

Status and prospects of the ~~LEGEND~~ experiment in the quest for Neutrinoless Double-Beta Decay

Raoul Cesarano

on behalf of the ~~LEGEND~~ collaboration

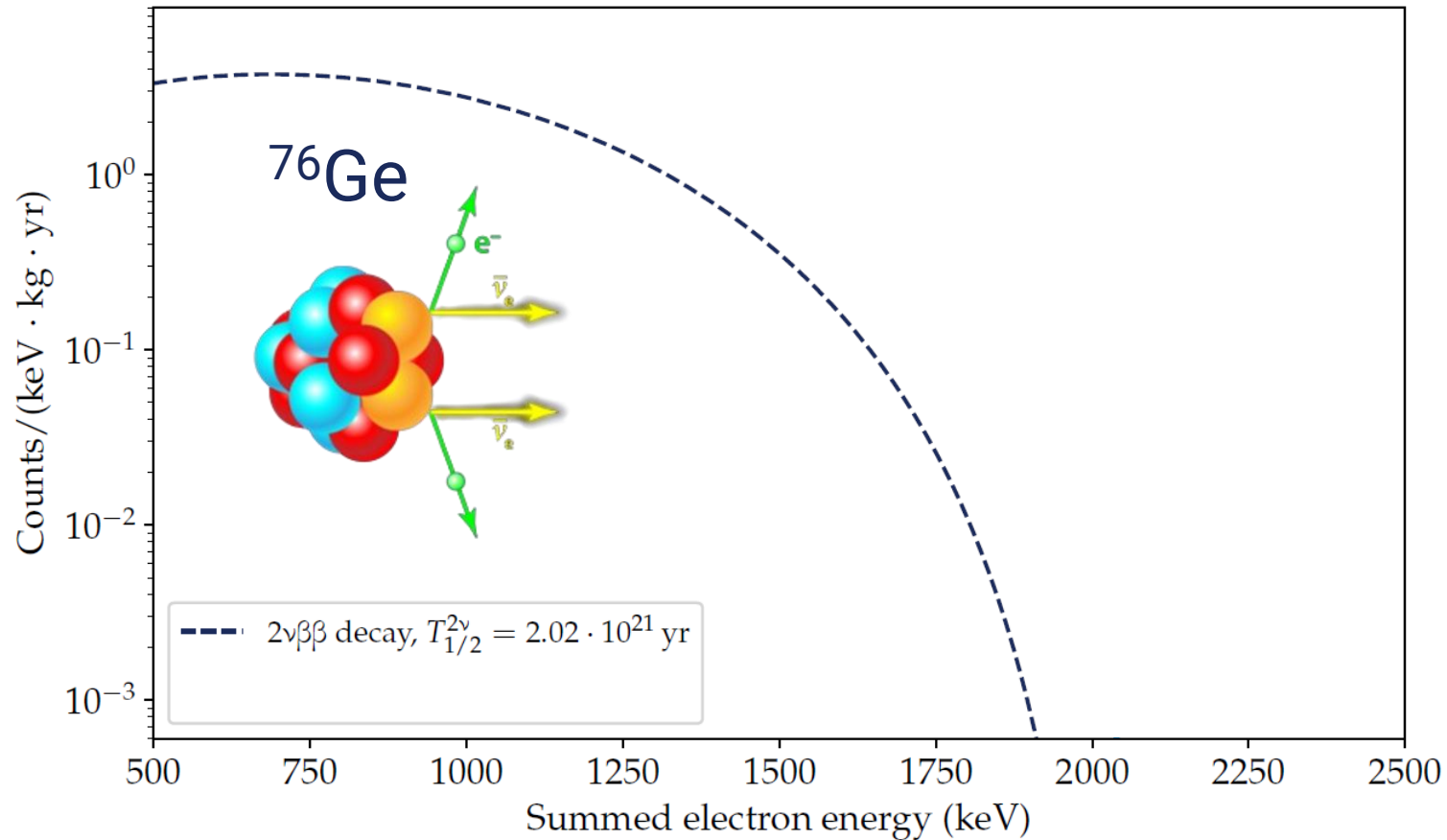
XIX International Conference on Interconnections
between Particle Physics and Cosmology

Sydney

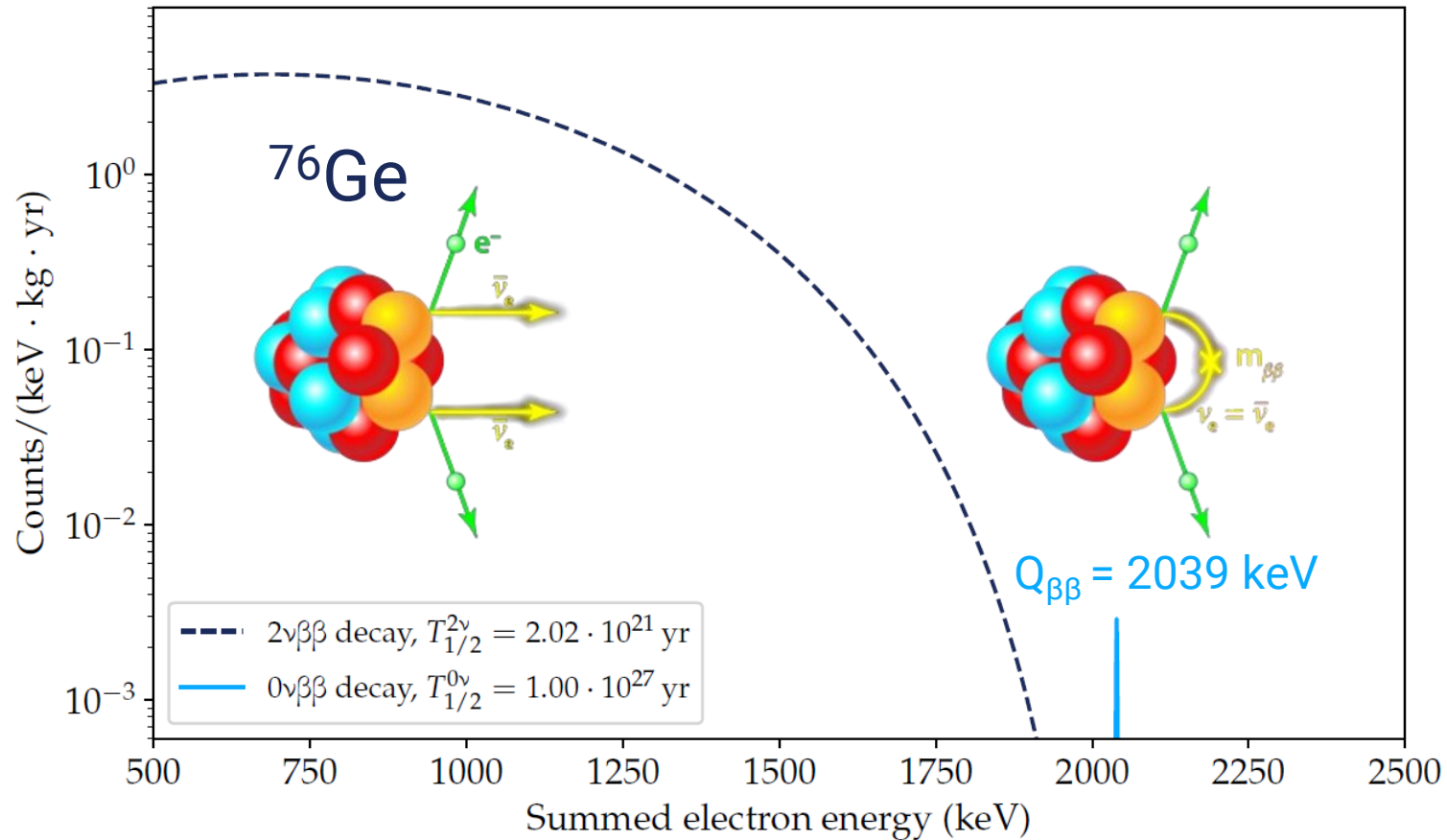


31/08/2026

Neutrinoless Double Beta Decay



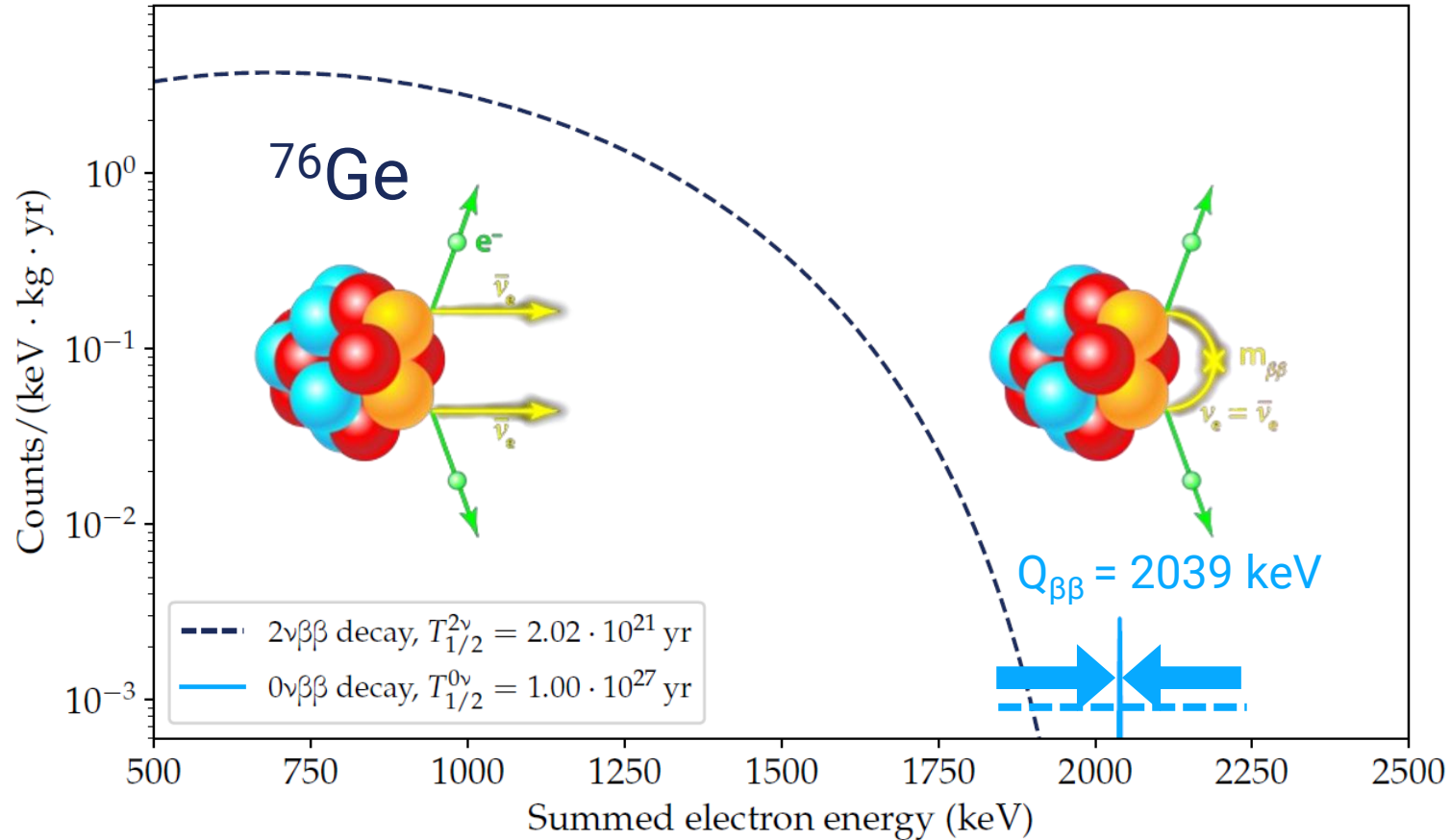
Neutrinoless Double Beta Decay



Ettore Majorana

- **Lepton-number** violation
- **Majorana** nature of neutrinos
- Matter-Antimatter asymmetry through **leptogenesis**

Neutrinoless Double Beta Decay



$$T_{1/2}^{0\nu\beta\beta} = \ln 2 \cdot \frac{N_A \cdot ia \cdot \epsilon}{n_\sigma \cdot m_A} \cdot \sqrt{\frac{M \cdot T}{B_i \cdot \Delta E}}$$

Isotopic abundance

Detector signal efficiency

Exposure

Sensitivity

Background index

Energy resolution

The LEGEND project

“The collaboration aims to develop a phased, ^{76}Ge based $0\nu\beta\beta$ experimental program with **discovery potential** $T_{1/2}^{0\nu\beta\beta} > 10^{28} \text{ yr}$, using existing resources as appropriate to expedite physics results.”

13 countries, 60 institutions, ~350 members



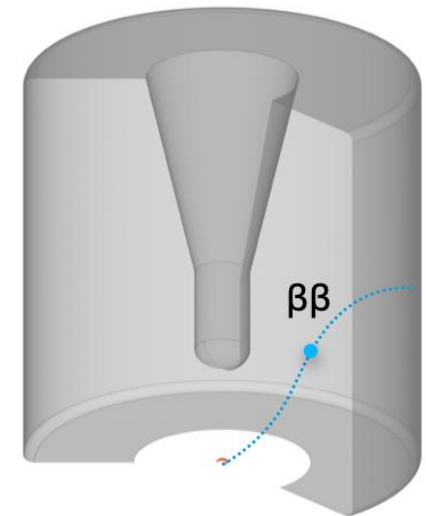


High Purity Germanium Detectors

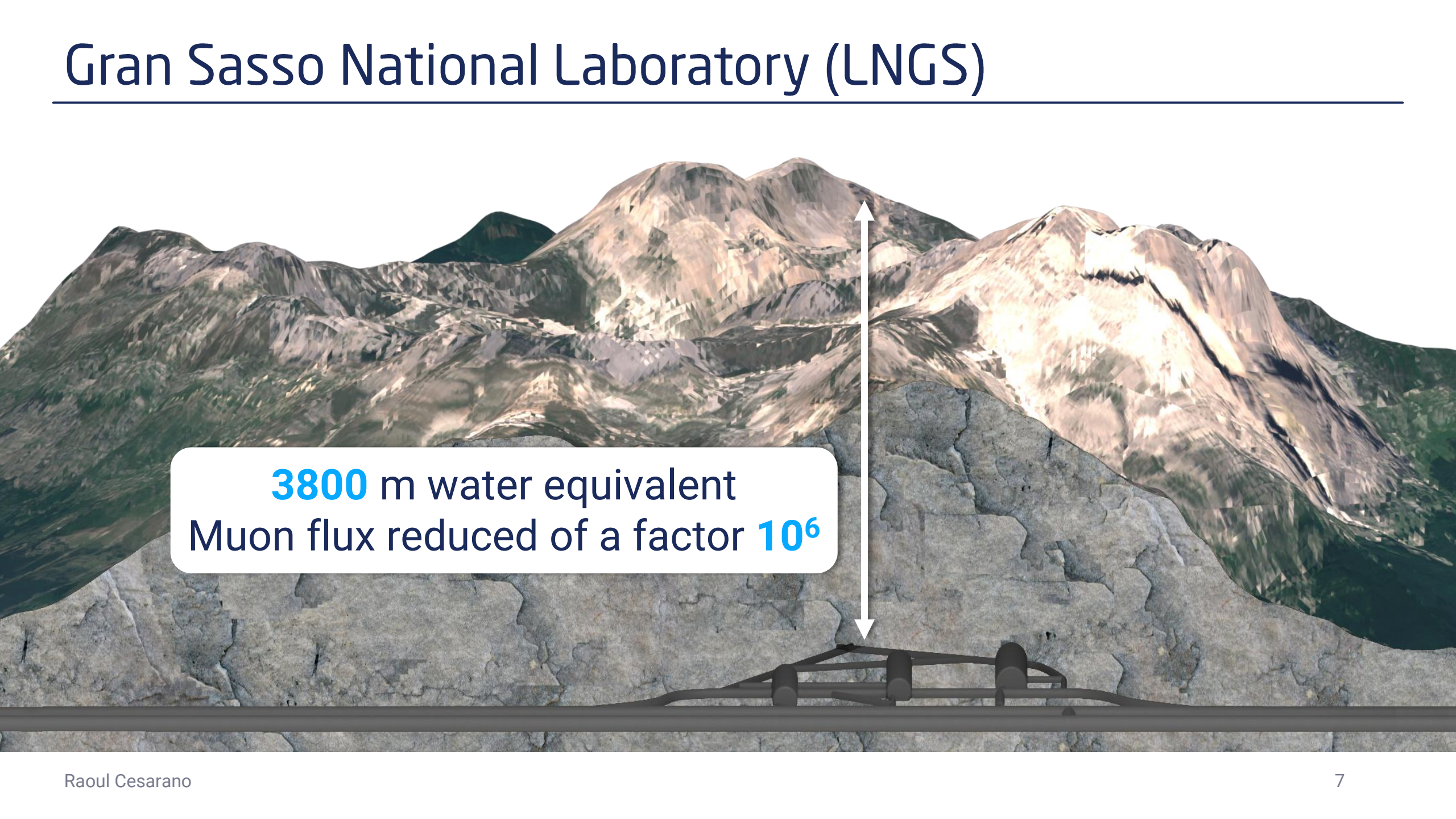


- Detector = Source $\rightarrow$ High detection **efficiency**
- High **Purity** $\rightarrow$ Low intrinsic background
- Excellent energy resolution $\rightarrow$ **$\sim 0.1\%$ FWHM at $Q_{\beta\beta}$**
- Topological discrimination $\rightarrow$ **Pulse Shape Discrimination (PSD)**

Natural abundance is low ($\sim 8\%$):
enrichment up to $\sim 92\%$ is possible

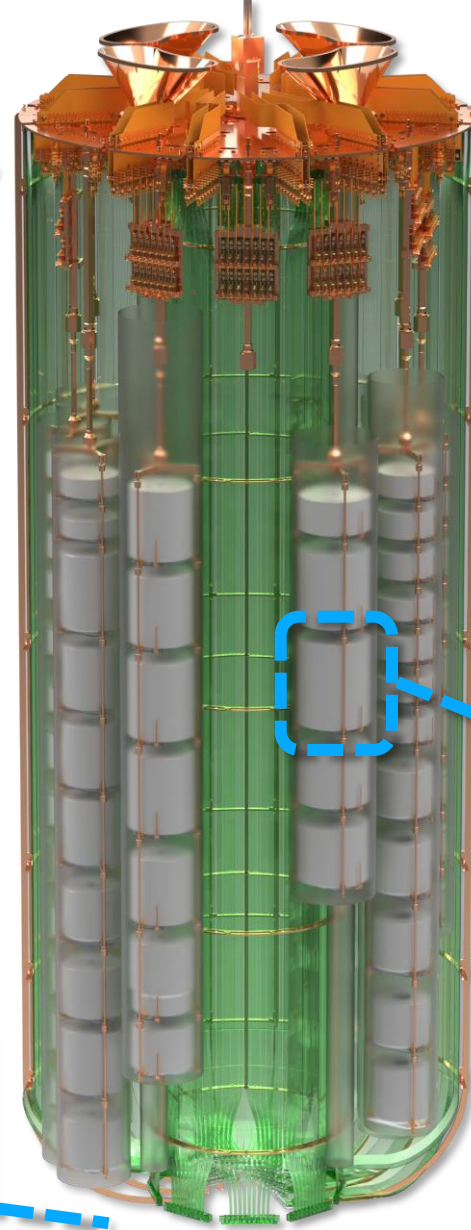
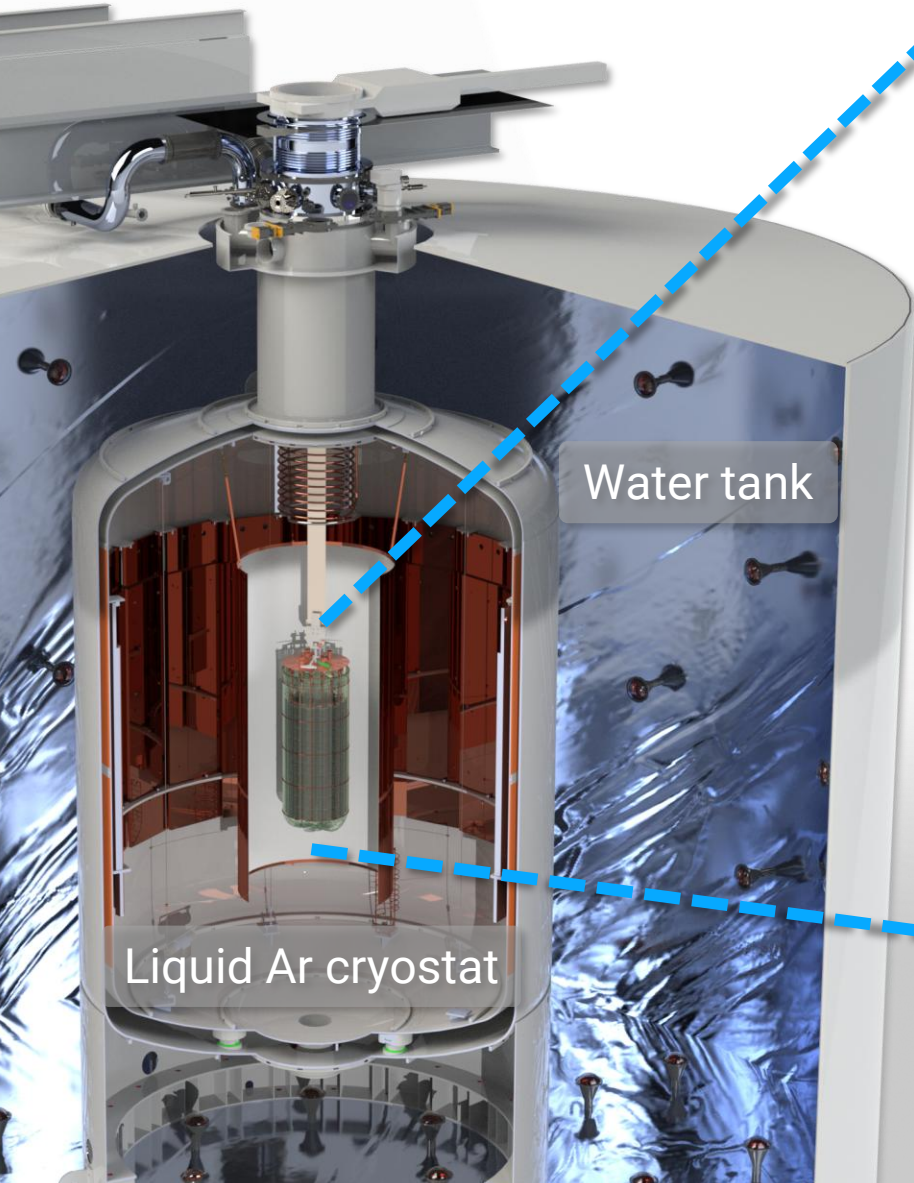


Gran Sasso National Laboratory (LNGS)

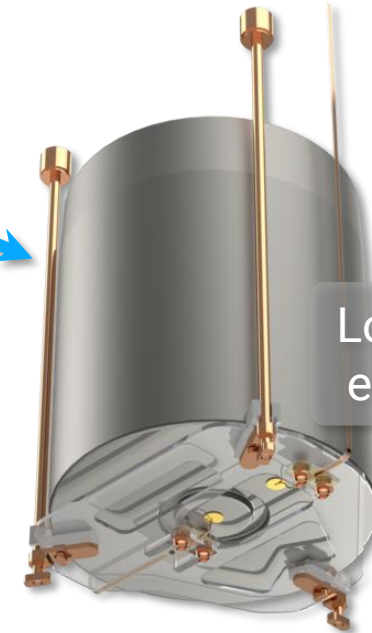


3800 m water equivalent
Muon flux reduced of a factor **10^6**

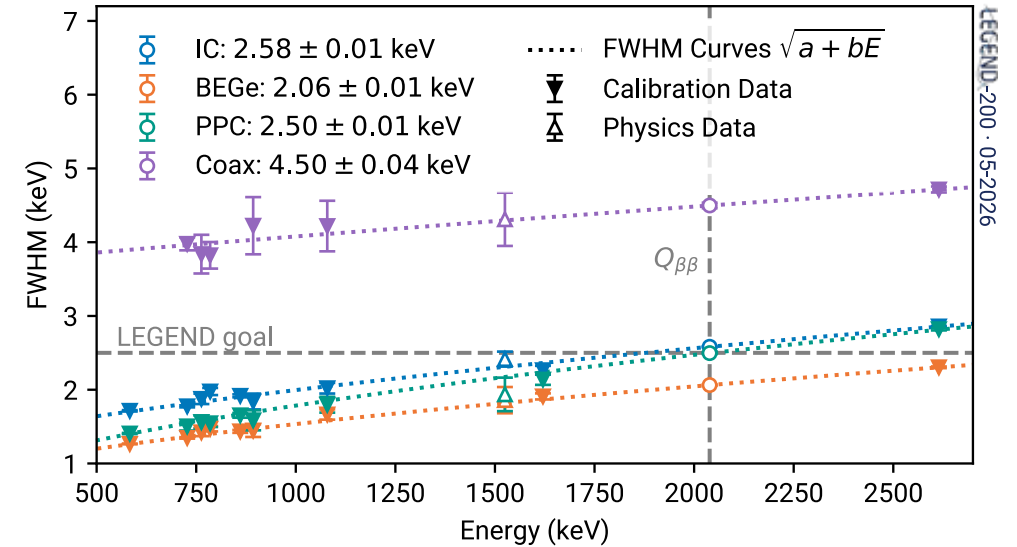
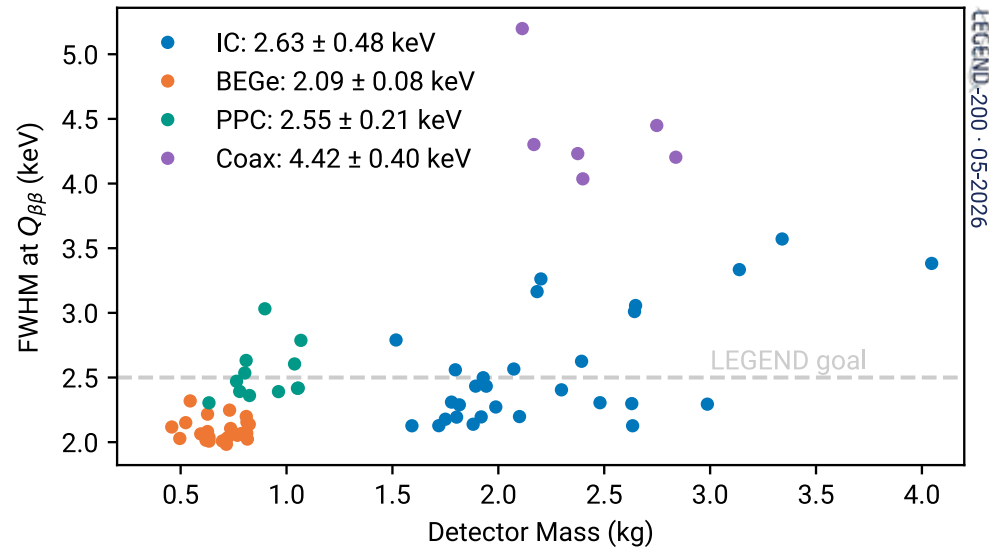
LEGEND - 200



90 tons of liquid Ar
Up to 200 kg of enriched Ge
Background index goal of
 2×10^{-4} cts/(keV kg yr)
 $T_{1/2}^{0\nu\beta\beta} > 10^{27}$ yr @ 90% CL (5 yrs)



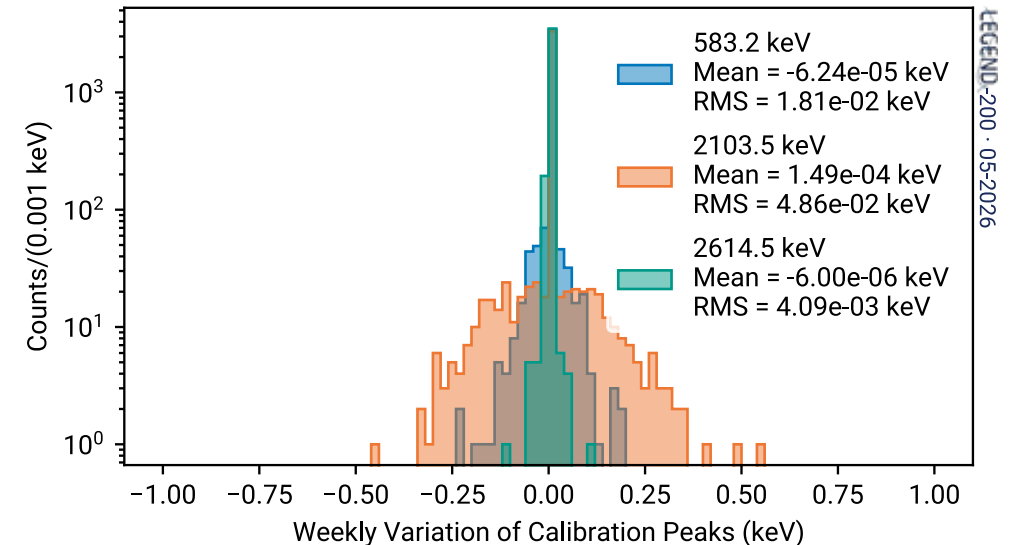
Energy Resolution and Stability



- Energy scale evaluated by **weekly ^{228}Th calibration** between physics runs
- Most of the detectors fulfilling LEGEND **energy resolution** goal (**0.12% at $Q_{\beta\beta}$**)
- **Stable energy** scale among calibrations

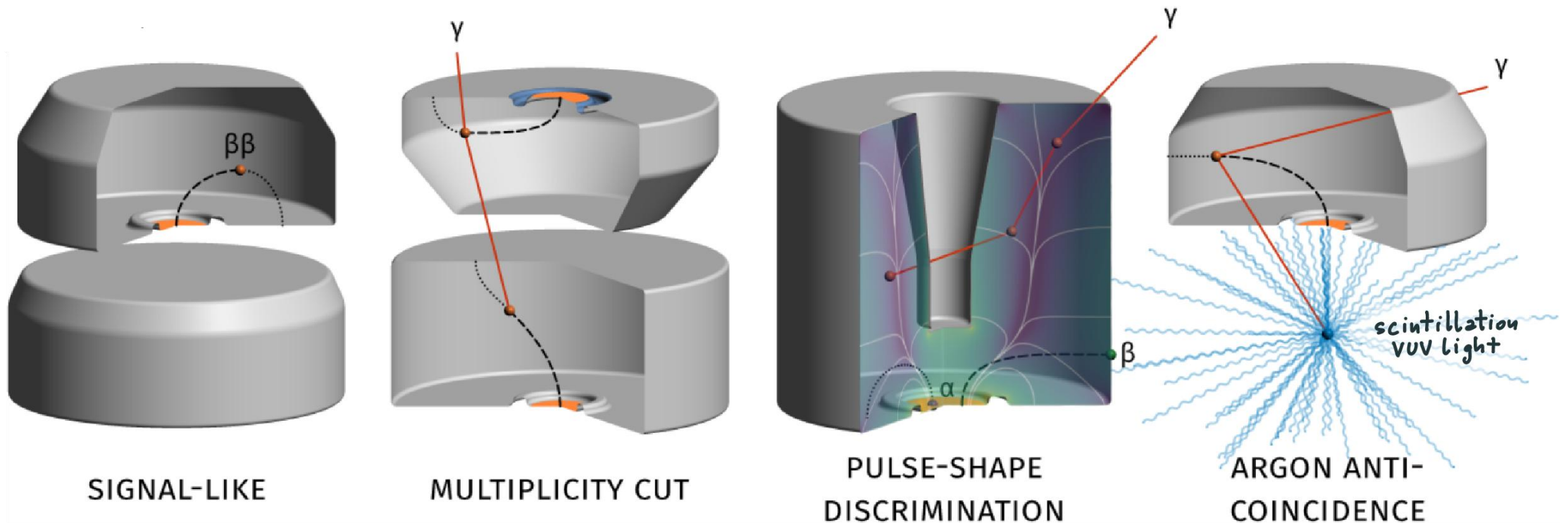
[arXiv:2605.22479](https://arxiv.org/abs/2605.22479) (Accepted by EPJC)

arXiv



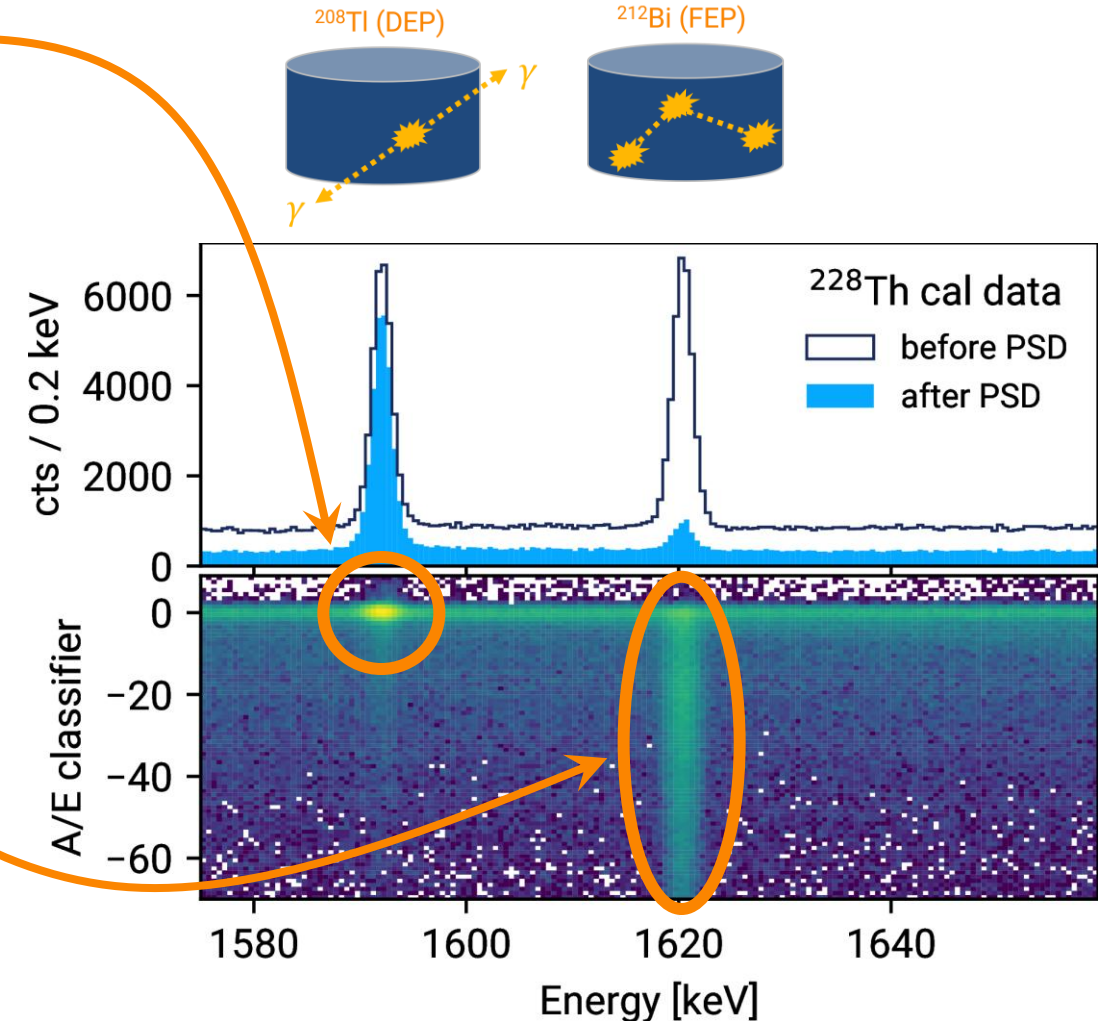
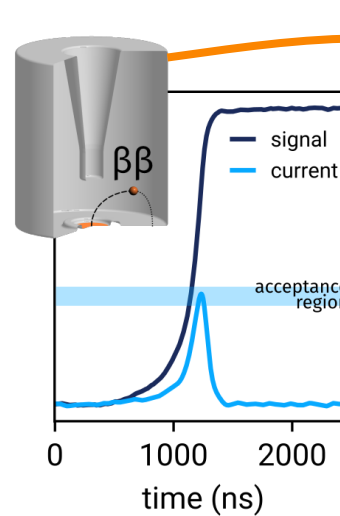
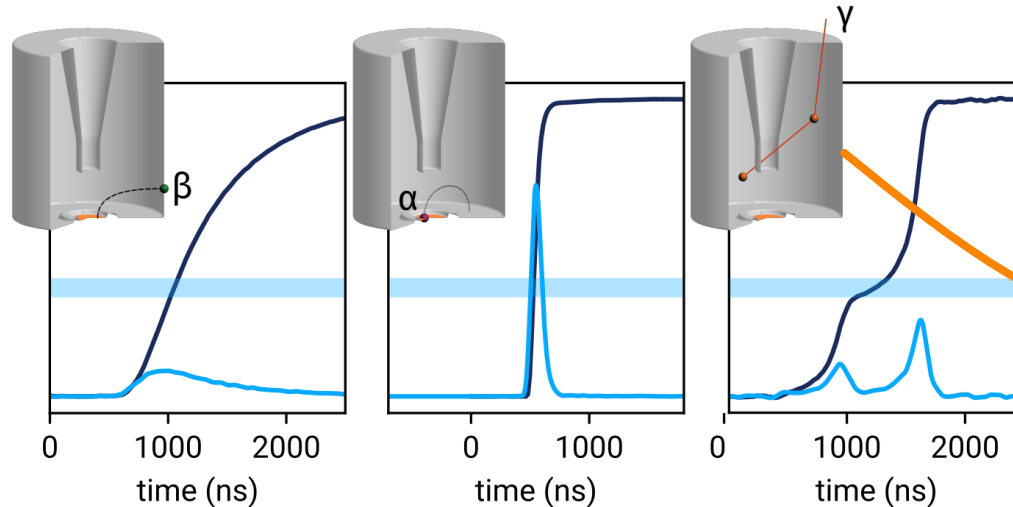
Active Background Rejection

In addition to **careful material selection** and **handling** during installation, **active techniques** allow to further reduce background components

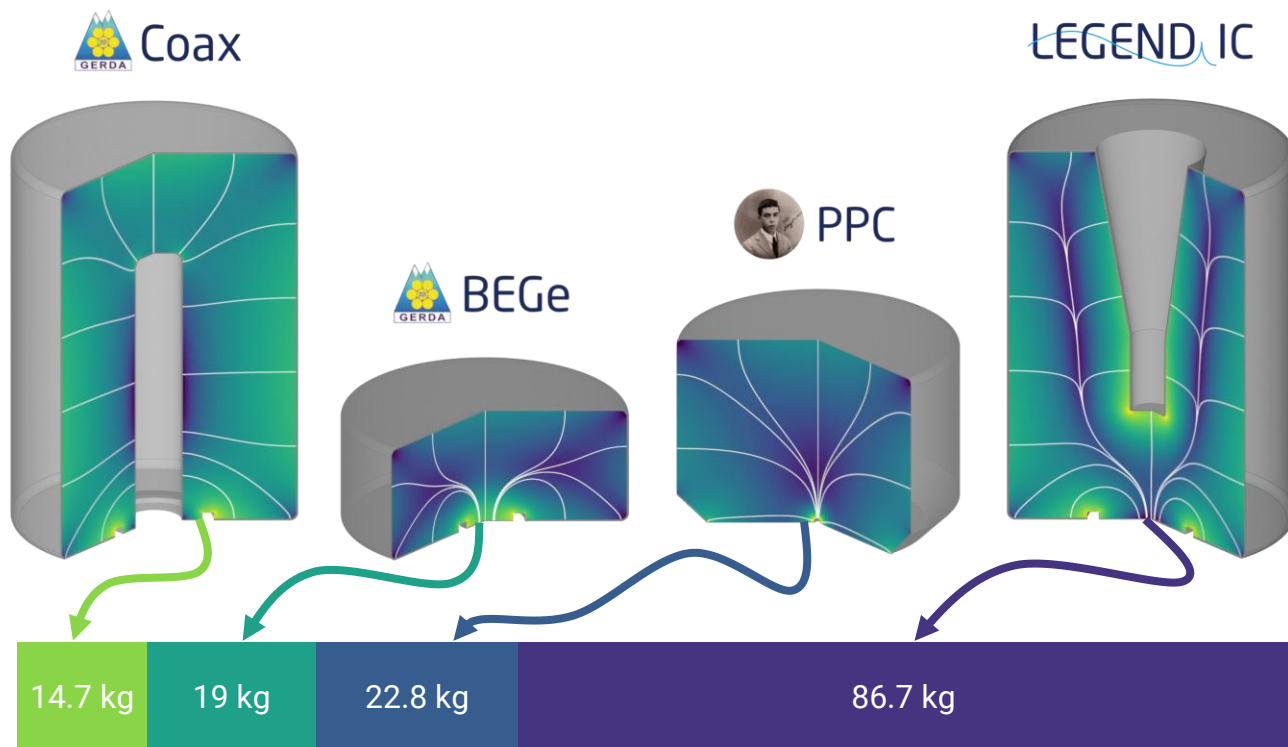


Pulse Shape Discrimination

- For IC and BEGe detectors PSD based on A/E parameter: **rejects multi-site, surface and alpha events effectively**
- Double Escape Peak (DEP) of ^{208}Tl used as single-site event proxy, cut tuned to 90% DEP survival
- Dedicated PSD cuts for other geometries



LEGEND First Deployment

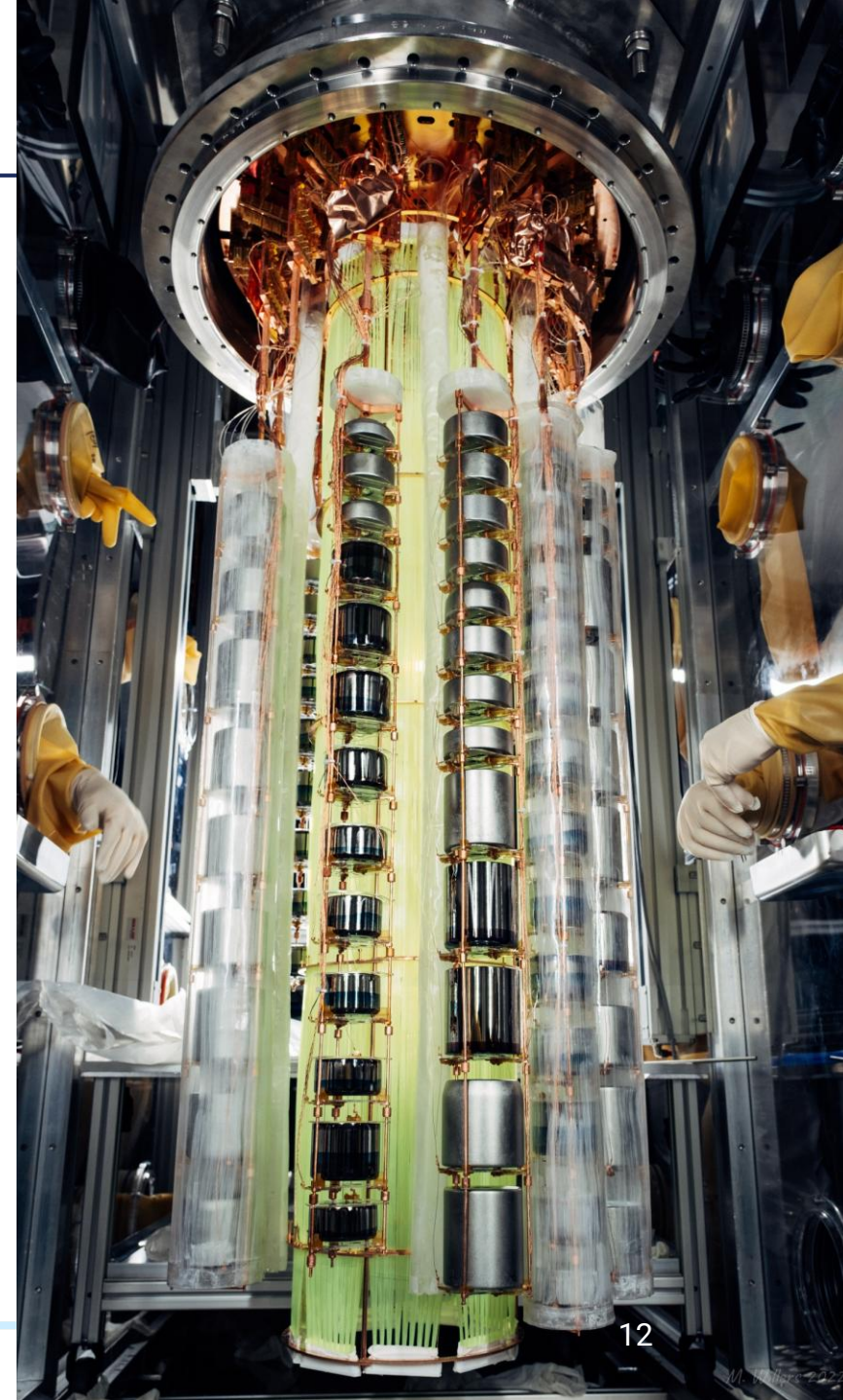


142 kg installation & commissioning

Physics data taking

2023

2024

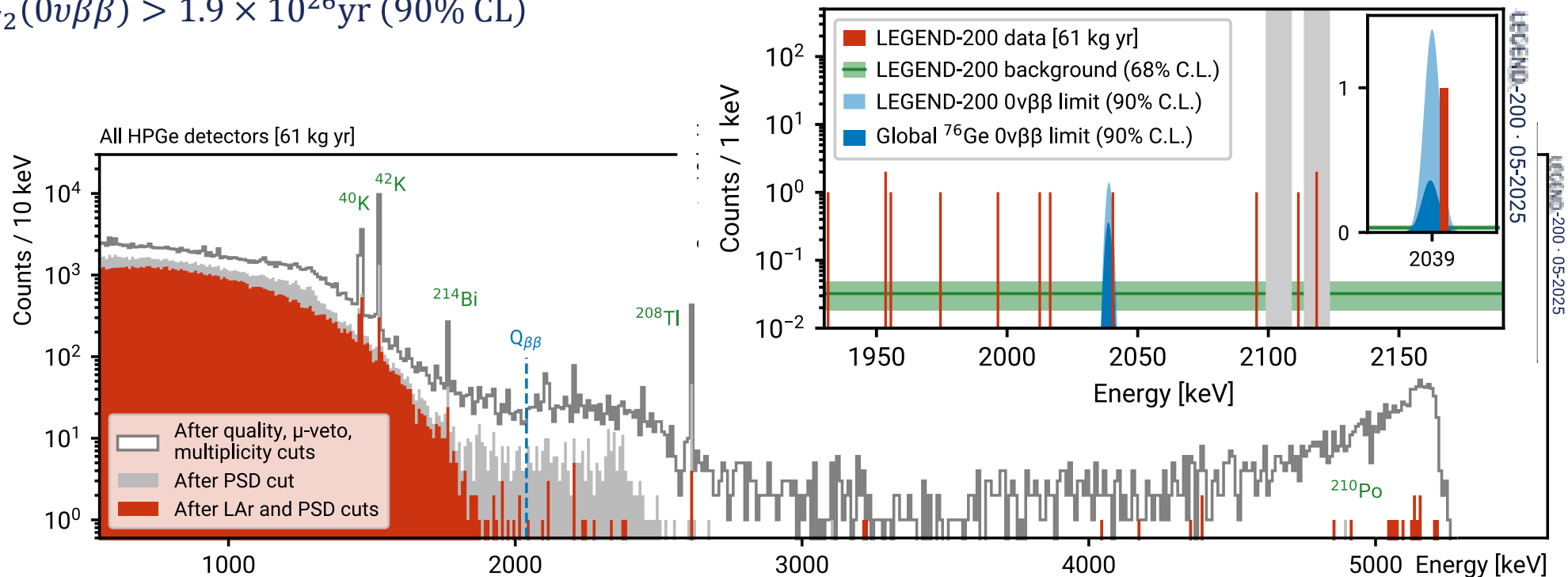


LEGEND First Results

- **11 events** surviving in the BI region after cuts, including 1 event near $Q\beta\beta$.
- **Background index:** $5, 4^{+2,7}_{-2,0} \times 10^{-4}$ cts/(keV · kg · yr) in the “**golden**” dataset (48 kg yr).
- **GERDA + MJD + LEGEND-200 combined:** Exclusion sensitivity: 2.8×10^{26} yr



$$T_{1/2}(0\nu\beta\beta) > 1.9 \times 10^{26} \text{ yr (90\% CL)}$$



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ning

Physics data taking

Background characterization,
maintenance, redeployment

Physics

2023

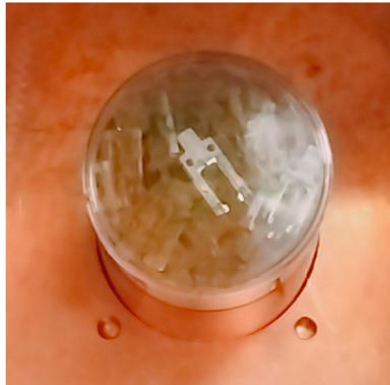
2024

2025

Background Investigations



- Final BI **~2.5 higher** than predicted $\rightarrow$ **elevated U (^{214}Bi)/Th (^{208}Tl)** levels before cuts
- **Forensic campaign:**
 - Special runs: **outer fiber barrel** and **nylon mini-shrouds** removed
 - Array dismantled and all components sent for **assay**
 - Results from assays: elevated U (^{214}Bi)/Th (^{208}Tl) in some components: hypothesized **surface contamination**, BI dominated by U (^{214}Bi)



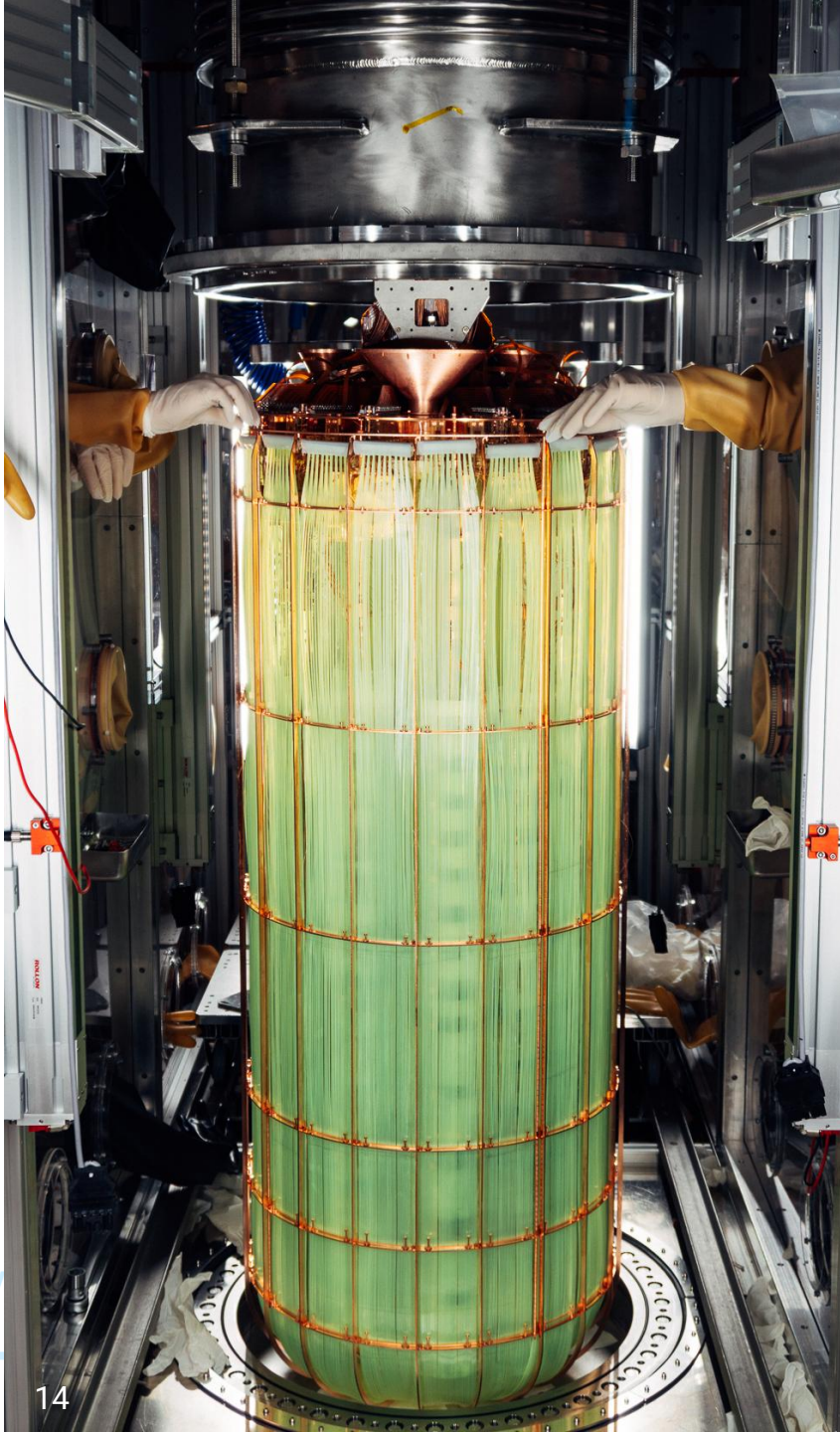
Background characterization,
maintenance, redeployment

ata taking

Phy

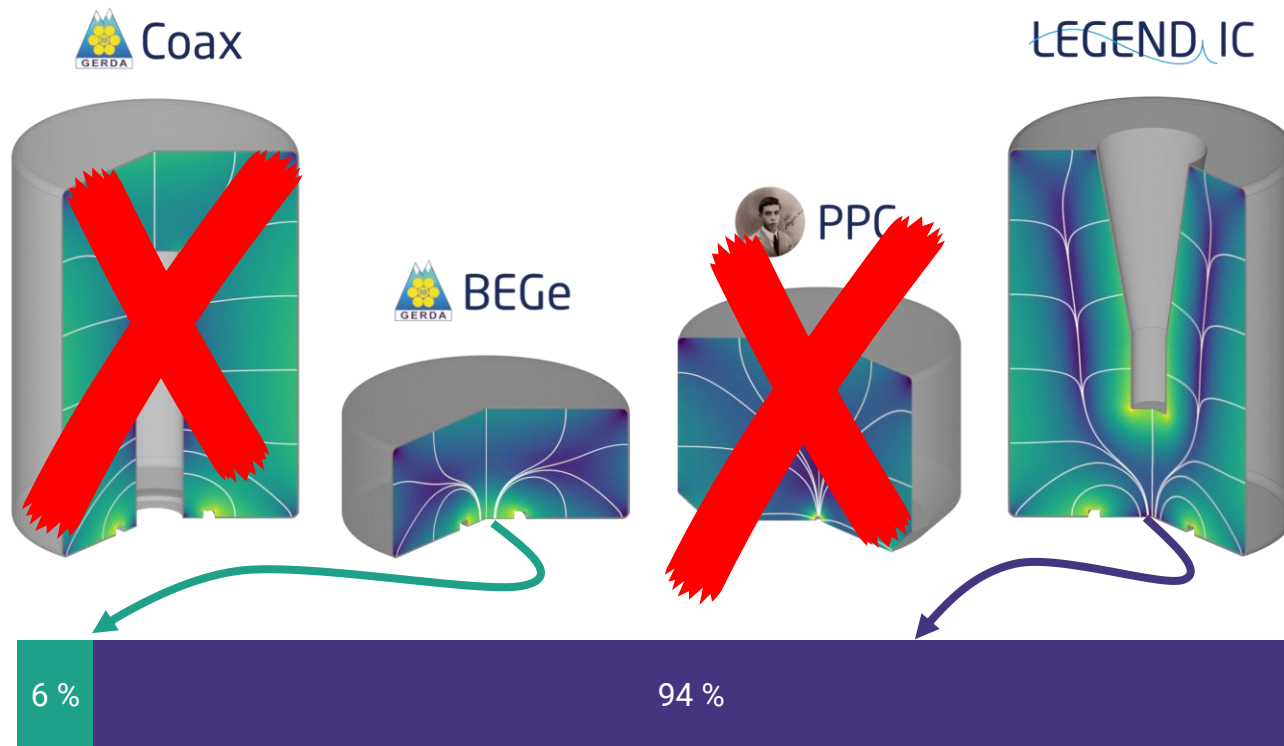
2024

2025



LEGEND Redeployment

- New deployment of **138 kg** HPGe in July 2025
 - Almost all **high performance IC** HPGe
 - All components re-etched/leached
- **Conversion** of Coax, PPC, BEGe and underperforming detectors **to IC**



ata taking

Background characterization,
maintenance, redeployment

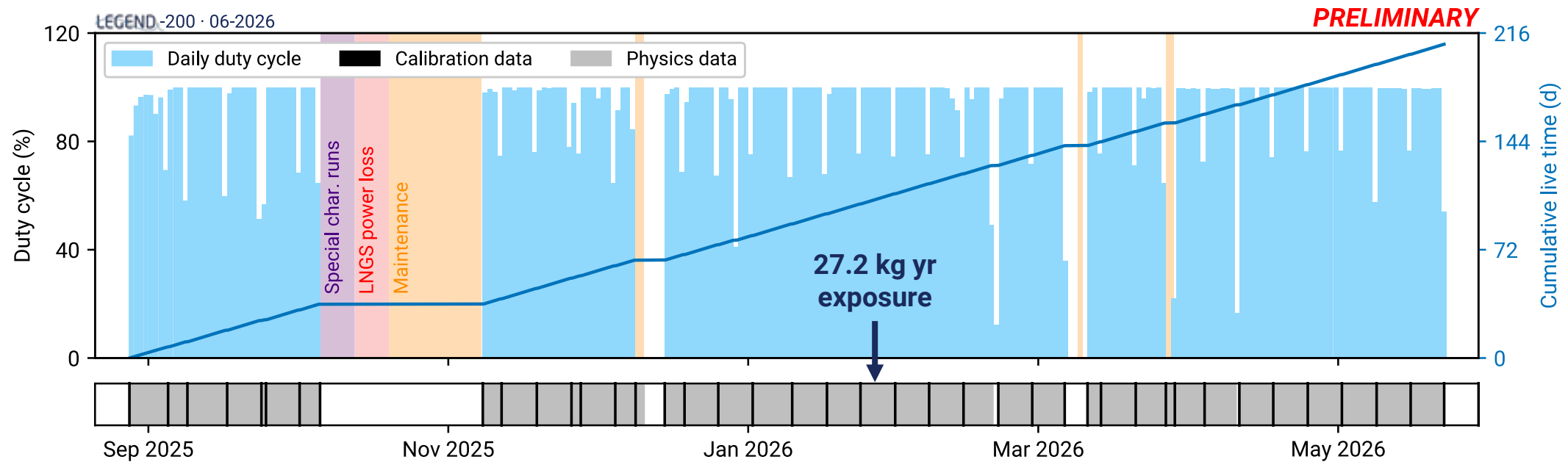
Phy

2024

2025



Back to Physics Data Taking



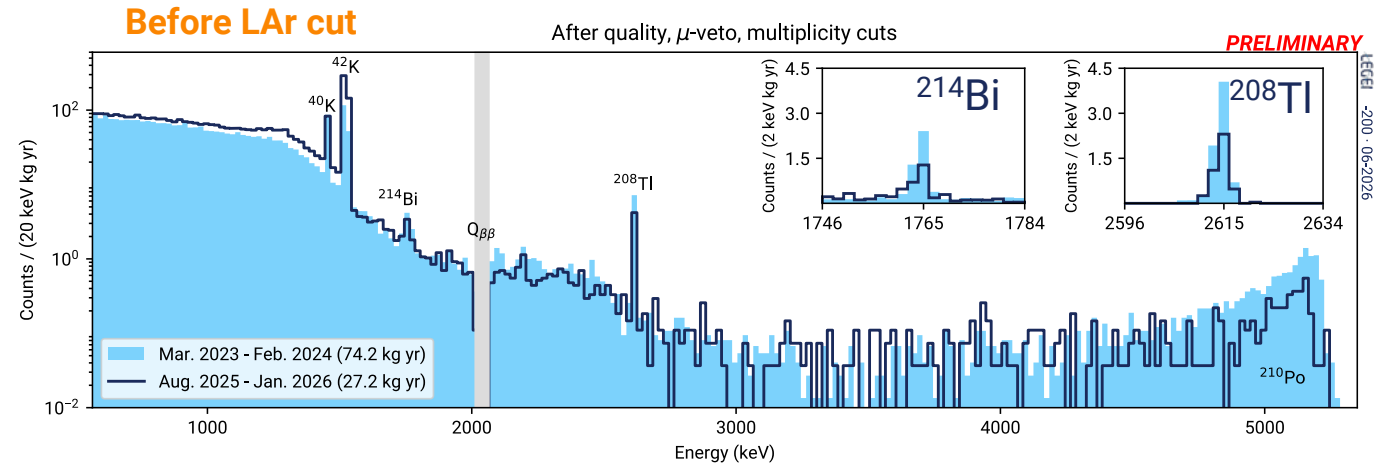
- Currently **taking stable physics data** since Fall 2025
- Downtimes for special calibrations and maintenance
- **Duty cycle**: 95% (70%) without/with downtimes
- Data validated and shown here up to end of Jan 2026: **27.2 kg yr exposure** (no PSD consideration)

Background characterization,
maintenance, redeployment

Physics data taking

LEGEND - 200 Current Background

^{214}Bi (U)/ ^{208}Tl (Th) reduced by $\sim x2$ before cuts relative to the first-year results



Background characterization,
maintenance, redeployment

Physics data taking

2024

2025

2026

17

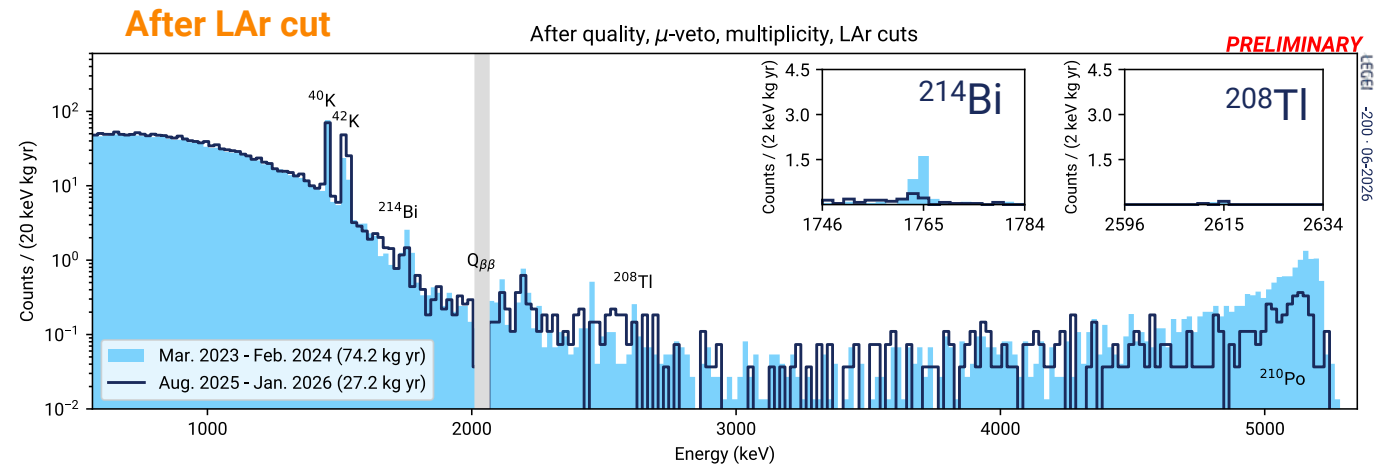
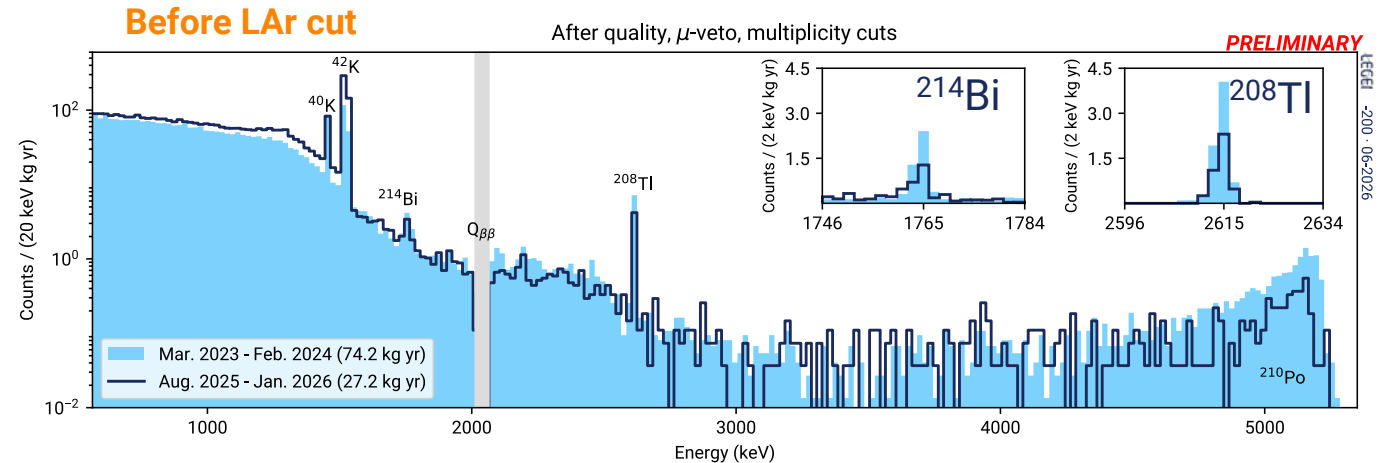
LEGEND - 200 Current Background

^{214}Bi (U)/ ^{208}Tl (Th) reduced by $\sim x2$ before cuts relative to the first-year results

After LAr cut:

- $x5$ overall reduction of ^{214}Bi 1764 keV gamma-line!
- $^{208}\text{Tl} \sim$ **eliminated** at current statistics

Successful cleaning campaign!



Background characterization,
maintenance, redeployment

Physics data taking

LEGEND - 200 Current Background

^{214}Bi (U)/ ^{208}Tl (Th) reduced by $\sim x2$ before cuts relative to the first-year results

After LAr cut:

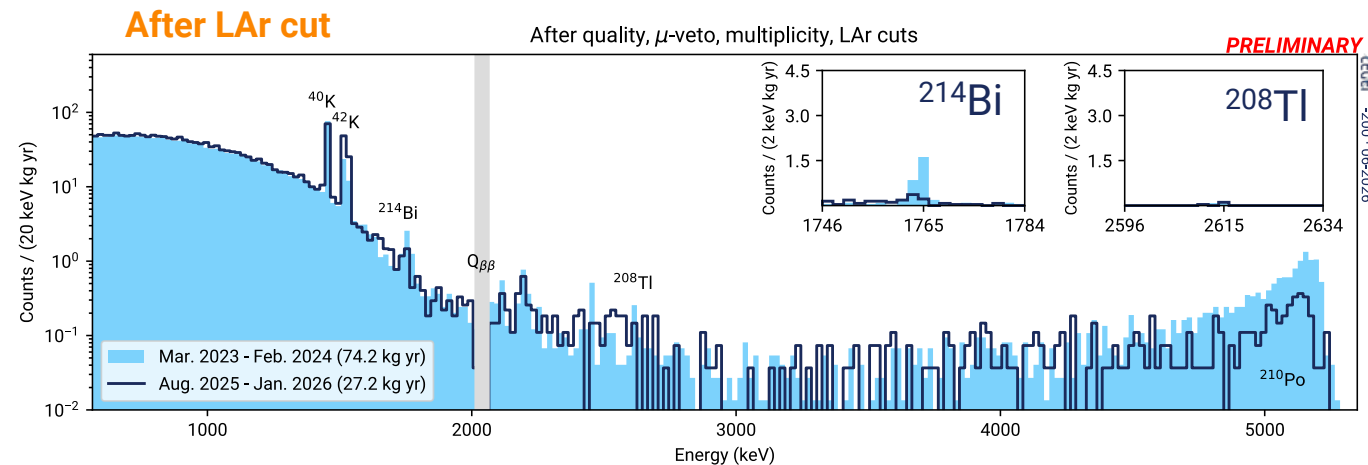
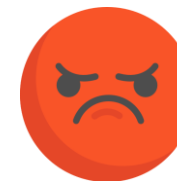
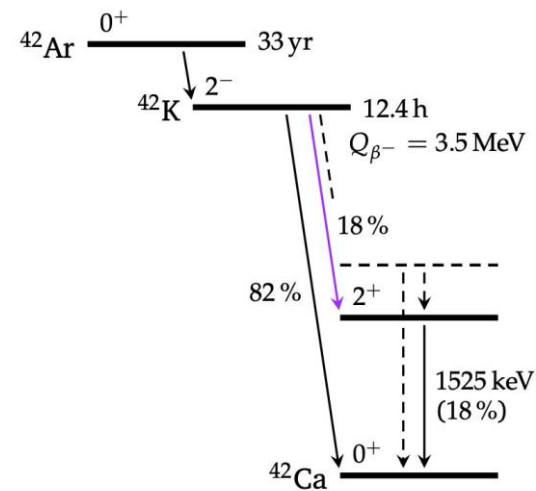
- $x5$ overall reduction of ^{214}Bi 1764 keV gamma-line!
- ^{208}Tl $\sim$ **eliminated** at current statistics

Successful cleaning campaign!



After LAr + PSD cuts: remaining backgrounds seem to be dominated by ^{42}K surface events

Work in progress: optimize analysis methods to **reject** ^{42}K surface events



Background characterization,
maintenance, redeployment

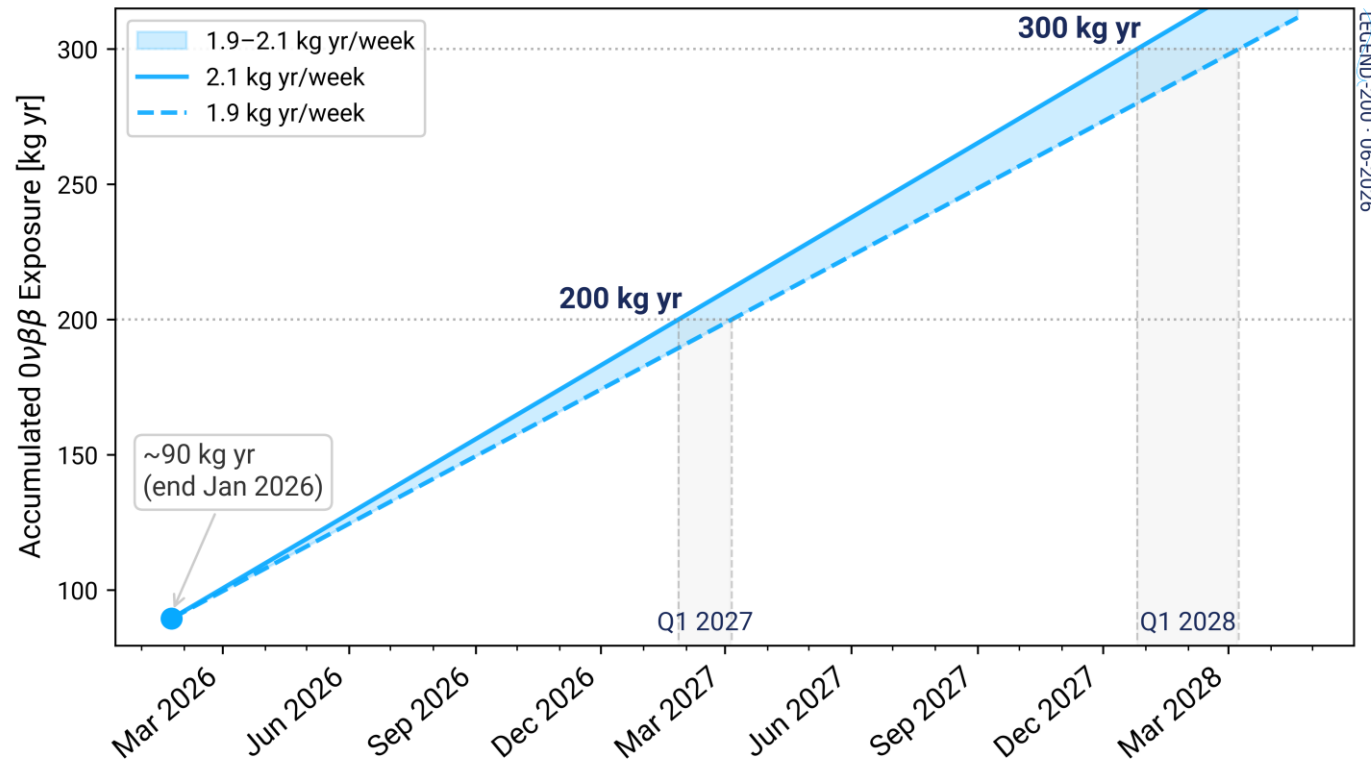
Physics data taking

LEGEND - 200 Future Plans

Current data taking:

- Currently in stable data taking to achieve **maximal exposure for both $0\nu\beta\beta$ and additional analysis**

L200 exposure projections



Next deployment:

- Planned for 2028 with a total of **~160 kg Ge detectors**
- Ongoing R&D** on PEN components and electronic noise mitigation
- Continue operation** until L1000 commissioning

LEGEND - 1000 Overview

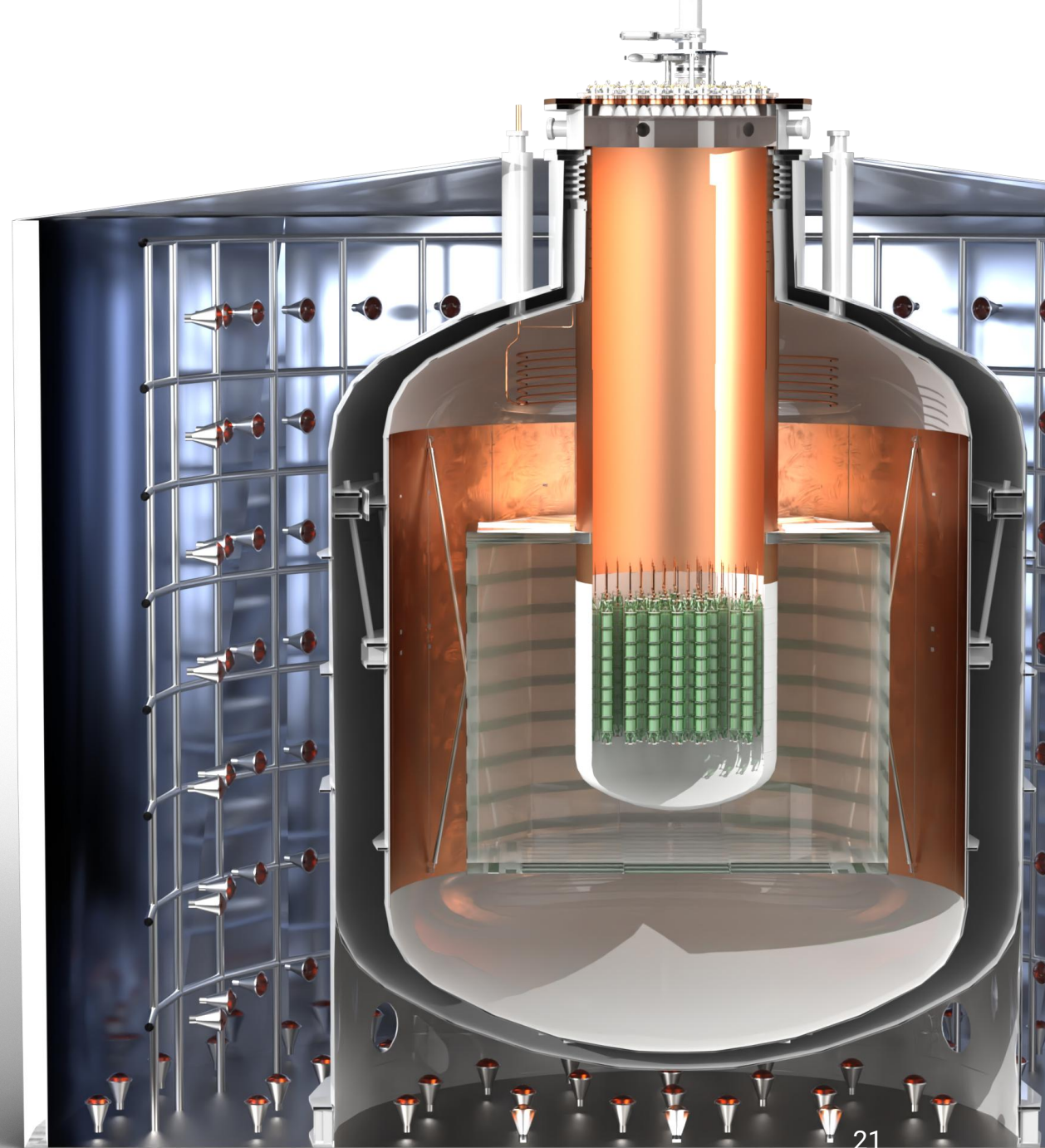
Second phase of LEGEND project

New experimental setup at LNGS

- **1 ton** of 90% enriched HPGe Detectors
- BI Goal: $\sim 10^{-5}$ cts/(keV kg yr)
- Discovery Sensitivity Goal: $T_{1/2}^{0\nu\beta\beta} > 10^{28}$

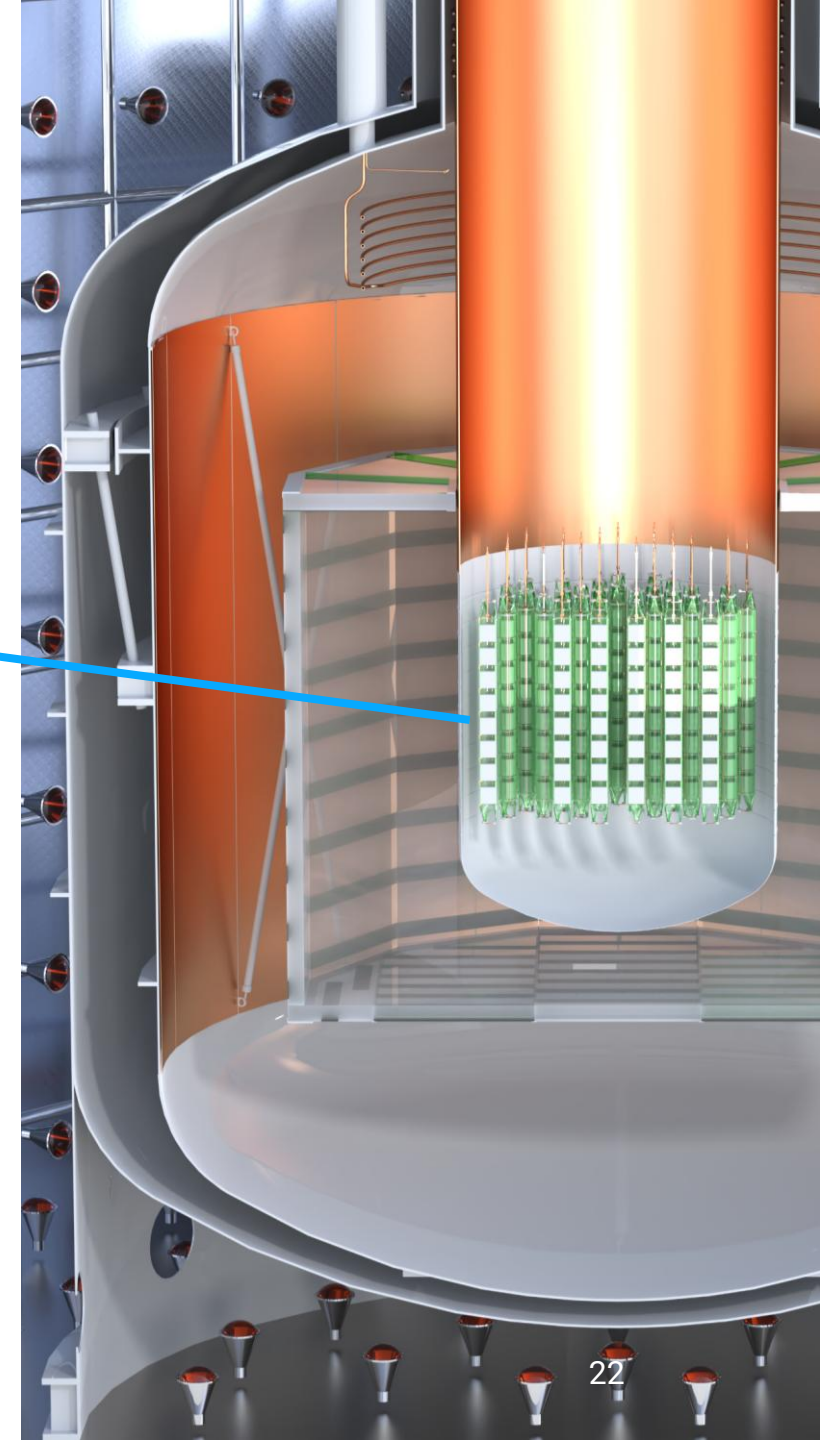
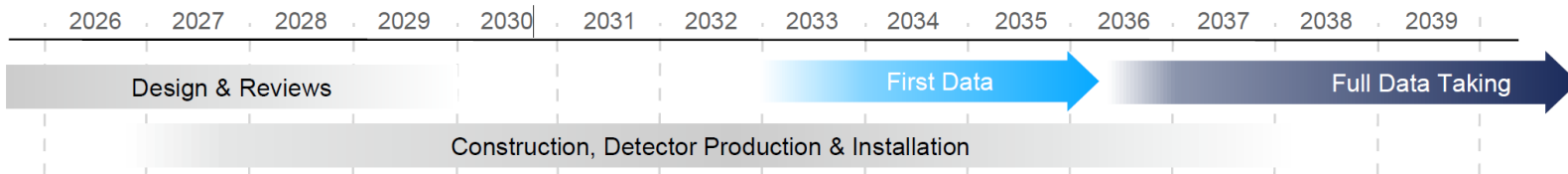
LEGEND-1000 **funding**:

- **US**: NSF (final design phase MREFC) & DOE (CD-1 review)
- **Europe**: MPG and DFG support; German FIS National Research Infrastructure process (decision July 2026); INFN flagship project; contributions from Switzerland and Poland; UK roadmap pending



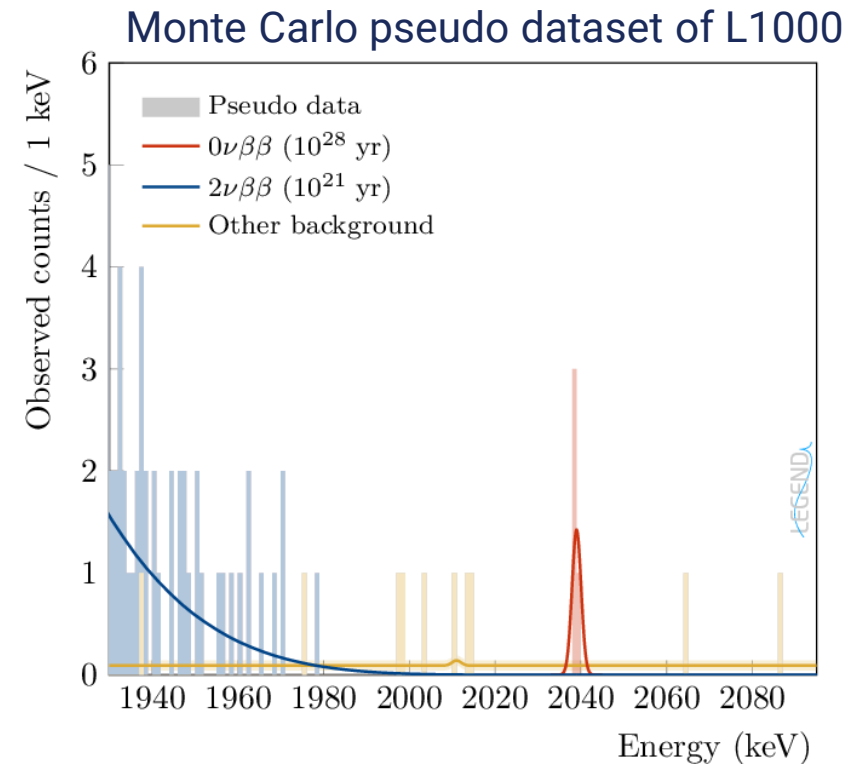
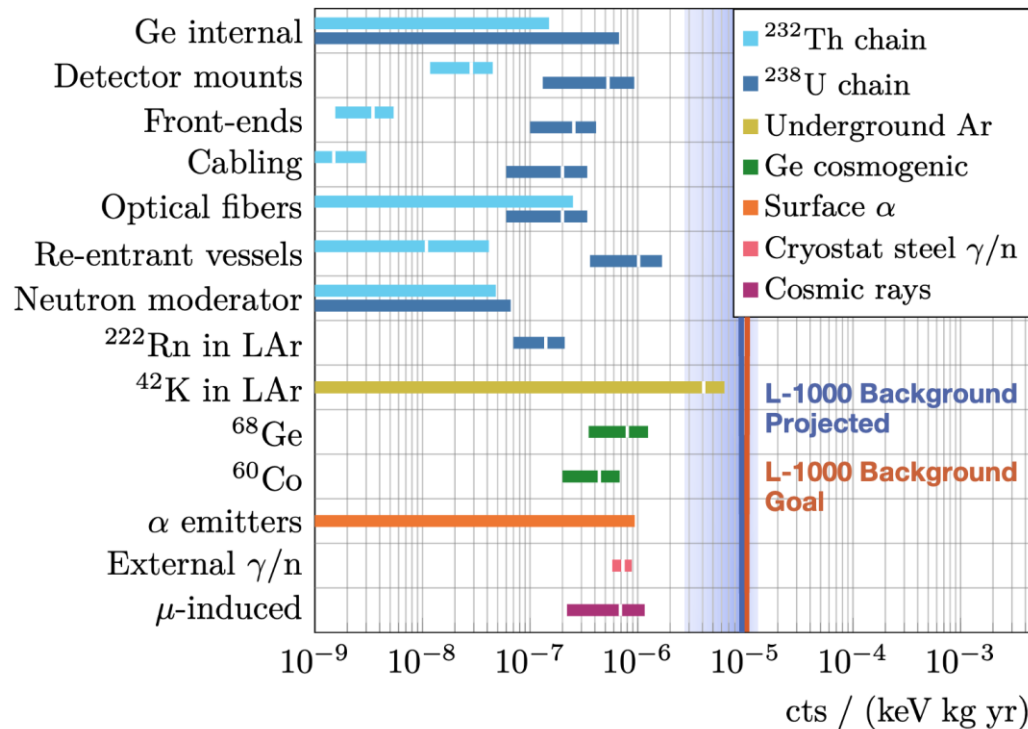
LEGEND - 1000 Key Improvements

- All larger-mass **IC detectors** (~3 kg)
- **Single-string modules**, individually deployable
- **ASIC-based** readout electronics
- Inner **underground liquid argon** volume to remove $^{42}\text{Ar}/^{42}\text{K}$ backgrounds
- **Atmospheric argon instrumentation** for cosmogenic background



LEGEND - 1000 Designed For Discovery

- **Dominant backgrounds:**
 - U/Th in the reentrant vessel
 - Residual ^{42}K in UAr (conservative estimate)
- L1000 improvements → **0.4 counts/(10 ton·yr) in the ROI** → **quasi-background-free operation**



Summary

LEGEND - 200

- First $0\nu\beta\beta$ unblinding successfully published
- Cleaning campaign successful; data taking resumed with 138-kg redeployment
- ^{42}K identified as a major background source; mitigation strategies under study
- New $0\nu\beta\beta$ unblinding and BSM results to come

LEGEND - 1000

- Strong momentum toward tonne-scale $0\nu\beta\beta$ search
- Technical preparations advancing toward construction

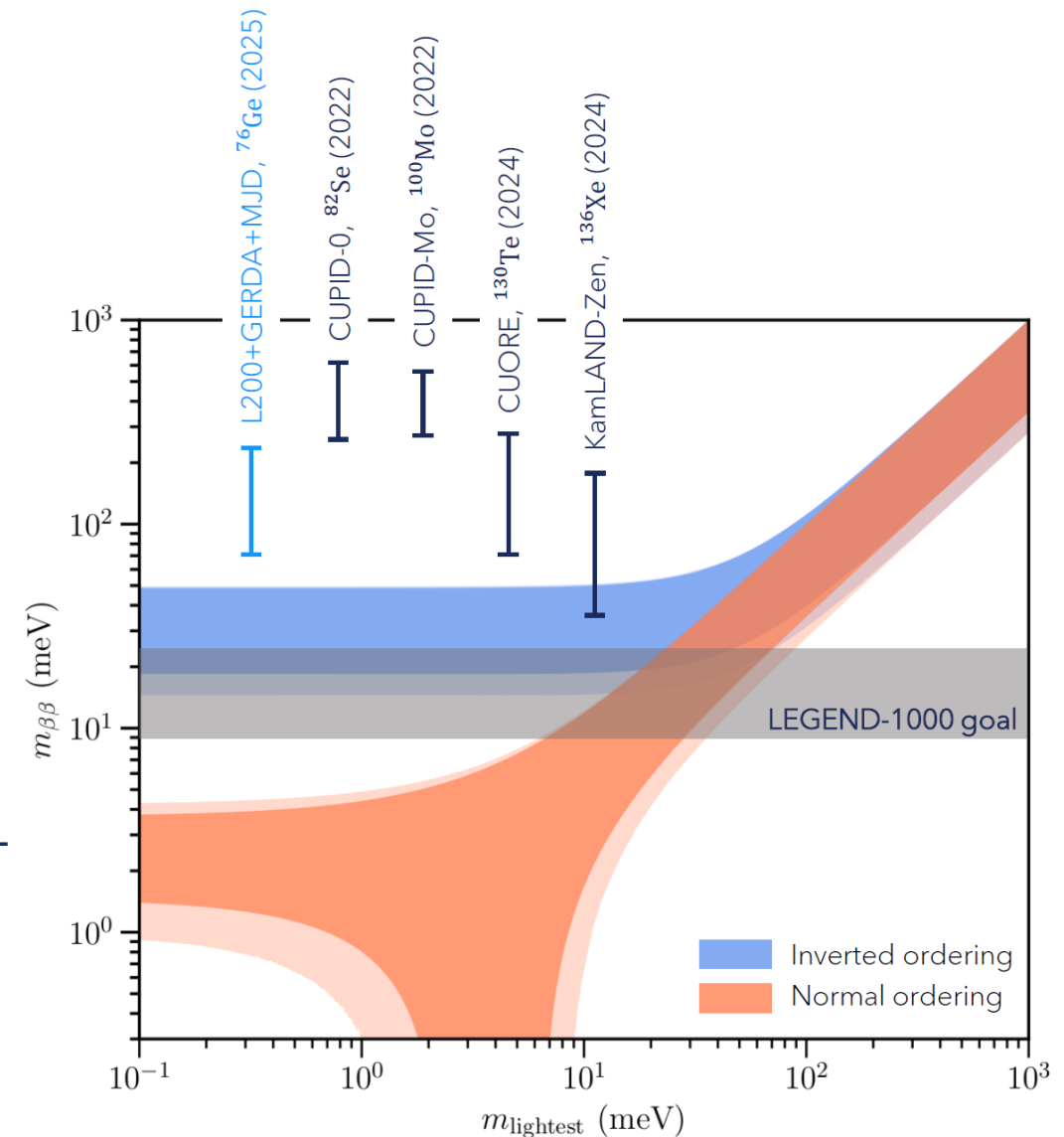
Backup

Limits on $m_{\beta\beta}$

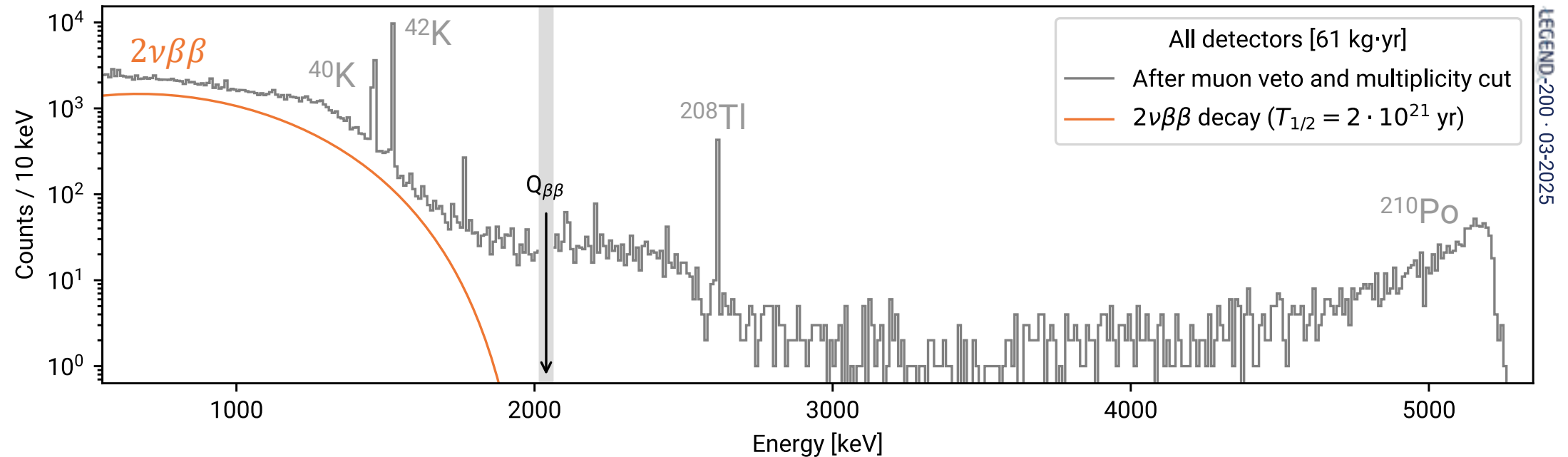
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z) \underset{\substack{\text{Nuclear} \\ \text{Matrix} \\ \text{Element}}}{|M^{0\nu}|^2} \left(\frac{m_{\beta\beta}}{m_e} \right)^2 \rightarrow \left| \sum_i U_{ei}^2 m_i \right|$$

Effective Majorana neutrino mass

- Assumption: light Majorana neutrino exchange
- Range of phenomenological NME (^{76}Ge : 2.35 – 6.34)
 - $m_{\beta\beta} < 75\text{-}200 \text{ meV @ 90\% CL}$
- Uncertainty-quantified NME (^{76}Ge : $2,6_{-1,36}^{+1,28}$)
 - Bayesian *ab-initio* calculation with quenching and short-range physics [Belley et al., PRL 132, 182502 (2024)]
 - $m_{\beta\beta} < 316 \text{ meV @ 90\% CL}$
 - A new era of uncertainty-quantified NME - however, uncertainties remain significant

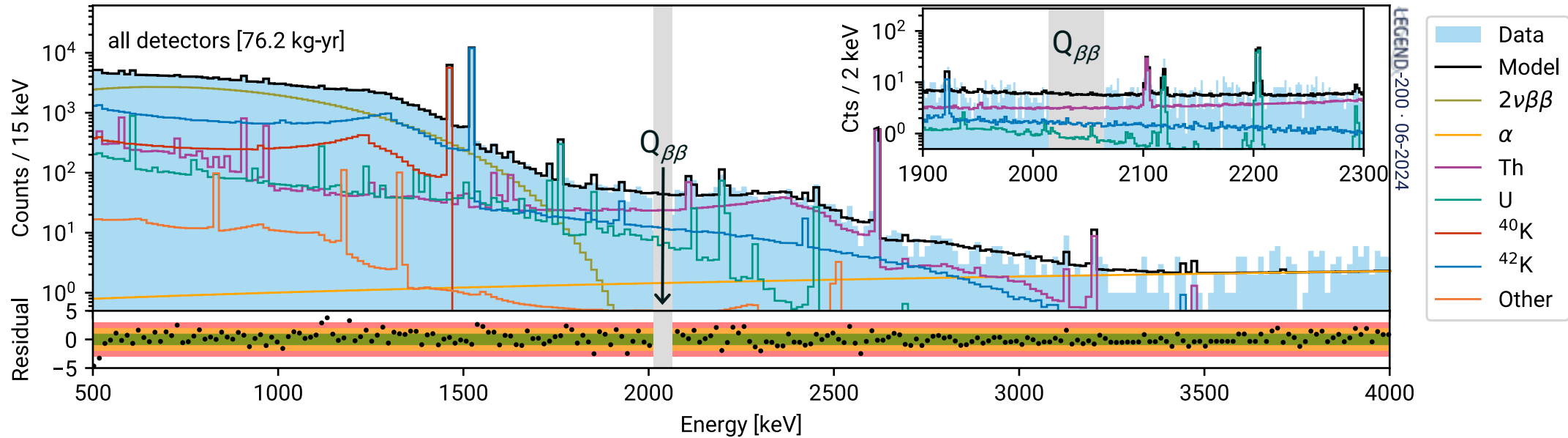


Energy Spectrum



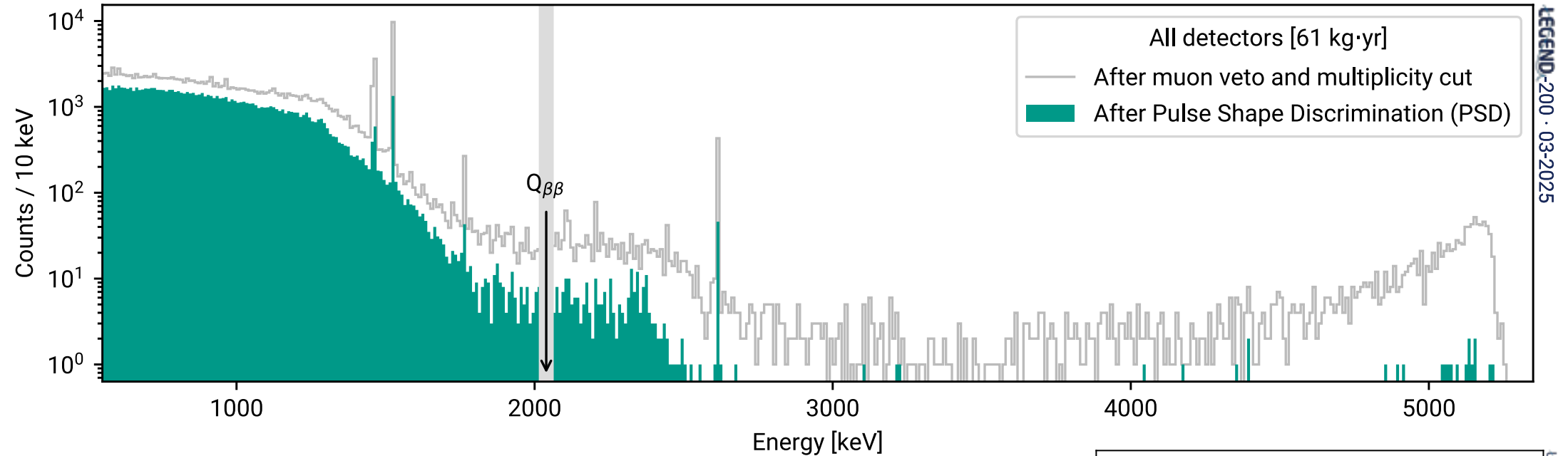
- **Blinded analysis in $Q_{\beta\beta} \pm 25$ keV**
- Spectrum after:
 - **data cleaning** → 95-99% survival after removal of unphysical events
 - **muon veto** → 2 events removed at $Q_{\beta\beta}$
 - **multiplicity cut** → 26% events removed at $Q_{\beta\beta}$

Background model [76.2 kg·yr]

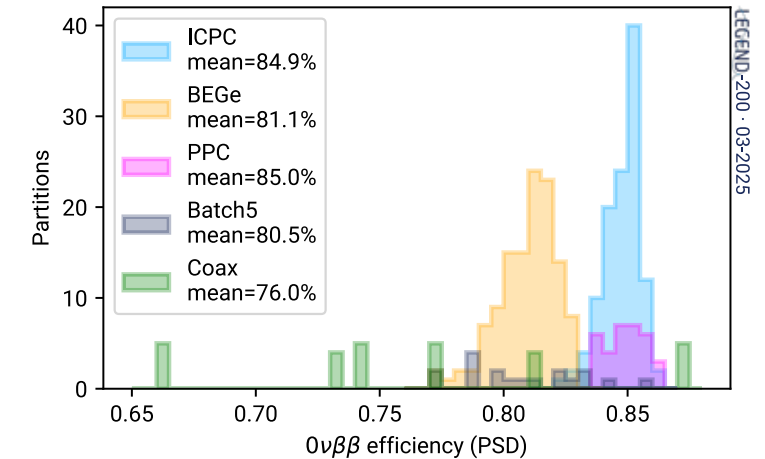


- **Bayesian background model** using the full dataset + extra 10.2 kg·yr of special runs
- Decomposition of the full-range energy spectrum: **no unexpected background components**
- **Flat background** in the region of interest for the $0\nu\beta\beta$ decay analysis
- ^{228}Th underprediction in physics data compared to radioassay predictions
 - **Cleaning campaign** to reduce background further
 - This background is efficiently suppressed by analysis cuts

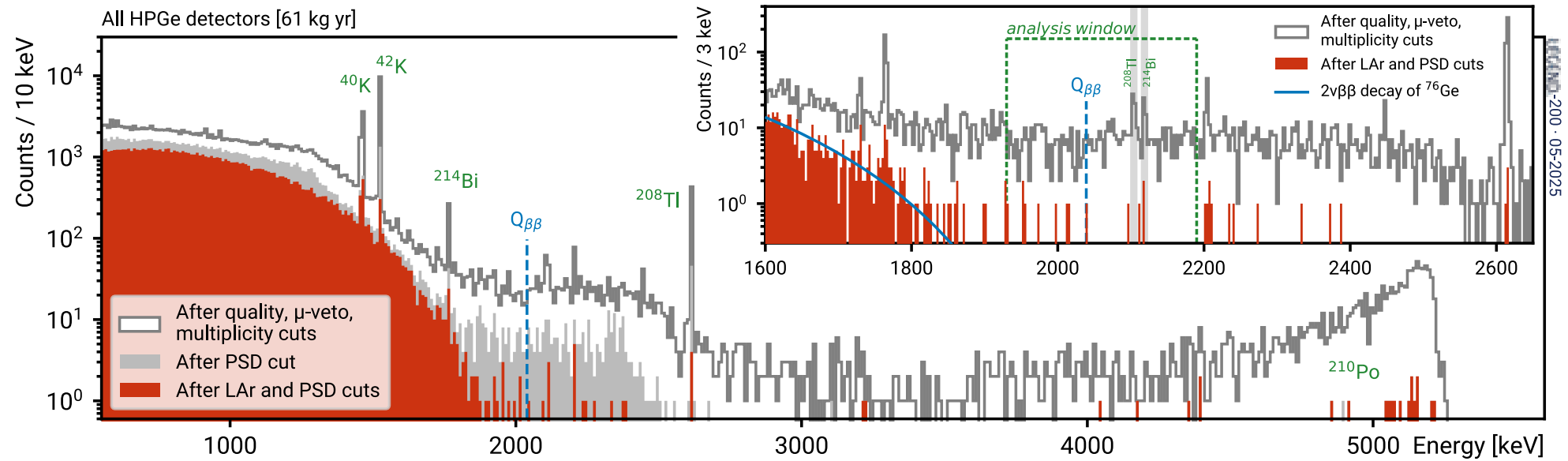
Energy Spectrum after PSD



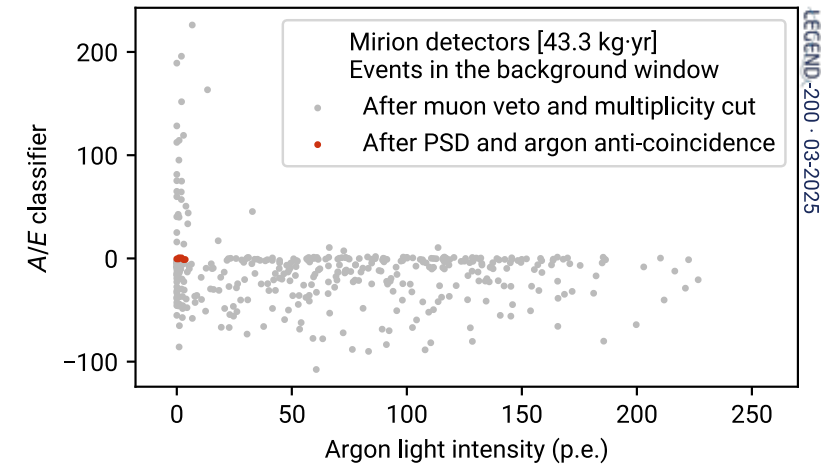
- Strong suppression of **surface α and β** (^{42}K) events
- **~60% suppression of Compton multi-site** events at $Q_{\beta\beta}$
- $0\nu\beta\beta$ decay survival fraction of 85%



Energy Spectrum after PSD & LAr cut

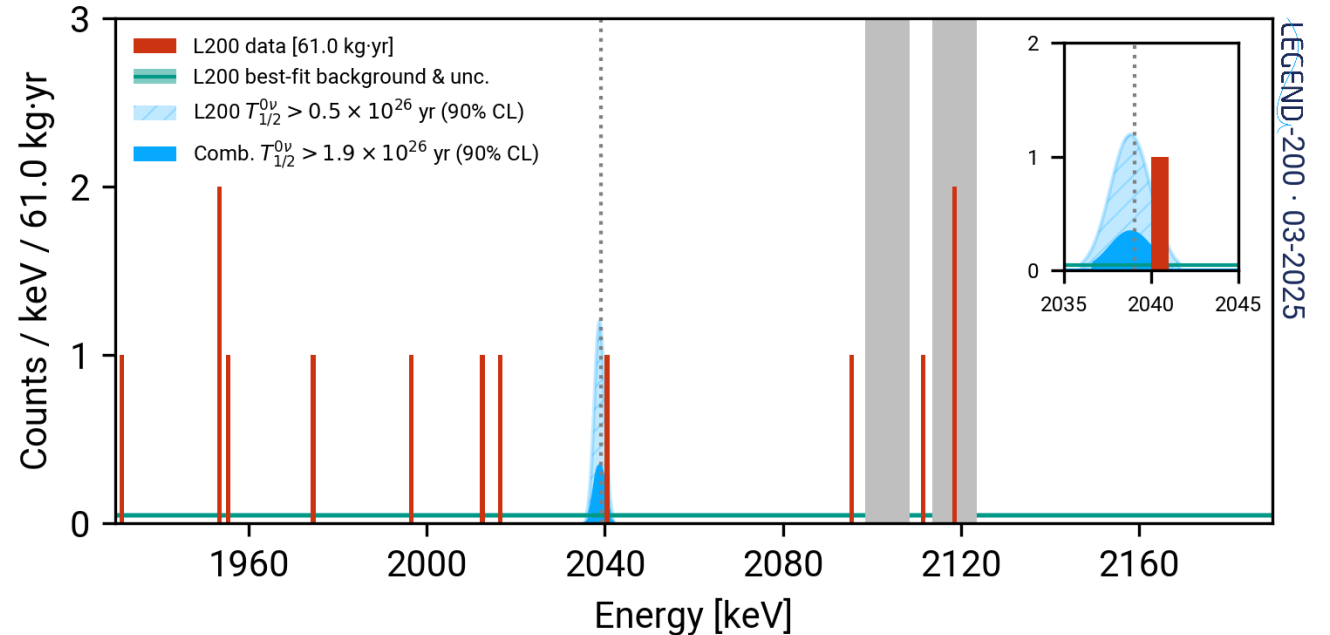


- LAr $\beta\beta$ decay signal acceptance of $\sim 93\%$
- **Strong anti-correlation of PSD & LAr cuts**
- Almost pure $2\nu\beta\beta$ distribution



LEGEND₂₀₀ - 200 Unblinded Results

- Analysis window: **1930-2190 keV**
(excluding ^{208}Tl and ^{214}Bi γ lines)
- **11 events surviving after cuts**
- **Background indices:**
 - $\text{BI}_{\text{gold}} = 5,4_{-2,0}^{+2,7} \times 10^{-4} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$
 - $\text{BI}_{\text{silver}} = 13_{-5,4}^{+8,0} \times 10^{-4} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$
(Detector with worse background rejection, mainly COAX)



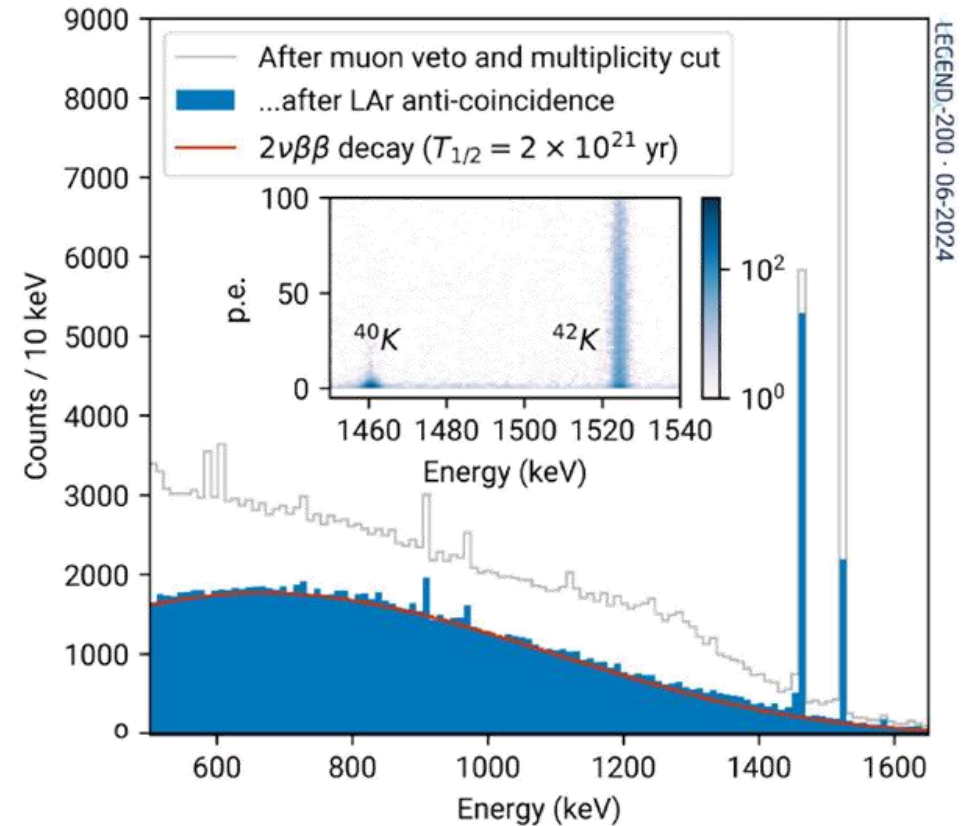
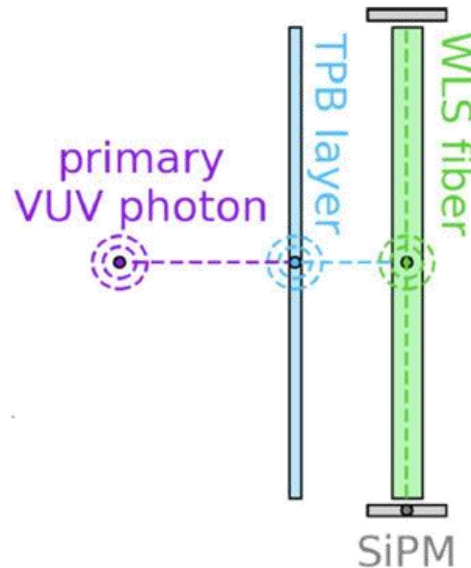
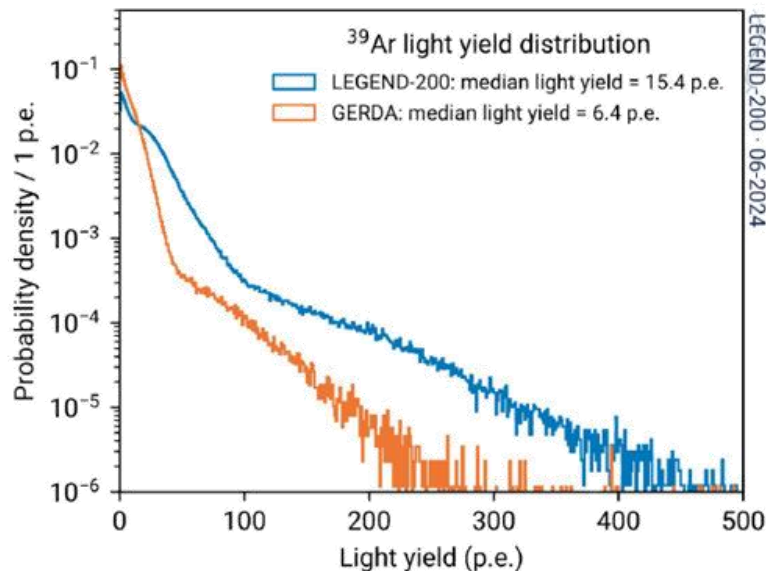
Combined fit GERDA + MJD + LEGEND₂₀₀

- Frequentist and Bayesian statistical analysis → **no evidence of $0\nu\beta\beta$ signal**
- **Lower limit $T_{1/2} > 1.9 \times 10^{26} \text{ yr}$ @ 90% CL → $m_{\beta\beta} < 70\text{--}200 \text{ meV}$**
- **World-leading sensitivity → $2.8 \times 10^{26} \text{ yr}$ @ 90% CL**
- One event at 1.4σ from $Q_{\beta\beta}$ weakens observed limit



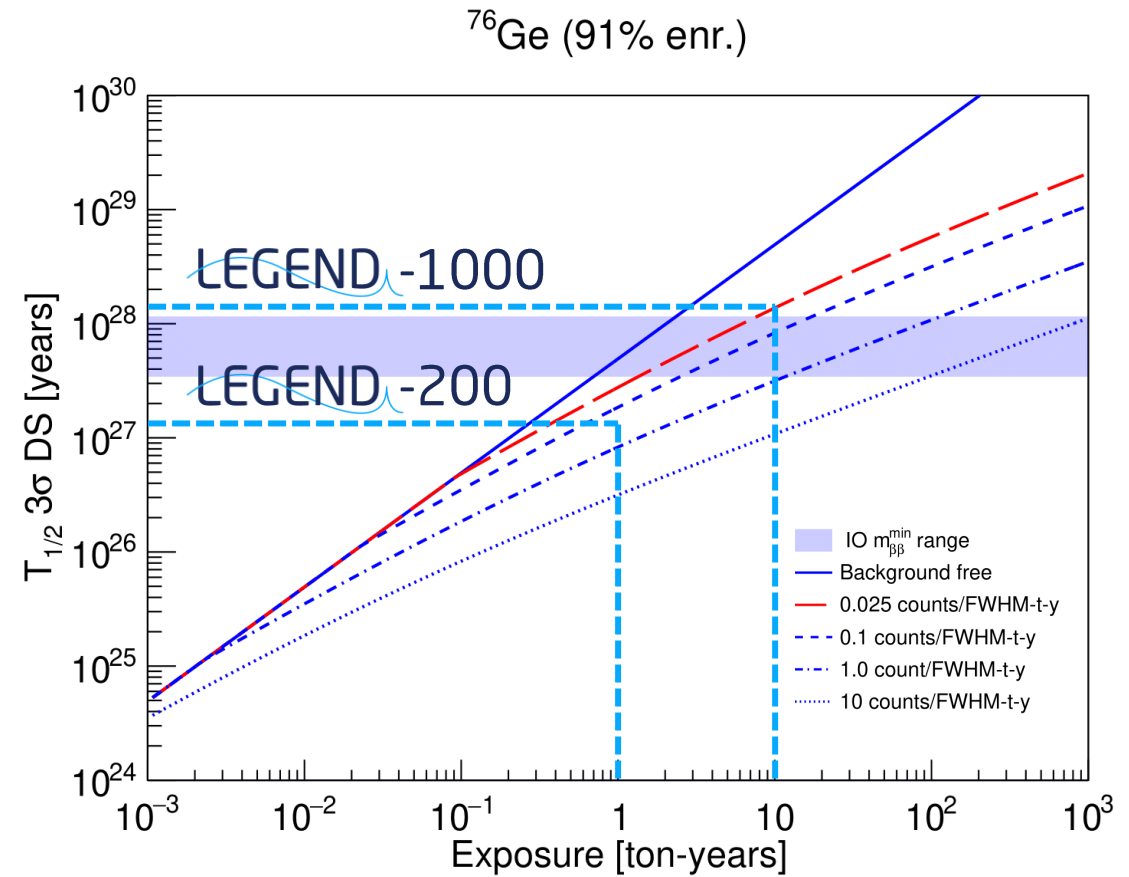
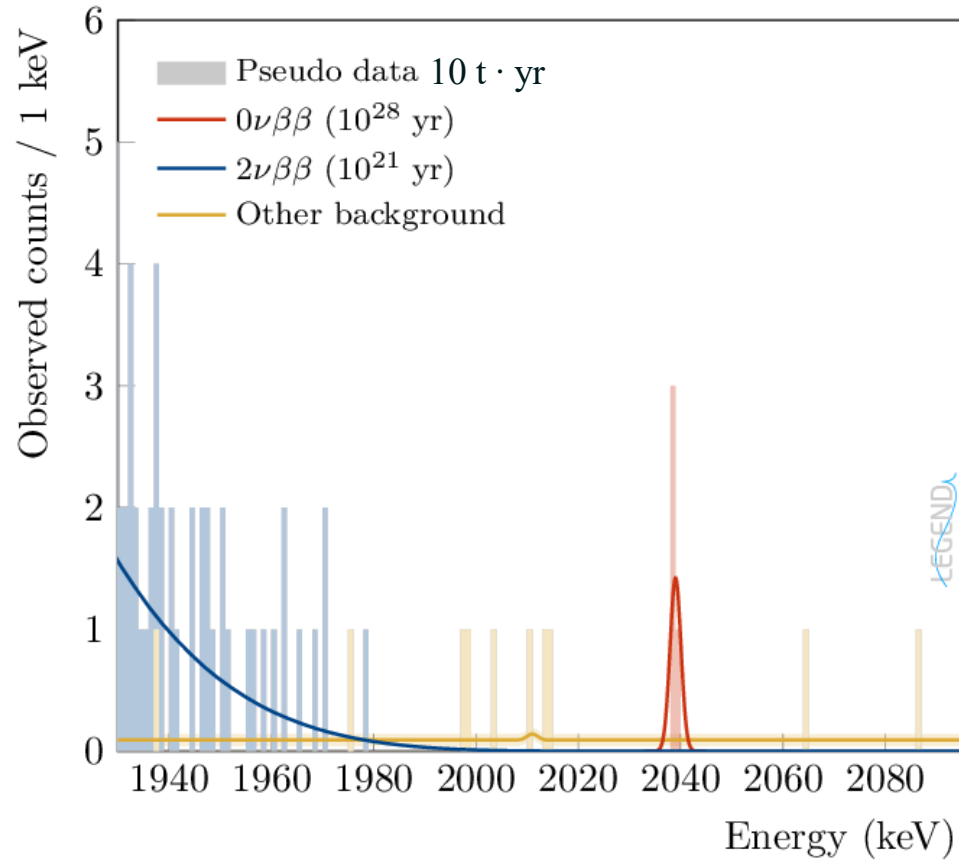
LAr instrumentation

- Detects and suppresses background events through detection of LAr scintillation light
- Background events can deposit energy in LAr creating 128 nm VUV photons, then shifted to visible light and read by SiPM arrays
- System successfully operated in GERDA, now with higher light yield and less shadowing

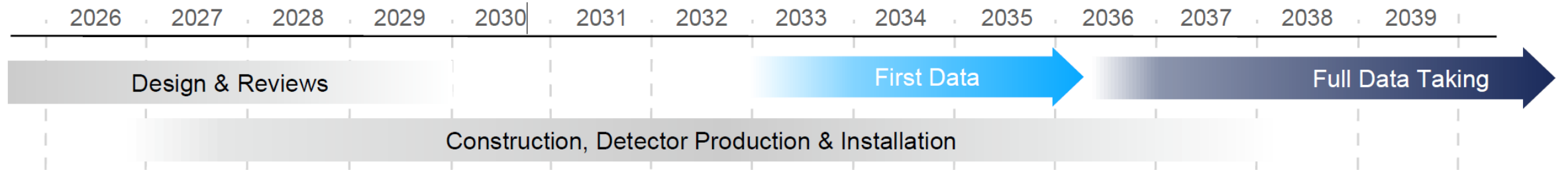


- ^{40}K EC process followed by a gamma not show coincidence with the LAr → **barely suppressed**
- ^{42}K beta followed by 1525 keV gamma have LAr coincidence → **strongly suppressed**

Designed for an unambiguous discovery



LEGEND timeline



Lowest BI



GERDA

Best energy resolution



MAJORANA

~~LEGEND~~-200

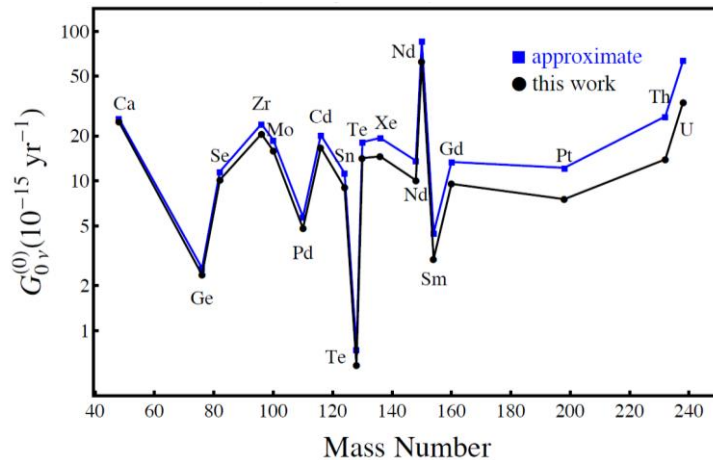
~~LEGEND~~-1000

	GERDA	MAJORANA	LEGEND -200	LEGEND -1000
Mass [kg]	45	30	200	1'000
Exposure [kg · yr]	100	26	1'000	10'000
BI [cts/(keV·kg·yr)]	$(5.2 \pm 1.6) \cdot 10^{-4}$	$(4.7 \pm 0.8) \cdot 10^{-3}$	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
Resolution [KeV]	2.6 ± 0.2	2.52 ± 0.08	2.5	2.5

$0\nu\beta\beta$ half life

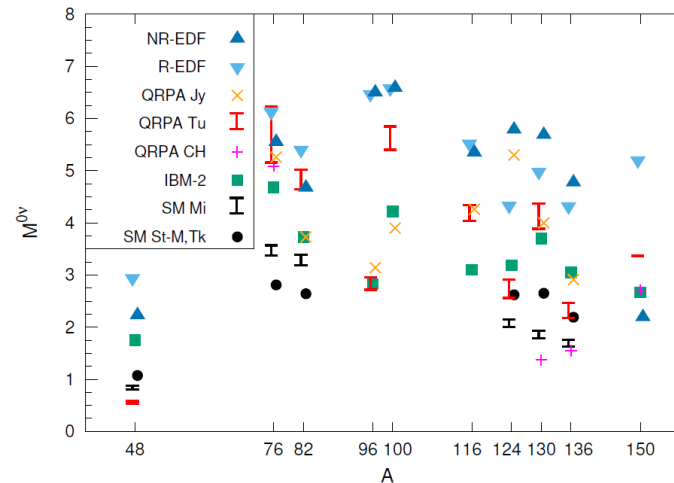
$$\Gamma^{0\nu} = (T_{1/2}^{0\nu})^{-1} = G_{0\nu} \times |M_{0\nu}|^2 \times \left| \frac{m_{\beta\beta}}{m_e} \right|^2$$

Phase space factor
Atomic physics



<https://doi.org/10.1103/PhysRevC.85.034316>

Nuclear matrix element
Nuclear physics



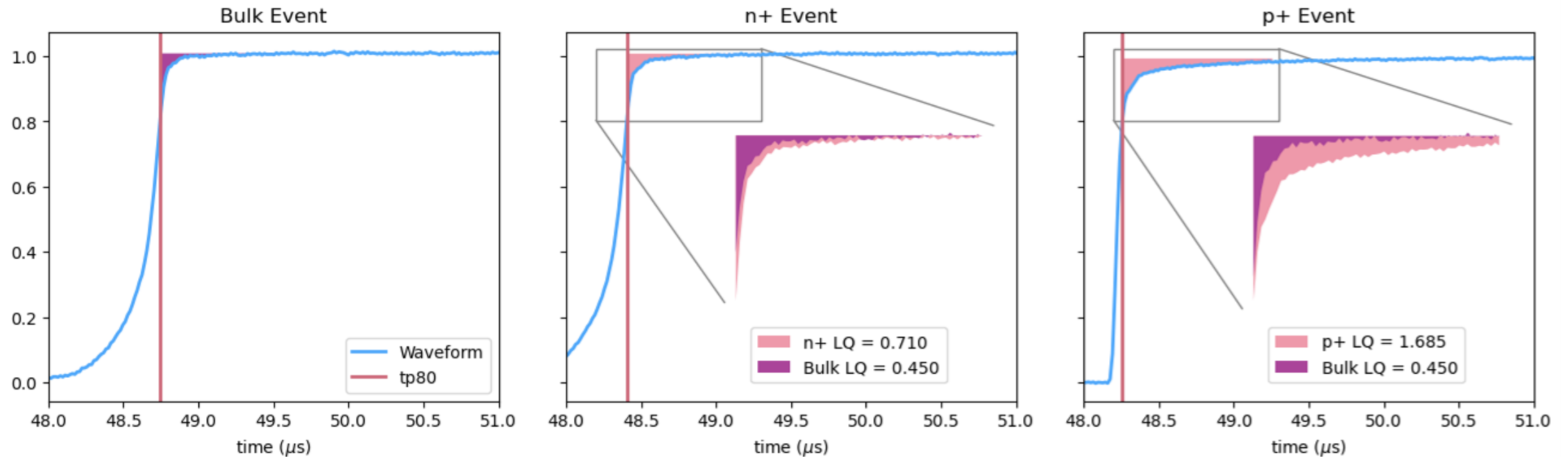
<https://doi.org/10.48550/arXiv.1610.06548>

Effective Majorana mass
Particle physics

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu 1} + s_{12}^2 c_{13}^2 m_{\nu 2} e^{i\phi_{12}} + s_{13}^2 m_{\nu 3} e^{i\phi_{13}}$$

$\phi \rightarrow \text{Majorana phases}$

Late Charge (LQ)



Late-charge (LQ) is the normalized **area above the last 20%** of the charge signal, used to tag **slow surface events**. The cut is used in detectors with large, thin passivated surfaces in place of high A/E.