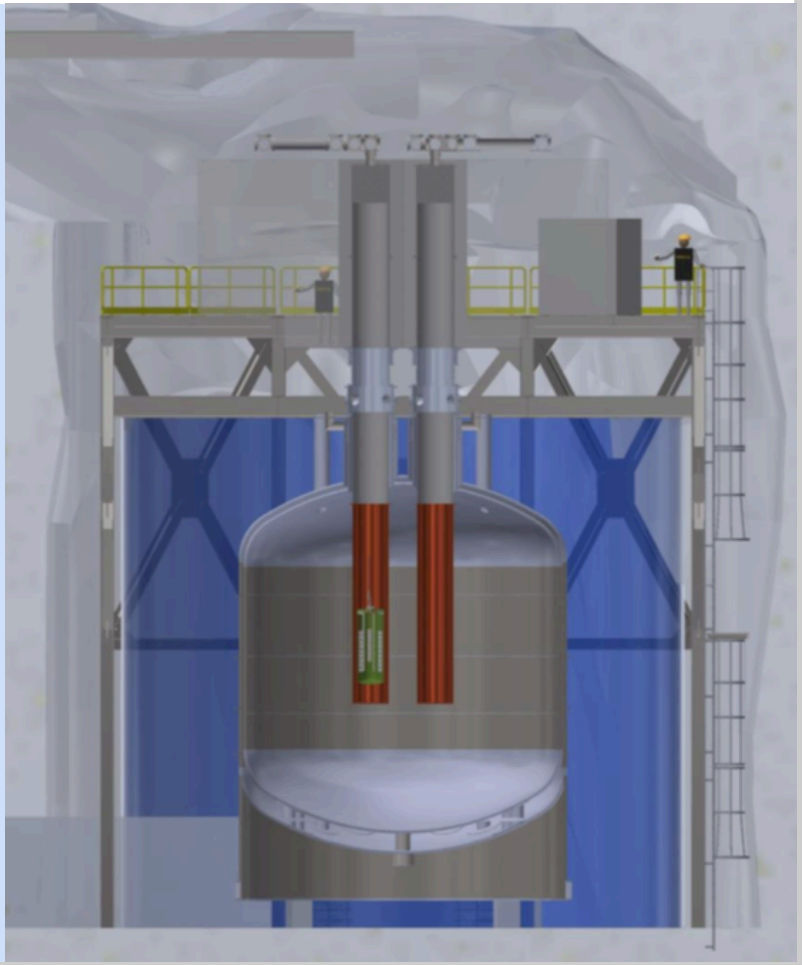
The LEGEND experiment in a search for neutrinoless double beta decay

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



JAGIELLONIAN UNIVERSITY IN KRAKÓW

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on behalf of the LEGEND collaboration

Conference on the Physics of the Two Infinities

27–30 Mar 2023, Kyoto

Double beta decay

- In some of even-even nuclei, beta decay due to energy/ angular momentum balance is forbidden,
- while **double beta ($2\nu\beta\beta$) decay** is allowed.

- what if… $0\nu\beta\beta$ decay is possible?

$2\nu\beta\beta$ $^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\bar{\nu}_e$

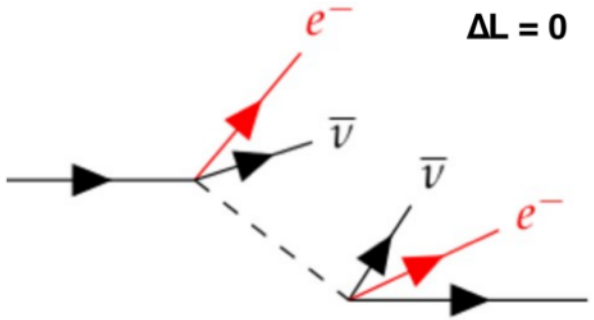
$0\nu\beta\beta$ $^{76}Ge \rightarrow {}^{76}Se + 2e^-$

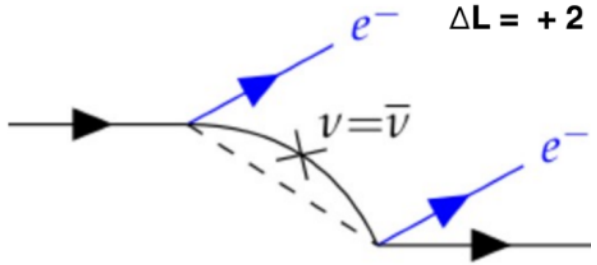
Majorana nature of neutrinos

Lepton number violation

Baryon asymmetry of the Universe

Neutrino mass scale and ordering (normal vs. inverted)

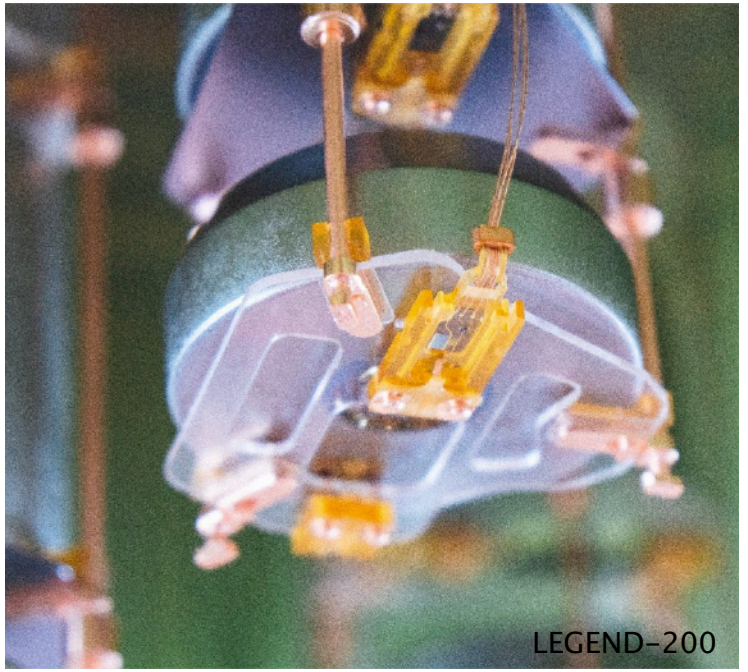


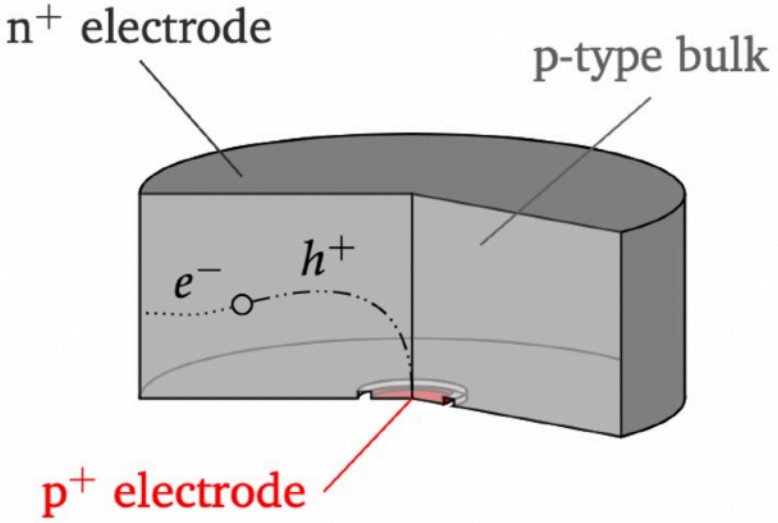


^{76}Ge: $Q_{\beta\beta}$ = 2039 keV

Germanium technology

- **Detector is the source**
  – excellent detection efficiency
- Semiconductor detectors made from high-purity germanium (HPGe) crystals – low intrinsic background
- Enrichment in ^{76}Ge is required (up to 92 %)
- Bare HPGe detectors can be directly immersed in Liquid Ar (coolant and active veto)
- Excellent energy resolution (~2.5 keV at $Q_{\beta\beta}$)





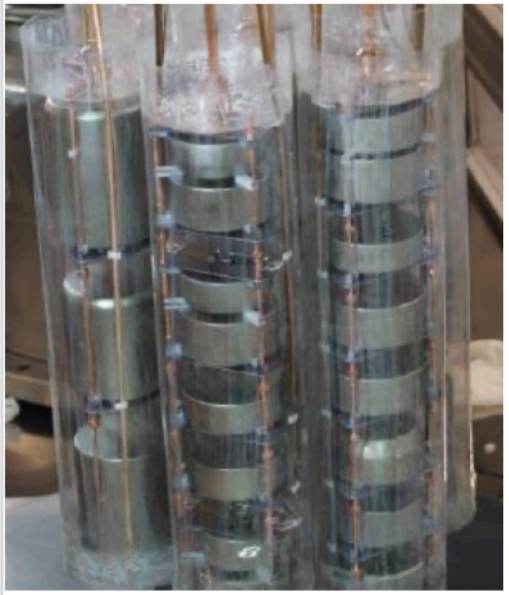
LEGEND concept

Merger of two successful programs:

GERDA (best background, LAr veto) **and**
MAJORANA (low noise, best FWHM, high purity VFE, low threshold) along with
several **new institutions** (presently ~270 members from 52 institutions and 11 countries)
to:

design, construct and operate of a ton-scale experiment

LEGEND-1000:



PRL 125 (2020) 252502

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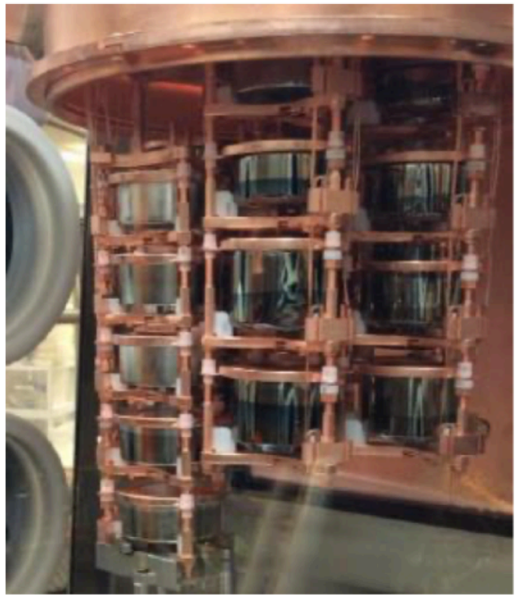

Phys. Rev. C **100** (2019) 025501

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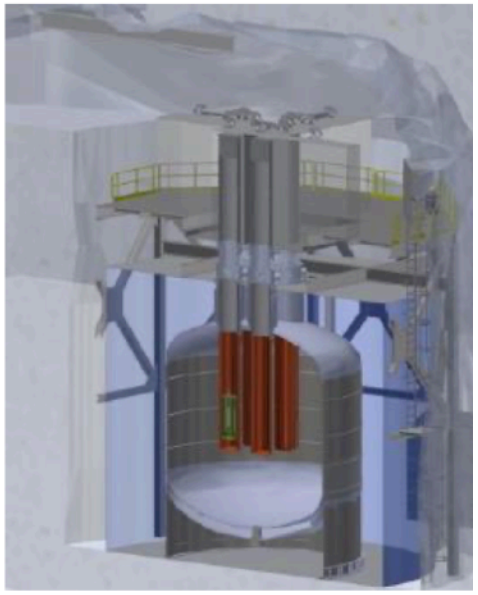

pCDR: arXiv:2107.11462

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LEGEND-1000:

"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" **[pCDR: arXiv:2107.11462]**

Energy resolution (FWHM) – Advantage for discovery

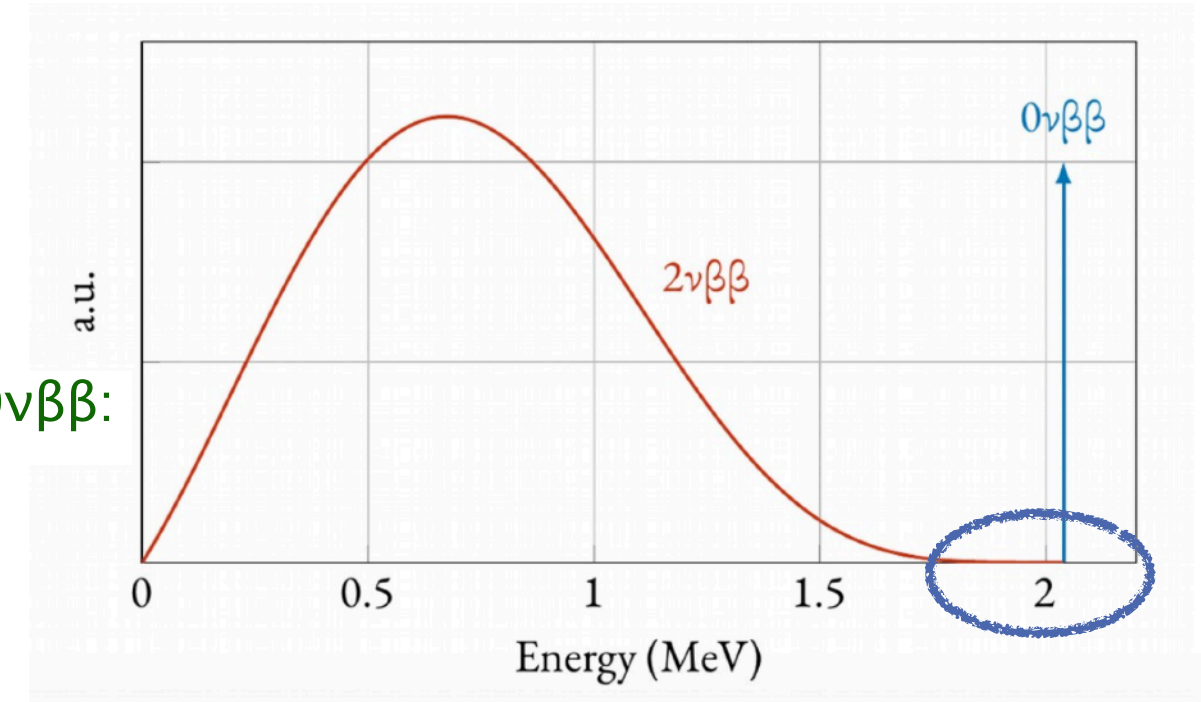
$0\nu\beta\beta$ $^{76}Ge \rightarrow {}^{76}Se + 2e^-$, $T_{1/2}^{exp} > 10^{26}$ yr

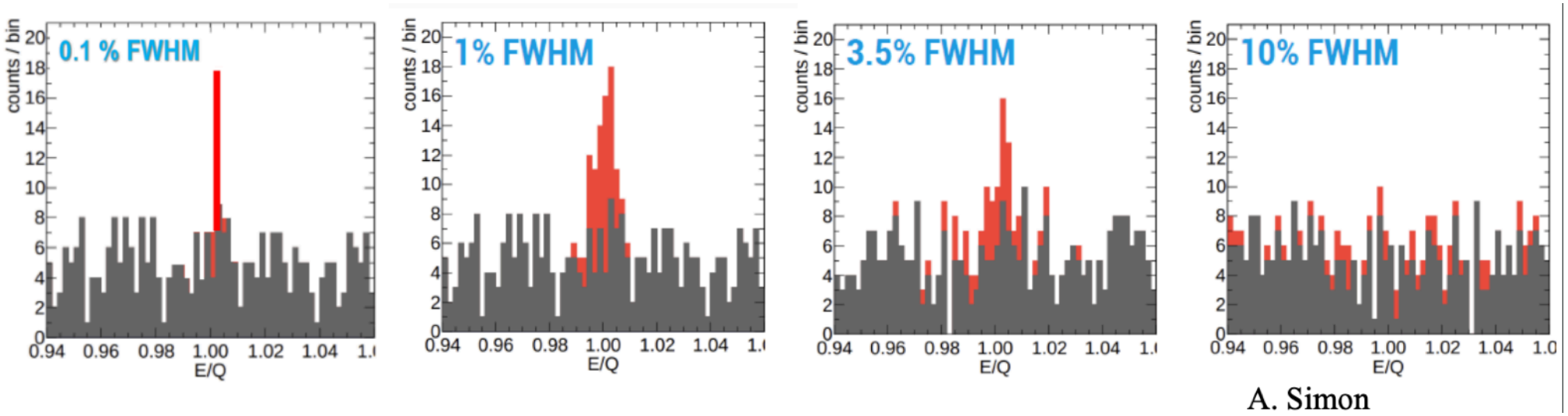
^{76}Ge: $Q_{\beta\beta} = 2039$ keV

From **MAJORANA:** Best energy resolution for 0νββ:

2.53 keV (FWHM) at Qββ (with 26 kg·yr of exposure)

[MAJORANA Collab., PRC 100, 025501 (2019)]





Half-life sensitivity – Background issue

$$T_{1/2} \sim f\epsilon\, Mt$$

Background free

$$T_{1/2} \propto f\,\epsilon\sqrt{\frac{Mt}{B\,\sigma_E}}$$

Non zero background

f: ^{76}Ge enrichment fraction
ε: Detection efficiency
M: HPGe mass
t: Measurement time
[$M\,t$: Exposure]

σ_E: Energy resolution at $Q_{\beta\beta}$

B: Background index = counts / (energy · mass · time)

From GERDA: Lowest background level for 0νββ:

Mean background in the Region of Interest: ($Q_{\beta\beta}\pm 2\sigma$) is **0.3 counts ~ quasi background free!**

(with 103.7 kg·yr of exposure)

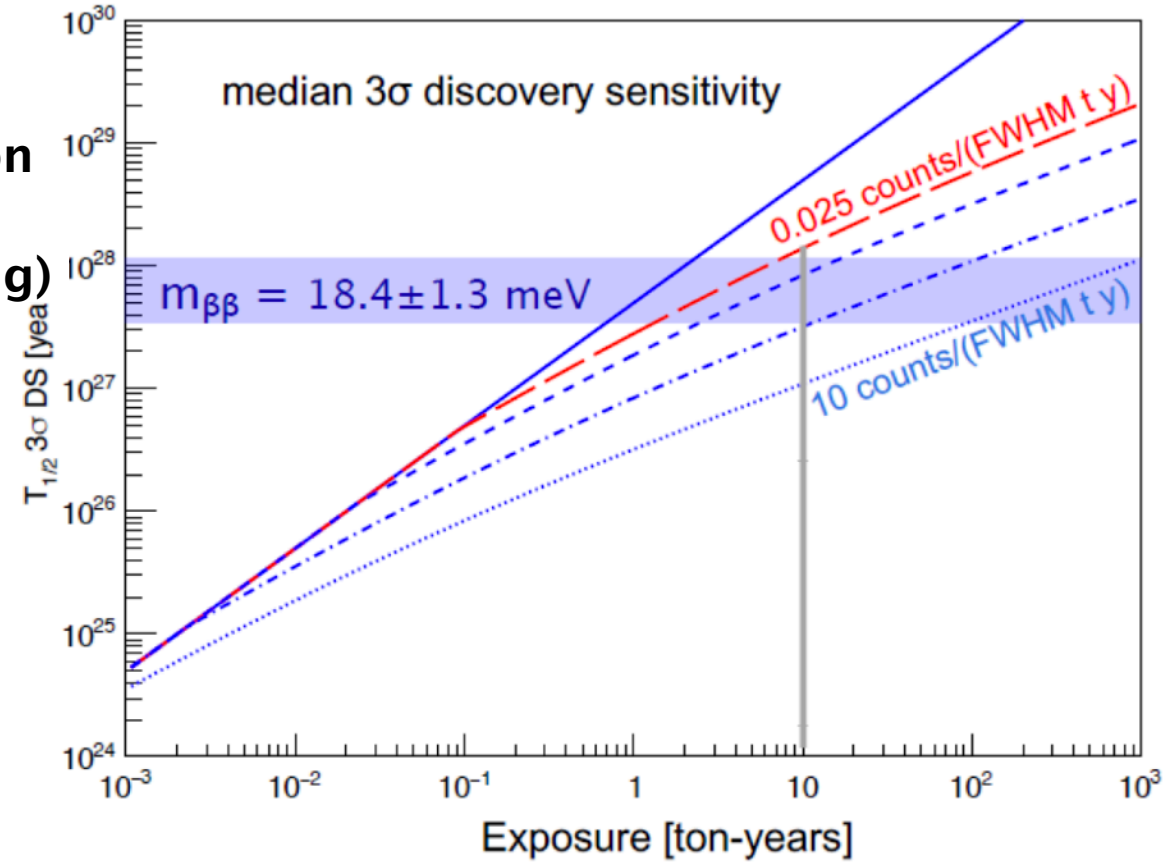
[GERDA Collab., PRL 125, 252502 (2020)]

LEGEND – quasi background free operation

- less than 1 background event expected in a 4σ ROI for 10 t yr exposure

- $T_{1/2} \sim 10^{28}$ yr less than **one decay per year per ton**
- 10 [t yr] of data is needed **(1 t, 10 yr of data taking)** to cover the inverted mass ordering regime
- very good signal-to-background ratio

  – extremely low background level
  (~20 times lower compared to GERDA)

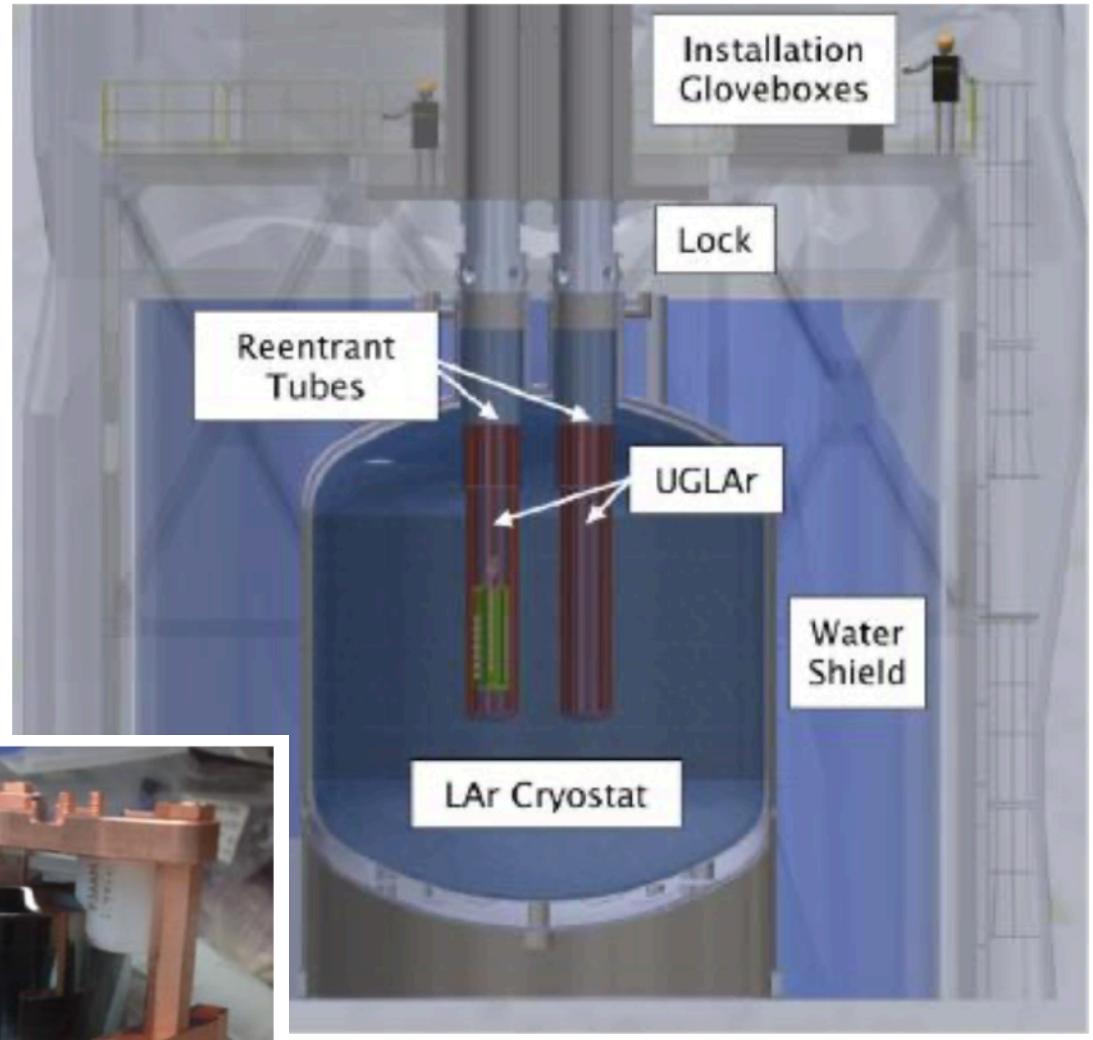


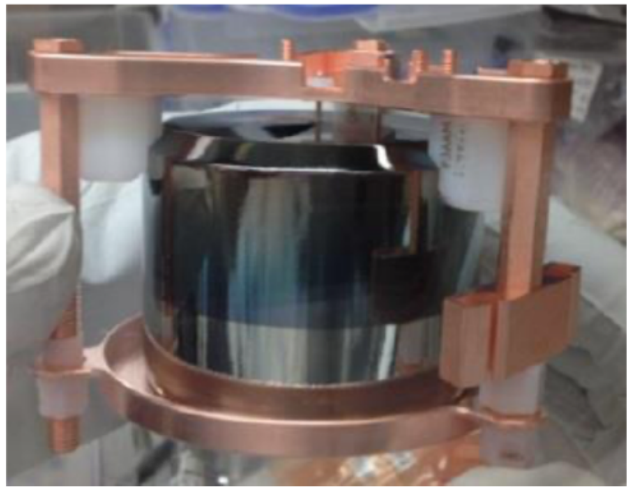
Our background goal is the red line on the plot (0.025 counts/(FWHM yr).

LEGEND-1000 in a deep underground location

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

- HPGe detectors: 2.6 kg average mass
- components made from electro-formed Cu and scintillating plastic, PEN
- Strings organized in 4 arrays
- Underground-sourced LAr active shield
- Dual fiber-curtain LAr instrumentation
- 4 EF-Cu Reentrant tubes



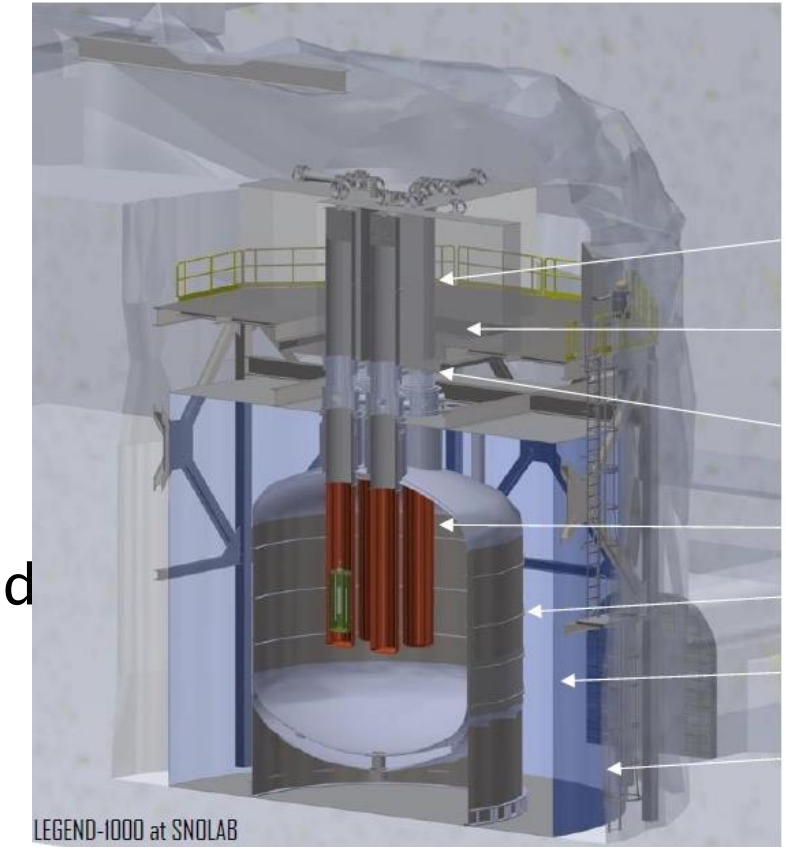


LEGEND-1000 in a deep underground location

- Deep underground – maximal reduction of cosmic muon induced background

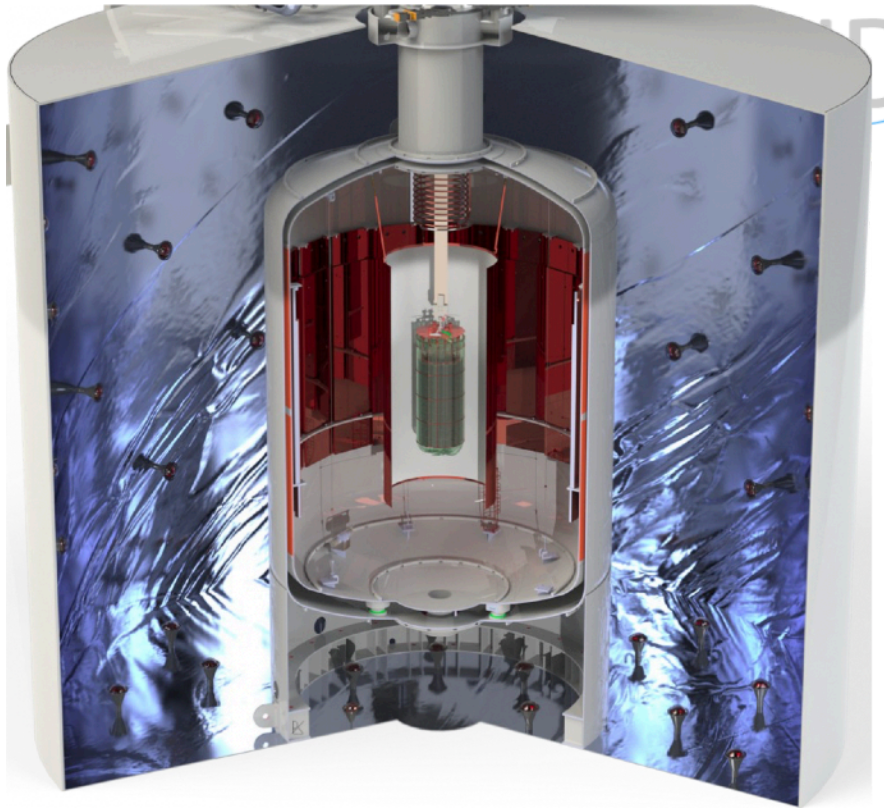
- **Baseline site: The SNOLAB "Cryopit"**
  - **~2 km underground (6000 m.w.e)**
  - In an active nickel mine in Sudbury
  - Vertical access through mine shaft

- **Alternative site: LNGS (Italy)**
  - 3500 m.w.e
  - Lower overburden somewhat increases background (can be tagged and reduced)
  - **Horizontal access** reduces cost/schedule risk



- Staff at **both sites** are actively involved in planning
- Design slightly varies for different sites

LEGEND-200 – initial phase in LNGS

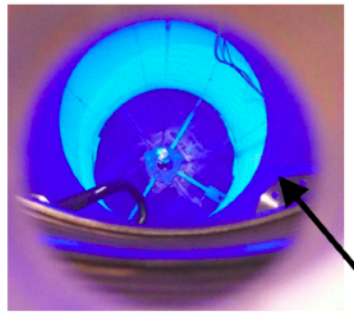


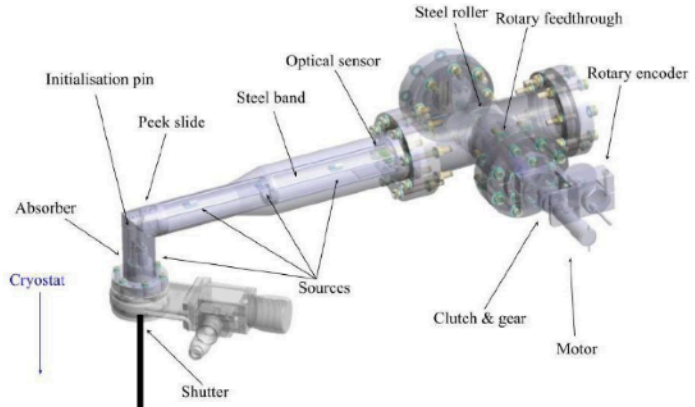
- **200 kg** of HP Ge **in existing GERDA infrastructure**
  (currently over 140 kg fully installed in LNGS and taking data)
- Anticipated exposure: 1 t yr (5 yr x 200 kg)
- Expected 2.5 keV FWHM resolution
- New type of Inverted Coaxial Point Contact HPGe detectors

- **Background goal:**
  3 x reduction w.r.t GERDA, BI < 2 x10^{-4} cts/(keV kg yr) ~ 0.6 cts/(FWHM t keV):
  gives **quasi-background free operation** for discovery of $0\nu\beta\beta$ decay up to 10^{27} yr
  - Improved electronics
  - Improved Pulse Shape Discrimination methods
  - Improved LAr veto

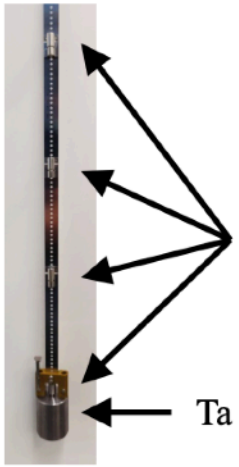
LEGEND-200

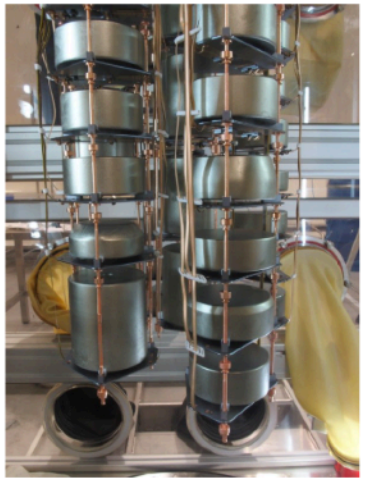
Wavelength-shifting reflector
Tetratex® coated with tetraphenyl butadiene (TPB)



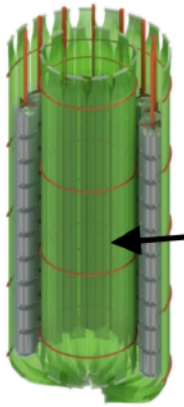


Calibration system

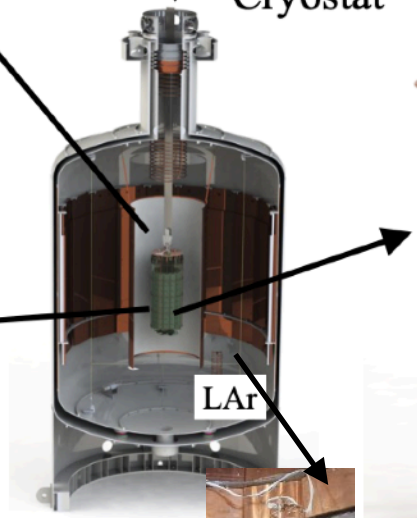


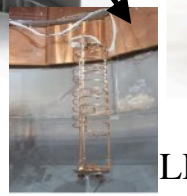


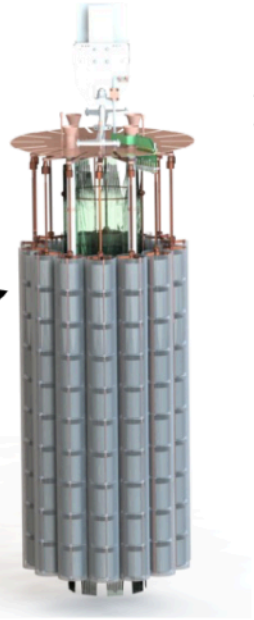
Cryostat



Fiber shrouds



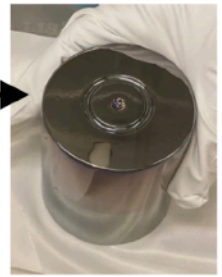




Detector array

- ~ 200 kg of detectors distributed over 12 strings
- Reuse of detectors from GERDA and MJD + 140 kg of additional *inverted-coaxial point-contact (ICPC)* detectors:
  - Active mass > 3 kg
  - Excellent PSD performance

PEN (Polyethylene naphthalate) base plate

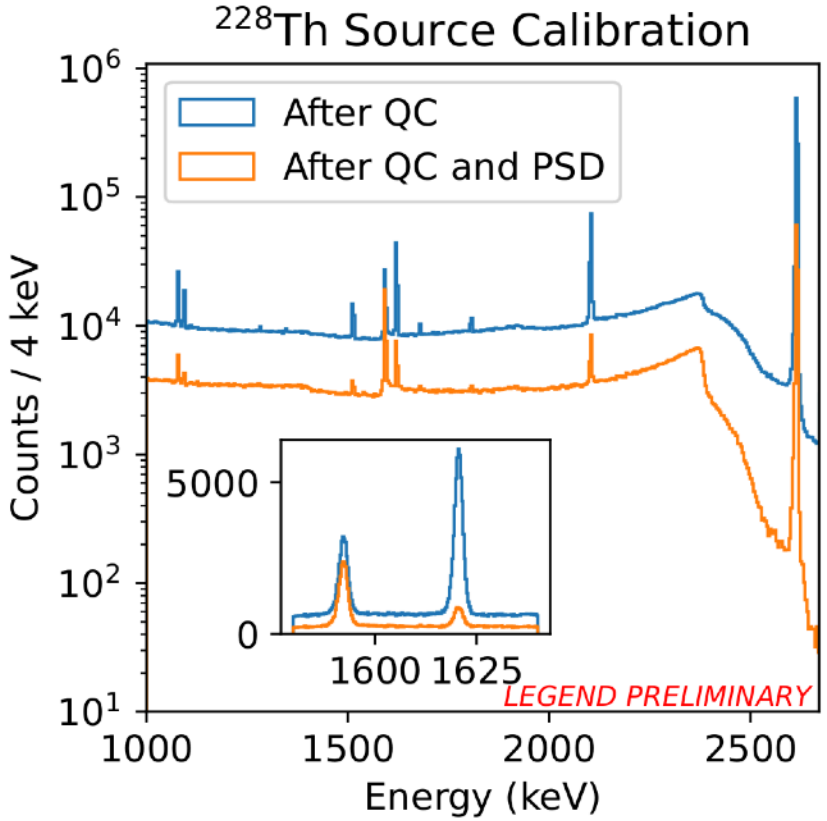


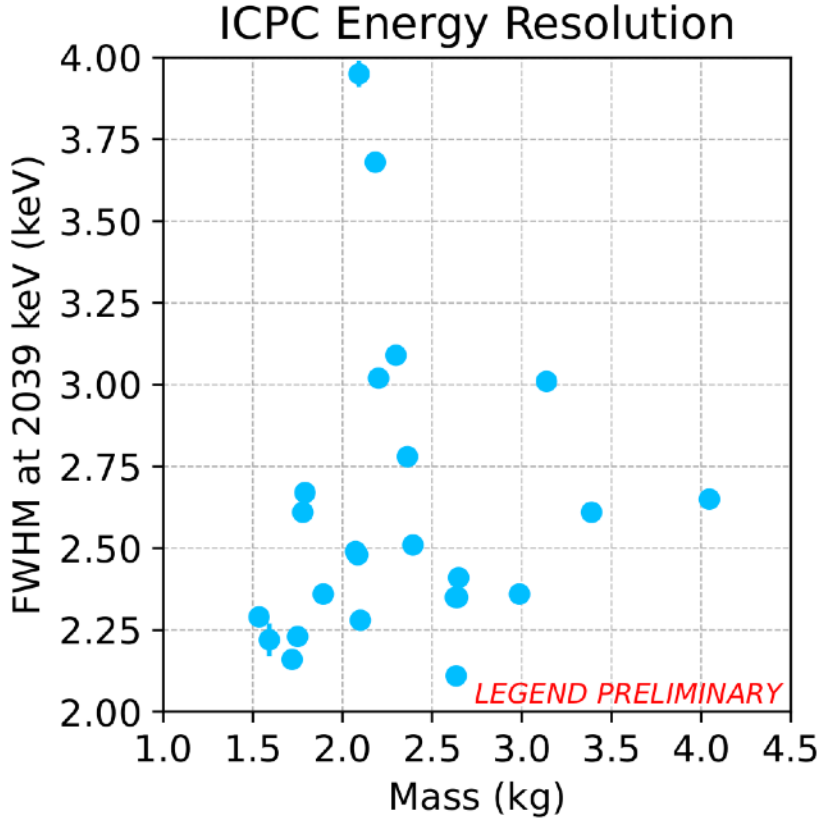
LEGEND Liquid Argon Monitoring Apparatus

[graphics credit: Pin-Jung Chiu]

LEGEND – 200 current status

- 140 kg of HPGe installed – taking data **now.**
- FWHM ~ 2.8 keV at Qββ achieved. No detector mass dependancy.

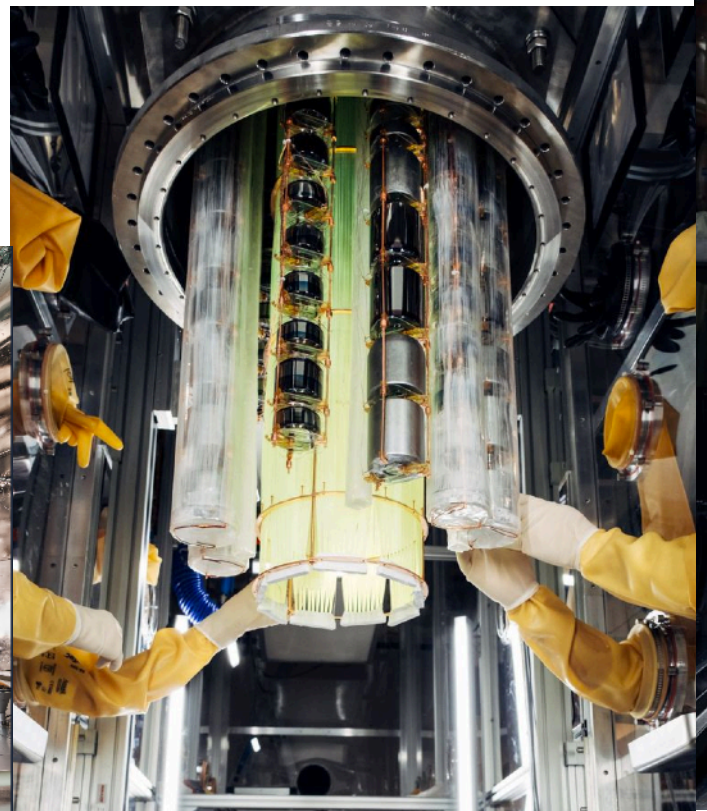


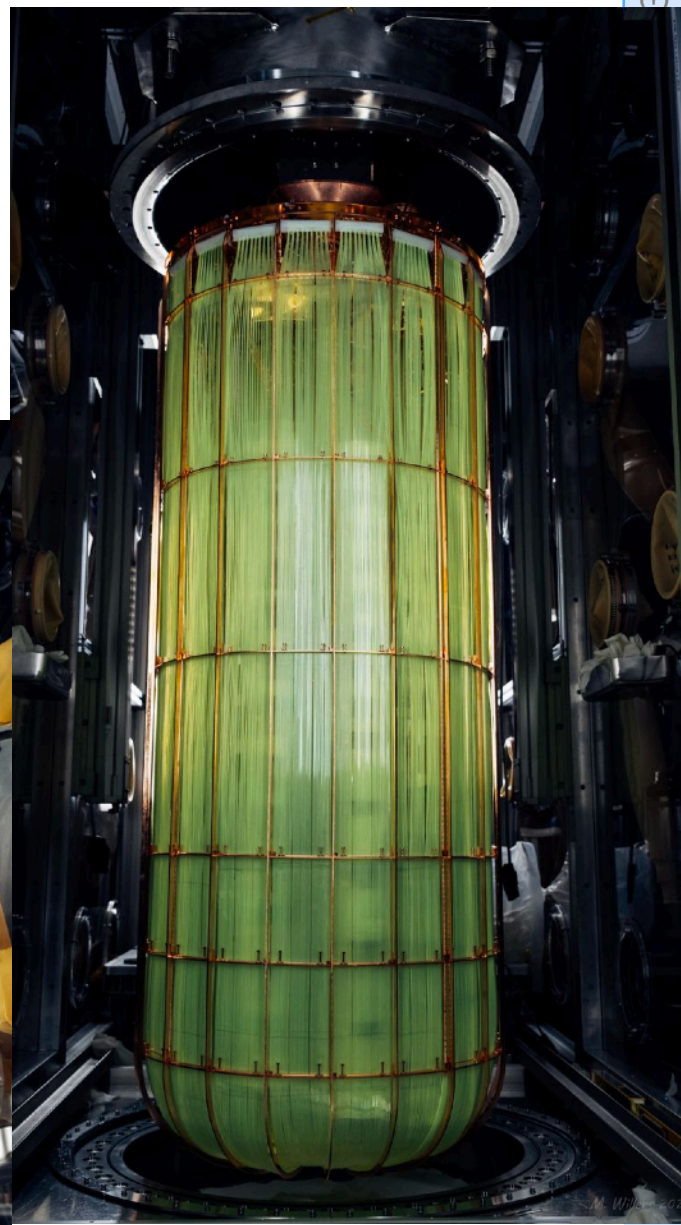


BOX: ^{208}Tl DEP (1592.5 keV, SSE signal proxy) and ^{212}Bi FEP (MSE)

LEGEND – 200 current status

- LAr veto operational
  - 90 tons of purified LAr (argon purity monitored in real time and kept at $\tau_3 = 1.15\ [\mu s]$)
  - two curtains of WLS optical fibers
  - read out by SiPMs
- Muon veto active (water tank full)





Summary

$0\nu\beta\beta$ **decay** if observed may solve several fundamental issues in particle physics and cosmology.

- **LEGEND collaboration believes in bringing people together**

  experience from **GERDA** and **MAJORANA** **in Germanium technology**

- **LEGEND-200** is under commissioning in LNGS, Italy and has already started taking physics data!

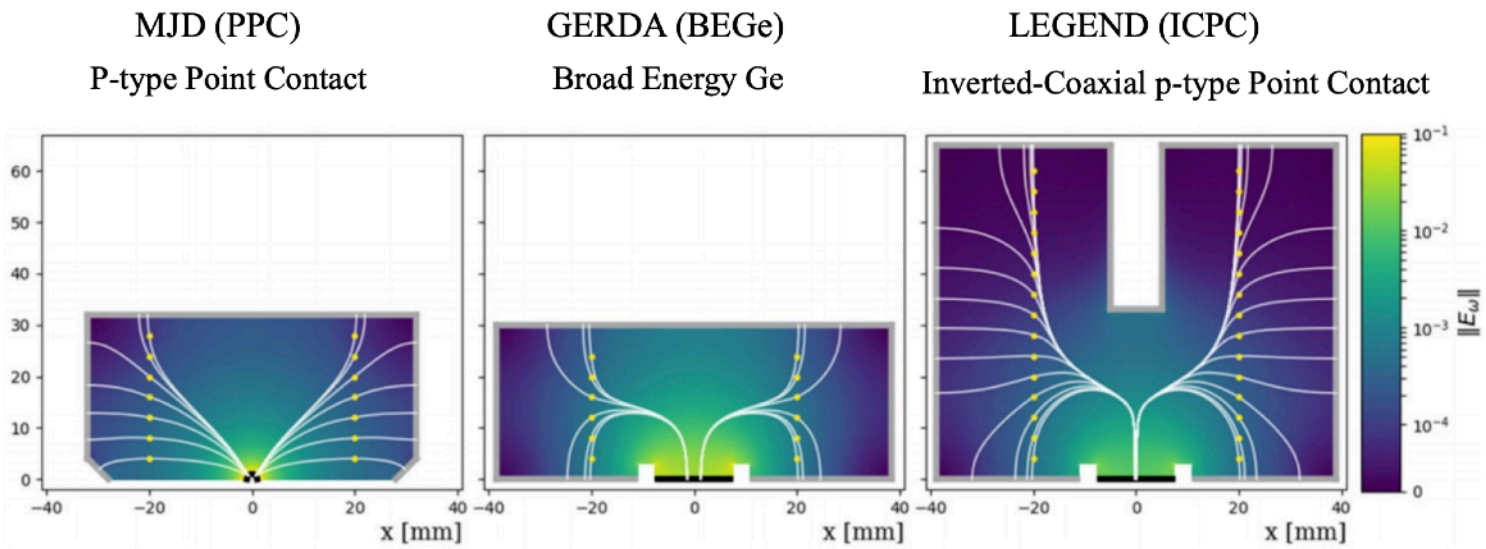
  – 5 years of operation, goal: $T_{1/2} \sim 10^{27}$ yr

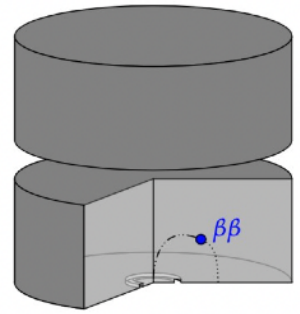
- Ton-scale **LEGEND-1000** will reach a discovery sensitivity of $T_{1/2} > 10^{28}$ **yr**, aiming to **cover the inverted mass ordering regime**

Thank you!

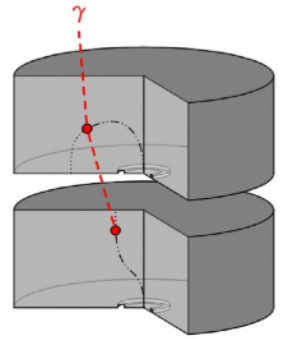
LEGEND – 200 detectors

- P-type detectors: insensitive to alphas on n^+ contact
- Small p^+ contact: event topology discrimination – PSD method
- Large-mass ICPC detectors: ~ ×4 lower backgrounds w.r.t. BEGe/PPC
- Proven long-term stable operation in LAr

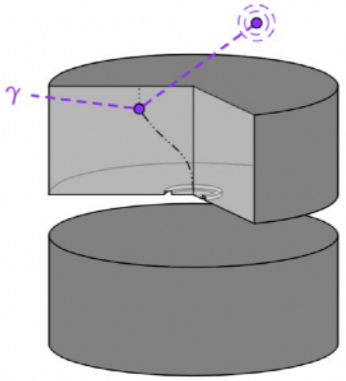




Ge Single-site
SIGNAL



Ge Multi-site
BCKG



Ge + LAr
BCKG

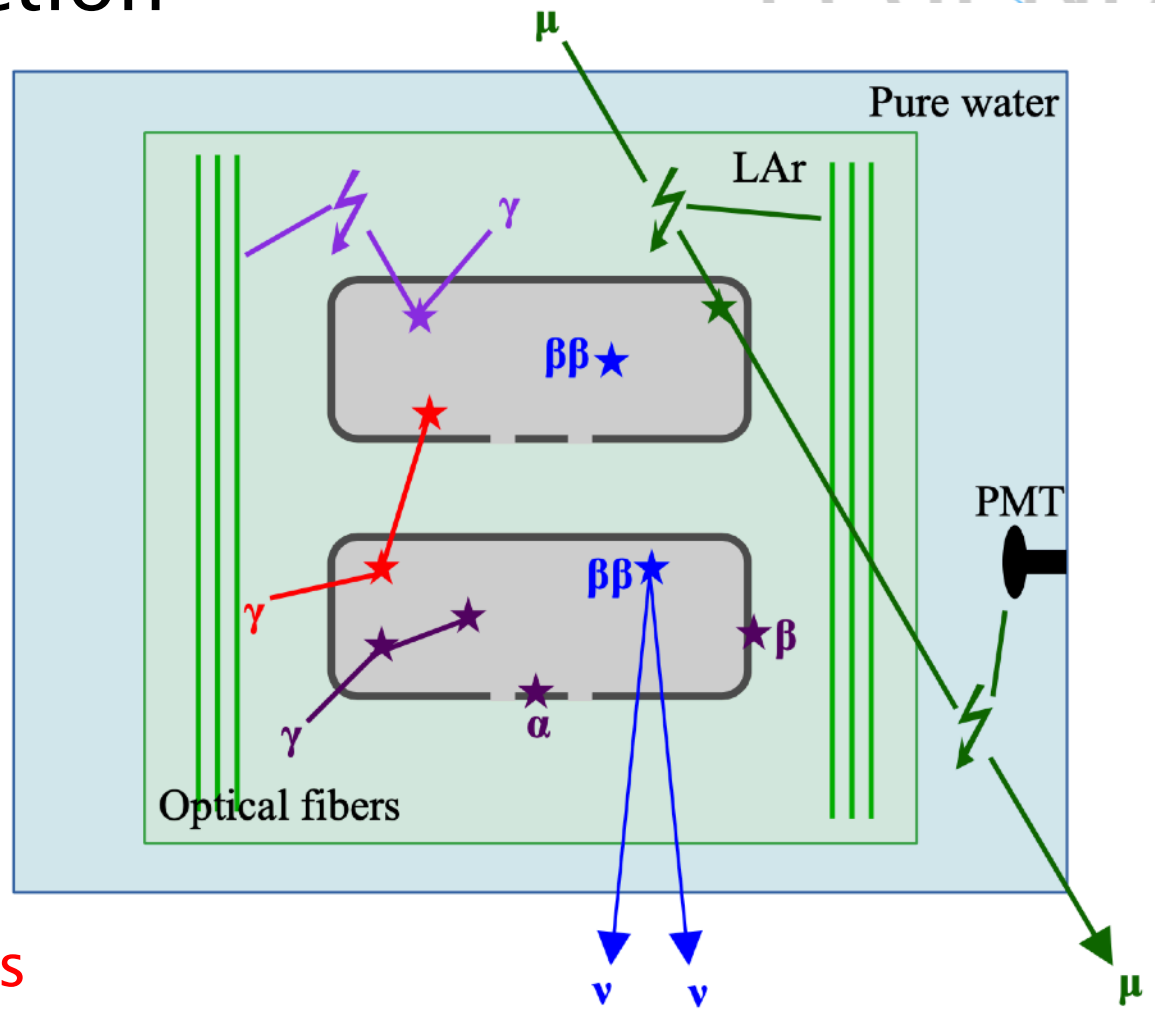
LEGEND – 200 background reduction

- ββ decay signal:

  localized energy deposition ~ O (1 mm)
  → Single-site event (SSE)

- cosmic μ: water Cherenkov veto

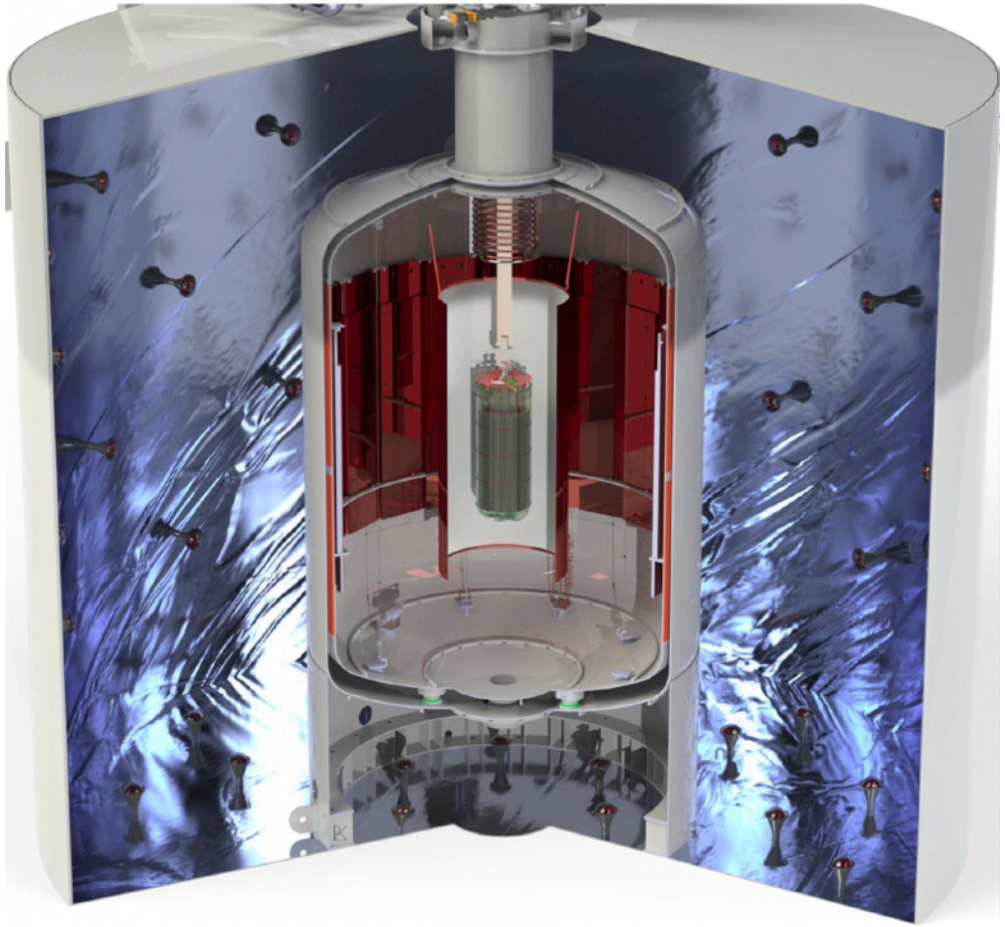
- γ with MeV energies:
  multiple energy depositions ~ O (1 cm)
  - LAr veto,
  - Anti-coincidence from multiple detectors
  - Multi-site event (MSE) in a single detector
  - Surface α and β

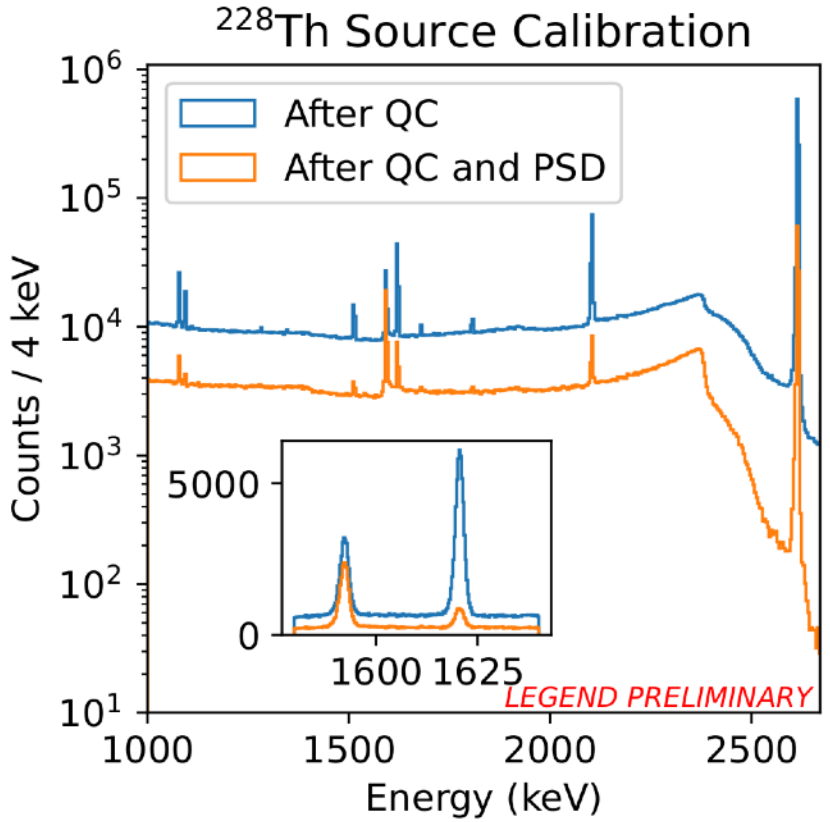


use of Pulse Shape Discrimination

LEGEND-200 – intermediate step

- **200 kg** of $HP^{enr}Ge$ **in existing GERDA infrastructure** at LNGS, Italy (currently over 140 kg fully installed and taking data)





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