Results from GERDA Phase I

Marco Salathe, marco.salathe@mpi-hd.mpg.de

Max Planck Institute for Nuclear Physics, Heidelberg

LAPP, Annecy, January 10, 2014
Outline

• Neutrinoless double beta decay - theory and experiment
• The Gerda experiment
• Data taking and data processing
• Background models and $2\nu\beta\beta$ analysis
• Background reduction methods
• $0\nu\beta\beta$ results
• Outlooks
Neutrinoless double beta decay

Postulation of the neutrino - single beta decay

Offener Brief an die Gruppe der Radioaktiven bei der Gauvertagung zu Tubingen.

Abschrift
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich, 4. Dez. 1930
Gloriastrasse

Lieber Radioaktive Damen und Herren,

Wie der Uberbringer dieser Zeilen, den ich baldvollst
anschreiben bitte, Ihnen das naheher auszudrucken wird, bin ich
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
des kontinuierlichen beta-Spektrums auf einen verwendeten Ausweg
verfallen um den "Wahrschein" (1) der Statistik und den Energiesatz
trotzen. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,
welche den Spin 1/2 haben und das Ausschlussungsprinzip befolgen und
sich von Lichtquellen ausseren noch dadurch unterscheiden, dass sie
nie mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen
dürfte von derselben Ordnungszahl wie die Elektronmassen sein und
keinesfalls nicht grösser als 0,01 Protonsmasse. - Das kontinuierliche
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim
Beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert
wird, darart, dass die Summe der Energien von Neutron und Elektron
konstant ist.

\[ t \quad p \quad u \quad \bar{d} \quad \bar{d} \quad \bar{u} \quad \bar{u} \quad e^- \]

\[ \nu_e \quad W^- \]
Neutrinoless double beta decay

Mass parabolas of odd-odd, even-even nuclei

- Even-even nuclides are more stable (smaller binding energy)
- Beta decay transforms even-even nuclides into odd-odd nuclides
- For a few isotopes the next odd-odd nuclide can have higher binding energy
  ⇒ In such a case single beta decay is forbidden:
  ⇒ Double beta decay is allowed \( 2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e \)
Neutrinoless double beta decay

Double beta decay spectrum

- Standard Model - two neutrino double beta decay:
  - Emission of two neutrinos and two electrons
  - Continuous spectrum (neutrinos usually escape)
  - Has been observed for 11 isotopes
Neutrinoless double beta decay

Double beta decay spectrum

- Standard Model - two neutrino double beta decay:
  - Emission of two neutrinos and two electrons
  - Continuous spectrum (neutrinos usually escape)
  - Has been observed for 11 isotopes

- Neutrinoless double beta decay:
  - Emission of only two electrons
  - Peak at $Q_{\beta\beta} = 2039$ keV (for $^{76}$Ge)
Neutrinoless double beta decay (0$\nu\beta\beta$)

- Process of form: $(A, Z) \rightarrow (A, Z + 2) + 2e^-$
- It violates Lepton number conservation by two units
- Implies physics beyond the standard model
- Schechter-Valle theorem: All realizations of $0\nu\beta\beta$ are connected to a Majorana neutrino mass

![Diagram of Neutrinoless Double Beta Decay]

Marco Salathe (MPIK)
Neutrinoless double beta decay

Neutrinoless double beta decay \((0\nu\beta\beta)\)

- Process of form: \((A, Z) \rightarrow (A, Z + 2) + 2e^-\)
- It violates Lepton number conservation by two units
- Implies physics beyond the standard model
- Schechter-Valle theorem: All realizations of \(0\nu\beta\beta\) are connected to a Majorana neutrino mass
- Simplest case: Annihilation of neutrino and anti-neutrino.
Neutrinoless double beta decay

Neutrinoless double beta decay \((0\nu\beta\beta)\)

- Process of form: \((A, Z) \rightarrow (A, Z + 2) + 2e^-\)
- It violates Lepton number conservation by two units
- Implies physics beyond the standard model
- Schechter-Valle theorem: All realizations of \(0\nu\beta\beta\) are connected to a Majorana neutrino mass
- Simplest case: Annihilation of neutrino and anti-neutrino.
- Any \(\Delta L = 2\) process possible
- Higgs triplet, SUSY,...: Important connections to high energy particle physics
- sub eV Majorana mass ↔ TeV scale physics
Neutrinoless double beta decay

Neutrino mass formula

\[
(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 m_{\beta\beta}^2
\]

- \((T_{1/2}^{0\nu})^{-1}\): Half life of isotope, measured
- \(G_{0\nu}(Q_{\beta\beta}, Z)\) phase space
- \(M_{0\nu}\): nuclear matrix element, calculated
- \(m_{\beta\beta}\): effective Majorana mass:
  \[m_{\beta\beta} = |\sum_{i=0}^{3} U_{ei}^2 m_i|\]
- \(U\): PMNS matrix (measured in neutrino oscillation experiments)
- \(m_i\): mass eigenvalue

Experimental limits

<table>
<thead>
<tr>
<th>Isotope</th>
<th>(Q_{\beta\beta}), keV</th>
<th>(T_{1/2}^{0\nu}), yr</th>
<th>(m_{\beta\beta}), eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{48}\text{Ca})</td>
<td>4272</td>
<td>(&gt; 5.8 \times 10^{22})</td>
<td>(&lt; 14)</td>
</tr>
<tr>
<td>(^{76}\text{Ge})</td>
<td>2039.0</td>
<td>(&gt; 1.9 \times 10^{25})</td>
<td>(&lt; 0.2 - 0.7)</td>
</tr>
<tr>
<td>(^{82}\text{Se})</td>
<td>2996</td>
<td>(&gt; 3.6 \times 10^{23})</td>
<td>(&lt; 0.8 - 2.4)</td>
</tr>
<tr>
<td>(^{96}\text{Zr})</td>
<td>3350</td>
<td>(&gt; 9.2 \times 10^{21})</td>
<td>(&lt; 3.9 - 13.7)</td>
</tr>
<tr>
<td>(^{100}\text{Mo})</td>
<td>3034.4</td>
<td>(&gt; 1.1 \times 10^{24})</td>
<td>(&lt; 0.3 - 0.7)</td>
</tr>
<tr>
<td>(^{116}\text{Cd})</td>
<td>2813.5</td>
<td>(&gt; 1.7 \times 10^{23})</td>
<td>(&lt; 1.2 - 2.2)</td>
</tr>
<tr>
<td>(^{128}\text{Te})</td>
<td>867</td>
<td>(&gt; 1.5 \times 10^{24})</td>
<td>(&lt; 1.8 - 4.2)</td>
</tr>
<tr>
<td>(^{130}\text{Te})</td>
<td>2527.5</td>
<td>(&gt; 2.8 \times 10^{24})</td>
<td>(&lt; 0.4 - 0.8)</td>
</tr>
<tr>
<td>(^{136}\text{Xe})</td>
<td>2458.7</td>
<td>(&gt; 1.6 \times 10^{25})</td>
<td>(&lt; 0.1 - 0.4)</td>
</tr>
<tr>
<td>(^{150}\text{Nd})</td>
<td>3371.4</td>
<td>(&gt; 1.8 \times 10^{22})</td>
<td>(&lt; 2.2 - 7.5)</td>
</tr>
</tbody>
</table>


Claim of observation: KKDC: 71.7 kg \cdot yr: \(T_{1/2}^{0\nu} = 1.2(0.7-4.2) \cdot 10^{25}\) yr (Phys Lett B586 (2004) 198)

Sensitivity of an experiment:

\[
T_{1/2}^{0\nu}(n_{\sigma}) = \frac{4.16 \times 10^{26} \text{yr}}{n_{\sigma}} \left(\frac{\epsilon a}{W}\right) \sqrt{\frac{M_{t}}{b\Delta(E)}}
\]

- \(\epsilon\): detection efficiency
- \(a\): abundance of isotope
- \(W\): molecular weight of source
- \(M_{t}\): exposure [kg yr]
- \(b\): background index (BI)
- \(\Delta(E)\): instrumental spectral width
The GERDA experiment - collaboration

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

16 institutions
~100 members
The GERDA experiment - milestones and location

GErmanium Detector Array

- 2004: Letter of Intent
- R&D: material selection and screening, tests of bare diodes in LAr
- 2008-2010: construction at LNGS (Laboratori Nazionali del Gran Sasso, Italy, 3400mwe)
- 2010-2011: commissioning
The GERDA experiment - milestones and location

**GERmanium Detector Array**

- 2004: Letter of Intent
- R&D: material selection and screening, tests of bare diodes in LAr
- 2008-2010: construction at LNGS (Laboratori Nazionali del Gran Sasso, Italy, 3400mwe)
- 2010-2011: commissioning
- Nov. 2011 - May 2013: data taking Phase I data
- Change to Phase II presently ongoing

![Graph showing 90% prob. lower limit T_1/2 vs Exposure [kg·years]](image-url)

- No background
- $10^{-4}$ counts/(kg·keV·y)
- $10^{-3}$ counts/(kg·keV·y)
- $10^{-2}$ counts/(kg·keV·y)
- Claim

(Phase II: BL=0.001, Phase I: BL=0.01, KKDC)
The GERDA experiment - construction

6 Mar '08

5 May '08

29 Feb '09

6 Apr '09

Aug '09

active cooling system inst.

0.03g LNGS galleria

0.52g peak ground acceleration

view inside water tank

18 May '10

inauguration 9 Nov 2011

glove box

Cryostat filled since December 2009
The GERDA experiment - setup

**Water tank**
- 590 m$^3$ ultra-pure water
- neutron moderator/absorber
- muon Cherenkov veto

**Large Cryostat**
- 64 m$^3$ LAr
- cooling medium
- passive shielding

**Ge detector array**
- 3-string arm with 9 coaxial detectors, 1-string arm with 5 BEGes
- bare germanium detectors on low mass holders

**Plastic scintillator**
- active muon veto

**Clean room**
- detector handling in glove box in nitrogen atmosphere
The GERDA experiment - detectors

- Why germanium?
  - Solid even at room temperature
  - Very good energy resolution
  - Detector material = source material

- Deployed detectors:
  - Refurbished semi-coaxial detectors from HdM and IGEX experiments
  - n+ conductive Li layer, separated by a groove from the boron implanted p+ contact
  - Phase II detector type, already used: BEGe - broad energy Ge detector
  - Semi-coaxial detectors: 2 - 2.8kg, BEGe ~0.7kg
The GERDA experiment - production of new diodes
The GERDA experiment - strings

- Used in this analysis:
  
  since Nov. 11: 6 enriched semi-coaxial: ANG2,3,4,5, RG1,2 14.63kg  
  1 natural semi-coaxial: GTF112 2.96kg  
  since Jul. 12: 4 enriched BEGe: GD32B,C,D, GD35B 3.00kg  

- Enrichment of $^{76}$Ge: 86-87%
Analysis

- Processing: diode → amplifier → FADC → digital filter → energy/pulse shape/etc
- Selection: anti-coincidence muon / 2nd Ge (~20% rejected at $Q_{\beta\beta}$), quality cuts (~9% rej.), pulse shape discrimination (~50% rej.)
- Calibration: $^{228}$Th (bi)weekly and pulser every 20 seconds for short term drifts

Results

- shifts are small compared to FWHM ~0.2% $Q_{\beta\beta}$
- peak pos. within 0.3keV at correct position (here for $^{42}$K)
- FWHM ~4% larger than expected from calibration data
The GERDA experiment - data taking

- Stable data taking during most of the time (492 d, duty cycle 88%)
- total exposure: 21.6 kg·yr
- Blue spikes indicate calibration measurements
- Break during deployment of BEGe detectors
The GERDA experiment - data blinding

- Blinding is done for avoiding biases (due to low statistics)
- During data taking: All events in $Q_{\beta\beta} \pm 20$keV removed
- May 2013: All events up to $Q_{\beta\beta} \pm 5$keV unblinded $\Rightarrow$ additional check
- 2 copies of raw data kept for processing after unblinding
The GERDA experiment - data blinding

- Blinding is done for avoiding biases (due to low statistics)
- During data taking: All events in $Q_{\beta\beta} \pm 20\text{keV}$ removed
- May 2013: All events up to $Q_{\beta\beta} \pm 5\text{keV}$ unblinded ⇒ additional check
- 2 copies of raw data kept for processing after unblinding
- Data processing details fixed before unblinding:
  - quality cuts
  - pulse shape discrimination parameters
  - analysis method: three data sets
    - golden coaxial = 17.9 kg·yr
    - silver coaxial = 1.3 kg·yr
    - BEGe = 2.4 kg·yr
The GERDA experiment - data blinding

- Blinding is done for avoiding biases (due to low statistics)
- During data taking: All events in $Q_{\beta\beta} \pm 20$keV removed
- May 2013: All events up to $Q_{\beta\beta} \pm 5$keV unblinded $\Rightarrow$ additional check
- 2 copies of raw data kept for processing after unblinding
- Data processing details fixed before unblinding:
  - quality cuts
  - pulse shape discrimination parameters
  - analysis method: three data sets
    - golden coaxial = 17.9 kg·yr
    - silver coaxial = 1.3 kg·yr
    - BEGe = 2.4 kg·yr
- Date unblinded in June 2013
Visible backgrounds:

- Double beta decay of $^{76}\text{Ge}$
- $\beta$ decay of cosmogenic $^{39}\text{Ar}$
- Alphas (decay on p+ surface, $^{226}\text{Ra}$, $^{222}\text{Rn}$ $^{210}\text{Po}$)
- Decay of $^{42}\text{K}$ on the surface or close to the detector from $^{42}\text{Ar}$ (mini shroud was deployed to reduce this background)

http://arxiv.org/abs/1306.5084 (accepted by EPJC)
The GERDA experiment - background model

- Fit of combination of MC spectra to data between 570 keV and 7500 keV
- Good fits, however not unique (different models possible)
- Close background sources dominate: $^{42}$Ar, $^{228}$Th, $^{226}$Ra in holders, $\alpha$ particles on detector surfaces.

http://arxiv.org/abs/1306.5084 (accepted by EPJC)
• Background flat between 1930 keV - 2190 keV w/o 2104 keV and 2119 keV peaks
• No line expected in the blinded window
• Linear fit with flat background excluding $2104 \pm 5$ keV and $2119 \pm 5$ keV peak regions
• For $0\nu\beta\beta$ analysis a flat background around $Q_{\beta\beta}$ can be used

http://arxiv.org/abs/1306.5084 (accepted by EPJC)
The GERDA experiment - $2\nu\beta\beta$

- Region between 600 keV and 1400 keV dominated by $2\nu\beta\beta$ decay
- Global fit of background model contains this distribution
- It is possible to extract $2\nu\beta\beta$ half-life

$$T^{2\nu}_{1/2} = (1.84 \pm 0.14) \cdot 10^{21} \text{ yr}$$

- This is the best current limit for this decay
The GERDA experiment - pulse shape discrimination

- Exploit different pulse structure of
  - single-site events (SSE)
  - multi-site events (MSE).

- $0\nu\beta\beta$ events are SSE: (1 MeV electron has range of $\sim 1\text{mm}$)

- Compton scatted MeV $\gamma$’s more than $10 \times$ larger range $\Rightarrow$ MSE

- Surface events: only electrons or holes drift $\Rightarrow$ characteristic pulse shape

- Coaxial and BEGe diodes have very different E-fields $\Rightarrow$ different PSD properties and algorithms

- PSD developed with calibration and physics data: $^{228}\text{Th}$ spectrum, certain features used as proxies for signal-like ($\text{DEP,Compton Edge,}^{2\beta\beta}$) and background-like events ($\text{FEP}$).

http://arxiv.org/abs/1307.2610 (accepted by EPJC)
The GERDA experiment - pulse shape discrimination

**BEGe detectors:**

- \( A \) = Amplitude of current pulse
- \( E \) = energy reconstructed with shaping filter
- \( A / E \) is a robust, simple and well understood cut parameter

---

http://arxiv.org/abs/1307.2610 (accepted by EPJC)
The GERDA experiment - pulse shape discrimination

BEGe detectors:

- SSE accepted for $0.965 < \text{A/E} < 1.07$
- $0\nu\beta\beta$ efficiency = $(92 \pm 2)$ % (from DEP efficiency and simulation)
- $2\nu\beta\beta$ efficiency = $(91 \pm 5)$ % (good agreement with DEP eff.
- 80% of background events rejected around $Q_{\beta\beta}$

http://arxiv.org/abs/1307.2610 (accepted by EPJC)
The GERDA experiment - pulse shape discrimination

Coaxial detectors:

- Artificial neural network (ANN): TMlpANN implemented in TMVA (ROOT)
- Input: time when charge signal reaches 1%, 3%, ..., 99% of maximum amplitude
- $0\nu\beta\beta$ efficiency (from DEP and simulation): (90 ±0.05/-0.09) %
- About 45% events rejected around $Q_{\beta\beta}$
- Cross checks:
  - $2\nu\beta\beta$ eff = (85 ± 2) %
  - 2.6 MeV $\gamma$ Compton edge eff. = 85 - 94 %
  - Co-56 DEP (1576 and 2231 keV) eff. = 83 - 93 %
  - Simulations

http://arxiv.org/abs/1307.2610 (accepted by EPJC)
The GERDA experiment - pulse shape discrimination

Coaxial detectors:

Cross check ANN classification with 2 other methods:

- Projective likelihood trained with Compton edge events
- Current pulse asymmetry $\times A/E$
- 90% of ANN rejected events also rejected by both, 3% only rejected by ANN
  $\Rightarrow$ Classification of background like events meaningful

http://arxiv.org/abs/1307.2610 (accepted by EPJC)
0νββ analysis - unblinding

Expected background from interpolation:
5.1 events w/o PSD
2.5 events with PSD

Expected background from interpolation:

- 5.1 events w/o PSD
- 2.5 events with PSD

0νββ analysis - calculating the half life

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

\[
\varepsilon = f_{76} \cdot f_{av} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd}
\]

<table>
<thead>
<tr>
<th>Data set</th>
<th>Exposure (kg·yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden-coax</td>
<td>17.9</td>
</tr>
<tr>
<td>Silver-coax</td>
<td>1.3</td>
</tr>
<tr>
<td>BEGe</td>
<td>2.4</td>
</tr>
</tbody>
</table>

\( N_A \) Avogadro number,
\( m_{enr} \) molar mass of enriched Ge,
\( N^{0\nu} \) signal counts/limit,
\( \mathcal{E} \) total exposure,
\( \varepsilon \) exposure averaged efficiency
\( f_{76} \) enrichment fraction,
\( f_{av} \) fraction of active detector volume,
\( \varepsilon_{fep} \) full energy peak efficiency for 0νββ,
\( \varepsilon_{psd} \) signal acceptance

\[
\begin{array}{cccccc}
< f_{76} > & < f_{av} > & < \varepsilon_{fep} > & < \varepsilon_{psd} > & < \varepsilon > \\
\hline
\text{Coax} & 0.86 & 0.87 & 0.92 & 0.90^{+0.05}_{-0.09} & 0.619^{+0.044}_{-0.070} \\
\text{BEGe} & 0.88 & 0.92 & 0.90 & 0.92 \pm 0.02 & 0.663 \pm 0.022 \\
\end{array}
\]

0νββ analysis - unblinding

Profile likelihood fit to the 3 data sets: constant (bgnd) + gaussian

- Given param.: \( \mu = (2039.06 \pm 0.2)\text{keV}, \sigma = (2.0 \pm 0.1)/(1.4 \pm 0.1)\text{keV coax/BEGe} \)

open box = w/o PSD
grey box = with PSD
$0\nu\beta\beta$ analysis - unblinding

Profile likelihood fit to the 3 data sets: constant (bgnd) + gaussian

- Given param.: $\mu = (2039.06 \pm 0.2)\text{keV}$, $\sigma = (2.0 \pm 0.1)/(1.4 \pm 0.1)\text{keV coax/BEGe}$
- Frequentist: best fit $N^{0\nu} = 0 \Rightarrow T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}\text{yr} (90\% \text{ C.L.})$
- Bayes: best fit $N^{0\nu} = 0 \Rightarrow T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}\text{yr} (90\% \text{ C.L., flat } 1/T \text{ prior})$

open box = w/o PSD
grey box = with PSD
$0\nu\beta\beta$ analysis - other $^{76}\text{Ge}$ experiments

- This can be combined with previous $^{76}\text{Ge}$ experiments (IGEX and HdM)
- Almost identical limits with Frequentist and Bayes approach

\[
T_{1/2}^{0\nu} > 3.0 \cdot 10^{25} \text{yr (90\% C.L.)}
\]
$0\nu\beta\beta$ analysis - other $^{76}\text{Ge}$ experiments

- This can be combined with previous $^{76}\text{Ge}$ experiments (IGEX and HdM)
- Almost identical limits with Frequentist and Bayes approach

\[ T_{1/2}^{0\nu} > 3.0 \cdot 10^{25} \text{yr} \ (90\% \ C.L.) \]

- KK claim (observation with $T_{1/2}^{0\nu} = 1.2 \cdot 10^{25} \text{yr}$) strongly disfavoured
- Assuming the KK claimed signal, GERDA should see $5.9 \pm 1.4$ $0\nu\beta\beta$ events in $\pm 2\sigma$ interval above bkg = $2.0 \pm 0.3$
- Probability $p(N_{0\nu} = 0|H1 = signal + bkg) = 1\%$, claim ruled out at 99%
- Bayes factor $H1(= signal + bkg)/H0(= bkg \ only) = 0.024$
0\nu\beta\beta \text{ analysis - limit from } ^{136}\text{Xe}

Coaxial detectors:

Bayes factors:
- EXO 0.23
- KamLAND-Zen 0.40
- GERDA 0.024
- All combined 0.002

HdM claim even stronger disfavoured
⇒ the quest for 0\nu\beta\beta \text{ decay is open again!}
Outlook - Gerda Phase II

sensitivity $T_{1/2}^{0\nu}(^{76}\text{Ge}) \sim 1.4 \cdot 10^{26}$ yr at 100 kg·yr

- Reduce BI by another order of magnitude to 0.001 cts/(keV·kg·yr)
- more BEGe detectors with better PSD and resolution
- instrumentation of LAr to veto specific backgrounds
- less and cleaner material in detector holders, cables, ...
- double detector mass (15 kg coaxial + 20 kg BEGe)
- new readout electronics, radio-purer + better resolution
- get exposure of $\sim100$ kg·yr within 3 years
## Outlook - The next generation of $0\nu\beta\beta$ experiments

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Isotope</th>
<th>Mass of Isotope (kg)</th>
<th>Sensitivity of $T_{1/2}$ (years)</th>
<th>Sensitivity of $m_{\beta\beta}$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE (2013)</td>
<td>$^{130}\text{Te}$</td>
<td>200</td>
<td>$6.5 \times 10^{26}$</td>
<td>20 - 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$2.1 \times 10^{26}$</td>
<td>35 - 90</td>
</tr>
<tr>
<td>GERDA (2011)</td>
<td>$^{76}\text{Ge}$</td>
<td>40</td>
<td>$2 \times 10^{26}$</td>
<td>70 - 300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>$6 \times 10^{27}$</td>
<td>10 - 40</td>
</tr>
<tr>
<td>MAJORANA (2013)</td>
<td>$^{76}\text{Ge}$</td>
<td>30-60</td>
<td>$1 - 2 \times 10^{26}$</td>
<td>70 - 300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>$6 \times 10^{27}$</td>
<td>10 - 40</td>
</tr>
<tr>
<td>EXO (2011)</td>
<td>$^{136}\text{Xe}$</td>
<td>200</td>
<td>$6.4 \times 10^{25}$</td>
<td>95 - 220</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>$8 \times 10^{26}$</td>
<td>27 - 63</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}\text{Se}$</td>
<td>100-200</td>
<td>$1 - 2 \times 10^{26}$</td>
<td>40 - 100</td>
</tr>
</tbody>
</table>


All sensitivities beyond $10^{26}$ yr!
Outlook - Aims of $0\nu\beta\beta$ research

\[
(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{0\nu}\right|^2 m_{\beta\beta}^2 \quad \Rightarrow \quad m_{\beta\beta} < 0.2\text{–}0.4\text{eV}
\]

- 1T scale experiments are required
GERDA Phase I results:

- unprecedented BI of $0.011 \pm 0.002$ cts/(keV · kg · yr) with PSD
- no indication of peak at 2039 keV
- half life limit for $0\nu\beta\beta$ decay of Ge-76:

\[
T_{1/2}^{0\nu} > 2.1 \times 10^{25} \text{ yr (90\% C.L.)}
\]
\[
T_{1/2}^{0\nu} > 3.0 \times 10^{25} \text{ yr (90\% C.L.) with HdM + IGEX}
\]

- The HdM claim is strongly disfavoured
- The quest for $0\nu\beta\beta$ decay is open again!
- The next years will see a variety of experiments searching for $0\nu\beta\beta$ decay of $^{76}$Ge, $^{130}$Te and $^{136}$Xe with largely improved sensitivities.
What HdM value to compare with?

a) 2004 publications: NIM A522 371 & PL B586 198

entire data set: 71.7 kg·yr (active mass)
28.75 ± 6.86 signal events

$$T_{1/2}^{0\nu} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25} \text{ yr}$$

data for PSD analysis: 51.4 kg·yr
19.58 ± 5.41 signal events

$$T_{1/2}^{0\nu} = (1.25^{+0.49}_{-0.27}) \cdot 10^{25} \text{ yr}$$

with PSD applied:
12.36 ± 3.72 events
DEP survival fraction ~ 62%
$$T_{1/2}^{0\nu} = 1.23 \cdot 10^{25} \text{ yr}$$

Without efficiency correction:
$$T_{1/2}^{0\nu} = 1.98 \cdot 10^{25} \text{ yr}$$

No efficiency correction is applied in any publication!
b) 2006 publication: Mod Phys Lett A21  p. 1547-1566

PSD based on 3 previous methods
(2 neural networks + pulse boardness) & library of SSE pulses:
Event accepted IF pulse in library OR found by neural network of Ref. 16 but not by the other two neural networks
NO event overlap between the 2 sets!? 

statement of publication:
- “multi site events are suppressed by 100%”,
- $0\nu\beta\beta$ efficiency = 1 used for $T^{0\nu}_{1/2}$

fit gives 11.32±1.75 signal events
→ $T^{0\nu}_{1/2}=(2.23^{+0.44}_{-0.31})\cdot10^{-25}$ yr

error on signal count not correct since smaller than Poisson error

efficiency factor not considered
→ calculation of $T^{0\nu}_{1/2}$ not correct
→ GERDA does not use this result
Results from GERDA Phase I
LAPP, Annecy, January 10, 2014
$\sin^2 2\theta_{13} = 0.10$

$\Delta m_{31}^2 < 0$

$\Delta m_{31}^2 > 0$