LEGEND-1000
Technical Update

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

D. Radford

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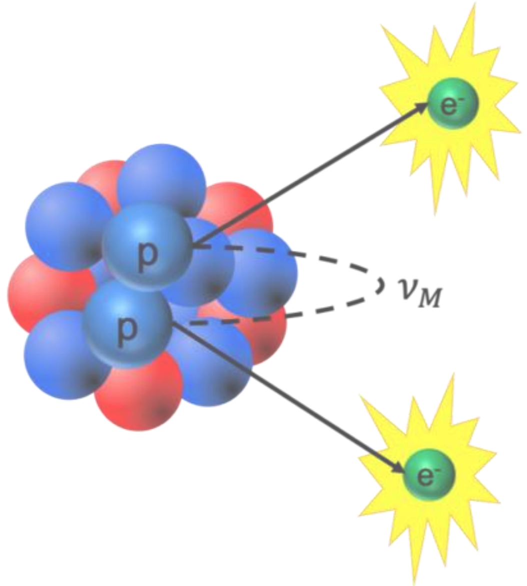
Why Neutrinoless Double Beta Decay?

- The discovery of 0νββ decay would dramatically revise our foundational understanding of physics and the cosmos
  - Lepton number is not conserved
  - The neutrino is a fundamental Majorana particle
  - There is a potential path for understanding the matter – antimatter asymmetry in the cosmos, through leptogenesis
  - There is a new mechanism demonstrated for the generation of mass



- The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics
- The LEGEND Collaboration aspires to meet this challenge through a ton-scale search for 0νββ decay of ^{76}Ge

The LEGEND Collaboration

- The goal of the LEGEND Collaboration is to design, construct, and field LEGEND-1000, a ton-scale experiment
  - *"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 LEGEND collaboration was formed in 2016 through a merger of the MAJORANA and GERDA collaborations, along with several new institutions
- It includes about 260 members, 48 institutions, 11 countries

The LEGEND Collaboration

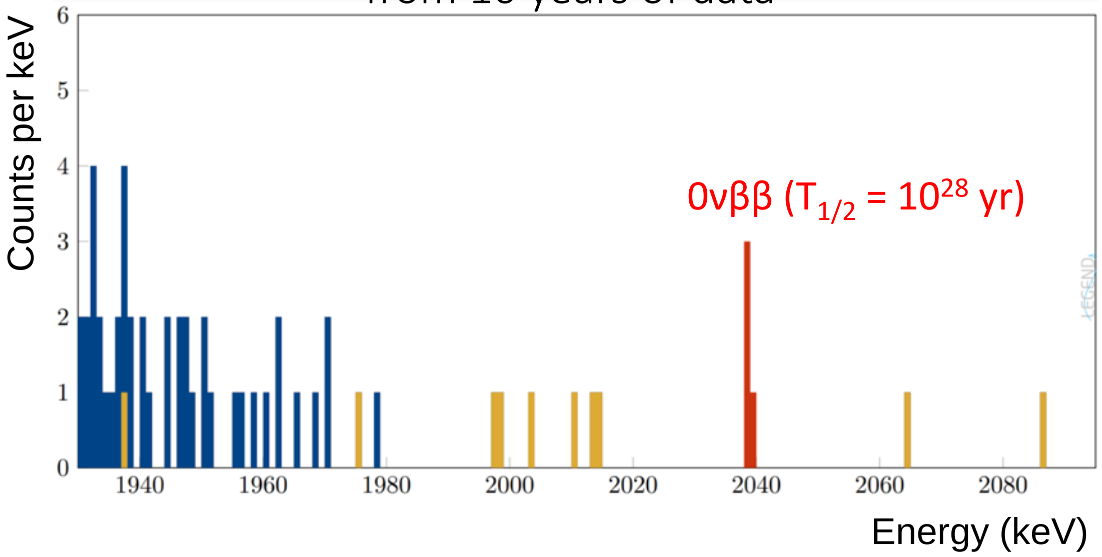
260 members, 48 institutions, 11 countries

The LEGEND-1000 Discovery Sensitivity

"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..."

- What is required for a discovery of $0\nu\beta\beta$ decay at a half-life of 10^{28} years?
- This is less than one decay per year per ton of material
  - Need 10 ton-years of data to get a few counts
  - Need a good signal-to-background ratio to get statistical significance
    - A very low **background event rate**
    - The best possible **energy resolution**

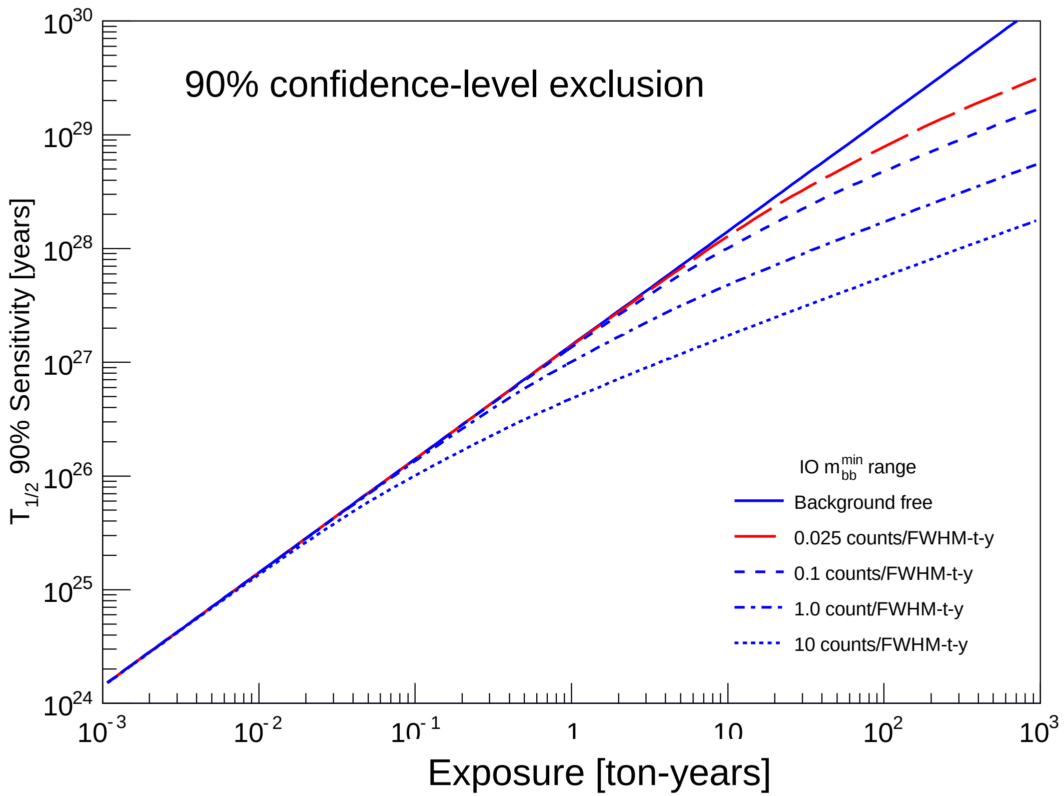
Typical simulated example spectrum, after cuts, from 10 years of data

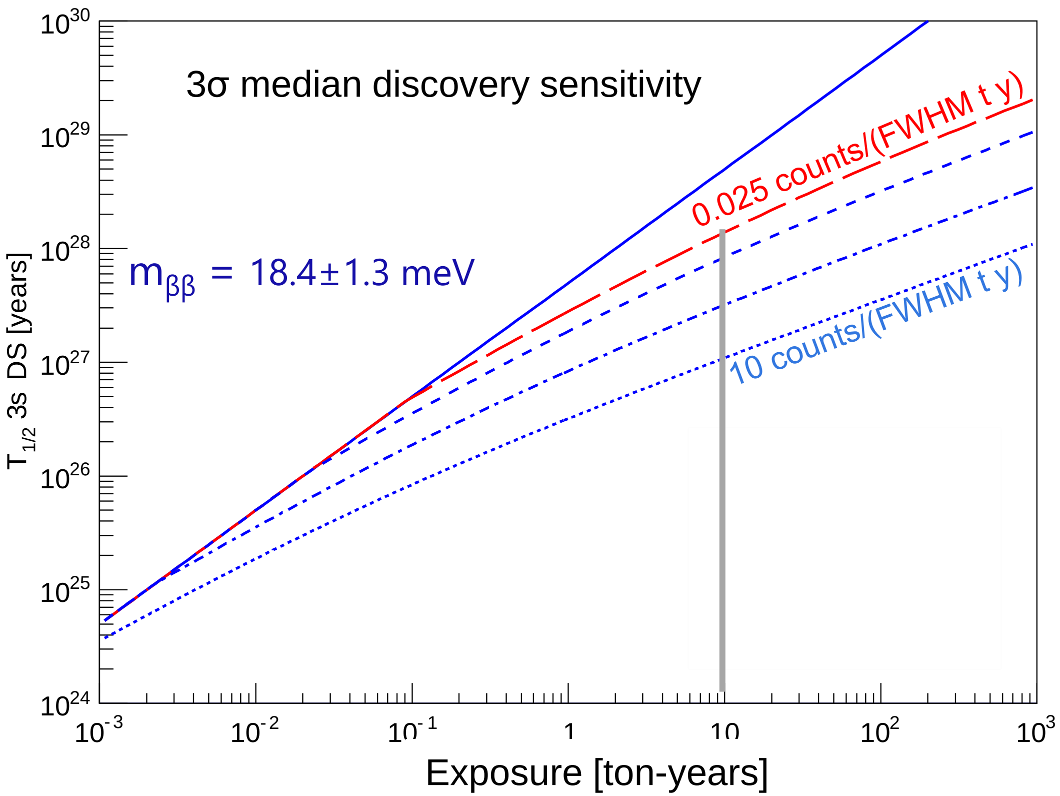


The Effect of Background

- Background-free: Sensitivity rises linearly with exposure
  Background-limited: Sensitivity rises as the square root of exposure
- Our background goal is the red line, 0.025 counts/(FWHM t y), “quasi-background-free”
  - *Less than one background count* expected in a 4σ Region of Interest (ROI) with 10 t y exposure

    (FWHM: Full Width at Half Maximum; 2.355 σ for a Gaussian peak)





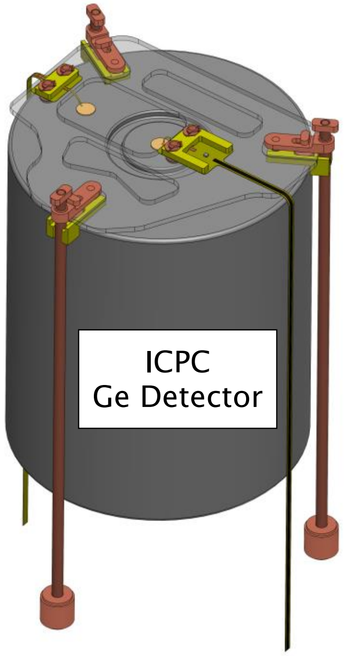
LEGEND-1000: Experiment Overview

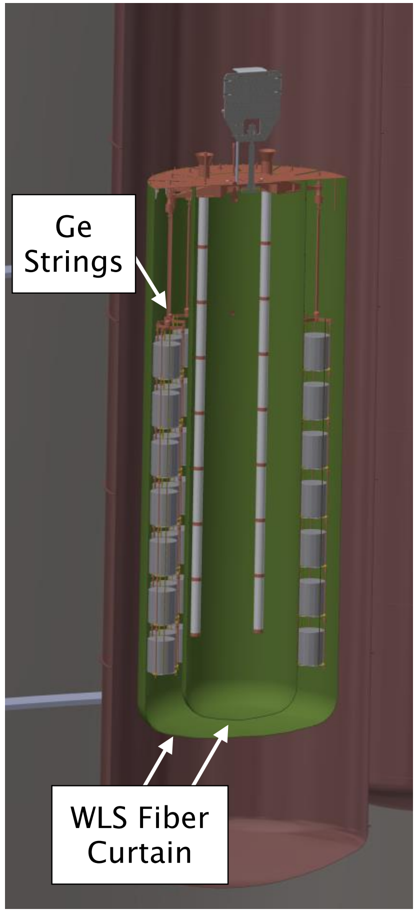
1000 kg of enriched Ge detectors (92% ^{76}Ge)

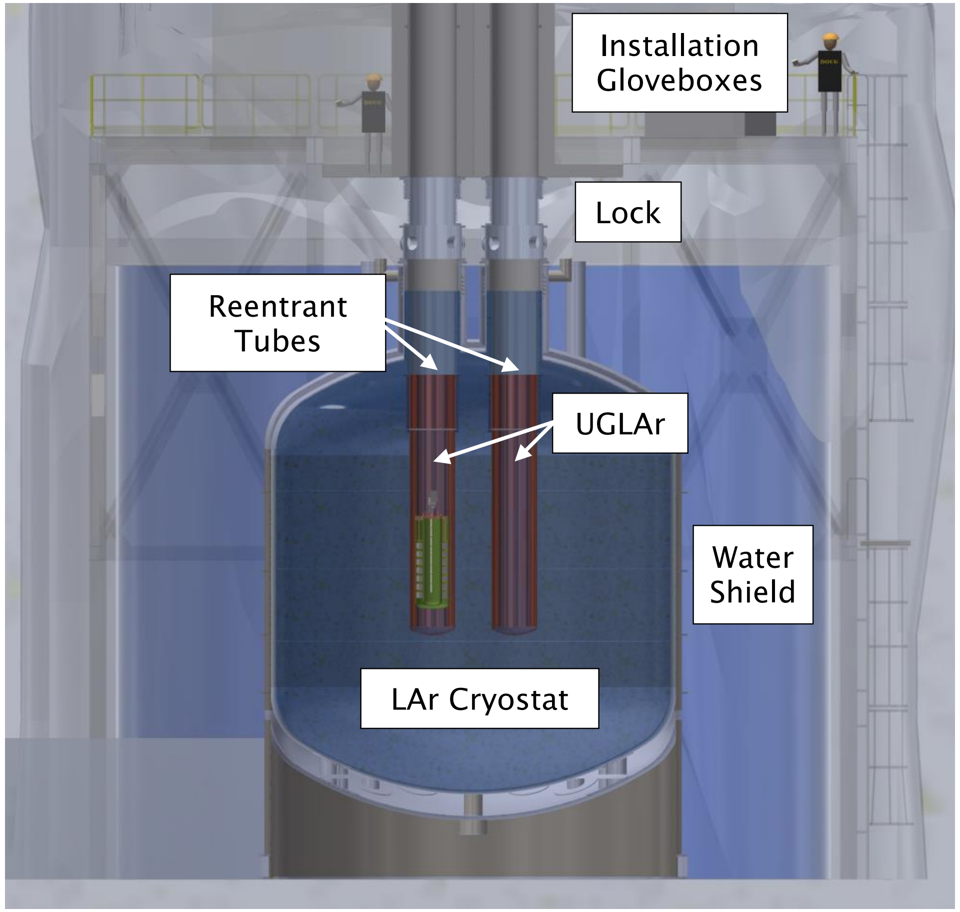
- 2.6 kg average mass
- Mounted in “strings” using components made from electro-formed Cu and scintillating plastic, PEN
- ASIC readout front-end electronics

- Arranged in 4 modules
- ~100 detectors per module

- Underground-sourced LAr active shield
- Dual fiber-curtain LAr instrumentation
- EFCu Reentrant tubes



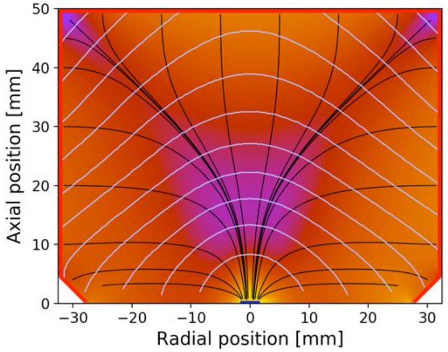




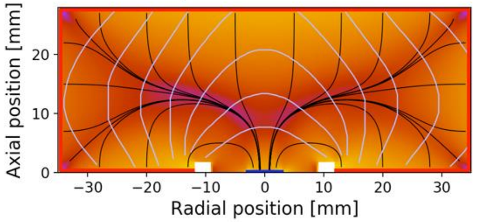
Innovation toward LEGEND-1000: ^{enr}Ge Detectors

- Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
- P-type detectors: Insensitive to alphas on n^+ outer contact
- Small p^+ contact: Event topology discrimination
- Large-mass ICPC detectors: About 4 times lower backgrounds compared to BEGes / PPCs
- Proven long-term stable operation in LAr

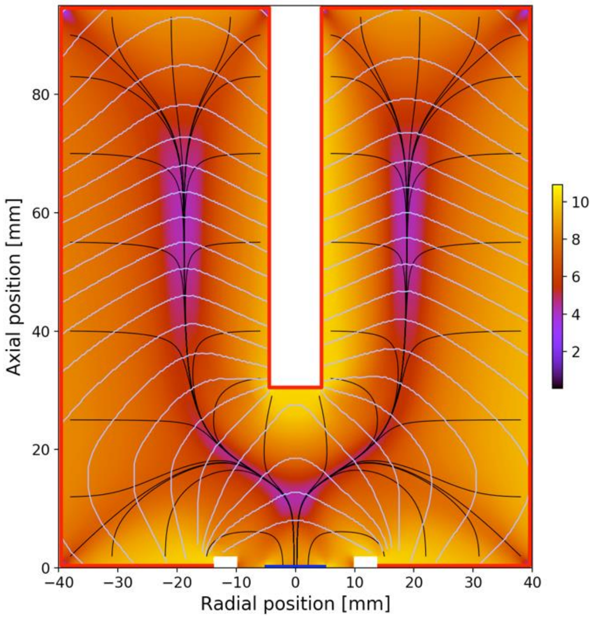
MAJORANA (PPC)

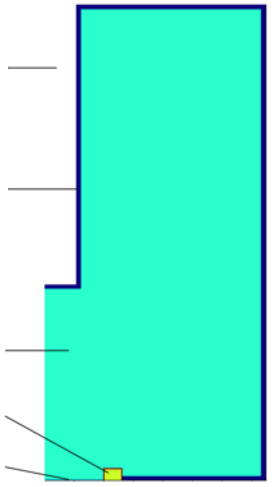


GERDA (BEGe)



LEGEND (ICPC)

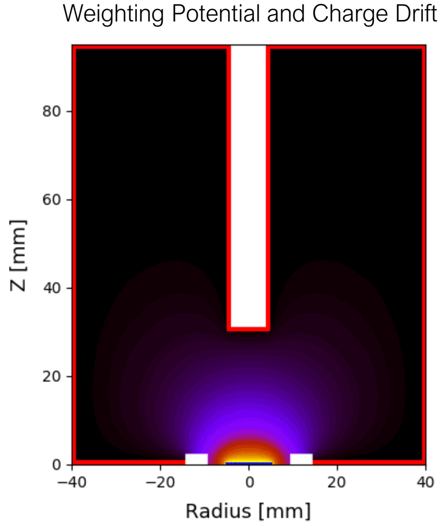


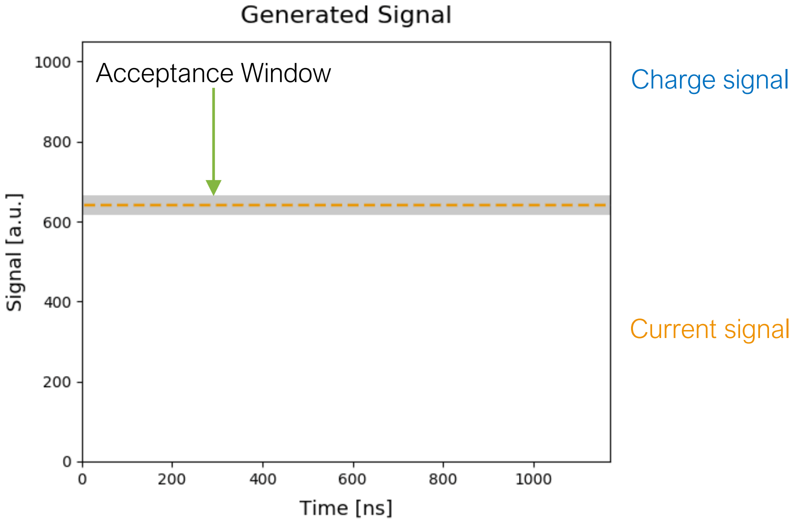


Innovation toward LEGEND-1000: ICPC Ge Detectors

$0\nu\beta\beta$ signal candidate (single-site)

Event Topologies





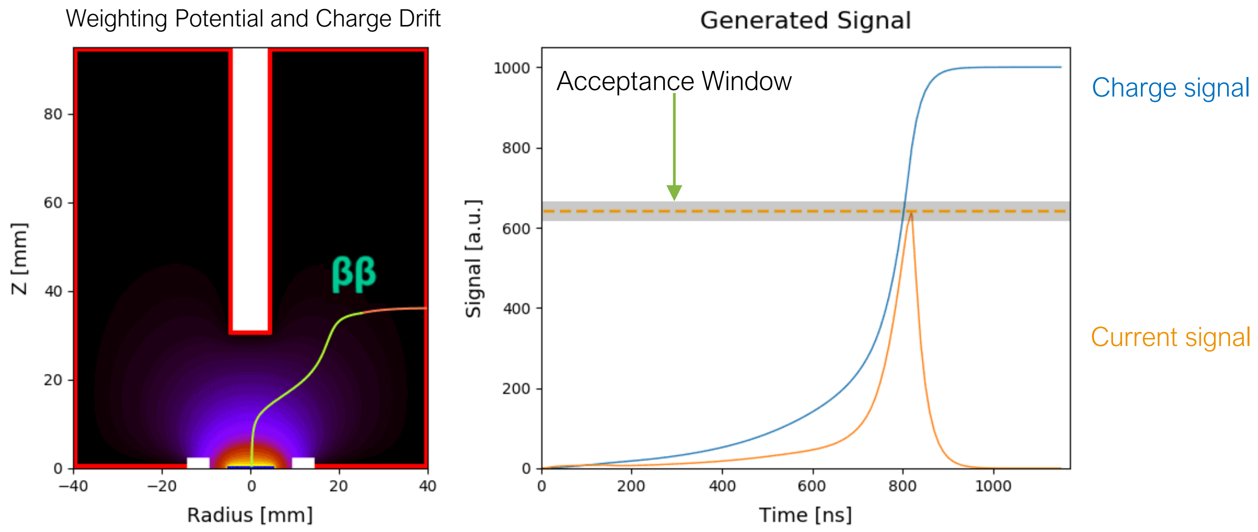
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

Weighting Potential: ϕ_w

animation only visible in pptx

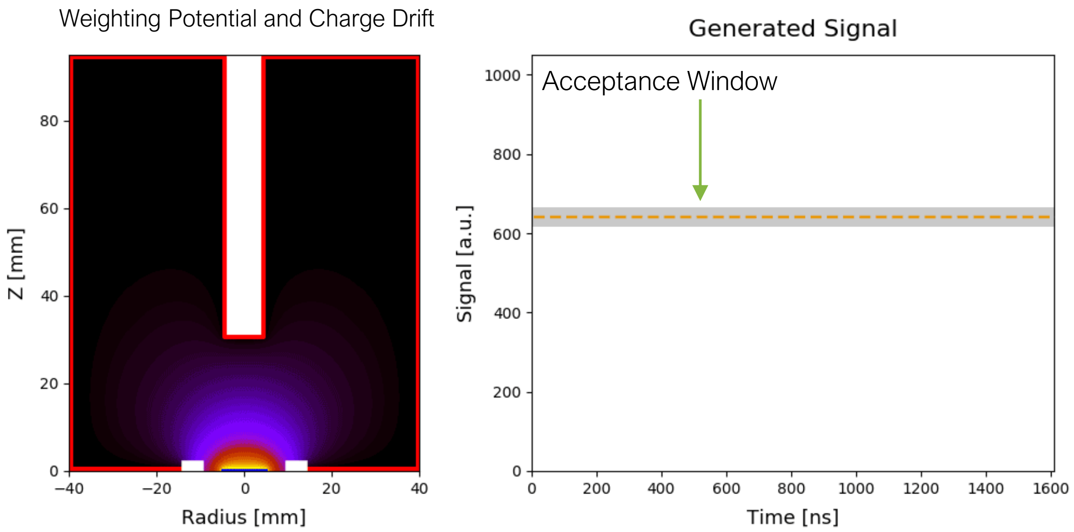
Innovation toward LEGEND-1000: ICPC Ge Detectors

0νββ signal candidate (single-site)



Event Topologies

γ-background (multi-site)



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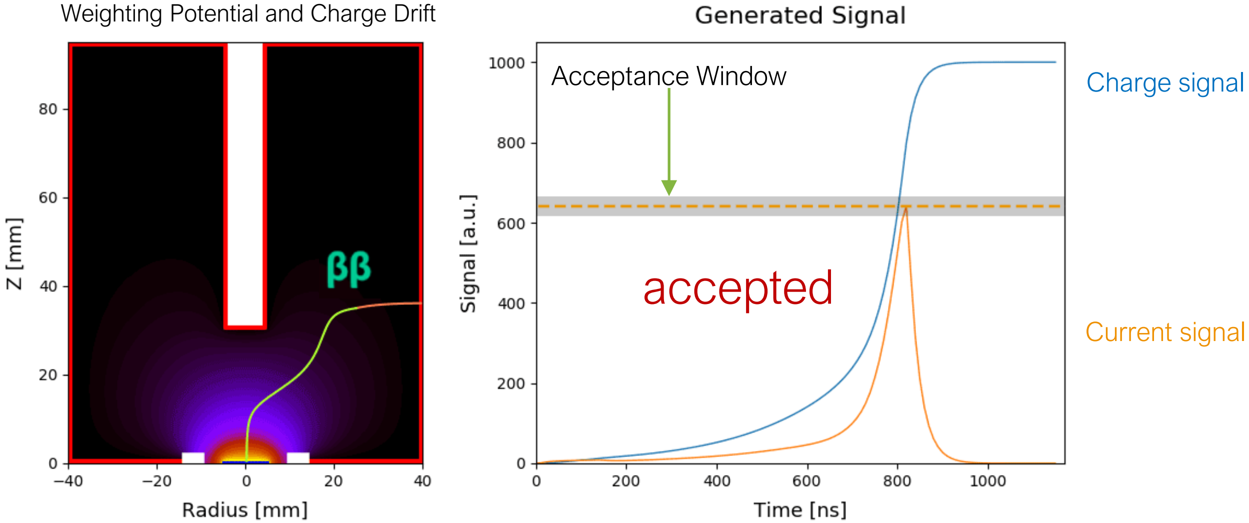
Innovation toward LEGEND-1000: ICPC Ge Detectors

Event Topologies

$0\nu\beta\beta$ signal candidate (single-site)



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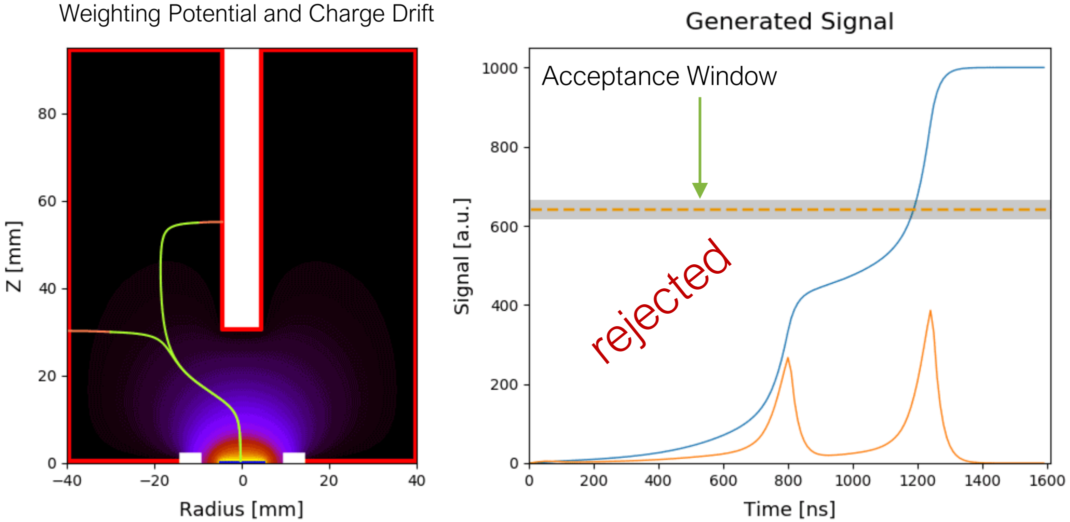


Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

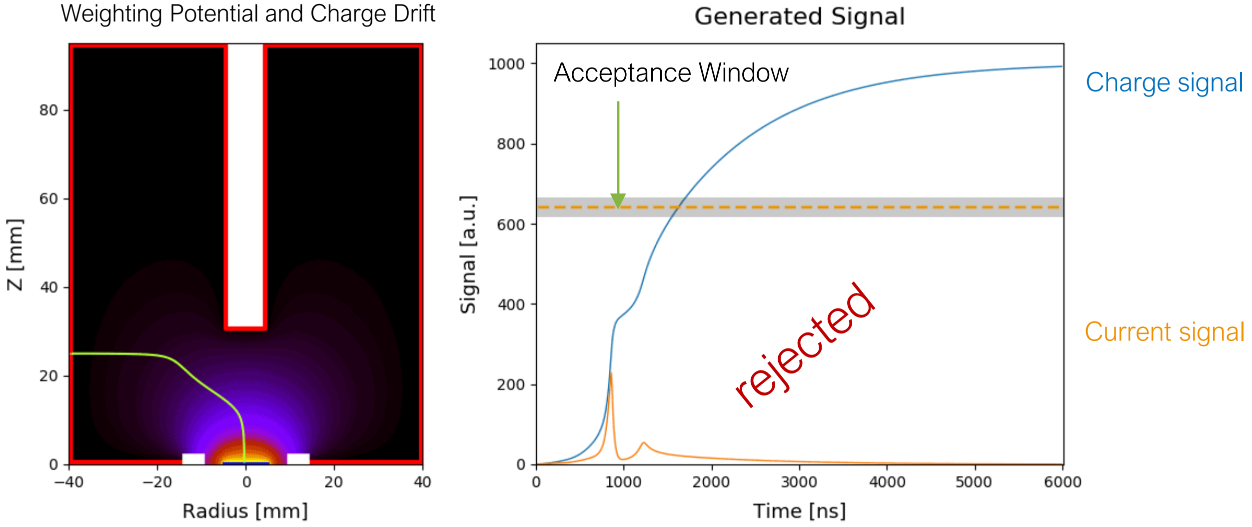
Weighting Potential: ϕ_w

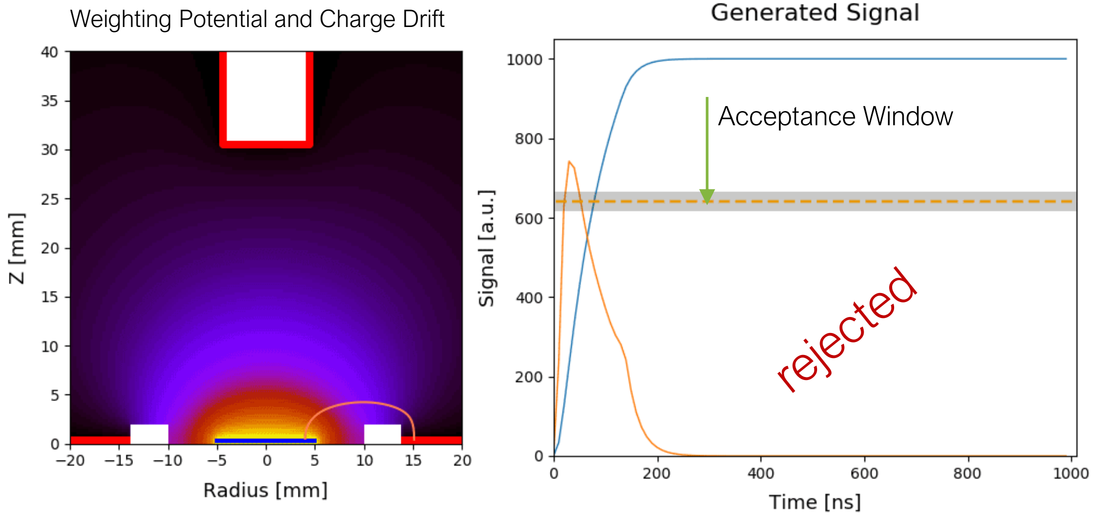
Innovation toward LEGEND-1000: ICPC Ge Detectors

Surface-β-background ^{42}K (^{42}Ar) on n+ contact

Event Topologies

α-background on p+ contact





Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

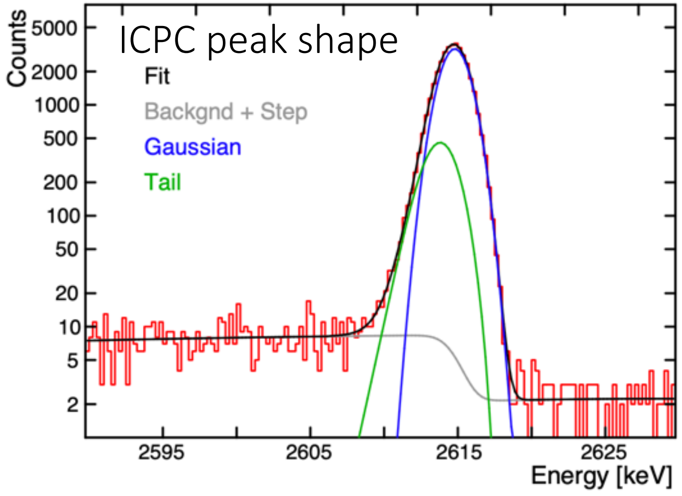
Weighting Potential: ϕ_w

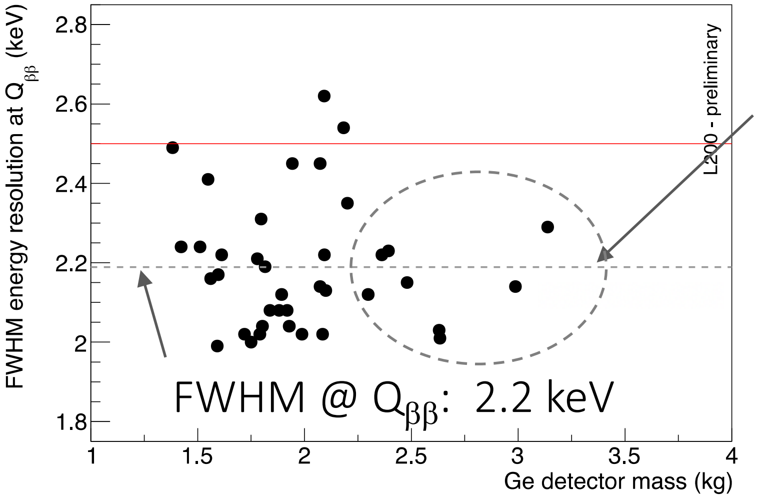
animation only visible in pptx

Innovation toward LEGEND-1000: LEGEND-200

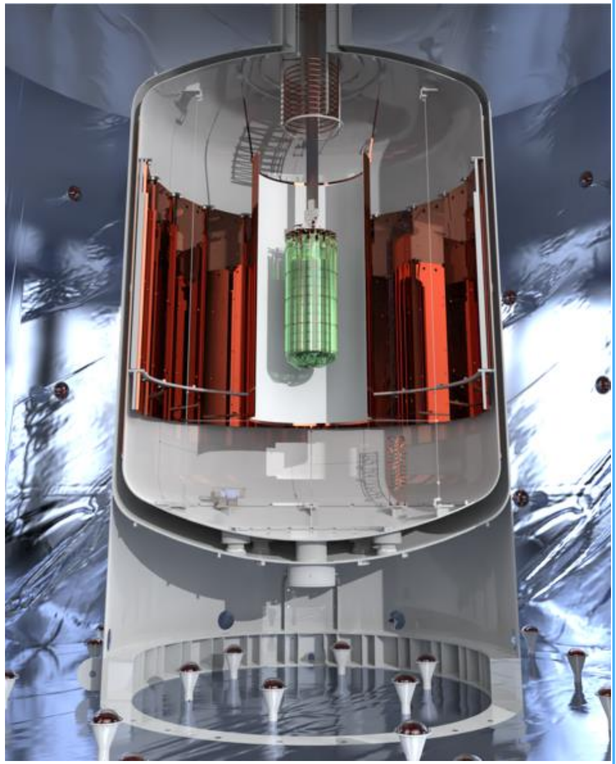
First phase of the LEGEND program, located at Gran Sasso (LNGS)

- Re-uses GERDA cryostat and infrastructure
- Improved LAr system
- About 135 kg of novel ICPC detectors (92% enr. ^{76}Ge) plus 62 kg of PPC and BEGe detectors
- Low-background materials
- Sensitivity goal: 10^{27} years
- Commissioning now





Large mass detectors show excellent energy resolution

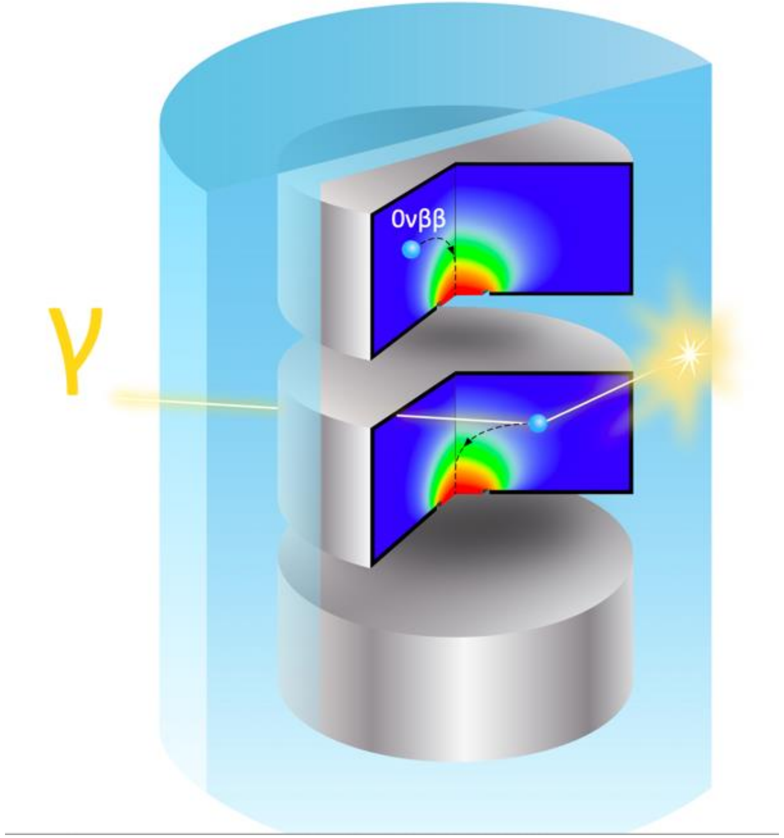


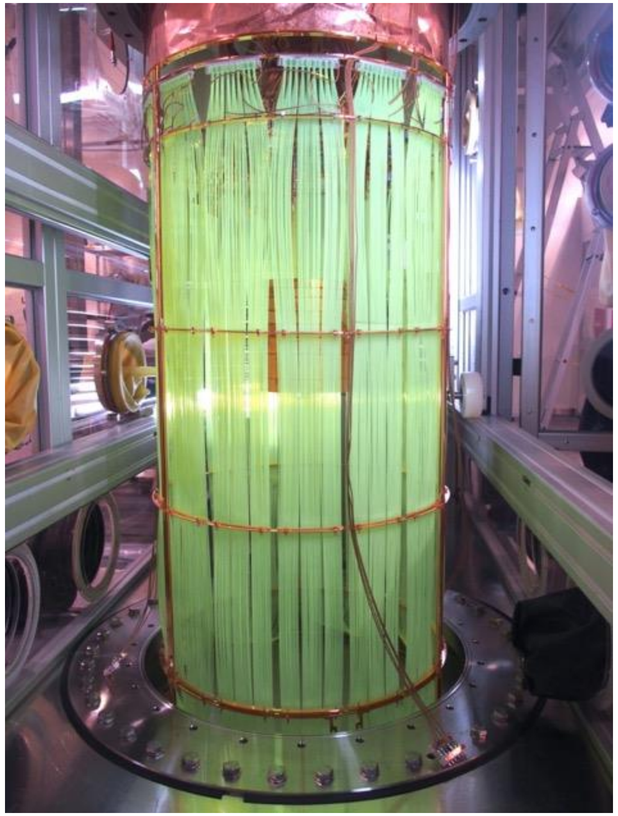
ICPC average resolution @ $Q_{\beta\beta}$: 2.2 keV (FWHM)

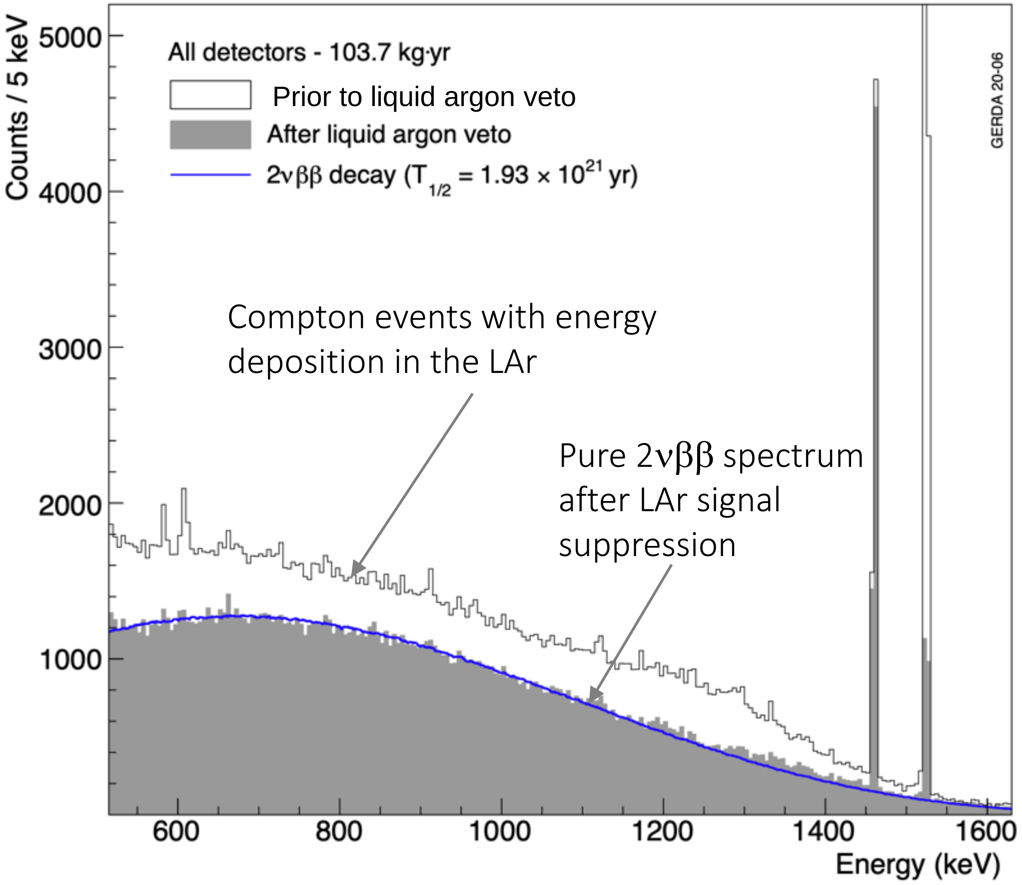
Innovation toward LEGEND-1000: LAr Instrumentation

GERDA: Detection of liquid argon scintillation light

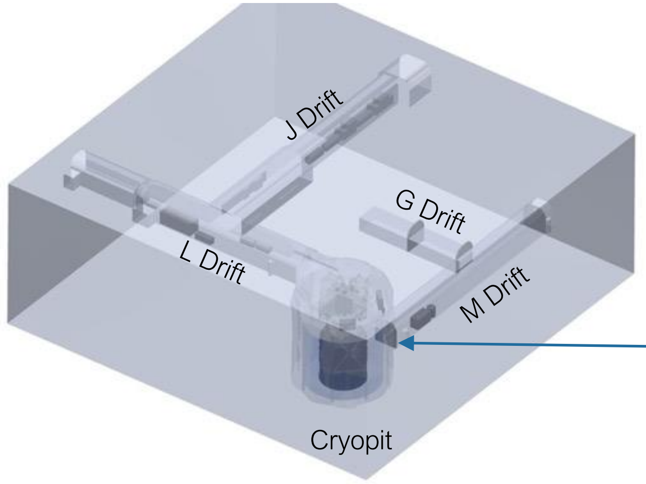
Low-background wavelength-shifting fibers and SiPM arrays for 128 nm single photon detection

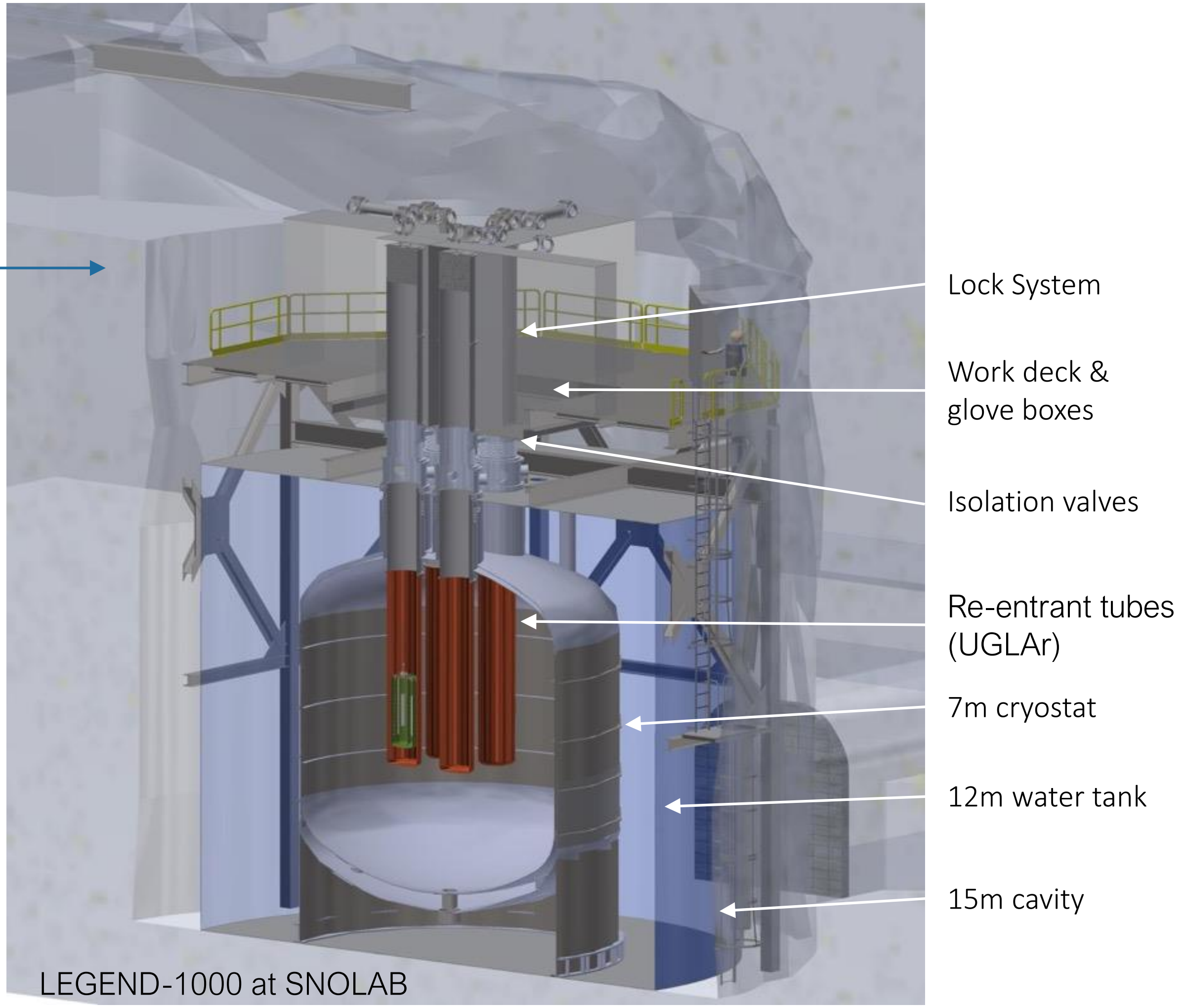






The Baseline Design: Underground Site

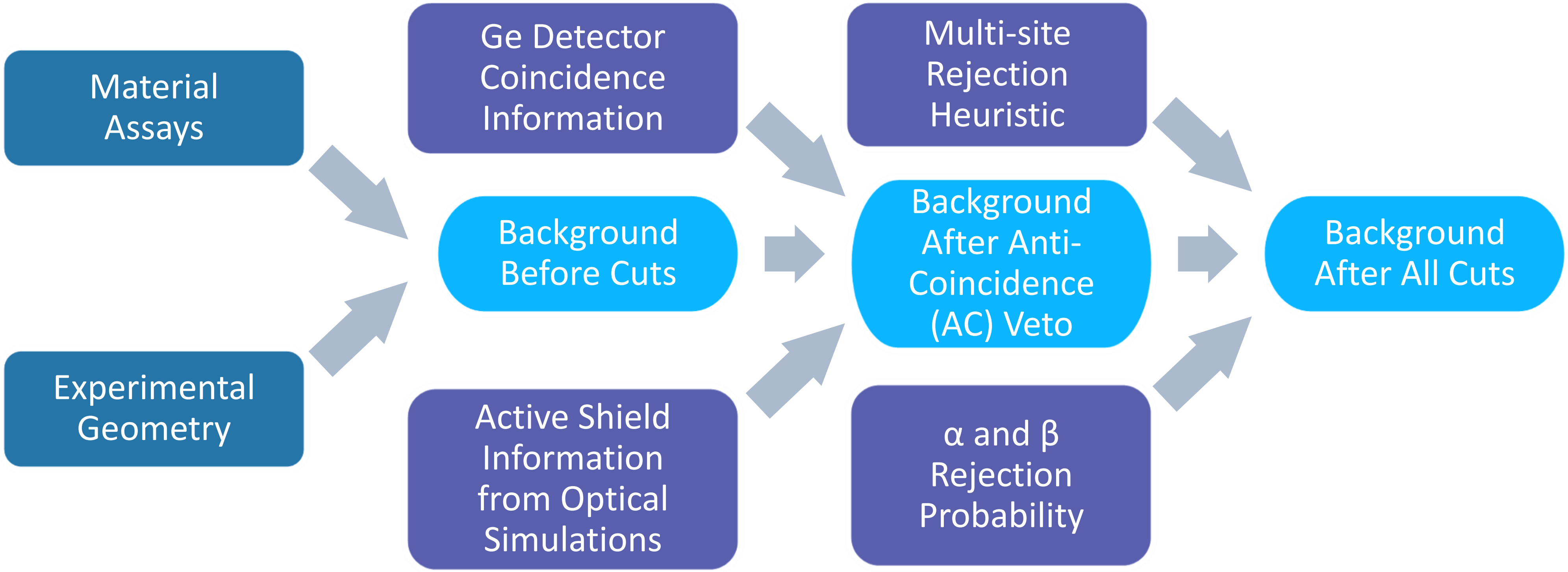




- Baseline site in the SNOLAB Cryopit
  - Rock overburden 6000 m.w.e.
  - Vertical access through mine shaft
  - All experimental areas are class 2000 clean rooms
- Alternative site: LNGS (Italy)
  - Space available in either Hall A or Hall C
  - Lower overburden somewhat increases background
  - Horizontal access reduces cost/schedule risk
- Staff at both sites are actively involved in planning

Background Model

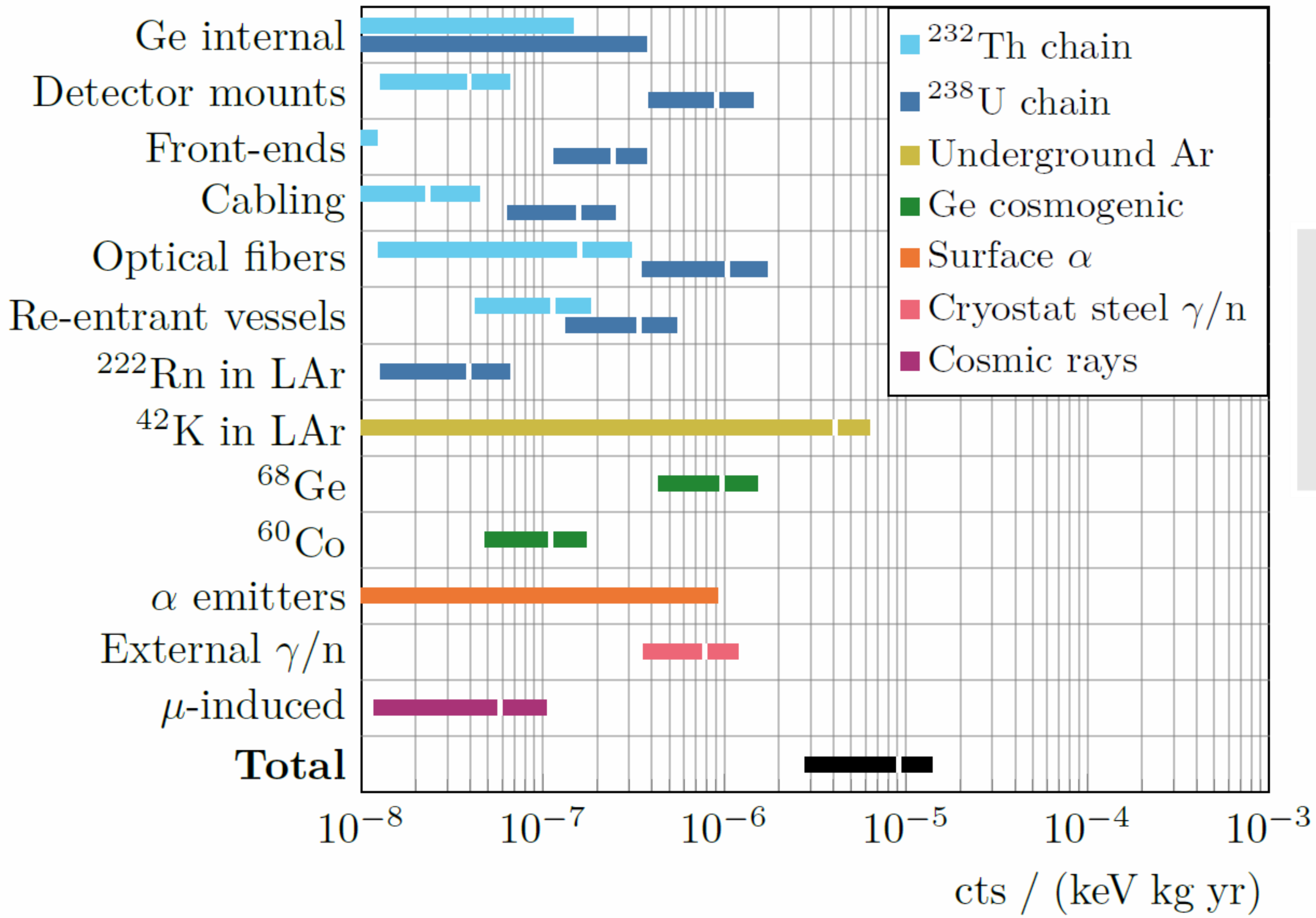
- Built using proven MAJORANA & GERDA methods
- Based on demonstrated/measured activities, including new LEGEND assays
- Monte Carlo simulations of full geometry with MaGe (Geant4)
- Dedicated Monte Carlo of external γ rays and muon-induced nuclei
- Modeling of active shield and pulse shape discrimination (PSD) validated using MAJORANA and GERDA data



Total Backgrounds: Components

LEGEND

Background Index After Cuts

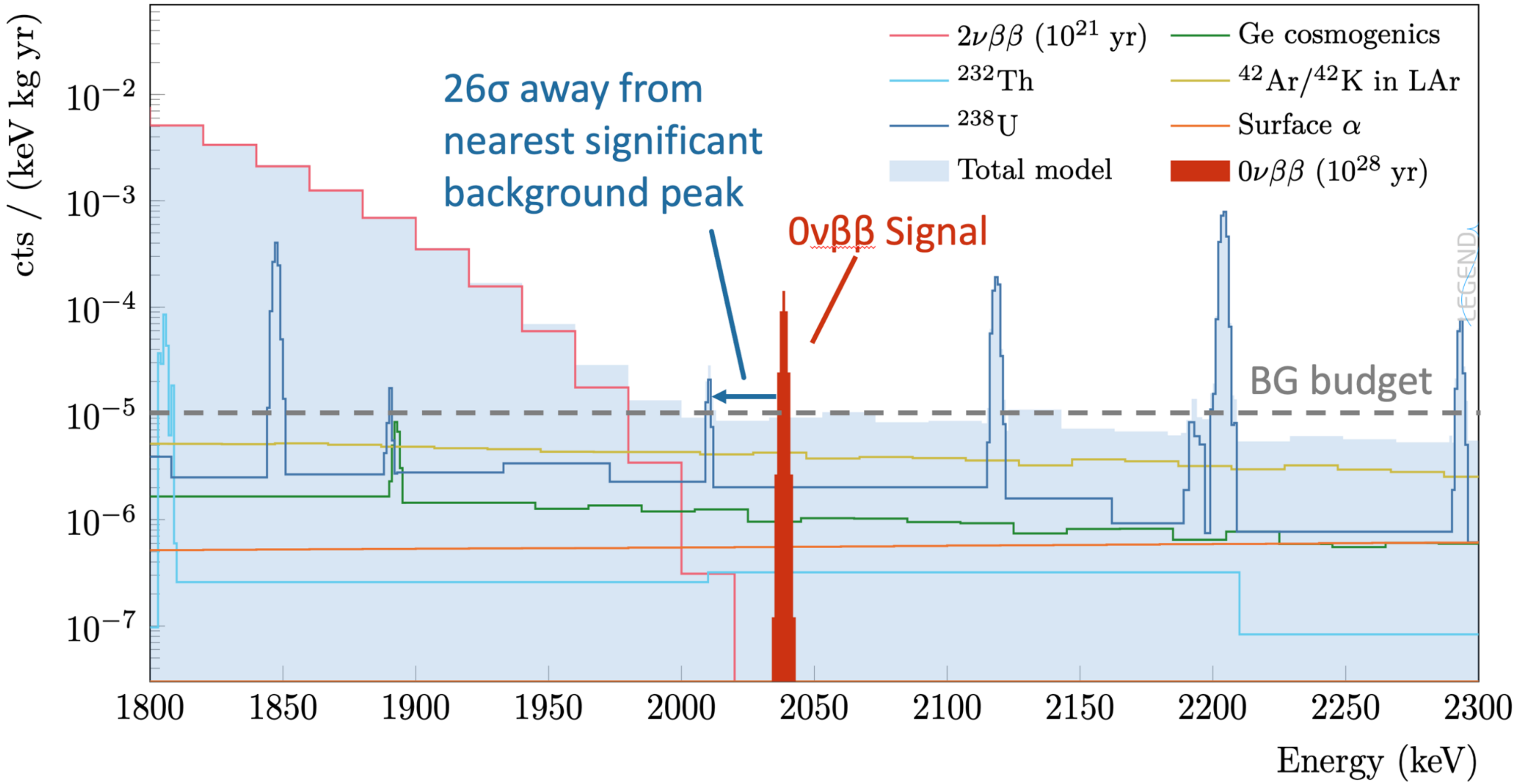


Projected background index after all cuts:

$$9.1^{+4.9}_{-6.3} \times 10^{-6} \text{ counts/(keV kg yr)}$$

Assay and background suppression modeling uncertainties are included

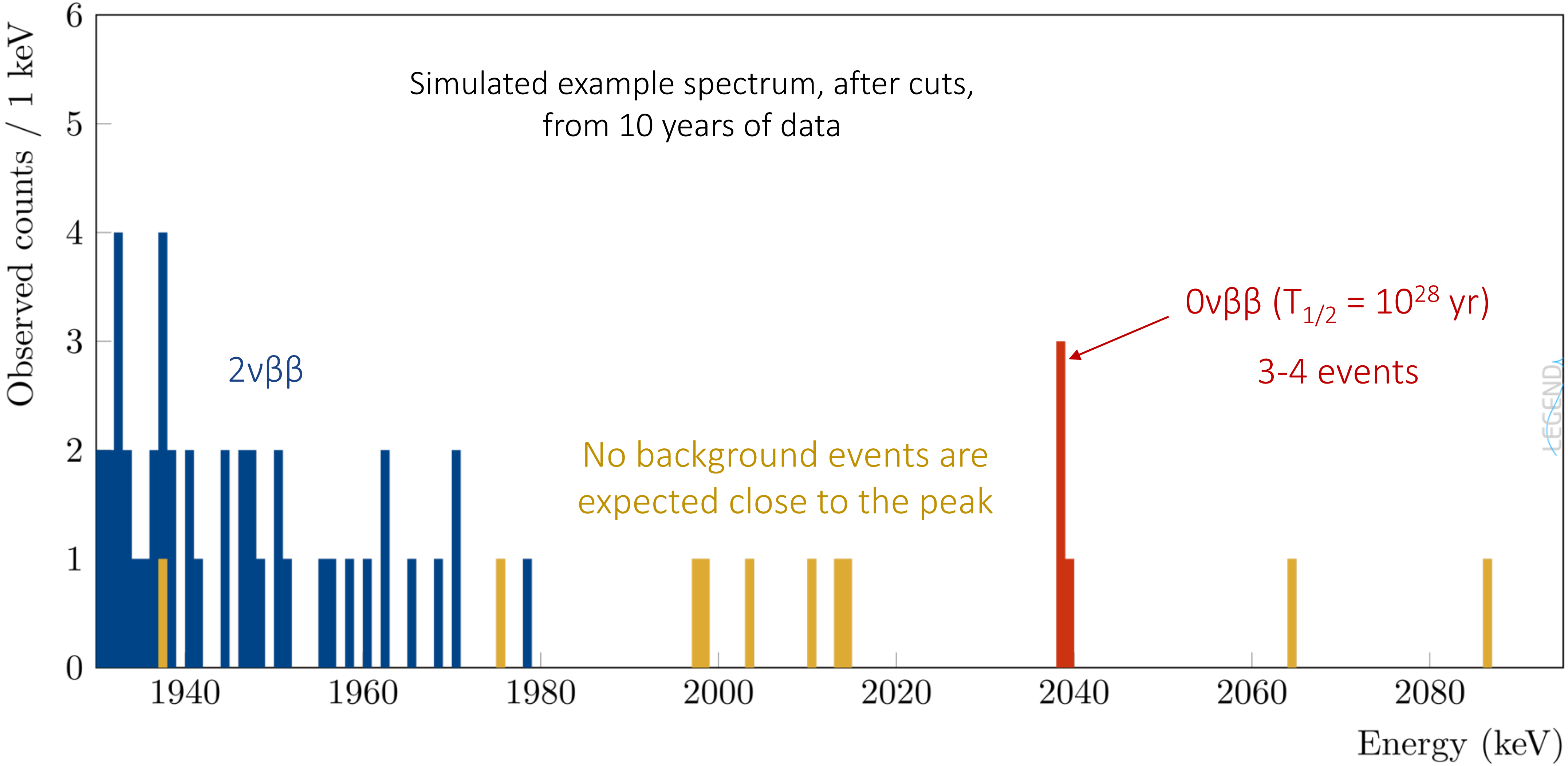
The LEGEND-1000 Background Model



- Flat, featureless background is calculated to be below our budget
- Will be measured

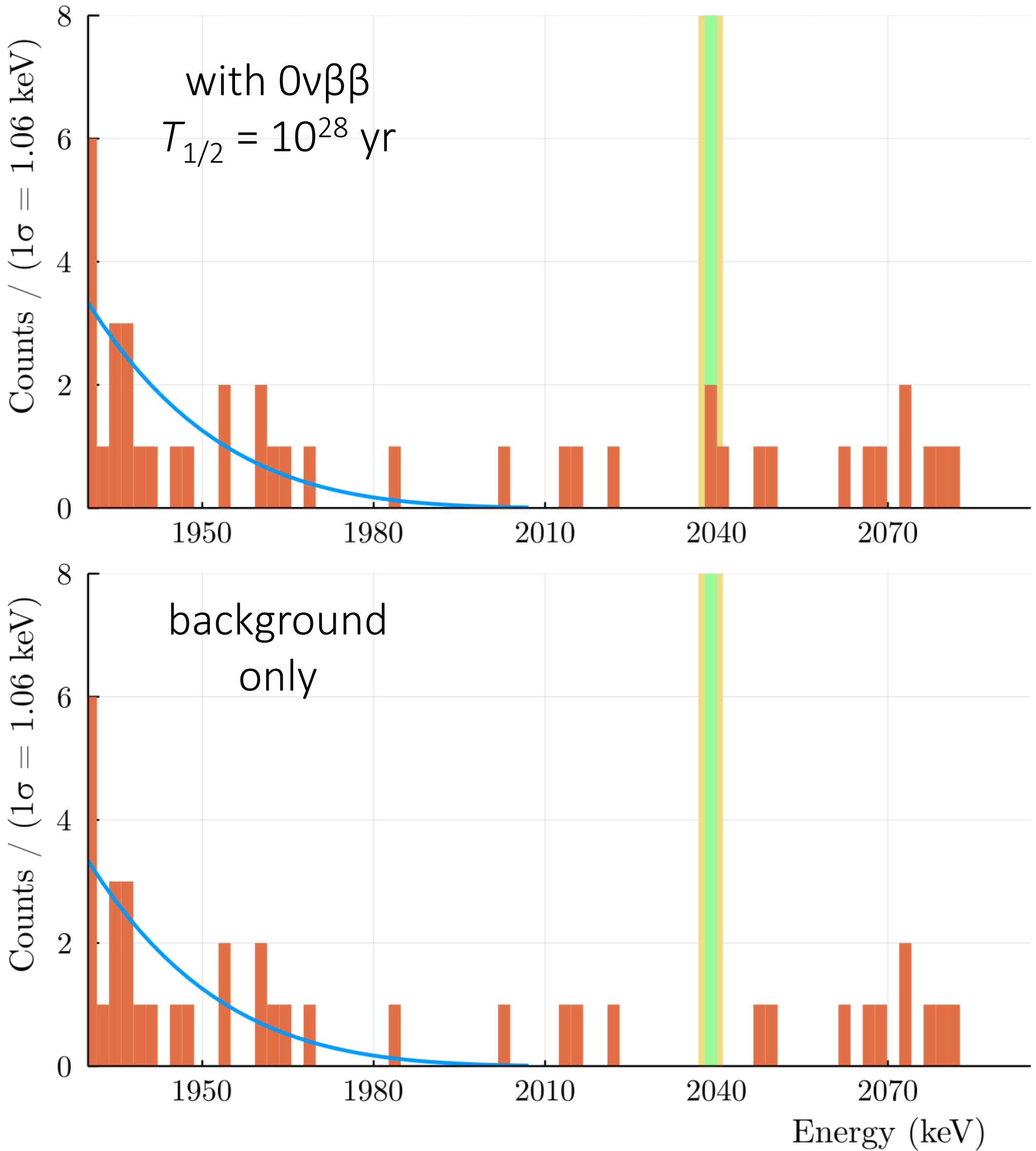
Designed for an Unambiguous Discovery

Even a signal at the bottom of the inverted ordering will be visible to the eye.

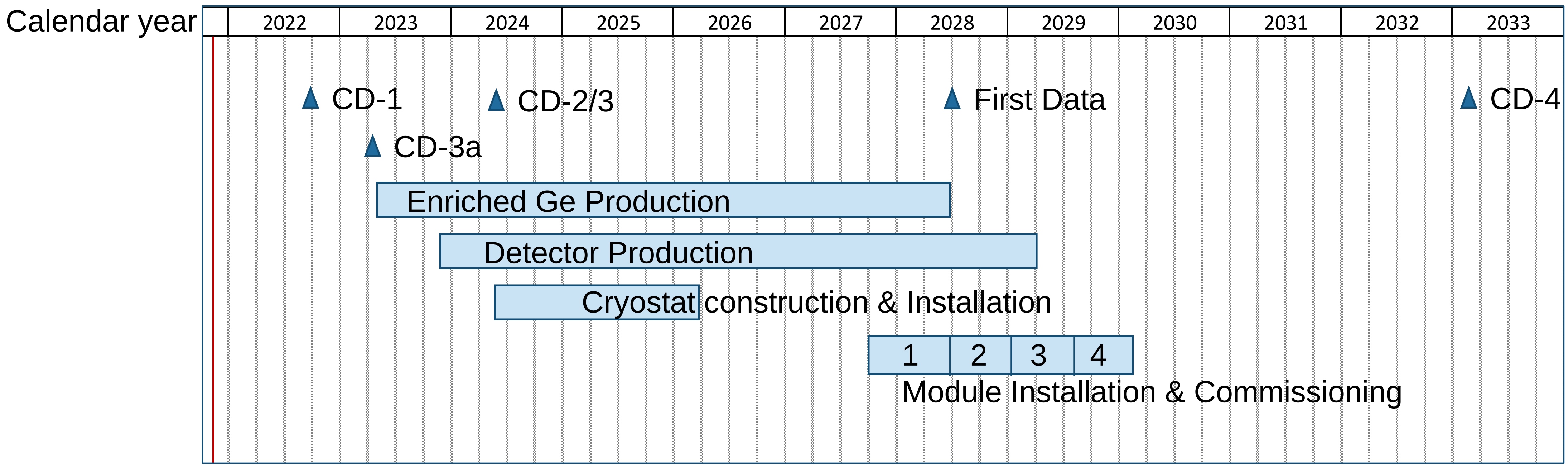


100 Simulated Experiments

- Background is flat and well understood.
- No reliance on background modeling
- No risk of 2νββ background



Technically Driven Schedule



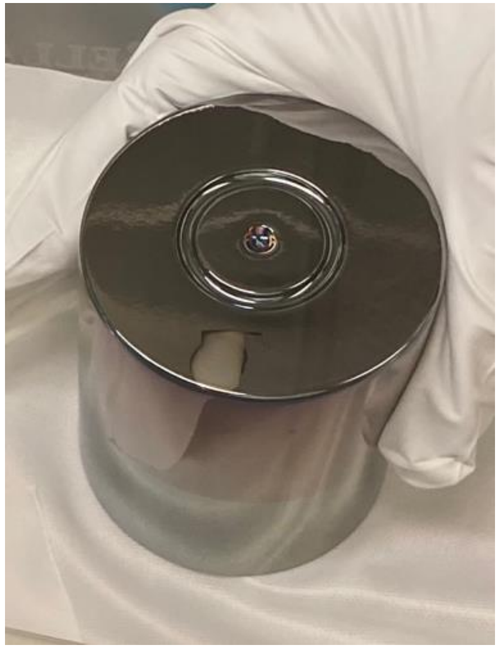
- Assumes technically driven funding profile
- Key Dates:
  - CD-1: Q4,FY22
  - **Module 1 Commissioning Complete: Q3,FY28 69 months (relative to CD-1)**
  - Early Finish: Module 4 Commissioning Complete: Q2,FY30 89 months
  - Late Finish (36 months of float): Q2,FY33 125 months

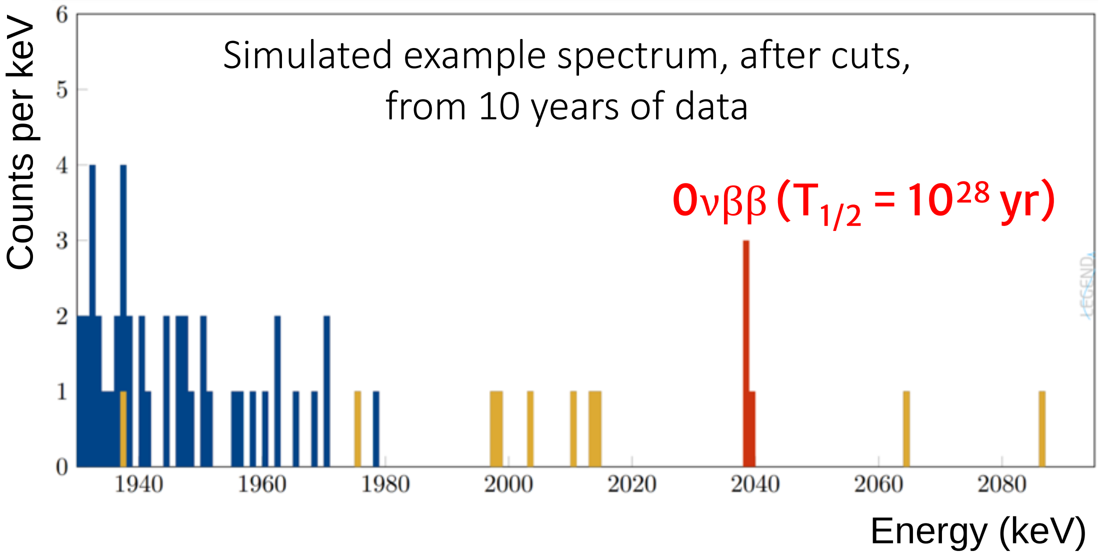
DOE Scope and Cost

- Total DOE cost point estimate is $257M
  - Includes 56% contingency
  - Assumes technically driven funding profile
- Anticipated DOE Project scope is 60% of the total ($442M)
  - Total scope estimate uses DOE accounting; fully burdened, escalated costs with 50% contingency
- International collaborators intend to contribute the remaining 40%
  - Raw cost (unburdened procurements only) for international scope is $50M

Why Germanium?

- Solid basis for unambiguous discovery
  - Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
  - No background peaks anywhere near the energy of interest
  - Background is flat and well understood
  - Background will be measured, with no reliance on background modeling
  - All this leads to an excellent likelihood that an observed signal will be *convincing*
- Low risk, high impact
  - Demonstrated performance of the entire technology chain
  - GERDA has produced the lowest background per FWHM of any experiment
  - Majorana has produced the best resolution
  - Requires no extrapolation from current detector performance
  - Proven track record, with history of leading limits
  - The team is experienced and moving forwards from LEGEND-200 construction to LEGEND-1000





Conclusion

- LEGEND-1000 is optimized for a quasi-background-free 0νββ search
  - It builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
  - Its background model is based on the demonstrated success of MAJORANA and GERDA, detailed simulations, and well-understood improvements
  - LEGEND has a low-risk path to meeting its background goal of 10^{-5} counts/(keV kg yr)
  - Low backgrounds, excellent resolution, and topology discrimination allow for an unambiguous discovery of 0νββ decay at $T_{1/2} = 10^{28}$ years
- An experienced and cohesive LEGEND Collaboration is ready to deliver the LEGEND-1000 experiment and its science
- Moving forward to CD-1 as quickly as possible

LEGEND-1000 Preconceptual Design Report: https://arxiv.org/pdf/2107.11462.pdf