The LEGEND project: Majorana neutrinos beyond the inverted ordering

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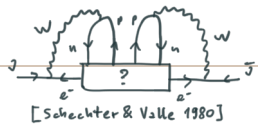
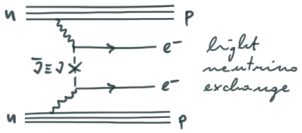
TU München, INFN Padova

Why neutrinoless double-β decay?

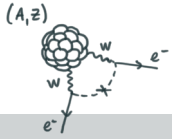


$(A, Z) \longmapsto (A, Z+2) + 2e^- + 2\cancel{\nu}_e$



"The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics" [1]

- 0νββ observation ⇒ Majorana neutrino and Lepton Number Violation
- Lepton number ⟷ Barion number ⟼ new physics, baryogenesis?



Light neutrino mass mechanism

The (Majorana) neutrino that mediates 0νββ is the one that oscillates and the Standard Model is an effective theory *(seesaw mechanism)*

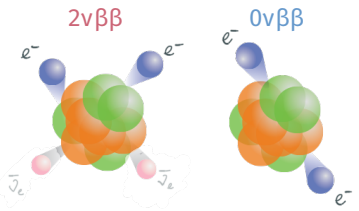
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Majorana effective mass

More during Marco's talk!

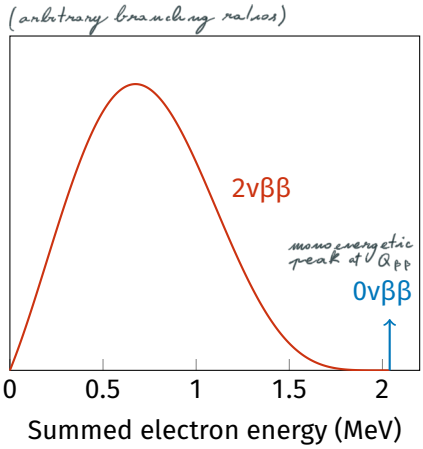
[1] 100+ papers per year with "0νββ" in the title [INSPIRE-HEP statistics]

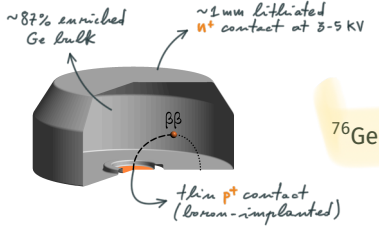
Experimental signature

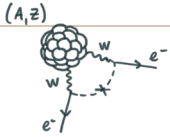


All experiments measure the total energy of the two emitted electrons

⟼ *necessary and sufficient* for discovery

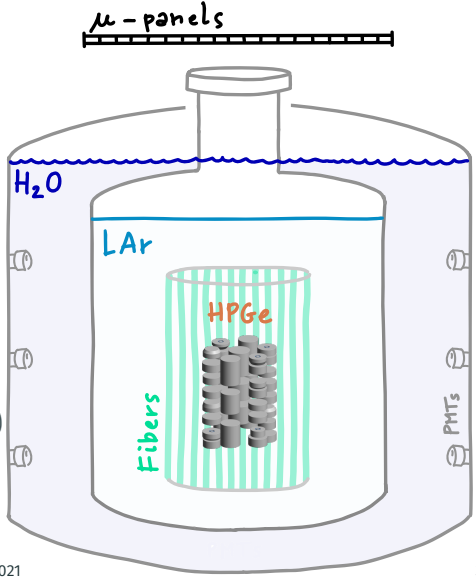






$^{76}Ge \xrightarrow{0\nu\beta\beta} {}^{76}Se + 2e^-$

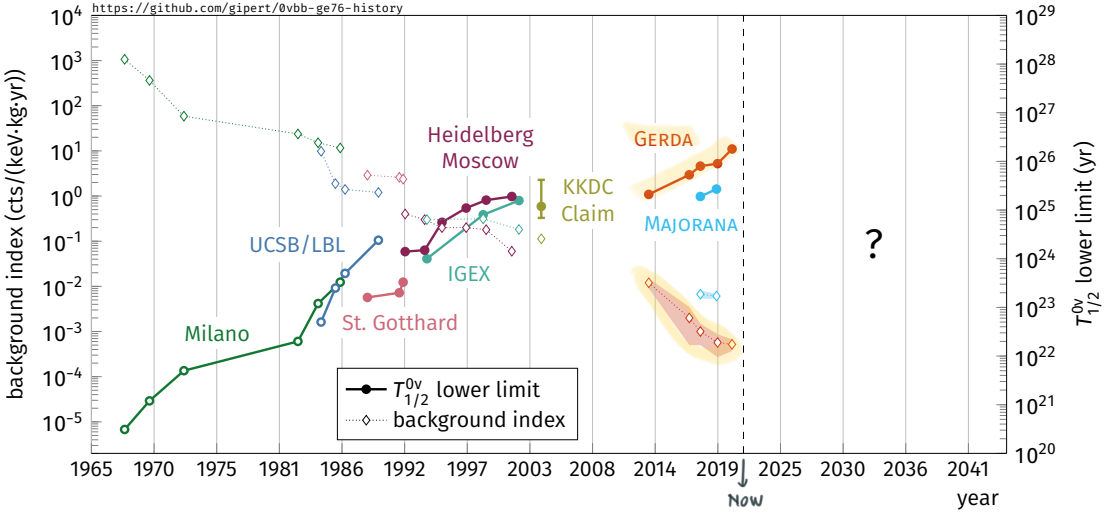
$Q_{\beta\beta} = 2039$ keV



High-Purity Germanium detectors enriched in ^{76}Ge

- source = detector ⟼ *high efficiency*
- pure ⟼ *low intrinsic background* 99.9999% Ge (6N)
- Ge crystal ⟼ *outstanding energy resolution* 0.1% @ $Q_{\beta\beta}$ (FWHM)
- solid-state TPC ⟼ *topological discrimination* Pulse Shape Analysis

50 years of Double Beta decay with ^{76}Ge



REF *Phys. Rev. C 100, 025501*

- HPGe detectors in vacuum cryostat
- Excellent energy resolution

Key technologies:

- Ultra-clean elecro-formed copper (EFCu)
- Low-noise front-end electronics

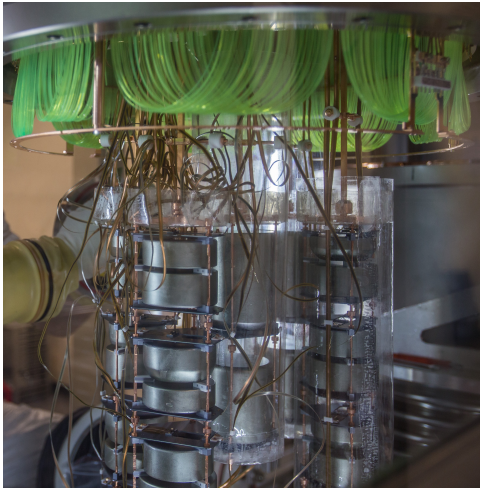
REF Phys. Rev. Lett. 125, 252502 (2020) REF Eur. Phys. J. C 78 (2018) 388

- HPGe detectors in liquid argon
- Quasi-background-free operation

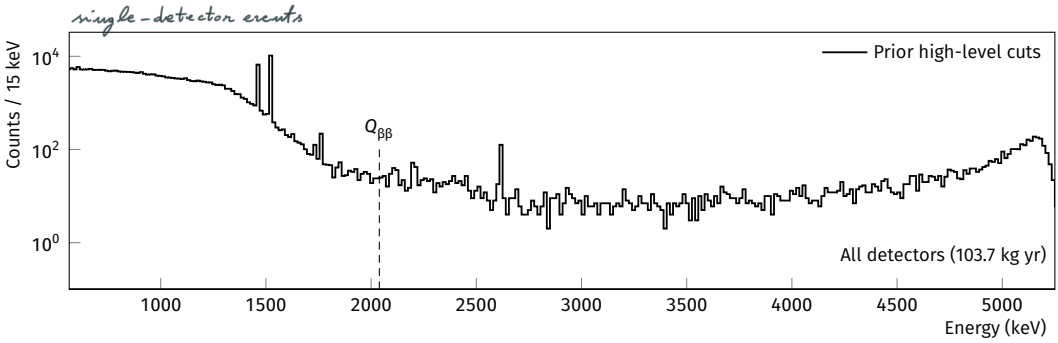
Key technologies:

- Bare HPGe detectors in liquid argon cryostat
- Cryostat in instrumented water shield
- Liquid argon instrumentation (here at TUM)
- Event topology by pulse-shape and argon scintillation

Pioneer of the LEGEND experimental concept



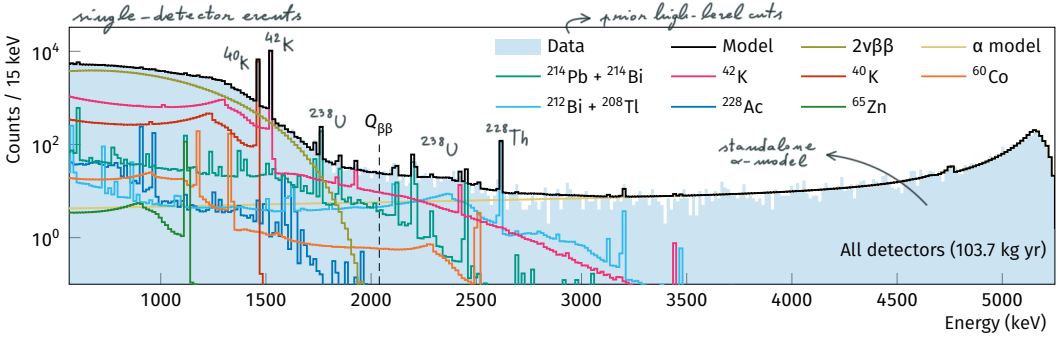
GERDA PHASE II DATA ENERGY SPECTRUM BEFORE HIGH-LEVEL CUTS



- Data taken from Dec 2015 to Nov 2019 (~90% duty cycle, including upgrade works)
- Energy resolution: ~ 0.1% FWHM at $Q_{\beta\beta}$ REF *Eur. Phys. J. C 81 (2021) 8, 682*
- 103.7 kg yr of exposure selected for analysis, largest ever collected with ^{enr}Ge

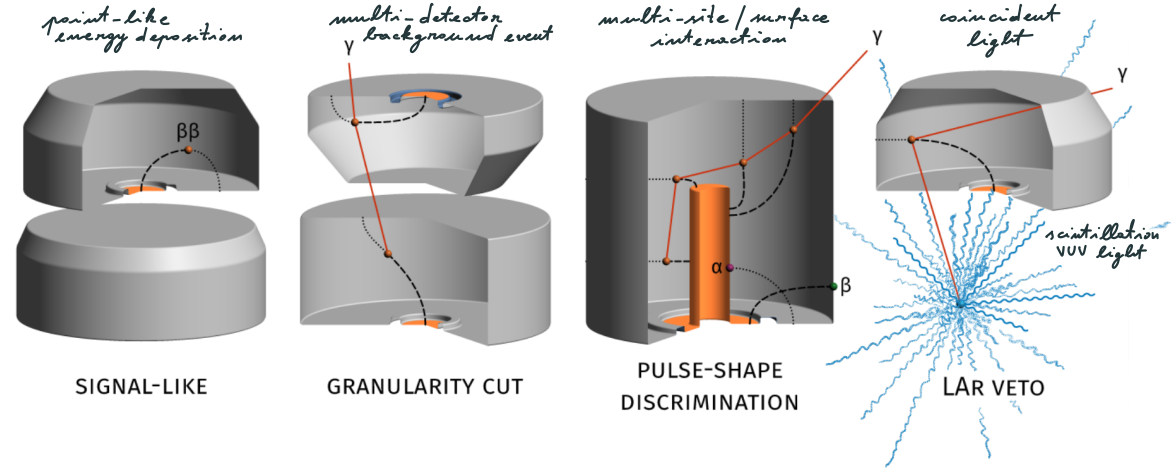
GERDA PHASE II DATA MODELING

REF J. HIGH ENERG. PHYS. 03 (2020) 139

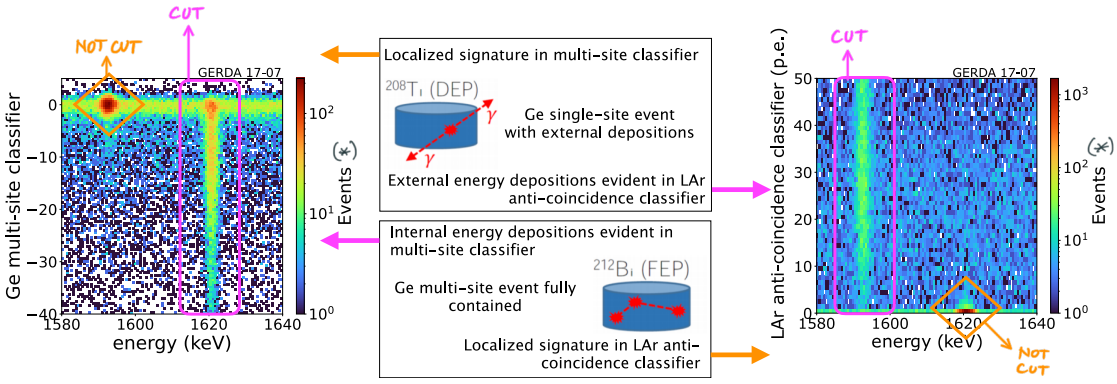


- Bayesian multivariate fit of Monte Carlo predictions *(with screening measurements as priors)*
- $Q_{\beta\beta}$ dominated by β from ^{42}K (from ^{42}Ar in LAr), α from ^{210}Po, γ from ^{228}Th and ^{238}U chains
- Results are input to several physics analyses and inform LEGEND

Signal and background discrimination techniques



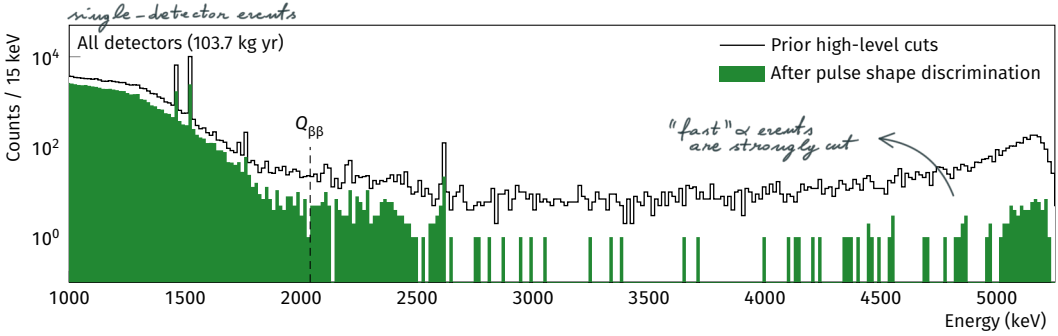
GIF attached!



DEP = double-escape peak
FEP = full-energy peak

[(*) GERDA ^{228}Th calibration data]

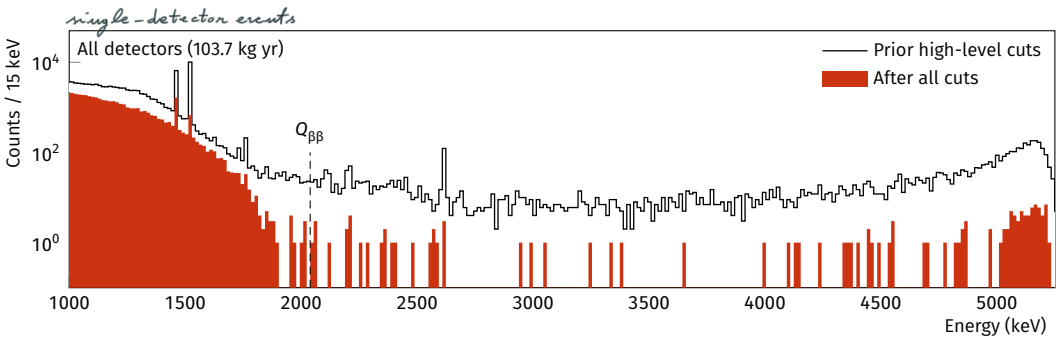
Pulse shape discrimination...



- Point-contact detectors: two-sided univariate A/E cut [REF JINST 4 (2009) P10007]
- Coaxial detectors: artificial neural network and risetime cut [REF EPJC 73 (2013) 10, 2583]
- 0νββ signal efficiency: 90% (70% for coaxials)

^{228}Th calibration data as training sample

...AND LIQUID ARGON ANTI-COINCIDENCE

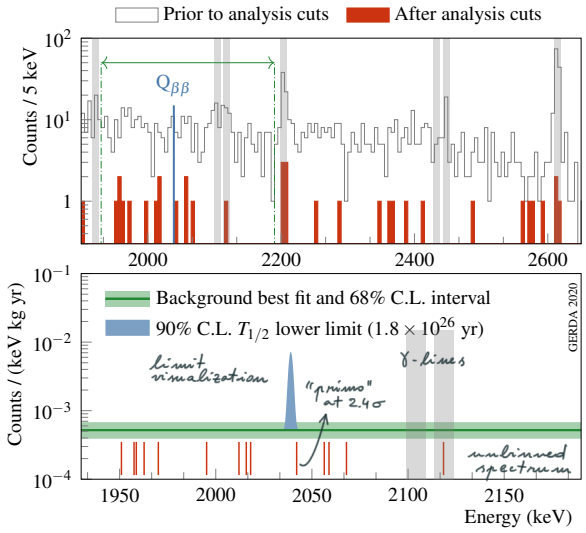


- Anti-coincidence between HPGe trigger and SiPM/PMT data *(≥ 0.3 p.e. in a 5 µs window)*
- Extremely low event rate at $Q_{\beta\beta}$ of ~ $5 \cdot 10^{-4}$ cts / (keV kg yr) ⟼ *quasi-background-free*
- Few events at $Q_{\beta\beta}$ ⟼ *"simple" background-model-free analysis*

~ 0.3 counts per FWHM in full exposure!

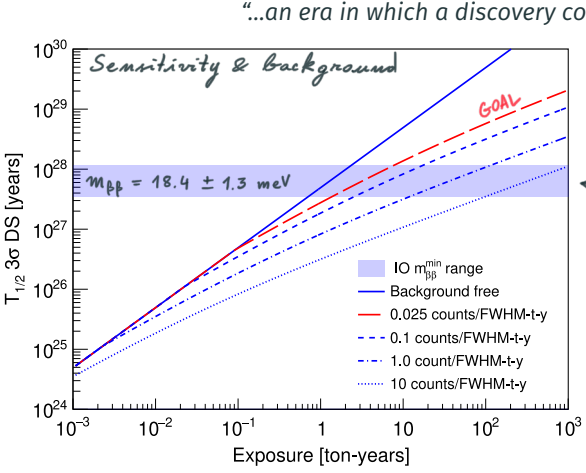
"The world's best-performing 0νββ experiment"

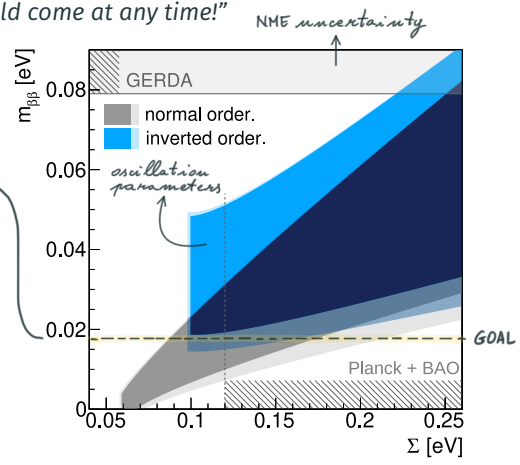
- $5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts / (keV kg yr) at $Q_{\beta\beta}$
- No signal in 127.2 kg yr of exposure
  (includes 23.5 kg yr from Phase I with a background of ~10^{-2} cts / (keV kg yr))
- $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ yr (90% C.L. frequentist)
  (equal to median expectation in absence of signal)
- $\langle m_{\beta\beta} \rangle$ < 79–180 meV



What next?

"...an era in which a discovery could come at any time!"





*"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} yr**, using existing resources as appropriate to expedite physics results."*

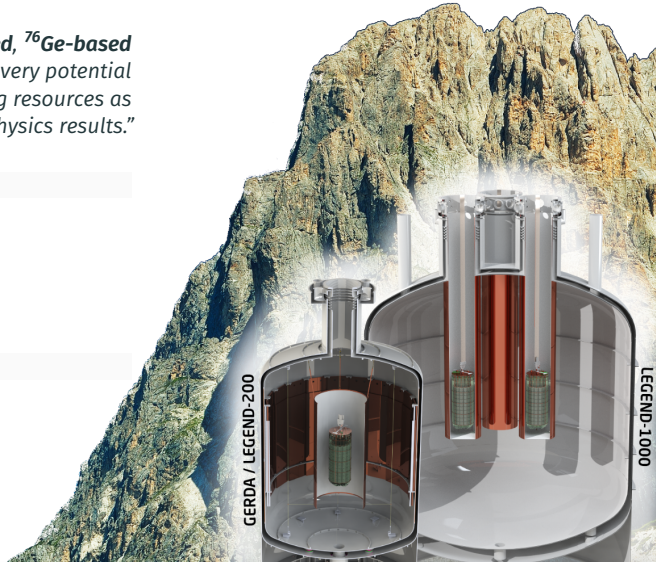
LEGEND-200

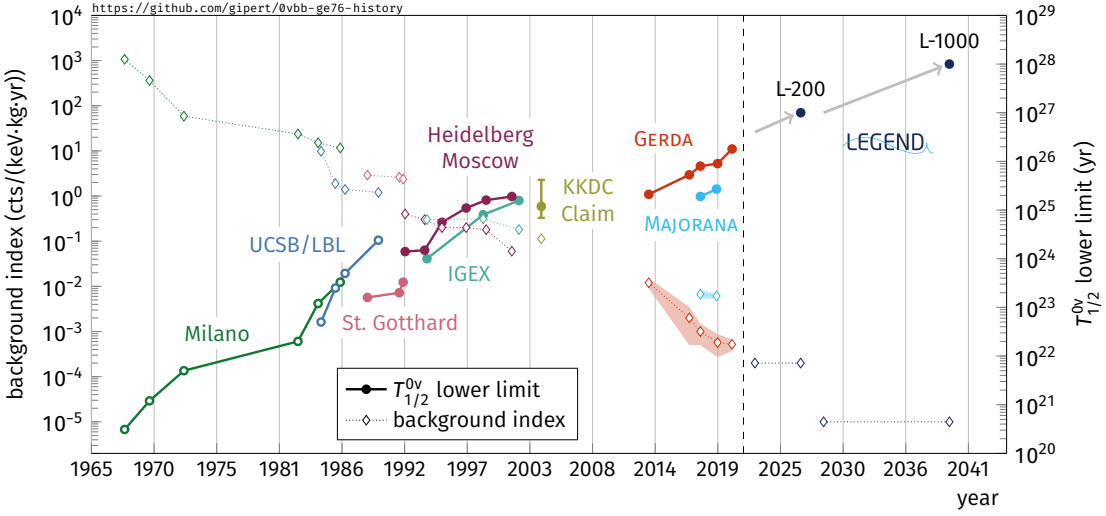
- **200 kg** of ^{enr}Ge (×5 yr), in GERDA cryostat
- Funded, under commissioning
- $B \sim 2 \cdot 10^{-4}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > 10^{27}$ **yr**

LEGEND-1000 arXiv 2107.11462

"pre-conceptual design report"

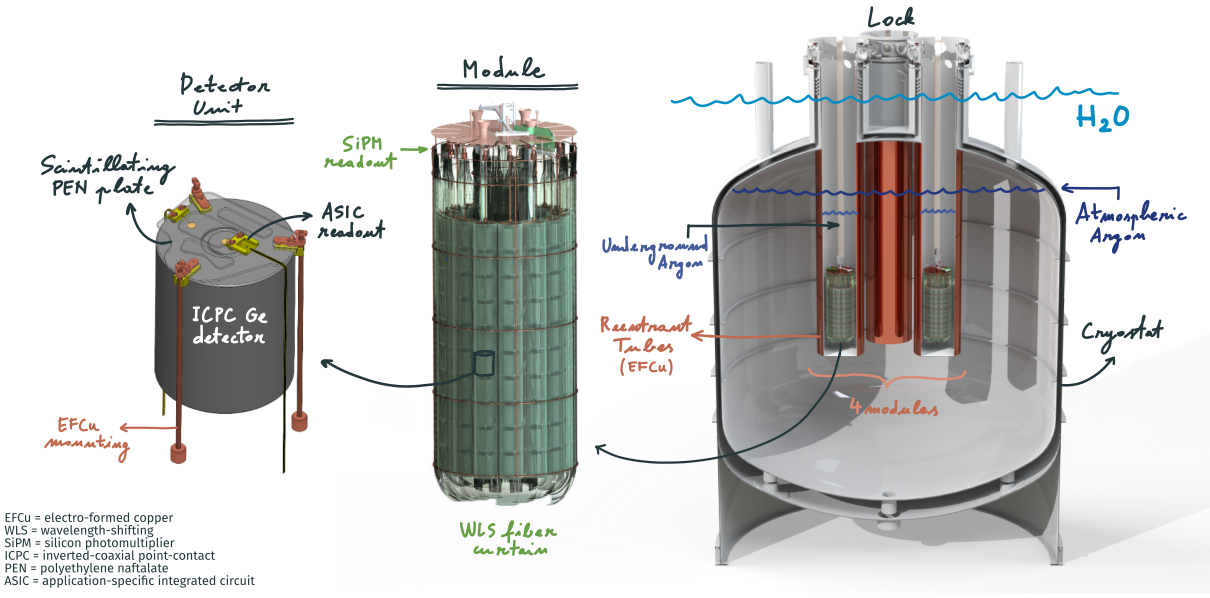
- **1 ton** of ^{enr}Ge (×10 yr), awaiting funding
- $B < 10^{-5}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > 10^{28}$ **yr**
- Cover full $\langle m_{\beta\beta} \rangle$ inverted ordering region



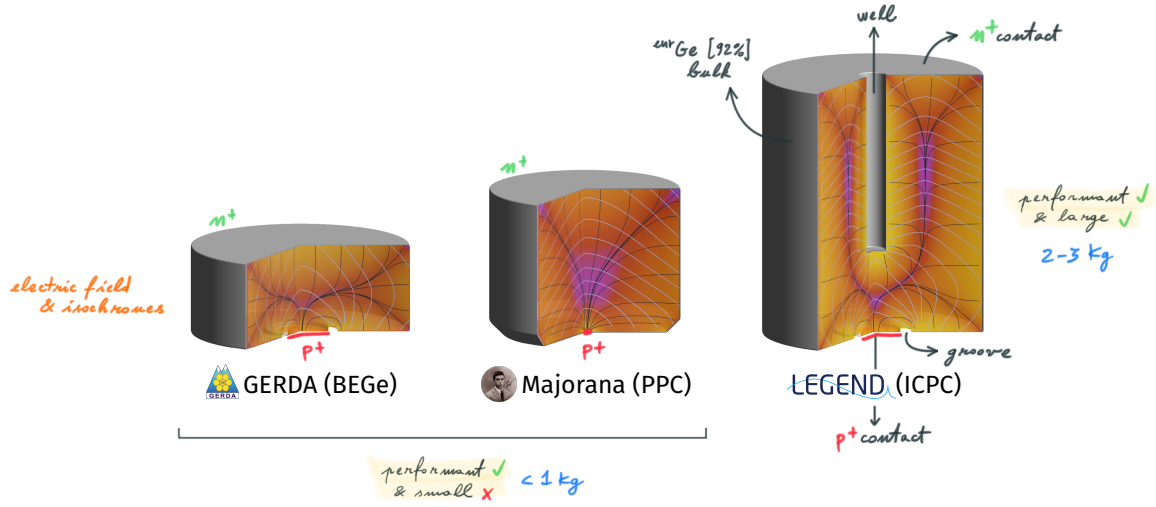

https://github.com/gipert/0vbb-ge76-history
background index (cts/(keV·kg·yr))
$T^{0\nu}_{1/2}$ lower limit (yr)
year
Heidelberg Moscow
KKDC Claim
GERDA
MAJORANA
L-200
L-1000
LEGEND
UCSB/LBL
IGEX
St. Gotthard
Milano
$T^{0\nu}_{1/2}$ lower limit
background index


GERDA
+ MAJORANA
+ new institutes
Canada
Hudson Bay
Labrador Sea
United States
Mexico
Gulf of Mexico
North Atlantic Ocean
Ireland
Norway
Finland
Denmark
Belarus
Ukraine
France
Romania
Spain
Portugal
Greece
Turkey
Syria
Iraq
Tunisia
Morocco
Algeria
Libya
Egypt
Western Sahara
Saudi Arabia

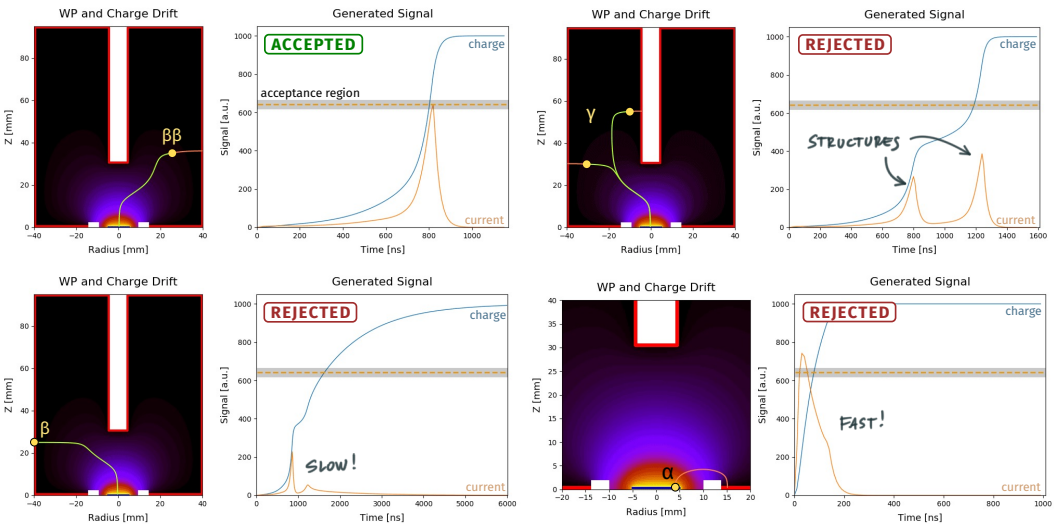
THE LEGEND -1000 BASELINE DESIGN

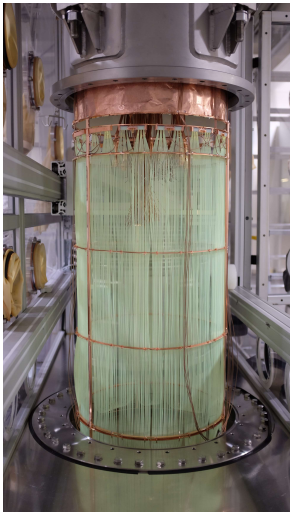


EFCu = electro-formed copper
WLS = wavelength-shifting
SiPM = silicon photomultiplier
ICPC = inverted-coaxial point-contact
PEN = polyethylene naftalate
ASIC = application-specific integrated circuit


electric field
& isochrones
n+
p+
GERDA (BEGe)
n+
p+
Majorana (PPC)
well
n+ contact
enr Ge [92%]
Bulk
performant ✓
& large ✓
2-3 kg
groove
LEGEND (ICPC)
p+ contact
performant ✓
& small ✗
< 1 kg

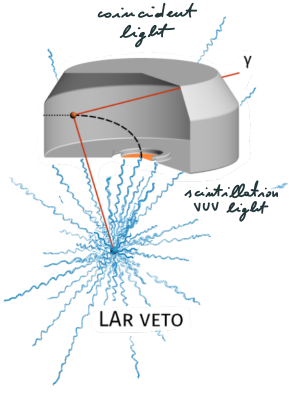
event signatures

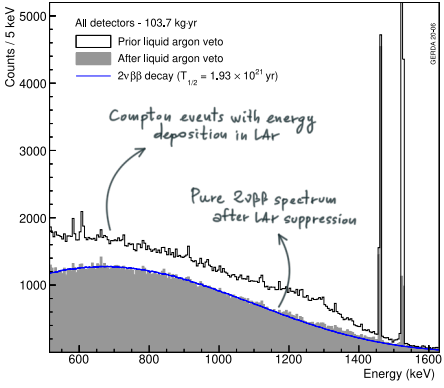




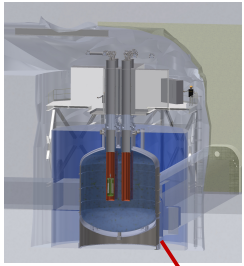
GERDA: detection of liquid argon scintillation light

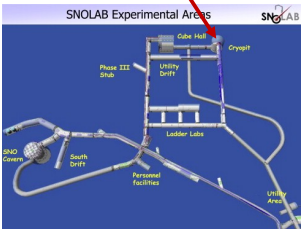
Low-background wavelength-shifting fibers for 128 nm single photon detection



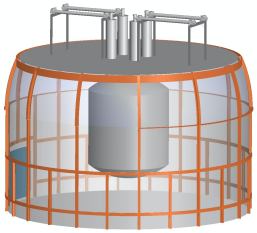


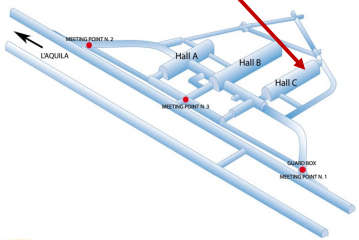
LEGEND-1000 underground sites





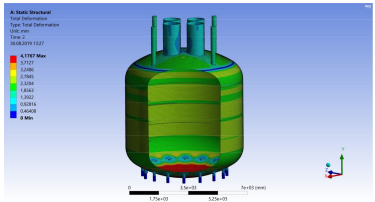
SNOLAB: cryopit committed for ton-scale 0nbb experiment





LNGS: Re-purpose BOREXINO tank and infrastructures

- SNOLAB **deeper** than LNGS;
- LNGS **depth sufficient** with tagging in-situ produced cosmogenic isotopes
- Possible repurposing of **BOREXINO** tank and infrastructures for LEGEND-1000
- LNGS option opportunity for **Germany/Europe**
- Commitment from **LNGS director** and **INFN**

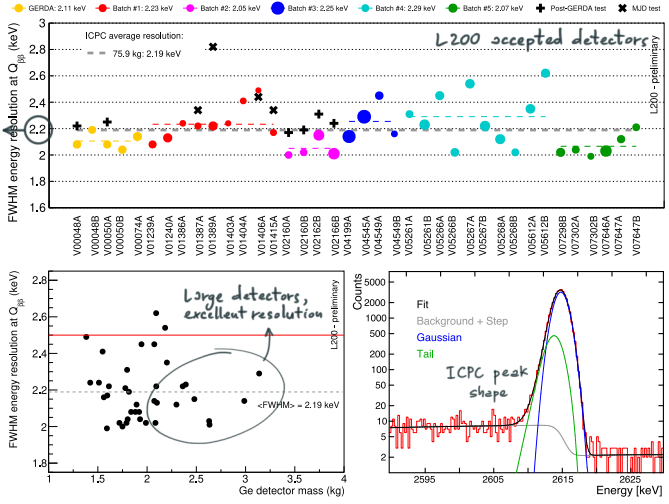


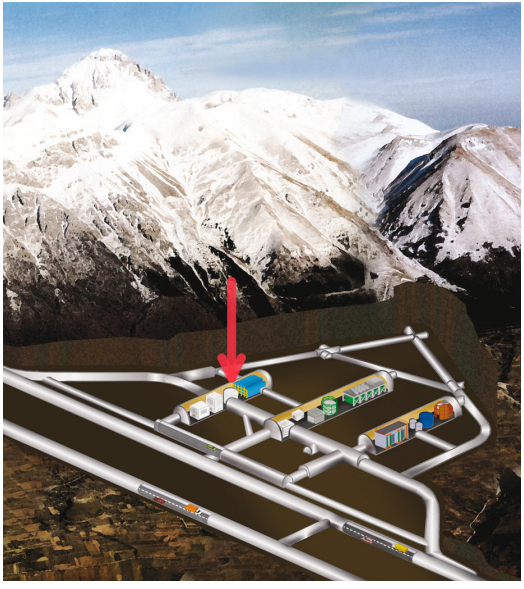
Deformation of cryostat for seismic event at LNGS

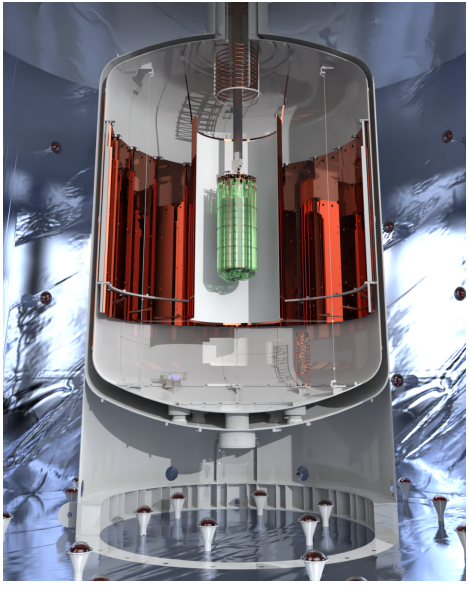
TOWARDS LEGEND -1000: LEGEND -200

- Procurement of ^{enr}Ge (92% enrichment)
- New ICPC detectors
- Improved LAr system
- Low-background materials
- **Under commissioning** at LNGS
- Commissioning/physics **data taking in 2021/2022**

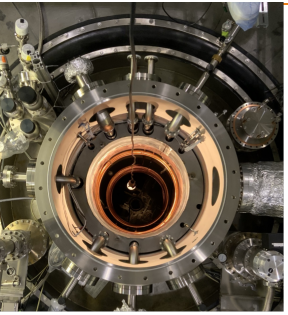
2.2 keV (FWHM) @ $Q_{\beta\beta}$

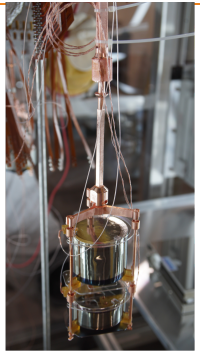


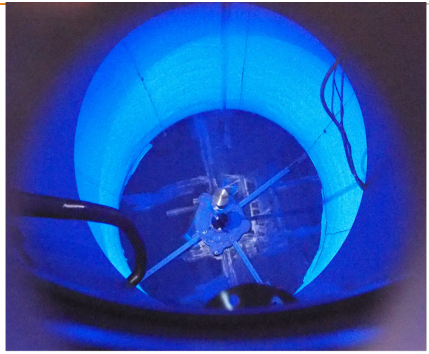


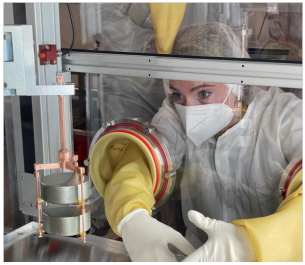


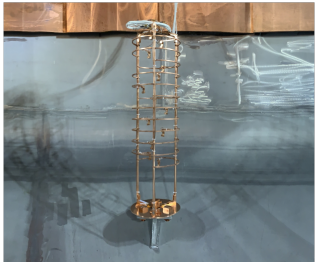
LEGEND-200 COMMISSIONING AT LNGS



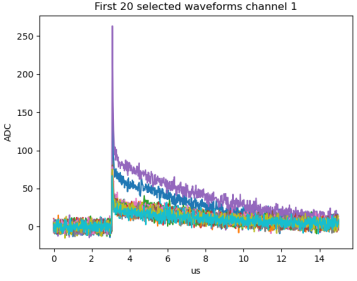


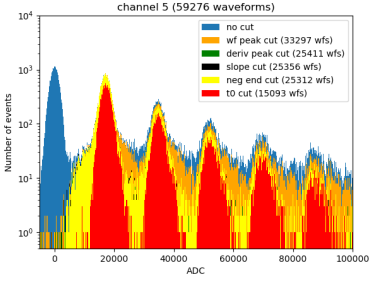






First SiPM waveforms with the “inner fiber barrel” in liquid argon





Multi-site

- ^{238}**U / ^{228}Th** from near-detector components, **external γ/n** from cryostat steel
  - ≫ *clean materials, remove opaque/inactive materials, large detectors, efficient LAr instrumentation*

Cosmogenic

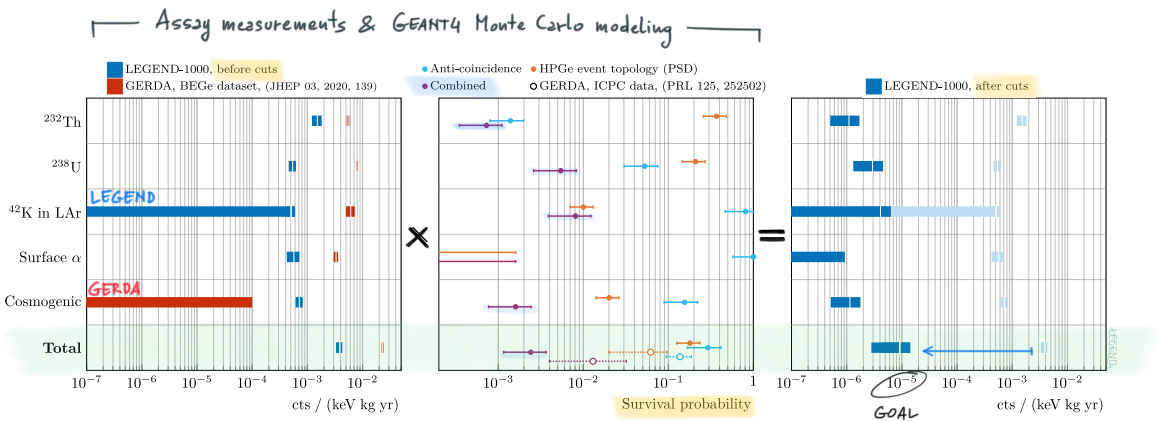
- ***in-situ*** μ-induced from **neutron capture on ^{76}Ge**
  - ≫ *underground laboratory, μ-veto, delayed coincidence cuts*
- ***ex-situ*** above-ground **activation of Ge**
  - ≫ *reduce above-ground exposure, cool-down period underground*

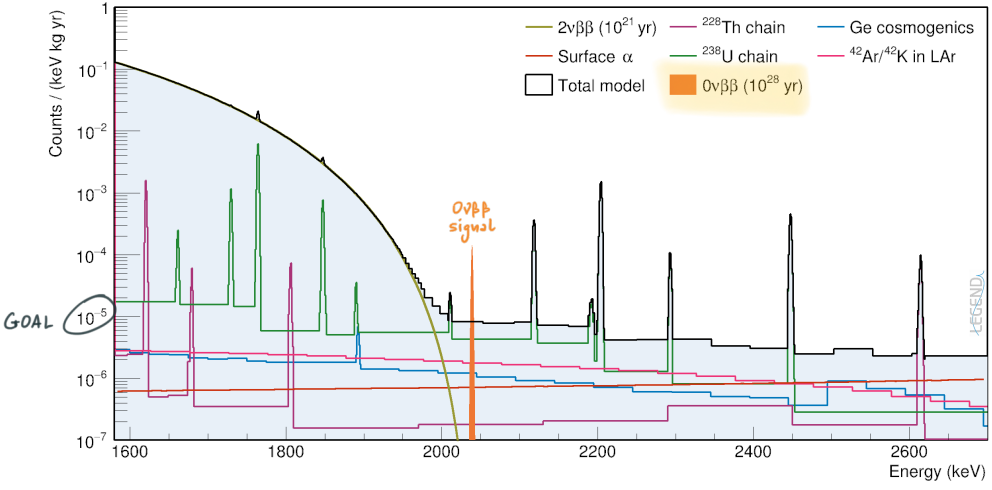
Detector surface

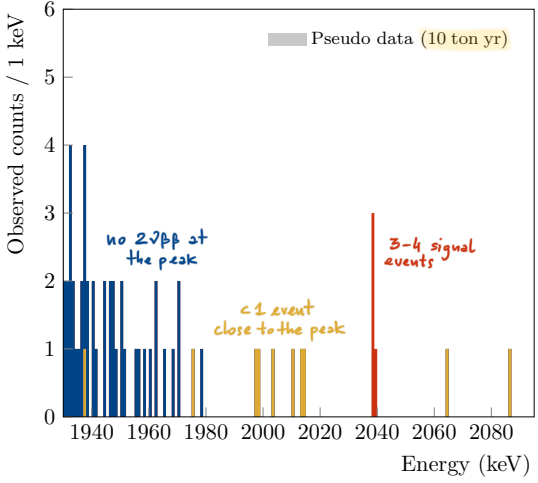
- **^{42}K events**: β decay from cosmogenic activation of argon
  - ≫ *cleaner underground argon*
- **α events** from radon deposition on detectors
  - ≫ *large detectors*

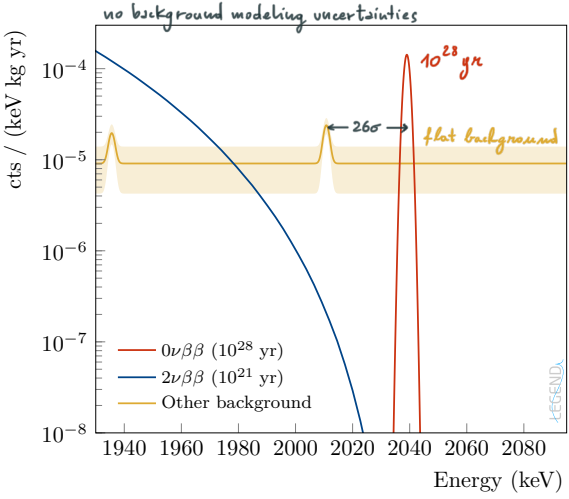
-1000 BACKGROUND PROJECTIONS

A detailed, careful background model

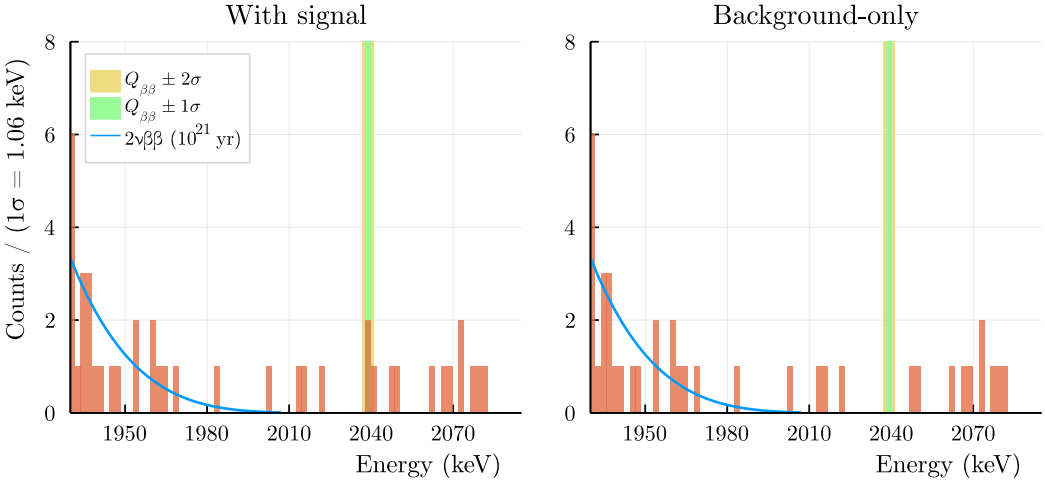



2νββ (10^21 yr)
228Th chain
Ge cosmogenics
Surface α
238U chain
42Ar/42K in LAr
Total model
0νββ (10^28 yr)
Counts / (keV kg yr)
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
GOAL
0νββ signal
1600
1800
2000
2200
2400
2600
Energy (keV)
LEGEND


Pseudo data (10 ton yr)
Observed counts / 1 keV
Energy (keV)
no 2νββ at the peak
3–4 signal events
< 1 event close to the peak


no background modeling uncertainties
cts / (keV kg yr)
Energy (keV)
10^{23} yr
26σ
flat background
$0\nu\beta\beta$ (10^{28} yr)
$2\nu\beta\beta$ (10^{21} yr)
Other background
LEGEND

GIF attached!



NOT ONLY 0νββ!

TABLE II. A non-exhaustive listing of recent and proposed BSM physics searches by Ge-based experiments.

Physics	Signature	Energy Range	Experiment
Bosonic dark matter	Peak at DM mass	< 1 MeV	MAJORANA[65], GERDA [66]
Electron decay	Peak at 11.8 keV	~ 10 keV	MAJORANA [65]
Pauli exclusion principle violation	Peak at 10.6 keV	~ 10 keV	MAJORANA [65]
Solar axions	Peaked spectra, daily modulation	< 10 keV	MAJORANA[65, 67]
Majoron emission	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	GERDA [68]
Exotic fermions	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [69, 70]
Lorentz violation	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [71–73]
Exotic currents in $2\nu\beta\beta$ decay	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$	(proposed) [74]
Time-dependent $2\nu\beta\beta$ decay rate	Modulation of $2\nu\beta\beta$ spectrum	$< Q_{\beta\beta}$	(proposed) [75]
WIMP and related searches	Exponential excess, annual modulation	< 10 keV	CDEX [76]
Baryon decay	Timing coincidence	> 10 MeV	MAJORANA [77]
Fractionally charged cosmic-rays	Straight tracks	few keV	MAJORANA [78]
Fermionic dark matter	Nuclear recoil/deexcitation	$<$ few MeV	(proposed) [79]
Inelastic boosted dark matter	Positron production	$<$ few MeV	(proposed) [80]
BSM physics in Ar	Features in Ar veto spectrum	ECEC in ^{36}Ar	GERDA [81]

From our pCDR [ArXiV: 2107.11462]

Agostini, Bossio, Ibarra, Moreno [PLB 815 2021, 136127]

— SFB 1258 —

April 2016 LEGEND collaboration formed

Dec 2019 Completion of GERDA ⟼ LEGEND-200 commissioning start

2021/2022 Commissioning/physics data taking of LEGEND-200

July 2021 DOE Portfolio Review (LEGEND-1000, nEXO, CUPID) arXiv 2107.11462

Sep 2021 North American / European Summit at LNGS: *stakeholders strive for international funding for two ton-scale* 0νββ *experiments, one at SNOLAB and one at LNGS*

Oct 2021 DOE verbally announced that LEGEND-1000 emerged as the portfolio review winner in all but one category. CUPID not considered as ton-scale

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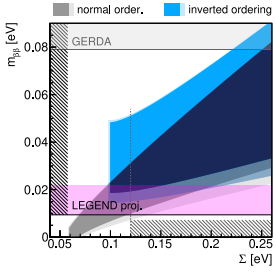
Jul 2022 *Critical Decision 1*: need to strategize funding

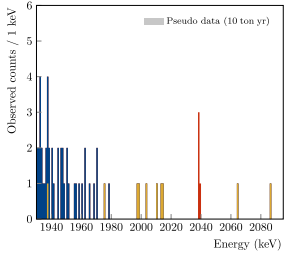
2022/2023 Start of procurement of long-lead items (Ge, cryostat, infrastructure)

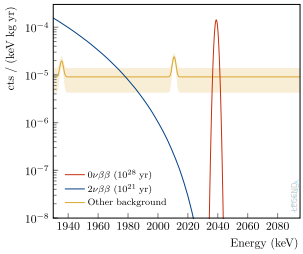
2027/2028 Deployment of first 250 kg Ge module

Wrapping up

- LEGEND-1000 is optimized for a *quasi-background-free*, 0νββ search in discovery mode
- The collaboration builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
- LEGEND has a **low-risk path** to meeting its background goal of 10^{-5} cts / (keV kg yr)
- Low backgrounds, excellent resolution, and topology reconstruction allow for a **unambiguous discovery of 0νββ decay**
- LEGEND will pioneer the exploration of new energy frontiers, achieving the highest half-life sensitivity in the field, and go even beyond the bottom of the inverted ordering

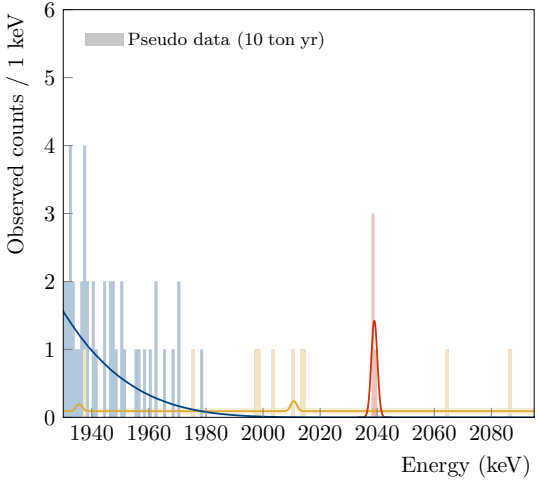


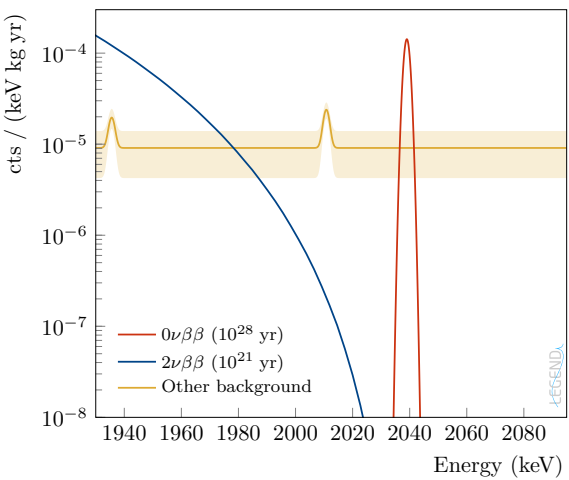




Backup

THE LEGEND -1000 DISCOVERY POWER





Not just a counting experiment

Powerful exclusion of alternative hypotheses

- 0νββ decay ⟼ narrow cluster of events
- γ line at $Q_{\beta\beta}$ ⟼ spread in Ge classifier
- α events ⟼ spread in Ge classifier
- γ continuum ⟼ spread in LAr classifier
- all γ ⟼ structures in energy spectrum

LEGEND has many handles to confirm a signal and reject any background hypotheses

Three counts in the 0νββ region: what's their origin?