The GERDA Experiment for the Search of Neutrinoless Double Beta Decay:

Phase I Results and Phase II Upgrades

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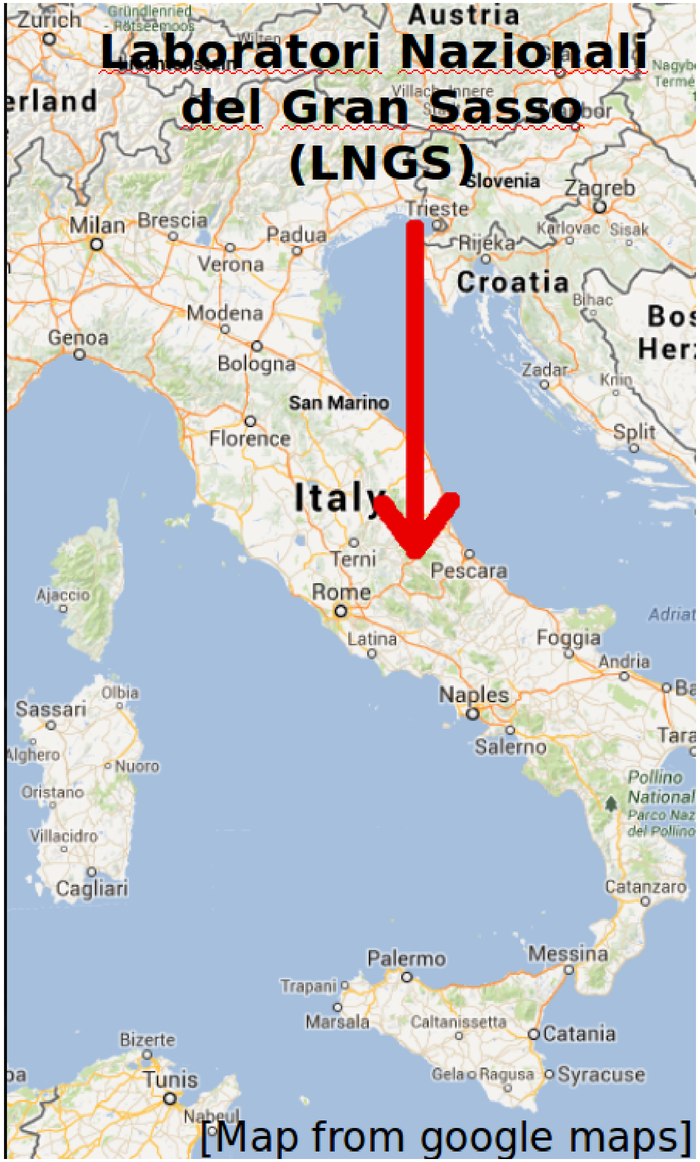
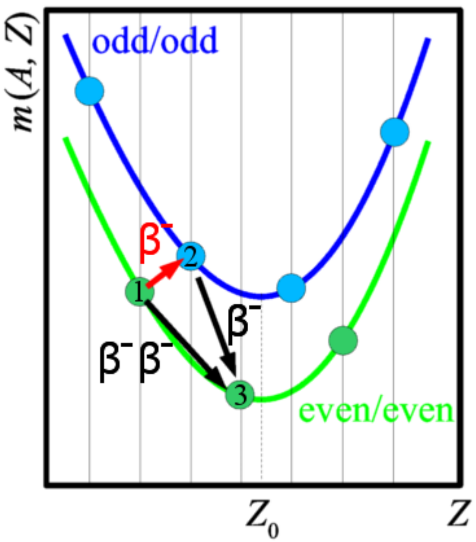
Rencontres de Blois, 31. May - 5. June 2015

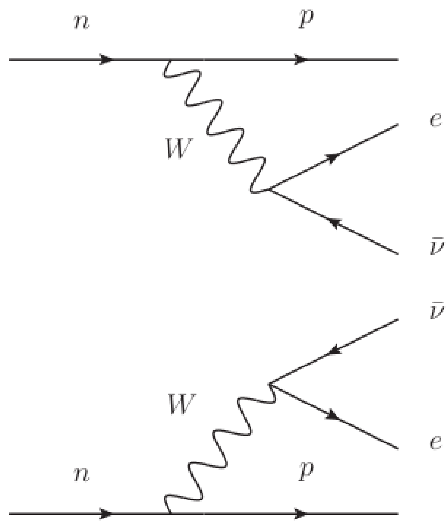
Experiment Site



GERDA employs Ge detectors enriched in ^{76}Ge doing double beta decay => detector = source

Double Beta Decay



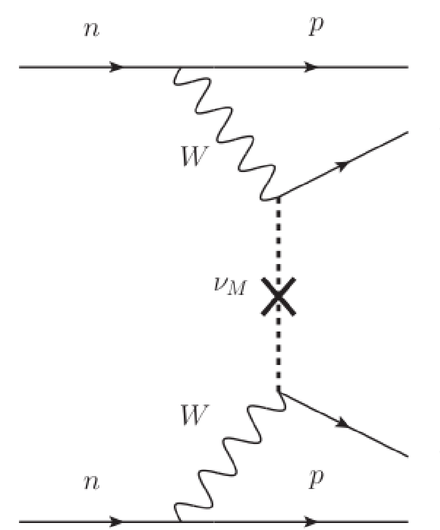


Standard Model 2νββ decay:

- known for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, ^{130}Ba, ^{136}Xe
- $T_{1/2}(2\nu)$ in the range of $10^{18\text{-}24}$ yr
- ^{76}Ge: $T_{2\nu} = 1.9^{+0.14}_{-0.10} \cdot 10^{21}$ yr [1]

GERDA is searching for the 0νββ decay:

- a likely mechanism is ”massive Majorana neutrino exchange”, see e.g. [2]



If it is discovered:

- lepton number is violated ($\Delta L = 2$)
- requires physics beyond the Standard Model

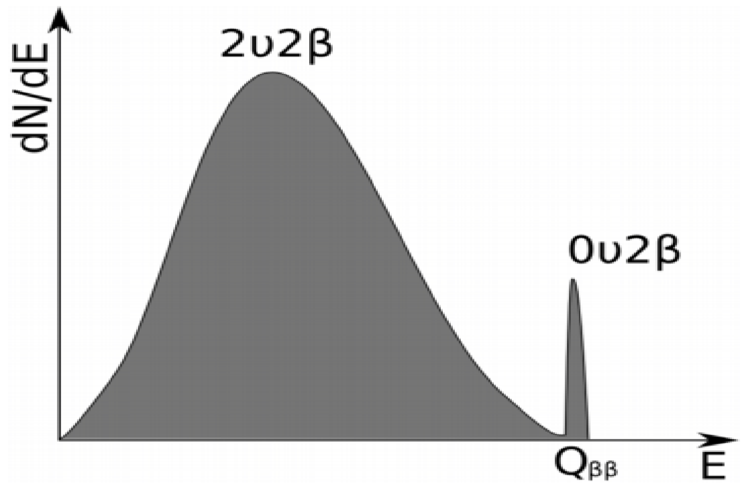
[1] GERDA Collaboration, arXiv:1501.02345 [nucl-ex] (2015)

[2] W. Rodejohann, Int. J. Mod. Phys. E20, 1833-1930 (2011)

Experimental Method

Signature:

- measuring the energy of the two decay electrons in Ge diodes
- peak at $Q_{\beta\beta} = m(A, Z) - m(A, Z - 2)$
  $= 2039$ keV for ^{76}Ge



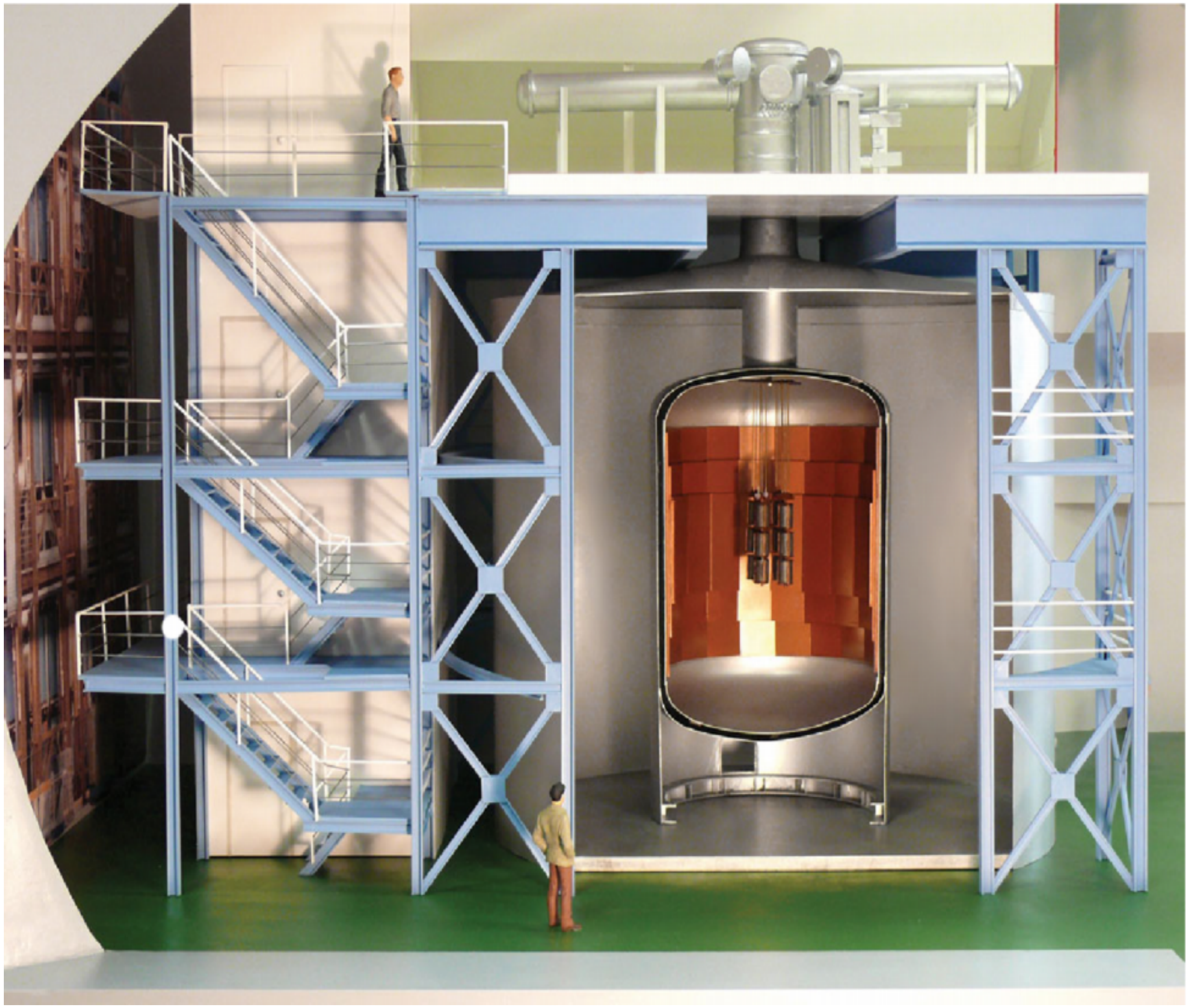
Staged approach:

- Phase I:
  - used refurbished coaxial type enriched Ge diodes from former Heidelberg-Moscow and IGEX experiments
  - run time: Nov 2011 – May 2013
- Phase II (currently upgrading):
  - additional BEGe type enriched Ge diodes
  - additional background reduction

The GERDA Experiment
(Phase I)

Experimental set-up:

- bare Ge diodes enriched to 86 % of ^{76}Ge:
  - directly immersed in a 5.5 m high 64 m^3 liquid Ar cryostat: cooling and shielding
  - enclosed by shrouds
- water Cherenkov detector (590 m^3 , 8.5 m heigh): veto muons, absorb neutrons, γ rays
- plastic scintillator to veto muons going through the cryostat neck



Mockup of the GERDA experiment

[GERDA Collab., Eur. Phys. J. C 73 (2013) 2330]

Sensitivity

Quasi background free:

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{N_{sign}} \frac{f_{76}}{m_{76}} \cdot \varepsilon \cdot M \cdot t$$

N_{sign} = number of signal events

f_{76} = enrichment fraction

m_{76} = molar mass of ^{76}Ge

ε = detection efficiency

M = detector mass

t = run time

Ways to reduce background:

- selection of radio-clean materials
- physical blocking of radioactive Ar impurities: "shrouds"
- pulse shape discrimination
  - coaxial detectors
  - BEGe detectors
- veto:
  - muons
  - γ rays ⇒ liquid Ar veto

Two Phases:	Mass [kg]	BI [cts/(keV·kg·yr)]	Exposure [kg·yr]	$T^{0\nu}_{1/2}$ Sensitivity [yr]
I (finished)	18	10^{-2}	21.6	$2 \cdot 10^{25}$
II (expected)	35	10^{-3}	100	$1.4 \cdot 10^{26}$

Background Sources

α decays on the p+ surface

- have specific pulse shapes ⇒ PSD
- the outer n+ electrode of the detectors is not active ⇒ does not see α events

β decay of ^{42}K (from ^{42}Ar) on the surface or close to the detector

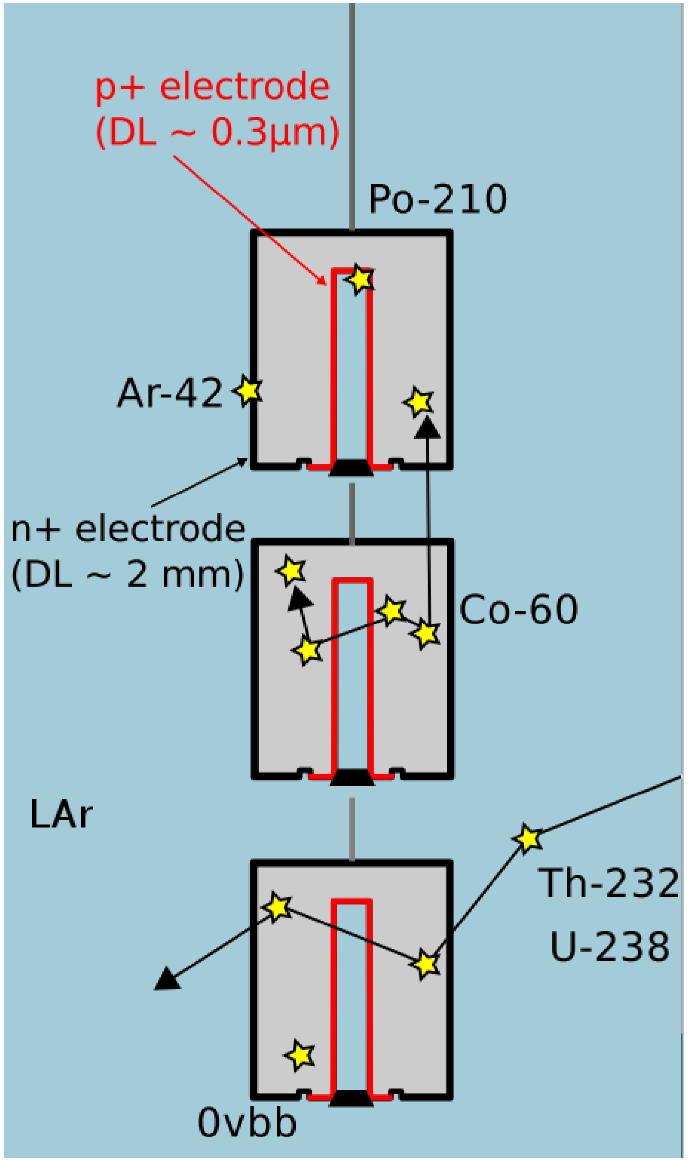
- can penetrate the n+ electrode
- have specific pulse shape, some deposit energy in LAr ⇒ PSD, veto (Phase II)

β decay of ^{60}Co inside the detectors

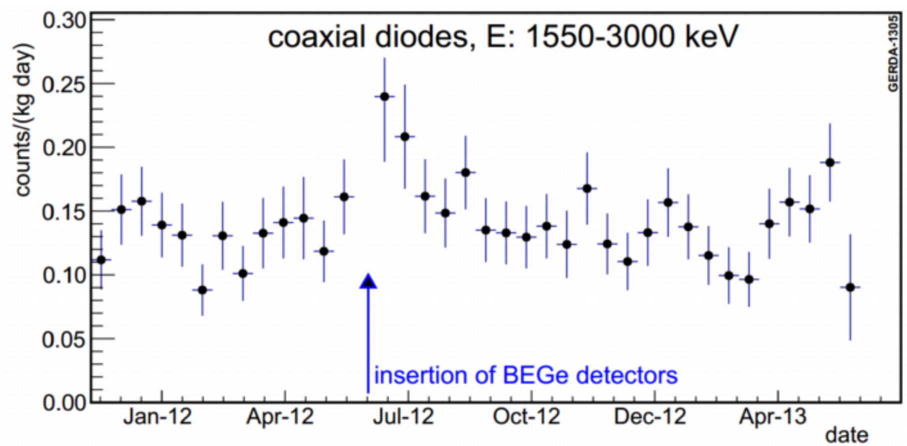
- in coincidence with γ = multi site event (MSE) ⇒ PSD, veto (Phase II)

γ rays from ^{208}Tl, ^{214}Bi from various set-up components

- often multi site events ⇒ PSD, veto (PhaseII)



Phase I Background & Datasets

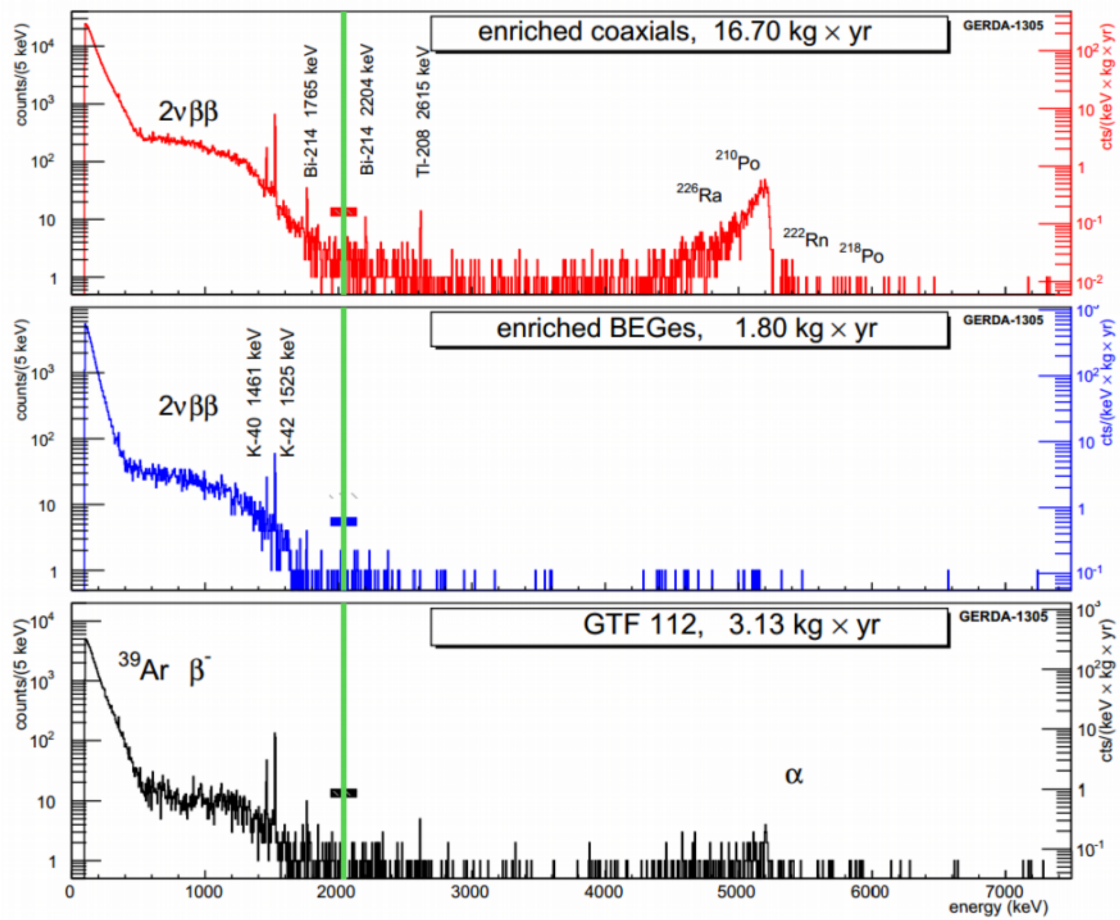


dataset	exposure [kg·yr]
Golden	17.90
Silver	1.30
BEGe	2.40

data taken with blinded ROI

Increased background after removal of two natural coaxial and insertion of BEGe detectors:

- Silver: enriched coax data taken in June and July 2012
- Gold: all other enriched coax data
- BEGe data kept separately, due to different energy resolution and background
- natural detectors

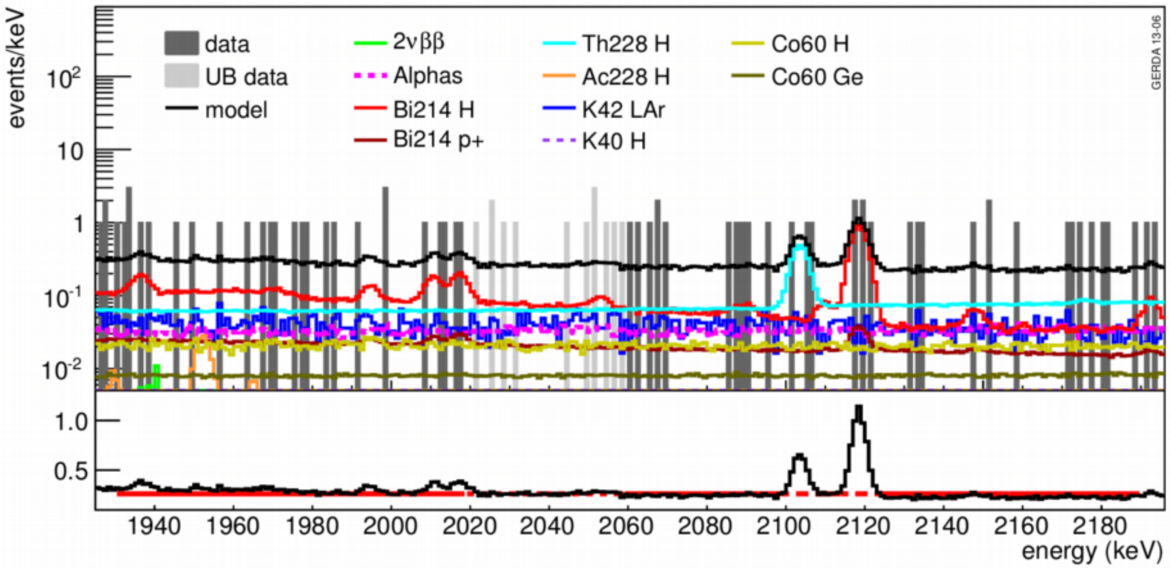


GERDA Phase I Background at $Q_{\beta\beta}$

- minimum model containing only known and visible background sources
- alternative (maximum model) containing the same isotopes but more possible locations
- both models predict a flat background at $Q_{\beta\beta}$

For $0\nu2\beta$ analysis:

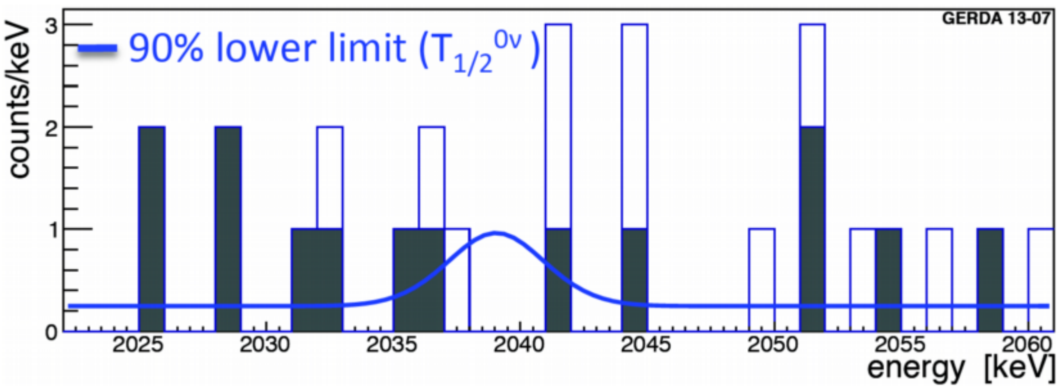
- interpolation by a constant excluding known γ peaks at 2104 (^{208}Tl SEP) and 2119 keV (^{214}Bi)
  - consistent with model predictions



background before and after PSD in ROI

$[10^{-3}$cts/(keV·kg·yr)]	GOLD-coax	SUM-BEGe
interpolation	17.5[15.1, 20.1]	36.1[26.4, 49.3]
minimum	18.5[17.6, 19.3]	38.1[37.5, 38.7]
maximum	21.9[20.7, 23.8]	-
after PSD	11[9, 13]	5[2, 9]

Phase I Results



Spectrum around $Q_{\beta\beta}$

empty bins: rejected by PSD

filled bins: accepted by PSD

Events at $Q_{\beta\beta}$ ±5 keV

PSD	Dataset	Obs.	Exp. bkg
no	golden	5	3.3
	silver	1	0.8
	BEGe	1	1.0
yes	golden	2	2.0
	silver	1	0.4
	BEGe	0	0.1

Profile Likelihood Method:

- best fit $N_{0\nu} = 0$
- no excess over background
- 90% C.L. lower limit:

$$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}\ \mathrm{yr}$$

[GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503]

Comparison with other Experiments

Claimed observation of 0νββ decay $T_{0\nu} = 1.19 \cdot 10^{25}$ yr [1]:

- prediction for GERDA: 5.9 ±1.4 signal cts over 2.0 ±0.3 bkg cts in $Q_{\beta\beta}$ ±2σ
- GERDA observed 3 cts in $Q_{\beta\beta}$ ±2σ, 0 cts in $Q_{\beta\beta}$ ± 1σ
  ⇒ claim disfavoured with 99% probability

Combining with HdM 2001 and IGEX 2002:

- $T_{1/2} > 3.0 \cdot 10^{25}$ yr (90%) C.L.
- combined ^{76}Ge limit on effective Majorana neutrino mass:
  $m_{\beta\beta} < 0.2 - 0.4$ eV (depends on nuclear matrix element and phase space factor)

Searches with ^{136}Xe

- KamLAND-Zen (combined):
  - $T_{0\nu} > 2.6 \cdot 10^{25}$ yr [2]
  - $m_{\beta\beta} < 0.14 – 0.28$ eV
- Exo-200:
  - $T_{0\nu} > 1.1 \cdot 10^{25}$ yr [3]
  - $m_{\beta\beta} < 0.19 – 0.45$ eV
- Cuore-0 (combined):
  - $T_{0\nu} > 4.0 \cdot 10^{24}$ yr [4]
  - $m_{\beta\beta}$ 0.27 < 0.76 eV

[1] Phys. Lett. B 586,198 (2004)
[2] Phys. Rev. C86:021601 (2012)
[3] Nature (2014), doi:10.1038/nature13432
[4] arXiv:1504.02454 [nucl-ex]

Phase II Upgrades

Additional BEGe detectors

- enhanced PSD performance
- factor 1.5 better energy resolution

Total mass ≈ 35 kg

Improved preamplifier and contacting

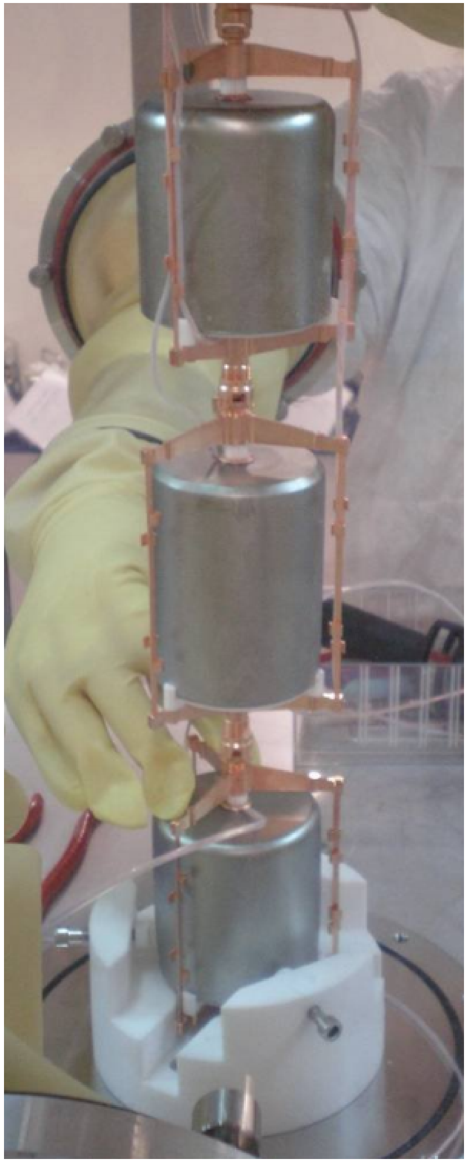
Radio cleaner holder

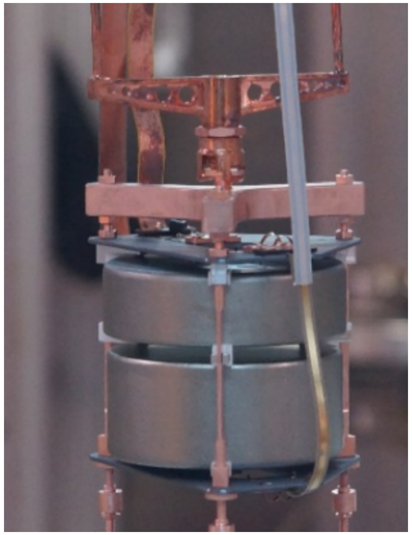
Active liquid Ar Veto

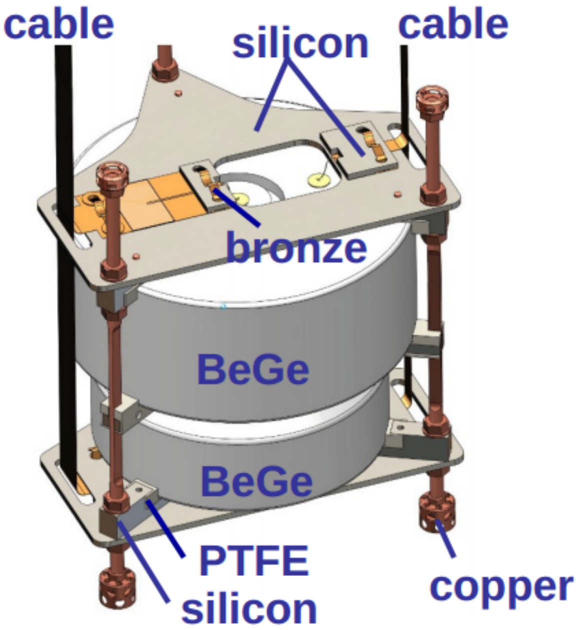
Low n-flux custom calibration sources

Total background reduction by 1 order of magnitude:

- 10^{-3} counts/(keV·kg·yr)



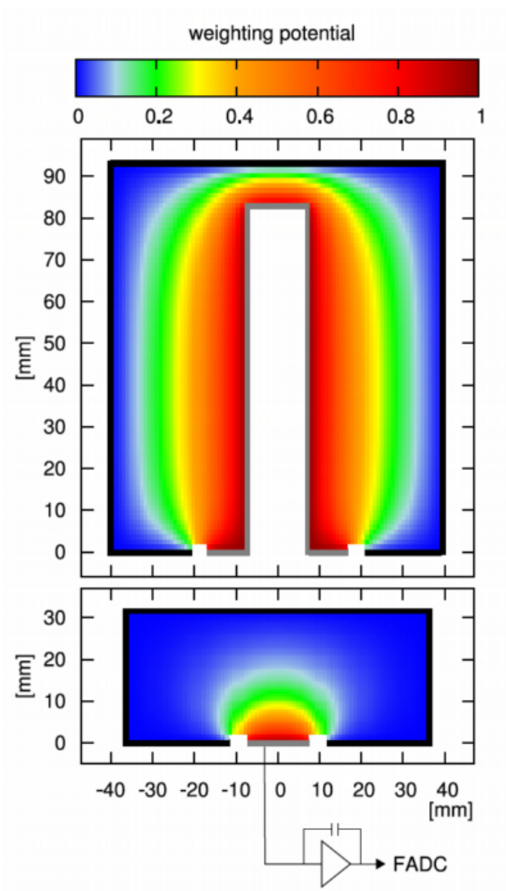


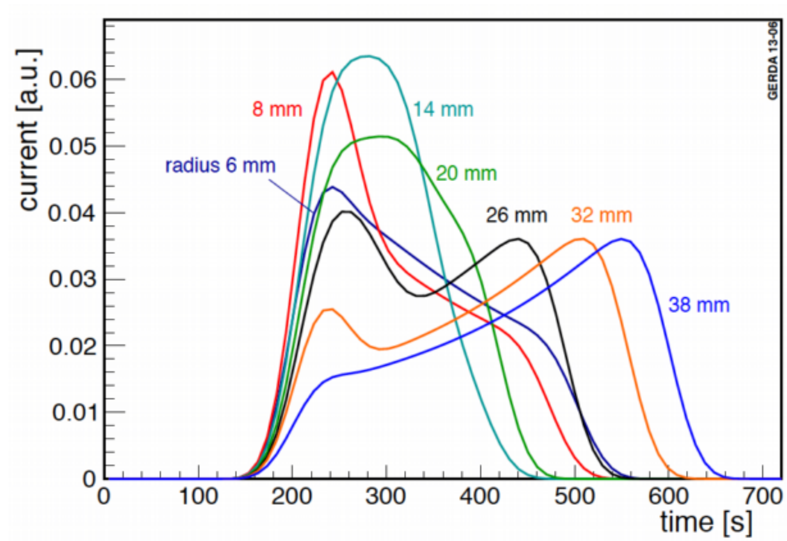


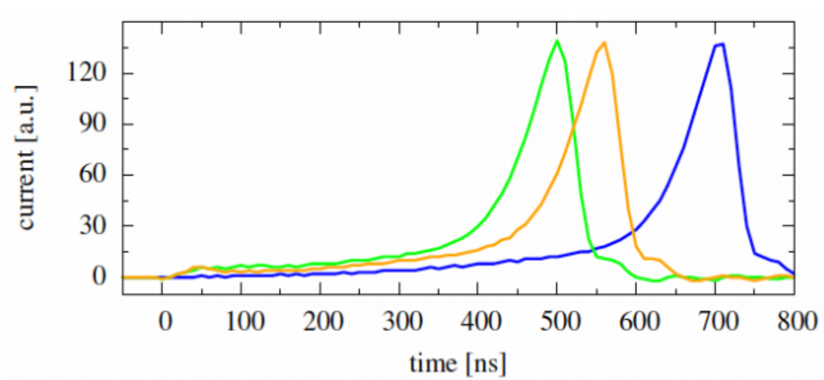
Pulse Shape Discrimination

BEGe and Coaxial geometry result in different el. fields and pulse shapes

- require different PSD methods

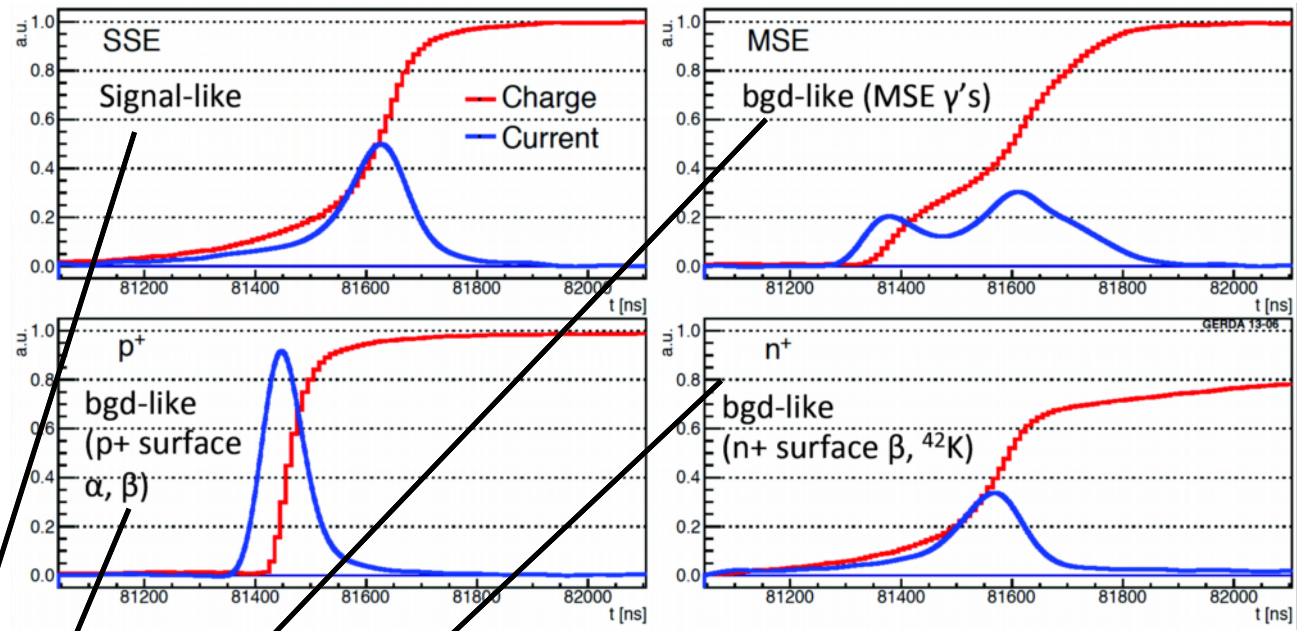






- simulated SSE current pulse in coaxial detector
- low PSD capabilities
  - use Artificial Neural Network
- simulated SSE current pulse in BEGe
- high PSD capabilities
  - cut based method

PSD with BEGe detectors

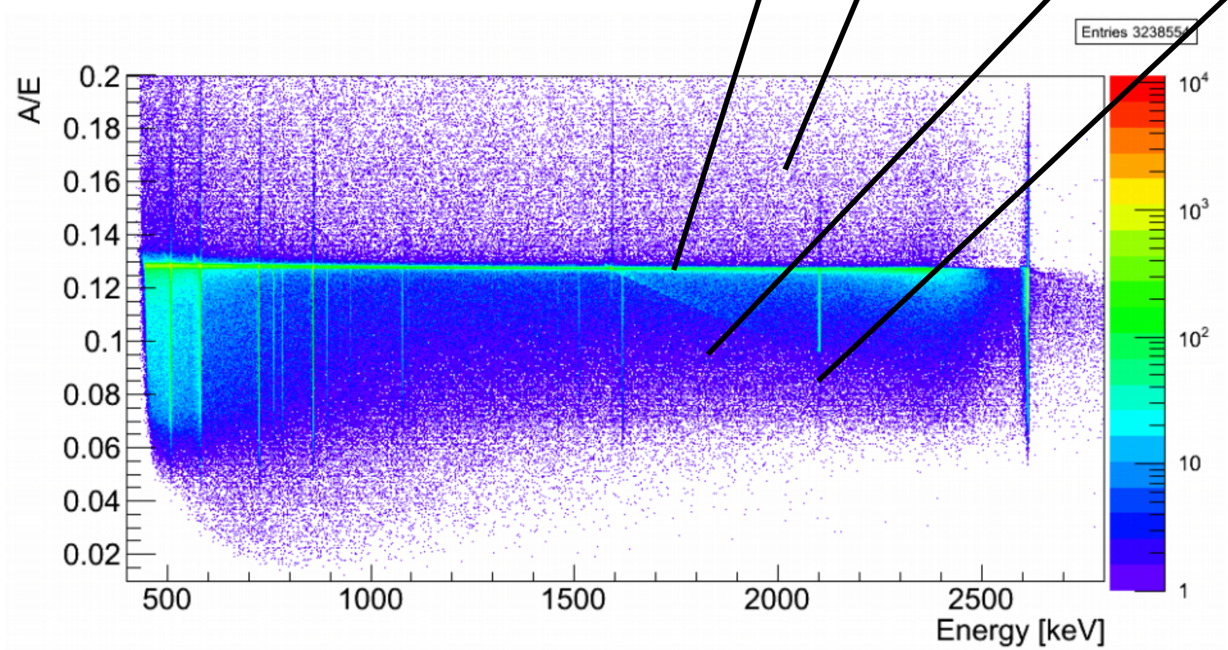


Signal events:

- single location in the detector bulk (SSE)

Background:

- γ: mostly multiple interaction sites (MSE)
- α and β: mostly surface

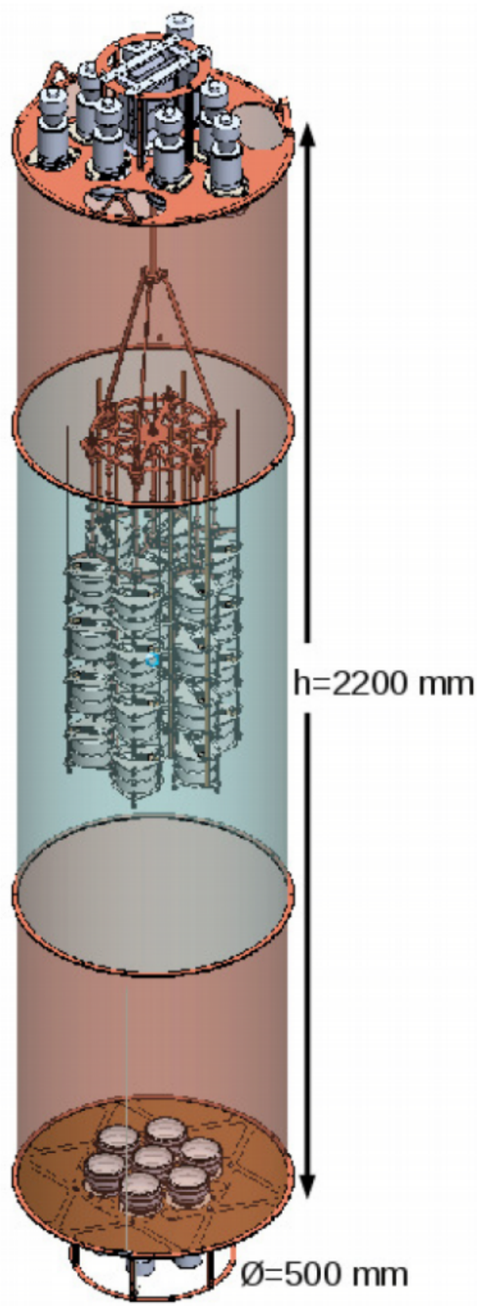


Background rejection:

- cut on amplitude A of current pulse / energy E (amplitude of charge pulse)
- efficiency strongly dependent on electronic noise

  ⇒ improve noise reduction for Phase II e.g. using wavelets

Phase II Upgrade: Liquid Ar Veto

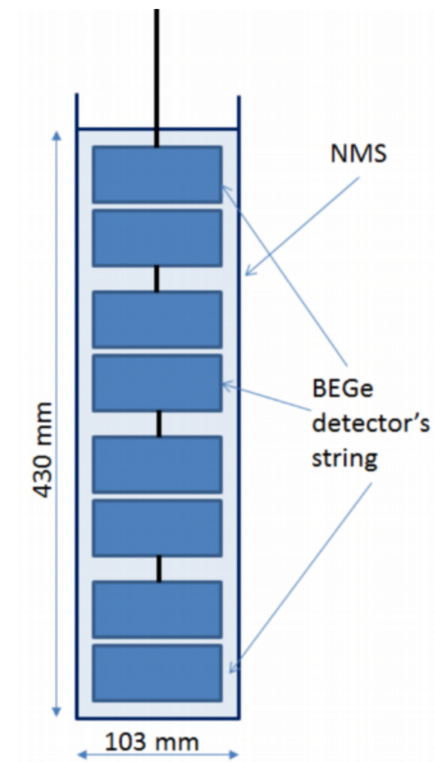


Principle:

- background events in Ge often in coincidence with a Compton scatter or a second γ in liquid Ar
    - ⇒ produces scintillation of 128 nm
- VUV light is shifted to blue light and detected by PMTs and SiPMs

Veto setup:

- each detector string surrounded by TPB + PS coated transparent nylon
- top and bottom reflector and PMT array
- central fibre cylinder coupled to SiPMs



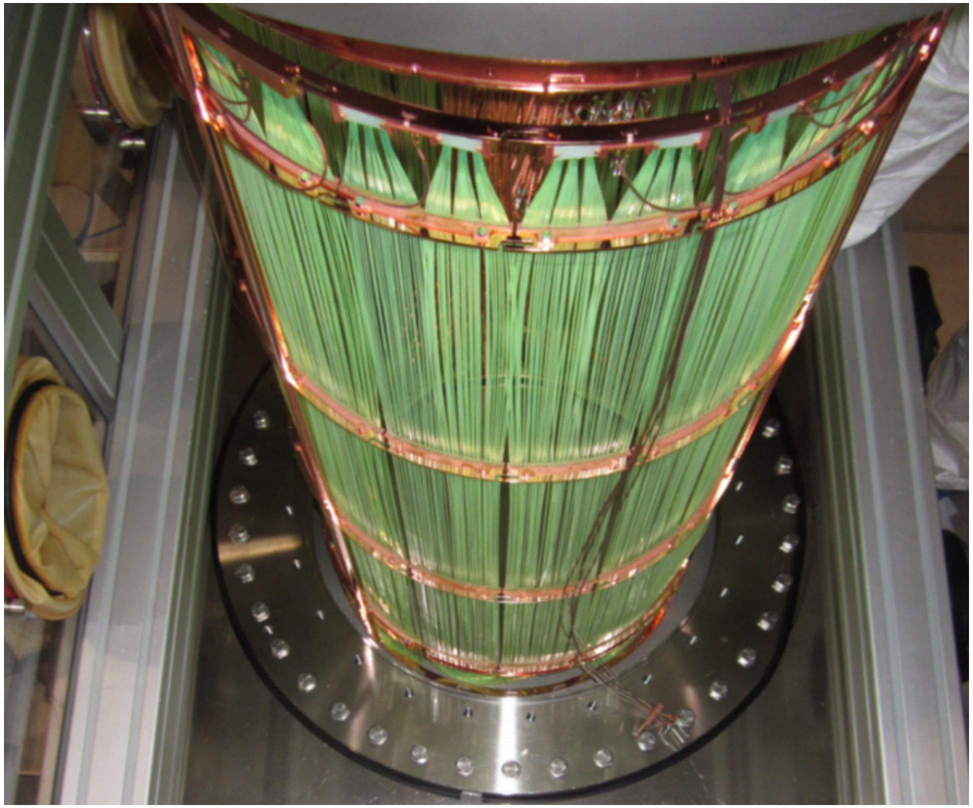
Preliminary measured suppression factors:

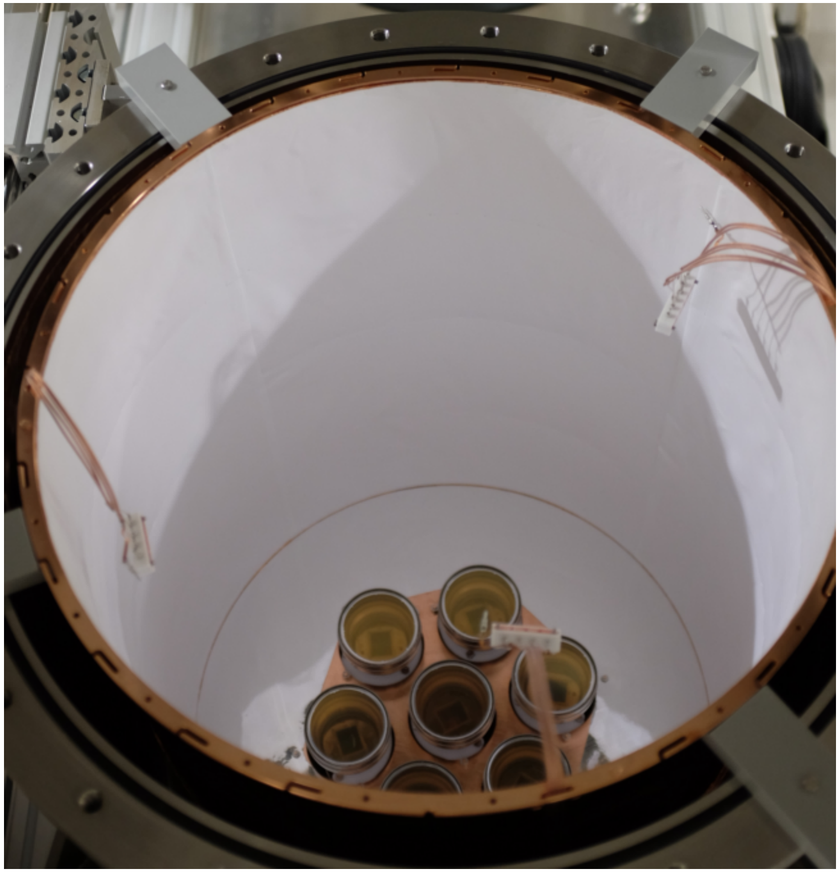
- ^{228}Th source: ≈ 45
- ^{226}Ra chain: ongoing

Liquid Ar Veto

Top and bottom array:

- 3” R11065-21 PMTs
  - 9 top + 7 bottom
- Cu cylinder lined with Tetratex®
  - coated with wavelength shifter TPB (Tetraphenyl Butadiene)





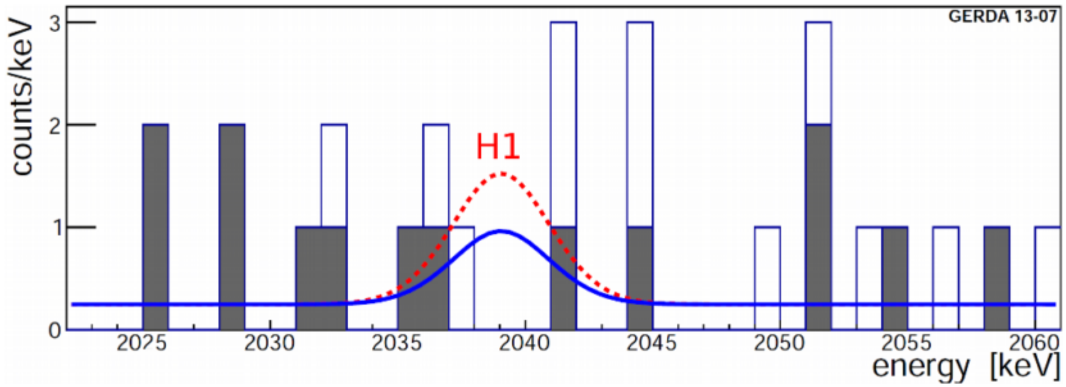
Central part:

- coated nylon minishrouds
- large cylinder of TPB coated BFC-91A fibres
  - read out by SiPMs

Conclusion and Outlook

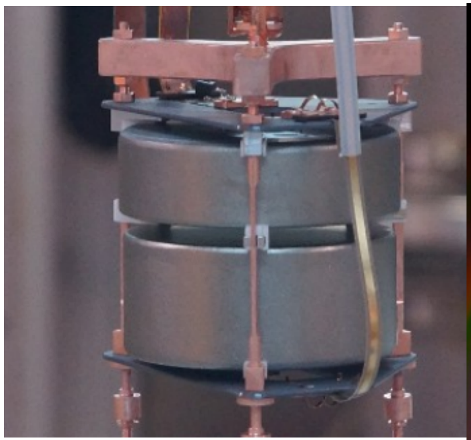
Phase I:

- $T_{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- combined with HdM 2001 and IGEX 2002:
  - $T_{0\nu} > 3.0 \cdot 10^{25}$ yr (90%) C.L.
  - $m_{\beta\beta} < 0.2$-0.4 eV

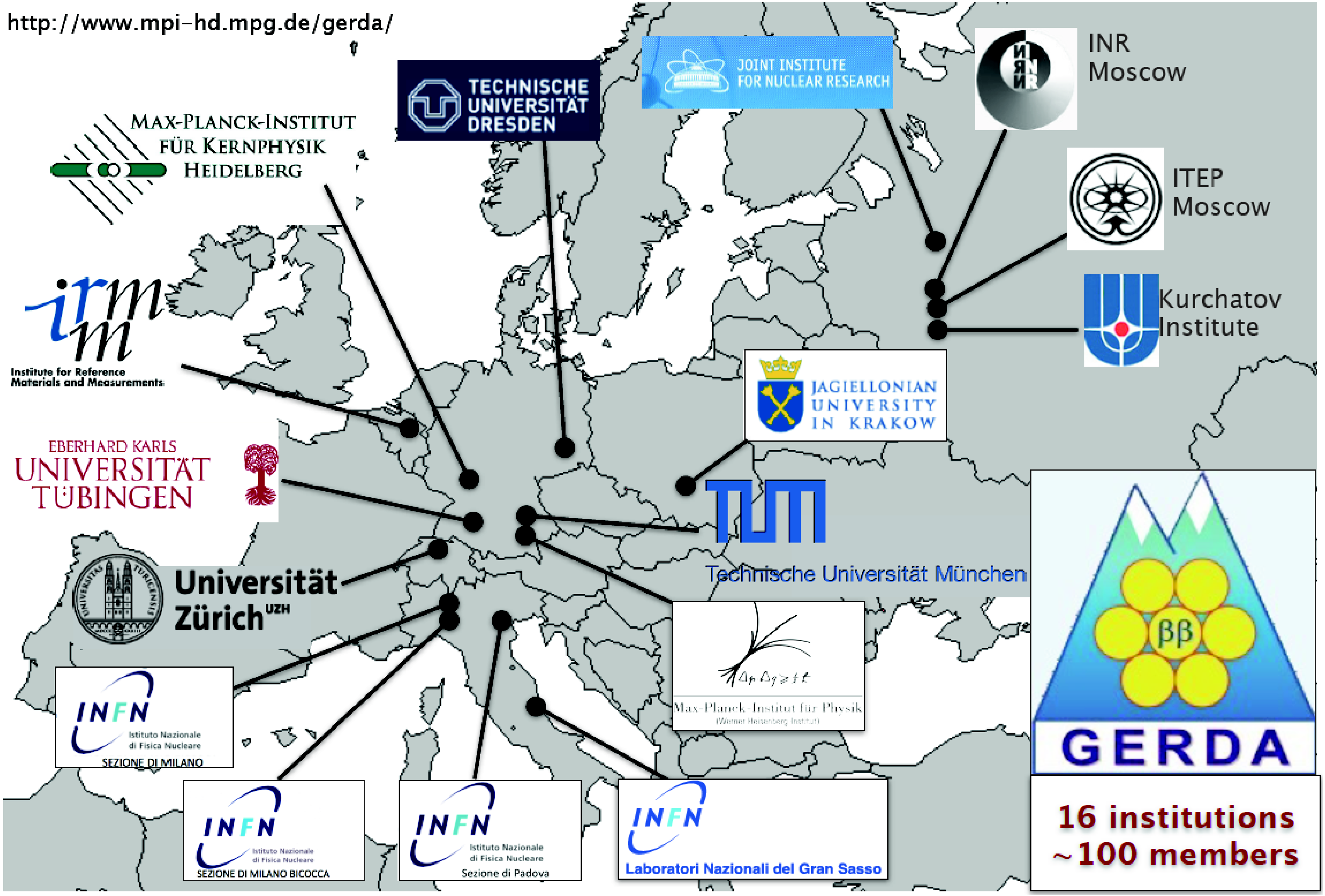


Phase II:

- 20 kg of BEGe + 15 kg of coaxial detectors
- liquid Ar veto
- exposure goal: 100 kg·yr
- background goal: $1 \cdot 10^{-3}$ cts/(keV·kg·yr)
- sensitivity: $T_{0\nu} \approx 1.4 \cdot 10^{26}$ yr
- start in 2015



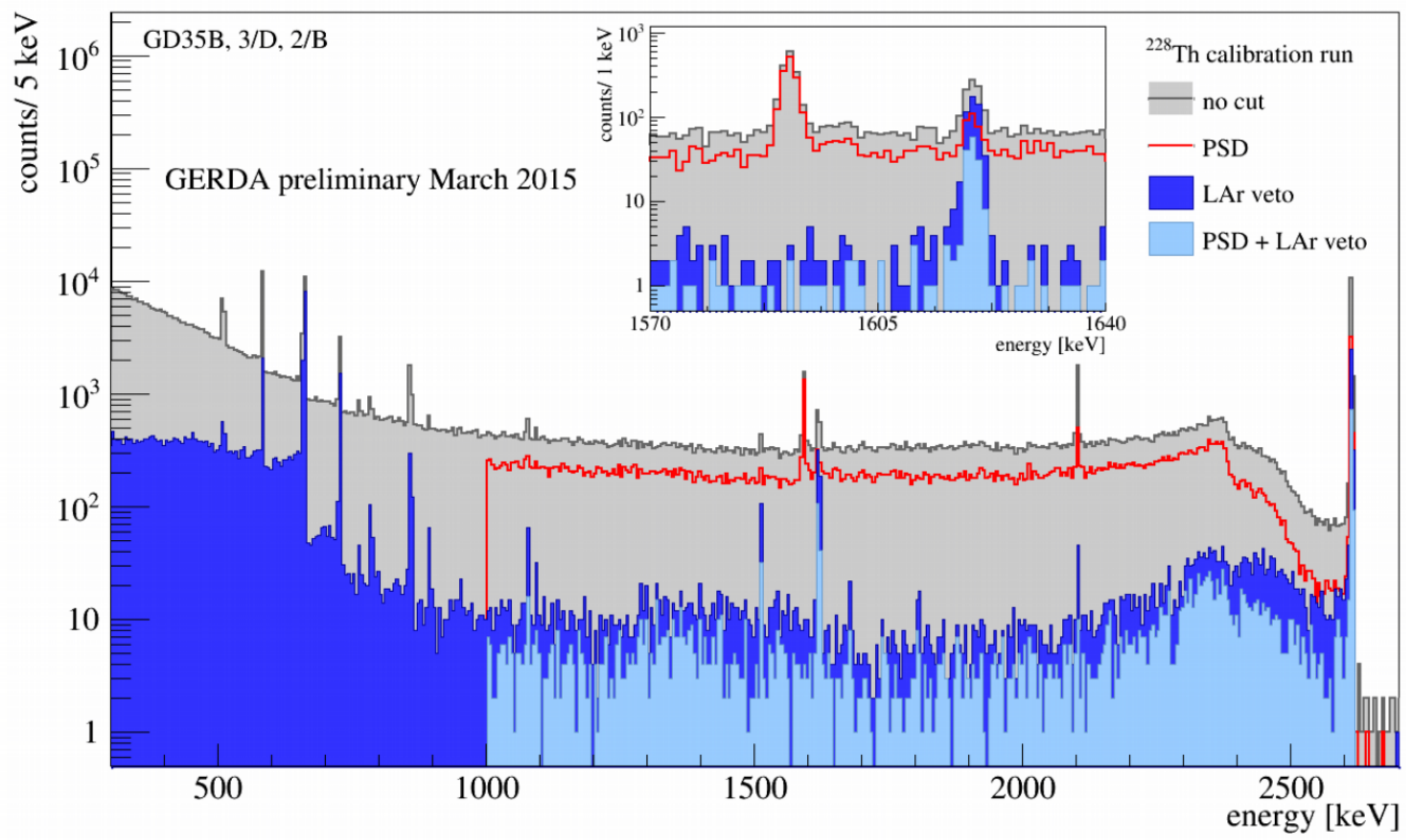
The GERDA Collaboration



Thank you for your attention!

Backup Slides

Preliminarily Measured ^{228}Th Suppression



- LAr: ≈ 45 (PMT: ≈ 28, SiPM: ≈ 13)
- combined with PSD ≈ 90

Detectors

Coaxial detectors (Phase I)

- 5 enr-Ge (“ANG”) detectors from Heidelberg-Moscow (HdM), 3 enr-Ge (“RG”) from IGEX, 3 nat-Ge from GeniusTest Facility (GTF)
- detectors reprocessed at Canberra before being used
- two detectors turned off because of high leakage current
  - ⇒ total mass of remaining enriched detectors: 14.6 kg
- ~2‰ FWHM at 2.6 MeV

BEGe detectors (design for Phase II, BEGe = Broad Energy Germanium)

- ~1.5‰ FWHM at 2.6 MeV
- enhanced Pulse Shape Discrimination (PSD)
- ~ 20 kg of BEGe’s successfully produced and tested in 2012
- 5 BEGe’s inserted in GERDA in July 2012
- one showed instabilities in the energy calibration and was not used

Phase I Data Taking

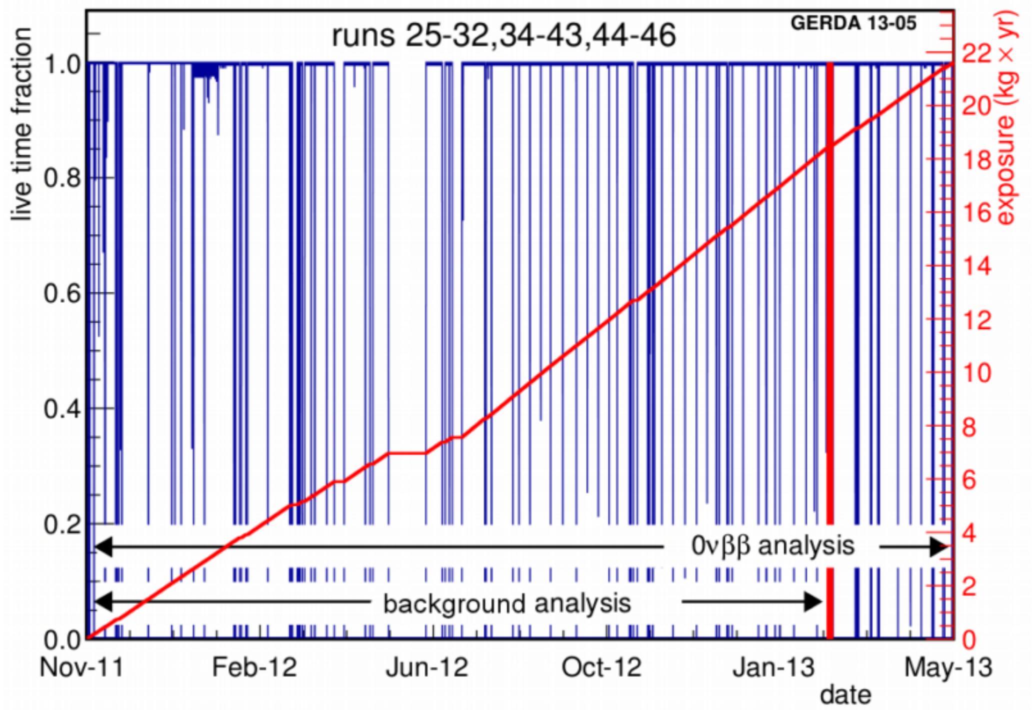
High average live time fraction.

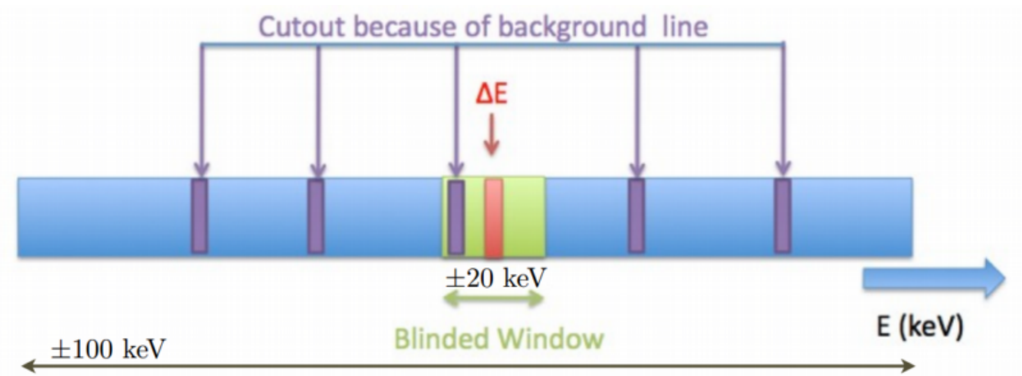
- spikes due to calibration.

Total exposure of enriched Ge detectors 21.6 kg yr [1].

Data was taken with a blinded energy window of $Q_{\beta\beta} \pm 20$ keV (FWHM ≈ 4.5 keV):

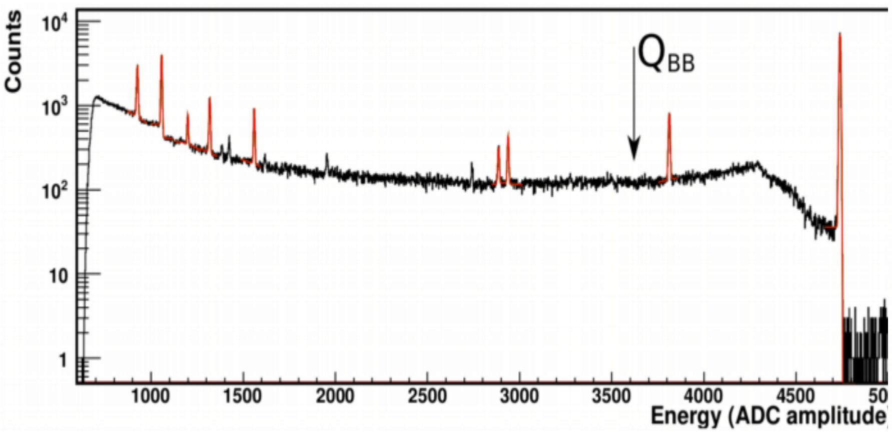
- background models and analysis methods were developed.
- unblinding of side bands: background models verified and analysis methods frozen.
- final unblinding performed on 14th of June and the analysis applied.

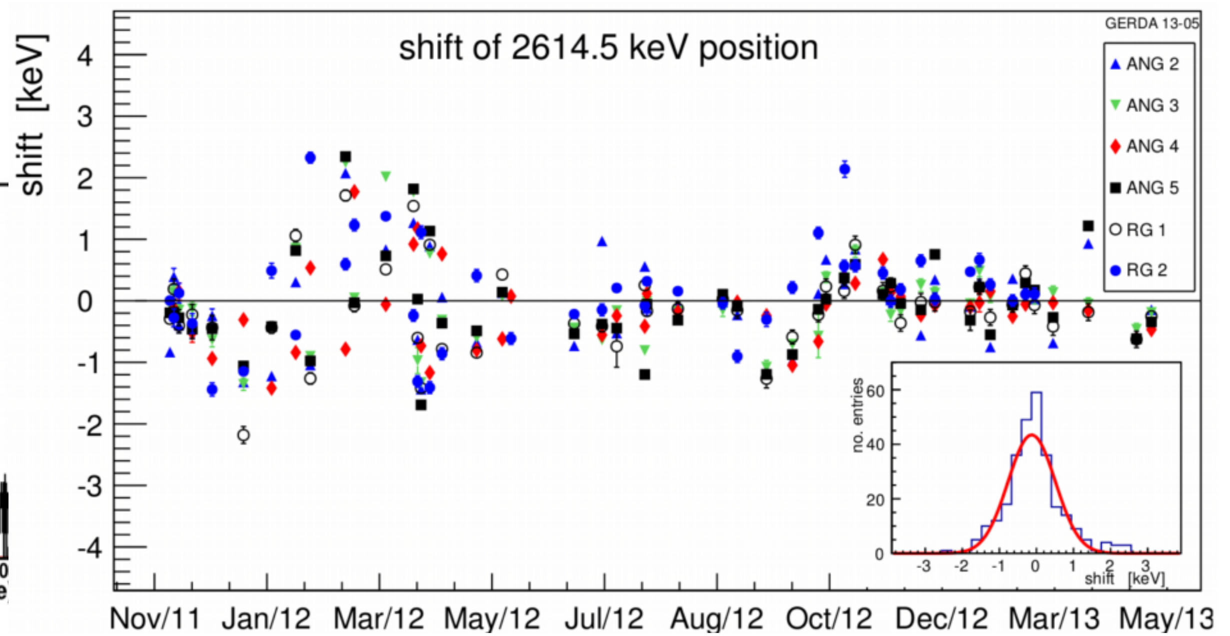




Detector Stability

Calibrate with ≈10 peaks from ^{228}Th source

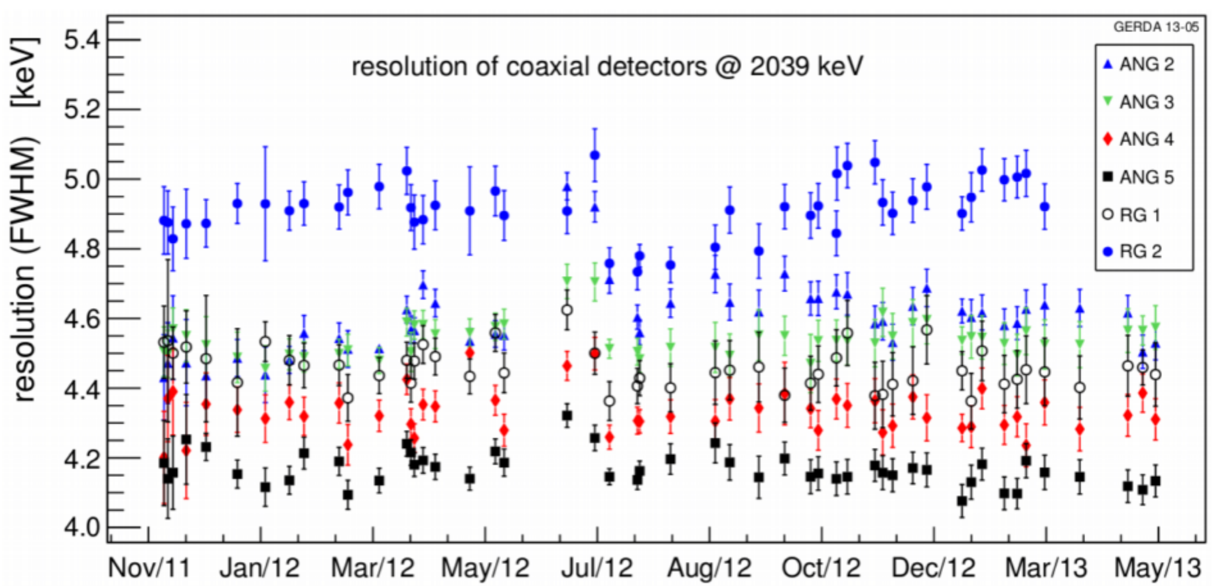




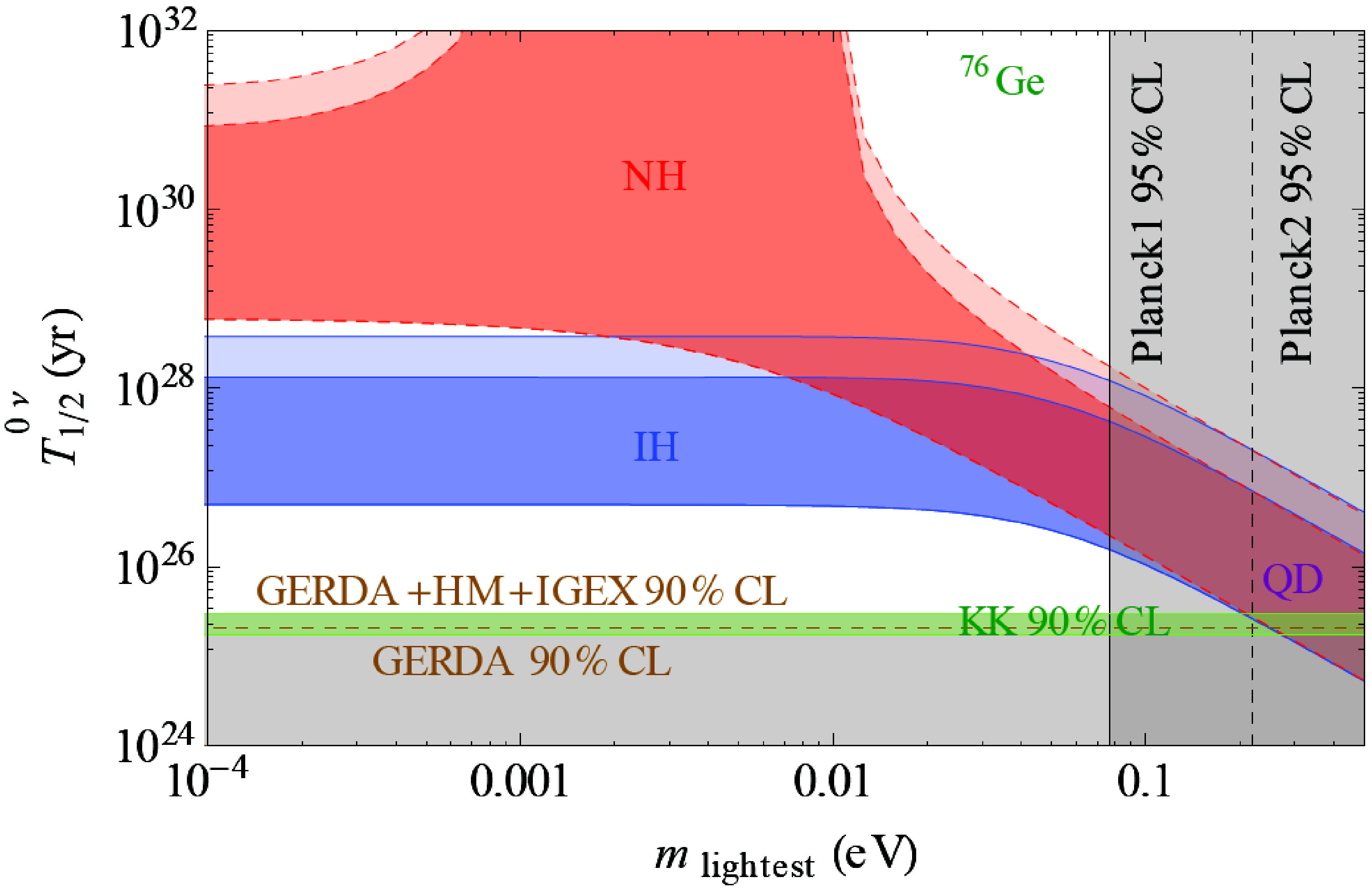
Stable energy calibration: shift < 2 keV over the full data taking period.

- as important as the energy resolution.

Stable energy resolution.



Scanning the Inverse Hierarchy

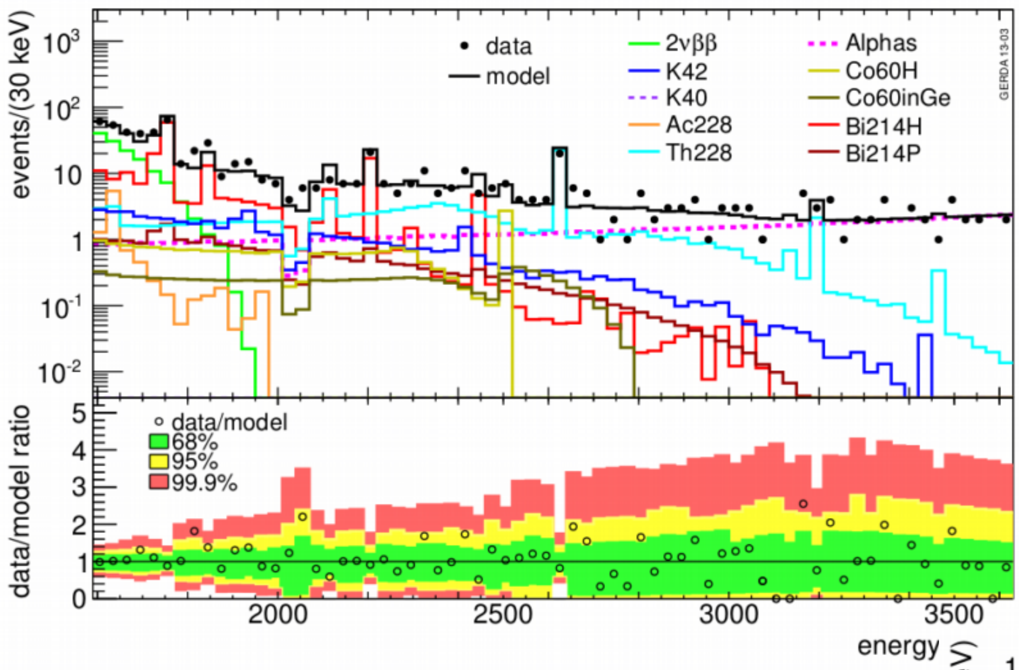


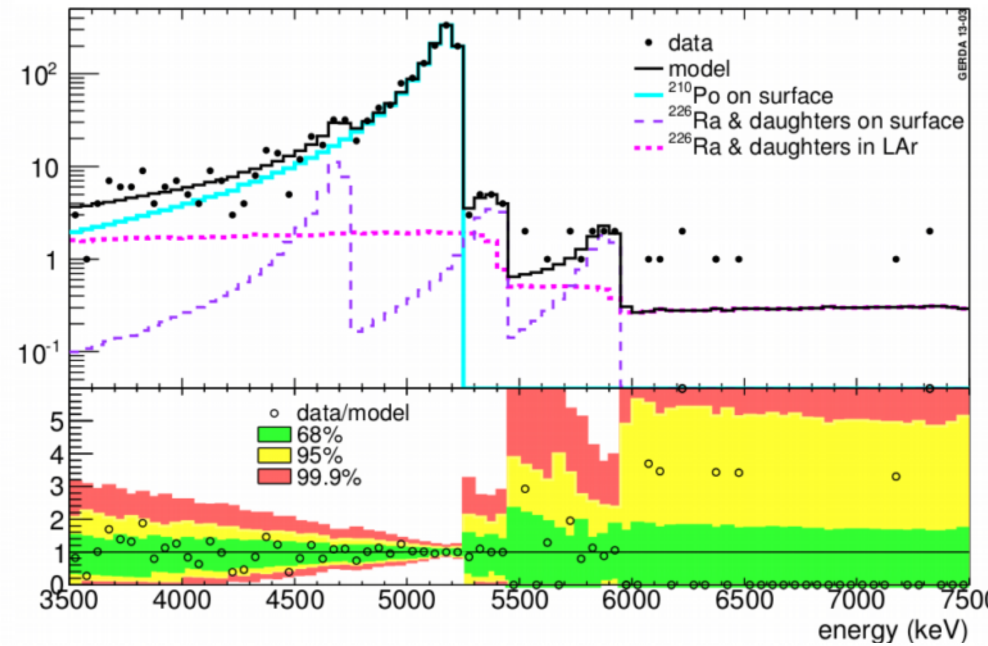
Need to reach a sensitivity of ~ 10^{28} yr on $T_{0\nu}$ in order to test IH [1]

GERDA Phase II will reach ~ $2 \cdot 10^{26}$ yr

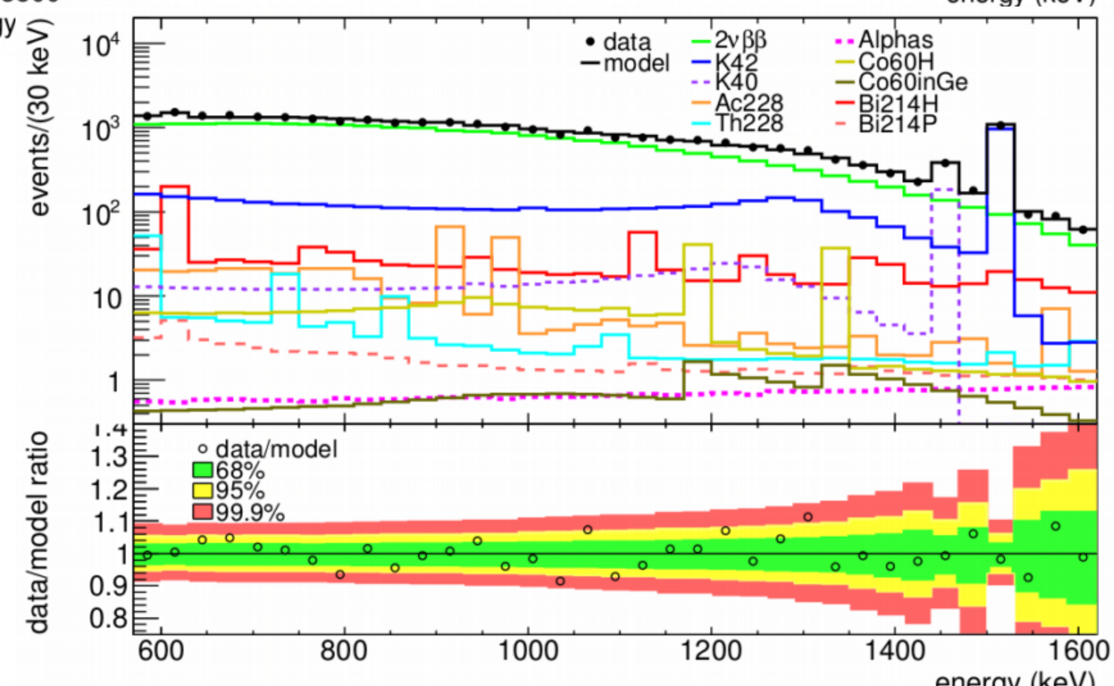
[1] P. S. Bhupal et al., arXiv:1305.0056v2

Minimum Background Model





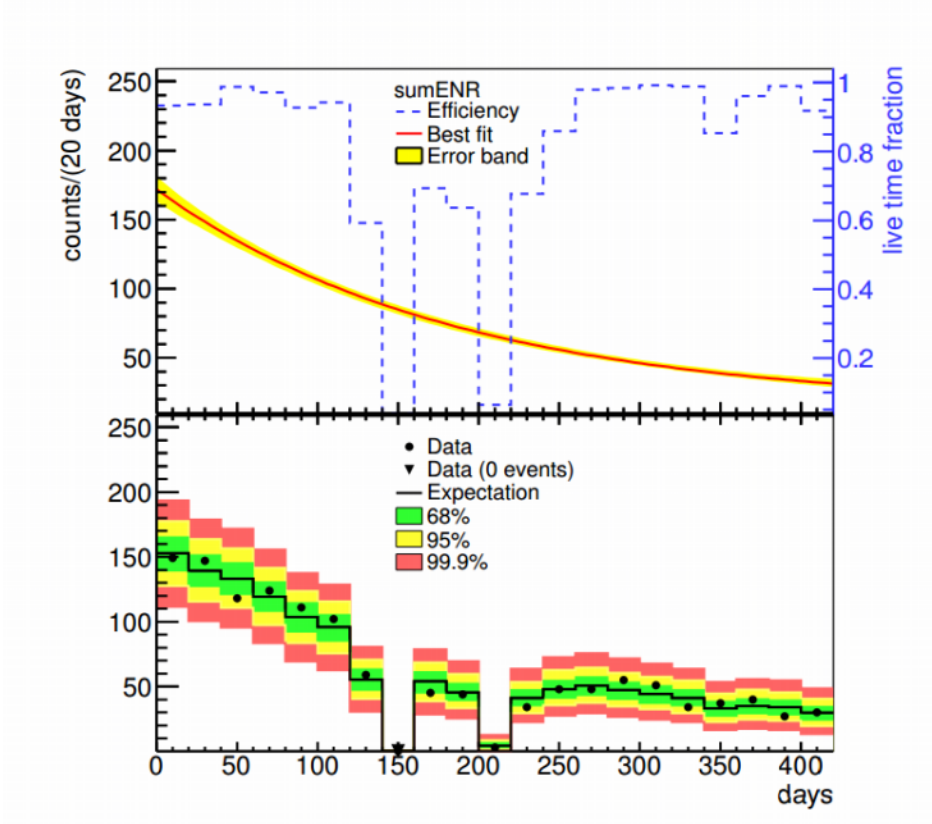
Both background models provide a half life which is consistent with our previously published value of $T_{1/2\ 2\nu\beta\beta} = 1.84^{+0.14}_{-0.10} \cdot 10^{21}$ yr [1].



[1] GERDA collaboration, J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

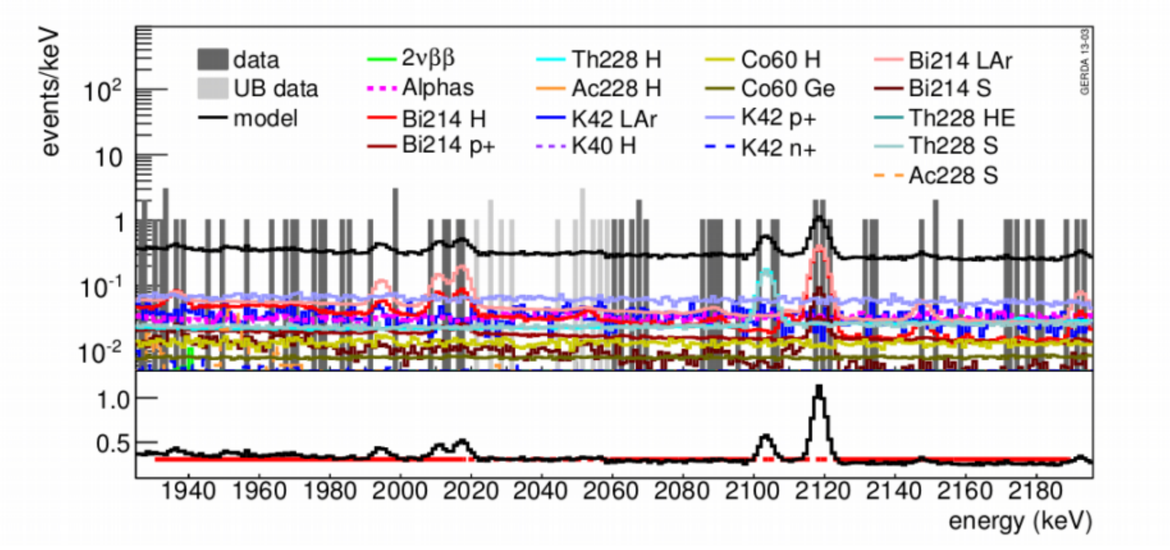
Alpha background & Maximum Model

In the range of 3.5 to 5.3 MeV a decrease of the event rate with time is observed with $T_{1/2}$=138.4 ± 0.2 d (statistical uncertainty only), which is compatible with the half life of ^{210}Po of 138.38 d.



Maximum Model:

- use same isotopes as for the Minimum Model but more possible source positions to fit the background
  - higher ^{42}K contribution



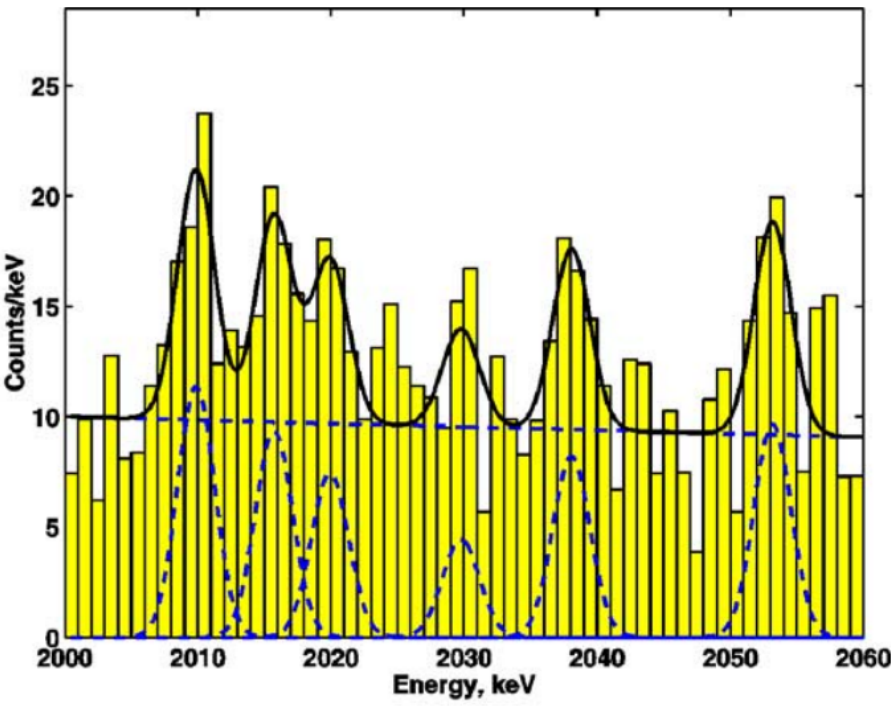
Controversial Claim

Claiming a 4.2σ confidence level of the observation of $0\nu\beta\beta$ in ^{76}Ge.

Extending the energy window increases the background and decreases the signal count by up to 40 %. [2]

2006 limit is not considered:

- half-life can be reconstructed only with ε_{PSD}=1



[1] H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B586, 198 (2004).

[2] O.Chkvorets, PhD thesis, Universität Heidelberg, arXiv:0812.1206

Noise Dependency of Rejection Efficiency

Surface event rejection

- high noise
- low noise