

Status of the Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay (LEGEND)

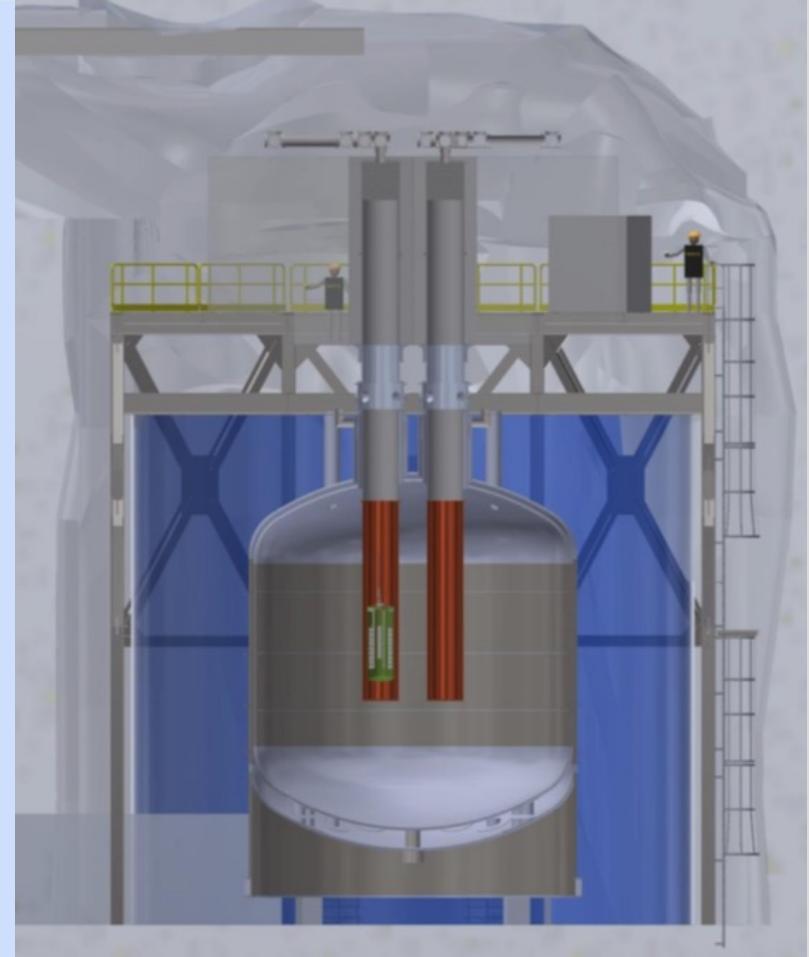
LEGEND

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(on behalf of the LEGEND collaboration)

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31st International Symposium on Lepton Photon
Interactions at High Energies

Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ Decay

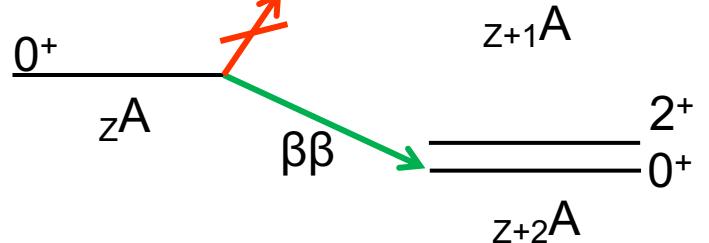


Neutrinoless Double Beta Decay

LEGEND

$\beta\beta$ decays:

- 2nd order weak decay.
- 35 even – even candidate nuclei, where β decay is energy / spin suppressed.



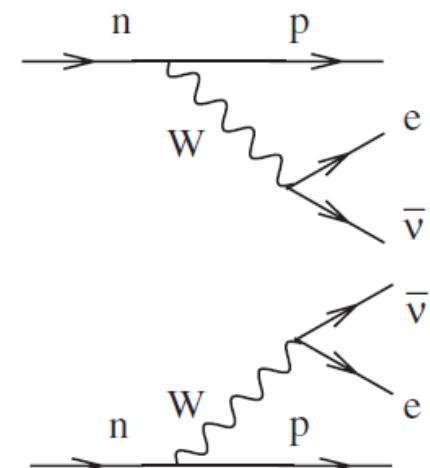
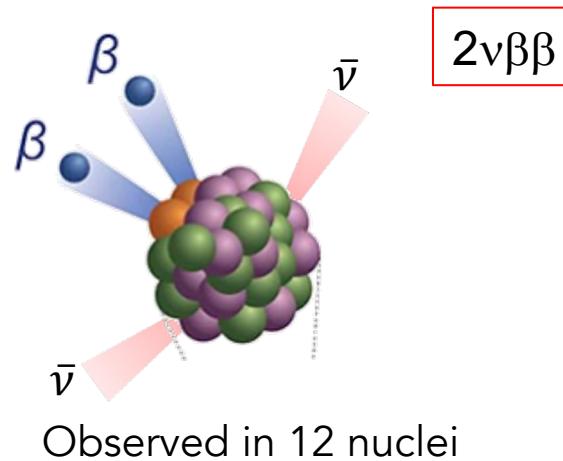
Major physics implications if $0\nu\beta\beta$ is discovered!:

- Majorana nature of neutrino (neutrino is its own antiparticle)
- Lepton number violation ($\Delta L = 2$).
- Explanation for matter-antimatter symmetry.
- Sensitive to the absolute neutrino mass.

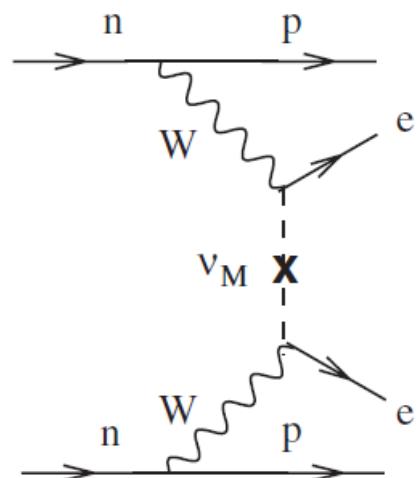
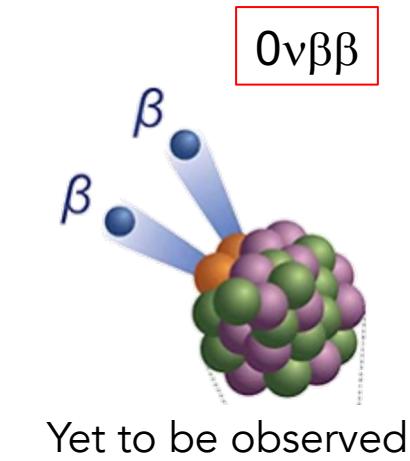
$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

$\langle m_{\beta\beta} \rangle = \left| \sum U_{ei}^2 m_i \right|$

Half-life Phase-space Nuclear Matrix Element



SM process
 $T_{1/2}^{2\nu}$ ranges from $10^{18} - 10^{24}$ yr.

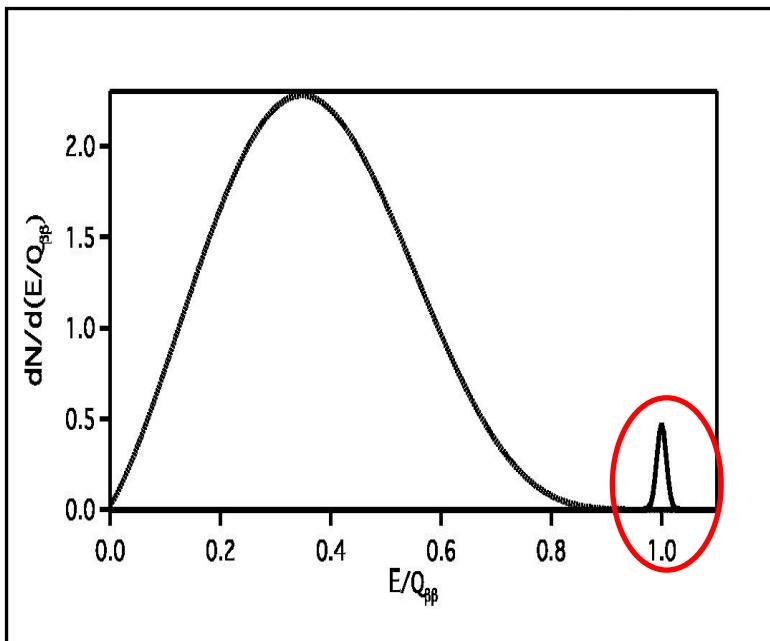


BSM process!

Experimental considerations

Experimental signature:

Peak at $Q_{\beta\beta}$ in the electron sum energy spectrum.



“Background-free”

$$T_{1/2}^{0\nu} = \frac{\ln 2 N_A \epsilon i M t}{A N_{obs}}$$

Finite background

$$T_{1/2}^{0\nu} > \frac{\ln 2 N_A \epsilon i}{A k_{CL}} \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

ϵ : efficiency

N_{obs} : observed counts

i : isotopic abundance

BI : Background index

M : mass

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

Desirable experimental design for $0\nu\beta\beta$:

- Large mass of the isotope of interest
- Long runtime
- Large $Q_{\beta\beta}$
- Low background
- High detection efficiency for the electrons
- Good energy resolution of the detector

Current Best Limits

Best sensitivity limits at (90% C.L.) for current $0\nu\beta\beta$ experiments:

KamLANDZen (^{136}Xe):

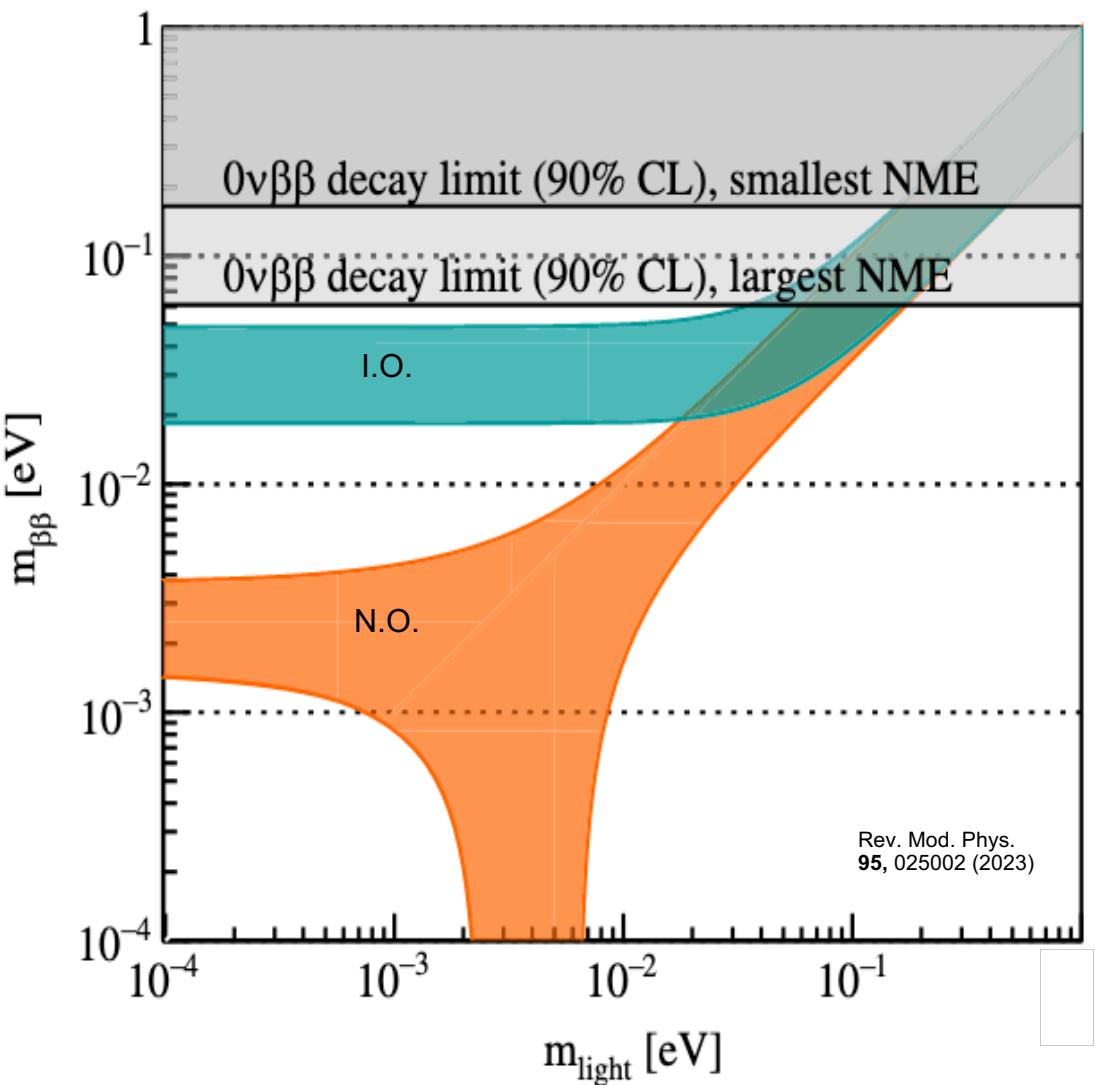
$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26} \text{ yr}, \langle m \rangle < 0.036 - 0.156 \text{ eV}$$

GERDA (^{76}Ge):

$$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{26} \text{ yr}, \langle m \rangle < 0.08 - 0.182 \text{ eV}$$

CUORE (^{130}Te):

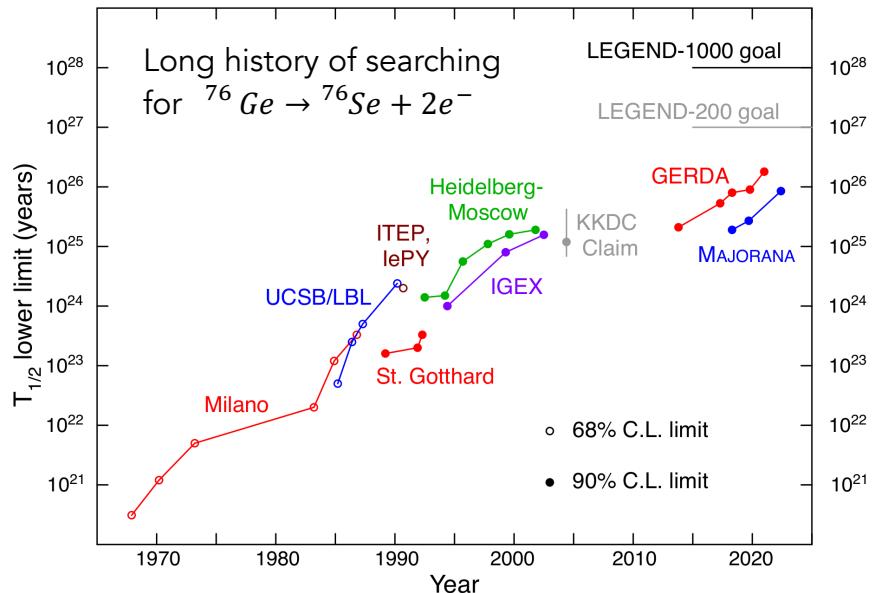
$$T_{1/2}^{0\nu\beta\beta} > 2.2 \times 10^{25} \text{ yr}, \langle m \rangle < 0.090 - 0.305 \text{ eV}$$



Search for $0\nu\beta\beta$ in ^{76}Ge

LEGEND

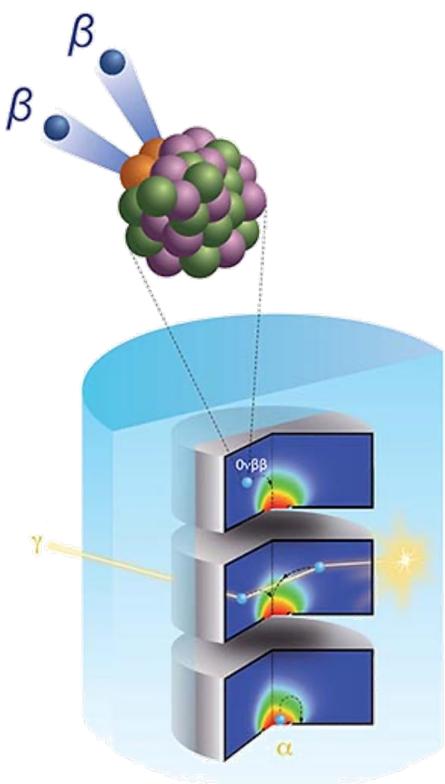
Improved sensitivity driven by innovations in technology and larger exposure



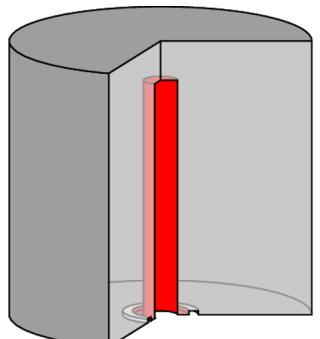
What makes ^{76}Ge a good candidate? :

- Decades of experience with the detector technology
- Reasonable $Q_{\beta\beta}$ (2039.061 ± 0.007 keV)
- ^{76}Ge enrichment of more than 90% possible
- Highly radiopure detectors
- High detection efficiency for the electrons
- Excellent energy resolution of the detector (**FWHM $\sim 0.1\%$ @ $Q_{\beta\beta}$**)
- Event-topology based background discrimination

Source = Detector Configuration

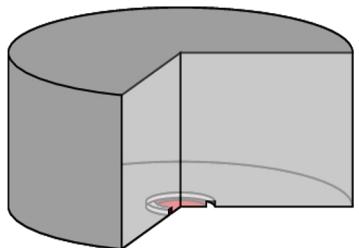


past (big)
large mass: $\sim 2\text{-}3$ kg
imperfect background rejection



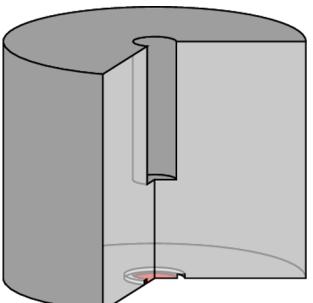
(semi-)coaxial

recent (performant)
small mass: < 1 kg
excellent background rejection



JINST 4, P10007 (2009)

present (big & performant)
large mass: up to 4 kg
excellent background rejection



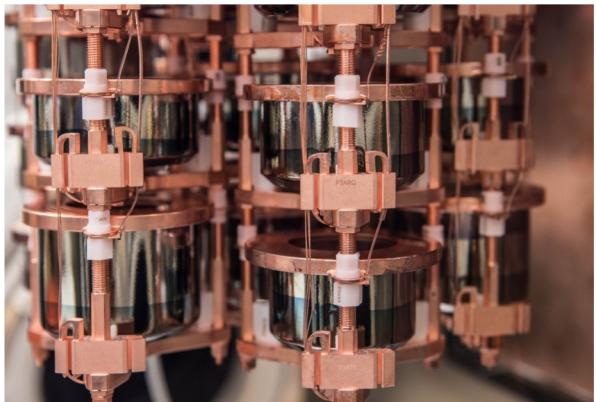
ICPC

NIM A 665, 25 (2011)

LEGEND – Combining the best of the field



MAJORANA DEMONSTRATOR

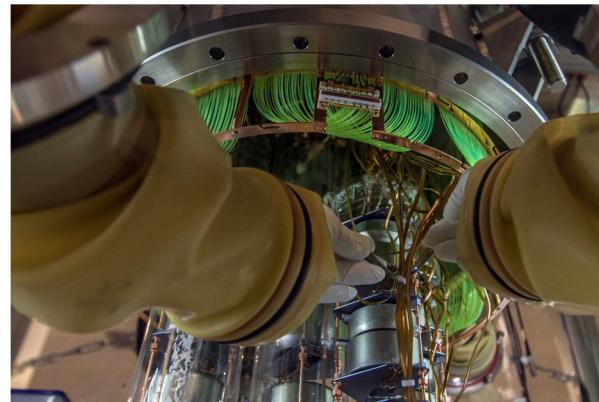


The best energy resolution!

Highly radiopure EFCu,
Low noise electronics

GERDA

Germanium Detector Array



The lowest background index!

LAr active veto,
Low Z shield (no Pb)

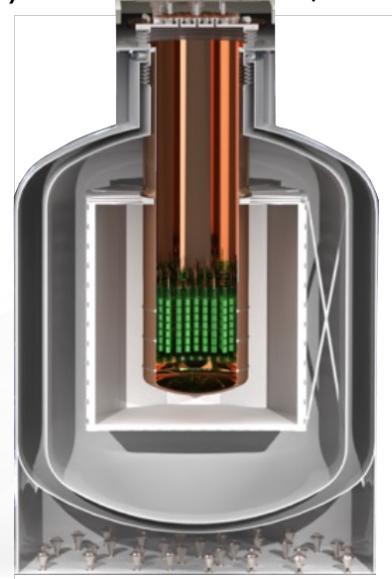


LEGEND

*Large Enriched Germanium Experiment
for Neutrinoless $\beta\beta$ Decay (LEGEND)*



LEGEND-200



LEGEND-1000

	MJD	GERDA	LEGEND-200	LEGEND-1000
Mass [kg]	29.7	44.2	Up to 200	1000
B.I. [cts/(keV.kg.yr)]	$(4.7 \pm 0.8) \times 10^{-3}$	$5.2_{-1.3}^{+1.6} \times 10^{-4}$	2×10^{-4}	10^{-5}
Resolution [keV] (FWHM)	(2.52 ± 0.08)	(2.6 ± 0.2)	2.5	2.5
Location	SURF (USA)	LNGS (Italy)	LNGS (Italy)	LNGS or SNOLab

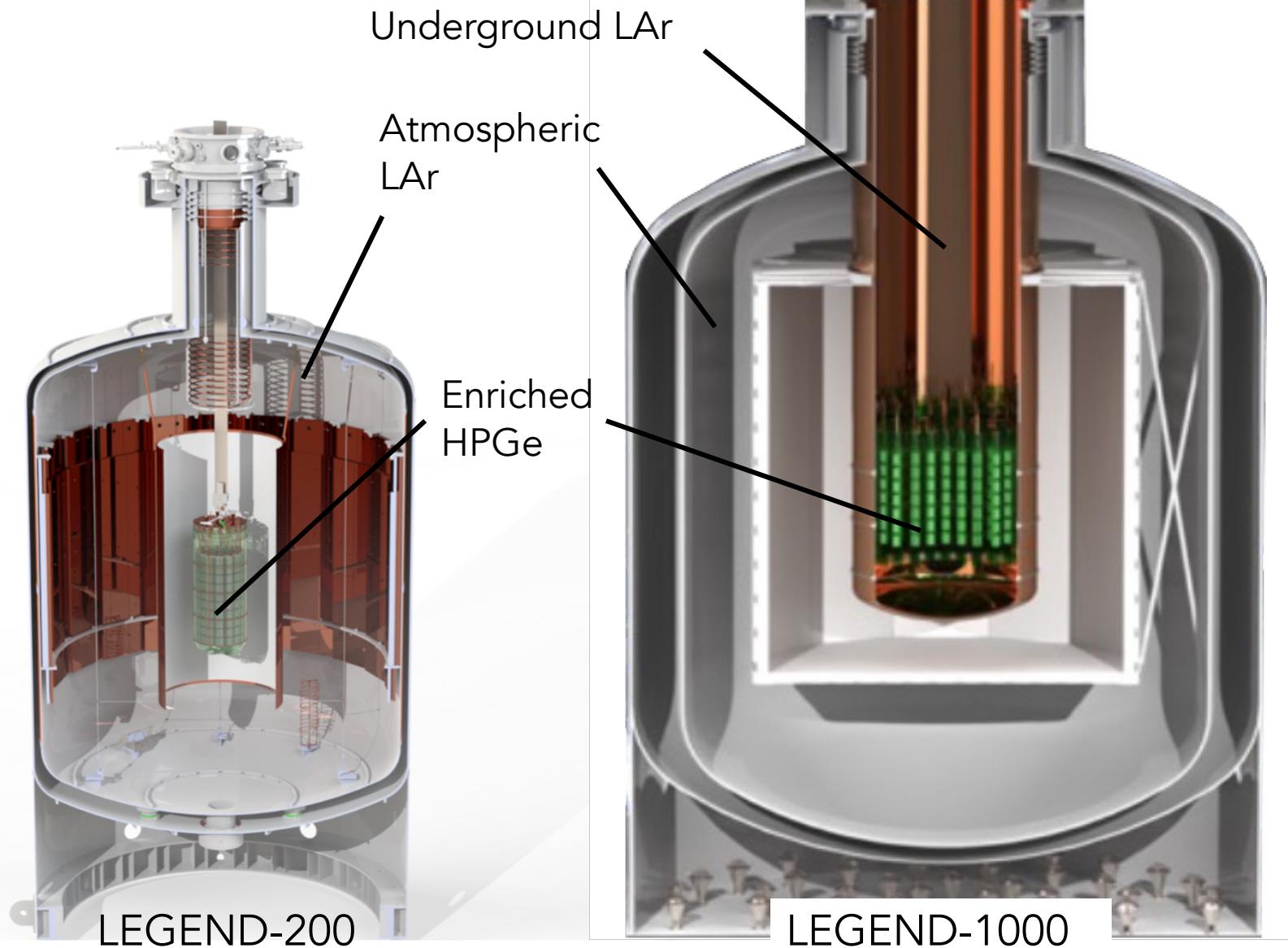
A two-phase approach

LEGEND-200:

- Status: Taking data with 142 kg of detectors
- Detectors deployed in atmospheric LAr.
- Situated in the existing GERDA infrastructure at LNGS
- 1 ton-yr exposure goal

LEGEND-1000:

- Status: In design with a timeline contingent on the review process (in preparation for CD1).
- 1000 kg of detectors will be deployed in **underground LAr**.
- Location to be decided.
- 10 ton-yr exposure goal



Background reduction

Shielding

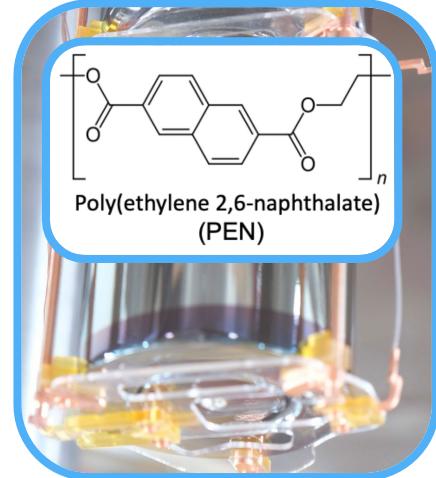
- Rock
- Water
- LAr
- Copper



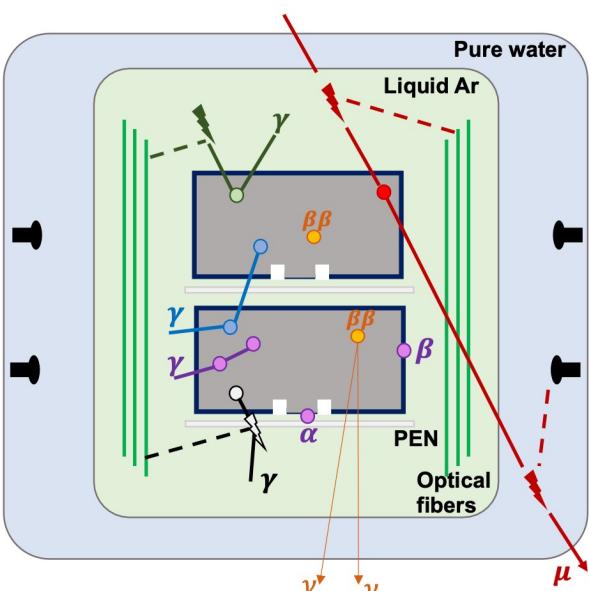
Electroformed
copper produced
underground at
SURF



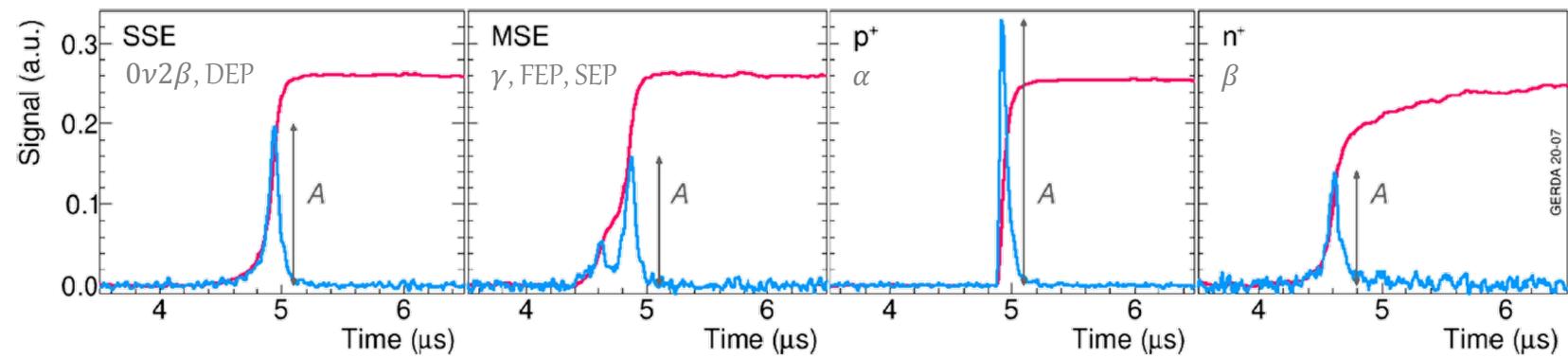
Scintillating PEN Baseplates



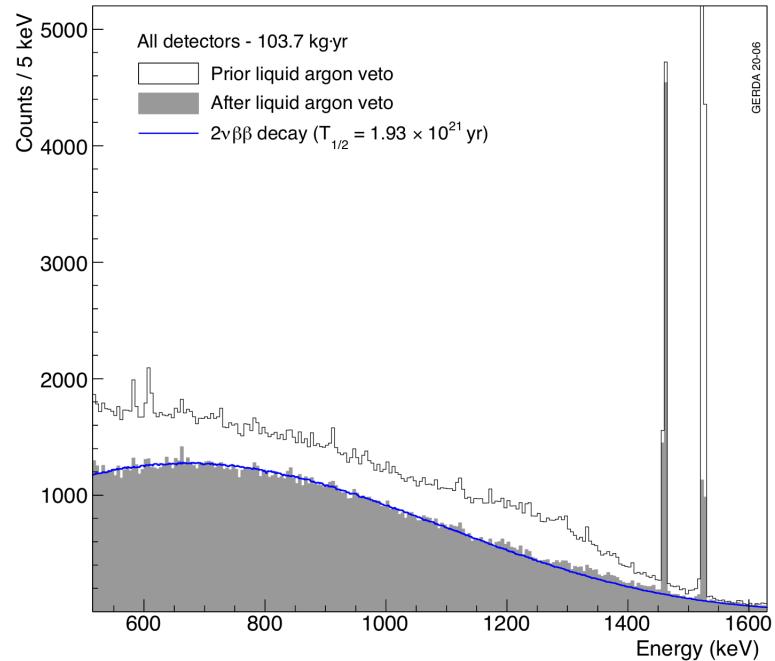
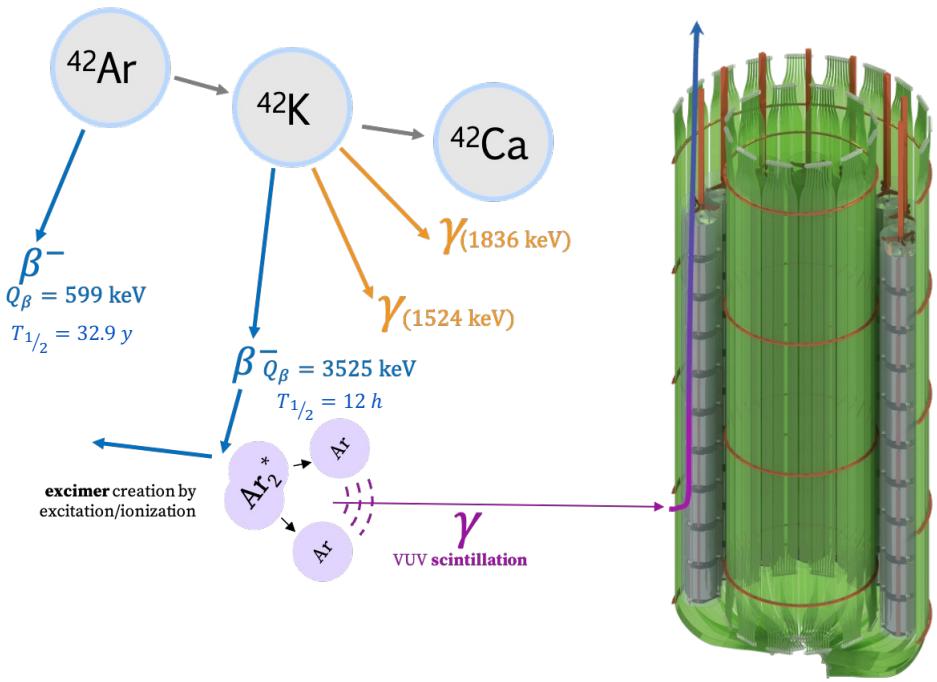
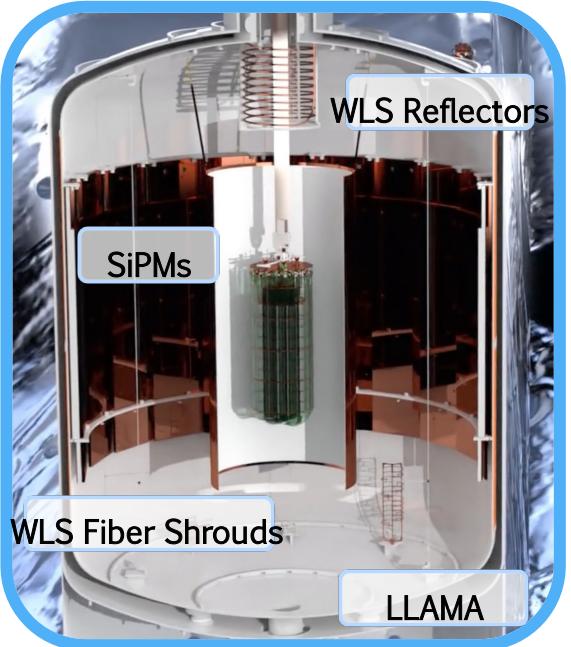
Low Mass Front End



Pulse Shape Discrimination



LAr instrumentation



Liquid Argon Veto in GERDA helped suppress the background greatly.

Argon cryostat: cools detectors to approximately 87 K

Low-Z, *active shielding material*

L1000: Detectors will be immersed in underground liquid argon, to mitigate the background from ^{42}K .

LEGEND-200

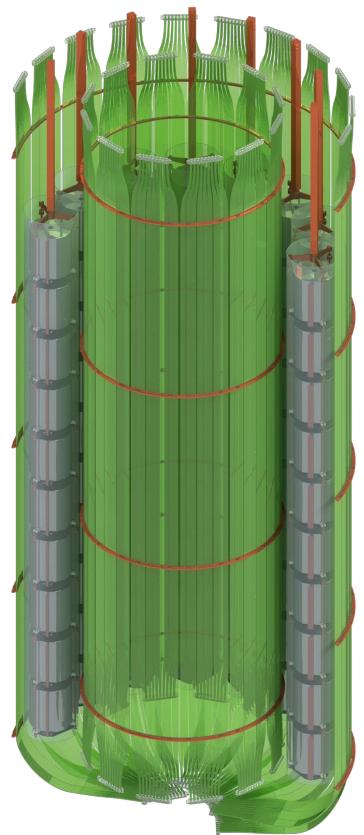
LEGEND

12 string array
of HPGe



LAr veto
58 read-out modules of
SiPMs coupled to WLS
fibers

Inner Barrel (9+9)



Outer Barrel (20+20)

Cryostat

- $\varnothing 4\text{m}$, H 5.88m
- (Atm) LAr: 64 m^3

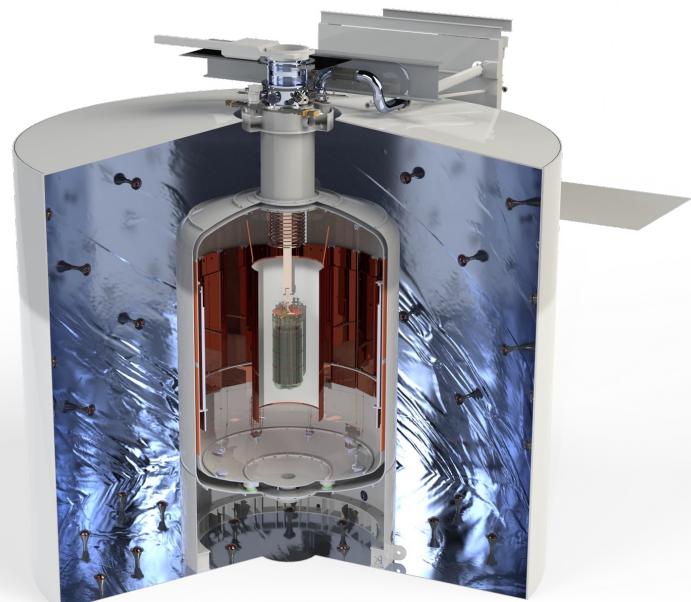


Location: Hall A, LNGS.
Muon flux is reduced by
6 orders of magnitude!



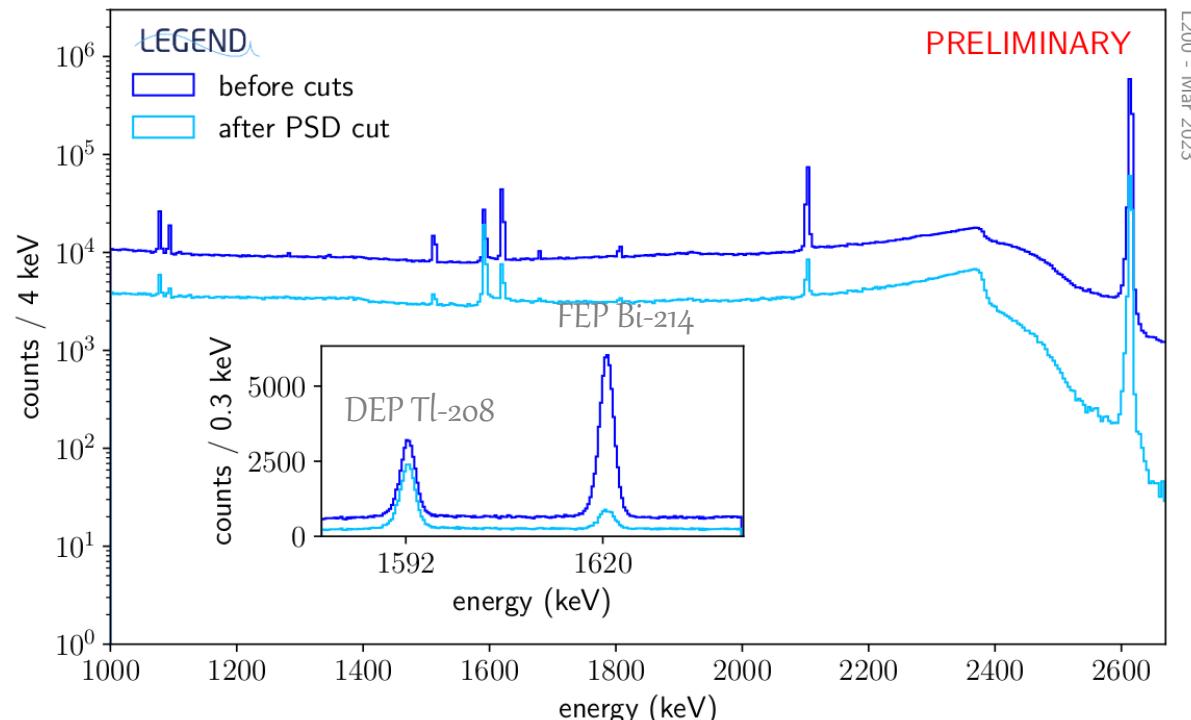
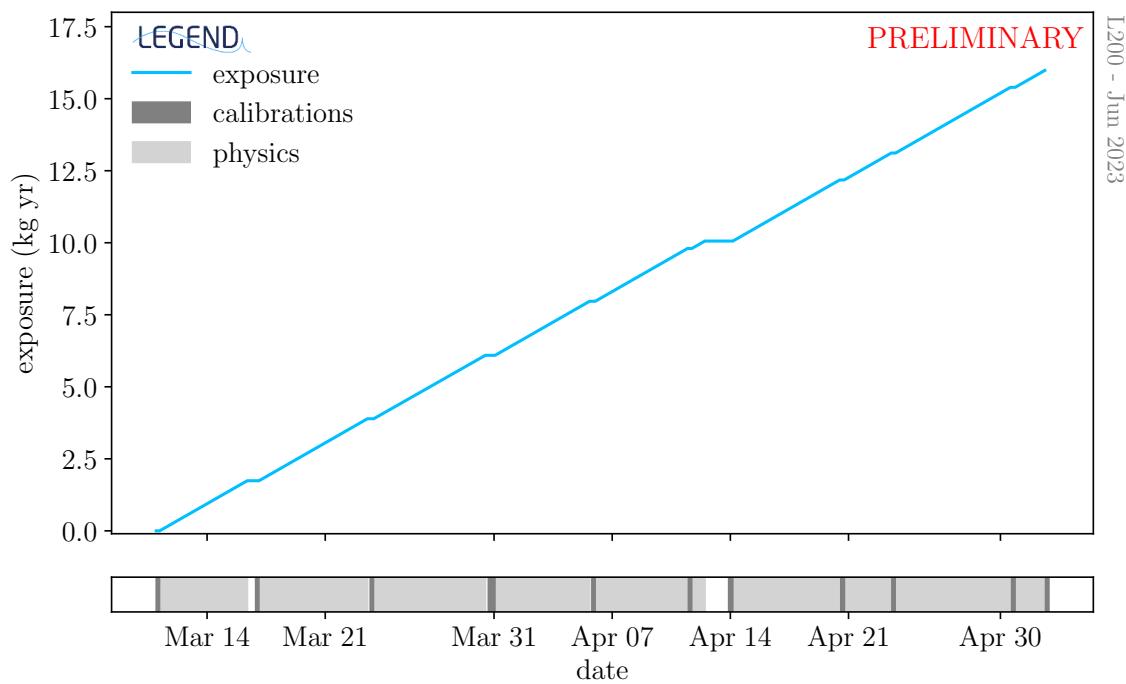
Ultrapure water tank

- Shields n, γ
- 66 PMTs (Cherenkov) + plastic scintillators for μ
- $\varnothing 10\text{m}$, H 8.5 m, V 590 m^3



L200 current status

- 101 detectors (10 strings): 6 coaxials, 26 PPC, 28 BEGe, 41 ICPCs
- $m_{\text{tot}} = 142.4 \text{ kg}$ (122 kg for the analysis)
- Stable data taking started **12 March 2023**
- Excluded unstable detectors (pulser, $R=0.05 \text{ Hz}$)

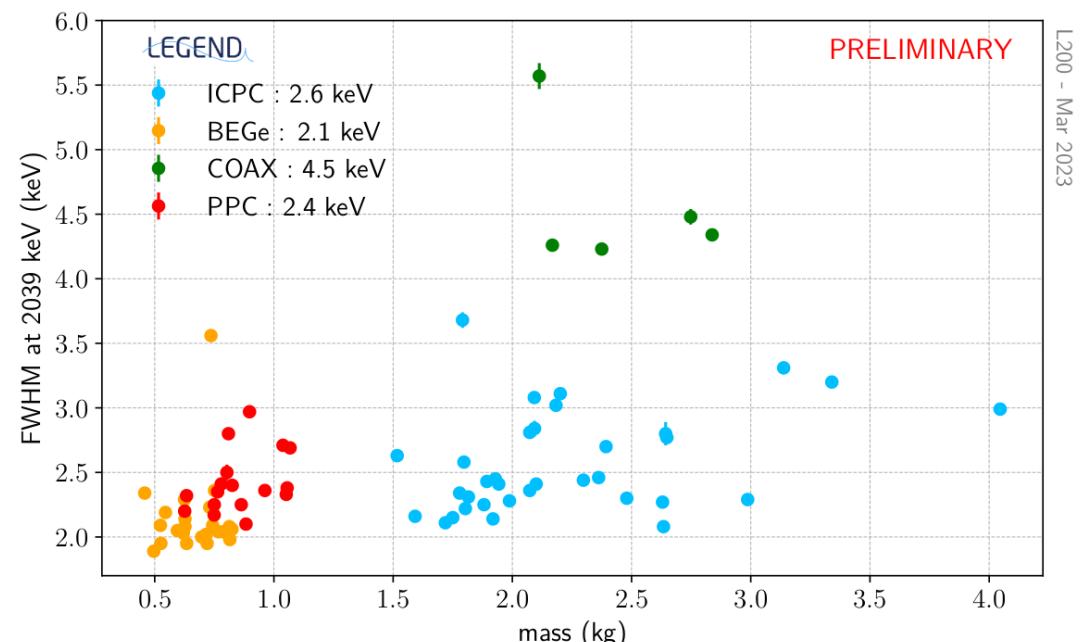


PSD tested with **13 sources of Th-228:**
multi-site events (FEP Bi-214): ~10% s.f.
single-site events (DEP Tl-208): ~90% s.f.

L200 performance

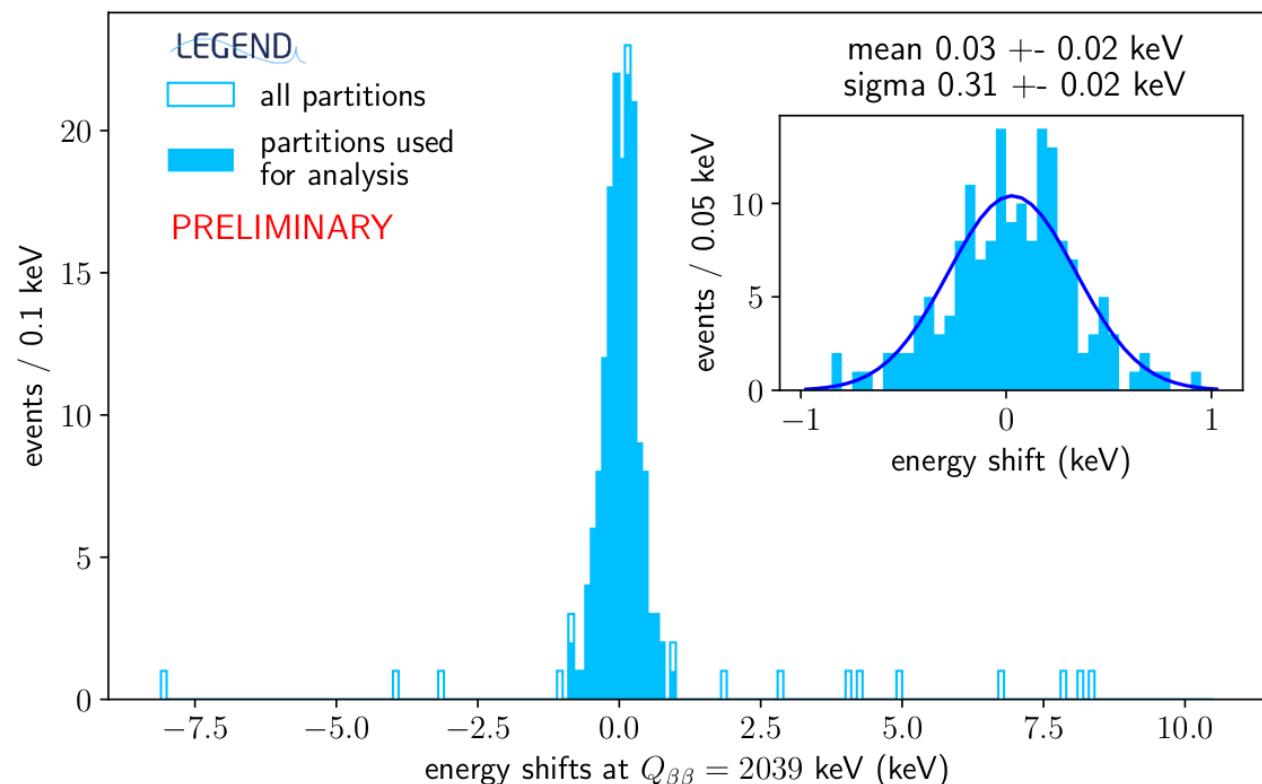
LEGEND

World-leading resolution



Energy resolution:
FWHM ~ 2.4 keV @ $Q_{\beta\beta}$
(4.5 keV for coaxials)

Extremely stable for >120 kg of detectors



Energy shifts
between subsequent
calibrations

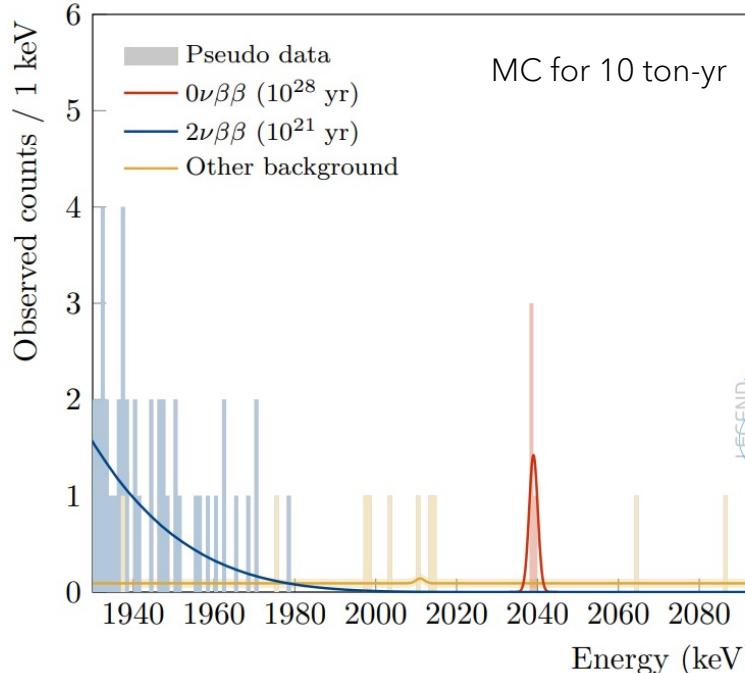
Anticipate BI in late Summer 2023
First 0v $\beta\beta$ result in 2024

L1000 discovery potential

LEGEND

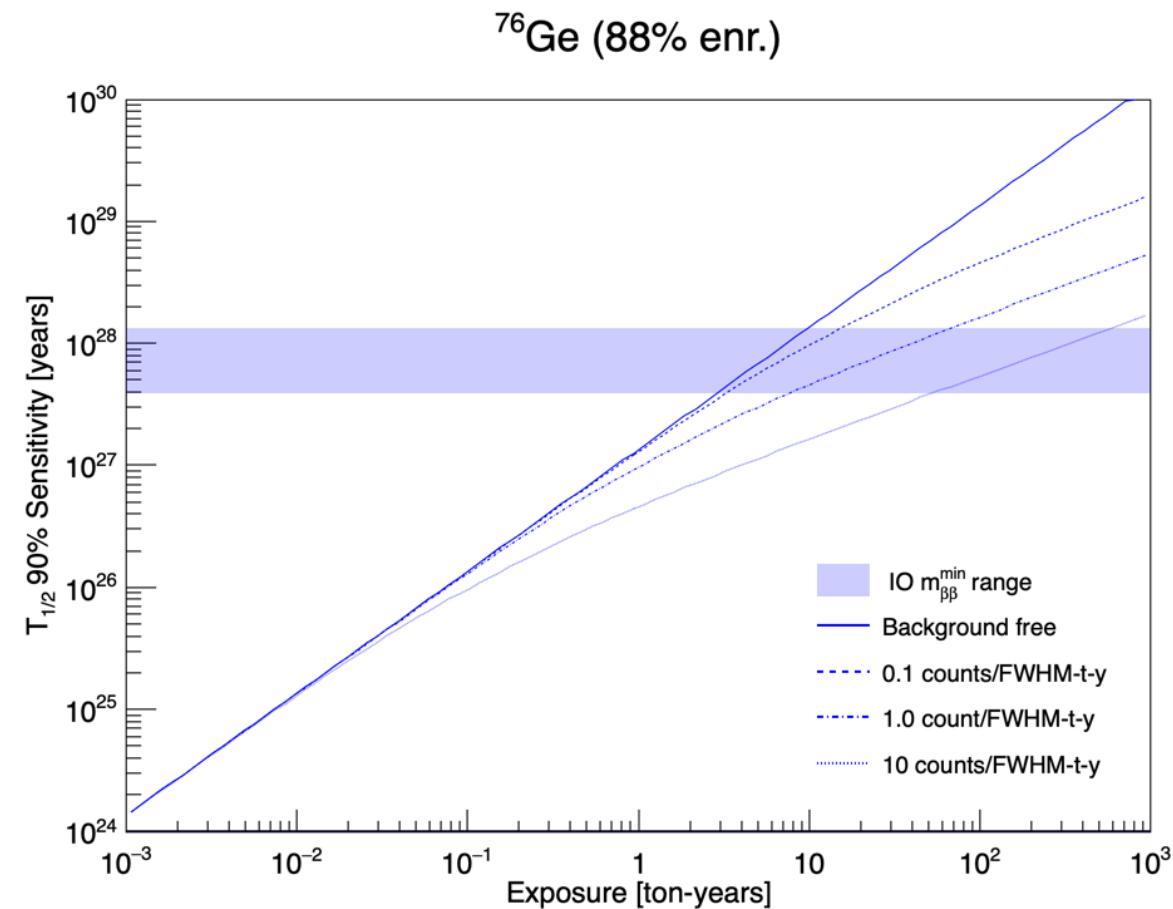
Goal Background Index: 10^{-5} cts/(keV.kg.yr)

50x lower than GERDA!



Virtually *background free*!

Would be capable of an unambiguous *discovery* with only a handful of counts!



LEGEND-1000 will have a sensitivity goal of $T_{1/2}^{0\nu} \sim 10^{28}$ yr. It will be capable of fully testing the *inverted ordering* space and partially testing the *normal ordering* space.

Summary

- LEGEND-200 is currently taking data with 142 kg in a stable manner. Background Index for LEGEND-200 is anticipated in late summer 2023 and the first $0\nu\beta\beta$ result is anticipated in 2024.
- LEGEND-1000 is in the **design stage**, in preparation for CD1.
- The goal background index for LEGEND-200 and LEGEND-1000 is 2×10^{-4} cts/(keV.kg.yr) and 10^{-5} cts/(keV.kg.yr), respectively → **Quasi – background free**.
- LEGEND-1000 will have a sensitivity goal of $T_{1/2}^{0\nu} \sim 10^{28} \text{ yr}$ and will be capable of fully testing the inverted ordering space and partially testing the normal ordering space!
- LEGEND-1000 Beyond Standard Model White Paper is also in preparation!



LEGEND Website
www.legend-exp.org

Preconceptual Design Report
<https://arxiv.org/abs/2107.11462>

LEGEND Collaboration



- Large international collaboration
 - ~55 institutions, ~280 members
 - MAJORANA + GERDA + more!



Thanks for your attention!! Questions?