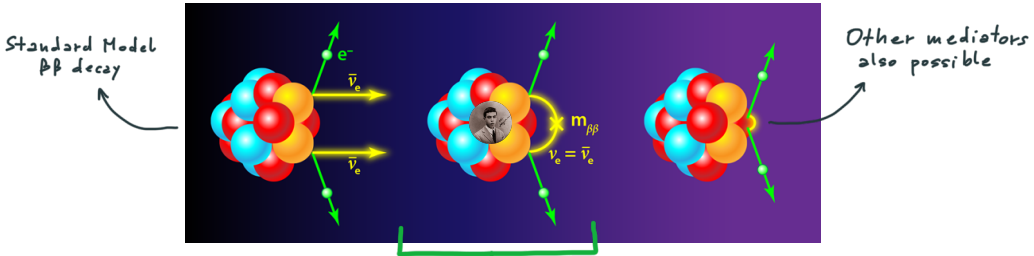
First results on neutrinoless double beta decay from LEGEND-200

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

Roma • April 2025

TU München, INFN Padova

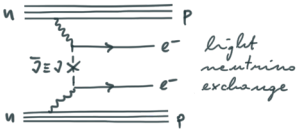
Electron creation via neutrinoless double-β decay



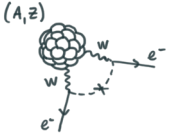
Light neutrino exchange mechanism

- 0νββ is mediated by a Majorana neutrino ($\nu \equiv \bar{\nu}$)
- This particle is the one we have already observed (involved in ν oscillations)
- The Standard Model is an effective theory *(seesaw mechanism)*

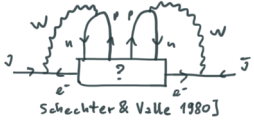
REF REV. MOD. PHYS. 95, 025002



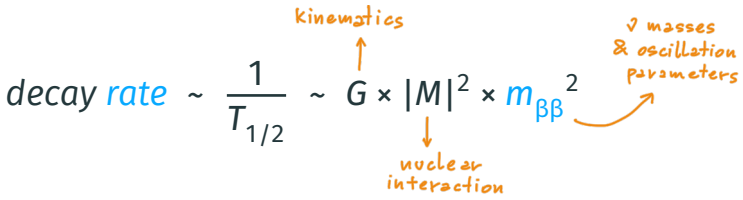
The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics [1]



- Lepton number (LN) conservation is accidental in the Standard Model (SM)
- ν masses are suspiciously tiny
- Our universe is made of matter (baryogenesis) $\longmapsto$ need for matter-creation
- 0νββ observation $\Rightarrow$ Majorana neutrino [Schechter & Valle, 1980] and lepton creation
- Many theories beyond the SM that address these also predict 0νββ



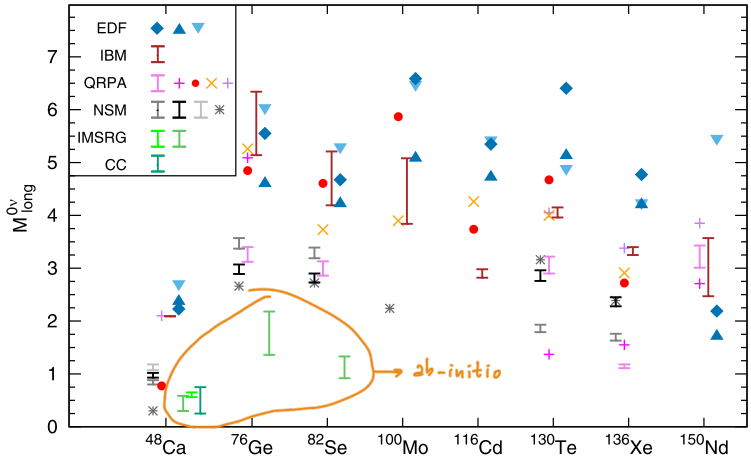
[1] 100+ papers per year with "0νββ" in the title [INSPIRE-HEP statistics]



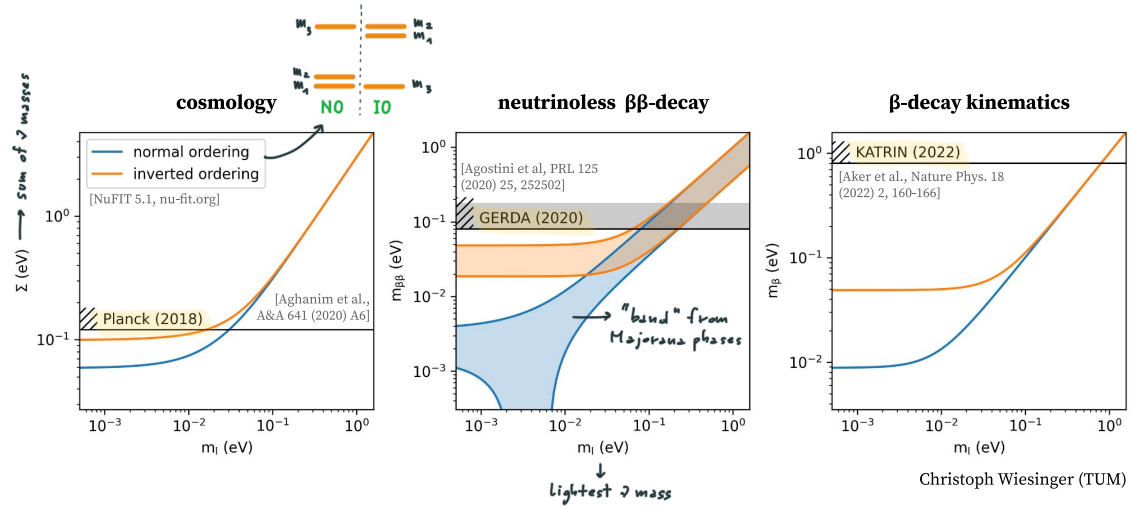
$$\text{decay rate} \sim \frac{1}{T_{1/2}} \sim G \times |M|^2 \times m_{\beta\beta}{}^2$$

- The phase space factor G is well known
- The nuclear matrix elements M are **not**
- Majorana effective mass $m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 \, m_i\right|$, where U is the PMNS matrix

Computing Nuclear Matrix Elements is a complex task

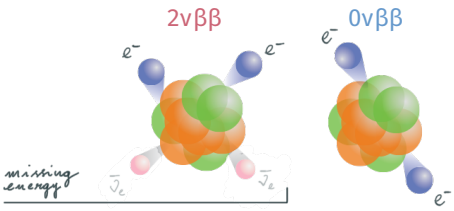


$m_{\beta\beta}$ CONSTRAINTS AND COMPLEMENTARITY WITH OTHER ν MASS PROBES



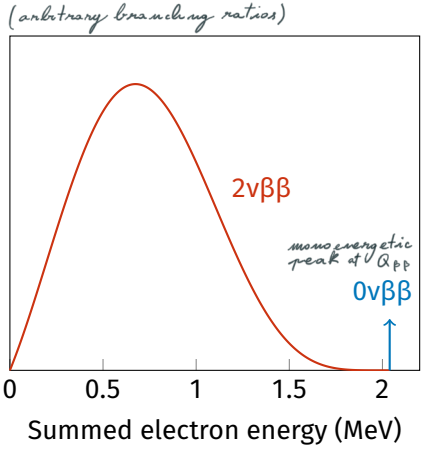
Christoph Wiesinger (TUM)

Experimental signature

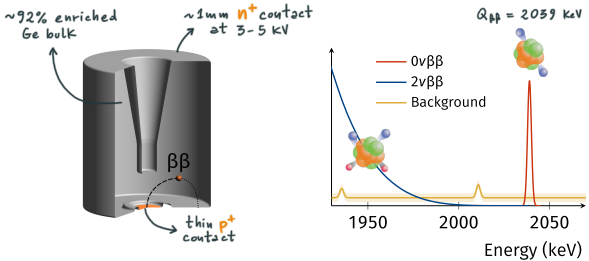


All experiments measure the total energy of the two emitted electrons

⟼ *necessary and sufficient* for discovery

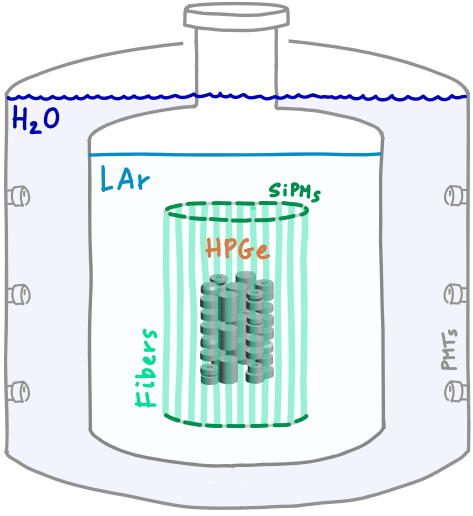


Searching for 0νββ with Germanium: concept

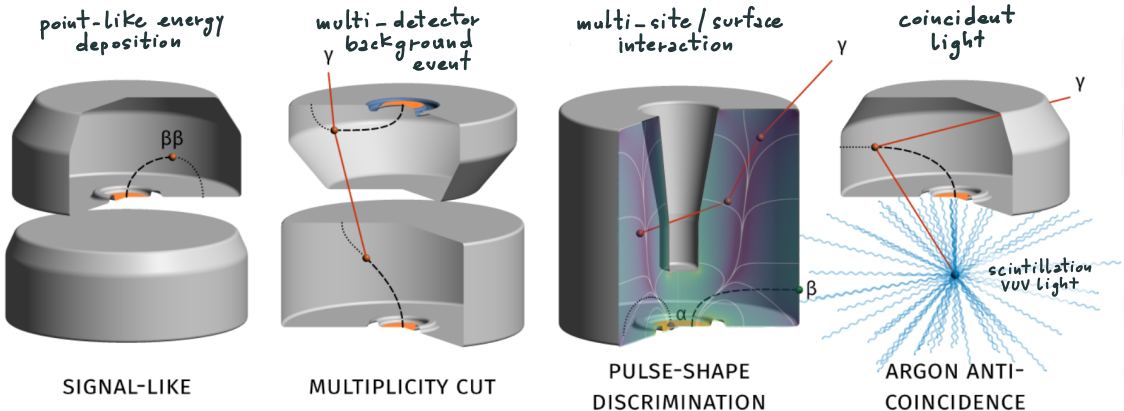


High-Purity Germanium detectors enriched in ^{76}Ge

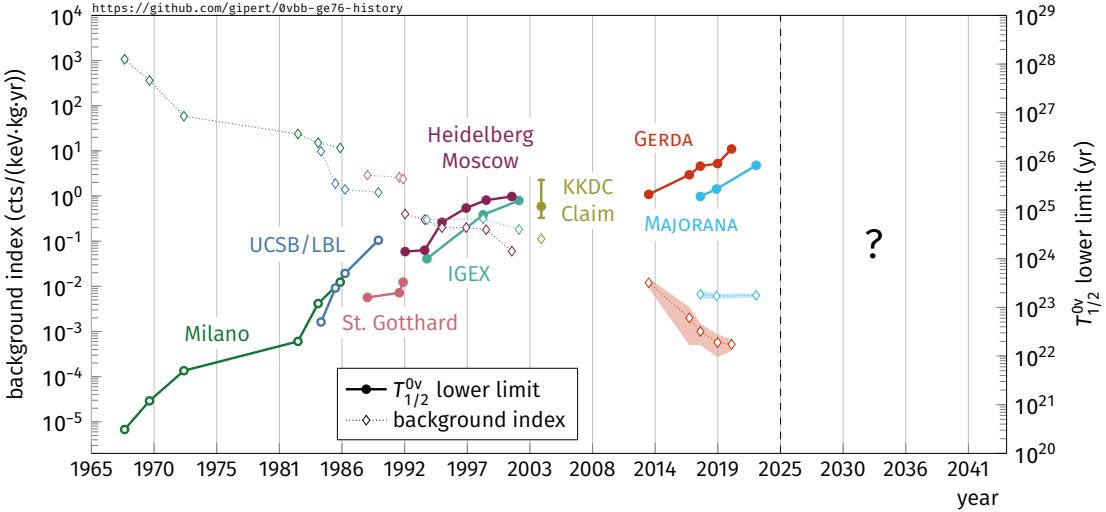
- source = detector ⟼ *high efficiency*
- pure ⟼ *low intrinsic background*
- Ge crystal ⟼ *outstanding energy resolution*
- charge drift in E-field ⟼ *topological discrimination*



Signal and background discrimination techniques

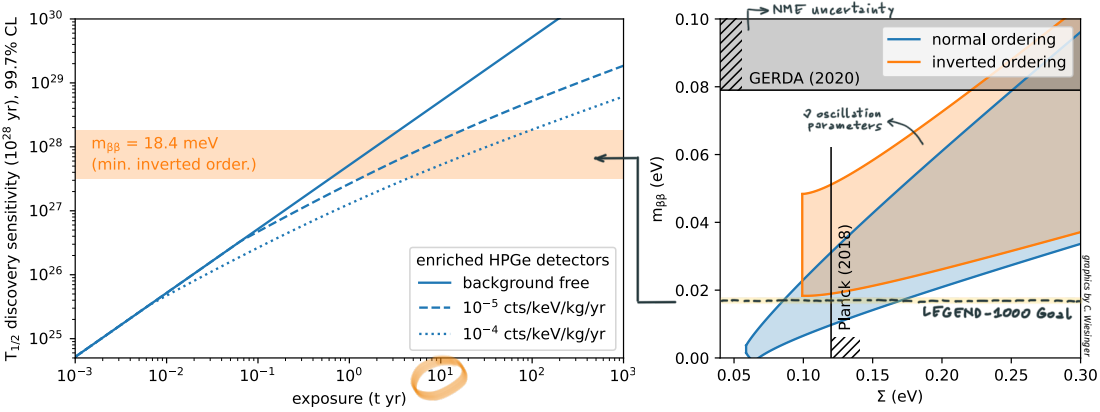


50 years of Double Beta decay with ^{76}Ge



The next scientific milestone in the search for 0νββ with ^{76}Ge

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



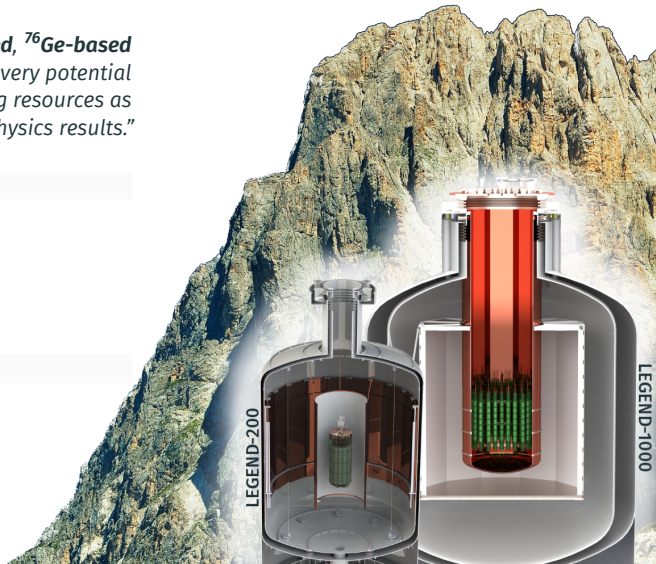
*"The collaboration aims to develop a **phased**, **^{76}Ge-based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} yr**, using existing resources as appropriate to expedite physics results."*

LEGEND-200

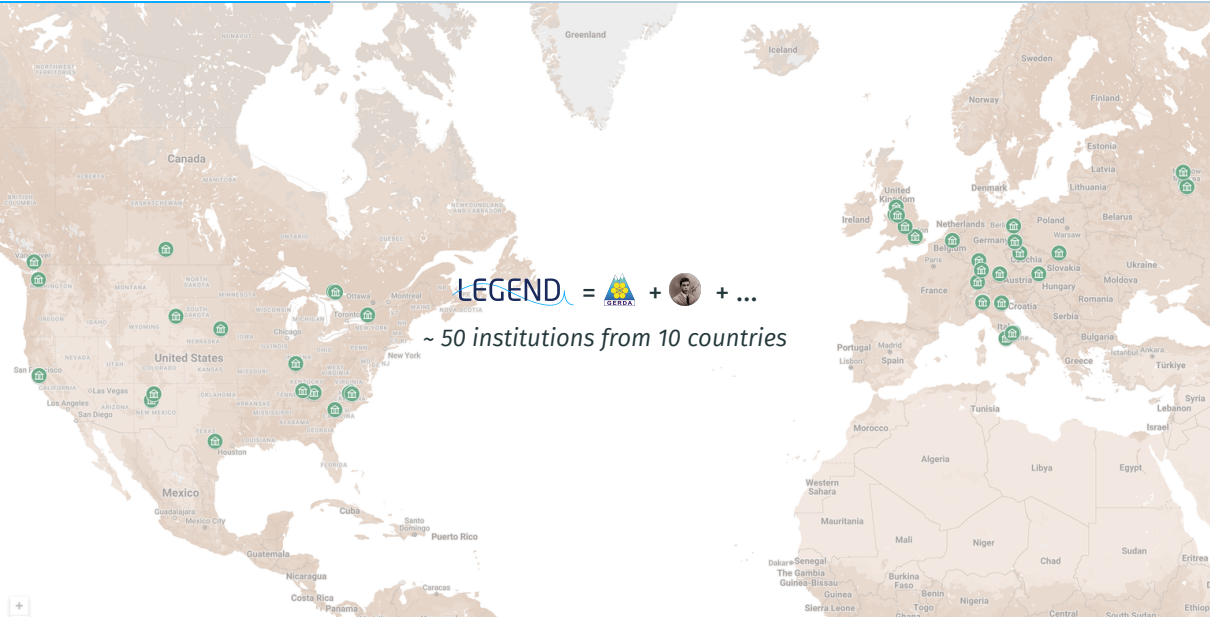
- **200 kg** of ^{enr}Ge (×5 yr), in GERDA cryostat
- Operating with 140 kg of ^{enr}Ge
- $B \sim \mathbf{2 \cdot 10^{-4}}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > \mathbf{10^{27}}$ **yr**

LEGEND-1000 arXiv 2107.11462 "pre-conceptual design report"

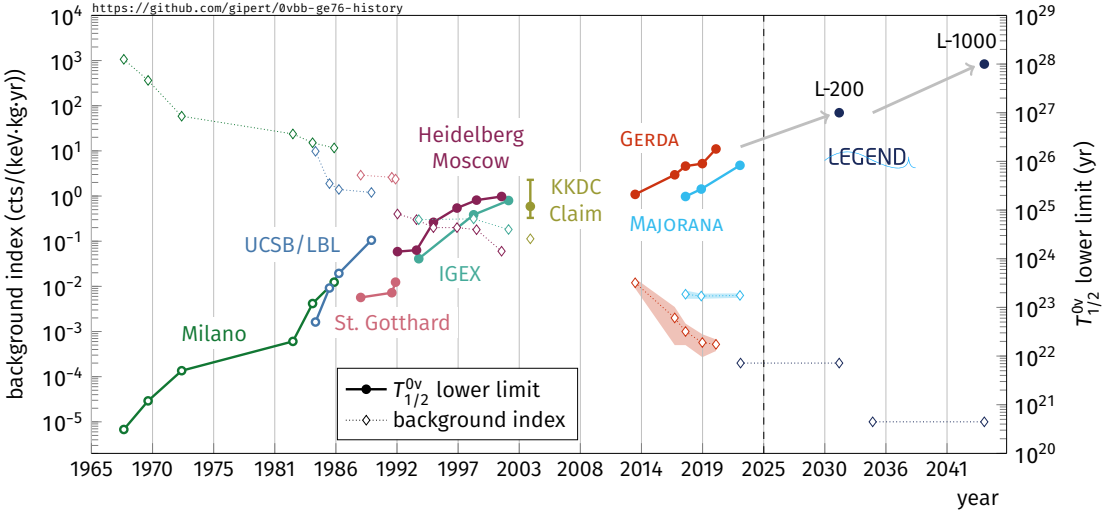
- **1 ton** of ^{enr}Ge (×10 yr), awaiting funding
- $B < \mathbf{10^{-5}}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > \mathbf{10^{28}}$ **yr**
- Cover full $m_{\beta\beta}$ inverted ordering region



The collaboration

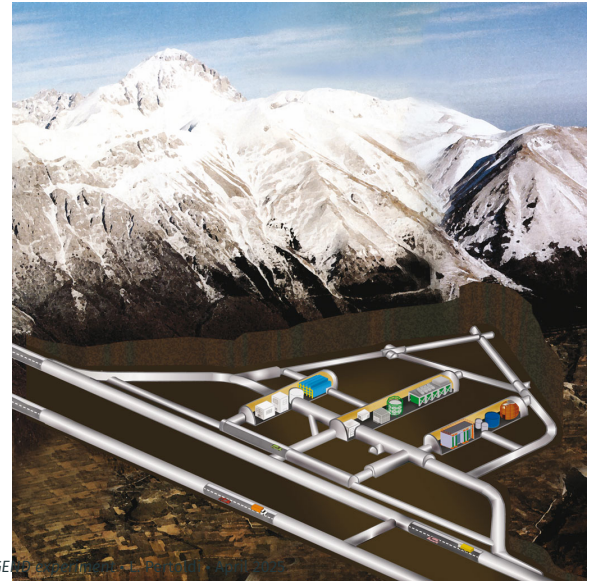


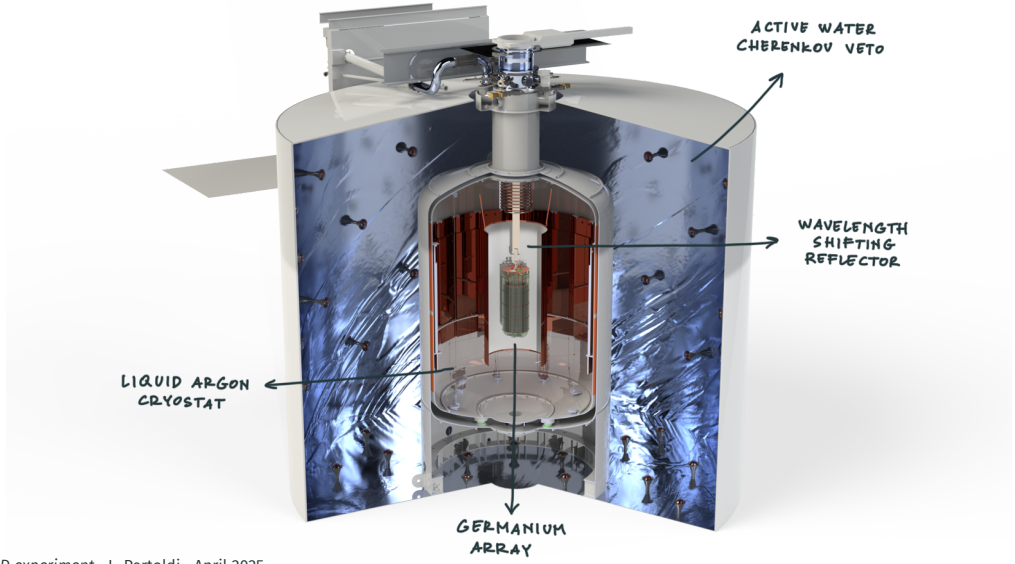
50 years of Double Beta decay with ^{76}Ge



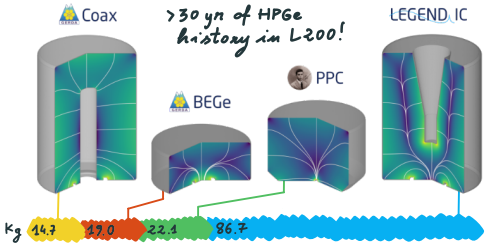
LEGEND -200

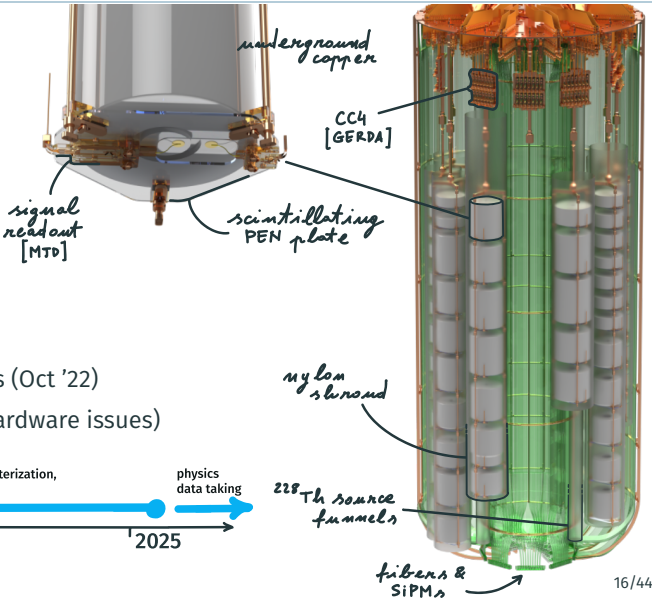
THE LEGEND -200 EXPERIMENT AT LNGS




ACTIVE WATER
CHERENKOV VETO
WAVELENGTH
SHIFTING
REFLECTOR
LIQUID ARGON
CRYOSTAT
GERMANIUM
ARRAY

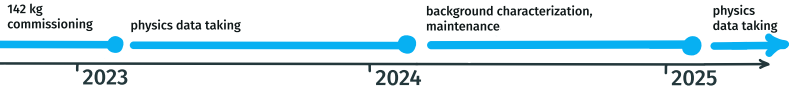
THE FIRST CONFIGURATION OF LEGEND-200



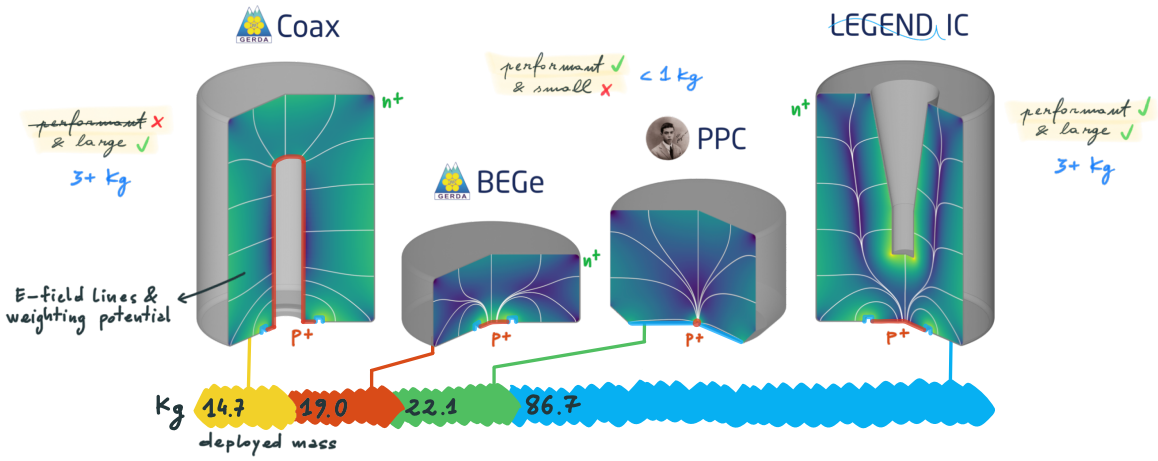


Hardware status — see talk at [TAUP23]

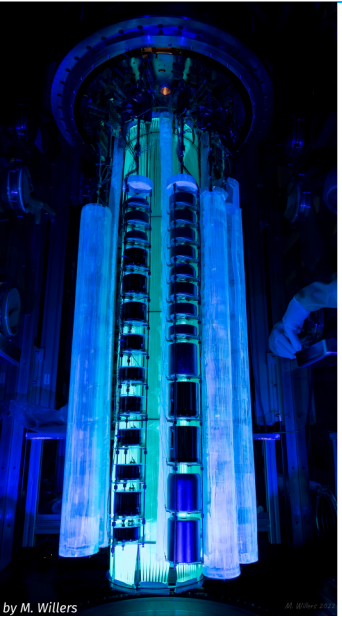
- Installed first **142 kg** of HPGe detectors (Oct '22)
- 130 kg operational (12 kg OFF due to hardware issues)

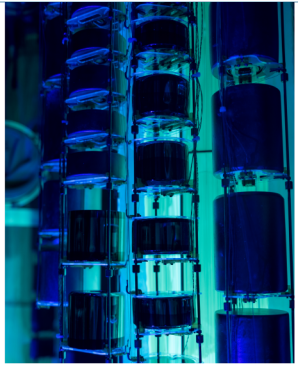


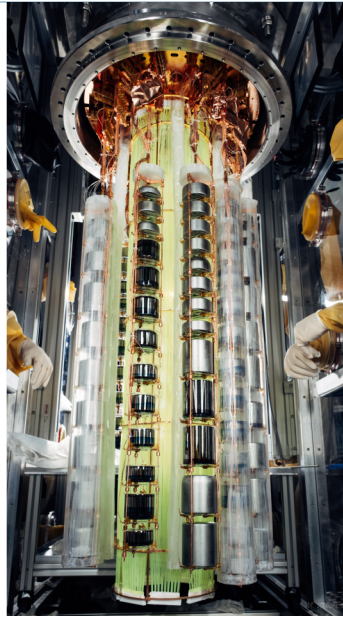
THE LEGEND -200 GERMANIUM DETECTORS



THE LEGEND -200 COMMISSIONING

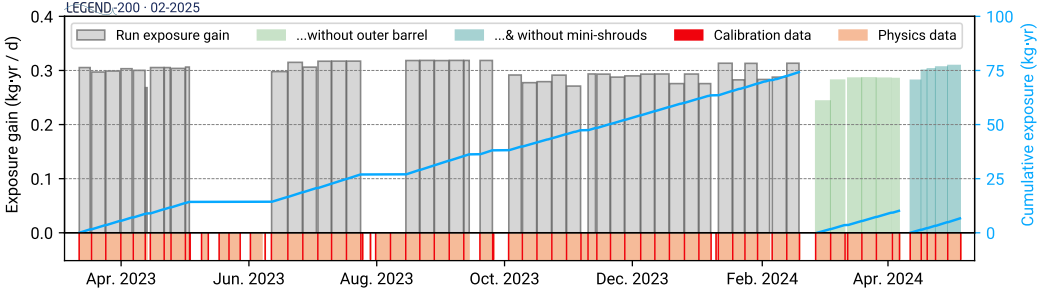






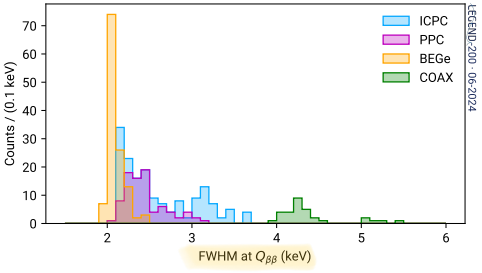
Exposure accumulated over 1 year valid for:

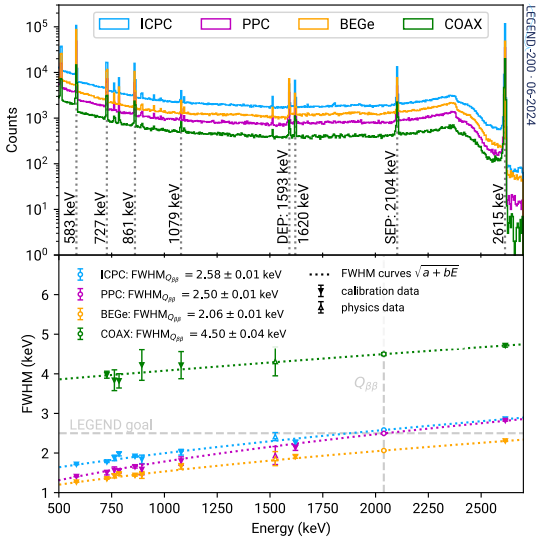
- Background and performance characterization data set: 76.2 kg yr
  - *plus 10.2 kg yr of special "background characterization" runs*
- 0νββ data set: 61 kg yr
  - *includes only data with fully vetted Pulse Shape Discrimination (PSD) parameters*



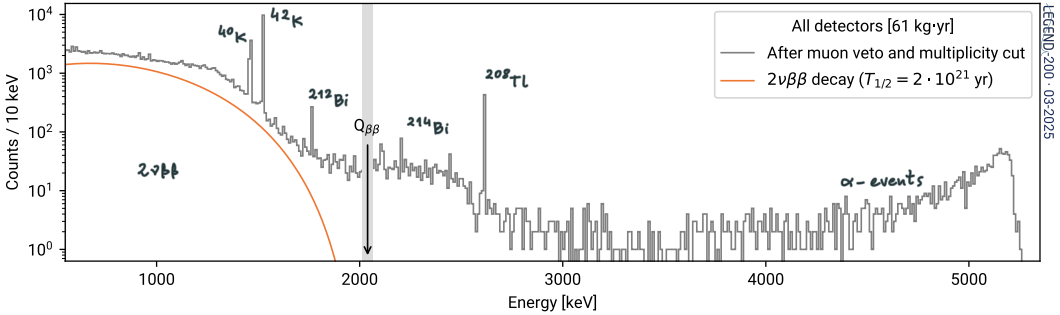
Energy scale and resolution

- ~0.1% FWHM at $Q_{\beta\beta}$
  - *including large inverted-coaxial detectors*
- **Stable** energy observables
  - *monitored with weekly ^{228}Th calibrations*
- Second-order variations **tracked in time**
  - *data set partitioned according to stability*



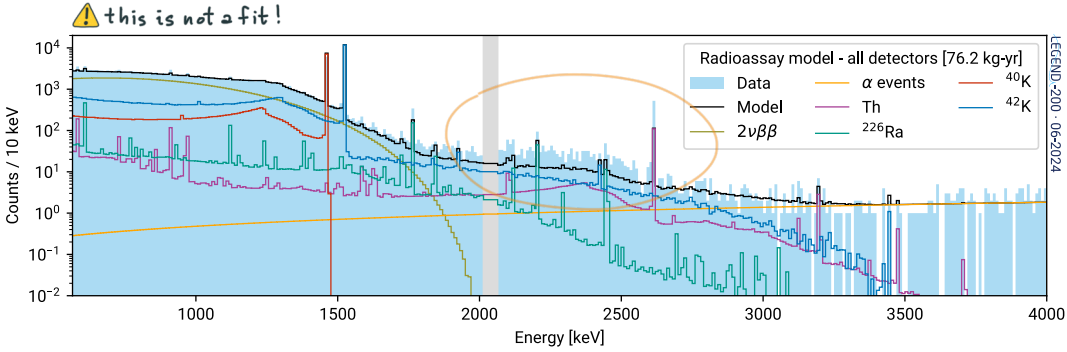


Data after Muon Veto and multiplicity cut



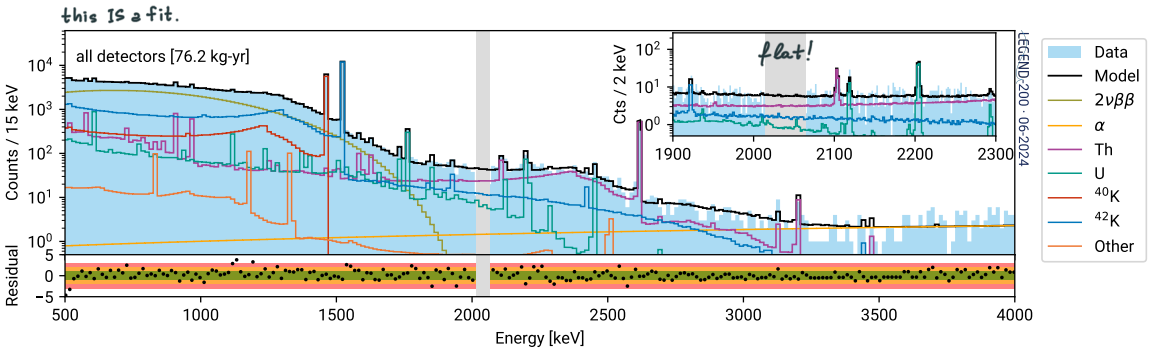
- Blinding applied at $Q_{\beta\beta}$ = 2039 keV (50 keV window)
- 95–99% survival of physical events after data cleaning at $Q_{\beta\beta}$
- Multiplicity cut rejects 26% of events at $Q_{\beta\beta}$
- 2 events removed by Muon Veto at $Q_{\beta\beta}$

Modeling data before analysis cuts



- Simulations and material radioassay underpredict ^{228}Th in physics data
  - *Hard to estimate systematic uncertainty on the assay results*
  - *ICP-MS not predictive if secular equilibrium is broken*
- This background is efficiently suppressed by analysis cuts

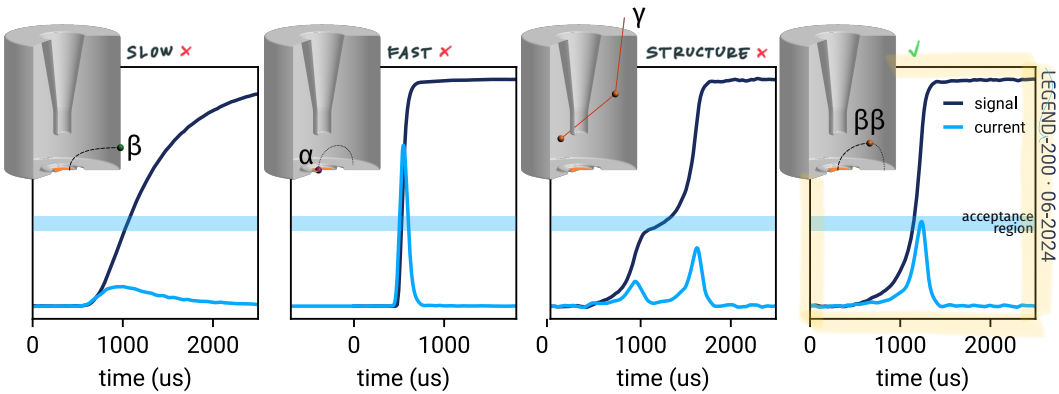
Modeling data before analysis cuts



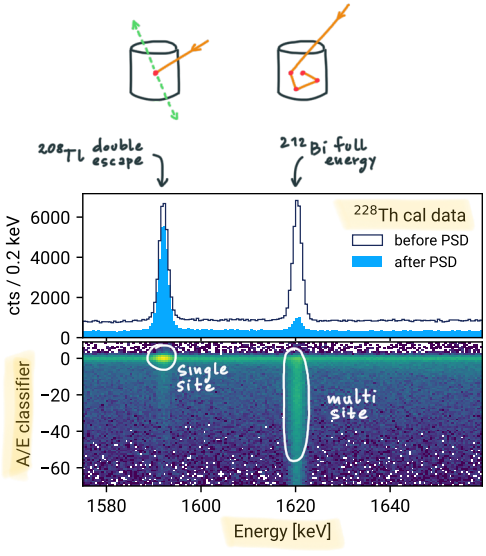
- Bayesian background model using data before analysis cuts
  - *Includes 10.2 kg yr from special "background characterization" runs*
- Data well reproduced, model is flat at $Q_{\beta\beta}$
  - *No "hotspot" or significant asymmetry observed in data*
  - *Model can test hypotheses on the origin of ^{228}Th*

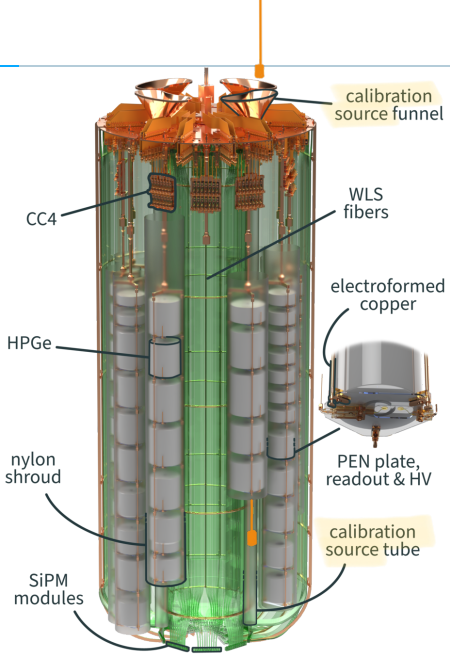
HPGe Pulse Shape Discrimination (PSD)

Pulse shape classifier: A/E = *max(current) / energy*

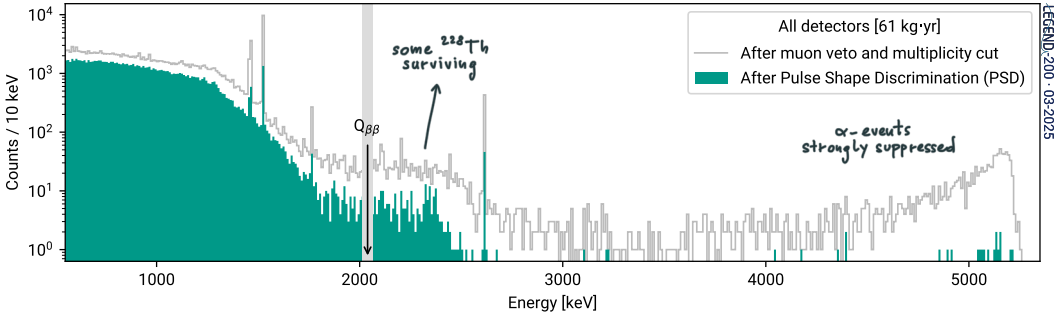


Understanding PSD with ^{228}Th calibrations



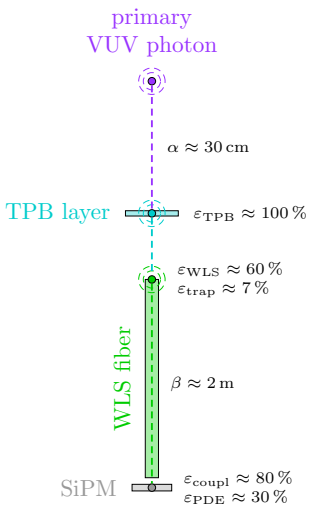


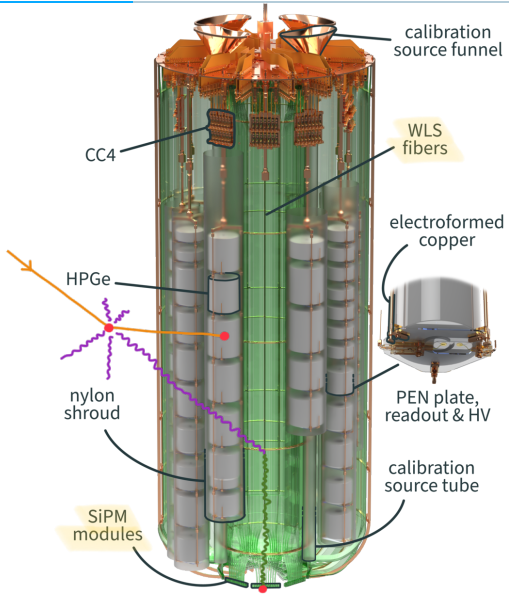
Data after pulse shape discrimination



- Strong suppression of surface α and β (^{42}K) events
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$
- 0νββ survival fraction of ~85%

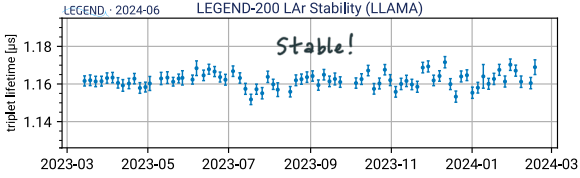
Argon instrumentation

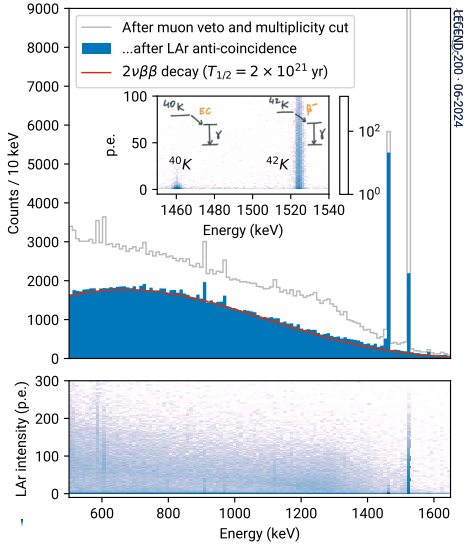




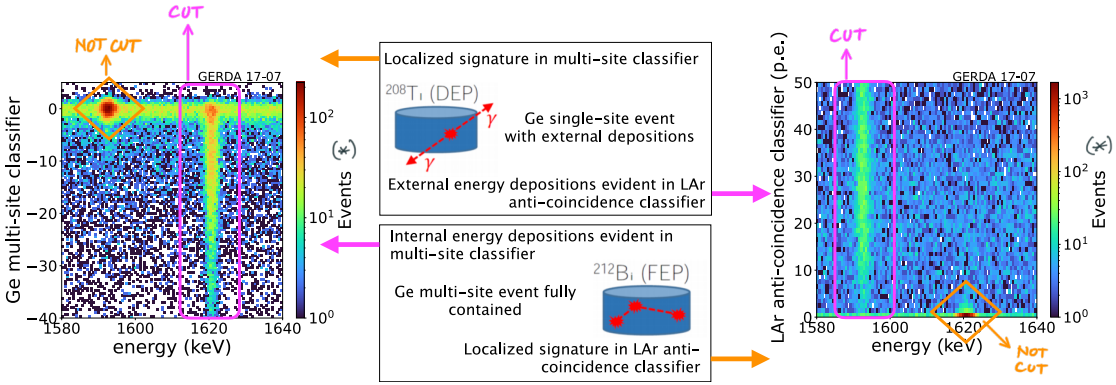
Argon instrumentation

- Improved light yield compared to GERDA (×3)
- **Stable** argon properties
  - *Monitoring through LLAMA instrumentation*
- **Characterized** with special calibration runs
  - *~1 photoelectron per 10 keV deposited in argon*
- **Strong suppression** of background above 2νββ
  - ββ *decay signal acceptance of ~93%*





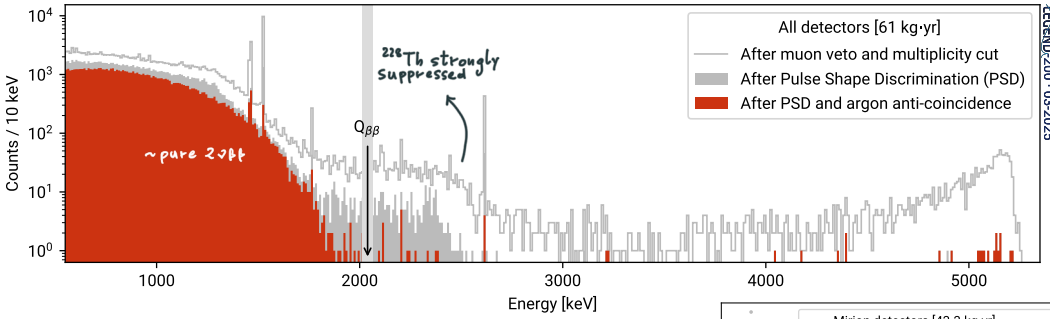
Powerful combination of background tagging techniques



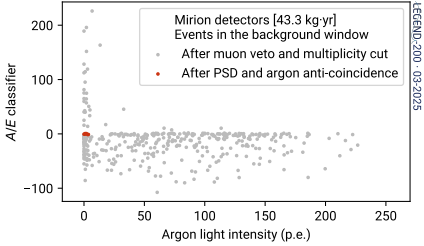
DEP = double-escape peak
FEP = full-energy peak

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

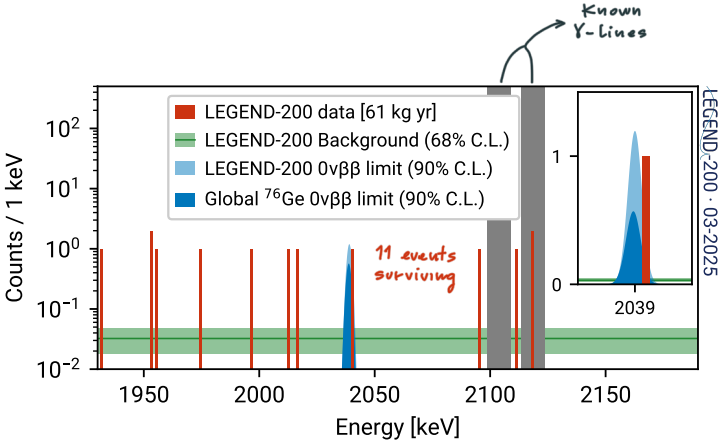
Data after pulse shape discrimination and argon anti-coincidence cut



- Strong anti-correlation of argon and PSD cuts
- Overall 0νββ survival fraction of ~60%
- "Pure" 2νββ distribution, few events surviving at $Q_{\beta\beta}$



Data in the region of interest



Background index:

- 48.3 kg yr unblinded in 2024: $0.5^{+0.3}_{-0.2}$ cts / (keV tonne yr)
- extra 12.8 kg yr unblinded this year: $1.3^{+0.8}_{-0.5}$ cts / (keV tonne yr)

Background compatible with GERDA but we are working on improving it!

GERDA (127 kg yr), **MAJORANA DEMONSTRATOR** (65 kg yr) and **LEGEND** (61 kg yr) **combined** 0νββ fit

- p-value of background-only = 29%
- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

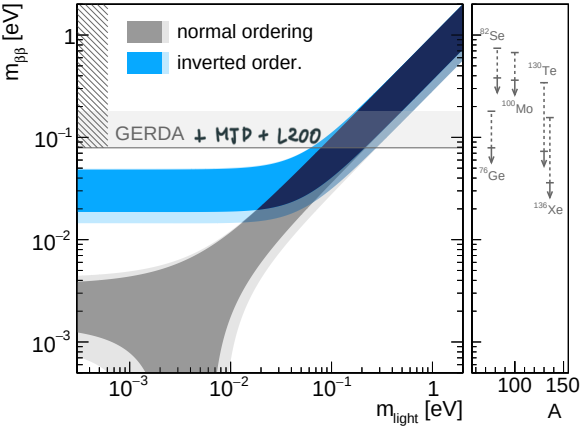
Observed	Sensitivity
$> 1.9 \cdot 10^{26}$ yr	$2.8 \cdot 10^{26}$ yr

- Majorana effective mass upper limits (90% C.L.): $m_{\beta\beta} < 70 - 200$ meV phenomenological NME range

LEGEND-200 contribution

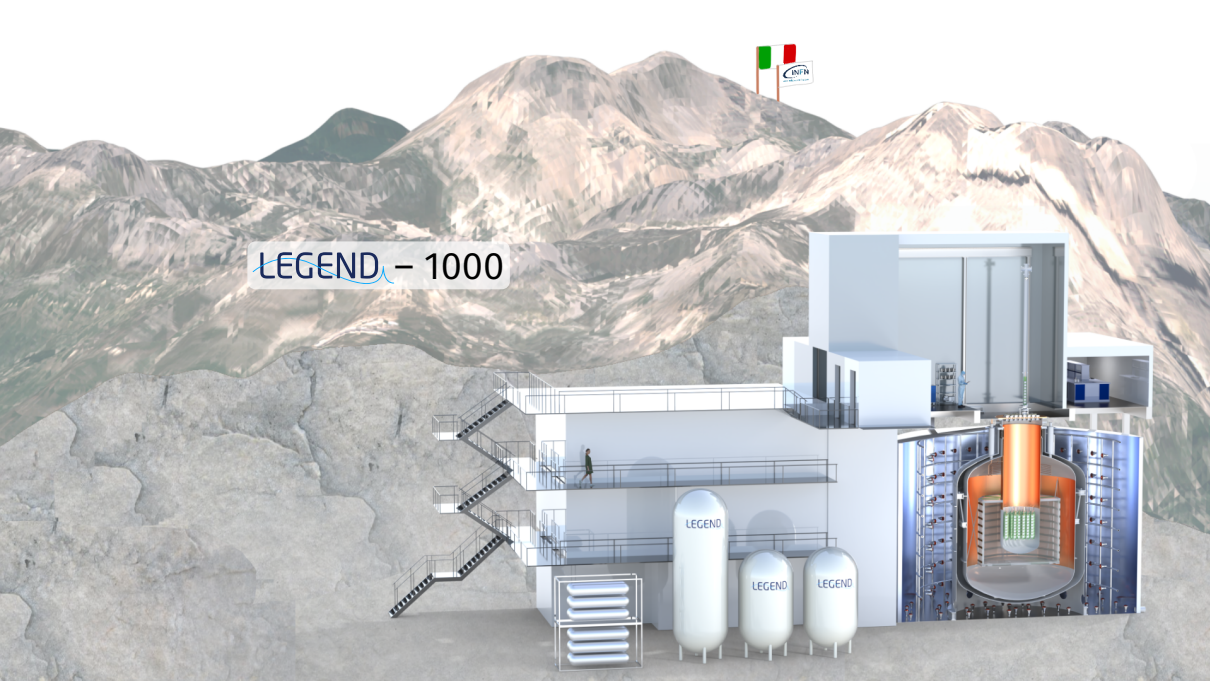
- +30% of limit median expectation
- event at 1.3 σ from $Q_{\beta\beta}$ weakens combined limit

Results from other experiments

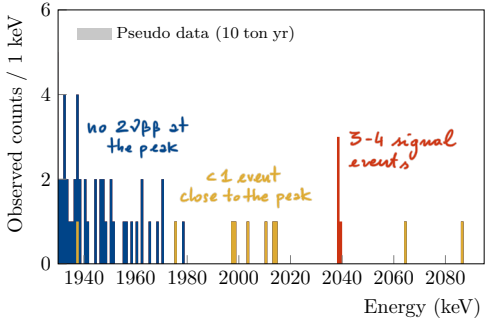


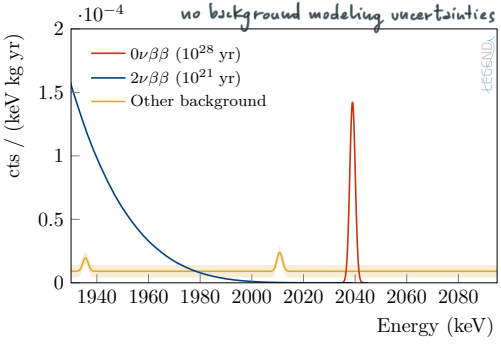
- ^{136}Xe, ^{76}Ge (and ^{130}Te) place the most stringent limits
  - *Note: ^{76}Ge limits on $m_{\beta\beta}$ are weakened by a less favorable phase space factor*
- Latest KamLAND-Zen800 results:
  - *Phys. Rev. Lett. 130, 051801*
  - $T^{0\nu}_{1/2} > 2.3 \cdot 10^{26}$ *yr (90% C.L.)*
  - $m_{\beta\beta} < 36$–156 *meV*
  - *Improved limits presented in 2024*

- About to restart data taking with an improved configuration
  - *meticulous radioassay campaign*
  - *improved material cleaning techniques*
  - *repair/refurbishment of problematic detectors*
- Analysis/simulation efforts ongoing
  - *characterize the background suppression performance*
  - *improve background diagnostic capabilities*
- Keep accumulating exposure on the way to LEGEND-1000

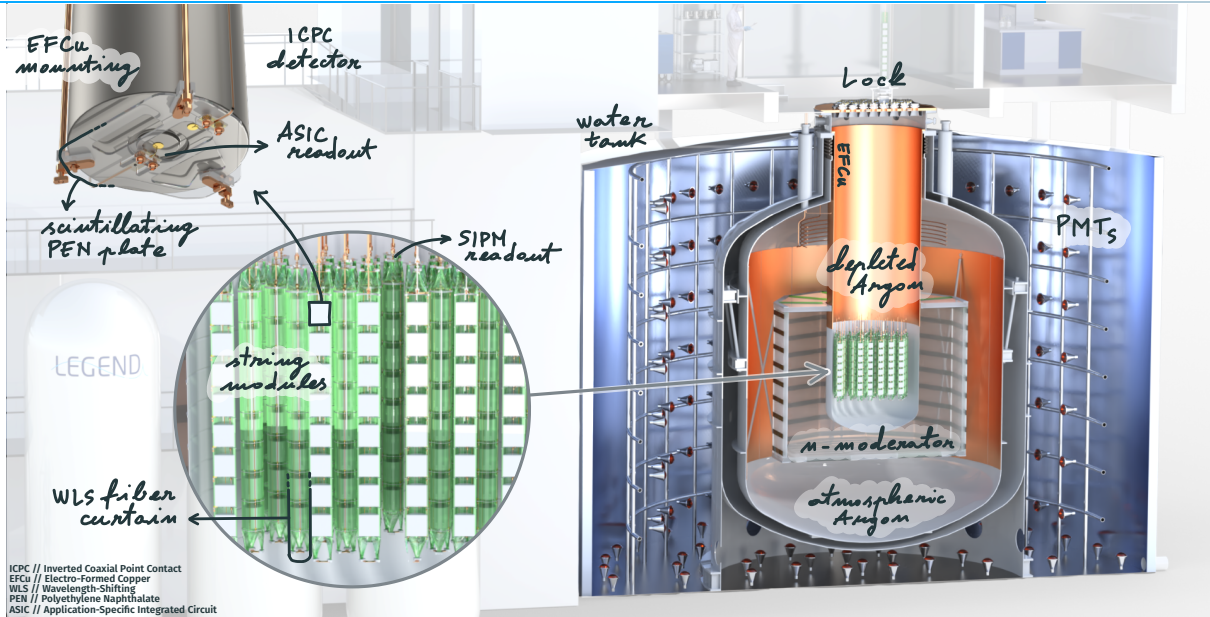

LEGEND – 1000
LEGEND
LEGEND
LEGEND

- Optimized for 0νββ *discovery* sensitivity beyond 10^{28} yr
- Background goal: 10^{-5} cts / (keV kg yr) ⟼ quasi-background-free for 10 ton yr exposure
- Has a low-risk path to meeting its goal based on MAJORANA, GERDA and LEGEND-200





THE LEGEND -1000 BASELINE DESIGN AT LNGS



ICPC // Inverted Coaxial Point Contact
EFCu // Electro-Formed Copper
WLS // Wavelength-Shifting
PEN // Polyethylene Naphthalate
ASIC // Application-Specific Integrated Circuit

Multi-site

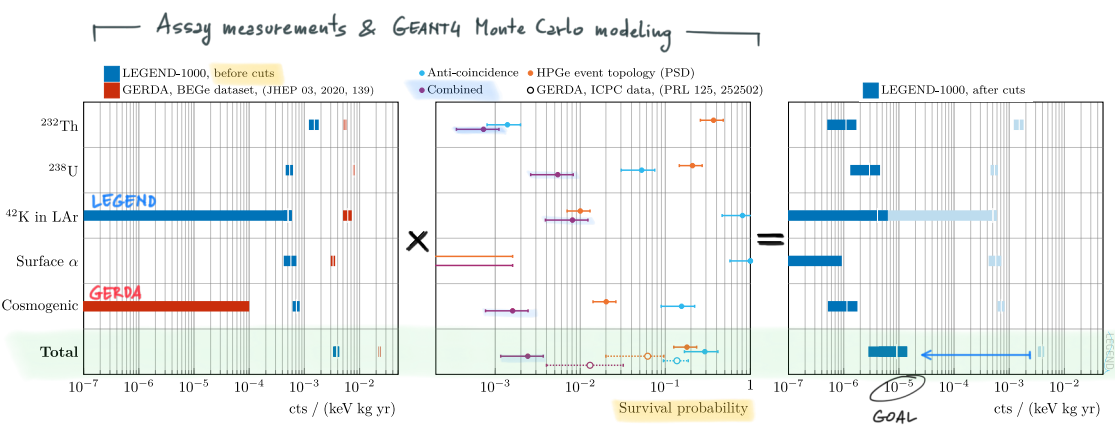
- ^{238}**U / ^{228}Th** from near-detector components, **external γ/n** from cryostat steel
  - ≫ *clean materials, remove opaque/inactive materials, large detectors, efficient LAr instrumentation*

Cosmogenic

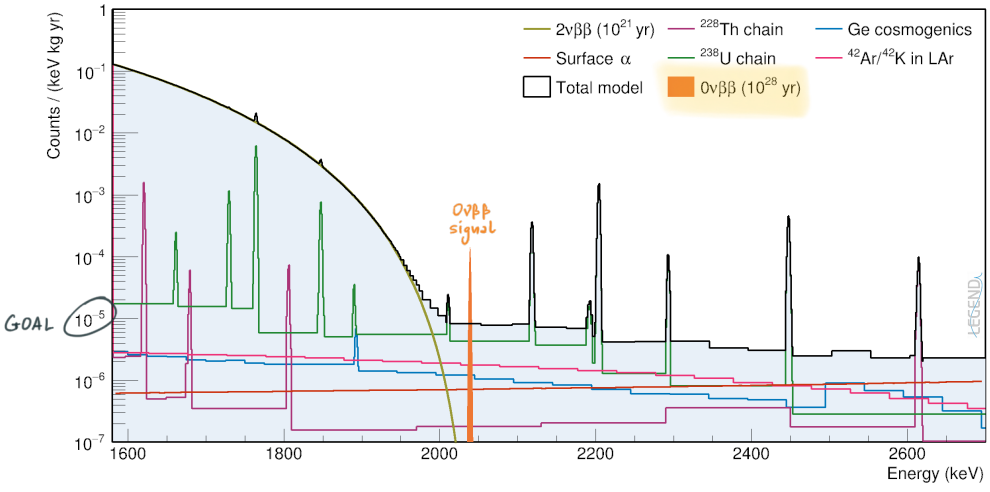
- ***in-situ*** μ-induced from **neutron capture on ^{76}Ge**
  - ≫ *underground laboratory, μ-veto, delayed coincidence cuts*
- ***ex-situ*** above-ground **activation of Ge**
  - ≫ *reduce above-ground exposure, cool-down period underground*

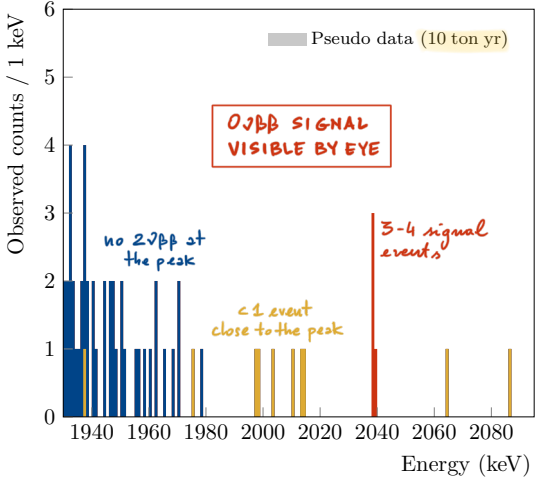
Detector surface

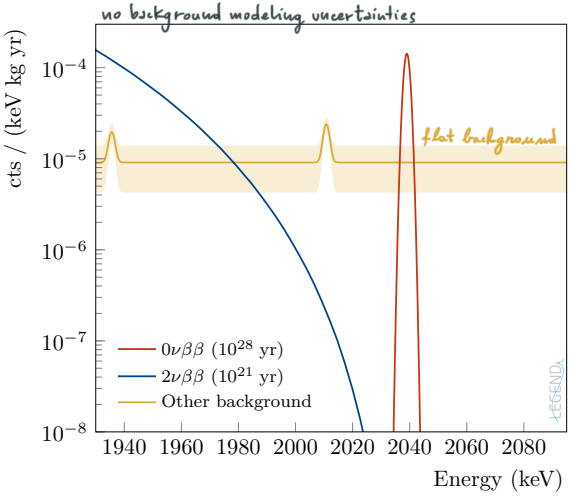
- **^{42}K events**: β decay from cosmogenic activation of argon
  - ≫ *underground-sourced argon*
- **α events** from radon deposition on detectors
  - ≫ *large detectors*


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
flat background
0νββ (10^28 yr)
2νββ (10^21 yr)
Other background
cts / (keV kg yr)
Energy (keV)
LEGEND

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

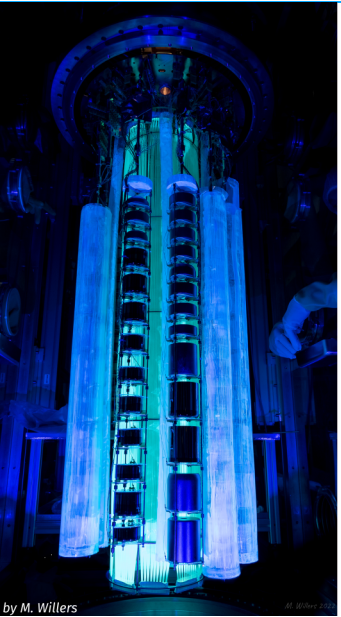
2022/2023 Commissioning/physics data taking of LEGEND-200

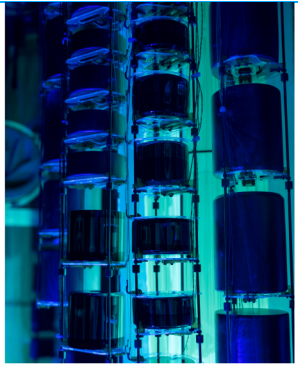
2025 *Critical Decision 1*: preliminary reference design, strategize funding

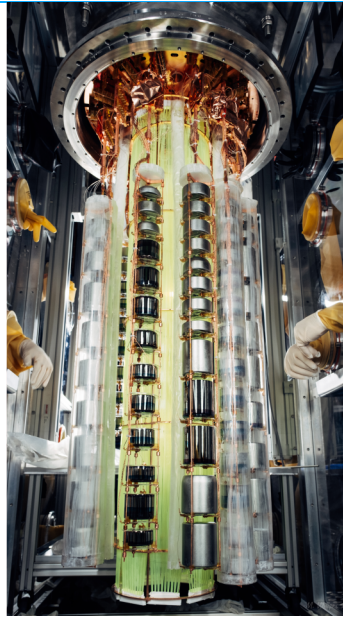
2026/27 Start of procurement of long-lead items (Ge, cryostat, infrastructure)

2030/31 Commissioning and first data

THANK YOU!



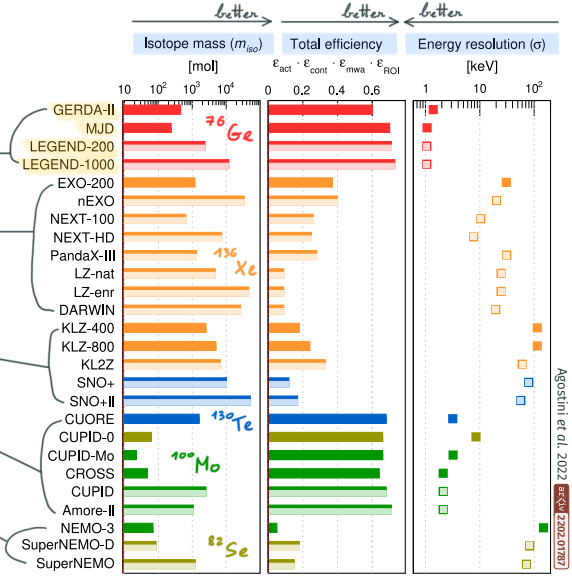




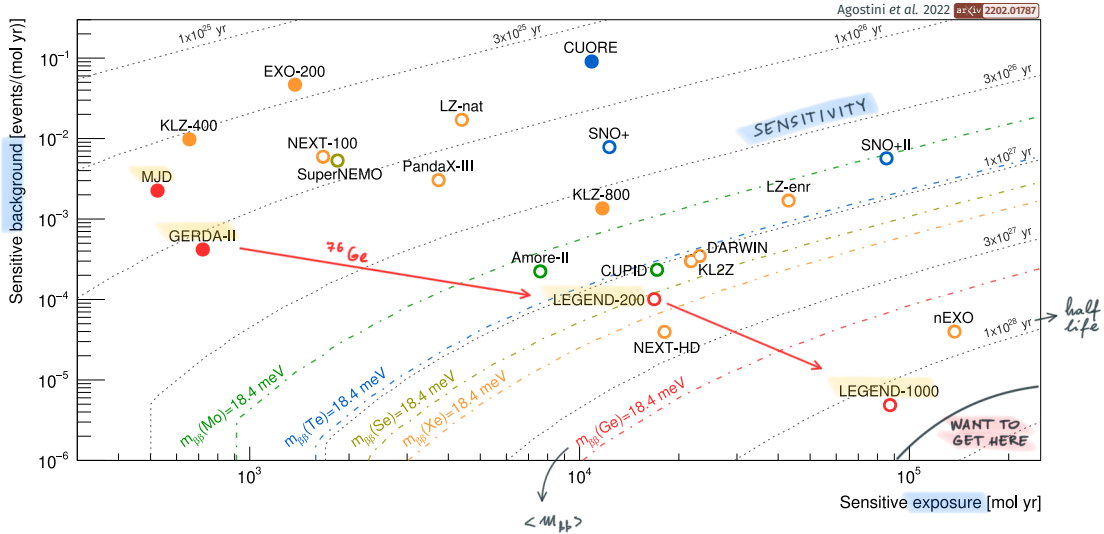
Backup

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



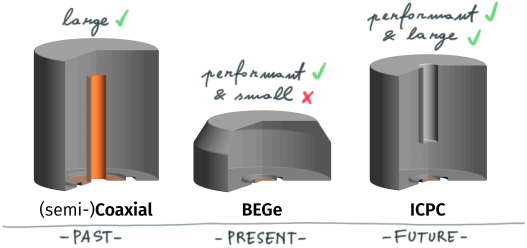
Detector concepts: sensitivity



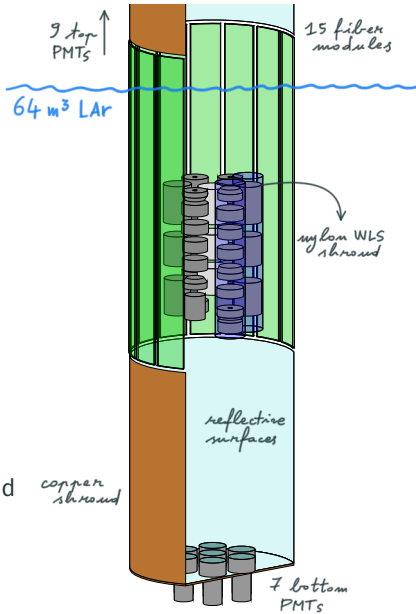
GERDA PHASE II SETUP

REF EPJC 78 (2018) 388

- 35.6 kg (later 44.2 kg) of HPGe REF EPJC 79 (2019) 11, 978 REF EPJC 81 (2021) 505



- Hybrid LAr light collection system: WLS fibers / SiPMs / PMTs
- μ-veto: water Cherenkov, scintillating panels REF EPJC 76 (2016)298
- Ultra radio-pure materials, small passive mass, deep underground



SEARCHING FOR NEW PHYSICS WITH ββ EVENTS

REF JCAP 12(2022)012