Mitigation studies of ^{42}K in liquid argon for LEGEND

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Low Radioactivity Techniques (LRT2024)
1-4 October 2024, Kraków, Poland

LEGEND

- The **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay
- International collaboration searching for neutrinoless double beta decay (0νββ)
- Staged experimental implementation @ LNGS:
  - LEGEND-200: operational in Hall A @ LNGS; first results at Nu 2024
  - LEGEND-1000: under preparation for Hall C @ LNGS

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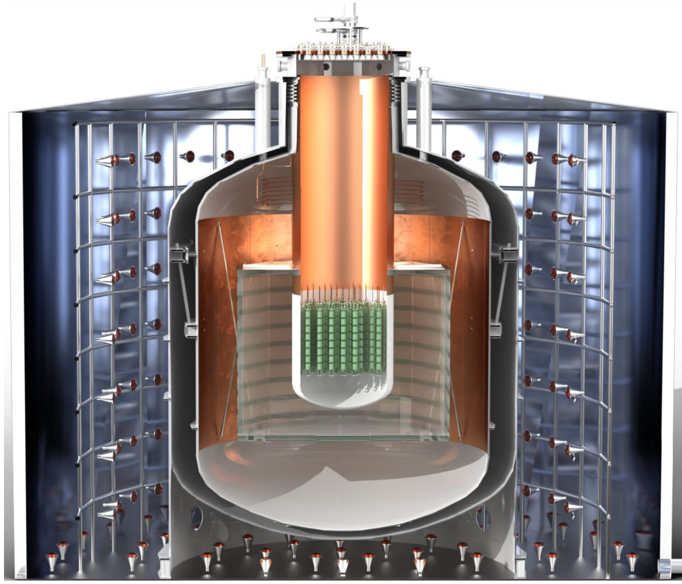
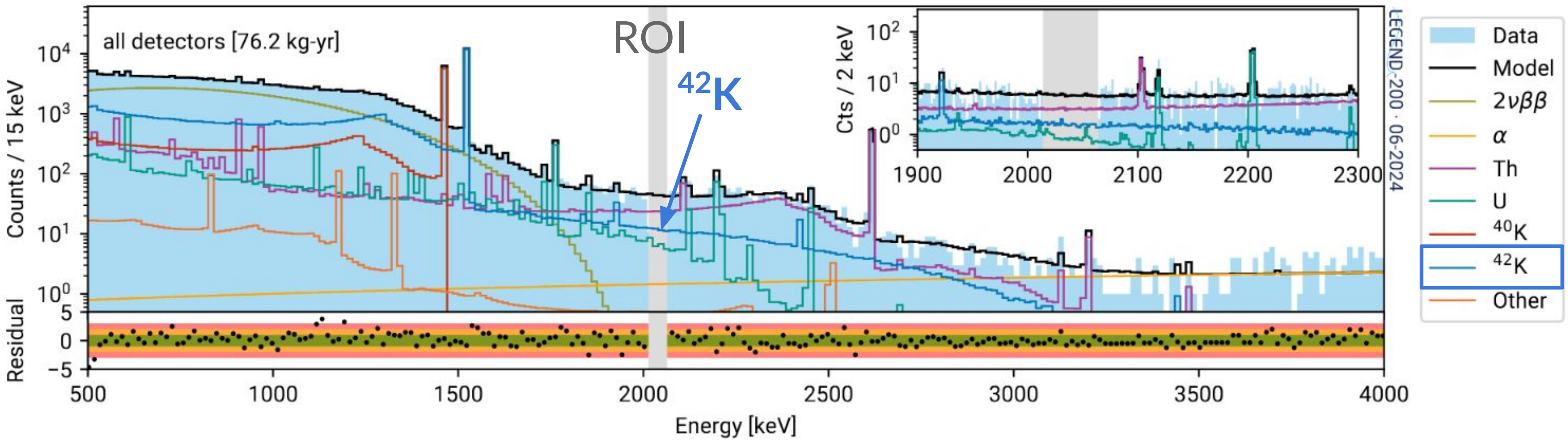
  - LEGEND-1000: under preparation for Hall C @ LNGS
- Operation of High-Purity Germanium (HPGe) detectors enriched in ^{76}Ge
- HPGe's deployed in instrumented liquid argon (LAr) → cooling & active shield
- Quasi-background-free search for 0νββ as pioneered by GERDA
- Uses best technologies developed by GERDA and MJD

LEGEND-1000

- Aiming for a 0νββ discovery sensitivity beyond 10^{28} years
- Requires ultra-low background of $< 1 \times 10^{-5}$ cts/(keV kg yr), i.e. “background-free search”
- ^{42}K is a critical background source around the 0νββ region of interest (ROI)



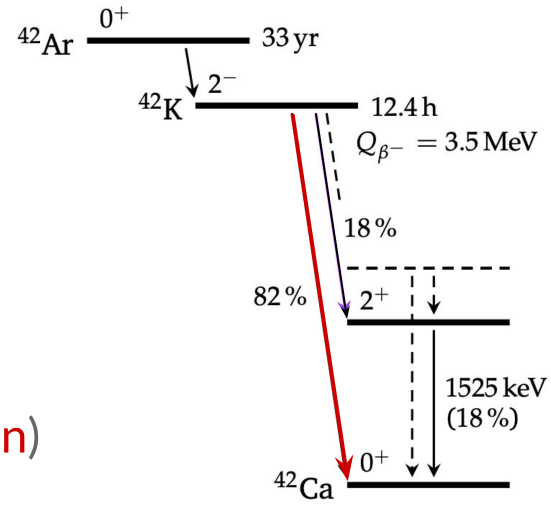
Background composition in LEGEND-200 (before analysis cuts) :



^{42}K known from GERDA [arXiv:1909.02522]

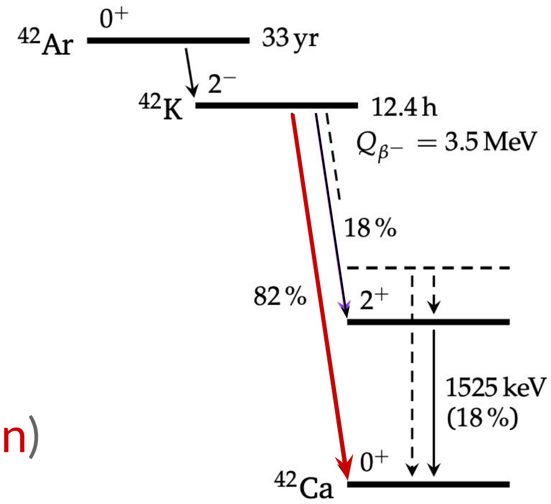
^{42}Ar / ^{42}K Background

- ^{42}K is progeny of ^{42}Ar
  (present in commercial argon,
  71 – 101 mBq/t [1] , 40 mBq/t [2])
- ^{42}K: Q_β = 3.5 MeV (ground-state transition)
  → above $Q_{\beta\beta}$ of ^{76}Ge (2039 keV)



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

^{42}Ar / ^{42}K Background



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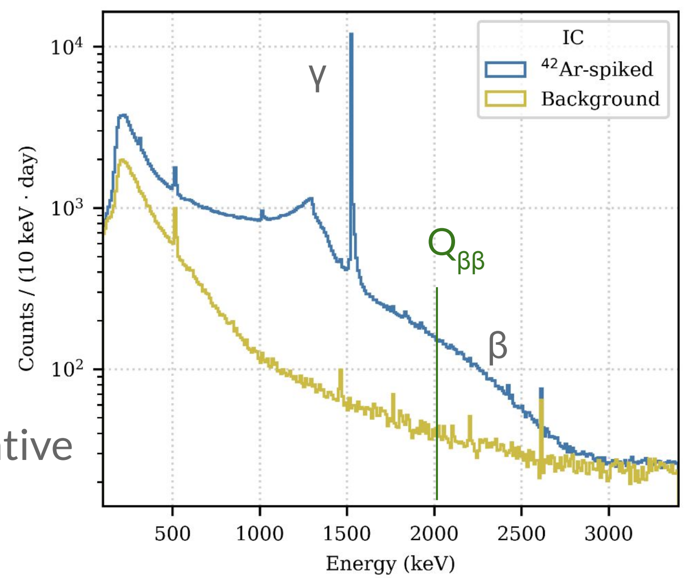
- ^{42}K: Q_β = 3.5 MeV (ground-state transition) → above $Q_{\beta\beta}$ of ^{76}Ge (2039 keV)
- Collection of ^{42}K ions on HPGe surface by E-fields
- Known background from GERDA & critical background for LEGEND

Measured in SCARF @ TUM



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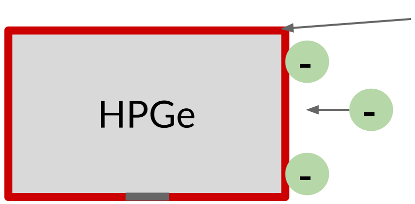
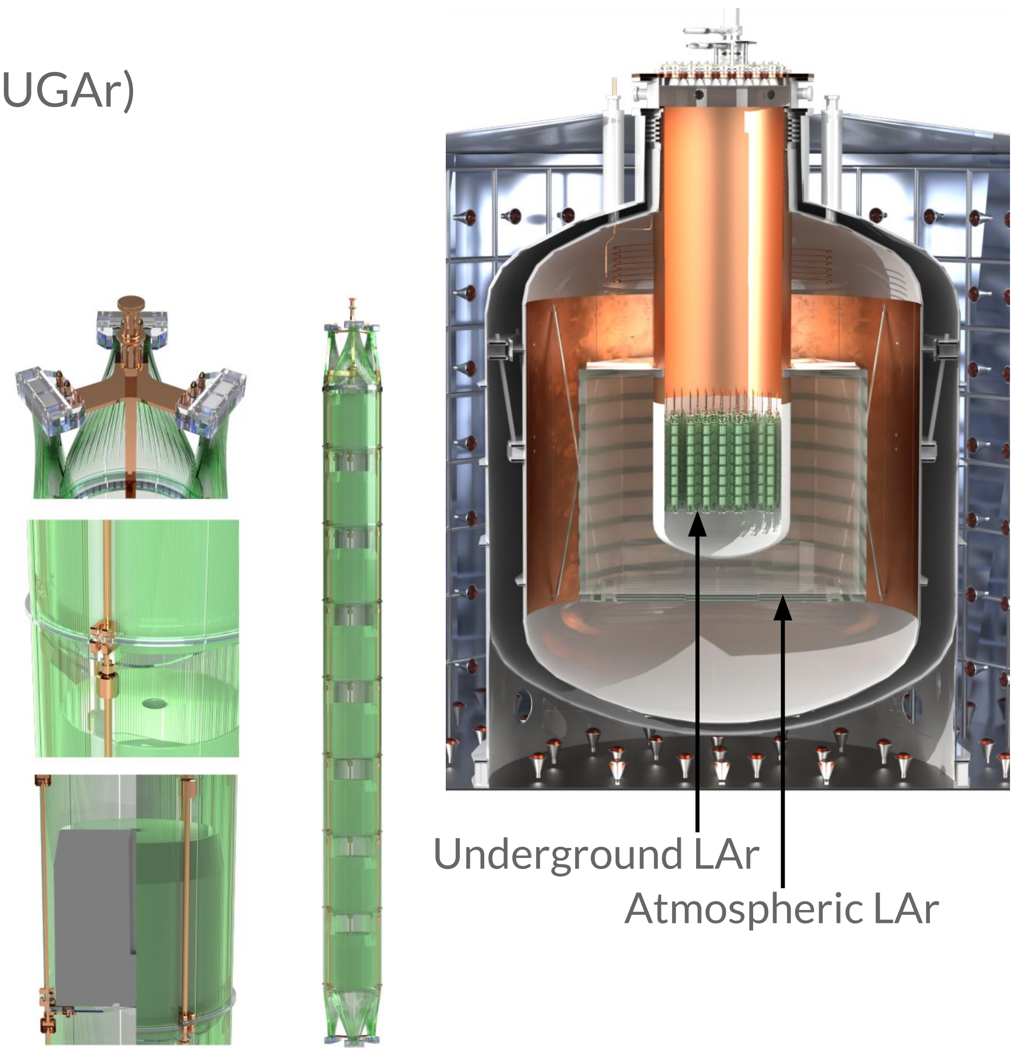


n^{+} surface at ≈ +3000 V → Collect negative ^{42}K ions or complexes (-)

^{42}K mitigation in LAr for LEGEND-1000

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



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

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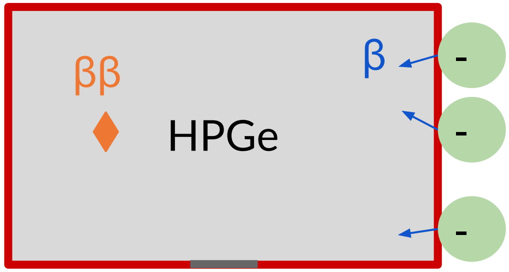

Betas:
energy deposition in transition layer below n^+
→ slow charge collection → slow pulse shape

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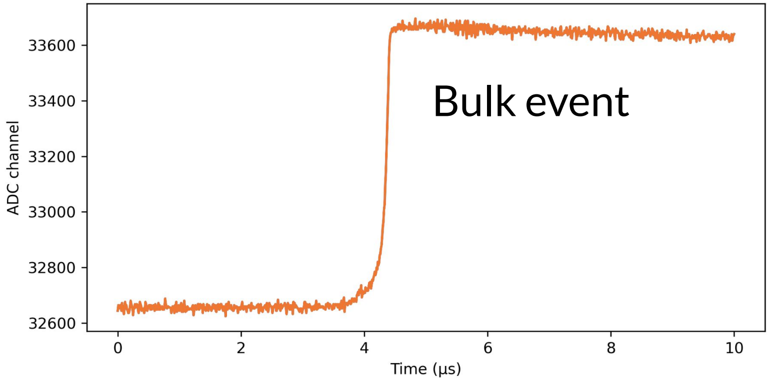

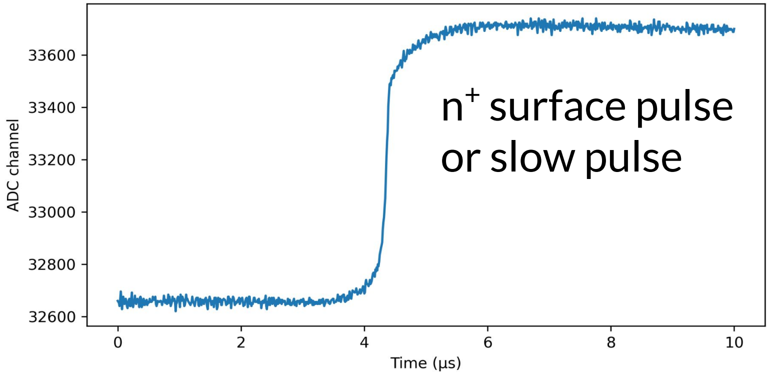

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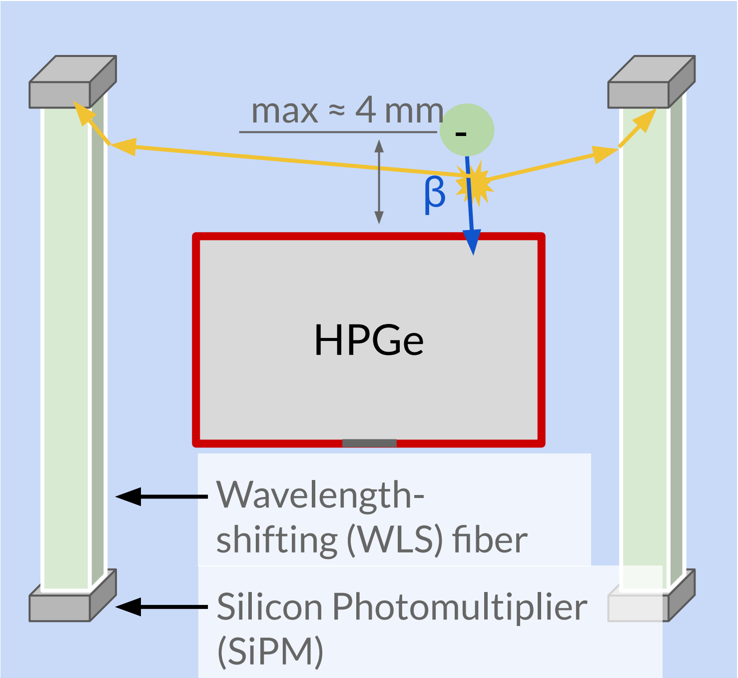

^{42}K on / very close to surface → beta invisible in LAr

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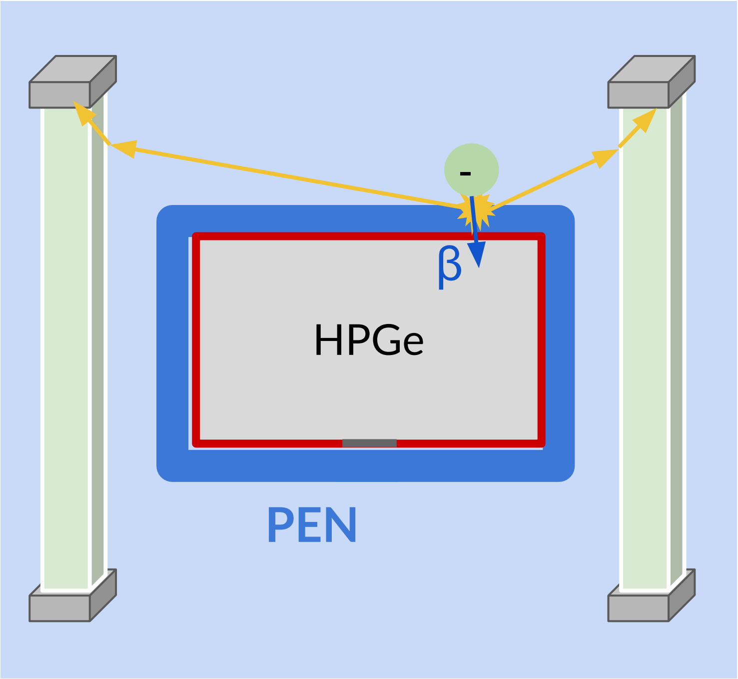
- Risk mitigation in case of unavailability of UGLAr
  - Scintillating enclosure
    → passive suppression & enhanced LAr AC
    → PEN (polyethylene naphthalate)

→ Talk by A. Leonhardt tomorrow



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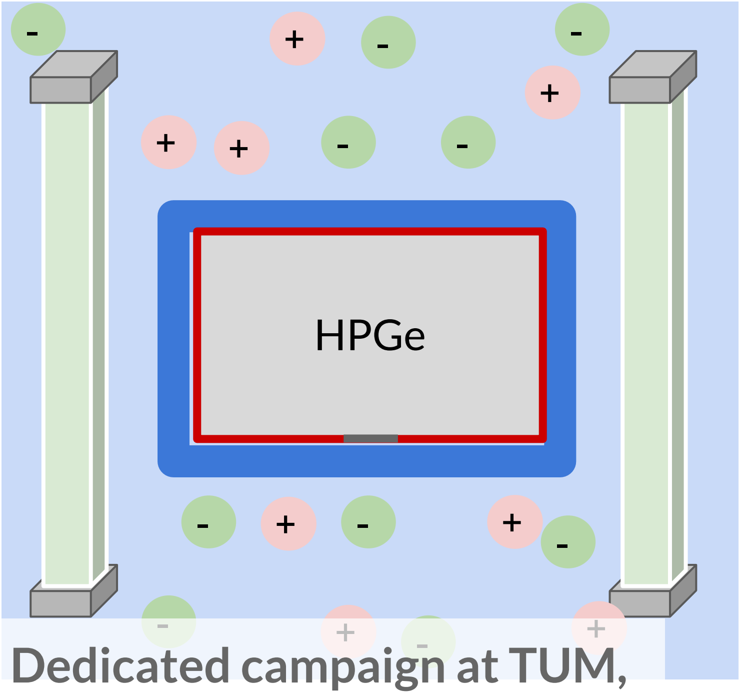

Dedicated campaign at TUM, using ^{42}K-spiked LAr

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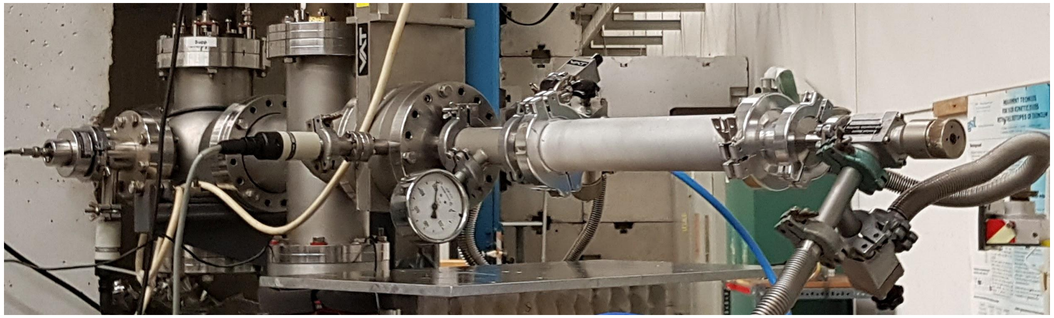
^{42}Ar production

Tandem Van-de-Graaff Accelerator at MLL in Munich



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

- Two beam times in 2018 and 2019, each ~ 1 week

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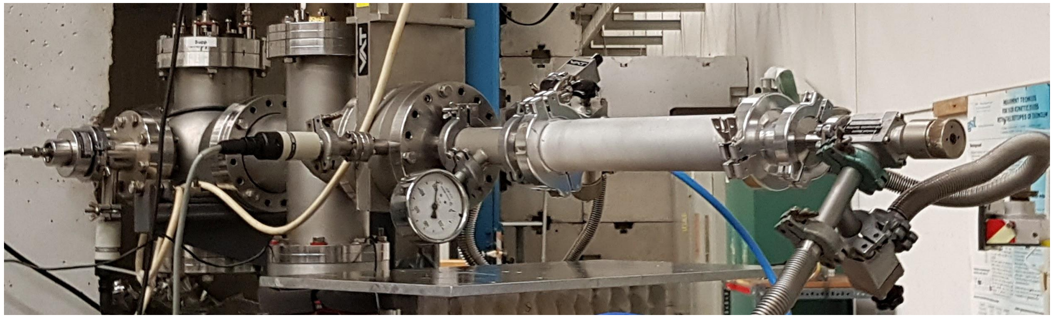

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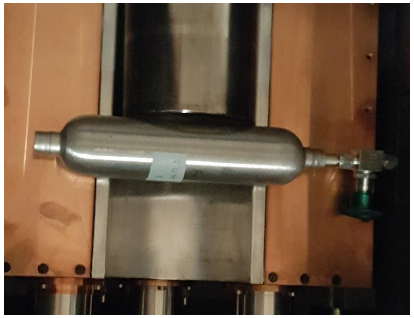
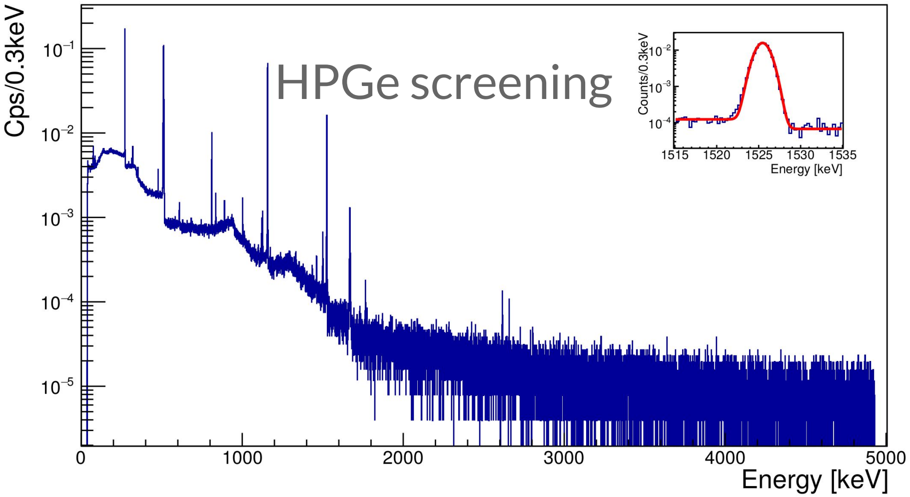
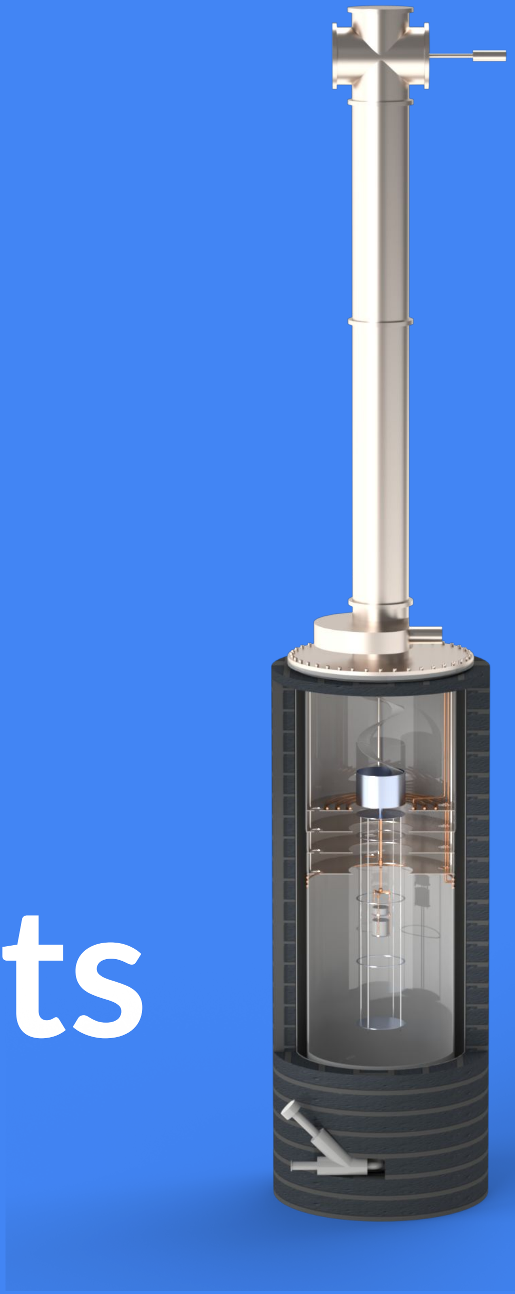




- Two beam times in 2018 and 2019, each ~ 1 week
- Total activity at time of injection: 435 Bq ^{42}Ar

Setup & Measurements



The SCARF test facility & setups

- SCARF = Subterranean Cryogenic Argon Research Facility @ TUM underground laboratory
- A 1 ton LAr cryostat for Ge detector tests, SiPM characterization, LAr scintillation studies, …

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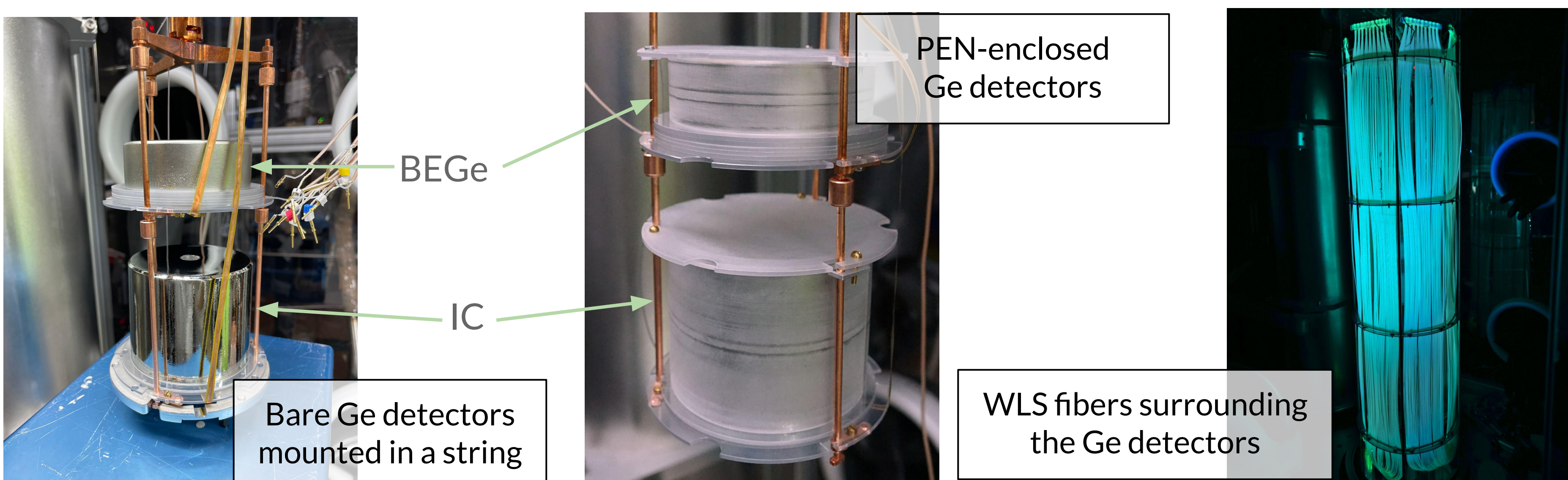

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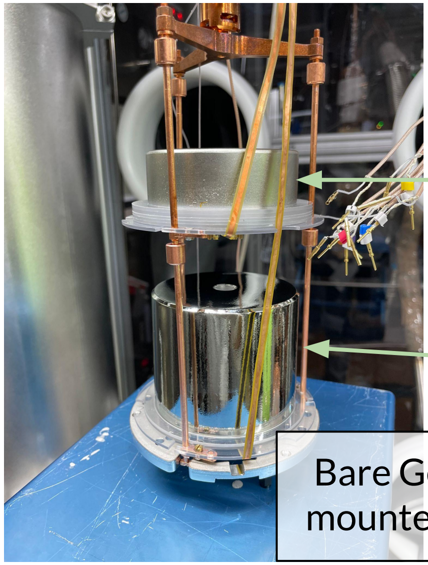
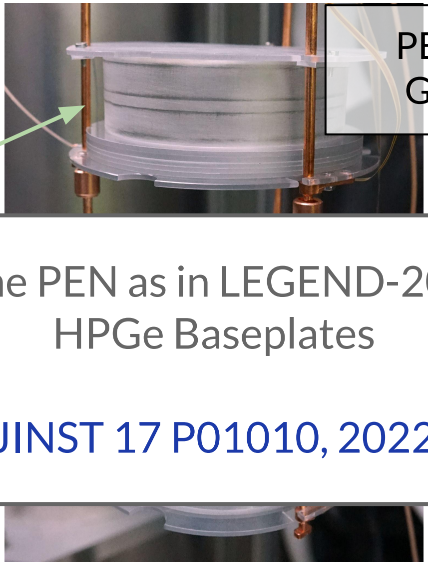
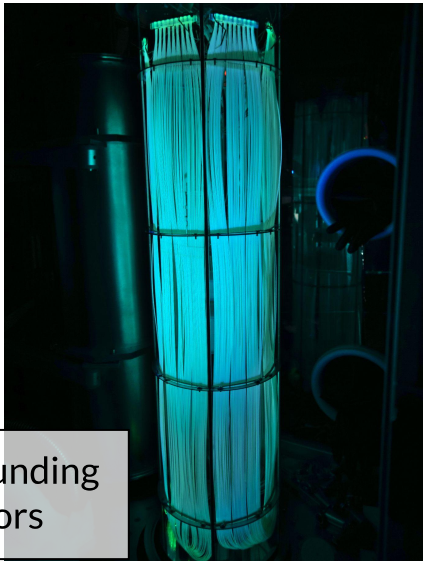


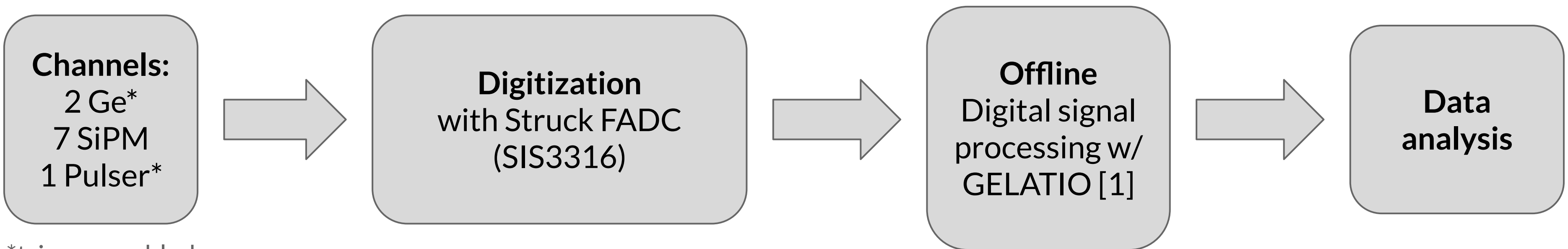


Same PEN as in LEGEND-200's HPGe Baseplates

[JINST 17 P01010, 2022]



Data acquisition & processing



*trigger enabled

[1: GELATIO (2011) arXiv:1106.1780]

^{42}Ar injection and ^{42}K build-up & transfer to liquid

Pressurized ten ^{42}Ar bottles & injected through LAr purification system into gas phase of SCARF

Accumulated ^{42}K retained in purification system

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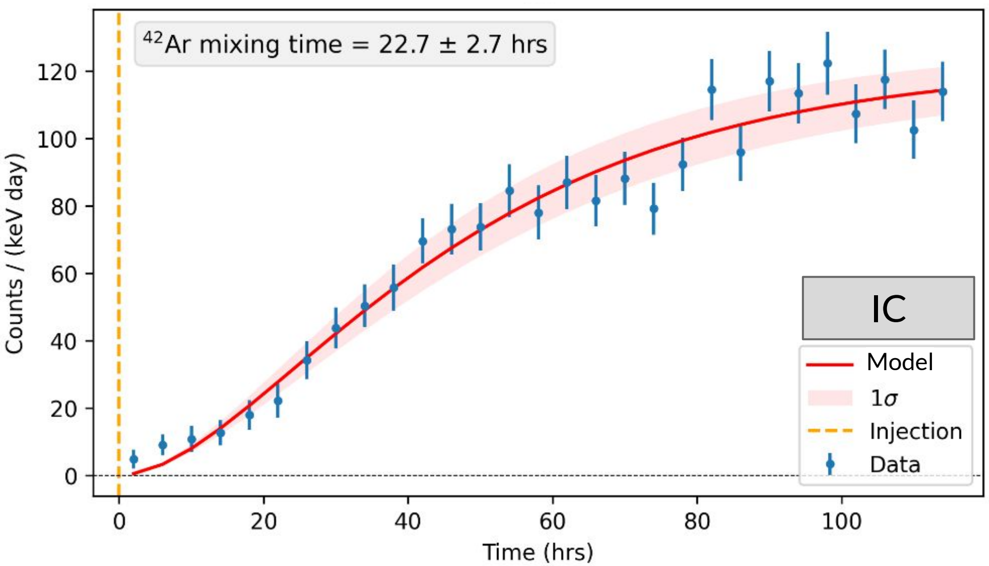
Pressurized ten ^{42}Ar bottles & injected through LAr purification system into gas phase of SCARF

Accumulated ^{42}K retained in purification system

^{42}K build-up due to ^{42}Ar decay & mixing into liquid phase

Observed build-up through gamma line at 1525 keV

Count rate in the 1525 keV line by ^{42}K



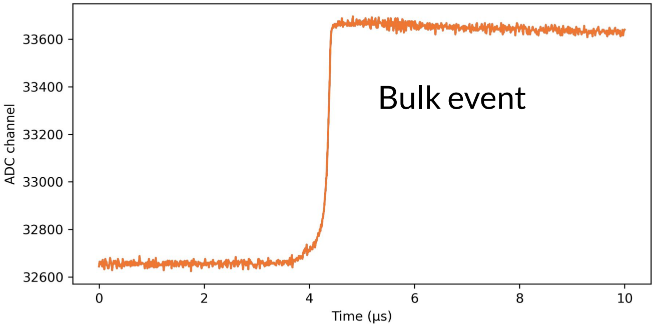
Rate equations → model follows

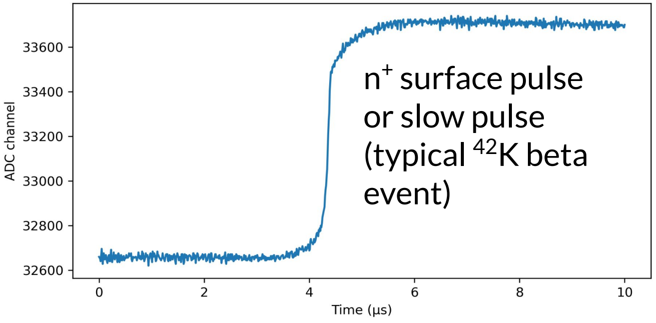
$\Gamma(t) = A - B\exp(-\lambda_k t) + C\exp(-\lambda_{mix} t)$,

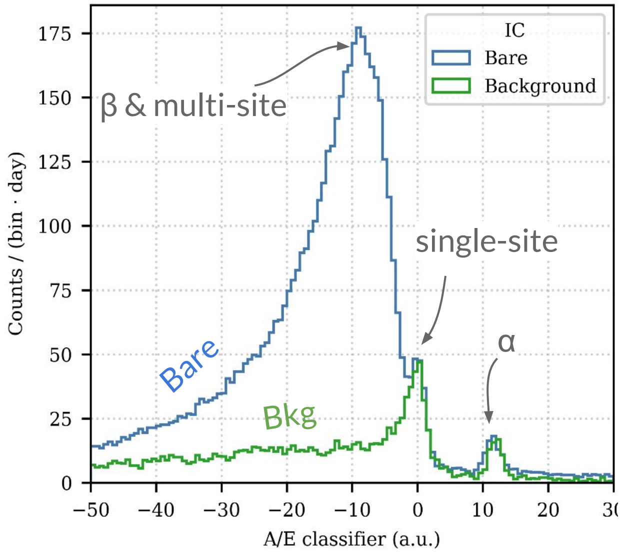
with ^{42}K decay rate λ_k and mix rate λ_{mix}

^{42}K suppression by PSD with the A/E method

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







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

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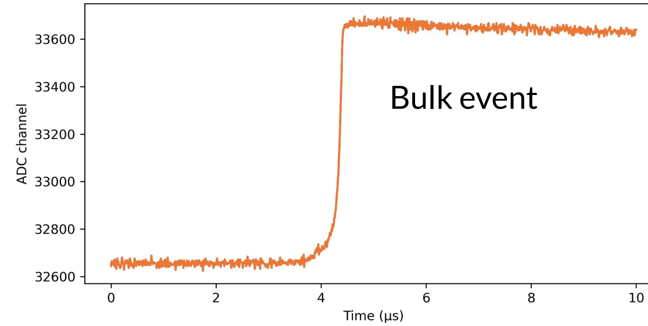
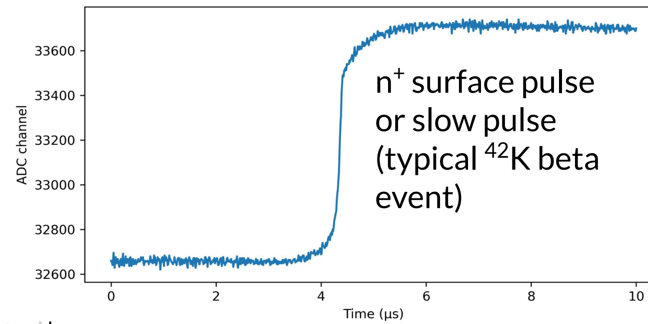
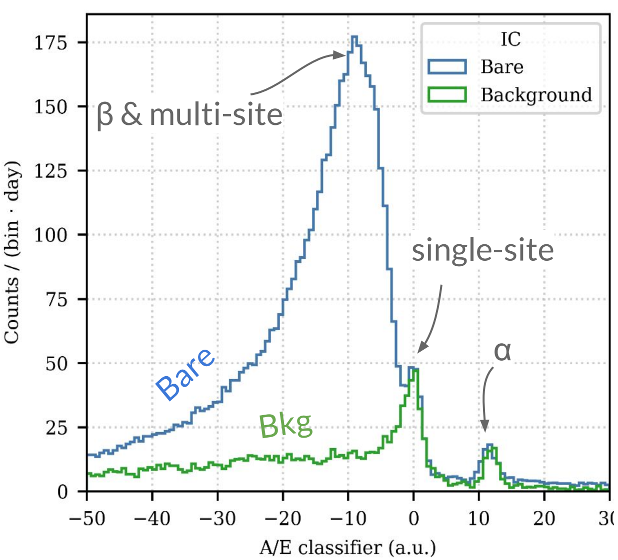


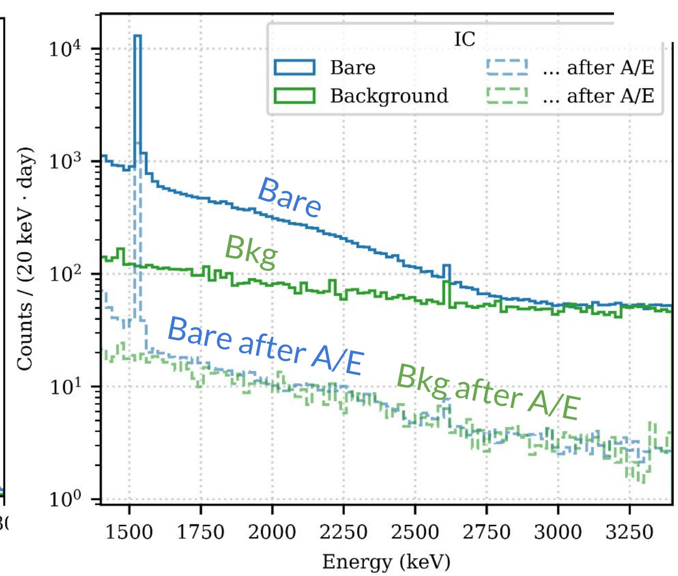


Measured efficiency of PSD cut with bare inverted coaxial (IC) Ge detector in beta region (1839–2239 keV):

Survival Fraction

SF = (3.8 ± 1.5)× 10^{-3} [(2)]





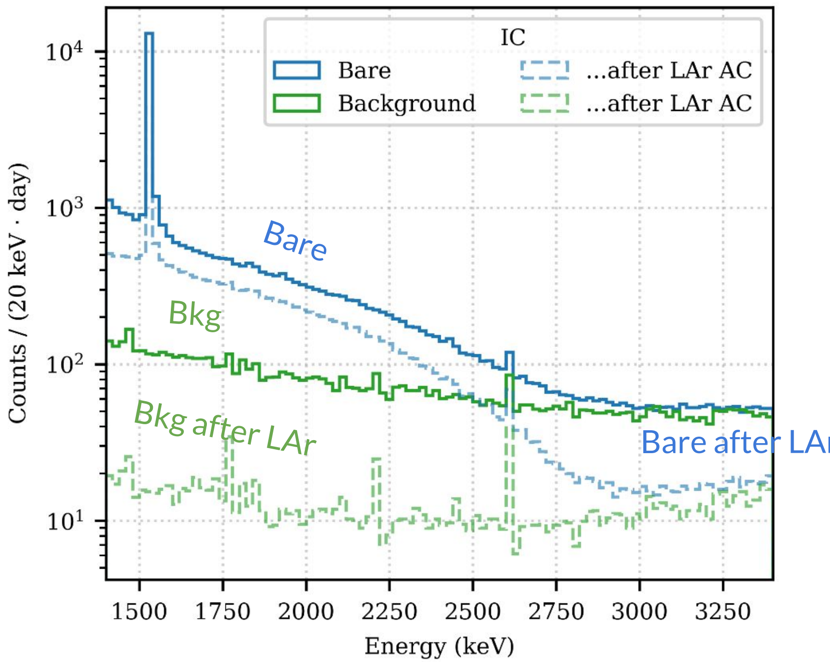
[(1)] Here, the A/E method was used for PSD. For details, see, e.g., JINST 4 P10007 (2009).

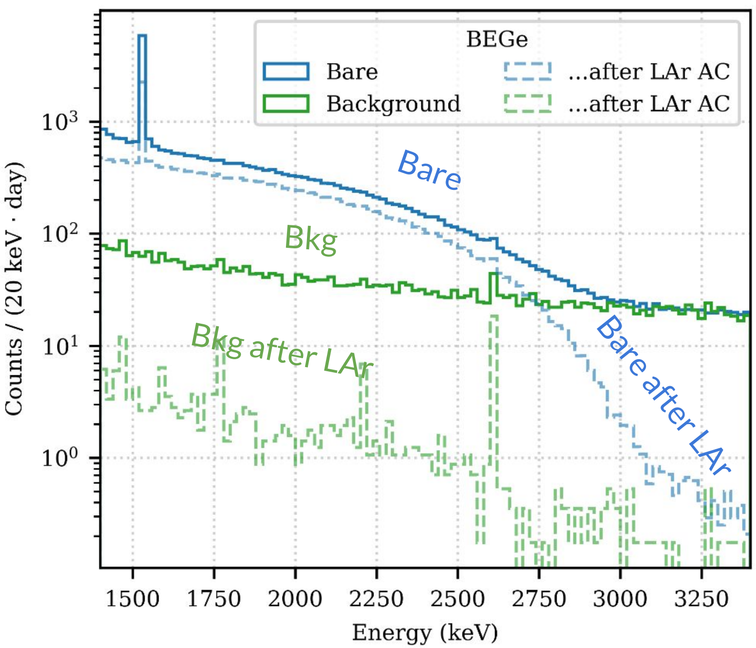
[(2)] This is a similar SF to what we previously found for broad-energy germanium (BEGe) detectors in Eur. Phys. J. C (2018) 78:15.

^{42}K suppression with scintillation light read-out

Most ^{42}K beta decays **on** the **Ge surface**
→ **'dark' events** which don't produce LAr scintillation light

A few decays occur in the LAr, **close to** the **Ge surface**
→ **'bright' events,** which can be vetoed



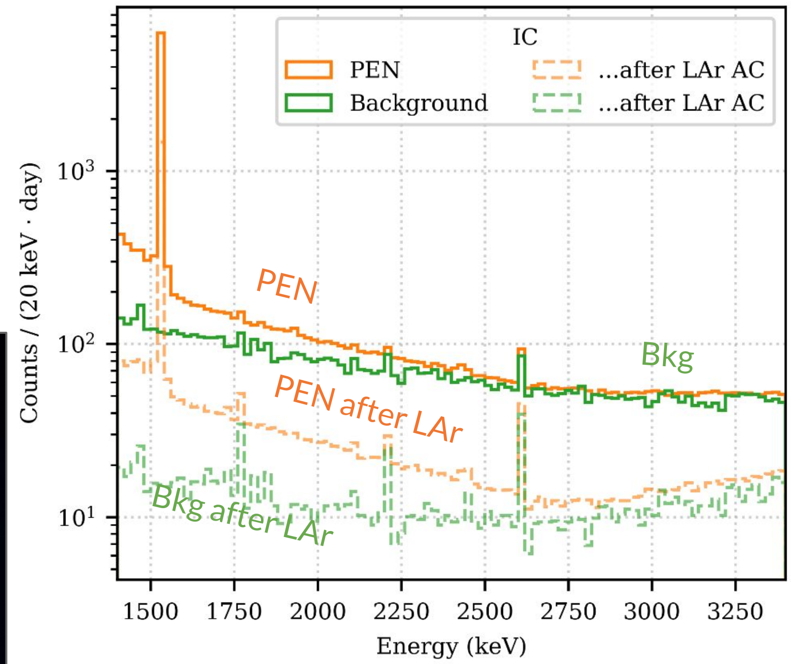


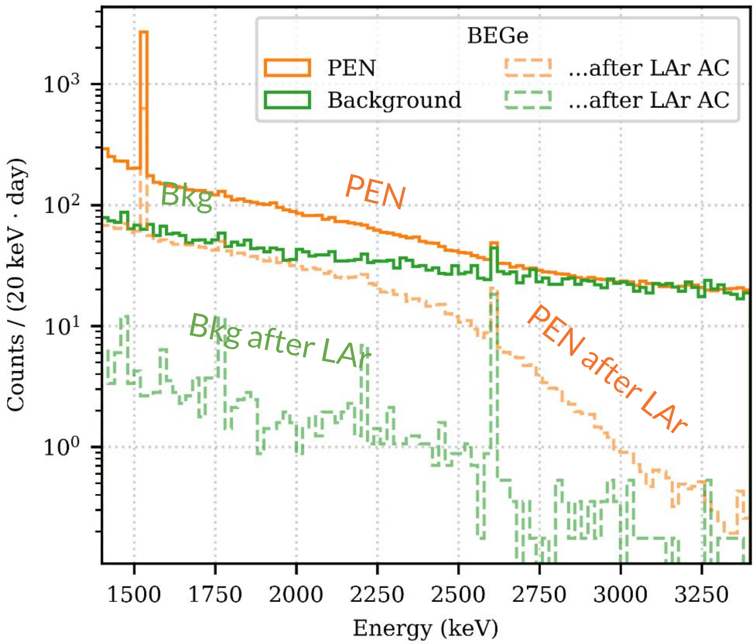
Measured survival fractions (SF) of ^{42}K beta events due to LAr anticoincidence (AC) cut:

BEGe: **SF = 0.854 ± 0.004**
IC: **SF = 0.883 ± 0.005**

Improvement of scintillation AC with PEN enclosure

PEN enclosures provide a **scintillating barrier**
Most ^{42}K betas must pass it, before penetrating the Ge
→ PEN scintillation light is produced, and detected





Measured SF of ^{42}K beta events of LAr AC cut w/ enclosure:

BEGe: **SF = 0.793 ± 0.014**
IC: **SF = 0.81 ± 0.04**

Only modest improvement with current enclosure design and light read out system. To be improved!

Passive shielding by PEN enclosures

Enclosures:
- physical barrier (1.75 mm)
- “electrostatic barrier”: charge up[(1)]

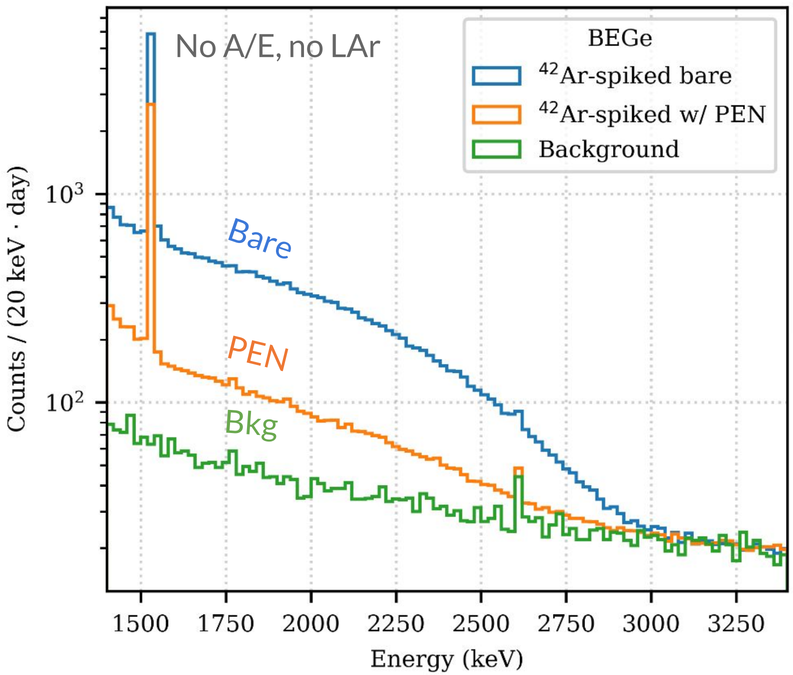
→ reduced attraction of ^{42}K ions

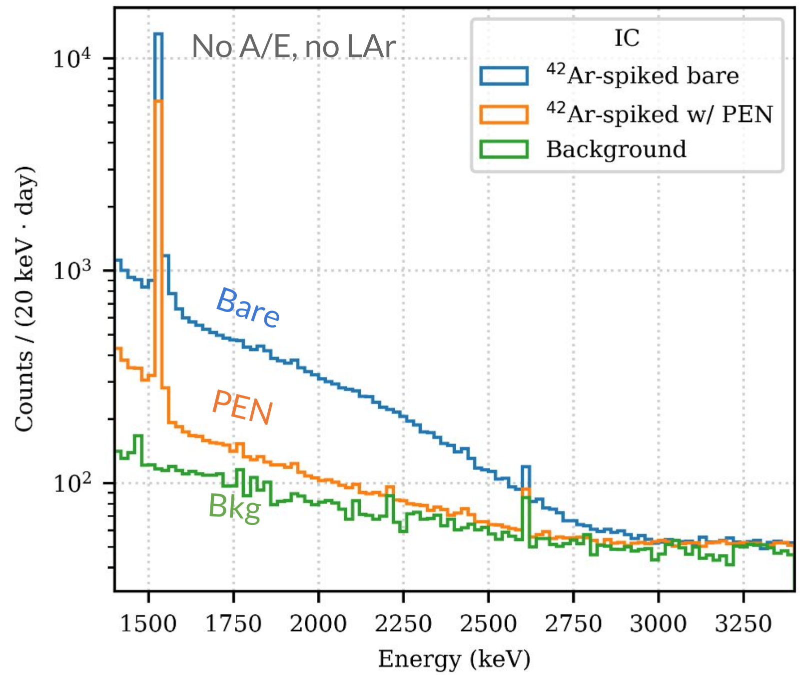
→ decreased beta rate around $Q_{\beta\beta}$

Measured ^{42}K beta survival fraction in beta region (1839–2239 keV) due to passive shielding:

BEGe: **SF = 0.171 ± 0.002**

IC: **SF = $0.093^{+0.004}_{-0.002}$**





(1) Charge-up observed at timescale of days. Spectra & results obtained after steady state was reached.

Combining techniques: Grand total suppression

Compare event rate in bare configuration with rate with PEN enclosure after A/E and LAr AC cut for the IC.

No significant amount of events left
→ upper limit on the survival fraction:

Measurement:

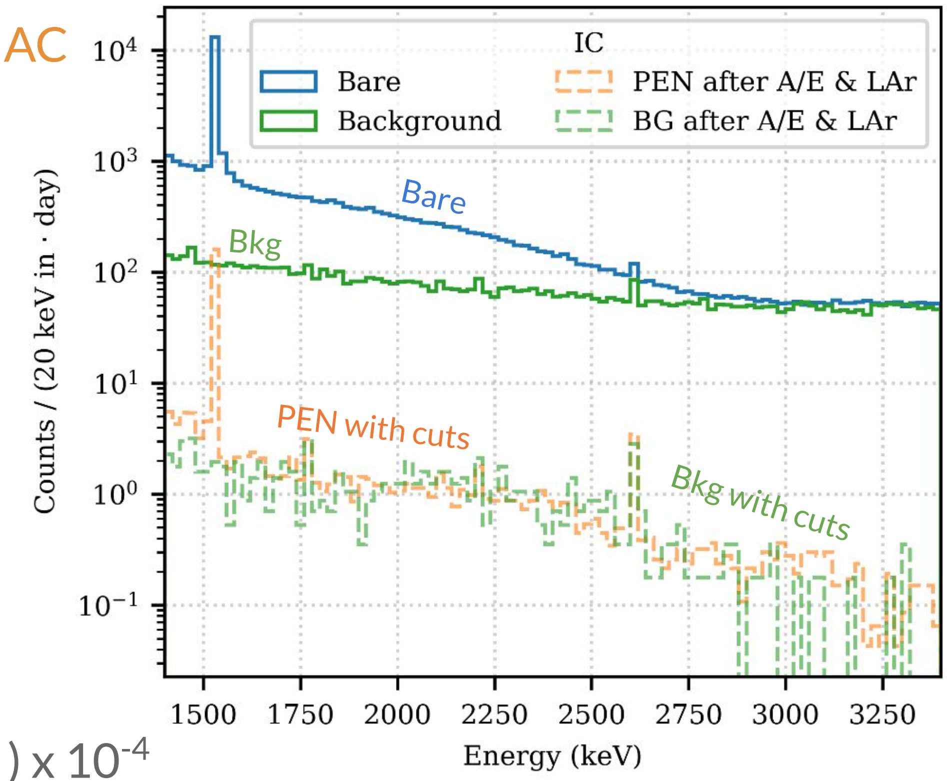
$$SF_{all} < 4 \times 10^{-4} \text{ @ 90 \% CL}$$

Using individual survival fractions:

$$\left.\begin{aligned} SF_{PSD} &= 0.0029 \pm 0.0008 \\ SF_{LAr} &= 0.81 \pm 0.04 \\ SF_{pass} &= 0.093 \pm 0.003 \end{aligned}\right\} SF_{all} = (2.2 \pm 0.6\,) \times 10^{-4}$$

assuming no correlations

SF_{PSD}: uses PEN data set after LAr AC here



Conclusion & Outlook

^{42}K testing campaign at TUM, using ^{42}Ar-spiked LAr

Benchmarked ^{42}K suppression techniques:

- Pulse-shape discrimination with A/E
- LAr anti-coincidence
- Scintillating PEN enclosure

Combined survival fraction: **$< 4 \times 10^{-4}$**

Unsuppressed ^{42}K-induced **background index**:

0.34 cts/keV/kg/yr(*)

becomes:

$BI(^{42}K) < 1.4 \times 10^{-4}$ cts/keV/kg/yr

(*)Measured in LEGEND-200 (run without Mini-shrounds [LEGEND private communications])

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LEGEND-1000 overall background goal:

1 x 10^{-5} cts/keV/kg/yr

→ Need two orders of magnitude in ^{42}K suppression to be viable fall-back when UGLAr unavailable

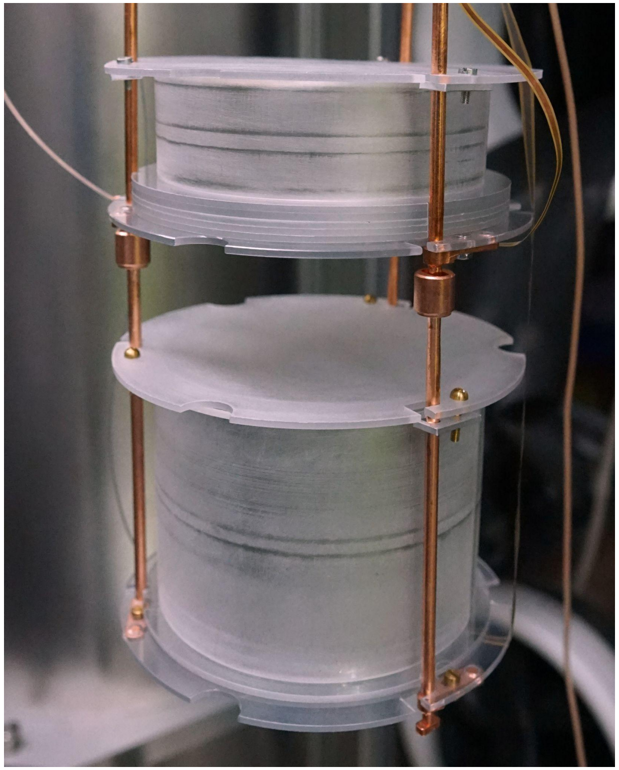
- Specialized PSD → Talk by N. Lay
- LAr AC → Improved light output of PEN (or better scintillator), better light collection by LAr instrumentation
- Optimized PEN thickness for improved passive suppression;
  improved radiopurity required

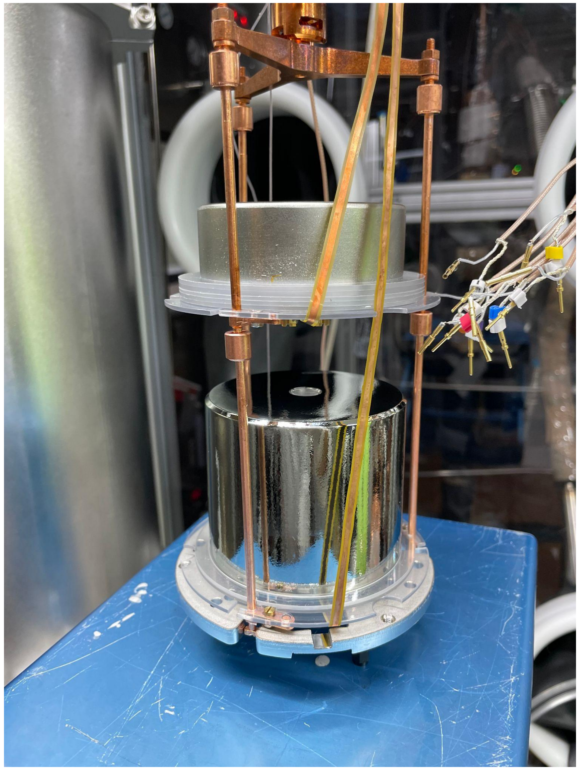
→ More ^{42}Ar/^{42}K statistics required for improved benchmark

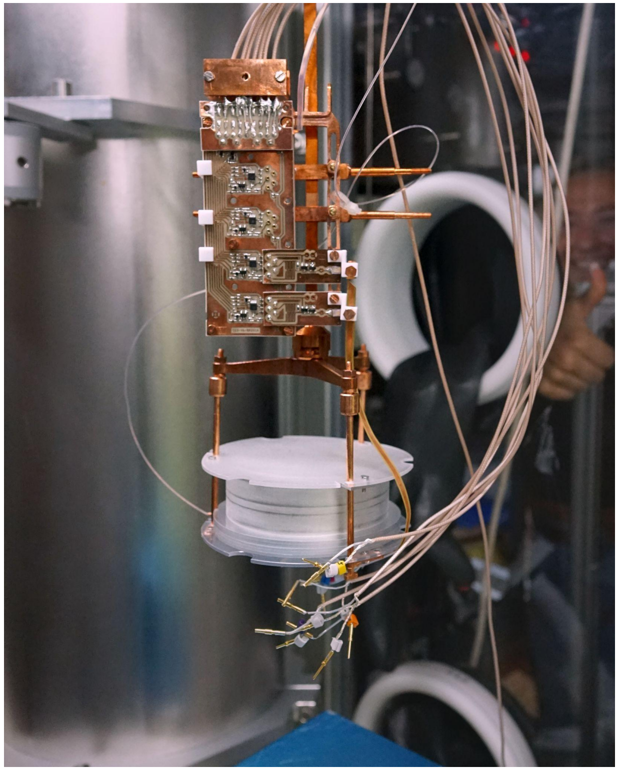
Backup

Two HPGe detectors enclosed in PEN and mounted

Left: BEGe mounted above IC. **Middle:** IC w/o top plate; stacked PEN in bore hole. **Right:** CC3
PEN was sanded on the outside to reduce light trapping and facilitate isotropic emission

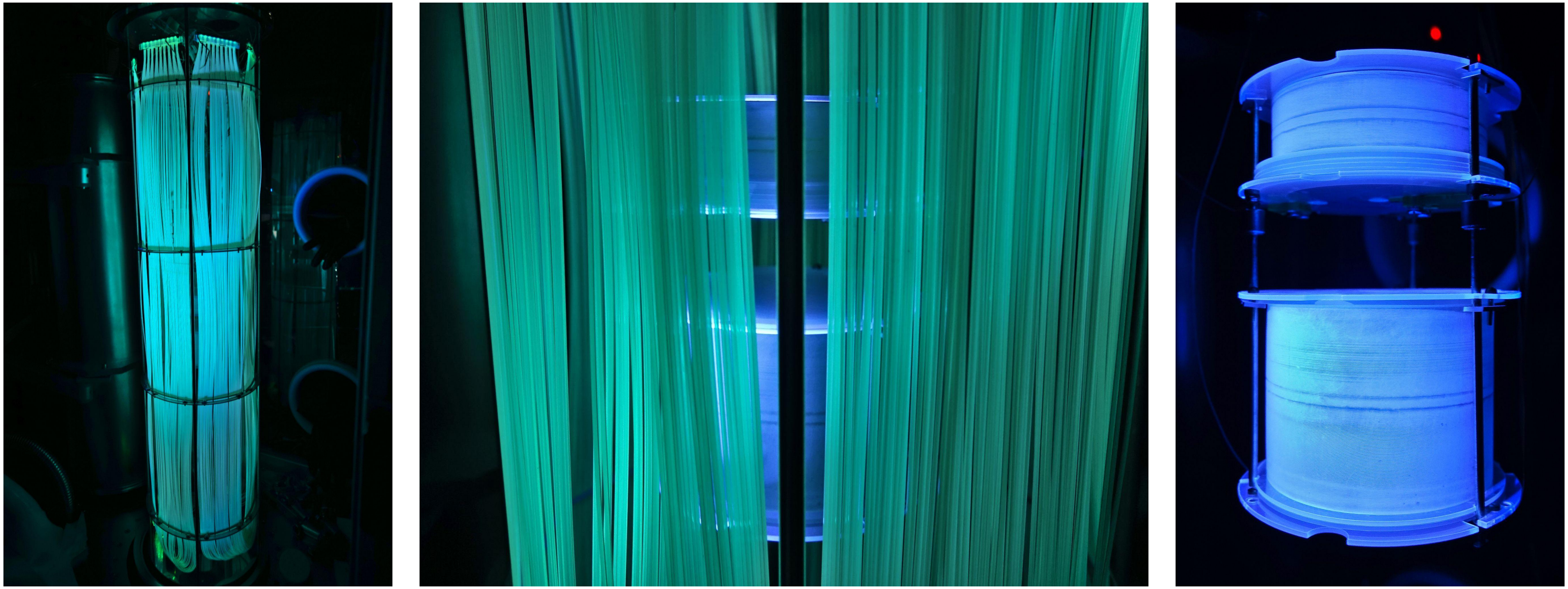






Installation of fiber shroud around the two detectors

3 double fiber modules, 1 single module → 7 SiPM arrays. Fibers and arrays reused from GERDA.
Left: Fiber shroud. **Middle:** Both Ge detectors shining through the fiber shroud. **Right:** BEGe and IC shining



Modelling of ^{42}Ar mixing into liquid phase

Assume

- Exponential transfer of ^{42}Ar into liquid phase
- Population of ^{42}K exclusively through ^{42}Ar decay

Construct differential rate equations and solve them.

Neglect

- Transfer of ^{42}K
- Change in ^{42}Ar activity

$$Rate(t') = \xi \cdot \frac{\lambda_{Ar} N_{0,Ar}}{1+\frac{V_g}{V_l}} \cdot \frac{\lambda_\gamma}{10\ keV} \cdot \lambda_{mix} \left(\frac{1}{\lambda_{mix}\lambda_K} - \frac{e^{-\frac{\lambda_K \Delta t}{2}} - e^{\frac{\lambda_K \Delta t}{2}}}{{\lambda_K}^2(\lambda_K - \lambda_{mix})\Delta t} e^{-\lambda_K t'} + \frac{e^{-\frac{\lambda_{mix} \Delta t}{2}} - e^{\frac{\lambda_{mix} \Delta t}{2}}}{{\lambda_{mix}}^2(\lambda_K - \lambda_{mix})\Delta t} e^{-\lambda_{mix} t'} \right)$$

Two free parameters

- Detection efficiency ξ
- Mixing time ^{42}Ar gas → liquid λ_{mix}

Method to calculate survival fractions

Question: How well does *[mitigation technique]* suppress ^{42}K beta events?

Answer: Calculate the survival fraction of *[mitigation technique]*:

$$\text{Survival Fraction} = \text{SF} = \frac{N_S - B_S}{N_0 - B_0}$$

BACKGROUND SUBTRACTION NEEDED TO REMOVE RADIOACTIVITY FROM THE SURROUNDINGS!

With

N_0 … raw signal counts, B_0 … raw background counts

N_S … suppressed signal counts, B_S … suppressed background counts

Construct **Feldman-Cousin confidence interval of SF**

In case SF is compatible with 0, or even negative, construct upper limit on SF.

Result table

Individual Mitigation Technique	Survival Fraction	
	BEGe	**IC**
A/E (bare)	MLE: 51.19 % 50.9-51.5 %	MLE:0.38 % 0.23-0.53 %
LAr AC (bare)	MLE: 85.42 % 85.09-85.80 %	MLE: 88.29 % 87.82-88.77 %
LAr AC (PEN)	MLE: 79.26 % 77.87-80.81 %	MLE: 80.89 % 77.08-85.15 %
PEN passive	MLE: 17.05 % 16.86-17.28 %	MLE: 9.33 % 9.10-9.66 %

Combination of analysis cuts	Survival Fraction	
	BEGe	**IC**
A/E + LAr AC (both bare)	MLE: 45.49 % 45.26-45.72 %	MLE: 0.13 % 0.07-0.18 %

Grand total	Survival Fraction	
	BEGe	**IC**
Analysis cuts + PEN passive	n/a	< 0.04 % @ 90 % CL
Analysis cuts + PEN passive [extrapolation]	0.78 % +/- 0.02 %	0.012 % +/- 0.006 %

p-value plot for combined suppression

Bare to PEN after cuts. MLE for SF around 0. Can only quote upper limit.