Cosmogenic background and its consequences for rare event searches with germanium

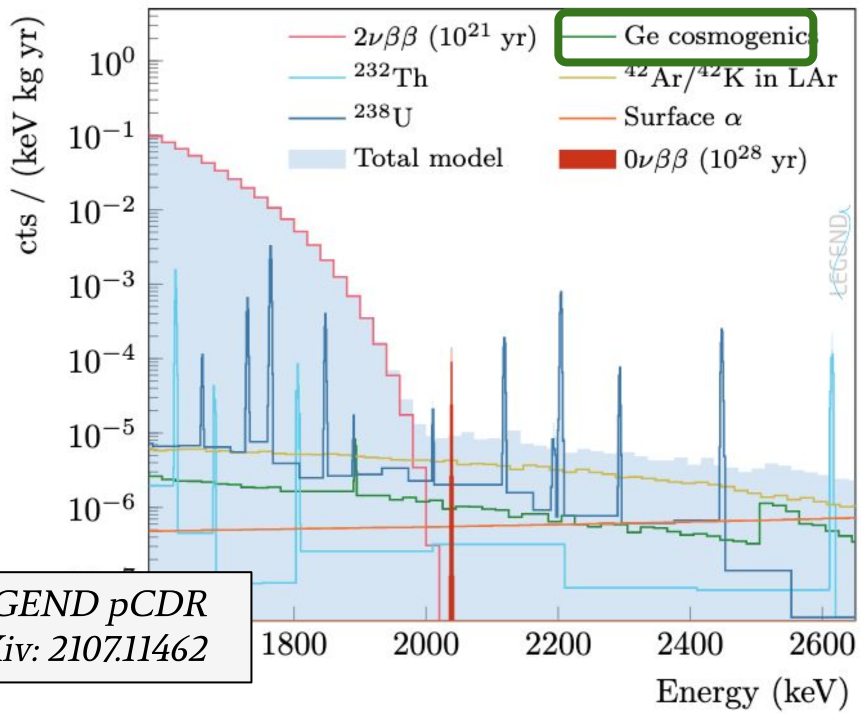
Ralph Massarczyk for the MAJORANA collaboration

Los Alamos National Laboratory

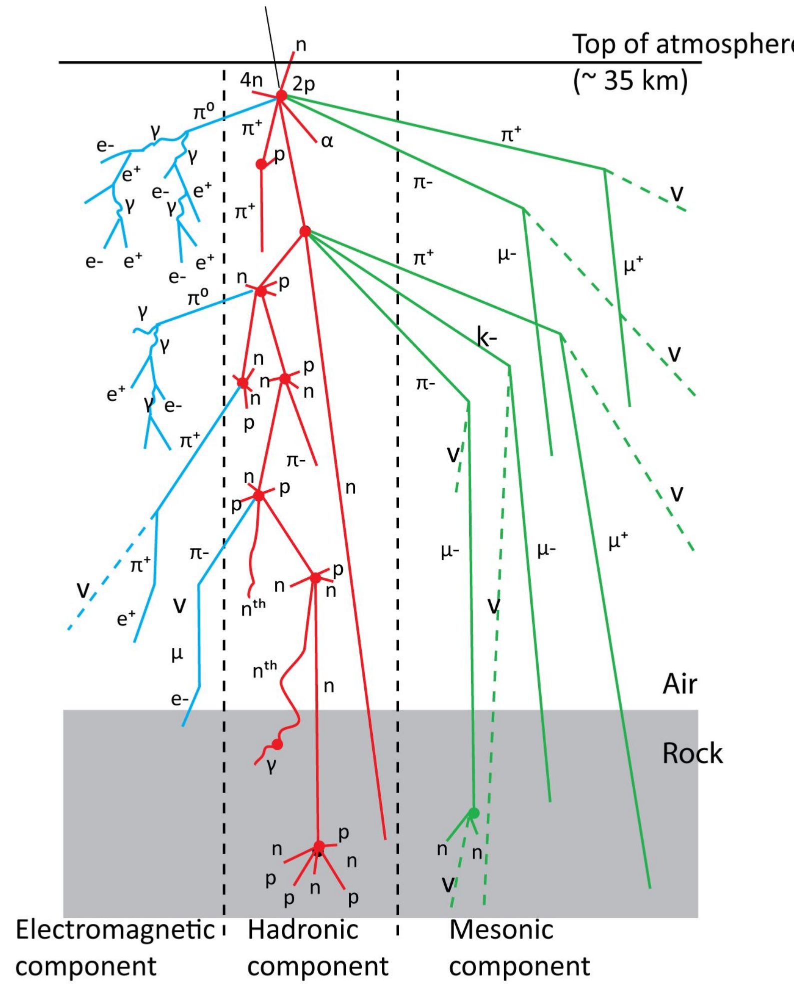
LA-UR-22-25347

Cosmogenic Induced Background Sources

- Cosmogenic radiation created when high energy particles interact with the atmosphere.
- Most components can be shielded
  - Heavy shielding (surface)
  - Rock (Underground)
- Deep penetrating components are:
  - Neutrinos
  - Muons
  - Neutrons

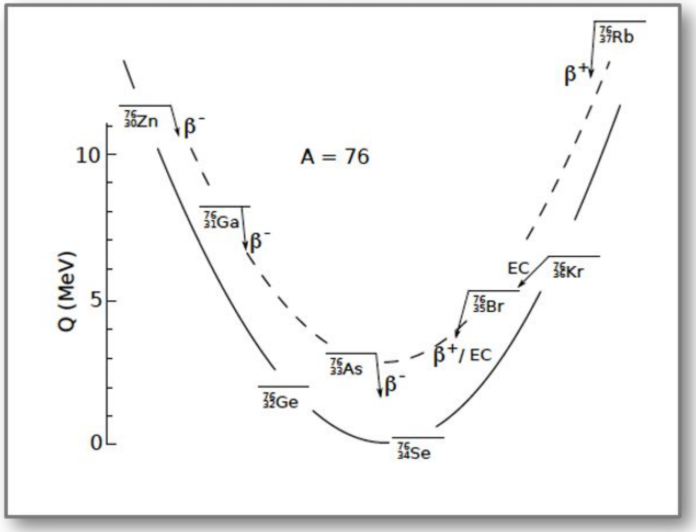


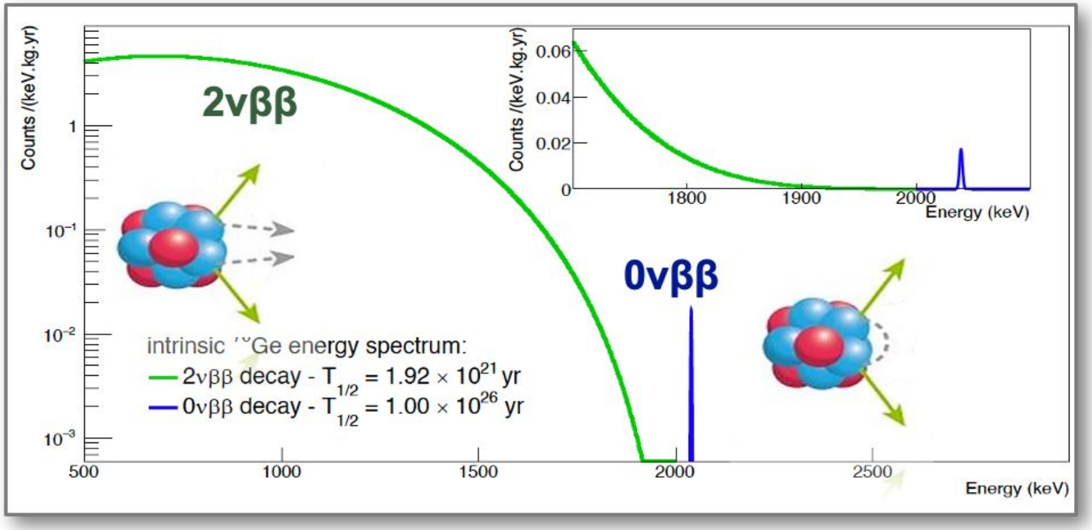
LEGEND pCDR arXiv: 2107.11462



From antarcticglaciers.org

Neutrinoless Double Beta-Decay





- Double-beta decay is observable when energetically favored, e.g. single β-decay to neighbors not possible
- Neutrinoless double-beta decay 0νββ searches:
  - Test if lepton number violating processes exist (violation by ΔL = 2)
  - Probe the Majorana or Dirac nature of massive neutrinos
  - Allow to shed light on neutrino mass scale (if observed)
  - Can in combination with leptogenesis give hint to observed matter-antimatter asymmetry

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

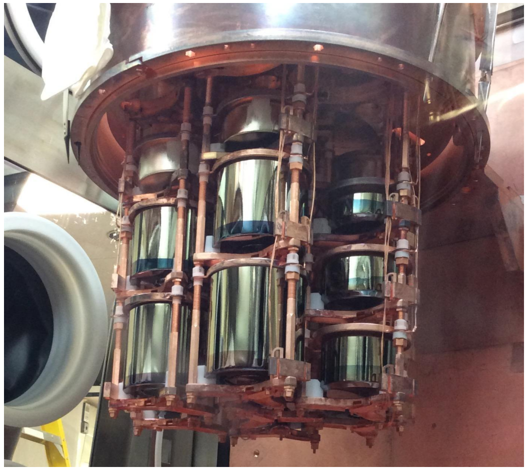
Phase Space Factor

Nuclear Matrix Element

Effective Neutrino Mass

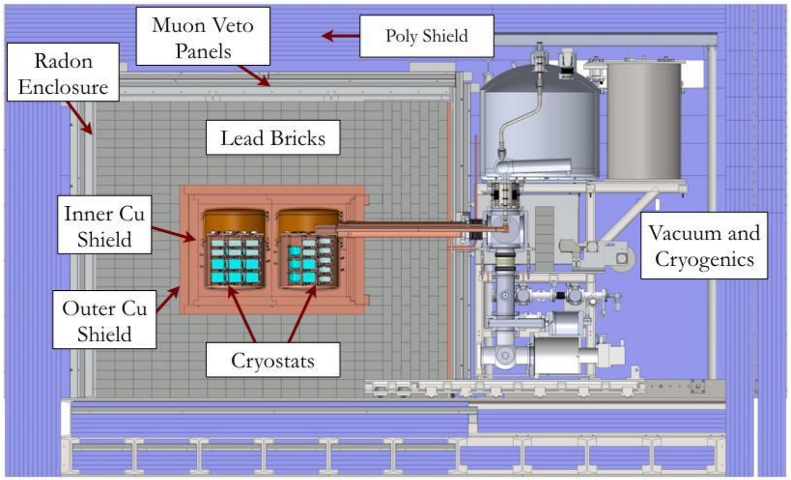
THE MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment



- **Source & Detector:**
  - Array of p-type, point contact detectors 30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals
  - Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run
- **Excellent Energy Resolution**: 2.5 keV FWHM @ 2039 keV
- **Analysis Threshold:** 1 keV
- **Low Background:** 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS

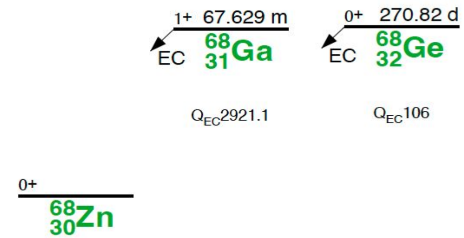


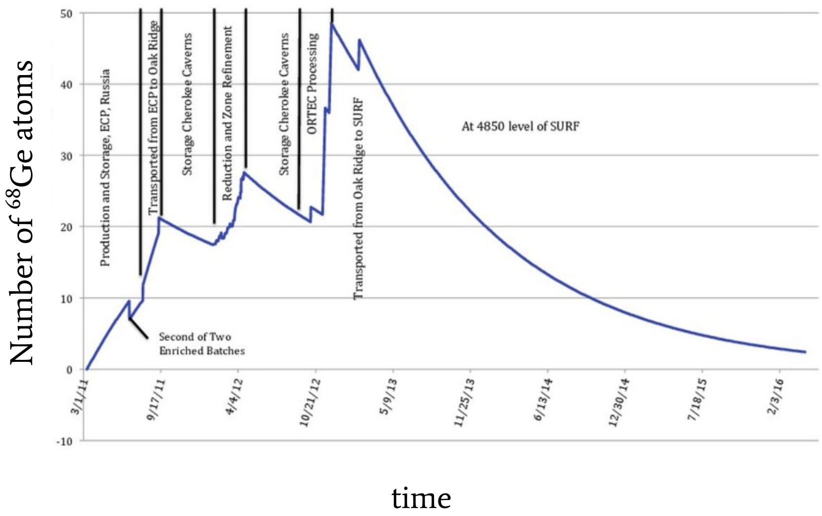
Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics (^{180m}Ta decay search, see Poster Sam Schleich)

Minimizing The Surface Exposure

NIM A 877 (2018) 314,
EPJ C 75 (2015) 39

- Production and transport on surface exposes Ge-crystals to cosmogenic flux
- Production of various (mostly) short lived isotopes
- ^{68}Ge is a known issue
  - long-half-life of 271 days
  - Daughter Q-value spans over 0νββ-ROI
- Other isotopes limit searches for BSM physics
- Reduction of surface impact by:
  - Use of shielded shipping containers
  - Minimized surface exposure
  - Underground storage location at vendor sites

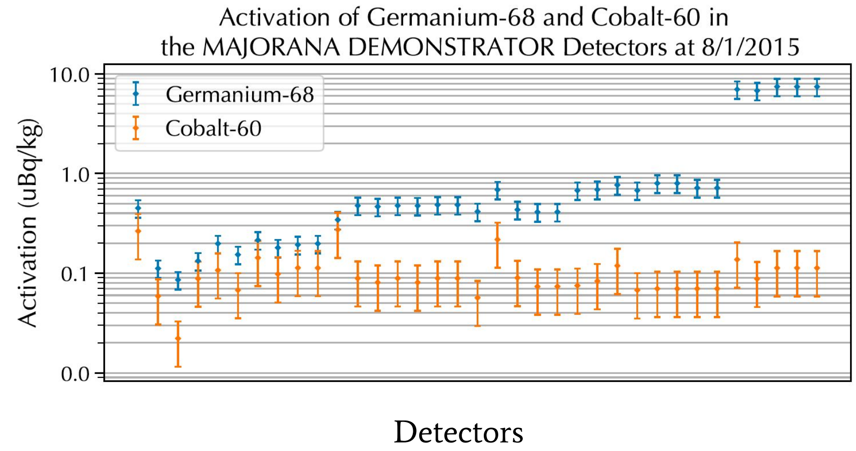


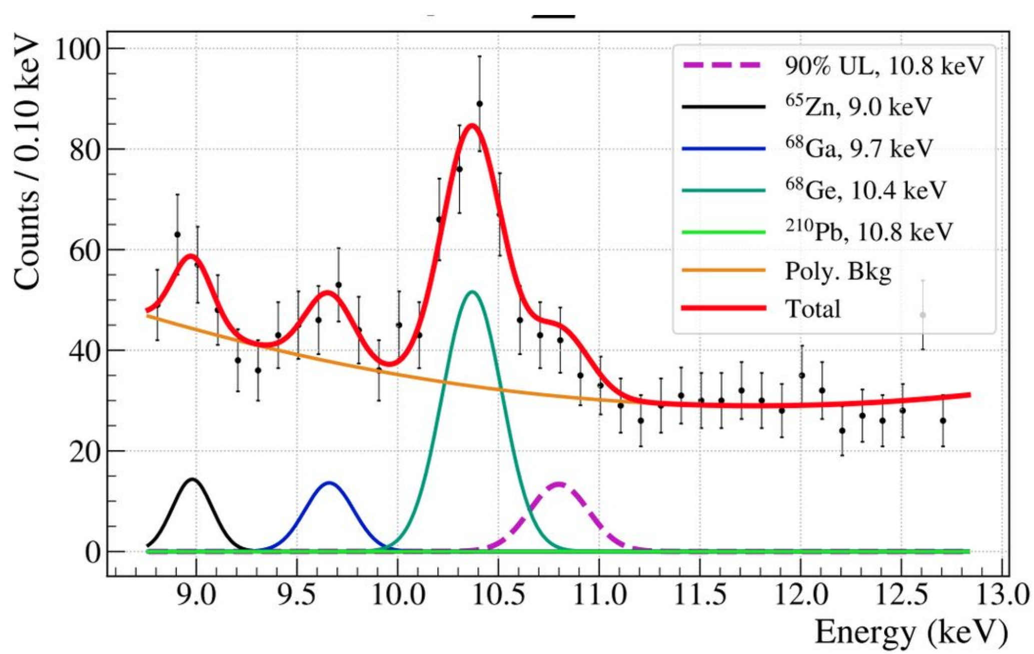


Minimizing The Surface Exposure

NIM A 877 (2018) 314,
EPJ C 75 (2015) 39

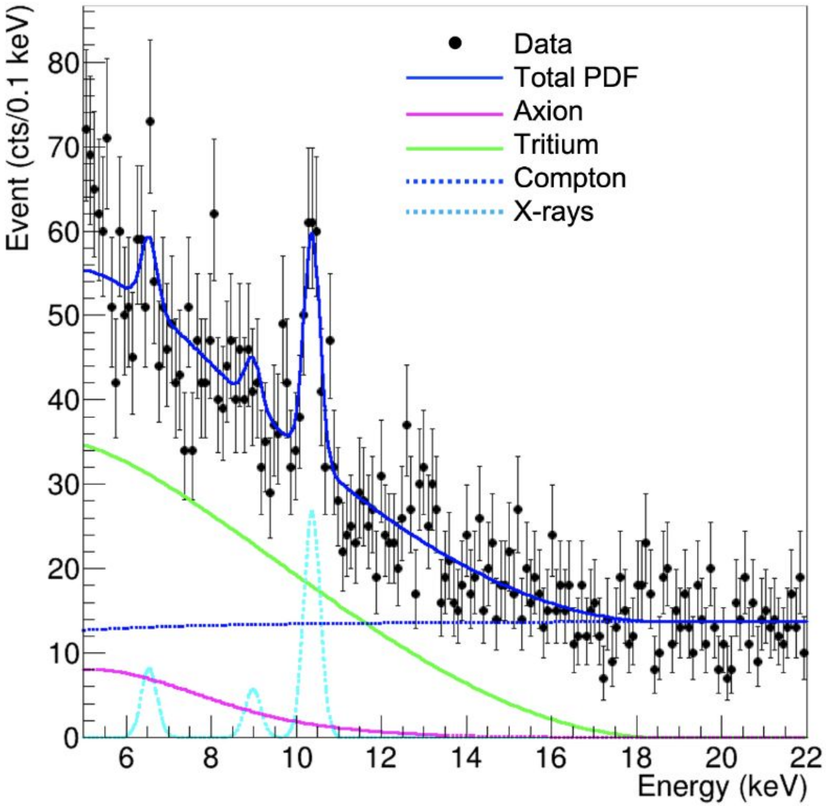
- Production and transport on surface exposes Ge-crystals to cosmogenic flux
- Production of various (mostly) short lived isotopes
- ^{68}Ge is a known issue
  - long-half-life of 271 days
  - Daughter Q-value spans over $0\nu\beta\beta$-ROI
- Other isotopes limit searches for BSM physics
- Reduction of surface impact by:
  - Use of shielded shipping containers
  - Minimized surface exposure
  - Underground storage location at vendor sites

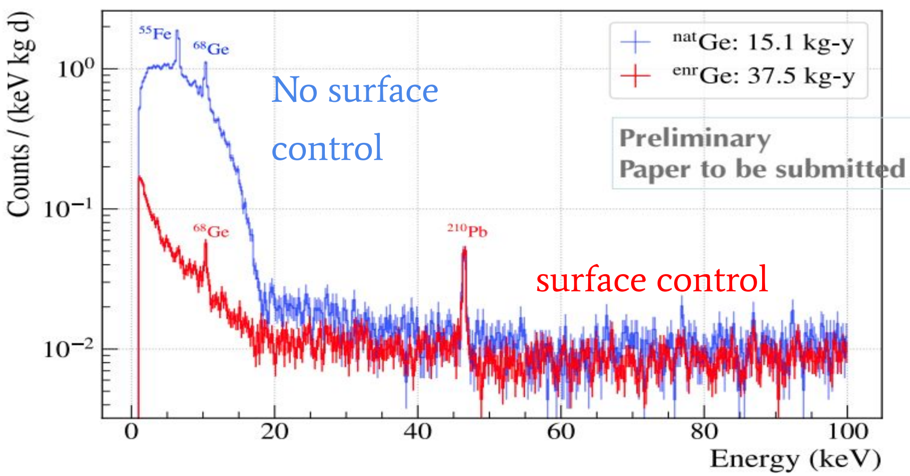




Searches Beyond The Standard Model in MJD

- Clear identification of decay signatures at low energies
- Enriched (surface exposure controlled) detector show le contributions by ^{3}H and other isotopes
- Allows competitive searches with small exposures
  - Fermionic Dark Matter
  - Bosonic Dark Matter
  - Sterile Neutrino
  - Solar Axions
  - Fractional Charge Particles
  - Other BSM physics like
    Pauli Exclusion Principle violation or
    Wave Function Collapse





C. Wiseman
NDM 2022

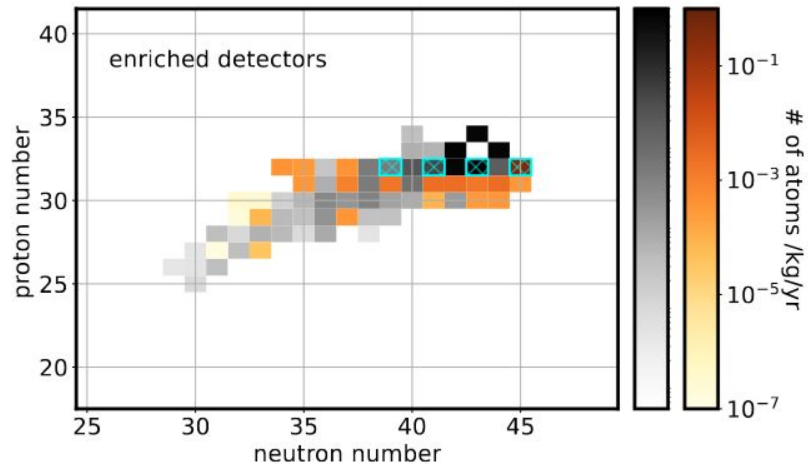
To be submitted

arxiv 2206.05789

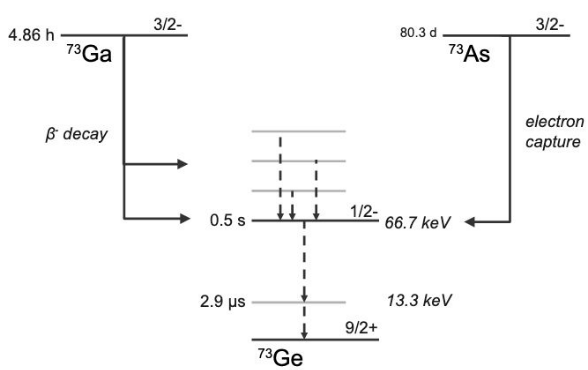
arxiv 2202.01343

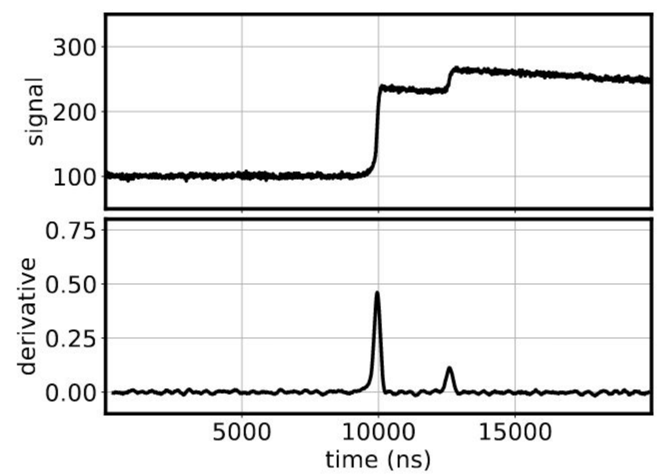
In-Situ Cosmogenic Production

- Production Deep Underground driven by muons and secondary particles from showers (in rock, shielding materials)
- 99.9% within 1 s
- Heavy Z-shield (Lead) increase the production of showers
- Wide-range of isotopes created
- Complex simulations
  - High-energy muons (up to several hundred GeV)
  - Various materials
  - Various particles in showers (short-lived, γ, α, n ...)
  - Wide energy range and reaction channels
- Search for meta-stable Ge isotopes
  - Ultra low background conditions
  - Excellent energy resolution



PRC 105 (2022) 014617

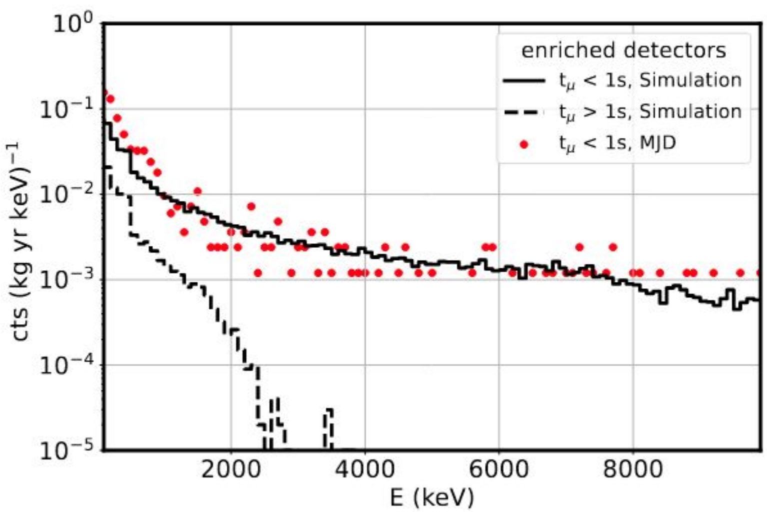


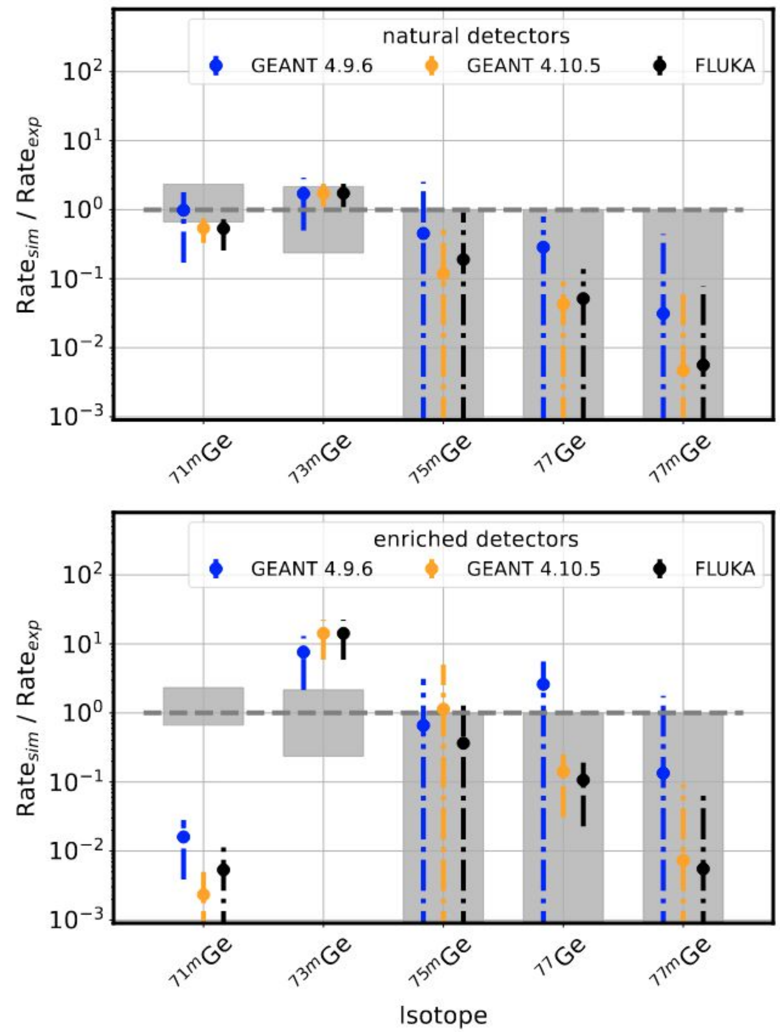


In-Situ Cosmogenic Production

PRC 105 (2022) 014617

- Comparison of simulated and experimental isotope rate
- Mostly neutron driven reactions
- Sensitivity to fast (^{71}Ge & ^{73}Ge) and slow (^{75}Ge & ^{77}Ge) neutrons
- Differences between different simulation codes were identified → **Allows an estimation of uncertainty for simulated results**





Neutrinoless Double Beta Decay Search (NEW)

- **Final** enriched detector active exposure:

  64.5 ± 0.9 kg yrs

- Background Index at 2039 keV:

  6.2 ± 0.6 x 10^{-3} cts / (keV kg yr)

- Only minor contribution by cosmogenics to the 0νββ-ROI

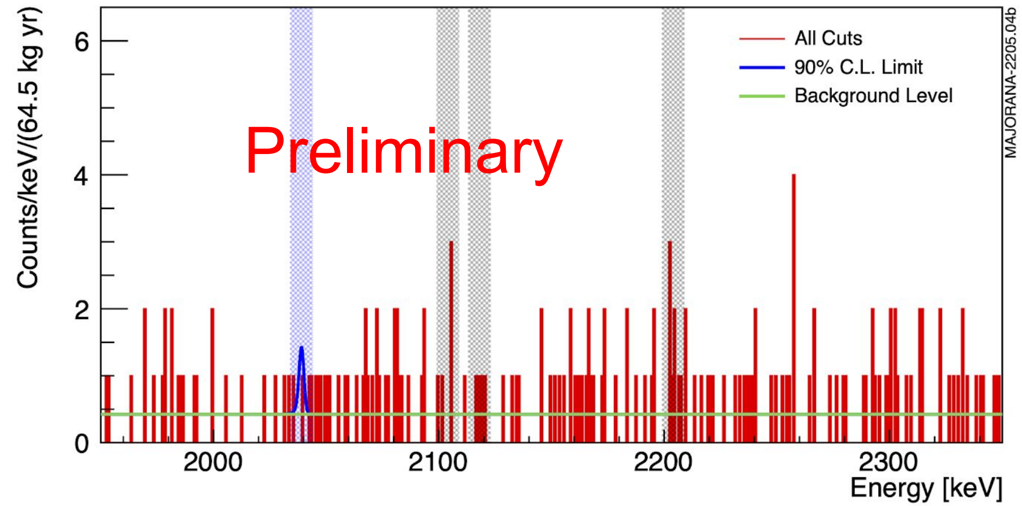
  ~10^{-5} cts / (keV kg yr)

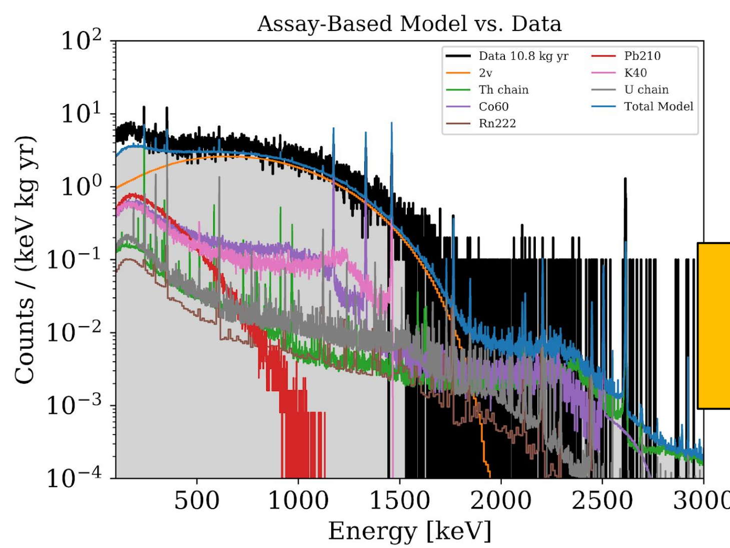
- MJD results for full data set

  8.1×10^{25} yr (90% C.I., sensitivity)

  $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I. limit)

  $m_{\beta\beta}$ < 113 - 269 meV





J. Gruszko Neutrino '22

To be submitted

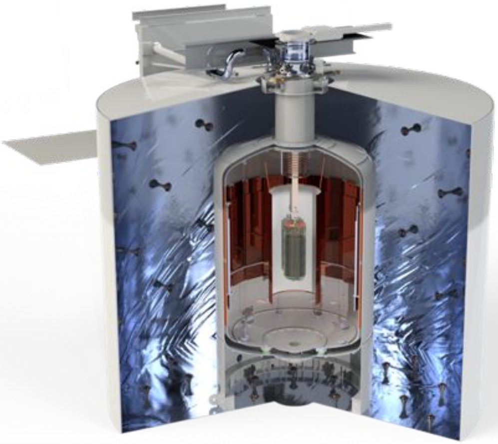
Details see C. Haufe's talk later today

THE NEXT GENERATION:

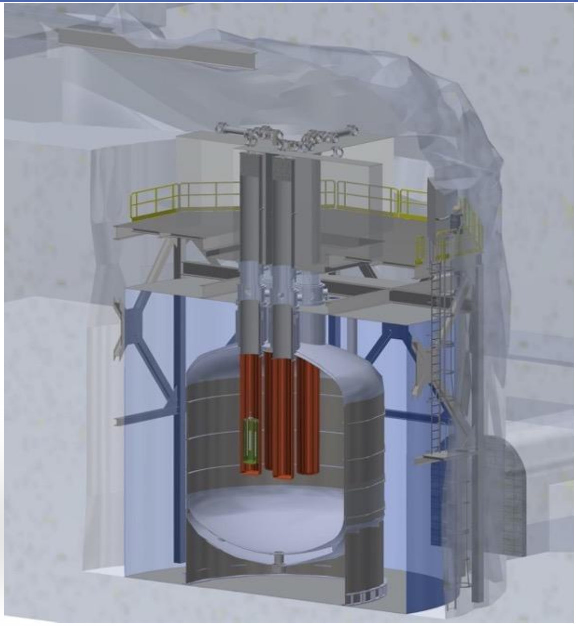
MJD: New final exposure results

GERDA: Final $0\nu\beta\beta$ results published

PRL 125, 252502 (2020)



LEGEND-200: Now in commissioning



LEGEND-1000: Conceptual design development continuing

arXiv: 2107.11462

LEGEND mission: "The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} years**, using existing resources as appropriate to expedite physics results."

The Next Generation:

LEGEND-200:

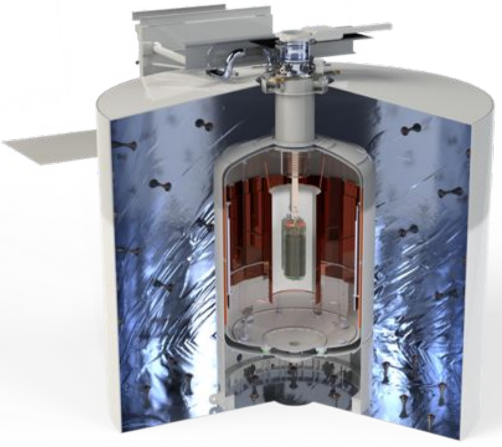
- 200 kg, upgrade of existing GERDA infrastructure at Gran Sasso
- 2.5 keV FWHM resolution
- Background goal

  < 0.6 cts/(FWHM t yr)

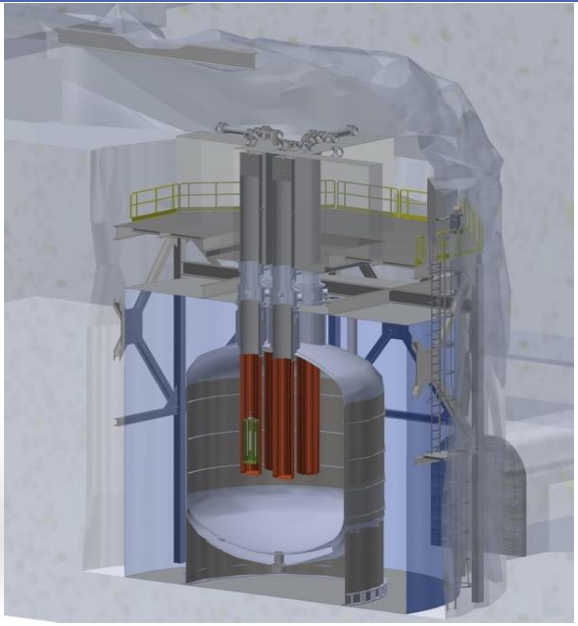
  < $2\text{x}10^{-4}$ cts/(keV kg yr)
- Now in commissioning, physics data starting in 2022

LEGEND-1000:

- 1000 kg, staged via individual payloads (~400 detectors)
- Timeline connected to review process
- Background goal <0.025 cts/(FWHM t yr), <$1\text{x}10^{-5}$ cts/(keV kg yr)
- Location to be selected



LEGEND-200: Now in commissioning



LEGEND-1000: Conceptual design development continuing

arXiv: 2107.11462

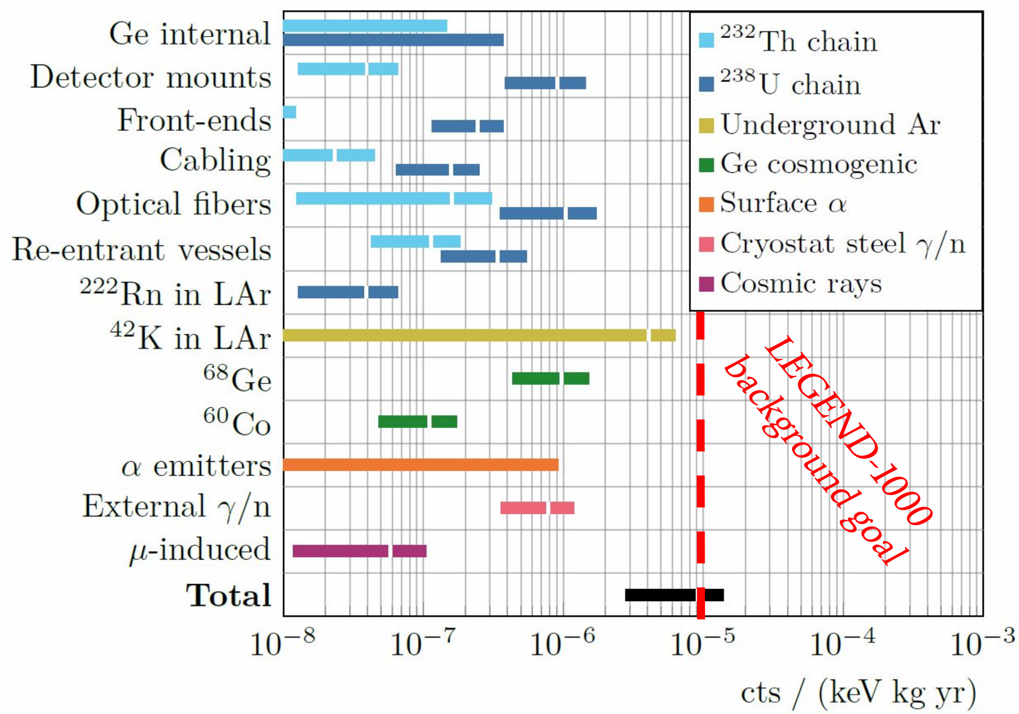
The Next Generation:

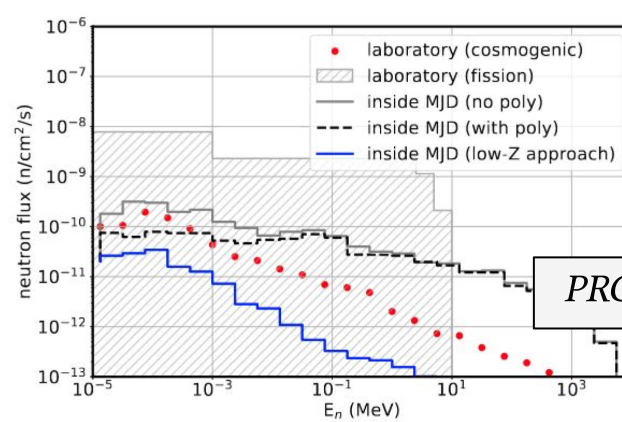
LEGEND:

- Some effects can cause an increase of the cosmogenic background:
  - Larger array (more Ge per μ)
  - Less dense packing (lower multiplicity)
  - Depth

- Several key items and R&D will result in a lower contribution by cosmogenic particles
  - Low-Z Material (reduced shower)
  - Active veto surrounding each detector
  - Depth (SNOLAB)
  - Additional R&D to further reduce effect (LNGS):
    - Neutron tagging
    - Additional neutron moderator

arXiv: 2107.11462

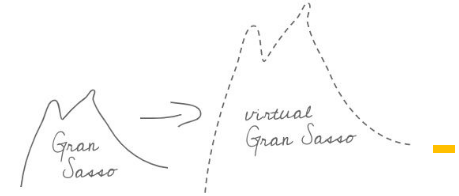




See B. Lehnert's talk later today

PRC 105 (2022) 014617

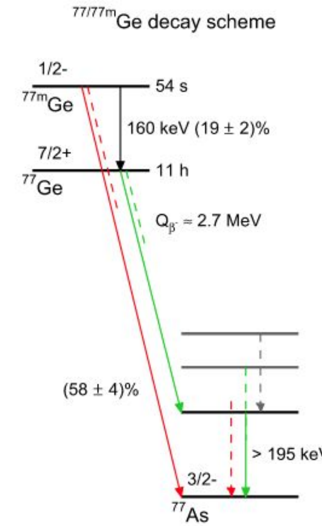
R&D to Achieve a Virtual Depth

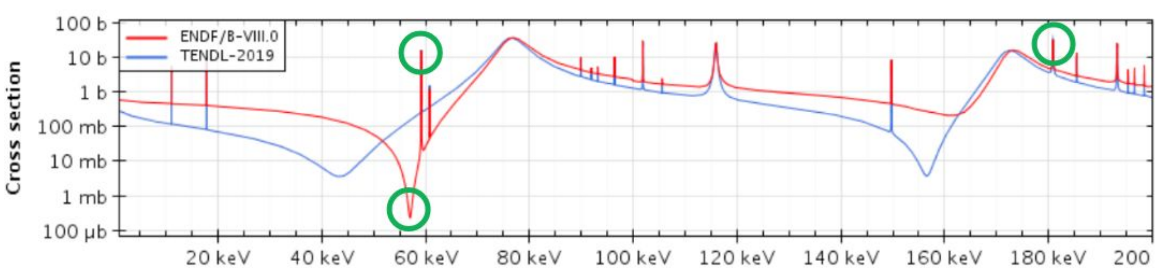


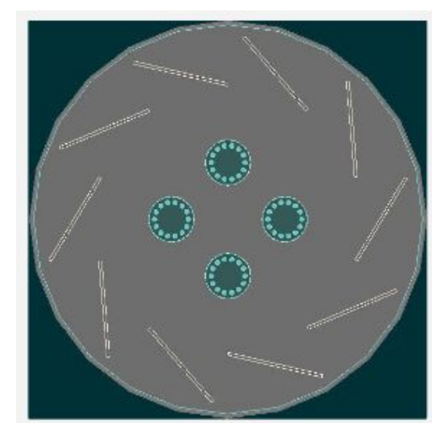
- Goal:
  <u>Reduce in-situ production or contribution of $^{77(m)}$Ge</u>

- **Neutron sibling** tagging
  - Usually high neutron multiplicity within a cosmogenic shower
  - Identify delayed ^{77m}Ge events by coincident events in Argon (tag ^{41}Ar decay) or even a Gd-doped water shield
- **Additional neutron moderating** materials close by
  - Active moderation slows neutrons down
  - Increased neutron capture by Argon (less Ge capture and more vetoing of sibling)
  - Optimization between newly introduced radiogenic background vs moderation effect

EPJ C 78 (2018) 597







Work by C. Wiesinger, M. Neuberger, CJ Barton, I. Costa, M. Morella and others

SUMMARY

- Creation of radioisotopes in germanium crystals is a potential background
  - ^{68}Ge (on surface)
  - $^{77(m)}$Ge (in-situ)
- Mitigation by short transport times and shielding on surface
- Active vetoing allows suppression of prompt in-situ background
- Delayed decays can be suppressed by delayed coincidence tagging techniques
- Additional R&D that makes use of shower characteristics and "over moderation" to avoid and tag $^{77(m)}$Ge contributions

Majorana Collaboration

Duke University, Durham, NC, and TUNL:
Matthew Busch

Indiana University, Bloomington, IN:
Walter Pettus

Joint Institute for Nuclear Research, Dubna, Russia:
Sergey Vasilyev

Lawrence Berkeley National Laboratory, Berkeley, CA:
Yuen-Dat Chan, Alan Poon

Los Alamos National Laboratory, Los Alamos, NM:
Pinghan Chu, Steven Elliott, In Wook Kim, Ralph Massarczyk, Samuel J. Meijer, Keith Rielage, Danielle Schaper, Brian Zhu

National Research Center Moscow, Russia:
Alexander Barabash

North Carolina State University, Raleigh, NC and TUNL:
Matthew P. Green, Ethan Blalock, Rushabh Gala

Oak Ridge National Laboratory, Oak Ridge, TN:
Vincente Guiseppe, Charlie Havener, José Mariano López-Castaño, David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan:
Hiroyasu Ejiri

Pacific Northwest National Laboratory, Richland, WA:
Isaac Arnquist, Maria-Laura di Vacri, Eric Hoppe, Richard T. Kouzes

Queen's University, Kingston, Canada:
Ryan Martin

South Dakota Mines, Rapid City, SD:
Cabot-Ann Christofferson, Jessica Peterson, Ana Carolina Sousa Ribeiro, Jared Thompson

Technische Universität München, and Max Planck Institute, Munich, Germany:
Susanne Mertens

Tennessee Tech University, Cookeville, TN:
Mary Kidd

University of North Carolina, Chapel Hill, NC, and TUNL:
Kevin Bhimani, Brady Bos, Thomas Caldwell, Morgan Clark, Aaron Engelhardt, Julieta Gruszko, Ian Guinn, Chris Haufe, Reyco Henning, David Hervas, Aobo Li, Eric Martin, Gulden Othman, Anna Reine, Jackson Waters, John F. Wilkerson

University of South Carolina, Columbia, SC:
Franklin Adams, Frank Avignone, Thomas Lannen, David Tedeschi

University of South Dakota, Vermillion, SD:
C.J. Barton, Laxman Paudel, Tupendra Oli, Wenqin Xu

University of Tennessee, Knoxville, TN:
Yuri Efremenko

University of Washington, Seattle, WA:
Micah Buuck, Clara Cuesta, Jason Detwiler, Alexandru Hostiuc, Nick Ruof, Clint Wiseman

Williams College, Williamstown, MA:
Graham K. Giovanetti