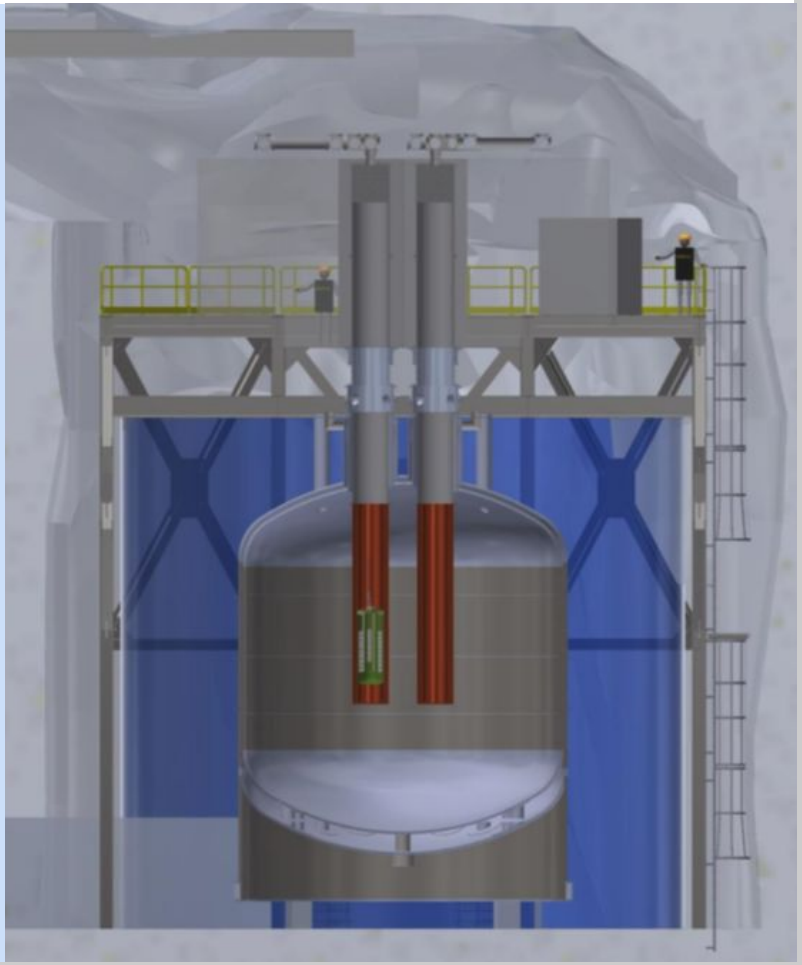
LEGEND experiment: status and outlook



LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Valentina Biancacci

on behalf of the LEGEND collaboration

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN LNGS

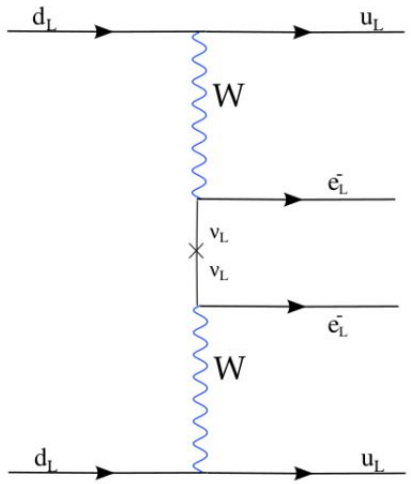
Rencontres du Vietnam 08.08.2023

Double beta-decay without neutrinos

The neutrinoless double beta (0νββ) decay is a hypothesized nuclear transition.

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

"creation of matter without antimatter"



see Saakyan's talk

0νββ can be mediated by the exchange of two massive Majorana neutrinos.

$$\frac{1}{T^{0\nu}_{1/2}} = |M^{0\nu}|^2 G^{0\nu}(Q, Z) \left(\frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$$

nuclear matrix element

phase space factor

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

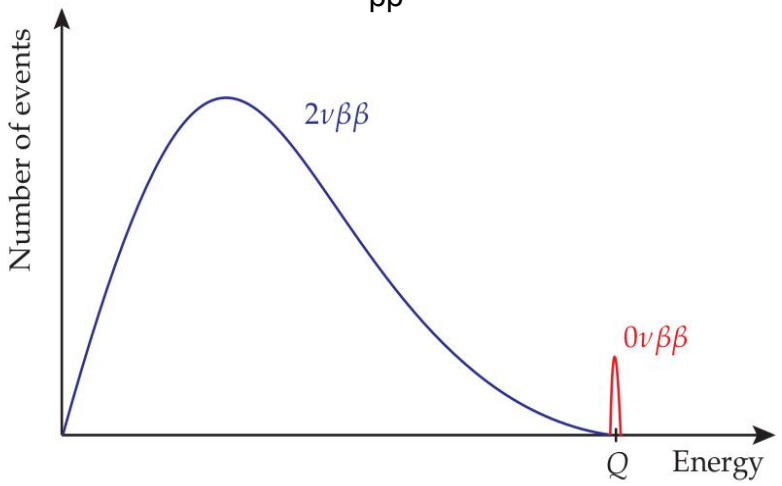
effective neutrino mass

Motivation for 0νββ decay searches

- Establish **lepton number violation** (LNV) → ΔL=2
- Best way to determine **if neutrino is its own antiparticle** ($\nu = \bar{\nu}$)
- Important to understand the **origin of the neutrino mass**
- Probe the a**bsolute neutrino mass scale** and **neutrino mass ordering**
- Provide important **input to cosmology**

0νββ signature and half-life

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



0νββ signal = monoenergetic peak

$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot a \cdot \sqrt{\dfrac{M \cdot t}{BI \cdot \Delta E}} & \text{with background} \\ \epsilon \cdot a \cdot M \cdot t & \text{without background} \end{cases}$$

ϵ: detection efficiency
a: isotopic abundance
M: total detector mass
t: run time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

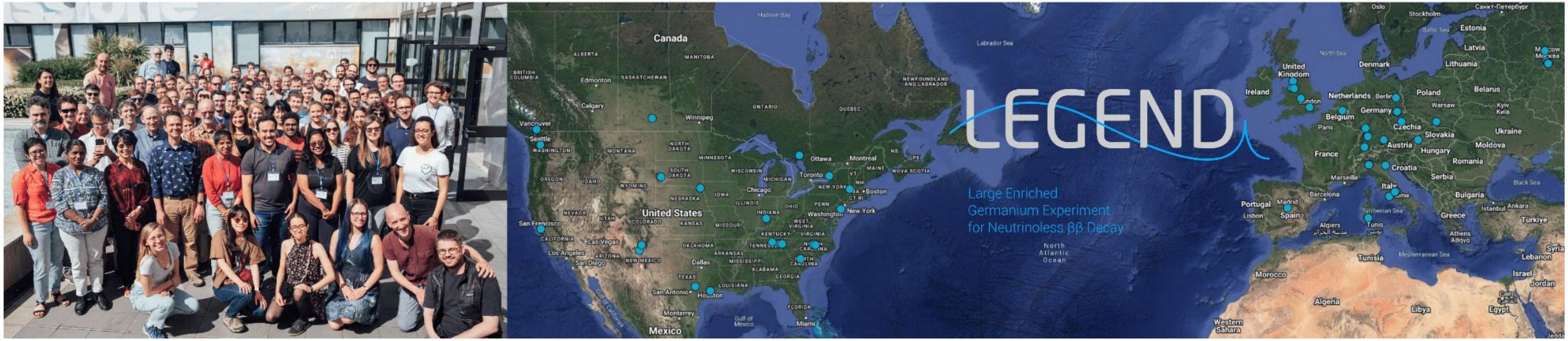
Desirable design for an experiment searching for 0νββ signal

- Low background level
- Good energy resolution of the detector
- Large $Q_{\beta\beta}$
- Large exposure

LEGEND collaboration

LEGEND = **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless Double-Beta **D**ecay

270+ members, 50+ institutions, 11 countries Collaboration formed in October 2016



LEGEND mission:

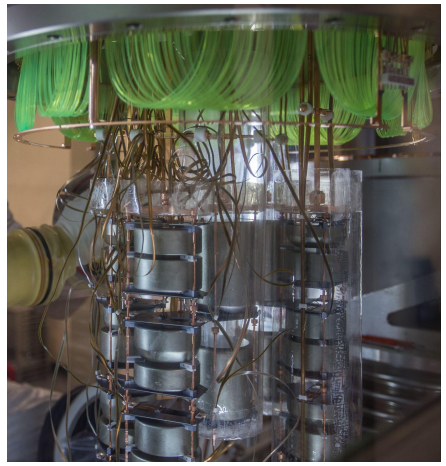
"The collaboration aims to develop a phased Ge-76 based double beta decay experimental program with discovery potential at a half-life significantly longer than 10^{28} years, using existing resources as appropriate to expedite physics results".

LEGEND collaboration

Majorana Demonstrator

+

GERDA



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LEGEND-200

Situated in the existing GERDA infrastructure at LNGS

LEGEND-1000

Emerged as the portfolio review winner in all but one category

Best energy resolution
2.52 ± 0.08 KeV FWHM at $Q_{\beta\beta}$

Lowest background index (BI)
$5.2\ ^{+1.6}_{-1.3} \cdot\ 10^{-4}$ cts/(keV kg yr)

completed in ~ **2020**

data taking started in **2023**

first data in ~ **2031**

...

LEGEND-200

[LEGEND, AIP 894:020027 (2017)]

First Stage

- Upgrade of the existing infrastructure of GERDA experiment
- ~200 kg of detector mass: 35 kg from GERDA + 30 kg from MJD + 140 kg which are new, distributed to 14 strings

rest of the detectors in early 2024

- Current data taking with ~142 kg of detectors deployed in LAr
- Reduction of the BI of a factor 2.5 w.r.t. GERDA Phase II results
- Total planned exposure 10 times larger than GERDA, up to 1 ton yr
- Expected energy resolution at $Q_{\beta\beta}$ equal to 2.5 keV FWHM

L200 Goals	
half-life discovery sensitivity	10^{27} yrs
mass sensitivity	30-70 meV
background index	$2 \cdot 10^{-4}$ cts/(keV · kg · yr)

LEGEND-1000

[LEGEND, arxiv:2107.11462 (2021)]

Further Stage

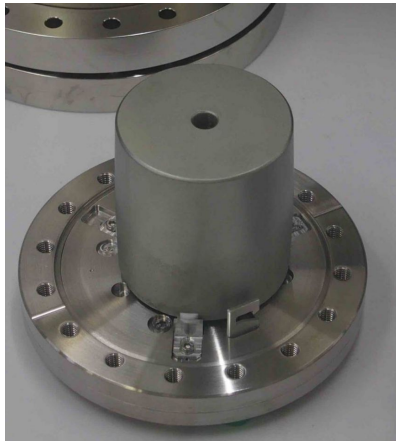
- Staged installation of 1000 kg detector mass (ICPC)
- Detector strings immersed in radiopure underground LAr (UGLAr)
- Background reduction of a factor 50 w.r.t. GERDA Phase II results
- Location to be defined (SNOLAB or LNGS)

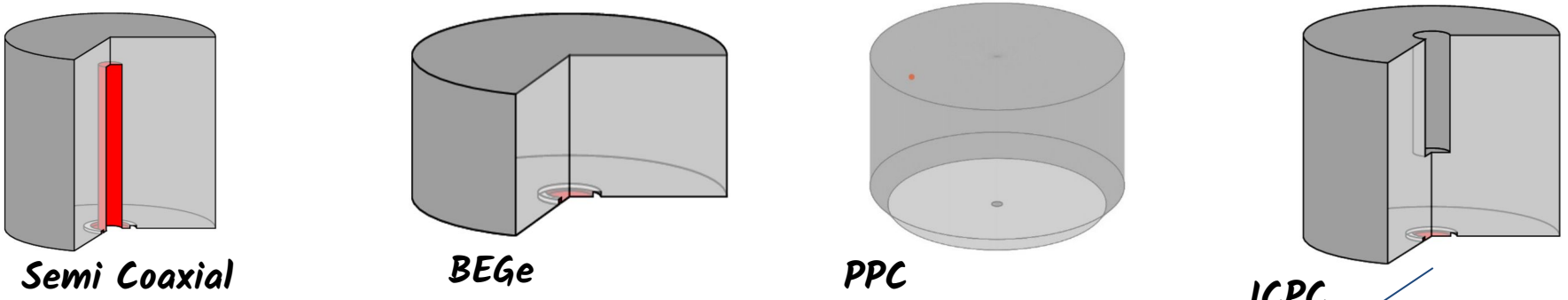
L1000 Goals

half-life discovery sensitivity	10^{28} yrs
mass sensitivity	10-20 meV
background index	10^{-5} cts/(keV · kg · yr)

Why germanium detectors?

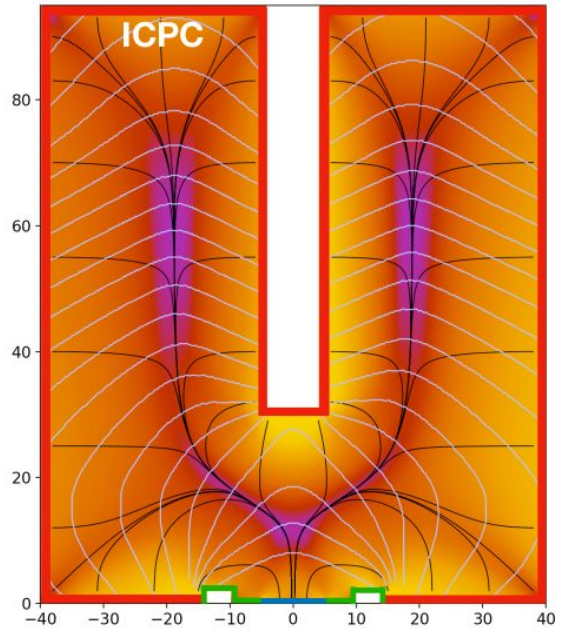
- High detection efficiency (detector = ββ source)
- Best proved energy resolution at the Q-value
- High pulse shape analysis capabilities
- Lowest background per FWHM energy resolution in the field
- Well-established technology





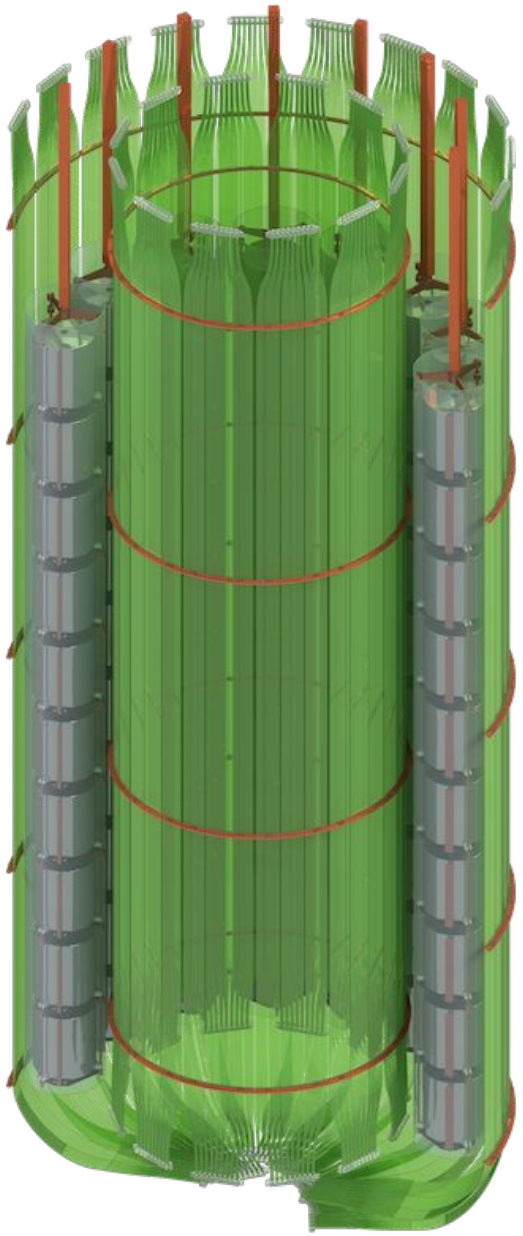
Inverted Coaxial Point Contact (ICPC) detectors: *new*

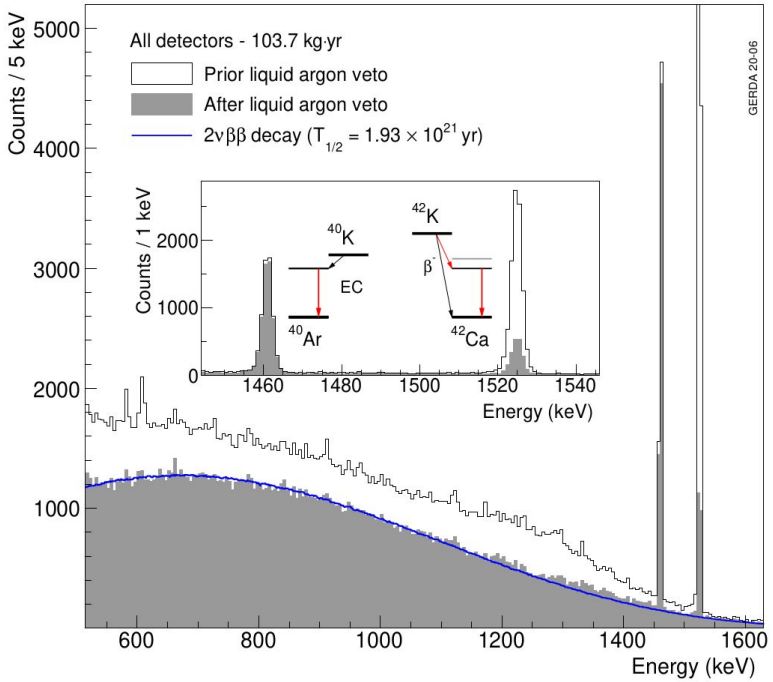
- Enriched detectors, 92% of detector material is ^{76}Ge
- Excellent resolution and pulse shape discrimination
- Significantly larger w.r.t. BEGe or PPC (up to 3 kg)
- Less channels, less background
- Better surface to volume-ratio (30-40%)

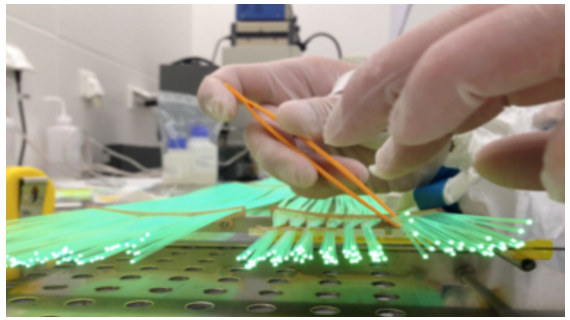


Liquid Argon veto and monitoring

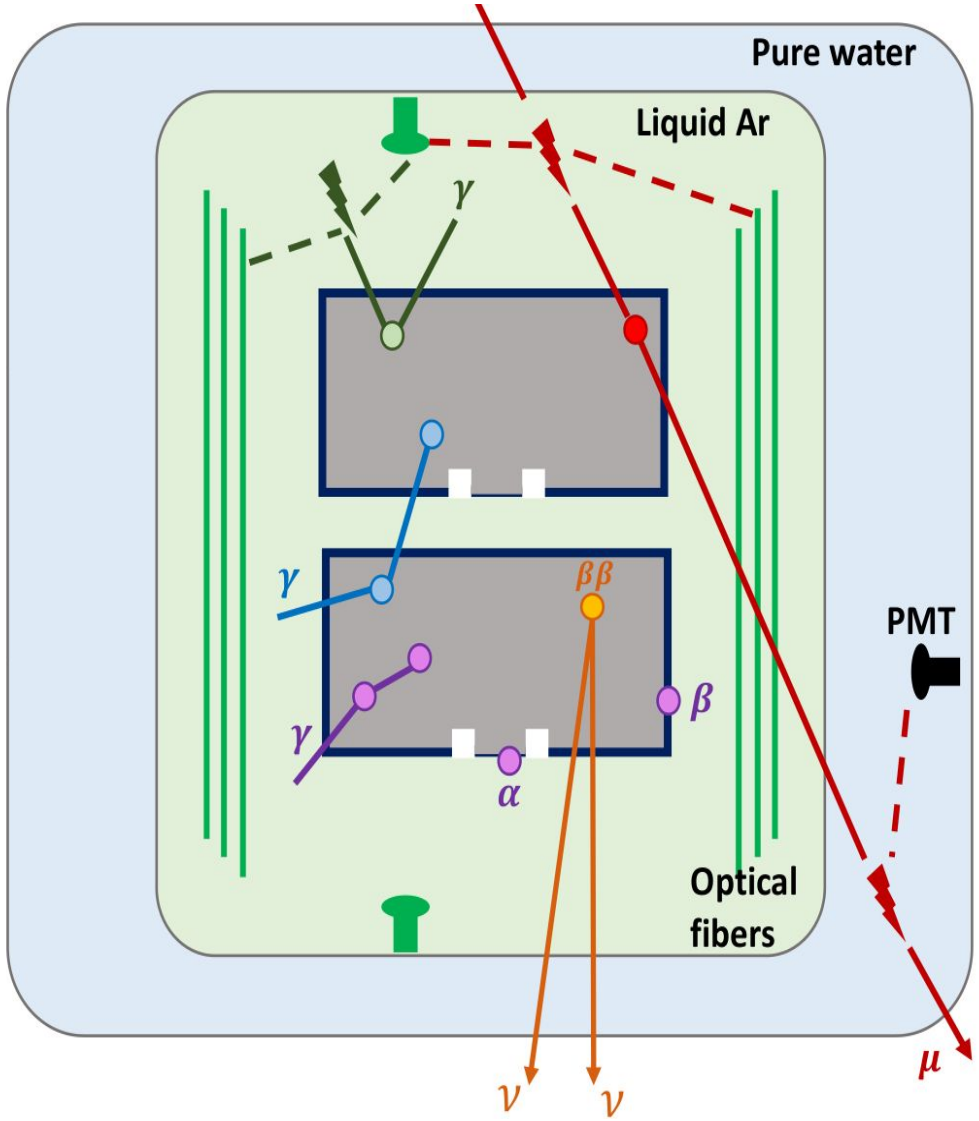
- The LAr scintillation-light detector acts as an active shield from any backgrounds source in the materials surrounding the array
- It is read out via wavelength-shifting (WLS) fibers coupled to SiPMs.
- Liquid Argon Veto suppresses the background events that deposit energy in the Ar
- Argon cryostat: cools detectors to approximately 87 K
- It has proven successful in GERDA and is being implemented in LEGEND-200 as two-barrel geometry.

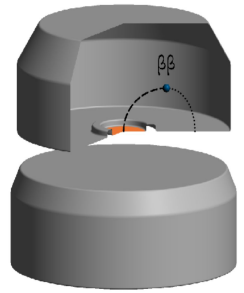




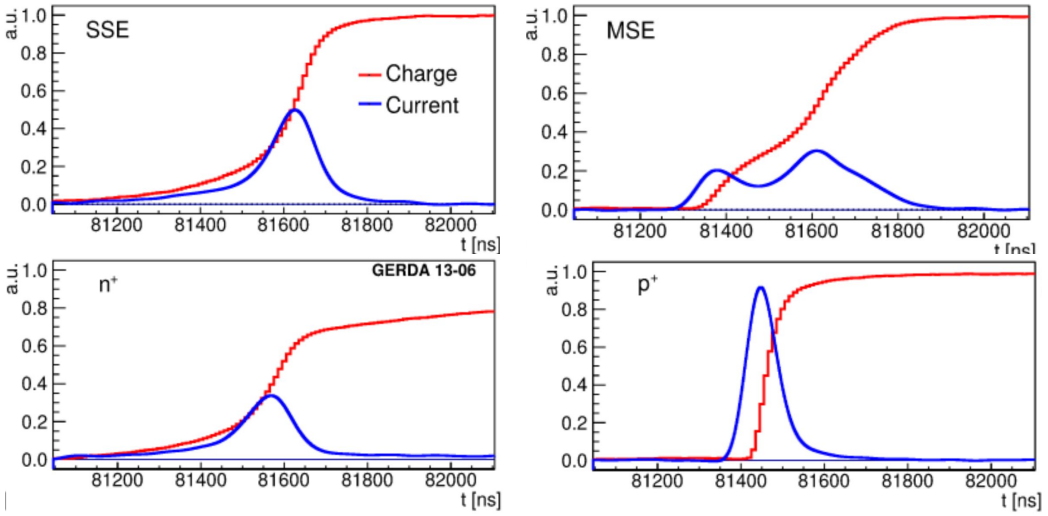


Active background reduction tools



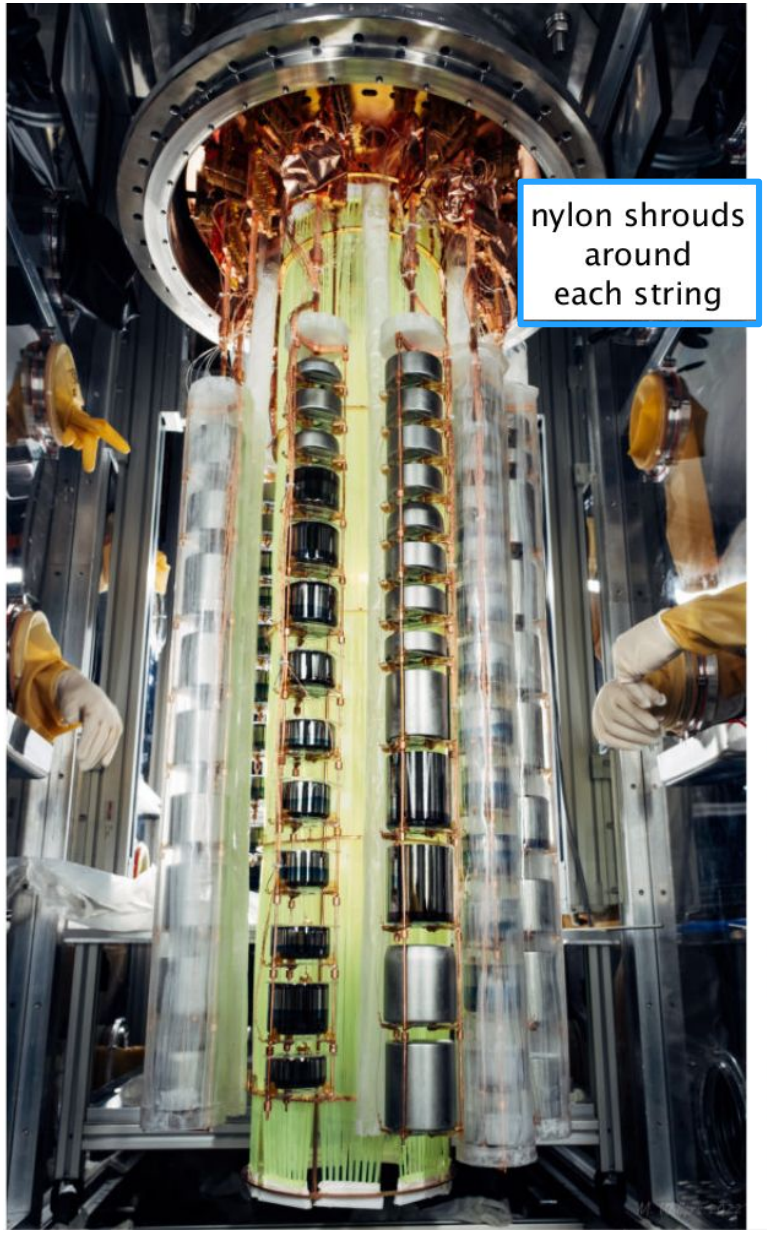


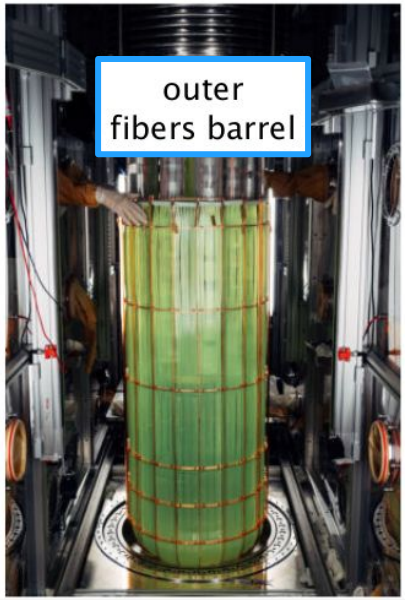
- ββ decay signal: single-site event energy deposition in a 1 mm^3 volume
- Anti-coincidence with the muon veto
- Anti-coincidence between detectors (cuts multi-site)
- Active veto using LAr scintillation (LAr Veto)
- Pulse shape discrimination (PSD)



LEGEND-200: current status

- Location at hall A, LNGS: muon flux is reduced by 6 orders of magnitude respect to the surface
- HPGe:
  - 12 string array
- Low Mass Front End
- LAr:
  - 64 m^3 LAr Volume in a stainless steel cryostat
  - 58 read-out modules of SiPMs coupled to WLS fibers
- Electroformed copper plates
  - produced underground at SURF
- Ultrapure water tank:
  - shields n, γ
  - 66 PMTs (Cherenkov) + plastic scintillators for μ





LEGEND-200: current status

Stable data taking since March 12th :

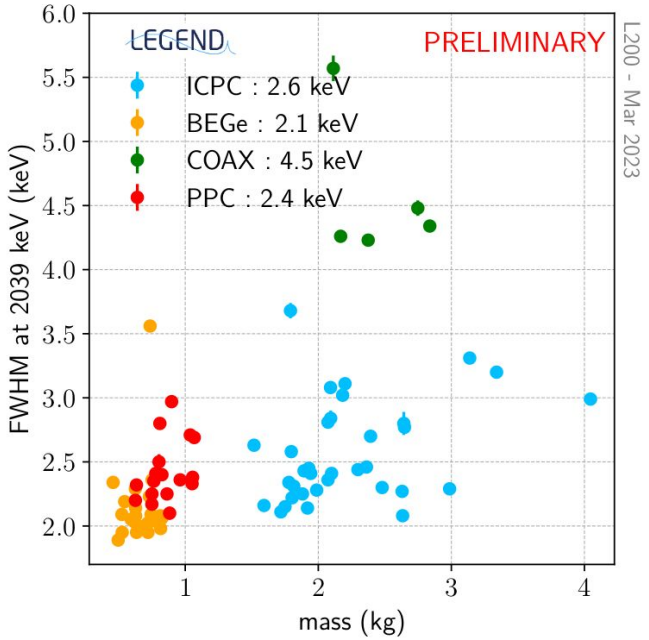
- 142 kg of detectors
- > 2 kg · yr / week
- 100 kg · yr by the end of the year

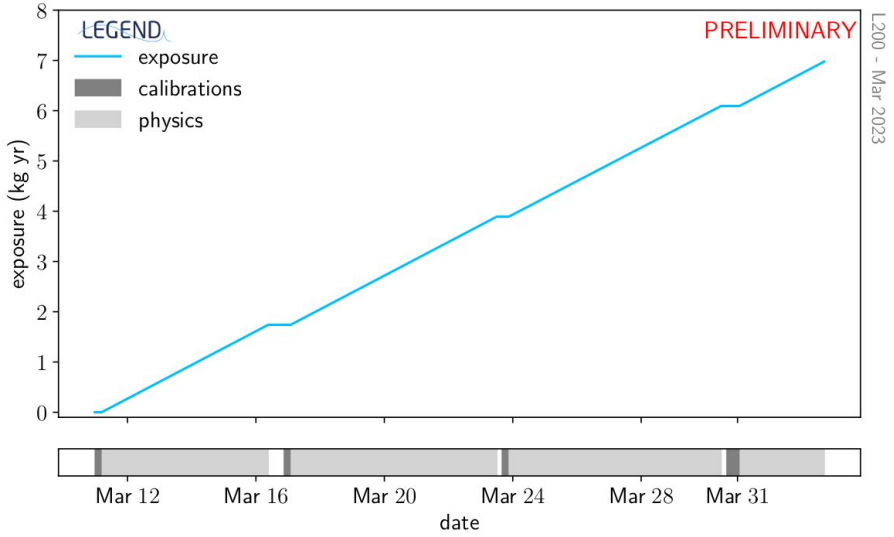
Energy resolution:

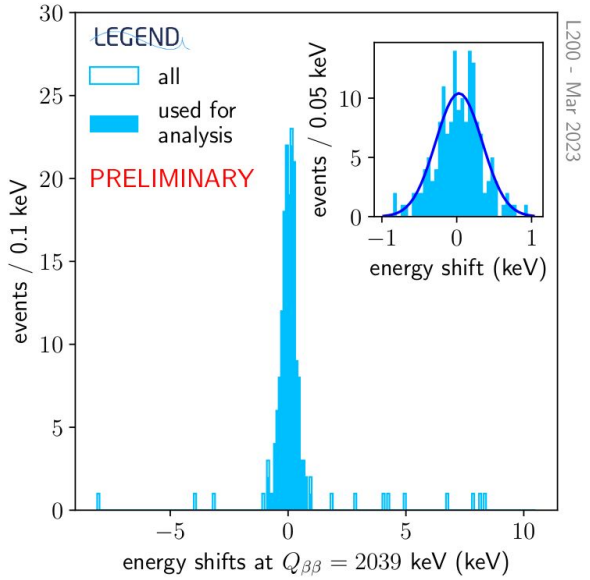
- FWHM ~ 2.4 keV at $Q_{\beta\beta}$
- ICPC detectors already fulfilling L1000 goals

Energy stability:

- shifts monitored between subsequent calibrations
- extremely stable for 120 kg of detectors

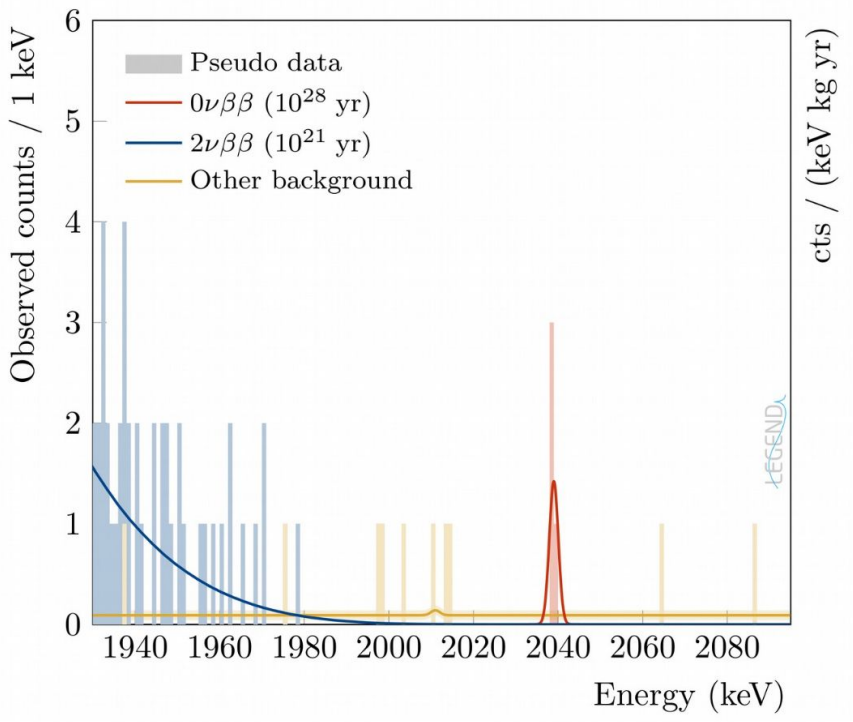






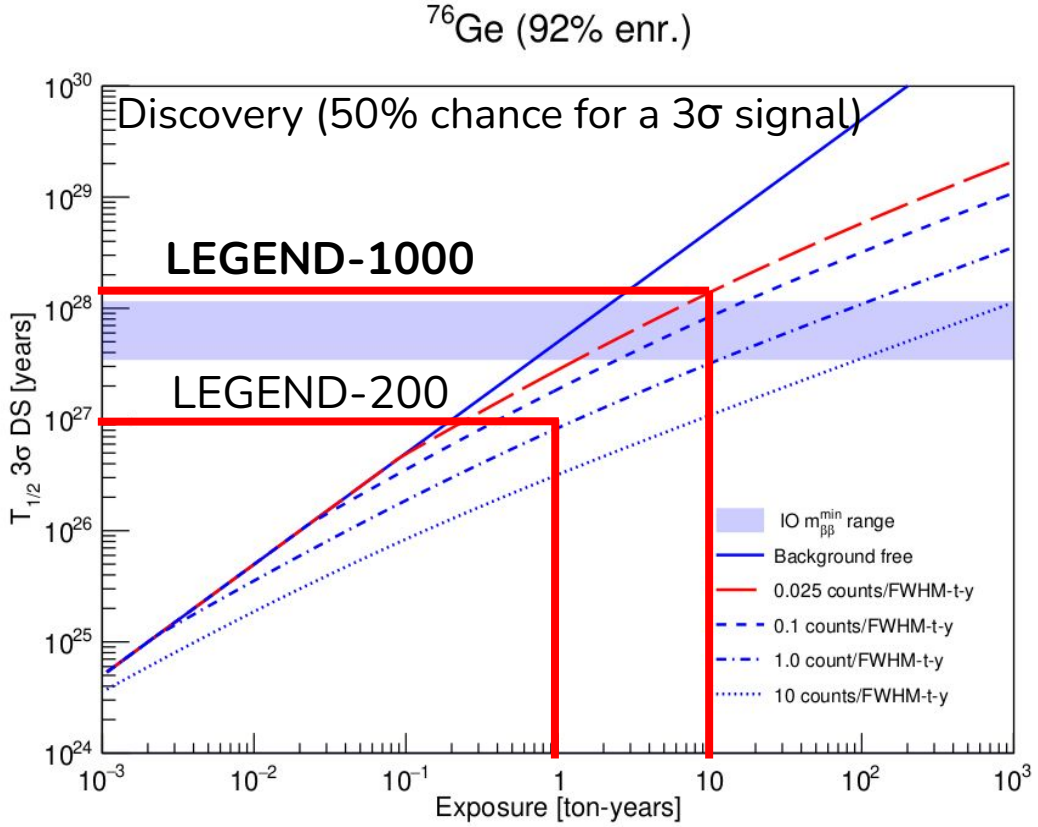
LEGEND-1000: prospects

- Flat background - no γ peaks close to $Q_{\beta\beta}$
- Unambiguous discovery of 0νββ achievable even with a handful of counts - signal will be visible to the eye



Bkg Index
cts/(FWHM·ton·yr)

LEGEND-200	0.6
LEGEND-1000	**0.025**



Conclusion

- LEGEND will search for 0νββ decay in ^{76}Ge via 2 stages.
- LEGEND-200 is currently taking data with >120 kg in a stable manner.
- Background Index for LEGEND-200 is anticipated in late summer and the first 0nbb result will be announced in 2024
- LEGEND-1000 is in the design stage and aims to fully cover inverted hierarchy
- More about LEGEND in https://legend-exp.org

...stay tuned!