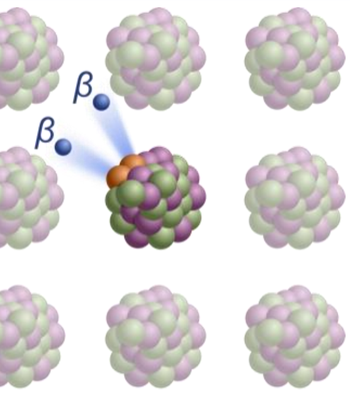
The Ton-Scale Search for Neutrinoless Double-Beta Decay in Germanium with LEGEND-1000

Sofia Calgaro, sofia.calgaro@pd.infn.it – on behalf of the LEGEND collaboration

ICHEP 2024

INFN PADOVA · UNIVERSITÀ DEGLI STUDI DI PADOVA

THEORY AND MOTIVATION



"The only known, feasible probe of the Majorana nature of the neutrino is the neutrinoless double-beta 0νββ decay"

- $2\nu\beta\beta$: 2nd order weak process allowed in SM (measured)
  - ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd
- $0\nu\beta\beta$ is a lepton number violating process forbidden in SM
- Observation would give insight into:
  - matter-antimatter asymmetry
  - neutrinos are Majorana particles, $\nu = \bar{\nu}$
  - absolute mass scale / hierarchy of neutrinos

Isotope choice mostly based on experimental preferences (costs, energy resolution, background level, scalability, …)

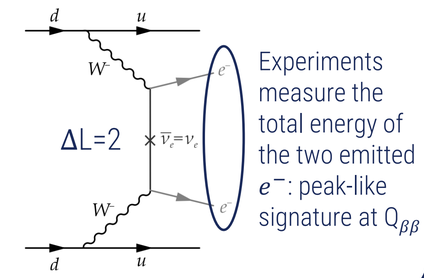
Sensitivity

$$T_{1/2}^{0\nu} \propto \epsilon \cdot f \cdot \begin{cases} \sqrt{\frac{\varepsilon}{B \cdot \Delta E}} & B \neq 0 \\ \varepsilon & B = 0 \end{cases}$$

ϵ: efficiency
f: isotopic fraction
$\varepsilon = M \cdot t$: exposure
ΔE: resolution at $Q_{\beta\beta}$
B: bkg index

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,|M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

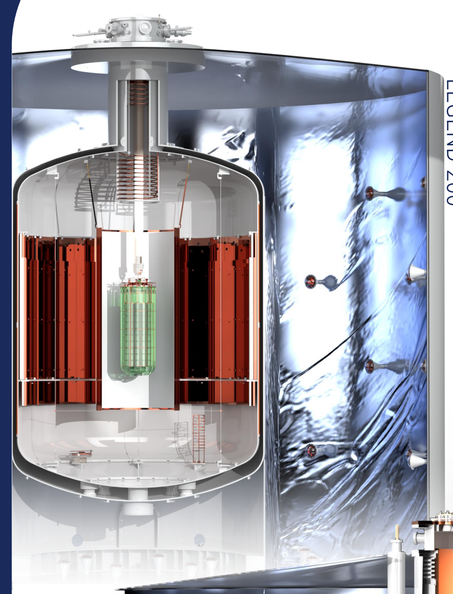
$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$ effective neutrino mass (isotope independent)



Experiments measure the total energy of the two emitted e^-: peak-like signature at $Q_{\beta\beta}$

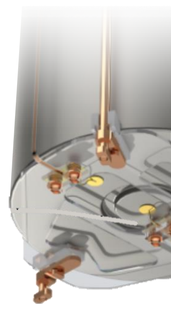
THE LARGE ENRICHED GE EXPERIMENT FOR NEUTRINOLESS ββ DECAY

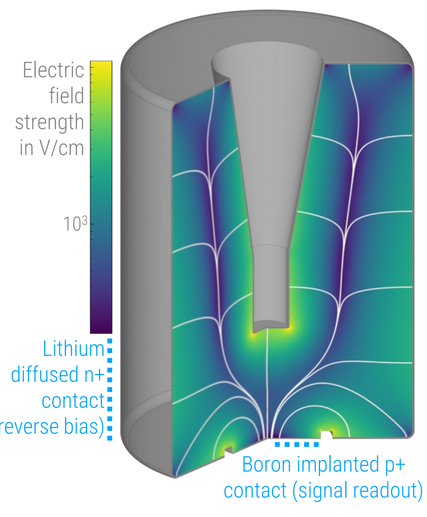
"The collaboration aims to develop a phased, ^{76}Ge-based 0νββ decay experimental program with discovery potential at a half-life beyond 10^{28} yr, using existing resources as appropriate to expedite physics results" [1]



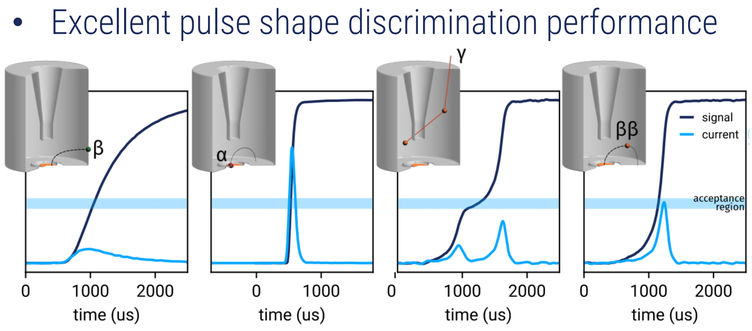
- Already established technology (>1960s)
- Source ≡ detector: high efficiency
- High purity: low intrinsic background
- Outstanding resolution: FWHM~0.1% @ $Q_{\beta\beta}$

- LEGEND uses **GERDA & MAJORANA experience**
- **L-200 under operation** (first result @ Neutrino 2024): test-bed for L-1000
- L-1000 will deploy **130 kg of L-200 ICPC** detectors + **new 870 kg**
- Background reduction strategies for performing a **quasi-bkg-free search**
- Transparent, scintillating, radiopure **PEN as Ge baseplate**
- H-rich **neutron moderator** to slow down and capture n on ^{40}Ar
  - μ-induced bkg @ LNGS: $2 \cdot 10^{-5}$ ckky (goal: 10^{-7} ckky)
  - **instrumented AtLAr** to tag μ-induced $^{77(m)}$Ge events
  - Reduction down to $(6.8 \pm 4.3) \cdot 10^{-7}$ ckky [2]
- ^{39}Ar in **UGLAr** is 1400x times lower than in AtLAr: **reduction of ^{42}K** (progeny of ^{42}Ar)
  - UGLAr extraction from underground CO_2 wells @ Ar Extraction Facility (Cahone, CO)
  - Commission of **26.5t** (extraction after DarkSide-20k)





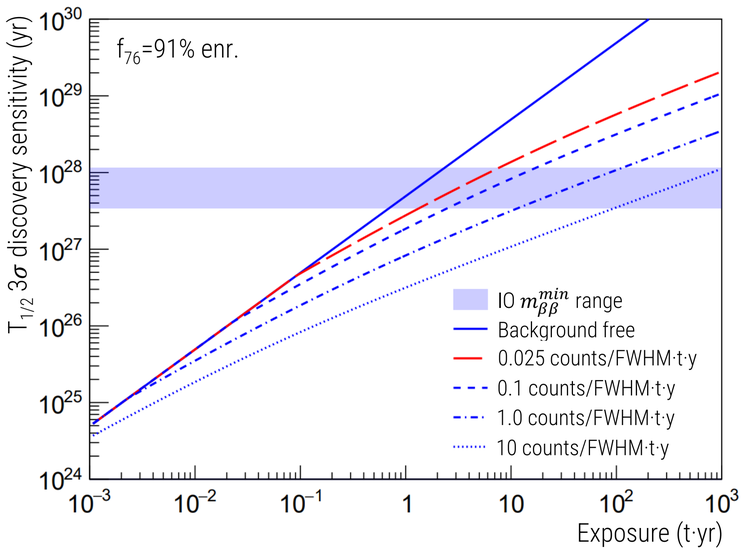
Inverted Coaxial Point Contact (ICPC) detector
- **Large masses** (>3 kg) = lower bkg
- Reduce surface-volume ratio & cables/supports mass
- Excellent pulse shape discrimination performance

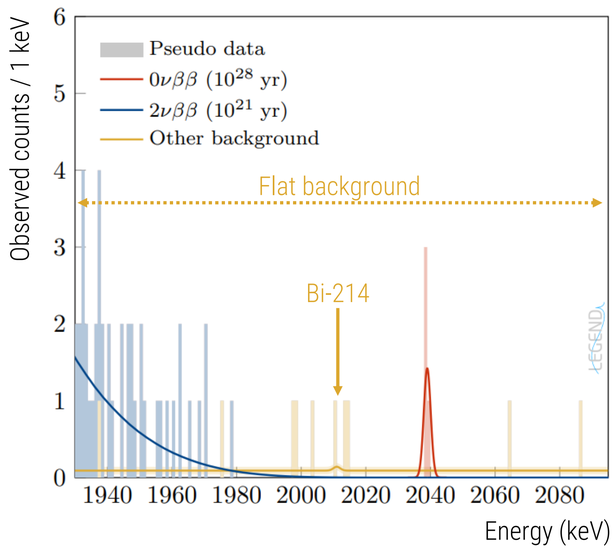


LEGEND-1000 DISCOVERY POTENTIAL

"By combining the lowest background levels and the best energy resolution in the field, LEGEND-1000 will perform a quasi-background-free search and can make an unambiguous discovery of 0νββ decay with just a handful of counts at the $Q_{\beta\beta}$"

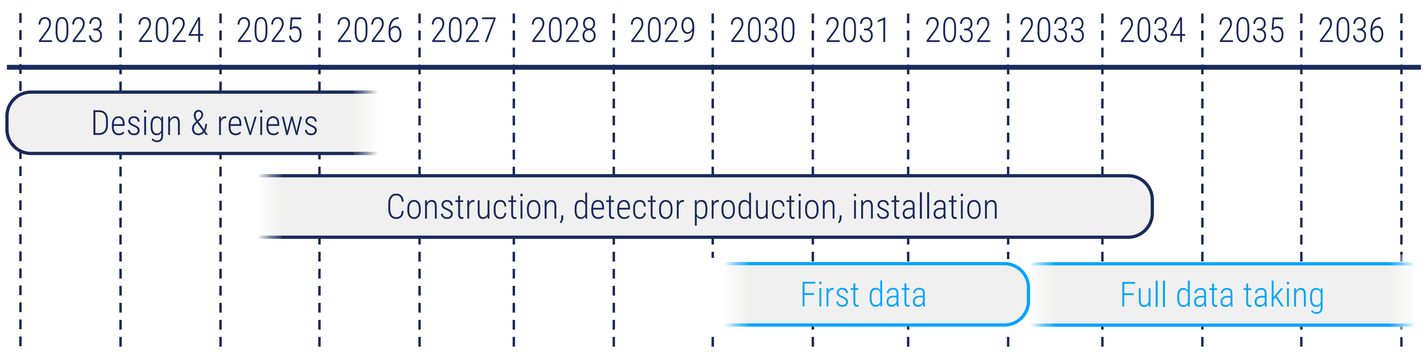
LEGEND-1000 is designed to span over the full inverted ordering mass region ($m_{\beta\beta}$ < 9 – 21 meV in 10 years), guaranteeing a discovery if this is the true scenario in a quasi-background free regime





- **Background goal: 10^{-5} counts/(keV·kg·yr) @ $Q_{\beta\beta}$**
  - 50x (20x) times less than GERDA (L-200)
- Strict procedures for material selection + handling
- Material screening & assay: **stringent radiopurity requirements**
  - study of ^{238}U, ^{232}Th, ^{222}Rn (+daughters) in all materials
  - mass spectroscopy, γ-ray counting, n activation analysis, radon emanation analysis, surface assays
- **Background rejection**
  - pulse shape discrimination analysis
  - timing coincidences (LAr scintillation, Cherenkov μ veto)
  - granularity cut

TIMELINE & READINESS



- Funding from U.S. (DOE, NSF) + Europe
- Funding already in hand from several European institutions
- **Preparations underway following Borexino decommissioning**

3500 m.w.e. rock overburden
μ_{LNGS} ~1.25/(m²·h) [3]

LNGS of INFN, Italy – Hall C

REFERENCES: [1] N. Abgrall et al. (LEGEND Collaboration), arXiv:2107.11462(2021) - [2] Courtesy of M. Morella – [3] M. Agostini et al. (GERDA Collaboration), Eur. Phys. J. C 78 (2018) 388

This work is supported by the U.S. DOE and the NSF, the LANL, ORNL and LBNL LDRD programs; the European ERC and Horizon programs; the German DFG, BMBF, and MPG; the Italian INFN; the Polish NCN and MNiSW; the Czech MEYS; the Slovak SRDA; the Swiss SNF; the UK STFC; the Russian RFBR; the Canadian NSERC and CFI; the LNGS, SNOLAB, and SURF facilities.

INSTITUITIONS: Centre for Energy, Environmental and Technological Research,Comenius Univ., Czech Technical Univ. in Prague and IEAP, Daresbury Laboratory, Duke Univ. and Triangle Universities Nuclear Laboratory, Gran Sasso Science Institute, Indiana Univ. Bloomington, Institute for Nuclear Research Russian Academy of Sciences, Jagiellonian Univ., Joint Institute for Nuclear Research, Joint Research Centre Geel, Laboratori, Nazionali del Gran Sasso, Lancaster Univ., Leibniz Institute for Crystal Growth, Leibniz Institute for Polymer Research, Los Alamos National Laboratory, MPI for Nuclear Physics, MPI for Physics, National Research Centre "Kurchatov Institute«, National Research Nuclear Univ. MEPhI, North Carolina State Univ., Oak Ridge National Laboratory, Polytechnical Univ. of Milan, Princeton Univ., Queen's Univ., Roma Tre Univ. and INFN, Simon Fraser Univ., SNOLAB, South Dakota School of Mines and Technology, Technical Univ. of Dresden, Technical Univ. of Munich, Tennessee Technological Univ., Univ. of California and Lawrence Berkeley, National Laboratory, Univ. College London, Univ. of L'Aquila and INFN, Univ. of Cagliari and INFN, Univ. of California San Diego, Univ. of Houston, Univ. of Liverpool, Univ. of Milan and INFN, Univ. of Milano Bicocca and INFN, Univ. of New Mexico, North Carolina at Chapel Hill, Univ. of Padova and INFN, Univ. of Regina, Univ. of South Carolina, Univ. of South Dakota, Univ. of Tennessee, Knoxville, Univ. of Texas at Austin, Univ. of Tuebingen, Univ. of Warwick, Univ. of Washington and Center for, Experimental Nuclear Physics and Astrophysics, Univ. of Zurich, Williams College