Neutrinoless double-beta decay with LEGEND

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Outline:

- The LEGEND experiment: general aspects
- The first step: LEGEND-200
- LEGEND-1000

The Legend Experiment: general aspects

- For the **physics motivation** and **experimental situation** of the 0νββ research field: *plenary talks of Giuliani and Benato*
- For news about **GERDA**: *Comellato's talk*

Large Enriched Germanium Experiment for Neutrinoless ββ Decay - LEGEND

LEGEND mission:

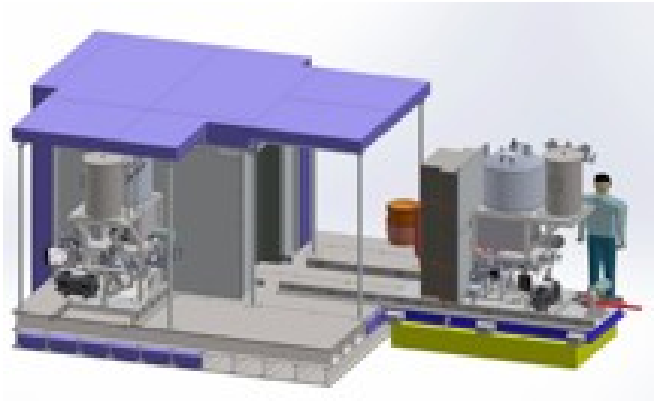
"The collaboration aims to develop a phased Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results"

The ^{76}Ge experiments: GERDA & MJD

GERDA

- Bare ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon/H_2O
- Phase I: 17 kg (HdM/IGEX)
- Phase II: 35.8 kg enriched in ^{76}Ge

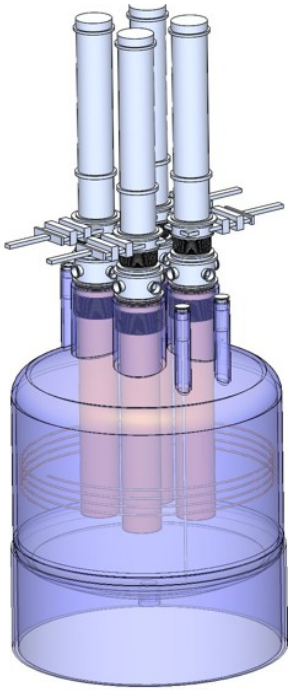
MAJORANA-DEMONSTRATOR (MJD)



- Arrays of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper/lead
- 30 kg enriched in ^{76}Ge

- **Physics goals**: degenerate mass range
- **Technology**: study of backgrounds and exp. techniques

- exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for future large scale ^{76}Ge experiment selecting the best technologies tested in GERDA & MJD



LEGEND: a staged approach

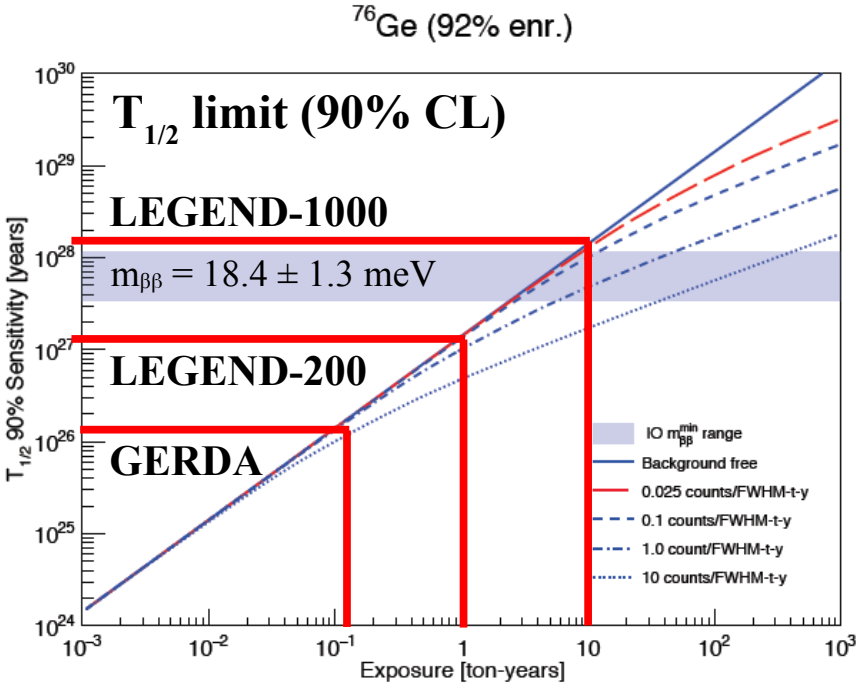
First Stage (LEGEND-200):

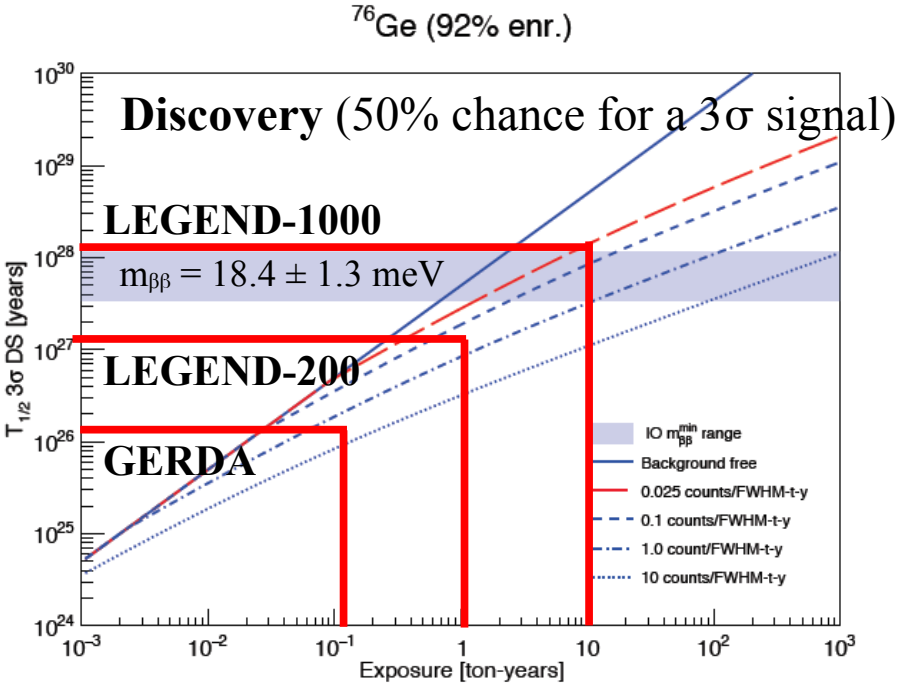
- upgrade of the existing infrastructure of GERDA up to 200 kg
- reduction of the BI of a factor 5 w.r.t. GERDA Phase II goal
- to reach 200 kg: 35 kg from GERDA + 30 kg from MJD. The remaining 140 kg are new

Further Stages (LEGEND-1000):

- 1000 kg (staged)
- timeline and budget: highest priority from DOE after the recent Portfolio review (July 2021)
- Background reduction of a factor 20 w.r.t. LEGEND-200
- Location to be defined
- Presently SNOLAB is the baseline site
- LNGS could be a solution: mitigation of cosmogenic $^{77(m)}$Ge background under investigation

sensitivity and discovery





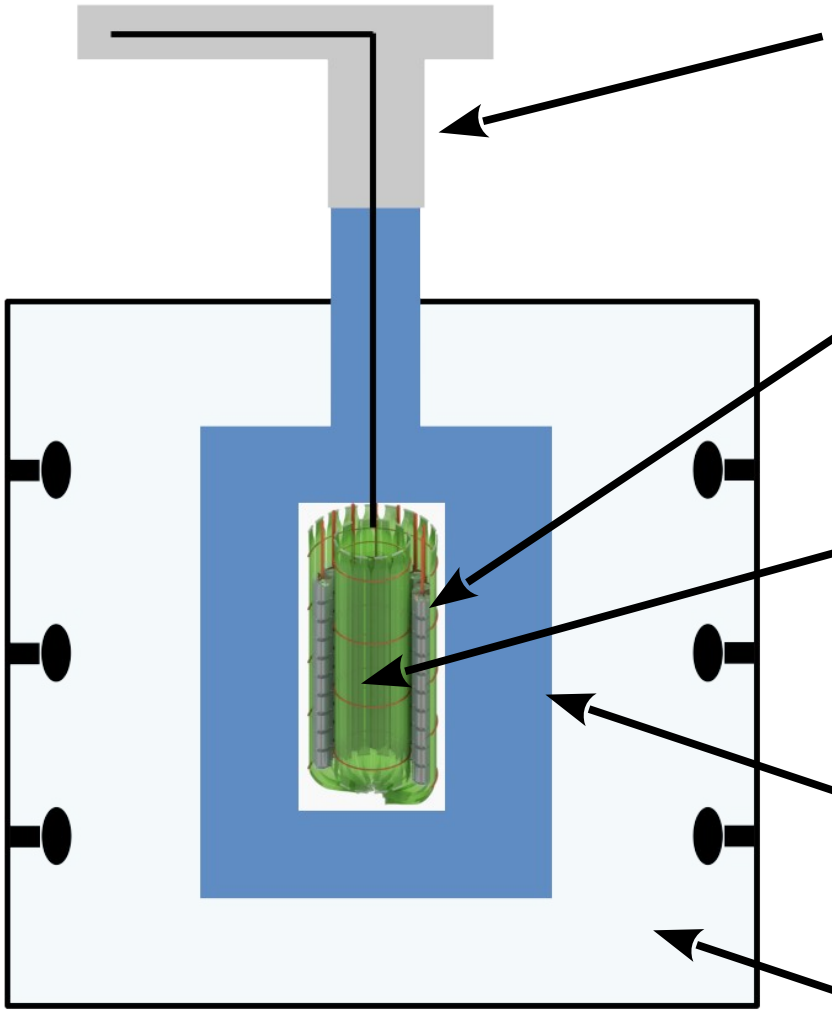
Plots details:

- ~69% efficiency (including: isotopic fraction, active volume fraction, analysis cuts)
- GERDA Phase II: 1.5 counts/(FWHM·ton·yr)
- LEGEND-200: 0.5 counts/(FWHM·ton·yr)
- LEGEND-1000: 0.025 counts/(FWHM·ton·yr)

N.B.: **background-free(*) condition is a prerequisite for a discovery**

(*) average expected bkg events < 1.0 in the ROI for the entire exposure

LEGEND: general layout



lock system:
for the deployment of the Ge detectors

detectors arrays:
strings of naked enriched germanium detectors

LAr veto:
shrouds with scintillating fibers for the detection of the light

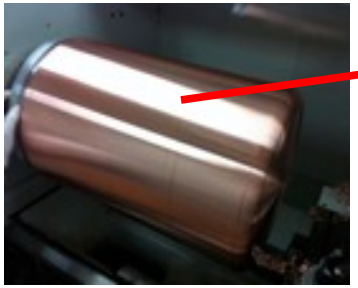
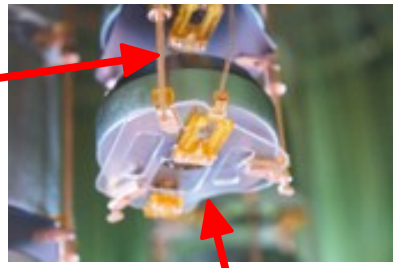
LAr cryostat:
coolant, shielding

water tank:
neutron moderator/absorber
muon Cherenkov veto
(if instrumented)

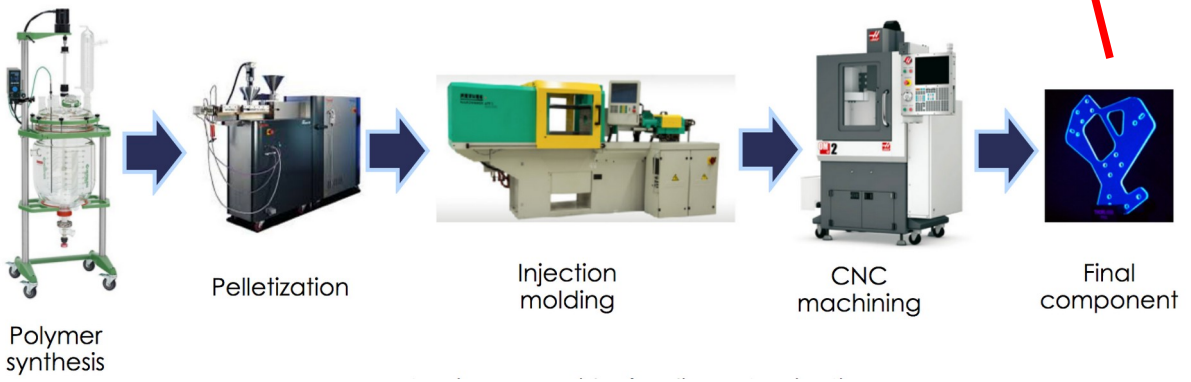
clean materials

- **Underground electroformed copper**
  reduces U/Th cosmogenic activation of ^{60}Co in Cu
  $< 0.017 \pm 0.03$ pg(^{238}U)/g
  $< 0.011 \pm 0.05$ pg(^{232}Th)/g

Underground electroformed copper

- **Polyethylene naphtalene (PEN)**
  replaces optically inactive structural materials
- Shift 128 nm LAr scintillation light to ~440 nm
- Yield strength higher than copper at cryogenic temperatures
- Evaluated in L-200

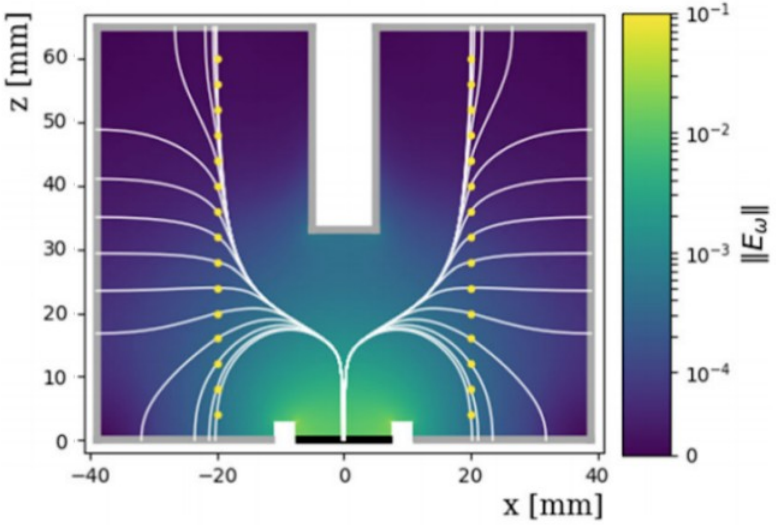


PEN: scintillating high purity detector support

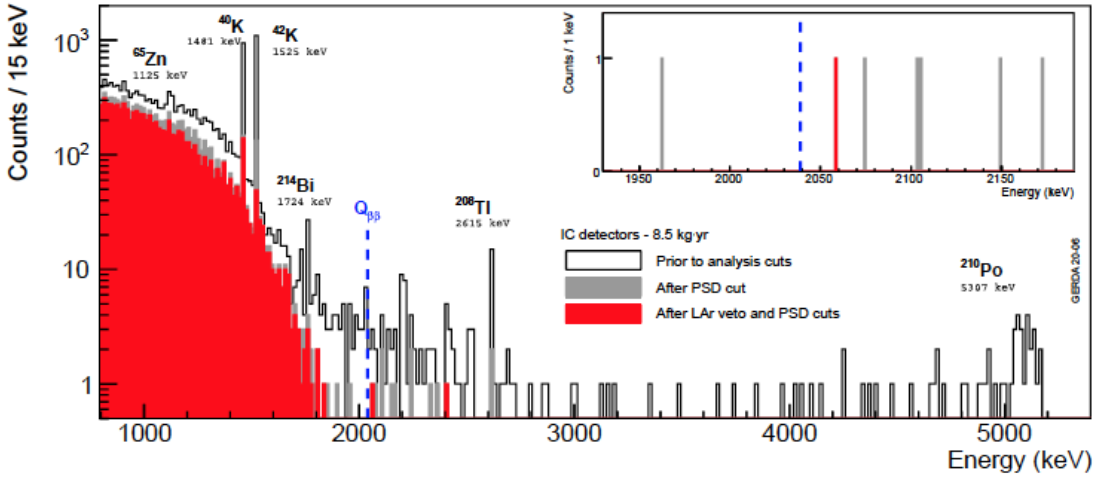
Inverted Coaxial Point Contact (ICPC) detector

- **ICPC** is the detector chosen for **LEGEND**
- It has the same **excellent energy resolution** and **pulse shape discrimination** power of the point-contact detector (used in GERDA and in MJD)
- but **higher mass** (> 2 kg) respect to the previous point-contact det. (~0.7-0.9 kg)
- this means less cables, less electronics channels ⟶ **less background**
- already **successfully used in GERDA** for 18 months

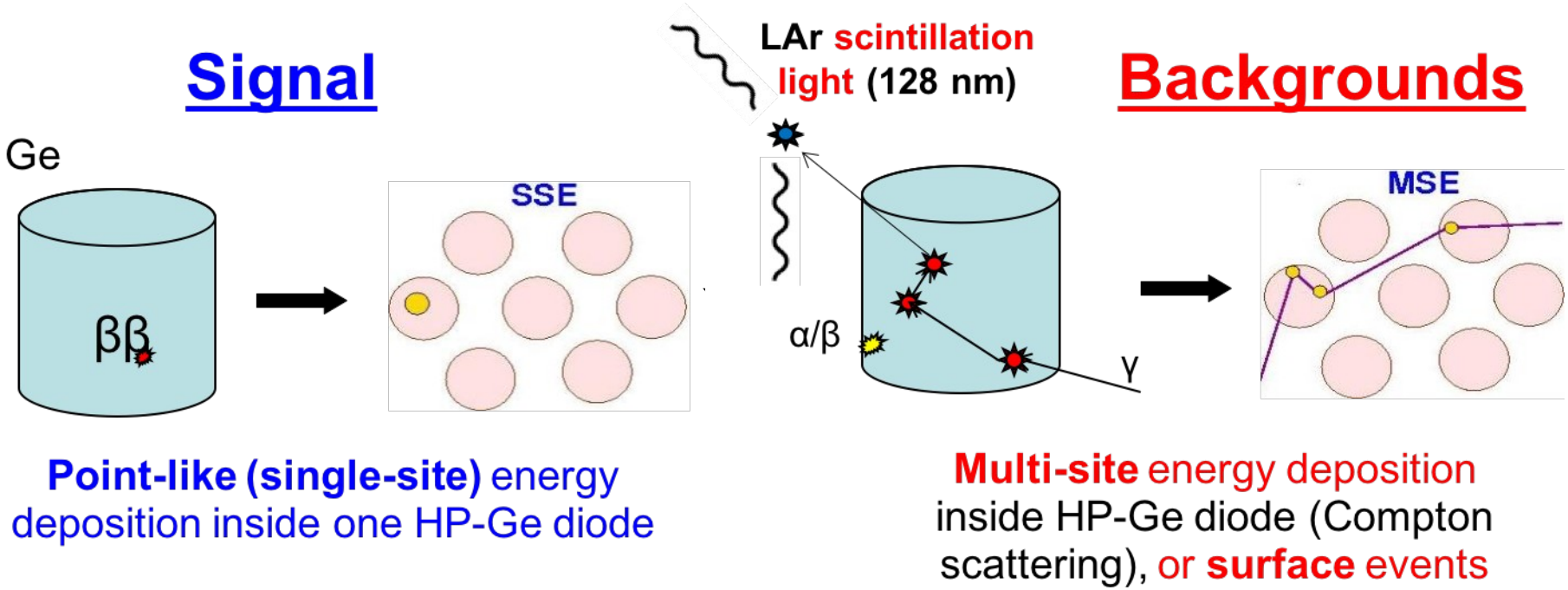
ICPC detector geometry



GERDA ICPC spectrum: exposure = 8.5 kg·yr
FWHM @ $Q_{\beta\beta}$ = 2.9 keV; BI = $4.9^{+7.3}_{-3.4}\cdot10^{-4}$cts/(keV·kg·yr)

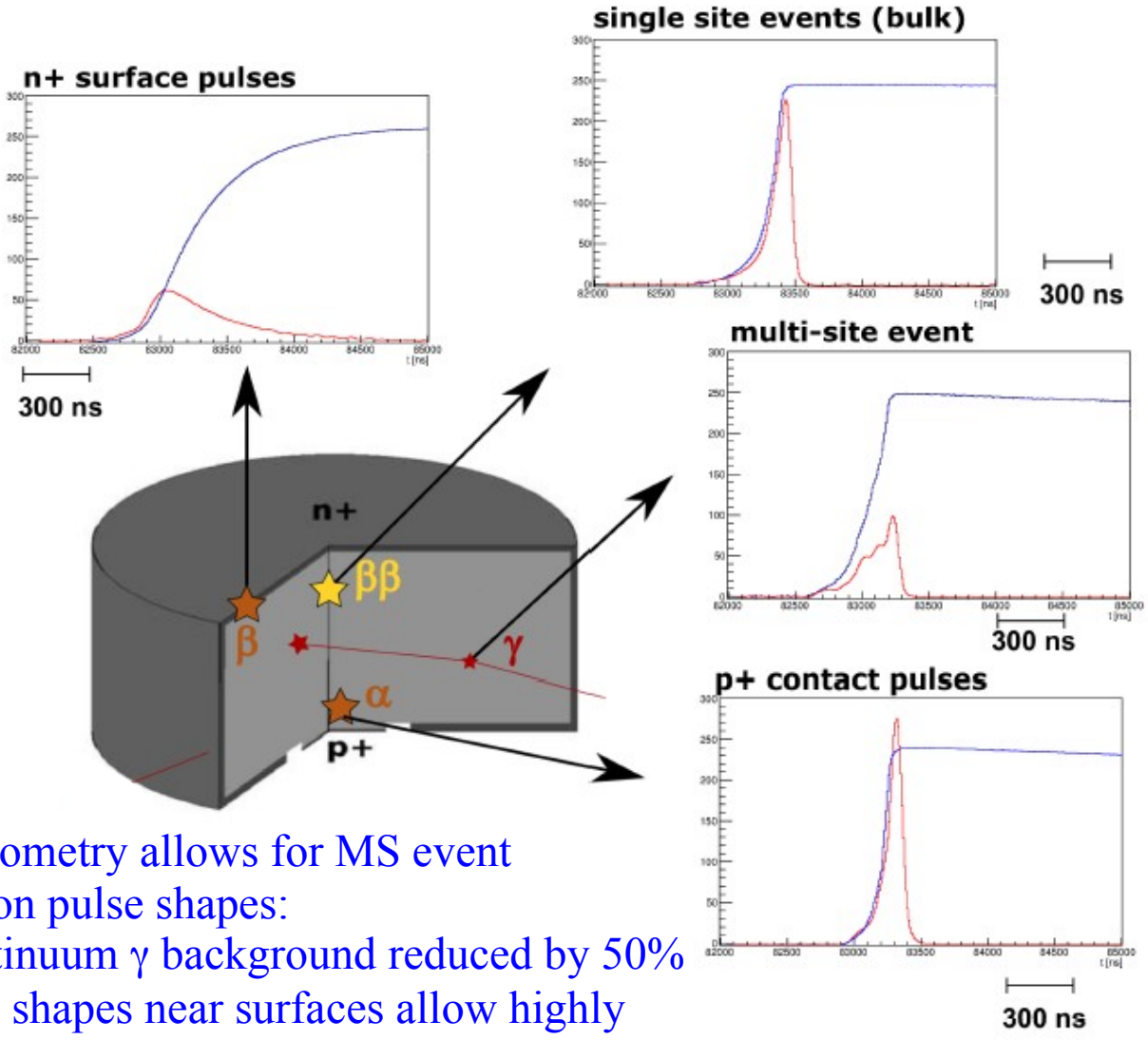


active background reduction tools



- **Anti-coincidence** with the **muon veto**
- Anti-coincidence **between detectors** (cuts multi-site)
- **Active veto** using LAr scintillation (LAr Veto)
- **Pulse shape** discrimination (PSD)

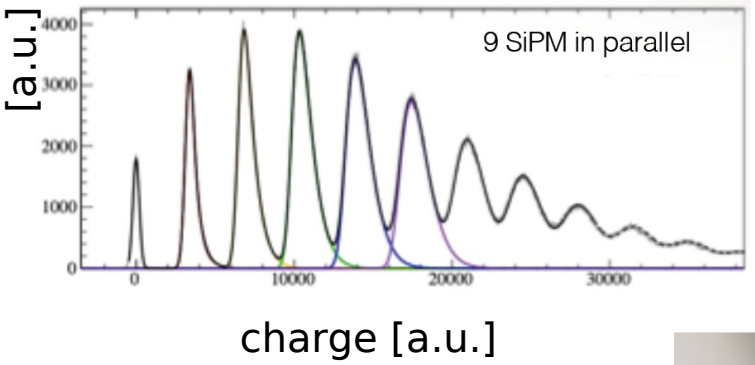
Pulse Shape Discrimination (PSD)

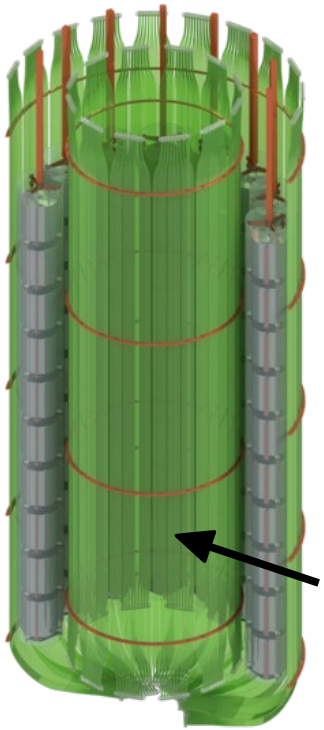


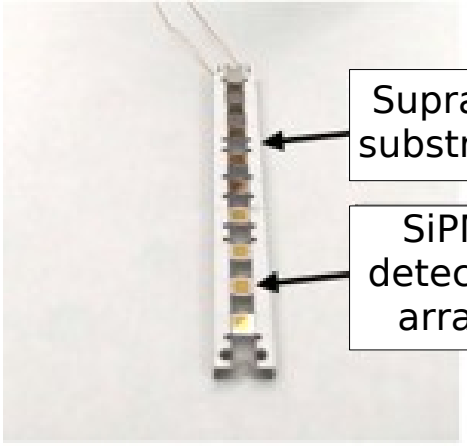
- Point-contact geometry allows for MS event rejection based on pulse shapes:
  - Compton continuum γ background reduced by 50%
- Distinctive pulse shapes near surfaces allow highly efficient surface event rejection:
  - α and β events reduced ≥ 99%

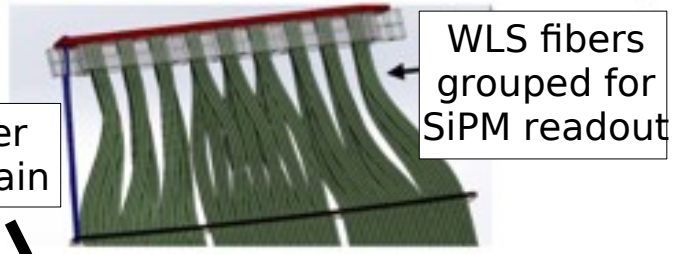
Liquid Argon Veto

- 128 nm LAr scintillation light readout by TPB coated WLS fibers coupled to SiPMs arrays
- Single photo-electron resolution







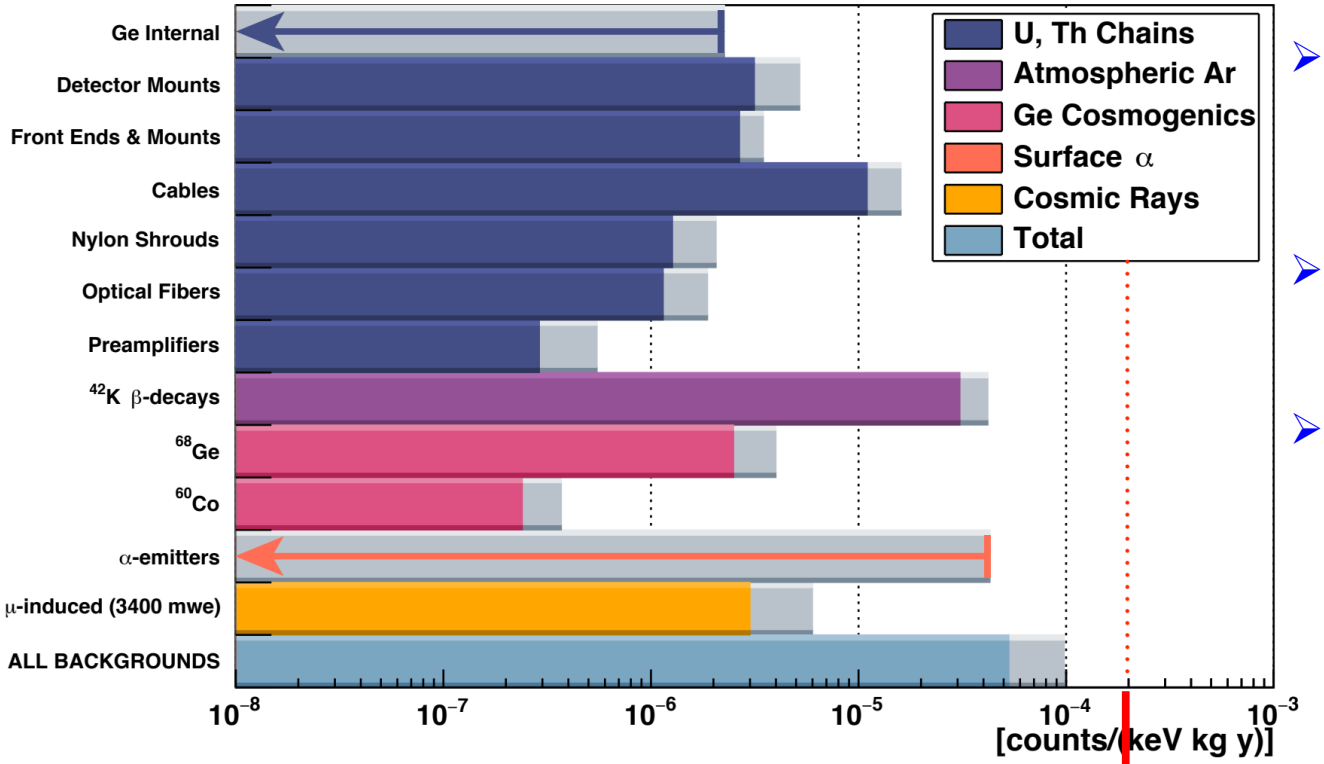


The first step: Legend-200

LEGEND-200

- L-200 uses the GERDA infrastructure (cryostat, clean room, water plan, …) at LNGS
- new elements: part of the enriched Ge detectors, cables, LAr veto, FE electronics, DAQ
- **February 2020**: L-200 took over the GERDA infrastructure
- **November 2021**: start commissioning
- End of 2022: start of the physics run with ~150 kg of enriched detectors
- In 2023: upgrade to ~ 200 kg of enriched detectors

LEGEND-200 background projections



- Monte Carlo simulations based on experimental data and material assays
- Assay limits correspond to the 90% CL upper limit
- Grey bands indicate uncertainties in overall background rejection efficiency

L-200 Background Index goal at $Q_{\beta\beta}$: **$2 \cdot 10^{-4}$ cts/(keV·kg·yr)**

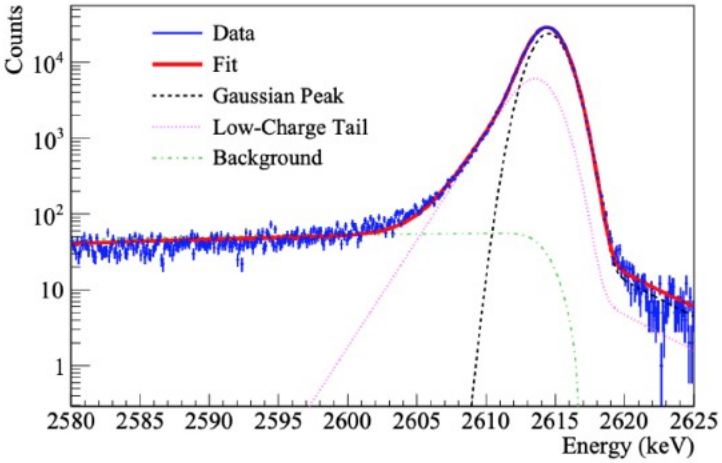
L-200 Sensitivity goal:

$T_{1/2} > 10^{27}$ years (90% CL) after **1 ton·yr** of exposure

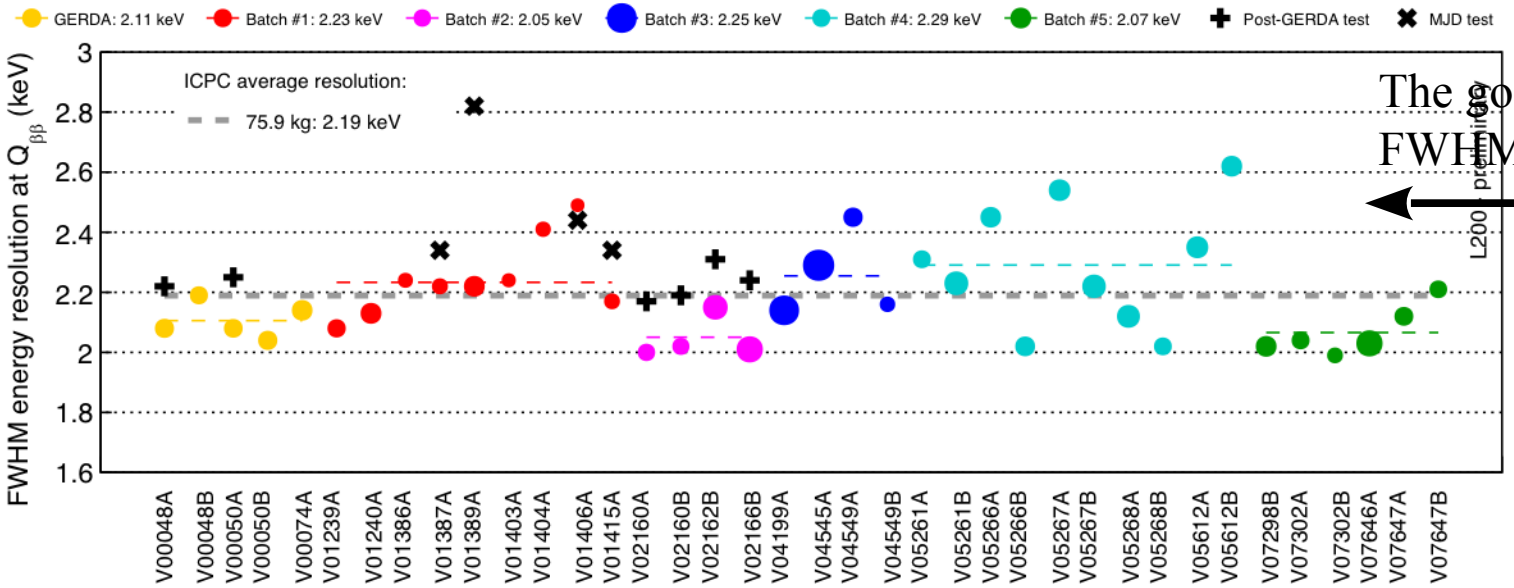
$m_{\beta\beta} < 34 - 78$ meV

ICPC: energy resolution

- Excellent energy resolution leads to lower backgrounds and higher discovery potential
- No resolution degradation seen in higher-mass ICPCs
- Well-understood peak shape, energy scale stability, and linearity (better than 0.1%) lead to improved confidence in results

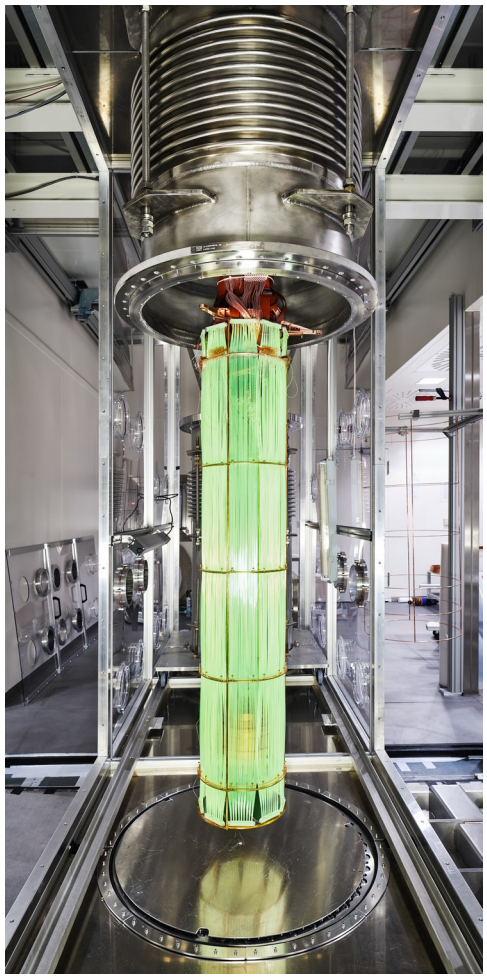


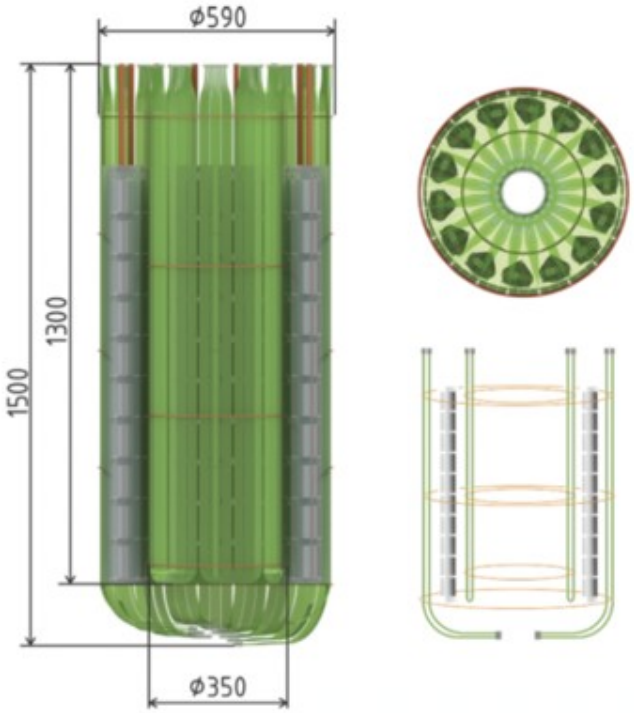
Energy resolution of ICPCs from characterization tests and calibration runs in GERDA and MJD

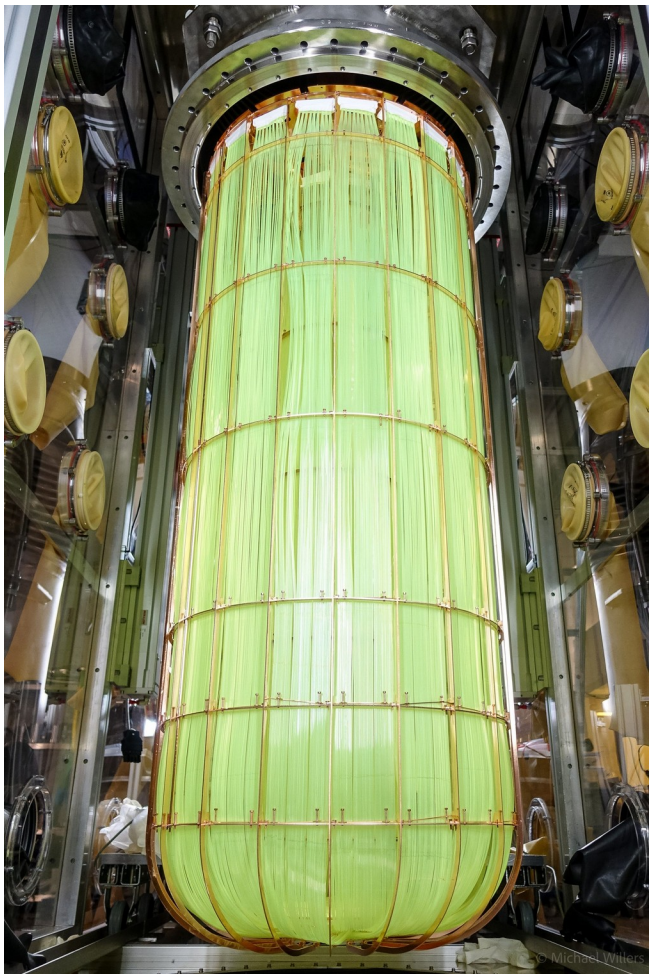


The goal is to reach a FWHM @ $Q_{\beta\beta}$ = **2.5 keV**

LAr veto



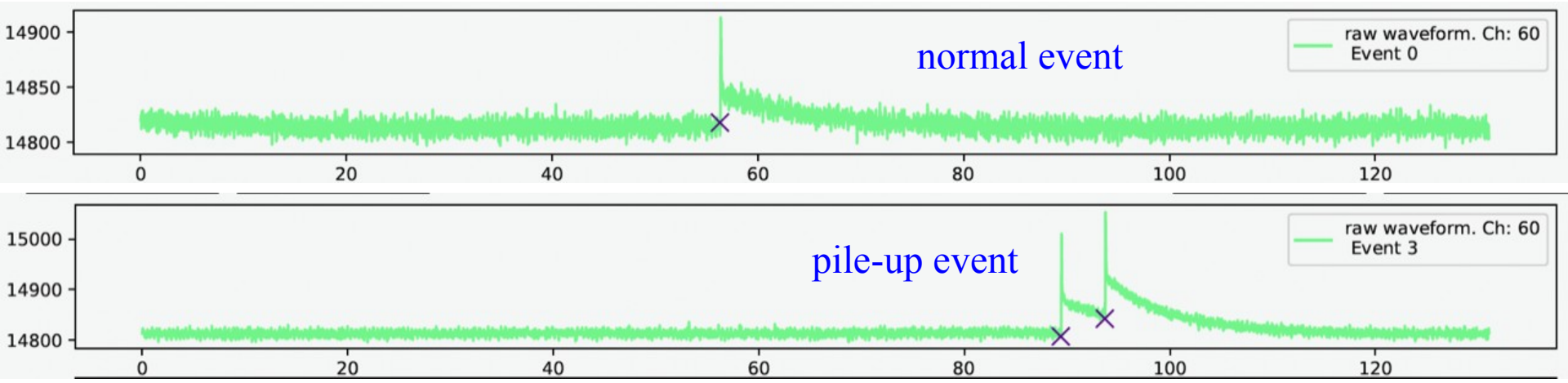


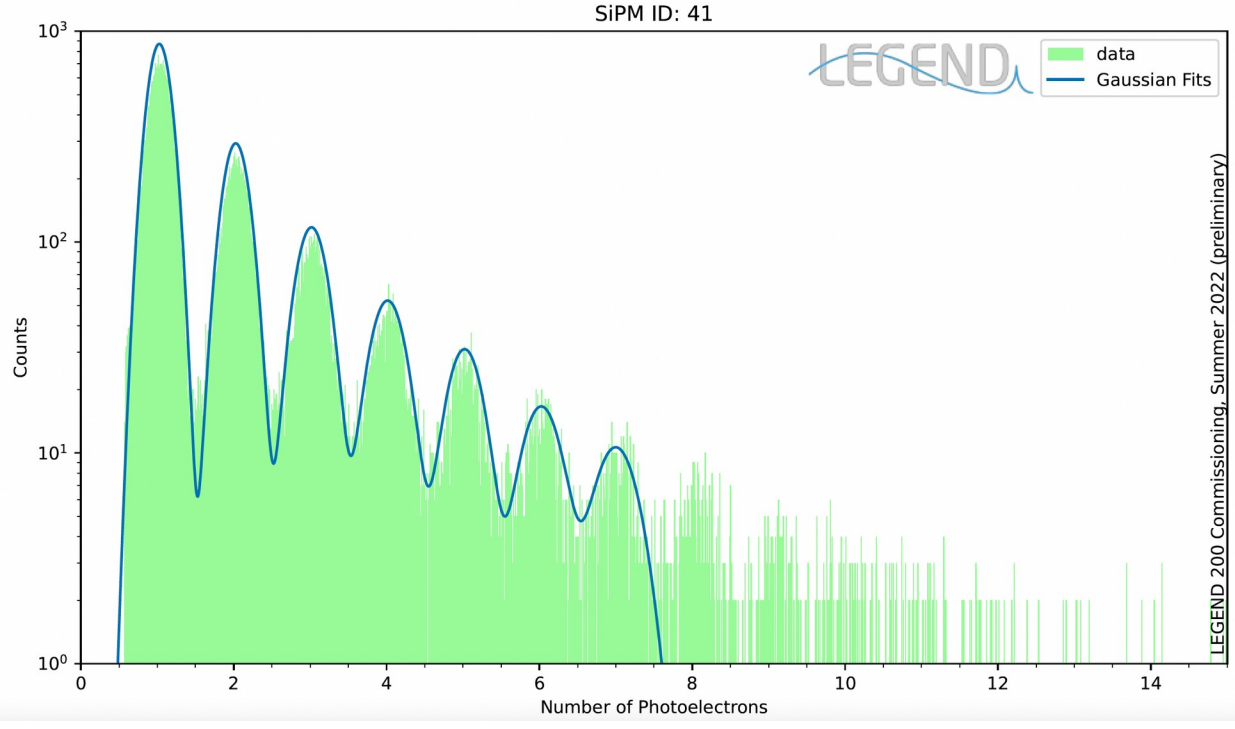


Internal LAr Veto :
9 modules, 18 readout channels

External LAr Veto:
20 modules, 40 readout channels

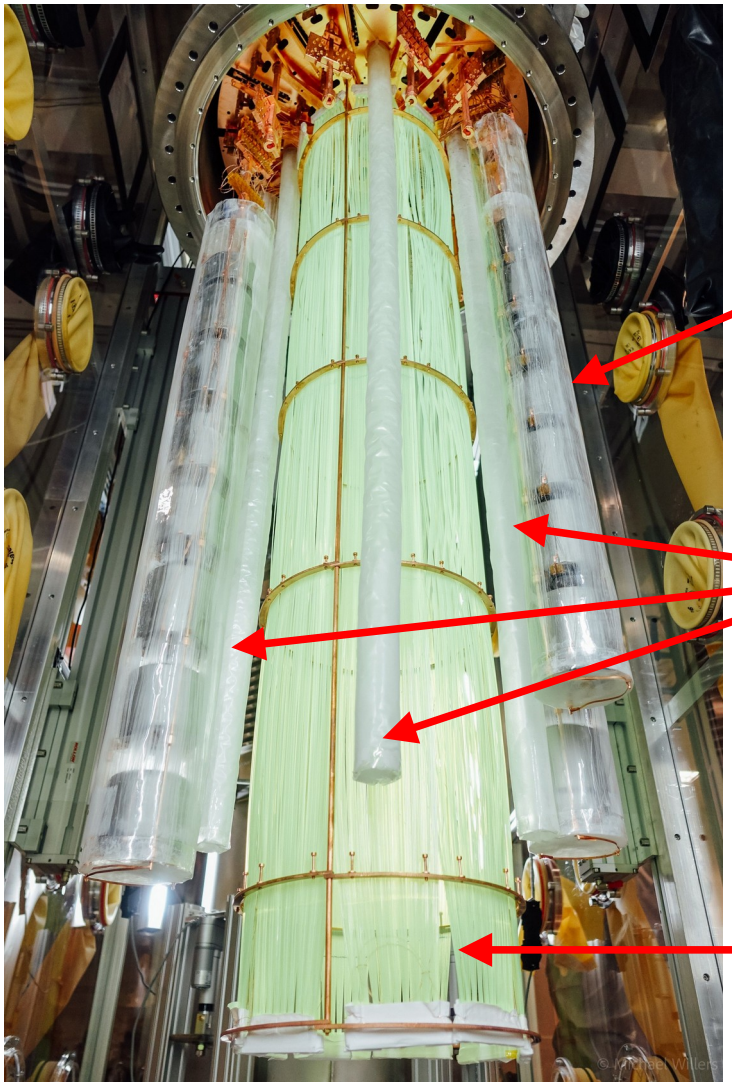
LAr veto: commissioning





- Single and pile-up events of a typical channel in events within [-1, 10] μs of a Ge detector trigger
- Excellent baseline (few tens of μV
- PE spectrum allows for SPE separation (small random coincidences rate)

LEGEND-200: present status

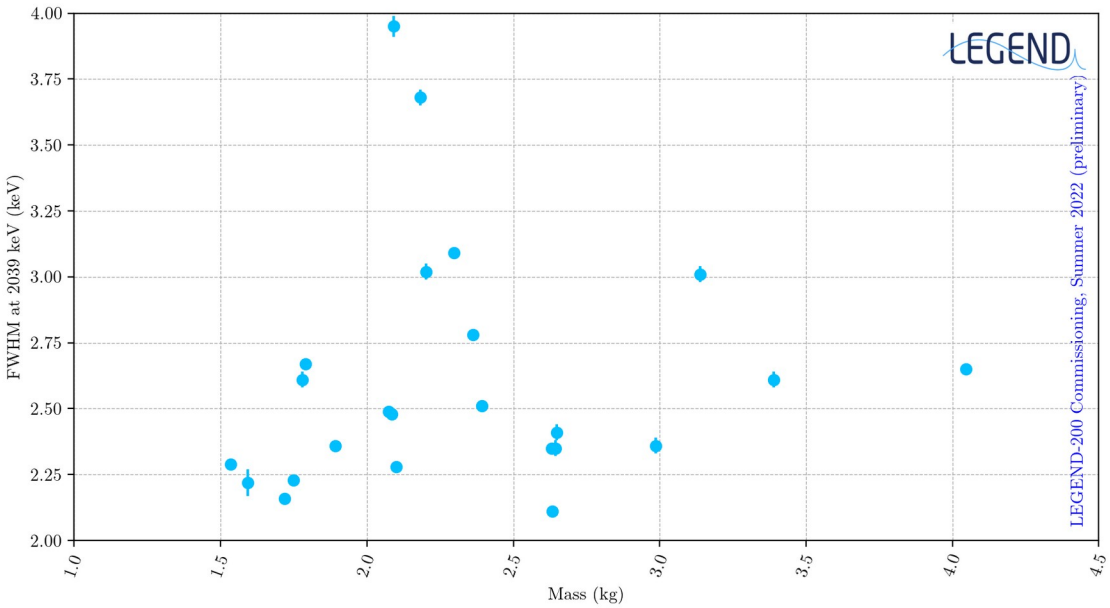


4 strings with 28 detectors (ICPC for ~64 kg of enriched Ge detectors)

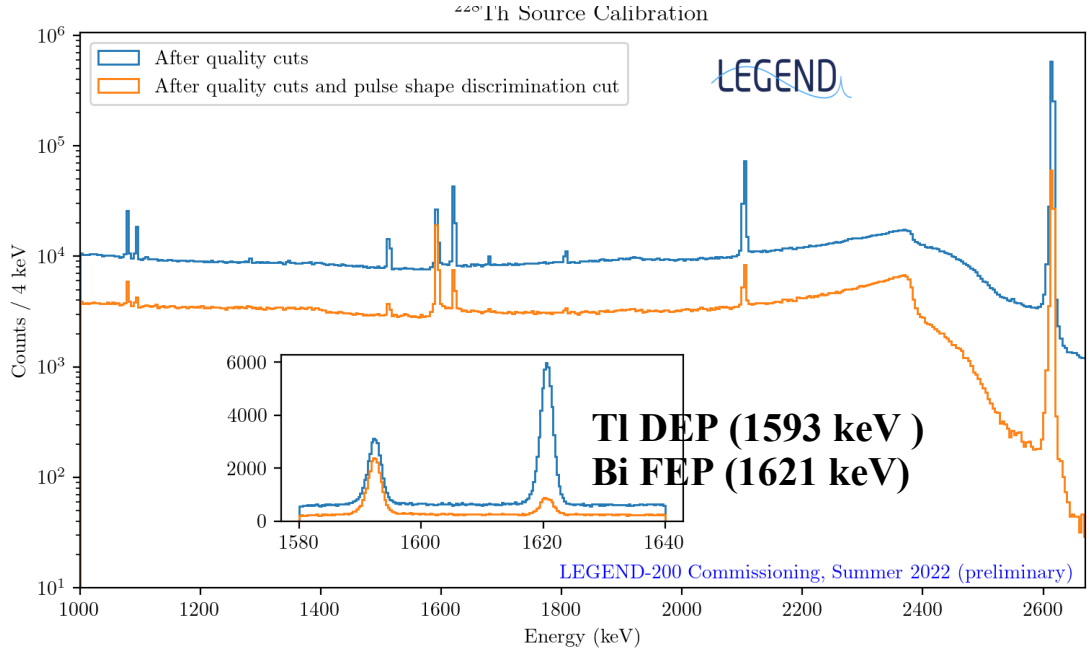
guides for the calibration sources

Internal LAr Veto

LEGEND-200: present status



- Preliminary energy resolution (FWHM) of the detectors vs their masses. (using data from Th calibration runs)
- Resolution does not depend on detector mass, heavier detectors sport excellent resolution
- Work on-going on read-out/noise to improve resolution on some channels



- First checks of the PSD cut (using data from Th calibration runs)

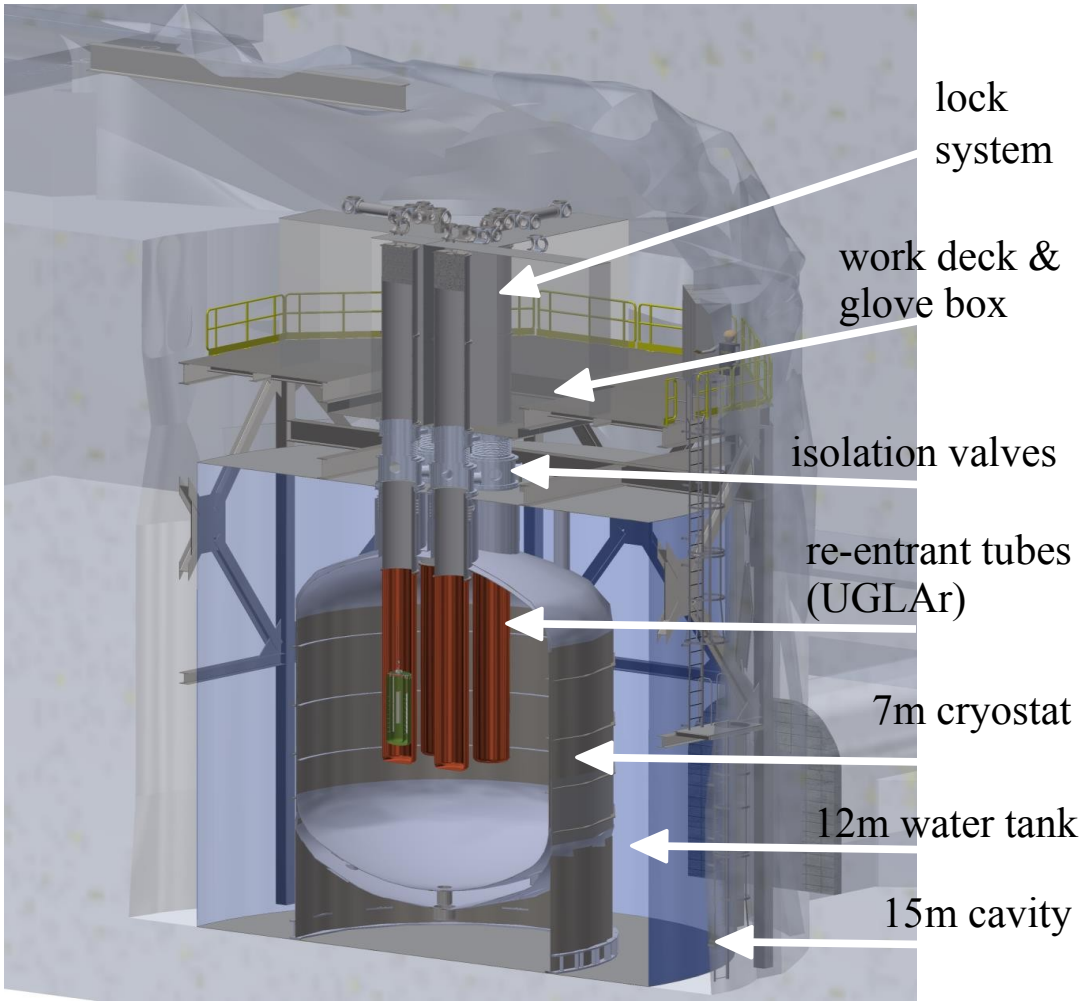
LEGEND-1000

LEGEND-1000: performance parameters

$0\nu\beta\beta$ decay isotope	^{76}Ge
$Q_{\beta\beta}$	2039 keV
Total mass	1000 kg
Energy resolution at $Q_{\beta\beta}$	2.5 keV FWHM
Overall signal acceptance	0.69
Live time goal	10 yr
Total exposure goal	10 t yr
Background goal	$< 1 \times 10^{-5}$ cts/(keV kg yr)
	< 0.025 cts/(FWHM t yr)
$T^{0\nu}_{1/2}$	1.3×10^{28} yr (99.7% C.L. discovery)
	1.6×10^{28} yr (90% C.L. sensitivity)
$m_{\beta\beta}$	9.4 – 21.4 meV (99.7% C.L. discovery)
	8.5 – 19.4 meV (90% C.L. sensitivity)

Cryostat and Water Tank

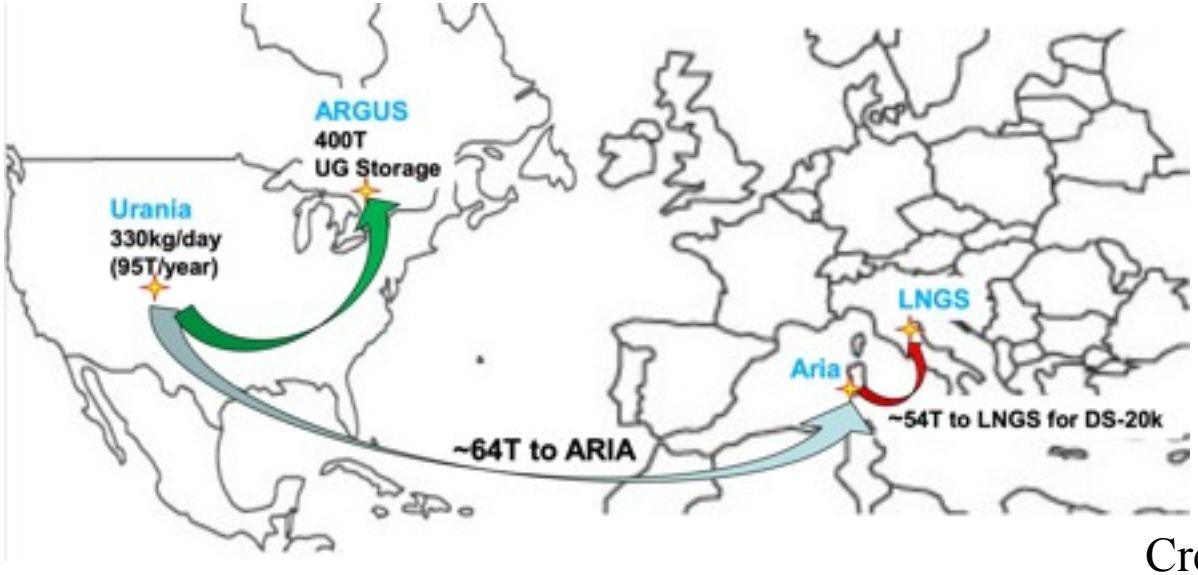
- Baseline cryostat allows deployment of 4 separate Ge payloads, each 250 kg of detectors (max. 420 kg)
- Allows staging: physics data taking with 1st payload
- 4 re-entrant tubes (1 m diam, 3.3 m^3) contain underground Ar



LEGEND-1000 @ SNOLAB

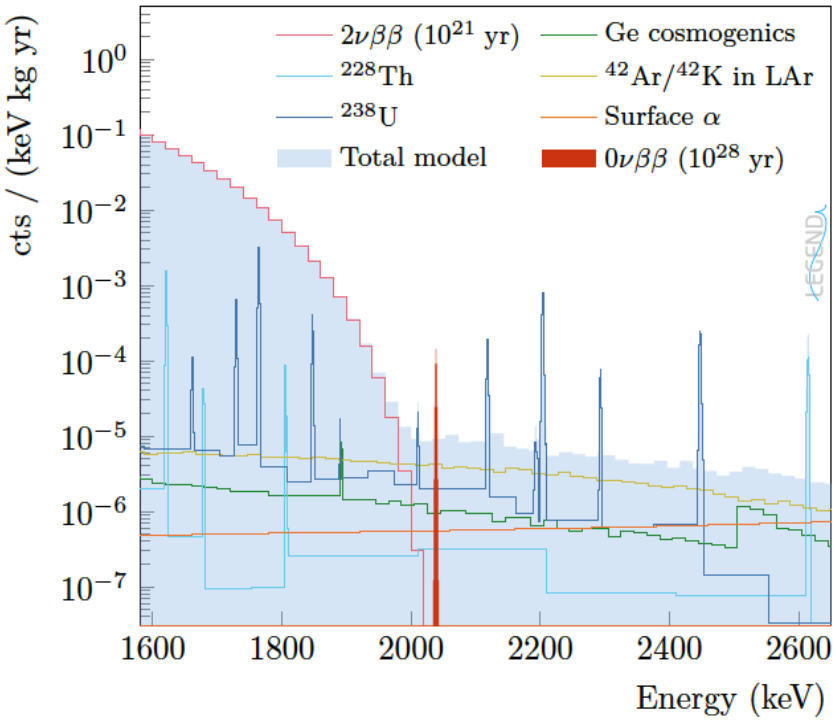
Underground Liquid Argon

- one of the most important background: ^{42}K from ^{42}Ar (produced in atmosphere by cosmic rays)
- in GERDA and in LEGEND-200 under control thanks to nylon minishrouds and PSD
- in LEGEND-1000 we think to use underground Ar (~18.5 t in the 4 re-entrant tubes)
- technology developed by the DarkSide collaboration
- expected a reduction factor of ~1400 in ^{42}Ar respect to the ^{42}Ar content in atmospheric Ar (similar to the reduction of ^{39}Ar)

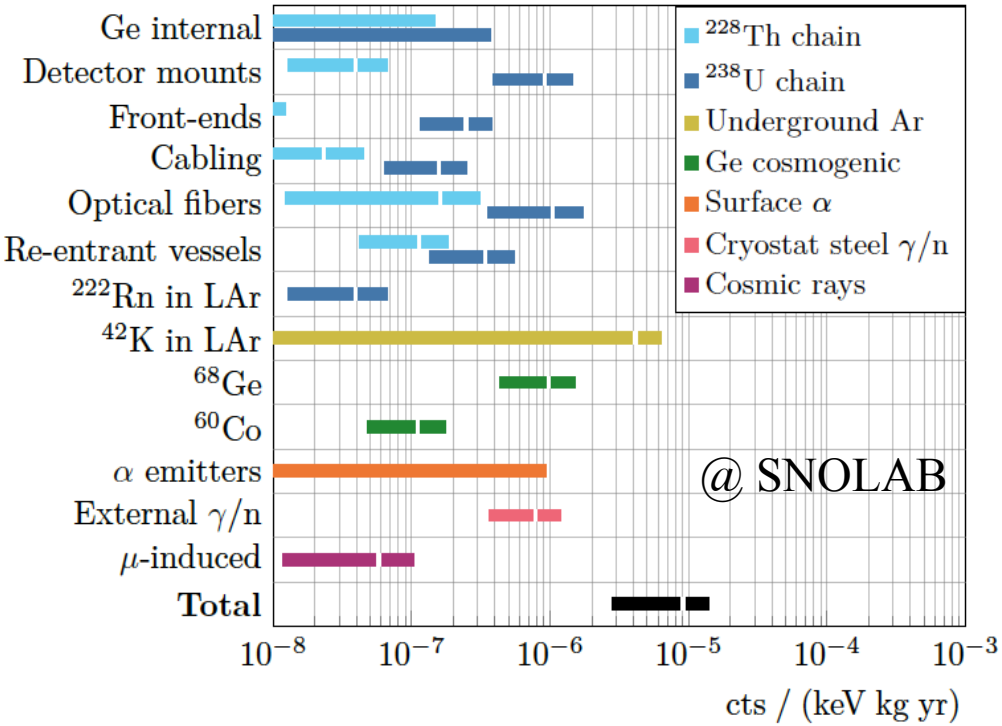


Credit: DarkSide/Argo collaboration

LEGEND-1000 background projections



Expected total spectrum from 2νββ decay and from all background components after all cuts



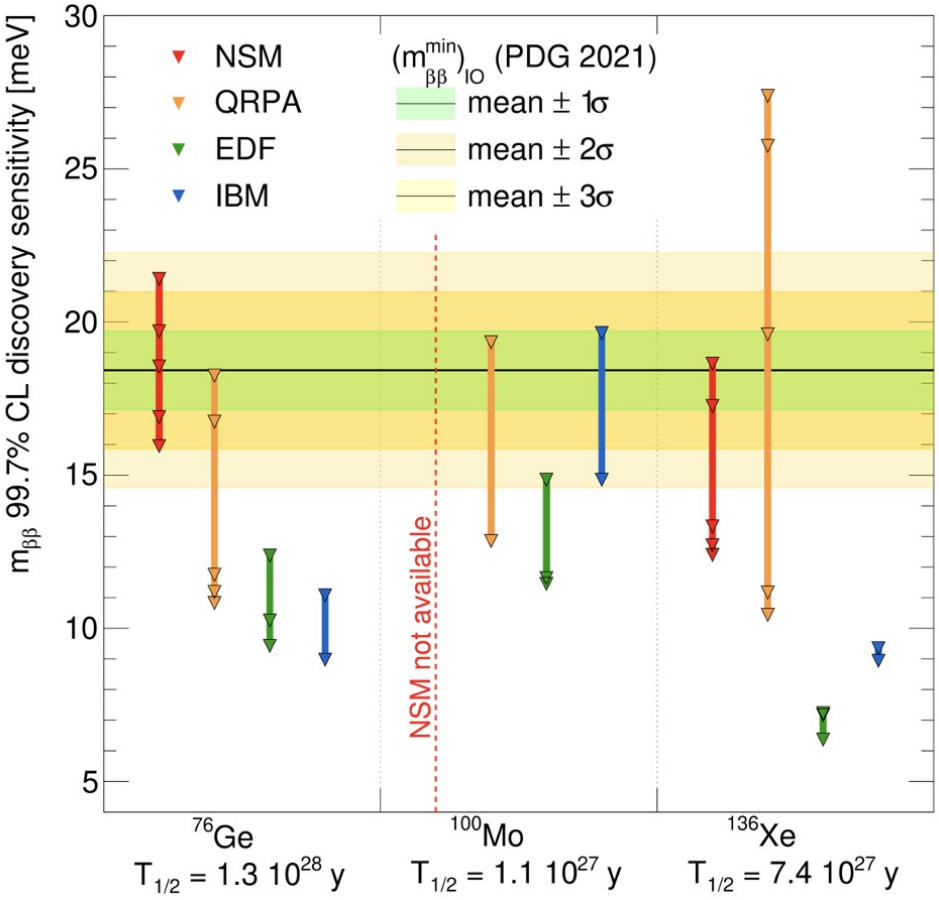
Expected contribution to the background index of L-1000 after all cuts:

BI = $9.1^{+6.3}_{-4.9} \cdot 10^{-6}$ cts/(keV·kg·yr)

LEGEND-1000 target sensitivities

- $m_{\beta\beta} = m_e / \sqrt{G g_A^4 M^2 T_{1/2}}$
- Inverted Ordering: $m_{\beta\beta} > 18.4 \pm 1.3$ meV
- the discovery sensitivity required depends on the matrix element used
- the range of values given depends on the matrix elements that has been calculated for each isotope
- LEGEND-1000 will fully test inverted order and a large part of the normal ordering

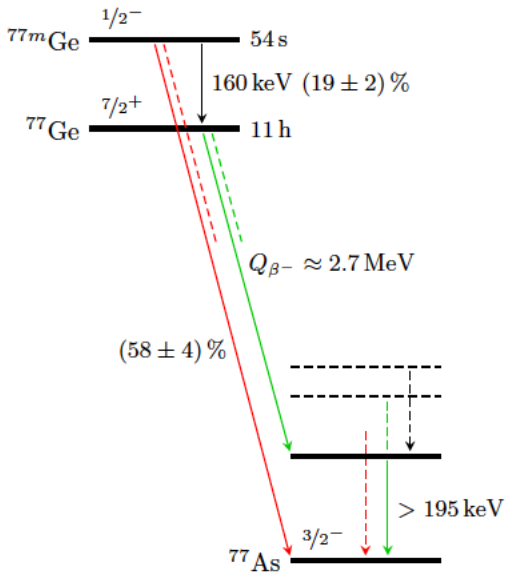
Agostini, Detwiler, Benato, Menendez, Vissani
PRC, 104 (4) L042501 (2021)

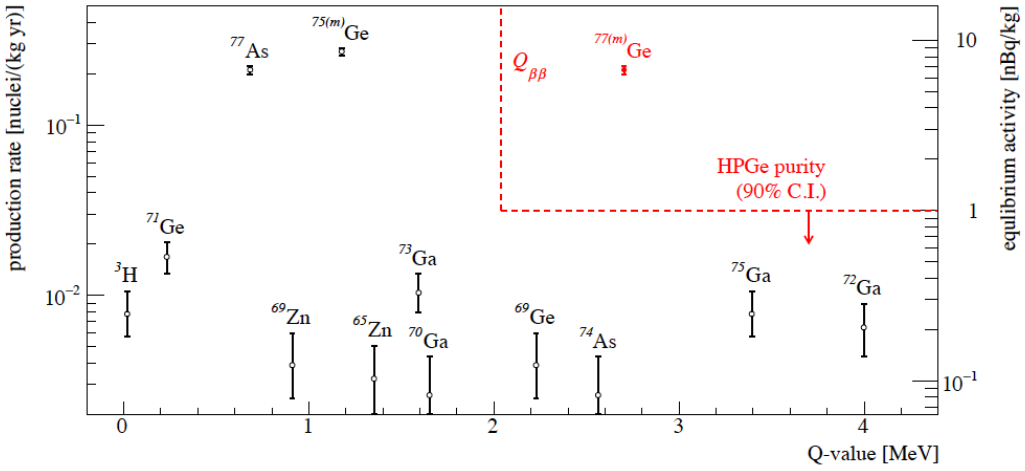


LEGEND CUPID NEXO

Alternative site: LNGS

- Baseline site: SNOLAB due to the depth: 6010 m.w.e.
  Reduction of a factor 100 of the muon flux and cosmogenic backgrounds respect to LNGS (3500 m.w.e.)
- Main concern is the muon-induced background ^{77m}Ge
- This background can be reduced at a manageable size by the use of delayed coincidence.
- Optimize rejection strategy with L-200





Summary

- The use of Ge detectors has permitted to obtain leading results in the search for $0\nu\beta\beta$ decay
- The LEGEND experiment combines the best technologies from the two Ge experiments: GERDA and MAJORANA-DEMONSTRATOR
- Key feature is the staged approach: leading results at each phase
- The **first phase is LEGEND-200 at LNGS** using the GERDA infrastructure: the aim is to reach the limit of 10^{27} yr in the half-life of the $0\nu\beta\beta$ decay of ^{76}Ge
- LEGEND-200 is **now in commissioning phase**, foreseen **start of physics run fall 2022**
- **The ultimate phase will be LEGEND-1000** able to reach an half-life greater than 10^{28} yr covering the entire inverted ordering region
- The LEGEND-1000 approval process is already begun: DOE Portfolio review (July 2021) for the choice of the best Ton-scale experiment put highest priority on LEGEND-1000.