The way to zero background search with LEGEND -1000

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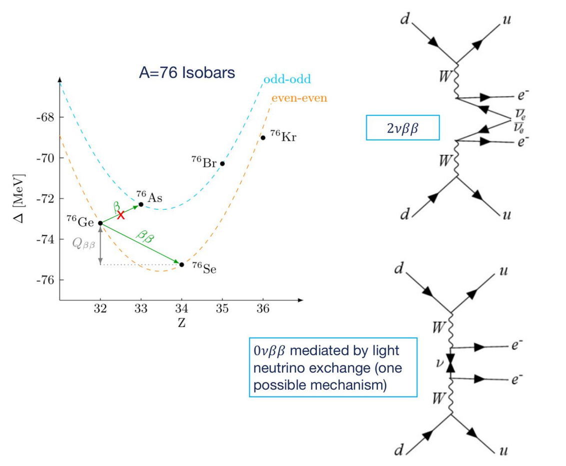
On behalf of LEGEND — Large Enriched Germanium Experiment for Neutrinoless ββ Decay

The LEGEND project

The LEGEND (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay) Collaboration was born in 2016, building on the expertise of GERDA and Majorana DEMONSTRATOR experiments [10.48550/arXiv.2107.11462]


13 countries, 60 institutions, ~350 members



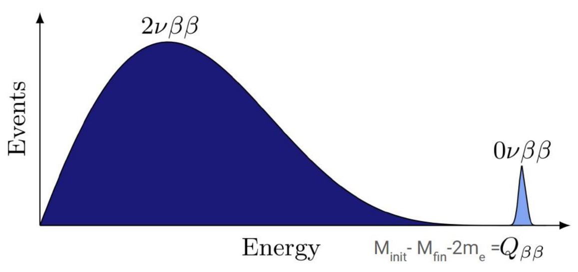
Main goal: Detection of Neutrinoless double beta decay of ^{76}Ge

Neutrinoless double beta decay ($0\nu\beta\beta$) is an hypothetical decay where no neutrinos are emitted its half life is given by:

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

- $G^{0\nu}$: Phase-space factor, well known ($10^{-15}/10^{-13}$ yr^{-1})
- $M^{0\nu}$: Nuclear matrix element strongly model dependent
- $m_{\beta\beta}$ Effective Majorana mass: estimated by measuring $T_{1/2}$

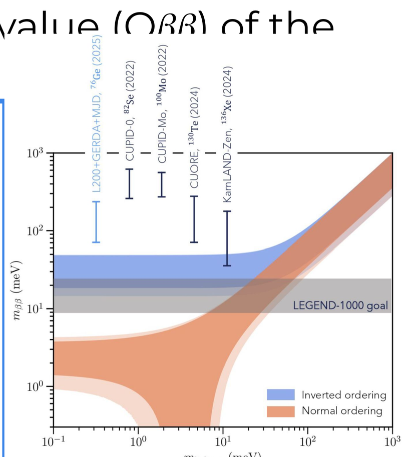
$$\langle m_{\beta\beta}\rangle = |U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3|$$



The signature would be a **peak** at the Q-value ($Q_{\beta\beta}$) of the decay in the 2e- energy spectra

A discovery of $0\nu\beta\beta$ will imply that: Rev. Mod. Phys. 95, 025002

- Neutrinos are Majorana particles (Light Majorana Mass)
- Beyond Standard Model mechanism for ν's mass generation
- Independent determination of the neutrino mass ($m_{\beta\beta}$)
- Lepton Number conservation is violated ΔL=2
- Matter-Antimatter asymmetry in early universe via Leptogenesis



Sensitivity:
$$T^{0\nu}_{1/2} \propto \begin{cases} M\cdot t\cdot a\cdot\varepsilon & \textbf{Background Free} \\ \sqrt{\dfrac{M\cdot t}{BI\cdot\sigma}}\cdot a\cdot\varepsilon \end{cases}$$

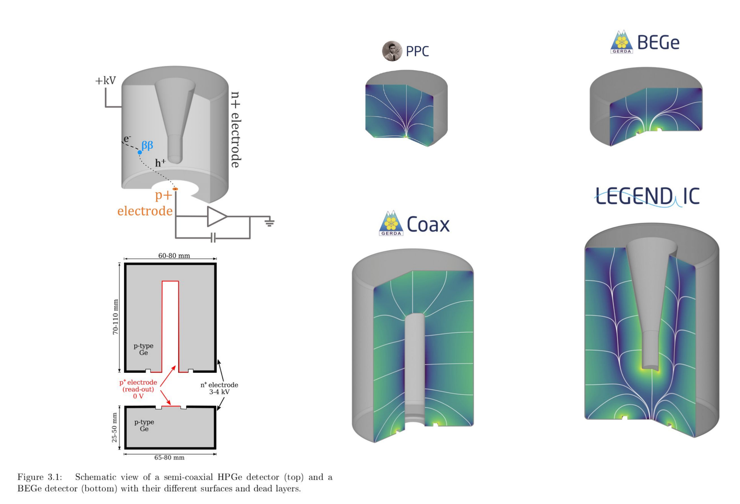
- **M:** total active mass
- **t:** exposure time
- **a:** isotopic abundance
- **ε:** detection efficiency
- **BI:** background index
- **σ:** width of energy ROI

LEGEND Search for $0\nu\beta\beta$ decay of ^{76}Ge (Natural abundance: ~8%): **^{76}Ge → ^{76}Se+2e$^-$** with $Q_{\beta\beta}$ = 2039.061 (7) keV using **High Purity Germanium Detectors (HPGes)**

HPGes are **Ionization detectors** consisting in semiconductor crystal operated at cryogenic temperature. They exploit a p-n junction, where the depletion zone is used as the active volume

- Excellent energy resolution: **0.12% FWHM** at $Q_{\beta\beta}$
- High radiopurity →low intrinsic background
- Detectors are enriched to ~90% in ^{76}Ge
- High detection efficiency (Detector = Source)
- Point contact design allows for pulse shape discrimination (PSD)

Detector types used in LEGEND



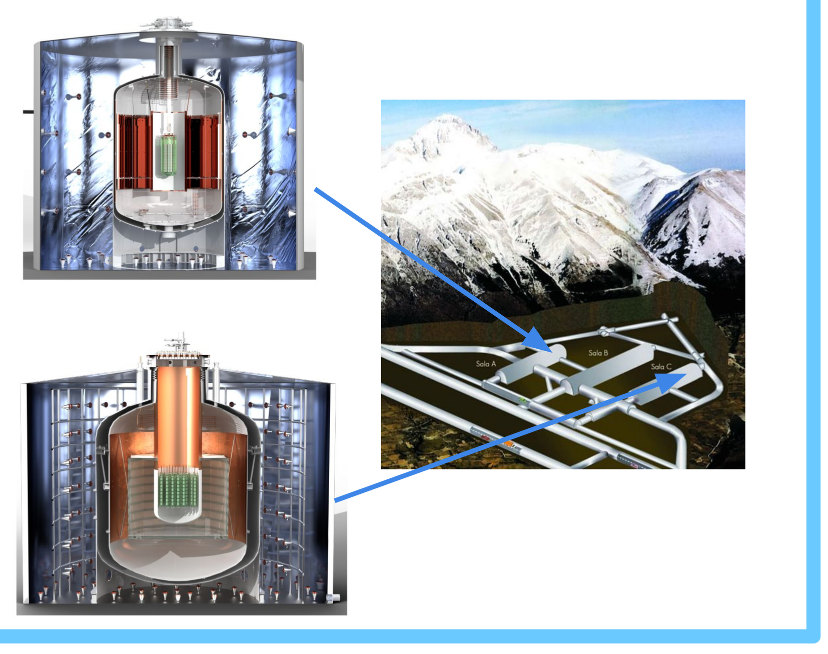
A Phased Program at Laboratori Nazionali del Gran Sasso

LEGEND-200: Currently taking data at LNGS

- Up to 200kg HPGe detectors
- Planned exposure: 1 ton yr
- BI Goal: ~2×10^{-4} cts/(keV kg yr)
- Sensitivity Goal: $T_{1/2} > 10^{27}$ yr

LEGEND-1000: Plans to start data taking in 2030s

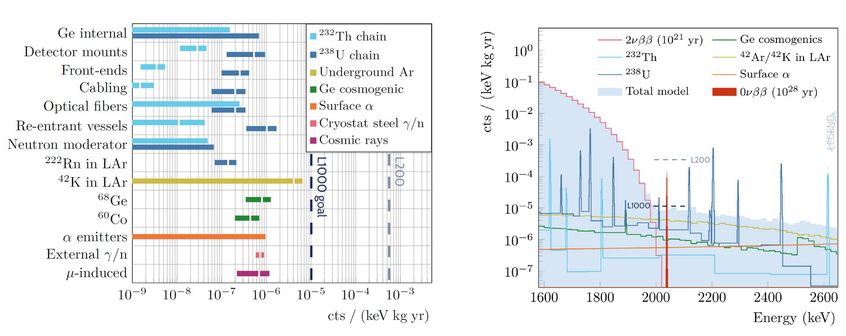
- 1 ton of HPGe detectors
- Planned exposure: 10 ton yr
- **BI Goal: ~1×10^{-5} cts/(keV kg yr)**
- Sensitivity Goal: $T_{1/2} > 10^{28}$ yr



Background Goal in LEGEND-1000

The main Expected background contribution can be grouped into three categories:

- Radiogenic (^{232}Th and ^{238}U chains)
- ^{42}K background
- μ-induced background

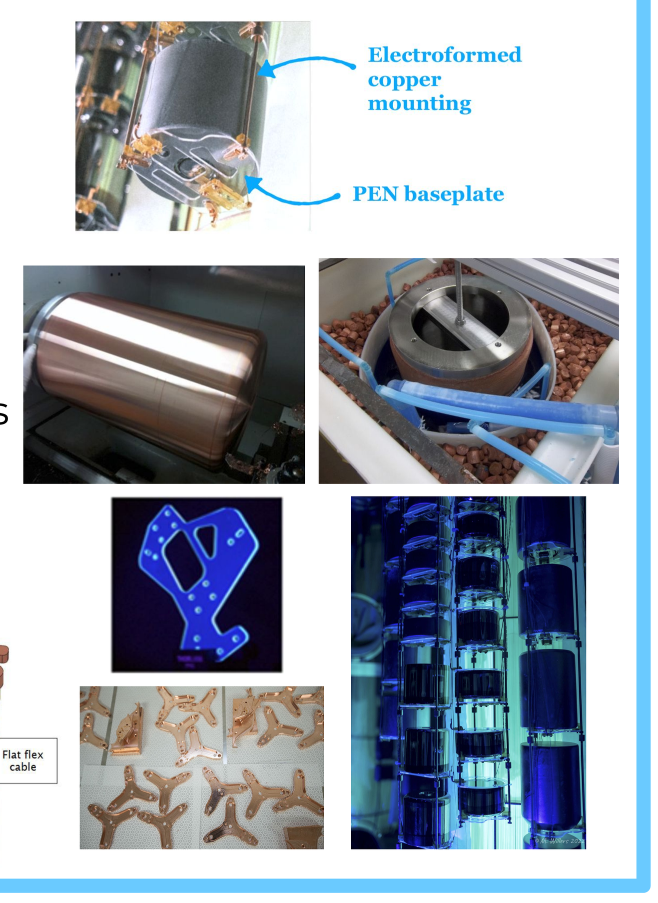


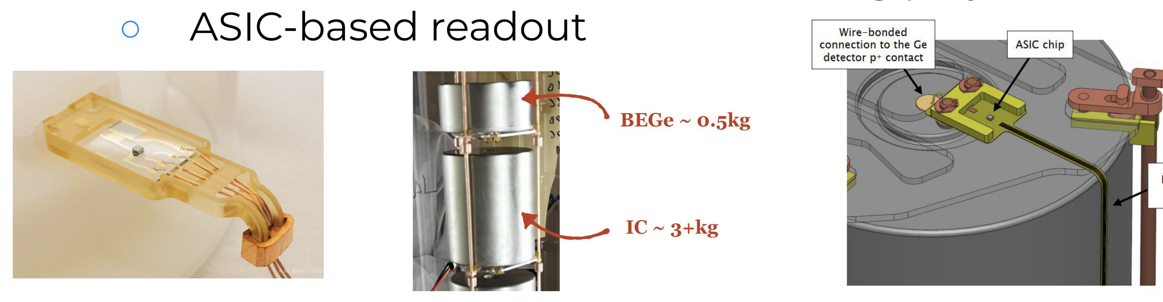
To reach the Background Index goal of 1×10^{-5} cts/(keV kg yr) several **suppression strategies and techniques** have been deployed

Radiogenic Background

Contamination of materials coming from ^{232}Th and ^{238}U chains, can be mitigated via:

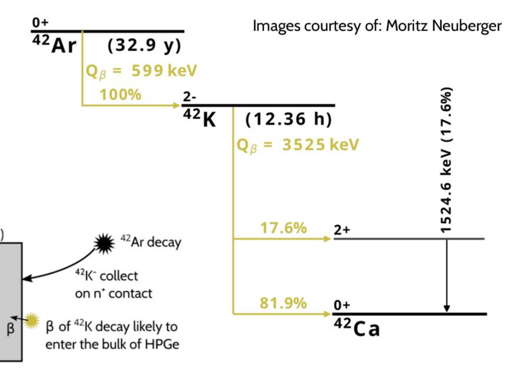
- Thorough **screening** of final material candidates
- Larger Inverted Coaxial detectors with better **bulk/surface ratio**
- In house production for high-risk parts, closer to detectors
- **Reduction** of structural/dead material and electronics
  - Underground electroformed copper used as structural material
  - PEN as clean structural scintillating polymer
  - ASIC-based readout



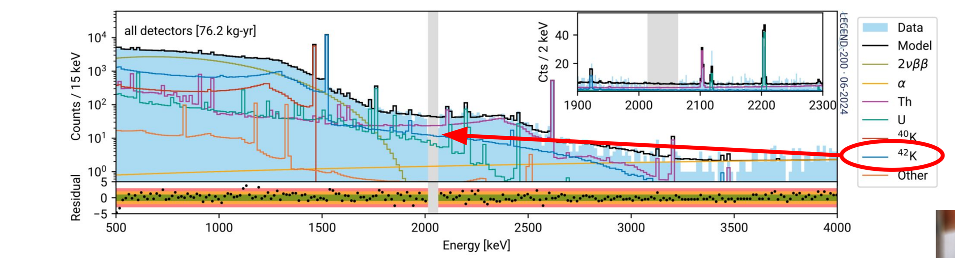


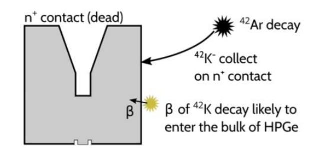
^{42}K Background

Commercial/Atmospheric Argon has a concentration **40-110 mBq/t of ^{42}Ar** Its daughter ^{42}K is produced as negative ion and **drift** towards HPGe n+ contact which is inactive (dead layer)



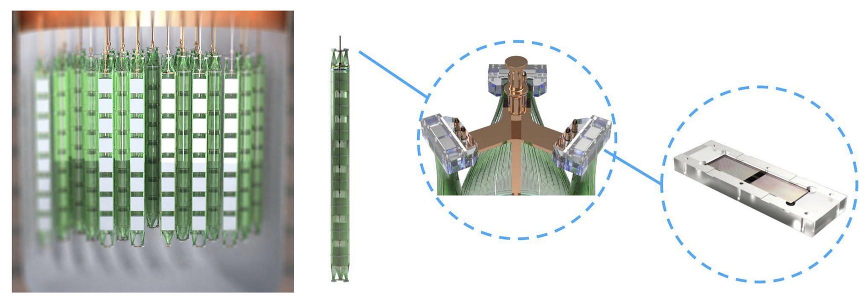
^{42}K then decays β close to the detectors producing a spectrum that **extends into the $Q_{\beta\beta}$ region**





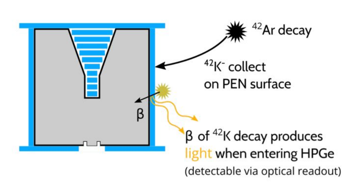
Use of **Underground Argon** in the inner volume with ^{42}Ar concentration ~1400x lower

- Extracted in URANIA facility, Colorado after DarkSide campaign
- Purified in ARIA facility, Sardegna



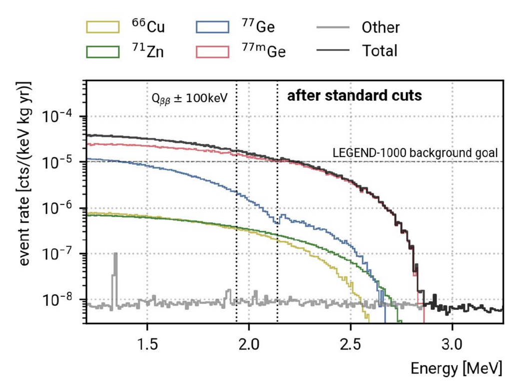
ULAr scintillation light read by the single string **Inner LAr Instrumentation**

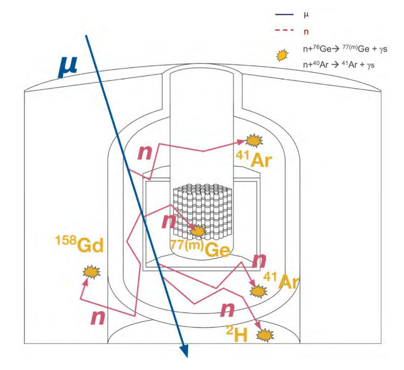
Alternative: Optically active HPGe PEN enclosures combined with PSD

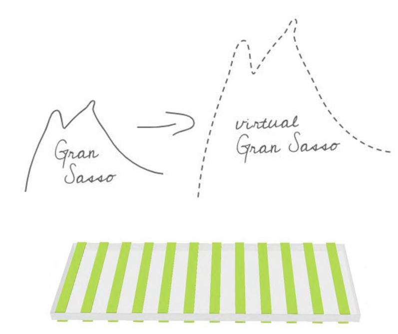


μ-induced Background

Cosmic Muons interacting with the experimental setup produces a cascade of neutrons whom can be captured by ^{76}Ge and produce **^{77}Ge and ^{77m}Ge cosmogenic isotopes** via the reaction ^{76}Ge(n,γ). which contributes to a non negligible background rate in LEGEND-1000 even in the underground laboratory



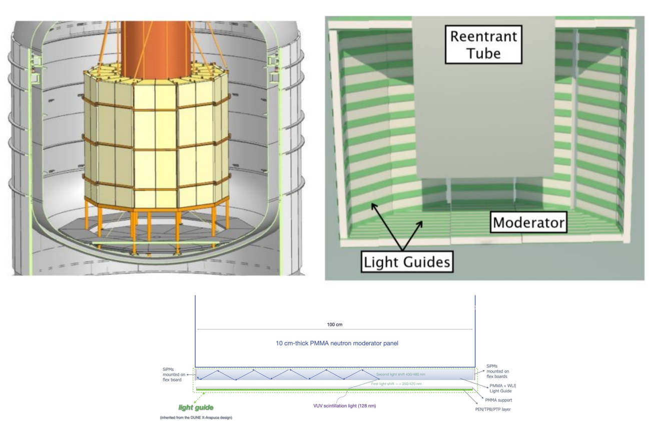




The idea: Make Gran Sasso "Virtually Deeper" by actively tagging cosmic induced neutron captured on ^{40}Ar nuclei with an **Outer LAr Instrumentation** composed of:

1. **Neutron moderation:** via a passive layer of a hydrogen-rich material to enhance the fraction of neutrons captured in ^{40}Ar
2. **Detection:** through a dedicated LAr instrumentation

Reference Design: PMMA (10 cm thick) structure acting as neutron moderator around the inner cryostat immersed in Atmospheric LAr



- **Light Guides:** made of WLS doped PMMA
- **Wavelength Shifter:** PEN foil or coated TPB/PTP shifting the 128 nm Ar light to visible
- **Readout:** at the ends of the Light Guides with SiPMs.

Summary and Outlook

Final design for LEGEND-1000 is being reviewed, while **site preparation** at LNGS (hall C) is underway

With the aimed background goal a clear and unambiguous **detection of 0νββ decay** is achievable even with only a few events at $Q_{\beta\beta}$