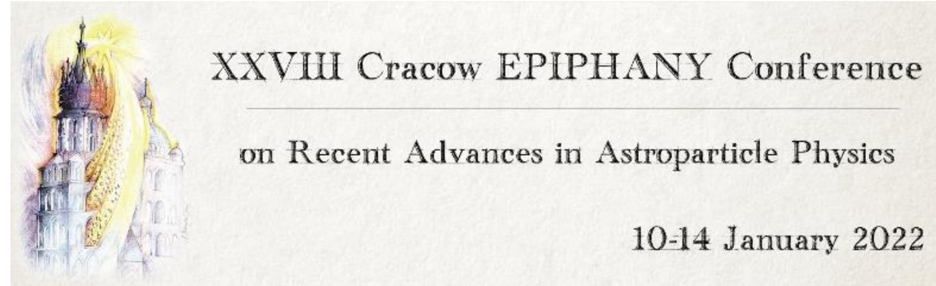


Search for Neutrinoless Double Beta Decay of ^{76}Ge with GERDA – latest results

Grzegorz Zuzel
on behalf of the GERDA Collaboration

Outline

- Double beta decay
- Design and goals of GERDA
- Background reduction strategy
- GERDA latest (final) result
- Summary

ββ decay

GERDA design

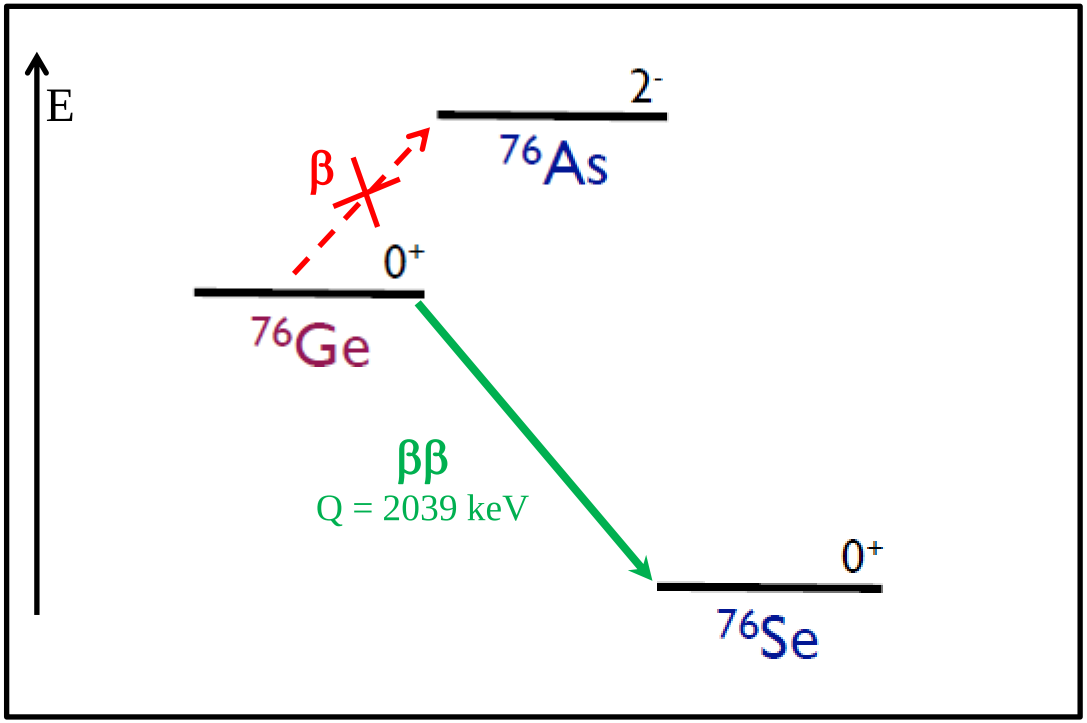
Bkg reduction

Latest results

Summary

Double Beta Decay

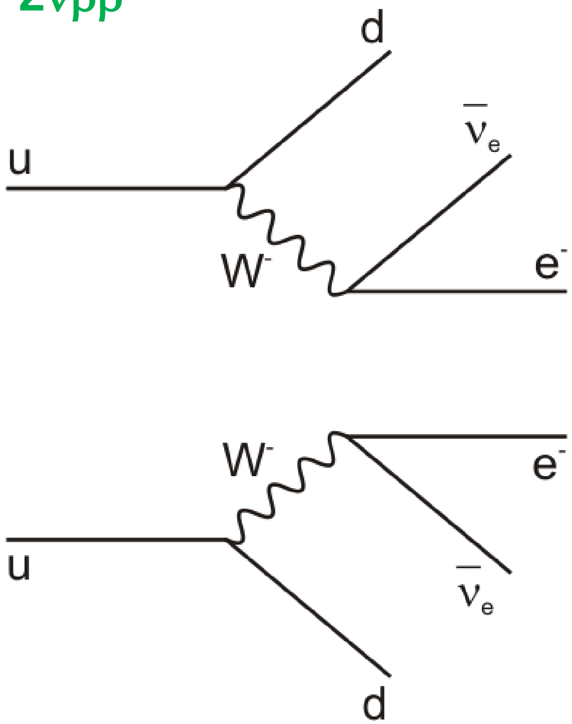
In a number of even-even nuclei, β decay due to energy/angular momentum balance is forbidden, while double beta decay from a nucleus (A,Z) to (A, Z+2) is energetically allowed.



^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

Double Beta Decay Modes

2νββ

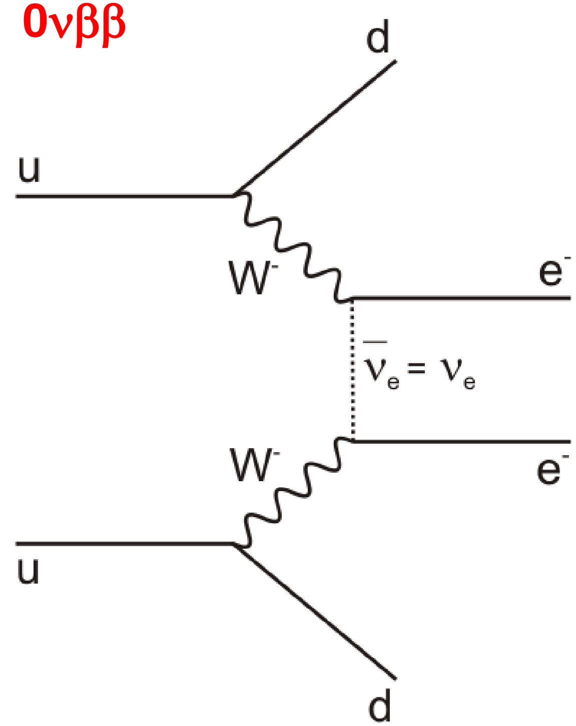


$(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

$\mathbf{\Delta L = 0}$

$\mathbf{T_{1/2} \sim 10^{18} - 10^{24}}$ **yr**

0νββ



$(A,Z) \rightarrow (A, Z+2) + 2e^-$

$\mathbf{\Delta L = 2}$

$\mathbf{T_{1/2}^{exp} > 10^{26}}$ **yr**

Neutrinoless Double Beta Decay

ββ decay
GERDA design
Bkg reduction
Latest results
Summary

If $0\nu\beta\beta$ 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

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

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

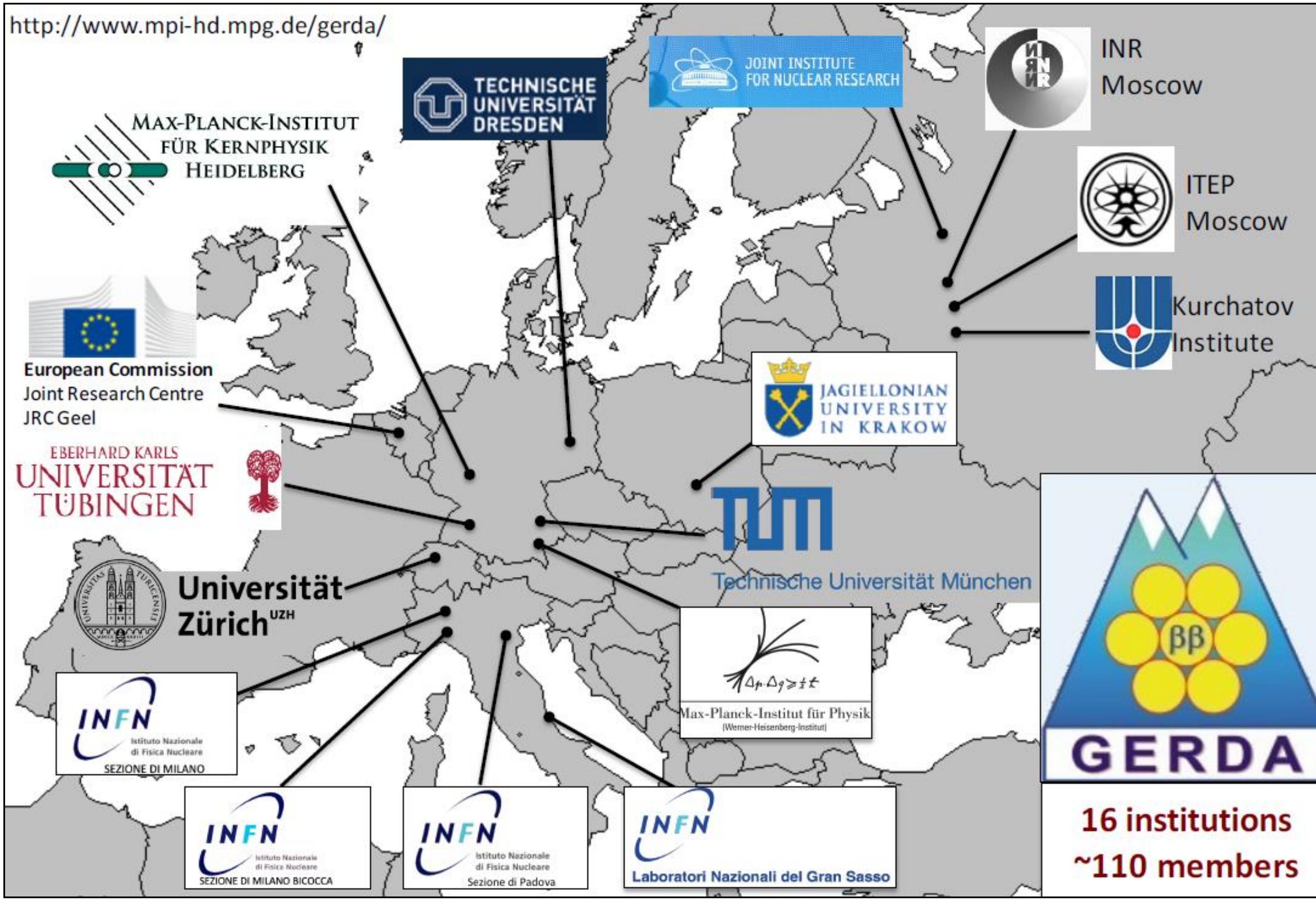
$$< \boldsymbol{m_{ee}} > \sim \frac{\mathbf{1}}{\sqrt{\boldsymbol{T_{1/2}}}} \sim \sqrt[4]{\frac{\boldsymbol{B \cdot \Delta E}}{\boldsymbol{M \cdot T}}}$$

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

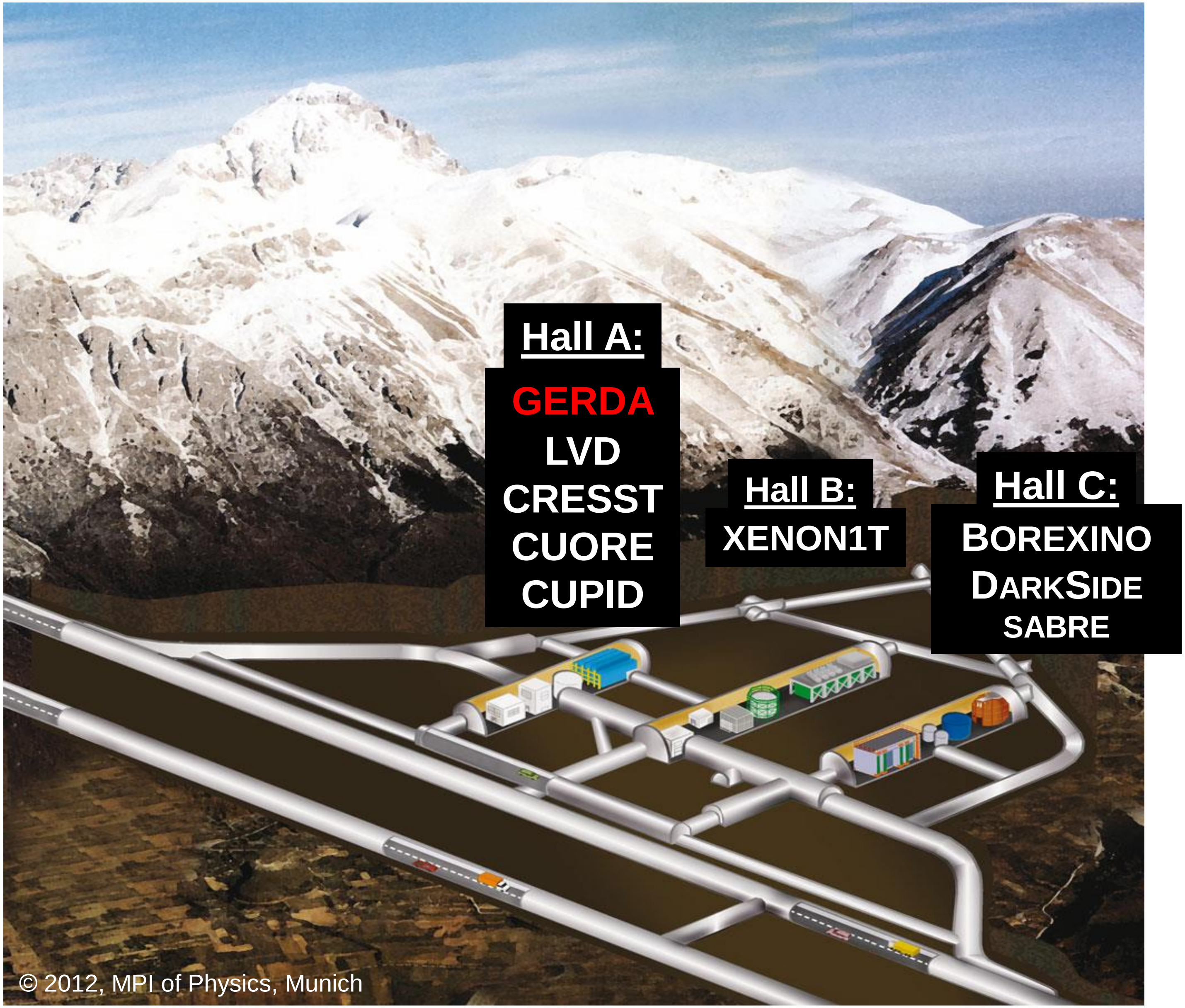
GERDA

- 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 % → 88 – 92 %)
  - **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

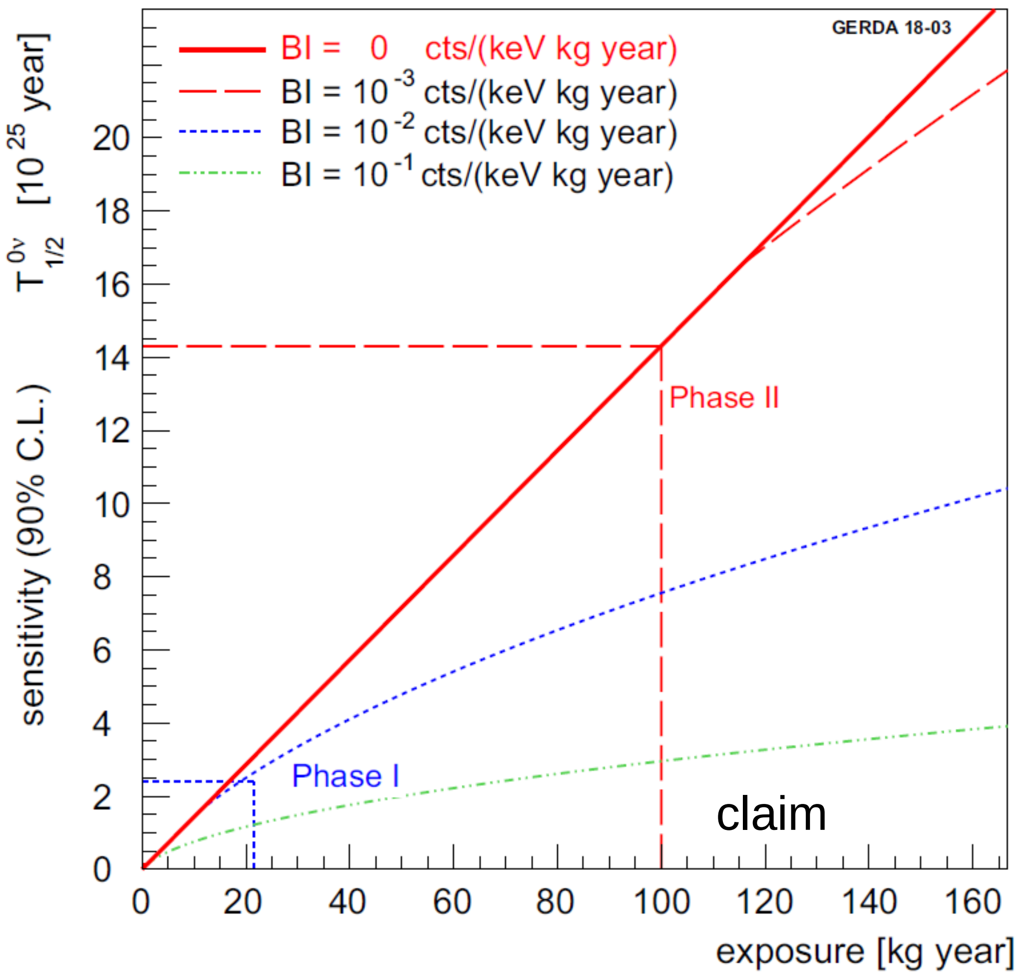


GERDA at LNGS



GERDA Sensitivity

- ββ decay
- GERDA design
- Bkg reduction
- Latest results
- Summary

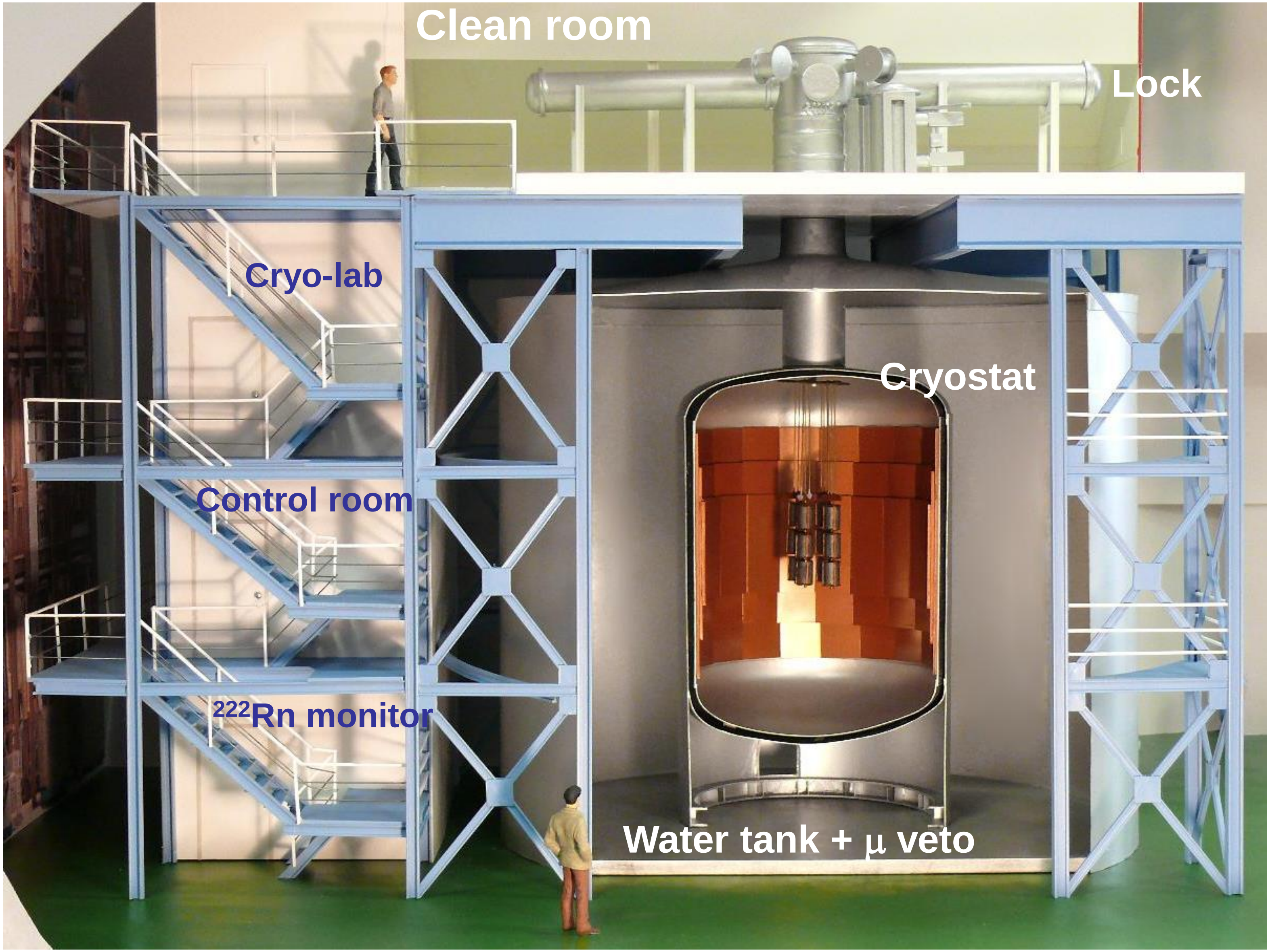


LEGEND:
^{76}Ge mass ~1 t
BI ≈ 10^{-5} cts / (keV×kg×yr)
Sensitivity: ~1×10^{28} yr
<m_{ee}> ~ 10 meV

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

ββ decay

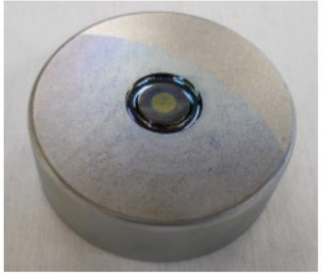
GERDA design

Bkg reduction

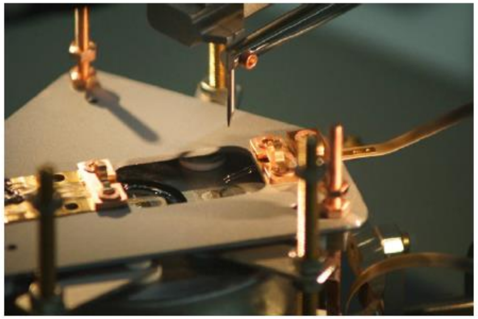
Latest results

Summary

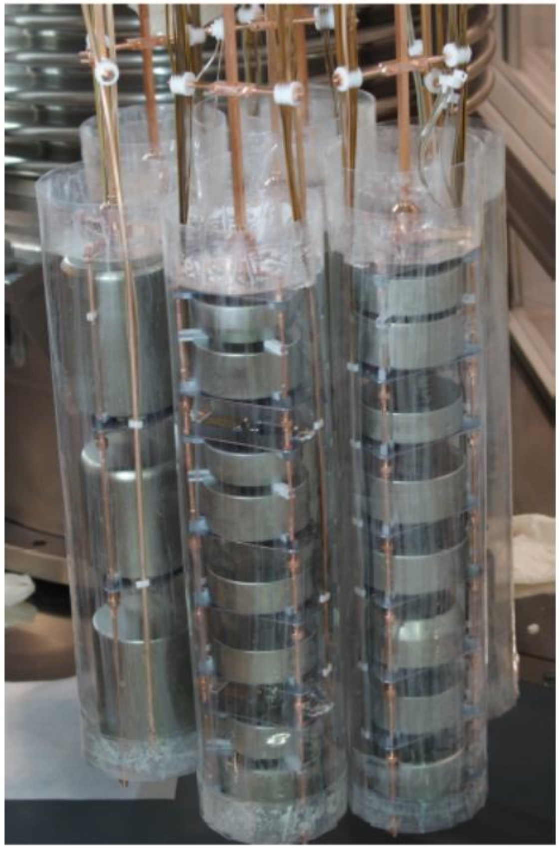
New low-mass detector holders (Si, Cu, PTFE)



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

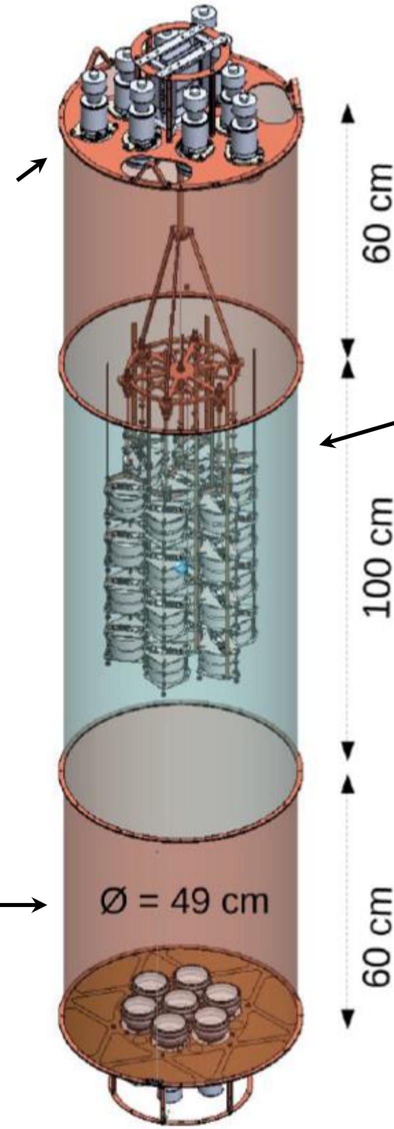
30 enriched BEGe (20.0 kg), 7 enriched coax (15.8 kg), 3 natural coax (7.6 kg) replaced later by 5 enriched IC detectors

TBP = tetraphenyl butadiene

Hybrid LAr veto: PMTs + Fibers

ββ decay
GERDA design
Bkg reduction
Latest results
Summary

16 3” PMTs
Cylinder with WLS
(TETRATEX foil)

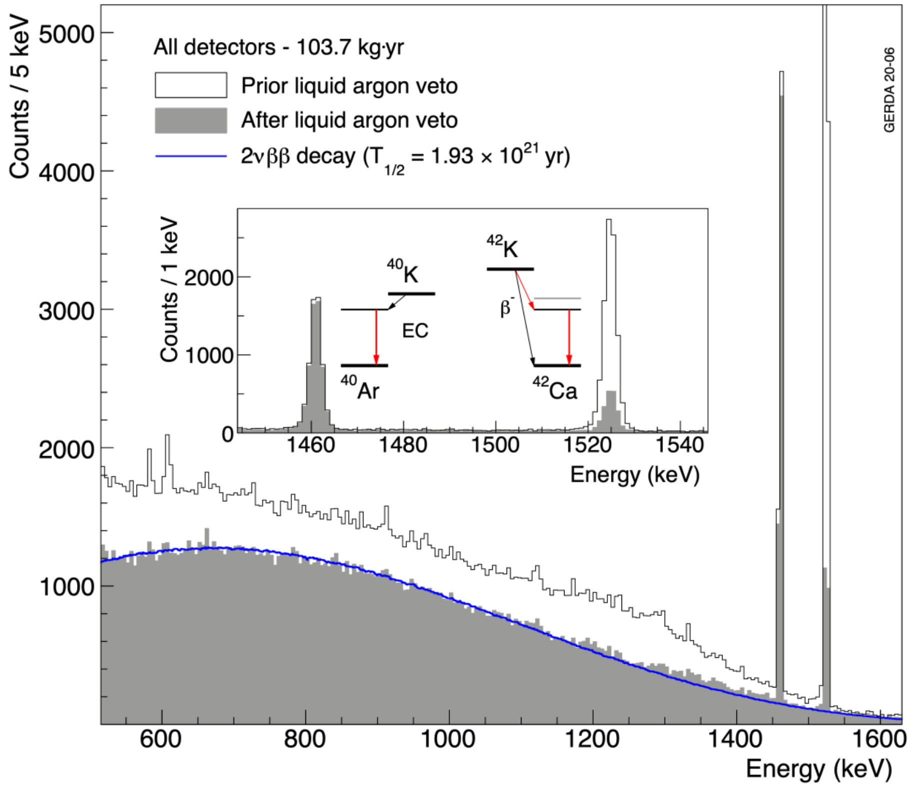


810 wavelength
shifting fibers
coupled to 90 SiPMs

LAr Veto

- ββ decay
- GERDA design
- Bkg reduction
- Latest results
- Summary

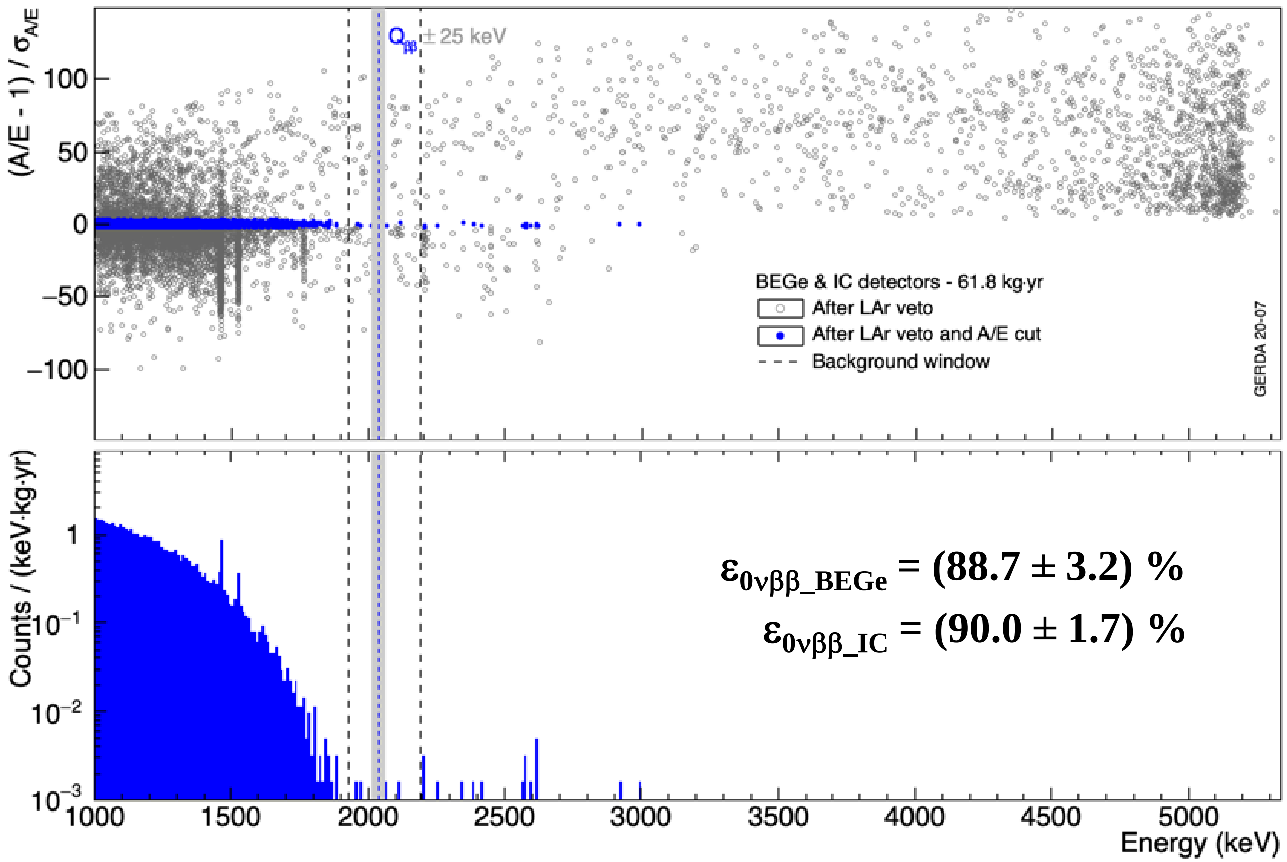
- Channel-wise (PMT/SiPM) anti-coincidence condition
- Thresholds at ~ 0.5 P.E.
- Acceptance determined from random triggers: (97.9 ± 0.1) %
- $^{40}K/^{42}K$ Compton continua completely suppressed
- γ-rays survival fractions: ^{40}K (EC) = ~100 %, ^{42}K (β^-) ~20 %
- Almost pure 2νββ spectrum after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



PSD for BEGe/IC Detectors

- ββ decay
- GERDA design
- Bkg reduction
- Latest results
- Summary

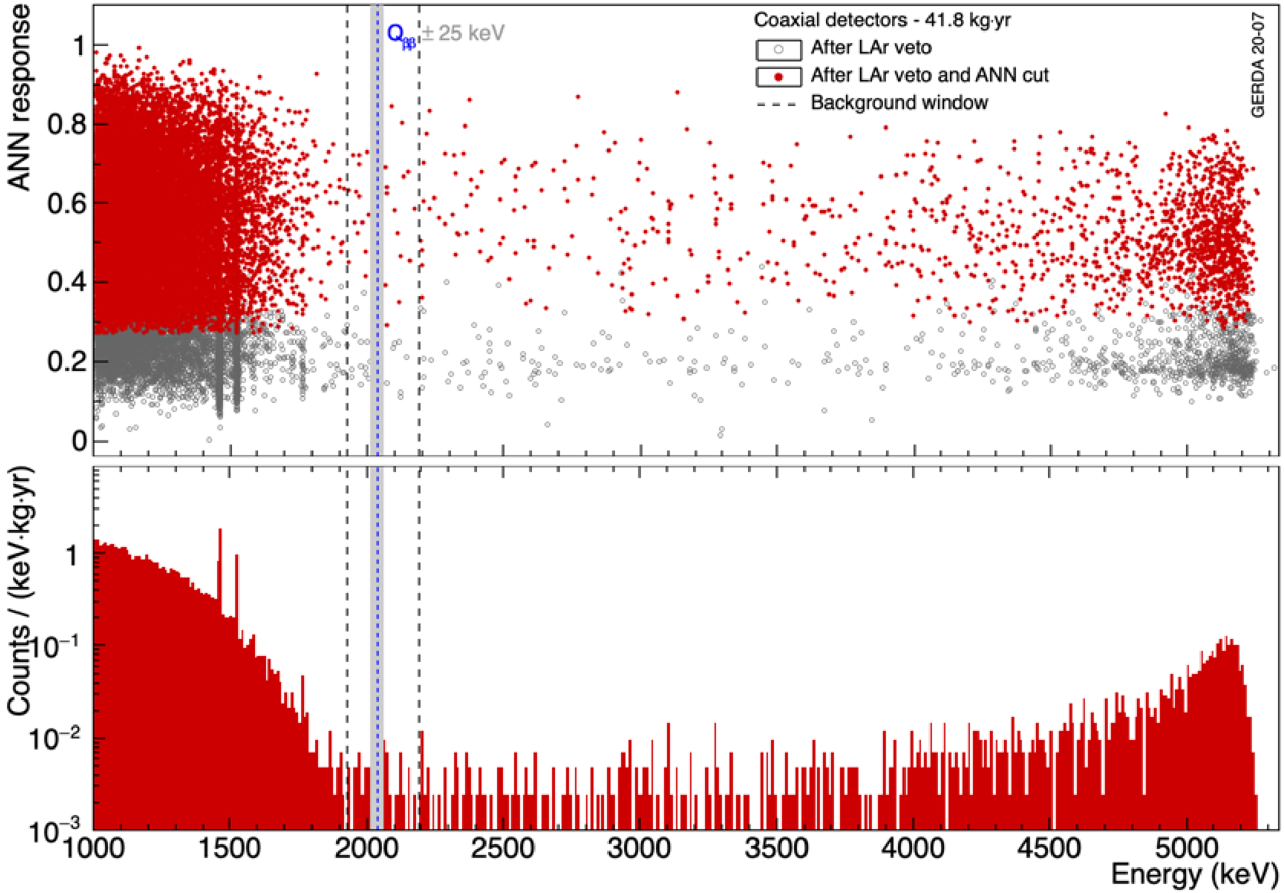
- Discrimination on a single A/E parameter (A – current amplitude, E – energy)
- Cut values defined from calibrations assuming 90 % DEP acceptance
- high A/E: fast events on p+ electrode (e.g. αs from ^{210}Po)
- low A/E: slow events on n+ electrode, multiple scattering



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

PSD for Coax Detectors

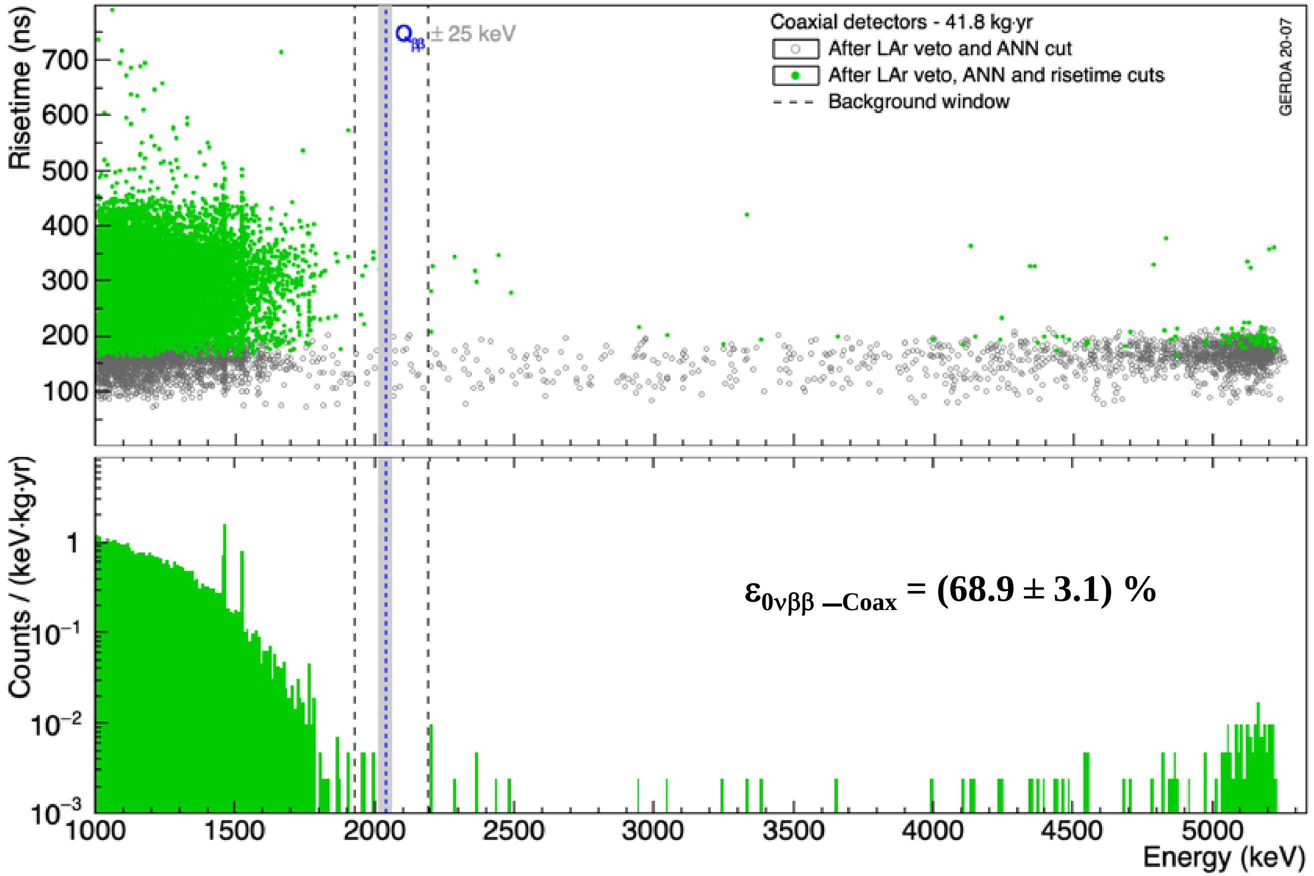
- MSE rejected with ANN (EPJC 73 (2013) 2583)
- Alphas (fast surface events) rejected with ANN- α / Rise Time (RT) cut
- ANN training on calibration data DEP and FEP as proxies for SSE and MSE, respectively.
- RT optimized on the 2νββ (1 – 1.3 MeV) and α sample (E > 3.5 MeV)



PSD for Coax Detectors

ββ decay
GERDA design
Bkg reduction
Latest results
Summary

- MSE rejected with ANN (EPJC 73 (2013) 2583)
- 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 $2\nu\beta\beta$ (1 – 1.3 MeV) and α sample (E > 3.5 MeV)

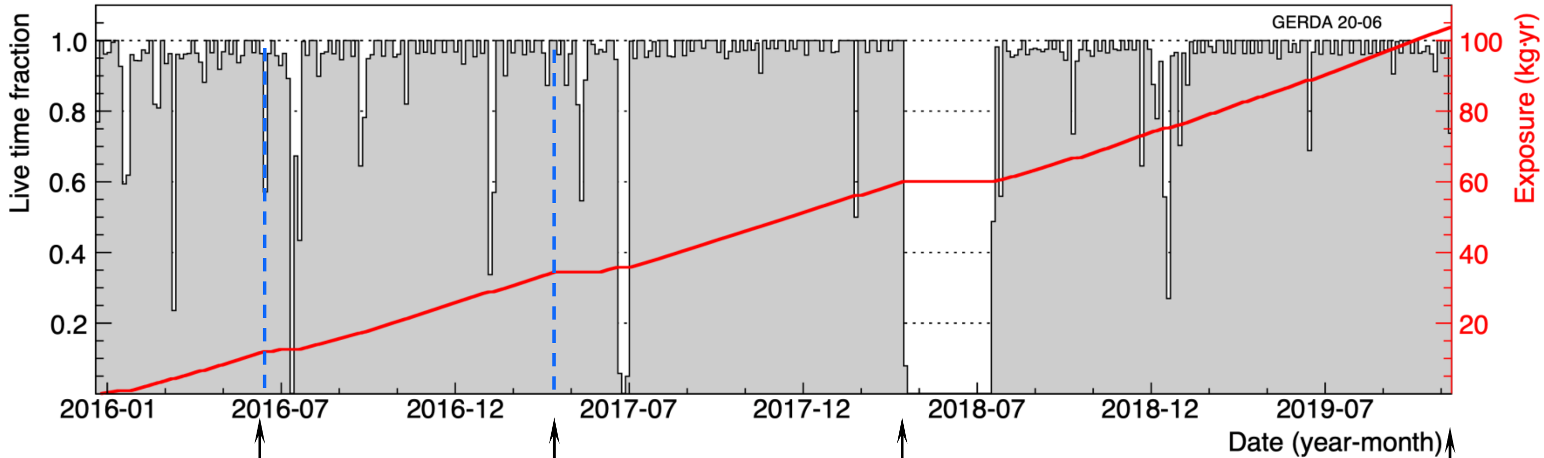


Accumulation of Data

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

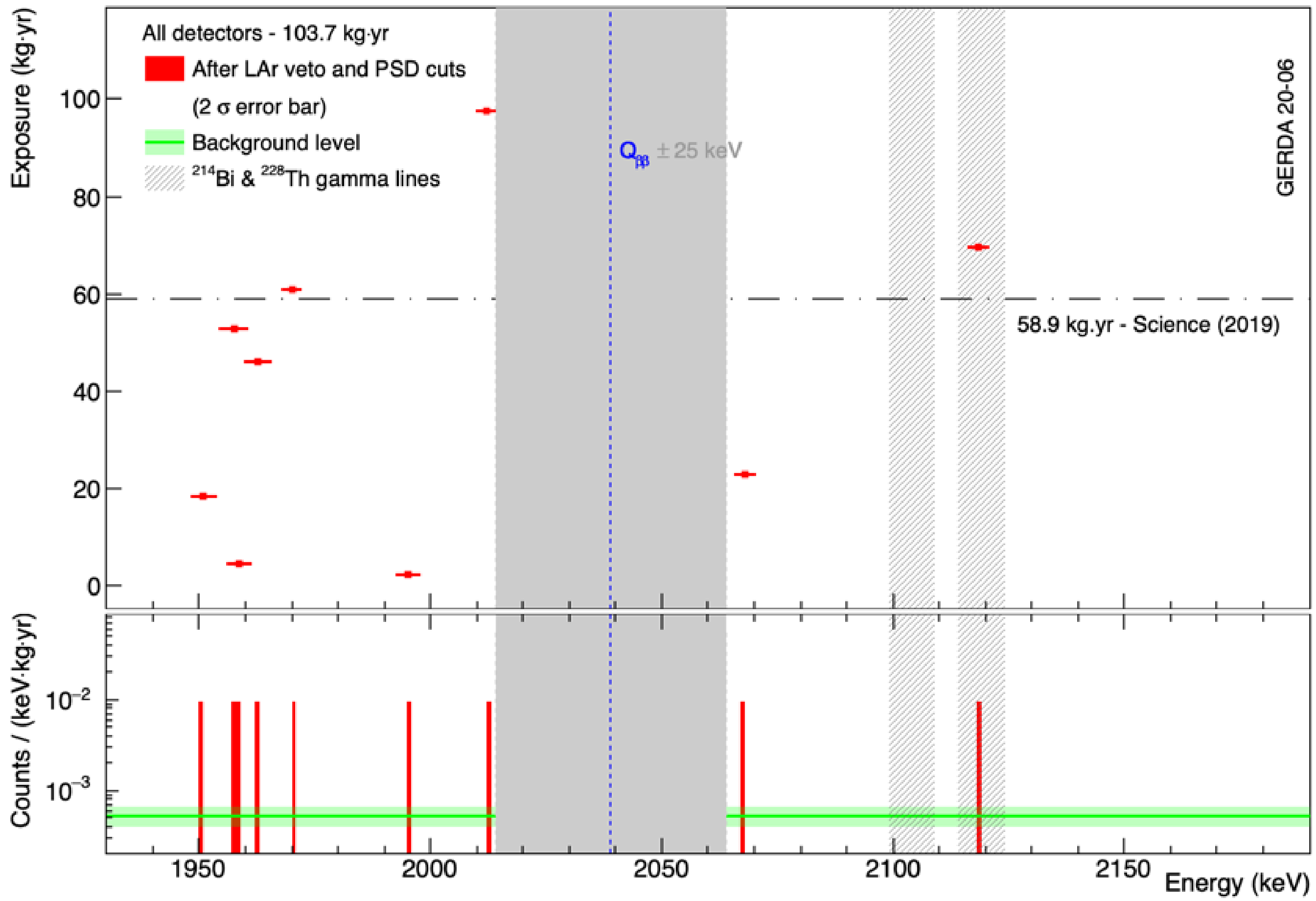
Post-upgrade

44.8 kg×yr
44.2 kg of ^{enr}Ge

Background Index in BW

- ββ decay
- GERDA design
- Bkg reduction
- Latest results
- Summary

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

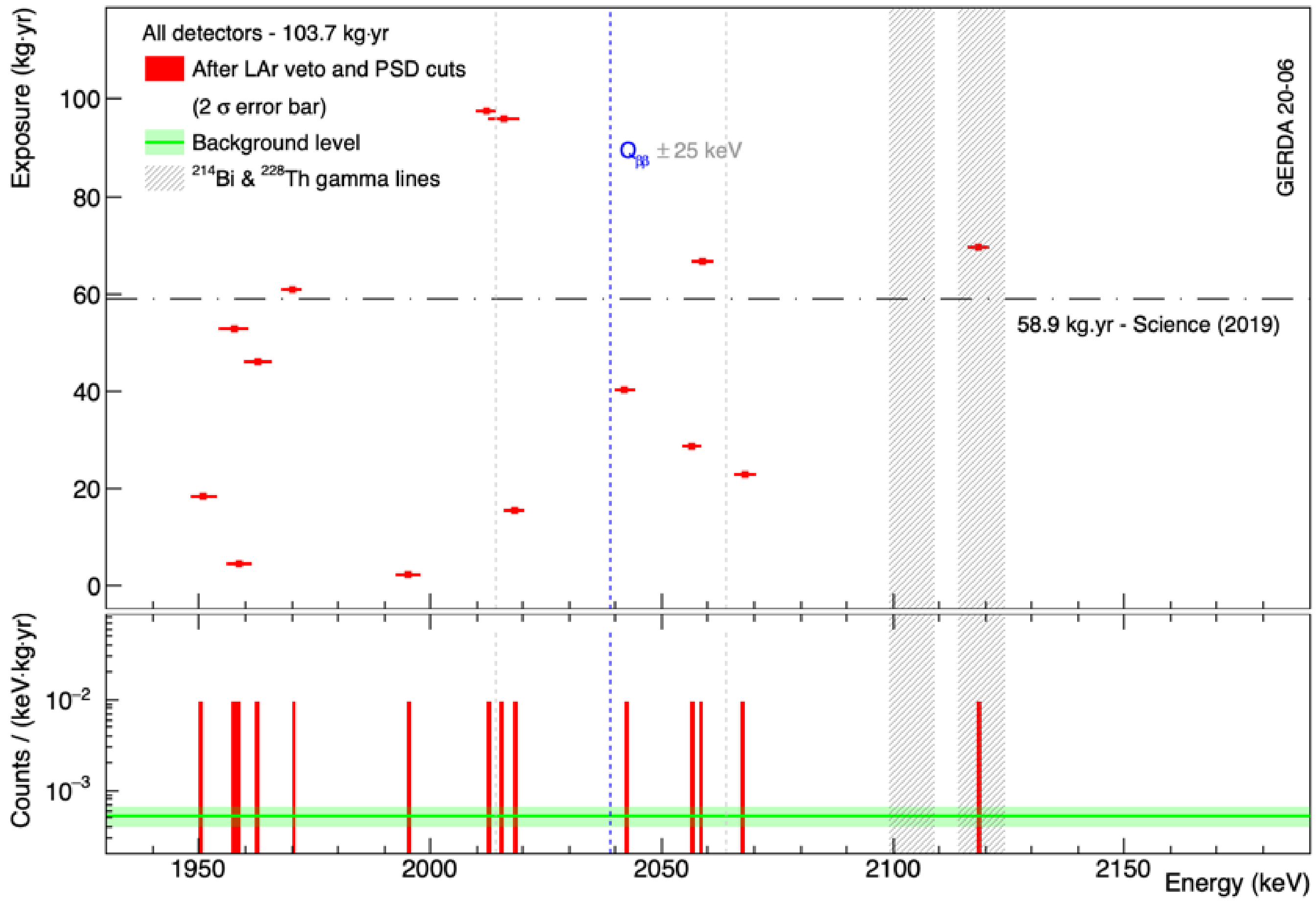


Before cuts: BI = 143×10^{-4} cts/(keV×kg×yr)
After cuts: BI = 5.2×10^{-4} cts/(keV×kg×yr)

~30 reduction

Unblinded ROI

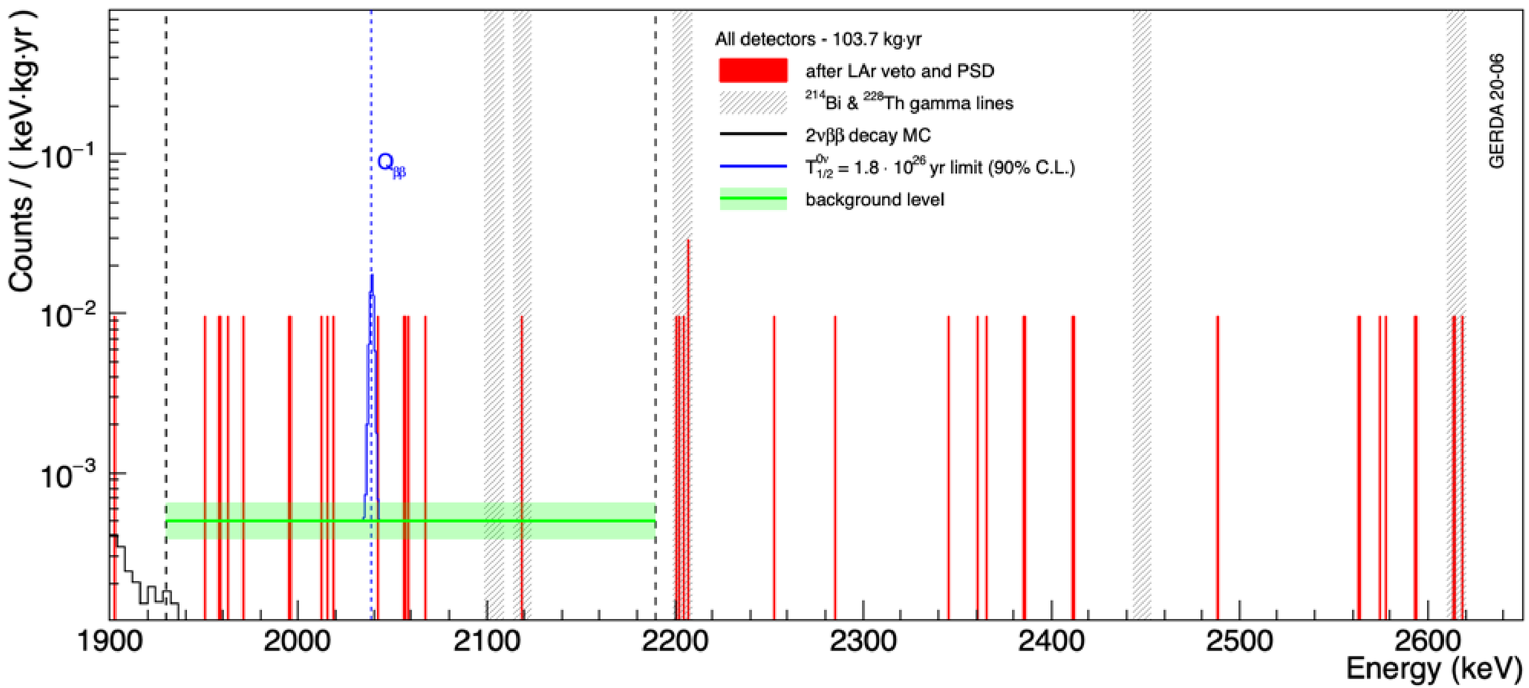
BW: [1930,2190] keV, excl. ±5 keV around ^{208}Tl (SEP), ^{214}Bi (FEP) and $Q_{\beta\beta} \pm 25$ keV



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

Statistical Analysis

Statistical analysis based on detectors-wise partitioning over stable periods



<u>Frequentist:</u>

– best fit $N_{0\nu} = 0$

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

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

<u>Bayesian:</u>

– $T_{1/2}$ (0νββ) > 1.4×10^{26} yr (90% C.L.)

– median sensitivity for limit setting $T_{1/2}$ (0νββ) = 1.4×10^{26} yr at 90% C.L.

Summary

GERDA

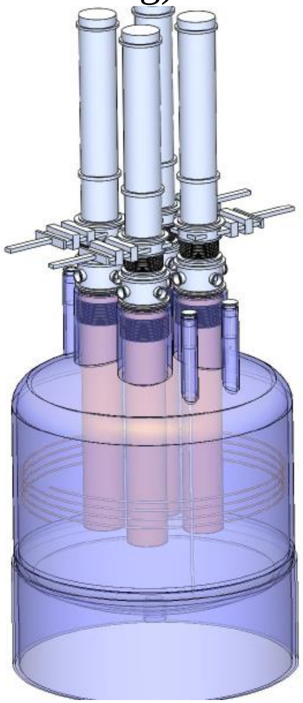
- **GERDA Phase I design goals reached:**
  - No $0\nu\beta\beta$ signal observed at $Q_{\beta\beta}$; best fit: $N^{0\nu} = 0$
  - Background index: $\sim 10^{-2}$ cts / (keV×kg×yr)
  - Exposure 21.6 kg×yr
  - $T_{1/2}$ $(0\nu\beta\beta) > 2.1\times10^{25}$ yr (90% C.L.)
- **GERDA Phase II achievements:**
  - 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)**
  - Exposure 103.9 kg×yr (127.2 kg×yr in total)
  - **$T_{1/2}$ $(0\nu\beta\beta) > 1.8\times10^{26}$ yr (90% C.L.)**
  - $m_{\beta\beta} \leq (0.080 – 0.182)$ eV
- **GERDA Phase II goals:**
  - Background index: $\sim 10^{-3}$ cts / (keV×kg×yr)
  - Exposure: ~100 kg×yr
  - Sensitivity: $\sim 10^{26}$ yr
- **GERDA: background-free $0\nu\beta\beta$ experiment (best sensitivity and discovery potential)**
- LEGEND – next generation experiment for $T_{1/2}^{0\nu} \sim 10^{28}$ yr
- LEGEND-200 at LNGS (GERDA technology) ready in 2022

Beyond GERDA → LEGEND

- ββ decay
- GERDA design
- Bkg reduction
- Latest results
- Summary

First stage:

- GD + MJD + new groups
- Based on existing GERDA infrastructure (LNGS)
- Up to 200 kg of ^{enr}Ge (L-200)
- Approved by LNGS in Aug. 2018
- Under preparation, cryostat filled, commissioning
- Background reduction w.r.t GERDA: ~3
- Anticipated start of data taking in 2022
- $T_{1/2}$ (0νββ) ≥ 10^{27} yr (~5 yr data taking)



Subsequent stages:

- Up to 1000 kg of ^{enr}Ge (L-1000)
- Background reduction w.r.t GERDA: ~30
- Approved by DOE in 2021
- Location still to be defined (LNGS or SNO Lab)
- $T_{1/2}$ (0νββ) ≥ 10^{28} yr (IH excluded)
- pCDR: http://arxiv.org/abs/2107.11462

GD/LEGEND: Strong support of from the Polish MEN, NCN, FNP

Background Model

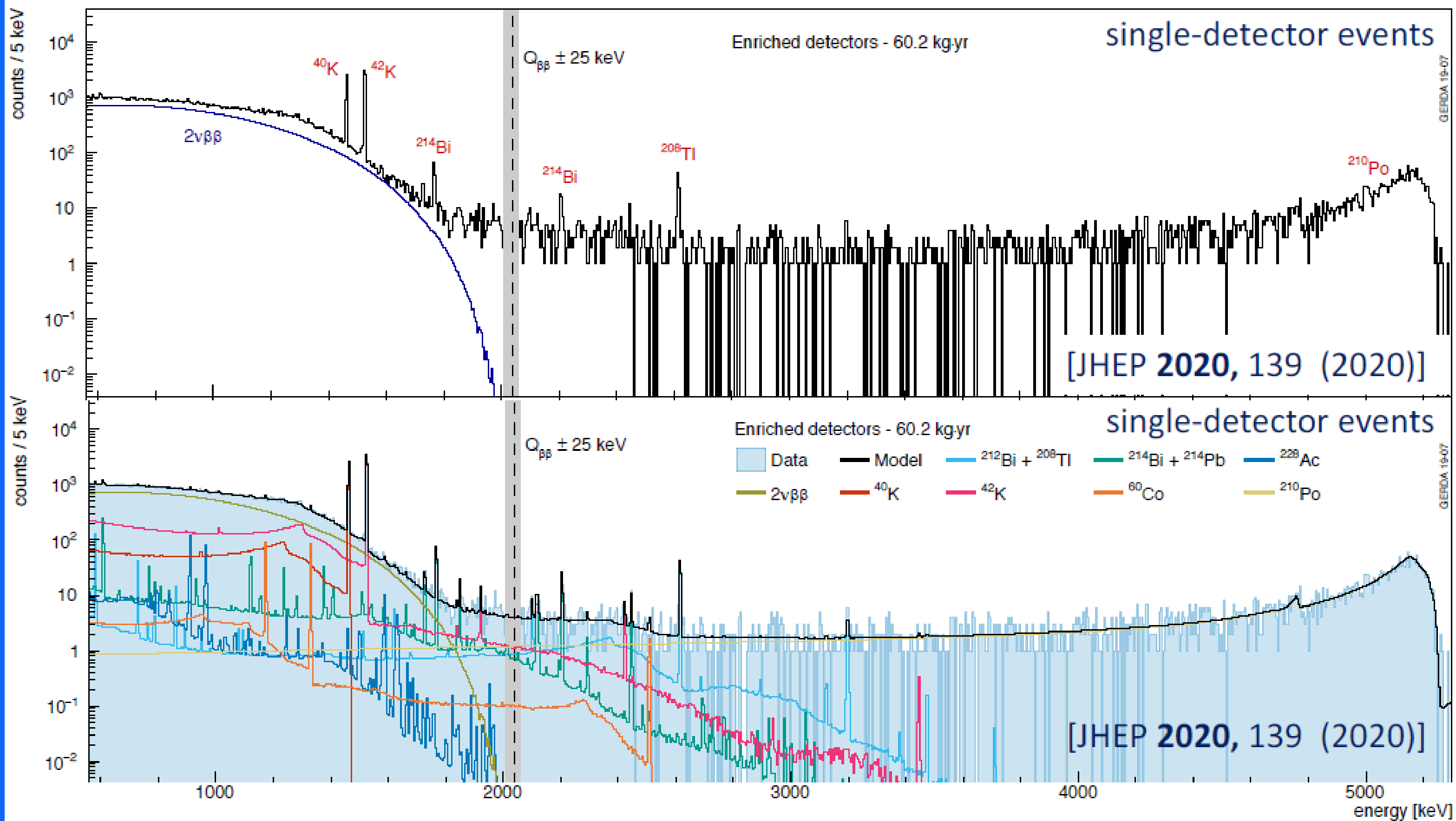
ββ decay

GERDA design

Bkg reduction

Latest results

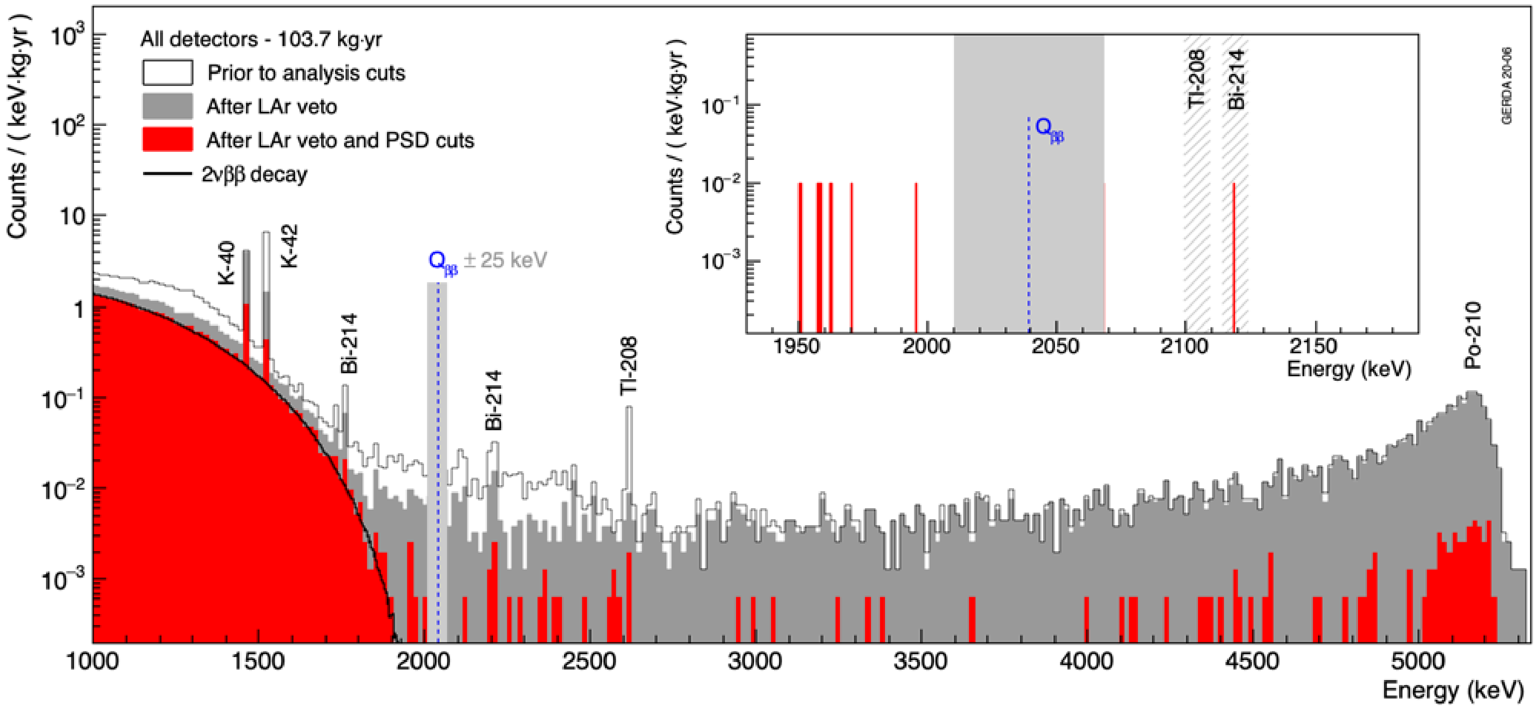
Summary



- Data after application of quality cuts and muon veto
- MaGe (Geant4) modelling of GERDA
- Simulation of contribution of all individual parts
- Input from screening measurements
- **No full energy peak or other structures close to $Q_{\beta\beta}$**

Application of LAr veto and PSD

- ββ decay
- GERDA design
- Bkg reduction
- Latest results
- Summary



- LAr veto and PSD are complementary
- Almost pure 2νββ decay spectrum
- Strong reduction of $^{40}K/^{42}K$
- Strong reduction of ^{214}Bi and ^{208}Tl lines
- Strong suppression of αs (^{210}Po on p^{+} contact)