Search for Neutrinoless Double Beta Decay with GERDA

Grzegorz Zuzel

on behalf of the GERDA Collaboration

International Workshop on "Double Beta Decay and Underground Science" DBD18, October 21-23, Hawaii, USA

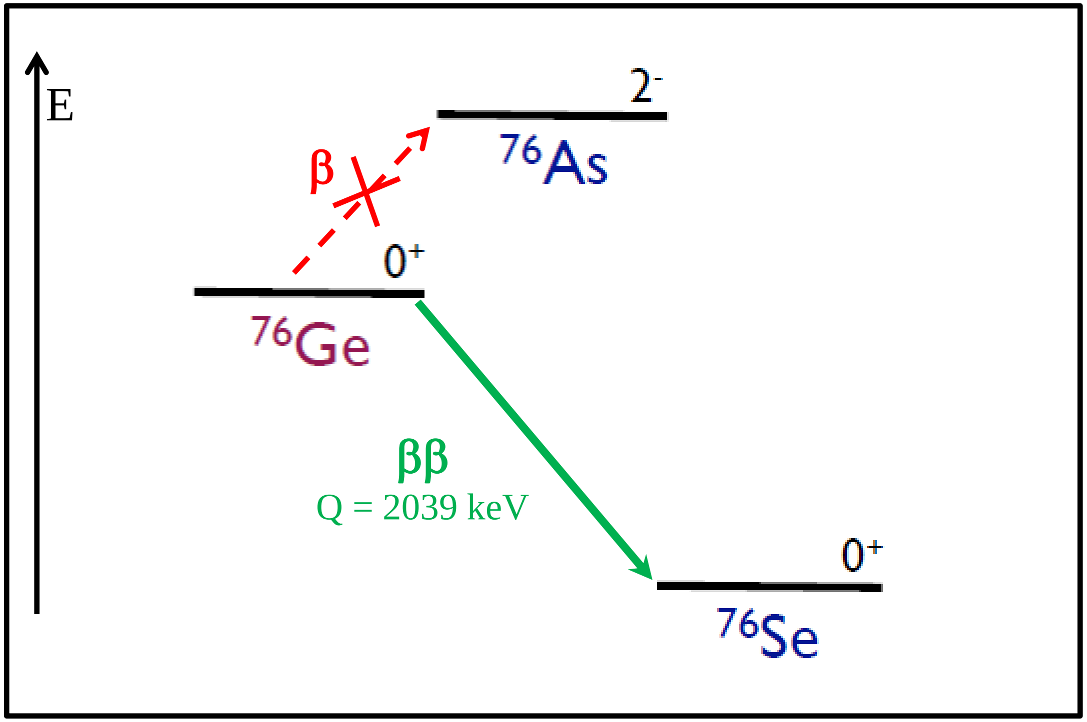
Outline

- Double beta decay
- Design and goals of GERDA
- Background reduction strategy
- GERDA latest results
- Summary

ββ decay
GERDA design
Bkg reduction
Latest results
Summary

Double Beta Decay

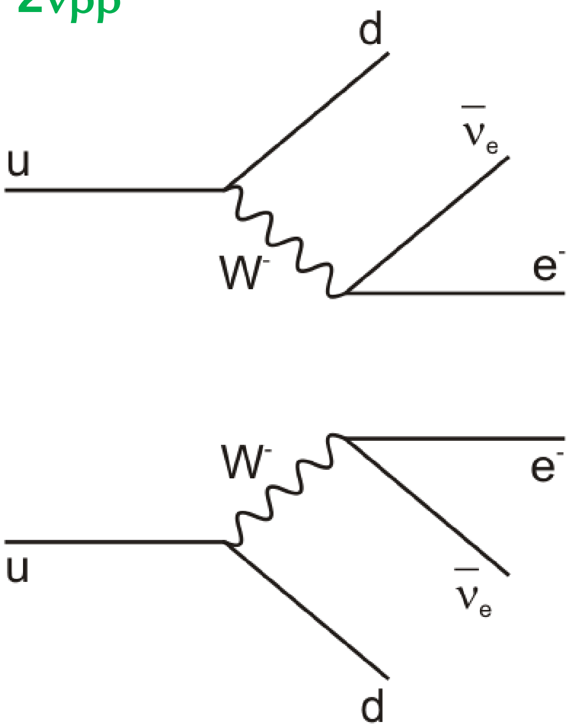
In a number of even-even nuclei, β decay due to energy/angular momentum balance is forbidden, while double beta decay from a nucleus (A,Z) to (A, Z+2) is energetically allowed.



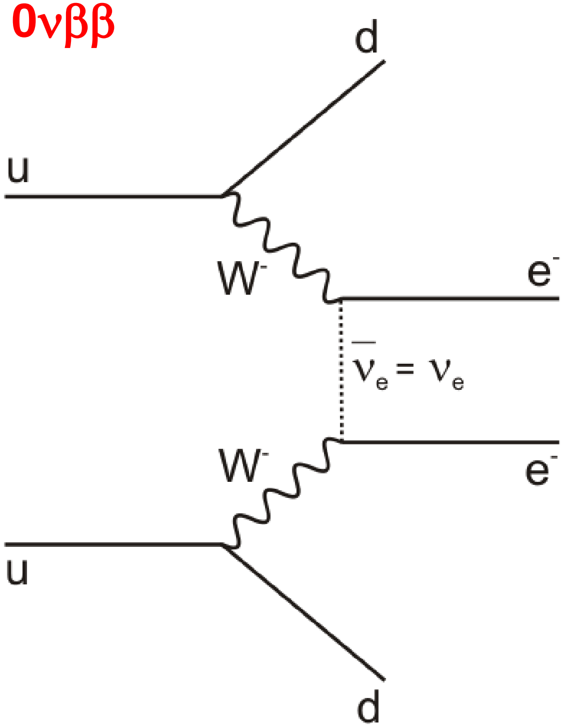
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

Double Beta Decay Modes

ββ decay
GERDA design
Bkg reduction
Latest results
Summary



2νββ



0νββ

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

$\Delta L = 0$

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

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

$\Delta L = 2$

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

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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

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

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

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

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

GERDA

ββ decay
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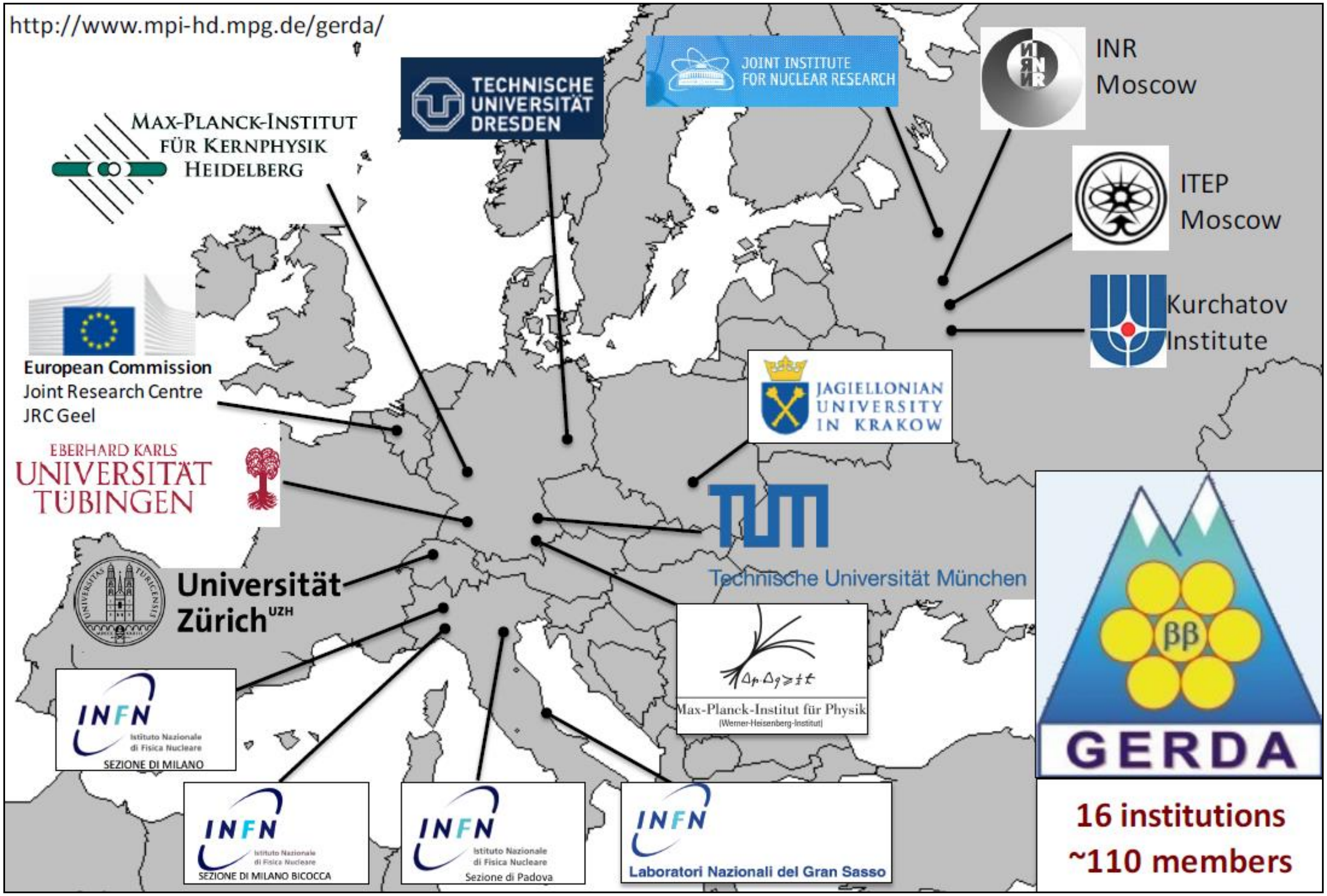
Summary

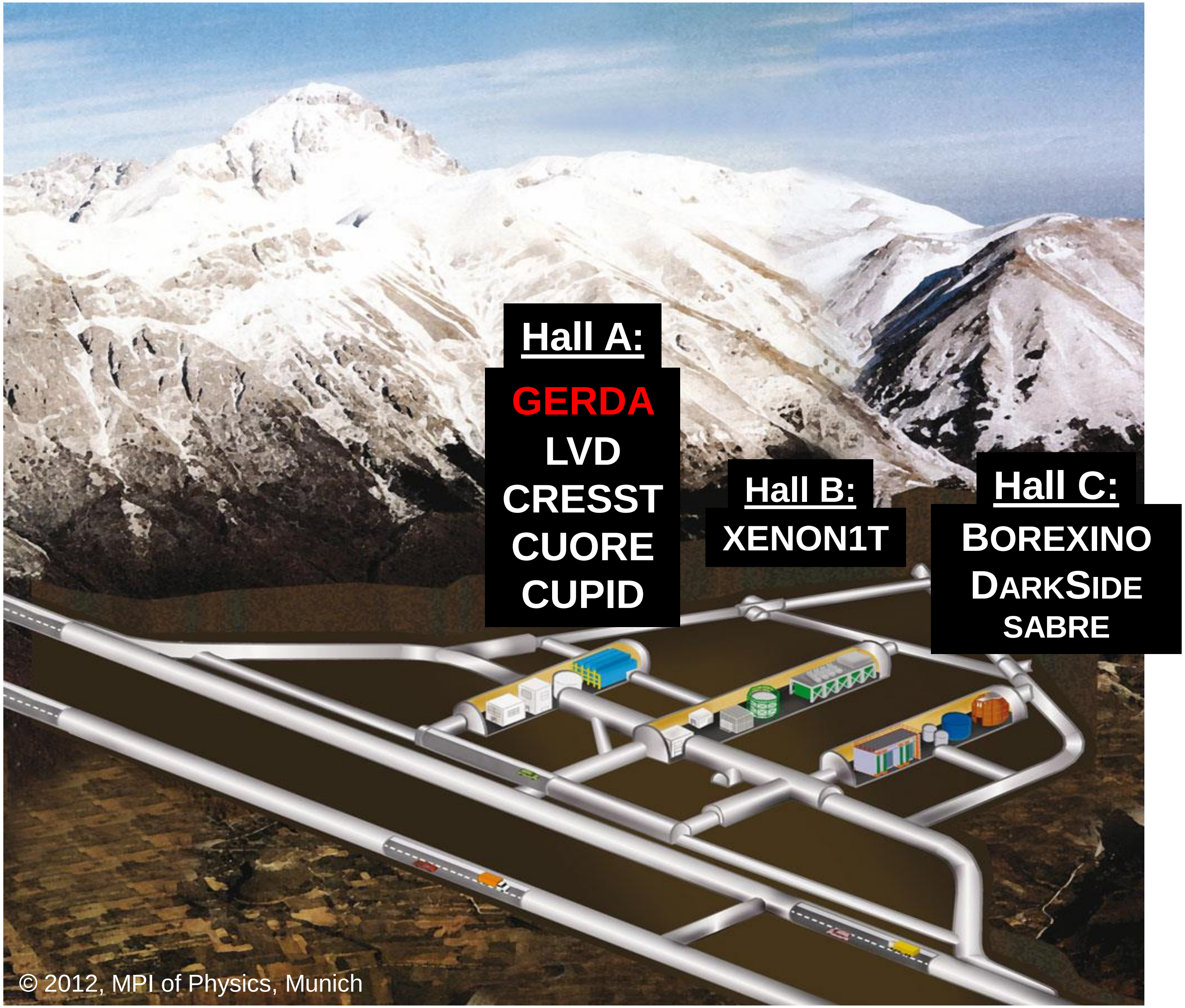
- GERDA (GERmanium Detector Array) has been designed to investigate neutrinoless double beta decay of ^{76}Ge ($Q_{\beta\beta}$ = 2039 keV)
  - Ge mono-crystals are very pure
  - Ge detectors have excellent energy resolution
  - Detector = source ($\varepsilon \approx 1$)
  - Enrichment required (7.4 % → 86 %)
  - **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

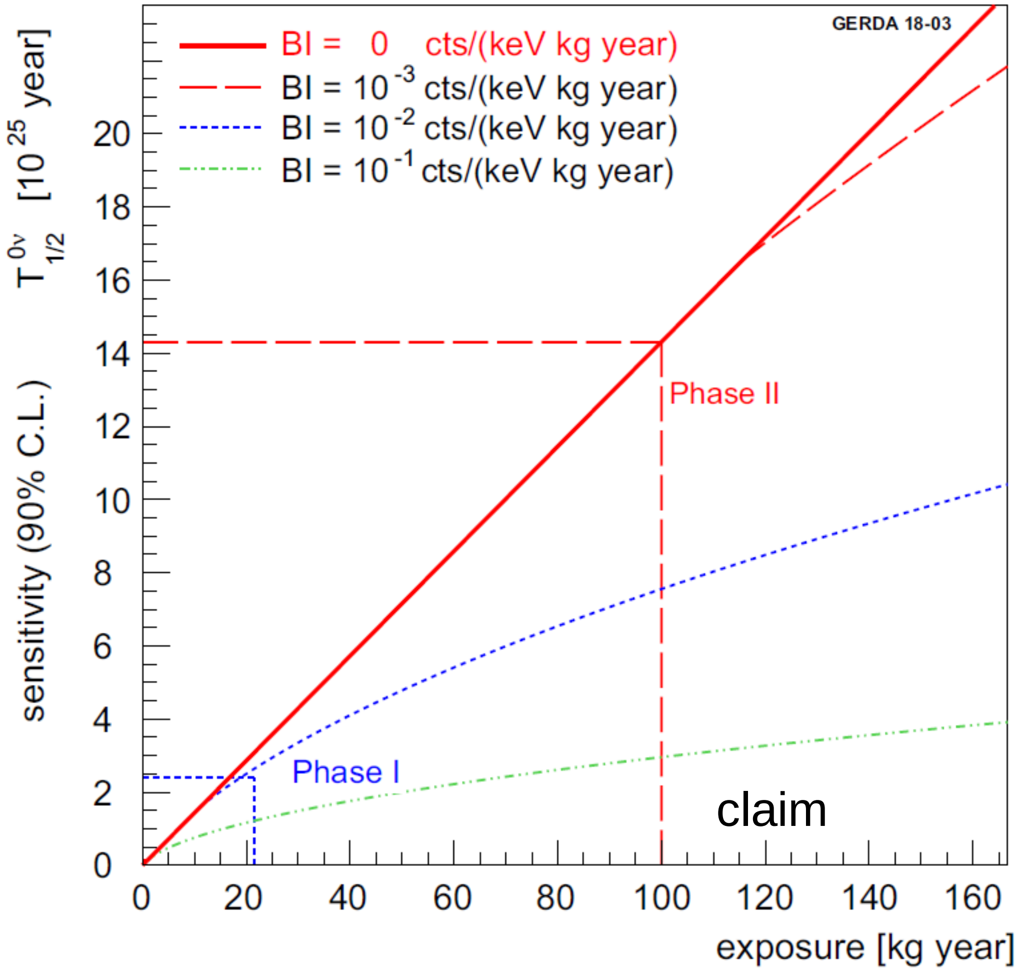

http://www.mpi-hd.mpg.de/gerda/

16 institutions
~110 members

GERDA at LNGS



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 detectors (+20 kg, 35 kg tot.)

BI ≈ 10^{-3} cts / (keV×kg×yr)

Sensitivity after 100 kg×yr

Phase I:

Use refurbished HdM & IGEX (18 kg)

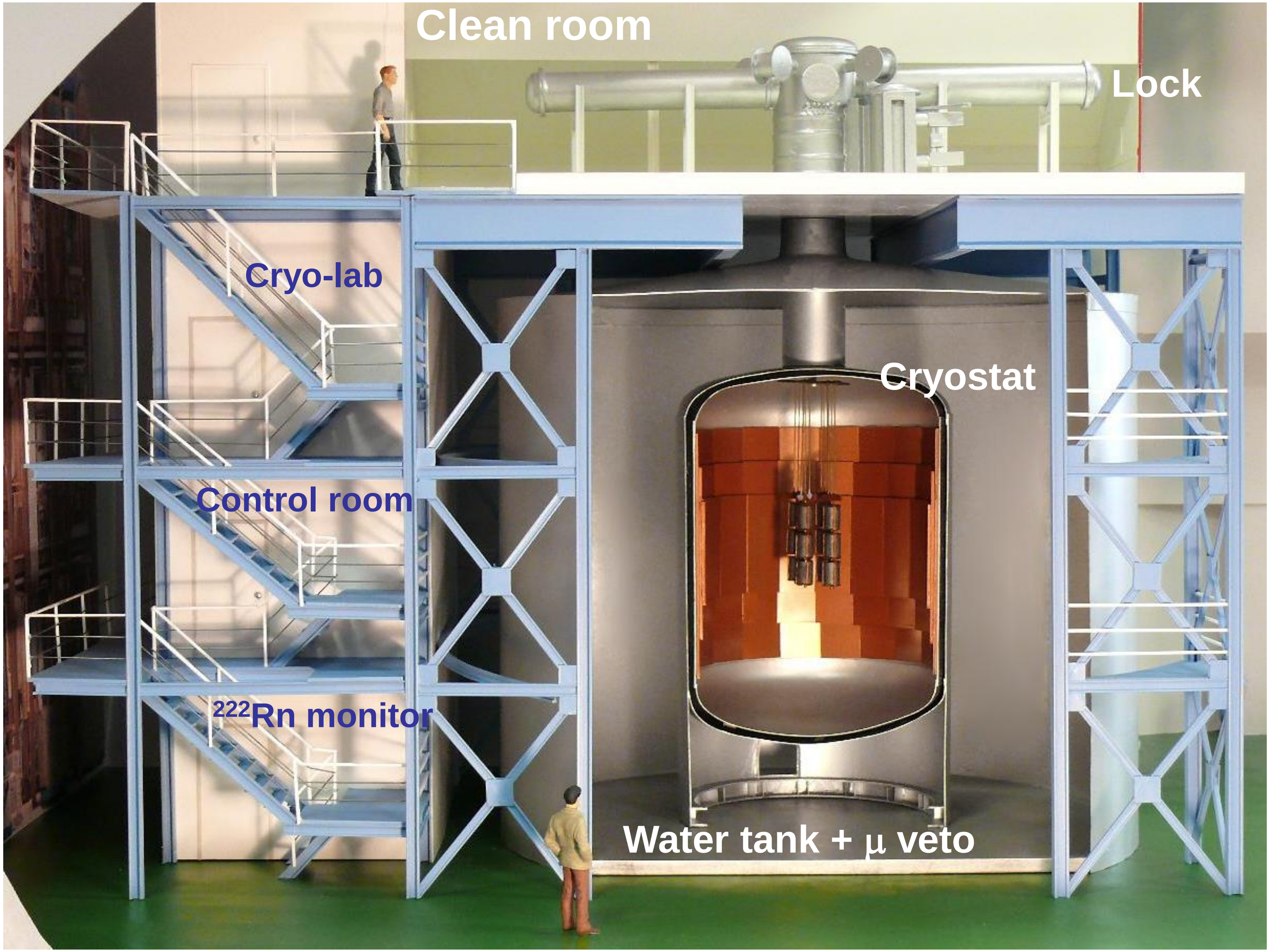
BI ≈ 10^{-2} cts / (keV×kg×yr)

Sensitivity after 20 kg×yr

GERDA History

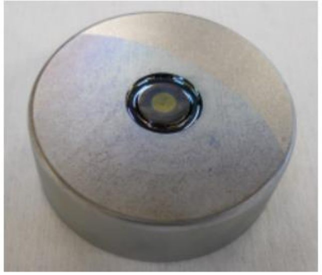
- 2004 – 2005: The collaboration was formed
- 2005 – 2010: GERDA funded, designed and constructed in LNGS Hall A
- 2010 – 2011: Phase I commissioning
- June 2011: Deployment of the first string of ^{enr}Ge (3 detectors, 6.7 kg)
- 01.11.2011: Start data taking with all 8 Phase I ^{enr}Ge crystals (17.8 kg) and 1 ^{nat}Ge crystal (from GTF)
- June 2012 5 Phase II enr. BEGe detectors inserted into the cryostat
- Phase I data: 09.11.11 – 09.05.13 (21.6 kg×yr acquired)
- 2013 – 2015: upgrade to Phase II
- December 2015: Phase II data taking starts
- April – May 2018: Phase II upgrade

GERDA Phase I

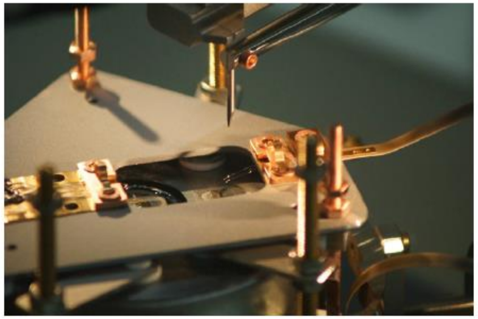


GERDA Phase II Setup

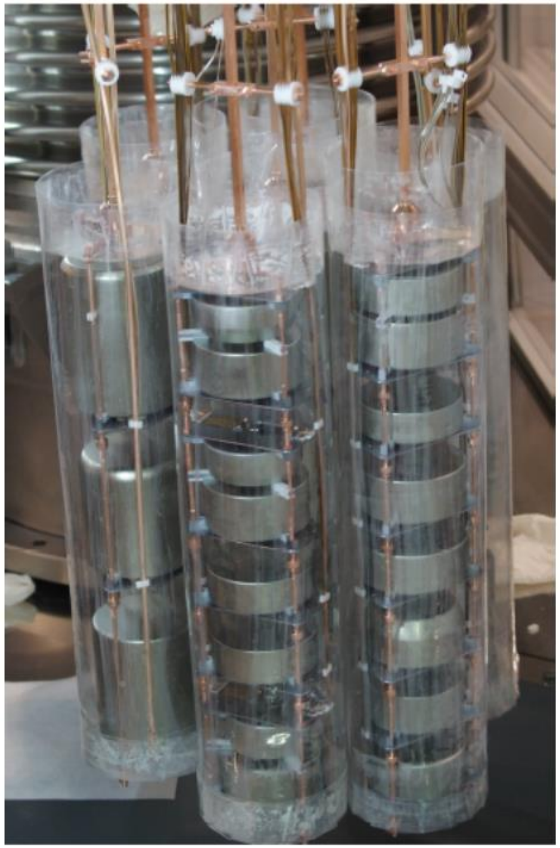
New low-mass detector holders (Si, Cu, PTFE)



New thick-window BEGe detectors



New signal and HV contacting by wire bonding flat ribbon cables



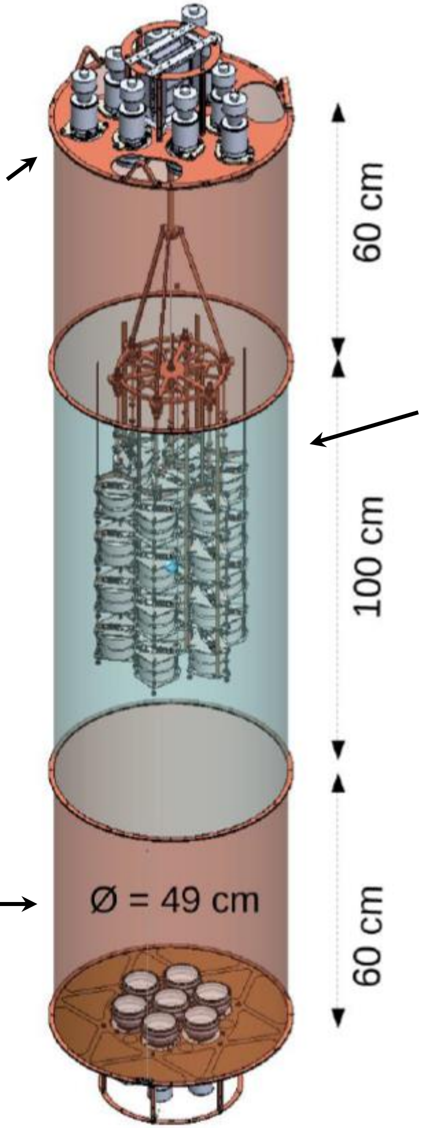
New TPB coated nylon mini-shrouds to reduce attraction of ^{42}K ions (from decays of ^{42}Ar) to n^+ surface

TBP = tetraphenyl butadiene

Hybrid LAr veto: PMTs + Fibers

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

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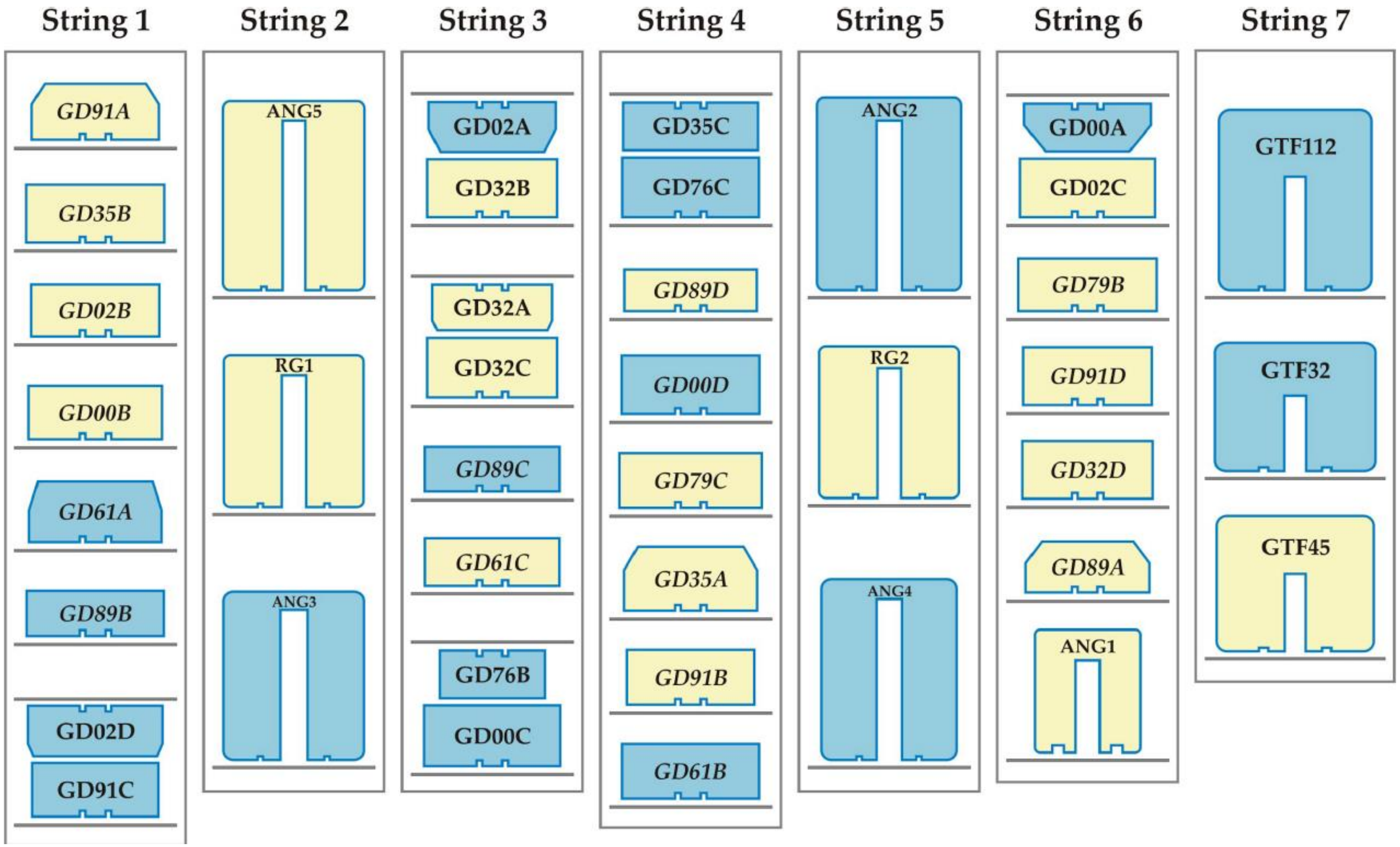
GERDA Phase II Array

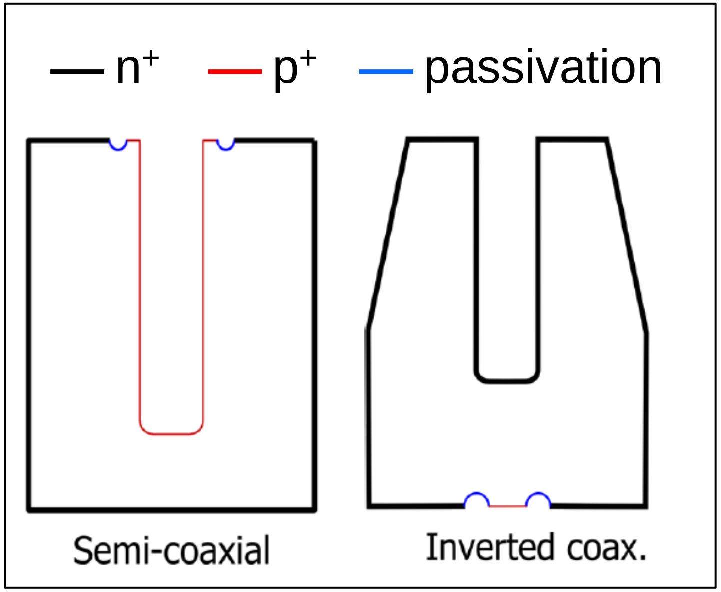


GERDA Phase II (Dec 2015 -)

- 30 enriched BEGe (20.0 kg), 7 enriched coax (15.8 kg), 3 natural coax (7.6 kg)
- LAr instrumentation: 90 (SiPMs) + 16 (PMTs) channels
- BI ~ 10^{-3} cts/(keV×kg×yr)

Upgrade of Phase II

- Natural coax replaced with 9 kg (5 detectors) enriched inverted coax type
- New LAr instrumentation: installation of denser fibre curtain and middle string curtain
- 3 Ge channels recovered
- Few detectors etched to reduce their leakage current
- Some cables replaced with lower activity version



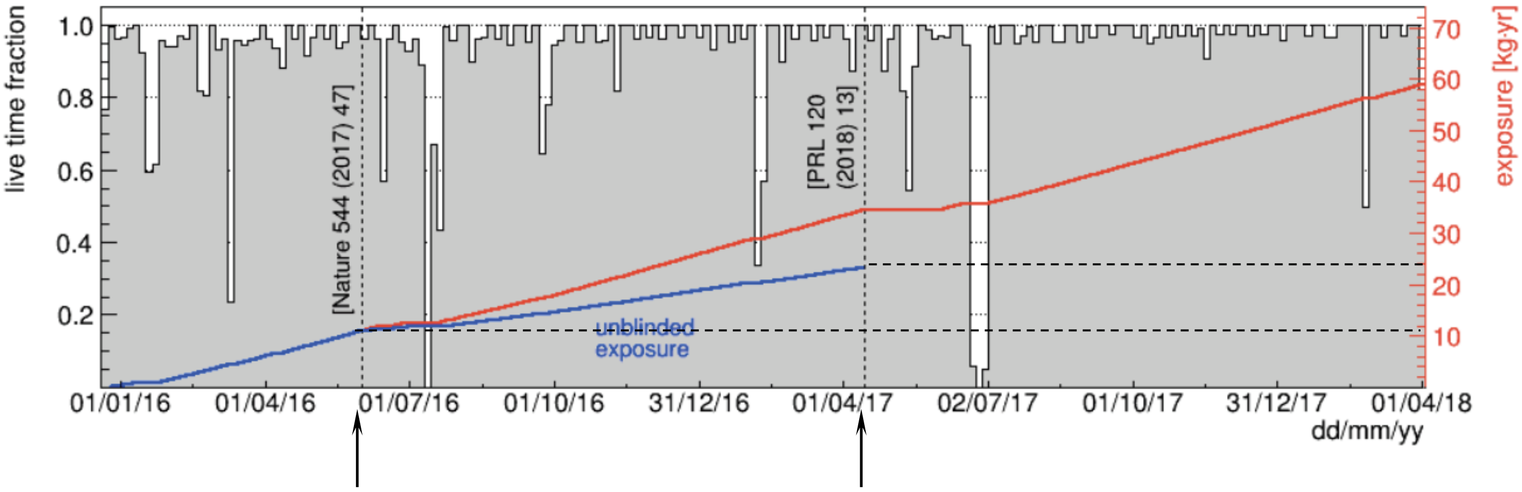
Accumulation of Data

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

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

Phase II: 23.2 kg·yr

- Live time: 834.8 d between Dec. 2015 and April 2018
- Duty cycle: 92.9 %
- Data quality cut: 80.4 %
- Phase II exposure analyzed: 58.9 kg×yr
- **Total GERDA exposure (April 2018): 82.4 kg×yr**

Energy Scale and Stability

ββ decay

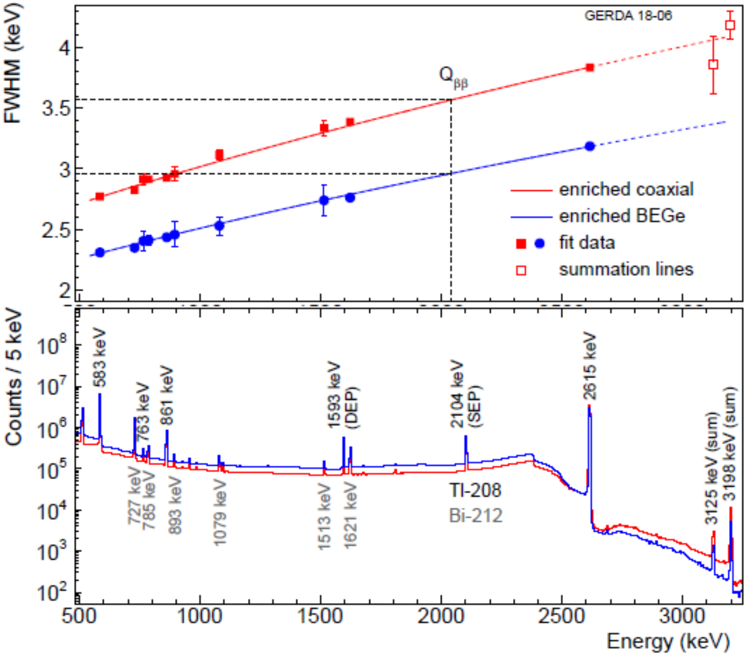
GERDA design

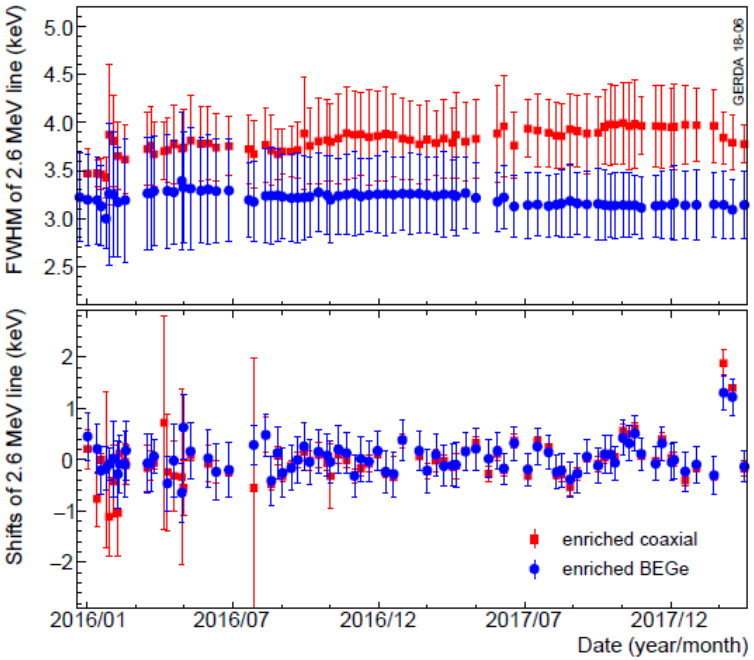
Bkg reduction

Latest results

Summary

- 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 @ $Q_{\beta\beta}$: Coax: 3.6(1) keV

BEGe: 3.0(1) keV

LAr Veto

ββ decay
GERDA design
Bkg reduction
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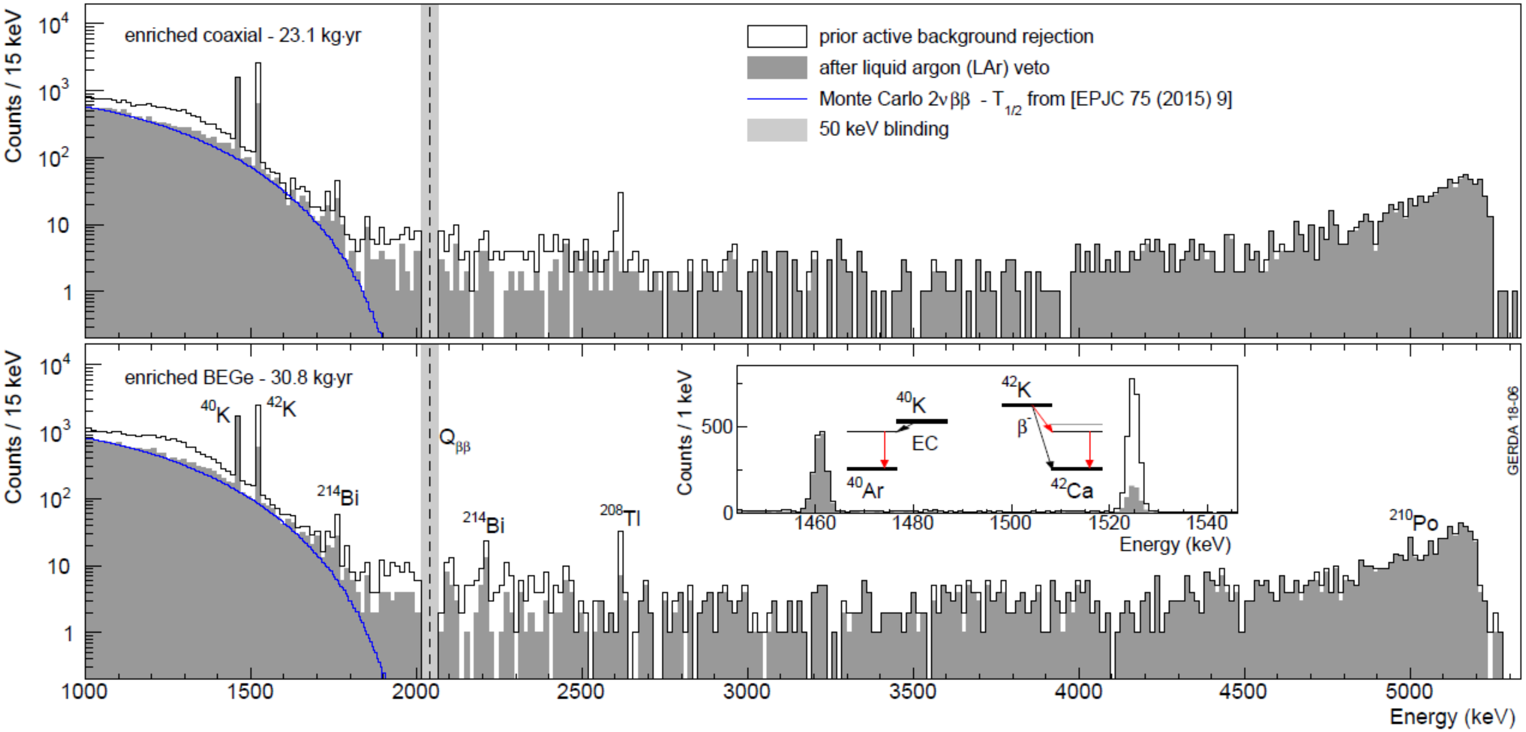
Summary

- Channel-wise (PMT/SiPM) anti-coincidence condition
- Thresholds at ~0.5 P.E.
- Acceptance determined from random triggers: 97.7(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)



PSD for BEGe Detectors

ββ decay

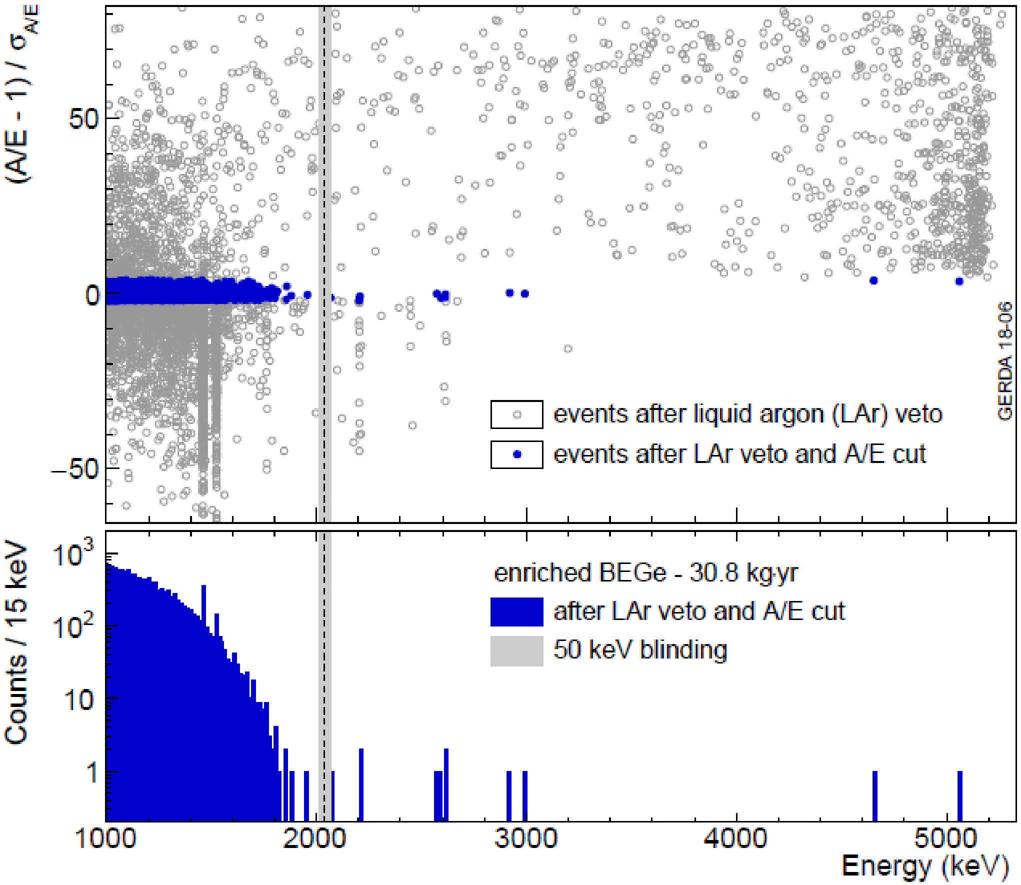
GERDA design

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

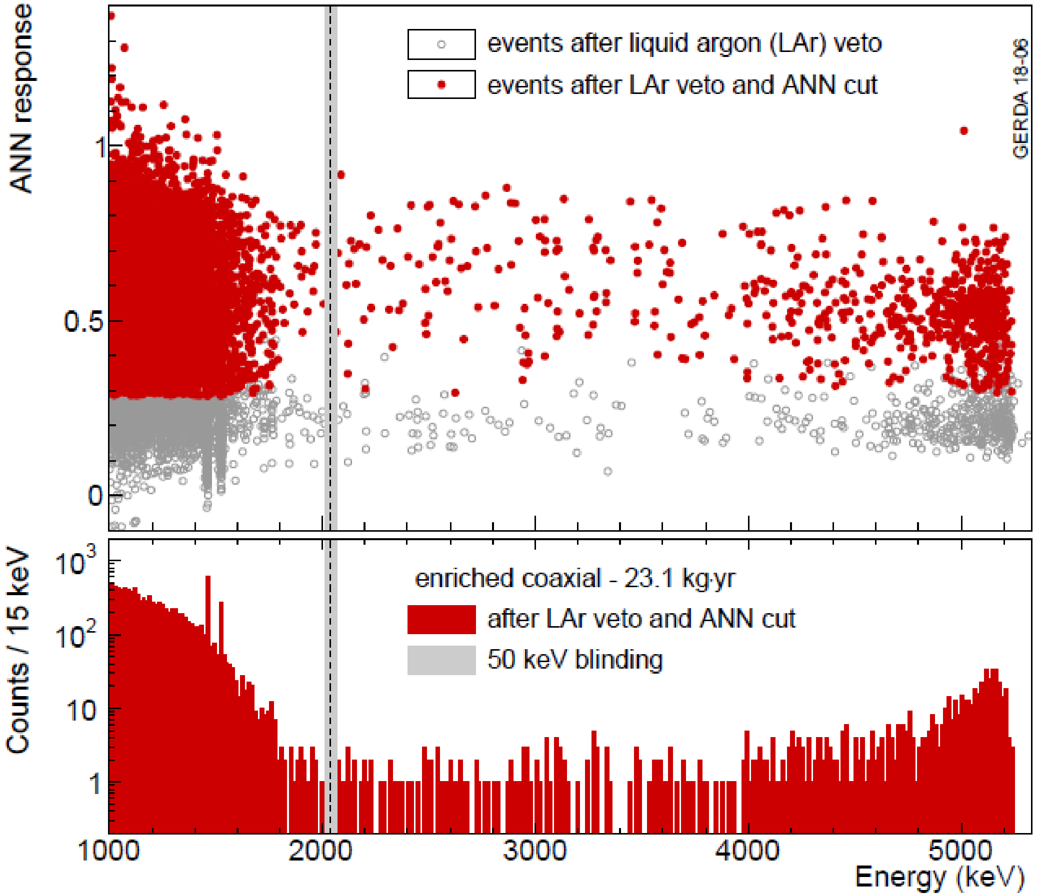


SF_{BW} = 82 %
$\varepsilon_{0\nu\beta\beta}$ = (87.6 ± 2.5) %

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

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)



$\varepsilon_{0\nu\beta\beta}$ **(ANN) = (85.0 ± 5.0) %**

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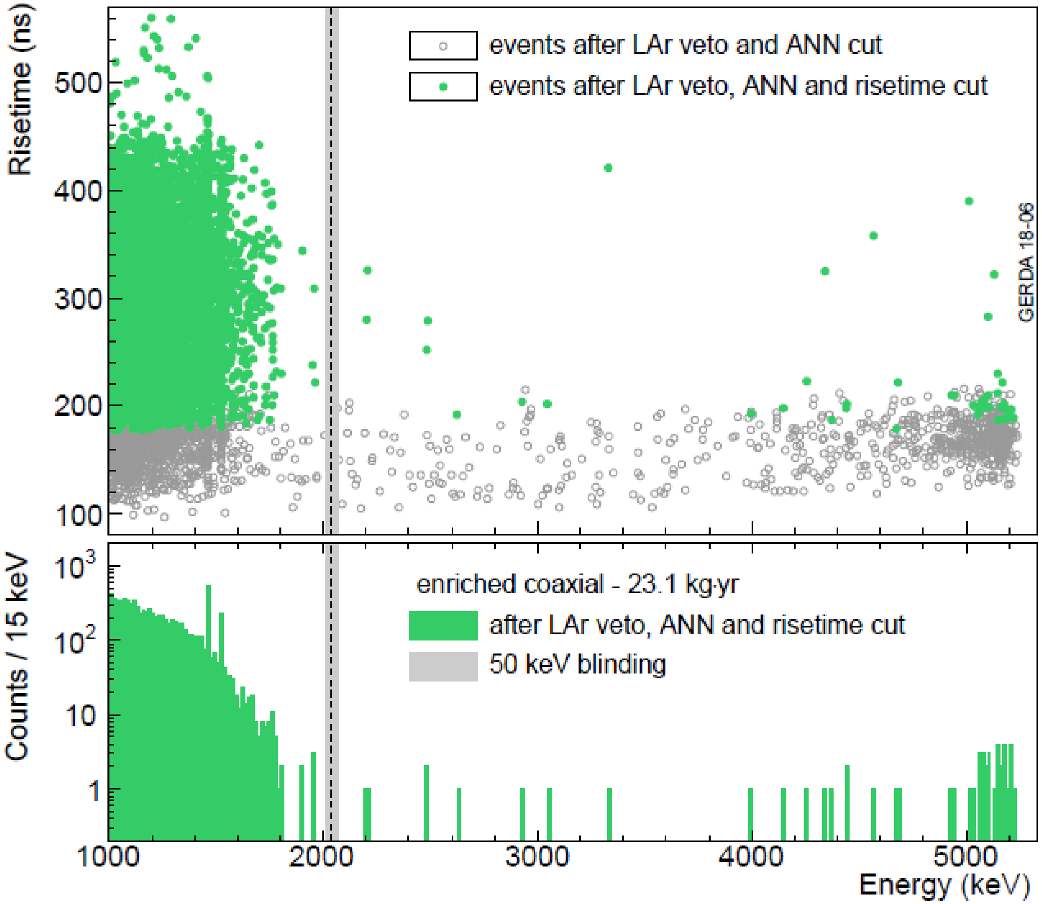

$\varepsilon_{0\nu\beta\beta}$ (ANN) = (85.0 ± 5.0) %
$\varepsilon_{0\nu\beta\beta}$ (RT) = (84.3 ± 1.1) %
$\varepsilon_{0\nu\beta\beta}$ = (71.6 ± 4.3) %

Application of LAr veto and PSD

ββ decay
GERDA design
Bkg reduction
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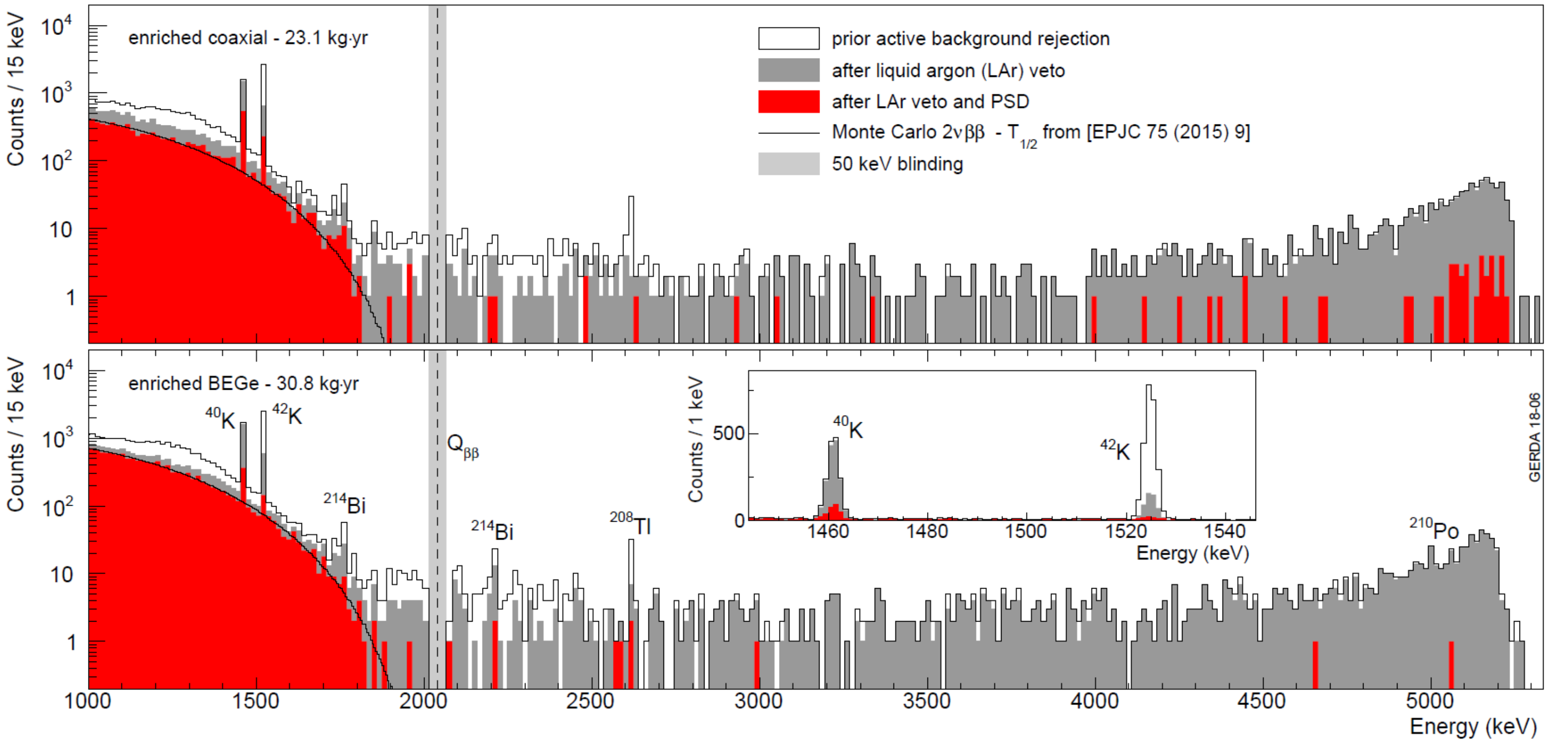
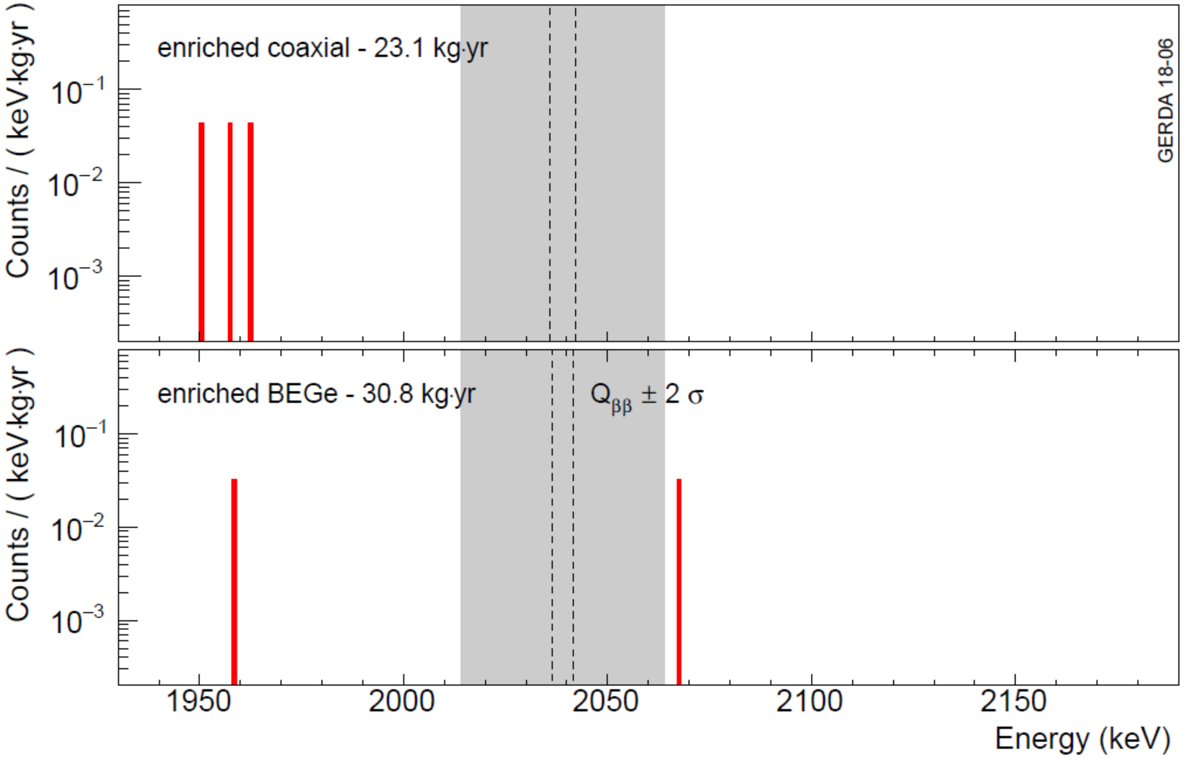
Summary



- LAr veto and PSD are complementary
- Strong reduction of ^{40}K/^{42}K and αs
- Combined efficiency for the 0νββ decay:
  70 % for coax detectors
  86 % for BEGe detectors

Background Index in BW



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

$$\textbf{Coax}:\ \mathrm{BI} = 5.7^{+4.1}_{-2.6} \cdot 10^{-4}\ \mathrm{cts/(keV{\cdot}kg{\cdot}yr)}$$

$$\textbf{BEGe}:\ \mathrm{BI} = 5.6^{+3.4}_{-2.4} \cdot 10^{-4}\ \mathrm{cts/(keV{\cdot}kg{\cdot}yr)}$$

Less than 1 background event expected in ROI → background-free operation

Statistical Analysis

ββ decay
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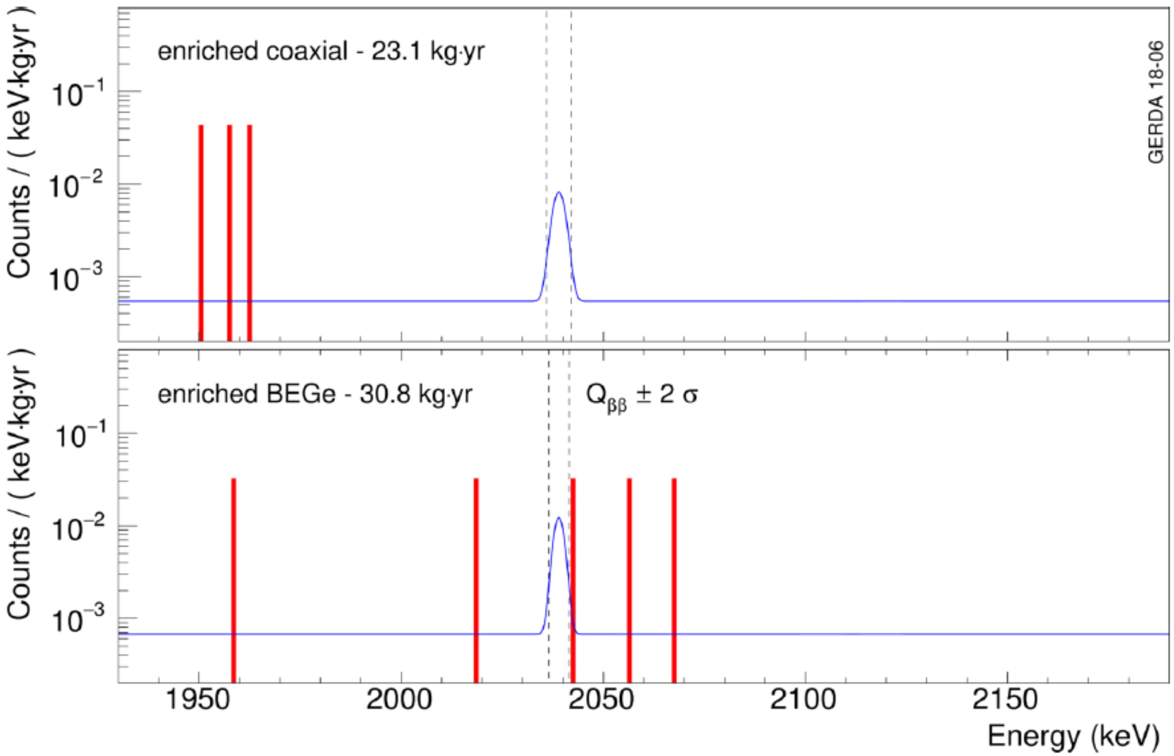


Frequentist:

– best fit $N_{0\nu} = 0$

– $T_{1/2}$ ($0\nu\beta\beta$) > 0.9×10^{26} yr, median sensitivity $T_{1/2}$ ($0\nu\beta\beta$) > 1.1×10^{26} yr at 90% C.L.

Bayesian:

– $T_{1/2}$ ($0\nu\beta\beta$) > 0.8×10^{26} yr, median sensitivity $T_{1/2}$ ($0\nu\beta\beta$) > 0.8×10^{26} yr at 90% C.I.

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: $\sim 10^{-2}$ 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: $\sim 5.7\times10^{-4}$ cts / (keV×kg×yr)**
  - Exposure 58.9 kg×yr (April 2018, 82.4 kg×yr in total)
  - **$T_{1/2}$ ($0\nu\beta\beta$) > 0.9×10^{26} yr (90% C.L.)**
  - $m_{\beta\beta} \leq (0.11 – 0.26)$ eV

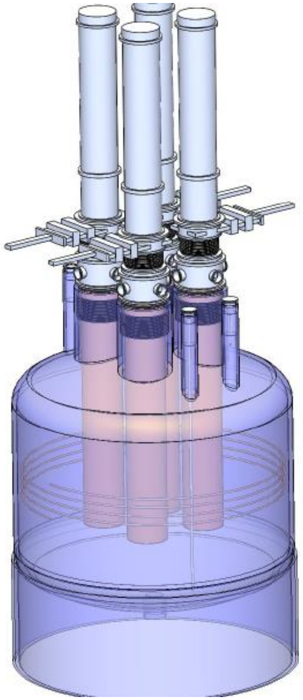
- **GERDA Phase II goals:**
  - Background index: $\sim 10^{-3}$ cts / (keV×kg×yr)
  - Exposure: ~100 kg×yr
  - Sensitivity: $\sim 10^{26}$ yr

- **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 2020/2021

Beyond GERDA → LEGEND

First stage:

- Based on existing GERDA infrastructure
- Up to 200 kg of ^{enr}Ge
- Approved by LNGS (Aug. 2018)
- Under preparation
- 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

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GERDA

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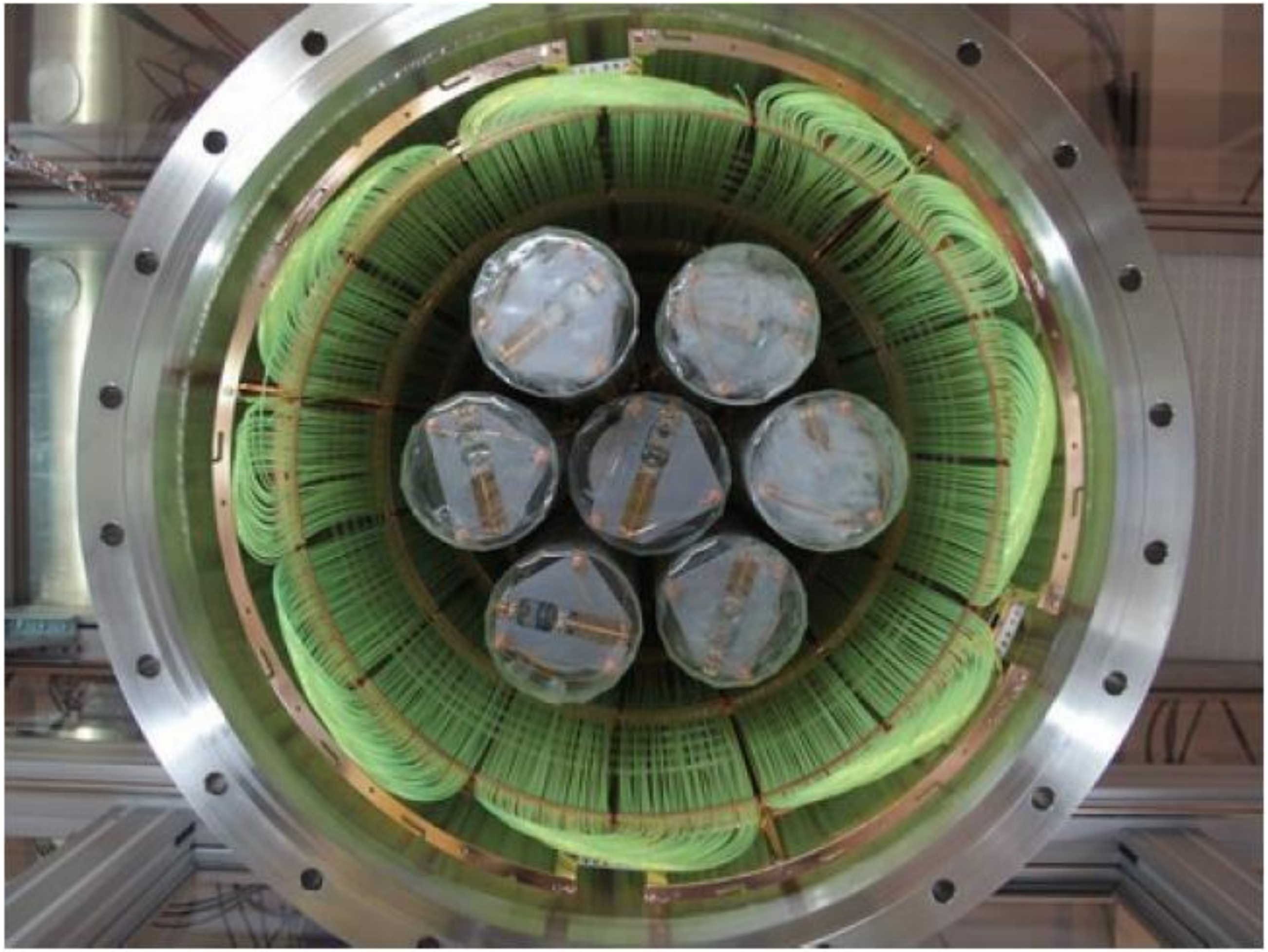

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Achieved what was envisioned in 2004