Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

LEGEND-1000

Stefan Schönert for the LEGEND Collaboration

30 Sept. 2021

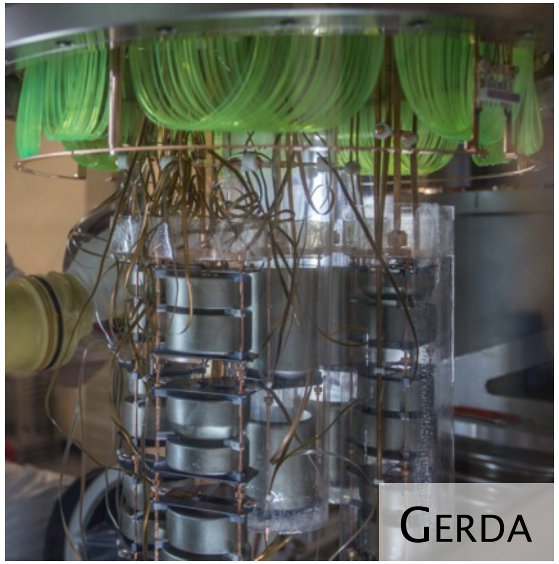
North America - Europe Workshop on Future of Double Beta Decay

Technical University of Munich

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 266 members, 48 institutions, 11 countries



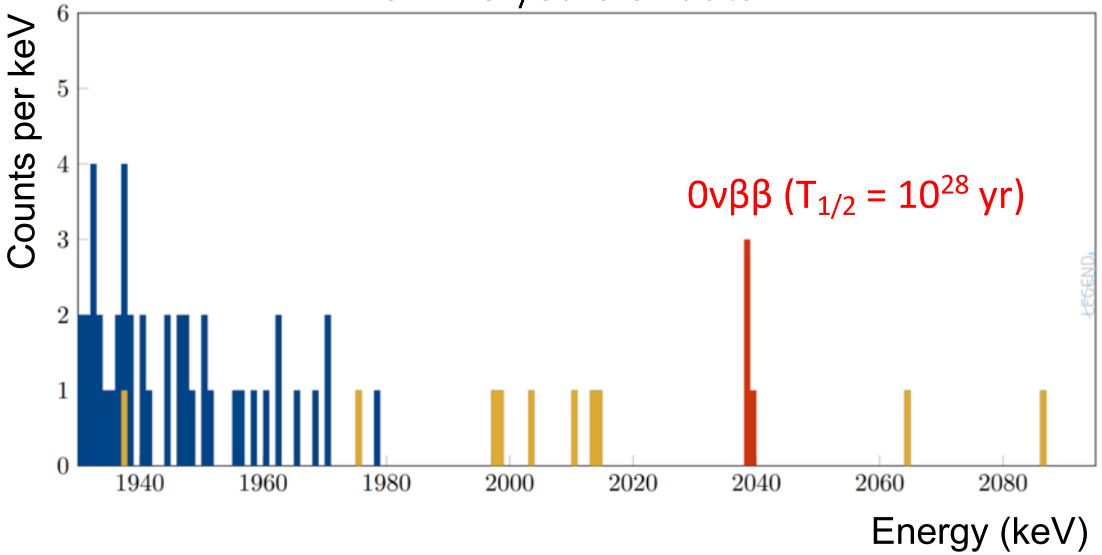
The LEGEND Collaboration

The LEGEND-1000 Discovery Sensitivity

"The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with <u>discovery potential</u> at a half-life beyond 10^{28} years..."

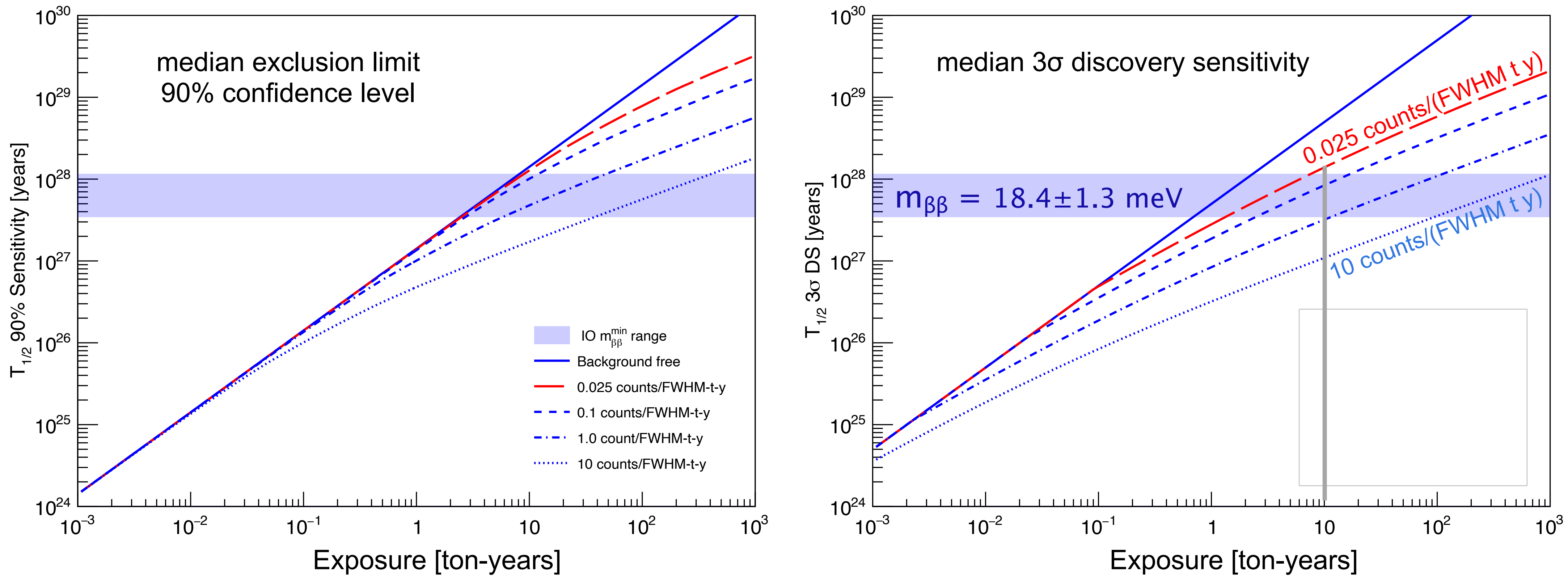
- What is required for a discovery of 0νββ decay at a half-life of 10^{28} years?
- This is less than one decay per year per ton of material
  - Need 10 ton-years of data to get a few counts
  - Need a good signal-to-background ratio to get statistical significance
    - A very low **background event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

Simulated example spectrum, after cuts, from 10 years of data



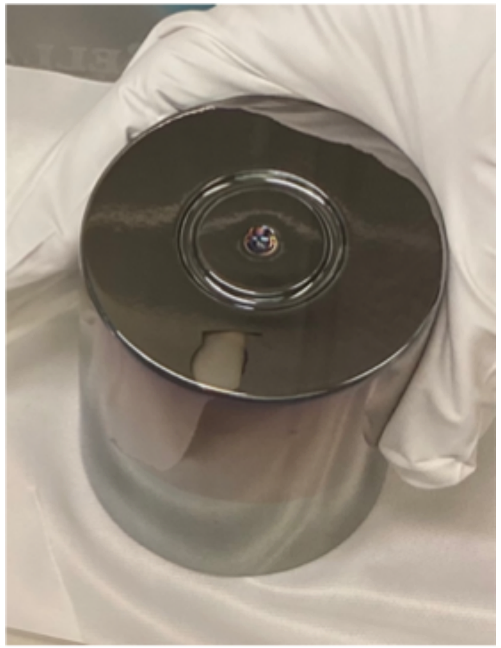
The Effect of Background

- 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)



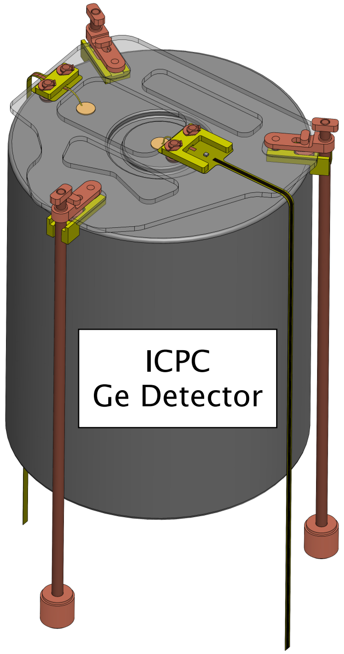
Why Germanium?

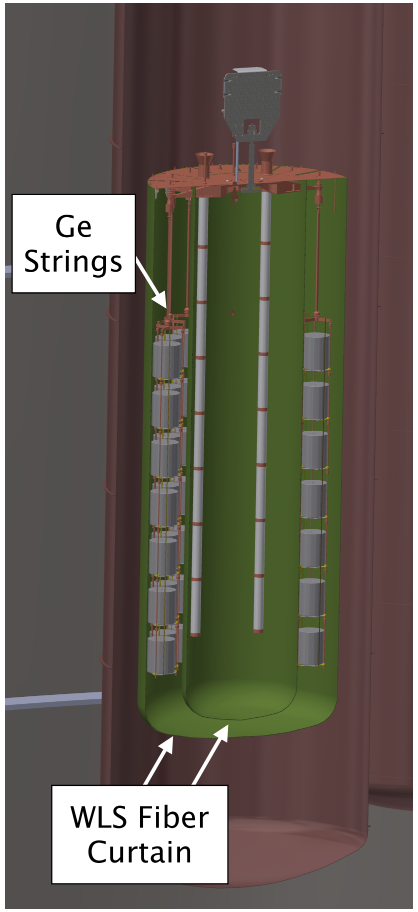
- Solid basis for unambiguous discovery
  - Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
  - Therefore, no background peaks anywhere near the energy of interest
  - Background is flat and well understood
  - Background will be measured, with no reliance on background modeling
  - All 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 ready to transition from LEGEND-200 construction to LEGEND-1000
  - A stable cost estimate, with appropriate contingency

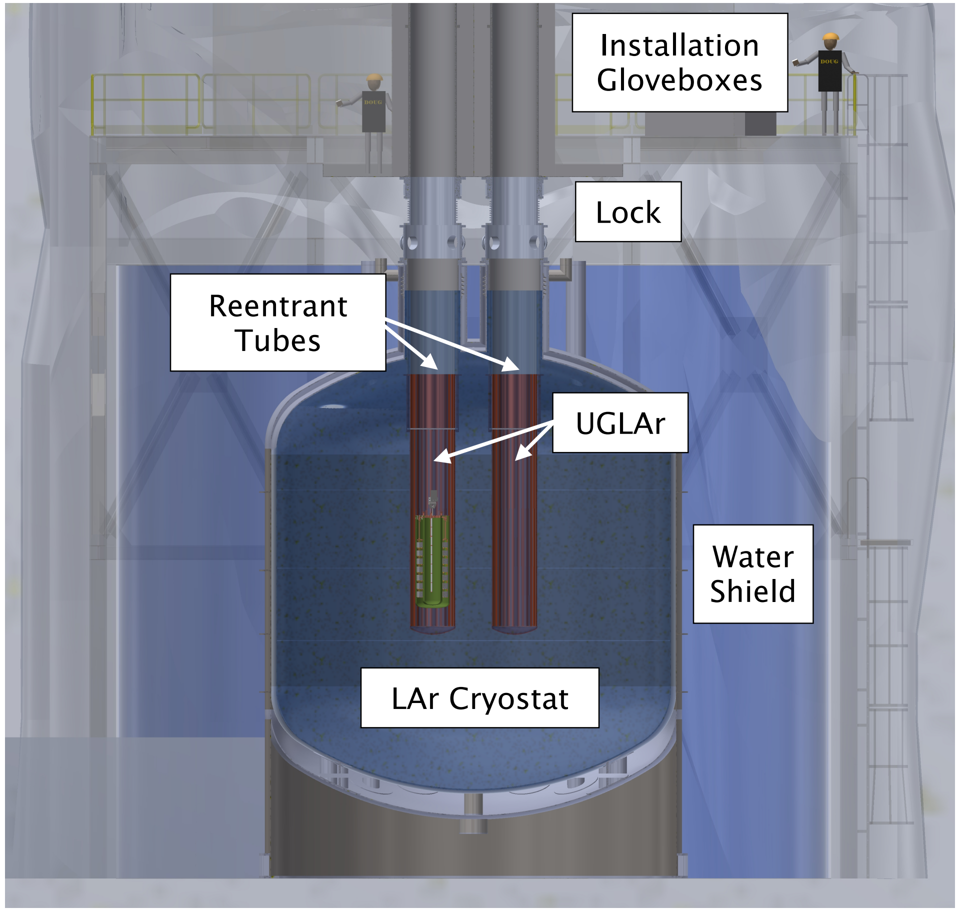


LEGEND-1000: A discovery experiment for 0νββ of ^{76}Ge

Quasi-background-free search for 0νββ decays of ^{76}Ge at $Q_{\beta\beta}$ = 2039.06 keV







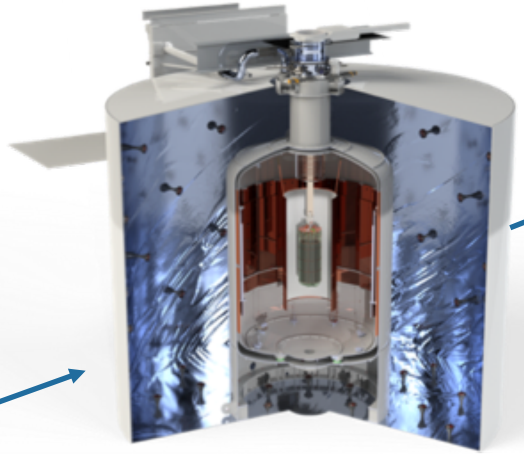
ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar

Innovation toward LEGEND-1000

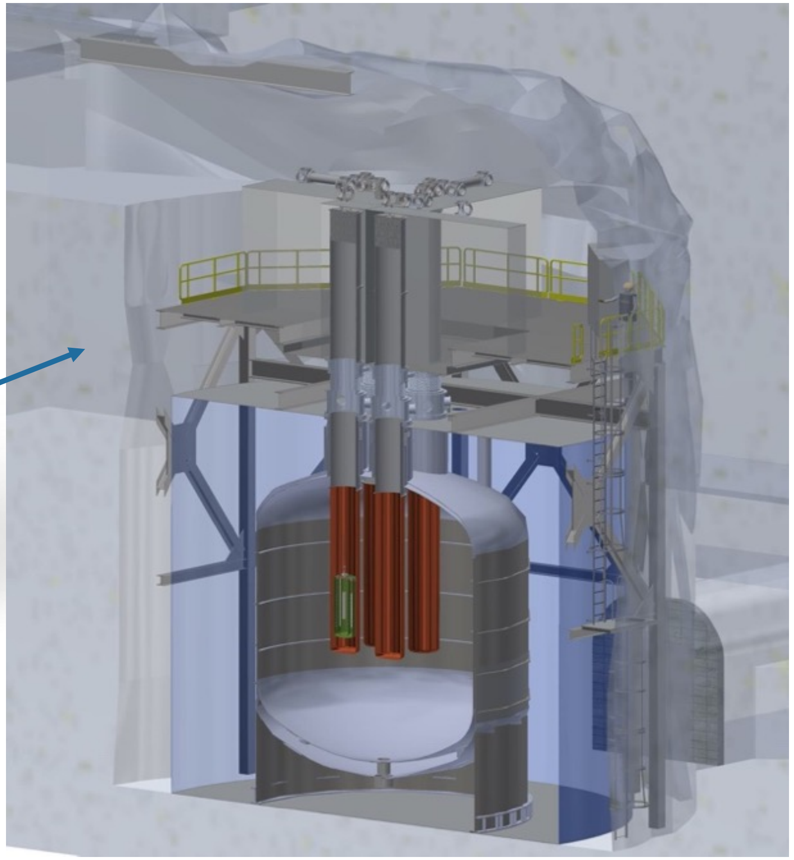
The LEGEND-1000 design builds on a track record of breakthrough developments

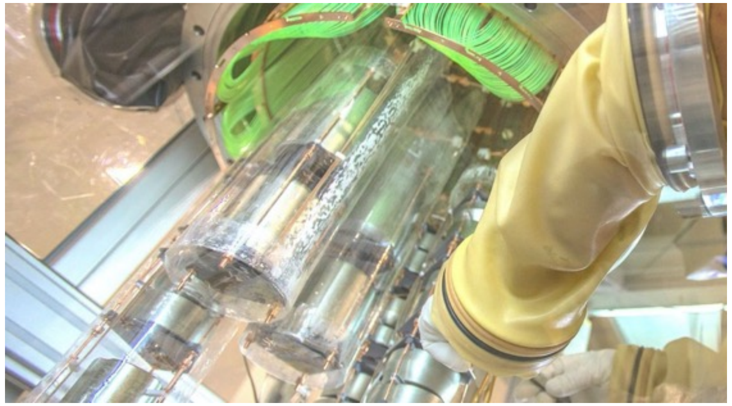
- GERDA : BEGe, LAr instrumentation, cryostat in water shield, fast detector deployment, …
- MAJORANA DEMONSTRATOR (MJD): PPC, EFCu, low-noise front-end electronics,…
- LEGEND-200 (commissioning 2021): Inverted-Coaxial Point Contact (ICPC) detectors, polyethylene naphthalate (PEN)…

LEGEND-200



LEGEND-1000





GERDA

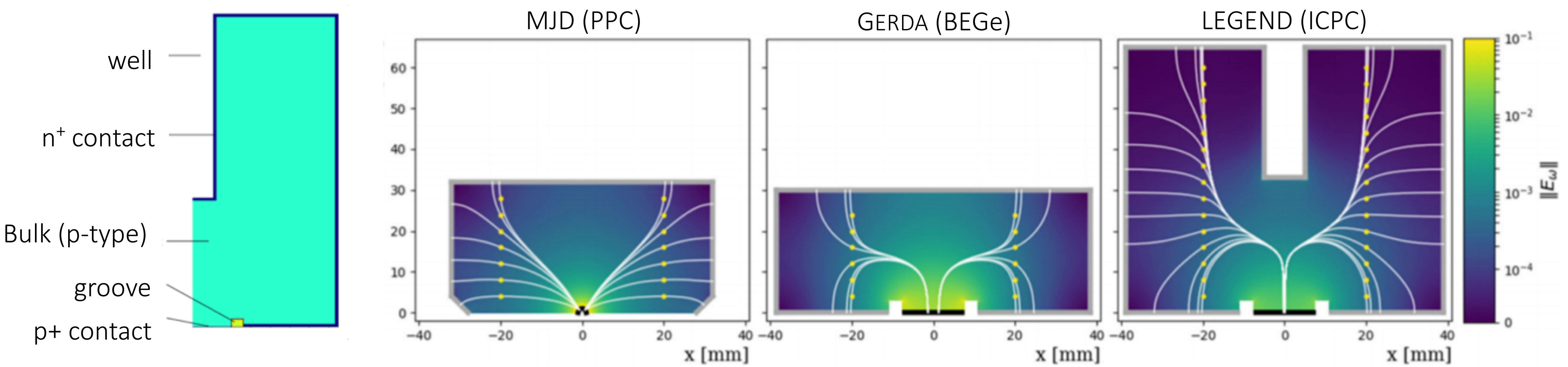
MJD

PPC: p-type Point Contact Ge detectors

BEGe: (modified) Broad Energy Ge detectors

EFCu: Electroformed copper

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

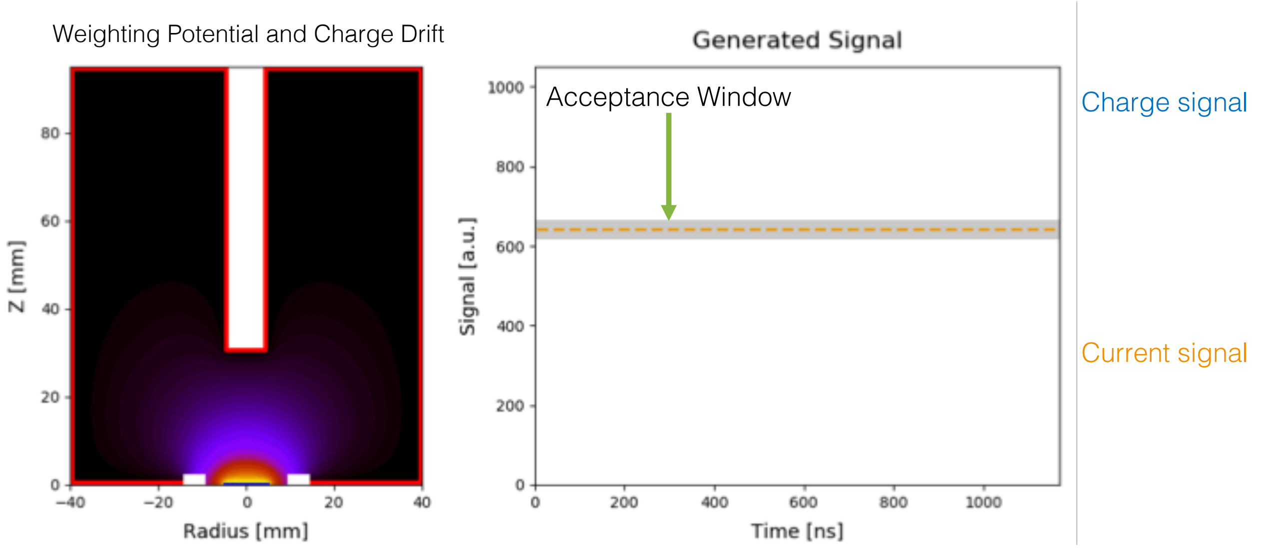


- P-type detectors: Insensitive to alphas on n^+ contact
- Small p^+ contact: Event topology discrimination
- Large-mass ICPC detectors: About 4 times lower backgrounds with respect to BEGe/PPC
- Proven long-term stable operation in liquid argon

Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



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

N.B. animation only visible in pptx

Event Topologies

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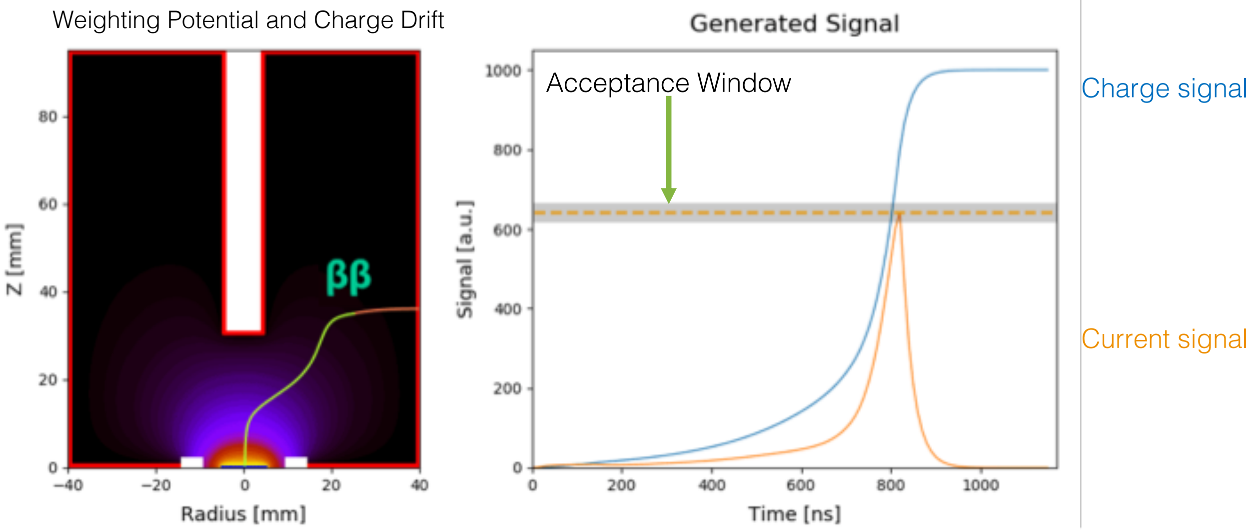

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Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

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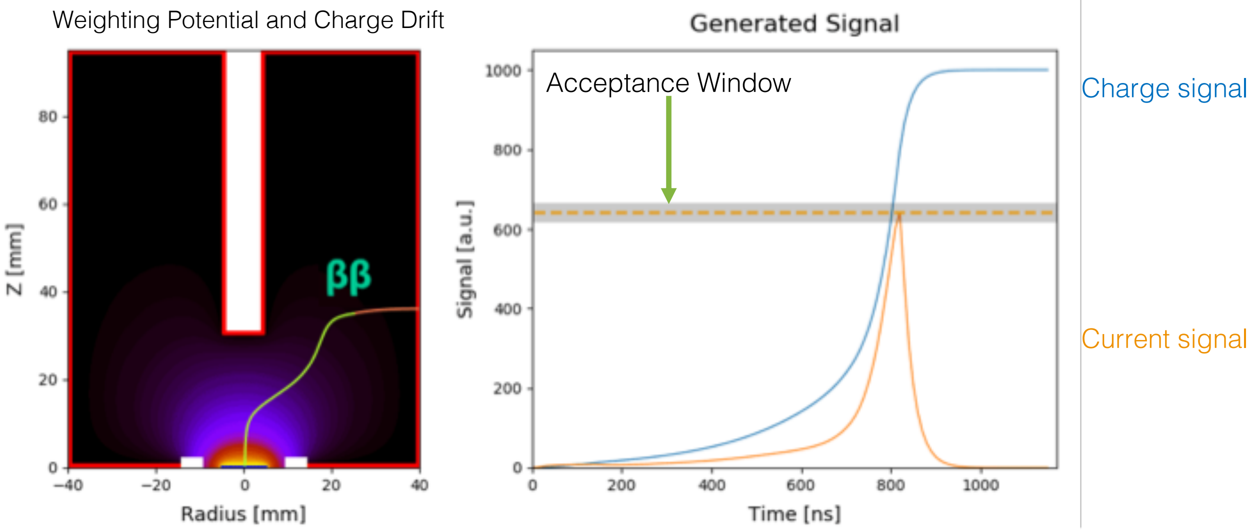
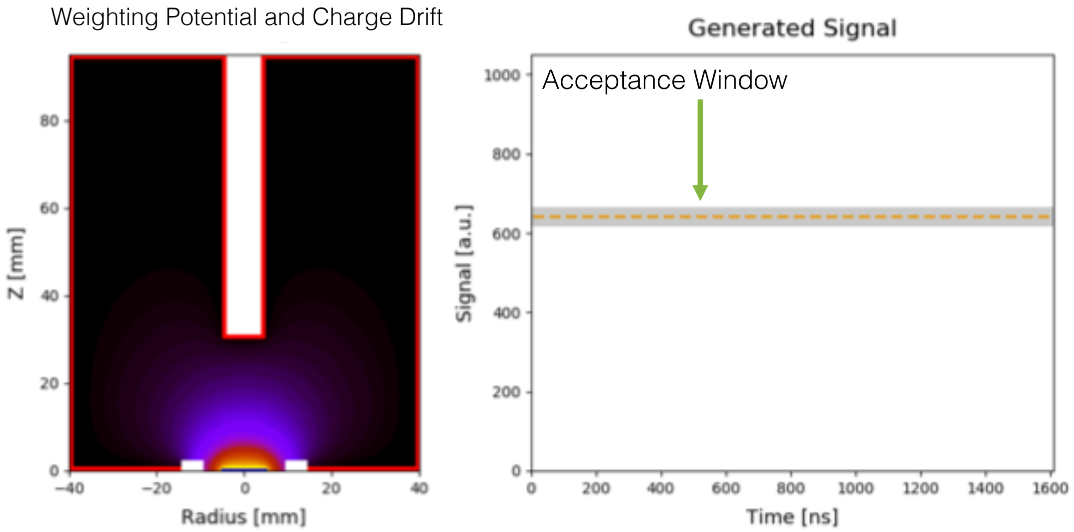


γ-background (multi-site)



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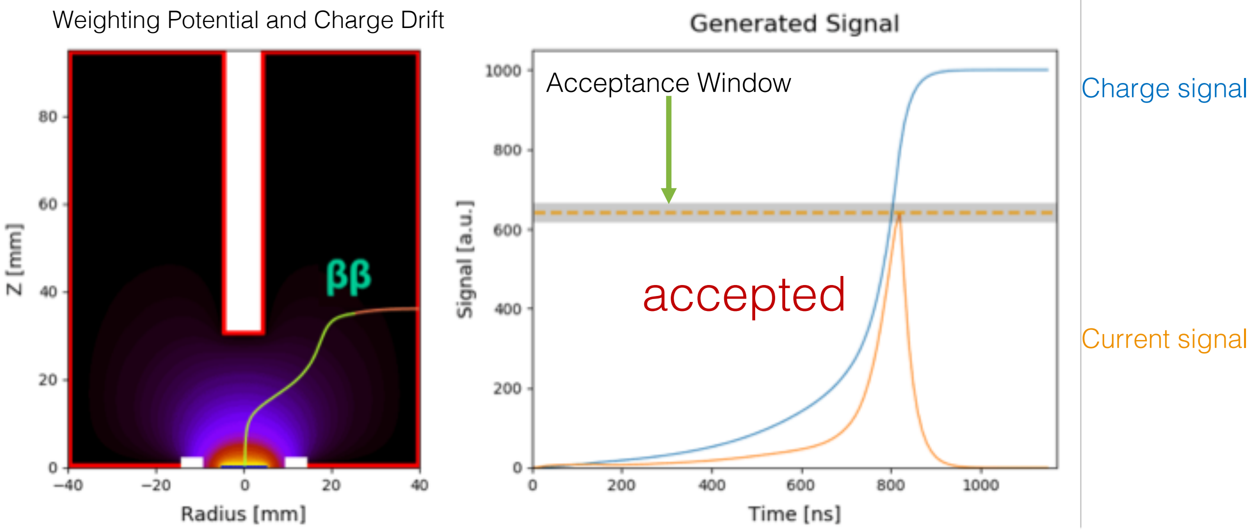
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



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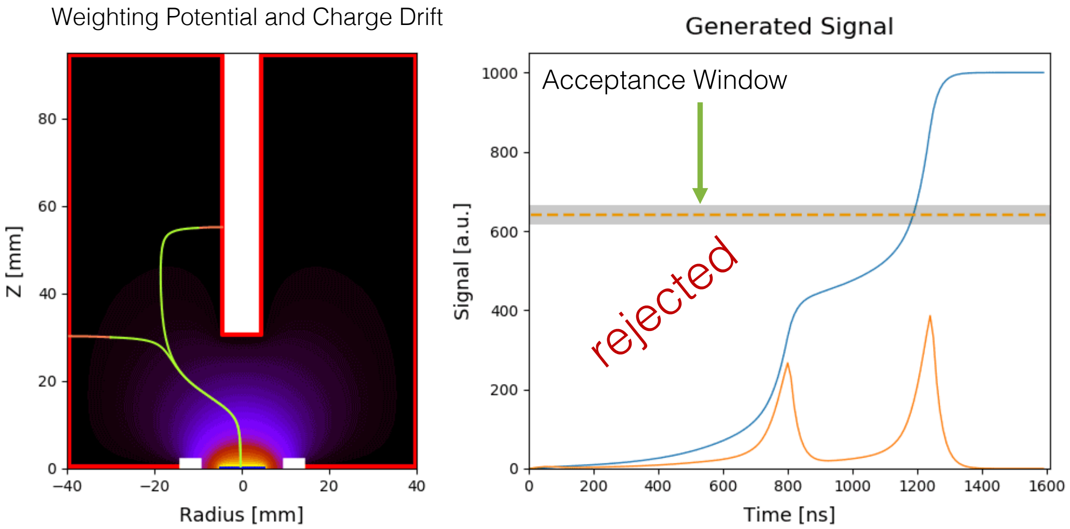


Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

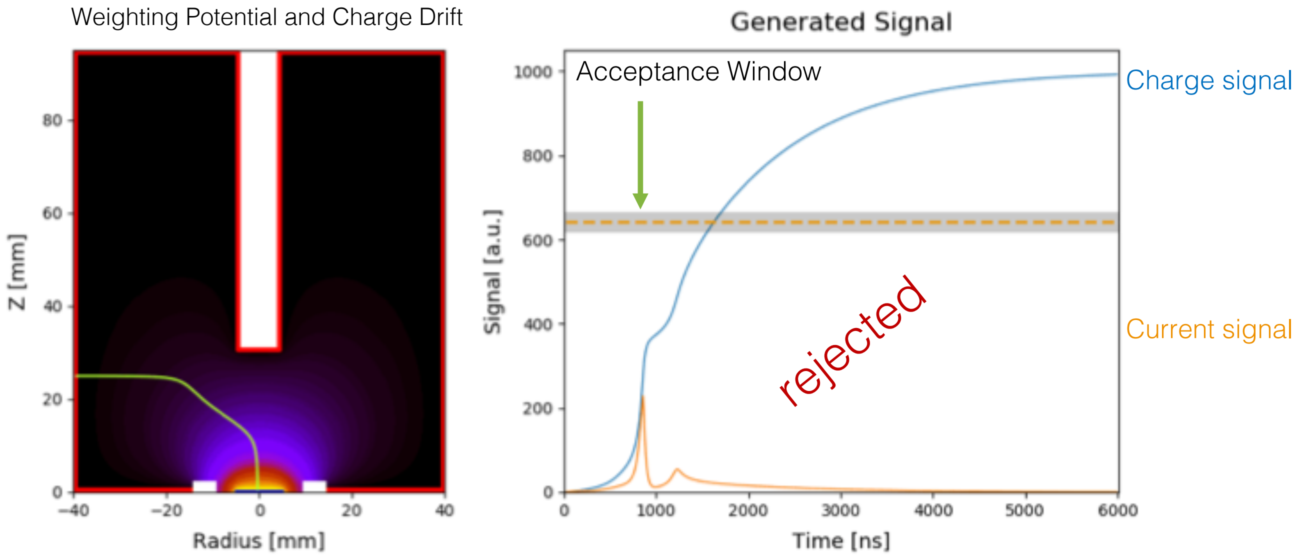
Weighting Potential: ϕ_w

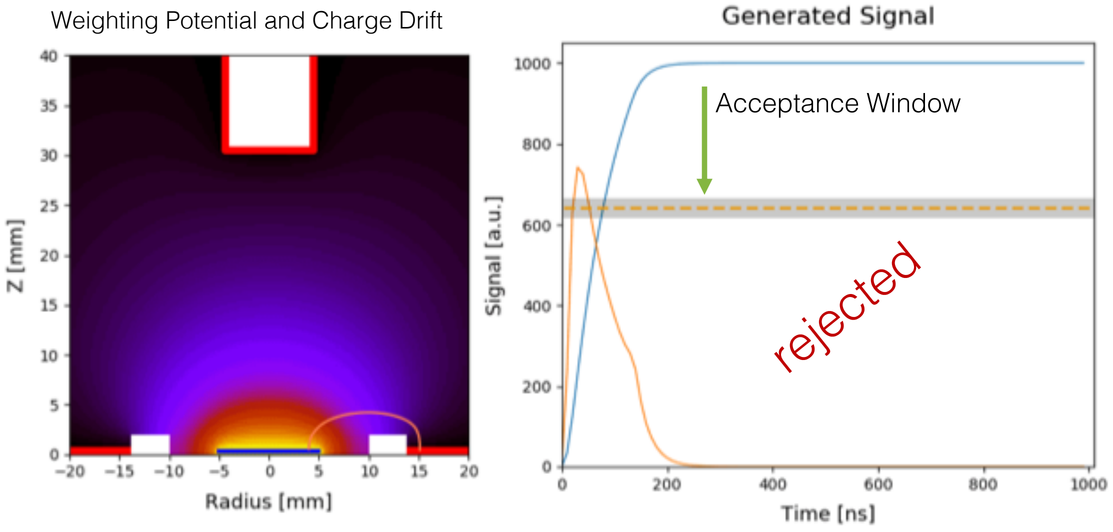
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

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

α-background on p+ contact





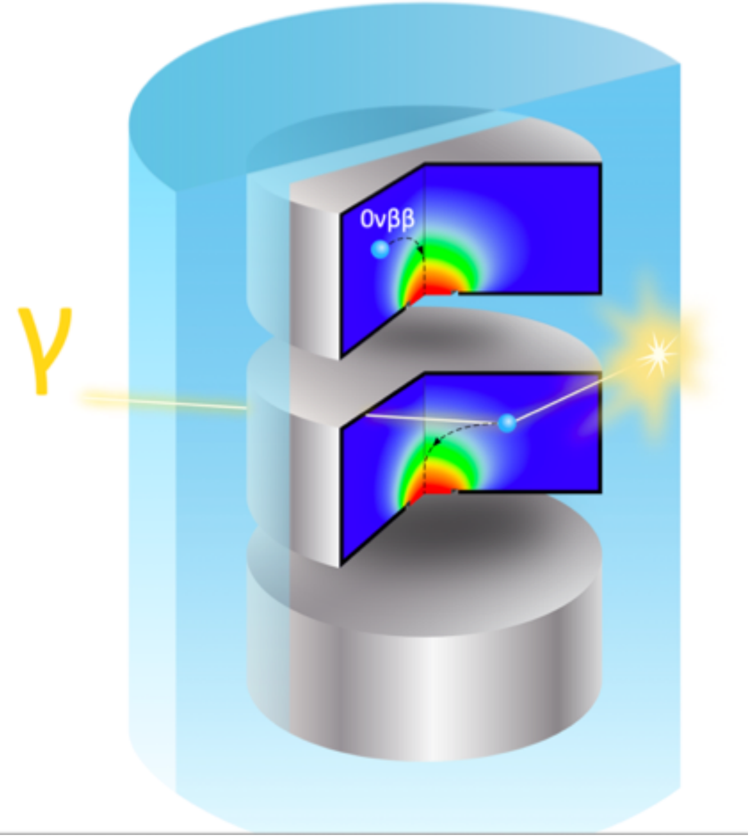
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

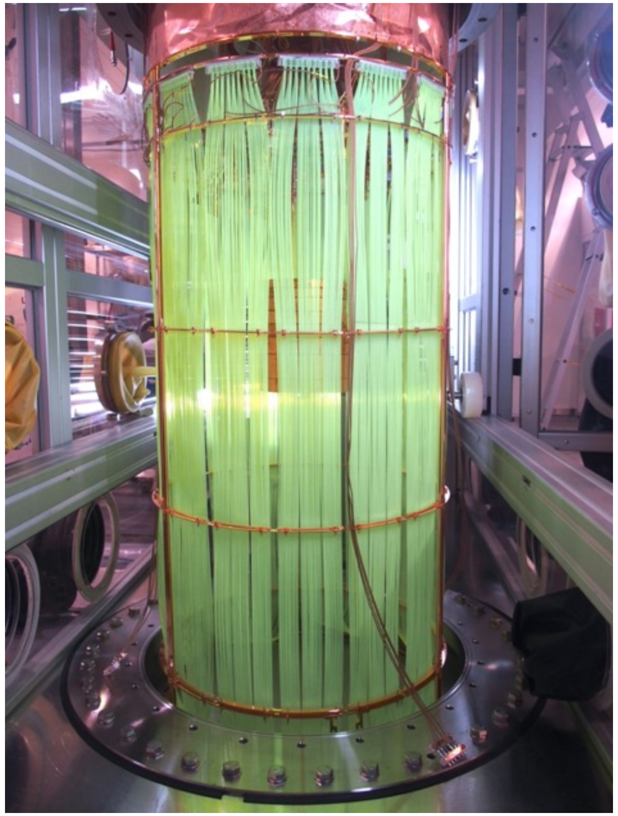
Weighting Potential: ϕ_w

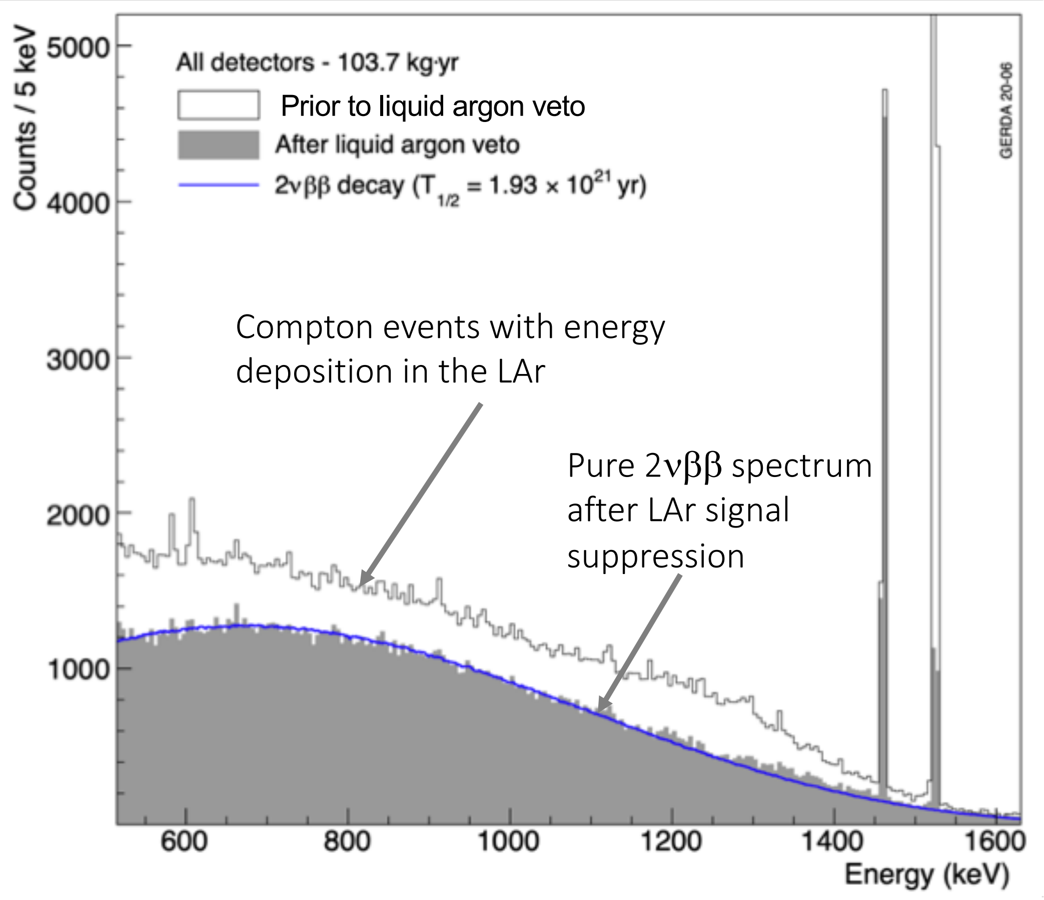
Innovation toward LEGEND-1000: LAr Instrumentation

GERDA: Detection of liquid argon scintillation light

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



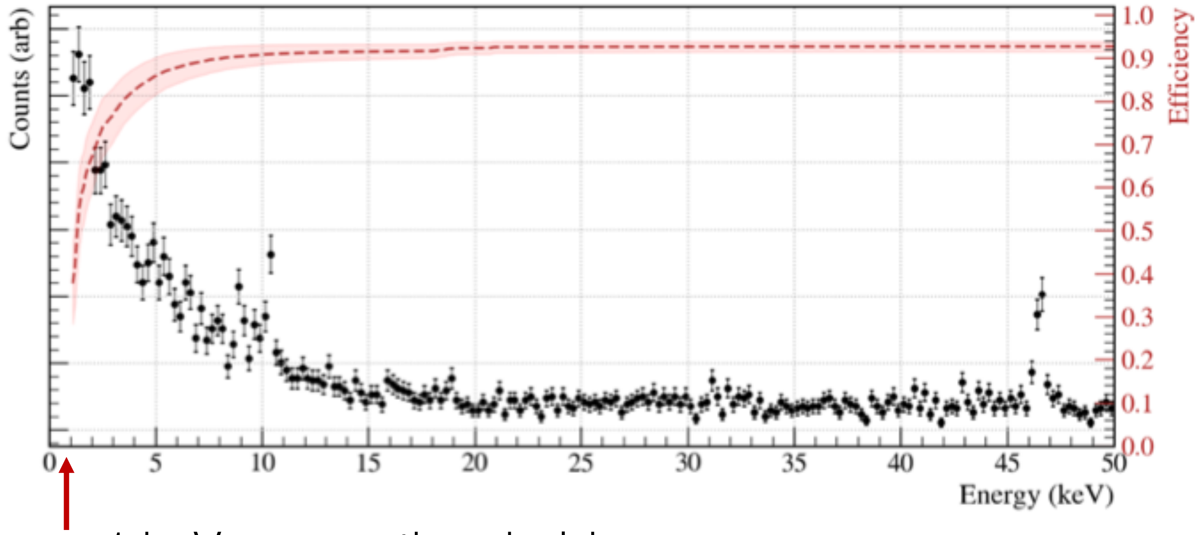




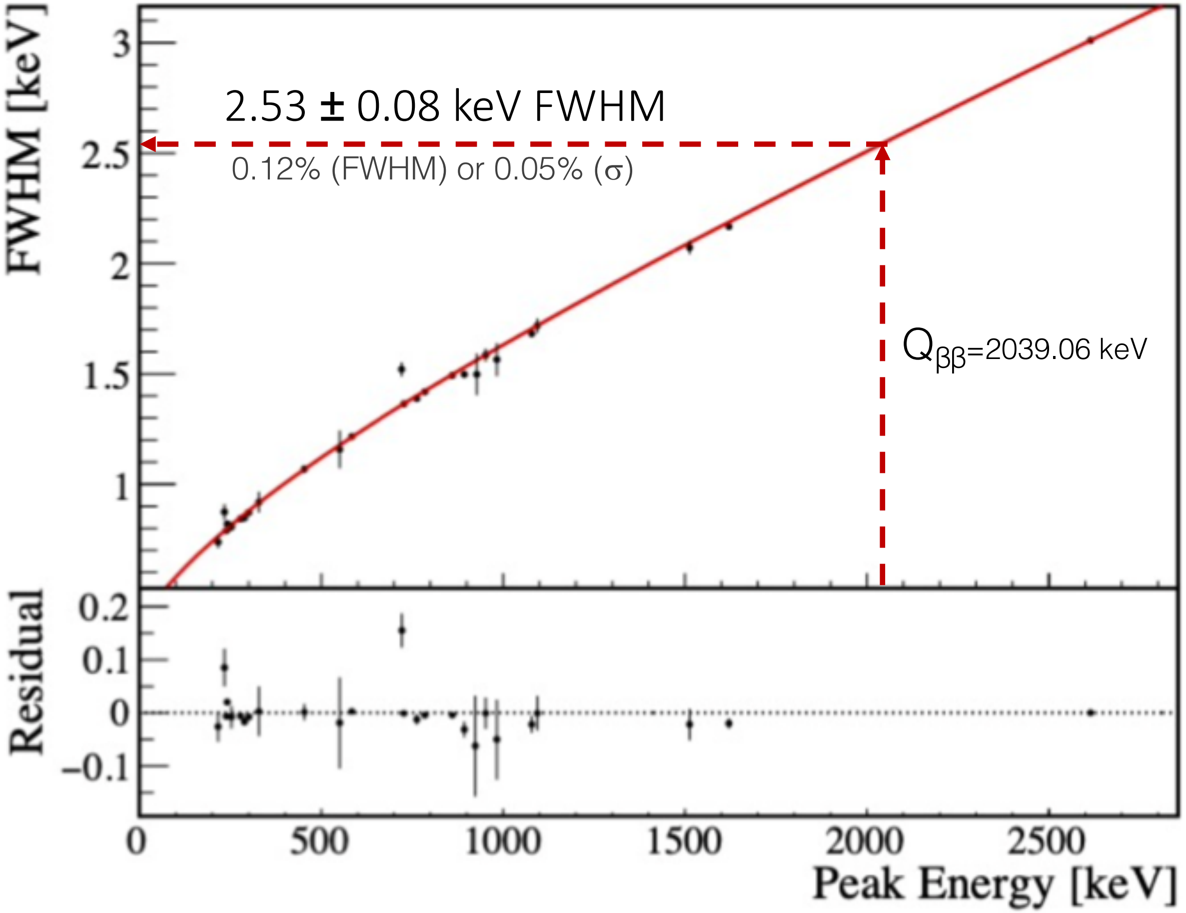
Innovation toward LEGEND-1000: Electronics & Materials

MJD: Low noise front-end electronics required for

- excellent energy resolution
- optimal pulse shape analysis
- low-energy threshold



~1 keV energy threshold



MJD: APS April Meeting D19.00007 (2021)

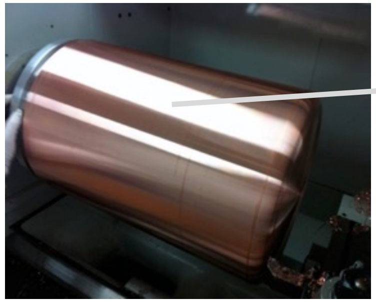
Innovation toward LEGEND-1000: Electronics & Materials

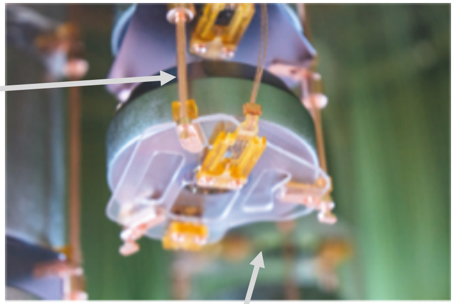
- **Minimize** materials close to Ge detectors and use of **highest purities**:
  - Underground electroformed copper (EFCu) reduces U, Th, and cosmogenic activation

    $< 0.017 \pm 0.03$ pg/g ^{238}U

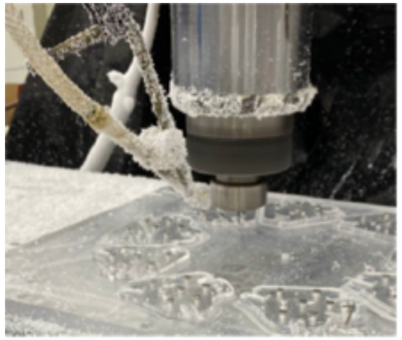
    $< 0.011 \pm 0.05$ pg/g ^{232}Th
  - Copper-Kapton laminated cables
- **Optically active** structural materials:
  - Polyethylene naphthalate (PEN) shifts 128 nm LAr scintillation light to ~440 nm and scintillates
  - Yield strength higher than copper at cryogenic temperatures

EFCu for holders and reentrant tube

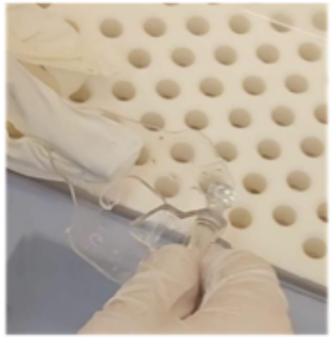




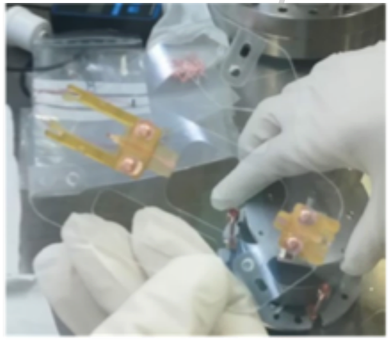
PEN: scintillating (self-vetoing) high-purity detector support



Machining



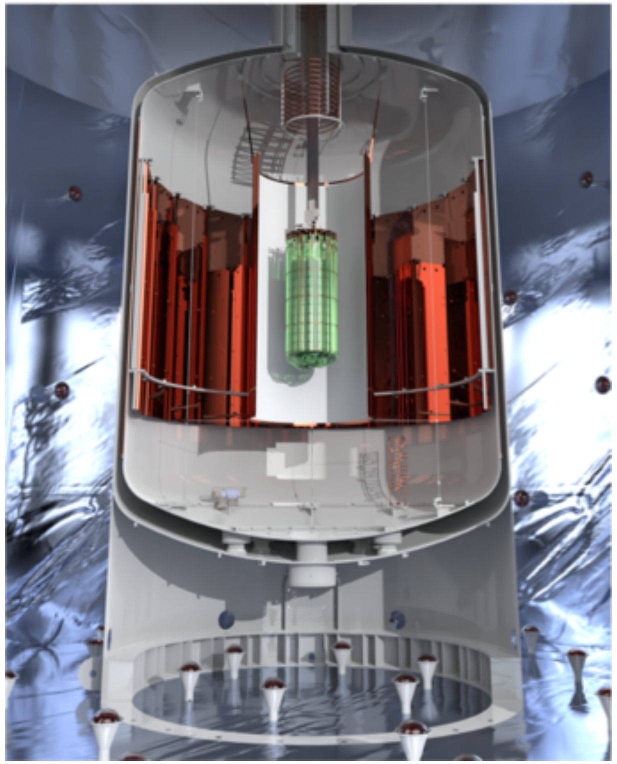
Cleaning

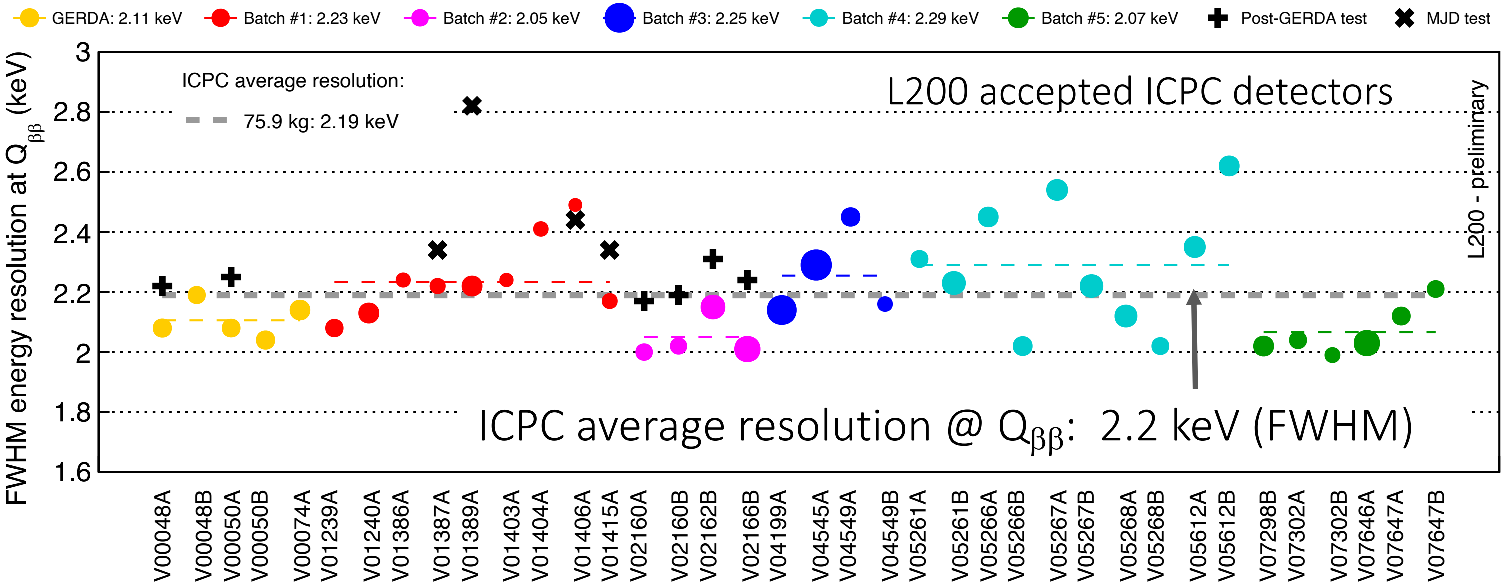


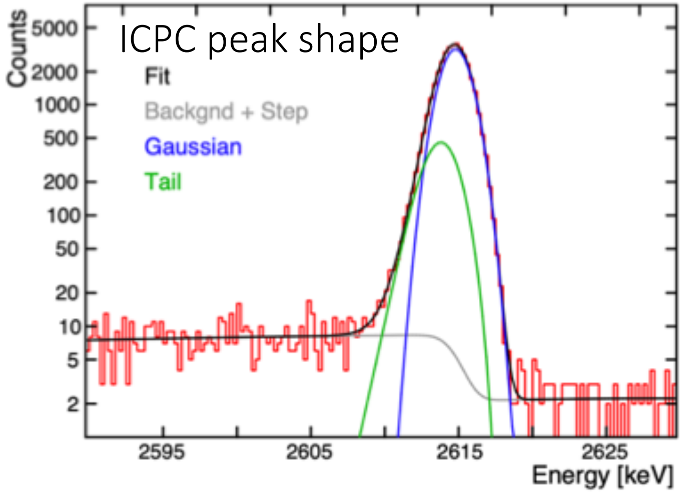
PEN plate

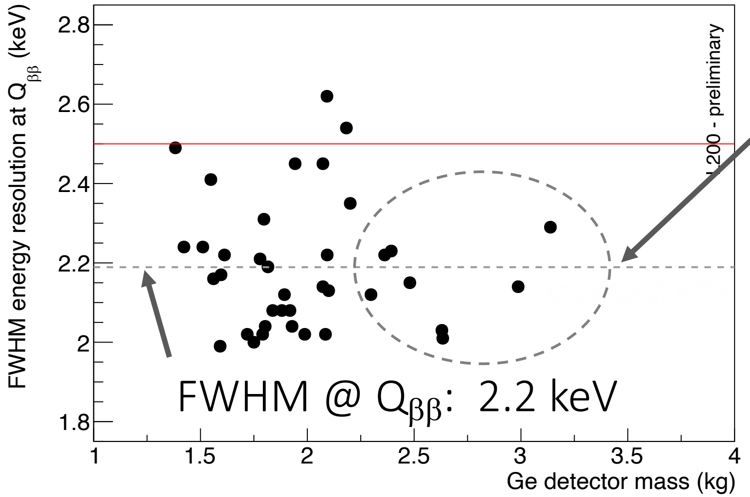
Innovation toward LEGEND-1000: LEGEND-200

- Procurement of ^{76}Ge (92% enr.)
- Novel ICPC detectors
- Improved LAr system
- Low-background materials
- Commissioning 2021









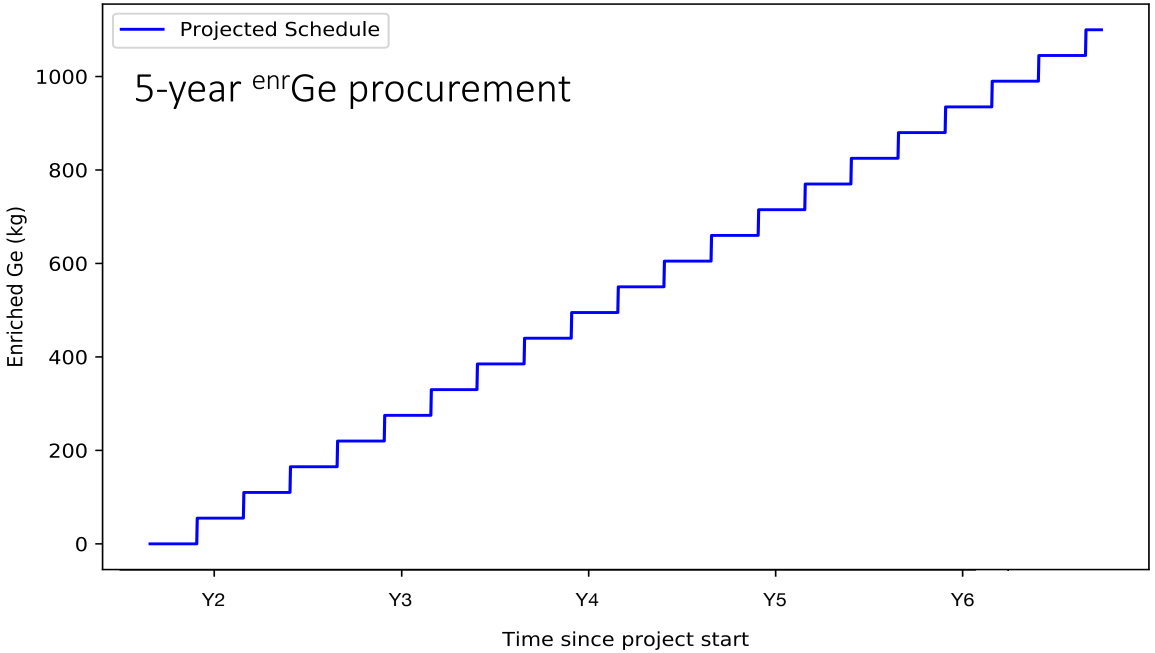
Large mass detectors show excellent energy resolution

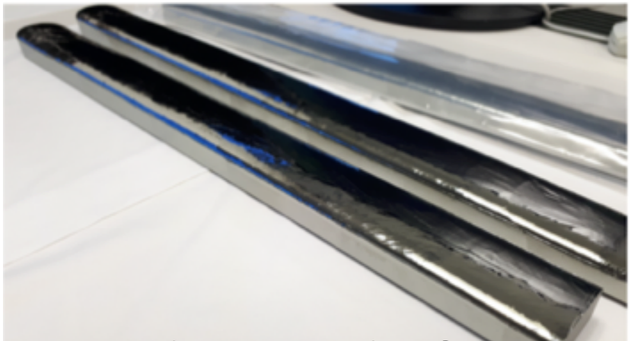
The Baseline Design: Ge-76 Acquisition & Processing

LEGEND

1000 kg of enriched Ge detectors:

- Fabricate 870 kg of new detectors; use 130 kg from LEGEND-200; recycle 50 kg of small detectors
- Procure 1100 kg of enriched Ge (92% ^{76}Ge)
- 220 kg/y for 5 years through ECP(JSC) & Urenco
- No interference of world annual production (130 t/y)
- ^{enr}Ge metal production (50 Ω-cm) and chemical recycling at VPMS[1,2]
- LEGEND-200 experience:
  - Reliable production of 185 kg enriched isotope from ECP(JSC) and Urenco
  - Zone refinement at VPMS (and IKZ[1])
  - Chemical purification and recovery at VPMS & LNGS[1]

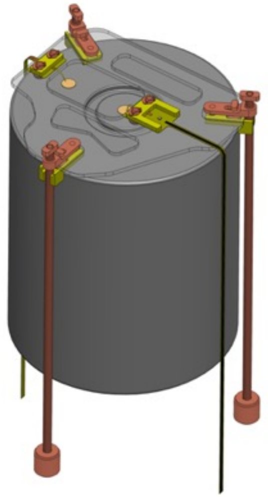


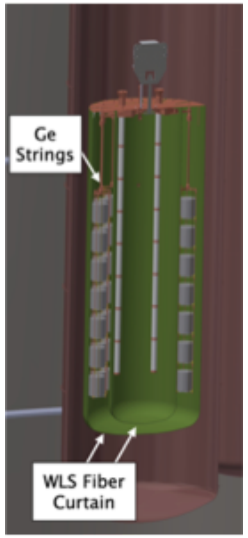

Zone refinement of ^{enr}Ge

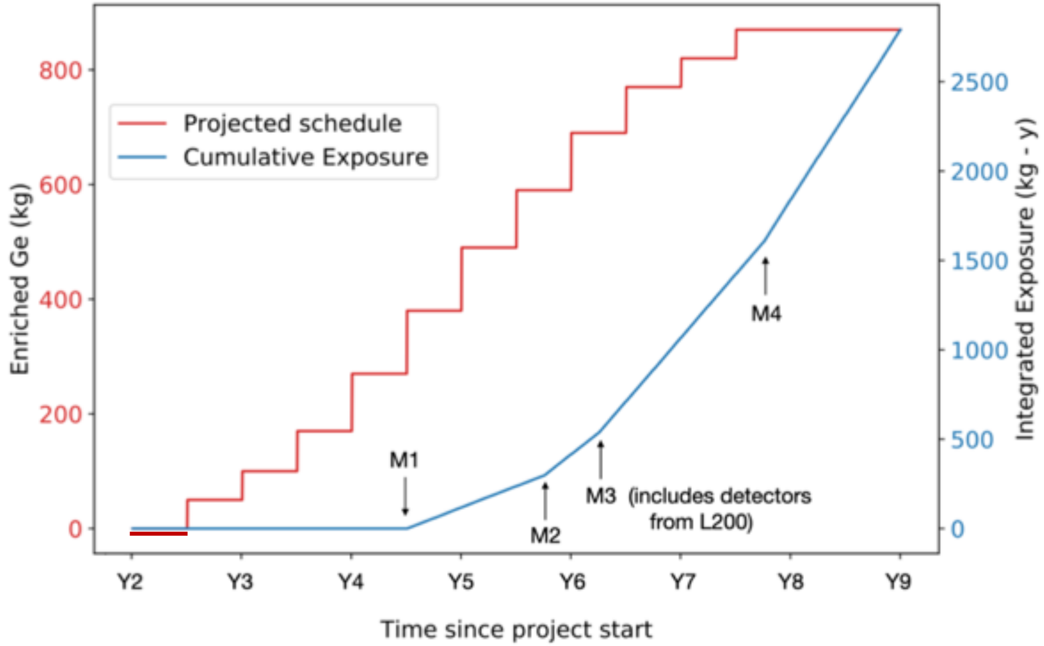

Chem. recycling

[1] Technology expertise also internal to LEGEND: IKZ, INR, USD, USC
[2] Purification system at VPMS owned by UNC

The Baseline Design: Detector Arrays







ICPC detector assembly:

- 2.6 kg average mass
- EFCu
- PEN
- **ASIC front end**
- Flat flex cables

Detector arrays:

- 4 arrays
- 100 ICPCs / array
- 1000 kg total mass
- 0.12% FWHM (0.05% σ) at $Q_{\beta\beta}$
- Double-barrel LAr instrumentation
- **Underground argon**
- **Reentrant tubes**

ICPC detector production:

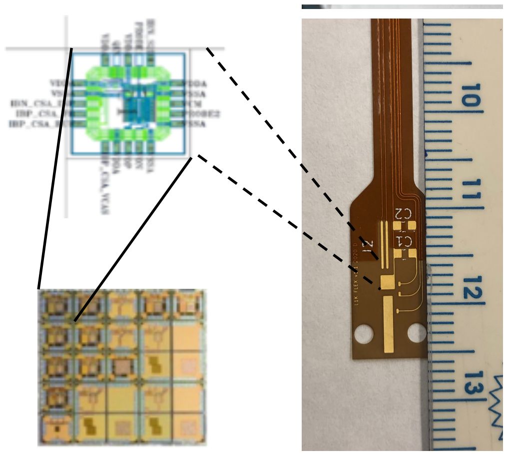
- Two established vendors plus 2 additional vendors
- 1st year: 50 detectors / y
- Subsequent years: 110 / y
- LEGEND-1000 staged approach: Detectors for first module are ready 2.5 years after start of production

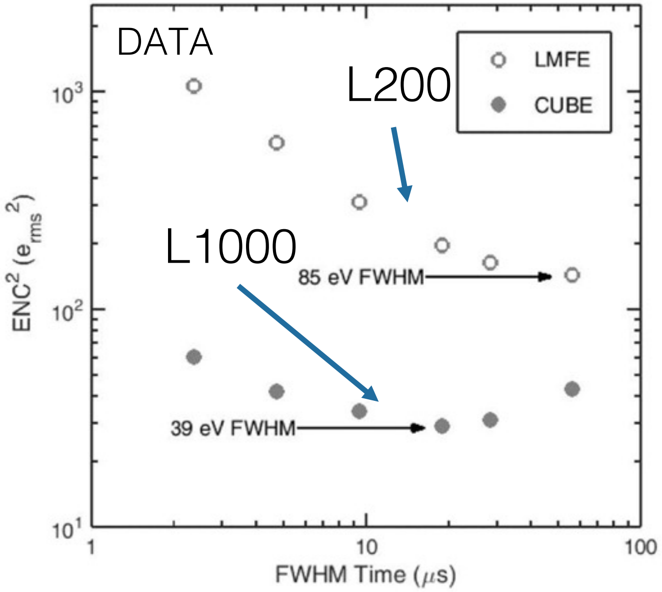
The Baseline Design: Front-End Electronics & DAQ

Front-end CSA ASIC:

- Low noise / threshold: <1 keV
- Large dynamic range: 10 MeV
- Sufficient bandwidth: 50 MHz
- Detector capacitance: 5 pF

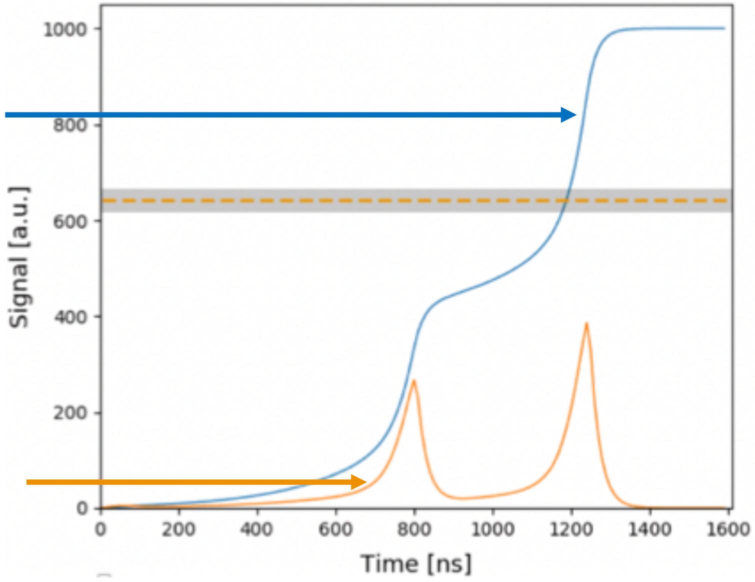
LEGEND-1000 prototype





Data Acquisition:

- Full digitization of Ge, LAr system, water Cherenkov systems
- Off-line filtering



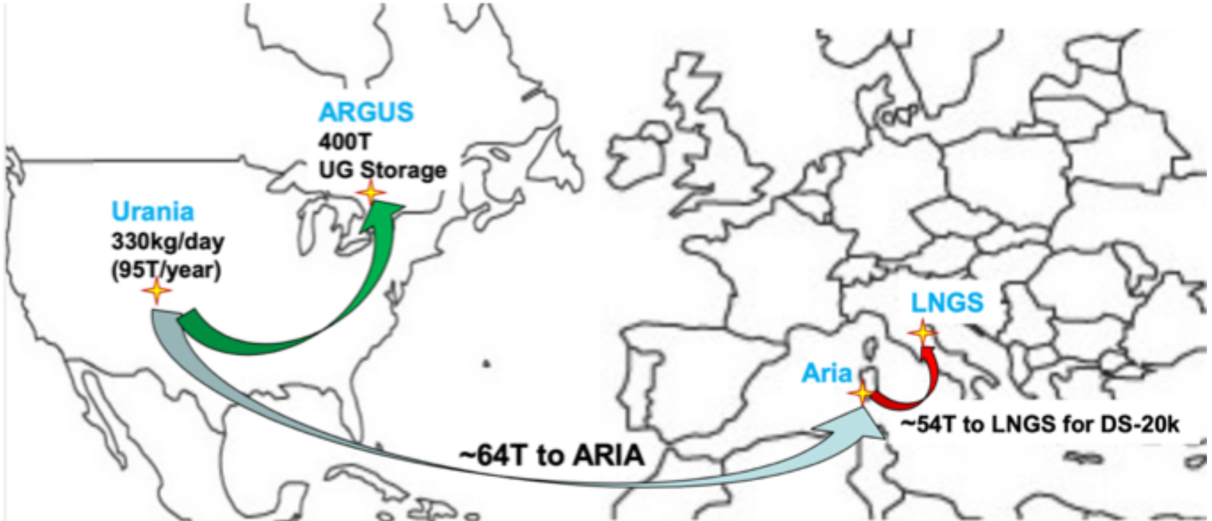
- LEGEND-1000 DAQ built on LEGEND-200 design; successfully operated during Post-GERDA Test (PGT)

The Baseline Design: Underground Liquid Argon

- L1000 needs 20-25 t of UGLAr
- Builds on pioneering work of DarkSide collaboration
- UGAr will be mined at Urania facility (U.S.) 95 t/y
- Logistics and storage technology under development by DarkSide/ARGO collaboration for LNGS and SNOLAB
- Expression of interest from INFN president[1] and DarkSide leadership
- UGAr production for LEGEND-1000 in 2023 (after DS-20k)

UGAr is depleted in ^{42}Ar (^{39}Ar)

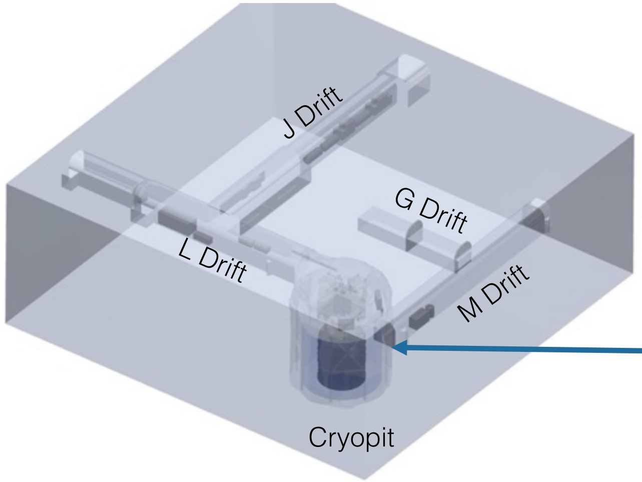
Isotope	Abundance	Half-life ($t_{1/2}$)	Decay mode	Product
^{36}Ar	0.334%	stable		
^{37}Ar	syn	35 d	ε	^{37}Cl
^{38}Ar	0.063%	stable		
^{39}Ar	trace	269 y	β^-	^{39}K
^{40}Ar	99.604%	stable		
^{41}Ar	syn	109.34 min	β^-	^{41}K
^{42}Ar	syn	32.9 y	β^-	^{42}K

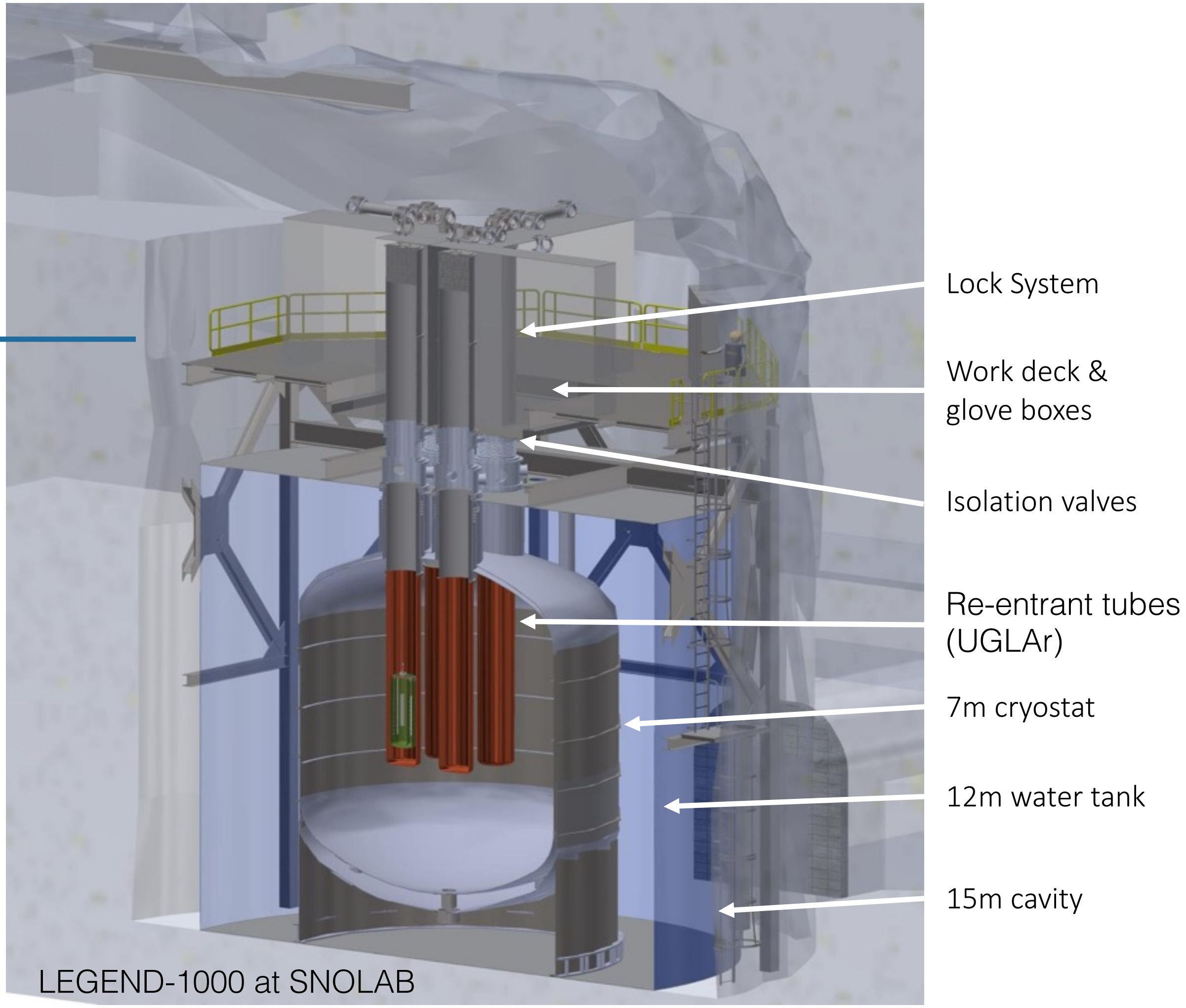


Credit: DarkSide / ARGO collaboration

[1] " ...we are confident that the production of the required UAr can be completed in a time scale useful for the accomplishment of the LEGEND-1000 experiment.. The present statement is an expression of interest and availability from INFN..."

The reference Design is (nearly) identical for SNOLAB and LNGS

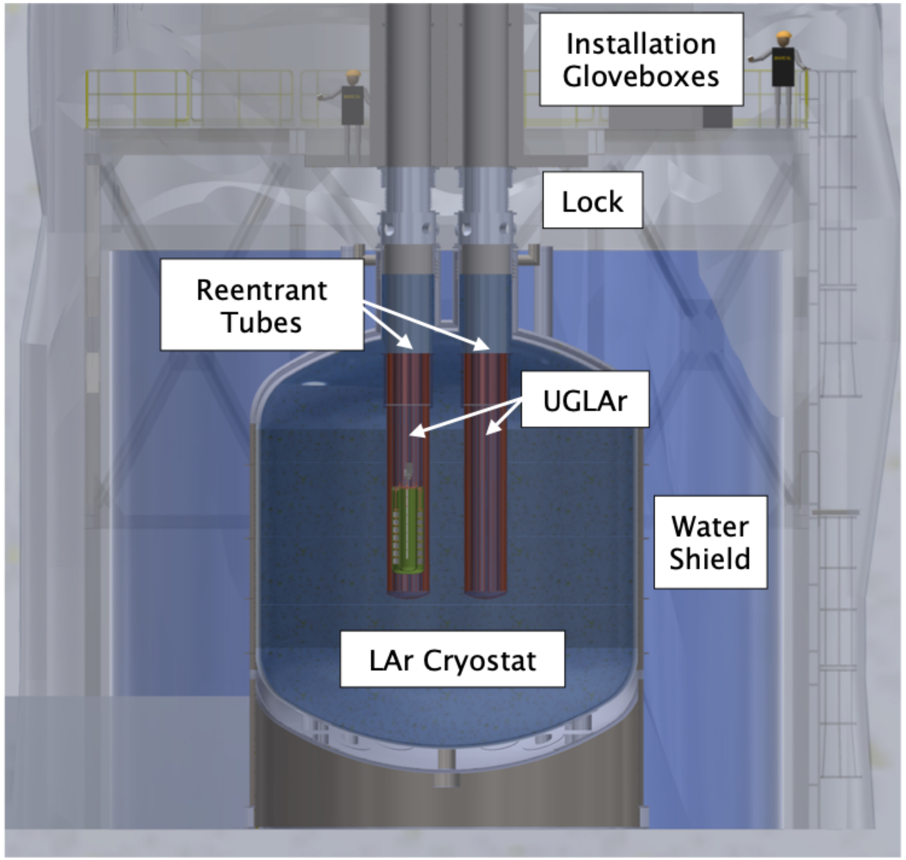




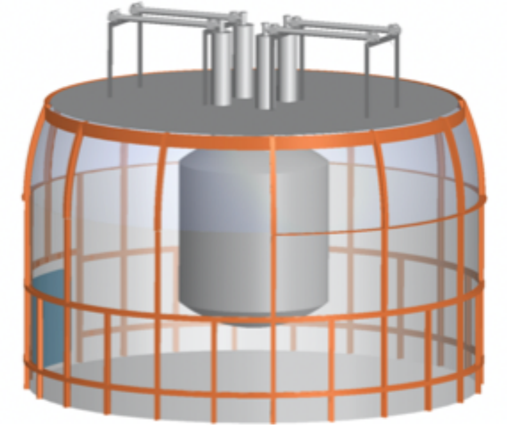
- SNOLAB (Canada) baseline site
- Rock overburden: 6000 m.w.e.
- Access through mine shaft
- All experimental areas class 2000 clean rooms
- Cryopit committed for ton-scale $0\nu\beta\beta$ experiment
- LNGS (Italy) alternative site

Detector Layout Concepts Change for Different Sites

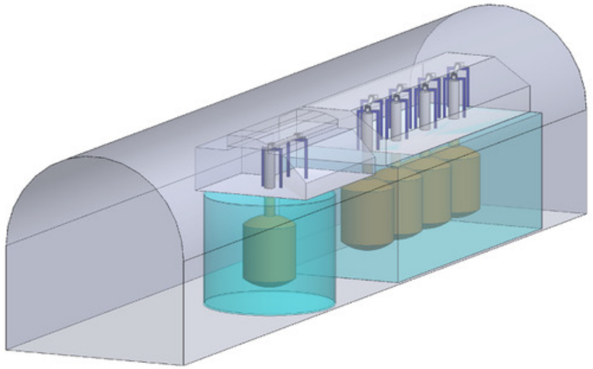
- Water tanks minimize the contribution of fission neutrons from rock and surroundings
- Argon-cryostat size influences the number of secondary particles (neutrons, gammas, …) per incoming muon; doubling the argon shield doubles the total number of neutrons;
- LNGS can accommodate 7-m baseline design as well as a 4 x 4-m diameter cryostat alternative design (smaller argon shield requires increased copper internal liner)



SNOLAB – baseline 7-m diameter cryostat geometry at SNOLAB



LNGS Hall C - baseline 7-m diameter cryostat design re-purposing the BOREXINO water tank

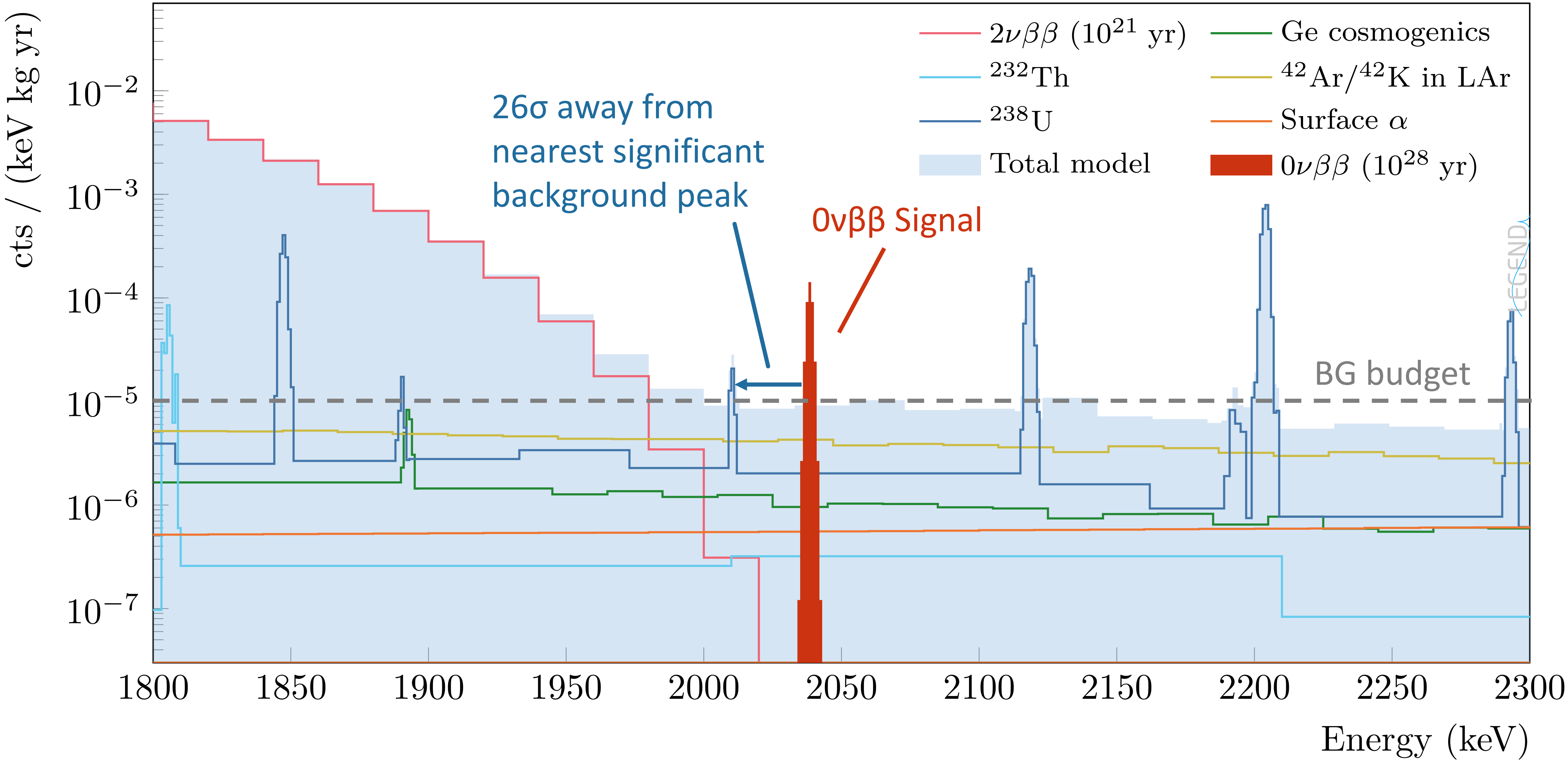


LNGS Hall A - design (4 additional 4-m diameter cryostats)

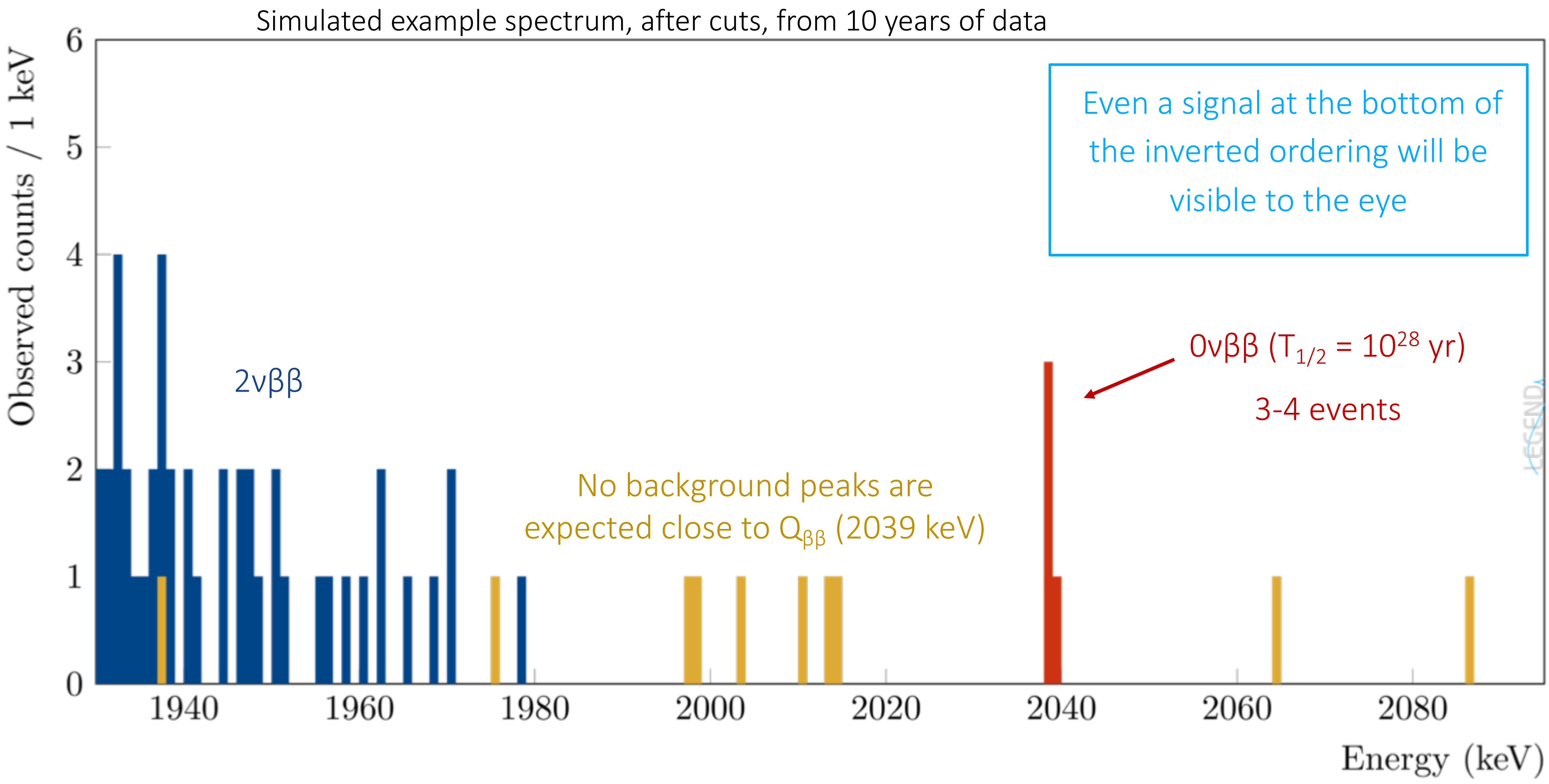
Muon-induced background estimates ($^{77(m)}Ge$)

- At **SNOLAB depth :**
  - 5.8 x 10^{-8} cts /(keV kg yr)
  - 0.6% of the background budget; even assuming a large uncertainty, the in-situ background contribution remains small.
- At **LNGS depth**
  - **Including a minimal implementation of delayed coincidence suppression, but no further measures,**
    - 5.4 x 10^{-6} cts /(keV kg yr) (7-m baseline detector layout),
      2.0 x 10^{-6} cts /(keV kg yr) (4 x 4-m cryostats).
    - 20-50% of the total background budget
  - Adding neutron moderating materials in the LAr, tagging sibling neutrons in the LAr and in the Gd-loaded water shield, and using topology information
    - <1 x 10^{-6} cts /(keV kg yr) (7-m baseline detector layout)
    - This is < 10 % of the total background budget

The LEGEND-1000 Background Model



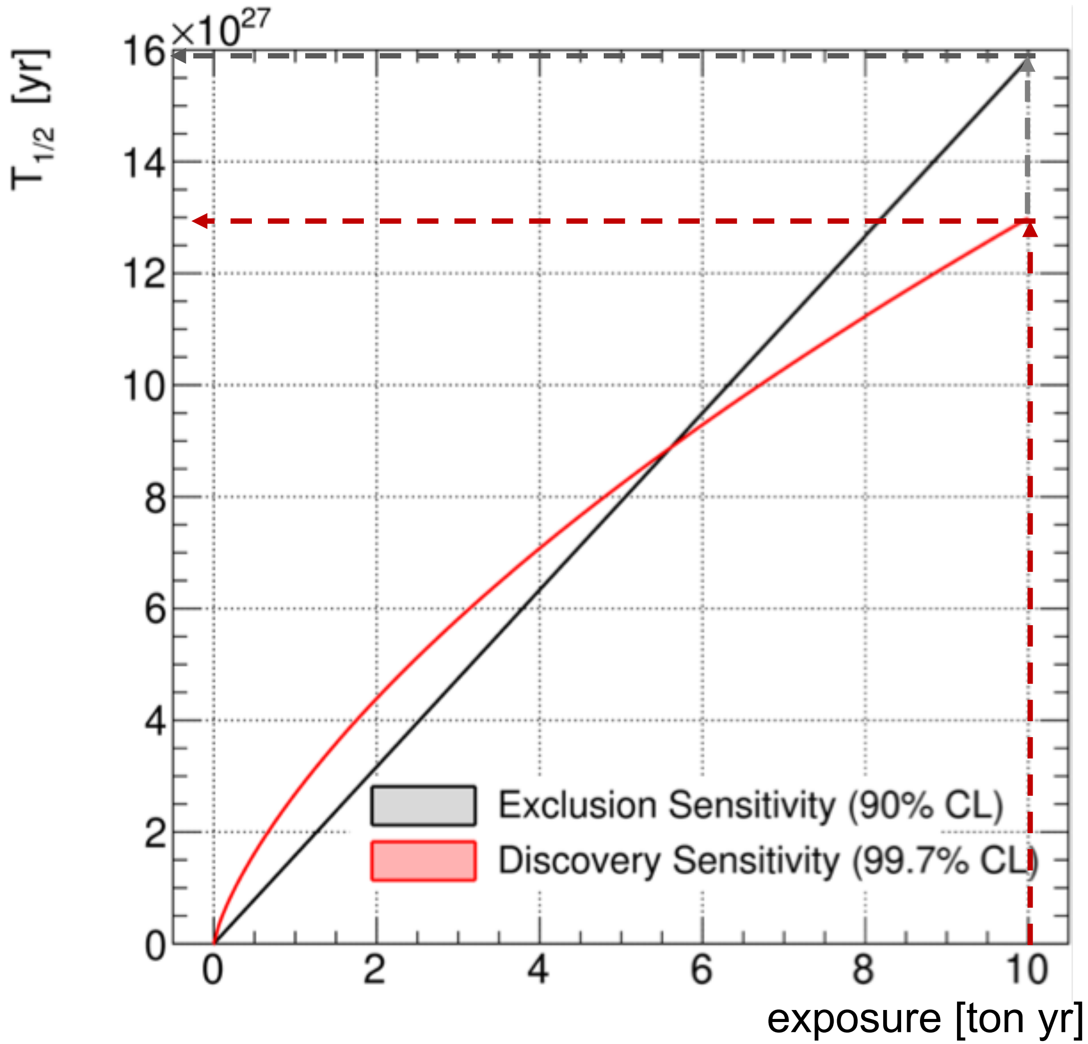
Designed for an Unambiguous Discovery



Sensitivity $T_{1/2}$

90% CL exclusion sensitivity @ 10 ton-yr	1.6 10^{28} yr
3σ discovery sensitivity @ 10 ton-yr	1.3 10^{28} yr

- $T_{1/2} \propto \mathcal{E}/N_{0\nu\beta\beta}$
- Background free ➜ linear sensitivity growth
- 10^{28} yr in discovery mode (x100 better than GERDA & MAJORANA)



LEGEND will explore uncharted territory and open new energy frontiers

New physics can manifest at any $T_{1/2}$ value!

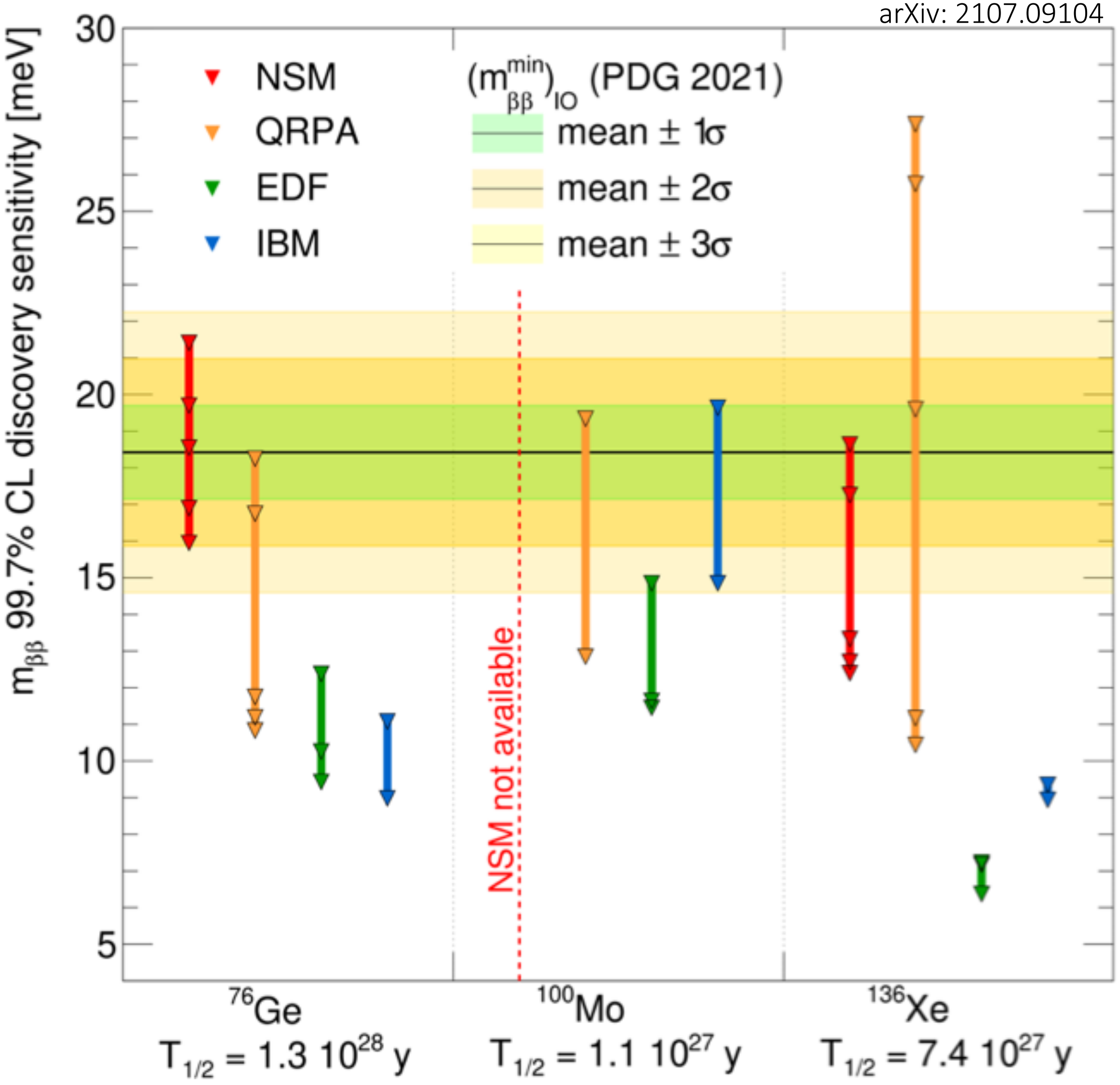
Sensitivity $m_{\beta\beta}$

- $m_{\beta\beta} = m_e / \sqrt{G\ g_A^4\ M^2\ T_{1/2}}$
- Inverted ordering: $m_{\beta\beta} > 18.4 \pm 1.3$ meV
- M → 4 many-body methods, each with specific systematics (soon also ab initio)
- Multiple, different set of calculations for each many-body method and isotope

LEGEND will fully test inverted ordering and a large part of the normal ordering space

Discovery sensitivity <18.4 meV for 3/4 many-body methods & 12/15 calculations

Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
arXiv: 2107.09104



LEGEND Collaboration Organization

Funding Agencies

LEGEND Institutional Board
- Institutional Representatives
- Early-Career Members

Project Support
- Project Controls/Scheduler
- ES&H Support
- Project Engineer

Budgetary Committee
- Funded Inst. Reps.

Director, host laboratory

LEGEND Steering Committee (Membership as of June 2021)

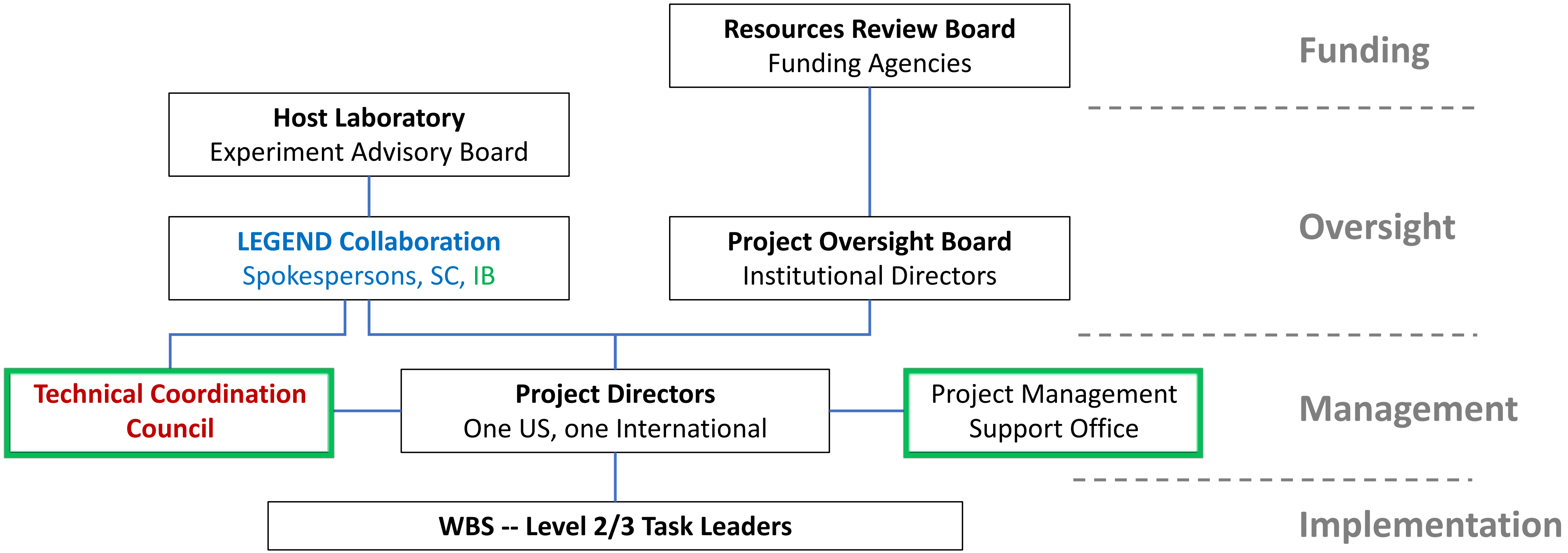
Spokespersons: Steve Elliott, Stefan Schönert
LEGEND-200 Project Director: Bernhard Schwingenheuer
LEGEND-200 Deputy Project Director: John Wilkerson
LEGEND-1000 Down-Select Coordinator: John Wilkerson
At-large: David Radford, Laura Baudis, Riccardo Brugnera
Analysis/Simulation Co-coordinator: Matteo Agostini & Jason Detwiler
Early-Career Representative: David Hervas Aguilar
Institutional Board Chair/Vice-Chair (ex officio): Iris Abt / Matt Green
Diversity Officers: Matteo Agostini & John Wilkerson

Technical Council
- **L200** Instrument science (WG leads) (chaired by project director)
  - Task Leads
- Data analysis (chaired by analysis coordinators)

Speakers Bureau

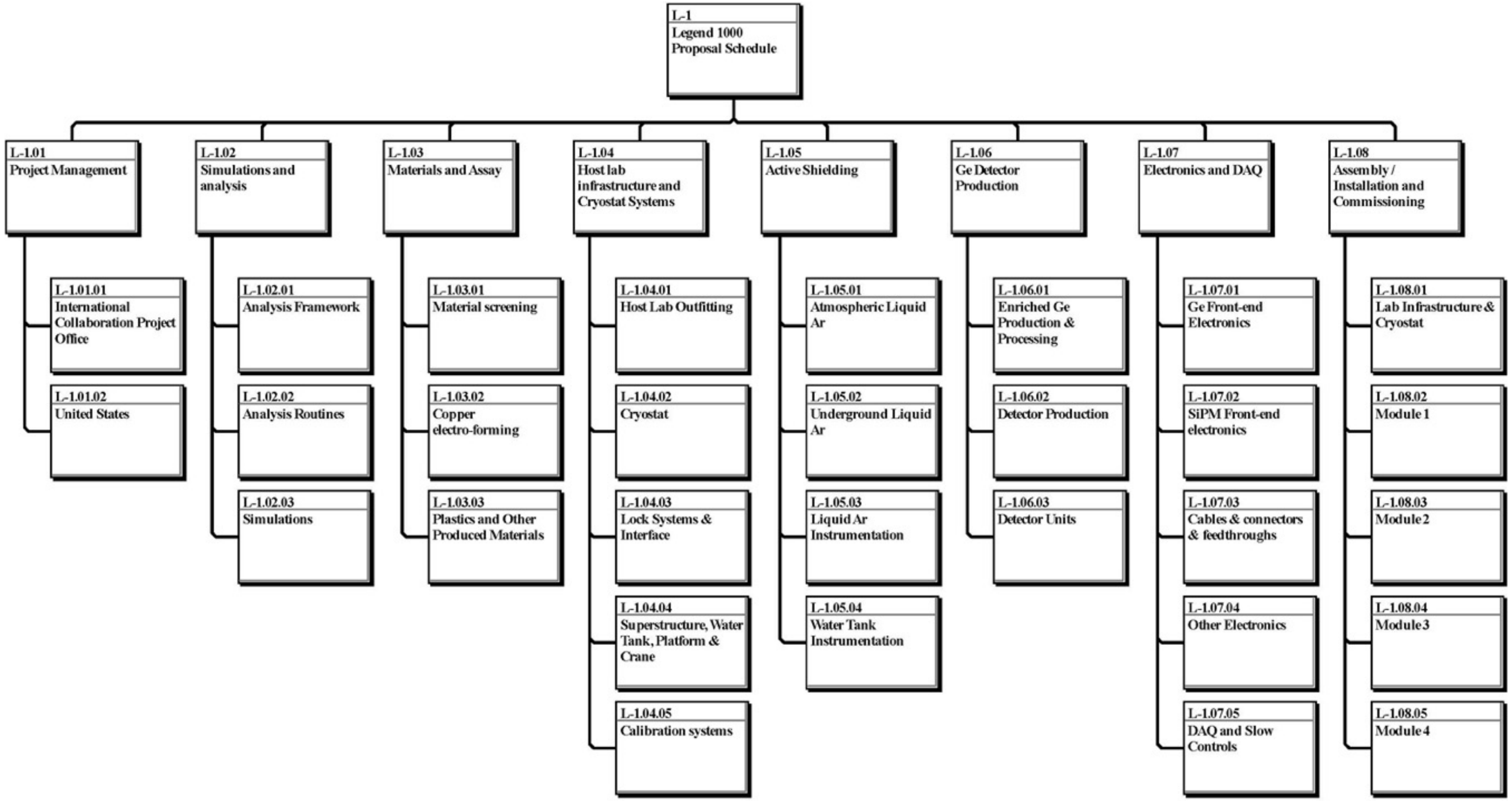
Editorial Board

LEGEND-1000 International Project Organization



- Project Management Support Office
  - Maintain cost and schedule, develop tailored PM practices, and guide a disciplined, structured application
- Technical Coordination Council (modeled on the current Technical Council)
  - Chaired by Project Dir’s; level-2 task leaders, representatives from PM Support Office and host laboratory
  - Meets weekly to plan and coordinate work, identify potential issues, and discuss schedule status

LEGEND-1000 International Project: WBS

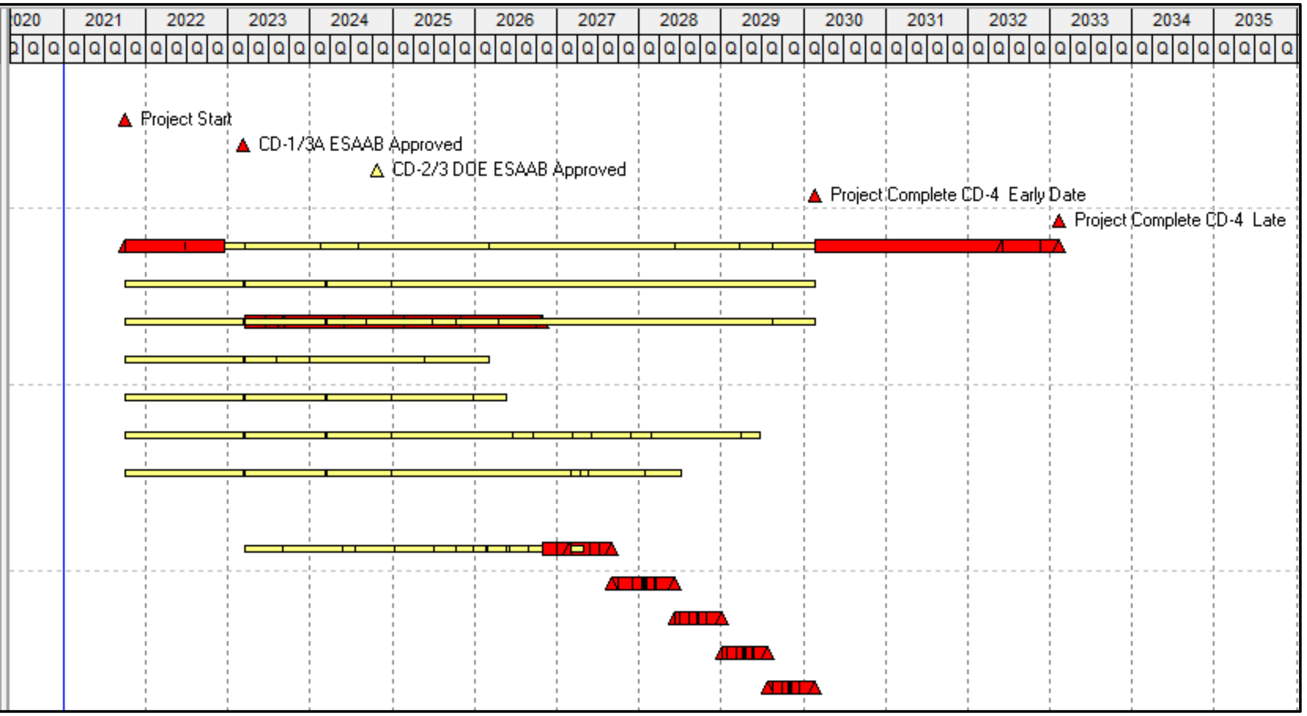


- *8 level-2 nodes*
- *30 level-3 nodes*
- *89 nodes total*

- Includes the full scope and deliverables required to complete the project in the pCDR
- Product / Deliverable-oriented, regardless of contributor or funding
- Aligned along major subsystems

LEGEND-1000 International Project: SNOLAB (baseline site)

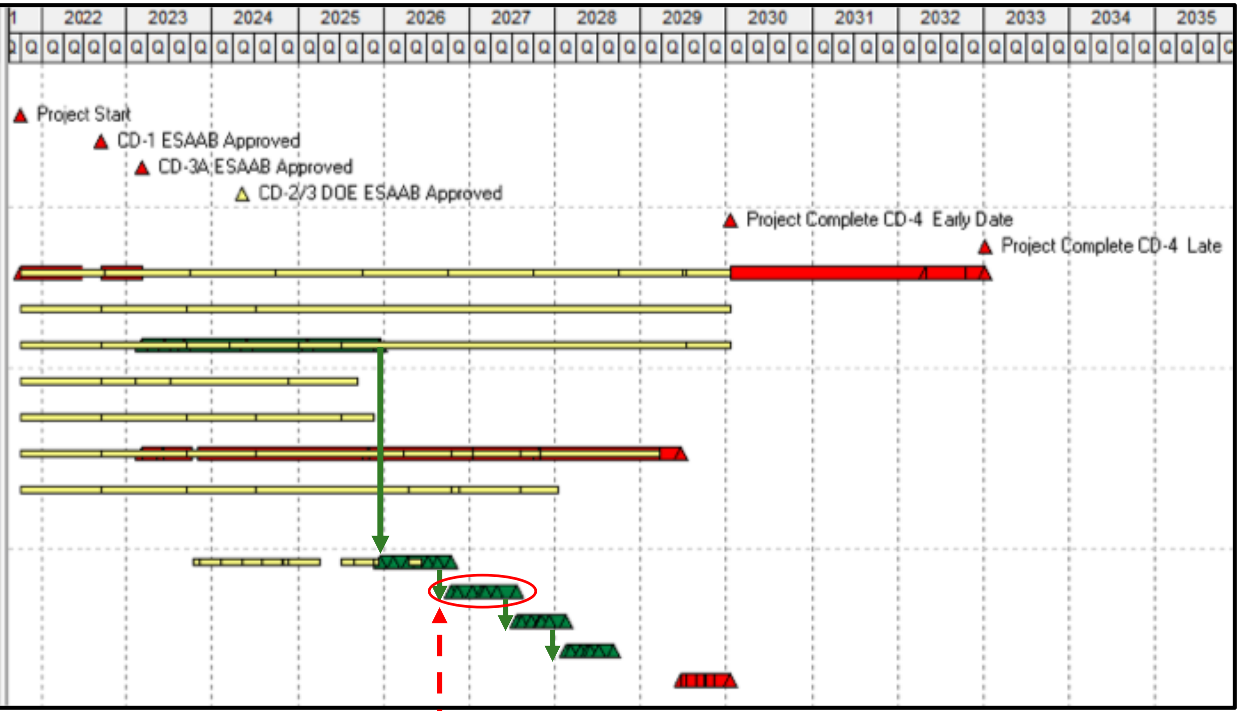
Activity ID	Activity Name	Start	Finish
L-1	Legend 1000 Proposal Schedule	01-Oct-21	09-Feb-33
A1090	Project Start	01-Oct-21*	
A1790	CD-1/3A ESAAB Approved		13-Mar-23
A1980	CD-2/3 DOE ESAAB Approved		25-Oct-24
A8130	Project Complete CD-4 Early Date		19-Feb-30
A1420	Project Complete CD-4 Late		09-Feb-33
L-1.01	Project Management	01-Oct-21	08-Feb-33
L-1.02	Simulations and analysis	01-Oct-21	19-Feb-30
L-1.03	Materials and Assay	01-Oct-21	19-Feb-30
L-1.04	Host lab infrastructure and Cryostat Systems	01-Oct-21	09-Mar-26
L-1.05	Active Shielding	01-Oct-21	19-May-26
L-1.06	Ge Detector Production	01-Oct-21	20-Jun-29
L-1.07	Electronics and DAQ	01-Oct-21	06-Jul-28
L-1.08	Assembly / Installation and Commissioning	14-Mar-23	19-Feb-30
L-1.08.01	Lab Infrastructure & Cryostat	14-Mar-23	02-Sep-27
L-1.08.02	Module 1	03-Sep-27	07-Jun-28
L-1.08.03	Module 2	08-Jun-28	02-Jan-29
L-1.08.04	Module 3	03-Jan-29	25-Jul-29
L-1.08.05	Module 4	26-Jul-29	19-Feb-30



- Key Dates:
  - Tentative Project Start: Q1,FY22
  - **Module 1 Commissioning Complete: Q3,FY28 81 months (relative to start)**
  - Early Finish: Module 4 Commissioning Complete: Q3,FY29 97 months
  - Late Finish (36 months of float): Q2,FY32 133 months

LEGEND-1000 International Project: LNGS (alternative site)

Activity ID	Activity Name	Start	Finish
L-LNGSCD-1	Legend 1000 Post Proposal Schedule - LNGS	01-Oct-21	06-Jan-33
A1090	Project Start	01-Oct-21*	
A1790	CD-1 ESAAB Approved		16-Sep-22
A9510	CD-3A ESAAB Approved		13-Mar-23
A1980	CD-2/3 DOE ESAAB Approved		07-May-24
A8130	Project Complete CD-4 Early Date		15-Jan-30
A1420	Project Complete CD-4 Late		06-Jan-33
L-LNGSCD-1.01	Project Management	01-Oct-21	05-Jan-33
L-LNGSCD-1.02	Simulations and analysis	01-Oct-21	15-Jan-30
L-LNGSCD-1.03	Materials and Assay	01-Oct-21	15-Jan-30
L-LNGSCD-1.04	Host lab infrastructure and Cryostat Systems	01-Oct-21	12-Sep-25
L-LNGSCD-1.05	Active Shielding	01-Oct-21	21-Nov-25
L-LNGSCD-1.06	Ge Detector Production	01-Oct-21	20-Jun-29
L-LNGSCD-1.07	Electronics and DAQ	01-Oct-21	14-Jan-28
L-LNGSCD-1.08	Assembly / Installation and Commissioning	22-Jun-22	15-Jan-30
L-LNGSCD-1.08.01	Lab Infrastructure & Cryostat	22-Jun-22	16-Oct-26
L-LNGSCD-1.08.02	Module 1	19-Oct-26	22-Jul-27
L-LNGSCD-1.08.03	Module 2	23-Jul-27	16-Feb-28
L-LNGSCD-1.08.04	Module 3	17-Feb-28	07-Sep-28
L-LNGSCD-1.08.05	Module 4	21-Jun-29	15-Jan-30



- Near Critical Path: Installation of the Cryostat
- The commissioning of Module 1 initiates first science and is a priority objective for the project
- Installation schedule for start of module 1 reduced approx. by 1 year
- Cost saving - using US DOE accounting and labor costs – correspond to approx. 20 M$
- Potential early start with design studies and material procurement of cryostat with European funding.

Conclusion

- LEGEND-1000 is optimized for a quasi-background-free 0νββ search
  - It builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
  - Our 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
- The reference design plans for the instrument to be sited in the SNOLAB Cryopit (baseline site)
- Alternatively, the instrument can be sited at LNGS (Hall C) (alternative site)
- LEGEND-1000 International Project Organization established with ORNL as US DOE leadlab
- We have a strong, experienced, international collaboration that "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-1000 Preconceptual Design Report: https://arxiv.org/pdf/2107.11462.pdf