The LAr Veto for LEGEND

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on behalf of the LEGEND Collaboration
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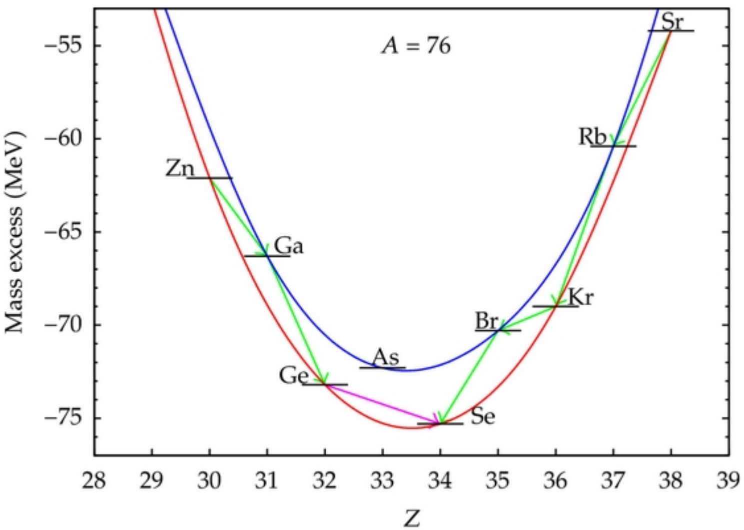
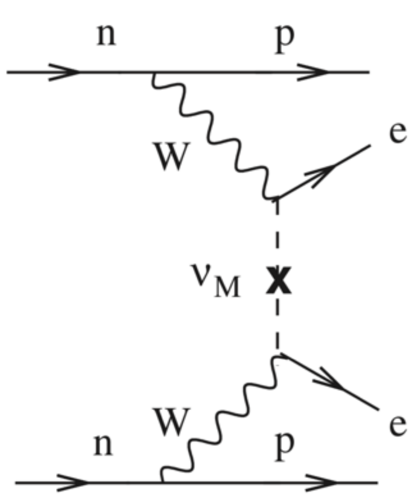
CENPA
Center for Experimental Nuclear Physics and Astrophysics

Neutrinoless Double–Beta Decay

- Double-beta decay with two neutrinos is the rarest weak nuclear process
  - Proposed by Maria Goeppert-Mayer in 1935
  - First measured in lab in 1987 for ^{82}Se
- Only directly measured in 10 isotopes
  - $t_{1/2} = 7 \times 10^{18} - 9 \times 10^{21}$ yr



Giuliani and Poves, AHEP (2012)
doi:10.1155/2012/857016



Avignone *et al.* Rev. Mod. Phys. (2008)
doi:10.1103/RevModPhys.80.481

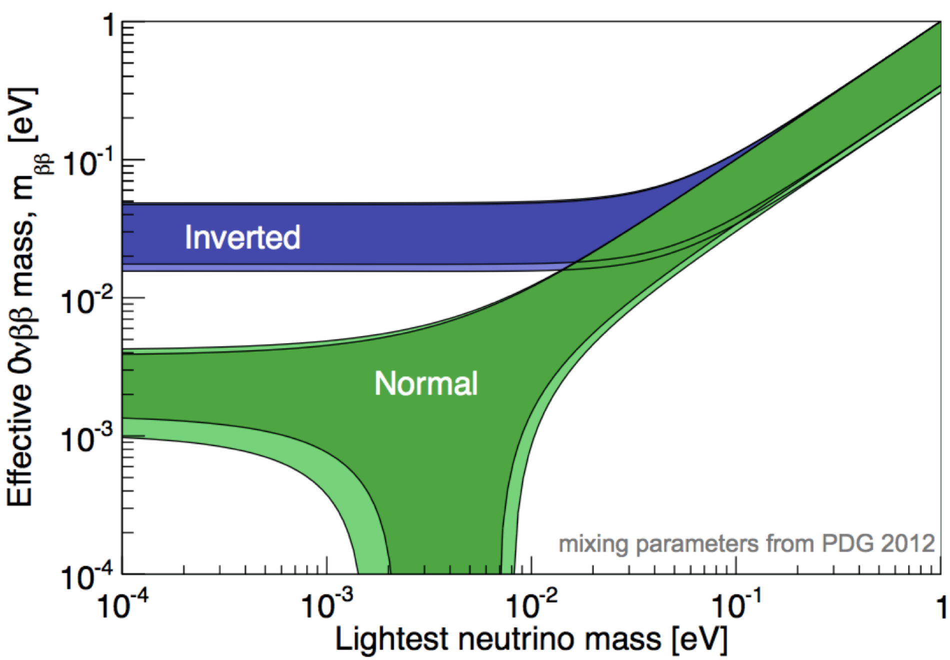
- Neutrinoless double-beta decay is an analogous proposed nuclear process wherein lepton number is violated
  - Requires neutrinos be Majorana particles
  - $t_{1/2} > 10^{25}$ yr (^{76}Ge, ^{130}Te, ^{136}Xe)

Mass Hierarchy from 0νββ

> **Half-life of 0νββ related to neutrino mass scale**

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

– $\langle m_{\beta\beta}\rangle = \left|\sum U_{ei}^2 m_i\right|$



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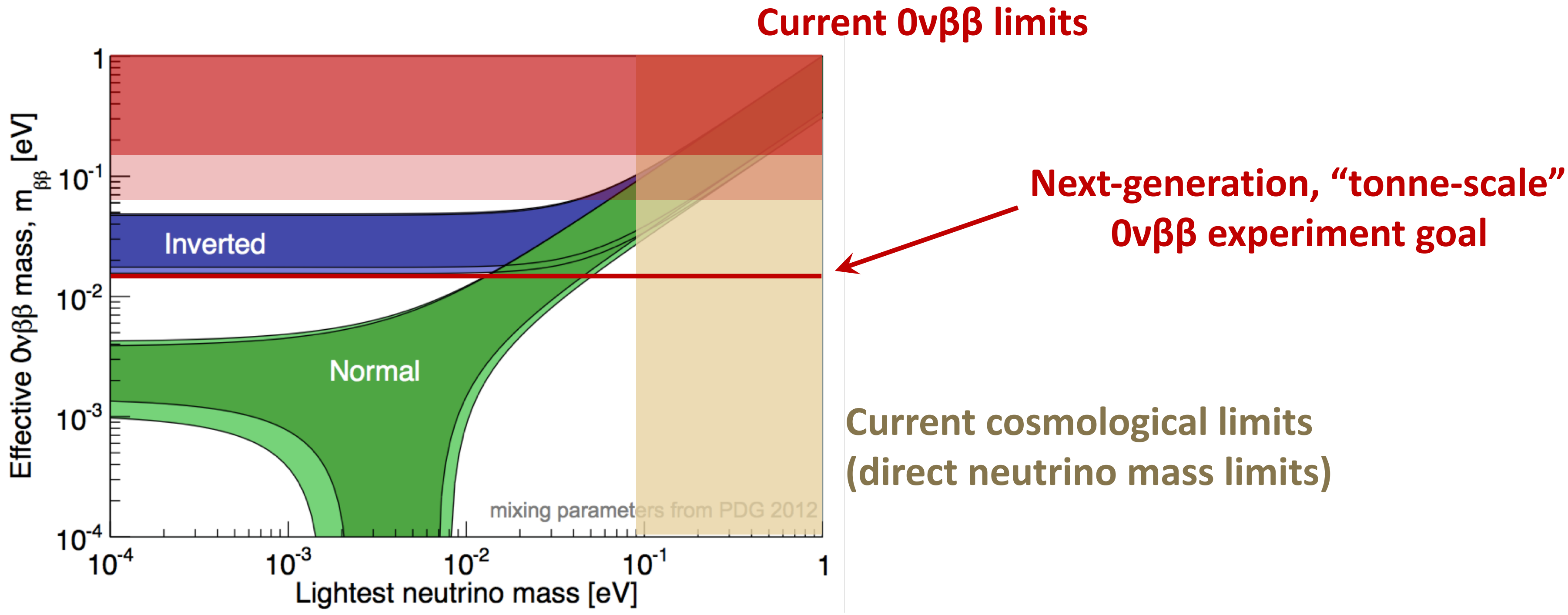
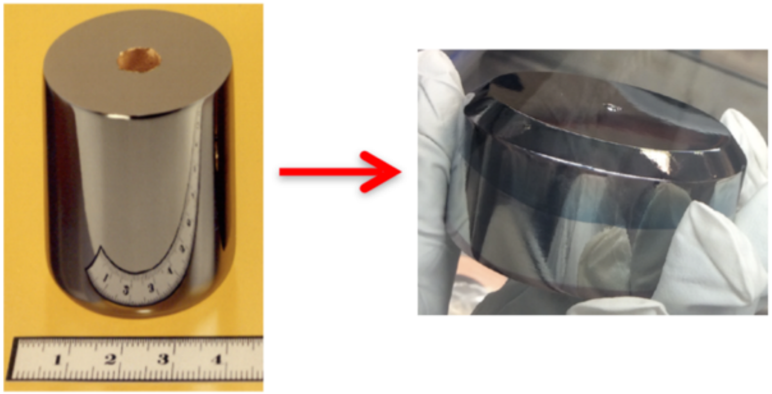
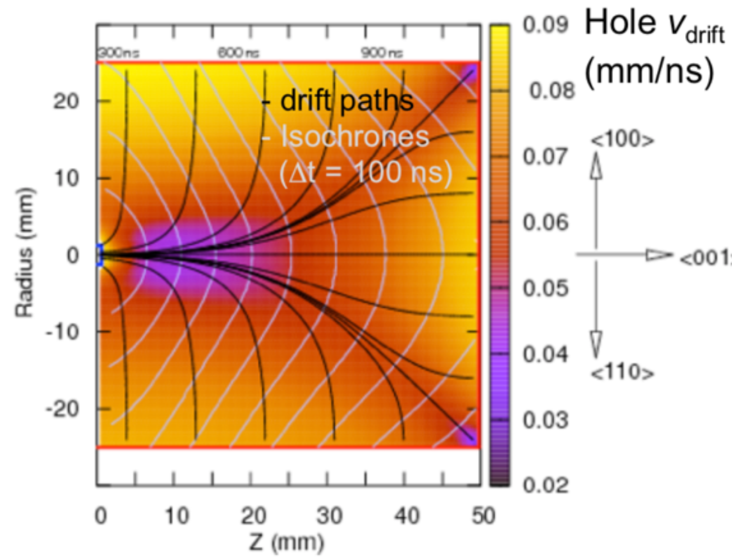
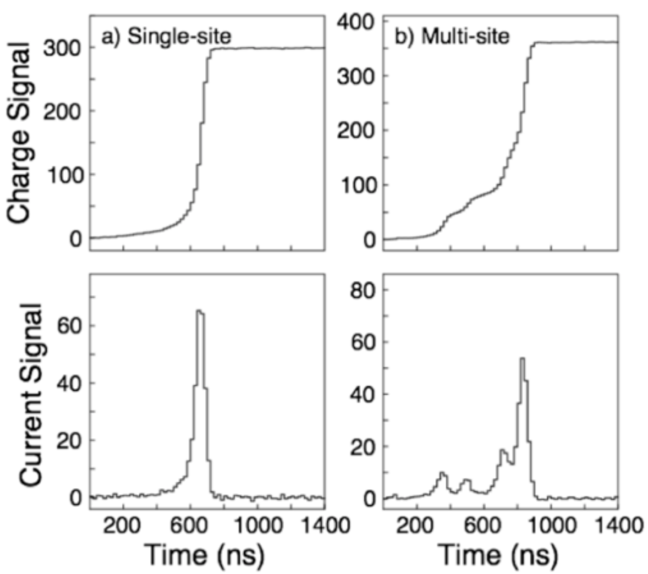
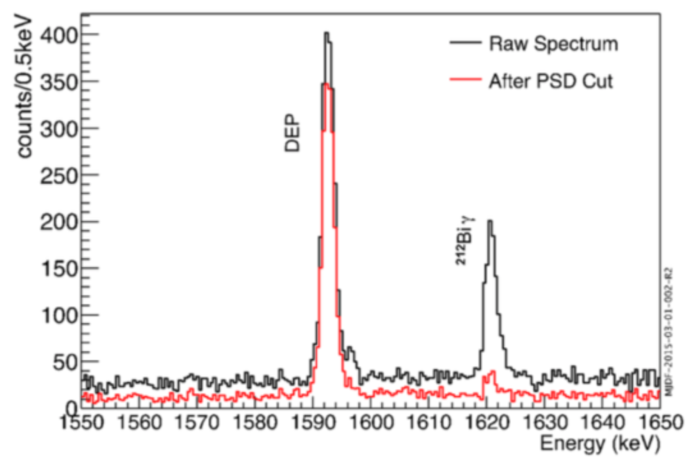


Point-Contact ^{76}Ge Detectors









Luke et al., IEEE trans. Nucl. Sci. 36 , 926 (1989)
Barbeau, Collar, and Tench, J. Cosm. Astro. Phys. 0709 (2007).

GERDA and MAJORANA

MAJORANA DEMONSTRATOR

Traditional vacuum cryostats in passive graded shield with ultra-clean materials

GERDA

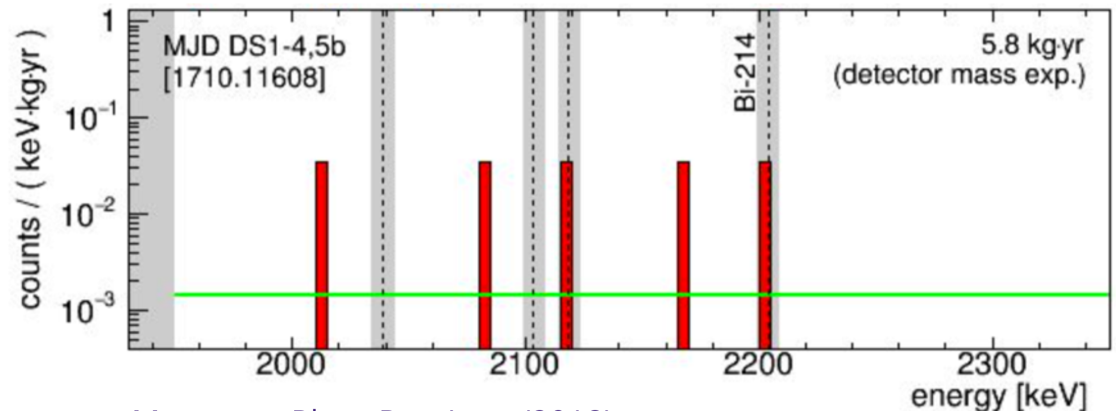
Novel direct immersion in active LAr shield

GERDA and MAJORANA

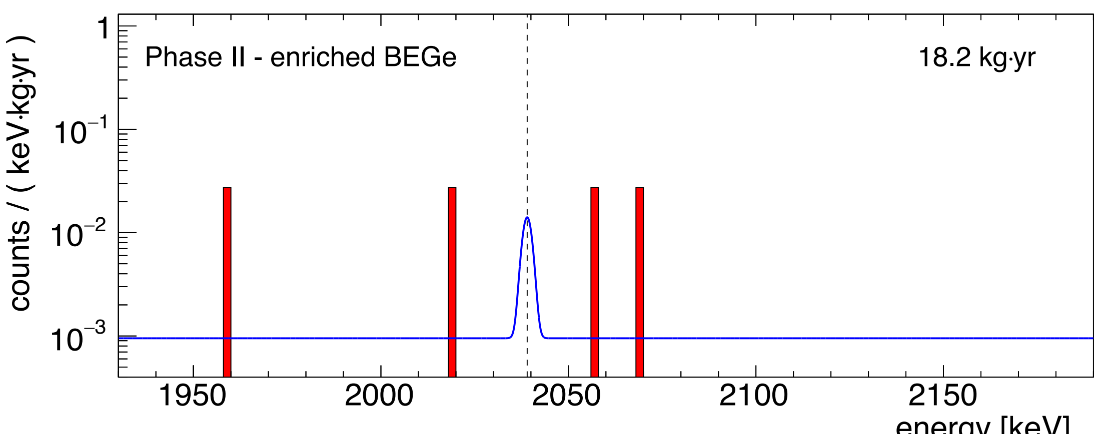
MAJORANA DEMONSTRATOR

BG: $4.0^{+3.1}_{-2.5}$ ct/FWHM/t/yr

$t_{1/2} > 1.9 \times 10^{25}$ yr



MAJORANA, Phys. Rev. Lett. (2018)
doi:10.1103/PhysRevLett.120.132502



GERDA, Phys. Rev. Lett. (2018)
doi:10.1103/PhysRevLett.120.132503

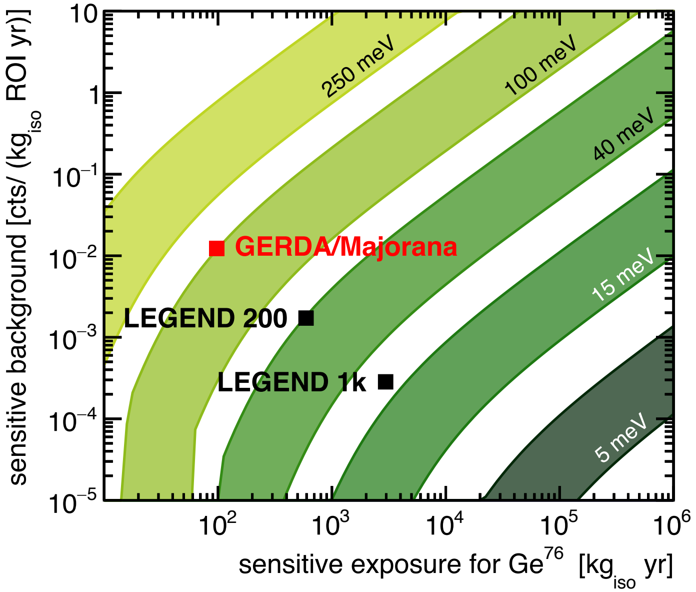
GERDA

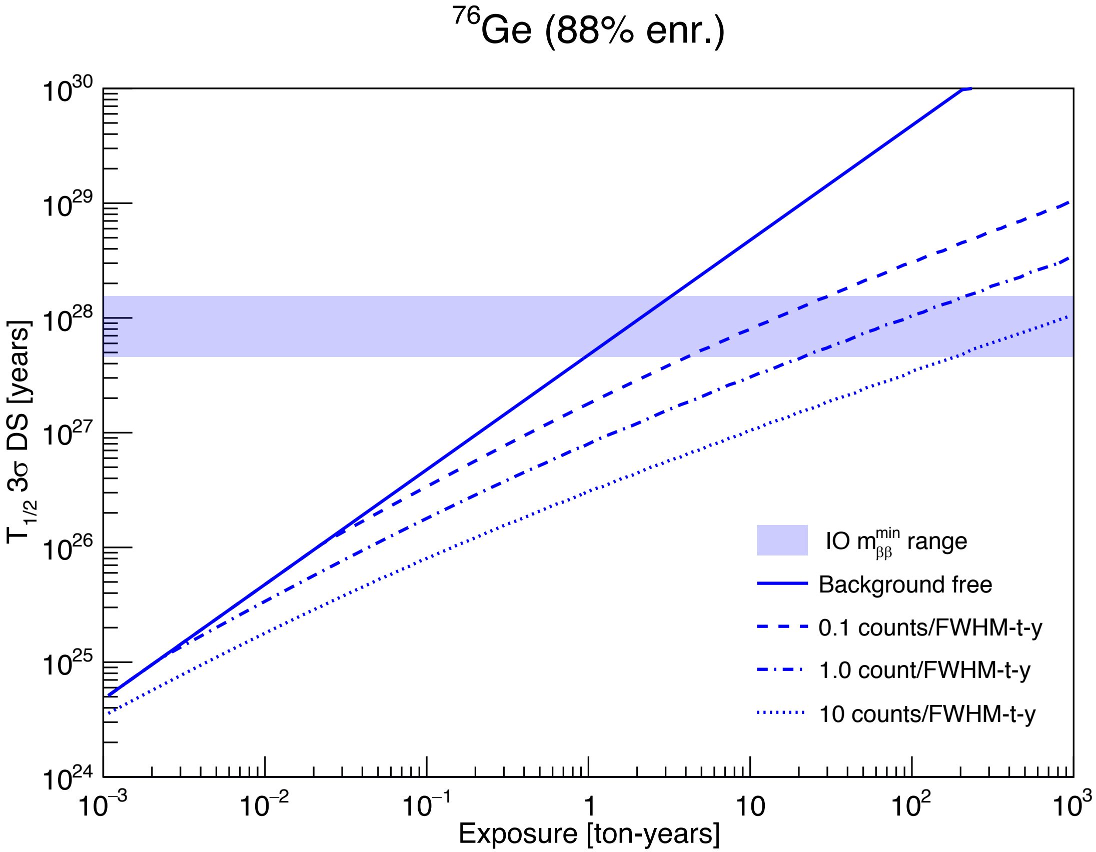
BG: $2.9^{+1.8}_{-1.2}$ ct/FWHM/t/yr

$t_{1/2} > 8.0 \times 10^{25}$ yr

Discovery Potential and Background

Agostini *et al.* Phys. Rev. D (2017)
doi:10.1103/PhysRevD.96.053001

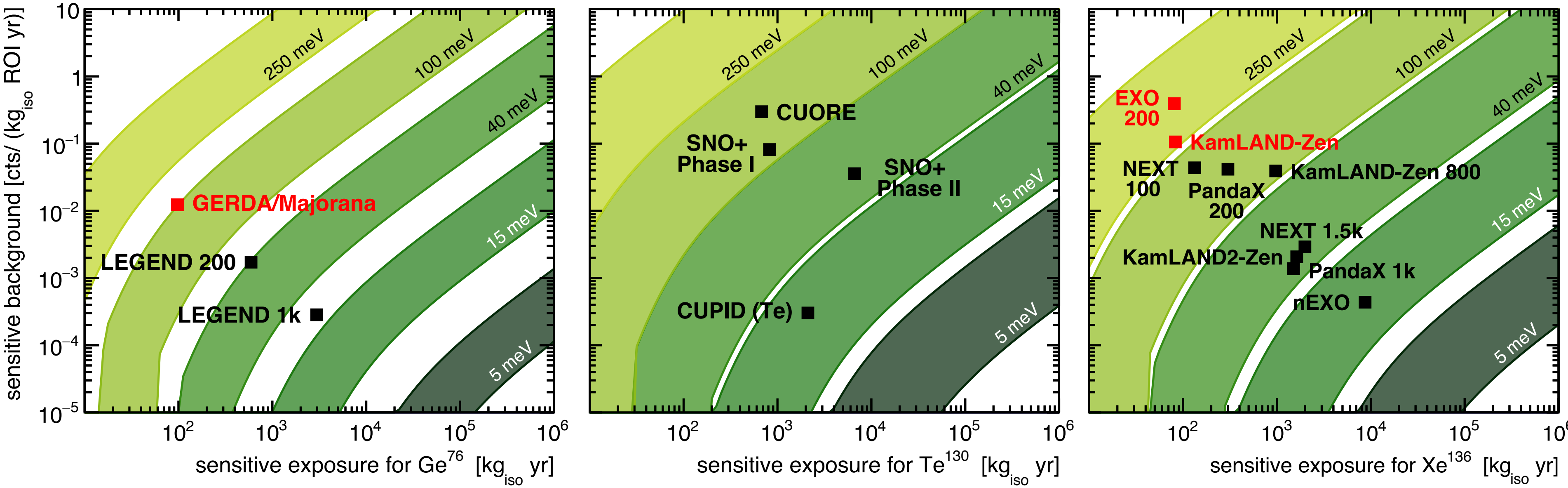




- **Germanium experiments have demonstrated excellent background-free (at current exposure) performance**
- **Must significantly increase exposure and decrease background to cover inverted hierarchy**

Discovery Potential and Background

> **Increased exposure and decreased backgrounds required for all isotopes of interest for 0νββ searches**



Agostini *et al.* Phys. Rev. D (2017); doi:10.1103/PhysRevD.96.053001

– **"sensitive exposure" is exposure weighted by fiducial mass, enrichment fraction, detection efficiency**
– **"sensitive background" is background per enriched mass in ROI**

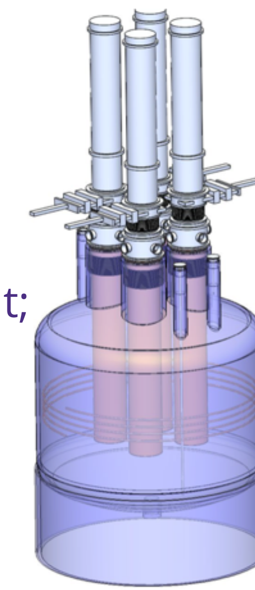
LEGEND Experiment
Large Enriched Germanium Experiment For Neutrinoless Double Beta Decay

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.

> Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments

First Stage
- Sensitivity >10^{27} yr
- Up to 200 kg
- Upgrade existing GERDA infrastructure at LNGS
- BG goal x5 improvement; 0.6 ct/FWHM/t/yr
- Start by 2021
- Include existing enriched MAJORANA and GERDA detectors

Subsequent Stages
- Sensitivity >10^{28} yr
- 1000 kg, staged deploy
- Location TBD based on depth studies (^{77m}Ge)
- BG goal x30 improvement; 0.1 ct/FWHM/t/yr
- Timeline connected to first stage and US DOE downselect



Achieving Background Goal

Background reduction of x5 for LEGEND-200, x30 for LEGEND-1000 from GERDA demonstrated level

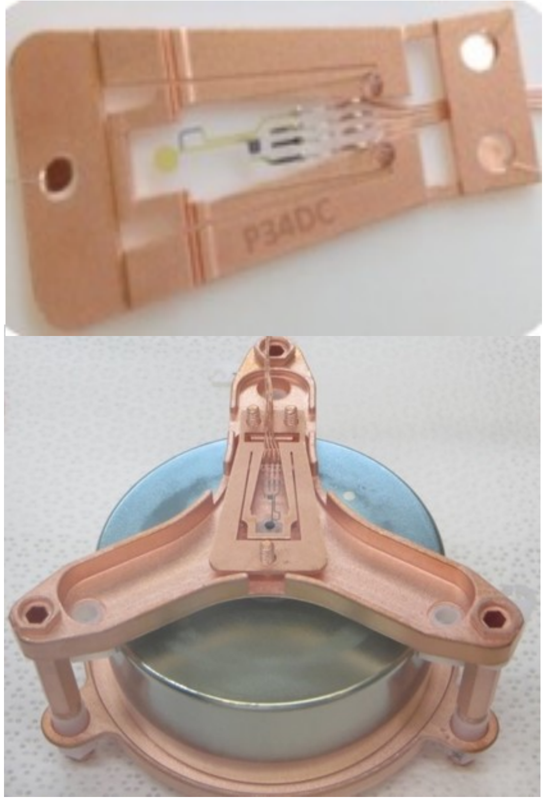
GERDA background equal parts ^{42}K, degraded alphas, ^{214}Bi/^{208}Tl

- **Improved radiopurity levels of components**
  - **Underground electroformed copper**
  - **Cables and connectors**
- **Low-noise electronics**
  - **Excellent energy resolution and improved PSA**
- **Optimized germanium detectors**
  - **Larger inverted coaxial detector geometry with improved surface/volume and mass/electronics ratios**
  - **Increased dead-layer thickness to improve ^{42}K rejection**
- **Upgraded liquid argon active veto**
  - **Improved purity of LAr for higher light yield (+ recirculation?)**
  - **Increased coverage and light readout for more PE recorded**

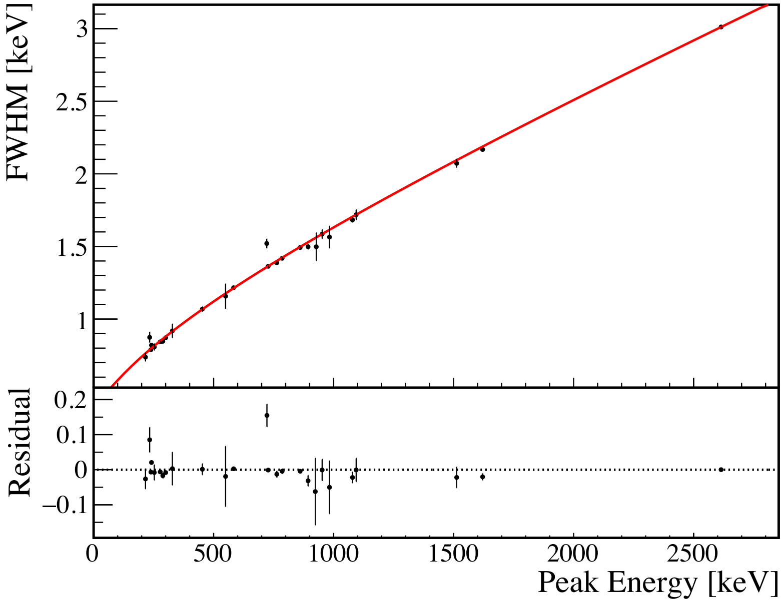
Reduction feasibility demonstrated in MAJORANA and LArGe teststand

LMFE and Energy Resolution

- Low-mass front-end electronics from MAJORANA DEMONSTRATOR exihibit low noise with acceptable radiopurity
  - Low-energy analysis and excellent PSA performance enabled by low noise performance of electronics

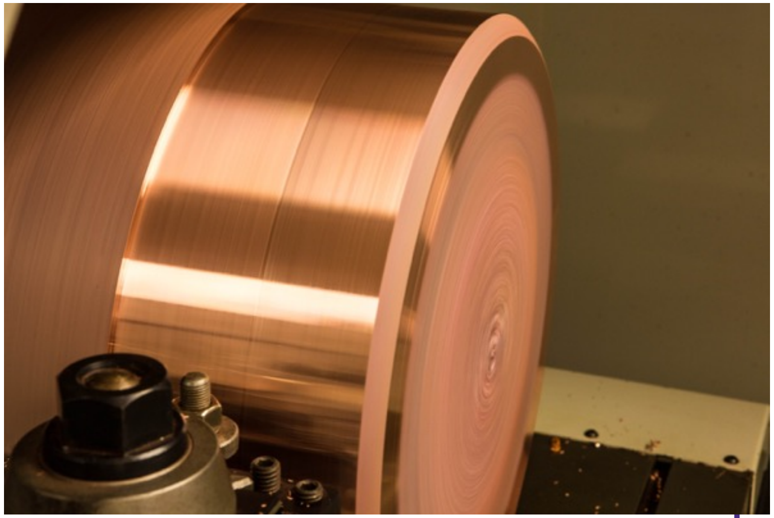


- Energy resolution of 2.52 ± 0.08 keV at $Q_{\beta\beta}$ achieved
  - Best of any 0νββ experiment



Underground Electroformed Copper

- Copper was electroformed at PNNL and SURF 4850’ level
- All machining conducted underground
- Over 2 tons of copper produced, 1.2 tons in MJD
- Th decay chain ≤ 0.1 μBq/kg
- U decay chain ≤ 0.1 μBq/kg
- Etched to remove surface contamination, stored under N_2 flow

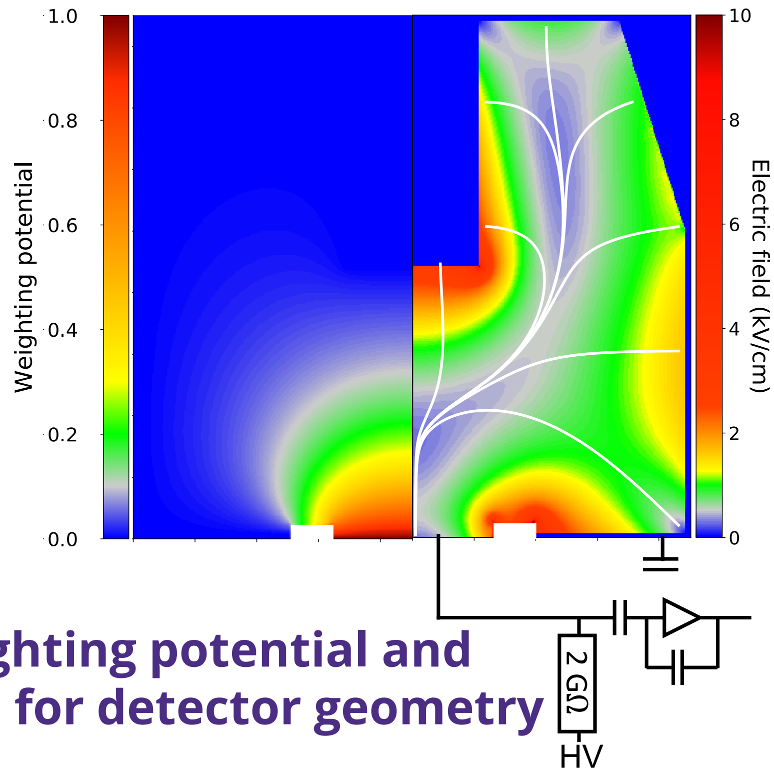


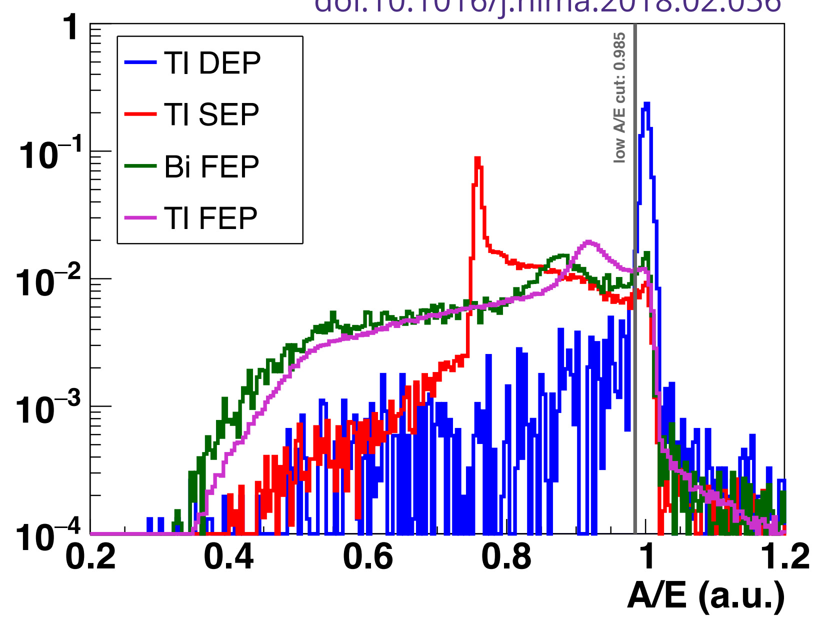
Photos by Matt Kapust

Inverted Coaxial Detectors

> New geometry to scale up mass of individual detectors
  – From <1 kg/detector to few kg/detector
  – Possible to maintain PSA performance

A. Domula *et al.*, NIM A (2018)
doi:10.1016/j.nima.2018.02.056



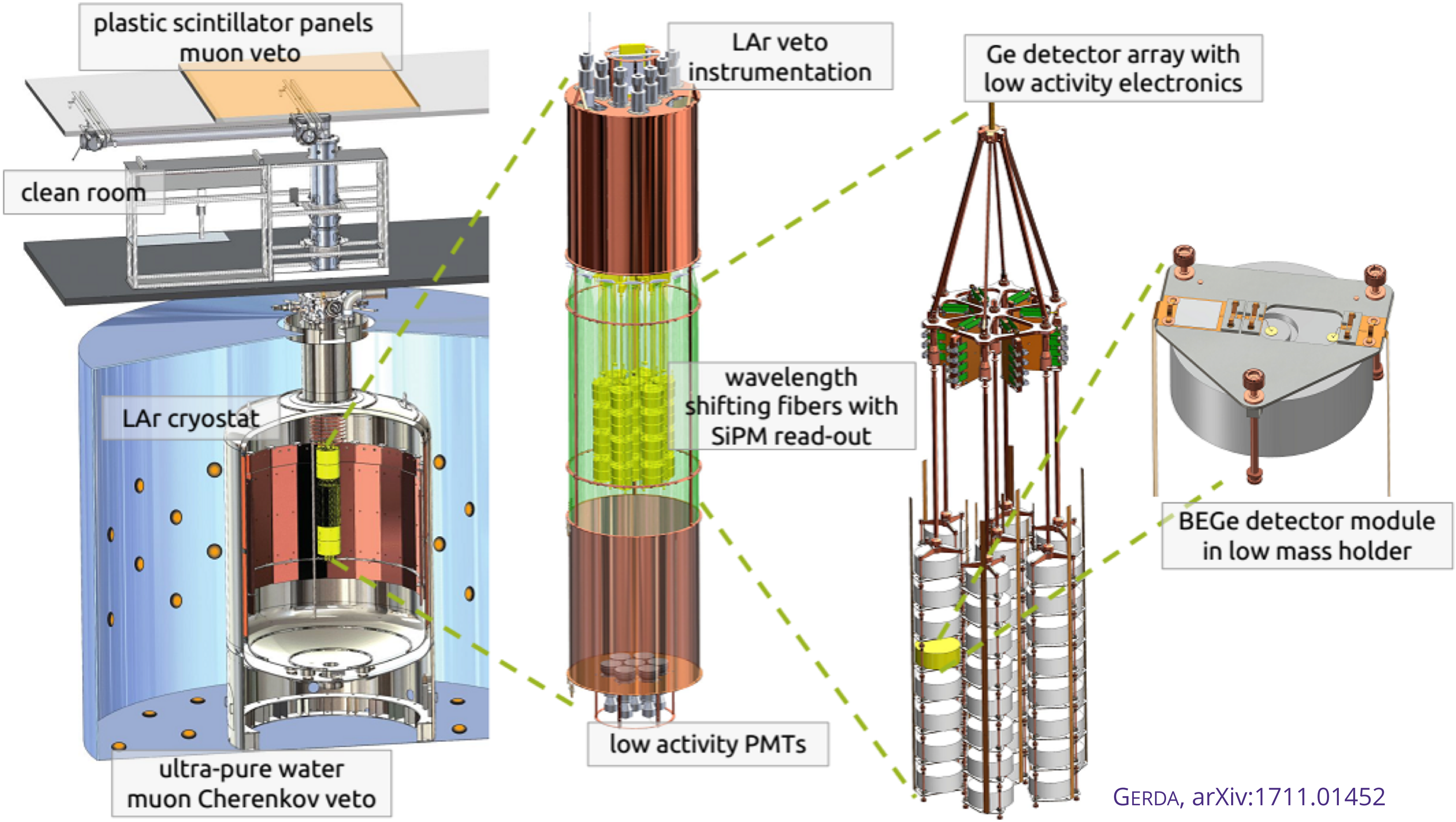


Weighting potential and field for detector geometry

PSA performance provides >90% rejection of SEP background

2.6 kg demonstrator Ge crystal from Canberra

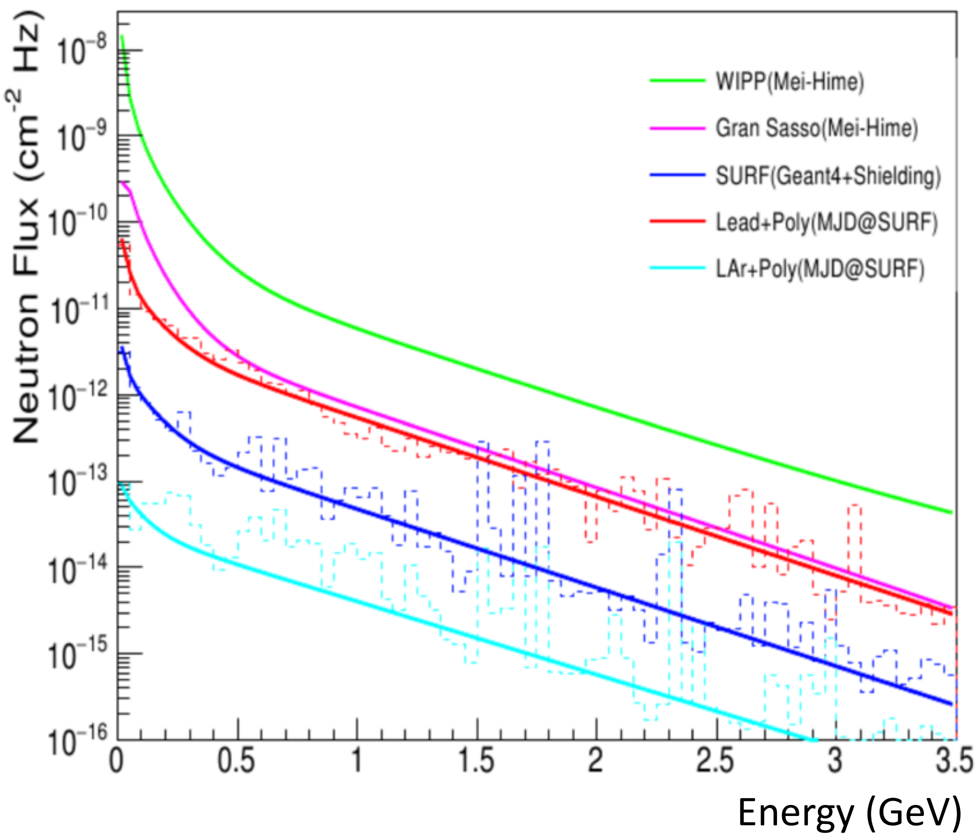
GERDA phase II LAr Veto



GERDA, arXiv:1711.01452

LAr and Neutron Background

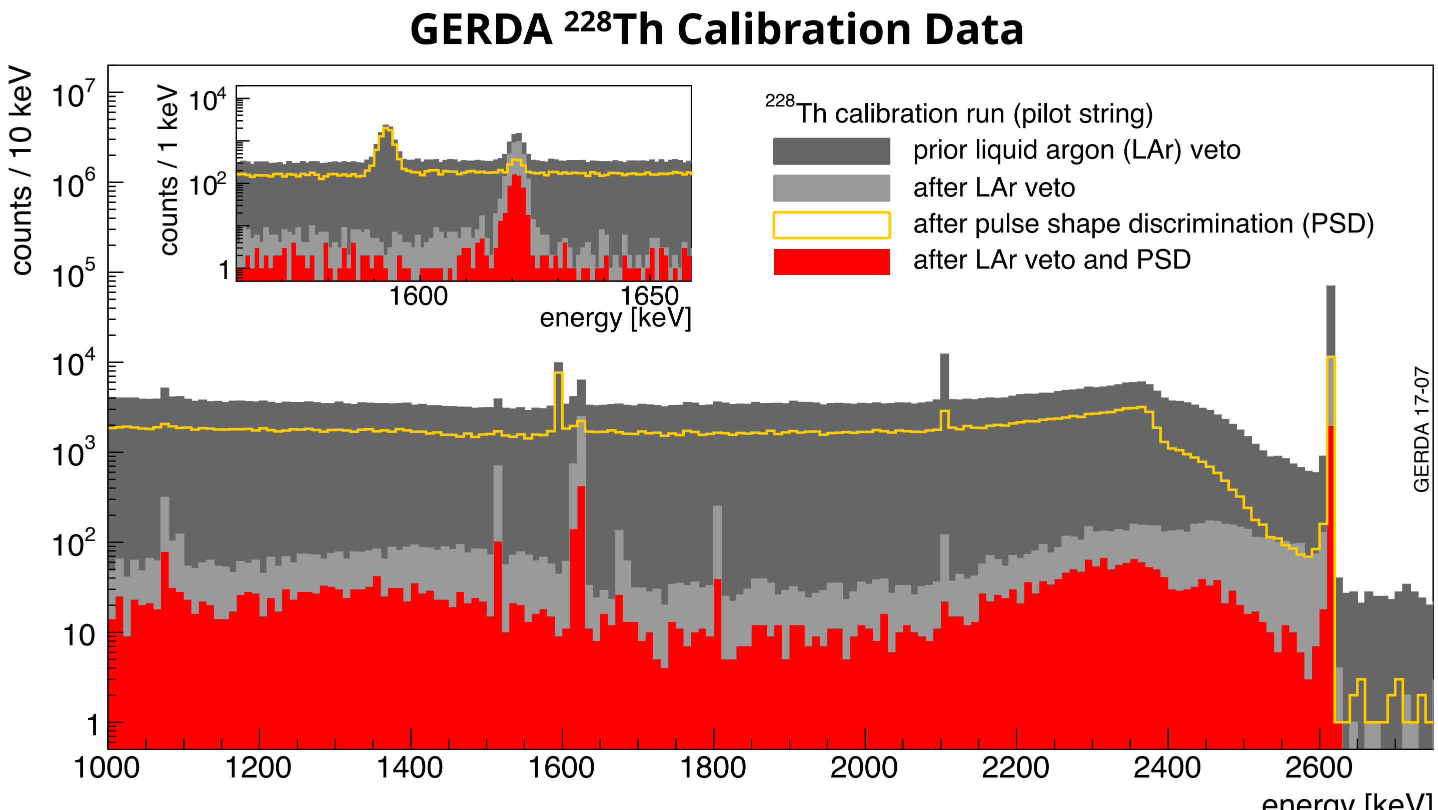
- Passive shielding of liquid argon veto also beneficial
- Factor of ~100 reduction in neutron flux seen by detectors



Ralph Massarczyk

LAr Background Rejection : Calibration

> Powerful discrimination of Compton scatters and events with coincident gammas by LAr veto

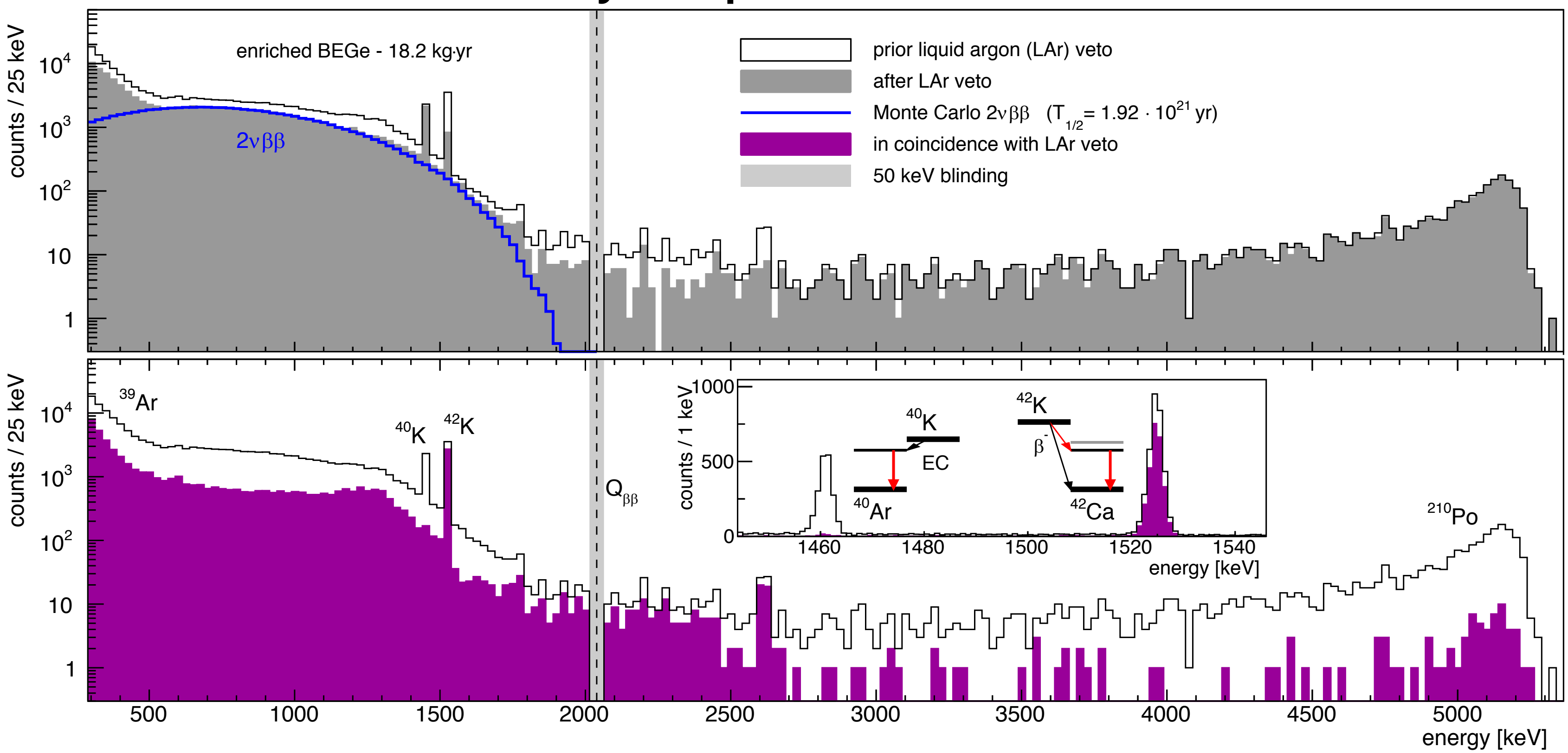


GERDA, arXiv:1711.01452

LAr Background Rejection : Physics

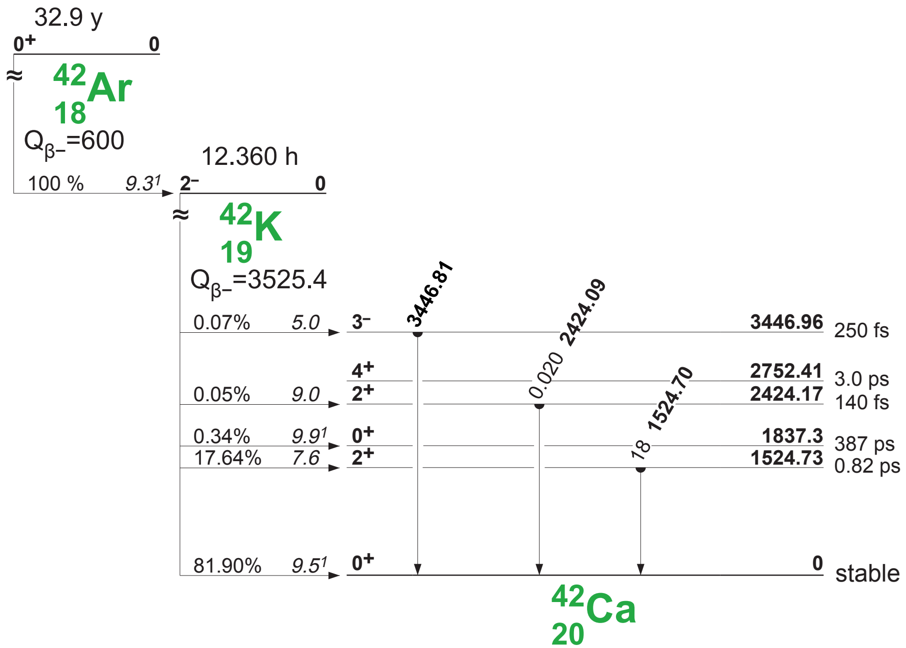
- LAr veto leaves 2νββ spectrum as dominant feature
- Surface alpha and beta decays are inefficiently removed by LAr veto, but cut by PSA

GERDA Physics Spectrum with LAr Cuts



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

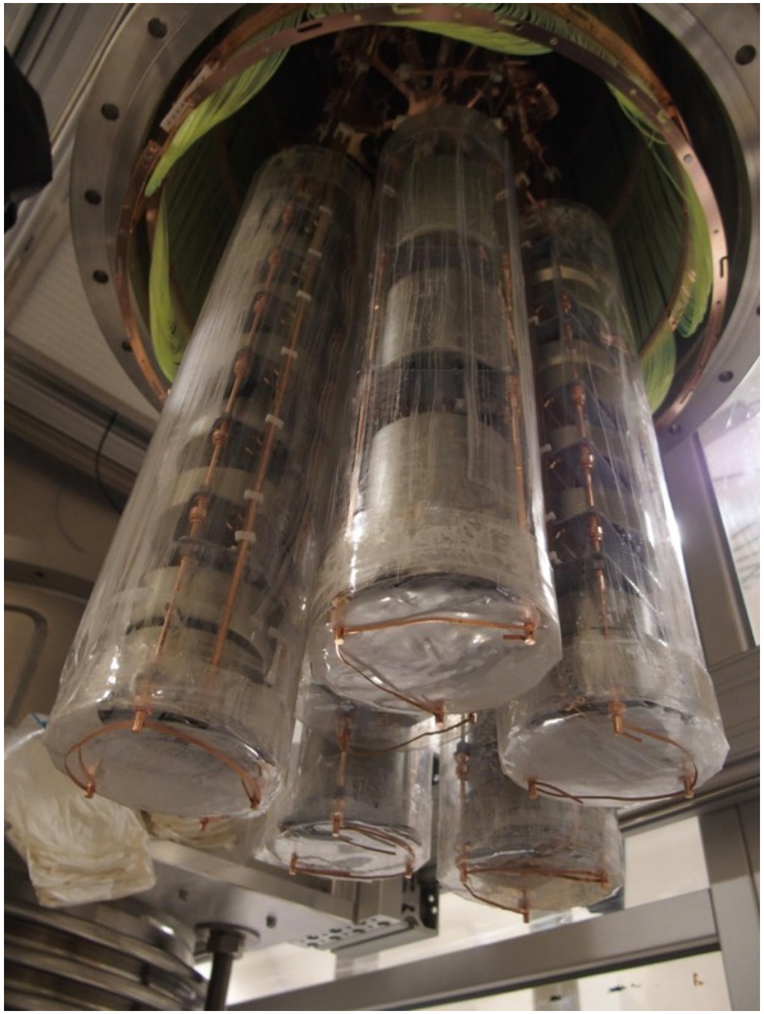
- ^{42}Ar decays produce positive ^{42}K ions
  - Ions drift to detector surfaces, where beta can penetrate crystal transition layer
  - Q_{β} of 3.5 MeV allows for events in ROI
- Activity of ~100 μBq/kg measured in GERDA and LArGe



Lubashevskiy *et al.* Eur. Phys. J C (2018) doi:10.1140/epjc/s10052-017-5499-9

^{42}Ar / ^{42}K Mitigation with Mini-Shrouds

- Nylon "mini-shrouds" limit the drifting volume around crystal strings
- Coated with TPB to convey VUV light out to detectors



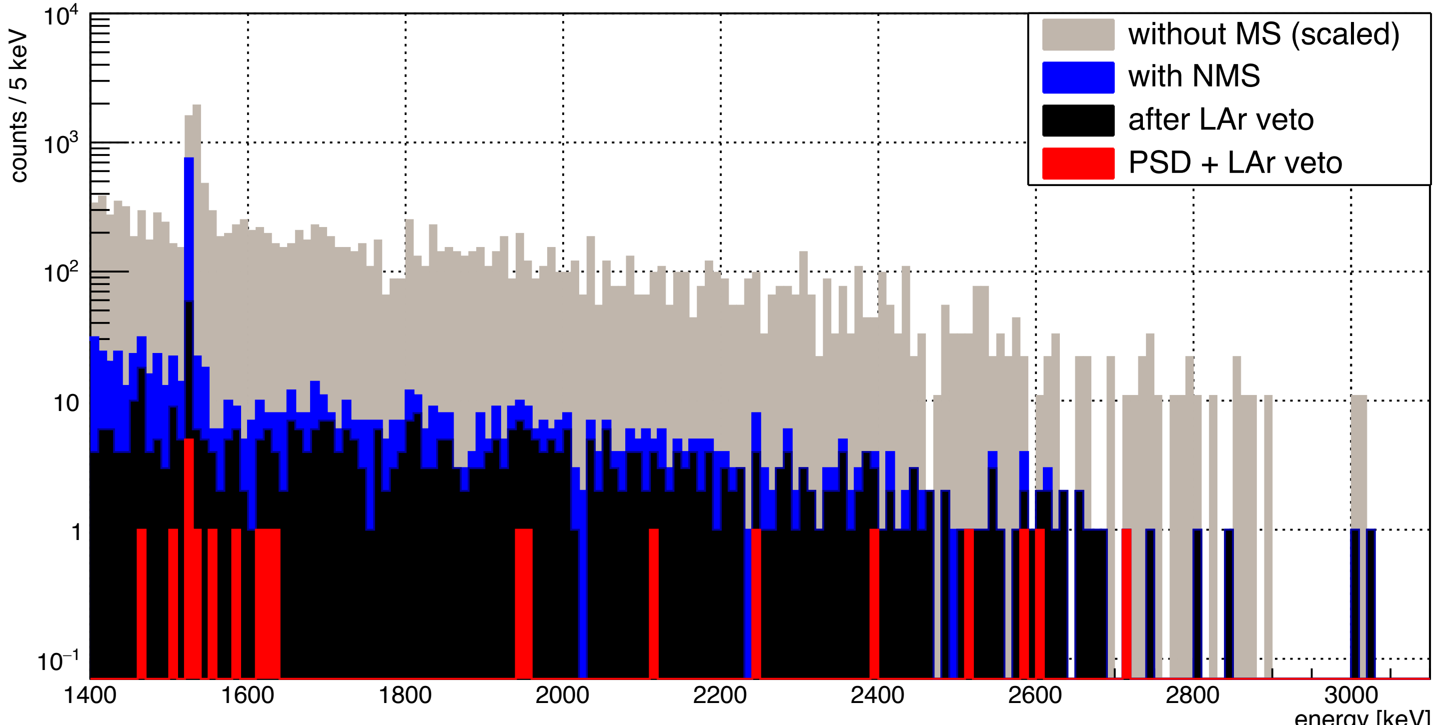
Lubashevskiy *et al.* Eur. Phys. J C (2018) doi:10.1140/epjc/s10052-017-5499-9

$^{42}Ar/^{42}K$ Mitigation with PSA

> LAr veto has good tagging of 1525 keV coincident gamma events, but poor rejection of ^{42}K pure beta decays

> Remaining decays cut with ~99% efficiency by PSA

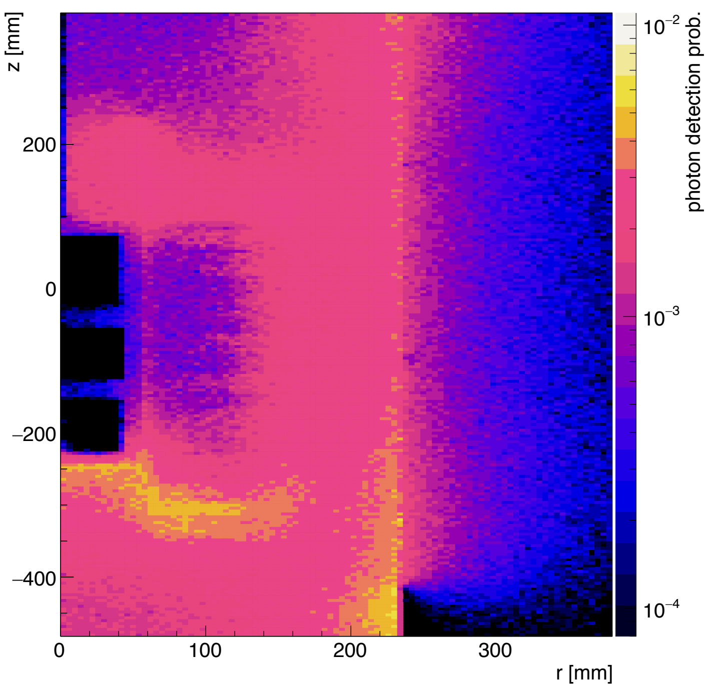
  – Energy deposits in transition layer have slow charge collection

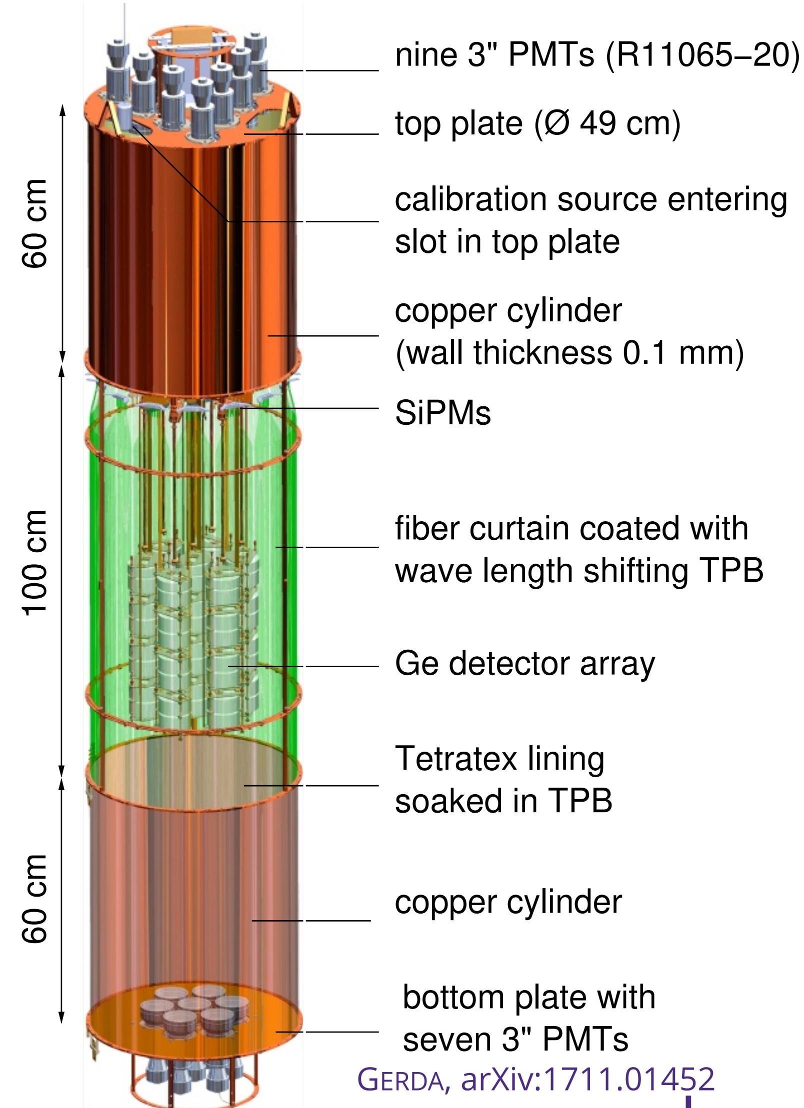


GERDA, arXiv:1711.01452

LAr Light Collection

- Shadowing from Ge detectors creates inhomogeneous light collection efficiency inside array
- Incomplete PMT coverage and fiber losses diminish total light collection



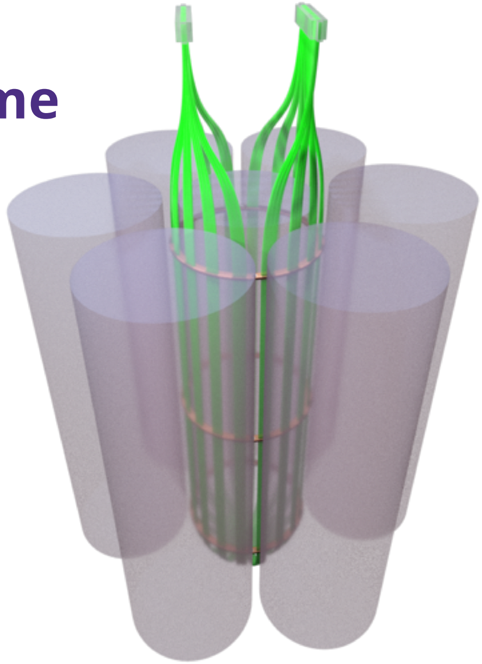


GERDA, arXiv:1711.01452

LEGEND LAr Light Collection R&D

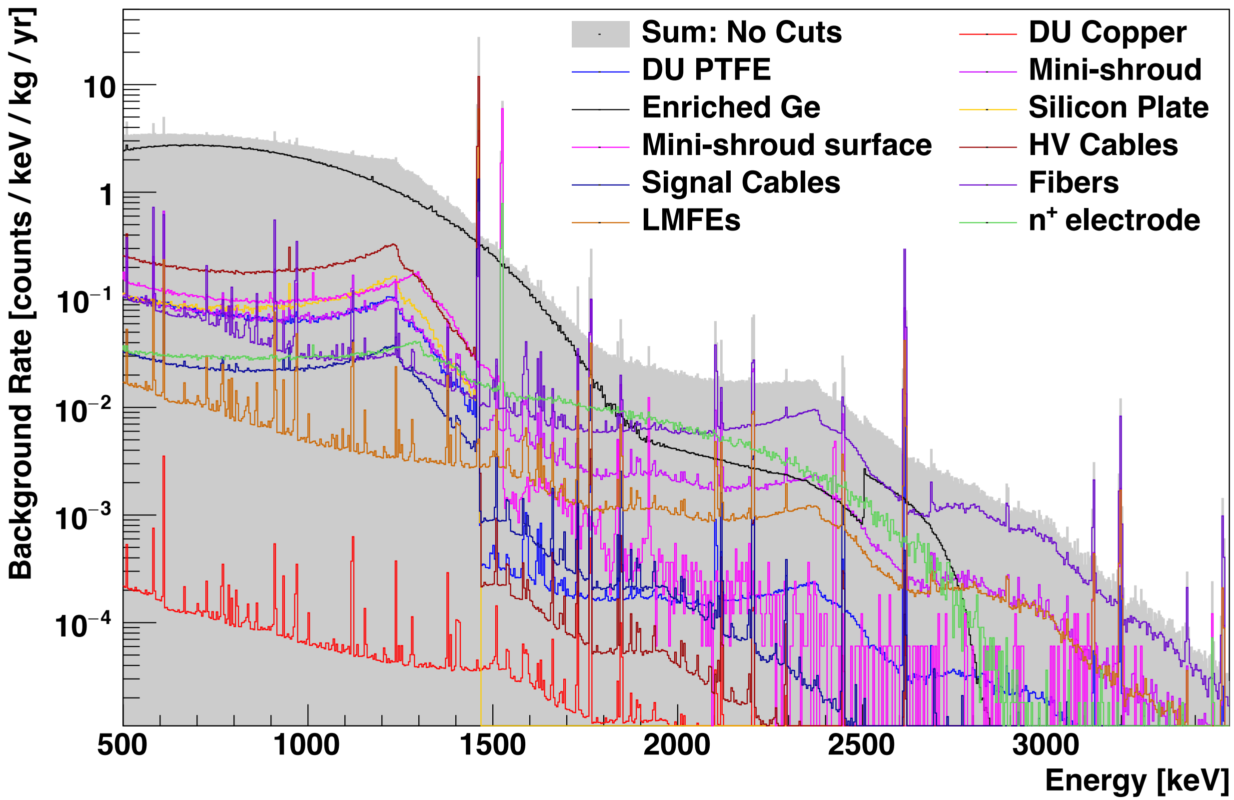
Active development between R&D testbeds and simulation, front-end electronics WG's to develop new ideas

- **Scintillating PEN detector holders (replace Si plates)**
- **Fiber shrouds for individual strings**
- **Improved fiber radiopurity from dedicated production with controlled source materials**
- **Large-area SiPM readout of cylindrical volume endcaps (replace cryogenic PMTs)**
- **Cold electronics for *in situ* amplification and/or digitization**
- **Improved light collection and guide geometries**



LEGEND–200 Background Model

- Background estimate based on demonstrated radiopurity in GERDA and MAJORANA shows background goal in reach
- Cables, connectors, and fibers are significant in model
  - Active area of R&D in MAJORANA, GERDA, and test stands

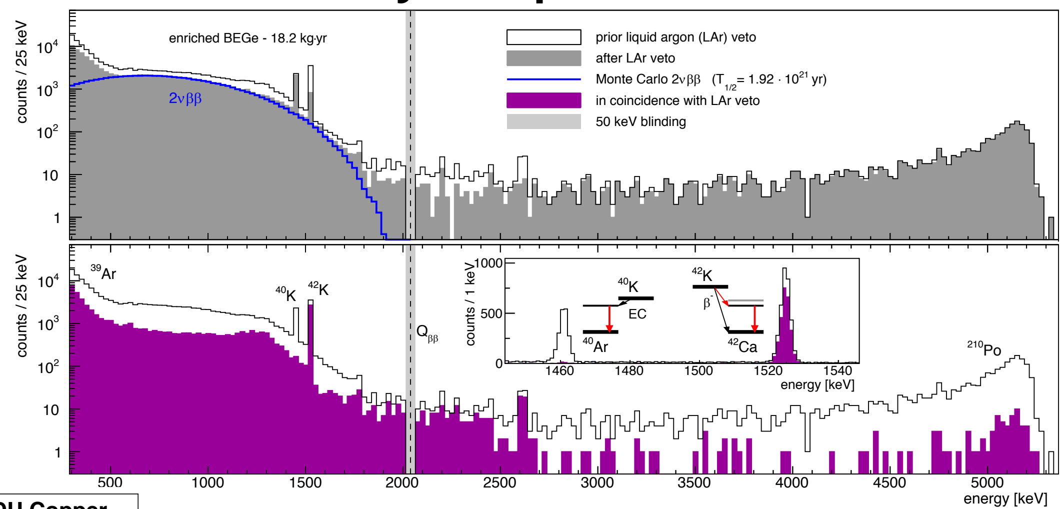


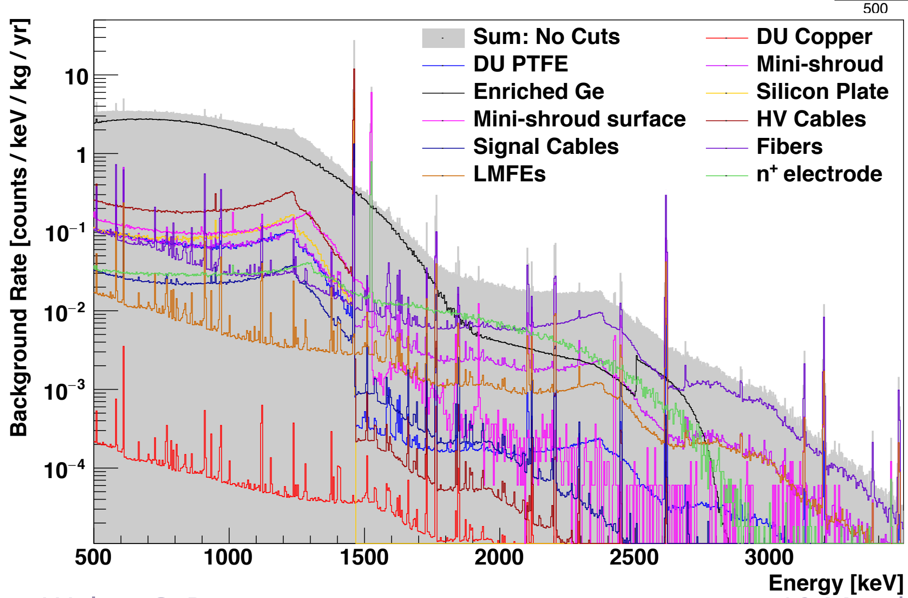
Reaching goal requires ~ x100 suppression from active veto and PSA cuts

Argon Background Highlights

- Loss of all spectral information below 500 keV in GERDA due to ^{39}Ar
- ^{42}K background estimate significant in ROI for LEGEND-200

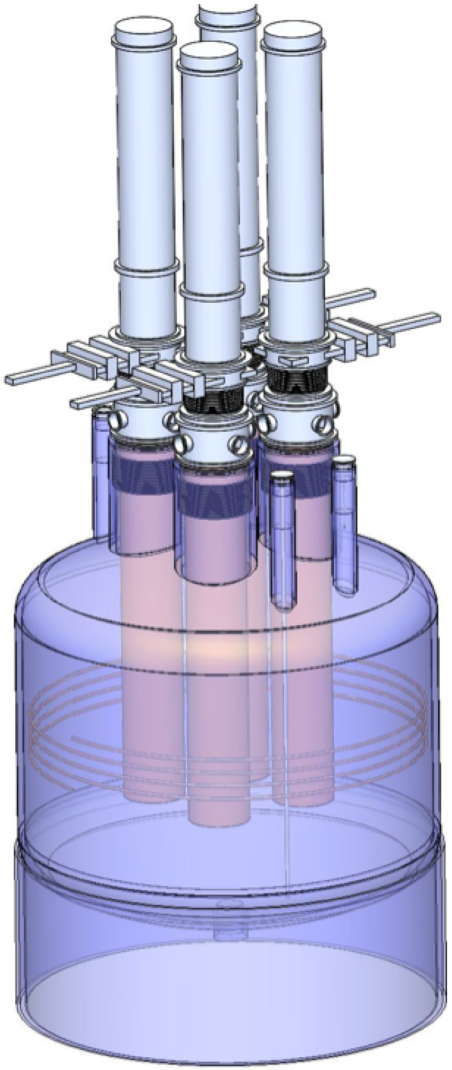
GERDA Physics Spectrum with LAr Cuts



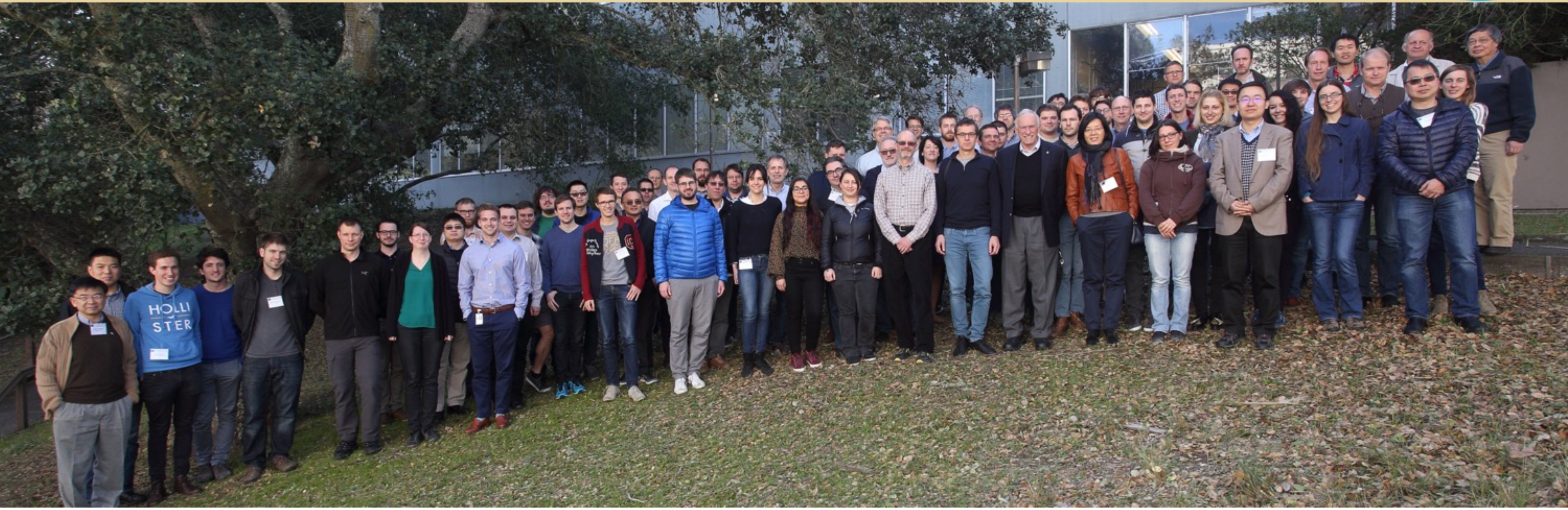


LEGEND–1000 and Underground Argon

- Liquid argon cryostat could be divided into four UAr detector volumes and large ^{nat}Ar volume
  - Copper dividing walls separate instrumentation of near-detector and broad veto
- Each detector tower assembly could be deployed into segregated UAr volume
  - Removes nylon mini-shrouds and allows near-detector argon volumes to be optimized for light collection efficiency
- Estimated UAr need:
  - 21 tons, 15 m^3



LEGEND Collaboration



47 institutions, 219 members

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Institute of Nuclear Research, RAS
Jagiellonian University
Joint Institute for Nuclear Research, Dubna
Joint Research Centre, Geel
Lab for Experimental Nuclear Physics, MEPhI
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