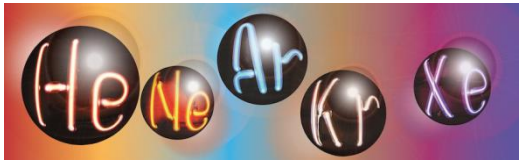
LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



Present status of the LEGEND experiment

Grzegorz Zuzel

on behalf of the LEGEND Collaboration

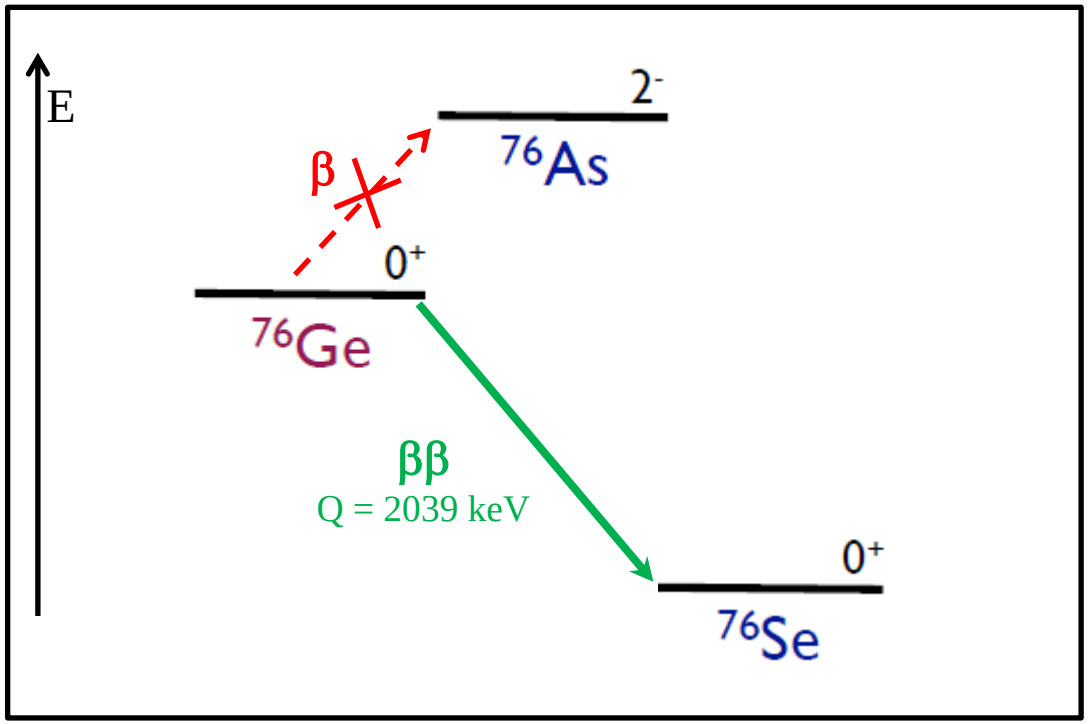
LIDINE 2022: LIght Detection In Noble Elements, 21-23.09.2022, Warsaw, Poland

Outline

- Double beta decay
- GERDA technology
- LEGEND overview
- LEGEND-200
- Summary

Double Beta Decay

In a number of even-even nuclei, β decay due to energy/angular momentum balance is forbidden, while double beta decay from a nucleus (A,Z) to (A, Z+2) is energetically allowed.



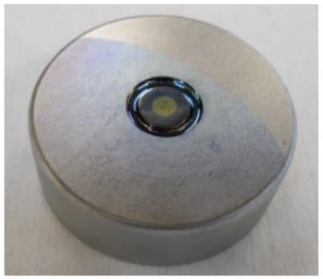
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

GERDA technology

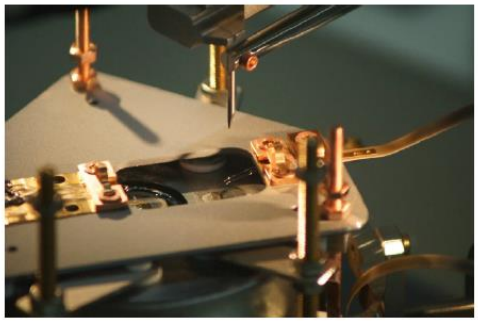
- GERDA (GERmanium Detector Array) has been designed to investigate neutrinoless double beta decay of ^{76}Ge ($Q_{\beta\beta}$ = 2039 keV)
  - Ge mono-crystals are very pure
  - Ge detectors have excellent energy resolution
  - Detector = source ($\varepsilon \approx 1$)
  - Enrichment required (7.4 % $\rightarrow$ 88 – 92 %)
  - **Bare HP ^{enr}Ge detectors immersed in LAr**
- Background (index) around $Q_{\beta\beta}$: 10^{-2} – 10^{-3} cts/(keV×kg×yr); 10 – 100 times lower compared to previous experiments (HdM/IGEX)

GERDA technology

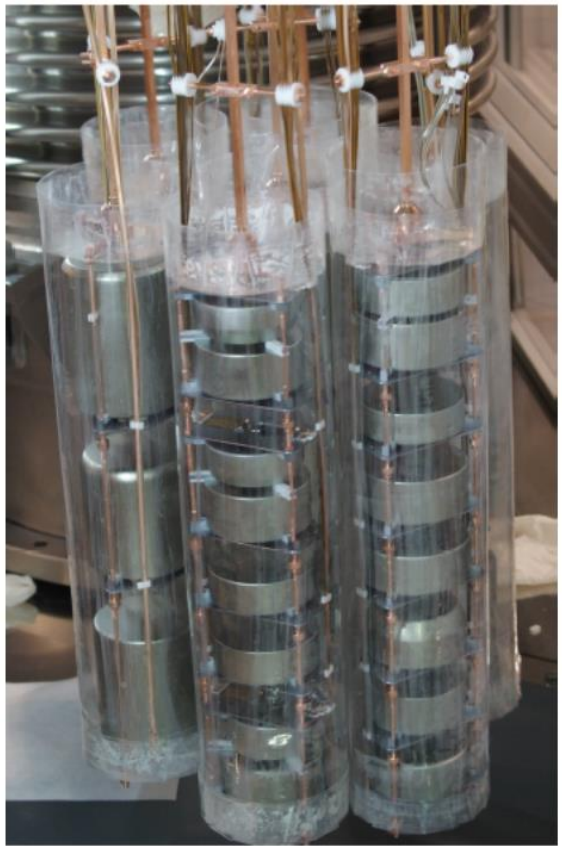
New low-mass detector holders (Si, Cu, PTFE)



New thick-window BEGe detectors



New signal and HV contacting by wire bonding flat ribbon cables



New TPB coated nylon mini-shrouds to reduce attraction of ^{42}K ions (from decays of ^{42}Ar) to n^+ surface

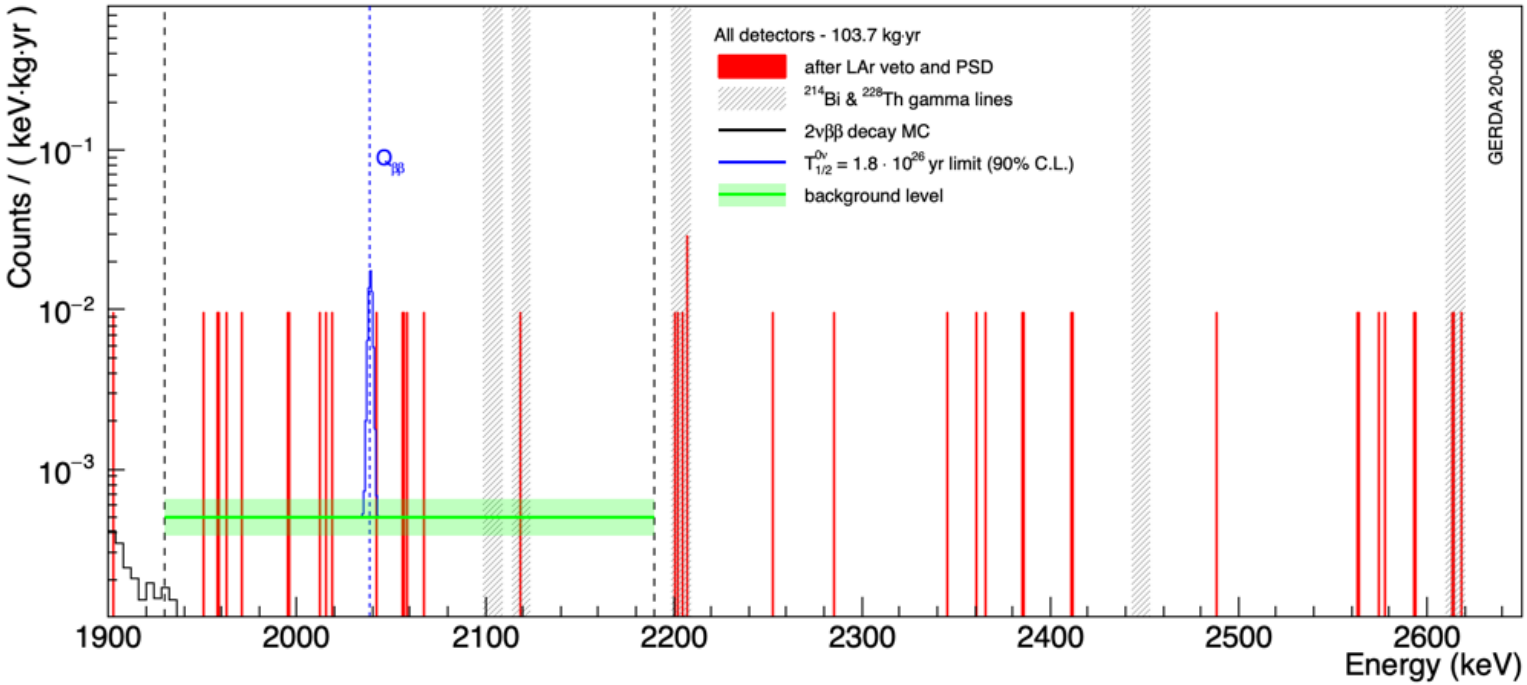
TBP = tetraphenyl butadiene

30 enriched BEGe (20.0 kg), 7 enriched coax (15.8 kg), 3 natural coax (7.6 kg) replaced later by 5 enriched IC detectors

GERDA final result

- ββ decay
- GERDA
- LEGEND
- LEGEND-200
- Summary

Statistical analysis based on detectors-wise partitioning over stable periods



Full data set (127.2 kg):

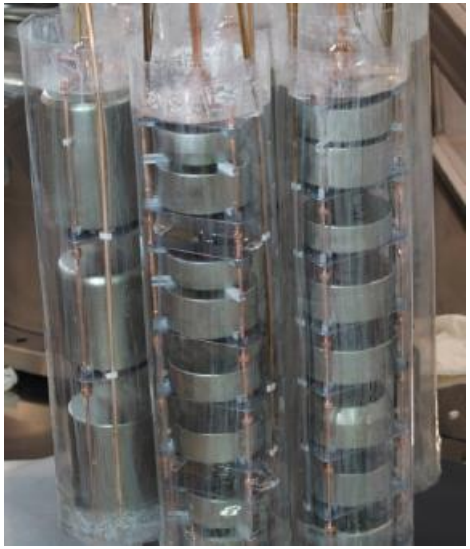
– BI: 5.2×10^{-4} cts/(keV×kg×yr), no events in ROI ($Q_{\beta\beta} \pm 2\sigma$)
– best fit $N_{0\nu} = 0$
– **$T_{1/2}$ ($0\nu\beta\beta$) $> 1.8 \times 10^{26}$ yr (90% C.L.)**
– **$m_{\beta\beta} \leq$ (80 – 182) meV**
– median sensitivity for limit setting: $T_{1/2}$ ($0\nu\beta\beta$) = 1.8×10^{26} yr at 90% C.L.

PRL 111 (2013) 122503
Nature 544 (2017) 47
PRL 120 (2018) 132503
Science 365, 1445 (2019)
PRL 125 (2020) 252502

LEGEND concept

- The goal of the LEGEND Collaboration is to design, construct, and field LEGEND-1000, a ton-scale experiment:
  „The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results".
- The LEGEND collaboration was formed in 2016 by a merger of the Majorana and GERDA collaborations, along with several new institutions (presently 266 members from 48 institutions and 11 countries)

GERDA: best background, LAr shield/veto



PRL 125 (2020) 252502

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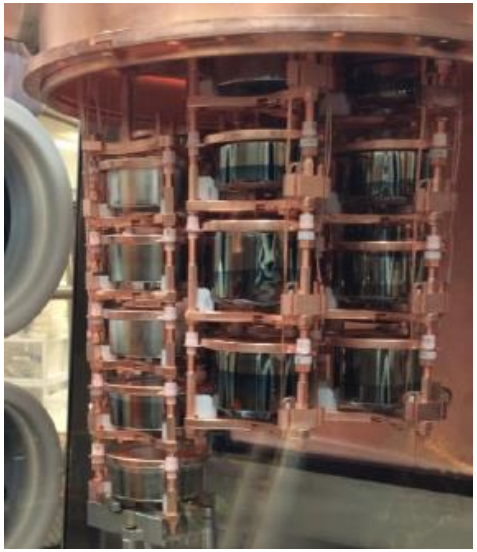
Majorana: low noise, best FWHM, high purity VFE, low threshold



Phys. Rev. C **100** (2019) 025501

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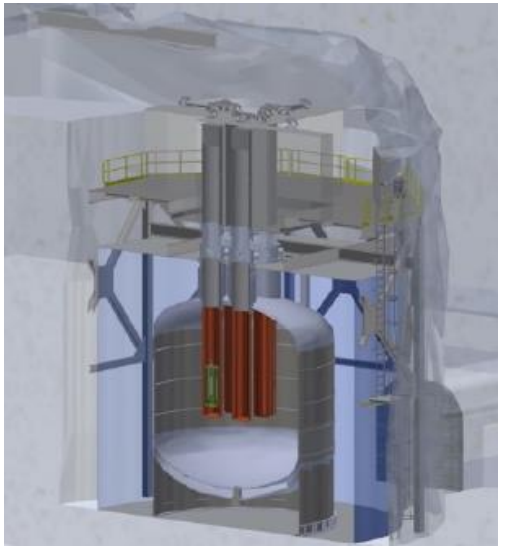
LEGEND-1000



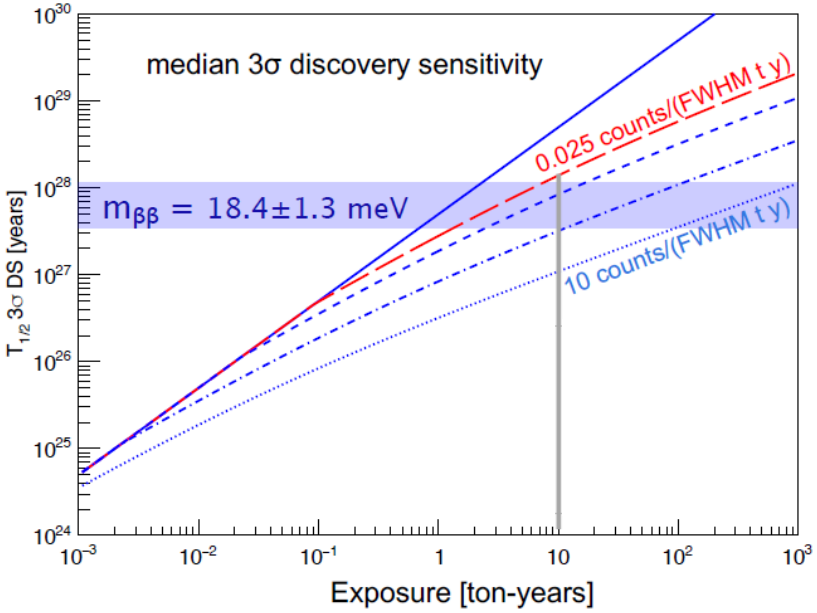
pCDR: arXiv:2107.11462

LEGEND overview

$T_{1/2}$ (0νββ) ~ 10^{28} yr → less than one decay per year per ton of material

- 10 t×yr of data is needed to get a few counts (1 t, 10 yr of data taking)
- very good signal-to-background ratio to get statistical significance
  → extremely low background (~20 times lower compared to GERDA)
  → best possible energy resolution (~2.5 keV at $Q_{\beta\beta}$)

Our background goal is the red line on the plot, 0.025 counts/(FWHM×t×yr), "quasi-background-free" operation: ≤ 1 background event expected in a 4σ ROI for 10 t×yr exposure



Background-free operation:

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a \cdot M \cdot T$$

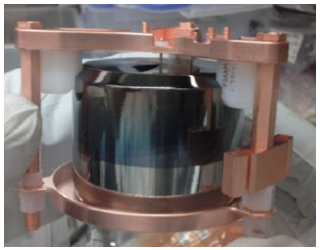
Non-zero background:

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

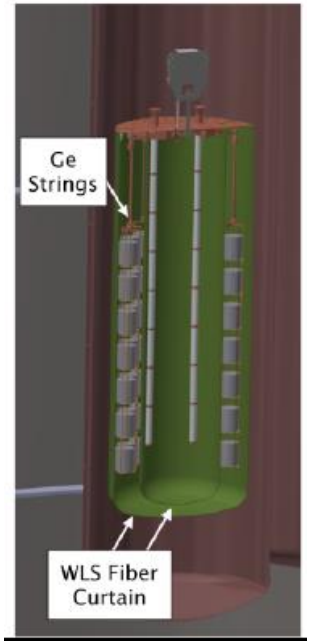
LEGEND overview

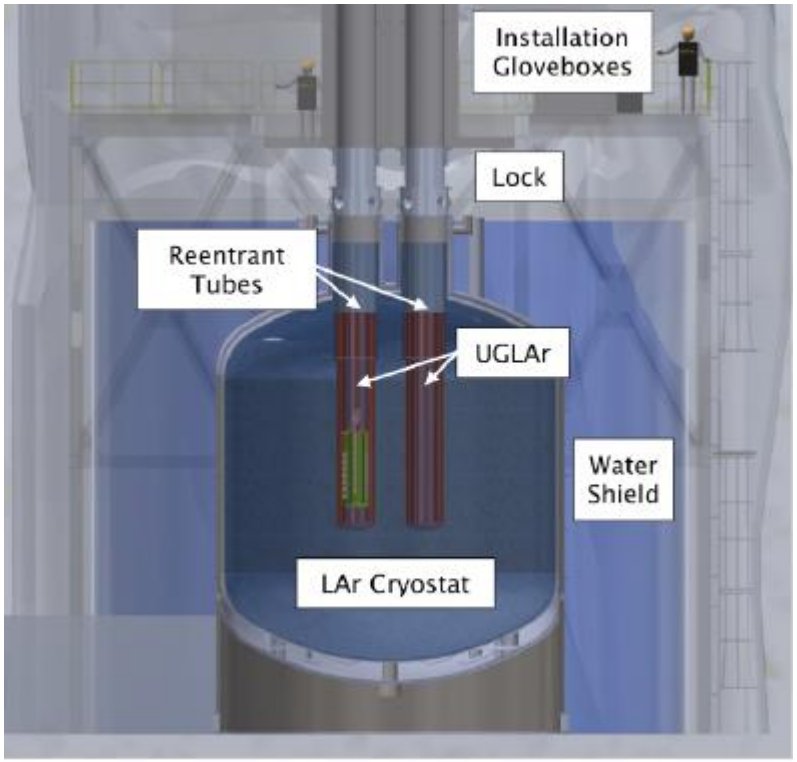
1000 kg of enriched Ge detectors (92% ^{76}Ge)

- HPGe detectors: 2.6 kg average mass
- Mounted in "strings" using components made from electro-formed Cu and scintillating plastic, PEN
- Strings organized in 4 arrays
- Underground-sourced LAr active shield
- Dual fiber-curtain LAr instrumentation
- 4 EFCu Reentrant tubes



HP^{enr}Ge detectors

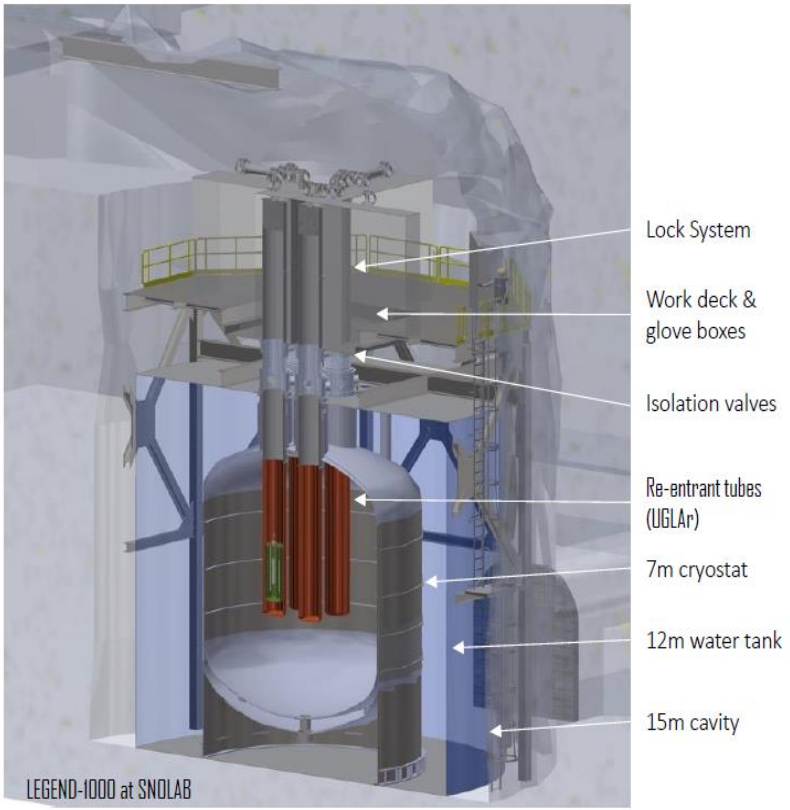




LEGEND overview

A deep-underground site is needed to shield the experiment from backgrounds generated by cosmic rays

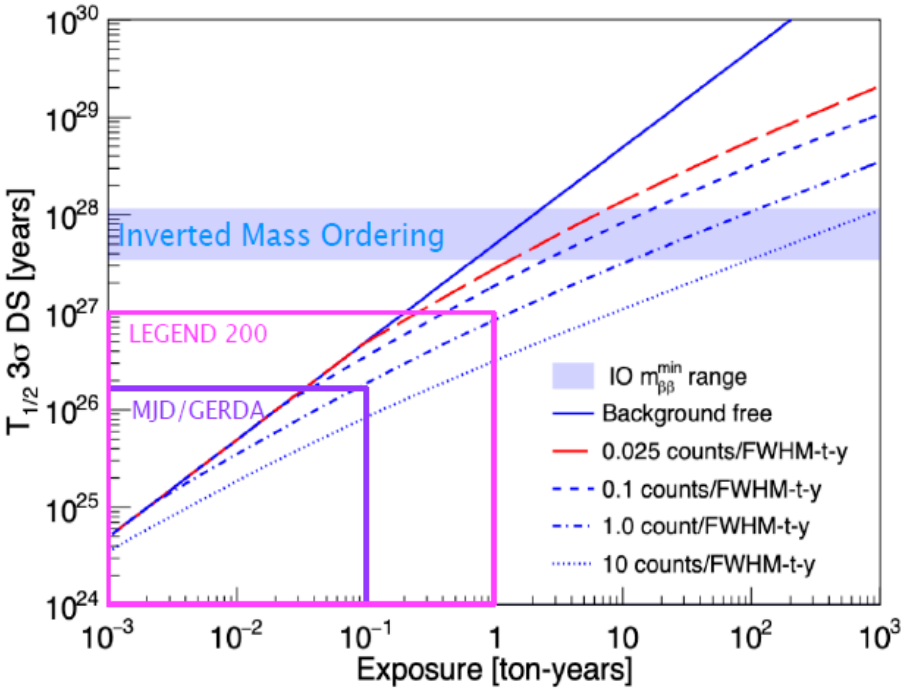
- Baseline site: The SNOLAB "Cryopit"
  - ~2 km underground (6000 m.w.e)
  - In an active nickel mine in Sudbury
  - Vertical access through mine shaft
- Aalternative site: LNGS (Italy)
  - 3500 m.w.e
  - Lower overburden somewhat increases background (can be tagged and reduced)
  - Horizontal access reduces cost/schedule risk
- Staff at both sites are actively involved in planning



We are currently assuming that we need to carry both sites forward through CD-1

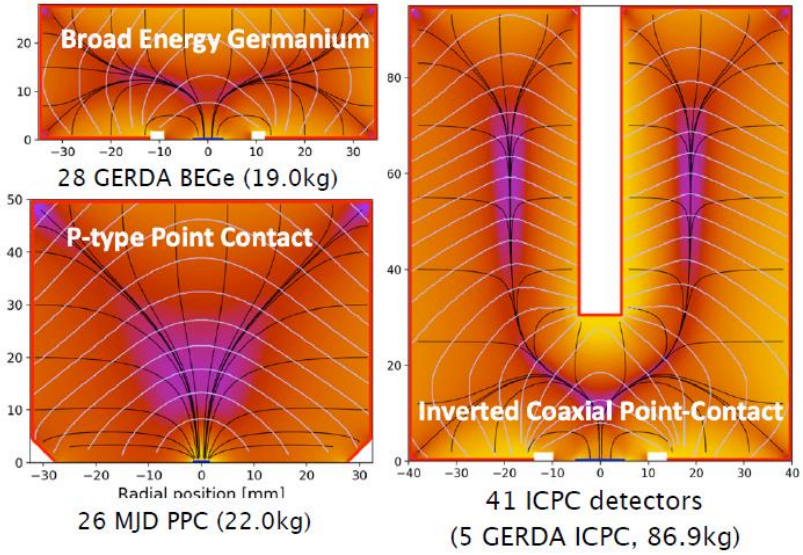
LEGEND-200

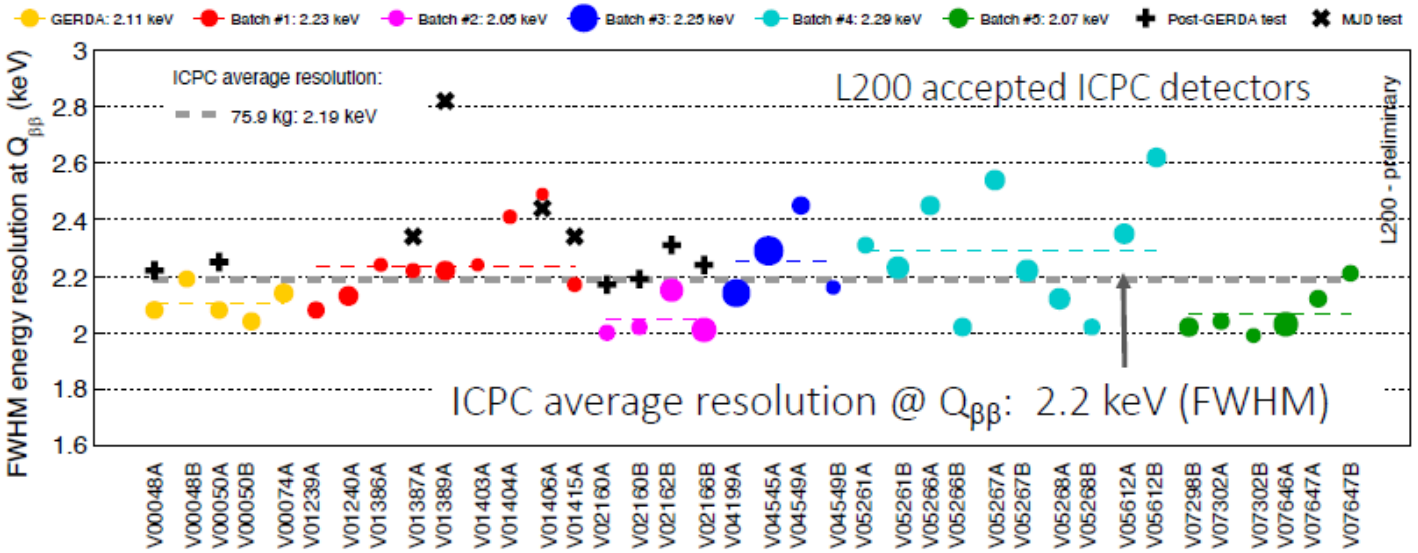
- 200 kg of HP^{enr}Ge in existing GERDA infrastructure at LNGS, Italy
- Anticipated exposure: 1 t×yr
- Expected 2.5 keV FWHM resolution
- Background goal: 3×reduction w.r.t GERDA, BI < 2×10^{-4} cts/(keV×kg×yr) ~ 0.6 cts/(FWHM×t×keV): quasi-background free operation for unambiguous discovery of 0νββ decay up to 10^{27} yr
  - Improved VFE electronics
  - Improved PSD methods
  - Improved LAr veto
- Anticipated data taking start in 2022



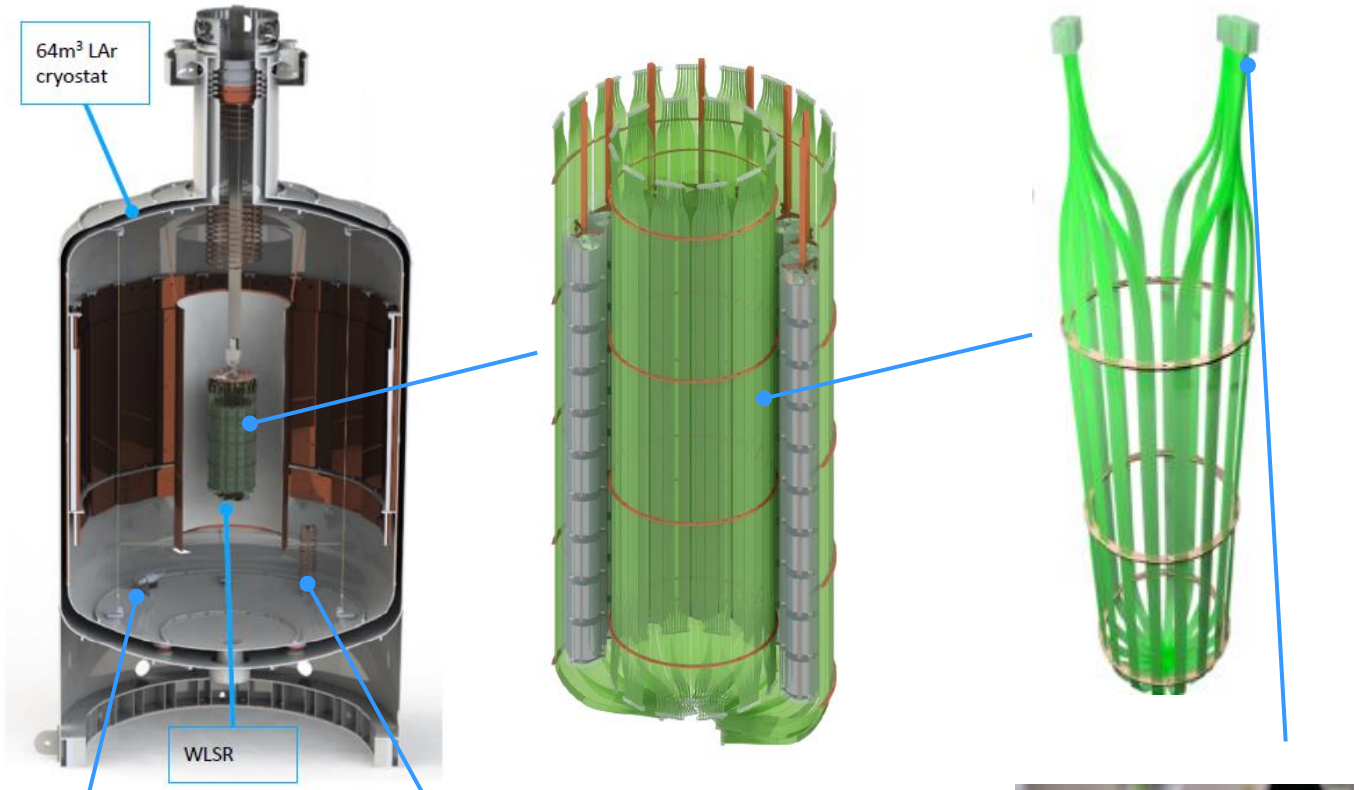
LEGEND-200 detectors

- p-type detectors: insensitive to alpha decays (^{210}Po) on n+ contact
- Small p+ contact: event topology discrimination (PSD)
- Large-mass ICPC detectors (60 % of total detector inventory): about 4× lower backgrounds with respect to BEGe/PPC
- Proven long-term stable operation in liquid argon





LEGEND-200 LAr veto



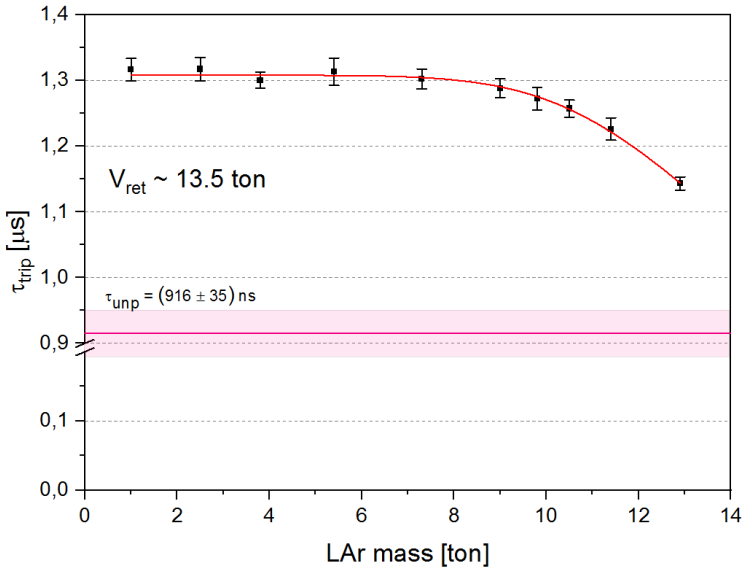
Liquid Argon Pump

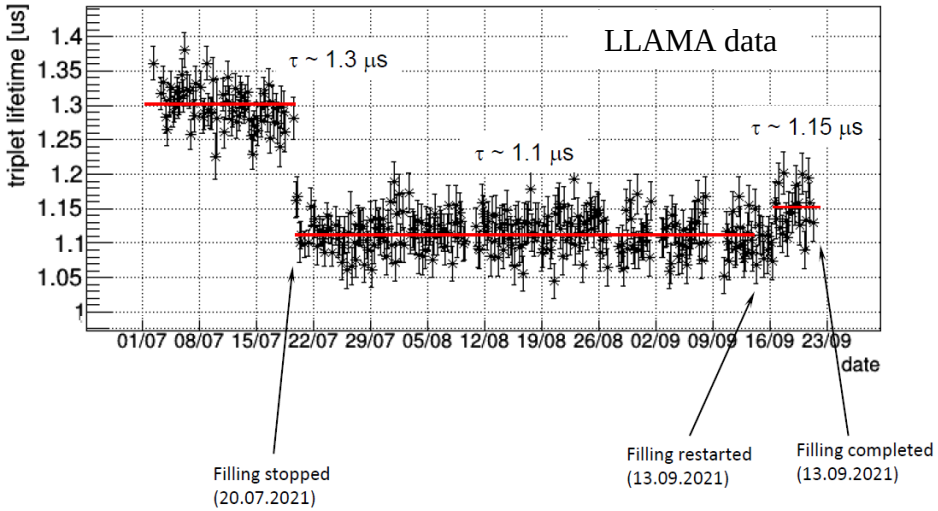
LEGEND **L**iquid **A**rgon **M**onitoring **A**pparatus

LEGEND-200 LAr veto

- ββ decay
- GERDA
- LEGEND
- LEGEND-200
- Summary

LAr purification during cryostat filling

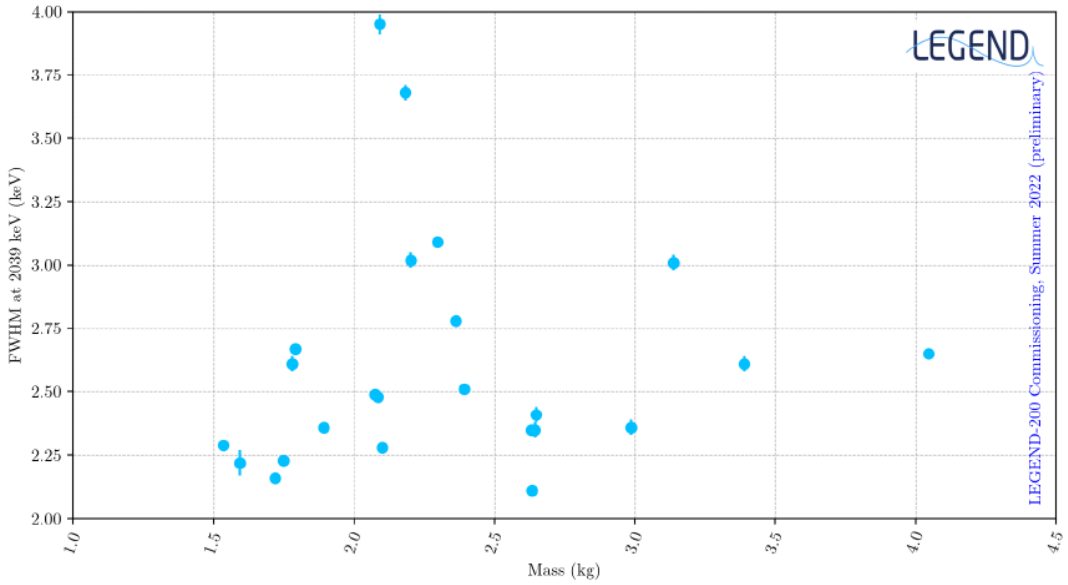


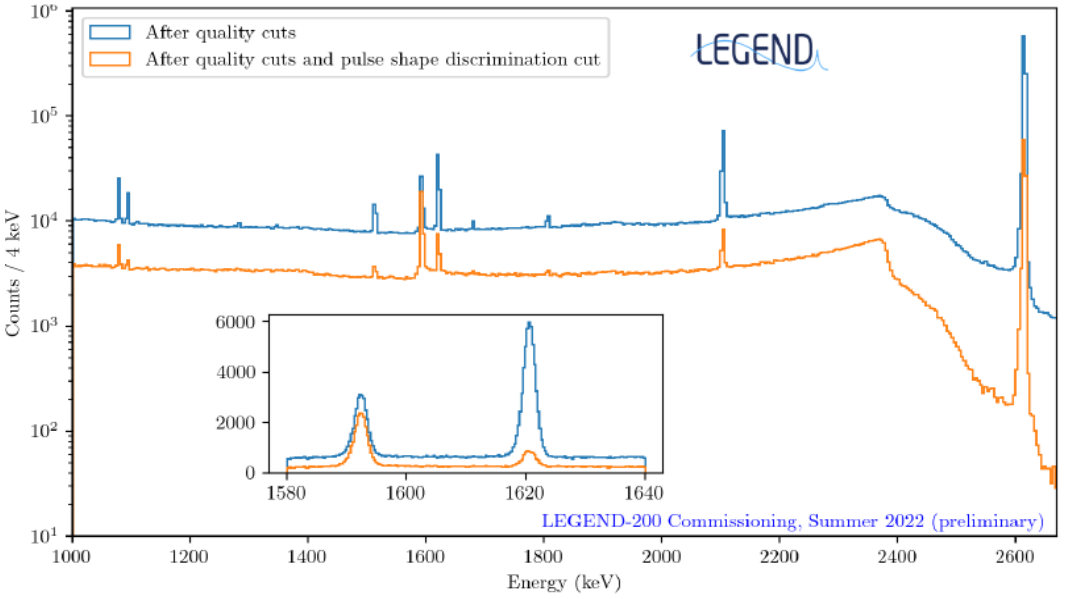


M. Harańczyk:
talk tomorrow

LEGEND-200 commissioning

- ββ decay
- GERDA
- LEGEND
- LEGEND-200
- Summary





60 kg of ^{enr}Ge in full LEGEND set-up. Preliminary data from August commissioning runs

- Calibration performed with a 5 kBq ^{228}Th source
- Resolution does not depend on detector mass
- Optimization of data acquisition conditions ongoing

LEGEND-200 commissioning

- ββ decay
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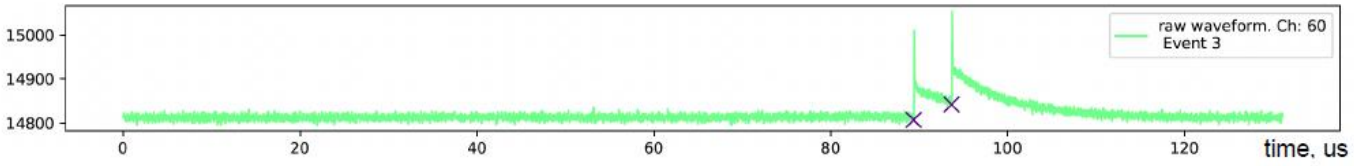
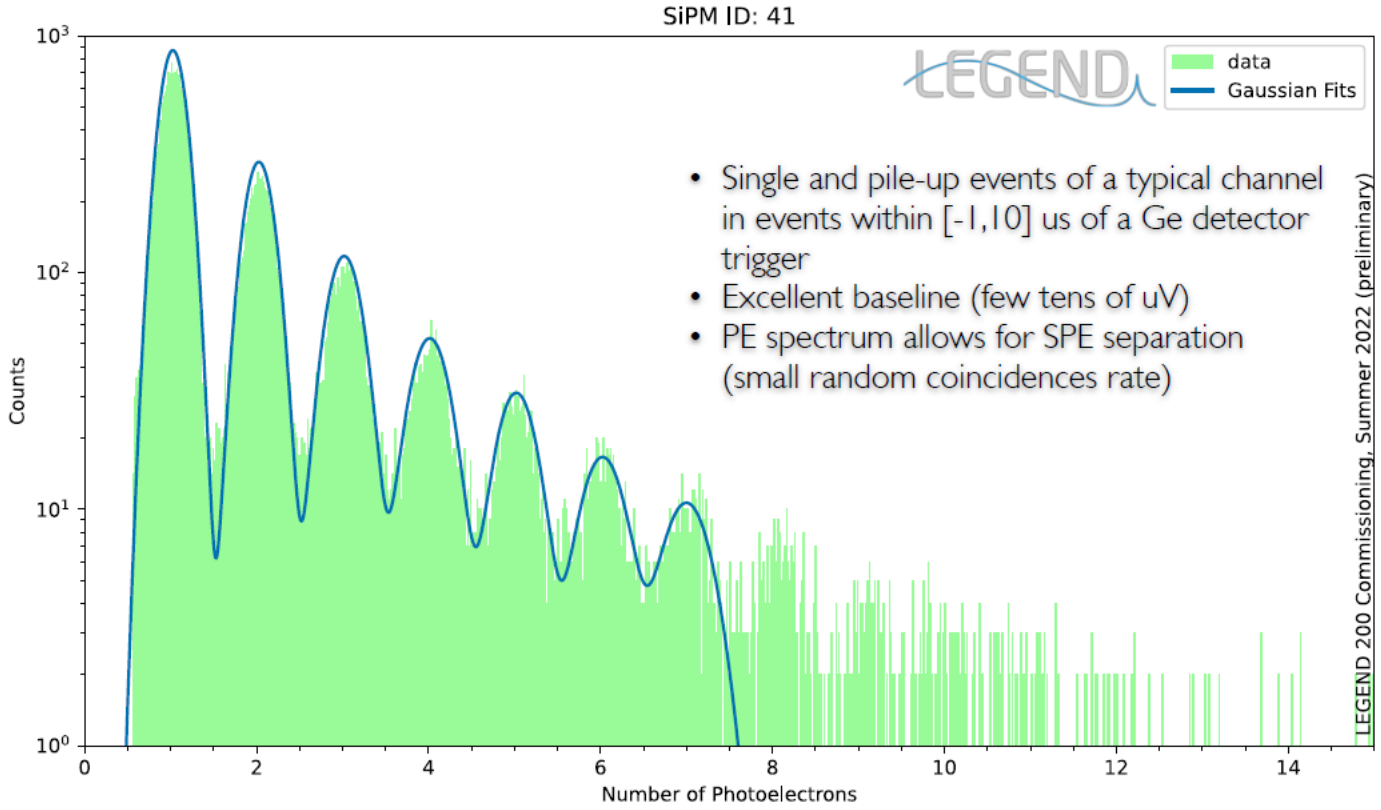
LAr veto performance



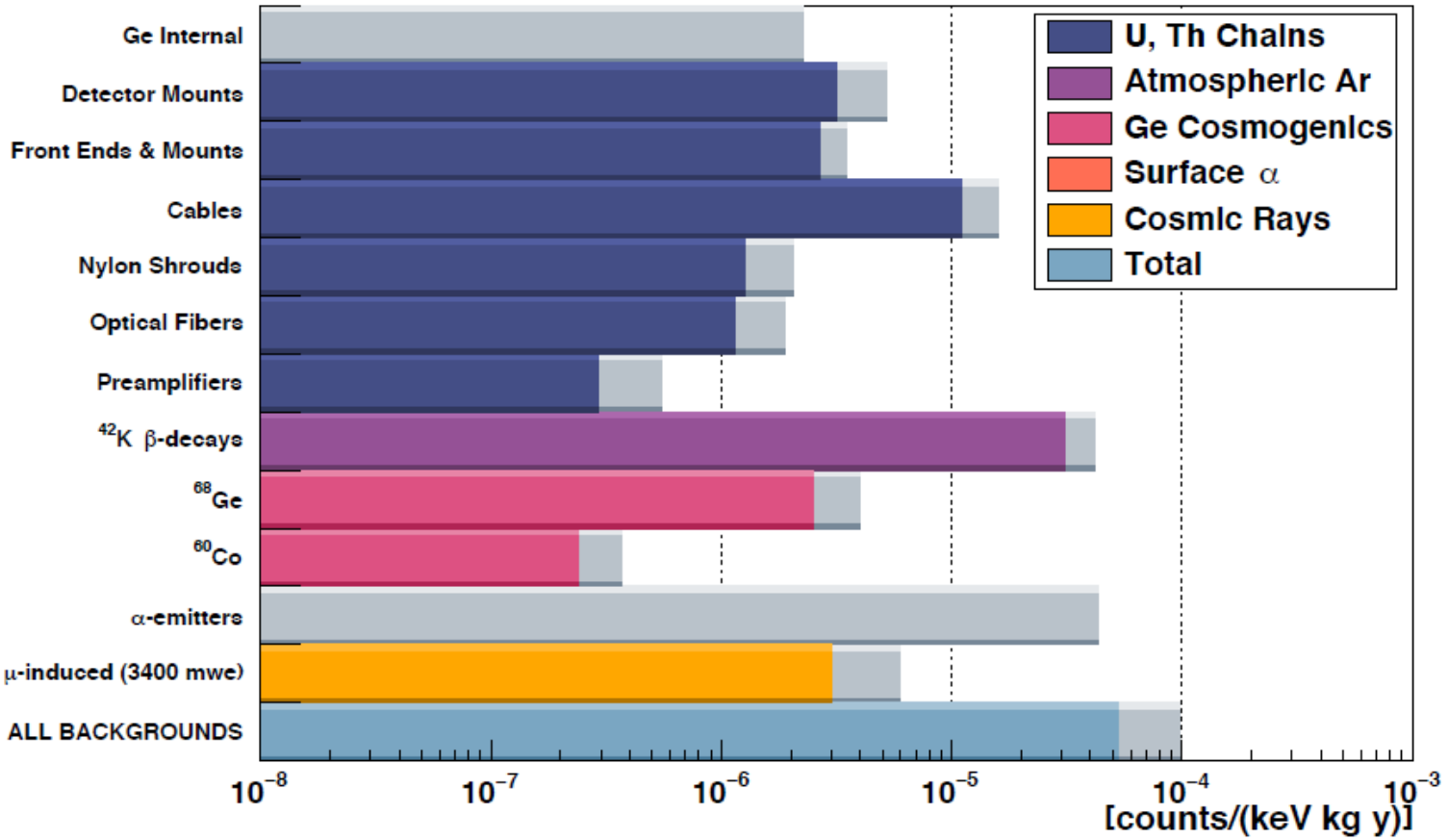


Summary

- GERDA: first background-free 0νββ decay experiment
- LEGEND – next generation experiment for $T_{1/2}^{0\nu} \sim 10^{28}$ yr and exploration of the inverted neutrino mass hierarchy
  - 13 – 16 July 2021: DOE-NP Portfolio Review of three experiments: LEGEND-1000, nEXO, CUPID,
  - LEGEND performed exceedingly well and emerged as the leader,
  - LEGEND-1000 is now being supported by DOE-NP to proceed to the next step, "CD-1",
  - Location still to be defined (SNOLAB lab or LNGS),
  - Construction should start in 2024, Pre-Conceptual Design Report available: arXiv:2017.11462,
- First phase, LEGEND-200 aims for $T_{1/2}^{0\nu} \sim 10^{27}$ yr with 200 kg of ^{enr}Ge
- LEGEND-200 at LNGS (GERDA technology) is presently under commissioning:
  - cryostat filled with purified LAr
  - 60 kg of HP^{enr}Ge deployed
  - LAr veto operational
- LEGEND-200 data taking to start still in 2022

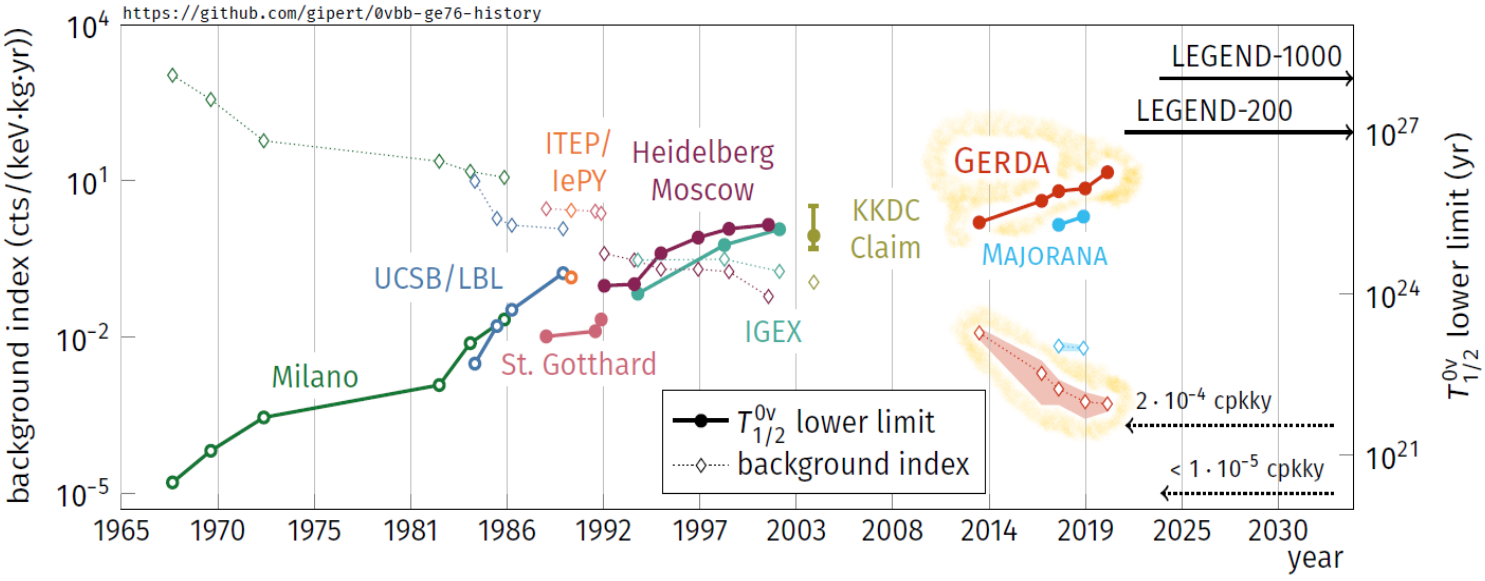
Backup

LEGEND-200 background budget



Backup

50 years of 0νββ decay searches with ^{76}Ge



- Impressive technological progress and scientific production
- A new exciting era begins now with LEGEND

Backup

Experiments searching for the 0νββ decay

Experiment	Iso.	Iso. mass [kg]	Run Time [yr]	FWHM [keV]	BI [FWHM]]	BI [keV]	Eff.	3σ Discovery $T^{0\nu}_{1/2}$ [10^{27} yr]	3σ Discovery $\langle m_{\beta\beta}\rangle$ [meV]	Sensitivity $T^{0\nu}_{1/2}$ [10^{27} yr]	Sensitivity $\langle m_{\beta\beta}\rangle$ [meV]
LEGEND-200	^{76}Ge	180	5	2.5	0.6	0.2	0.69	0.9	35 – 73	1.4	29 – 60
LEGEND-1000	^{76}Ge	910	10	2.5		0.01	0.70	12.	10 – 20	14	9 – 19
CUPID	^{100}Mo	253	10	5		0.1	0.71	1.1	12 – 20	1.5	10 – 17
AMoRE-II	^{100}Mo	200	5	5		0.1	0.91			1.1	12 – 20
SNO+ Ph. I	^{130}Te	442	5	190		0.1				0.2	41 – 99
SNO+ Ph. II	^{130}Te									1	
KamLAND-Zen 800	^{136}Xe	745	5	235						0.5	
KamLAND2-Zen	^{136}Xe	1000									
nEXO	^{136}Xe	4038	10	58	0.14		0.74	5.7	7.3 – 22.3	9.2	5.7 – 17.7
PandaX-III 200	^{136}Xe	180	3	74		0.1	0.35			0.1	65 – 165
PandaX-III 1000	^{136}Xe	900	3	74		0.01	0.35			1	20 – 50
LUX-ZEPLIN natural	^{136}Xe	500	2.7	58						0.11	53 – 164
LUX-ZEPLIN enriched	^{136}Xe	5040	2.7	58						1.06	17 – 52
DARWIN	^{136}Xe	311	2.8	58		0				8.5	