Search for Neutrinoless Double Beta Decay of ^{76}Ge in the GERDA Experiment

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— on behalf of the Gerda Collaboration —

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Lake Louise Winter Institute

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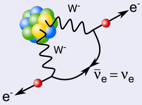
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Outline

1. Motivation for $0\nu\beta\beta$



2. GERDA experiment

3. Results from Phase I

4. Towards Phase II

Neutrino oscillation

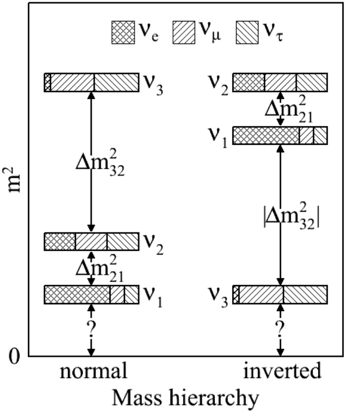
Flavour eigenstates ν_α (with $\alpha = \mathrm{e}, \mu, \tau$) as linear superposition of mass eigenstates ν_i

$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U=\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$



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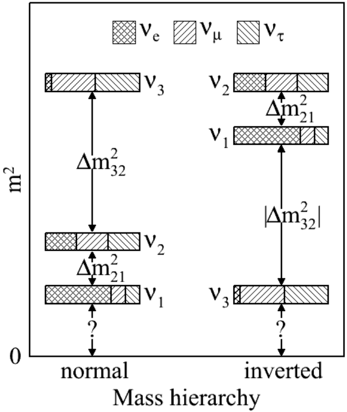

What we know

- squared mass differences Δm^2_{12} and $|\Delta m^2_{23}|$
- mixing angles θ_{12}, θ_{23} and θ_{13}

from e.g. solar neutrino + long baseline reactor, atmospheric neutrino + long baseline accelerator or short baseline reactor / accelerator experiments

What we do not know

- nature of the neutrino (Dirac or Majorana?)
- new physics beyond SM
- absolute mass scale
- mass hierarchy

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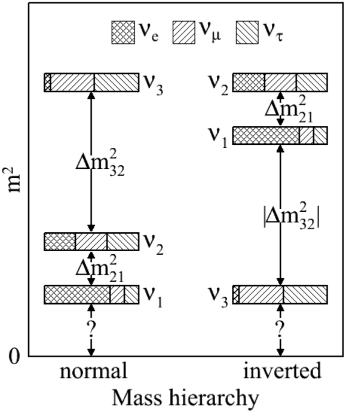

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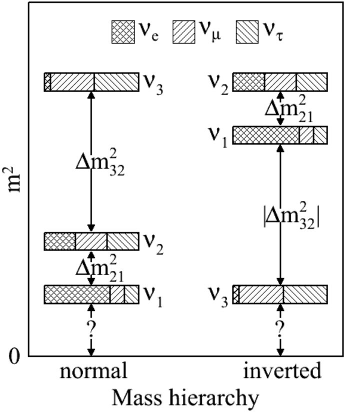

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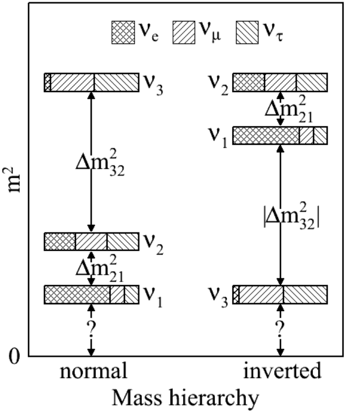

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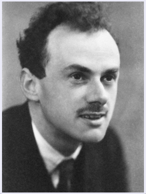
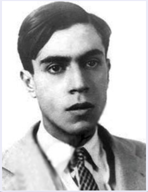
Unveiling the nature of the neutrino …

Dirac: $\nu \neq \overline{\nu}$



vs.

Majorana: $\nu = \overline{\nu}$



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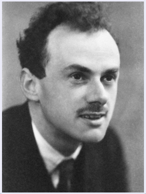

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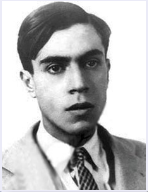
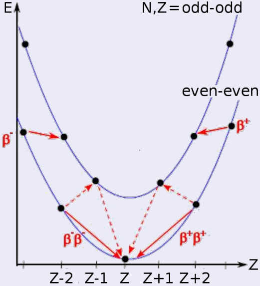


... by Double Beta ($\beta\beta$) decay

- rare second order nuclear transition
- occurs between 2 even-even isobars
- if single β decay energetically forbidden or ΔJ large
- 35 isotopes in nature



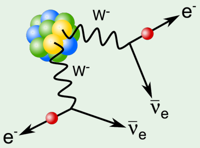
- $\beta\beta$ emitters used in experiments

^{48}Ca	CANDLES
^{76}Ge	GERDA, MAJORANA
^{82}Se	NEMO
^{100}Mo	
^{116}Cd	COBRA
^{130}Te	CUORE
^{136}Xe	EXO, KAMLAND-ZEN
^{150}Nd	SNO+

Double Beta ($\beta\beta$) decay

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

- allowed by Standard Model
- $\Delta L = 0$



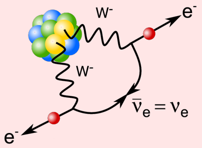
- so far observed in up to 12 nuclei with half lifes $\sim(10^{18} - 10^{24})$ yr

$T_{1/2}^{2\nu}(^{76}\mathrm{Ge}) = 1.926 \pm 0.095 \cdot 10^{21}$ yr

submitted to Eur. Phys. J. C (arXiv:1501.02345)

$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

- prohibited by Standard Model
- $\Delta L = 2$
- only if ν has Majorana mass component



- still hunted process; mediated by e.g. light Majorana ν exchange, R-handed weak currents, SUSY particles, ...

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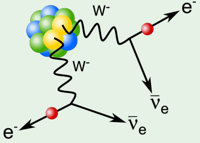

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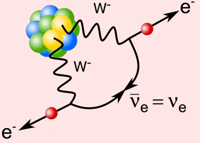

note → one claim by subgroup of HDM:

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Phys. Rev. Lett. B 586, 198-212 (2004)

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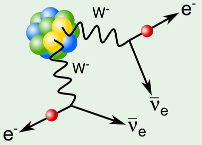

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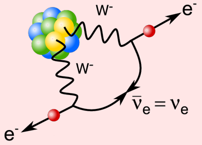

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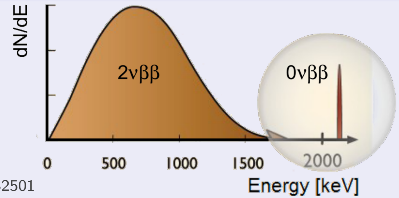
Experimental signatures

- measure the electrons sum energy spectrum
- continuum → $2\nu\beta\beta$ or $0\nu\beta\beta$ + Majoron(s)
- monoenergetic peak at $Q_{\beta\beta}$-value → $0\nu\beta\beta$

$Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$

for ^{76}Ge = (2039.061 ± 0.007) keV

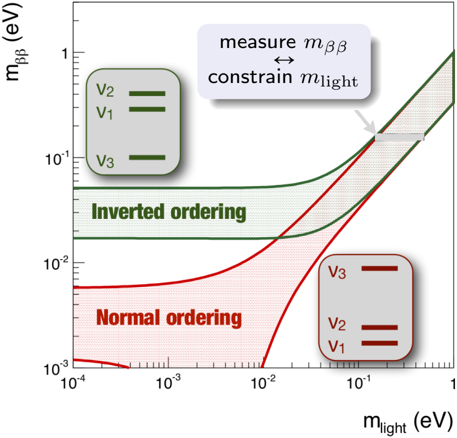
Phys. Rev. 401 C81 (2010) 032501



Neutrinoless Double Beta ($0\nu\beta\beta$) decay

Decay rate (if light Majorana ν exchange is dominating process)

$$(T^{0\nu}_{1/2})^{-1} = \underbrace{G^{0\nu}(Q_{\beta\beta}, Z)}_{\text{phase space integral } \propto Q^5_{\beta\beta}} \overbrace{|M^{0\nu}|}^{\text{nuclear matrix element}}{}^2 \underbrace{\langle m_{\beta\beta}\rangle}_{\text{effective } \nu \text{ mass } = |\sum_{i=1}^3 U_{ei} m_i|}{}^2$$



measure $m_{\beta\beta}$
$\leftrightarrow$
constrain m_{light}

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Experimental Sensitivity

1. Background $\ll 1$:
   $T_{1/2}^{0\nu} \propto \epsilon \cdot a \cdot M \cdot t$
2. Background $\gg 1$:
   $T_{1/2}^{0\nu} \propto \epsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$

- $\epsilon =$ total detection efficiency
- $a =$ abundance of $0\nu\beta\beta$ isotope
- $M \cdot t =$ exposure (detector mass $\times$ livetime)
- $BI =$ background index
- $\Delta E =$ energy resolution @ $Q_{\beta\beta}$

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Search in ^{76}Ge (using well established semiconductor technology)

Advantages

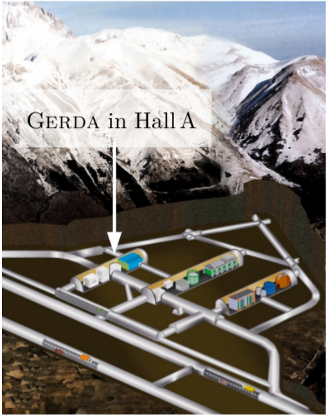
- source = detector → high ϵ
- High Purity Ge → low intrinsic BI
- FWHM @ $Q_{\beta\beta}$ $\sim$0.2% → excellent ΔE
- test of $0\nu\beta\beta$ observation by parts of HdM without depending on NME

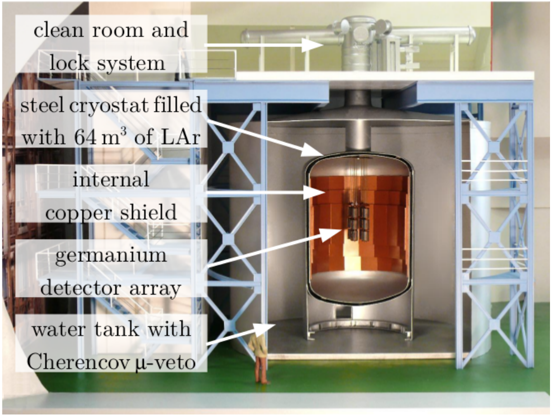
Disadvantages

- low $Q_{\beta\beta}$-value → possible external BI from e.g. ^{208}Tl + small $G^{0\nu}(Q_{\beta\beta}, Z)$
- a=7.8% for ^{76}Ge → enrichment needed
- rather long and costly process to get large active detector mass

GERmanium Detector Array

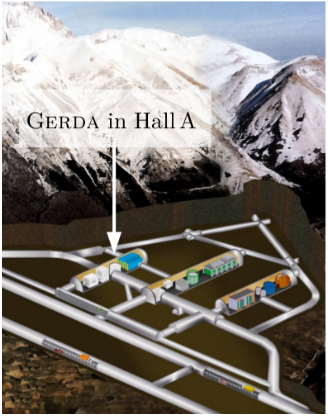
Eur. J. Phys. C73 (2013) 2330

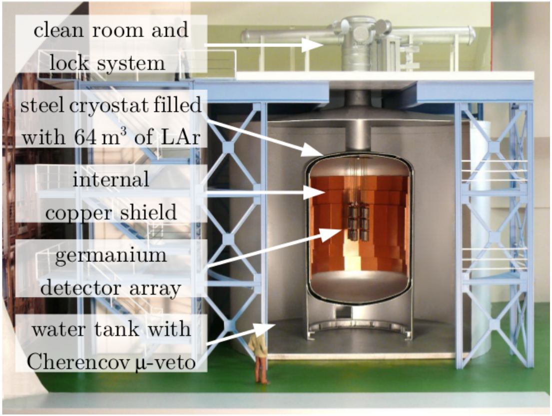




- located @ LNGS underground laboratory, Italy (3400 m w.e.→ cosmic μ flux reduced by 10^6)
- surrounding rock shielded by tank with ultra-pure water, the copper lined cryostat and LAr
- plastic scintillators above cryostat neck and water instrumented with PMTs as active μ-veto
- detectors are operated bare in LAr as coolant

GERmanium Detector Array Eur. J. Phys. C73 (2013) 2330





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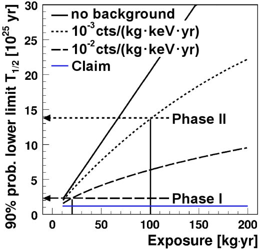
- minimal amount of (screened) material close to the detectors

component/ det. support	^{40}K [μBq]	^{226}Rn [μBq]	^{228}Th [μBq]
copper (80g)	<7.0	<1.3	<1.5
PTFE (10g)	6.0	0.25	0.31
Banana (125g)	$1.5 \cdot 10^7$	–	–

GERDA Timetable



Experiment proceeds in two phases:

Phase	Mass [kg]	BI $[\frac{\text{cts}}{\text{kg}\cdot\text{keV}\cdot\text{yr}}]$	Exposure $[\text{kg} \cdot \text{yr}]$	$T_{1/2}^{0\nu}$(90% C.L.) [yr]	Status
I	15	10^{-2}	20	$\sim 2 \cdot 10^{25}$	finished
II	35	10^{-3}	100	$1...2 \cdot 10^{26}$	in prep.

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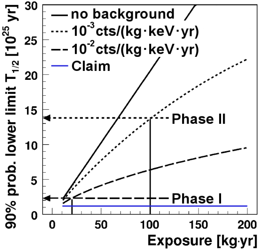

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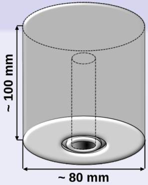
Semi-coaxial

- inherited from HdM (ANG1-5) and IGEX (RG1-3) experiments; all reprocessed at Canberra
- enrichment fraction of ^{76}Ge $\sim$86%

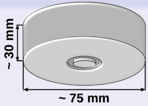


Phase I data taking

- Nov 2011 - May 2013: 8x
- 2 detectors not considered due to high leakage current
- total mass $= 14.6$ kg

Broad Energy Germanium (BEGe)

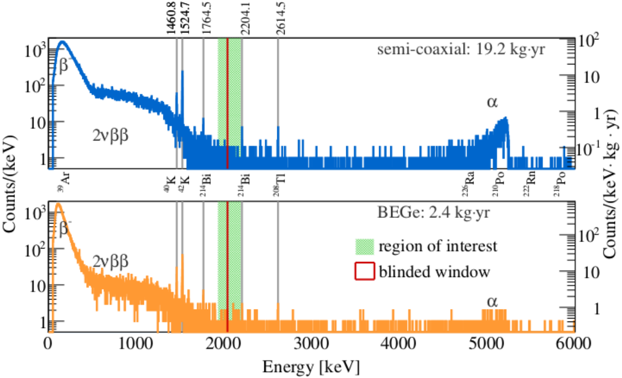
- $\sim$30 newly processed detectors
- enrichment fraction of ^{76}Ge $\sim$88%



- July 2012 - May 2013: 5x
- 1 detector not considered due to unstable behaviour
- total mass $= 3.0$ kg
- testing Phase II concept

Physics spectrum

- β-spectrum of ^{39}Ar
- $2\nu\beta\beta$-spectrum of ^{76}Ge
- γ-lines of ^{40}K, ^{42}K, ^{60}Co, ^{214}Bi, ^{212}Bi and ^{208}Tl
- α-spectrum of ^{238}U chain (in semi-coaxial detectors)
- BI before PSD @ $Q_{\beta\beta}$ for "golden" data-set = $0.018 \pm 0.002\ \frac{\text{cts}}{(\text{kg}\cdot\text{keV}\cdot\text{yr})}$



region of interest (ROI) = interval $[1930-2190]$ keV

blinded window @ $Q_{\beta\beta} \pm 20$ keV to not bias analysis

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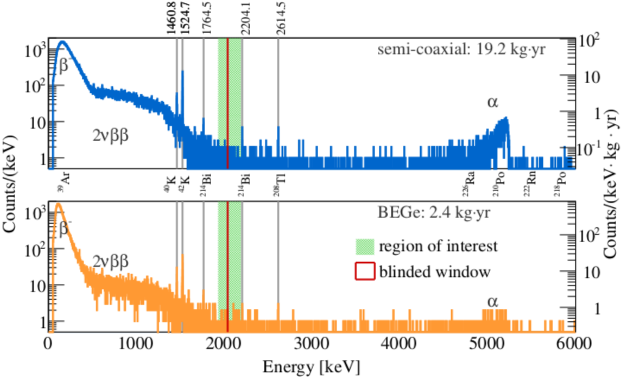
- γ-lines of ^{40}K, ^{42}K, ^{60}Co, ^{214}Bi, ^{212}Bi and ^{208}Tl
- α-spectrum of ^{238}U chain (in semi-coaxial detectors)



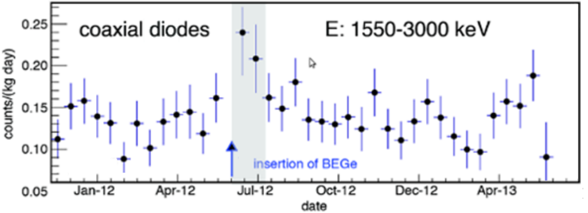
region of interest (ROI) = interval $[1930 - 2190]$ keV

blinded window @ $Q_{\beta\beta} \pm 20$ keV to not bias analysis

- BI before PSD @ $Q_{\beta\beta}$ for "golden" data-set = $0.018 \pm 0.002 \, \frac{\text{cts}}{(\text{kg}\cdot\text{keV}\cdot\text{yr})}$

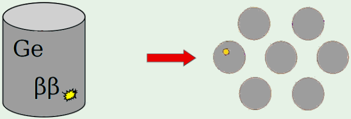
Division into 3 sub-sets:

data set	Exposure [kg·yr]	FWHM@ $Q_{\beta\beta}$ [keV]
golden	17.9	4.8 ± 0.2
silver	1.3	4.8 ± 0.2
BEGe	2.4	3.2 ± 0.2



Background reduction by off-line analysis

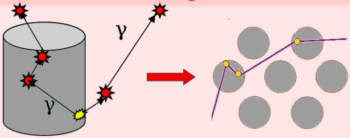
Signal



- $\beta\beta$ events; range of $\sim 1\,\mathrm{MeV}$ electron in Ge @ $1\,\mathrm{mm}$
- interaction via ionization or exitation of absorber atoms
- drift of electrons and holes originated close-by in a single located charge cloud

→ single-site event (SSE)

Background

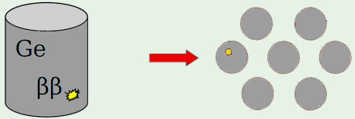


- γ events; range of $\sim 1\,\mathrm{MeV}$ gammas in Ge about $10\times$ larger (compared to electrons)
- interaction via compton scattering, e^+e^- pair creation or photelectric absorption
- sum of several separated electron-hole drifts

→ multi-site event (MSE)

Background reduction by off-line analysis

Signal



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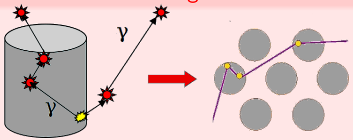

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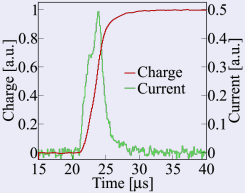
- interaction via compton scattering, e^+e^- pair creation or photelectric absorption
- sum of several separated electron-hole drifts

→ multi-site event (MSE)

Event processing (diode → amplifier → FADC → digital filter → E/PSD/etc...)

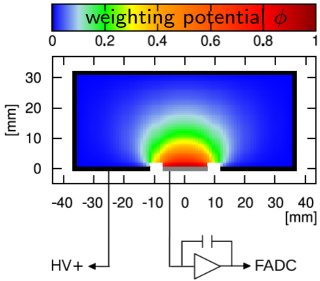
- quality cuts; E monitored by weekly calibration with movable ^{228}Th source: $\sim 9\%$ rejected @ $Q_{\beta\beta}$
- anti-coincidence muon/2nd Ge-diode: $\sim 20\%$ rejected @ $Q_{\beta\beta}$
- PSD based on location(s) of energy deposition inside the active volume: $\sim 50\%$ rejected @ $Q_{\beta\beta}$



Pulse shape: BEGe

Ramo-Shockley theorem

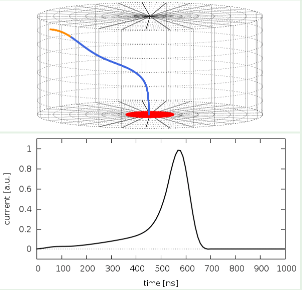
- Charge $Q(t)$
  $= -q \times [\phi(\boldsymbol{r}_\mathrm{h}(t)) - \phi(\boldsymbol{r}_\mathrm{e}(t))]$
- Current $I(t) = \mathrm{d}Q(t)/\mathrm{d}t$
  $= q \times [\mathcal{E}(\boldsymbol{r}_\mathrm{h}(t)) \cdot \boldsymbol{v}_\mathrm{h}(t) - \mathcal{E}(\boldsymbol{r}_\mathrm{e}(t)) \cdot \boldsymbol{v}_\mathrm{e}(t)]$



→ mostly holes (but hardly any electrons) do contribute to the signal formation!

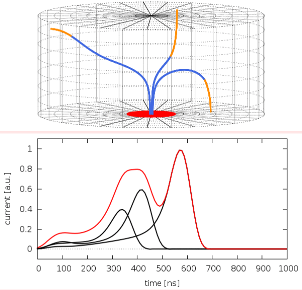
Signal-like single-site event (SSE)

$A \propto E$



Background-like multi-site event (MSE)

$A \not\propto E$



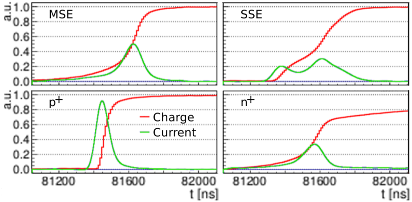
PSD parameter A/E

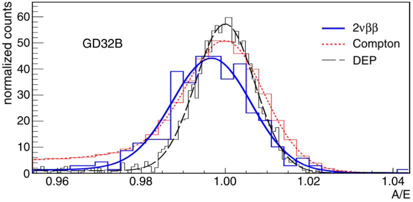
A = amplitude of current pulse

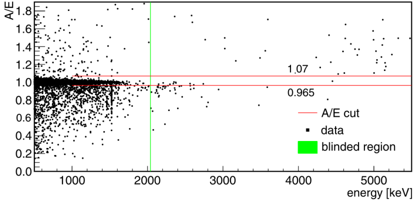
E = energy

- high capability of distinguising SSE from MSE and surface p^{+} or n^{+} events
- tuned using double escape peak (DEP) of ^{208}Tl (where per definition A/E=1), compton continuum and $2\nu\beta\beta$ events
- keep events with $0.965 < A/E < 1.07$
- $0\nu\beta\beta$-signal acceptance $= (92 \pm 2)\%$
  background acceptance @ $Q_{\beta\beta} \leqslant 20\%$
- well tested and documented method!

JINST 4 (2009) P10007
JINST 6 (2011) P03005
Eur. Phys. J. C73 (2013) 2583
...

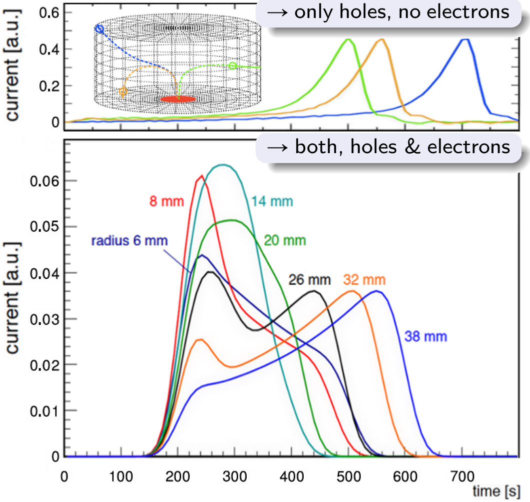






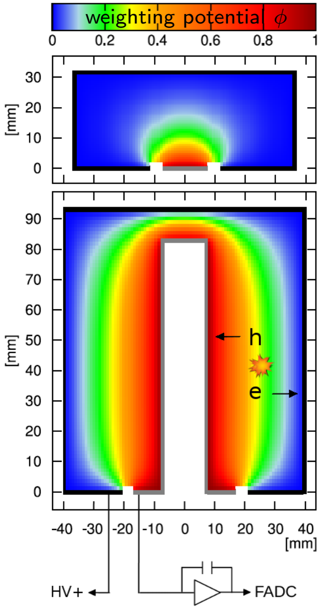
Pulse shape: semi-coaxial vs. BEGe

simulated current pulses for SSEs



→ only holes, no electrons

→ both, holes & electrons



Different PSD method than mono-parametric A/E needed for semi-coaxial detector type!

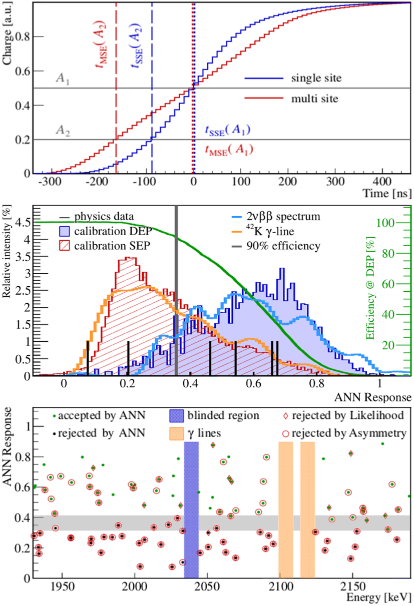
PSD method ANN Eur. Phys. J. C73 (2013) 2583

ANN = artificial neural network

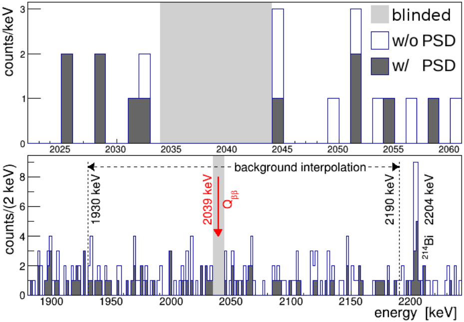
- input variables: time when charge pulse reaches 1%, 3%, ... , 99% of maximum amplitude (n_{var}=50)
- TMVA (TMlpANN algorithm) with 2 hidden layers of n_{var} and $n_{\text{var}}+1$ nodes
- training using ^{228}Th calibration data
  → SSE: ^{208}Tl DEP @ 1620.7 keV
  → MSE: ^{212}Bi FEP @ 1592.5 keV
- cut defined such that the acceptance of ^{208}Tl DEP is fixed to 90%

- $0\nu\beta\beta$-signal acceptance = $(90\,^{+\,5}_{-\,9})$%
  background acceptance @ $Q_{\beta\beta}\sim 55\%$

- further cross checked by:
  $2\nu\beta\beta$-event acceptance = (85 ± 2)%
  SSE part of compton edge = $(85 - 94)$%
  ^{60}Co calibration DEPs = $(83 - 95)$%
  two other independent PSD methods

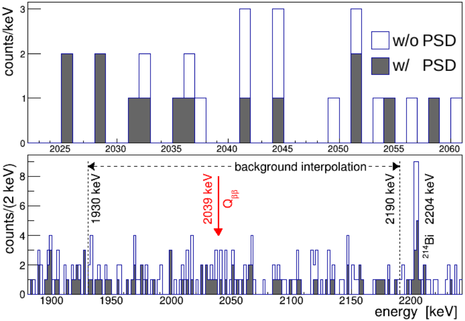


Unblinding @ $Q_{\beta\beta} \pm 5\,\text{keV}$ Phys. Rev. Let. 111 (2013) 122503



data set	PSD	Exposure [kg·yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Efficiency $a \cdot \epsilon$
golden	w/o	17.9	4.8±0.2	0.688
	w/			0.619
silver	w/o	1.3	4.8±0.2	0.688
	w/			0.619
BEGe	w/o	2.4	3.2±0.2	0.720
	w/			0.663

Unblinding @ $Q_{\beta\beta} \pm 5\,\mathrm{keV}$ Phys. Rev. Let. 111 (2013) 122503

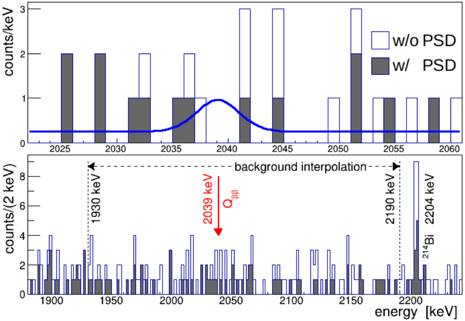


data set	PSD	Exposure [kg·yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Efficiency $a \cdot \epsilon$	Events @ ROI	N_{exp}	N_{obs}
golden	w/o	17.9	4.8±0.2	0.688	76	3.3	5
	w/			0.619	45	2.0	2
silver	w/o	1.3	4.8±0.2	0.688	19	0.8	1
	w/			0.619	9	0.4	1
BEGe	w/o	2.4	3.2±0.2	0.720	23	1.0	1
	w/			0.663	3	0.1	0

no peak observed @ $Q_{\beta\beta}$

→ GERDA sets limit on $0\nu\beta\beta$ half-live

Unblinding @ $Q_{\beta\beta} \pm 5\,\text{keV}$ Phys. Rev. Let. 111 (2013) 122503



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	w/			0.663

$$T^{0\nu}_{1/2} = \frac{\ln(2)\cdot N_A}{m_A \cdot N^{0\nu}} \cdot M \cdot t \cdot \overbrace{f_{76}\cdot f_{av}}^{\text{abundance } a} \cdot \underbrace{\varepsilon_{fep}\cdot\varepsilon_{psd}}_{\text{efficiency } \epsilon}$$

- frequentist approach: profile likelihood fit in $[1930-2190]$ keV interval with 4 free parameters:
  $3\times$ constant bkgd (different data sets)
  $1\times$ gauss with common $T^{0\nu}_{1/2} > 0$
  (systematic uncertainties on a, ϵ, μ, σ)

→ best fit $N^{0\nu}$=0

→ $T^{0\nu}_{1/2}(90\%\text{C.L.}) > 2.1 \cdot 10^{25}$ yr

→ median sensitivity: $2.4 \cdot 10^{25}$ yr

- Bayesian approach:
  flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}]\ \text{yr}^{-1}$

→ best fit $N^{0\nu}$=0

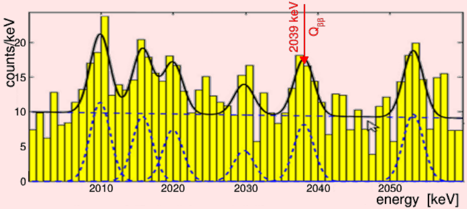
→ $T^{0\nu}_{1/2}(90\%\text{C.L.}) > 1.9 \cdot 10^{25}$ yr

→ median sensitivity: $2.0 \cdot 10^{25}$ yr

Comparison with other $0\nu\beta\beta$ experiments

Isotope	Experiment	$T_{1/2}^{0\nu}$ (90% C.L.) $[10^{25}$yr$]$	Ref.
^{76}Ge	HdM	> 1.9	[1]
	IGEX	> 1.6	[2]
	parts of HdM	$= 1.19^{+0.37}_{-0.23}$	[3]
	GERDA	> 2.1	[4]
^{136}Xe	EXO	> 1.1	[5]
	KamLAND-Zen	> 1.9	[6]
^{130}Te	CUORICINO	> 0.28	[7]
^{100}Mo	NEMO-3	> 1.1	[8]

- total exposure: $M \cdot t = 71.7$ kg·yr
- 28.75 ± 6.86 signal cts observed



[1] Eur. Phys. J. A12 (2001) 147-154
[2] Phys. Rev. D 65 (2002) 092007
[3] Phys. Lett. B 586 (2004) 198-212
[4] Phys. Rev. Let. 111 (2013) 122503
[5] Nature 510 (2014) 229-234
[6] Phys. Rev. Lett. 110 (2013) 062502
[7] Astropart. Phys. 34 (2011) 822-831
[8] Phys. Rev. D 89 (2014) 111101

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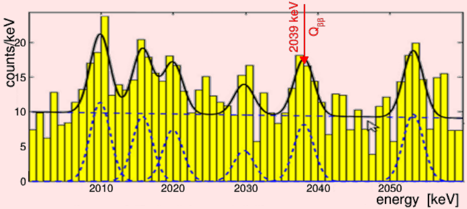
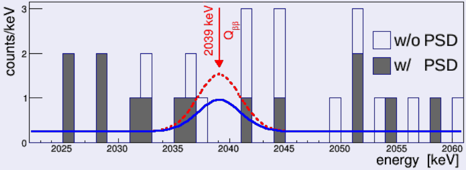


- total exposure: $M{\cdot}t = 21.6$ kg·yr



hypothesis test:

H0: background only

H1: GERDA sees signal from claim in Ref.[3]; add. 5.9 ± 1.4 signal cts in $Q_{\beta\beta} \pm 2\sigma_E$

→ profile likelihood: p($N^{0\nu}$=0|H1)=0.01

→ Bayes factor: p(H1) / p(H0)=0.024

→ search for $0\nu\beta\beta$-signal "open" again!

[1] Eur. Phys. J. A12 (2001) 147-154
[2] Phys. Rev. D 65 (2002) 092007
[3] Phys. Lett. B 586 (2004) 198-212
[4] Phys. Rev. Let. 111 (2013) 122503
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On the way to GERDA Phase II

Different strategies in parallel needed to push sensitivity

- Phase I: $20\ \mathrm{kg{\cdot}yr}$ with BI of $\sim 10^{-2}\ \mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$
- Phase II: $100\ \mathrm{kg{\cdot}yr}$ with BI of $\sim 10^{-3}\ \mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$

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- Phase II: $100\,\mathrm{kg{\cdot}yr}$ with BI of $\sim 10^{-3}\,\mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$

1. avoid close-by background sources:
    - use cleaner signal and HV cables
    - reduce material for holders
    - special care in crystal production

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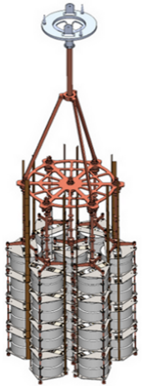
1. avoid close-by background sources:
   - use cleaner signal and HV cables
   - reduce material for holders
   - special care in crystal production
2. increase mass:
   30 additional BEGe detectors ($\sim20\,\mathrm{kg}$)



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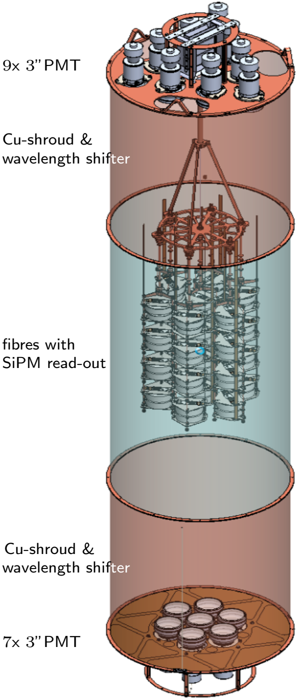
1. avoid close-by background sources:
   - use cleaner signal and HV cables
   - reduce material for holders
   - special care in crystal production
2. increase mass:
   30 additional BEGe detectors (~ 20 kg)
3. reject residual background radiation by:
   - optimized Pulse Shape Analysis
   - LAr scintillation light veto

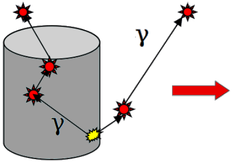


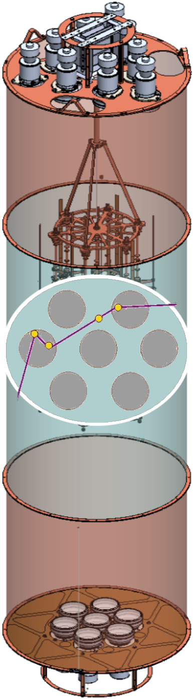
On the way to GERDA Phase II

Different strategies in parallel needed to push sensitivity

- Phase I: 20 kg·yr with BI of $\sim 10^{-2}$ cts/(kg·keV·yr)
- Phase II: 100 kg·yr with BI of $\sim 10^{-3}$ cts/(kg·keV·yr)

1. avoid close-by background sources:
   - use cleaner signal and HV cables
   - reduce material for holders
   - special care in crystal production
2. increase mass:
   30 additional BEGe detectors (~ 20 kg)
3. reject residual background radiation by:
   - optimized Pulse Shape Analysis
   - LAr scintillation light veto





On the way to GERDA Phase II

Different strategies in parallel needed to push sensitivity

- Phase I: $20\ \mathrm{kg{\cdot}yr}$ with BI of $\sim 10^{-2}\ \mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$
- Phase II: $100\ \mathrm{kg{\cdot}yr}$ with BI of $\sim 10^{-3}\ \mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$

1. avoid close-by background sources:
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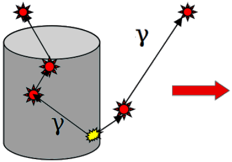
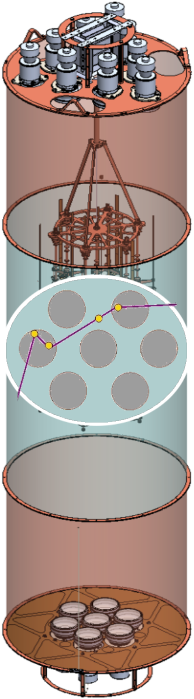




- expected Phase II sensitivity $\simeq 1.4 \cdot 10^{26}$ yr (90% C.L.); factor 7 better than Phase I

- first data from pilot string taken these days!

Conclusion: Phase I $(2011 - 2013)$

- data taking completed with an exposure of $21.6\,\mathrm{kg{\cdot}yr}$
- blind analysis performed (for the first time in this field)
- unprecedented BI of $1{\cdot}10^{-2}\,\mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$ after PSD
- half-life of $0\nu\beta\beta$:

  $T^{0\nu}_{1/2}(90\%\,\mathrm{C.L.}) > 2.1{\cdot}10^{25}\,\mathrm{yr}$ (GERDA alone)

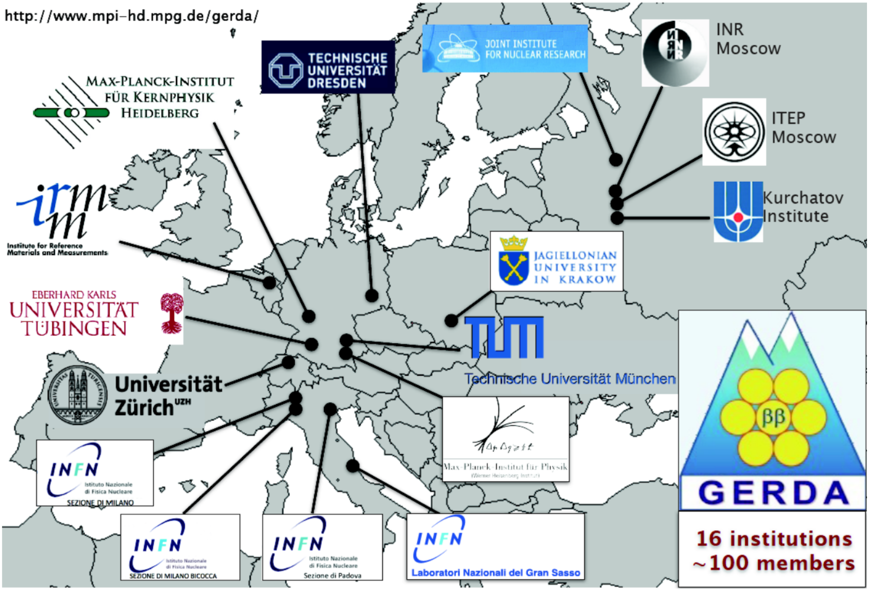
  $T^{0\nu}_{1/2}(90\%\,\mathrm{C.L.}) > 3.0{\cdot}10^{25}\,\mathrm{yr}$ (GERDA+HDM[1]+IGEX[2])
- effective neutrino mass: $\langle m_{\beta\beta}\rangle = (0.2-0.4)\,\mathrm{eV}$
- many additional results like e.g. $2\nu\beta\beta$ half-life or limits on $0\nu\beta\beta/2\nu\beta\beta$ decays to excited states, $0\nu\beta\beta\chi$, etc...)

[1] Euro Phys J A12 (2001) 147
[2] Phys Rev D65 (2002) 092007

Outlook: Phase II (upcoming)

- new BEGe detectors of additional $\sim 20\,\mathrm{kg}$ → available
- upgrade of infrastructure (lock system, glove box, ...) → finished
- liquid argon scintillation veto → installed
- last integration tests (new contacting, electronics, ...) → ongoing

The Collaboration



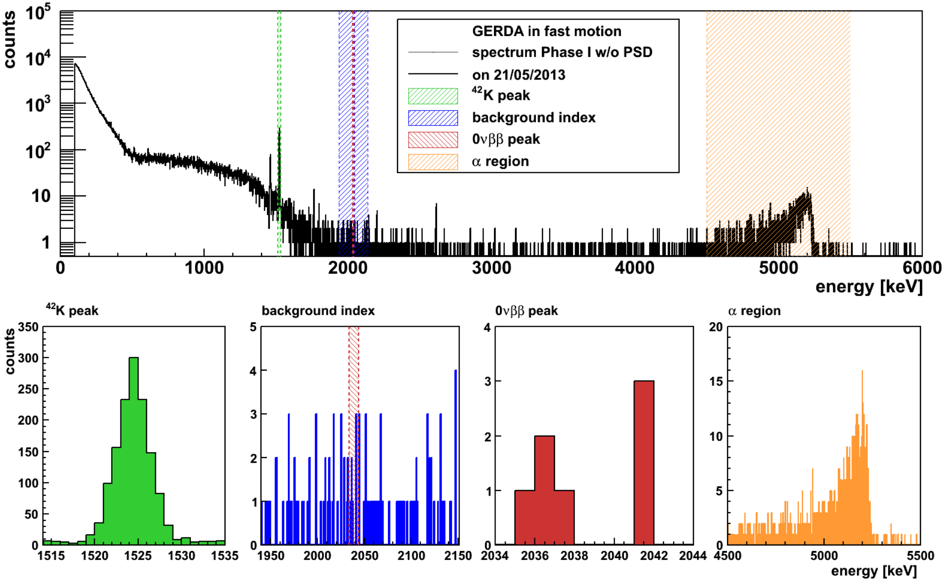
The Collaboration

... and the people behind the experiment.

Picture taken during last GERDA Meeting in June 2014 hosted by the Max-Planck-Institut für Kernphysik @ Heidelberg, Germany

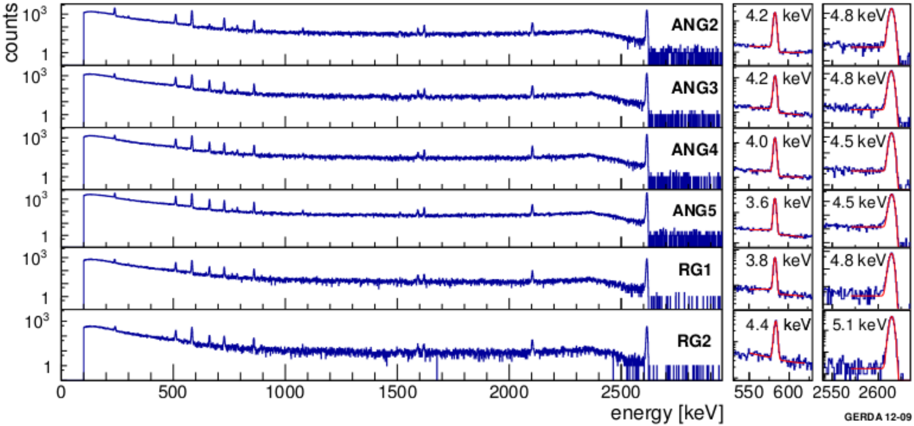
BONUS Slides

GERDA in fast motion



Calibration, time stability and energy resolution

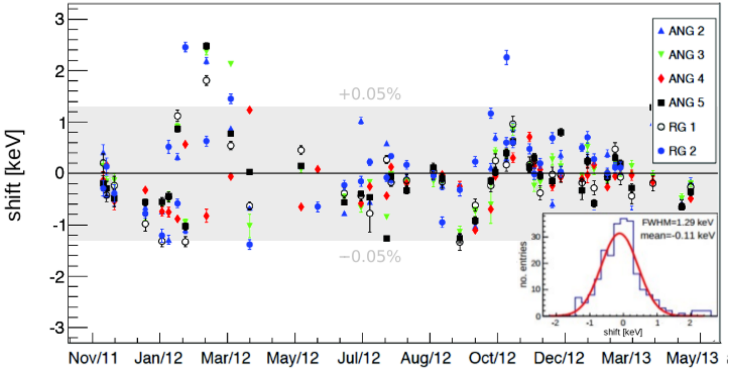
- (bi-) weekly calibration with movable ^{228}Th sources
- offline energy reconstruction (semi-Gaussian filter)
- also to check resolution and gain stability over time



- short term drifts monitored with test pulser (0.05 Hz)

Calibration, time stability and energy resolution

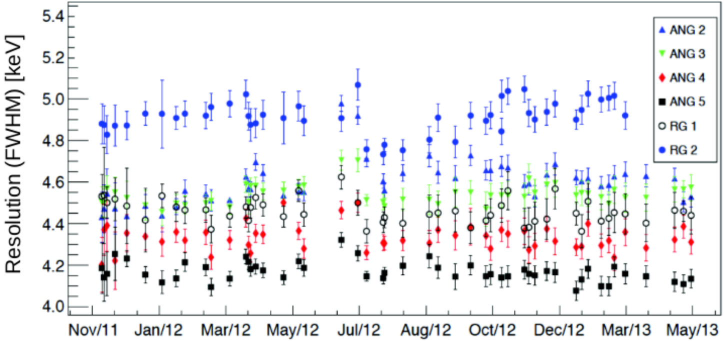
- shift of ^{208}Tl FEP position @ $2614.5\,\mathrm{keV}$ relative to previous calibration



- drifts small compared to FWHM @ $Q_{\beta\beta}$ $\sim 0.2\%$
- peak within $0.3\,\mathrm{keV}$ at correct position (from ^{42}K peak)

Calibration, time stability and energy resolution

- energy resolution @ $Q_{\beta\beta}$



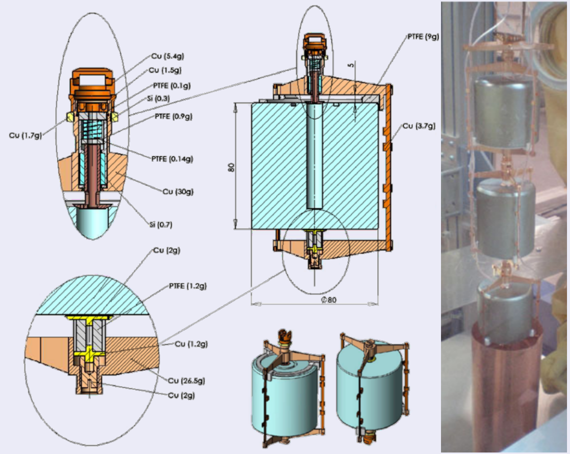
- FWHM from physics runs $\sim 4\%$ larger than expected from calibration data
- exposure weighted FWHM @ $Q_{\beta\beta}$ is:
  1. (4.8 ± 0.2) keV for semi-coaxial
  2. (3.2 ± 0.2) keV for BEGe

Phase detector properties & run times

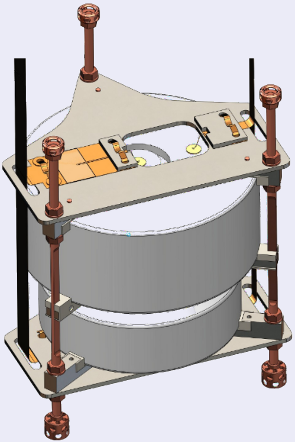
detectors	t [days]	M [kg]	f_{76} [%]	f_{AV} [%]
enriched coaxial detectors				
ANG2	485.5	2.833	86.6 ± 2.5	$87.1 \pm 4.3 \pm 2.8$
ANG3	485.5	2.391	88.3 ± 2.6	$86.6 \pm 4.9 \pm 2.8$
ANG4	485.5	2.372	86.3 ± 1.3	$90.1 \pm 4.9 \pm 2.9$
ANG5	485.5	2.746	85.6 ± 1.3	$83.1 \pm 4.0 \pm 2.7$
RG1	485.5	2.110	85.5 ± 1.5	$90.4 \pm 5.2 \pm 2.9$
RG2	384.8	2.166	85.5 ± 1.5	$83.1 \pm 4.6 \pm 2.7$
enriched BEGe detectors				
GD32B	280.0	0.717	87.7 ± 1.3	89.0 ± 2.7
GD32C	304.6	0.743	87.7 ± 1.3	91.1 ± 3.0
GD32D	282.7	0.723	87.7 ± 1.3	92.3 ± 2.6
GD35B	301.2	0.812	87.7 ± 1.3	91.4 ± 2.9

Detector assembly

Phase I



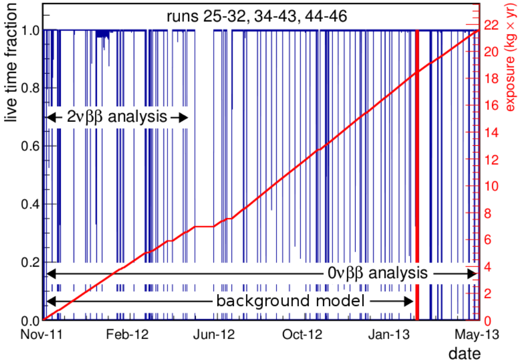
Phase II



Overview of data taking and publications

duty cycle

- (bi-) weekly calibration with ^{228}Th source → spikes
- in between: Phase I physics measurements
- flat parts: BEGe insertion & maintenance
- total livetime $= 492.3$ days



- Run $1-24$ for commissioning
- Run 33 not considered

Overview of data taking and publications

background model

- Run 25-43 = exposure of 18.5 kg·yr
  → 15.4 kg·yr for "golden"
  → 1.3 kg·yr for "silver"
  → 1.8 kg·yr for "BEGe"

Eur. Phys. J. C74 (2014) 2764

$0\nu\beta\beta$ analysis

- Run 25-46 = exposure of 21.6 kg·yr
  → 17.2 kg·yr for "golden"
  → 1.3 kg·yr for "silver"
  → 2.4 kg·yr for "BEGe"

Phys. Rev. Let. 111 (2013) 122503

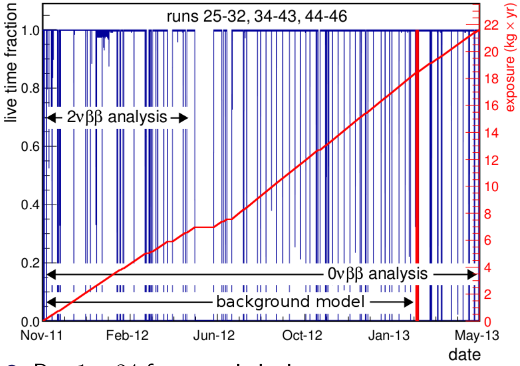
$2\nu\beta\beta$ and $0\nu\beta\beta\chi$ analysis

- Run 25-46 = exposure of 20.3 kg·yr
  → 17.2 kg·yr for "golden"
  → 2.4 kg·yr for "BEGe"

submitted to Eur. Phys. J. C (arXiv:1501.02345)

duty cycle

- (bi-) weekly calibration with ^{228}Th source → spikes
- in between: Phase I physics measurements
- flat parts: BEGe insertion & maintenance
- total livetime = 492.3 days

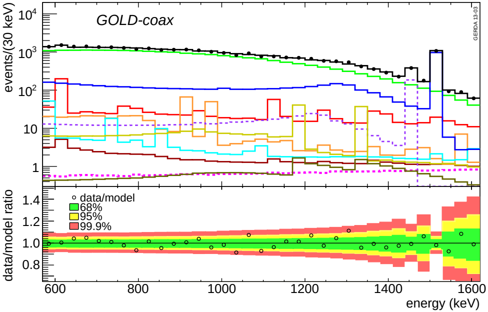


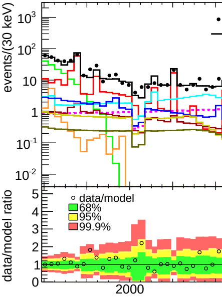
- Run 1 – 24 for commissioning
- Run 33 not considered

Background model Eur. Phys. J. C74 (2014) 2764

General procedure

- simulation of known (material screening) and observed background sources
- spectral fit with combination of all components in $[570-7500]$ keV on the 3 data-sets
- 2 extremes: "minimum" (all known + visible contributions) & "maximum" (additional contributions from other possible locations)





Background model Eur. Phys. J. C74 (2014) 2764

General procedure

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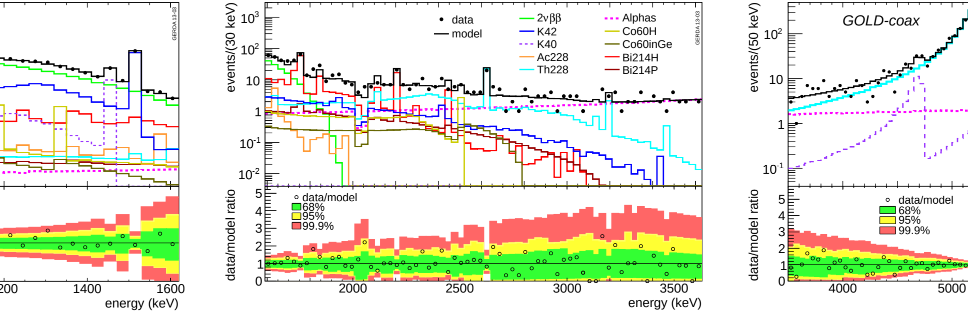

Background model Eur. Phys. J. C74 (2014) 2764

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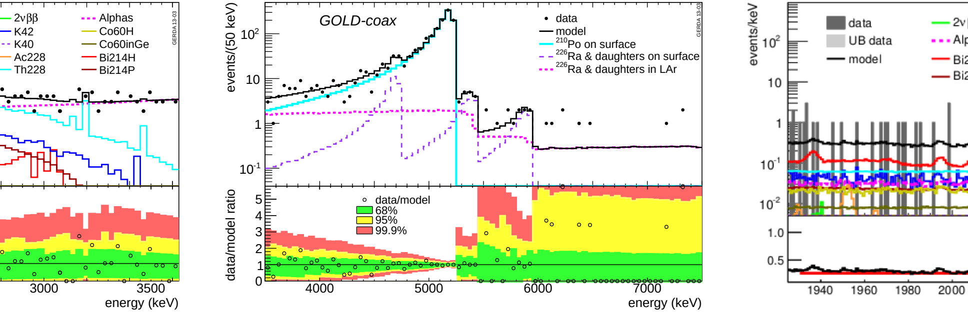

Background model Eur. Phys. J. C74 (2014) 2764

General procedure

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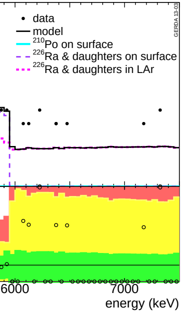
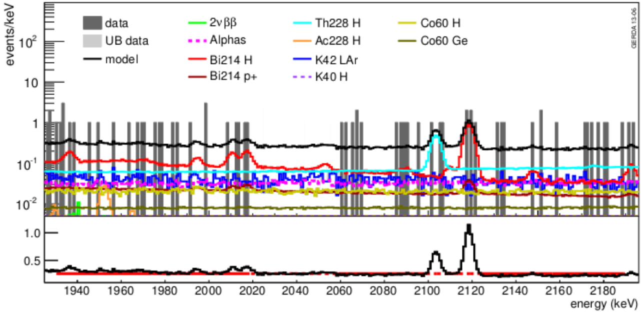
- spectral fit with combination of all components in $[570-7500]$ keV on the 3 data-sets
- 2 extremes: "minimum" (all known + visible contributions) & "maximum" (additional contributions from other possible locations)

Results

- no γ-line expected around $Q_{\beta\beta}$
- flat background for ROI excluding known peaks @ $2103\,$keV (^{208}Tl), $2119\,$keV (^{214}Bi)
- "golden": $BI = 1.75^{+0.26}_{-0.24} \cdot 10^{-2}\ \frac{\text{cts}}{\text{kg}\cdot\text{keV}\cdot\text{yr}}$

  "BEGe": $BI = 3.6^{+1.3}_{-1.0} \cdot 10^{-2}\ \frac{\text{cts}}{\text{kg}\cdot\text{keV}\cdot\text{yr}}$





Background model Eur. Phys. J. C74 (2014) 2764

General procedure

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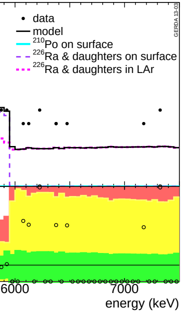
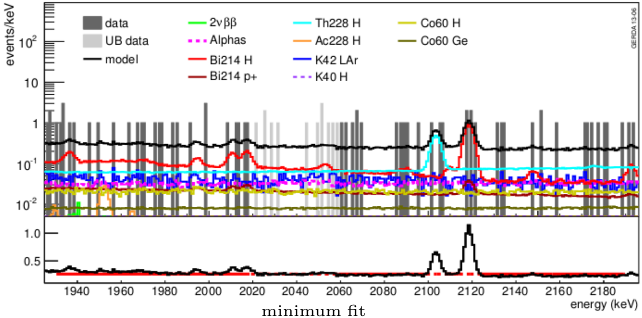
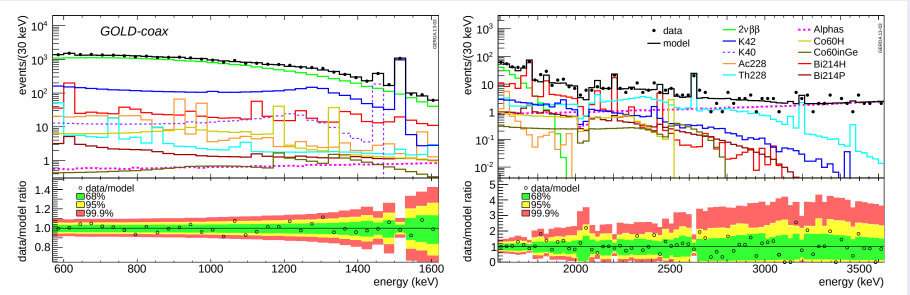
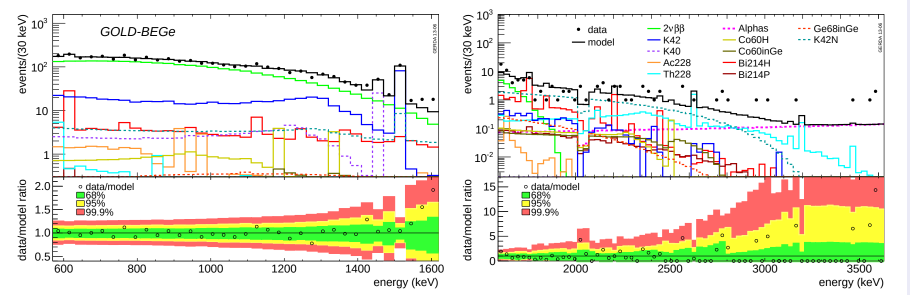




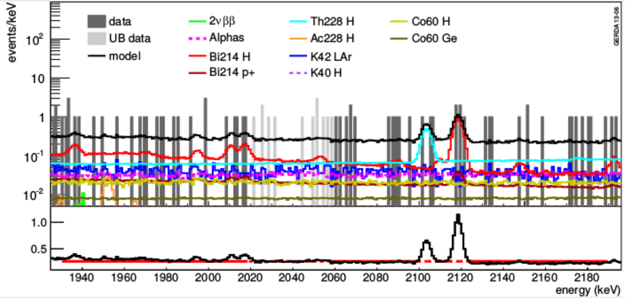
Partial unblinding @ $Q_{\beta\beta} \pm 20\,\mathrm{keV} \rightarrow \pm 5\,\mathrm{keV}$ with $\overbrace{8.6}^{\text{minimum fit}}$ / $\underbrace{10.3}_{\text{maximum fit}}$ expected and 13 observed events

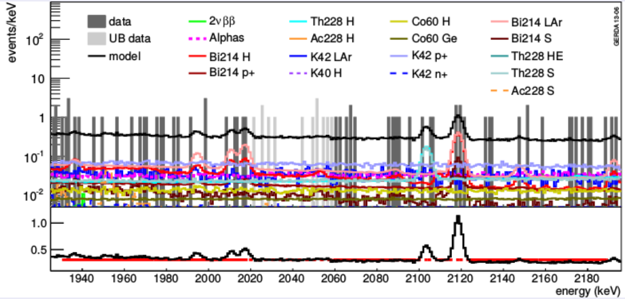
Background model: “coax” vs. “BEGe”





Background model: “minimum” vs. “maximum” @ $Q_{\beta\beta}$





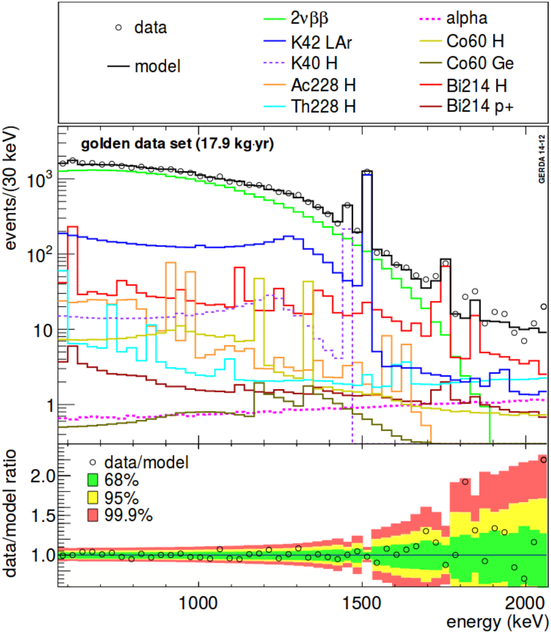
$T_{1/2}^{2\nu}$ measurement of ^{76}Ge submitted to Eur. Phys. J. C (arXiv:1501.02345)

- "golden" data-set: $17.9\ \mathrm{kg{\cdot}yr}$ exposure used to evaluate half-life of $2\nu\beta\beta$ decay
- fit range: $(570-7500)\ \mathrm{keV}$
- binned maximum likelihood approach
- minimum background model

- $2\nu\beta\beta$ half-life important for understanding of $0\nu\beta\beta$ (e.g. nuclear matrix element)

Final result:

$T_{1/2}^{2\nu} = 1.926 \pm 0.095 \cdot 10^{21}$ yr (unprecedented precision)



$0\nu\beta\beta\chi$ search in ^{76}Ge

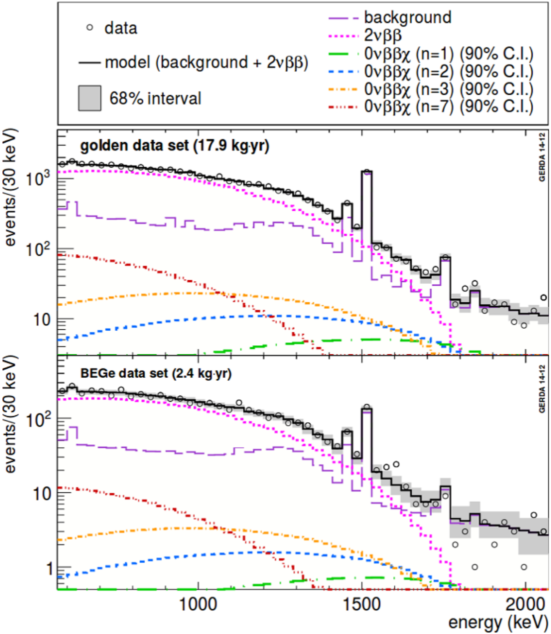
submitted to Eur. Phys. J. C (arXiv:1501.02345)

- search for Majoron accompanied $0\nu\beta\beta$ decay
- "golden" + "BEGe" data-set with 20.3 kg·yr total exposure

Model	n	Mode	Goldstone boson	L	$T^{0\nu\chi}_{1/2}$ $[10^{23}\text{yr}]$
IB	1	χ	no	0	> 4.2
IC	1	χ	yes	0	> 4.2
ID	3	$\chi\chi$	no	0	> 0.8
IE	3	$\chi\chi$	yes	0	> 0.8
IF	2	χ	bulk field	0	> 1.8
IIB	1	χ	no	-2	> 4.2
IIC	3	χ	yes	-2	> 0.8
IID	3	$\chi\chi$	no	-1	> 0.8
IIE	7	$\chi\chi$	yes	-1	> 0.3
IIF	3	χ	gauge boson	-2	> 0.8

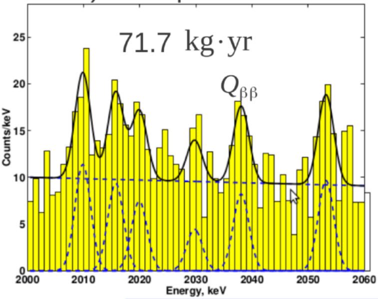
Most stringent limits for ^{76}Ge:

- n=1, 3 improved by factor 6
- n=7 improved by factor 5
- n=2 reported for first time



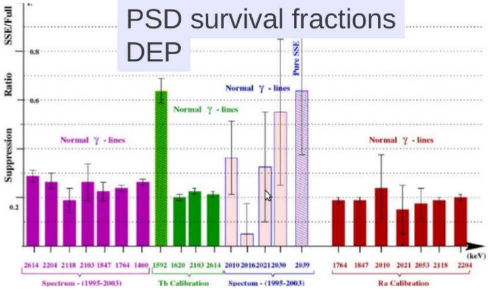
Why GERDA does not use HDM result from 2006 ?!

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



entire data set: 71.7 kg·yr (active mass)
28.75 ± 6.86 signal events
$T^{0\nu}_{1/2} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr

data for PSD analysis: 51.4 kg·yr
19.58 ± 5.41 signal events
$T^{0\nu}_{1/2} = (1.25^{+0.49}_{-0.27}) \cdot 10^{25}$ yr



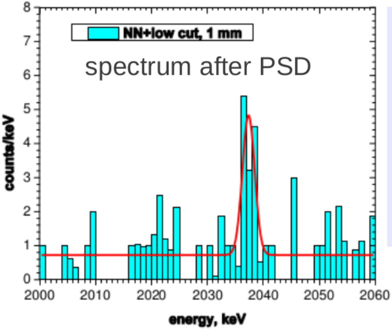
with PSD applied:
12.36 ± 3.72 events
DEP survival fraction ~ 62%
→ $T^{0\nu}_{1/2} = 1.23 \cdot 10^{25}$ yr

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

No efficiency correction is applied in any publication!

Why GERDA does not use HDM result from 2006 ?!

b) 2006 publication: Mod Phys Lett A21 p. 1547-1566



fit gives 11.32±1.75 signal events

$\rightarrow T_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr

error on signal count not correct since smaller than Poisson error

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 $T_{1/2}^{0\nu}$

efficiency factor not considered
→ calculation of $T_{1/2}^{0\nu}$ not correct
→ GERDA does not use this result