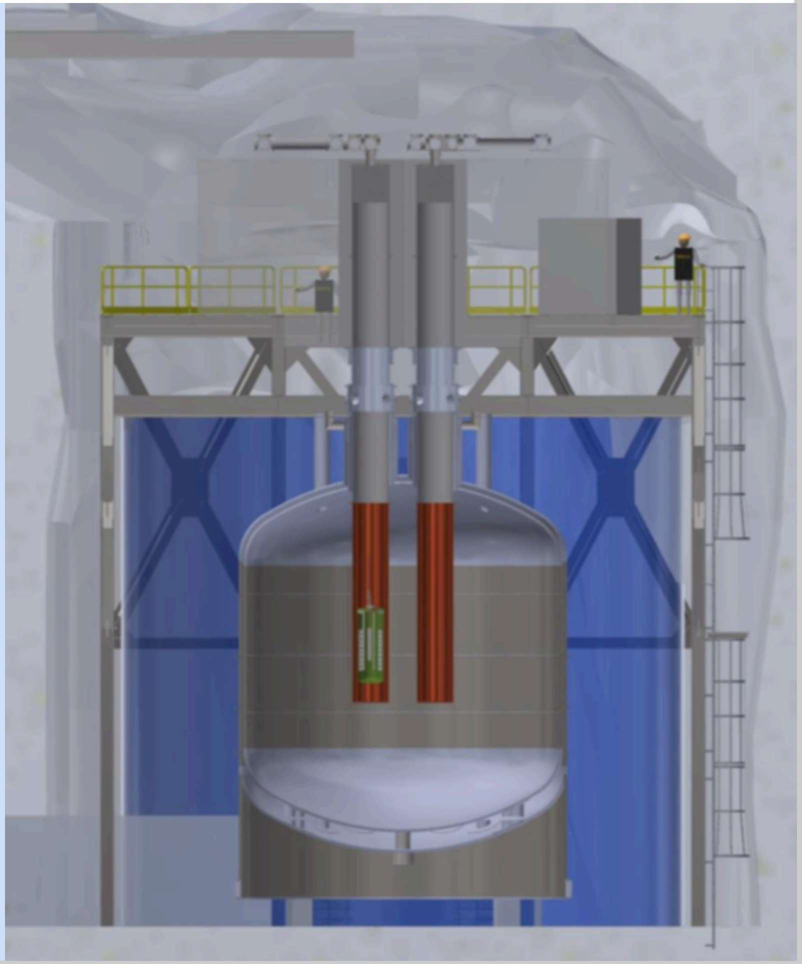
Estimation of Backgrounds in LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



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October 9, 2020

The 5th International Conference on Particle Physics and Astrophysics (ICPPA)

NC STATE UNIVERSITY
OAK RIDGE National Laboratory
TUNL Triangle Universities Nuclear Laboratory

Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay:

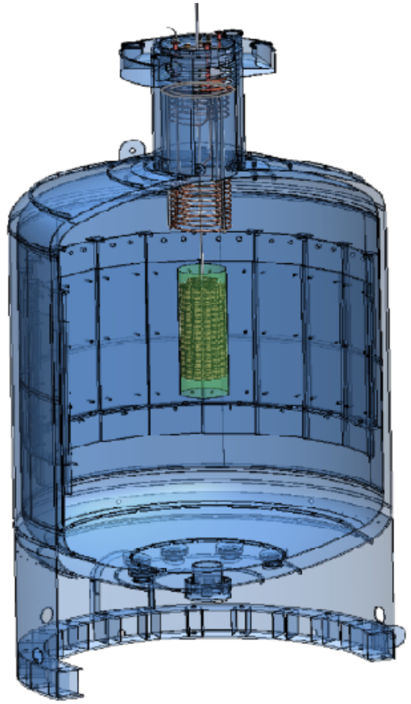
LEGEND mission: “The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life **beyond 10^{28} years**, using existing resources as appropriate to expedite physics results.”

LEGEND strategy: **Select the best technologies** based on what has been learned **from GERDA and the MAJORANA DEMONSTRATOR**, as well as contributions from other groups and experiments.

MAJORANA	**GERDA**	**Both:** Clean fabrication techniques
Radiopure nearby parts	LAr veto	Surface exposure control
Low noise / Low threshold electronics	Low-A shield	Development of large point-contact detectors

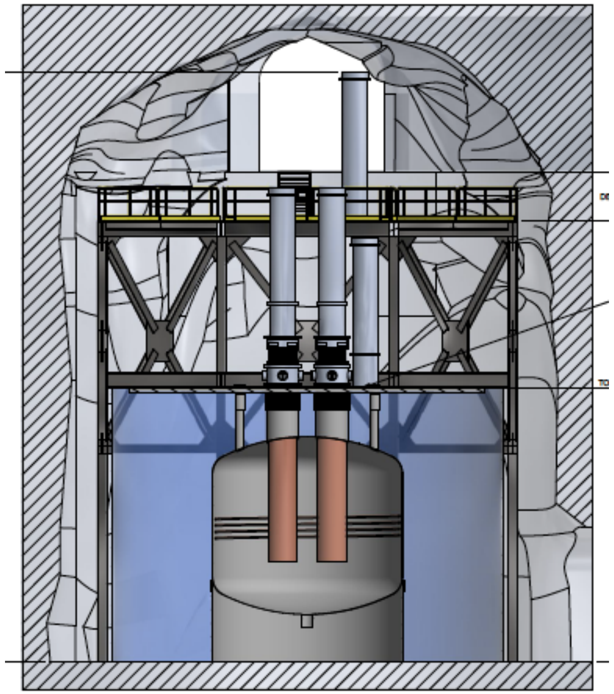
LEGEND-200

- 200 kg ^{enr}Ge in upgrade of existing infrastructure at LNGS
- Resolution: 2.5 keV FWHM
- BG goal:
  < 0.6 cts/(FWHM t yr)
- Will use GERDA and MAJORANA DEMONSTRATOR enriched detectors
- Data start ~2021

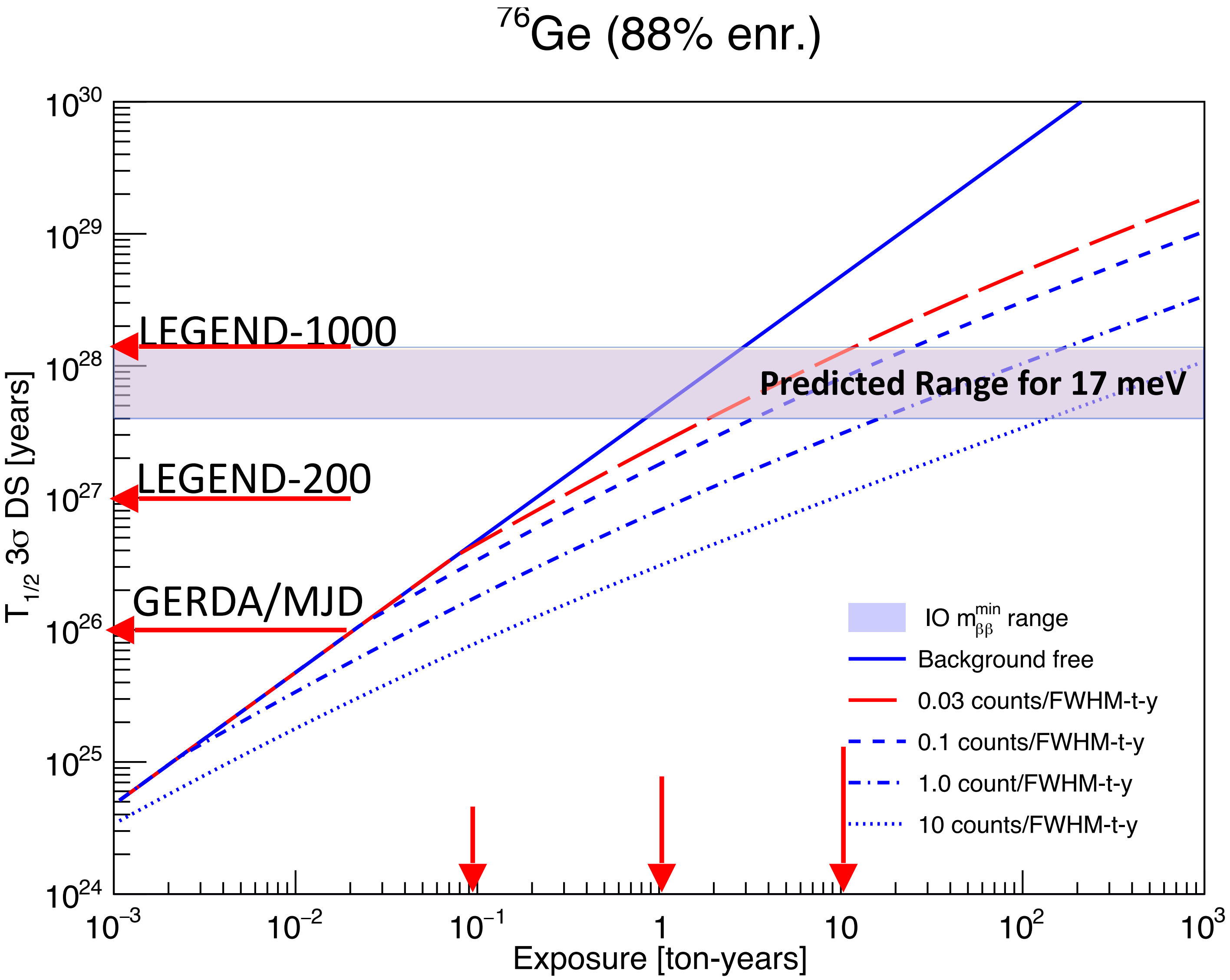


LEGEND-1000

- 1000 kg ^{enr}Ge (staged)
- Resolution: 2.5 keV FWHM
- BG goal:
  < 0.03 cts/(FWHM t yr)
- UG Location to be selected



Ge Discovery Potential



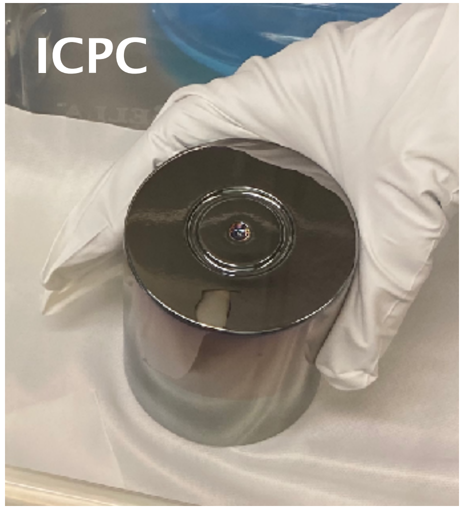
$>10^{28}$ yr or $m_{\beta\beta}$ = 17 meV for worst case matrix element of 3.5 and unquenched g_A.

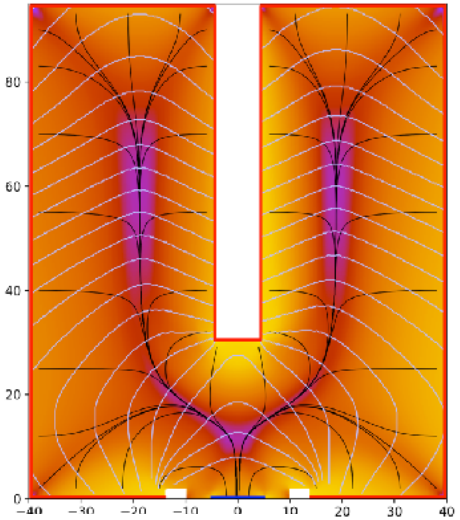
3σ discovery level to cover inverted ordering, given matrix element uncertainty.

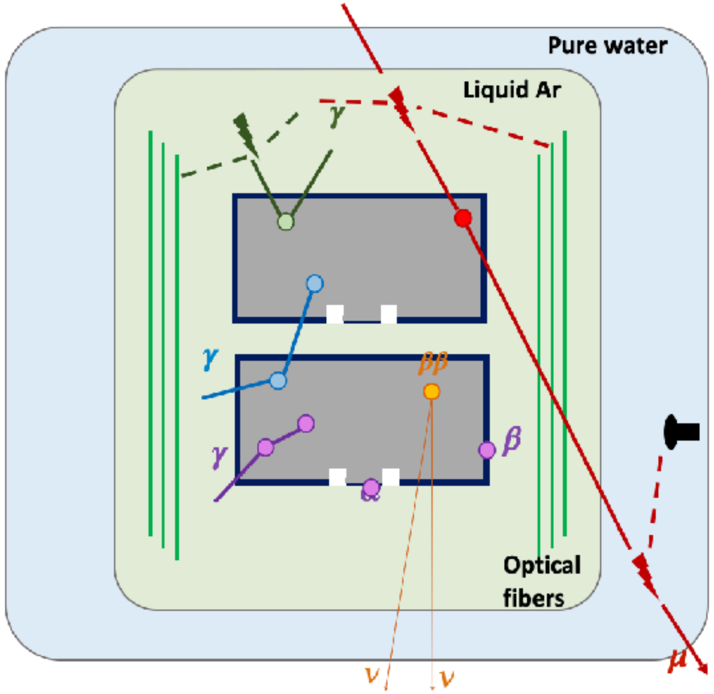
The LEGEND Approach to Backgrounds

- **Minimizing radioactive background:**
  - **Excellent energy resolution** afforded by PPC HPGe detectors (2.5 keV FWHM) yields a narrow $0\nu\beta\beta$ acceptance region
  - **Radiopure materials** developed for use in the MAJORANA DEMONSTRATOR and GERDA are used throughout LEGEND-200 and LEGEND-1000
  - **Large detectors** with masses in excess of 2 kg each (new ICPC detector design) to reduce backgrounds that scale with channel count.

- **Active background suppression:**
  - **Array granularity** removes multi-detector coincident events.
  - **Liquid argon veto** and low-mass components to maximize event energy collection and reject compton scatter events
  - **Pulse-shape discrimination** selects single-site events within germanium detectors ($0\nu\beta\beta$ events are characteristically single-site)



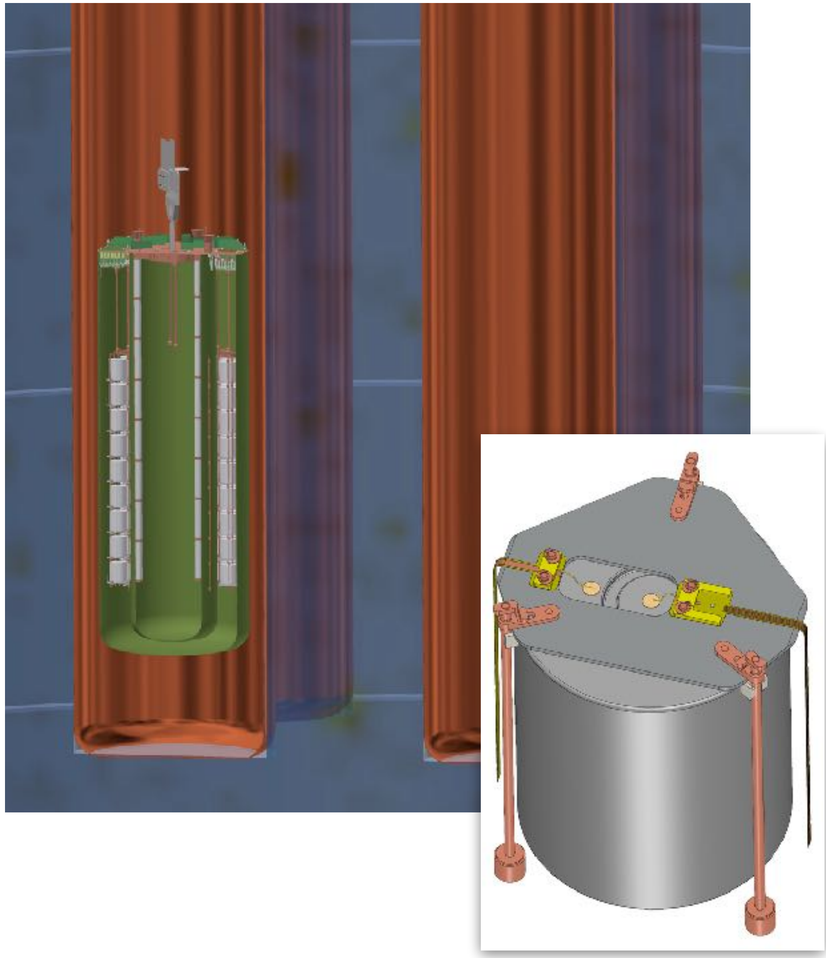




Primary Backgrounds in LEGEND

- Trace radioimpurities in **components near the array**.
- Cosmogenically-produced ^{42}**Ar present in LAr** active shield.
- **Cosmogenic activation of ^{enr}Ge** through material transport, detector fabrication, and detector delivery to site.
- **Alpha decays** on sensitive detector surfaces.
- Gamma and neutron backgrounds from **cryostat materials**.
- **Muon-Induced** backgrounds, prompt & delayed.

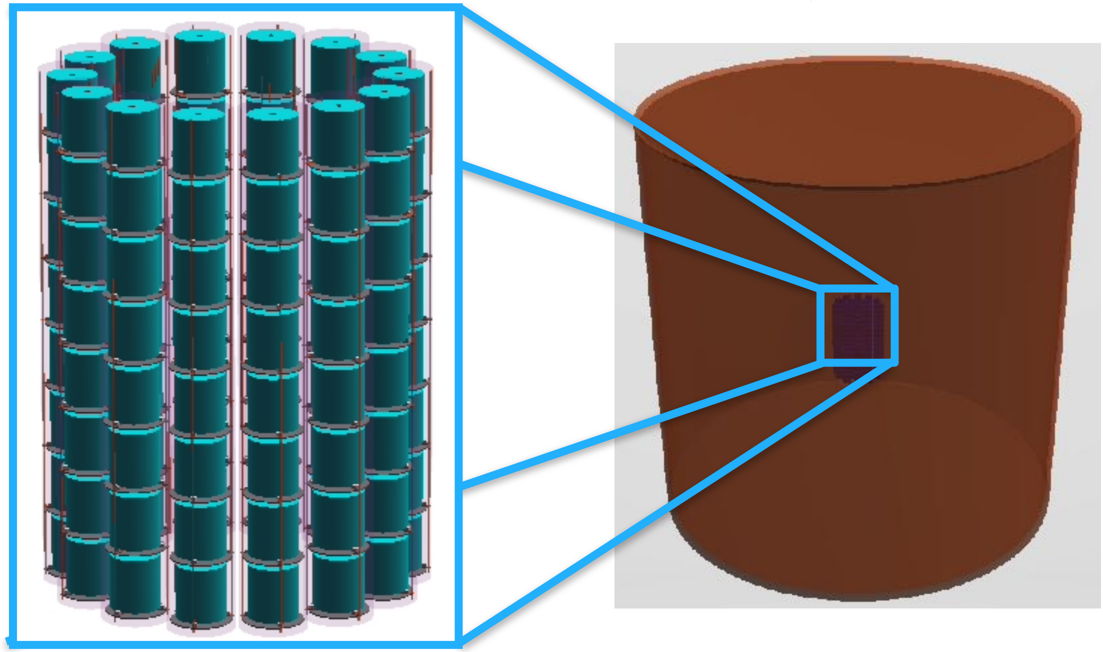
LEGEND-1000 4-Payload Baseline Configuration

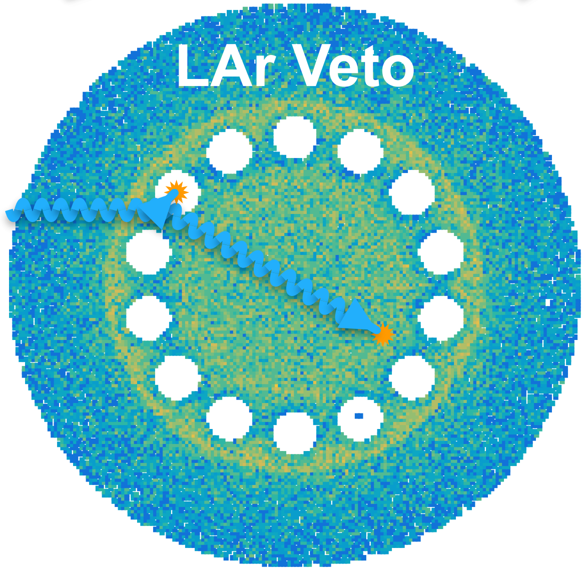


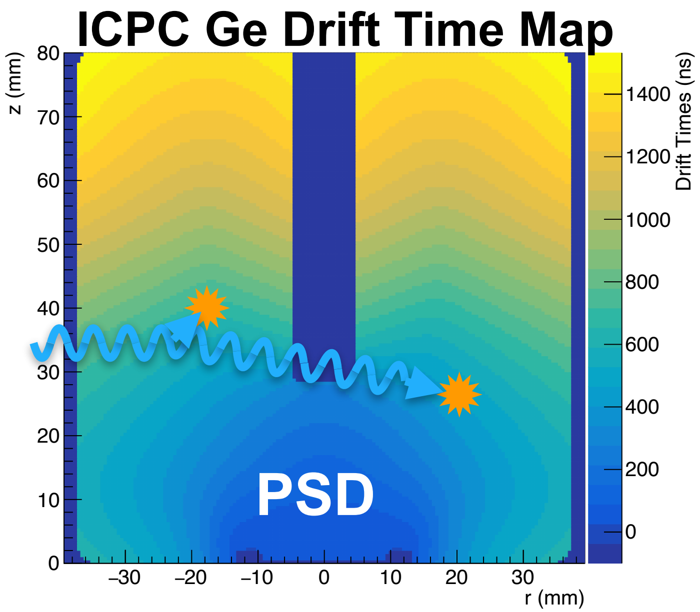
LEGEND Detector Unit

Background Simulations Overview

- MC simulations performed in Geant4 application: **MaGe**
  - Developed and used by GERDA and MAJORANA
  - Records energy-depositing steps in Ge, LAr
- Post-processing in **GAT**
  - Applies detector response to stepping data (resolution, transition layer)
  - Calculates expected number of detected scintillation photons in LAr veto
  - Estimates Pulse-Shape Discrimination







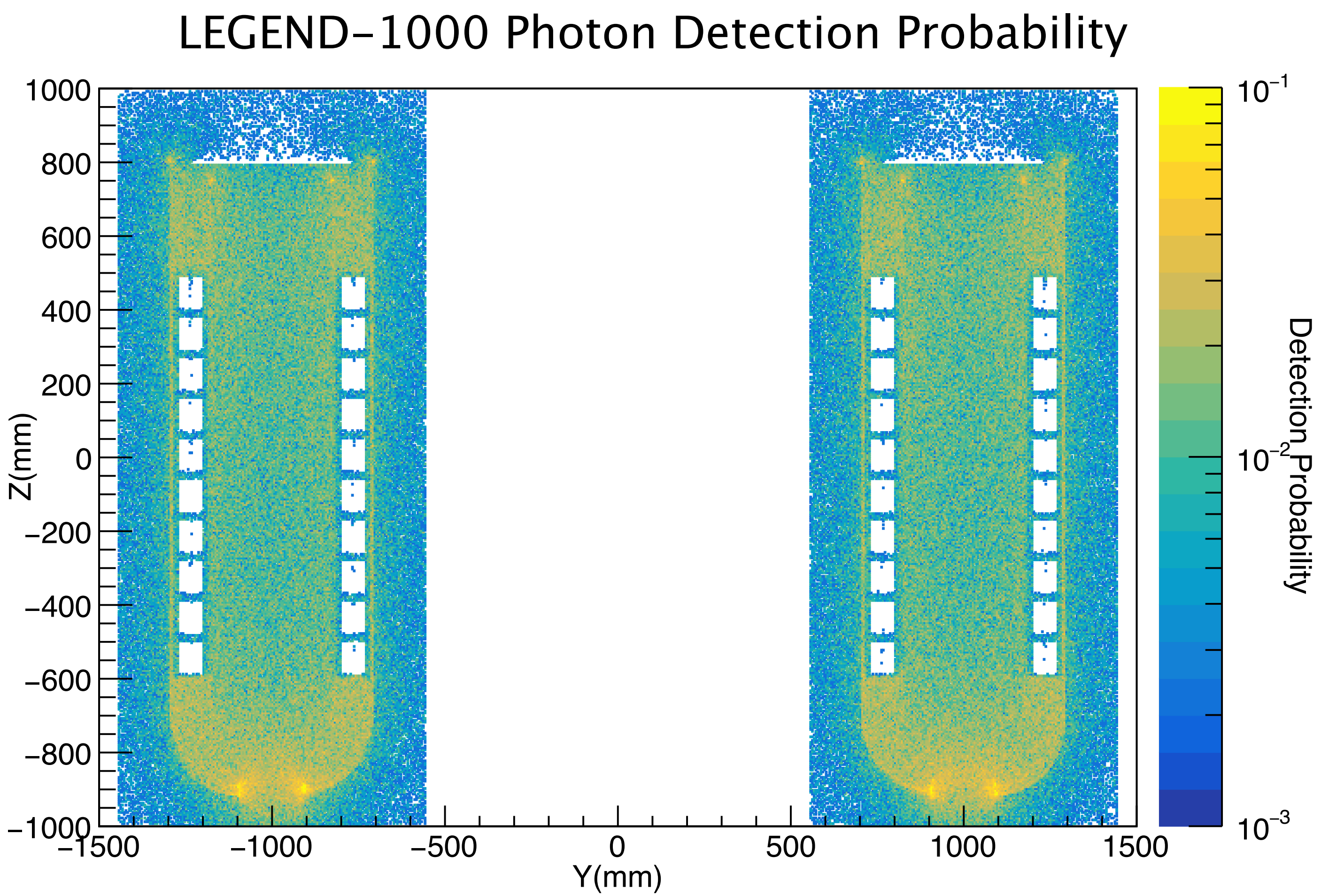
Background Suppression Estimation – LAr Veto

- Scintillation light propagation simulated separately from radioactive decays
- Photon detection probability maps generated
  - Internal to the array: 3D (x, y, z) map, $(5\text{mm})^3$ voxels
  - External to the array: 2D (r, z) map

$$\langle NPEs \rangle = \sum_{i}^{\text{steps}} E_i \times P_i(x, y, z) \times Y \times QE$$

- For these calculations:
  - LAr photon yield (Y): 20,000 / MeV
  - SiPM QE: 0.164
- LAr veto cut emulated by weighting each event by the likelihood of detecting 0 PEs, assuming Poisson distribution with mean <NPEs>:

$$W_{event} = \exp\left(- \langle NPEs \rangle\right)$$



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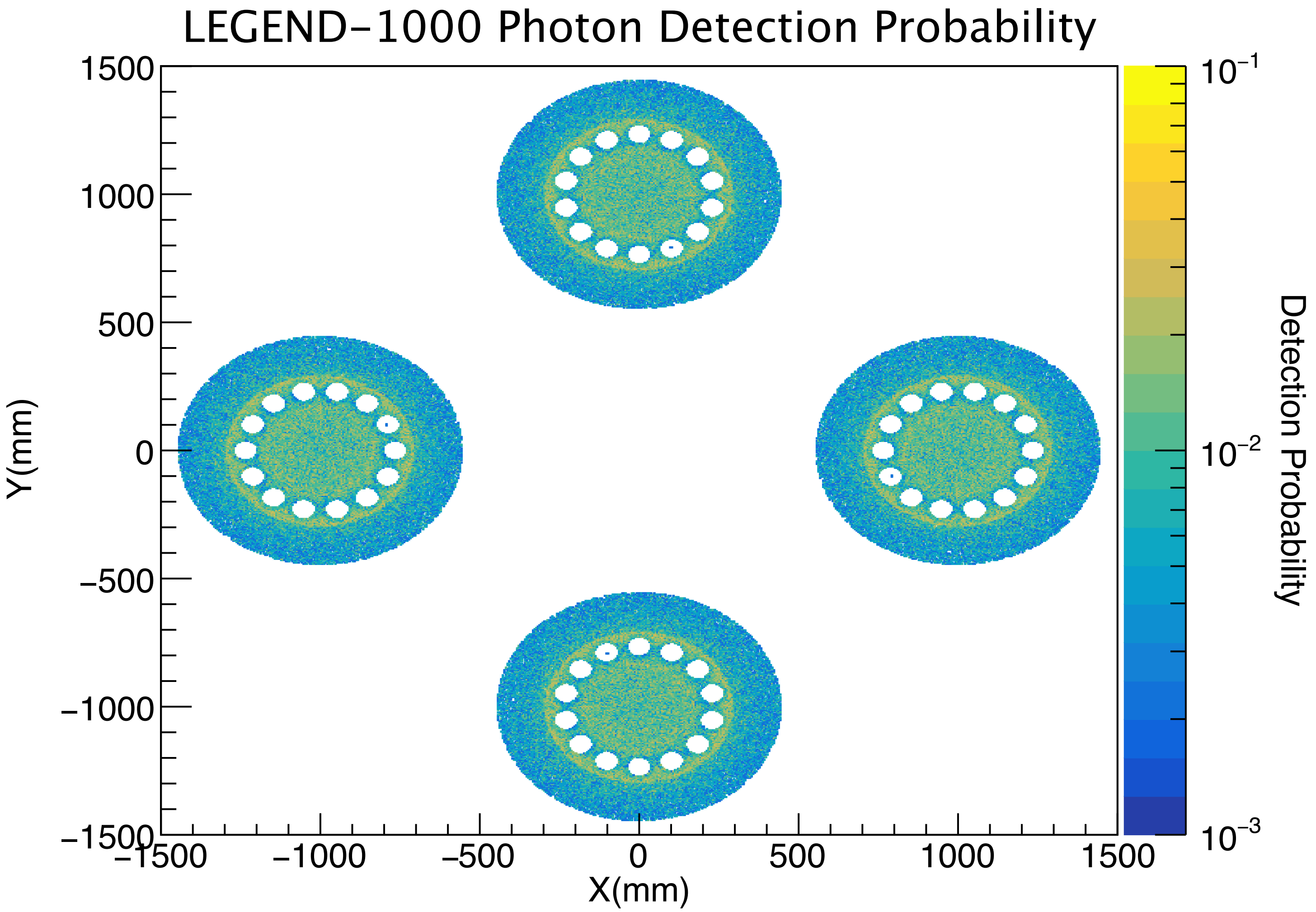
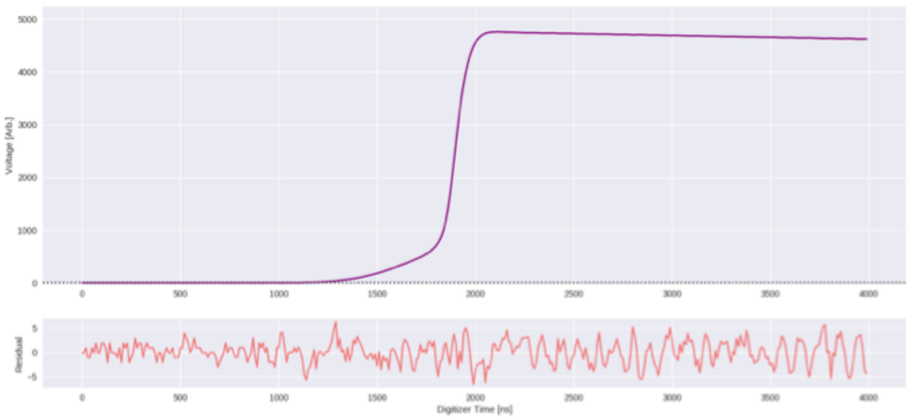
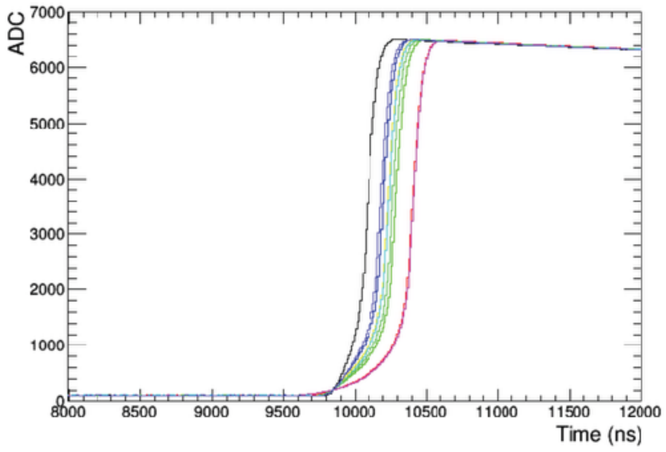


Background Suppression Estimation – PSD

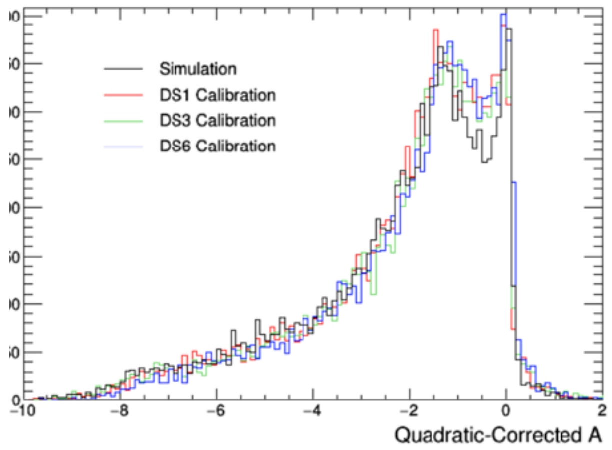
- Currently use drift time separation heuristic method to estimate PSA effectiveness for multi-site gamma events.
  - Tuned to detector characterization measurements.
- Beta n+ response modeling requires PSS.
- Pulse Shape Simulations:
  - SIGGEN-based PSS developed for MJD simulations post-processing. Requires understanding of electrical response of individual channels.
  - Parameters can be set and tuned for prototypical ICPC detector, post-processing evaluated for LEGEND sims.



Simulation Calibration Data



FEP A_{corr} Comparison

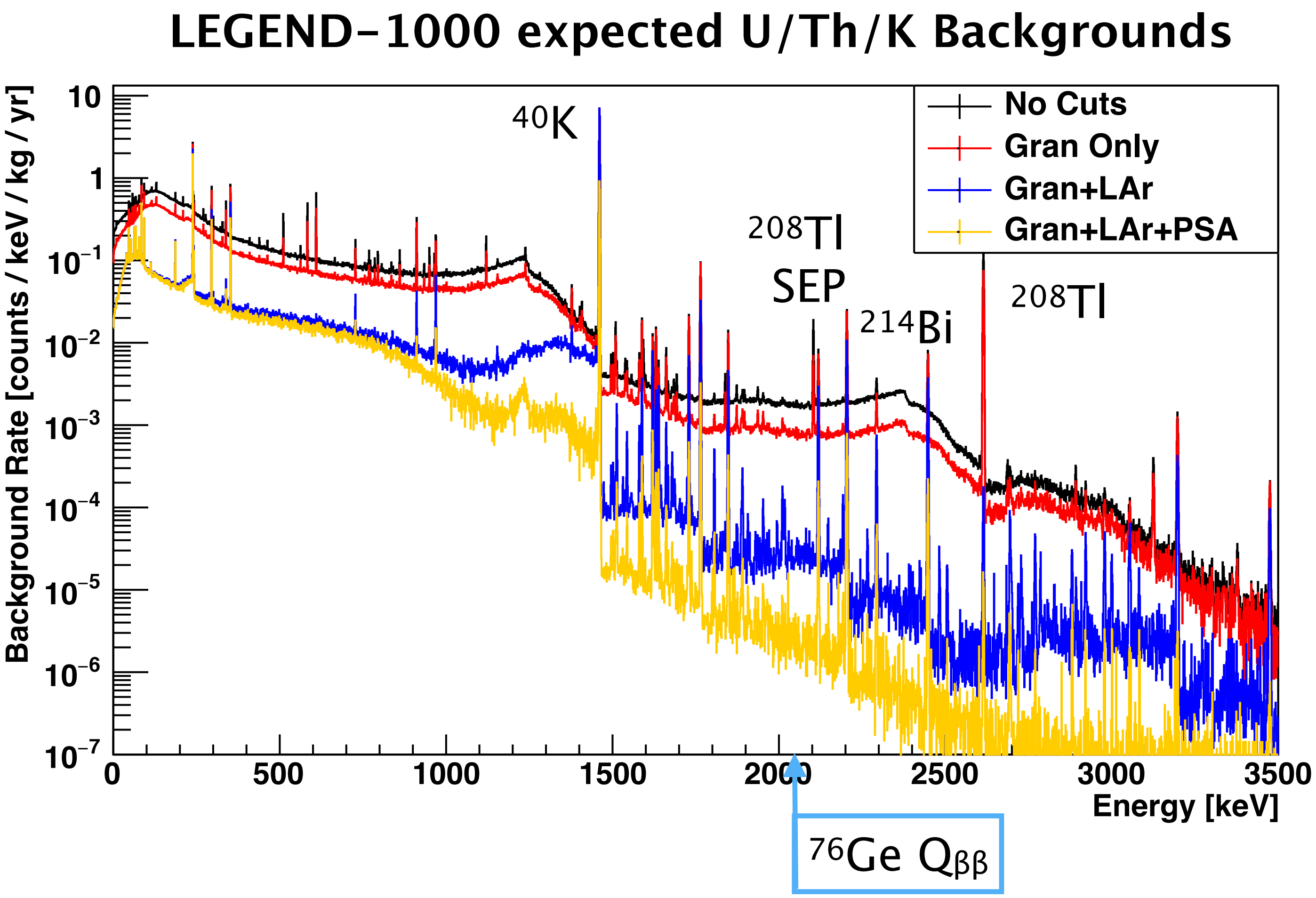


PDFs & Efficiency Estimation

370-keV window [1950-2350, excluding known gamma lines] used for estimation of efficiencies and background indices

Efficiency (counts / decay / keV) calculated for sequentially applied background suppression cuts:

- No cuts
- Granularity Cut: single germanium detector only
- LAr: Event weighted by likelihood of not triggering LAr veto
- PSA: Drift time separation below threshold (16ns for 1 MeV)

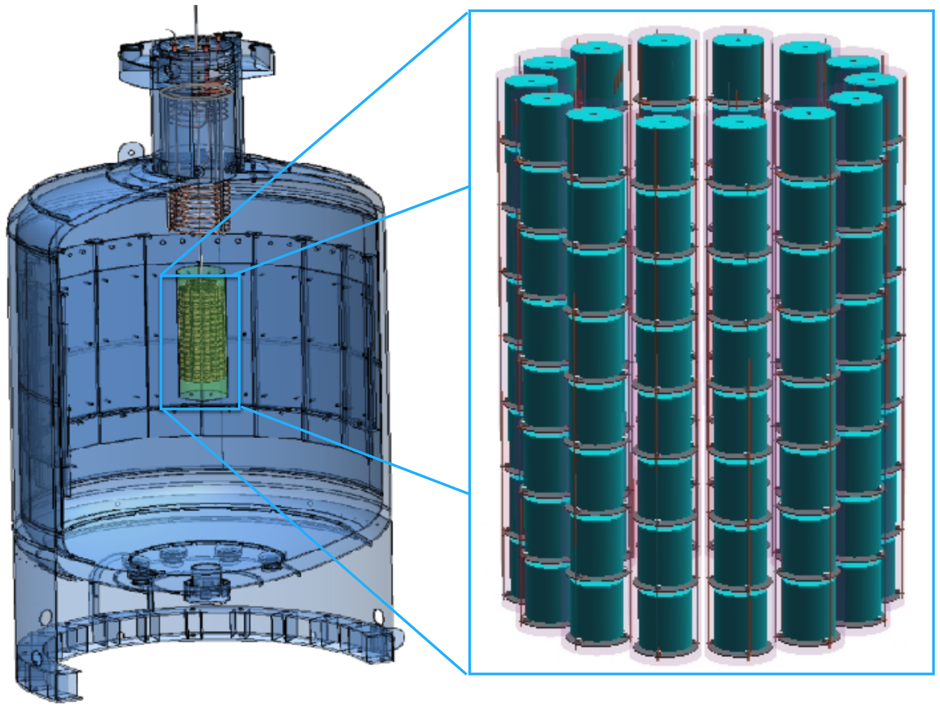


Estimated Background Suppression:
^{238}U chain: 10^2
^{232}Th chain: 10^4

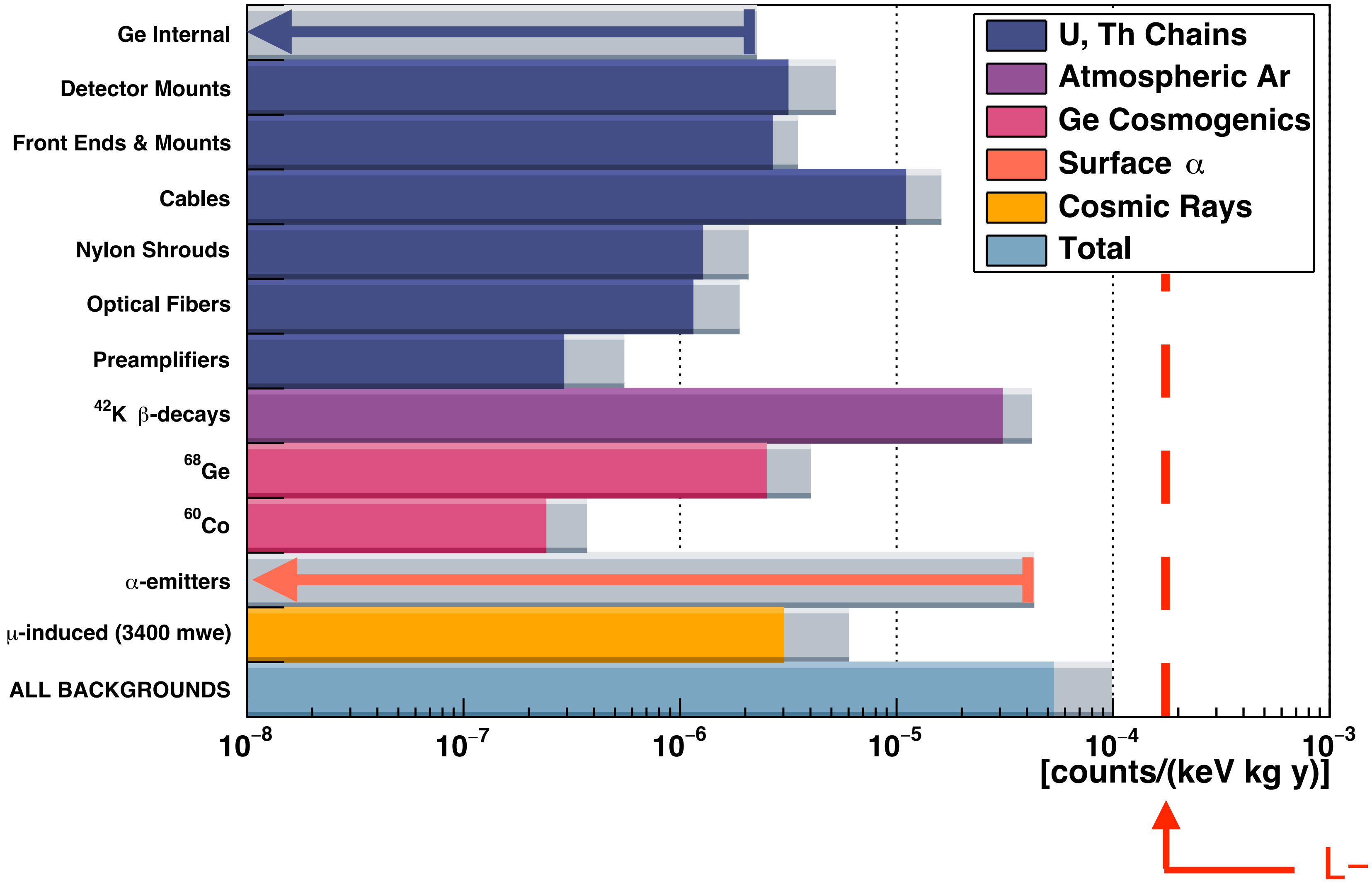
LEGEND-200 Backgrounds

Improvements over GERDA:

- Improved material radiopurity.
- Sparse array lowers likelihood for detection at $0\nu\beta\beta$ energy.
- Improved rejection through larger detectors (PSD) and better scintillation light collection.



LEGEND-200 Background Projections



Background contributions near $Q_{\beta\beta}$ after all cuts

Monte Carlo + data-driven projections of Ge U/Th, ^{42}K, α based on GERDA, MJD data

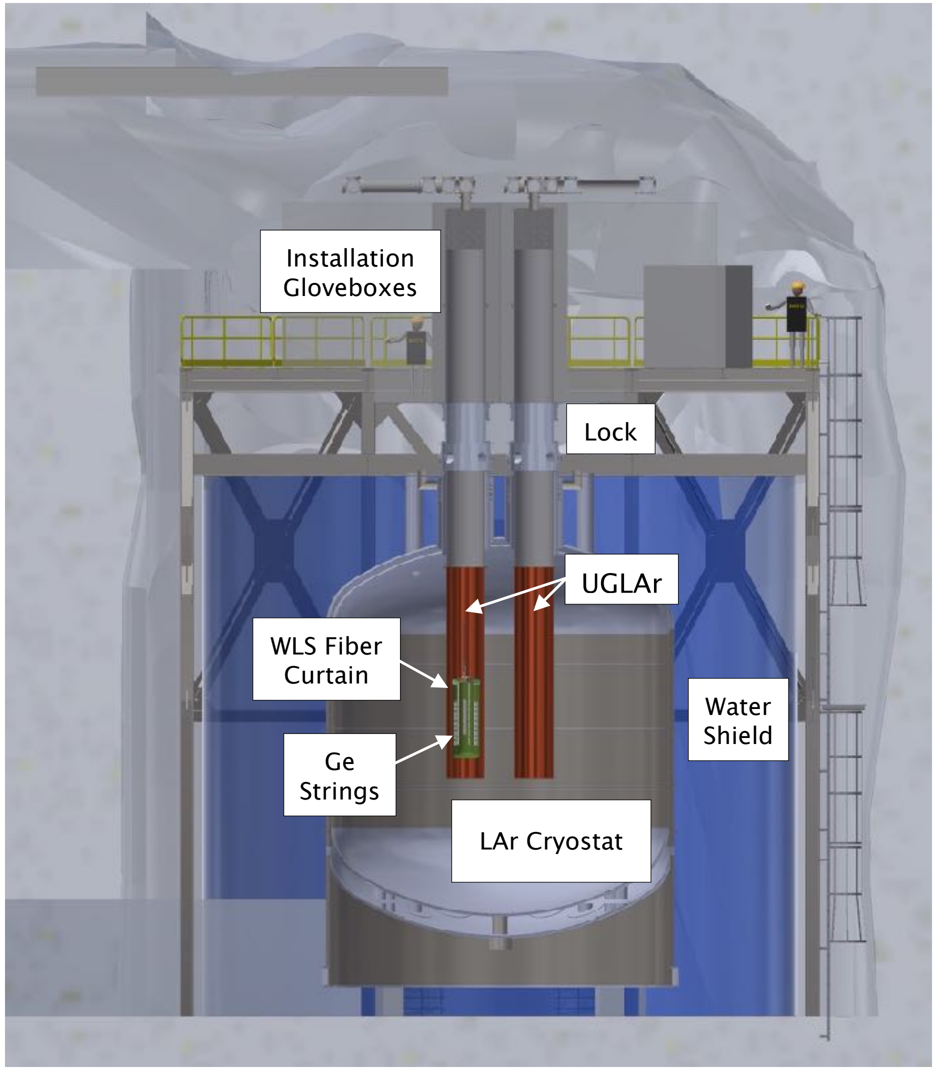
All others: Monte Carlo + assay-based projections

Grey bands indicate uncertainties in assays and background rejection

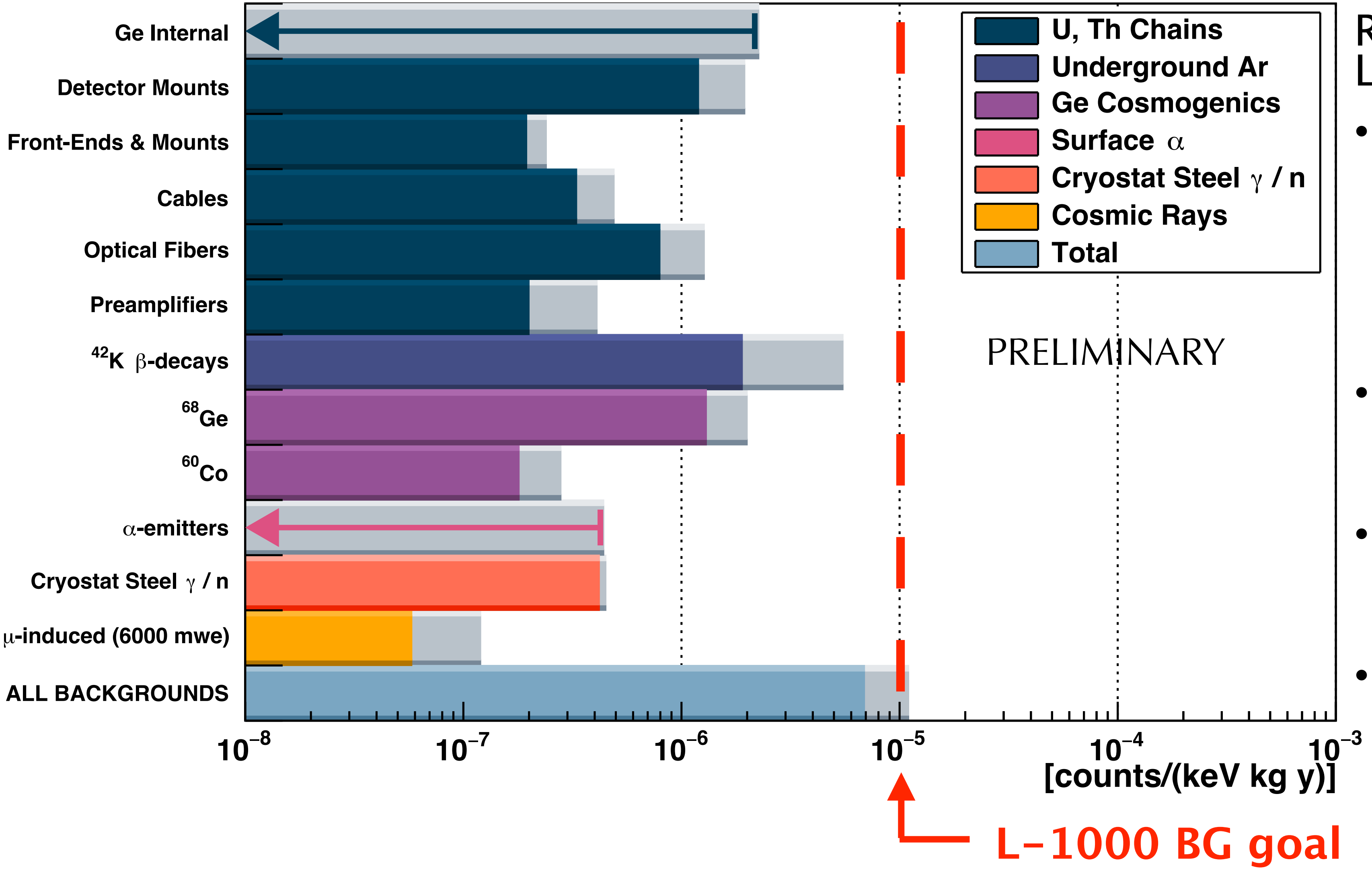
LEGEND-1000 Baseline Design Backgrounds

Improvements over LEGEND-200:

- Argon sourced from underground deposits reduced in ^{42}Ar (pioneered by DarkSide).
- Additional overburden to reduce muon-induced backgrounds (prompt & delayed).
- New detector designs: larger mass, less sensitive to surface α-emitters.
- Lower background front-end electronics (ASIC) and cabling.



LEGEND-1000 Background Projections



Reductions for LEGEND-1000:

- **U/Th**: optimized array spacing, minimize opaque materials, larger detectors, better light collection, cleaner materials
- **^{42}Ar**: drastically reduced by using underground sourced Ar
- **μ-induced**: Improved shielding, SNOLab depth assumed
- **Surface α's**: assumes achieved UL for BEGes and ICPCs in GERDA

Conclusion

- LEGEND-200, a straightforward design evolution of GERDA and the MAJORANA DEMONSTRATOR, is very likely to meet its background goal of **$2x10^{-4}$ counts/(keV-kg-yr),** enabling discovery sensitivity for 0νββ lifetimes in excess of 10^{27} years within 5 years of operation.

- The LEGEND-1000 baseline design, which further builds upon this model, is projected to reach a background below its goal of of **$1x10^{-5}$ counts/(keV-kg-yr),** enabling 0νββ discovery sensitivity at half-lives in excess of 10^{28} years within 10 years of operation.

- As simulations are completed and processed, and new material assays performed, this model will be refined and the background estimate updated.

- Detector characterization measurements, LEGEND-200 data will validate LEGEND-1000 background model, drive adjustments to methods and estimates as necessary to inform necessary design modifications.

The LEGEND Collaboration

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University of South Carolina
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48 Institutions, ~240 Scientists