# Search for neutrinoless double beta decay beyond $10^{26}$ yr half life sensitivity with GERDA

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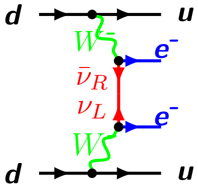
# Aims of $0\nu\beta\beta$ decay search

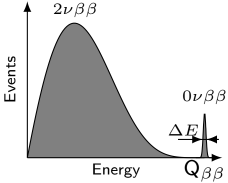
Some open question in neutrino physics:

- What is the mass of $\nu_{lightest}$?
- What is the neutrino mass hierarchy?
- Are neutrinos Dirac or Majorana particles?
- Is lepton number violated in nature?




$0\nu\beta\beta$ -decay

- A(Z, N) $\rightarrow$ A(Z+2, N) + 2e$^-$
- Hypothetical non-SM process, $\Delta$L=2
- The signature: peak at the end-point of electrons energy spectra, at $Q_{\beta\beta}$



# Search for the $0\nu\beta\beta$ decay

The observation is possible for O(10) nuclei

- For expected background rate, BI:

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

- Background-free case:

$$T^{0\nu}_{1/2} \propto \epsilon \cdot Mt$$

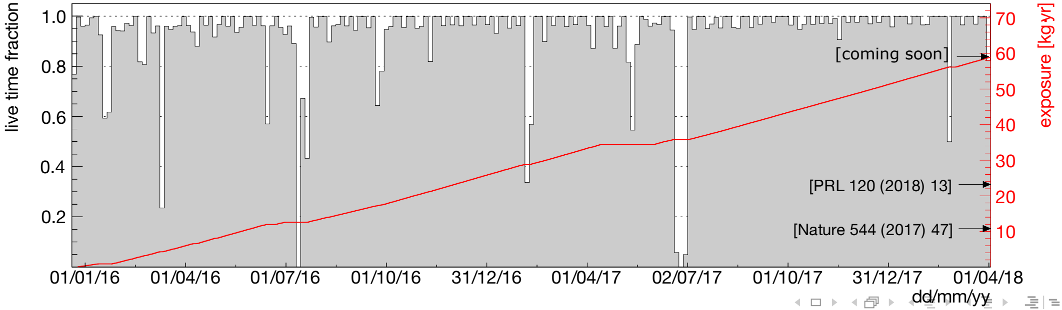
Mt - exposure
BI - backgr. index $\epsilon$ - detection efficiency

## $^{76}$Ge detectors

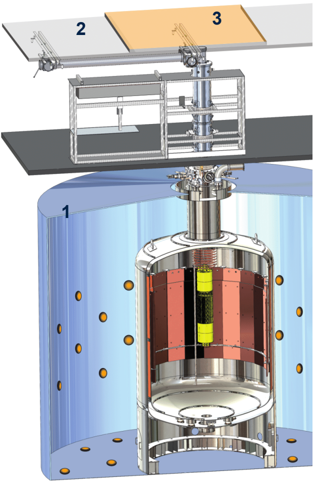
- High intrinsic purity
- Best energy resolution (3 - 4 keV FWHM at $Q_{\beta\beta}$ (≈2039 keV))
- $88\%$ enrichment of $^{76}$Ge

# GERDA data taking

- Phase I finished in 2013 [Phys. Rev. Lett. 111, 122503]
- Phase II since Dec. 2015:
  - Nature 544, 47–52
  - Phys. Rev. Lett. 120, 132503
  - Neutrino2018 - focus of this talk
- Total collected exposure: 82.4 kg·yr



# The GERDA experiment




- Located at the LNGS underground laboratory
  - 3.5 km w.e. of rock

1. Water tank, muon veto
2. Clean room
3. Plastic muon veto system

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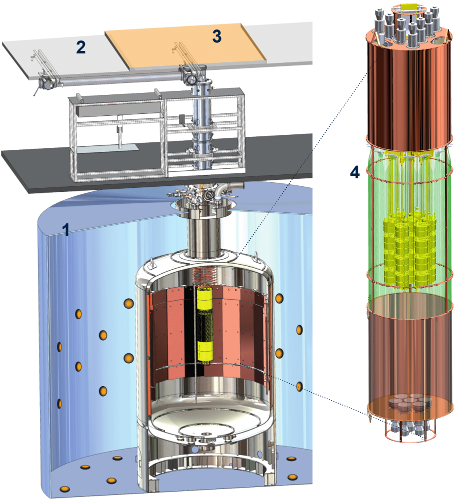


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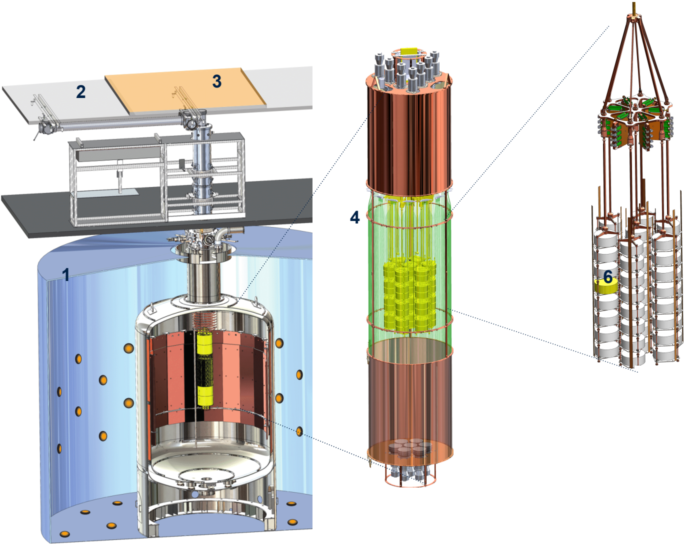


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5. Detector array

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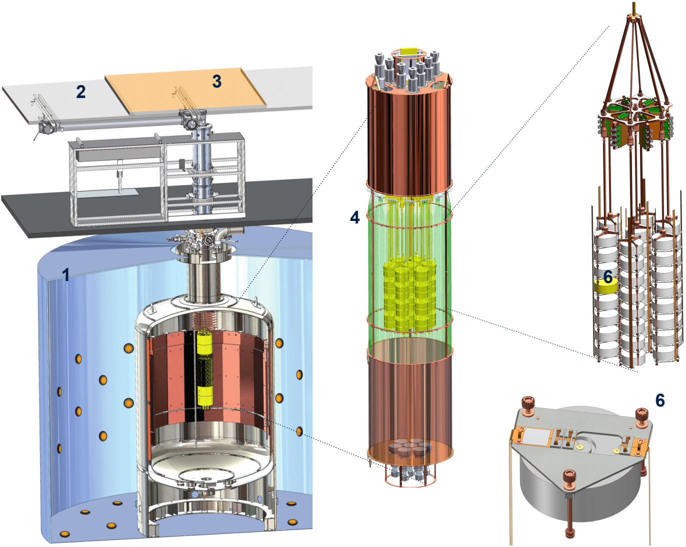


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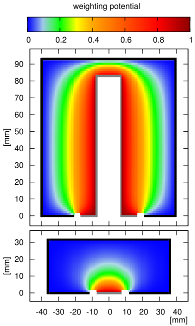
5. Detector array
6. Detector module

# Germanium detectors in GERDA

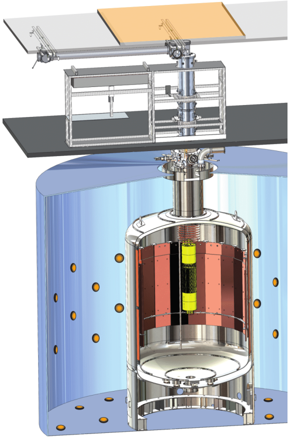



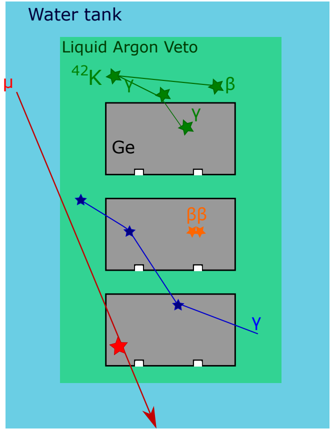

- In GERDA: Semi-Coaxial, broad energy germanium (BEGe) detectors
- Signal readout from p$^+$ - contact: charge collection due to electric potential created by depletion voltage

[Eur.Phys.J. C 78 (2018) 388]
[Eur. Phys. J. C 73 (2013) 2583]

# Background rejection

In coincidence with Ge-detectors, Muon and LAr veto





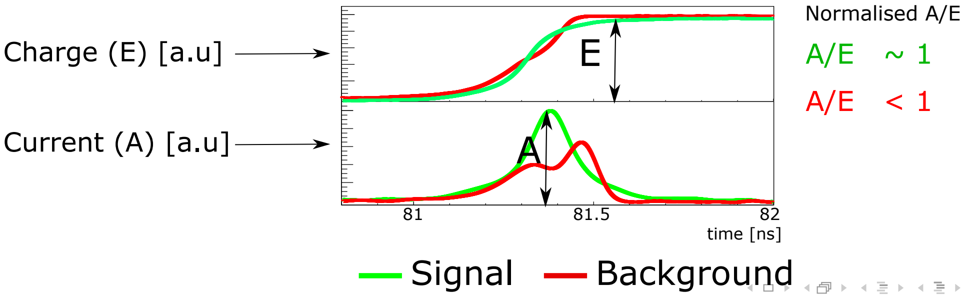

Only events with the energy deposition in a single detector remain

# Pulse Shape Discrimination

There are still $\gamma$ with energy deposition in multiple location or $\alpha$ on the surface

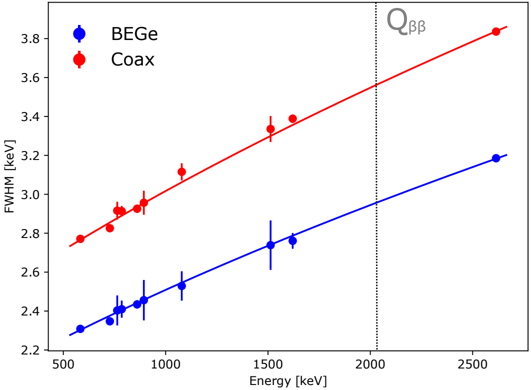
Pulse Shape Discrimination (PSD) [Eur. Phys. J. C 73 (2013) 2583]

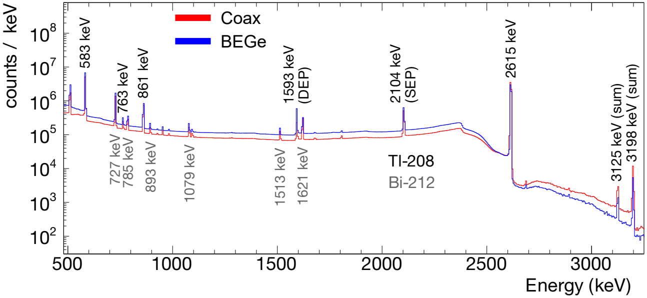
- Charge $\sim$ energy of the event
- Pulse shape depends on event topology



# Energy calibration

- Determine energy scale and resolution
- Weekly exposure to $^{228}$Th sources: O(100) calibrations for the Phase II
- Monitor detectors stability with gamma line from $^{208}$Tl decay at 2.6 MeV

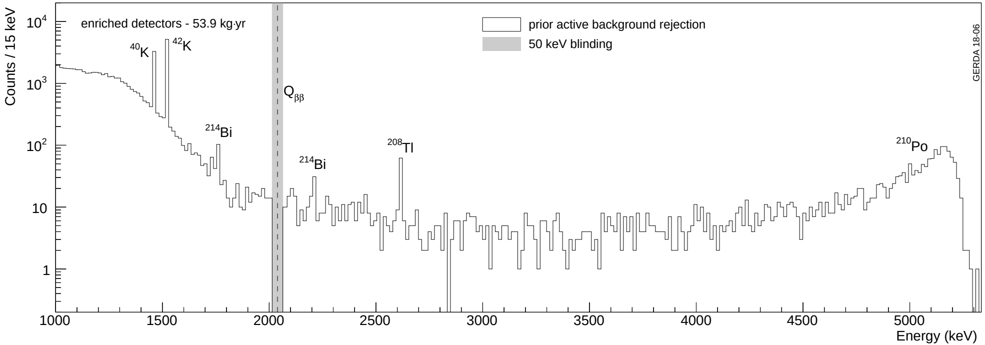



Resolution at $Q_{\beta\beta}$:

- Coaxial: FWHM = 3.6±0.1 keV
- BEGe: FWHM = 3.0±0.1 keV

# GERDA Phase II spectra




- Blind analysis in $Q_{\beta\beta}\pm 25\,keV$

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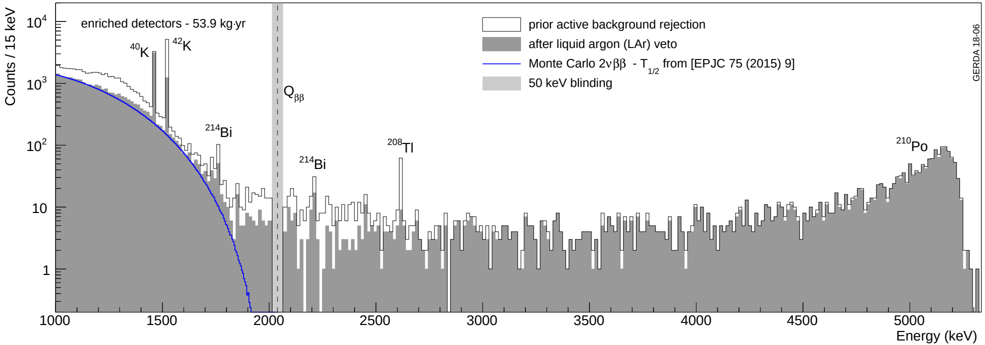


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- After LAr veto

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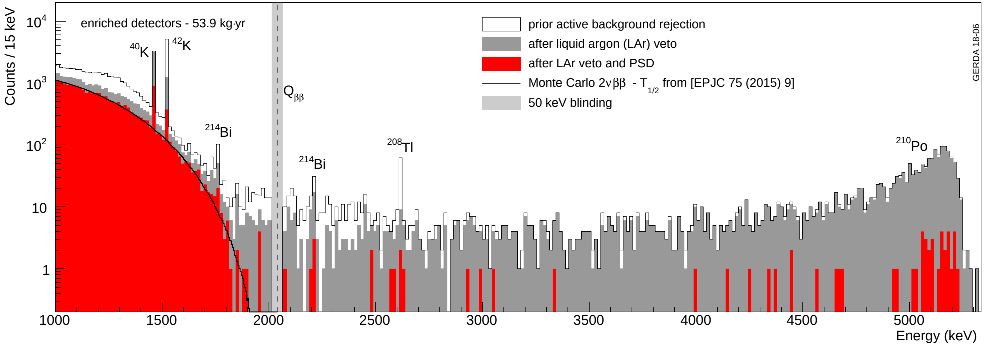
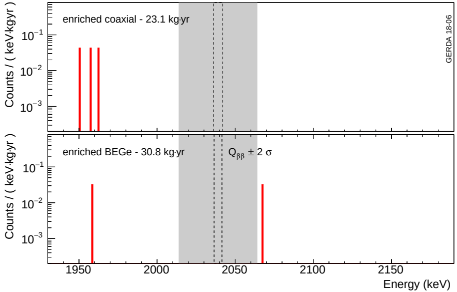



- Blind analysis in $Q_{\beta\beta}$±25 keV
- After LAr veto
- After PSD cut

# Energy spectra in ROI

Region of Interests (ROI): $Q_{\beta\beta} \pm 25$ keV
BI is estimated from 1930 - 2190 keV

- Enriched BEGe:
  - BI: $5.6^{+3.4}_{-2.6} \cdot 10^{-4}$ cts/kg·yr
- Enriched Coaxial:
  - BI: $5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/kg·yr



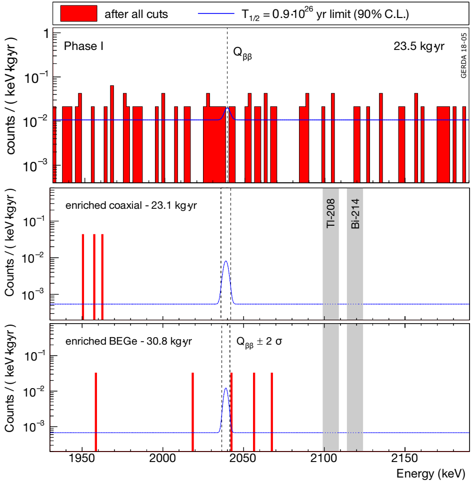

Half life sensitivity does not depend on the BI $\longrightarrow$
GERDA is effectively "background free" experiment

# Unblinding of ROI

Few events in the opened box

Unbinned maximum likelihood fit:

- Best fit value for zero $0\nu\beta\beta$ events
- Frequentist:
  $T^{0\nu}_{1/2} > 0.9{\cdot}10^{26}$ yr. (90% C.L.)
  Median sensitivity:
  $1.1{\cdot}10^{26}$ yr. (90% C.L.)!

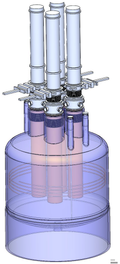


# LEGEND is coming

- Joint effort from GERDA and Majorana collaborations
- Combine the best of the developed techniques
- LEGEND-200:
  - 200 kg of active mass
  - New type of the detectors are currently being tested
  - Location at LNGS
  - Existing GERDA infrastructure
  - BG goal: $0.6 \cdot 10^{-3}$ cts/(FWHM·kg·yr)
  - Will start in 2021
- LEGEND-1000:
  - Location TBD
  - Existing GERDA infrastructure
  - BG goal: $0.1 \cdot 10^{-3}$ cts/(FWHM·kg·yr)
  - The start is connected to funding

GERDA infrastructure

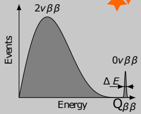
LEGEND-100 cryostat

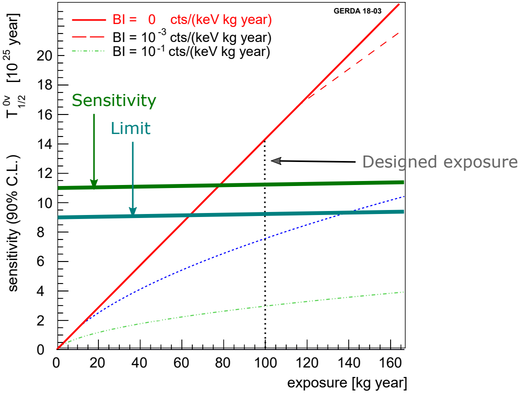


# Conclusion and outlook

GERDA:

- Dec. 2015: PhaseII
- "Background free"
- Excellent FWHM: 2‰ at $Q_{\beta\beta}$



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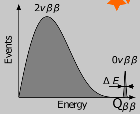
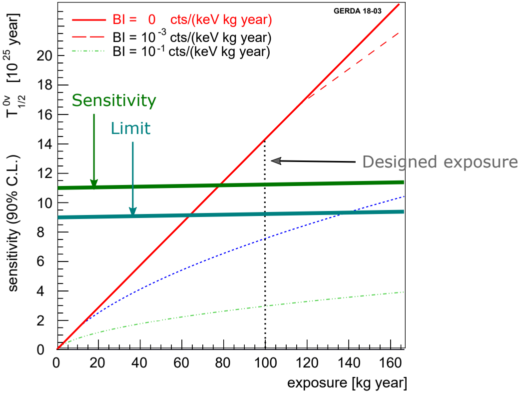



In the near future:

- LEGEND-200: almost fully funded
  will reach sensitivity of $10^{27}$ yr
  start in 2021
- LEGEND-1000: the goal is to reach sensitivity of $10^{28}$ yr




LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

# Thank you!

Bonus slides

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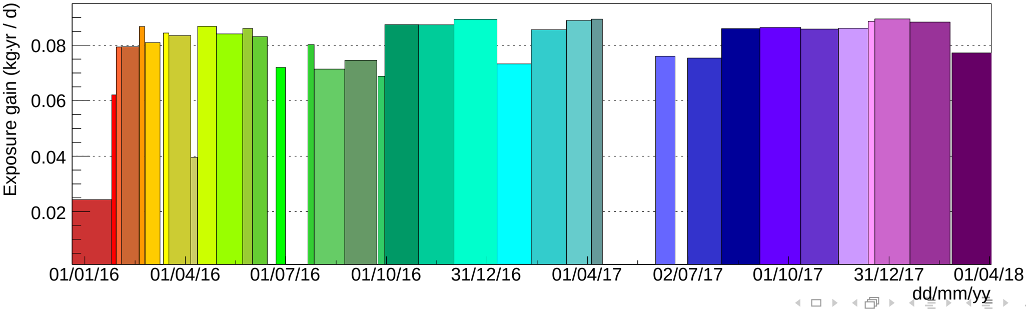

# On the mbb and NME

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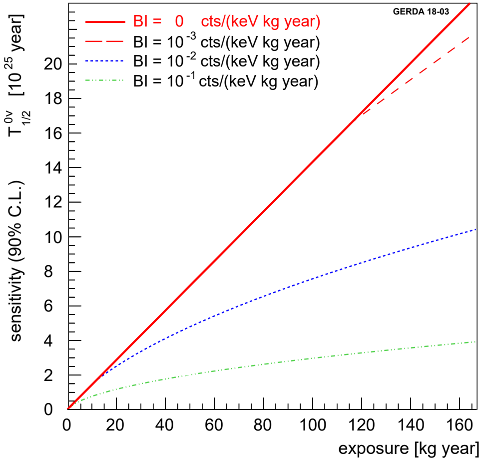

# Effective Majorana mass