

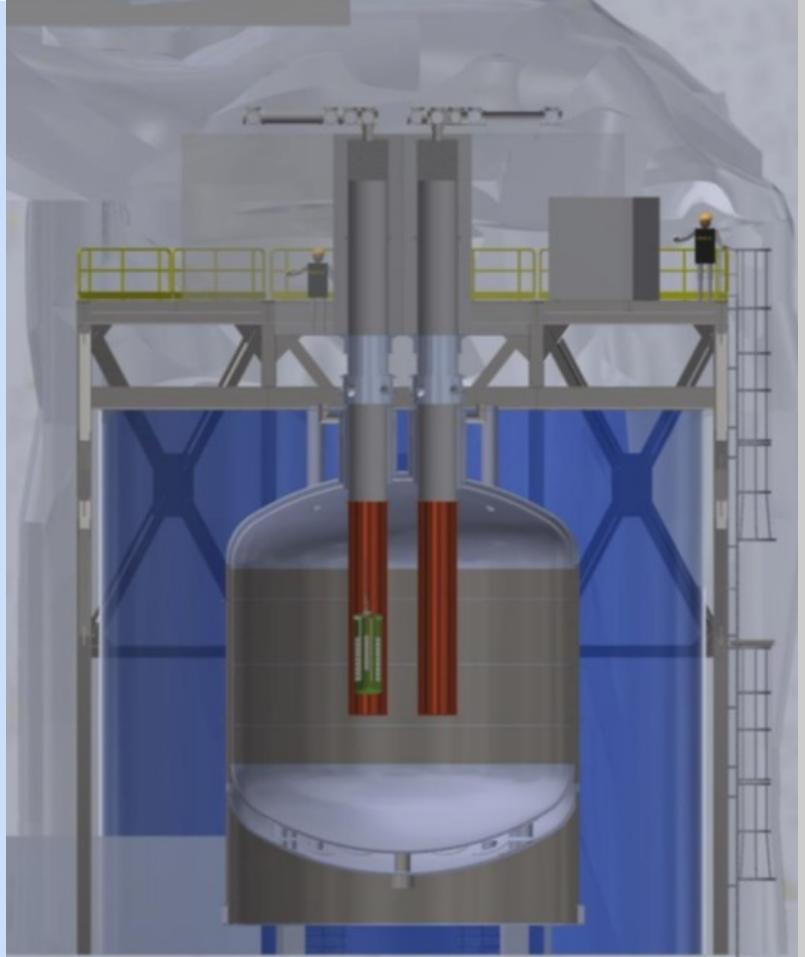
The LEGEND experiment to search for neutrinoless double beta decay

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ Decay

Dr. Pin-Jung Chiu

pin-jung.chiu@physik.uzh.ch
Physik-Institut, University of Zurich
on behalf of the LEGEND collaboration



University of
Zurich^{UZH}

November 10th, 2022
4th World Summit on Exploring the Dark Side of the Universe

The LEGEND experiment to search for neutrinoless double beta decay

Nov. 11. Fri.
8:25-8:50
Bjoern Lenhert

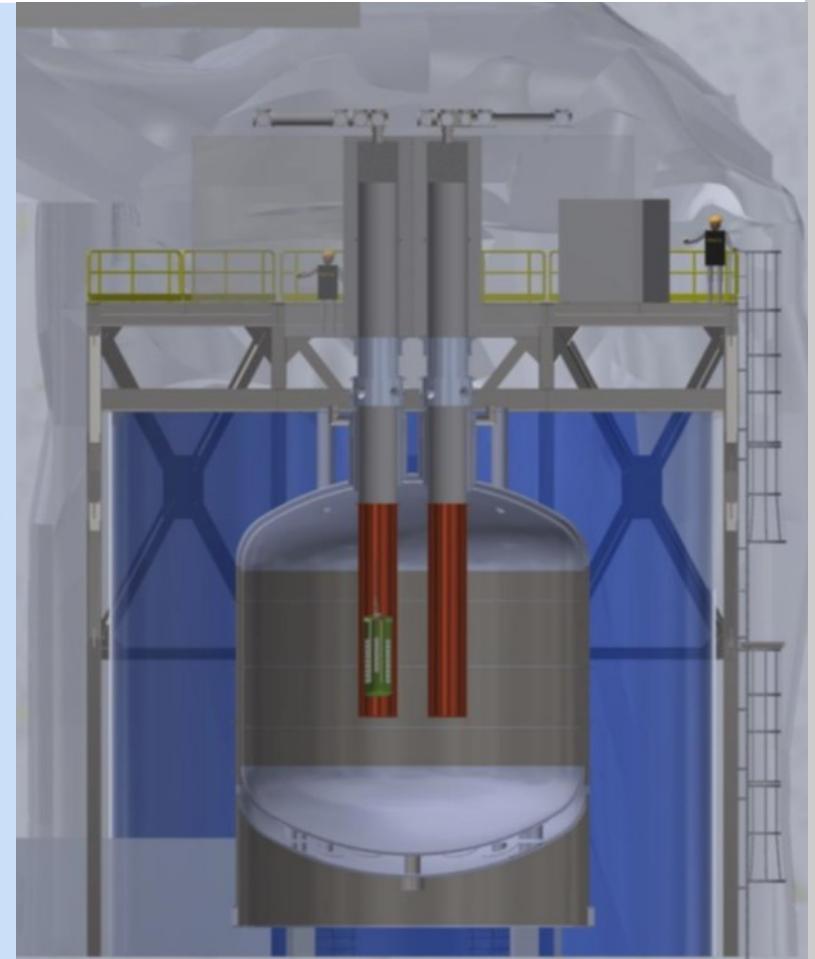
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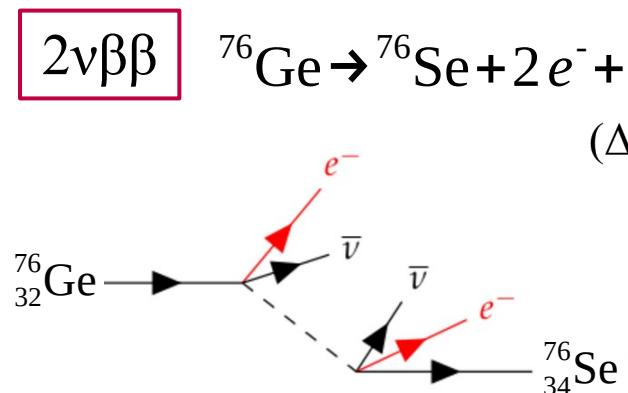


University of
Zurich^{UZH}

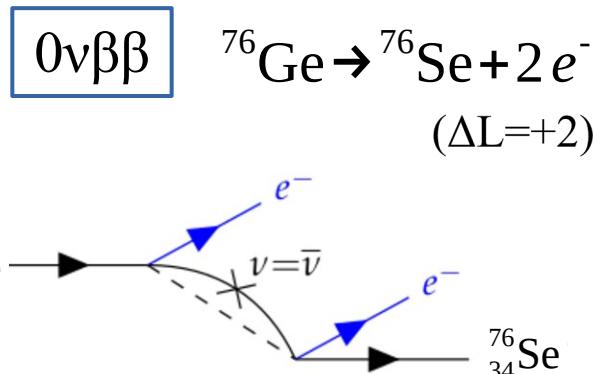
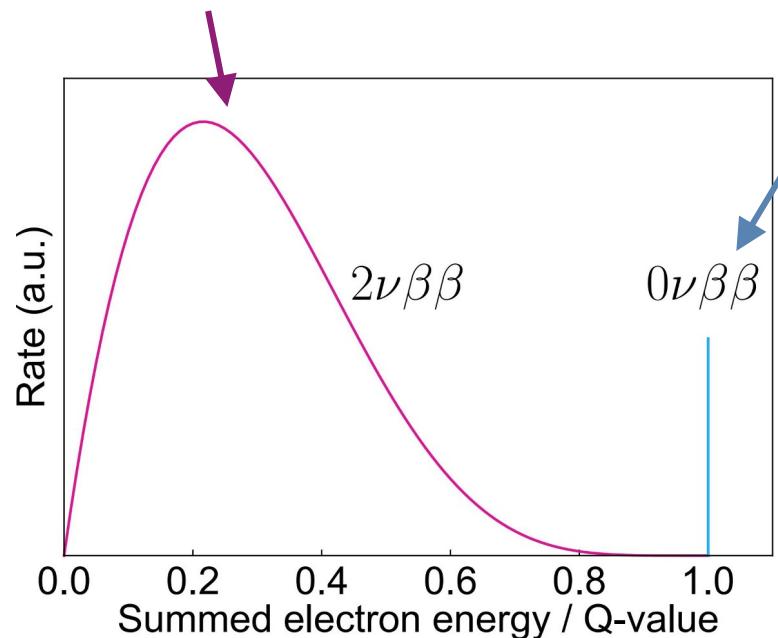
November 10th, 2022

4th World Summit on Exploring the Dark Side of the Universe

Double beta decay in ^{76}Ge



Continuous broad spectrum



Peak at $Q_{\beta\beta} = 2039$ keV

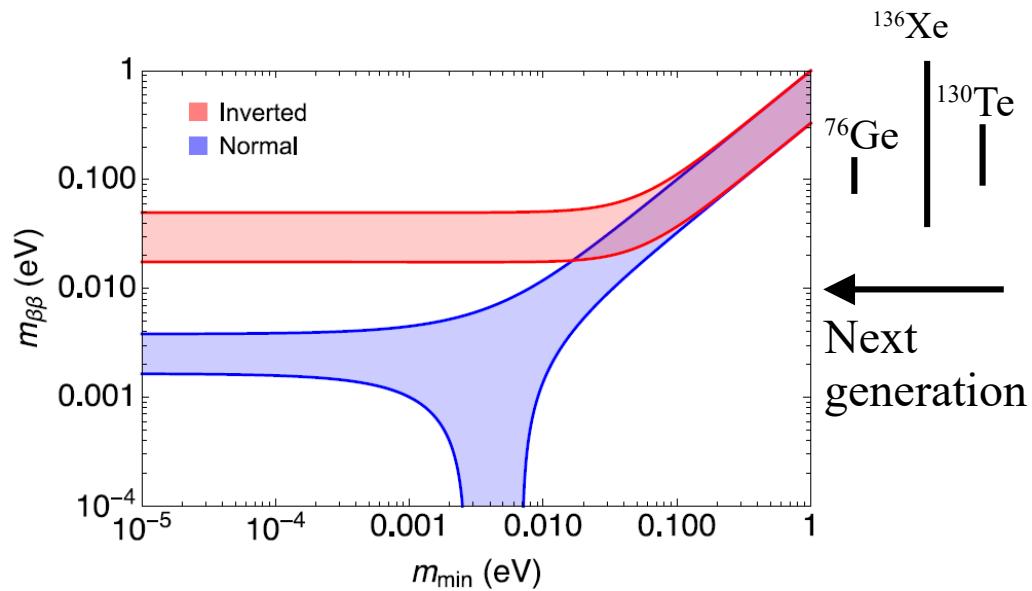
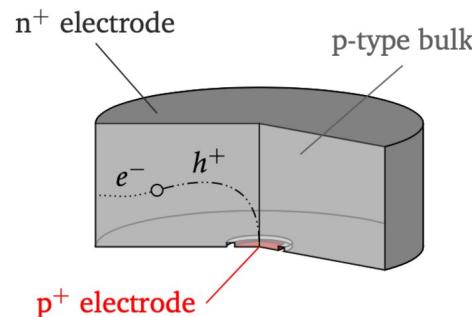


Image credit:
J. Huang (modified)

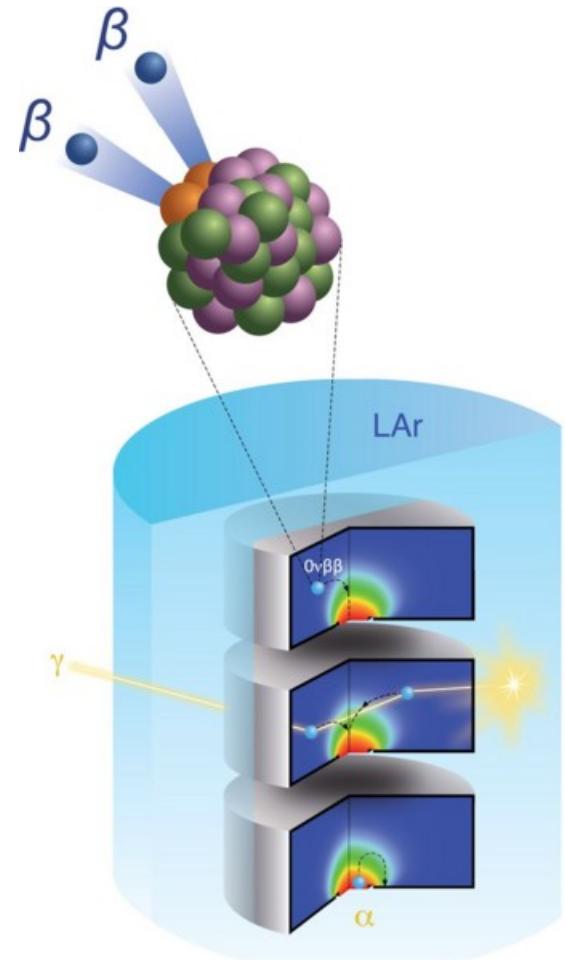
- Majorana nature of neutrinos
- Lepton number violation
- Baryon asymmetry of the Universe
- Neutrino mass scale and ordering (normal vs. inverted)

Why germanium?

- Source = detector → excellent detection efficiency
(e.g., ~ 46-66% in GERDA)
- Commercial, semiconductor detectors made from high-purity germanium (HPGe) material



- Enrichment at the level of > 90% isotopic ^{76}Ge is possible
- Best energy resolution of any $\beta\beta$ detector
(e.g., 2.53 keV FWHM at $Q_{\beta\beta}$ from MJD)
- Requires operation in cryogenic temperatures
→ Liquid argon (LAr) cryostat: serves as coolant, passive shield, and active veto system



Ref.: M. Agostini et al.,
[Science 10.1126/science.aav8613](https://science.org/doi/10.1126/science.aav8613) (2019)

$0\nu\beta\beta$ decay life time

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

$$T_{1/2} \propto f \epsilon \sqrt{\frac{Mt}{B \sigma_E}}$$

- f : ^{76}Ge enrichment fraction
 - ϵ : Detection efficiency
 - M : HPGe mass
 - t : Measurement time
 - B : Background index
= counts / (energy·mass·time)
 - σ_E : Energy resolution at $Q_{\beta\beta}$
- Mt : Exposure

GERDA + MAJORANA DEMONSTRATOR (MJD) + new institutes → LEGEND



Lowest background level for $0\nu\beta\beta$:

Mean background in $(Q_{\beta\beta} \pm 2\sigma)$ is 0.3 counts
(with 103.7 kg·yr of exposure)

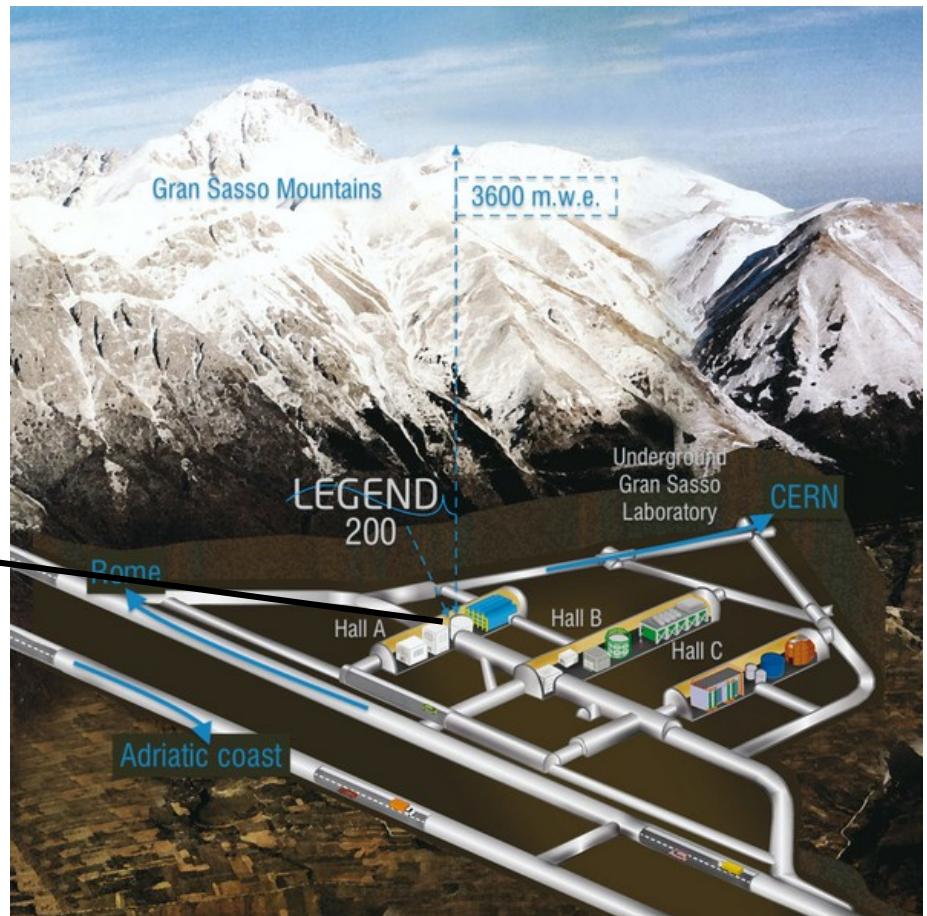
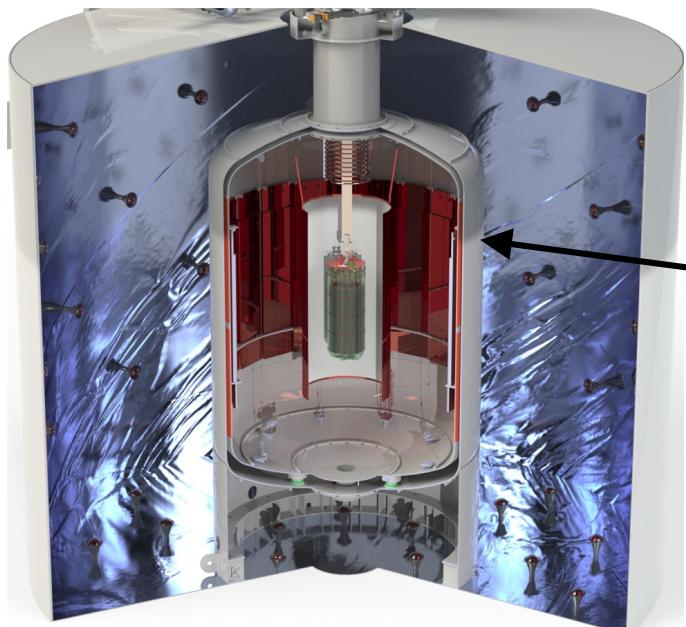
Best energy resolution for $0\nu\beta\beta$:

2.53 keV (FWHM) at $Q_{\beta\beta}$
(with 26 kg·yr of exposure)

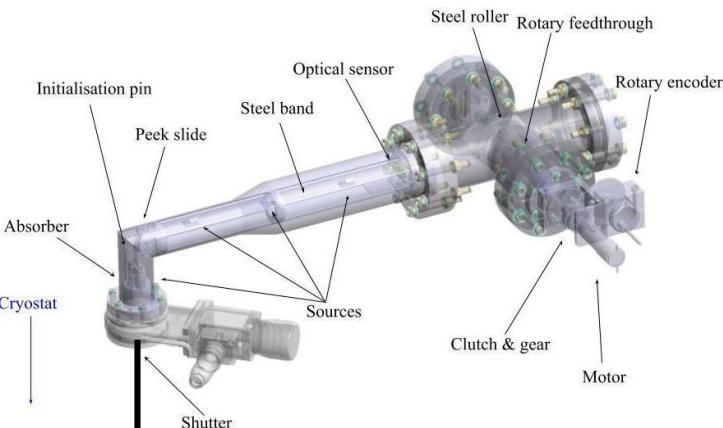
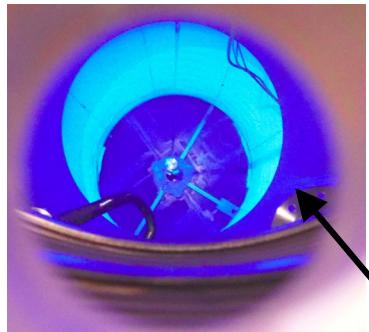
Ref.: GERDA Collab., [PRL 125, 252502](#) (2020)

Ref.: MAJORANA Collab., [PRC 100, 025501](#) (2019)

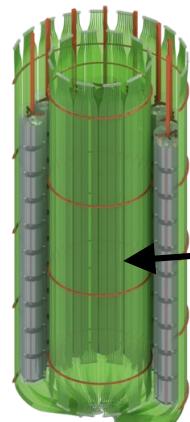
- Underground at Laboratori Nazionali del Gran Sasso (LNGS) of INFN, Italy:
 - 1400 m rock overburden (3600 m.w.e.): reduces cosmic muons by $\mathcal{O}(10^6)$
- Took over from [GERDA](#) facilities (in Feb. 2020) at LNGS, after upgrades on e.g., clean room roof, lock system, cryo piping, LAr veto and purification systems, calibration system, etc.



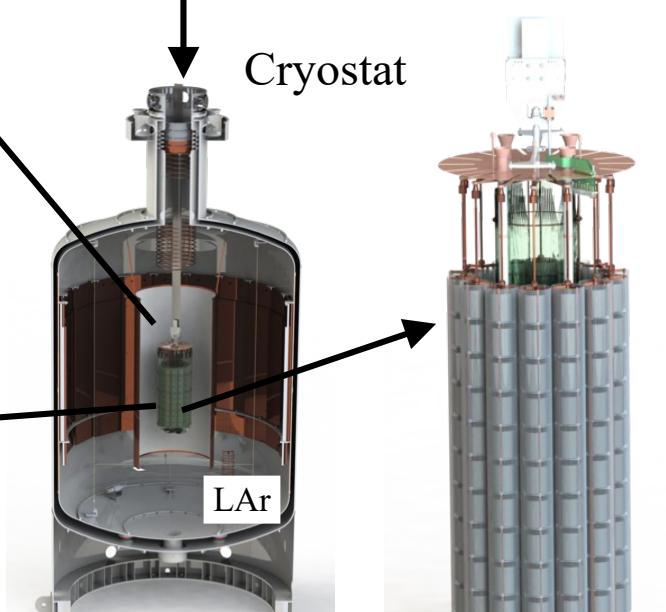
Wavelength-shifting reflector
Tetratex® coated with tetraphenyl
butadiene (TPB)



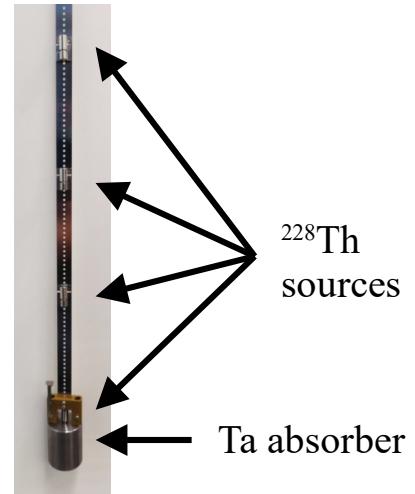
Cryostat



Fiber shrouds



Calibration system

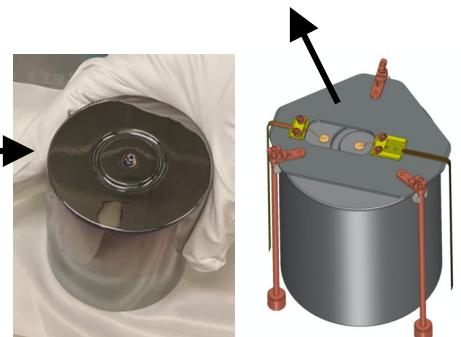


Detector array

- ~ 200 kg of detectors distributed over 12 strings
- Reuse of detectors from [GERDA](#) and [MJD](#)
- $+ 140$ kg of additional *inverted-coaxial point-contact (ICPC)* detectors:
 - Active mass > 3 kg
 - Excellent PSD performance

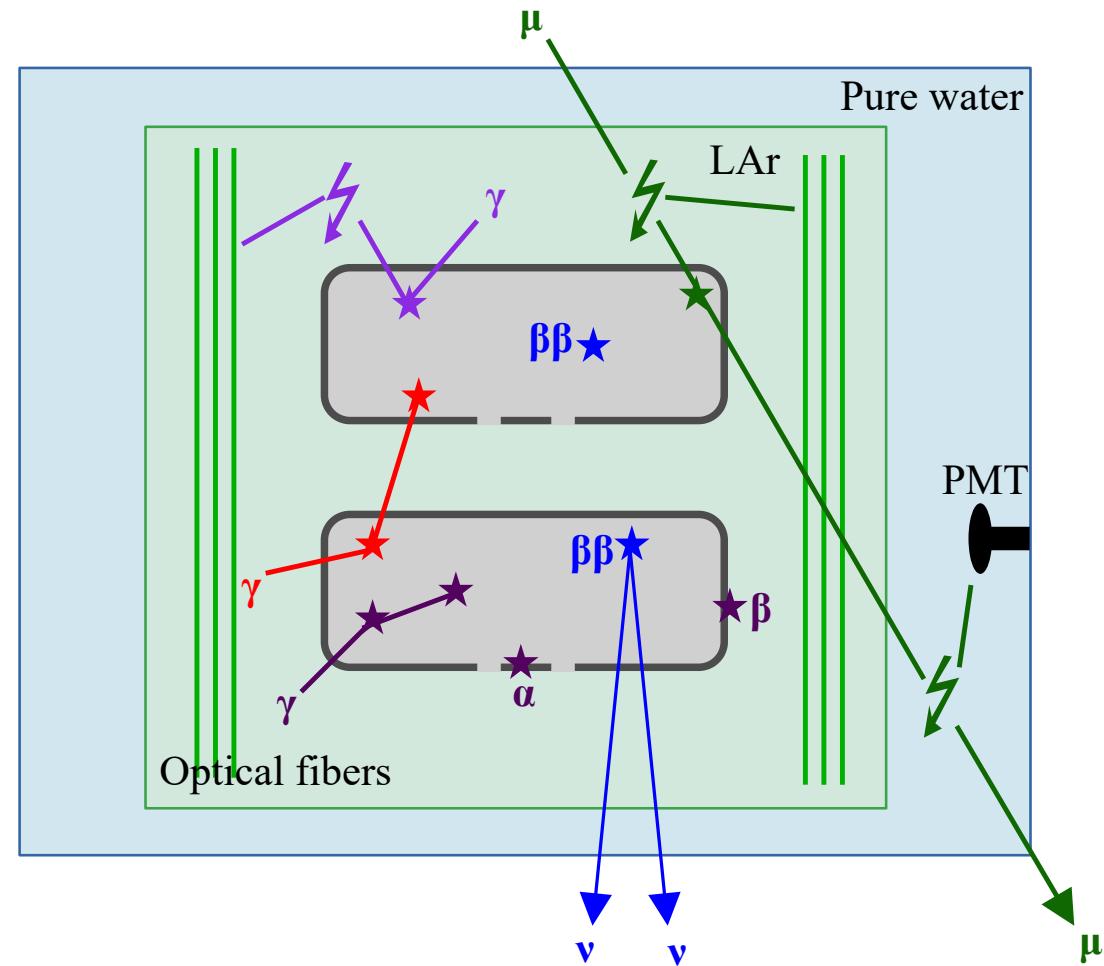
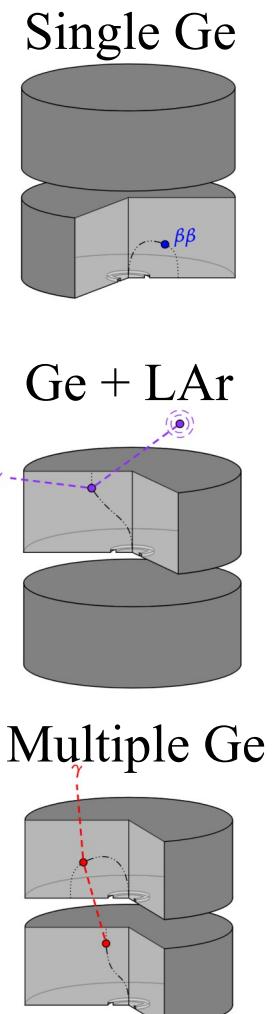


PEN (Polyethylene naphthalate) base plate



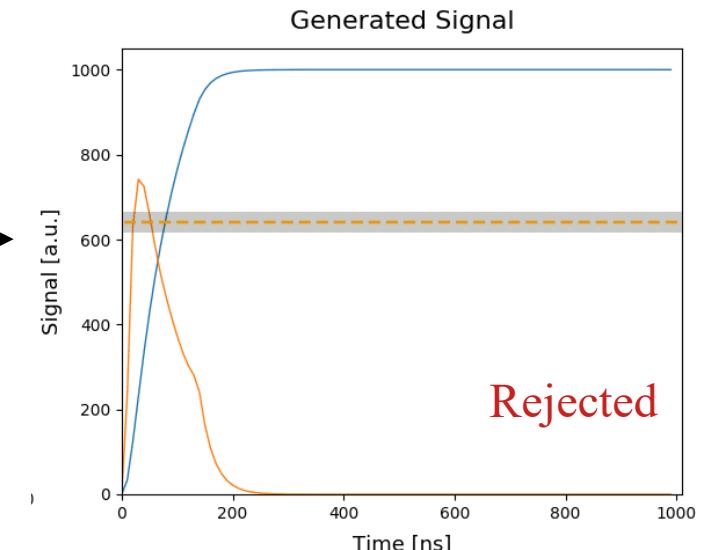
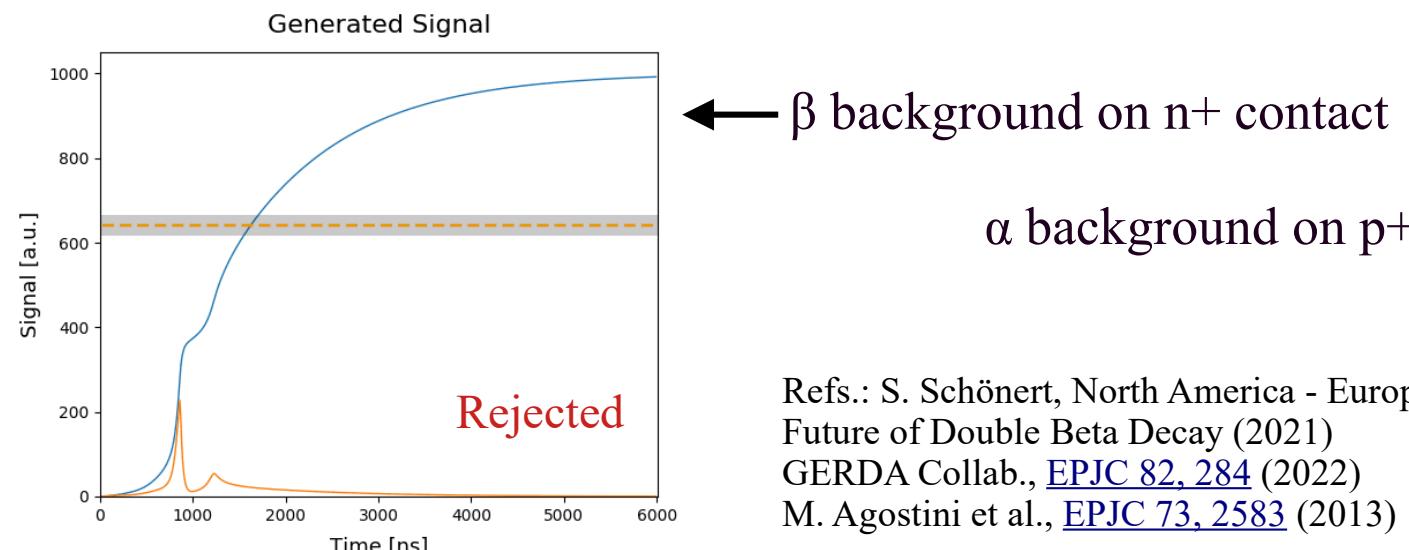
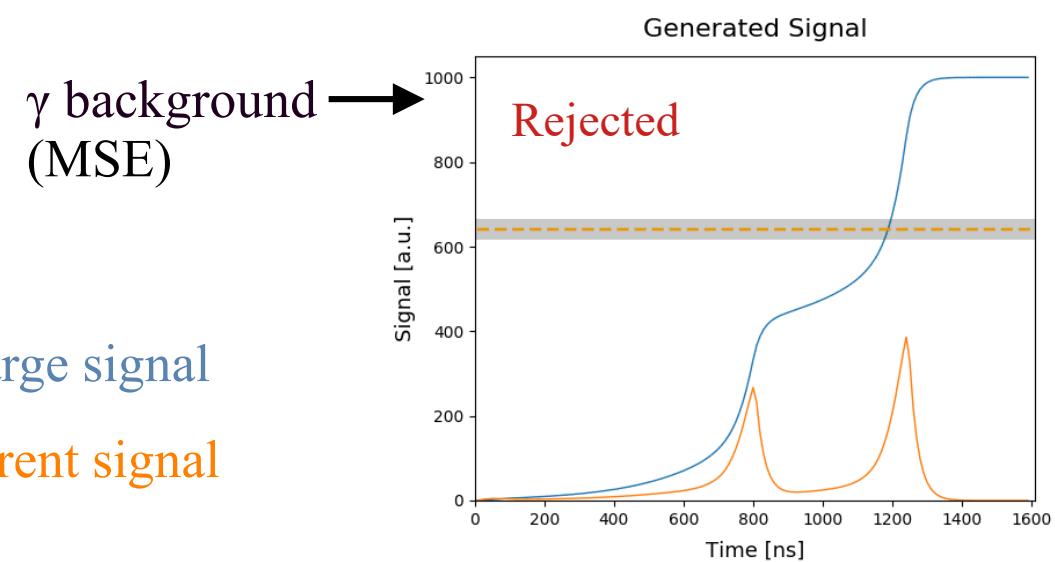
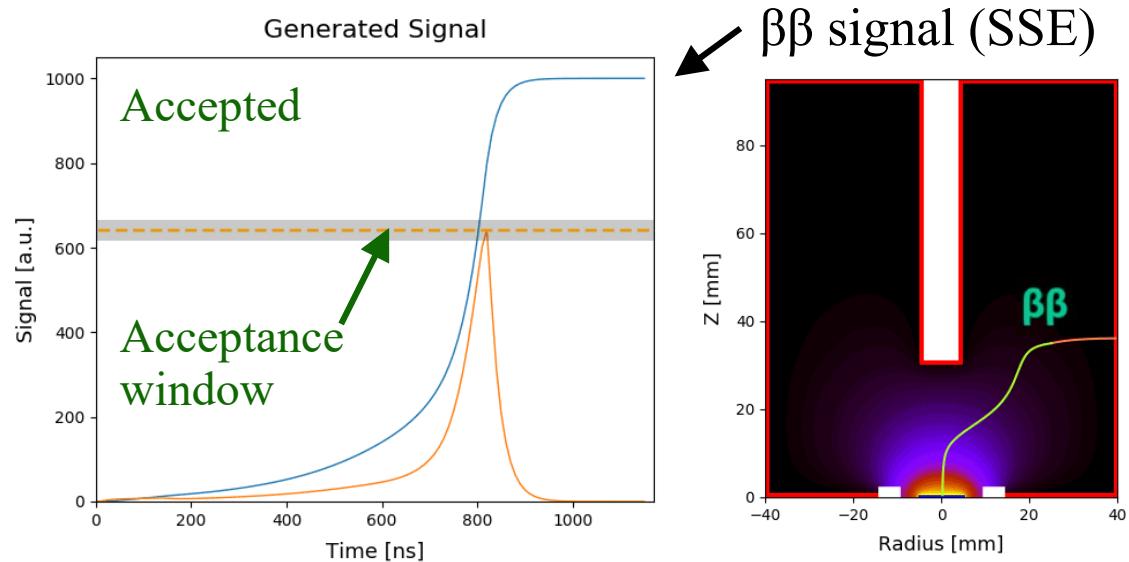
Background reduction

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



Event topology --- pulse shape discrimination (PSD)

LEGEND



Refs.: S. Schönert, North America - Europe Workshop on Future of Double Beta Decay (2021)
GERDA Collab., [EPJC 82, 284](#) (2022)
M. Agostini et al., [EPJC 73, 2583](#) (2013)

Where are we now?

- Until July 2022, we installed:
 - $\sim 60 \text{ kg} = 28 \text{ ICPC detectors}$
 - LAr veto
 - Muon veto (water tank full)
- Currently commissioning all hardware and software; will start physics data in 2022 with $\sim 140 \text{ kg}$ of detectors
- Take physics data for $\sim 1 \text{ yr}$; afterwards, install more detectors to $\sim 200 \text{ kg}$
- Requires only $\times 2\text{--}3$ background improvement w.r.t. GERDA (background index = 5.2×10^{-4} counts / $(\text{keV}\cdot\text{kg}\cdot\text{yr})$)
- Goal (5 yr runtime):
 - Discovery sensitivity $T_{1/2} > 10^{27} \text{ yr}$ (99.7% C.L.)
 $\rightarrow m_{\beta\beta} < 33 - 71 \text{ meV}$

$\text{FWHM} \sim 2.8 \text{ keV at } Q_{\beta\beta}$ achieved

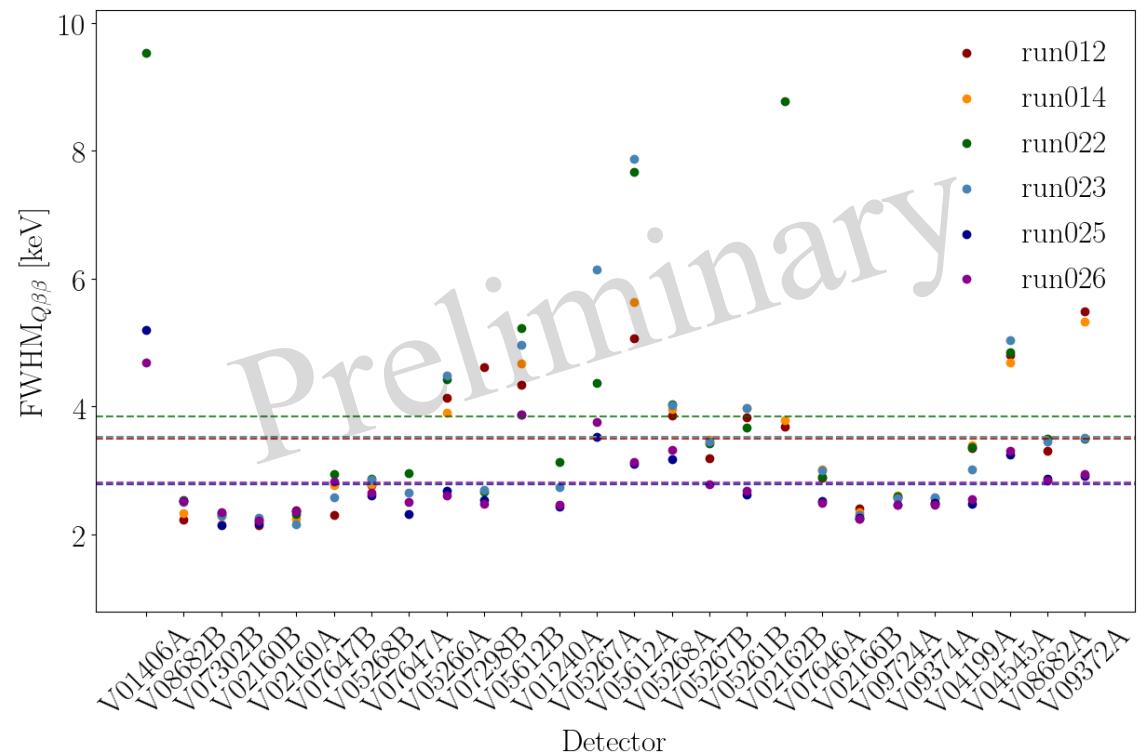


Figure credit: Y. Mueller

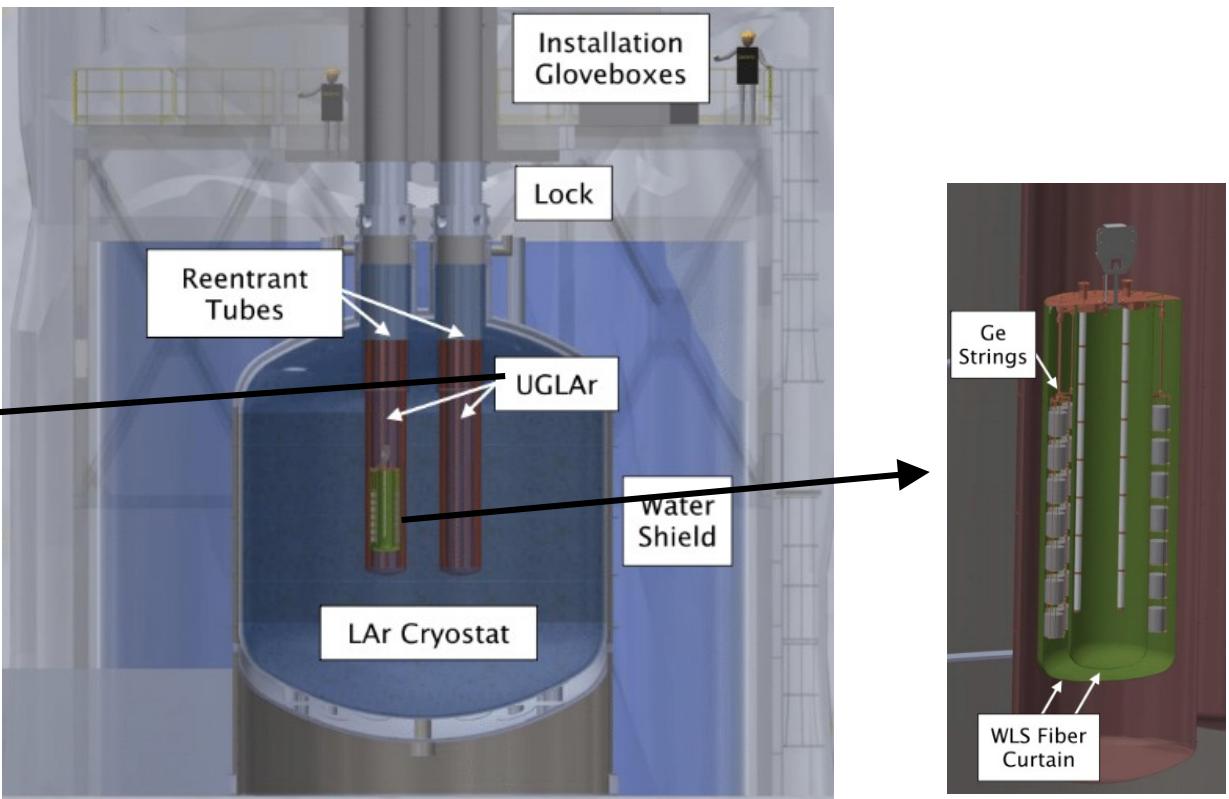
From LEGEND-200 towards LEGEND-1000

LEGEND-1000 (proposed design)

LEGEND

- 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 ($\phi = 1.9$ m) with > 50 strings
- Background improvement of $\sim \times 20$ w.r.t. LEGEND-200:
 - Radiopure *underground* argon (UGLAr) provides direct mitigation of ^{42}K background

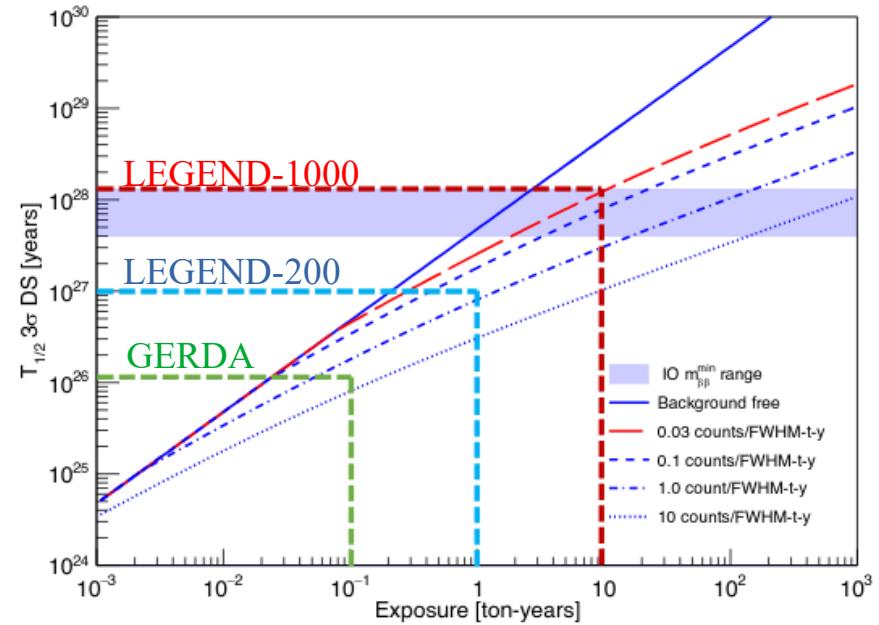
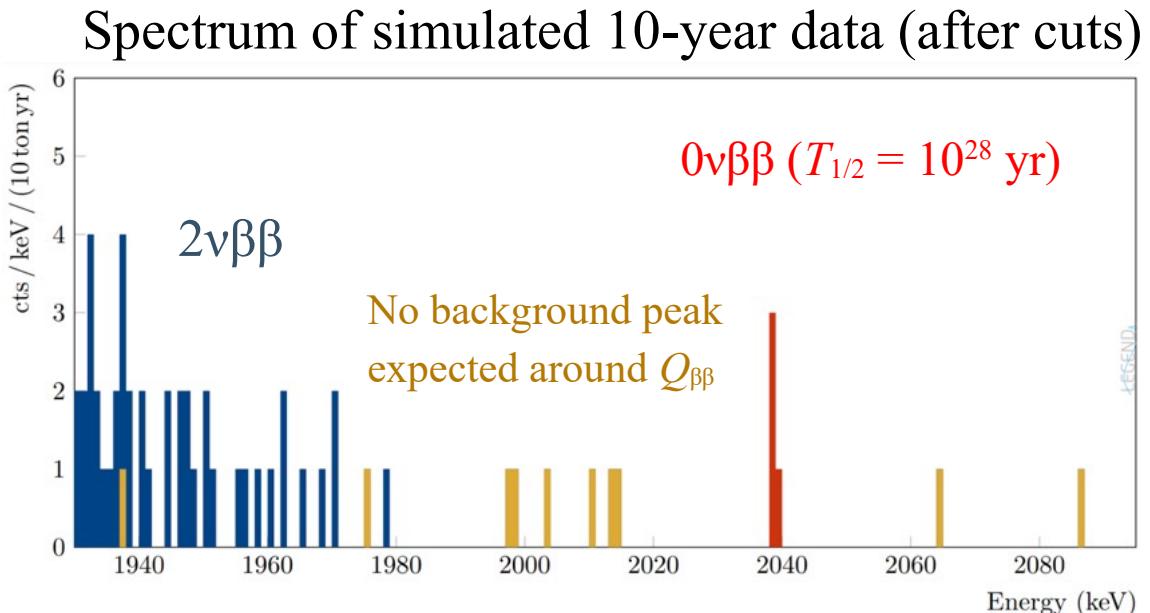
- Planned staged commissioning ~ 2030
- Goals (10 yr runtime):
 - Background index $< 10^{-5}$ counts / (keV·kg·yr)
 - Discovery sensitivity $T_{1/2} > 10^{28}$ yr (99.7% C.L.)
 $\rightarrow m_{\beta\beta} < 9 - 19$ meV



The LEGEND-1000 discovery sensitivity



- < 1 decay / (ton·yr)
 - Needs 10 ton-yr of data to get a few counts
 - Needs a good signal-to-background ratio to get statistical significance
 - A very low background-event rate
 - The best possible energy resolution



Background-free: $T_{1/2} \propto f \epsilon M t$

Background-limited: $T_{1/2} \propto f \epsilon \sqrt{M t / B \sigma_E}$

Our background goal: 0.025 counts / (FWHM·ton·yr)

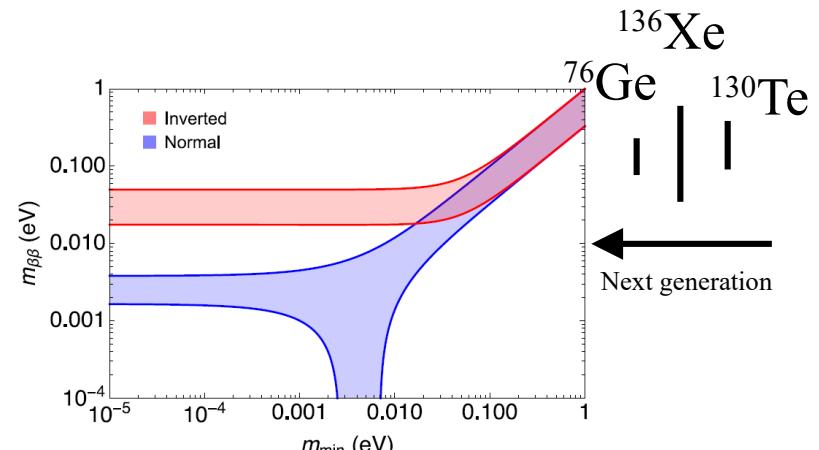
→ < 1 count in 10 years of measurement

→ “Quasi-background-free”

Summary

- Majorana neutrinos may solve several fundamental issues in particle physics and cosmology:
 - Origin of neutrino mass, mass scale, and ordering
 - Matter-antimatter asymmetry
- $0\nu\beta\beta$ is a promising probe → HPGe approach provides **excellent energy resolution** and **low background**
- LEGEND will benefit from previous experience from GERDA and MJD
- LEGEND-200 is under commissioning and will start data taking in 2022
- Ton-scale LEGEND-1000 will reach a discovery sensitivity of $T_{1/2} > 10^{28}$ yr, aiming to cover the inverted mass ordering regime

Photo: [Enrico Sacchetti](#)



Thank you for your attention ~

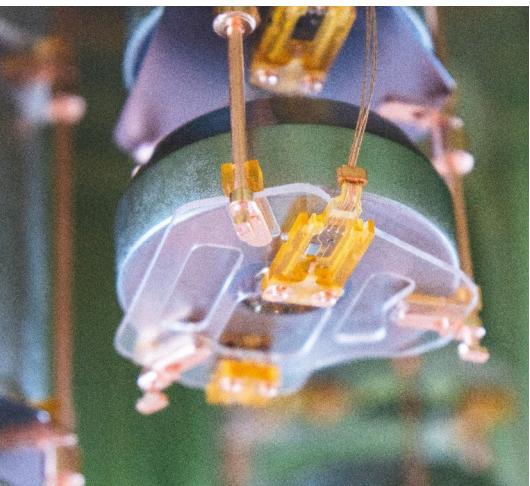
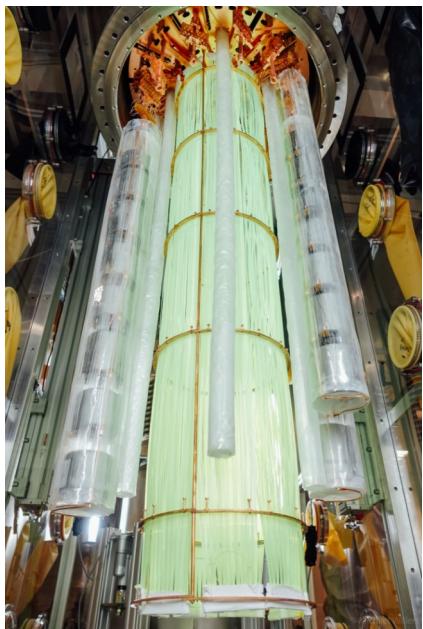


Photo: Michael Willers



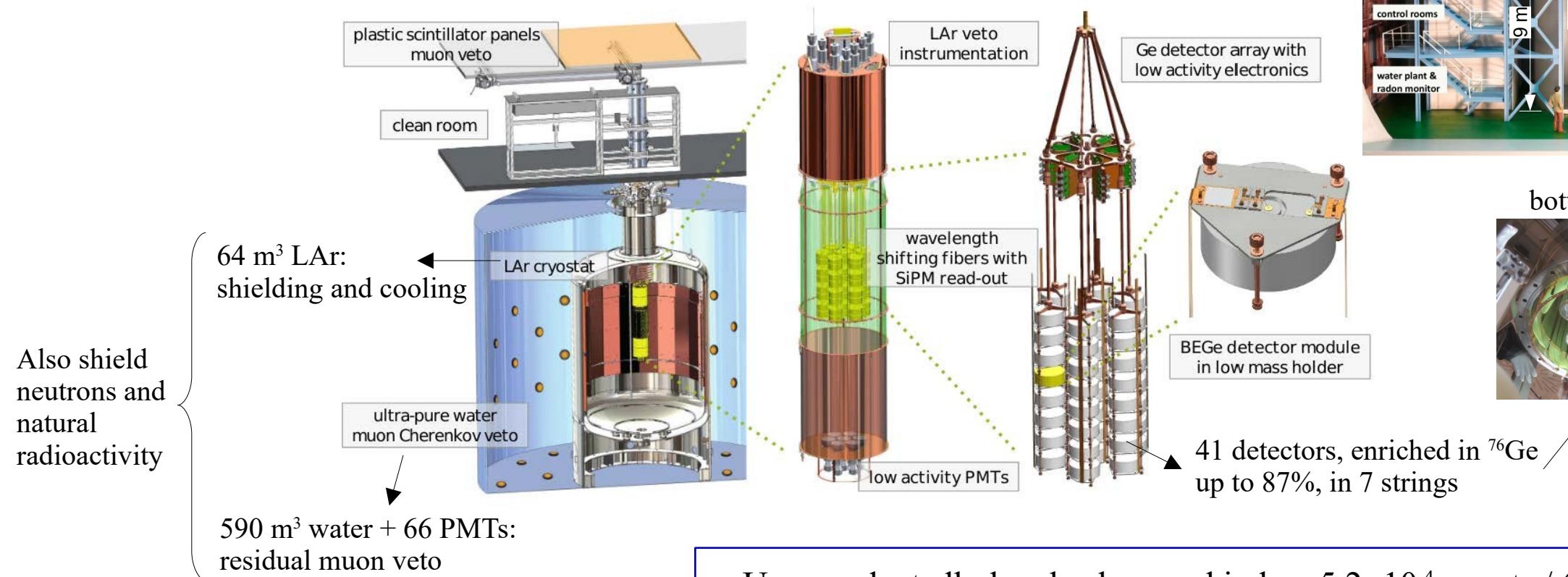
LEGEND collab. meeting, 10-14. Oct. 2022, GSSI, Italy

Backup slides

GERmanium Detector Array

LEGEND

- Underground at Laboratori Nazionali del Gran Sasso (LNGS) of INFN, Italy:
 - 1400 m rock overburden (3600 m.w.e.): reduces cosmic muons by $\mathcal{O}(10^6)$



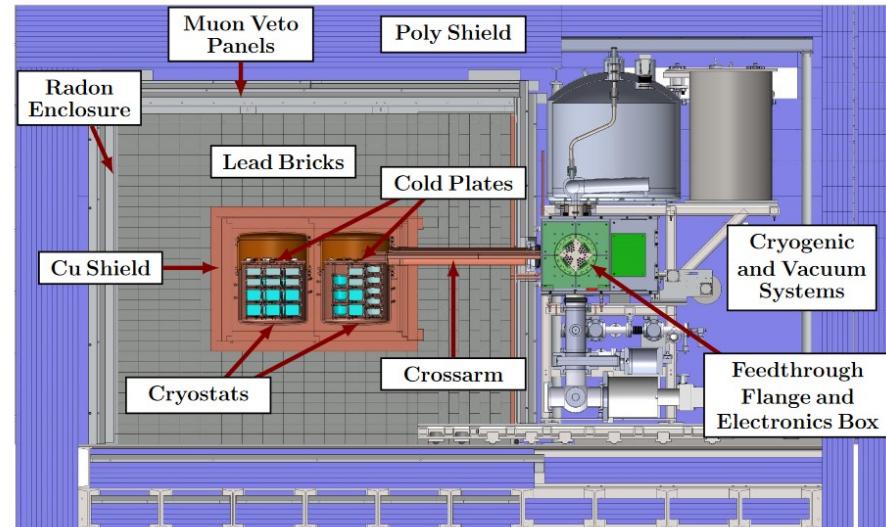
Ref.: GERDA Collab., [PRL 125, 252502 \(2020\)](#)
Image credit: GERDA Collab.

- Unprecedentedly low background index: 5.2×10^{-4} counts / (keV·kg·yr)
- Half-life limit on $0\nu\beta\beta$ decay: $T_{1/2} > 1.8 \times 10^{26}$ yr (90% C.L.)
 - Effective Majorana neutrino mass: $m_{\beta\beta} < 79 - 180$ meV

Majorana Demonstrator

LEGEND

- Located at Sanford Underground Research Facility in Lead, South Dakota, US (1490 m rock overburden, 4300 m.w.e.)
- 2 modules within a compact graded shield (consisting of layers of Cu, Pb, an active muon veto, polyethylene, and borated polyethylene). Each within an electroformed copper cryostat and uses ultra-clean materials (radiopurity of near-by parts)
- Low-noise front-end electronics improves PSD
- Low energy threshold helps reject cosmogenic background
- Consists of 44.1 kg of p-type point contact (PPC) Ge detectors (29.7 kg enriched to 88% in ^{76}Ge)



Ref.: MAJORANA Collab., [JINST, 17, T05003](#) (2022)

- Best energy resolution in the field: 2.53 ± 0.08 keV (FWHM) at $Q_{\beta\beta}$
 - Measured background 11.9 ± 2.0 counts / (FWHM·ton·yr)
 - Half-life limit on $0\nu\beta\beta$ decay: $T_{1/2} > 2.7 \times 10^{25}$ yr (90% C.L.)
→ Effective Majorana neutrino mass: $m_{\beta\beta} < 200 - 433$ meV

Ref.: MAJORANA Collab., [PRC 100, 025501](#) (2019)

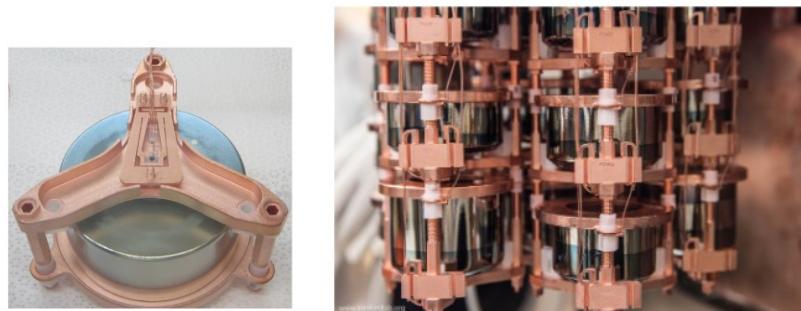


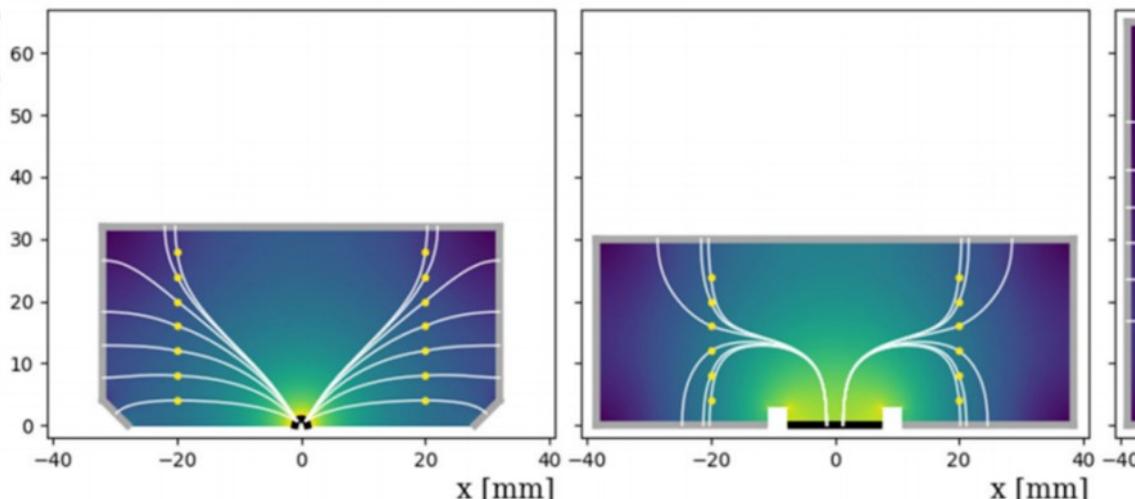
Image credit: MAJORANA Collab.

Detector types

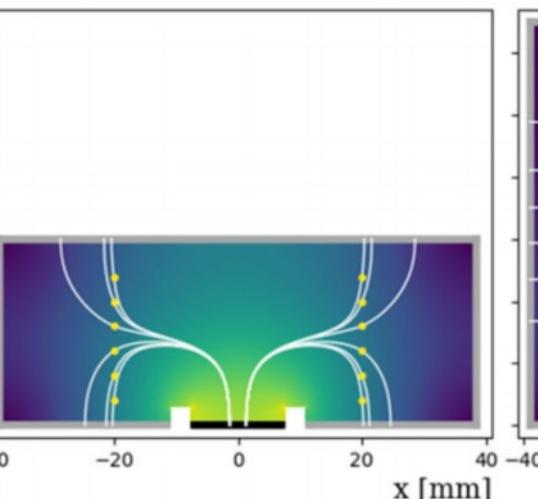
- P-type detectors: insensitive to alphas on n⁺ contact
- Small p⁺ contact: event topology discrimination
- Large-mass ICPC detectors: ~×4 lower backgrounds w.r.t. BEGe/PPC
- Proven long-term stable operation in LAr

Refs.: S. Schönert, North America - Europe Workshop on Future of Double Beta Decay (2021)
 T. Comellato et al., [EPJC 81, 76](#) (2021)
 M. Agostini et al., [EPJC 74, 2764](#) (2014)

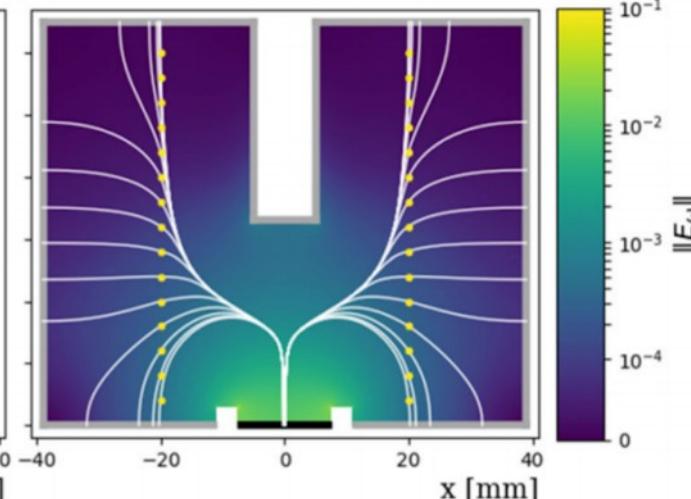
MJD (PPC)
P-type Point Contact



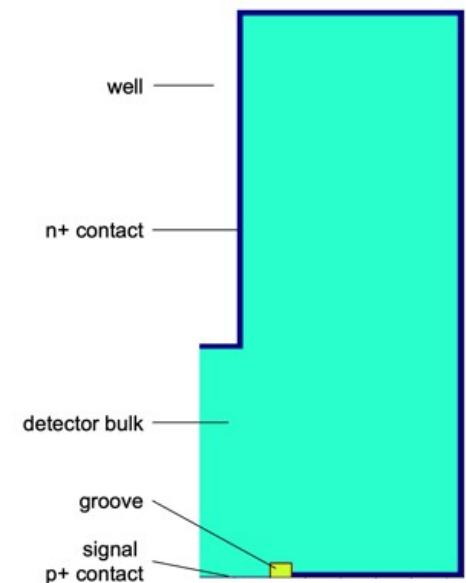
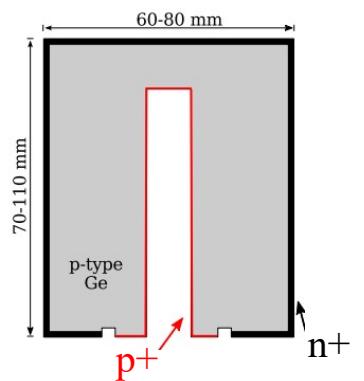
GERDA (BEGe)
Broad Energy Ge



LEGEND (ICPC)
Inverted-Coaxial p-type Point Contact



GERDA (Coax)



Decay life time vs. Majorana neutrino mass

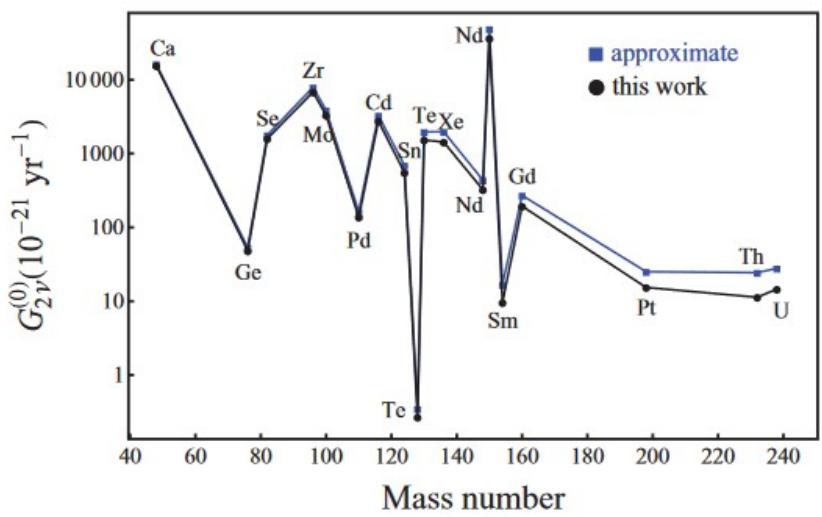
LEGEND

$$m_{\beta\beta} \equiv \left| \sum_k m_k U_{ek}^2 \right| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i(\alpha_2 - \alpha_1)} + m_3 |U_{e3}|^2 e^{i(-\alpha_1 - 2\delta)} \right|$$

δ : Dirac phase
 α_1, α_2 : Majorana phases

$$1/T_{1/2} = G(Q_{\beta\beta}, Z) g_A^4 |M_{\text{nucl}}|^2 m_{\beta\beta}^2$$

Phase space factor

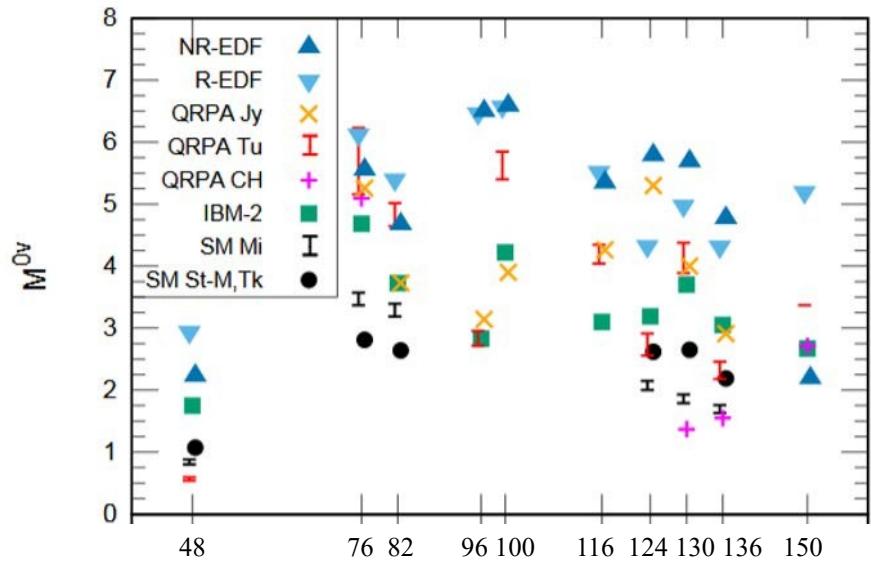


Axial coupling

$$g_A = \begin{cases} 1.27 & (\text{free nucleon}) \\ 1 & (\text{quark}) \end{cases}$$

$$g_{A,\text{eff}} \sim 0.6 - 0.8$$

(taking into account “quenching”)



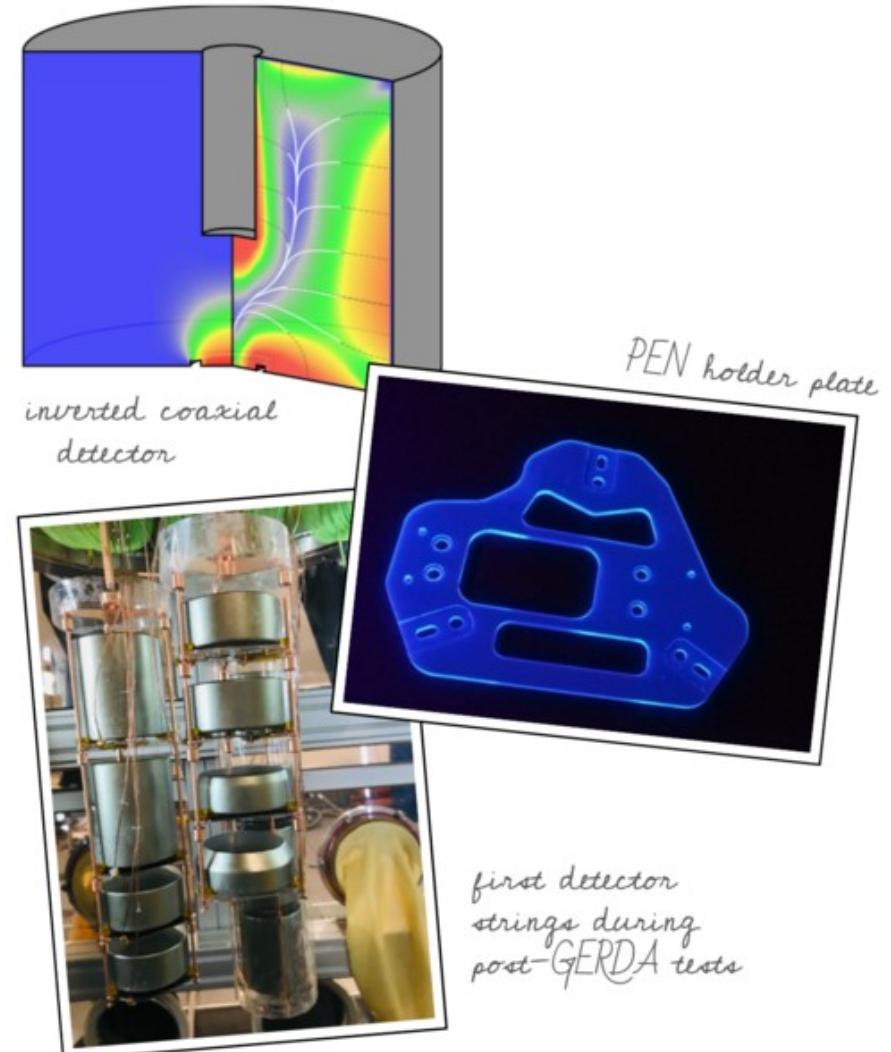
Ref.: J. Kotila and F. Iachello, [PRC 85, 034316](#) (2012)

Ref.: J. Engel and J. Menéndez, [Rep. Prog. Phys. 80, 046301](#) (2017)

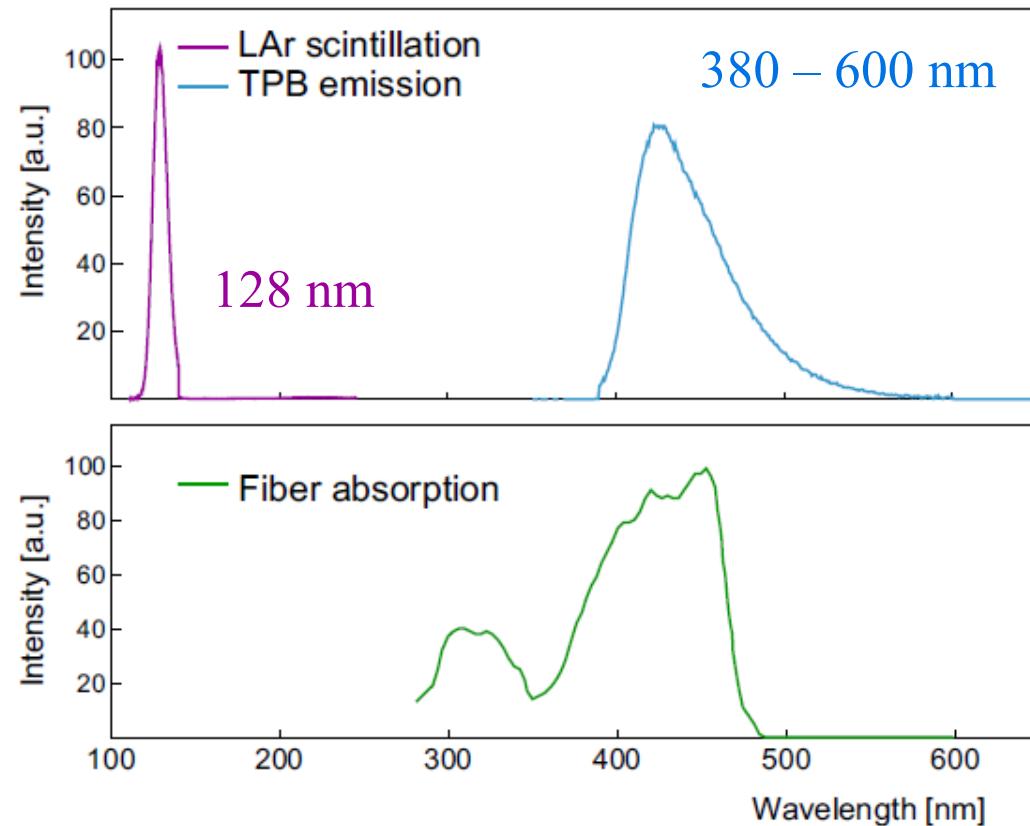
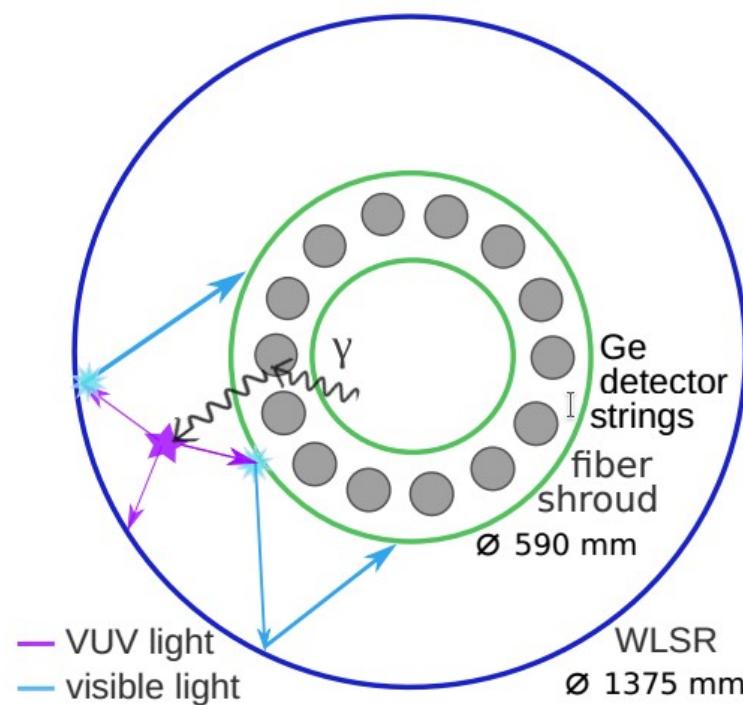
LEGEND-1000 background improvement

LEGEND

- Increasing detector mass: surface to volume ratio
- Active light readout, e.g., polyethylene naphthalate (PEN) holder plate
- Cleaner materials, e.g., underground LAr, underground electroformed Cu, copper-kapton laminated cables
- Neutron shielding/absorbing materials around Ge detectors, e.g., polymethyl methacrylate (PMMA), polyethylene (PE)
- Neutron moderator in LAr
- SNOLAB is deeper (rock overburden: 6000 m.w.e.)



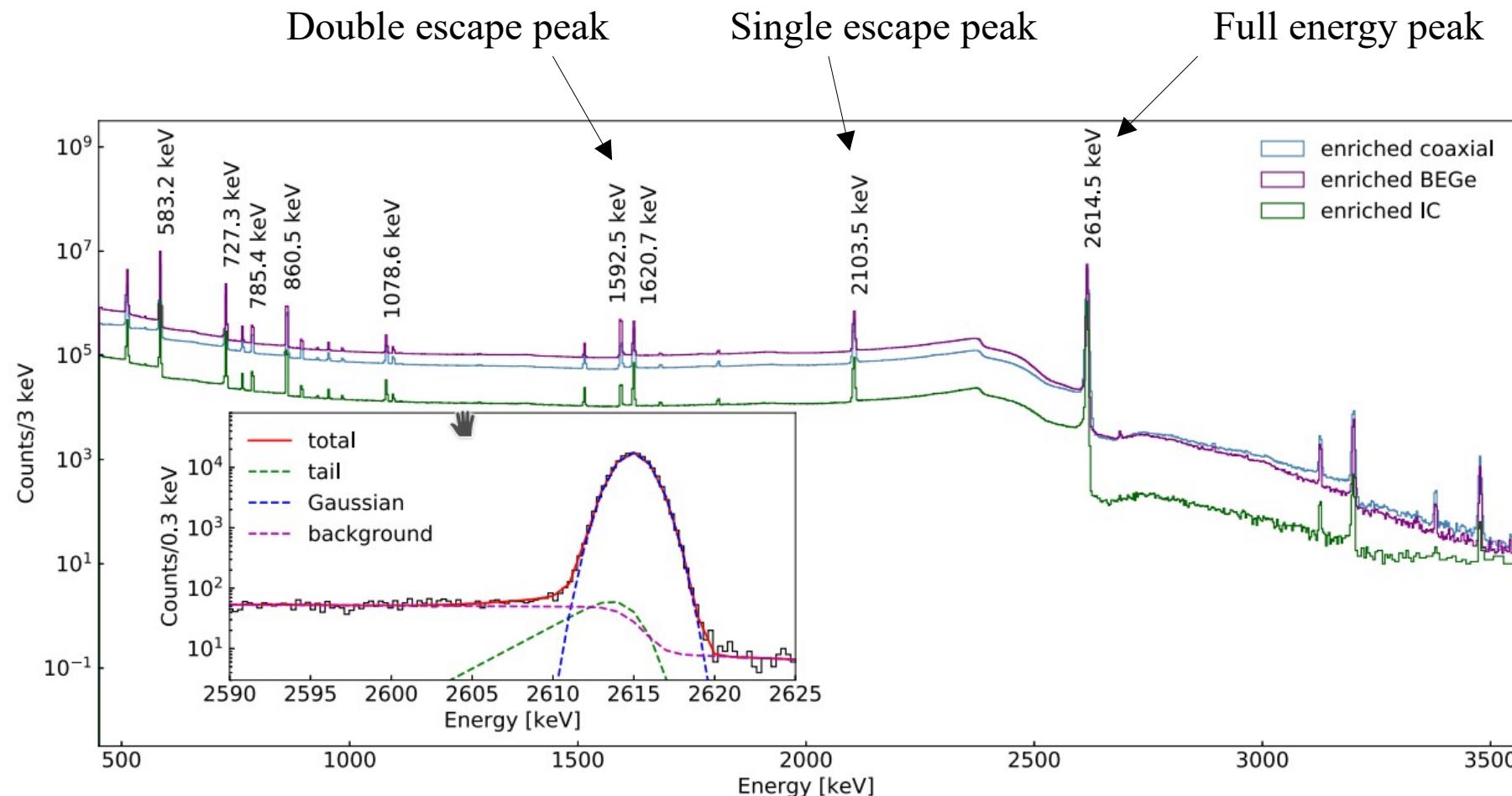
Wavelength shifter



Ref.: G. R. Araujo et al., [EPJC 82, 442](#) (2022)

Energy calibration with ^{228}Th

γ ray from the decay of ^{208}Tl



Ref.: GERDA Collab., EPJC 81, 682 (2021)

Muon flux from various labs

- Waste Isolation Pilot Plant (WIPP), United States:
Store transuranic radioactive waste
- Soudan underground lab, United States:
E.g., MINOS, CDMS, NOvA
- Kamioka observatory, Japan:
E.g., Super-K, T2K, KamLAND
- Boulby underground lab, United Kingdom:
E.g., material screening, dark-matter search
- LNGS, Gran Sasso, Italy:
E.g., LEGEND-200, XENON, Borexino
- Sanford underground research facility (SURF), Homestake,
United States:
E.g., LUX, MJD
- Laboratoire Suoterrain de Modane (LSM), Fréjus, France:
E.g., NEMO, EDELWEISS
- Sudbury neutrino observatory, Canada:
E.g., SNO+, DEAP-3600

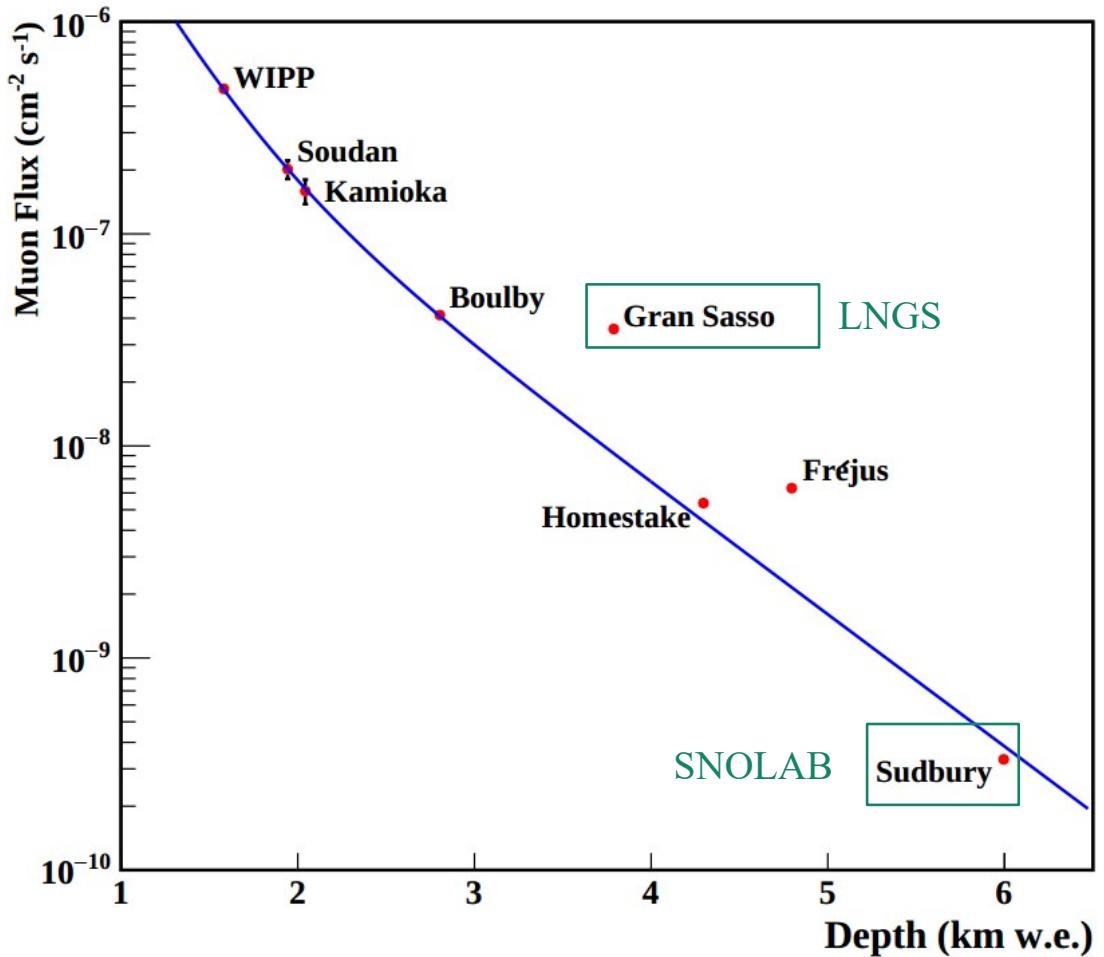


Image credit: J. J. Cuenca-García, (2022)
Ref.: D.-M. Mei and A. Hime, [PRD 73, 053004](#) (2006)

Majorana mass and mass ordering

Isotope	Experiment	year	$T_{1/2}$ limit (yr)	$m_{\beta\beta}$ (meV)	Ref.
^{76}Ge	GERDA	2020	1.8×10^{26}	79 – 180	[1]
^{76}Ge	MAJORANA DEMONSTRATOR	2019	2.7×10^{25}	200 – 433	[2]
^{136}Xe	KamLAND-Zen	2022	2.3×10^{26}	36 – 156	[3]
^{136}Xe	EXO-200	2019	3.5×10^{25}	93 – 286	[4]
^{130}Te	CUORE	2022	2.2×10^{25}	90 – 305	[5]

- Refs.: [1] GERDA Collab., [PRL 125, 252502](#) (2020)
 [2] MAJORANA Collab., [PRC 100, 025501](#) (2019)
 [3] KamLAND-Zen Collab., [arXiv:2203.02139](#) [hep-ex] (2022)
 [4] EXO-200 Collab., [PRL 123, 161802](#) (2019)
 [5] CUORE Collab., [Nature 604, 53–58](#) (2022)

