Current status of the ^{76}Ge $0\nu\beta\beta$ decay search and future prospects with Legend

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Seminar

LPNHE Paris

07 January 2019

Understanding the matter-antimatter asymmetry of the Universe

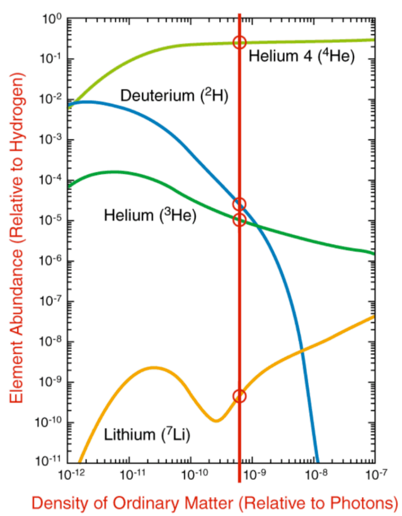
Number of baryons / antibaryons
(matter) / (antimatter)

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)

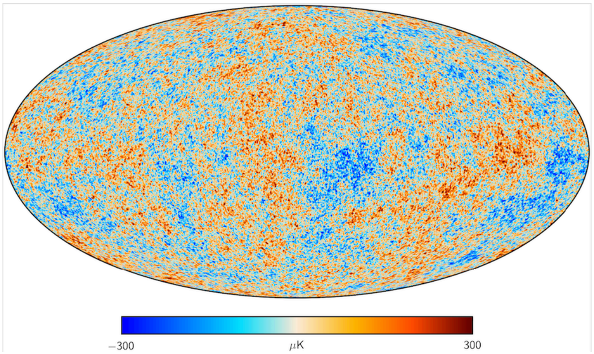
Measure of the element abundance probing the primordial nucleosynthesis



[Cooke, 2014]

Independant estimates agrees

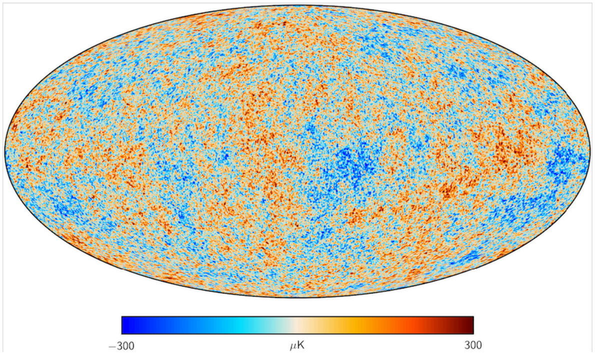
Measure of the CMB



[Planck, 2015]

Understanding the matter-antimatter asymmetry of the Universe

Baryonic asymmetry of the Universe :



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

- Sakharov criteria: [Sakharov, 1967]
  - *$\not{B}$, $\not{C}$, $\not{CP}$, int. out of equilibirium*
- Many theoretical scenarios including
  - ***High energy scale leptogenesis*** *(electroweak baryogenesis …)*
- Leptogenesis popular because ν is a unique particle
  - *Only left-handed, $\nu = \bar{\nu}$?, no electric charge*

Standard Model scenario	Beyond SM scenario
Baryogenesis **Excluded** - m_{H} too high / phase transition of 1st order - Too weak CPV $\boldsymbol{\eta \sim 10^{-26}}$	**Leptogenesis** **Plausible - to be falsified** - Enriched neutrino sector - CPV in the neutrino sector - **Majorana ν** - Lepton Number Violation

[Huet, 1994]

[Fukugita, 1986]

The « Standard » neutrino sector

- **There are 3 left-handed $\boldsymbol{\nu}$** -> e.g. LEP / Planck satellite

  where are the right-handed ones? is there a 4-th hidden neutrino? (SoLiD, …)

- **$\boldsymbol{\nu}$ flavours oscillate** ($\nu_e \leftrightarrow \nu_\mu$) -> Super K in 1998

  neutrinos are not massless!

KATRIN at KIT has started in 2018!
ECHO at the Heidelberg university
PROJECT8 at UW - Seattle
CMB (Planck satellite) : $\sum_{\nu=1}^{3} m(\nu_i) < 120 - 660$ meV [Planck - PDG, 2018]

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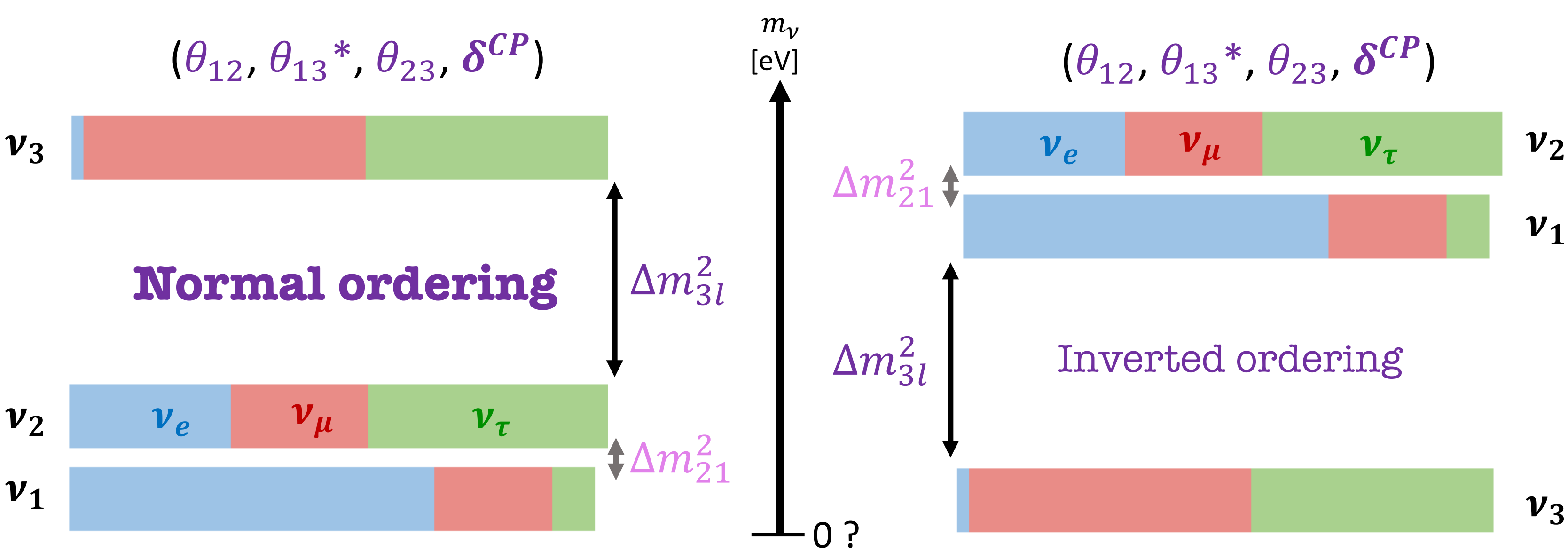
  coherent modelling of these oscillations -> PMNS framework (CKM-like for quarks)



[NuFit, 2018]

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  why neutrino masses are so small?

  1. **standard Higgs mechanism?**
     - successful for explaining electron, muon, quarks, … masses
     - but for neutrinos: couplings to Higgs should be extremely small ($< 10^{-12}$)
  2. **See-saw mechanism?**
     - requires neutrinos to be Majorana - Lepton Number is violated
     - new mass term in the Lagrangian explaining the smallness of masses
     - provides a mechanism for effective leptogenesis

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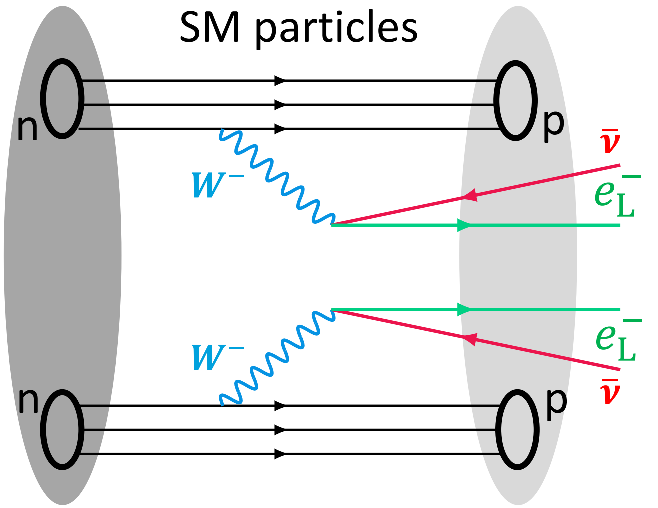
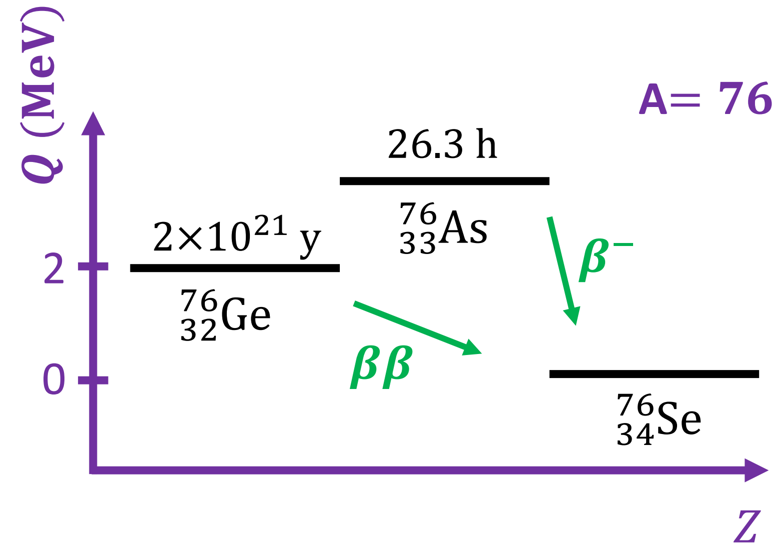
HOW TO RELATE THIS TO ^{76}Ge?

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



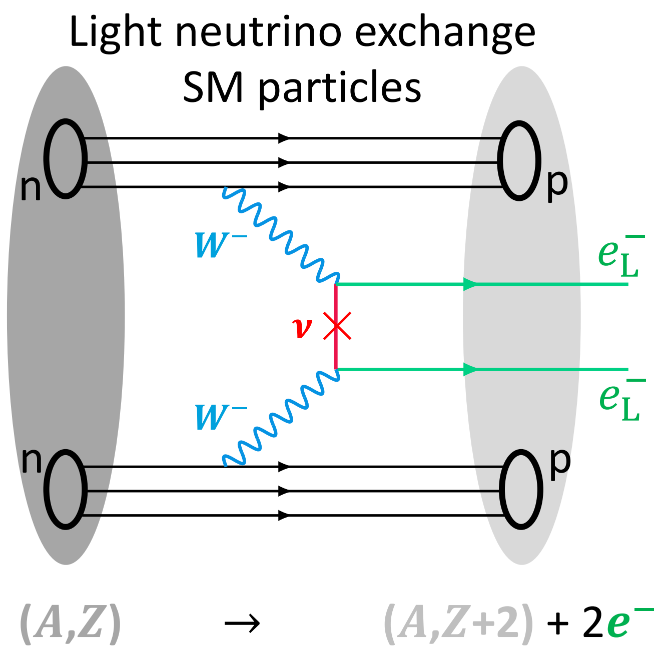
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$

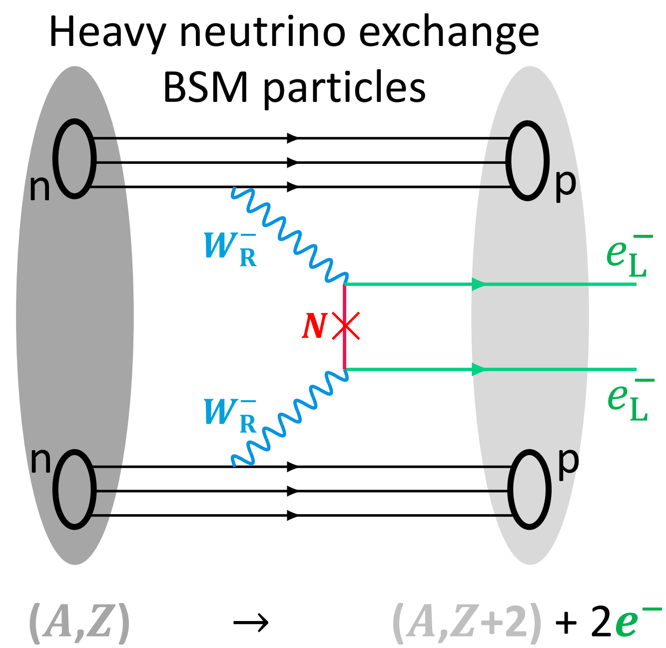


Such process:

- ✓ 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 - $0\nu\beta\beta$





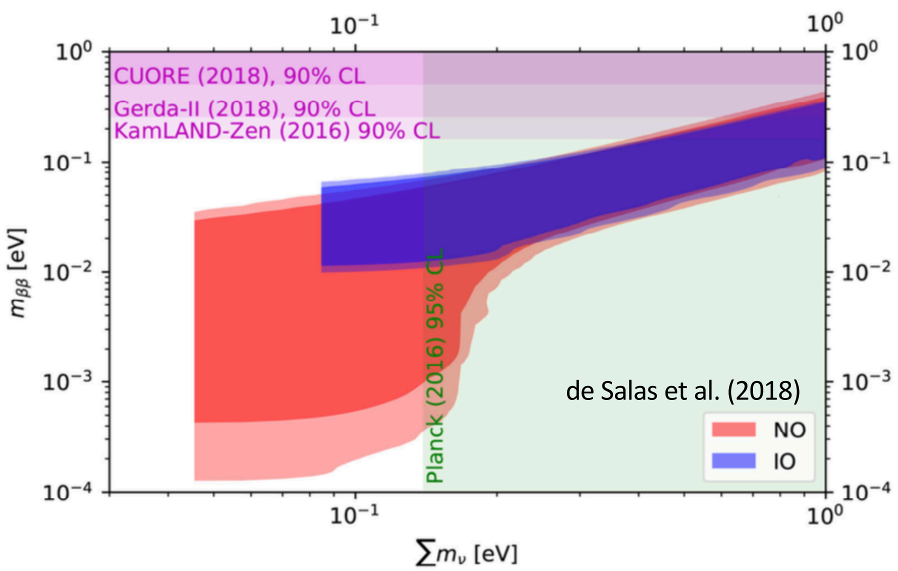
Such process:

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

Experiments comparison

Light neutrino exchange model:

$$ {T_{1/2}^{0\nu}}^{-1} = g_A^4 \, G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} $$



- $T_{1/2}^{0\nu}$ experimentally probed half-life
- g_A axial vector coupling cnst = 1.25(?)
- $M^{0\nu}$ nuclear matrix element (NME)
- $G^{0\nu}$ phase space factor
- m_e electron mass
- $m_{\beta\beta}$ coupling strength (function of lightest ν mass) $= \sum_{i=1}^{3} m_i \, {U_{ei}}^2$ ($U = 3\times3$ PMNS matrix)

Challenges

Experiments comparison

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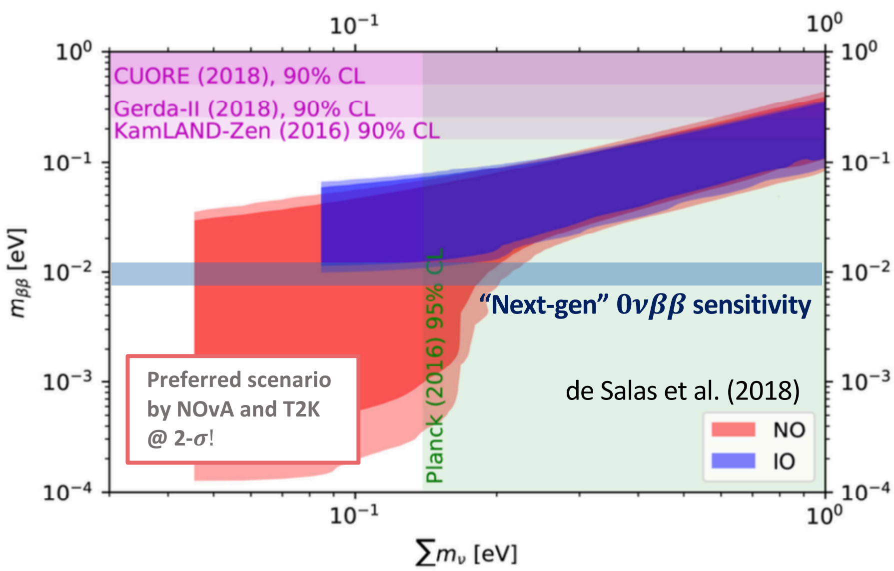
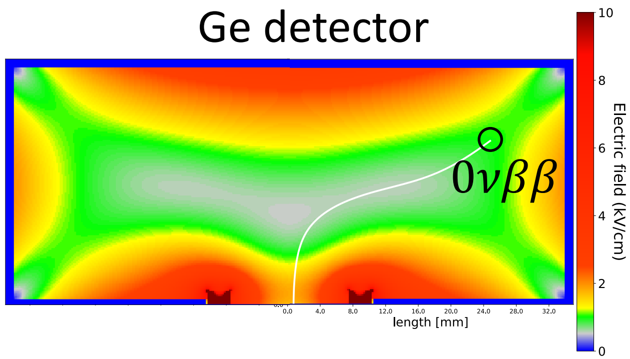
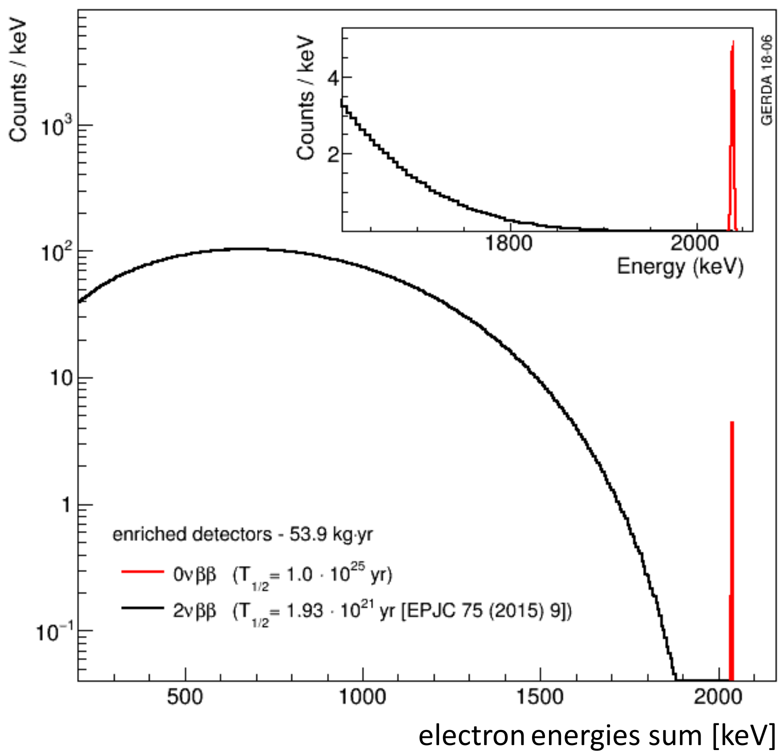


Sensitivity to reach $m_{\beta\beta} = 0.01$ eV

Isotope	$G^{0\nu}$ [$\times 10^{-15}$ yr]	$M^{0\nu}$	$T_{1/2}^{0\nu}$ [$\times 10^{28}$ yr]
^{76}Ge	2.3	[3 – 6]	2.3
^{82}Se	10	[2.5 – 5.5]	1.2
^{130}Te	14	[1.5 – 5.5]	0.5
^{136}Xe	15	[1.5 – 4.5]	0.6
	Stoica & Mirea (2013)	Engels & Menéndez (2017)	$g_A = 1.25$

^{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**
  - 2β 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	mid-term	long-term
30 kg	200 kg	1 ton
$T^{0\nu}_{1/2} > 10^{26}$ yr	$T^{0\nu}_{1/2} > 10^{27}$ yr	$T^{0\nu}_{1/2} > 10^{28}$ yr

U.S. DEPARTMENT OF ENERGY | Office of Science

MAJORANA DEMONSTRATOR

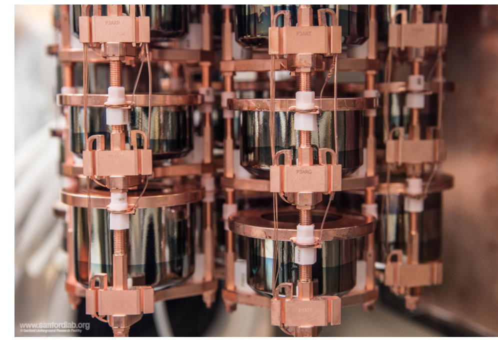
Courtesy: Vincente Guiseppe

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors and additional physics beyond the standard model

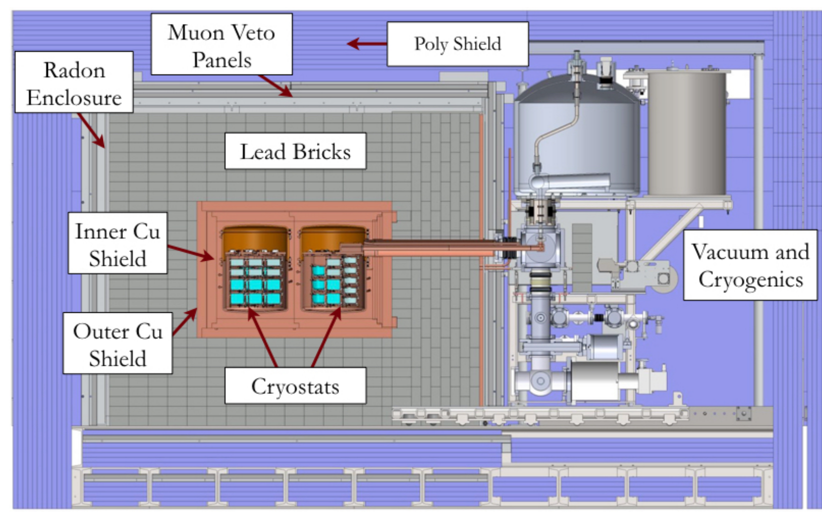
Source & Detector: Array of p-type, point contact detectors
29.7 kg of 88% enriched ^{76}Ge crystals

Excellent Energy resolution: 2.5 keV FWHM @ 2039 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials



Operating underground at the 4850' level of the Sanford Underground Research Facility



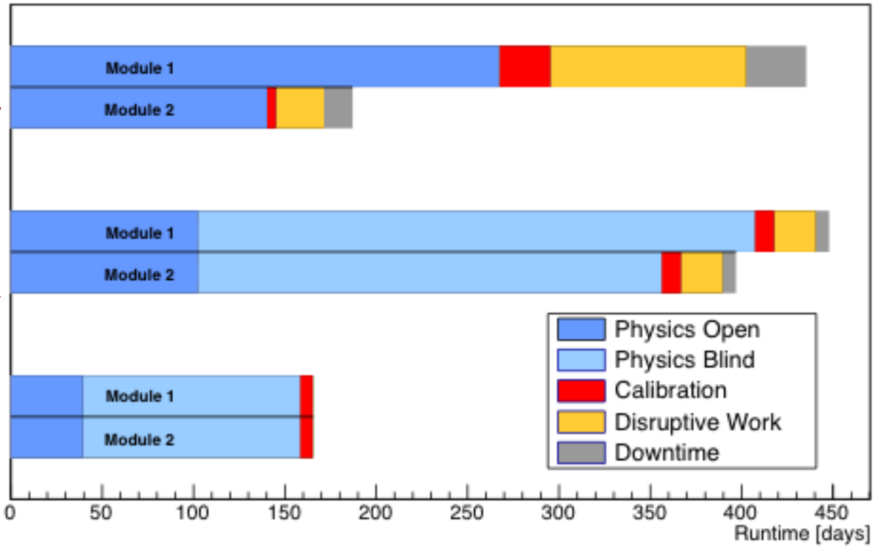
Runtime and Exposure

Courtesy: Vincente Guiseppe

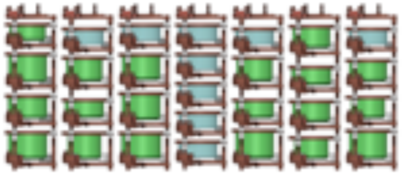
Open data: Jun. 2015 - Mar. 2017
9.95 kg-yr

All blind data: Jan. 2016 - Apr. 2018
New Open Data: Mar. 2017 - Apr. 2018
+16.1 kg-yr

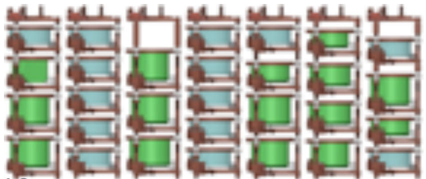
April 2018 - Present*



Jun. 2015 - Module 1: 16.9 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge



Aug. 2016 - Module 2: 12.9 kg (15) ^{enr}Ge
8.8 kg (14) ^{nat}Ge



2017 Release

9.95 kg-yr open data

PRL **120** 132502 (2018)

2018 Release

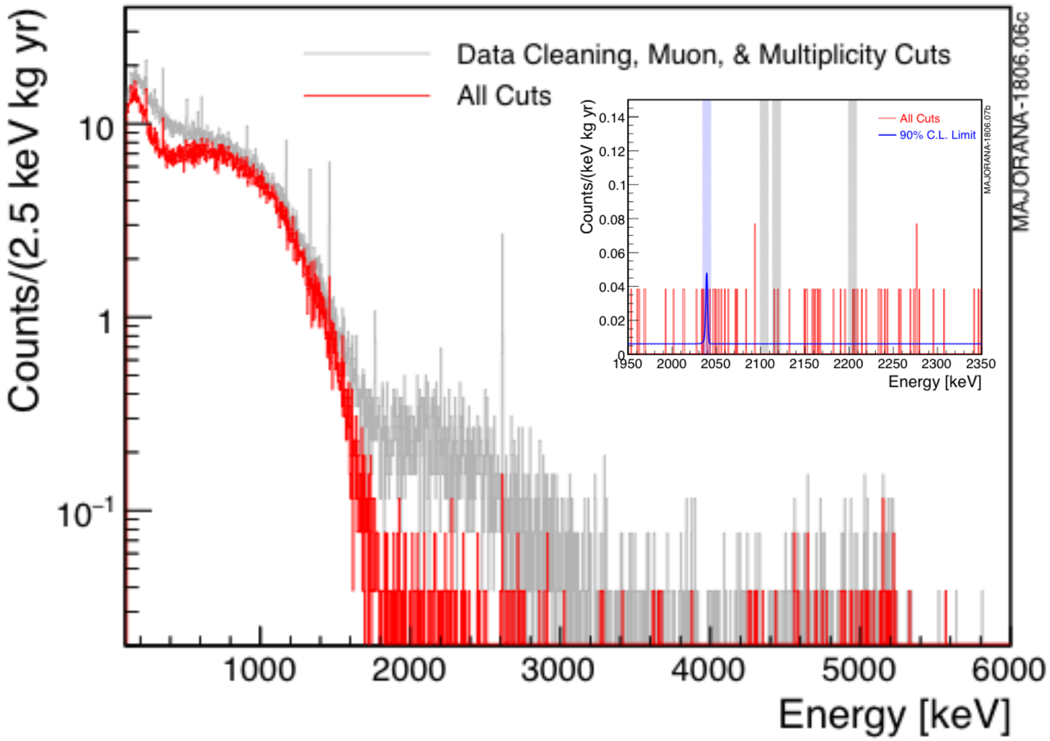
26 kg-yr open+blind

Neutrino 2018
DOI:10.5281/zenodo.1286900

*runtime as of Oct. 1, 2018, still collecting data

2018 0νββ Result

Courtesy: Vincente Guiseppe



26 kg-yr active ^{enr}Ge exposure

The low backgrounds, low threshold, high resolution spectra allows beyond the standard model searches:

Bosonic Dark Matter, Solar Axions, etc. [Phys. Rev. Lett. **118** 161801 (2017)]

Lightly ionizing particles [Phys. Rev. Lett. **120** 211804 (2018)]

Tri-Nucleon Decay [arXiv:1812.01090]

Initial Release:

PRL 120 132502 (2018)

Latest Release:

First unblinding of data

26 kg-yr of exposure

Neutrino 2018

DOI:10.5281/zenodo.1286900

Median half-life sensitivity:

$$4.8 \times 10^{25}\ \mathrm{yr}$$

Full Exposure Limit:

$$T^{0\nu}_{1/2} > 2.7 \times 10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{CL})$$

Background index at 2039 keV in the lowest background configuration:

$$11.9 \pm 2.0\ \mathrm{cts/(FWHM\ t\ yr)}$$

21.3 kg-yr active ^{enr}Ge exposure

Background Model Development

Courtesy: Vincente Guiseppe

Observed background of 11.9 +/- 2.0 c/(FWHM t y) based on the 1950-2350 keV window

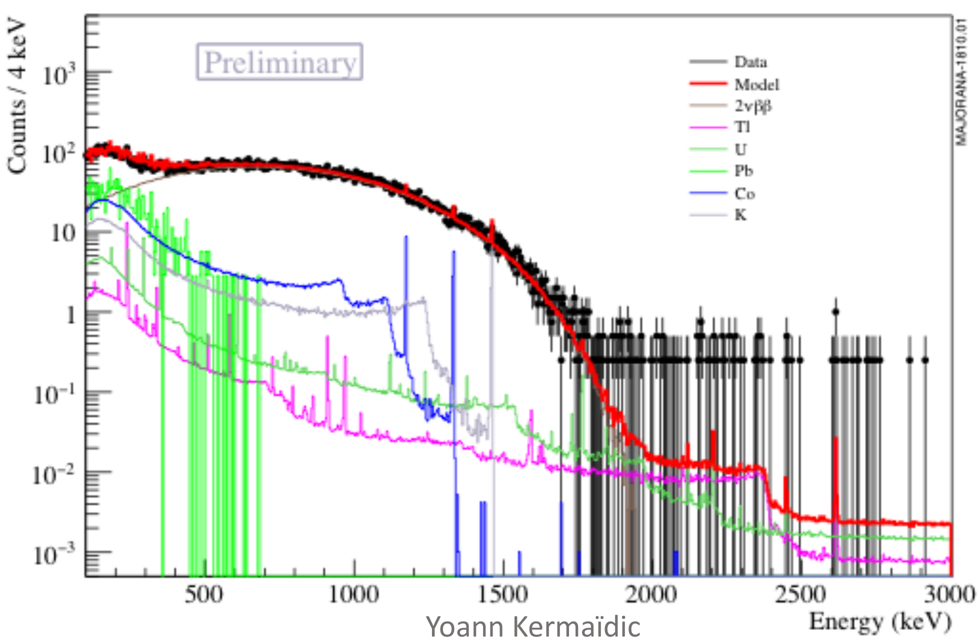
Currently reviewing available assay information and updating the assay-based model with as-built simulations, detector configurations, and updated physics lists

Complete background model fits under development

Initial spectral fits suggest that the dominant source of background above assay estimates is not from nearby components

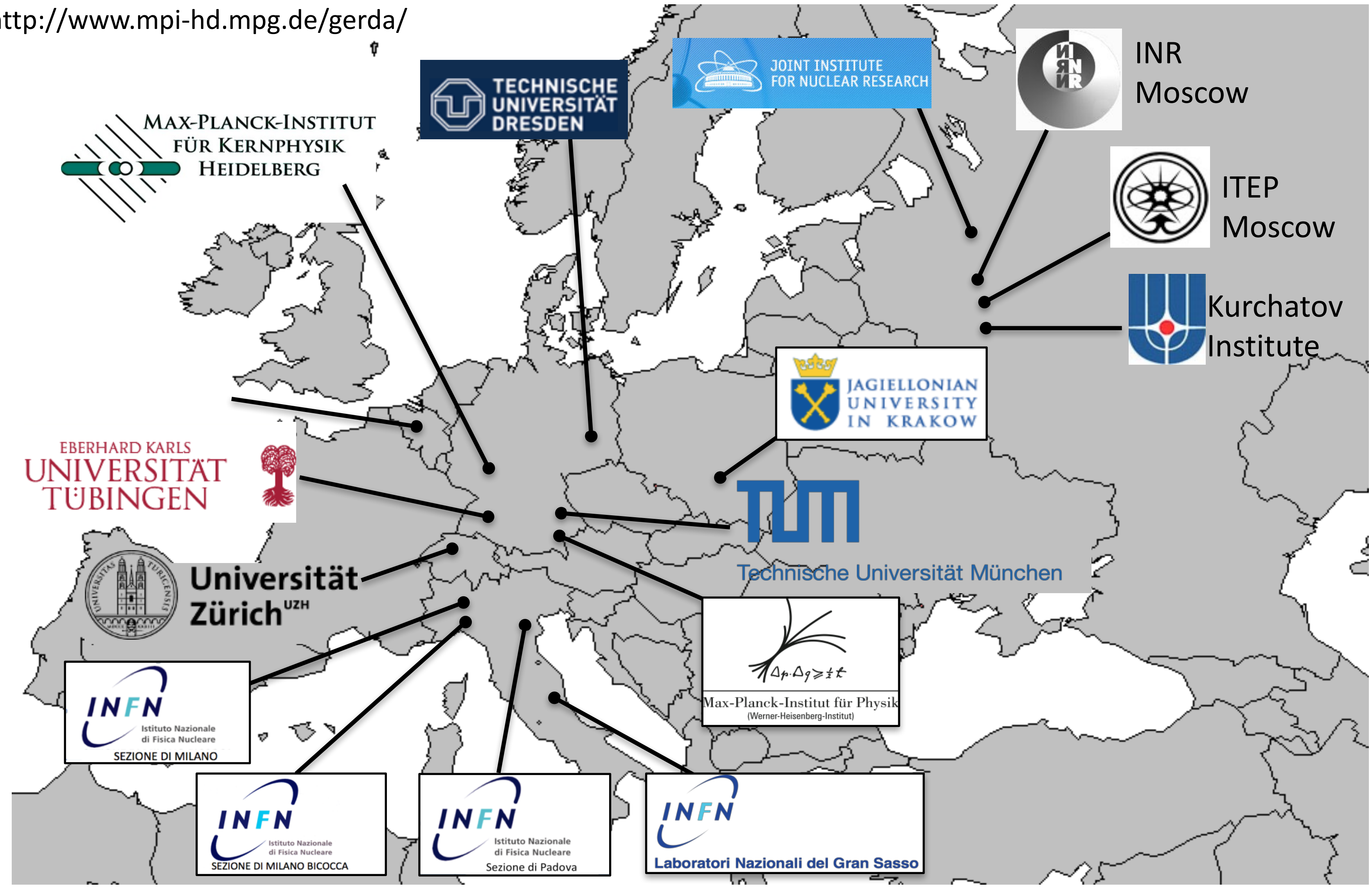
Developing a plan to implement a change in cables/connectors, components, and detector configuration to increase ultimate exposure and study backgrounds

All cuts, components fixed to assay estimate



GERDA collaboration

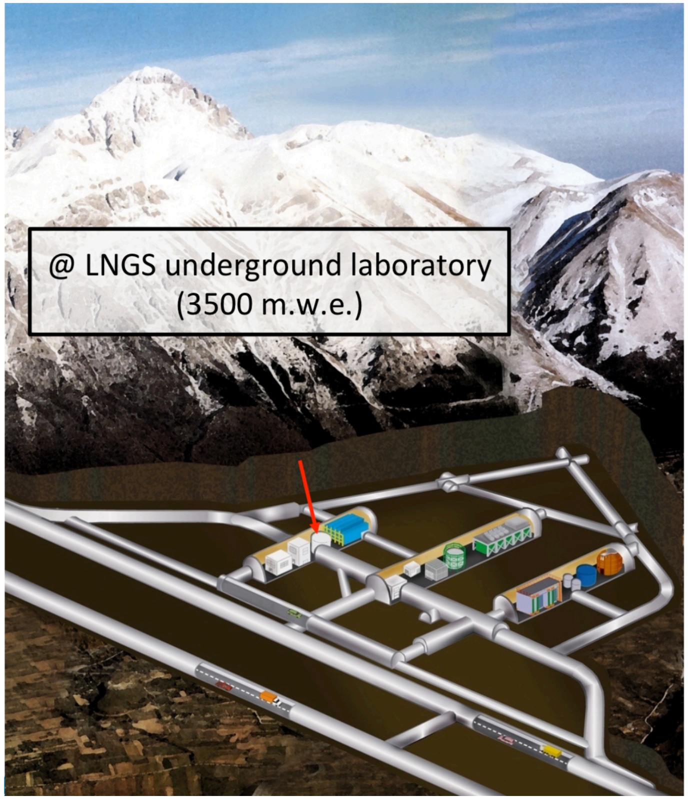
http://www.mpi-hd.mpg.de/gerda/



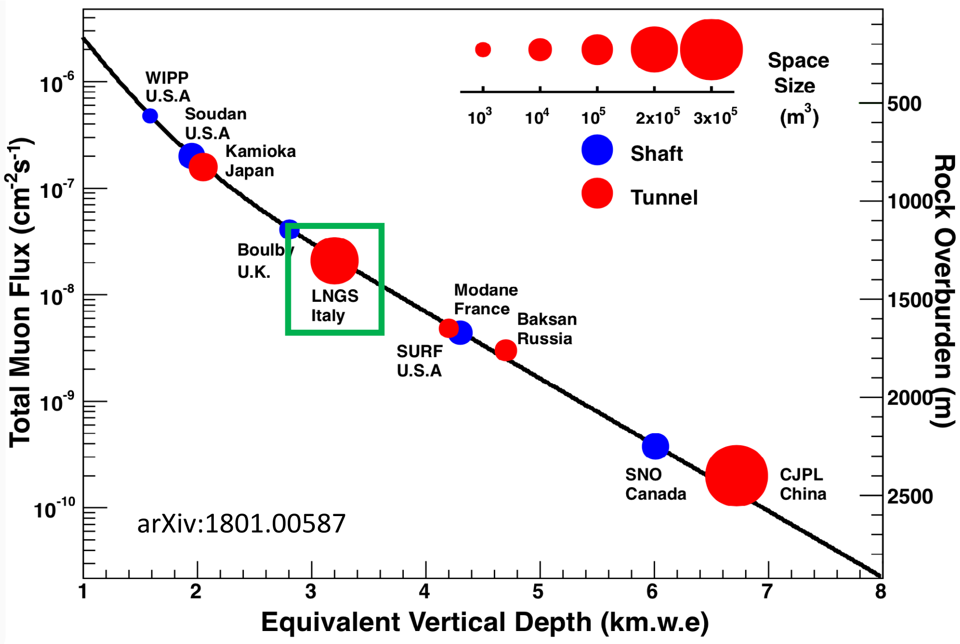
GERDA location @ LNGS

- Cosmic ray background mitigation

Deep underground lab
➢ Muon flux suppression



Large space available at LNGS
+ convenient access via highway



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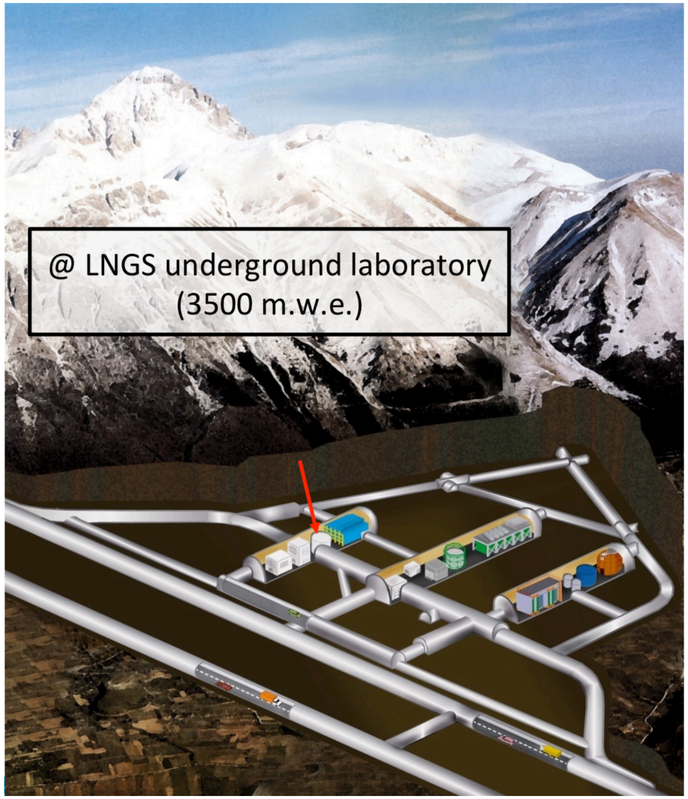
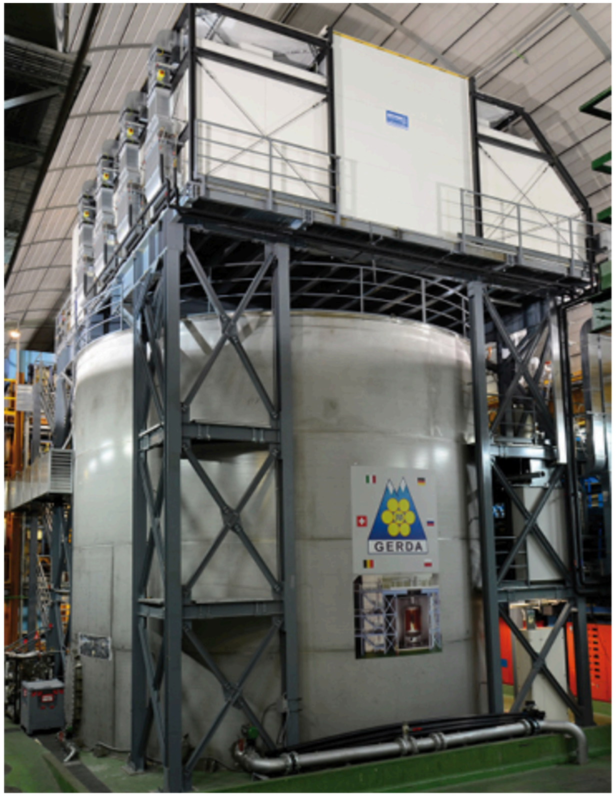


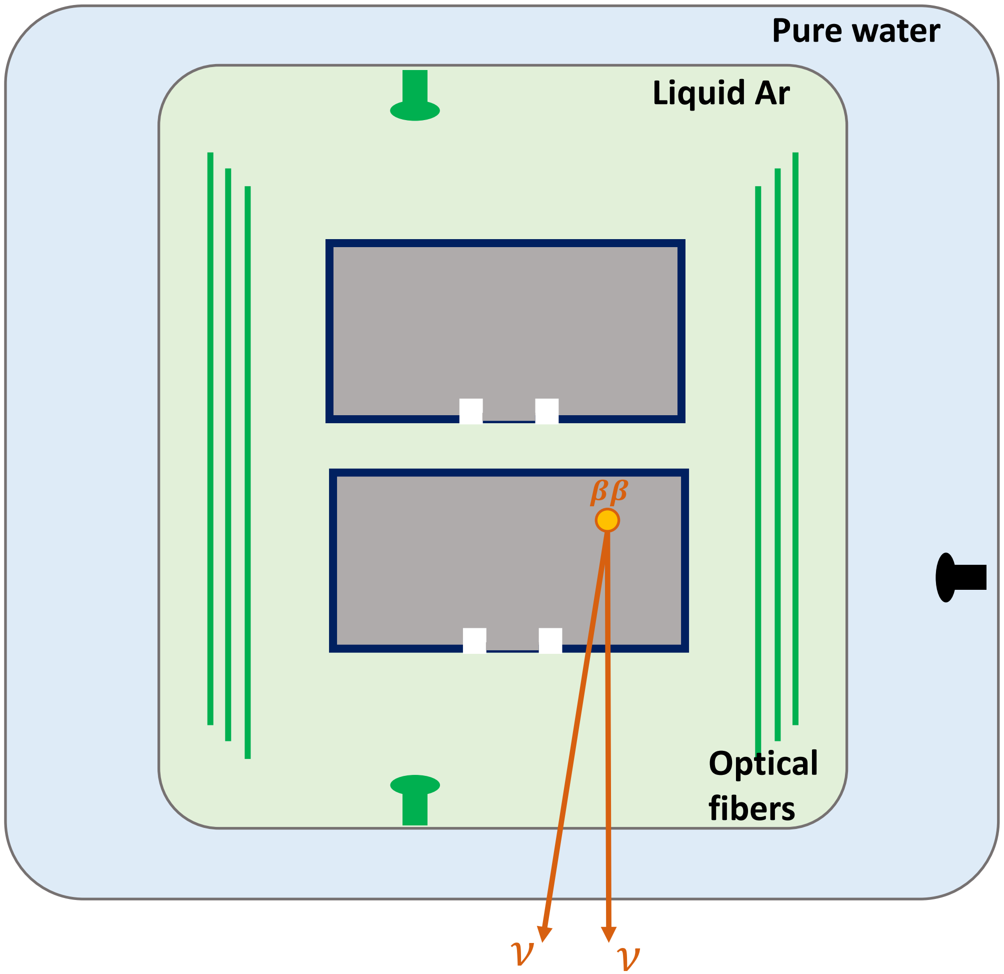
Pure water tank equipped with PMTs
- ➢ Muon and neutron induced mitigation



Toward the background-free regime

- signal signature

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



Toward the background-free regime

- background mitigation

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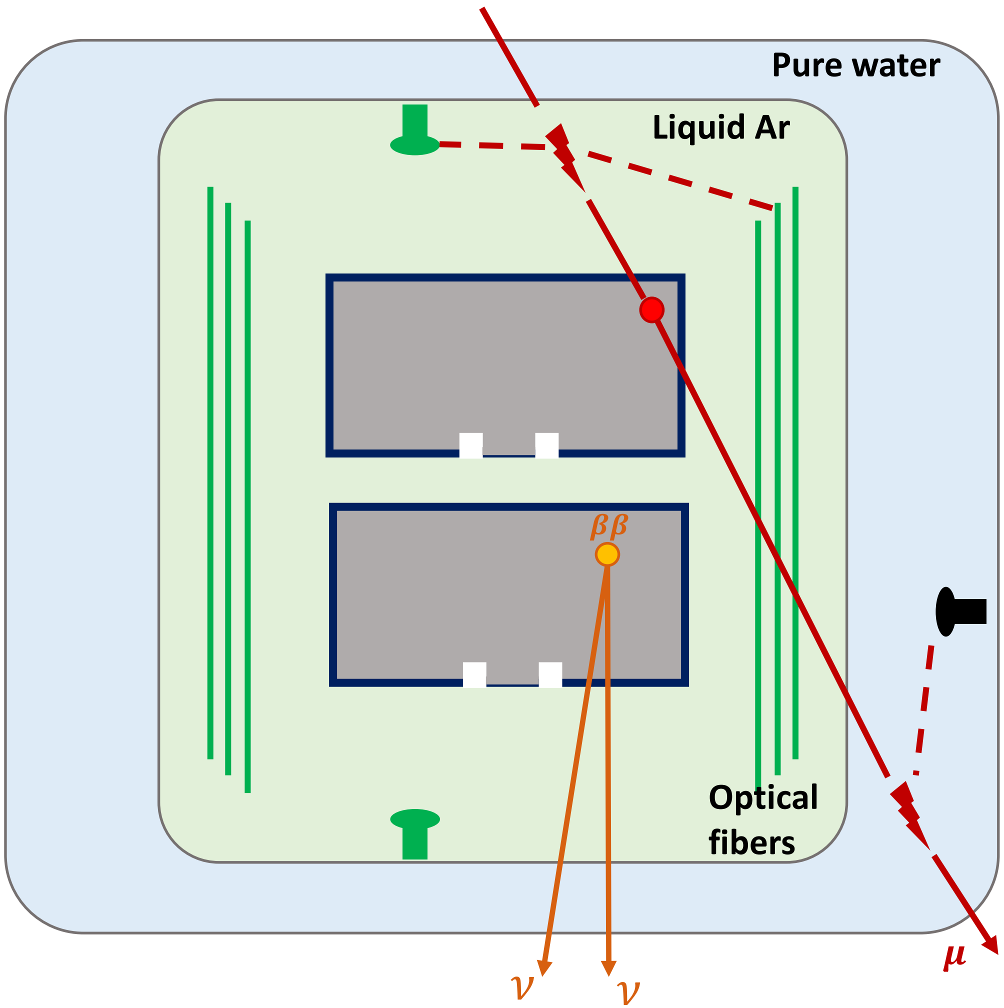
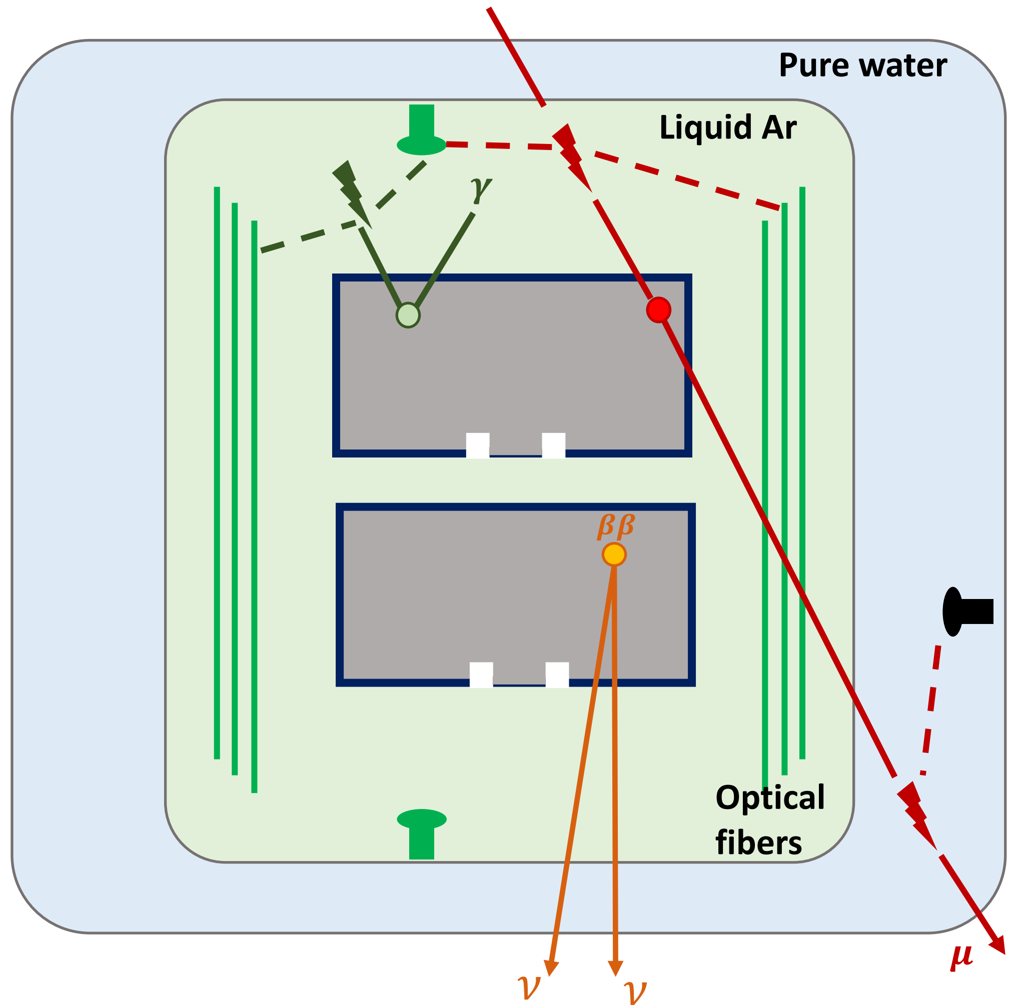


Muon veto based on Cherenkov light and plastic scintillator

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

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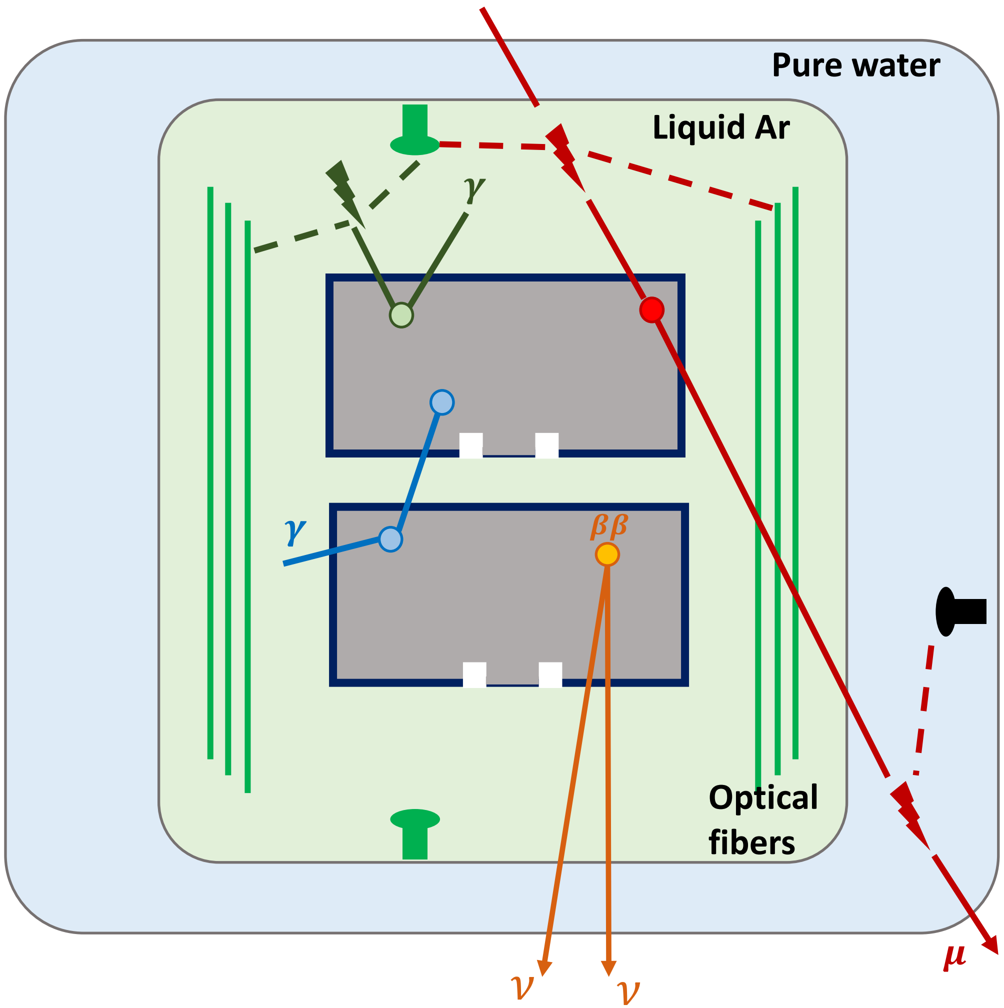


Ge detector anti-coincidence

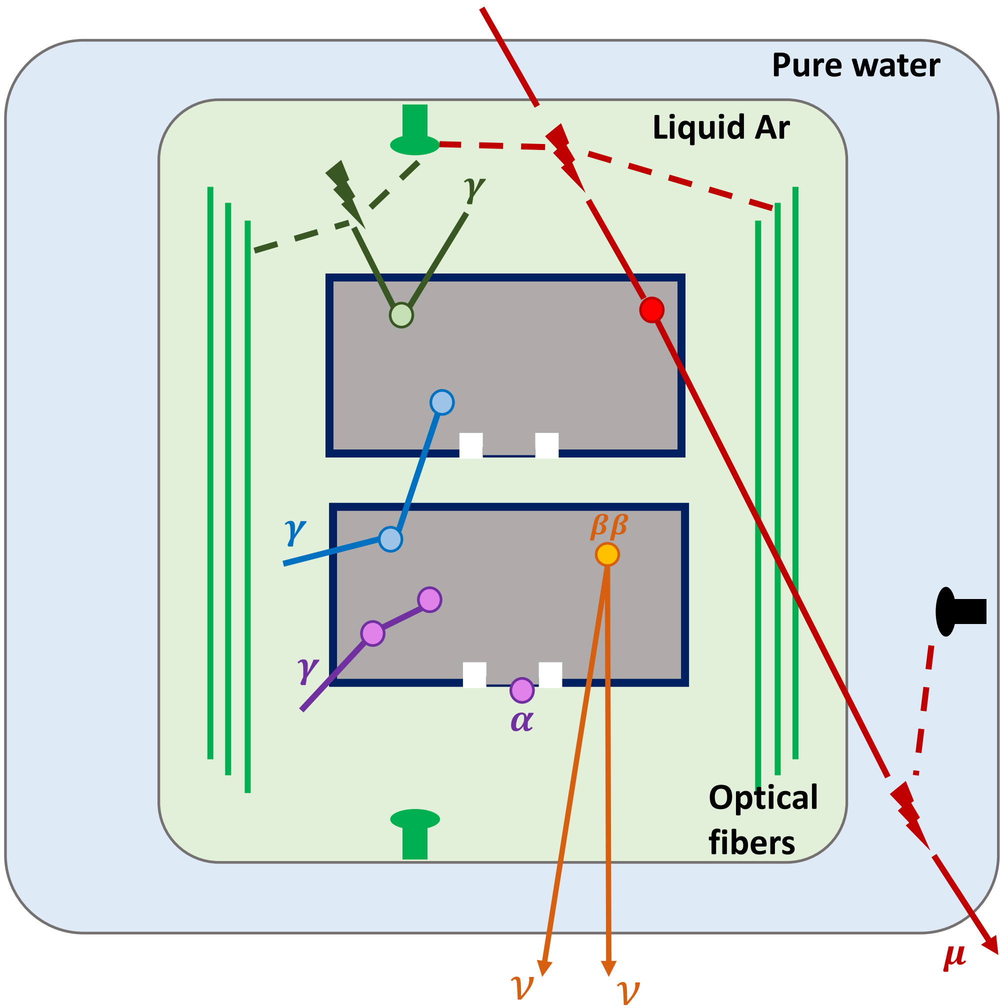
LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

Toward the background-free regime

- background mitigation

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



Pulse shape discrimination (PSD) for multi-site and surface α events

Ge detector anti-coincidence

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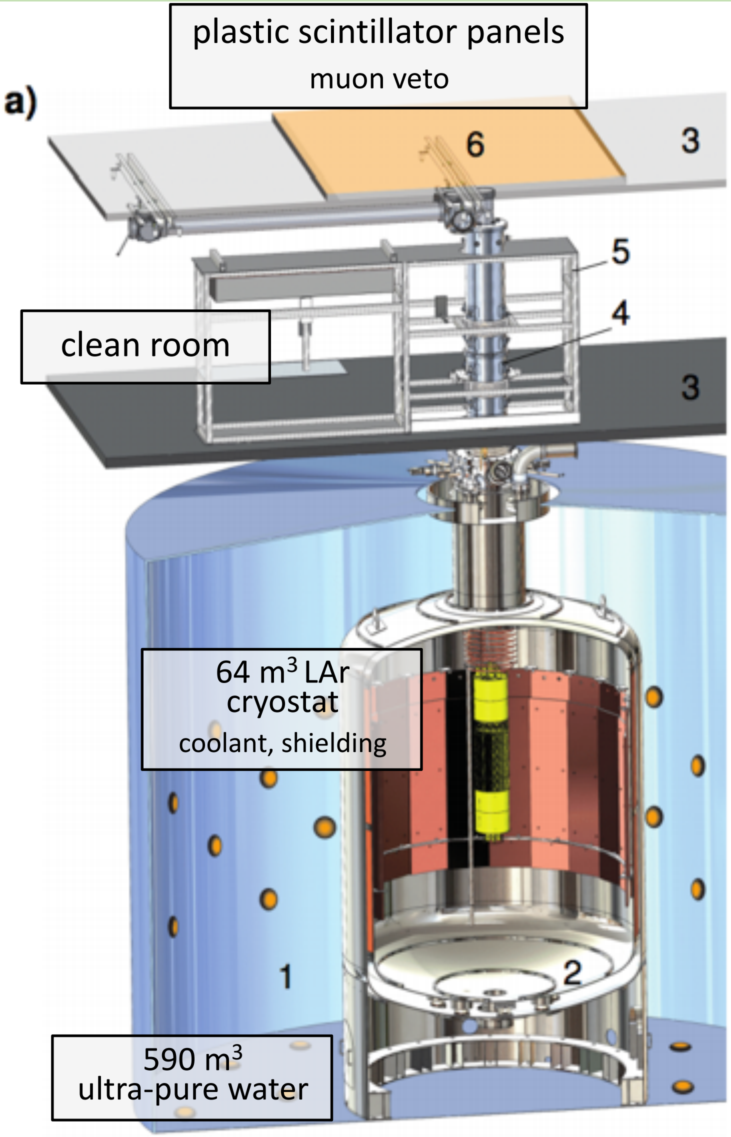
GERDA Phase II: From concept to design



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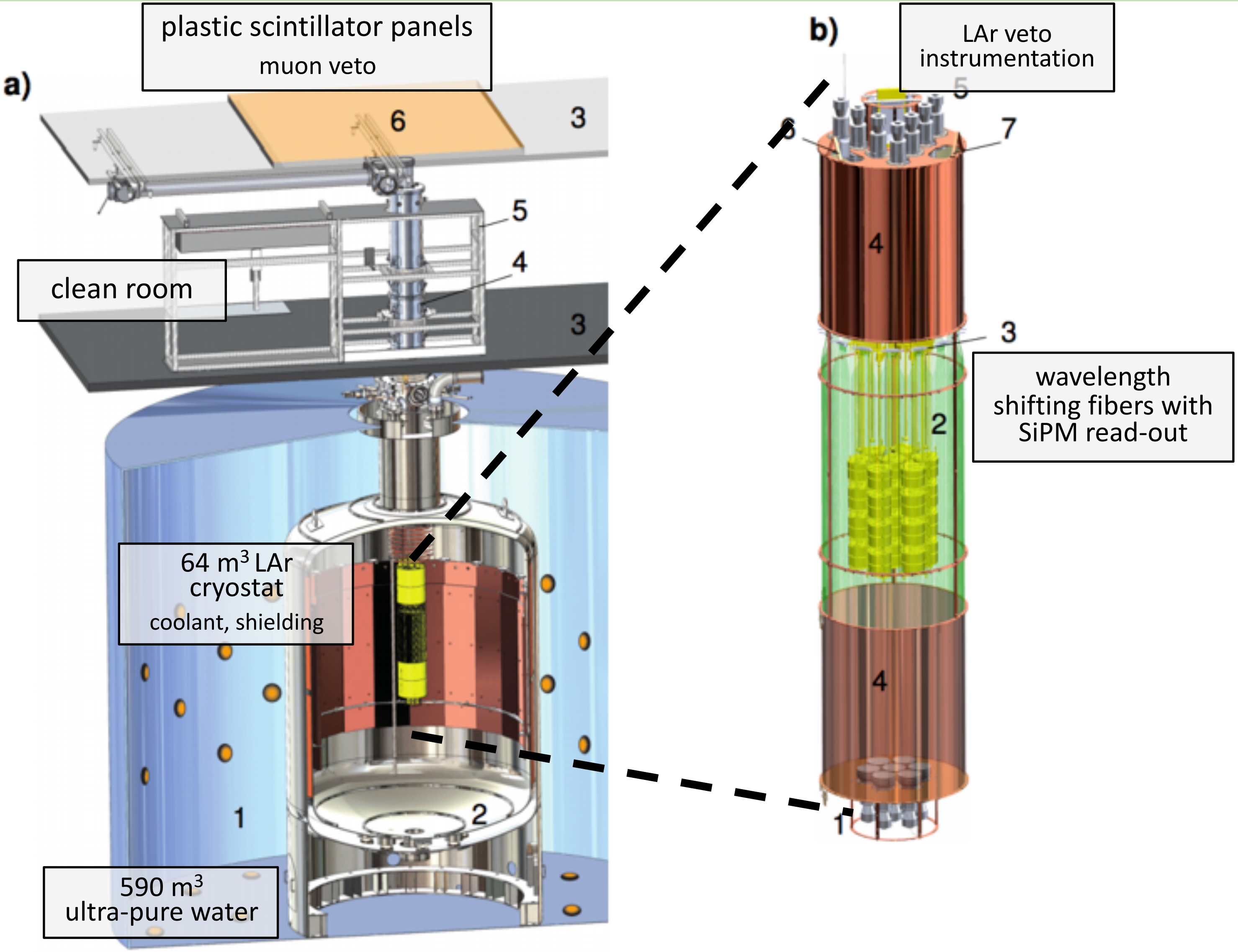

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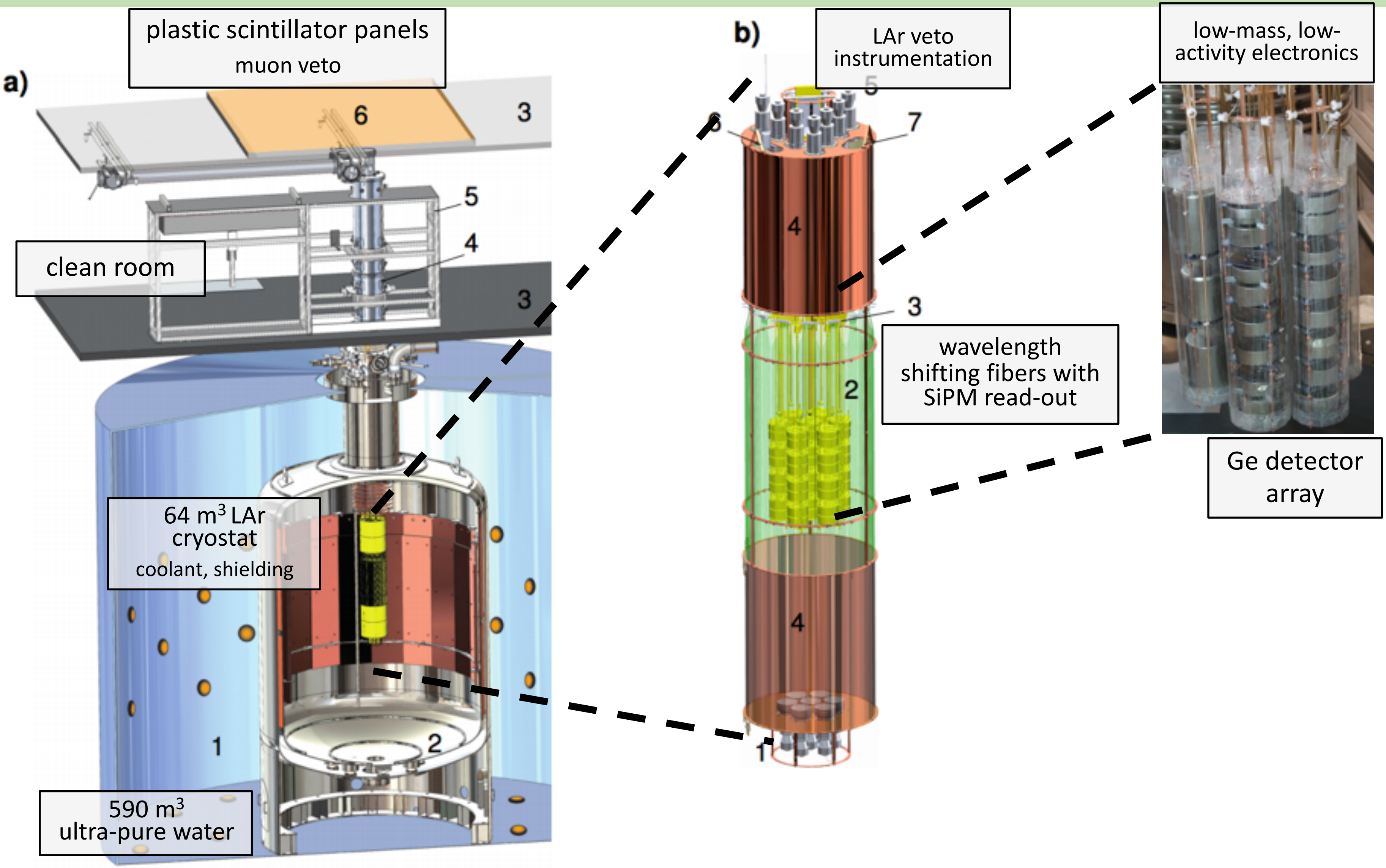

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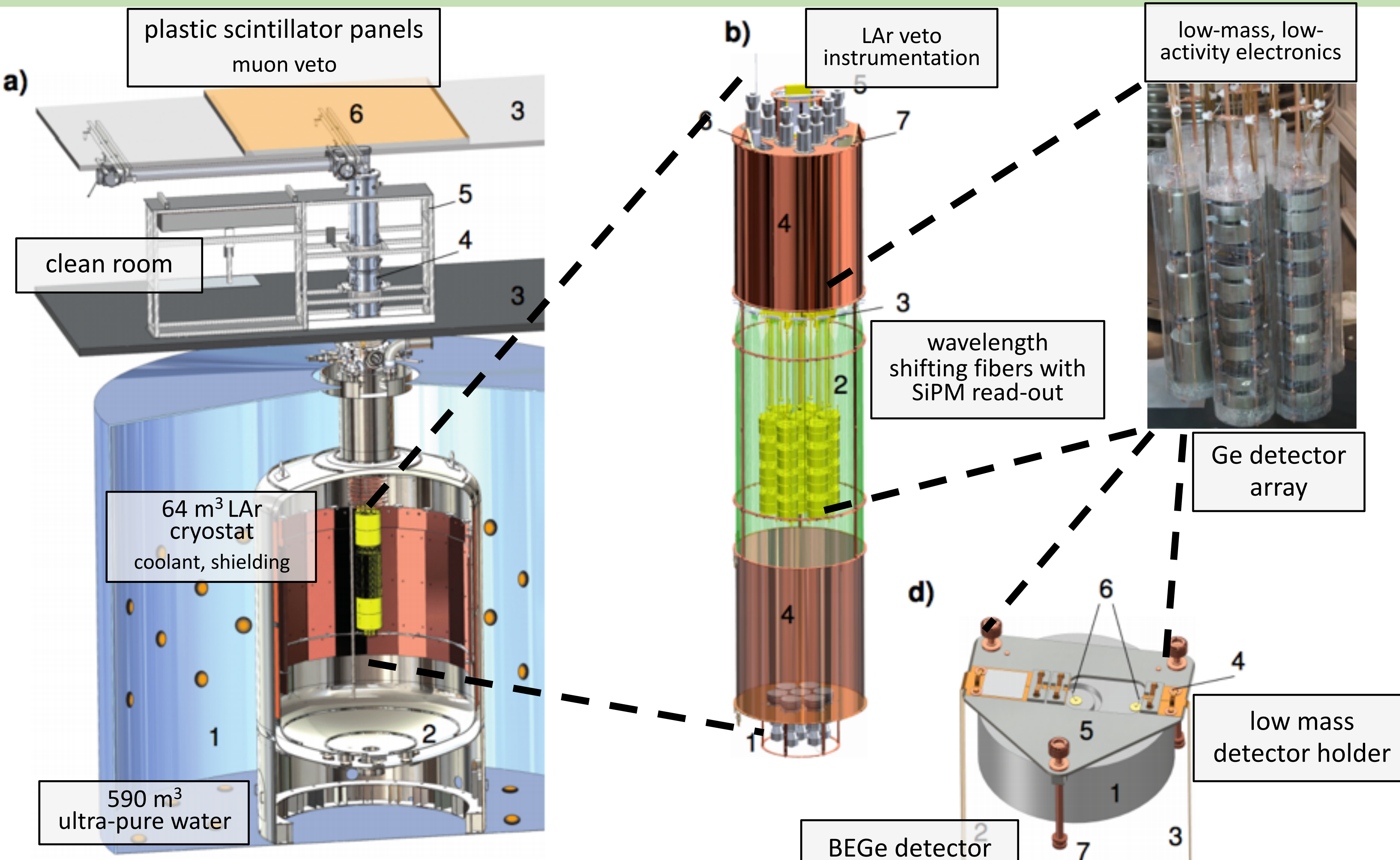
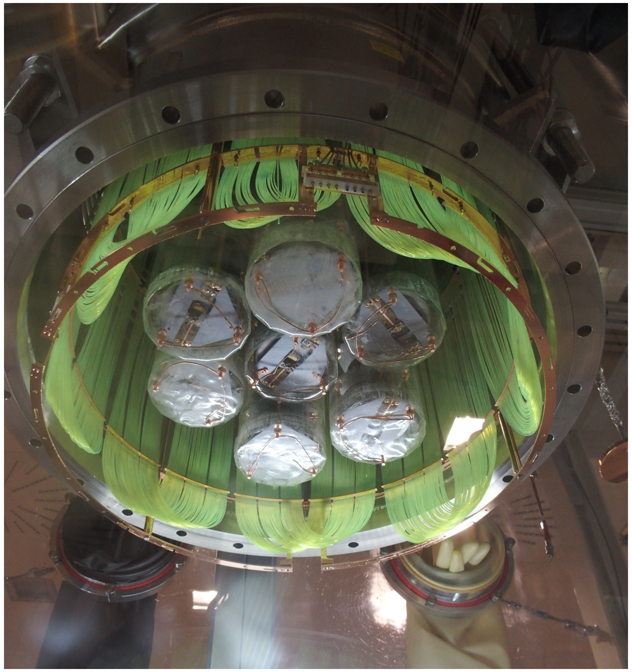
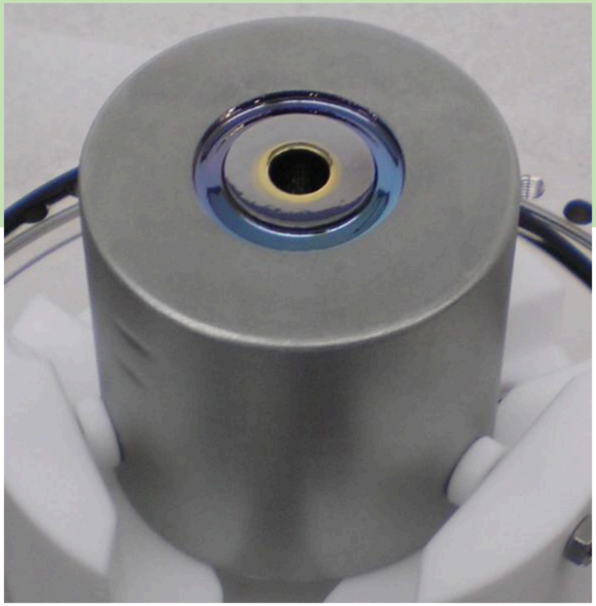
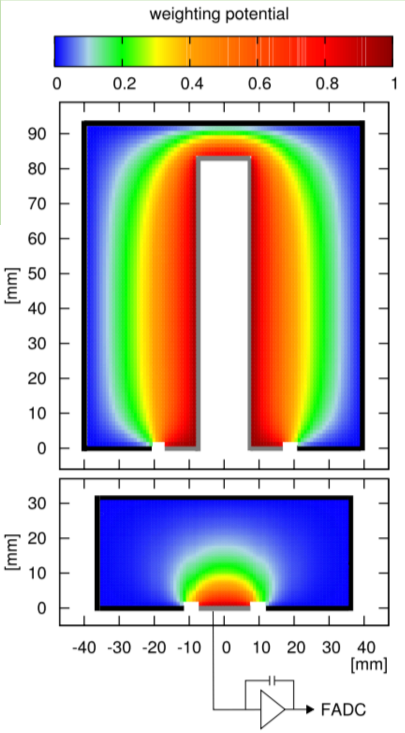


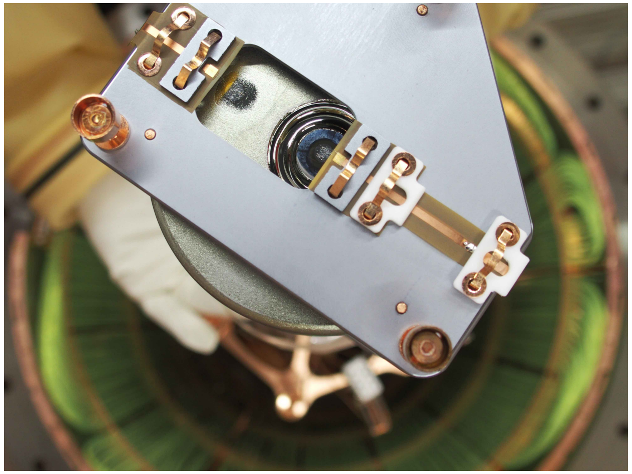
Slide: L. Pandola – TAUP 2017

Ge detectors phase II



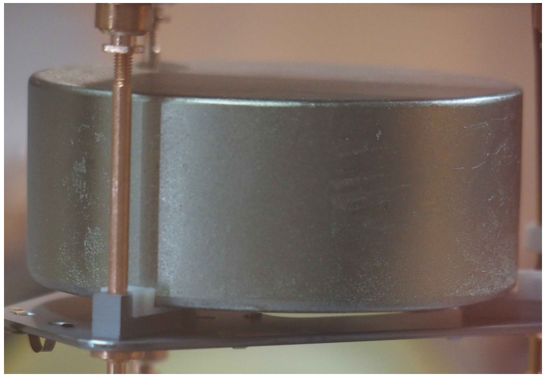


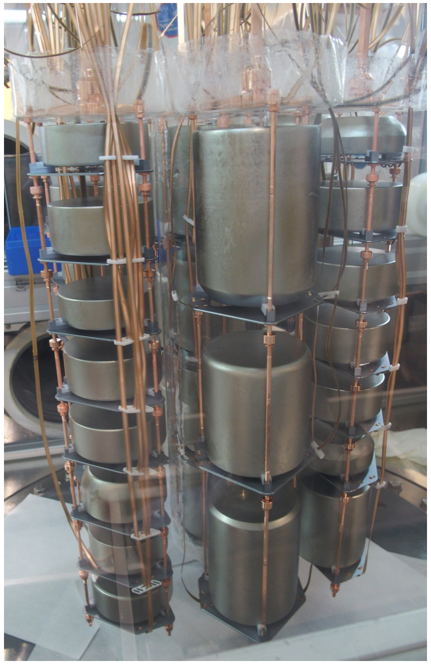




7 strings with 40 detectors:

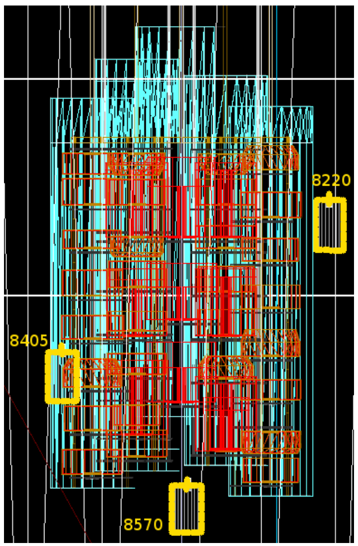
- *3 natural semi-coaxial (7.6 kg)*
- **7 enriched semi-coaxial (15.6 kg)**
  - Large contact = large capacitance
  - Signal from all charge carriers
- **30 enriched BEGe (20.0 kg)**
  - Point-contact = small capacitance
  - Signal from holes only

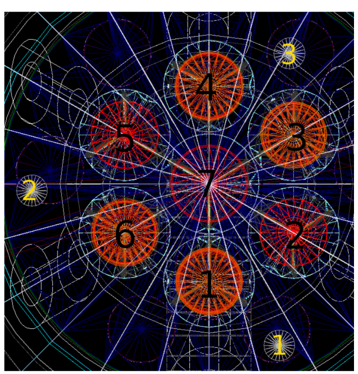


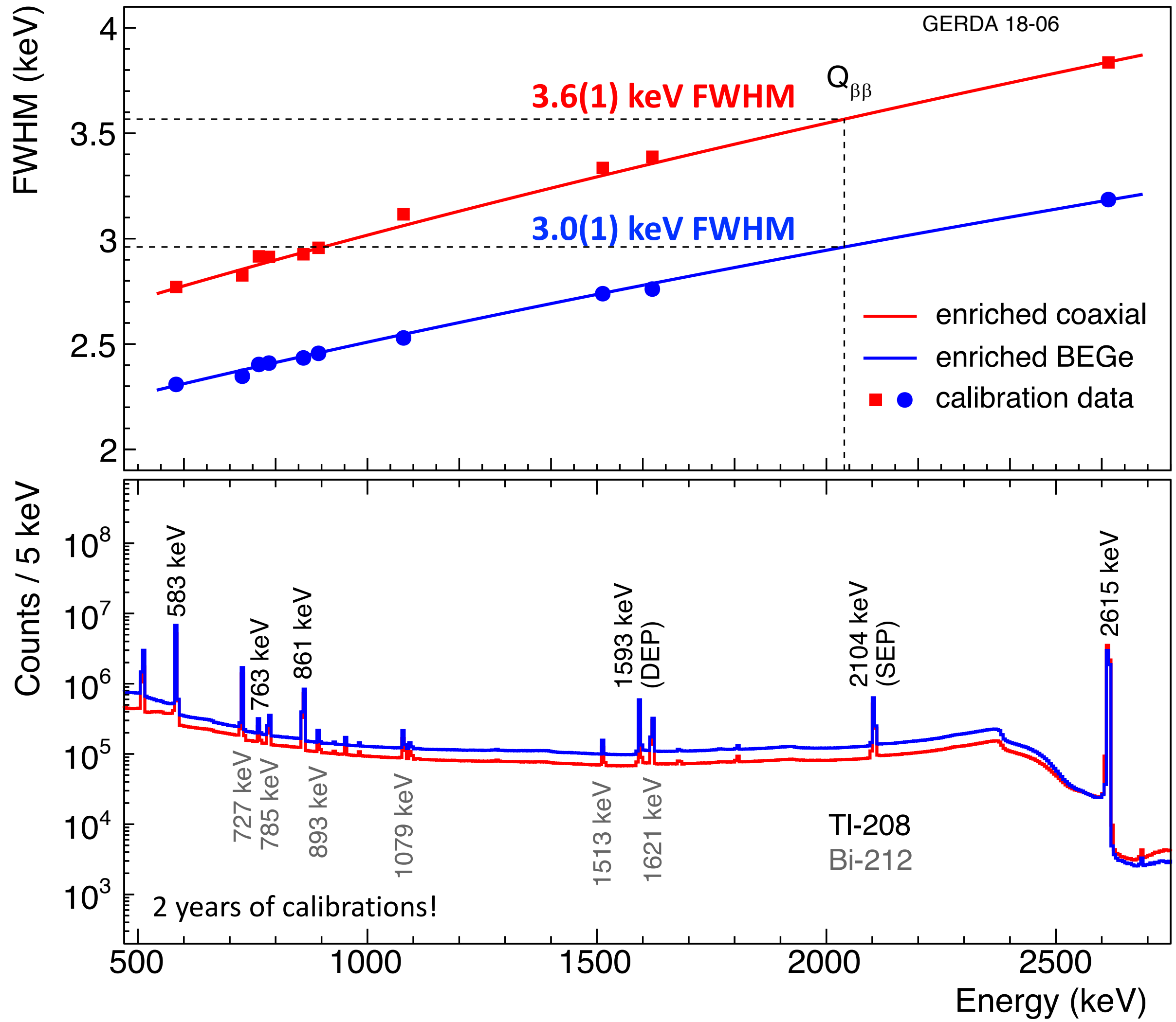


Energy calibration

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



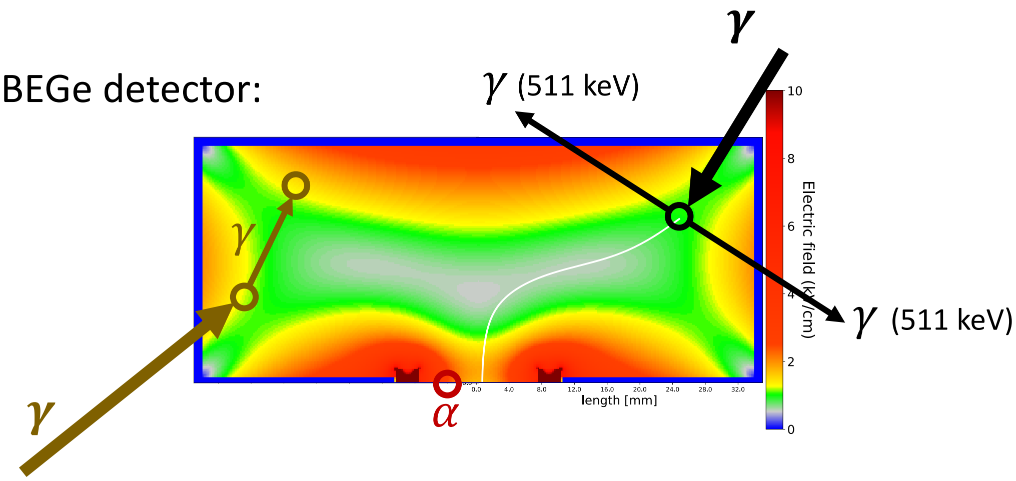




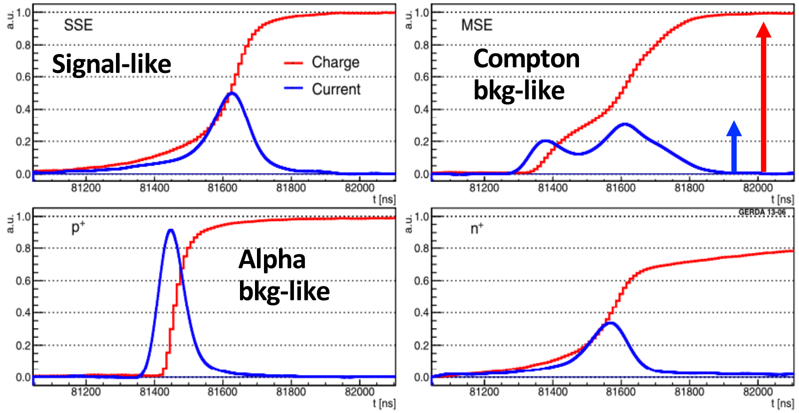
Pulse shape discrimination calibration

- **^{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** cut due to specific signal time profile

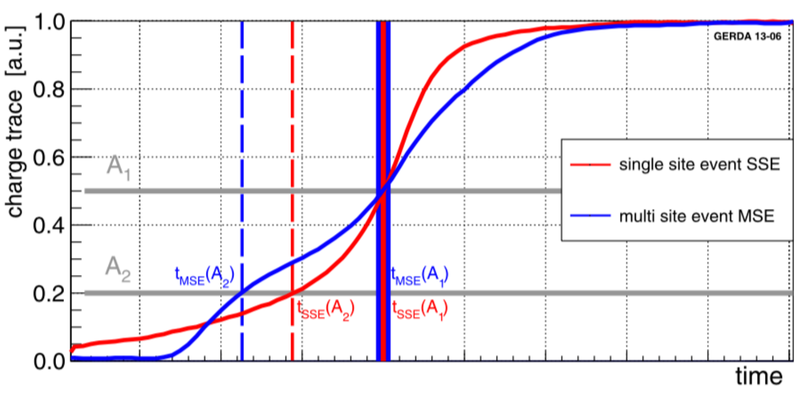
BEGe detector:



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

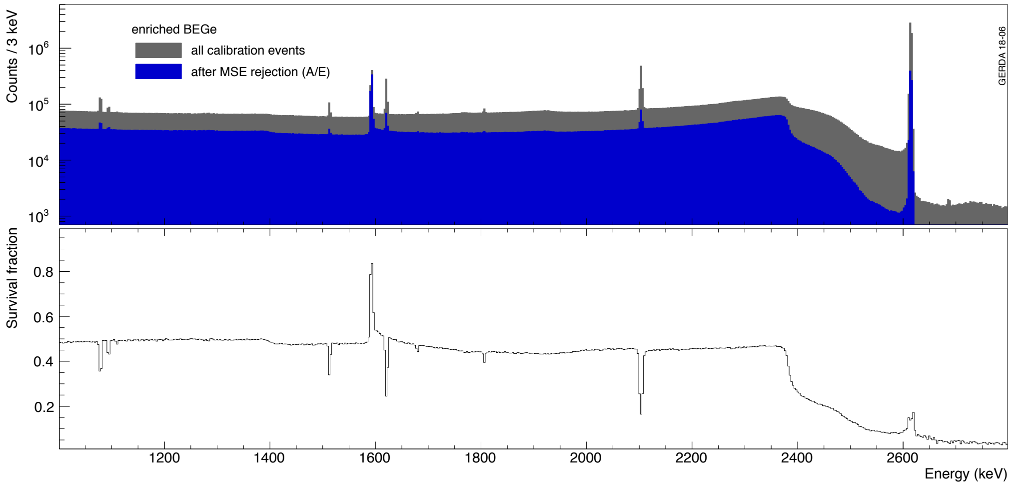


- **Coax** cut parameter: Artificial Neural network

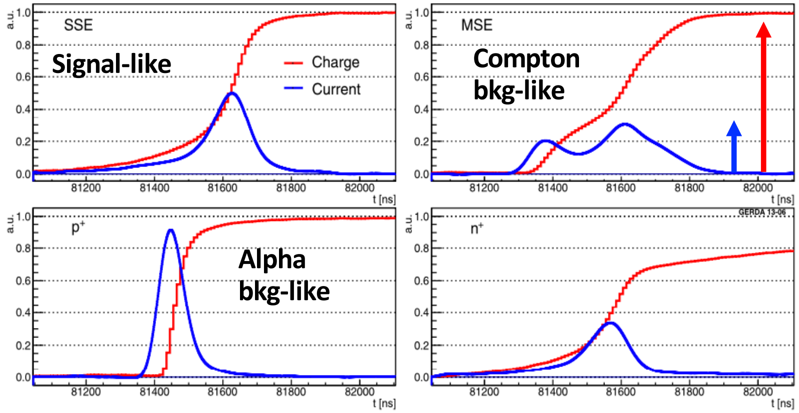


Pulse shape discrimination calibration

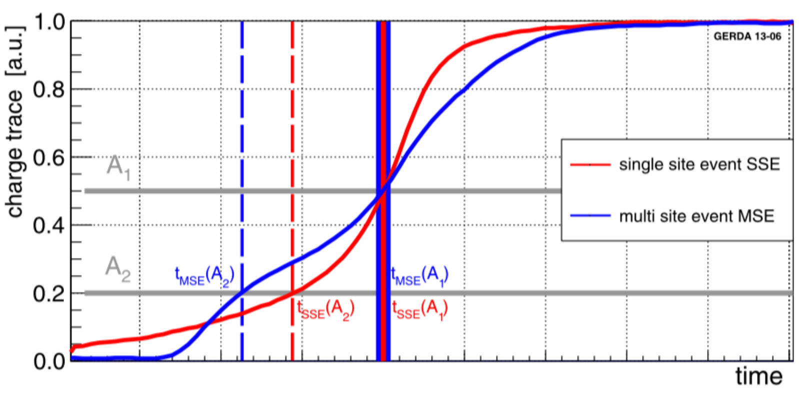
- **^{208}Tl DEP** (1592 keV) used as a proxy for **Single-Site Events** (SSE)
- **Multi-Site Events** (MSE) cut set such that 90% of ^{208}Tl DEP events survive
- **Alphas** cut due to specific signal time profile



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

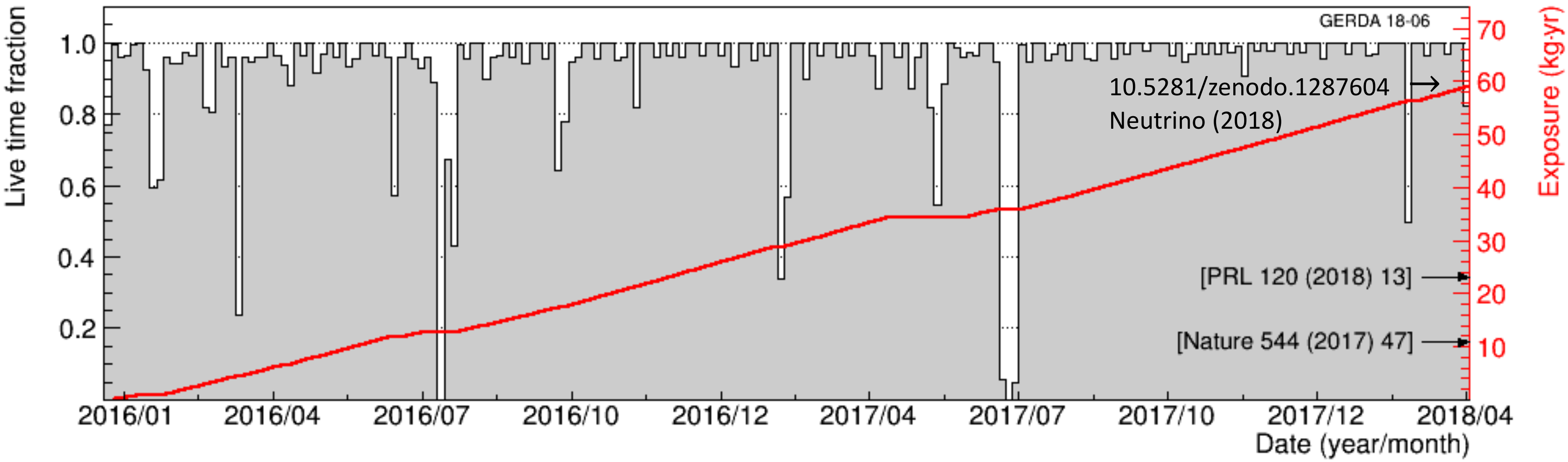


- **Coax** cut parameter: Artificial Neural network



Phase II data taking overview

- Phase II started in Dec. 2015
- Online data blinding: store events at $Q_{\beta\beta} \pm 25$ keV in non-public repository
- Unblinding session ~once per year



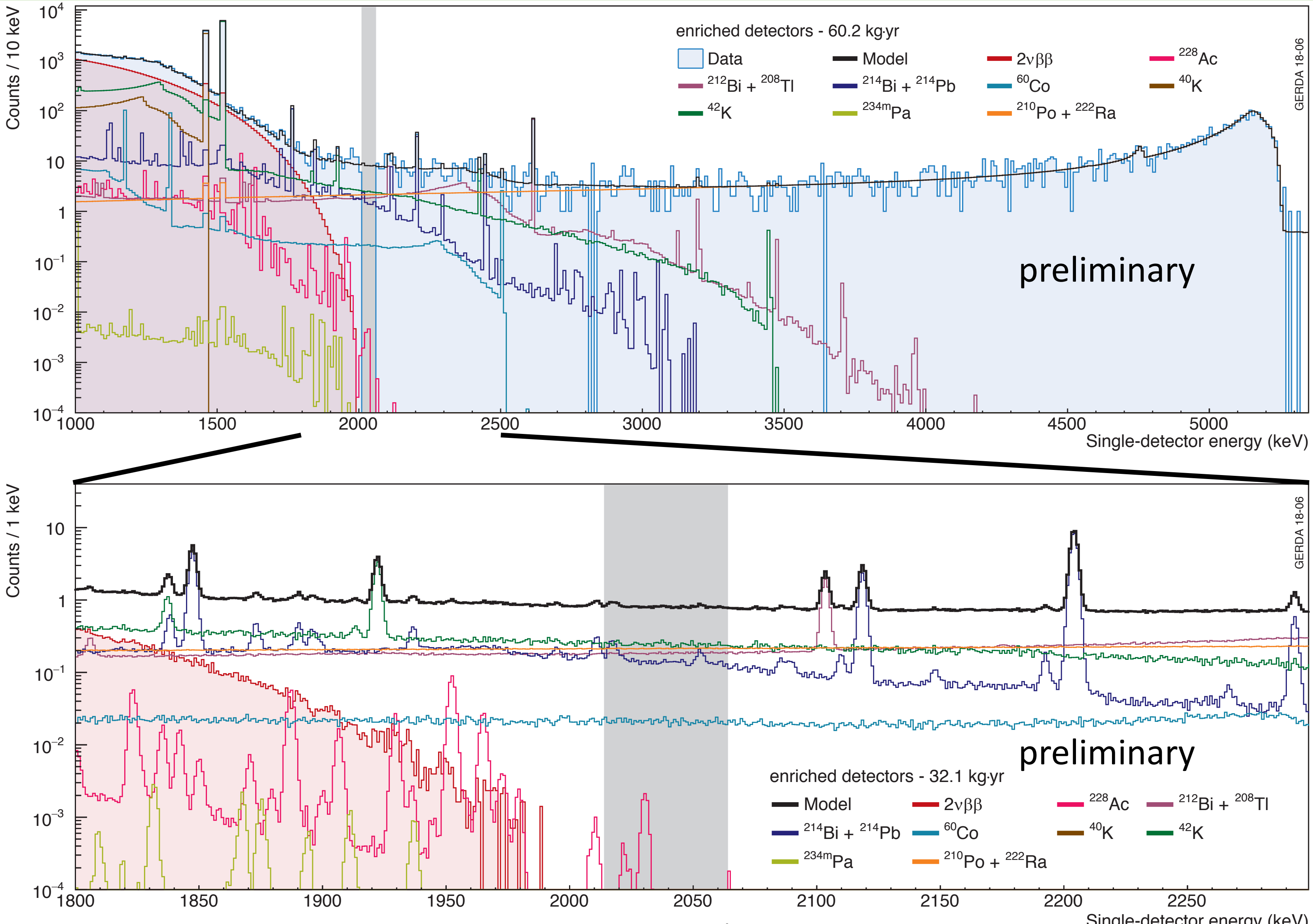
June 2016
10.8 kg.yr exposure

June 2017
23.2 kg.yr exposure
BEGe data

June 2018
58.9 kg.yr exposure
BEGe + Coax data

- Very stable operation especially during the last 9 months of phase II

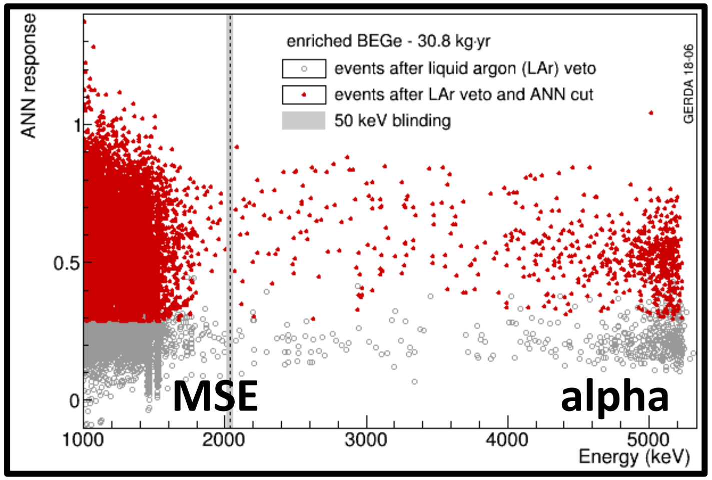
Phase II physics data modeling before cuts



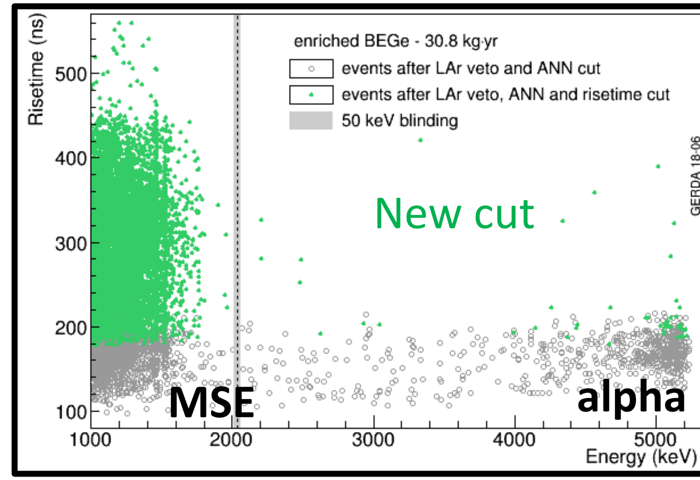
Phase II PSD cut topology

Coax

Neural network

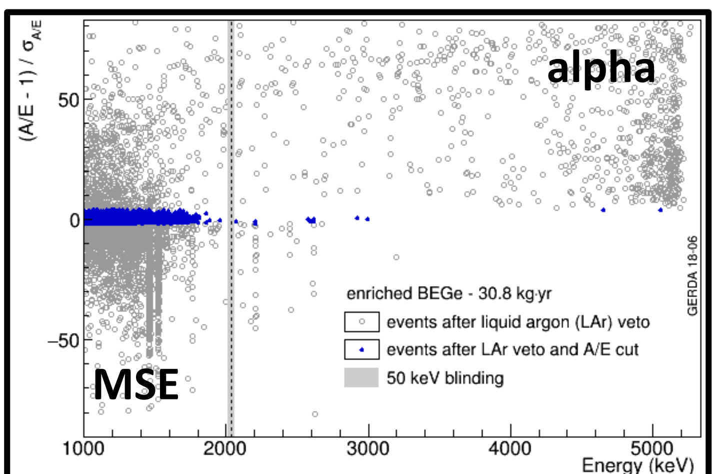


Signal rise time



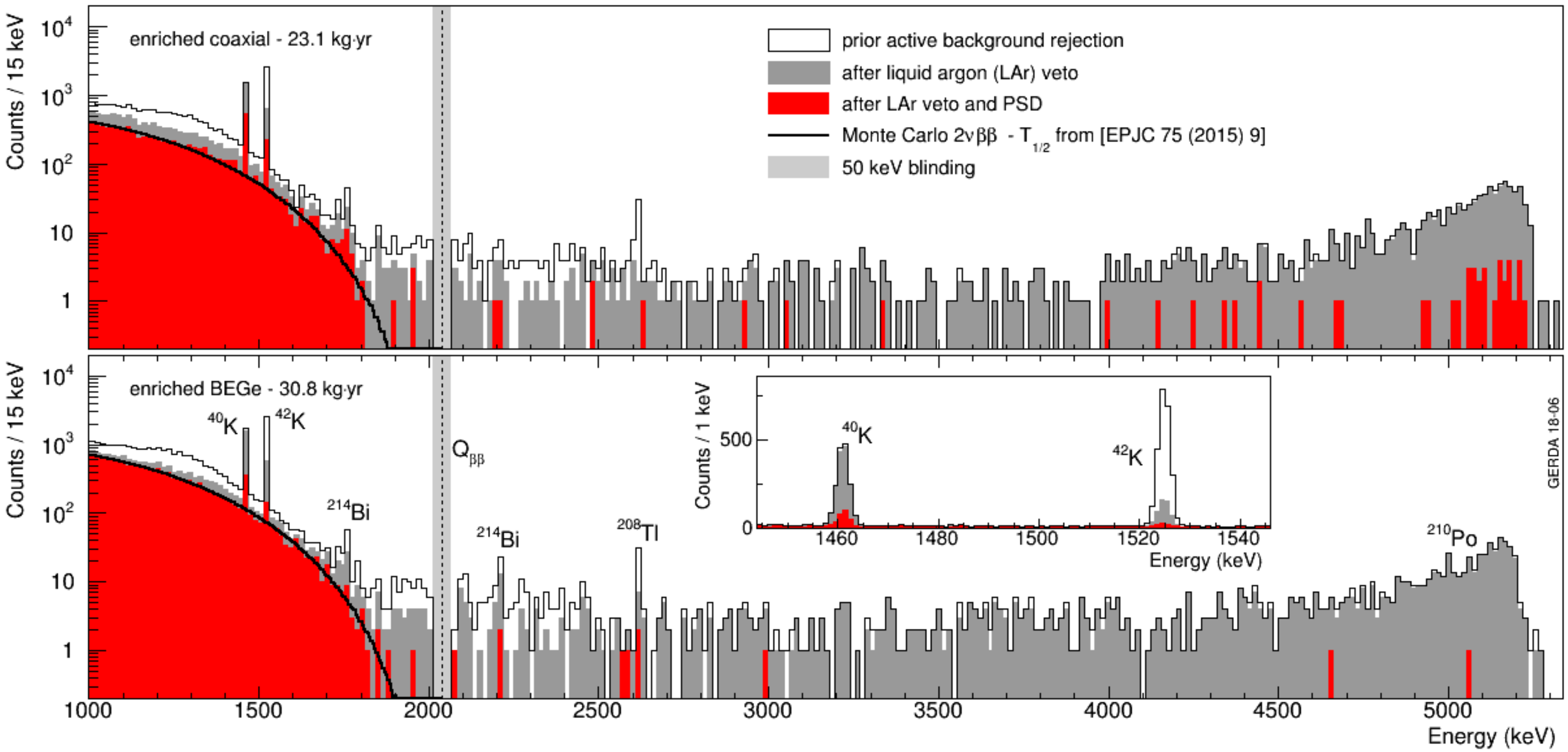
BEGe

A/E



- 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

Phase II physics data after PSD and LAr

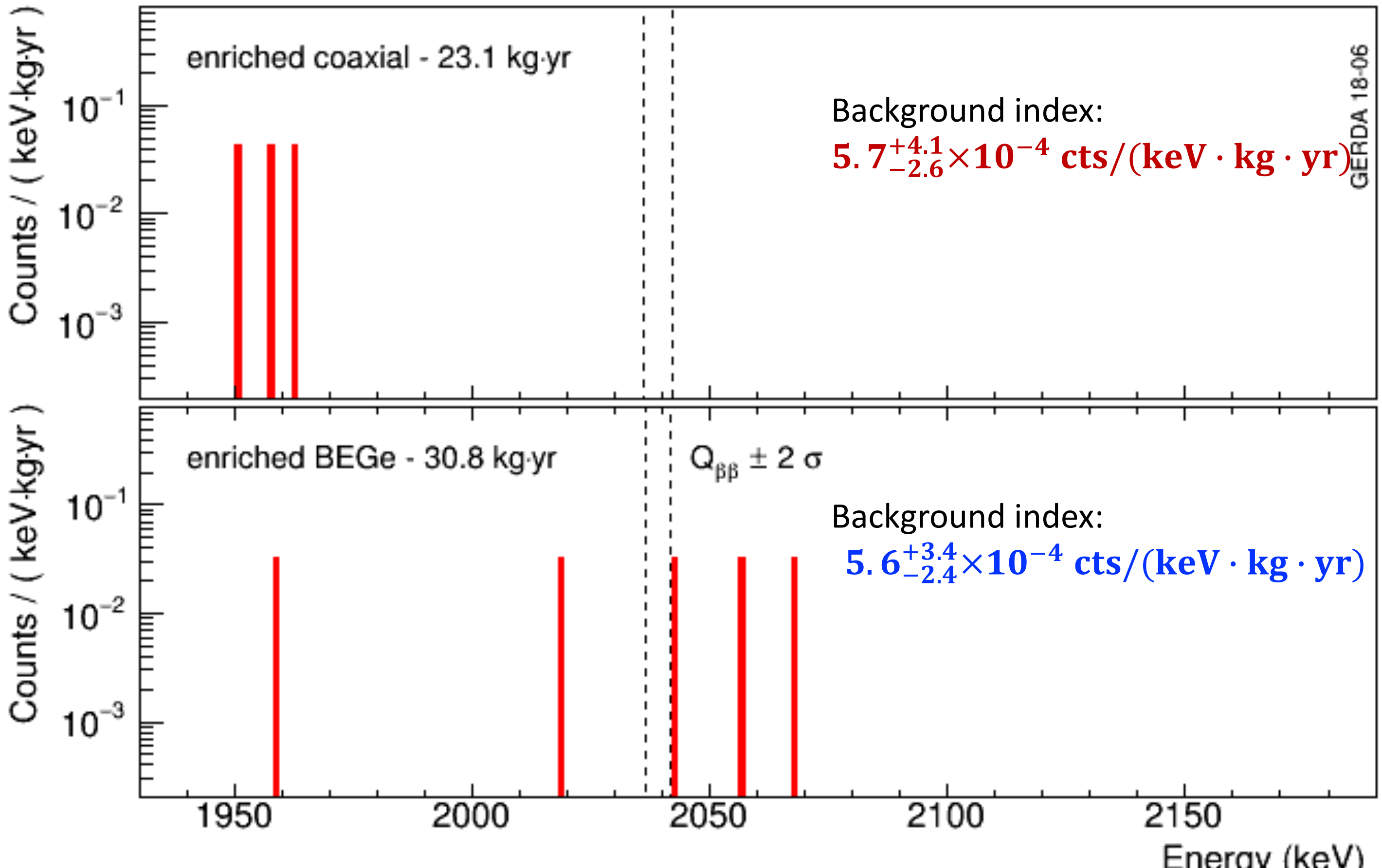


- [600-1300] keV - $2\nu\beta\beta$ decays produce single-site events -> No suppression
- [1450-1530] keV - Strong suppression of ^{40}K and ^{42}K gamma lines (MSE)
- [> 3000] keV - Suppression of almost all α events (p+ contact)

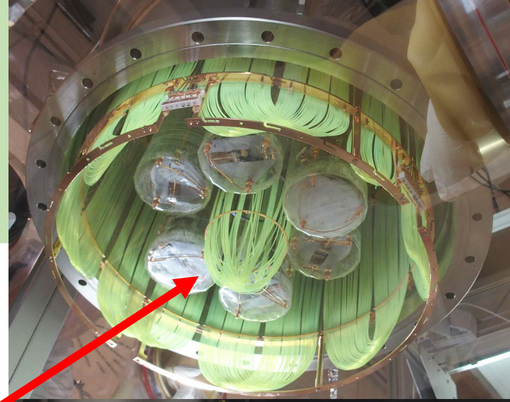
Energy spectrum after unblinding!

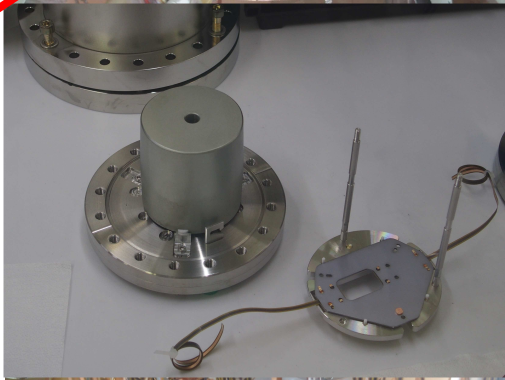
No new events in the **Coax dataset**

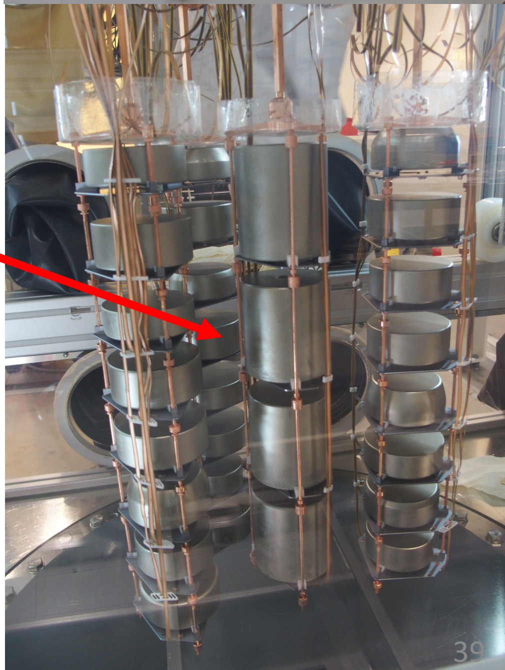
3 events in the former **BEGe dataset**
+ one new @ 2042 keV ($Q_{\beta\beta} = 2039$ keV / FWHM = 3 keV)



Since May 2018 #1







Gerda upgrade:

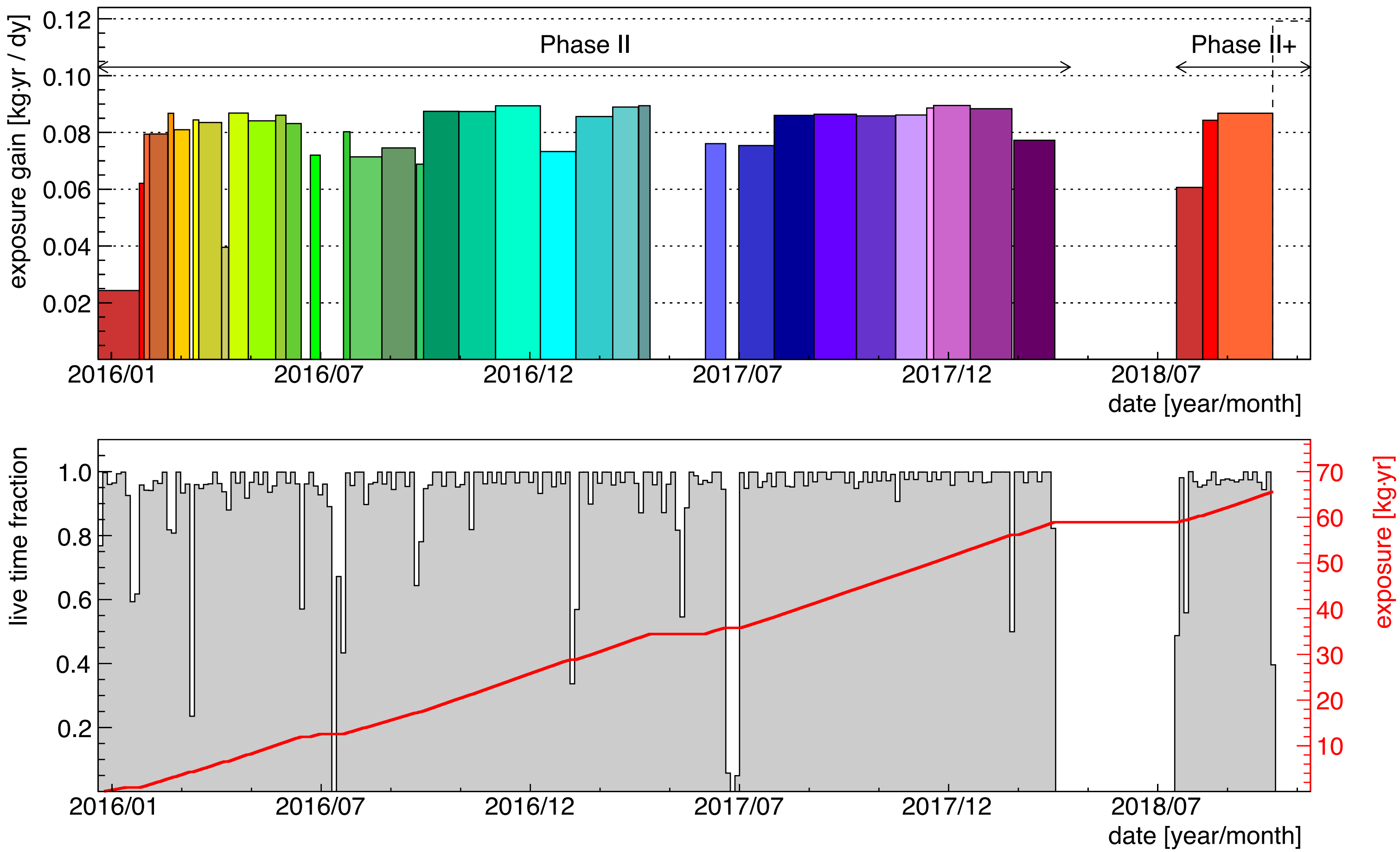
- Improved electronics noise
- Increased LAr light collection
  (new fibers + new central module)
- Increased the enriched mass by 9.5 kg
  (remove nat. detectors -> add inverted coax “IC”)

Since May 2018 #2

Restart of the data taking

New

- Already 6.6 kg.yr exposure validated



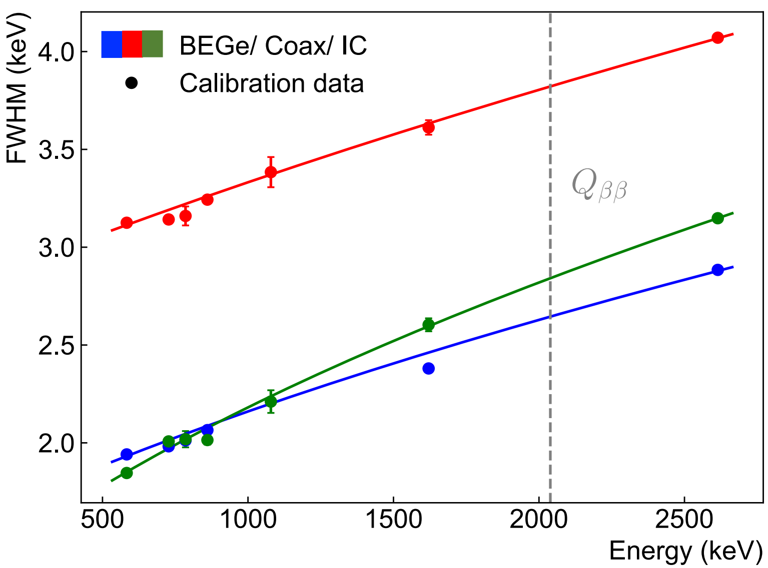
Since May 2018 #3

Restart of the data taking

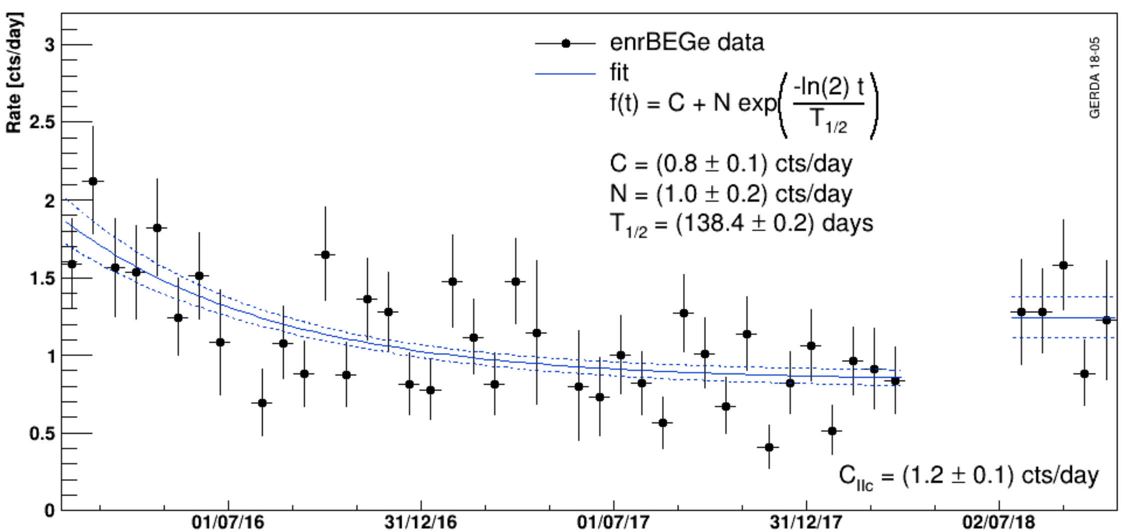
New

- 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



After GERDA and Majorana:

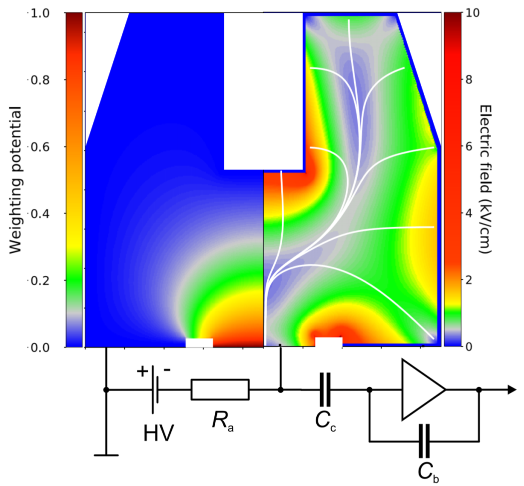
Legend collaboration:
- 52 institutions, ~250 members
- GERDA / Majorana / external contributors

Staged approach to reach 10^{28} yr sensitivity:
- LEGEND-200 → 10^{27} yr after 5 years
- LEGEND-1000 → 10^{28} yr (hosting lab under investigation)

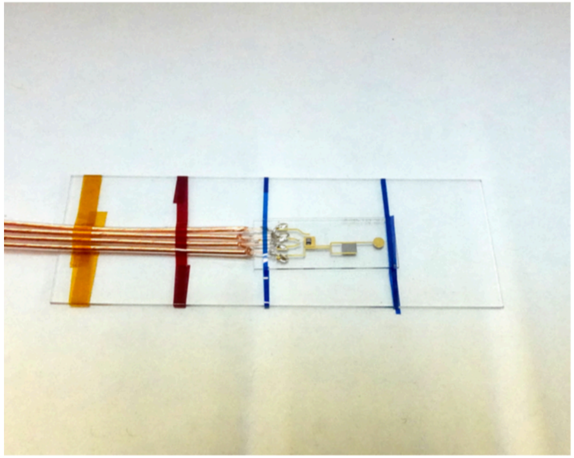
LEGEND-200 phase:
- Up to 200 kg of ^{76}Ge
- Modification of existing GERDA infrastructure at LNGS
- Improved background index
- Start in 2021
- **NEWS:**
  - Most of funding already secured
  - First detectors delivery expected early next year!

Hardware improvements #1

- **New Inverted Coaxial Point-Contact Ge detector technology**
  - ➢ First design proposed in 2011 [R. Cooper et al, 11']
  - ➢ **Large active mass up to 3 kg** (R&D for 6 kg!)
  - ➢ Excellent Pulse Shape Discrimination (PSD) between signal and background events [YK et al 18']
  - ➢ **Reduced background due to smaller number of channels**



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

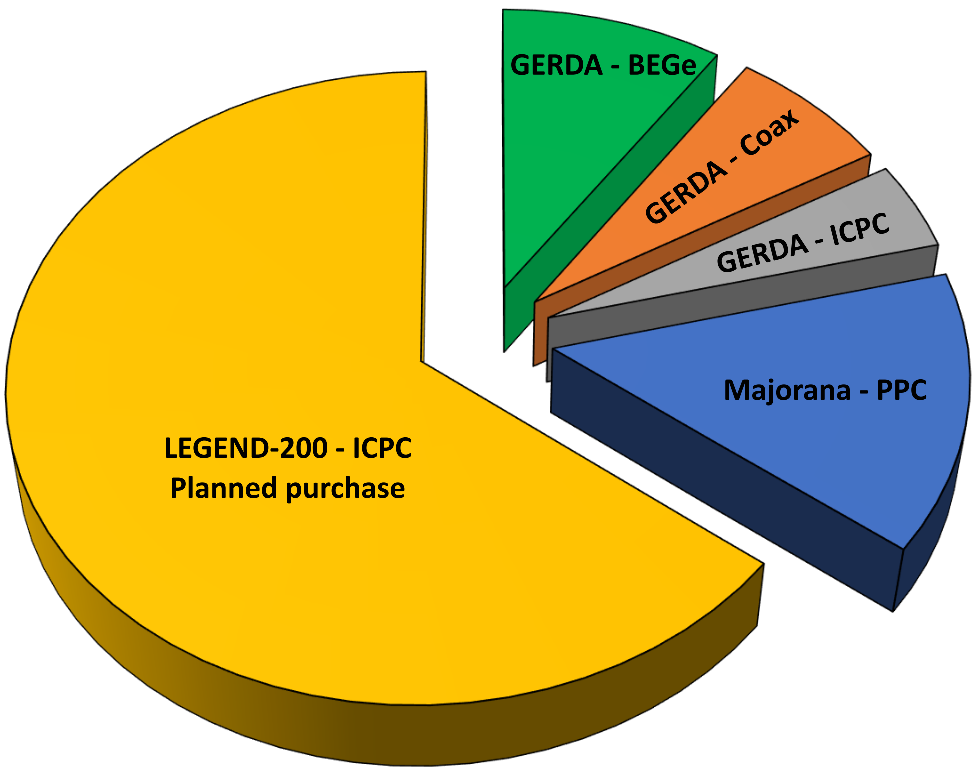


Hardware improvements #2

- **LAr veto**
  - Take advantage of GERDA experience
  - Design studies ongoing
  - Optimization of light collection

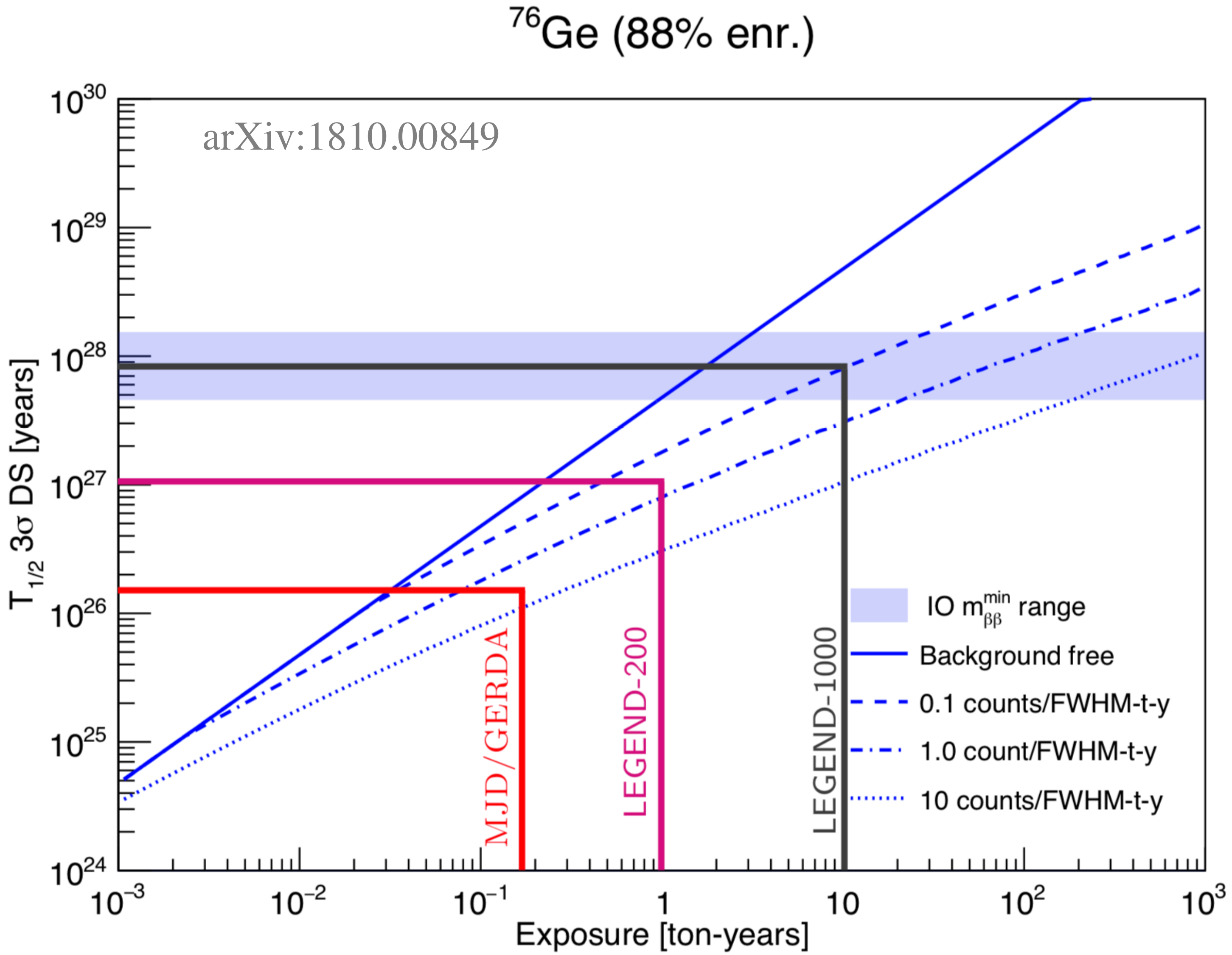
- **Ge detector strings positioning**
  - Extensive Monte-Carlo simulations
  - Compromise between background and cuts efficiency
  - Statistics for weekly calibration

LEGEND Timescale



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

3σ discovery sensitivity projection at full exposure



Summary

- $0\nu\beta\beta$ decay, if discovered, has far reaching consequences in particle physics! $\boldsymbol{\nu = \bar{\nu}}$ / **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!