Final results of Gerda on the search for neutrinoless double-β decay

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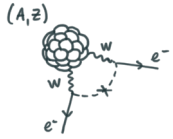
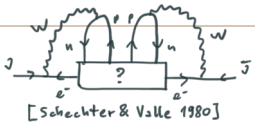
Why neutrinoless double-β decay?

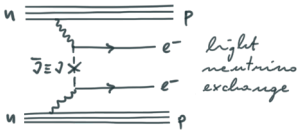
$$(A,Z) \longmapsto (A,Z+2) + 2e^- + 2\cancel{\nu_e}$$





Quite a peculiar and interesting process[1]

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



Light neutrino mass mechanism

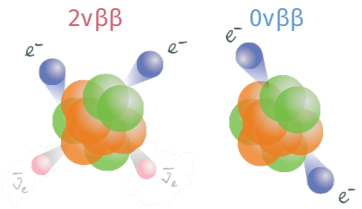
The (Majorana) neutrino that mediates 0νββ is the one that oscillates and the Standard Model is an effective theory *(seesaw mechanism)*

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

Majorana effective mass

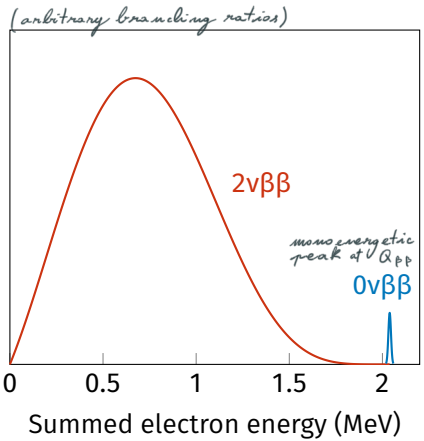
see also M. Lindner's talk

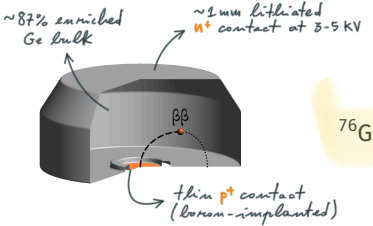
[1] 100+ papers per year with "0νββ" in the title [INSPIRE-HEP statistics]



All experiments measure the total energy of the two emitted electrons

⟼ *necessary and sufficient* for discovery



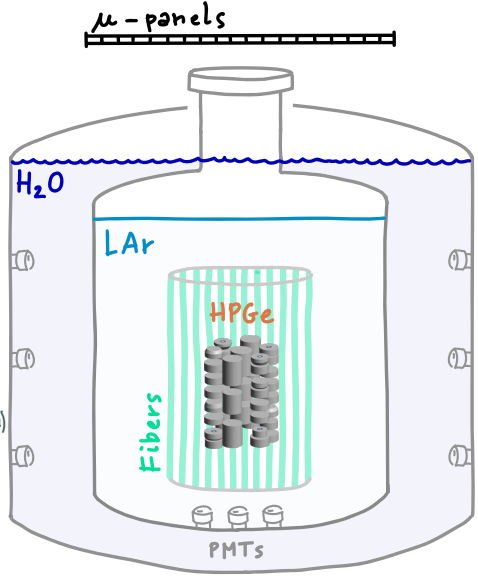


$^{76}Ge \xrightarrow{0\nu\beta\beta} {}^{76}Se + 2e^-$

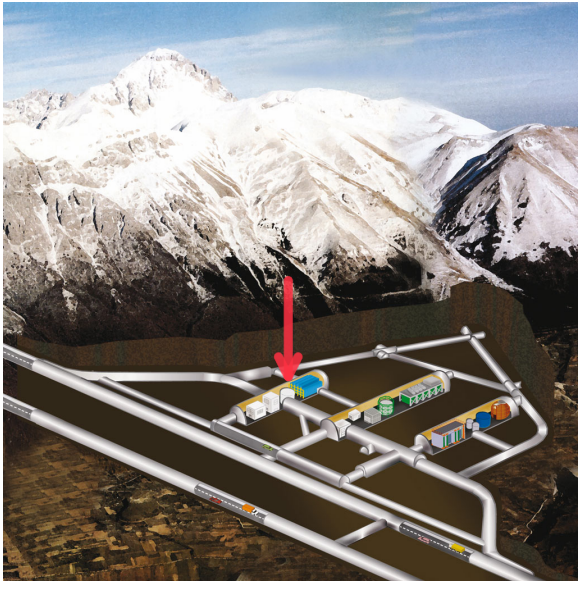
$Q_{\beta\beta} = 2039$ keV

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



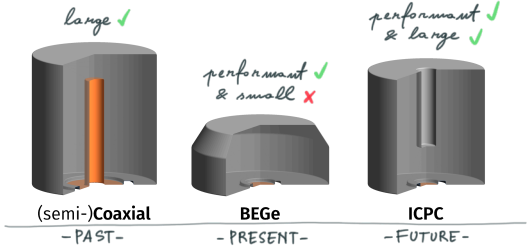
GERmanium Detector Array at LNGS — 3500 m.w.e. —



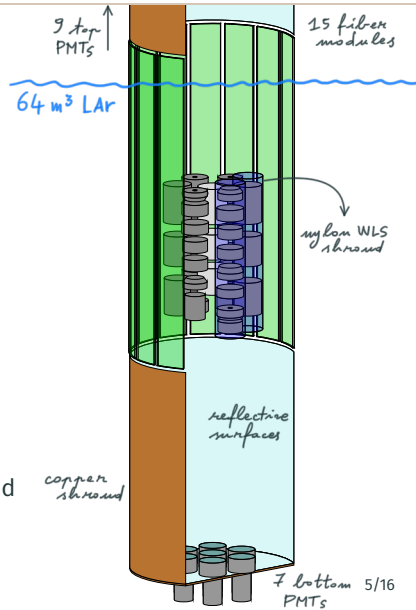
GERDA PHASE II SETUP

REF EUR. PHYS. J. C 78 (2018) 388

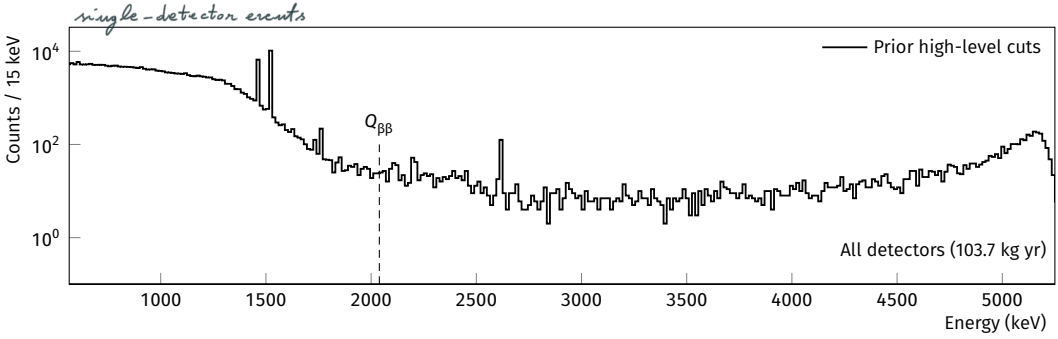
- 35.6 kg (later 44.2 kg) of HPGe REF EPJC 79 (2019) 11, 978 REF EPJC 81 (2021) 505



- 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



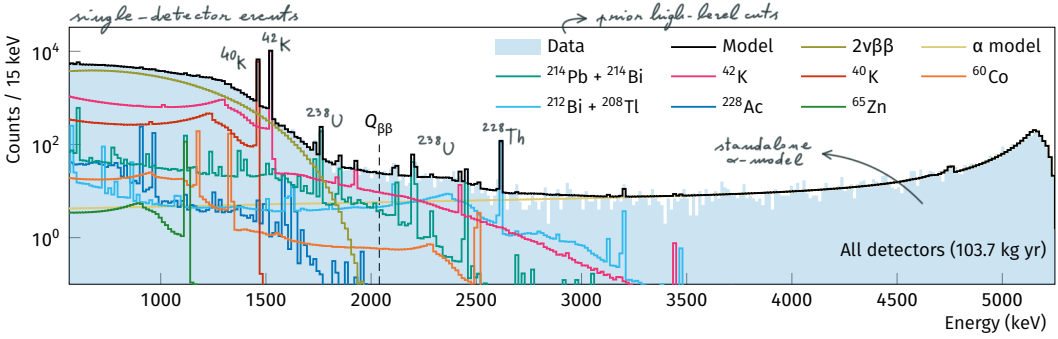
Phase II data energy spectrum before high-level cuts



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

PHASE II DATA MODELING

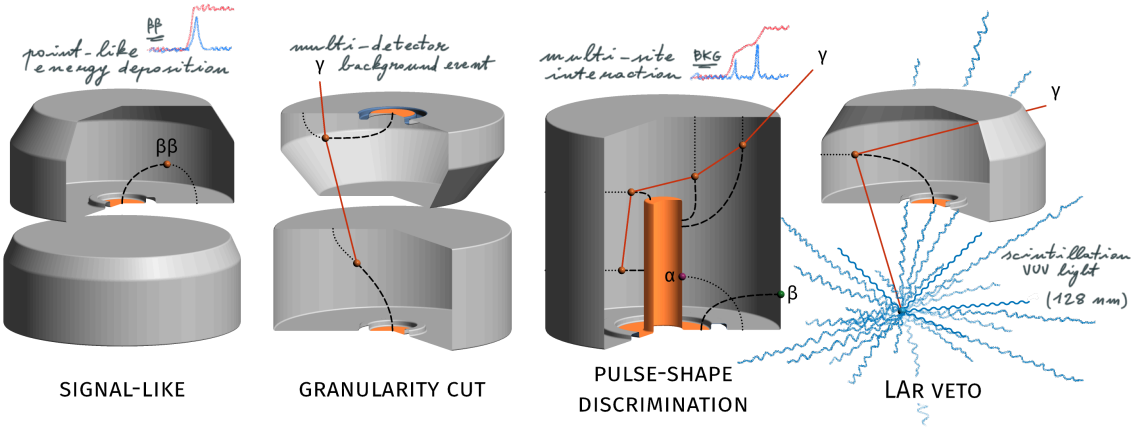
REF J. HIGH ENERG. PHYS. 03 (2020) 139



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

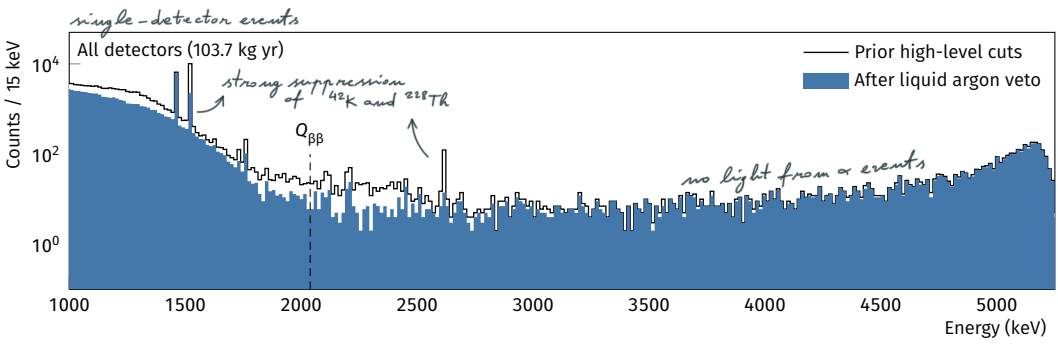
e.g. the 2νββ analysis

Signal and background discrimination techniques



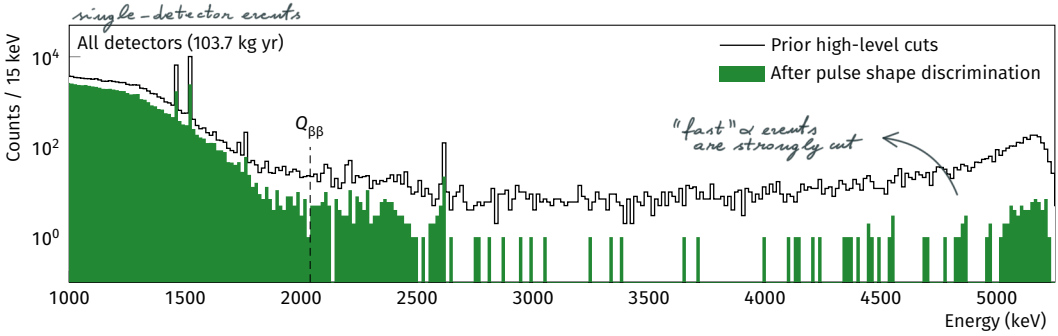
Combined $0\nu\beta\beta$ detection efficiency between 45–65% depending on the detector type

LAr veto cut



- Anti-coincidence between HPGe trigger and SiPM/PMT data *(≥ 0.3 p.e. in a 5 µs window)*
- 0νββ signal efficiency > 97% *(random coincidences)* ^{39}Ar, SiPM dark noise
- Publication on Monte Carlo modeling REF *in preparation*

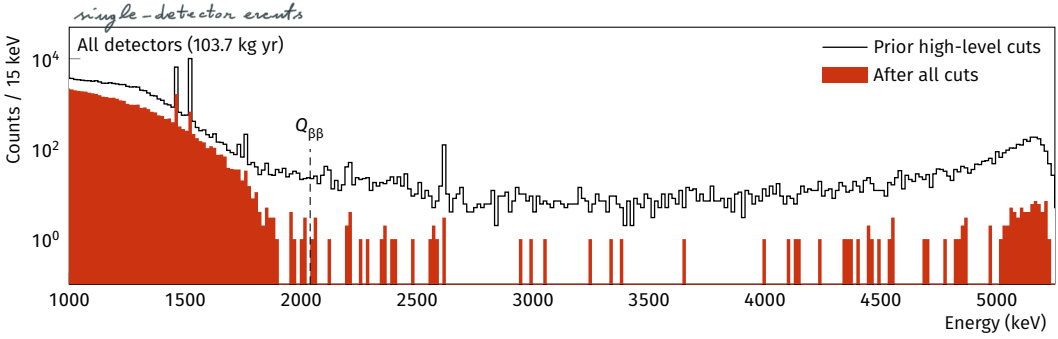
Pulse shape discrimination



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

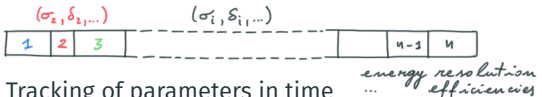
^{228}Th calibration data as tuning sample

The data after analysis cuts



~ 0.3 counts per FWHM in full exposure!

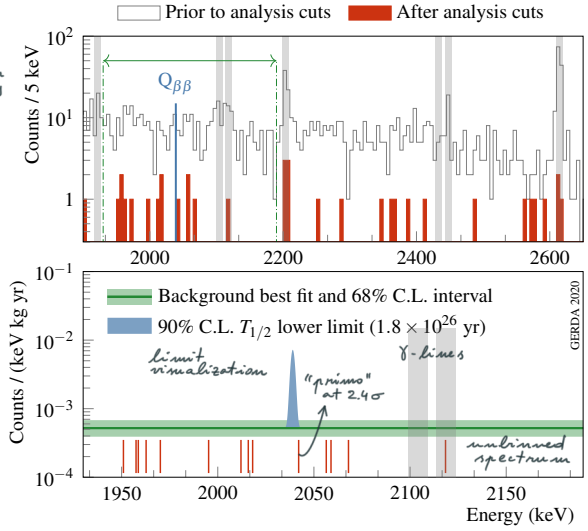
- Extremely low event rate at $Q_{\beta\beta}$ of ~ $5 \cdot 10^{-4}$ cts / (keV kg yr) ⟼ *quasi-background-free*
- Few events at $Q_{\beta\beta}$ ⟼ *"simple" background-model-free analysis*
- Nearly pure 2νββ spectrum



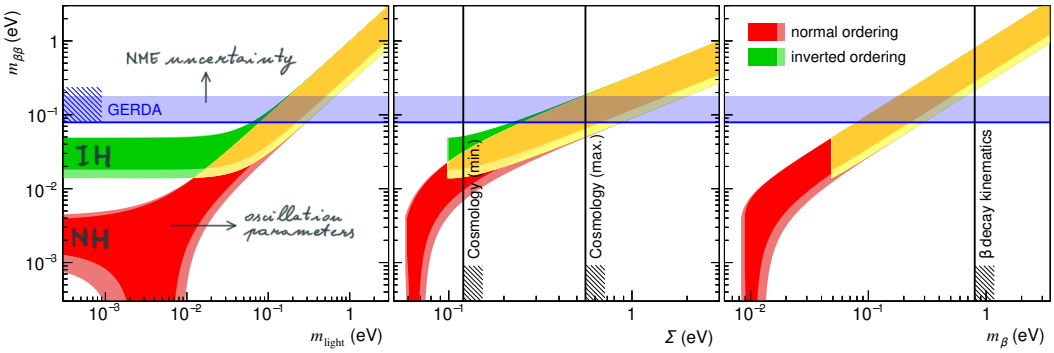
Tracking of parameters in time

⟼ *advanced statistical analysis*

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



Neutrino mass constraints

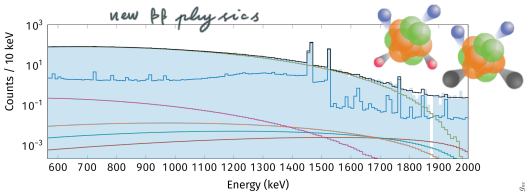


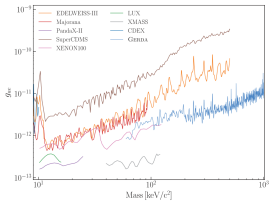
- Getting closer to the inverted ordering region, paving the way to ~~LEGEND~~
- Interplay with cosmology (Σ) and direct measurements (m_β)

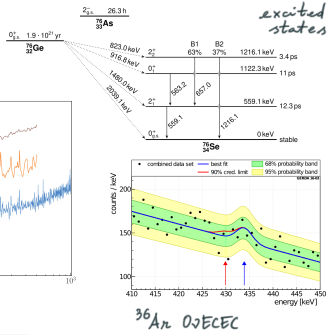
KATRIN: $m_\beta < 0.8$ eV

Planck + BAO: $\Sigma < 0.12 - 0.537$ eV

The GERDA scientific program: not just 0νββ!

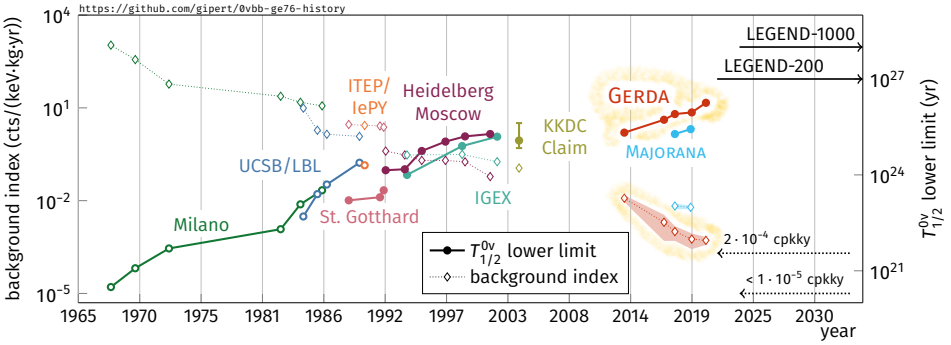






- 2νββ half-life measurement REF *Eur. Phys. J. C 75 (2015) 416* REF *new in preparation*
- New-physics searches (Majorons, Lorentz violation…) REF *Eur. Phys. J. C 75 (2015) 416* REF *new in preparation*
- ββ-decay excited states REF *J. Phys. G: Nucl. Part. Phys. 42 (2015) 115201* REF *new in preparation*
- Dark matter (WIMP) searches REF *Phys. Rev. Lett. 125, 252502 (2020)*
- ^{36}Ar double electron capture REF *Eur. Phys. J. C 76 (2016) 652* REF *new in preparation*
- Monte Carlo modeling of the LAr detector REF *in preparation*

50 YEARS OF DOUBLE-BETA DECAY WITH ^{76}Ge



- Impressive technological progress and scientific production
- A new exciting era begins now with LEGEND see S. Schönert's talk!

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

LEGEND-200

- 200 kg of ^{enr}Ge (×5 yr), in GERDA cryostat
- Funded, under construction
- $2 \cdot 10^{-4}$ cts / (keV kg yr) $\longmapsto$ > 10^{27} yr sensitivity

LEGEND-1000 arXiv 2107.11462

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

LEGEND @ PANIC
W. Pettus (overview), CJ Barton (cosmogenics),
M. Harańczyk (LAr purification)