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

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on behalf of the GERDA Collaboration

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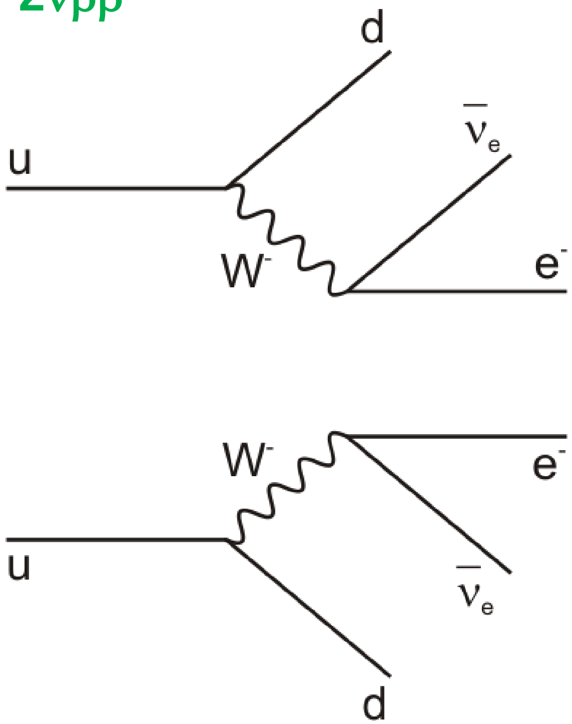
Outline

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

Double Beta Decay Modes

$2\nu\beta\beta$

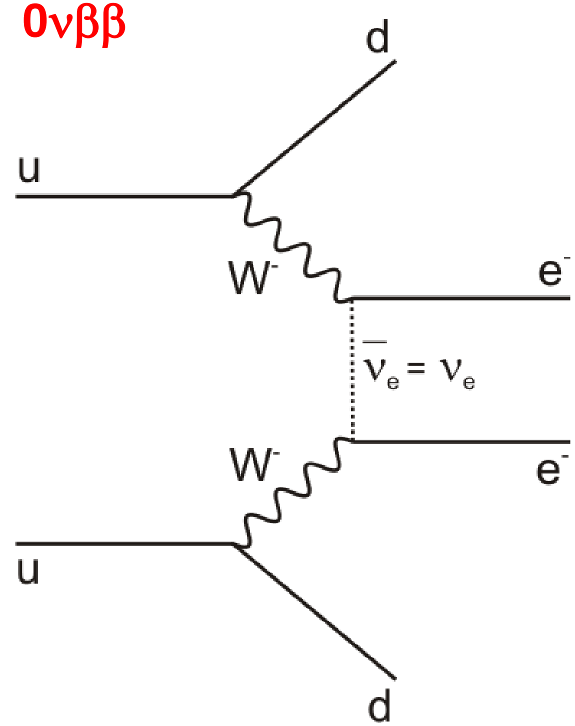


(A,Z) $\rightarrow$ (A, Z+2) + 2e⁻ + 2$\bar{\nu}_e$

$\Delta L = 0$

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

$0\nu\beta\beta$



(A,Z) $\rightarrow$ (A, Z+2) + 2e⁻

$\Delta L = 2$

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

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

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

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

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

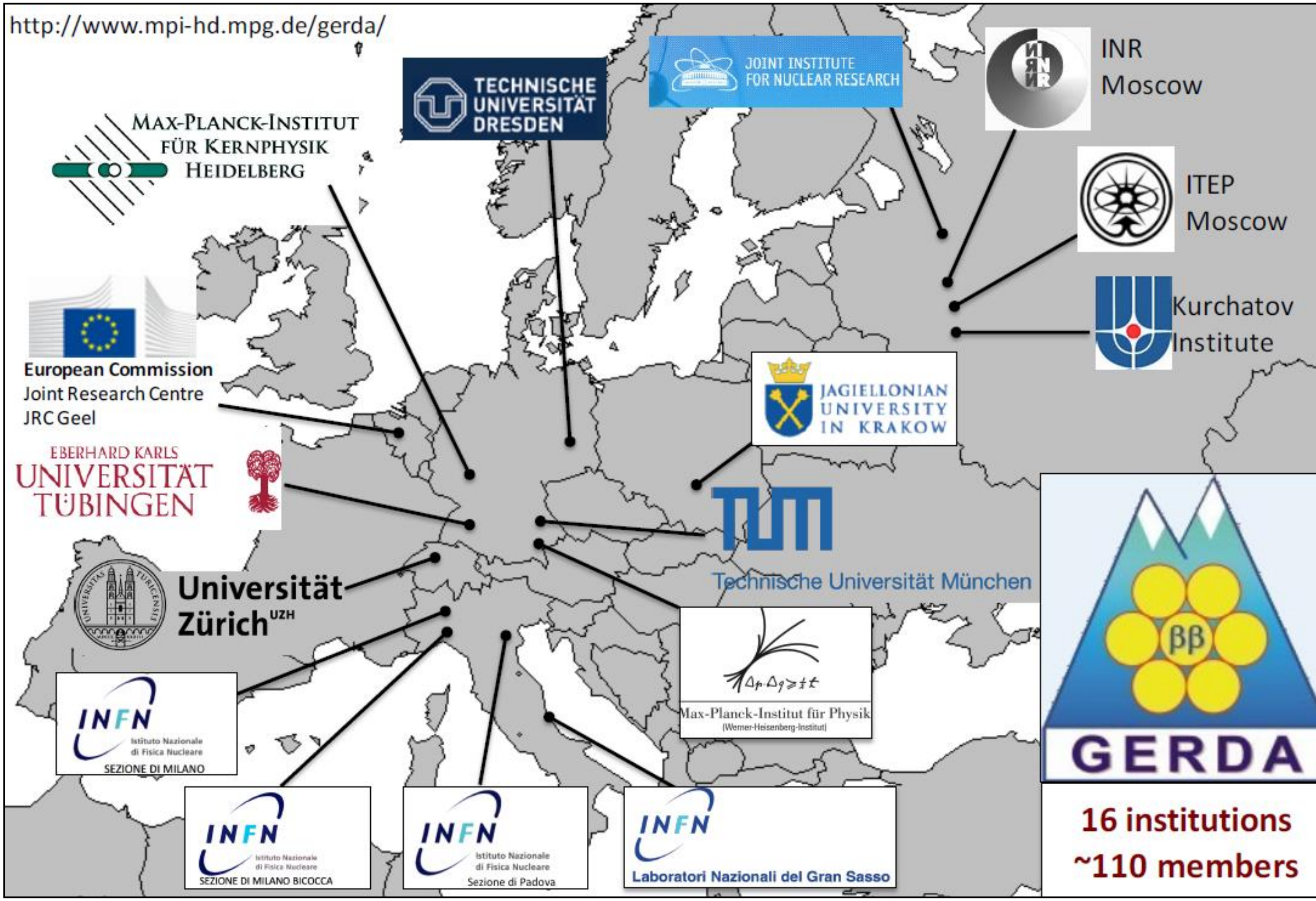
$$(\boldsymbol{M \cdot T})\uparrow \times \mathbf{100} \rightarrow \boldsymbol{T_{1/2}} \uparrow \mathbf{10} \rightarrow < \boldsymbol{m_{ee}} > \ \downarrow \times \sim \mathbf{3}$$

GERDA

- $\beta\beta$ decay
- GERDA design
- Bkg reduction
- Latest results
- Summary

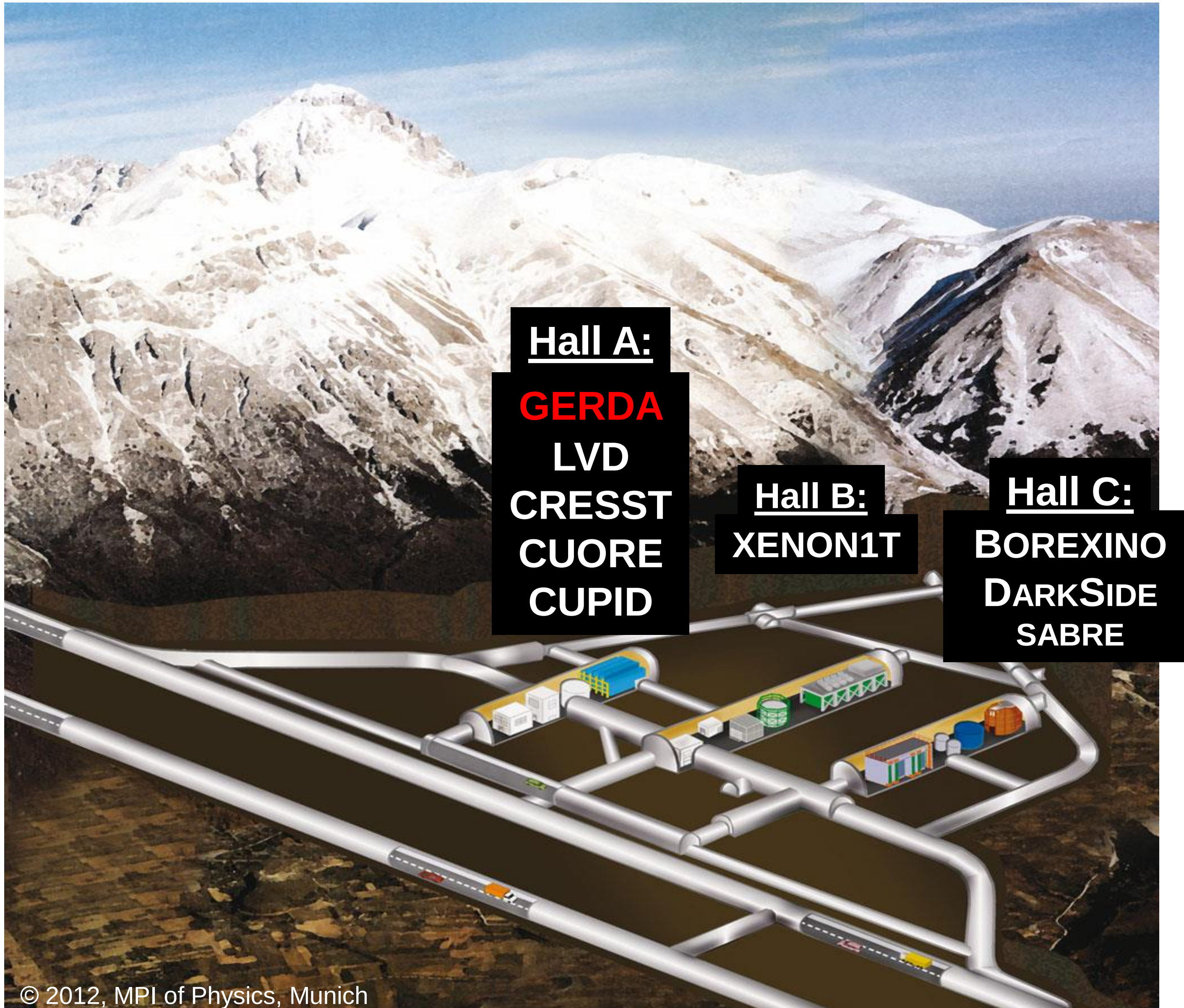
- GERDA (<u>GER</u>manium <u>D</u>etector <u>A</u>rray) has been designed to investigate neutrinoless double beta decay of ^{76}Ge ($Q_{\beta\beta}$ = 2039 keV)
  - Ge mono-crystals are very pure
  - Ge detectors have excellent energy resolution
  - Detector = source ($\varepsilon \approx 1$)
  - Enrichment 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

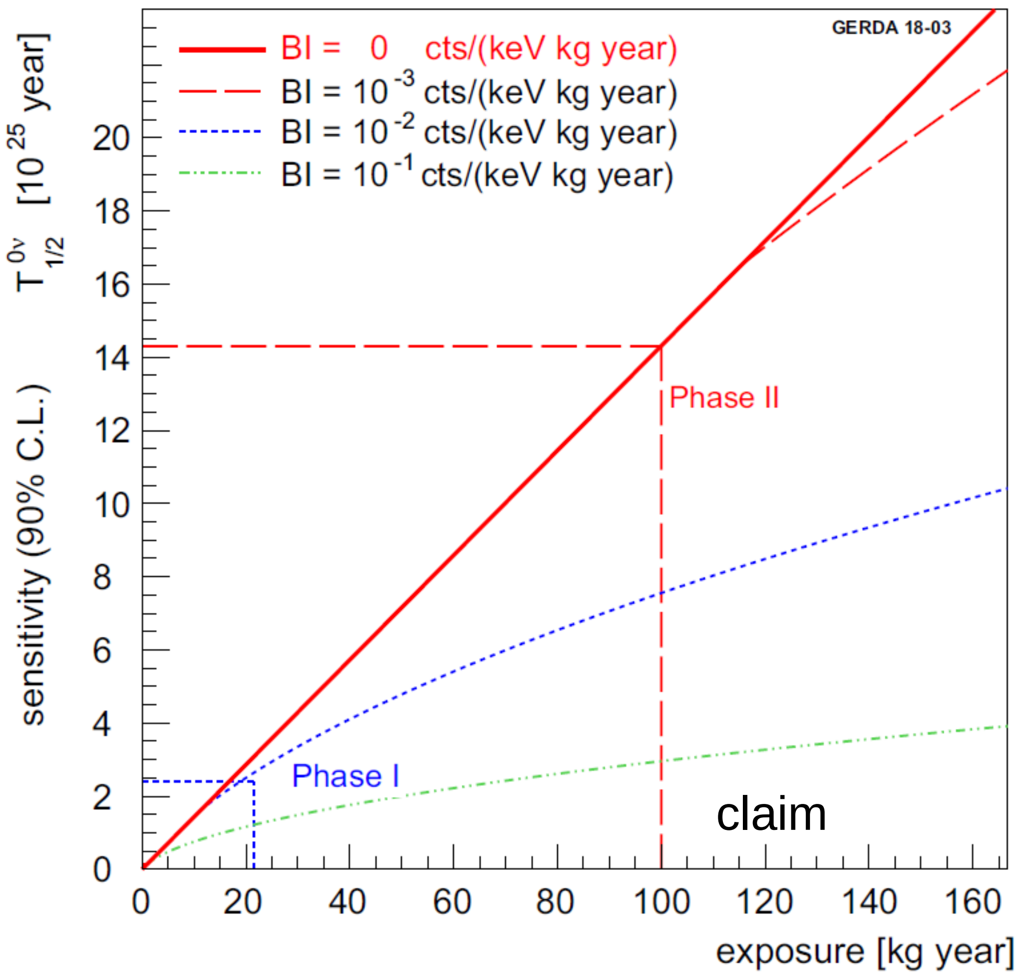


GERDA at LNGS

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



GERDA Sensitivity



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 Phase I

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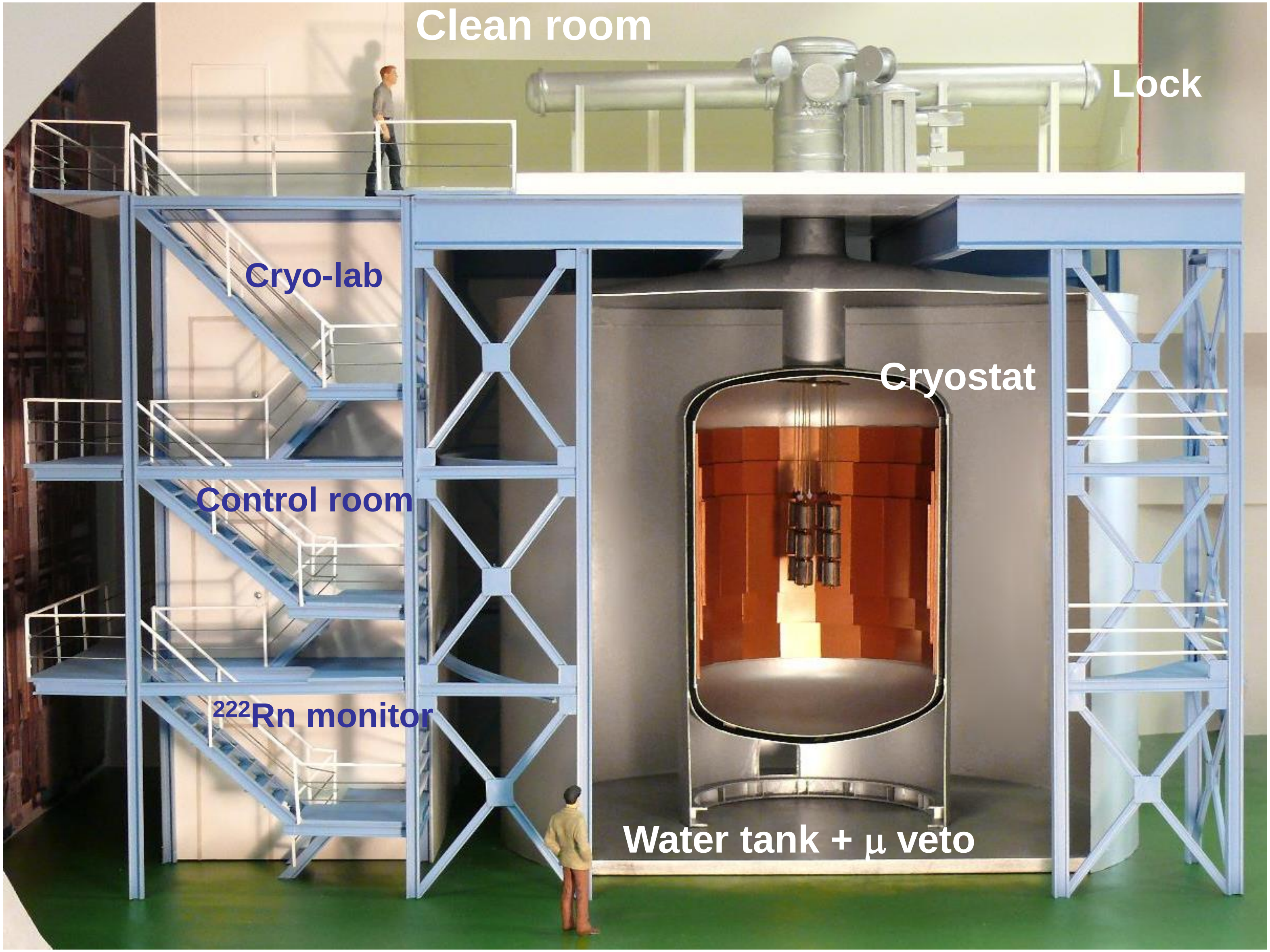
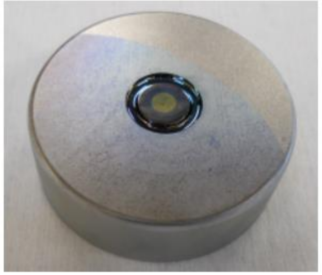


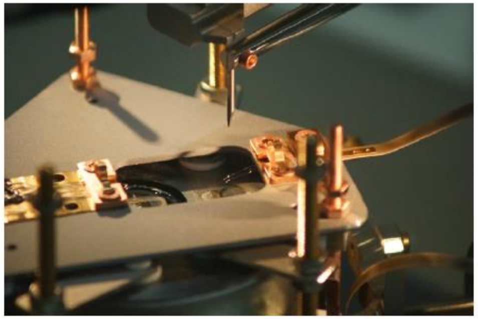
GERDA Phase II Setup

20 kg of 30 BEGes
15.8 kg of 7 coax,
7.6 kg of 3 natural coax

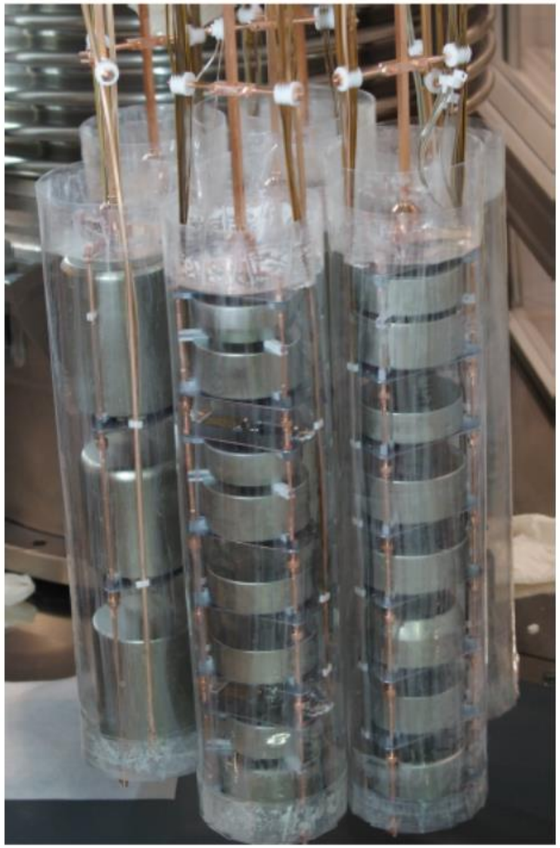
New low-mass detector holders (Si, Cu, PTFE)



New thick-window BEGe detectors



New signal and HV contacting by wire bonding flat ribbon cables

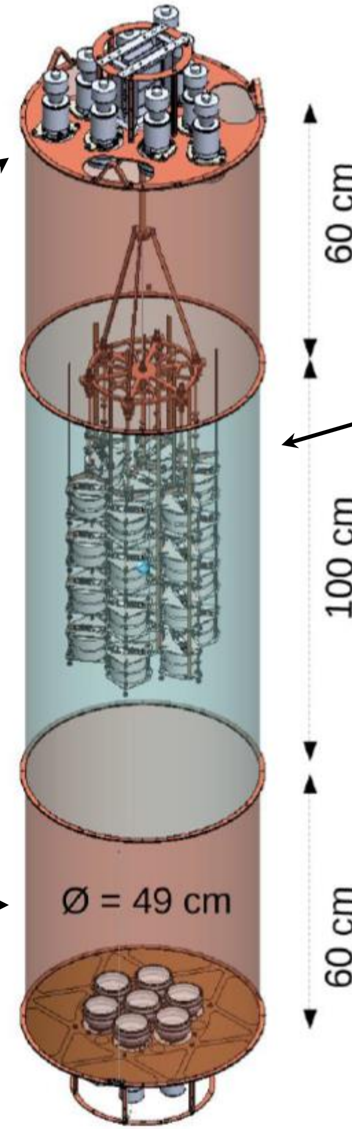


New TPB coated nylon mini-shrouds to reduce attraction of ^{42}K ions (from decays of ^{42}Ar) to n^{+} surface

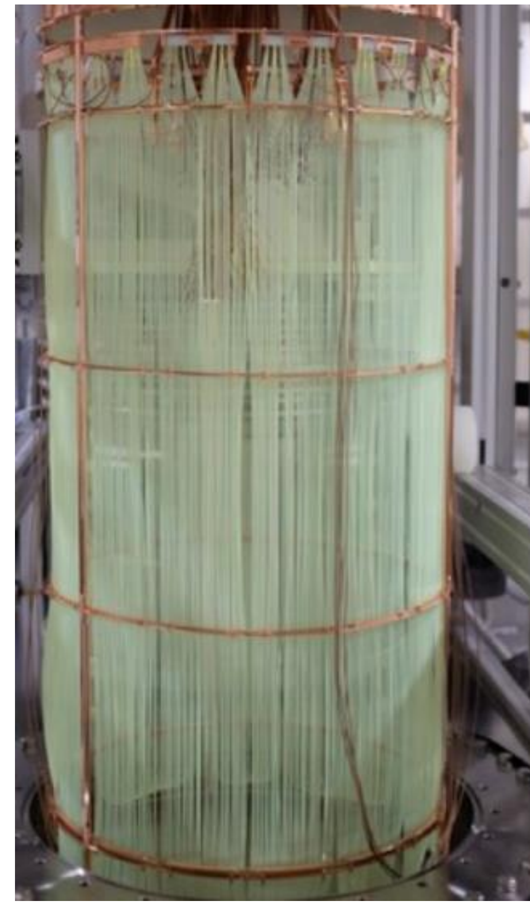
TBP = tetraphenyl butadiene

Hybrid LAr veto: PMTs + Fibers

16 3” PMTs
Cylinder with WLS
(TETRATEX foil)

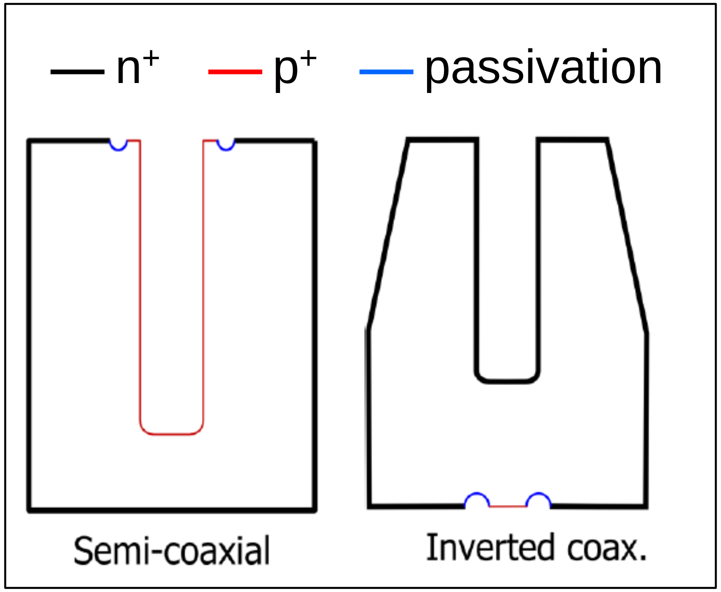


810 wavelength
shifting fibers
coupled to 90 SiPMs



Upgrade of Phase II

- Natural coax replaced with 9.6 kg (5 detectors) enriched inverted coax type
- New LAr instrumentation: installation of denser fibre curtain and middle string curtain
- Some Ge channels recovered
- Few detectors etched to reduce their leakage current
- Some cables replaced with lower activity version



βß decay
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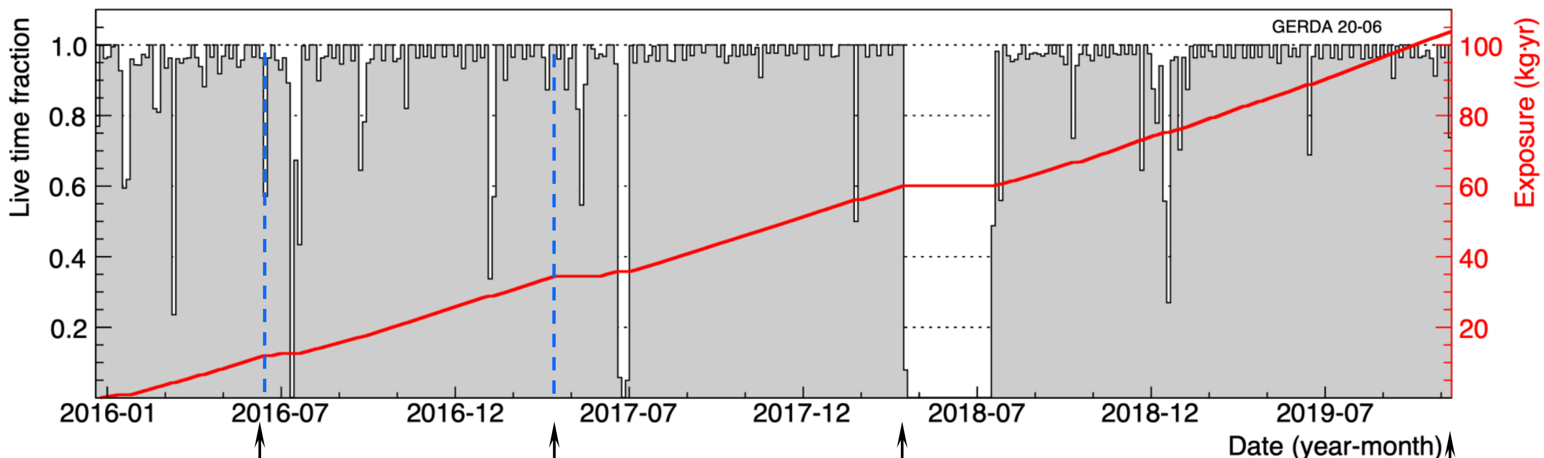
Accumulation of Data

Phase I

- 09.11.11 – 09.05.13: 21.6 kg×yr
- 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
This talk

Pre-upgrade

58.9 kg×yr
35.6 kg of ^{enr}Ge

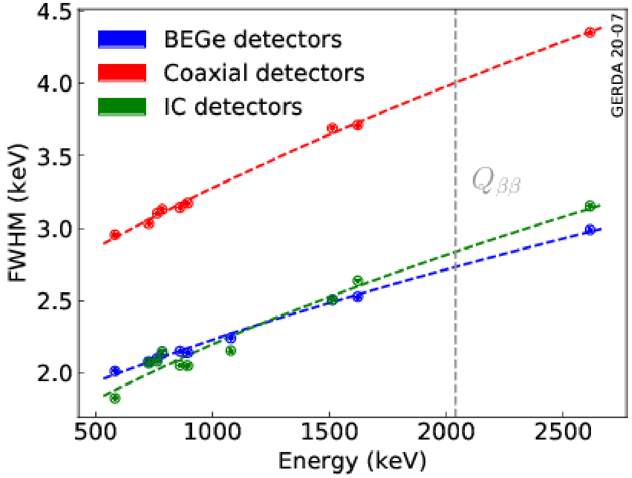
Post-upgrade

44.8 kg×yr
44.2 kg of ^{enr}Ge

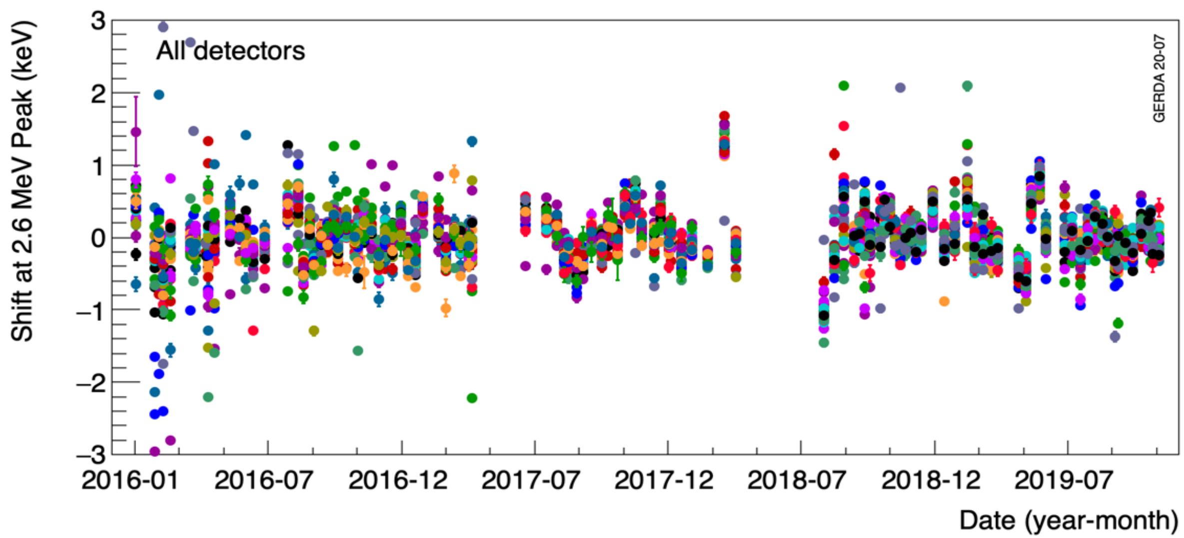
GERDA

Energy Scale and Stability

- Detectors calibrated weekly with ^{228}Th sources
- Shifts between calibrations < 1 keV
- Every 20 s test pulse injection for gain stability measurement
- "Zero area cusp" (ZAC) filter (Eur. Phys. J. C75 (2015) 255)

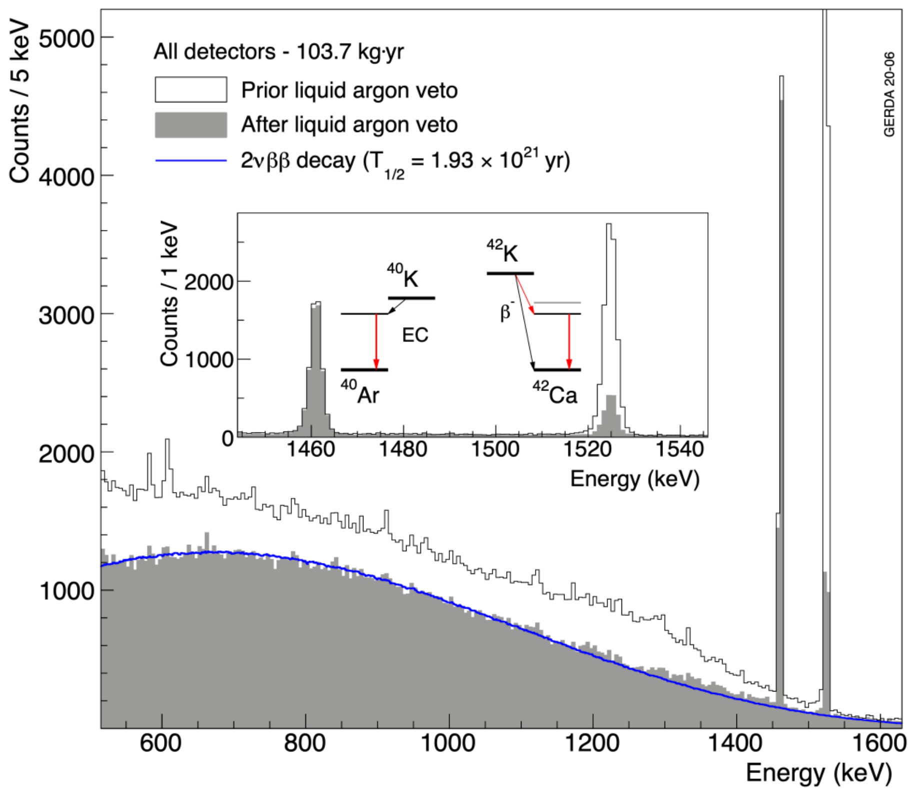


FWHM Energy Resolution at $Q_{\beta\beta}$ [keV]			
	Coax	**BEGe**	**Inverted Coax**
Pre-upgrade	3.6 ± 0.3	2.9 ± 0.3	--
Post-upgrade	5.6 ± 1.3	2.6 ± 0.2	2.9 ± 0.1



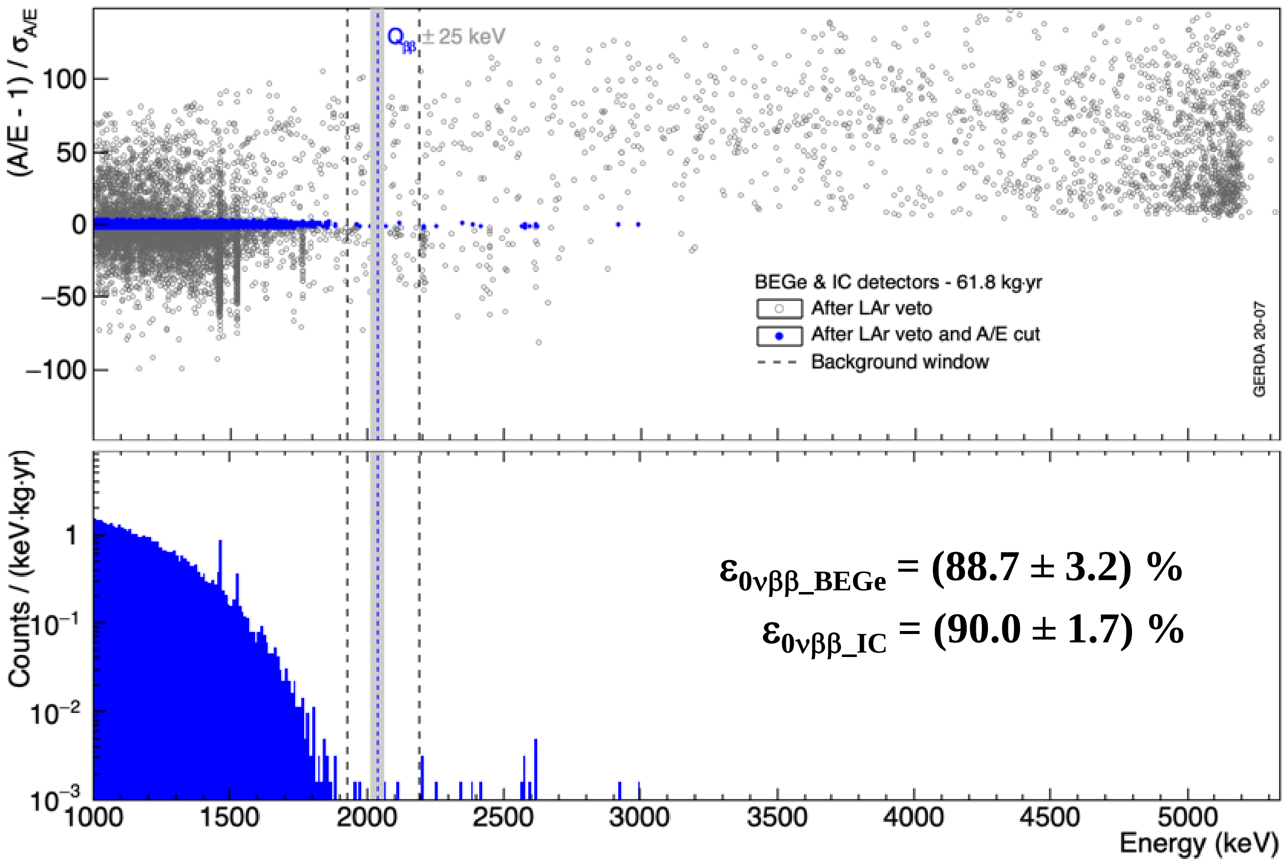
LAr Veto

- 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

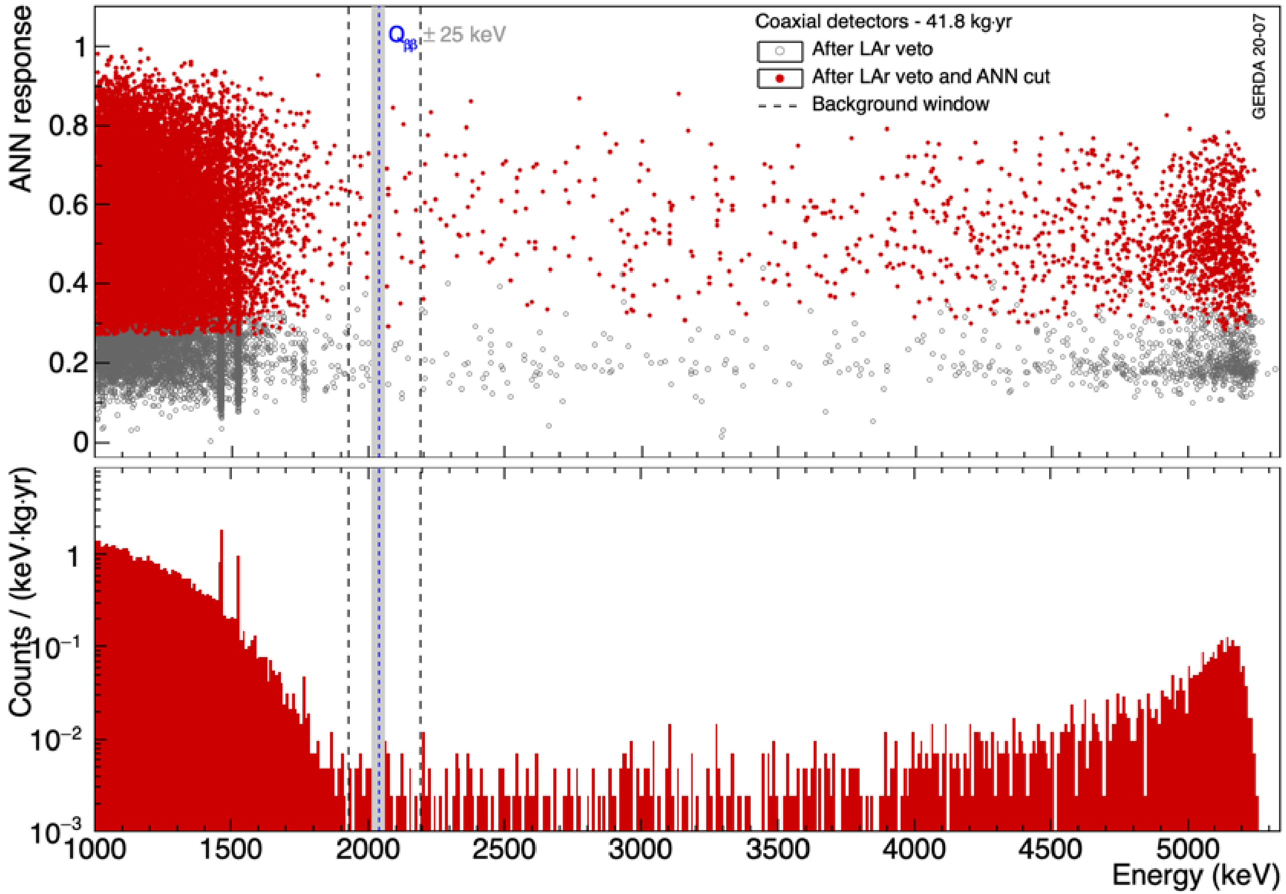
- Discrimination on a single A/E parameter (A – current amplitude, E – energy)
- Cut values defined from calibrations assuming 90 % DEP acceptance
- high A/E: fast events on p+ electrode (e.g. αs from ^{210}Po)
- low A/E: slow events on n+ electrode, multiple scattering



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 $2\nu\beta\beta$ (1 – 1.3 MeV) and α sample (E > 3.5 MeV)



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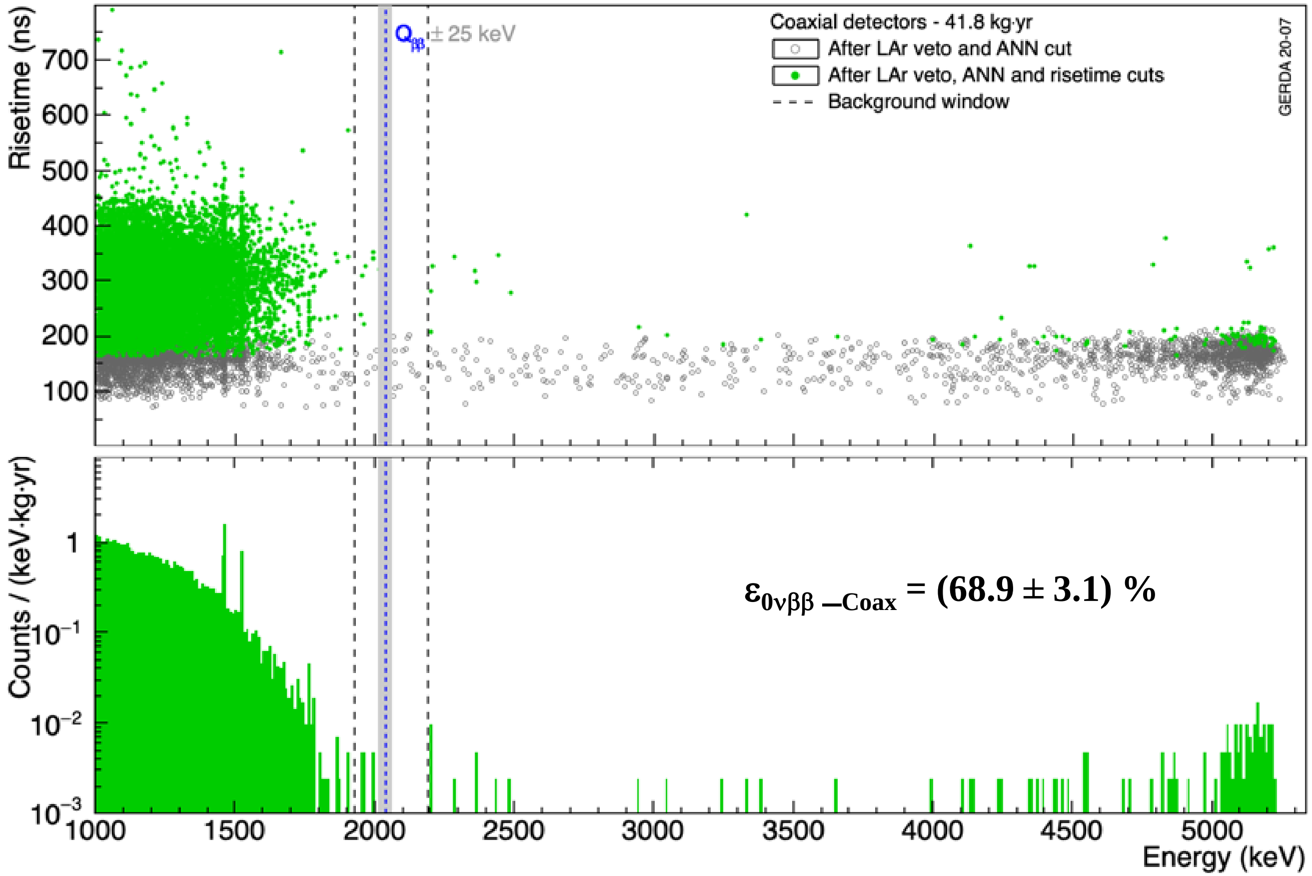

ββ decay

GERDA design

Bkg reduction

Latest results

Summary

Application of LAr veto and PSD

ββ decay

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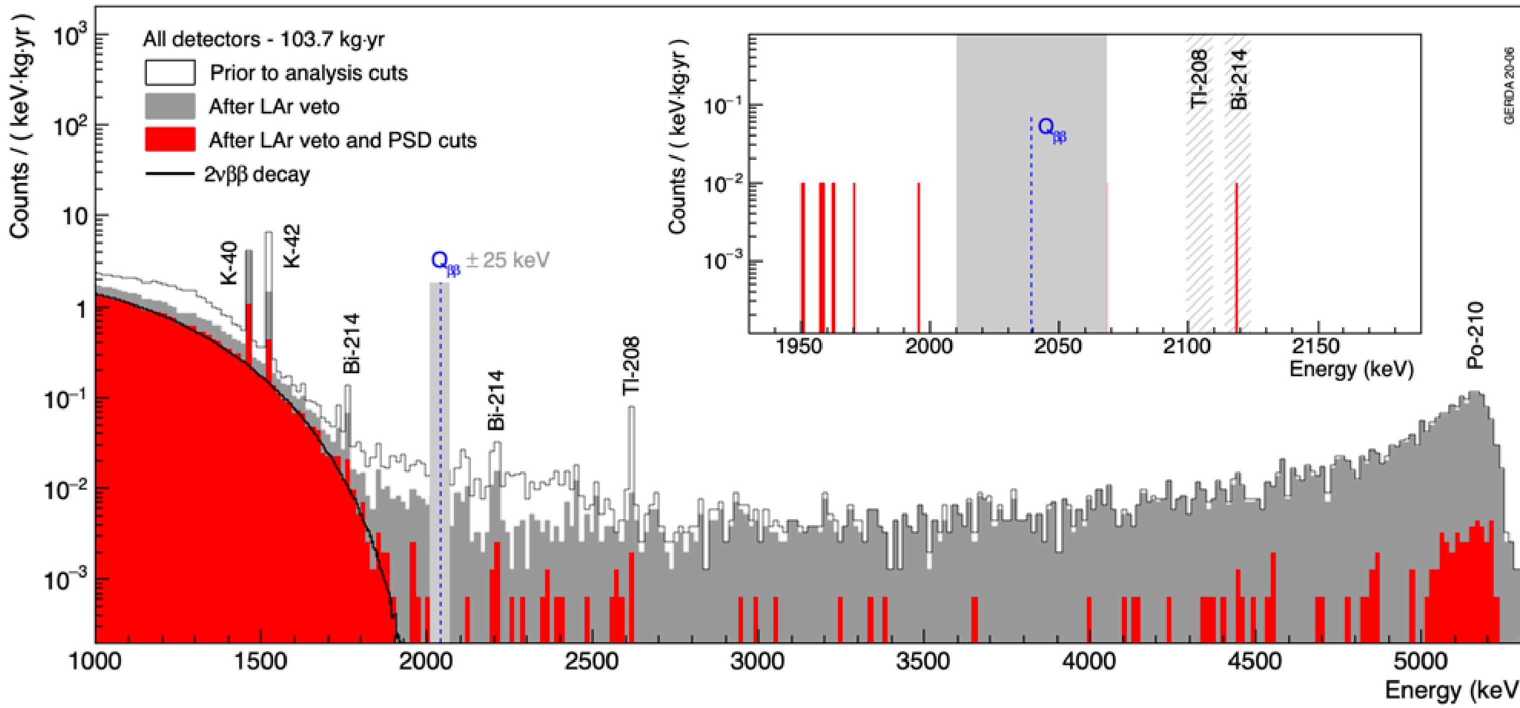

- LAr veto and PSD are complementary
- Almost pure 2νββ decay spectrum
- Strong reduction of $^{40}K/^{42}K$
- Strong reduction of ^{214}Bi and ^{208}Tl lines
- Strong suppression of αs (^{210}Po on p^+ contact)

Background Index in BW

- ββ decay
- GERDA design
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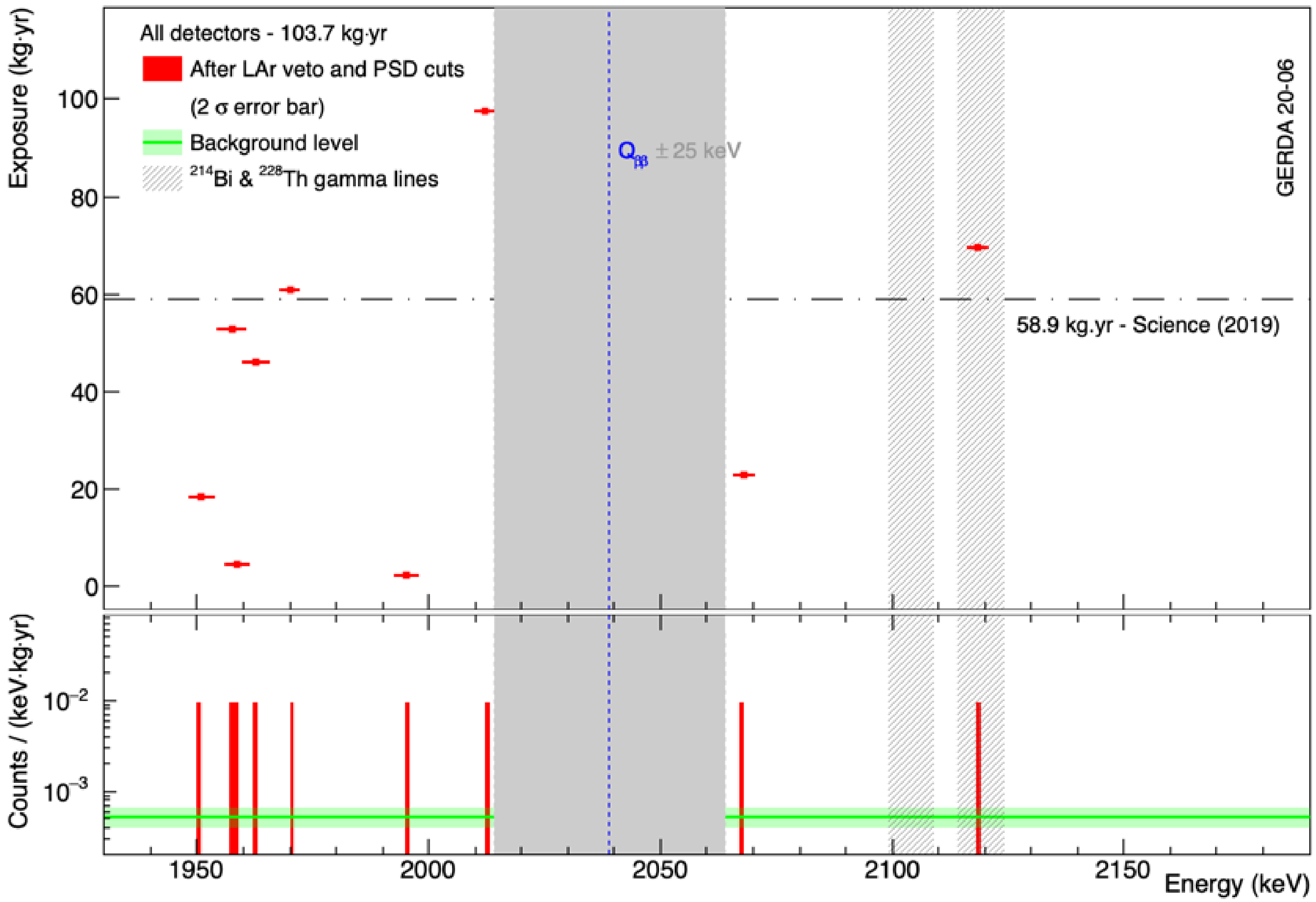
- Latest results
- Summary

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

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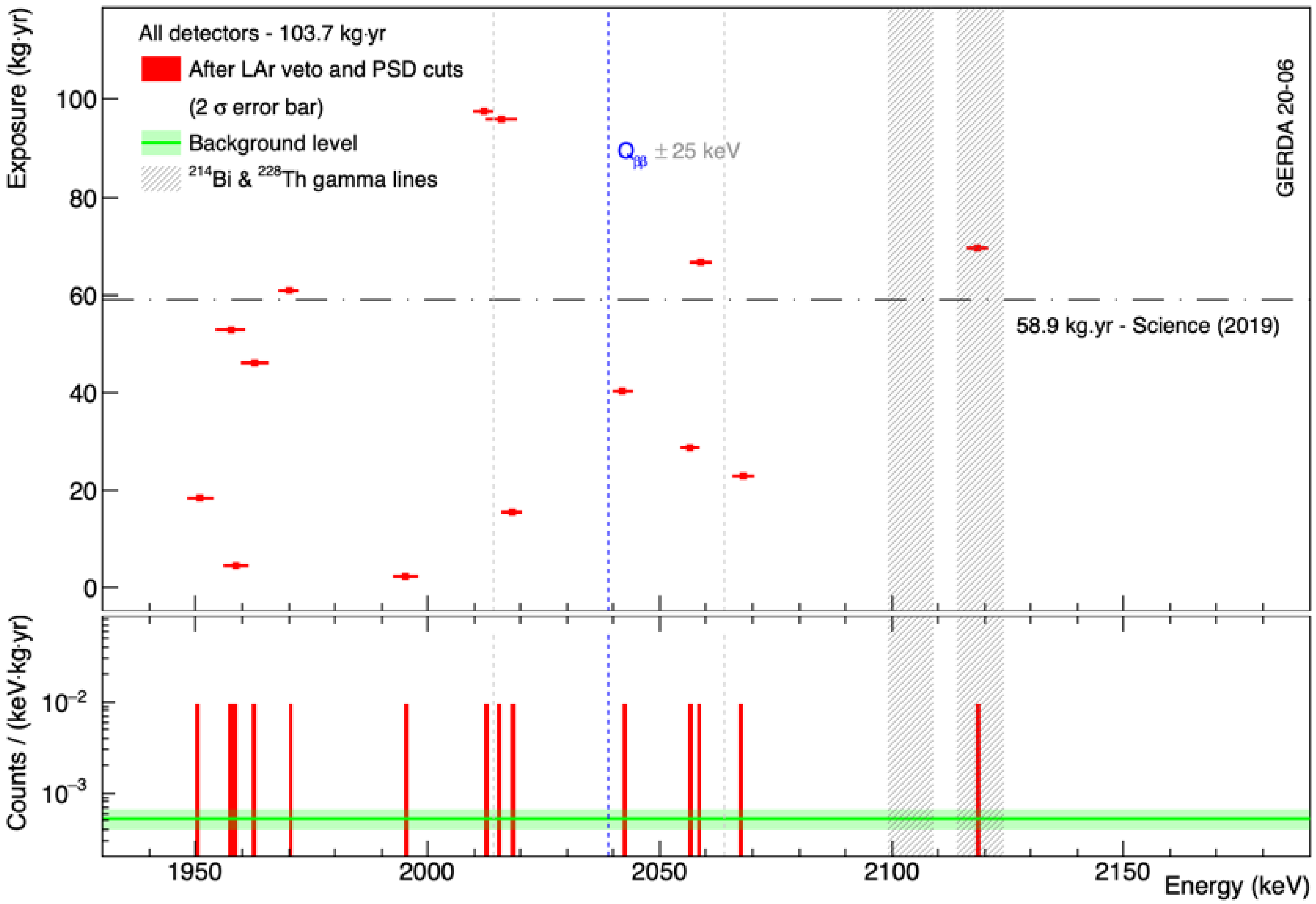
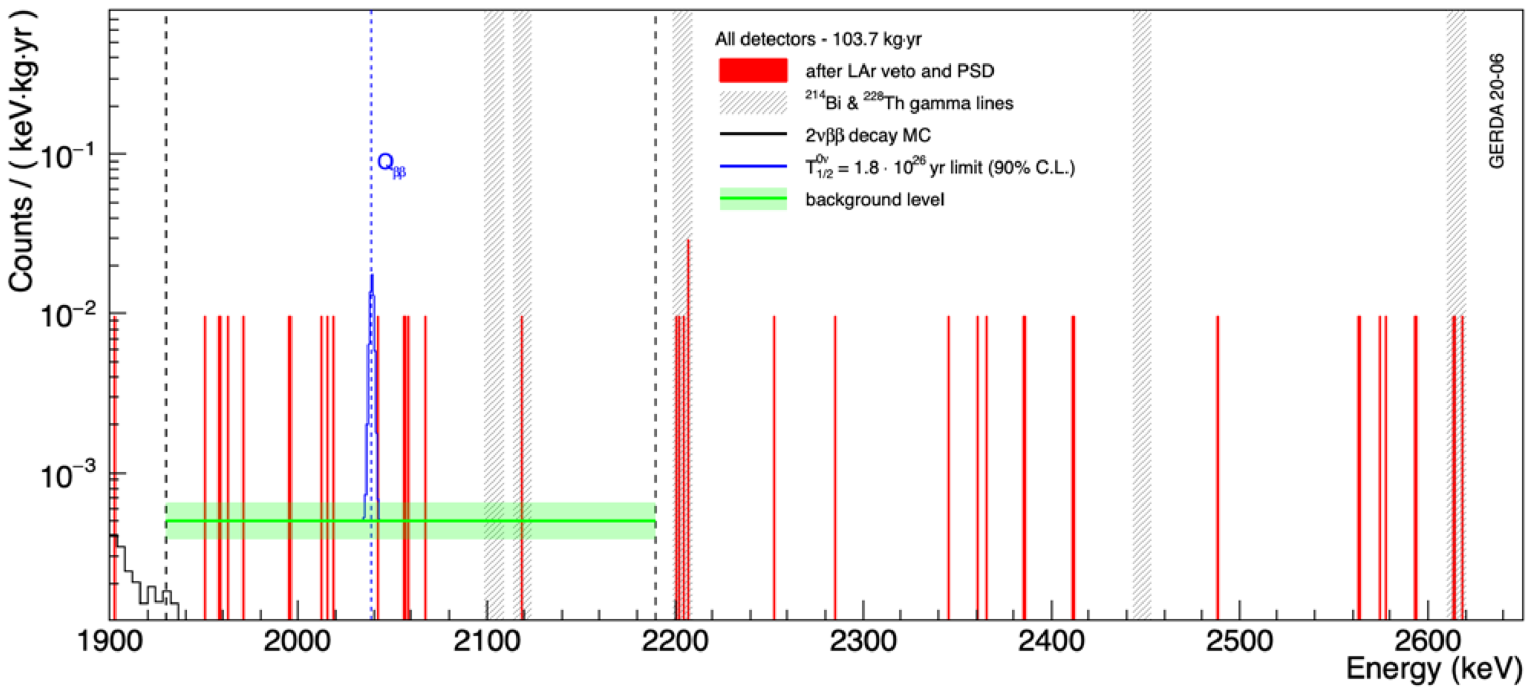
BW: [1930,2190] keV, excl. ±5 keV around ^{208}Tl (SEP), ^{214}Bi (FEP) and $Q_{\beta\beta} \pm 25$ keV



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

Statistical Analysis

Statistical analysis based on detectors-wise partitioning over stable periods



Frequentist:

– 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.

Bayesian:

– $T_{1/2}$ (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 Phase I design goals reached:**
  - No 0νββ 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
  - $T_{1/2}$ (0νββ) > 2.1×10^{25} yr (90% C.L.)

- **GERDA Phase II achievements:**
  - No 0νββ 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)
  - **$T_{1/2}$ (0νββ) > 1.8×10^{26} yr (90% C.L.)**
  - $m_{\beta\beta} \leq (0.080 – 0.182)$ eV

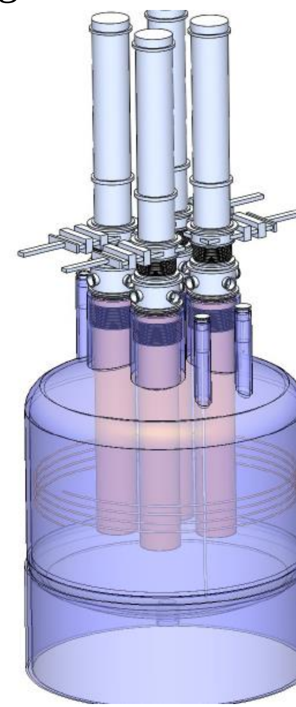
- **GERDA Phase II goals:**
  - Background index: ~10^{-3} cts / (keV×kg×yr)
  - Exposure: ~100 kg×yr
  - Sensitivity: ~10^{26} yr

- **GERDA: background-free 0νββ 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 2021

Beyond GERDA → LEGEND

First stage:

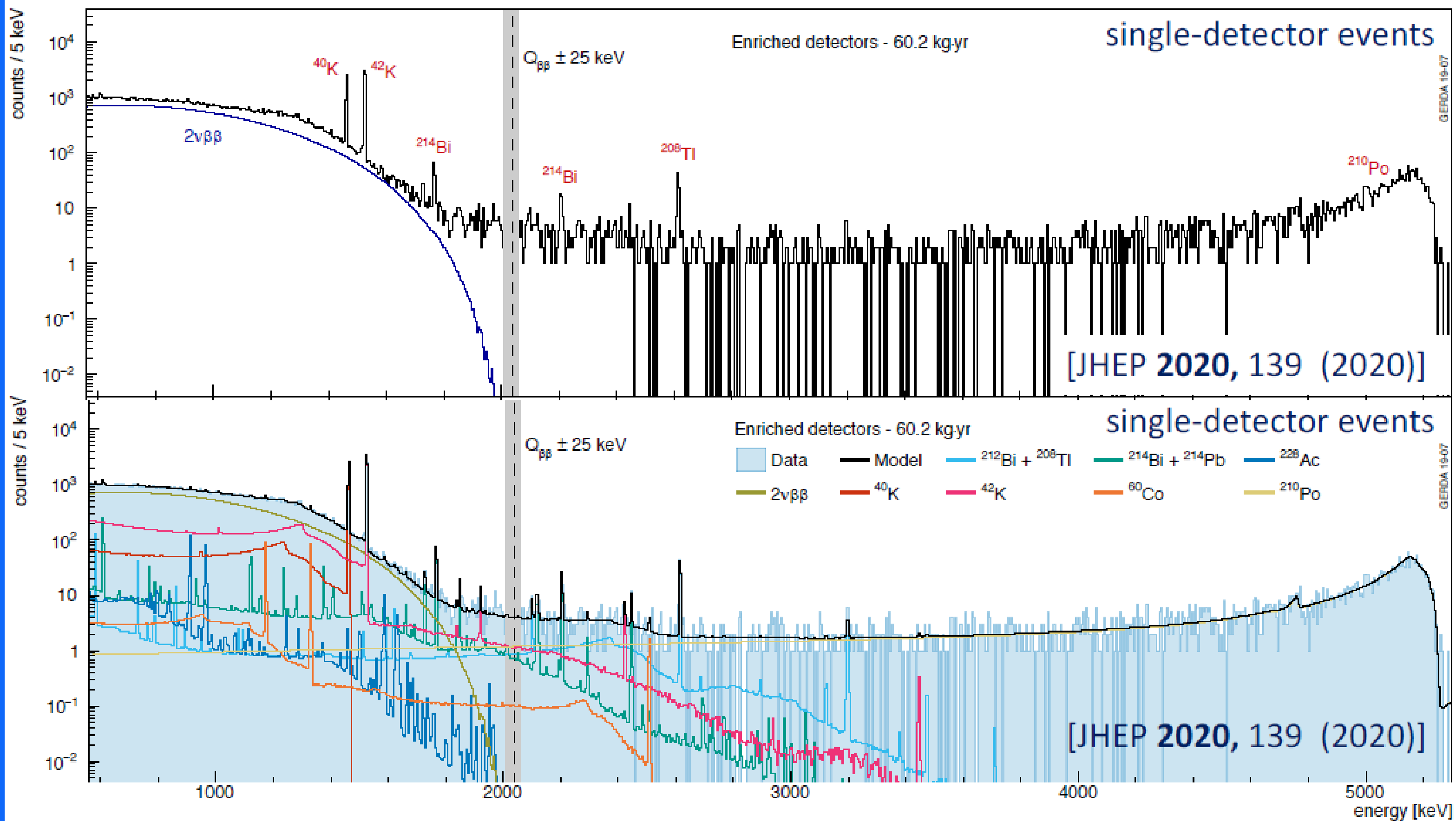
- GD + MJD + new groups
- Based on existing GERDA infrastructure
- Up to 200 kg of ^{enr}Ge
- Approved by LNGS in Aug. 2018
- Under preparation, PGT just finished
- Background reduction w.r.t GERDA: ~3
- Anticipated start of data taking in 2021
- $T_{1/2}$ ($0\nu\beta\beta$) $\geq 10^{27}$ yr



Subsequent stages:

- Up to 1000 kg of ^{enr}Ge
- Background reduction w.r.t GERDA: ~30
- Location to be defined
- Required depth (^{77m}Ge) under investigation
- pCDR almost ready

Background Model



- 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 $Q_{\beta\beta}$**