Results from LEGEND-200 and Prospects for LEGEND-1000

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On behalf of the LEGEND collaboration

Istituto Nazionale di Fisica Nucleare

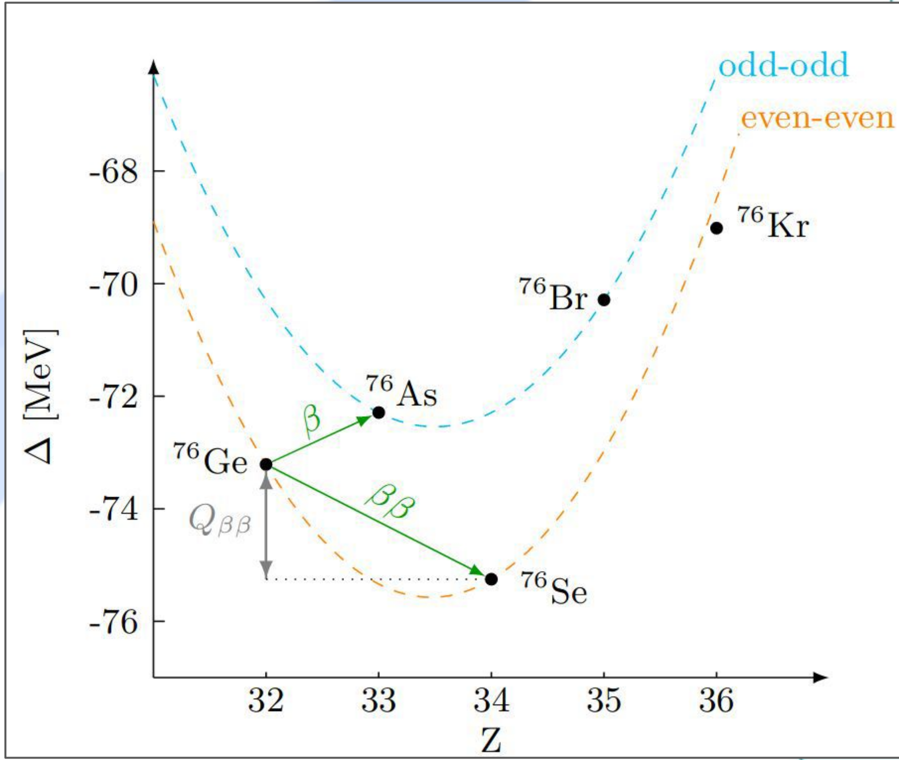
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

UNIVERSITÀ DEGLI STUDI ROMA TRE

Double beta decay (ββ decay)

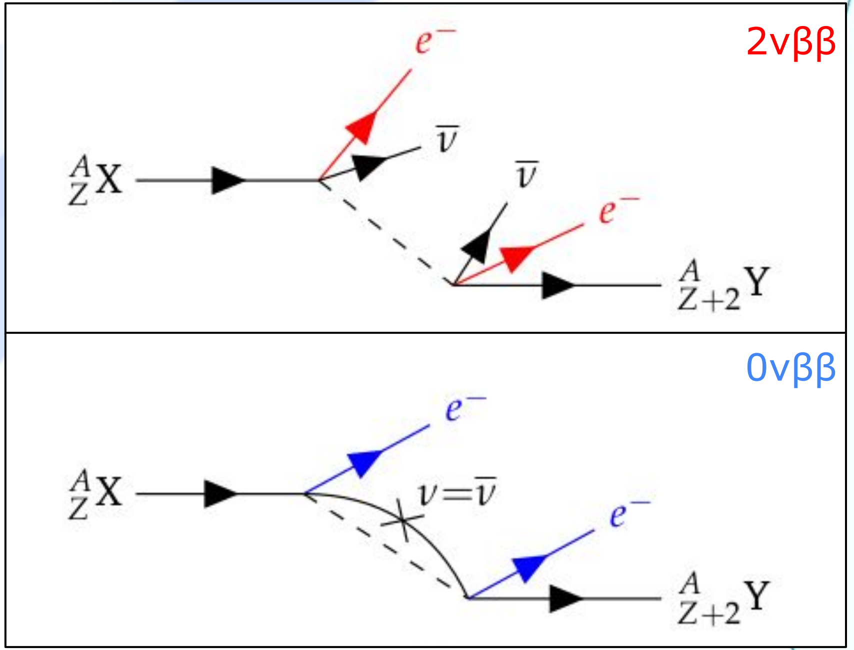
- 2nd order nuclear decay
- Observable if β decay is suppressed
  - 35 known even-even isotopes capable, 12 observed directly
- $T_{1/2}$ 10^{19}-10^{24} yrs (for observed isotopes)

$$^{A}_{Z}X \Rightarrow \, ^{A}_{Z+2}Y + 2e^{-} + 2\overline{\nu}_{e}$$



Neutrinoless double beta decay (0vββ)

- 2nd order nuclear decay
- Observable if β decay is suppressed
  - 35 known even-even isotopes capable, 0 observed
- $T_{1/2} > (10^{26})$ yrs
- Only possible if $\nu = \overline{\nu}$



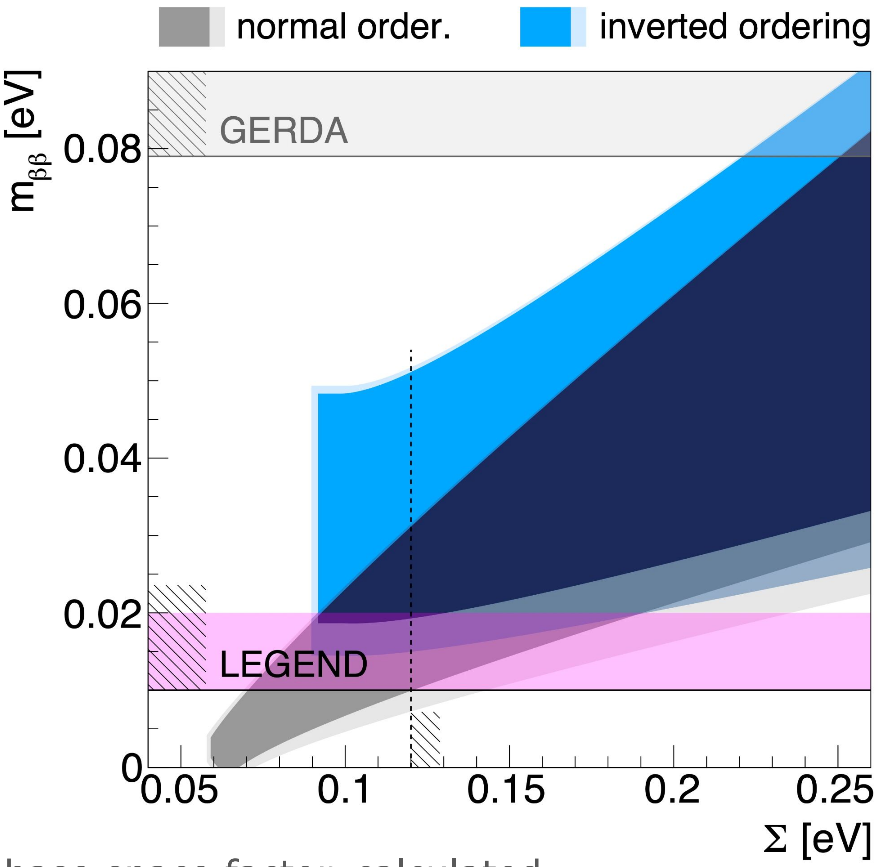
$$^{A}_{Z}X \Rightarrow \, ^{A}_{Z+2}Y + 2e^{-} + 2\overline{\nu}_e$$

$$^{A}_{Z}X \Rightarrow \, ^{A}_{Z+2}Y + 2e^{-}$$

Implications of 0vββ discovery

- Neutrino is a Majorana particle
- Lepton number violation ΔL = 2, potential for matter-antimatter asymmetry via leptogenesis
- Half-life of 0vββ directly related to effective neutrino mass* $m_{\beta\beta}$

*assuming light neutrino exchange as the mechanism

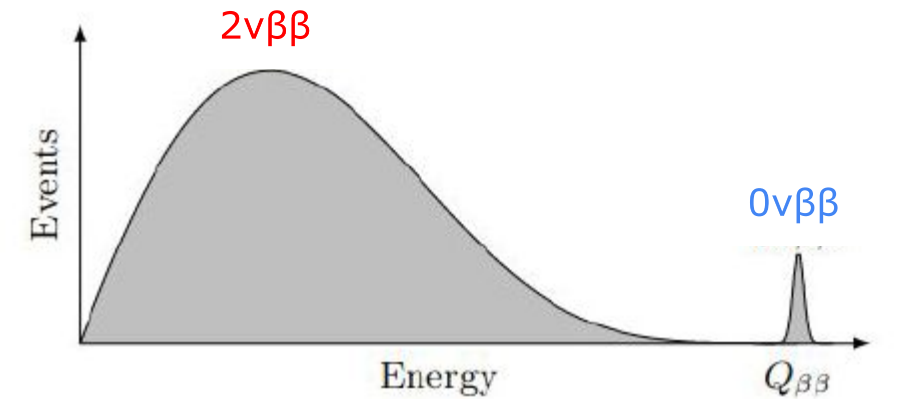


$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

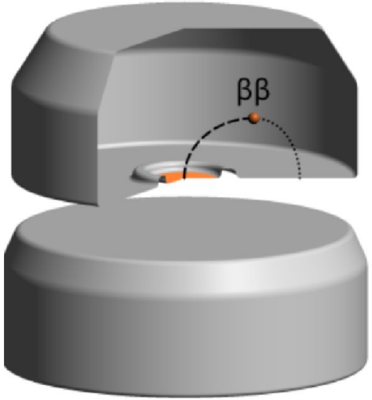
G^{0v} - phase space factor, calculated with low uncertainty
M^{0v} - Nuclear matrix elements of decay, calculated with high uncertainties

Searching for the 0νββ signal - general strategy

- 2νββ - energy split amongst 4 emitted particles, 2 of which escape detectors
- 0νββ - energy split between 2 electrons*, can detect full energy of decay ($Q_{\beta\beta}$)



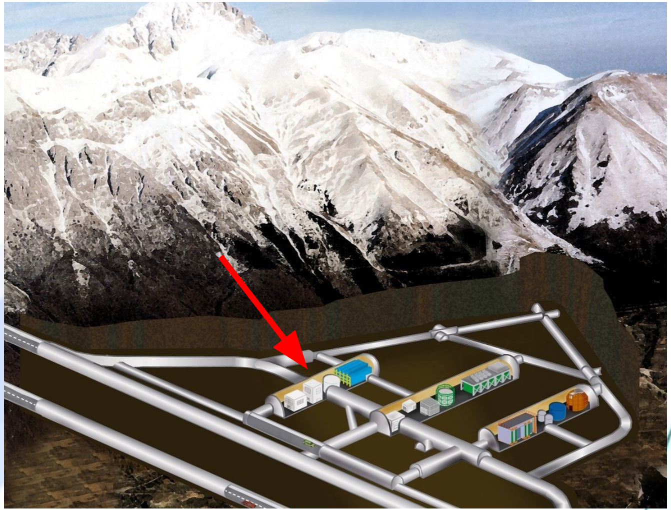
0νββ in ^{76}Ge should be single-site, monoenergetic signal at $Q_{\beta\beta}$=2039 keV



*Nuclear recoil energy can be neglected

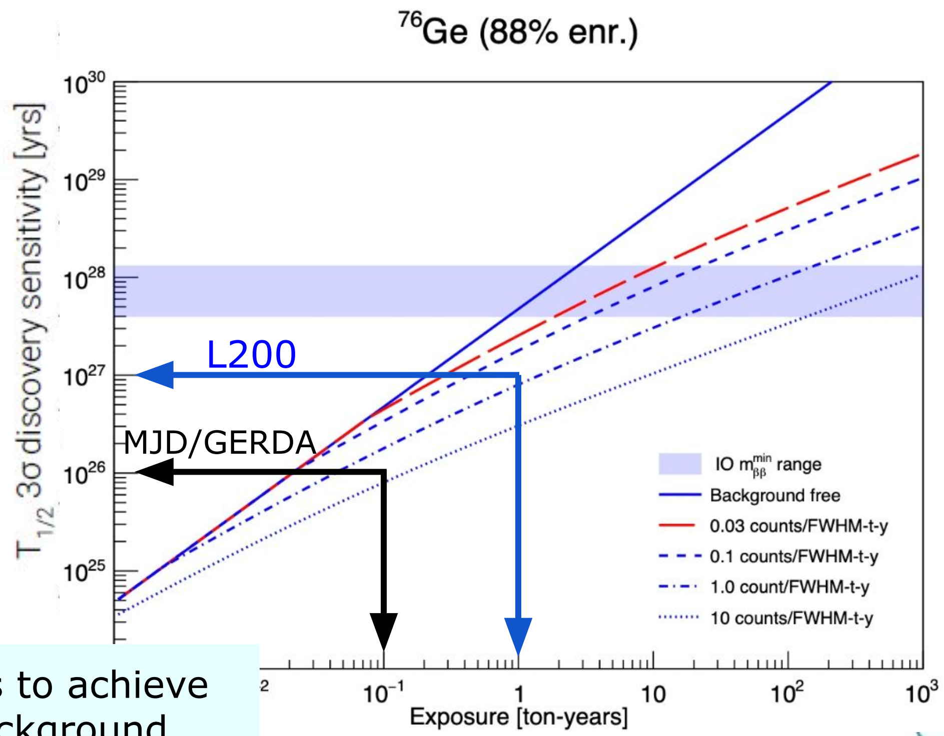
The LEGEND experiment

- Large Enriched Germanium Experiment for Neutrinoless ββ Decay
- At the Laboratori Nazionali del Gran Sasso (LNGS)
- Combines MAJORANA DEMONSTRATOR(MJD), GERDA, + new collaborators
- Multi-phased, currently in phase 1: LEGEND-200



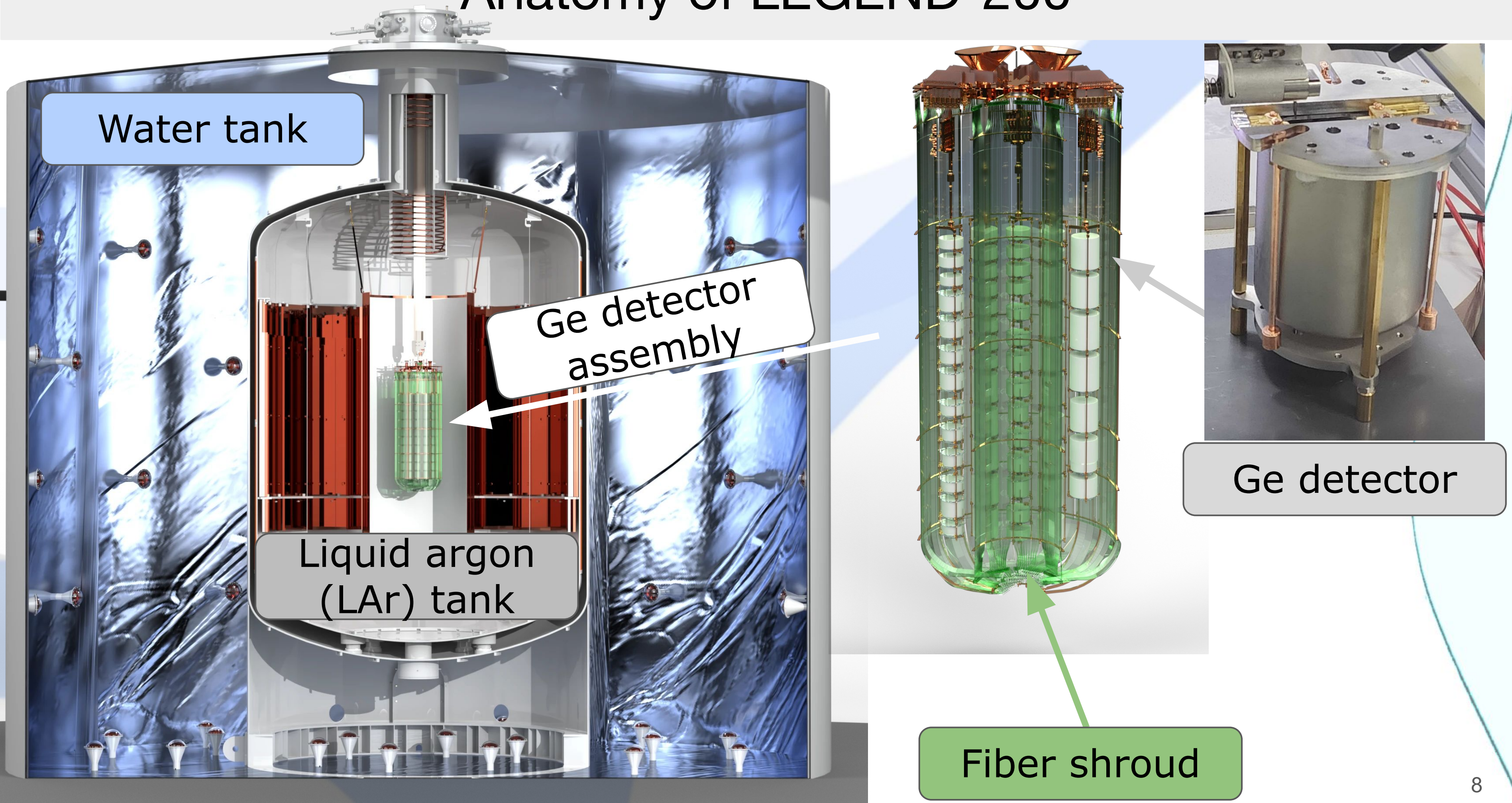
LEGEND-200 overview and goals

- Currently operating ~130 kg of enriched HPGe detectors, with a goal of 200 kg
- Data taking since ~March 2023 with breaks
- Goal: sensitive up to $T_{1/2}(0\nu\beta\beta) \geq 10^{27}$ yrs

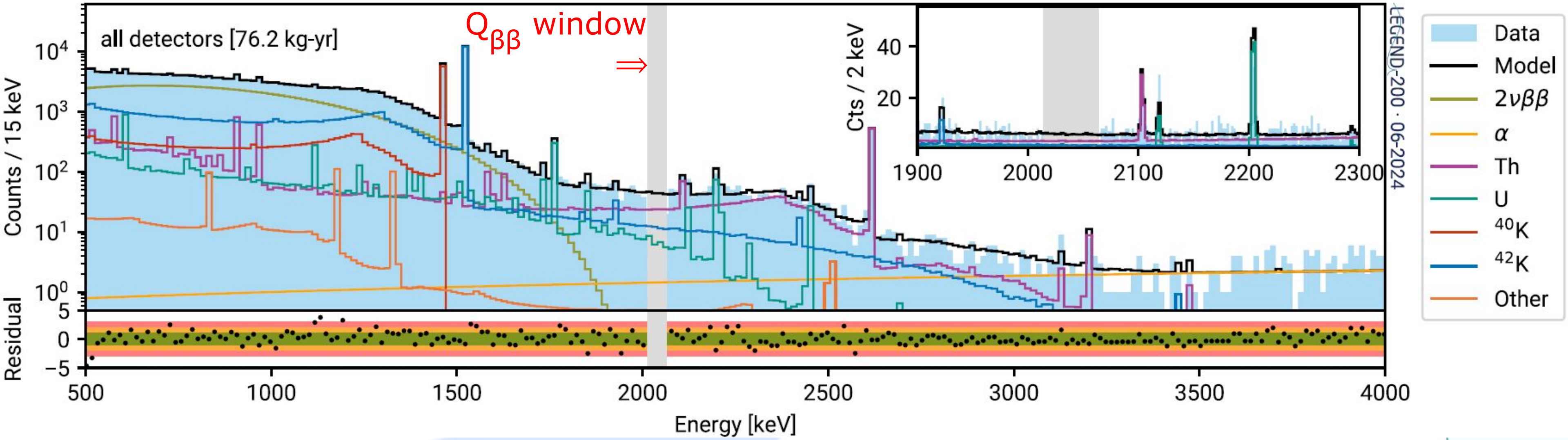


To achieve target sensitivity, LEGEND-200 aims to achieve 1 ton-year of total detector exposure with a background index (BI) < 2 x 10-4 cts/(keV kg yr) near $Q_{\beta\beta}$

Anatomy of LEGEND-200



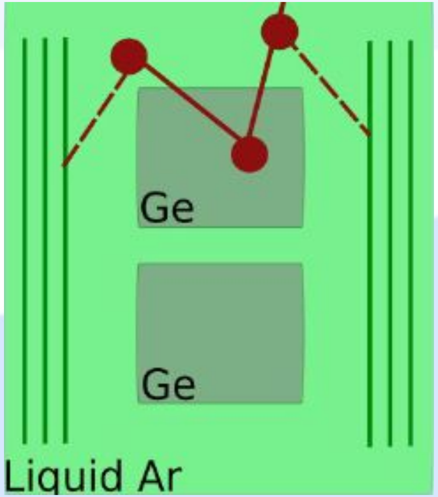
The LEGEND-200 background model



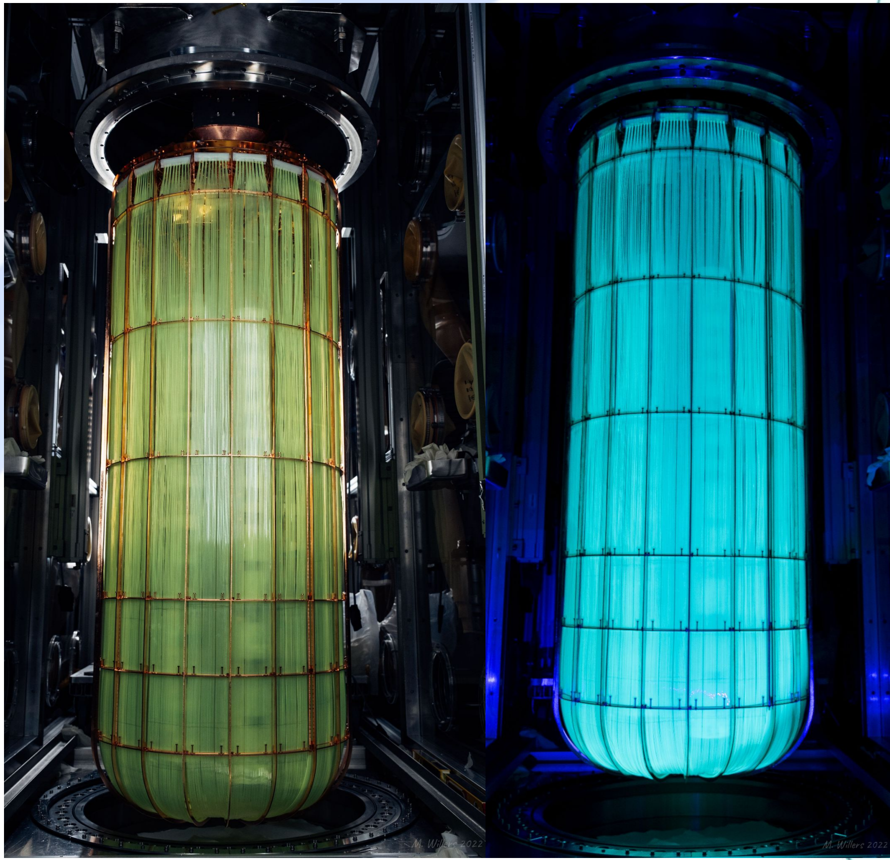
Multivariate fit of known background components
to the data using toy Monte Carlo

LAr scintillation instrumentation

- LAr scintillation peak at 128 nm
- WLS fiber guides coupled with SiPMs
- Coincident signals in Ge+LAr implies an event type other than ββ

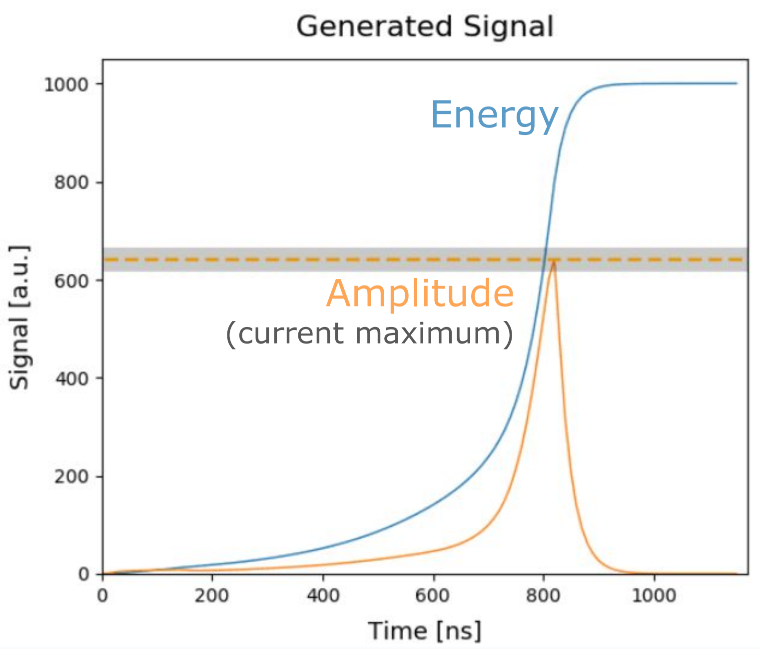


$0\nu\beta\beta$ should be spatially "point-like", monoenergetic signal at $Q_{\beta\beta}$=2039 keV

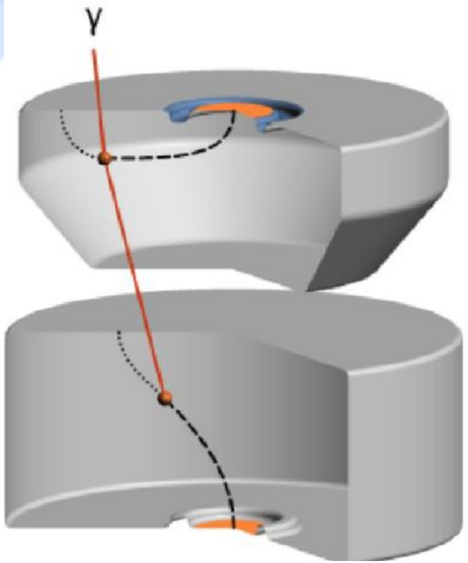


Ge detector cuts - multiplicity and A/E

- Multiplicity cut: coincident signals in ≥2 detectors, signal not single-site
- Amplitude maximum of current (A) / Energy e.g. time integral of current (E) - ratio is used for pulse shape discrimination (PSD)



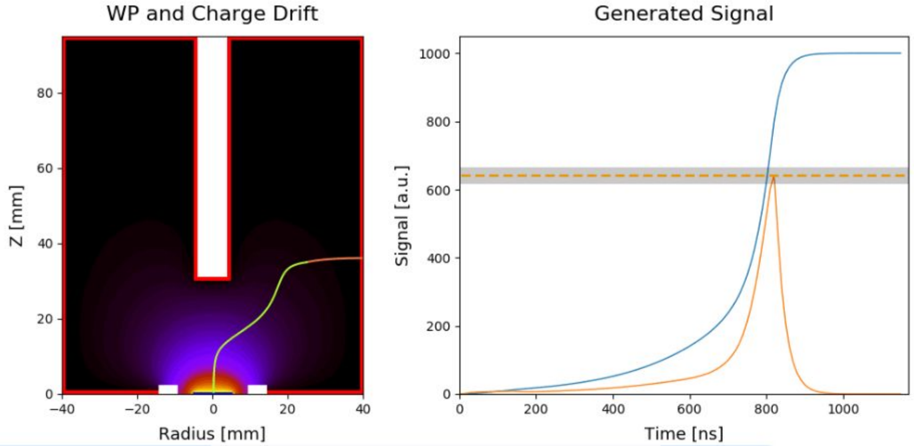
Acceptance window for A as point-like



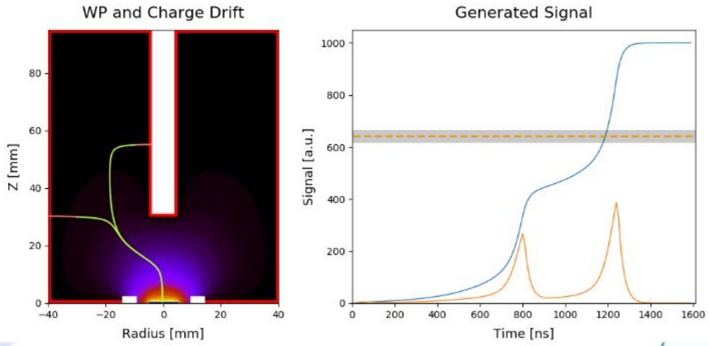
Multiplicity = 2

PSD in action

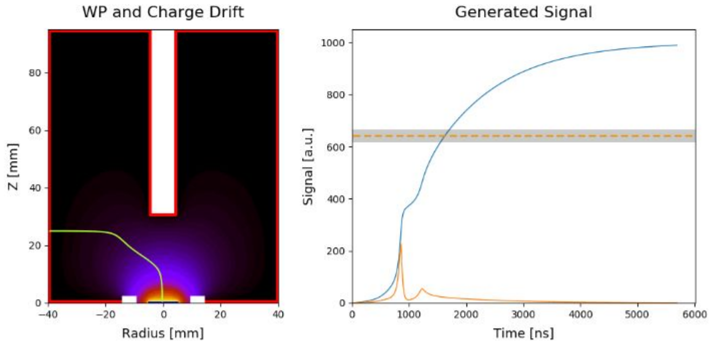
Signal collection time varies throughout detector volume and can be used to distinguish event types



Single-site event

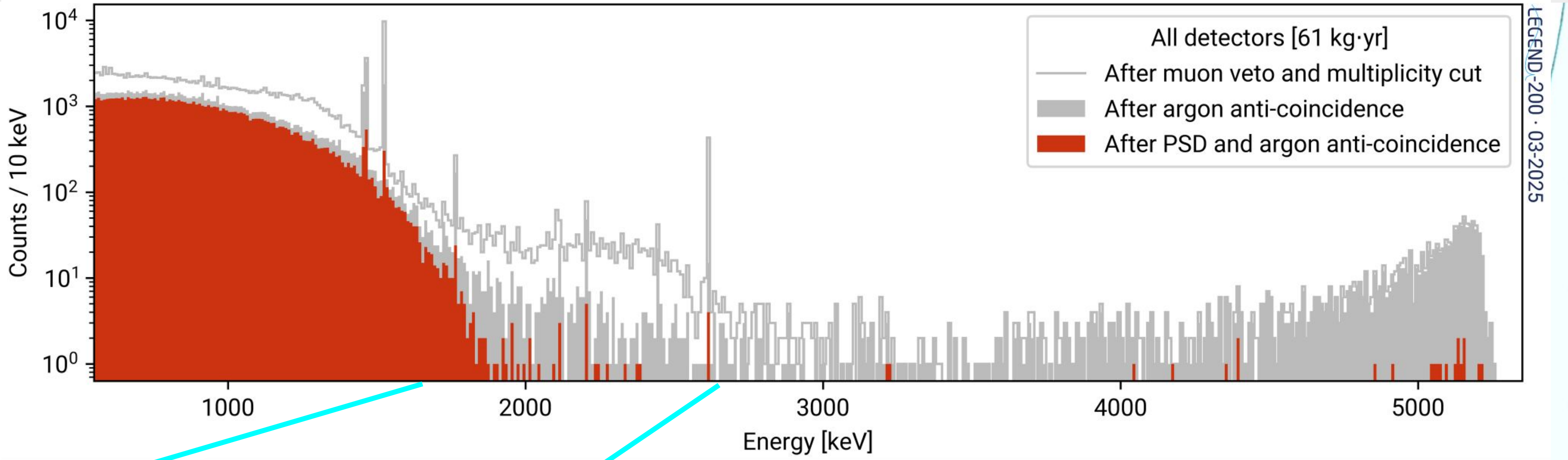


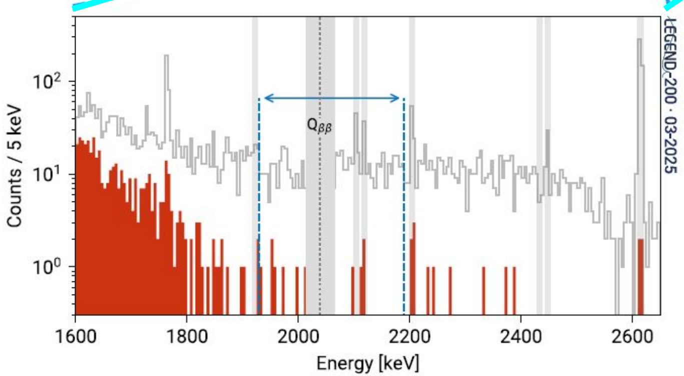
Multi-site event



Surface event

The new LEGEND-200 results with all cuts

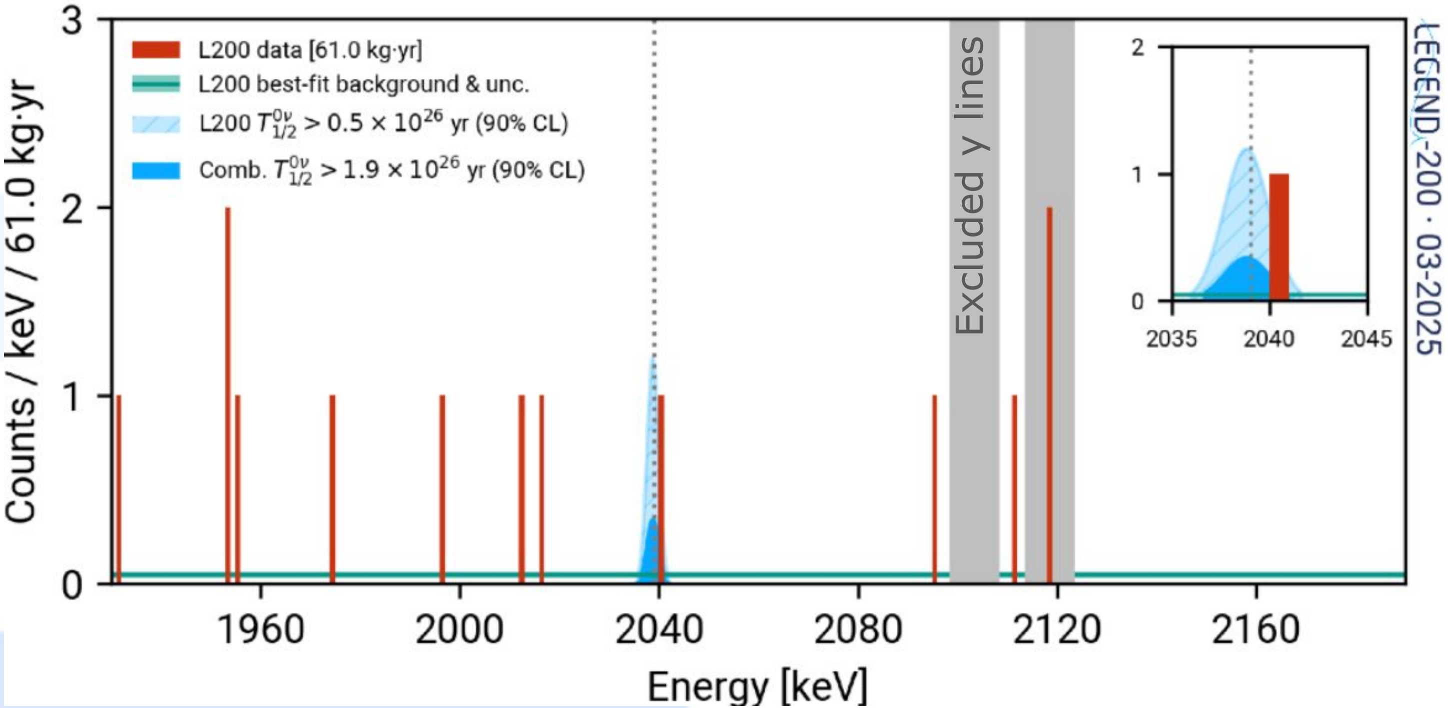




- [1930, 2190] keV analysis window
- Excluded γ-lines:
  - ^{208}Tl (2104 ± 5) keV
  - ^{214}Bi (2119 ± 5) keV

- ~ 93% LAr cut acceptance
- Strong anti-correlation of LAr and PSD cuts
- Mostly pure $2\nu\beta\beta$ distribution

Unblinding the $Q_{\beta\beta}$ window



- 11 events
- 1 event ~1.4σ from $Q_{\beta\beta}$

BI_{gold} [48 kg·yr]: $5.4^{+2.7}_{-2.0} \times 10^{-4}$ cts/(keV·kg·yr)

BI_{silver} [13 kg·yr]*: $13^{+8.0}_{-5.4} \times 10^{-4}$ cts/(keV·kg·yr)

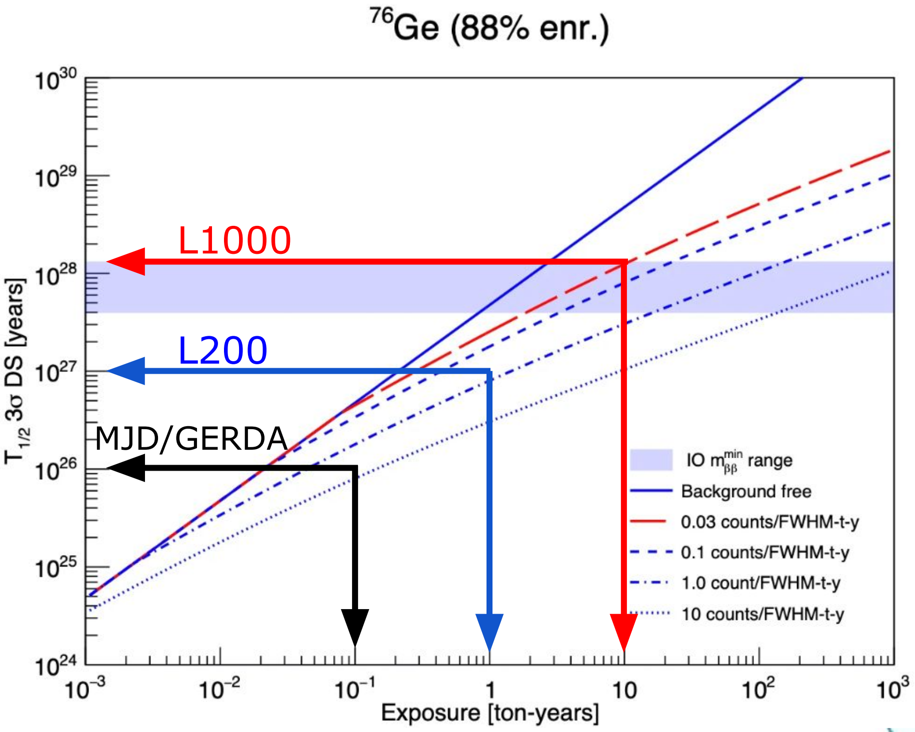
*primarily coaxial detectors with seemingly worse bkg rejection

Interpreting the results

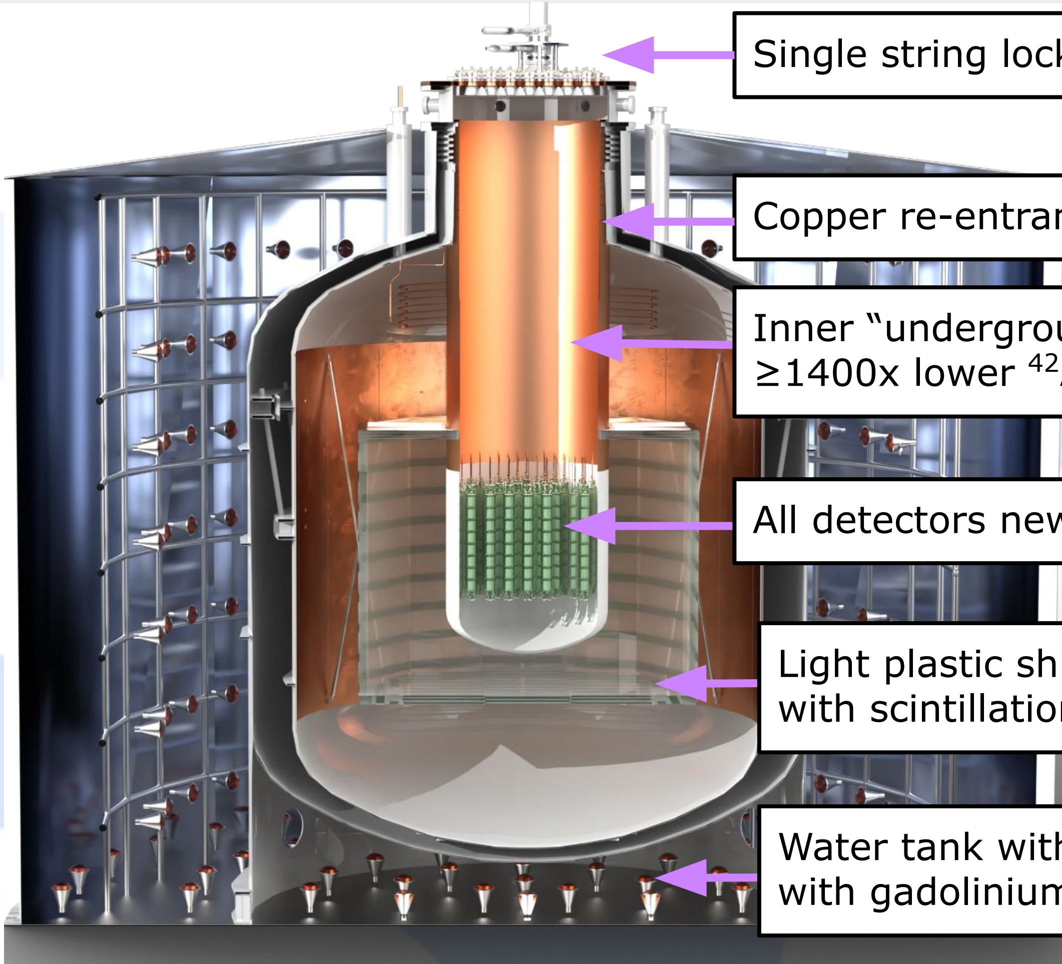
- Combined data from MJD, GERDA, and LEGEND-200 for analysis
- Both Bayesian and frequentist analysis give no evidence of 0νββ
- $T_{1/2}$ lower limit (90% confidence level): **$T_{1/2} > 1.9 \times 10^{26}$ yr**
- Median sensitivity (90% confidence level): **$T_{1/2} > 2.8 \times 10^{26}$ yr**
- World-leading limits on 0νββ
  - Limit weakened by background event 1.4σ from $Q_{\beta\beta}$ peak
- Background index (BI) higher than anticipated
  - Data taking was stopped and internal components were assayed/cleaned

The next phase: LEGEND-1000

- 1 tonne of enr HPGes
- 10 tonne years of exposure
- BI target: 1 x 10^{-5}
- Sensitive up to $T_{1/2}(0\nu\beta\beta) \geq 10^{28}$ yrs
- Covers entire parameter space for neutrinos for inverted ordering mass hierarchy



LEGEND-1000 baseline design/improvements from L200



Single string lock useful for easier opening/closing

Copper re-entrance tube separates LAr into two volumes

Inner “underground argon”
≥1400x lower ^{42}Ar concentration

Inverted **C**oaxial

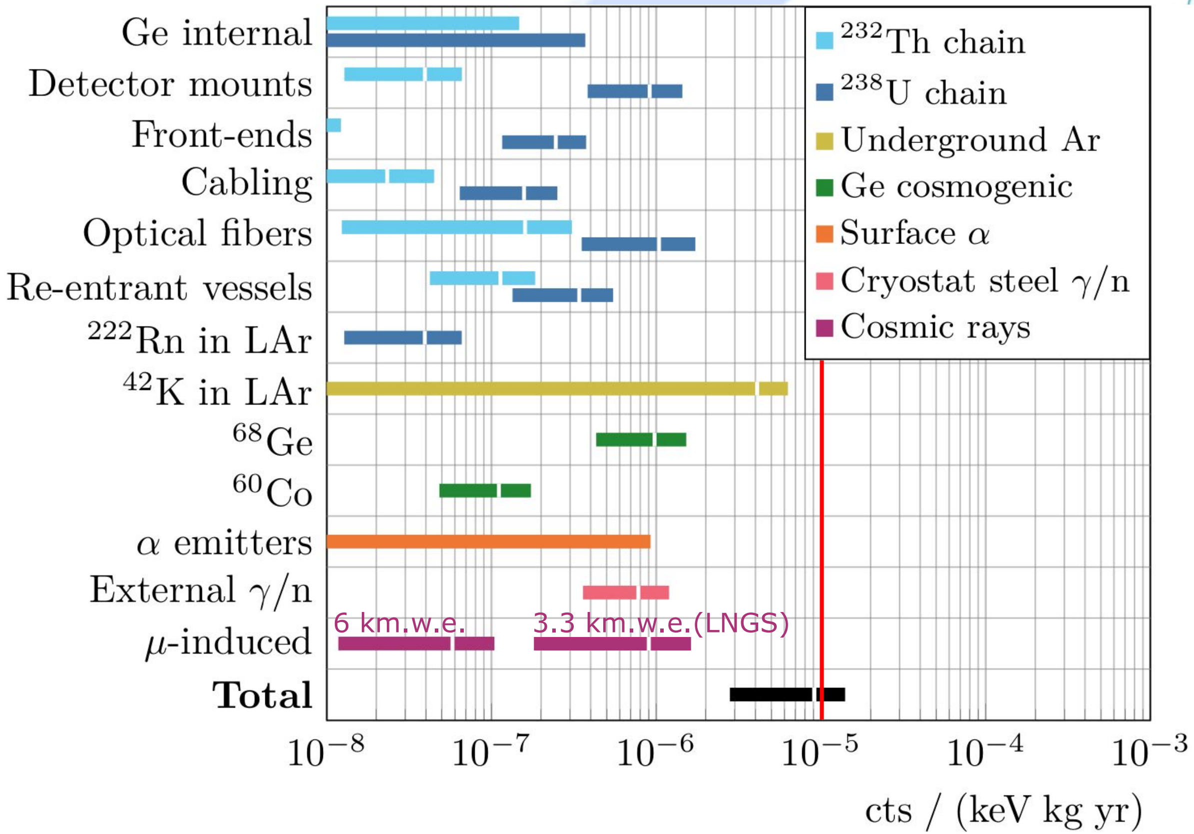
All detectors new for LEGEND, with novel IC design

Light plastic shield to moderate neutrons, instrumented with scintillation detectors to identify neutron captures

Water tank with higher density of PMTs, doped with gadolinium to identify neutron captures

The LEGEND-1000 preliminary background model

- ^{42}K, a beta emitter produced by decay of ^{42}Ar, is now a key background to reduce
- μ-induced background significant for LEGEND-1000 at LNGS, requires new instru-mentation and analysis

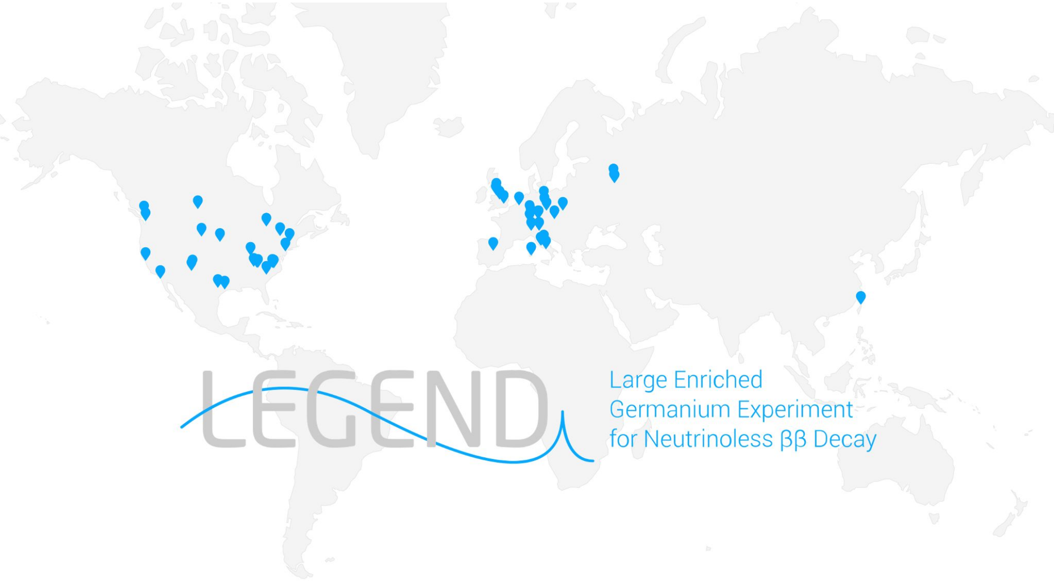


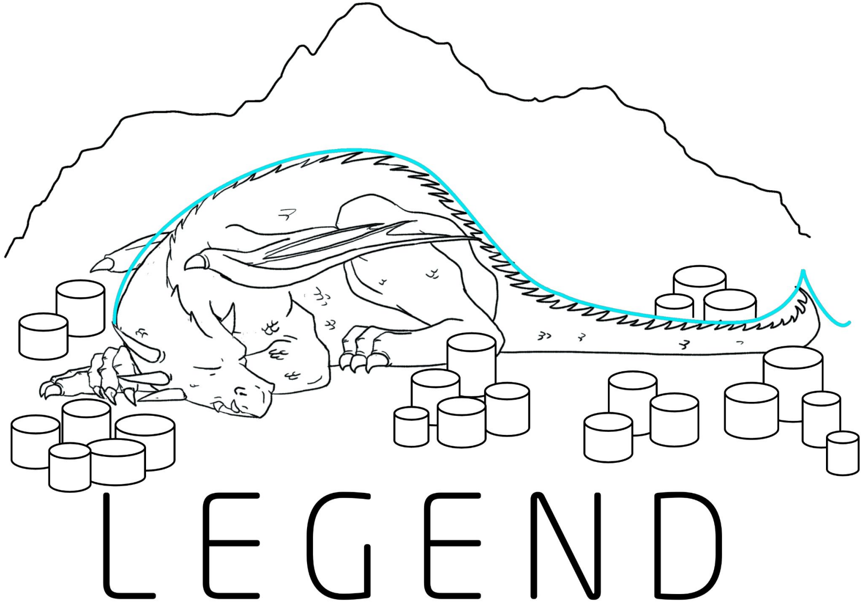
Conclusion

- LEGEND is a 15+ year campaign to search for 0νββ with half-life sensitivity up to 10^{28} years
- LEGEND-200 preprinted its first unblinded dataset May 19th 2025
- LEGEND-200 currently taking data, aims to stop soon to insert ~30 kg more Ge detectors
- LEGEND-1000 in active R&D, Conceptual Design Report should be released some time this year

Check out the preprint arXiv:2505.10440
"First Results on the Search for Lepton Number Violating Neutrinoless Double Beta Decay with the LEGEND-200 Experiment"

Thanks for listening!





Centre for Energy, Environmental and Technological Research, Comenius University, Daresbury, Duke University, Experimental Astroparticle Physics (E15), Technical University - Munich, Frascati, Gran Sasso Science Institute, IEAP Czech Technical University in Prague, Indiana University, Institute of Nuclear Research, Russian Academy of Sciences, Istituto Nazionale di Fisica Nucleare - Milano Bicocca, Istituto Nazionale di Fisica Nucleare - Padova, Istituto Nazionale di Fisica Nucleare - Sezione di Napoli, Jagiellonian University, Krakow, Joint Institute for Nuclear Research (Dubna), Joint Research Centre, Geel, L'Aquila University and INFN, Laboratori National di Frascati (LNF), Laboratori Nazionali del Gran Sasso (LNGS), Laboratory for Experimental Nuclear Physics of MEPhI (Moscow Engineering and Physics Institute), Lancaster University, Laurentian. Lawrence Berkeley National Laboratory, Leibniz Institute for Crystal Growth (IKZ Berlin), Leibniz-Institute of Polymer Research Dresden e.V., Los Alamos National Laboratory, Max-Planck-Institute for Nuclear Physics, Heidelberg, Particle Physics and High-Energy Astrophysics, Max-Planck-Institute for Physics, Munich, Development of Ge Detectors, Milano University and Milano INFN, National Research Center Kurchatov Institute (NRC KI), National Taiwan University (NTU), North Carolina State University, Oak Ridge National Laboratory, Padova University and Padova INFN, Politecnico di Milano, Princeton University, Queens University, Roma Tre University and INFN Roma Tre, SNOLAB, Simon Fraser University, South Dakota Mines, Technical University Dresden, Tennessee Tech University, Triangle Universities Nuclear Laboratory, University College London, University of Cagliari and INFN Cagliari, University of California, San Diego, University of Houston, University of Liverpool, University of New Mexico, University of North Carolina, Chapel Hill, University of Regina, University of South Carolina, University of South Dakota, University of Tennessee, University of Texas at Austin, University of Tuebingen, University of Warwick, University of Washington, University of Zurich

Special thanks to the National Mustard Museum in Middleton, WI!

(they didn’t support this talk in any way, but I had a lot of fun there)

LEGEND

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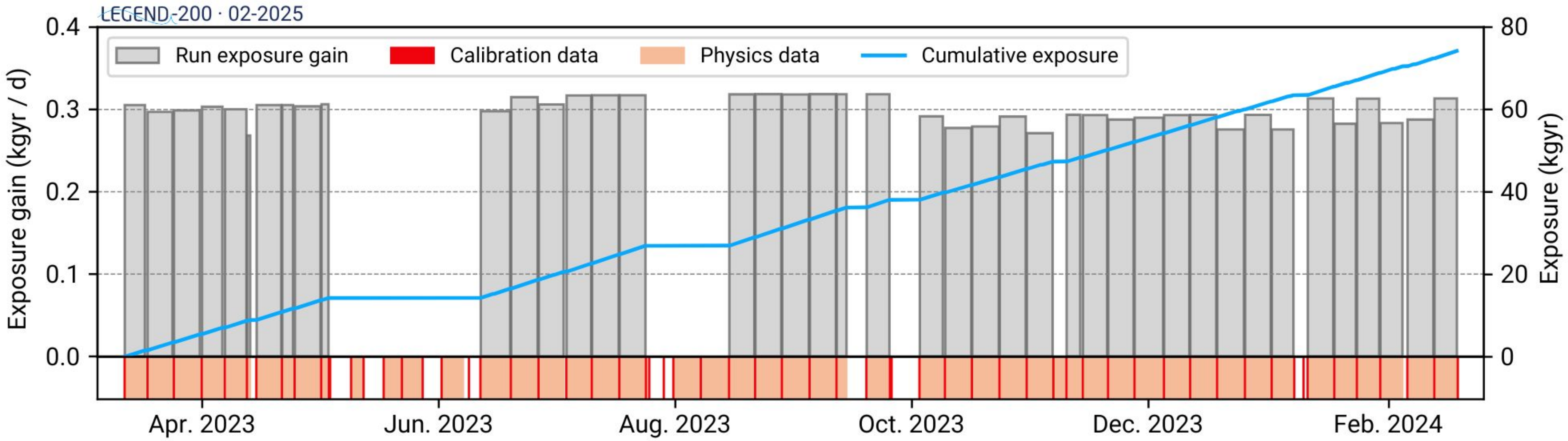
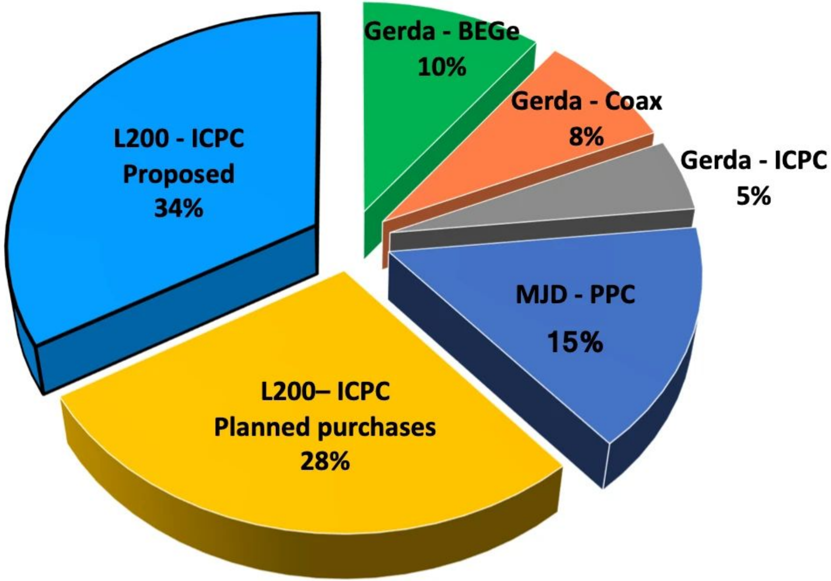
Backups

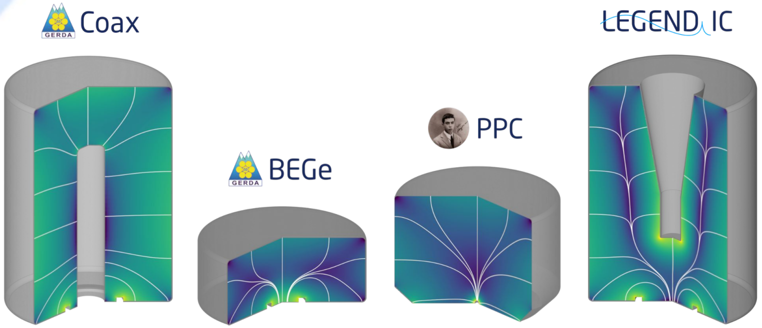
L200 data taking and uptime



L200 detectors by type

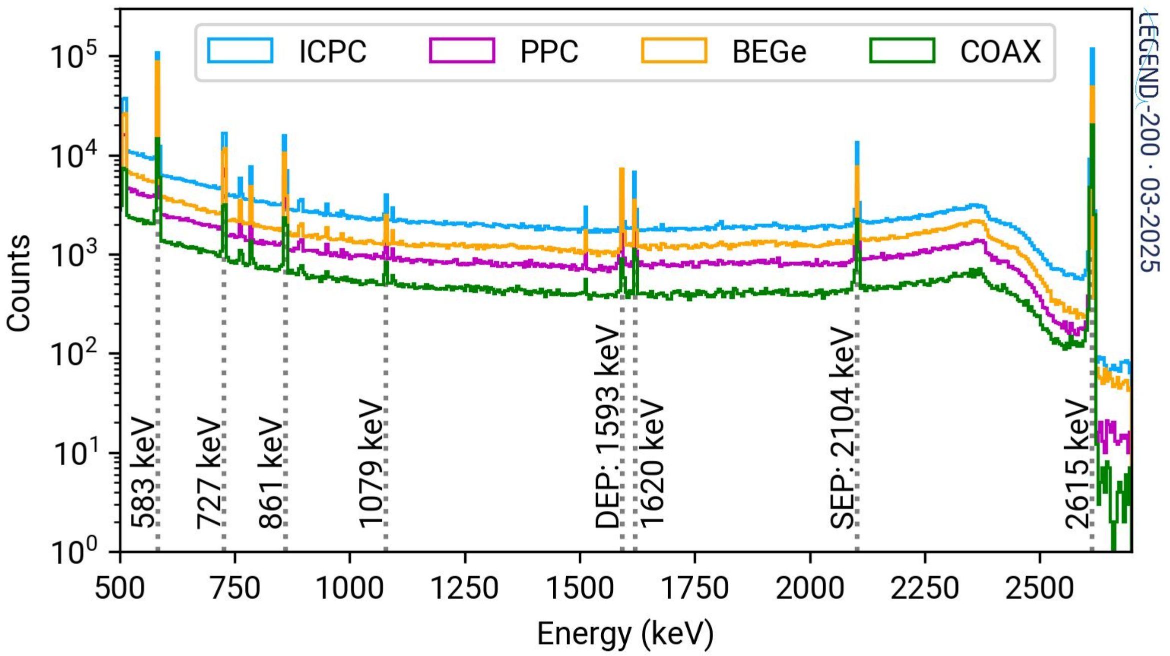
- L200 combines detectors used in MJD/GERDA with new detectors fabricated for use in LEGEND
- L1000 will use all new detectors of the “ICPC” (inverted coaxial point contact) design





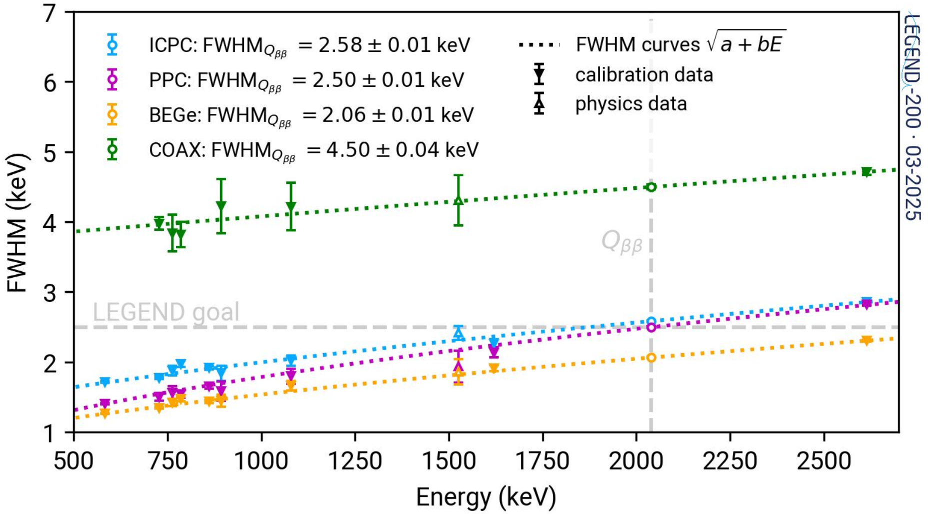
Calibrations using ^{228}Th decay chain

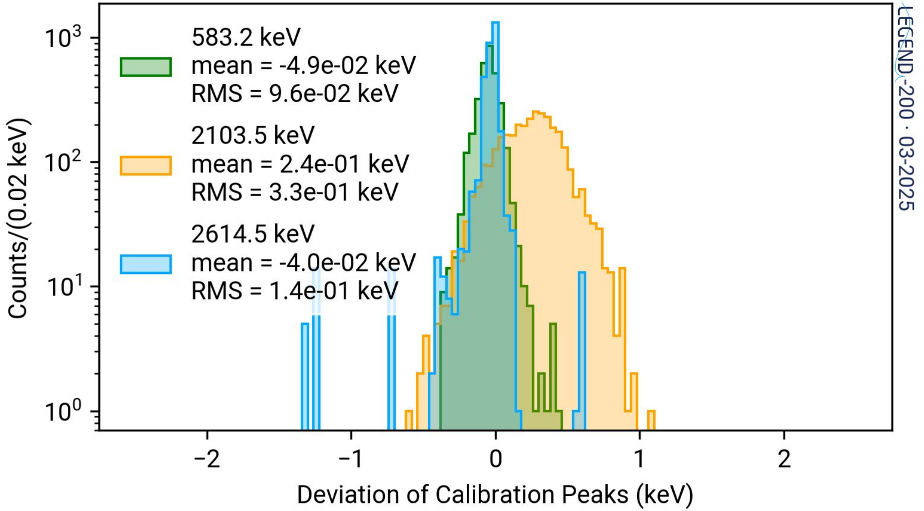
- Weekly short calibrations and long calibrations between physics runs
- Converts electronic readout to energy measurement
- Evaluates detector performance and stability over time



Energy resolution ΔE

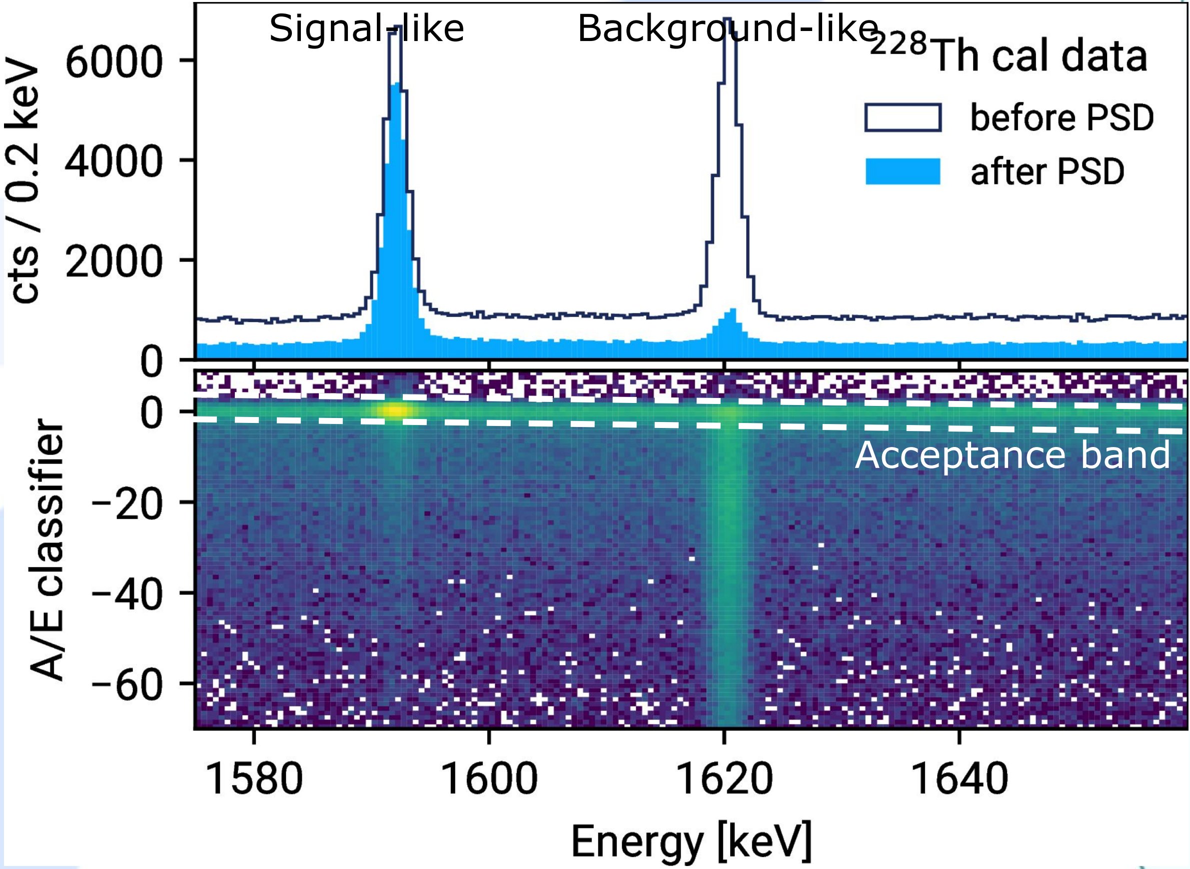
- Good ΔE is essential for LEGEND - shrinks analysis window, which shuts out background
- Attainable ΔE depends on detector type and operational condition
- Calibrations are used to determine ΔE at various energies





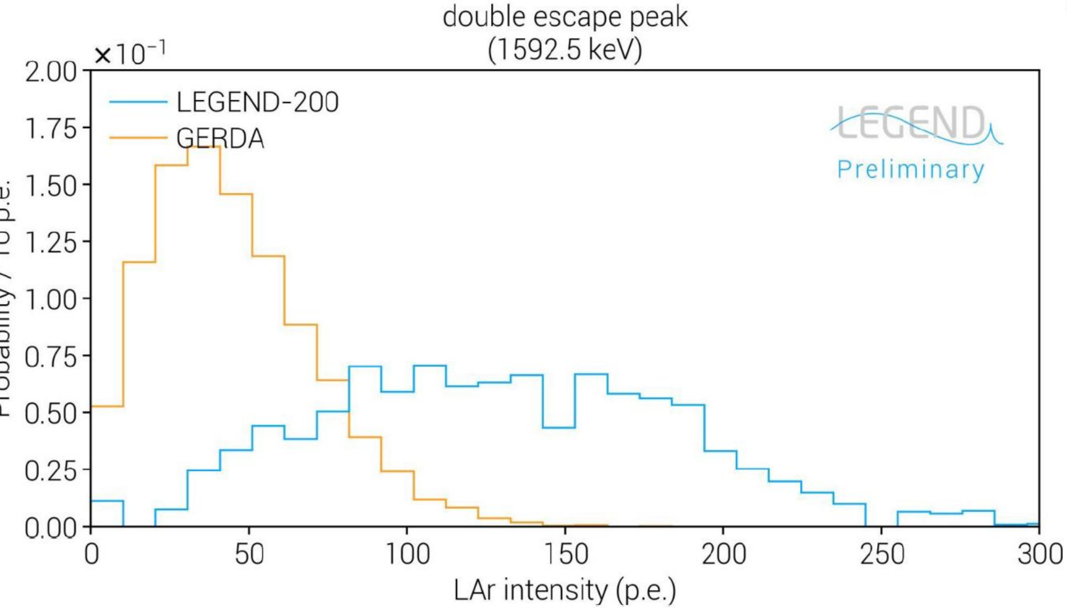
PSD performance and acceptance

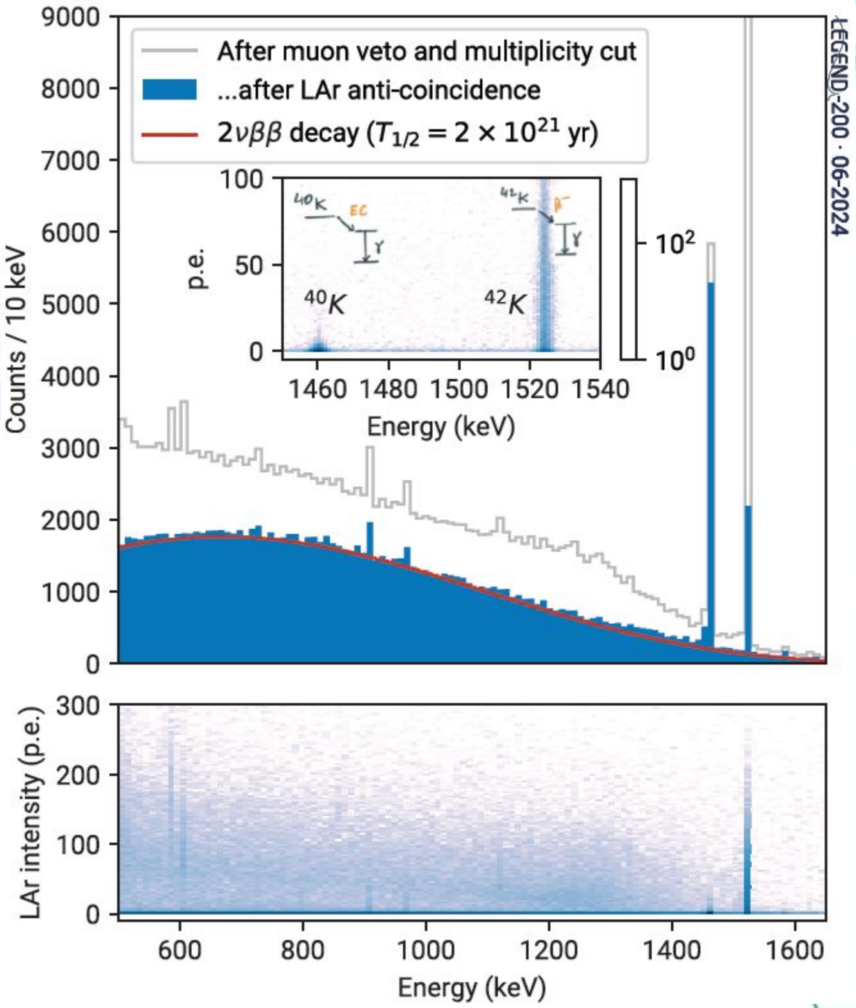
- “Signal-like” and “background-like” calibration energy peaks are used to determine efficiency of A/E cut as well as acceptance of signal-like events



LAr scintillation detectors

- L200 light collection significantly improved over GERDA, and will improve further for L1000





Facts about LEGEND

- 60 institutions
- >250 members
- Officially established in 2017
- NSF Major Research Equipment and Facility Construction (MREFC) Project