# Delayed Coincidence Based Active Suppression of In-Situ Muon-Induced Isotope Backgrounds in LEGEND

LOW RADIOACTIVITY TECHNIQUES 2026 WORKSHOP X

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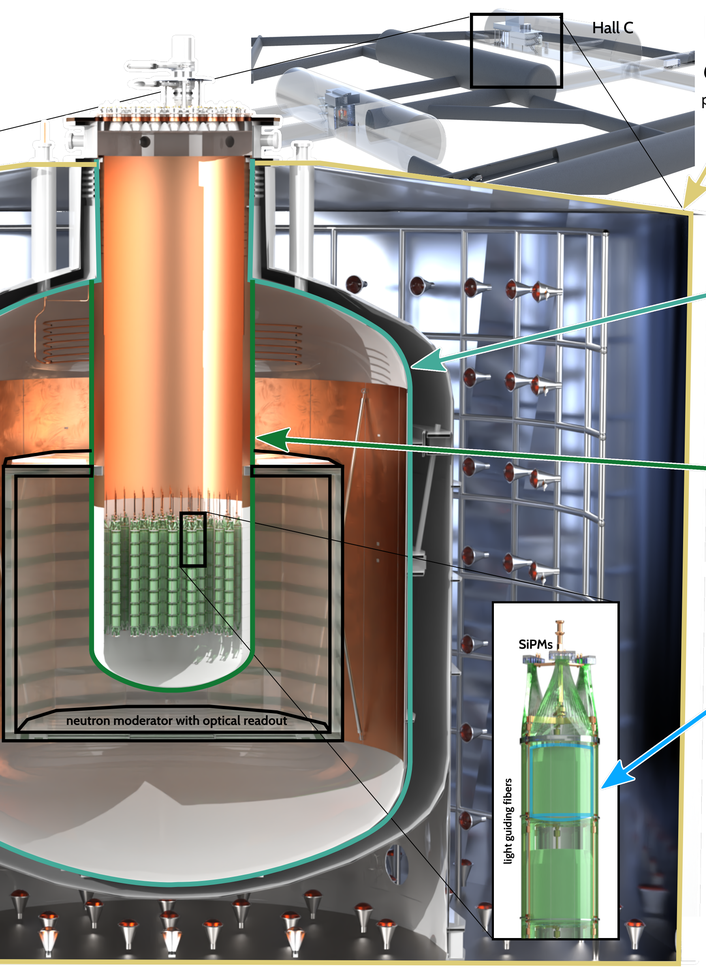
## Introducing LEGEND-1000




Located at the ***Laboratori Nazionali del Gran Sasso (LNGS)***
planned construction start: **late 2026**

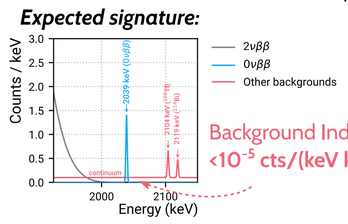
**Water Tank**
- tag crossing muons (>99%)
- shield external neutrons

**AtmLAr filled cryostat**
- shield external gammas
- moderator to shield neutrons and tag neutron captures

**UGLAr filled re-entrant tube**
- LAr from **U**nder**G**round wells with reduction of <7 x $10^{-4}$ in the cosmogenic $^{39}$Ar and $^{42}$Ar [1]
- tag beta/gamma background

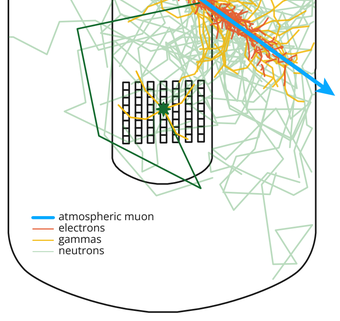
up to **1000 kg of** HPGe enriched in $^{76}$Ge
- search for **neutrinoless double-beta** ($0\nu\beta\beta$) decay ($Q_{\beta\beta}$=2039keV)

***Expected signature:***



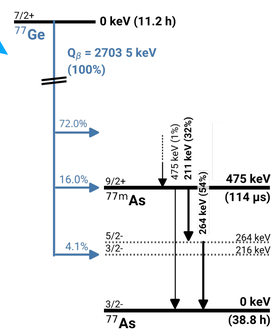

Background Index (BI) Goal at $Q_{\beta\beta}$: **<$10^{-5}$ cts/(keV kg yr)**

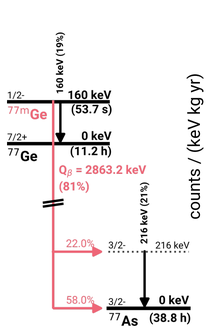
## Background from In-Situ Muon-Induced Isotope Decays



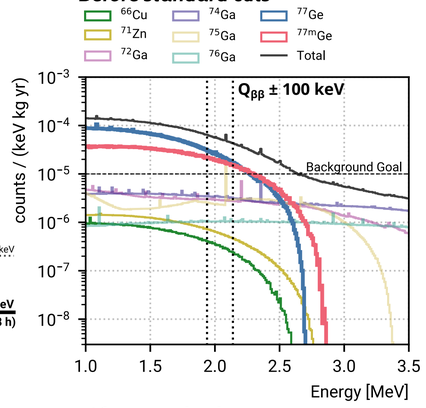

Argon has a (relatively) high muon-induced neutron yield [2].

$^{77(m)}$Ge is produced via $^{76}$Ge(n,γ), ground state $^{77}$Ge and metastable state $^{77m}$Ge produced at roughly equal rate.

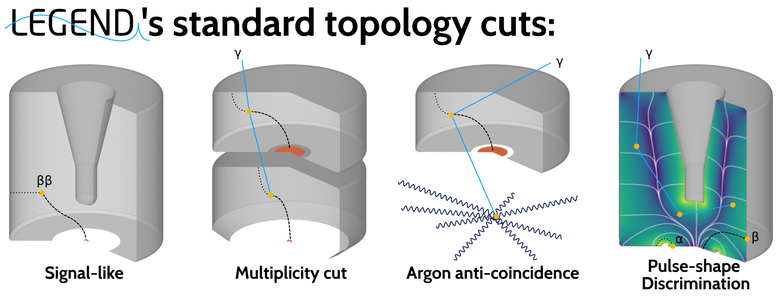


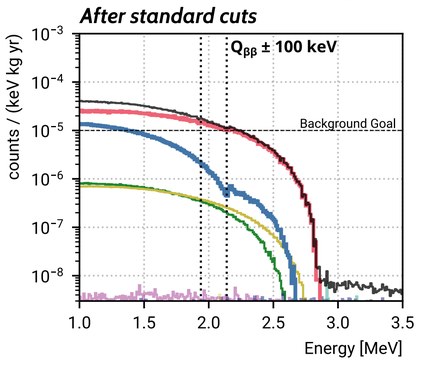

***Before standard cuts***




**LEGEND's standard topology cuts:**

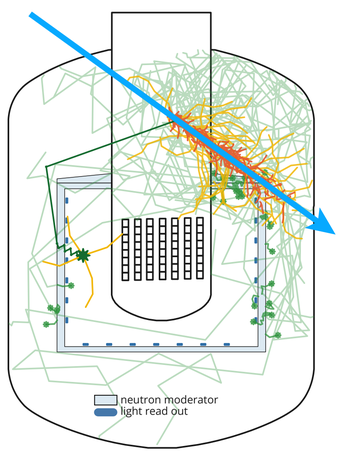



***After standard cuts***




After applying the standard topology cuts, $^{77m}$Ge **alone exceeds the background goal**:

**BI ($^{77m}$Ge) = 1.8×$10^{-5}$ cts/(keV kg yr) > $BI_{goal}$ (!!!)**

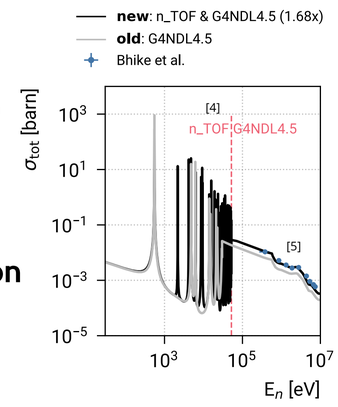



**Passive Suppression:**

A neutron moderator made of PMMA slows neutrons down and thus mores them more likely to be caught on the $^{40}$Ar. [3]
**$^{77(m)}$Ge production is halved**.
→ active suppression required to mittigate $^{77(m)}$Ge background
→ light read out to tag neutron captures in Argon

## Validating the Simulation

Cross-check the Cross-sections:
- Substitute newer cross-section measurement of $^{76}$Ge(n,γ)
  → **production increased by 1.47×**




Study Simulation Choices:
- G4 physics list/nuclear data library choices: **~20% deviation**
- FLUKA estimate vs G4 estimate: **~5% deviation**

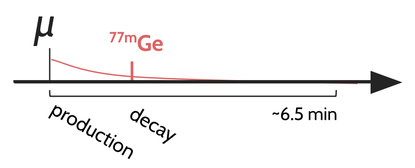
Comparison with Data:
- A search for $^{77}$Ge decays in GERDA constrains the production rate to **<1.8× the simulation estimate** (90% CL). [6]

Plans to use LEGEND -200 data:
- Measure the production rate of both $^{77}$Ge and $^{77m}$Ge separately.
- Measure the muon-induced neutron yield in Argon (new)

## Active Suppresion of $^{77(m)}$Ge Decays via Delayed Coincidence

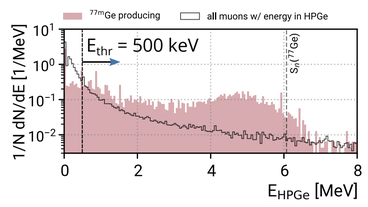
### $^{77m}$Ge suppression cut:

**Strategy:** Tag $^{77m}$Ge production in muon-shower and reject after using two complementary methods.

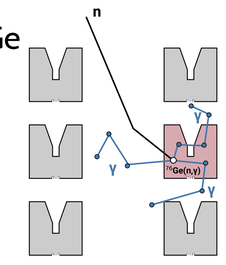



**Method 1:** Direct tagging of gamma cascade in HPGe detectors.

**Situation A:** energy in capture containing HPGe

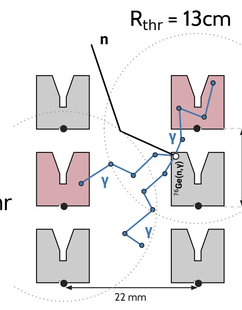



Gamma cascade model from [7].




**Situation B**: gamma cascade escapes HPGe

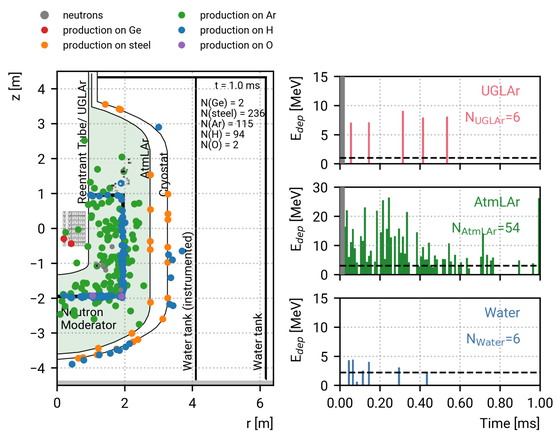
Tag all HPGe in a $R_{thr}$ sphere of HPGe with >$E_{thr}$ as $^{77(m)}$Ge producing.




**Method 2:** Indirect tagging of muon showers with high neutron multiplicity.

After a μ crossing, count the neutron captures in other parts of the experiment by setting thresholds on measured light.

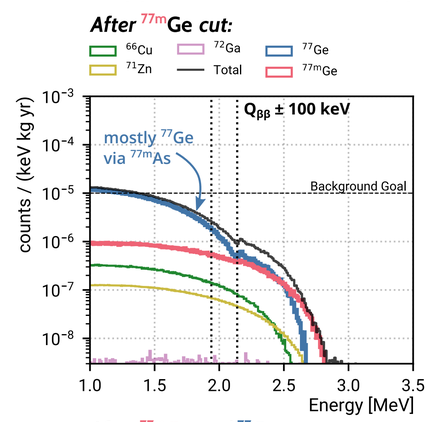
Tag a μ events as $^{77(m)}$Ge producing when either of the volumes counts more than a threshold number.



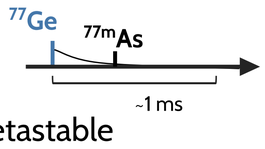

**Cut definition:** Reject events if they occur within 6.5 min (5τ) in either a tagged HPGe detector (Method 1) or a tagged μ event (Method 2).

**Performance:**
- **$^{77m}$Ge background** reduced to 4.1%
- **$0\nu\beta\beta$ decay** acceptance reduced to 97%

***After $^{77m}$Ge cut:***




### $^{77}$Ge suppression cut:

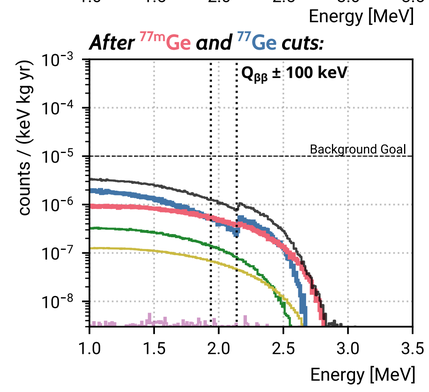



**Strategy:** Tag $^{77}$Ge decays via the metastable $^{77m}$As by searching for delaye de-excitaiton.

**Cut definition:** Reject events if they are followed by another event with >200keV within 1 ms.

**Performance:**
- **$^{77}$Ge background** reduced to 35%
- **$0\nu\beta\beta$ decay** acceptance reduction negligible

***After $^{77m}$Ge and $^{77}$Ge cuts:***




## Implications for LEGEND-1000:

**BI (μ-ind) = 1.0 $^{+0.5}_{-0.3}$ × $10^{-6}$ cts/(keV kg yr) ~ 10% $BI_{goal}$ (✔)**

LEGEND-1000 will not be limited by in-situ muon-induced isotope background and **can reach its sensitivity goal at LNGS**.

**LEGEND Institutions**

Centre for Energy, Environmental and Technological Research
Comenius Univ.
Czech Technical Univ. in Prague and IEAP
Daresbury Laboratory
Duke Univ. and Triangle Universities Nuclear Laboratory
Gran Sasso Science Institute
Hochschule RheinMain
Indiana Univ. Bloomington
INFN – Sezione di Napoli
Institute for Nuclear Research Russian Academy of Sciences
Jagiellonian Univ.
Joint Institute for Nuclear Research
Joint Research Centre Geel
Laboratori Nazionali del Gran Sasso
Laboratori Nazionali di Frascati
Lancaster Univ.
Leibniz Institute for Crystal Growth
Leibniz Institute for Polymer Research
Los Alamos National Laboratory
MPI for Nuclear Physics
MPI for Physics
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Princeton Univ.
Roma Tre Univ. and INFN
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Univ. of Texas at Austin
Univ. of Tuebingen
Univ. of Warwick
Univ. of Washington and Center for Experimental Nuclear Physics and Astrophysics
Univ. of Zurich
Williams College

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[6] GERDA Collaboration, Eur.Phys.J.C 85 (2025) 7, 809, DOI: 10.1140/epjc/s10052-025-14445-x
[7] Peter Grabmayr, Eur.Phys.J.A 60 (2024) 5, 115, DOI: 10.1140/epja/s10050-024-01336-0