Results of the LEGEND-200 background mitigation campaign

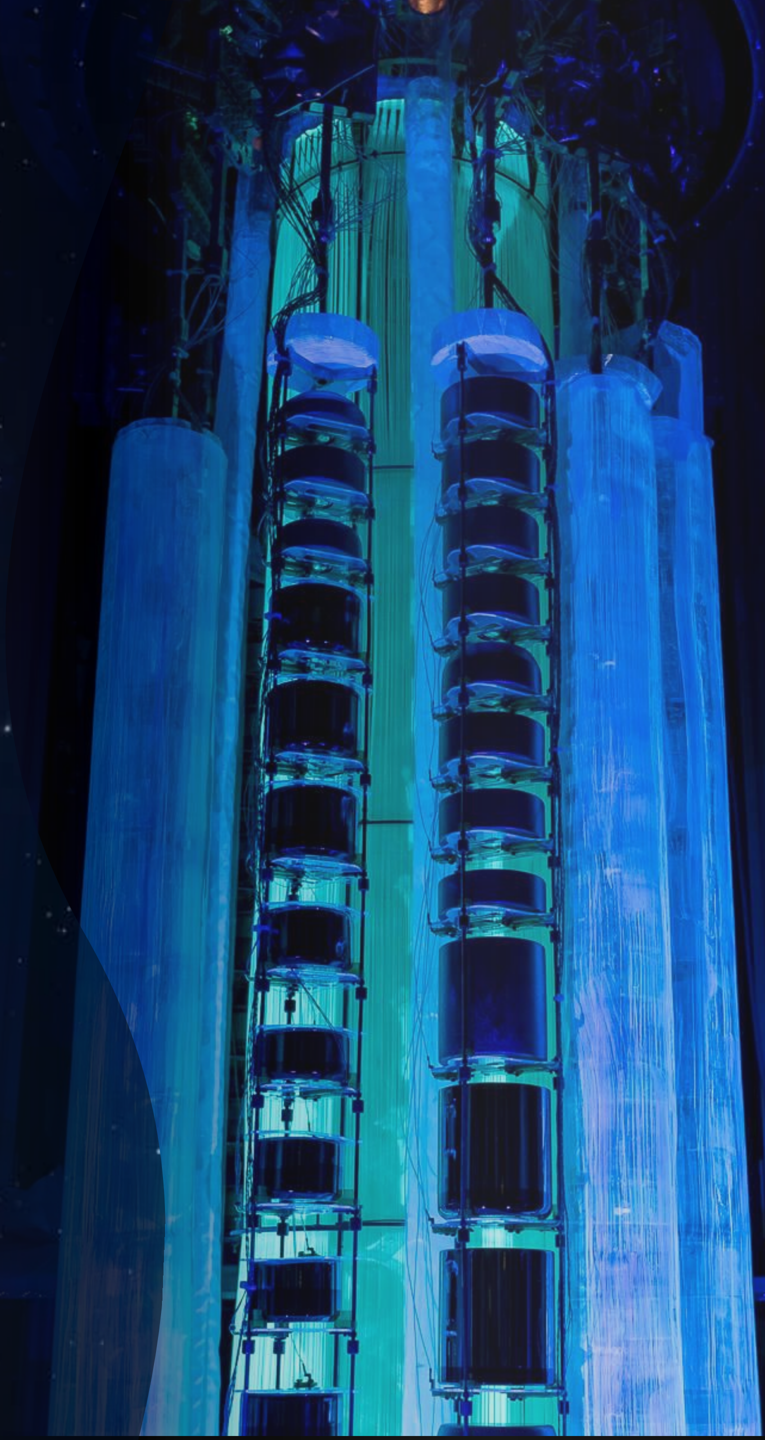
Sofia Calgaro

on behalf of the LEGEND Collaboration

Low Radioactivity Techniques Workshop

22 September 2026

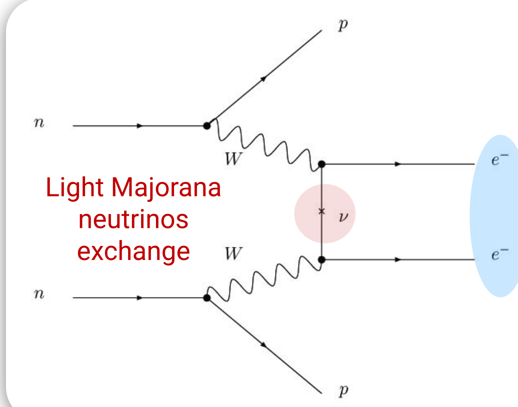
University of Zurich[UZH]

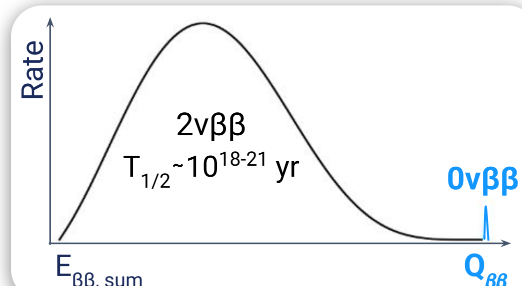


The LEGEND Project

- **Neutrinoless double beta decay ($0\nu\beta\beta$)** is a hypothetical nuclear transition in even-even nuclei where no neutrinos would be emitted; **possible if neutrinos are Majorana particles**
- The LEGEND (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay) Collaboration aims to develop a phased, ^{76}Ge-based $0\nu\beta\beta$ decay program with **discovery potential at $T^{0\nu}_{1/2} > 10^{28}$ yr** [10.48550/arXiv.2107.11462]
- Collaboration formed in 2016, building on the expertise of GERDA and Majorana DEMONSTRATOR  experiments; search for **$^{76}Ge \rightarrow {}^{76}Se + 2e^-$ at $Q_{\beta\beta}$=2039.061 (7) keV** [Phys. Rev. C 81, 032501 (2010)]

13 countries, 60 institutions, ~350 members





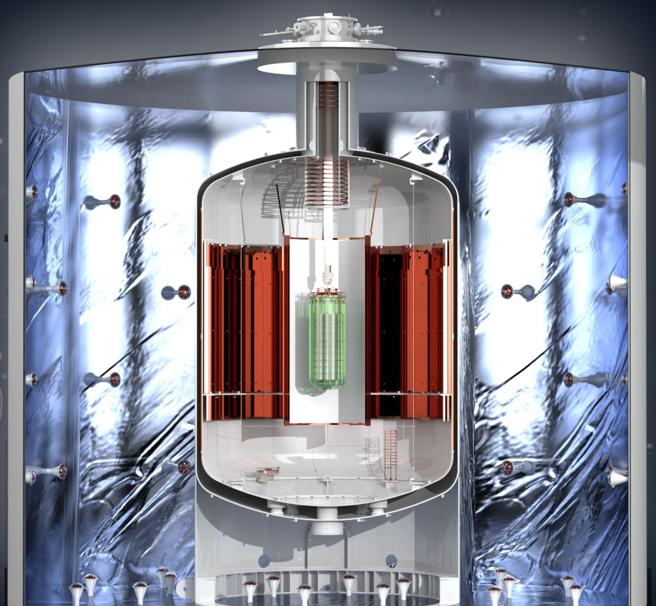
Mass capacity	200 kg
Target exposure	1 ton yr (5 yr)
Resolution in FWHM	2.5 keV
Background [cts/(keV ton yr)]	0.2
$T^{0\nu}_{1/2}$ **sensitivity**	10^{27} yr
Current status	Taking data

R. Biondi, “The way to zero background search with LEGEND-1000”, poster

M- Neuberger, “Delayed Coincidence Based Active Suppression of In-Situ Muon-Induced Isotope Backgrounds in LEGEND”, poster

Laboratori Nazionali del Gran Sasso (LNGS), Italy

LEGEND-200



Mass capacity	200 kg	$\xrightarrow{5x}$	1000 kg
Target exposure	1 ton yr (5 yr)	$\xrightarrow{10x}$	10 ton yr (10 yr)
Resolution in FWHM	2.5 keV		2.5 keV
Background [cts/(keV ton yr)]	0.2	$\xrightarrow{0.05x}$	0.01
$\mathbf{T^{0\nu}_{1/2}}$ **sensitivity**	10^{27} yr	$\xrightarrow{10x}$	10^{28} yr
Current status	Taking data		Under construction

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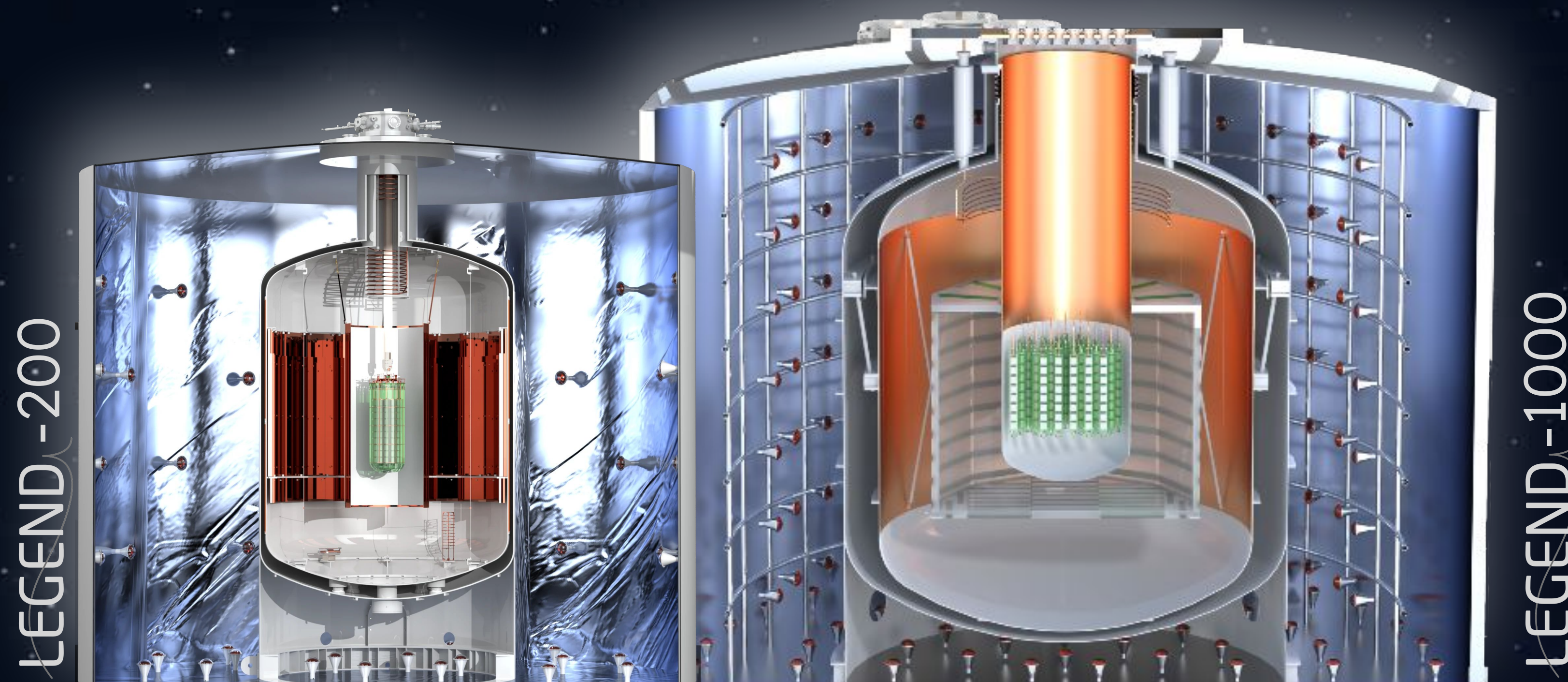

Laboratori Nazionali del Gran Sasso (LNGS), Italy

	LEGEND-200		LEGEND-1000
Mass capacity	200 kg	5x	1000 kg
Target exposure	1 ton yr (5 yr)	10x	10 ton yr (10 yr)
Resolution in FWHM	2.5 keV		2.5 keV
Background [cts/(keV ton yr)]	0.2	0.05x	0.01
$T^{0\nu}_{1/2}$ **sensitivity**	10^{27} yr	10x	10^{28} yr
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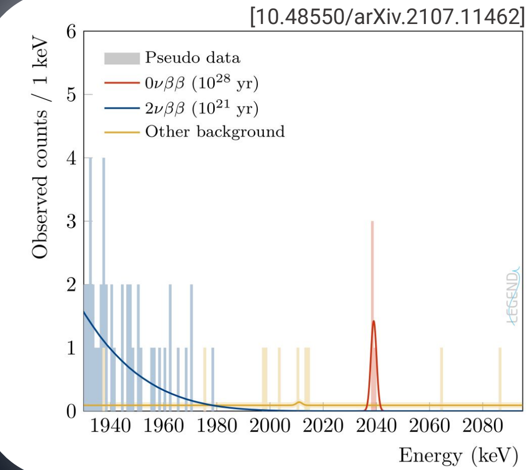

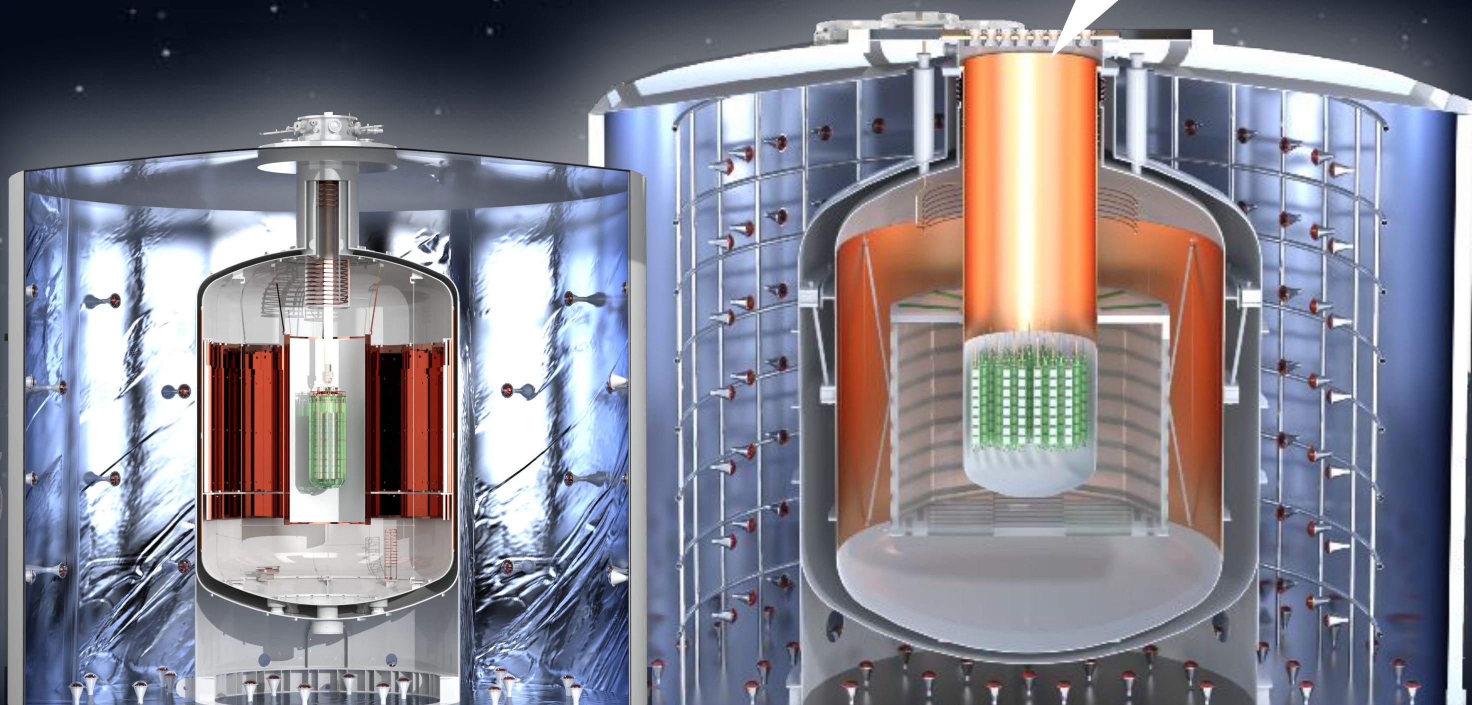

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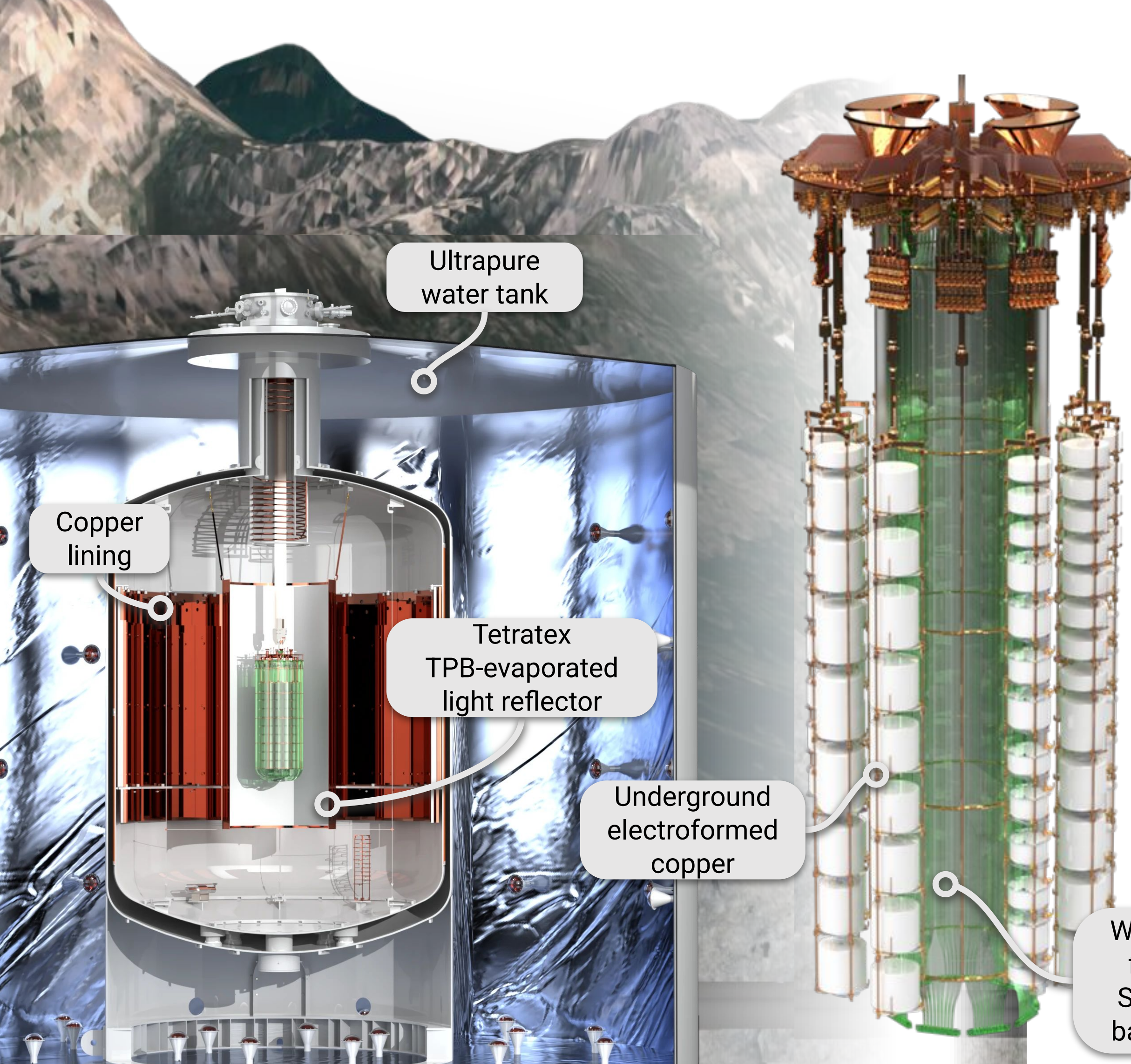
LEGEND-200

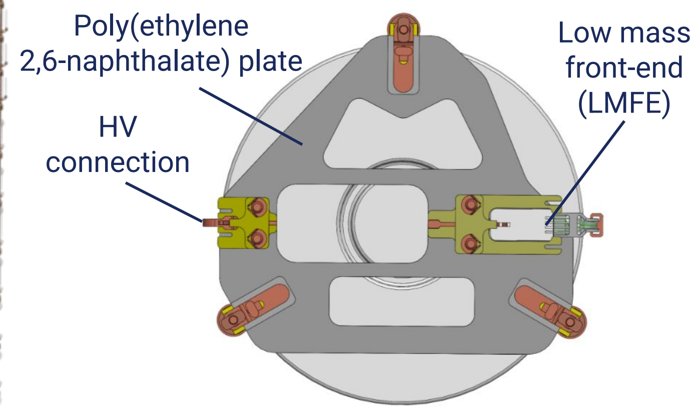
LEGEND-1000

LEGEND-200

- **Overburden of 3500 mwe** (R_μ~1.25/m^{2}h)
- First deployment (Mar. 2023- Feb. 2024): 142 kg of ^{76}Ge-enriched **p-type HPGe diodes** mounted on low-mass holders **immersed in LAr** (cryogenic coolant, active veto)



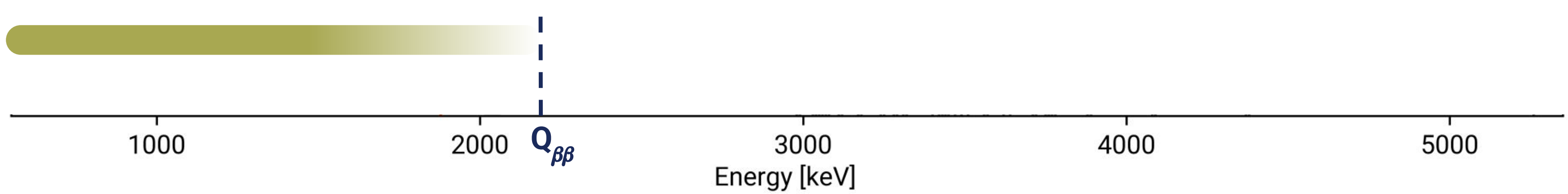
- HPGe strings surrounded by TPB-coated nylon shrouds to reduce ^{42}K ion drifts
- **Ultrapure water tank**: absorber around the cryostat + Cherenkov veto



bottom view

Background Components

Background	Origin	Signature in Ge	Comments	Mitigation
$2\nu\beta\beta$ decay	Ge detectors	Continuous spectrum, dominant below 1.5-1.7 MeV	Intrinsic background	Excellent energy resolution: 0.1-0.2% FWHM at $Q_{\beta\beta}$ (energy bias of 0.2±0.3 keV) [10.48550/arxiv.2605.22479, accepted by EPJC]



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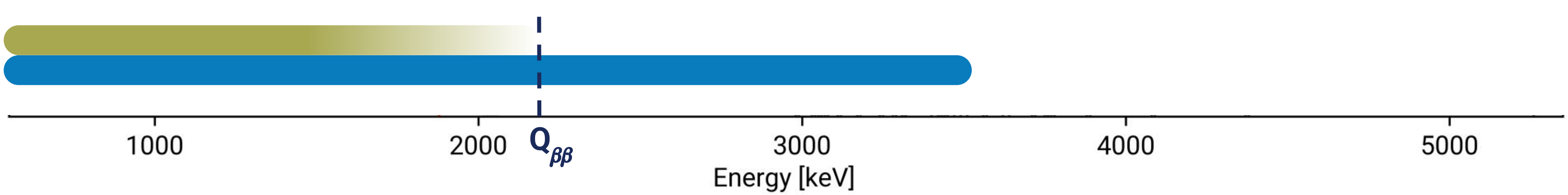
^{42}Ar/^{42}K in LAr	LAr volume; ^{42}K can drift toward detector surfaces	High energy γ and β from ^{42}K decay (Q_{β}=3.5 MeV)	No information available from screening; spatial distribution difficult to model	LAr veto; PSD cut; nylon mini shrouds around Ge strings



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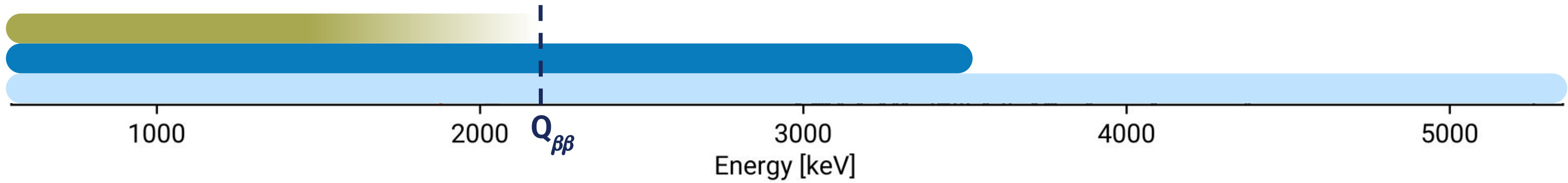
Natural radioactivity ^{232}U, ^{238}Th, ^{40}K	Detector and structural materials (bulk, surface)	High energy γ and β/α	Relevant across the ROI; μBq activities can matter	Radiopure materials; Ge diodes granularity; LAr veto; PSD cut; passive shields



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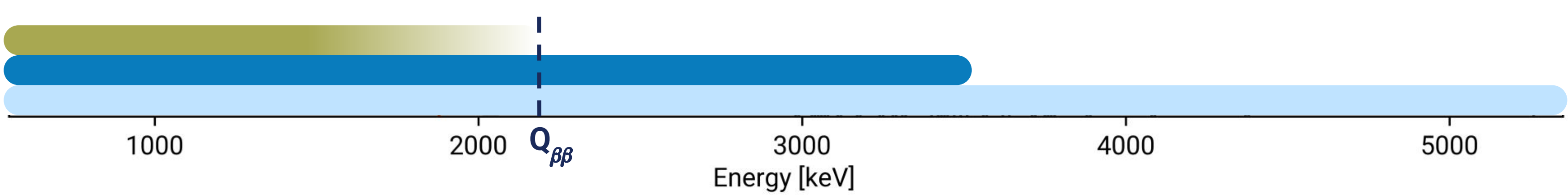
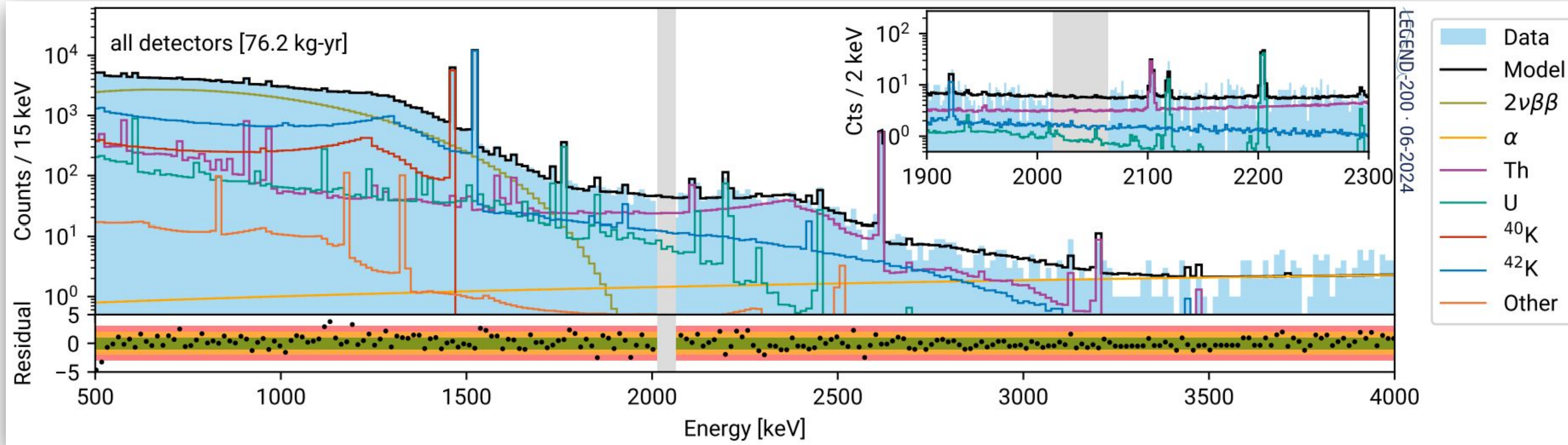
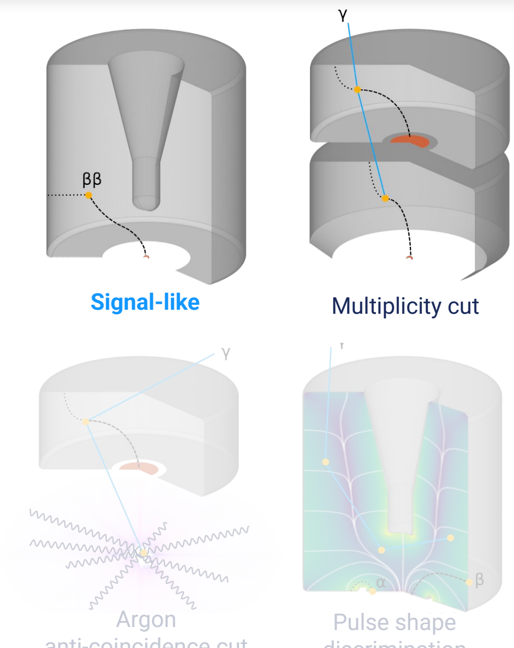
Cosmogenic activation	Ge and detector/material components exposed above ground	β/γ from cosmogenic isotopes; short- and long-lived isotopes	Negligible for L-200	Underground operations; controlled material handling; dedicated veto in L-1000



Background Model

Phys. Rev. Lett. 136, 022701 (2026)

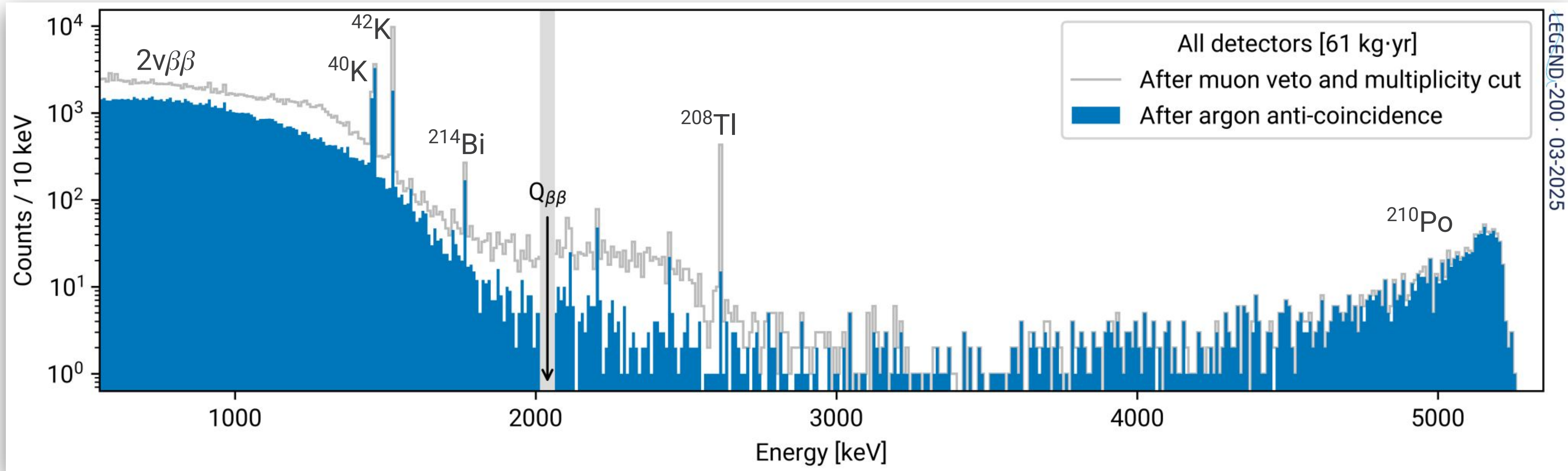


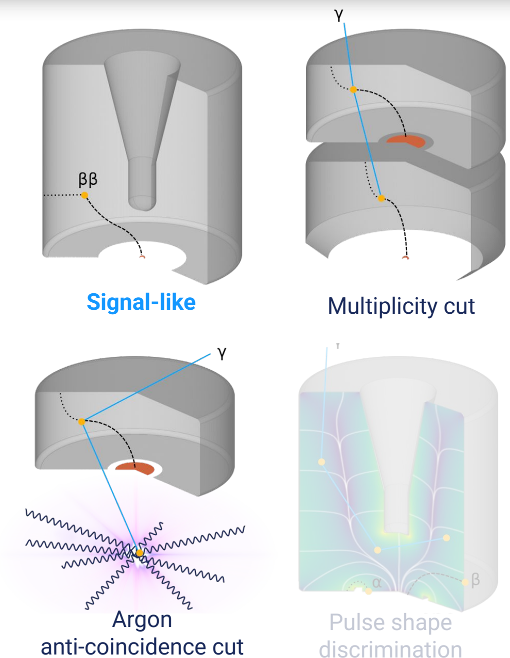


✂ Gamma coincident emission

First Results

Phys. Rev. Lett. 136, 022701 (2026)





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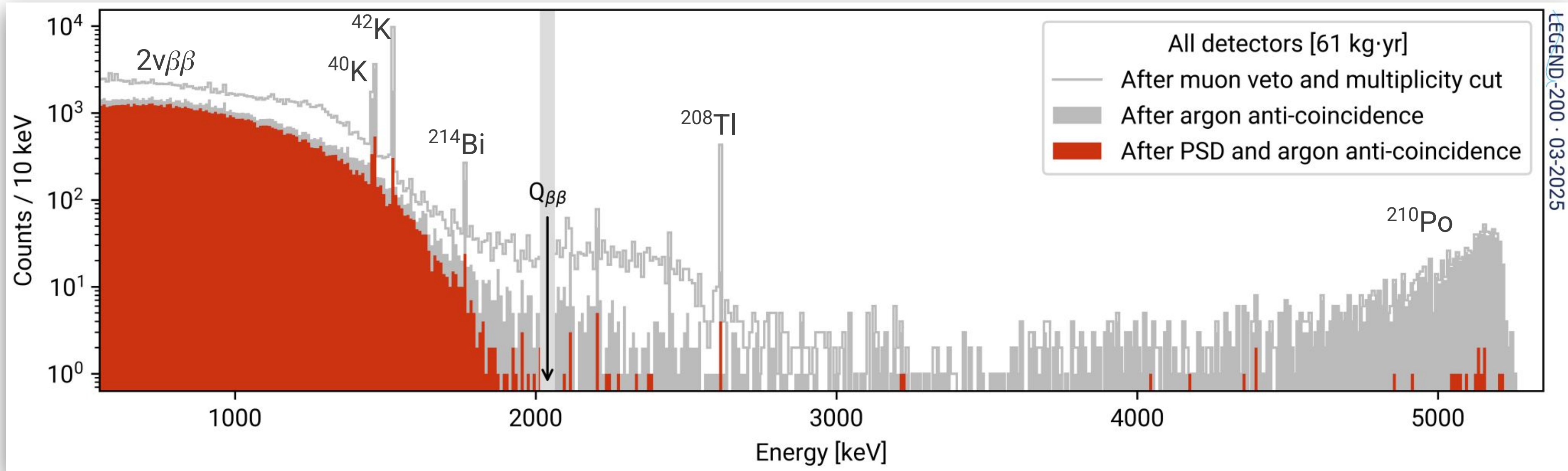
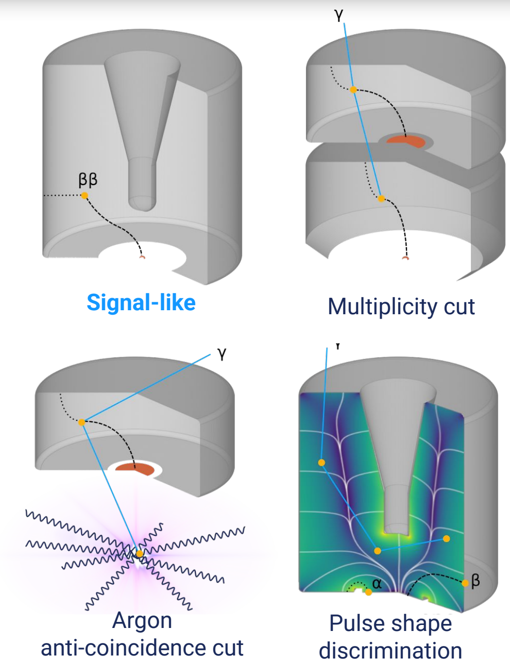
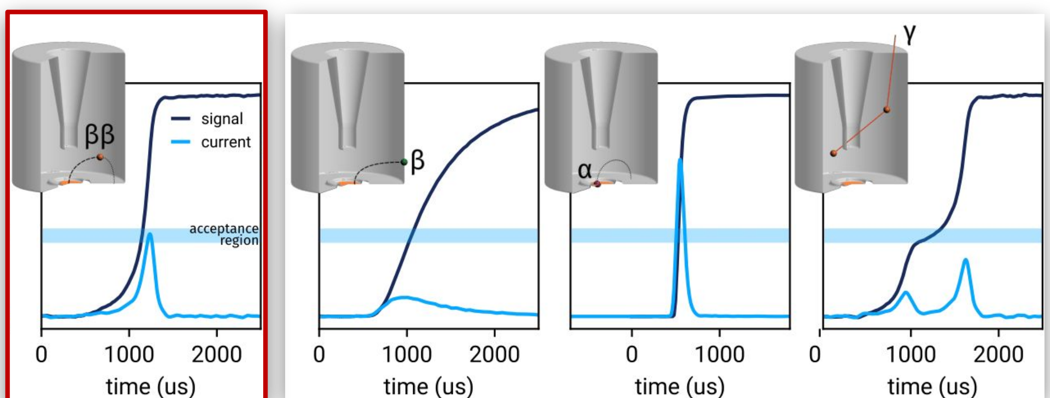




✂ Gamma coincident emission

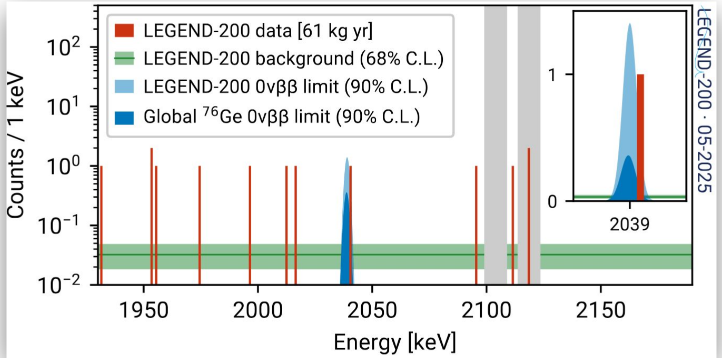
✂ Multi Compton, FEP, SEP, surface α/β



Background Around the ROI

Phys. Rev. Lett. 136, 022701 (2026)

- GERDA+MJD+LEGEND-200 combined analysis:
  - observed limit: **$T^{0\nu}_{1/2} > 1.9 \times 10^{26}$ yr @ 90% CL/CI**
  - world-leading sensitivity: **2.8×10^{26} yr**



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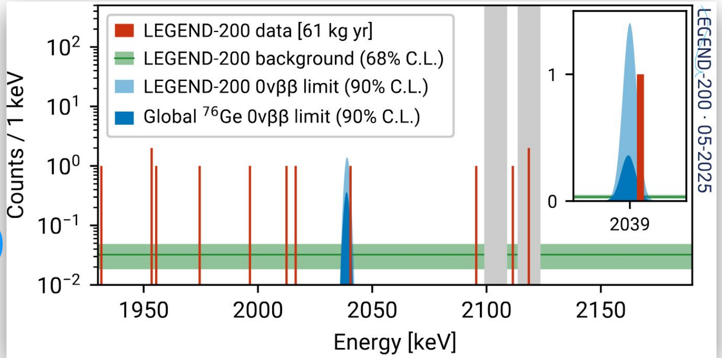
- ***Golden* dataset (48 kg yr): BI=$0.5^{+0.3}_{-0.2}$ cts/(keV · ton · yr)**
- *Silver* dataset (13 kg yr): BI=$1.3^{+0.8}_{-0.5}$ cts/(keV · ton · yr)



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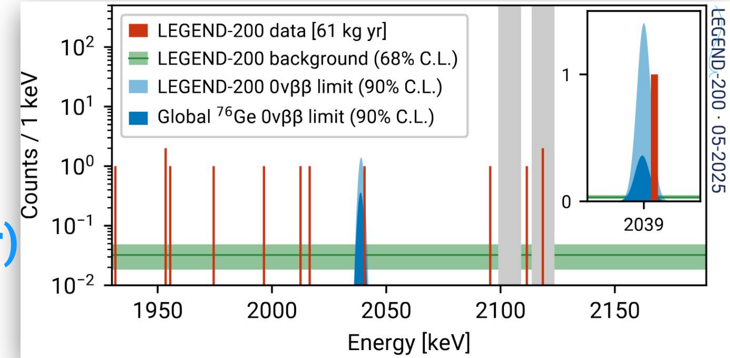
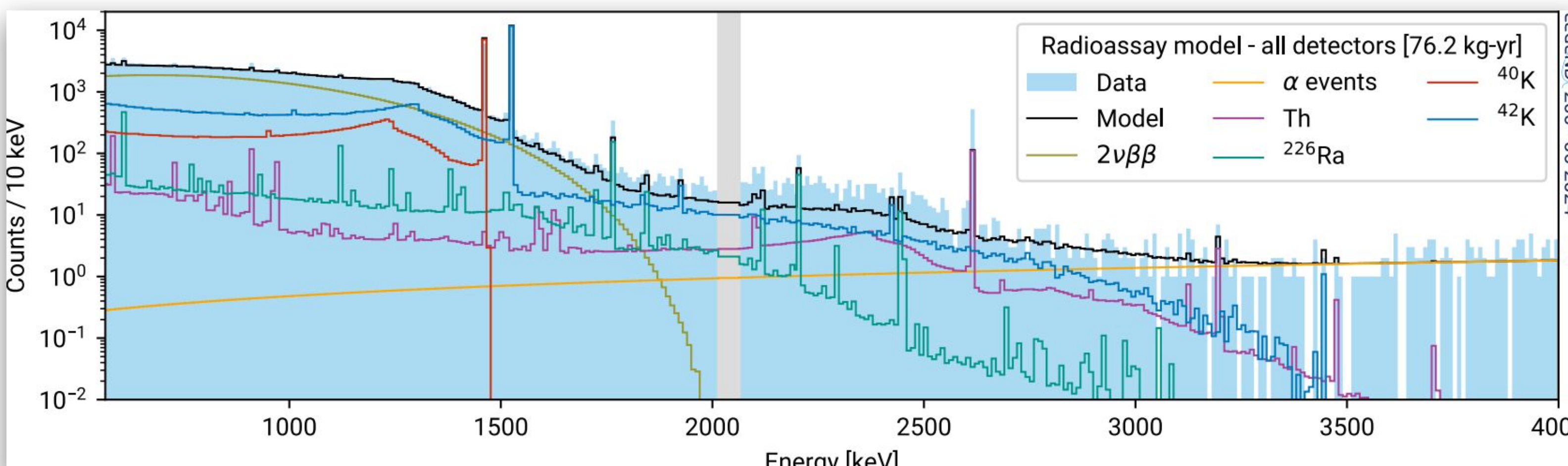


Simulations and material radioassay underpredicted data

⚠️ Some sources only have ICP-MS measurements

⚠️ Possible breaking of secular equilibrium in U/Th chains

⚠️ Systematics on assay values are hard to estimate



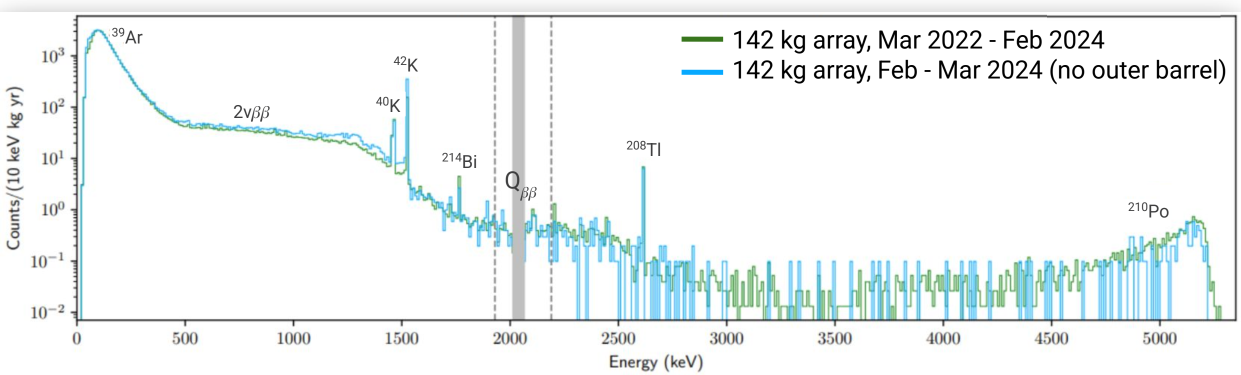
[T. Dixon, "Analysis of the backgrounds in the LEGEND-200 experiment", LRT24]

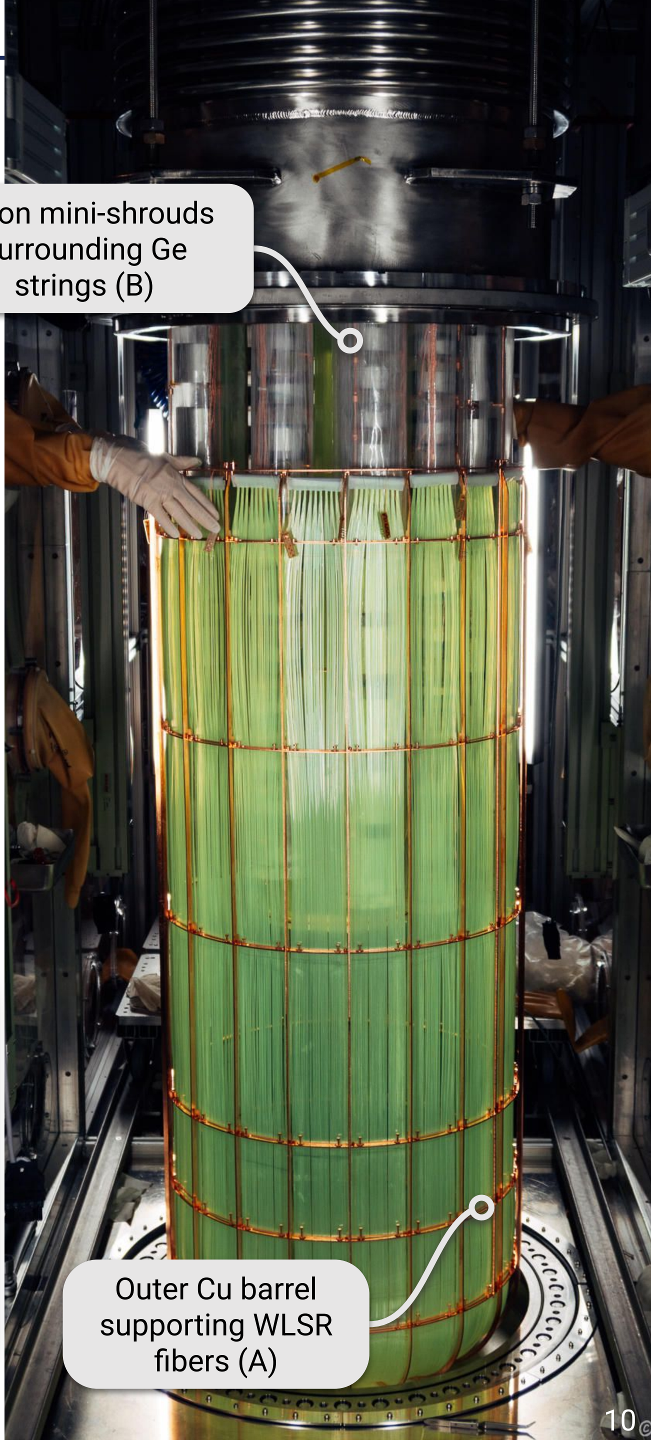
[L. Varriano, "Radioassays for the LEGEND 76Ge 0vbb search", LRT24]

In-situ Self Assaying

- Feb.-Apr. 2024: data taken with **two special configurations with components removed for *in-situ* self-assaying**
  - **outer barrel** (10.2 kg yr): *~50% of ^{238}U contamination could be explained via insufficient Cu cleaning*; assays indicated several tens of µm had to be etched
  - **nylon mini-shrouds** (5.9 kg yr): *^{238}U/^{232}Th contaminations are consistent with before*, but with large uncertainties (low exposure, higher ^{42}K background)

- Inspected γ rates and spatial distributions, LAr veto suppression and MC-data agreement, **exploiting Ge-array granularity to localize contaminations**
  - 1-diode hits: compatible with close/intermediate sources;
  - 2-diodes hits: excludes strong contamination on very close parts

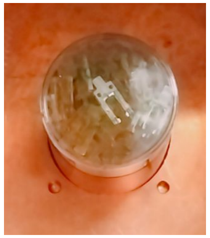




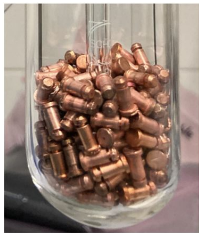
Forensic Campaign

- **Apr. 2024 - Jul. 2025: extensive material screening*** → elevated activities identified in **detector base-plate assemblies** (PEN, Ultem, Cu pins, phosphor-bronze springs) **+ WLS fibers**
- MC simulations suggest they largely explain the elevated ^{214}Bi(^{238}U) and ^{208}Tl(^{232}Th)
- Raw materials met cleanliness requirements; **surface contamination introduced during machining/handling/cleaning**
- Replaced/reused components underwent enhanced cleaning protocols and comprehensive quality assurance procedures before the latest array installation (**all materials were produced from screened raw materials)**

Poly(ethylene 2,6-naphthalate) plate

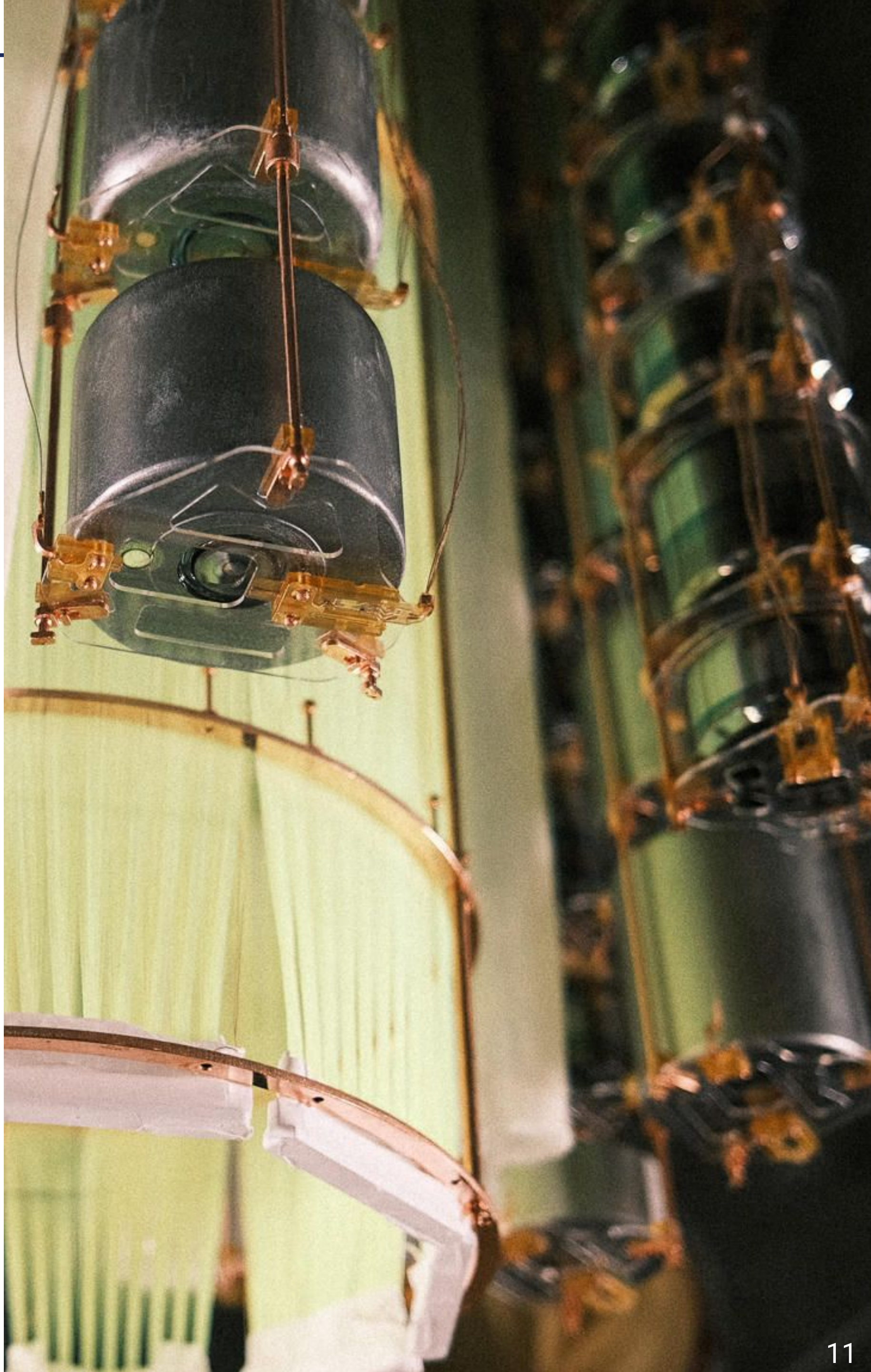


Ultem γ assay



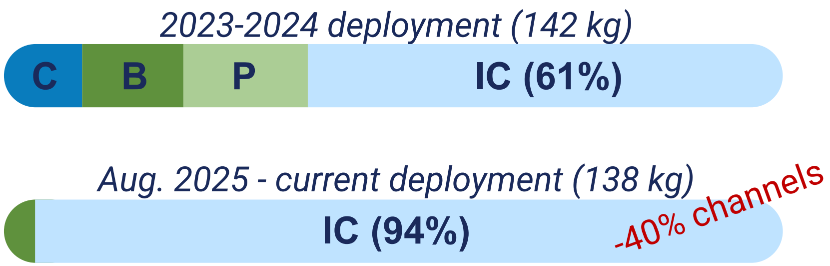
Cu pins Rn emanation assay

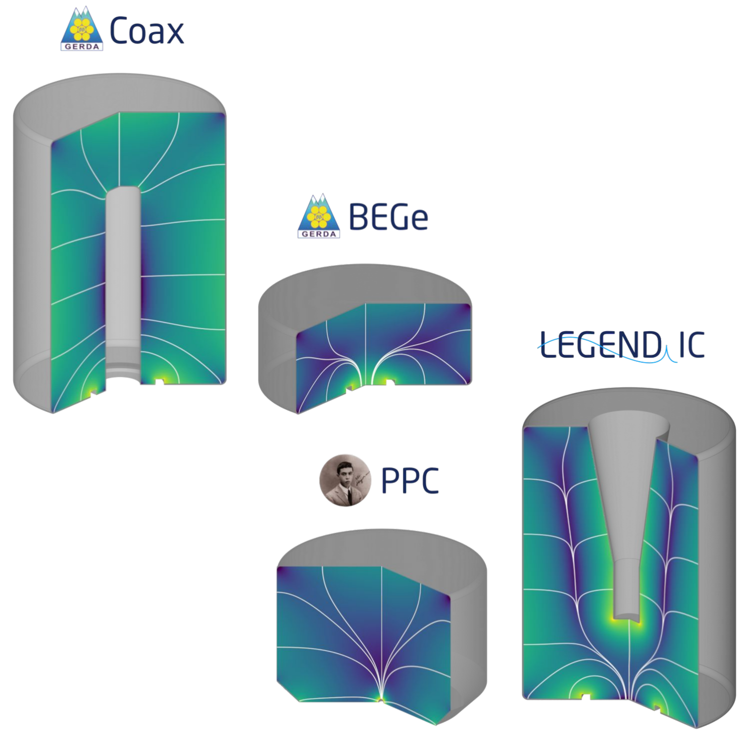
** γ screening @ GeMPI, Gator (LNGS) / HADES / Boulby / GeRysy (LSC), α spectroscopy @ Jagiellonian University, radon emanation @ MPIK*



The 2025 Deployment

- **August 2025: 138 kg deployed,** after converting COAX/PPC/BEGe/underperforming detectors





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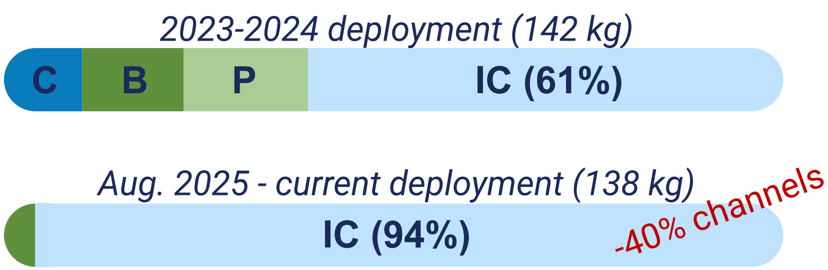
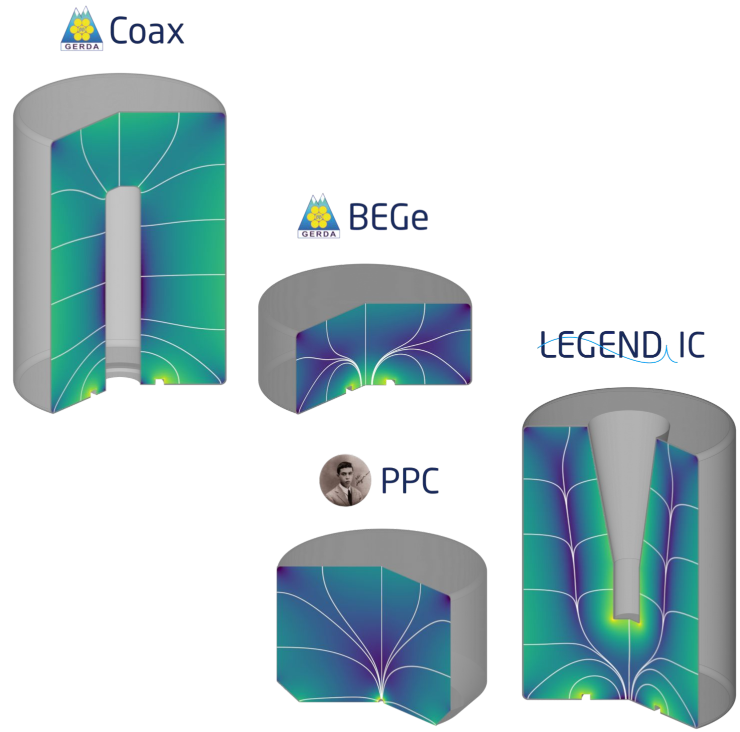
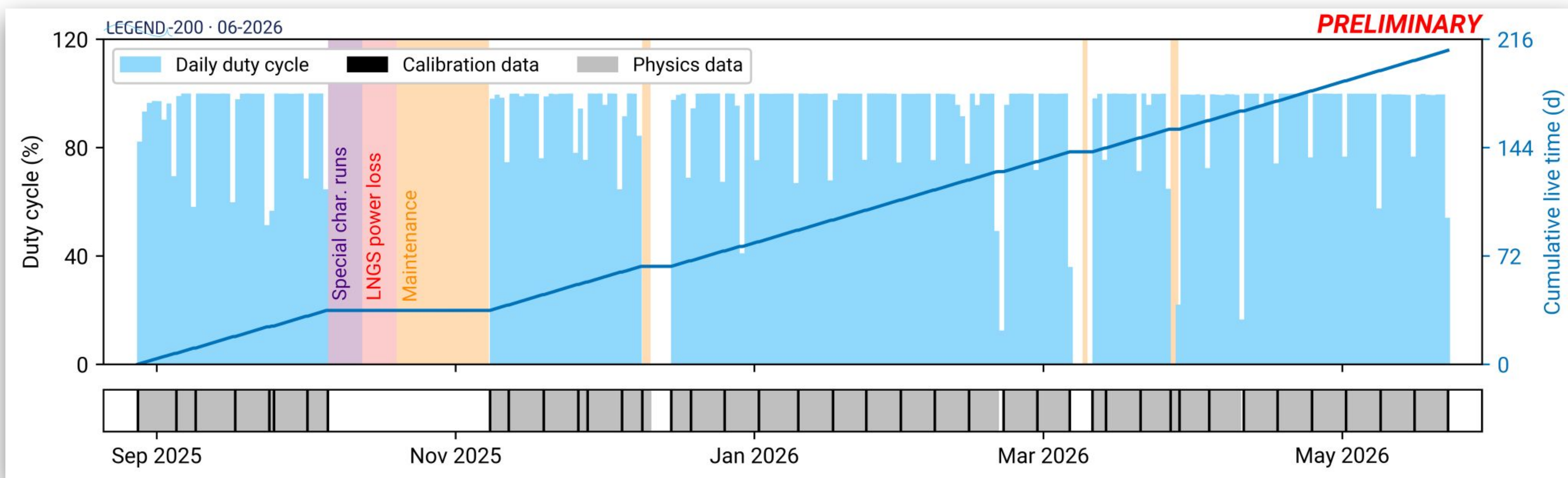
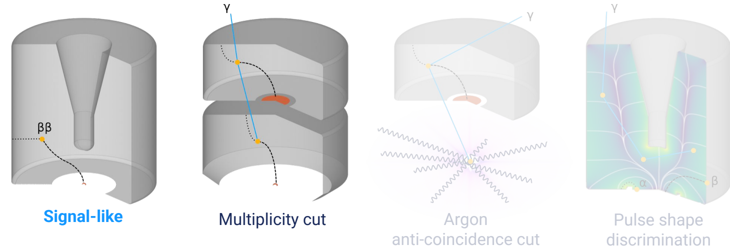
- **Stable physics data taking** since August 2025
  - 93% duty cycle without downtimes

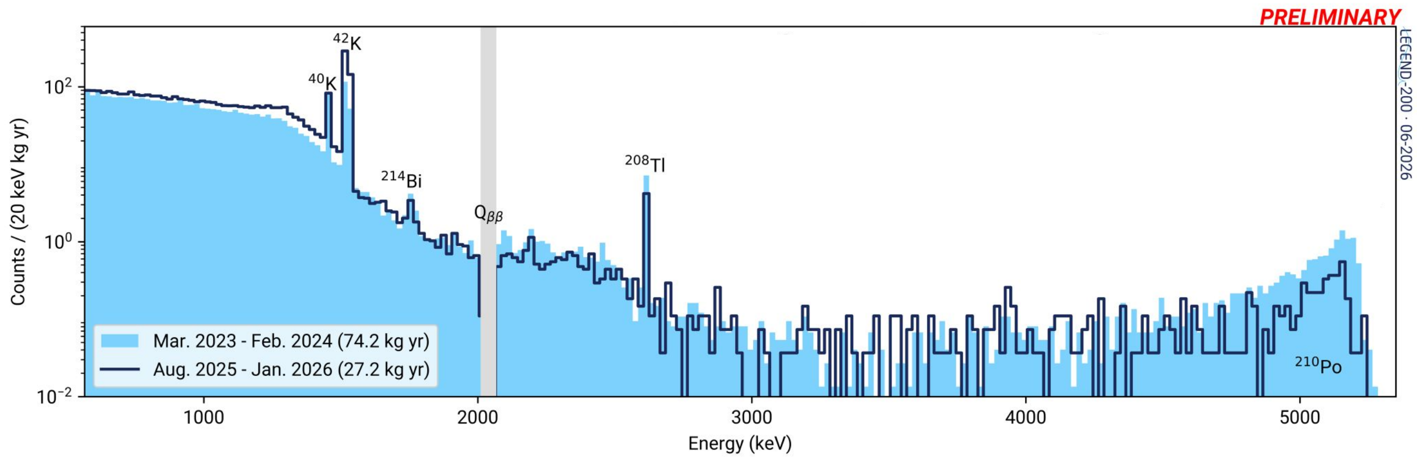






Background Before Cuts





- **Validated new data up to the end of January 2026 (27.2 kg yr)**

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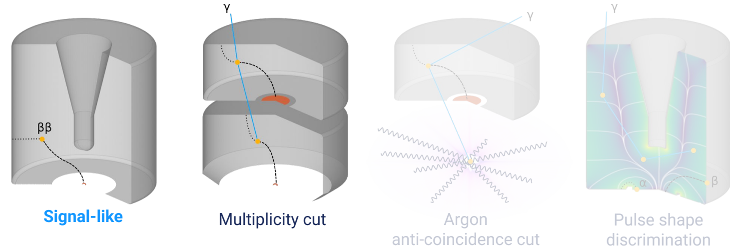
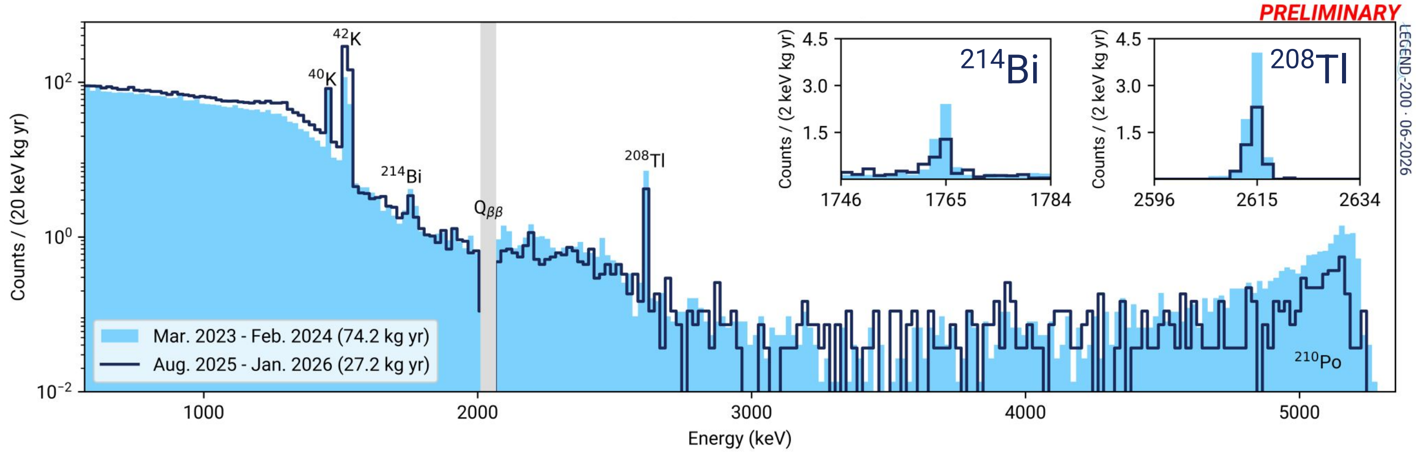
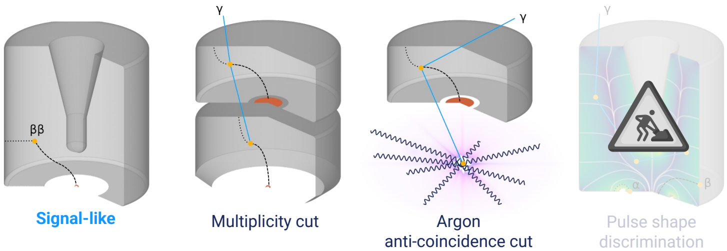
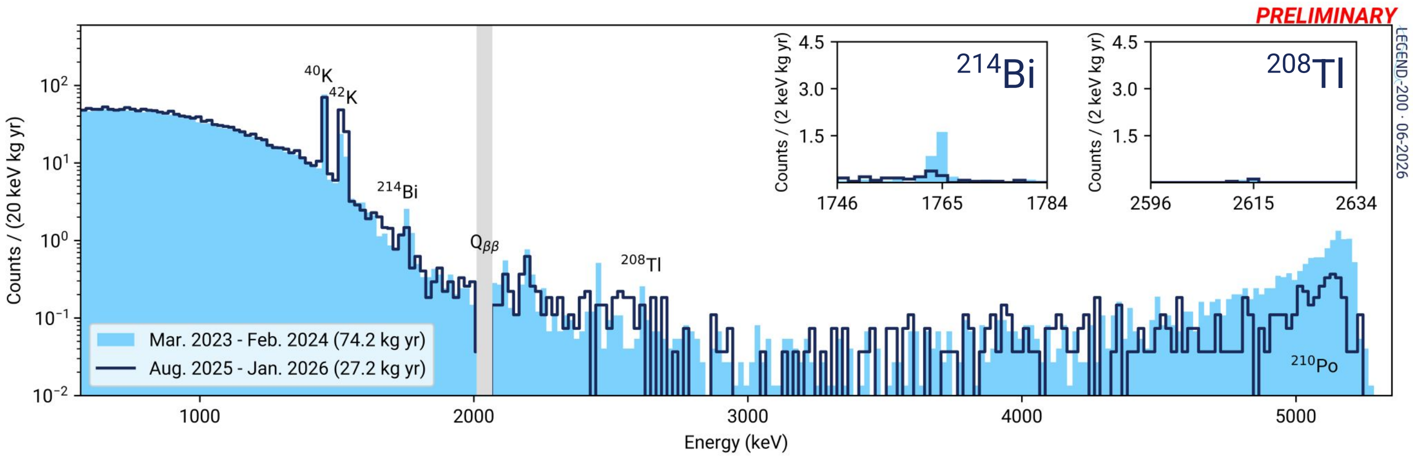




- **Validated new data up to the end of January 2026 (27.2 kg yr)**
- Removal of large p+ contact detectors (COAX) resulted in a reduction of α events
- Higher ^{42}K 1.5 MeV γ content; affected by ion drift in electric fields, detectors bias voltages and geometry, presence of shields, ….; decreases with time, while $Q_{\beta\beta}$ continuum remains constant
- **^{214}Bi(^{238}U)/^{208}Tl(^{232}Th) reduced by ~2 before cuts**
    - preliminary **γ count rate is compatible with the new assays predictions**

Background After Cuts





- **Rates after LAr veto compatible with the removal of surface contamination**
  - 5x overall reduction of ^{214}Bi 1764 keV γ-line, ^{208}Tl ~eliminated
- **Proves effectiveness of cleaning campaign**

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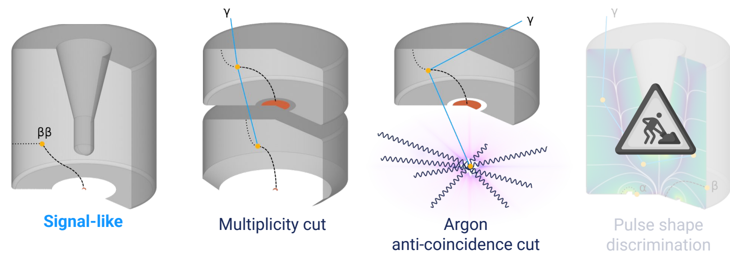

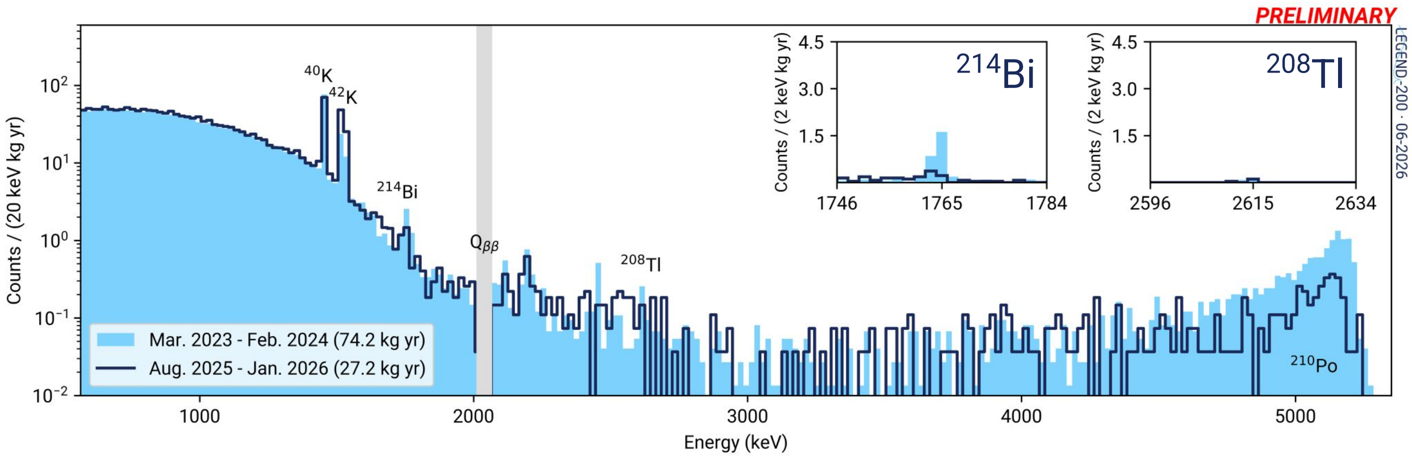

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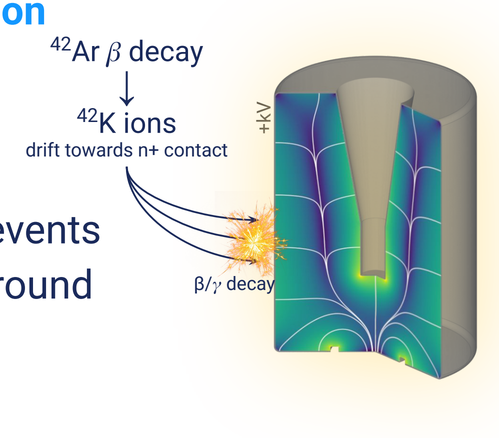
  - optimization of rejection analysis methods, e.g. joint PSD cuts



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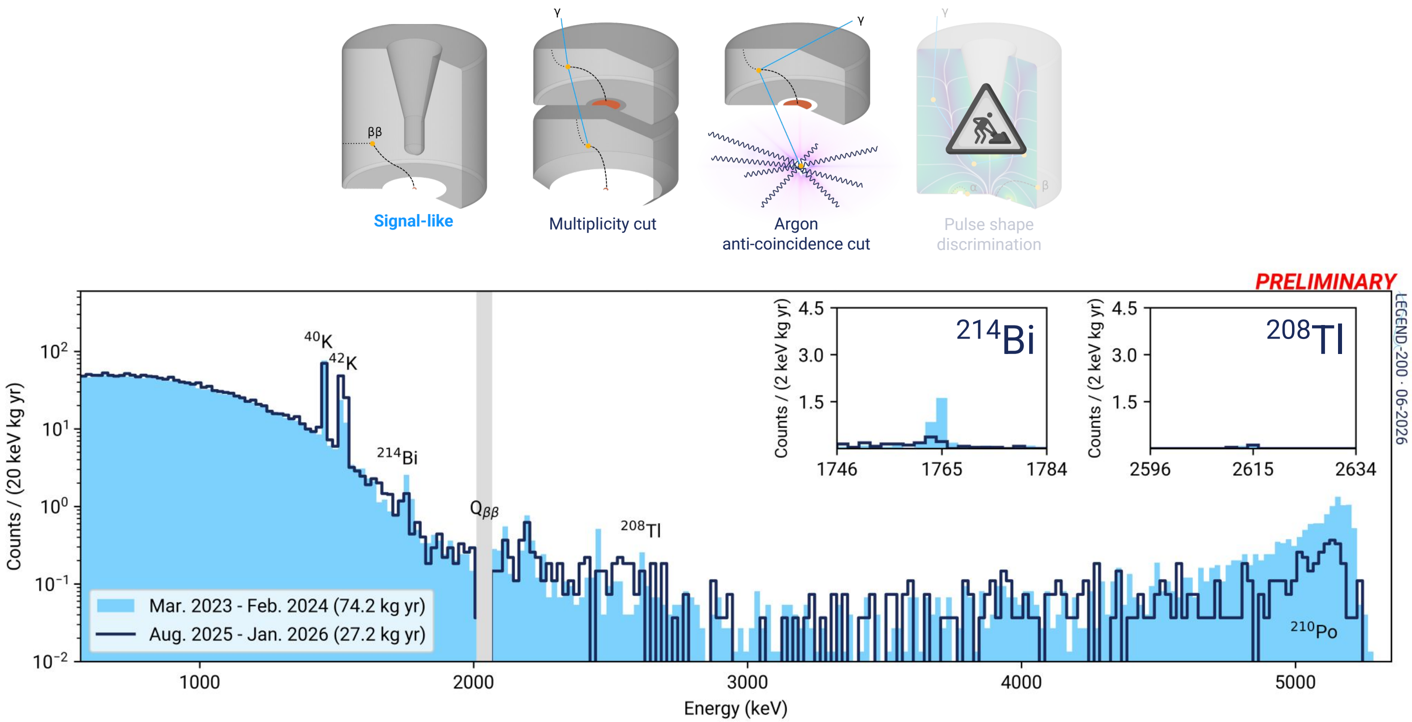

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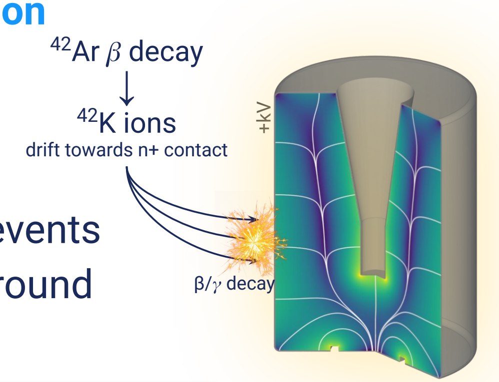
  - **dedicated ^{42}K task force** coordinating efforts to address this background
  - optimization of rejection analysis methods, e.g. joint PSD cuts
- **^{42}K background expected to be mitigated in LEGEND-1000**



C. Vogl, "K-42 mitigation studies in Ar-42 spiked liquid argon for LEGEND", talk

Next Steps

- **Maximize exposure collection while building background model & radioassay material interpretation** for >2025 data

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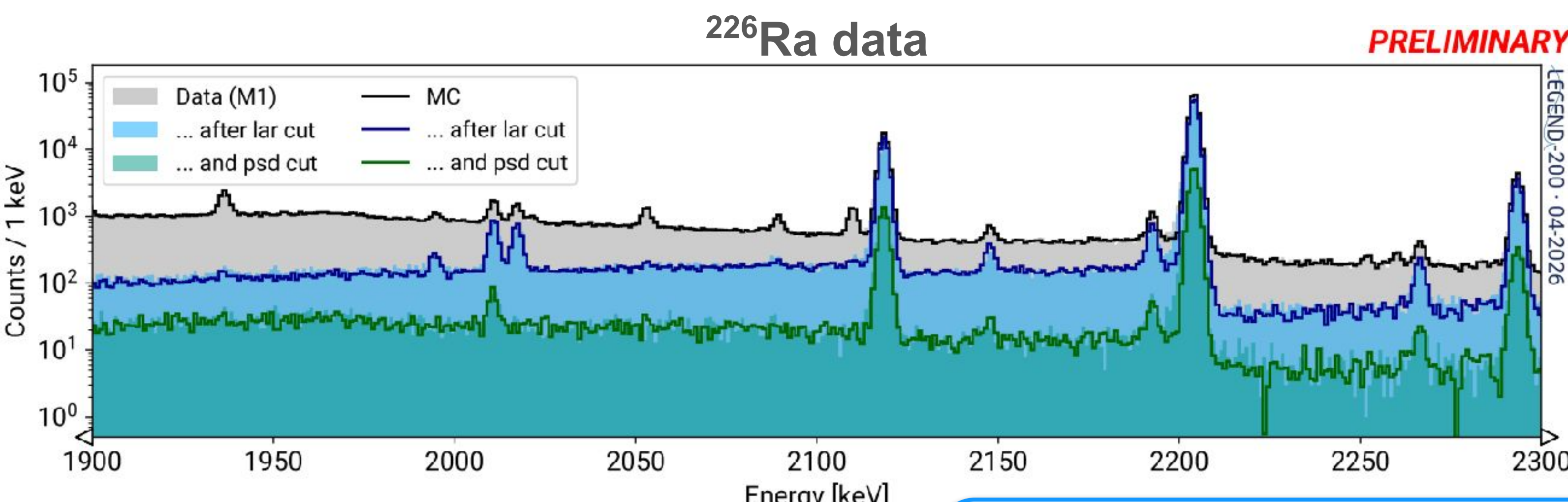
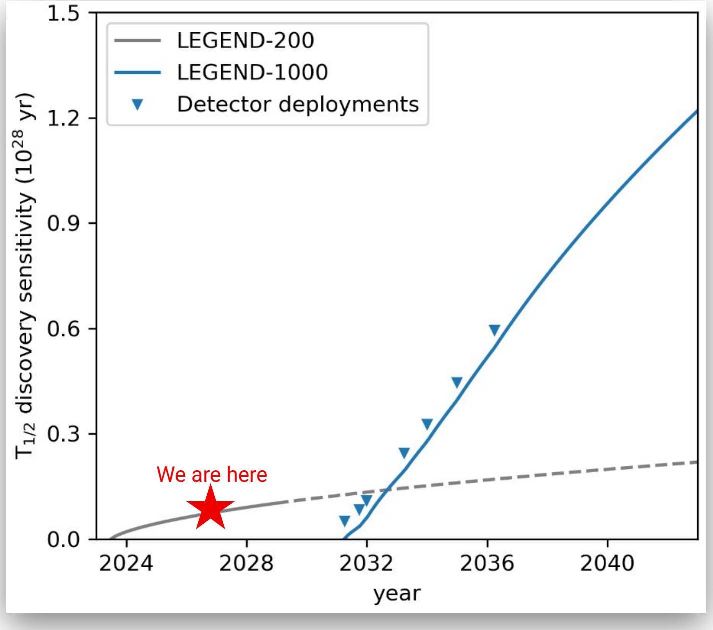
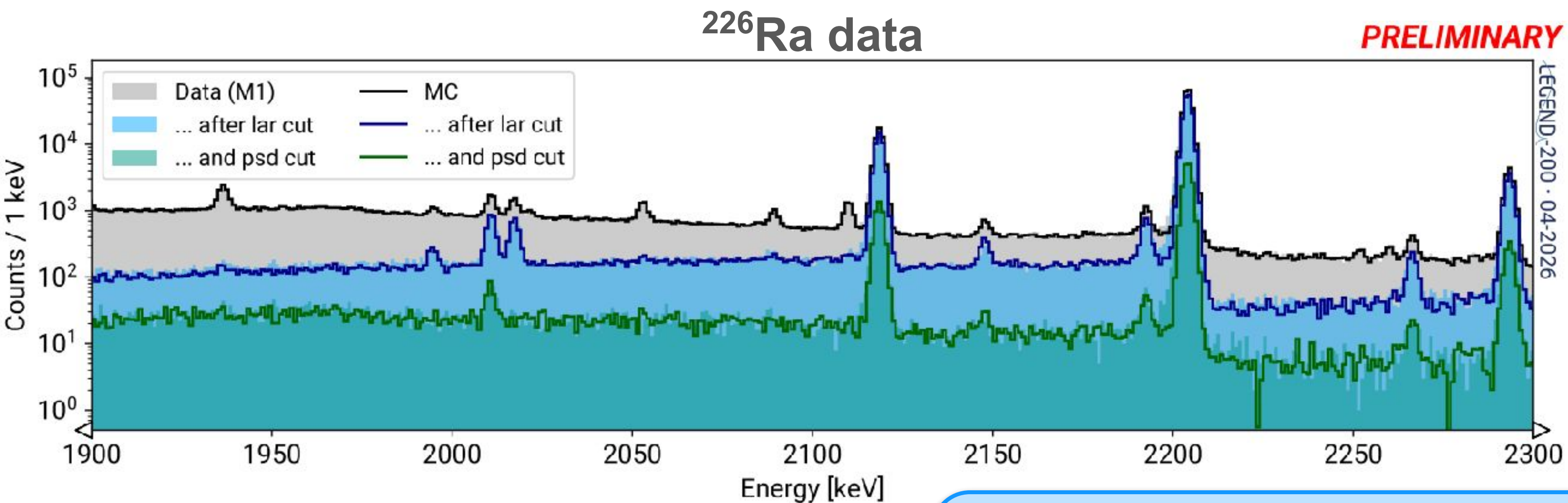


L. Pertoldi, "remage: a modern simulation framework for low-background physics experiments", poster

Next Steps

- **Maximize exposure collection while building background model & radioassay material interpretation** for >2025 data
- Ongoing work for modeling ***in-situ* special characterization data** (^{228}Th, ^{226}Ra) after cuts
- LEGEND-200 provides a **test bed for technology development and risk reduction** for the tonne phase



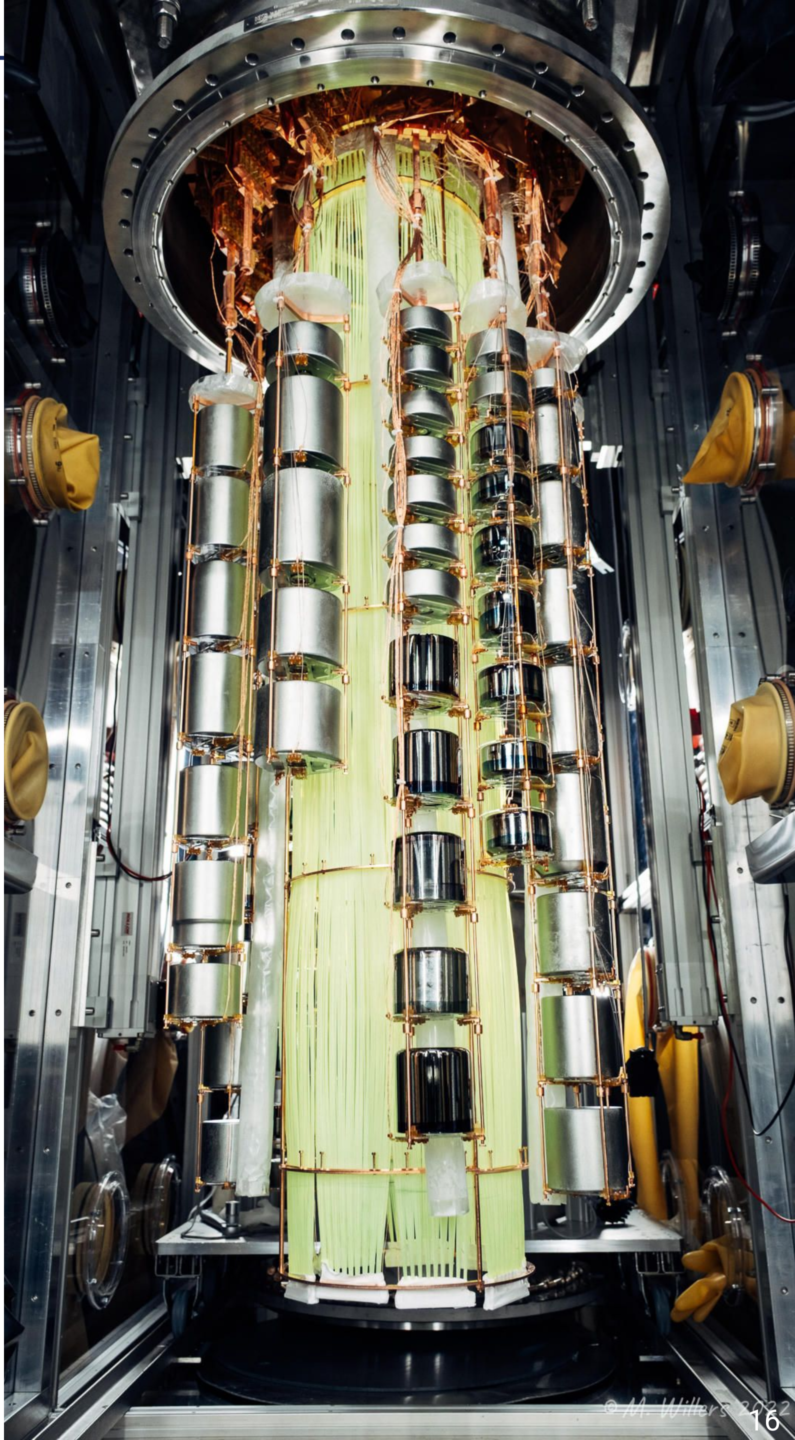


L. Pertoldi, "remage: a modern simulation framework for low-background physics experiments", poster

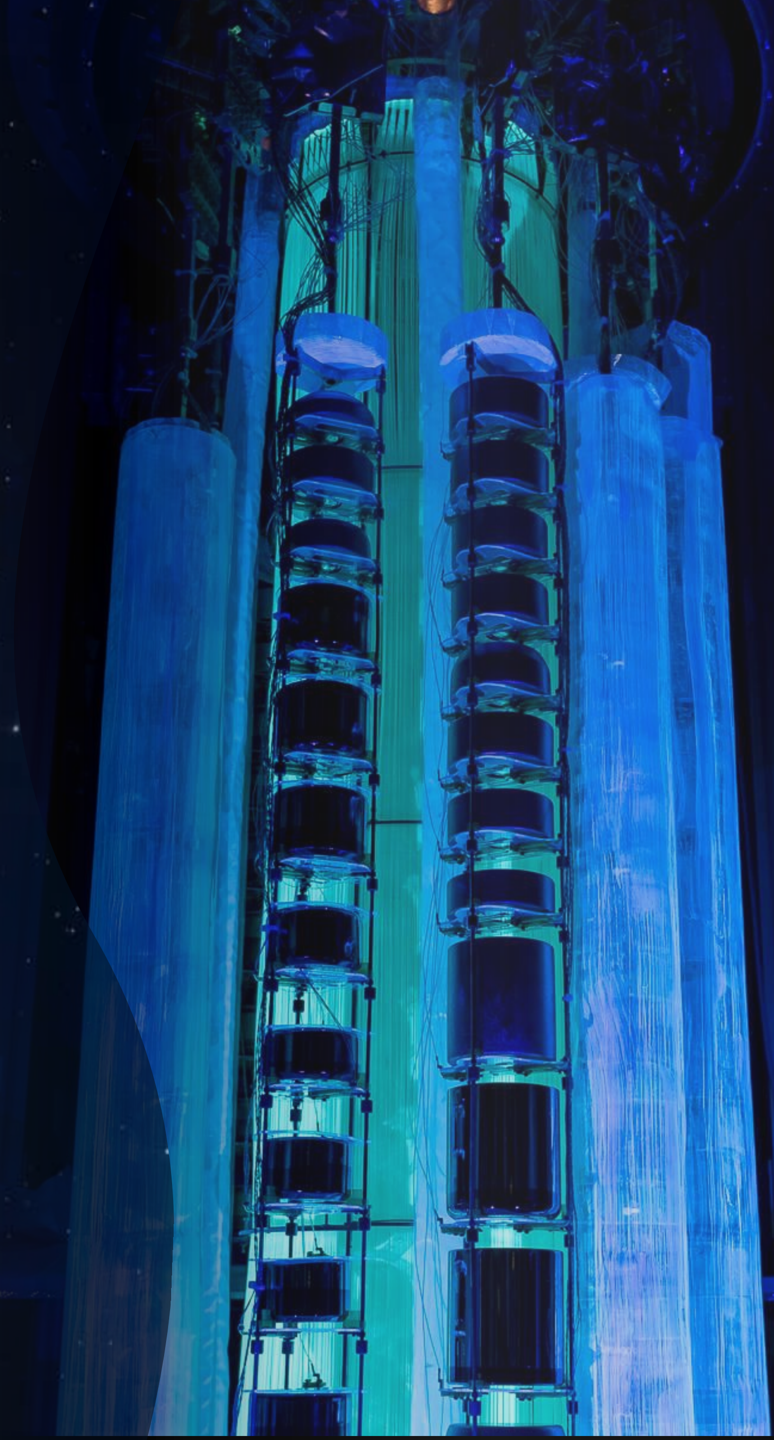
Summary

- **World-leading $0\nu\beta\beta$ sensitivity** with 142 kg of ^{76}Ge
- **Higher-than-expected background source likely identified** via assay and cleaning campaign in close-by components to HPGe diodes (2024-2025)
- Ongoing validation of data collected since August **2025 deployment (94% IC detectors)**
- **Leading experiment** until LEGEND-1000 comes online ($0\nu\beta\beta$ quasi-free background decay search with discovery sensitivity beyond 10^{28} yr)
- **Advanced background-mitigation strategies** under development for the tonne phase
- Data taking is expected to start in the early 2030s

Thank You!



Backup



July 2025 Deployment

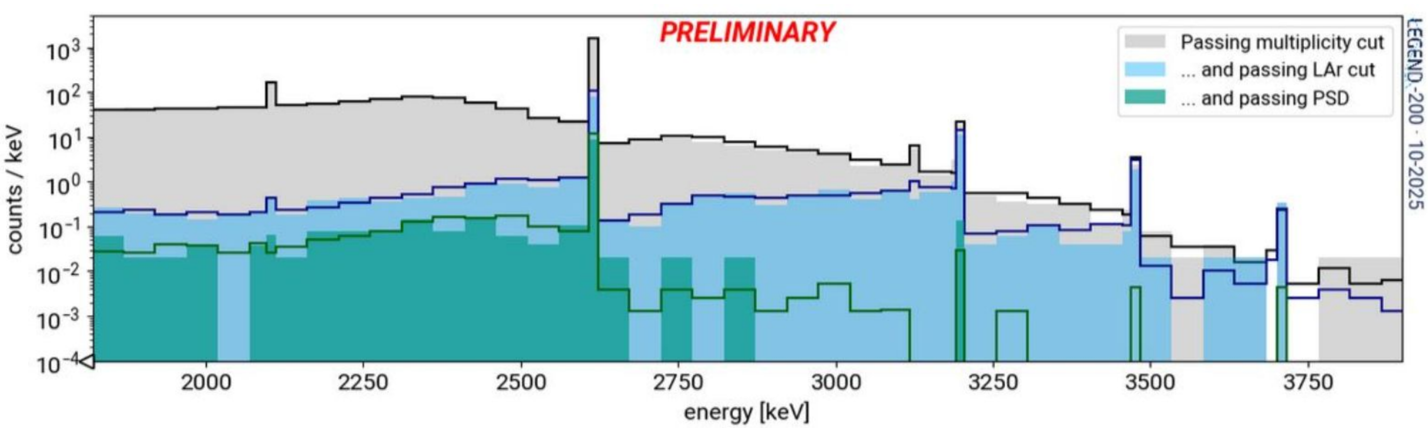
- Several new components have been produced and prepared for installation
  - **all materials were produced from screened raw materials**
- Newly machined EFCu rods, tri-stars, and spacers were fabricated at MPIK, chemically etched, passivated, and quality-controlled
- PEN holders were newly manufactured at IPF and underwent washing, leaching, and QC verification
- Ultem insulators and shims were newly machined at UNC and subjected to the same cleaning and inspection procedures
- Other components (Ultem receptacles and phosphor-bronze springs) were recycled from existing stock, with the latter re-etched and passivated
- Newly produced PhBr washers, EDM-cut at MPIK, were also etched and passivated prior to quality control

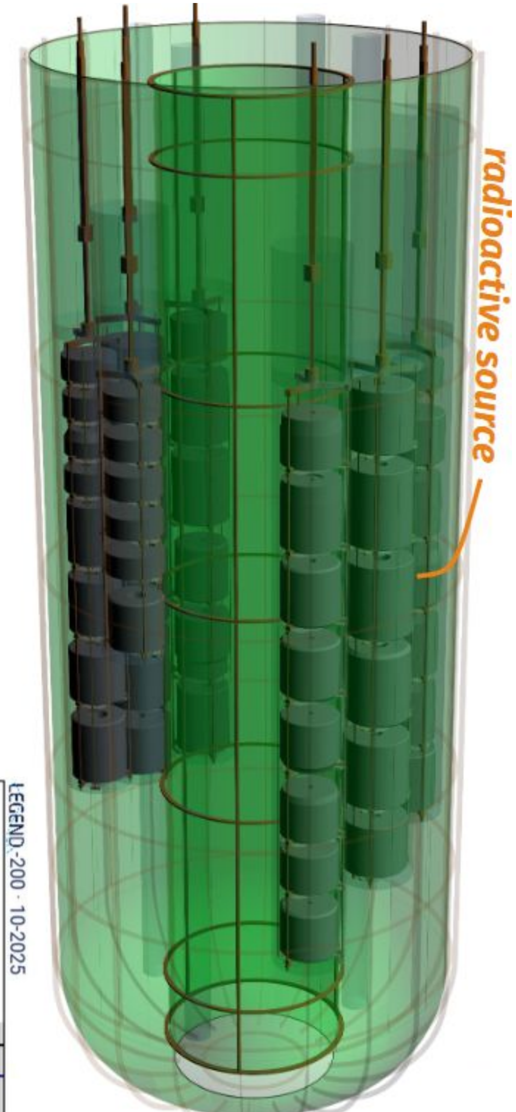
All cleaning and quality control was carried out at MPIK with processes and procedures developed by Cabot-Ann Christofferson (South Dakota School of Mines and Technology) and supported by Andreas Leonhard (TUM)

Special Characterization Runs

- **High-statistics ^{228}Th and ^{226}Ra data taken in Fall 2025**
  - validate/tune optical and PSD models
  - study Th/U background signatures
  - study interplay between LAr and PSD cuts
- ^{228}Th measurement with HPGe array used to quantify optical impact of the array
- Tagging events with HPGe is a powerful tool to select interesting LAr interaction topologies

Slide adapted from [L. Pertoldi, “Modeling Background Rejection in LEGEND with the LAr Instrumentation”, LIDIN2025 talk]



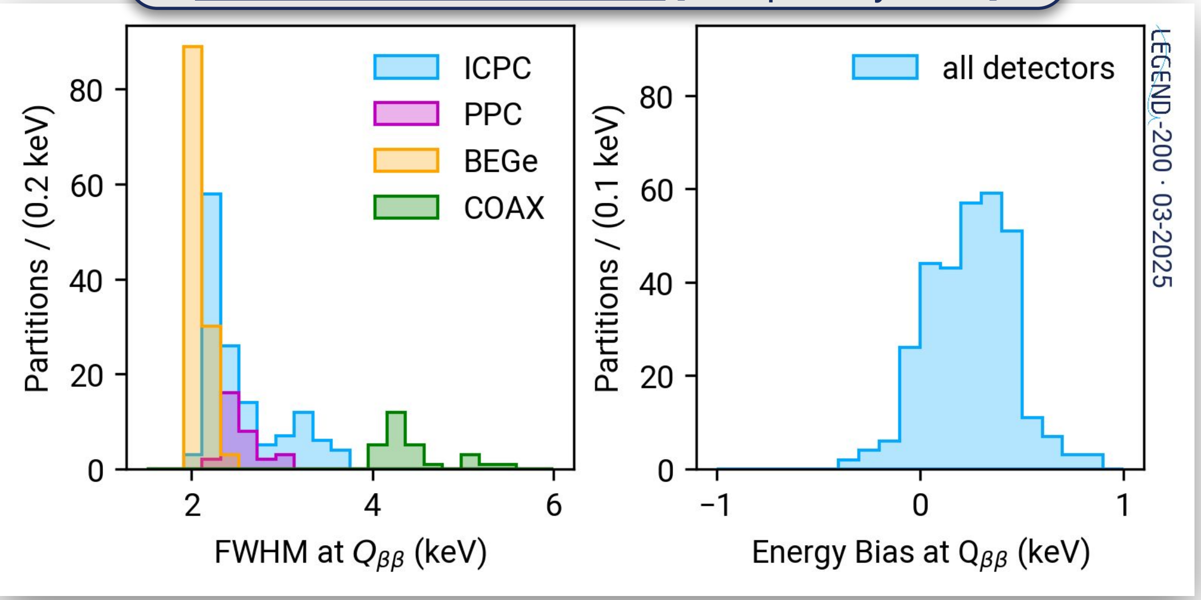


Energy Scale and Resolution

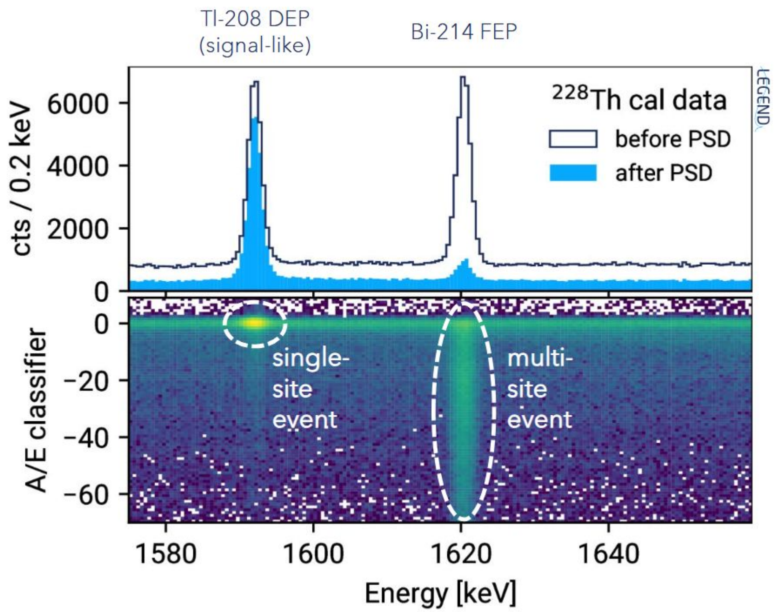
JINST 18 (2023) P02001 [2211.05026]

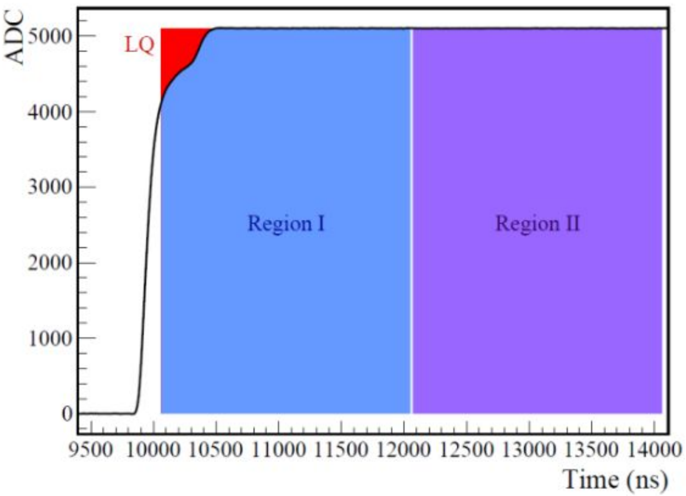
- Weekly calibrations using up to 16 ^{228}Th sources deployed in the array via 4 source insertion systems
- Leading energy resolution: **0.1-0.2% FWHM at $Q_{\beta\beta}$**
- Very stable energy scale: **energy bias 0.2±0.3 keV at $Q_{\beta\beta}$**

10.48550/arxiv.2605.22479 [accepted by EPJC]



PSD cuts





- A/E: gaussian (SSE) + tail at low energies (MSE)

$$f(x = A/E) = \frac{n}{\sigma_{A/E} \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x-\mu_{A/E})^2}{2\sigma^2_{A/E}}}$$

$$+ m \cdot \frac{e^{f\cdot(x-l)} + d}{e^{(x-l)/t} + l}$$

- A/E cuts are performed for each detector separately
- “A/E classifier”: energy independent,

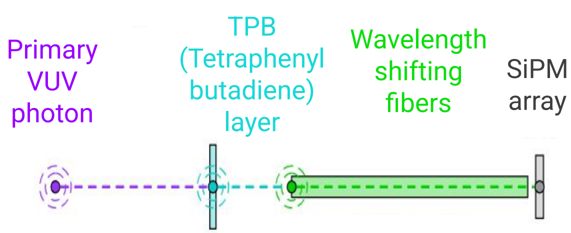
$$\zeta = ([A/E] / \mu_{A/E}(E) - 1) / \sigma_{A/E}$$

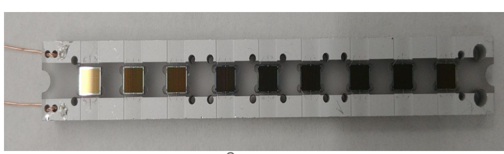
distributed around 0, with std=2 for SSEs

- COAX: due to the geometry, the pulse formation is affected both by the hole and electron
  - different pulse shapes throughout the HPGe volume
  - artificial neutral network (ANN) used to discriminate SSEs from MSEs + pulse risetime cut for fast events close to the p+ contact
- Late charge (LQ) cut is a measure of the “slowness” of the final 20% of charge carriers of an event
  - Very sensitive to events with slow components or kinks (surface α & β)
  - applied to ORTEC detectors due to a wider passivated surface

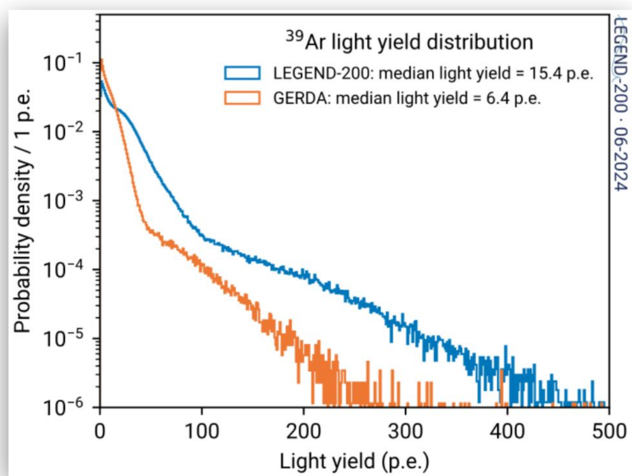
LAr instrumentation system

- **Instrumented LAr volume to read out scintillation light** from background events
  - creation of 128 nm VUV γ in LAr
  - γ shifted to visible light in fiber
  - γ read by SiPM arrays
- **Improved light yield** with respect to GERDA
  - 2 shrouds of optical WLS fibers for enhanced coverage
  - SiPM arrays with new front-end electronics
  - TPB coated TetraTex-Cu WLS reflective foil around the outer shroud to increase light collection



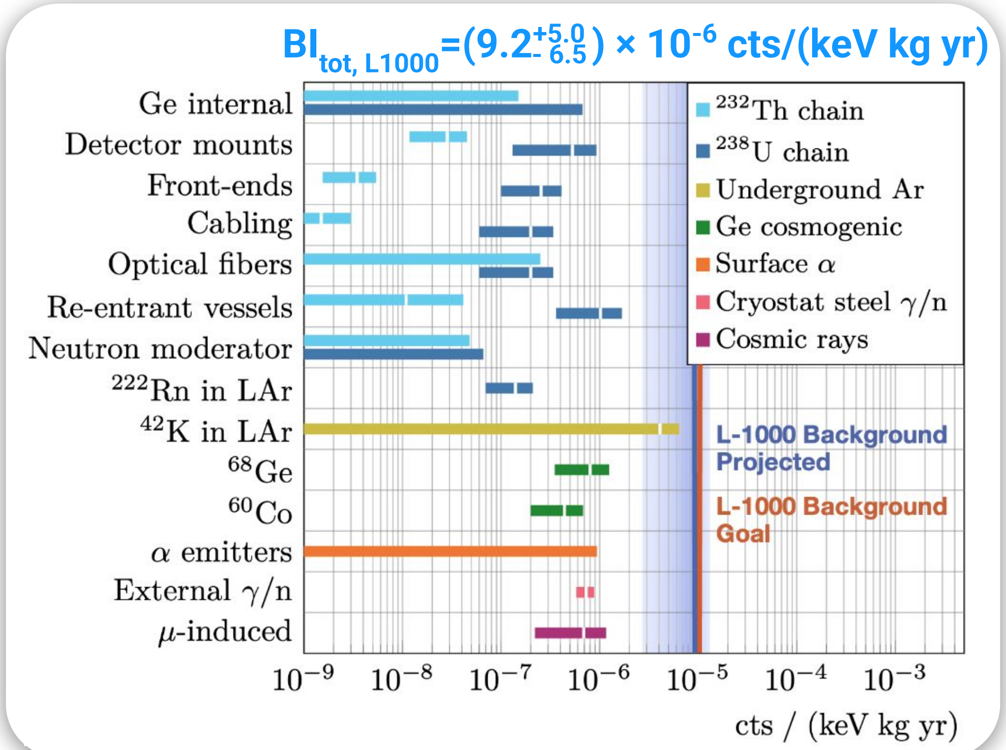


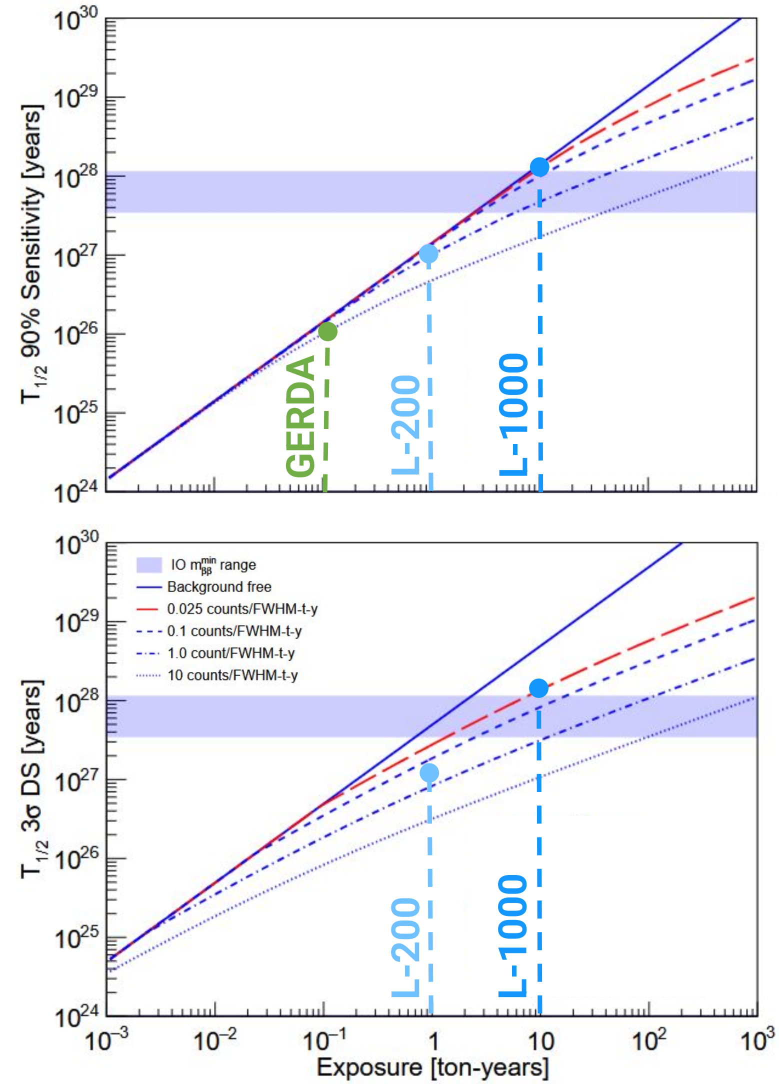
9 3x3 mm^2 KETEK SiPM connected in parallel



LEGEND-1000 projections

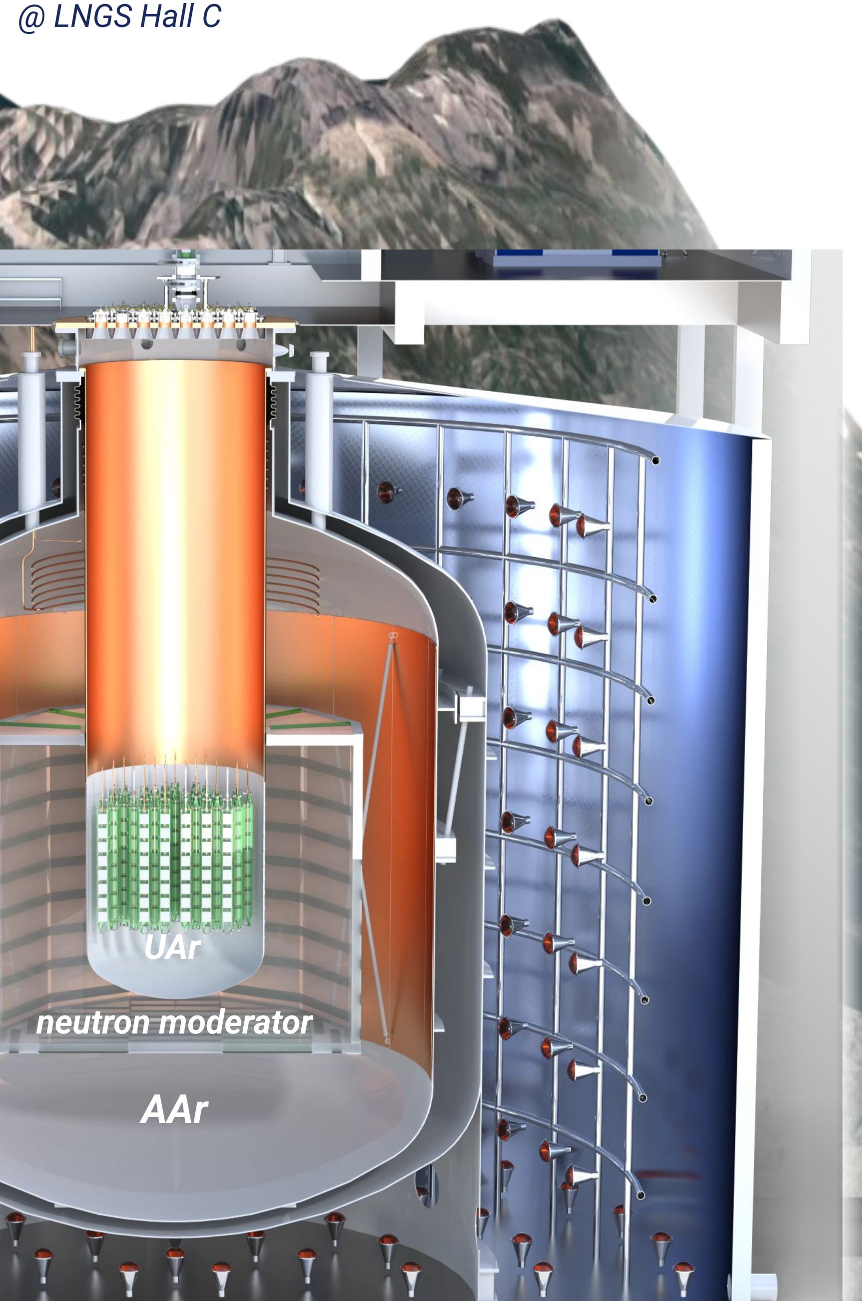
- UAr + improvements in material purity & handling lead to required background reduction
- Dominant contributions from:
  - U/Th in the reentrant vessel
  - conservative estimate of ^{42}K in the UAr

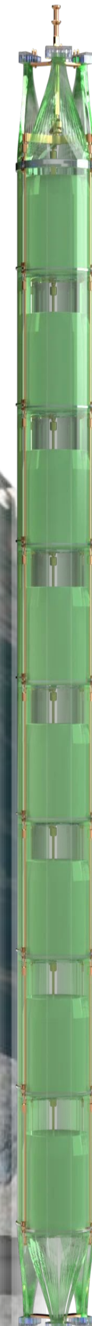




LEGEND-1000

@ LNGS Hall C

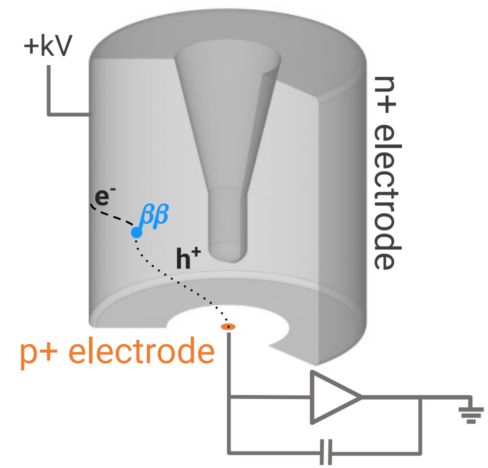




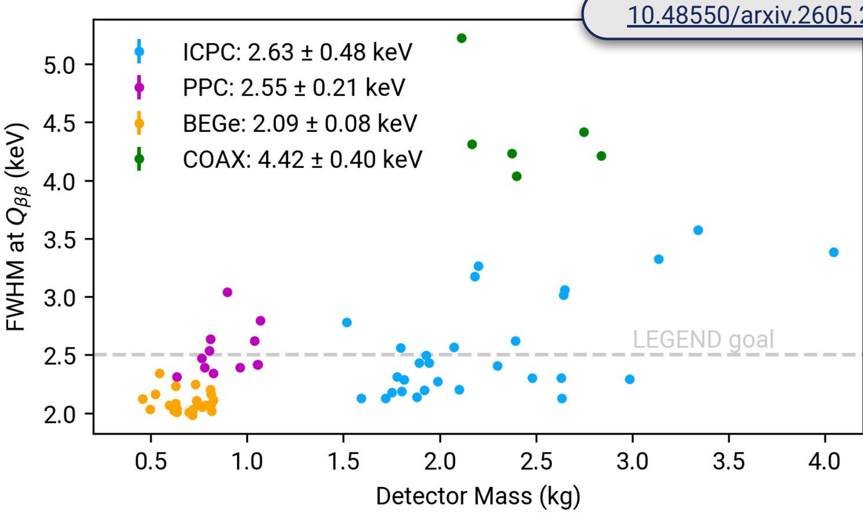
- Independent strings to allow production and modular installation of **~400 HPGe detectors** spread over time
- 48 string modules immersed in dedicated **underground Ar (UAr) re-entrant vessel** to reduce $^{42}Ar/^{42}K$
- **Neutron veto system** (+light detection modules) **in outer atmospheric Ar (AAr)** volume to reduce (cosmogenic) background
- ASIC based readout electronics
- **Several material improvements**

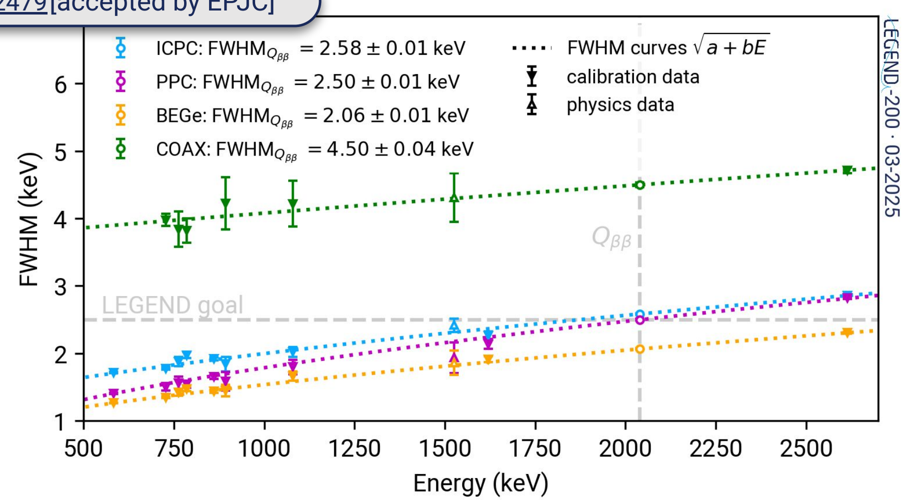
Inverted Coaxial HPGe

- Baseline design for LEGEND-1000
- **Larger mass** (up to ~3 kg), lower cost per kg
  - retain excellent energy resolution
  - less cables and support mass → reduced bkg
  - **reduced surface-to-volume ratio** → reduced α/β
- Retain **similar charge drift times** across the majority of the volume
  - optimal for PSD
  - **higher $\beta\beta$ efficiency**



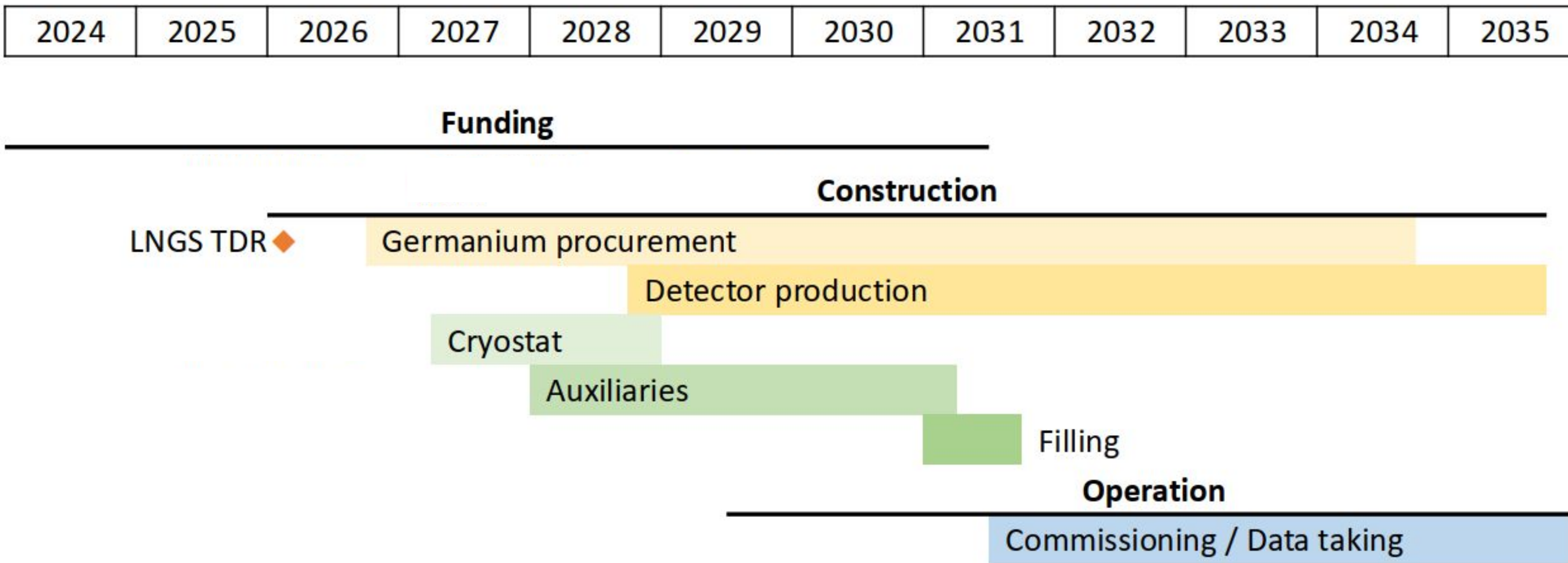
10.48550/arxiv.2605.22479 [accepted by EPJC]



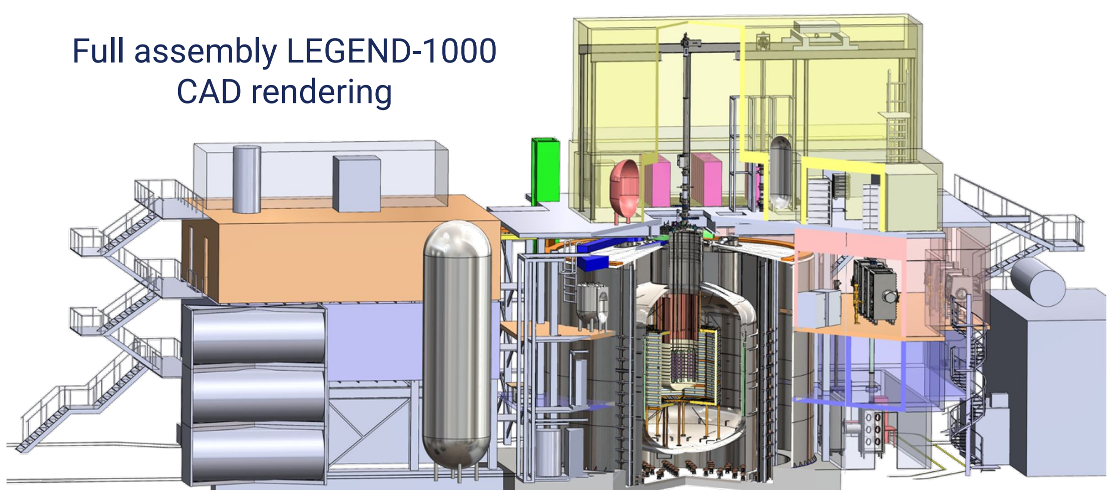


LEGEND-1000 indicative schedule

** technically driven*



Full assembly LEGEND-1000
CAD rendering



Enriched Ge production chain

- **~1000 kg of HPGe detectors enriched to > 90% in ^{76}Ge with average mass of 3 kg**
  - procurement from multiple qualified commercial suppliers
  - dedicated enrichment capacity of **order 200 kg/yr** to meet the production schedule
  - **detector-material recycling** essential to maximize the enriched-Ge yield

Enrichment
Urenco (Netherlands)

→

Reduction & Purification
IKZ (Germany)
VPMS (Germany)

→

Crystal growth
Mirion (Oak Ridge)
Umicore (Belgium)

→

Diode production (Large IC detectors)
Mirion (Belgium)

High Purity Ge Detectors

$0\nu\beta\beta$ decay half-life experimental sensitivity

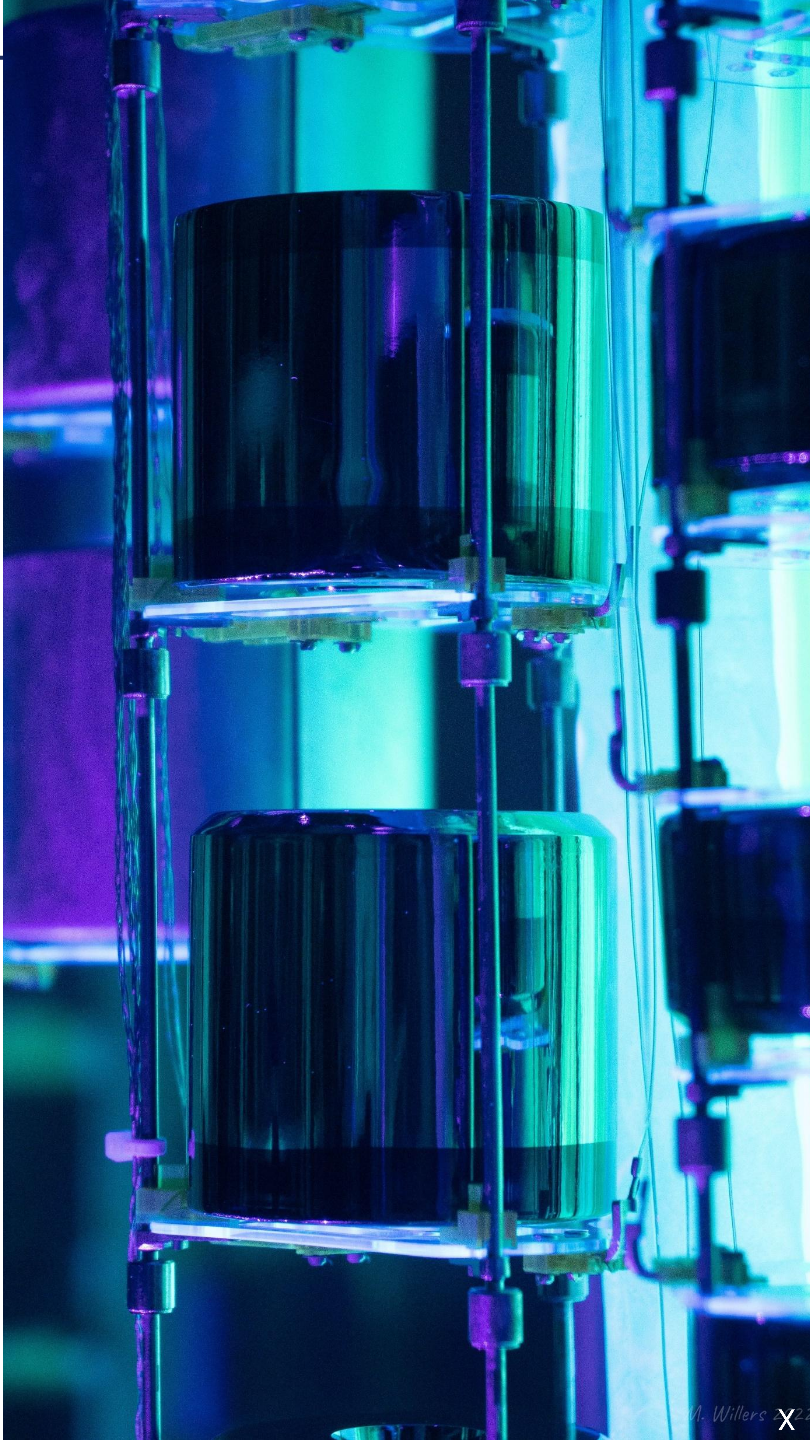
$$T^{0\nu}_{1/2} \propto \begin{cases} \epsilon \cdot f \cdot \sqrt{\dfrac{\varepsilon}{BI \cdot \Delta E}} & \textit{with background} \\ \epsilon \cdot f \cdot \varepsilon & \textit{without background} \end{cases}$$

ϵ: efficiency ↑
f: isotropic fraction ↑
ε: mass × time = exposure ↑
ΔE: energetic resolution at $Q_{\beta\beta}$ ↓
BI: background index ↓

✓ **Large exposure**
- enrichment in ^{76}Ge up to **92%**
- source = detector → **high efficiency**
- large masses (**>3 kg**)
- already established (**scalable**) technology

✓ **World-leading energy resolution**
- **0.1% FWHM** @ $Q_{\beta\beta}$

✓ **Low background level**
- **high purity material**
- operable in liquid argon (**LAr**)
- signal-like selection via pulse shape discrimination (**PSD**)



LEGEND physics portfolio

- **Broad physics program beyond 0v$\beta\beta$** [10.48550/arXiv.2107.11462]
- Multiple signatures: peaks in the energy spectrum, accumulation of events at low energy, 2v$\beta\beta$ decay spectral shape deformations, ….
- **Some searches already started using LEGEND-200 data:** bosonic DM (axion-like particles and dark photons), baryon and electron decays, fractionally charged particles, ^{36}Ar 0νECEC

Physics	Signature	Energy Range	Experiment
Bosonic dark matter (axionlike particle and dark photon)	Peak at DM mass	< 1 MeV	Majorana[72, 73], Gerda [74]
Sterile neutrino transition magnetic moment	Peak at 1/2 the sterile neutrino mass	< 1 MeV	Majorana [75]
Electron decay	Peak at 11.1 keV	~ 10 keV	Majorana [75]
Pauli exclusion principle violation	Peak at 10.6 keV	~ 10 keV	Majorana [72]
Solar axions	Peaked spectra, time-energy pattern	< 10 keV	Majorana[72, 76]
Majoron emission	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	Gerda [77, 78]
Exotic fermions	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	Gerda [78]
Lorentz violation	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	Gerda [78]
Exotic currents in $2\nu\beta\beta$ decay	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [79]
Time-dependent $2\nu\beta\beta$ decay rate	Modulation of $2\nu\beta\beta$ spectrum	$< Q_{\beta\beta}$	(proposed) [80]
Test of wave function collapse models	1/E X-ray radiation	< 100 keV	Majorana [81]
WIMP and related searches	Exponential excess, annual modulation	< 10 keV	CDEX [82]
Baryon decay	Timing coincidence	> 10 MeV	Majorana [83], Gerda [84]
Fractionally charged cosmic-rays	Straight tracks	few keV	Majorana [85]
Fermionic dark matter	Nuclear recoil/deexcitation	$<$ few MeV	Majorana [73]
Inelastic boosted dark matter	Positron production	$<$ few MeV	(proposed) [86]
BSM physics in Ar	Features in Ar instrumentation spectrum	ECEC in ^{36}Ar	Gerda [87]

Non-exhaustive list; updated version of Table II from [10.48550/arXiv.2107.11462]