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

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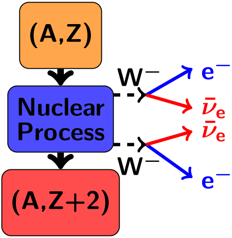
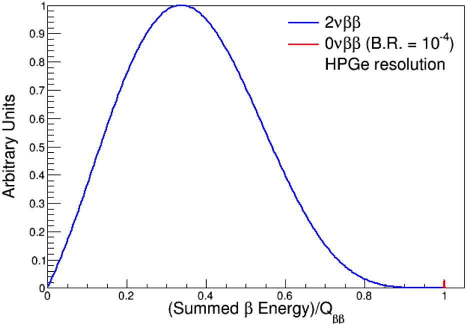
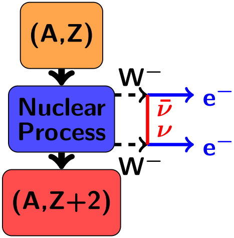
# Double-beta decay




**$2\nu\beta\beta$-decay**



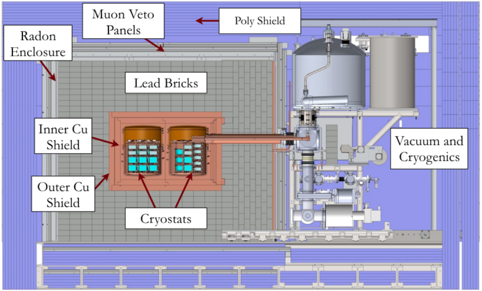

**$0\nu\beta\beta$-decay**

(“vanilla model”)

- $2\nu\beta\beta$-decay: SM allowed and observed.
- $0\nu\beta\beta$-decay: Violates lepton number conservation (a requirement of some neutrino mass models). Not yet observed.
- For $^{76}$Ge (Q = 2039 keV):
  - $T^{2\nu}_{1/2} \sim 10^{21}$ y $\rightarrow$ Rare process.
  - $T^{0\nu}_{1/2} > 10^{26}$ y $\rightarrow$ Need ultra-low background, large mass, long counting time to search for it.
    - e.g. $T^{0\nu}_{1/2} \sim 10^{28}$ y would give signal of $\sim 0.5$ counts/ton·year.

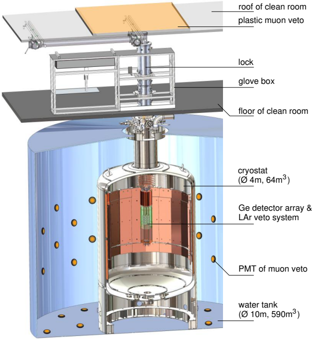
# A tale of two experiments

## MAJORANA DEMONSTRATOR (SURF)




- Detectors (29.7 kg enr$^{76}$Ge) in 2 vacuum cryostats.
- Surrounded by passive shield.
- Ultra-clean materials used.

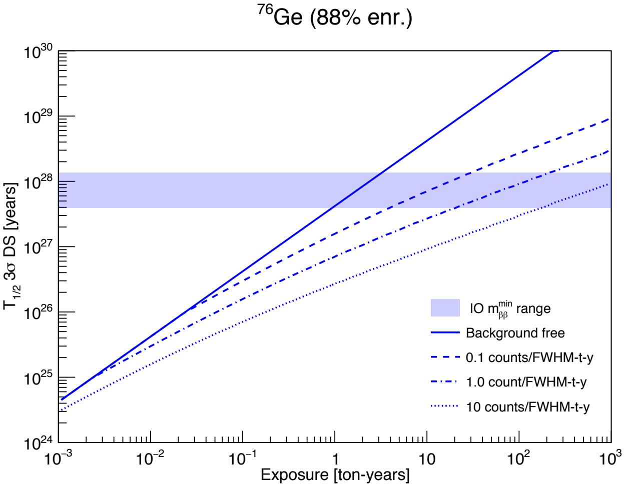
## GERDA (LNGS)




- Detectors (37.6 kg enr$^{76}$Ge) in liquid argon (LAr).
- LAr acts as an active shield
  - Tag backgrounds with scintillation light.

- **Both have achieved backgrounds of**: $\sim 3\ \mathrm{counts}/(\mathrm{FWHM} \cdot \mathrm{t} \cdot \mathrm{y})$

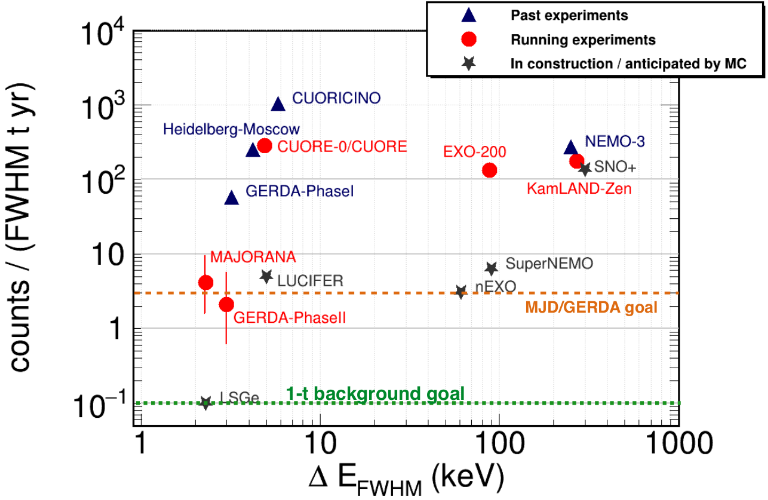
# Discovery potential vs. exposure




- Need a tonne-scale detector with backgrounds $<\sim$ 0.1 c/FWHM·t·y for 3$\sigma$ discovery at bottom of IO-allowed region on a reasonable time scale.

Colored band shows expected half-life range for $m_{\beta\beta} = 17$ meV, with unquenched axial vector coupling, and nuclear matrix elements ranging from 3.5 to 5.5.

# Status of the field




- This plot effectively assumes an ROI for each experiment $\Delta E_{FWHM}$ wide.
- $^{76}$Ge detector arrays have demonstrated the lowest backgrounds and highest energy resolution of all $0\nu\beta\beta$ experiment technologies.

# Next Generation $^{76}$Ge: LEGEND

**L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless $\beta\beta$ **D**ecay

**Mission:** "The collaboration aims to develop a phased, Ge-76 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."

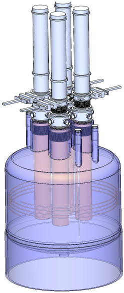
Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

**First phase:**

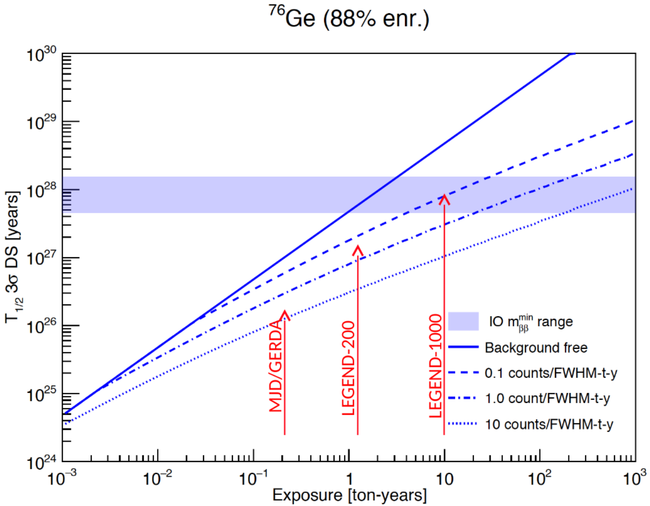
- (Up to) 200 kg.
- Modification of existing GERDA infrastructure at LNGS.
- BG goal ($\times$5 lower) 0.6 c/(FWHM·t·y)
- Start by 2021.

**Subsequent stages:**

- 1000 kg (staged).
- Timeline connected to U.S. DOE down select process.
- BG goal ($\times$30 lower) 0.1 c/(FWHM·t·y)
- Location: TBD.
- Required depth (Ge-77m) under investigation.



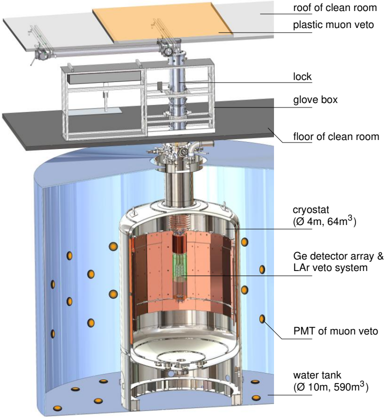
# LEGEND discovery potential




- Reduction of backgrounds is crucial to achieve good discovery potential.
- MAJORANA and GERDA technologies combined with new R&D to accomplish this.

# LEGEND-200

- Initial 200 kg phase permits early science with a world-leading experiment.
- Exposure 1 ton·yr, sensitivity $> 10^{27}$ yr
- Keeps young people involved and maintains skilled workers.
- Reduces risk for a future ton-scale phase.
- Reuse of GERDA infrastructure and MAJORANA/GERDA detectors (60 kg) permits possible data taking in 2021-2022.
- Room in GERDA cryostat for 200 kg of enriched detectors.




- **Required reduction in background for LEGEND-200 has already been demonstrated as feasible in the MAJORANA DEMONSTRATOR, GERDA, and dedicated test stands.**

# Background reduction

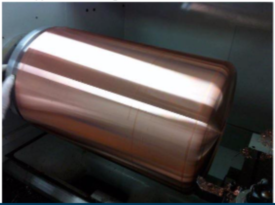
# Electroformed copper

- MAJORANA DEMONSTRATOR copper electroformed underground at PNNL and SURF.
  - Th decay chain (avg): $\leq 0.1\ \mu$Bq/kg
  - U decay chain (avg): $\leq 0.1\ \mu$Bq/kg
    - At least an order of magnitude lower background than commercial OFHC copper.
- Machined and stored underground to reduce cosmogenic activation ($^{60}$Co).
- Using MAJORANA electroforming practices should improve on GERDA radiopurity for LEGEND-200.
  - Facilities at SURF should be able to produce enough copper for LEGEND-200 in the next 14 months.

Electroforming Baths in TCR

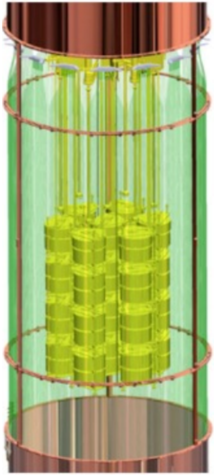
Inspection of EF copper on mandrels

EF copper after turning on lathe



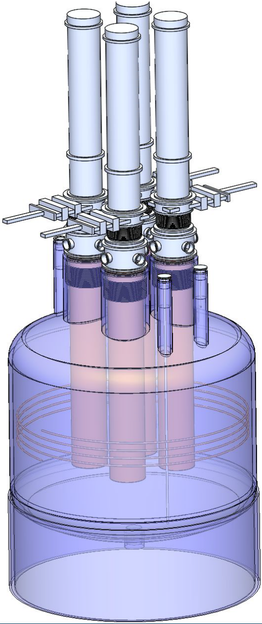
# LEGEND-200: Liquid argon veto

- GERDA employs PMTs above and below the array and a surrounding wavelength shifting fibre shroud to read out LAr scintillation light.
- Different geometries of fibres between the detector strings being studied to improve light collection in LEGEND-200.
- Can improve LAr purity to improve light yield and attenuation.
- Also investigating more radiopure fibres and amplification or digitization in LAr, but may be on longer timeline.

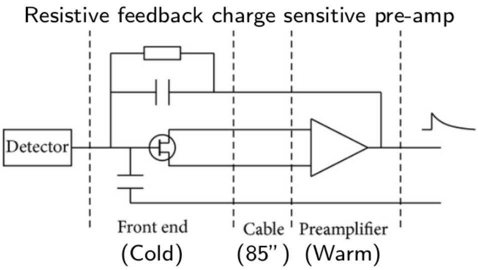


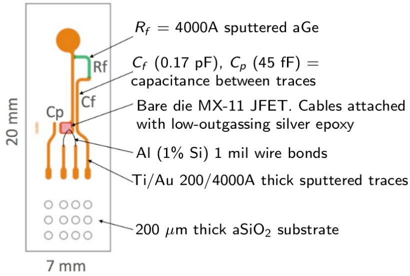
# LEGEND-1000: Liquid argon veto

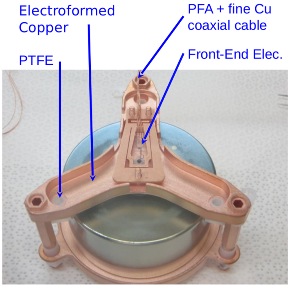
- Natural Ar includes $^{42}$Ar.
  - Decays to $^{42}$K ion, drifts to detectors, decays to $^{42}$Ca with $Q_\beta = 3.5$ MeV. ($0\nu\beta\beta$ background).
- Drift of $^{42}$K limited in GERDA and LEGEND-200 with nylon shrouds.
- In GERDA, LAr veto tags coincident $\gamma$ events well, pure $\beta$-decays cut with $\sim$ 99% efficiency by PSA.
- For LEGEND-1000, could remove this background completely using depleted underground argon.
  - Separate into four underground Ar volumes and one large natural Ar volume.
  - Copper dividing walls between to separate instrumentation.
  - Estimated underground Ar need: 21 tons, 15 m$^3$.



# The MAJORANA Low-Mass Front-End (LMFE) LEGEND



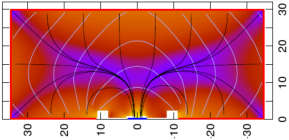



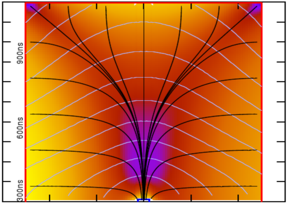

- Most radiopure front-end in the world.
- Lowest-noise front-end readout electronics in a large Ge array.
- LMFE in baseline design for LEGEND-200.
  - Should result in reduced backgrounds and noise.
  - R&D ongoing on LMFE performance in LAr and with longer cables.
- R&D for LEGEND-1000: ASIC pre-amp.

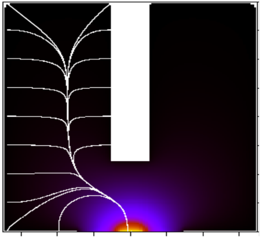
# Larger $^{enr}$Ge detectors



- GERDA BEGes average 0.66 kg.
- MAJORANA PPCs average 0.85 kg.
- Both have:
  - Excellent energy resolution.
  - Superb pulse-shape sensitivity to reject multi-site and surface background events.
- Larger detectors require fewer cables and pre-amp front-ends for the same total mass.
  - Lower backgrounds.
- New design: Inverted-Coaxial Point Contact Detectors
  - Allows detectors at least as large as normal coax, with similar performance to BEGes and PPCs.
  - 5 new enriched detectors in production, each $\sim$ 1.9 kg.
  - Baseline 1.5-2.0 kg.
  - Also studying natural detectors near 3 kg.



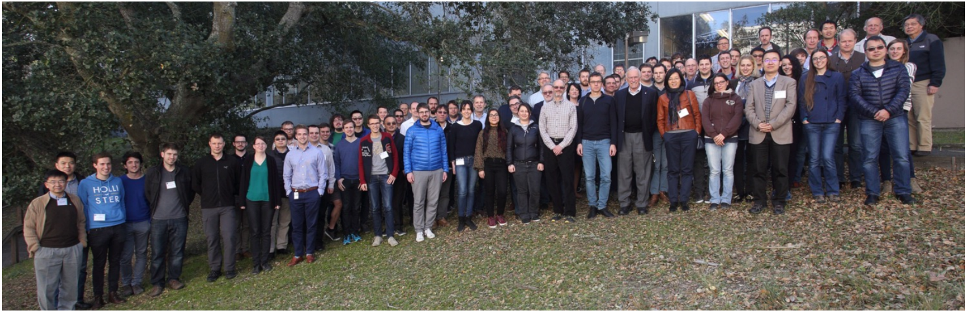



# Conclusions

- The next generation of neutrinoless double-beta decay experiments requires reduced backgrounds and additional mass.
- $^{76}$Ge detector arrays have demonstrated the lowest backgrounds and best energy resolution of all the next generation experiment technologies.
- The LEGEND collaboration plans to take the best of MAJORANA and GERDA, and perform additional R&D to build a detector with $0\nu\beta\beta$-decay discovery potential at a half-life beyond $10^{28}$ years.
- LEGEND will proceed in a phased approach, started with the 200 kg LEGEND-200.
  - Factor of 5 background reduction goal is realistic and consistent with the most conservative assay and simulation results.
- R&D directed towards LEGEND-200 and LEGEND-1000 is ongoing.

# The LEGEND Collaboration




**250 people, 47 institutions**

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