Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

# New physics search with $^{76}$Ge $0\nu\beta\beta$ decay

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**On behalf the GERDA and LEGEND collaborations**

**Les Rencontres de Physique de la Vallée d'Aoste**

**La Thuile, Italy**

11 March 2019

# Crucial open issues in particle physics

**Number of baryons / antibaryons**
*(matter) / (antimatter)*

[Cooke, 2014]
[Planck, 2015]

**Baryonic asymmetry of the Universe**

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.05 \pm 0.07)\times 10^{-10}$$

**Number of photons**
*(light)*

Among many theoretical models: the **leptogenesis!?**

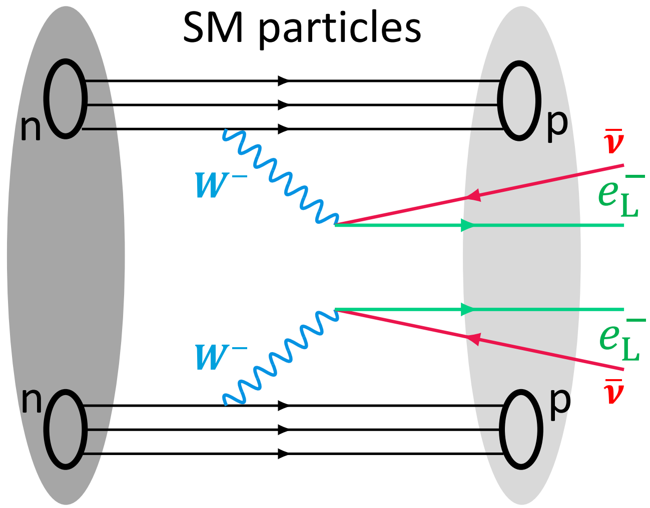
**Non-zero but tiny neutrino masses**

**See-saw** mechanism?

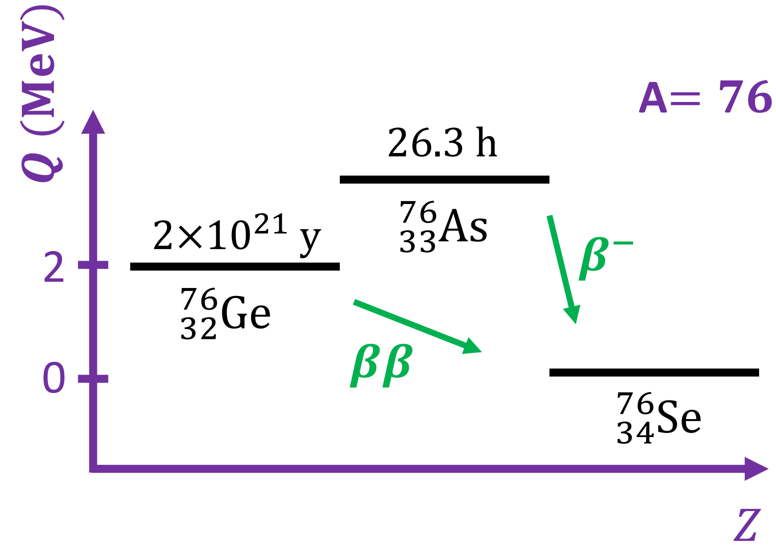
- requires neutrinos to be **Majorana** - **Lepton Number is violated** in general
- new mass term in the Lagrangian **explaining the smallness of masses**
- provides a mechanism for **effective leptogenesis**

**HOW TO RELATE THIS TO $^{76}$Ge?**

# Two neutrinos double beta decay - $2\nu\beta\beta$




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

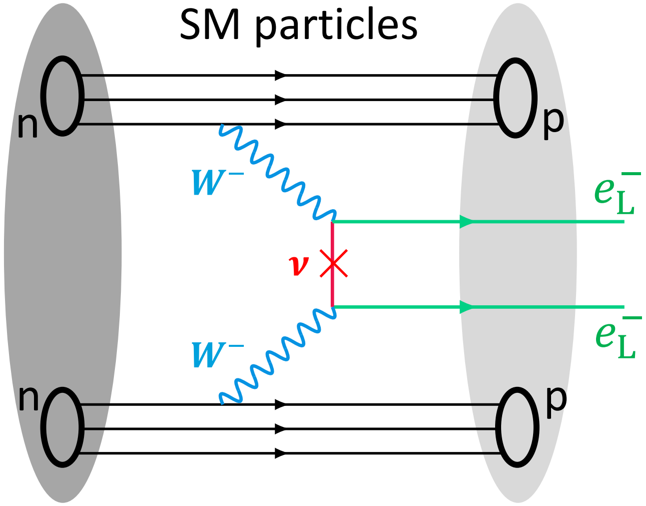



Such process:

- ✓ energetically favored in some isotopes ($^{76}$Ge, $^{82}$Se, $^{130}$Te, $^{136}$Xe, …)
- ✓ is predicted by the SM
- ✓ is measured experimentally

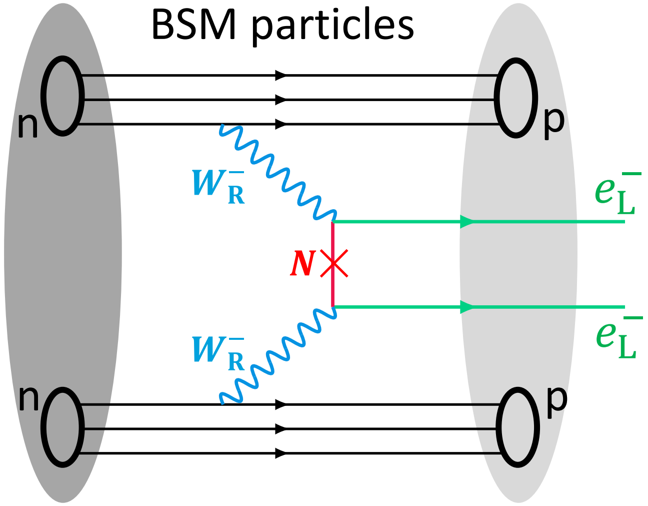
# Neutrinoless double beta decay - $0\nu\beta\beta$

Light neutrino exchange
SM particles




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

Heavy neutrino exchange
BSM particles



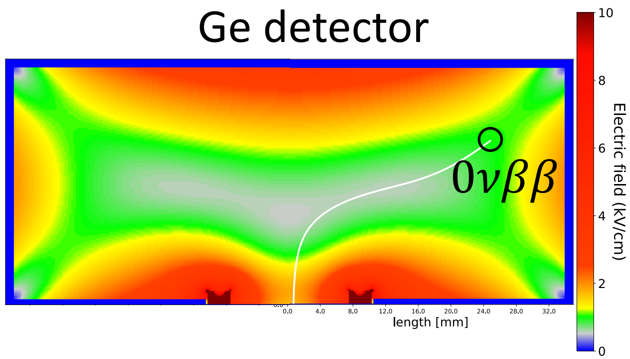

$(A,Z) \rightarrow (A,Z+2) + 2e^-$

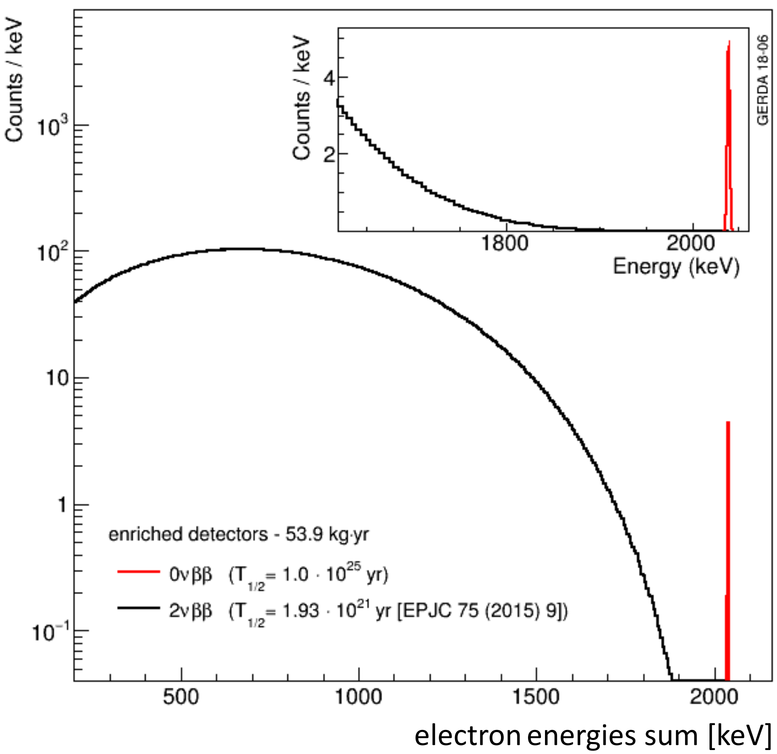
Such process:

- ✓ **violates the Lepton Number** by 2 units = New Physics!
- ✓ determines the nature of neutrinos: **Majorana particle** $\boldsymbol{\nu = \bar{\nu}}$
- ✓ gives information on the $\nu$ mass via $m_{\beta\beta}$ (light neutrino exchange scenario)
- ✓ has never been observed so far

➢ High sensitivity due to the Avogadro number: $\sim 10^{25}$ Ge nuclei / kg

# $^{76}$Ge based $0\nu\beta\beta$ decay experiment




- $Q_{\beta\beta} = 2039$ **keV**
  - relatively low value as compared to other isotopes
- **Calorimetry**
- **High detection efficiency**
  - $2\beta$ decay source = detector
- **Excellent energy resolution**
  - 3 keV FWHM @ $Q_{\beta\beta}$ (0.15%)
- **Enrichment up to 88% in $^{76}$Ge**
  - current mass scale: 30 - 40 kg
- **“Background-free experiment” :**
  - Nbkg < 1 expected at full exposure (~100 kg.yr)

$$\sigma T^{0\nu}_{1/2} \propto M.t$$

➢ **Motivating larger mass $^{76}$Ge based experiment for the future**

# Current and planned experiments

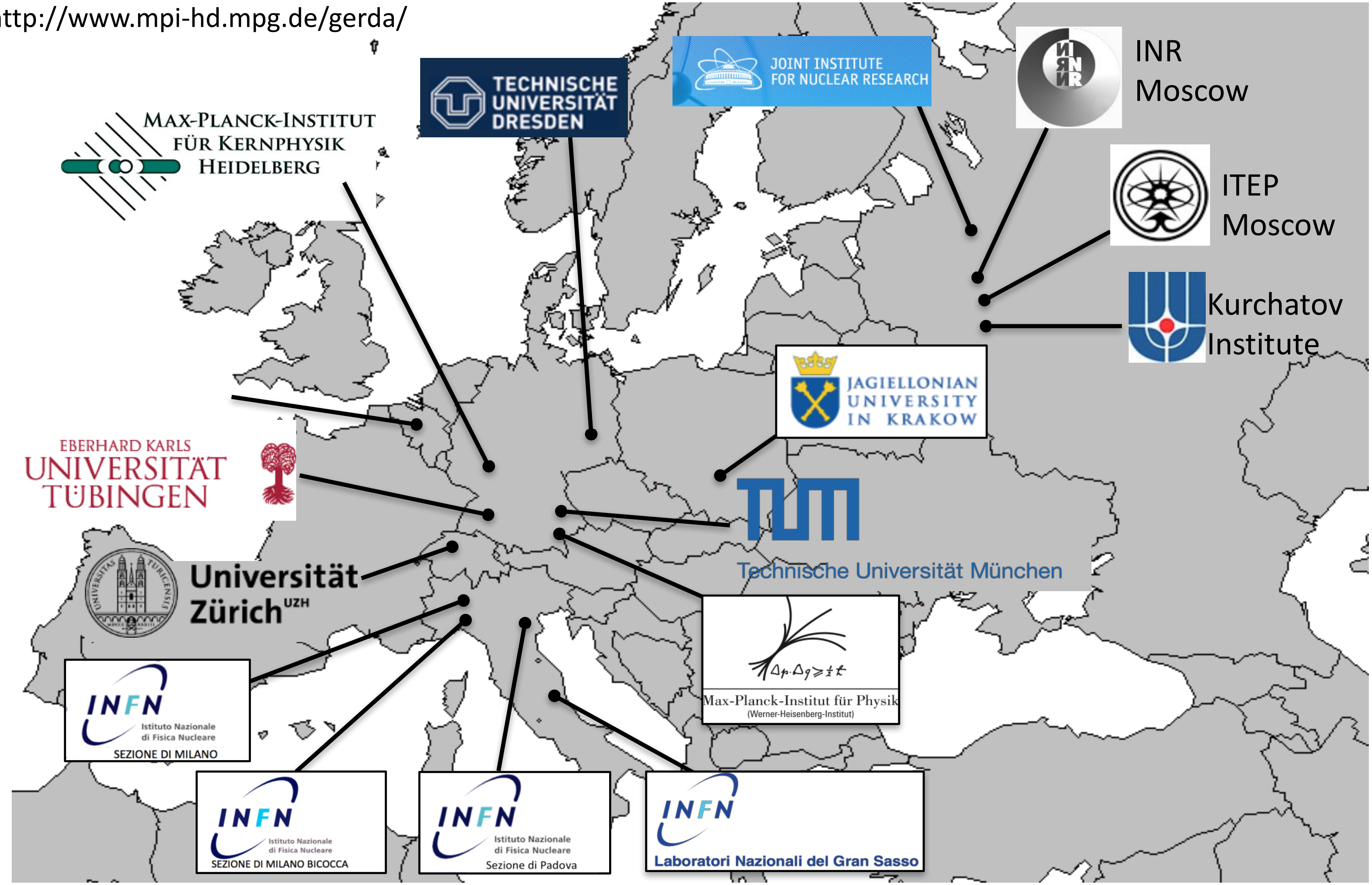
running
30 kg
$T_{1/2}^{0\nu} > 10^{26}$ yr

mid-term
200 kg
$T_{1/2}^{0\nu} > 10^{27}$ yr

long-term
1 ton
$T_{1/2}^{0\nu} > 10^{28}$ yr

# GERDA collaboration

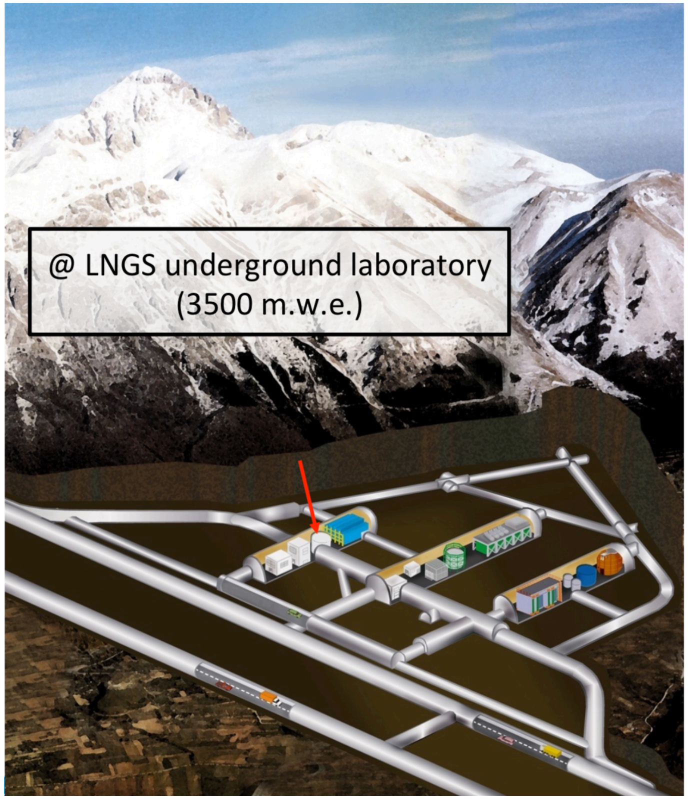
http://www.mpi-hd.mpg.de/gerda/



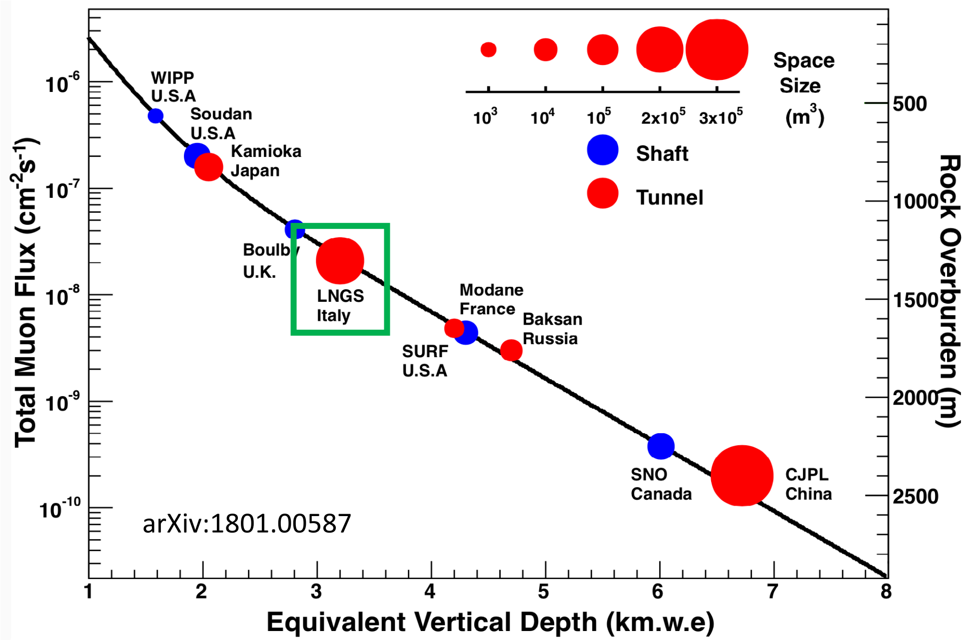
# GERDA location @ LNGS

- Cosmic ray background mitigation

Deep underground lab
➢ Muon flux suppression



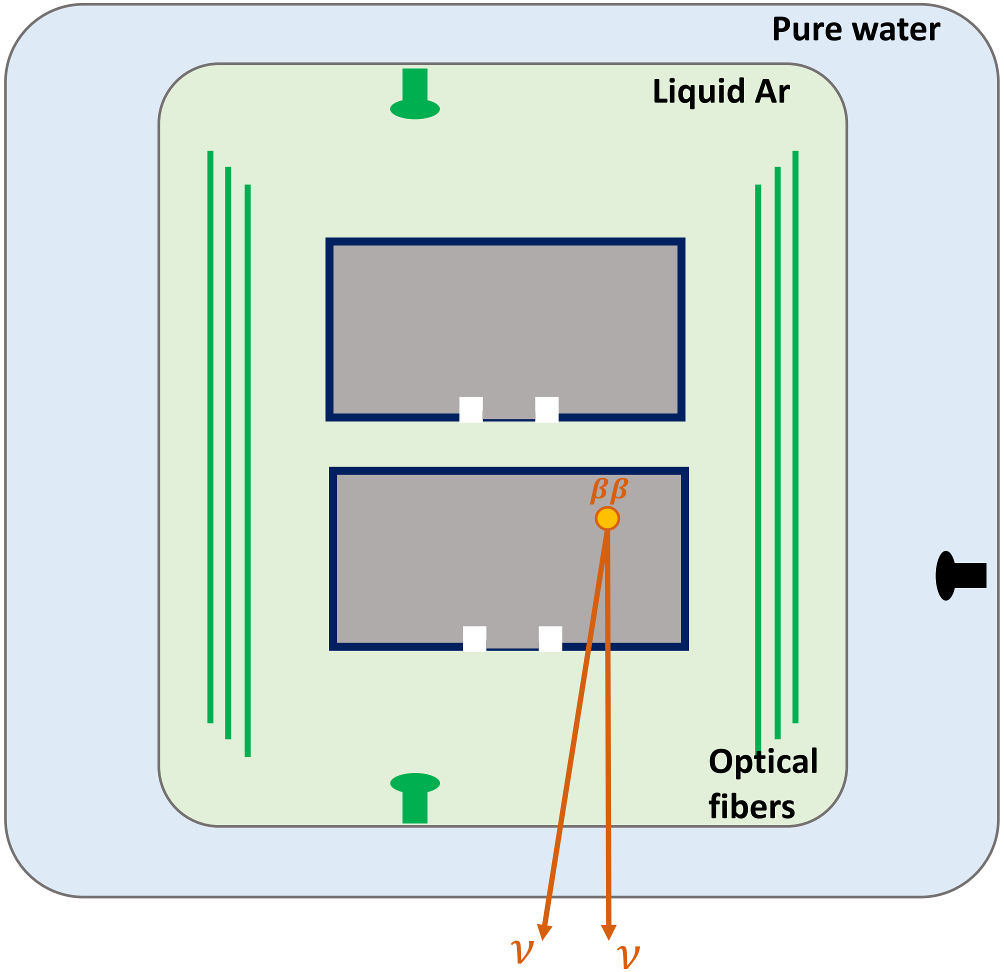

Large space available at LNGS
+ convenient access via highway



# Toward the background-free regime

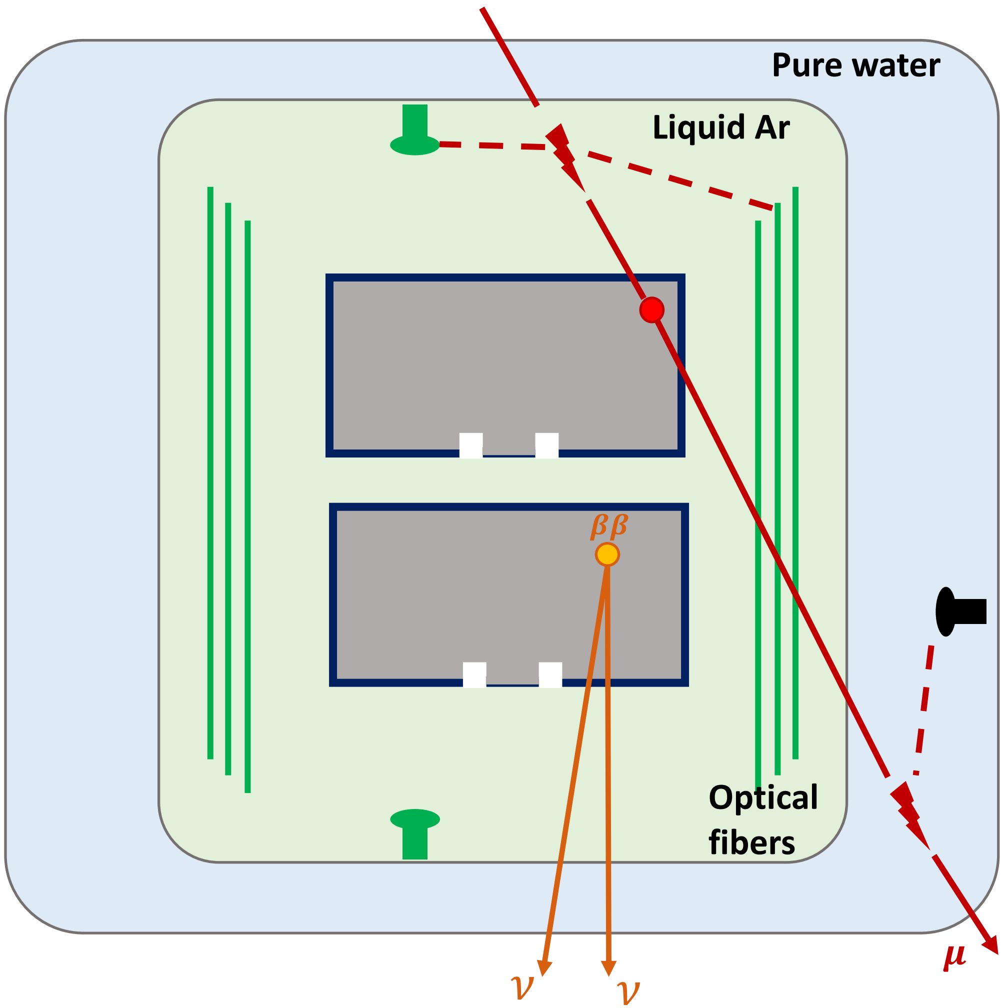
- signal signature

$\beta\beta$ decay signal: single energy deposition in a 1 mm³ volume



# Toward the background-free regime

- background mitigation



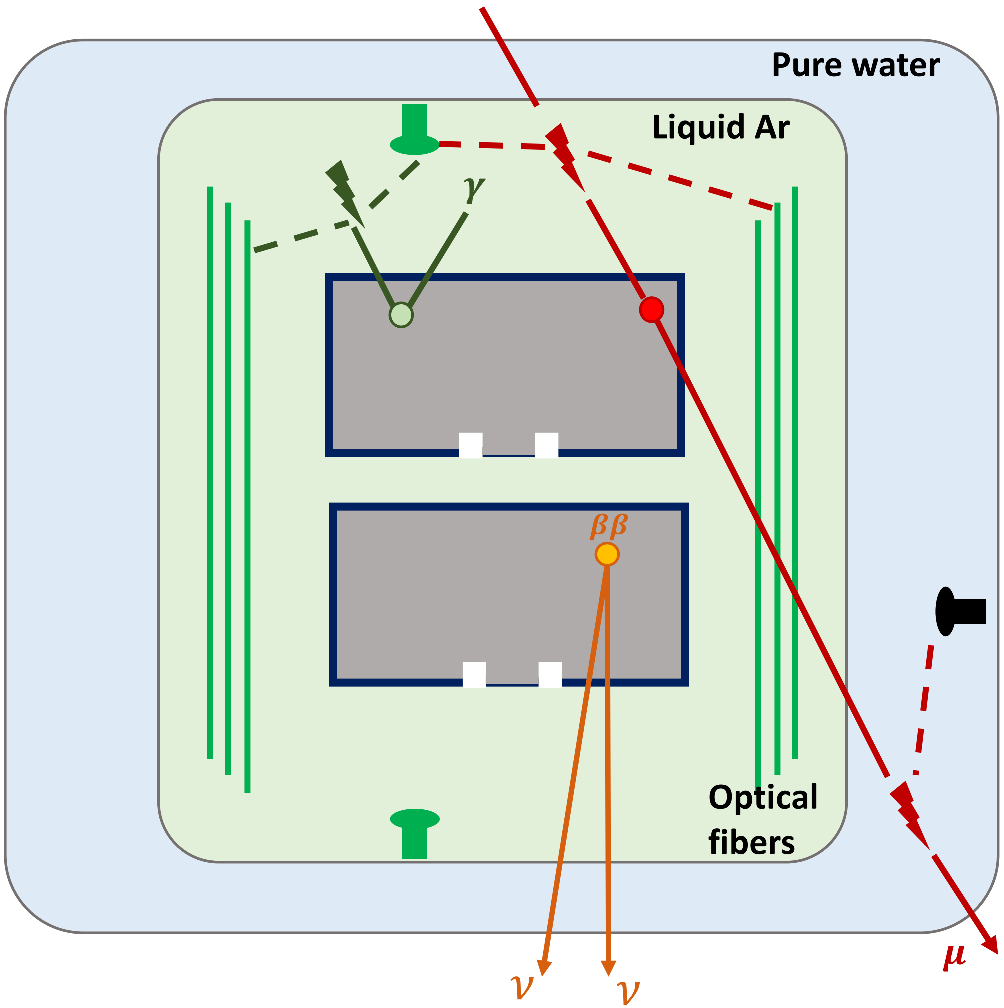

$\beta\beta$ decay signal: single energy deposition in a 1 mm$^3$ volume

Muon veto based on Cherenkov light and plastic scintillator

# Toward the background-free regime

- background mitigation

$\beta\beta$ decay signal: single energy deposition in a 1 $mm^3$ volume




LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

# Toward the background-free regime

- background mitigation

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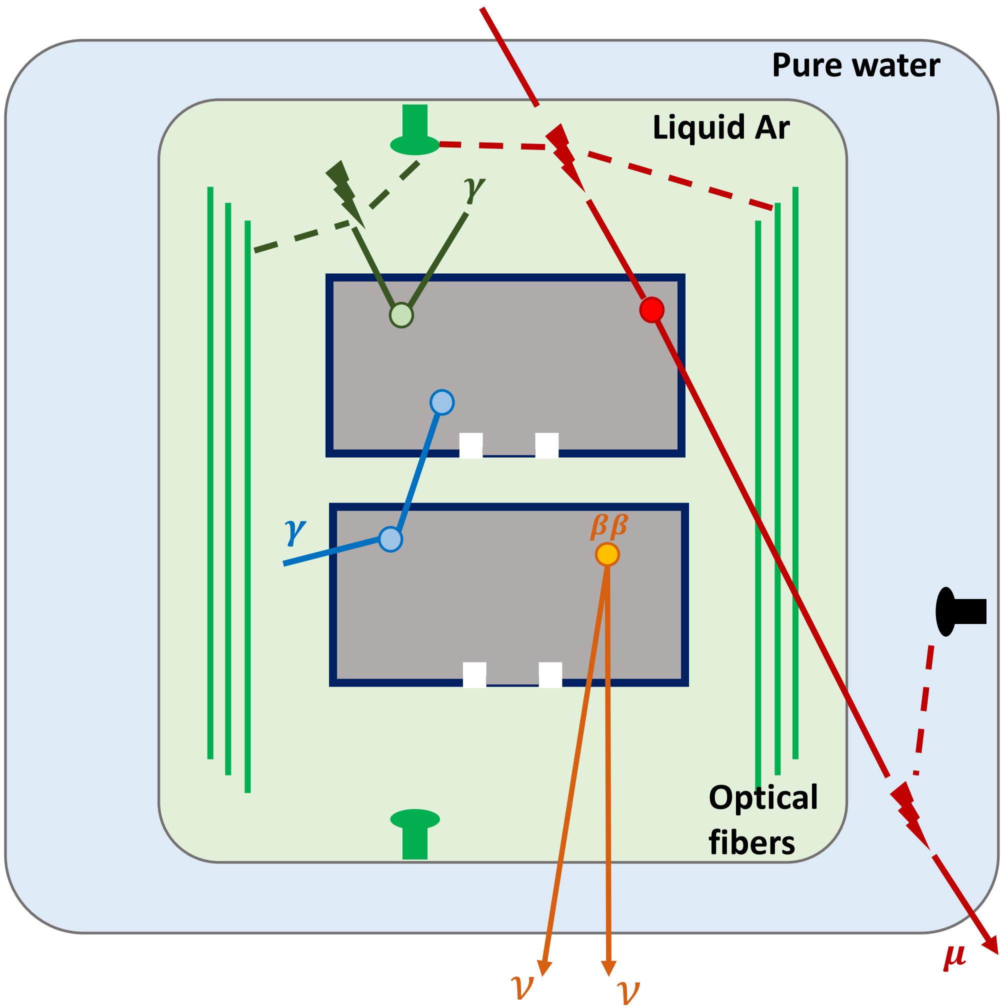


Ge detector anti-coincidence

LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

# Toward the background-free regime

- background mitigation

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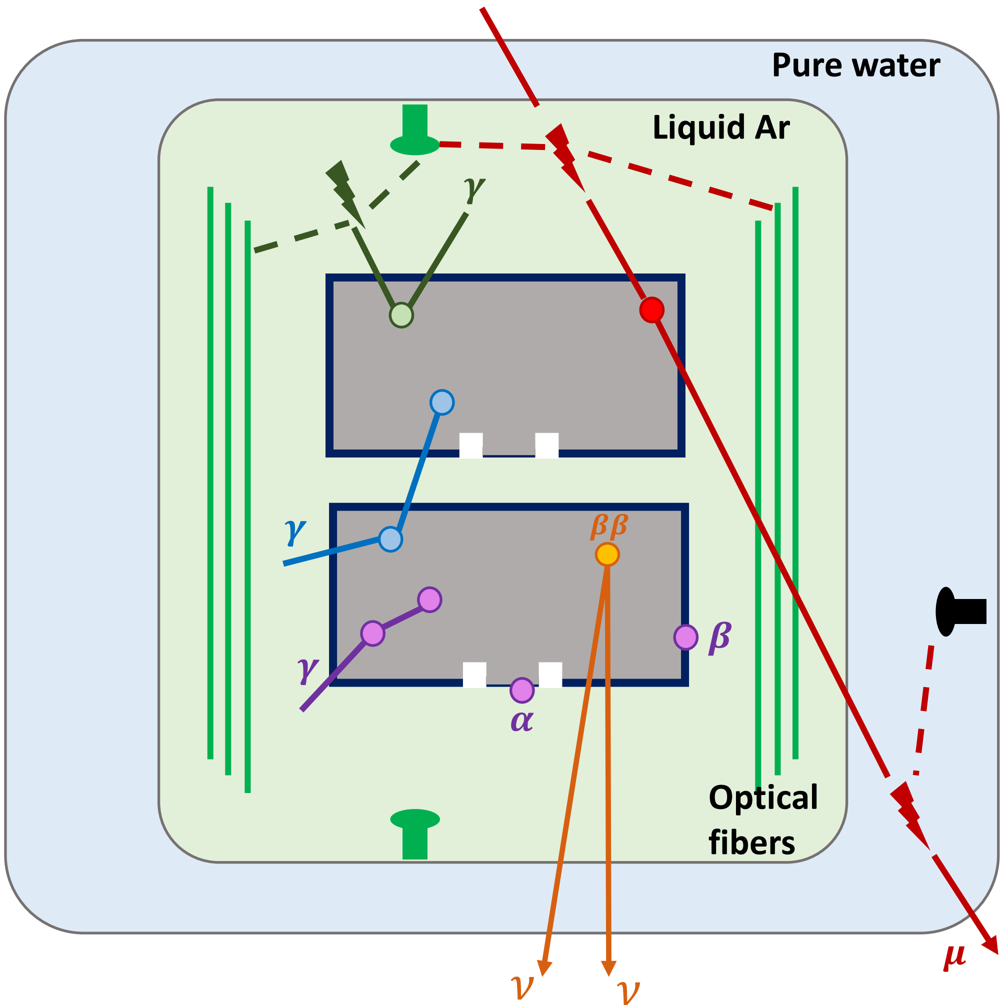


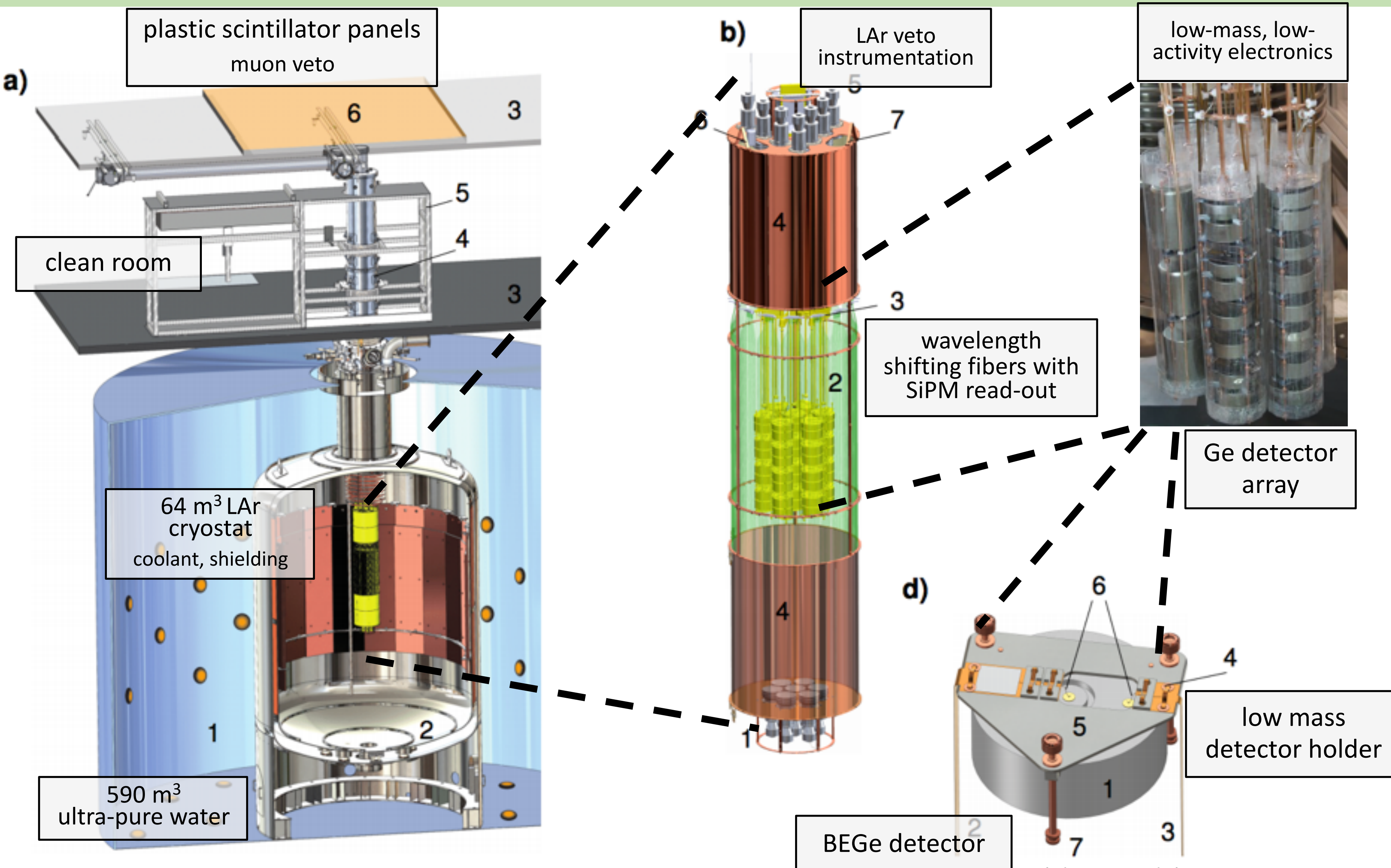

Pulse shape discrimination (PSD) for multi-site and surface $\alpha$, $\beta$ events

Ge detector anti-coincidence

LAr veto based on Ar scintillation light read by fibers and PMT

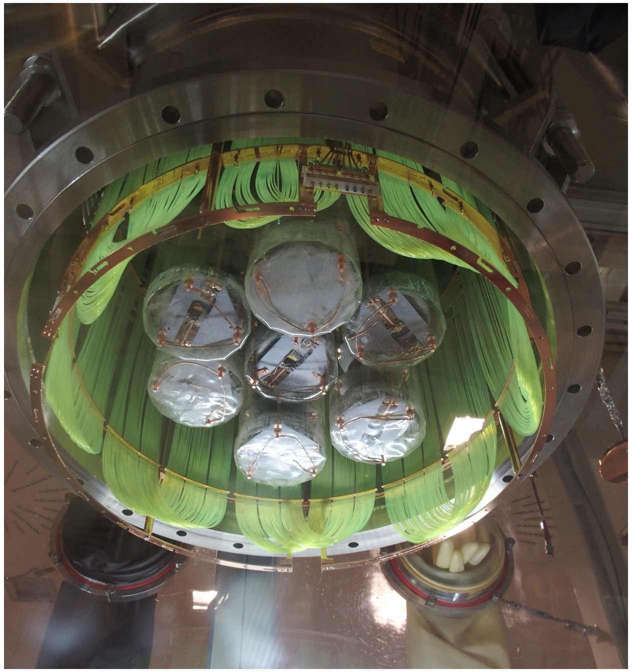
Muon veto based on Cherenkov light and plastic scintillator

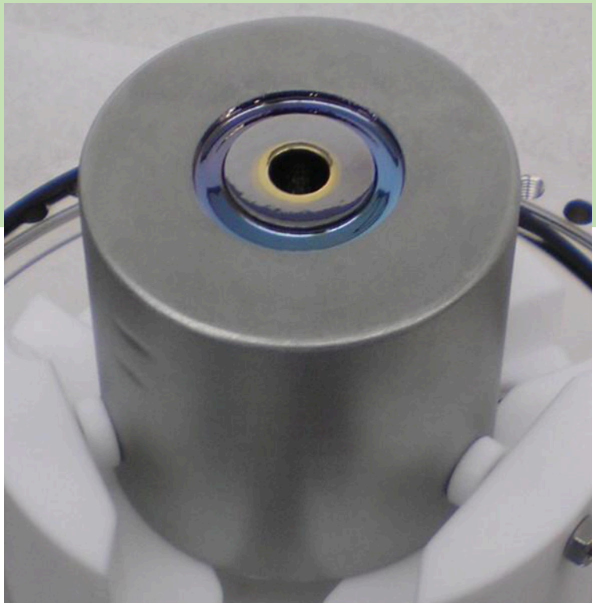
# GERDA Phase II: From concept to design

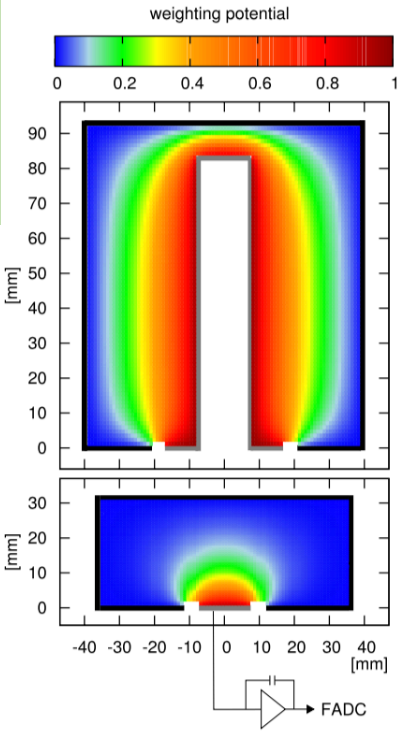



Slide: L. Pandola – TAUP 2017

# Ge detectors phase II

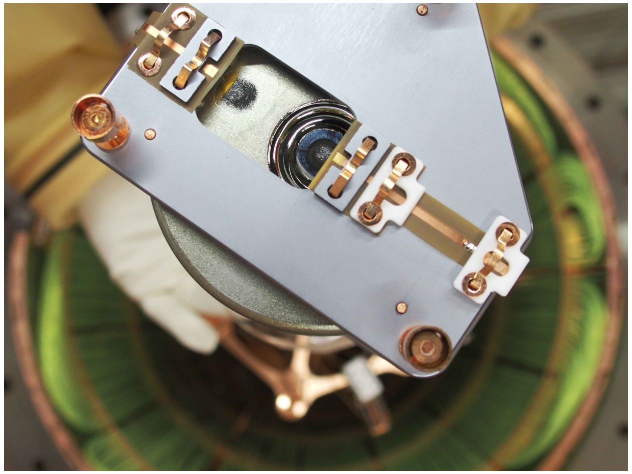


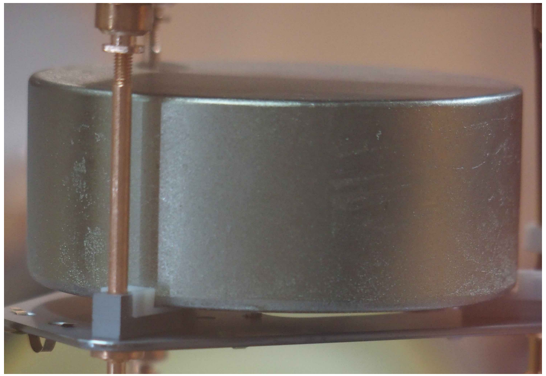


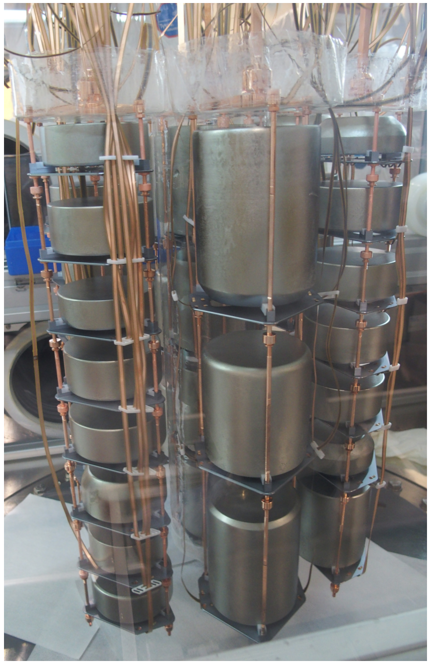



**7 strings with 40 detectors:**

- *3 natural semi-coaxial (7.6 kg)*
- **7 enriched semi-coaxial (15.6 kg)**
  - Large contact = large capacitance
- **30 enriched BEGe (20.0 kg)**
  - Point-contact = small capacitance



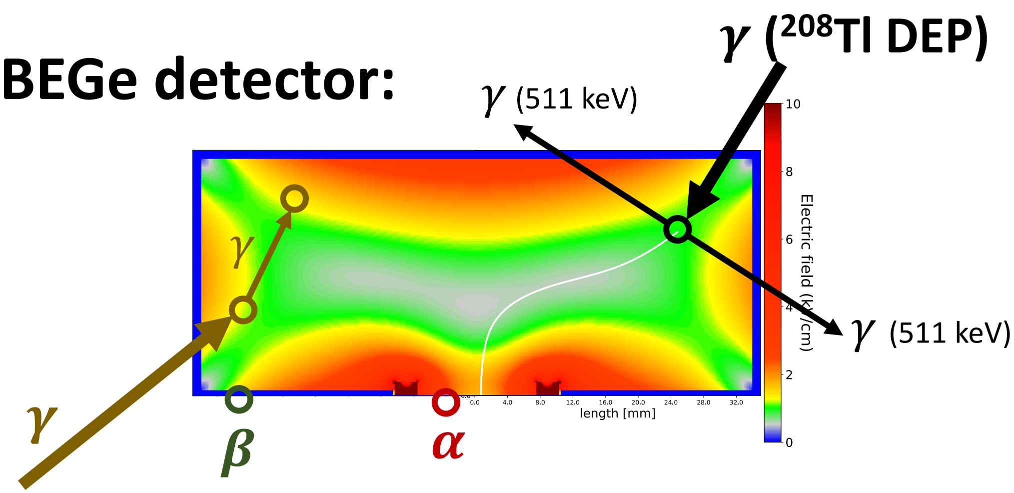




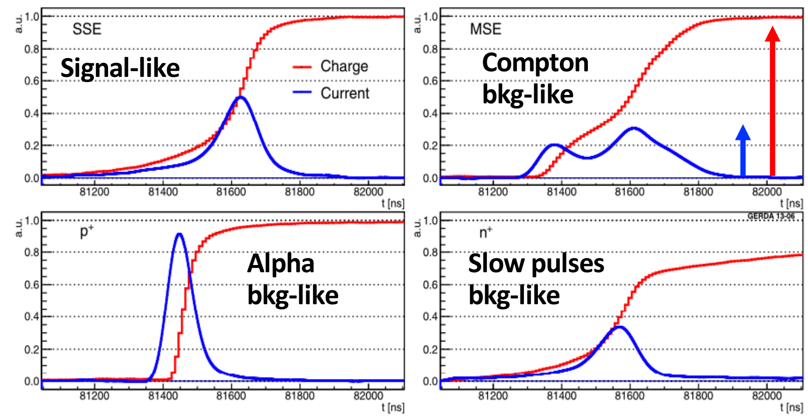
# Pulse shape discrimination

- **$^{208}$Tl DEP** (1592 keV) used as a proxy for **Single-Site Events** (SSE)
- **Multi-Site Events** (MSE) cut set such that 90% of $^{208}$Tl DEP events survive
- **Alphas** and **Betas** cut due to specific signal time profile

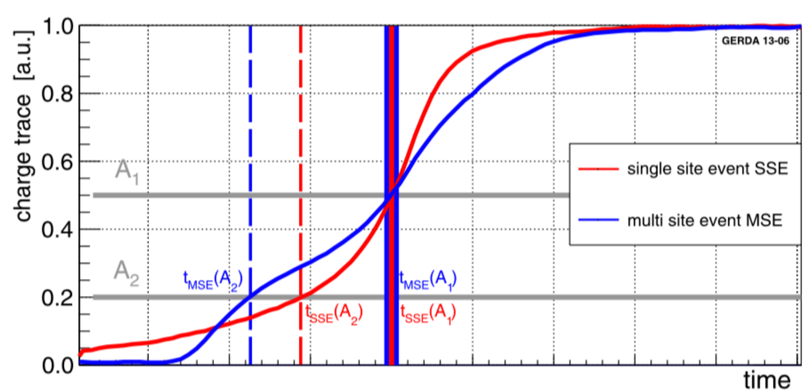
**BEGe detector:**




- **BEGe** cut parameter: **A/E**




- **Coax** cut parameter: Artificial Neural network

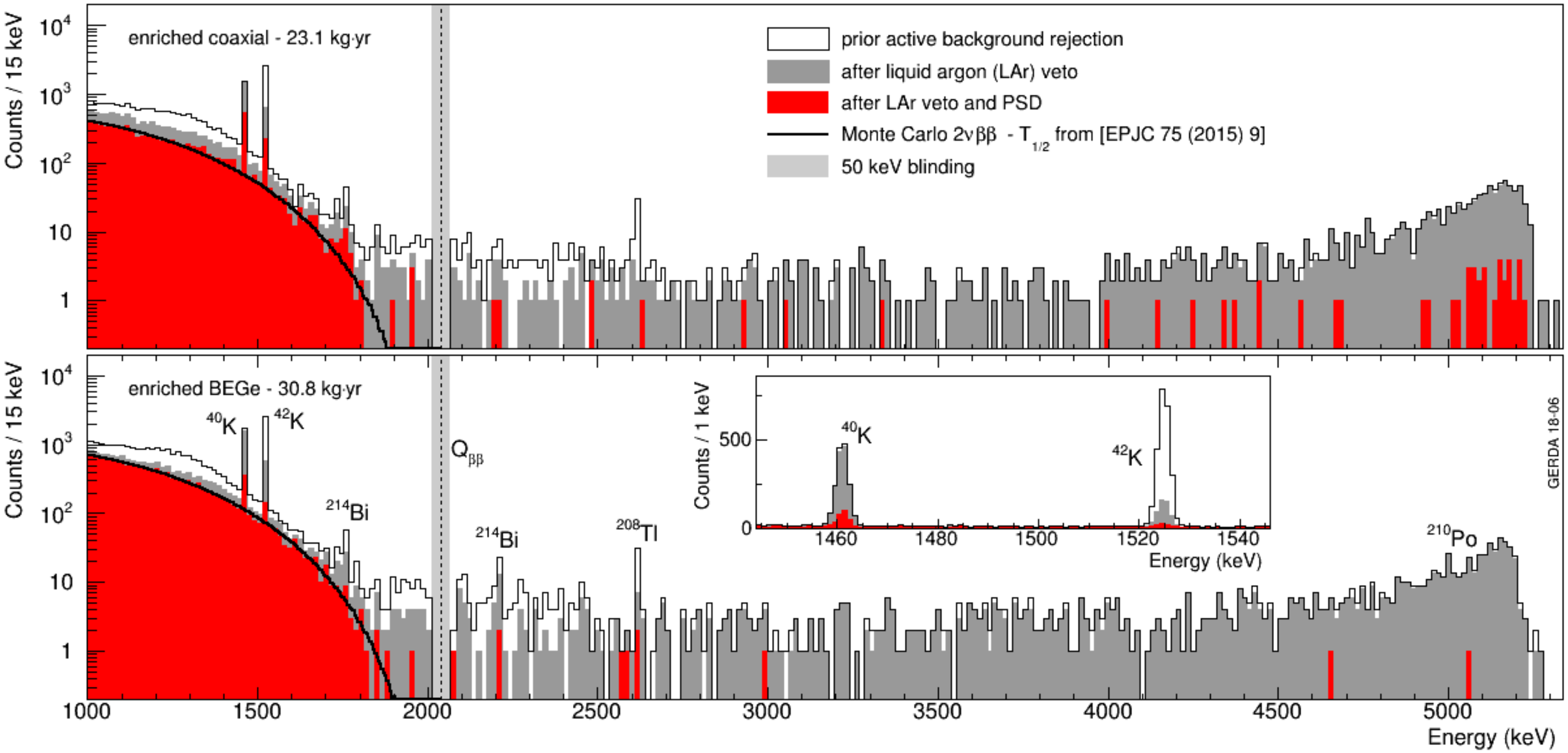



NB: 100 MHz x 10 ns trace

# Phase II physics data release at Nu18

Data taking from Dec. 2015 to April 2018

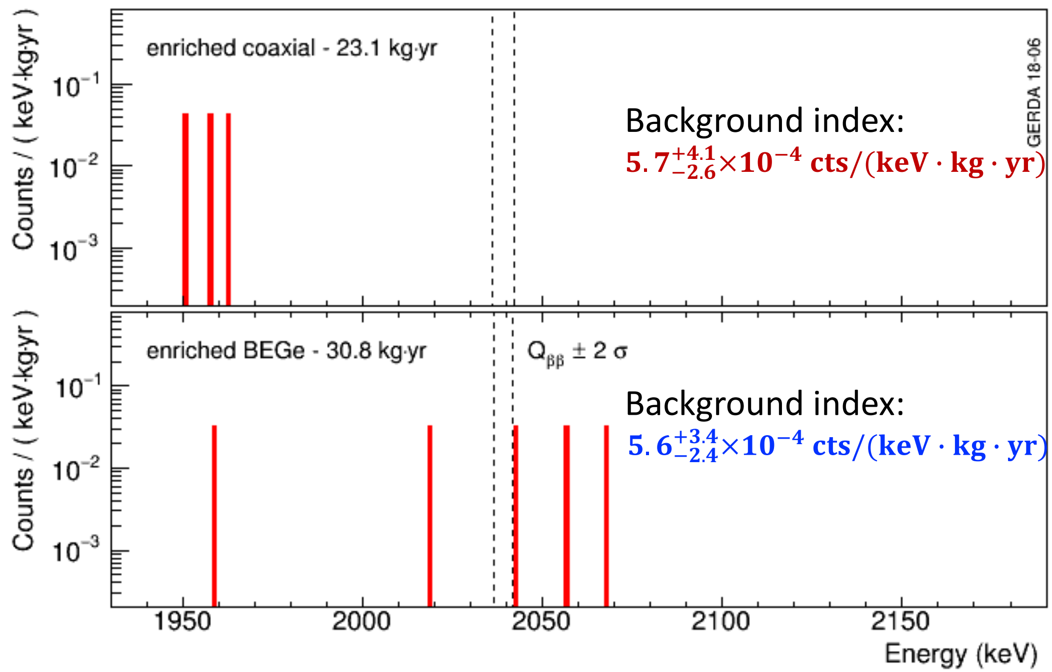
10.5281/zenodo.1287604
Neutrino (2018)

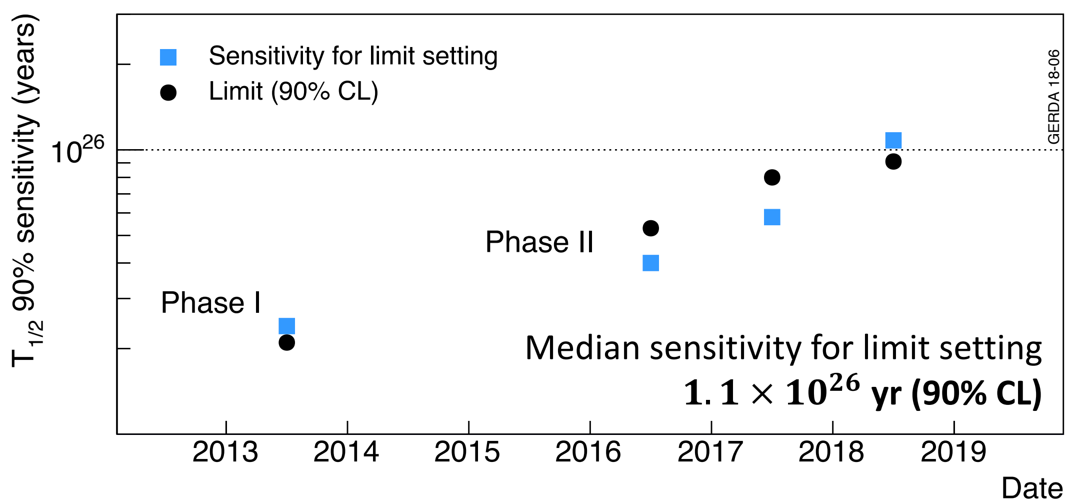



- [600-1300] keV - $2\nu\beta\beta$ decays produce single-site events -> No suppression
- [1450-1530] keV - Strong suppression of $^{40}K$ and $^{42}K$ gamma lines (MSE)
- [> 3000] keV - Suppression of almost all $\alpha$ events (p+ contact)

# Energy spectrum after unblinding!

10.5281/zenodo.1287604
Neutrino (2018)

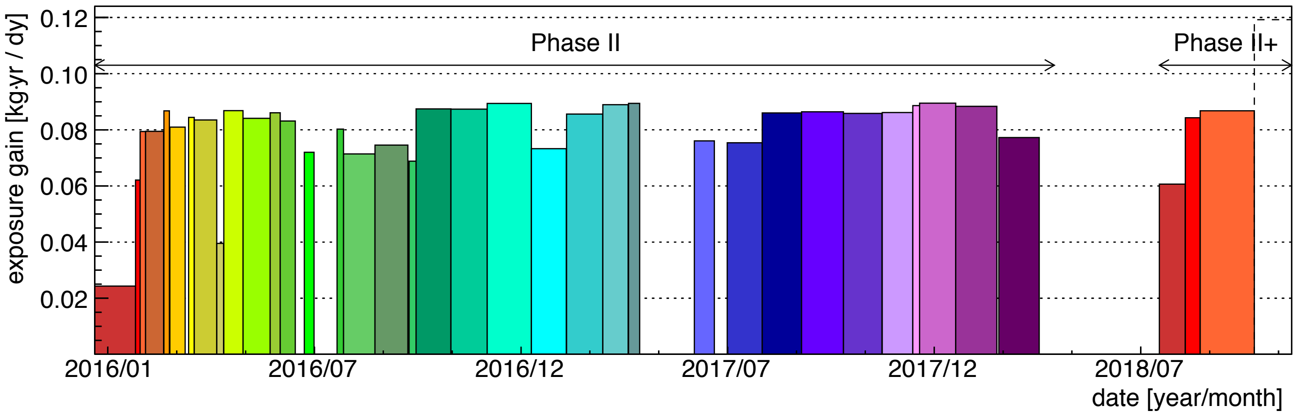


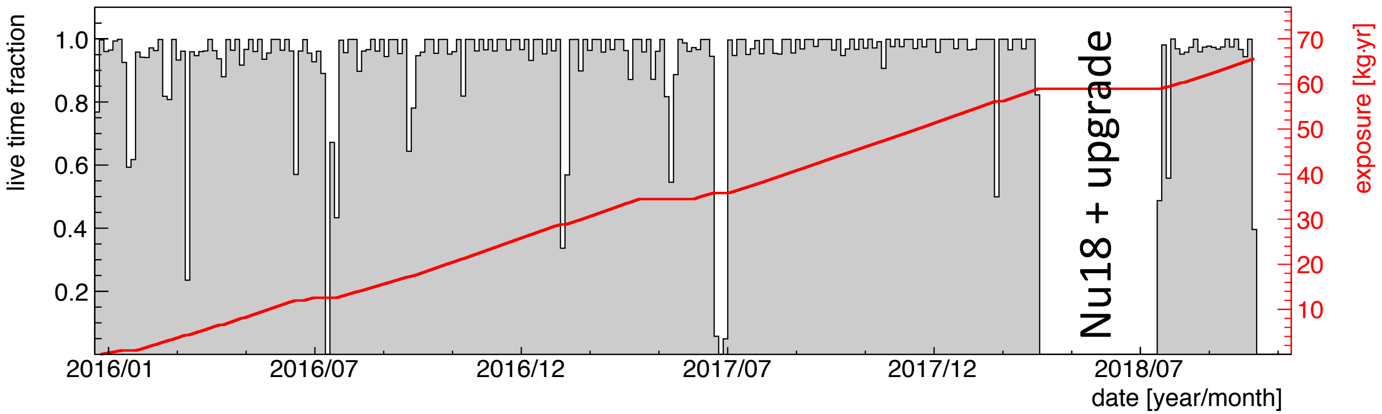



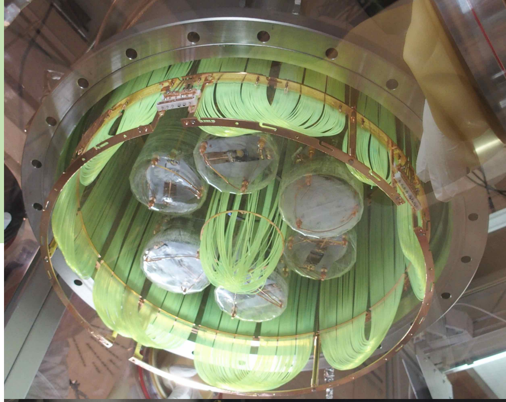
# Since Neutrino 2018

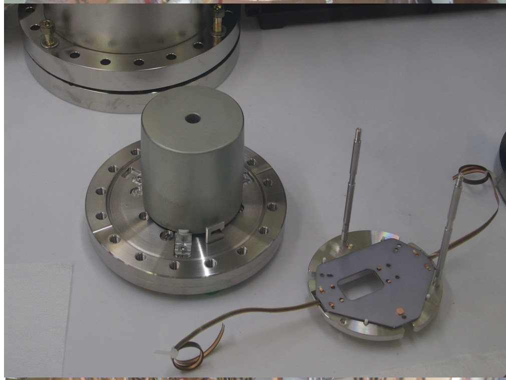
## Restart of the data taking

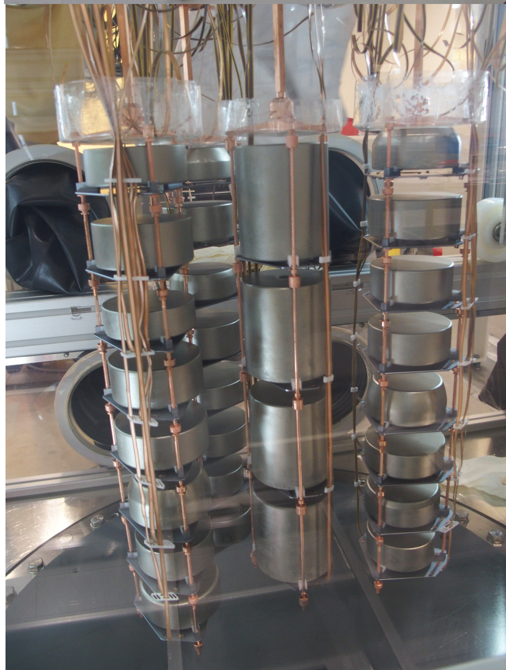
- Upgrade of the detector array + LAr veto
- Run until we reach 100 kg.yr







# After GERDA and MAJORANA:

**Legend collaboration:**

- 52 institutions, ~250 members
- GERDA / MAJORANA / external contributors

**Staged approach to reach $10^{28}$ yr sensitivity:**

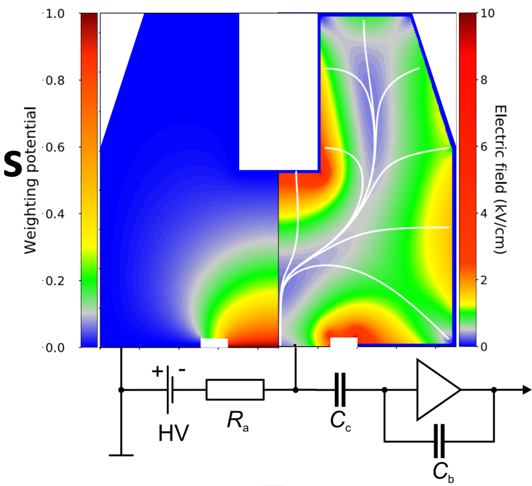
- LEGEND-200 $\rightarrow 10^{27}$ yr after 5 years
- LEGEND-1000 $> 10^{28}$ yr (hosting lab under investigation)


**LEGEND-200 phase:**

- Up to 200 kg of $^{76}Ge$
- Modification of existing GERDA infrastructure at LNGS
- Improved background index
- Data start in 2021
- NEWS:
  - **Most of funding already secured**
  - **First isotopes from both ECP/URENCO have arrived!**

# Hardware improvements

- **New Inverted Coaxial Point-Contact Ge detector technology**
  - ➢ Large active mass up to 3 kg (R&D for 6 kg!)
  - ➢ Characterization campaign starting in a few months
  - ➢ **Reduced background due to smaller number of channels**




- **Low Mass Front End (LMFE) electronics**
  - ➢ Experience from MAJORANA
  - ➢ Reduce the signal noise w.r.t. GERDA situation
  - ➢ Ongoing R&D in test stand
  - ➢ **Better energy resolution + pulse shape discrimination**

- **LAr veto**
  - ➢ Experience from GERDA
  - ➢ Design studies ongoing
  - ➢ **Optimization of light collection to better tag bkg**

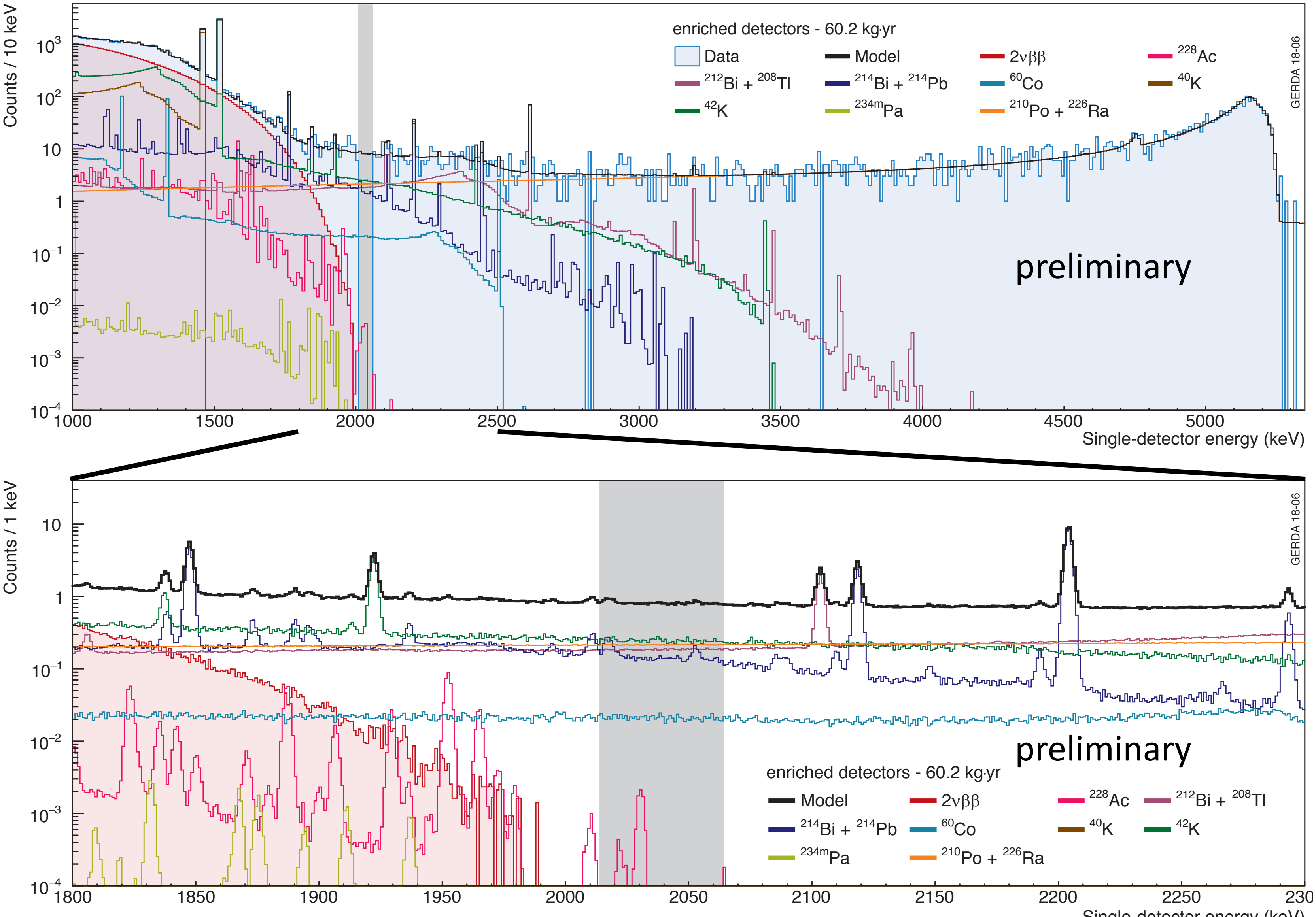
# Summary

- $0\nu\beta\beta$ decay, if discovered, has far reaching consequences in particle physics! $\boldsymbol{\nu = \overline{\nu}}$ / **LNV** / **interplay with cosmology** (many isotopes needed!)

- $^{76}$Ge isotope offers excellent properties especially for signal discovery
  - Energy resolution, background-free regime, high detection efficiency
  - Possibility to reach $T_{1/2}^{0\nu} > 10^{28}$ yr sensitivity
  - "the new physics is at **any** corner!" therefore we should continue measuring in all directions, regardless of physics models

- GERDA and MAJORANA DEMONSTRATOR best technologies provide the path to next generation experiment
  - First time **to surpass the $\mathbf{10^{26}}$ yr sensitivity**: $\mathbf{1.1 \times 10^{26}}$ **yr (90% CL)**
  - LEGEND-200 phase has secured funding
    Ongoing efforts to start in 2021!

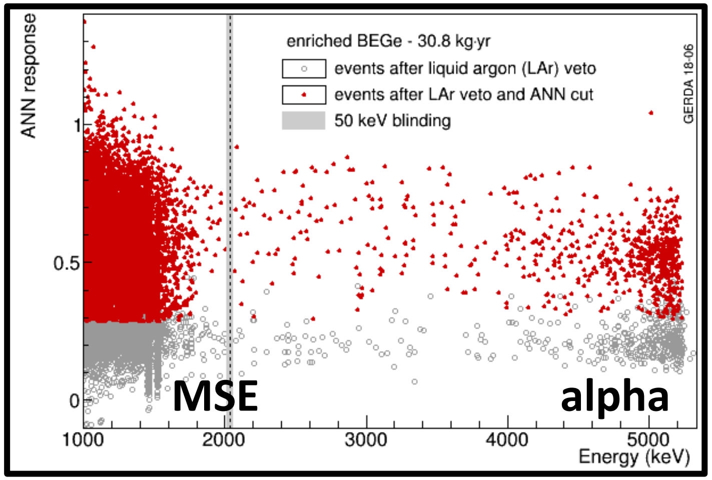
# Phase II physics data modeling before cuts



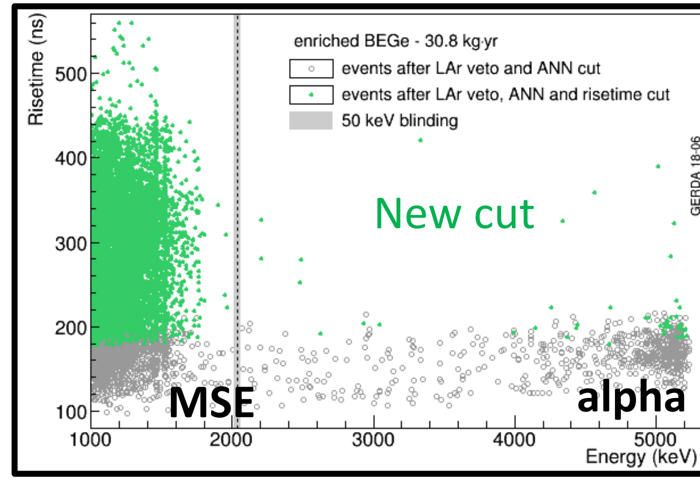
# Phase II PSD cut topology

Neural network

Coax

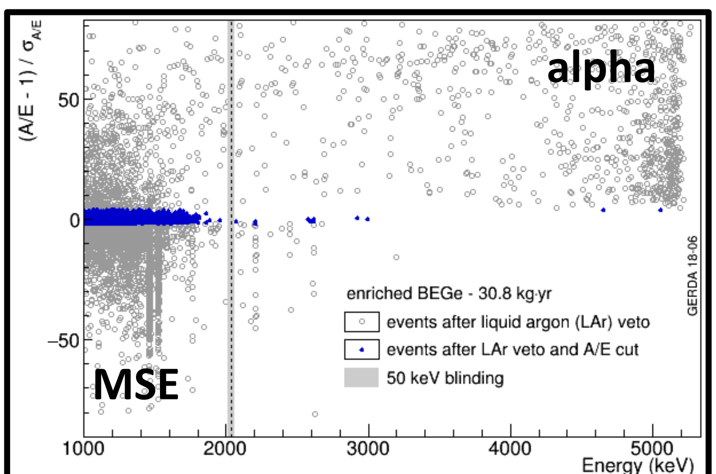



Signal rise time




A/E

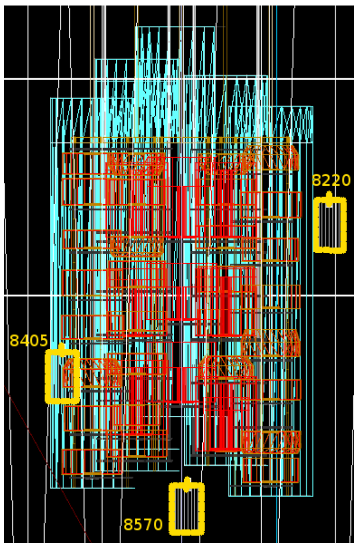
BEGe

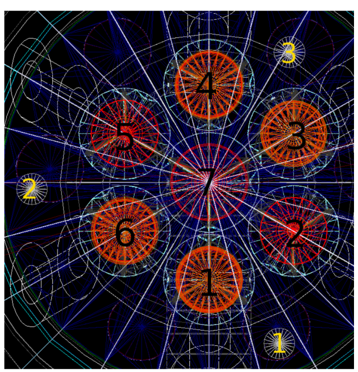


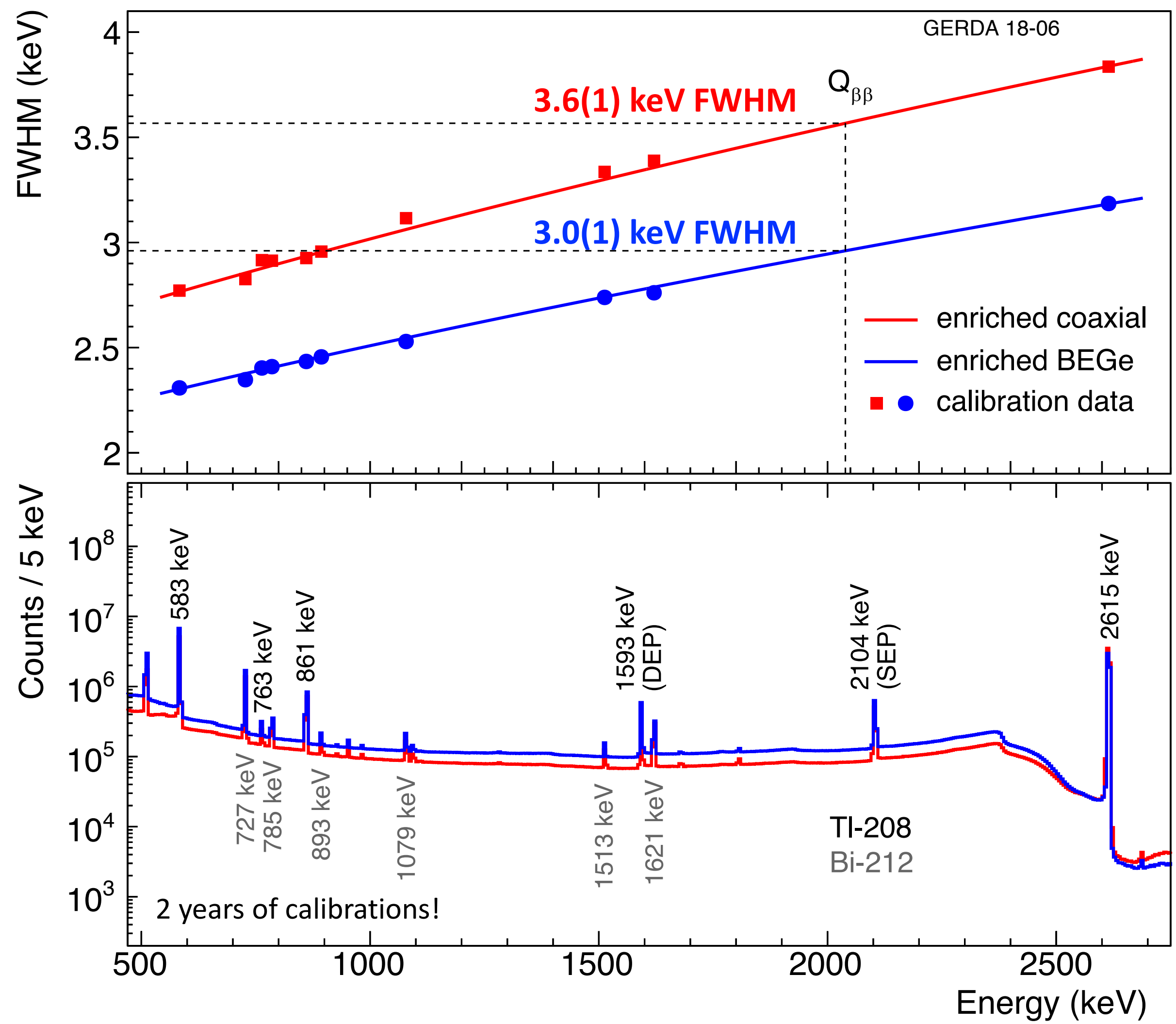

- Strong suppression of $^{40}$**K** and $^{42}$**K** gamma lines (MSE) [1450-1530] keV
- Suppression of almost all ***α* events** (p+ contact) [> 3000] keV
  Rise time cut for coax

# Energy calibration

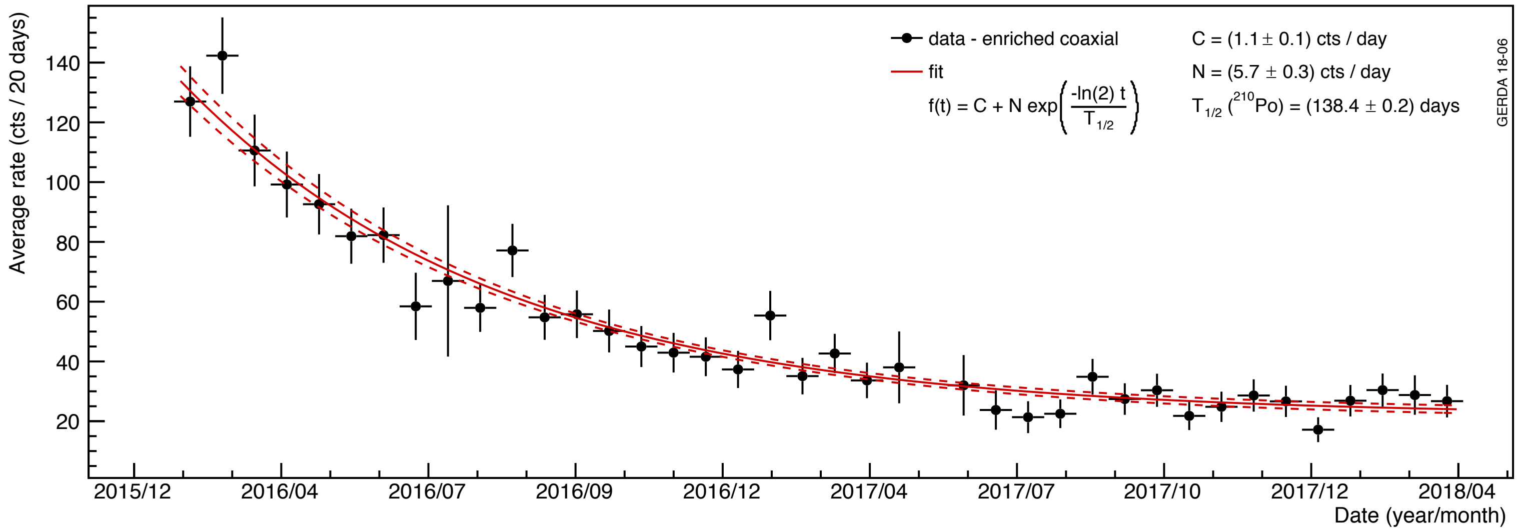
3 weak $^{228}$Th sources
lowered every ~ week

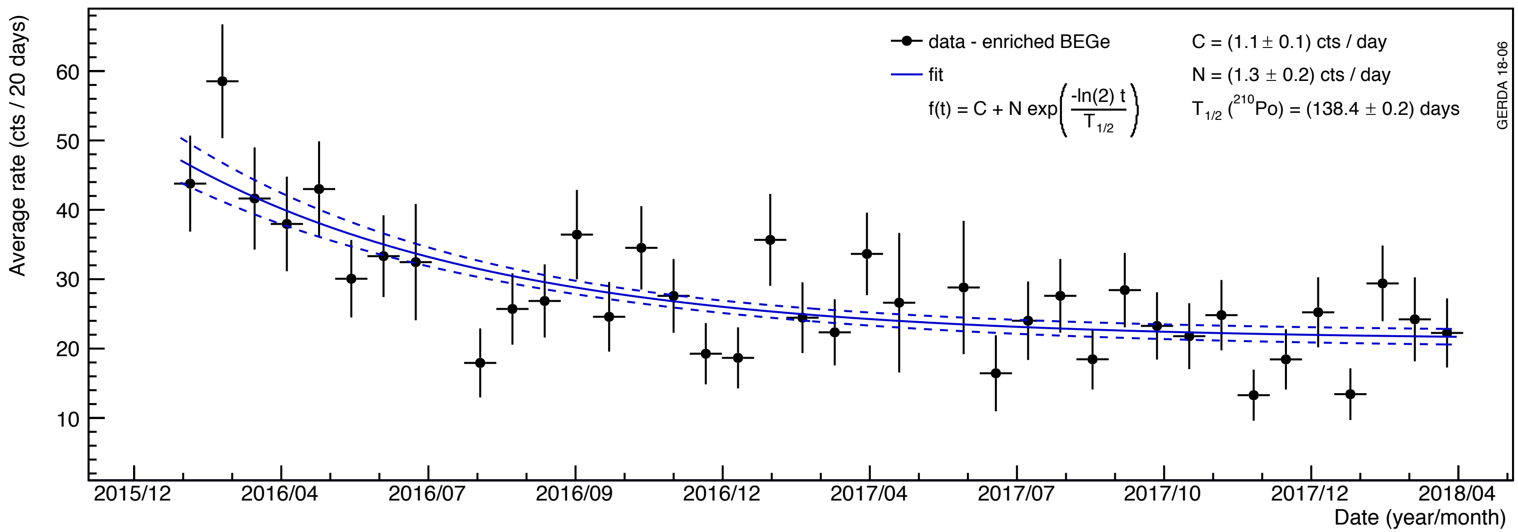


# Alpha background decay



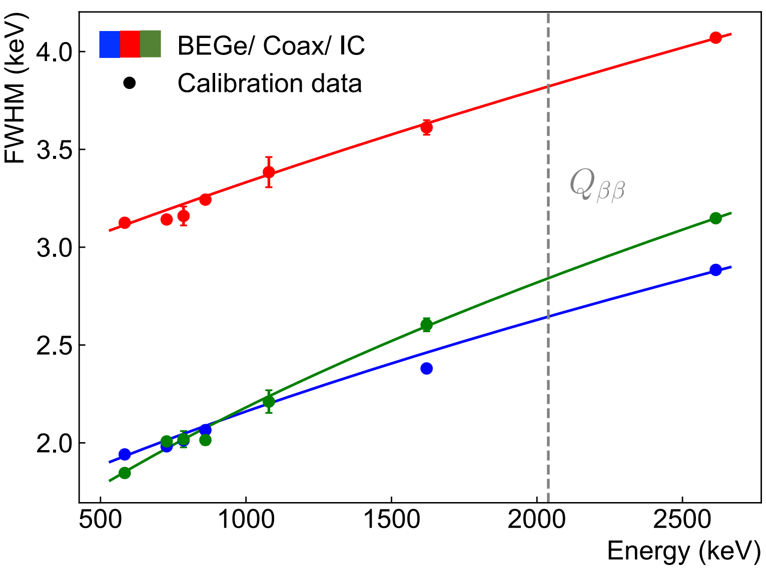
# Since May 2018 #3

## Restart of the data taking

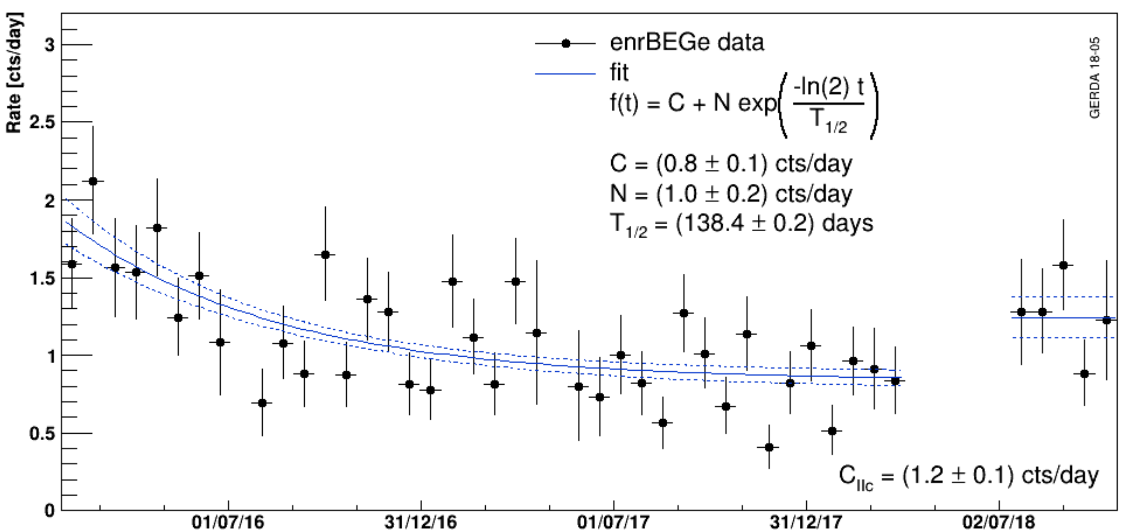
New

- Already 6.6 kg.yr exposure validated
- Improved energy resolution in BEGe strings
- No sign of significant alpha re-contamination
- Run until we reach 100 kg.yr

**Energy resolution**



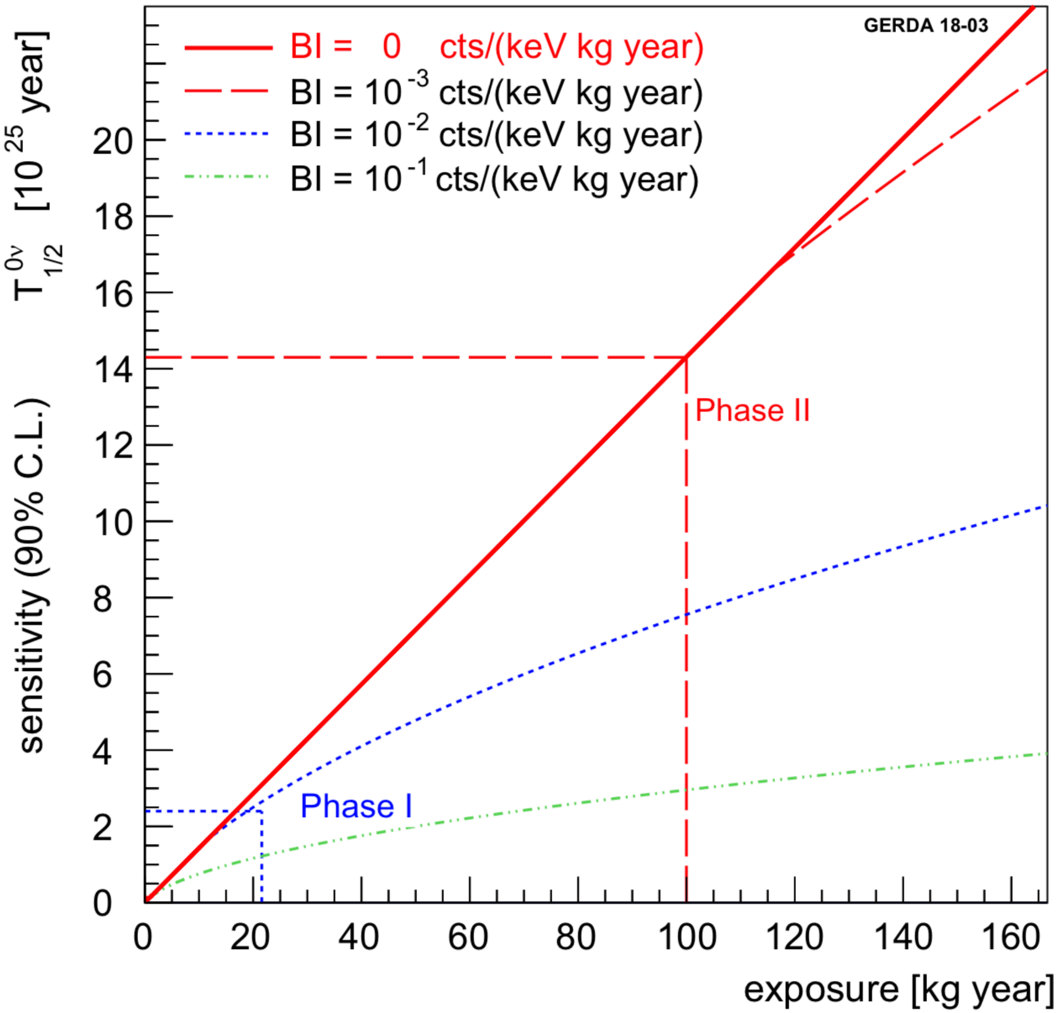

**Alpha count rate**



# GERDA datasets

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

# « Background-free » regime



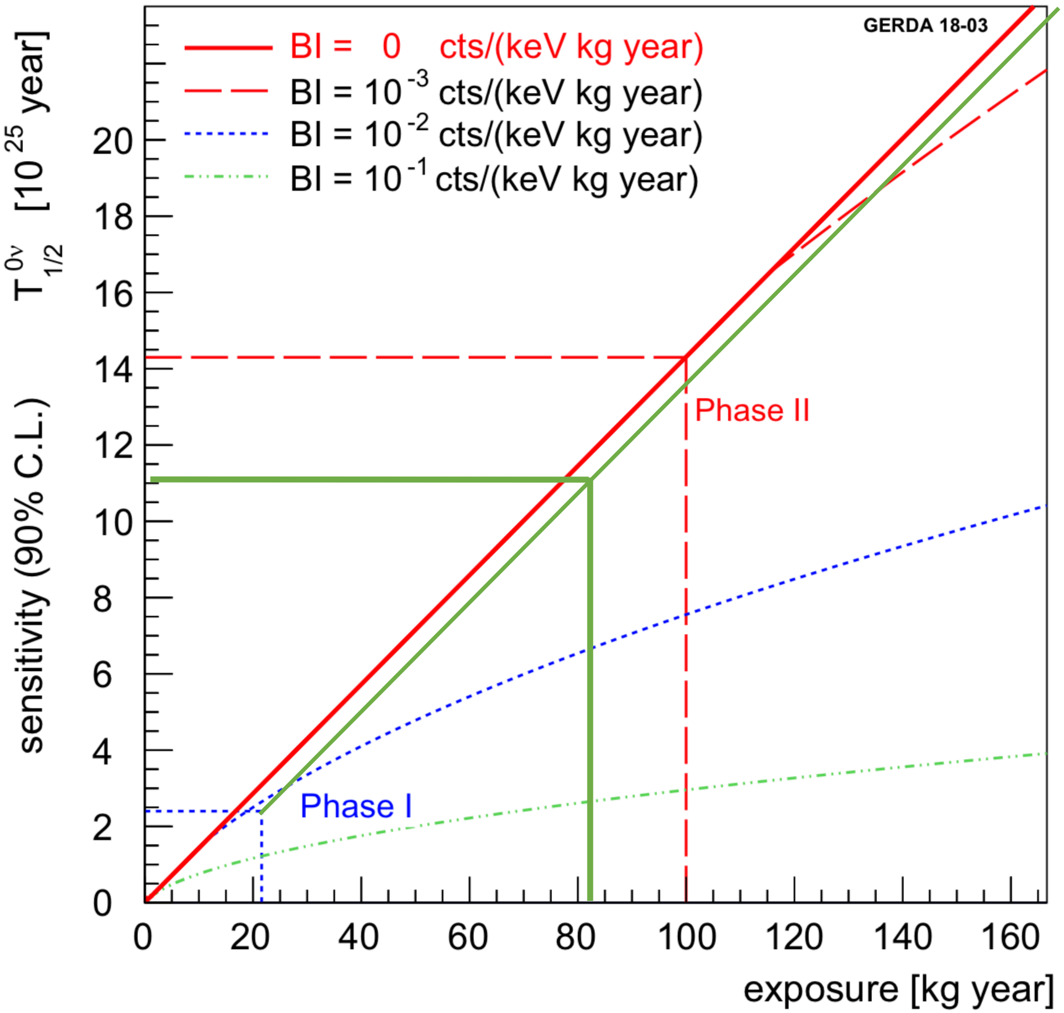

<FWHM>:
$\mathbf{3.25\ keV}$

Exposure:
$\mathbf{58.9 - 100\ kg.yr}$

<Background index>:
$\mathbf{8.1 \times 10^{-4}\ cts/(keV \cdot kg \cdot yr)}$

Counts in $Q_{\beta\beta} \pm \mathrm{FWHM}$:
- **0.32 – 0.52**

# « Background-free » regime

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