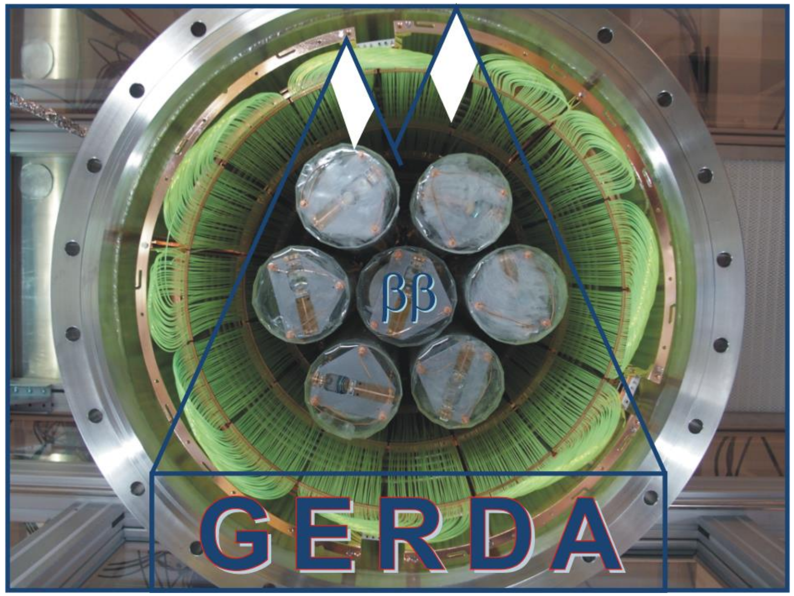

Neutrinoless double beta decay search with the "background free" GERDA experiment

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on behalf of the GERDA collaboration,

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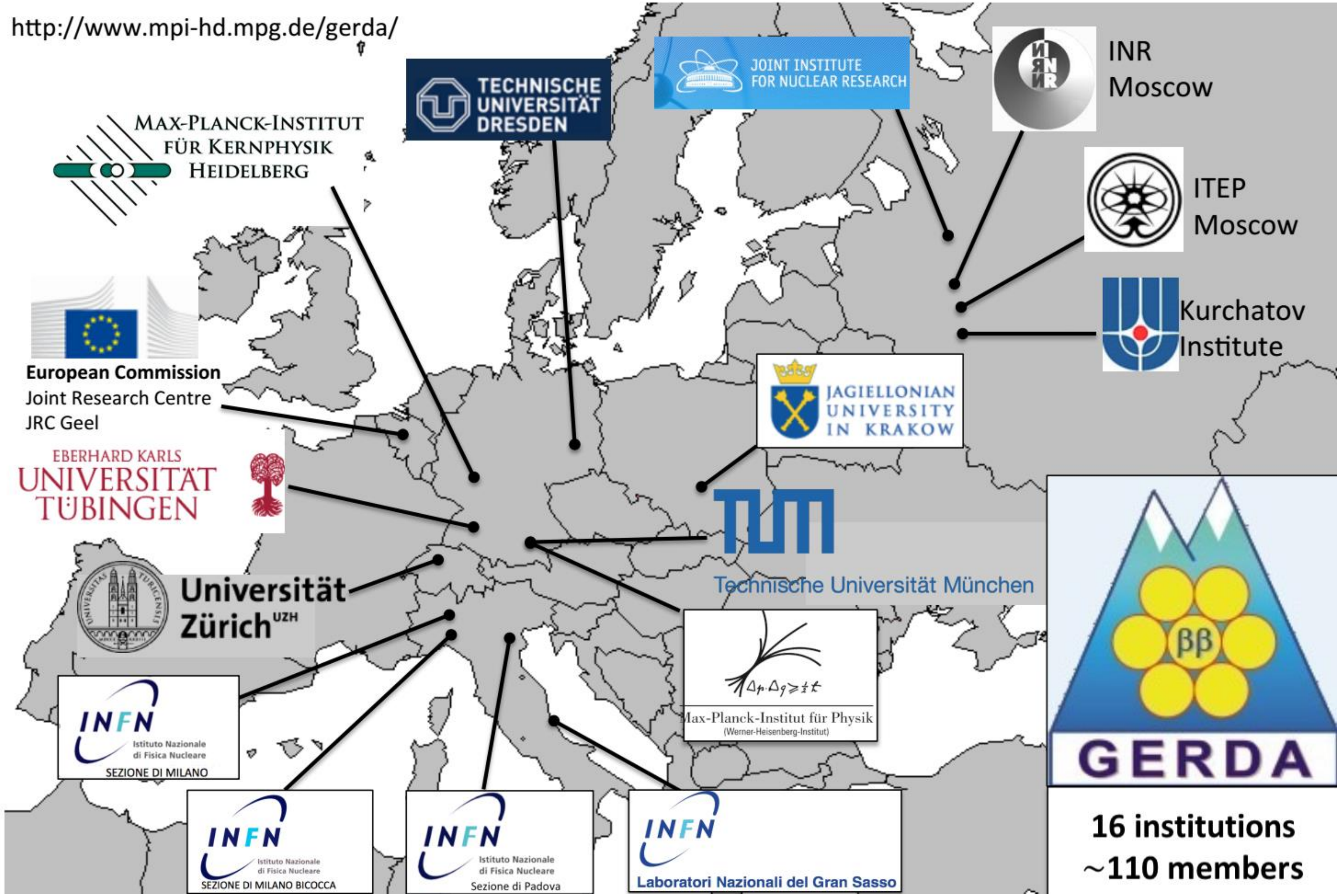
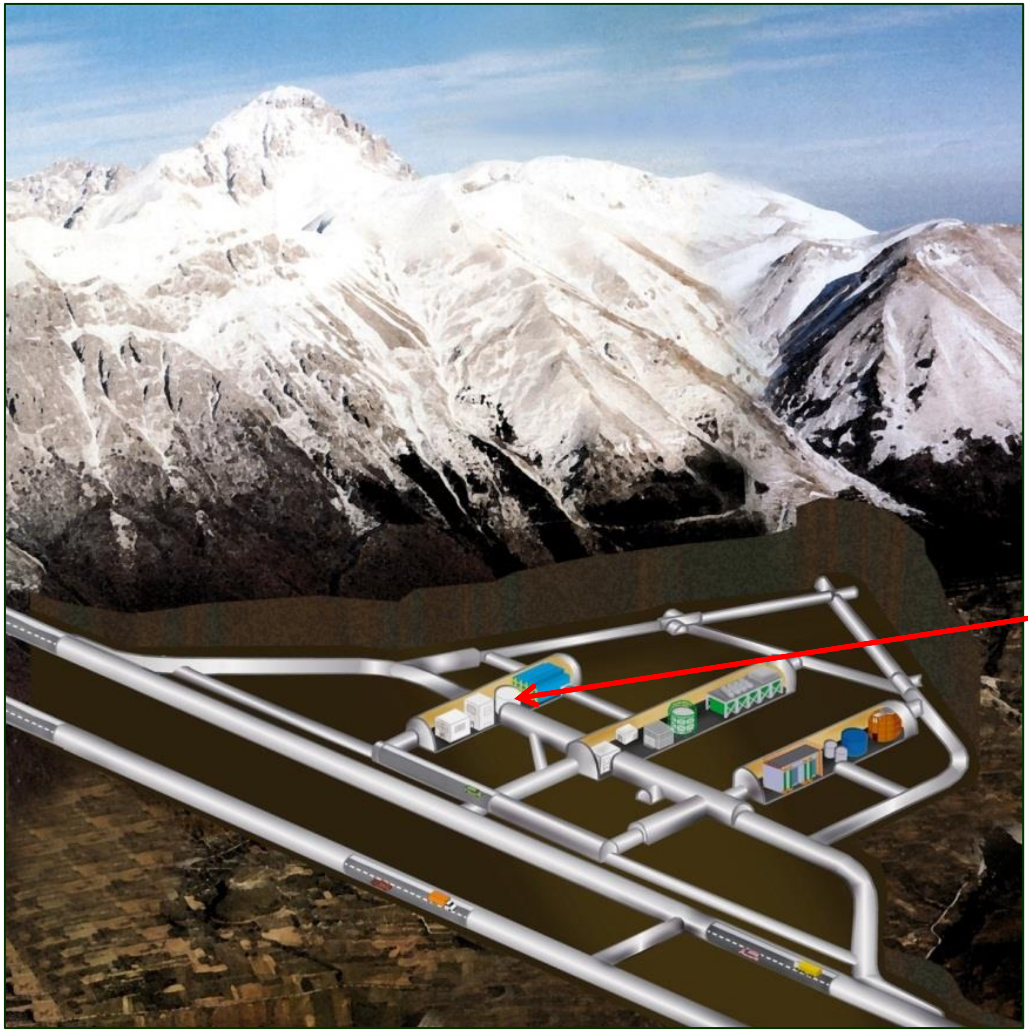
GERDA collaboration



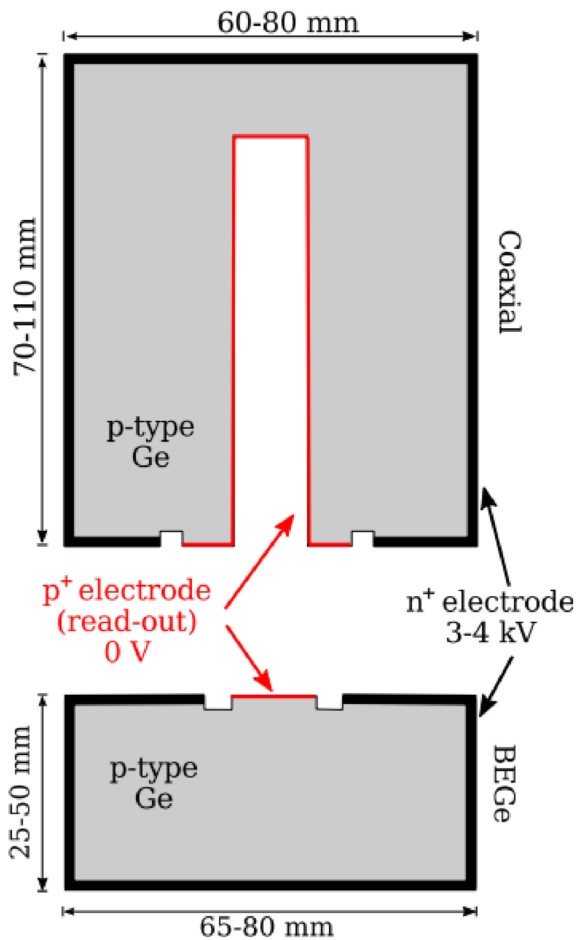
Background reduction

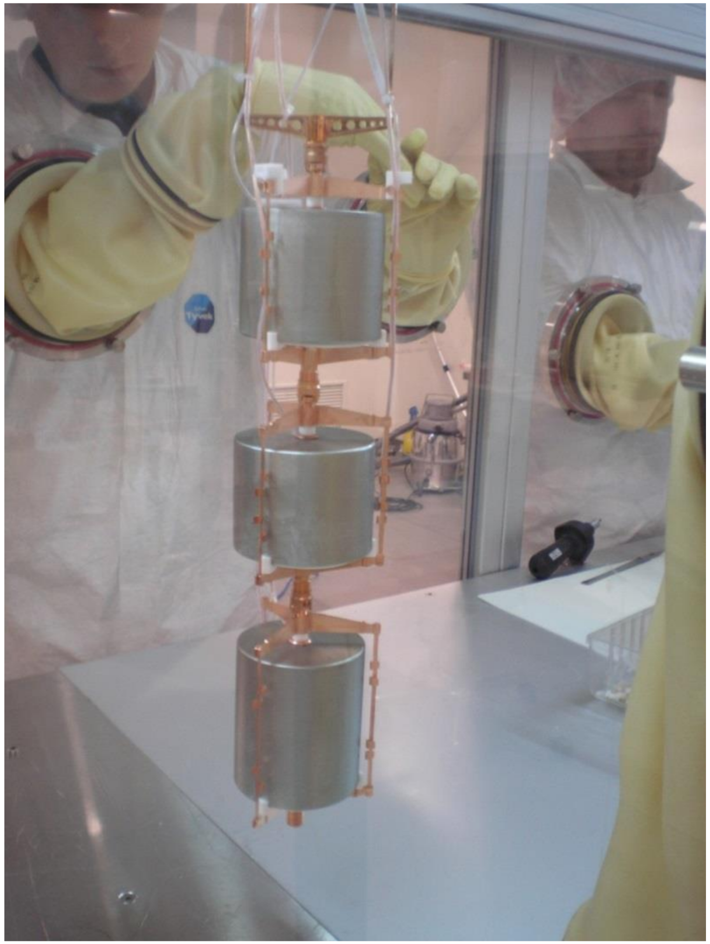
GERDA experimental setup is located at LNGS underground laboratory of INFN (Italy). The rock overburden is equivalent to 3500 m w.e. This allows to reduce μ (~ 10^6 times) and neutron flux induced by cosmic radiation.



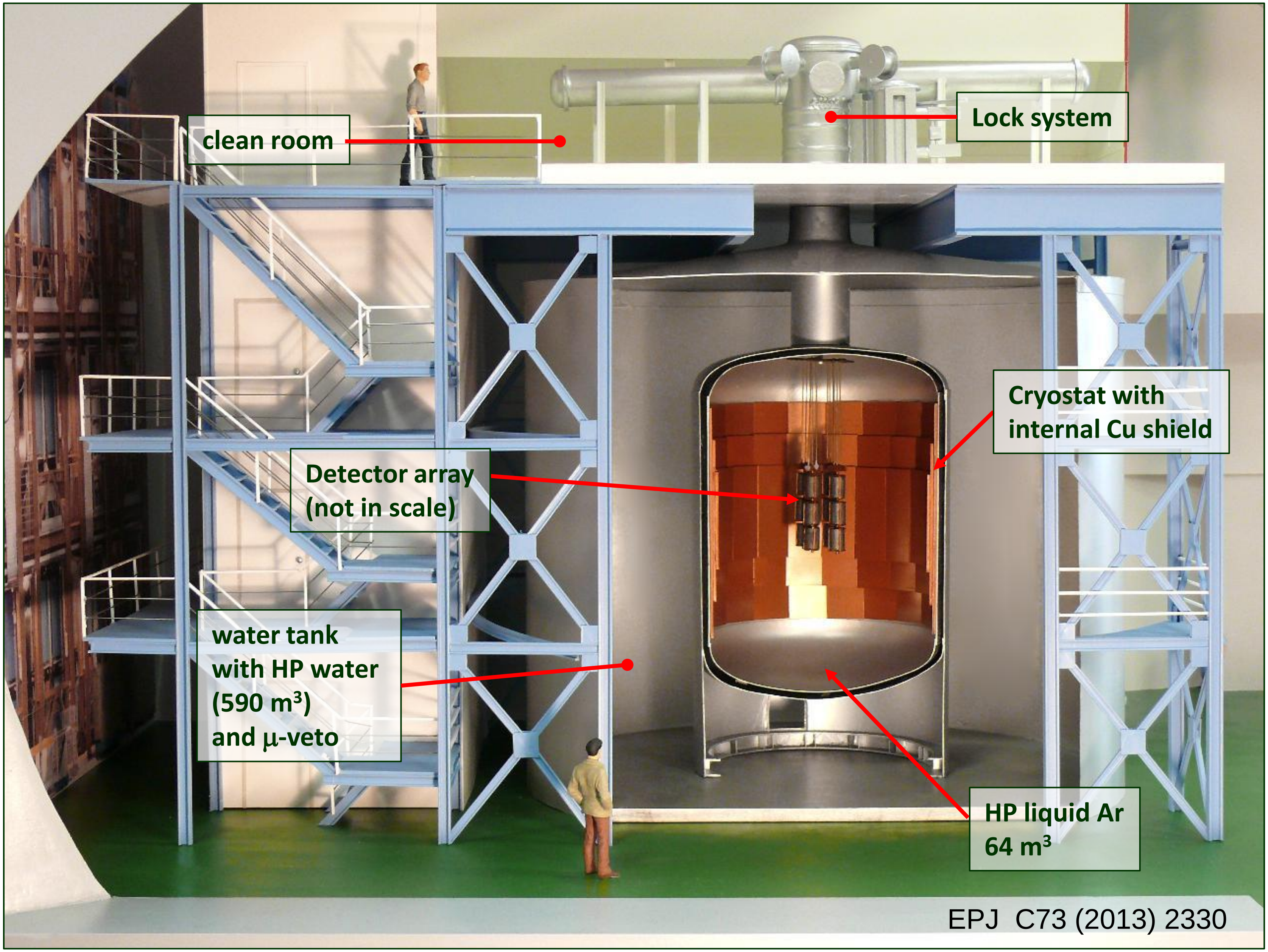
General concept

The search is performed with High Purity Ge detectors enriched to ~ 86% in ^{76}Ge. They are submerged into liquid argon (LAr). LAr shields (passively and actively) from the radiation and cools down the Ge detectors. The Ge diodes have excellent energy resolution and pulse shape discrimination.



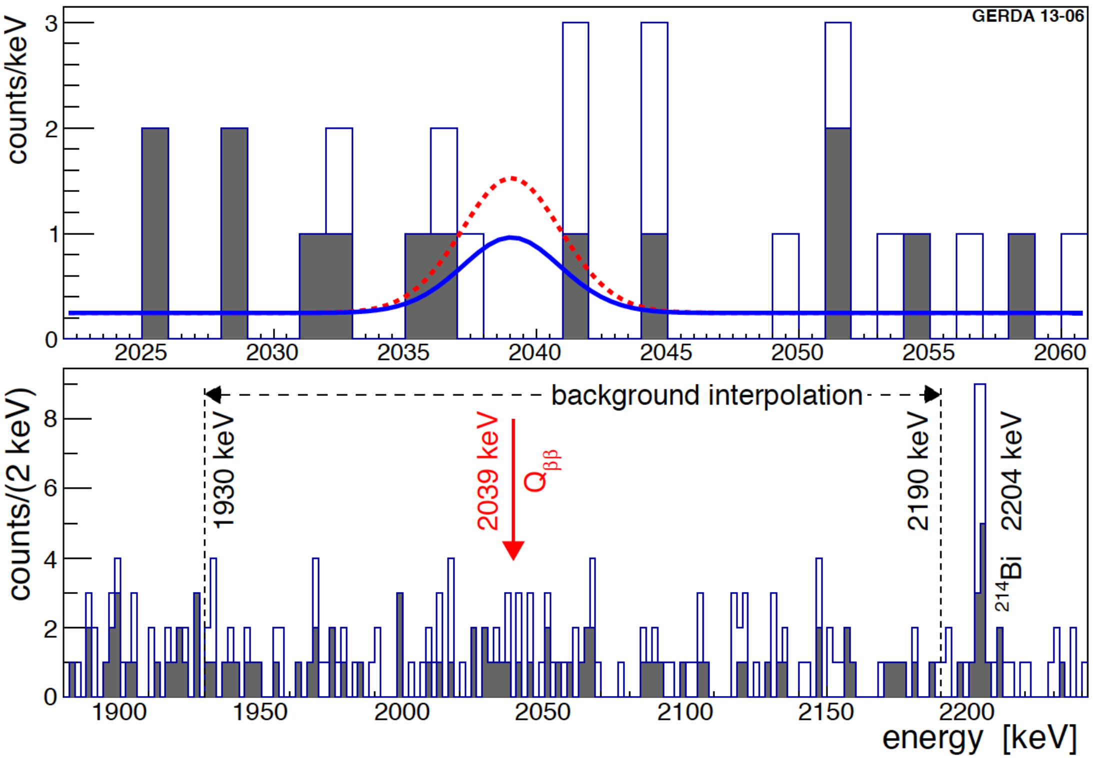


Scheme of GERDA experiment



GERDA Phase I results

Energy spectrum from all enriched Ge detectors with and without the PSD selection.



GERDA: 90% lower limit ($T_{1/2}^{0\nu}$) [Phys. Rev. Lett. 111 (2013) 122503]

Claim: $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ (Phys. Lett. B 586 198 (2004))

Accumulated statistics: 21.6 kg·yr

The limit on the half-life of 0νββ decay is:

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

GERDA Phase I
(Nov 2011 – May 2013)

Background index **~ 10^{-2} cts/(kg·keV·yr).** About 10 better than in previous Ge-based experiments.

No event remain within $Q_{bb} \pm \sigma$ after PSD cut.

The **"claim"** of a signal for 0νββ decay of ^{76}Ge is **ruled out** by GERDA with **99%** probability.

From Phase I to Phase II

If background << 1:

$$T_{1/2}^{0\nu} \propto \varepsilon \cdot a \cdot M \cdot t$$

If background >> 1:

$$T_{1/2}^{0\nu} \propto \varepsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

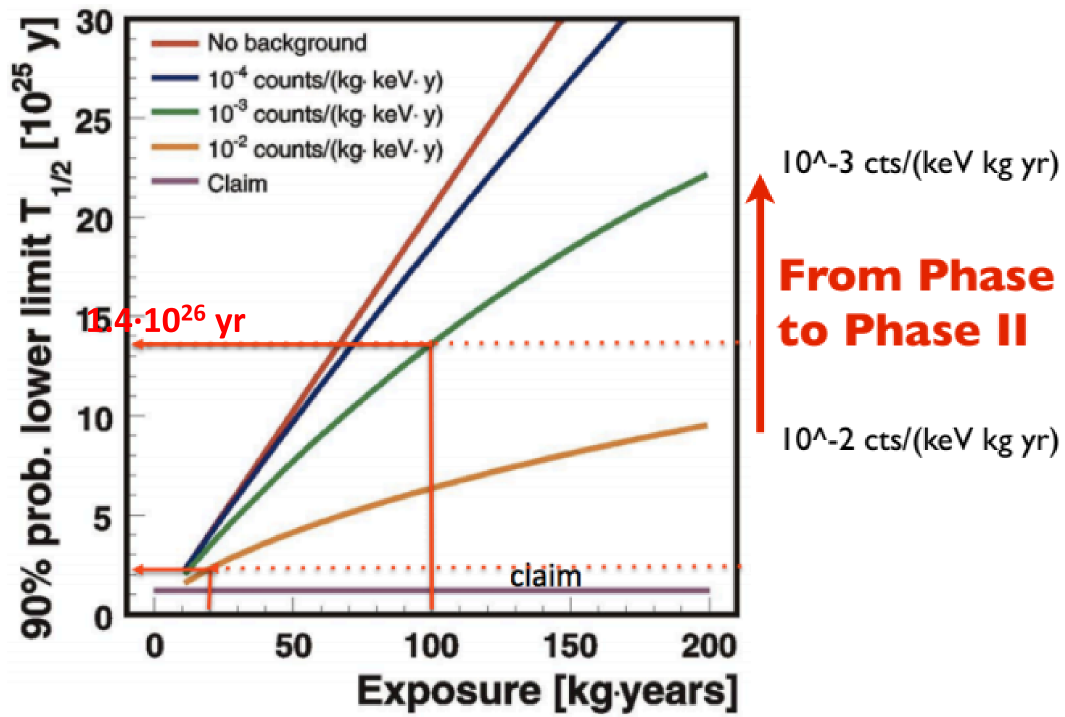
ε Efficiency

$M \cdot t$ Mass·Time = Exposure

a Abundance

ΔE Energy resolution

BI Background Index



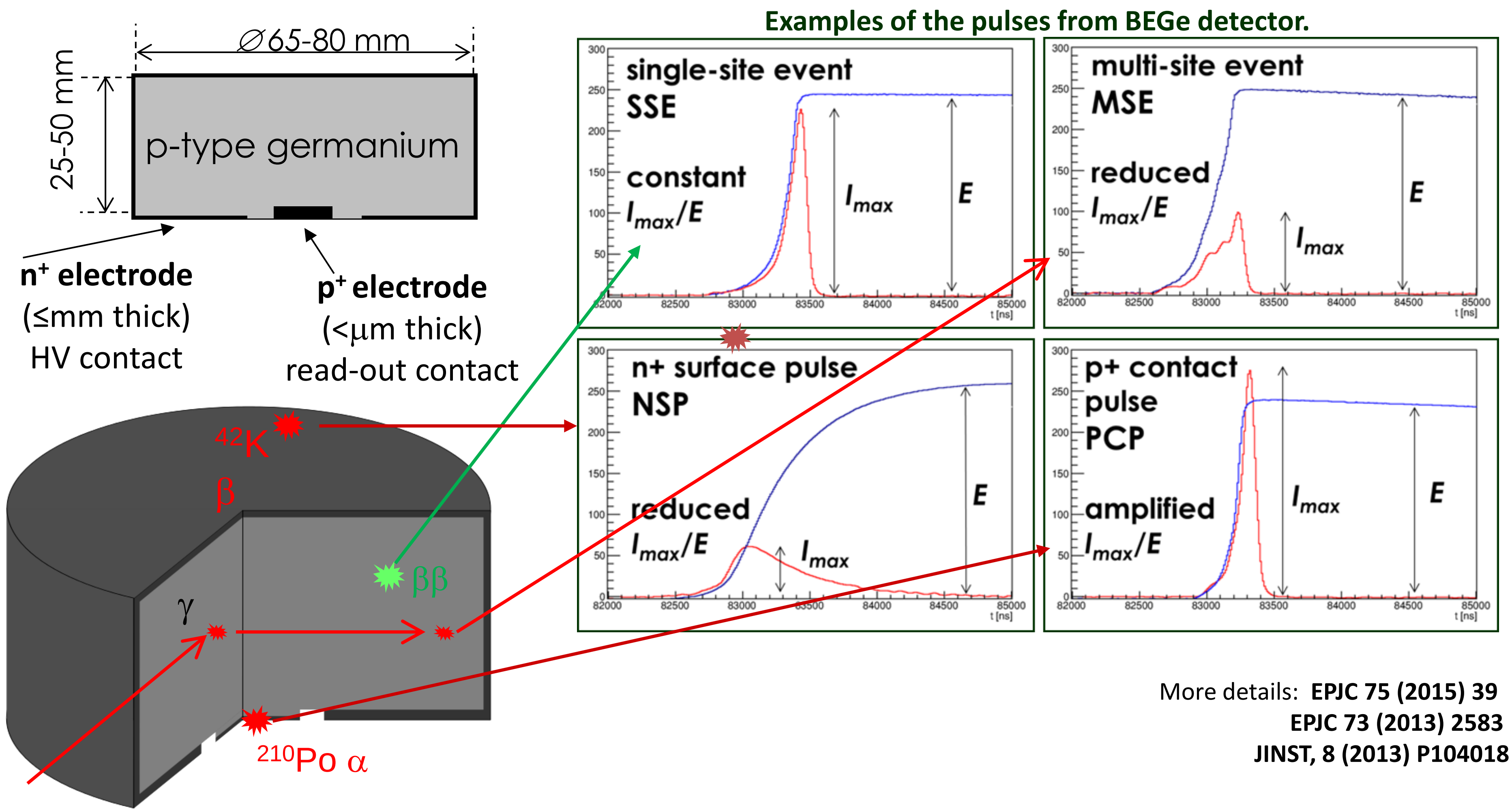
To increase sensitivity of the experiment:

- Increase mass: 30 new BEGe detectors with total mass of ~ 20 kg.
- Exposure: 20 kg·yr → 100 kg·yr (within 3 years).
- Reduce background: (from **10^{-2} cts/(keV kg yr)** → **10^{-3} cts/(keV kg yr)**):
  - ✓ Power Pulse Shape Discrimination (PSD) of new BEGe detectors.
  - ✓ LAr light scintillation veto.
  - ✓ Cleaner materials.

GERDA Phase II preparations

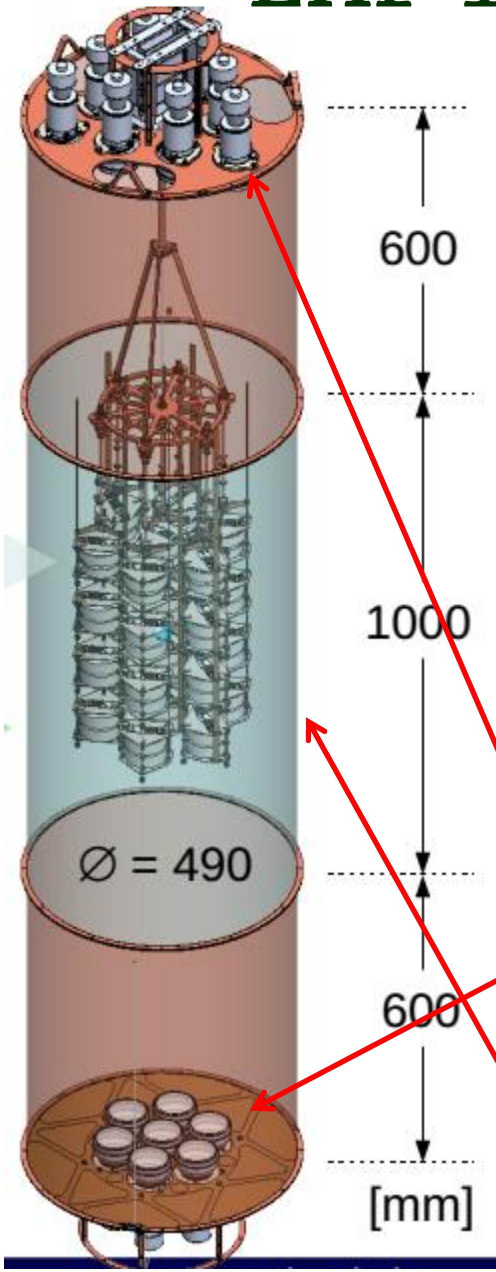
BEGe detectors of GERDA Phase II:

- Better energy resolution.
- Powerful pulse shape discrimination.



More details: **EPJC 75 (2015) 39**
EPJC 73 (2013) 2583
JINST, 8 (2013) P104018

LAr light instrumentation



LAr scintillation veto works in the coincidence with Ge detectors allowing to suppress background events which deposit energy in LAr.

PMTs readout consist of 16 3” PMTs

Scintillation fibers and SiPM readout

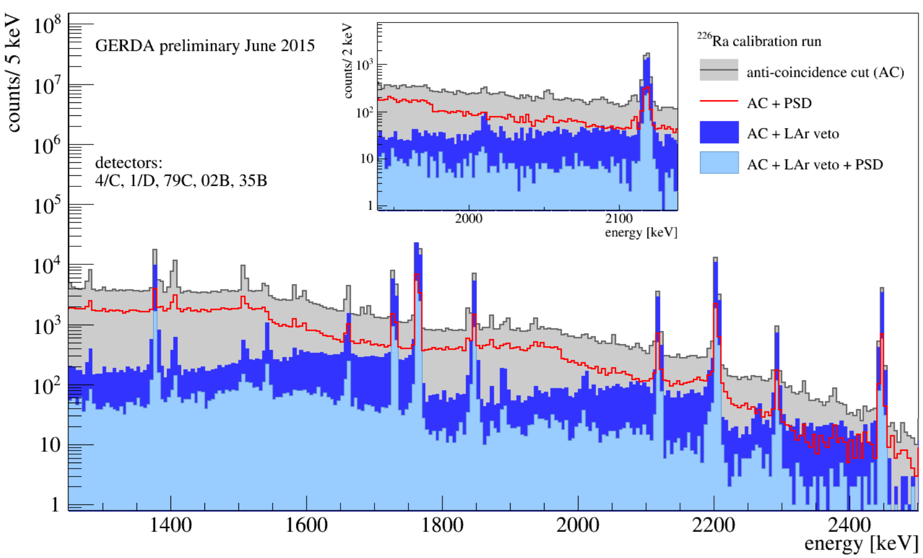
LAr veto performance

LAr veto lowered into the cryostat

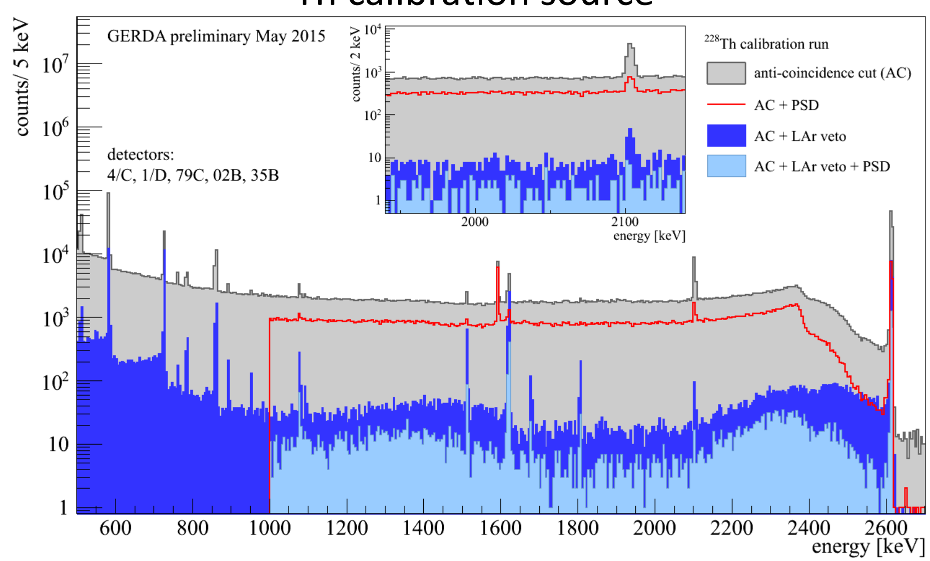
The performance of LAr veto in GERDA Phase II was tested with calibration sources.

Combined suppression factors:
29±3 (for ^{226}Ra) and **345±25** (for ^{228}Th).
Suppression factors depend on isotopes, location and detector configuration.

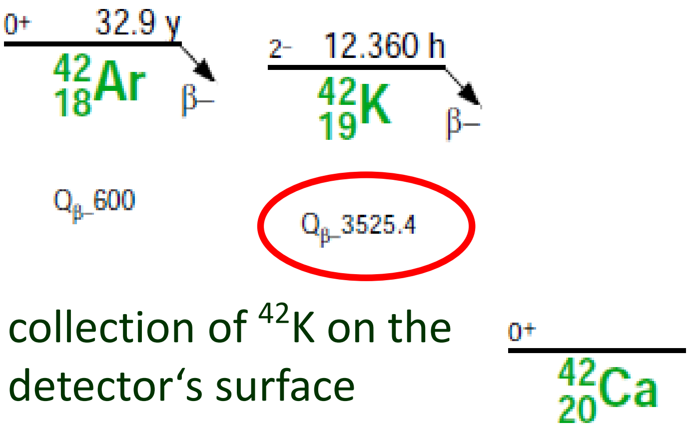
^{226}Ra calibration source



^{228}Th calibration source



^{42}Ar background mitigation



In Phase I mini-shroud made from a copper foil placed around the detectors was used to decrease a collection of ^{42}K ions towards to the detector. For GERDA Phase II copper MS would block the scintillation light -> decrease efficiency of LAr veto significantly.
Transparent **nylon mini-shroud (NMS)** covered with wavelength shifter is used for Phase II.

Copper MSs for Phase I

NMS for Phase II in UV light

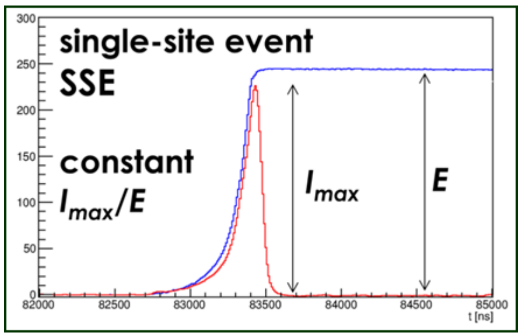
Thanks to Princeton for providing such clean nylon foils (which was developed for Borexino).

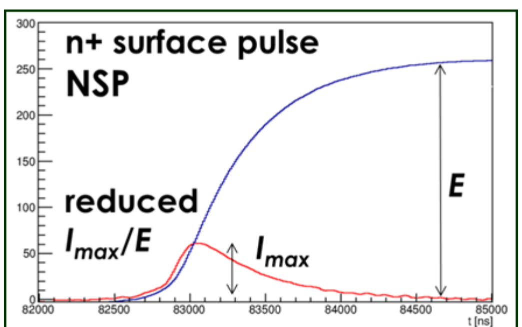
NMS around the detector’s string

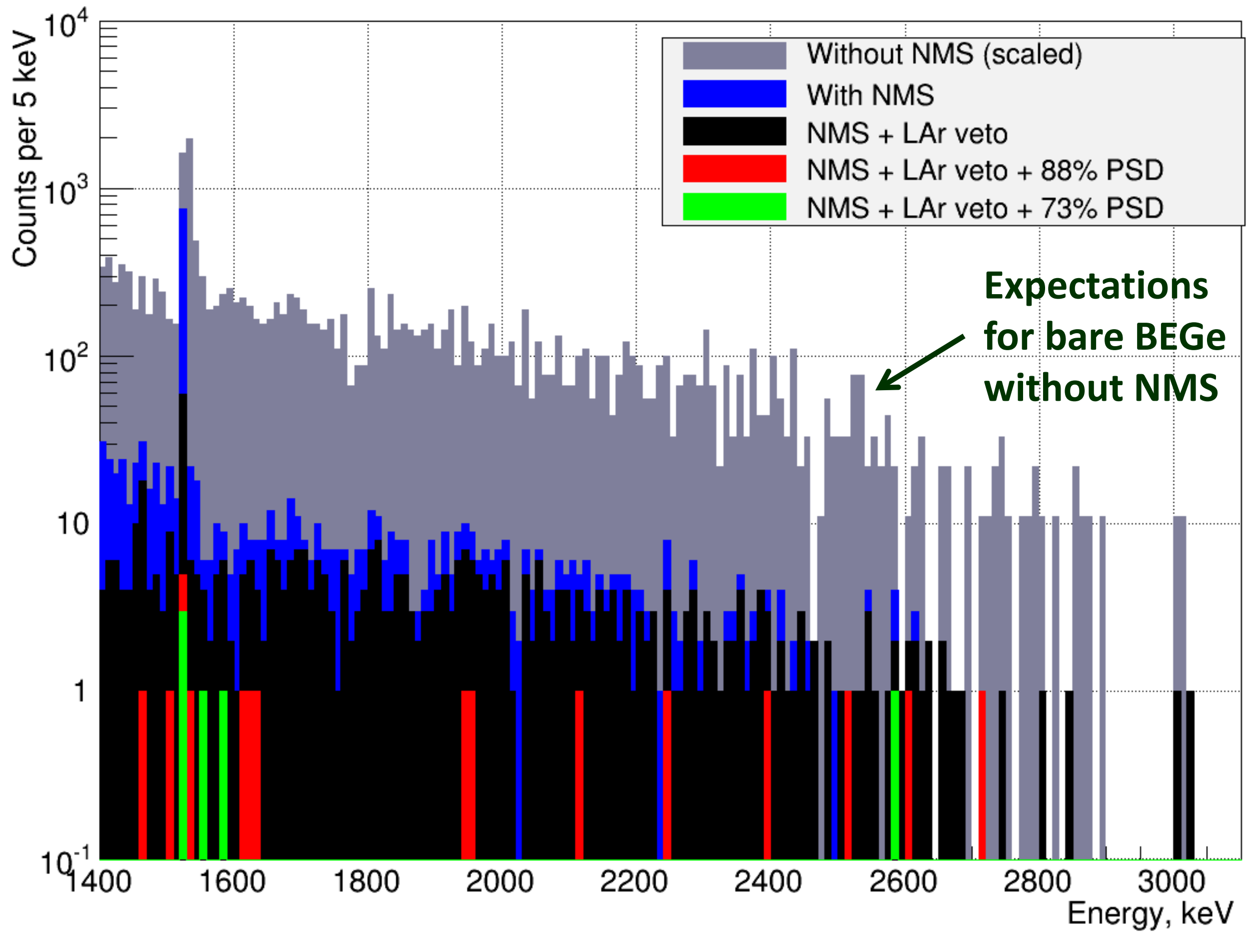
^{42}Ar background mitigation

By measurements in the LArGe test facility with spiked ^{42}Ar it was shown that it is possible to dramatically decrease ^{42}K background by use of the NMS and application of all the cuts (PSD+PMT): a suppression factor of more than 1000 was obtained.

Surface beta events are efficiently suppressed by PSD.

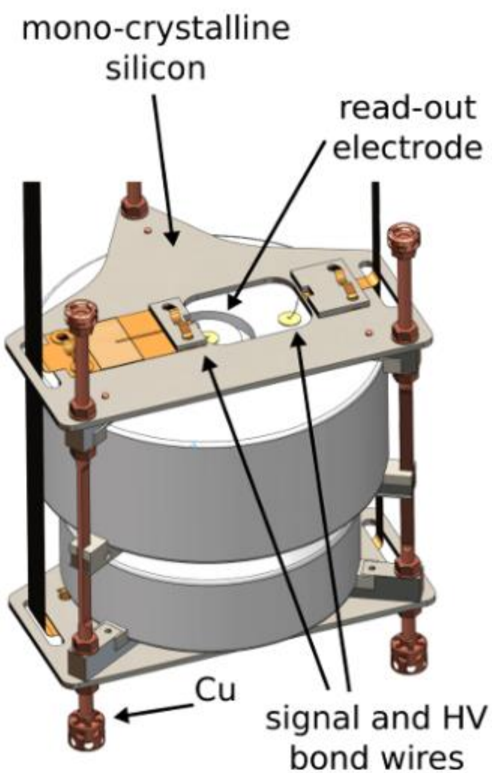


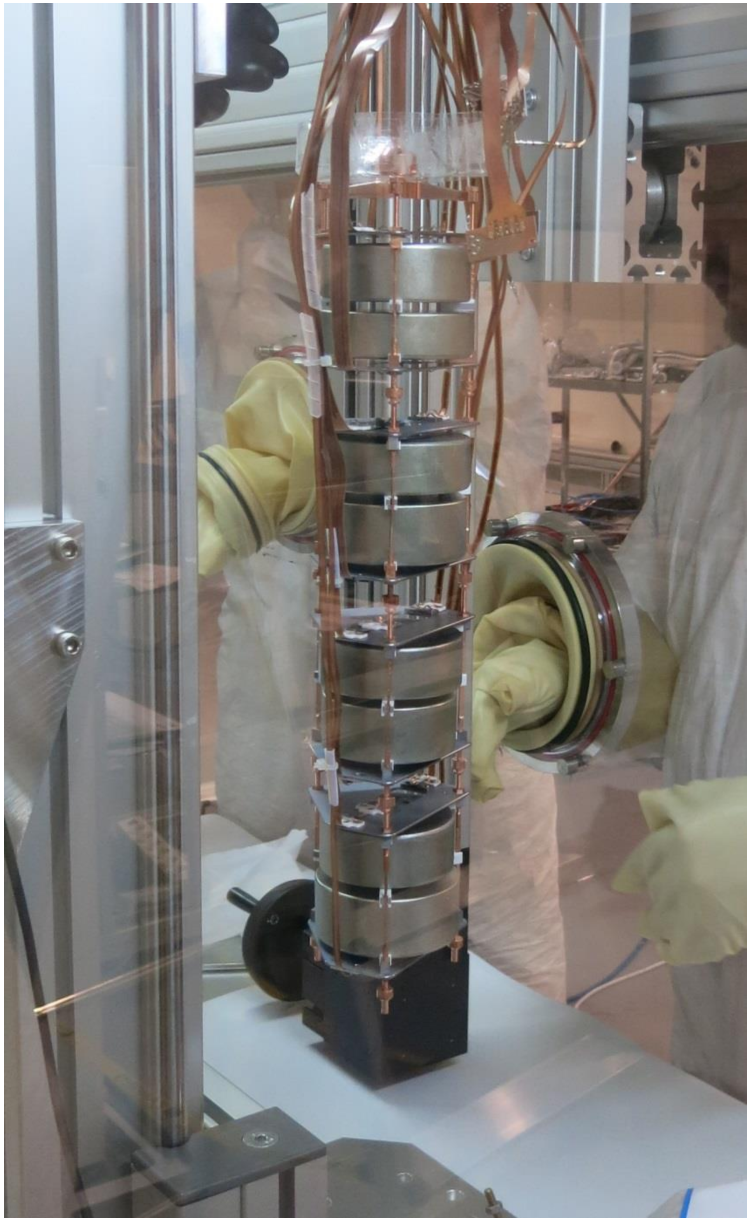




GERDA Phase II preparations

Cleaner components:
- New low radioactive holders
- New electronics
- New cables
- Connection by bonding



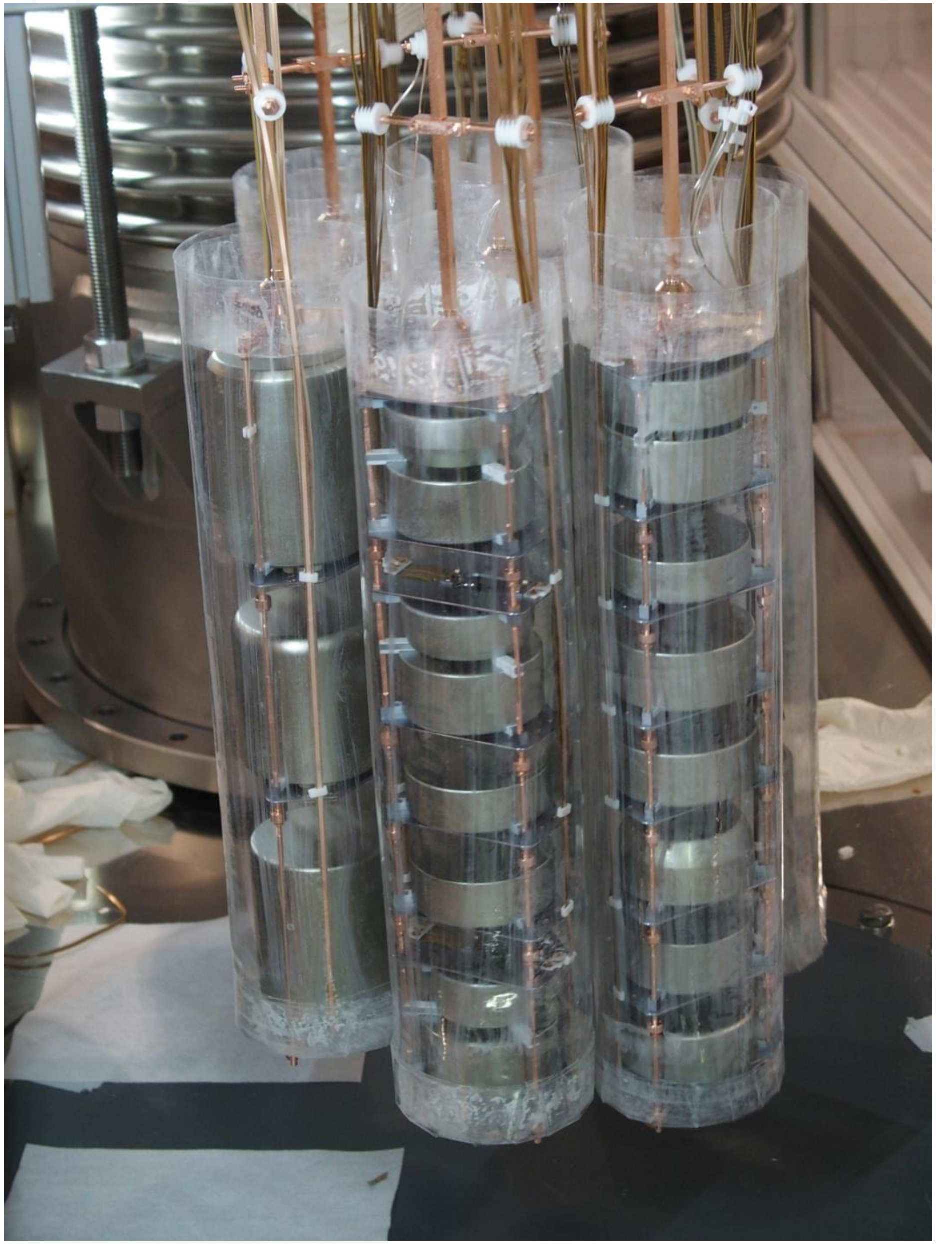


GERDA Phase II configuration

Deployed in December 2015:

- 7 detectors strings
- 40 detectors:
  - 30 enriched BEGe (20 kg)
  - 7 enriched coax (15.8 kg)
  - 3 natural coax (7.6 kg)

Total: 35.8 kg of enriched Ge



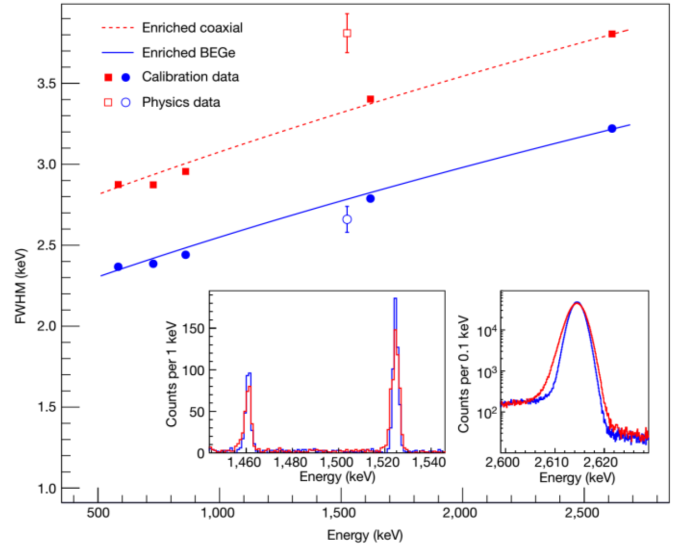
Data taking

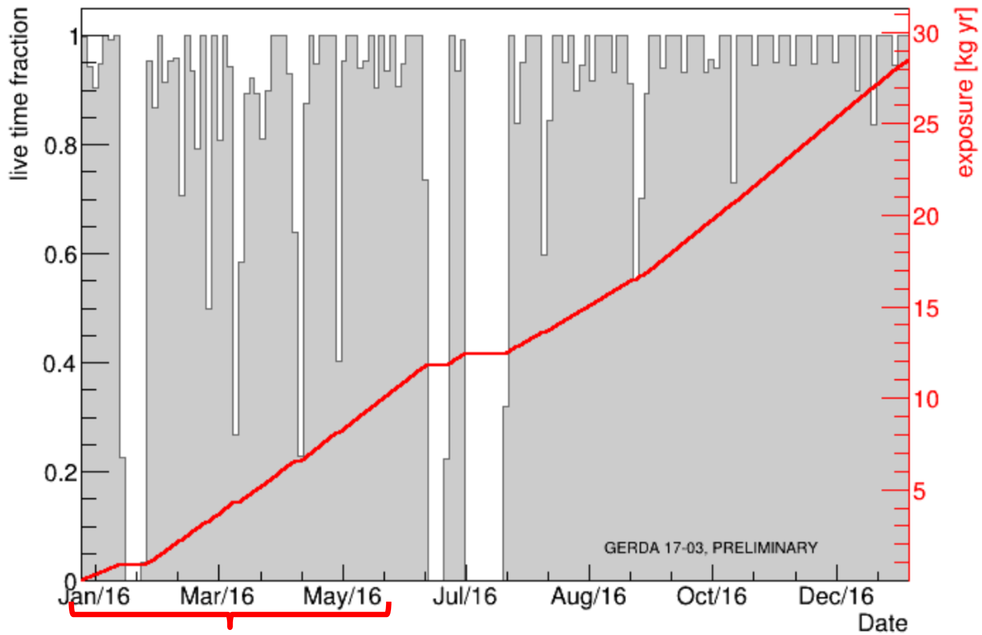
All channel are working after introducing detectors in LAr of GERDA. Performance of full physics data set:

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

Data taking:

- **December 2015 – …**
- Energy region $Q_{\beta\beta}$± 25 keV **is blinded.**
- First unblinding in June 2016: Phase IIa data

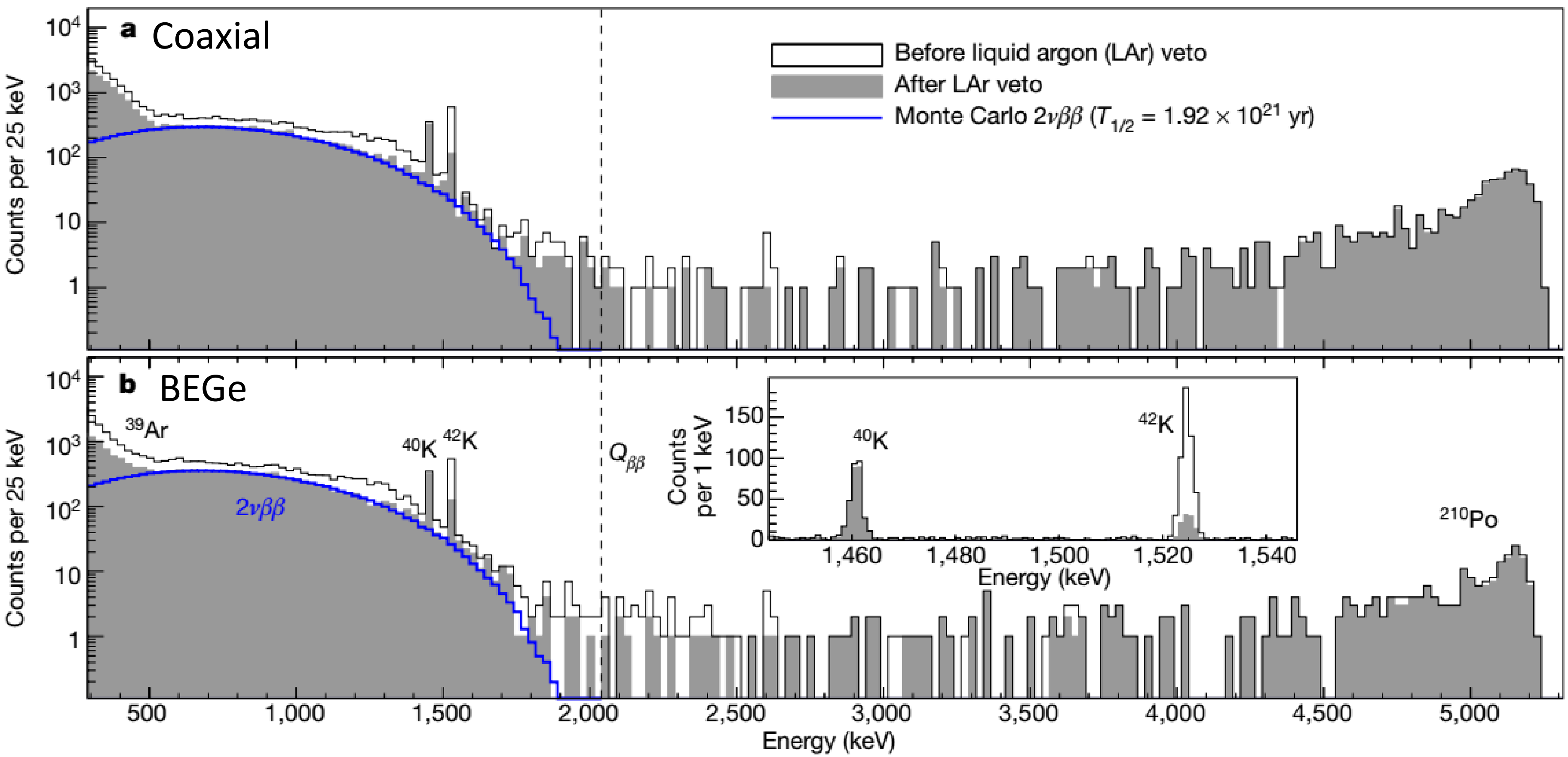




Phase IIa

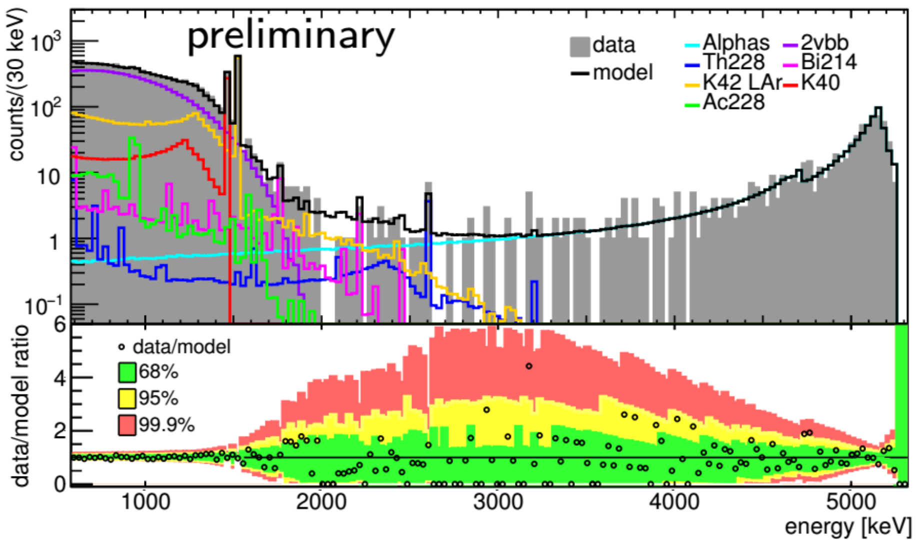
Background spectra before PSD

Phase IIa: Dec 2015 – May 2016
Exposure:
Coaxial 5.0 kg · yr
BEGe 5.8 kg · yr

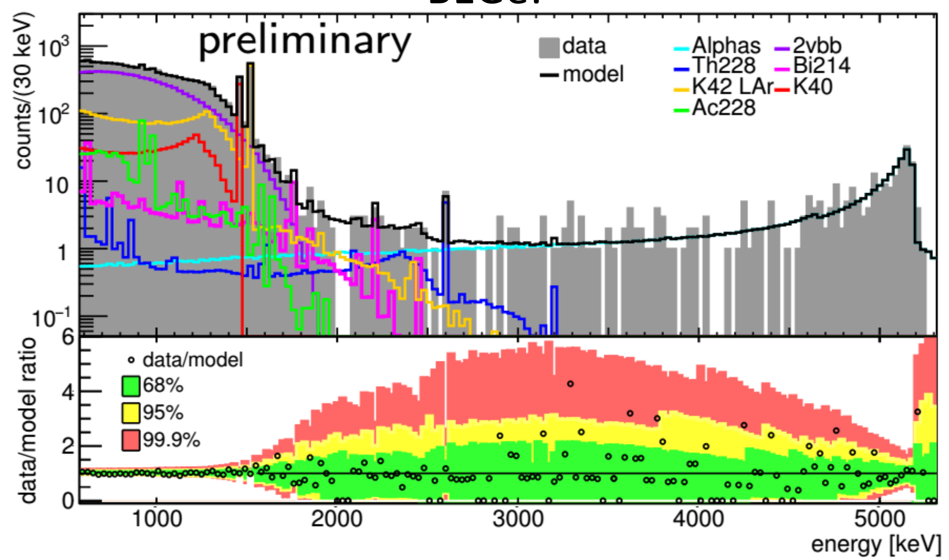


Background modeling

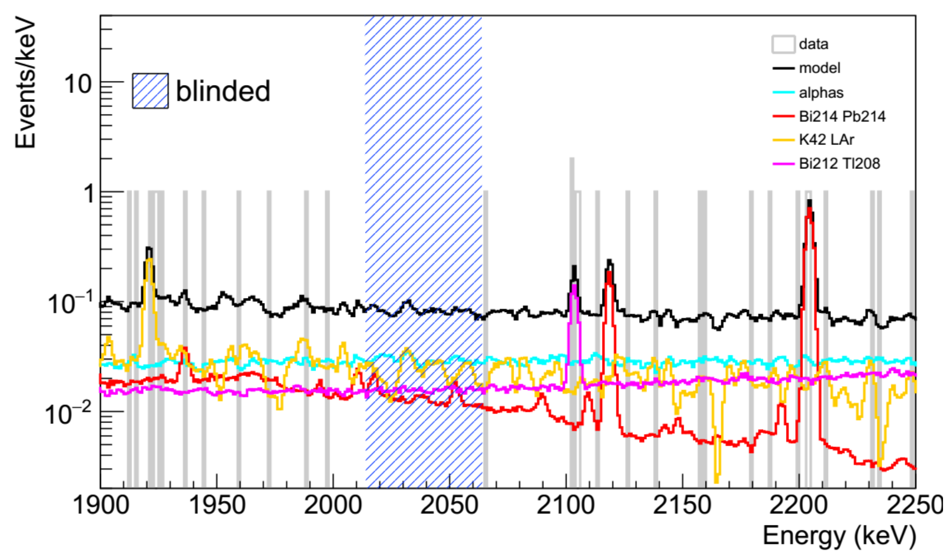
coaxial:



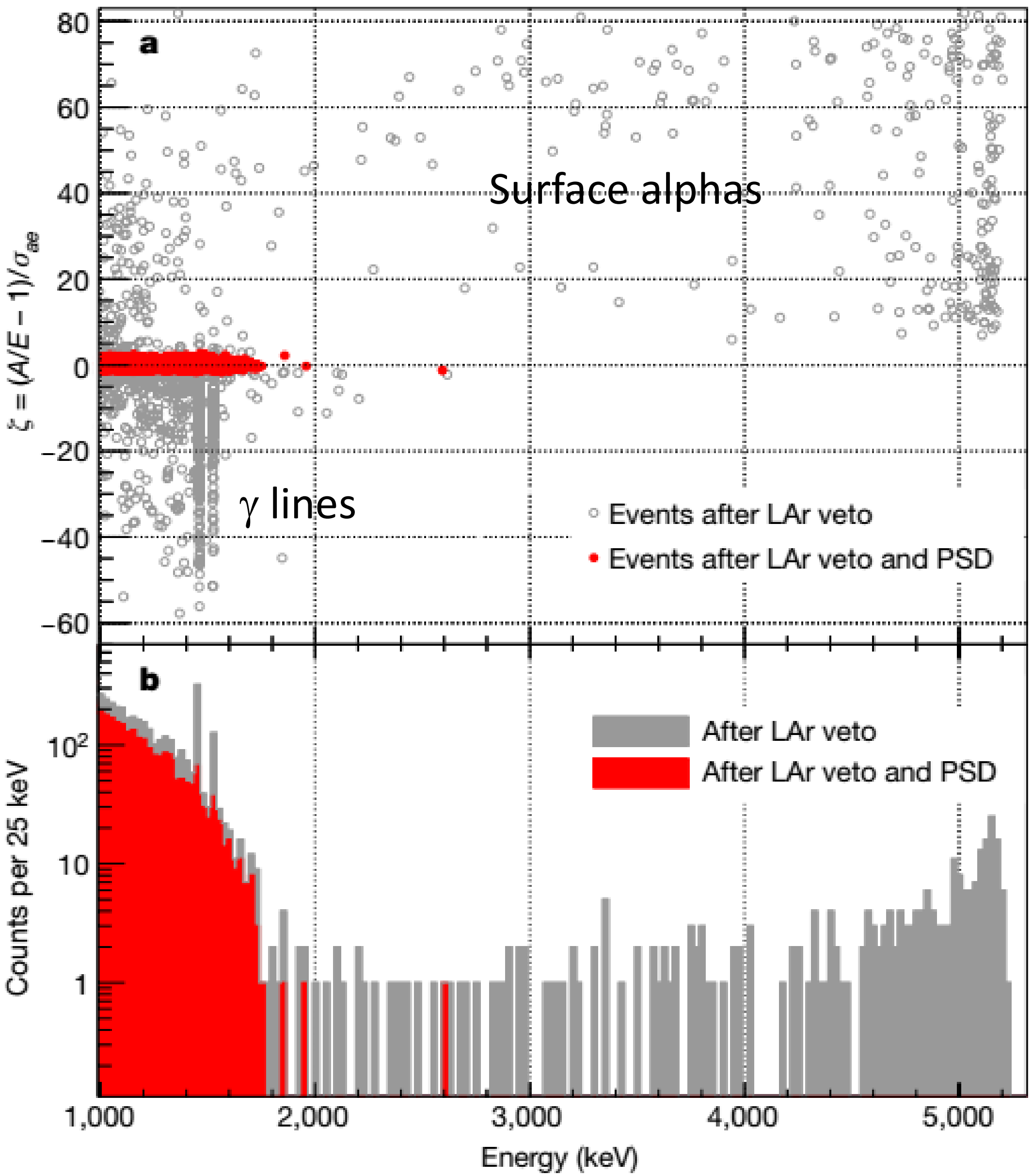
BEGe:



- Simulation of the background well describes observed data.
- Same isotopes like in Phase I.
- Main background components before PSD and LAr:
  - α from ^{210}Po,^{226}Ra
  - β from ^{42}K
  - γ from ^{214}Bi,^{208}Tl
- Flat background at ROI is expected.



PSD analysis for BEGe



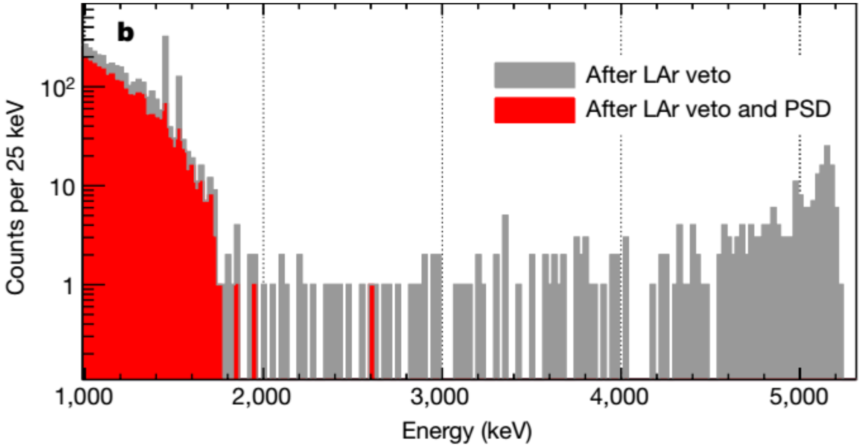
Mono-parametric PSD:
A/E cut for BEGe detectors removes most of the background events

Parameters of PSD cuts are obtained from ^{228}Th calibration using double-escape peak (DEP) and Compton continuum .

Efficiences:
- DEP: (87.3±0.2±0.8)%
- 2νββ: (85.4±0.8±1.7)%

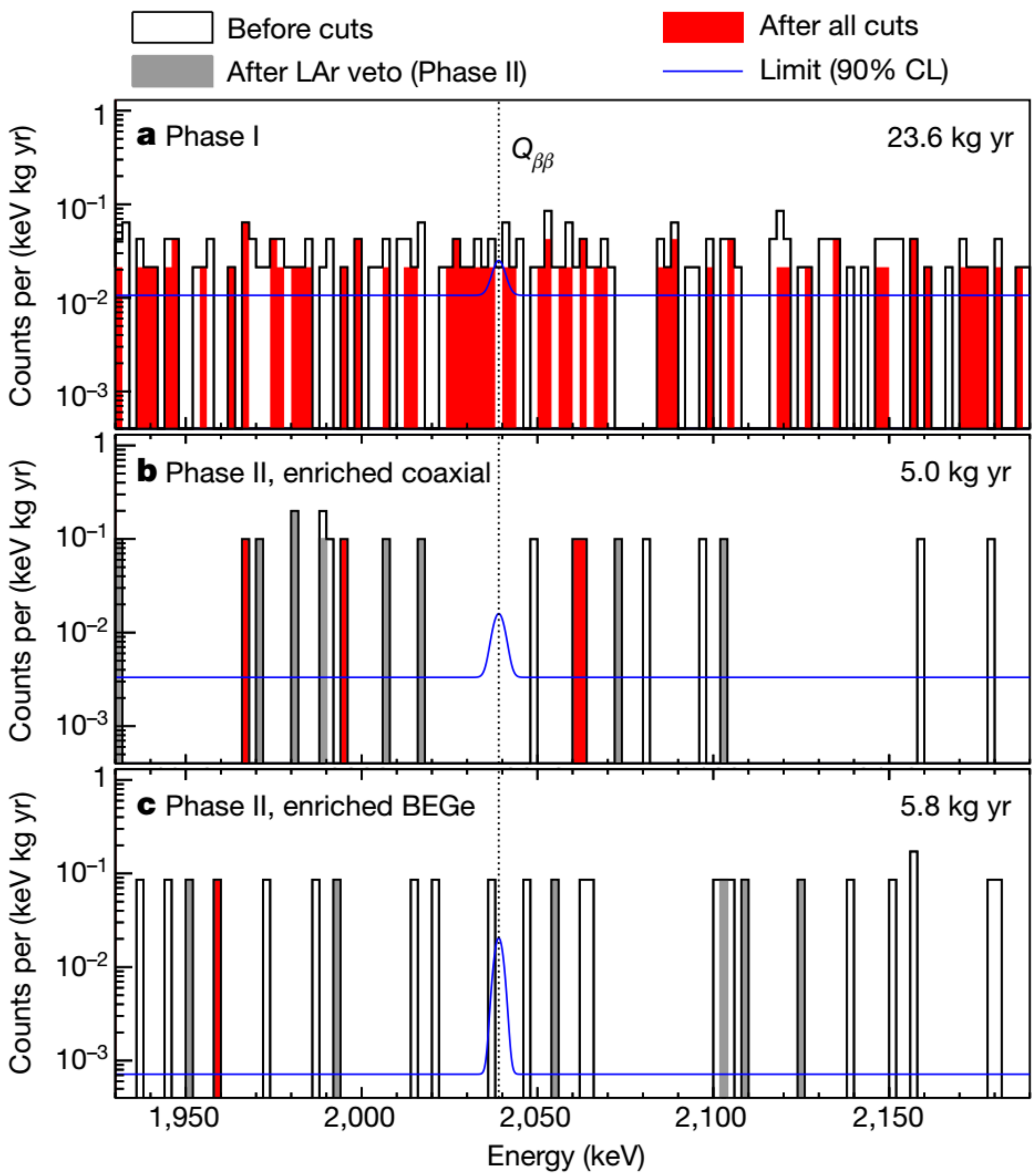
Background Indexes

Data set	$\mathcal{E}$ (kg yr)	FWHM (keV)	ϵ	BI (10^{-3} counts keV^{-1} kg^{-1} yr^{-1})
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI silver	1.3	4.3(1)	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}
PIIa coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PIIa BEGe	5.8	3.0(2)	0.60(2)	$0.7^{+1.1}_{-0.5}$



Background goal reached.
Best BI in ROI ever achieved!

ROI of 0νββ



June 2016:

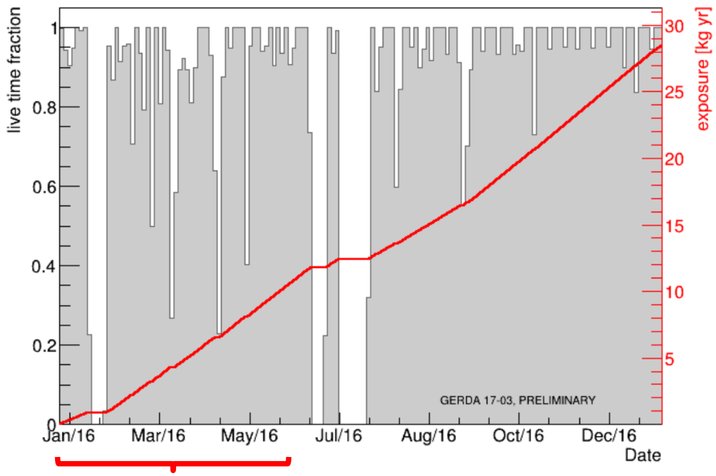
- No events from 0νββ decay observed so far.
- Sensitivity of unblinded data – $4.0 \cdot 10^{25}$ yr (90 % C.L.)

The limit on the half-life of 0νββ decay is:

$$T_{1/2}^{0\nu} > 5.3 \cdot 10^{25}\text{yr}$$

Nature 544 47 (2017)

Current status (preliminary!)

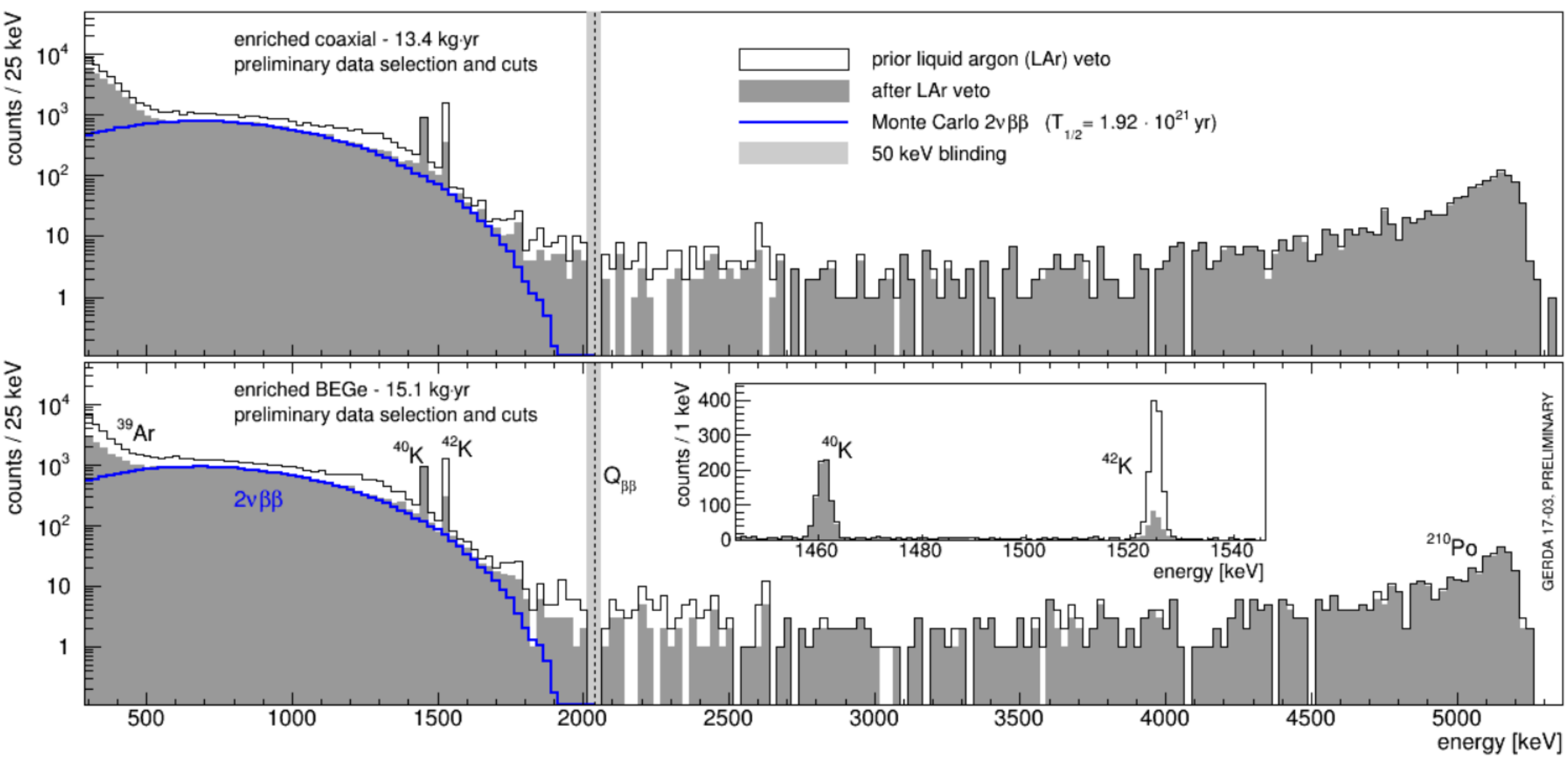


- Next unblinding - this month
- Additional (blinded) data > 20 kg yr

Preliminary background indexes after LAr veto and PSD:

Enriched coax: $2.2^{+1.1}_{-0.8} \cdot 10^{-3} \mathrm{cts/(keV \cdot kg \cdot yr)}$

Enriched BEGe: $0.6^{+0.6}_{-0.4} \cdot 10^{-3} \mathrm{cts/(keV \cdot kg \cdot yr)}$

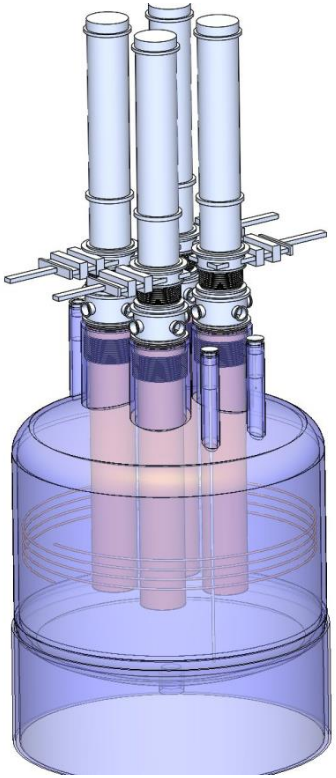


LEGEND

- LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay) – new collaboration since October 2016.
- GERDA+Majorana+new members
- Sensitivity to 10^{28} yr

First stage:

- (up to) 200 kg in upgraded GERDA experimental setup
- Goal for the BI: 3-5 times better current GERDA BI



Second stage:

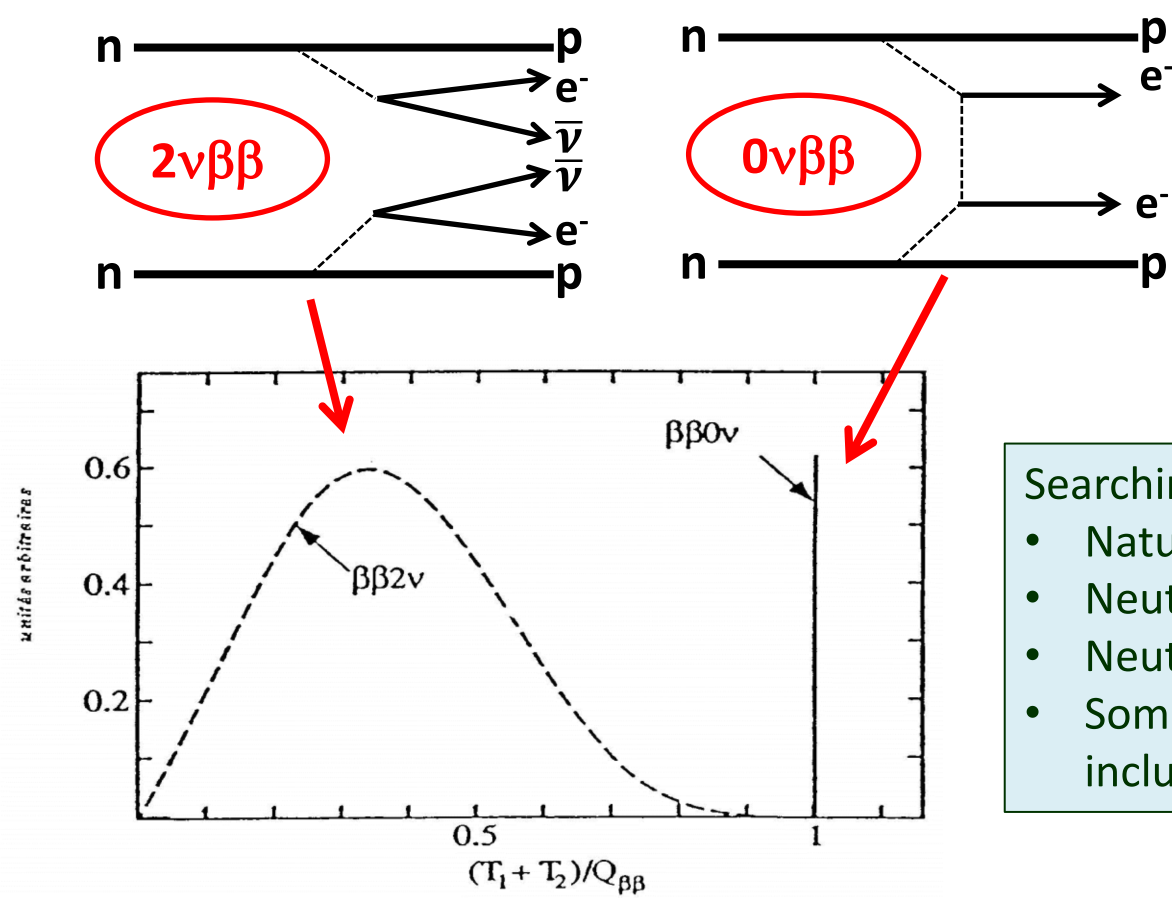
- 1000 kg
- Location tbd
- Goal for the BI: ~ 30 times better current GERDA BI

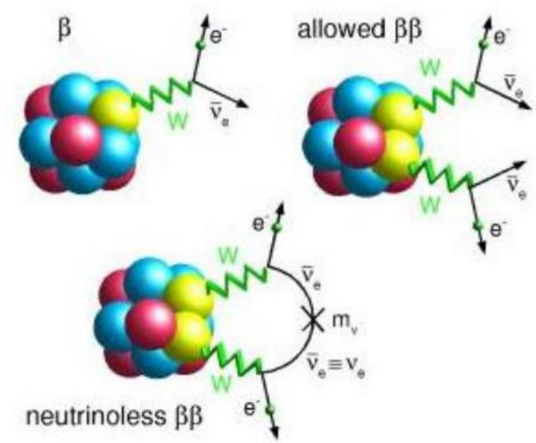
Summary

- GERDA Phase II successfully started in December 2015.
- Best resolution and lowest background in ROI ever achieved in $0\nu\beta\beta$ experiments.
- No $0\nu\beta\beta$ signal is observed so far.
- Results (June 2016):
  - The obtained limit is $T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr.
  - $|m_{\beta\beta}| < [150,330]$ meV (90% C.L.), [Nature 544 47 (2017)]
- GERDA Phase II is accumulated statistics now at “zero” background mode. More results with higher sensitivity is expected in coming years.
- LEGEND collaboration formed in October 2016. First stage will be based on the existing GERDA infrastructure.

Motivation

Neutrinoless double beta (0νββ) decay experiments is a good way to search for the physics beyond the Standard Model. The observation of such a decay would prove that lepton number is not conserved. Lepton number (L) is accidentally conserved in Standard Model → L number violation is expected. Most of the SM extension predict $\boldsymbol{\nu = \bar{\nu}}$.





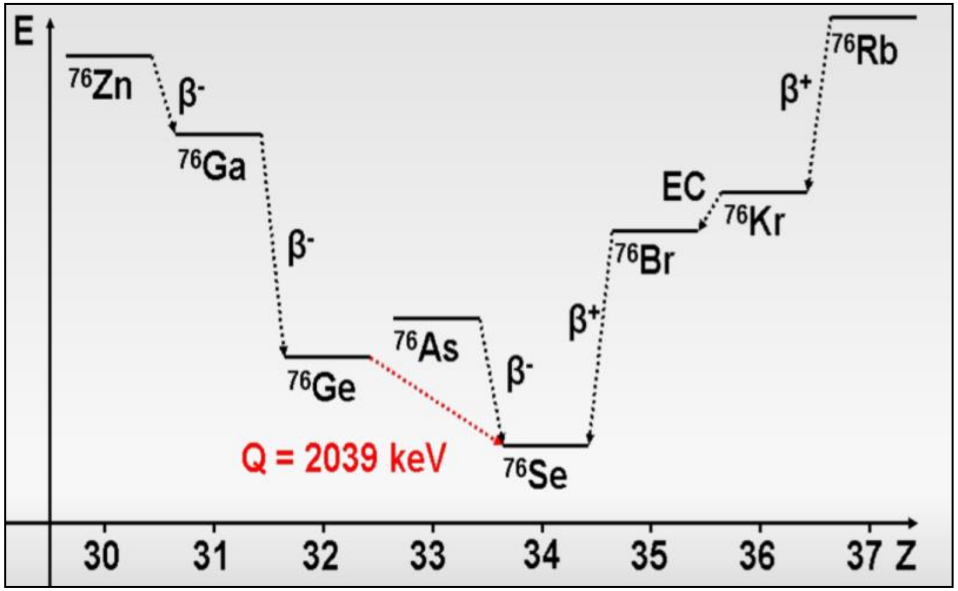
Searching for 0νββ helps to understand:

- Nature of ν (Dirac or Majorana)
- Neutrino mass scale
- Neutrino hierarchy
- Some fields in particle physics including cosmology

Other types of 0νββ decay are also considered

0νββ decay

2νββ decay has been observed already in more than ten isotopes, but 0νββ not found yet.



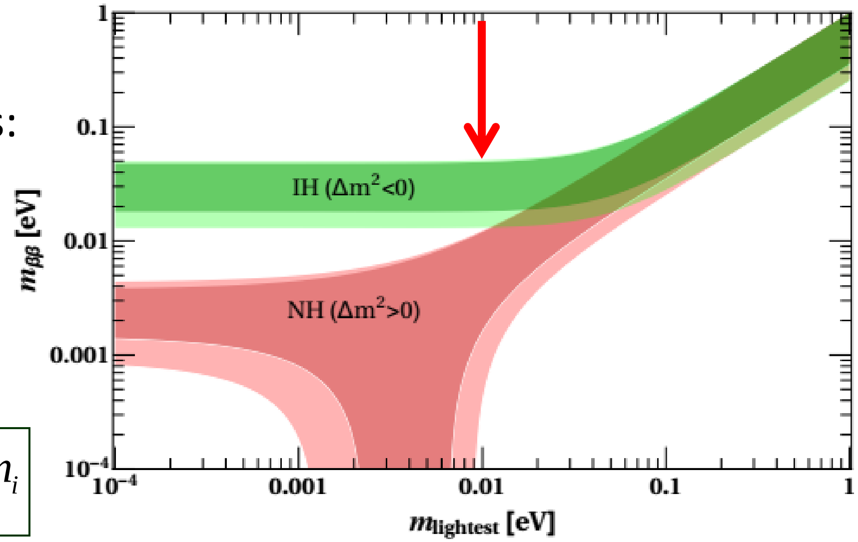
Nuclei	$Q_{2\beta}$, keV	Abundance, %
1. ^{48}Ca	4272	0.187
2. ^{150}Nd	3371.4	5.6
3. ^{96}Zr	3350	2.8
4. ^{100}Mo	3034.4	9.63
5. ^{82}Se	2996	8.73
6. ^{116}Cd	2805	7.49
7. ^{130}Te	2527.5	34.08
8. ^{136}Xe	2458.7	8.87
9. ^{124}Sn	2287	5.79
10. ^{76}Ge	2039.0	7.61
11. ^{110}Pd	2000	11.72

For 0νββ mediated by light Majorana neutrinos:

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto G^{0\nu}(\mathrm{Q,Z}) \cdot \left|M^{0\nu}\right|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$G^{0\nu}$ – phase space factor ~ Q^5
$M^{0\nu}$ – nuclear matrix element
$m_{\beta\beta}$ – effective Majorana mass

$$\left\langle m_{\beta\beta} \right\rangle = \sum_i U_{ei}^2 m_i$$



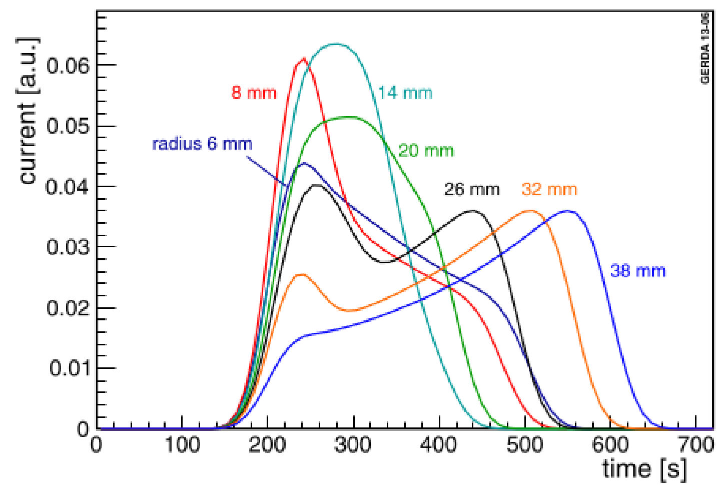
Phys. Rev. D 90, 033005 (2014).

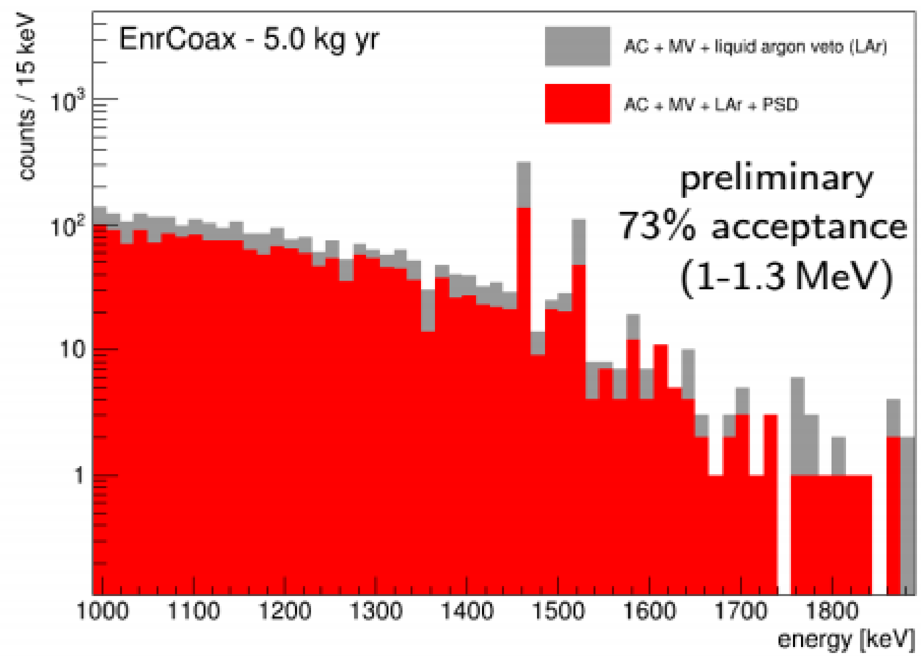
PSD analysis for coax

- The PSD for coaxial detector is more complicate to perform due to difference of the SSE pulses.
- For multi-site event suppression there is no single parameter -> neural network is used. Two different PSD methods for cross check was used.
- New PSD method was applied for α-events!

Preliminary efficiency of the PSD cuts for coaxial is (77 ± 9)% (enlarged uncertainty).

Current pulses for SSE





see also EPJC 73 (2013) 2583