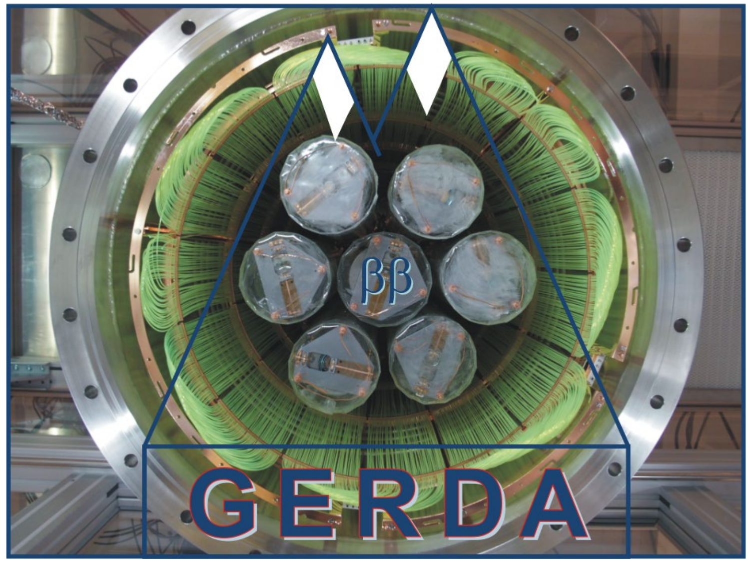



# Status of the search for neutrinoless double-beta decay with GERDA

A.V. Lubashevskiy[1]

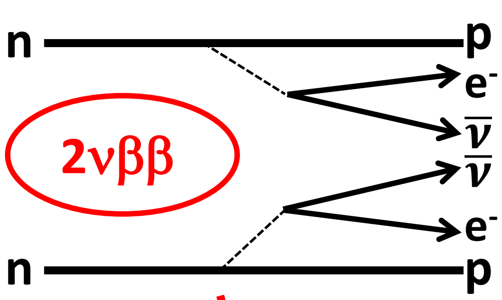
on behalf of the GERDA and LEGEND collaborations,

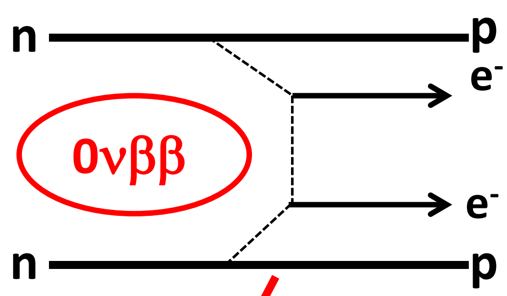
[1]Joint Institute for Nuclear Research, Dubna, Russia

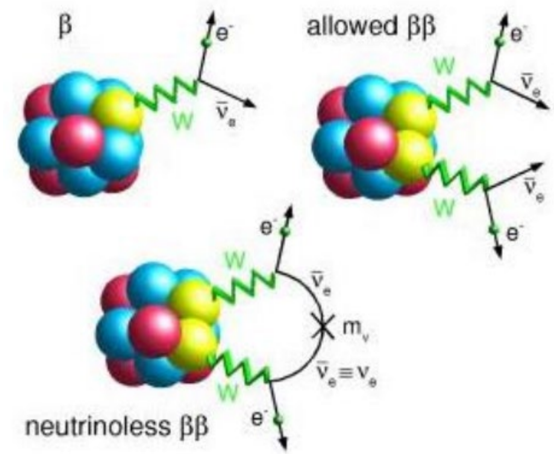
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

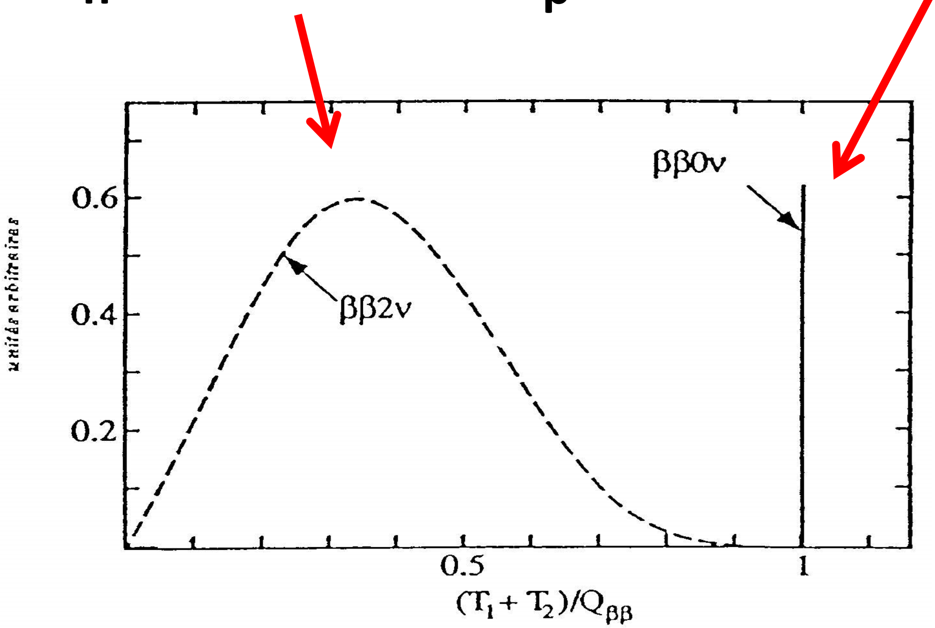
# Motivation

Neutrinoless double beta ($0\nu\beta\beta$) decay experiments are 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 $\boldsymbol{\nu} = \bar{\boldsymbol{\nu}}$.



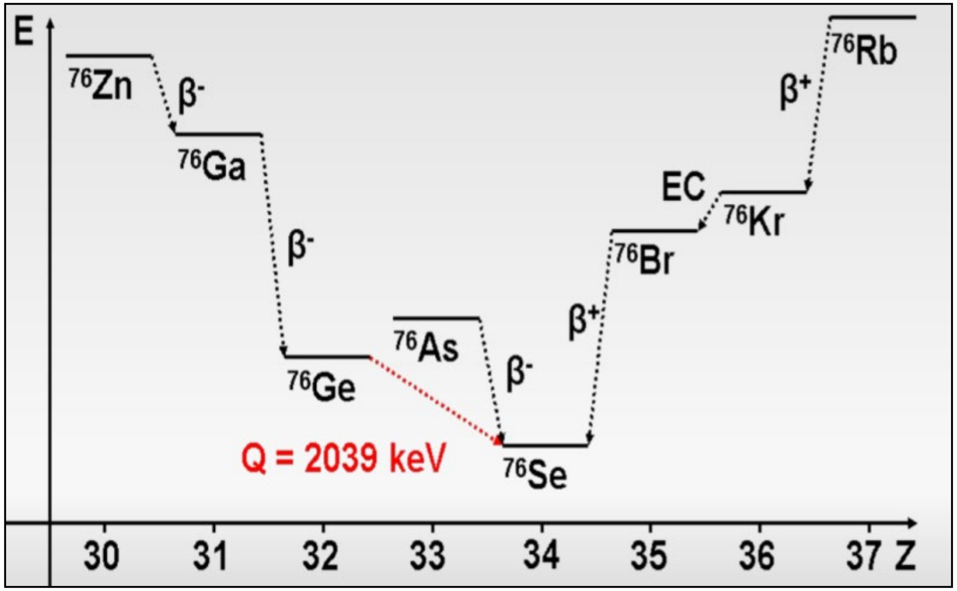

Searching for $0\nu\beta\beta$ helps to understand:

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

Other types of $0\nu\beta\beta$ decay are also considered

# $0\nu\beta\beta$ decay

$2\nu\beta\beta$ decay has been observed already in more than ten isotopes, but $0\nu\beta\beta$ not found yet.



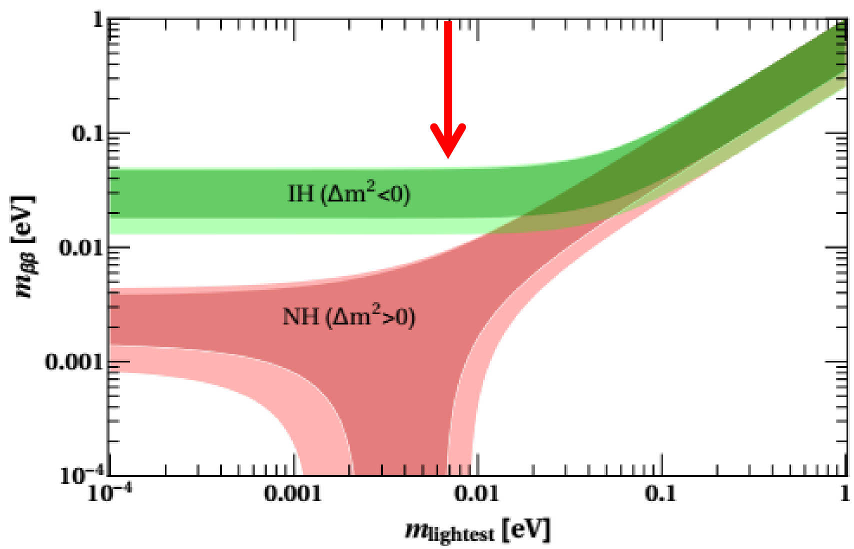

| Nuclei | $Q_{2\beta}$, keV | Abundance, % |
|---|---|---|
| 1. $^{48}Ca$ | 4272 | 0.187 |
| 2. $^{150}Nd$ | 3371.4 | 5.6 |
| 3. $^{96}Zr$ | 3350 | 2.8 |
| 4. $^{100}Mo$ | 3034.4 | 9.63 |
| 5. $^{82}Se$ | 2996 | 8.73 |
| 6. $^{116}Cd$ | 2805 | 7.49 |
| 7. $^{130}Te$ | 2527.5 | 34.08 |
| 8. $^{136}Xe$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

For $0\nu\beta\beta$ 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).

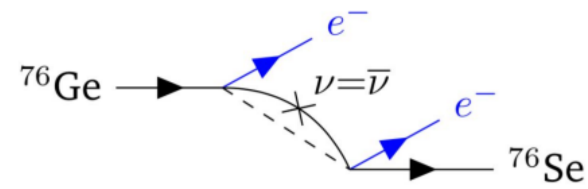
# Experimental sensitivity

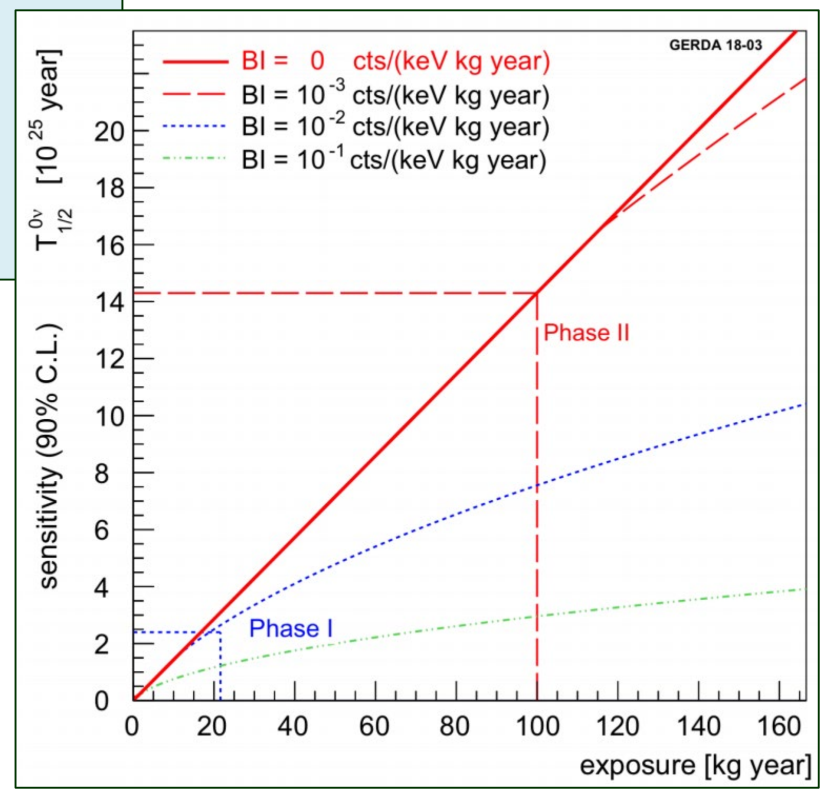
Experimental sensitivity expressed:

**If background << 1:** $$\boxed{T^{0\nu}_{1/2} \propto \varepsilon \cdot a \cdot M \cdot t}$$

If background >> 1: $$\boxed{T^{0\nu}_{1/2} \propto \varepsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}}$$

$\varepsilon$ Efficiency
$M \cdot t$ Mass·Time = Exposure
$a$ Abundance
$\Delta E$ Energy resolution
$BI$ Background Index

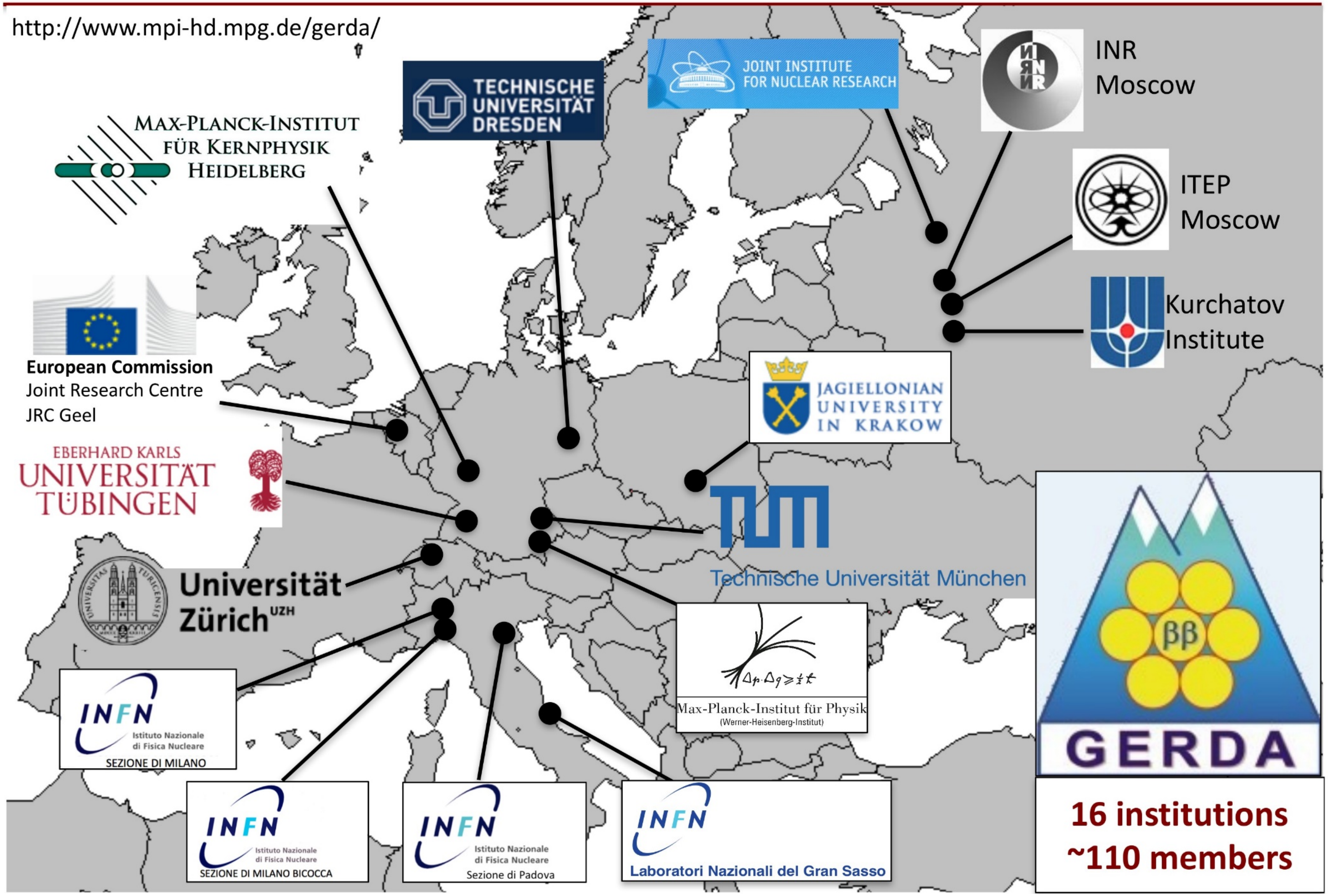



To maximize sensitivity:

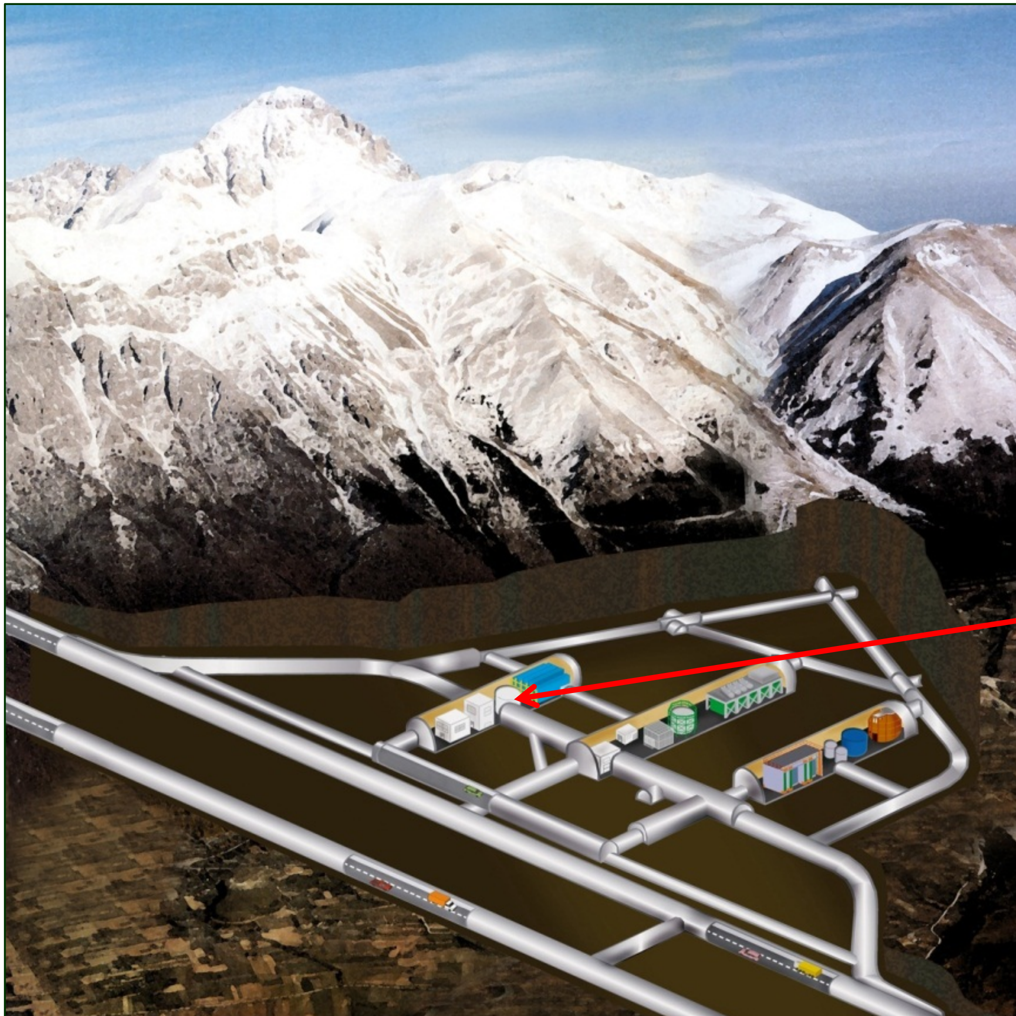
- As low background as possible
- Very good energy resolution
- Large isotope mass and time of the measurement
- High detector efficiency
- Enriched material with high abundance

# The GERDA Collaboration



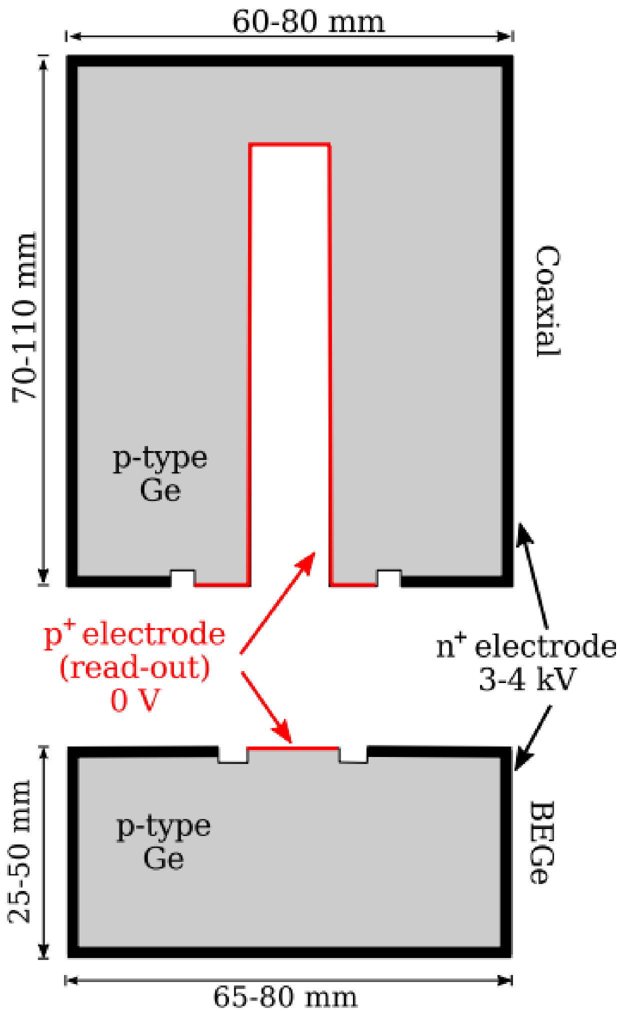
# Background reduction

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

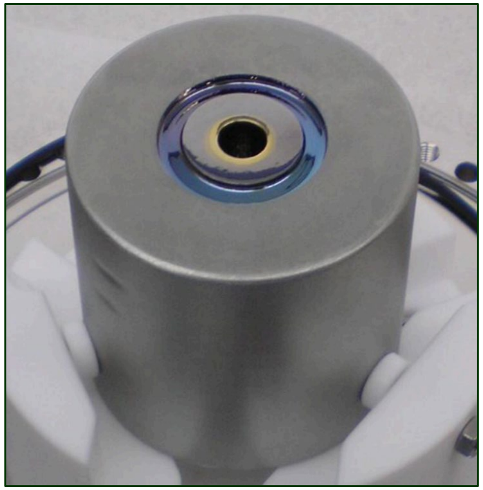


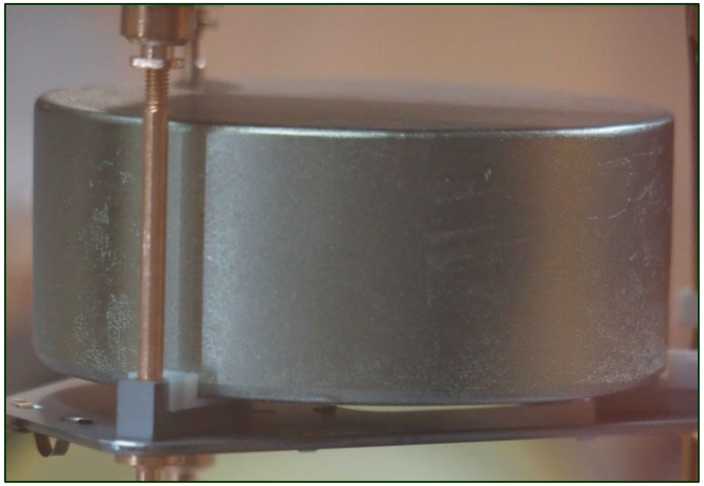
# HPGe detectors

The search is performed with High Purity Ge detectors enriched up to 88% in $^{76}$Ge. They are submerged into liquid argon (LAr). LAr shields from the radiation and cools down the germanium detectors.



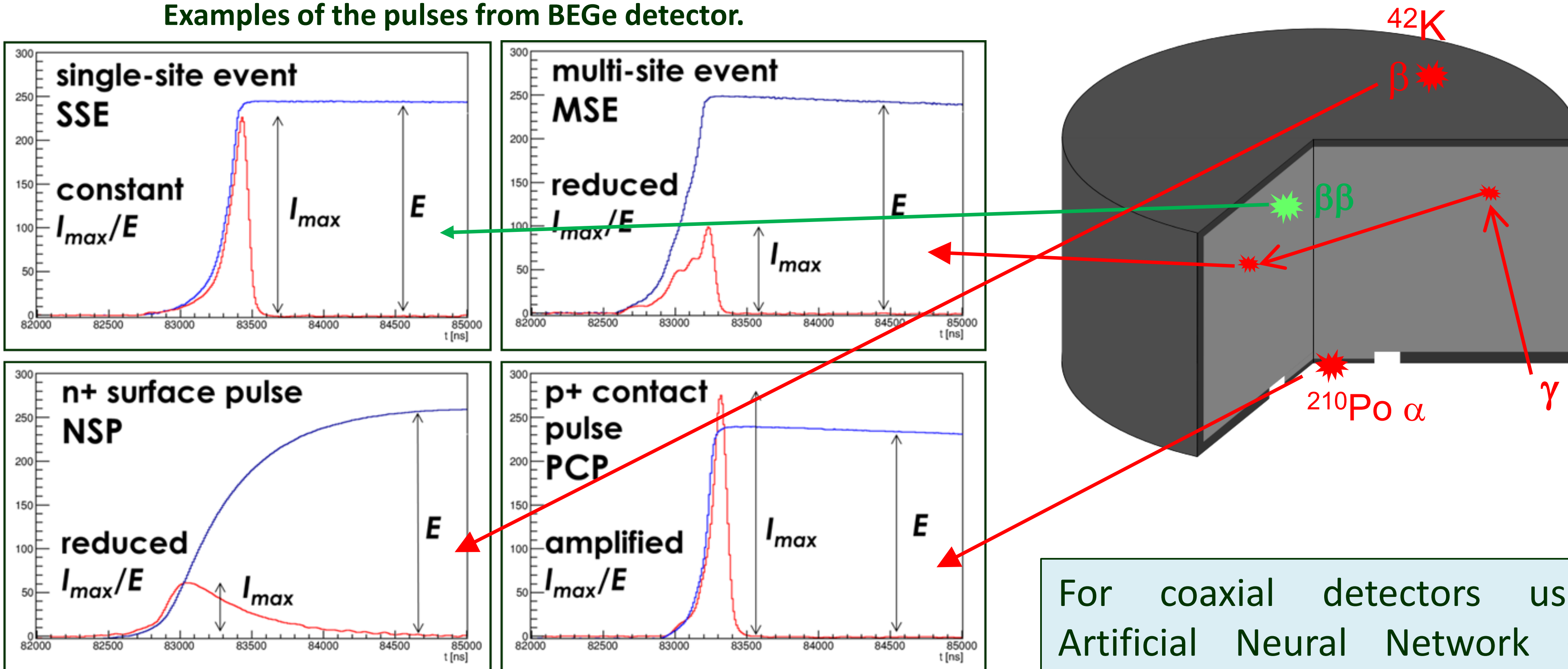

- $Q_{\beta\beta}$ = 2039 keV
- Detector = source
- Intrinsically pure material
- Excellent energy resolution ~ 3 keV (FWHM) @ $Q_{\beta\beta}$
- Powerful Pulse Shape Discrimination (PSD) allows to suppress different backgrounds





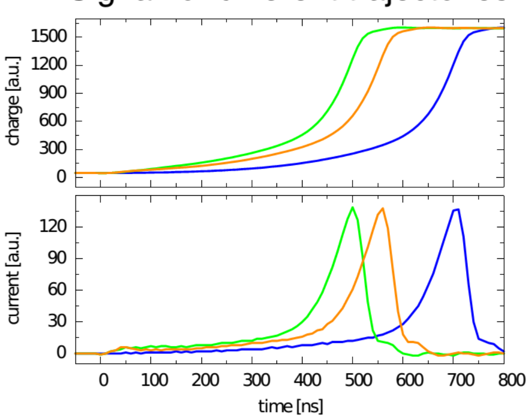
# Pulse Shape Discrimination

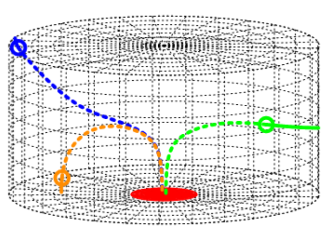
**Examples of the pulses from BEGe detector.**



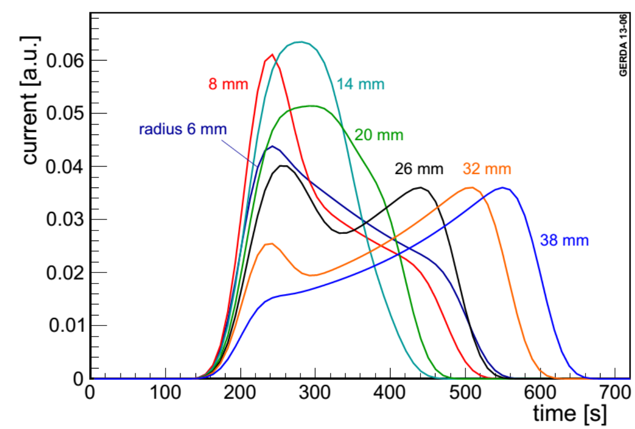

For coaxial detectors use Artificial Neural Network + risetime cut

Signal for different trajectories

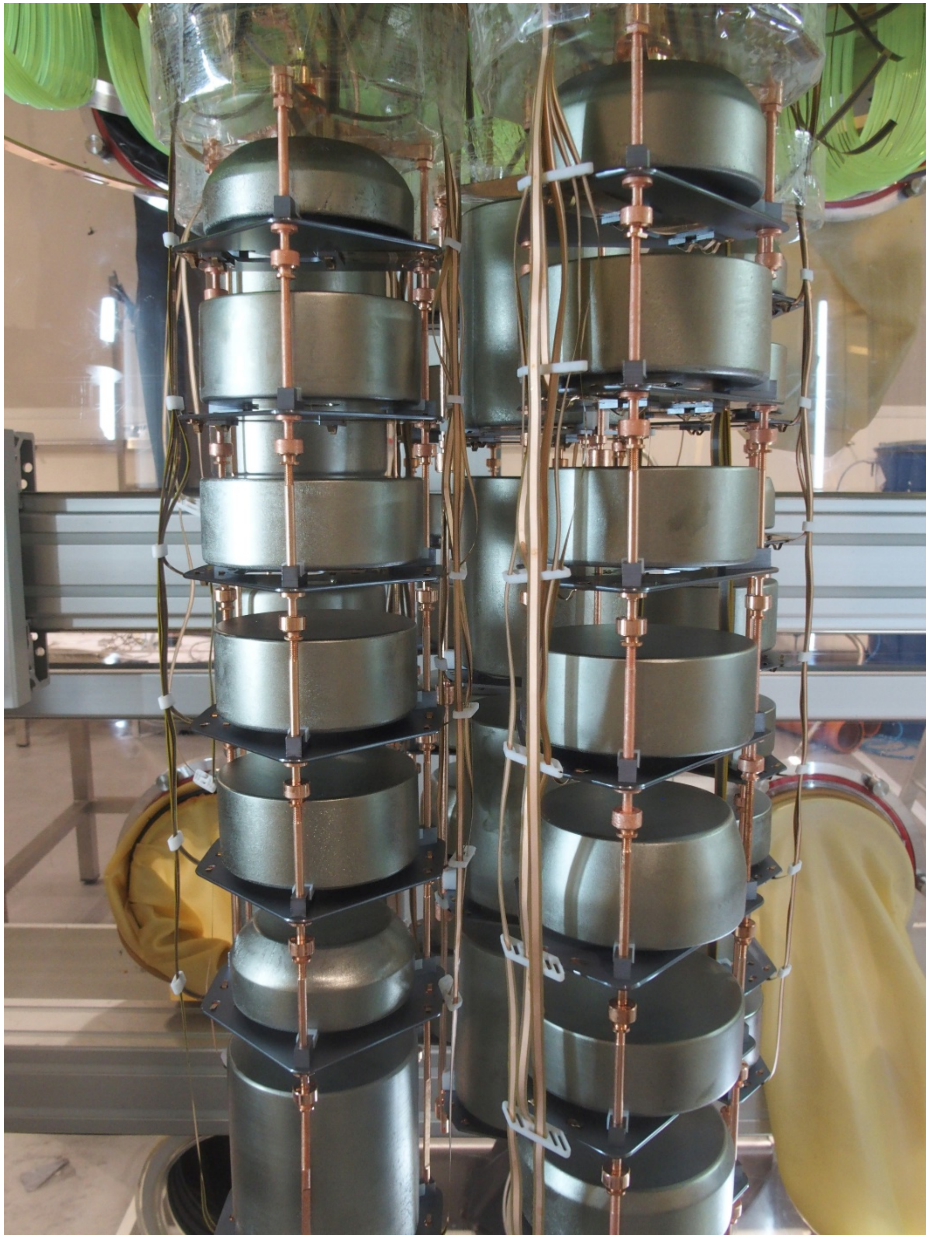


More details: **EPJC 75 (2015) 39**
**EPJC 73 (2013) 2583**
**JINST, 8 (2013) P104018**
**NIMA 891 (2018) 106-110**

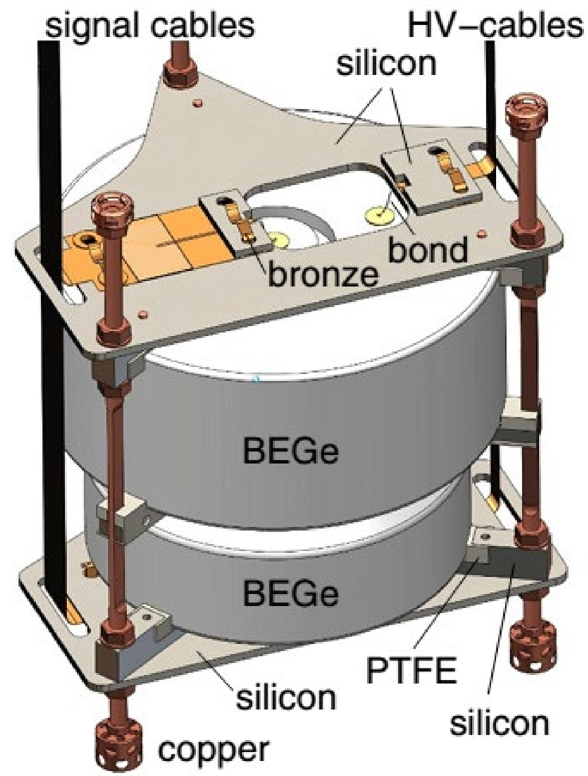


# Detector array



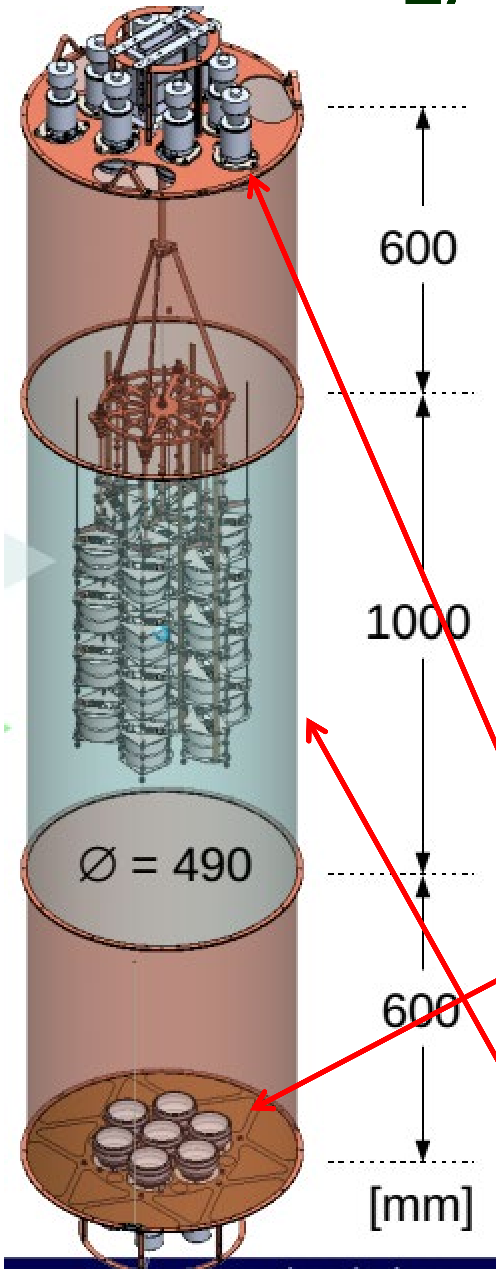
To minimize contamination from the detector's surrounding GERDA uses:

- Low mass holder made from copper and silicon plates.
- Low radioactive electronics and cables




Eur. Phys. J. C 78 (2018) 388

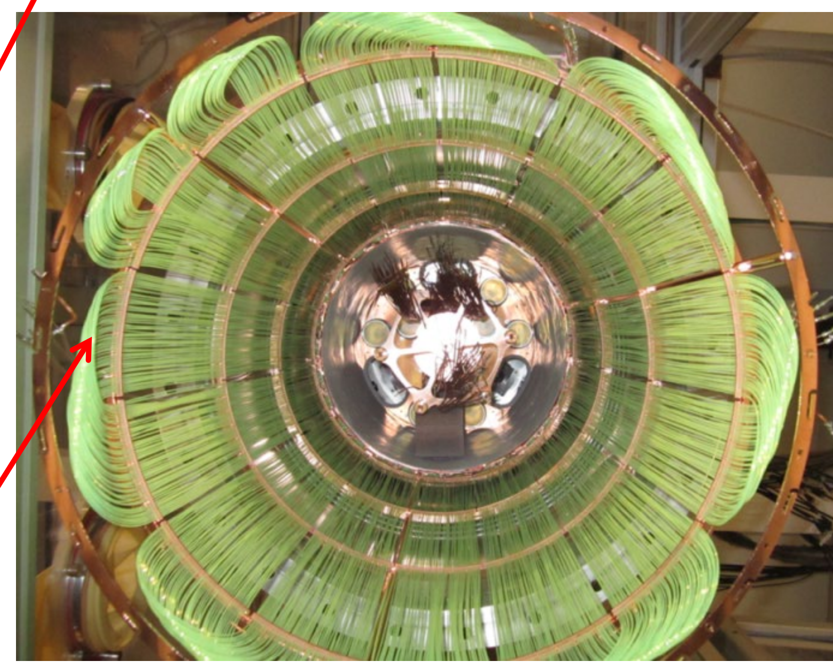
# LAr light instrumentation



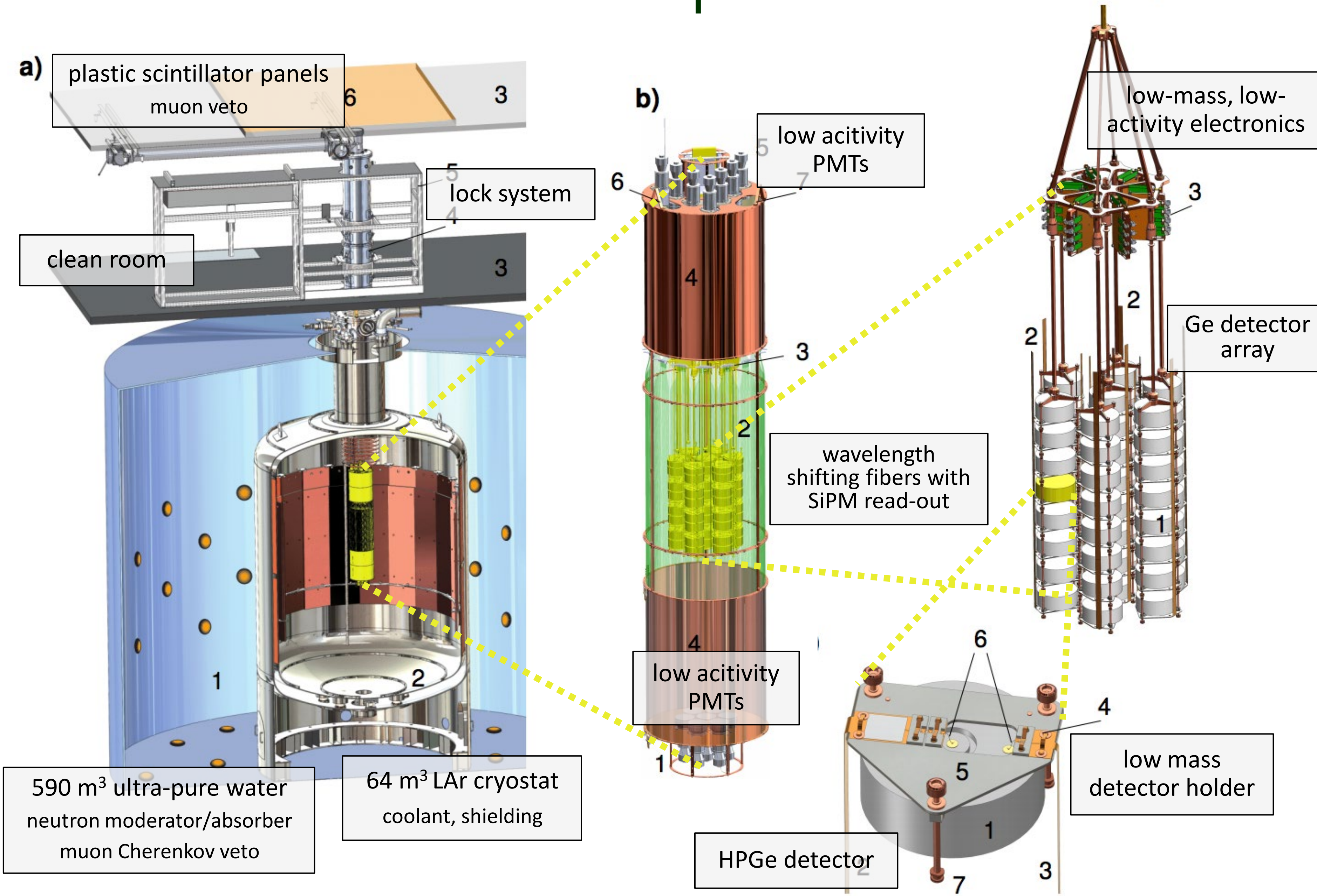

LAr scintillation veto works in the coincidence with Ge detectors allowing to suppress background events which deposit energy in LAr.

PMTs readout consist of 16 3” PMTs

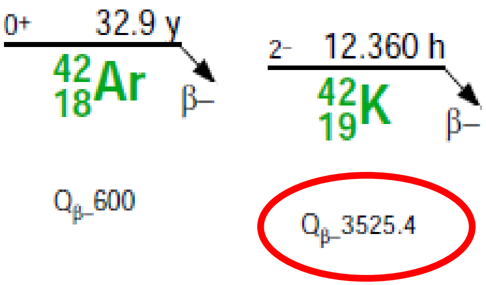
Scintillation fibers and SiPM readout



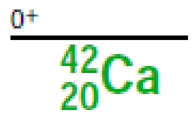
# General concept of GERDA



# $^{42}$Ar background mitigation



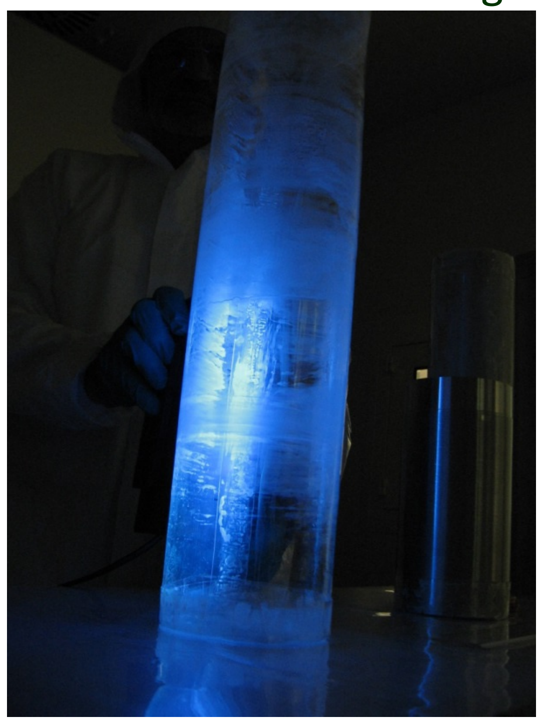

**Collection of $^{42}$K on the detector's surface**




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 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.

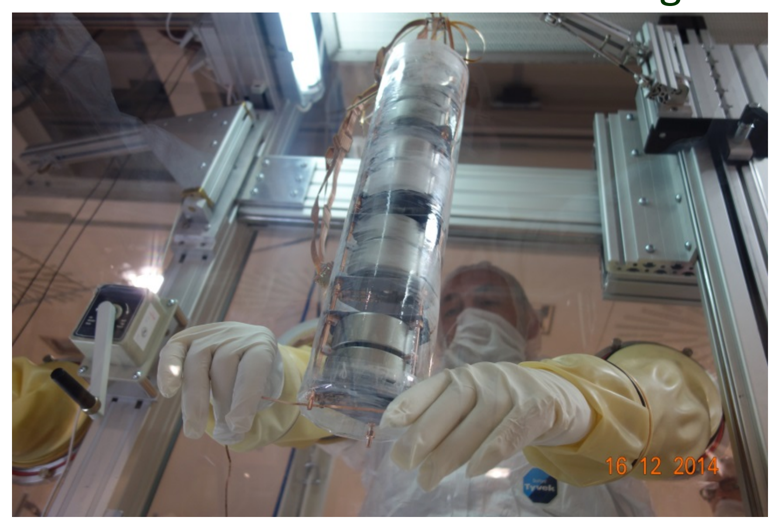
Copper MSs for Phase I

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 string




See more **Eur. Phys. J. C (2018) 78:15**

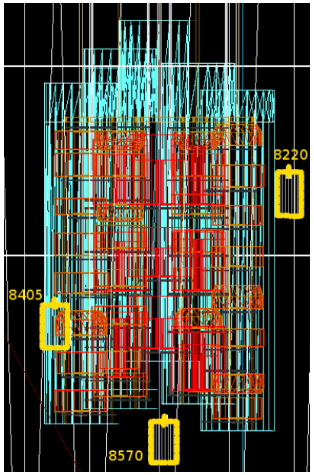
# GERDA Phase II configuration

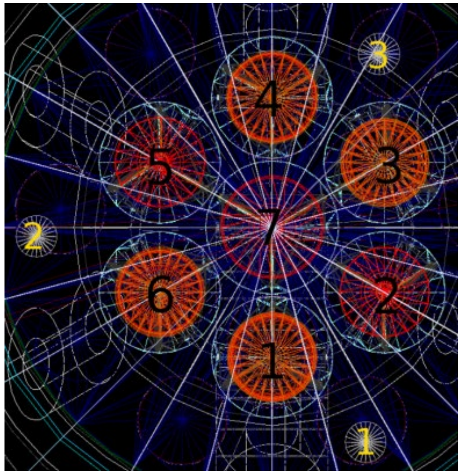
Configuration from December 2015 to May 2018:

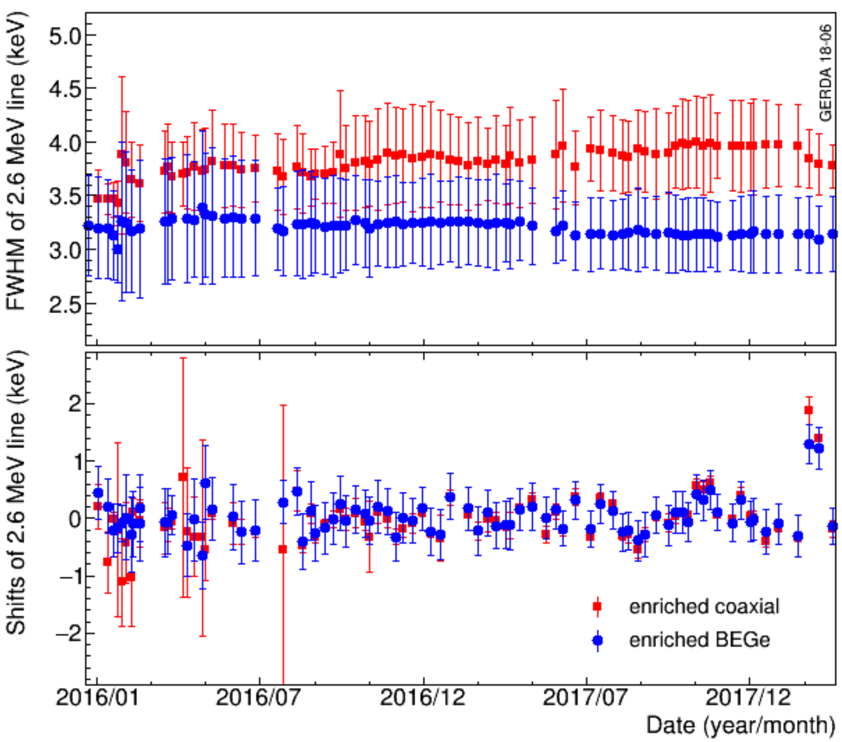
- 7 enriched **(semi-)coaxial (15.6 kg)**
- 30 enriched **BEGe (20.0 kg)**
- 3 natural semi-coaxial (7.6 kg)

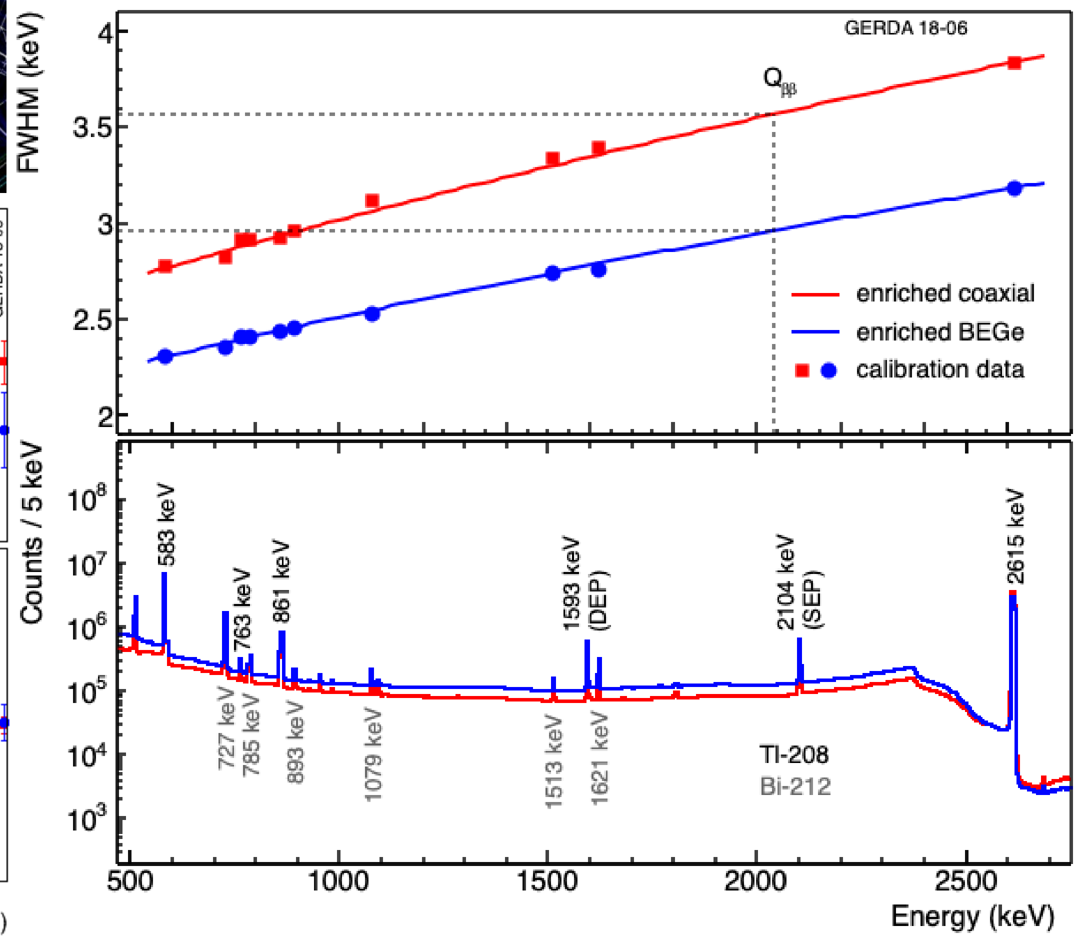
# Calibration and stability check

- Weekly calibrations with three weak $^{228}Th$ sources
- Test pulses generated to additionally check stability

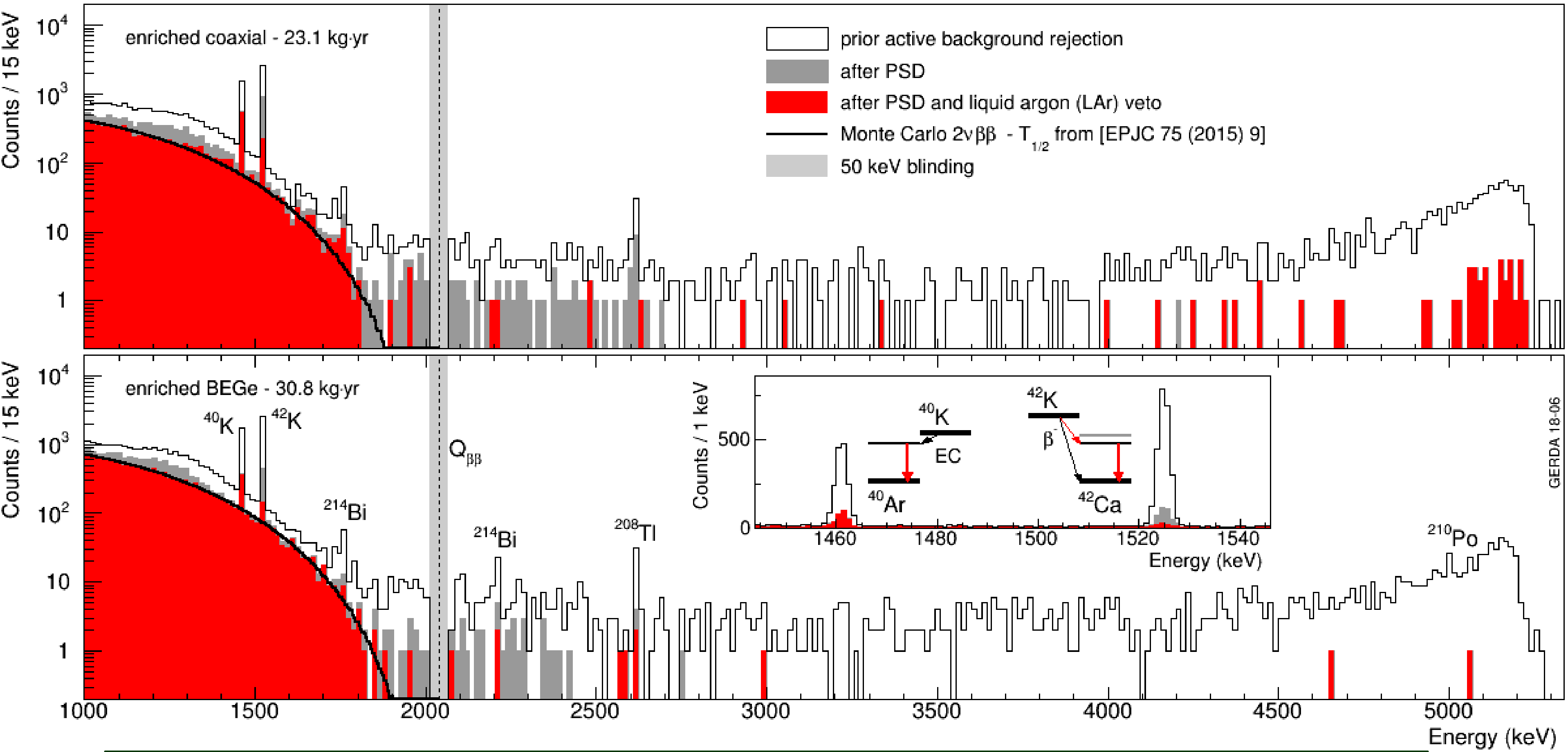


# Background suppression




Energy region $Q_{\beta\beta} \pm$ 5keV is blinded until analysis is fixed. Background index (BI) in energy region of [1930,2190] keV:

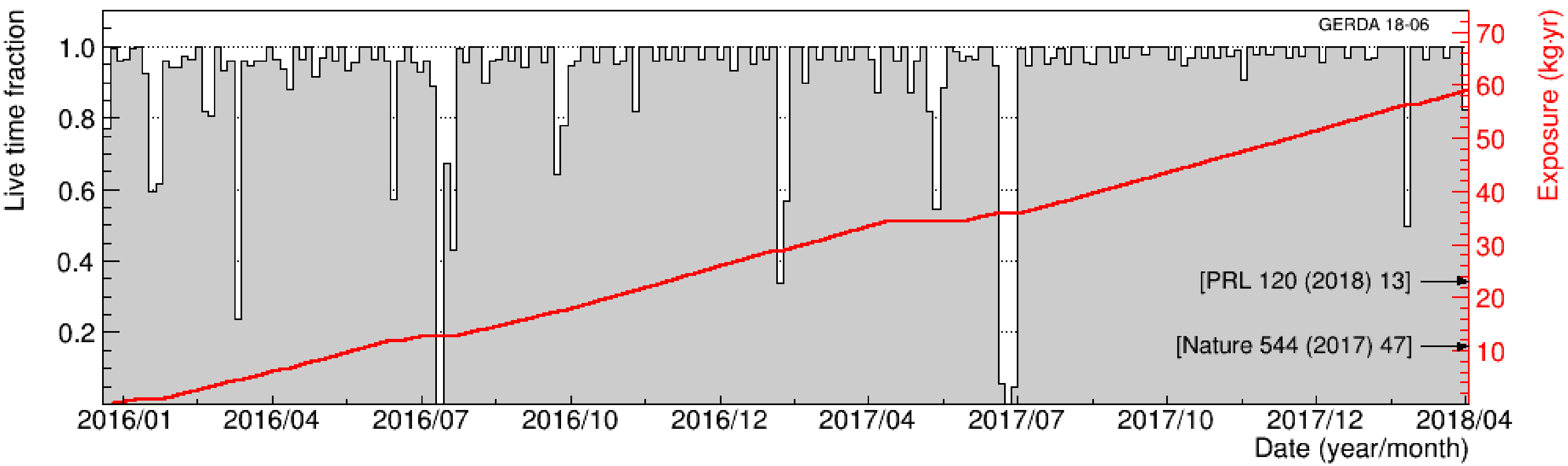
- For enriched coaxial: **$5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)**
- For enriched BEGe: **$5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)**

**"Background free"** regime achieved - sensitivity scales linearly with exposure!

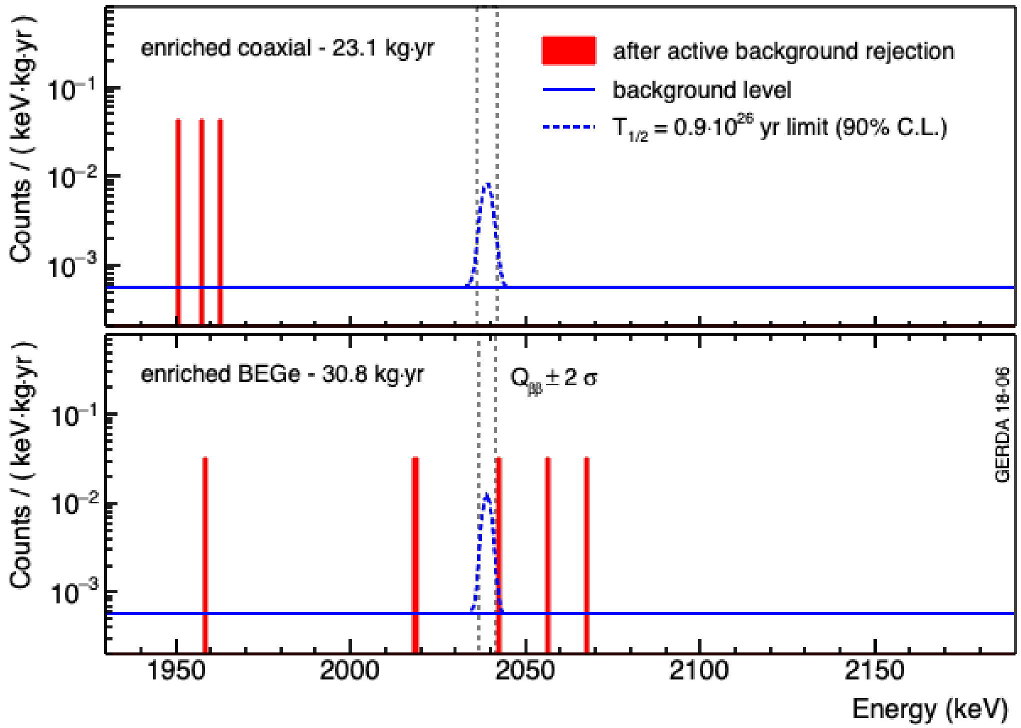
# Data taking until upgrade 2018

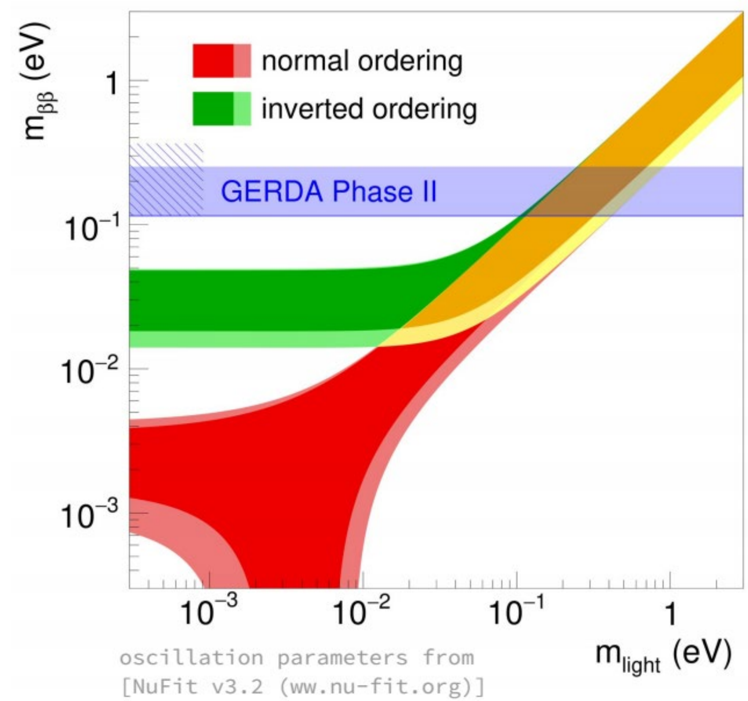
| Dataset | Exposure [kg·yr] | FWHM [keV] | ε | BI [$10^{-3}$ cts/(keV·kg·yr)] |
|---|---|---|---|---|
| Phase I golden | 17.9 | 4.3 ± 0.1 | 0.57 ± 0.03 | 11 ± 2 |
| Phase I silver | 1.3 | 4.3 ± 0.1 | 0.57 ± 0.03 | 30 ± 10 |
| Phase I BEGe | 2.4 | 2.7 ± 0.2 | 0.66 ± 0.02 | $5^{+4}_{-3}$ |
| Phase I extra | 1.9 | 4.2 ± 0.2 | 0.58 ± 0.04 | $5^{+4}_{-3}$ |
| Phase II coax-1 | 5.0 | 3.6 ± 0.1 | 0.52 ± 0.04 | $3.5^{+2.1}_{-1.5}$ |
| **Phase II coax-2** | **23.1** | **3.6 ± 0.1** | **0.48 ± 0.04** | $\mathbf{0.6^{+0.4}_{-0.3}}$ |
| **Phase II BEGe** | **30.8** | **3.0 ± 0.1** | **0.60 ± 0.02** | $\mathbf{0.6^{+0.4}_{-0.2}}$ |

Requirements to the BI were achieved even for coax detectors! Duty cycle: 92.9%. Data quality: 80.4%. Total exposure including Phase I is **82.4 kg·yr**



# GERDA Phase II results




**Frequentist** analysis:

- Best fit $\rightarrow$ no signal.
- **$T_{1/2}$ > 0.9·10$^{26}$ yr** (median sensitivity for limit **1.1 ·10$^{26}$ yr** ) @ 90% C.L.

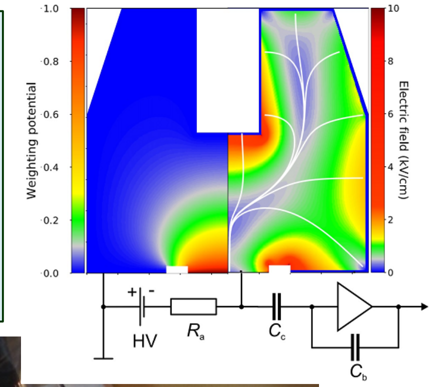
**Bayesian** analysis:

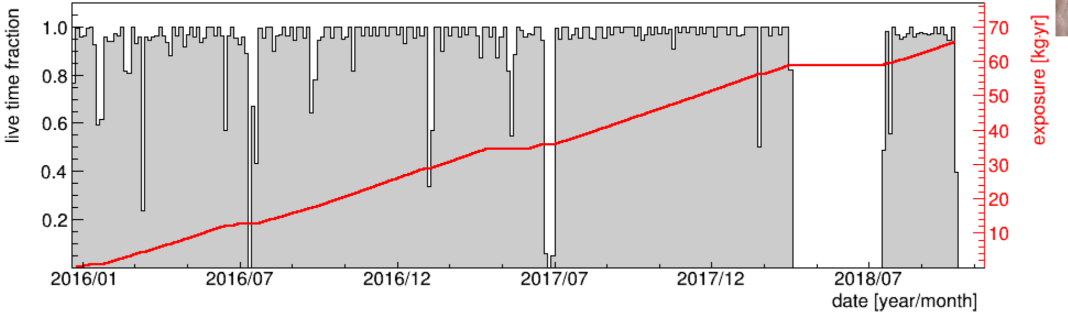
- Best fit $\rightarrow$ no signal. Bayes factor = 0.054
- $T_{1/2}$ > 0.8·10$^{26}$ yr (median sensitivity for limit 0.8 ·10$^{26}$ yr ) @ 90% C.I.

The median limit on effective Majorana mass is **< (0.11-0.26) eV** NME range from [Rept.Prog.Phys. 80 (2017) no.4, 046301]

# GERDA upgrade 2018

Major upgrade of the experimental setup (May 2018):
- New **5 enriched inverted coaxial (9.5 kg)** installed instead of natural
- **Improved LAr veto:** new fibers + central fiber shroud
- **Improved electronic noise**
- **Cleaner materials (cables and electronics)**



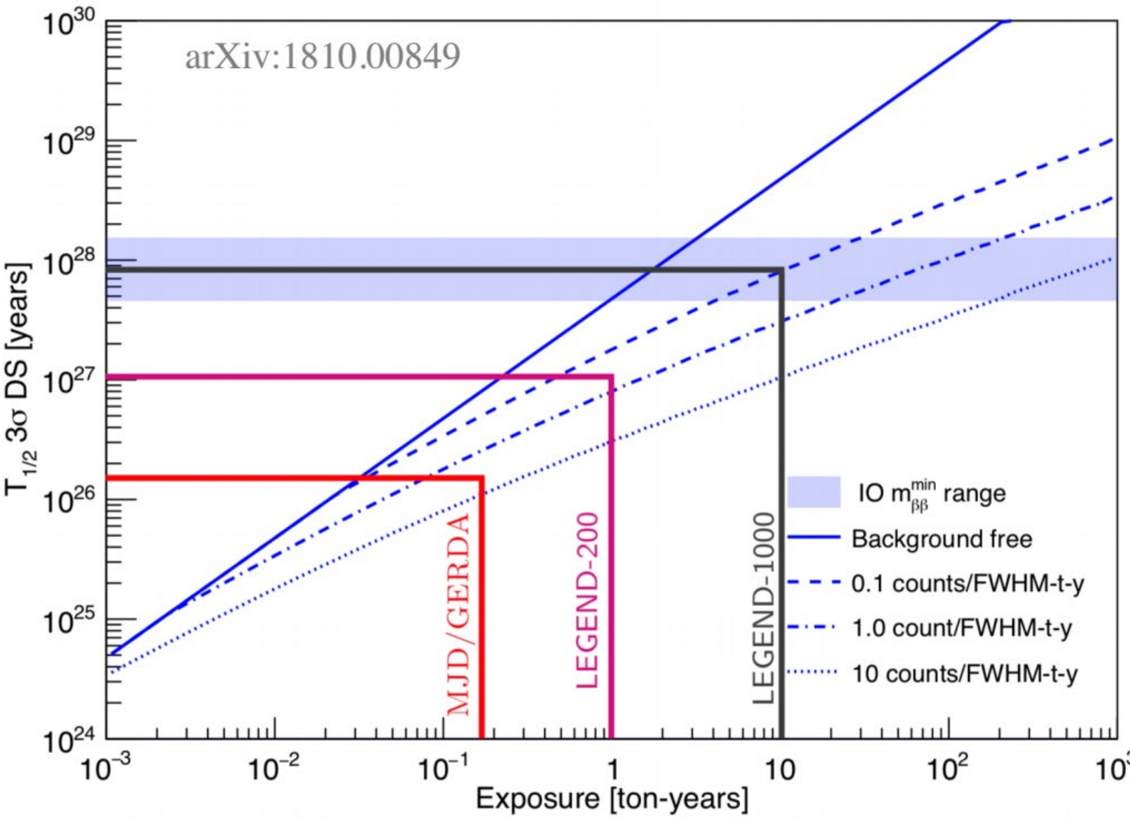




- Data taking now
- Phase II goal (exposure of 100 kg·yr) will be reached soon!

# Beyond GERDA: LEGEND

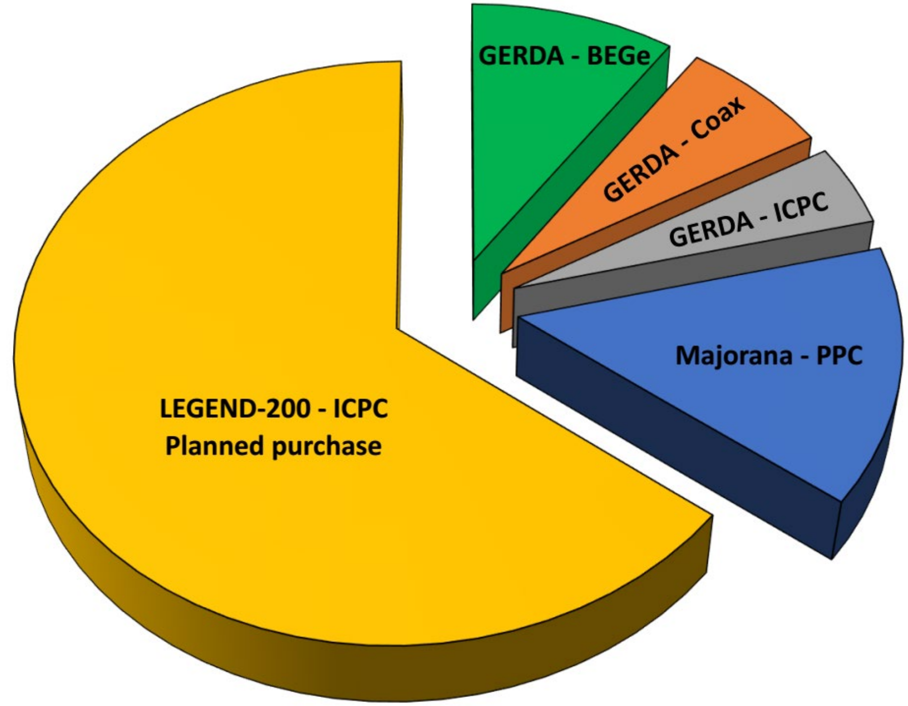
**LEGEND** collaboration:
- **GERDA + MAJORANA** + external contributions
- **52** institutes
- ~ **250** members


Staged approach:
- **LEGEND 200:** up to 200 kg of $^{76}$Ge in the existing GERDA cryostat at LNGS. Sensitivity ~ $10^{27}$ yr.
- **LEGEND 1000:** 1 ton detector mass, proposal for the future, location is under discussion. Sensitivity ~ $10^{28}$ yr



# LEGEND-200

- Increased detector mass up to 200 kg
- Funding basically secure
- Inverted coaxial point contact HPGe detectors with mass up to 3 kg
- New Low Mass Front End (LMFE) electronics with reduced noise $\rightarrow$ better resolution and PSA
- Optimization of LAr veto using GERDA experience
- Radiopure detector surrounding
- Ultra-pure electroformed copper
- BI goal: 0.6 cts/(FWHM·t·yr) – factor of 3 better than now in GERDA.




| Anticipated schedule | |
|---|---|
| Jan 2018 | First LEGEND-200 enriched material purchase |
| 2019 / 2020 / 2021 | LEGEND-200 Detectors production |
| Nov 2020 | Start installation of detectors |
| July 2021 | Data taking with LEGEND-200 |

# Summary

- Lowest background per ROI ever achieved in $0\nu\beta\beta$ experiments. Background Index:
  - for coaxial detectors: $5.7 \cdot 10^{-4}$ cts/(kg·keV·yr)
  - for BEGe detectors **$5.6 \cdot 10^{-4}$** cts/(kg·keV·yr)
- Excellent energy resolution and "background free" regime offer very good conditions for discovery of $0\nu\beta\beta$ decay. More results with higher sensitivity are expected in coming years.
- No $0\nu\beta\beta$ signal is observed so far.
- The obtained limit is $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.).
- GERDA keeps taking data.
- Preparations for LEGEND-200 are ongoing. Most of the funding for LEGEND-200 is secured.
- Data taking in LEGEND-200 is planning to start in 2021.

# Thank you!

# $^{42}Ar$ background mitigation

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

Surface beta events are efficiently suppressed by PSD.