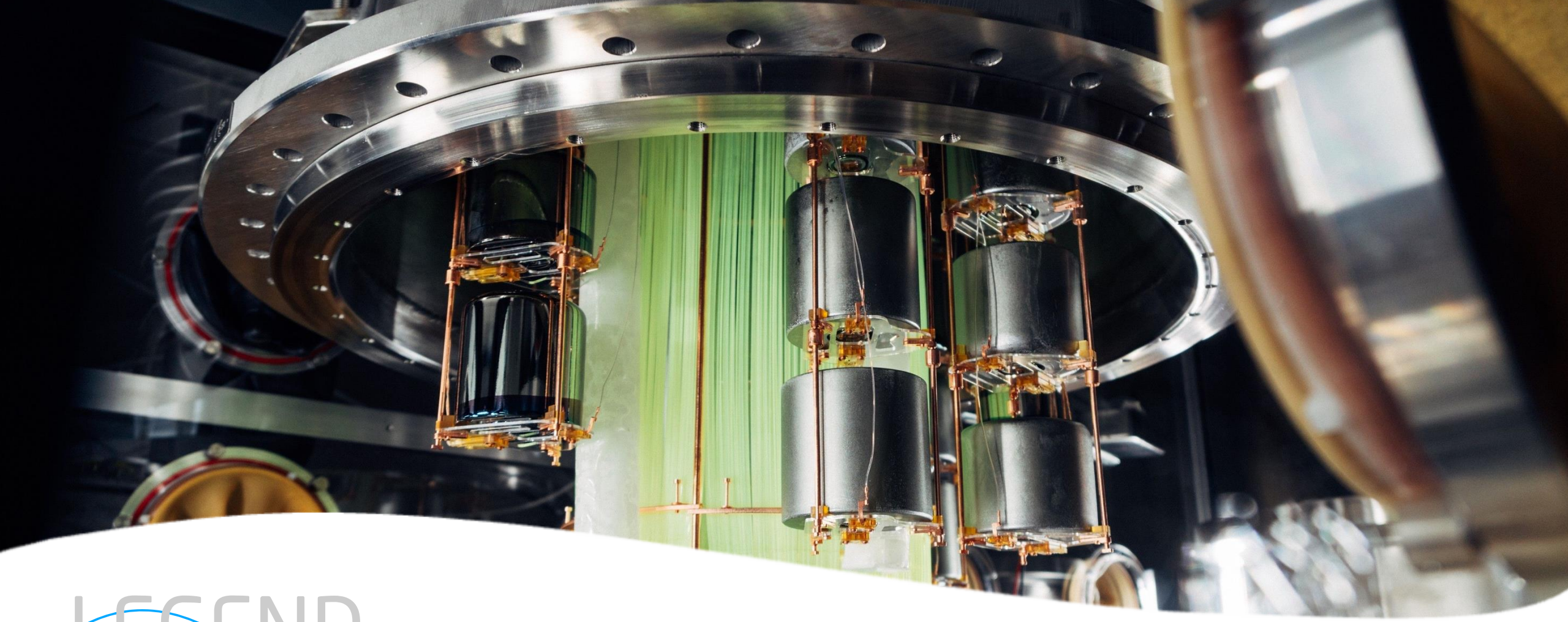
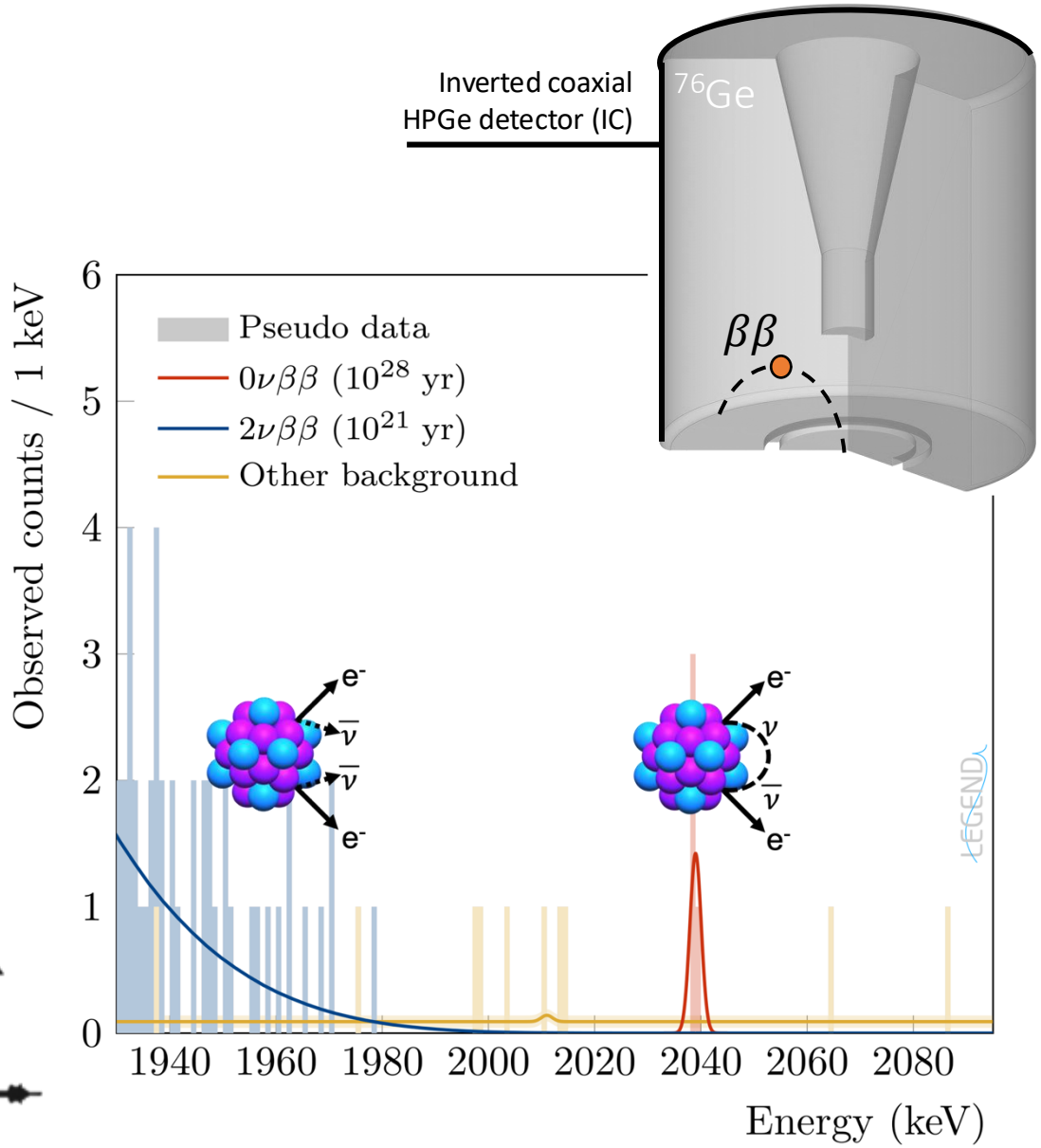


LEGEND

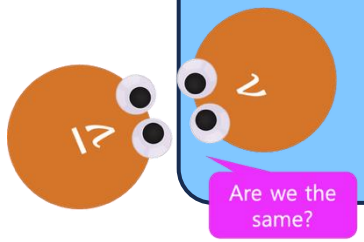
Searching for Neutrinoless Double Beta Decay
with Germanium Detectors

David Hervas Aguilar
<david.hervas@tum.de>

Neutrinoless double beta decay (0νββ) in ^{76}Ge



- 0νββ is only allowed if neutrinos are Majorana particles and have mass
- Violates lepton number conservation
- Observation would provide insight into
  - Matter-antimatter asymmetry
  - The nature of the neutrino
  - The absolute mass scale of the neutrino

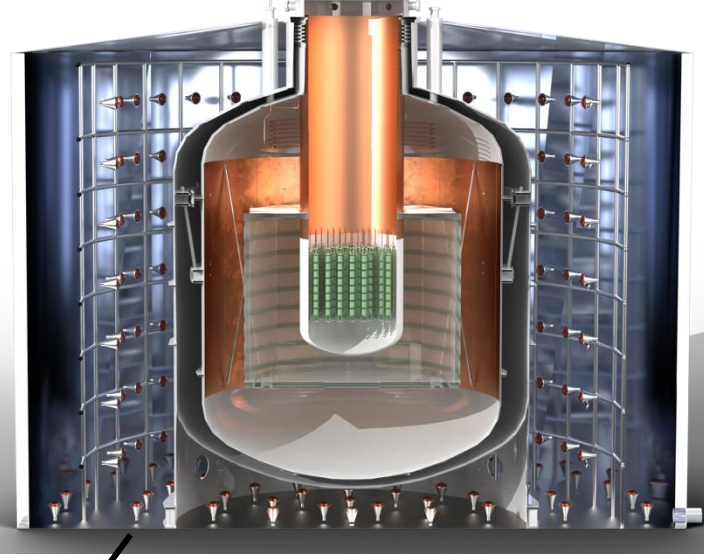


$^{76}Ge \rightarrow {}^{76}Se + 2e^{-}$ $Q_{\beta\beta}$ = 2039 keV

- Ge is routinely enriched up to 92%
- Source = detector → high detection efficiency
- High density → 0νββ single-site (energy deposited within ~ 1 mm)
- Lowest background and best energy resolution of all 0νββ experiments

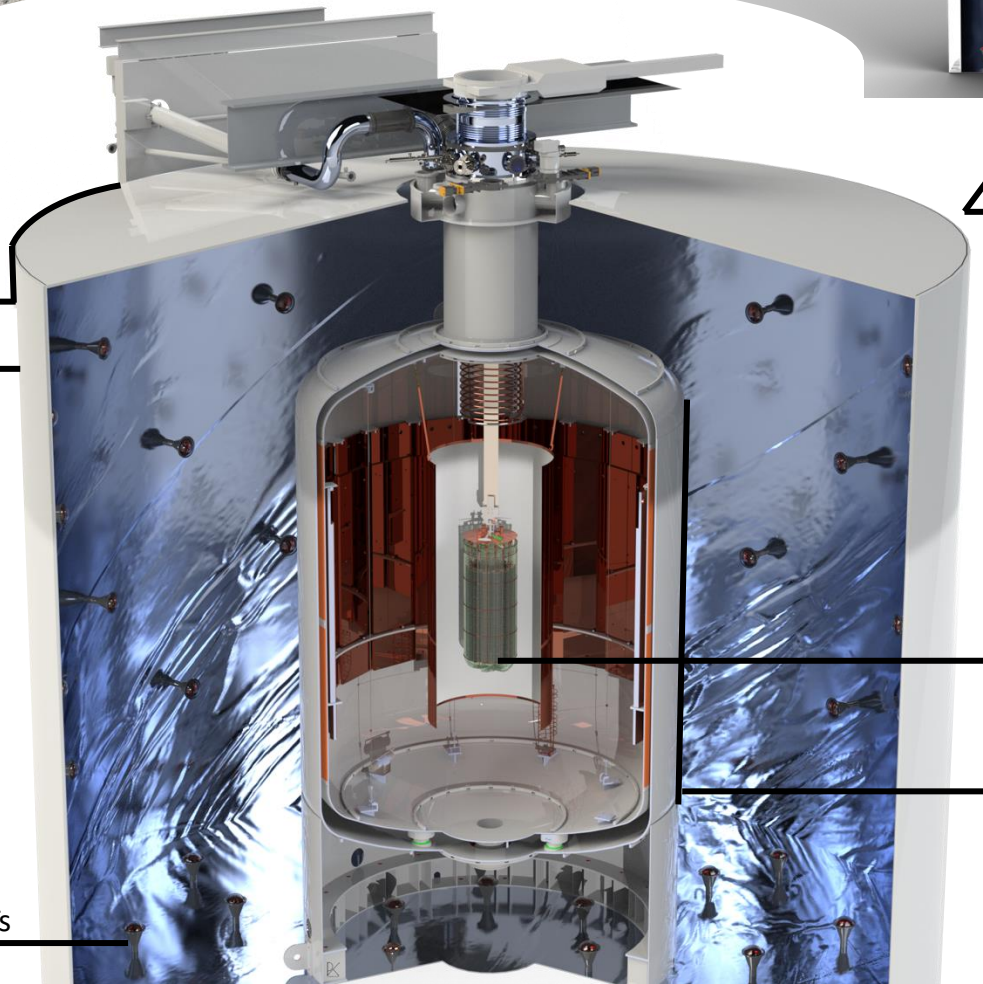
The LEGEND project *A phased ^{76}Ge experimental program using existing resources*





LEGEND 200

- Up to 200 kg ^{76}Ge in modified existing GERDA infrastructure at Gran Sasso
- Match current best energy resolution: 2.5 keV FWHM
- Reduce current background by a factor of 2-3: 0.2 cts/(keV ton yr)
- $T_{1/2}$ discovery sensitivity (3σ): $1x10^{27}$ yr
- Design exposure goal: 1 ton yr
- Taking physics data since 2023



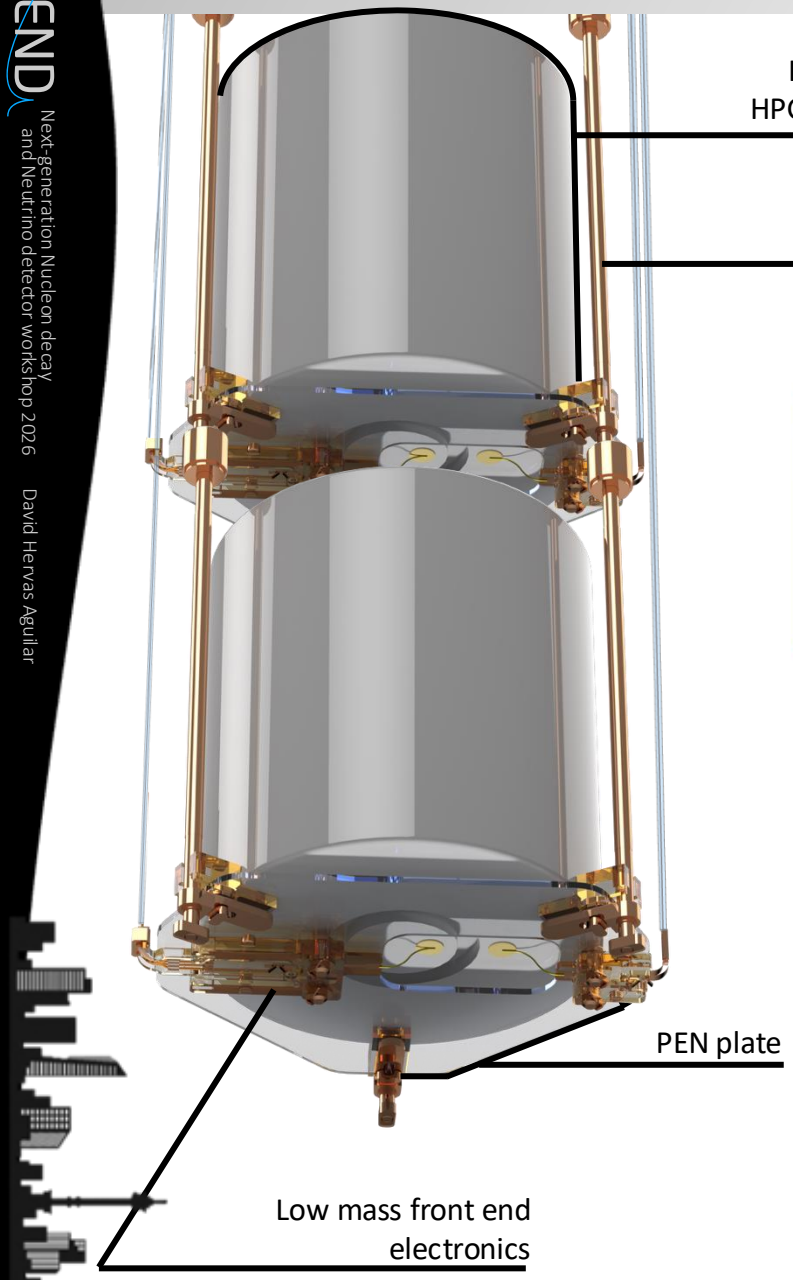
LEGEND 1000

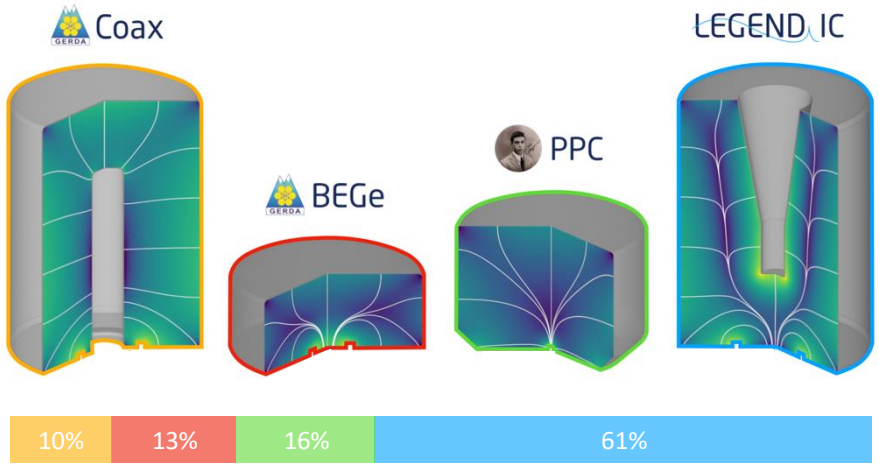
arXiv 2107.11462

- Up to 1000 kg ^{76}Ge, payloads deployed in stages. 10 ton yr exposure
- Background goal (20x lower)

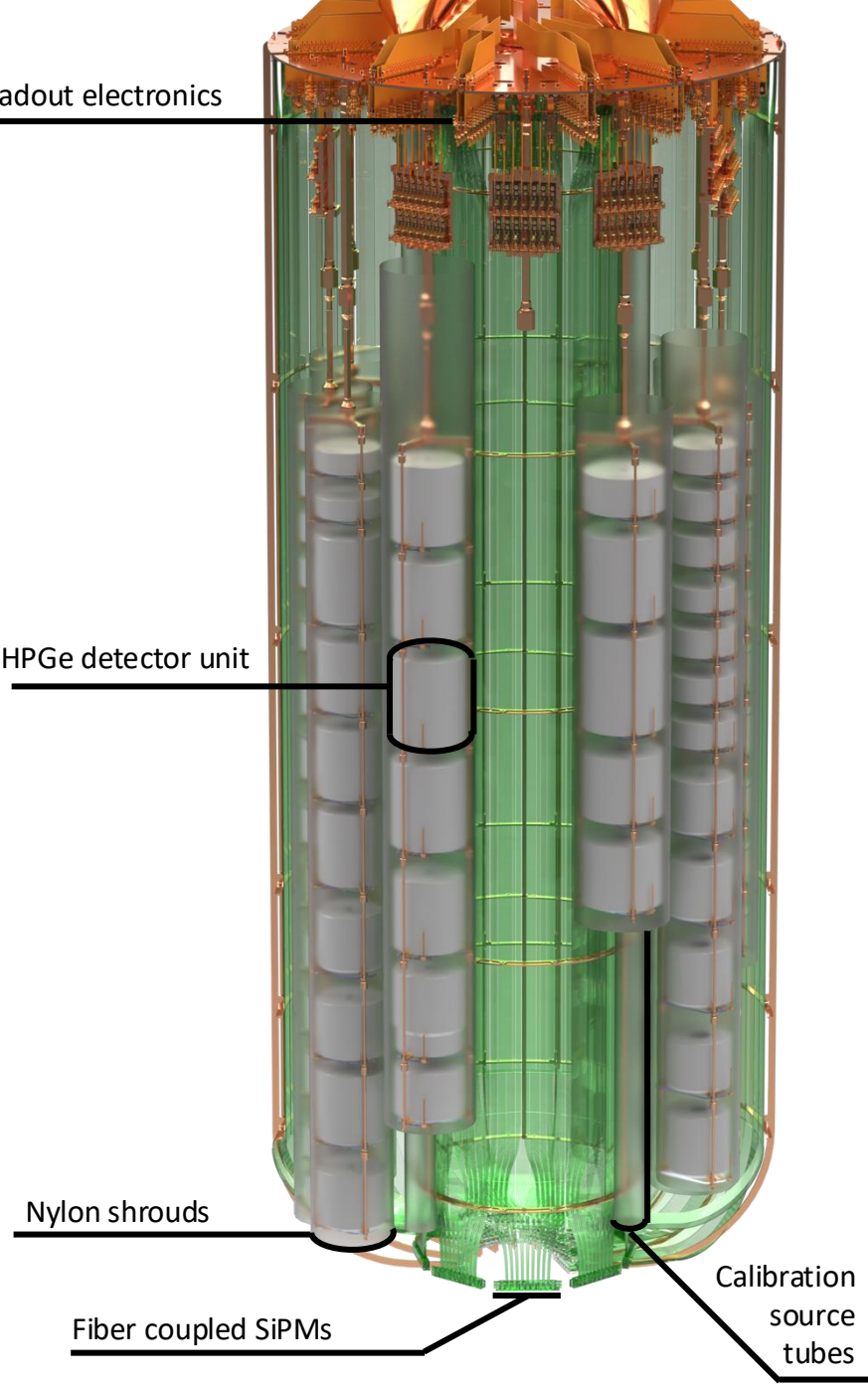
  < 0.01 cts/(keV ton yr)
- $T_{1/2}$ discovery sensitivity (3σ): $1.3x10^{28}$ yr
- Fully cover the $m_{\beta\beta}$ inverted ordering region

The first LEGEND deployment



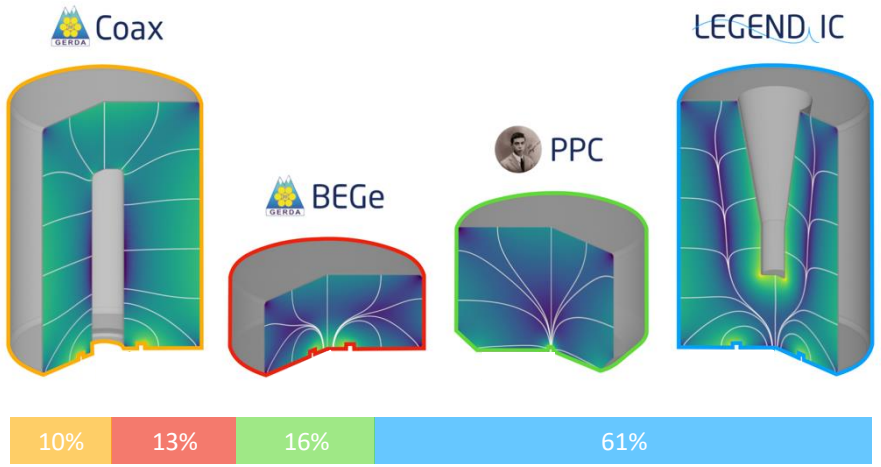


- Installed HPGe detectors with 4 different geometries in 2022 totaling 142 kg (130 kg operational)
- Used existing resources from GERDA and the MAJORANA DEMONSTRATOR including GERDA Coax and BEGe detectors and MAJORANA PPCs + new ICs

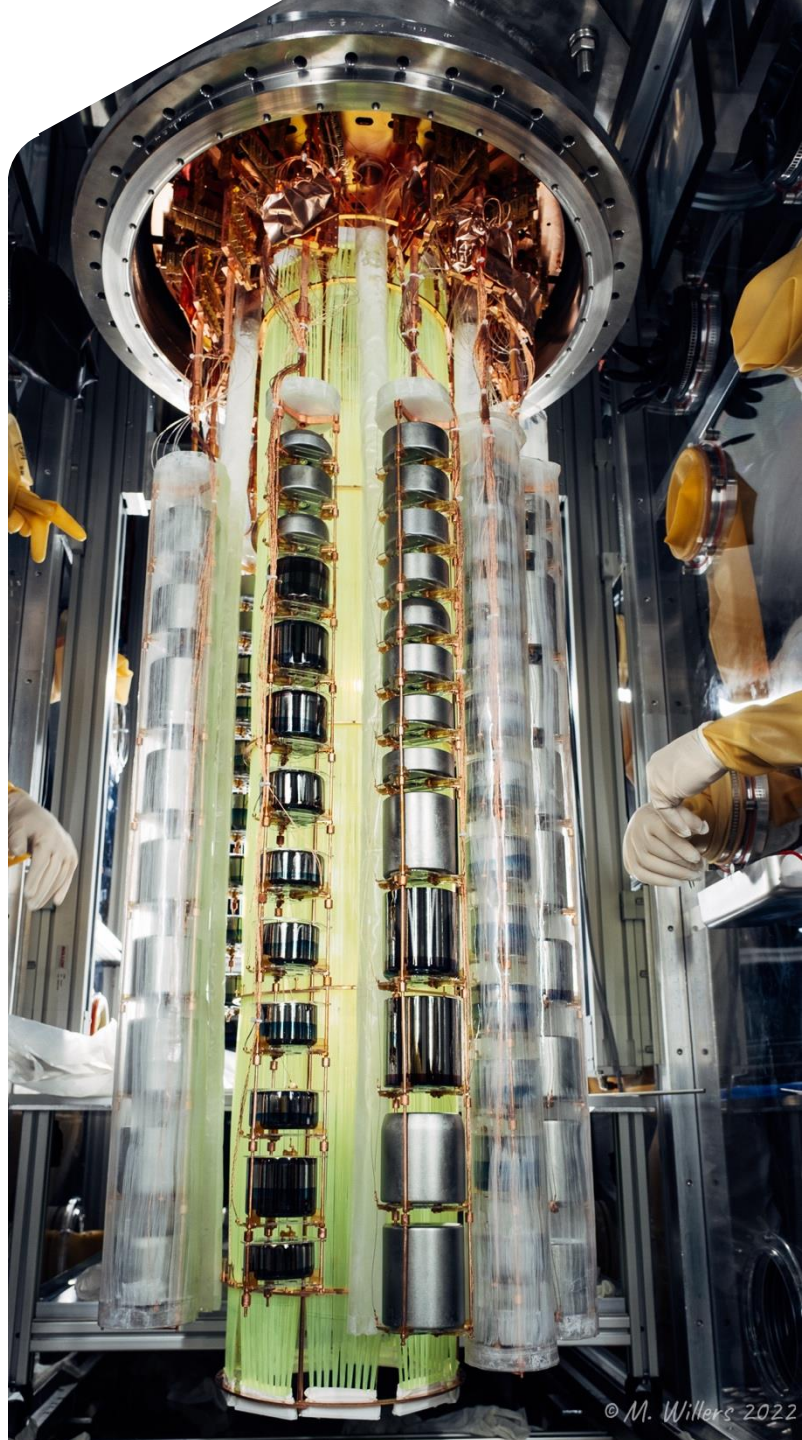


The first LEGEND deployment



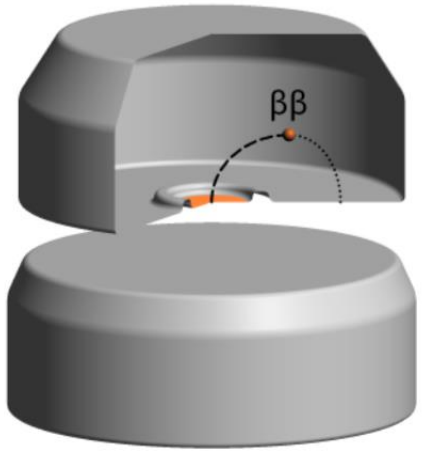


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Background mitigation strategy

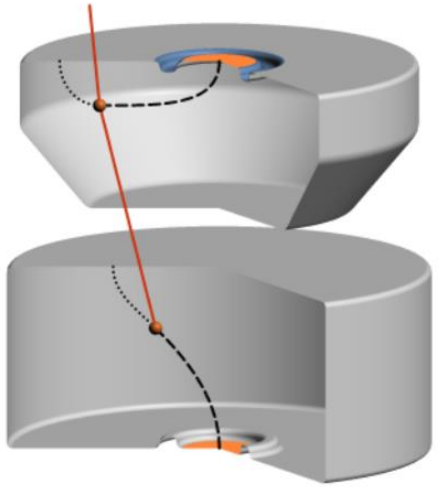
Point-like energy deposition



Signal-like

ββ decay deposits energy within 1mm: a point- like interaction. The 2νββ background is irreducible but negligible due to the superior energy resolution of HPGe detectors.

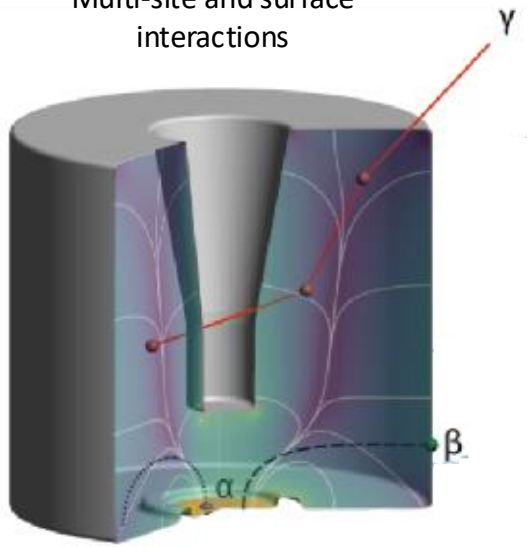
Multiple detectors hit in coincidence



Multiplicity cut

Coincident energy depositions are likely caused by Compton scattered gammas: a background signal.

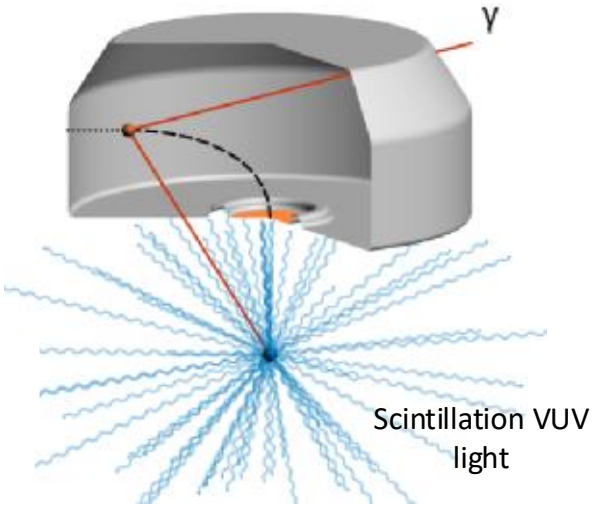
Multi-site and surface interactions



Pulse-shape discrimination

Multi-site (Compton scatters contained within one detector) and surface interaction induce signals with district shapes.

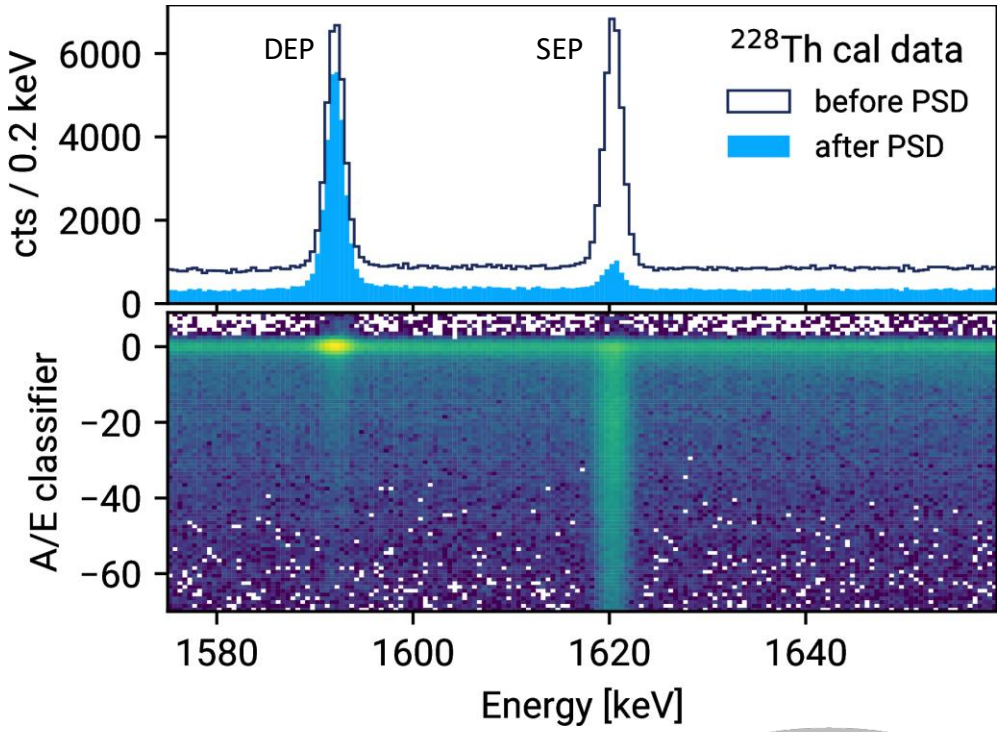
Coincident light



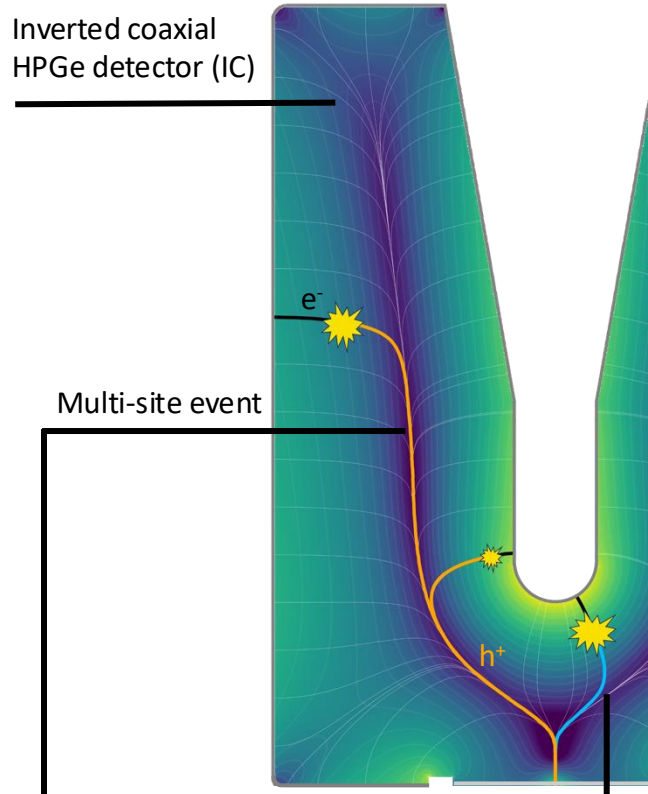
Argon anti-coincidence

Liquid argon acts as a cooling medium, a passive shield and an active medium. The argon and light readout system effectively instrument most of the volume surrounding the HPGe detectors.

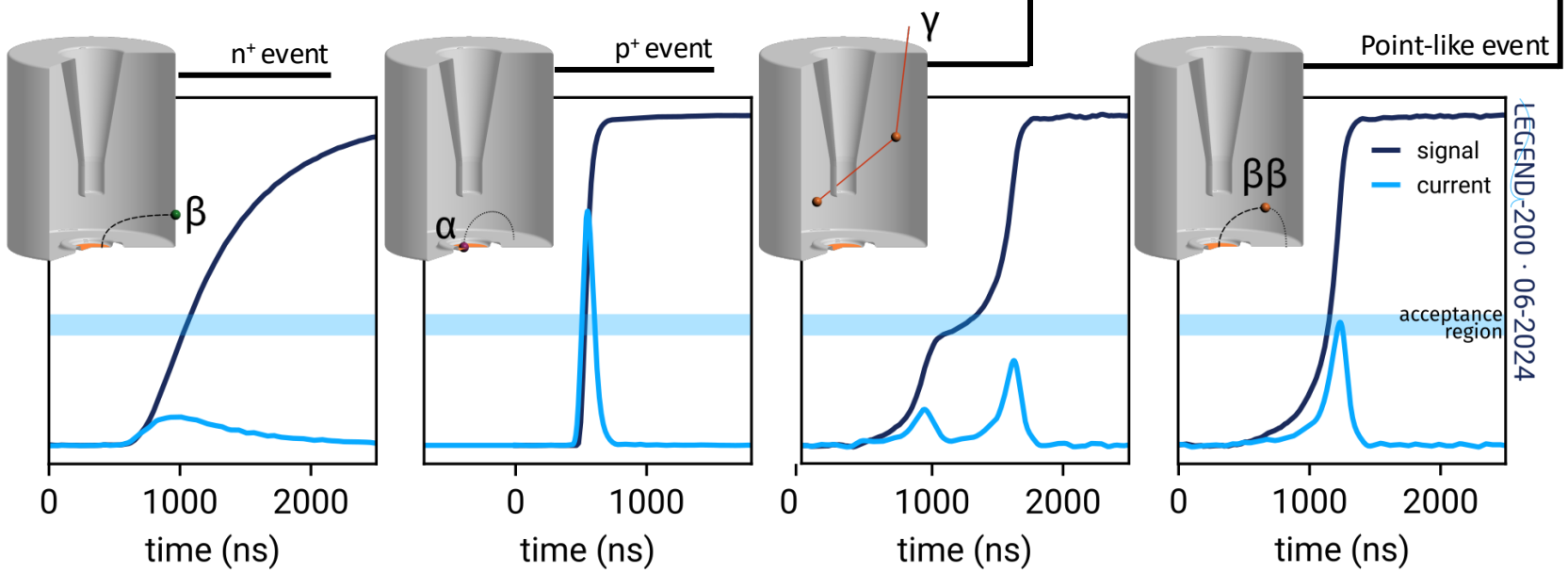
Pulse-shape discrimination (PSD)



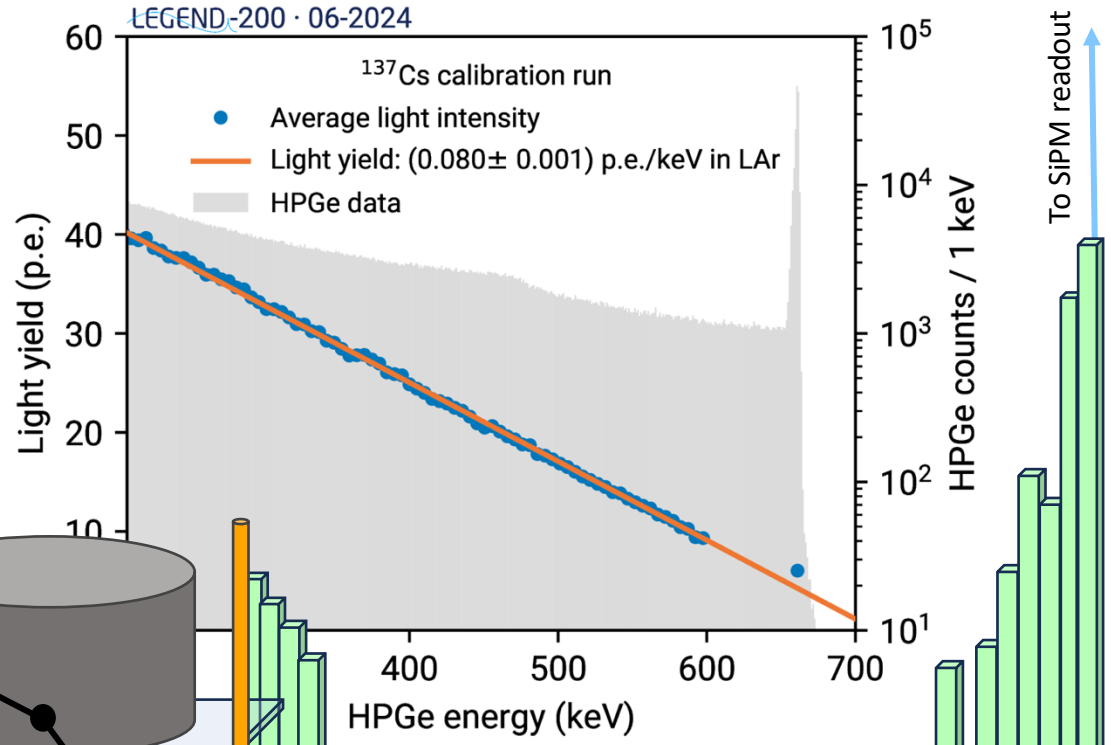
- The energy-normalized maximum current amplitude A is a powerful pulse-shape classifier (A/E)
- A/E is calibrated using double escape peak (DEP) events a proxy signal-like population
- Single escape peak (SEP) events can be used to evaluate multi-site event suppression

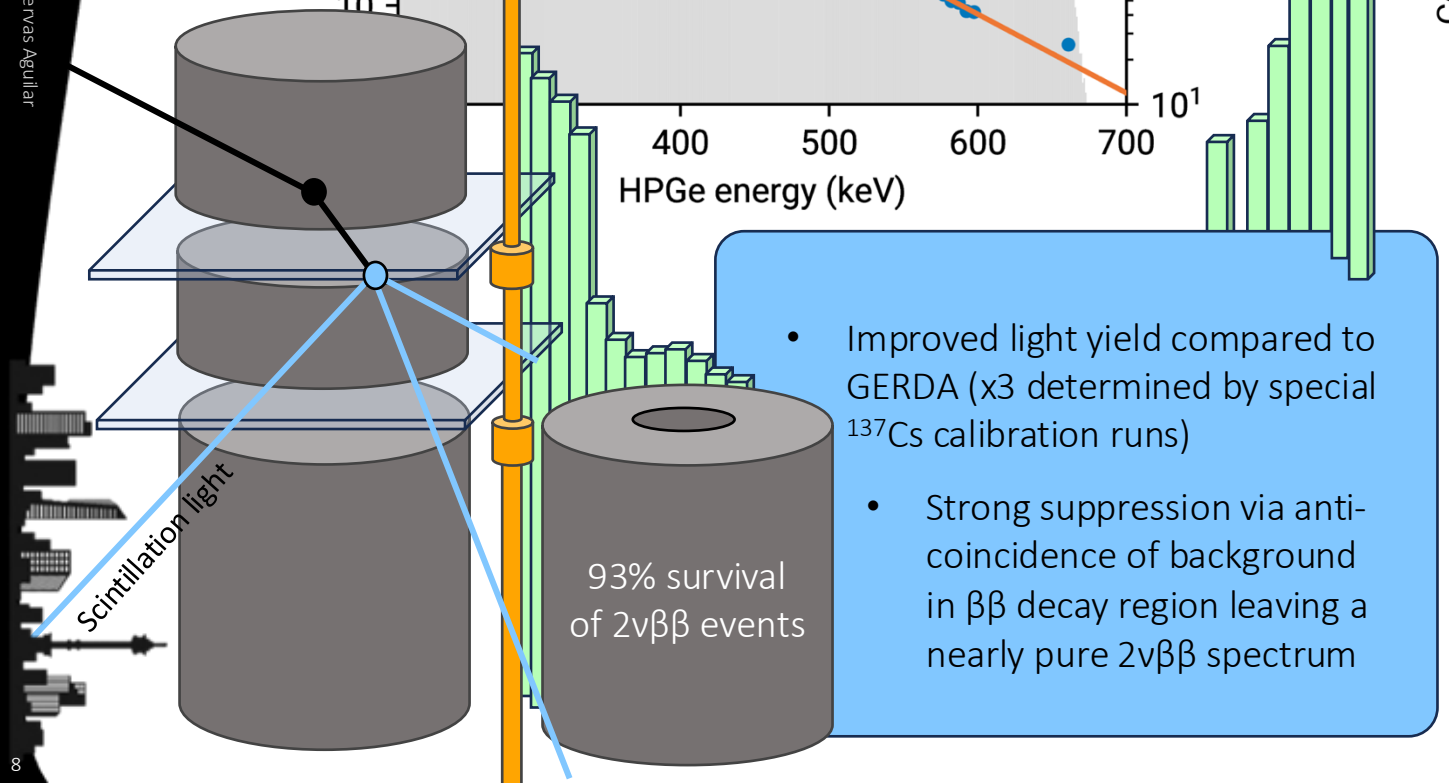


- Other pulse-shape discriminators used:
  - Artificial neural network for Coax detectors
  - Late Charge (LQ) for detectors with large passivated surfaces

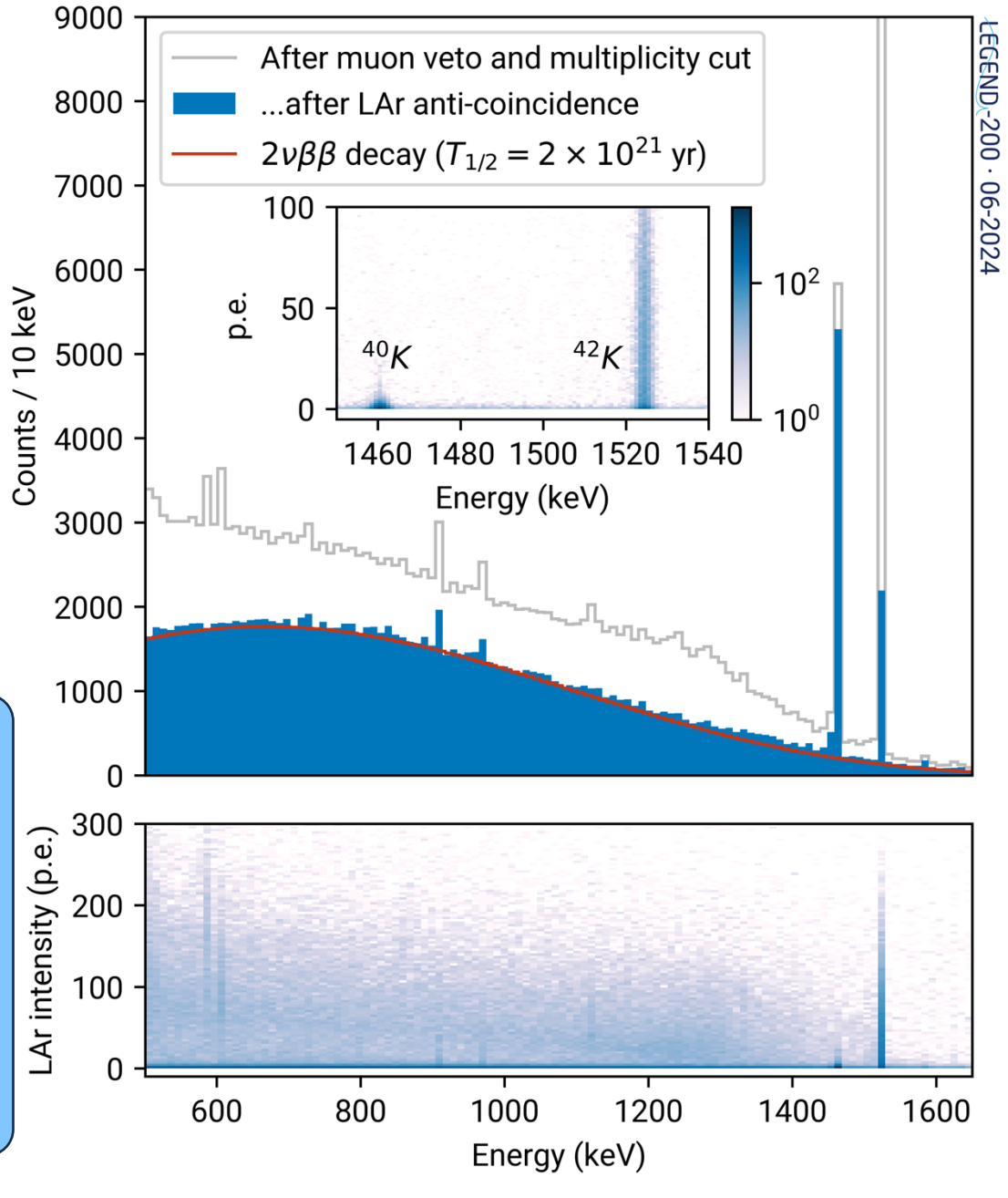


Argon instrumentation





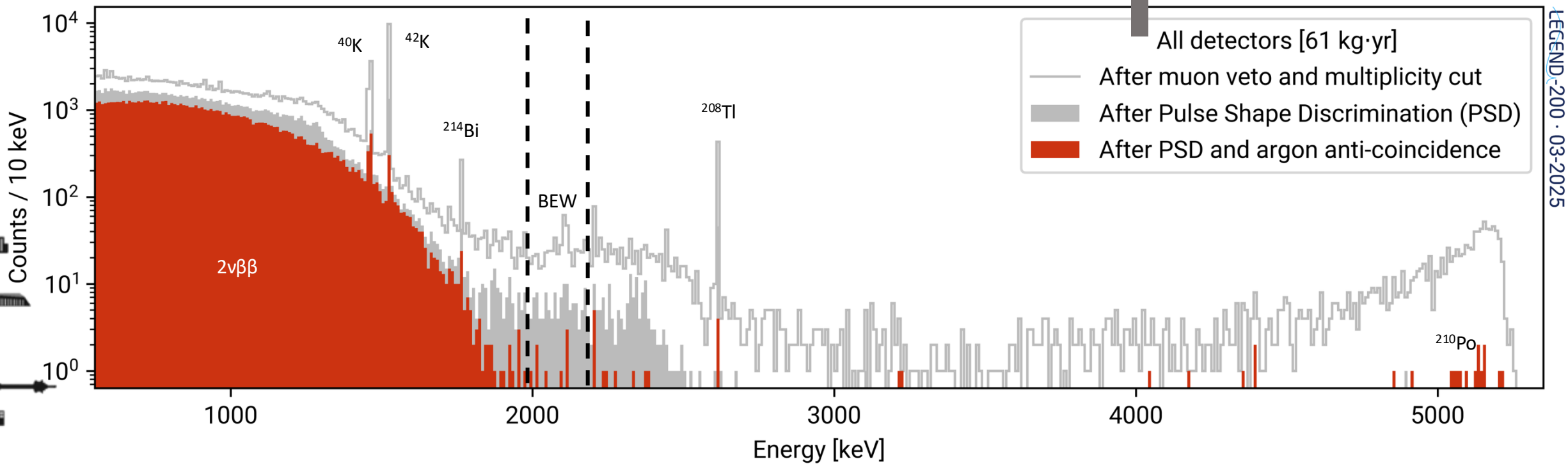
- Improved light yield compared to GERDA (x3 determined by special ^{137}Cs calibration runs)
- Strong suppression via anti-coincidence of background in ββ decay region leaving a nearly pure 2νββ spectrum



2025 results - Phys. Rev. Lett. 136, 022701 (2026)

- Background before cuts is higher than predicted by assay-based background model. Dominated by ^{208}Tl Compton continuum.
- After all cuts nearly pure 2νββ spectrum remains, with an expected flat background close to $Q_{\beta\beta}$
- Background index is compatible with GERDA's world leading result

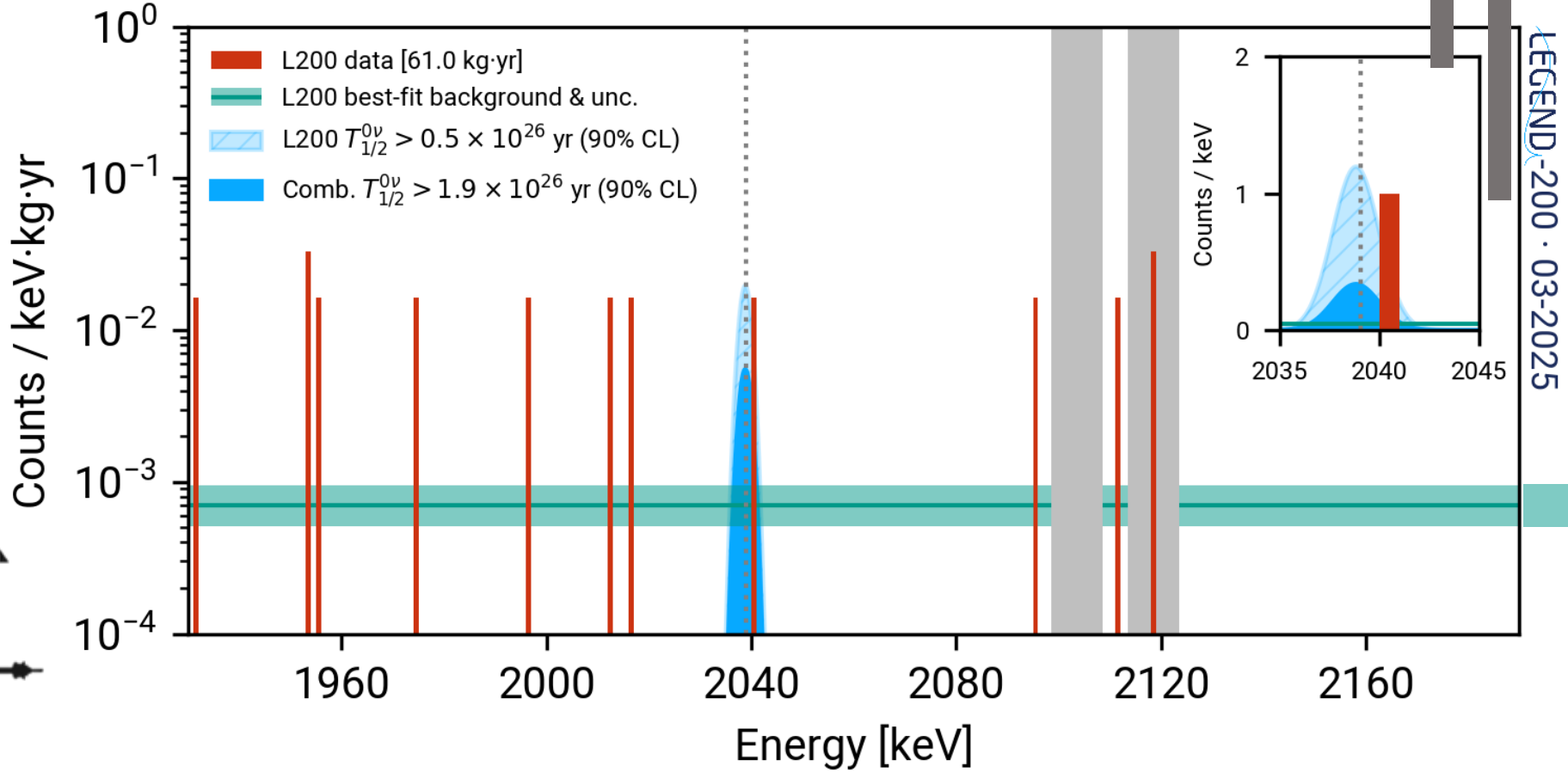
- In background estimation window (BEW) 11 counts remain after all counts
  - BEW = 1930 – 2190 keV excluding ^{208}Tl and ^{214}Bi gamma lines
    - **Background index**: $0.5^{+0.3}_{-0.2}$ cts/ (keV ton yr) in the golden dataset (48/61 kg yr)



2025 results - Phys. Rev. Lett. 136, 022701 (2026)

GERDA + MAJORANA + LEGEND 200 combined fit

Frequentist 90%	Observed	Sensitivity
$T_{1/2}^{0\nu} >$	1.9 x 10^{26} yr	2.8 x 10^{26} yr



Majorana effective mass

Limits (90% CL) assume light neutrino exchange mechanism

Using range of $M_{0\nu}$ for ^{76}Ge: **2.35 - 6.34**

$m_{\beta\beta}$ < 75 - 200 meV

Ab-initio uncertainty quantified $M_{0\nu}$: $2.6^{+1.28}_{-1.36}$ PRL 132, 182502 (2024)

$m_{\beta\beta}$ < 320 meV

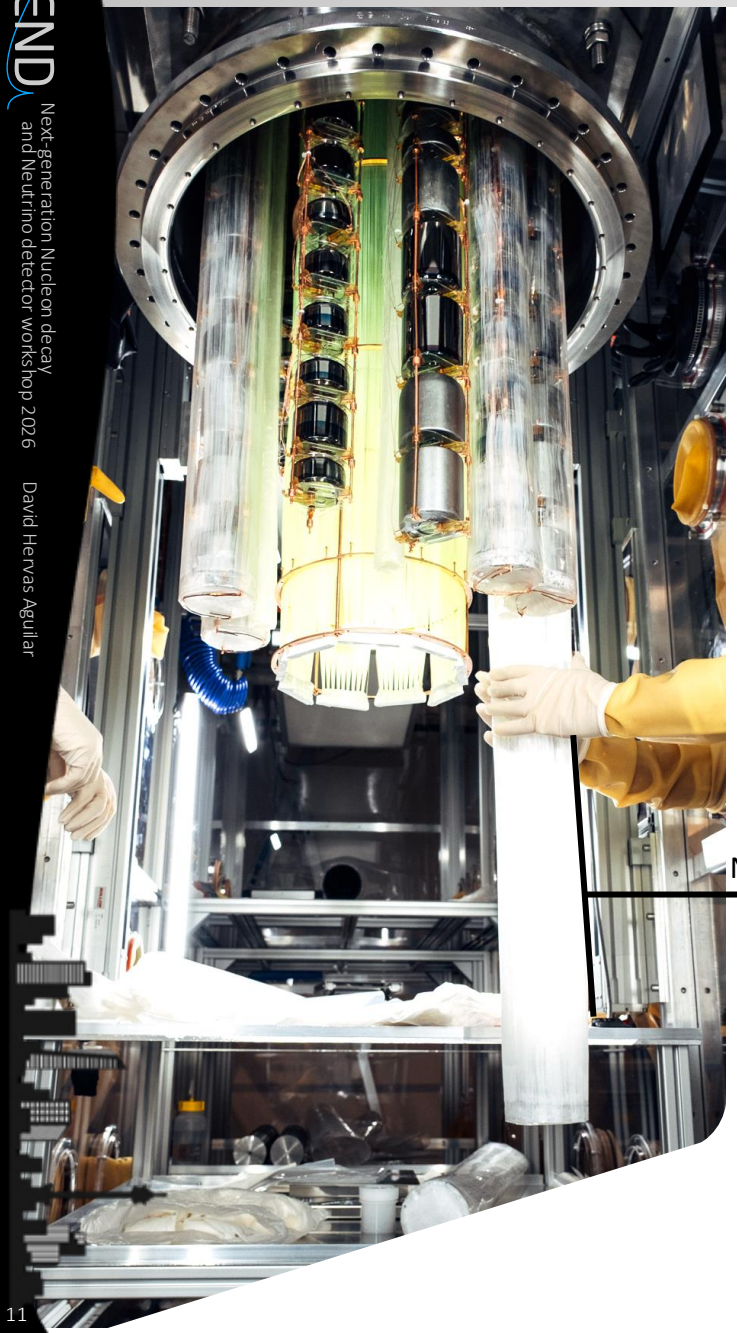
1 event at 1.4σ from $Q_{\beta\beta}$ worsens limit

Combined fit results in world leading sensitivity

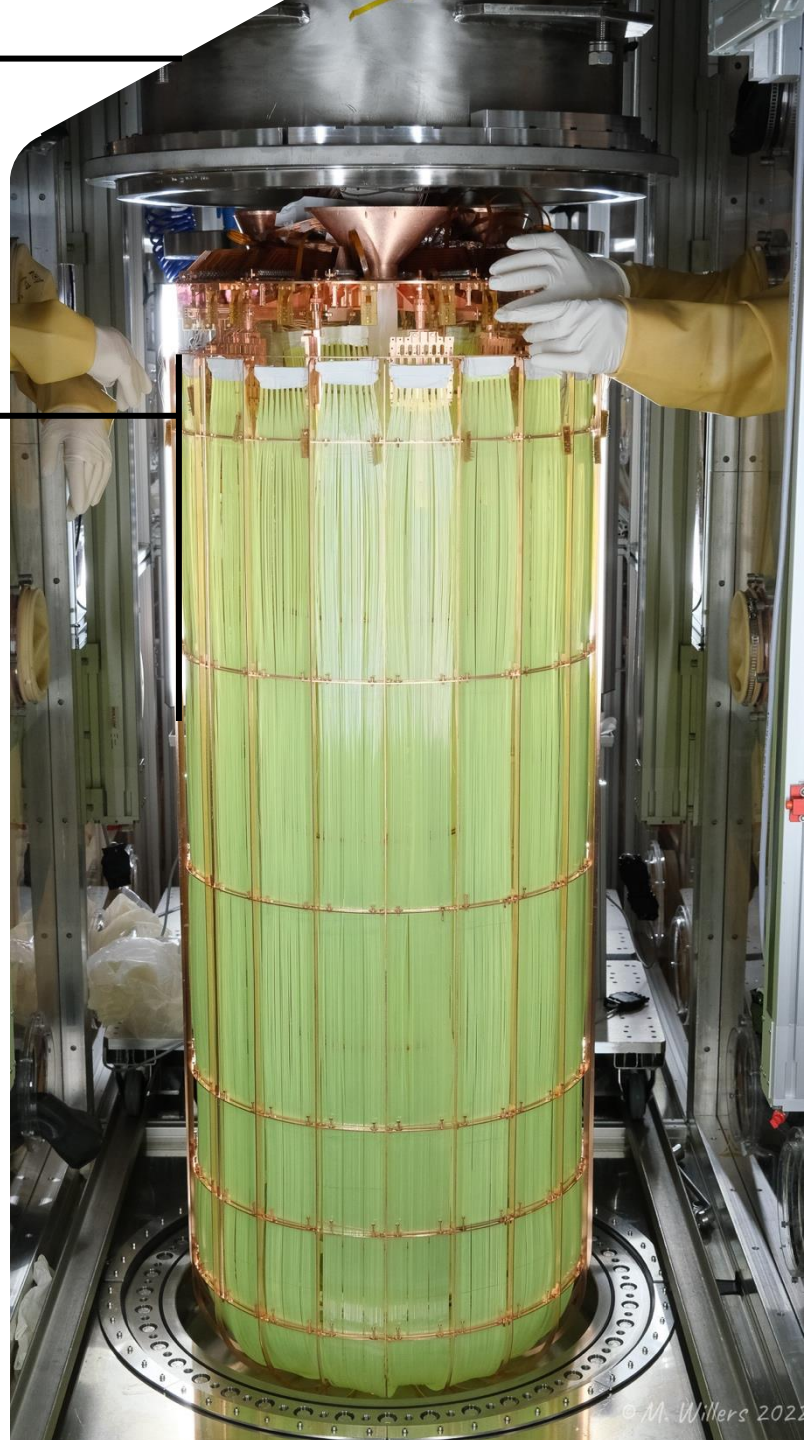
In-situ assay of array

Physics data taking

2024 2025



Two special background characterization runs



Outer barrel removed (10.2 kg yr)

- Compatible ^{208}Tl gamma line rate, reduction of ^{214}Bi
- Suggests insufficient Cu cleaning
- Confirmed via assay, significant etching needed

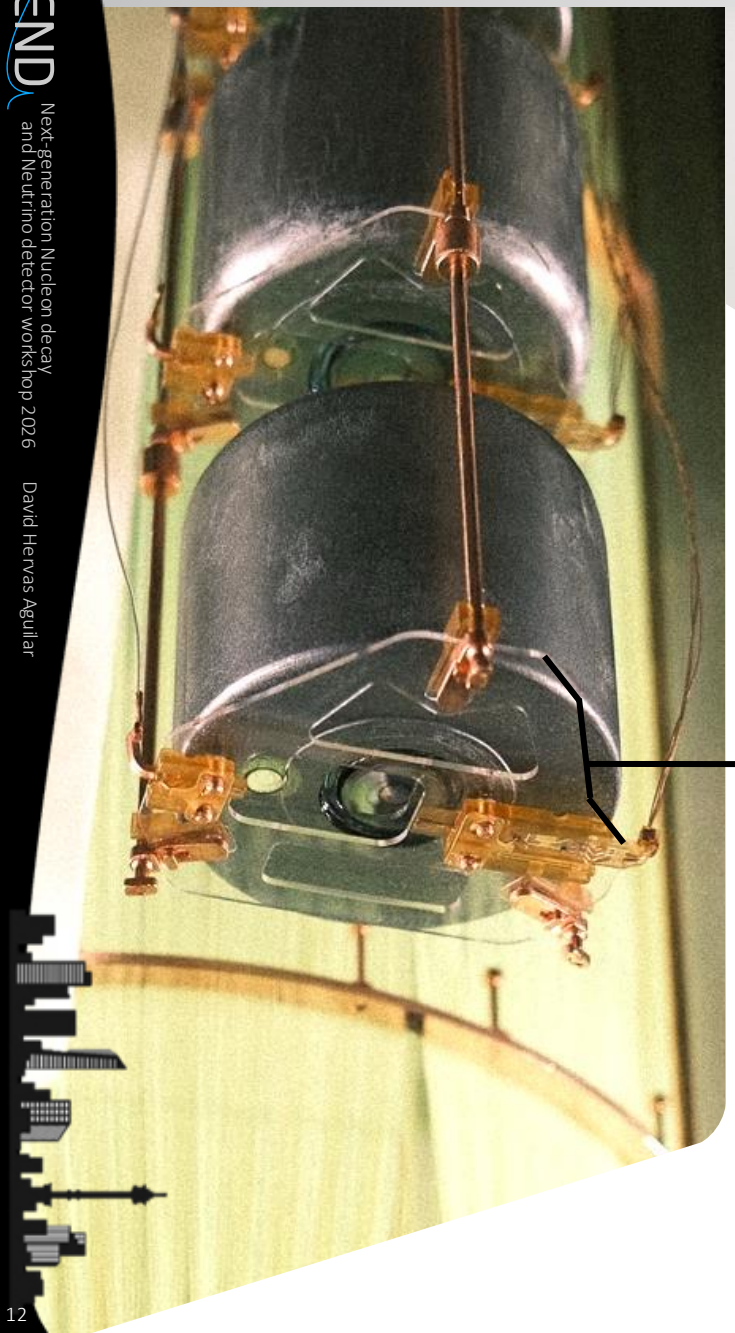
Nylon mini-shrouds removed (5.9 kg yr)

- Compatible ^{208}Tl/^{214}Bi rates but large uncertainties due to:
  - Low statistics
  - Elevated ^{42}K background (expected)
- Can be used to study ^{42}K background

Forensics campaign

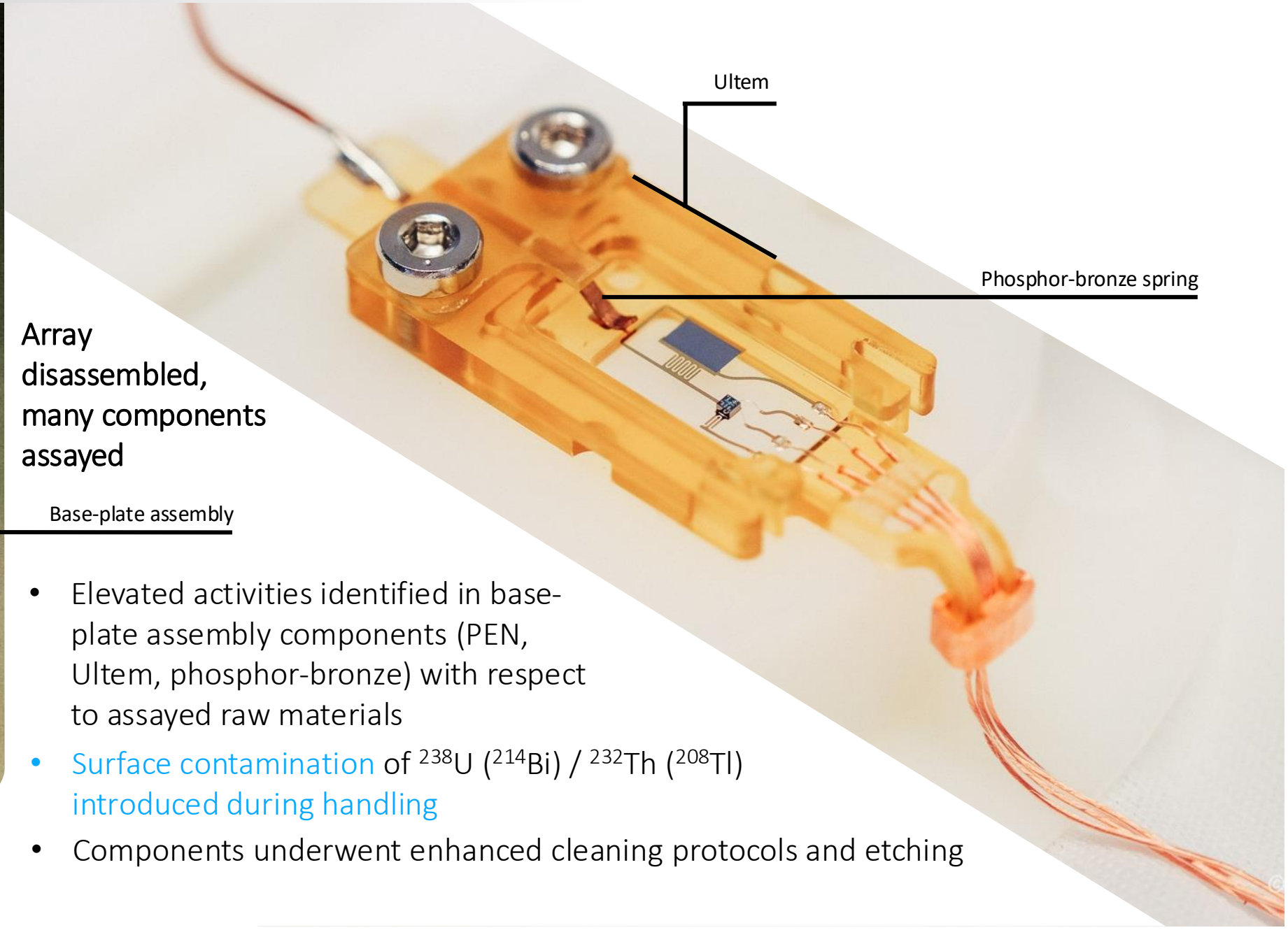
Physics data taking — Maintenance

2024 — 2025 — 2026 — 2027



Array disassembled, many components assayed

Base-plate assembly

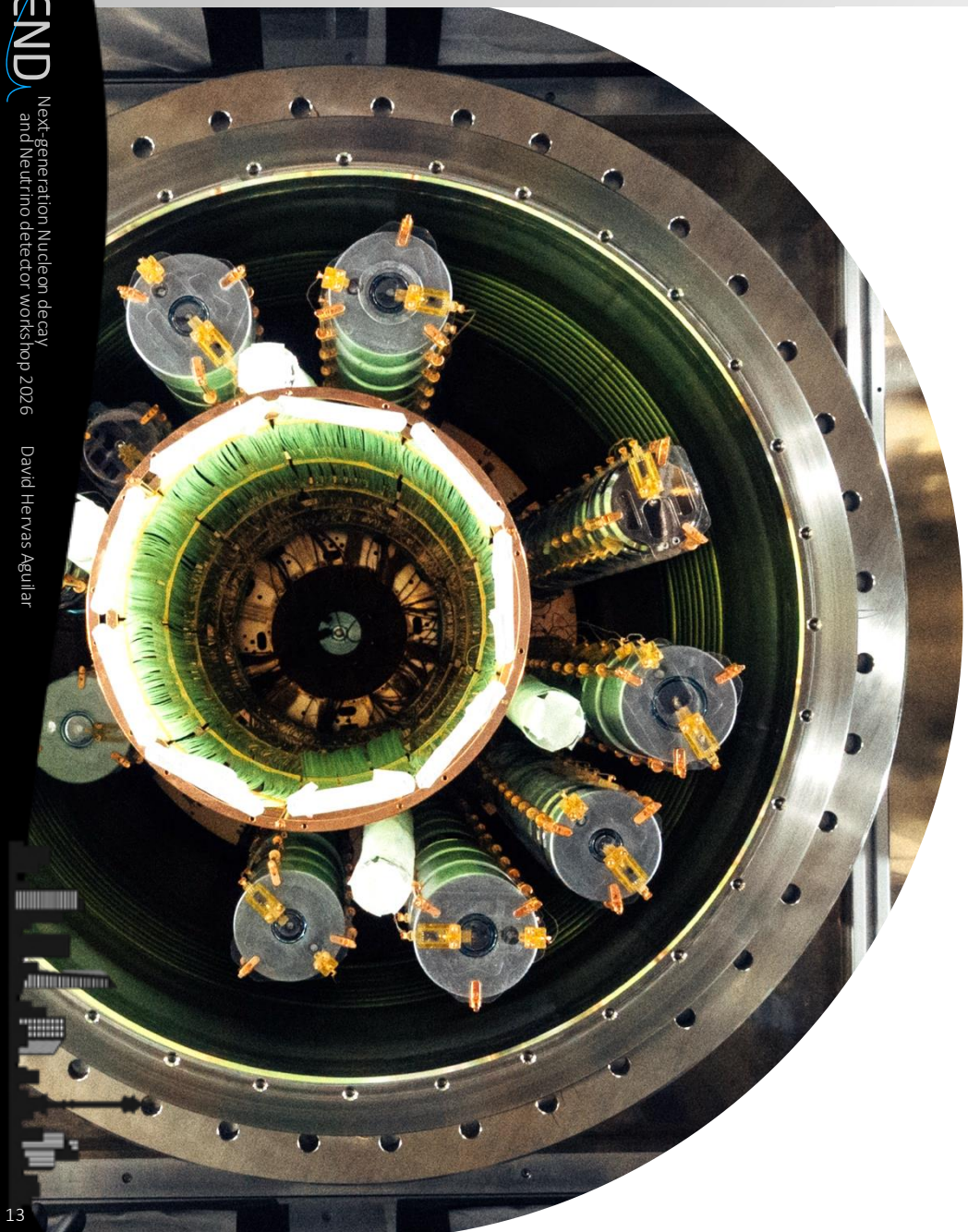


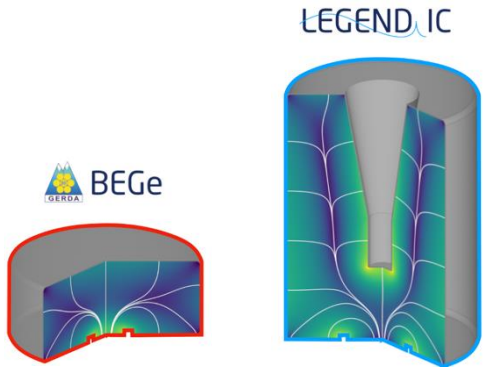
- Elevated activities identified in base-plate assembly components (PEN, Ultem, phosphor-bronze) with respect to assayed raw materials
- Surface contamination of ^{238}U (^{214}Bi) / ^{232}Th (^{208}Tl) introduced during handling
- Components underwent enhanced cleaning protocols and etching

The 2025 deployment

Physics data taking | Maintenance | Deployment

2024 2025





94%

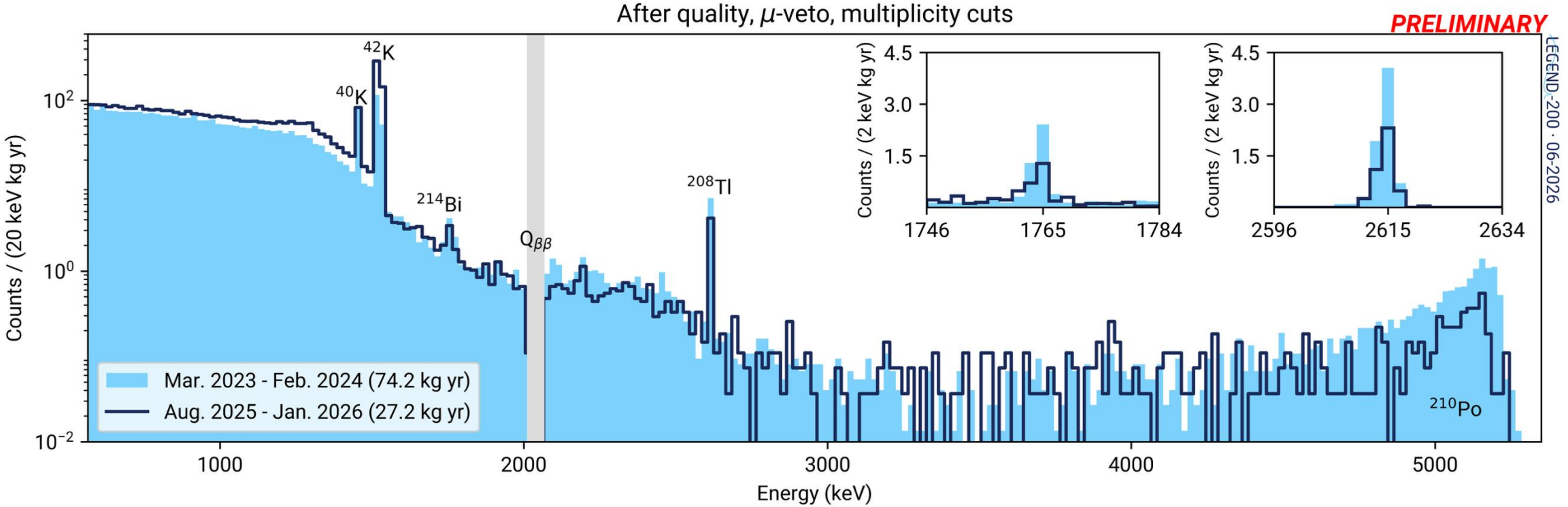
- Removed Coax, PPC, and smallest BEGe detectors and installed new IC detectors
- Total deployment: 138 kg
- Reduced total number of Ge channels by 40%



The 2025 deployment

Physics data taking | Maintenance | Deployment | Physics data taking

2024 | 2025 | 2026 | 2027

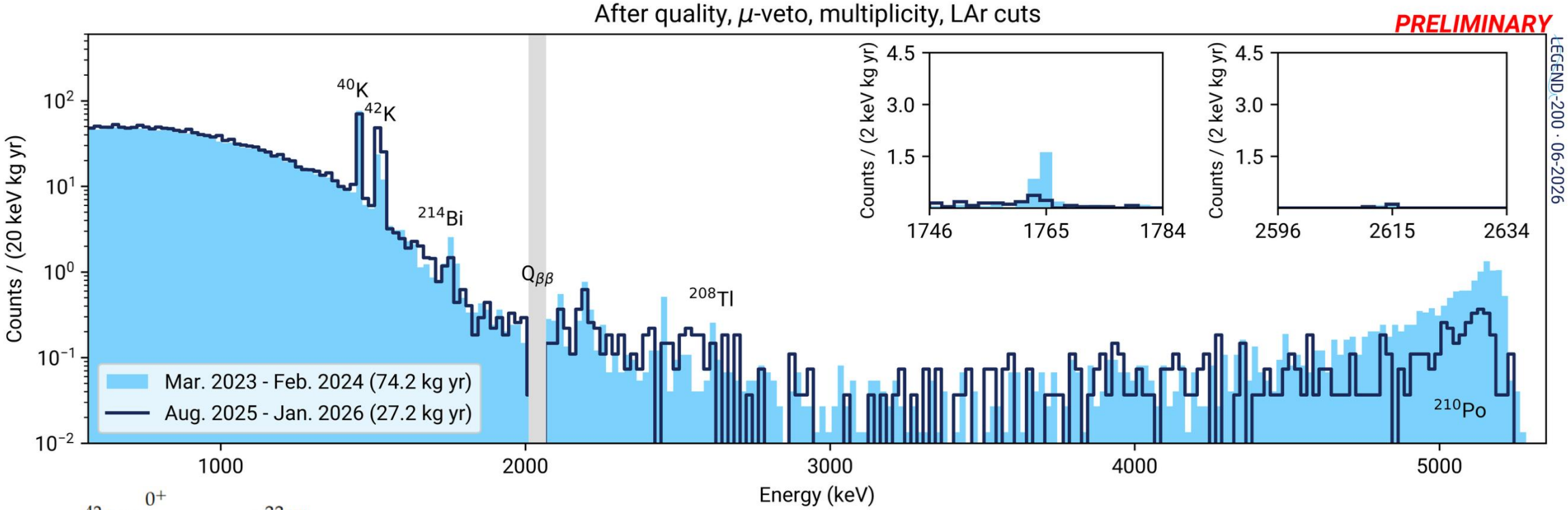


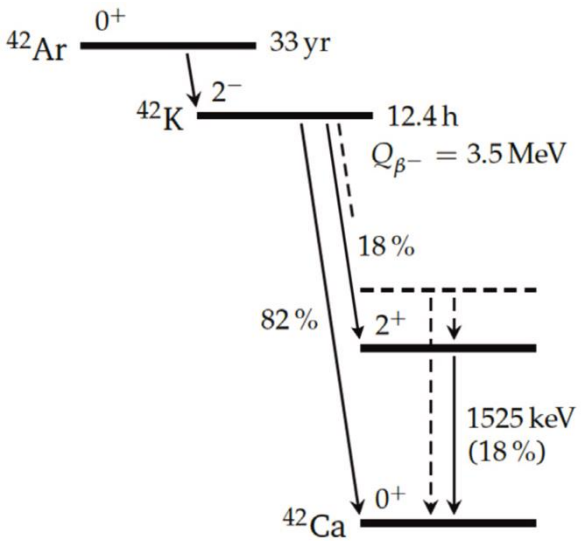
- Reduction of $^{208}Tl/^{214}Bi$ rates by a factor of approximately 2 before cuts
- Significant reduction of ^{210}Po due to the removal of Coax detectors (large p+ contacts with very thin dead layer)
- Increase in ^{42}K 1525 keV gamma line. Usually higher after re-deployment of array. Rate is decreasing.

The 2025 deployment

Physics data taking | Maintenance | Deployment | Physics data taking

2024 | 2025 | 2026 | 2027





- Reduction of ^{214}Bi rates by a factor of 5 after cuts. ^{208}Tl always strongly suppressed.
- Residual background seems to be dominated by ^{42}K surface betas.
  - **^{42}K task force** in place, mitigation strategies under study
    - Physical barriers to ^{42}K ion drift with variations of shroud geometries
    - New pulse shape discrimination techniques

Summary

- Legend-200 has completed its first unblinding with over a year of data with 142 kg of detectors
- Combining this data with GERDA and MAJORANA results in the world leading 0νββ sensitivity
- The background index (BI) is slightly higher than the program goal but on par with GERDA which has the world leading BI
- Background studies and maintenance are complete and the array has been reconfigured to use the best performing and newly produced detectors. Significant reduction of $^{208}Tl/^{214}Bi$ levels.
- Residual ^{42}K background is under investigation. Many mitigation strategies are being considered.
- LEGEND-1000 design and technical preparations are well underway. Funding is being pursued in the US and Europe.

