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

Andrea Kirsch
— on behalf of the Gerda Collaboration —

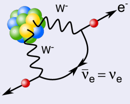
Max-Planck Institut für Kernphysik, Heidelberg

Lake Louise Winter Institute

20$^{\text{st}}$ February 2015

Outline

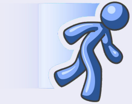
1. Motivation for $0\nu\beta\beta$-search



2. GERDA experiment

3. Results from Phase I

4. Towards Phase II



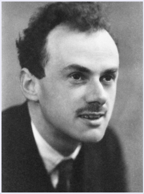
Unveiling the nature of the neutrino…

- absolute mass scale?
- mass hierarchy (normal or inverted)?
- physics beyond SM (e.g. lepton number violation, see-saw mechanism, …)?

… and …

Unveiling the nature of the neutrino ...

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

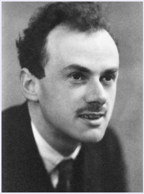


vs.

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

Unveiling the nature of the neutrino …

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

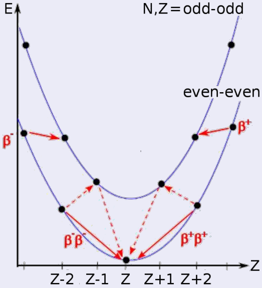


vs.

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

… 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

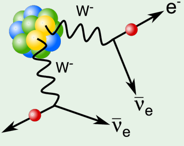


- $\beta\beta$ emitters used in experiments

^{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+

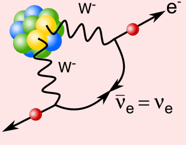
Double Beta ($\beta\beta$) decay

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



- allowed by Standard Model
- $\Delta L = 0$
- so far observed in up to 12 nuclei with half lifes $\sim(10^{18} - 10^{24})$ yr
  $T_{1/2}^{2\nu}(^{76}\mathrm{Ge}) = 1.84^{+0.14}_{-0.10} \cdot 10^{21}$ yr
  J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

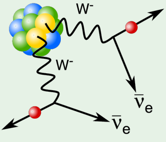
$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$



- prohibited by Standard Model
- $\Delta L = 2$
- only if ν has Majorana mass component
- still hunted process; mediated by e.g. light Majorana ν, R-handed weak currents, SUSY particles, ...

Double Beta ($\beta\beta$) decay

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

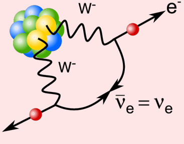


- allowed by Standard Model
- $\Delta L = 0$
- so far observed in up to 12 nuclei with half lifes $\sim(10^{18} - 10^{24})$ yr

$T_{1/2}^{2\nu}(^{76}\mathrm{Ge}) = 1.84^{+0.14}_{-0.10} \cdot 10^{21}$ yr

J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

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



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

note → one claim by subgroup of HdM:

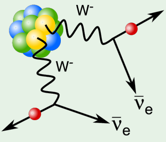
$T_{1/2}^{0\nu}(^{76}\mathrm{Ge}) = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr

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

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

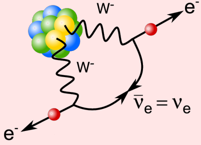


$T^{2\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.84^{+0.14}_{-0.10} \cdot 10^{21}$ yr

J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

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

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



note → one claim by subgroup of HdM:

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr

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

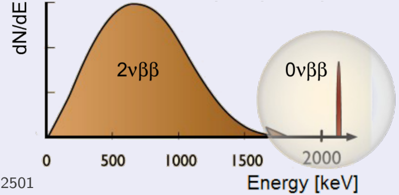
Experimental signatures

- 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

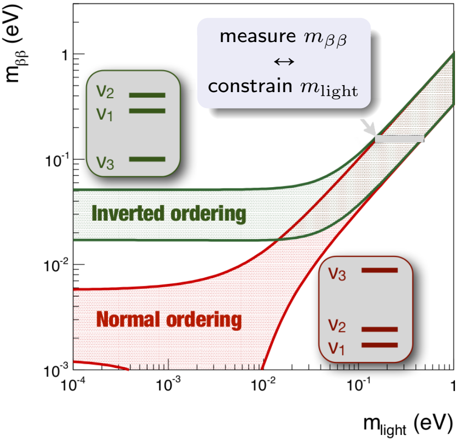


Neutrinoless Double Beta $(0\nu\beta\beta)$ decay

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

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

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



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

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

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

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

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

Experimental Sensitivity

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

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

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

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

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

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

Experimental Sensitivity

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

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

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

Advantages

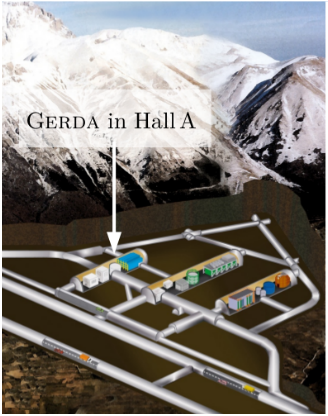
- source = detector → high ϵ
- High Purity Ge → low intrinsic BI
- FWHM @ $Q_{\beta\beta}$ $\sim 0.2\%$ → excellent ΔE
- test of $0\nu\beta\beta$ observation byparts of HdM without depending on NME

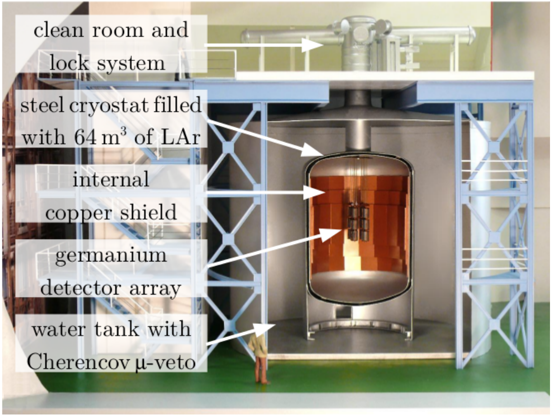
Disadvantages

- 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

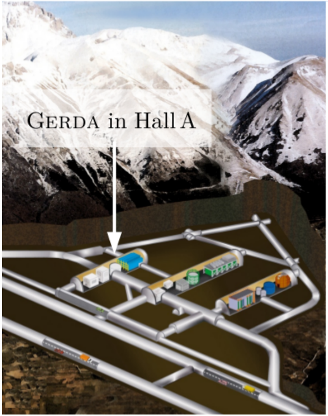
Eur. J. Phys. C73 (2013) 2330

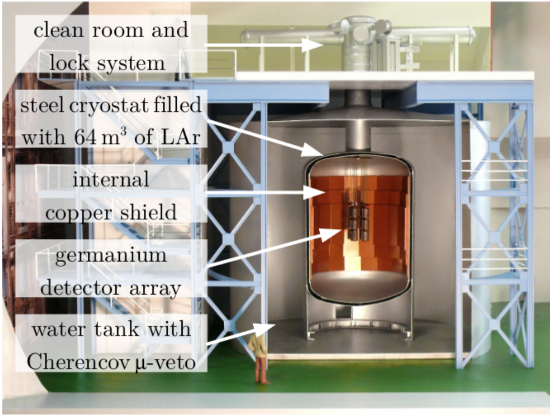




- located @ LNGS underground laboratory, Italy (3400 m w.e.→ cosmic μ flux reduced by 10^6)
- surrounding rock shielded by tank with ultra-pure water, the copper lined cryostat and LAr
- plastic scintillators above cryostat neck and water instrumented with PMTs as active μ-veto
- detectors are operated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

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



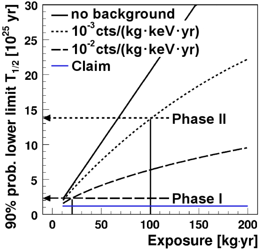


- located @ LNGS underground laboratory, Italy (3400 m w.e.→ cosmic μ flux reduced by 10^6)
- surrounding rock shielded by tank with ultra-pure water, the copper lined cryostat and LAr
- plastic scintillators above cryostat neck and water instrumented with PMTs as active μ-veto
- detectors are operated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

- 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)	$1.5\cdot10^7$	–	–

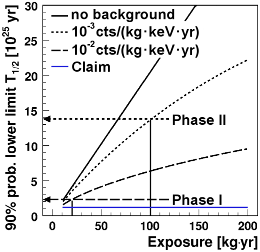
GERDA Timetable



Experiment proceeds in two phases:

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

GERDA Timetable

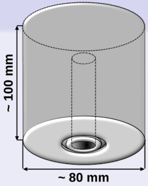


Experiment proceeds in two phases:

Phase	Mass	Aspired BI	Exposure	$T_{1/2}^{0\nu}$(90% C.L.)	Status
	[kg]	$[\frac{\text{cts}}{\text{kg·keV·yr}}]$	[kg · yr]	[yr]	
I	15	10^{-2}	20	$\sim 2 \cdot 10^{25}$	finished
II	35	10^{-3}	100	$1\ldots2 \cdot 10^{26}$	in prep.

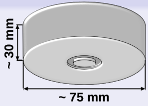
Semi-coaxial

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

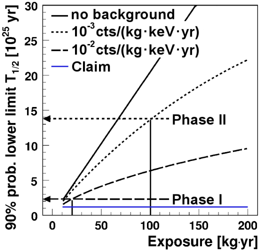


Broad Energy Germanium (BEGe)

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



GERDA Timetable

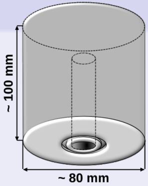


Experiment proceeds in two phases:

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

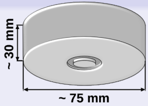
Semi-coaxial

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



Broad Energy Germanium (BEGe)

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



Phase I data taking

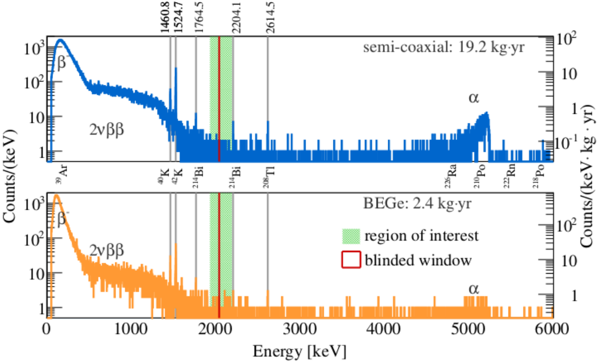
- Nov 2011 - May 2013: 8x
- 2 detectors not considered due to high leakage current
- total mass $= 14.6$ kg

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

Physics spectrum

- β-spectrum of ^{39}Ar (with $Q = 565$ keV)
- $2\nu\beta\beta$-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)

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



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

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

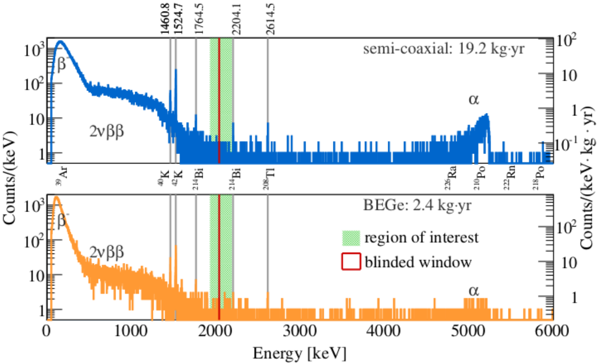
Physics spectrum

- β-spectrum of ^{39}Ar (with $Q = 565$ keV)
- $2\nu\beta\beta$-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)

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

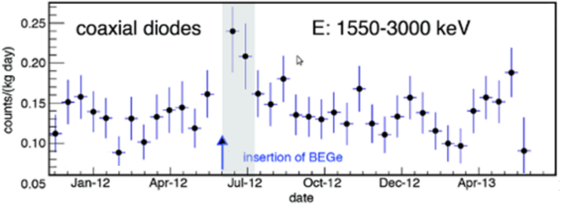
Division into 3 sub-sets:

- semi-coaxial data splitted in "golden"/"silver" due to BI
- "BEGe" kept seperated because of better E resolution



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

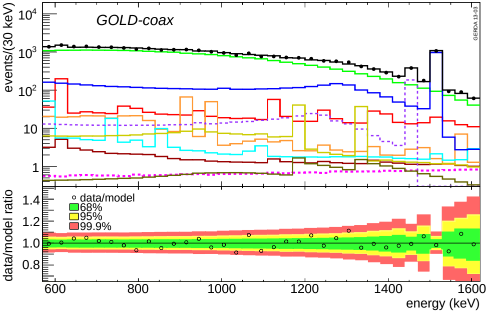
blinded window @ $Q_{\beta\beta} \pm 20$ keV to not bias analysis

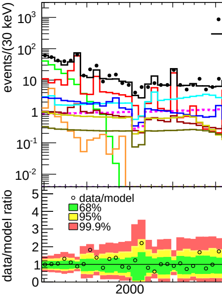


Background model Eur. Phys. J. C74 (2014) 2764

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)

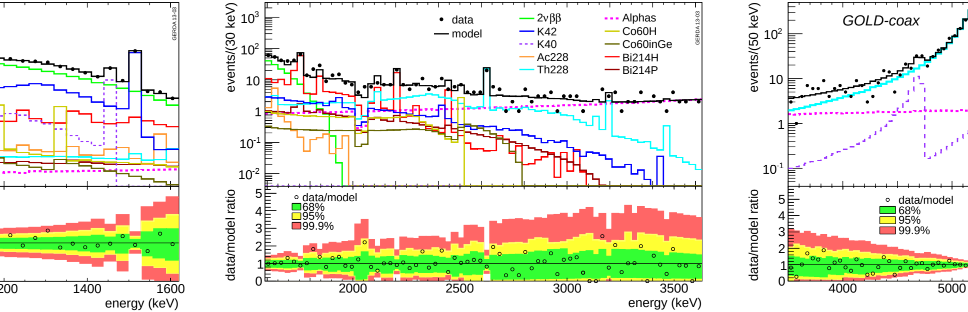




Background model Eur. Phys. J. C74 (2014) 2764

General procedure

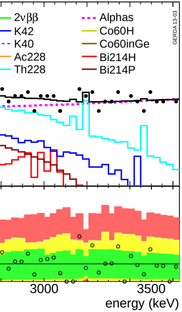
- simulation of known (material screening) and observed background sources
- spectral fit with combination of all components in $[570-7500]$ keV on the 3 data-sets
- 2 extremes: "minimum" (all known + visible contributions) & "maximum" (additional contributions from other possible locations)

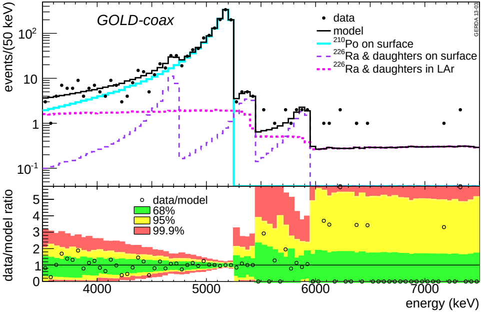


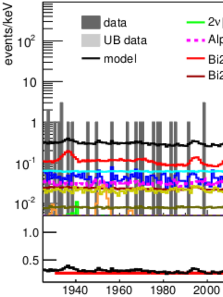
Background model Eur. Phys. J. C74 (2014) 2764

General procedure

- 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

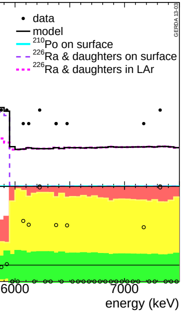
General procedure

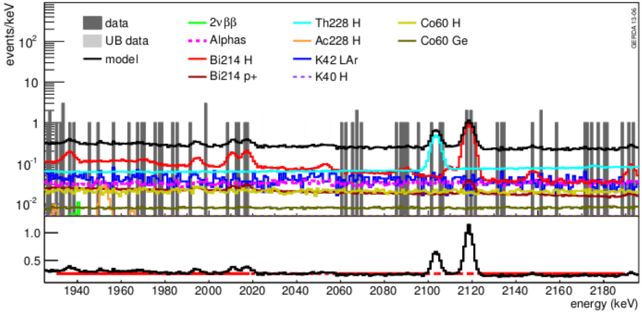
- simulation of known (material screening) and observed background sources
- spectral fit with combination of all components in $[570 - 7500]$ keV on the 3 data-sets
- 2 extremes: "minimum" (all known + visible contributions) & "maximum" (additional contributions from other possible locations)

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

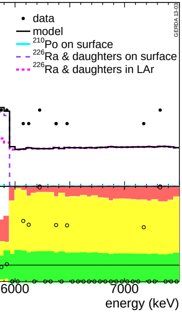
General procedure

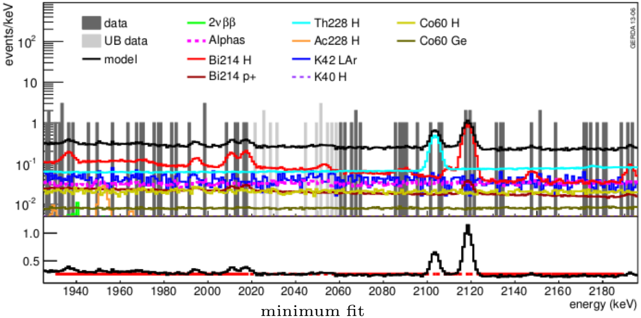
- simulation of known (material screening) and observed background sources
- spectral fit with combination of all components in $[570-7500]$ keV on the 3 data-sets
- 2 extremes: "minimum" (all known + visible contributions) & "maximum" (additional contributions from other possible locations)

Results

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

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

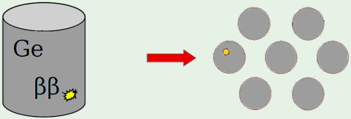




Partial unblinding @ $Q_{\beta\beta} \pm 20\,\mathrm{keV} \rightarrow \pm 5\,\mathrm{keV}$ with $\overbrace{8.6}^{\text{minimum fit}} / \underbrace{10.3}_{\text{maximum fit}}$ expected and 13 observed events

Background reduction by off-line analysis

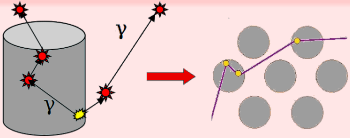
Signal



- $\beta\beta$ 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

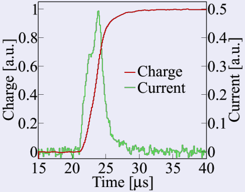


- γ events;
  range of $\sim 1\mathrm{MeV}$ gammas in Ge about $10\times$ larger (compared to electrons)
- interaction via compton scattering, e^+e^- pair creation or photelectric absorption
- sum of several separated electron-hole drifts

→ multi-site event (MSE)

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 @ $Q_{\beta\beta}$

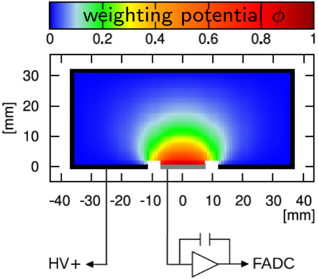


Pulse shape: BEGe

Ramo-Shockley theorem

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

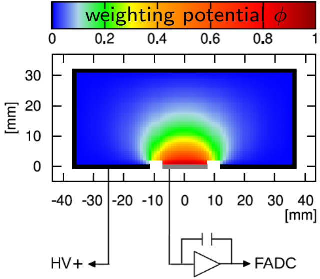
→ mostly holes (but hardly any electrons)
do contribute to the signal formation!



Pulse shape: BEGe

Ramo-Shockley theorem

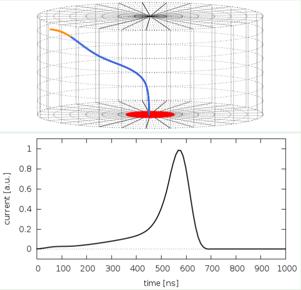
- Charge $Q(t)$
  $= -q \times [\phi(\boldsymbol{r}_\mathrm{h}(t)) - \phi(\boldsymbol{r}_\mathrm{e}(t))]$
- Current $I(t) = \mathrm{d}Q(t)/\mathrm{d}t$
  $= q \times [\mathcal{E}(\boldsymbol{r}_\mathrm{h}(t)) \cdot \boldsymbol{v}_\mathrm{h}(t) - \mathcal{E}(\boldsymbol{r}_\mathrm{e}(t)) \cdot \boldsymbol{v}_\mathrm{e}(t)]$



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

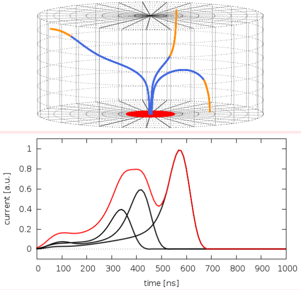
Signal-like single-site event (SSE)

$A \propto E$



Background-like multi-site event (MSE)

$A \not\propto E$

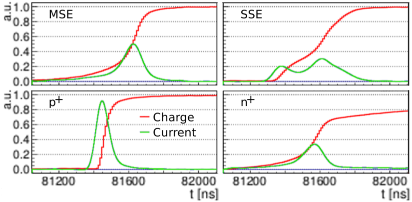


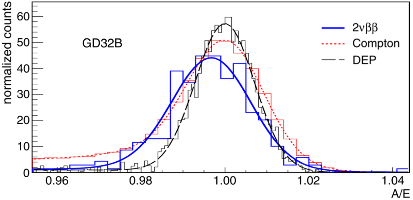
PSD parameter A/E

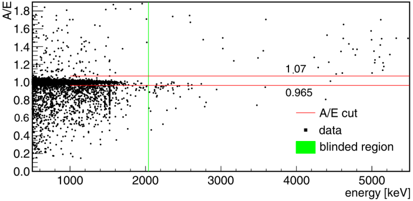
A = amplitude of current pulse

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
  ...

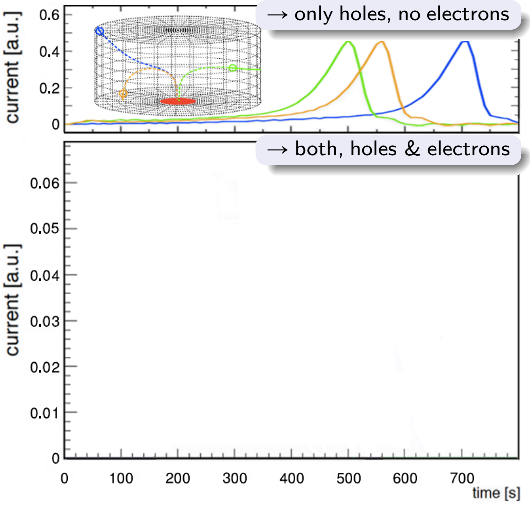






Pulse shape: semi-coaxial vs. BEGe

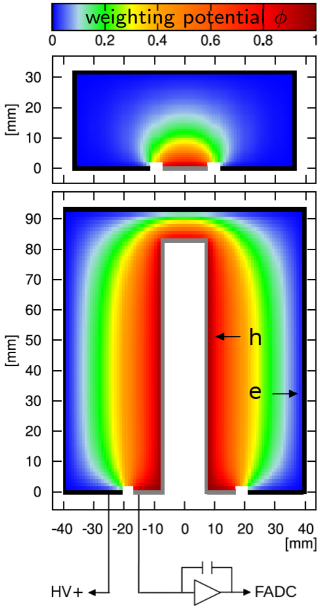
simulated current pulses for SSEs



→ only holes, no electrons

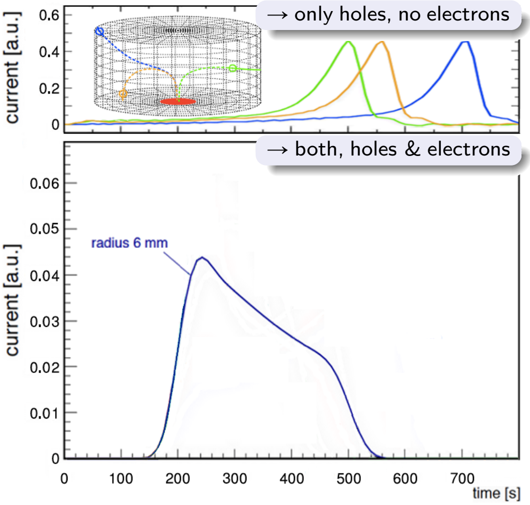
→ both, holes & electrons

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



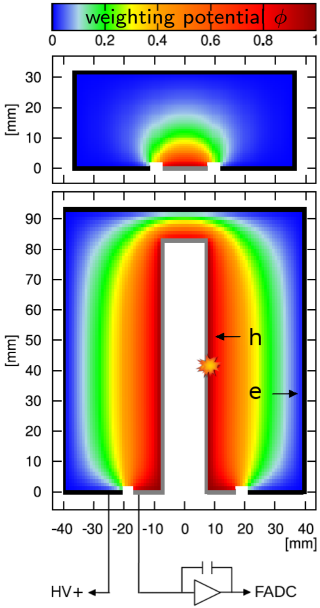
Pulse shape: semi-coaxial vs. BEGe

simulated current pulses for SSEs



→ only holes, no electrons

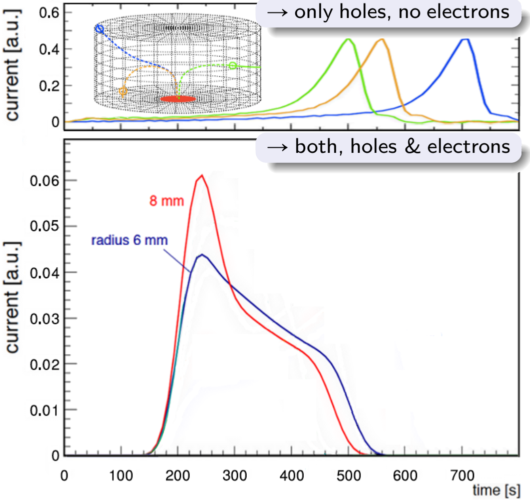
→ both, holes & electrons



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

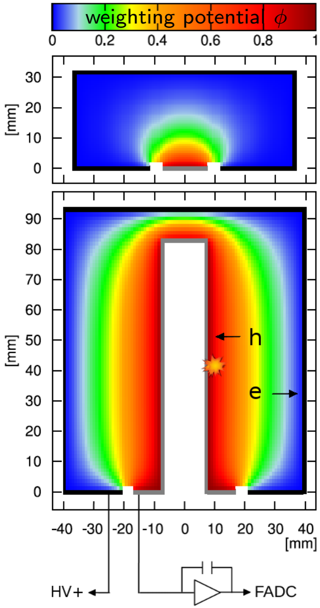
Pulse shape: semi-coaxial vs. BEGe

simulated current pulses for SSEs



→ only holes, no electrons

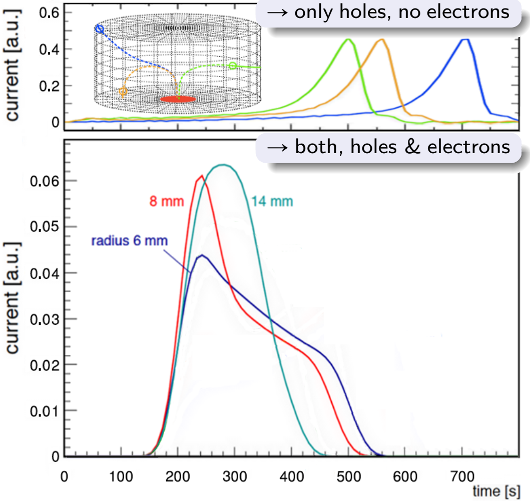
→ both, holes & electrons



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

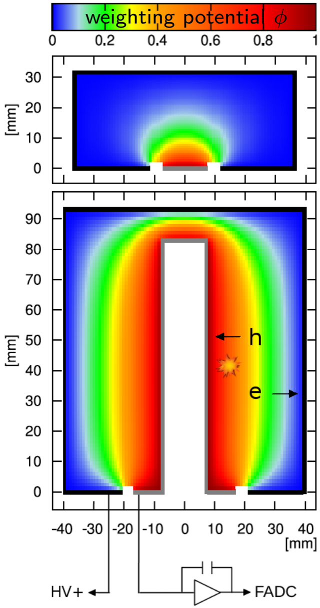
Pulse shape: semi-coaxial vs. BEGe

simulated current pulses for SSEs



→ only holes, no electrons

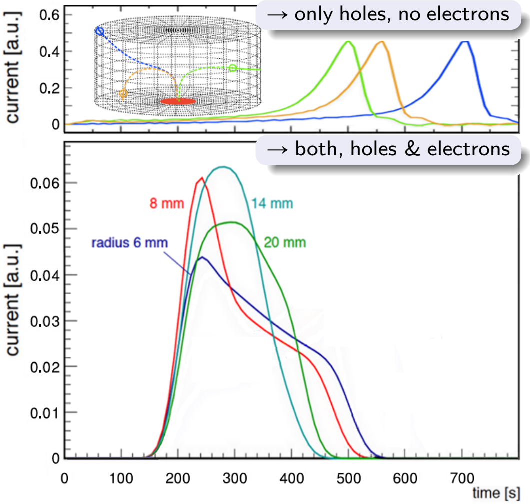
→ both, holes & electrons



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

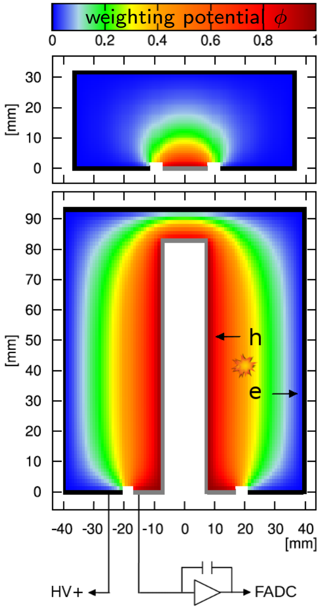
Pulse shape: semi-coaxial vs. BEGe

simulated current pulses for SSEs



→ only holes, no electrons

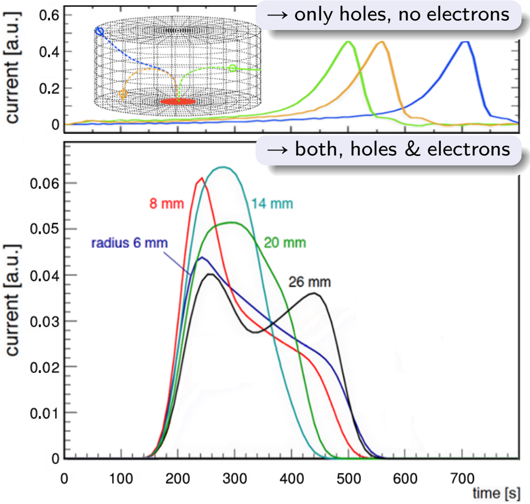
→ both, holes & electrons



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

Pulse shape: semi-coaxial vs. BEGe

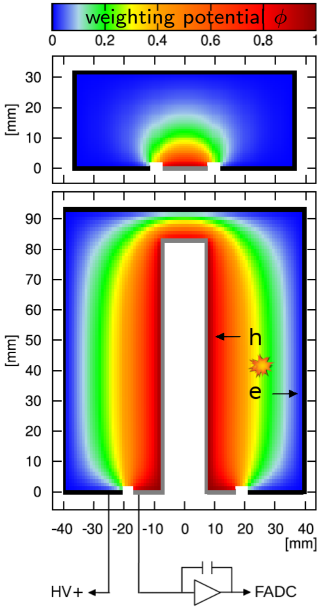
simulated current pulses for SSEs



→ only holes, no electrons

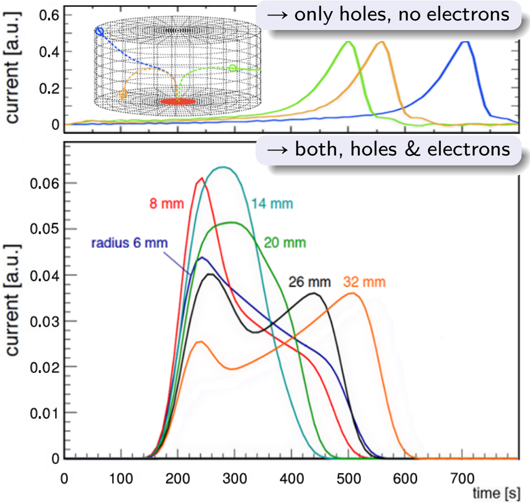
→ both, holes & electrons

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



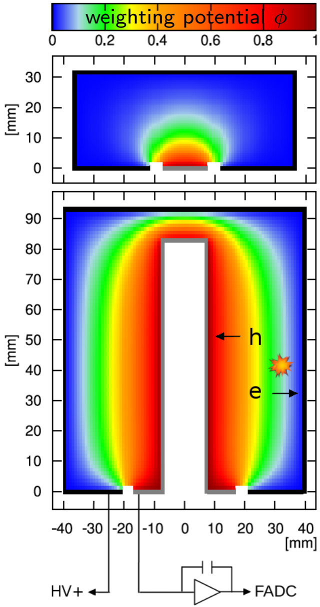
Pulse shape: semi-coaxial vs. BEGe

simulated current pulses for SSEs



→ only holes, no electrons

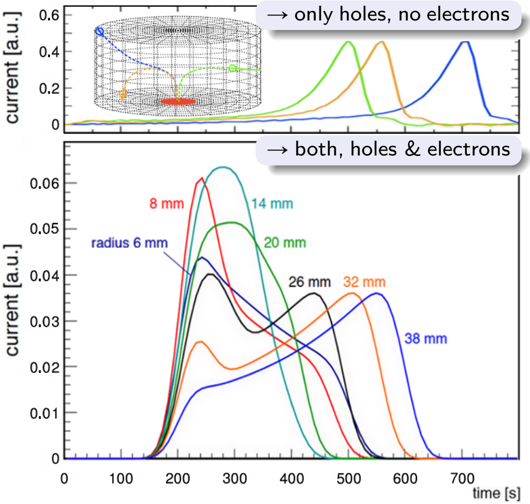
→ both, holes & electrons



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

Pulse shape: semi-coaxial vs. BEGe

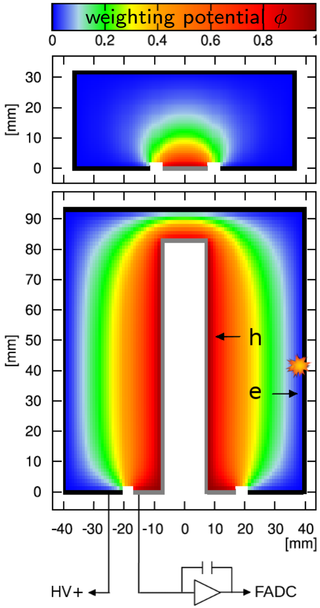
simulated current pulses for SSEs



→ only holes, no electrons

→ both, holes & electrons

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

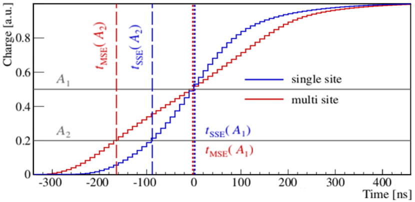


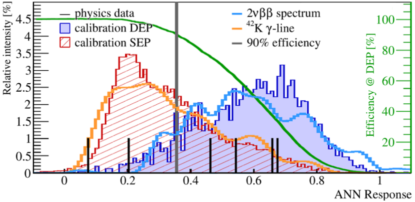
PSD method ANN

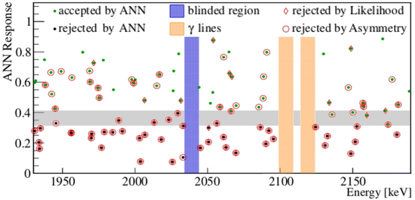
Eur. Phys. J. C73 (2013) 2583

ANN = artificial neural network

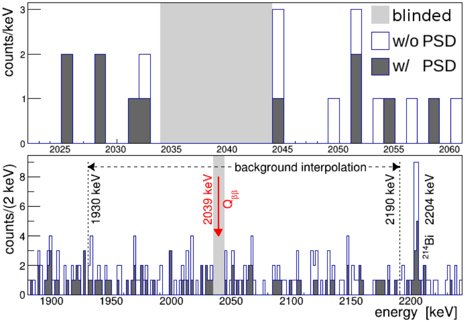
- input variables: time when charge pulse reaches 1%, 3%, … , 90% of maximum amplitude (n_{var}=50)
- TMVA (TMlpANN algorithm) with 2 hidden layers of n_{var} and $n_{\text{var}}+1$ nodes
- training using ^{228}Th calibration data
  → SSE: ^{208}Tl DEP @ 1620.7 keV
  → MSE: ^{212}Bi FEP @ 1592.5 keV
- 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 = $(85 \pm 2)\%$
  SSE part of compton edge = $(85-94)\%$
  ^{60}Co calibration DEPs = $(83-95)\%$
  two other independent PSD methods







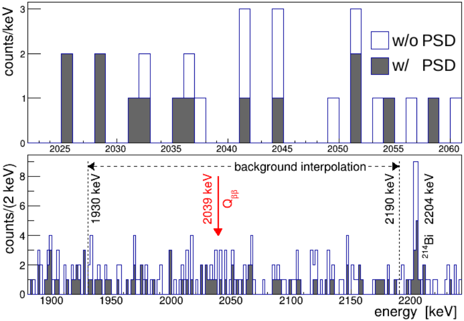
Unblinding @ $Q_{\beta\beta} \pm 5\,\text{keV}$ Phys. Rev. Let. 111 (2013) 122503



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

data set	PSD	Exposure [kg·yr]	FWHM @ $Q_{\beta\beta}$ [keV]	$a \cdot \epsilon$
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



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

data set	PSD	Exposure [kg·yr]	FWHM @ $Q_{\beta\beta}$ [keV]	$a \cdot \epsilon$
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

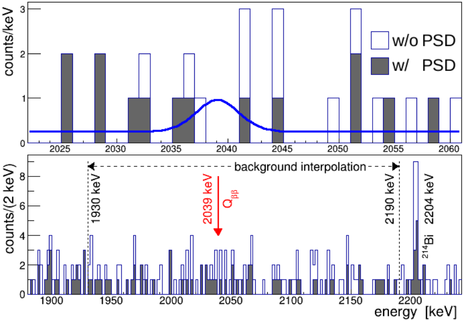
Events @ ROI	N_{exp}	N_{obs}
76	3.3	5
45	2.0	2
19	0.8	1
9	0.4	1
23	1.0	1
3	0.1	0

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

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

Unblinding @ $Q_{\beta\beta} \pm 5\,\mathrm{keV}$

Phys. Rev. Let. 111 (2013) 122503



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

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

- 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 $N^{0\nu}{=}0$

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

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

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

→ best fit $N^{0\nu}{=}0$

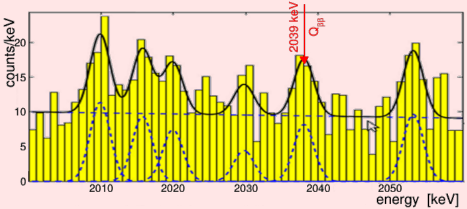
→ $T^{0\nu}_{1/2}(90\%\mathrm{C.L.}) > 1.9 \cdot 10^{25}$ yr

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

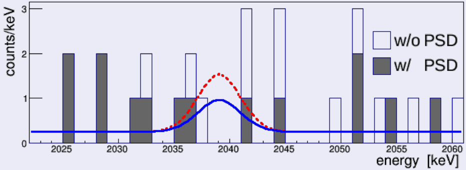
Comparison with other $0\nu\beta\beta$ experiments

Isotope	Experiment	$T^{0\nu}_{1/2}$(90% C.L.) $[10^{25}\text{yr}]$	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



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



H0: bkgd compatible with GERDA result;
only 2.0 ± 0.3 bkgd cts in $Q_{\beta\beta} \pm 2\sigma_\mathrm{E}$

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

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

→ Bayes factor: $\mathrm{p}(\mathrm{H1})\,/\,\mathrm{p}(\mathrm{H0}){=}0.024$

→ 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
[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

On the way to GERDA Phase II

Different strategies in parallel needed to push sensitivity

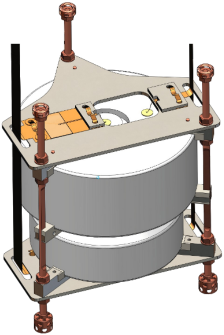
- Phase I: $20\ \mathrm{kg{\cdot}yr}$ with BI of $\sim 10^{-2}\ \mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$
- Phase II: $100\ \mathrm{kg{\cdot}yr}$ with BI of $\sim 10^{-3}\ \mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$

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 $\sim 10^{-3}\ \mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$

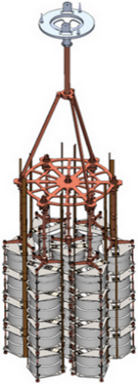
1. avoid close-by background sources:
    - use cleaner signal and HV cables
    - reduce material for holders
    - special care in crystal production



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:
    - use cleaner signal and HV cables
    - reduce material for holders
    - special care in crystal production
2. increase mass:
   30 additional BEGe detectors ($\sim 20\ \mathrm{kg}$)

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 $\sim 10^{-3}\,\mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$

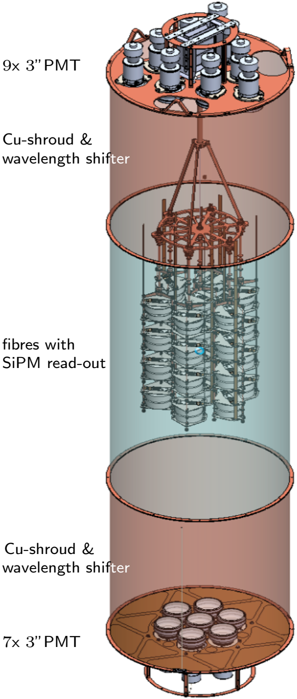
① avoid close-by background sources:

- use cleaner signal and HV cables
- reduce material for holders
- special care in crystal production

② increase mass:
30 additional BEGe detectors ($\sim 20\,\mathrm{kg}$)

③ reject residual background radiation by:

- optimized Pulse Shape Analysis
- LAr scintillation light veto

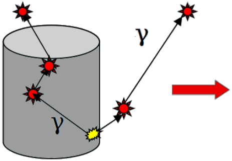


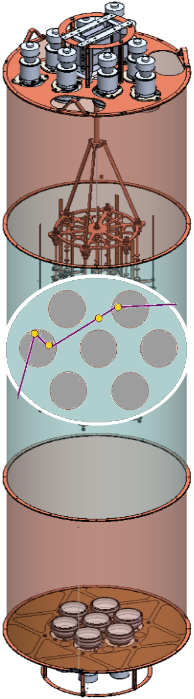
On the way to GERDA Phase II

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:
    - 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



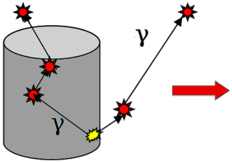


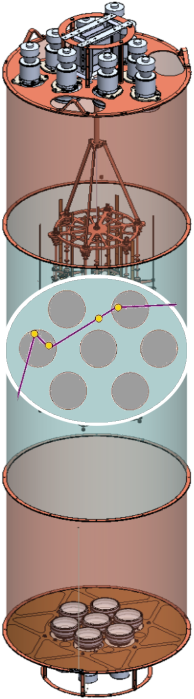
On the way to GERDA Phase II

Different strategies in parallel needed to push sensitivity

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

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 ($\sim 20\,\text{kg}$)
3. reject residual background radiation by:
    - optimized Pulse Shape Analysis
    - LAr scintillation light veto





- 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 $\sim 10^{-2}\ \mathrm{cts/(kg{\cdot}keV{\cdot}yr)}$ after PSD
  (order of magnitude lower than previous experiments)
- <u>upper half-life limit from profile likelihood fit:</u>

  $T^{0\nu}_{1/2}(90\%\mathrm{C.L.}) > 2.1{\cdot}10^{25}\ \mathrm{yr}$ with GERDA alone
  → HdM claim (2004) rejected @ 99% level
  $T^{0\nu}_{1/2}(90\%\mathrm{C.L.}) > 3.0{\cdot}10^{25}\ \mathrm{yr}$ with GERDA+HdM[1]+IGEX[2]
  → for light Majorana ν exchange: $\langle m_{\beta\beta}\rangle = (0.2{-}0.4)\ \mathrm{eV}$

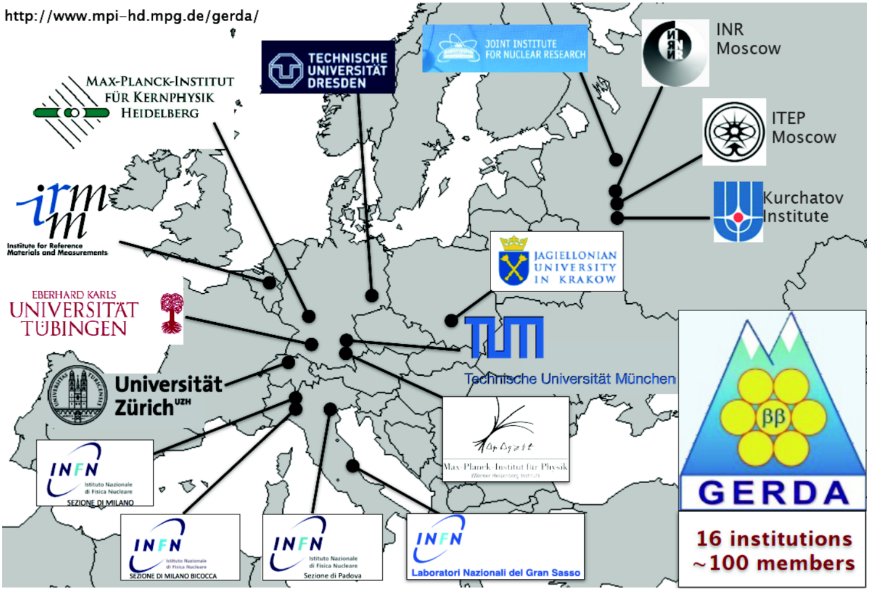
  [1] Euro Phys J A12 (2001) 147
  [2] Phys Rev D65 (2002) 092007

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

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



16 institutions
~100 members

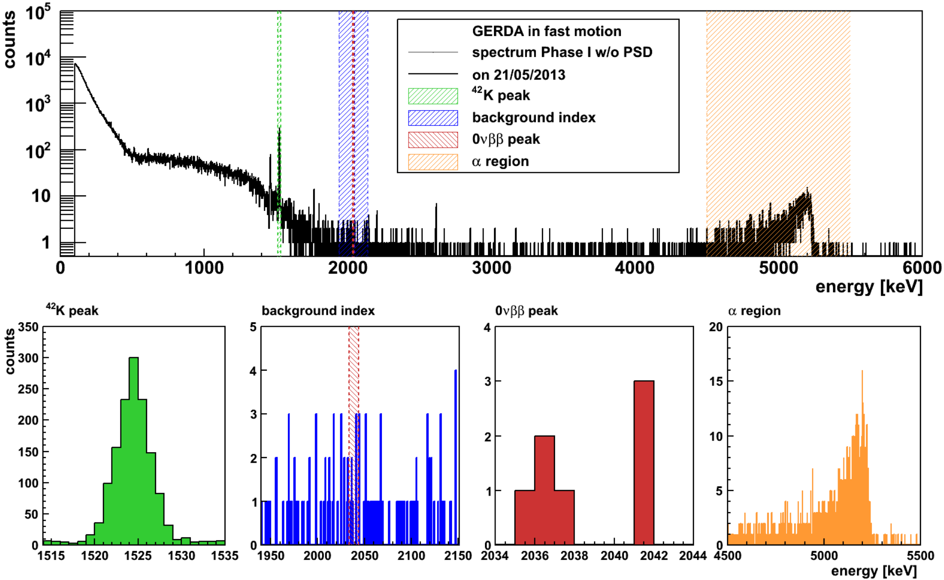
The Collaboration

... 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

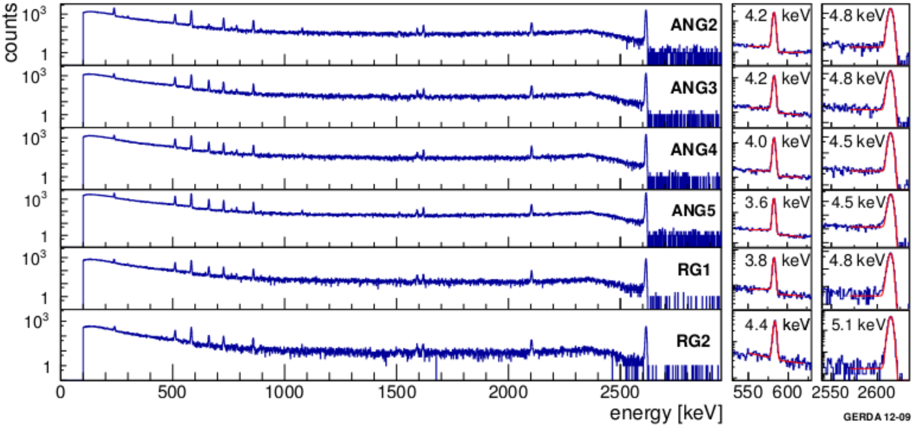
BONUS Slides

Gerda in fast motion



Calibration, time stability and energy resolution

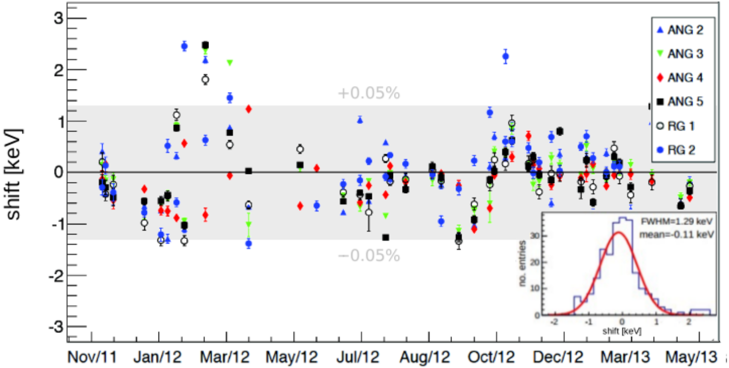
- (bi-) weekly calibration with movable ^{228}Th sources
- offline energy reconstruction (semi-Gaussian filter)
- also to check resolution and gain stability over time



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

Calibration, time stability and energy resolution

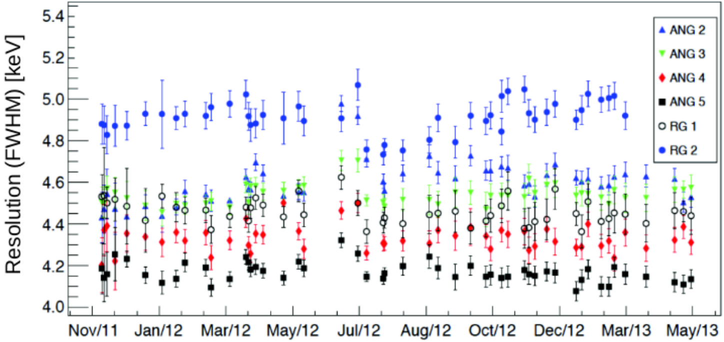
- shift of ^{208}Tl FEP position @ $2614.5\,\mathrm{keV}$ relative to previous calibration



- 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 @ $Q_{\beta\beta}$

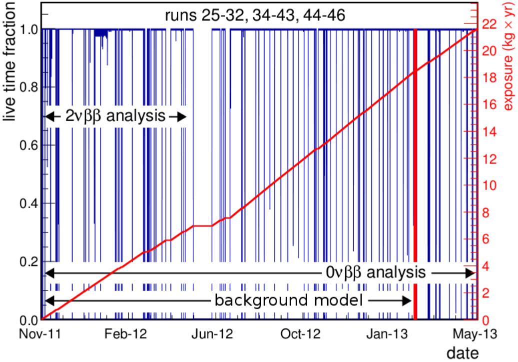


- FWHM from physics runs $\sim 4\%$ larger than expected from calibration data
- exposure weighted FWHM @ $Q_{\beta\beta}$ is:
  1. (4.8 ± 0.2) keV for semi-coaxial
  2. (3.2 ± 0.2) keV for BEGe

Overview of data taking and publications

duty cycle

- (bi-) weekly calibration with ^{228}Th source → spikes
- in between: Phase I physics measurements



- Run $1 - 24$ for commissioning
- Run 33 not considered
- flat parts: BEGE insertion & maintenance
- total livetime $= 492.3$ days

Overview of data taking and publications

$2\nu\beta\beta$ analysis

- Run 25-32 = exposure of 5.04 kg·yr

J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

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

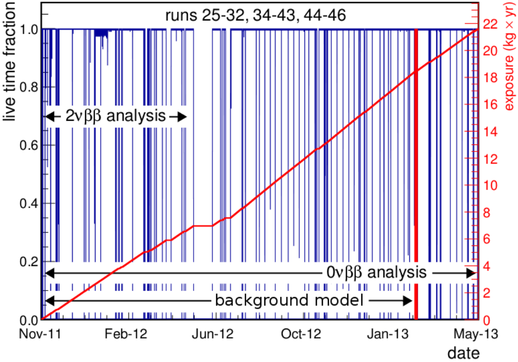
$0\nu\beta\beta\chi$ analysis

- 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



- Run $1 - 24$ for commissioning
- Run 33 not considered
- flat parts: BEGE insertion & maintenance
- total livetime $= 492.3$ days

$T_{1/2}^{2\nu}$ measurement of ^{76}Ge

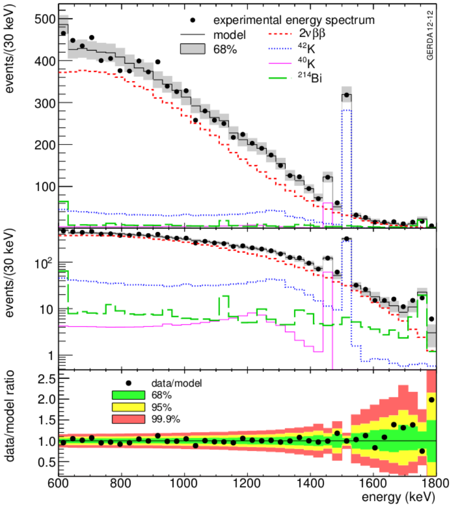
J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

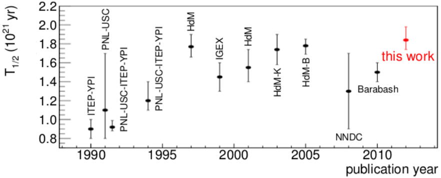
- data sub-set: first 5.04 kg·yr were used to evaluate the half-life of the $2\nu\beta\beta$ decay
- fit window: $(600-1800)$ keV
- binned maximum likelihood approach
- model contains MC spectra of $2\nu\beta\beta$, ^{42}K, ^{40}K, ^{214}Bi

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

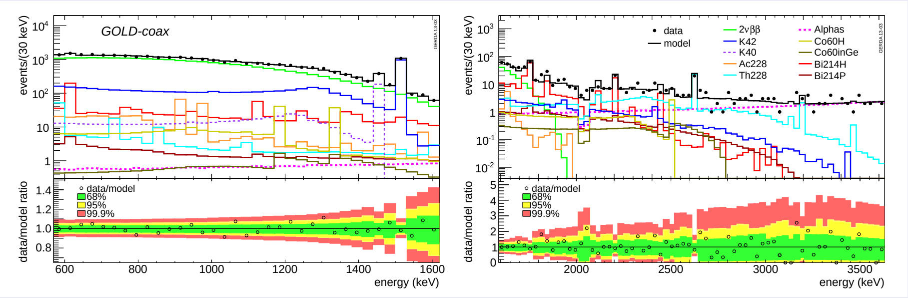
Final result:

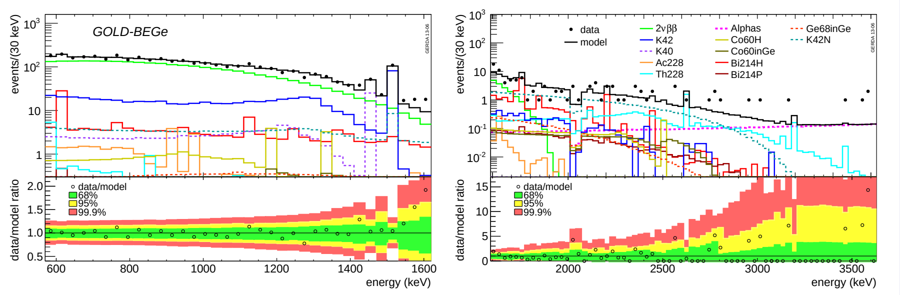
- $T_{1/2}^{2\nu} = 1.84^{+0.14}_{-0.10} \cdot 10^{21}$ yr





Background model: “coax” vs. “BEGe”





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