Searching for matter creation with GERDA and beyond

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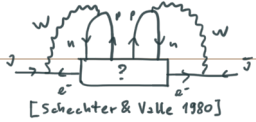
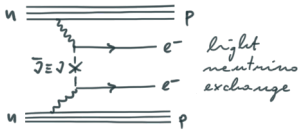
Erice • 19 June 2022

TU München, INFN Padova

Why neutrinoless double-β decay?

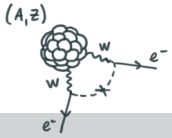


$(A,Z) \longmapsto (A,Z+2) + 2e^- + 2\cancel{\nu_e}$



"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

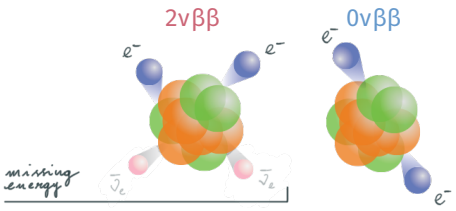
The (Majorana) neutrino that mediates 0νββ is the one that oscillates and the Standard Model is an effective theory *(seesaw mechanism)*

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

Majorana effective mass

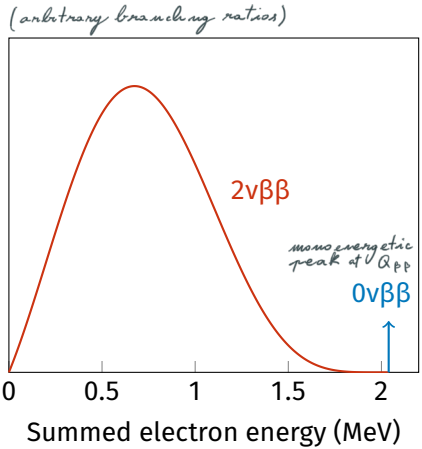
[1] 100+ papers per year with "0νββ" in the title [INSPIRE-HEP statistics]

Experimental signature



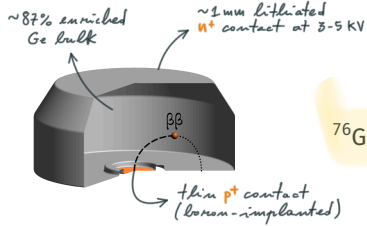
All experiments measure the total energy of the two emitted electrons

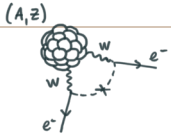
⟼ *necessary and sufficient* for discovery



The GERDA Experiment

The GERDA experimental concept



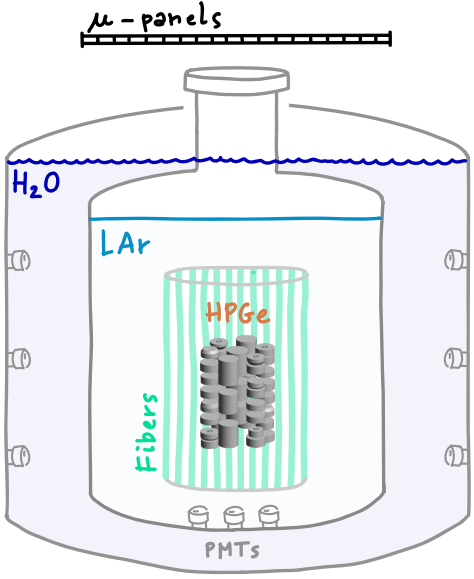


$^{76}Ge \xrightarrow{0\nu\beta\beta} {}^{76}Se + 2e^-$

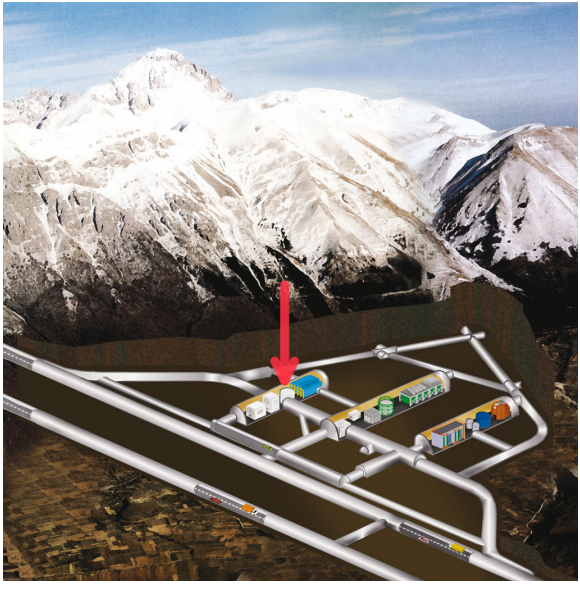
$Q_{\beta\beta} = 2039$ keV

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

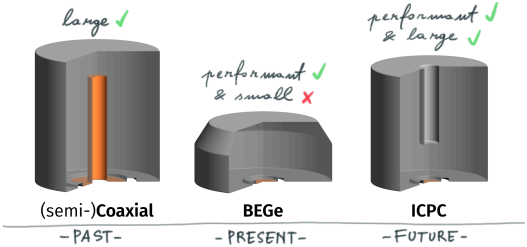


GERmanium DEtector ARray at LNGS — 3500 m.w.e. —

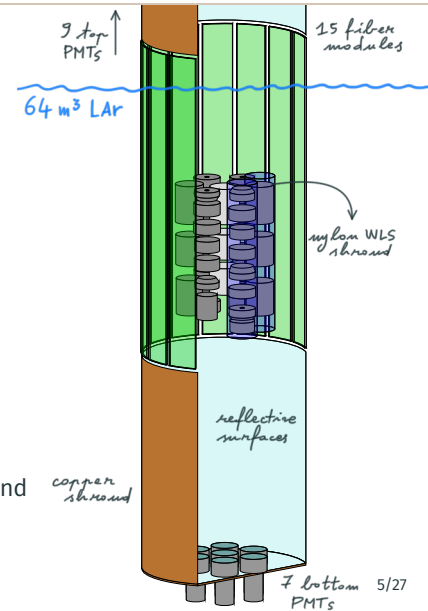


GERDA PHASE II SETUP REF EPJC 78 (2018) 388

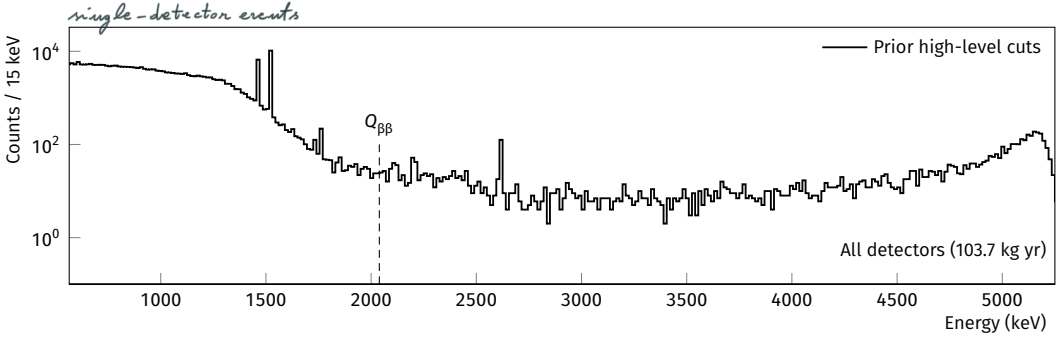
- 35.6 kg (later 44.2 kg) of HPGe REF EPJC 79 (2019) 11, 978 REF EPJC 81 (2021) 505



- 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



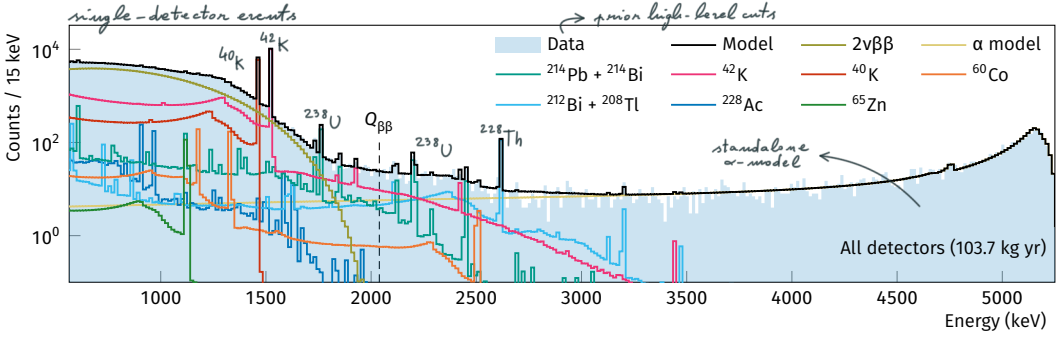
Phase II data energy spectrum before high-level cuts



- 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

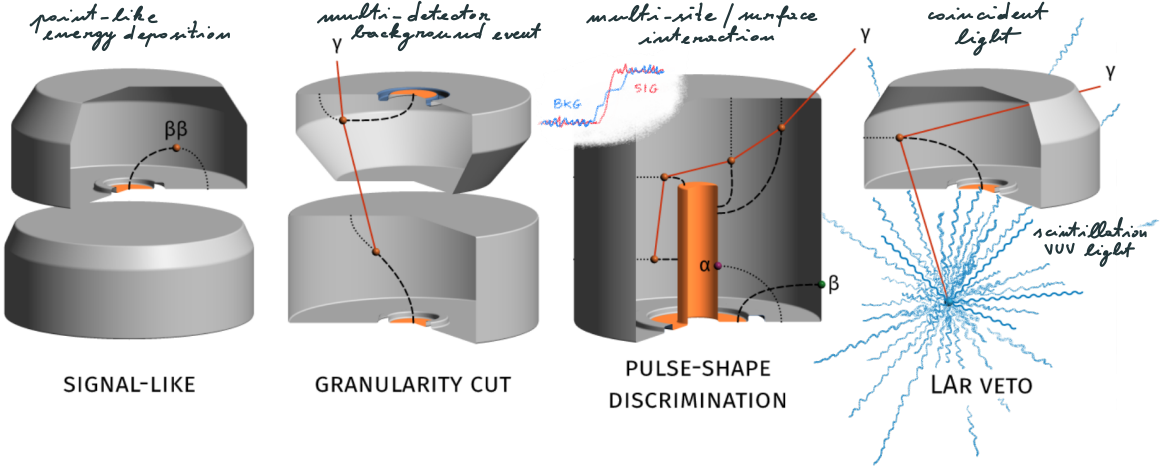
PHASE II DATA MODELING

REF JHEP 03 (2020) 139

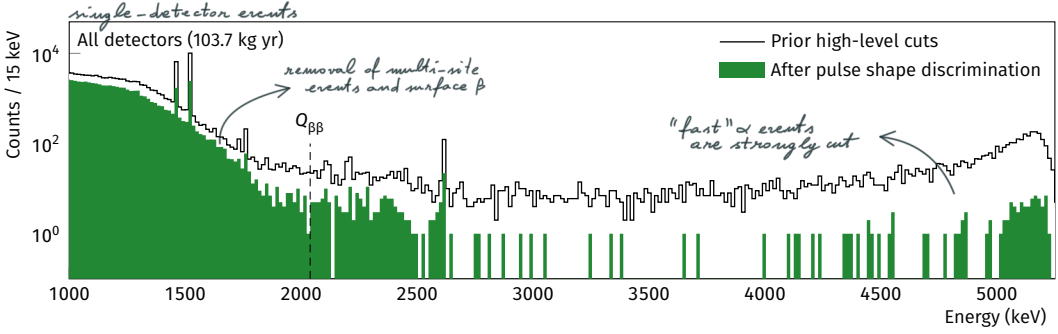


- Bayesian multivariate fit of Monte Carlo predictions *(with screening measurements as priors)*
- $Q_{\beta\beta}$ dominated by β from ^{42}K (from ^{42}Ar in LAr), α from ^{210}Po, γ from ^{228}Th and ^{238}U chains
- Results are input to several physics analyses and inform future experiments (LEGEND)

Signal and background discrimination techniques



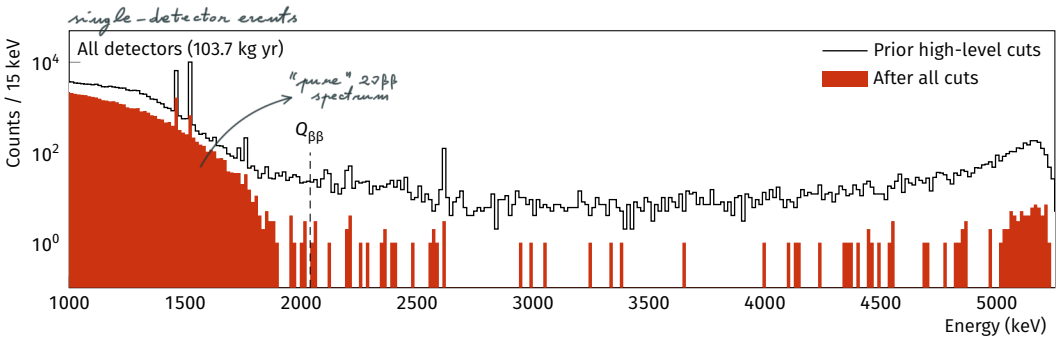
Pulse shape discrimination...



- 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) EPJC 82 (2022) 284

^{228}Th calibration data as tuning sample

...AND LIQUID ARGON ANTI-COINCIDENCE

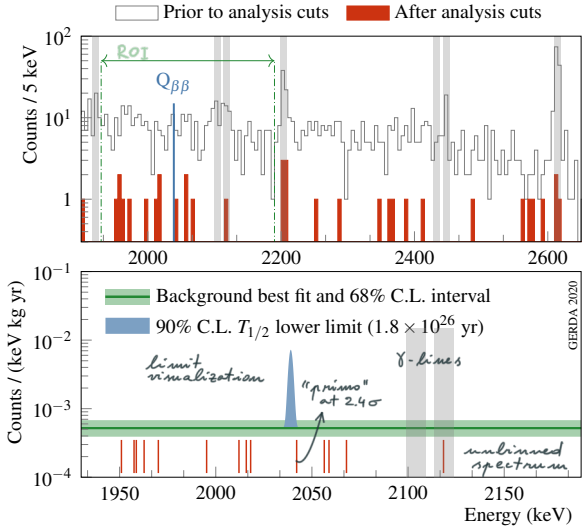


- Anti-coincidence between HPGe trigger and SiPM/PMT data *(≥ 0.3 p.e. in a 5 µs window)*
- Extremely low event rate at $Q_{\beta\beta}$ of ~ $5 \cdot 10^{-4}$ cts / (keV kg yr) ⟼ *quasi-background-free*
- Few events at $Q_{\beta\beta}$ ⟼ *"simple" background-model-free analysis*

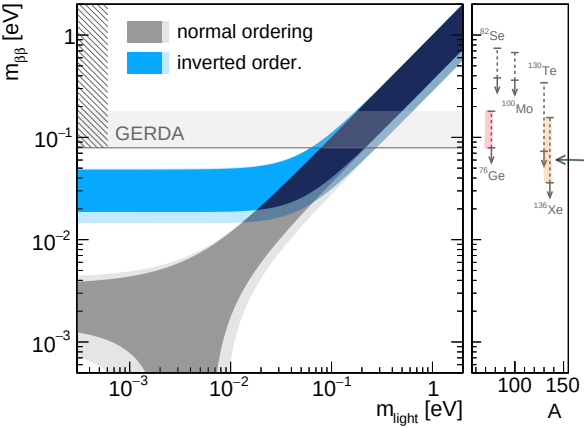
~ 0.3 counts per FWHM in full exposure!

"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)



Results from other experiments

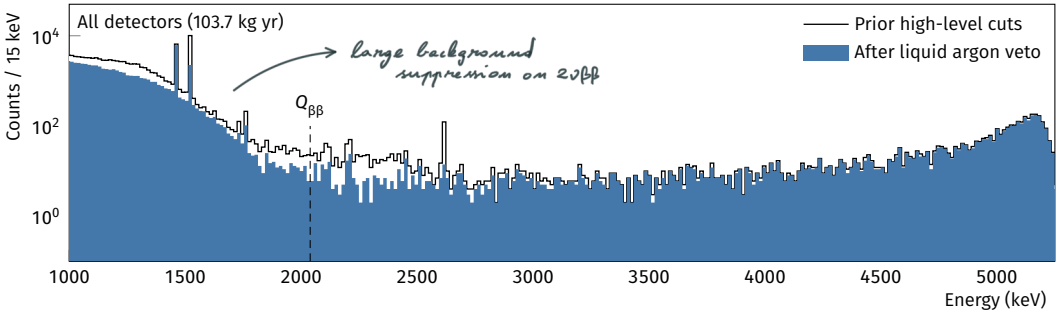


- ^{136}Xe, ^{76}Ge (and ^{130}Te) place the most stringent limits
  - *Note:* ^{76}Ge limits on $\langle m_{\beta\beta} \rangle$ are weakened by a less favorable phase space factor
- Recent: KamLAND-Zen800 results:
  - arXiv 2203.02139
  - $T^{0\nu}_{1/2} > 2.3 \cdot 10^{26}$ yr (90% C.L.)
  - $\langle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

(• GERDA has still the best sensitivity)

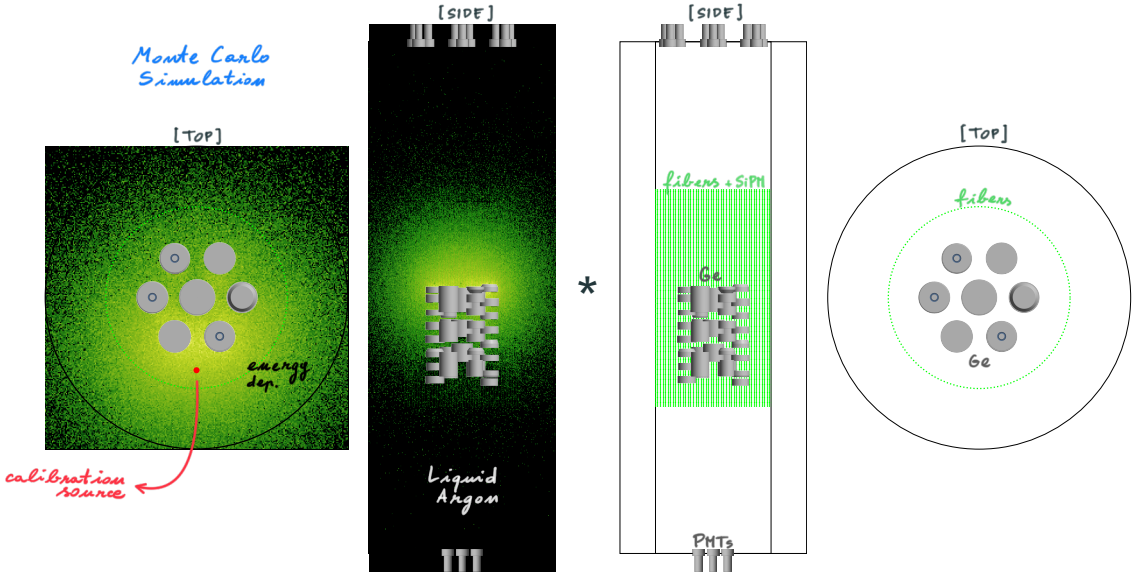
Not only 0νββ

Understanding data after LAr veto cut

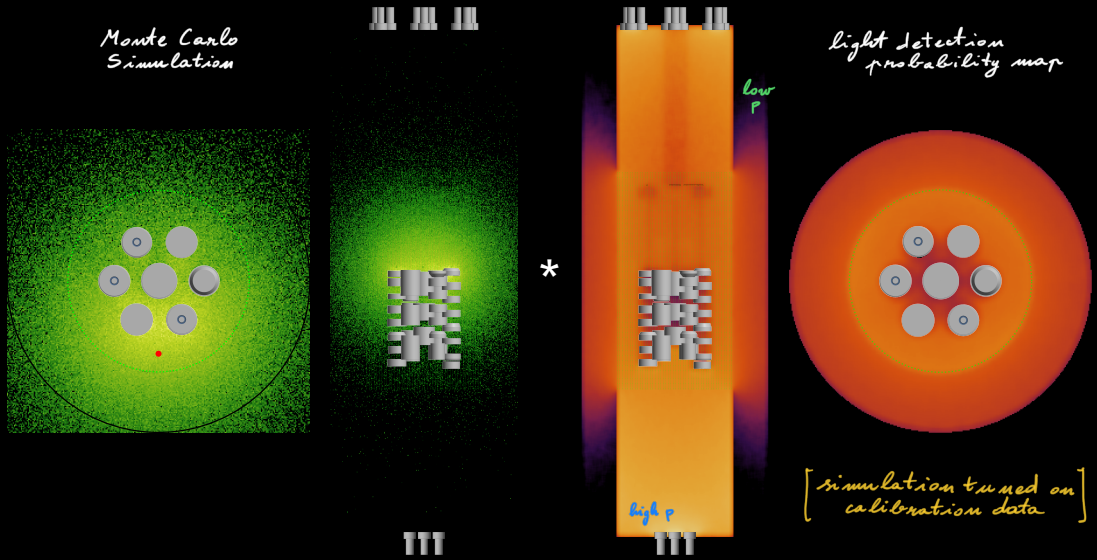


- ββ event survival probability > 97% *(random coincidences)*
- Cleaner, high-statistics 2νββ spectrum ⟼ precision SM test bench
- Need a model for signal and background after the cut, but how to simulate the LAr veto classifier?

Modeling the liquid argon detector response



Modeling the liquid argon detector response (lights off)



Data modeling before cuts

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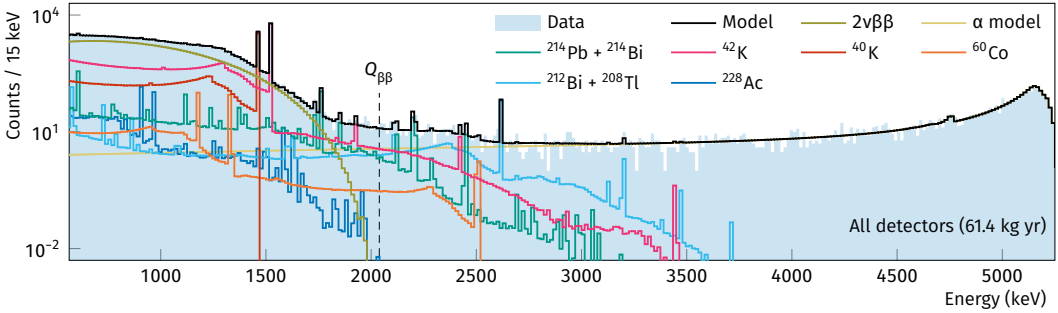
VETO OFF



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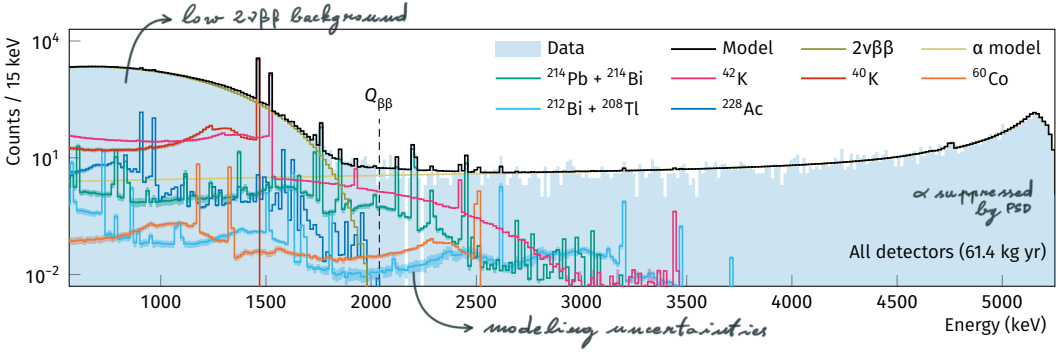
- Results are input to several physics analyses and inform future experiments (LEGEND)

Data modeling after LAr veto cut

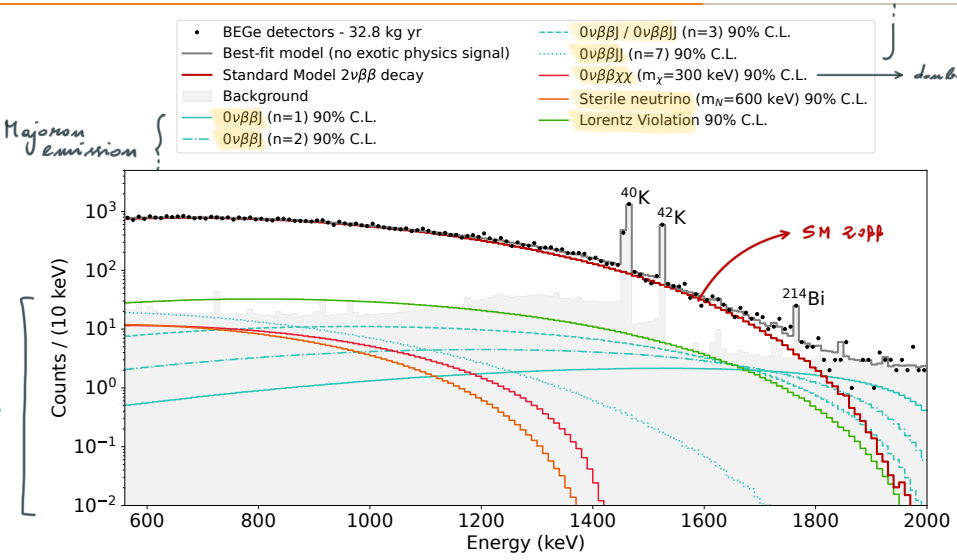
PRELIMINARY IN PREPARATION

VETO ON



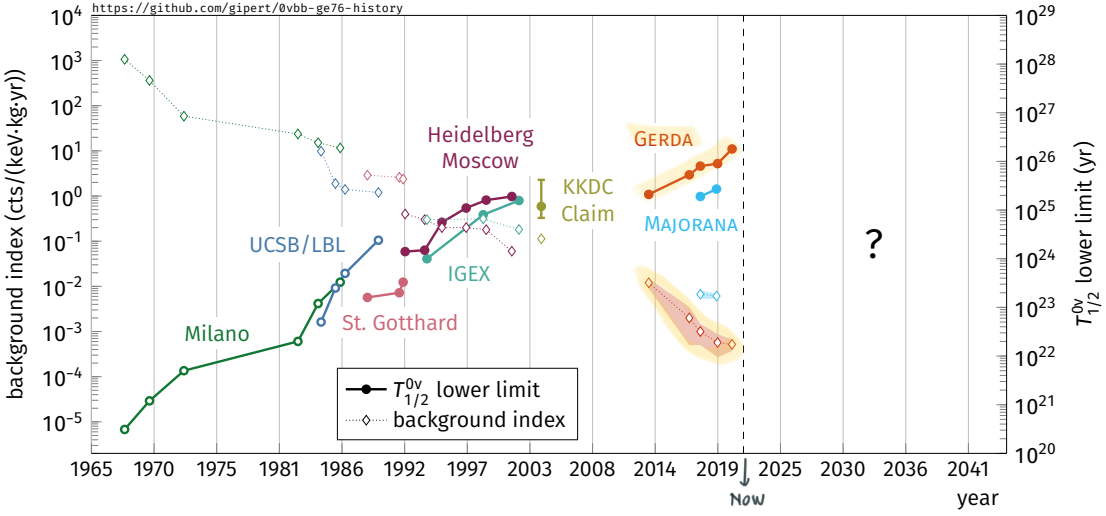
- Little or no light from β and α surface events *(but suppressed by pulse-shape cut)*
- γ from ^{228}Th and ^{238}U efficiently suppressed *(99.7% and 85%, respectively)*
- Can now use model to isolate and study 2νββ events

presented @ MEDEX'22



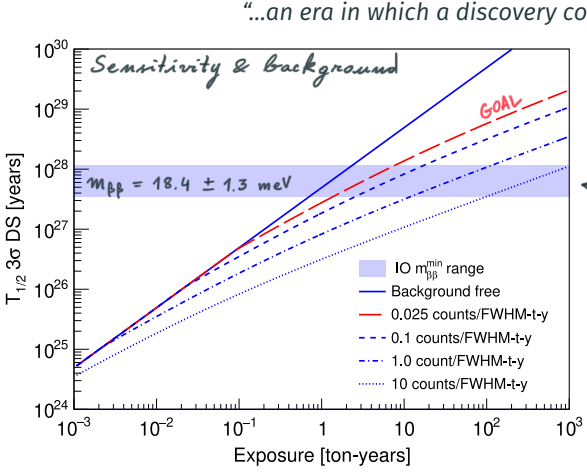
The Future

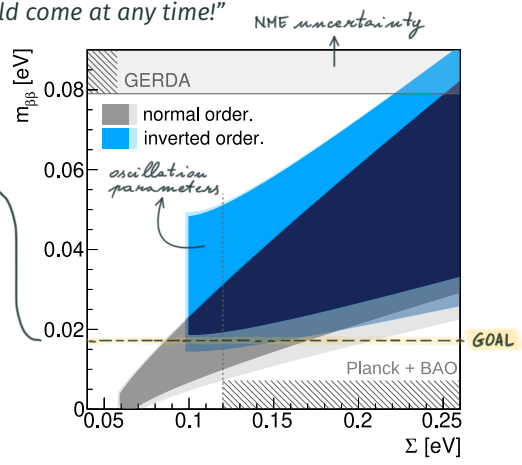
50 years of Double Beta decay with ^{76}Ge



What next?

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





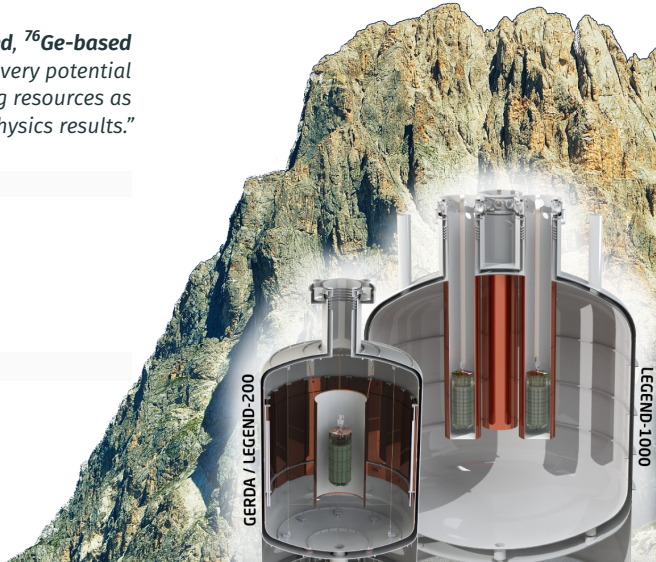
*"The collaboration aims to develop a **phased**, **^{76}Ge-based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} yr**, using existing resources as appropriate to expedite physics results."*

LEGEND-200

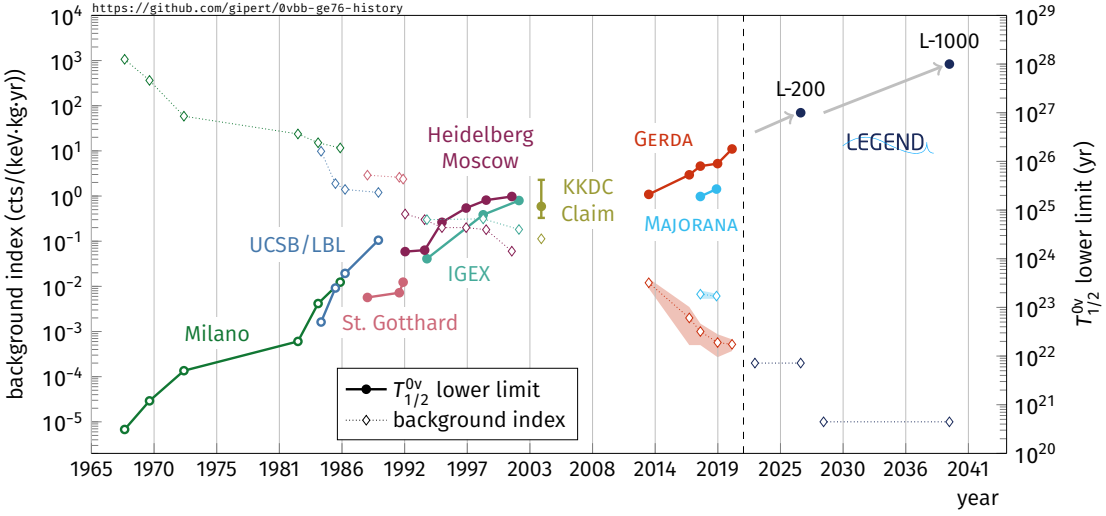
- **200 kg** of ^{enr}Ge (×5 yr), in GERDA cryostat
- Funded, under commissioning
- $B \sim 2 \cdot 10^{-4}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > 10^{27}$ **yr**

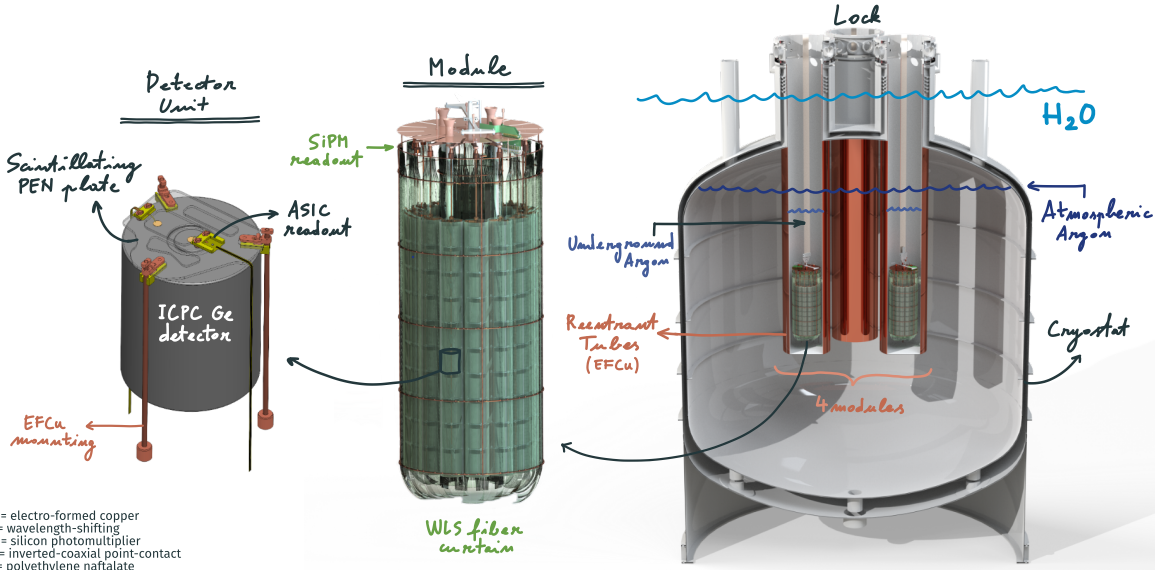
LEGEND-1000 arXiv 2107.11462 "pre-conceptual design report"

- **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

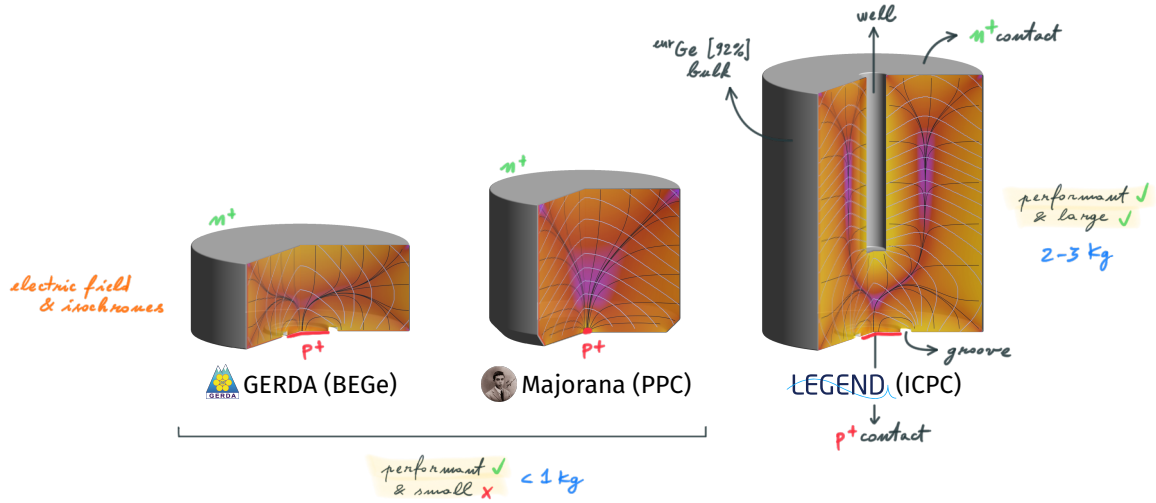


50 years of Double Beta decay with ^{76}Ge

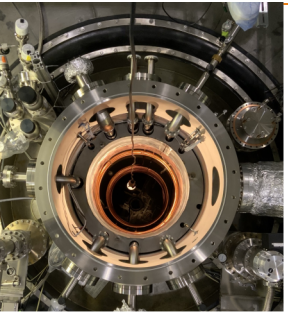


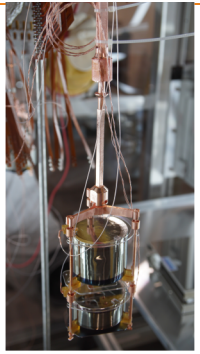


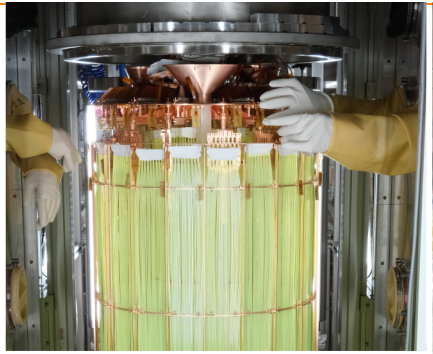
EFCu = electro-formed copper
WLS = wavelength-shifting
SiPM = silicon photomultiplier
ICPC = inverted-coaxial point-contact
PEN = polyethylene naftalate
ASIC = application-specific integrated circuit

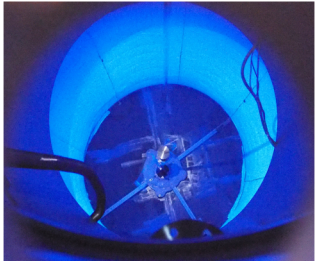

well
n^+ contact
^{enr}Ge [92%]
Bulk
n^+
n^+
performant ✓
& large ✓
2-3 kg
electric field
& isochrones
p^+
p^+
groove
GERDA (BEGe)
Majorana (PPC)
LEGEND (ICPC)
p^+ contact
performant ✓
& small ✗
< 1 kg

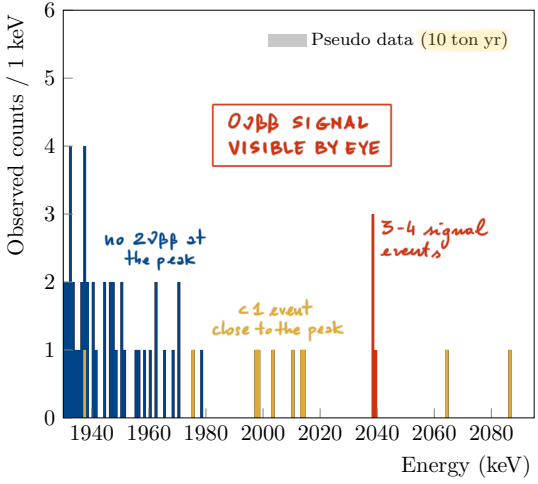
LEGEND-200 COMMISSIONING AT LNGS

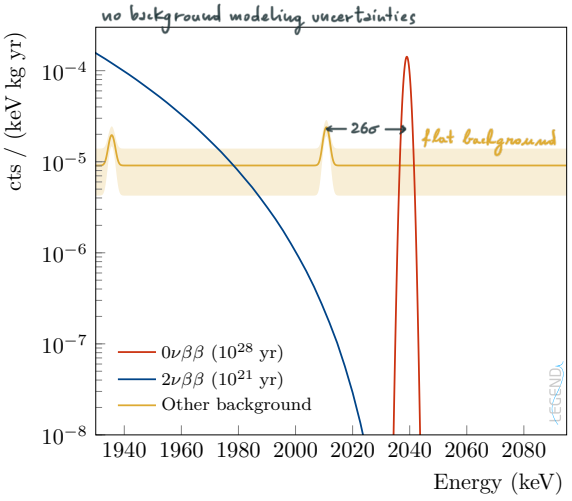









Pseudo data (10 ton yr)
0νββ SIGNAL VISIBLE BY EYE
no 2νββ at the peak
3-4 signal events
< 1 event close to the peak
Observed counts / 1 keV
Energy (keV)


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

GERDA:

- has searched for 0νββ in a *quasi-background-free* regime
- has led the worldwide effort by providing strong half-life limits
- has 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*