Status of the LEGEND experiment

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Dr. Marta Babicz
Physik Institut, Universität Zürich
on behalf of the LEGEND collaboration

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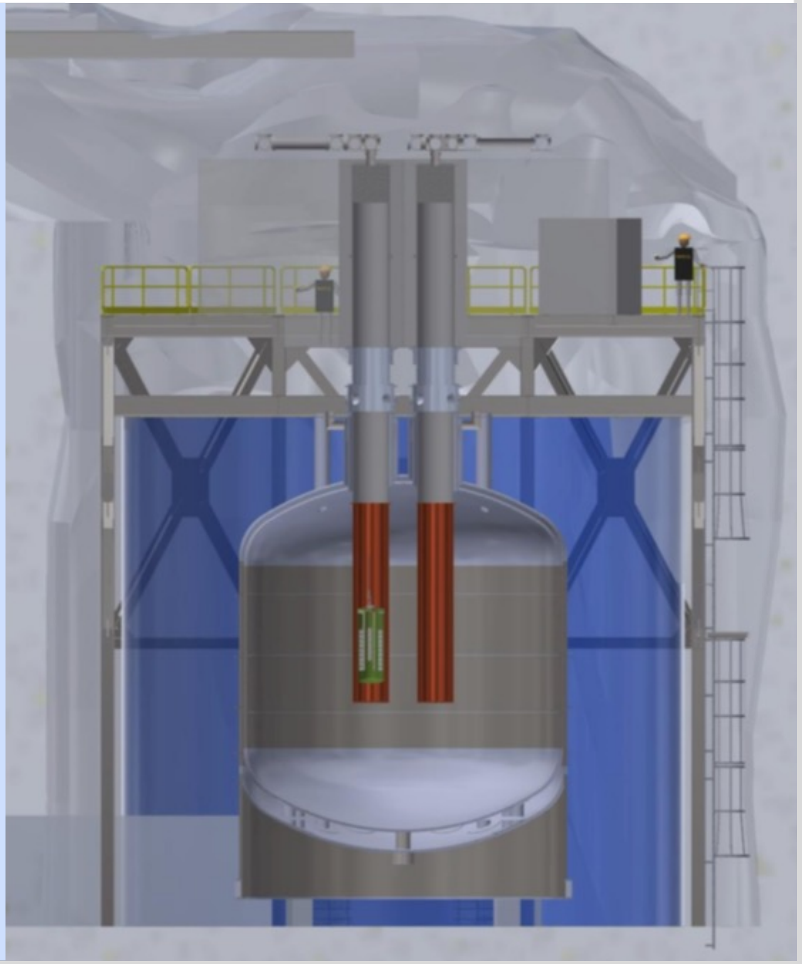


Universität Zürich UZH

Double beta decay without neutrinos

Neutrinoless double beta ($0\nu\beta\beta$) decay is a hypothesised nuclear process:

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

The decay rate:

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

nuclear matrix element

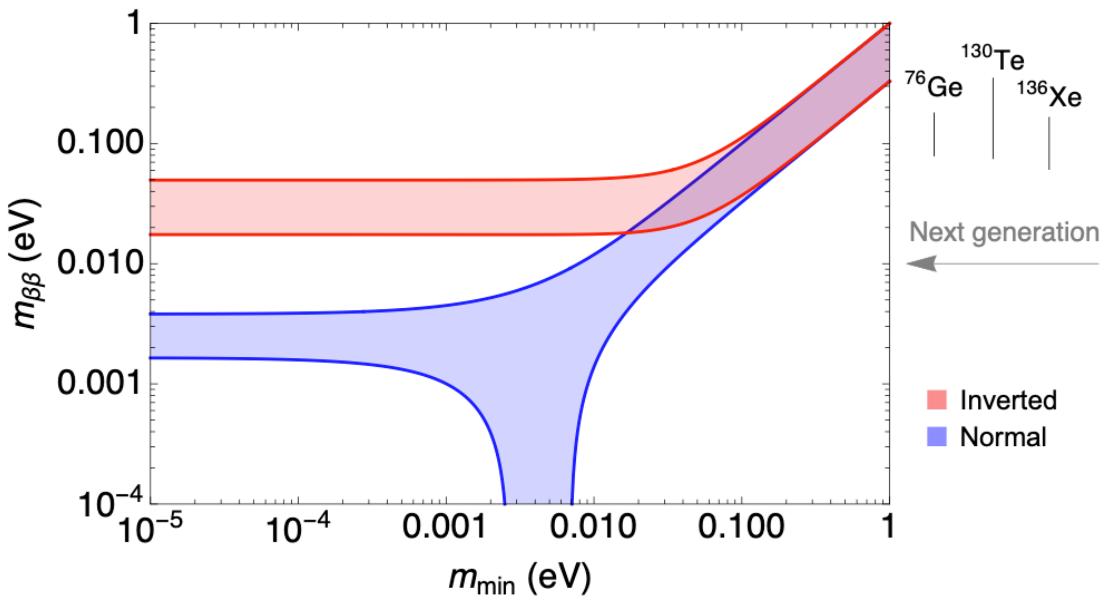
phase space factor

half-life of the decay

effective Majorana mass

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

where U_{ei} represents the elements of the PMNS matrix.

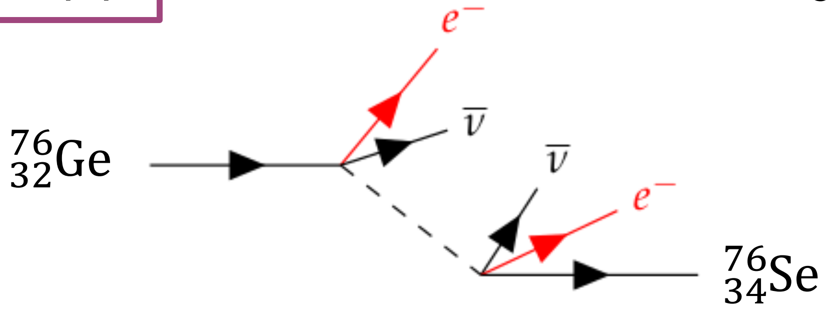


Motivation for $0\nu\beta\beta$ searches:

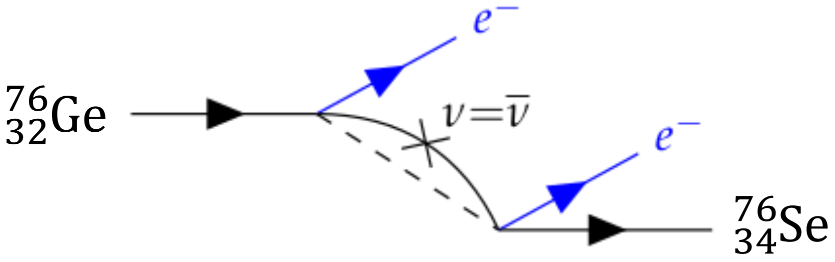
- Uncovering Majorana nature of neutrinos
- Gaining insights into neutrino mass scale and ordering (normal vs inverted)
- Studying lepton number violation
- Exploring baryon asymmetry of the Universe

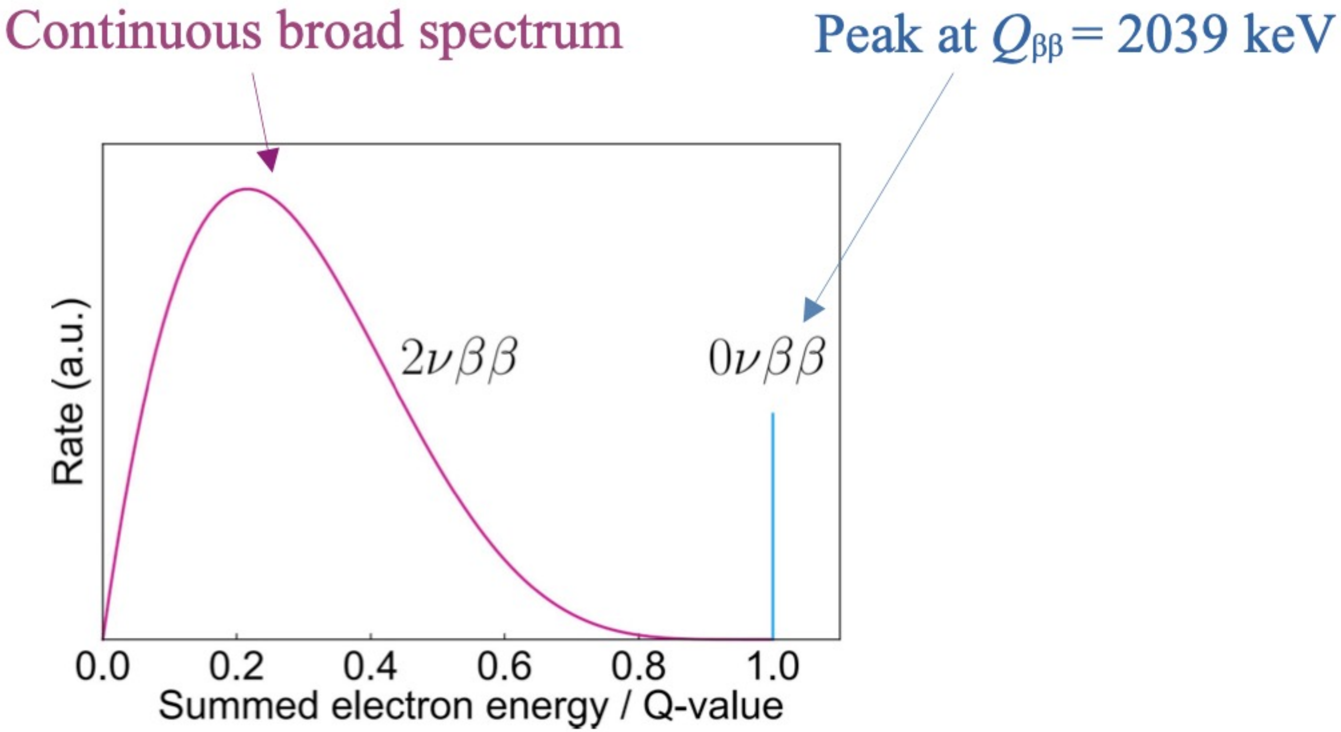
Double beta decay in ^{76}Ge

2νββ $^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\bar{\nu}_e$



0νββ $^{76}Ge \rightarrow {}^{76}Se + 2e^-$





Half-life ($T_{1/2}$) sensitivity

$$T_{1/2} \propto \begin{cases} f \cdot \epsilon \cdot \sqrt{\dfrac{M \cdot t}{BI \cdot \sigma_E}} & \text{, with background} \\ f \cdot \epsilon \cdot M \cdot t & \text{, without background} \end{cases}$$

- f: ^{76}Ge enrichment factor
- ϵ: Detection efficiency
- M: Total detector mass
- t: Measurement time
- BI: Background index
- σ_E: Energy resolution at $Q_{\beta\beta}$

GERDA + MAJORANA DEMONSTRATOR + new institutions → LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Lowest background index for 0νββ: $5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)

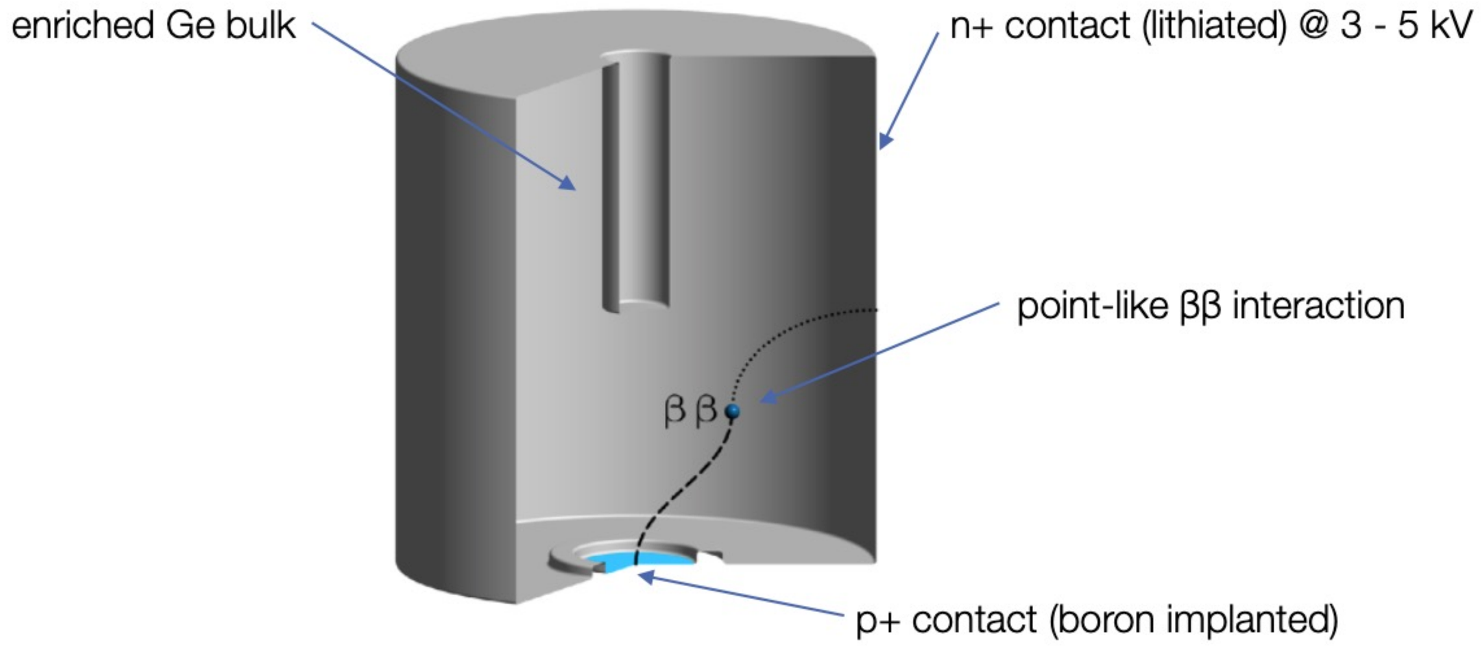
Best energy resolution for 0νββ: 2.52 ± 0.08 keV (FWHM) at $Q_{\beta\beta}$

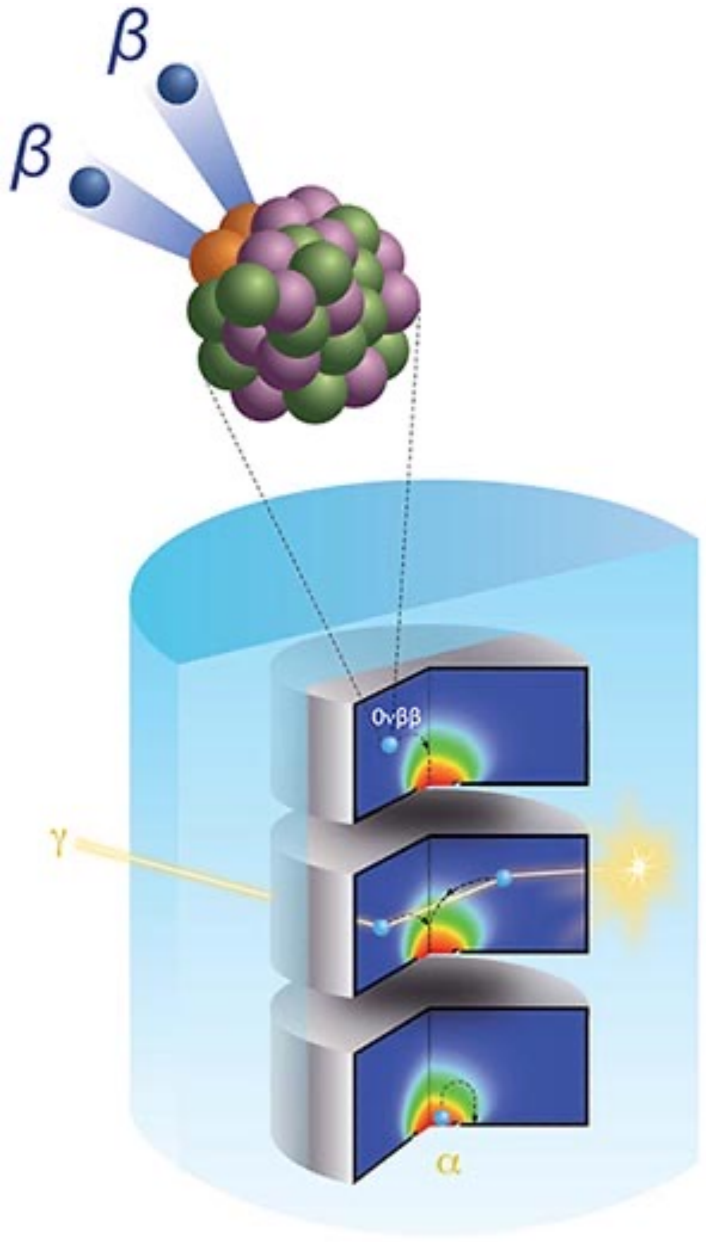
Ref.: GERDA Collab., PRL 125, 252502 (2020)

Refs.: MAJORANA Collab., PRL130, 062501 (2023)

High-**P**urity **Ge**rmanium detectors enriched in ^{76}Ge

- $\beta\beta$ source = detector → excellent detection efficiency
- Made from high-purity germanium (HPGe) material → low intrinsic background
- Enrichment in ^{76}Ge isotope at the level of > 90% is possible
- Best energy resolution of any ββ detector → ~0.1% FWHM at $Q_{\beta\beta}$
- Topological discrimination using pulse-shape discrimination and argon scintillation signal





Ref.: M. Agostini et al., Science 10.1126/science.aav8613 (2019)

LEGEND-200

First stage:

- Situated in the existing GERDA infrastructure at LNGS with various upgrades in subsystems
- ~200 kg of detector mass distributed into 12 strings
- Current data taking with ~142 kg of detectors (10 strings) deployed in LAr
- BI goal: 2.6 times lower than GERDA Phase II results
- 10 times larger exposure than GERDA (up to 1 ton-yr)

L200 Goals:

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

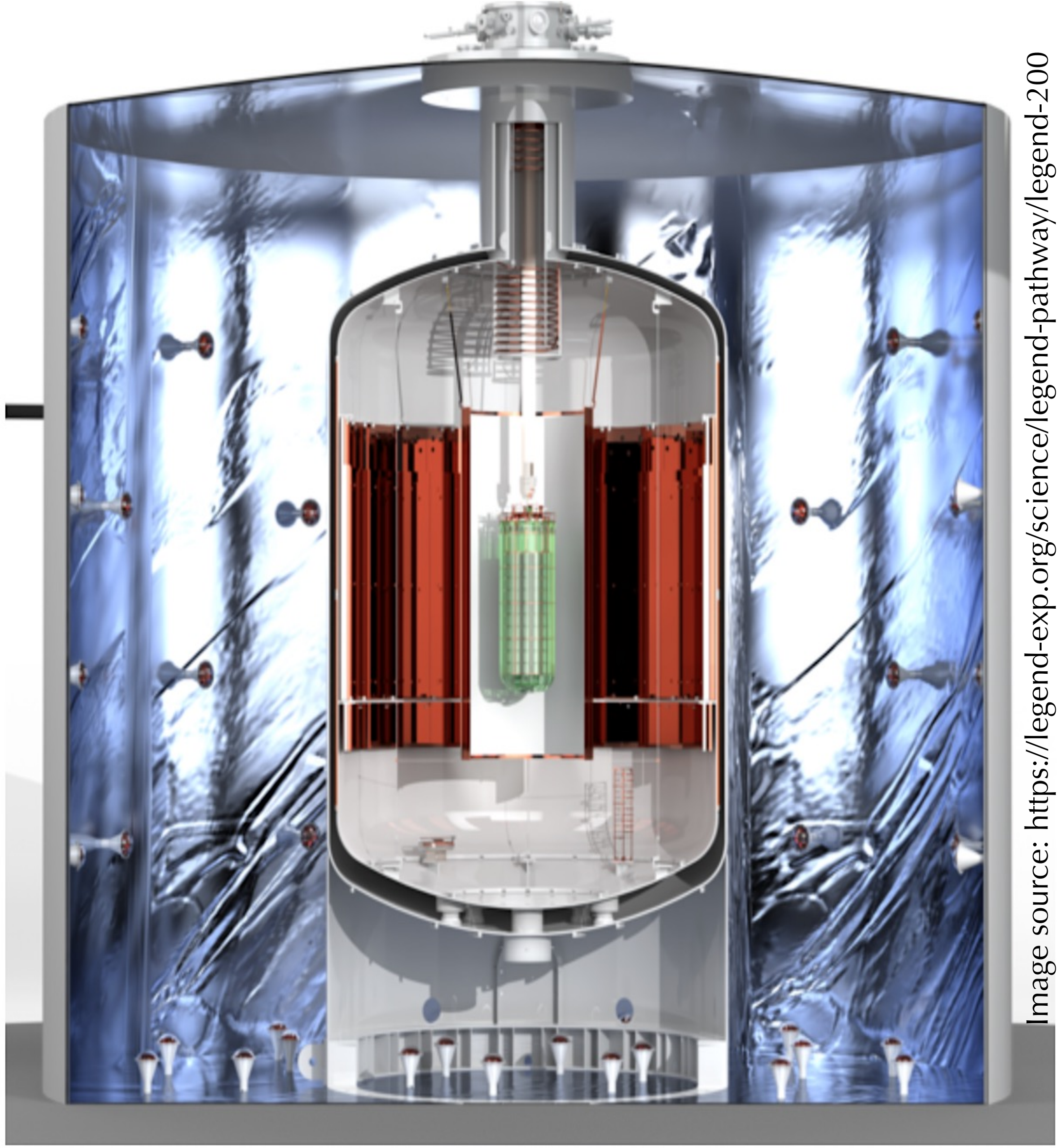
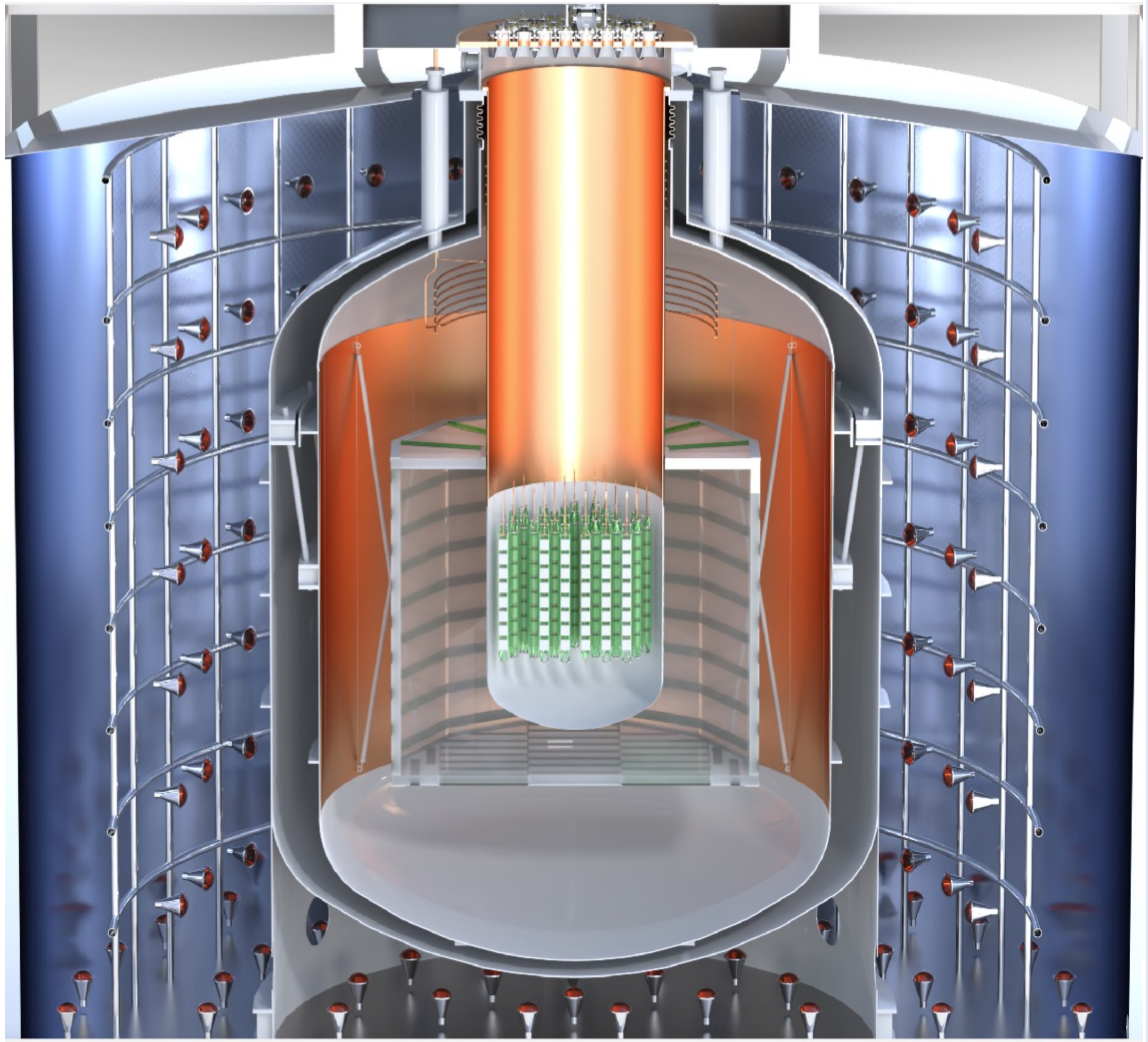


Image source: https://legend-exp.org/science/legend-pathway/legend-200

LEGEND-1000

- Next stage:
- Location to be defined (LNGS or SNOLAB)
- Staged installation of 1000 kg detector mass
- Detector strings immersed in radiopure underground LAr (UGLAr)
- Background index goal 50 times lower than GERDA Phase II results
- Aiming to cover the inverted neutrino mass ordering regime



L1000 Goals:

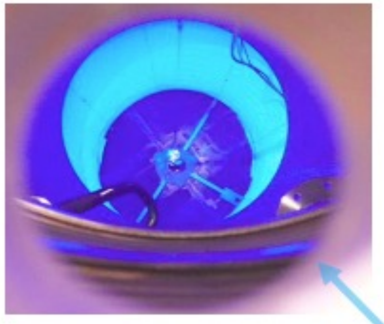
background index	10^{-5} cts/(keV kg yr)
half-life discovery sensitivity	10^{28} years
mass sensitivity	10 – 20 meV

LEGEND200: Current experimental setup

Underground at LNGS in Italy, shielded by 1400 m rock (3500 m.w.e.) reducing cosmic muons by $\mathcal{O}(10^6)$

Wavelength-shifting (WLS) reflector:

Tetratex® coated with TPB



Calibration system

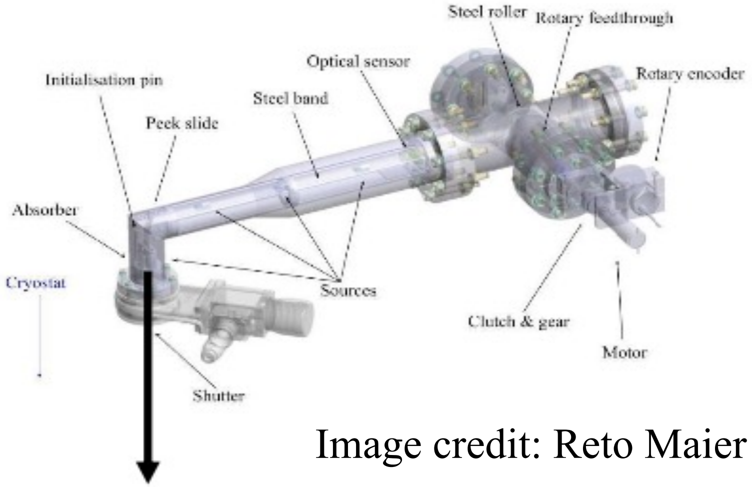
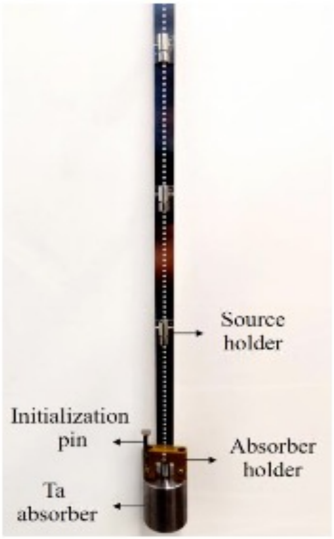
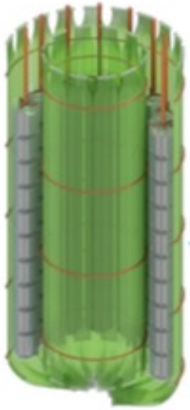
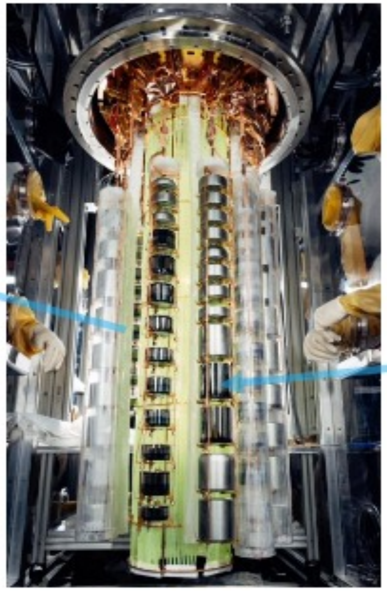


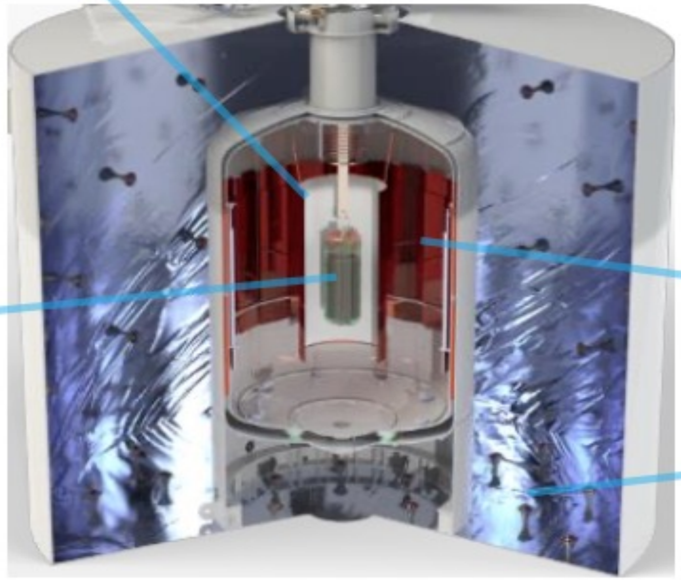
Image credit: Reto Maier



Wavelength-shifting (inner/outer) fibre shrouds







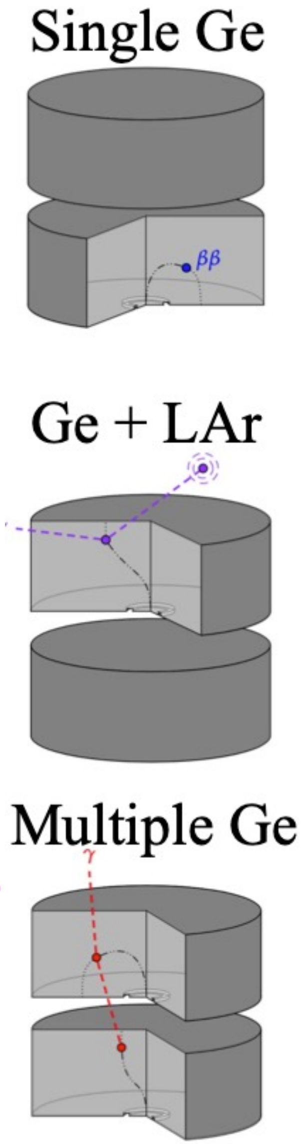
LAr cryostat and veto system

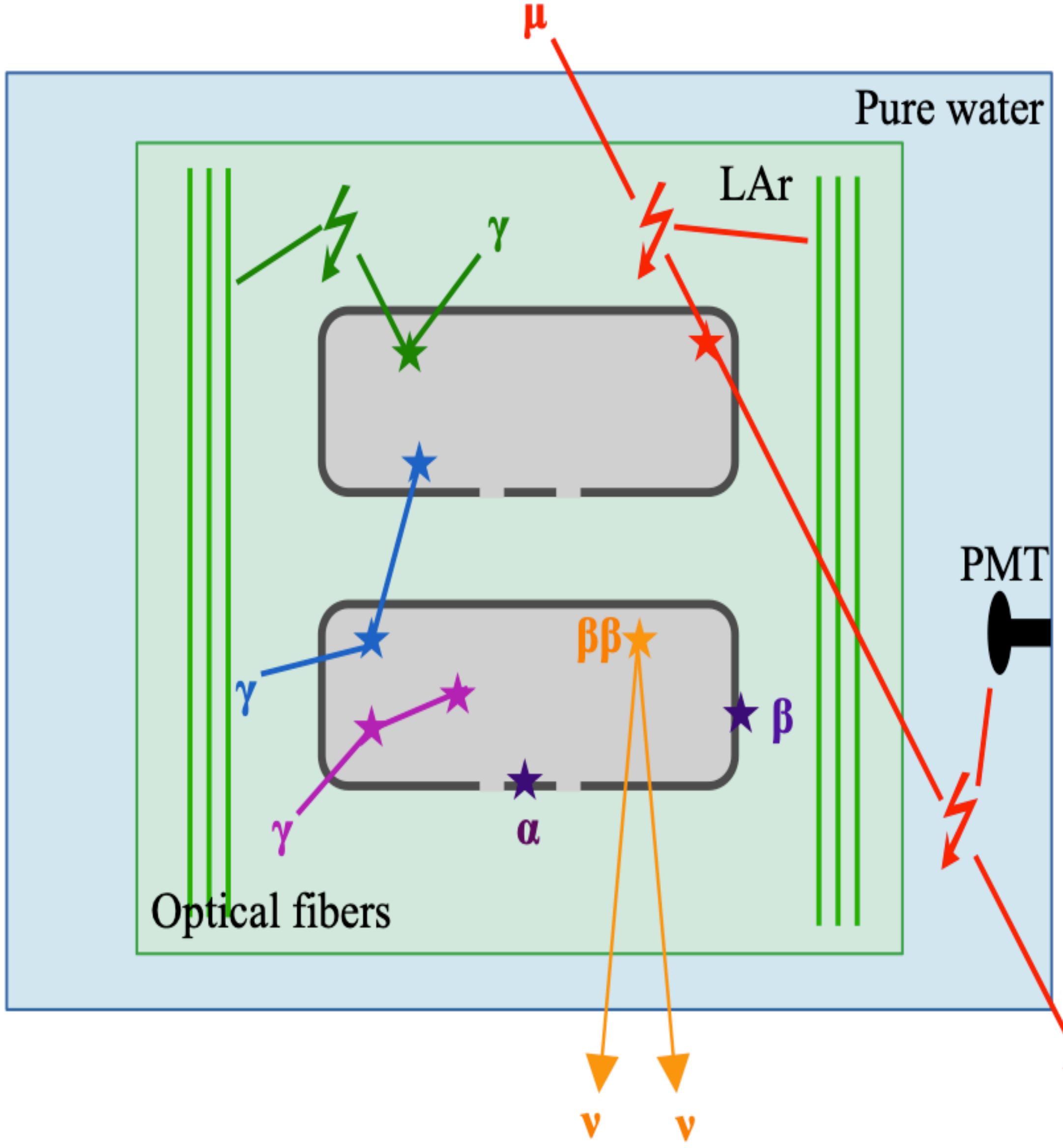
Water tank with PMTs

101 HPGe detectors distributed into 10 strings surrounded by WLS fibres

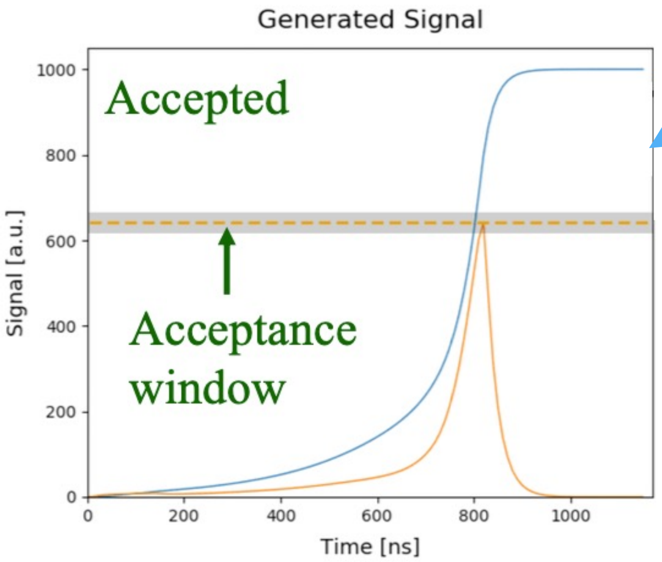
Background reduction

- ββ decay signal: localized energy deposition ~$\mathcal{O}(1\ \text{mm}^3)$
  → Single-site event (SSE)
- μ: water Cherenkov veto
- γ: at MeV energies ~$\mathcal{O}(1\ \text{cm})$
  → Multi-site event (MSE)
  – LAr veto,
  – Anti-coincidence from multiple detectors
  – Pulse shape discrimination (PSD in a single detector
- Surface α and β: PSD



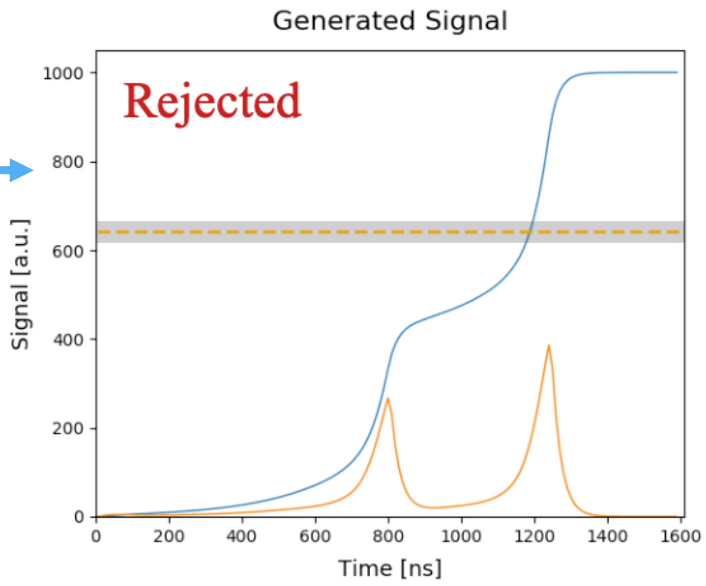


Event topology: pulse shape discrimination



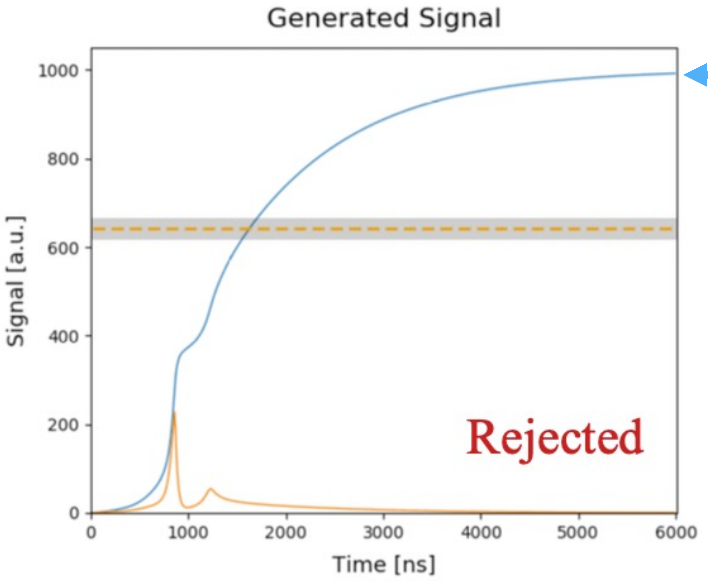
ββ signal (SSE)

γ background (MSE)



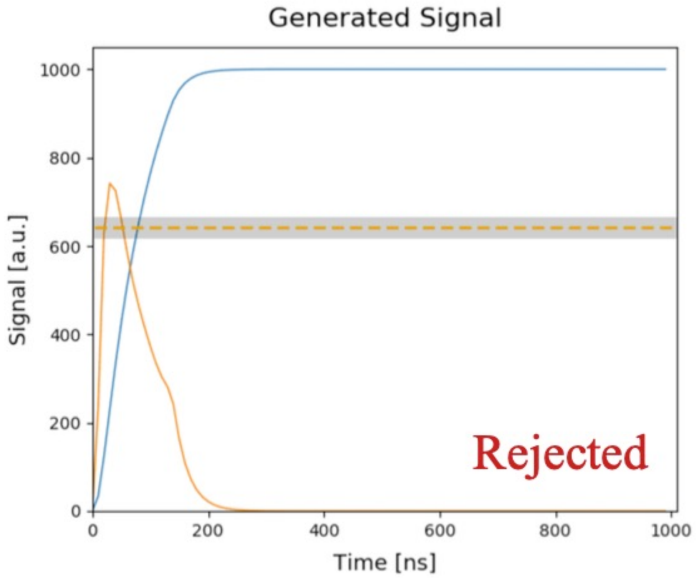
Charge signal

Current signal



β background on n+ contact

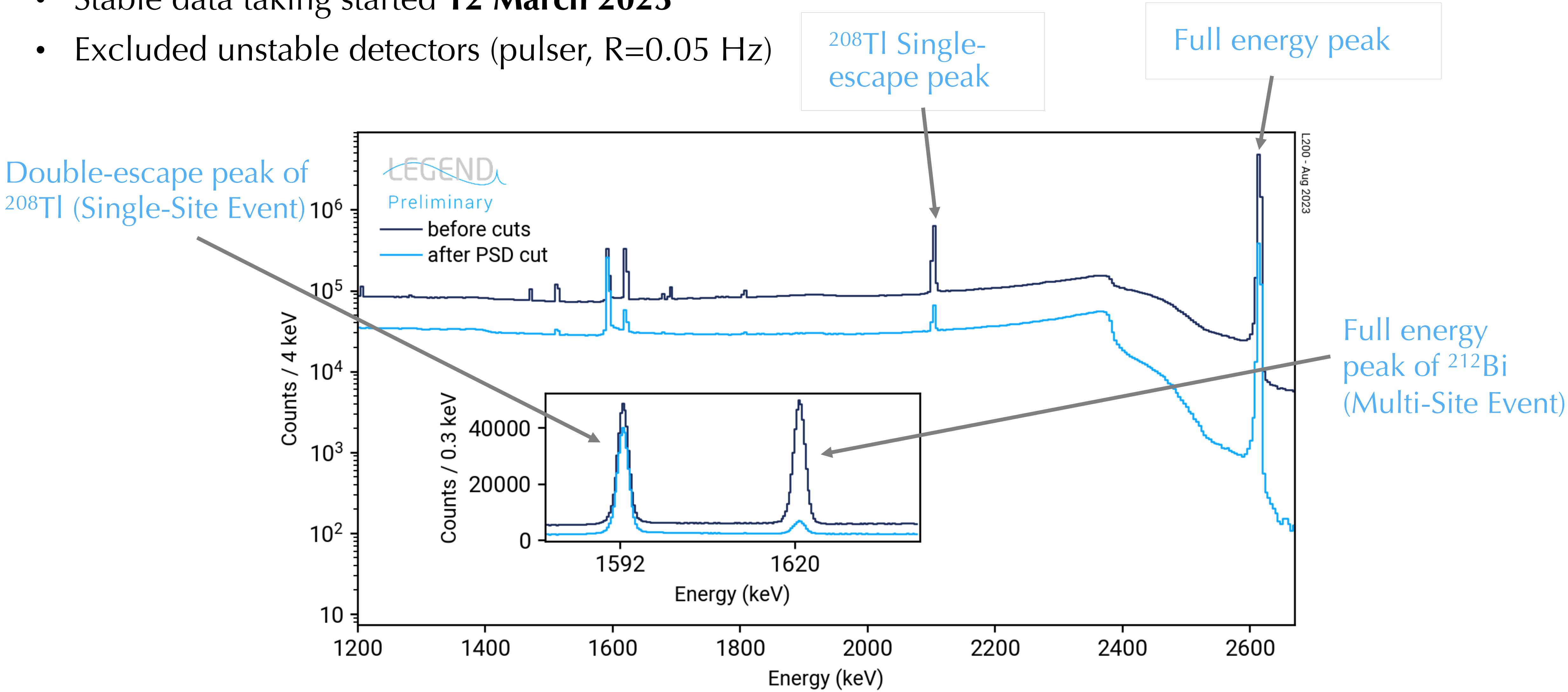
α background on p+ contact



LEGEND-200: first results

- m_{tot}=142.4 kg (122 kg for the analysis)
- Stable data taking started **12 March 2023**
- Excluded unstable detectors (pulser, R=0.05 Hz)

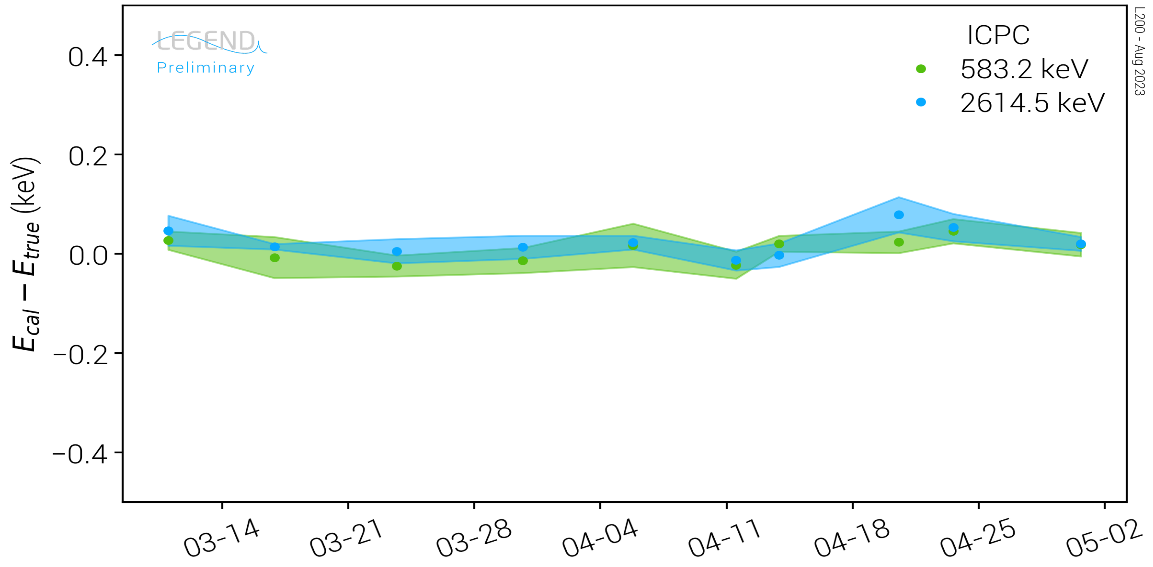
PSD tuned to 90% survival at ^{208}Tl DEP
→ very good rejection of multi-site events

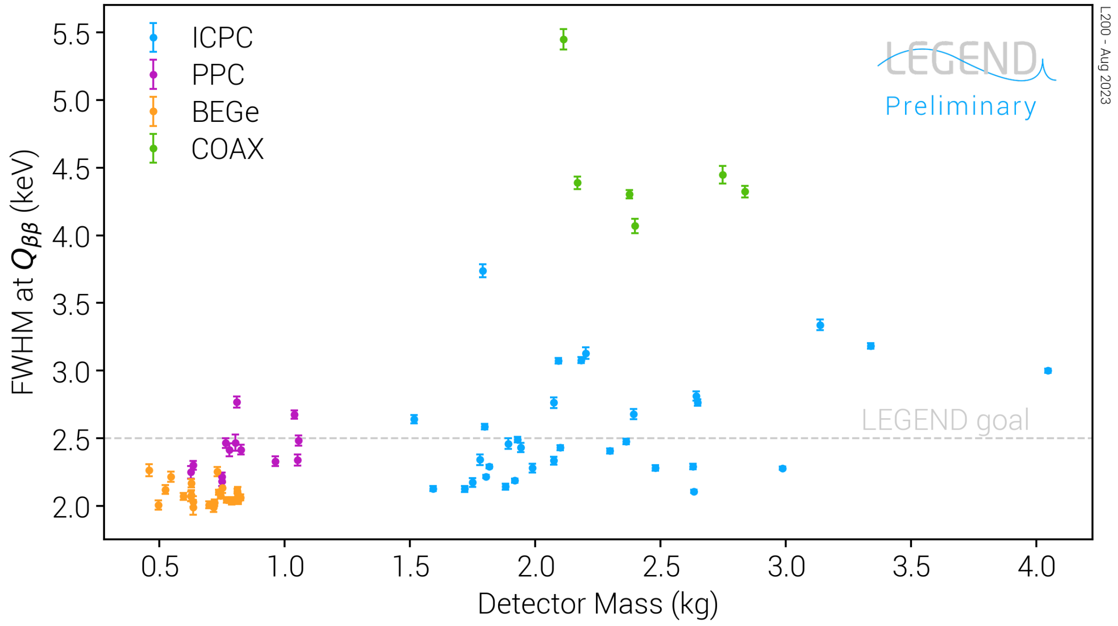


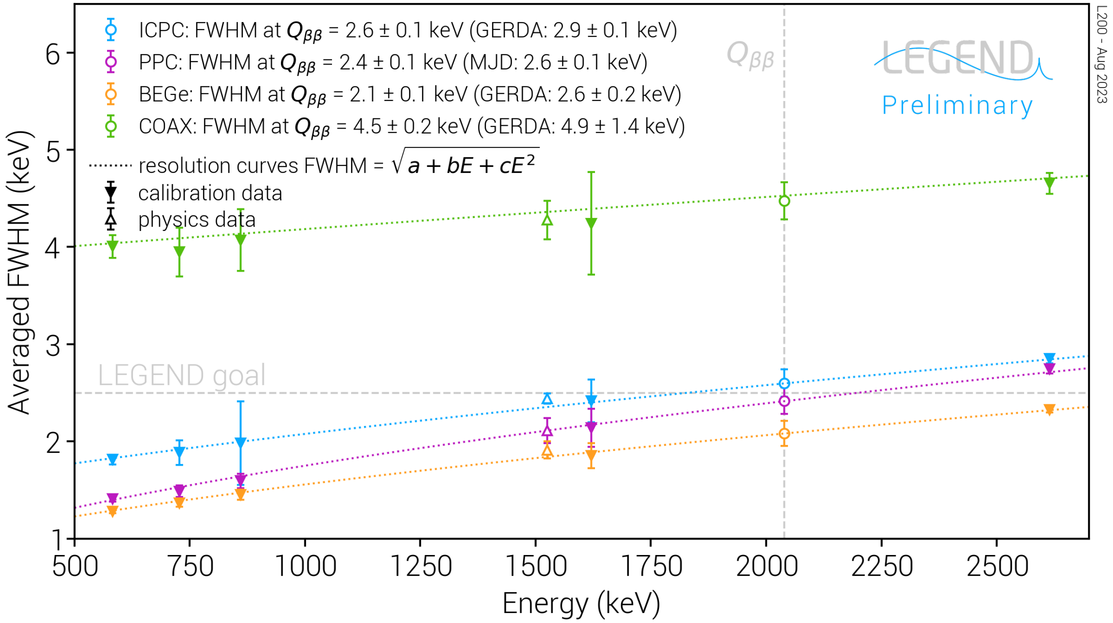
LEGEND-200: performance at $Q_{\beta\beta}$

Weekly energy calibration between physics runs using 228Th sources

- Energy scale very stable between calibrations
- Overall improvement in energy resolution at Qββ







Conclusions

- Majorana neutrinos may solve several fundamental issues in particle physics and cosmology:
  - origin of neutrino mass, mass scale, and mass hierarchy
  - matter-antimatter asymmetry
- $0\nu\beta\beta$ is a promising probe: HPGe approach provides excellent energy resolution and low background

LEGEND-200:

- Transitioned successfully from GERDA / Majorana Demonstrator
- Upgraded infrastructure to accommodate larger detector array
- Installed & commissioned first 140 kg of HPGe detectors in October 2022
- Ongoing data collection, with new detectors in 2024

LEGEND-1000:

- Ton-scale LEGEND-1000 will reach a discovery sensitivity of $T_{1/2} > 10^{28}$ yr, aiming to cover the inverted neutrino mass ordering regime

Backup Slides

LAr instrumentation for LEGEND-200

Goal: Detect scintillation from background events (e.g., gamma rays) in LAr and apply veto

LAr scintillation light is captured and guided by fibres to SiPMs on either end, allowing for:

- Rejection events with simultaneous energy depositions in LAr surroundings
- Particle identification based on Ar excimer light proportions
- Auto-identification of correlated backgrounds
- Cooling HPGE detectors to approximately 87K

Detector holders, crafted from polyethylene naphthalate (PEN) to improve light collection

Current status: 90 tons of purified LAr (argon purity monitored in real time and kept at $\tau_3 = 1.15\ \mu s$)

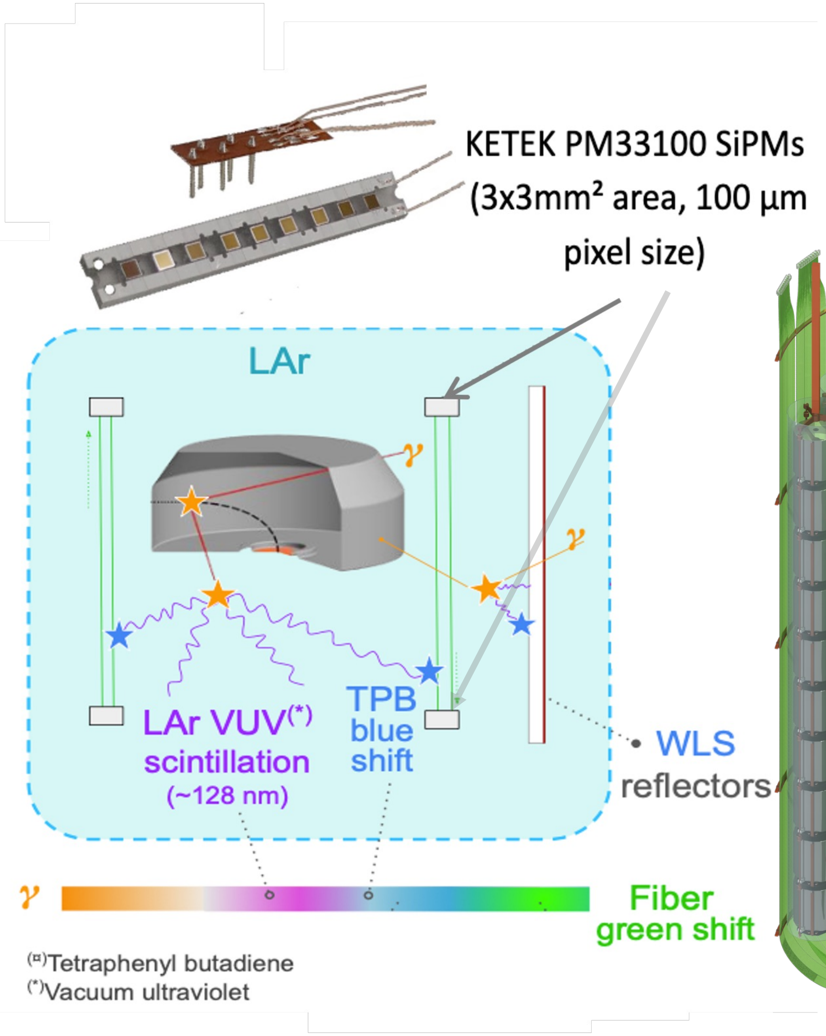
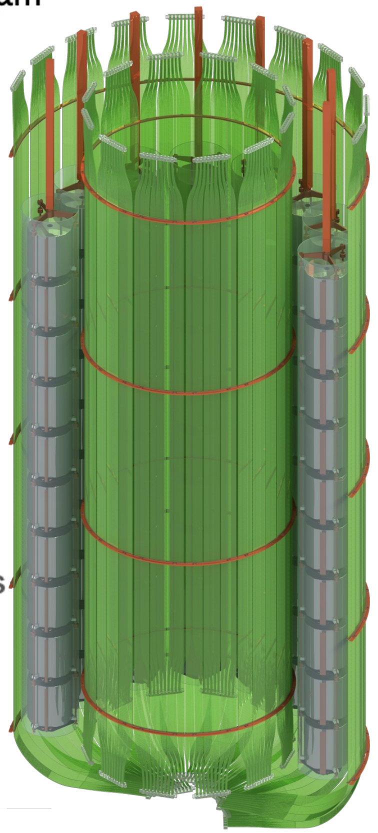
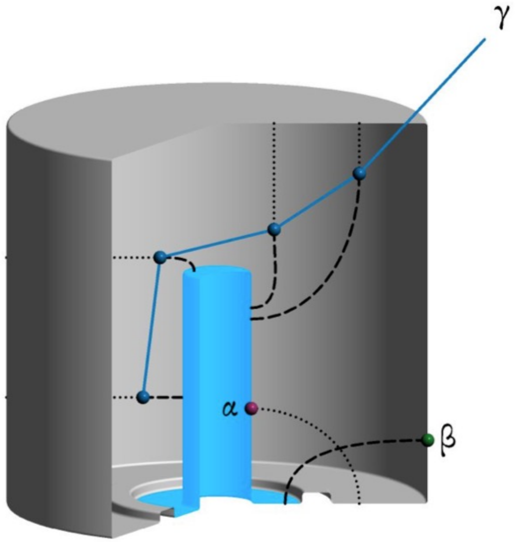


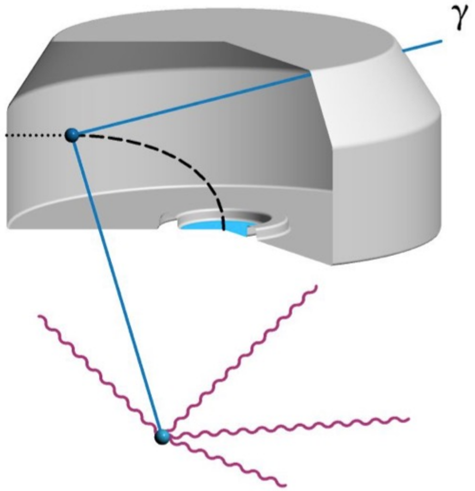
Image credit: G. Araujo

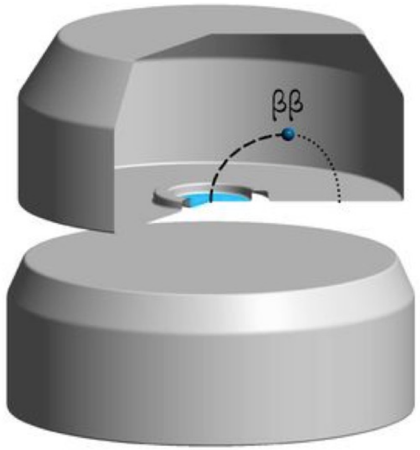


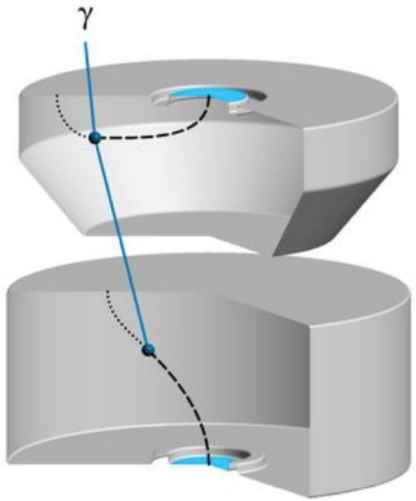
Background reduction

Single Ge	Ge + LAr	Single Ge	Multi Ge









Pulse Shape Discrimination (PSD)
- scattered multi-site events (MSE)
- surface events

LAr anti-coincidence
- intrinsic backgrounds
- Ge cosmogenics

Water Cherenkov anti-coincidence
- muons

Single-site event (SSE) topology
- $2\nu\beta\beta$
- $0\nu\beta\beta$

Detector multiplicity
- scattered events

LEGEND-1000

- A total of ~1000 kg of ^{76}Ge detectors (ICPC detectors enrichment up to 92%)
- Experimental site and detector array design to be determined
  - SNOLAB (CA): four, 250-kg modules
  - LNGS (IT): single reentrant tube (φ = 1.9 m)
  - with > 50 strings
- Background improvement of ~ ×20 ($B < 10^{-5}$ counts/(keV·kg·yr) w.r.t. LEGEND-200:
  - Radiopure *underground argon* (UGLAr) provides direct mitigation of ^{42}K background
- Many R&D projects on-going:
  - Increasing Ge detector mass
  - Neutron moderator in LAr
  - Polyethylene naphthalate (PEN) as wavelength-shifting materials for LAr scintillation

- Planned staged commissioning ~ 2030
- Goal: $T_{1/2} > 10^{28}$ yr (99.7% C.L.) sensitivity with 10 tonne·yr of exposure (10 yr runtime)