First results from Phase II of the neutrinoless double beta decay experiment GERDA

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Double beta decay: Theory and observation

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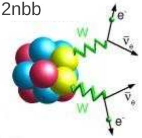
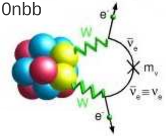


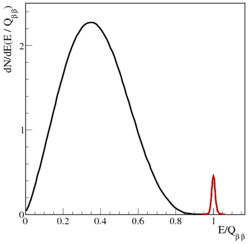
0nbb



Double beta decay: $2\nu\beta\beta$ versus $0\nu\beta\beta$

1. $2\nu\beta\beta$ decay: Allowed by SM
   $(A,Z) \rightarrow (A,Z+2) + 2\ e^- + 2\ \bar{\nu}_e\ (\Delta L = 0)$
   $\rightarrow$ Signature: β -like spectrum
   $\rightarrow$ Observed in 12 candidates: $O(T_{1/2})$=10^{18}-10^{24} yr
2. $0\nu\beta\beta$ decay: Forbidden by SM
   $(A,Z) \rightarrow (A,Z+2) + 2\ e^-\ (\Delta L = 2)$
   $\rightarrow$ Signiture: Full energy peak at $Q_{\beta\beta}$

Signature from $2\nu\beta\beta$ and $0\nu\beta\beta$:



Observable: half-life

- $(T_{1/2})^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$
- $T_{1/2} \propto \begin{cases} a \cdot \epsilon \cdot M \cdot T \ , & \text{background-free} \\ a \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, & \text{w background} \end{cases}$

The GERDA experiment

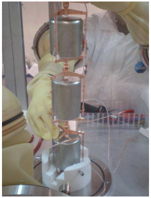
Location:
Laboratori Nazionali del Gran Sasso,
Assergi, Italy

Setup and background reduction:

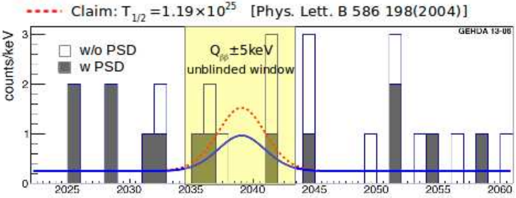
- 1.4 km overburden
  → Reduction of cosmic muon flux by 6 orders of magnitude (PB)
- Water tank and plastic scintillator
  → neutron moderator/absorber (PB)
  → muon Cherenkov veto (AB)
- Liquid argon (LAr) cryostat:
  → cooling medium for diodes (80 K)
  → attenuation of external radiation (PB)
  → LAr scintillation light used for bg rejection (AB)
- GERmanium Detector Array:
  - Operate bare diodes in LAr with low-mass, ultra-radiopure copper holders (PB)
  - Detectors enriched in ^{76}**Ge**:
    $Q_{\beta\beta}$ of ^{76}Ge = 2039 keV
    Concept: DBD source = Detector
  - Coincidence modus between Ge diodes and auxiliary systems (AB)
  - Particle identification via pulse shape (AB)

Legend:
PB = passive background rejection
AB = active background rejection

String with
coaxial Ge diodes



String with
Broad Energy Ge diodes



Results from GERDA Phase I

- Physics goal fullfilled: 21.6 kg·yr with B≈0.01 cts/(kg·yr·keV) at $Q_{\beta\beta}$ incl. pulse shape discrimination (PSD) cuts (unprecedented !)
- Detector performance: excellent energy resolution at 0.2%, energy scale very stable
- Data analysis: fully **blinded** (unprecedented !)
- Physics results:
  - No evidence for peak, → $\mathbf{T^{0\nu}_{1/2} > 2.1\times10^{25}}$ **yr (90% C.L.)**
  - combined Ge experiments: $T^{0\nu}_{1/2} > 3.0\times10^{25}$ yr (90% C.L.))
    → Combined Ge experiments (HdM + IGEX + GERDA): $\langle m_{\beta\beta}\rangle$ <(0.2-0.4) eV

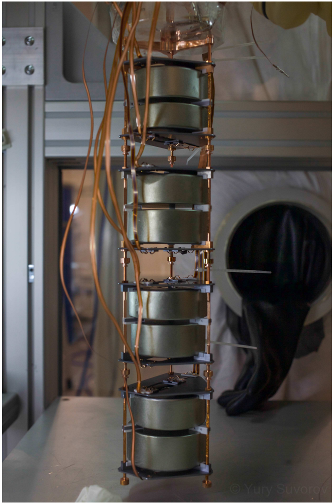
GERDA: From Phase I to Phase II

Strategy: improve $T_{1/2}$ sensitivity by applying modifications *inside* the LAr cryostat

Starting point: $T_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$, assuming non-zero background

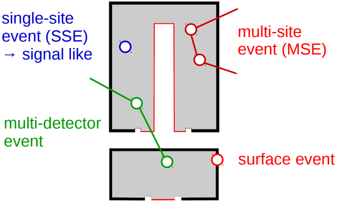
Parameter	**Phase I**	**Phase II**
M(^{76}Ge enr.) (all operational channels)	6 coax: 14.6 kg 4 BEGe: 3.0 kg	7 coax: 15.2 kg 30 BEGe: 20.0 kg
M · T	Goal: 20 kg·yr Achieved: 21.6 kg·yr	Goal: 100 kg·yr
ΔE at $Q_{\beta\beta}$ (full-width at half-maximum)	coax: 4.2-5.7 keV BEGe: 2.6-4.0 keV	Goal: as good as in P I or improve via new filters
B at $Q_{\beta\beta}$	Goal: 10^{-2} cts/(kg·keV·yr) Achieved (incl. PSD): coax: 1.1-3.0·10^{-2} cts/(kg·keV·yr) BEGe: 0.5·10^{-2} cts/(kg·keV·yr) * PSD: reduced for coax * Signal contact: mech. spring * FE electronics + preampl. * Copper mini-shroud – – –	Goal: 10^{-3} cts/(kg·keV·yr) * PSD: enhanced for BEGe * Signal contact: bonding * New development * Nylon mini-shroud * LAr scintillation light: - PMTs - Glass fibers with SiPMs

String with 8 BEGe detectors

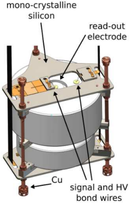


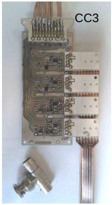
Background mitigation:

- pulse shape discrimination and Ge detector anti-coincidence:

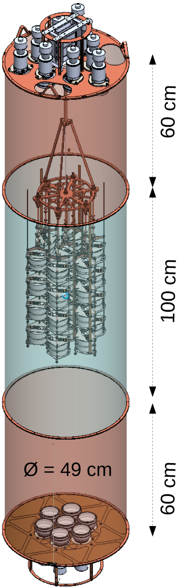


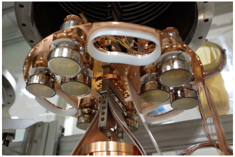
- low mass holder of low activity + new contacting / electronics

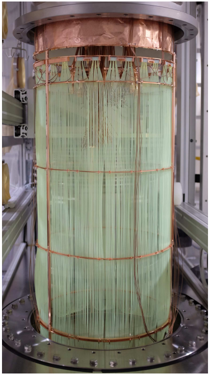




GERDA Phase II upgrade: LAr scintillation light instrumentation

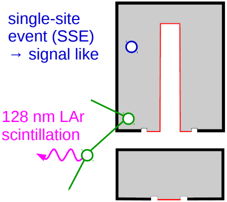






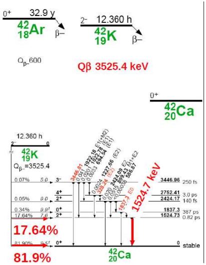
Background mitigation:

- Ge detectors in anti-coincidence with LAr scintillation light read-out:



- Hybrid design:
  1. 16 x 3" low background PMTs Ham RG11065-10/20 MOD
  2. 810 x scintillating fibers coupled to 90 KETEK SiPMs
  3. 100 μm Cu shrouds with wavelength shift TETRATEX foil

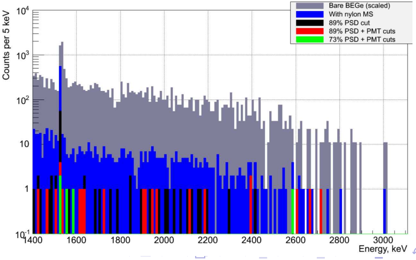
GERDA Phase II upgrade: A special barrier against ^{42}Ar



^{42}Ar background mitigation:

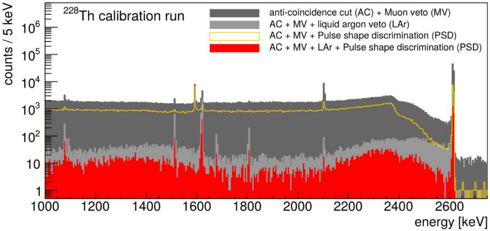
- Mechanical barrier against ^{42}Ar ions attracted by high E field (GERDA Phase I: copper shroud)
- Requirements to GERDA Phase II shroud:
  1. transparent for LAr scintillation light λ=128 nm
     $\rightarrow$ use nylon
  2. match PMT and SiPM sensitivity
     $\rightarrow$ use nylon coated with wavelength shifter
  3. mech. robustness, no ageing, low intrinsic contamination

Proof of principle in LArGe test stand

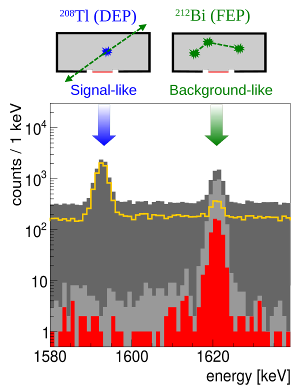


GERDA Phase II commissioning: Active background suppression

Calibration with external sources:



Strength of PSD:



Results:

Isotope	LAr Veto	LAr Veto + det. anti-coincidence + pulse shape discrimination
^{228}Th	85±3	390±28
^{226}Ra	5.1±0.2	25±2.2

- Suppression factors depend on isotopes, source location & detector configuration
- For external γ's: LAr veto more efficient than pulse shape discrimination (PSD)

In case of peak discovery at $\approx Q_{\beta\beta}$ possibility to check if event has:

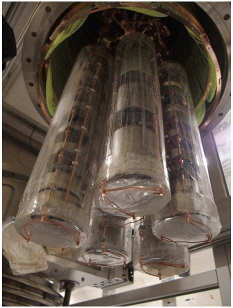
a) multi-site energy dep. $\rightarrow$ bg-like

b) single energy dep. $\rightarrow$ **$0\nu\beta\beta$-like** !

GERDA Phase II: Data collection

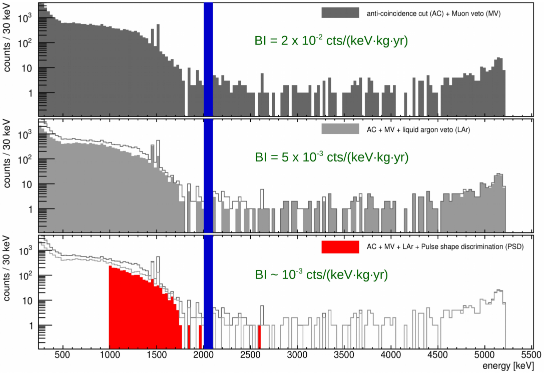
Data collection start: December 15, 2015

All 7 strings mounted & all Ge detectors + LAr veto working !



Data set of GERDA Phase II used for 1. data release:

- From Run 53: First event: UTC Fri Dec 25 00:45:09 2015
- To Run 64: Last event: UTC Wed Jun 1 07:43:10 2016
- Live time: 130.67 d = 0.358 yr ($\rightarrow$ Duty cycle: 82.0%)



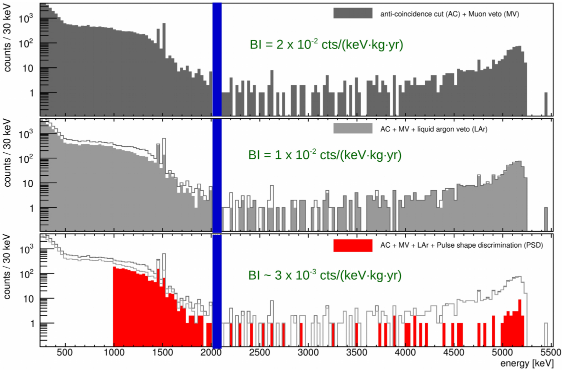
BEGe

Blinded region:

$Q_{\beta\beta}\pm 25$ keV

- LAr veto cut: $\rightarrow$ For ^{40}K: fully accepted; ^{42}K: SF$\sim$5
  $\rightarrow$ Below 2 MeV: basically only $2\nu\beta\beta$ spectrum
  $\rightarrow$ In 1839-2239 keV: survival fraction = $\sim$1/3
- Pulse shape: $\rightarrow$ Events in ROI: signal accep. 87.3$\pm$0.9 %, Bg reject. 80%
  $\rightarrow$ α events: very efficient rejection

GERDA Phase II: Background suppression of coaxial detectors



Coax

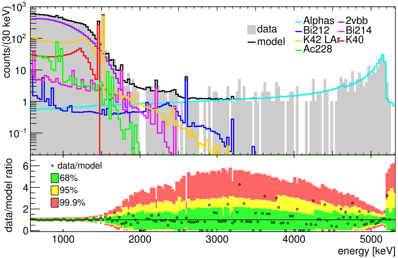
Blinded region:

$Q_{\beta\beta}\pm$25 keV

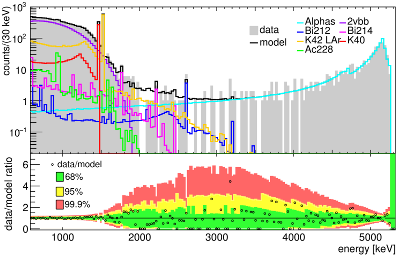
- LAr veto cut: $\rightarrow$ In 1839-2239 keV: survival fraction$\sim$1/2
- Pulse shape:
  $\rightarrow$ Multi-site events: rejected via artificial neural network (ANN) + projective Likelihood: ϵ_{mse}=(80±9)% $0\nu\beta\beta$ acceptance
  $\rightarrow$ α events: rejected via ANN: ϵ_{α}=(96±1)% $0\nu\beta\beta$ acceptance
  $\rightarrow$ **Total eff.**: $\epsilon_{psd} = \epsilon_{mse} \cdot \epsilon_{\alpha}$=(77±9)%, while bg. rejected at 65%

Global fit prior application of LAr veto and PSD cut

BEGe: p-value=0.3



Coax: p-value=0.6



- Fit [570,5300] keV with 30 keV binning
- Well understood bg composition
- Expect flat bg in ROI at $Q_{\beta\beta}$
- Bg model still preliminary!

- Fit predicts again flat bg in ROI
- Main components before LAr veto and PSD cut similar to Phase 1:
  - α from ^{210}Po and ^{226}Ra
  - β from ^{42}K
  - γ from ^{214}Bi and ^{208}Tl

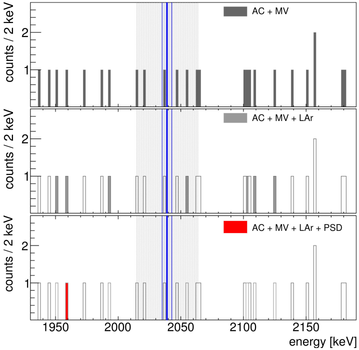
GERDA Phase II: Unblinding of first data set

GERDA Collaboration Meeting on Ringberg castle (GER), June 15-18, 2016

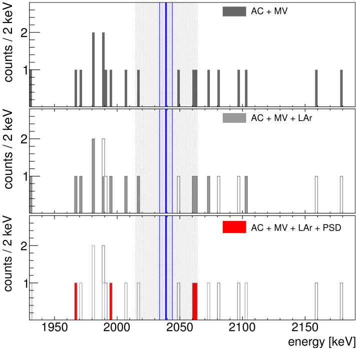
Final steps prior unblinding the $Q_{\beta\beta}\pm 25$ keV window:

- Freeze analysis cuts (energy reconstruction, quality cuts, flags...)
- Freeze data periods from Phase 1 and 2
- Freeze background model
- Freeze LAr veto and PSD cuts for BEGe and Coax
- Fix and agree on statistical methods ... $\rightarrow$

BEGe: Exposure $=$ 5.8 kg·yr



Coax: Exposure $=$ 5.0 kg·yr



Counts	Region	**BEGe**	**Coax**
expected, w PSD	$Q_{\beta\beta}\pm 25$ keV	0.3	0.8
	1930-2190 keV	1.2	3.6
observed, w PSD	$Q_{\beta\beta}\pm 25$ keV	0	1
	1930-2190 keV	1	4

$\rightarrow$ Like in Phase I,
no hint for γ-line at $Q_{\beta\beta}$!
Background is **flat**.

GERDA Phase I and II: Statistical analysis

List of used data sets and of relevant quantities

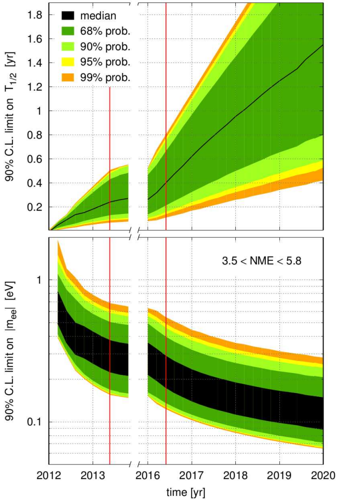
Data set	Exposure [kg·yr]	Signal eff.	Background [cts/(keV·kg·yr)]	Resolution FWHM [keV]
Phase I, coax golden	17.9	0.57(3)	$11 \pm 2 \cdot 10^{-3}$	4.3(1)
Phase I, coax silver	1.3	0.57(3)	$30 \pm 10 \cdot 10^{-3}$	4.3(1)
Phase I, BEGe	2.4	0.66(2)	$5^{+4}_{-3} \cdot 10^{-3}$	2.7(2)
Phase I, extra	1.9	0.58(4)	$5^{+4}_{-3} \cdot 10^{-3}$	4.2(2)
Phase II, coax	5.0	0.51(7)	$3.5^{+2.1}_{-1.5} \cdot 10^{-3}$	4.0(2)
Phase II, BEGe	5.8	0.60(2)	$\mathbf{0.7}^{+1.1}_{-0.5} \cdot 10^{-3}$	3.0(2)

Analyses based on two methods:

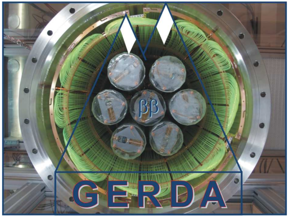
	unbinned profile likelihood 2-side test-stat	Bayesian flat prior on cts
$0\nu\beta\beta$ cts best fit value	0 cts	0 cts
$T^{0\nu}_{1/2}$ lower limit	$>5.2 \cdot 10^{25}$ yr (90% CL)	$>3.5 \cdot 10^{25}$ yr (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity	$4.0 \cdot 10^{25}$ yr (90% CL)	$3.0 \cdot 10^{25}$ yr (90% CI)

- **Result from Phase I + first Phase II period**:
  - Sensitivity: $T^{0\nu}_{1/2} > 4.0 \cdot 10^{25}$ yr (90% CL)
  - No $0\nu\beta\beta$ signal found
    $\rightarrow T^{0\nu}_{1/2} > 5.2 \cdot 10^{25}$ yr (90% CL)
    $\rightarrow m_{eff} <$ (0.15-0.33) eV
- **Goal for Phase II (next 3-4 yr)**:
  - Exposure of 100 kg·yr
  - Only a fraction of bg event in ROI expected
    $\rightarrow$ first bg free experiment
- **Discovery potential**:
  - Find γ-line at $Q_{\beta\beta}$
    $\leftarrow$ very good energy res. and low bg
  - Identify origin of γ-line at $Q_{\beta\beta}$
    $\leftarrow$ capability to distinguish $\beta\beta$ from other bg events on event-by-event basis

Based on current BI and duty cycle:



THANK YOU FOR YOUR ATTENTION !



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