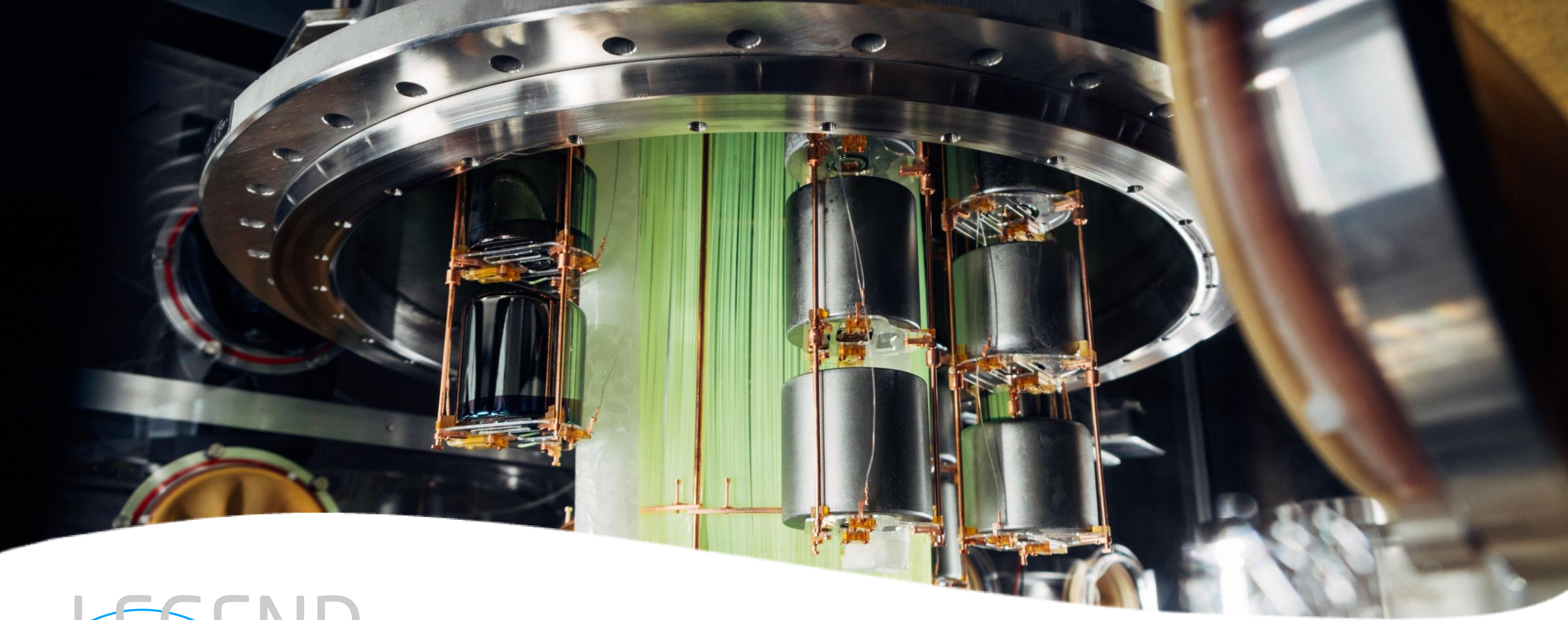
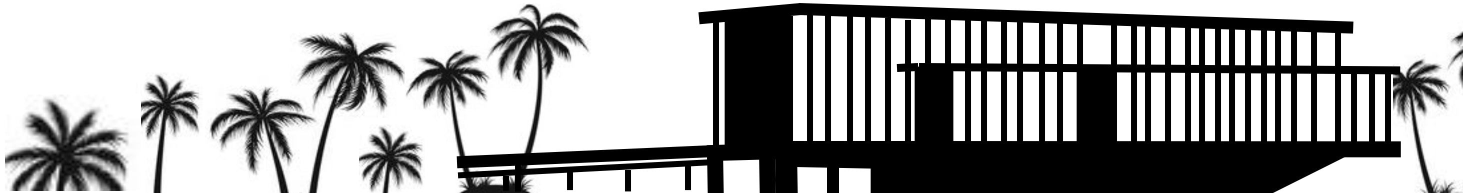
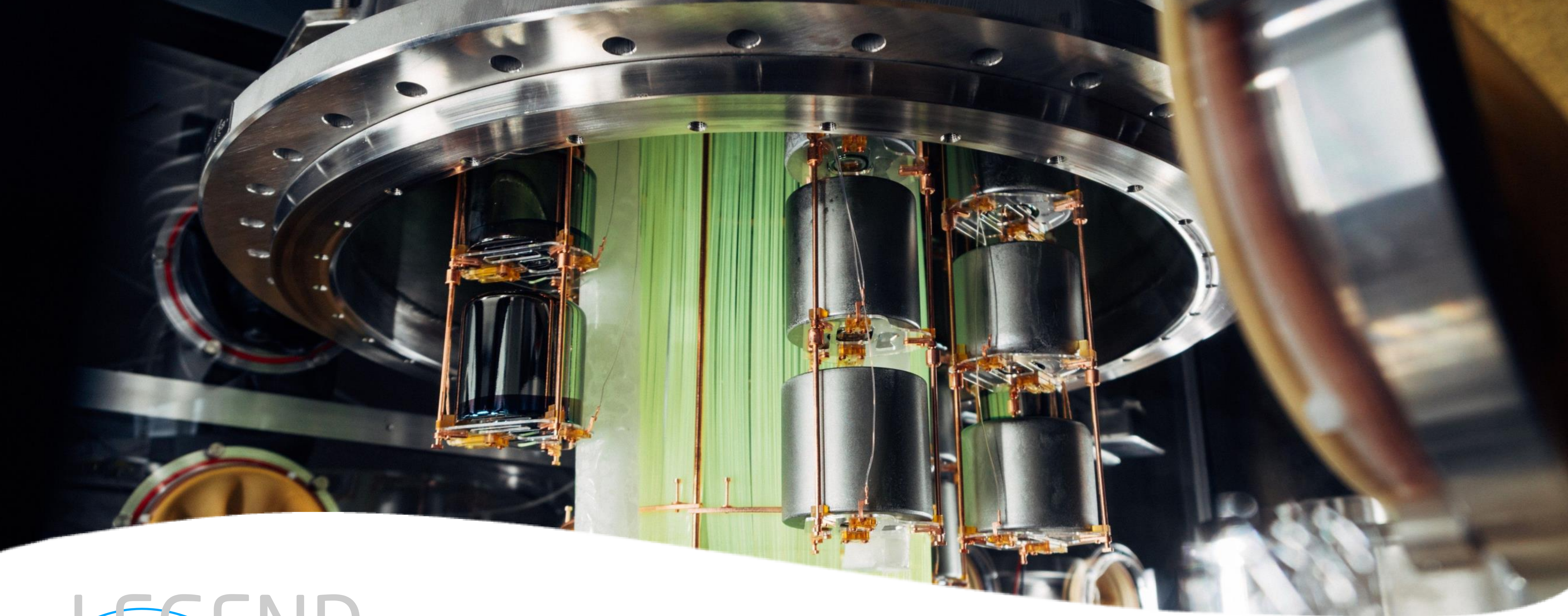


LEGEND

Searching for Neutrinoless Double Beta Decay
with Germanium Detectors

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





LEGEND

~~Searching for Neutrinoless Double Beta Decay with Germanium Detectors~~

RESULTS

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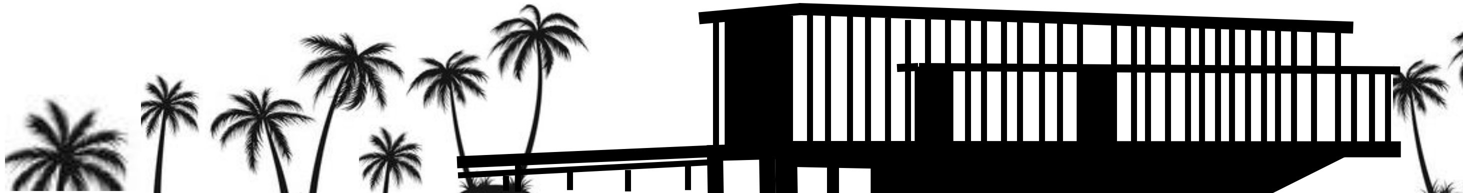
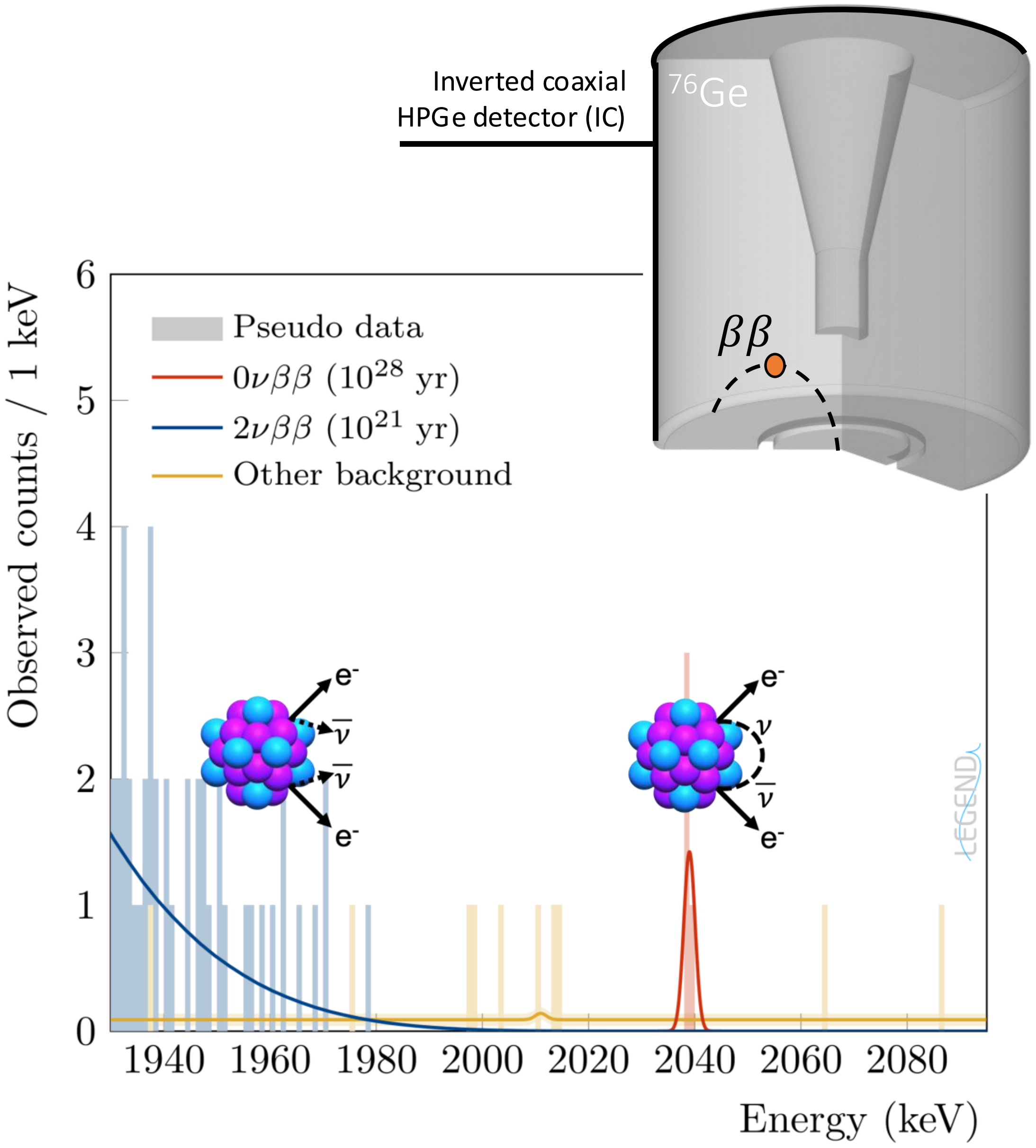
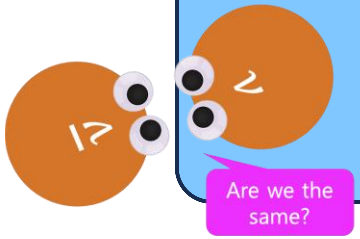


Neutrinoless double beta decay (0νββ) in ^{76}Ge



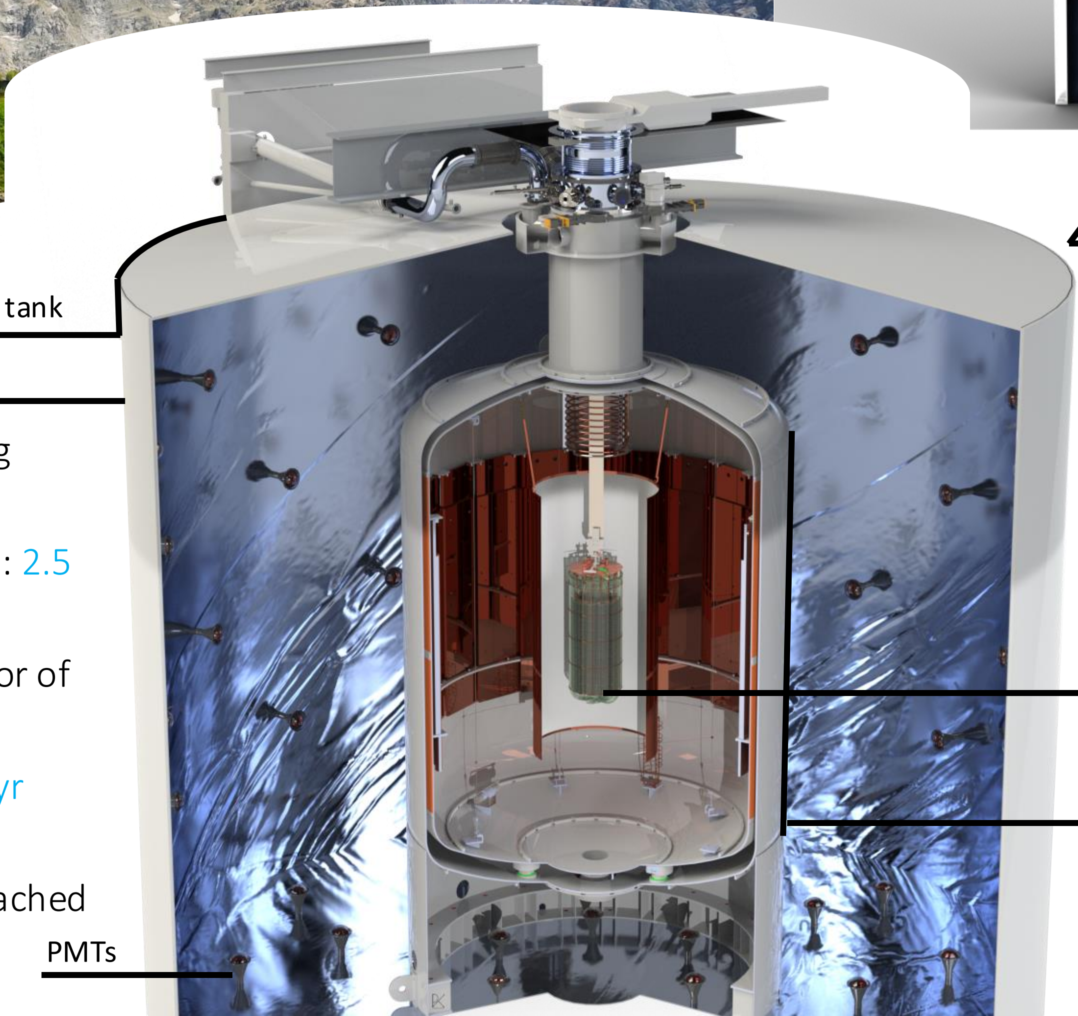
- 0νββ is only allowed if neutrinos are Majorana particles and have mass
- Violates lepton number conservation
- Observation would provide insight into
  - Matter-antimatter asymmetry
  - The nature of the neutrino
  - The absolute mass scale of the neutrino



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

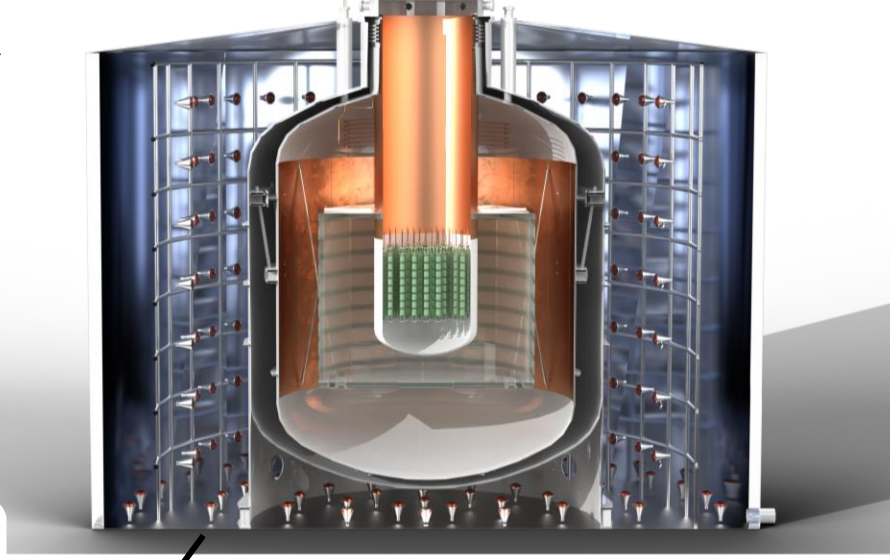
- Ge is routinely enriched up to 92%
- Source = detector → high detection efficiency
- High density → 0νββ single-site (energy deposited within ~ 1 mm)
- Lowest background and best energy resolution of all 0νββ experiments

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): $1\text{x}10^{27}$ yr
- Taking physics data since 2023. Will continue until 1 ton yr exposure is reached



LEGEND 1000 arXiv 2107.11462

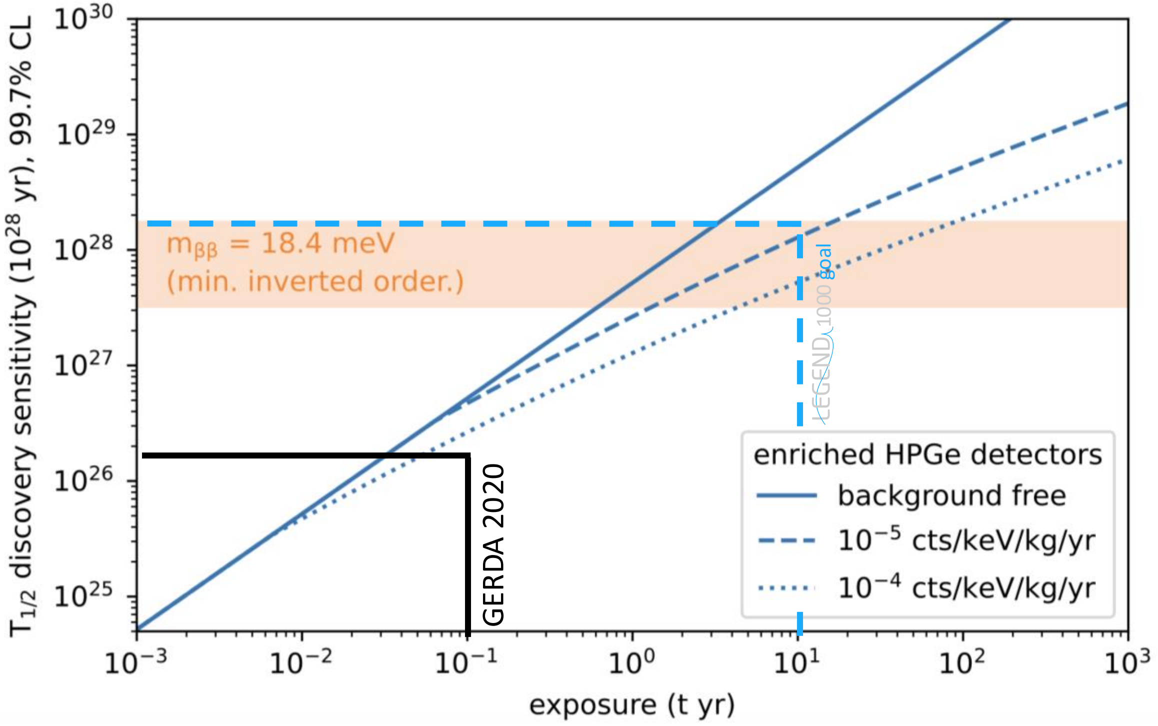
- Up to 1000 kg ^{76}Ge, payloads deployed in stages. 10 ton yr exposure
- Background goal (20x lower) < 0.01 cts/(keV ton yr)
- $T_{1/2}$ discovery sensitivity (3σ): $1.3\text{x}10^{28}$ yr
- Fully cover the $m_{\beta\beta}$ inverted ordering region

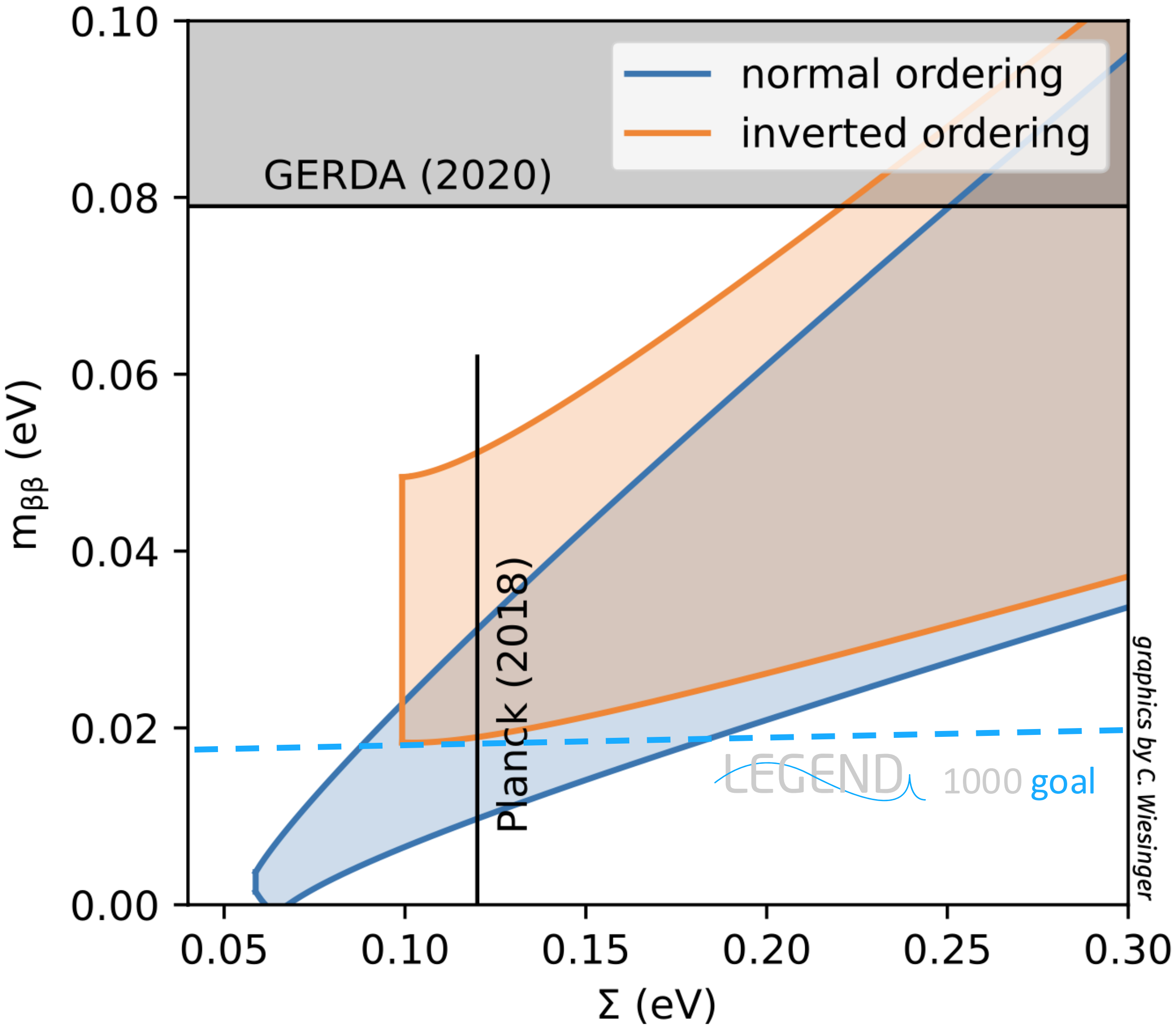
Neutrinoless double beta decay ($0\nu\beta\beta$) in ^{76}Ge

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

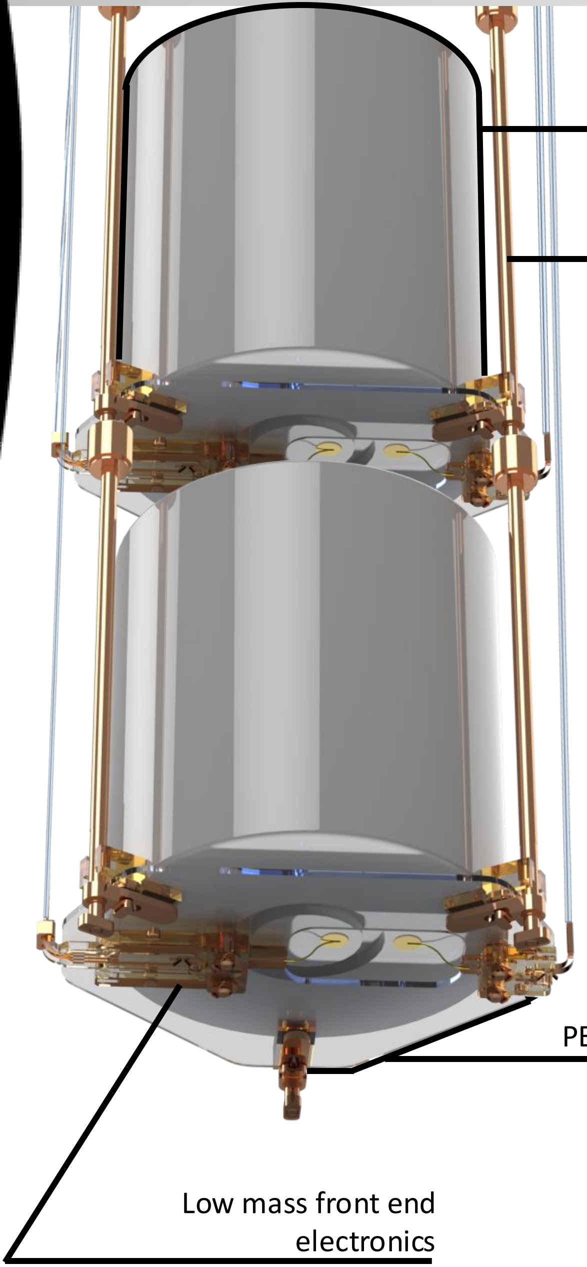
$$\langle m_{\beta\beta}\rangle = \left|U_{e1}^2 m_1 + U_{e2}^2 e^{i\alpha_{21}} m_2 + U_{e3}^2 e^{i\alpha_{31}} m_3\right|$$

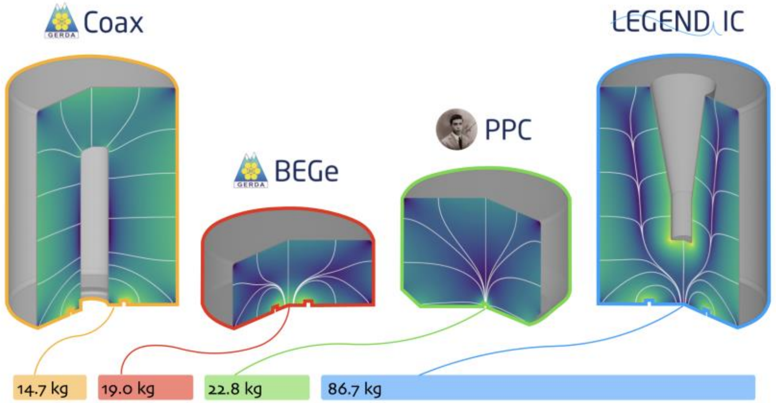
Effective Majorana mass



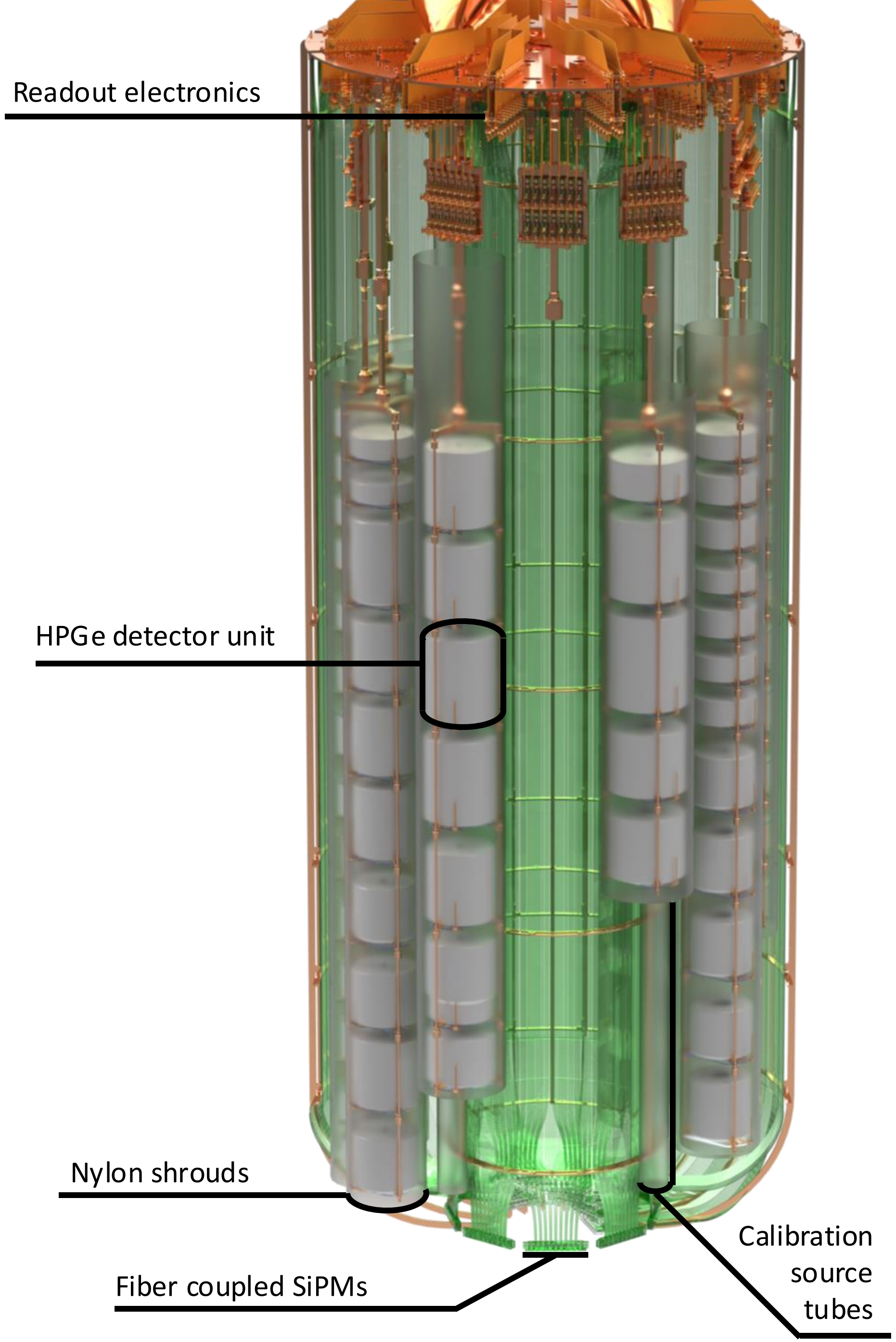


The LEGEND-200 HPGe array

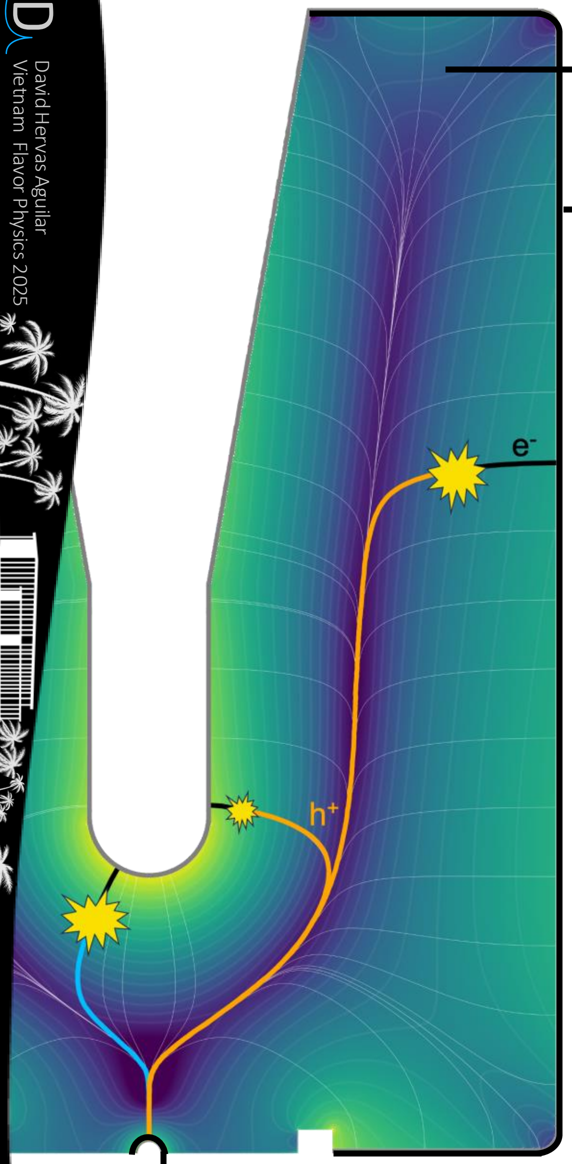


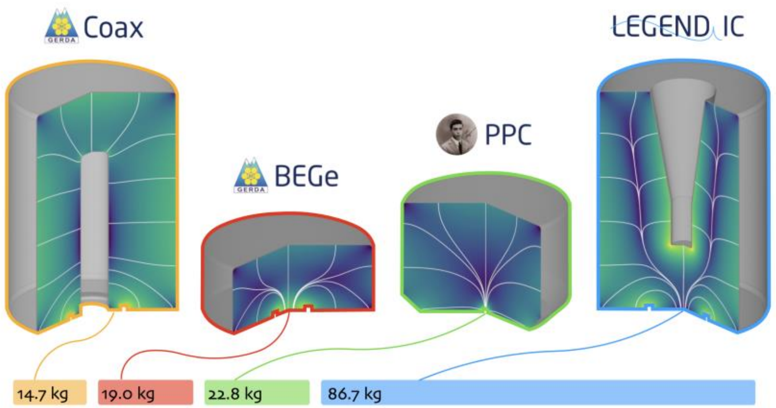


- Installed HPGe detectors with 4 different geometries in 2022 totaling 142 kg (130 kg operational)
- Used existing resources from GERDA and the MAJORANA DEMONSTRATOR including GERDA Coax and BEGe detectors and MAJORANA PPCs + new ICs



The LEGEND-200 HPGe array





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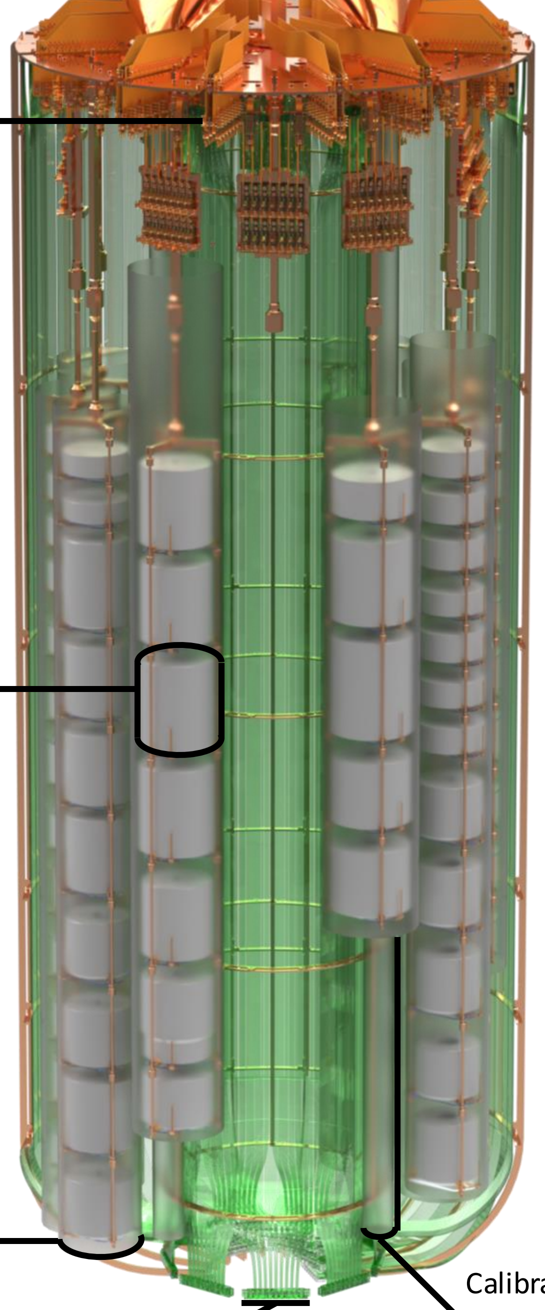
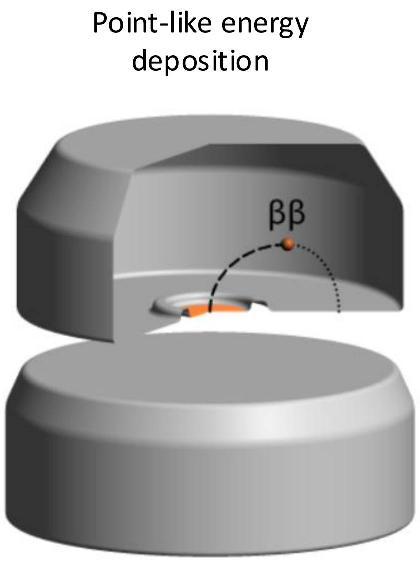
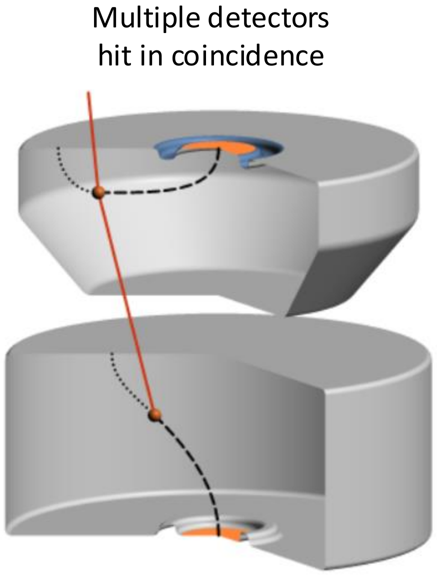


Background mitigation strategy



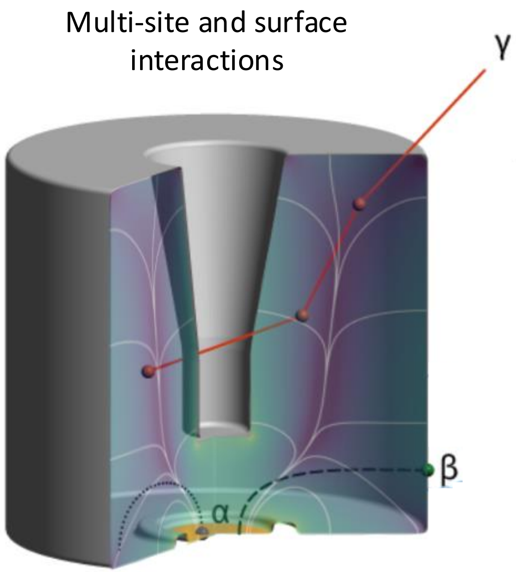
Signal-like

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.



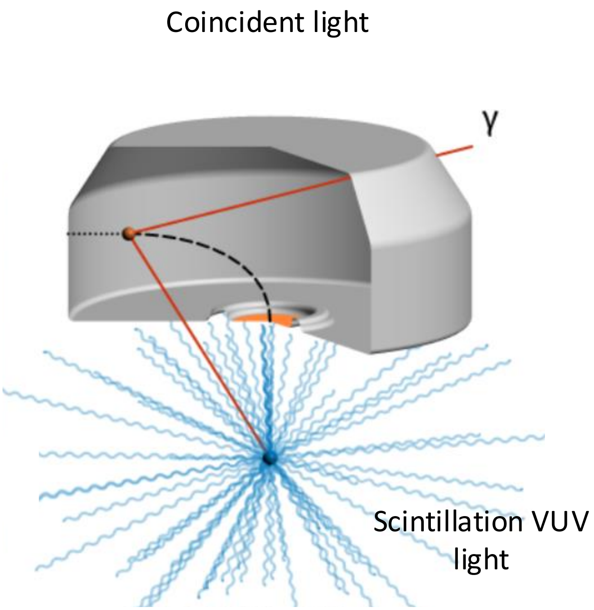
Multiplicity cut

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



Pulse-shape discrimination

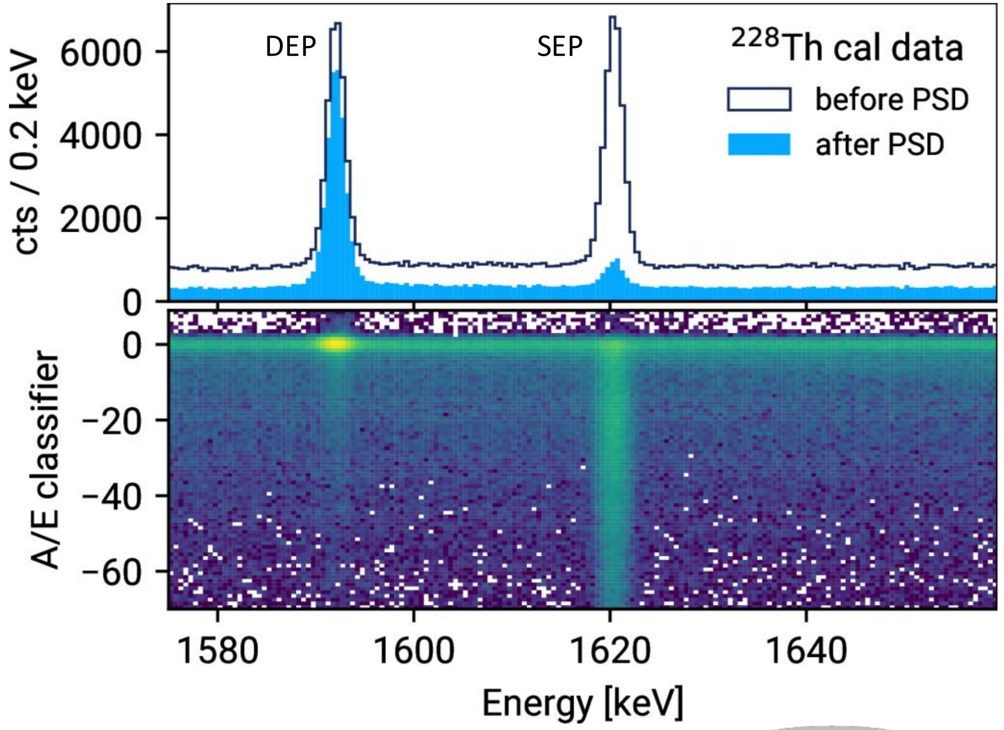
Multi-site (Compton scatters contained within one detector) and surface interaction induce signals with district shapes.



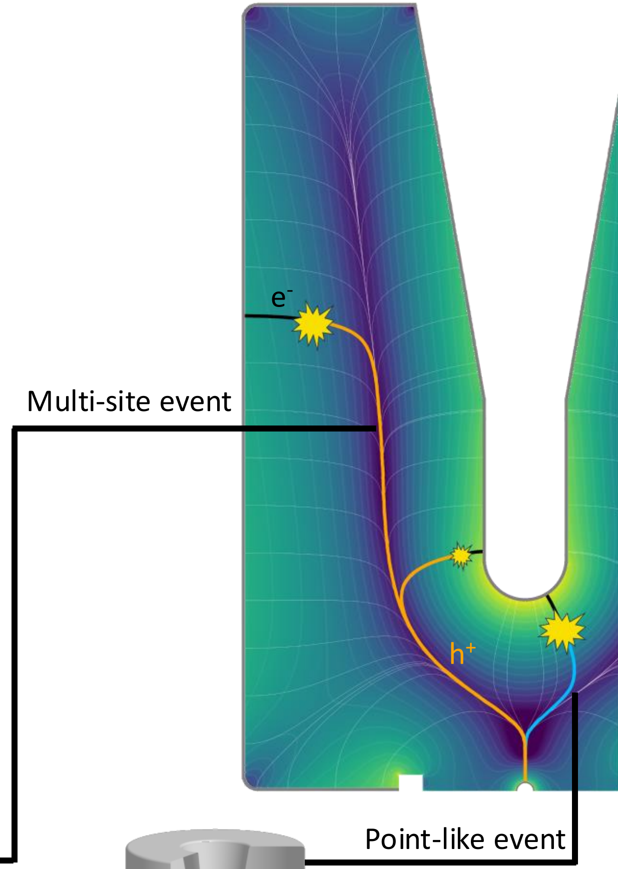
Argon anti-coincidence

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.

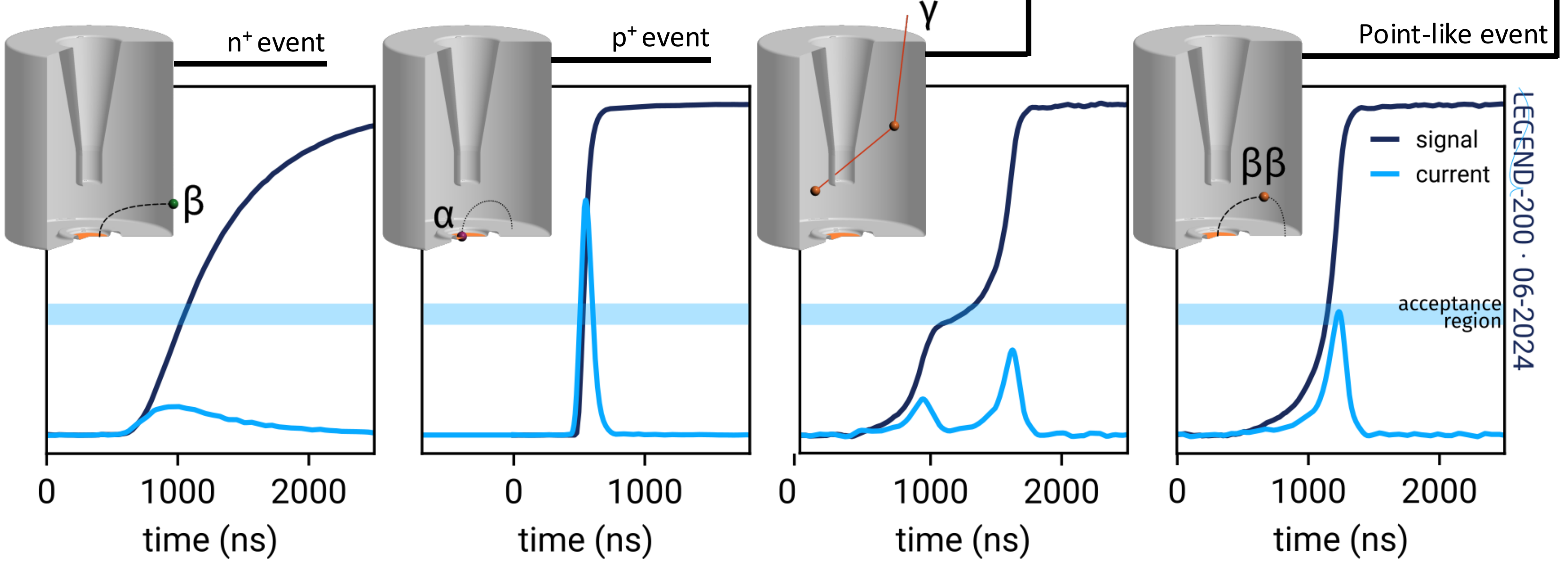
Pulse-shape discrimination (PSD)



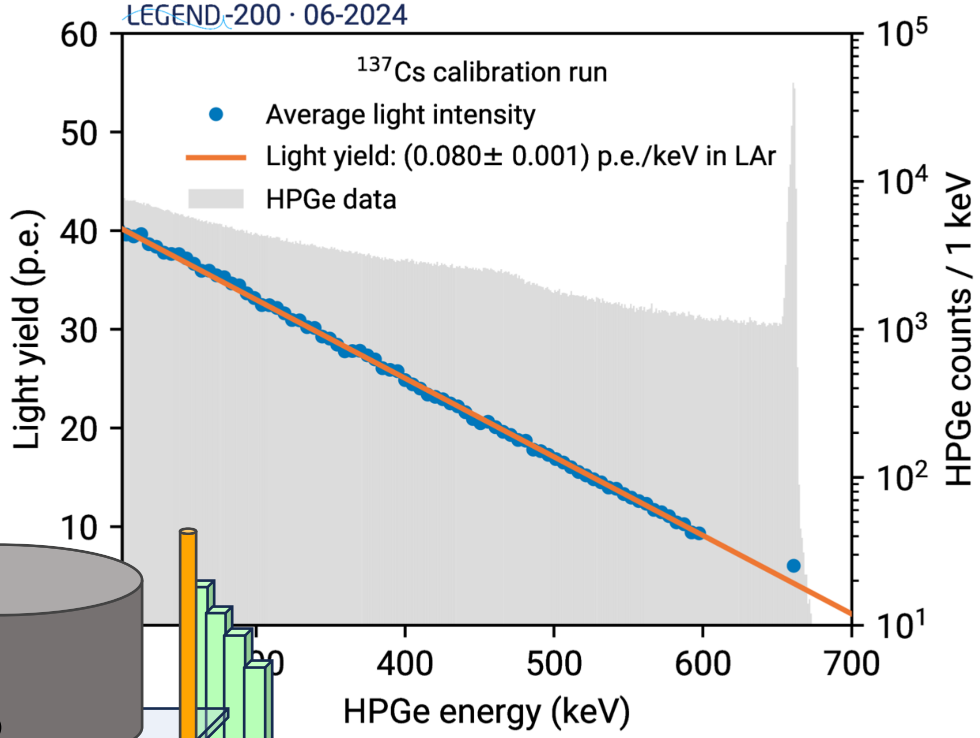
- The energy-normalized maximum current amplitude A is a powerful pulse-shape classifier (A/E)
- A/E is calibrated using double escape peak (DEP) events a proxy signal-like population
- Single escape peak (SEP) events can be used to evaluate multi-site event suppression

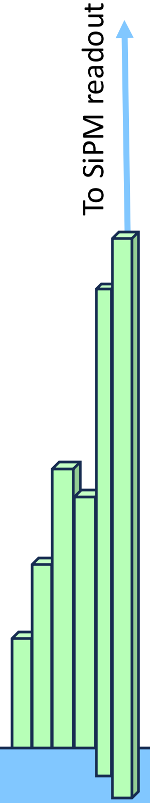


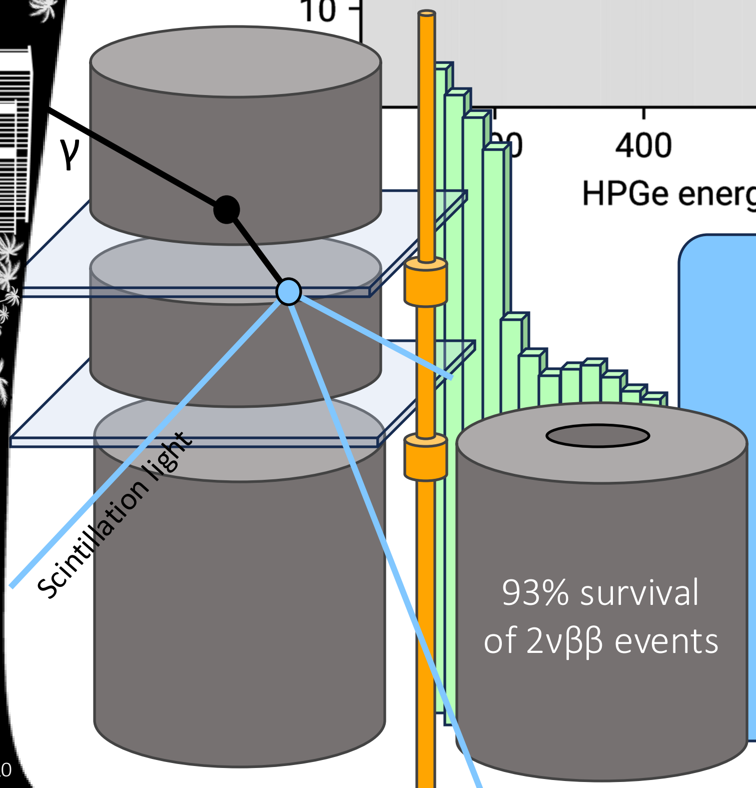
- Other pulse-shape discriminators used:
  - Artificial neural network for Coax detectors
  - Late Charge (LQ) for detectors with large passivated surfaces



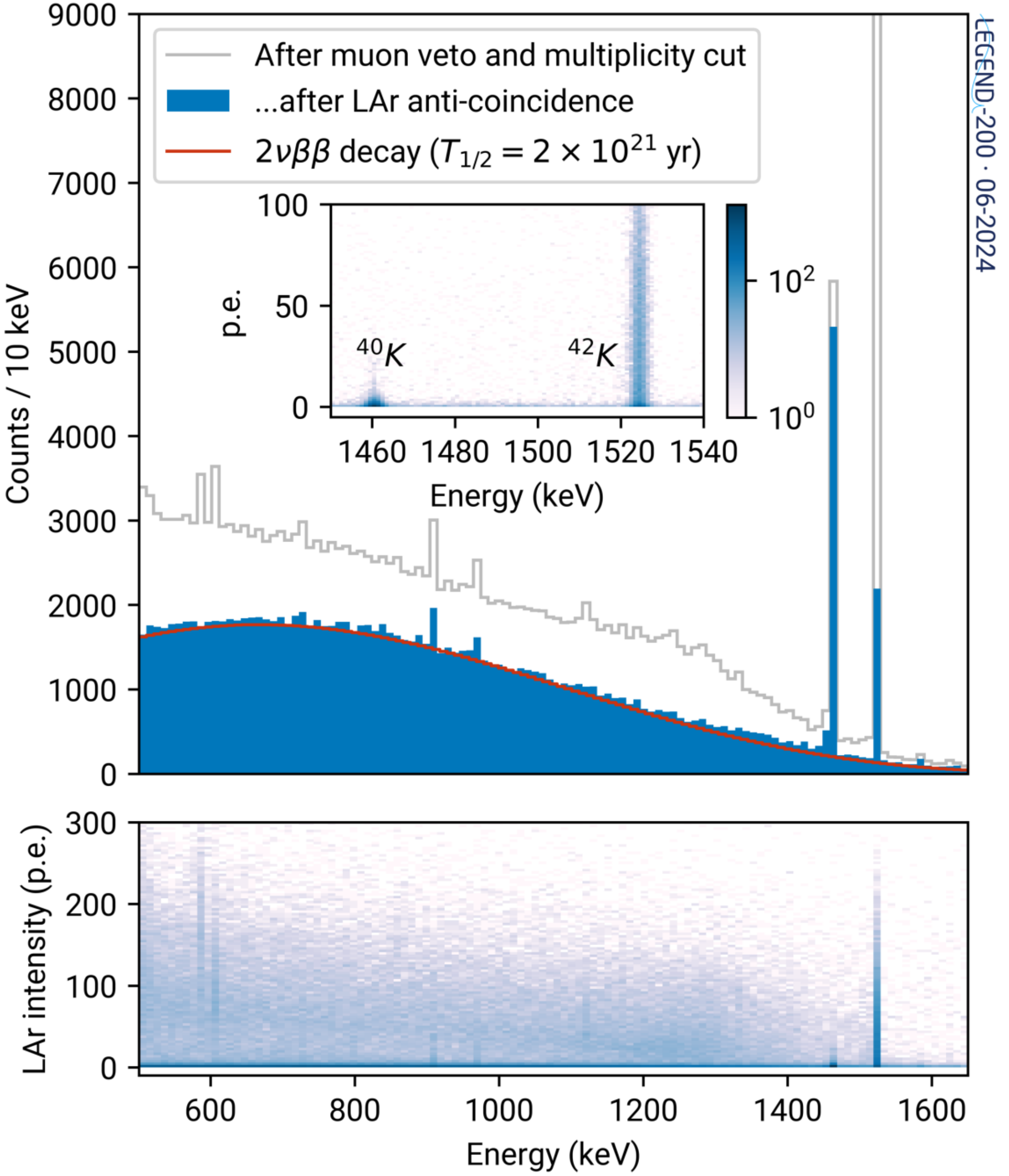
Argon instrumentation



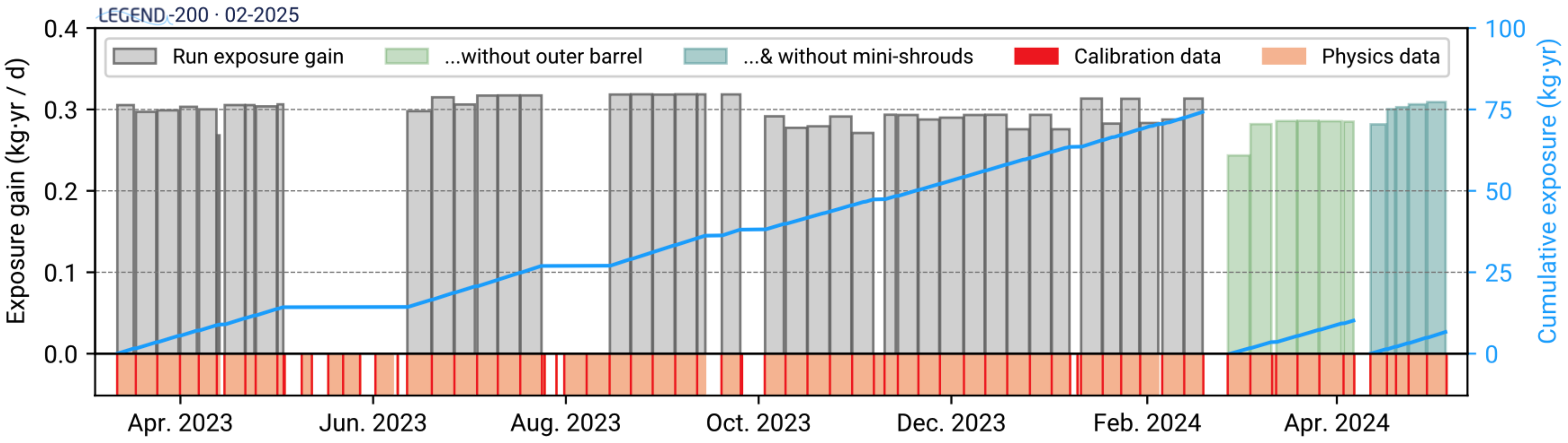




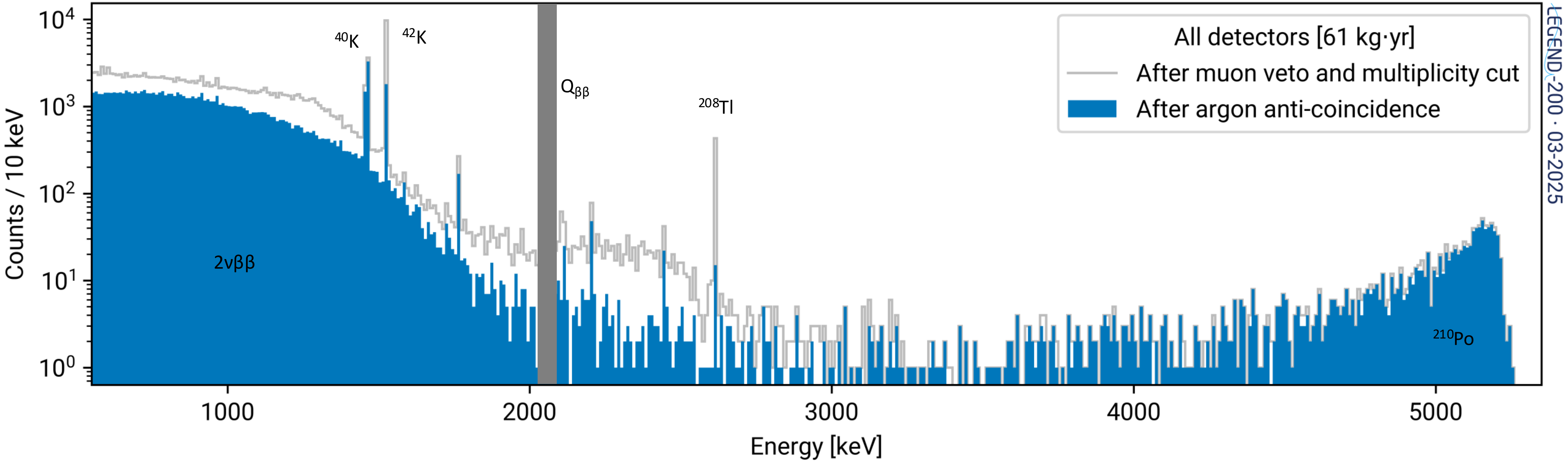
- Improved light yield compared to GERDA (x3 determined by special ^{137}Cs calibration runs)
- Strong suppression via anti-coincidence of background in ββ decay region leaving a nearly pure 2νββ spectrum



Data taking and spectrum after LAr anti-coincidence



- Strong suppression of ^{208}Tl Compton events
- Signal acceptance of 93%



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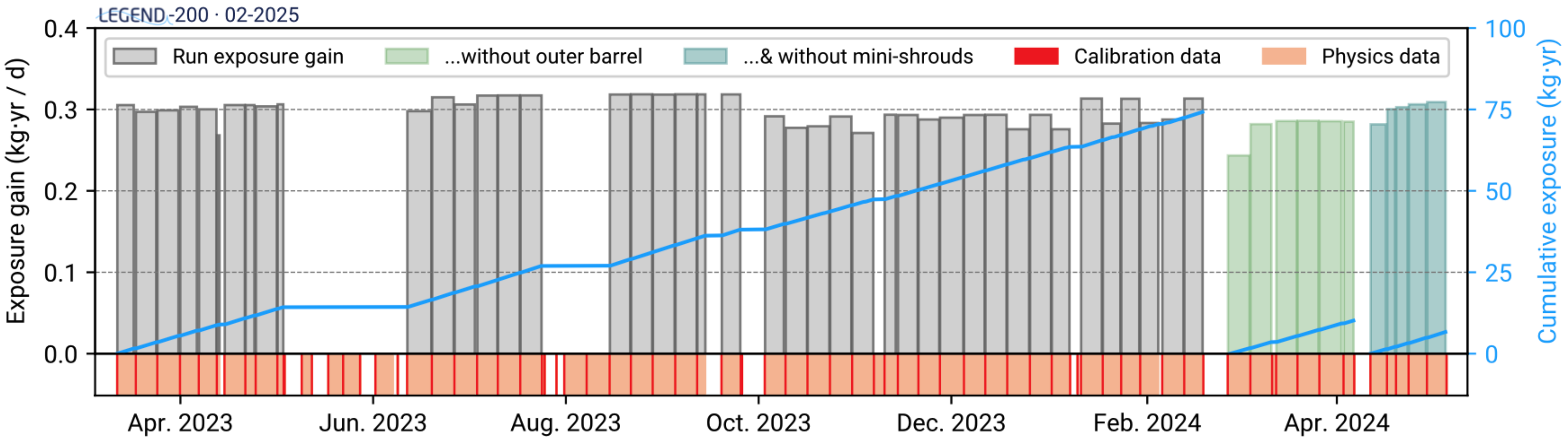
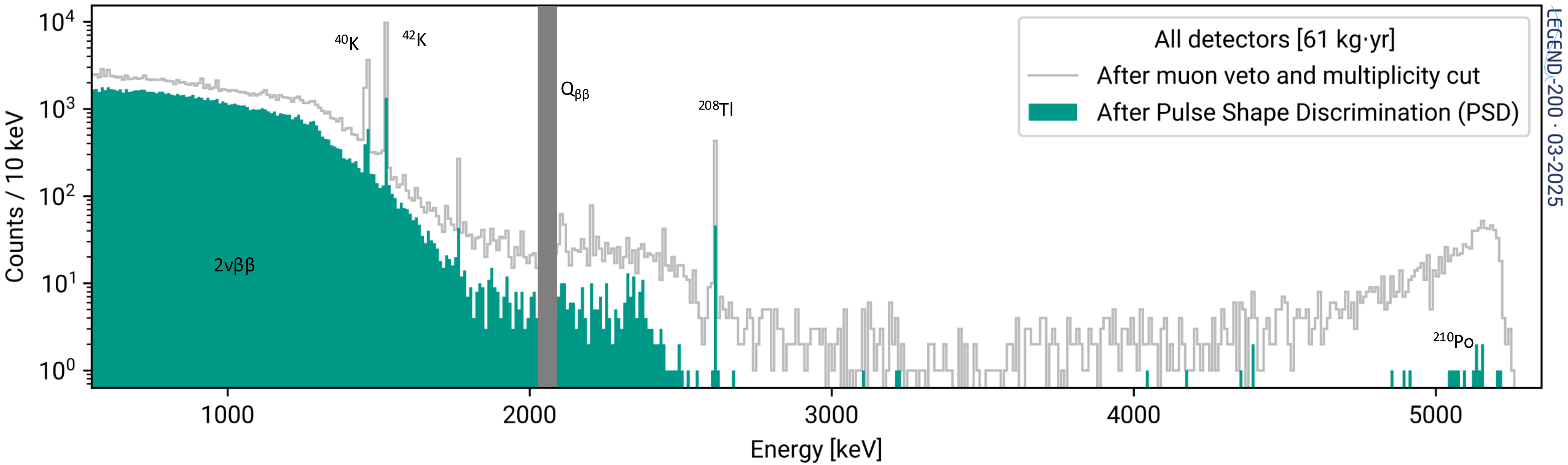
Spectrum after PSD cuts



- Surface events (α + β) strongly suppressed by PSD
- Compton events at $Q_{\beta\beta}$ and over 2νββ region are moderately rejected (63% at $Q_{\beta\beta}$)
- Signal acceptance of 85%



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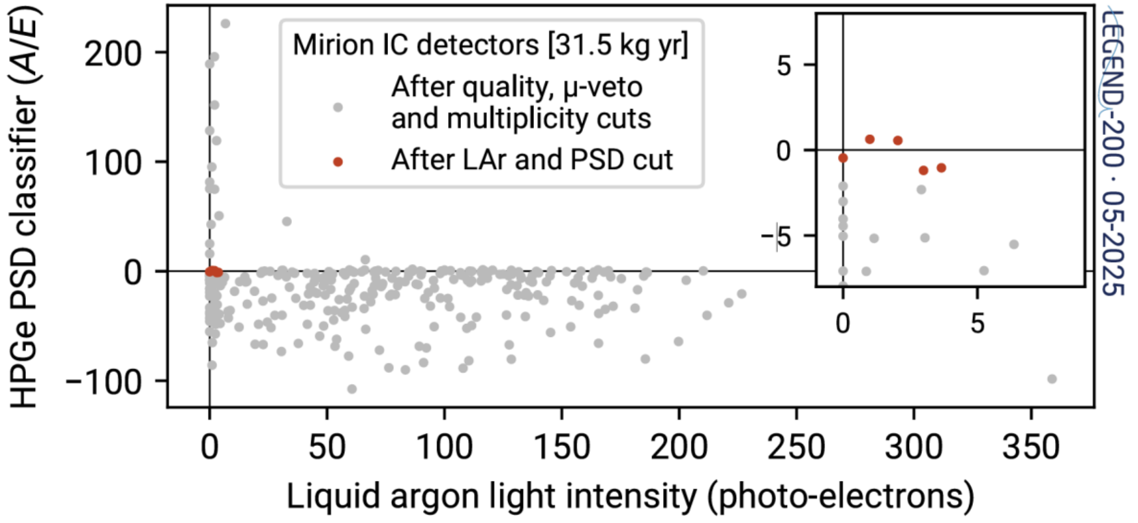
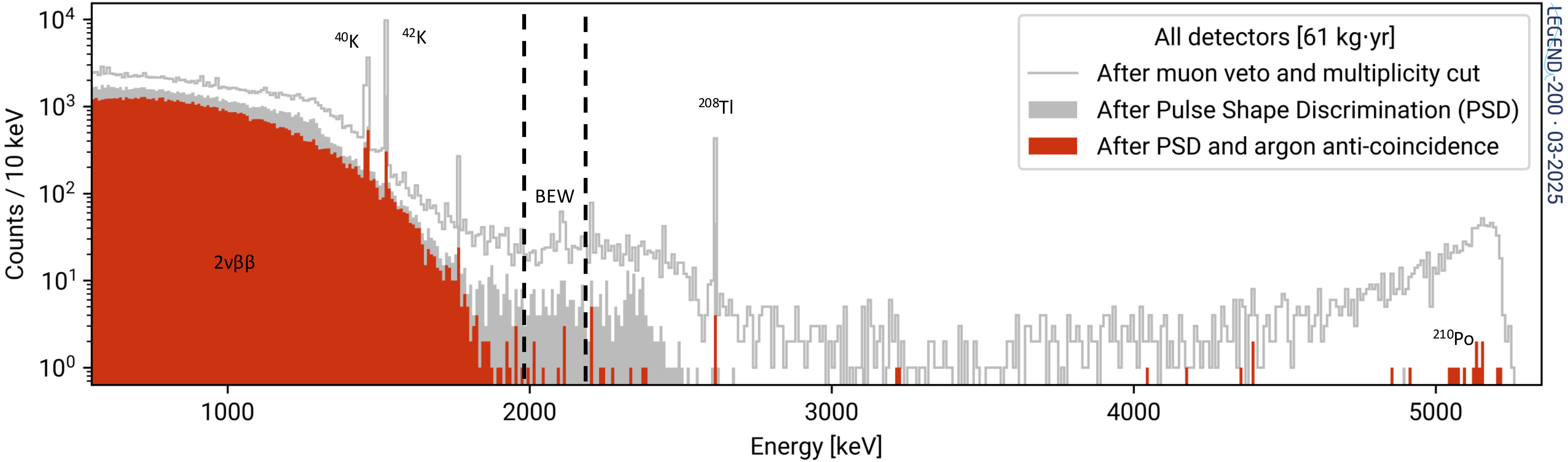
Spectrum after all cuts

- PSD and LAr anti-coincidence cuts are complimentary
- After all cuts nearly pure 2νββ spectrum remains, with an expected flat background close to $Q_{\beta\beta}$

- In background estimation window (BEW) 11 counts remain after all counts
  - BEW = 1930 – 2190 keV excluding gamma lines at
    - ^{208}Tl: (2104 ±5) keV
    - ^{214}Bi: (2104 ±5) keV





Events remaining in region of interest

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

- Combined fit results in world leading sensitivity
- 1 event at 1.4σ from $Q_{\beta\beta}$ worsens limit
- Paper is submitted to PRL arXiv 2505.10440

Background index

Silver dataset

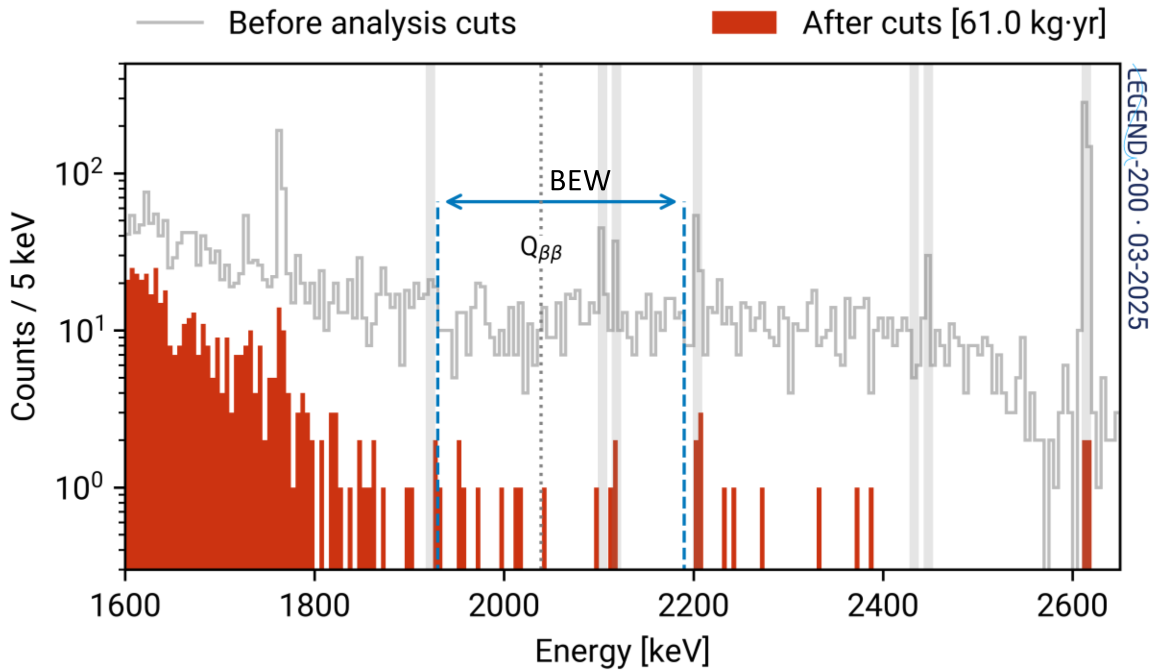
$1.3^{+0.8}_{-0.5}$ cts/ (keV ton yr)

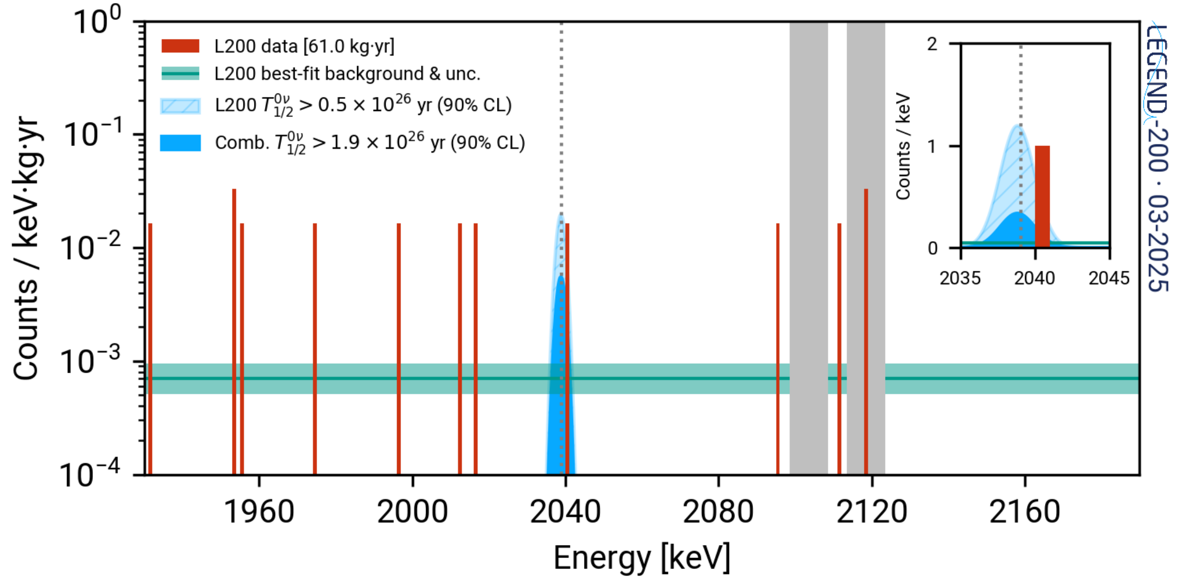
Excluding detectors with poor background rejection (mainly COAX)

↓

Golden dataset

$0.5^{+0.3}_{-0.2}$ cts/ (keV ton yr)





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Limits on the effective Majorana mass

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

- Combined fit results in world leading sensitivity
- 1 event at 1.4σ from $Q_{\beta\beta}$ worsens limit
- Paper is submitted to PRL arXiv 2505.10440

Effective Majorana mass

Limits (90% CL) assume light neutrino exchange mechanism

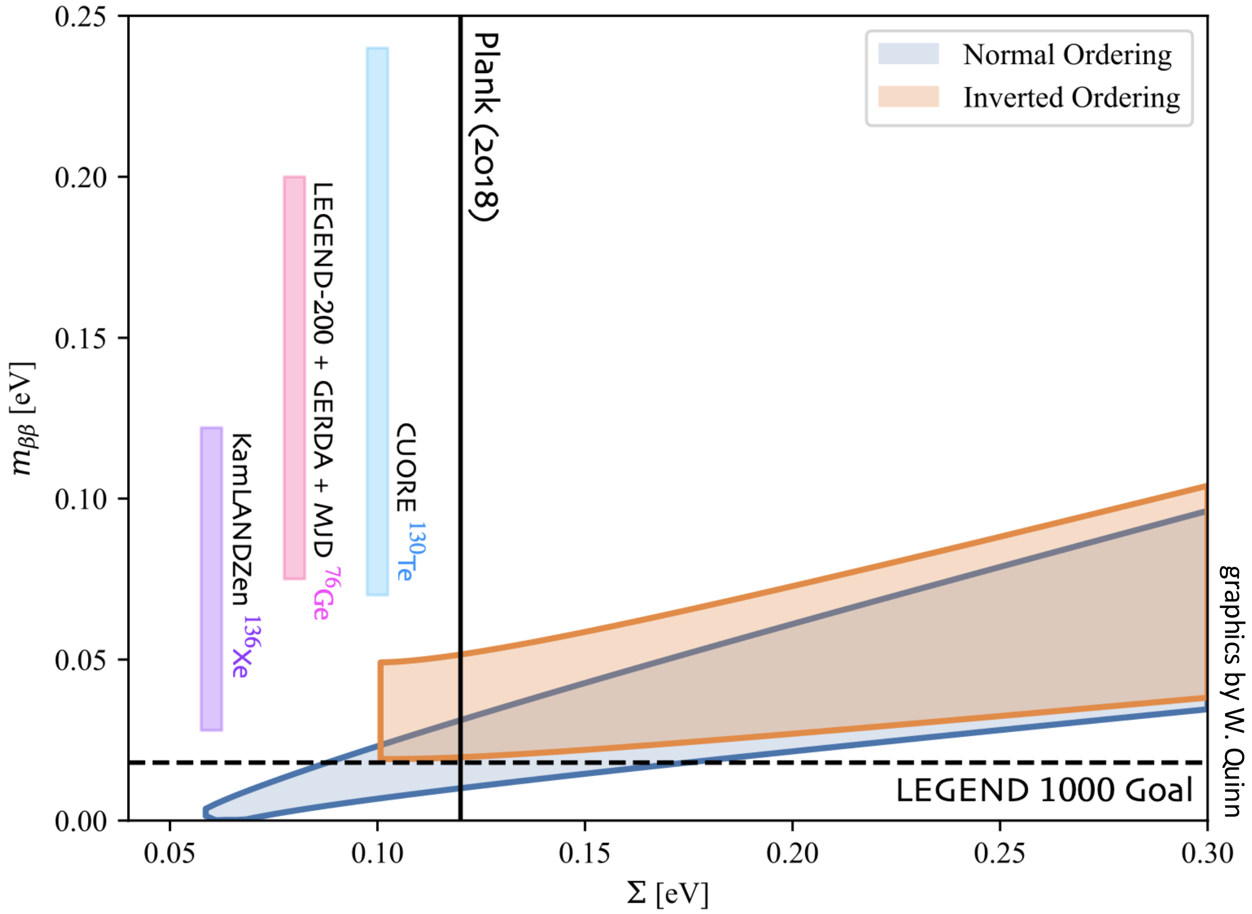
Using range of $M_{0\nu}$ for ^{76}Ge: **2.35 - 6.34**

$m_{\beta\beta}$ < 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



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

Summary

- Legend-200 has completed its first unblinding with over a year of data with 142 kg of detectors mounted on the array
- Combining this data with GERDA and MAJORANA results in the world leading 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. First data indicates lower background.
- Calibration data taking is ongoing. Physics data taking will restart in the next month
- LEGEND-1000 design and technical preparations are well underway. Funding is being pursued in the US and Europe.