Search for Neutrinoless Double Beta Decay with GERDA

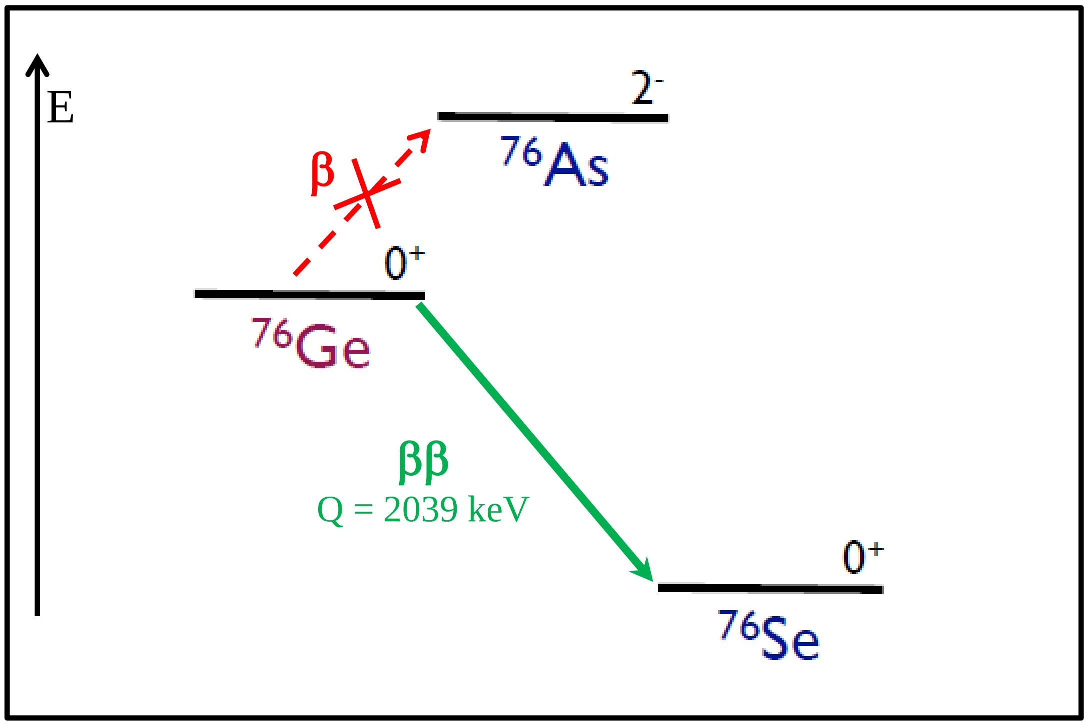
Grzegorz Zuzel
on behalf of the GERDA Collaboration

Outline

- Double beta decay
- Design and goals of GERDA
- Background reduction strategy
- GERDA 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.

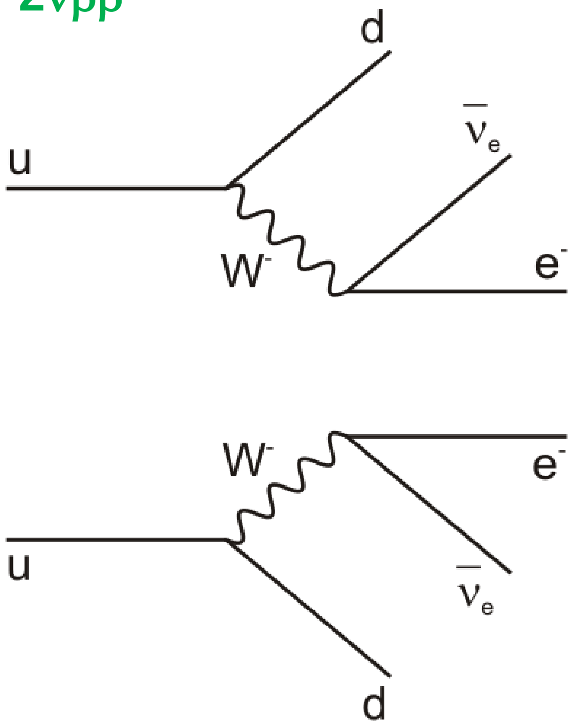


^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

Double Beta Decay Modes

ββ decay
GERDA design
Bkg reduction
Latest results
Summary

$2\nu\beta\beta$

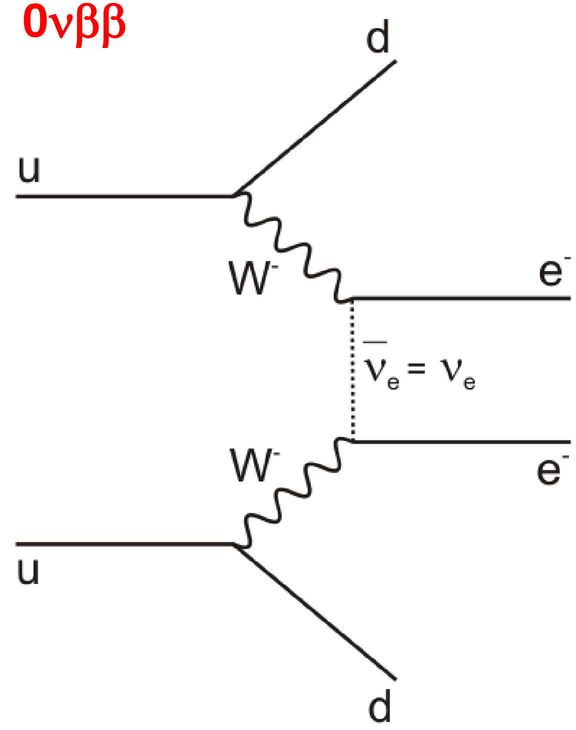


$(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

$\Delta L = 0$

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

$0\nu\beta\beta$



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

$\Delta L = 2$

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

Background Issue

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

No background

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

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

Background

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

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

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

GERDA

ββ decay

GERDA design

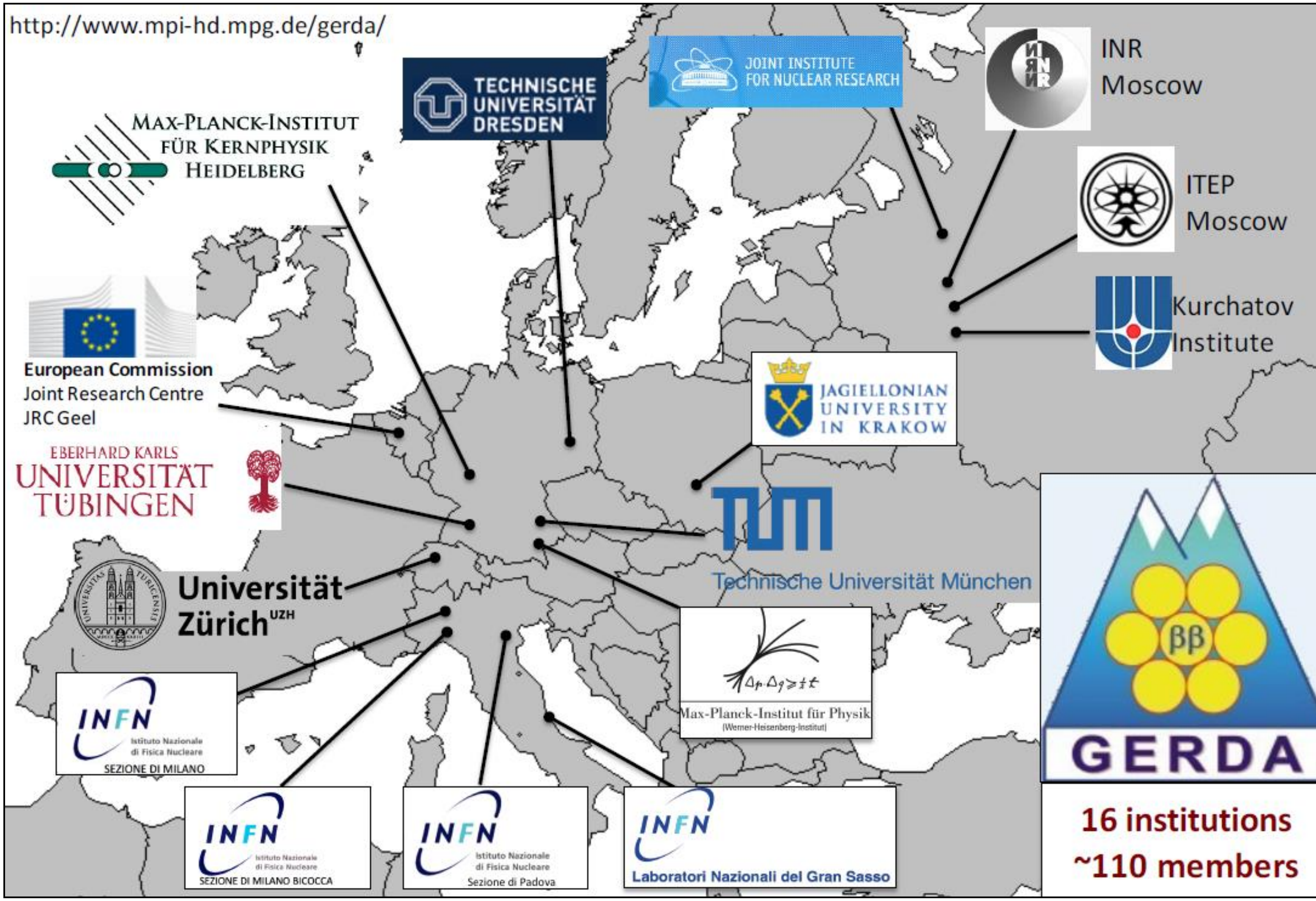
Bkg reduction

Latest results

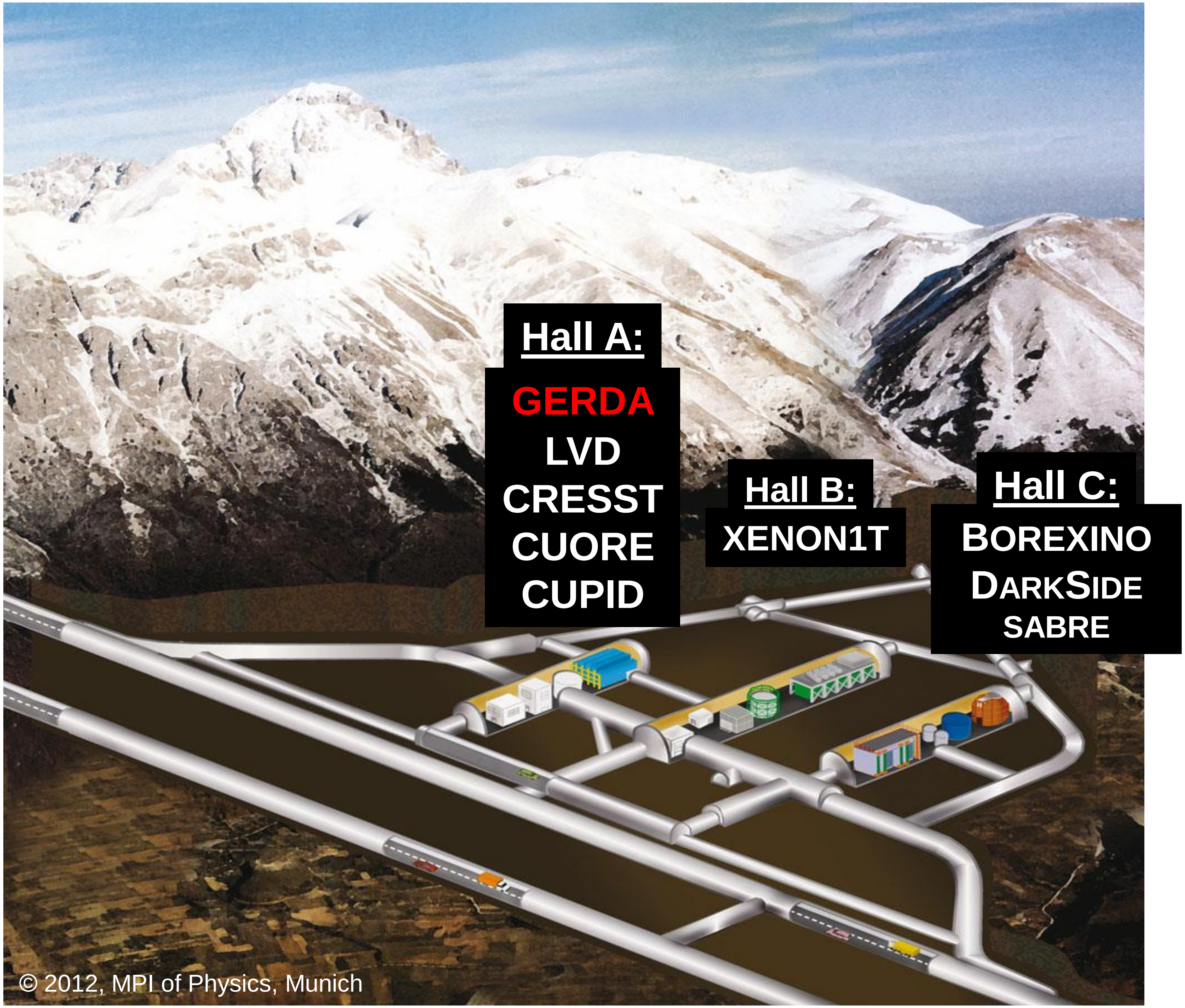
Summary

- 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 % $\rightarrow$ 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)

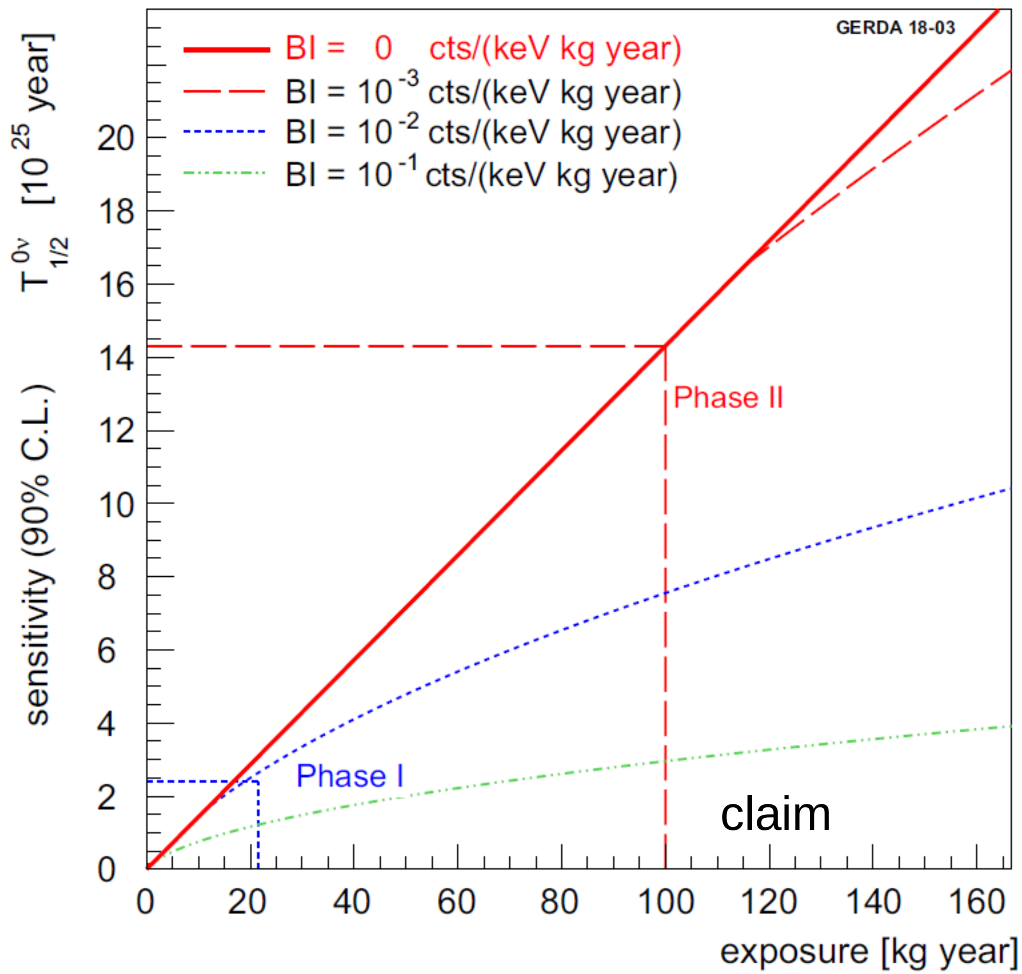
The GERDA Collaboration



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)

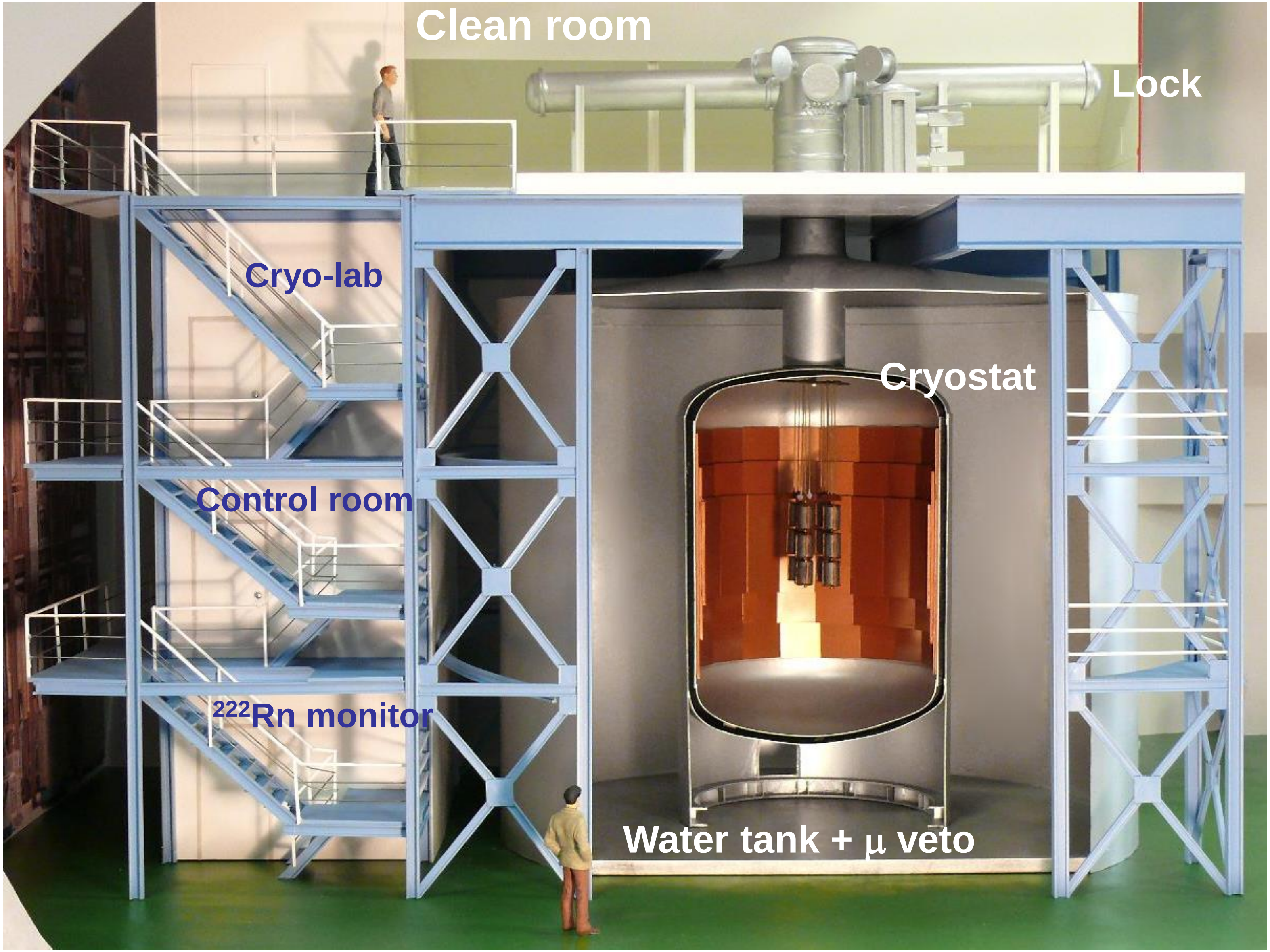
Sensitivity after 20 kg×yr

Development of GERDA

ββ decay
GERDA design
Bkg reduction
Latest results
Summary

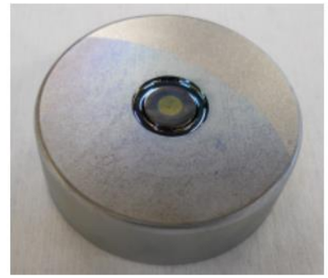
- 2004 – 2005: The collaboration was formed
- 2005 – 2010: GERDA funded, designed and constructed in LNGS Hall A
- 2010 – 2011: Phase I commissioning
- June 2011: Deployment of the first string of ^{enr}Ge (3 detectors, 6.7 kg)
- 01.11.2011: Start data taking with all 8 Phase I ^{enr}Ge crystals (17.8 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

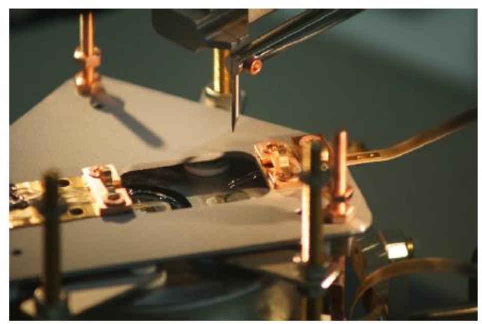


GERDA Phase II Setup

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



New thick-window BEGe detectors



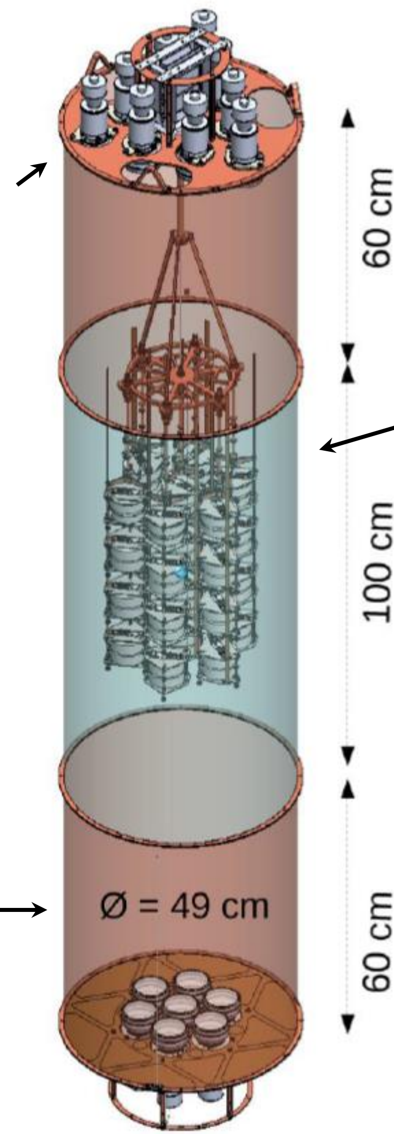
New signal and HV contacting by wire bonding flat ribbon cables

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

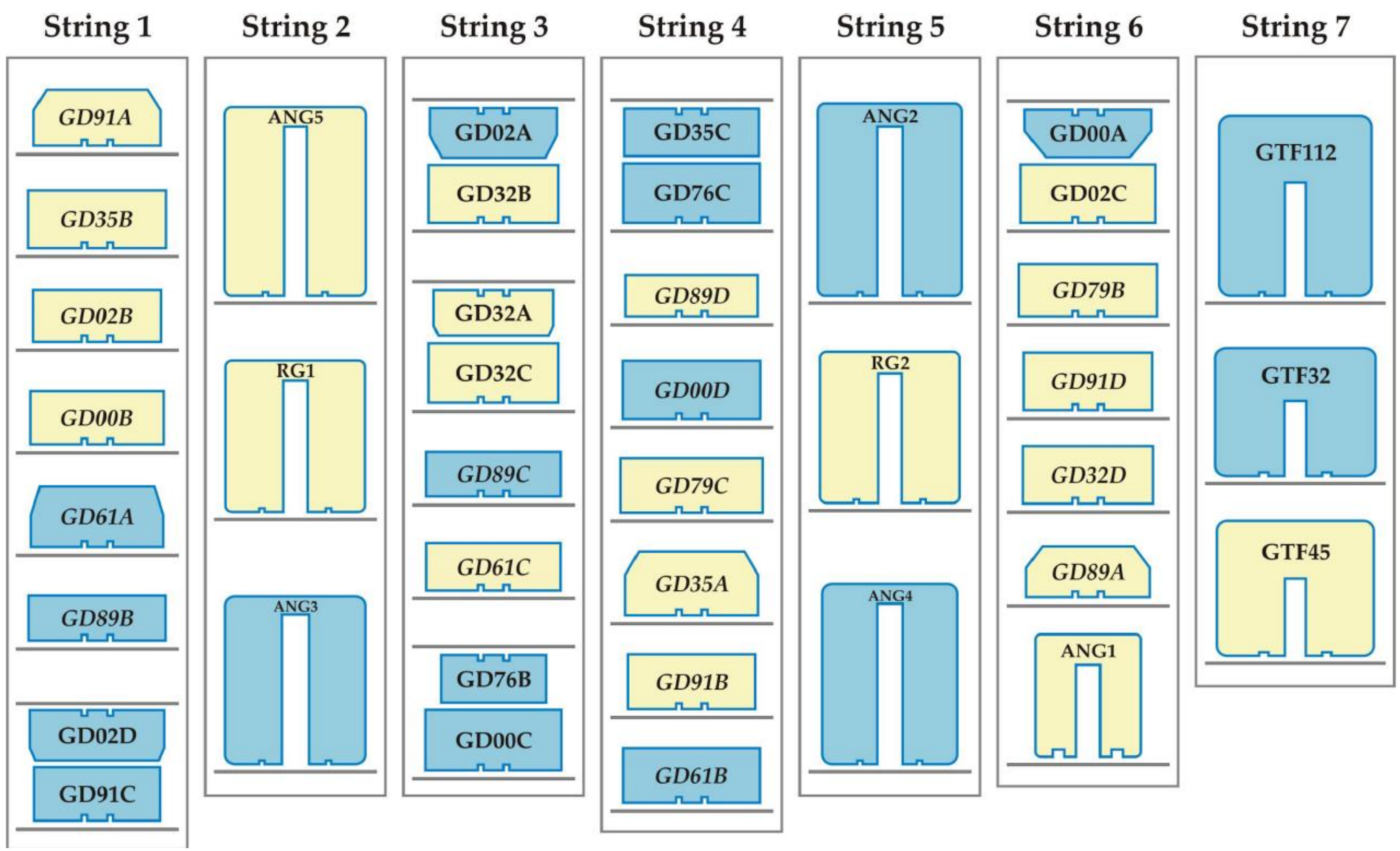
16 3” PMTs
Cylinder with WLS
(TETRATEX foil)



810 wavelength
shifting fibers
coupled to 90 SiPMs

GERDA Phase II Array

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



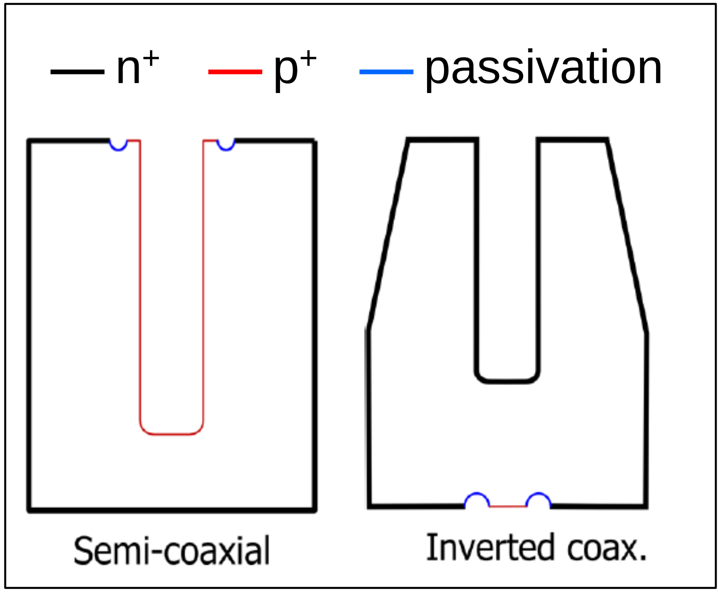
GERDA Phase II (Dec 2015 -)

- 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

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

- Natural coax replaced with 9 kg (5 detectors) enriched inverted coax (IC) 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 a lower activity version

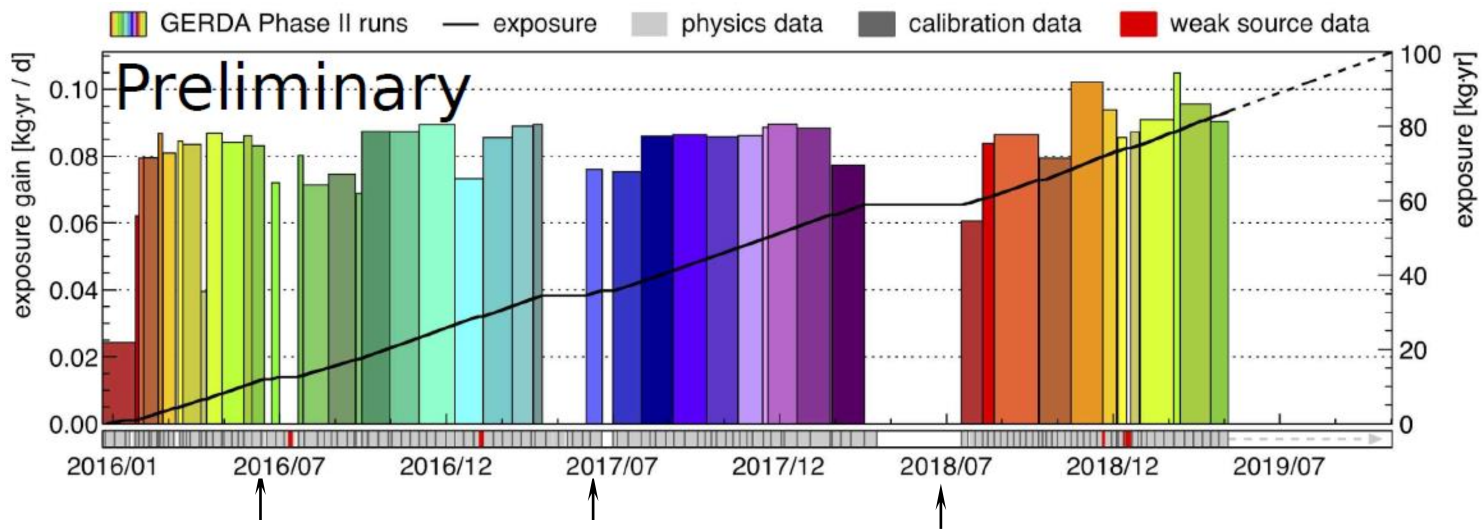


Accumulation of Data

Phase I

- 09.11.11 – 09.05.13: 21.6 kg·yr
- Additional Phase I data before upgrade: 1.9 kg·yr

Phase II



June 2016: 10.8 kg·yr
Nature 554, 47

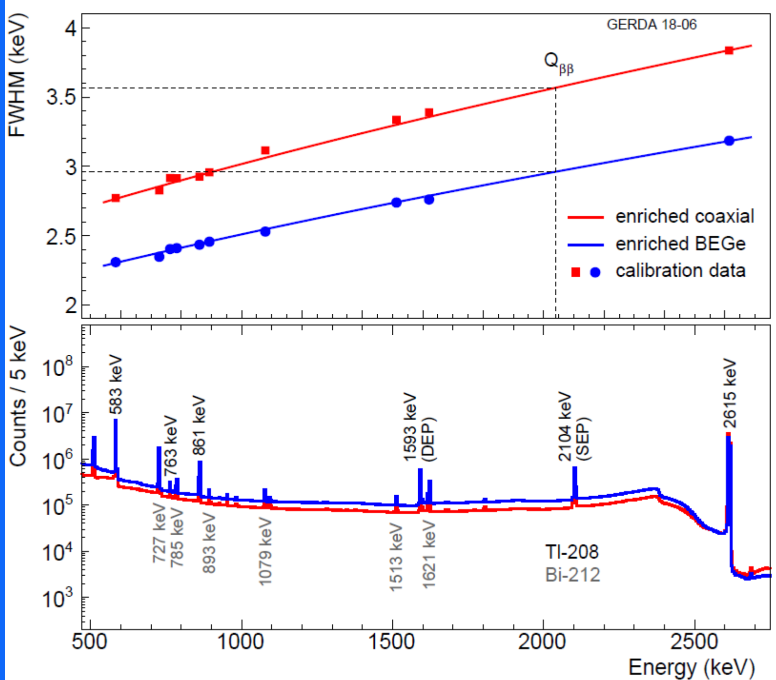
June 2017: 23.2 kg·yr
PRL 120, 132503

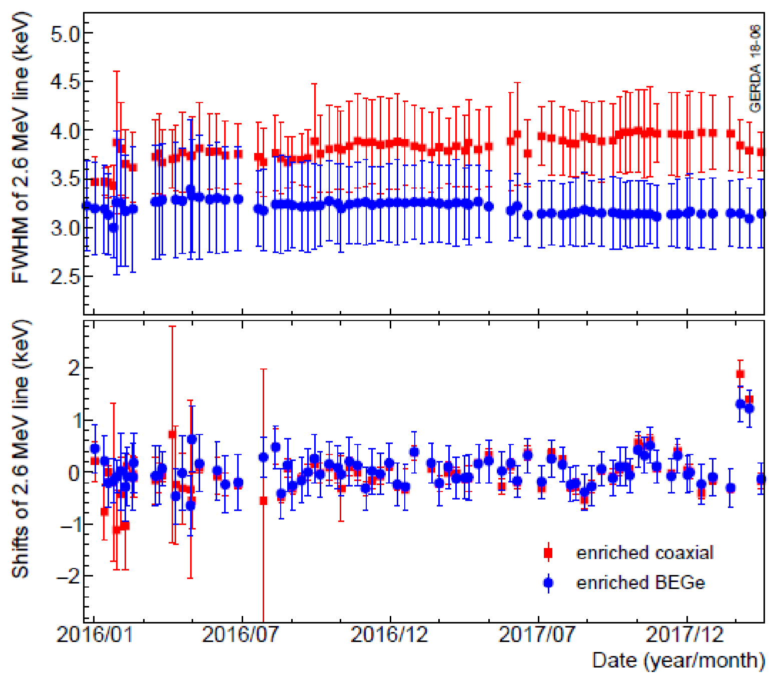
June 2018: 58.9 kg·yr
Science, in print

- Duty cycle: ~93 %
- Data quality cut: 80.4 %
- IC detectors perform well (2.9 keV FWHM)
- Approaching 100 kg·yr (~ Nov. 2019)

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)

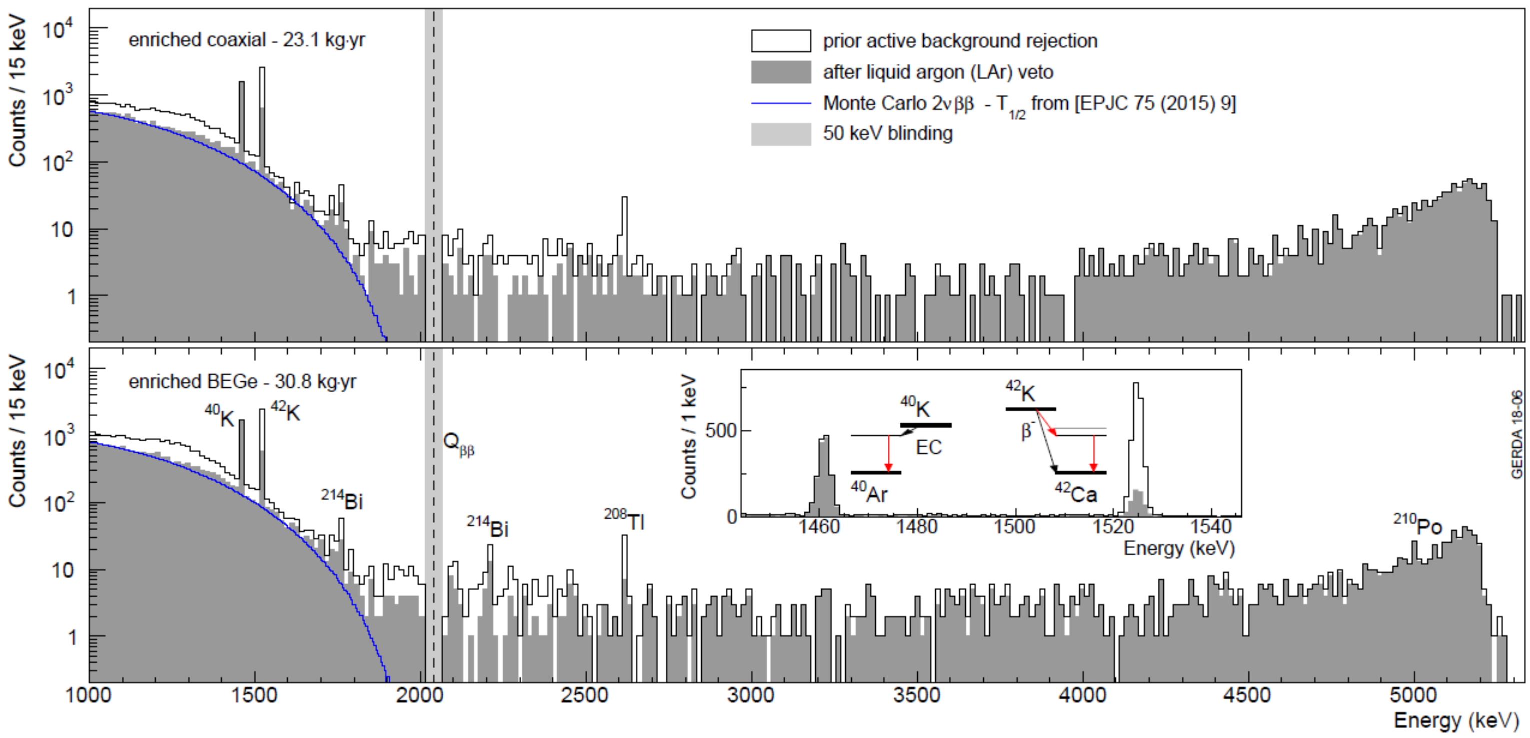




FWHM @ $Q_{\beta\beta}$: Coax: 3.6(1) keV
BEGe: 3.0(1) keV

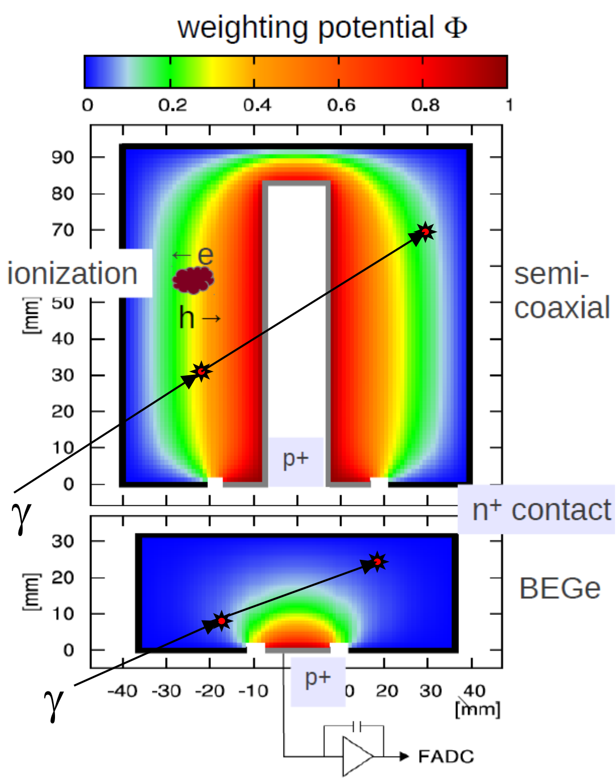
LAr Veto

- 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)



Pulse Shape Discrimination

- In 2νββ / 0νββ decays energy deposition (electrons) is very local – Single Site Event (SSE)
- Multiple Compton scatterings of γs in Ge: separate interaction vertexes – Multi Site Events (MSE)
- Surface events (α/β): depending on the location may generate pulses with short/long rise times (RT)
- PSD: Identification and rejection of MSE and events with short/long RT



$$\text{current signal} = q \cdot v \cdot \nabla \Phi$$

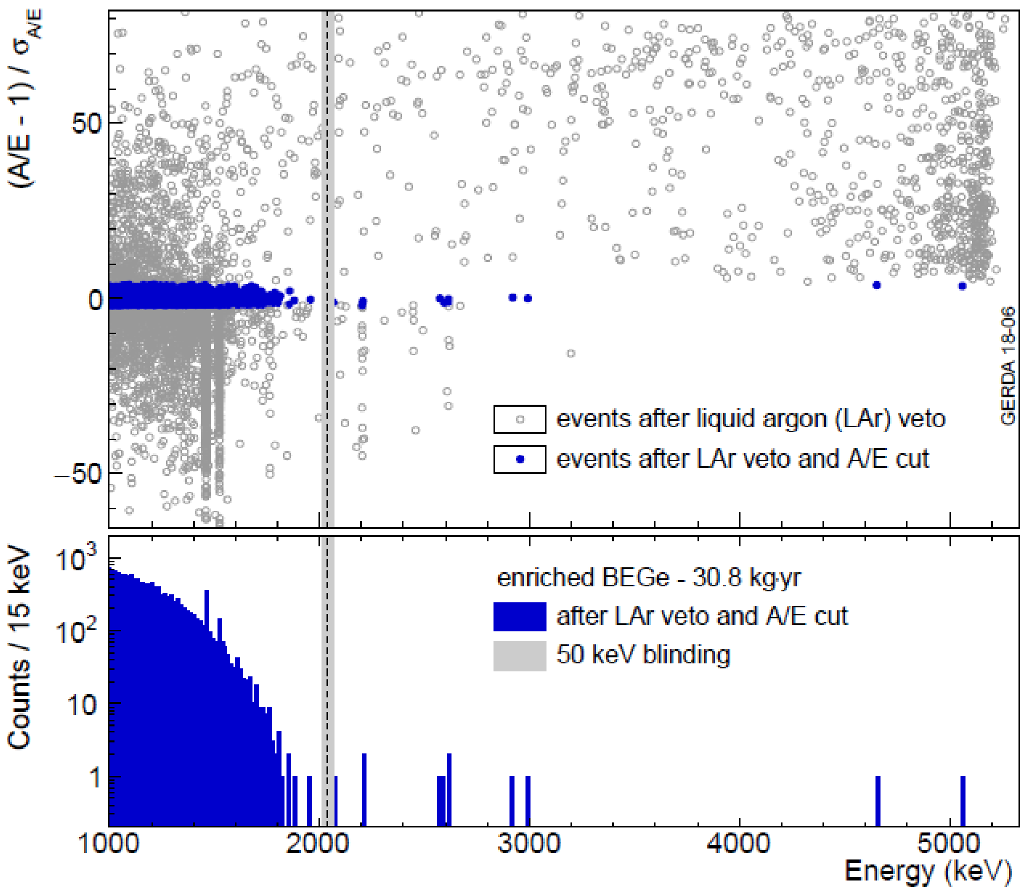
q= charge, v = velocity
(Shockley-Ramo theorem)

Interactions in vertexes of „similar" potential gradient

Interactions in vertexes of different potential gradient

PSD for BEGe 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



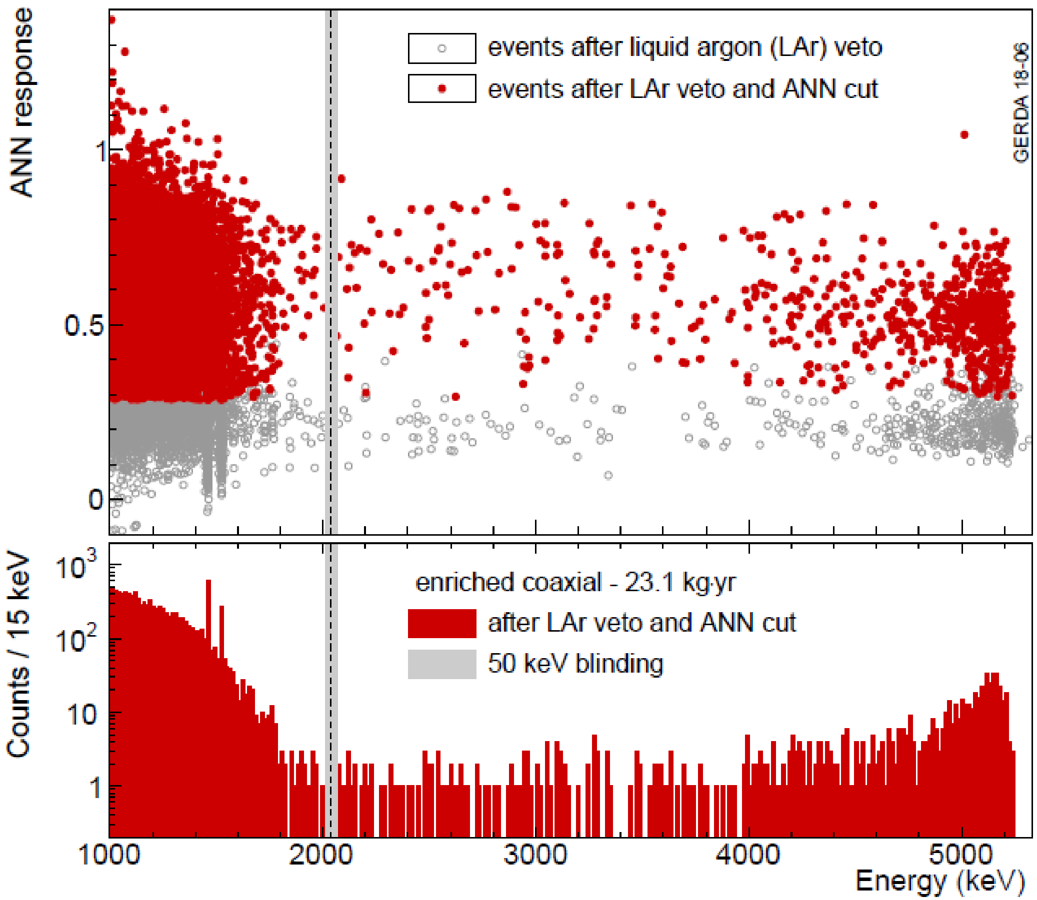
SF_{BW} = 82 %
$\varepsilon_{0\nu\beta\beta}$ = (87.6 ± 2.5) %

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

PSD for Coax Detectors

- $\beta\beta$ 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)

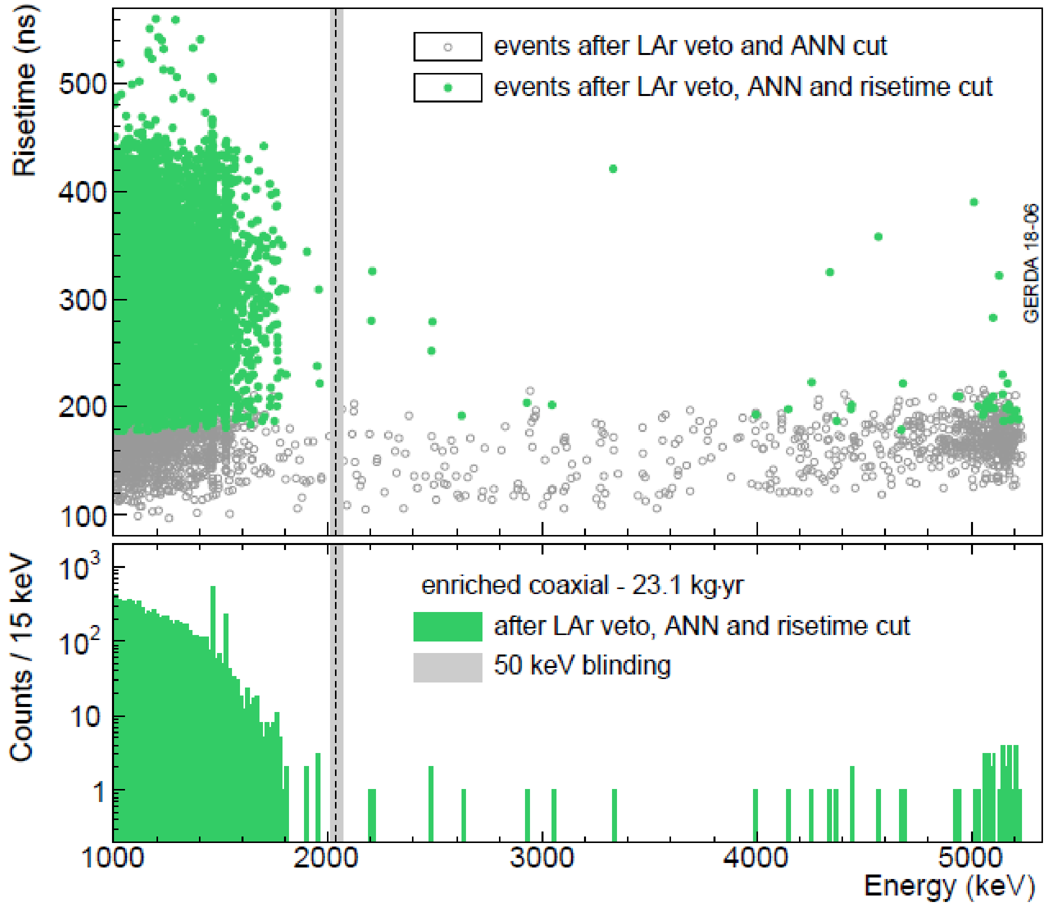


$\varepsilon_{0\nu\beta\beta}$ **(ANN) = (85.0 ± 5.0) %**

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)



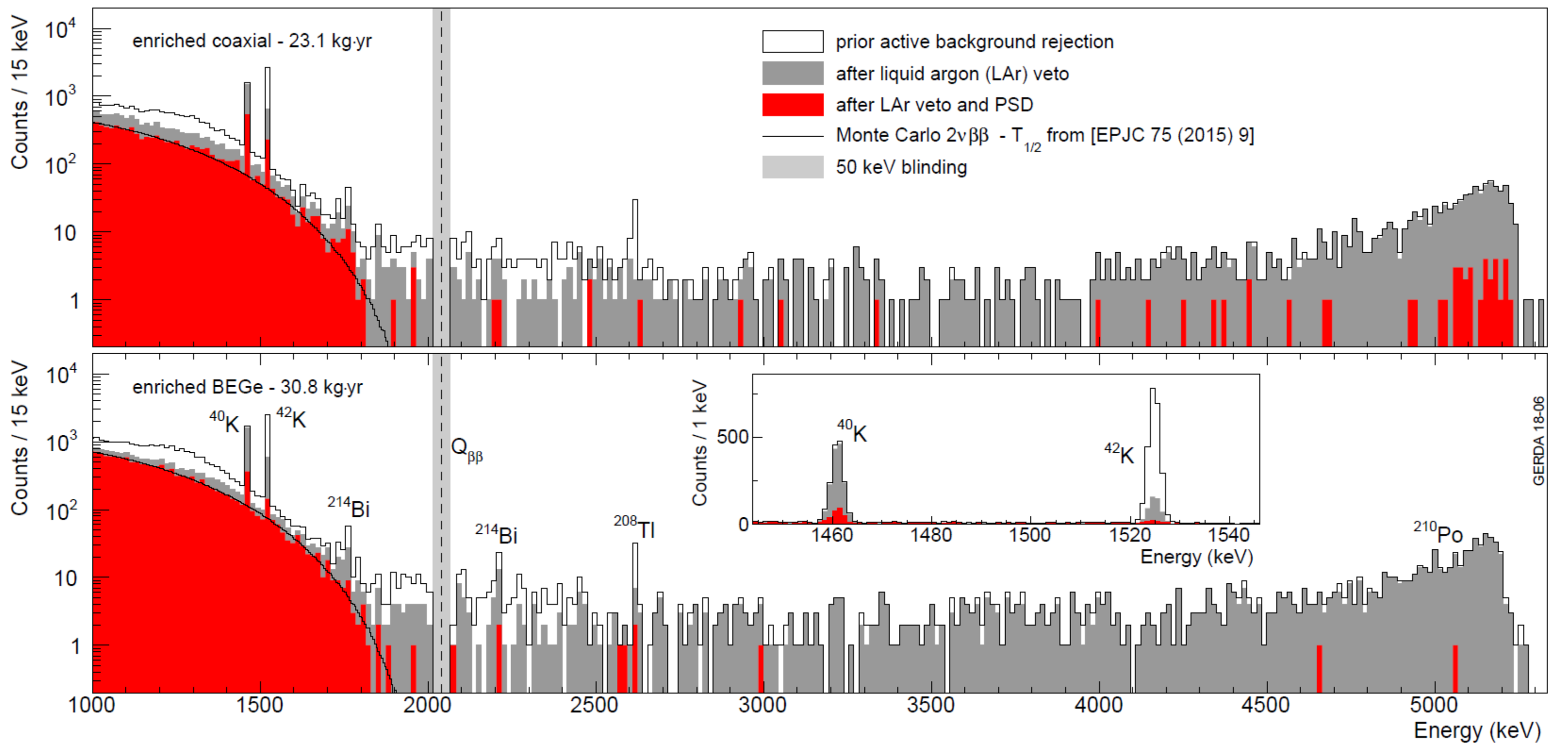
$\varepsilon_{0\nu\beta\beta}$ (ANN) = (85.0 ± 5.0) %

$\varepsilon_{0\nu\beta\beta}$ (RT) = (84.3 ± 1.1) %

$\varepsilon_{0\nu\beta\beta}$ = (71.6 ± 4.3) %

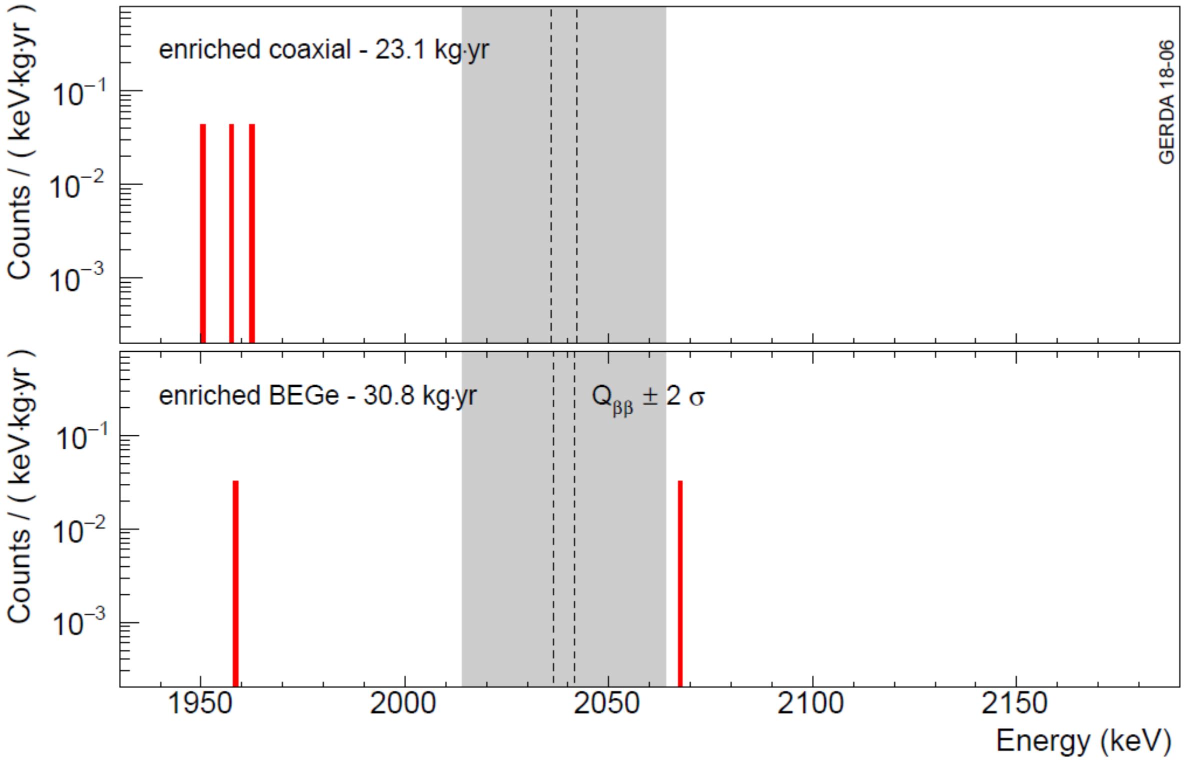
Application of LAr veto and PSD

ββ decay
GERDA design
Bkg reduction
Latest results
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 $Q_{\beta\beta}$

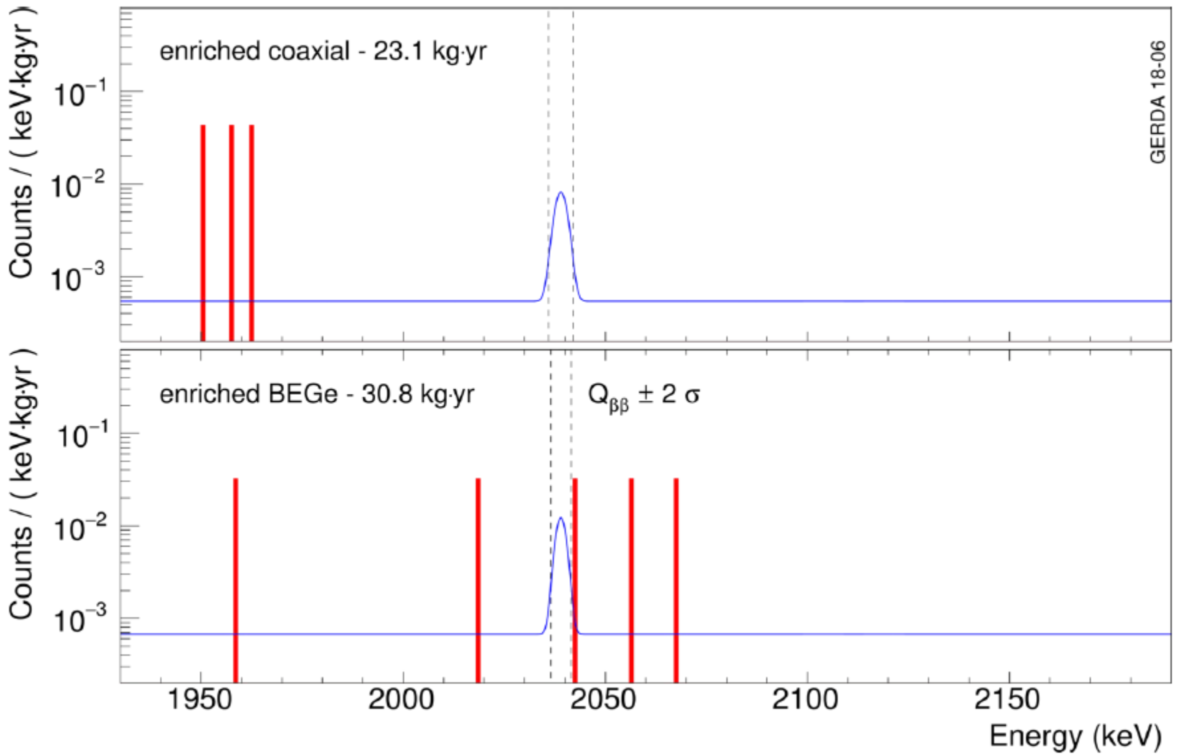
$$\textbf{Coax}: \ \mathrm{BI} = 5.7^{+4.1}_{-2.6} \cdot 10^{-4} \ \mathrm{cts/(keV{\cdot}kg{\cdot}yr)}$$

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

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

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

Statistical Analysis



Frequentist:

– best fit $N_{0\nu} = 0$

– $T_{1/2}$ $(0\nu\beta\beta) > 0.9\times10^{26}$ yr, median sensitivity $T_{1/2}$ $(0\nu\beta\beta) > 1.1\times10^{26}$ yr at 90% C.L.

Bayesian:

– $T_{1/2}$ $(0\nu\beta\beta) > 0.8\times10^{26}$ yr, median sensitivity $T_{1/2}$ $(0\nu\beta\beta) > 0.8\times10^{26}$ 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.)**
  - **Median Sensitivity $T_{1/2}$ ($0\nu\beta\beta$) > 1.1×10^{26} yr (90% C.L.)**
  - $m_{\beta\beta} \le (0.11 – 0.26)$ eV
  - New data to be released at TAUP 2019
- **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 (presently with the 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

GERDA

ββ decay
GERDA design
Bkg reduction
Latest results
Summary