The search for neutrinoless double beta decay ($0\nu\beta\beta$) with GERDA

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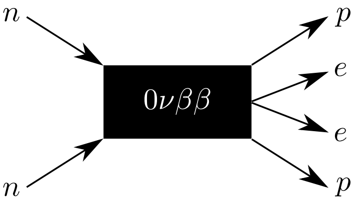
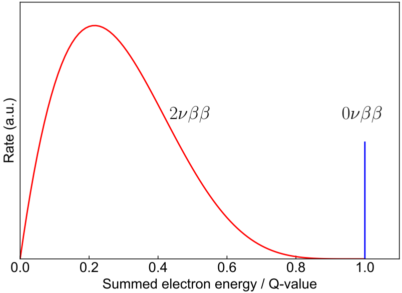
4th September 2018

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

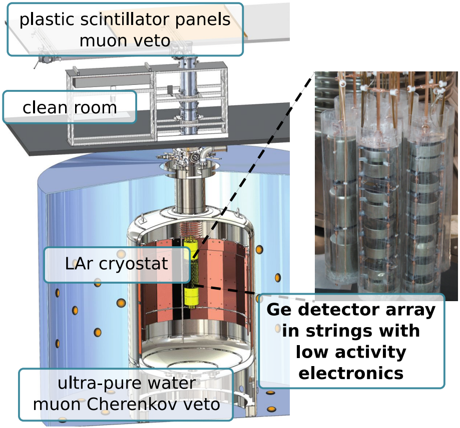




- Would demonstrate Majorana nature of neutrino
- Hypothetical lepton number violating process
- Allowed for some nuclei with $2\nu\beta\beta$ decay
- Signature in calorimeters would be peak in electron spectrum at $Q_{\beta\beta}$

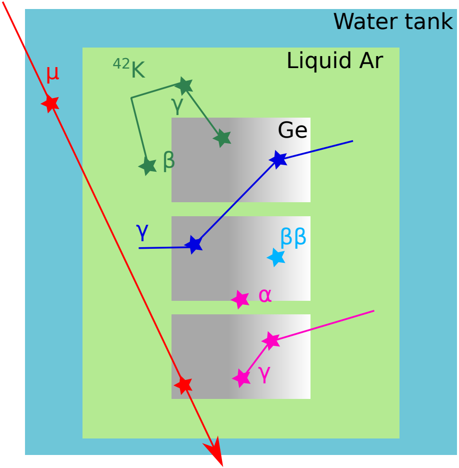
Searching for $0\nu\beta\beta$ with GERDA

- GERDA searches for $0\nu\beta\beta$ of ^{76}Ge at LNGS
- Diodes isotopically enriched up to 88%, act as both source and detector
- 36 kg enriched detectors, two types: Coaxial/BEGe
- Operated in LAr $\rightarrow$ scintillation light as veto



Nature 554 (2017):	10.8 kg· yr
PRL 120 (2018):	23.2 kg· yr
June 2018:	58.9 kg· yr

Background reduction techniques



- Signal! Single-site event
- Cherenkov water veto for muons
- LAr scintillation veto for γ, β
- Detector anti-coincidence cut
- Pulse shape discrimination (PSD) for multi-site and surface α events

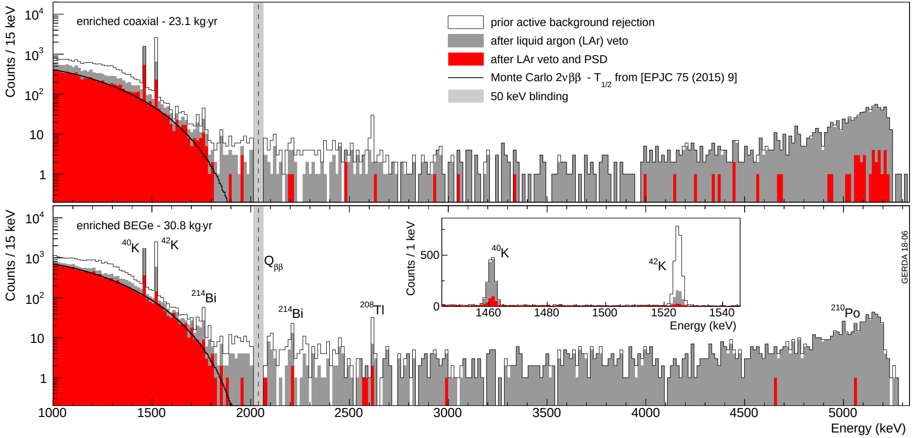
Background index at $Q_{\beta\beta}$:

Coax: $5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)

BEGe: $5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)

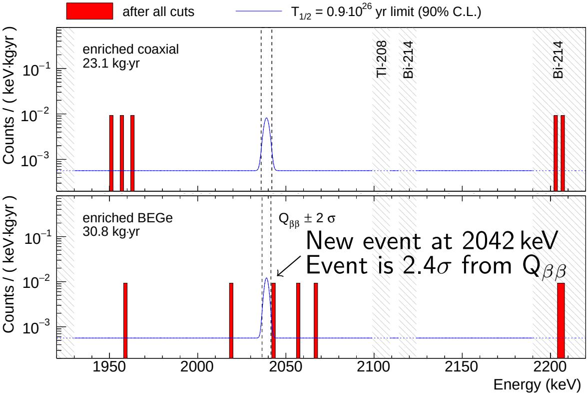
Background-free regime!

Energy spectrum



- After muon veto, detector anti-coincidence cuts
- Compton continuum suppressed
- Remaining features: $2\nu\beta\beta$, ^{40}K, ^{42}K, α

Unblinded spectrum

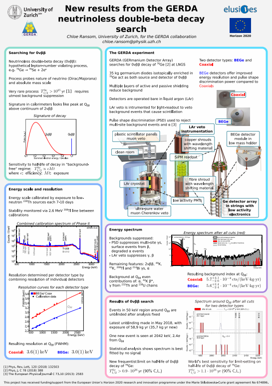


Frequentist analysis

- Exposure 58.9 kg· yr (+23.6 kg· yr Phase I)
- Best fit: no signal
- $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.)
- Sensitivity for limit setting: $1.1 \cdot 10^{26}$ yr (90% C.L.)

Conclusion

- GERDA continues to operate smoothly
- Exposure 58.9 kg$\cdot$ yr (+23.6 kg$\cdot$ yr Phase I), c.f. aim of 100 kg$\cdot$ yr
- New limit on half-life of $0\nu\beta\beta$-decay for ^{76}Ge: $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.)
- World's best sensitivity $> 10^{26}$ yr
- Future: ton-scale experiment, LEGEND



See poster at lunch for more details

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Bonus slides

$0\nu\beta\beta$: isotopes

- Different isotope choice for different experimental approaches
- Various considerations: natural abundance/ enrichment, detector technology, resolution etc.
- If signal, potential complementarity between experiments for determining process mechanism

Isotope	Natural abundance	$Q_{\beta\beta}$ (keV)
^{48}Ca	0.2%	4263
^{76}Ge	7.6%	2039
^{82}Se	9.2%	2998
^{96}Zr	2.8%	3348
^{100}Mo	9.6%	3035
^{116}Cd	7.6%	2813
^{130}Te	34.1%	2527
^{136}Xe	8.9%	2459
^{150}Nd	5.6%	3371

Detecting $0\nu\beta\beta$

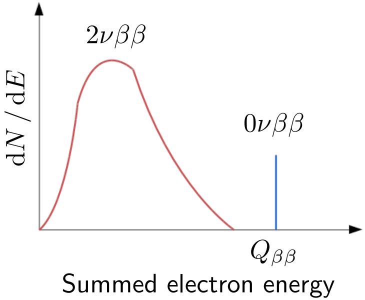
- Signature in calorimeters would be monoenergetic line, $Q_{\beta\beta}$, in energy spectrum of emitted electrons
- Sensitivity to half-life of decay depends on background
- Background limited:

$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{Mt}{BI \cdot \Delta E}}$$

- Background free:

$$T_{1/2}^{0\nu} \propto \epsilon Mt$$

where ϵ: efficiency; Mt: exposure; BI: background events per kg·yr·keV; ΔE: resolution



Detector types

Semi-coaxial Ge detector (Coax)

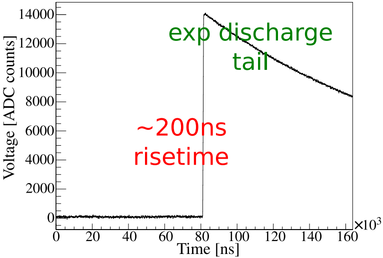
- 7 enriched detectors
- 3 non-enriched detectors
- Total enriched mass 15.6 kg

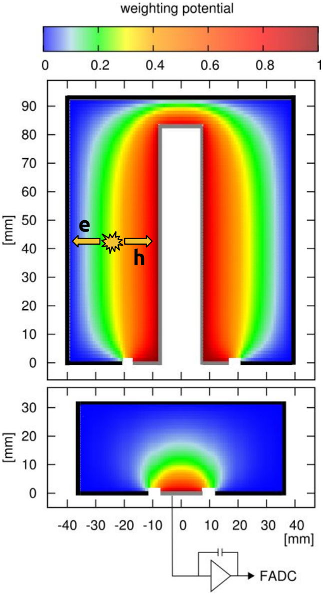
Broad Energy Ge detector (BEGe) [The European Physical Journal C 75.2 (2015): 39.]

- 30 enriched detectors
- Superior pulse shape discrimination (PSD), energy resolution
- Total enriched mass 20.0 kg

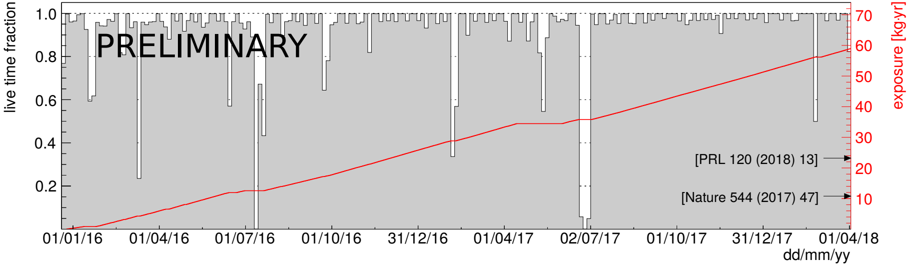
Ge detector signals

- Ionising radiation... ionises!
- Number of charge carriers proportional to energy deposition
- Electron/hole pairs drift in electric field
- Shockley-Ramo theorem gives charge/current at readout electrode
- Different electric field for Coax/BEGe detectors





Data taking



Phase II data taking since December 2015

Events with energy $Q_{\beta\beta}\pm25\,\text{keV}$ 'blinded' before analysis and cuts finalised

June 2016: 10.8 kg· yr ("PhIIa")

- Published in **Nature 554 (2017)**

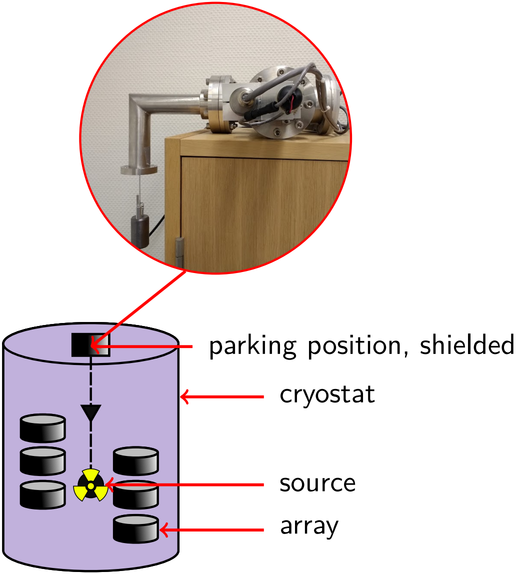
June 2017: 23.2 kg· yr ("PhIIa + PhIIb")

- Published in **PRL 120 (2018)**

June 2018 (this presentation): 58.9 kg· yr

Energy scale calibration

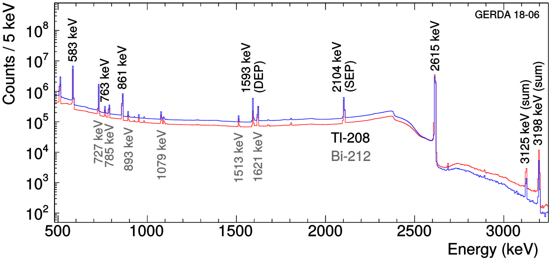
- Knowledge of energy scale, resolution vital for all physics analyses
- Energy scale calibrated by ^{228}Th sources ea. 7-10 days
- Remotely lowered to three positions from above cryostat for $\approx$ 2h $\rightarrow$ all detectors exposed
- Source Insertion System (SIS): two independent measurement systems determine position of source to $\pm 1\,\mathrm{mm}$

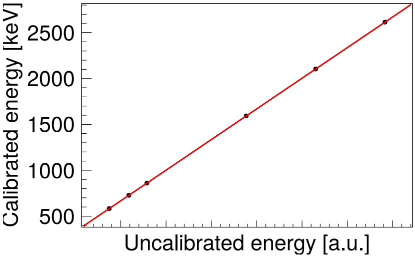


Energy calibration sources

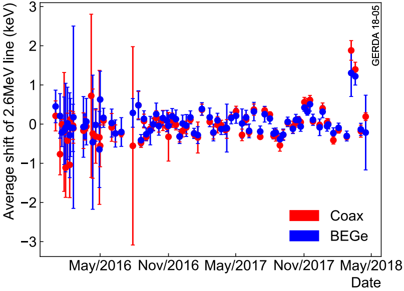
[Journal of Instrumentation 10.12 (2015): P12005.]

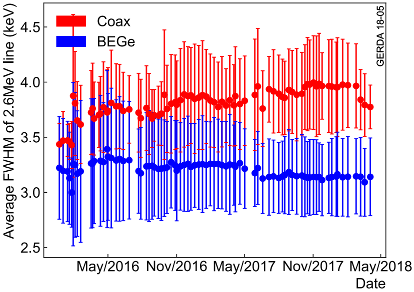
- 3 low neutron emission ^{228}Th sources $\sim 10^{-6}$ n/(s·Bq)
- Half-life 1.9 yr $\rightarrow$ new sources in production
- Strong peaks at 2615 keV, 583 keV, range of peaks between for accurate calibration





Energy scale stability

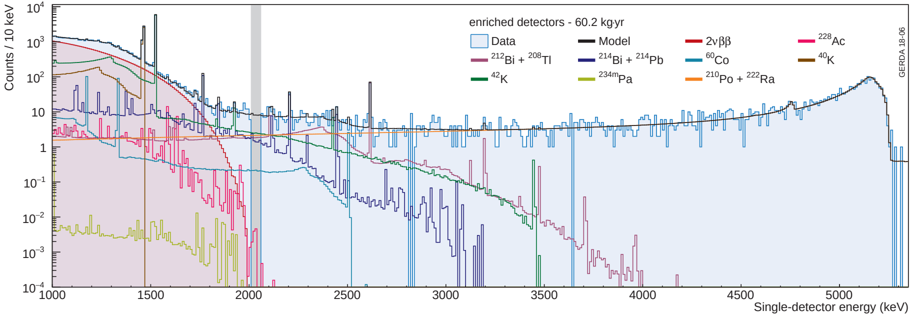




- Stability monitored via 2.6 MeV ^{208}Tl line
- Between calibrations, stability monitored via pulser
- If detector shifts beyond its resolution, excluded from analysis dataset
- Resolution stable for more than two years

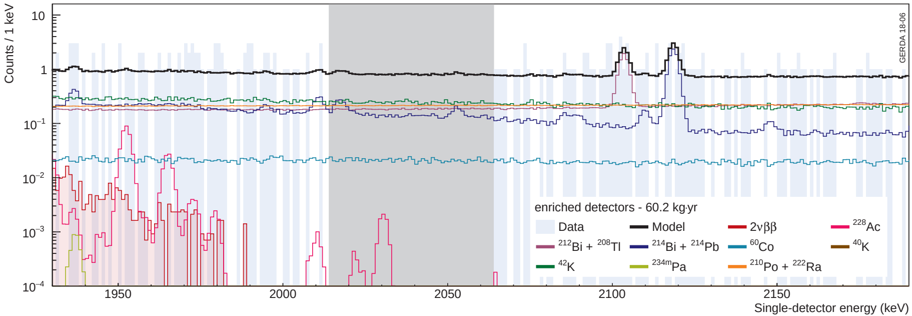
Background model

[The European Physical Journal C 74.4 (2014): 2764.]



- Spectrum before LAr and PSD cuts
- Fitted using screening measurements as priors
- Low energy region dominated by $2\nu\beta\beta$ continuum

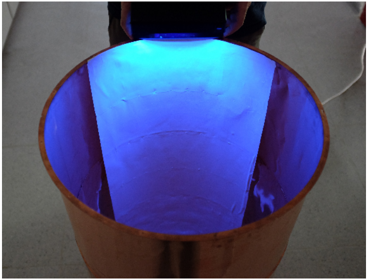
Background model: predictions at $Q_{\beta\beta}$

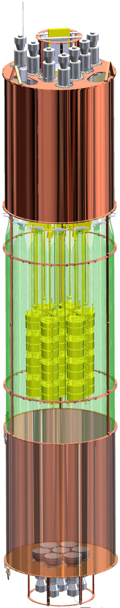


- Predicted flat background in $Q_{\beta\beta}$ region
- Even contributions from α, ^{42}K β^-, γ from ^{232}Th and ^{238}U chains

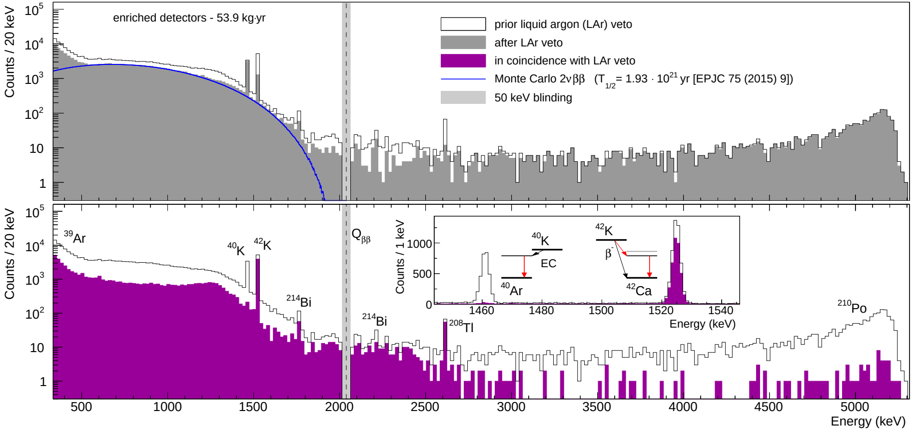
LAr veto

- Background γs and βs deposit energy in LAr $\rightarrow$ scintillation
- Scintillation light wavelength shifted: 128 nm $\rightarrow$ 430 nm
- Light observed by PMTs, SiPMs





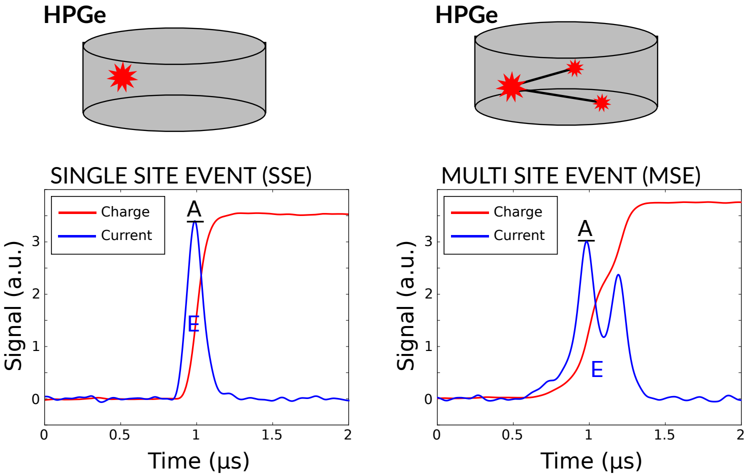
LAr veto: suppression



- Suppression of ^{42}K β peak observed $\rightarrow$ factor of 5 suppression
  [The European Physical Journal C, 78(5), 388]
- Acceptance calculated through pulser events (97.7±0.1)%

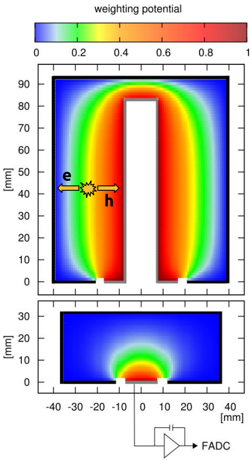
Pulse shape discrimination

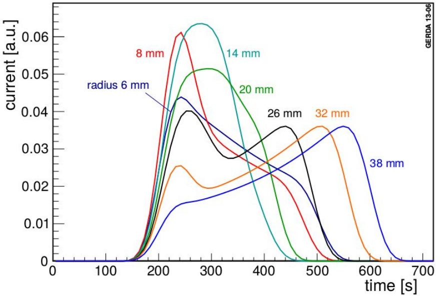
- Reject multi-site events by pulse shape differences
  [The European Physical Journal C 73.10 (2013): 2583.

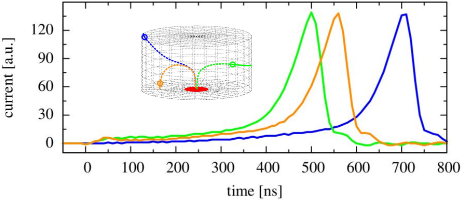


- BEGe: cut on ratio of current amplitude (A) to energy (E)
- Coax: artificial neural network (ANN)

Pulse shape discrimination

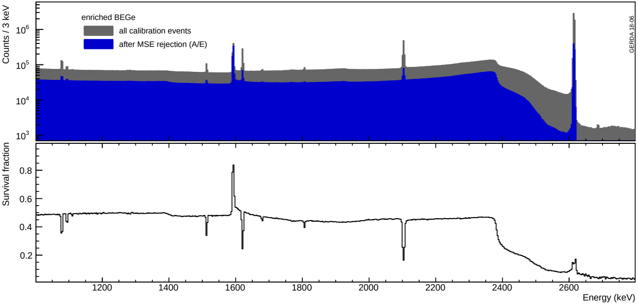


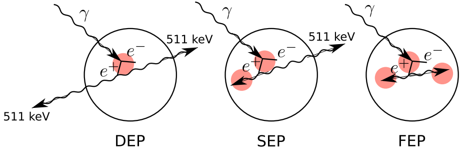




- Coaxials have large p contact $\rightarrow$ uniform field, electrons and holes contribute to signal
- BEGes have point p contact $\rightarrow$ only holes contribute to signal

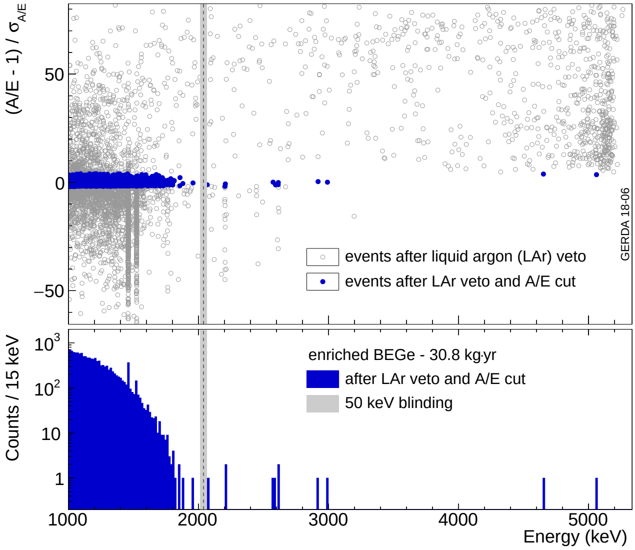
Pulse shape discrimination: calibration





- Double escape peak (DEP) from ^{208}Tl: single-site sample
- Full energy peak (FEP) from ^{212}Bi: multi-site sample
- Cut value at 90% DEP survival for A/E and ANN

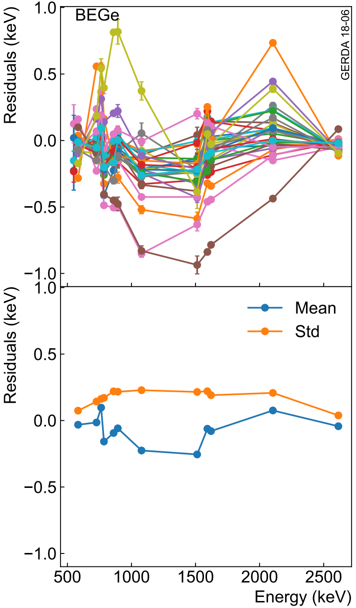
Pulse shape discrimination: suppression



- Both K lines, high energy α events strongly suppressed

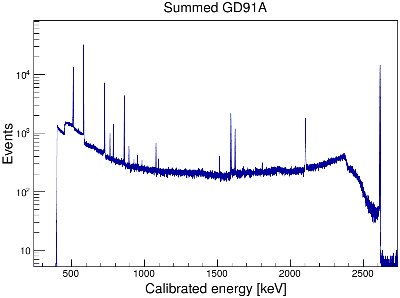
Deviations from linearity

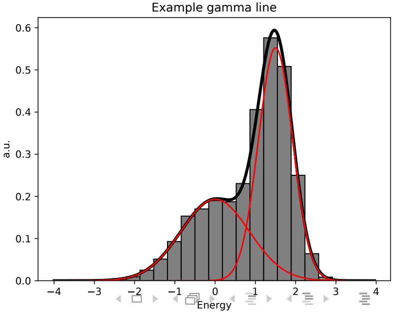
- Combined calibration spectrum tests deviations from linearity: deviation of peak positions from literature positions
- Systematic uncertainty on energy scale: 0.2 keV for BEGe/Coax



Resolution at $Q_{\beta\beta}$: combining detectors

- Knowledge of resolution at $Q_{\beta\beta}$ vital for $0\nu\beta\beta$ analysis
- Detector resolutions measured from combined calibration spectra: best statistics
- Effective dataset resolution combines individual detectors according to individual exposures
- Combination of many Gaussians with negligible offsets: $\mathrm{FWHM}^2 = \frac{1}{\epsilon}\Sigma_i \epsilon_i \mathrm{FWHM}_i^2$ with sum over detectors, ϵ is exposure



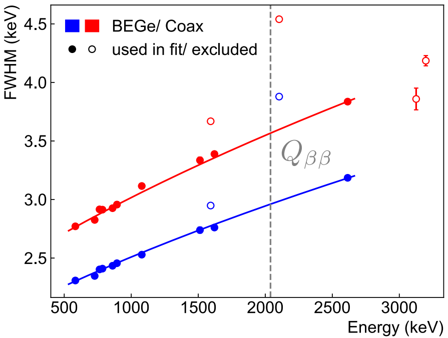


Resolution at $Q_{\beta\beta}$

- Dataset resolution curves are fit:

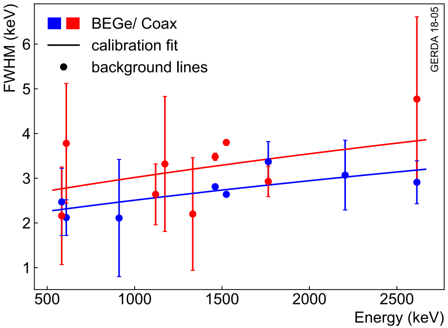
$$\mathrm{FWHM} = \sqrt{A + BE}$$

  where A accounts for electronics noise, B is fluctuations in produced charge carriers
- Some peaks excluded due to topology
- Resolution at $Q_{\beta\beta}$ (preliminary):
  Coax: 3.6(1) keV
  BEGe: 3.0(1) keV

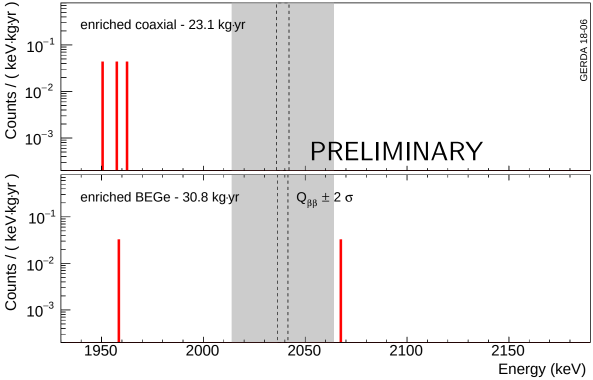


Resolution: cross-check with physics data

- Resolution curve from calibration data cross-checked with resolution of background peaks in physics data
- Previously, statistics too low for many background peaks
- Ad-hoc constant term applied to Coax as a correction for ^{42}K
- Now none, disfavoured by other lines

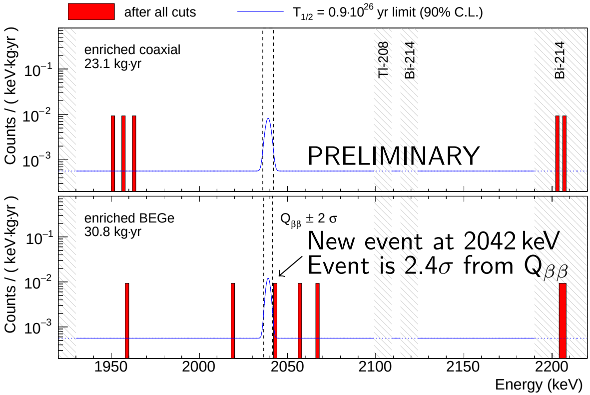


Background index



- Background index determined in region 1930-2190 keV, excluding two known γ lines and $Q_{\beta\beta}\pm5$ keV
- Estimated background index at $Q_{\beta\beta}$ from unblinded region:
  Coax: $0.7^{+0.5}_{-0.3} \cdot 10^{-3}$ cts/(keV·kg· yr)
  BEGe: $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/(keV·kg· yr)
- Sensitivity is not limited by background, but by exposure

Unblinding



Dataset	Background index 10^{-4} cts/(keV·kg·yr) Expected	True	Events in 50 keV Expected	True	Events in $Q_{\beta\beta} \pm 2\sigma$ Expected	True
Coax	7^{+5}_{-3}	$5.7^{+4.1}_{-2.6}$	0.8	0	0.11	0
BEGe	6^{+4}_{-3}	$5.6^{+3.4}_{-2.4}$	0.4	1	0.1	0

Statistical analysis

- Combined fit of Phases I and II
- Flat background + Gaussian signal

Frequentist (preliminary)

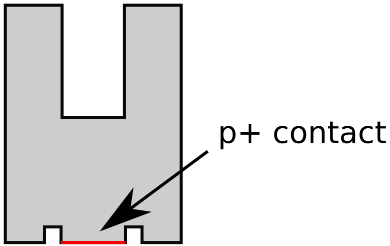
- Sensitivity for limit setting: $1.1 \cdot 10^{26}$ yr (90% C.L.)
- Best fit: no signal
- $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.)

Bayesian (preliminary)

- Sensitivity for limit setting: $8.2 \cdot 10^{25}$ yr (90% C.I.)
- Best fit: background only
- $T^{0\nu}_{1/2} > 7.6 \cdot 10^{25}$ yr (90% C.I.)

GERDA upgrade: new detectors

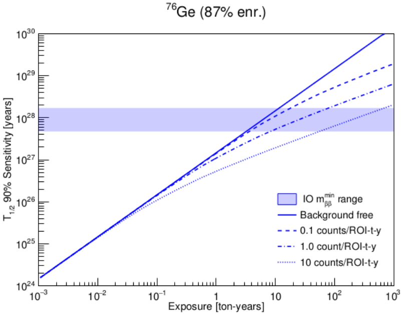
- Upgrade April-May 2018
- 5 new enriched detectors (9.5 kg)
- Inverted Coaxial Point Contact (IC) detectors
- Similar energy resolution and PSD power as BEGe detectors
- Larger mass $\rightarrow$ make up loss in exposure due to upgrade time with mass increase



GERDA upgrade: other activities

- Denser fibre shroud $\rightarrow$ increase in veto efficiency
- Lower activity cables
- JFET repair and exchange $\rightarrow$ improved reliability
- Detector holder modification $\rightarrow$ less ‘dead’ material per Ge mass

LEGEND



- Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay
- Majorana and GERDA collaborations join (among others)
- Aim for discovery potential above 10^{27} yr
- Phased approach, 200 kg $\rightarrow$ 1 t Ge

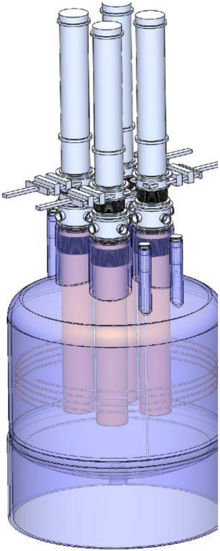
LEGEND

LEGEND-200

- 200 kg stage at LNGS using GERDA cryostat
- Begin operation $\sim$ 2021
- Use IC detectors as tested in GERDA
- Background aim 0.2 cts/(keV·t·yr) $\rightarrow$ 1/5 GERDA Phase II

LEGEND-1T

- Modular approach, deploy 200-250 kg stages

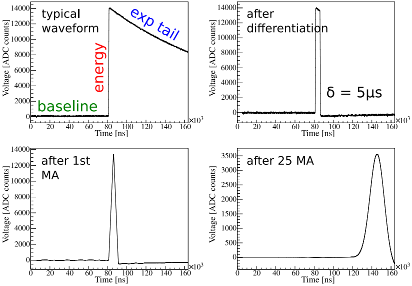


Energy reconstruction

Two main energy filters reconstruct energy: [Physics Procedia 61 (2015) 673]

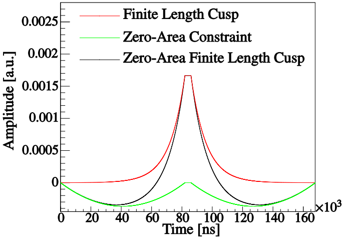
Pseudo-Gaussian:

- 25×5 μs moving average
- Fast, robust → online processing



Zero area cusp (ZAC):

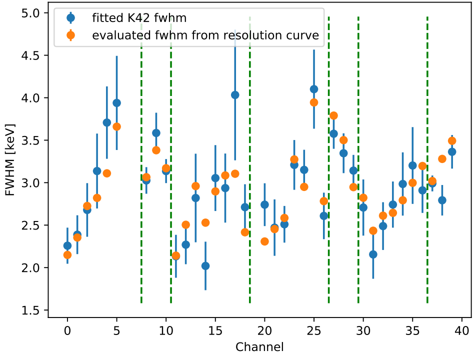
- Finite cusp with zero-area constraint
- Parameters optimised for each detector/calibration
- Improved energy resolution (Coax: 0.2-0.5 keV)
- Used for all final physics analysis

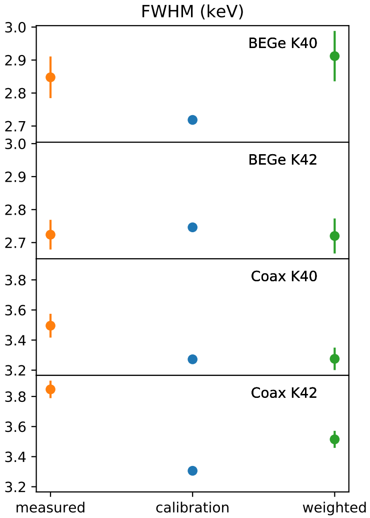


In both cases, extracted energy observable is height of filtered signal

K lines comparison

- Discrepancy in K lines resolution partially due to inhomogeneous exposure of detectors





Checking of event 3 keV from $Q_{\beta\beta}$

- Waveform checked by eye
- Detector stable in energy and resolution at time of event
- No significant deviations from linearity observed