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

15' + 5'

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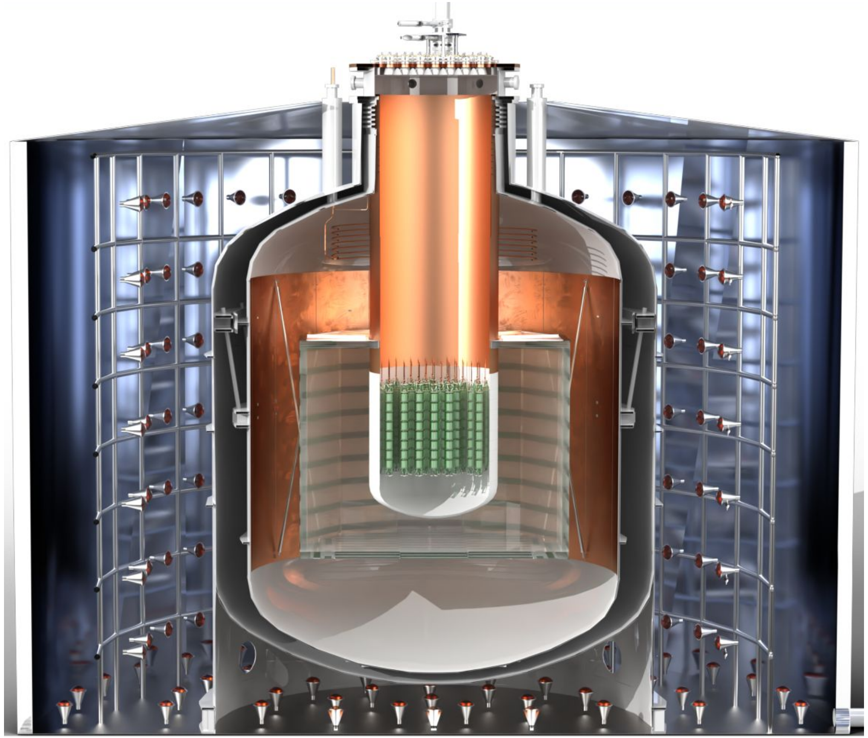
The LEGEND experiment searches for 0νββ in ^{76}Ge

- 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: Phys. Rev. Lett. 136, 022701]
  - 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



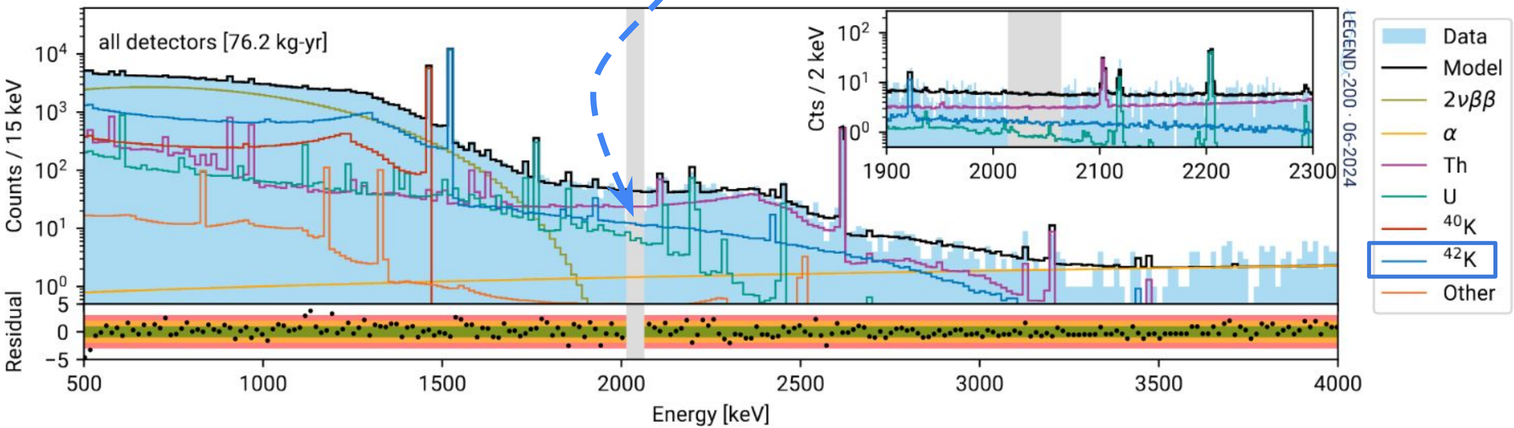
LEGEND-1000 rendering

^{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), *Eur. Phys. J. C* **78**, 15 (2018)]

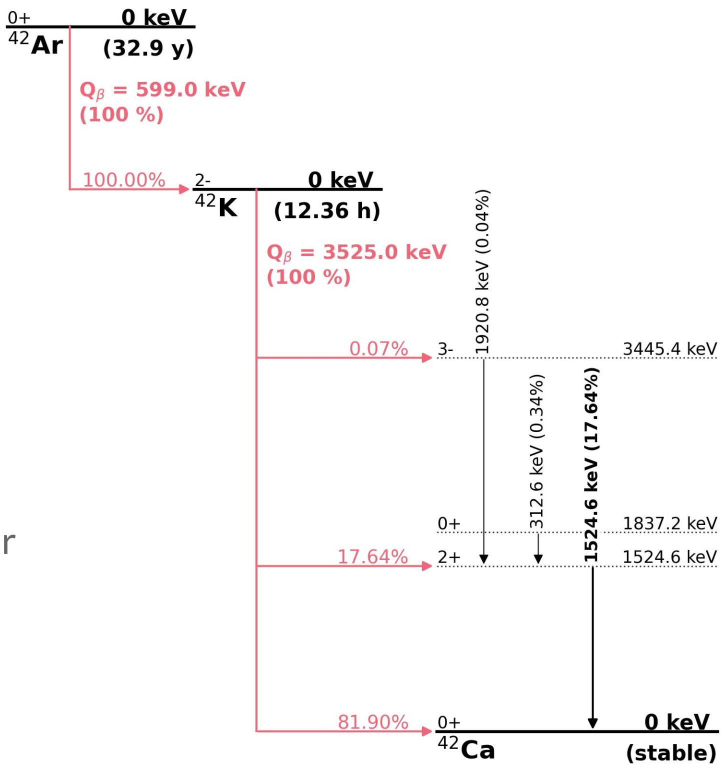
LEGEND-200 background composition before cuts
[L. Pertoldi for the LEGEND collab. @ Neutrino 2024, see link]



Origin of ^{42}K background

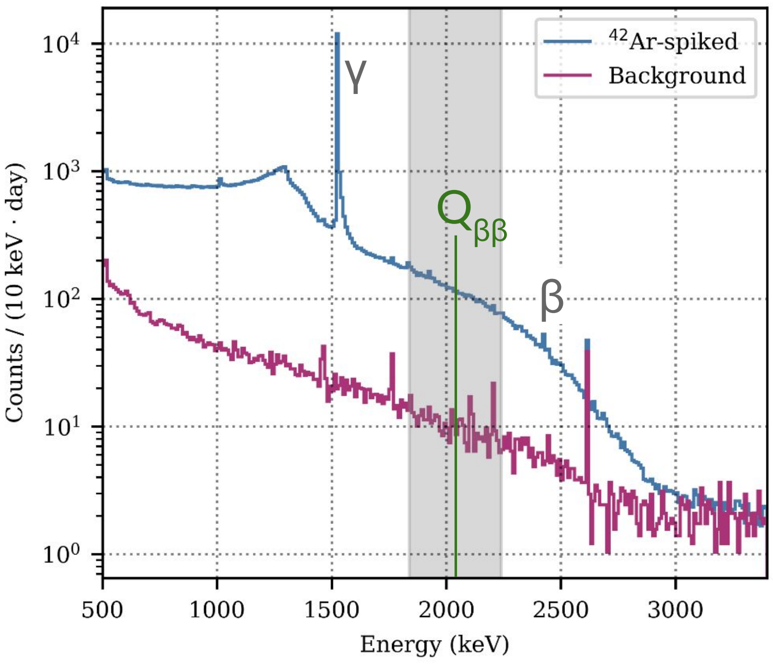
- ^{42}K is continuously produced by ^{42}Ar
- ^{42}Ar is a cosmogenic isotope present in commercial argon in trace amounts: A(^{42}Ar) = 61±5 μBq/kg [[Nat. Phys. **22**, 665–671 (2026)]]
- $Q_\beta(^{42}K) = 3.5$ MeV > $Q_{\beta\beta}(^{76}Ge) = 2.0$ MeV
- Ge detectors' electric fields collect charged ^{42}K

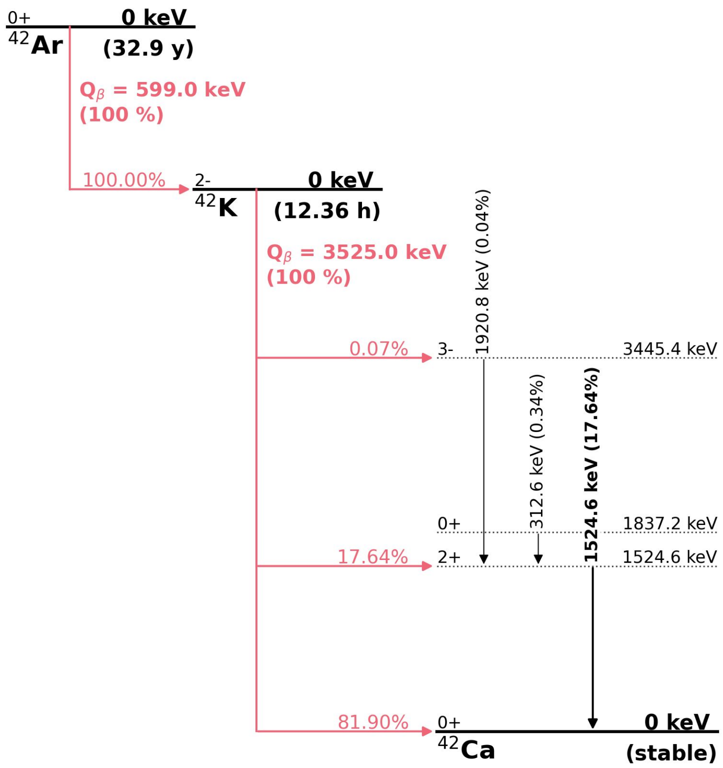
n^+ surface at ≈ +3000 V
→ Collect negative ^{42}K ions or complexes (-)



Origin of ^{42}K background

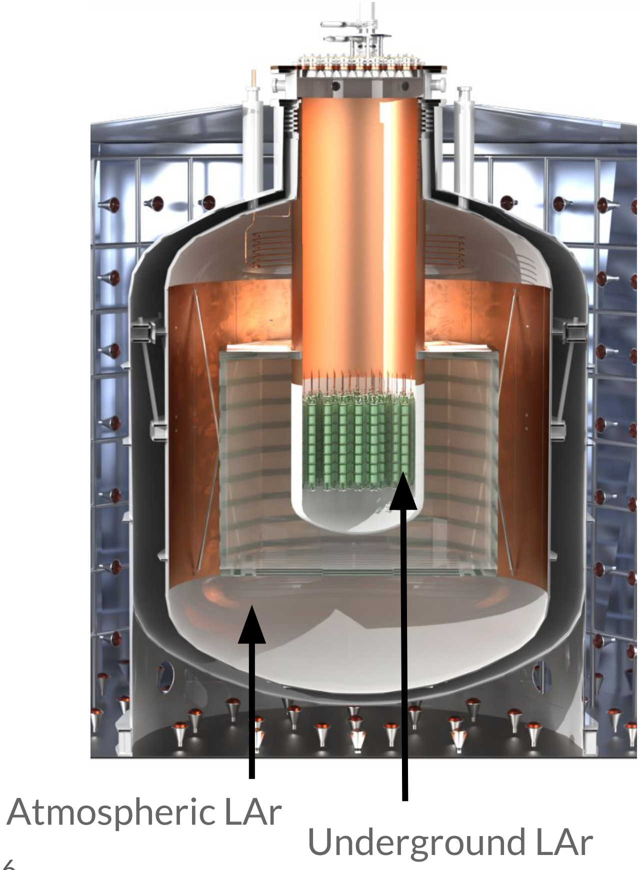
Measured in SCARF @ TUM





^{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)
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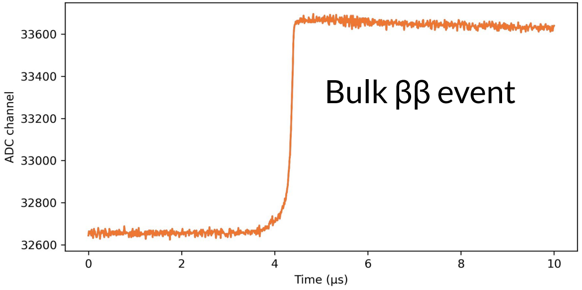
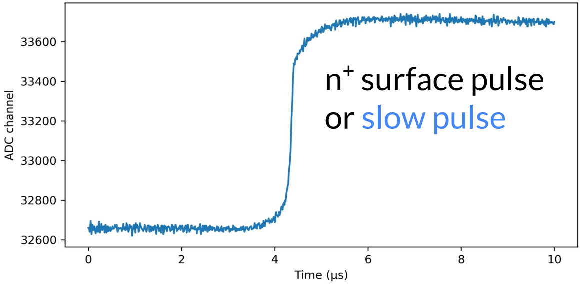
- Pulse-shape discrimination (PSD) of beta-events **on** the n^+ surface

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

Measured in SCARF @ TUM





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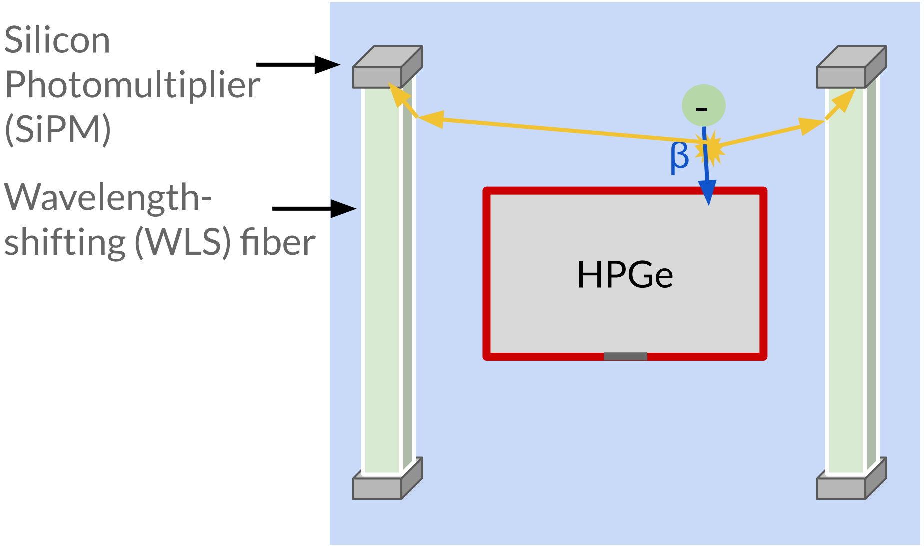
- LAr scintillation anti-coincidence (AC) for beta events **close to** the n+ surface



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

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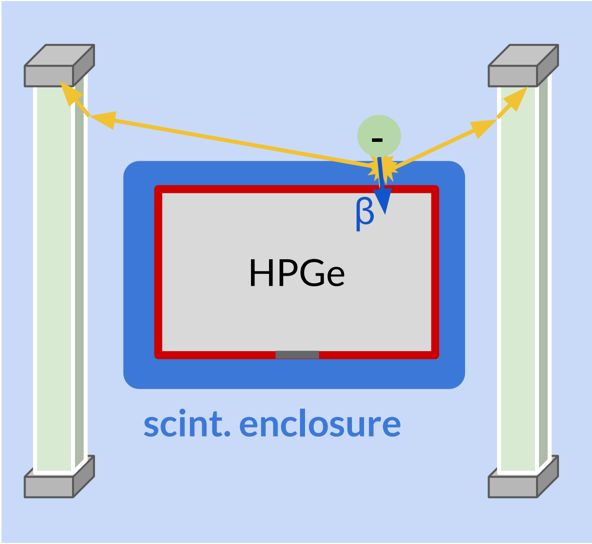
- Risk mitigation in case UGLAr is not sufficiently available: **Scintillating enclosures**
  - passive suppression and enhanced LAr AC
  - **PEN** (polyethylene naphthalate)



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  - passive suppression and enhanced LAr AC
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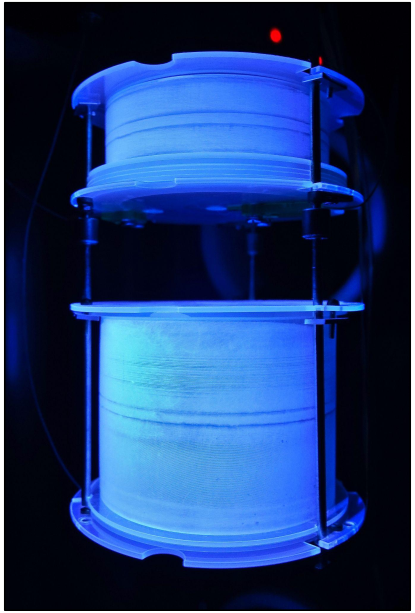
Dedicated measurement campaign at TUM, using ^{42}Ar-spiked LAr
(For detector performance with PEN-enclosures see PoS(TAUP2025)375)



Scintillating PEN enclosures

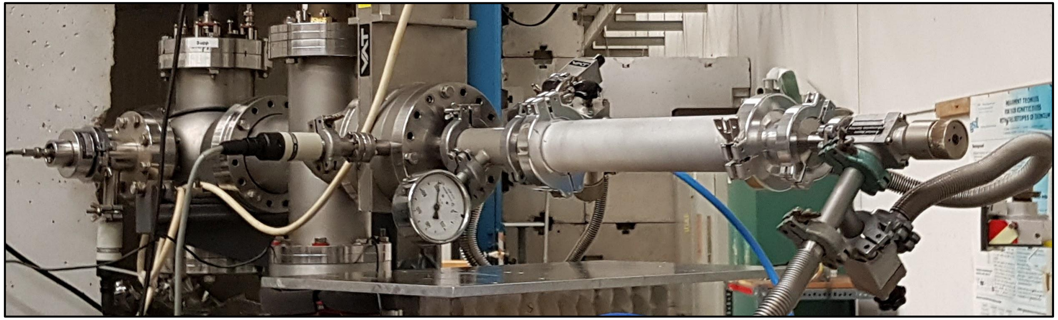
[1: LEGEND pCDR (2021) arXiv:2107.11462]

Artificial ^{42}Ar production

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

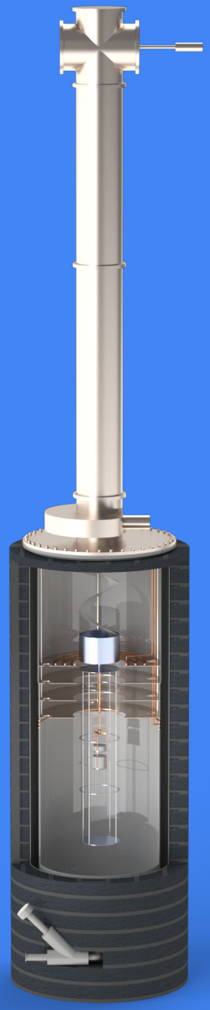
Details in
NIM A 1087 (2026) 171434

Tandem Van-de-Graaff Accelerator
at MLL in Munich



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

Setup & Measurements

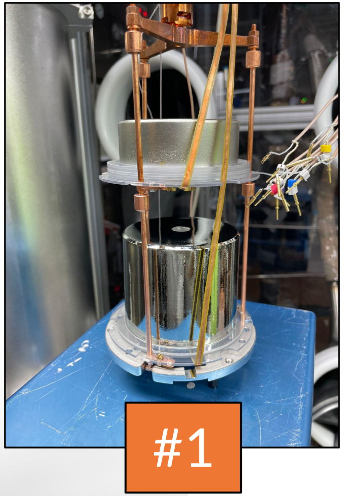


We operated three hardware configurations in a LAr cryostat

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



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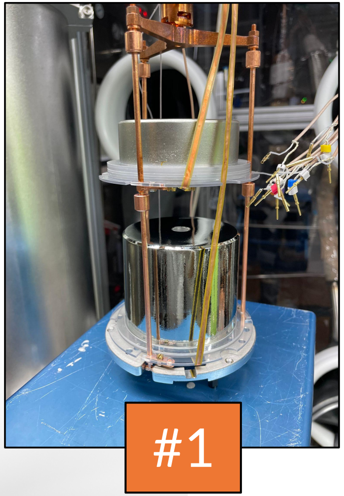

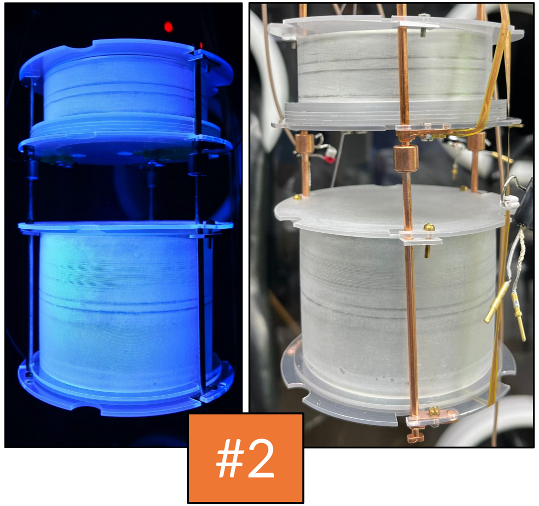

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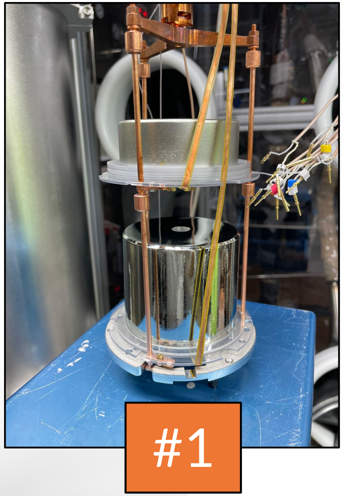
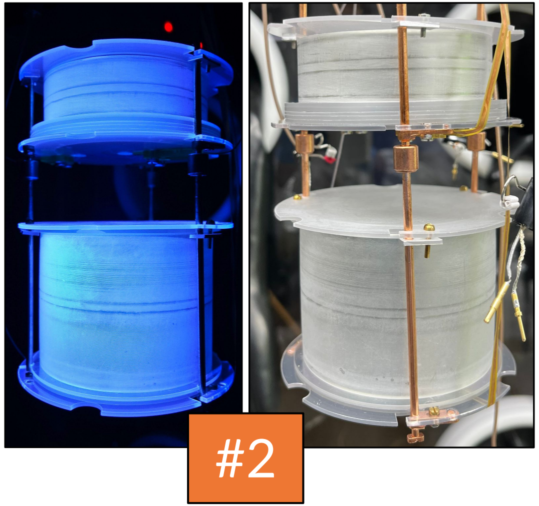
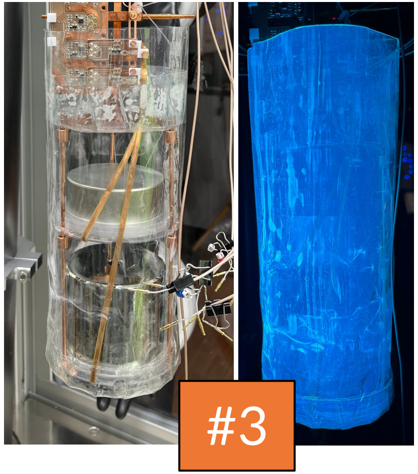
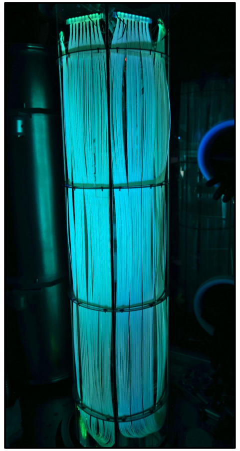
Bare Ge detectors mounted in a string	*PEN-enclosed* Ge detectors	*Nylon mini-shroud (NMS)-enclosed* Ge detectors	WLS fibers



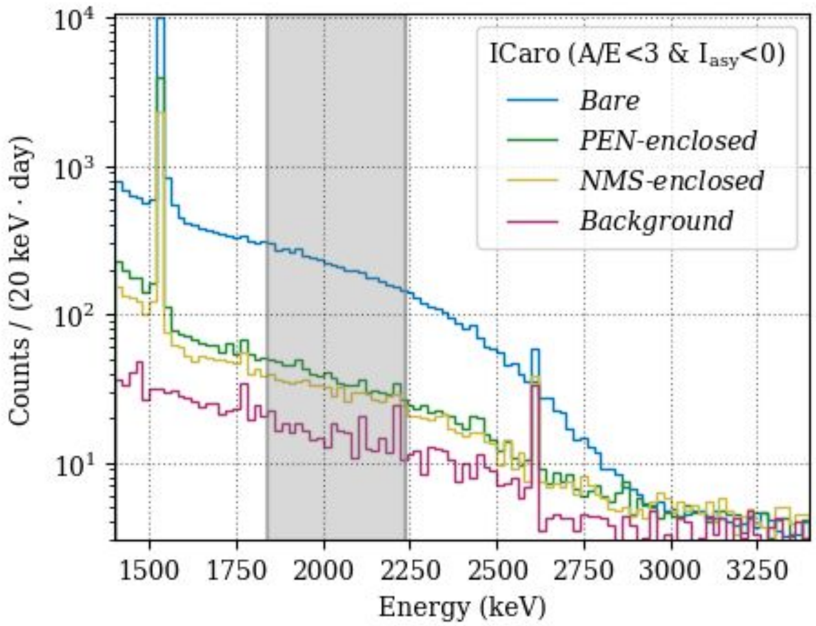


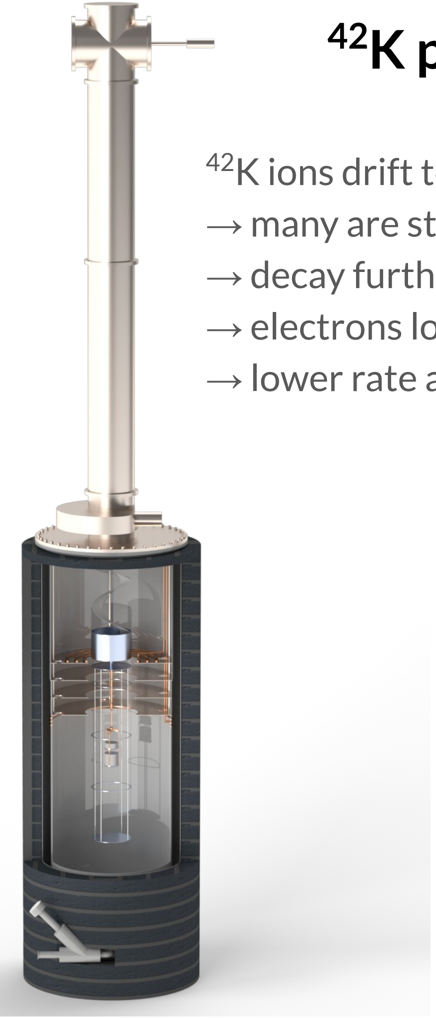




*all results in this talk are generated from data taken by the IC detector

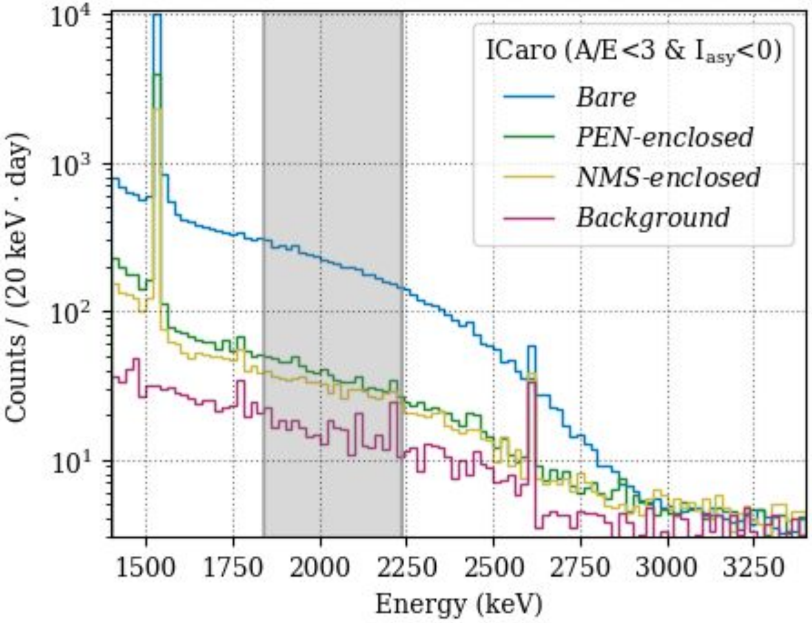
^{42}K passive suppression by PEN- and NMS-enclosures





^{42}K passive suppression by PEN- and NMS-enclosures

^{42}K ions drift toward Ge detectors
→ many are stopped by PEN- or NMS-enclosure
→ decay further away from Ge detector
→ electrons lose energy in enclosure and/or LAr
→ lower rate around $Q_{\beta\beta}$



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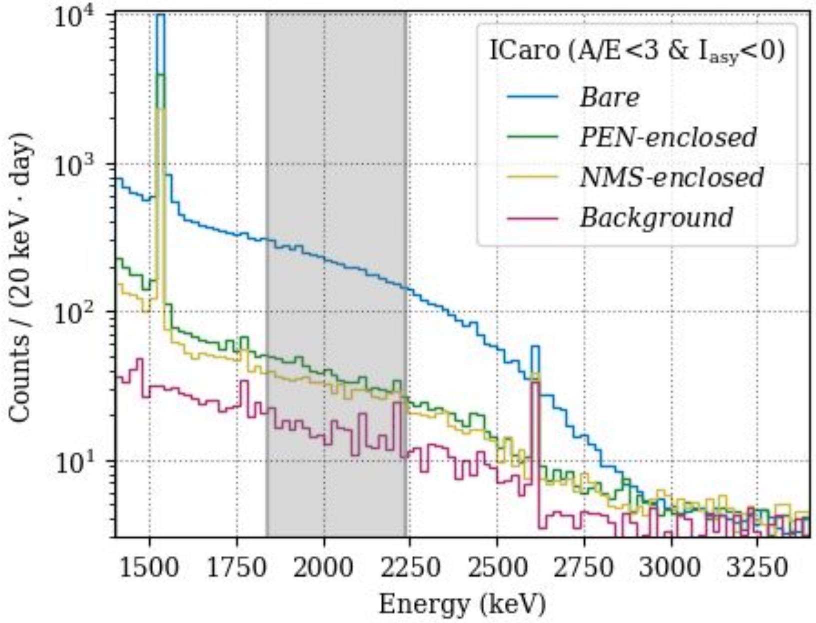
Preliminary!

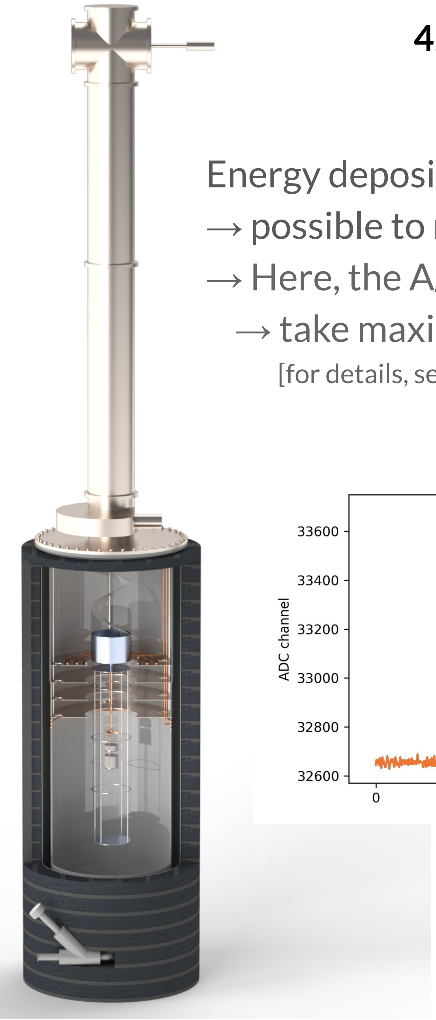
Measurement	Survival fraction (%)
PEN-enclosed	10.8 ± 0.3
NMS-enclosed	7.3 ± 0.3



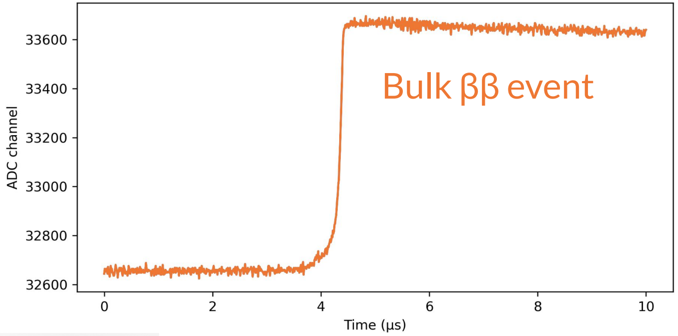
- ➢ Similar reduction
- ➢ NMS slightly better

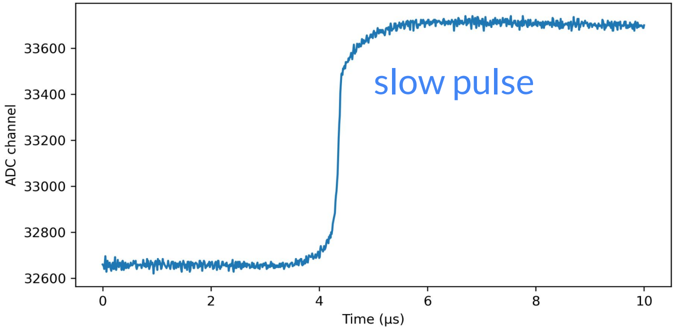
Note: Survival fractions depend a lot on geometry, not easily generalizable!

^{42}K suppression by pulse-shape discrimination

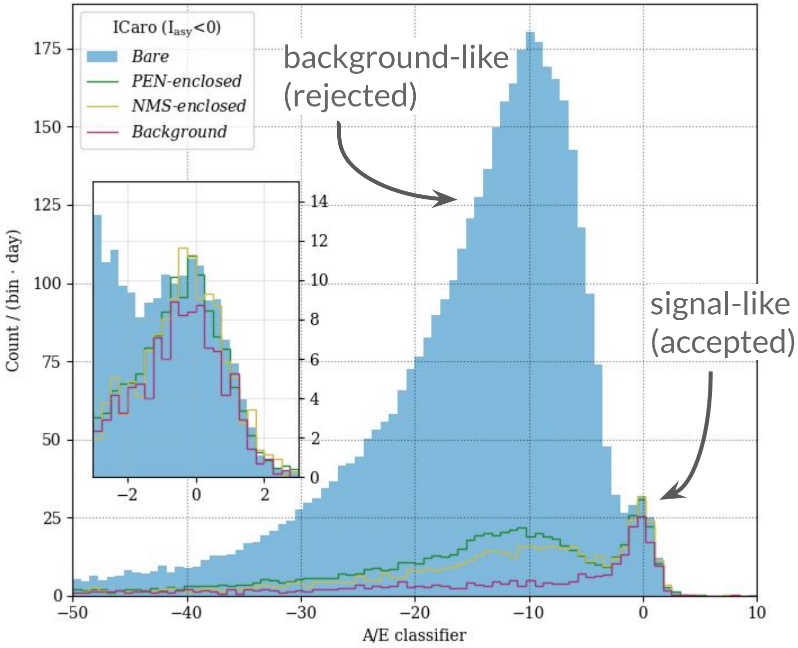


Energy depositions in the **transition layer** of the n$^+$ surface lead to slow pulses
→ possible to reject with **pulse-shape discrimination (PSD)**
→ Here, the A/E method was used for PSD
→ take maximum current A, divide by energy E
[for details, see, e.g., JINST 4 P10007 (2009)]





^{42}K suppression by pulse-shape discrimination

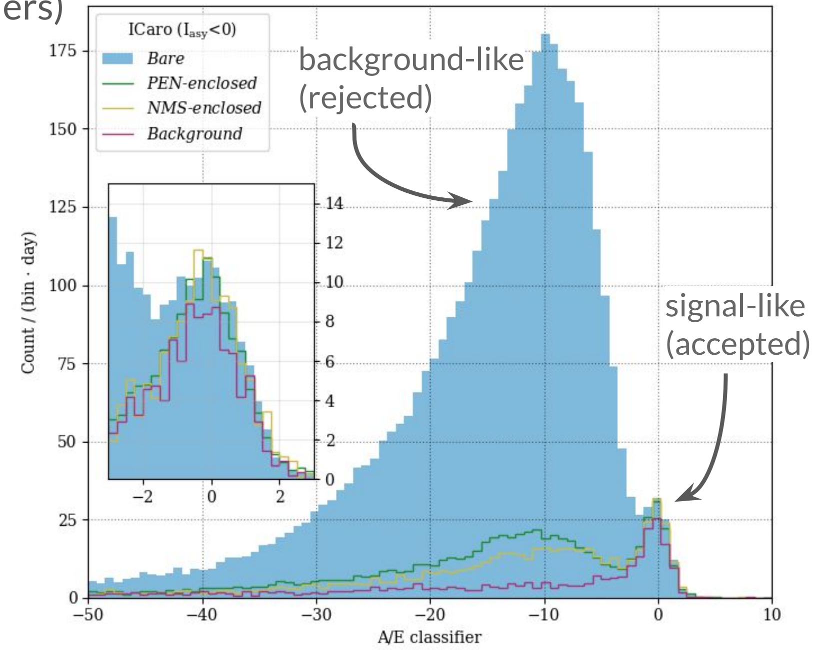


^{42}K suppression by pulse-shape discrimination

With PSD[(1)] strongest suppression when detectors are bare

Weaker suppression with enclosures (mechanical barriers)

- ^{42}K further from detector
- Less electrons with similar γ and bremsstrahlung
- → larger survival fraction



(1) Here, the A/E method was used for PSD. For details, see, e.g., [JINST 4 P10007 (2009)](https://doi.org/10.1088/1748-0221/4/10/P10007).

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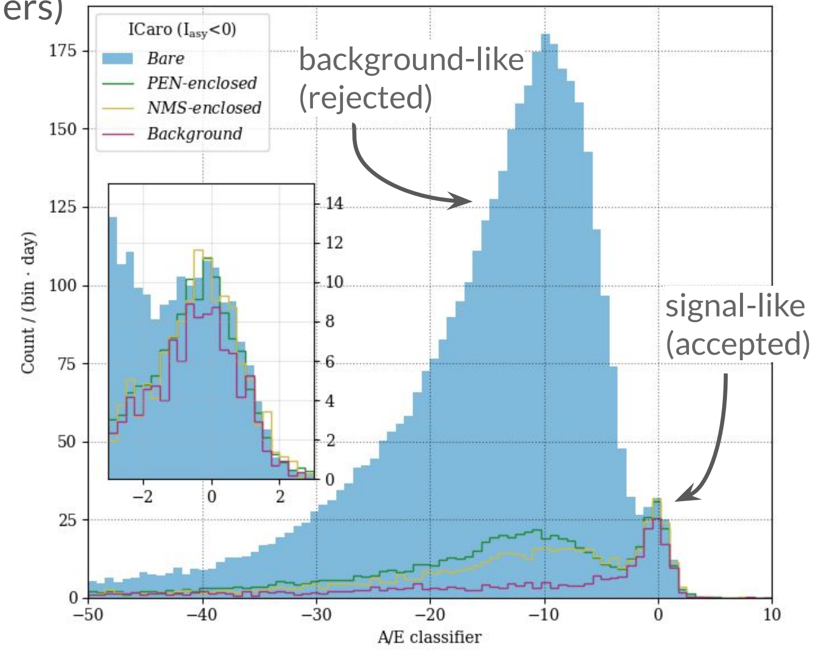
Weaker suppression with enclosures (mechanical barriers)

- ^{42}K further from detector
- Less electrons with similar γ and bremsstrahlung
- → larger survival fraction

Preliminary!

Measurement	Survival fraction (%)
Bare	0.55 ± 0.12
PEN-enclosed	4.7 ± 1.1
NMS-enclosed	6.9 ± 1.7



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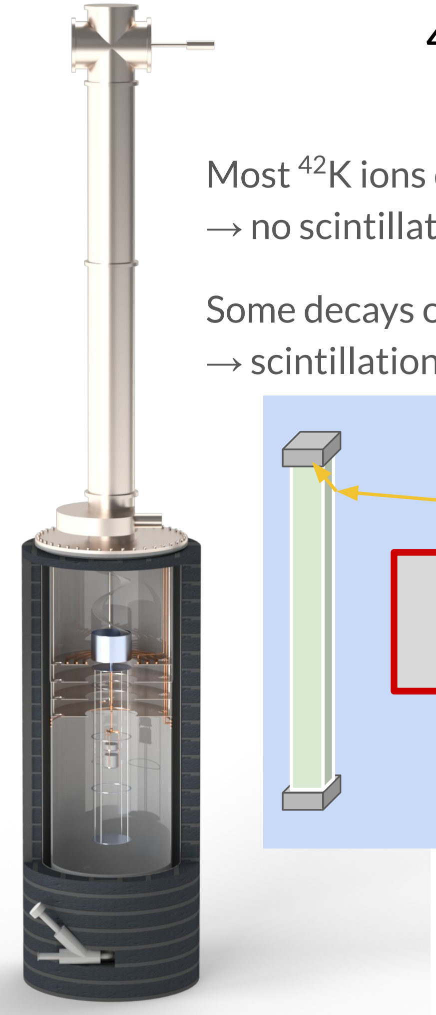
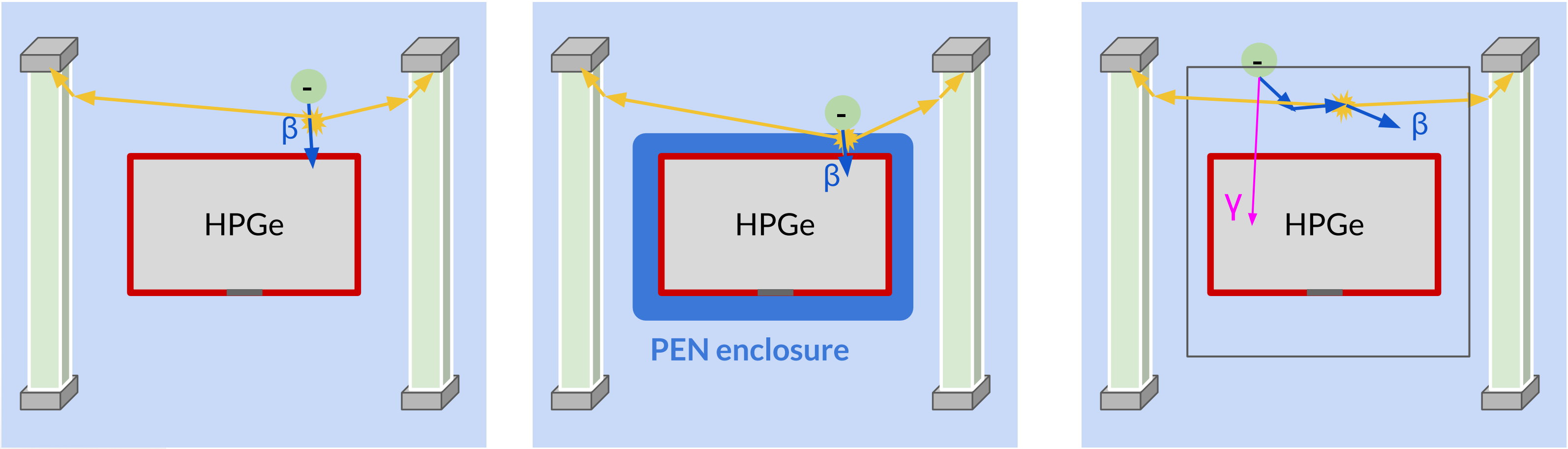
^{42}K suppression by LAr scintillation light veto



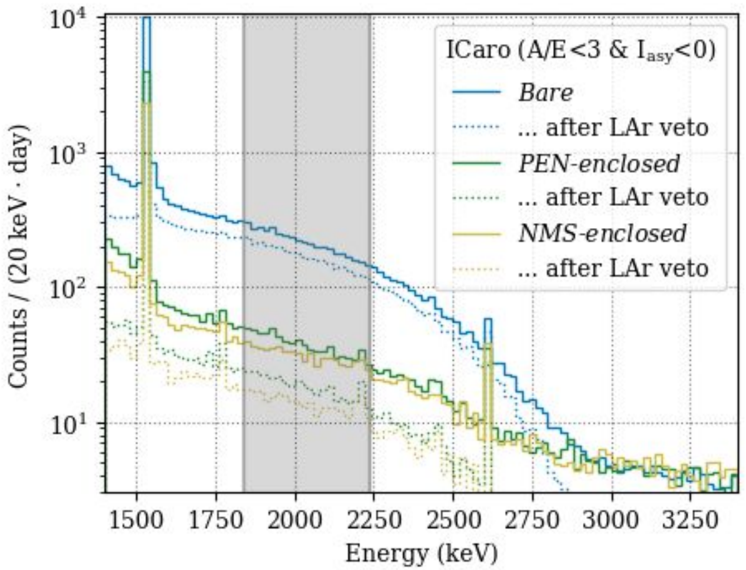
Most ^{42}K ions decay **on** the Ge surface
→ no scintillation light!

Some decays occur **close** to the Ge surface, **on** the PEN enclosure, or **on** the NMS enclosure[(1)]
→ scintillation light!



[(1)] Electrons starting on the NMS loose too much energy to populate the region around $Q_{\beta\beta}$. But gammas and bremsstrahlung can reach the Ge detector.

^{42}K suppression by LAr scintillation light veto



^{42}K suppression by LAr scintillation light veto

Most ^{42}K ions decay **on** the Ge surface
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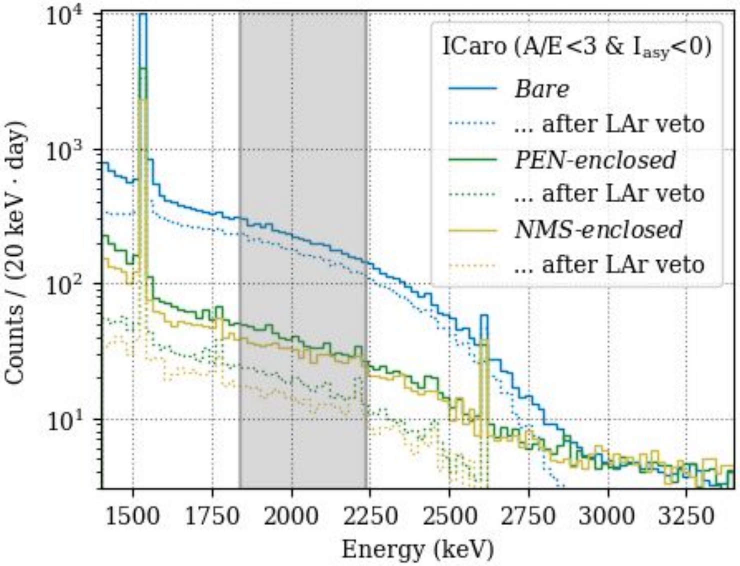
Some decays occur **close** to the Ge surface, **on** the PEN enclosure, or **on** the Nylon mini-shroud (NMS) → scintillation light!

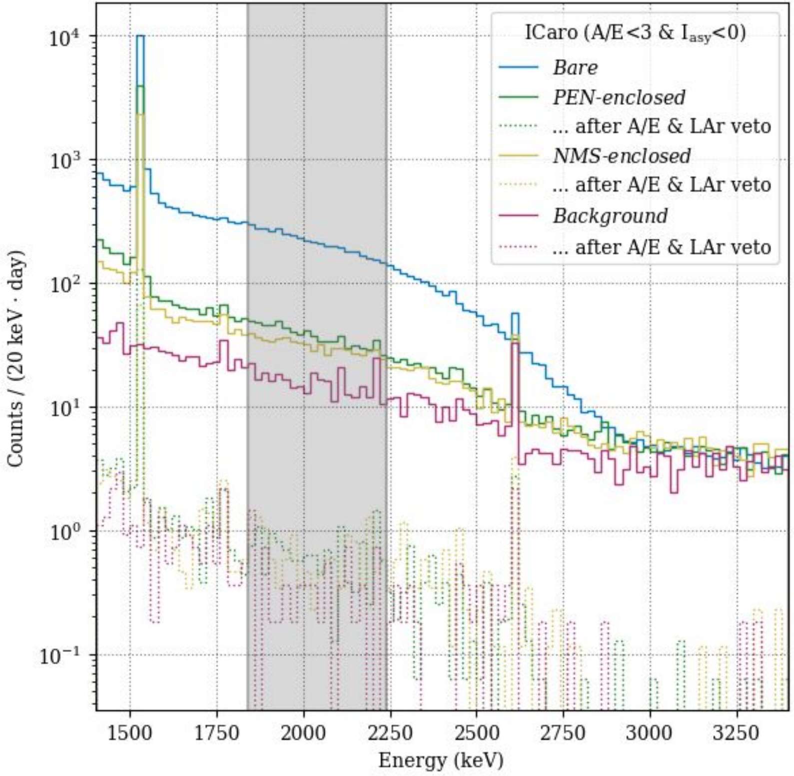
Preliminary!

Measurement	**Survival fraction (%)**
Bare	89.4 ± 0.2
PEN-enclosed	77.6 ± 1.7
NMS-enclosed	81.5 ± 3.0



- ➢ PEN enclosure slightly improves ^{42}K rejection of LAr veto!
- ➢ *Can be improved!* Brighter scintillator, optimized geometry, thicker enclosures, …

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



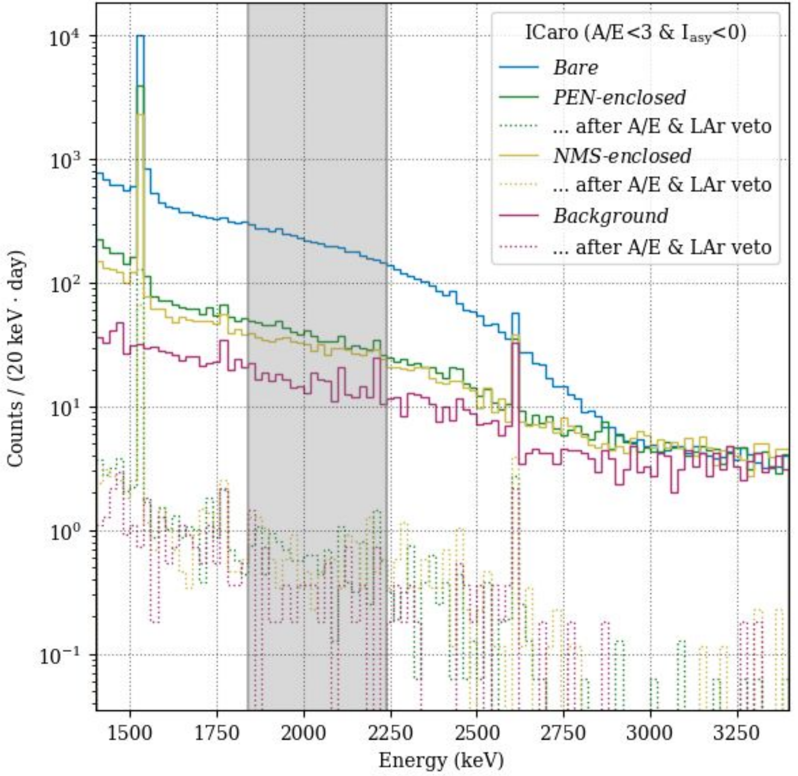
Grand total ^{42}K suppression: PSD+LAr+enclosure

Best survival fraction when all three techniques are combined.

All in all, PEN- & NMS-enclosed configurations perform similar!

Preliminary!

Measurement	Survival fraction (%)
PEN-enclosed	0.15 ± 0.04
NMS-enclosed	0.16 ± 0.05



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 PEN enclosures

PSD & LAr & PEN-enclosure yields a total ^{42}K survival fraction of

SF = 0.15 ± 0.04 %

Not yet sufficient. But a good baseline to start optimization:

- thicker enclosures (more energy loss)
- brighter scintillator (stronger LAr AC)
- conducting & grounded enclosures (reduce attraction)
- optimized PSD (catch remaining ɣ and Bremsstrahlung events)

Backup

Measurements and data

Acquired datasets:

- *Bare (#1)*
- *PEN-Enclosed (#2)*
- *NMS-enclosed (#3)*
- *Background (no ^{42}Ar)*

Background was taken before ^{42}Ar-spiking

The other datasets feature high ^{42}Ar/^{42}K activity

Comparing datasets before and after ^{42}Ar-spiking yields ^{42}K survival fractions

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

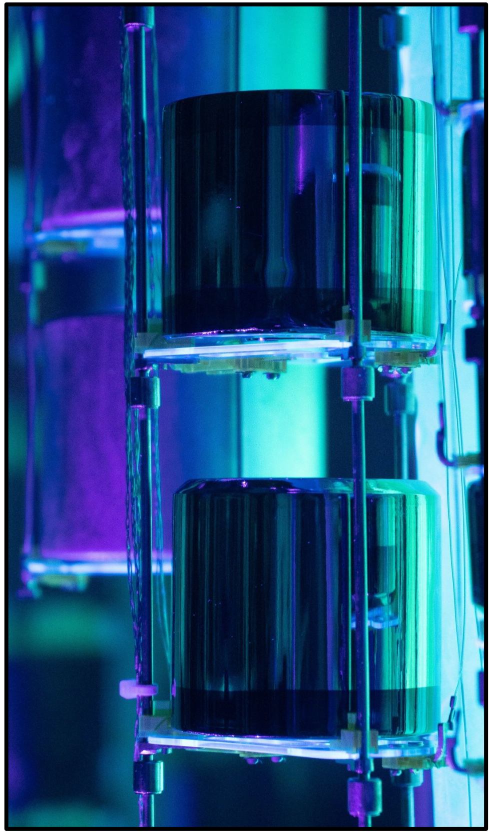
Data analysis

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:

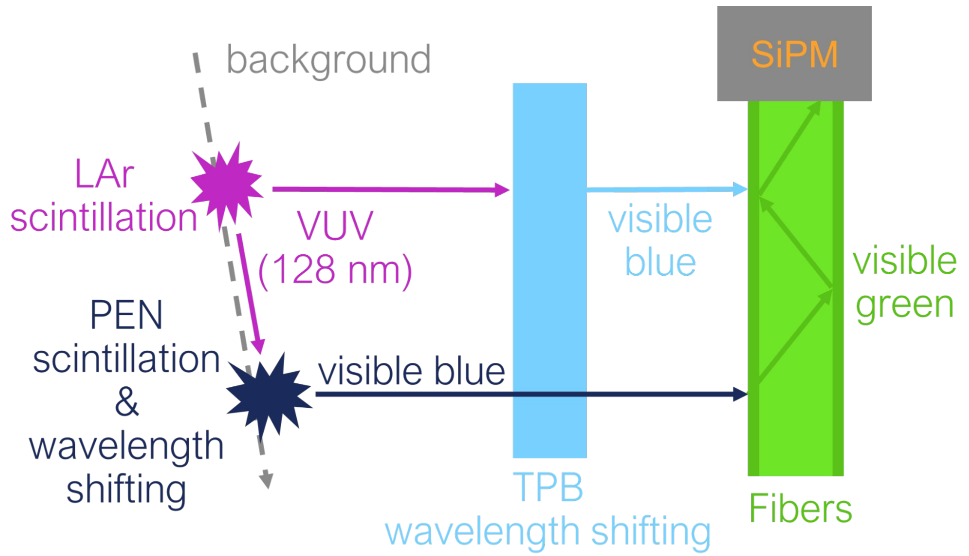
Light yield	5440 ± 200 photons/MeVe^-
Time constant	25.3 ± 0.2 ns
Bulk absorption length	62 ± 3 mm at 450 nm
Emission spectrum max	440 ± 3 nm



References:

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

Scintillation light path in LEGEND-1000



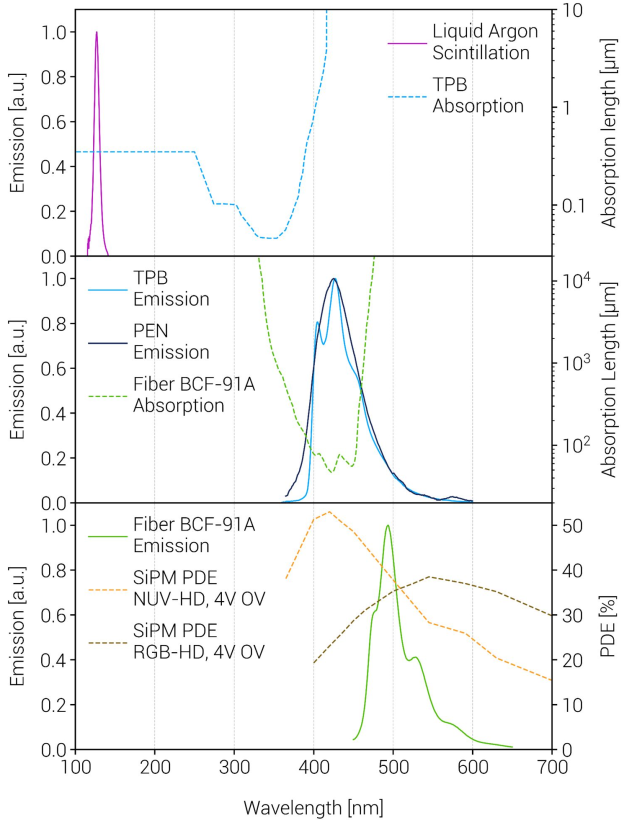


Image credits to Andreas Leonhardt

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)]