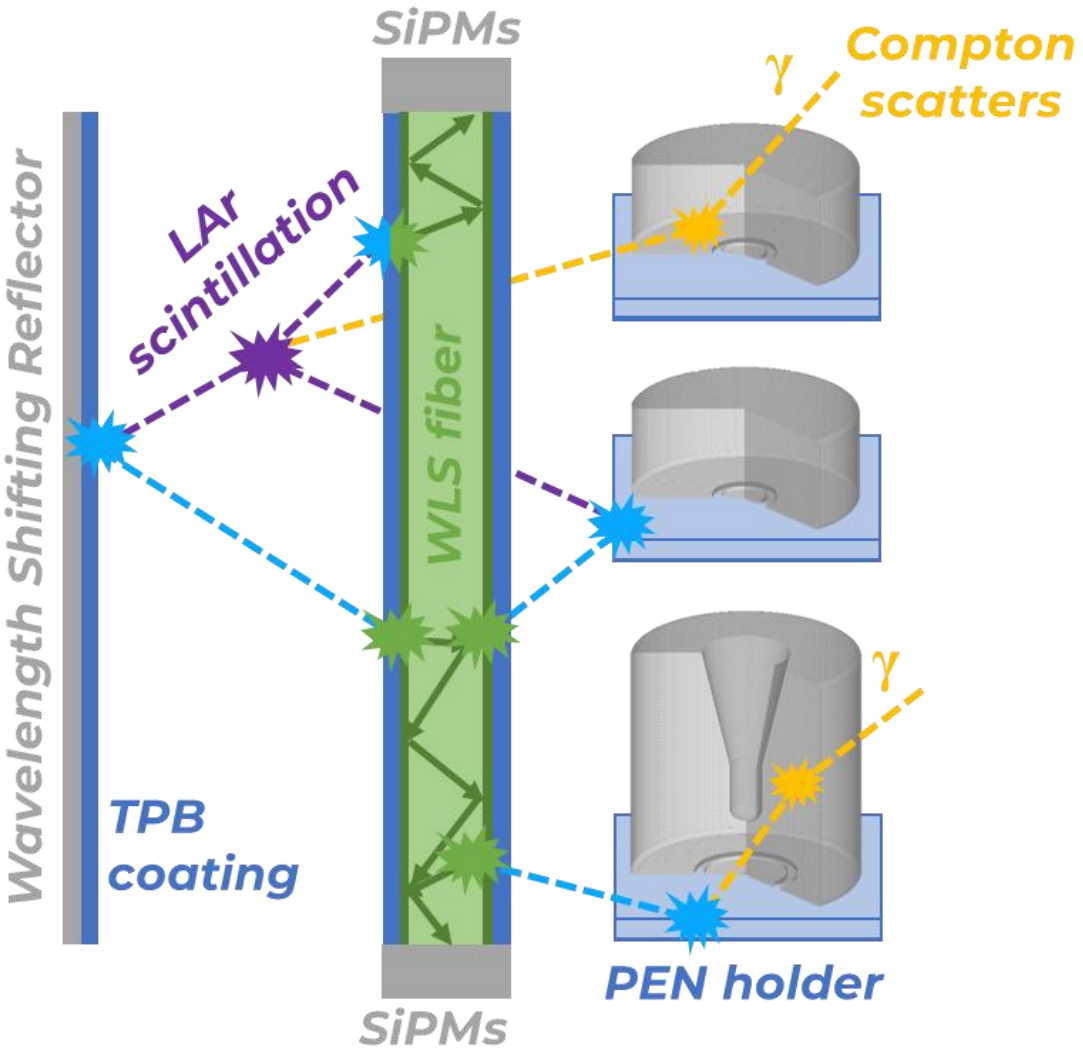


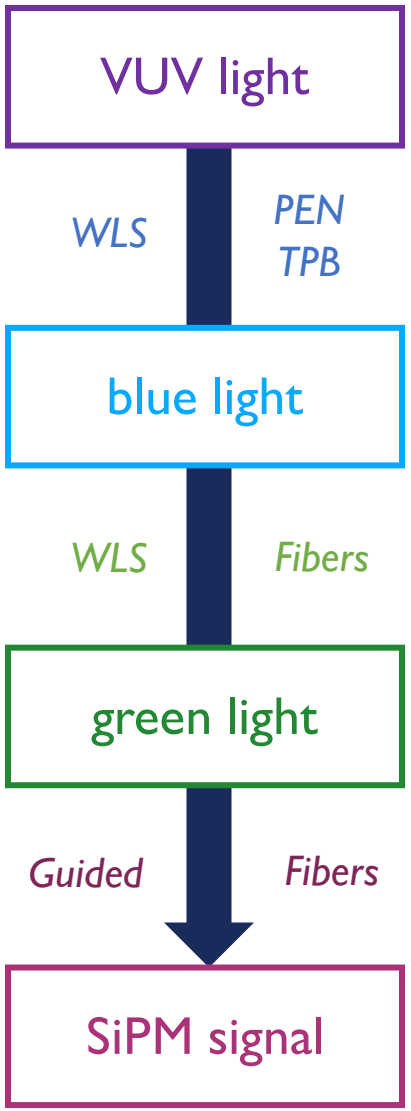
argon anti-coincidence

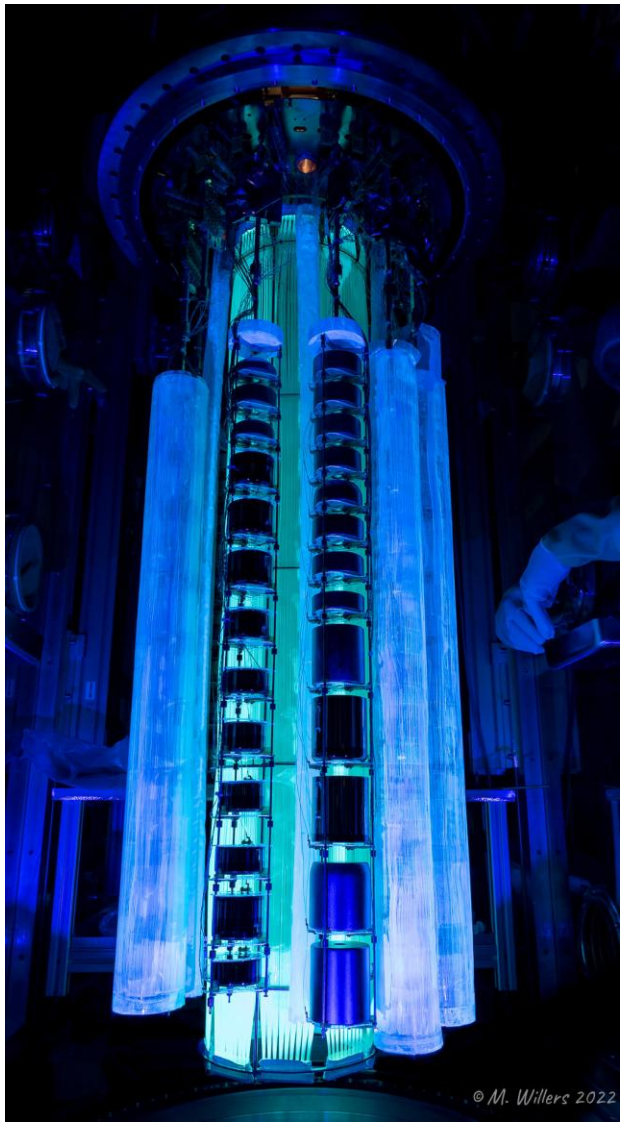


pulse shape discrimination

LEGEND-200: Liquid argon instrumentation



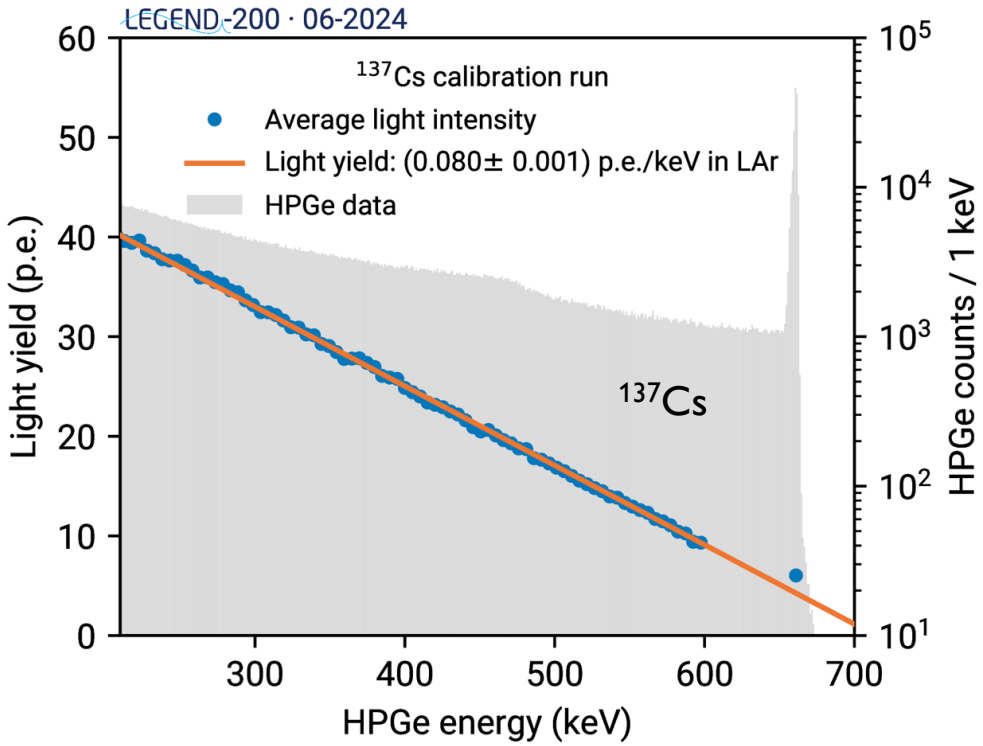


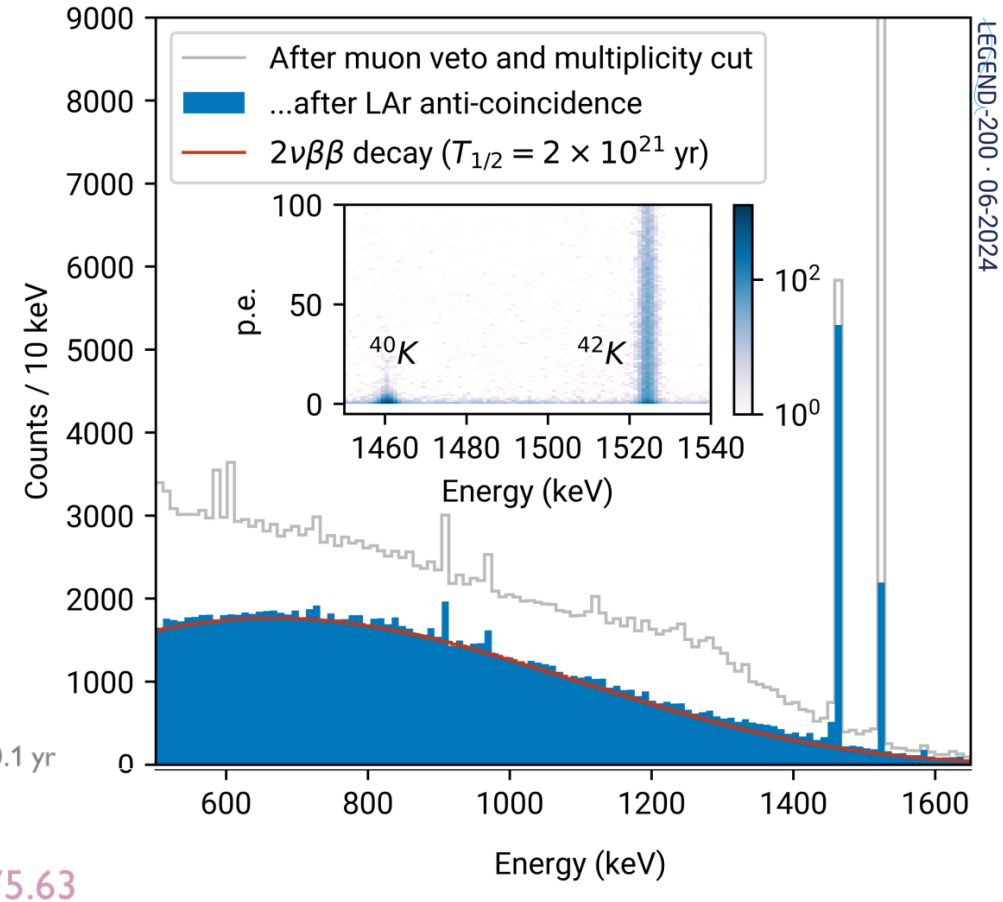


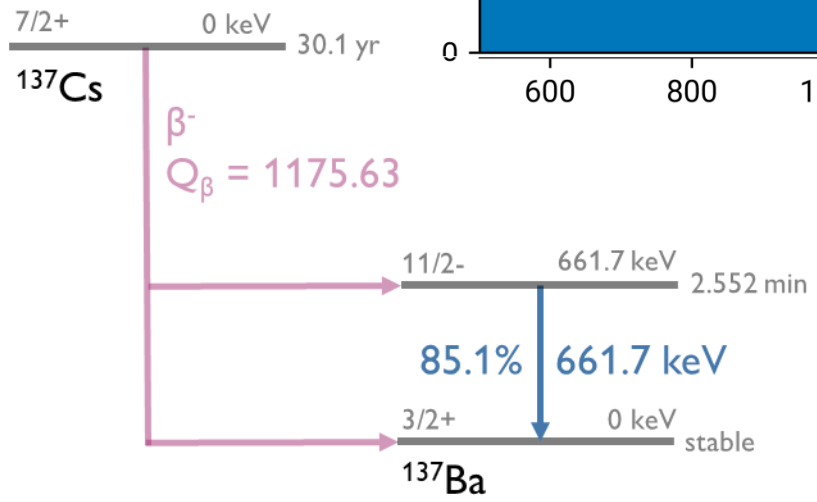
LEGEND-200: Liquid argon instrumentation

Performance of the LAr instrumentation

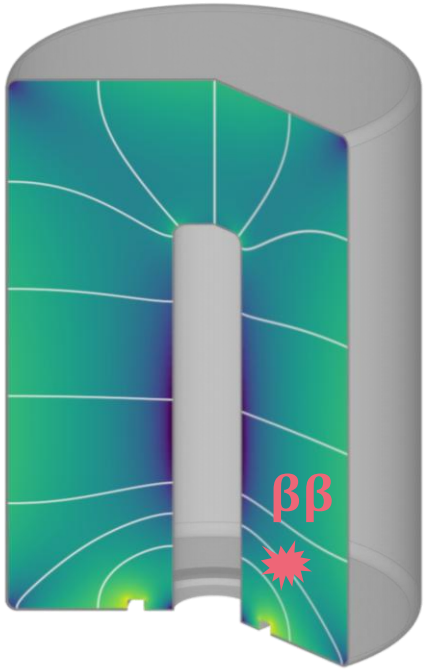
- Improved light yield compared to GERDA (3x)
- Strong suppression via anti-coincidence at ROI for 0νββ



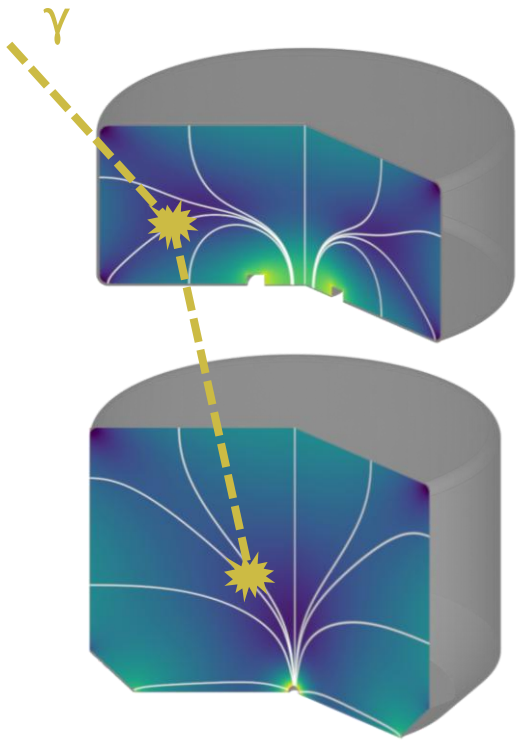




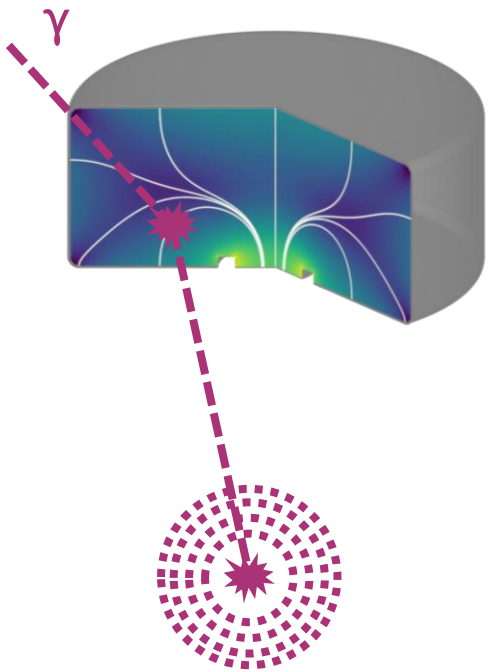
LEGEND-200: Event selection



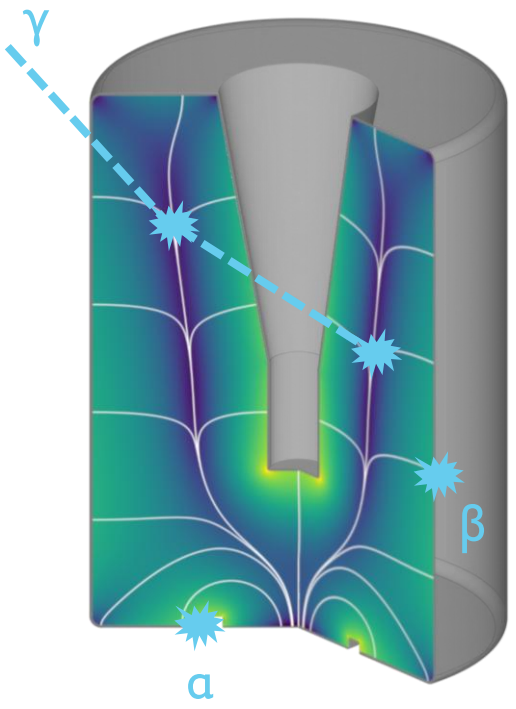
single-site event



multiplicity cut



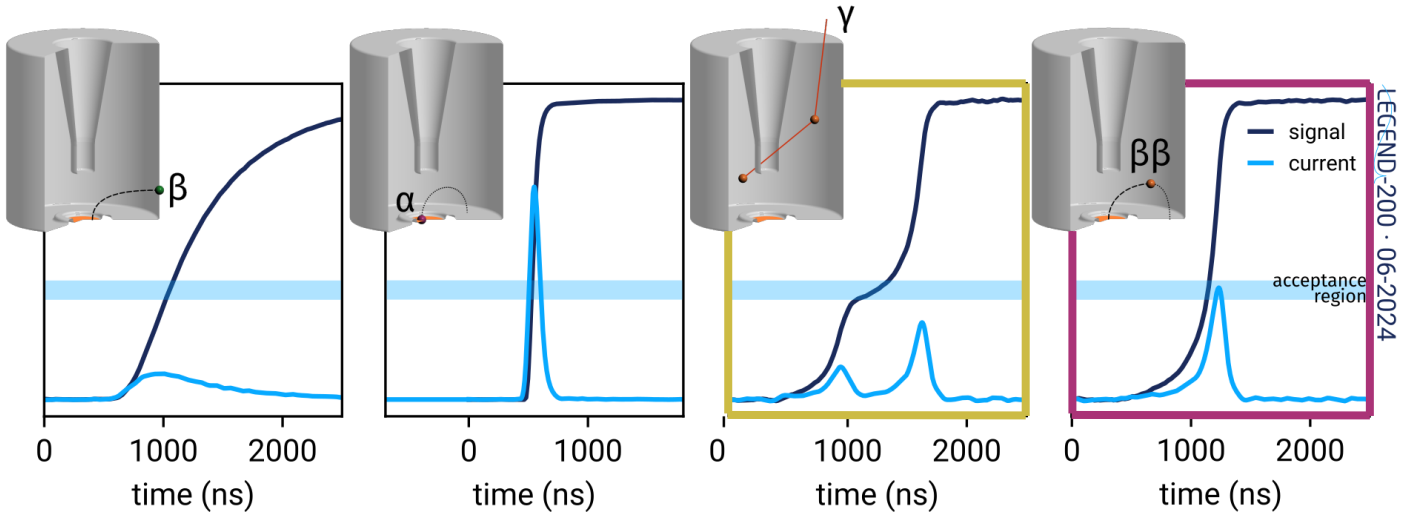
argon anti-coincidence



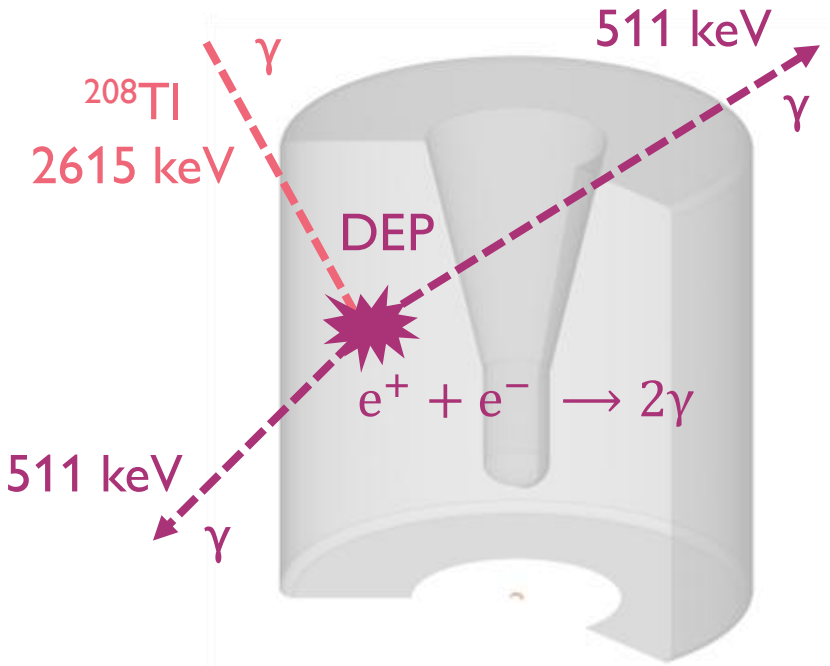
pulse shape discrimination

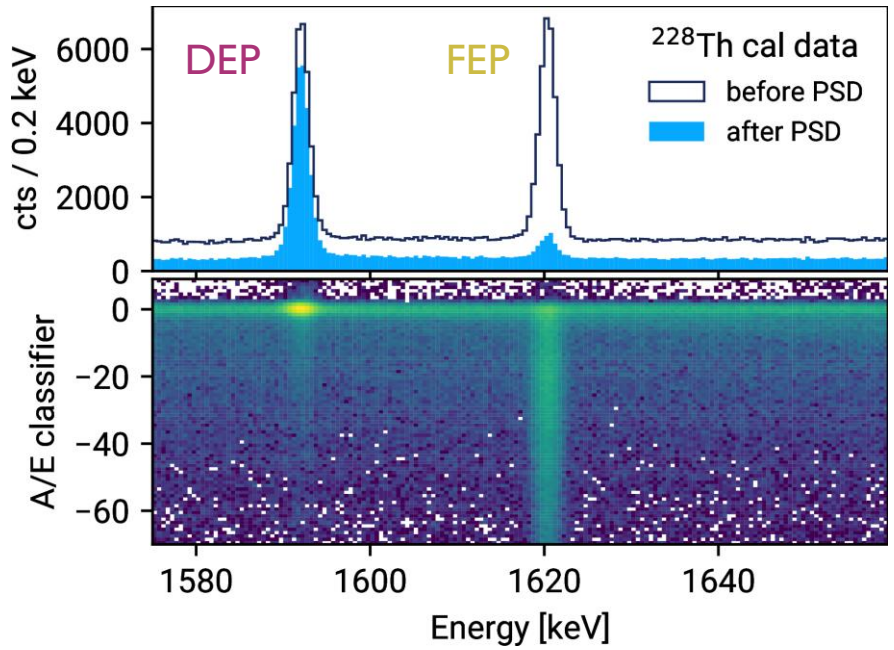
LEGEND-200: Pulse shape discrimination

- A (max. current) / E (energy)
  ⟶ select single-site events (SSE)
- PSD monitoring through weekly calibration
- DEP of ^{208}Tl as proxy for SSE
  (tuned to 90% survival)



- Late Charge (LQ) cut for PPC & IC*
- ANN for Coax detectors

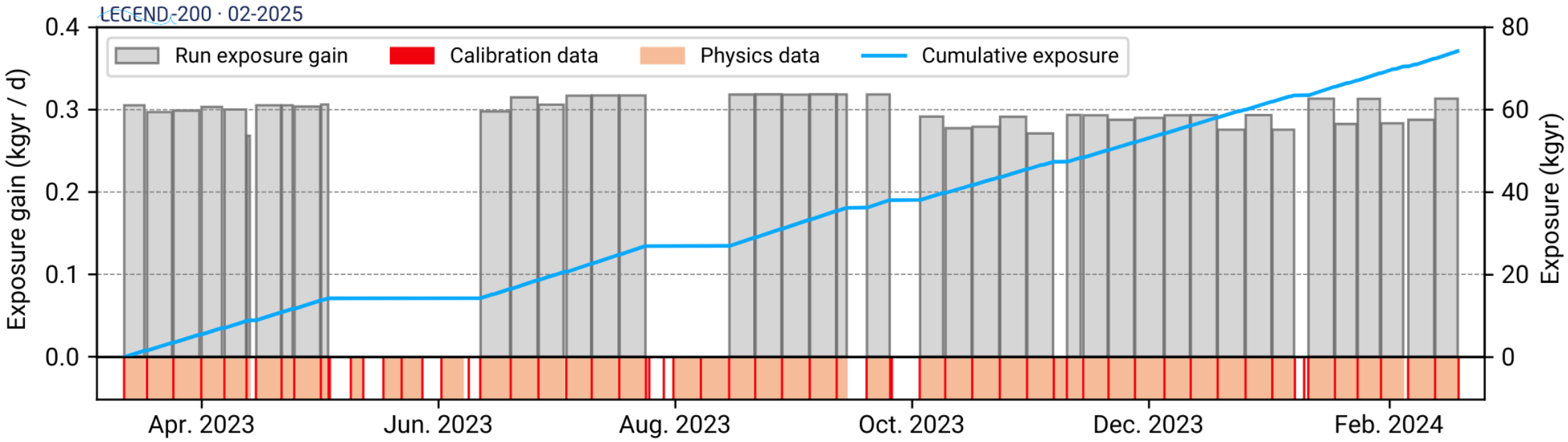




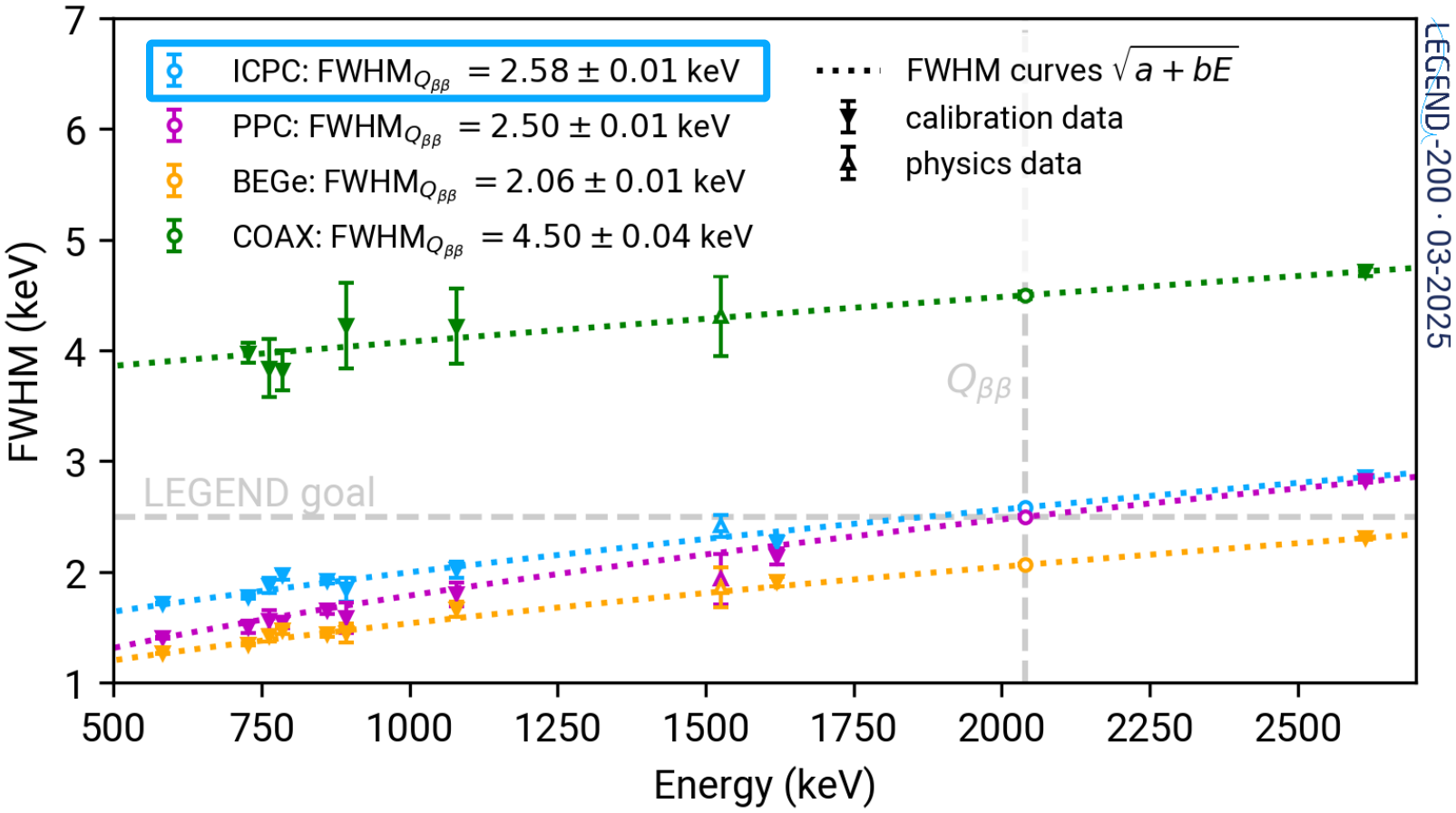
LEGEND-200: First data and results

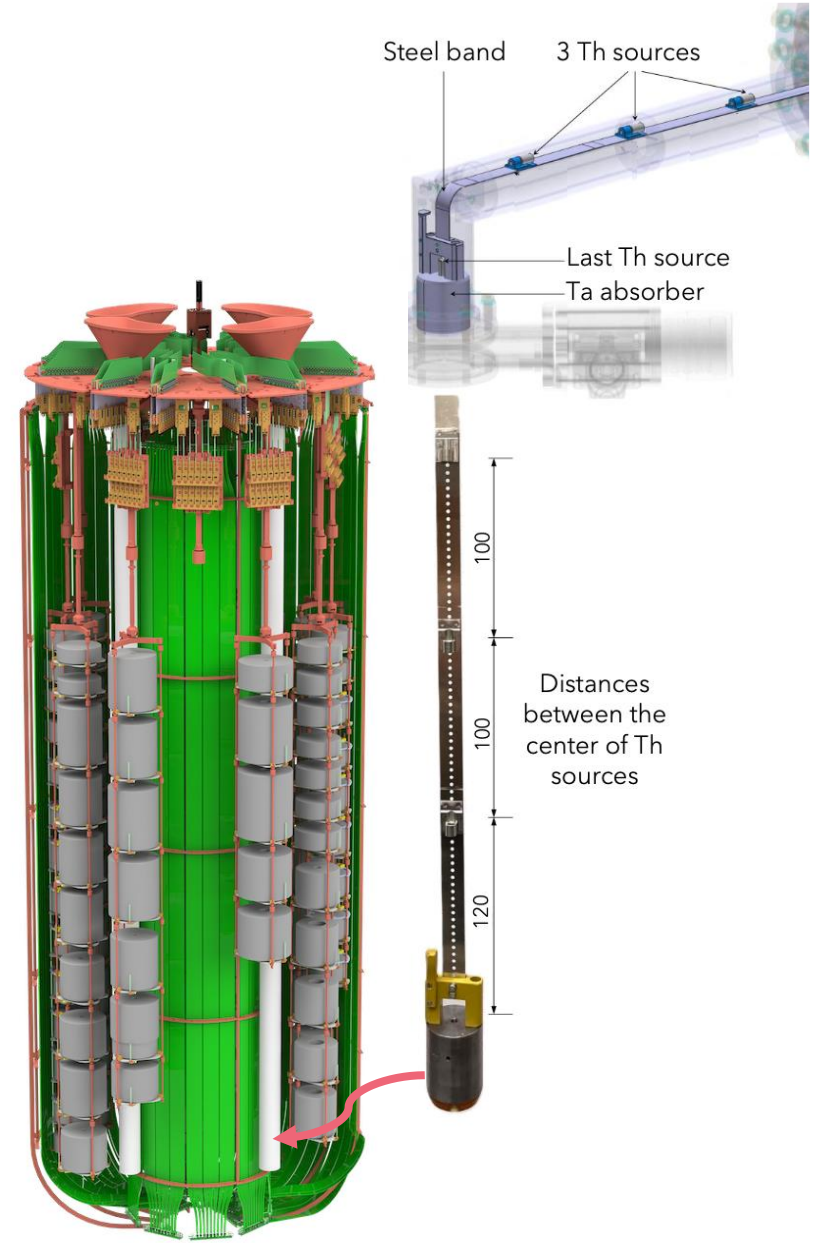
March 2023 to February 2024: 142.5 kg of deployed HPGe (130 kg operational)

- background characterization: 76.2 kg×yr (all detectors)
- 0νββ search: 61.0 kg×yr (valid PSD)



LEGEND-200: Energy calibration

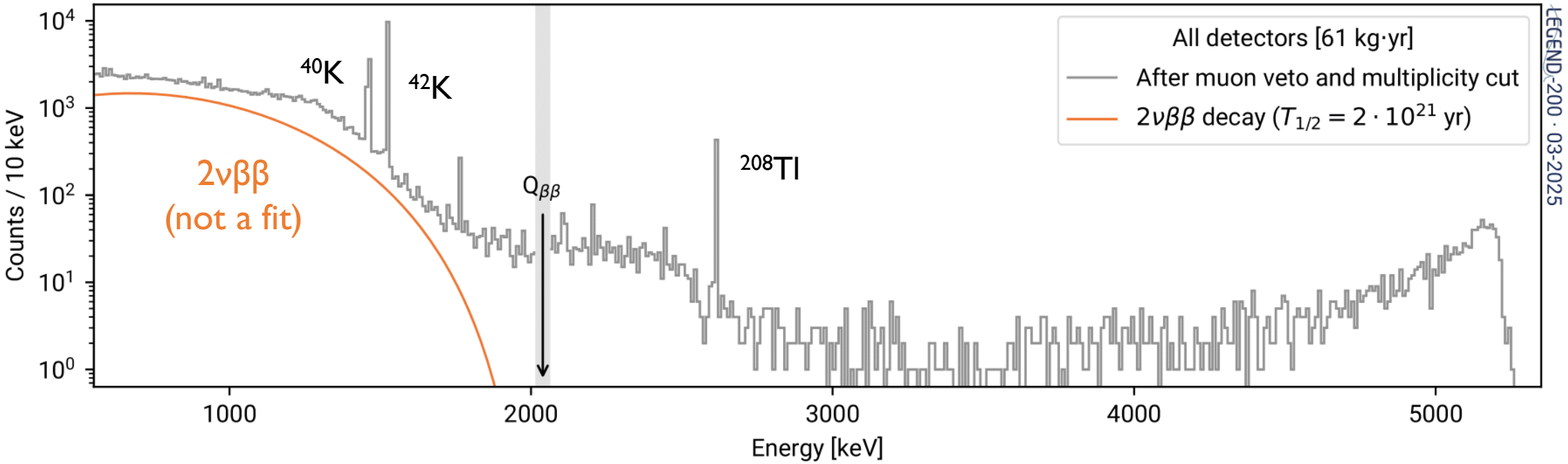




Energy resolution:
0.1 – 0.2 % FWHM at $Q_{\beta\beta}$

★ best in 0νββ field

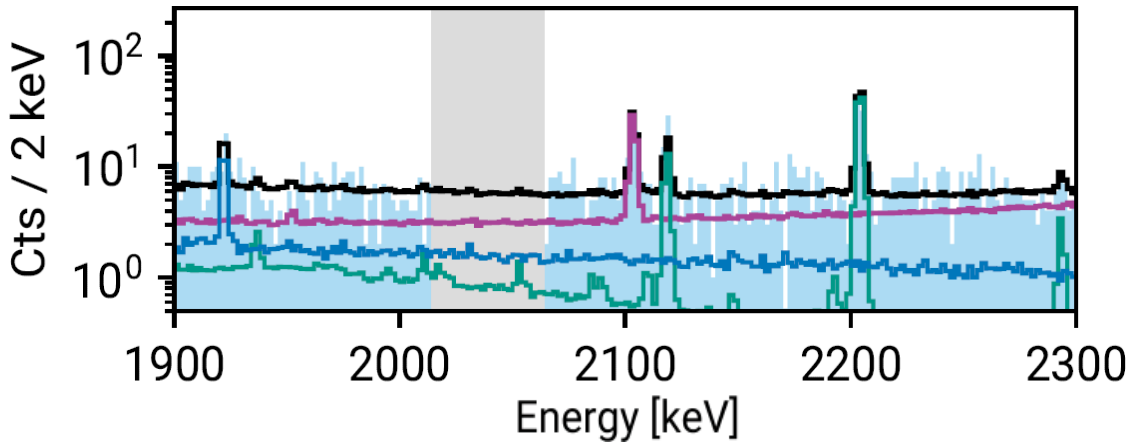
LEGEND-200: Energy spectrum



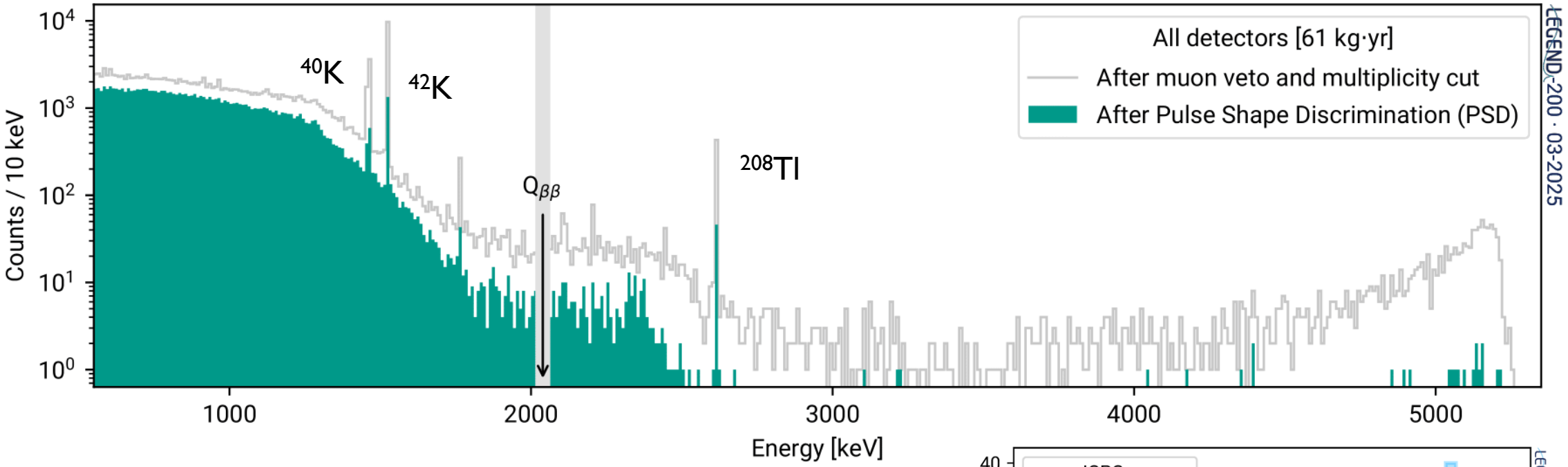
Blind analysis in $Q_{\beta\beta}$ ± 25 keV (ROI)

Spectrum after data cleaning, muon veto, & multiplicity cut

Flat background in the ROI

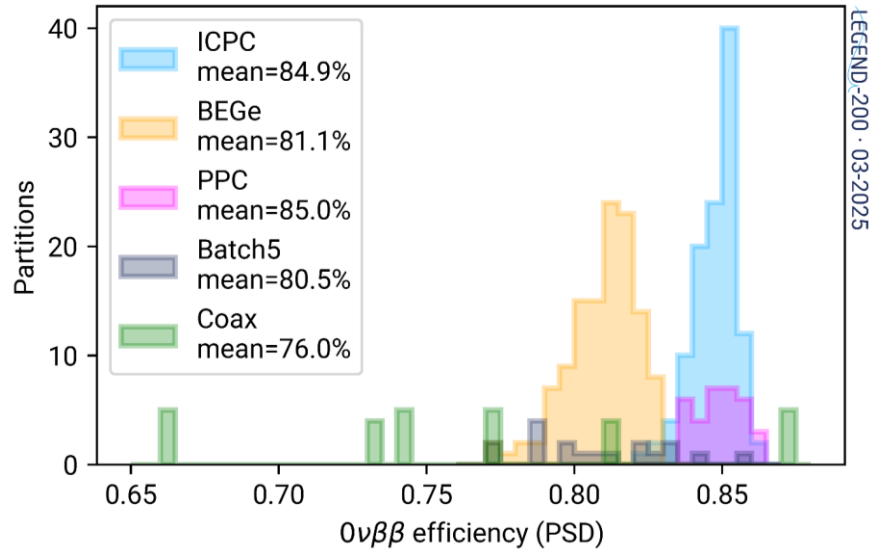


LEGEND-200: Energy spectrum after PSD cut

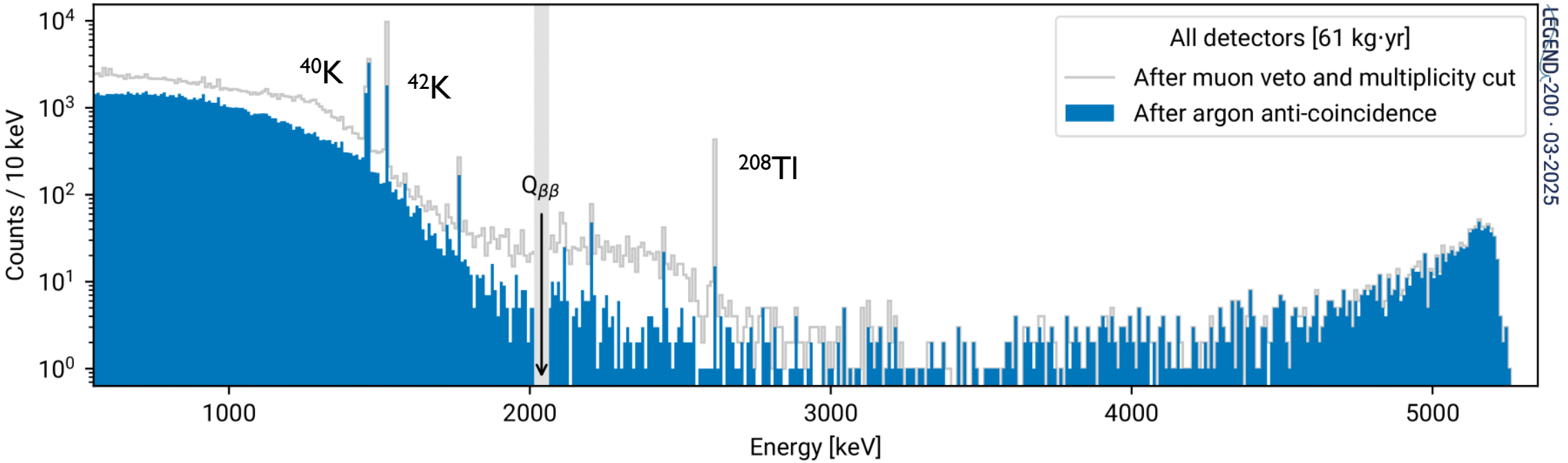


Cut on A/E PSD parameter

- ~60% suppression of Compton MSE at ROI
- strong suppression of surface events (alphas & ^{42}K betas)



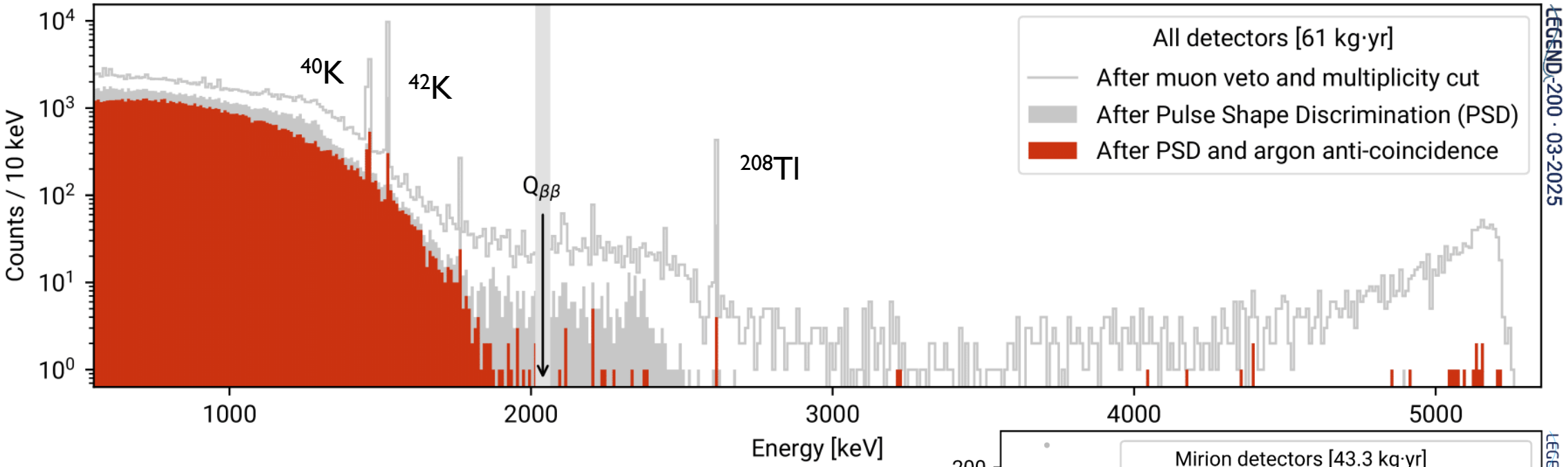
LEGEND-200: Energy spectrum after LAr cut



Cut on 4 pe signals or >4 triggered modules

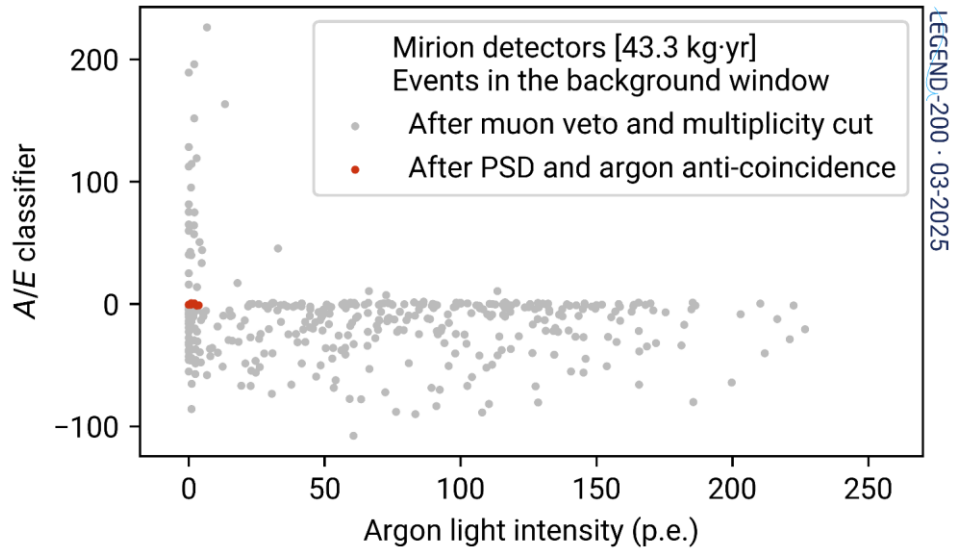
- ββ-event acceptance of ~ 93% (SSE)
- strong suppression above 2νββ

LEGEND-200: Energy spectrum after cuts

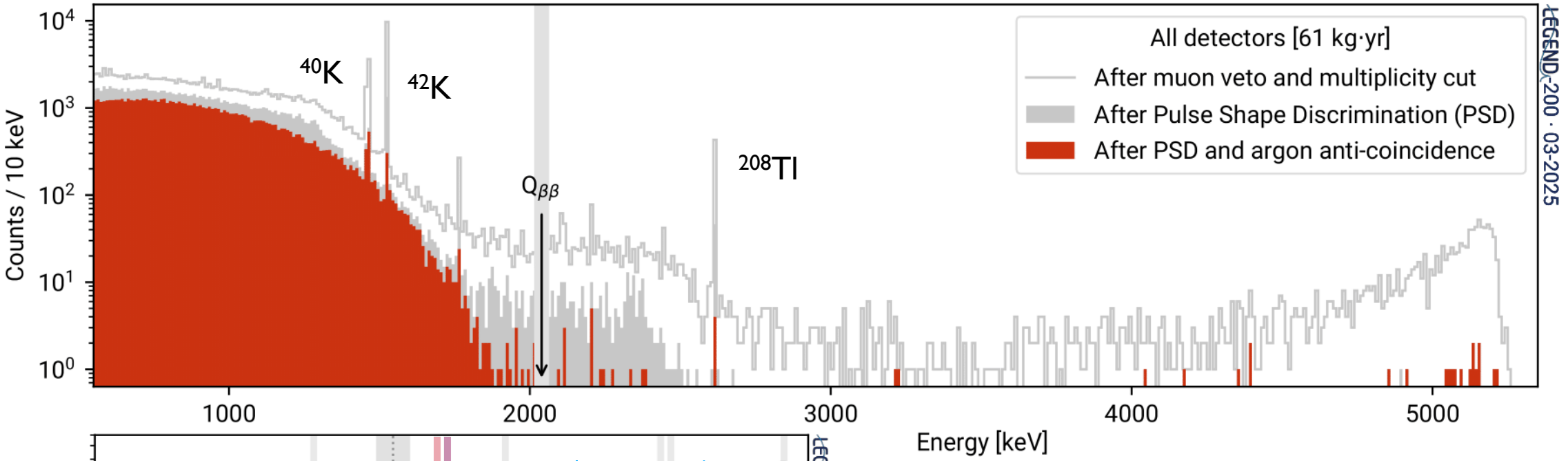


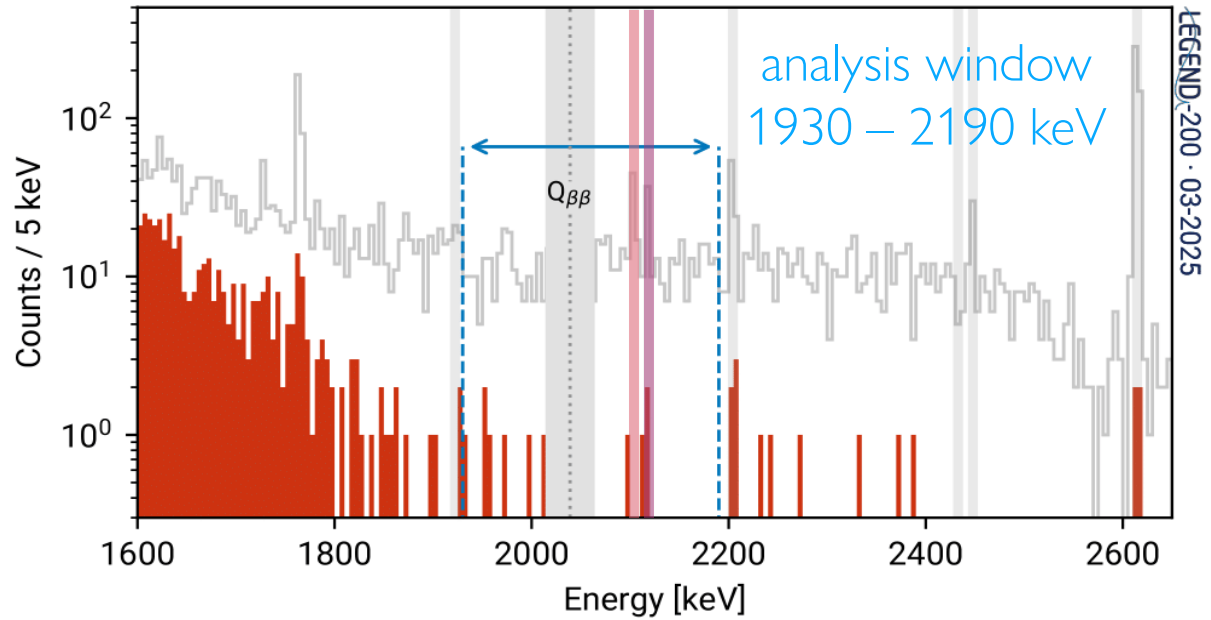
Strong anti-correlation of PSD & LAr cuts

- overall 0νββ survival fraction of ~60%
- few events surviving in analysis window



LEGEND-200: Unblinding Results



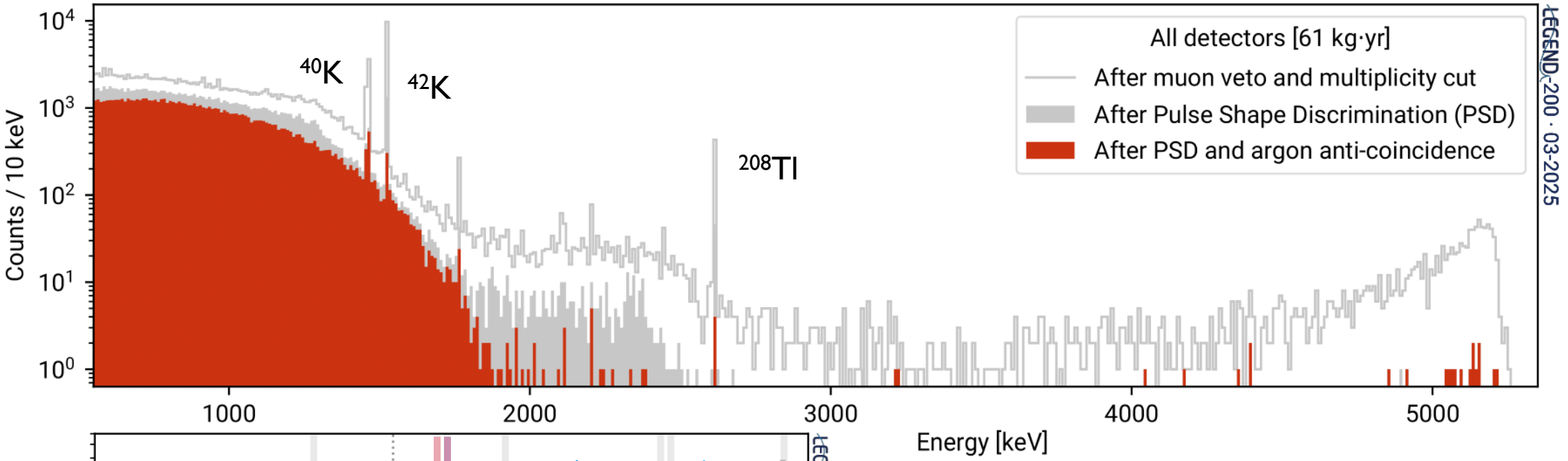


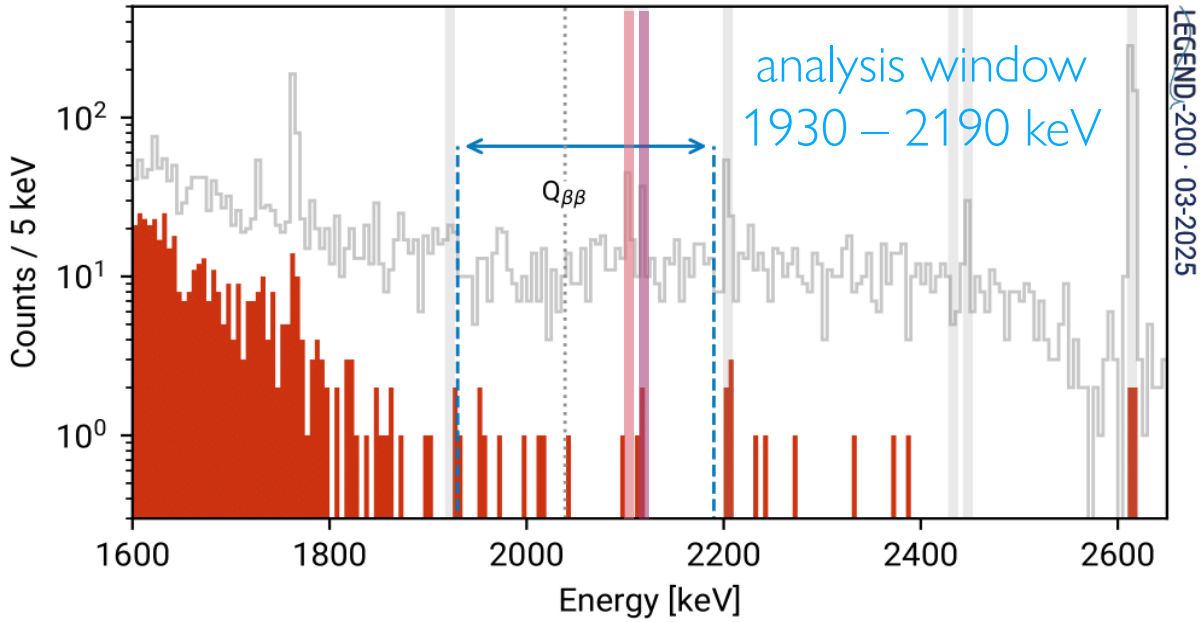
9 events in analysis window before unblinding

Excluded lines:

(2104 ± 5) keV [^{208}Tl]
(2119 ± 5) keV [^{214}Bi]

LEGEND-200: Unblinding Results



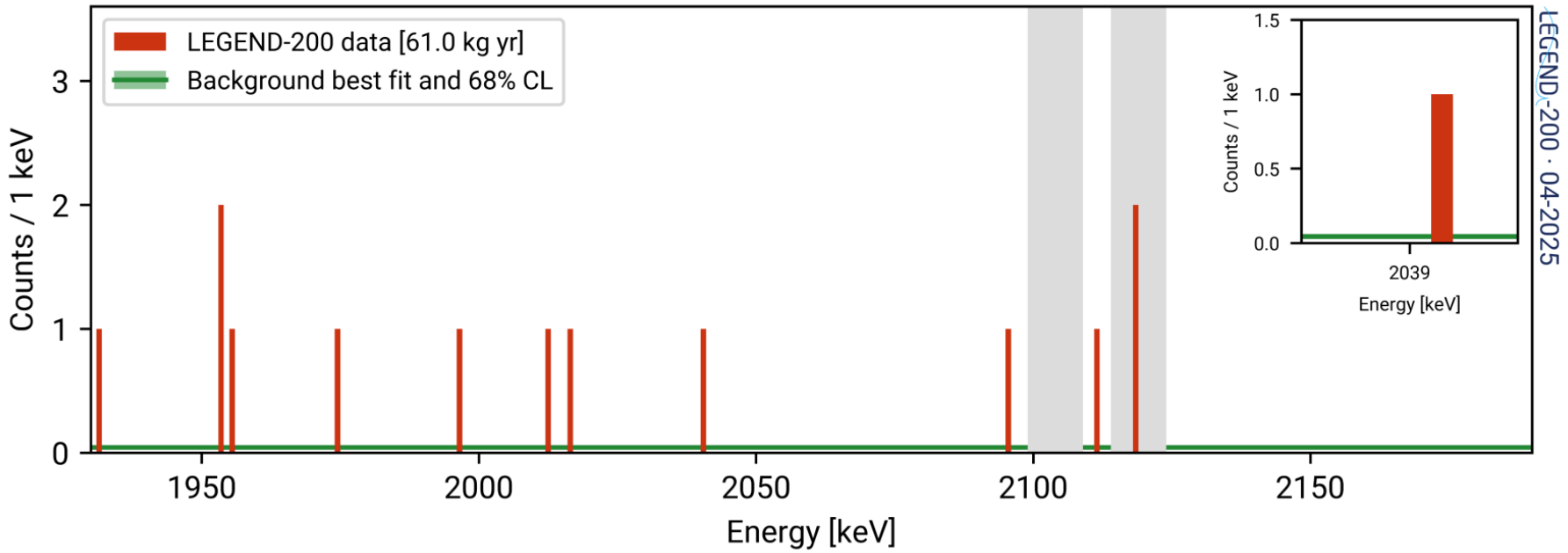


9+2 events in analysis window after unblinding

Excluded lines:

(2104 ± 5) keV [^{208}Tl]
(2119 ± 5) keV [^{214}Bi]

LEGEND-200: Background Index



11 events surviving cuts

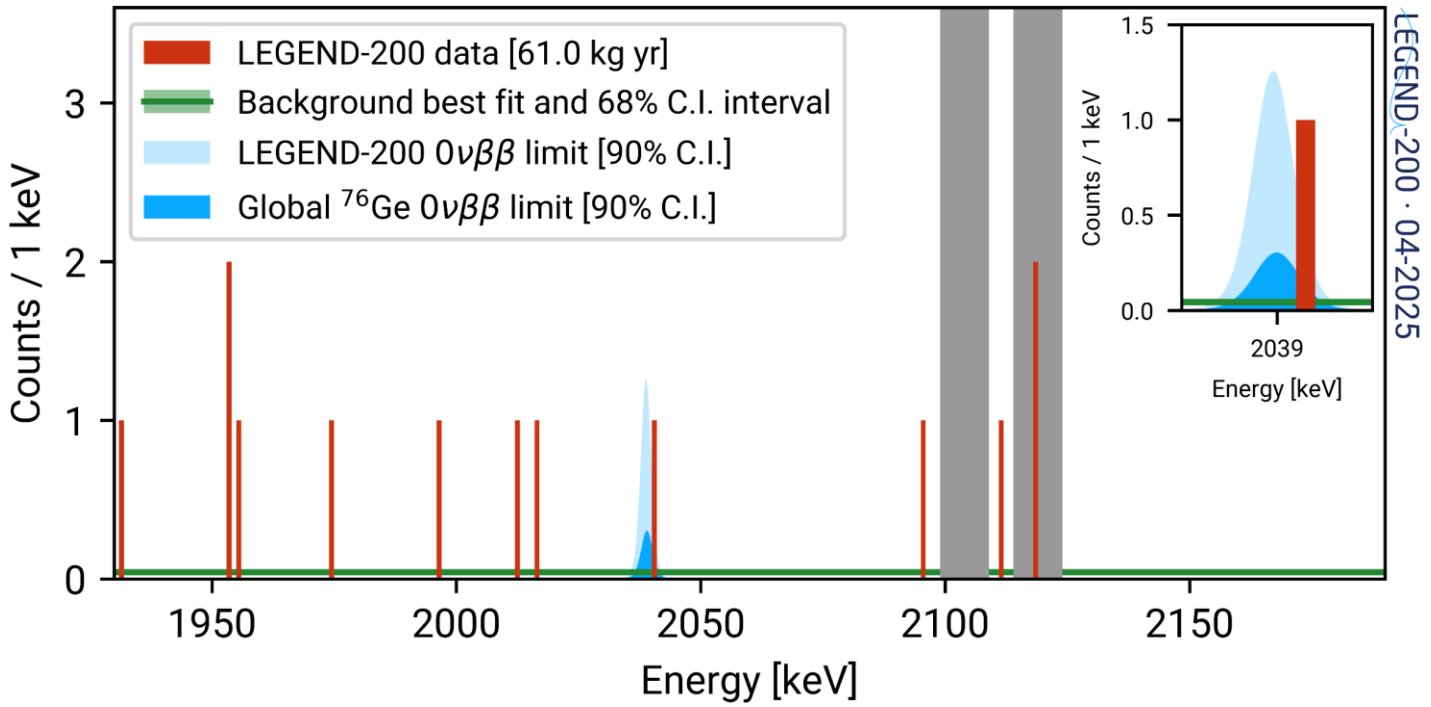
- "golden": 48 kg×yr
- "silver": 13 kg×yr
  with worse background rejection (mainly COAX)

best in 0νββ field ★

$$\mathrm{BI}_{\mathrm{golden}} = 0.5^{+0.3}_{-0.2} \times 10^{-3}\ \mathrm{cts/(keV\ kg\ yr)}$$

$$\mathrm{BI}_{\mathrm{silver}} = 1.3^{+0.8}_{-0.5} \times 10^{-3}\ \mathrm{cts/(keV\ kg\ yr)}$$

LEGEND-200: Neutrinoless Double-Beta Decay



weakened by 1 event at 1.4σ from $Q_{\beta\beta}$

LEGEND-200:

Observed: $T_{1/2}^{0\nu} > 0.5 \times 10^{26}$yr @90% CL

Sensitivity: $T_{1/2}^{0\nu} > 1.0 \times 10^{26}$yr @90% CL

Frequentist and Bayesian analysis

Combined fit of
GERDA + MJD + LEGEND-200

No observed signal
(p-value: 0.29)

Observed:
$T_{1/2}^{0\nu} > 1.9 \times 10^{26}$ yr @90% CL

Sensitivity:
★ $T_{1/2}^{0\nu} > 2.8 \times 10^{26}$ yr @90% CL

best in 0νββ field

GERDA: PRL 125 252502 (2020)
MJD: PRL 130 062501 (2023)

LEGEND-200: Limits on effective majorana mass

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

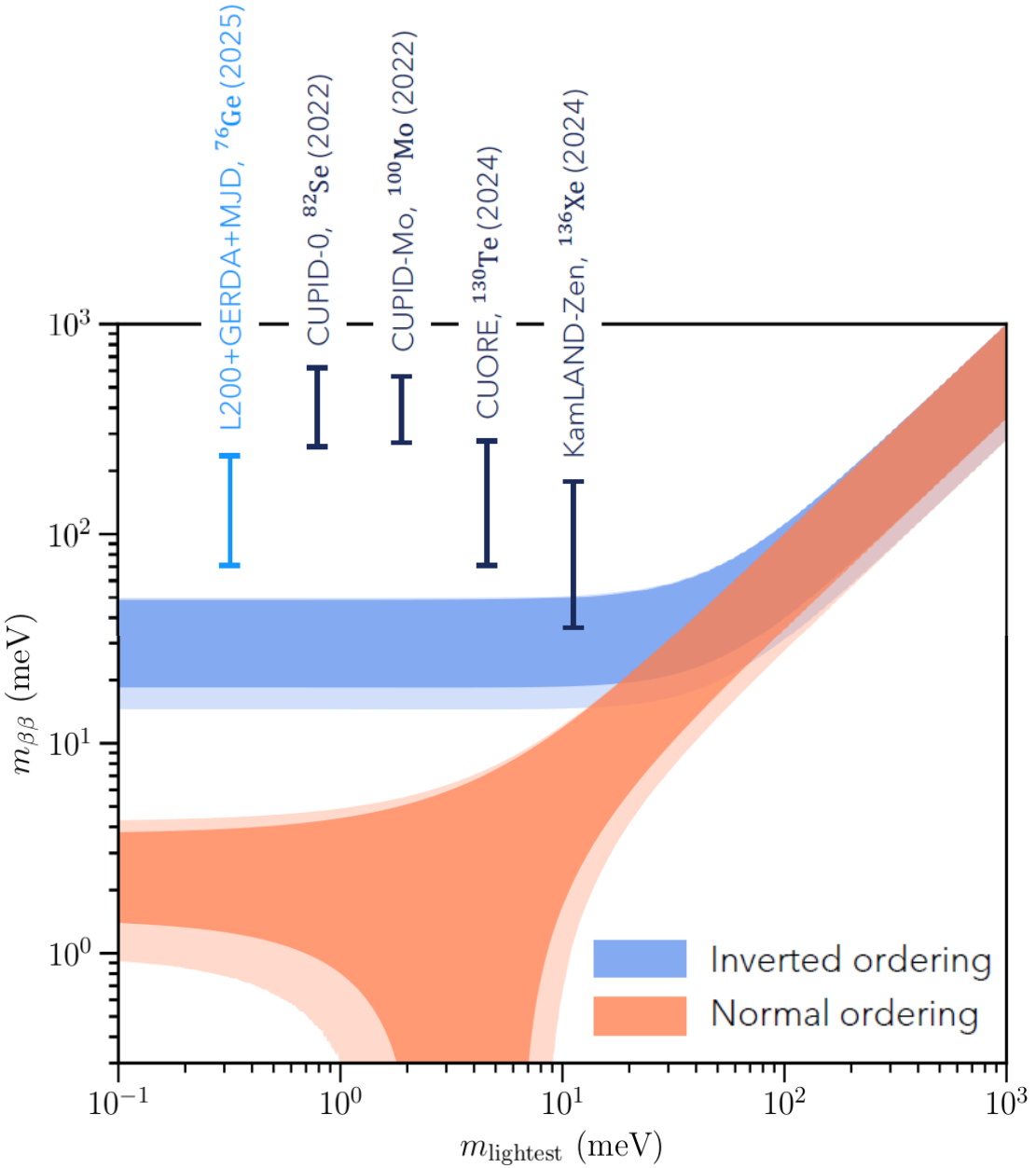
Half-life of 0νββ (observable) | Nuclear matrix element | effective majorana mass

Phenomenological NME for ^{76}Ge: 2.35 – 6.34

$m_{\beta\beta}$ < 75 – 200 meV @90% CL

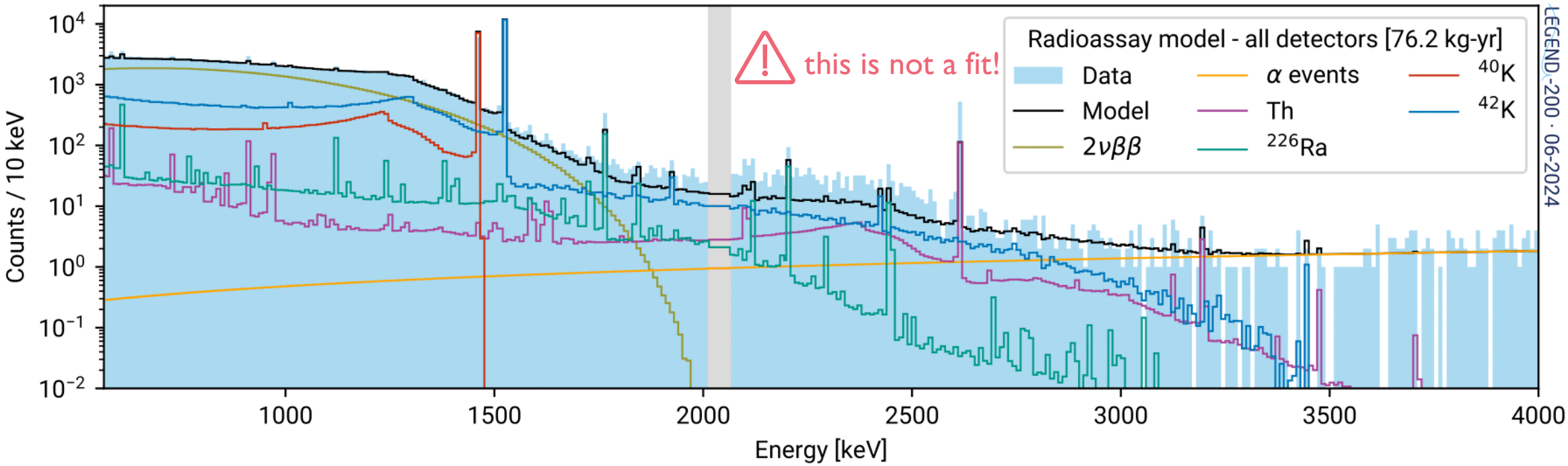
Uncertainty quantified NME for ^{76}Ge: $2.6^{+1.28}_{-1.36}$ (Bayesian ab-initio calculation)[1]

$m_{\beta\beta}$ < 320 @90% CI



[1]Phys. Rev. Lett. 132, 182502 (2024)

LEGEND-200: Background model



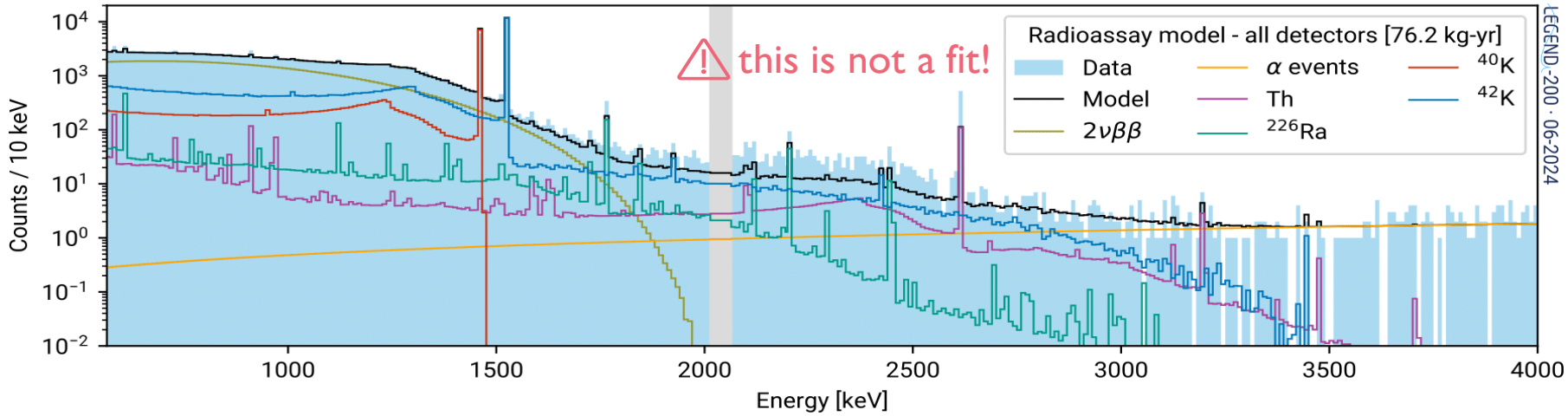
Bayesian background model using the full dataset and special runs

- No unexpected background components
- Radio-assay of materials underpredicts ^{228}Th in physics data

Background is still efficiently suppressed by analysis cuts

Enhancing the sensitivity of LEGEND-200

Elevated ^{228}Th background compared to radioassay



Investigation

Special runs
Background simulation
Screening campaign

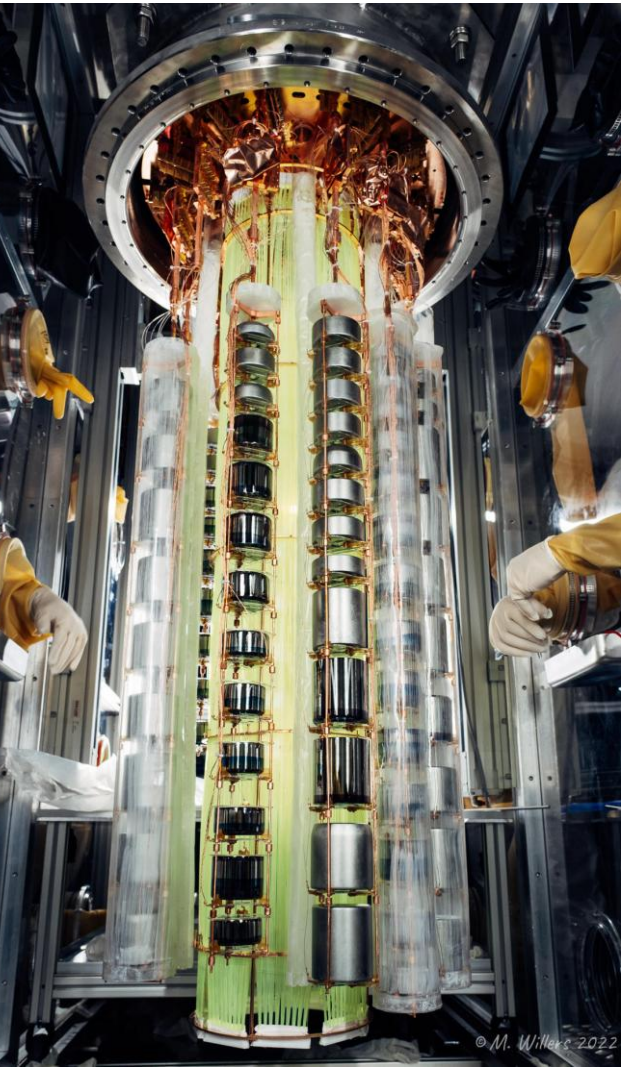
Cleaning

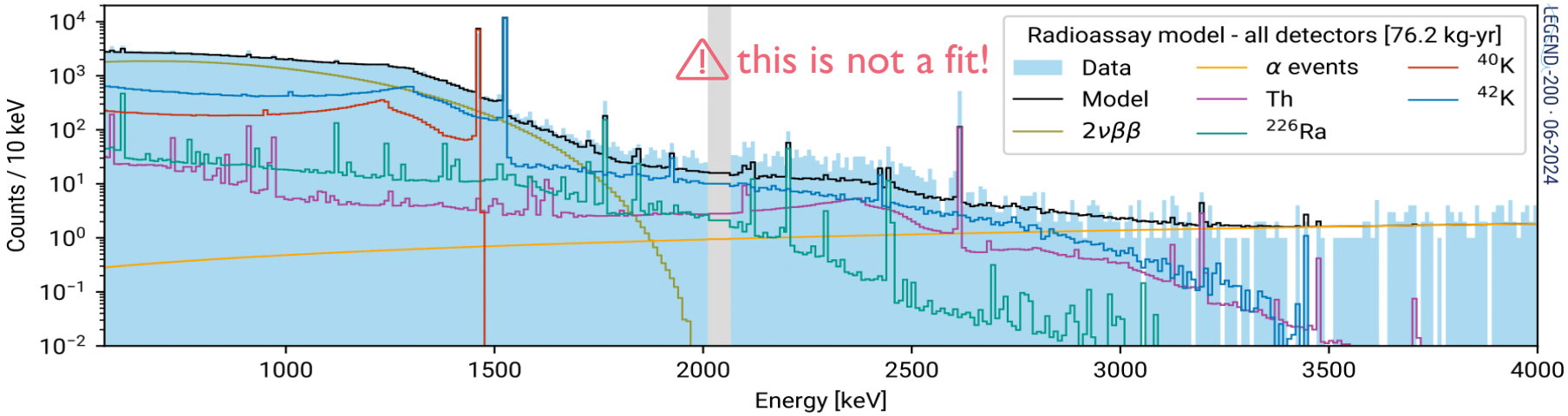
Re-evaluation of techniques
Recleaning of close components

Improvement

Maintenance
New detectors
Higher IC mass

Enhancing the sensitivity of LEGEND-200





Investigation

Cleaning

Improvement

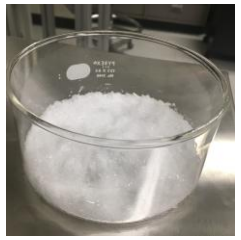
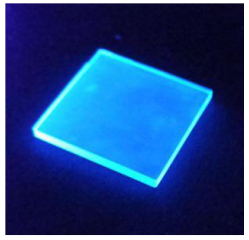
Restarted data taking (summer 2025)

- 138 kg of HPGe detectors
- BeGe and IC detectors
- indication of reduced background levels

The road to LEGEND-1000

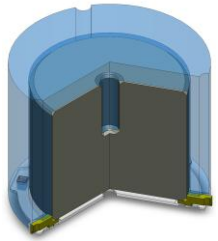
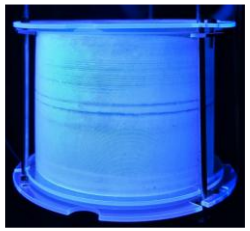
Optically active materials

- additive manufacturing (3D printing)
- self-synthesized PEN

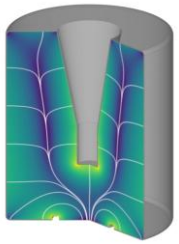
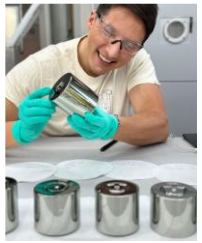
^{42}Ar/^{42}K mitigation

- underground-sourced argon
- active enclosures

Germanium detectors

- production pipeline
- machine learning for PSD
- simulation of HPGe detectors

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Poster "The Quest for No Neutrinos: Advancing the Search with LEGEND-1000" by M. Neuberger

Summary

First LEGEND-200 results

stable operations with 142 kg of HPGe

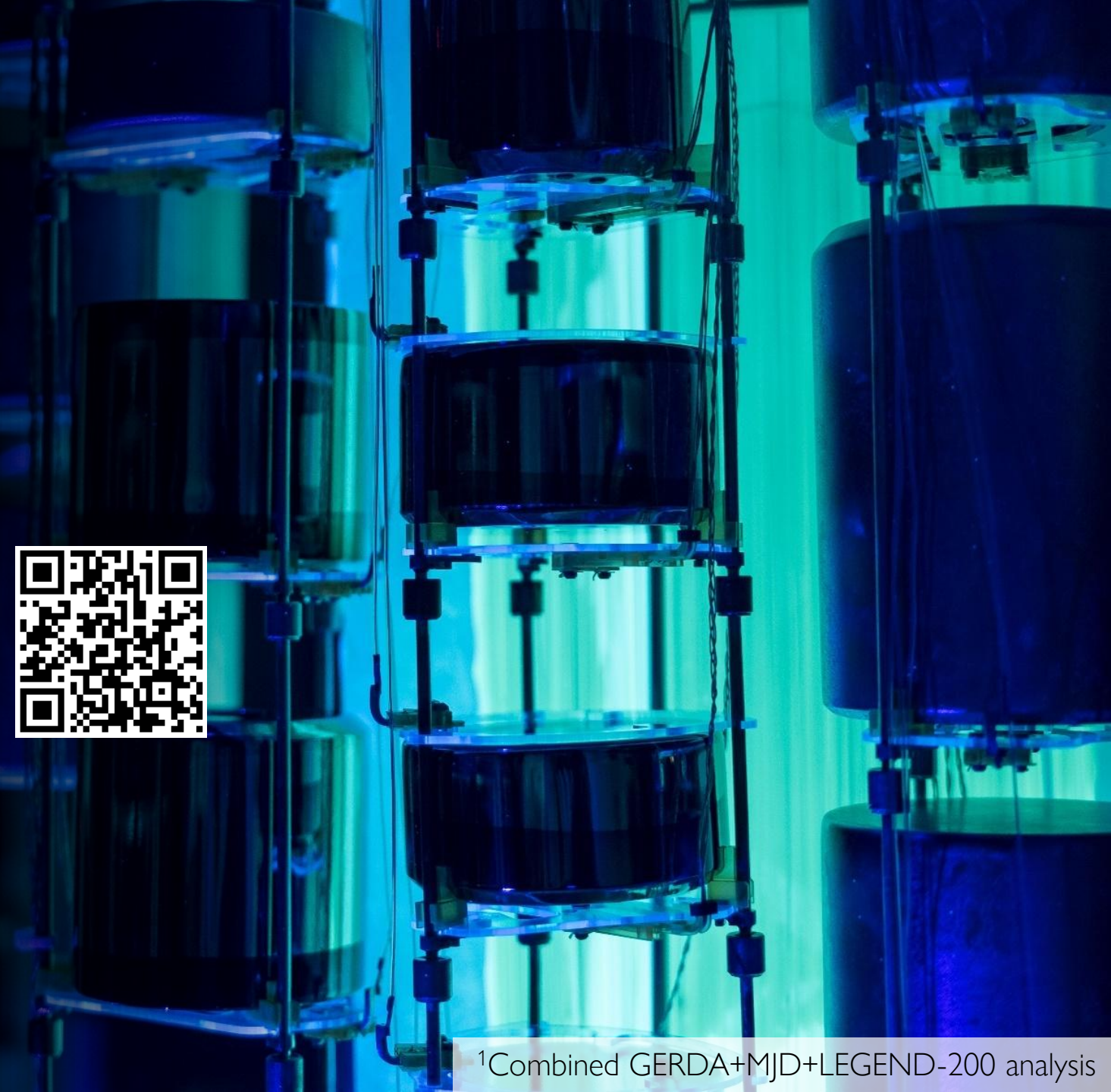
Observed[1]	$T_{1/2}^{0\nu} > 1.9 \times 10^{26}$ yr @90% CL
Sensitivity[1]	$T_{1/2}^{0\nu} > 2.8 \times 10^{26}$ yr
Effective mass	$m_{\beta\beta}$ < 75 – 200 meV @90% CL

Accepted to PRL [arXiv:2505.10440]
[https://doi.org/10.1103/25tk-nctn]

Improving on LEGEND

- extensive study on backgrounds & cleaning
- deployment of 35 kg of new IC detectors
- restarted data taking in summer 2025

The road to LEGEND-1000 is set before us …



[1]Combined GERDA+MJD+LEGEND-200 analysis