Highlights from GERDA: approaching the neutrino IH region

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INFN MiB
ICNFP – 7 July 2018
GERDA Goals & Physics reach

- Look for $0\nu\beta\beta$ of $^{76}\text{Ge}$ ($Q_{\beta\beta} = 2039$ keV)
- Design Sensitivity:
  - $T_{1/2}^{0\nu} > 1.3 \times 10^{26}$ yr (90% CL)
- Discovery potential up to $10^{26}$ yr (50% prob. chance for a 3σ signal)
- $<m_{\odot}> \leq 0.09 - 0.15$ eV ($g_A = 1.26$)
- Achieve Energy Resolution @ $Q_{\beta\beta} < 0.1$
- collect an exposure of $\sim 100$ kg·yr

<table>
<thead>
<tr>
<th></th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design $T_{1/2}^{0\nu}$ Sensitivity</td>
<td>$1.2 \times 10^{25}$ yr @ 90% CL to Check $\beta\beta$ claim</td>
<td>$&gt; 10^{26}$ yr</td>
</tr>
<tr>
<td>Exposure</td>
<td>$\sim 20$ kg·yr</td>
<td>$\sim 100$ kg·yr</td>
</tr>
<tr>
<td>$T_{1/2}^{0\nu}$ achieved</td>
<td>$2.1 \times 10^{25}$ yr @ 90% CL</td>
<td></td>
</tr>
<tr>
<td>Background index</td>
<td>$10^{-2}$ cts · (keV·kg·yr)$^{-1}$</td>
<td>$10^{-3}$ cts · (keV·kg·yr)$^{-1}$</td>
</tr>
</tbody>
</table>
GERDA Goals & Physics reach

- \(e\) = detection efficiency
- \(a\) = bb isotope fraction \(\rightarrow\) enrichment
- \(M\) = mass of detector in kg
- \(T\) = data taking time [y]
- \(B\) = background index in cts/(keV kg y)
- \(R\) = energy resolution at \(Q_{bb}\) [keV]

- operate in linear regime of sensitivity vs exposure, i.e. background of \(10^{-3}\) cts/(keV·kg·yr) to
The GERDA Collaboration

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

16 institutions
~110 members
• 2004: Proposal
• 2005: Funding (MPI, BMBF, INFN, in-kind contributions from ITEP, INR, JINR)
• 2007-2010: Infrastructures/structures construction (WT, Cryostat, Building, Clean room)
• 2010-2011: GERDA I Commissioning
• 2011-2013: GERDA I data taking
• 2013-2015: Setup upgrade to Phase II
• December 2015: GERDA II Physics data taking started. Ongoing
  – Upgrade to Phase II.v2 (towards LEGEND-200) in april-may & july 2018
• Data taking will continue until completion of the scientific programe and readiness of LEGEND-200
GERDA Setup

- Clean room with lock (old version) & clean bench
- Muon & cryogenic infrastructure
- Control rooms
- Water plant & radon monitor
- Ge-76 array (enlarged)
- LAr cryostat, Ø4m, with internal Cu shield
  - Detector = source
  - Water tank, Ø10m, part of μ-veto detector
The GERDA setup

GERDA I detectors

10/07/18
GERDA II: Setup Upgrade

- Upgrade in 2013-2015
- Start data taking in December 2015
- 30 enrBEGe (20 kg) detectors
- 7 enrCoaxials (already in Phase I)
- 3 natCoaxials (already in Phase I)
- New lower mass holders
- Spring loaded contacts changed to wire bonded to improve contact quality
- New low-mass low-activity FE electronics and detector-to-FE contacts

- 3 Detectors lost: JFET burnt
- Few Detectors show instabilities

35.8 kg enrGe
Hybrid Veto Instrumentation
- 16 PMTs (9 top/ 7 btm)
- 800 m fibers coated with WLS+90 SIPMs
- Nylon Minishroud (instead of Cu) around each string, coated with WLS

Parameters optimized for each channel:
- \(~ 0.5\) pe threshold
- \(~ 5-6\) \(\mu s\) anticoincidence window
First 10.8 kg·yr released in 2016  
Nature 544, 47 (2017)  
+ additional 1.9 kg·yr  
Phase I unpublished data
GERDA II Exposure

First 10.8 kg·yr released in 2016
Nature 544, 47 (2017)
+ additional 1.9 kg·yr
Phase I unpublished data
$T_{1/2}^{0\nu} > 5.2 \times 10^{25}$ yr (90% CL)
$<m_{ee}> \leq 0.16 - 0.26$ eV

+12.4 kg·yr (BEGe)
Total 23.2 kg·yr released in 2017
PRL 120, 132503 (2018)
no signal found: lower limit
$T_{1/2}^{0\nu} > 8.0 \times 10^{25}$ yr (90% CL)
$<m_{ee}> \leq 0.12 - 0.26$ eV
GERDA Exposure II build-up

First 10.8 kg·yr released in 2016
Nature 544, 47 (2017)
+ additional 1.9 kg·yr Phasel unpublished data

\[ T_{1/2}^{0\nu} > 5.2 \cdot 10^{25} \text{ yr (90\% CL)} \]
\[ <m_{ee}> \leq 0.16 - 0.26 \text{ eV} \]

+12.4 kg·yr (BEGe)
Total 23.2 kg·yr released in 2017
PRL 120, 132503 (2018)
no signal found: lower limit

\[ T_{1/2}^{0\nu} > 8.0 \cdot 10^{25} \text{ yr (90\% CL)} \]
\[ <m_{ee}> \leq 0.12 - 0.26 \text{ eV} \]

• +23.07 kg·yr (Coax) + 12.64 kg·yr (BEGe)
• June 2018 Release
• Total Phase II data analyzed: 58.93 kg·yr
GERDA II: Energy Scale Determination & Stability

Procedure:
- ~ bi-weekly $^{228}$Th calibrations
- pulser injected into FE every 20 s to monitor stability
- calibrate and sum-up physics data: FWHM of integrated phy-data provide quality of calibration procedure
- Digital Filter applied: Customized Cusp Filter [EPJC 75 (2015) 255]
Energy Resolution in Calibrations and PHY-DATA

LAr veto not applied

\[ \text{enrBEGe: } \text{FWHM} @ Q_{\beta\beta} = 2.96 \]

\[ \text{enrCoax: } \text{FWHM} @ Q_{\beta\beta} = 3.57 \]

Good Energy Resolution in integrated spectra

Stability of the Calibrated Energy Scale

Quality of GERDA Setup & Calibration Procedures (SW,HW)
Background analysis

- The GERDA experimental setup is reproduced in a GEANT4 framework
- Background sources: $^{42}\text{K}$ in LAr, $^{40}\text{K}$, $^{226}\text{Ra}$, $^{238}\text{U}$, $^{232}\text{Th}$, $^{60}\text{Co}$
- Background locations: All the components within $\sim$80 cm from the detectors. Detectors holders, FE contacts, LAr readout fibers and devices, FE Electronic PCBs....
- PDFs built from the MC output and used later in the fits
- Runtime ON/OFF detectors and run livetimes are taken into account
- Both anticoincidence and coincidence spectra simultaneously taken into account
- Bayesian statistical analysis fits
- Known inventory screening used as priors
Background analysis

![Graph showing single and two-detector events with various elements and enriched detectors - 60.2 kg yr on the y-axis and energy (keV) on the x-axis.](image)
Background in ROI

- Background in the ROI (before LAr and PSD)
  - $\alpha$ from $^{210}$Po and $^{222}$Rn daughters
  - $\beta$ from $^{42}$K
  - $\gamma$ from $^{212}$Bi, $^{208}$Tl and $^{214}$Bi, $^{214}$Pb
- Flat background expected at $Q_{\beta\beta}$
- Adopt the same analysis window as Phase I
- BI evaluated in 1930 – 2190 keV excluding blinded region (50 keV) and 2104 ±5 keV and 2119 ±5 keV of known peaks $\rightarrow$ 190 keV
LAr suppression for $^{42}$K and $^{40}$K

- LAr readout only when there is a trigger in Ge
  - Dead time 2.3% (from pulser acceptance)
- $\gamma$-rays Survival Fractions (SF):
  - $^{40}$K (EC: only $\gamma$): 100%
  - $^{42}$K ($\beta^- + \gamma$): ~20%

$^{40}$K (EC: only $\gamma$) no energy in LAr

- SF in range 0.6 - 1.3 MeV:
  (70.4 ± 0.3)%
- $^{40}$K and $^{42}$K continua completely suppressed

$^{42}$K ($\beta^- + \gamma$) $\beta$ in LAr

Only 2v$\beta\beta$ left

$T_{1/2}(2v\beta\beta) = 1.92 \cdot 10^{21} \text{ yr}$ fixed param.

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LAr suppression for $^{238}\text{U}$ and $^{232}\text{Th}$

Tested with $^{228}\text{Th}$ and $^{226}\text{Ra}$ sources

➢ Suppression Factors (SF):

$^{228}\text{Th}$: $(98(4))$

$^{226}\text{Ra}$: $(5.7(2))$

➢ When combining with PSD and anti-coincidence

the SFs become:

$^{228}\text{Th}$: $345\ (25)$

$^{226}\text{Ra}$: $29\ (3)$

Difference between $^{228}\text{Th}$ & $^{226}\text{Ra}$ SFs is due to more energy released in LAr in the decay
Pulse Shape Discrimination (PSD) to discriminate ββ-like (SSE) to γ-like (MSE) events

Different weighting potentials for Coax and BEGe

COAX: Artificial Neural Network (ANN) estimator or TMVA of pulse profile used as PSD parameter

BEGe: Amplitude of Current/Amplitude of Charge Pulse (A/E) is the PSD parameter
**PSD for BEGe detectors**

- **Event-per-event** selection
  - **Above band**: events on p+ electrode (e.g. α's from $^{210}$Po)
  - **Below band**: events on n+ electrode, multiple scattering

Acceptance for 0ν2β events:

$$\left(87.6 \pm 2.5\right)\%$$

- Estimated from $^{208}$Tl DEP

Double-check at low energy with 2νββ events (LAr cut) $$\left(85.4 \pm 1.9\right)\%$$
PSD Survival Fractions of Physics Data

![Graph showing survival fractions for different events]
PSD for coaxials

- PSD for coax detectors less effective than for BEGes
- Artificial neural network (ANN), as in Phase I
  - Trained on signal (SSE): $^{208}$Tl (2614 keV) DEP at 1592 keV
  - Background (MSE): $^{212}$Bi @ 1620 keV $\gamma$-line
  - Acceptance for $0\nu\beta\beta$ events: $(84\pm5)\%$
  - Double check with Compton edge and $2\nu\beta\beta$
- RT cut for $\alpha$
  - Test/train sample from data
  - Acceptance for $0\nu2\beta$ events: $(85\pm1)\%$

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PSD for Coaxials: $\alpha$ cut

Events with rise time (10%90% of the rising part of the pulse) faster than 180 - 220 ns (depending on specific detector) are rejected as $\alpha$ events.
Applying PSD cuts to $2\nu\beta\beta$ we estimate:

- RT Acceptance for $0\nu\beta\beta$ events $(85 \pm 1)\%$
- Combined acceptance (ANN and RT) for $0\nu\beta\beta$ events : $(71 \pm 4)\%$
GERDA II: BEGe: 30.8 kg y + COAX– 23.1 kg y

BI (LAr & PSD) prior unblinding = $0.6 \pm 0.4 \times 10^{-3}$ cts/(kky)

190 keV netto range

BI LAr & PSD prior unblinding = $0.7 \pm 0.5 \times 10^{-3}$ cts/(kky)

190 keV netto range
BI: $3.5^{+2.1}_{-1.5}\cdot10^{-3}$ cts/(keV·kg·yr)

BI: $0.7^{+0.5}_{-0.3}\cdot10^{-3}$ cts/(keV·kg·yr)
in 190 keV range

BI: $0.3^{+0.3}_{-0.3}\cdot10^{-3}$ cts/(keV·kg·yr)
in 190 keV range
Unblinding in the ROI

**Counts / (keV·kg·yr)**

- **enriched coaxial - 23.1 kg·yr**
  - BI: $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/(keV·kg·yr)
  - in 230 keV range

- **enriched BEGe - 30.8 kg·yr**
  - $Q_{\beta\beta} \pm 2 \sigma$
  - BI: $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/(keV·kg·yr)
  - in 230 keV range
The maximum signal fitting the ROI

Frequentist:
- Best fit $N_{0\nu} = 0$
- $T_{1/2}^{0\nu} > 0.9 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.L.}$
- Median Sensitivity (NO Signal) $T_{1/2}^{0\nu} > 1.1 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.L.}$
- $63\%$ of MC realizations yield limit stronger than data
- $<m_{\text{ee}} > \leq 0.11 - 0.26 \text{ eV}$

Bayesian:
- Best fit $N_{0\nu} = 0$
- $T_{1/2}^{0\nu} > 0.7 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.L.}$
- Median Sensitivity (NO Signal) $T_{1/2}^{0\nu} > 0.8 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.L.}$
- $59\%$ of MC realizations yield limit stronger than data
- Bayes factor: $P(H1)/P(H0) = 0.054$

H1: signal+background hypothesis
H0: background only hypothesis
GERDA II: Main facts

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Exposure (kg·yr)</th>
<th>Energy resolution FWHM (keV)</th>
<th>Efficiency (arb. unit)</th>
<th>BI $10^{-3}$ cts/(keV·kg·yr)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhaseI-Golden</td>
<td>17.9</td>
<td>4.3(1)</td>
<td>0.57(3)</td>
<td>11 ± 2</td>
<td>46</td>
</tr>
<tr>
<td>PhaseI-Silver</td>
<td>1.3</td>
<td>4.3(1)</td>
<td>0.57(3)</td>
<td>30 ± 10</td>
<td>10</td>
</tr>
<tr>
<td>PhaseI-BEGe</td>
<td>2.4</td>
<td>2.7(2)</td>
<td>0.66(2)</td>
<td>$5^{+4}_{-3}$</td>
<td>3</td>
</tr>
<tr>
<td>PhaseI-Extra</td>
<td>1.9</td>
<td>4.2(2)</td>
<td>0.58(4)</td>
<td>$5^{+4}_{-3}$</td>
<td>2</td>
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<tr>
<td>PhaseII-Coax1</td>
<td>5.0</td>
<td>3.57(1)</td>
<td>0.52(4)</td>
<td>$3.5^{+2.1}_{-1.5}$</td>
<td>4</td>
</tr>
<tr>
<td>PhaseII-Coax2</td>
<td>23.1</td>
<td>3.57(1)</td>
<td>0.48(4)</td>
<td>$0.6^{+0.4}_{-0.3}$</td>
<td>3</td>
</tr>
<tr>
<td>PhaseII-BEGe</td>
<td>30.8</td>
<td>2.96(1)</td>
<td>0.60(2)</td>
<td>$0.6^{+0.4}_{-0.3}$</td>
<td>5</td>
</tr>
</tbody>
</table>

Background
- **COAX**: Factor $\sim$20 reduction from PI to PII
- **BEGE**: Factor $\sim$8 reduction from PI to PII

Energy Resolution
- **COAX**: 17% improvement from PI to PII
- **BEGE**: Stable within errors from PI to PII
Comparison of 2016 projections and achieved results

- ★: published limits
Latest results from **MAJORANA DEMONSTRATOR**

1 event at 2040 keV
Expected 0.66 counts in optimal ROI (4.13 keV)

Median Sensitivity (90% C.L.): \( T_{1/2} > 4.8 \cdot 10^{25} \text{ yr} \)
Frequentist limit (90% C.L.): \( T_{1/2} > 2.7 \cdot 10^{25} \text{ yr} \)

Full Exposure (26 kg-yr)
Background: \( 15.4 \pm 2.0 \text{ cts/(FWHM)} \)

Lowest Background Configuration:
\( 11.9 \pm 2.0 \text{ cts/(FWHM·t·yr)} \)
\( (5 \cdot 10^{-3} \text{ cts/(keV·kg·yr)}, \ 2.5 \text{ keV FWHM}) \)
Active Exposure: 21.3 kg·yr (\(^{76}\)Ge)
Comparison of Ge vs Xe & Te projects

<table>
<thead>
<tr>
<th></th>
<th>Total Mass</th>
<th>Expected/</th>
<th>Expect/</th>
<th>Exposure</th>
<th>$T_{1/2}$</th>
<th>$T_{1/2}$</th>
<th>$m_{ee}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isot.</td>
<td>Achi.vd BI</td>
<td>Achi.vd</td>
<td>[kg·y]</td>
<td>Sensitivity (90%CL) [y]</td>
<td>Ach. Limit (90%CL) [y]</td>
<td>Limit (90%CL) [meV]</td>
</tr>
<tr>
<td>Gerda II</td>
<td>38.5</td>
<td>$10^{-3}$</td>
<td>$3.0-3.7$</td>
<td>~100</td>
<td>&gt; $10^{26}$</td>
<td>9.0 · $10^{25}$</td>
<td>90-150</td>
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<tr>
<td>Gerda II</td>
<td>38.5</td>
<td>$0.6·10^{-3}$</td>
<td>3.2-4.8</td>
<td></td>
<td>59</td>
<td>1.1·$10^{26}$</td>
<td>2.1·$10^{25}$</td>
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<tr>
<td>GERDA I</td>
<td>16</td>
<td>$~10^{-2}$</td>
<td></td>
<td>~100</td>
<td>1.2·$10^{25}$</td>
<td>200-400</td>
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<tr>
<td>Majorana Dem.nstrat</td>
<td>30</td>
<td>&lt; $10^{-3}$</td>
<td>&lt; 4</td>
<td>26</td>
<td>&gt; $10^{26}$</td>
<td>2.7 · $10^{25}$</td>
<td></td>
</tr>
<tr>
<td>Dem.nstrat</td>
<td></td>
<td>$~10^{-3}$</td>
<td>&lt; 3</td>
<td>26</td>
<td>4.8 · $10^{25}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuore Cuoricino</td>
<td>206</td>
<td>$10^{-2}$</td>
<td>5</td>
<td>1000</td>
<td>9.5 · $10^{25}$</td>
<td>1.5 · $10^{25}$</td>
<td>50-190</td>
</tr>
<tr>
<td>Cuore</td>
<td>11.6</td>
<td>$1.4·10^{-2}$</td>
<td>7</td>
<td>83.6</td>
<td>7.0 · $10^{24}$</td>
<td>300 – 700</td>
<td></td>
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<tr>
<td>Cuoricino</td>
<td></td>
<td>$15.3·10^{-2}$</td>
<td>6.3</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>n-EXO EXO 200 ult.</td>
<td>5000</td>
<td>$1.7·10^{-3}$</td>
<td>73</td>
<td>100</td>
<td>1.1 · $10^{25}$</td>
<td>10</td>
<td>50</td>
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<tr>
<td>EXO 200</td>
<td>200</td>
<td></td>
<td>112</td>
<td></td>
<td>1.1 · $10^{25}$</td>
<td>190-450</td>
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<tr>
<td>KZ KZ comb.</td>
<td>348</td>
<td>$3.0·10^{-4}$</td>
<td>265</td>
<td>138</td>
<td>5.6 · $10^{25}$</td>
<td>1.1·$10^{26}$</td>
<td>20</td>
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<tr>
<td>348</td>
<td></td>
<td>$6.0·10^{-4}$</td>
<td>265</td>
<td>126</td>
<td>9.6·$10^{25}$</td>
<td>1.3·$10^{25}$</td>
<td>60-160</td>
</tr>
<tr>
<td>Kam-Zen II</td>
<td>320</td>
<td></td>
<td>285</td>
<td>285</td>
<td>29.6</td>
<td>1.9·$10^{25}$</td>
<td>100</td>
</tr>
</tbody>
</table>

† Design Sensitivity; † † 5 yr projected sensitivity

Blue: Achieved
RED: $~10^{26}$ range
GERDA & KZEN limit on $m_{ee}$

arXiv:1806.11051v1
GERDA PHASE II.5: Upgraded

- natCOAX string substituted by a string of \( 5 \text{ enr InvertedCoaxials} \) (9.5 kg). These are the candidate detectors of the GERDA Phase II follow-up project: LEGEND-200

- Upgrade of FE HV contacts with lowest background ones

- Upgrade of LAr scintillating fiber detector to increase the background SF (now \( \sim 2 \) on top of the PSD cut)
  - \( x 2 \) improvement in Light Yield (increase of SciFibers density)
  - installation of new SciFiber module surrounding the central \( \text{enr InvertedCoaxials} \) string to reduce shadowing effect

- Installation of protecting diodes on FE boards to protect JFETs (at the price of some extra-noise)

→ Take data until GERDA scientific program will be fulfilled
LEGEND: the collaboration

Univ. New Mexico
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Res. Centre, Geel

Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ
Queens Univ.

Univ. Tennessee
Argonne Natl. lab.
Univ. Liverpool
Univ. College London

Los Alamos Natl. Lab.
Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Lab. for Exper. Nucl. Phy. MEPhI
Max Planck Inst., Munich
Technical Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich
The LEGEND program

200 kg (38 kg GERDA + 30 kg Majorana + new $^{enr}$Ge (in form of BEGe). Already presented and approved at LNGS

**LEGEND-200 (first phase):**
- up to 200 kg of detectors
- $\text{BI} \sim 0.6 \text{ cts/(FWHM t yr)}$
- use existing GERDA infrastructure at LNGS
- design exposure: 1 t yr
- Sensitivity $10^{27}$ yr
- Isotope procurement ongoing
- Start in 2021

**LEGEND-1000 (second phase):**
- 1000 kg of detectors (deployed in stages)
- $\text{BI} < 0.1 \text{ cts/(FWHM t yr)}$
- Location tbd
- Design exposure 12 t yr
- $1.2 \times 10^{28}$ yr

Sensitivity for 3σ signal discovery

200 kg (38 kg GERDA + 30 kg Majorana + new $^{enr}$Ge (in form of BEGe). Already presented and approved at LNGS
Conclusions

• After successful operation of GERDA I (2009-2013), GERDA II, is in operation since 12/2015 at LNGS: it is close to completion of the GERDA scientific goal

• The recentest (june 2018) data release
  – Total exposure: 59 kg yr of $^{76}$Ge (~87%)  
  – No Signal has been observed: Best fit $N_{0\nu} = 0$
  – $T_{1/2}^{0\nu} > 0.9 \cdot 10^{26}$ yr @ 90% C.L.
  – Median Sensitivity (NO Signal)
    \[ T_{1/2}^{0\nu} > 1.1 \cdot 10^{26} \text{ yr} @ 90\% \text{ C.L.} \text{ (Best world sensitivity!)} \]
  – $<m_\nu > \leq 0.11 - 0.26$ eV

• The GERDA technique of operating bare Ge detectors in LAr as cooling and shielding medium proved to be reliable and performant
  – FWHM @ $Q_{bb}$ (2.04MeV) = 3 keV for low capacity detectors for spectra integrated over years of data taking!!!
  – The know-how to mount, contact, operate the Ge detectors while keeping an ultralow background has been deeply worked out
  – Background Index: GERDA I (10$^{-2}$ cts/(keV kg yr)) $\rightarrow$
    GERDA II (0.6 $\cdot$ 10$^{-3}$ cts/(keV kg yr)) (Best world Background Index at ROI evaluated on 240 keV!)
  i.e. Factor 20 reduction thanks to the top quality of the original setup (water shield, muon veto, cryostat etc.) new HW (new holders, FE, contacts, LAr SciLight readout) and SW (PSD) development.
  – Customized production of $^{76}$Ge well performing detectors by leader company has been demonstrated

• Next experimental step to fully probe the neutrino mass inverted hierarchy region is
  LEGEND-200 (new collaboration) @ LNGS
Few personal thoughts

• With the present knowledge in the neutrino sector of SSM, the most natural way for neutrino to have light masses is that they are Majorana particles, hence $0\nu\beta\beta$ decay should be observed, provided $g_A$ or specific NME do not suppress it.

• If we don’t see $0\nu\beta\beta$ within next 10 years, then, unless nature chose something really weird, the neutrino is most likely not its own antiparticle.

• Particle physics and cosmological observation, tell us there is not much more wiggle room for the neutrino to still be its own antiparticle, and for us not to have seen it.
14 years ago: The $0\nu\beta\beta$ observation claim


- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for $0\nu\beta\beta$
- reported $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

N.B. Half-life $T_{1/2}^{0\nu} = 2.23 \times 10^{25}$ yr $T_{1/2}^{0\nu}$ after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with $\epsilon_{psd} = 1$ (previous similar analysis $\epsilon_{psd} \approx 0.6$)
- $\epsilon_{fep} = 1$ (also in NIM A 522, PLB 586 (2004))
  (GERDA value for same detectors: $\epsilon_{fep} = 0.9$)

(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):
GERDA II: Results

- GERDA Phase II is running stable
- 3-4 keV energy resolution at $Q_{\beta\beta}$
- lowest background in ROI ever achieved: $35^{+21}_{-15} \cdot 10^{-4} \text{ cts/(keV} \cdot \text{kg} \cdot \text{yr)}$ for Coax
  $7^{+11}_{-5} \cdot 10^{-4} \text{ cts/(keV} \cdot \text{kg} \cdot \text{yr)}$ for BEGe
- combined Phase I+II sensitivity: $T_{1/2}^{0\nu} > 4.0 \cdot 10^{25} \text{ yr (90\% C.L.)*}$
- blind analysis, no $0\nu\beta\beta$ signal: $T_{1/2}^{0\nu} > 5.2 \cdot 10^{25} \text{ yr (90\% C.L.)*}$
  $|m_{ee}| < [160,260] \text{ meV (90\% C.L.)*}$
  (* preliminary, $\epsilon_{\text{coax}}^{PSD}$ to be finalized)

GERDA Phase II is the high-resolution and background-free experiment!

[see poster on next gen $^{76}\text{Ge}$ exp: P4.057]
GERDA I: $T_{1/2}^{0\nu}$

Performed Profile Likelihood fit of the 3 data sets

- B+S: described by constant term + Gaus($Q_{\beta\beta}, \sigma_E$)
- 4 free parameters in the fit $B_{\text{gold}}, B_{\text{silv}}, B_{\text{BEGe}}, 1/ T_{1/2}^{0\nu}$
- Systematics folded in

Frequentist approach
Best fit: $N^{0\nu} = 0$
$N^{0\nu} < 3.5$ cts $\times 90\%$ C.L.

$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr $\times 90\%$ CL

Median sensitivity:
$T_{1/2}^{0\nu} > 2.4 \times 10^{25}$ yr

Bayesian approach
Flat prior for $1/ T_{1/2}^{0\nu}$
Best fit: $N^{0\nu} = 0$

$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr $\times 90\%$ CI

Median sensitivity:
$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr
GERDA I vs $0\nu\beta\beta$ observation claim

For $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

Expected Signal (after PSD): $5.9 \pm 1.4$ cts in $\pm 2\sigma$

Expected Bckgd (after PSD): $2.0 \pm 0.3$ cts in $\pm 2\sigma$

Observed: $3.0$ (0 in $\pm 1\sigma$)

From profile likelihood
Assuming H1 true $\Rightarrow$
$P(N^{0\nu}=0)=1\%$

Comparing
H1: Claimed signal
H0: Background only

Bayes factor
$P(H1)/P(H0)=0.024$

(uncertainties on claim included)

Claim poorly credible
GERDA I: Unblinded data

\[ T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N_{0\nu}} \cdot \mathcal{E} \cdot \varepsilon \]

\[ \varepsilon = \frac{f_{76} \cdot f_{\nu
u} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd}}{1} \]

<table>
<thead>
<tr>
<th>data set</th>
<th>( \mathcal{E} ) [kg·yr]</th>
<th>( \langle \varepsilon \rangle )</th>
<th>bkg</th>
<th>BI (^\dagger)</th>
<th>cts</th>
</tr>
</thead>
<tbody>
<tr>
<td>without PSD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>golden</td>
<td>17.9</td>
<td>0.688 ± 0.031</td>
<td>76</td>
<td>18 ±2</td>
<td>5</td>
</tr>
<tr>
<td>silver</td>
<td>1.3</td>
<td>0.688 ± 0.031</td>
<td>19</td>
<td>63^{+16}_{-14}</td>
<td>1</td>
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<tr>
<td>BEGe</td>
<td>2.4</td>
<td>0.720 ± 0.018</td>
<td>23</td>
<td>42^{+10}_{-8}</td>
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<tr>
<td>with PSD</td>
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<tr>
<td>golden</td>
<td>17.9</td>
<td>0.619^{+0.044}_{-0.070}</td>
<td>45</td>
<td>11 ±2</td>
<td>2</td>
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<tr>
<td>silver</td>
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<td>0.619^{+0.044}_{-0.070}</td>
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<td>30^{+11}_{-9}</td>
<td>1</td>
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<tr>
<td>BEGe</td>
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<td>0.663 ± 0.022</td>
<td>3</td>
<td>5^{+4}_{-3}</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^\dagger\) in units of \(10^{-3}\) cts/(keV·kg·yr).

Expected background only

\[ \text{In 230 keV} \]
\[ \text{In ROI} \pm 5\text{ keV} \]

Bckgrd Rej \(_{PSD}\) BEGe \(~ 87\%\)

Bckgrd Rej \(_{PSD}\) Coax \(~ 43\%\)

10/07/18
Detectors:
- 6 (of 8) $^{68}$Ge COAX
- 4 (of 5) $^{68}$BEGe-type Ge
- 1 $^{46}$nat Ge COAX
(not in $\beta\beta$ data-set)

Achieved BI (evaluated in 230 keV around $Q_{\beta\beta}$):
- COAX:
  BI: $(18 \pm 2) \times 10^{-3}$ cts/(kky)
- BEGe
  BI: $(5 \pm 4) \times 10^{-3}$ cts/(kky) w. PSD

BEGe insertion

$2\nu\beta\beta T_{1/2}$ published $(5.01 \text{ kg yr})$

$\Rightarrow$ FWHM @ $Q_{\beta\beta} = 4.8$ keV

$\Rightarrow$ FWHM @ $Q_{\beta\beta} = 3.2$ keV

Goals
- Scrutinize $\beta\beta$ claim
- Demonstrate BI: $10^{-2}$ cts/(kky)
- Exposure: 21.6 kg yr

10/07/18
C.M. Cattadori – ICNFP 2018
GERDA II: Data taking

• 131 live days:
  25\textsuperscript{th} Dec 2015 to 1\textsuperscript{st} Jun 2016
• 82.0% duty factor
• Blinding applied at $Q_{\beta\beta} \pm 25$ keV

• Usable for analysis \textbf{10.8 kg\cdot yr}
  ✓ 5.8 kg\cdot yr BEGe (~81% of $^{\text{enr}}$BEGe mass)
  ✓ 5.0 kg\cdot yr coax (~77% of $^{\text{enr}}$coax mass) plus
  ✓ 2.8 kg\cdot yr $^{\text{nat}}$Ge (for background studies)
  About 0.4 kg\cdot yr of BEGe data not considered due to poor PSD

• Additional \textbf{unpublished data} from Phase I (\textbf{1.9 kg\cdot yr})
  Taken after the freezing of the Phase I release dataset (Jul-Sep 2013)
  Never unblinded since 2013