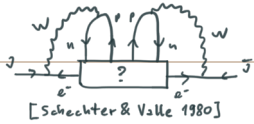
Searching for matter creation with LEGEND

L. Pertoldi <luigi.pertoldi@tum.de>

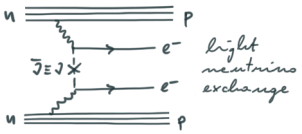
Karlsruhe • 8 March 2023

TU München, INFN Padova

Why neutrinoless double-β decay?

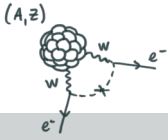


$(A, Z) \longmapsto (A, Z+2) + 2e^- + 2\bar{\nu}_e$



"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

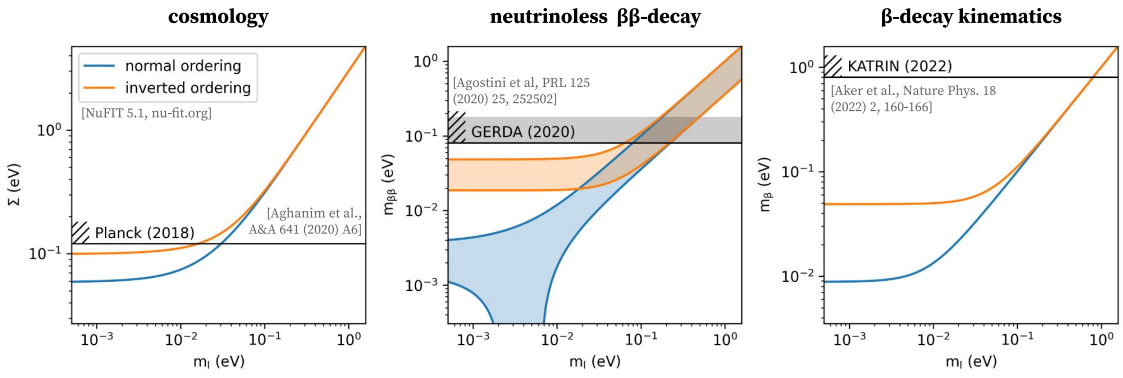
The (Majorana) neutrino that mediates 0νββ is the one that oscillates and the Standard Model is an effective theory *(seesaw mechanism)*

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

Majorana effective mass

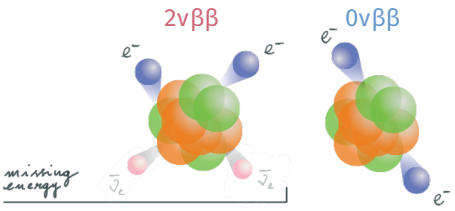
[1] 100+ papers per year with "0νββ" in the title [INSPIRE-HEP statistics]

Complementarity with other ν mass probes



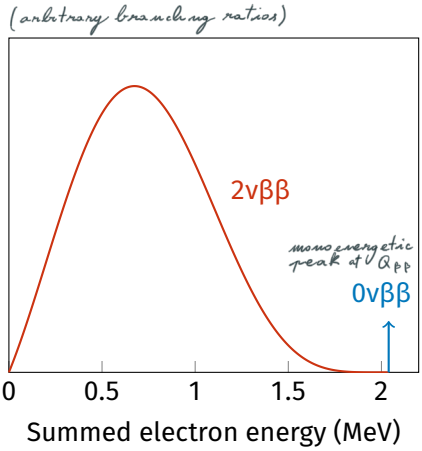
Christoph Wiesinger (TUM)

Experimental signature



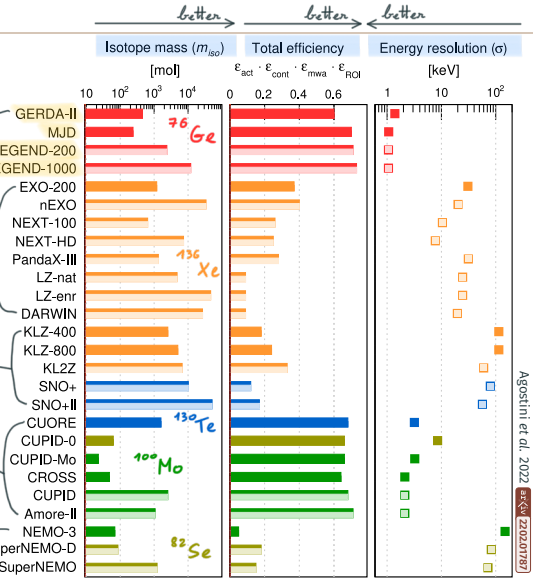
All experiments measure the total energy of the two emitted electrons

⟼ *necessary and sufficient* for discovery

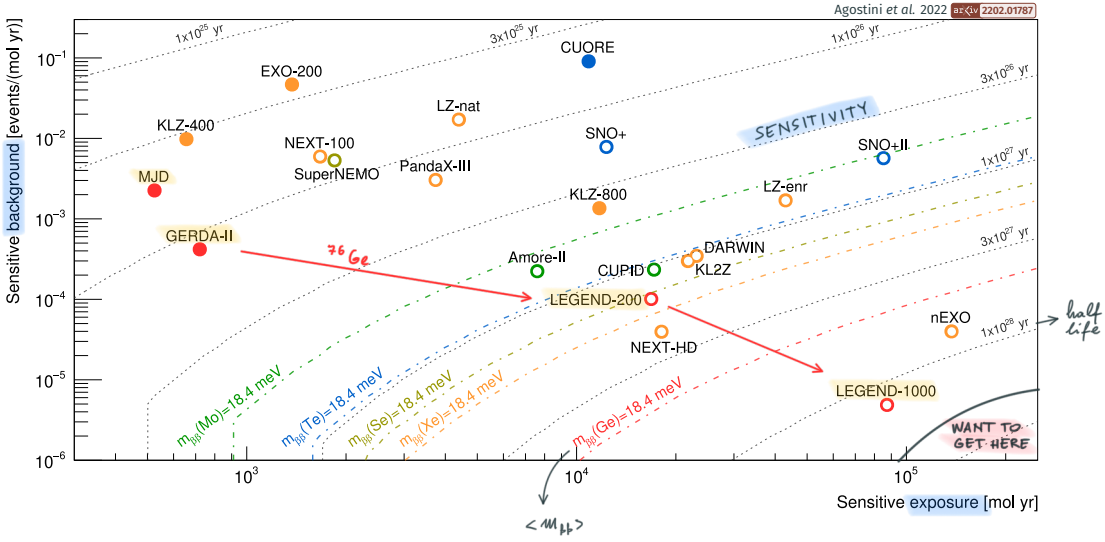


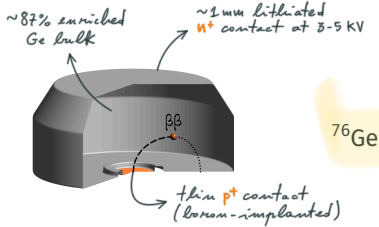
A ZOO OF DETECTOR CONCEPTS

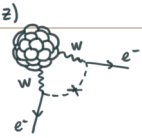
- **High-purity Germanium detectors**
  energy resolution, efficiency, background
- **Xenon Time Projection Chambers**
  isotope mass, particle tracking
- **Large Liquid Scintillators**
  isotope mass
- **Cryogenic Calorimeters**
  energy resolution, efficiency, granularity
- **Tracking Calorimeters**
  particle tracking, decay kinematics



Detector concepts: sensitivity





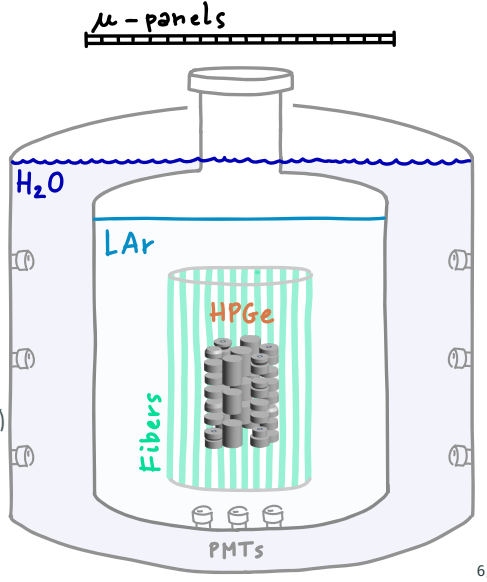


$^{76}Ge \xrightarrow{0\nu\beta\beta} {}^{76}Se + 2e^-$

$Q_{\beta\beta} = 2039$ 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



REF Adv. High Energy Phys. 2014 (2014) 365432

REF Phys. Rev. Lett. 130, 062501 (2023)

- HPGe detectors in vacuum cryostat
- Excellent energy resolution

Key technologies:

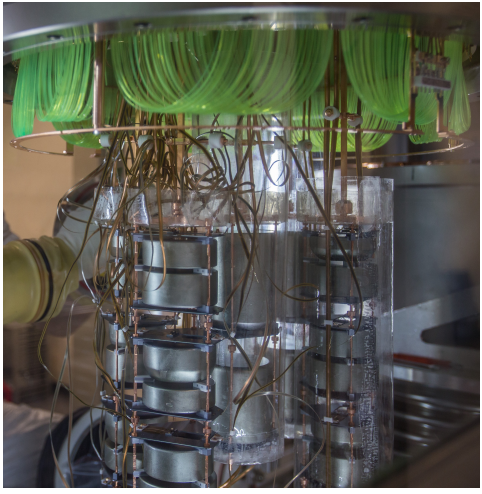
- Ultra-clean elecro-formed copper (EFCu)
- Low-noise front-end electronics

REF Phys. Rev. Lett. 125, 252502 (2020) REF EPJC 78 (2018) 388

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

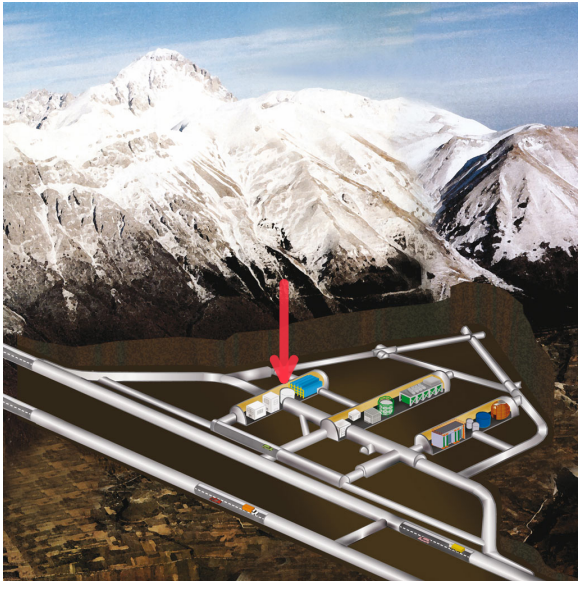
Key technologies:

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

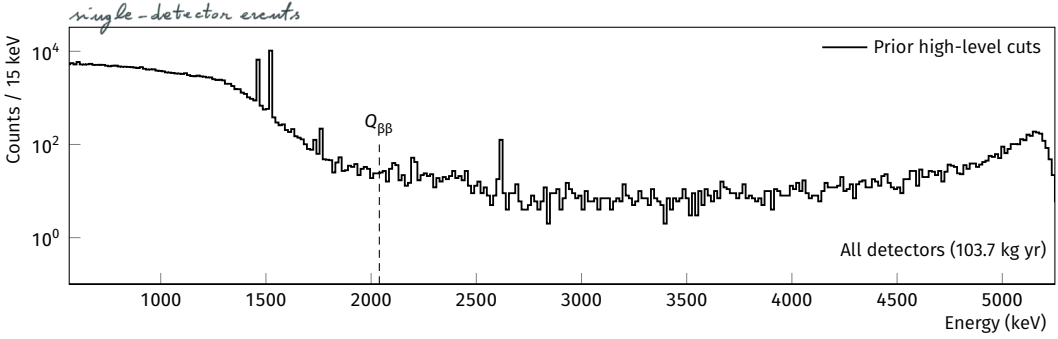


The pioneers

GERmanium DEtector ARray at LNGS — 3500 m.w.e. —



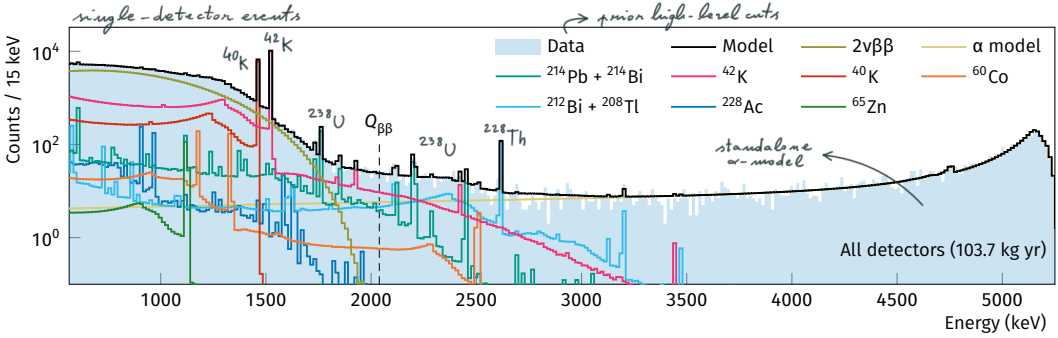
Phase II data energy spectrum before high-level cuts



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

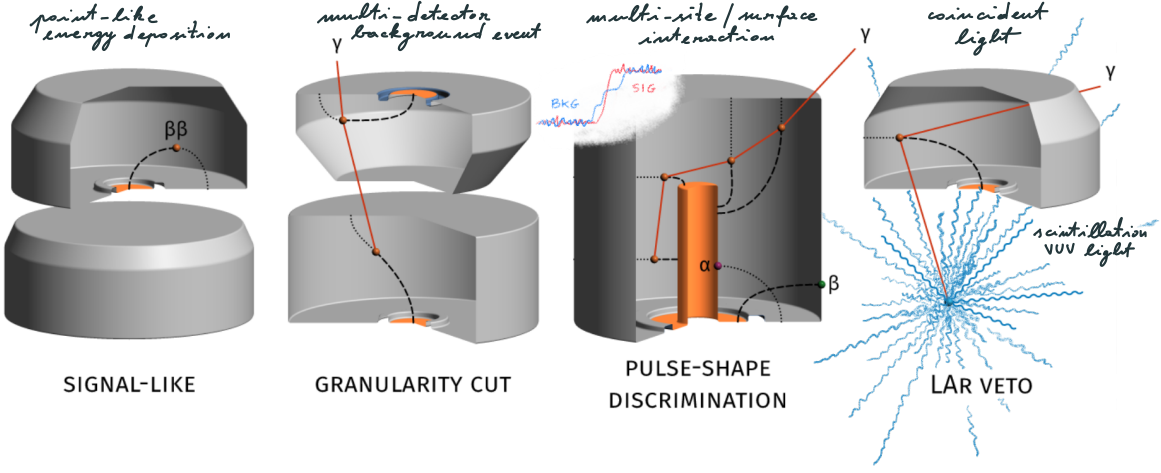
PHASE II DATA MODELING

REF JHEP 03 (2020) 139

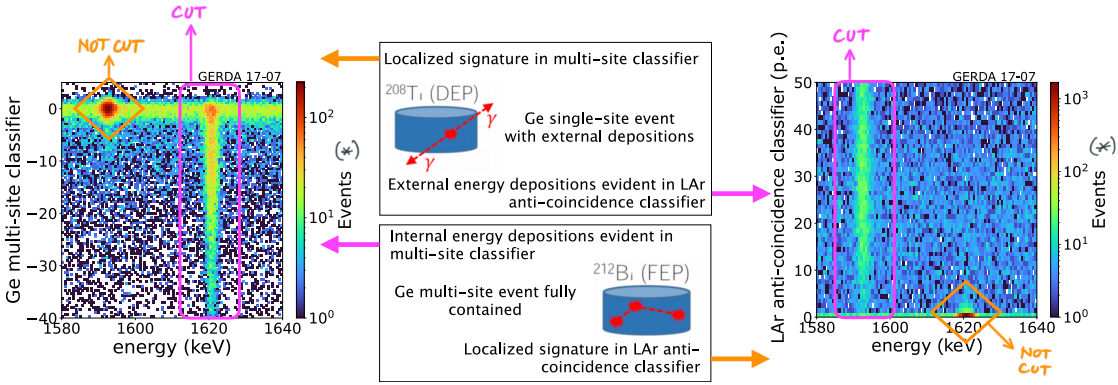


- Bayesian multivariate fit of Monte Carlo predictions *(with screening measurements as priors)*
- $Q_{\beta\beta}$ dominated by β from ^{42}K (from ^{42}Ar in LAr), α from ^{210}Po, γ from ^{228}Th and ^{238}U chains
- Results are input to several physics analyses and inform future experiments (LEGEND)

Signal and background discrimination techniques



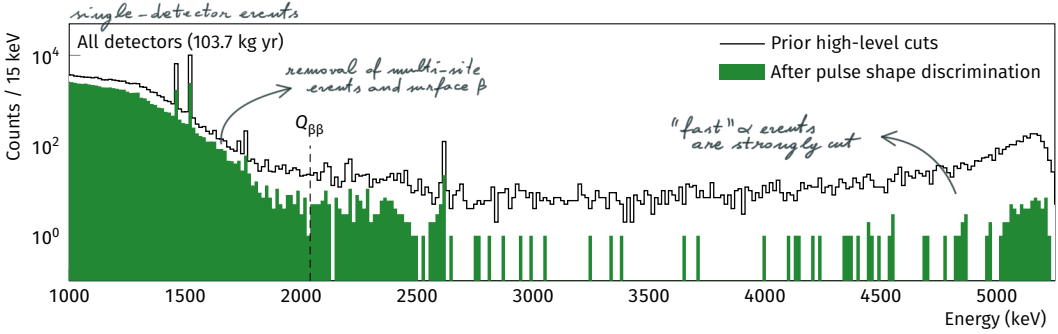
Powerful combination of background tagging techniques



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

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

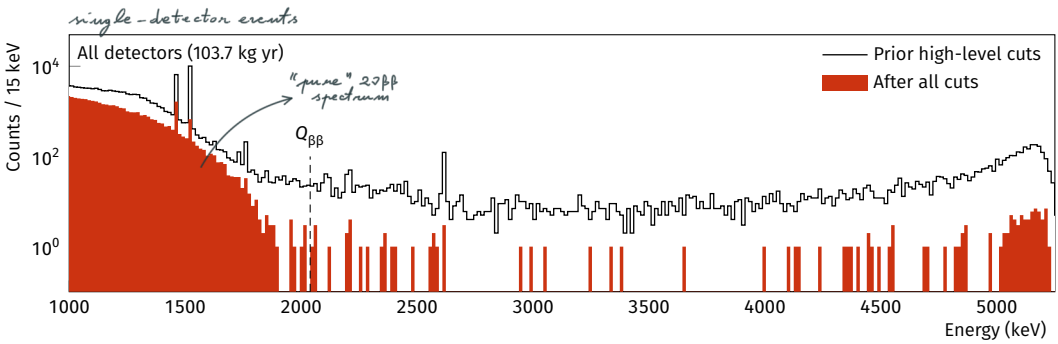
Pulse shape discrimination...



- Point-contact detectors: two-sided univariate A/E cut
- Coaxial detectors: artificial neural network and risetime cut
- 0νββ signal efficiency: 90% (70% for coaxials) EPJC 82 (2022) 284

^{228}Th calibration data as tuning sample

...AND LIQUID ARGON ANTI-COINCIDENCE

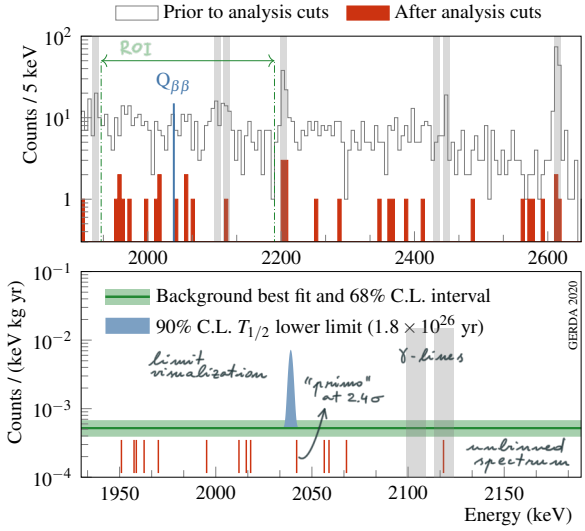


- Anti-coincidence between HPGe trigger and SiPM/PMT data *(≥ 0.3 p.e. in a 5 µs window)*
- Extremely low event rate at $Q_{\beta\beta}$ of ~ $5 \cdot 10^{-4}$ cts / (keV kg yr) ⟼ *quasi-background-free*
- Few events at $Q_{\beta\beta}$ ⟼ *"simple" background-model-free analysis*

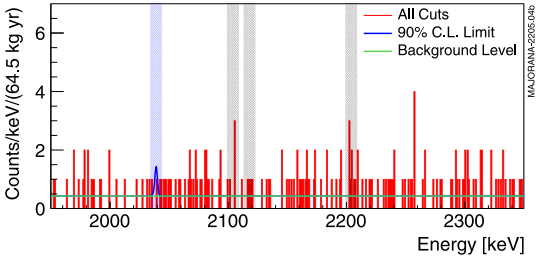
~ 0.3 counts per FWHM in full exposure!

"One of the world's best-performing 0νββ experiments"

- $5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts / (keV kg yr) at $Q_{\beta\beta}$
- No signal in 127.2 kg yr of exposure *blind analysis*
- $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ yr (90% C.L. frequentist)
- $\langle m_{\beta\beta} \rangle$ < 79–180 meV (NME uncertainty)



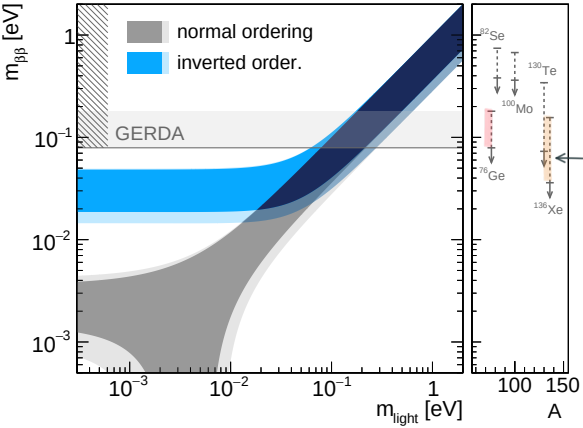
- Energy resolution of 2.52 keV FWHM at $Q_{\beta\beta}$
- No signal in 64.5 kg yr of *active* exposure
- $T^{0\nu}_{1/2} > 0.83 \cdot 10^{26}$ yr (90% C.L. frequentist)
- $\langle m_{\beta\beta} \rangle$ < 113–269 meV



+

$T^{0\nu}_{1/2} > 2.6 \cdot 10^{26}$ yr *(90% C.L. frequentist)*

Results from other experiments

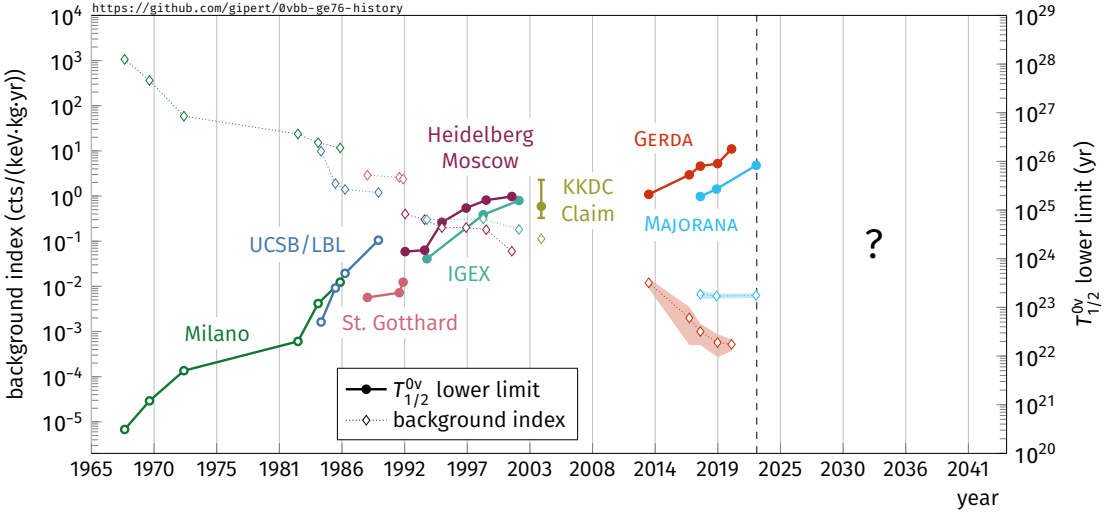


- ^{136}Xe, ^{76}Ge (and ^{130}Te) place the most stringent limits
  - *Note:* ^{76}Ge limits on $\langle m_{\beta\beta} \rangle$ are weakened by a less favorable phase space factor
- Latest KamLAND-Zen800 results:
  - arXiv 2203.02139
  - $T^{0\nu}_{1/2} > 2.3 \cdot 10^{26}$ yr (90% C.L.)
  - $\langle m_{\beta\beta} \rangle < 36$–$156$ meV

(• GERDA has still the best sensitivity)

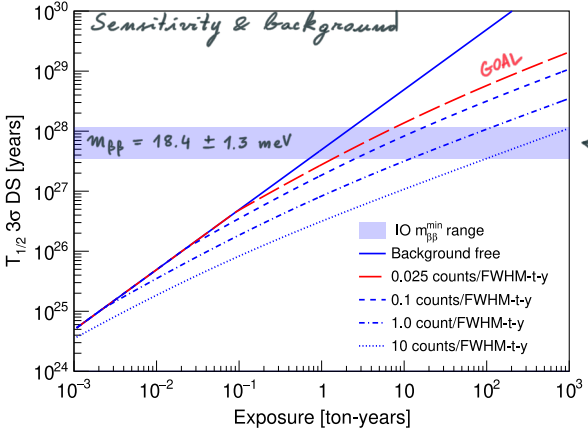
The Future

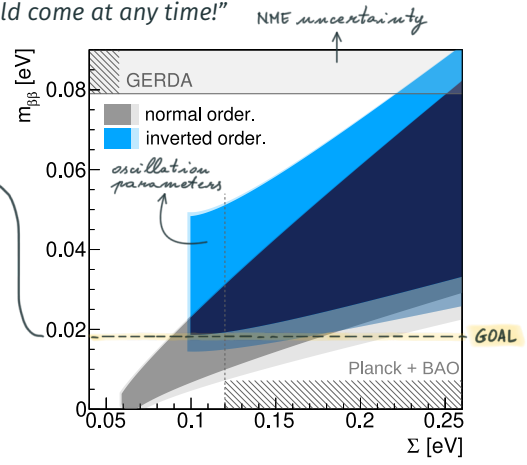
50 years of Double Beta decay with ^{76}Ge



What next?

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





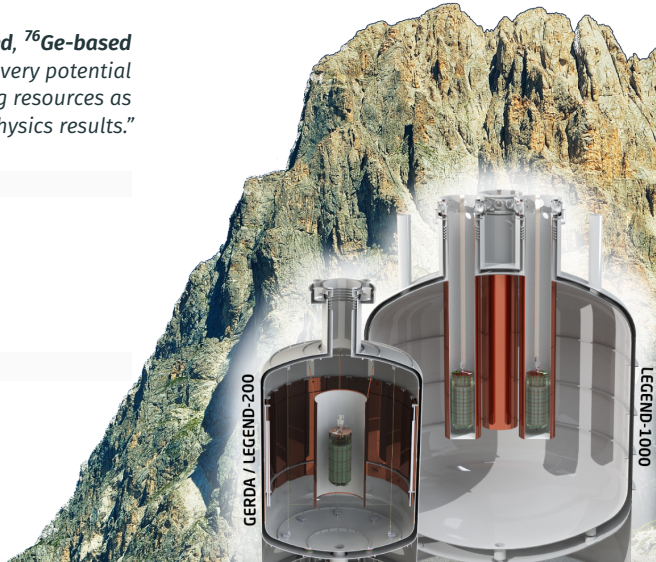
*"The collaboration aims to develop a **phased**, **^{76}Ge-based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} yr**, using existing resources as appropriate to expedite physics results."*

LEGEND-200

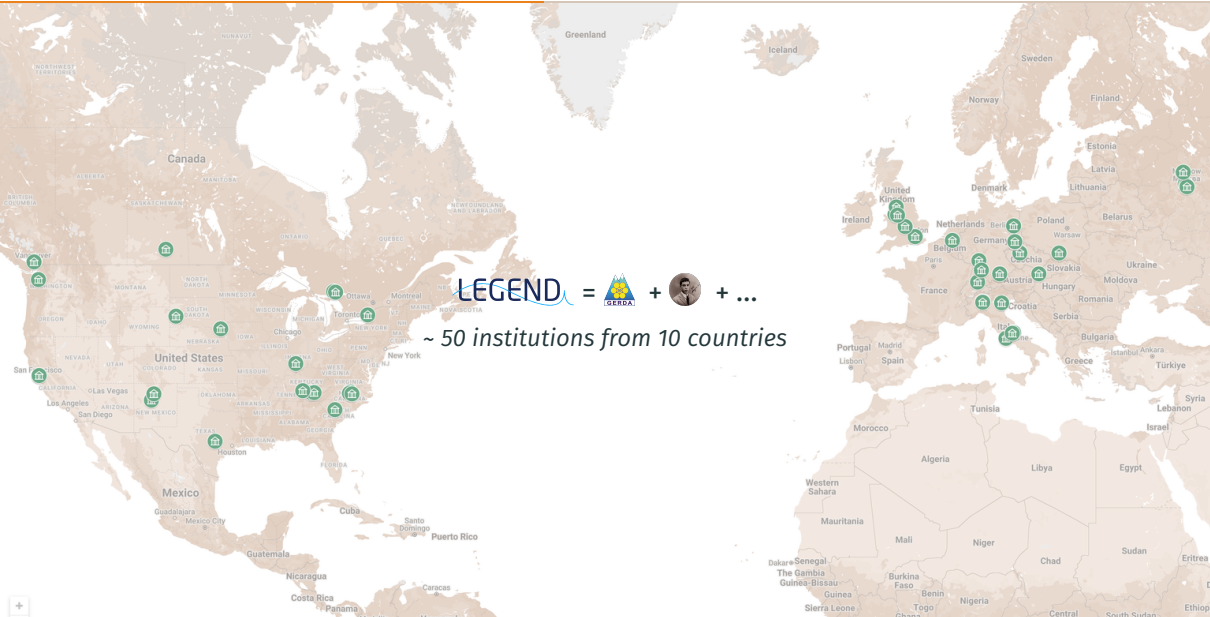
- **200 kg** of ^{enr}Ge (×5 yr), in GERDA cryostat
- Operating with 140 kg of ^{enr}Ge
- $B \sim 2 \cdot 10^{-4}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > 10^{27}$ **yr**

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



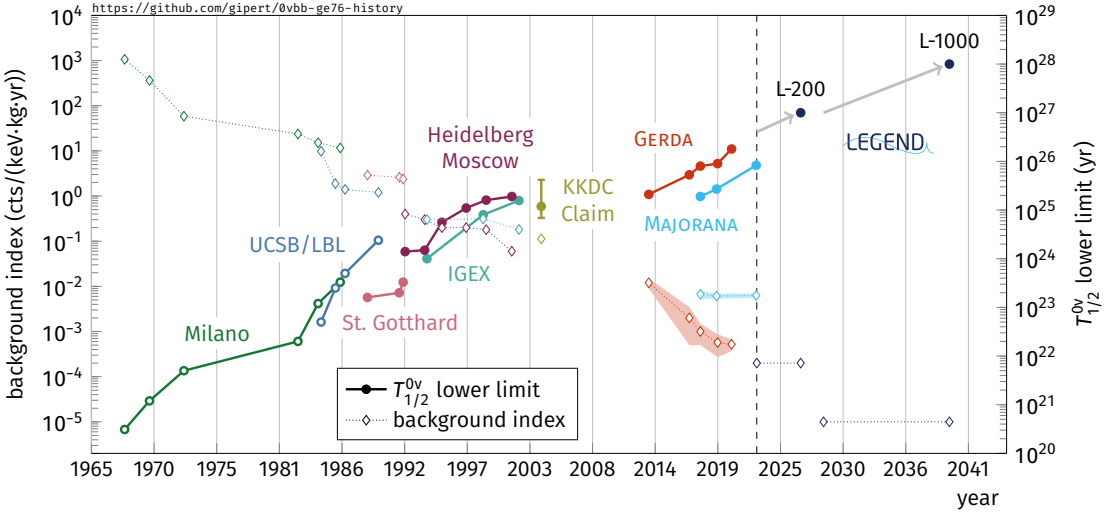
The collaboration



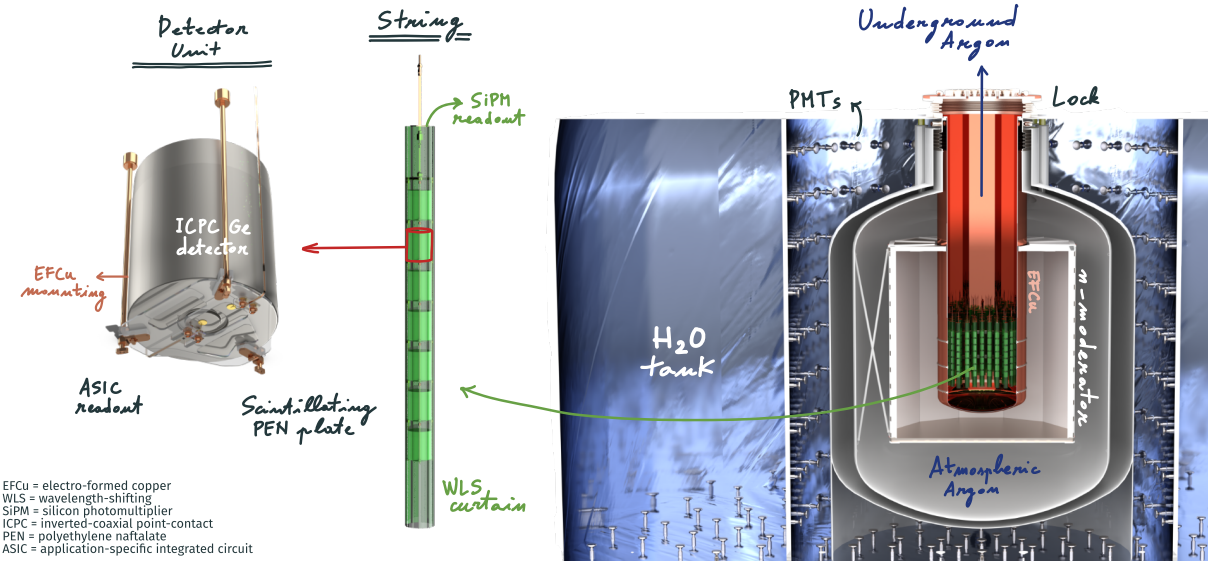
LEGEND = GERDA + + ...

~ 50 institutions from 10 countries

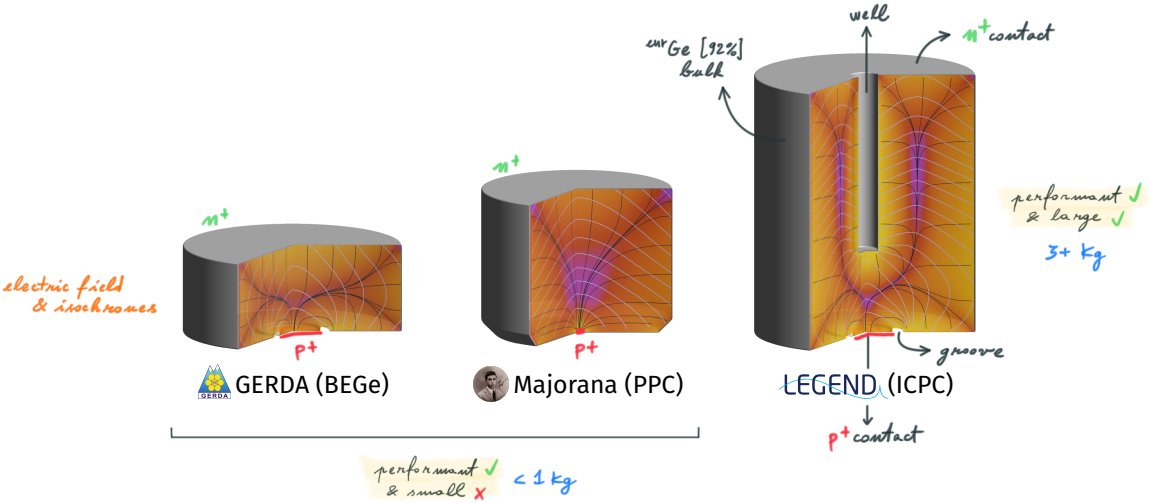
50 years of Double Beta decay with ^{76}Ge

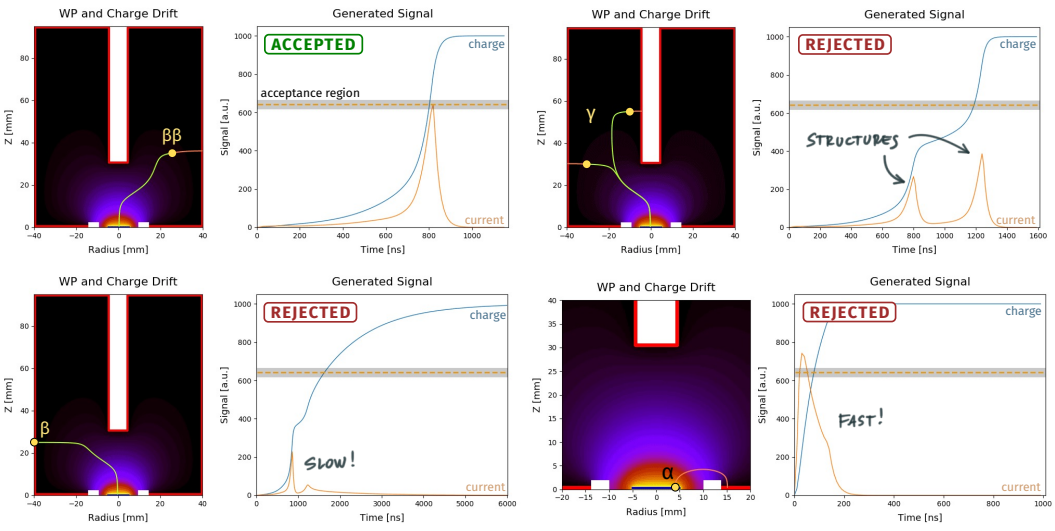


THE LEGEND -1000 (@ LNGS) BASELINE DESIGN



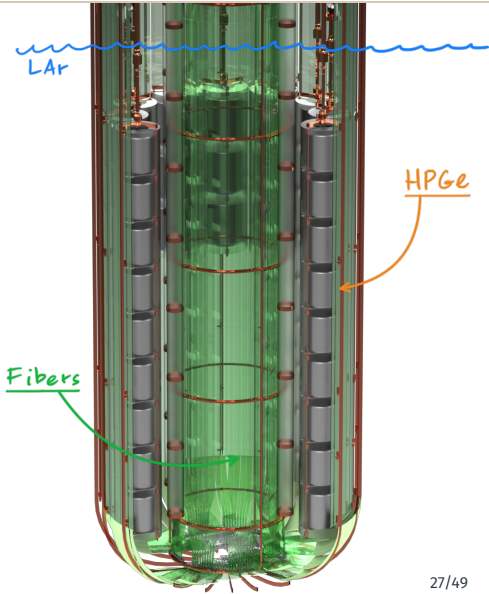
EFCu = electro-formed copper
WLS = wavelength-shifting
SiPM = silicon photomultiplier
ICPC = inverted-coaxial point-contact
PEN = polyethylene naftalate
ASIC = application-specific integrated circuit


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


WP and Charge Drift
Z [mm]
Radius [mm]
ββ
Generated Signal
ACCEPTED
charge
acceptance region
current
Signal [a.u.]
Time [ns]
WP and Charge Drift
γ
Generated Signal
REJECTED
charge
STRUCTURES
current
WP and Charge Drift
β
Generated Signal
REJECTED
charge
SLOW!
current
WP and Charge Drift
α
Generated Signal
REJECTED
charge
FAST!
current

- **In GERDA** • "only" a veto system
  - Modeling effort by the TUM group to be published on EPJC soon arXiv 2212.02856
  - Technique crucial to model data after the veto cut and predict LEGEND performance

- **In LEGEND** • a fully-fledged DETECTOR
  - To study e.g. Radon backgrounds in LAr, cosmogenic-induced events etc.



Multi-site

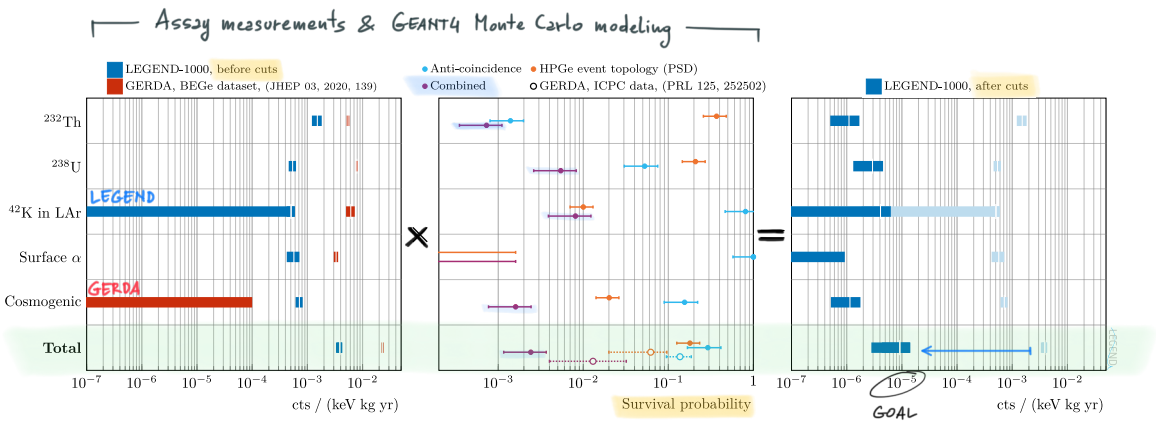
- ^{238}**U / ^{228}Th** from near-detector components, **external γ/n** from cryostat steel
  - ≫ *clean materials, remove opaque/inactive materials, large detectors, efficient LAr instrumentation*

Cosmogenic

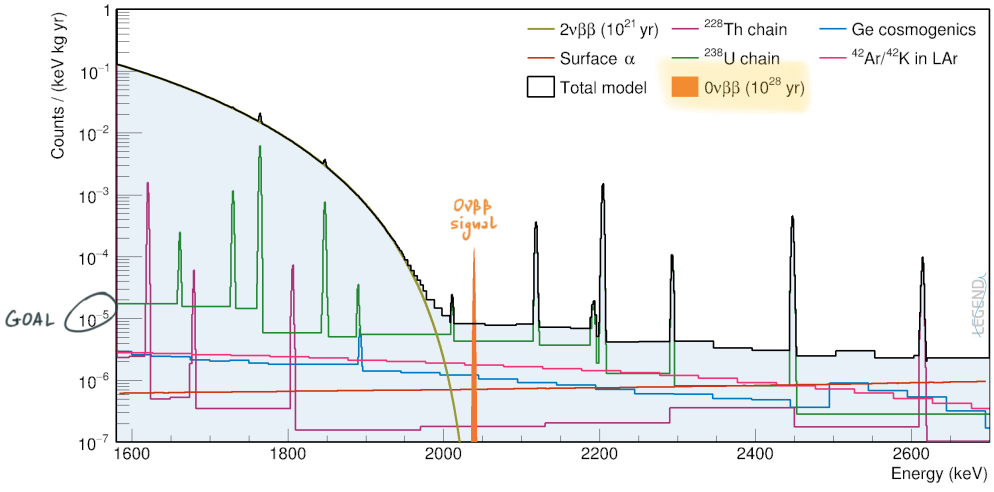
- ***in-situ*** μ-induced from **neutron capture on ^{76}Ge**
  - ≫ *underground laboratory, μ-veto, delayed coincidence cuts*
- ***ex-situ*** above-ground **activation of Ge**
  - ≫ *reduce above-ground exposure, cool-down period underground*

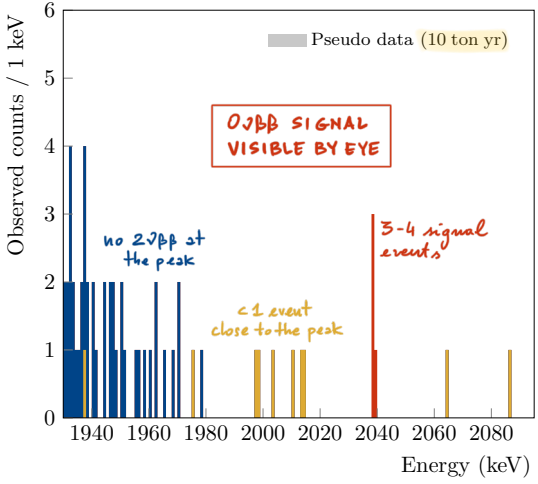
Detector surface

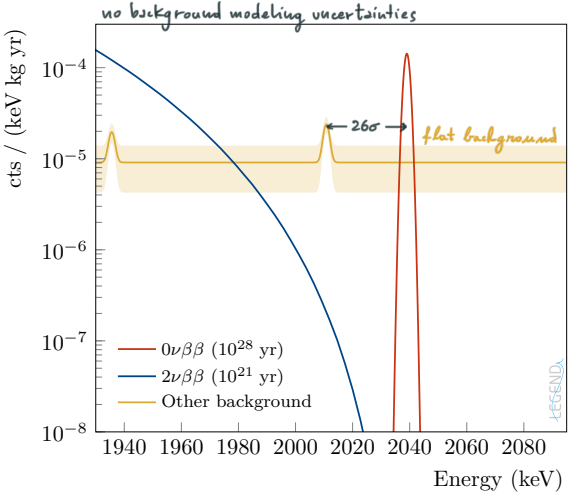
- **^{42}K events**: β decay from cosmogenic activation of argon
  - ≫ *underground-sourced argon*
- **α events** from radon deposition on detectors
  - ≫ *large detectors*

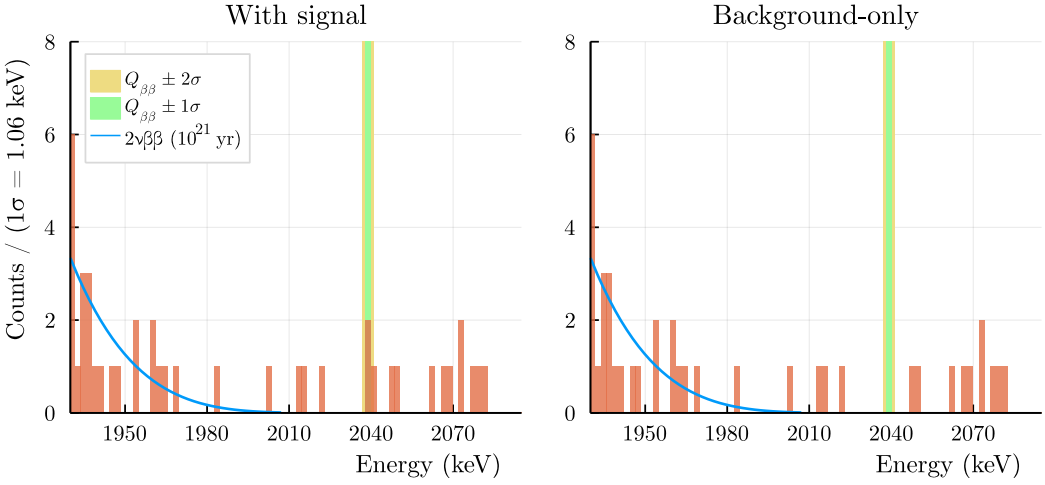

Assay measurements & GEANT4 Monte Carlo modeling
LEGEND-1000, before cuts
GERDA, BEGe dataset, (JHEP 03, 2020, 139)
Anti-coincidence
HPGe event topology (PSD)
Combined
GERDA, ICPC data, (PRL 125, 252502)
LEGEND-1000, after cuts
232Th
238U
42K in LAr
Surface α
Cosmogenic
Total
LEGEND
GERDA
cts / (keV kg yr)
Survival probability
GOAL
cts / (keV kg yr)

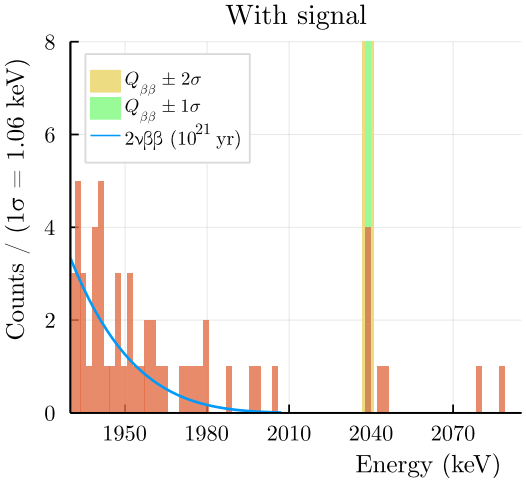
~1000 BACKGROUND PROJECTIONS

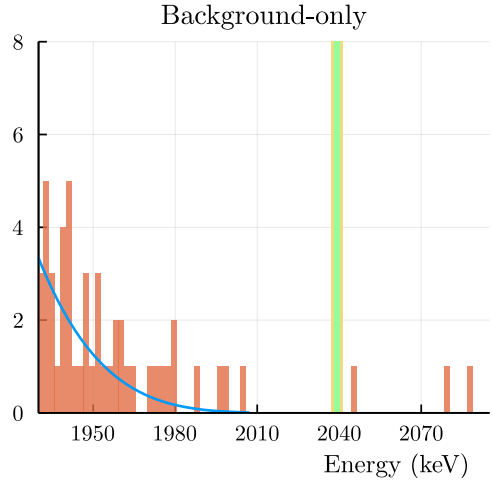



Pseudo data (10 ton yr)
0νββ SIGNAL VISIBLE BY EYE
no 2νββ at the peak
3-4 signal events
< 1 event close to the peak
Observed counts / 1 keV
Energy (keV)


no background modeling uncertainties
26σ
flat background
0νββ (10^28 yr)
2νββ (10^21 yr)
Other background
cts / (keV kg yr)
Energy (keV)
LEGEND


With signal
Background-only
$Q_{\beta\beta} \pm 2\sigma$
$Q_{\beta\beta} \pm 1\sigma$
$2\nu\beta\beta$ (10^{21} yr)
Counts / (1σ = 1.06 keV)
Energy (keV)
0
2
4
6
8
1950
1980
2010
2040
2070


With signal
$Q_{\beta\beta} \pm 2\sigma$
$Q_{\beta\beta} \pm 1\sigma$
$2\nu\beta\beta$ (10^{21} yr)
Counts / (1σ = 1.06 keV)
0
2
4
6
8
1950
1980
2010
2040
2070
Energy (keV)


Background-only
0
2
4
6
8
1950
1980
2010
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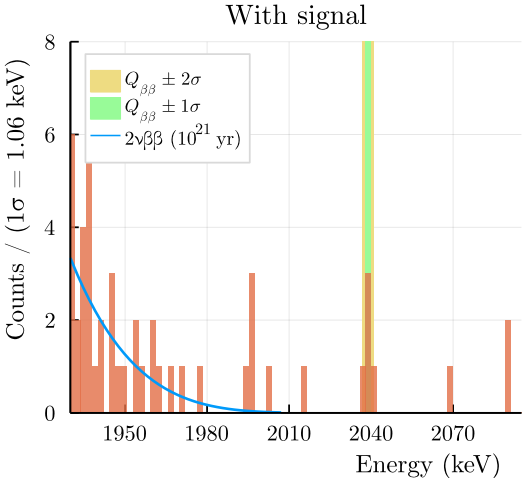
2070
Energy (keV)


With signal
$Q_{\beta\beta} \pm 2\sigma$
$Q_{\beta\beta} \pm 1\sigma$
$2\nu\beta\beta$ (10^{21} yr)
Counts / (1σ = 1.06 keV)
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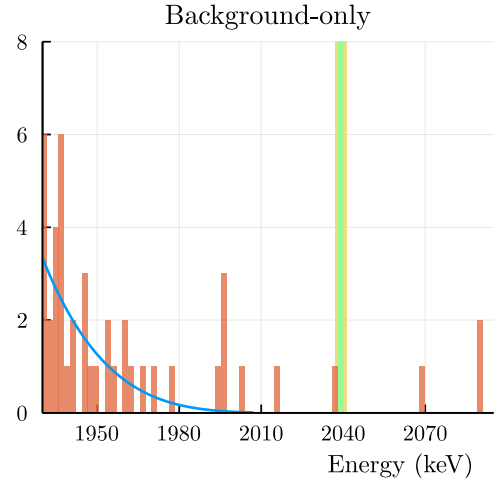
2040
2070
Energy (keV)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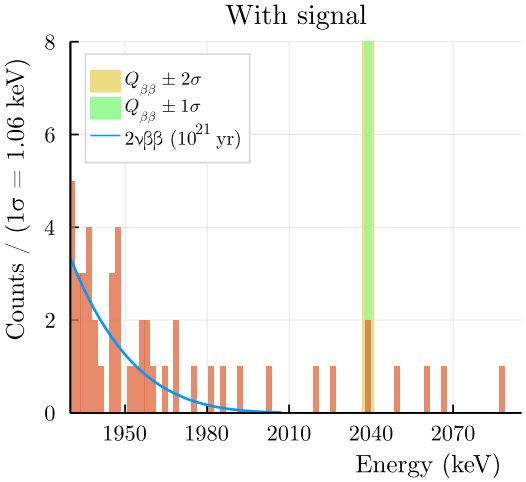
Energy (keV)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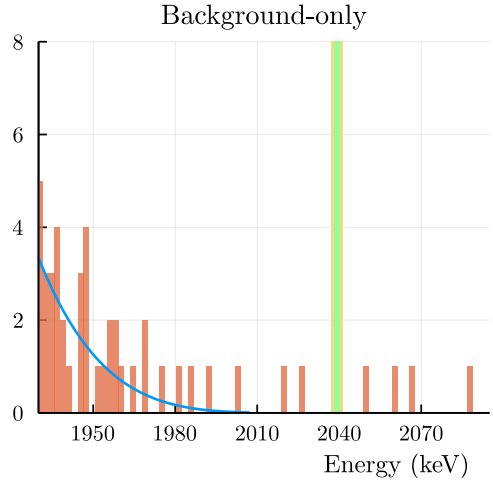
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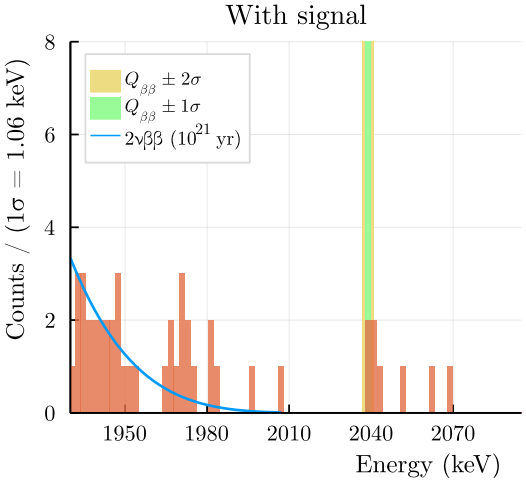
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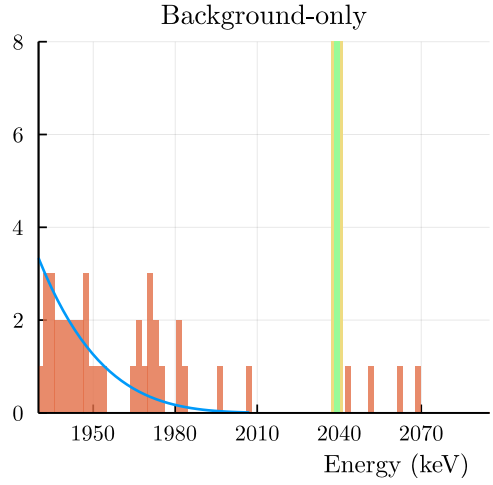
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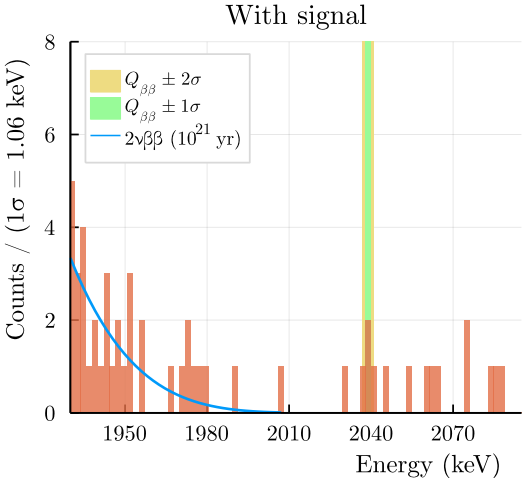
Energy (keV)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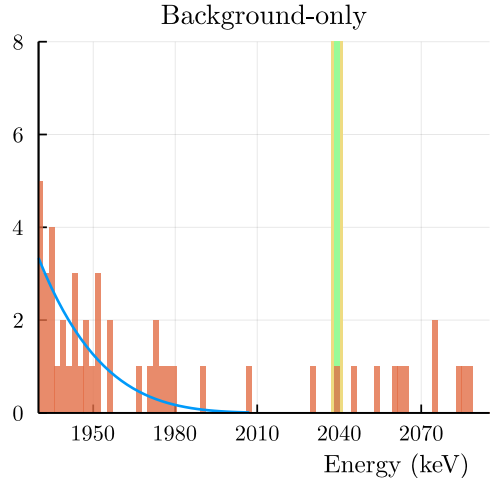
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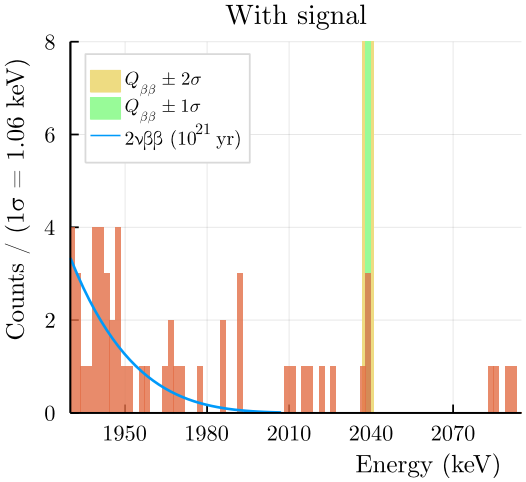
Energy (keV)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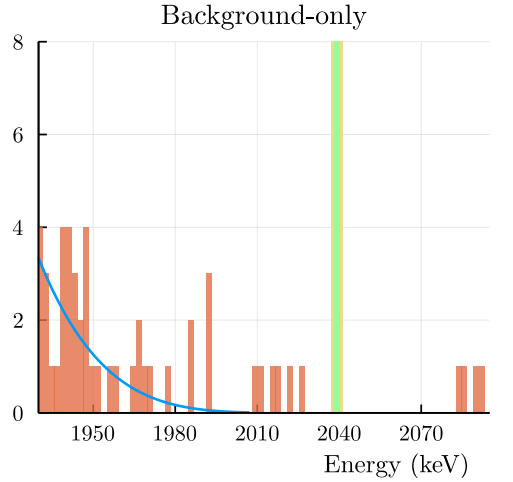
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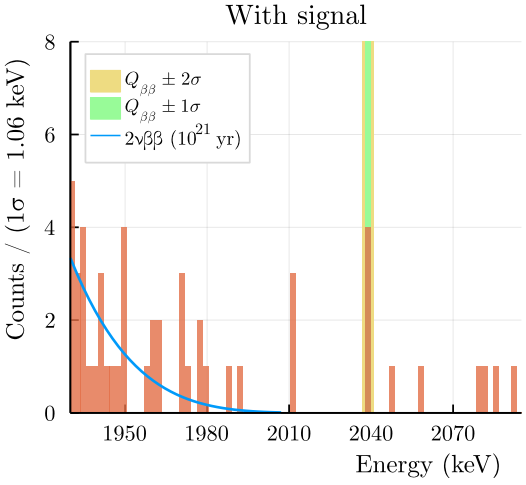
Energy (keV)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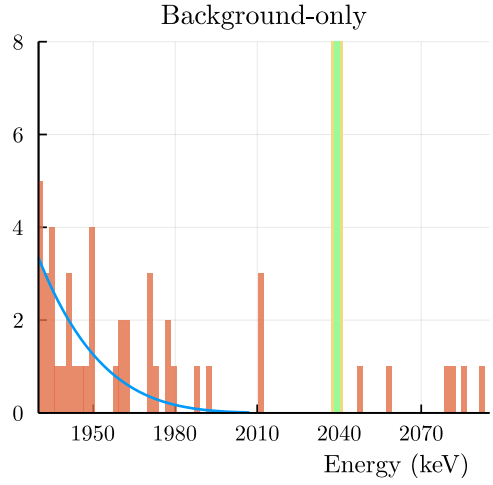
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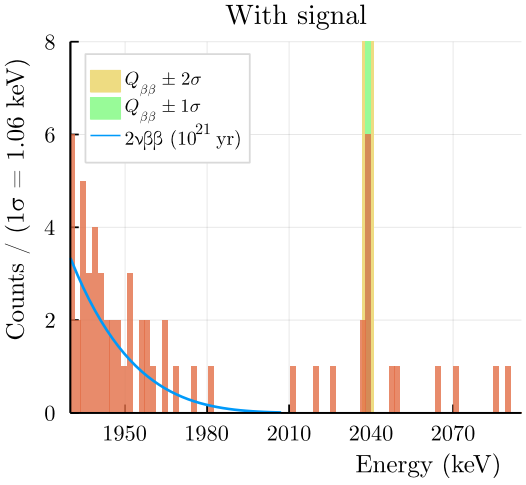
Energy (keV)


With signal
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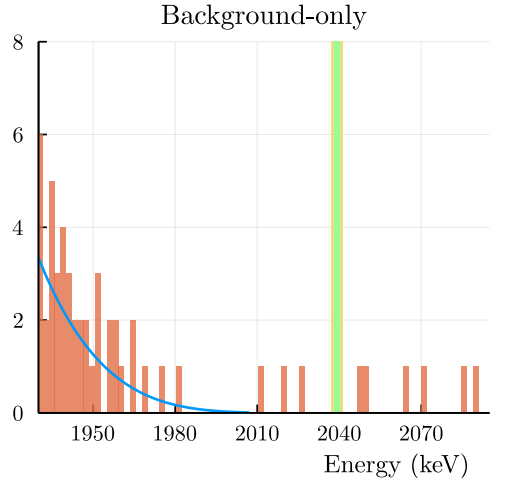
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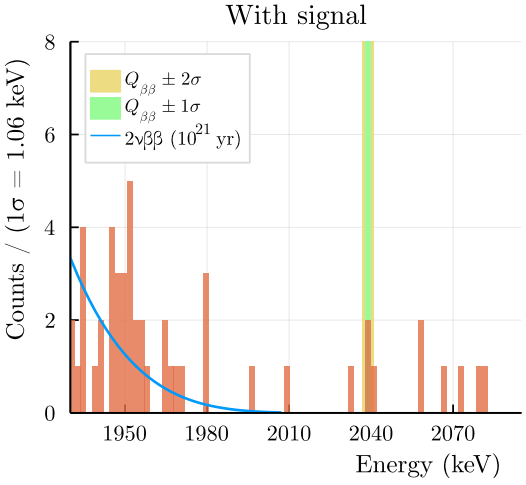
Energy (keV)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$2\nu\beta\beta$ (10^{21} yr)
Counts / (1σ = 1.06 keV)
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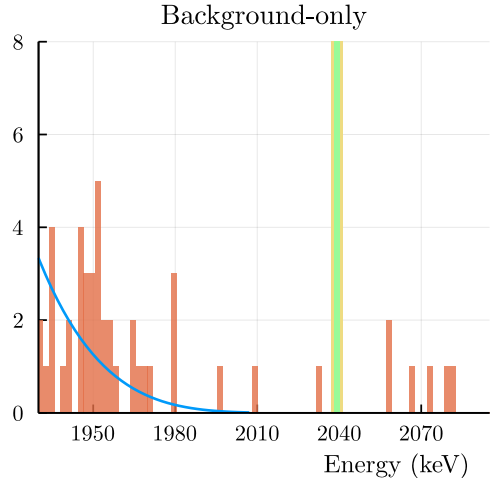
Energy (keV)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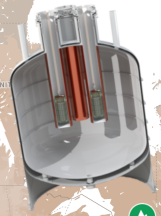
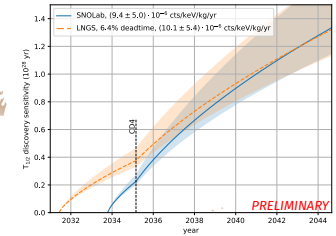
2070
Energy (keV)

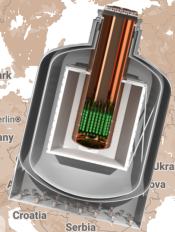
LEGEND-1000: SITE SELECTION PROCESS

SCIENCE GOAL ACHIEVABLE AT BOTH SITES!



SNOLAB





LNGS

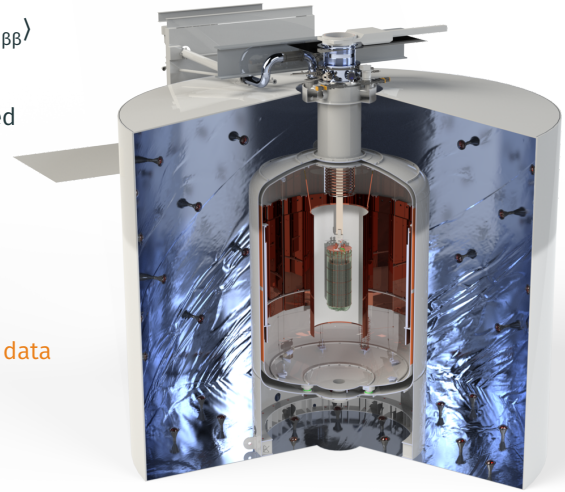
DOE site selection process soon (CD1)
→ criteria: *Schedule* • *Sensitivity* • *Cost*

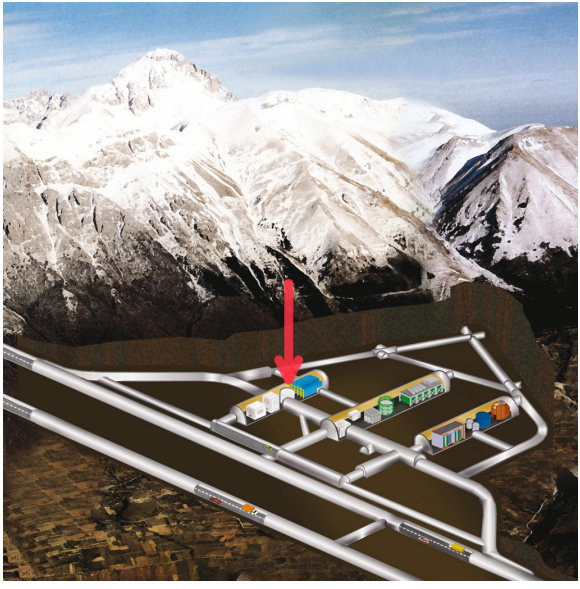
LEGEND-200 started probing the inverted $\langle m_{\beta\beta} \rangle$ region and informs the LEGEND-1000 design

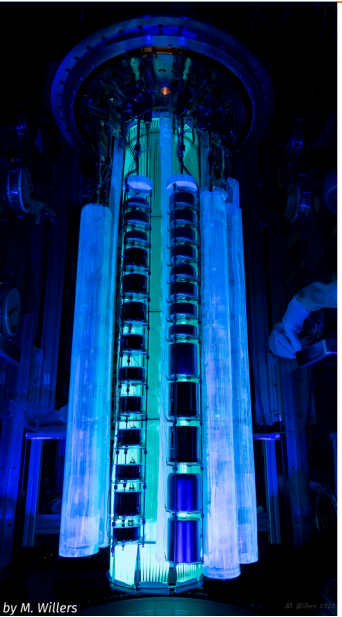
- ^{enr}Ge material (92% enrichment) secured
- Large ICPC detectors > 3 kg
- Improved LAr system efficiency

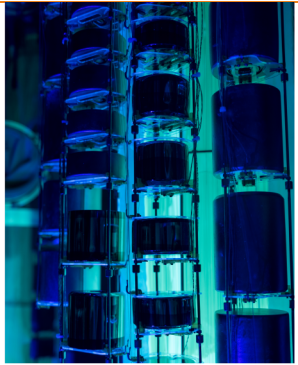
Status & plans:

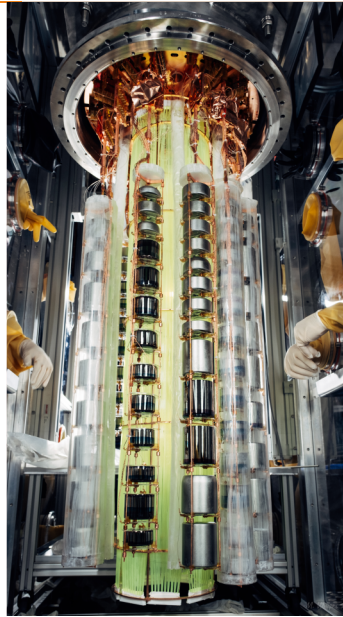
- Commissioning completed
- ~ 140 kg deployed, starting data taking data
- First report at the summer conferences



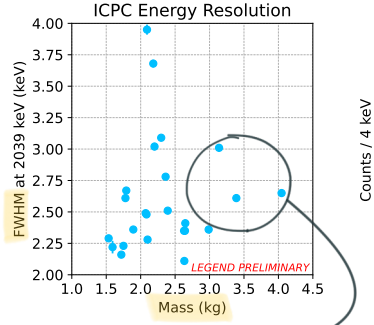



by M. Willers

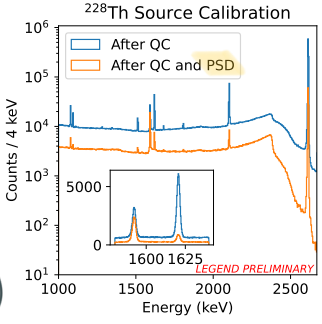


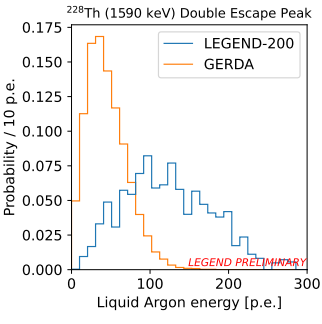


Pulse Shape Discrimination performance



Large HPGes show excellent energy resolution





More light than GERDA for 0νββ background

April 2016 LEGEND collaboration formed

Dec 2019 Completion of GERDA ⟼ LEGEND-200 commissioning start

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

2022/2023 Commissioning/physics data taking of LEGEND-200

2024 *Critical Decision 1*: preliminary reference design, strategize funding

2026 Start of procurement of long-lead items (Ge, cryostat, infrastructure)

2030/31 Commissioning and first data

GERDA and  MAJORANA:

- have searched for 0νββ in a *quasi-background-free* regime
- have led the worldwide effort by providing the best half-life sensitivity
- have demonstrated the maturity of germanium technology for a ton-scale project

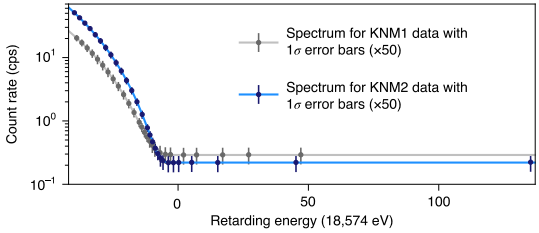
The scientific community:

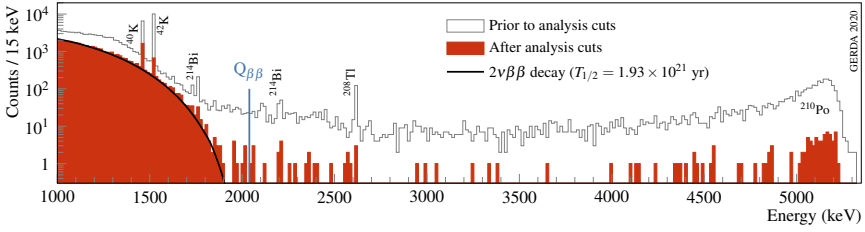
- has acknowledged the search for 0νββ as *one of the most compelling challenges in contemporary physics*
- strives for international funding for ton-scale 0νββ experiments

LEGEND:

- has a low-risk path to meeting its background goal and is optimized for discovering 0νββ
- will pioneer the exploration of *new energy frontiers beyond the inverted ordering scenario*

β or ββ?


Spectrum for KNM1 data with
1σ error bars (×50)
Spectrum for KNM2 data with
1σ error bars (×50)
Count rate (cps)
Retarding energy (18,574 eV)


Prior to analysis cuts
After analysis cuts
2νββ decay (T1/2 = 1.93 × 10^21 yr)
Counts / 15 keV
Energy (keV)
GERDA 2020
40K
42K
214Bi
Qββ
214Bi
208Tl
210Po