DBD23

International workshop on "Double Beta Decay and Underground Science"

Latest results of the GERDA experiment

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on behalf of the GERDA Collaboration

Outline

- Neutrinoless double beta decay
- Design and goals of GERDA
- Background reduction strategy
- GERDA final result
- Summary

Neutrinoless Double Beta Decay

If 0νββ observed:

- Neutrino is a Majorana particle (its own antiparticle)
- Lepton number is not conserved
- Dealing with physics beyond the Standard Model

May allow to determine:

- Absolute neutrino mass scale
- Neutrino mass hierarchy
- Majorana CP phases

Significant contribution to Particle Physics, Astrophysics and Cosmology

Background Issue

No background

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a \cdot M \cdot T$$

Background

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

$$\frac{1}{T_{1/2}} = G(Q,Z) \cdot |M_{nuc}|^2 \cdot < m_{ee} >^2$$

$$< \boldsymbol{m_{ee}} > \sim \frac{\mathbf{1}}{\sqrt{\boldsymbol{T_{1/2}}}} \sim \sqrt[4]{\frac{\boldsymbol{B \cdot \Delta E}}{\boldsymbol{M \cdot T}}}$$

$$(\boldsymbol{M \cdot T})\uparrow \times \mathbf{100} \rightarrow \boldsymbol{T_{1/2}} \uparrow \mathbf{10} \rightarrow < \boldsymbol{m_{ee}} > \downarrow \times \sim \mathbf{3}$$

GERDA

- 0νββ decay
- GERDA design
- Bkg reduction
- Latest results
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- GERDA (GERmanium Detector Array) has been designed to investigate neutrinoless double beta decay of ^{76}Ge ($Q_{\beta\beta}$ = 2039 keV)
  - Ge mono-crystals are very pure
  - Ge detectors have excellent energy resolution
  - Detector = source ($\varepsilon \approx 1$)
  - Enrichment required (7.4 % → 86 – 88 %)
  - **Bare HP ^{enr}Ge detectors immersed in LAr**
- Background (index) around $Q_{\beta\beta}$: $10^{-2} - 10^{-3}$ cts/(keV×kg×yr); 10 – 100 times lower compared to previous experiments (HdM/IGEX)

The GERDA Collaboration

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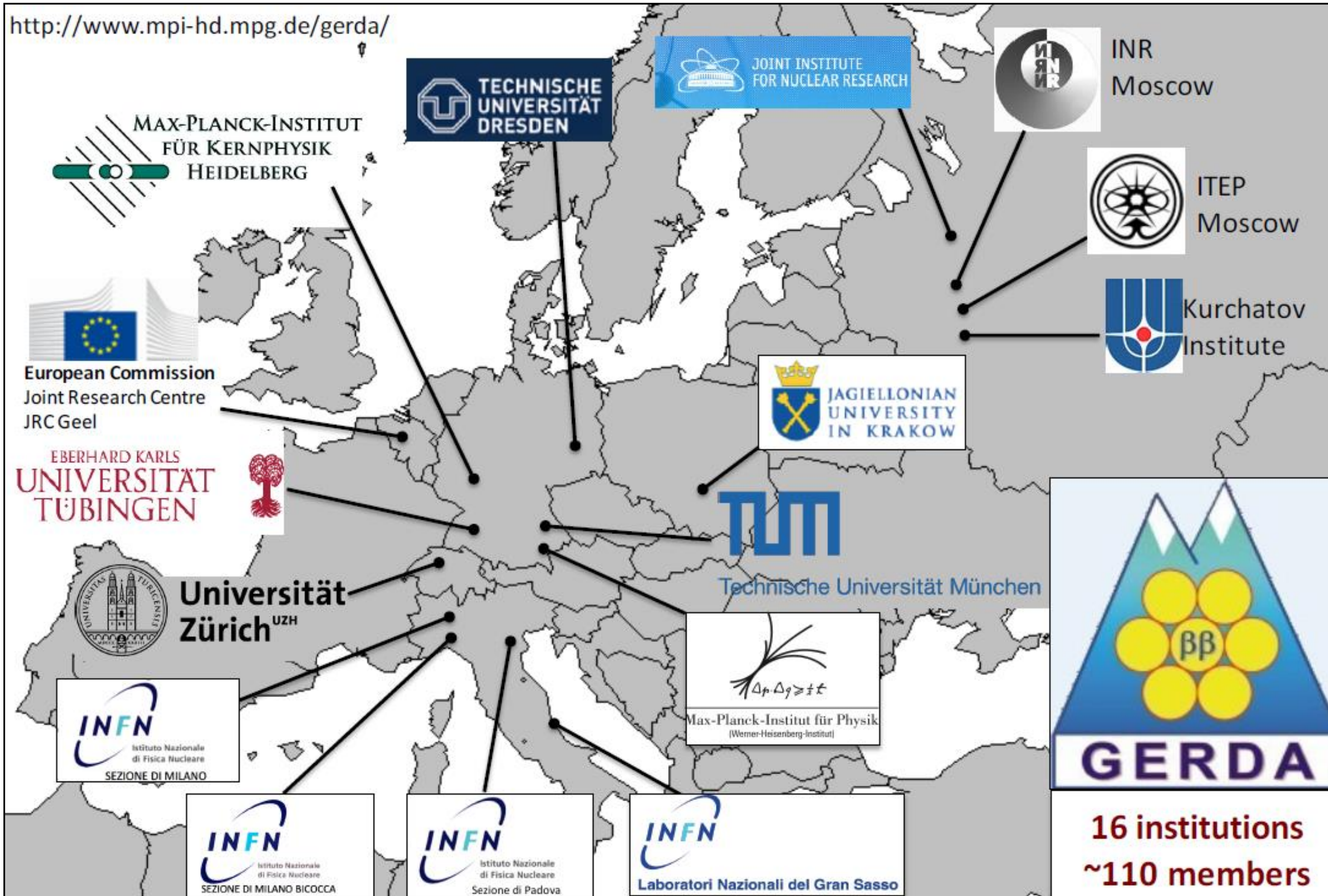
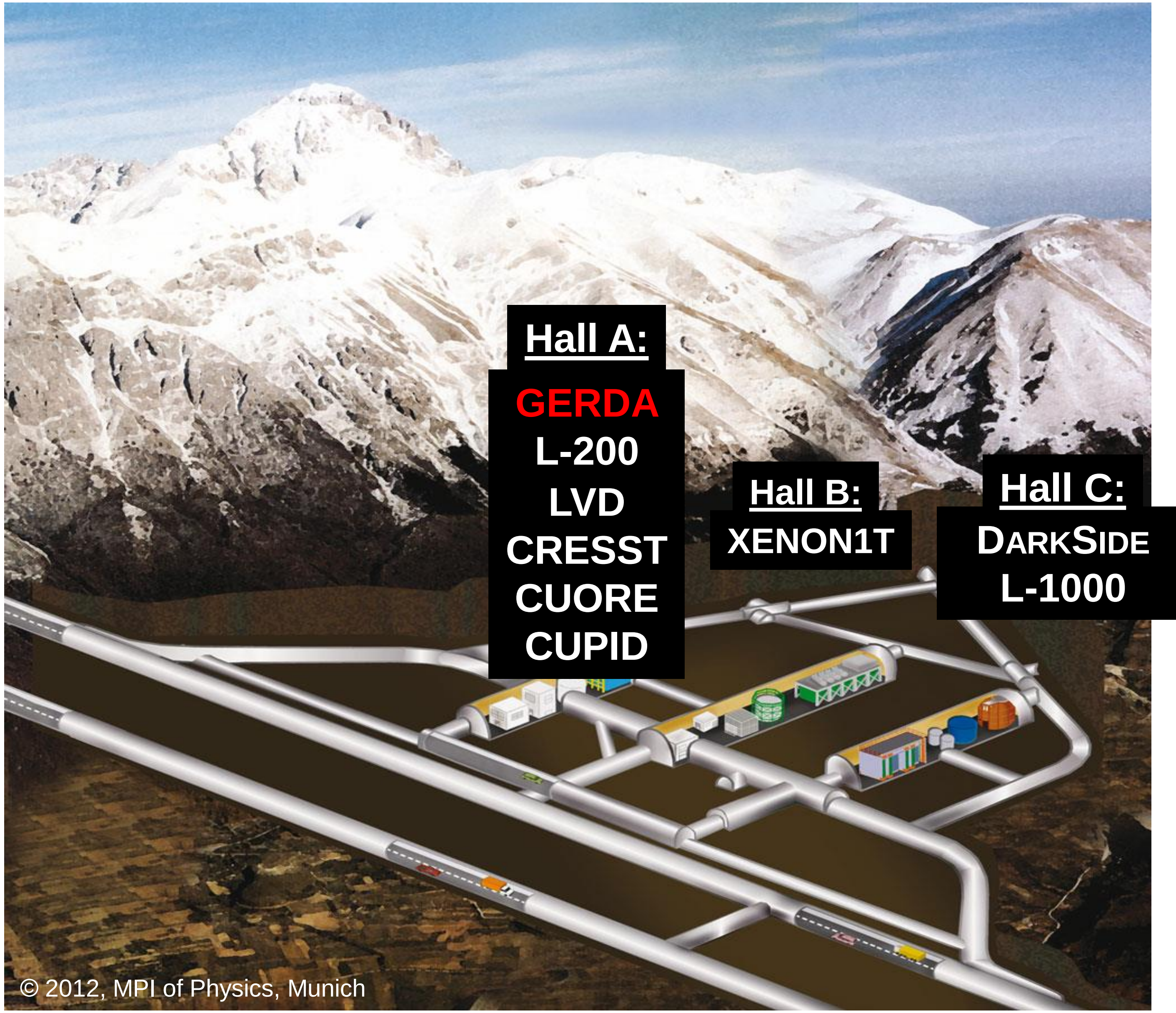
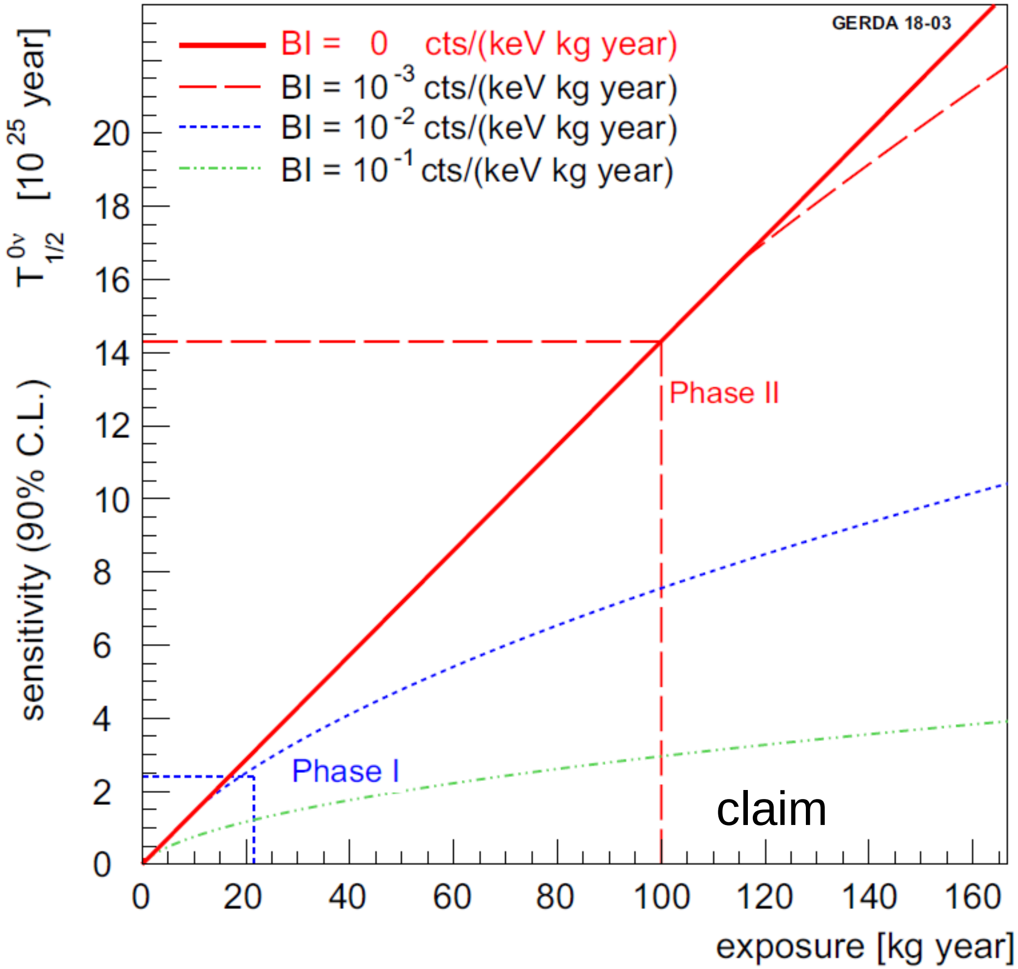


GERDA at LNGS



GERDA Sensitivity



LEGEND:

^{76}Ge mass ~1 t

BI ≈ 10^{-5} cts / (keV×kg×yr)

Sensitivity: ~1×10^{28} yr

$\langle m_{ee}\rangle$ ~ 10 meV

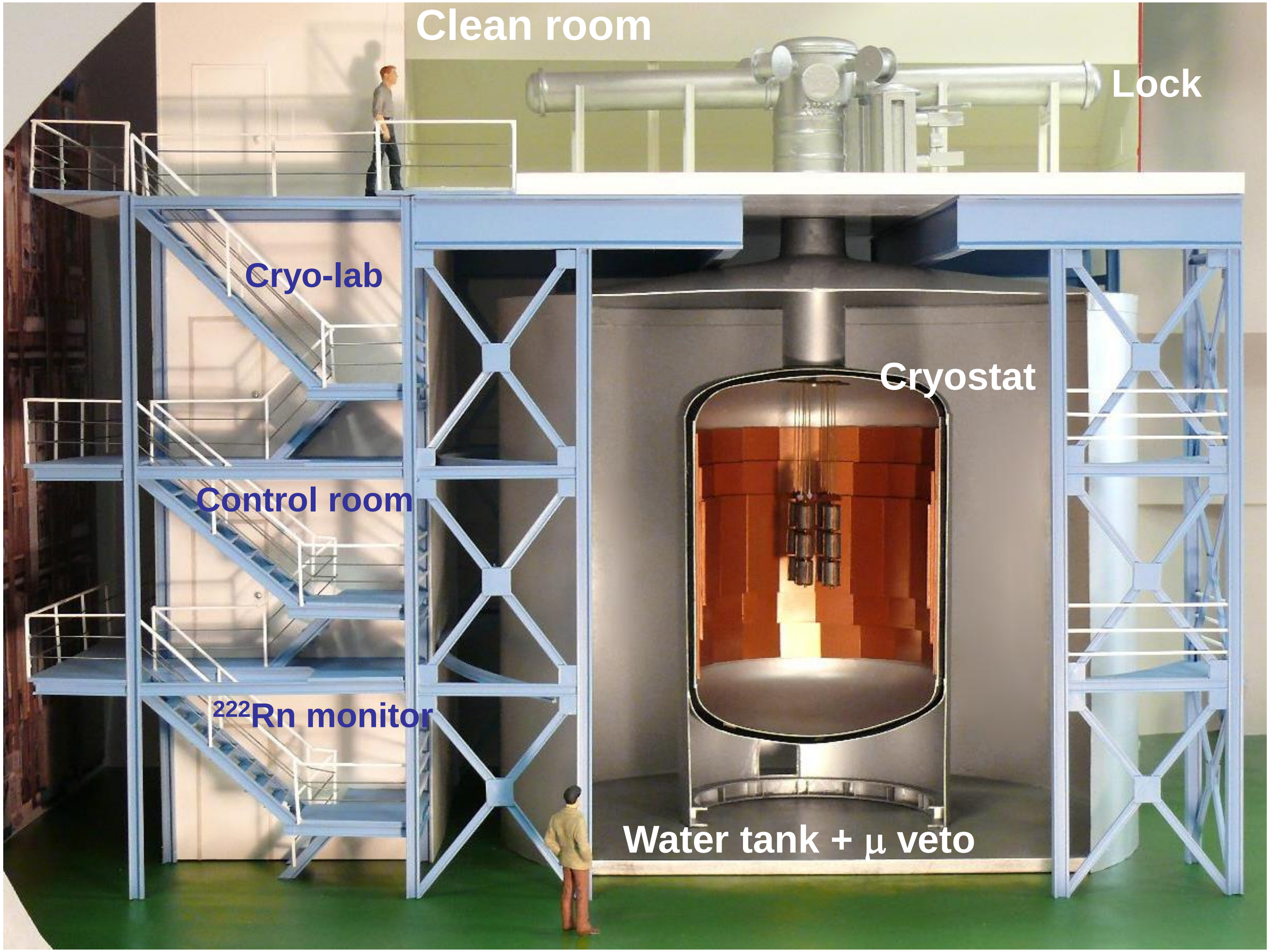
Phase II:

Add new enr. BEGe (IC) det.
(36 (44) kg of ^{enr}Ge in total)
BI ≤ 10^{-3} cts / (keV×kg×yr)
Sensitivity after 100 kg×yr

Phase I:

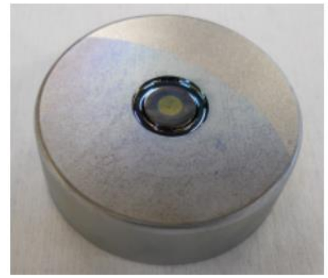
Use refurbished
HdM & IGEX (18 kg)
BI ≈ 10^{-2} cts / (keV×kg×yr)
Sensitivity after 20 kg×yr

GERDA Design

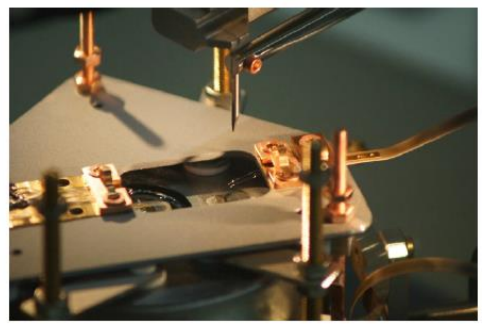


GERDA Phase II Array

New low-mass detector holders (Si, Cu, PTFE)



New thick-window BEGe detectors



New signal and HV contacting by wire bonding flat ribbon cables

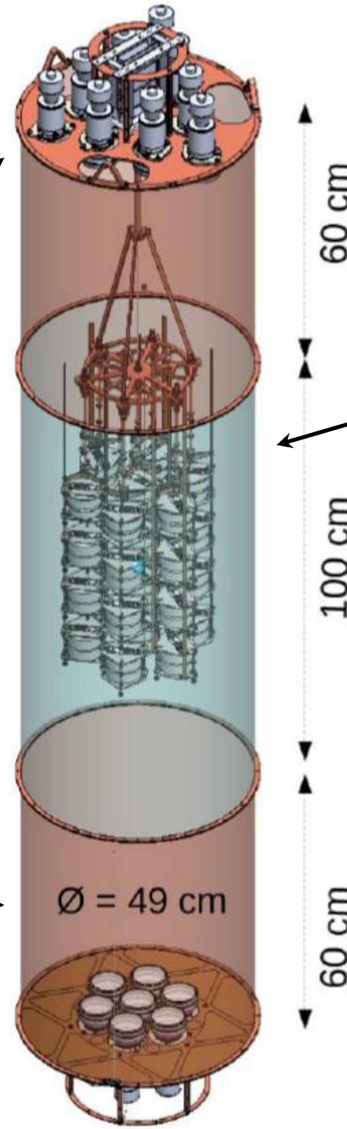
New TPB coated nylon mini-shrouds to reduce attraction of ^{42}K ions (from decays of ^{42}Ar) to n^+ surface

30 enriched BEGe (20.0 kg), 7 enriched coax (15.8 kg), 3 natural coax (7.6 kg) replaced later by 5 enriched IC detectors

TBP = tetraphenyl butadiene

Hybrid LAr veto: PMTs + Fibers

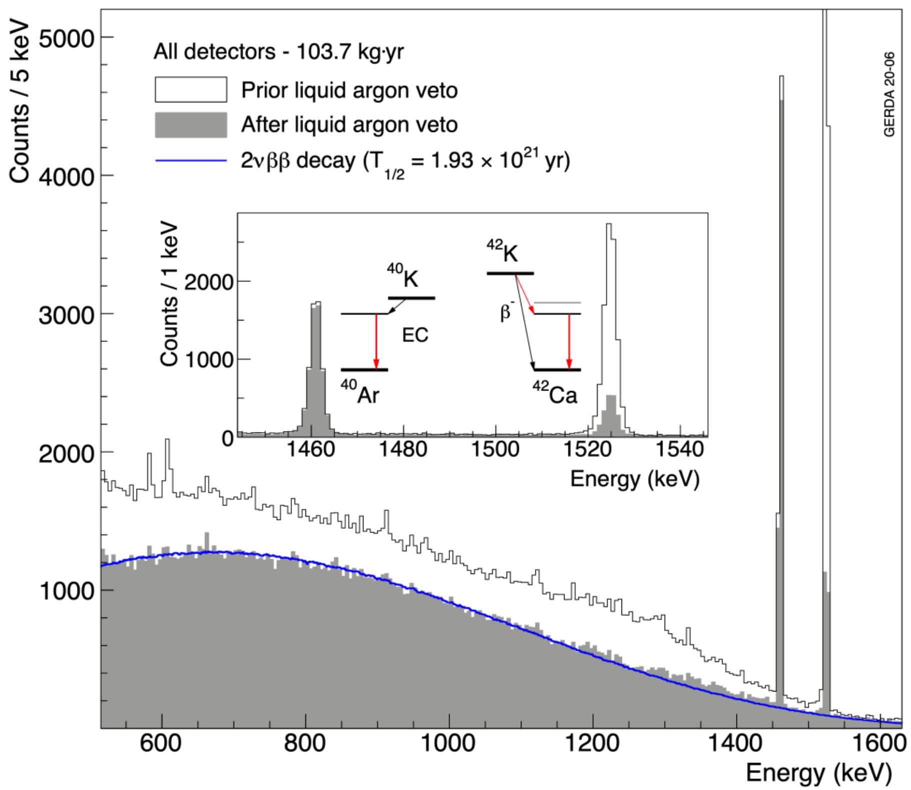
16 3” PMTs
Cylinder with WLS
(TETRATEX foil)



810 wavelength
shifting fibers
coupled to 90 SiPMs

LAr Veto

- Channel-wise (PMT/SiPM) anti-coincidence condition
- Thresholds at ~ 0.5 P.E.
- Acceptance determined from random triggers: (97.9 ± 0.1) %
- $^{40}K/^{42}K$ Compton continua completely suppressed
- γ-rays survival fractions: ^{40}K (EC) = ~100 %, ^{42}K (β^-) ~20 %
- Almost pure 2νββ spectrum after LAr veto cut (600 – 1300 keV)
- **Background suppression in ROI: × 6**



PSD for BEGe/IC Detectors

- 0νββ decay
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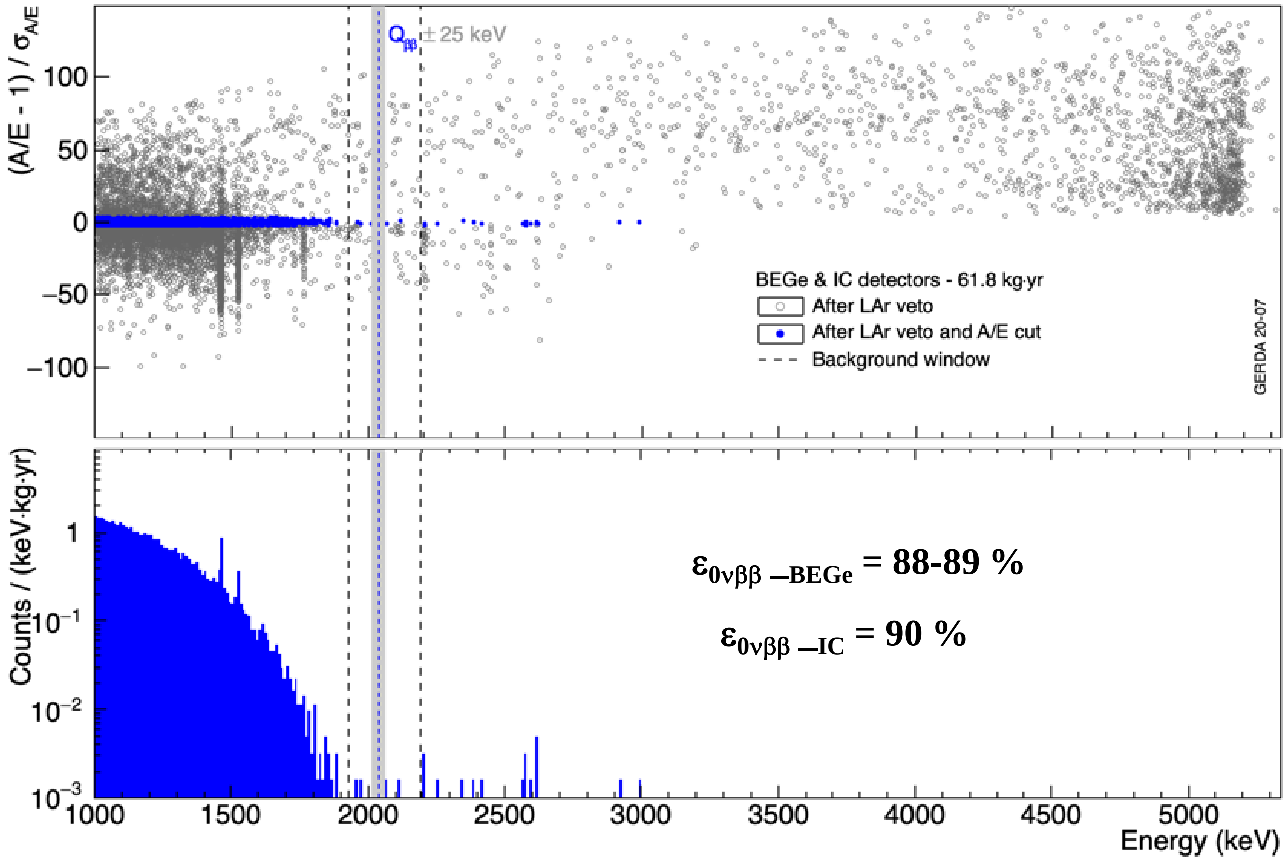
- Discrimination on a single A/E parameter (A – current amplitude, E – energy)
- Cut values defined from calibrations assuming 90 % DEP acceptance
- high A/E: fast events on p+ electrode (e.g. αs from ^{210}Po)
- low A/E: slow events on n+ electrode, multiple scattering



Background Window (BW): [1930,2190] keV,
excl. ±5 keV around ^{208}Tl (SEP), ^{214}Bi (FEP) and $Q_{\beta\beta}$ ± 25 keV

PSD for Coax Detectors

- 0νββ decay
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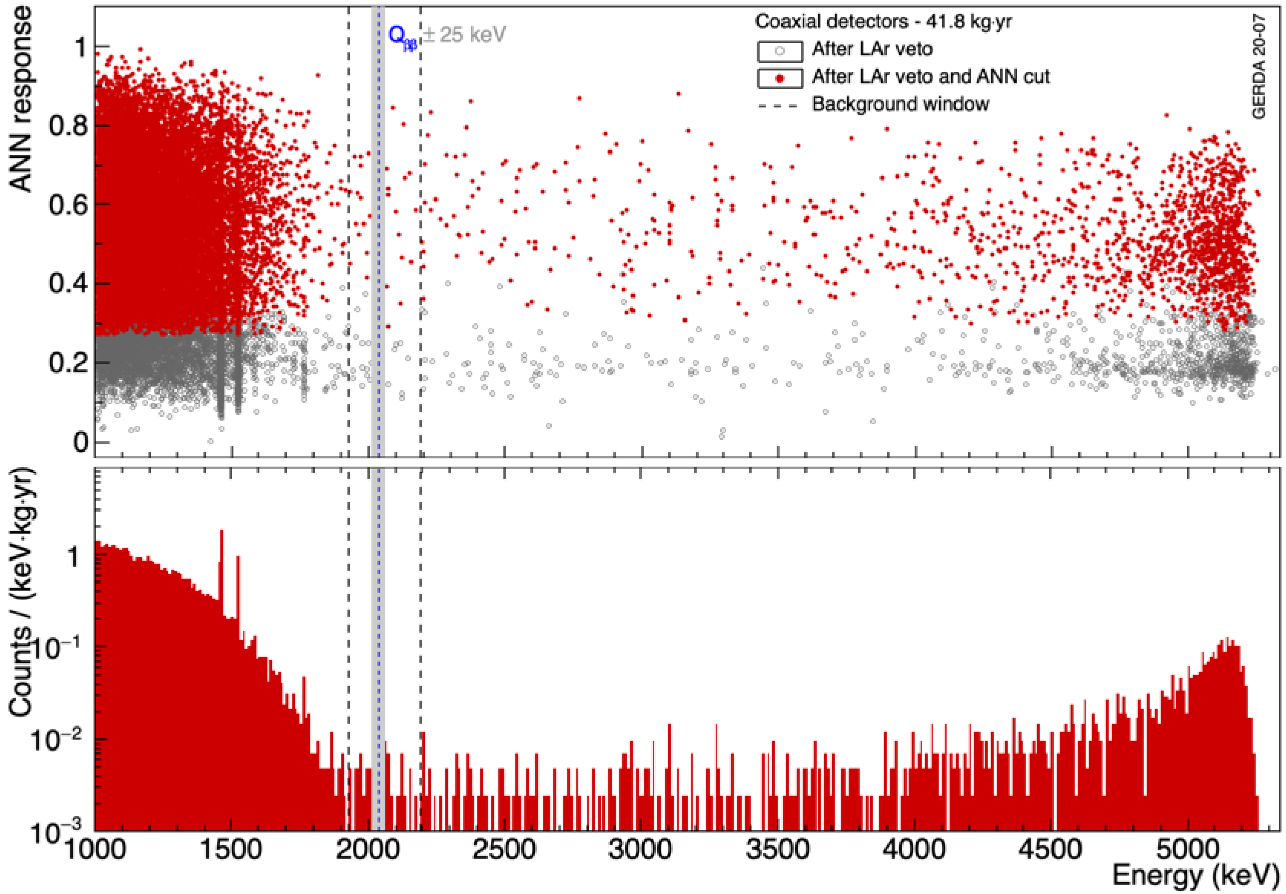
- MSE rejected with ANN (EPJC 73 (2013) 2583, EPJC 82 (2022) 284)
- Alphas (fast surface events) rejected with ANN- α / Rise Time (RT) cut
- ANN training on calibration data DEP and FEP as proxies for SSE and MSE, respectively.
- RT optimized on the 2νββ (1 – 1.3 MeV) and α sample (E > 3.5 MeV)



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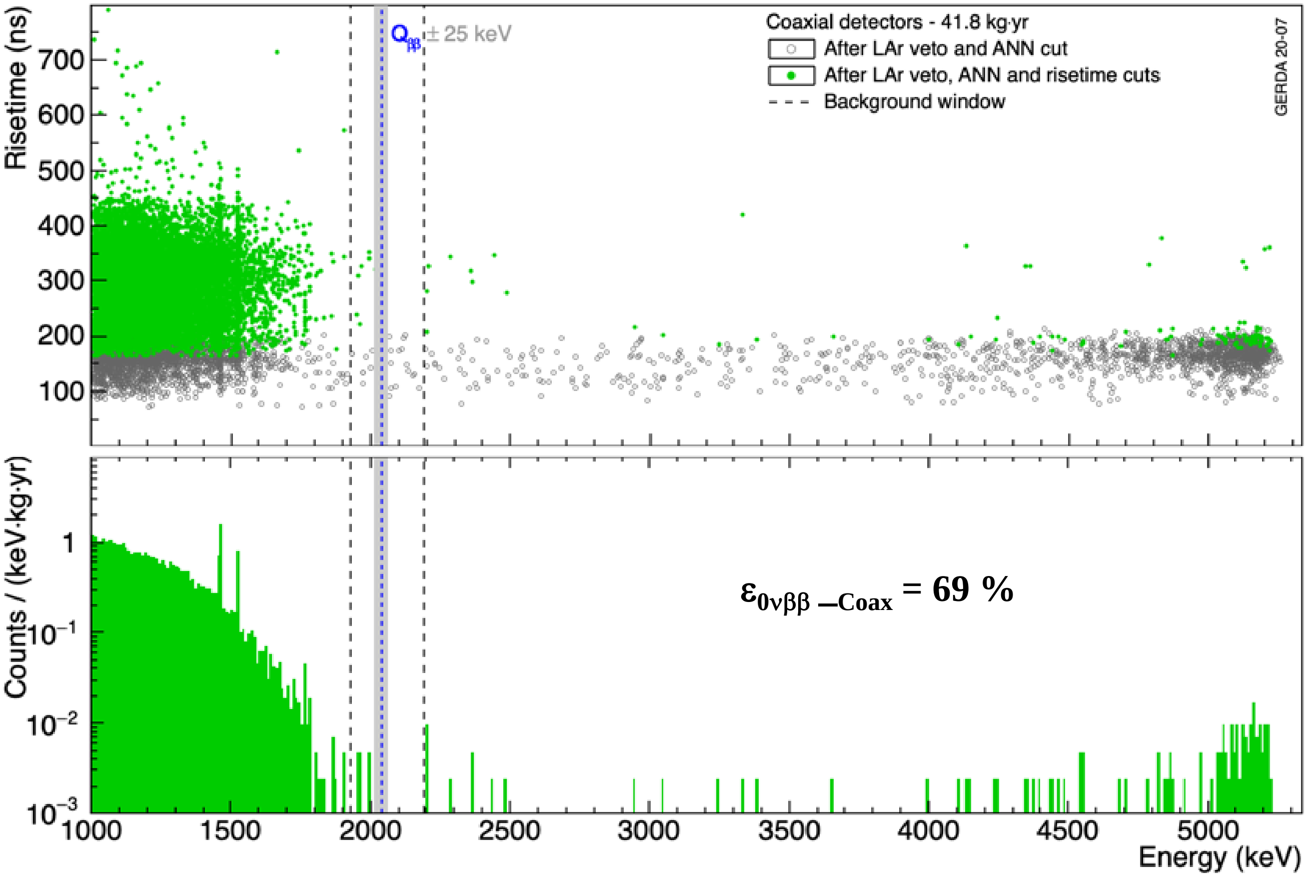
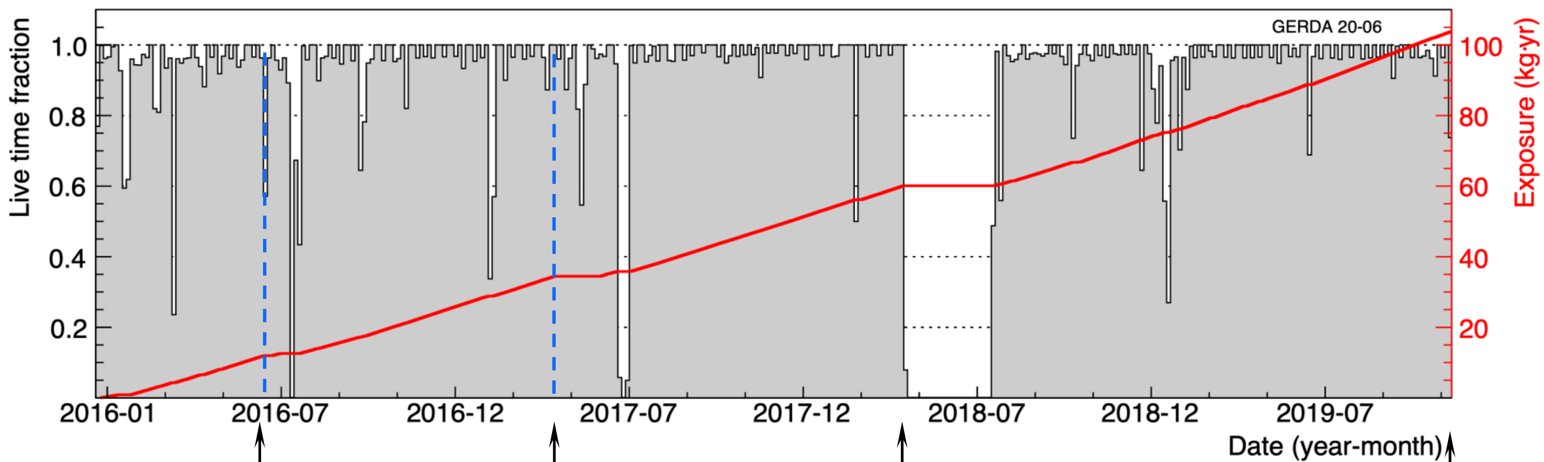


Accumulation of Data

Phase I

- 09.11.11 – 09.05.13: 21.6 kg×yr (*PRL 111 (2013) 122503*)
- Additional Phase I data before upgrade: 1.9 kg×yr

Phase II



Phase II: 10.8 kg·yr
Nature 544 (2017) 47

Phase II: 23.2 kg·yr
PRL 120 (2018) 13

Phase II: 58.9 kg·yr
Science 365 (2019) 6460

Phase II: 103.7 kg·yr
PRL 125 (2020) 252502

Pre-upgrade

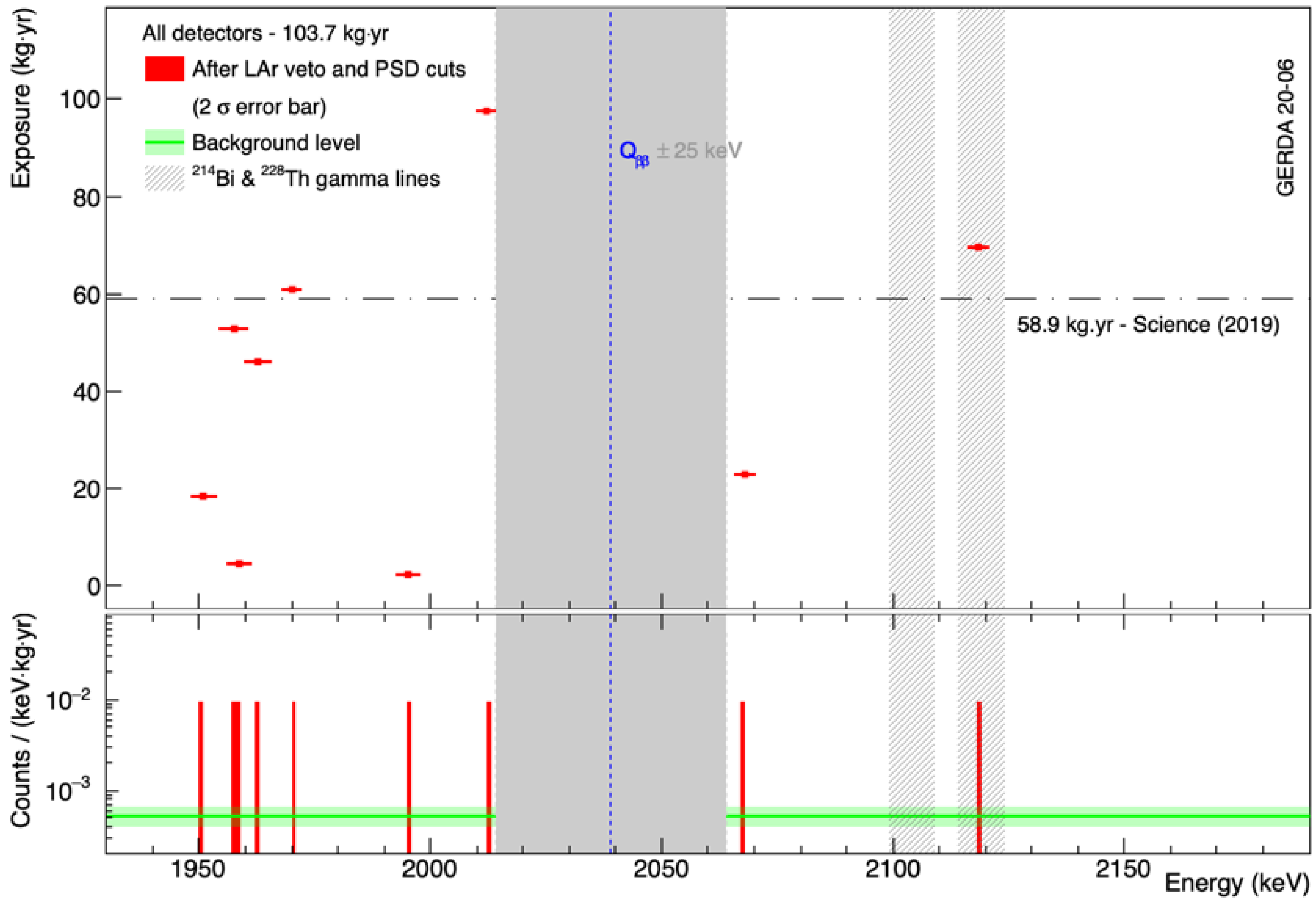
58.9 kg×yr
35.6 kg of ^{enr}Ge

Post-upgrade

44.8 kg×yr
44.2 kg of ^{enr}Ge

Background Index in BW

BW: [1930,2190] keV, excl. ±5 keV around ^{208}Tl (SEP), ^{214}Bi (FEP) and $Q_{\beta\beta} \pm 25$ keV



Before cuts: BI = 143×10^{-4} cts/(keV×kg×yr)
After cuts: BI = 5.2×10^{-4} cts/(keV×kg×yr)

~30 reduction

Unblinded ROI

0νββ decay

GERDA design

Bkg reduction

Latest results

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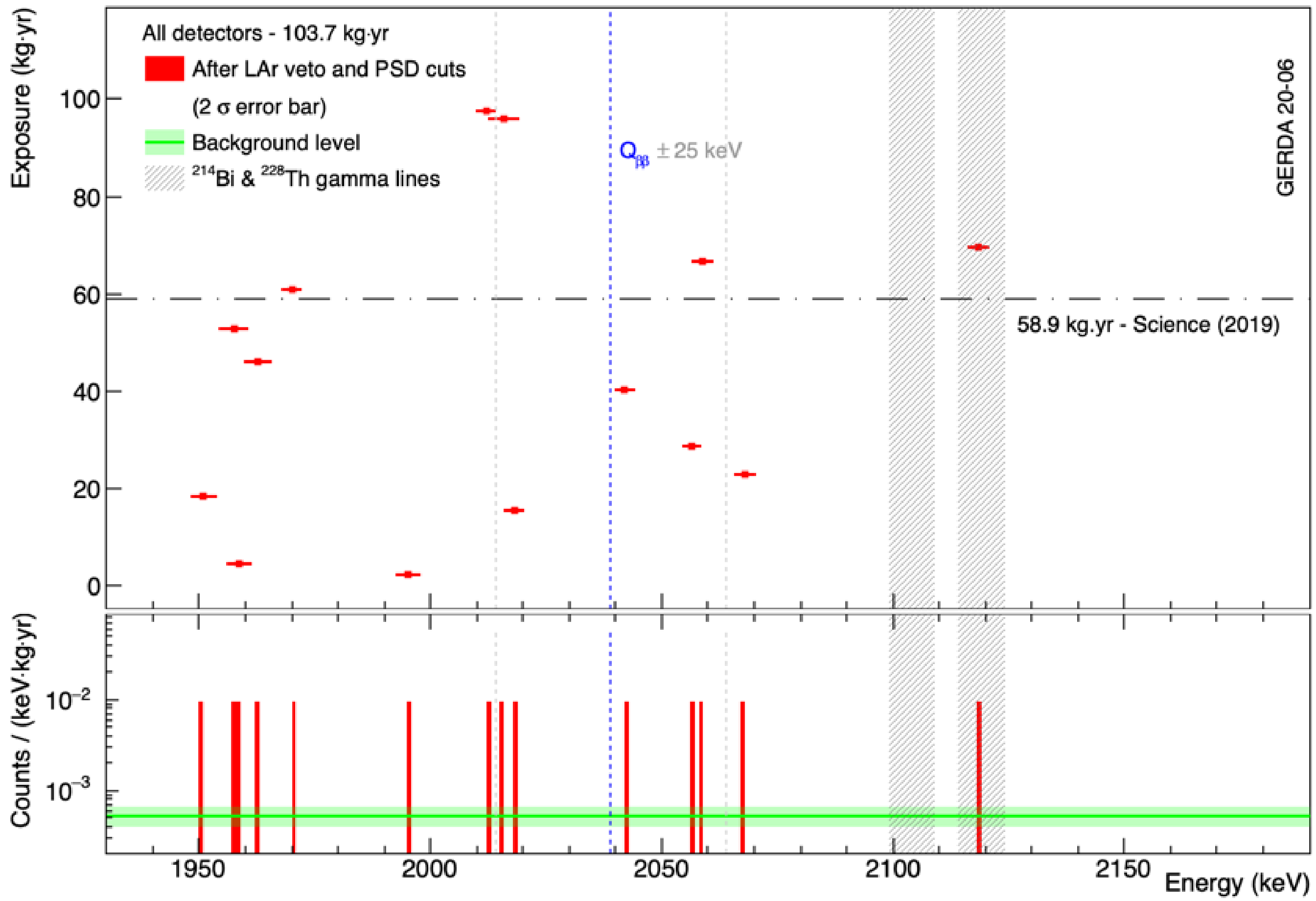
BW: [1930,2190] keV, excl. ±5 keV around ^{208}Tl (SEP), ^{214}Bi (FEP) and $Q_{\beta\beta} \pm 25$ keV



5 events in $Q_{\beta\beta} \pm 25$ keV but → **no counts in ROI: $Q_{\beta\beta} \pm 2\sigma$**

Statistical Analysis

0νββ decay

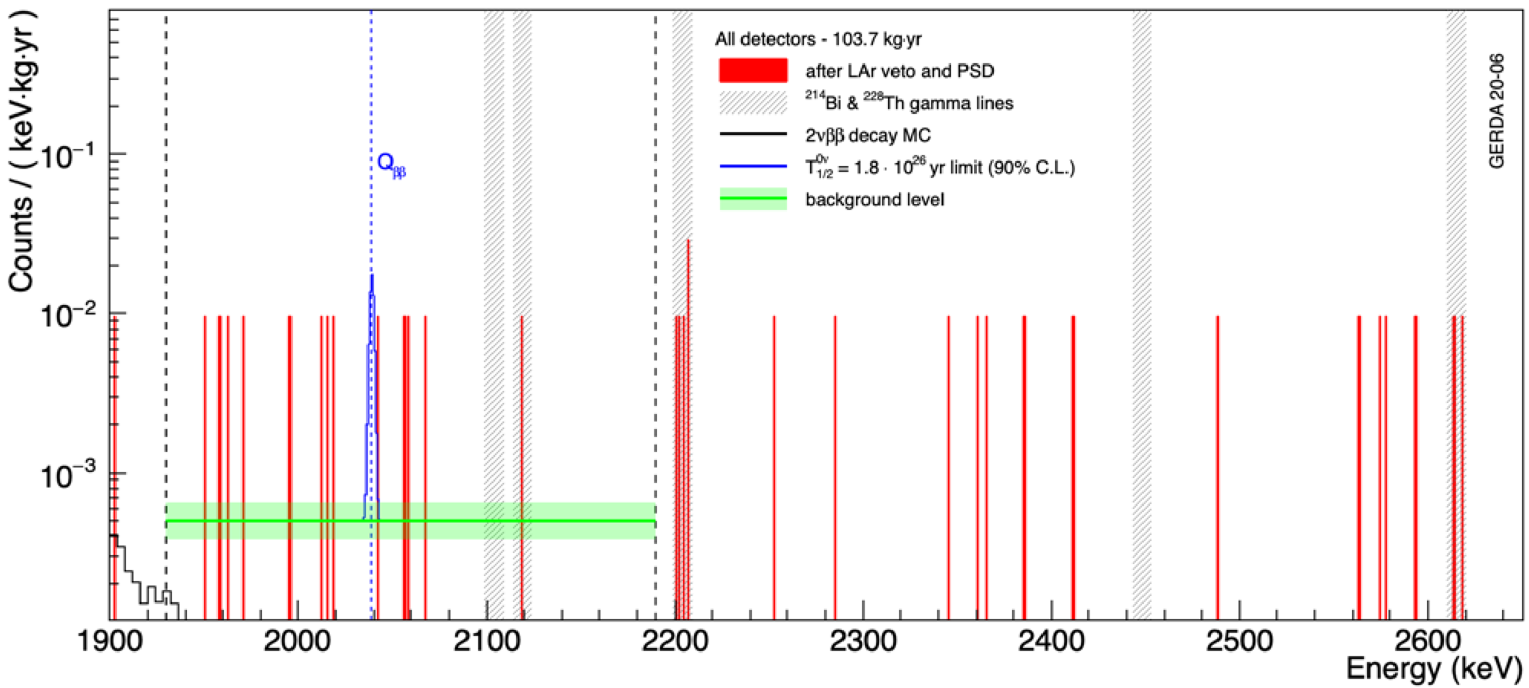
GERDA design

Bkg reduction

Latest results

Summary

Statistical analysis based on detectors-wise partitioning over stable periods



<u>Full data set (127.2 kg×yr):</u>

– BI: $5.2^{+1.6}_{-1.3} \times 10^{-4}$ cts/(keV×kg×yr)

No events in ROI ($Q_{\beta\beta}\pm2\sigma$); 0.3 events expected → **bcg free experiment**

– best fit $N_{0\nu} = 0$

– **$T_{1/2}$ (0νββ) > 1.8×10^{26} yr (90% C.L.)**

– **$m_{\beta\beta} \leq$ (79 – 180) meV**

– median sensitivity for limit setting: $T_{1/2}$ (0νββ) = 1.8×10^{26} yr at 90% C.L.

Beyond 0νββ decay

GERDA

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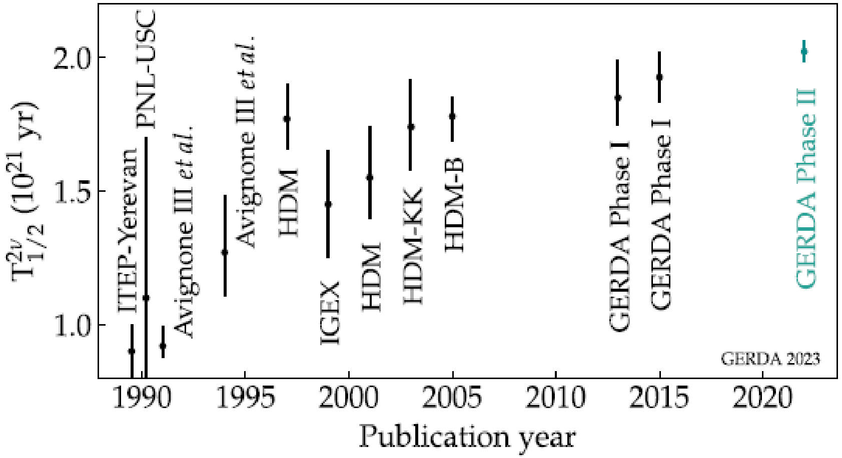
- 2νββ decay half-life of ^{76}Ge (PRL 131 (2023) 142501)



$$T_{1/2} = (2.022 \pm 0.018_{stat} \pm 0.038_{sys})\times 10^{21}\ \text{yr}$$

(most precise measurement)

- Searches for tri-nucleon decays (EPJC 83 (2023) 778)
- Searches for exotic double beta decays: emission of Majorons, light exotic fermions and Lorentz violation (JCAP 12 (2022) 012)
- Searches for bosonic dark matter particles (PRL 125 (2020) 011801, PRL 129 (2022) 089901)

Summary

- **GERDA Phase I design goals reached:**
  - No $0\nu\beta\beta$ signal observed at $Q_{\beta\beta}$; best fit: $N^{0\nu} = 0$
  - Background index: ~10^{-2} cts / (keV×kg×yr)
  - Exposure 21.6 kg×yr
  - $T_{1/2}$ ($0\nu\beta\beta$) > 2.1×10^{25} yr (90% C.L.)
- **GERDA Phase II achievements:**
  - No $0\nu\beta\beta$ signal observed at $Q_{\beta\beta}$; best fit: $N^{0\nu} = 0$
  - **Background index: 5.2×10^{-4} cts / (keV×kg×yr)** (10^{-3} in the proposal)
  - Exposure 103.9 kg×yr (127.2 kg×yr in total)
  - **$T_{1/2}$ ($0\nu\beta\beta$) > 1.8×10^{26} yr (90% C.L.)**
  - $m_{\beta\beta} \leq$ (79 – 180) meV
- **GERDA: first background-free $0\nu\beta\beta$ experiment**
- **LEGEND** – next generation experiment for $T_{1/2}^{0\nu}$ ~ 10^{28} yr (see talk of A-K. Schuetz)
- LEGEND-200 at LNGS (GERDA technology): presently 142 kg of ^{enr}Ge, 101 detectors, taking physics data; upgrade to 180-190 kg in 2024
- LEGEND-1000 (LNGS): supported by DOE-NP to proceed to CD-1, Pre-Conceptual Design Report available: arXiv: 2017.11462