The LEGEND-200 Liquid Argon Instrumentation: From a simple veto to a full-fledged detector

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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Igor Abritta[1], Gabriela Araujo[2], Laura Baudis[2], Nina Burlac[1], Valerio D'Andrea[1], **Rosanna Deckert[3]**, Maria Fomina[4], Konstantin Gusev[3,4], Patrick Krause[3], Andreas Leonhardt[3], Laszlo Papp[3], Nadya Rumyantseva[3,4], Giuseppe Salamanna[1], Mario Schwarz[3], Stefan Schönert[3], Egor Shevchik[4], Diego Tagnani[1], Christoph Vogl[3], Daniya Zinatulina[4] **for the LEGEND collaboration**

[1] Roma Tre University and INFN Roma Tre, [2] University of Zurich, [3] Technical University of Munich, [4] Joint Institute for Nuclear Research, Dubna

1. LAr instrumentation of LEGEND-200

Essential part of the LEGEND-200 experiment as active background suppression

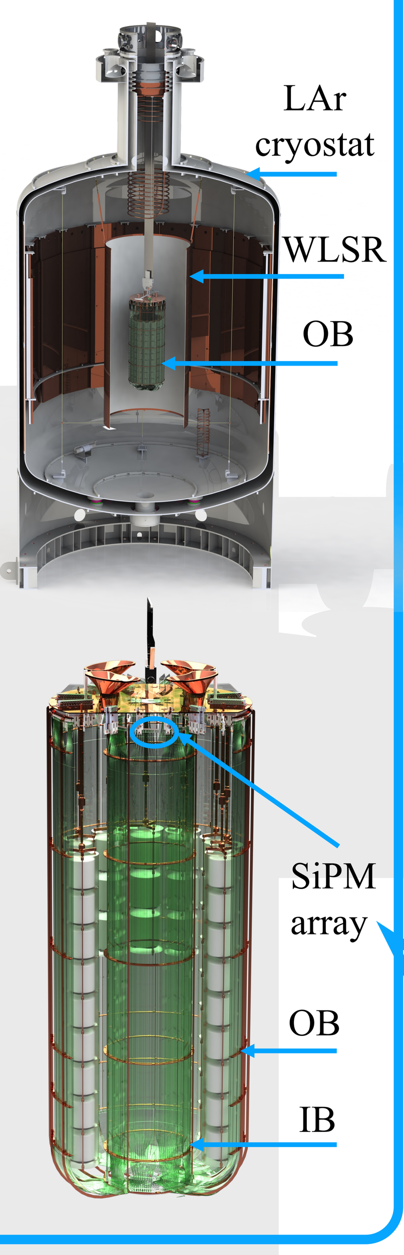
- tags and rejects backgrounds by detecting scintillation light emitted by liquid argon (LAr) upon interaction with ionizing radiation

Consists of two concentric barrels: Inner Barrel (IB) and Outer Barrel (OB).

- barrels equipped with wavelength-shifting (WLS) fibers coated with tetraphenyl butadine (TPB)
- fibers grouped to modules coupled to Silicon Photomultiplier (SiPM) arrays at the top and bottom
  - IB: 9 fiber modules ⟶ 18 SiPM channels
  - OB: 20 fiber modules ⟶ 40 SiPM channels

Wavelength-shifting reflector (WLSR) surrounds the innermost LAr volume

- TPB-coated Copper-Tetratex foil reflects and shifts VUV photons towards blue spectrum
- gives them second chance to be detected
- serves as optical barrier against ambient radiation, e.g., from cryostat walls and ^{39}Ar decays

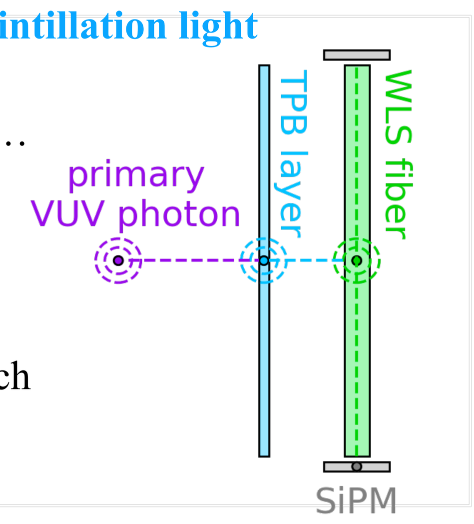


2. LAr scintillation and light collection

- Scintillation light emission is superposition of two excimer (Ar_2^*) states
  - unstable singlet state (lifetime ~ 6 ns)
  - metastable triplet state (lifetime 1.3 – 1.6 μs)
- excimers in both states emit 128 nm vacuum ultra-violet (VUV) scintillation light

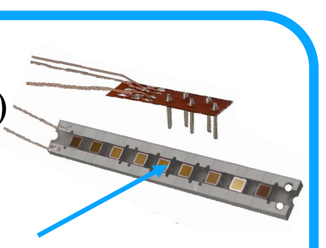
A primary VUV photon is…

- absorbed by the TPB and shifted to blue
- WLS fibers shift the blue light to green which is read out by SiPMs



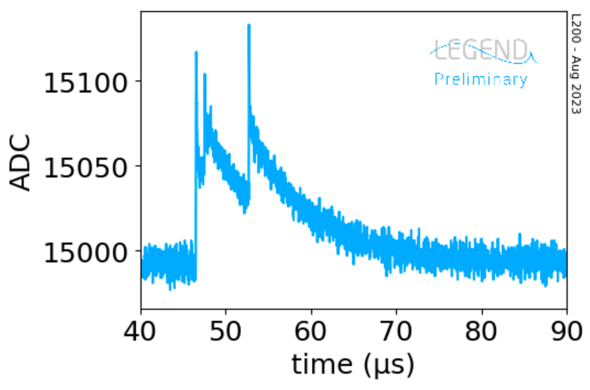
SiPM arrays

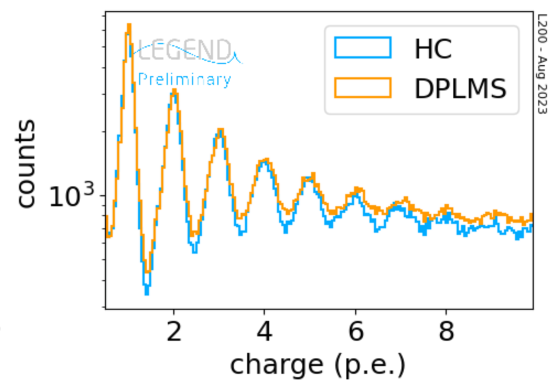
- 9 SiPMs per array and 2 arrays per fiber module (top and bottom)
- SiPM read out in parallel and differentially
- all arrays characterized



3. Data processing chain

- SiPM signals are amplified and read out with a low-noise front-end electronics (arXiv:2211.03069)
- Charge and time reconstruction with two independent methods:
  - Hyper current (HC) algorithm, based on rising edge of waveform (⟶ independent of decay time), exhibits 95% accurate charge reconstruction and 10 ns pulse onset time reconstruction precision
  - Digital Penalized Least Mean Squares (DPLMS)-filter-based reconstruction algorithm for treatment of more noisy waveforms performs equivalently to HC (EPJC 83, 149 (2023))
- p.e. spectrum (summed p.e. values for all working channels on an event-by-event basis) shows excellent charge reconstruction for all channels





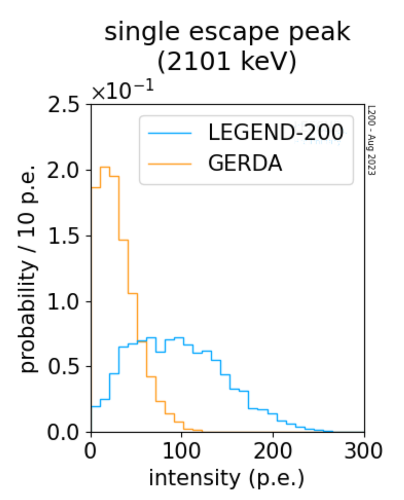
4. Special calibration runs from LEGEND-200 (L200) commissioning runs with 60 kg of Ge-detectors

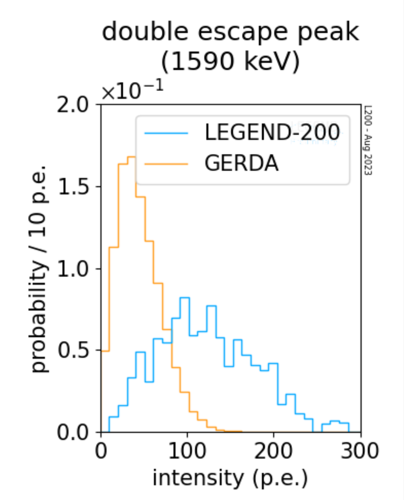
^{228}Th run: focus on intensities of LAr light coincidences to single escape peak (SEP) and double escape peak (DEP) of high-energy gamma line (^{208}Tl line at 2615 keV)

⟶ factor 3 to 4 higher p.e. yield obtained in L200 compared to GERDA (DEP)

Light shadowing (defined as observing < 1 p.e. of light in coincidence) of the LAr instrumentation in %:

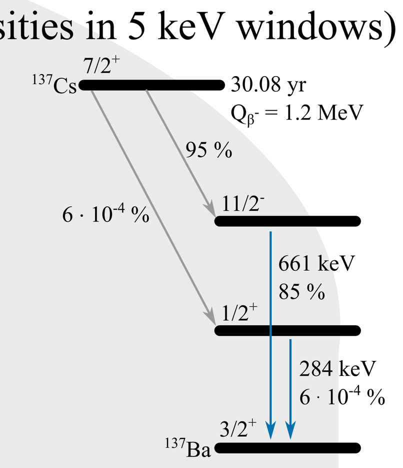
	L200	GERDA
SEP	0.11 ± 0.04	3.8 ± 0.1
DEP	0.2 ± 0.1	0.28 ± 0.05



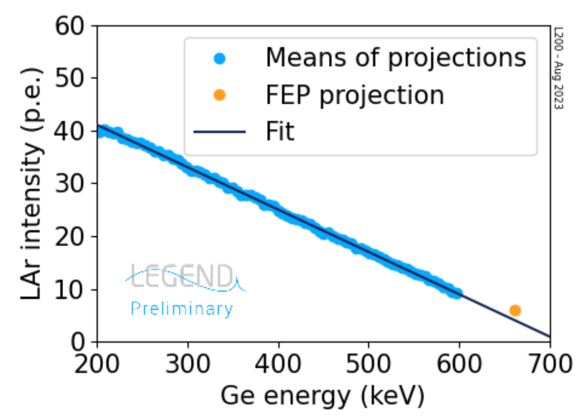


⟶ factor 34 improvement compared to GERDA (SEP)

^{137}Cs run: only one main line at 661keV ⟶ allows continuous calibration via Compton continuum (mean light intensities in 5 keV windows)



⟶ light yield ~ 0.1 p.e./keV (position dependent)

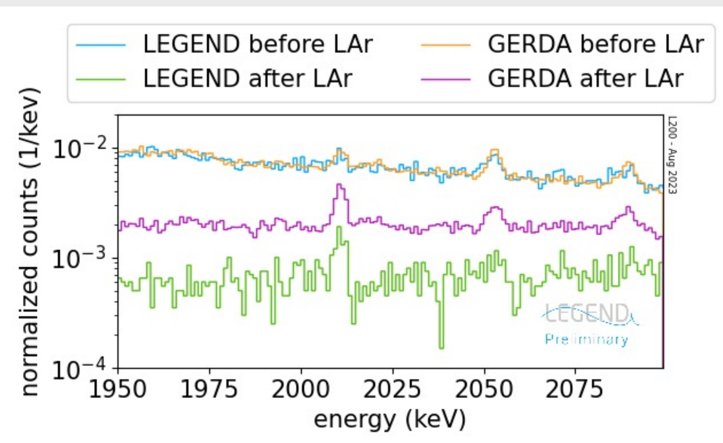


^{226}Ra run:

focus on LAr instrumentation's suppression power in the region of interest (ROI) at $E \in [1950, 2090]$ keV ($Q_{\beta\beta} = 2039$ keV)

- Rejection condition of LAr cut tuned on 95% pulser acceptance

⟶ Survival probability of events in the ROI is $(10.4 \pm 0.2)\%$ compared to $(30.4 \pm 0.2)\%$ in GERDA

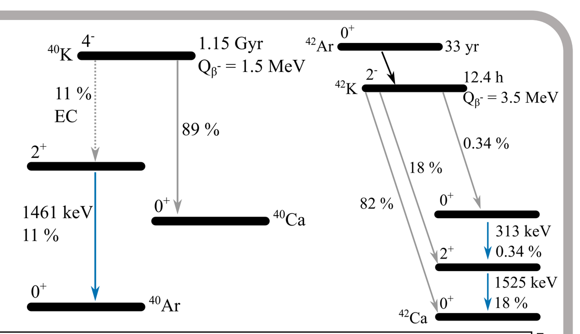


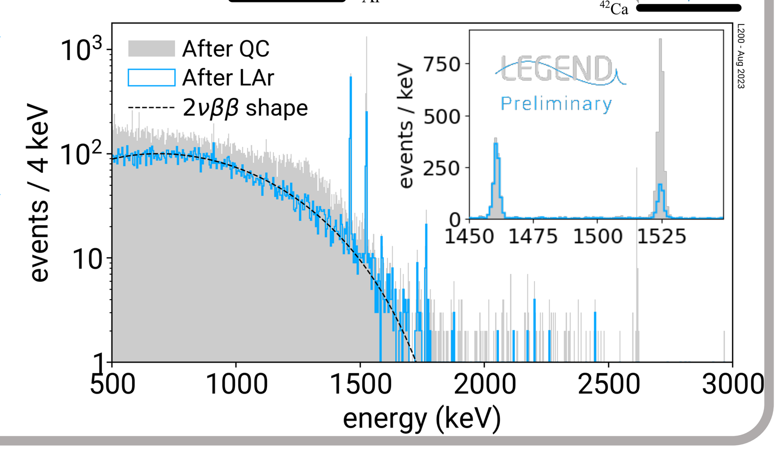
5. Performance in LEGEND-200

Potassium suppression:

^{40}K and ^{42}K as the two most intense lines in the LEGEND background spectrum

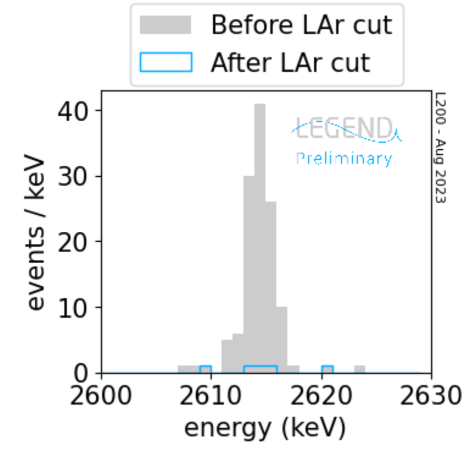
- ^{40}K line survives with $(93 \pm 1)\%$
- ^{42}K line survives with $(19 \pm 1)\%$
- Compton continuum suppressed

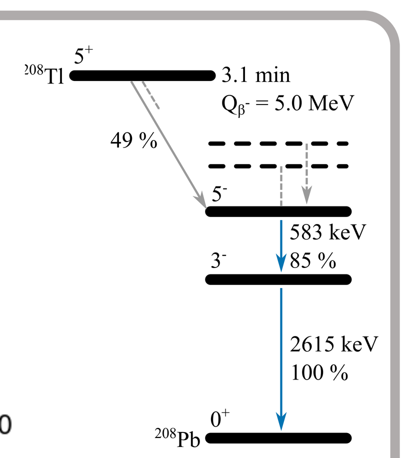




^{208}Tl-line

⟶ almost completely suppressed by LAr cut





6. Particle discrimination

LAr event topology classifier (ETC)

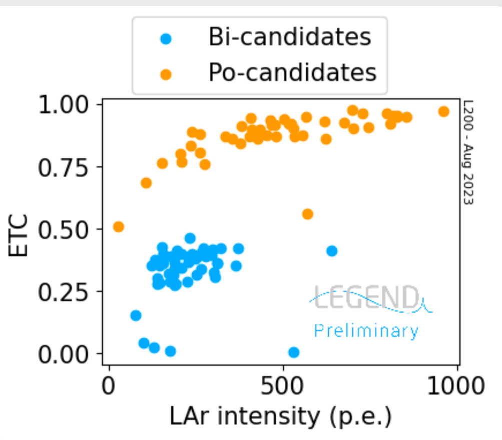
- The ratio R of singlet to triplet components in a scintillation event varies with radiation's linear energy transfer (LET) dE/dx
- Different radiation types have different LET's ⟶ particle discrimination via R-values
- Utilizing ETC parameter ($ETC = 1/[1 + 1/R]$) to identify background types in LEGEND-200 (e.g., radon activity via ^{214}Bi-Po coincident events, search for cosmogenic backgrounds)
- Limited to LAr-triggered data until Ge-trigger time reconstruction is enhanced

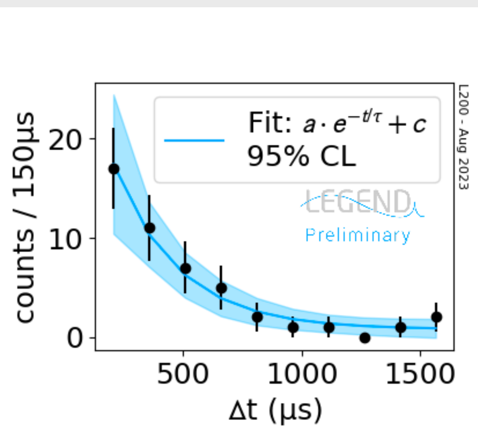
Application: ^{214}Bi-Po tagging

- ^{214}Bi β-decays to ^{214}Po ⟶ α decay of ^{214}Po with half-life of 164 μs produces time-correlated signals

⟶ half-life of (188 ± 46) μs

⟶ ^{214}Bi-Po activity of (23 ± 4) μBq or (3.8 ± 0.7) nBq/kg of LAr (in 6 t active LAr volume)





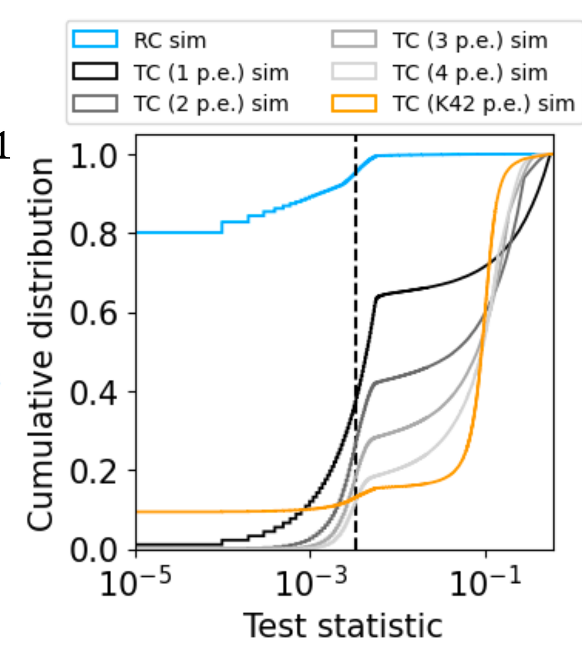
7. Time statistics

- Test-statistic-based LAr veto condition exploiting the time distribution of individual light pulses in a scintillation event:

$$f(t) = \frac{I_S}{\tau_S} \cdot e^{-\frac{(t-t_0)}{\tau_S}} + \frac{I_T}{\tau_T} \cdot e^{-\frac{(t-t_0)}{\tau_T}}, \quad I_S + I_T = 1$$

with $I_{S(T)}$ intensities of singlet (triplet) components

- $t_0 = t_{0,Ge}$ for true coincidences (TC), t_0 located randomly for random coincidences (RC)
- Test statistic T that maximizes TC rejection and RC acceptance $T = \sum_i^m \frac{f(t_i)}{m}$ with m the total number of p.e. in one event and t_i the arrival times



	Acc. (%)	Acceptance energy only (%)
RC	95	95
TC (1 p.e.)	37	100
TC (2 p.e.)	26	100
TC (3 p.e.)	18	100
TC (4 p.e.)	12	100
TC (^{42}K p.e.)	13	18

8. Conclusion

- Excellent energy and time reconstruction
- Special calibration runs showed significant light yield and shadowing improvements compared to GERDA
- Background suppression successfully demonstrated (e.g., ^{42}K, ^{208}Tl)
- Advanced methods such as the event topology classifier and the usage of test statistics introduced

⟶ LAr instrumentation elevated to a full-fledged detector

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