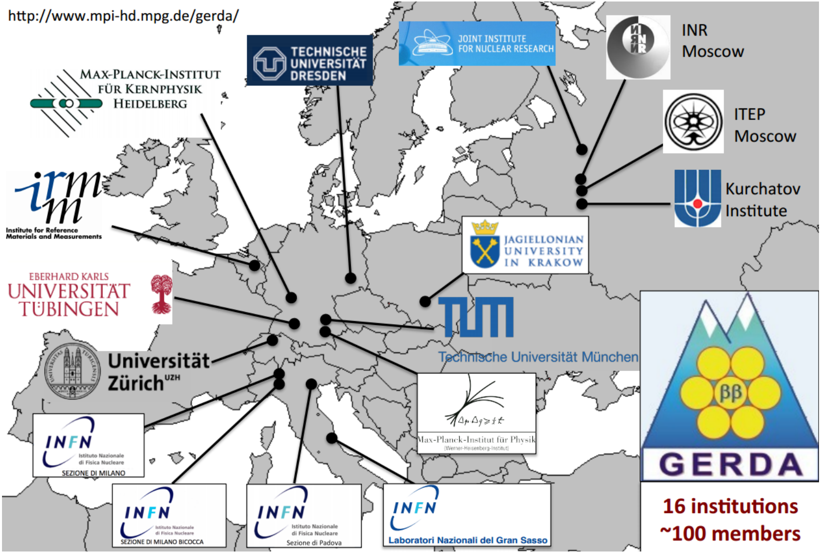
First results from GERDA Phase II

Matteo Agostini on behalf of the GERDA Collaboration

Gran Sasso Science Institute and National Laboratory (GSSI/LNGS), Italy

Neutrino 2016,
4 – 9 July 2016, London, UK

GERDA collaboration



GERDA detection strategy

- Search for neutrinoless double beta decay of ^{76}Ge:

$$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se} + 2e^-$$

$\Rightarrow$ $\boxed{\Delta L = 2}$ $\Rightarrow$ $\boxed{\text{beyond Standard Model physics}}$

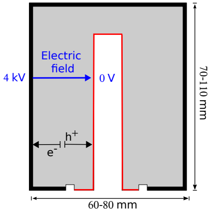
$\Rightarrow$ $\boxed{\text{Majorana mass or other L-violating physics}}$

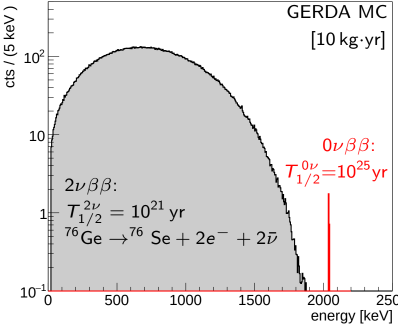
- Q-value of ^{76}Ge: $Q_{\beta\beta}$=2039 keV

- High purity Ge detectors (87% ^{76}Ge):
  - source=detector $\Rightarrow$ high detection efficiency
  - ultra radio-pure $\Rightarrow$ no intrinsic background
  - high density $\Rightarrow$ $0\nu\beta\beta$ point like events
  - semiconductor $\Rightarrow$ $\Delta E \approx 0.2\%$ at $Q_{\beta\beta}$

- $0\nu\beta\beta$ signature:
  - point-like energy deposition in detector bulk volume
  - sharp energy peak at 2039 keV (FWHM = 3-4 keV)

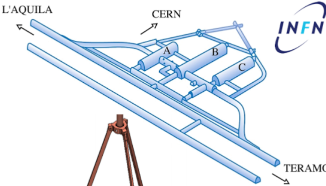
Coaxial geometry (Phase I)

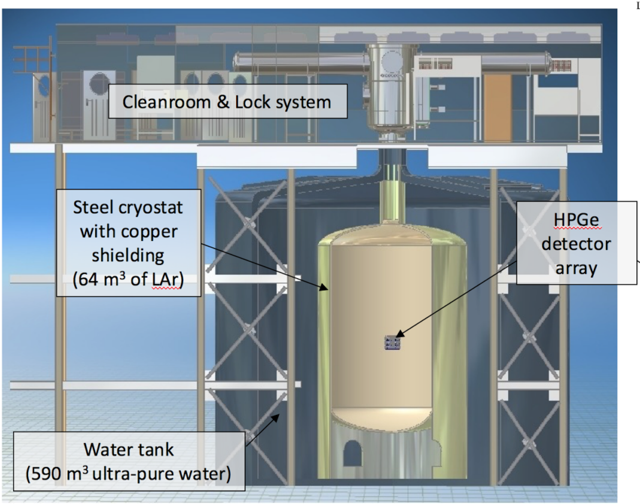


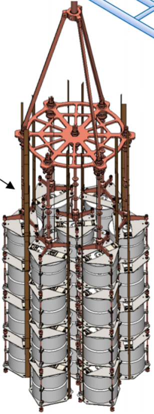


Shielding strategy and apparatus

LNGS (INFN) 3500 m.w.e.

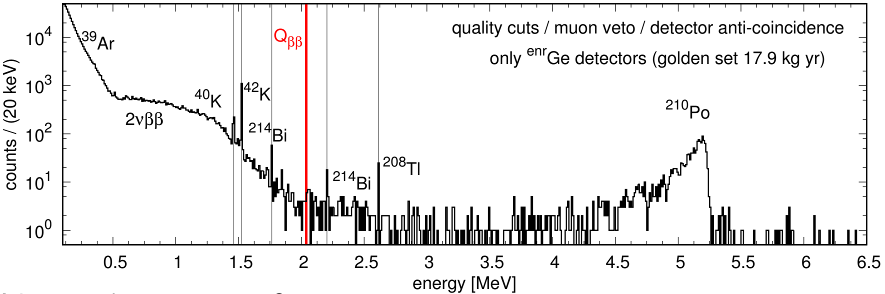






[EPJC 73 (2013) 2330]

Main spectral components in Phase I

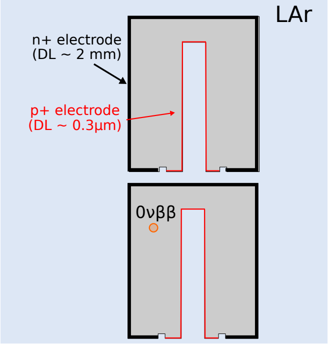


Main spectral components at $Q_{\beta\beta}$:

- γ: ^{208}Tl, ^{214}Bi
- β: ^{42}Ar (cosmogenic)
- α: ^{210}Po surface contamination or ^{222}Rn in LAr

Active suppression techniques:

- AC: detector anti-coincidence
- PSD: pulse shape discrimination
- LAr veto: read-out LAr scintillation light (new in Phase II)



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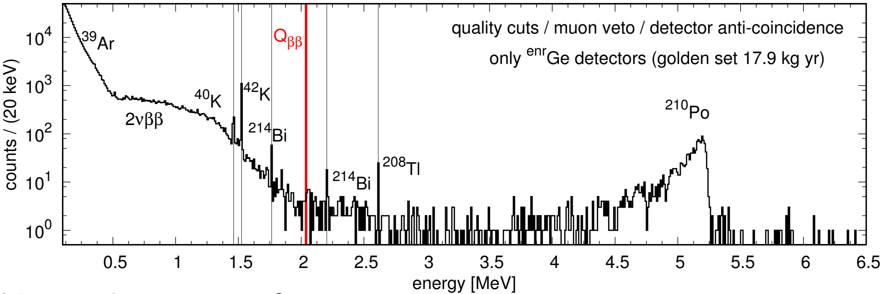

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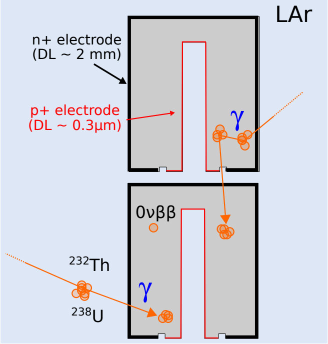

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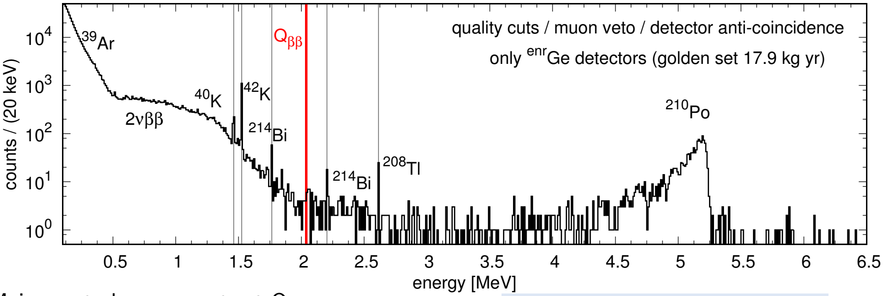

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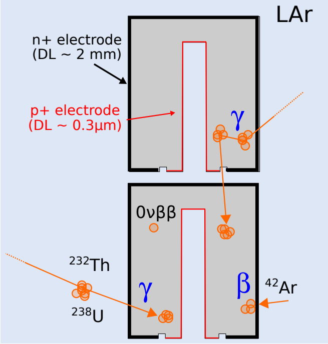

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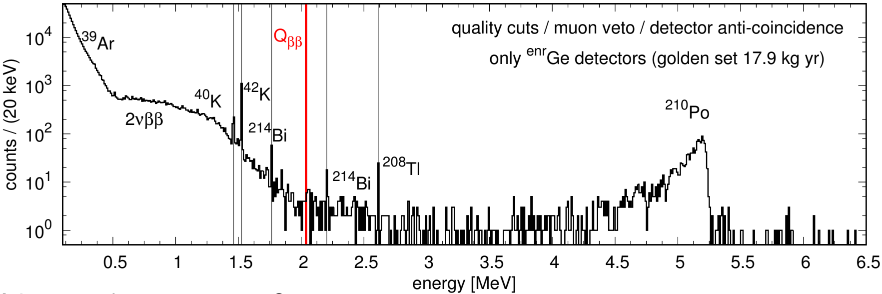

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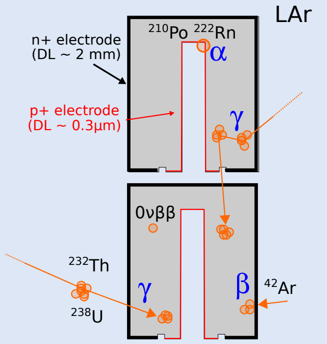
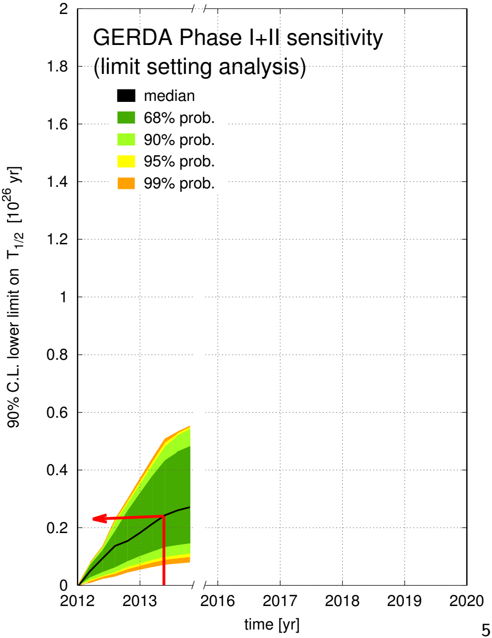


Sensitivity and background



Phase I achievements:	
background	$\sim 10^{-2}$ cts/(keV$\cdot$ kg$\cdot$ yr)
exposure	21.6 kg$\cdot$yr
limit	$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% CL)
	[PRL 111, 122503 (2013)]

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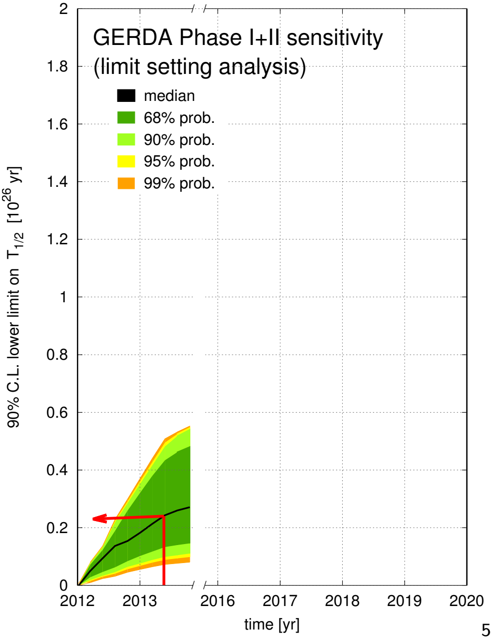

2013 –> 2015: upgrade & commissioning

- doubled target mass
- reduced background by factor ∼10

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Sensitivity and background

Phase II goals	
background	$\sim 10^{-3}$ cts/(keV· kg· yr)
exposure	$\gtrsim 100$ kg·yr
sensitivity	$T_{1/2}^{0\nu} \gtrsim 10^{26}$ yr

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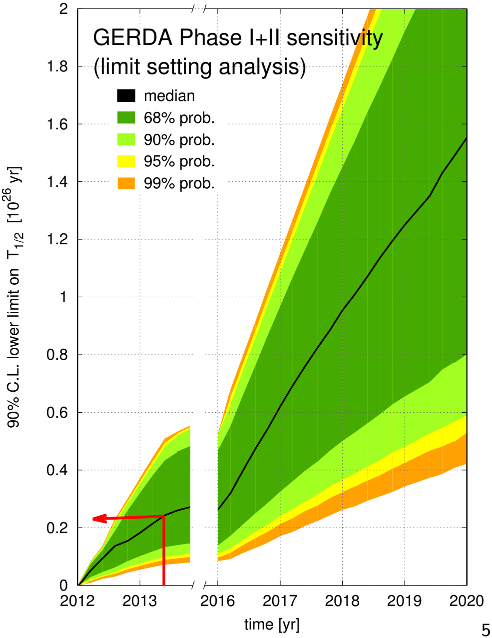

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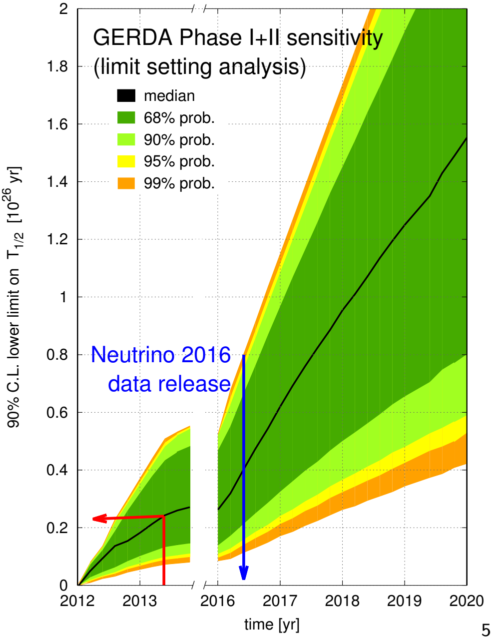
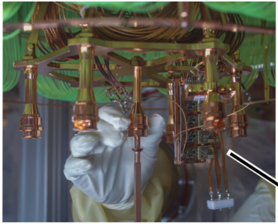
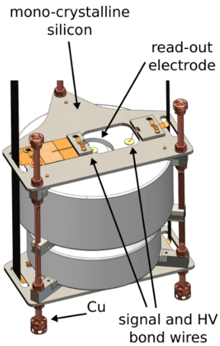
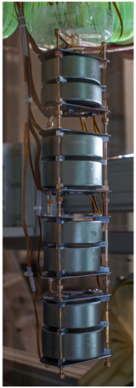


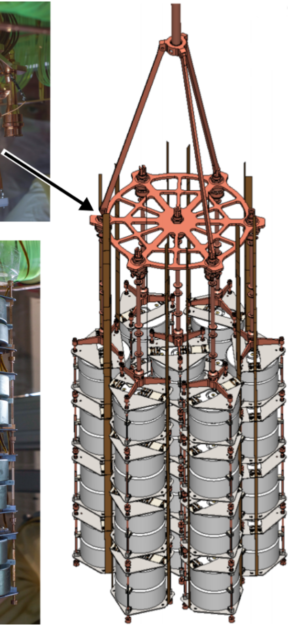
Phase II upgrade: detector array

- produced 30 custom-designed BEGe-type detectors in collaboration with Canberra [EPJC 75 (2015) 39]
- new lower mass holders and contacting solution (wire bonding)
- all BEGe installed in the array (20 kg of target mass)
- new low-mass low-activity electronics and detector-to-FE contacts



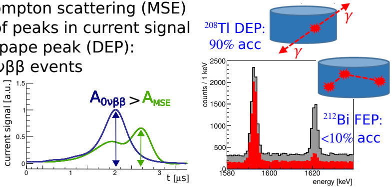


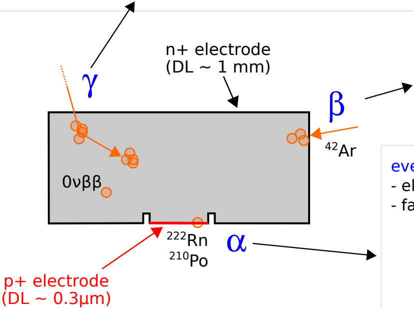




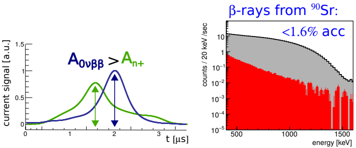
Phase II upgrade: BEGe detectors

γ interactions:
- multiple Compton scattering (MSE)
- sequence of peaks in current signal
- Double escpape peak (DEP): proxy for 0νββ events

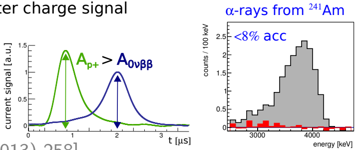




events on n+ surface:
- semiconductor junction -> weak E field
- slow current signal



events on p+ electrode:
- electron drift faster then holes
- faster charge signal



[JINST 6 2011 P03005, JINST 4 2009 P10007, EPJC 73 (2013) 258]

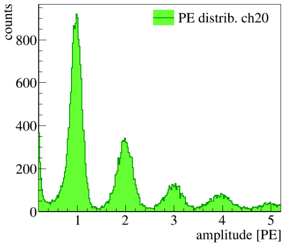
Phase II upgrade: LAr scintillation light veto

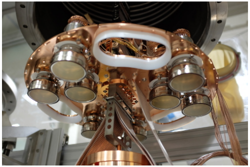
Hybrid veto instrumentation:

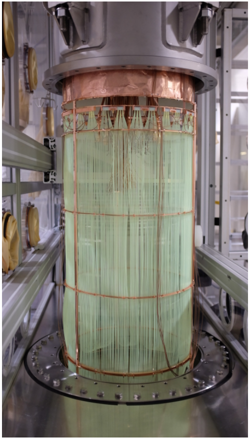
- 16 PMTs (9 top / 7 btm)
- 800 m fibers coated with WLS + 90 SiPMs
- nylon mini-shroud around each string coated with WLS

Parameters optimized for each channel:

- ~0.5 PE threshold
- $\sim 5 - 6\,\mu$s anticoincidence window



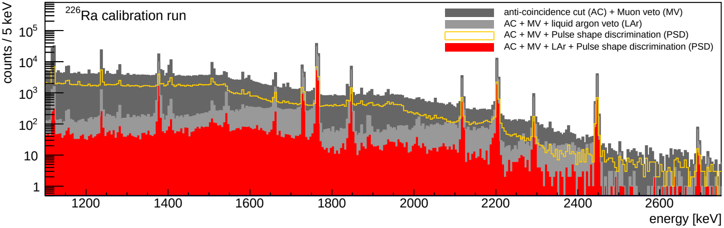


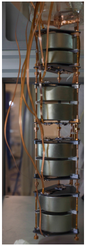


[see poster P4.057]

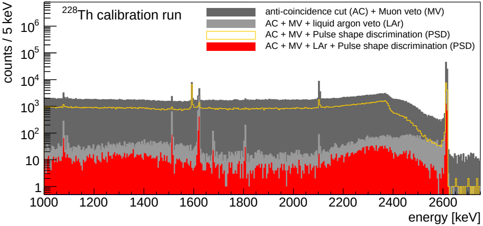
PSD and LAr veto during Phase II commissioning

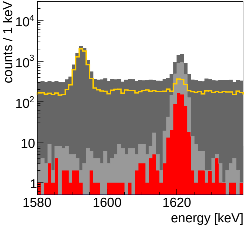
^{226}Ra calibration run (single BEGe string in GERDA):

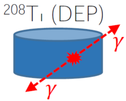


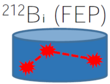


^{228}Th calibration run:









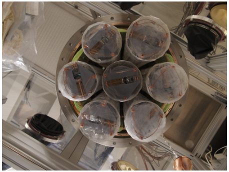
Combined suppression factors: 27±2 (for ^{226}Ra) and 300±28 (for ^{228}Th)

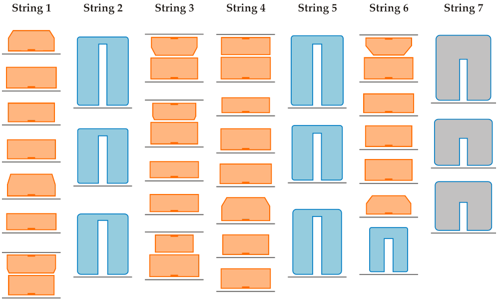
Suppression depends on isotope, location and detector configuration

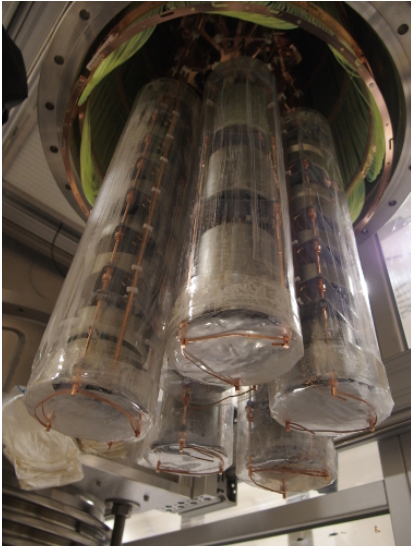
Phase II final array configuration

- Deployed in Dec 2015
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

⇒ 35.8 kg of enr detectors







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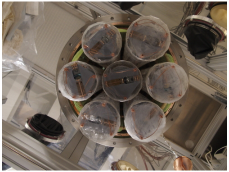
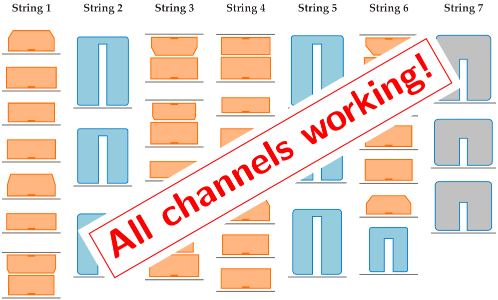
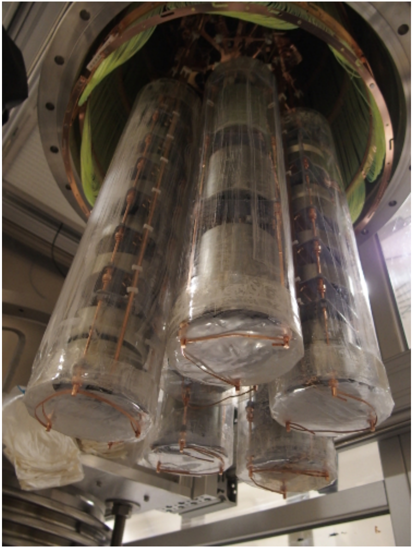




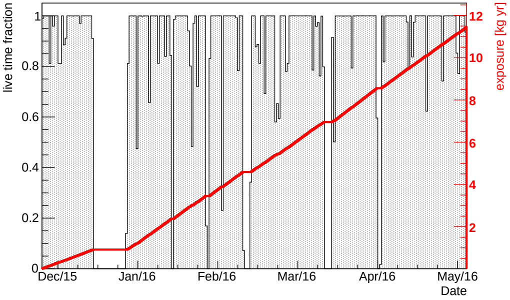


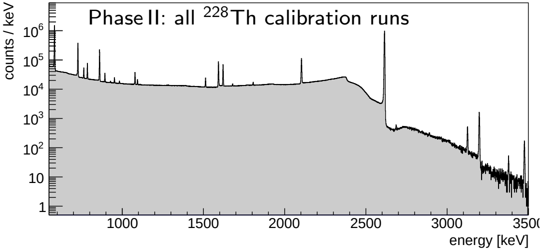
Overview of the data taking

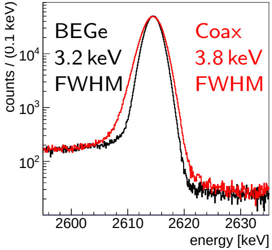
- Dec 2015 - May 2016
- 82% average duty cycle
- exposure used for analysis:

  5.8 kg·yr for enriched BEGe:

  5.0 kg·yr for enriched coax:
- weekly calibration runs with ^{228}Th
- blinding window $Q_{\beta\beta} \pm 25$ keV

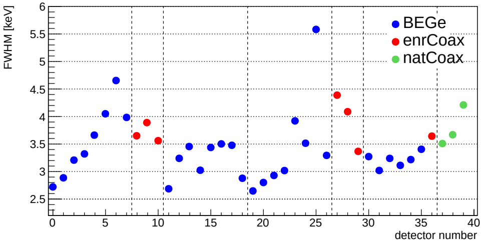


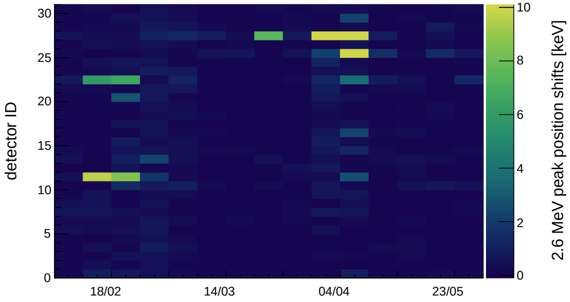




Energy scale and resolution

- energy reconstructed with "zero area cusp" filter [EPJC 75 (2015) 255]
- energy scale monitored with pulser
- $\lesssim$1 keV changes between successive calibrations
- data removed from $0\nu\beta\beta$ analysis if energy scale uncertain



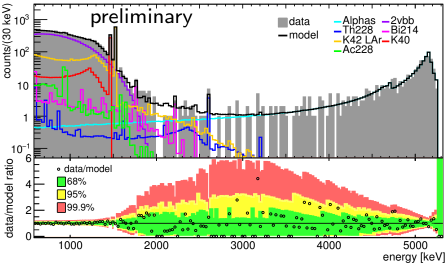


Performance on full physics data set (10.8 kg·yr):

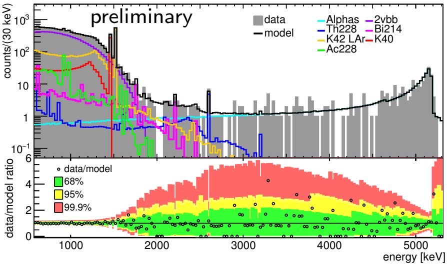
dataset	energy resolution (FWHM at $Q_{\beta\beta}$)
coaxial	4.0 (2) keV
BEGe	3.0 (2) keV

Background modeling before LAr veto and PSD

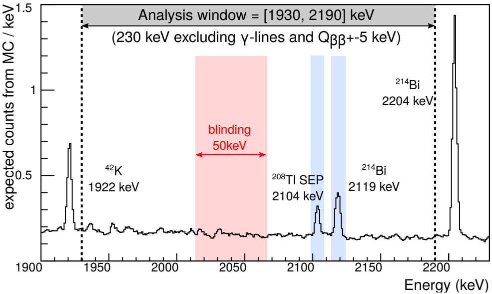
coax: global fit p-value=0.6



BEGe: global fit p-value=0.3

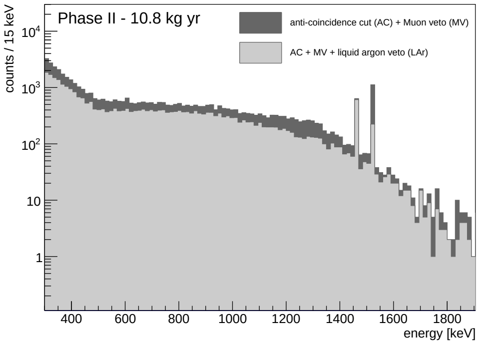


- same isotopes as in Phase I
- Th/Ra contributions consistent with screening results
- main components before LAr veto/PSD:
  - α from ^{210}Po,^{226}Ra
  - β from ^{42}K
  - γ from ^{214}Bi,^{208}Tl
- flat background in the ROI



[poster P2.009]

LAr veto background suppression

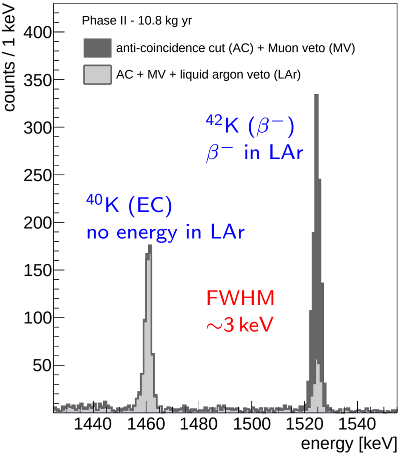


- ^{40}K/^{42}K Compton continuum fully suppressed
- (70.4±0.3)% survival fraction (0.6-1.3 MeV)
- LAr veto generates 2.3% dead time

γ-lines from:

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar} + \gamma\ (1.4\,\mathrm{MeV})\ [\mathrm{EC}]$$

$$^{42}\mathrm{K} \rightarrow {}^{42}\mathrm{Ca} + \gamma\ (1.5\,\mathrm{MeV}) + e^-\ (\text{up to } 2\,\mathrm{MeV})$$



[see poster P4.057]

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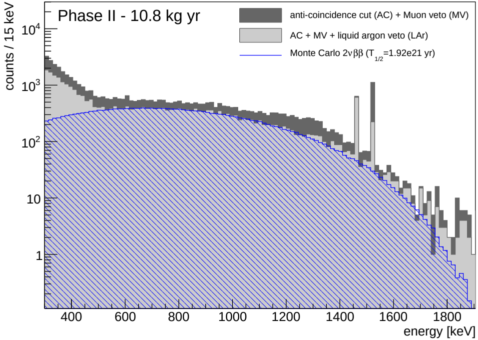

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- (70.4±0.3)% survival fraction (0.6-1.3 MeV)
- LAr veto generates 2.3% dead time
- $T^{2\nu}_{1/2} = 1.9 \cdot 10^{21}$ yr taken from Phase I
  [EPJC 75 (2015) 416]

[see poster P4.057]

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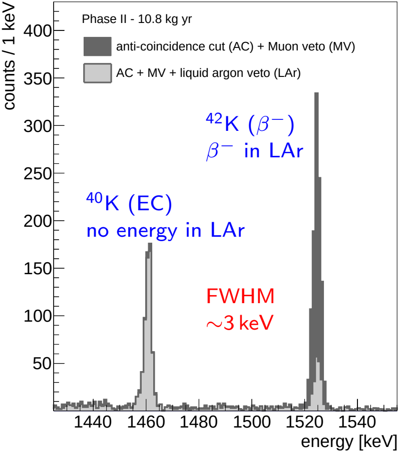


PSD for Coaxial detectors

Multiple site event suppressions:

- as in Phase I [EPJC 73 (2013) 10]
- two methods for cross check:
  - artificial neural network
  - projective Likelihood
- tuned with calibration data
- $\epsilon^{MSE}_{coax} = (80 \pm 9)\%$ $0\nu\beta\beta$ acceptance (preliminary, error bar will be reduced)

α-event suppressions (new!):

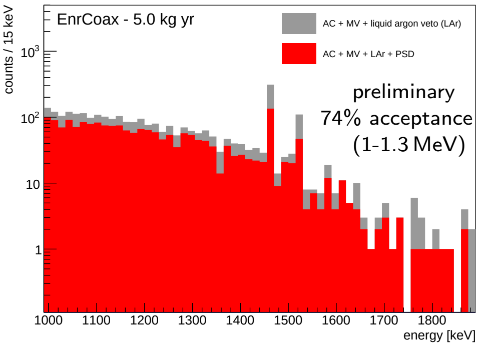
- artificial neural network
- test/train sample from data
- $\epsilon^{\alpha}_{coax} = (96 \pm 1)\%$ $0\nu\beta\beta$ acceptance

Combined $0\nu\beta\beta$ acceptance:

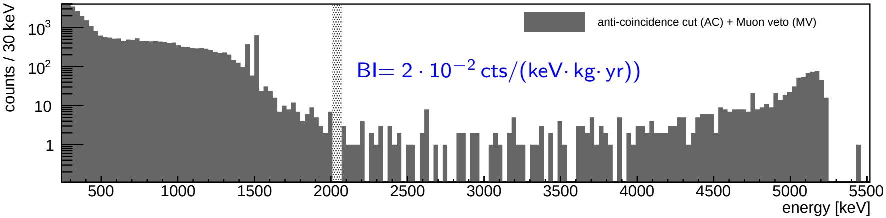
$$\boxed{\epsilon^{PSD}_{coax} = \epsilon^{MSE}_{coax} \cdot \epsilon^{\alpha}_{coax} = (77 \pm 9)\%}$$

(preliminary, to be finalized)

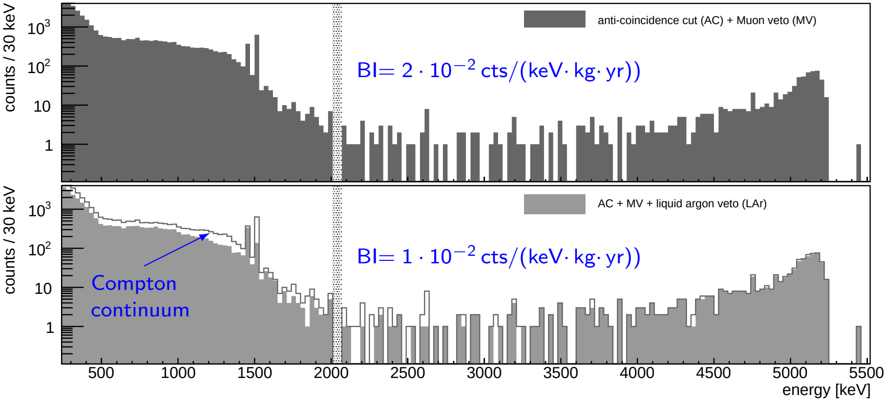
Cross check at lower energy with $2\nu\beta\beta$ events (after LAr veto):



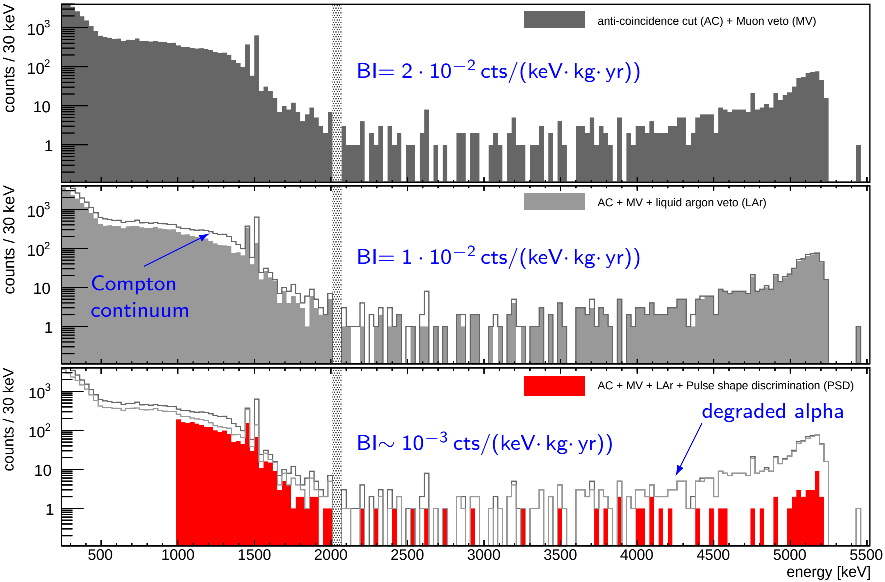
Coaxial detectors: background suppression



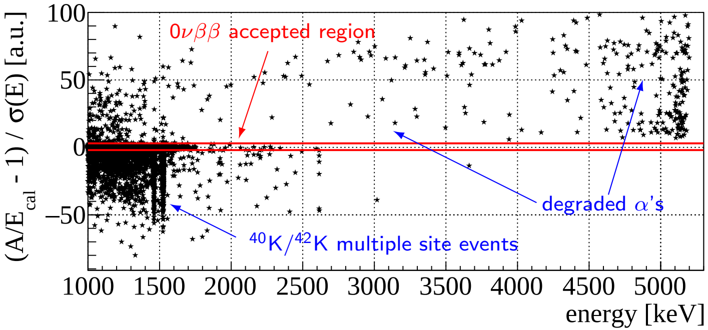
Coaxial detectors: background suppression



Coaxial detectors: background suppression



PSD for BEGe detectors



Event-by-event discrimination:

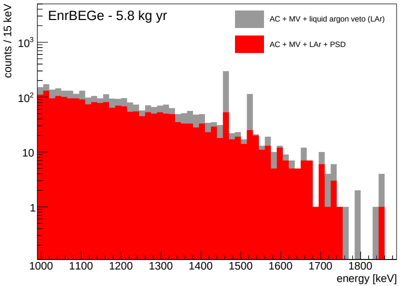
above red band:
events on p+ electrode
e.g. α's from ^{210}Po

below red band:
events on n+ electrode
multiple γ scattering

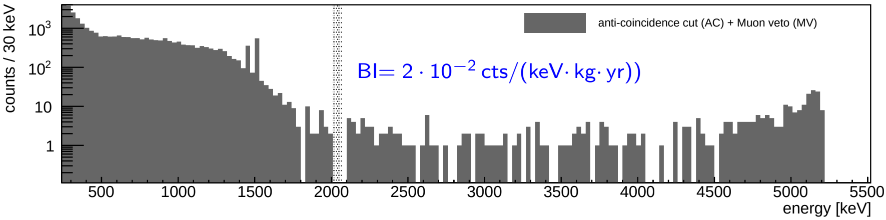
$0\nu\beta\beta$ acceptance from ^{228}Th calibrations (DEP):

$$\boxed{\epsilon^{PSD}_{BEGe} = (87.3 \pm 0.9)\%}$$

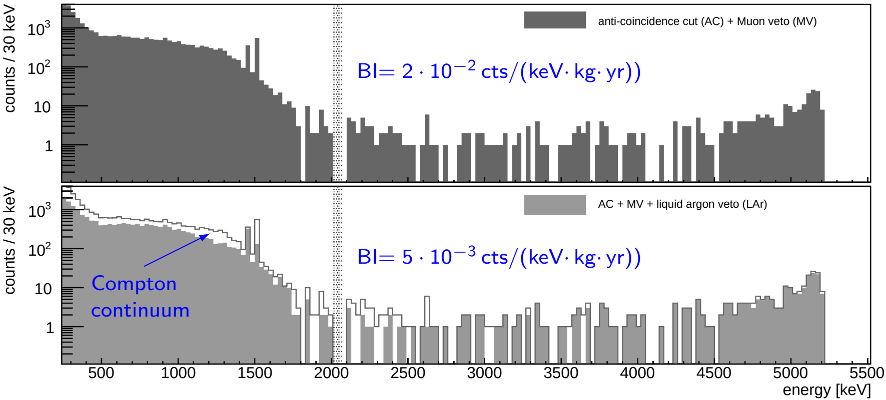
Cross check at lower energy with $2\nu\beta\beta$ LAr cut (1-1.3 MeV): $(85.4^{+1.9}_{-0.8})\%$



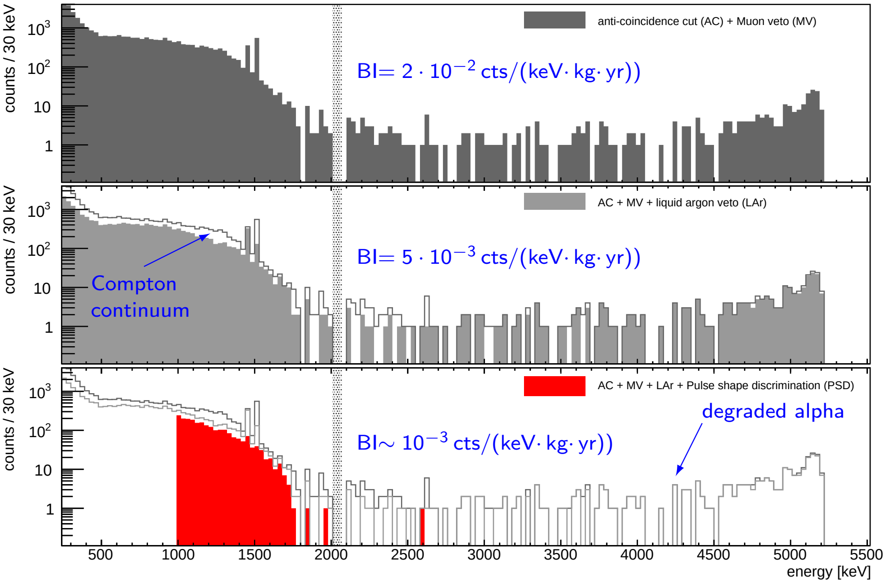
Background suppression - BEGe



Background suppression - BEGe



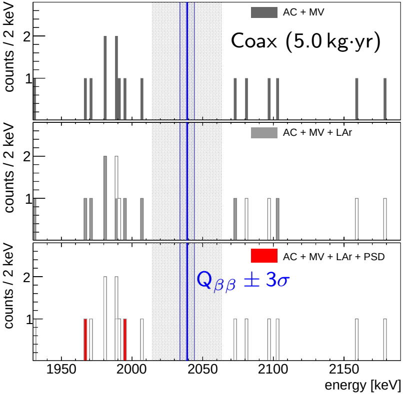
Background suppression - BEGe

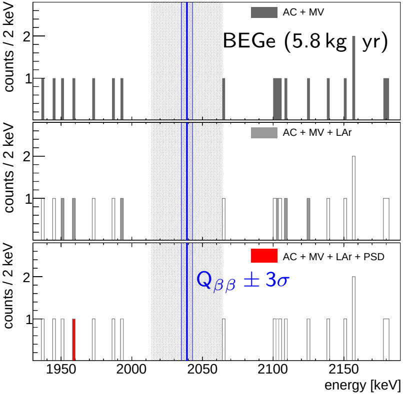


Unblinding

Collaboration meeting, Jun 17, 2016: unblinding data in $Q_{\beta\beta} \pm 25\,\mathrm{keV}$

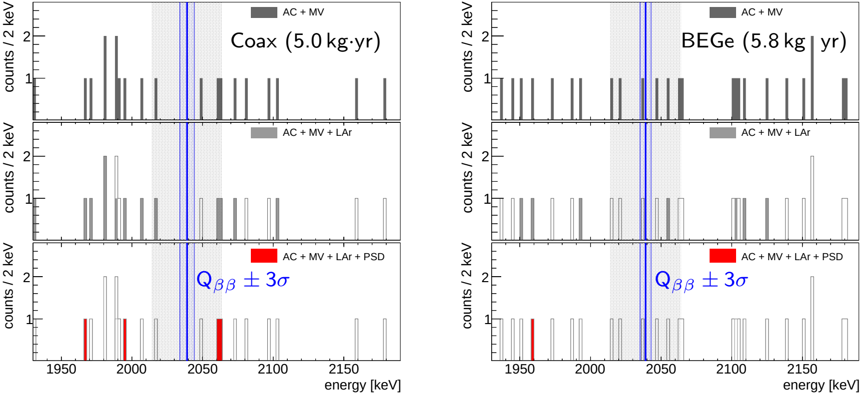
Unblinding: spectrum around $Q_{\beta\beta}$





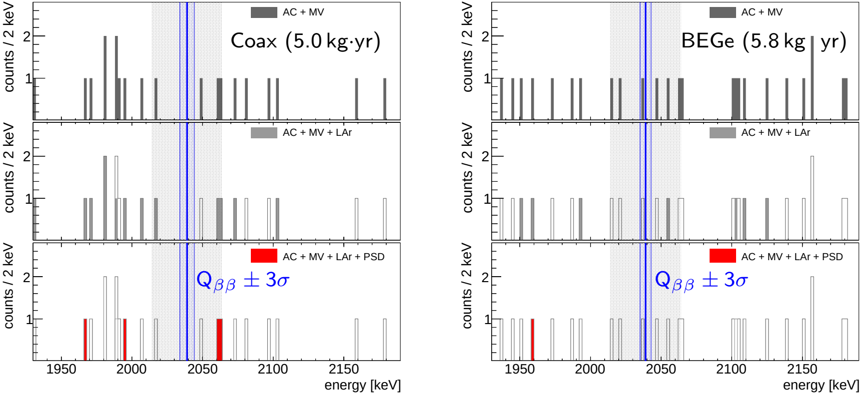
		Coax	BEGe
cts expected from bkg	$Q_{\beta\beta}\pm25$ keV	0.8	0.3
	1930-2190 keV	3.6	1.2

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



		Coax	BEGe
cts expected from bkg	$Q_{\beta\beta}$±25 keV	0.8	0.3
	1930-2190 keV	3.6	1.2
cts observed	$Q_{\beta\beta}$±25 keV:	2	0
	1930-2190 keV:	4	1

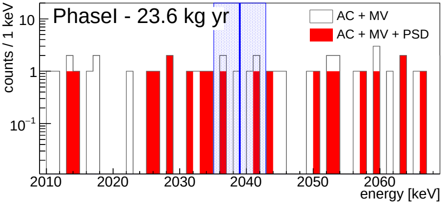
Unblinding: spectrum around $Q_{\beta\beta}$

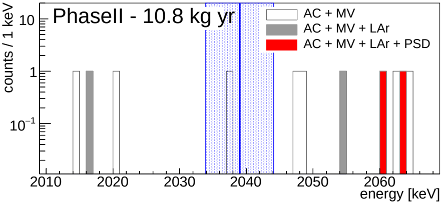


		Coax	BEGe
cts expected from bkg	$Q_{\beta\beta}\pm$25 keV	0.8	0.3
	1930-2190 keV	3.6	1.2
cts observed	$Q_{\beta\beta}\pm$25 keV:	2	0
	1930-2190 keV:	4	1
background index	1930-2190 keV	$35^{+21}_{-15} \cdot 10^{-4}$	$7^{+11}_{-5} \cdot 10^{-4}$

[cts/(keV· kg· yr)]

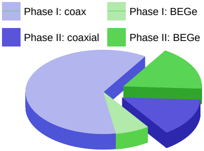
Statistical analysis



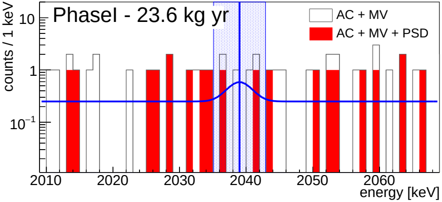


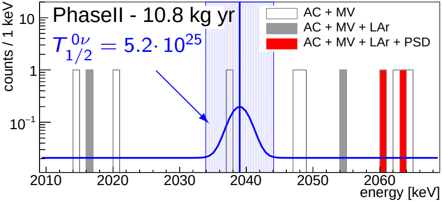
data set		exposure [kg·yr]	signal eff	background [cts/(keV· kg· yr)]	resolution [FWHM]
Phase I	golden	17.9	0.57 (3)	$11 \pm 2 \cdot 10^{-3}$	4.3 (1)
Phase I	silver	1.3	0.57 (3)	$30 \pm 10 \cdot 10^{-3}$	4.3 (1)
Phase I	BEGe	2.4	0.66 (2)	$5^{+4}_{-3} \cdot 10^{-3}$	2.7 (2)
Phase I	extra	1.9	0.58 (4)	$5^{+4}_{-3} \cdot 10^{-3}$	4.2 (2)
Phase II	coaxial	5.0	0.51 (7)	$35^{+21}_{-15} \cdot 10^{-4}$	4.0 (2)
Phase II	BEGe	5.8	0.60 (2)	$7^{+11}_{-5} \cdot 10^{-4}$	3.0 (2)

- Phase I improved res with new reconstruction [EPJC 75 (2015) 255]
- "Phase I extra" has been unblinded together with Phase II data sets



Statistical analysis





	profile likelihood 2-side test-stat	Bayesian flat prior on cts
$0\nu\beta\beta$ cts best fit value [cts]	0	0
$T^{0\nu}_{1/2}$ lower limit [10^{25} yr]	>5.2 (90% CL)	>3.5 (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity [10^{25} yr]	>4.0 (90% CL)	>3.0 (90% CI)

preliminary!

- unbinned profile likelihood: flat background (1930-2190 keV) + Gaussian signal
- frequentist test-statistics and methods *Cowan et al.*, EPJC 71 (2011) 1554
- ϵ^{PSD}_{coax} to be finalized

Conclusions and prospects

- GERDA Phase II is running stable
- 3-4 keV energy resolution at $Q_{\beta\beta}$
- lowest background in ROI ever achieved:

$35^{+21}_{-15} \cdot 10^{-4}$ cts/(keV$\cdot$ kg$\cdot$ yr) for Coax

$7^{+11}_{-5} \cdot 10^{-4}$ cts/(keV$\cdot$ kg$\cdot$ yr) for BEGe

- combined Phase I+II sensitivity:

$$T^{0\nu}_{1/2} > 4.0 \cdot 10^{25}\ \text{yr (90\% C.L.)}^*$$

- blind analysis, no $0\nu\beta\beta$ signal:

$$T^{0\nu}_{1/2} > 5.2 \cdot 10^{25}\ \text{yr (90\% C.L.)}^*$$

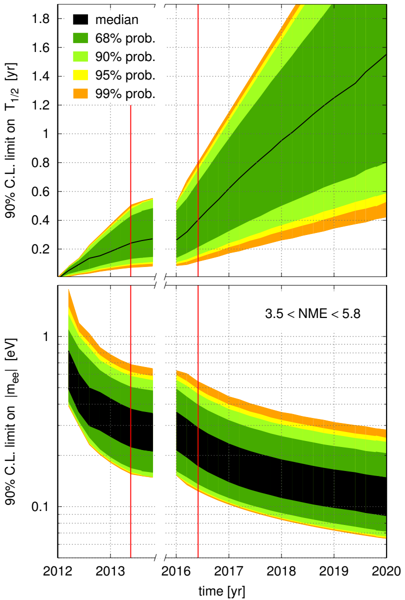
$$|m_{ee}| < [160,260]\ \text{meV (90\% C.L.)}^*$$

($*$ preliminary, ϵ^{PSD}_{coax} to be finalized)

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

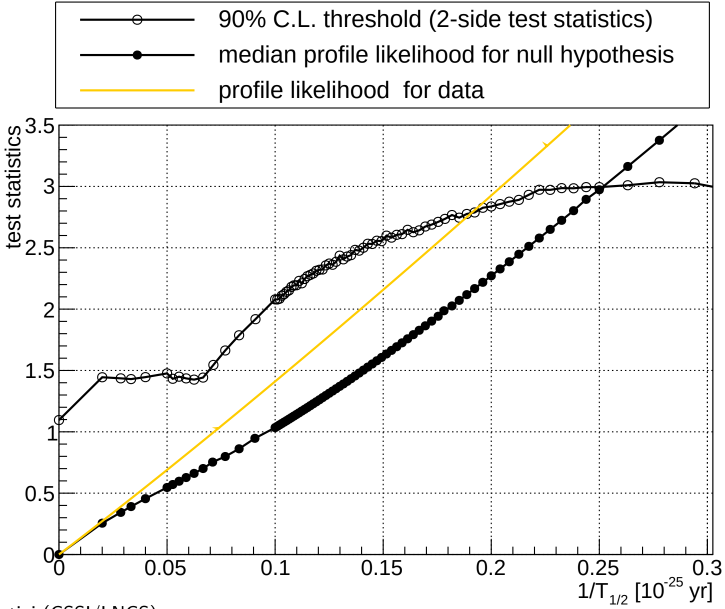
[see poster on next gen ^{76}Ge exp: P4.057]

Based on current BI and duty cycle:

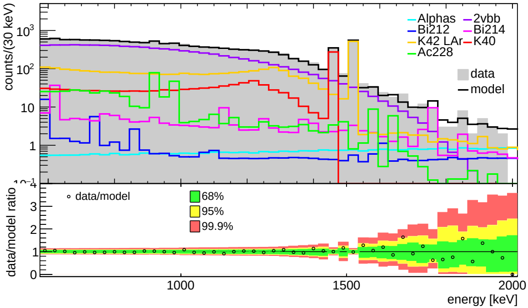


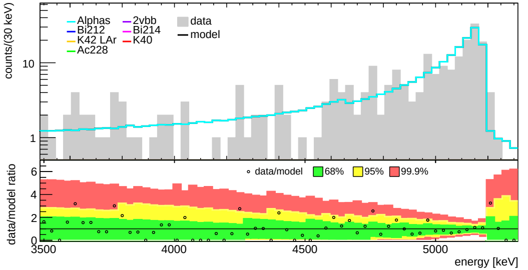
backup slides

Profile likelihood (2-side test statistics)

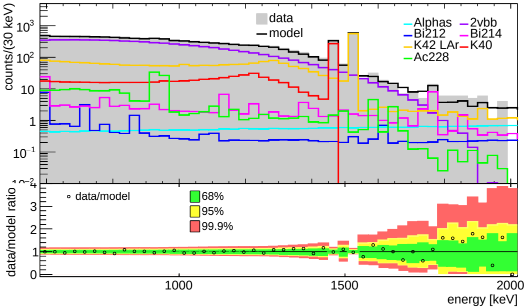


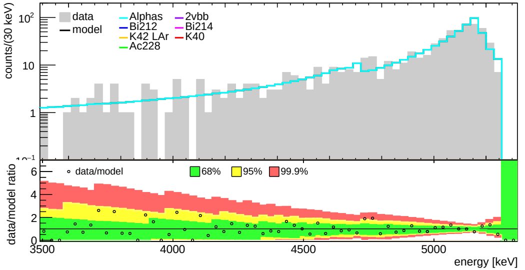
Preliminary background model BEGe Phase II





Preliminary background model Coax Phase II

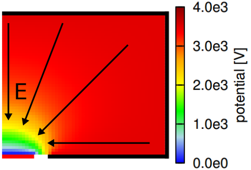




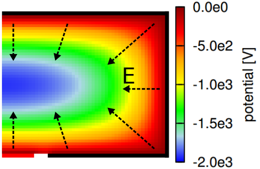
Electric field and charge collection

Contributions to the electric field (E):

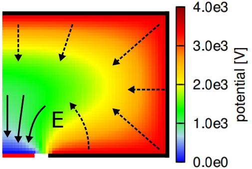
1) electrodes potentials:
$\phi_{p+} = 0\,\mathrm{V}$, $\phi_{n+} = 4\,\mathrm{kV}$



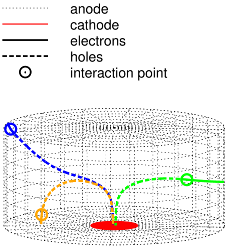
2) impurity concentration: negative charges for depleted p-type Ge



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**:

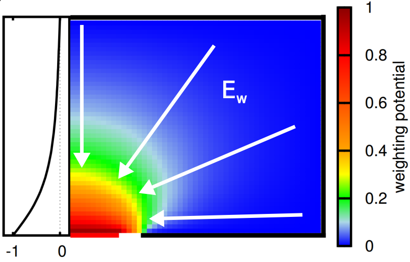


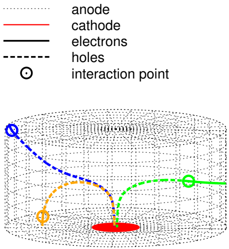
final part of hole trajectories independent of interaction positions

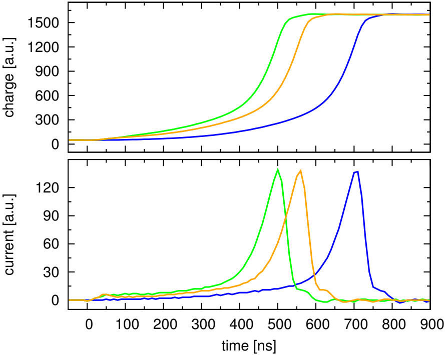
[JINST 6 (2011) P03005]

Signal formation and development

- the weighting potential (ϕ_w) has a strong gradient next to the p+ electrode
- signal induced: $Q(\vec{r}(t)) = -q_{tot}\,\phi_w(\vec{r}(t))$
- weak electron contribution
- holes drift toward the p+ electrode creates a peak in the current signal

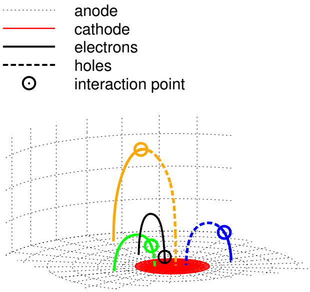


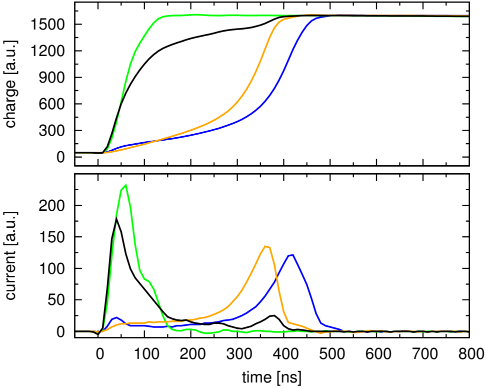




funnel effect + peaked weighting field —> **"reference" pulse shape**

Charge collection in the p+ electrode region





- both electrons and holes drift through the region of strong E_W
- signal given by the sum of the two contributions
- current signal shorter and higher