Searching $0\nu\beta\beta$ with GERDA Phase II

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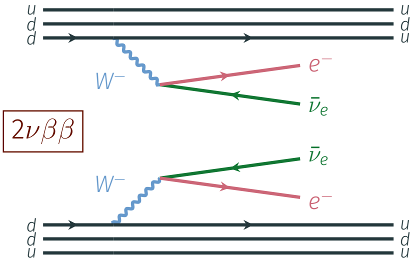
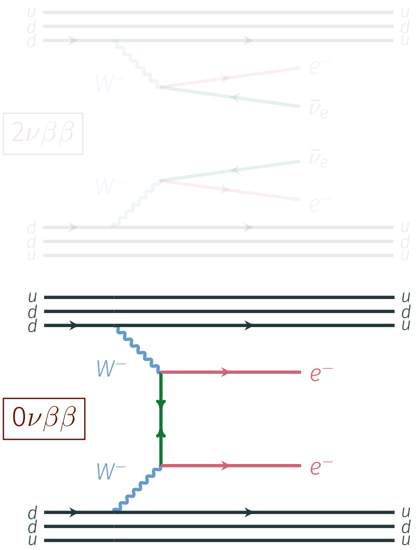
Double-β decay



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

- Standard Model: $T_{1/2}^{2\nu} \sim 10^{19} - 10^{24}$ yr
- GERDA: $T_{1/2}^{2\nu}[^{76}\text{Ge}] = 1.926 \pm 0.094 \cdot 10^{21}$ yr [EPJC 75 (2015) 416]

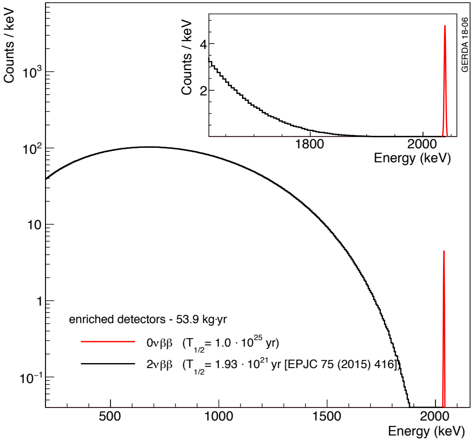
Double-β decay



$(A, Z) \to (A, Z+2) + 2e^-$

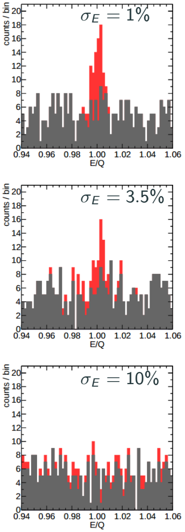
- Beyond the Standard Model, Lepton Number violation $\to$ Majorana neutrino
- GERDA: $T^{0\nu}_{1/2}[^{76}\mathrm{Ge}] > 0.9 \cdot 10^{26}$ yr (90% C.L.) `[10.5281/zenodo.1287604]`

Double-β decay: energy spectrum



A measure of the energy is *necessary* and *sufficient*, it is required:

- a good energy resolution
- background reduction techniques



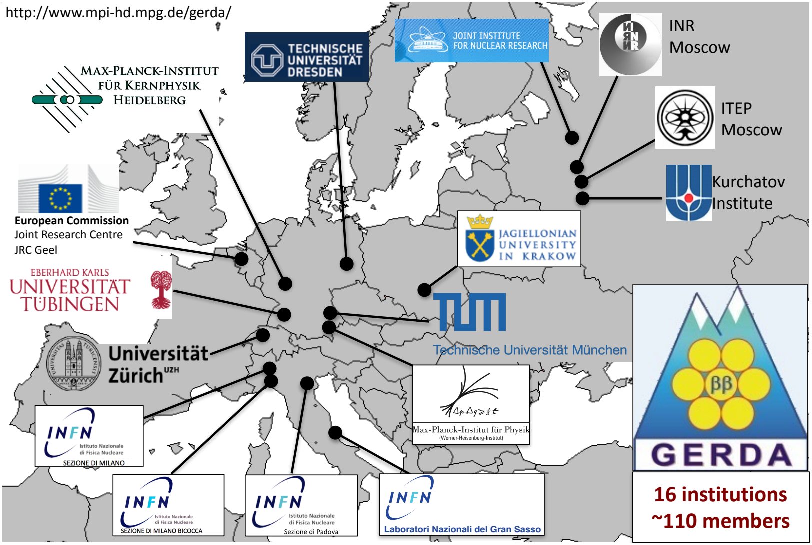
Why studying the double-β decay?

The search for $0\nu\beta\beta$ is not a mere measurement of neutrino's intrinsic properties, just look at the huge literature production[1]

- Lepton number $\longleftrightarrow$ Barion number $\rightarrow$ GUTs, baryogenesis (not guaranteed!)
- (almost always) Majorana mass term predicted (*black-box* theorem)
- provides access to lots of fundamental parameters, shared or not with other experimental techniques
- standard interpretation: *the neutrino that mediates $0\nu\beta\beta$ is the one that oscillates and the Standard Model is an effective theory of some GUT* (seesaw mechanism)
    - Connection with the Majorana effective mass: $(T^{0\nu}_{1/2})^{-1} = G_{0\nu}|\mathcal{M}_{0\nu}|^2 m^2_{\beta\beta} \rightarrow$ Oscillation parameters and absolute neutrino mass scale
- countless non-standard interpretations[1]

[1] W. Rodejohann, [IJMP, E 20 (2011) 1833]

The GERDA collaboration

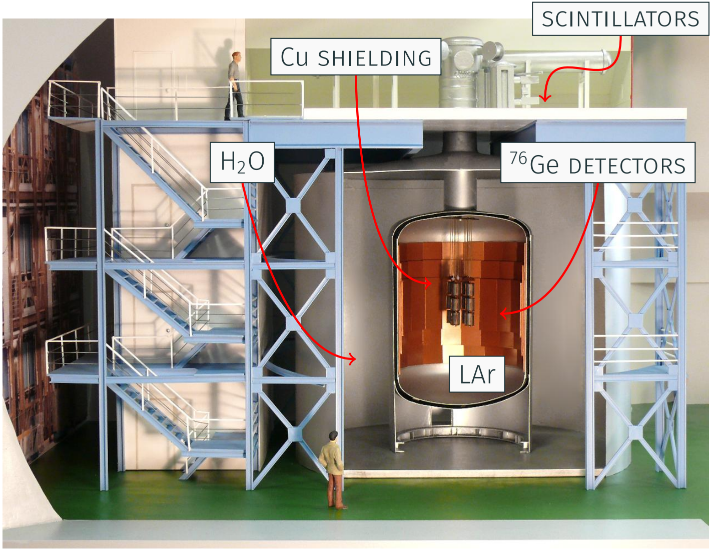


GERmanium Detector Array

GERDA looks for $0\nu\beta\beta$ with enriched, high-purity ^{76}Ge detectors

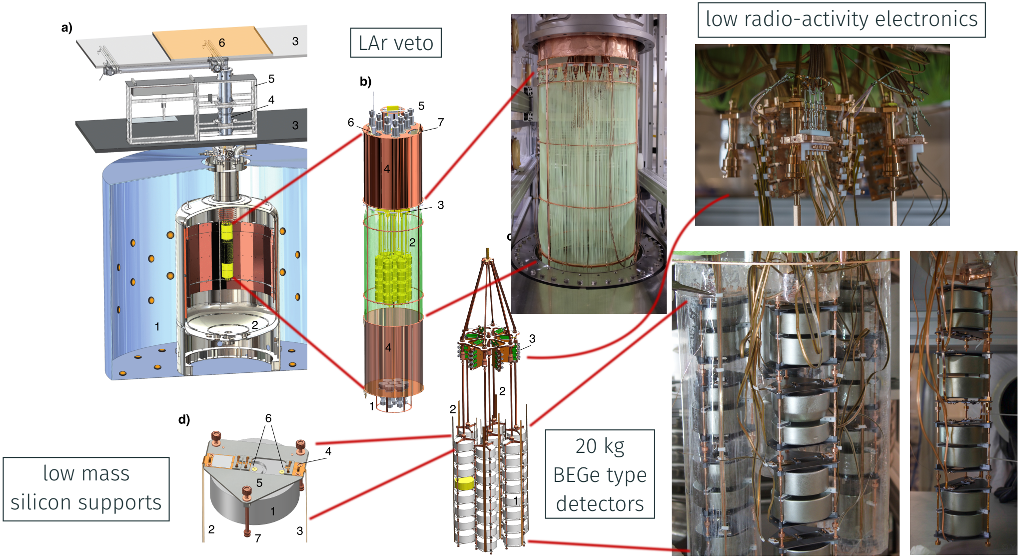
source = detector

- Installed at LNGS (3500 m.w.e.), in activity since 2009 → Phase I
- Hardware upgrade 2015 → Phase II

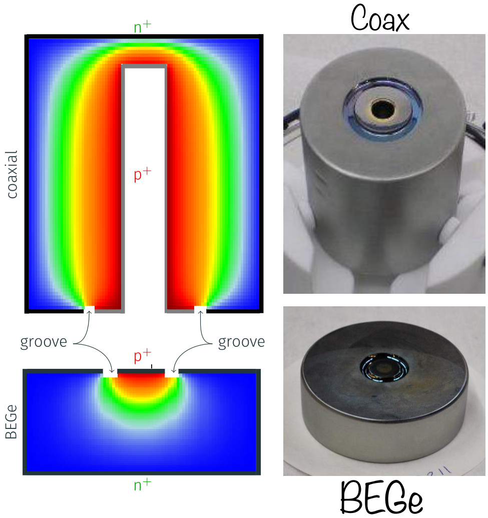


Gerda Phase II

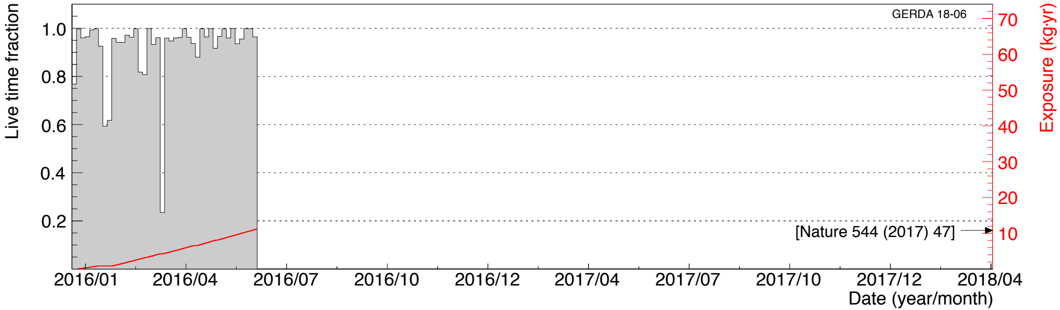
GERmanium Detector Array — Phase II [EPJC (2018) 78: 388]



- ^{76}Ge double-β decay: $^{76}\text{Ge} \to {}^{76}\text{Se} + 2e^-$
- Q-value: $Q_{\beta\beta} = 2039$ keV
- ^{76}Ge enriched (87%) ultra-pure detectors:
  - **source = detector**: high efficiency
  - radio-purity: almost **null intrinsic background**
  - high density: $0\nu\beta\beta$ **point-like** topology
  - semiconductor: **0.2% FWHM** at $Q_{\beta\beta}$
  - great for **Pulse Shape Discrimination (PSD)**
- two different geometries: BEGe (~ 20 kg) and semi-coaxial (~ 15 kg)

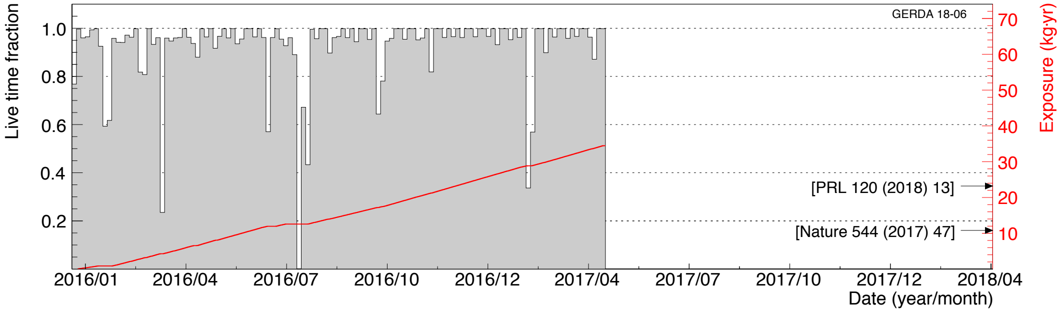


Phase II data taking



June 2016 10.8 kg·yr `[Nature 544 (2017) 47]`

Phase II data taking



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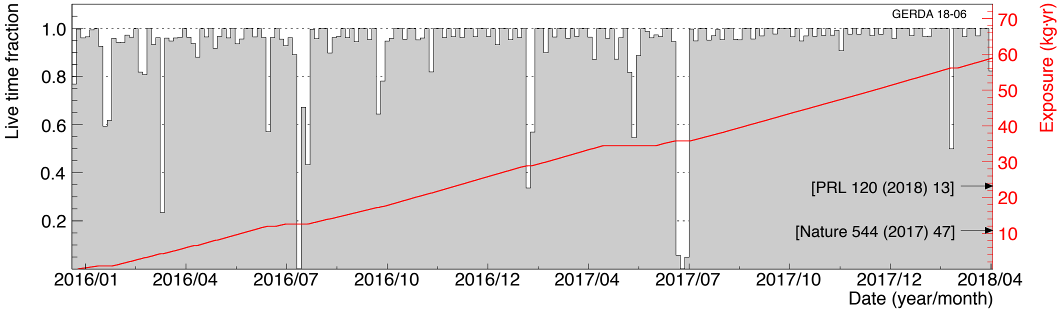
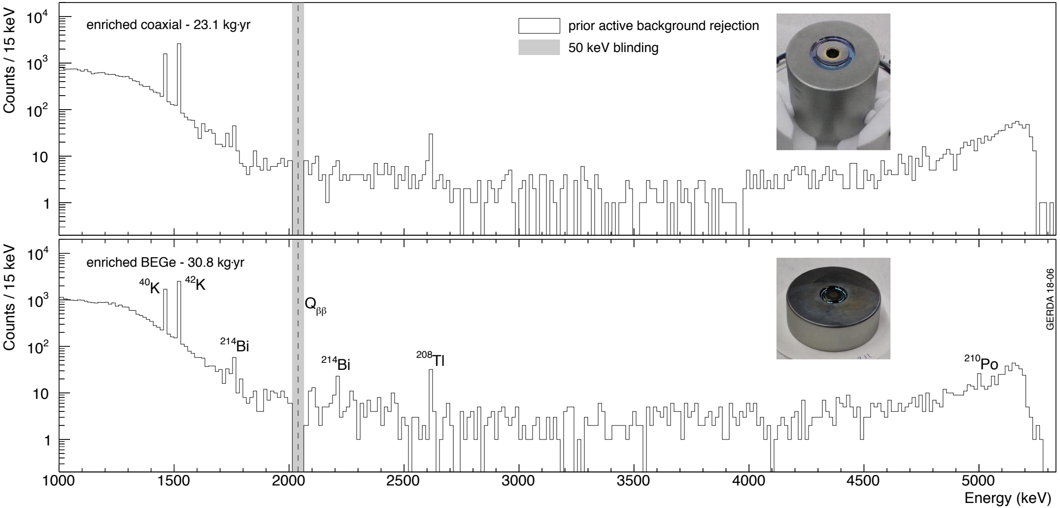


June 2016 10.8 kg·yr [`Nature 544 (2017) 47`]

June 2017 +14.2 kg·yr [`PRL 120 (2018) 132503`]

June 2018 +35.7 kg·yr [`10.5281/zenodo.1287604`]

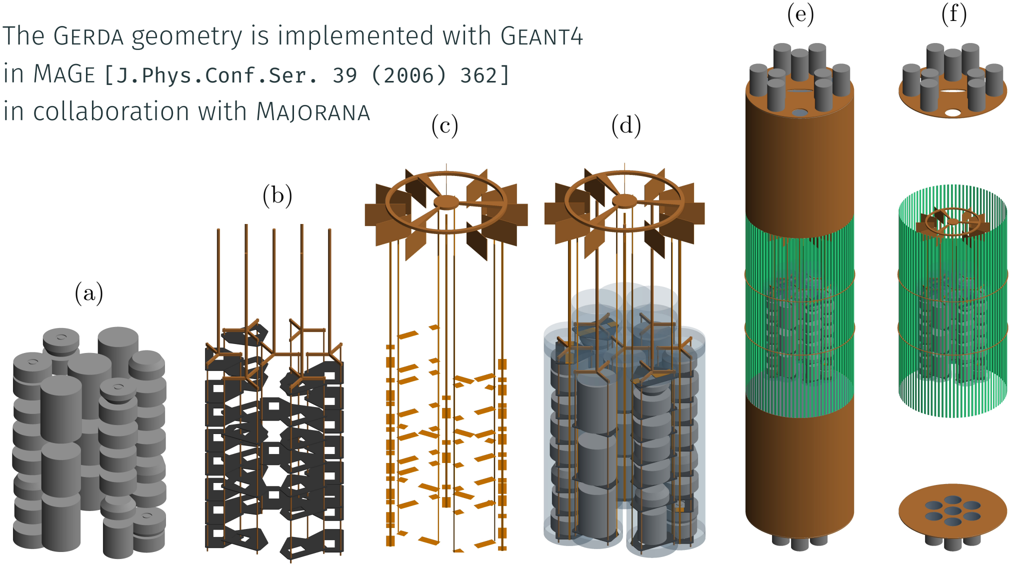
Data (before background cuts)



Background modeling

Background model

The GERDA geometry is implemented with GEANT4
in MAGE [J.Phys.Conf.Ser. 39 (2006) 362]
in collaboration with MAJORANA



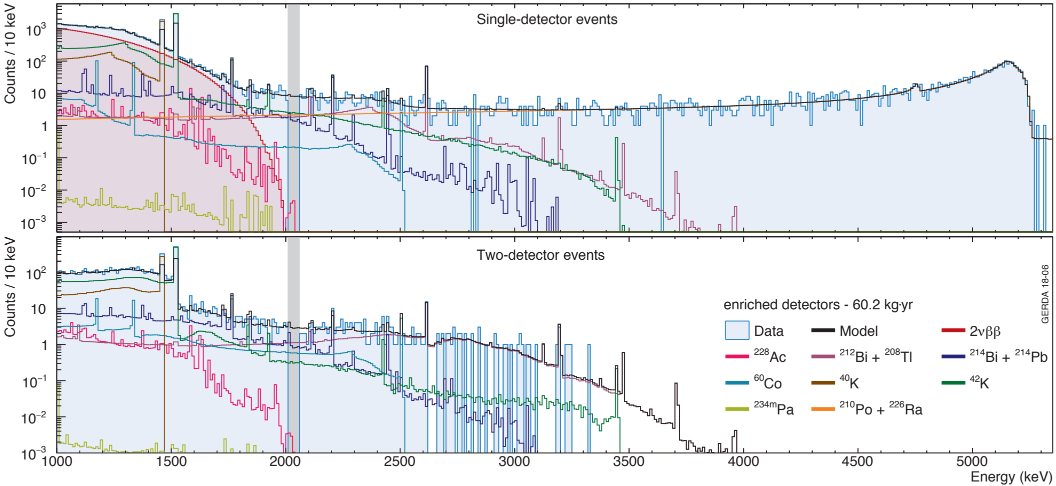
Background model

An accurate background model is essential in order to estimate the background composition around $Q_{\beta\beta}$ and to study the spectral shape of $2\nu\beta\beta$ ($0\nu\beta\beta$ with Majoron emission, Lorentz-violating processes…).

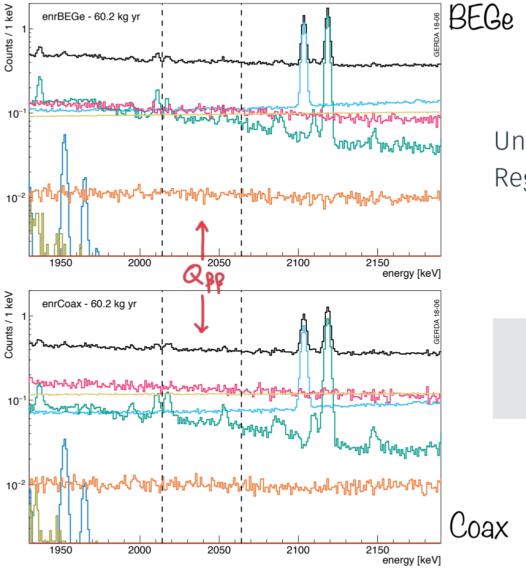
- Bayesian analysis with **screening measurements** as priors
- dedicated model for α-events and for potassium γ-lines
- [new] use two-detector events to better constrain the background

Background model (before cuts)

[preliminary] results for full Phase II exposure



Background model (before cuts) – ROI closeup



Understand composition of the background in the Region Of Interest (ROI):

- what kind of background do we have to fight?
- is the background flat for the $0\nu\beta\beta$ fit?

Background mainly from ^{42}K, α-events, ^{228}Th chain (^{212}Bi/^{208}Tl), ^{238}U chain (^{214}Bi/^{214}Pb)

Background Reduction

Background reduction techniques

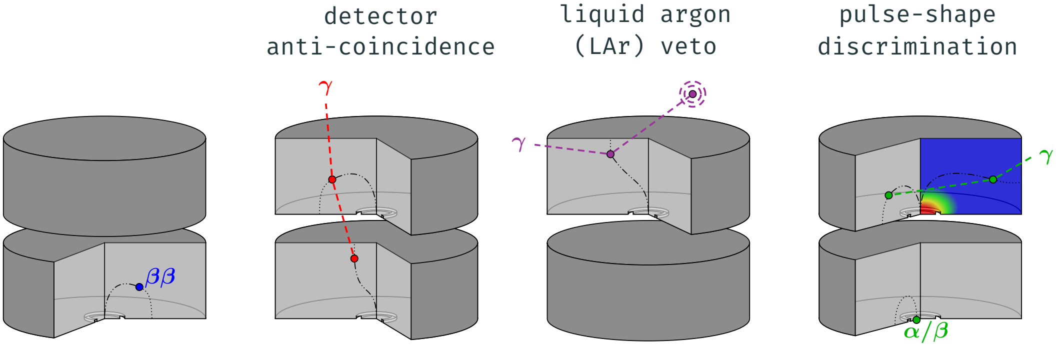


Image credits: Christoph Wiesinger

Liquid argon (LAr) veto

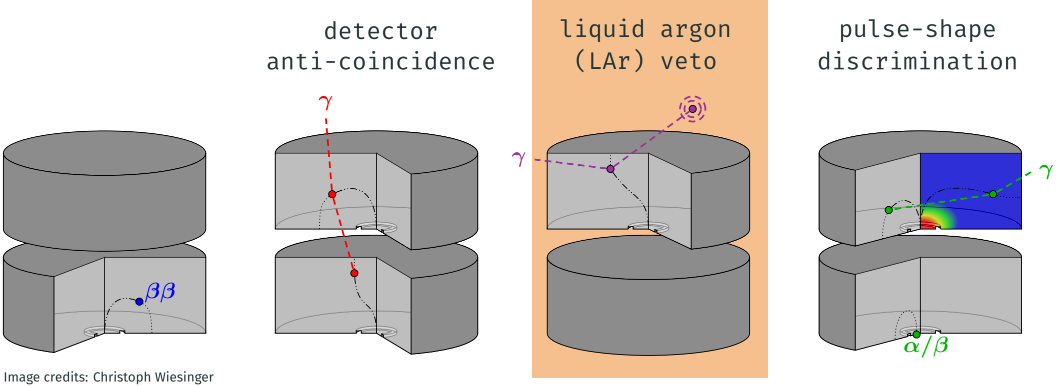
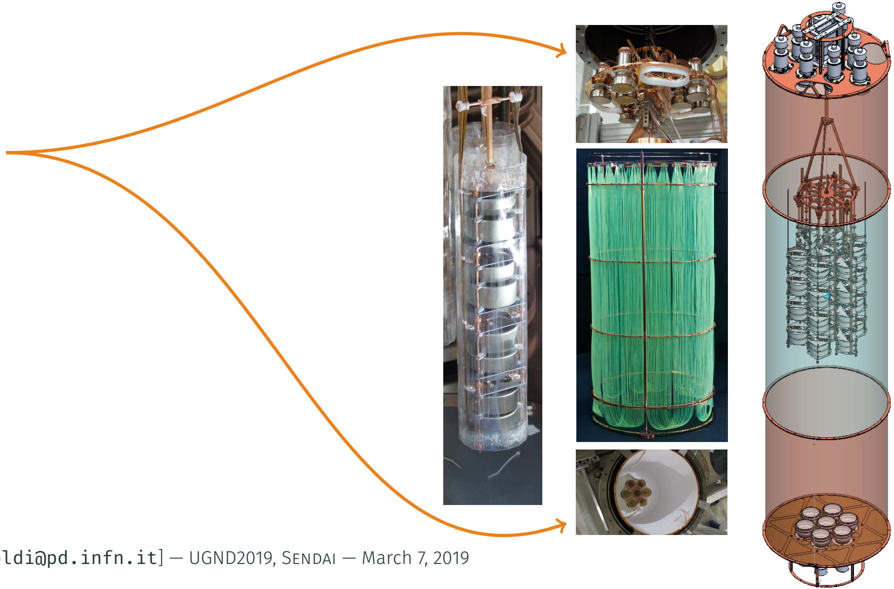


Image credits: Christoph Wiesinger

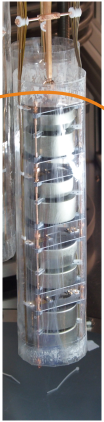
Collecting the LAr scintillation light

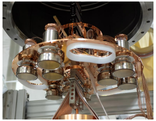
- 16 PMTs

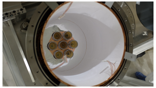


Collecting the LAr scintillation light

- 16 PMTs
- light-guiding fibers + SiPM readout

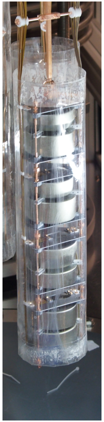


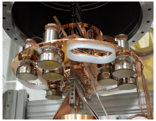


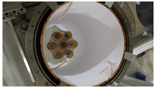


Collecting the LAr scintillation light

- 16 PMTs
- light-guiding fibers + SiPM readout
- nylon mini-shrouds for each string
  $\rightarrow$ mechanical barrier against ^{42}K ions







- 16 PMTs
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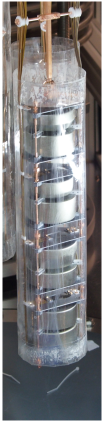
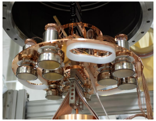
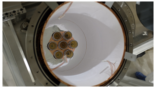
- nylon mini-shrouds for each string
  → mechanical barrier against ^{42}K ions

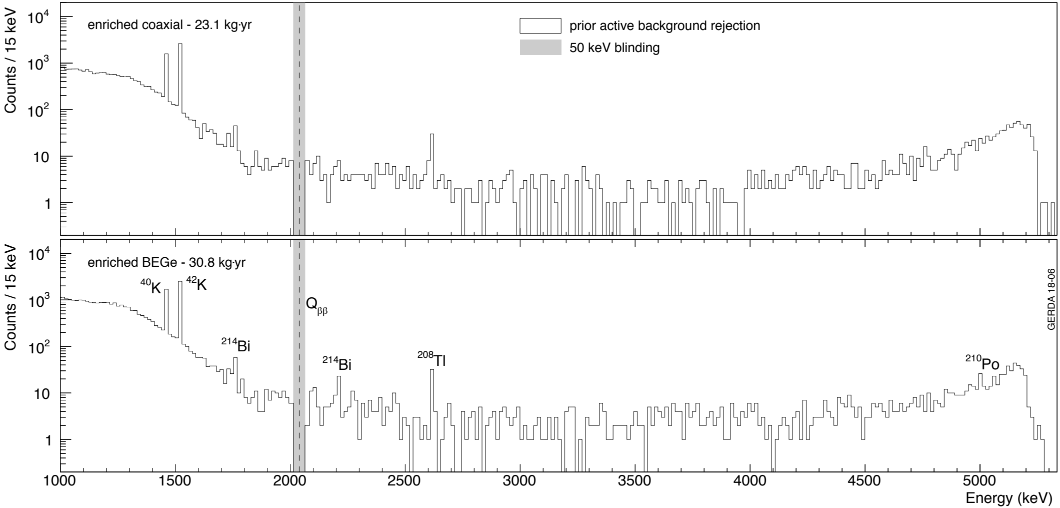
events that deposit energy in Ge and in LAr simultaneously are cut







LAr veto in action



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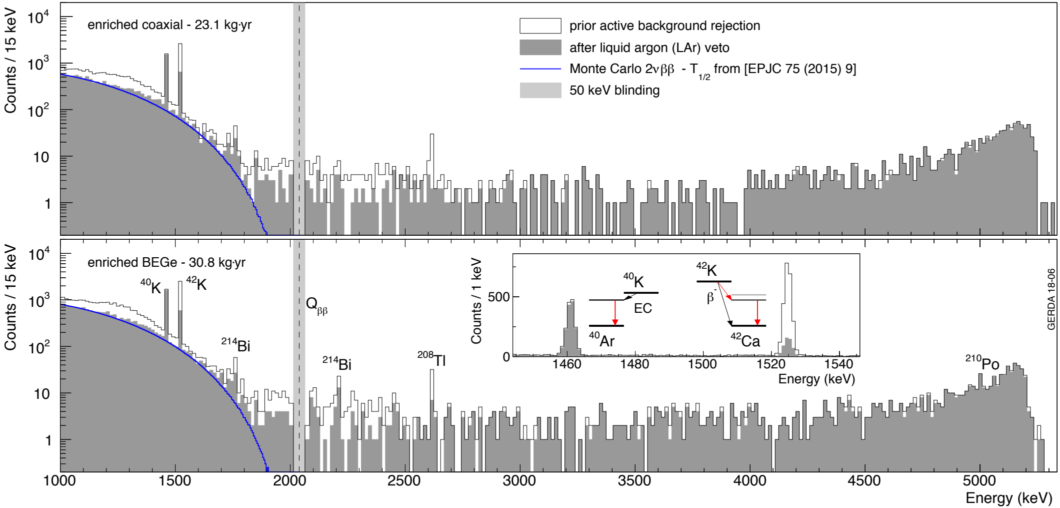

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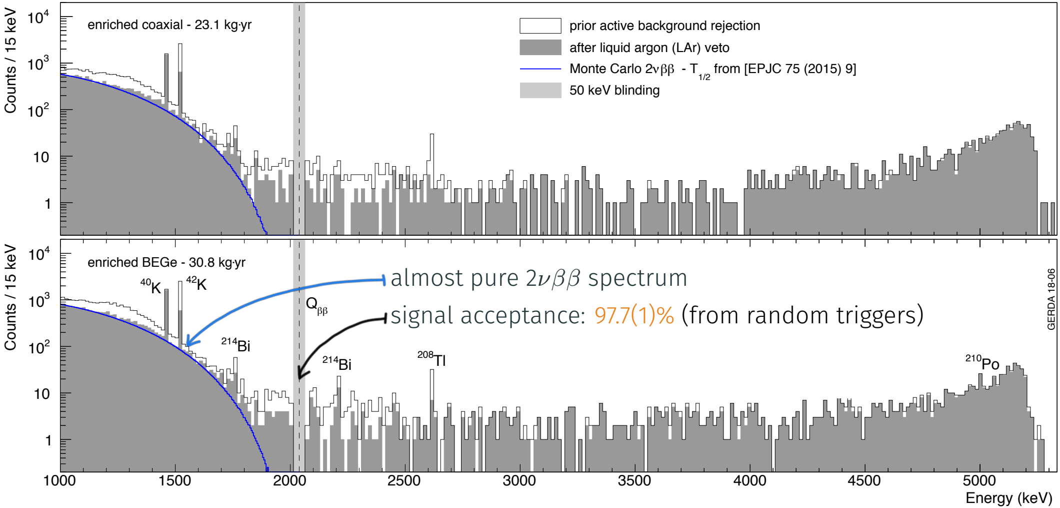


Pulse Shape Discrimination (PSD)

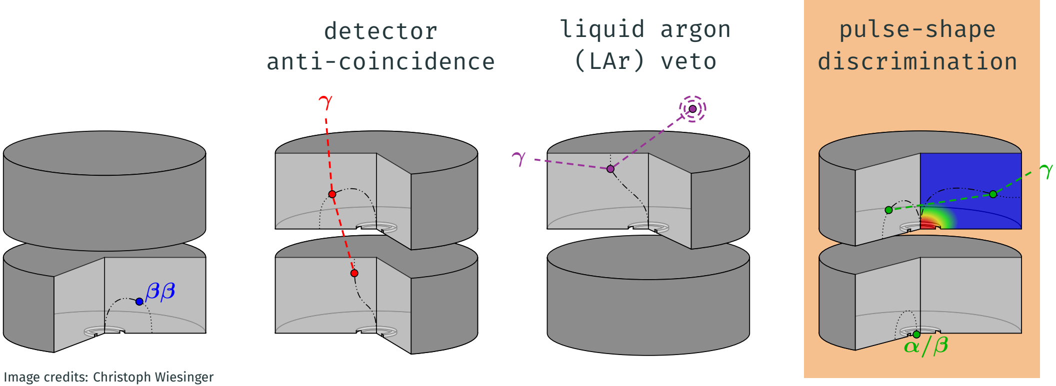
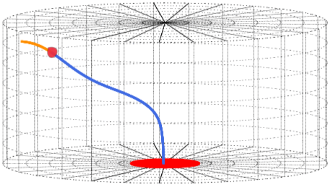


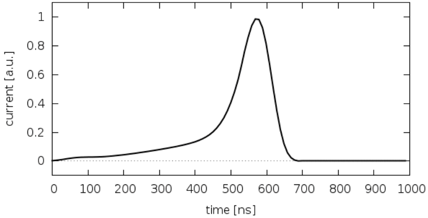
Image credits: Christoph Wiesinger

BEGe event topology

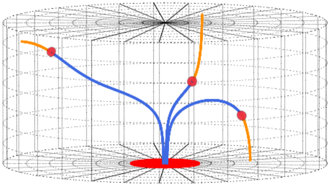
Single Site Event



M. Agostini et al.
JINST 6 (2011) P03005



Multiple Site Event



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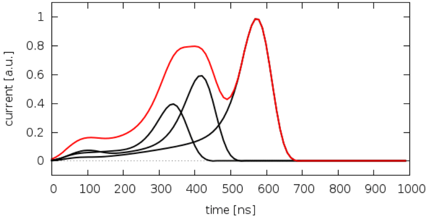
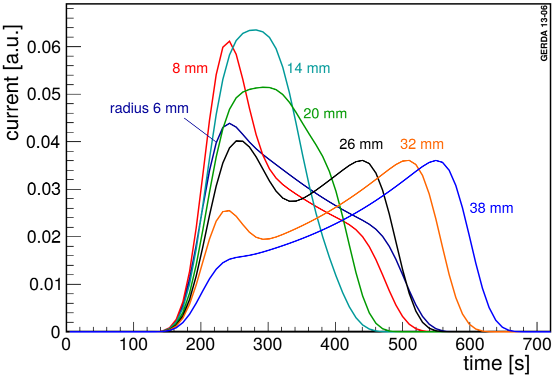
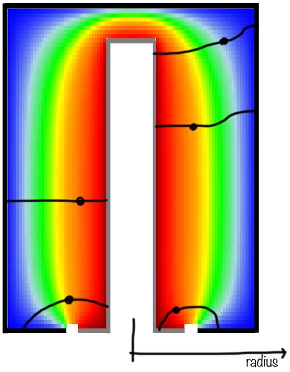


Semi-coaxial event topology

Both electrons and holes contribute to the signal
→ single-site events produce complex shapes





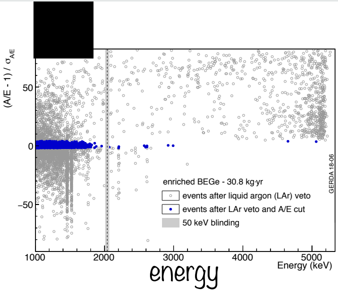
Pulse Shape Discrimination techniques

BEGe $\rightarrow$ cut on A/E parameter

A/E = current amplitude / energy

multi-site events have lower A/E than single-site events

single-site event have very similar pulse shapes



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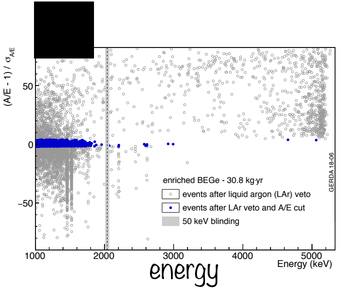
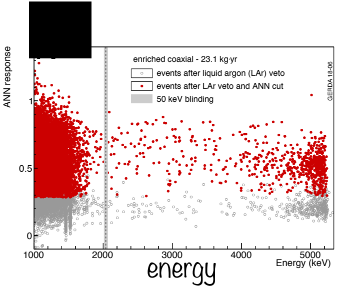
Coax → Neural Network (ANN)

input variables: times when the pulse reaches a given relative height (1% … 99%)





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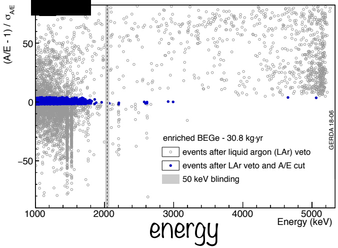
input variables: times when the pulse reaches a given relative height (1% … 99%)

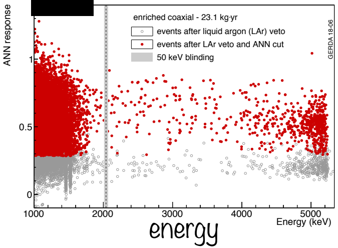
Coax → pulse rise-time cut [new]

to reject also fast surface events

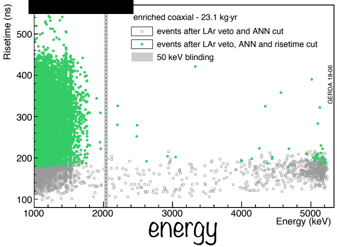
[redacted]



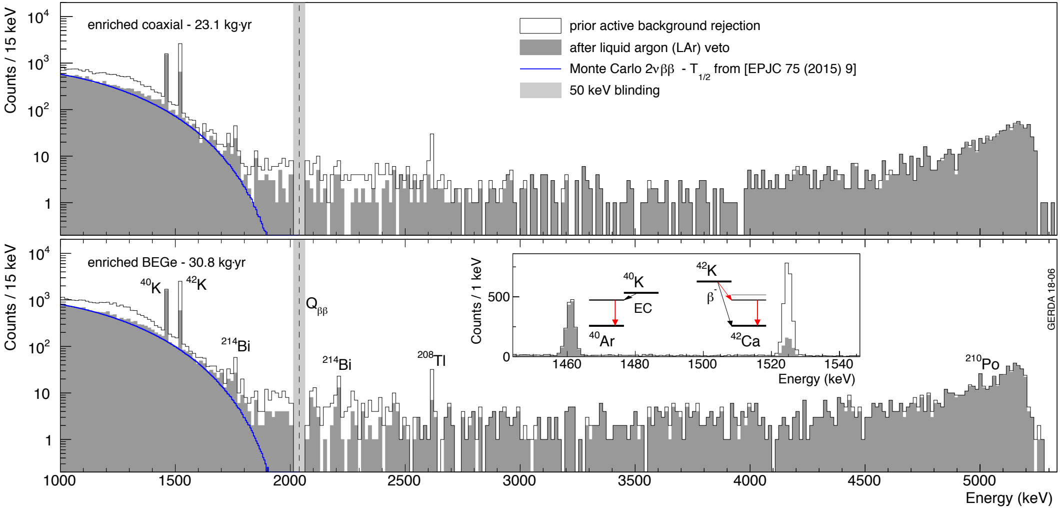
[redacted]



[redacted]



Pulse Shape Discrimination in action



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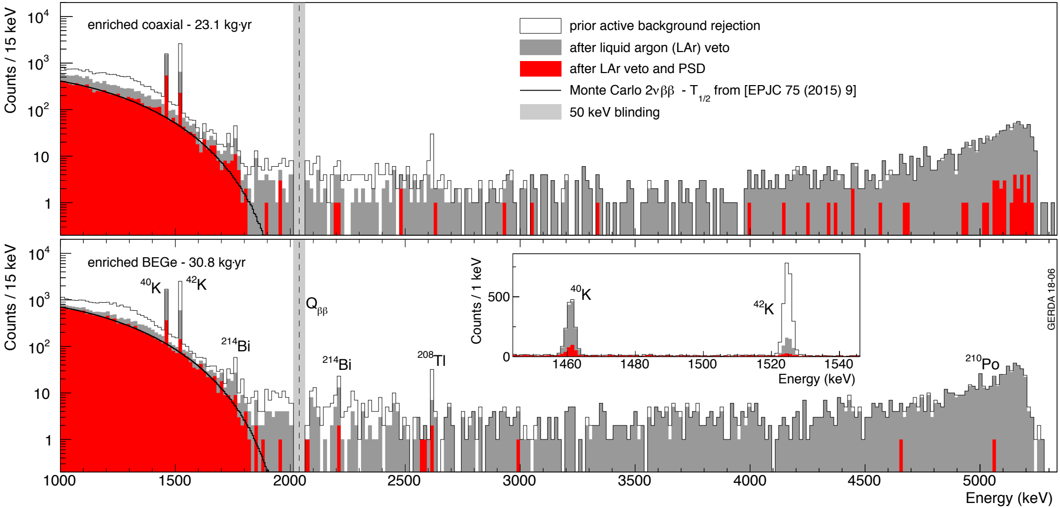

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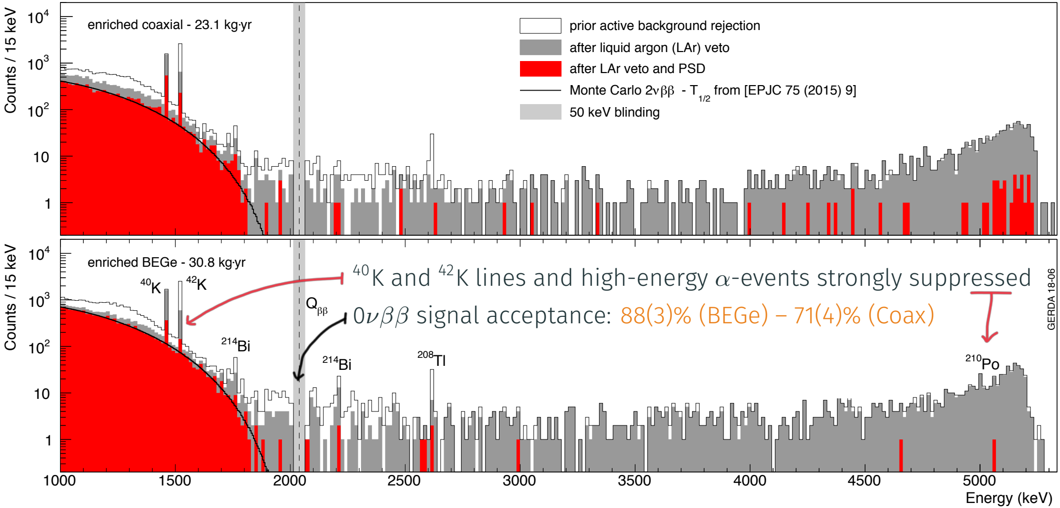


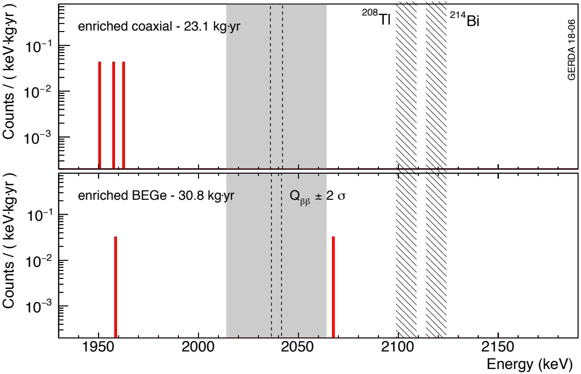
^{40}K and ^{42}K lines and high-energy α-events strongly suppressed

$0\nu\beta\beta$ signal acceptance: 88(3)% (BEGe) – 71(4)% (Coax)

$0\nu\beta\beta$ ANALYSIS

Background Index (BI)

Calculated in [1930, 2190] keV, excluding ±5 keV around ^{208}Tl, ^{214}Bi and $Q_{\beta\beta}$



After removing the blinding window...

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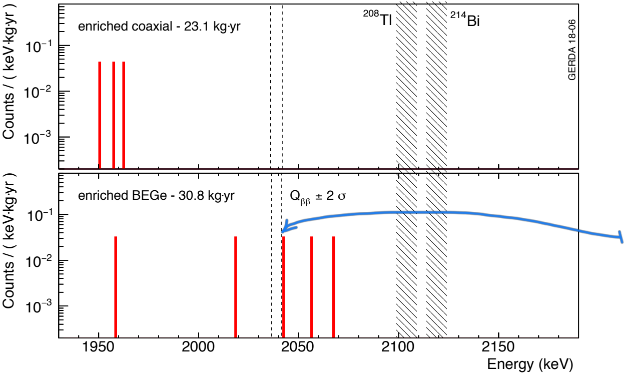

After removing the blinding window...

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

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

Last unblinding: one new event in the BEGe dataset with energy 2042 keV

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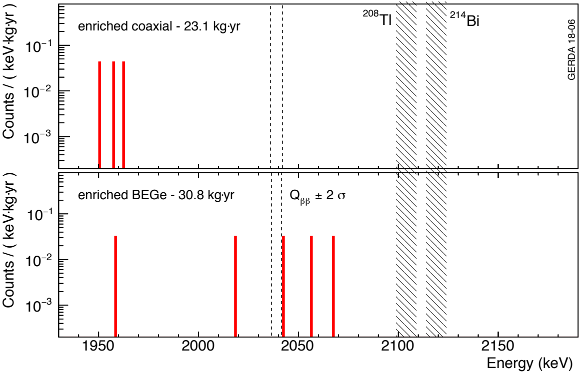

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Last unblinding: one new event in the BEGe dataset with energy 2042 keV

...let's speak of probability then

Statistical analysis

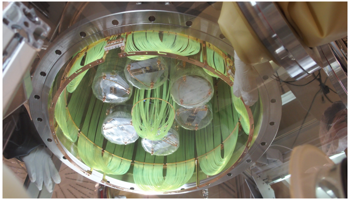
- Total exposure 82.4 kg·yr (including Phase I)
- flat background + gaussian for $0\nu\beta\beta$
- combined fit of 7 dataset

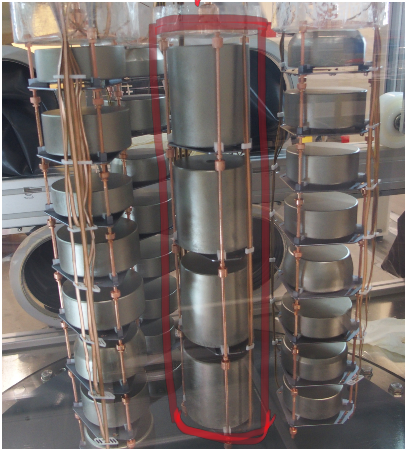
	frequentist	Bayesian
median sensitivity (limit setting)	$1.1 \cdot 10^{26}$ yr	$0.8 \cdot 10^{26}$ yr
best-fit number of $0\nu\beta\beta$ counts	0	0
$T^{0\nu}_{1/2}$	$> 0.9 \cdot 10^{26}$ yr	$> 0.8 \cdot 10^{26}$ yr
$\langle m_{\beta\beta} \rangle$	0.10–0.23 eV	
probability of a stronger limit	63%	59%

GERDA PHASE II+

GERDA Phase II+ upgrade

- New 5 Inverted Coaxial Point-Contact (ICoax) detectors (9 kg)
- exchanged some “dirty” cables
- new LAr veto: denser fibre curtain and middle string curtain
- run until we reach 100 kg·yr exposure





Summary

Summary

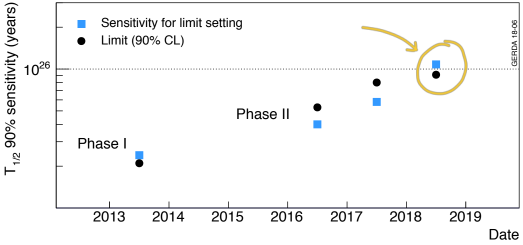
GERDA is a leading experiment in the $0\nu\beta\beta$ search, lowest background ever reached around $Q_{\beta\beta}$. *Background-free* regime maintained for the whole Phase II.

Important milestones of Phase II:

- $6 \cdot 10^{-4}$ cts/(keV·kg·yr) background index
- 10^{26} yr sensitivity for limit setting

2018 GERDA upgrade:

- new inverted coaxial type detectors → more ^{76}Ge mass
- new LAr veto system → improved light yield



Beyond GERDA

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

- new collaboration (GERDA + MAJORANA + ...) formed in October 2016
- goal: 1 ton of ^{76}Ge
- first phase (approved): 200 kg in GERDA
- further background reduction
- up to 10^{27} yr sensitivity in 5 years

backup

Phase I $\rightarrow$ Phase II

Phase I

- exposure: 21.6 kg·yr
- ROI background: $\sim 10^{-2}$ cts/(keV·kg·yr)
- sensitivity: 10^{25} yr

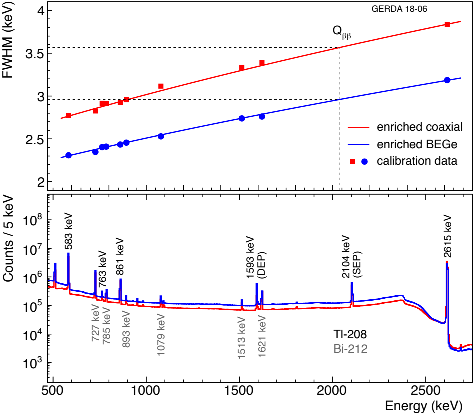
Upgrade and commissioning

- double ^{76}Ge mass
- veto system based on liquid argon (LAr) scintillation light

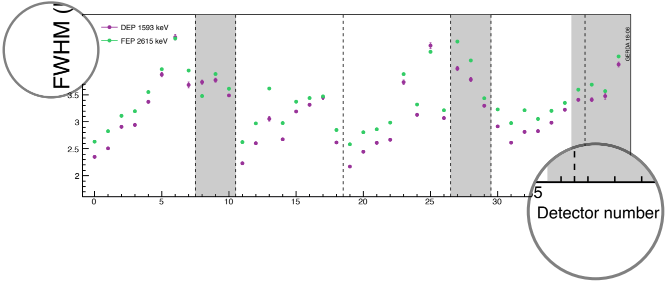
Phase II

- exposure: $\gtrsim 100$ kg·yr [almost]
- ROI background: $\lesssim 10^{-3}$ cts/(keV·kg·yr)
  $\rightarrow$ less than 1 count expected [done]
- sensitivity: 10^{26} yr [done]

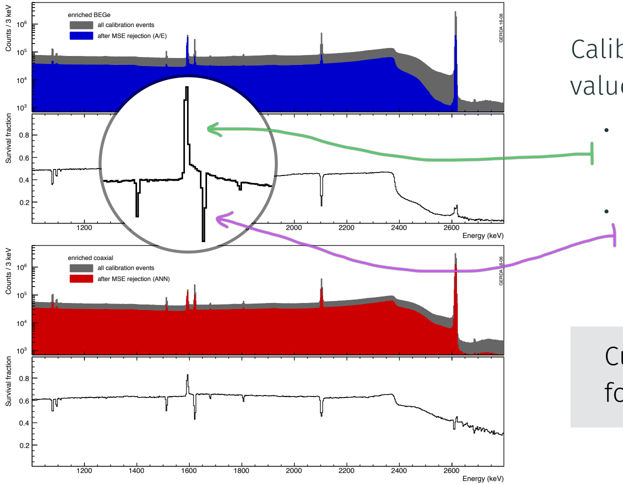
Energy scale



- Weekly calibrations with ^{228}Th sources
- Fluctuations between calibrations < 1 keV
- Resolution at $Q_{\beta\beta}$ better than 0.1% (3-4 keV FWHM)



PSD calibration



Calibration data (^{228}Th) are used to set cut values on PSD paramenters

- Double escape peak (DEP) from ^{208}Tl → single-site event sample
- Full energy peak (FEP) from ^{212}Bi → multi-site event sample

Cut value set at 90% DEP survival both for low side of A/E and ANN response