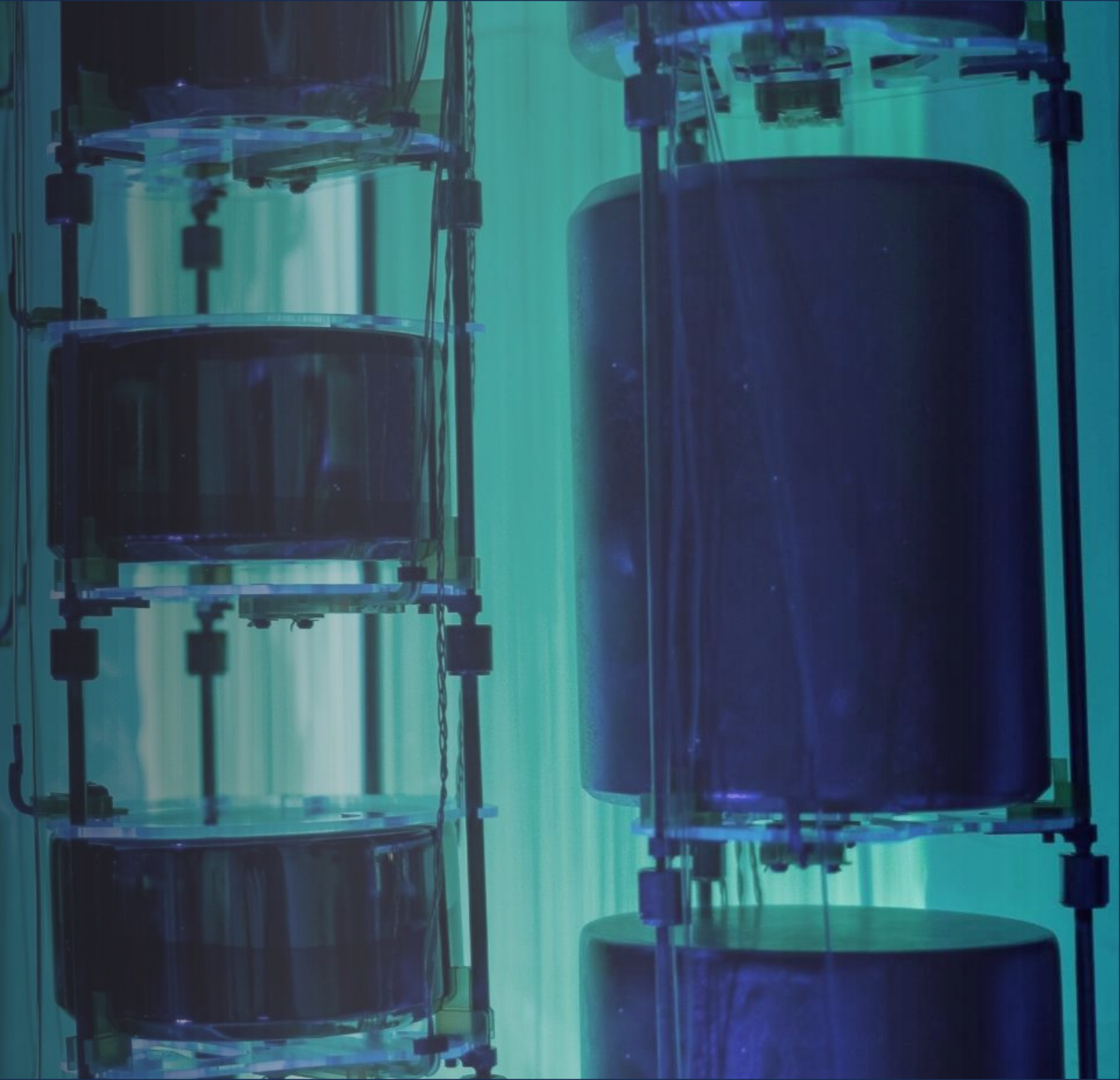
Unveiling the Majorana Nature of Neutrinos: First $0\nu\beta\beta$ Results from the LEGEND Experiment



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on behalf of the LEGEND Collaboration

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WIN 2025, Brighton, UK

The LEGEND Project

"The collaboration aims to develop a ^{76}Ge-based $0\nu\beta\beta$ decay program with **discovery potential** $T^{0\nu}_{1/2} > 10^{28}$ yr using existing resources to expedite physics results"

LEGEND-1000 Preconceptual Design Report

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

13 countries, 60 institutions, ~300 members

GERDA +  + new groups

GERDA and MAJORANA DEMONSTRATOR set most stringent constraints for $0\nu\beta\beta$ using ^{76}Ge

Phased approach

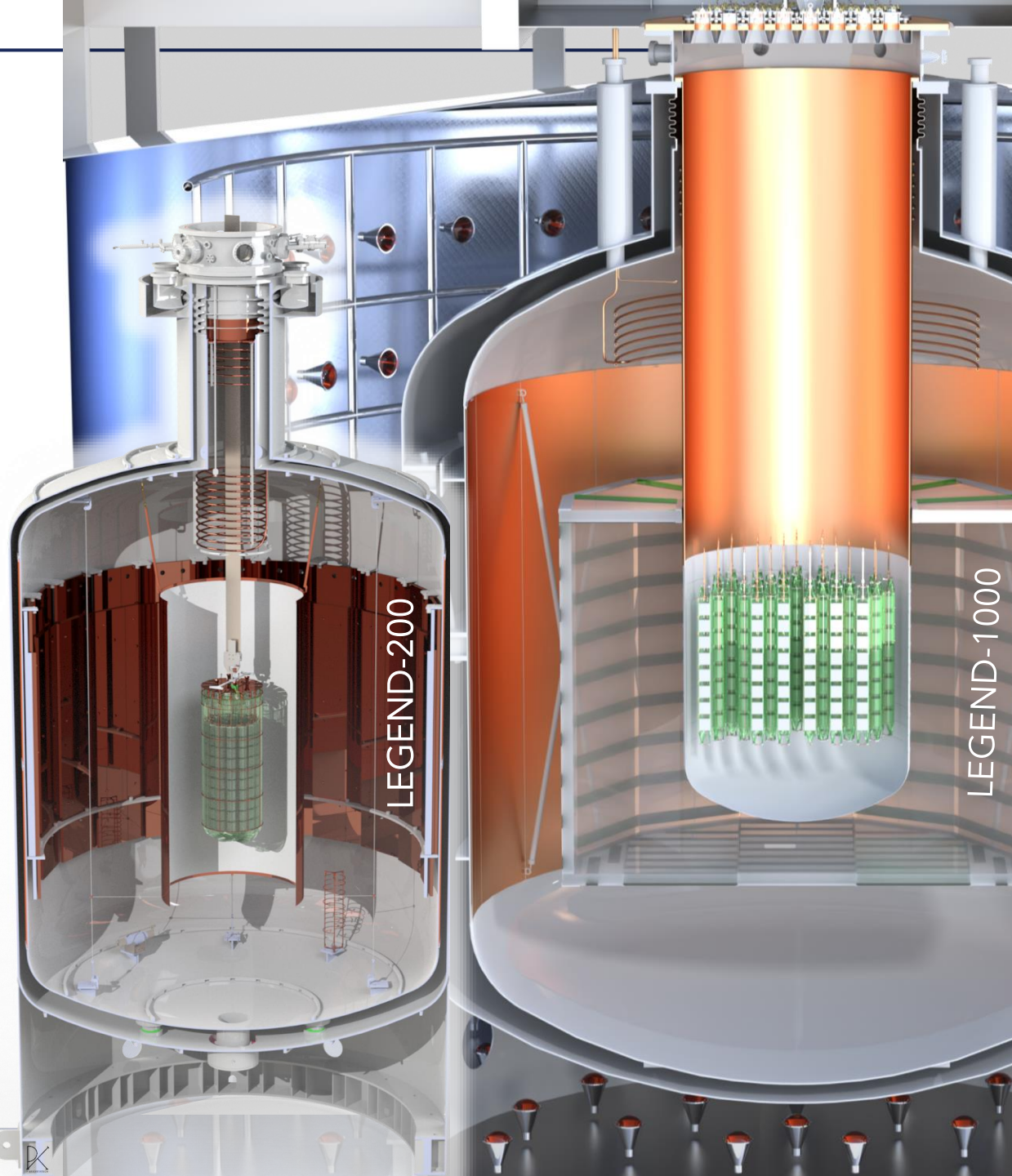
LEGEND-200

- Up to 200 kg of ^{76}Ge in the upgraded infrastructure of GERDA @ Hall A of LNGS, Italy
- Operative since 2023: $T_{1/2}^{0\nu} > 10^{27}$ yr after 5 yr

LEGEND-1000

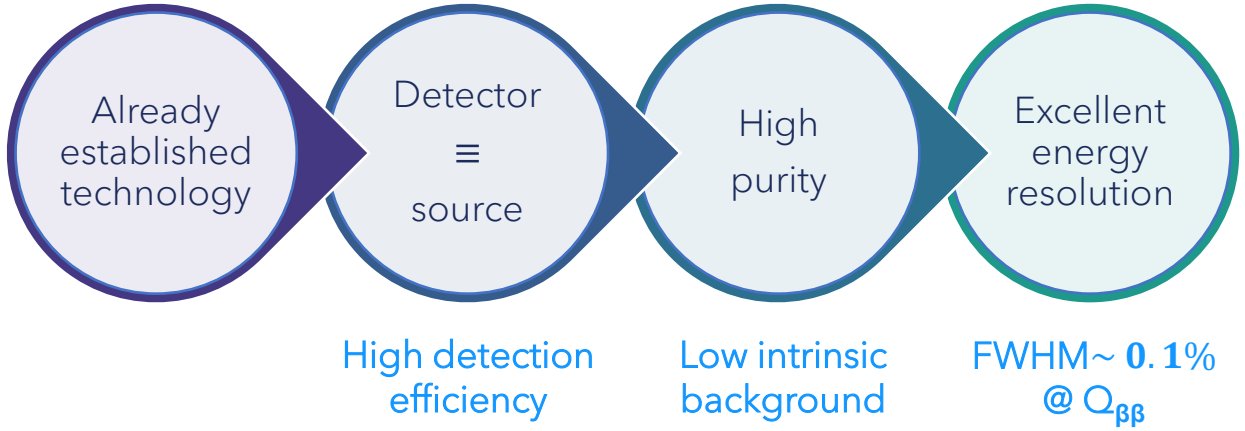
- 1 tonne of ^{76}Ge in a new infrastructure @ Hall C, LNGS
- Under construction: $T_{1/2}^{0\nu} > 1.3 \times 10^{28}$ yr after 10 yr
- Quasi-background-free: 0.01 cts/(keV · ton · yr)
- Unambiguous discovery with just a handful of counts

"Towards LEGEND-1000" poster by Mario Schwarz #13

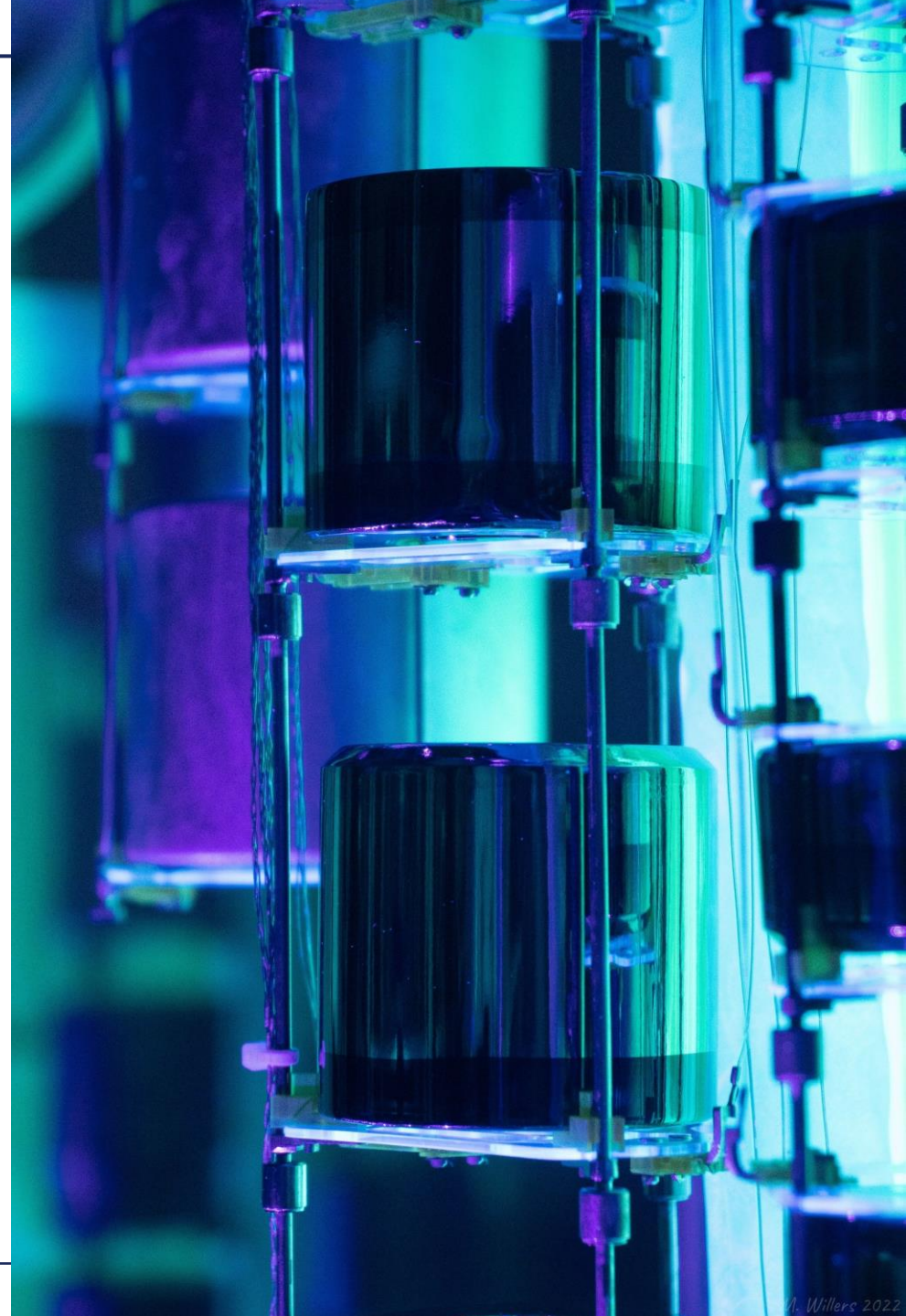


Why Germanium?

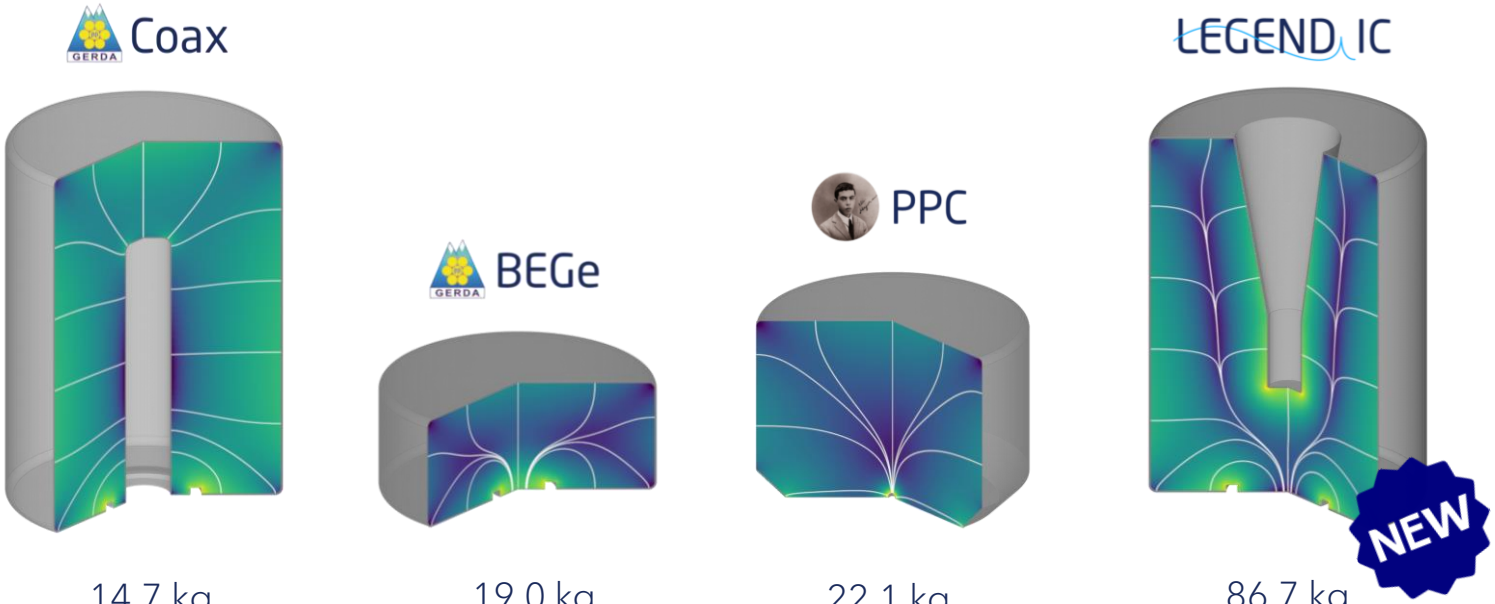
- A "golden" isotope does not exist…
- …mix of theoretical & experimental preferences: costs, energy resolution, background level, scalability (liquids, gas, crystals)



- $^{76}_{32}\mathrm{Ge} \rightarrow {}^{76}_{34}\mathrm{Se} + 2\mathrm{e}^{-}\ (+2\bar{\nu}_{\mathrm{e}})$ with $Q_{\beta\beta}$=2039.061 (7) keV
- $Q_{\beta\beta}$>2 MeV: less processes can mimic the $0\nu2\beta$ signal
- Natural abundance is low (~8%): enrichment up to ~92% is possible



LEGEND-200 diodes



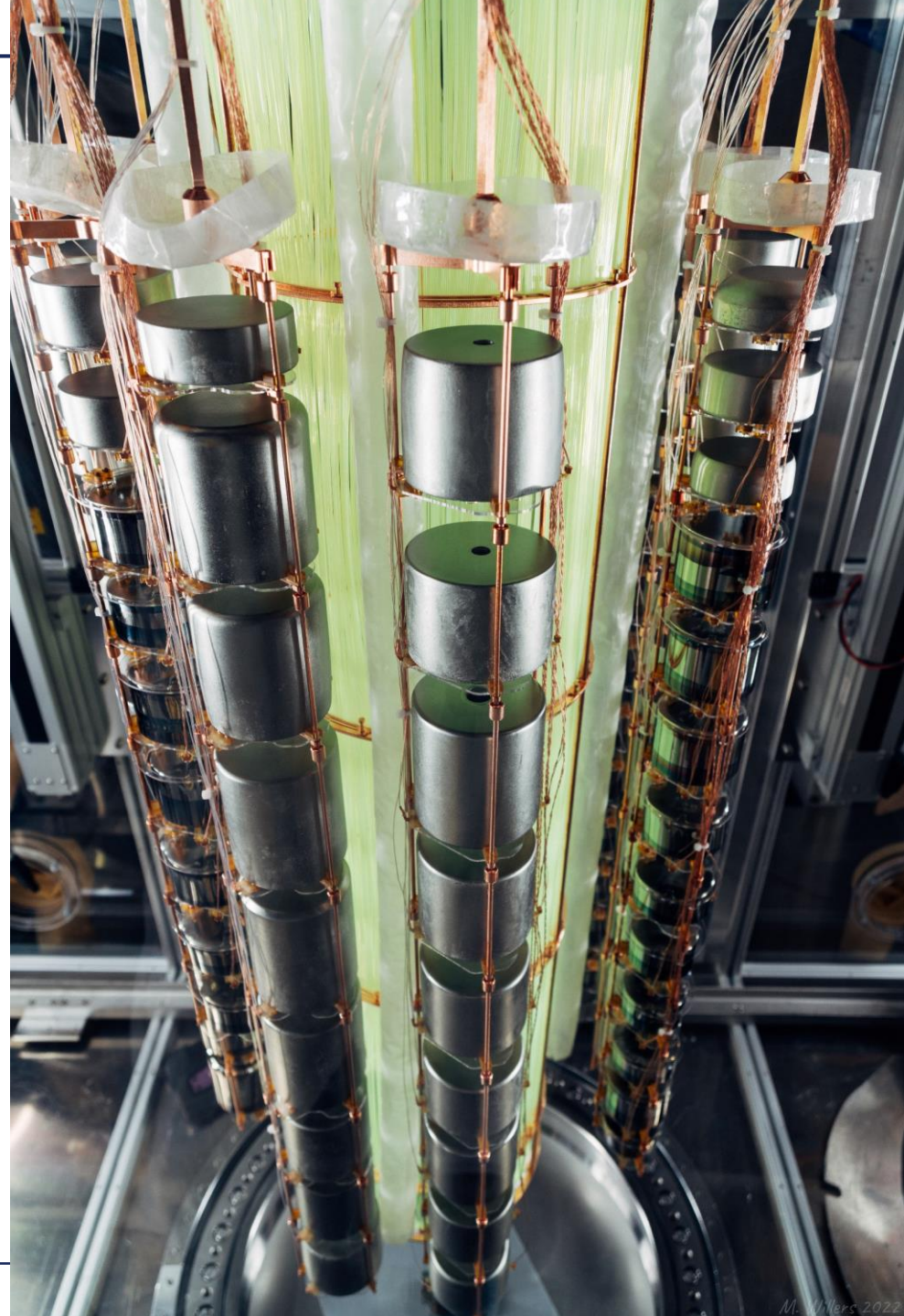
14.7 kg
10%

19.0 kg
13%

22.1 kg
16%

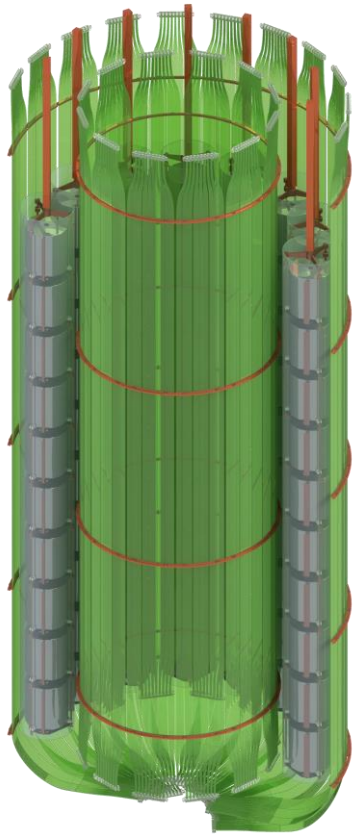
86.7 kg
61%

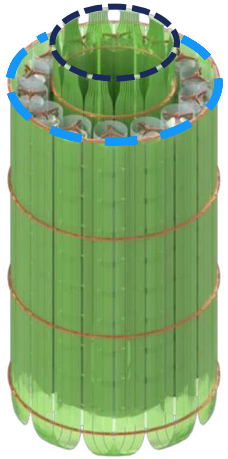
- p+ (implanted B), n+ (diffused Li), passivated groove
- Different geometries - mass: 0.7-4 kg
- Latest result: 142 kg in total



LEGEND-200 Setup

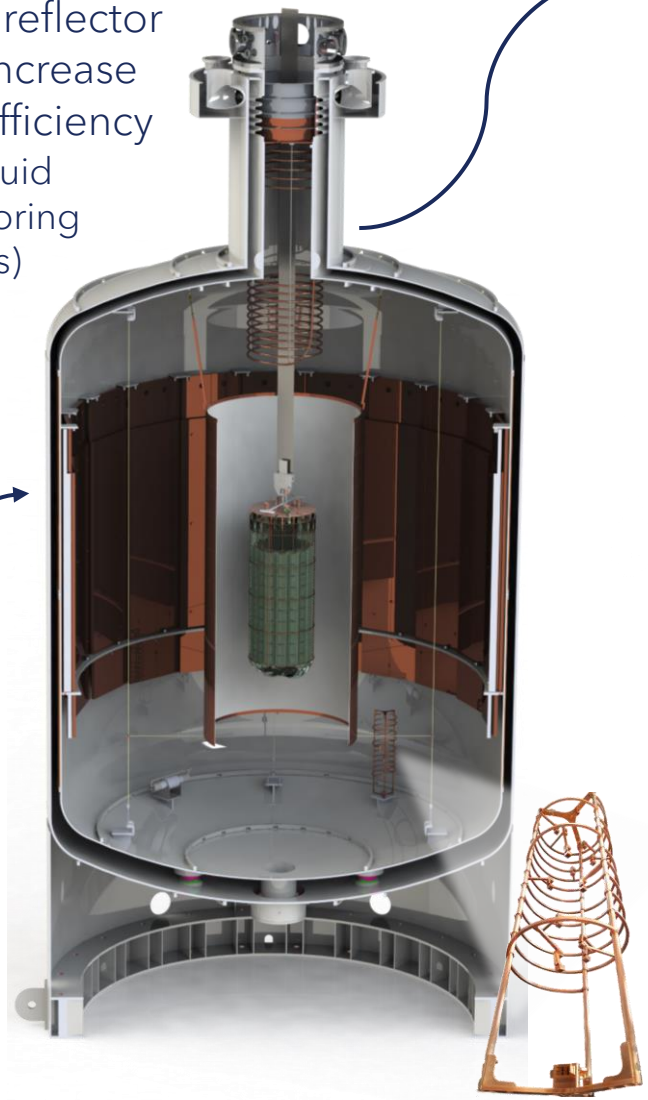
Ge array



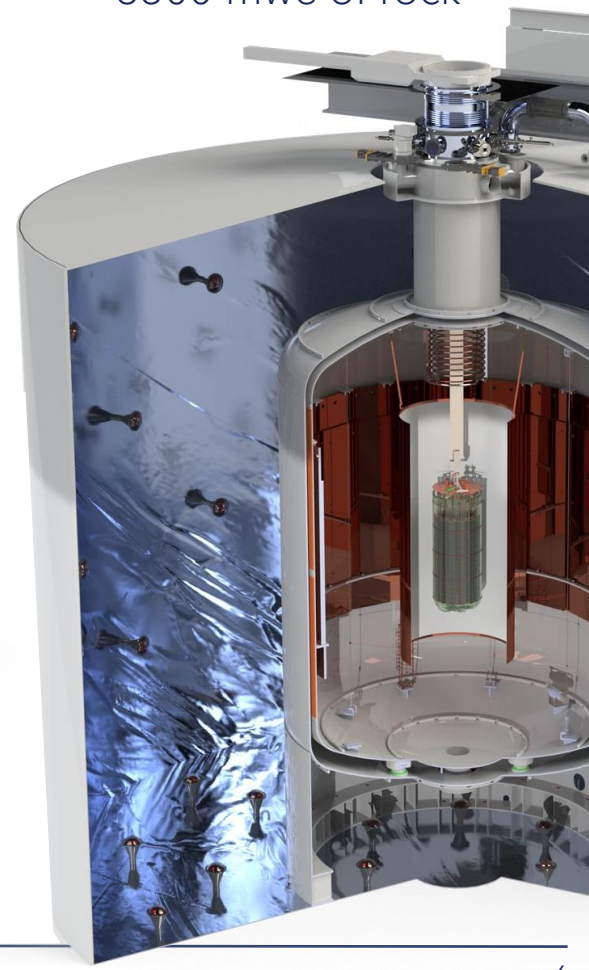


Liquid argon (LAr) system
58 read-out modules of
SiPMs coupled to WLS fibers

Cryostat
- Ø 4 m, H 5.88 m, V 64 m^3
- Cylindrical WLS reflector to shield and increase LAr detection efficiency
- LLAMA (Liquid Argon Monitoring Apparatus)

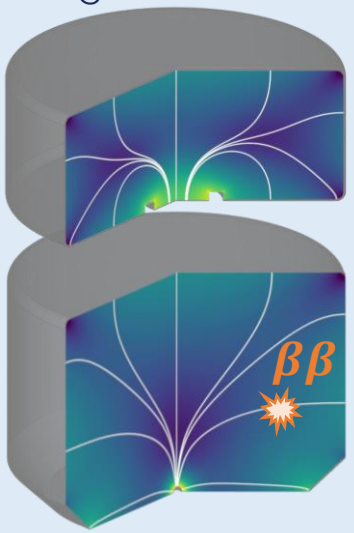


Ultrapure water tank
- Ø 10 m, H 8.5 m, V 590 m^3
- 66 PMTs + plastic scintillators for μ
- Shield for n, γ
- 3500 mwe of rock

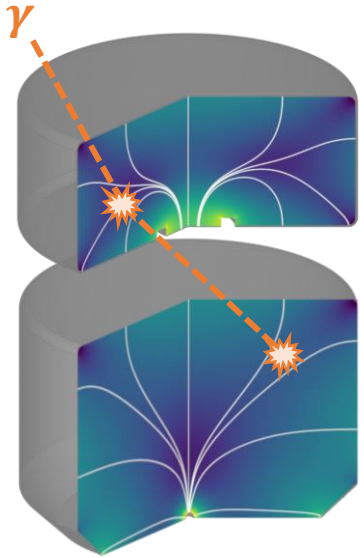


Background Reduction

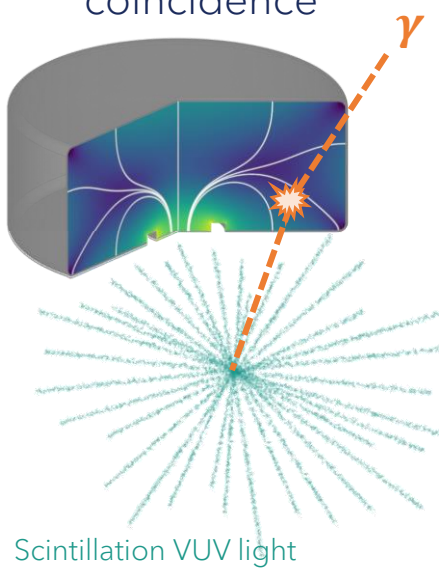
Signal-like single-site event



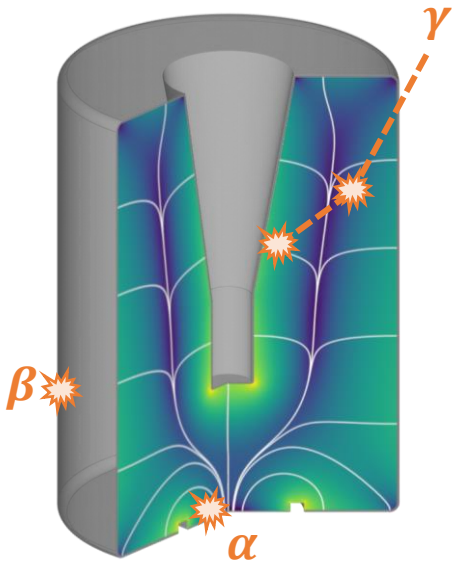
Multiplicity cut

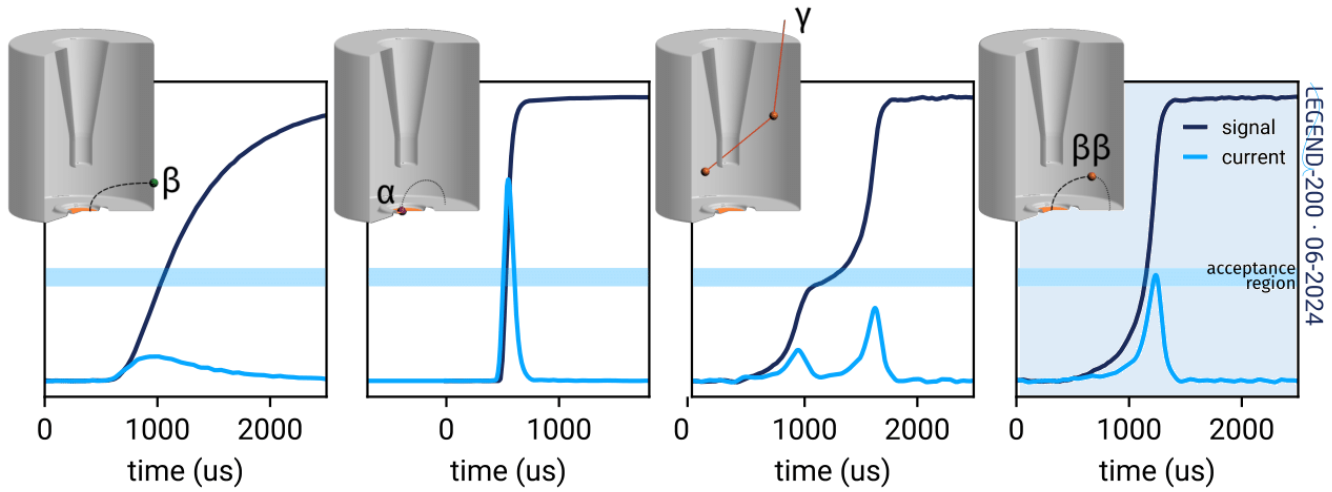


Det-LAr coincidence



Multi-site event, surface events





Pulse shape discrimination (PSD): discrimination based on the signal risetime and amplitude

Timeline

2020 – 2022 — **Construction phase**
& deployment of GERDA/MJD detectors and new IC detectors

2022 – 9/2022 — **60 kg commissioning**
Test of HPGe detectors, electronics, LAr, calibration system

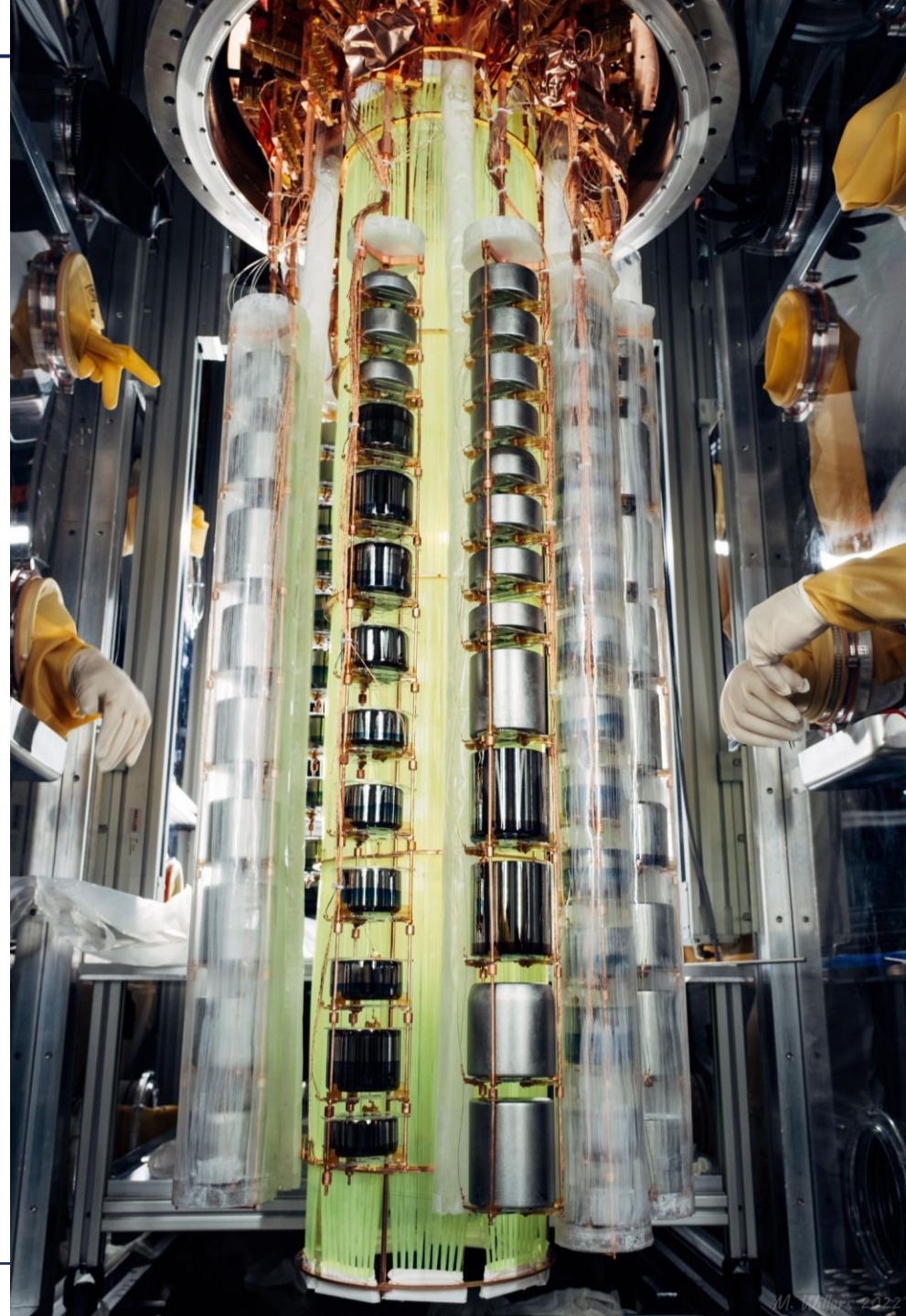
10/2022 – 2/2023 — **142 kg commissioning**

3/2023 – 2/2024 — **Stable physics data taking**

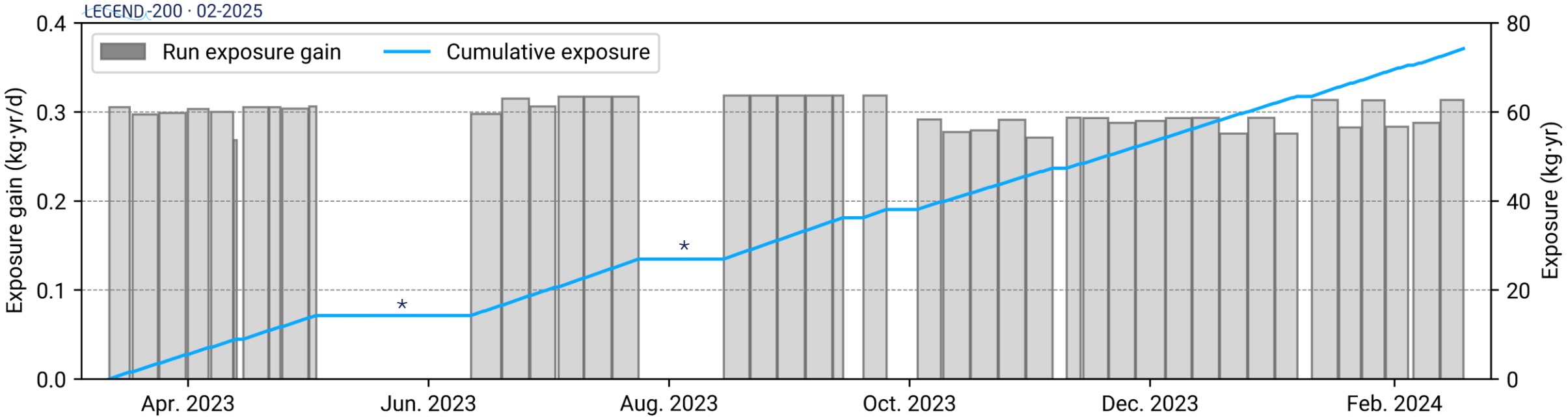
Neutrino'24: first results after 1st yr of data (48 kg·yr)

3/2024 – today — Background characterization runs, maintenance work, …
Start of data taking in May 2025

APS'25: updated results (48+13 kg·yr)



Exposure

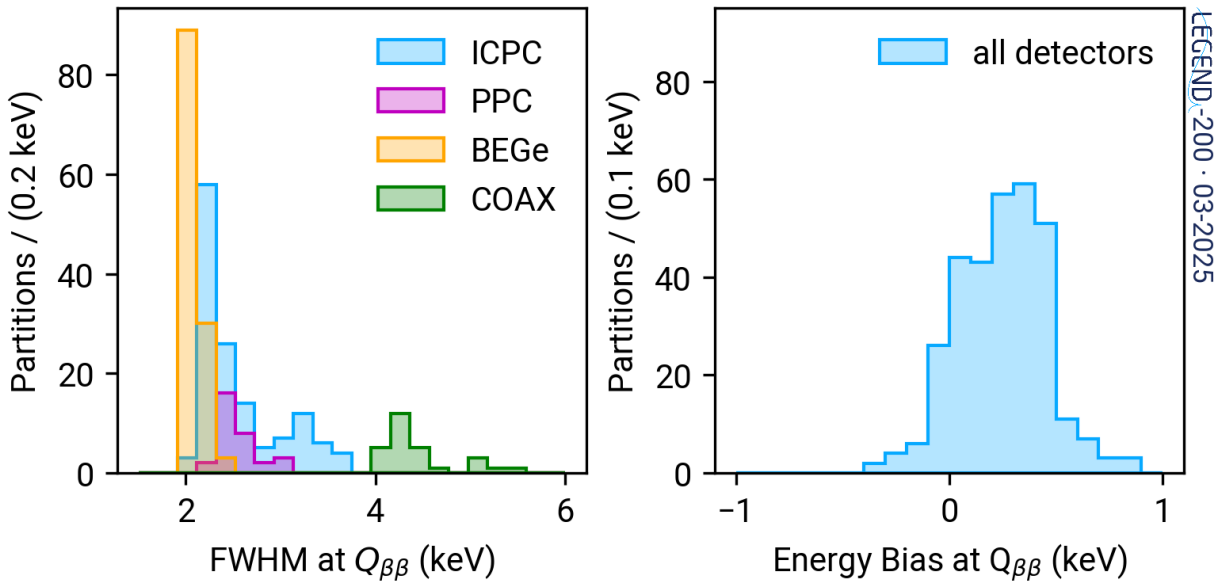


- Duty cycle of 91.4% over 242 days
- 76.2 kg·yr: background characterization dataset
  - All active detectors
- 61.0 kg·yr: $0\nu\beta\beta$ dataset
  - All active detectors <u>but</u> those with invalid PSD performance

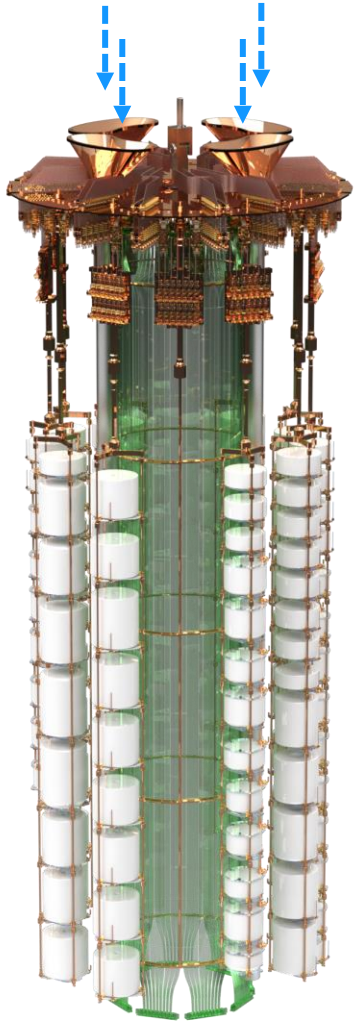
(*) Test runs / HV scans

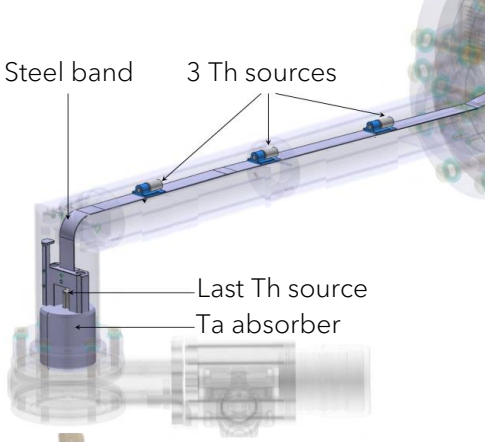
Energy Scale and Resolution

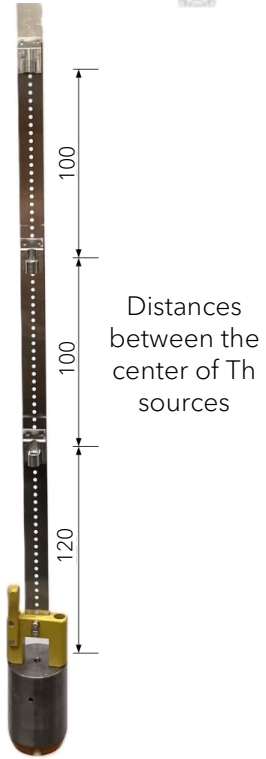
- Weekly energy calibrations using ^{228}Th sources
- Overall resolution of 0.1-0.2% FWHM at $Q_{\beta\beta}$
- Very stable energy scale - energy bias 0.2±0.3 keV at $Q_{\beta\beta}$



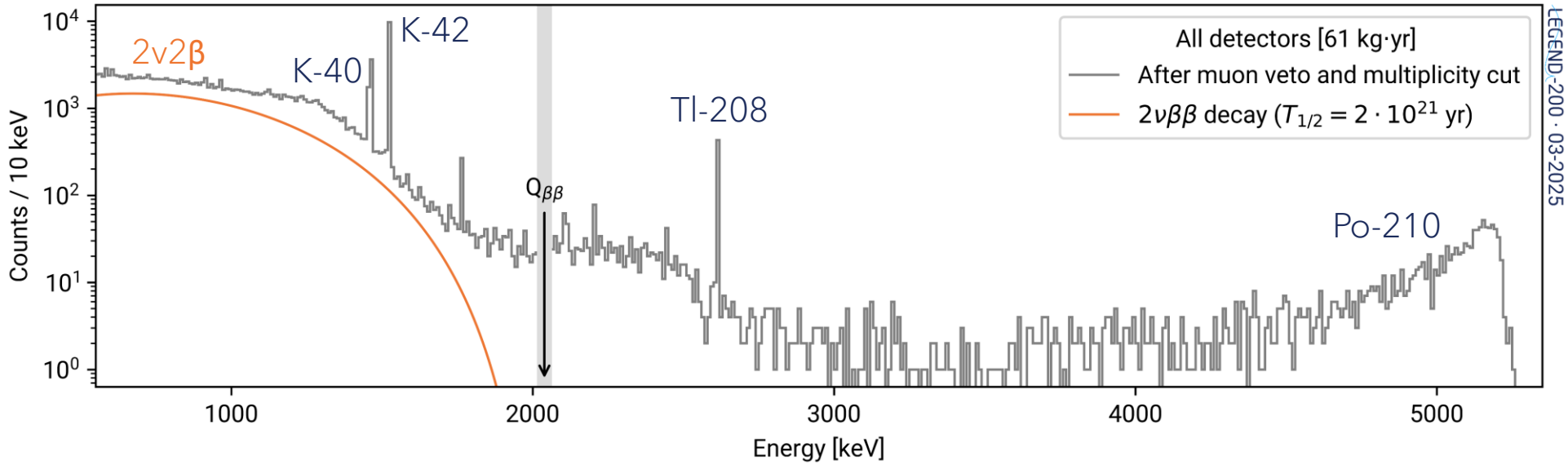
4 calibration source insertion systems





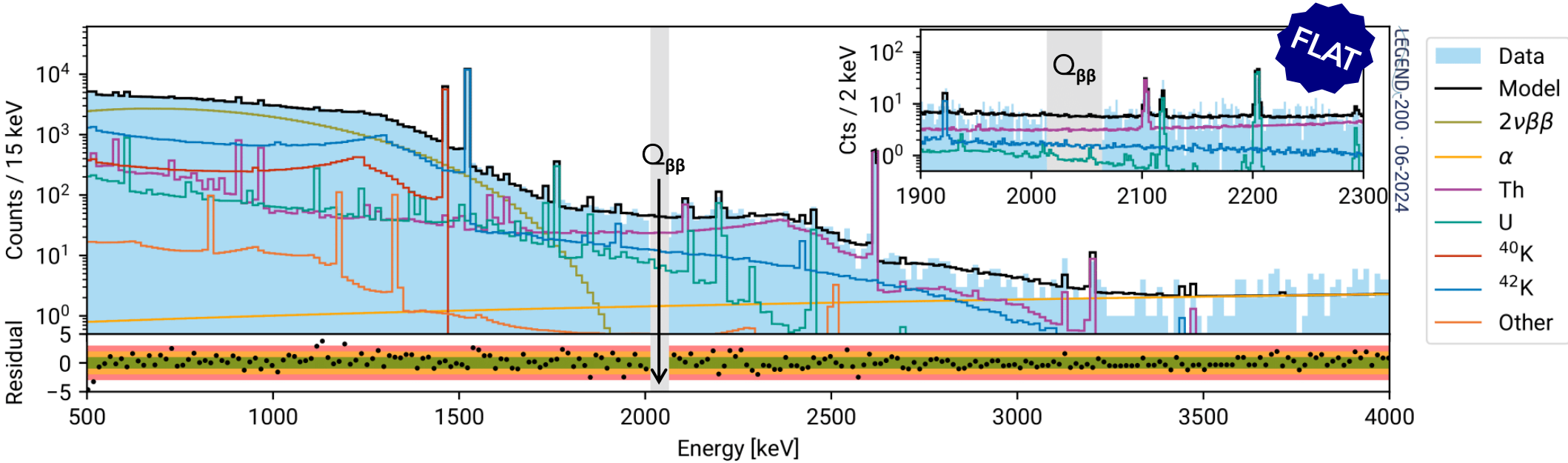


Energy Spectrum



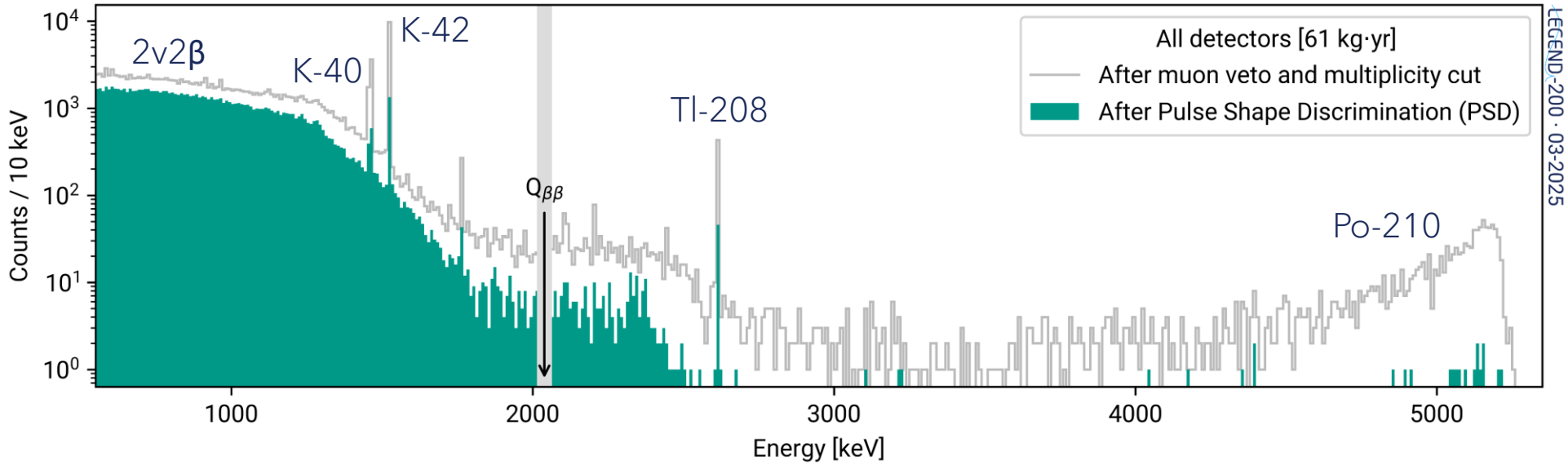
- Blinded analysis in $Q_{\beta\beta} \pm 25$ keV
- Spectrum after:
  - data cleaning → 95-99% survival after removal of unphysical events
  - muon veto → 2 events removed at $Q_{\beta\beta}$
  - multiplicity cut → 26% events removed at $Q_{\beta\beta}$
- $T_{1/2}^{2\nu} = 2.022 \pm 0.018_{\text{stat}} \pm 0.038_{\text{syst}} \times 10^{21}$ yr [GERDA Collab., PRL 131, 142501 (2023)]

Background Model [76.2 kg·yr]

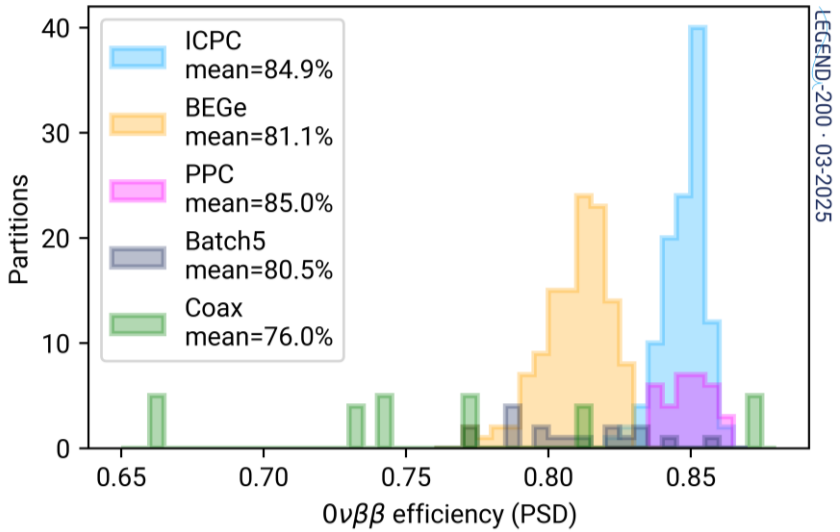


- Bayesian background model using the full dataset + extra 10.2 kg·yr of special runs
- Decomposition of the full-range energy spectrum: no unexpected background components
- ^{228}Th underprediction in physics data compared to radioassay predictions
  - Tested different ^{228}Th locations via the background model: no hotspots or asymmetries
  - Ongoing screening campaign & re-evaluation of cleaning techniques
  - This background is efficiently suppressed by analysis cuts

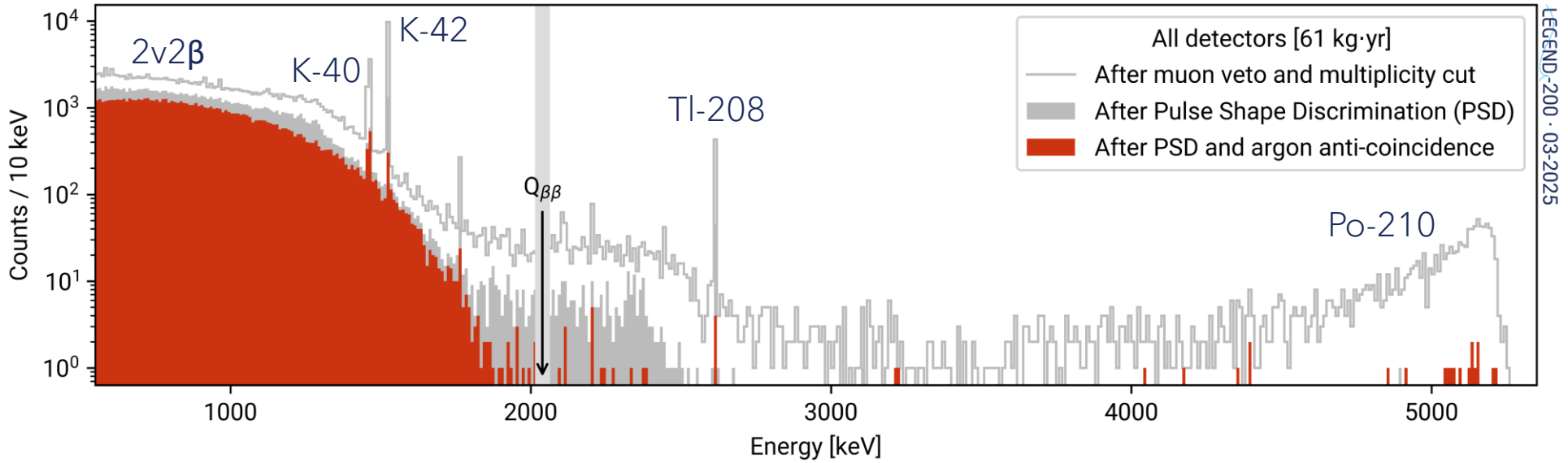
Energy Spectrum after PSD



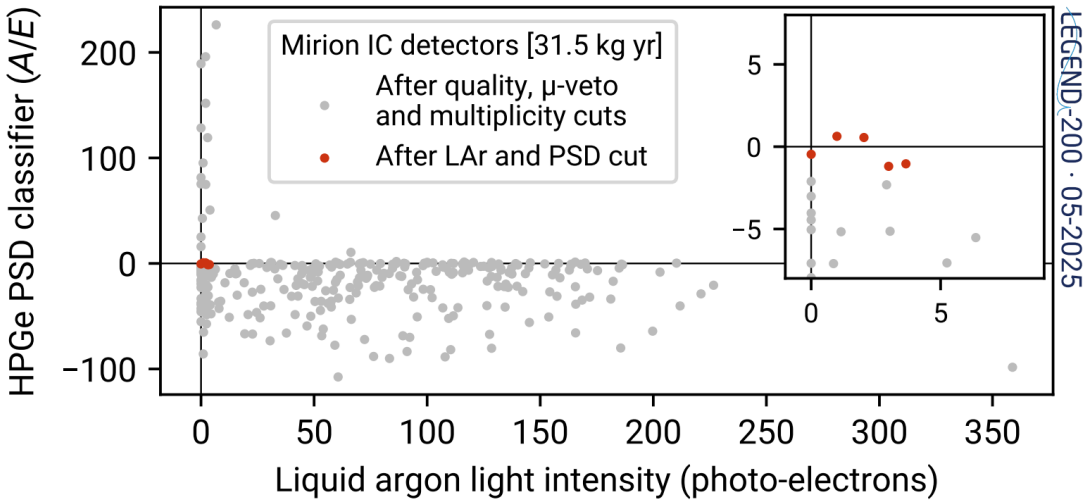
- Cut acting on A/E = max(current) / energy
  - Late charge cut for PPC (large passivated surface)
  - Neural-network methods developed for semi-coaxial
- ~60% suppression of Compton MSE at $Q_{\beta\beta}$



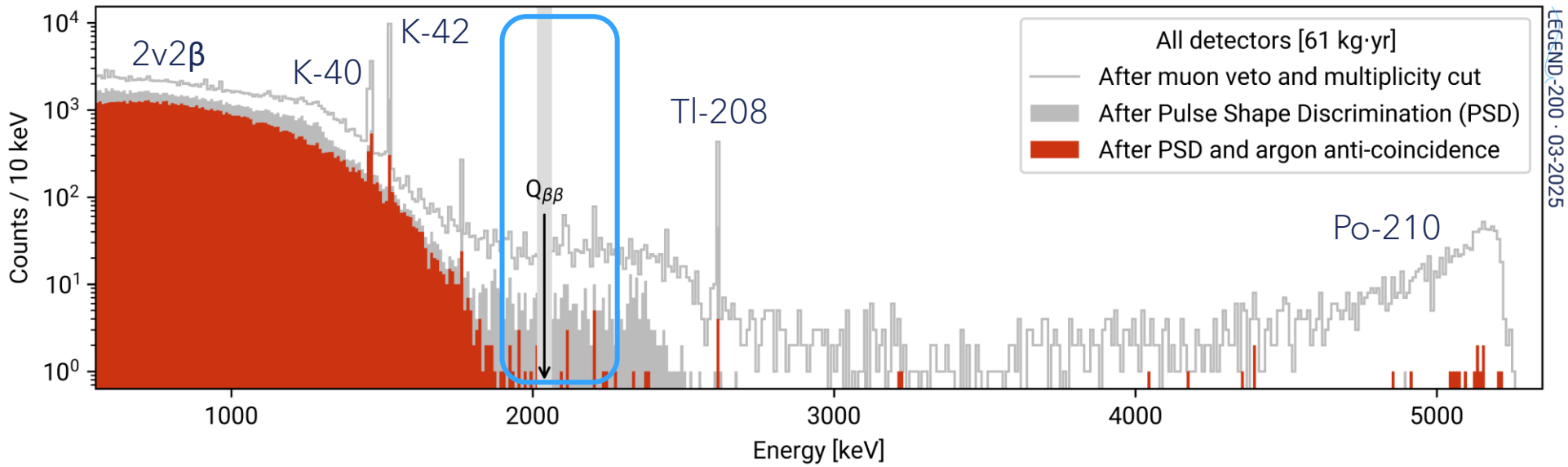
Energy Spectrum after PSD & LAr cut

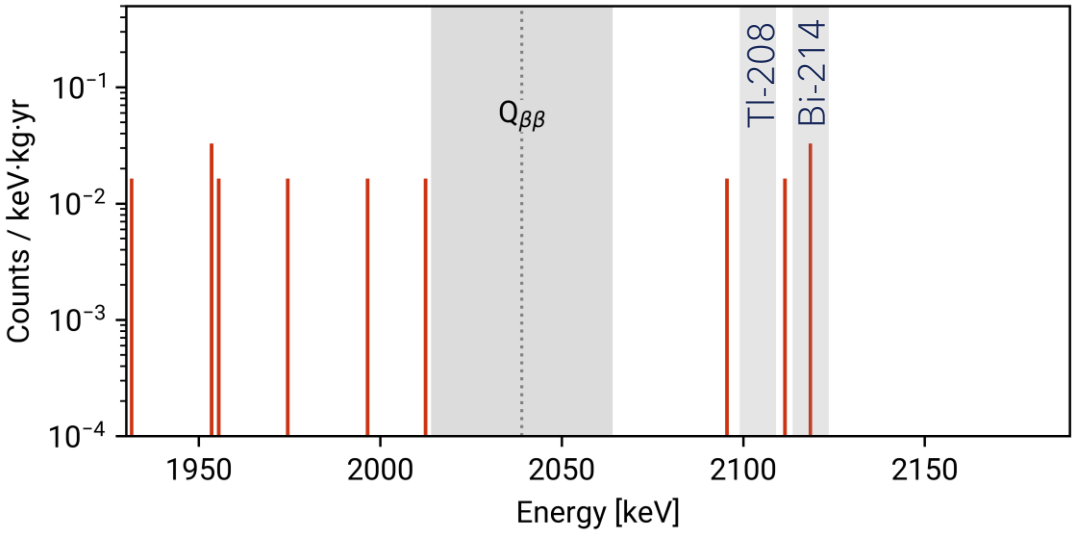


- Strong anti-correlation of PSD & LAr cuts
- Characterized via special runs: 1 p.e. per 10 keV
- LAr ββ decay signal acceptance of ~93%



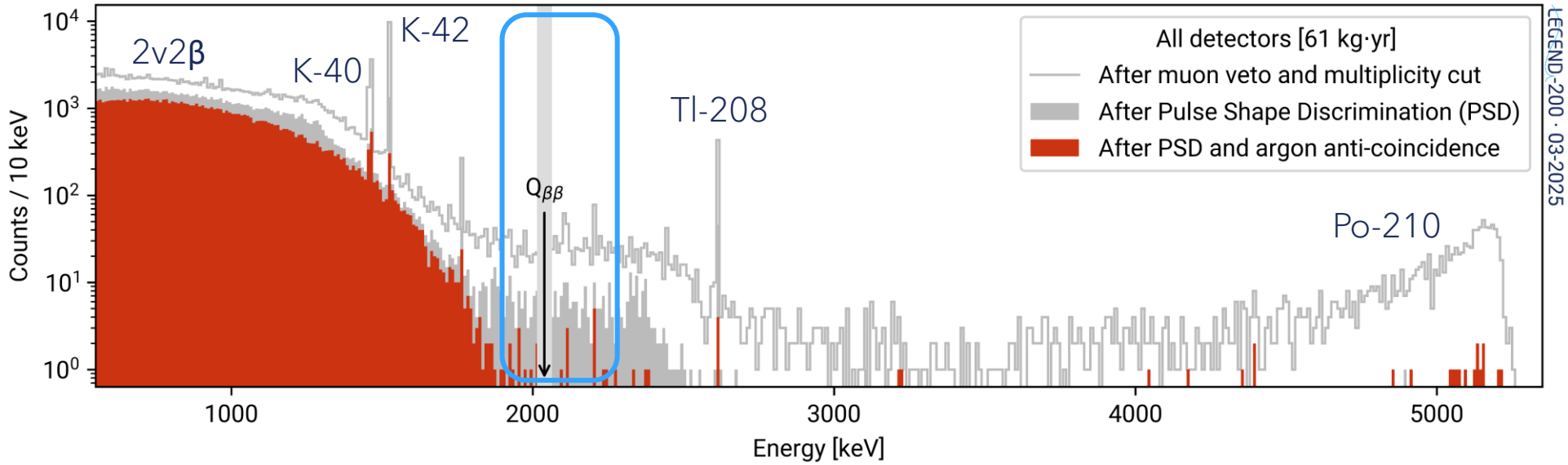
Energy Spectrum after PSD & LAr cut

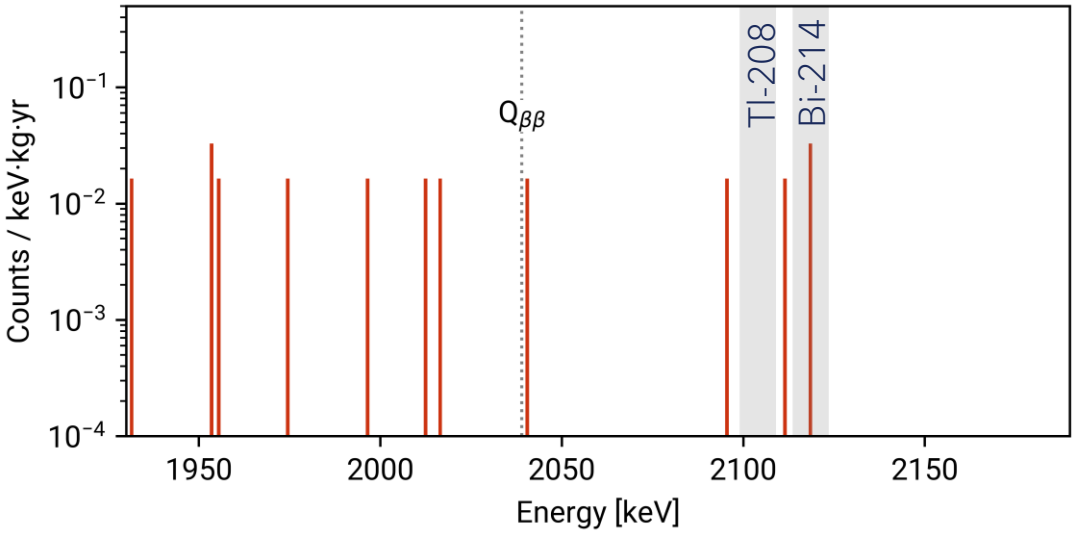




- Analysis window: 1930-2190 keV
- Excluded γ lines:
  - ^{208}Tl at (2104 ±5) keV
  - ^{214}Bi at (2119 ±5) keV
- 9 events before unblinding

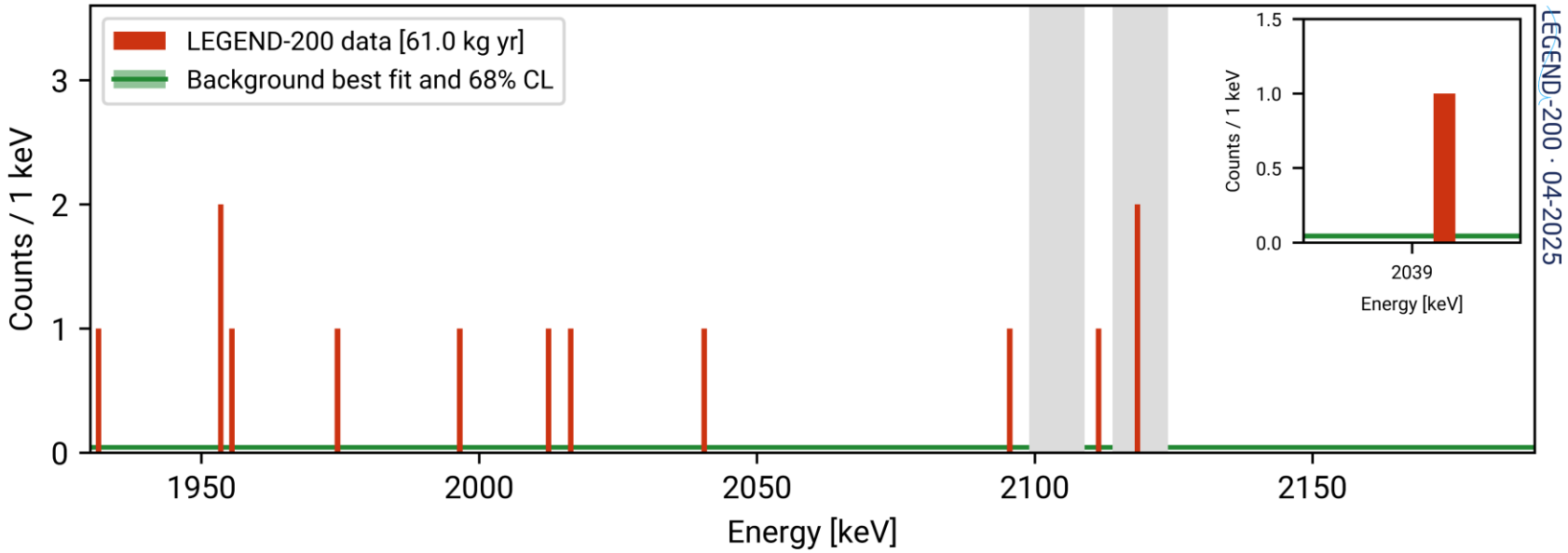
Energy Spectrum after PSD & LAr cut



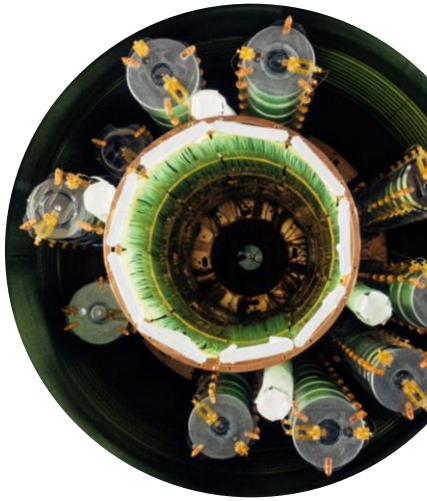


- Analysis window: 1930-2190 keV
- Excluded γ lines:
  - ^{208}Tl at (2104 ±5) keV
  - ^{214}Bi at (2119 ±5) keV
- 9 events before unblinding
- *+2 after unblinding*

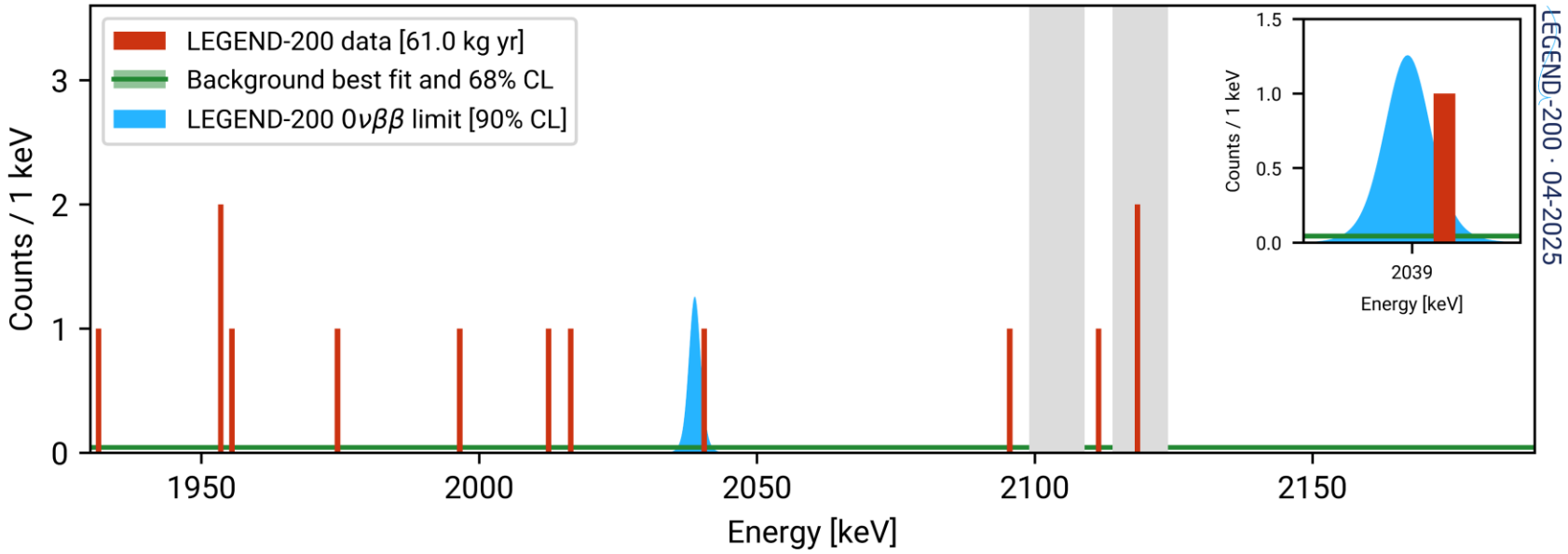
LEGEND-200 Background Index



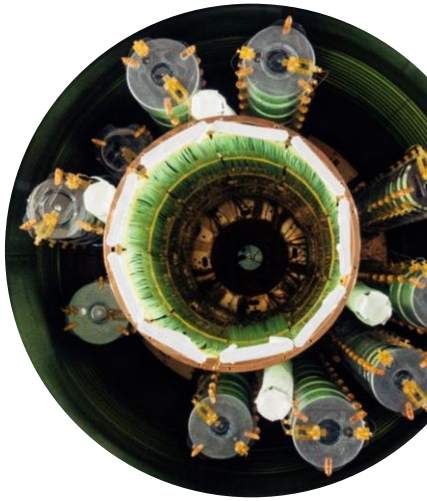
- 11 events surviving cuts
- 2 datasets
  - "golden" (48 kg·yr) - unblinded for Neutrino '24 [L. Pertoldi talk]
  - "silver" (13 kg·yr) - worse background rejection (mainly COAX)
- Background index
  - $\mathbf{BI_{golden} = 0.5^{+0.3}_{-0.2}\ cts/(keV \cdot ton \cdot yr)}$
  - $\mathbf{BI_{silver} = 1.3^{+0.8}_{-0.5}\ cts/(keV \cdot ton \cdot yr)}$



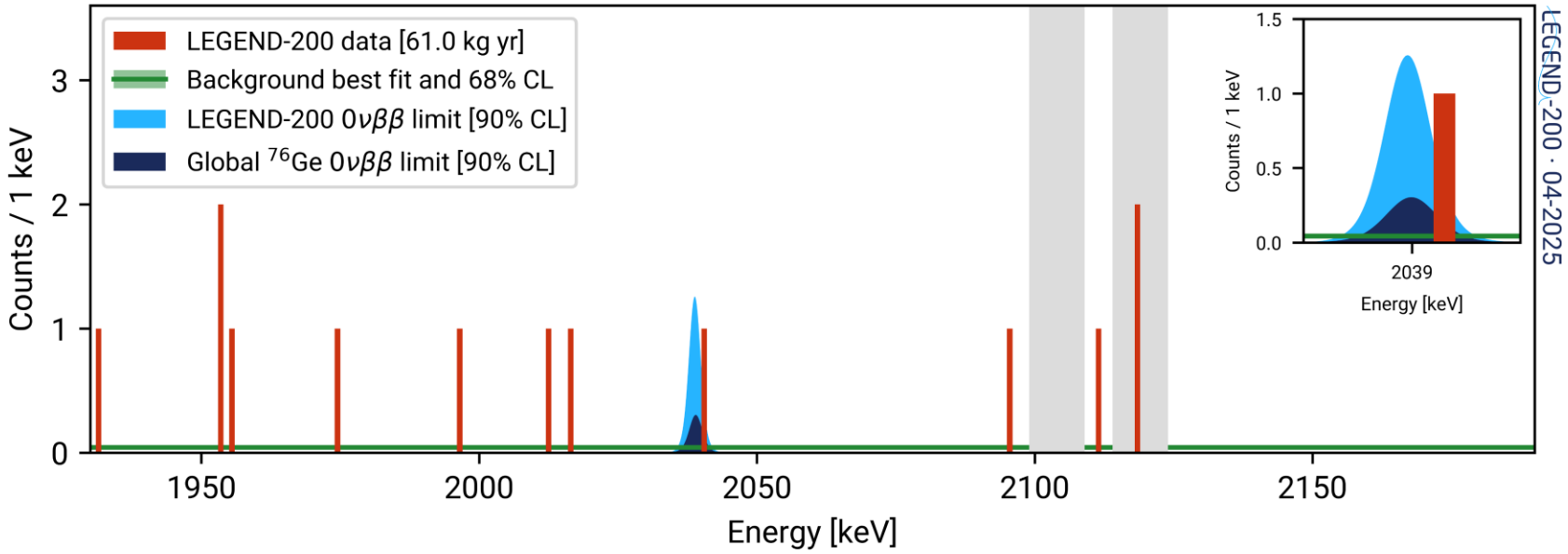
LEGEND-200 0ν2β Results



- Frequentist and Bayesian $0\nu\beta\beta$ analysis: no signal evidence
- Observed $T_{1/2} > 0.5 \times 10^{26}$ yr @ 90% CL/CI
- Sensitivity $T_{1/2} = 1.0 \times 10^{26}$ yr
- 1 event at 1.4σ from $Q_{\beta\beta}$ weakens the observed limit
- p-value (bkg. only) = 0.10 does not reach 3σ discovery



Global ^{76}Ge $0\nu2\beta$ Results



- Combined fit of GERDA(*) + MJD (**) + LEGEND-200
- Frequentist and Bayesian $0\nu\beta\beta$ analysis: no signal evidence
- Observed $T_{1/2} > 1.9 \times 10^{26}$ yr @ 90% CL/CI
- World-leading sensitivity $T_{1/2} = 2.8 \times 10^{26}$ yr
- *…paper [arXiv:2505:10440] submitted to PRL!*

(*) PRL 125 252502 (2020) (**) PRL 130 062501 (2023)

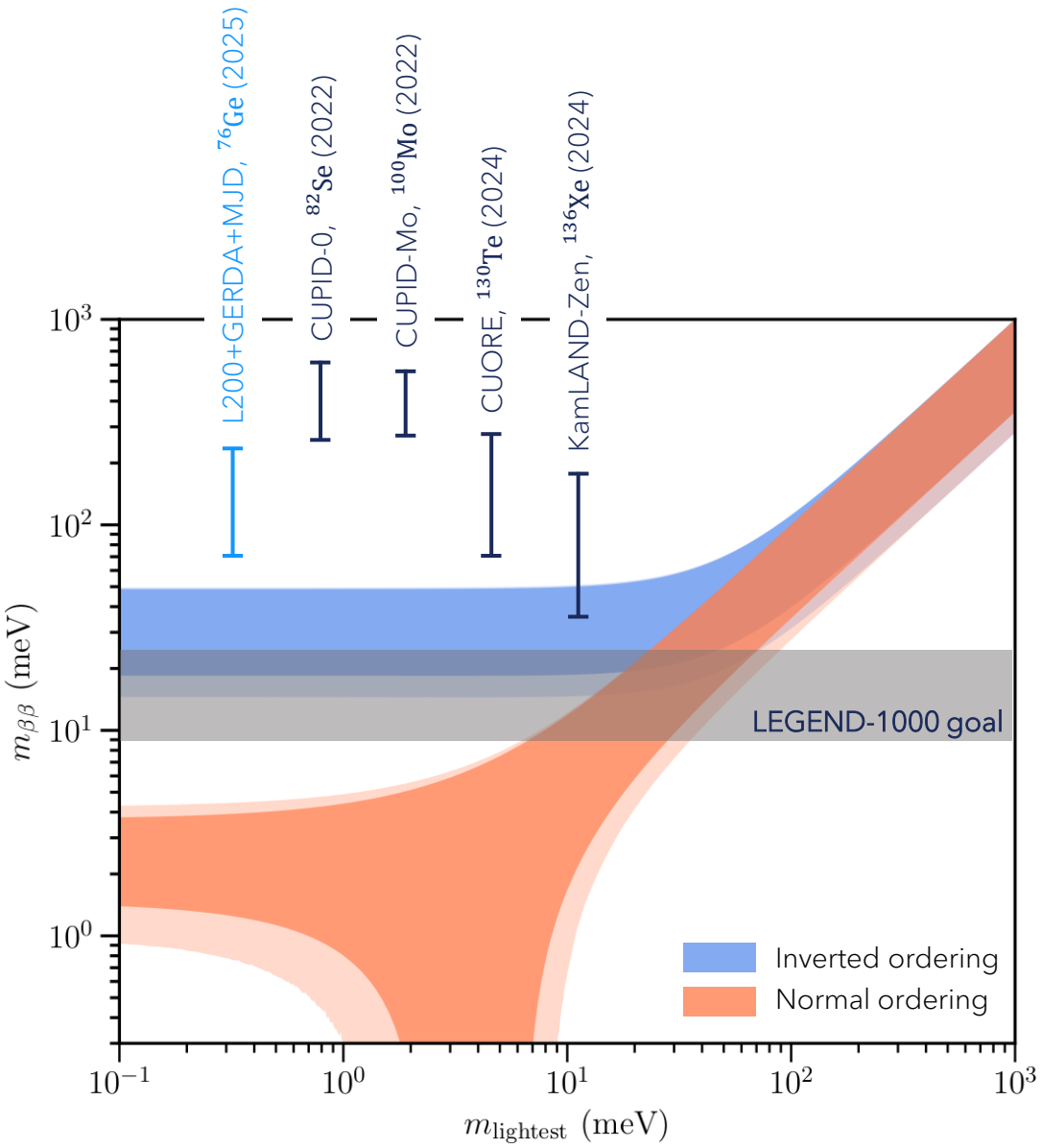
Limits on $m_{\beta\beta}$

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2 \rightarrow \left|\sum_i U_{ei}^2 m_i\right|$$

Nuclear Matrix Element

Effective Majorana neutrino mass

- Assumption: light Majorana neutrino exchange
- Range of phenomenological NME (^{76}Ge: 2.35 – 6.34)
  - $m_{\beta\beta}$<75-200 meV @ 90% CL
- Uncertainty-quantified NME (^{76}Ge: $2.6^{+1.28}_{-1.36}$)
  - Bayesian *ab-initio* calculation with quenching and short-range physics [Belley et al., PRL 132, 182502 (2024)]
  - $m_{\beta\beta}$<316 meV @ 90% CI
  - A new era of uncertainty-quantified NME - however, uncertainties remain significant



Summary

First LEGEND-200 results

- Stable operations and excellent performance with 142 kg of enr-Ge
- First LEGEND-200 $0\nu\beta\beta$ results based on 61 kg·yr
- Combined fit with GERDA and MJD set $T_{1/2} > 1.9 \times 10^{26}$ yr @ 90% CL/CI
- World-leading sensitivity of 2.8×10^{26} yr
- New effective Majorana neutrino mass $m_{\beta\beta}$<75-200 meV @ 90% CL or

  $m_{\beta\beta}$< 316 meV @ 90% CI using uncertainty-quantified NME

Future steps

- Restarted data taking in Spring 2025
- Deployment of new 35 kg in Summer 2025
- LEGEND-1000 preparations are underway at LNGS

Thank you for your attention!