Searching for matter creation with LEGEND

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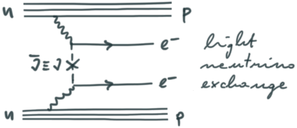
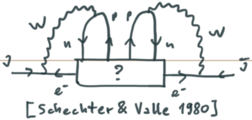
TU München, INFN Padova

Why neutrinoless double-β decay?

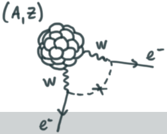
arXiv 2202.01787





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

"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?

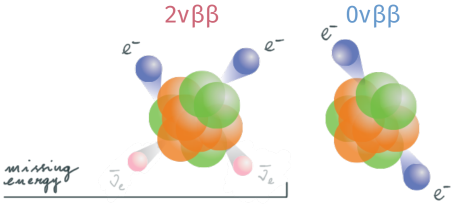
Light neutrino mass mechanism

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

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

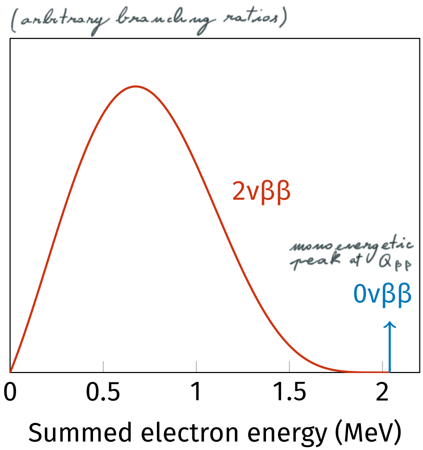
Majorana effective mass

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



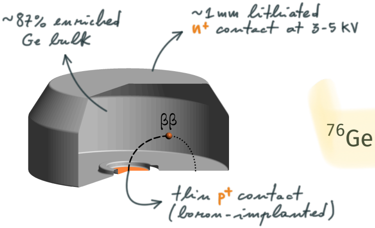
All experiments measure the total energy of the two emitted electrons

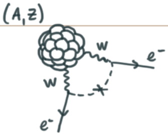
⟼ *necessary and sufficient* for discovery



--- holes (+)
.... electrons (-)

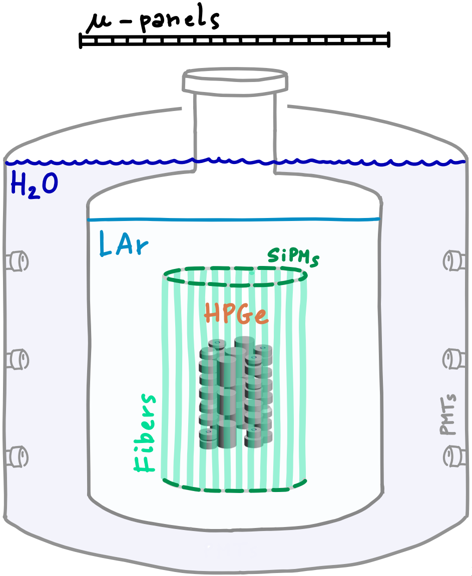
LEGEND





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

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



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

- source = detector ⟼ *high efficiency*
- pure ⟼ *low intrinsic background* ~ 10^{10} / cm^{-3} net impurities
- 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:

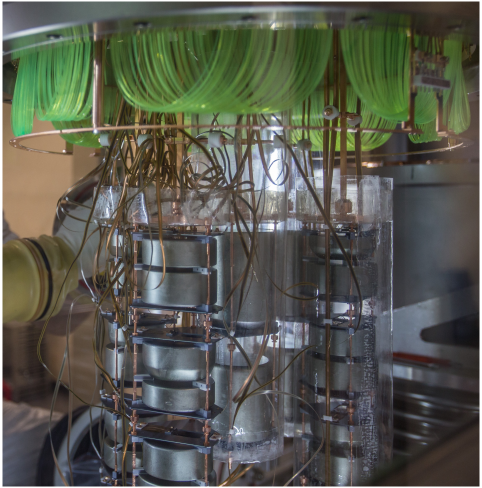
- Ultra-clean elecro-formed copper (EFCu)
- Low-noise front-end electronics

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

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

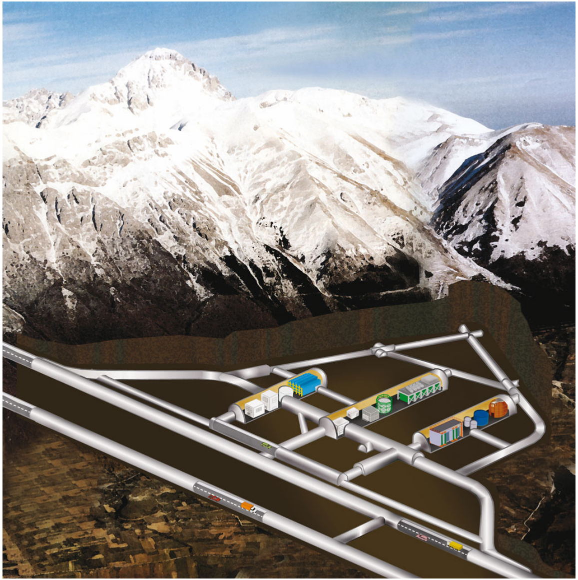
Key technologies:

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

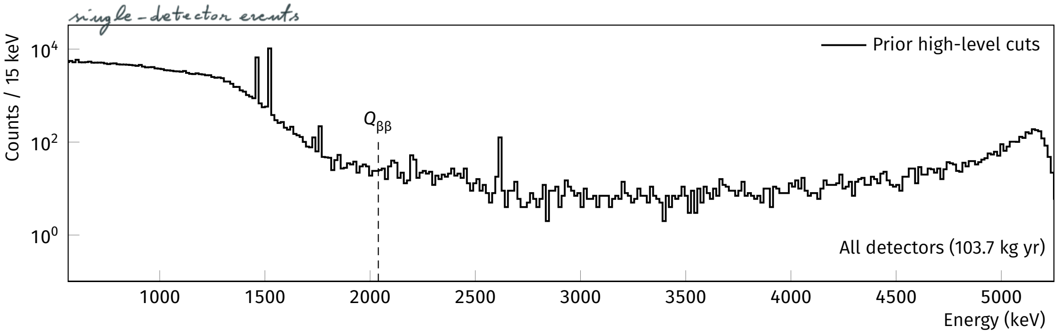


The pioneers

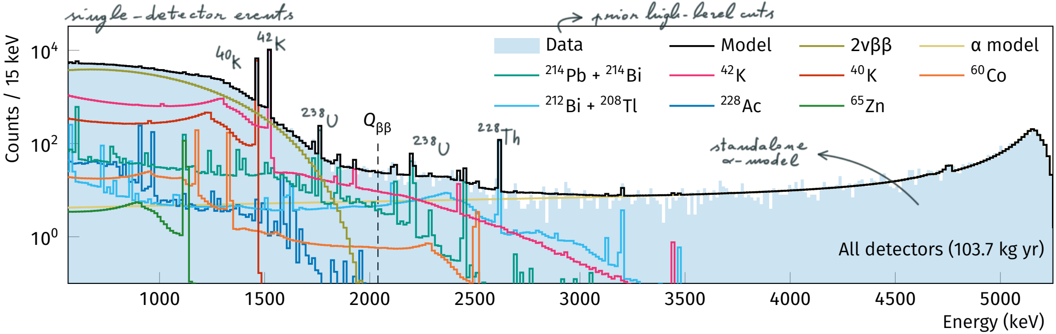
GERMANIUM DETECTOR ARRAY AT LNGS — 3.5 km water eq. —



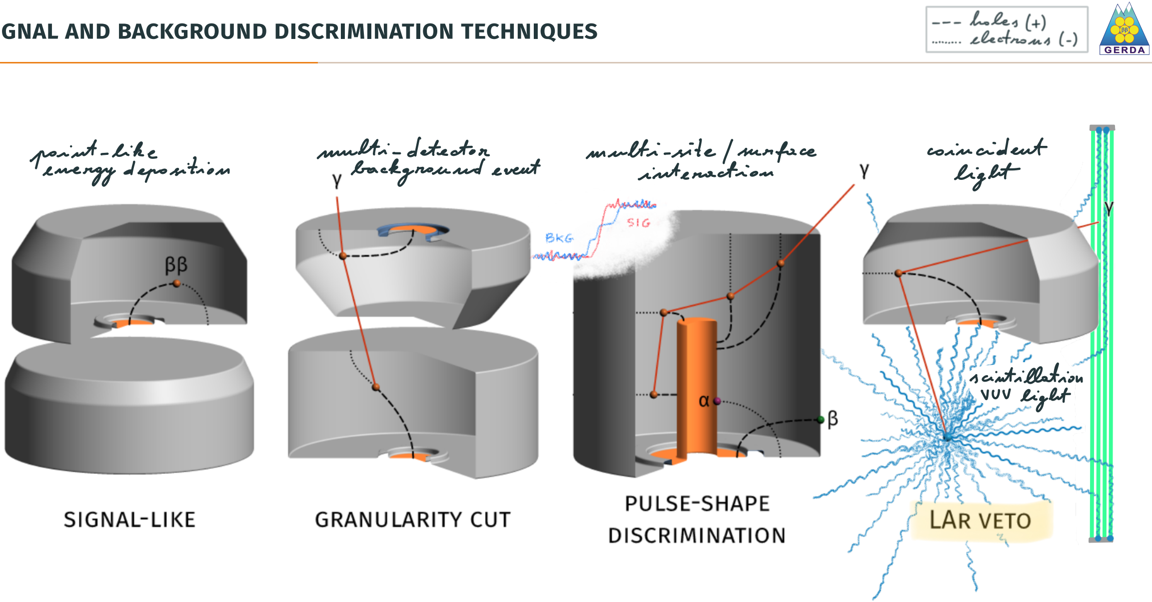
Phase II data energy spectrum before high-level cuts



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

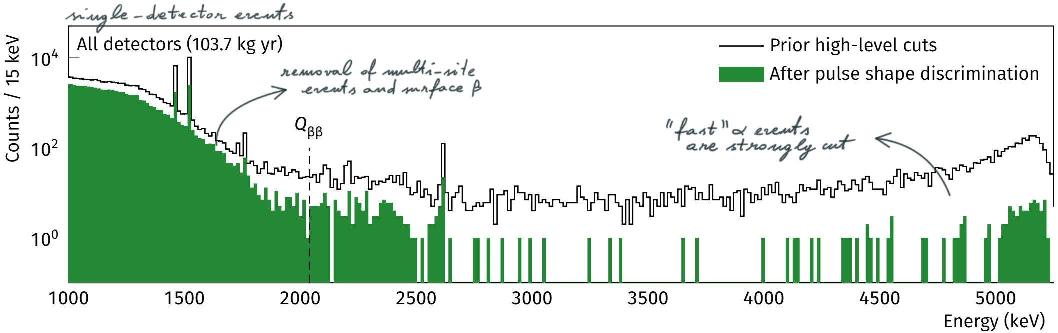


- Bayesian multivariate fit of Monte Carlo predictions *(with screening measurements as priors)*
- $Q_{\beta\beta}$ dominated by β from ^{42}K (from ^{42}Ar in LAr), α from ^{210}Po, γ from ^{228}Th and ^{238}U chains
- Results are input to several physics analyses and inform future experiments (LEGEND)



--- holes (+)
.... electrons (-)
point-like energy deposition
ββ
SIGNAL-LIKE
multi-detector background event
γ
GRANULARITY CUT
multi-site / surface interaction
BKG
SIG
γ
α
β
PULSE-SHAPE DISCRIMINATION
coincident light
γ
scintillation VUV light
LAr VETO

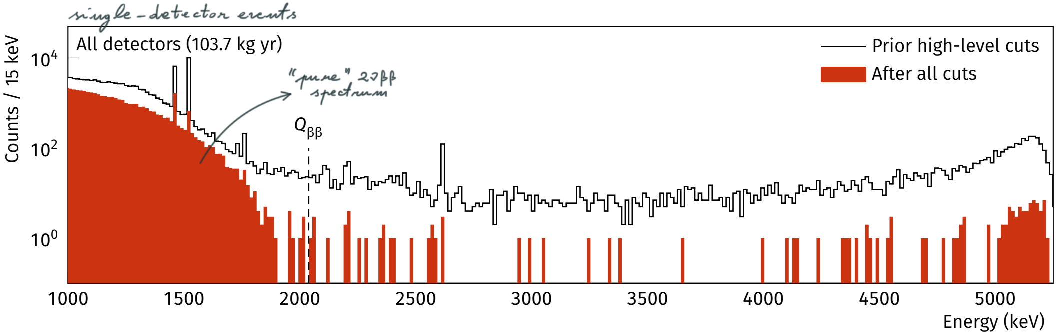
Pulse shape discrimination...



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

^{228}Th calibration data as tuning sample

...AND LIQUID ARGON ANTI-COINCIDENCE



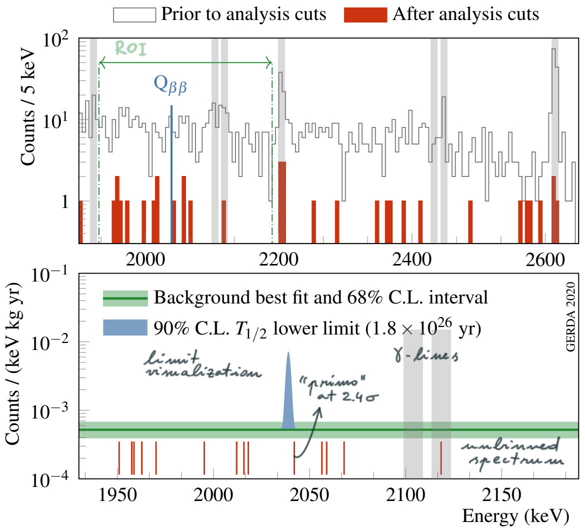
- Anti-coincidence between HPGe trigger and SiPM/PMT data (≥ 0.3 *p.e. in a 5 μs window)*
- Extremely low event rate at $Q_{\beta\beta}$ of ~ $5 \cdot 10^{-4}$ cts / (keV kg yr) ⟼ *quasi-background-free*
- Few events at $Q_{\beta\beta}$ ⟼ *"simple" background-model-free analysis*

~ 0.3 counts per FWHM in full exposure!

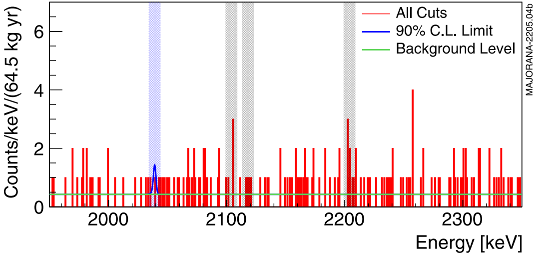
"One of the world's best-performing 0νββ experiments"

- $5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ 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 (†)

*) Phase II only
†) NME uncertainty



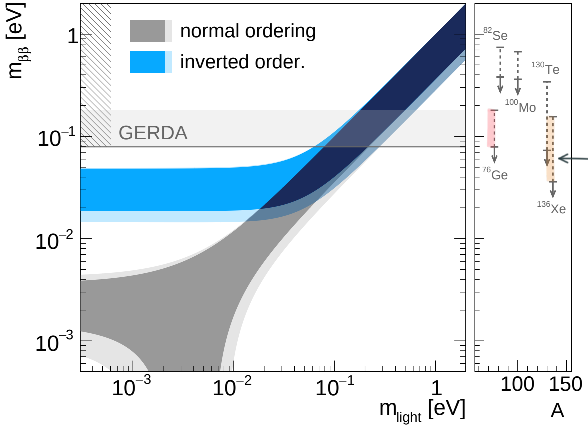
- Energy resolution of 2.52 keV FWHM at $Q_{\beta\beta}$
- No signal in 64.5 kg yr of *active* exposure
- $T^{0\nu}_{1/2} > 0.83 \cdot 10^{26}$ yr (90% C.L. frequentist)
- $\langle m_{\beta\beta} \rangle < 113\text{–}269$ meV



GERDA +

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

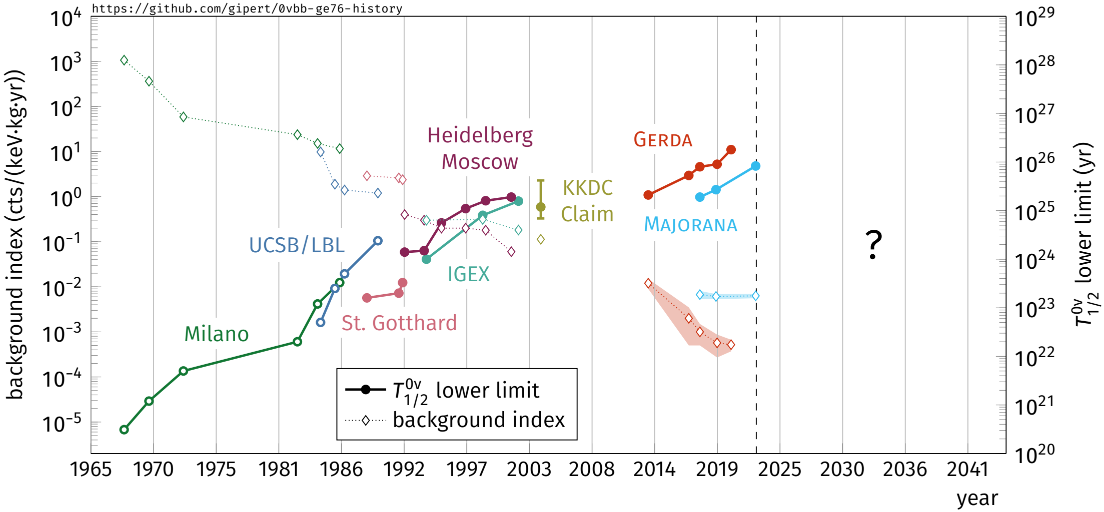
Results from other experiments



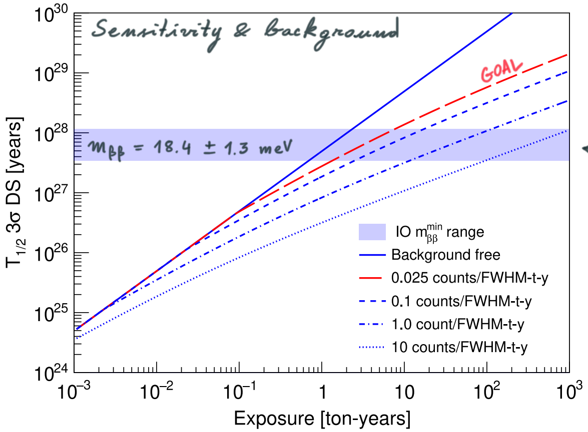
- ^{136}Xe, ^{76}Ge (and ^{130}Te) place the most stringent limits
  - *Note:* ^{76}Ge limits on $\langle m_{\beta\beta}\rangle$ are weakened by a less favorable phase space factor
- Latest KamLAND-Zen800 results:
  - arXiv 2203.02139
  - $T^{0\nu}_{1/2} > 2.3 \cdot 10^{26}$ yr (90% C.L.)
  - $\langle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

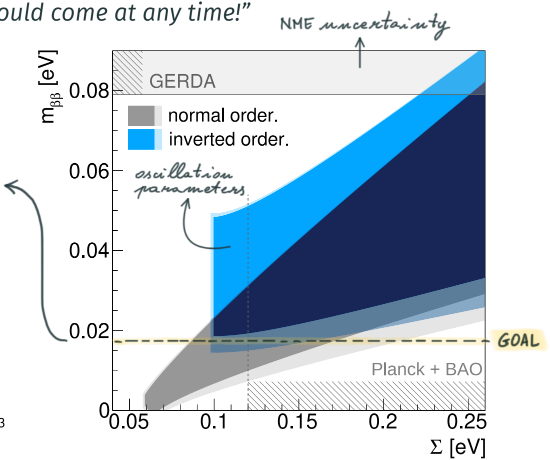
The Future

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



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





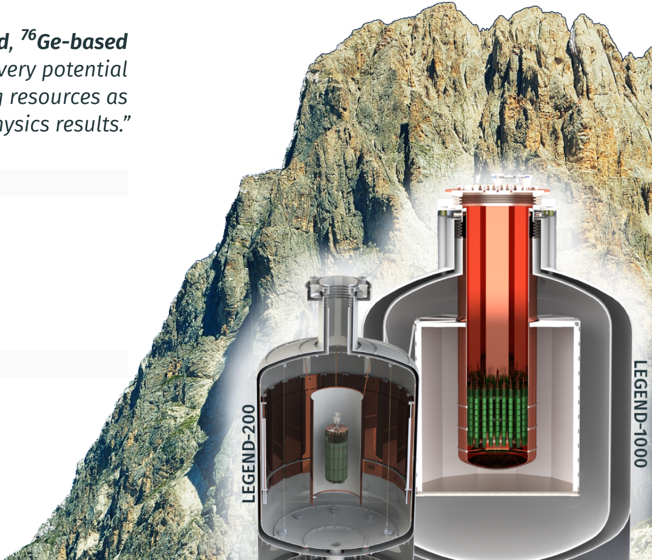
*“The collaboration aims to develop a **phased**, **^{76}Ge-based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} yr**, using existing resources as appropriate to expedite physics results.”*

LEGEND-200

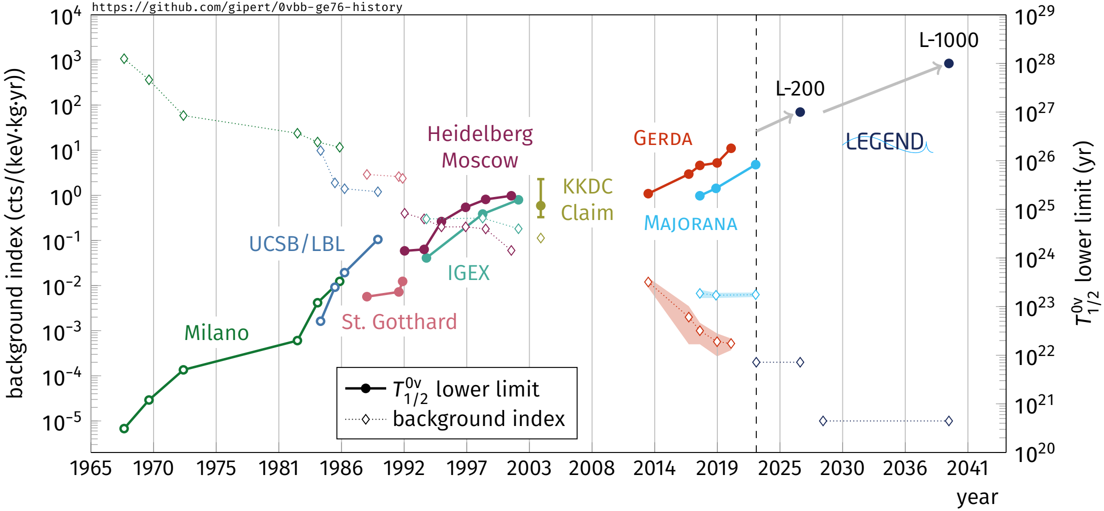
- **200 kg** of ^{enr}Ge (×5 yr), in GERDA cryostat
- Taking data with 142 kg of ^{enr}Ge
- $B \sim \mathbf{2 \cdot 10^{-4}}$ cts / (keV kg yr) $\longmapsto T^{0\nu}_{1/2} > \mathbf{10^{27}}$ **yr**

LEGEND-1000 arXiv 2107.11462 “pre-conceptual design report”

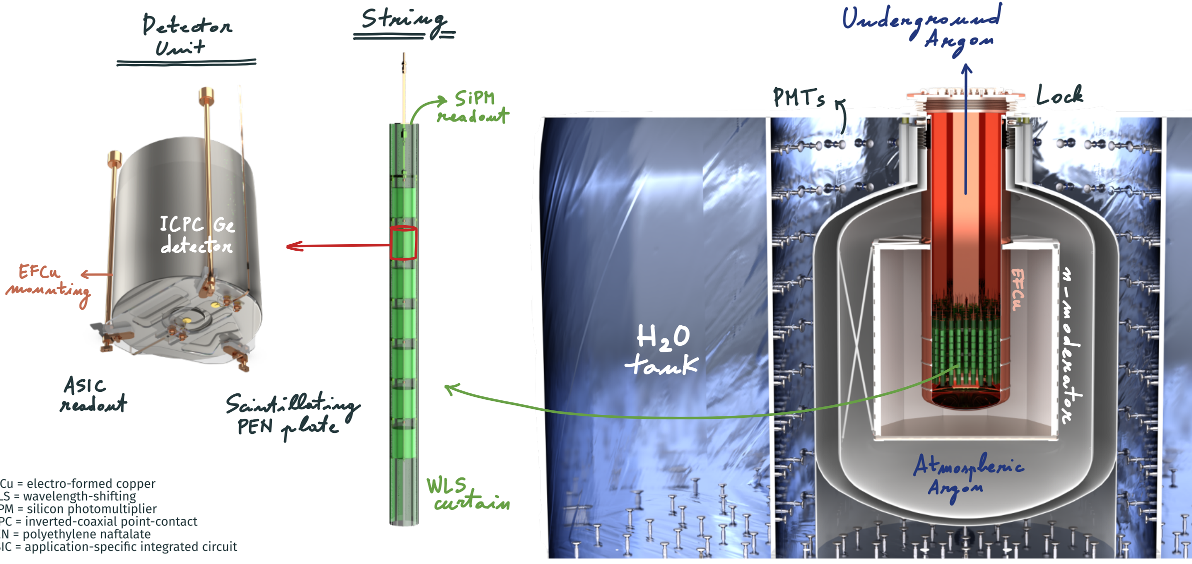
- **1 ton** of ^{enr}Ge (×10 yr), awaiting funding
- $B < \mathbf{10^{-5}}$ cts / (keV kg yr) $\longmapsto T^{0\nu}_{1/2} > \mathbf{10^{28}}$ **yr**
- Cover full $\langle m_{\beta\beta} \rangle$ inverted ordering region



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

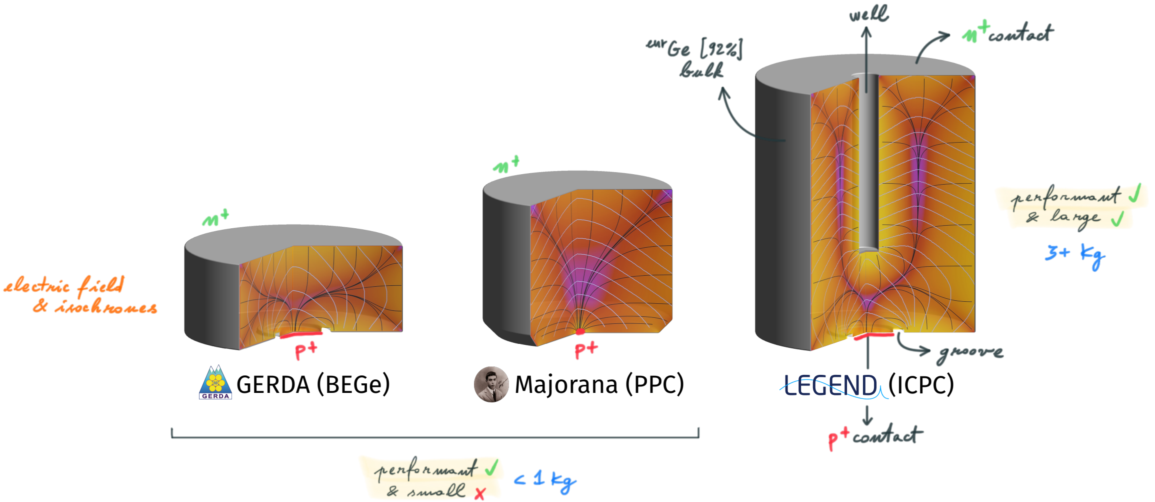


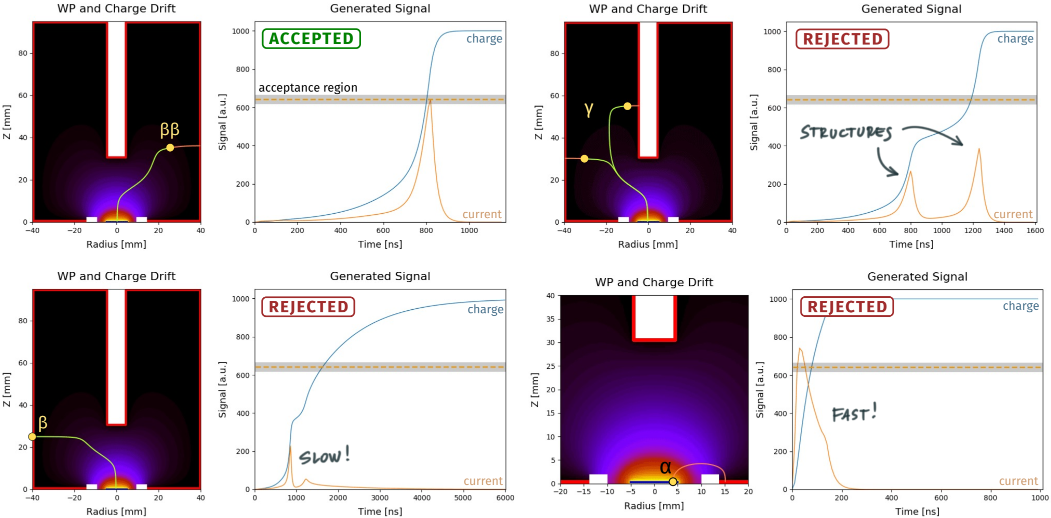
THE LEGEND -1000 (@ LNGS) BASELINE DESIGN



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

^{ENR}GE POINT-CONTACT DETECTORS

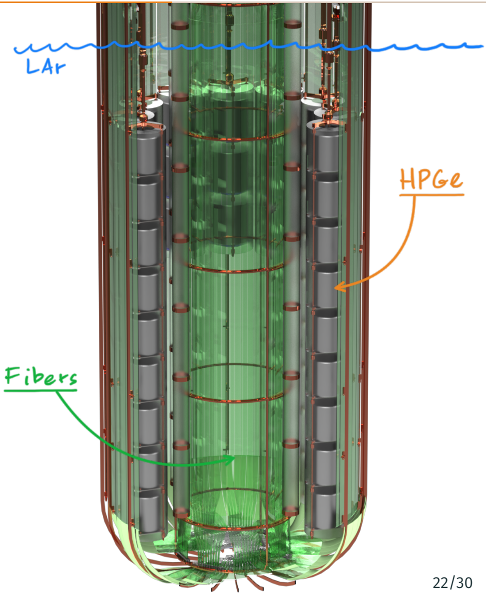



WP and Charge Drift
Generated Signal
ACCEPTED
acceptance region
charge
current
ββ
REJECTED
STRUCTURES
γ
β
SLOW!
α
FAST!
Radius [mm]
Z [mm]
Time [ns]
Signal [a.u.]

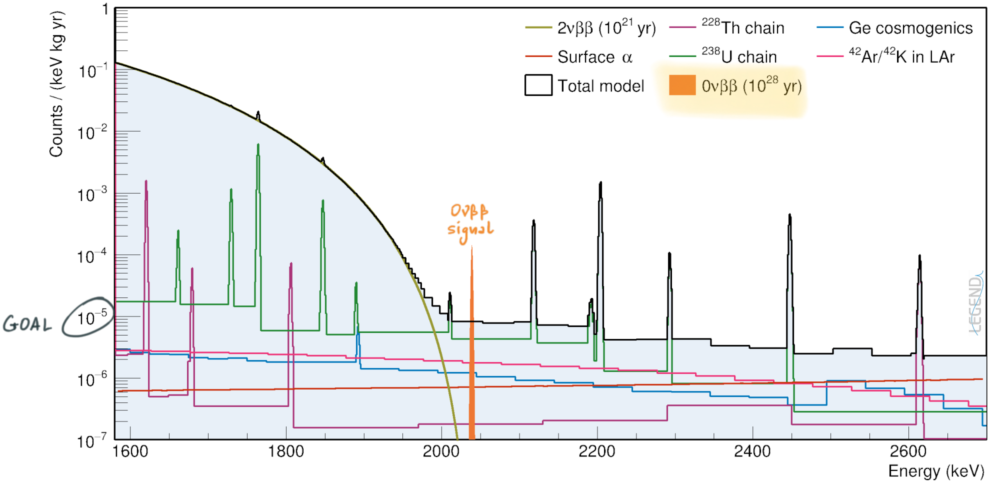
The role of the liquid argon instrumentation

- **In GERDA** • "only" a veto system
  - Modeling effort by the TUM group REF *EPJC 83 (2023) 4, 319*
  - Technique crucial to model data after the veto cut and predict LEGEND performance

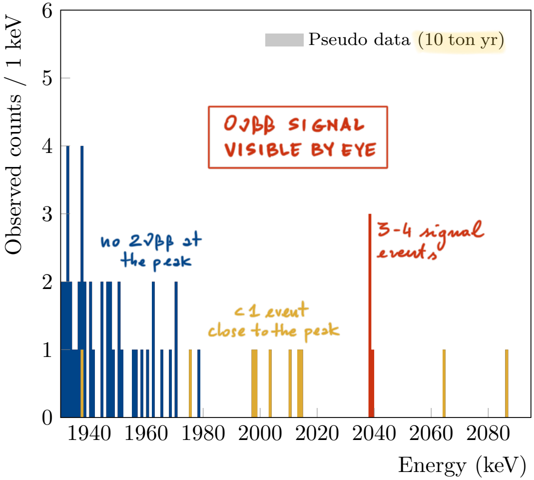
- **In LEGEND** • a fully-fledged DETECTOR
  - To study e.g. Radon backgrounds in LAr, cosmogenic-induced events etc.

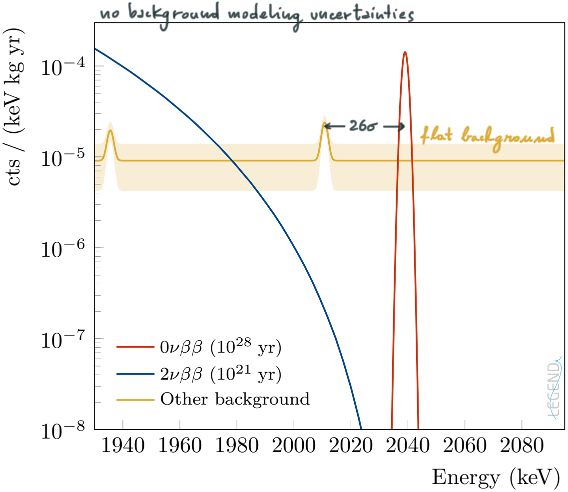


LEGEND-1000 BACKGROUND PROJECTIONS



LEGEND-1000: OPTIMIZED FOR DISCOVERY $T_{1/2}^{0\nu} = 10^{28}$ yr



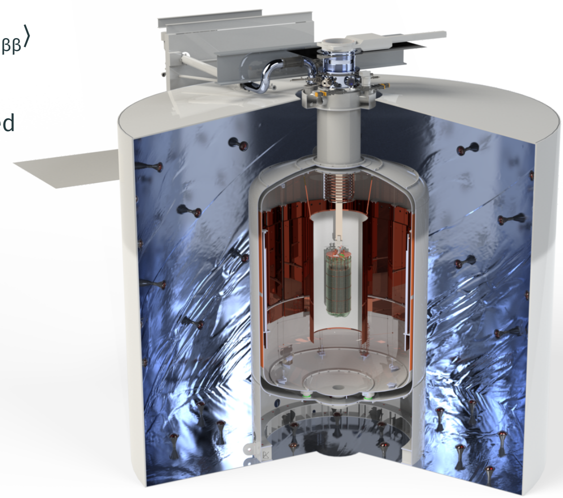


LEGEND-200 started probing the inverted $\langle m_{\beta\beta} \rangle$ region and informs the LEGEND-1000 design

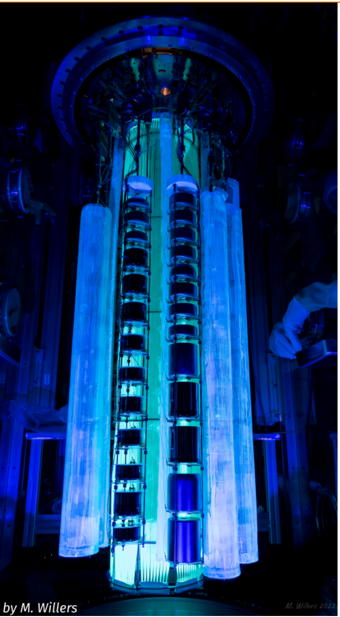
- ^{enr}Ge material (92% enrichment) secured
- Large ICPC detectors > 3 kg
- Improved LAr system efficiency

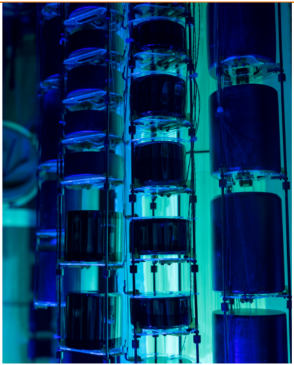
Status & plans:

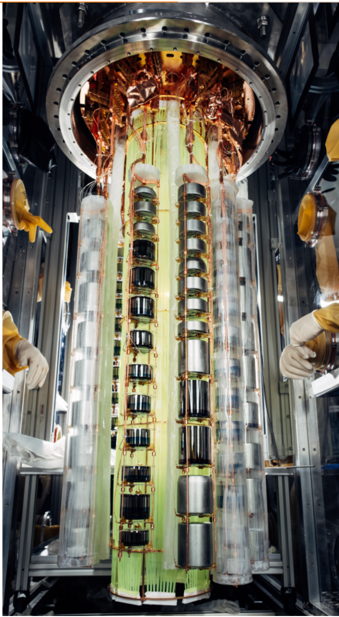
- Commissioning completed in Feb 2023
- 142 kg deployed, taking science data
- First report at TAUP 2023



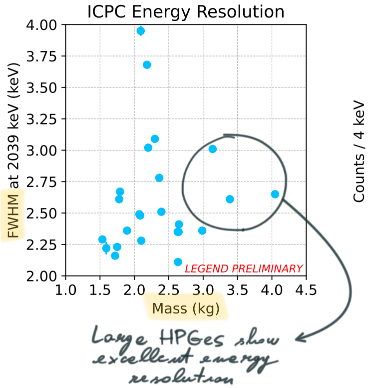
The LEGEND-200 commissioning at LNGS

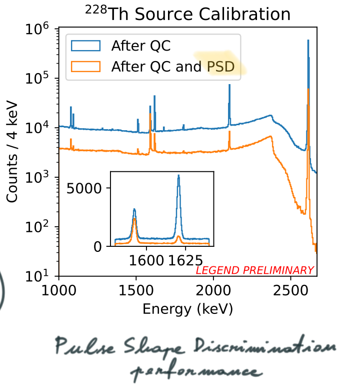


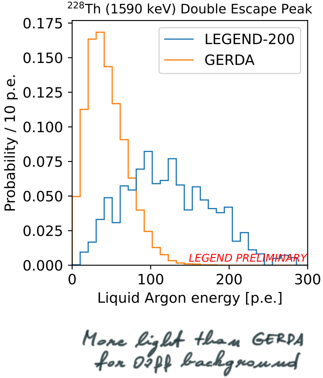




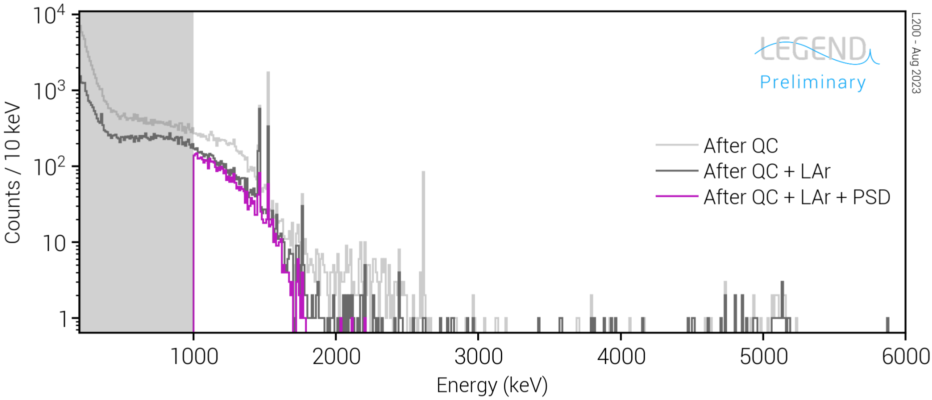
Calibration data





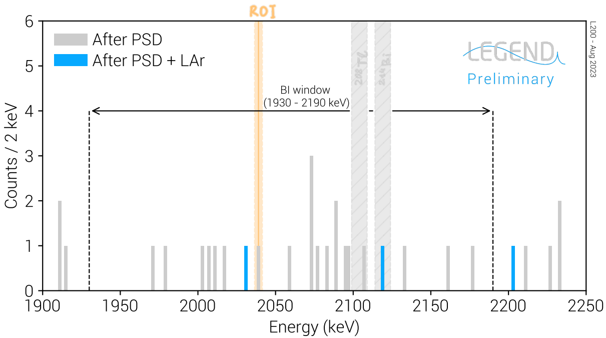


First **10.1 kg yr** of LEGEND-200 **physics data** (ICPC and BEGe detectors)



- *Background is compatible with goal of* $2 \cdot 10^{-4}$ cts / (keV kg yr)
- Expected 0.48 cts ⟼ probability to observe >1 counts = 38%

	exposure [kg yr]	background [cts / (keV kg yr)]
GERDA	103.7	$5.2\,[3.9, 6.8] \cdot 10^{-4}$
L-200	10.1	$4.1\,[1.5, 11.4] \cdot 10^{-4}$



More details presented at TAUP23:
commissioning, performance [1] background, physics data [2]

Wrapping up

Gerda and **Majorana**:

- have searched for $0\nu\beta\beta$ 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 $0\nu\beta\beta$ as *one of the most compelling challenges in contemporary physics*
- strives for international funding for ton-scale $0\nu\beta\beta$ experiments

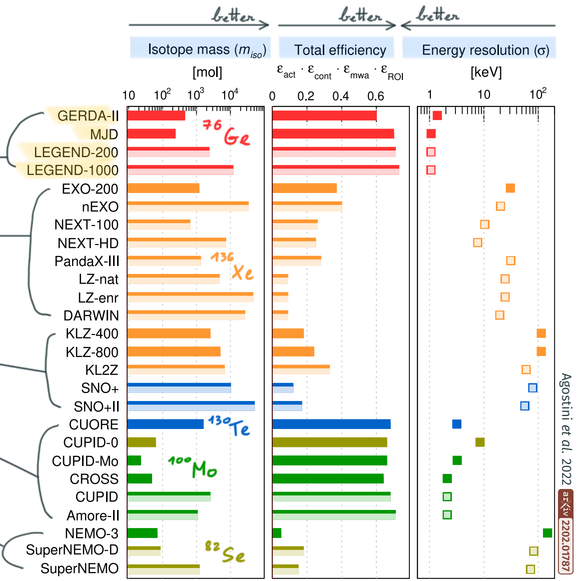
LEGEND:

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

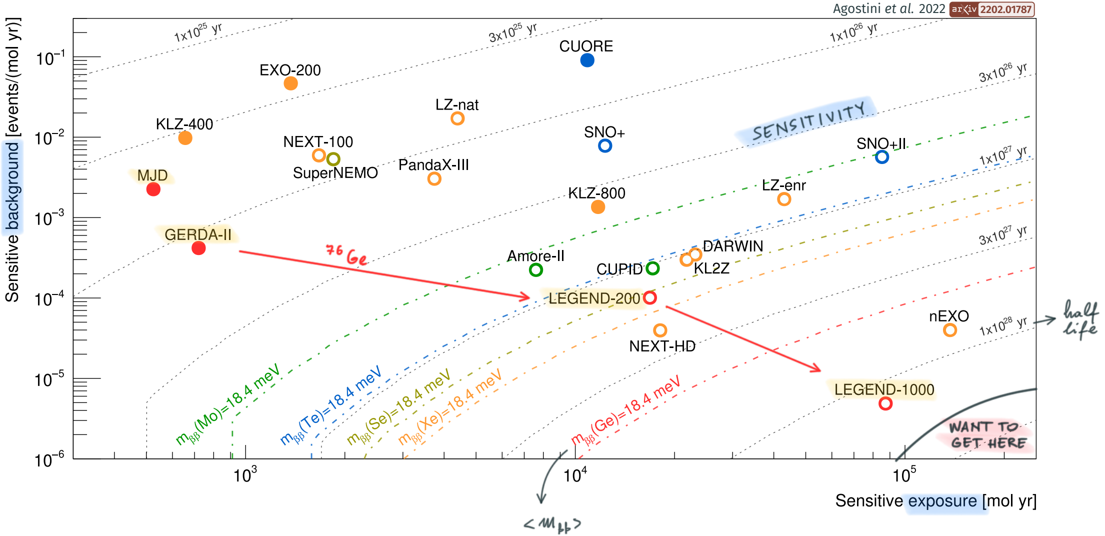
Backup

A ZOO OF DETECTOR CONCEPTS

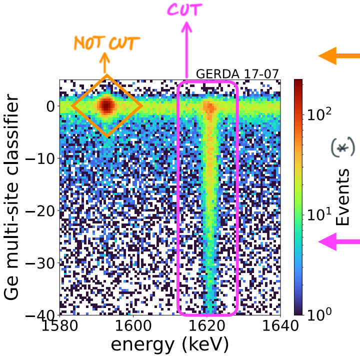
- **High-purity Germanium detectors**
  energy resolution, efficiency, background
- **Xenon Time Projection Chambers**
  isotope mass, particle tracking
- **Large Liquid Scintillators**
  isotope mass
- **Cryogenic Calorimeters**
  energy resolution, efficiency, granularity
- **Tracking Calorimeters**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



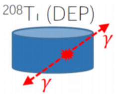
Detector concepts: sensitivity



POWERFUL COMBINATION OF BACKGROUND TAGGING TECHNIQUES



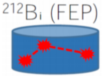
Localized signature in multi-site classifier



Ge single-site event with external depositions

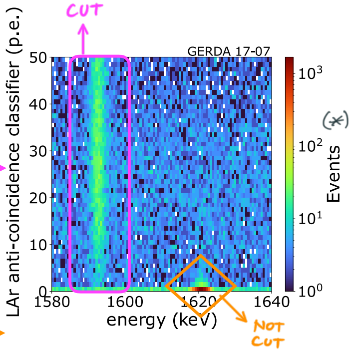
External energy depositions evident in LAr anti-coincidence classifier

Internal energy depositions evident in multi-site classifier



Ge multi-site event fully contained

Localized signature in LAr anti-coincidence classifier



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

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

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*

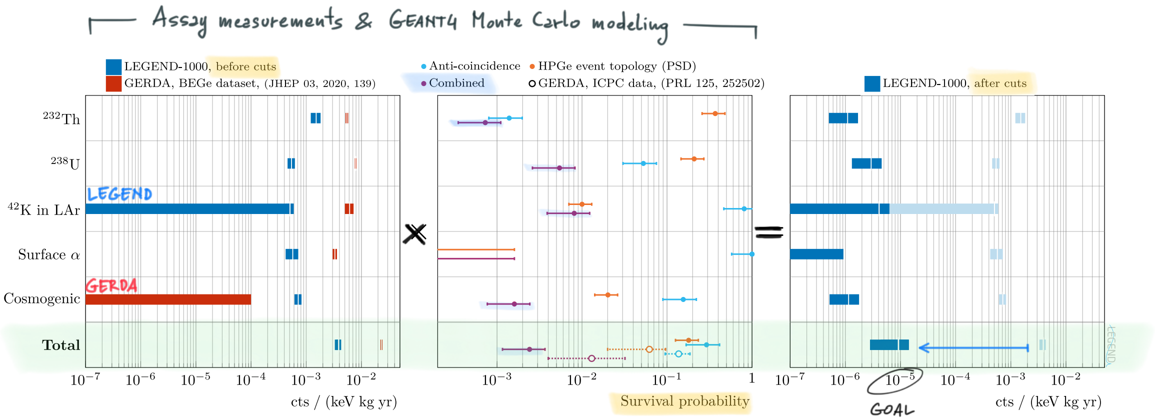
Cosmogenic

- ***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*

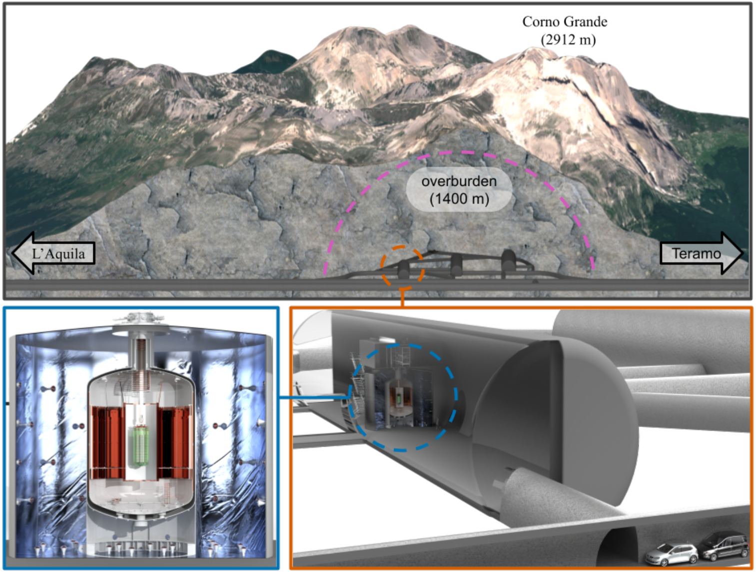
Detector surface

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

A detailed, careful background model

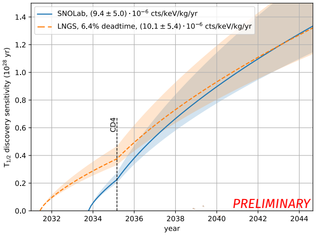


LEGEND-200 AT LNGS



LEGEND-1000: SITE SELECTION PROCESS

SCIENCE GOAL ACHIEVABLE AT BOTH SITES!



DOE site selection process soon (CD1)

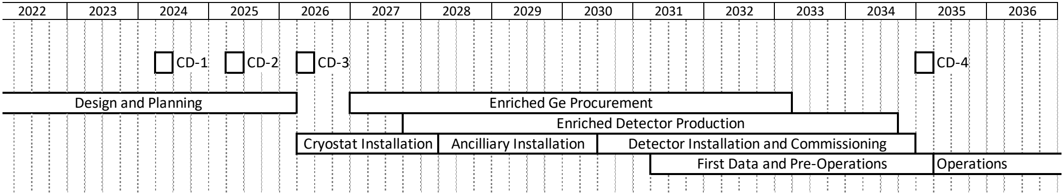
→ criteria: *Schedule* • *Sensitivity* • *Cost*

DOE STATEMENT ABOUT LEGEND-1000 AND THE PORTFOLIO REVIEW

“NP and its potential partners are jointly exploring the possibility of a campaign with more than one experiment to increase the likelihood of identifying and characterizing this rare decay mode […] NP continues to pursue the possibility, in collaboration with national and international partners, of a multi-experiment campaign capable of providing contemporaneous verification of any apparent observation of $0\nu\beta\beta$*. Should it not prove possible to implement multiple projects in the search of* $0\nu\beta\beta$*, LEGEND-1000 would receive priority based on it receiving the highest ranking from the portfolio review panel.”*

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* $0\nu\beta\beta$ *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 starts
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

L1000 SCHEDULE



THE COLLABORATION

LEGEND = GERDA + … + …

~ 50 institutions from 10 countries