

GERDA Phase II and the future of ^{76}Ge -based experiments

Matteo Agostini on behalf of the GERDA Collaboration

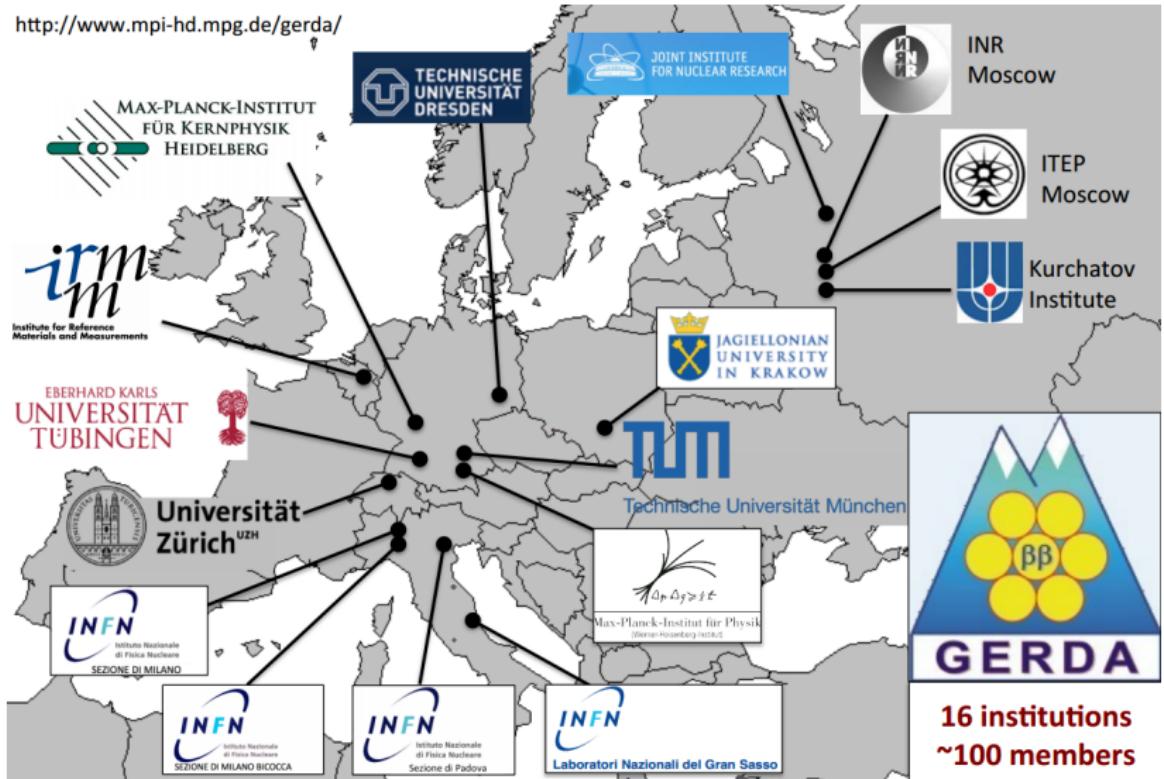
Technical University of Munich (TUM), Germany
and
Gran Sasso Science Institute (INFN), L'Aquila, Italy

EPS-HEP 2015 conference,
22 – 29 July 2015, Vienna, Austria



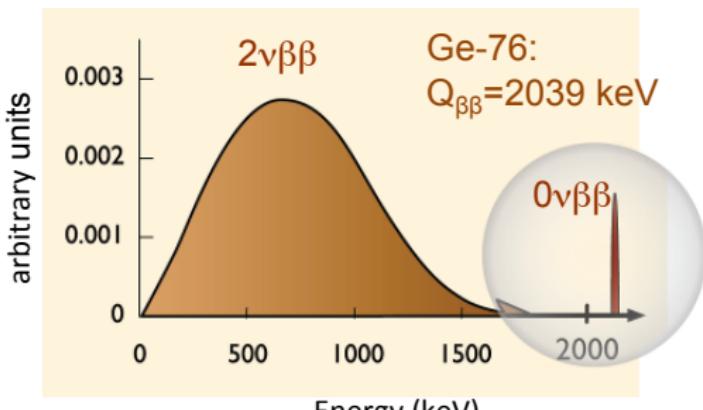
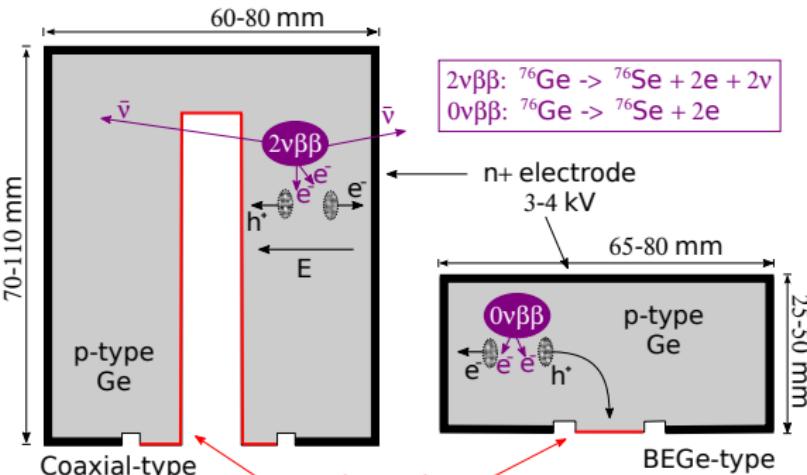
GERDA collaboration

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



Detectors

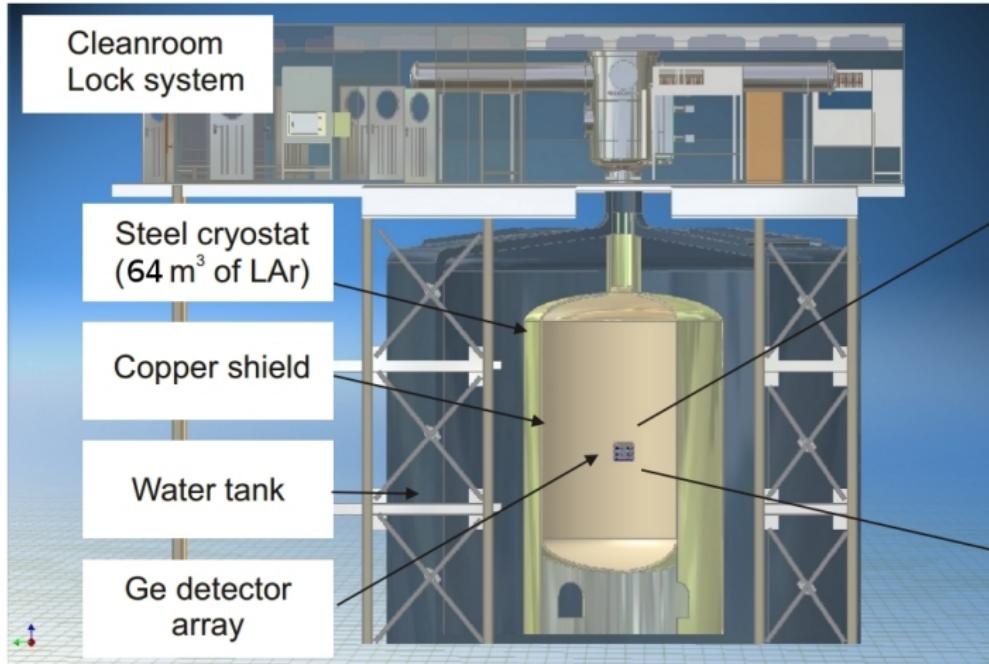
- HPGe detectors from material enriched in ^{76}Ge ($\sim 87\%$)
- detectors well established technology
- optimal spectroscopy performance:
 - long-term stability
 - $\Delta E \approx 0.1\%$ at $Q_{\beta\beta}$
 - radio purity



- Calorimeter detectors:
- source=detector
 - high detection efficiency
 - peak at Q -value ($Q_{\beta\beta}$)

Shielding strategy and apparatus

- bare Ge detectors in liquid Argon (LAr)
- shield: high-purity LAr/H₂O
- radio-pure material selection
- deep underground (LNGS, 3800 m.w.e.)

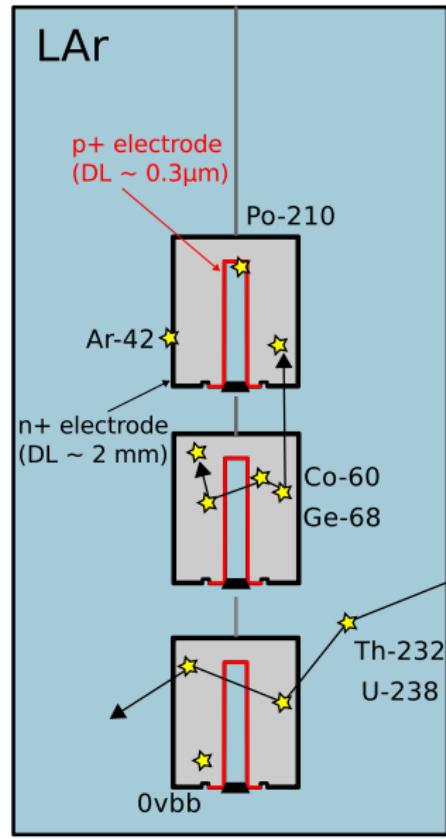


[EPJ C 73 (2013) 2330]

Backgrounds and mitigation techniques

Background sources:

- natural radioactivity (^{232}Th and ^{238}U chains):
 - γ -rays (e.g. ^{208}Tl , ^{214}Bi)
 - α -emitting isotopes from surface contamination (e.g. ^{210}Po) or ^{222}Rn in LAr
- long-lived cosmogenic Ar isotopes (^{39}Ar , ^{42}Ar)
- cosmogenic isotopes activated in Ge (^{68}Ge , ^{60}Co)



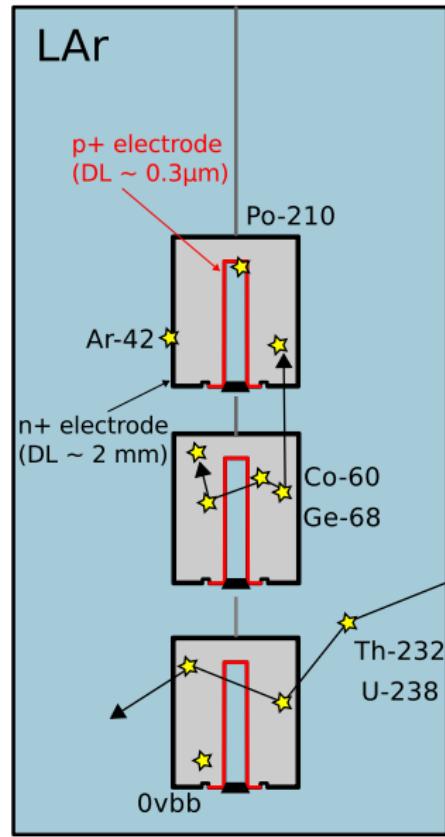
Backgrounds and mitigation techniques

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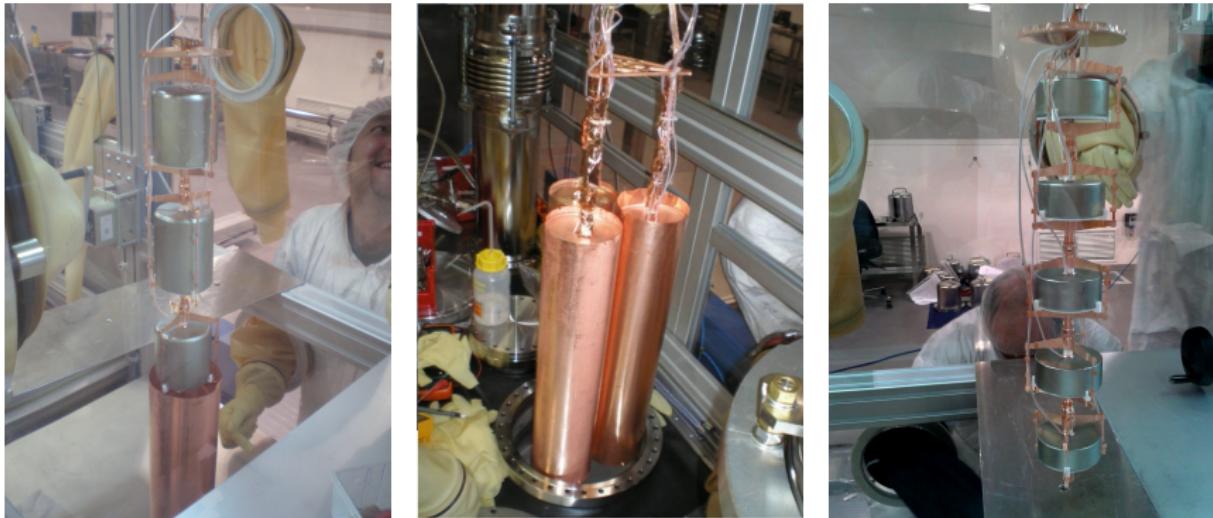
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Mitigation strategy:

- detector anti-coincidence
- **PSD: Pulse Shape Discrimination** (event topology inferred from time-structure of read-out signals)
- **detection of LAr-scintillation light** (only Phase II)



Phase I: detector array configuration



- 4 strings
- 14 detectors: 9 (coaxial) + 5 (BEGe)
- 21.3 kg of detector mass: 17.7 kg (coaxial) + 3.6 kg (BEGe)
- 17.6 kg of ^{enr}Ge mass for analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)

Data taking of Phase I (Nov 2011 - May 2013)

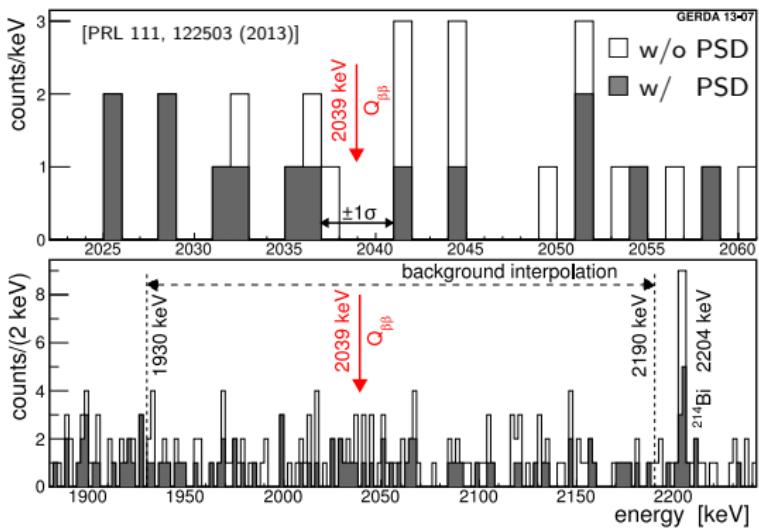
- bkg level at $Q_{\beta\beta} \sim 10^{-2}$ cts/(keV·kg·yr)
- exposure: 21.6 kg·yr

Data taking of Phase I (Nov 2011 - May 2013)

► bkg level at $Q_{\beta\beta} \sim 10^{-2}$ cts/(keV·kg·yr)

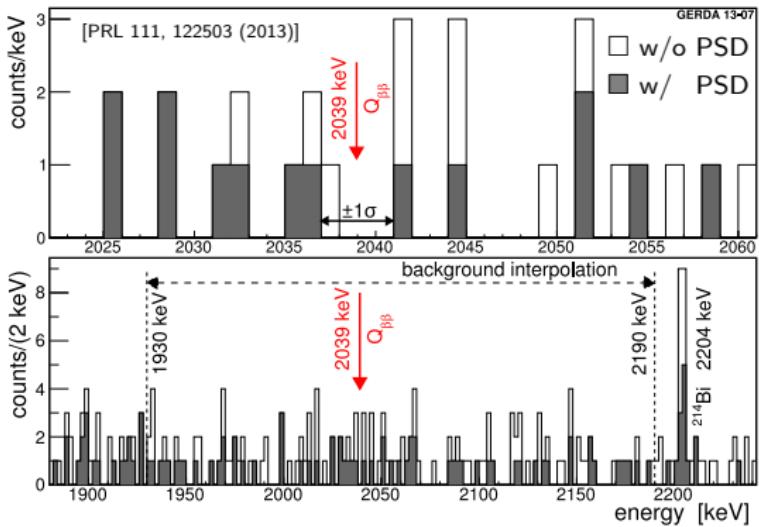
► exposure: 21.6 kg·yr

Unblinding: spectrum around $Q_{\beta\beta}$



- number of counts (after PSD):
expected from bkg: 2.5
- observed ($Q_{\beta\beta} \pm 5$ keV): 3
- data compatible with bkg only
- no indication for a signal

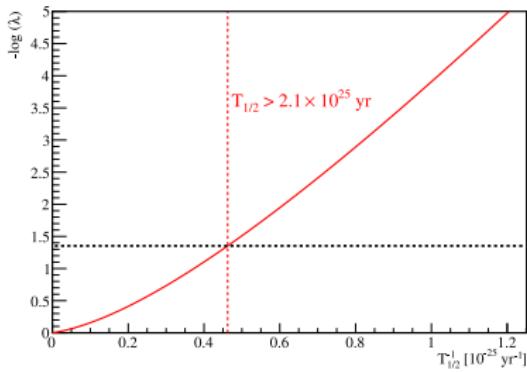
Unblinding: spectrum around $Q_{\beta\beta}$



- number of counts (after PSD):
expected from bkg: 2.5
observed ($Q_{\beta\beta} \pm 5$ keV): 3
- data compatible with bkg only
- no indication for a signal

Bounded profile likelihood analysis:

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $N_{0\nu\beta\beta} < 3.5$ cts at 90% C.L.
- $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal):
 $T_{1/2}^{0\nu} > 2.4 \cdot 10^{25}$ yr (90% C.L.)



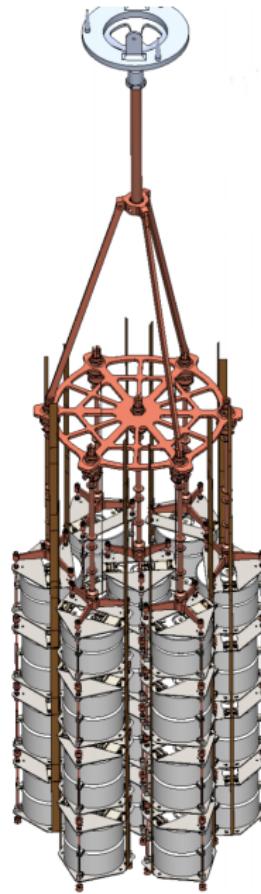
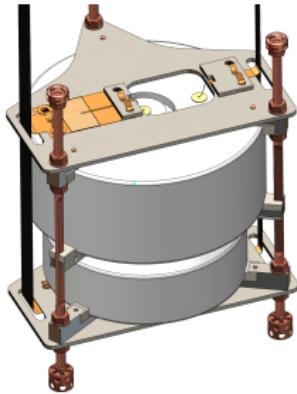
Phase II upgrade

Goals:

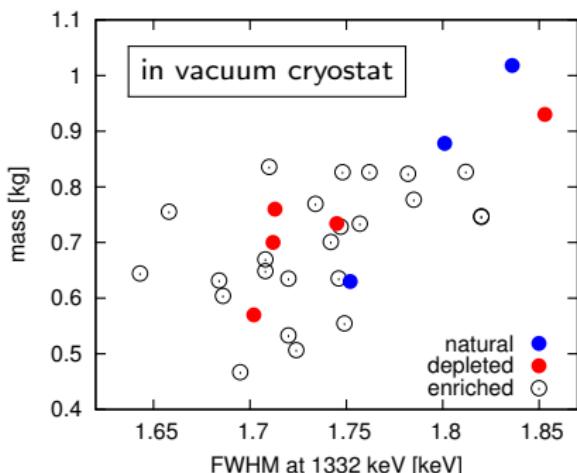
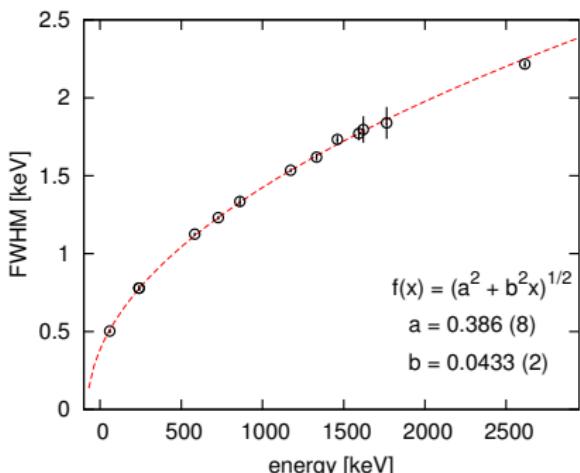
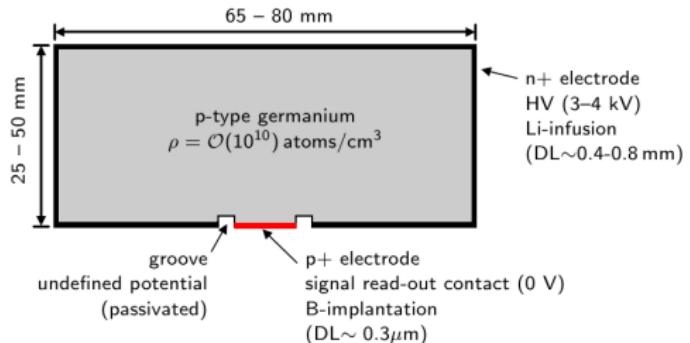
- 38 kg target mass (additional 17 kg of BEGe detectors)
- background at $Q_{\beta\beta}$: $\lesssim 10^{-3}$ cts/(keV·kg·yr)

Improvements:

- increased array granularity (anti-coincidence cut)
- enhanced PSD performance (BEGe)
- excellent energy resolution (BEGe)
- PMT and fibers+SiPM to detect LAr scintillation light
- lower-mass holders

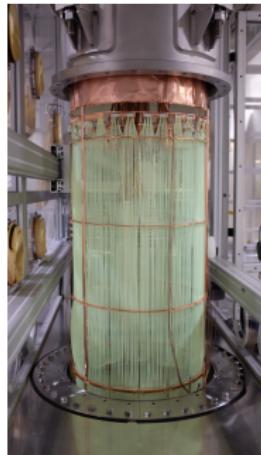
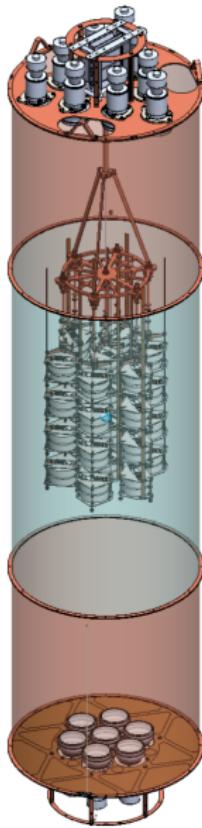


Broad Energy Germanium (BEGe) detectors



Signal formation and development

Detection of LAr scintillation light

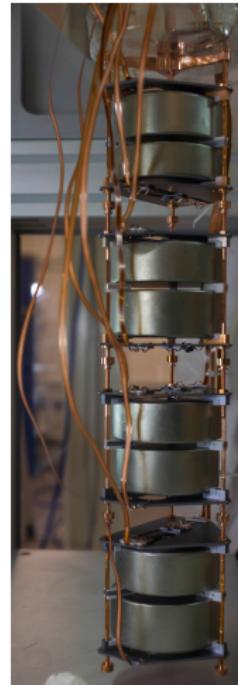
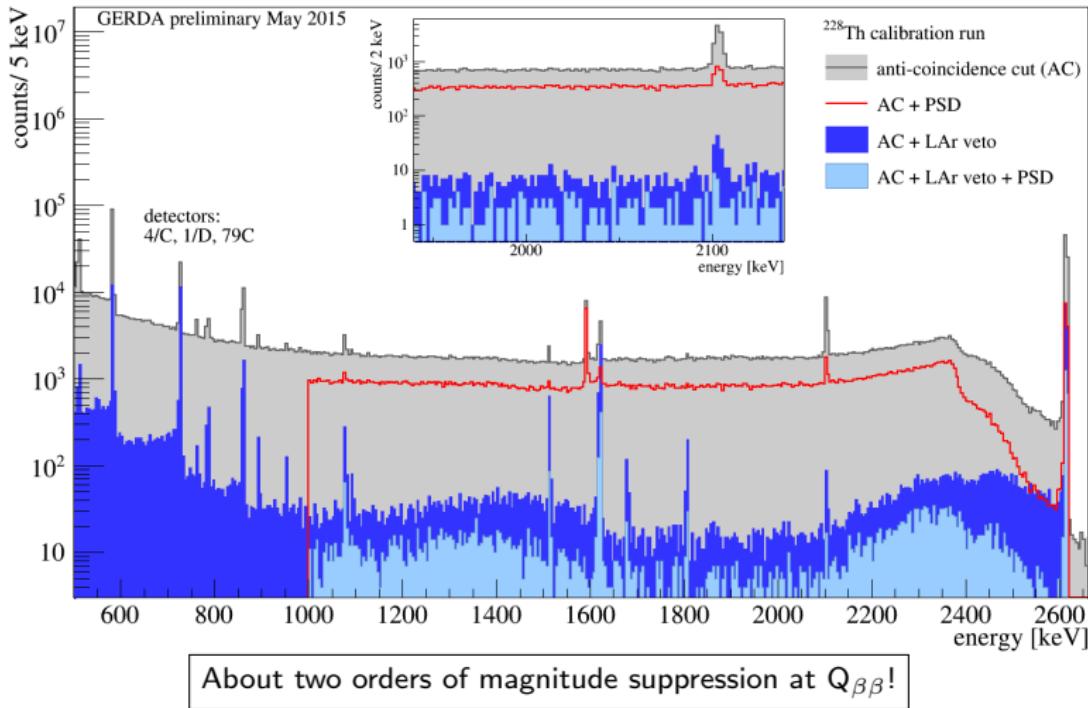


Design:

- low-background photo-multipliers (9 top, 7 bottom)
- wave-length-shifting fibers read-out by SiPMs
- wave-length-shifting nylon mini-shroud

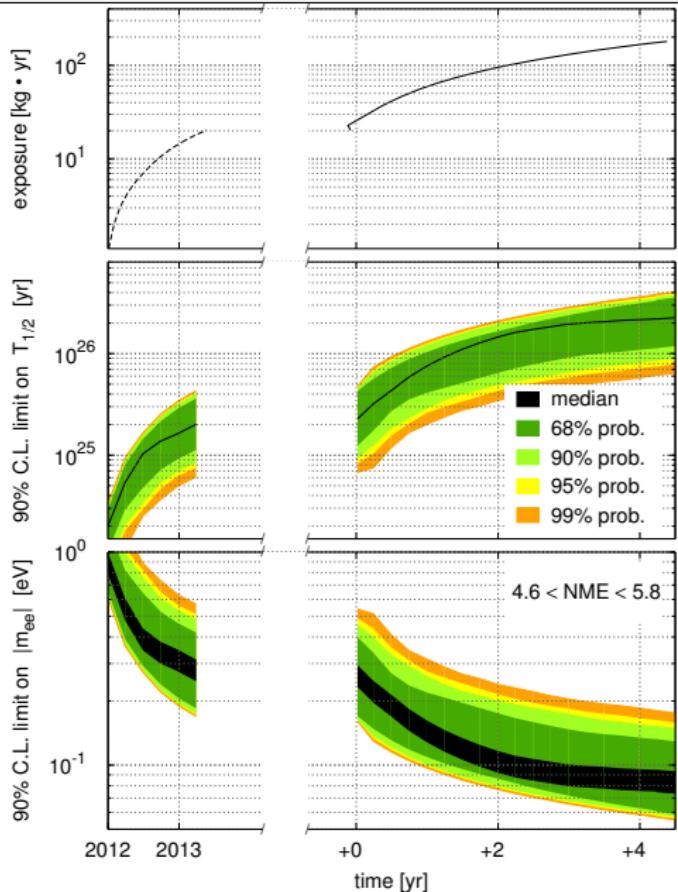


Last commissioning results (Th-228 irradiation)



GERDA sensitivity projection for limit setting

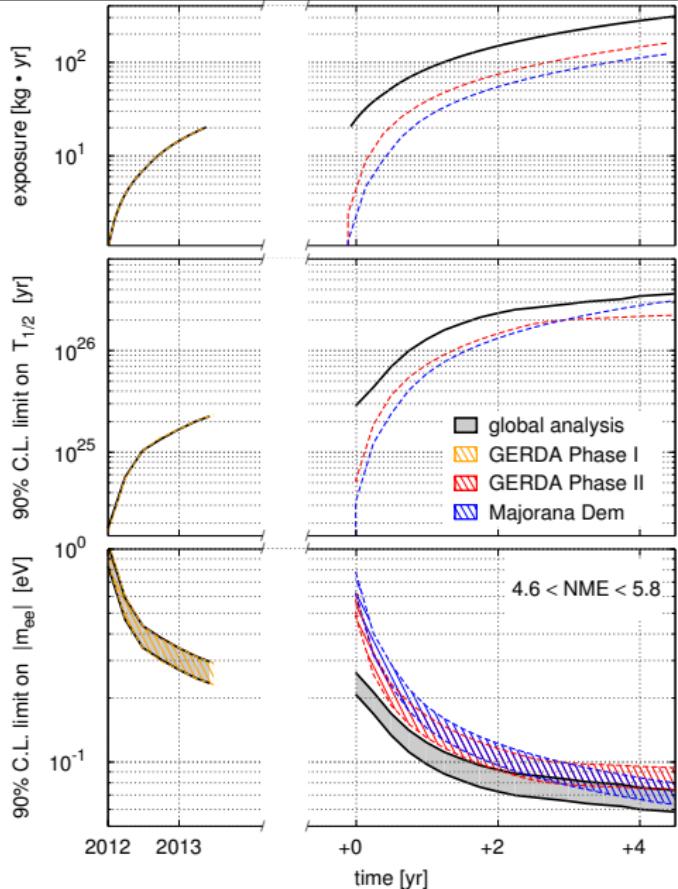
- profile likelihood analysis
- MC-realizations of the data sets
- limit extraction performed for each realization
- global analysis:
 - GERDA Phase I
 - GERDA Phase II:
(37 kg of ^{76}Ge , $1\text{e}-3 \text{cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$)
- median sensitivity after 2 yr of data taking:
 $T_{1/2}^{0\nu} \gtrsim 10^{26} \text{ yr}$
 $|m_{ee}| \lesssim 100 \text{ meV}$



sensitivity projection for GERDA + Majorana

- profile likelihood analysis
- MC-realizations of the data sets
- limit extraction performed for each realization
- global analysis of:
 - GERDA Phase I
 - GERDA Phase II:
(37 kg of ^{76}Ge , $1\text{e}-3 \text{cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$)
 - Majorana demonstrator
(30 kg of ^{76}Ge , $8\text{e}-4 \text{cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$)
- median sensitivity after 4 yr of data taking:

$$T_{1/2}^{0\nu} > 3 - 4 \cdot 10^{26} \text{ yr}$$
$$|m_{ee}| \lesssim 60 - 80 \text{ meV}$$



Conclusions

GERDA Phase I:

- 21.6 kg·yr of exposure
- background order of magnitude lower than previous Ge experiments:
 $\sim 0.01 \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$ at $Q_{\beta\beta}$
- blind analysis —> no positive $0\nu\beta\beta$ signal:
 $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr}$ at 90% C.L.

GERDA Phase II:

- commissioning ongoing:
almost complete array is being installed right now with full LAr-veto
- quasi background-free experiment
- start exploration of $T_{1/2}^{0\nu} > 10^{26} \text{ yr}$ in a $\sim 2 \text{ yr}$ of data taking

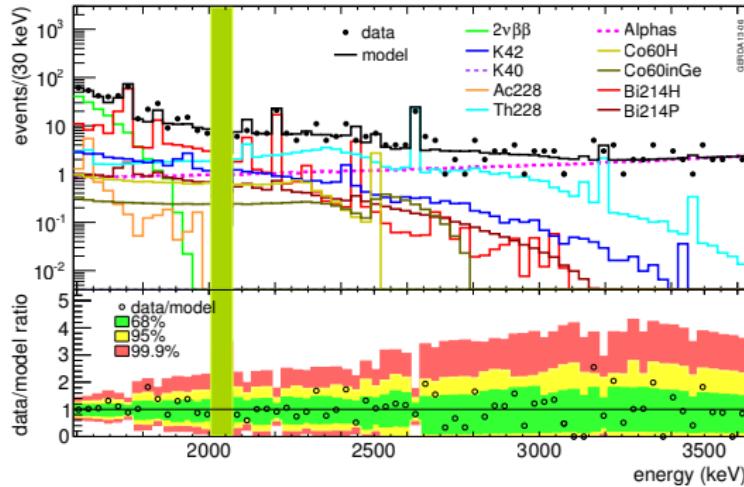
Collaboration



~100 members, 16 institutions, 6 countries

backup slides

Background modeling

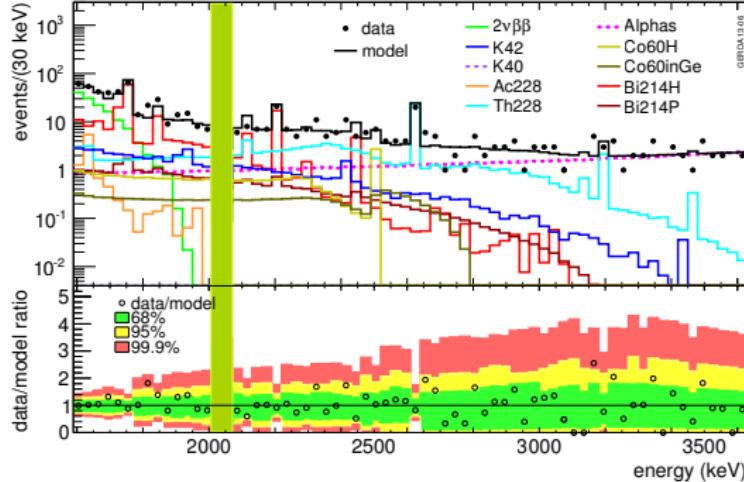


Contribution at $Q_{\beta\beta}$:

- γ -rays (close sources): Bi-214, Tl-208, K-42
- α - and β -rays (surface decays): Ra-226 daughter, Po-210, K-42

more details in [EPJ C74 (2014) 2764]

Background modeling



- no line expected in the blinded window
- background flat between 1930-2190 keV (excluding peaks at 2104 and 2119 keV)
- mean FWHM at $Q_{\beta\beta}$ (mass/exposure weighted):

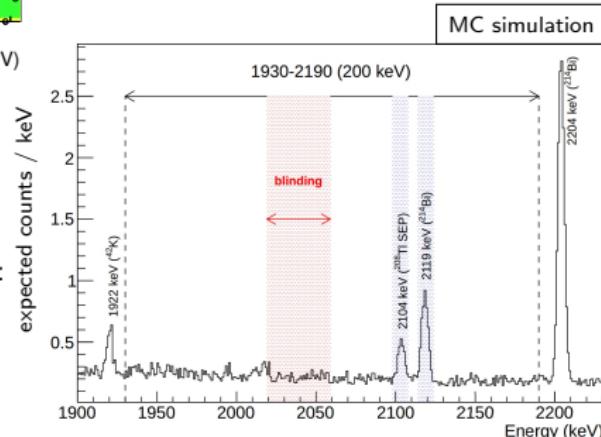
coax $\rightarrow 4.8 \pm 0.2$ keV

BEGe $\rightarrow 3.2 \pm 0.2$ keV

Contribution at $Q_{\beta\beta}$:

- γ -rays (close sources): Bi-214, Tl-208, K-42
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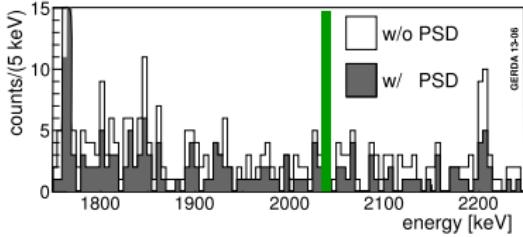
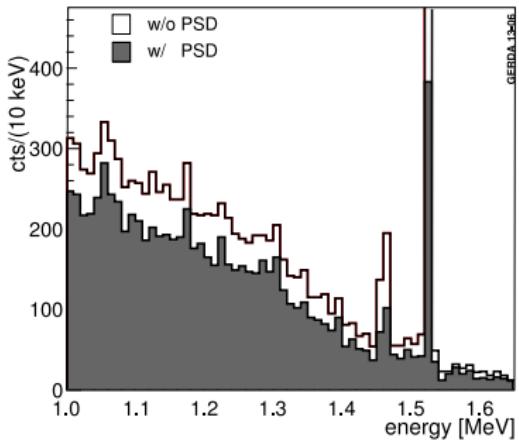
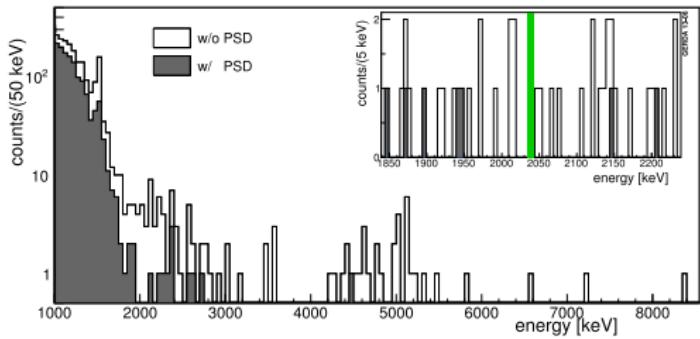
Pulse shape discrimination

Coaxial detectors:

- artificial neural network
- $0\nu\beta\beta$ acceptance = $90^{+5}_{-9}\%$
- background acc at $Q_{\beta\beta} = \sim 45\%$

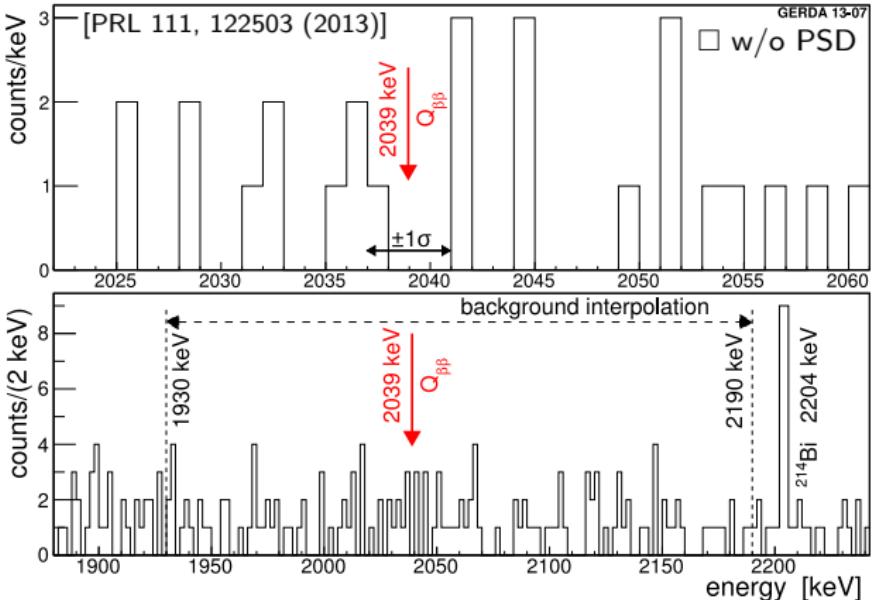
BEGe detectors:

- A/E parameter (mono-parametric PSD)
- $0\nu\beta\beta$ acceptance $92 \pm 2\%$
- background acc at $Q_{\beta\beta} \leq 20\%$



[Eur.Phys.J C73 (2013) 2583]

Unblinding: spectrum around $Q_{\beta\beta}$



Analysis cuts applied:

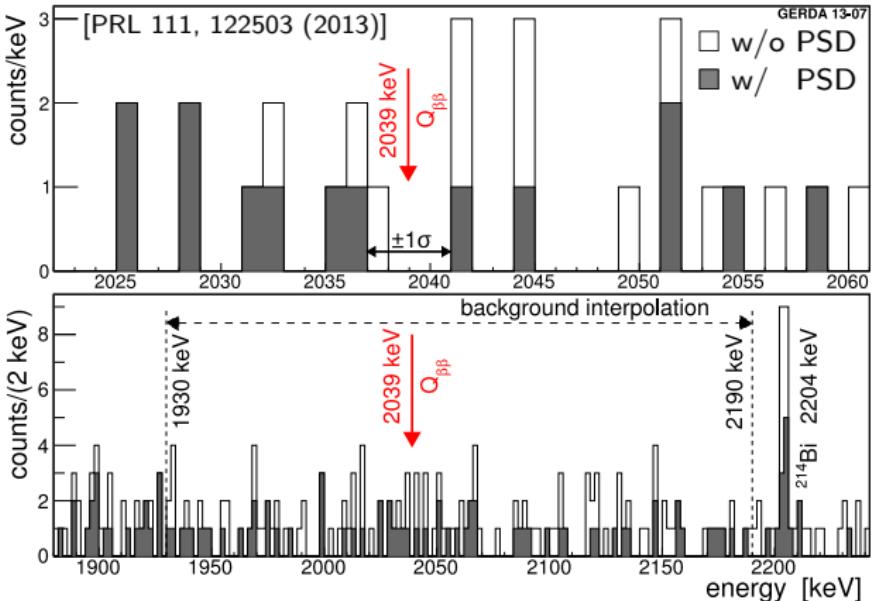
- 1) signals quality cuts
- 2) detector anti-coincidence
- 3) muon-veto
anti-coincidence
- 4) single-detectors time
coincidence (BiPo cut)

Survival fraction at $Q_{\beta\beta}$:

| | |
|-----|--------------|
| 1 | $\sim 99\%$ |
| 2+3 | $\sim 60\%$ |
| 4 | $\sim 100\%$ |

| | exposure [kg·yr] | background 10^{-2} cts/(keV·kg·yr) | expected cts ($Q_{\beta\beta} \pm 5$ keV) | observed cts ($Q_{\beta\beta} \pm 5$ keV) |
|---------|---------------------|---|---|---|
| w/o PSD | | | | |
| w/ PSD | | | | |

Unblinding: spectrum around $Q_{\beta\beta}$



Analysis cuts applied:

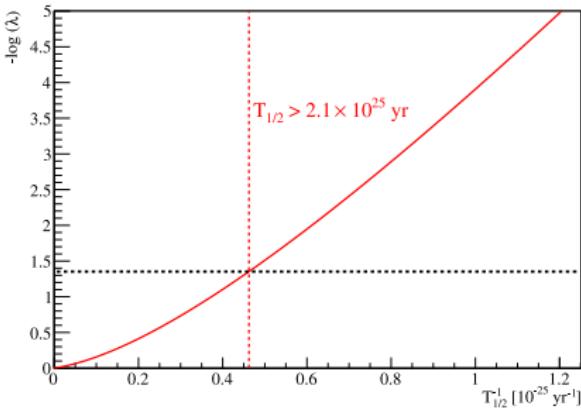
- 1) signals quality cuts
- 2) detector anti-coincidence
- 3) muon-veto anti-coincidence
- 4) single-detectors time coincidence (BiPo cut)
- 5) PSD

Survival fraction at $Q_{\beta\beta}$:

| | |
|-----|--------------|
| 1 | $\sim 99\%$ |
| 2+3 | $\sim 60\%$ |
| 4 | $\sim 100\%$ |
| 5 | $\sim 50\%$ |

| | exposure [kg·yr] | background $10^{-2} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$ | expected cts ($Q_{\beta\beta} \pm 5 \text{ keV}$) | observed cts ($Q_{\beta\beta} \pm 5 \text{ keV}$) |
|---------|---------------------|--|--|--|
| w/o PSD | golden | 17.3 | 1.8 | 1.1 |
| w/ PSD | BEGe | 2.4 | 4.2 | 0.5 |

Statistical analysis



Profile likelihood analysis:

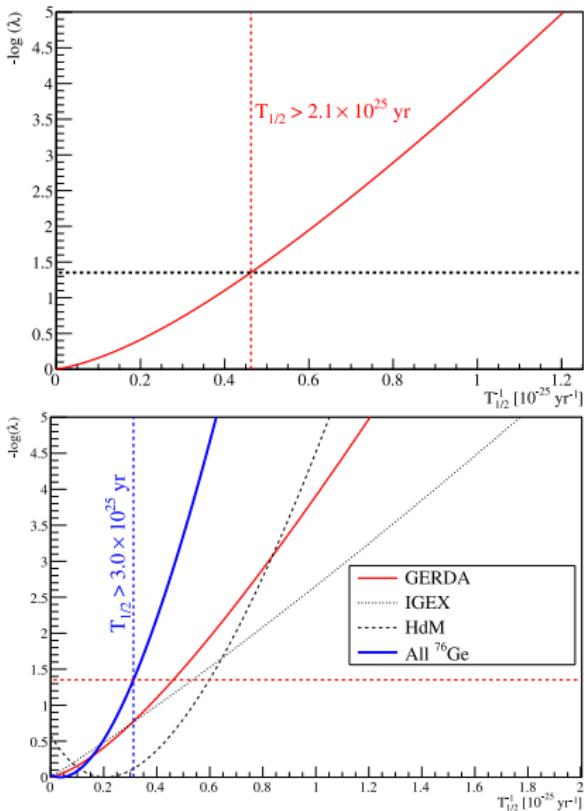
- ML fit
(constant+Gauss in 1930-2190 keV range)
- multiple data sets (common $T_{1/2}^{0\nu}$)
- $T_{1/2}^{0\nu} \geq 0$ (coverage tested)

Results (GERDA only):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr}$ (90% C.L.)
- MC Median sensitivity (for no signal):
 $T_{1/2}^{0\nu} > 2.4 \cdot 10^{25} \text{ yr}$ (90% C.L.)

PRL 111, 122503 (2013); [1] Phys.Rev. D65, 092007 (2002); [2] Eur.Phys.J. A12, 147 (2001)

Statistical analysis



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(constant+Gauss in 1930-2190 keV range)
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- MC Median sensitivity (for no signal):
 $T_{1/2}^{0\nu} > 2.4 \cdot 10^{25} \text{ yr}$ (90% C.L.)

Results (GERDA + IGEX [1] + HdM [2]):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25} \text{ yr}$ (90% C.L.)

PRL 111, 122503 (2013); [1] Phys.Rev. D65, 092007 (2002); [2] Eur.Phys.J. A12, 147 (2001)

Comparison with Phys.Lett. B586 198 (2004)

Hypothesis test:

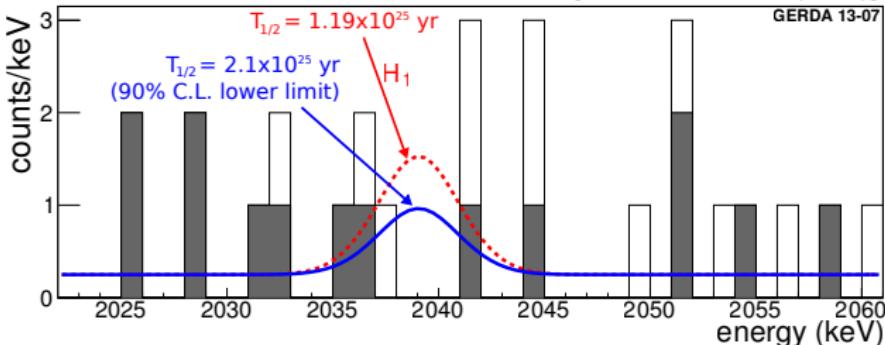
H_0 (bkg only)

vs

$H_1 (T_{1/2}^{0\nu} = 1.19^{+0.37}_{-0.23} \cdot 10^{25} \text{ yr} + \text{bkg})$

[PRL 111, 122503 (2013)]

- In $Q_{\beta\beta} \pm 2\sigma_E$ (after PSD):
- expected 2.0 ± 0.3 bkg cts
 - **expected 5.9 ± 1.4 signal cts (assuming H_1)**
 - observed 3 cts



GERDA only:

- Frequentist p-value ($N_{0\nu\beta\beta} = 0 | H_1$) = 0.01
- Bayes factor $P(H_1)/P(H_0) = 2.4 \cdot 10^{-2}$

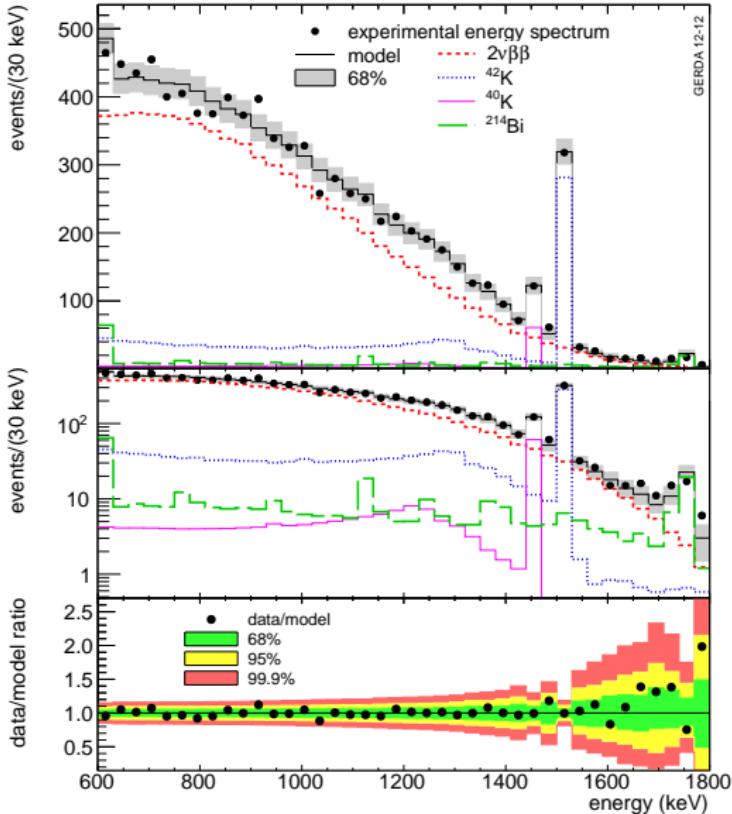
GERDA + IGEX + HdM:

- Bayes factor $P(H_1)/P(H_0) = 2 \cdot 10^{-4}$

**Long standing
claim strongly
disfavoured!**

$T_{1/2}^{0\nu}$ from Mod. Phys. Lett. A 21 (2006) 1547 is not considered because of inconsistencies (i.e. missing efficiency factors, problem in the conversion from counts to $T_{1/2}^{0\nu}$) pointed out in Ann. Phys. 525 (2013) 269.

Background model – $2\nu\beta\beta$ half-life



- Binned maximum likelihood (5 kg·yr)

- Nuisance parameters:

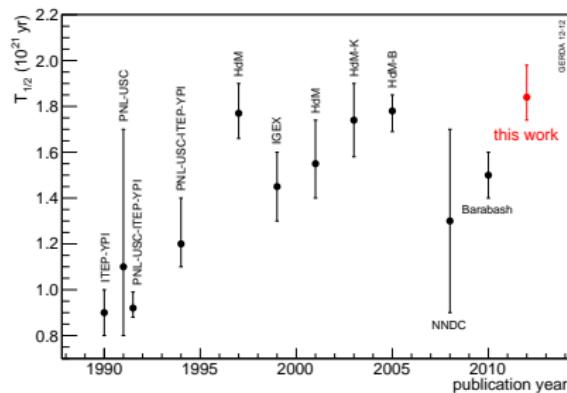
- Active detector masses (6+1)
- Ge-76 fractions (6)
- Background contributions (3x6)

- $T_{1/2}^{2\nu}$ common to all detectors

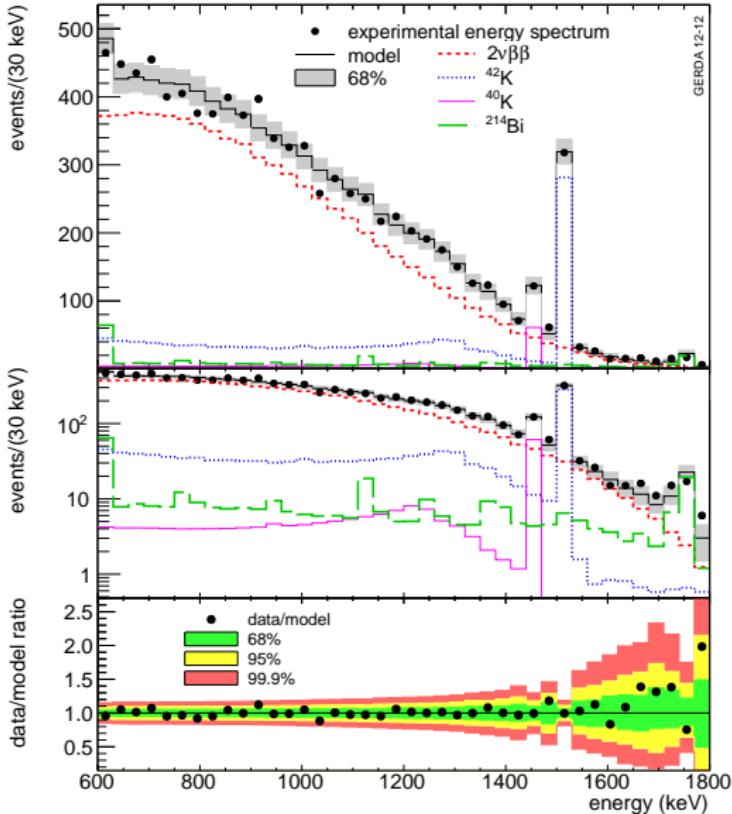
- After marginalizing:

$$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08} \text{ fit} \quad {}^{+0.11}_{-0.06} \text{ syst}) \cdot 10^{21}$$

[J.Phys.G 40 (2013) 035110]

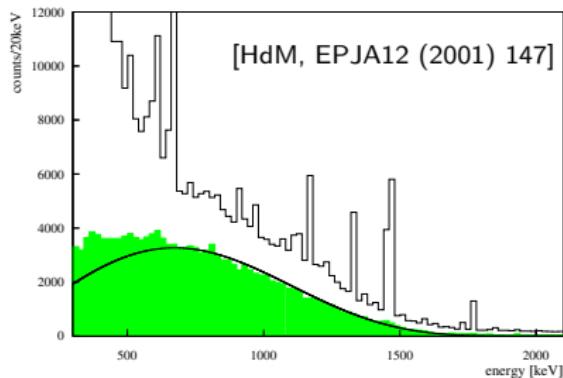


Background model – $2\nu\beta\beta$ half-life

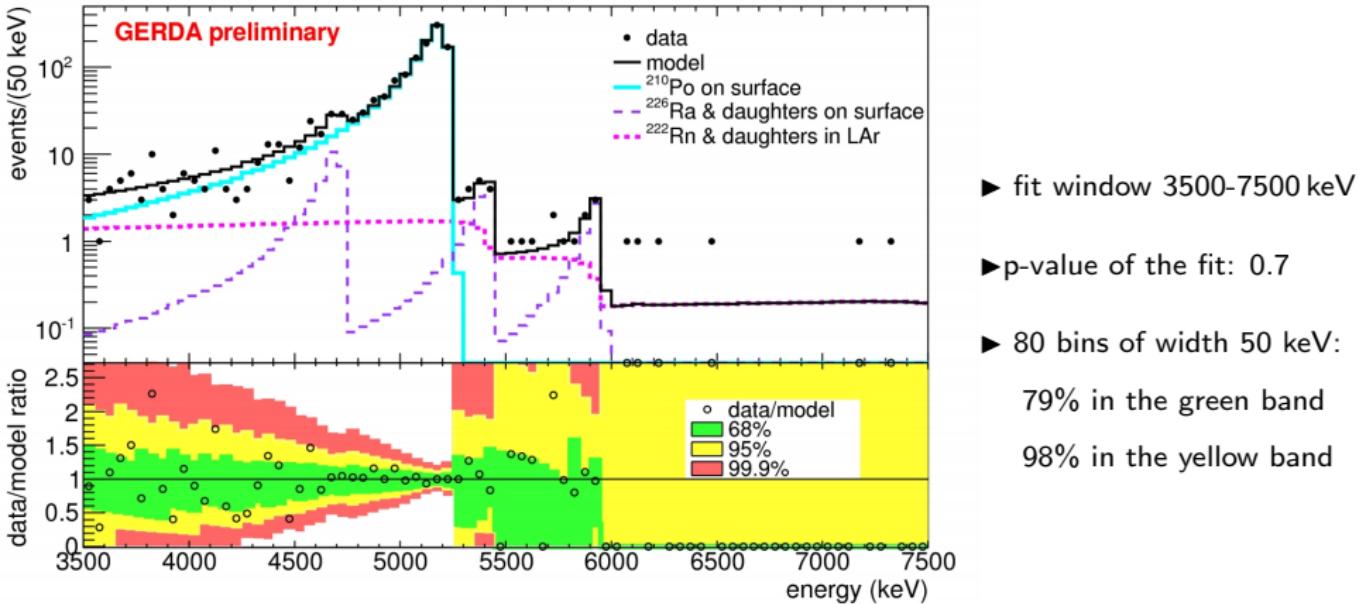


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[J.Phys.G 40 (2013) 035110]



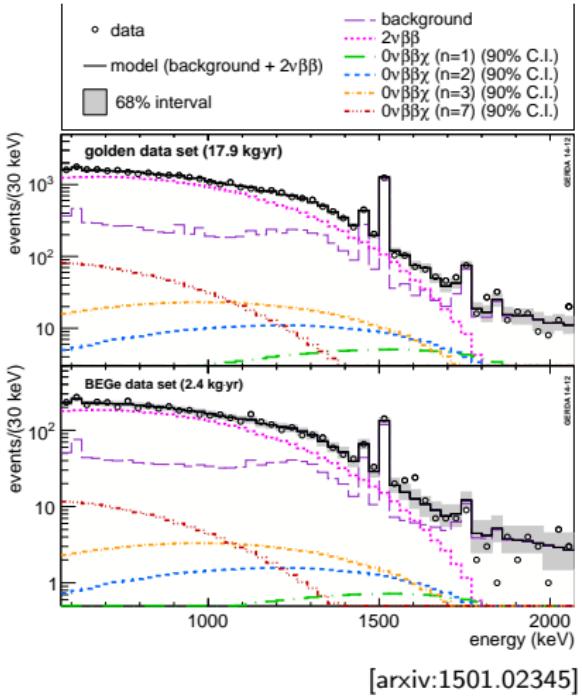
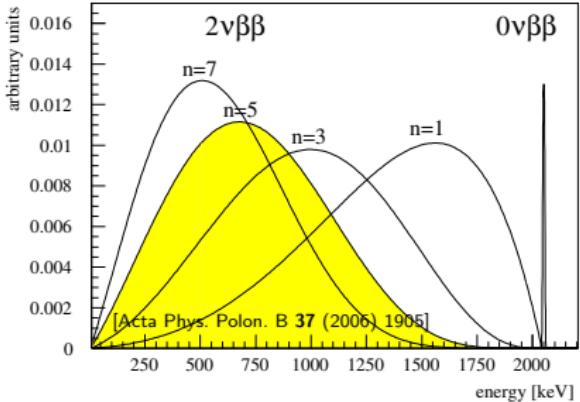
Background model – α -emitting isotopes



Colored probability intervals: [R. Aggarwal and A. Caldwell, Eur. Phys. J. Plus 127 24 (2012)]

Double- β decay with 2ν or Majorons emission

- Global fit of the energy spectrum
- Most accurate measurement of:
 $T_{1/2}^{2\nu}(^{76}\text{Ge}) = 1.926(95) \times 10^{21} \text{ yr}$
(68% probability)
- Most stringent limits on exotic processes:
 $T_{1/2}^{0\nu\chi} > 10^{23} \text{ yr}$ for $n=1,3,5,7$

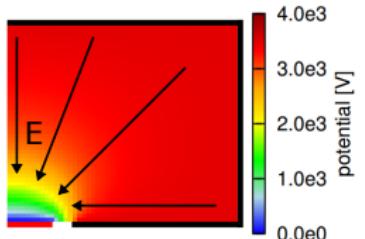


[arxiv:1501.02345]

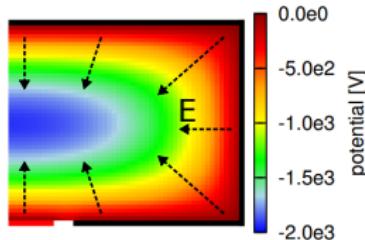
Electric field and charge collection

Contributions to the electric field (E):

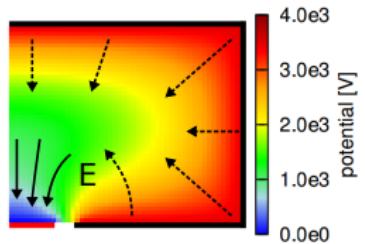
- 1) electrodes potentials:
 $\phi_{p+} = 0 \text{ V}$, $\phi_{n+} = 4 \text{ kV}$



- 2) impurity concentration:
negative charges for
depleted p-type Ge

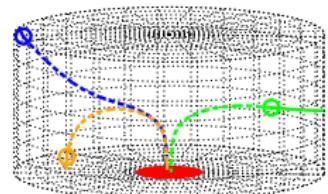


Total field (1+2):
holes are pushed to the
detector central slice (2)
and then collected to the
p⁺ electrode (1)



Interplay between (1) and (2)
results in the **funnel effect**:

..... anode
— cathode
— electrons
-·- holes
○ interaction point



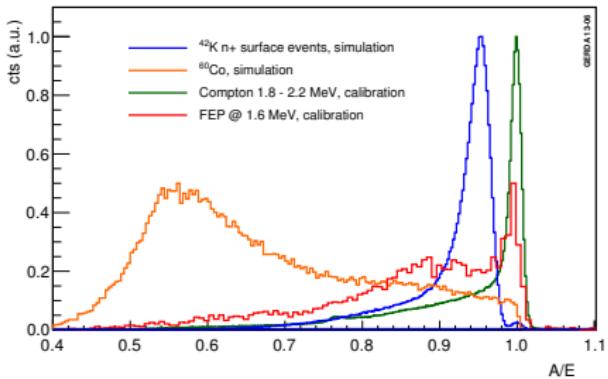
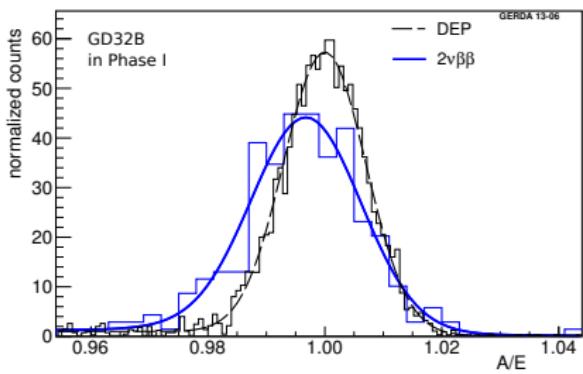
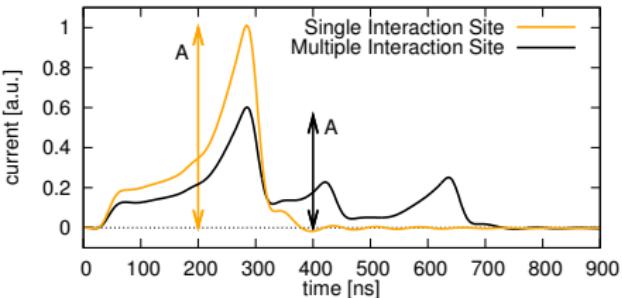
final part of hole trajectories independent of interaction positions

[JINST 6 (2011) P03005]

Pulse shape discrimination technique

A/E method:

E: integral of the current signal (energy)
A: maximum of the current signal



[Budjas et al. JINST 4 P10007, M.A et al. JINST 6 P03005, Eur.Phys.J C73 (2013) 2583]

Last commissioning results (Ra-226 irradiation)

