GERDA AND LEGEND

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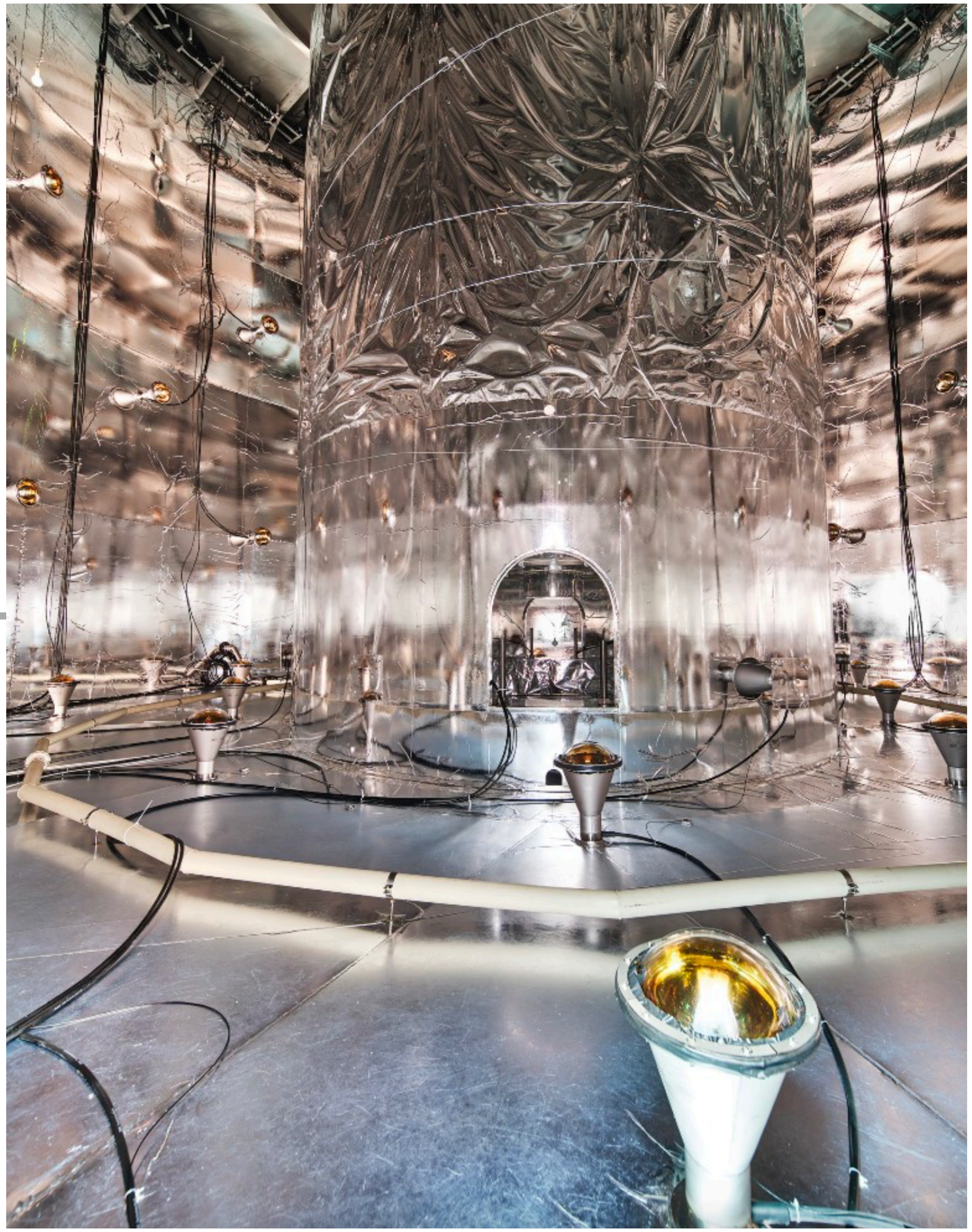
UNIVERSITY OF ZURICH

CHIPP ROADMAP WORKSHOP

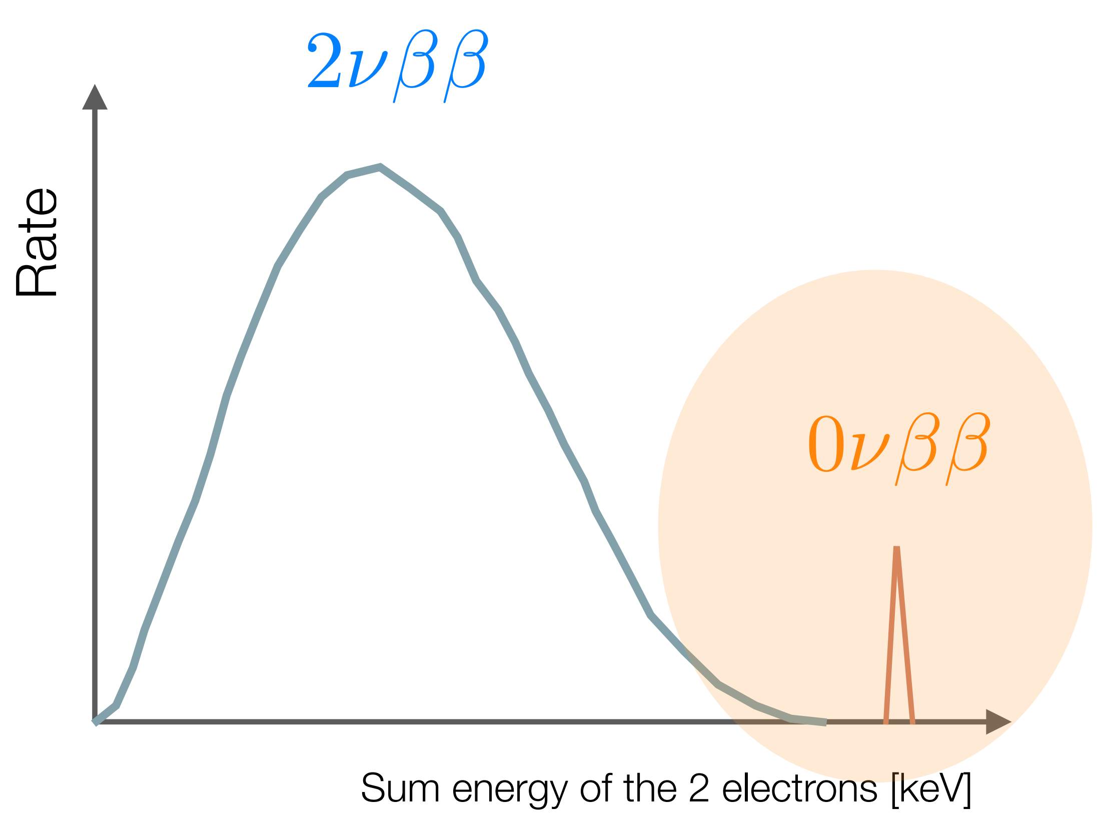
BALSTHAL, JANUARY 18-19, 2024



MAIN AIM OF THE LEGEND EXPERIMENT

- Determine the fundamental nature of neutrinos - Majorana versus Dirac fermions
- Search for the $0\nu\beta\beta$-decay of ^{76}Ge: observe the two final-state electrons (expect sharp peaks at Q-value of the decay)
- Essential for a discovery: ultra-low background level & excellent energy resolution & high efficiency to observe the two electrons (as demonstrated in GERDA and MAJORANA)

$$^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^- \qquad \Delta L = 2$$

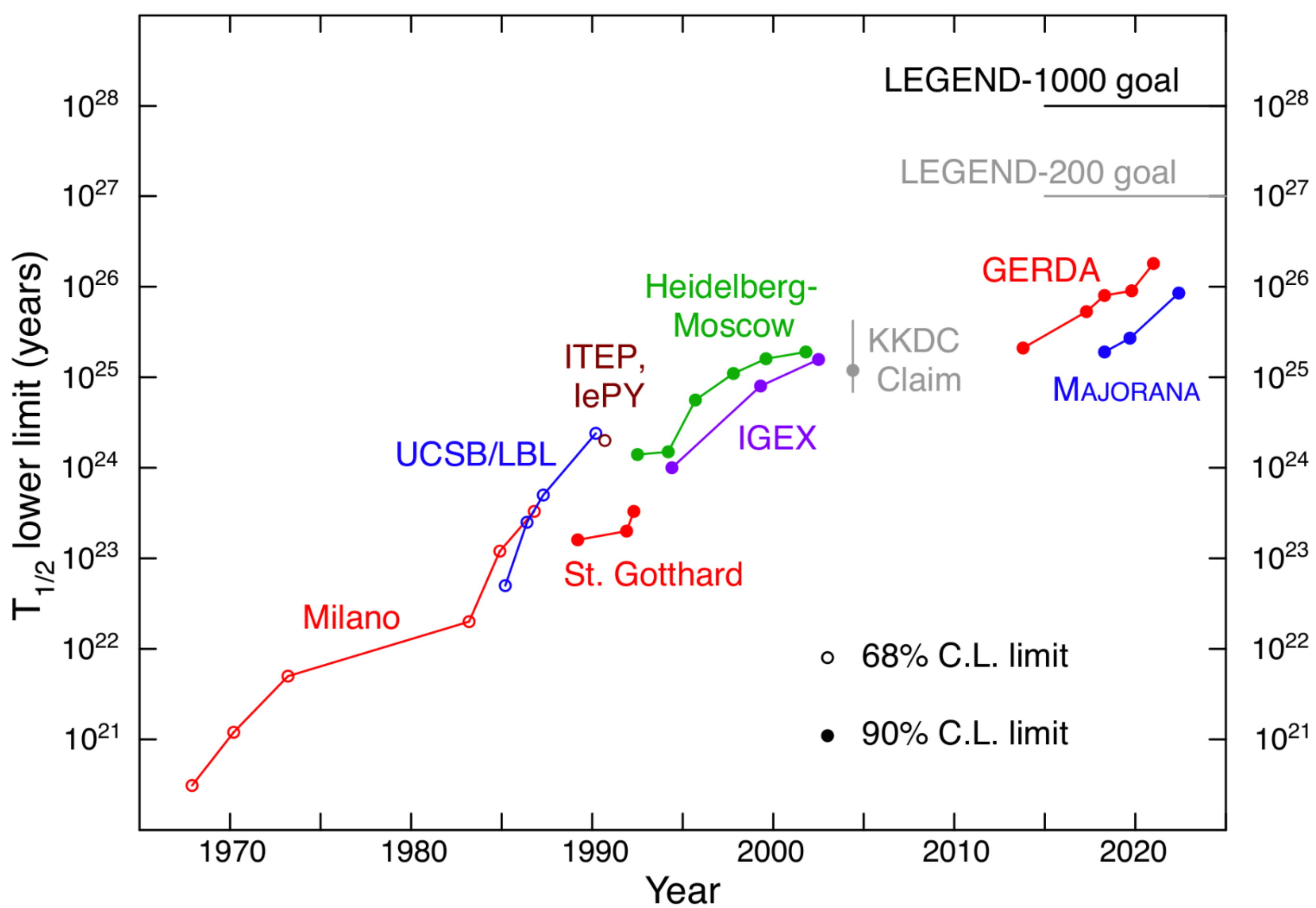


$$\Gamma^{0\nu} = \frac{\ln 2}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

$$Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e = 2039\,\mathrm{keV}$$

WHY A 76-GE EXPERIMENT?

- High Q-value, high efficiency, highly radio-pure
- ^{76}Ge enrichment to > 90% possible
- Excellent energy resolution (0.1% FWHM), event topology



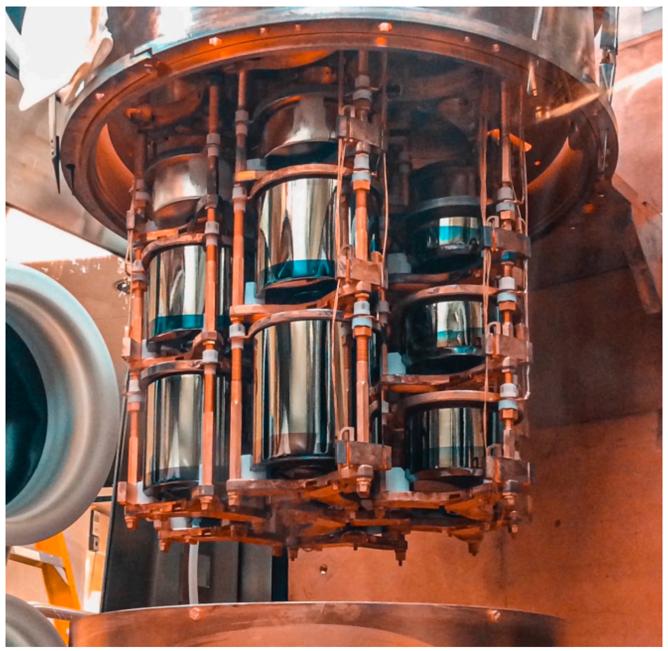
Half-life Efficiency Exposure

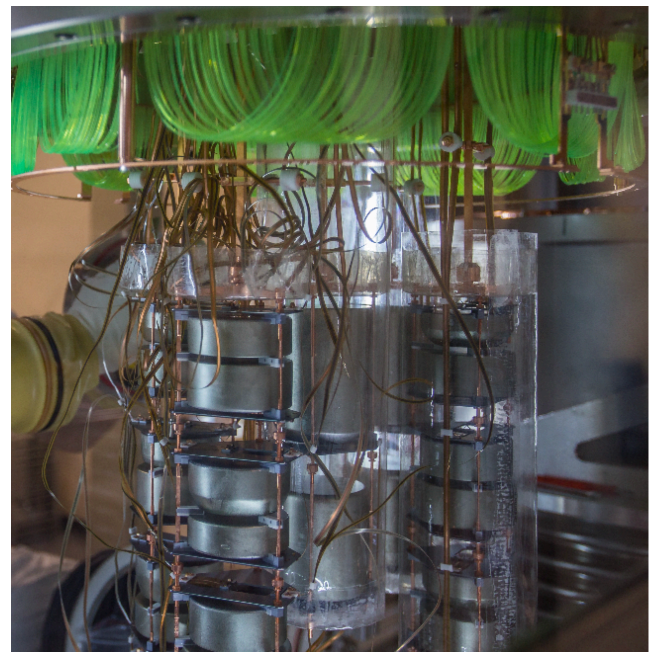
$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Enrichment Energy resolution

Background rate

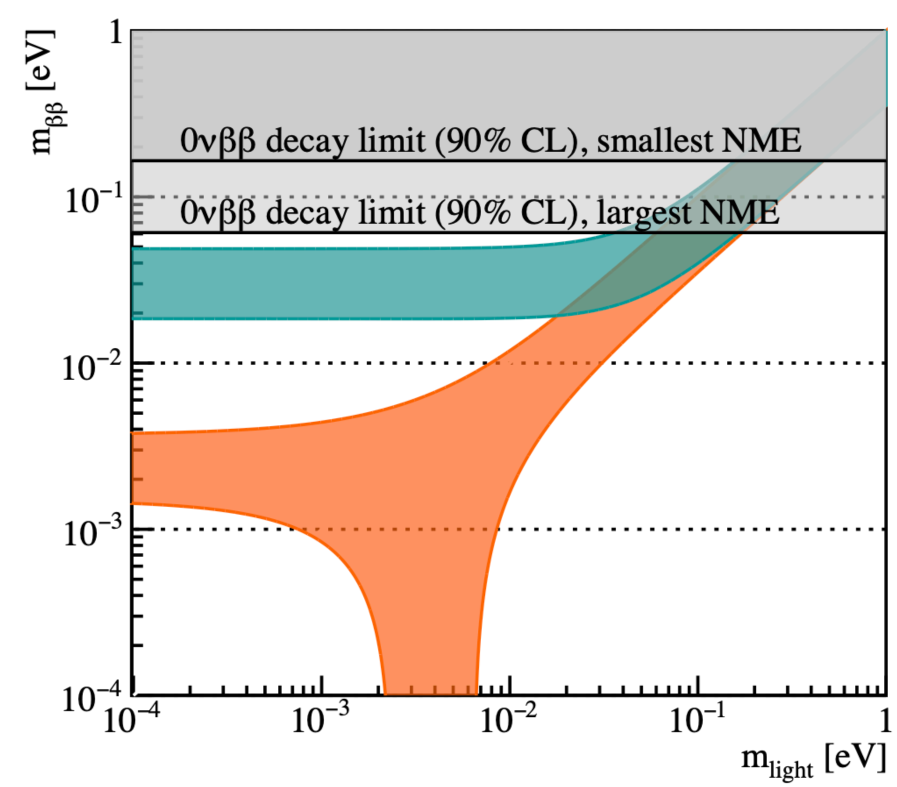
FINAL RESULTS FROM PREVIOUS GERMANIUM EXPERIMENTS





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

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



MAJORANA at SURF

27.2 kg of 88% enriched ^{76}Ge crystals

2.5 keV FWHM at 2039 keV* (0.12%)

64.5 kg y exposure; PRL 2023

$T_{1/2}$ > 8 x 10^{25} y (90% CL)

GERDA at LNGS

35.6 kg of 86% enriched ^{76}Ge crystals in liquid argon

3.0 keV FWHM at 2039 keV*

127.2 kg y exposure: PRL 125, 2020

$T_{1/2}$ > 1.8 x 10^{26} y (90% CL)

*$Q_{\beta\beta}$ = 2039.061±0.007 keV

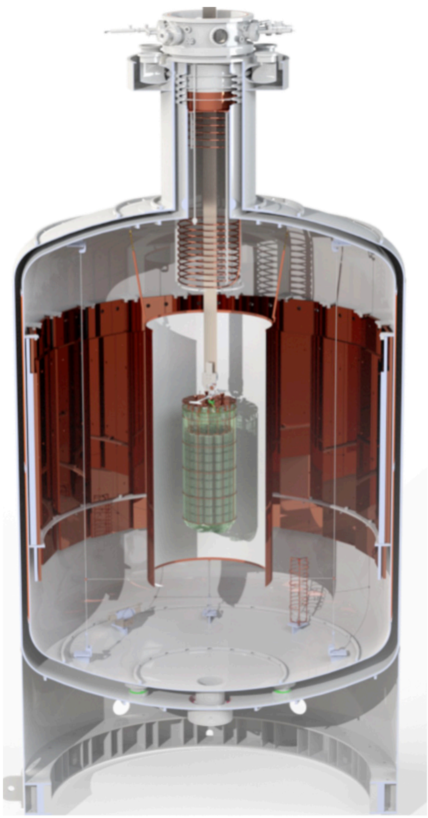
LEGEND: A TWO-PHASE APPROACH

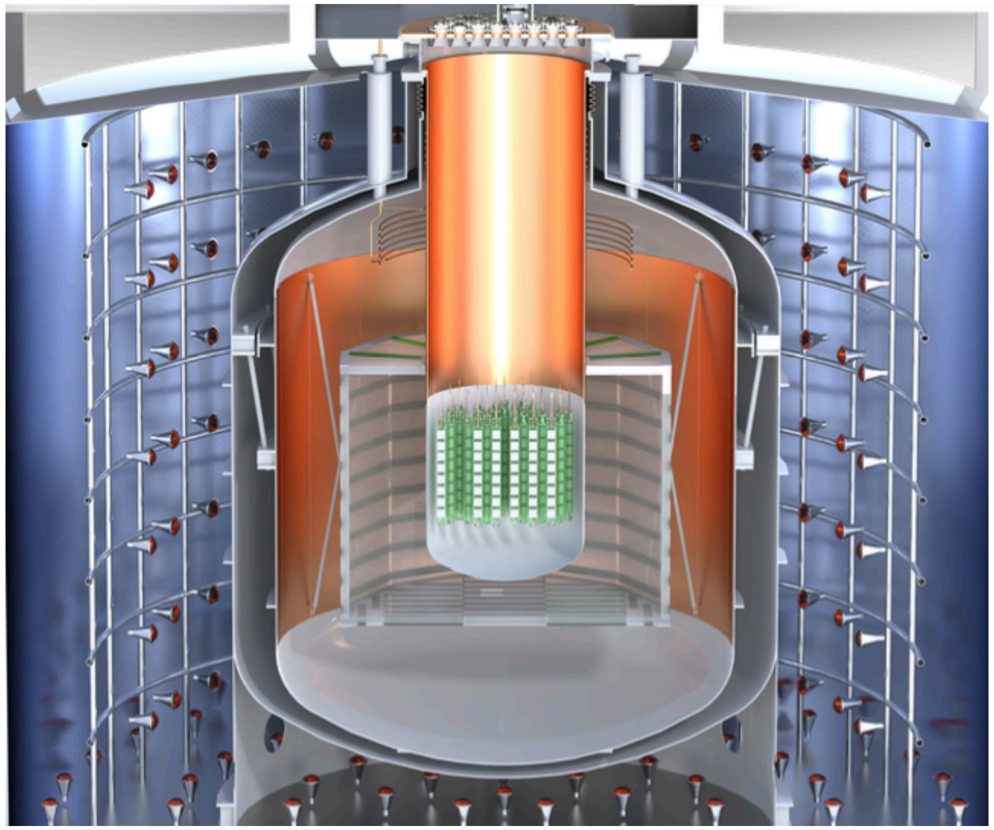
- LEGEND-200 (in upgraded GERDA infrastructure at LNGS, Hall A)
- LEGEND-1000, in Hall C of LNGS

LEGEND-200

Taking science data with 142 kg of HPGe detectors since early 2023

Background goal: 0.6 events/ (FWHM t y)





LEGEND-1000

CD1 review phase

First data ~ 2030

Background goal: 0.025 events/ (FWHM t y)

THE LEGEND COLLABORATION

270 scientists

55 institutions

11 countries

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

THE LEGEND-1000 EXPERIMENT

- Recommended in the APPEC Mid-Term Roadmap Update (2023) and in The 2023 Long Range Plan for Nuclear Science in the US

APPEC Roadmap Update

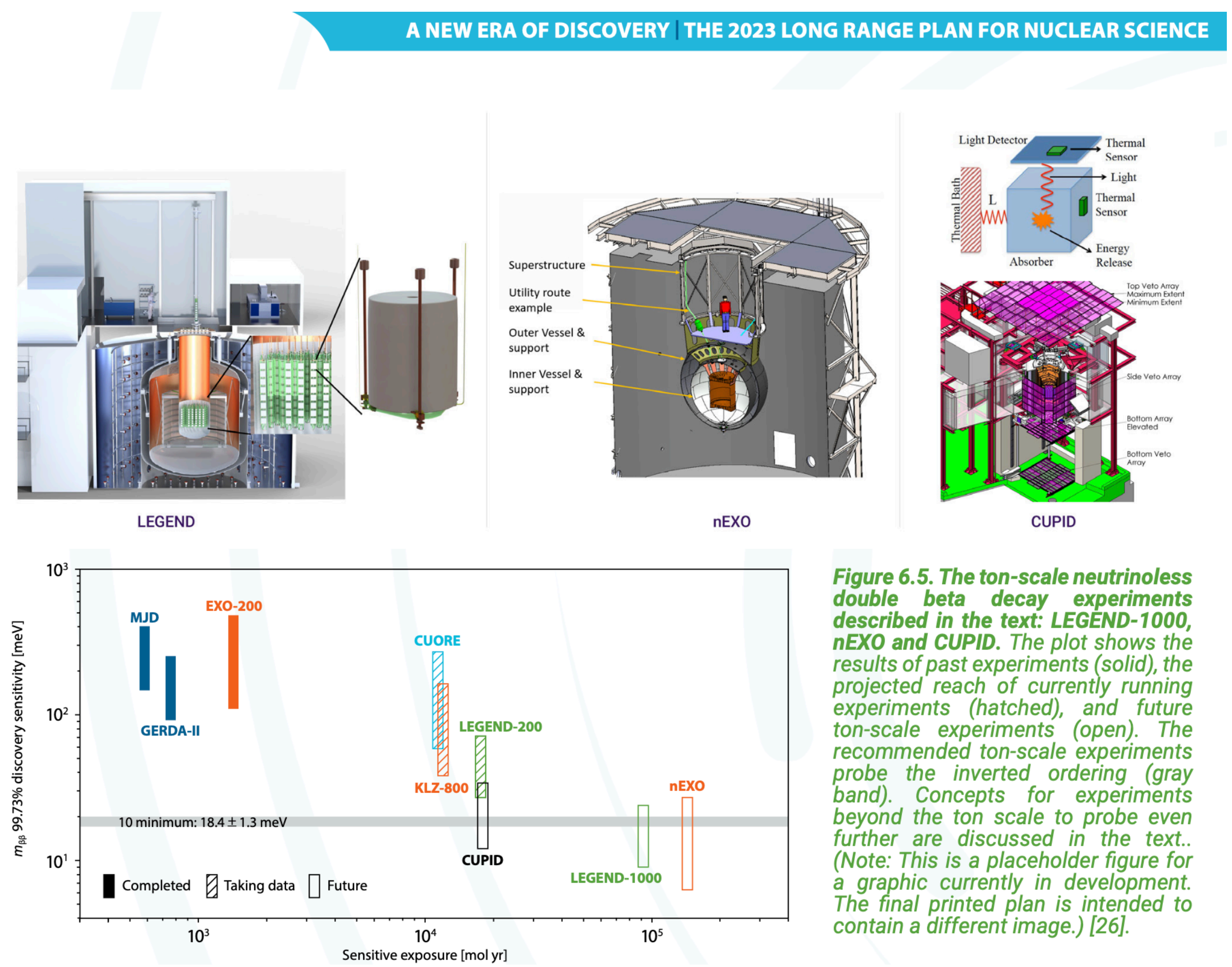
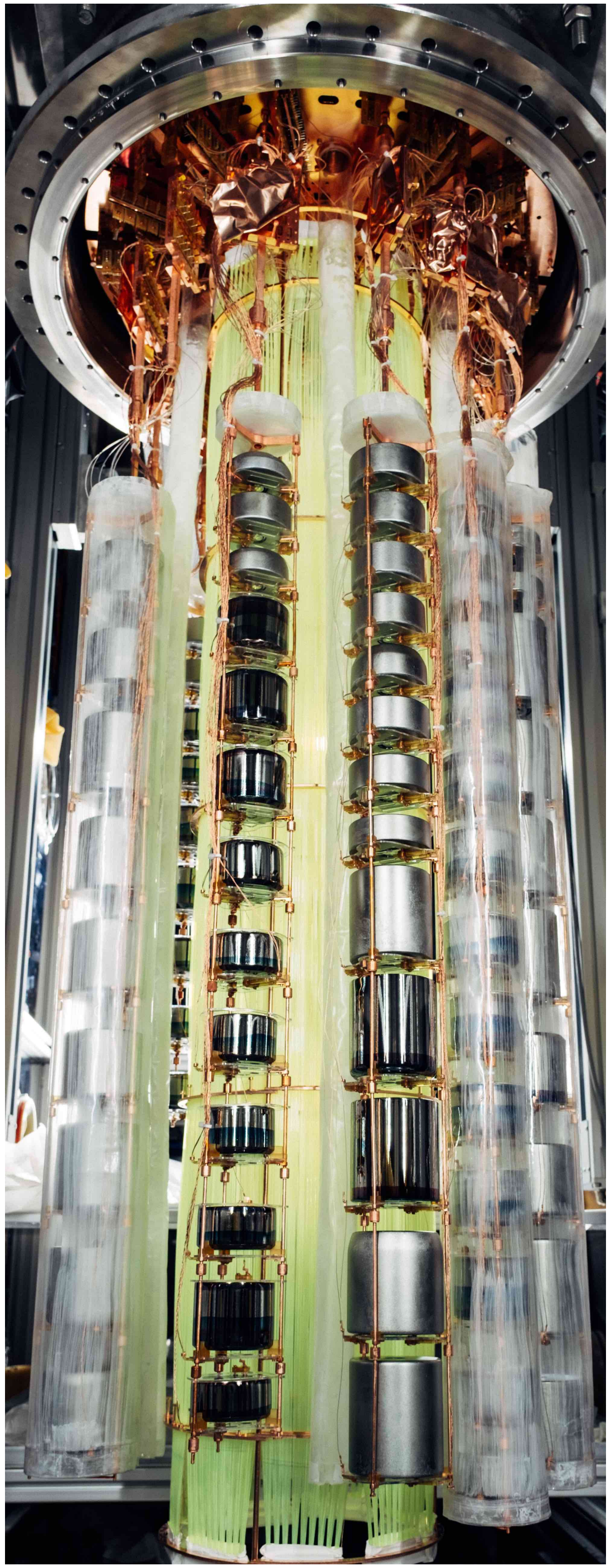


Figure 6.5. The ton-scale neutrinoless double beta decay experiments described in the text: LEGEND-1000, nEXO and CUPID. The plot shows the results of past experiments (solid), the projected reach of currently running experiments (hatched), and future ton-scale experiments (open). The recommended ton-scale experiments probe the inverted ordering (gray band). Concepts for experiments beyond the ton scale to probe even further are discussed in the text.. (Note: This is a placeholder figure for a graphic currently in development. The final printed plan is intended to contain a different image.) [26].

NS Long Range Plan

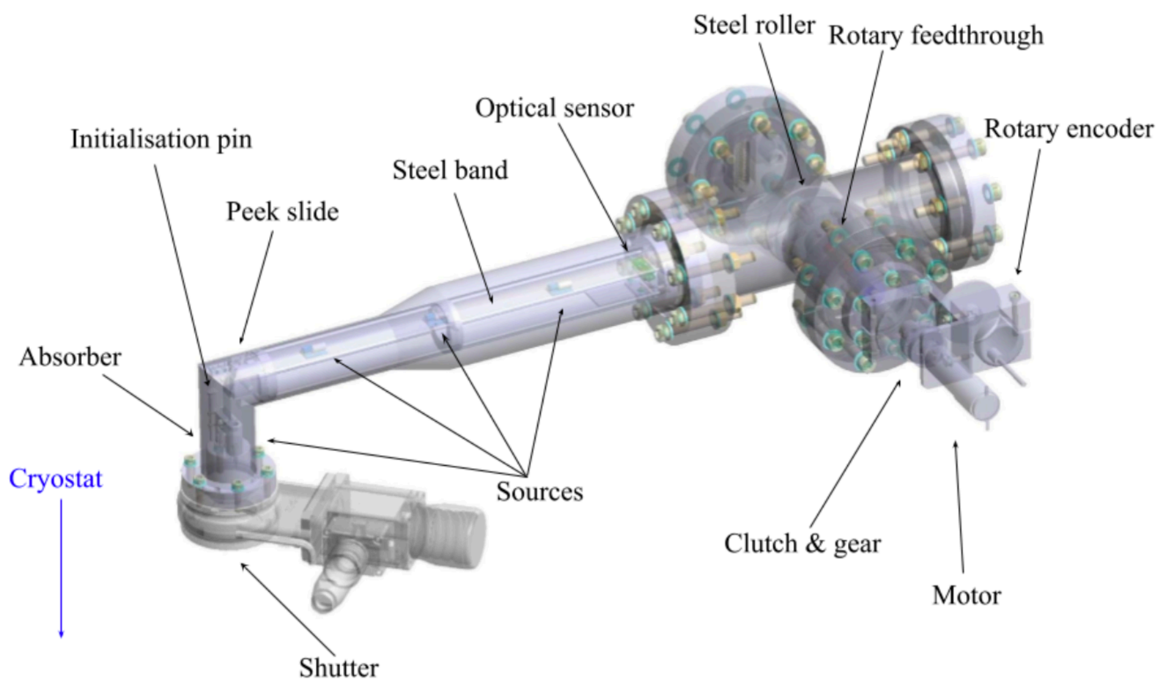
LEGEND-200 STATUS

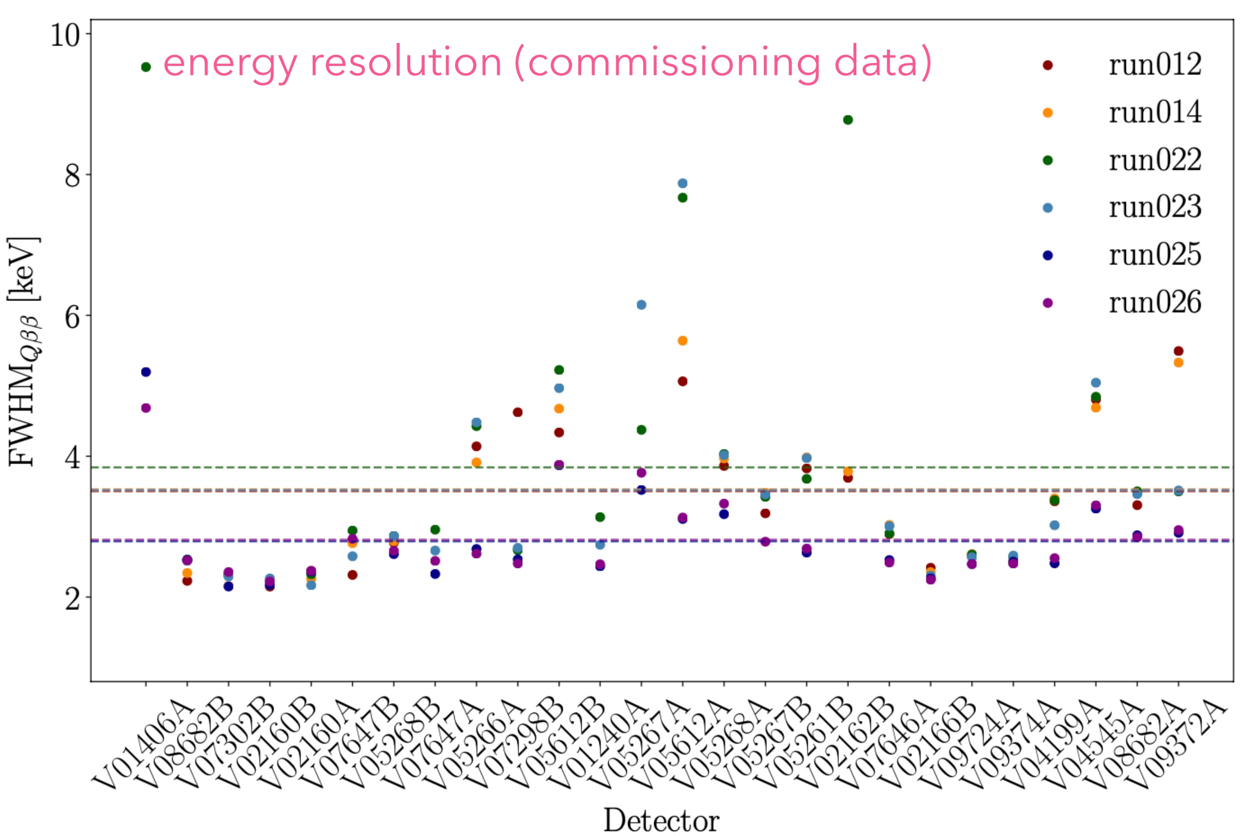
- Installed underground at LNGS
- Initial commissioning run with 60 kg payload (28 HPGe detectors) + liquid argon veto + muon veto
- Subsequent commissioning with 142 kg of Ge detectors, start of physics run in early 2023
- Goal: science run for one year, then install additional detectors for 200 kg total
- Overall goal: 5 years runtime
    - Discovery sensitivity $T_{1/2} > 10^{27}$ yr (99.7% CL)
    - $m_{\beta\beta} < 33 - 71$ meV

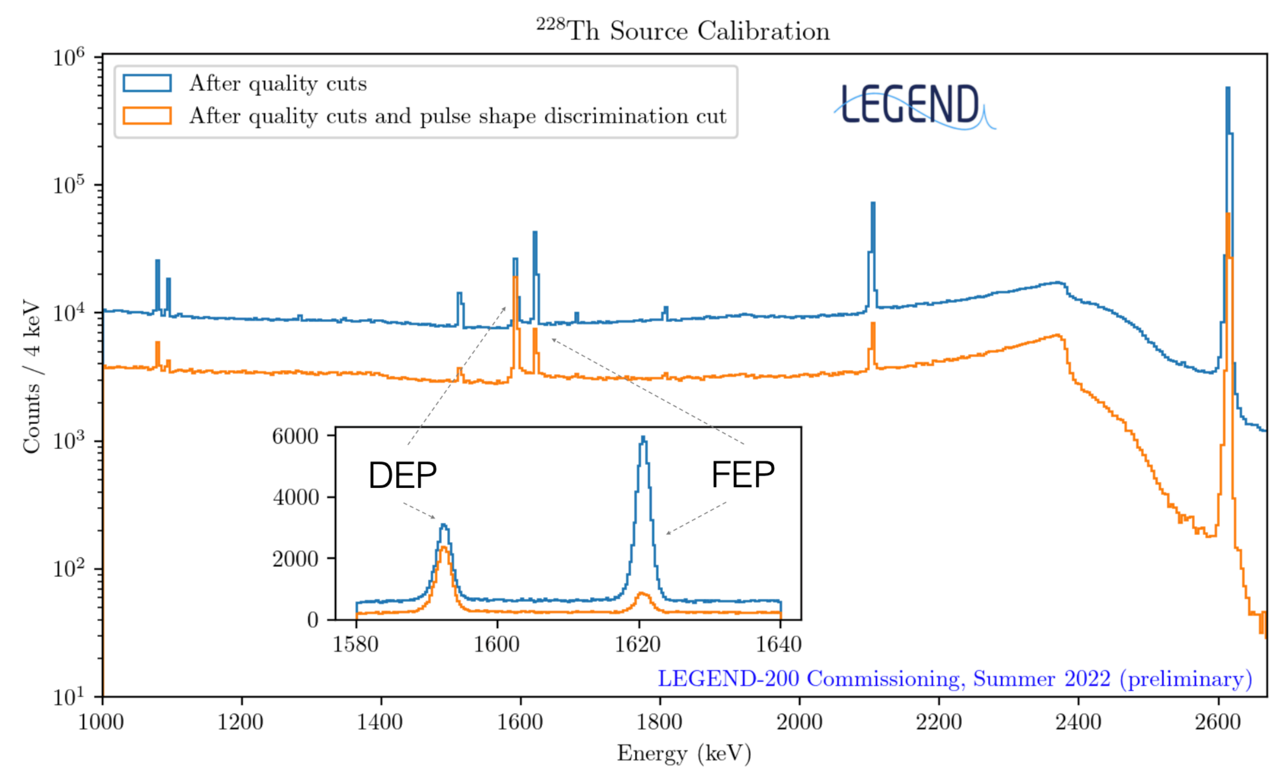


UZH CONTRIBUTIONS

- Four new source insertion systems, with four custom-made ^{228}Th sources/unit: weekly calibrations of the HPGe diodes
- Liquid argon instrumentation
- HPGe detector characterisation at HADES underground lab in Belgium

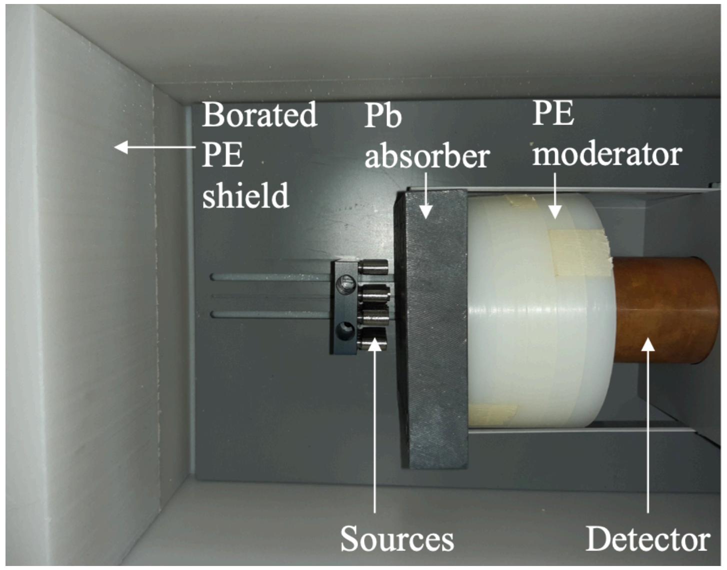




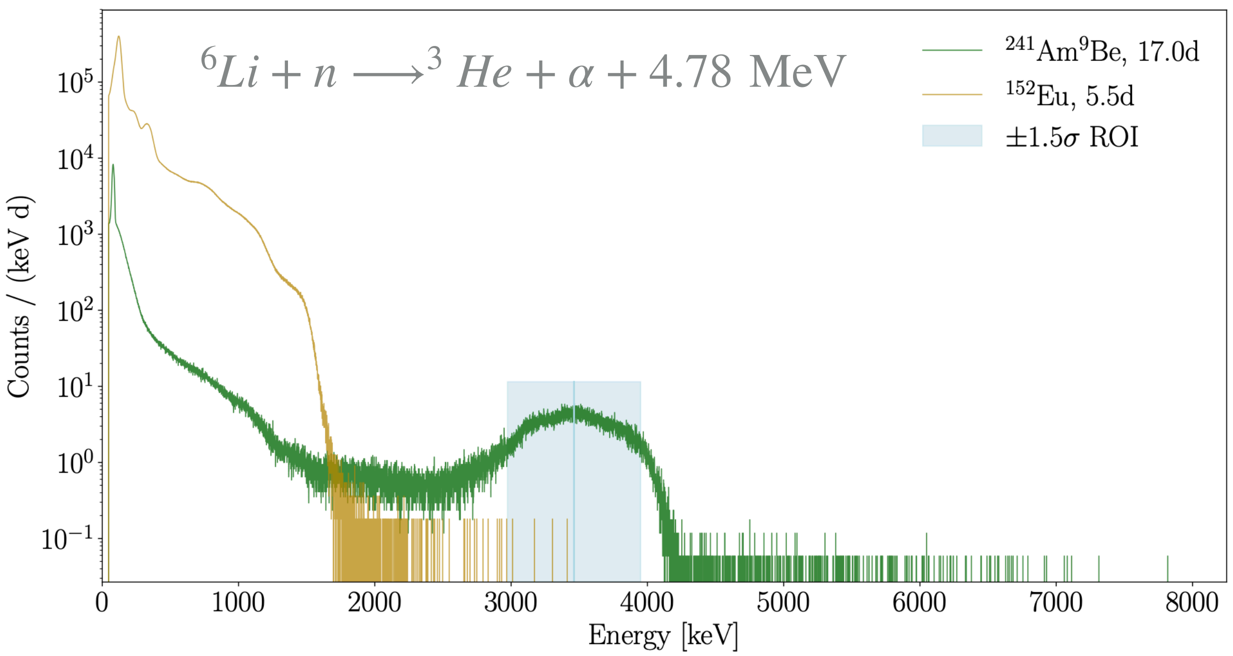


UZH CONTRIBUTIONS

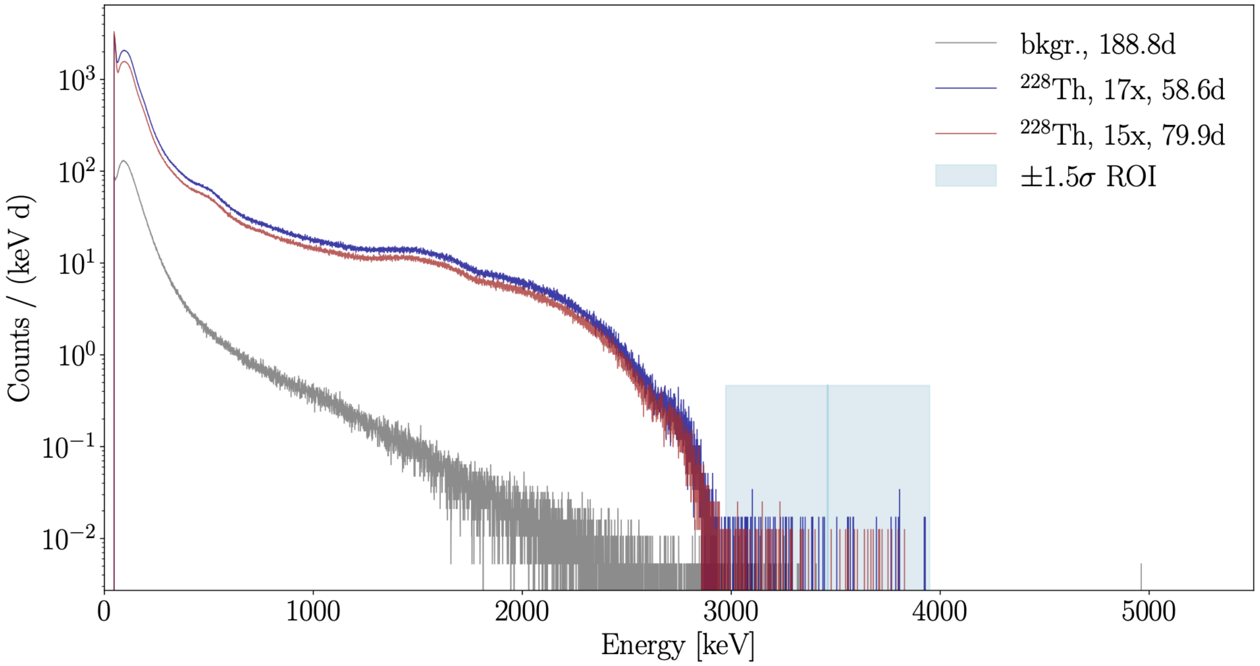
- Gamma and neutron rates of the new calibration sources with our HPGe and LiI(Eu)detectors at LNGS
- Liquid argon instrumentation
- HPGe detector characterisation at HADES underground lab in Belgium



Calibration of the LiI(Eu) detector



Spectra from the LEGEND-200 sources



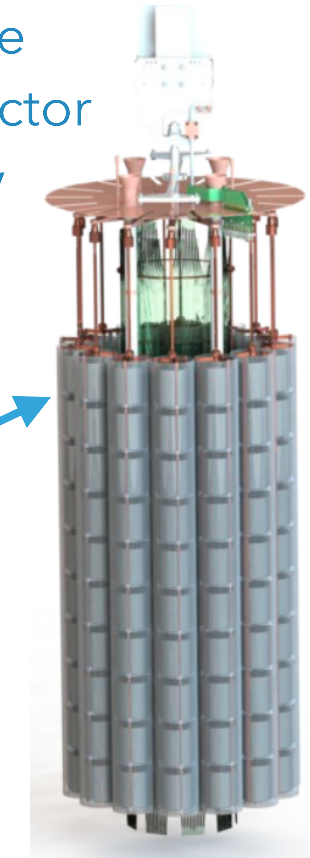
Calibration sources for the LEGEND-200 experiment, L. Baudis, G. Benato, E. M. Bond, P.-J. Chiu, S. R. Elliott, R. Massarczyk, S. Meijer, Y. Müller, arXiv:2211.05026 [physics.ins-det], accepted in JINST

$$\phi = (4.27 \pm 0.06_{\text{stat}} \pm 0.92_{\text{sys}}) \times 10^{-4} \text{n}/(\text{kBq} \cdot \text{s})$$

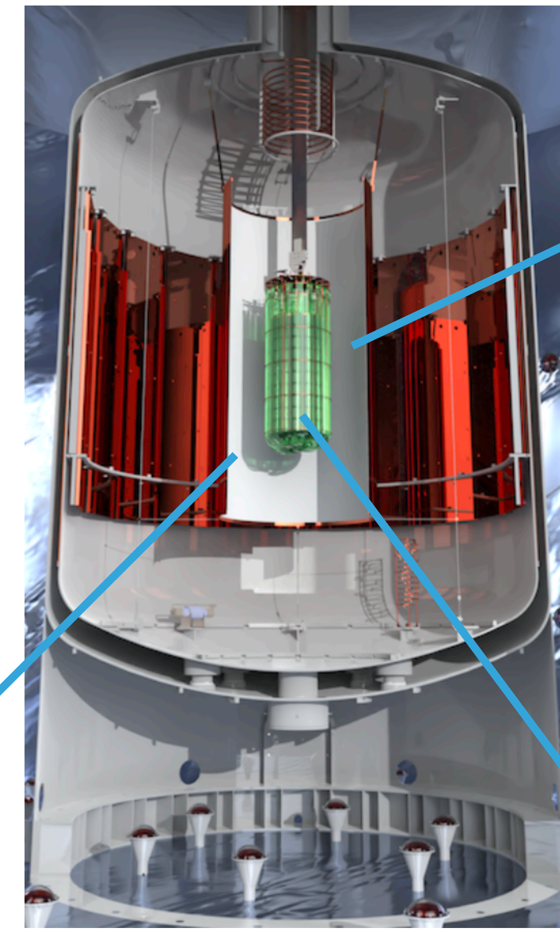
UZH CONTRIBUTIONS

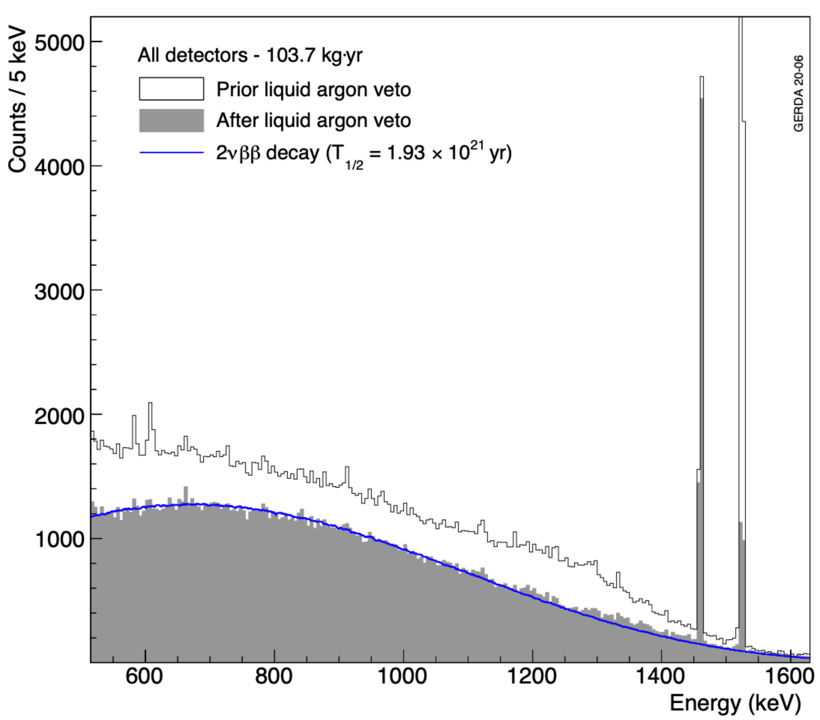
- Four new source insertion systems, with four custom-made ^{228}Th sources/unit: weekly calibrations of the HPGe diodes
- Liquid argon instrumentation
- HPGe detector characterisation at HADES underground lab in Belgium

HPGe detector array

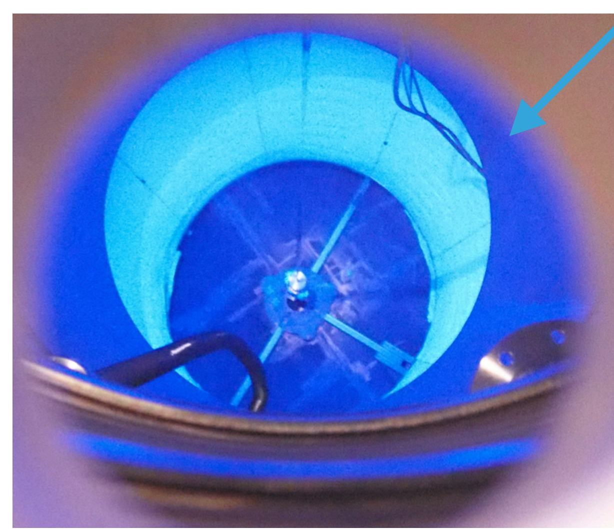


Cryostat filled with liquid argon

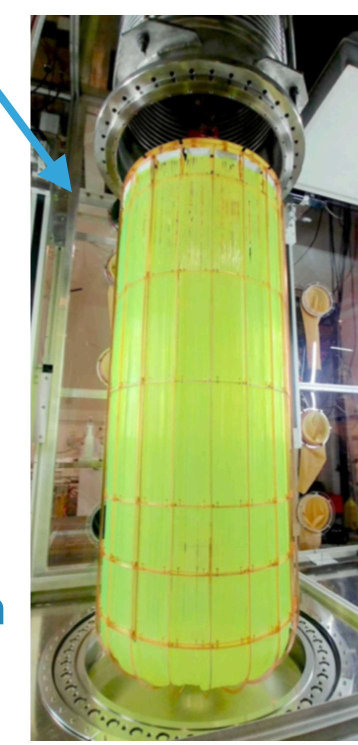




data from GERDA



WLSR coated in situ with TPB



Optical fibres (coated with TPB), coupled to SiPMs to detect the argon scintillation light

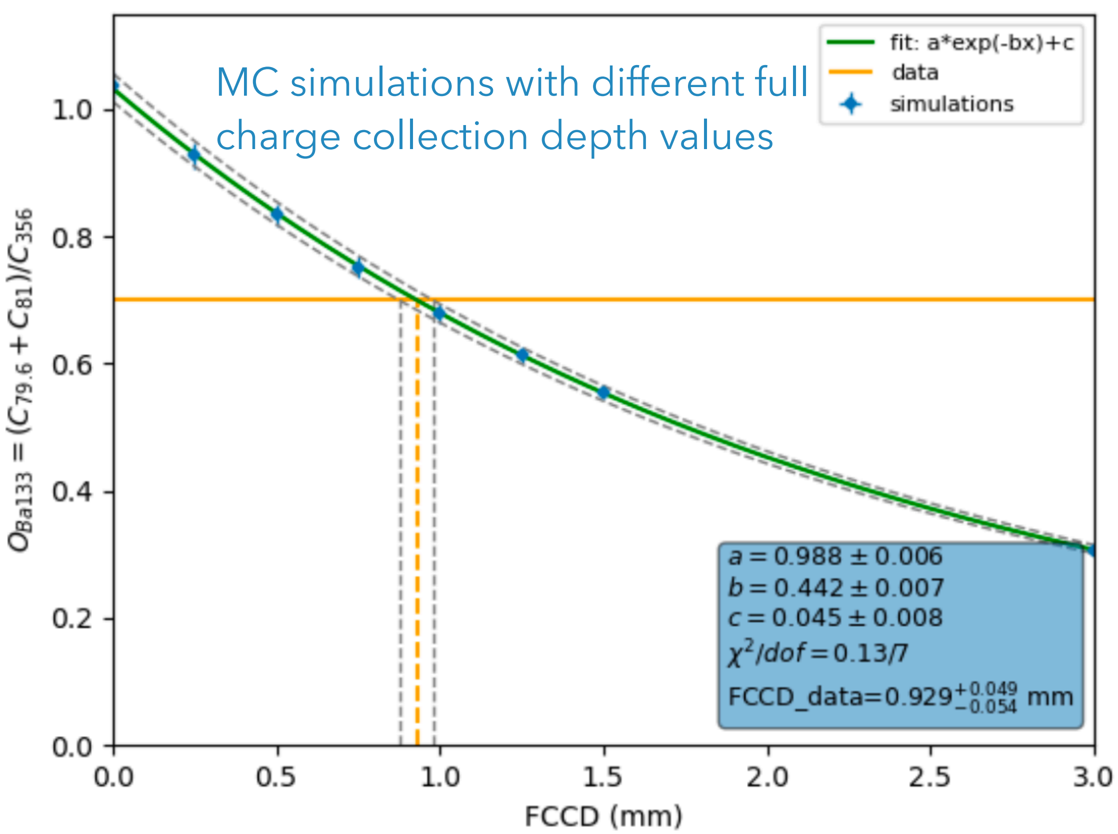
R&D published in: G.R. Araujo, L. Baudis, N. McFadden, P. Krause, S. Schönert, V. H. S. Wu, Eur.Phys.J.C 82 (2022) 5, 442

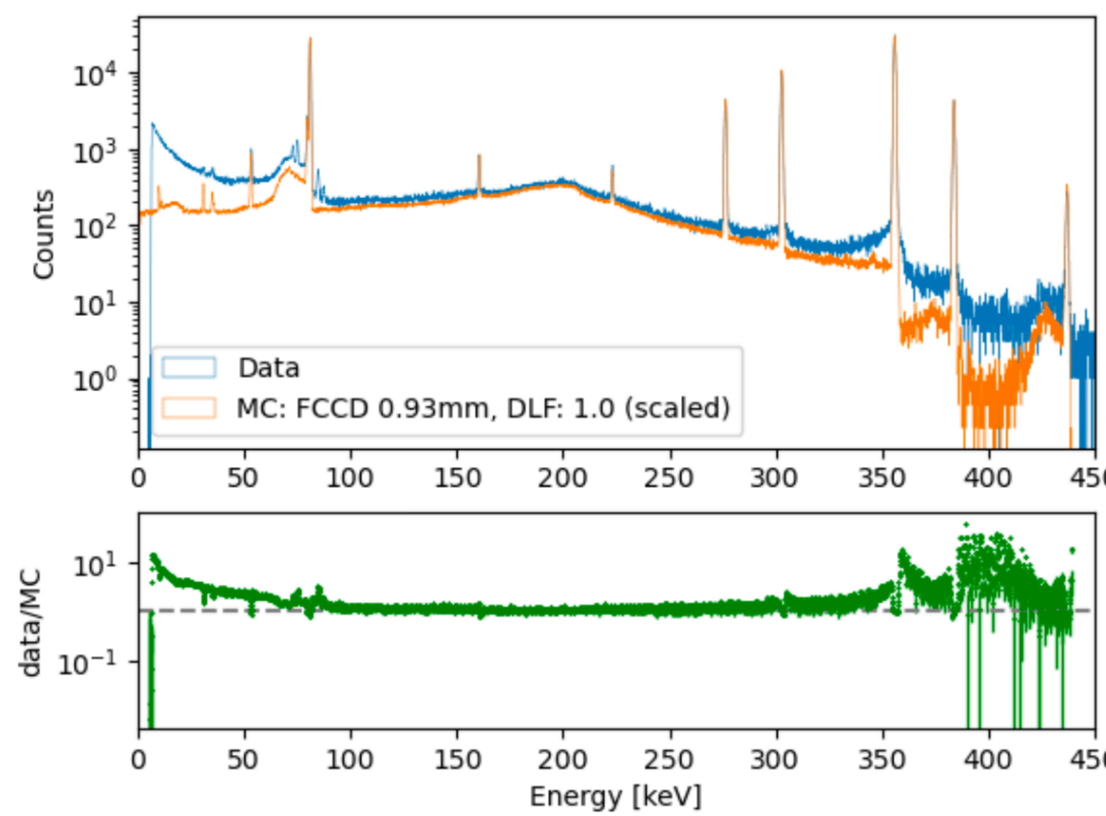
UZH CONTRIBUTIONS

- Four new source insertion systems, with four custom-made ^{228}Th sources/unit: weekly calibrations of the HPGe diodes
- Liquid argon instrumentation
- HPGe detector characterisation at HADES underground lab in Belgium

- Test setups at HADES:
  - Determine depletion voltage (with 60Co) and energy resolution (with 228Th)
  - Determine the active volume (with 133Ba)
  - Typical thickness of "dead-layer" due to n+ contact: ~ 1 mm

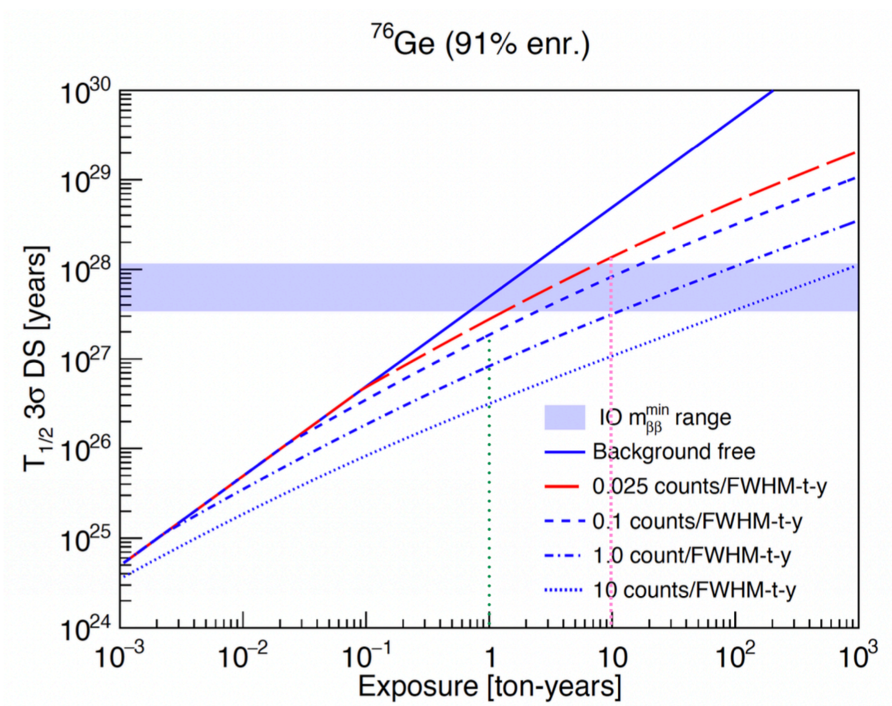
Dead-layer study with ^{133}Ba source

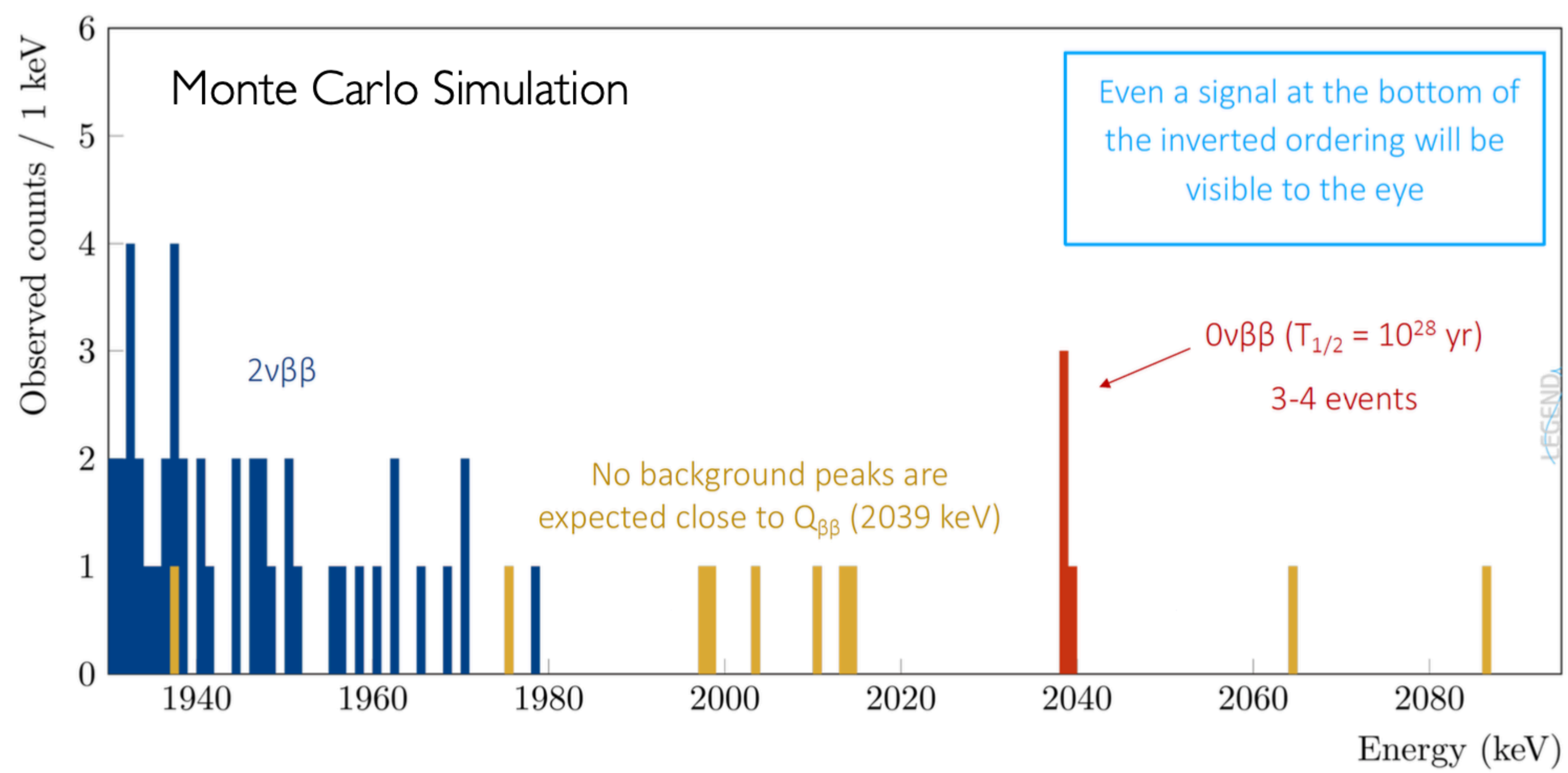




THE LEGEND-1000 EXPERIMENT

- What would a discovery look like?
  - Due to excellent energy resolution (σ/E ~ 0.05%) : no peaks near the ROI
  - Background measured in situ, no reliance on modelling





UZH MAIN RESPONSIBILITIES IN LEGEND-1000

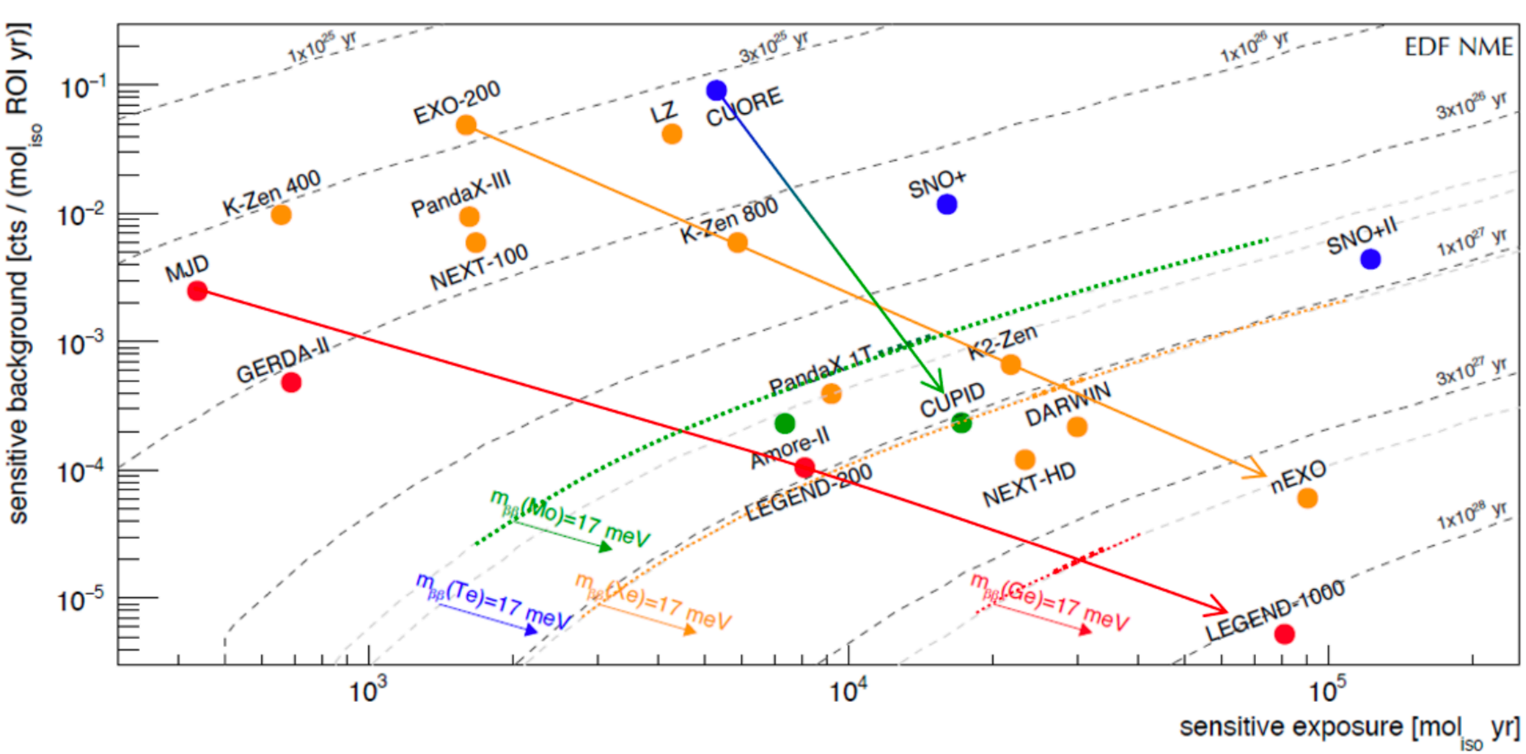
University of Zurich[UZH]

- Coordination of the production and characterisation of enriched ^{76}Ge detectors (co-leading HPGe Detector Production Task group, together with UNC)
- Design, construction and operation of new calibration systems (co-leading Calibration Task Group, together with LANL)
- Characterisation of custom-made ^{228}Th sources in terms of γ- and neutron rates (with HPGe and LiI(Eu) detectors operated by our group)
- Material screening with the HPGe detector (Gator) operated at LNGS by our group
- Instrumentation of liquid argon veto (together with TUM)
- R&D and design for the liquid argon veto, study PEN as alternative WLS (recently joined CERN neutrino platform)
- Provide weekly calibration parameters, detector stability etc; MC simulations, data analysis (also with respect to other BSM searches)

EXPECTED SENSITIVITY OF LEGEND

- **LEGEND-200**: 200 kg, 2.5 keV FWHM, 5 y, 1 tonne-y exposure, 0.5 events/(FWHM t y)
  - $T_{1/2}$ = 9.7 x 10^{26}y discovery (99.7% CL), 1.5 x 10^{27}y exclusion (90% CL)
  - $m_{\beta\beta}$ ~ 27- 64 meV
- **LEGEND-1000:** 1000 kg, 2.5 keV FWHM, 10 y, 10 tonne-y exposure, 0.025 events/(FWHM t y)
  - $T_{1/2}$ = 1.3 x 10^{28}y discovery (99.7% CL), 1.56 x 10^{28}y exclusion (90% CL)
  - $m_{\beta\beta}$ ~ 8.5- 19.4 meV

Backgrounds versus exposure



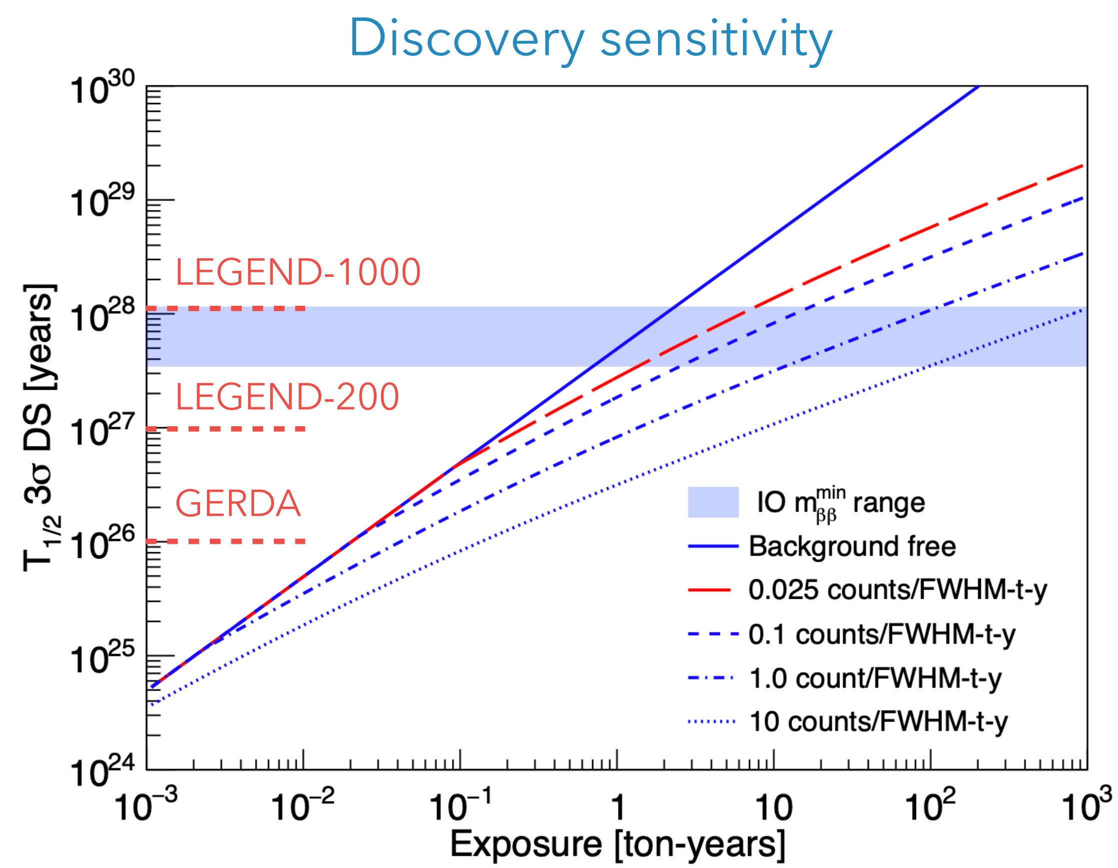
SUMMARY AND OUTLOOK

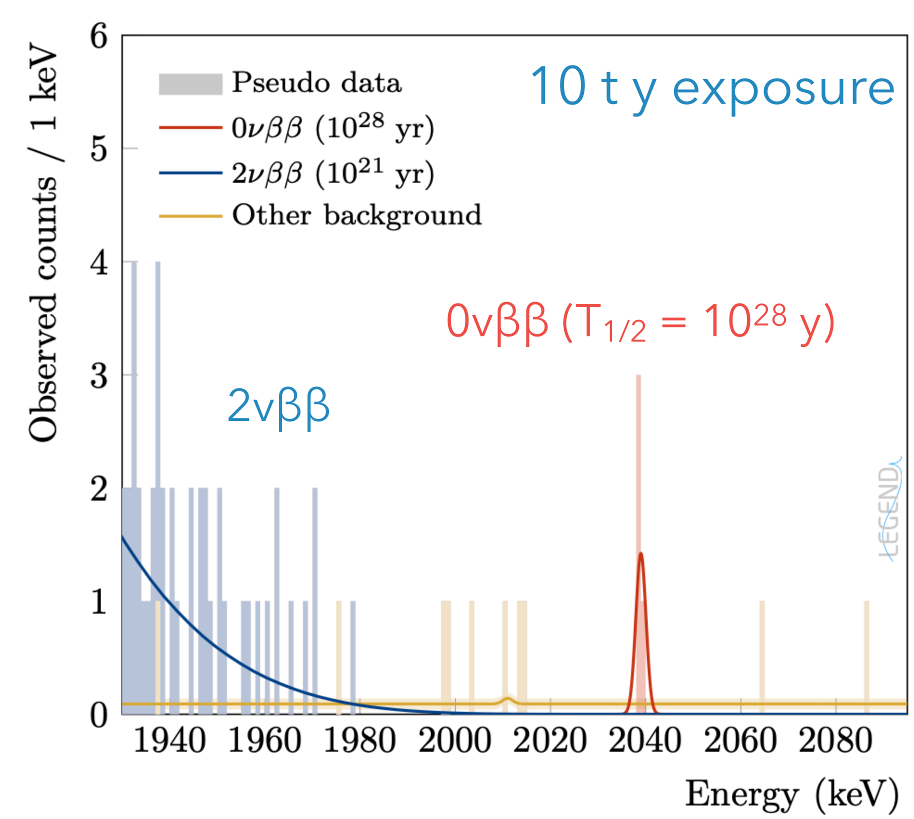
- GERDA: operated at LNGS until end of 2019; ultra-low background, excellent energy resolution: reached the then highest sensitivity to $0\nu\beta\beta$-decay ($T_{1/2} > 1.8 \times 10^{26}$ y) of any double beta decay experiment
- LEGEND-200 was constructed and commissioned at LNGS; physics data taking mode since early 2023 with 142 kg of detectors; remaining 60 kg to be installed after one year
- LEGEND-1000: pCDR published, CDR to define the detailed technical requirements and baseline being finalised; highest ranking from DOE Nuclear Physics Portfolio review; site decision in 2023: LNGS
- R&D and design efforts ongoing at UZH; UZH group co-leading two work packages (detector production and calibration), also involved in the liquid argon instrumentation and in material screening

END

THE LEGEND-1000 EXPERIMENT

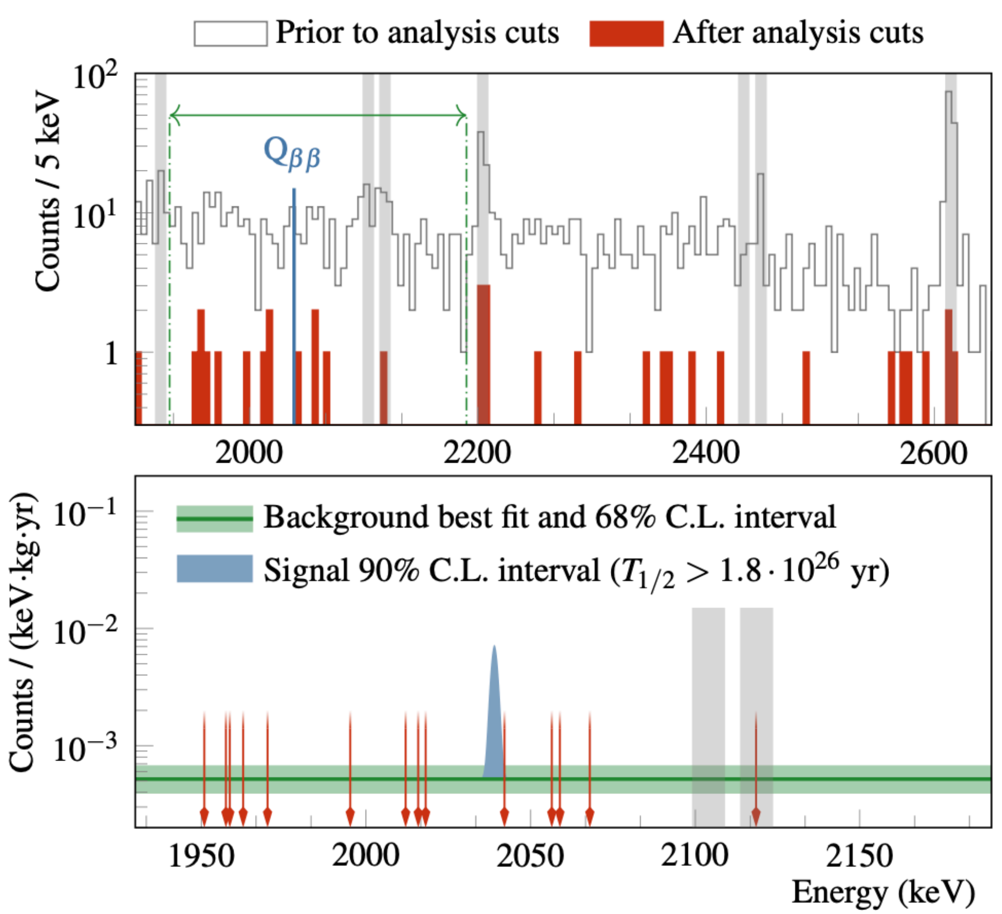
- pCDR published in 2021, CDR in preparation (part of DOE CD1-3A process)
- Site selection: within 2023 (also part of DOE CD1 process)
- DOE Office of Nuclear Physics Portfolio review in 2021, results were available in 2022: ranking is LEGEND-1000 (8), nEXO (7), CUPID (6.4)
  - "NP continues to pursue the possibility, in collaboration with national and international partners, of a multi-experiment campaign capable of providing contemporaneous verification of any apparent observation of 0νββ. Should it not prove possible to implement multiple projects in the search of 0νββ, **LEGEND-1000 would receive priority based on it receiving the highest ranking** from the portfolio review panel ."
- Discovery sensitivity: < 1 decay/(ton year)
- Ten-ton years of data to obtain a few counts





FINAL GERDA DOUBLE BETA DECAY RESULTS

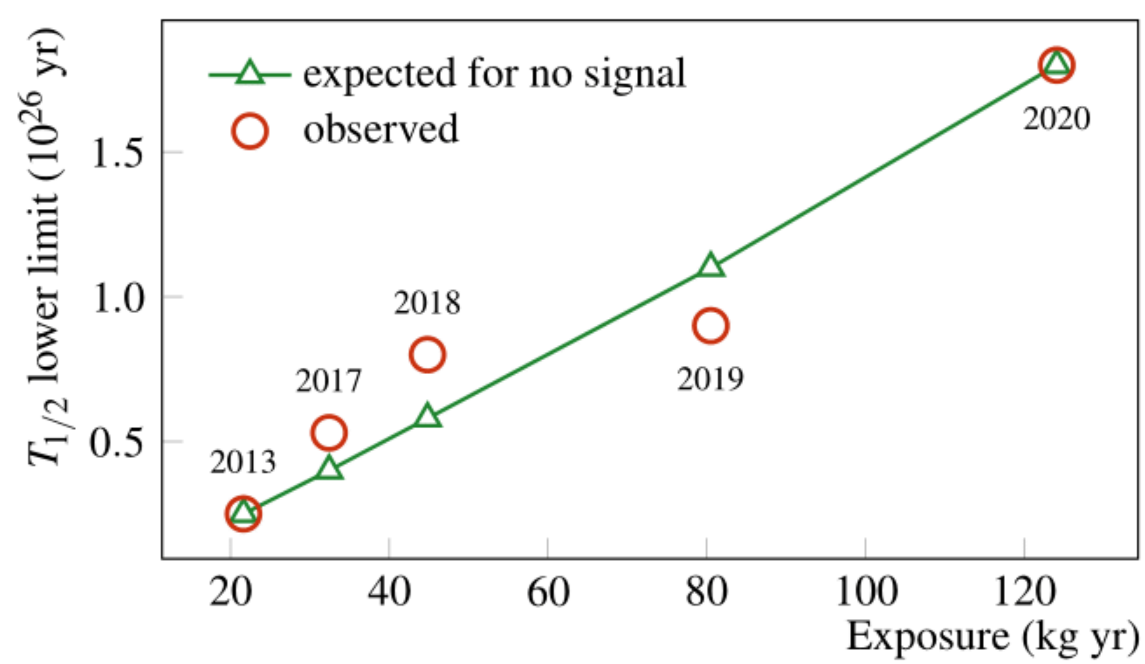
- Measured $T_{1/2}$ of the 2νββ-decay: $(1.926 \pm 0.094) \times 10^{21}$ y
- Background level: 5.2×10^{-4} events/(keV kg y) in 230 keV window around Q-value
- Lowest background in any double beta decay experiment (0.3 events expected in the ROI, $Q_{\beta\beta} \pm$ FWHM/2); full background model: GERDA collaboration, JHEP 03, 2020



GERDA collaboration, PRL 125, 2020

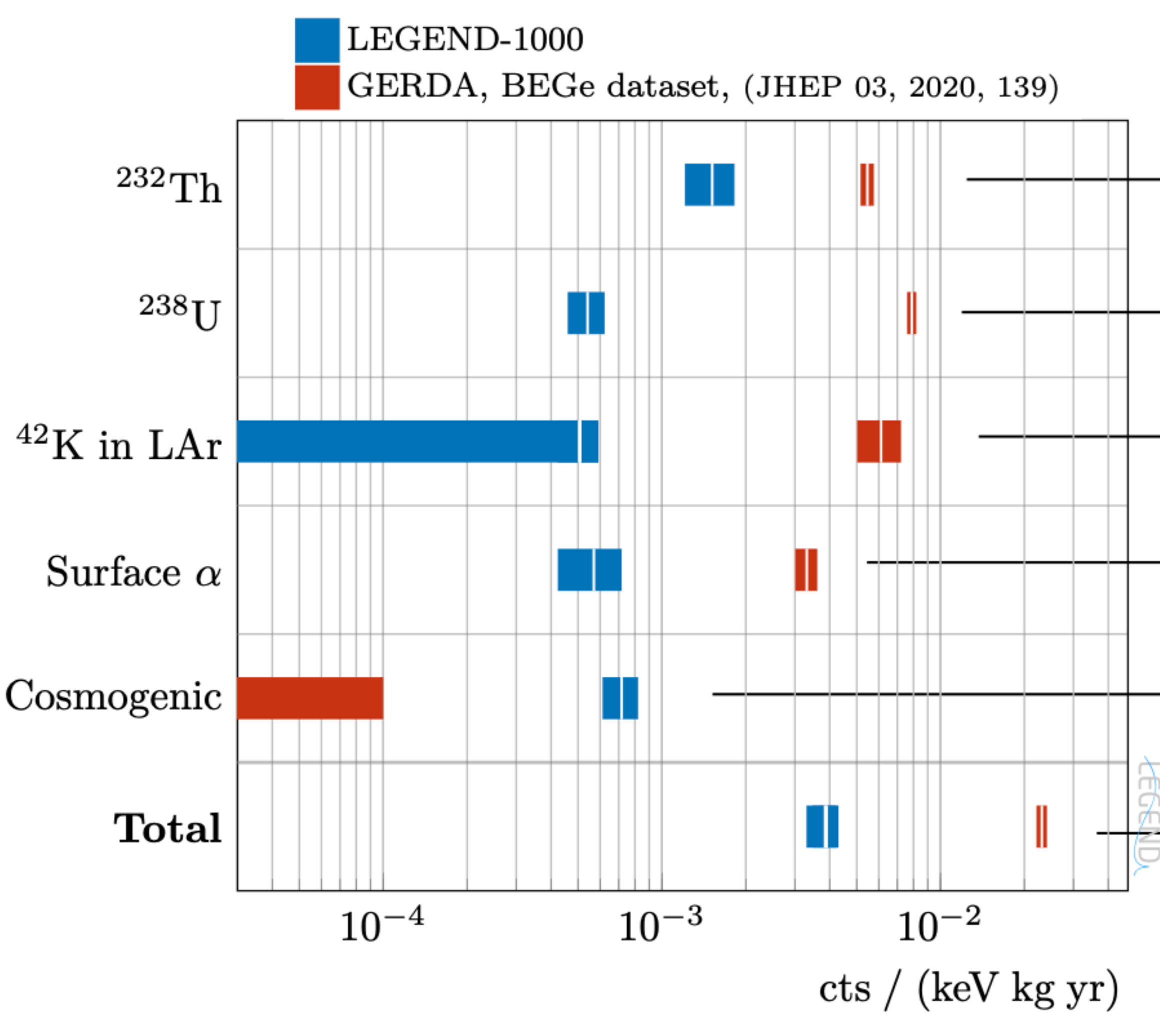
Constraints on the ^{76}Ge 0νββ-decay

$T_{1/2} > 1.8 \times 10^{26}$ y (90% CL); $m_{\beta\beta} < 80 - 182$ meV



LEGEND-1000 BACKGROUND PREDICTION

- Goal: 0.025 events/(FWHM t y) or ~1 x 10^{-5} events/(keV kg y)
- Detailed MC background predictions (based on measured activities or upper limits)



Background reduction due to:

- larger detectors ⇨ less cables and holders
  new cables & ASIC read-out
  increased detector spacing
- underground Ar
- larger detectors ⇨ larger surface-to-volume ratio
  only ^{210}Pb supported term
- ^{68}Ge decays away, 2 yr less cool down than in GERDA
- Factor 6 reduction, driven by underground Ar

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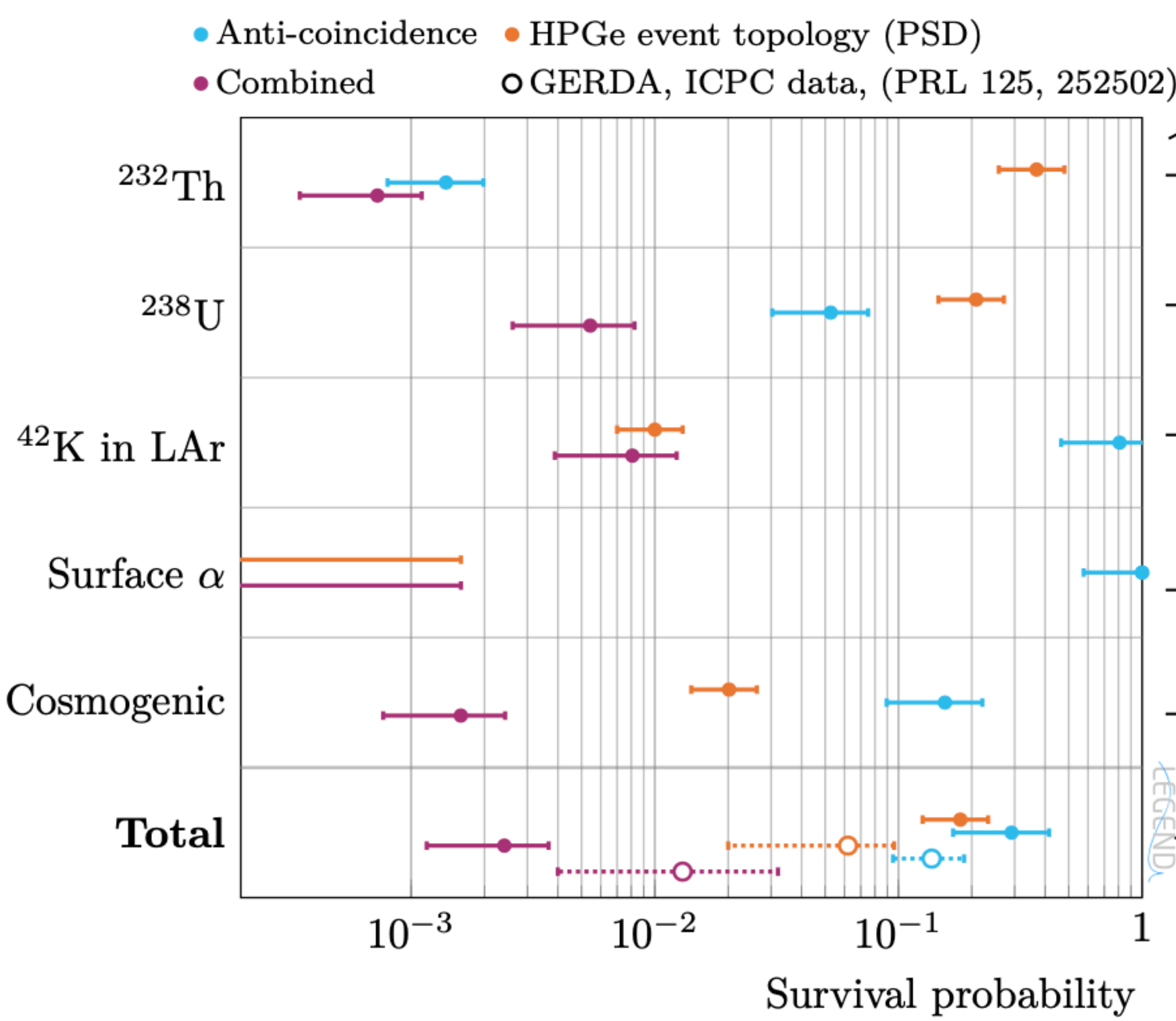
- Detailed MC background predictions (based on measured activities or upper limits)

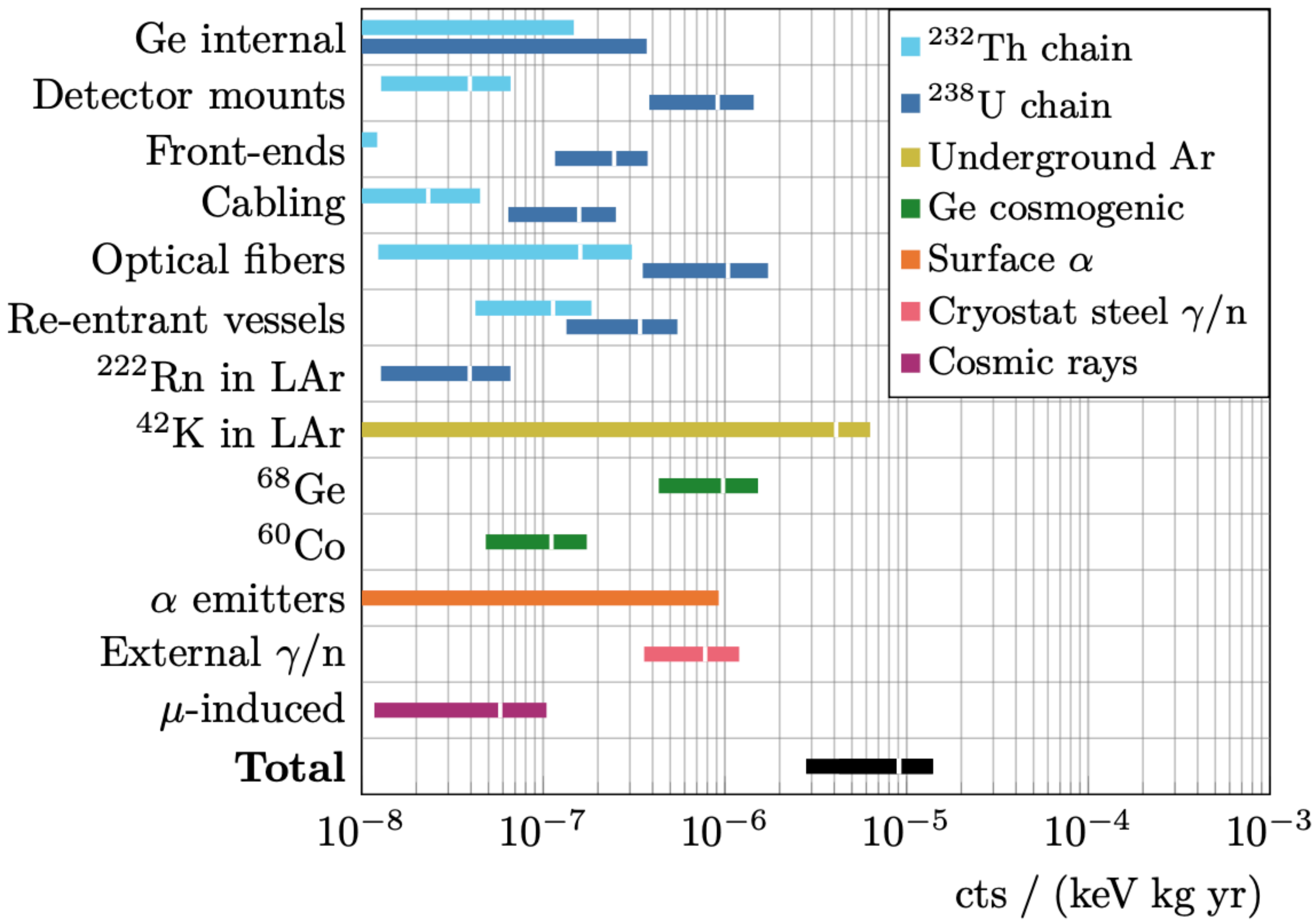


Effective background suppression due to:

- Greater ^{208}Tl γ energy: enhances suppression over ^{238}U chain
- Improved light collection through:
  - Ge detector spacing
  - Fiber coverage
  - SiPM quantum efficiency
- Minimization of inactive material to suppress γ events
- A PSD suppression demonstrated in GERDA
- Inherently multi-site
- Overall improvement in combined suppression relative to GERDA

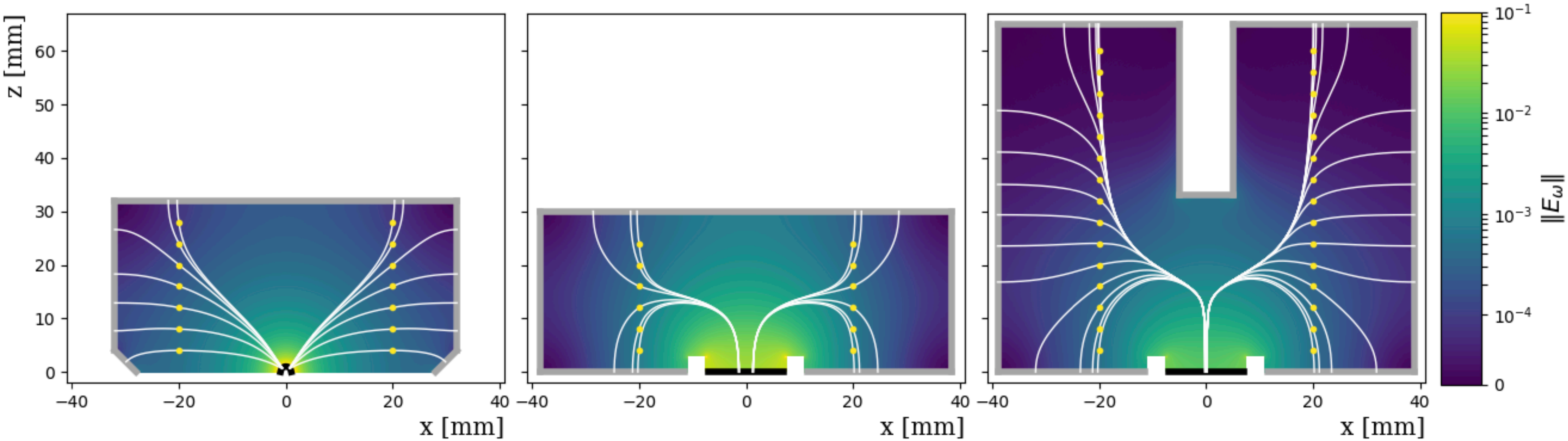
LEGEND-1000 BACKGROUND PREDICTION

- Goal: 0.025 events/(FWHM t y) or ~1 x 10^{-5} events/(keV kg y)
- Detailed MC background predictions (based on measured activities or upper limits)



DETECTORS

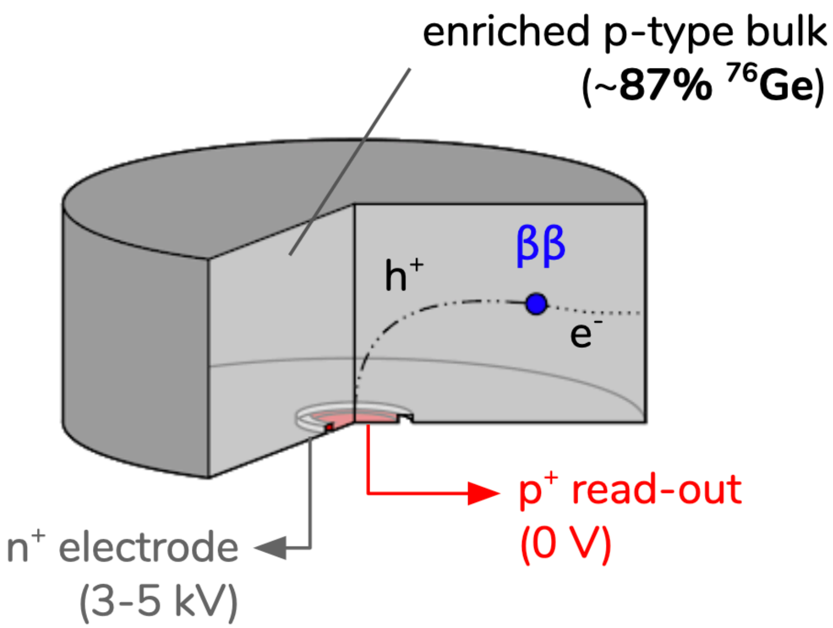
- Weighting field:
  - PPC (MAJORANA), BEGe (GERDA) and inverted coaxial (LEGEND) detectors



LEGEND-1000 WORK BREAKDOWN STRUCTURE

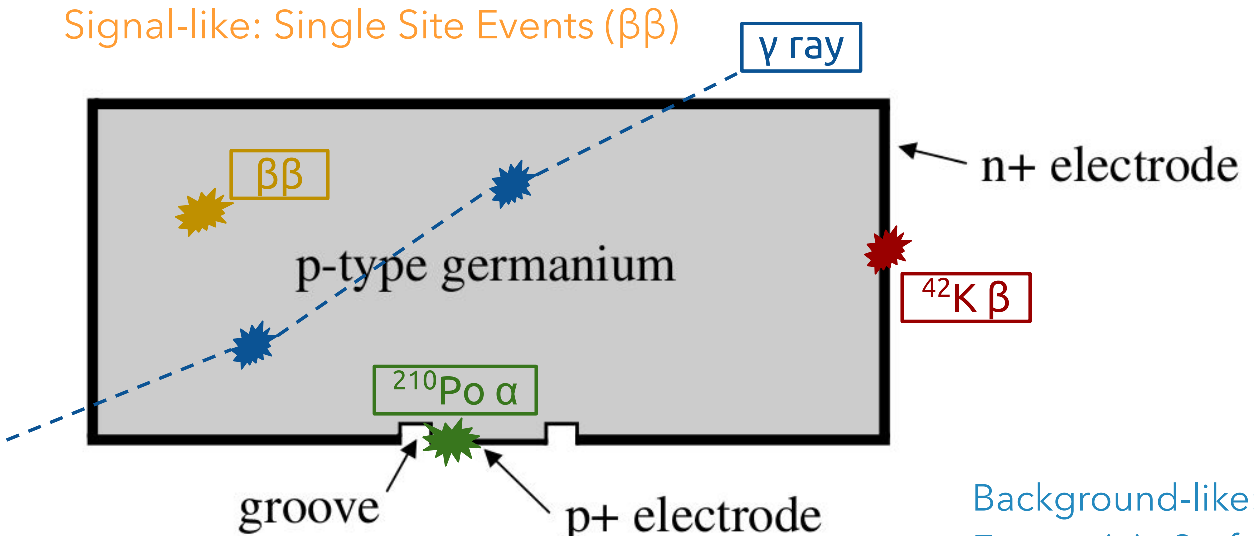
- L-1 LEGEND 1000
  - L-1.01 Project Management
    - L-1.01.01 Project Milestones
    - L-1.01.02 Project Management
    - L-1.01.03 L2 and CAM Management
  - L-1.02 Simulations and Analysis
    - L-1.02.01 Analysis Framework
    - L-1.02.02 Analysis Routines
    - L-1.02.03 Simulations
  - L-1.03 Materials and Assay
    - L-1.03.01 Material Screening
    - L-1.03.02 Copper Electro-forming
    - L-1.03.03 Plastics and other Produced Mat'ls
  - L-1.04 Host Lab Infr. and Cryostat Systems
    - L-1.04.01 Host Lab Infrastructure
    - L-1.04.02 Cryostat
    - L-1.04.03 Lock Systems and Interface
    - L-1.04.04 Water Tank
    - L-1.04.05 Calibration Systems
  - L-1.05 Active Shielding
    - L-1.05.01 Atmospheric Liquid Ar
    - L-1.05.02 Underground Liquid Ar
    - L-1.05.03 Liquid Ar Instrumentation
    - L-1.05.04 Water Tank Instrumentation
  - L-1.06 Ge Detector Production
    - L-1.06.01 Enriched Ge Production & Proc
    - L-1.06.02 Detector Production
    - L-1.06.03 Detector Units
  - L-1.07 Electronics and DAQ
    - L-1.07.01 Ge Front-End Electronics
    - L-1.07.02 SiPM Front-End Electronics
    - L-1.07.03 Cables, Connectors, and Feedthroughs
    - L-1.07.04 Other Electronics
    - L-1.07.05 DAQ and Slow Controls
  - L-1.08 Integration and Commissioning
    - L-1.08.01 Lab Infrastructure and Cryostat
    - L-1.08.02 Module 1
    - L-1.08.03 Module 2
    - L-1.08.04 Module 3
    - L-1.08.05 Module 4

GERMANIUM IONISATION DETECTORS

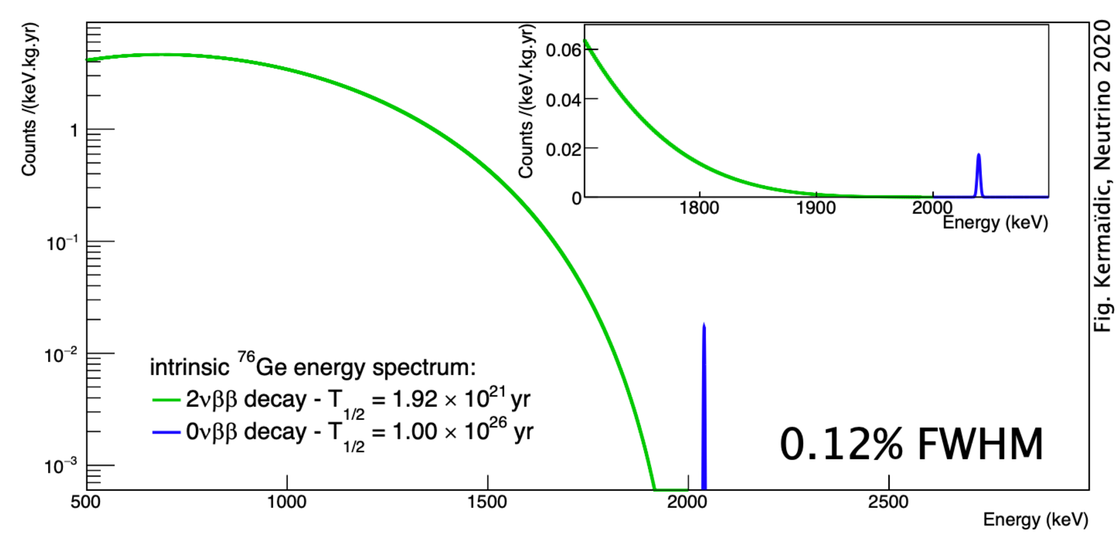


- HPGe detectors enriched in ^{76}Ge
    - Source = detector: high detection efficiency
    - High-purity material: no intrinsic backgrounds
    - Semiconductor: $\sigma/E < 0.1\%$ at $Q_{\beta\beta} = 2039.061 \pm 0.007$ keV
    - High stopping power: β absorbed within O(1) mm

Signal-like: Single Site Events (ββ)



Background-like: Multiple Site Events (γ), Surface events (α,β)

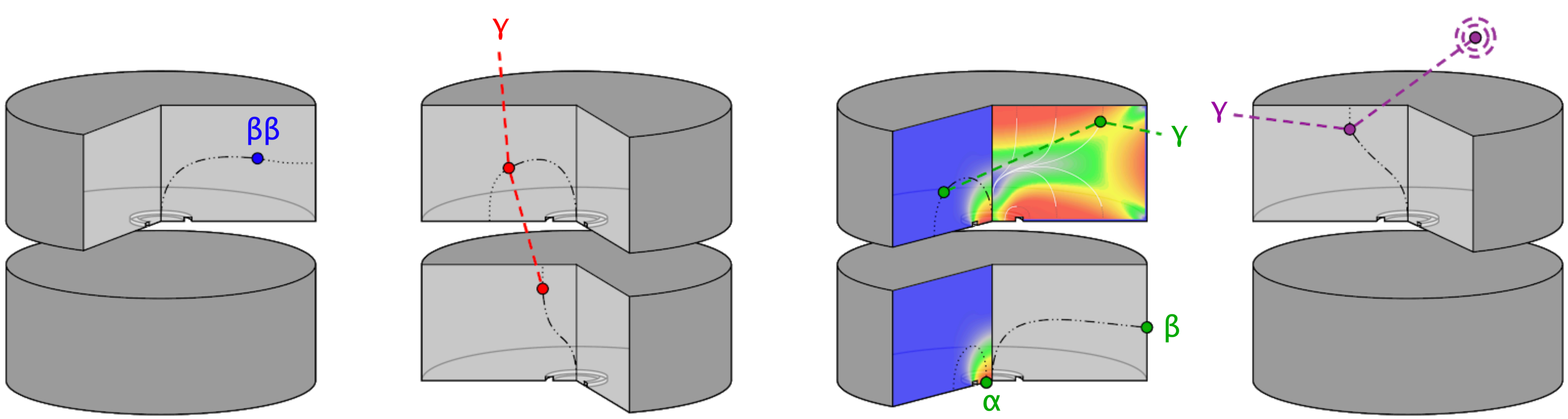


Neutrino 2020

BACKGROUND SUPPRESSION IN GERDA AND LEGEND

- Several handles:
    - Event topology + anti-coincidence between HPGe detectors + pulse shape discrimination + liquid argon veto

event topology | detector anti-coincidence | pulse shape discrimination (PSD) | detector-LAr anti-coincidence (LAr veto)



differentiate **point-like** (single-detector, single-site) ββ topology from:

multi-detector interactions

multi-site/surface interactions

interactions with **coincident energy deposition** in surroundings