LEGEND: The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay

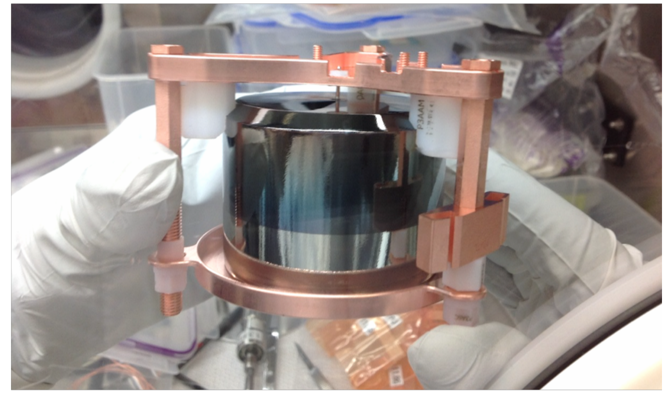
Julieta Gruszko on behalf of the LEGEND Collaboration

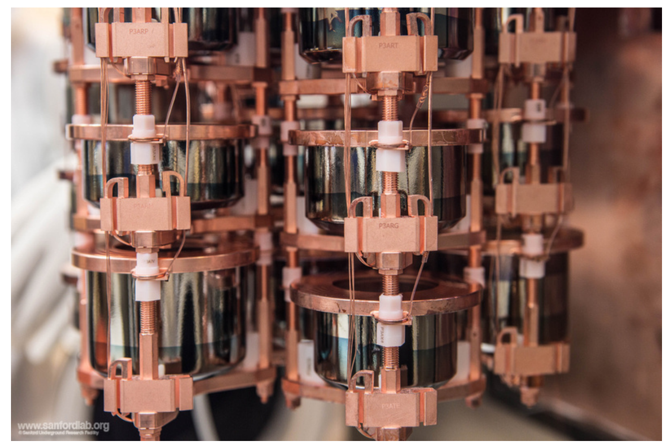
Massachusetts Institute of Technology

March 7, 2019

Why Use ^{76}Ge?

- High-Purity Ge (HPGe) detectors: intrinsically low background, high efficiency
- Excellent energy resolution: 2.5 keV FWHM @ 2039 keV ($Q_{\beta\beta}$)
- Demonstrated ability to enrich to > 87%
- Scalable technology: significant commercial market for HPGe detectors
- Background rejection capabilities:
  - Multiplicity-based rejection in arrays
  - Multi-site event rejection
  - Surface event rejection





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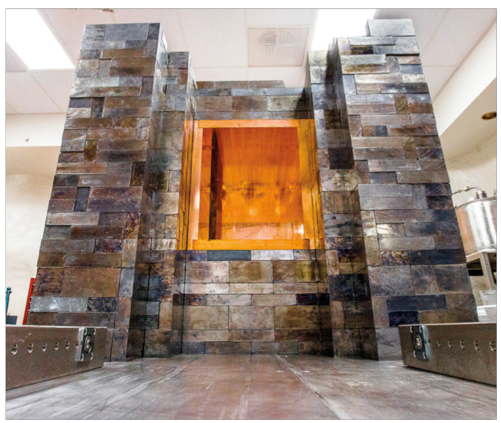
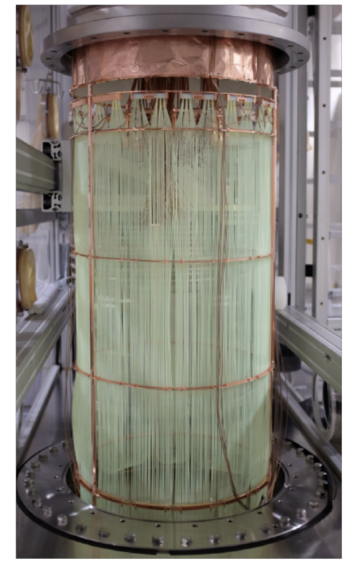
Currently-Operating Experiments



The MAJORANA DEMONSTRATOR

- Traditional approach: vacuum cryostats in passive shield, ultra-clean materials



GERDA

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- Novel configuration: bare crystals in LAr active veto

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P-PC Background Rejection: Multi-Site Events

- P-type Point Contact (P-PC) detectors:
  - Optimize noise performance w/ ~1kg masses
  - Pulse shape highly dependent on position
    → multi-site pulse shape discrimination (PSD)
  - Reduces Compton BG by 60% with 90% signal efficiency

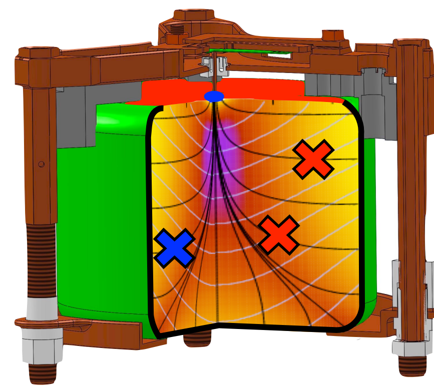
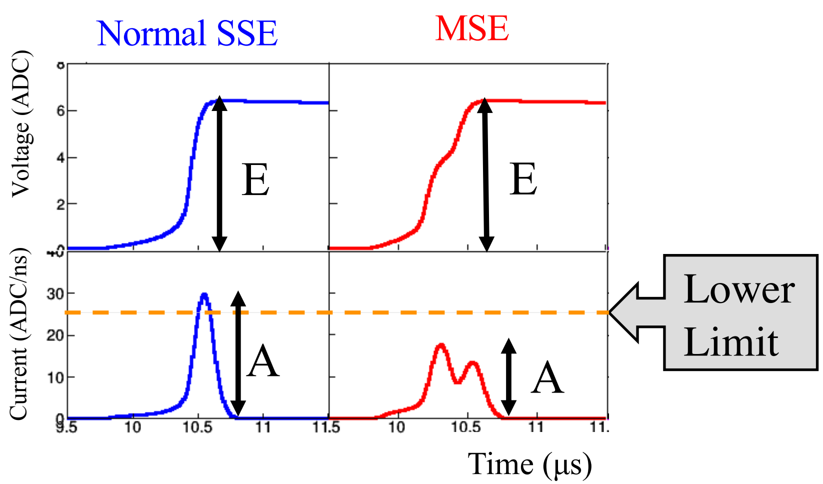
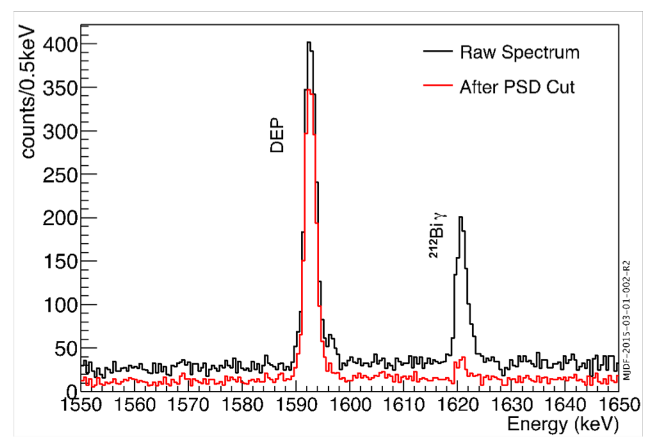


Fig. courtesy of C. Wiseman





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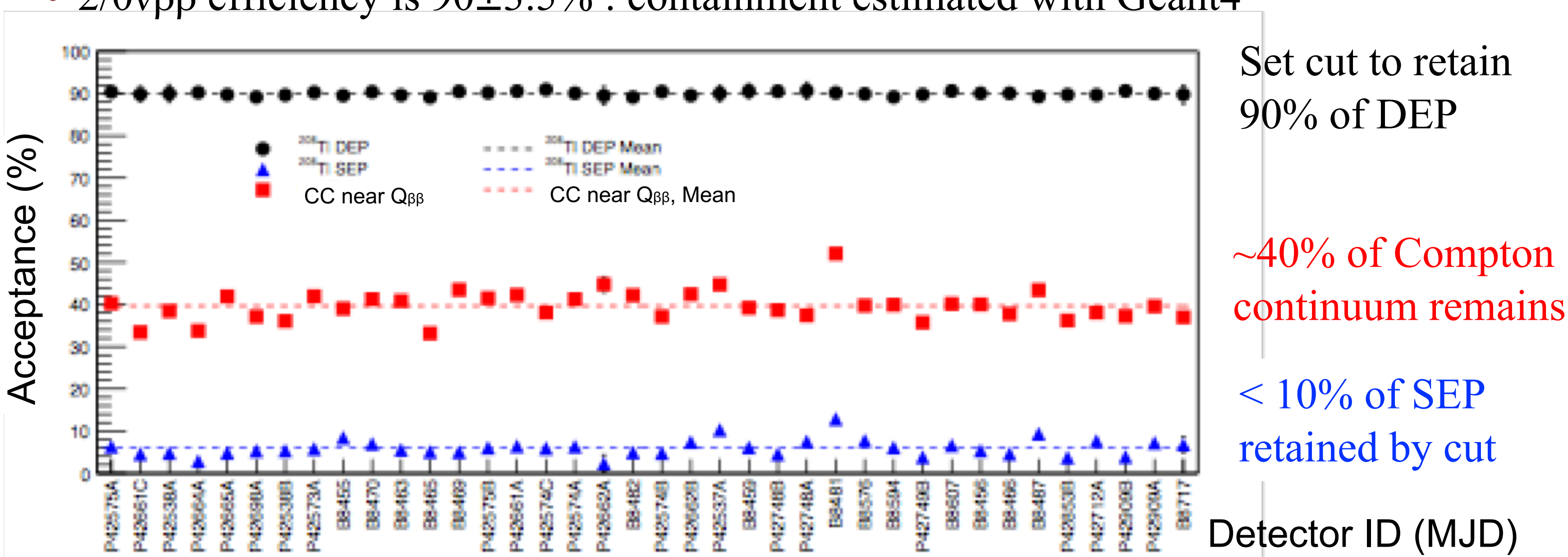
MJD, arXiv:1901.05388

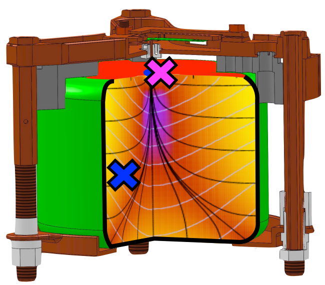
GERDA, Eur. Phys. J. C **73**, 2583 (2013)

Multi-site Rejection: Calibration and Performance

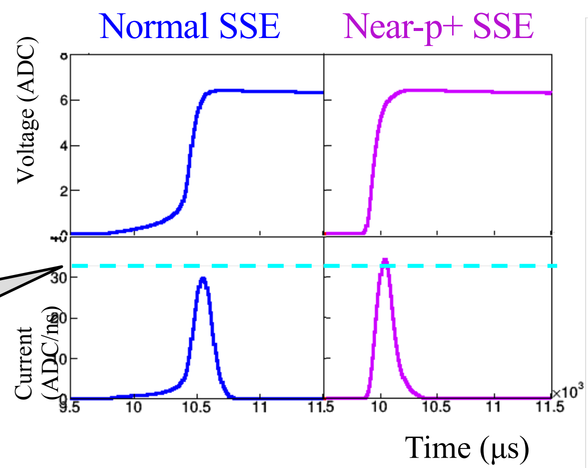
- Use pair-production events from 2614 keV γ from ^{208}Tl decay to calibrate:
  - $e^{\pm}$ have short range, e^{+} annihiliates to 2 γ's
  - DEP: both γ's escape, known single-site event
  - SEP: one γ escapes, known multi-site event
- Other γ lines reduced by a factor of 10-20, Compton BG reduced by 60%
- Check energy dependence with ^{56}Co calibration (MJD analysis is underway)
- 2/0νββ efficiency is 90±3.5% : containment estimated with Geant4



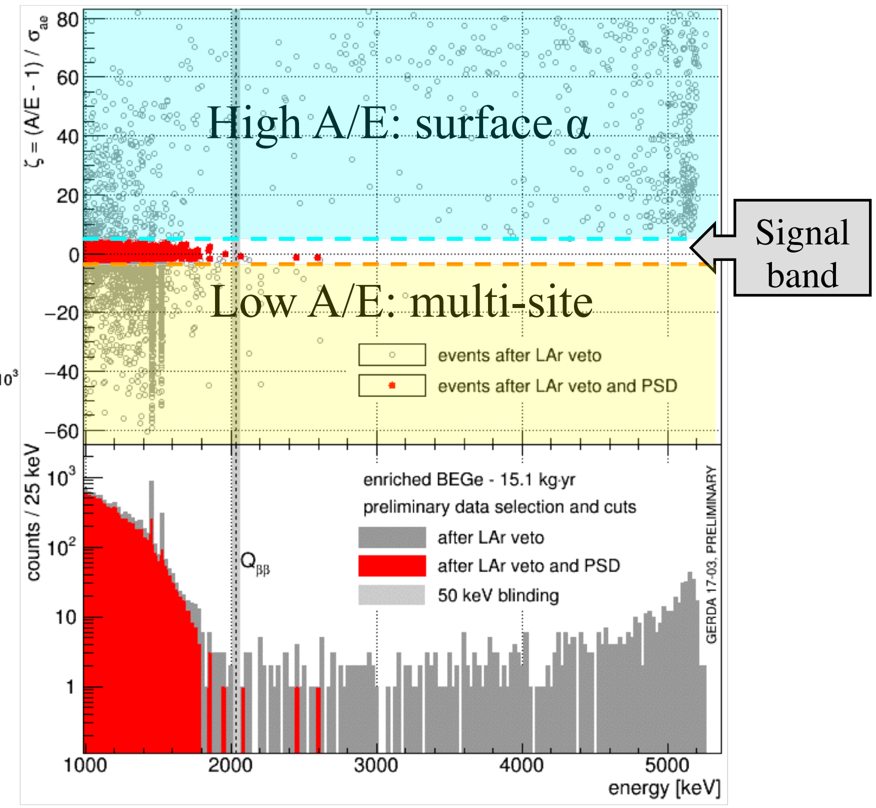
P-PC Background Rejection: Surface Events, GERDA-Style



Upper Limit



GERDA Phase II, J. Janicsko MEDEX'17



- Only the passivated surface and p+ contact are thin and α-sensitive
- In GERDA P-PCs, passivated surface radius is small
- A/E eliminates α's with 98% signal eff.

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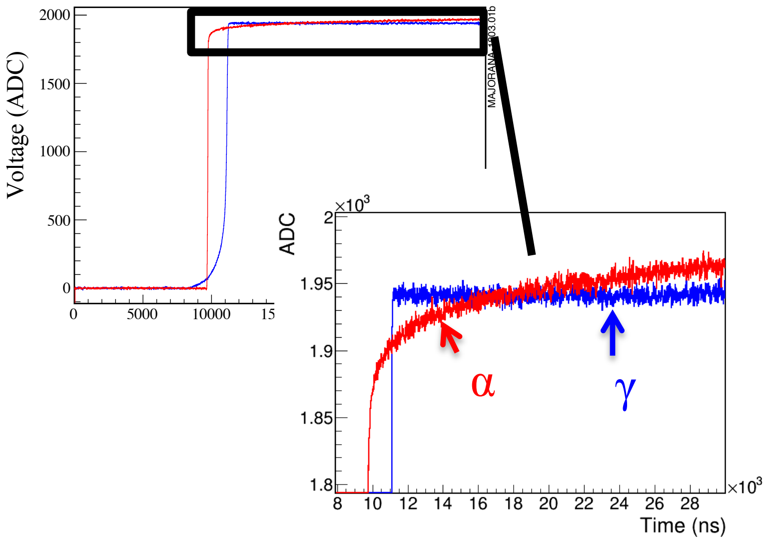
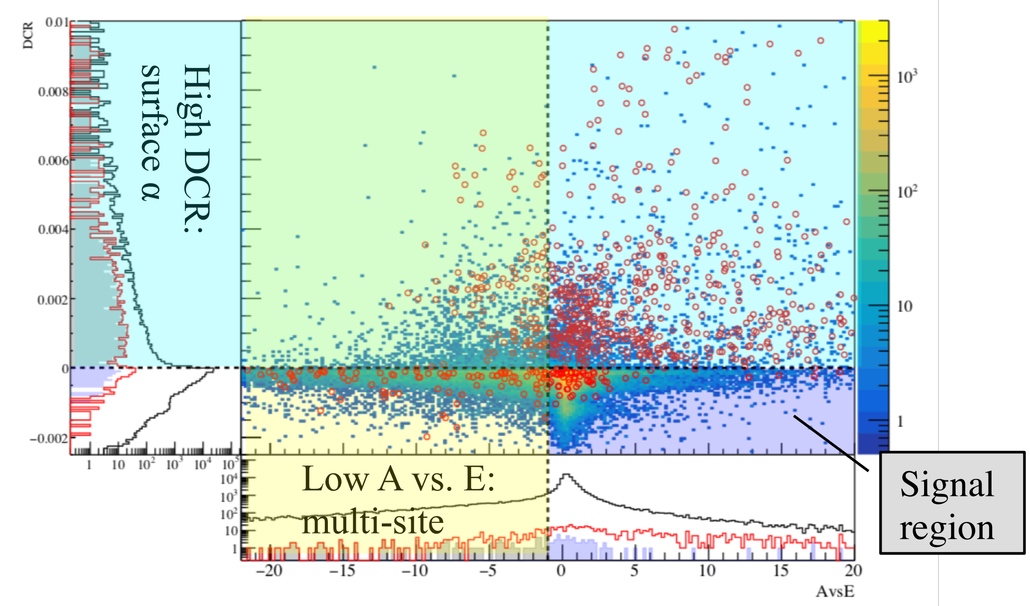
P-PC Background Rejection: Surface Events, MJD-Style





- In MJD P-PCs, passivated surface is large: GERDA-style cut has high signal sacrifice
- Surface alphas are degraded in energy; charge is being trapped
- Trapped charge is collected more slowly
- Delayed charge recovery PSD cuts 99% of alphas in ROI with 99% signal efficiency

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See **Gruszko, J.**, & Detwiler, Jason A. (2017). *Surface alpha interactions in P-Type point-contact HPGe detectors : Maximizing sensitivity of ^{76}Ge neutrinoless double-beta decay searches*. Seattle, University of Washington.

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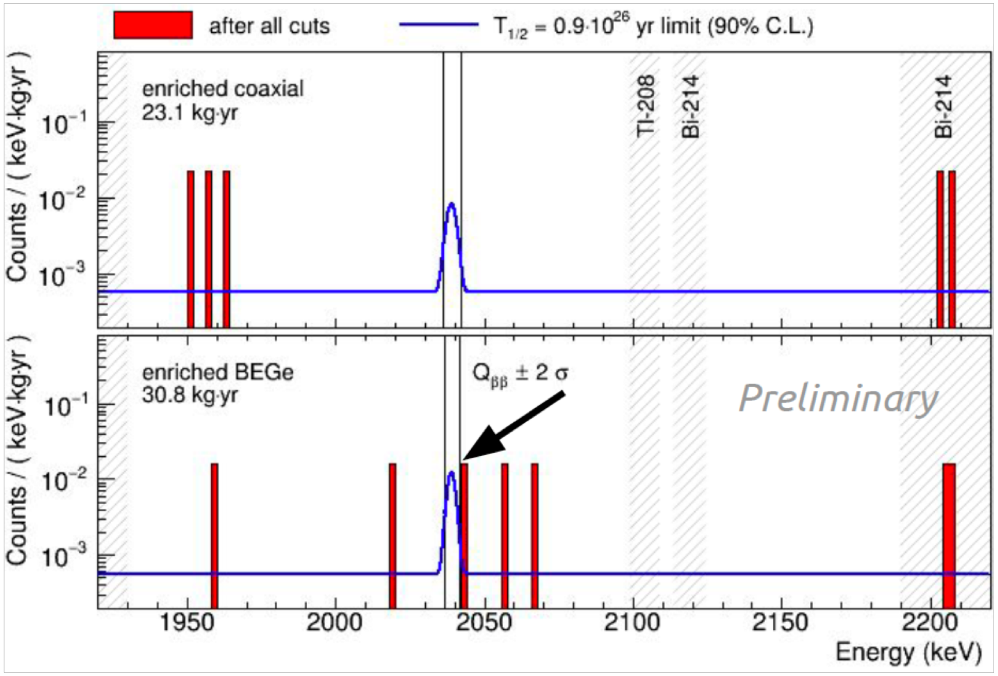
Recent Results: GERDA



- **Phase II BG Index:**

  $\mathbf{0.6^{+0.4}_{-0.2} \times 10^{-3}}$ **cnts/keV/kg/yr**

  $\mathbf{\sim 1.8^{+1.2}_{-0.6}}$ **cnts/FWHM/t/yr**

- Phase II Exposure: 58.9 kg-y
- Total Exposure:
- Resolution (FWHM): 3.0 keV @ $Q_{\beta\beta}$

From combined exposure:

- Sensitivity: 1.1 x 10^{26} yr (90% CL)
- Limit: $T_{1/2} > 0.9 \times 10^{26}$ yr (90% CL)

See "New Results from GERDA Phase II," A. J. Zsigmond, Neutrino 2018

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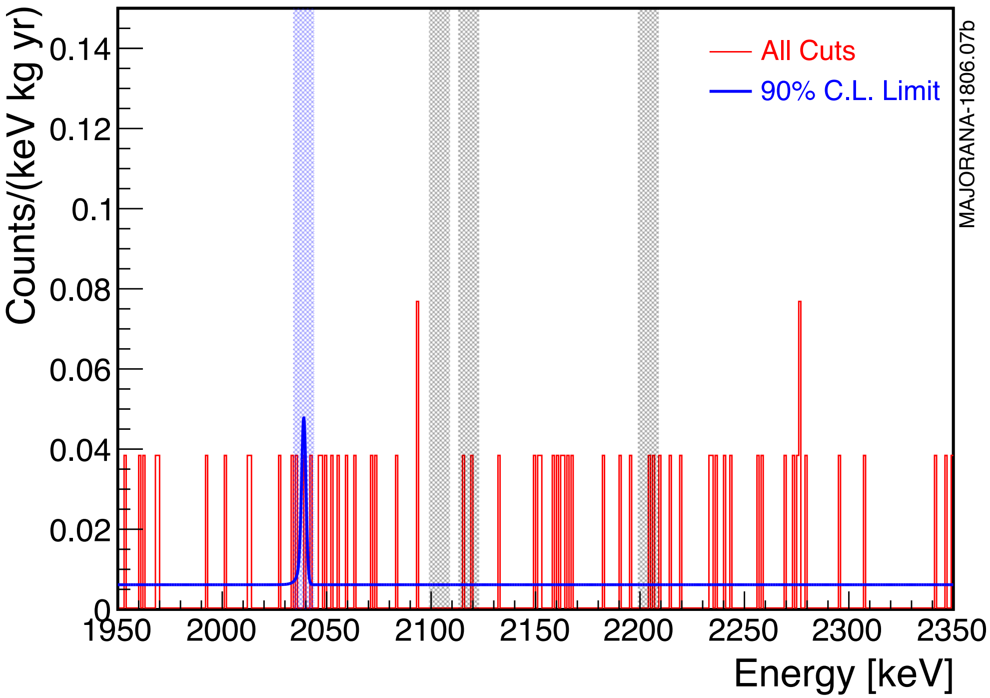
Recent Results: MAJORANA



- BG Index (for low-BG data sets):

  $4.7 \pm 0.8 \times 10^{-3}$ cnts/keV/kg/yr

  $\sim 11.9 \pm 2.0$ cnts/FWHM/t/yr
- Exposure: 26.0 kg-y
- **Resolution (FWHM): 2.5 keV @ $Q_{\beta\beta}$**
- Sensitivity: 4.8 x 10^{25} yr (90% CL)
- Limit: $T_{1/2} > 2.7$ x 10^{25} yr (90% CL)

See arXiv:1902.02299

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LEGEND: The Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay

Mission statement

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.*

47 Institutions,
250 Scientists,
worldwide

Univ. New Mexico
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Inst. Nucl. Res. Inst.
Nucl. Res. Russian Acad. Sci.

Joint Res. Centre, Geel
Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ.
Queens Univ.

Univ. Tennessee
Argonne Natl. lab.
Univ. Liverpool
Univ. College London
Los Alamos Natl. Lab.

Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Natl. Res. Center Kurchatov Inst.
Lab. for Exper. Nucl. Phy. MEPhI
Max Planck Inst., Munich
Tech. Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich

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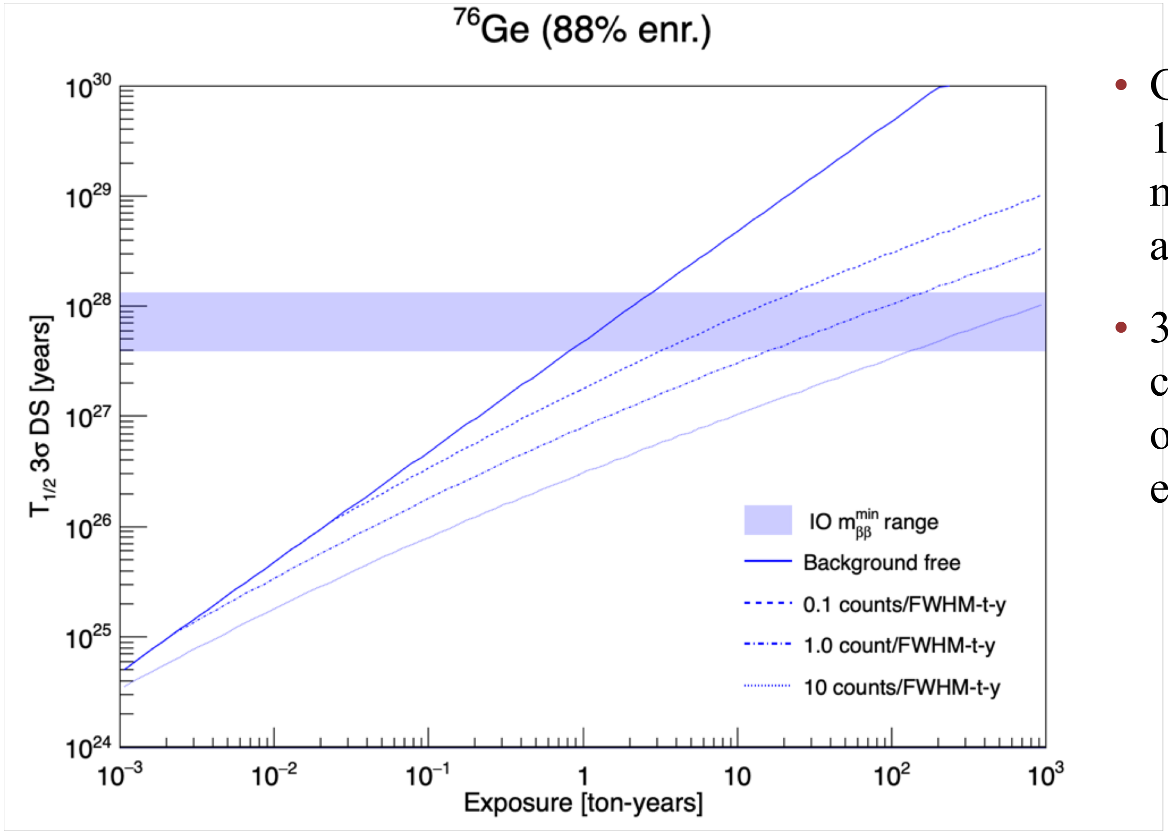
Discovery…



- Goal: $T_{1/2} > 10^{28}$ yrs or 17 meV for worst-case matrix element of 3.5 and unquenched g_A
- 3σ discovery level to cover inverted ordering, given matrix element uncertainty

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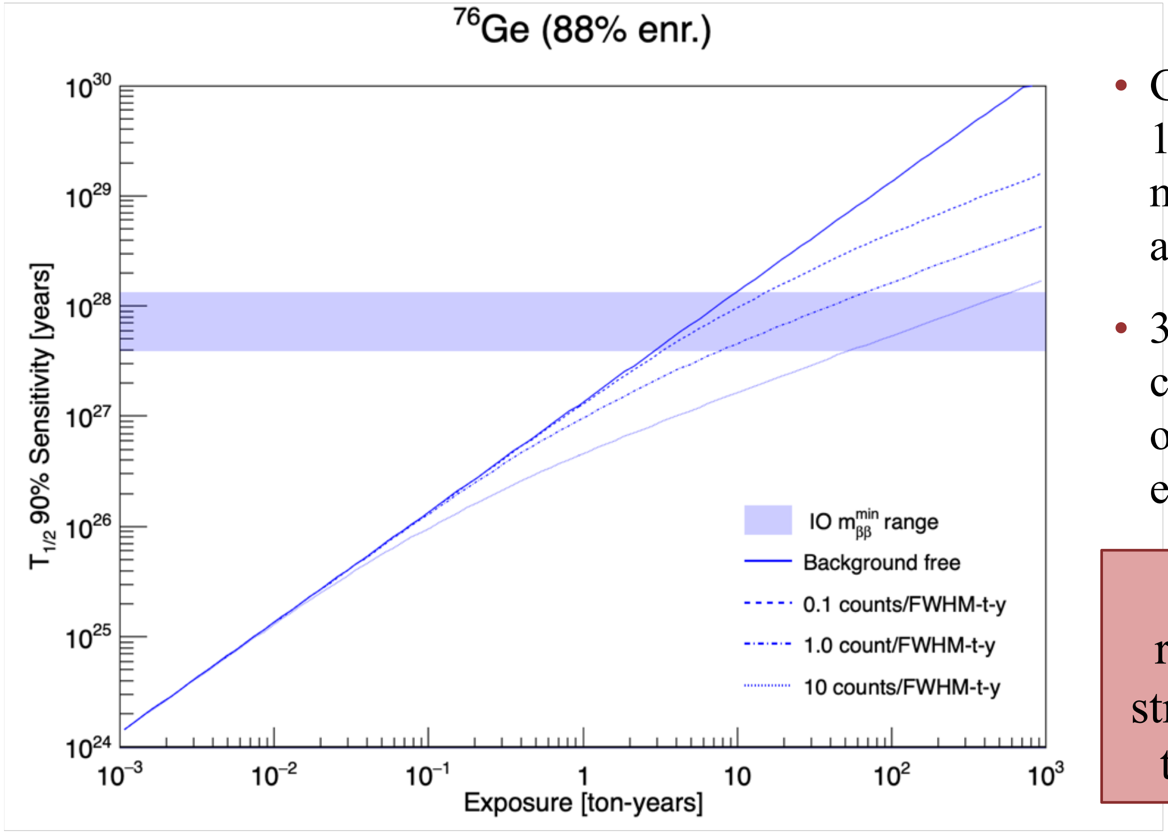
… vs. Sensitivity



- Goal: $T_{1/2} > 10^{28}$ yrs or 17 meV for worst-case matrix element of 3.5 and unquenched g_A
- 3σ discovery level to cover inverted ordering, given matrix element uncertainty

Background requirement is more stringent for discovery than for sensitivity!

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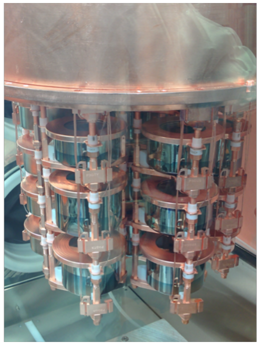
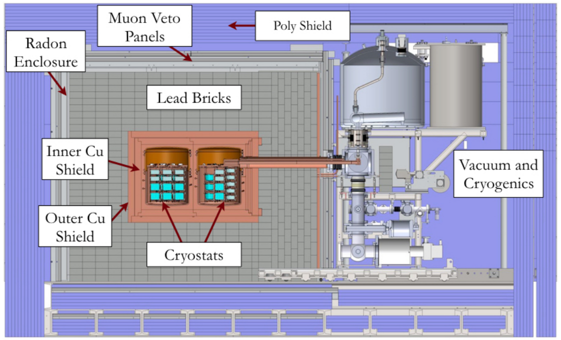
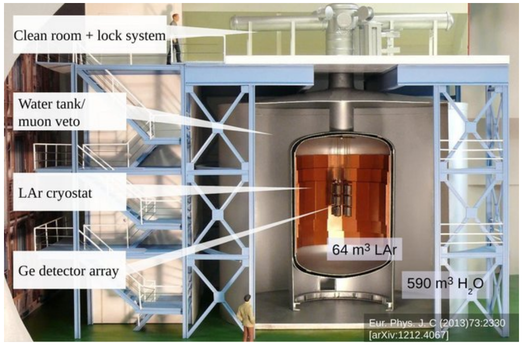
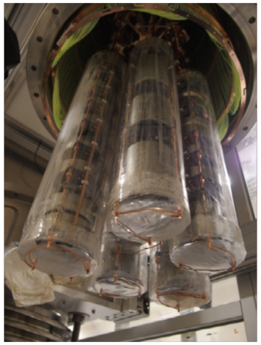
See Matteo Agostini, Giovanni Benato, and Jason A. Detwiler, Phys. Rev. D **96**, 053001 for more discussion

LEGEND Strategy: Best of Both Worlds







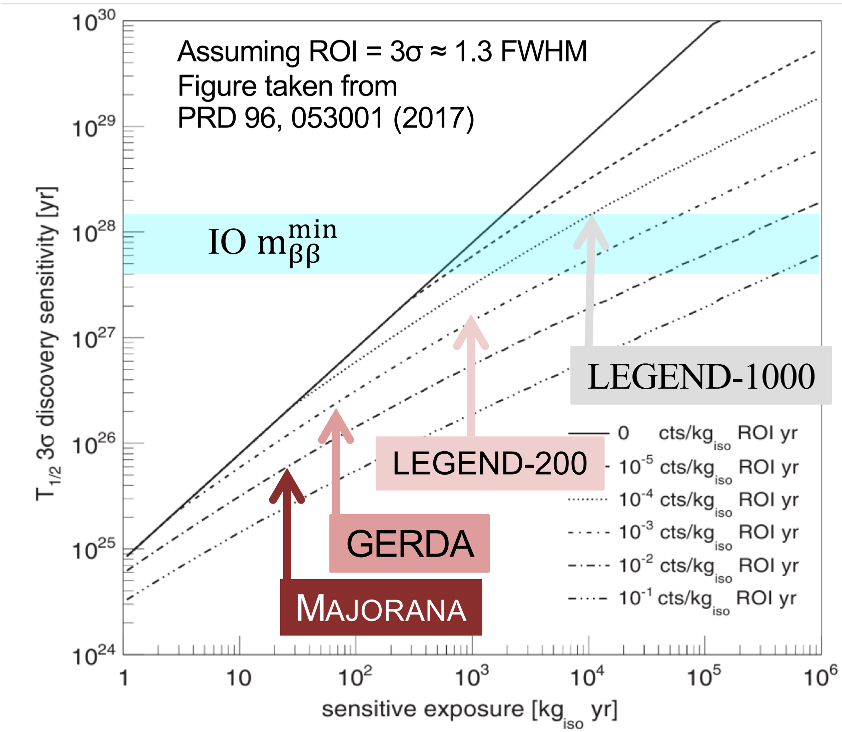


Combine the best of MAJORANA:
- Radiopurity of near-detector parts
- Low-noise electronics enables better PSD
- Low energy threshold

…with the best of GERDA:
- LAr active veto and instrumentation
- Low-A shielding, no Pb

and techniques developed in both experiments:
- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors

LEGEND Strategy: Phased Approach



- 200 kg: Use existing infrastructure to obtain near term physics results
  - Background goal: 0.6 c/(FWHM t yr)
  - Factor of 5 reduction below current best BI
- 1000 kg: New cryostat at new site
  - Background goal: < 0.1 c/(FWHM t yr)
  - Another factor of 6 reduction beyond L200
- Maintain FWHM of 2.5 keV @ $Q_{\beta\beta}$

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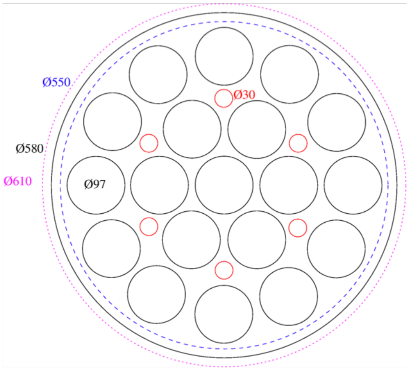
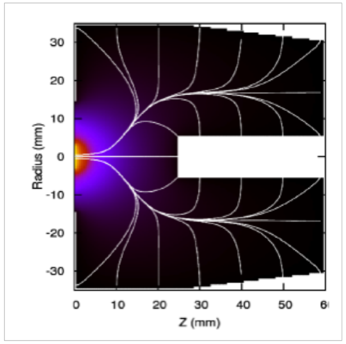
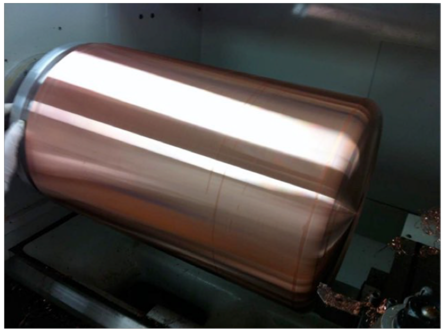
LEGEND-200







- Reuse existing GERDA infrastructure
- Data taking by 2021
- Reduced risk for future experiment, allows for early world-leading results
- Improvements:
  - Larger detectors (1.5 - 4.0 kg)
  - Improved LAr light collection
  - Cleaner, lower mass cables
  - Lower noise electronics
  - UGEFCu for detector mounts

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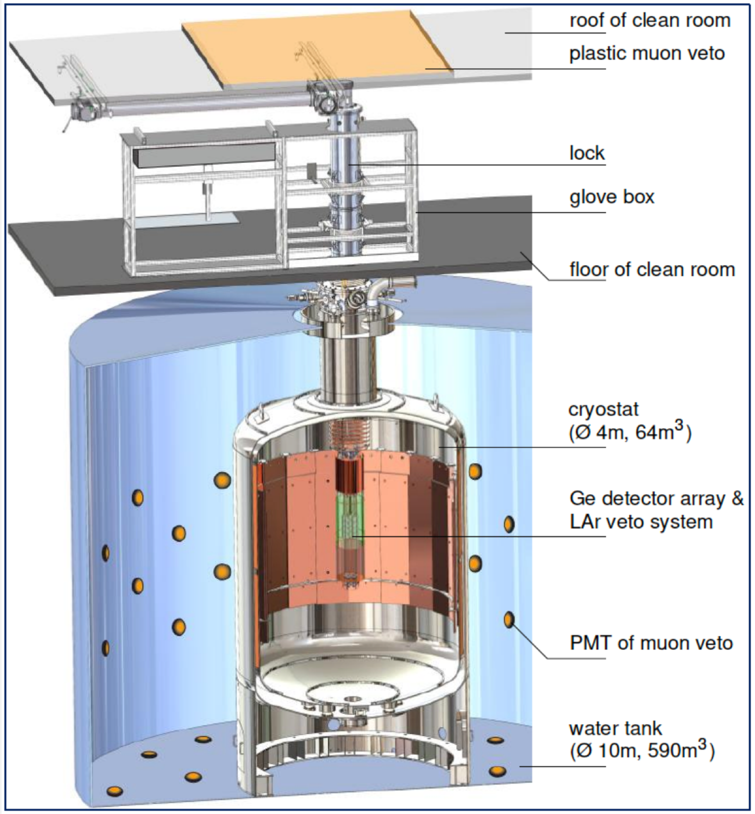
LEGEND-200 Design

- Current GERDA design: 7 strings with 40 detectors total
- Existing cryostat can accommodate 200 kg of detectors: 14 - 19 detector strings
- 60 kg of enriched detectors already exist: PPCs from MJD and GERDA
- Already characterizing the first new detectors



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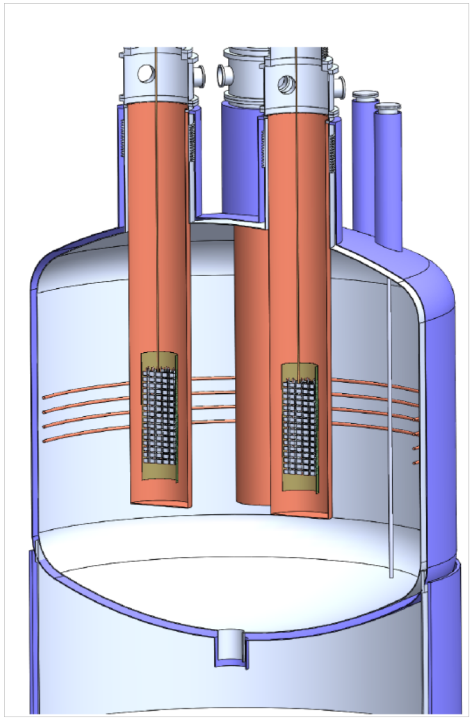
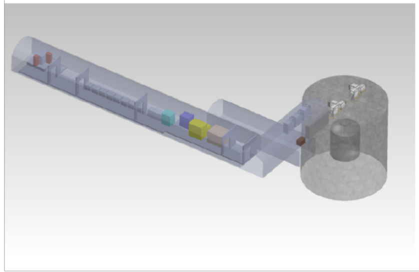
LEGEND-1000

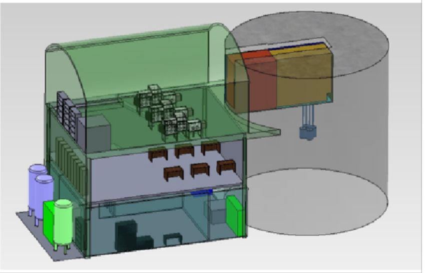


- 300-500 detectors total, 4-5 payloads in LAr cryostat in separate 3m^3 volumes, payload 200/250 kg
- Each payload “independent” with individual lock
- Depleted LAr in inner detector volumes
- Modest-sized LAr cryostat in “water tank” (6 m Ø LAr, 2-2.5 m layer of water) or large LAr cryostat w/o water (9 m Ø) with separate neutron moderator

SNOLAB cryopit concept



Generic Cavity design



- Host lab not yet determined
- Studies of cosmogenic backgrounds underway

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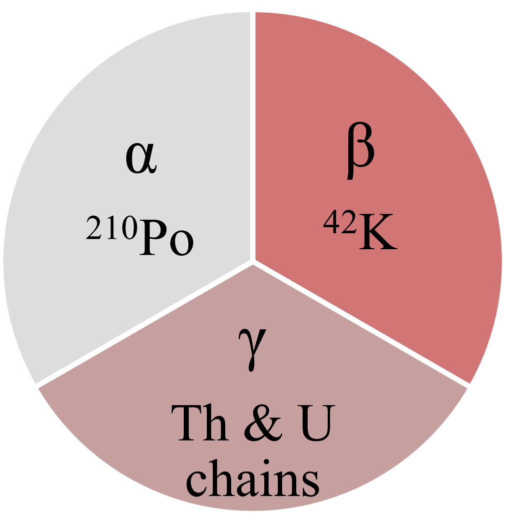
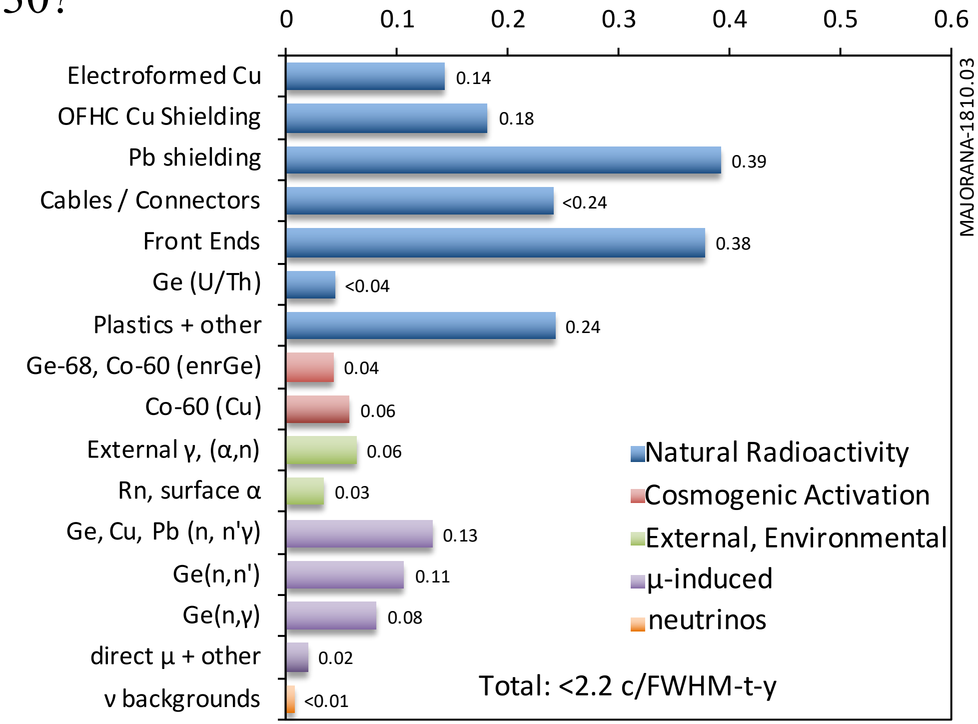
Background Budget Estimate

Based on GERDA and MJD, how do we improve by a factor of 30?

GERDA Background Estimate:



MJD Background Budget (c/FWHM-t-yr)



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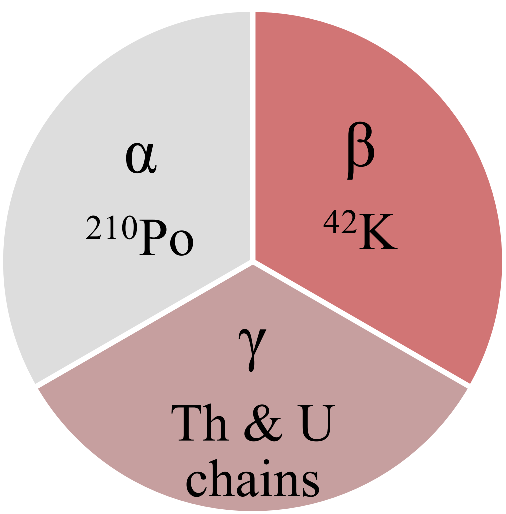

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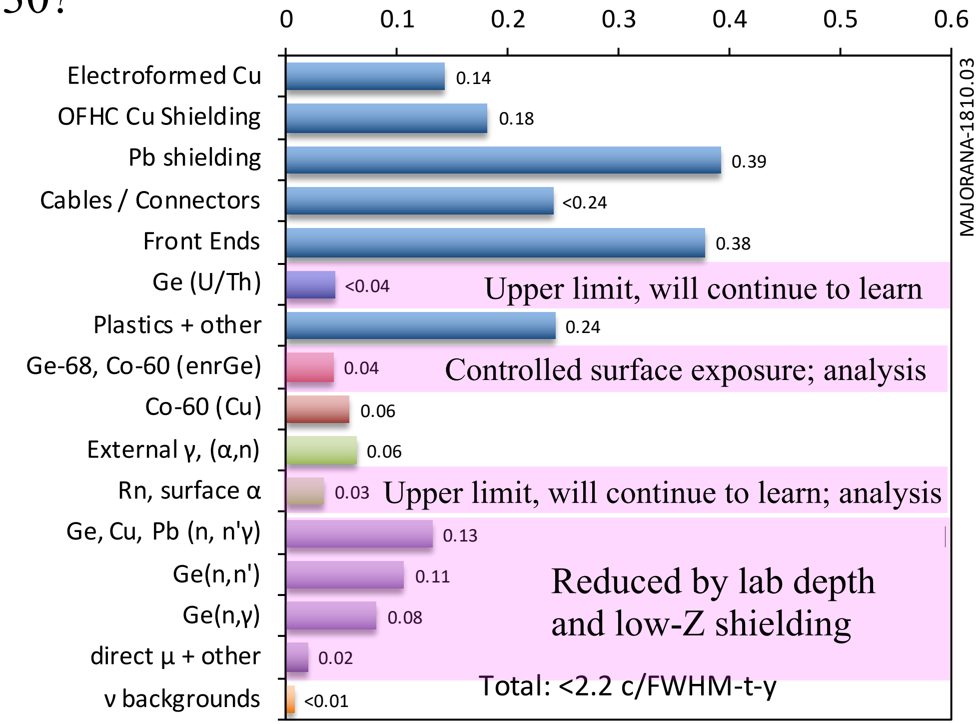

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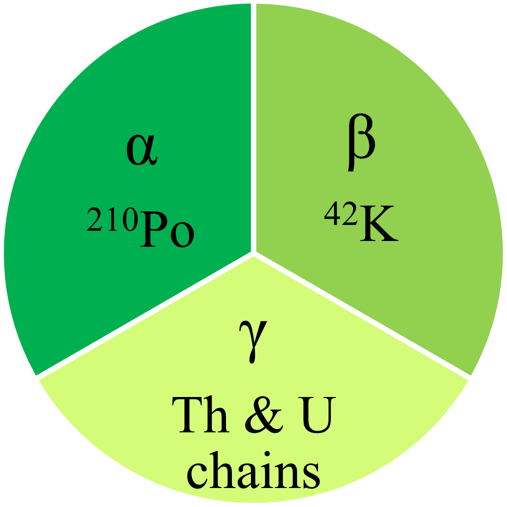
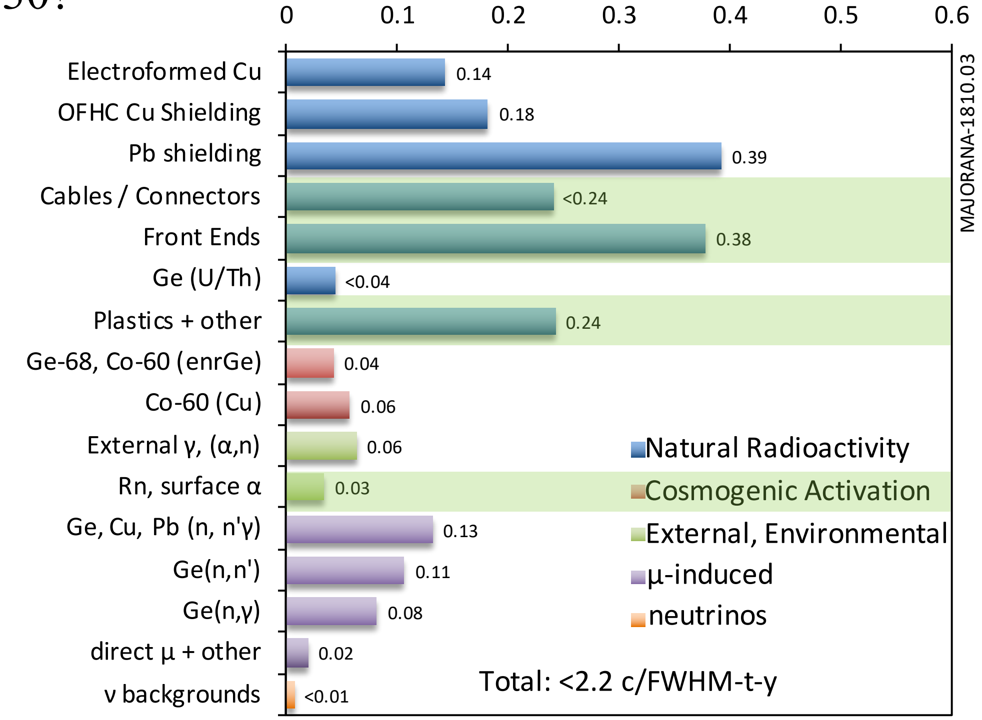


MJD Background Budget (c/FWHM-t-yr)



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R&D: Larger, Inverted Coaxial Detectors

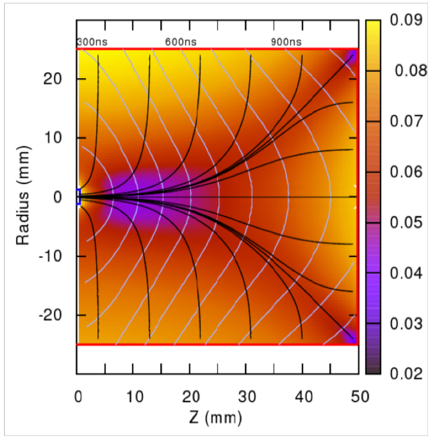
Benefits of larger detectors

- Reduced surface to volume ratio: α and β BG reduction
- Lower channel count: γ BG reduction
- Lower cost per kg, higher efficiency

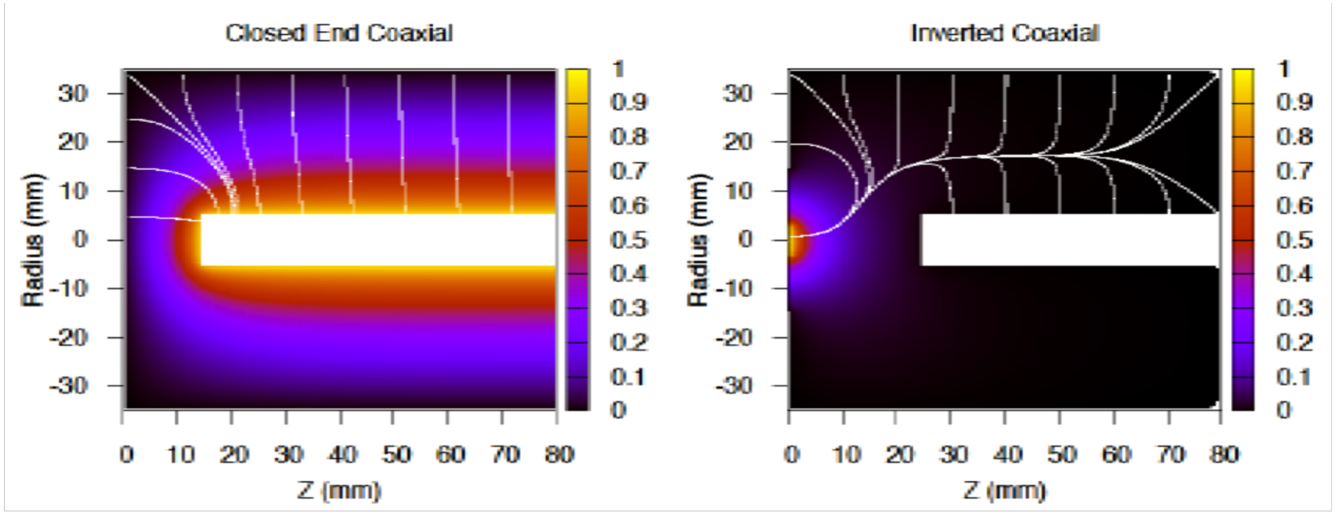
New design: Inverted Coaxial Point-Contact

- 1.5 – 2.0 kg for LEGEND-200
- Up to 4 – 6 kg for LEGEND-1000
- Keep multi-site PSD and low capacitance
- See R.J. Cooper et al., NIM A 665 (2012) 25

PPC



< 1 kg



1-2 kg

1-2 kg now, up to 6 kg

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Background Budget Estimate

Based on GERDA and MJD, how do we improve by a factor of 30?

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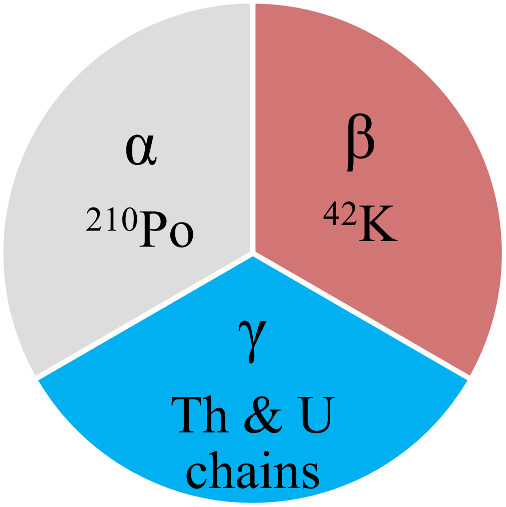
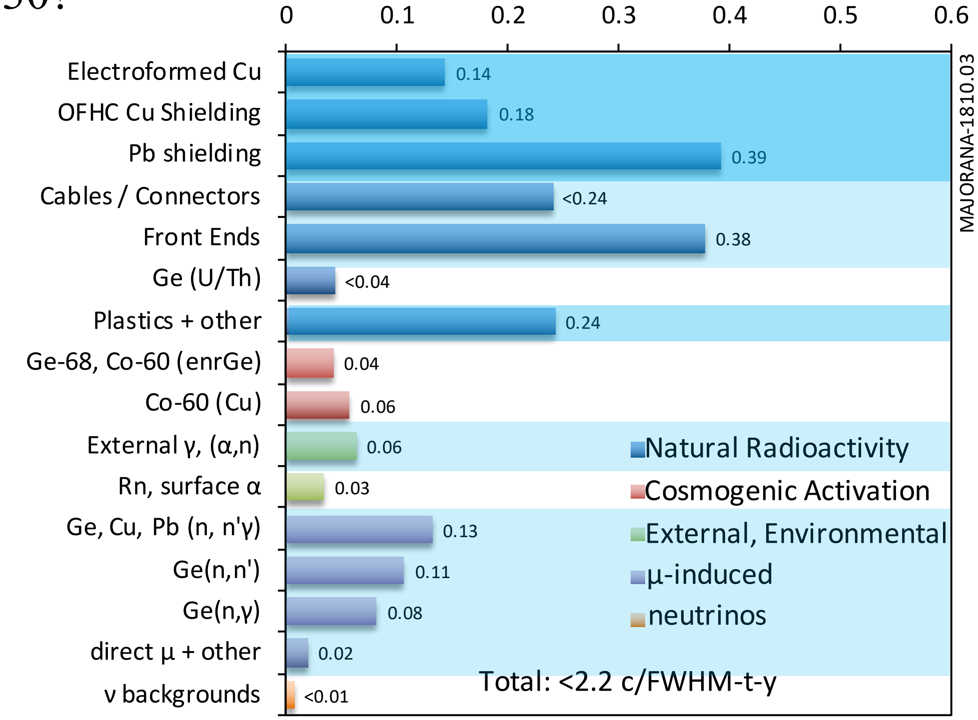


MJD Background Budget (c/FWHM-t-yr)



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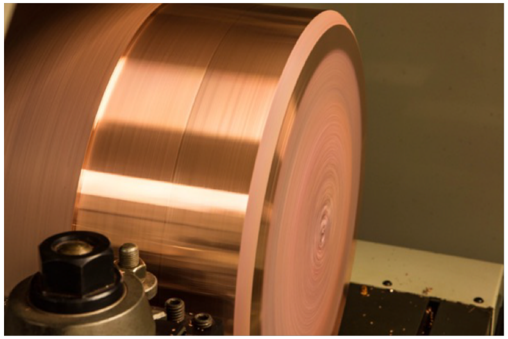
R&D: UGEFCu and Lower-Background Electronics

- 1.2 tons of UGEFCu used in MJD:
  - $\leq$ 0.1 μBq/kg Th & U decay chains, very low in ^{60}Co
  - New electroformed materials under study
- MJD low-mass low-background front end electronics can be placed next to detectors:
  - Improves resolution and PSD
  - Lower-background cable and connector options being tested



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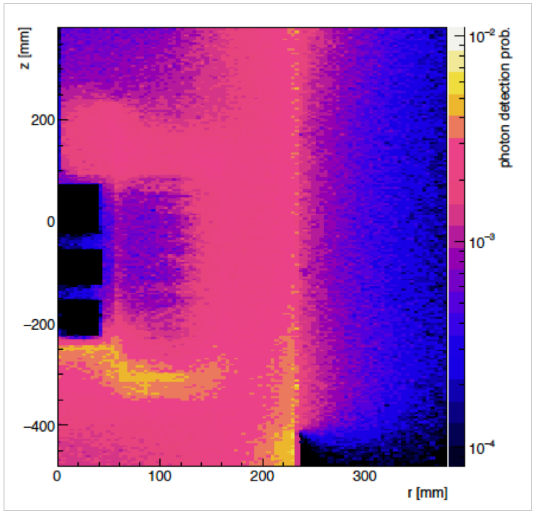
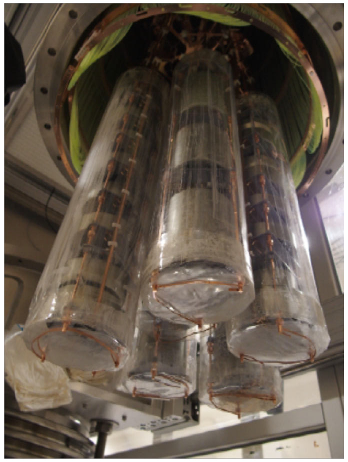
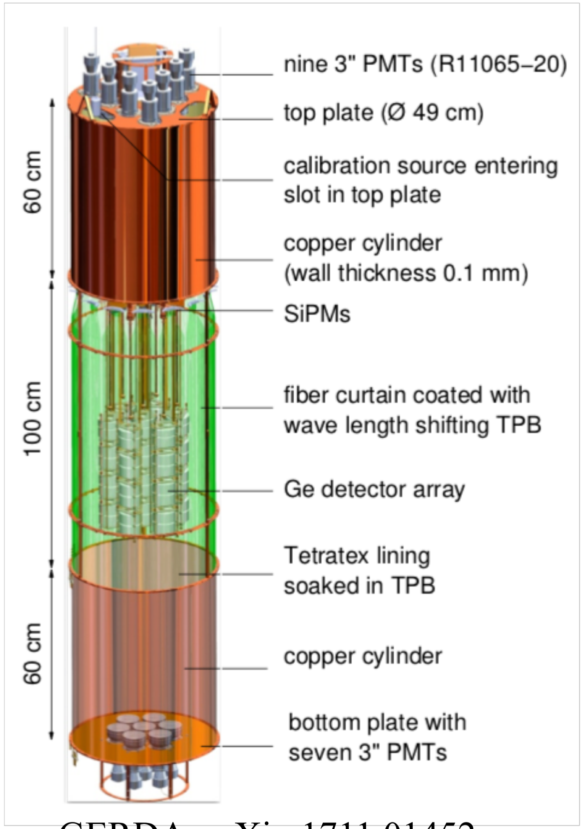
R&D: LAr Light Collection Improvements

- Current design has significant shadowing, uses nylon mini-shrouds to limit β backgrounds
- Improve LAr purity for higher light yield
- Increased coverage and light readout for more PE recorded
- Factor of 2 improvement shown in test stands







GERDA, arXiv:1711.01452

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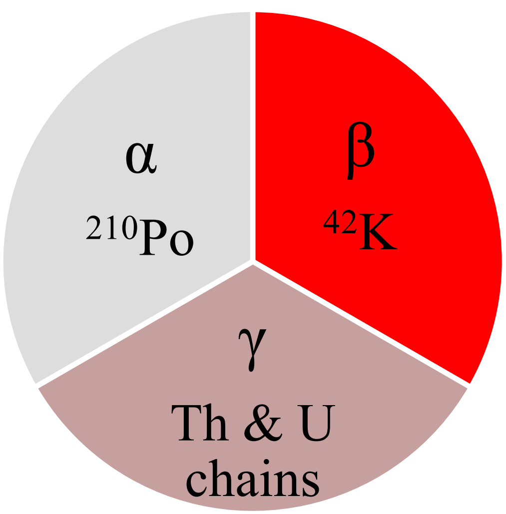
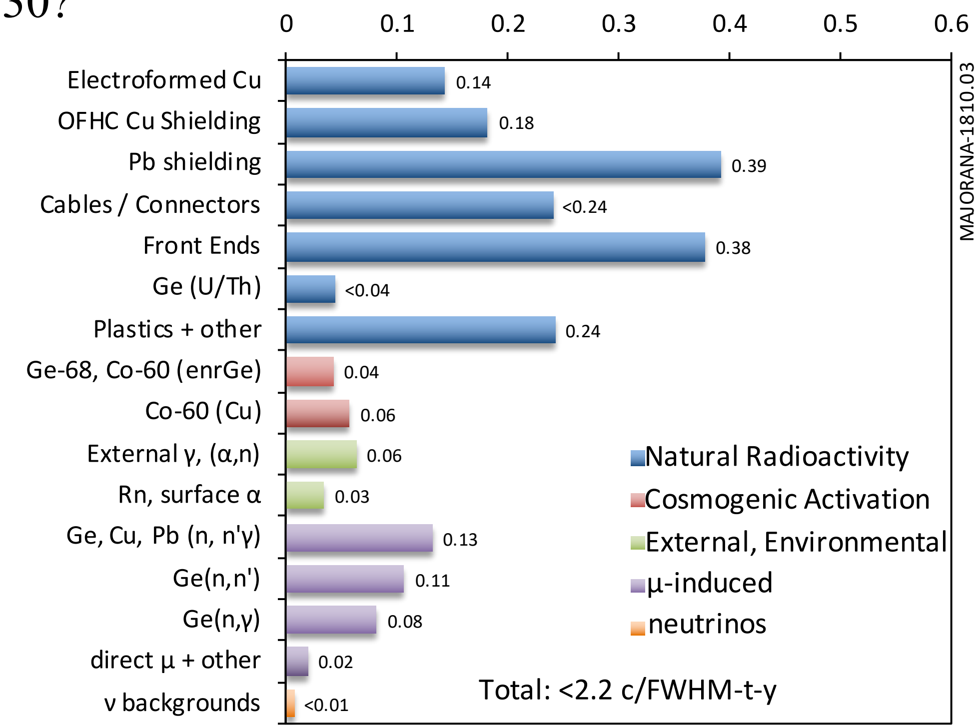
Background Budget Estimate

Based on GERDA and MJD, how do we improve by a factor of 30?

GERDA Background Estimate:

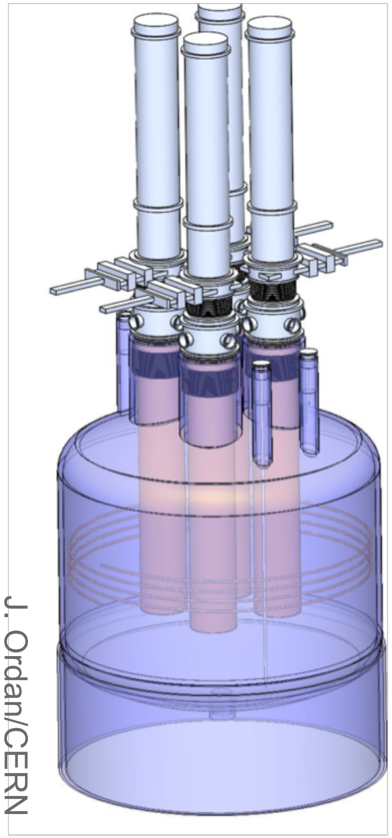


MJD Background Budget (c/FWHM-t-yr)



LEGEND-1000 Improvements: Underground LAr

- UAr for detector volumes would be low in ^{42}K, reduce/eliminate β backgrounds
- Removes mini-shrouds, geometry can be optimized for light collection efficiency
- Estimated UAr needed: 21 tons, 15 m^3

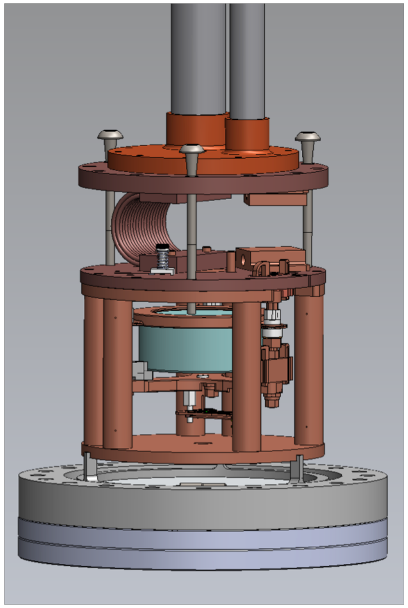


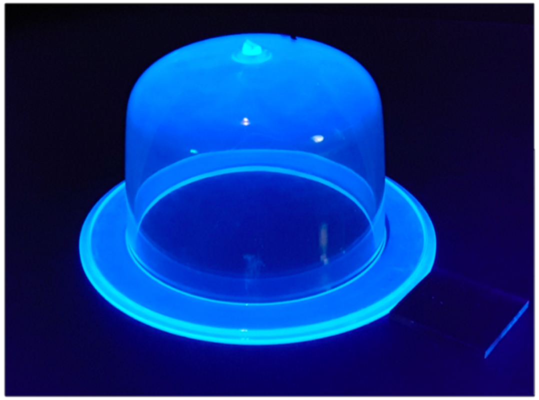
- ARIA purification plant under construction
- Planned to process ~1 ton/day

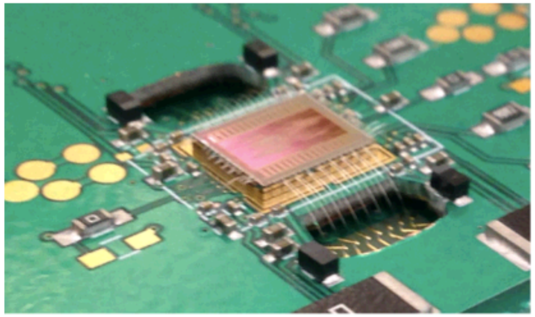
J. Ordan/CERN

Other LEGEND R&D

- Improved LAr readout
- Radon reduction techniques
- Electronics, front ends and cabling, including ASICs
- Alternative shielding/cooling materials (LNe, doped LAr)
- Active material mounts (PEN)
- Alternative cryostat designs
- Analysis – machine learning, advanced PSD







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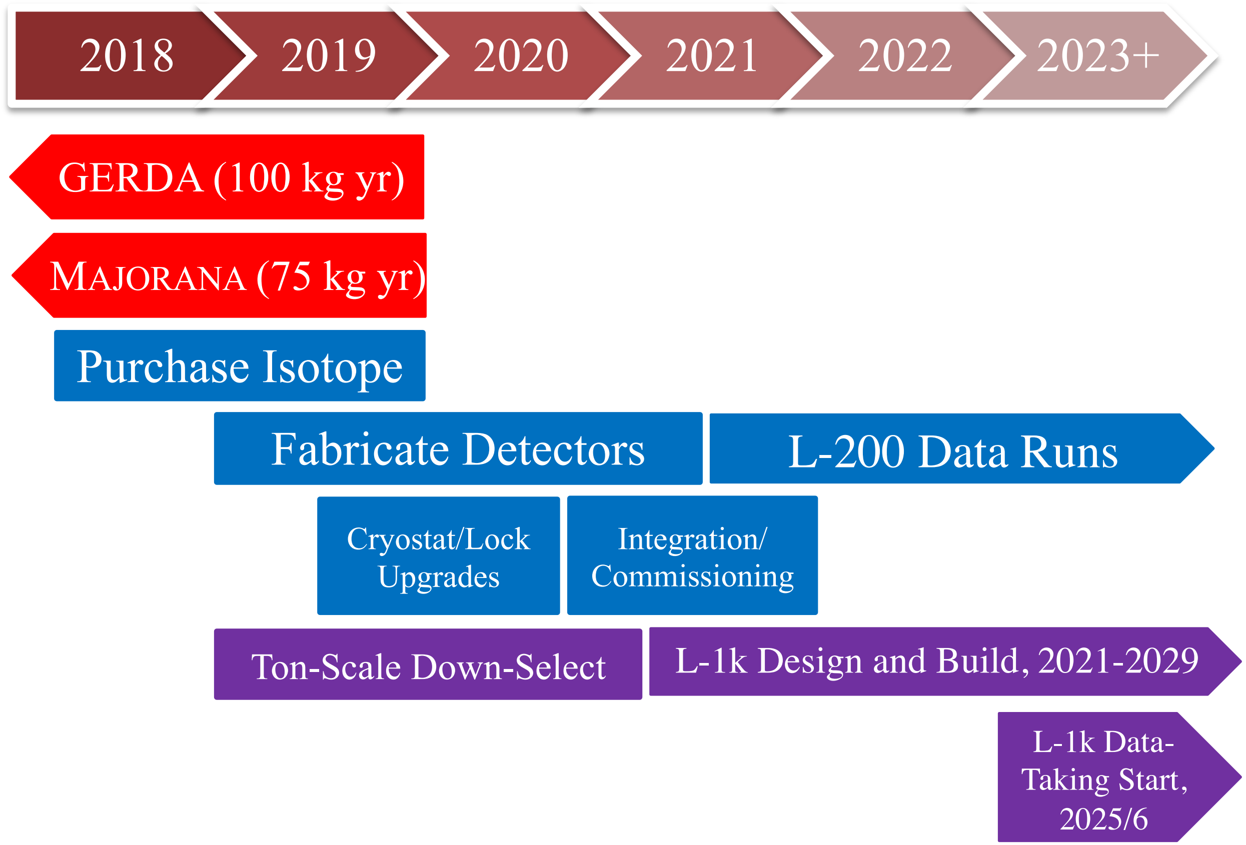
LEGEND-200 Status

- L-200 funding secured
- ICPC detectors are running in GERDA
- Enriched ^{76}Ge is being delivered
- First batch of ICPC detectors ordered
- String layout and detector unit design being finalized
- Simulations campaign is underway



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Summary

- ^{76}Ge $0\nu\beta\beta$ searches have a well-understood path to exploring the IO regime:
  - GERDA has the lowest ROI background experiment in the field
  - MJD has the best energy resolution of any experiment in the field
- LEGEND goals: exposure of 10 t-y, background of 0.1 c/FWHM-t-y
- Phased, stepwise implementation to reduce risk and begin as quickly as possible
- LEGEND-200:
  - Uses existing infrastructure
  - Data-taking planned to start in 2021
  - Factor of 5 reduction from current best background index
- LEGEND-1000:
  - Another factor of 6 reduction in background index
  - Conceptual design and R&D are underway

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