^{42}K mitigation studies in ^{42}Ar-spiked liquid argon for LEGEND

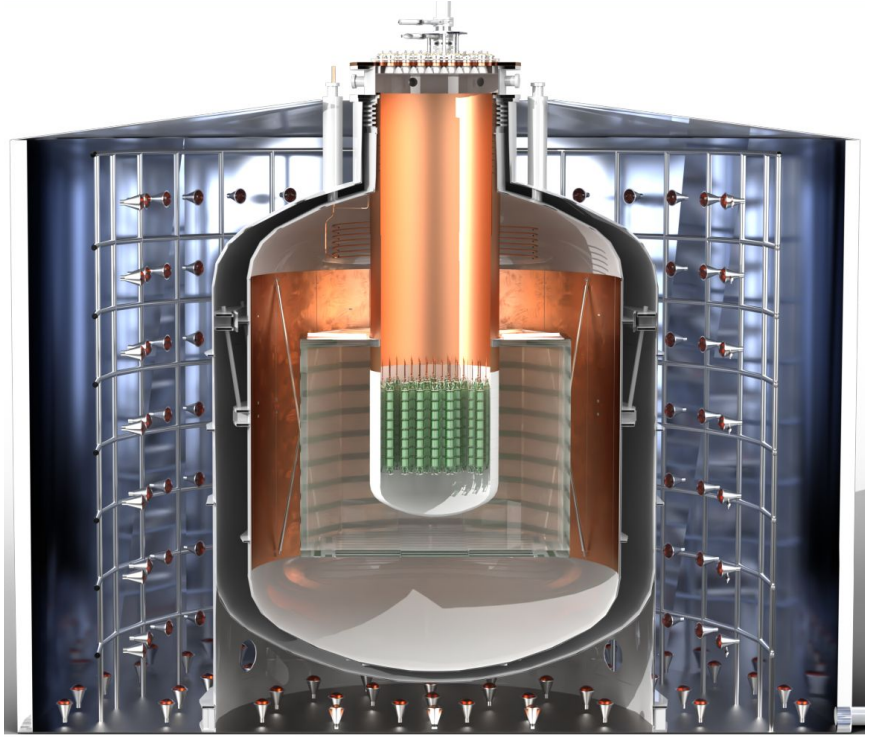
Christoph Vogl*, Tommaso Comellato, Maximilian Goldbrunner, Konstantin Gusev, Brennan Hackett, Patrick Krause, Niko Lay, Andreas Leonhardt, Bela Majorovits, Moritz Neuberger, Luigi Pertoldi, Nadezda Rumyantseva, Stefan Schönert, Mario Schwarz, Michael Willers

Topics in Astroparticle and Underground Physics (TAUP)
25–29 August 2025, Xichang, China

*christoph.vogl@tum.de

The LEGEND experiment searches for 0νββ in ^{76}Ge

- The **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay: LEGEND
- International collaboration searching for neutrinoless double beta decay (0νββ) of ^{76}Ge
- Staged experimental implementation @ LNGS:
  - LEGEND-200: operational in Hall A
    [first results: arXiv:2505.10440]
  - LEGEND-1000: under preparation in Hall C
- Operation of High-Purity Germanium (HPGe) detectors enriched in ^{76}Ge
- HPGe deployed in instrumented liquid argon (LAr) volume → cooling & active shield



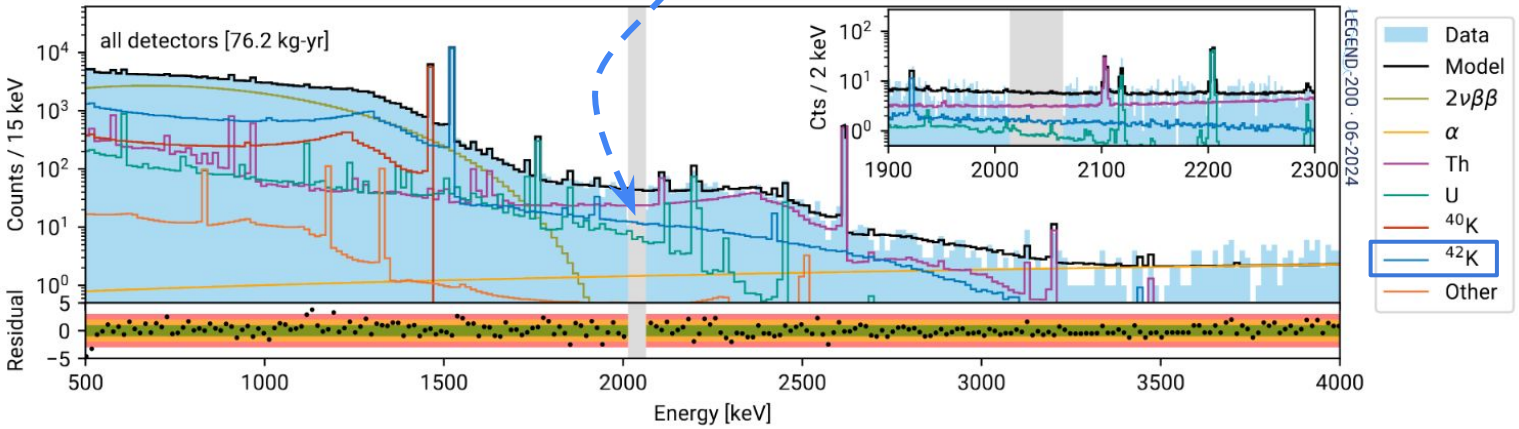
LEGEND-1000 rendering

^{42}K is a critical background source

- LEGEND-1000 aims for a 0νββ discovery sensitivity beyond 10^{28} years
- Requires ultra-low background index of **< 10^{-5} cts/(keV kg yr)** "background-free search"

- **^{42}K** is a **critical background** source around the 0νββ region of interest (ROI)
- ^{42}K known from GERDA [*J. High Energ. Phys.* **2020**, 139 (2020)]

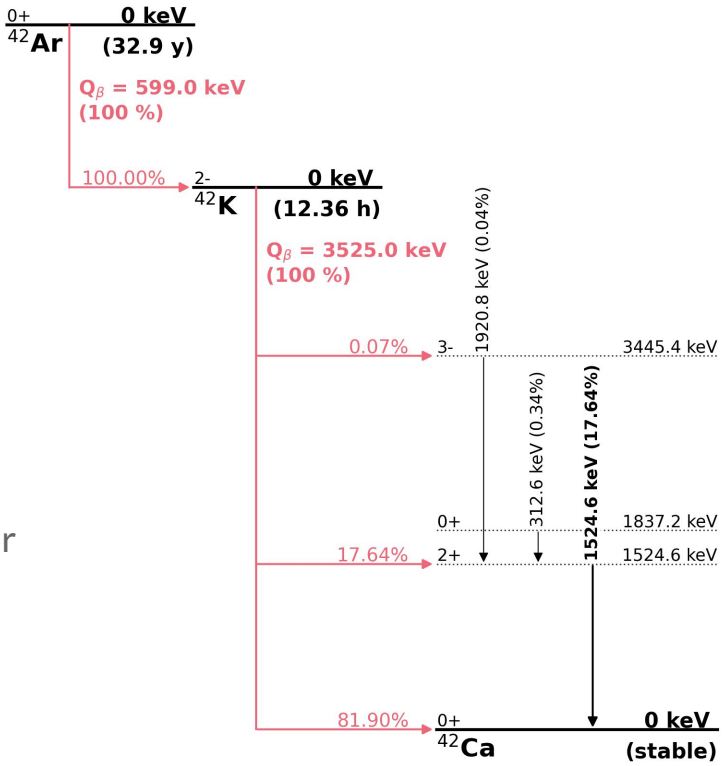
LEGEND-200 background composition before cuts [L. Pertoldi for the LEGEND collab. @ Neutrino 2024, see link]



Origin of ^{42}K background

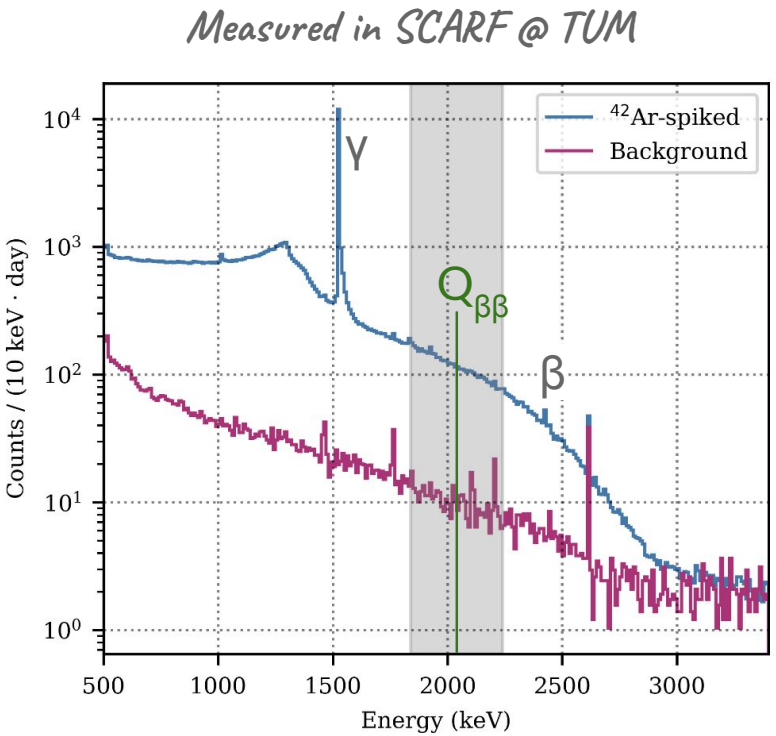
- ^{42}K is continuously produced by ^{42}Ar
- ^{42}Ar is a cosmogenic isotope present in commercial argon in trace amounts (71–101 mBq/t [1] , 40 mBq/t [2])
- $Q_\beta(^{42}K) = 3.5$ MeV $> Q_{\beta\beta}(^{76}Ge)$
- Ge detectors' electric fields collect charged ^{42}K

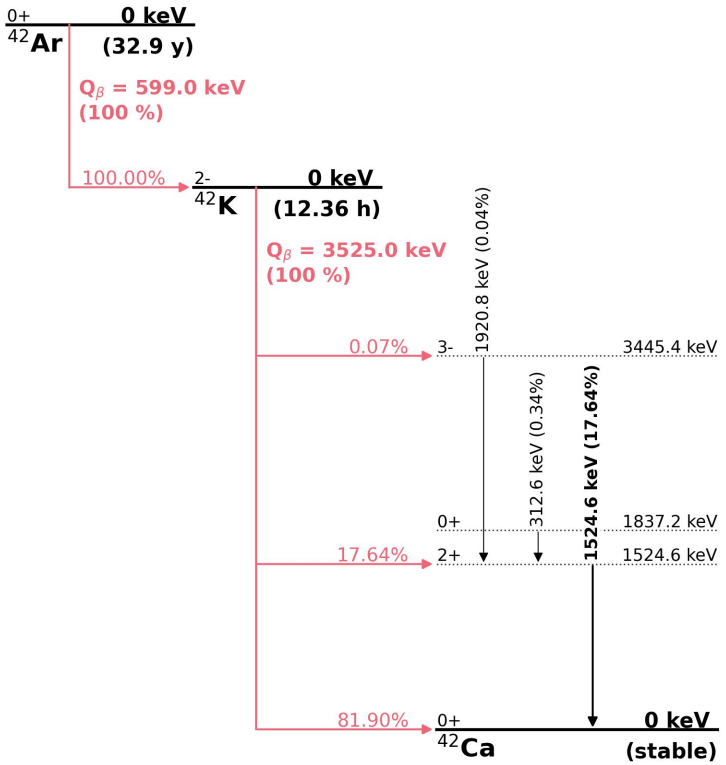
n^+ surface at ≈ +3000 V
→ Collect negative ^{42}K ions or complexes (-)



[1: GERDA internal report (2016),
2: DEAP arXiv:1905.05811 (2019)]

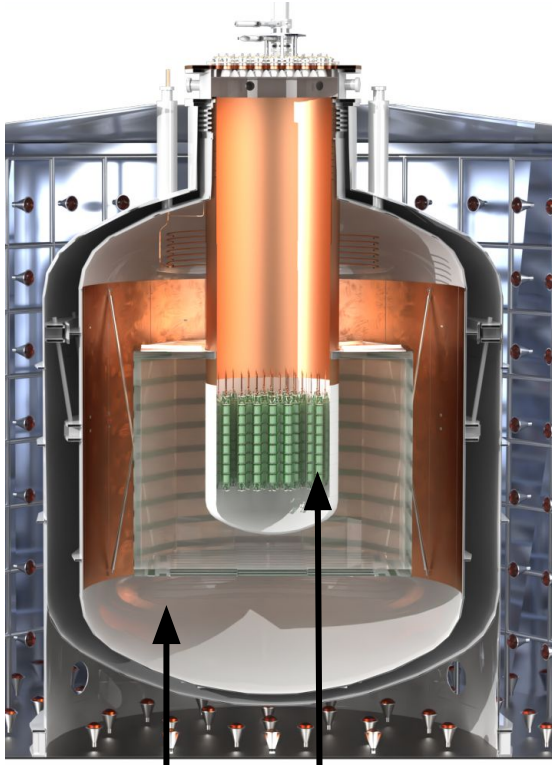
Origin of ^{42}K background





^{42}K mitigation in LEGEND-1000

- Use of underground-sourced LAr (UGLAr)
  - Baseline in LEGEND-1000
  - Factor of ≳1000 reduction [1]



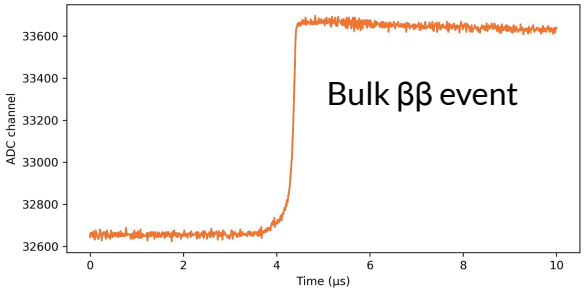
[1: LEGEND pCDR (2021) arXiv:2107.11462]

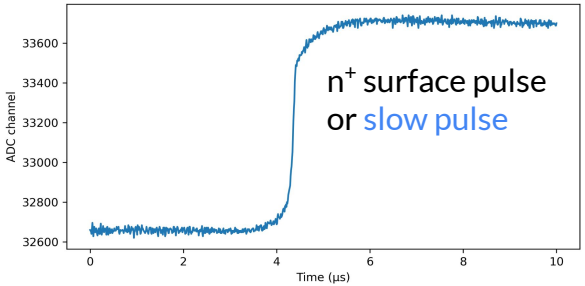
^{42}K mitigation in LEGEND-1000

- Use of underground-sourced LAr (UGLAr)
  - Baseline in LEGEND-1000
  - Factor of ≳1000 reduction [1]
- Pulse-shape discrimination (PSD) of beta-events **on** the n^+ surface

^{42}K betas:
energy deposition in transition layer of n^+
→ slow charge collection → slow pulse shape

Measured in SCARF @ TUM

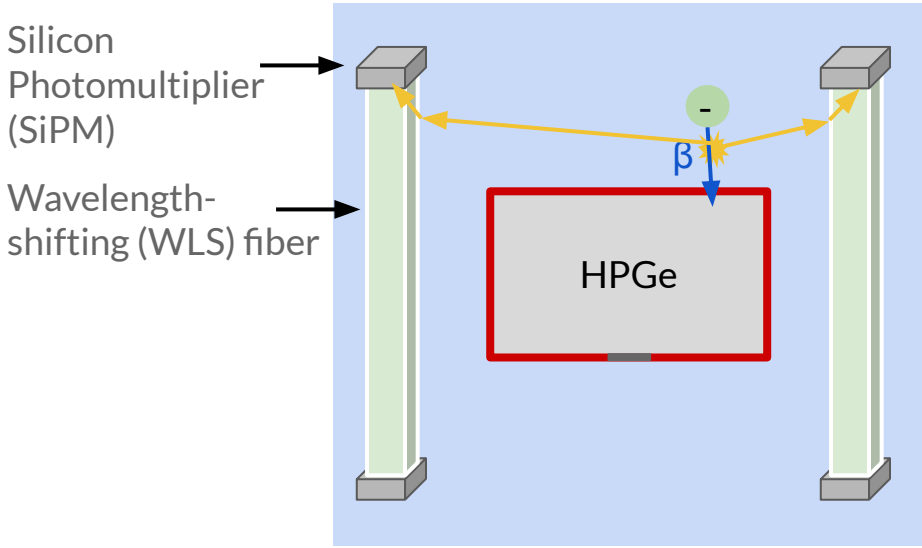




[1: LEGEND pCDR (2021) arXiv:2107.11462]

^{42}K mitigation in LEGEND-1000

- Use of underground-sourced LAr (UGLAr)
  - Baseline in LEGEND-1000
  - Factor of ≳1000 reduction [1]
- Pulse-shape discrimination (PSD) of beta-events **on** the n^+ surface
- LAr scintillation anti-coincidence (AC) for beta events **close to** the n+ surface

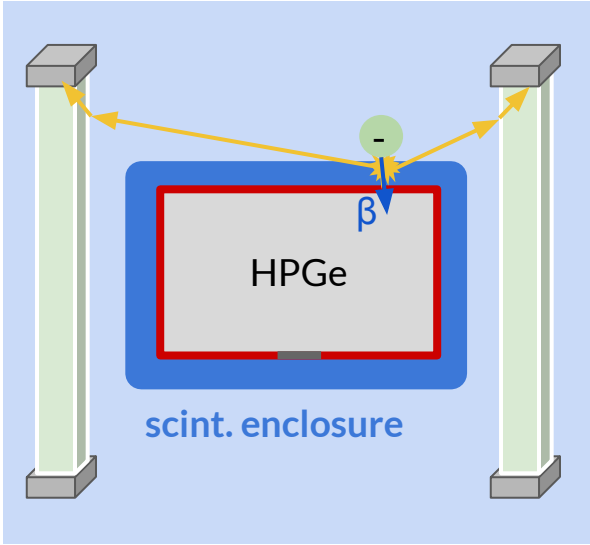


^{42}K on / very close to surface
→ beta invisible in LAr

[1: LEGEND pCDR (2021) arXiv:2107.11462]

^{42}K mitigation in LEGEND-1000

- Use of underground-sourced LAr (UGLAr)
  - Baseline in LEGEND-1000
  - Factor of ≳1000 reduction [1]
- Pulse-shape discrimination (PSD) of beta-events **on** the n^+ surface
- LAr scintillation anti-coincidence (AC) for beta events **close to** the n+ surface
- Risk mitigation in case UGLAr is not suffi-cently available: **Scintillating enclosures**
  - passive suppression and enhanced LAr AC
  - PEN (polyethylene naphthalate)

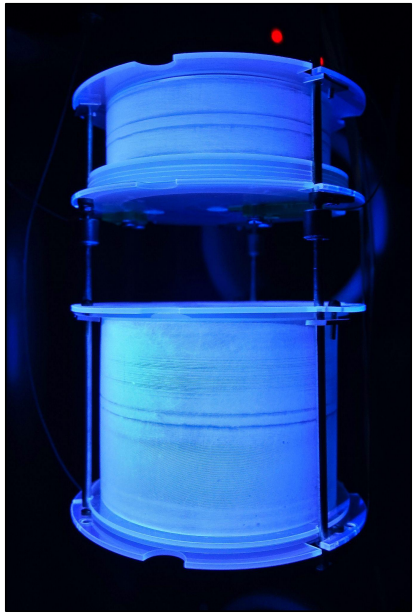


[1: LEGEND pCDR (2021) arXiv:2107.11462]

^{42}K mitigation in LEGEND-1000

- Use of underground-sourced LAr (UGLAr)
  - Baseline in LEGEND-1000
  - Factor of ≳1000 reduction [1]
- Pulse-shape discrimination (PSD) of beta-events **on** the n^+ surface
- LAr scintillation anti-coincidence (AC) for beta events **close to** the n+ surface
- Risk mitigation in case UGLAr is not suffi-cently available: **Scintillating enclosures**
  - passive suppression and enhanced LAr AC
  - PEN (polyethylene naphthalate)

Dedicated measurement campaign at TUM, using ^{42}Ar-spiked LAr



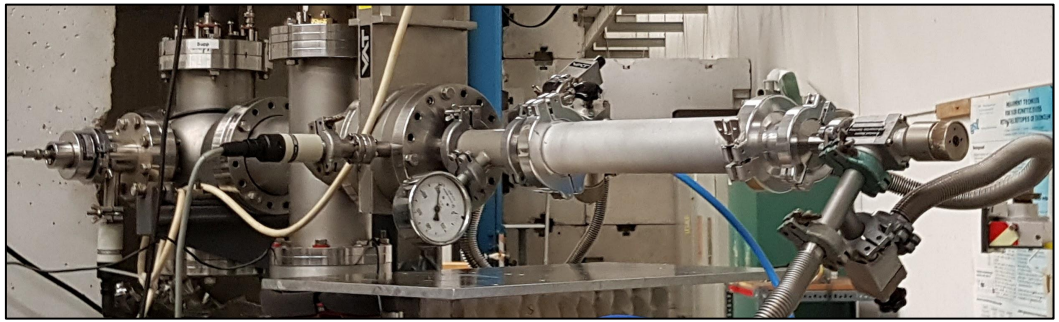
Scintillating PEN enclosures

[1: LEGEND pCDR (2021) arXiv:2107.11462]

Artificial ^{42}Ar production

- Two beam times in 2018 and 2019, each ~ 1 week
- Total activity at time of injection: 434±8 Bq ^{42}Ar

Tandem Van-de-Graaff Accelerator
at MLL in Munich



Target cell filled with GAr,
Irradiated with $^{7}Li^{3+}$ (34 MeV)

LEGEND contributions to TAUP 2025

Talks

- **Alberto Garfagnini** – *Search for neutrinoless double beta decay in ^{76}Ge with the LEGEND experiment at Gran Sasso*
  Monday, 25 Aug, 14:40
  North Hall #1, [indico]

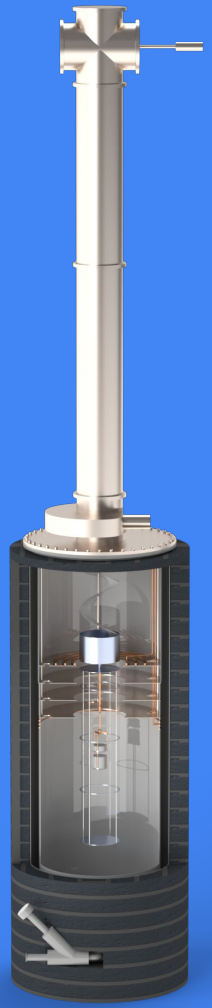
- **Difei Xu** – *Modelling of HPGe Detectors for the LEGEND Experiment and Low-Background Research*
  Wednesday, 27 Aug, 18:00
  North Hall #3, [indico]

Posters

- **Tobias Sterr** – *Status of the development of the water tank neutron tagger of LEGEND-1000*
  poster session: Wed, 27 Aug 18:00-20:00
  International Conference Center, [indico]

- **Raoul Cesarano** – *Background rejection by Pulse Shape Discrimination in the LEGEND experiment*
  poster session: Wed, 27 Aug 18:00-20:00
  International Conference Center, [indico]

Setup & Measurements

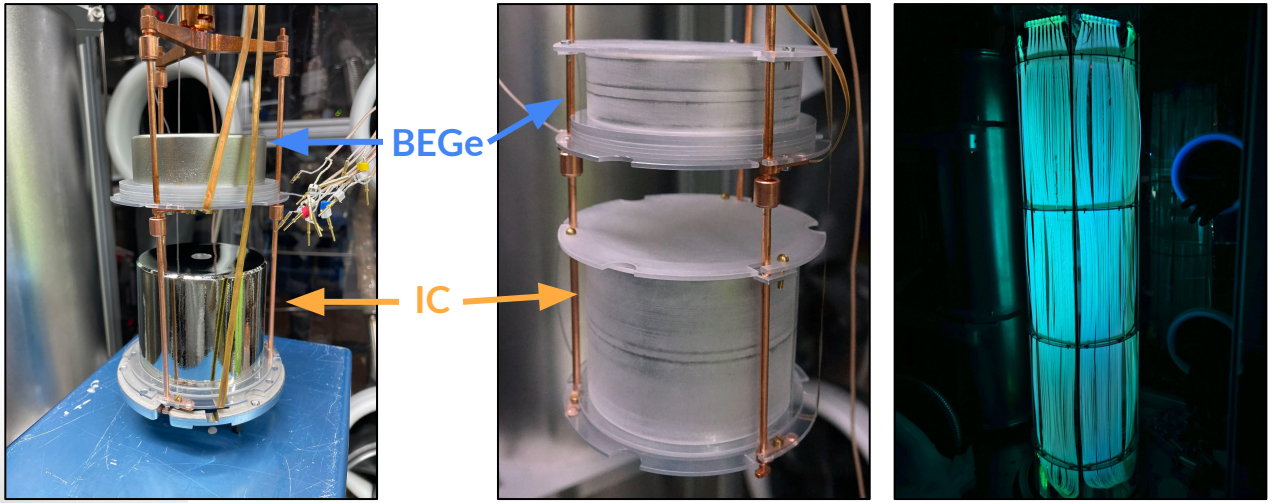


The Subterranean Cryogenic Argon Research Facility (SCARF)

SCARF = 1 ton LAr cryostat for Ge detector tests, SiPM characterization, scintillation studies, …

Used Ge detector types: BEGe (broad energy germanium) & **IC (inverted coaxial)***

Bare Ge detectors mounted in a string	*Enclosed* Ge detectors	WLS fibers surrounding the Ge detectors



*all following results generated from data taken by the IC detector only

Measurements and data

Acquired datasets:

- *Bare*
- *Enclosed*
- *Background*

Bare and *enclosed* contain ^{42}Ar-spiked timeframes

Background was taken before spiking

Comparing datasets before and after ^{42}Ar-spiking yields ^{42}K suppression efficiencies

Channels:
2 Ge*
7 SiPM
1 Pulser*

*trigger enabled

Digitization
160 µs trace @ 25 MHz
10 µs trace @ 100 MHz
centered around trigger

Data processing
with LEGEND
software tools*

*DSP provided by dspeed,
calibration routines by pygama

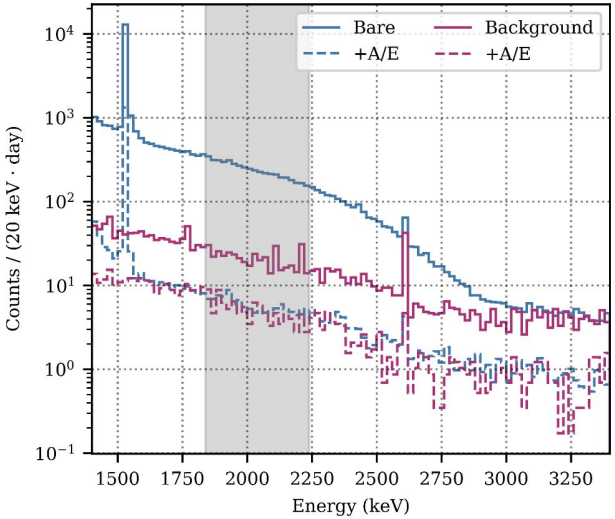
Data analysis

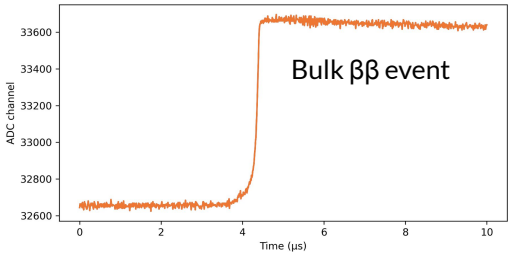
^{42}K suppression by pulse-shape discrimination

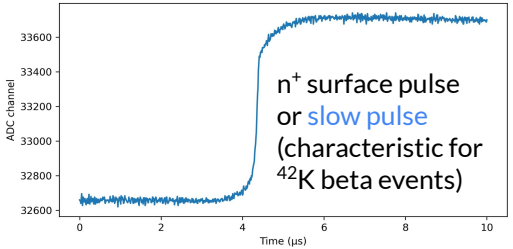
n^+ surface events are predominantly slow
→ possible to reject with **pulse-shape discrimination (PSD)** (1)

Measured efficiency of **PSD** cut with **bare** inverted coaxial (IC) Ge detector in ROI (1839–2239 keV):

Survival Fraction
SF = 0.24 ± 0.06 %







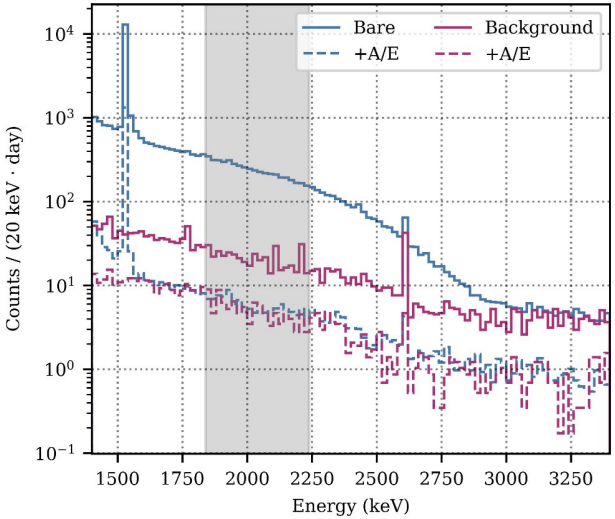
(1) Here, the A/E method was used for PSD. For details, see, e.g., JINST 4 P10007 (2009).

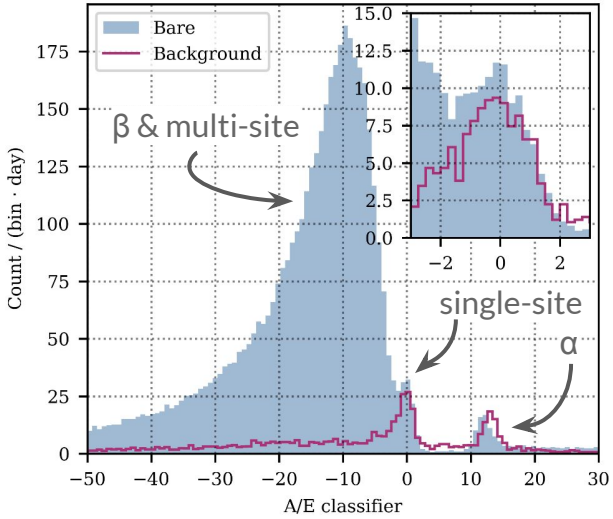
^{42}K suppression by pulse-shape discrimination

n^+ surface events are predominantly slow
→ possible to reject with **pulse-shape discrimination (PSD)** (1)

Measured efficiency of **PSD** cut with **bare** inverted coaxial (IC) Ge detector in ROI (1839–2239 keV):

Survival Fraction
SF = 0.24 ± 0.06 %





(1) Here, the A/E method was used for PSD. For details, see, e.g., JINST 4 P10007 (2009).

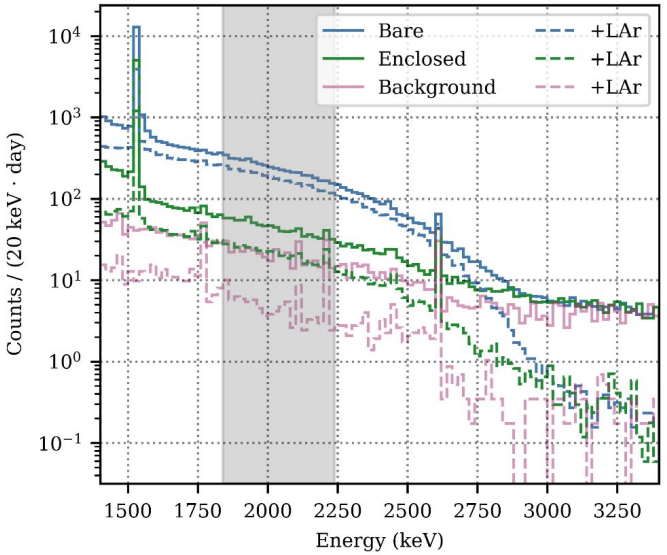
^{42}K suppression by LAr scintillation light read out

Most ^{42}K ions decay **on** the Ge surface
→ no scintillation light!

Some decays occur **close** to the Ge surface
or **on** the scintillating enclosure
→ scintillation light!

Measured LAr AC
survival fraction (SF):

bare:	**SF = 79.5 ± 0.2 %**
enclosed:	**SF = 70.7 ± 0.2 %**



➢ the scintillating enclosures decrease the LAr AC SF by approximately 10 percentage points

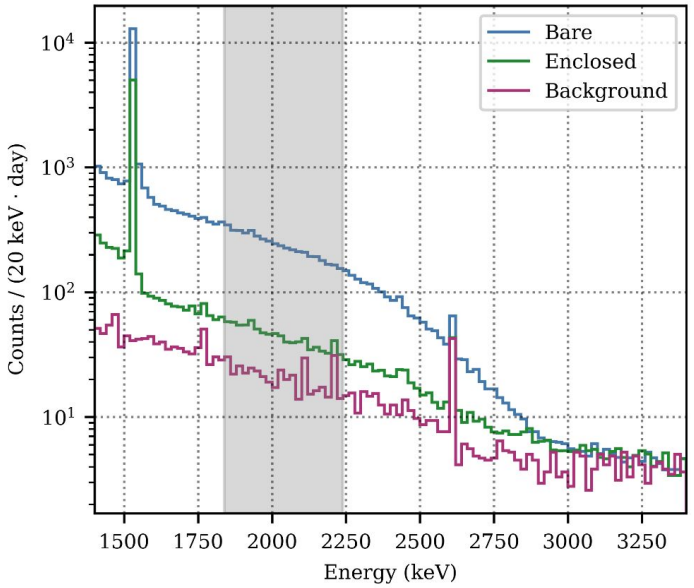
^{42}K passive suppression by scintillating enclosure

Most ^{42}K expected to decay **on enclosure** surface
→ enclosure acts as passive shield
→ electrons lose energy in enclosure
→ lower rate around $Q_{\beta\beta}$

Measured **passive** survival fraction (SF):

SF = 10.7 ± 0.2 %

➢ the enclosure decrease the impact of ^{42}K passively by one order of magnitude



Grand total ^{42}K suppression: PSD+LAr+enclosure

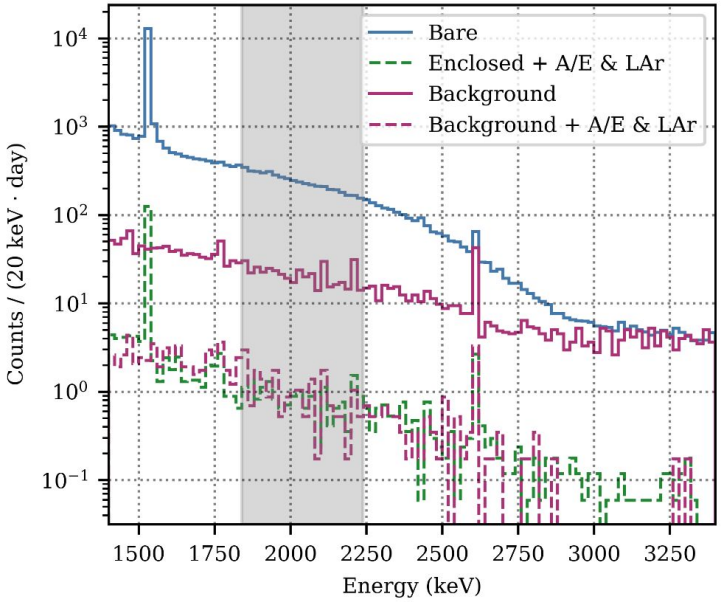
Lowest SF when all three techniques are combined

No excess of events found after cuts → place upper limit on SF

Measured **grand total** survival fraction (SF):

SF < 1.6 x 10^{-4}
(@ 90 % CL)

➢ improvement by factor 4 w.r.t. previous result measured in LArGe [*Eur. Phys. J. C* **78**, 15 (2018)]



Impact on LEGEND-1000

^{42}K-induced background index contribution before cuts estimated in the post-GERDA tests [1]:

0.72 cts / (keV kg y)

Measured combined survival fraction (SF) of PSD+LAr+enclosure:

SF < 1.6 x 10^{-4} (@ 90 % CL)

Background index contribution **after PSD+LAr+enclosure**:

< 1.2 x 10^{-4} cts / (keV kg y)

Promising results!
Need further research with increased ^{42}Ar activity and/or less background to strengthen statistical power

[1: LEGEND pCDR (2021) arXiv:2107.11462]

Conclusion & Outlook

^{42}K is a critical background for LEGEND-1000, and will be mitigated mainly by using **underground liquid argon (UGLAr)**

In this talk, we **explored alternatives** if UGLAr is not available:

- Pulse-shape discrimination (PSD)
- Liquid argon anticoincidence (LAr)
- Scintillating enclosures

PSD+LAr+enclosure yields a statistically limited survival fraction of

SF < 1.6 x 10^{-4} (@ 90 % CL)

Outlook:

- Produce more ^{42}Ar
- Repeat measurement with improved statistical power

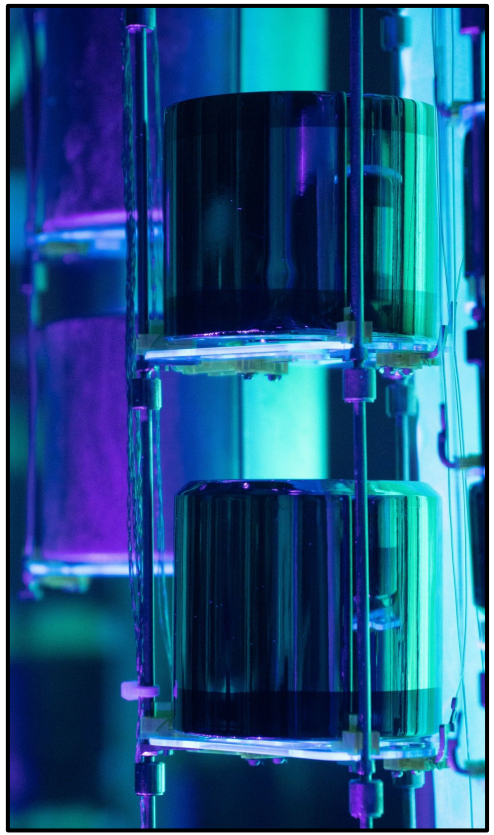
Backup

Polyethylene Naphthalate in LEGEND

Polyethylene Naphthalate (PEN) is an inherently **scintillating** and **wavelength-shifting** commercially available thermoplastic and can be produced **radio-pure**.

Measured LEGEND-200 PEN scintillation properties:

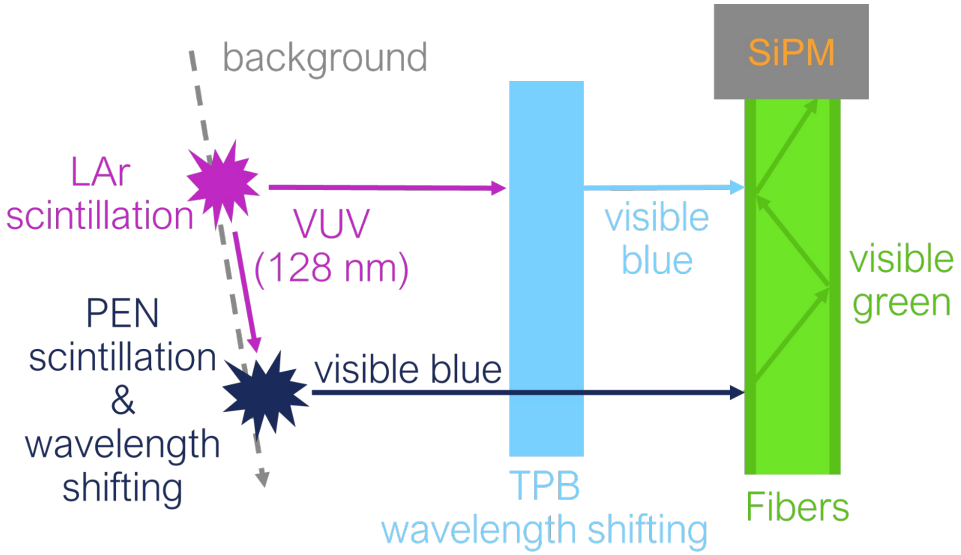
Light yield	5440 ± 200 photons/MeVe^-
Time constant	25.3 ± 0.2 ns
Bulk absorption length	62 ± 3 mm at 450 nm
Emission spectrum max	440 ± 3 nm

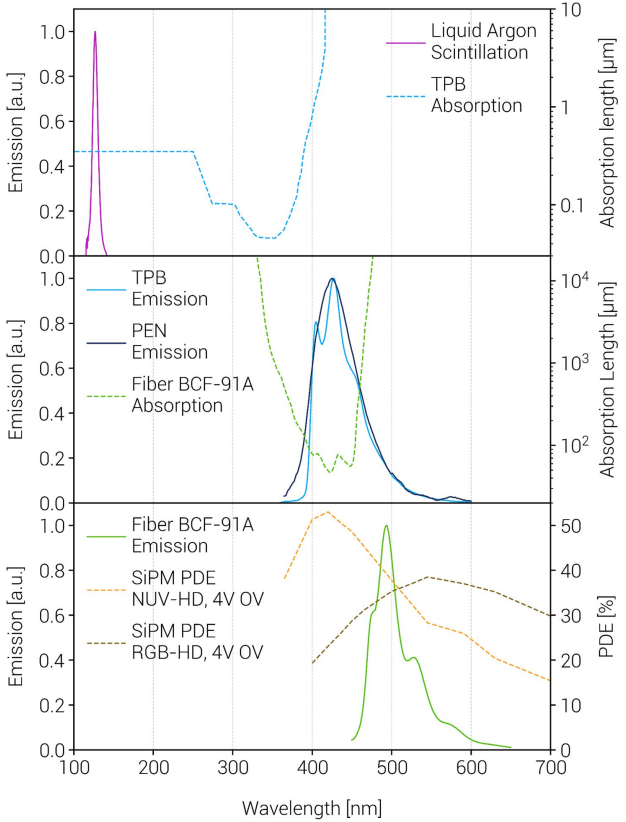


References:

- L. Manzanillas *et al* 2022 *JINST* **17** P09007
- Y. Efremenko *et al* 2022 *JINST* **17** P01010

Scintillation light path in LEGEND-1000





Wavelength-shifting of PEN

Wavelength-shifting efficiency increases with decreasing temperature
[A. Leonhardt et al. 2024 JINST 19 C05020]

Quantum efficiency QE > 49%
at LAr temperature and 128 nm excitation
[G.R. Araujo *et al. Eur. Phys. J. C* **82**, 442 (2022)]