Neutrinoless double beta decay searches with ^{76}Ge

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Outline:

- Double Beta Decay
- **GERDA** design
- Results from GERDA
- Beyond GERDA: **LEGEND**

motivation for $0\nu\beta\beta$ decay searches:

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

- would establish ***lepton number violation*** $\Delta L = 2$

  $(Z, A) \rightarrow (Z+2, A) + 2e^-$; half-life > 10^{26} years

  by far the most sensitive test of LNV

  other possibilities to test *LNV*:

  $\mu^- + (Z, A) \rightarrow e^+ + (Z\text{-}2, A)$; exp. $Br < 10^{-12}$ (90% CL)

  $K^+ \rightarrow \mu^+\mu^+\pi^-$; exp. $Br < 8.6\times10^{-11}$ (90% CL)

  $B^+ \rightarrow \mu^+\mu^+\pi^-$; exp. $Br < 4.0\times10^{-9}$ (90% CL)

- more ***physics beyond standard model***
  - the process stands on equal footing with baryon number violation (i.e. *p* decay)
  - important to understand the origin of the neutrino mass

motivation for $0\nu\beta\beta$ decay searches:

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

◆ Possible interpretations of $0\nu\beta\beta$:

- *Standard interpretation*: $0\nu\beta\beta$ decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution

- *Non-standard interpretations*: $0\nu\beta\beta$ decay is mediated by some other LNV physics (Higgs triplet, LR symmetric theories, SUSY theories, Majorons,...), and light and massive Majorana neutrinos (the ones which oscillate) potentially leading to $0\nu\beta\beta$ give negligible or no contribution

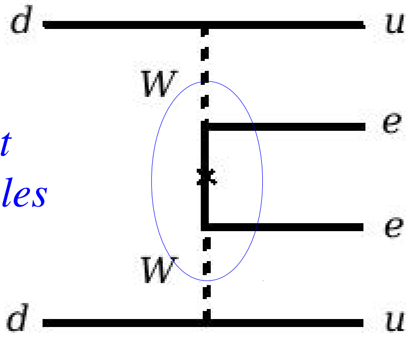
motivation for $0\nu\beta\beta$ decay searches:

(A, Z) → (A, Z+2)+2e$^-$

- Only way to determine if neutrino is its own antiparticle:

$\nu = \bar{\nu}$ ⇨ ***Majorana particle***

exchange of light
Majorana particles



If YES:

- would provide access to ***absolute neutrino mass scale***

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$

$$\langle m_{ee}\rangle = \left|\sum_i U^2_{ei} m_i\right|$$

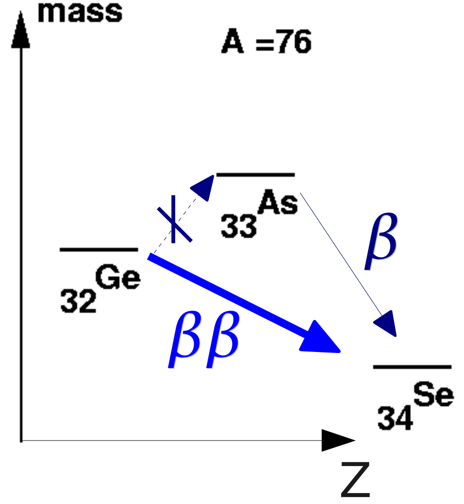
nuclear matrix element

phase space factor

effective Majorana neutrino mass

- would provide ***important input to cosmology***

$2\nu\beta\beta$ and $0\nu\beta\beta$ decays



$2\nu\beta\beta$: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$

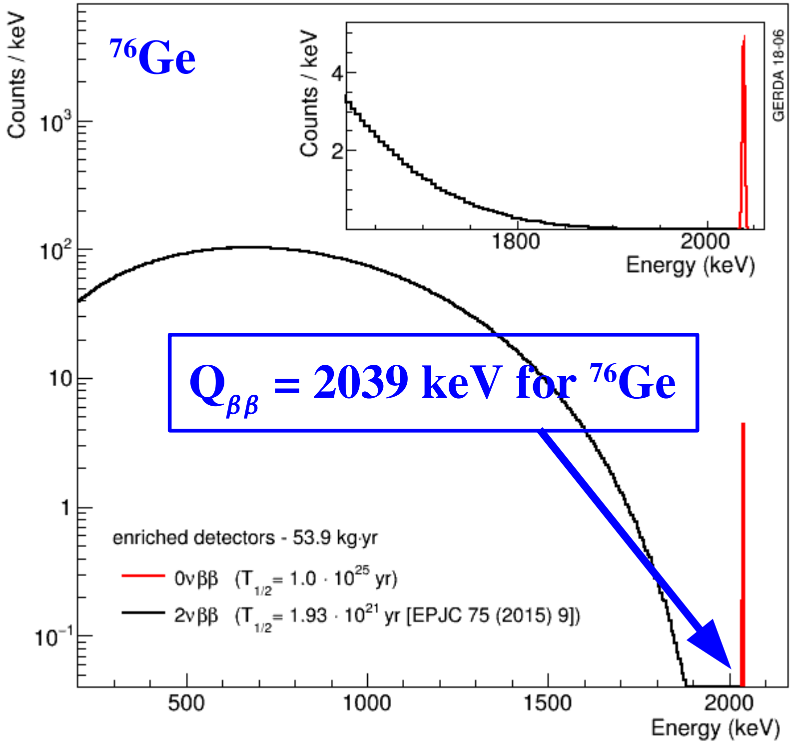
2^{nd} order process, observed, $T_{1/2} \sim 10^{19}\text{-}10^{24}$ yrs

^{76}Ge: $T_{1/2} \sim 10^{21}$ yrs

$0\nu\beta\beta$: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

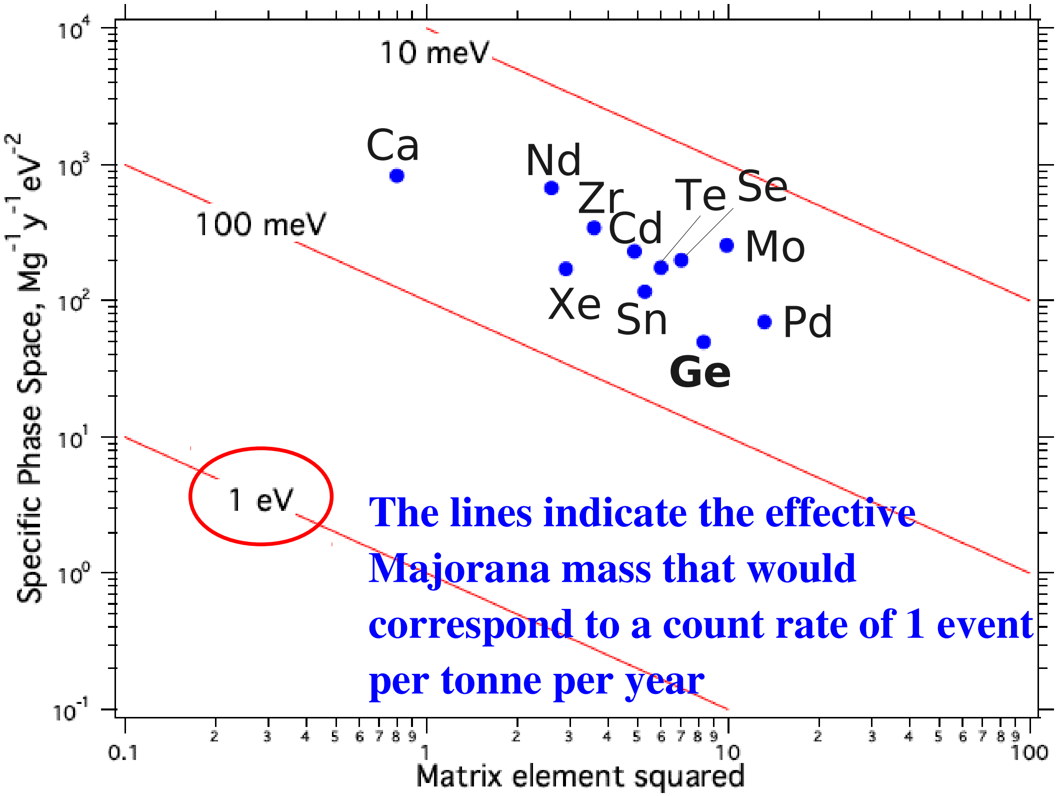
new physics, $T_{1/2} > 10^{25}$ yrs

Signature for $0\nu\beta\beta$ decays:



$Q_{\beta\beta}$ = 2039 keV for ^{76}Ge

Comparing different isotopes



R.G.H. Robertson arXiv:1301.1323

The lines indicate the effective Majorana mass that would correspond to a count rate of 1 event per tonne per year

No theoretical preference

- Phase Space and NME inversely correlated. Tend to compensate.
- Theoretical uncertainties very large

Experimental/practical criteria

- Enrichment cost
- Energy resolution
  - Narrow peak for discovery
- Background index
  - Ultraclean components
  - Avoid surfaces
    - Especially in a vacuum
- Scalability
  - Liquids, gases, large crystals

Searching in ^{76}Ge

$$\underset{\text{sensitivity}}{(T^{0\nu}_{1/2})^{-1}} \propto \begin{cases} \epsilon \cdot f \cdot M \cdot t_{run} & \text{without background} \\ \epsilon \cdot f \cdot \sqrt{\dfrac{M \cdot t_{run}}{BI \cdot \Delta E}} & \text{with background} \end{cases}$$

ϵ: efficiency

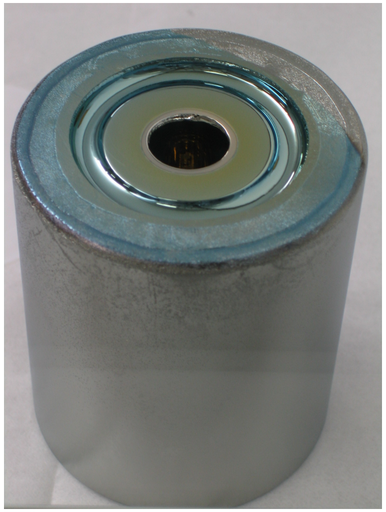
f: abundance of $0\nu\beta\beta$ isotope

M: detector mass

t_{run}: measurement time

BI: background index

ΔE: energy resolution at $Q_{\beta\beta}$



Germanium detector

Advantages of Germanium:

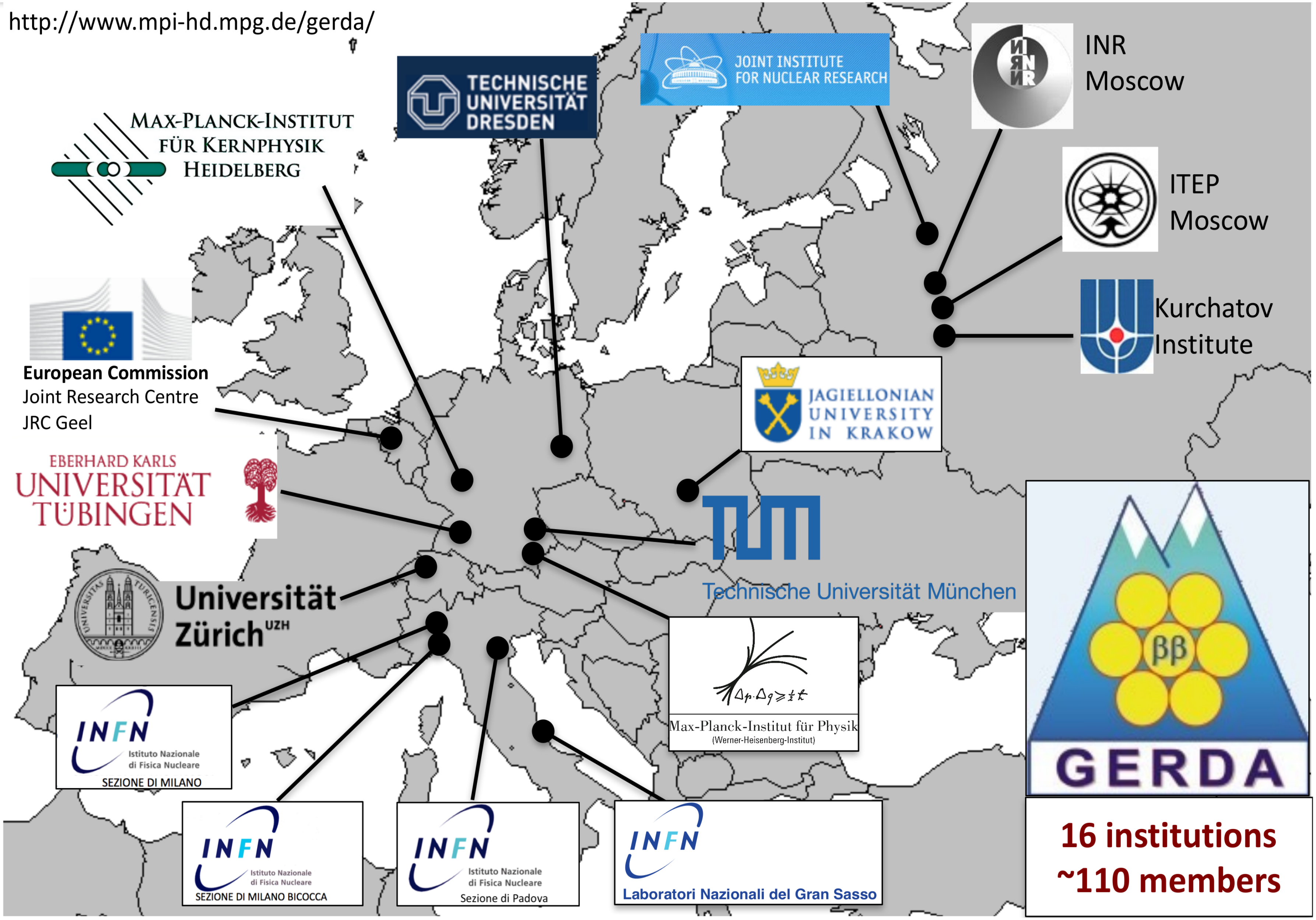
- **High ϵ**: Source = Detector
- **Small instrinsic BI**: High purity Ge
- **Excellent ΔE**: FWHM ~ (0.1-0.2)%
- Well-established technology

Disadvantages of Germanium:

- at $Q_{\beta\beta}$ = 2039 keV more challenging to reach **low enough background**
- **Small f of ^{76}Ge:** 7.8% → Enrichment needed! → ~ **86% in GERDA**
- Small $G^{0\nu}(Q_{\beta\beta},Z)$

The GERDA Collaboration

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

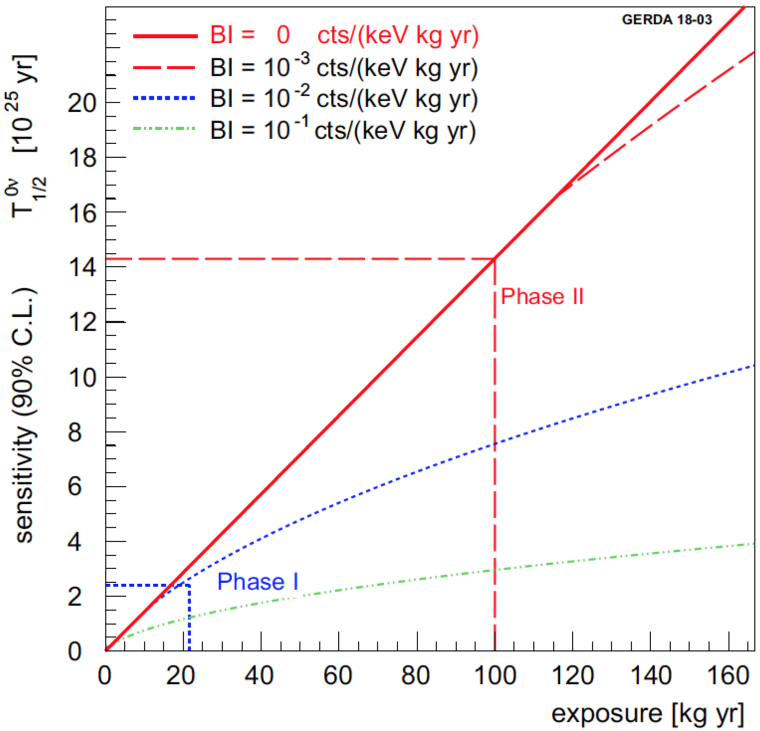


16 institutions
~110 members

GERDA Phase II physics goals

- reach background of **10^{-3} cts/(keV·kg·yr)**
- collect an exposure of **100 kg·yr**
- sensitivity: **$T^{0\nu}_{1/2}$ > 1.4·10^{26} yr** (90% CL)
- discovery potential up to **10^{26} yr**

  (*50% prob. chance for a 3σ* signal)
- <m$_{ee}$> ≤ 0.09-0.15 eV



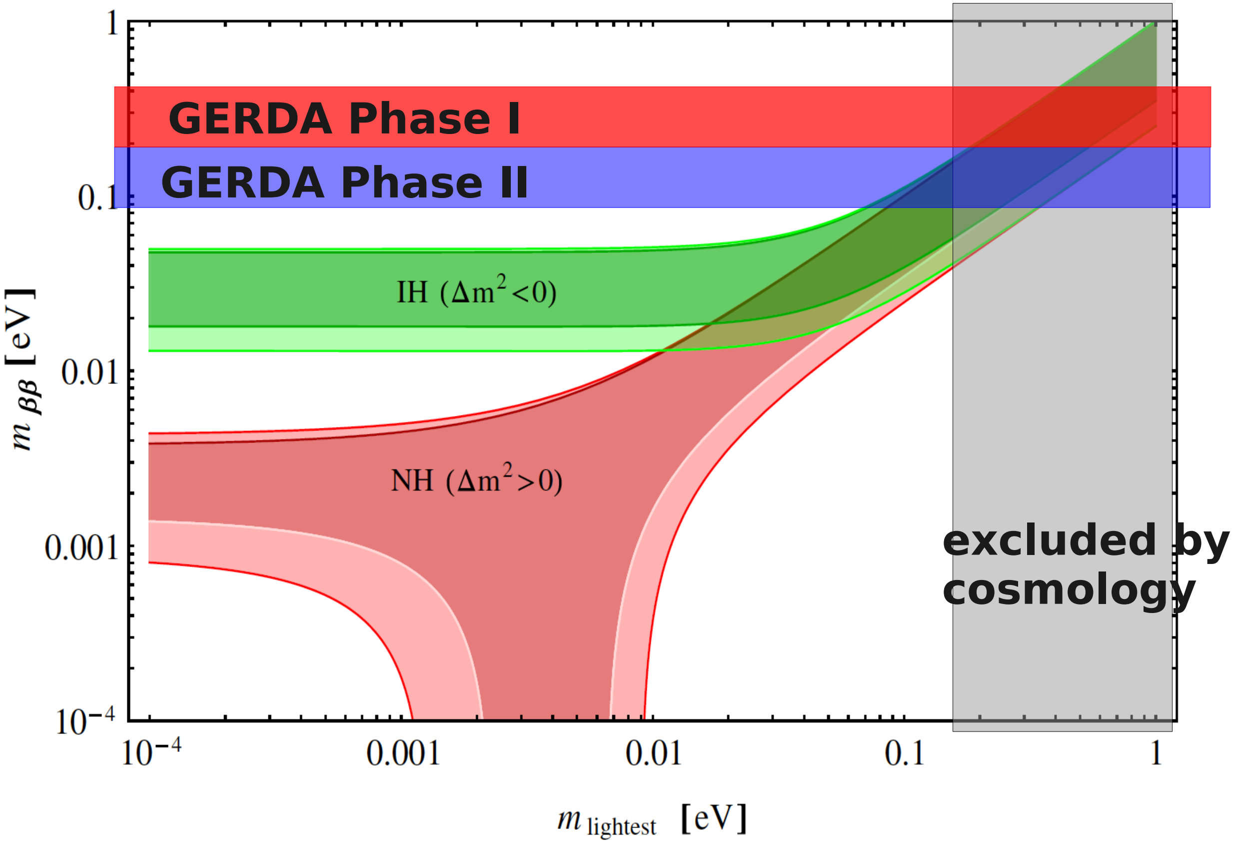
Phase II started at the end of 2015;
past achievements:

- reached background index of **10^{-3} cts/(keV·kg·yr)**
- fully analyzed an exposure of **23.2 kg·yr**
- sensitivity of **$T^{0\nu}_{1/2}$ = 5.8·10^{25} yr** (90% CL)
- no signal found: lower limit **$T^{0\nu}_{1/2}$ > 8.0·10^{25} yr** (90% CL)
- <m$_{ee}$> ≤ 0.12-0.26 eV

Nature 544, 47 (2017)
PRL 120, 132503 (2018)

GERDA physics goal

S. Dell'Oro, S. Marcocci, F. Vissani, PRD 90 (2014)



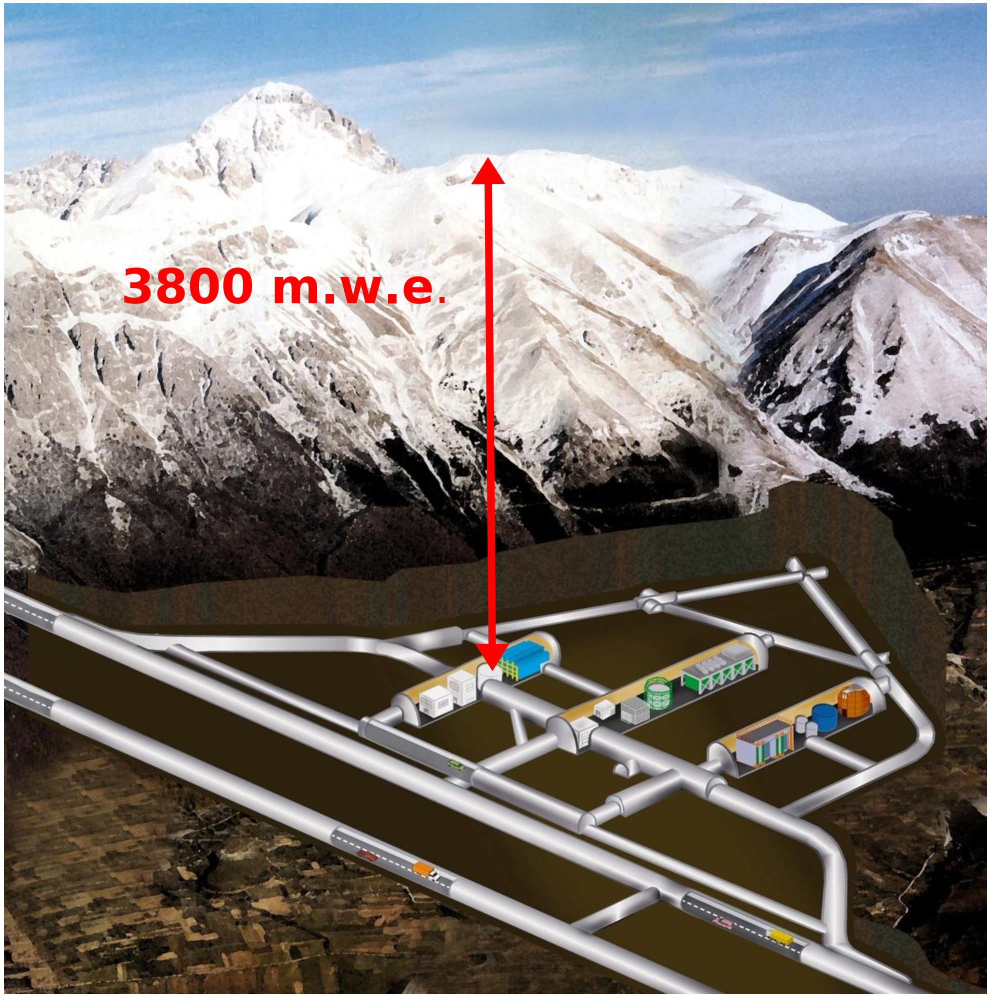
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$

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

Gerda @ LNGS: Background reduction

- **GERDA situated in LNGS underground laboratories**

- 3800 m.w.e.



Possible **backgrounds** from:

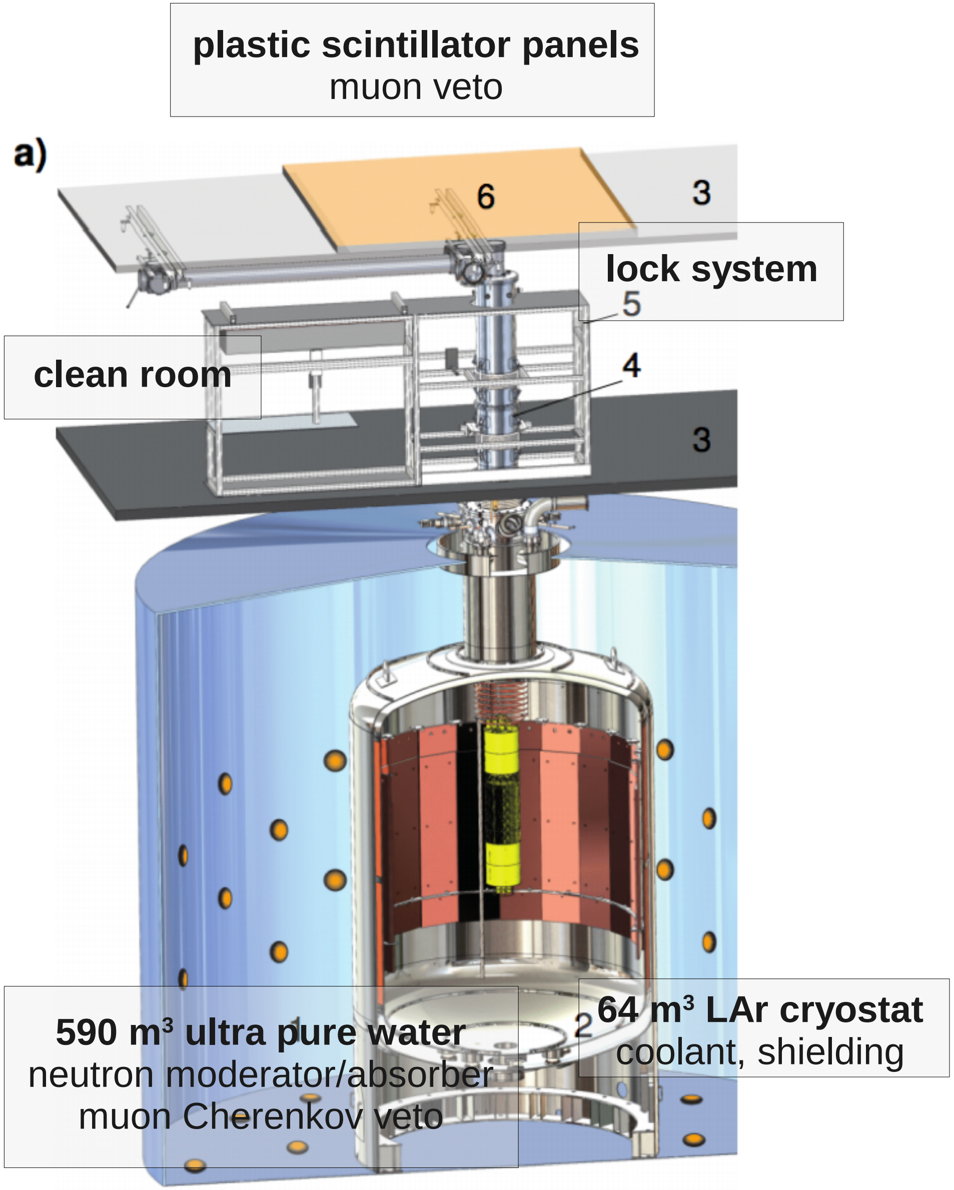
External:

- γ from Th and U chain
- neutrons
- μ from cosmic rays (prompt and delayed)

Internal:

- cosmogenic ^{60}Co ($T_{1/2}$=5.3 yr)
- cosmogenic ^{68}Ge ($T_{1/2}$=271 d)
- Radioactive surface contaminations

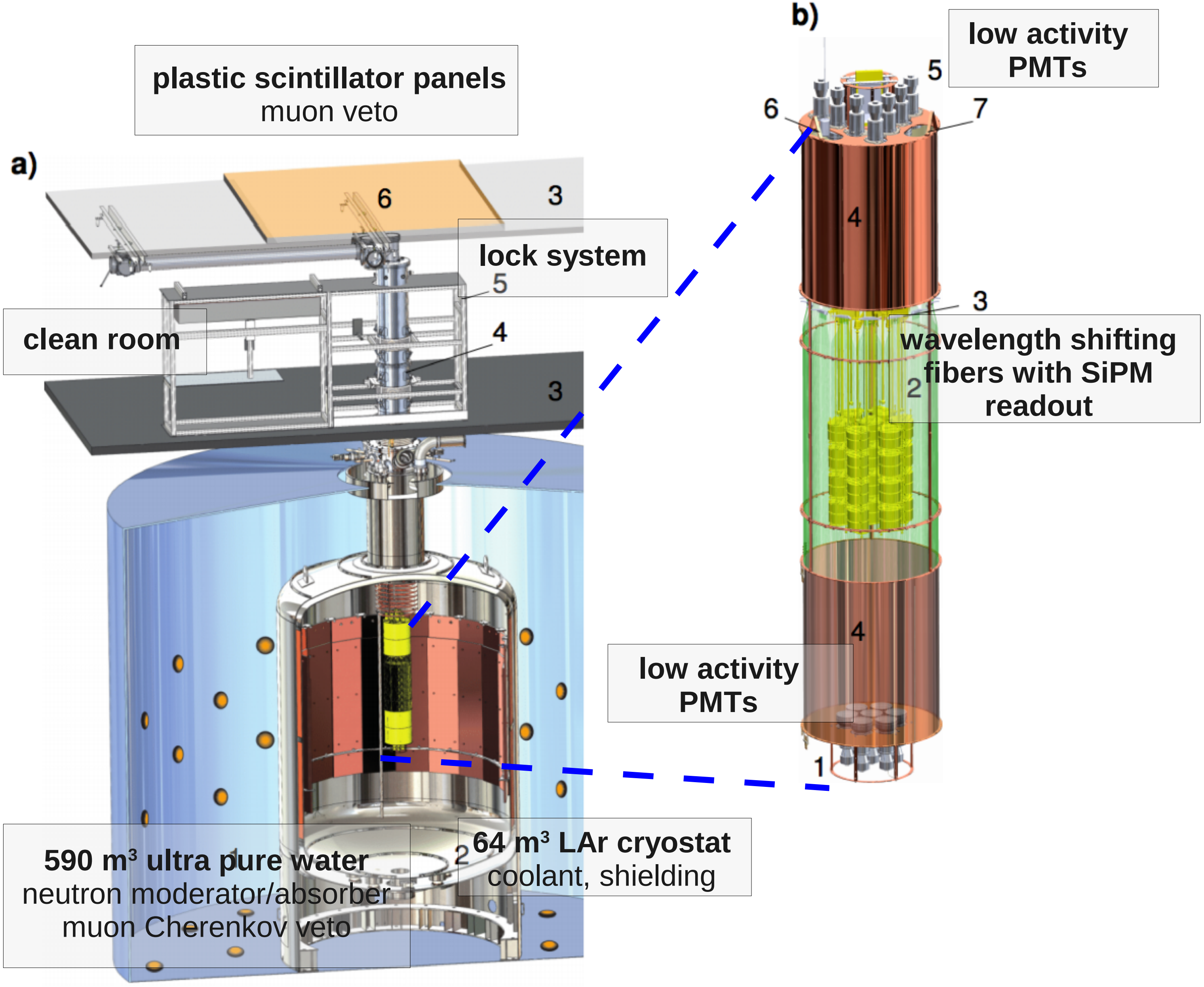
Phase I: Eur. Phys. C 73 (2013) 2330
Phase II: Eur. Phys. C 78 (2018) 388



a) overview

- ***bare HPGe detectors in liquid Ar*** (*)
- Graded shielding against ambient radiation
- Rigorous material selection
- Avoid exposure above ground for enriched (86% ^{76}Ge) Ge detectors
- ***Active background suppression***

(*) G. Heusser, Ann. Rev. Nucl. Part. Sci. 45 (1995) 543



plastic scintillator panels
muon veto

lock system

clean room

590 m³ ultra pure water
neutron moderator/absorber
muon Cherenkov veto

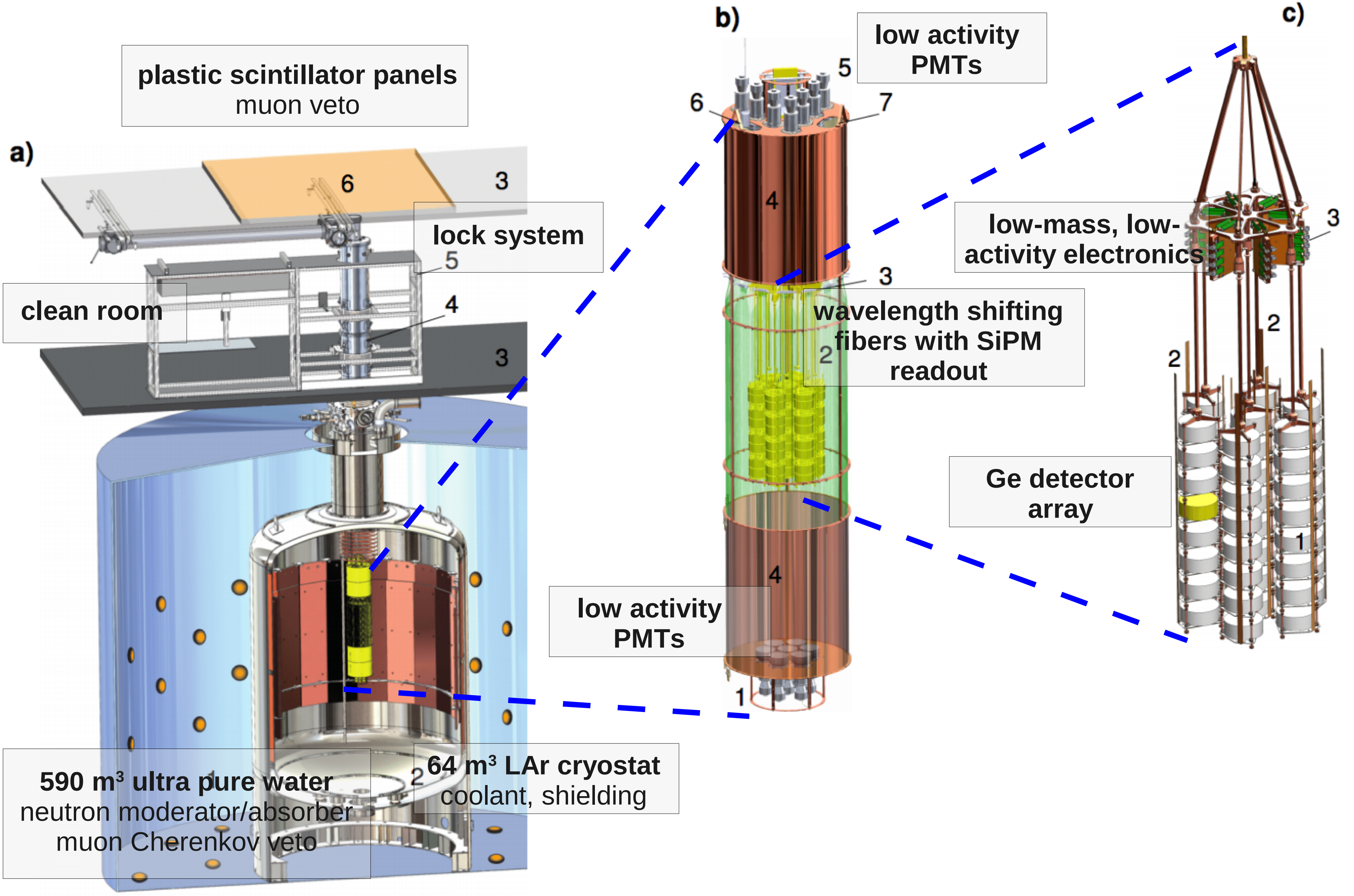
64 m³ LAr cryostat
coolant, shielding

low activity PMTs

wavelength shifting fibers with SiPM readout

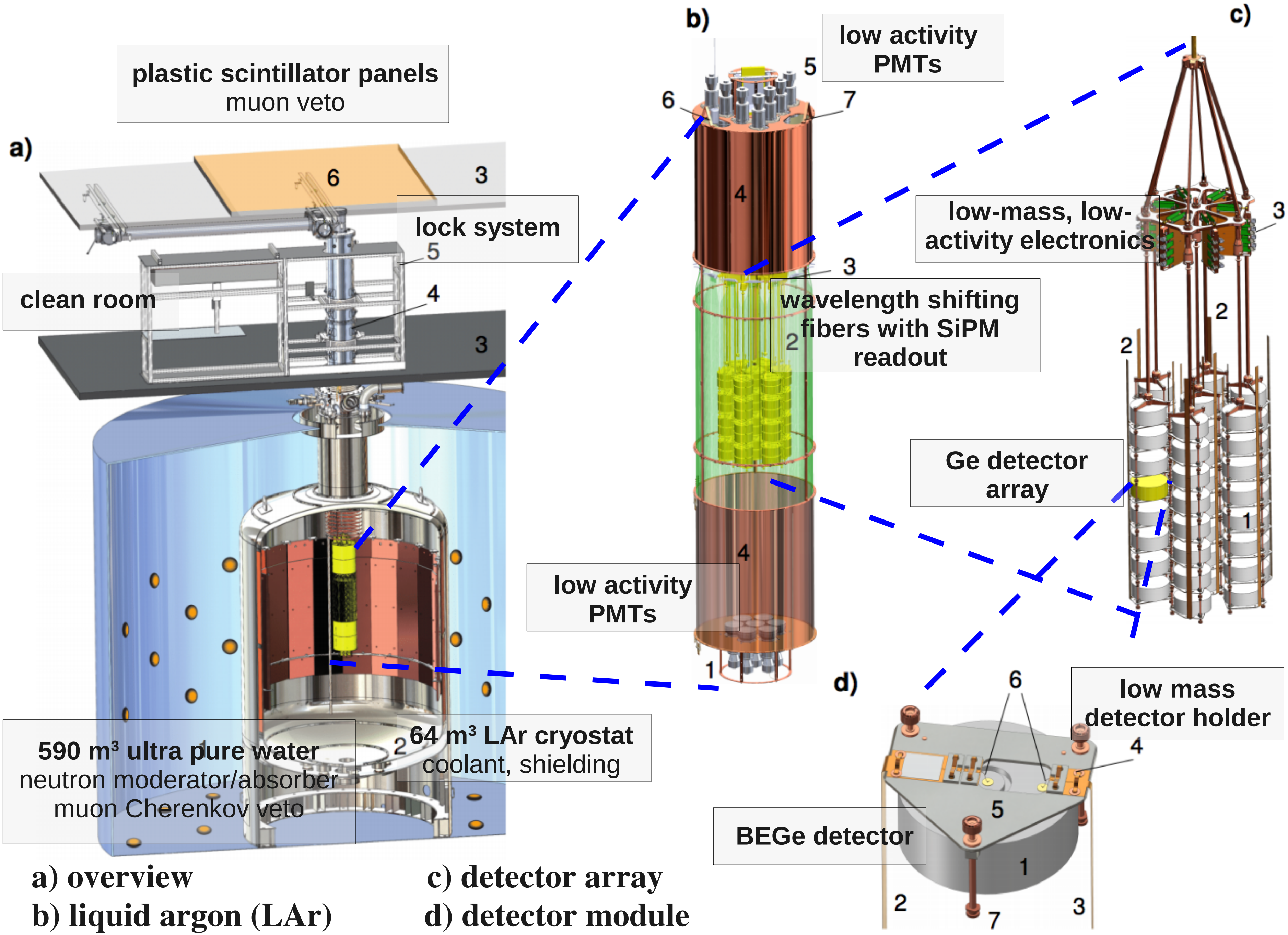
low activity PMTs

a) overview
b) liquid argon (LAr) veto instrumentation



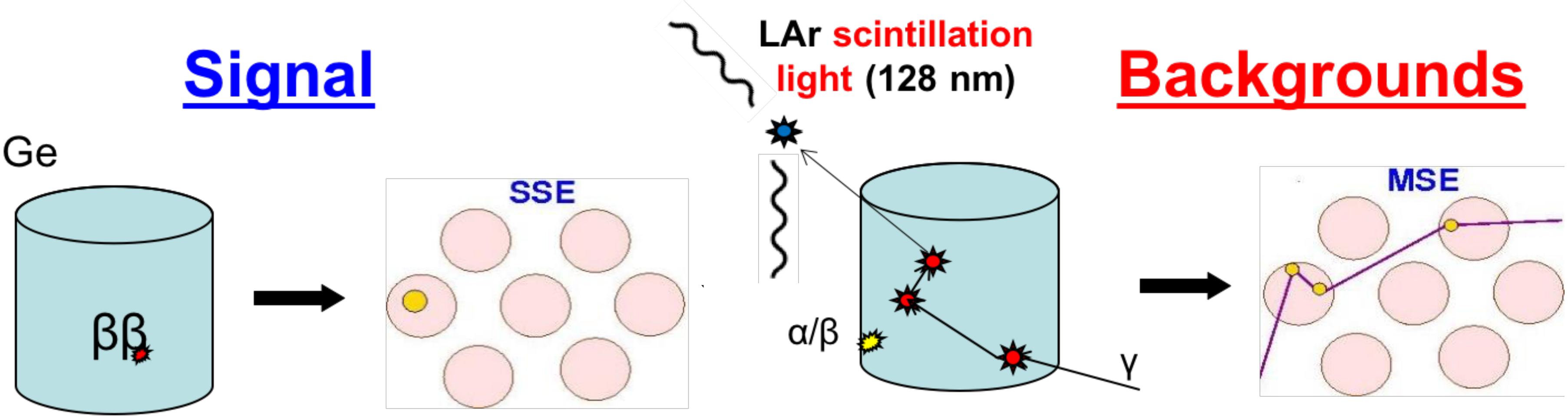
a) overview
b) liquid argon (LAr)
veto instrumentation

c) detector array



a) overview
b) liquid argon (LAr)
veto instrumentation
c) detector array
d) detector module

Active background reduction tools



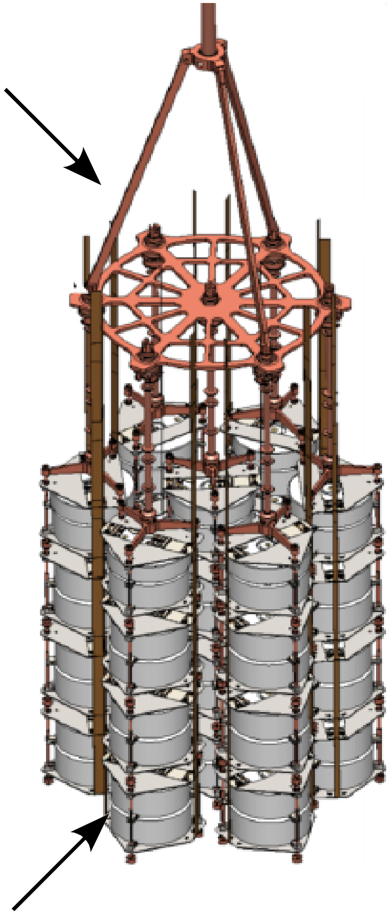
Point-like (single-site) energy deposition inside one HP-Ge diode

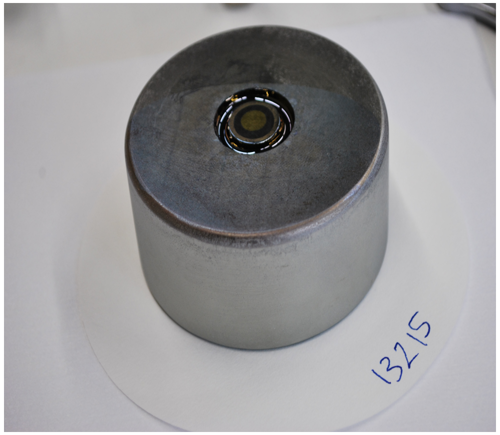
Multi-site energy deposition inside HP-Ge diode (Compton scattering), or **surface** events

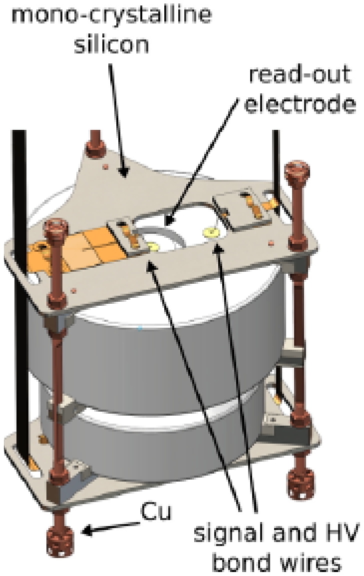
- **Anti-coincidence** with the **muon veto** (MV)
- Anti-coincidence **between detectors** (cuts multi-site) (AC)
- **Active veto** using LAr scintillation (LAr Veto)
- **Pulse shape** discrimination (PSD)

Phase II: detector array

- produced **30** custom-designed **BEGe-type detectors** in collaboration with Canberra [EPJC 75 (2015) 39]
- new lower mass holders and contacting solution (wire bonding)
- new low-mass low-activity electronics and cables

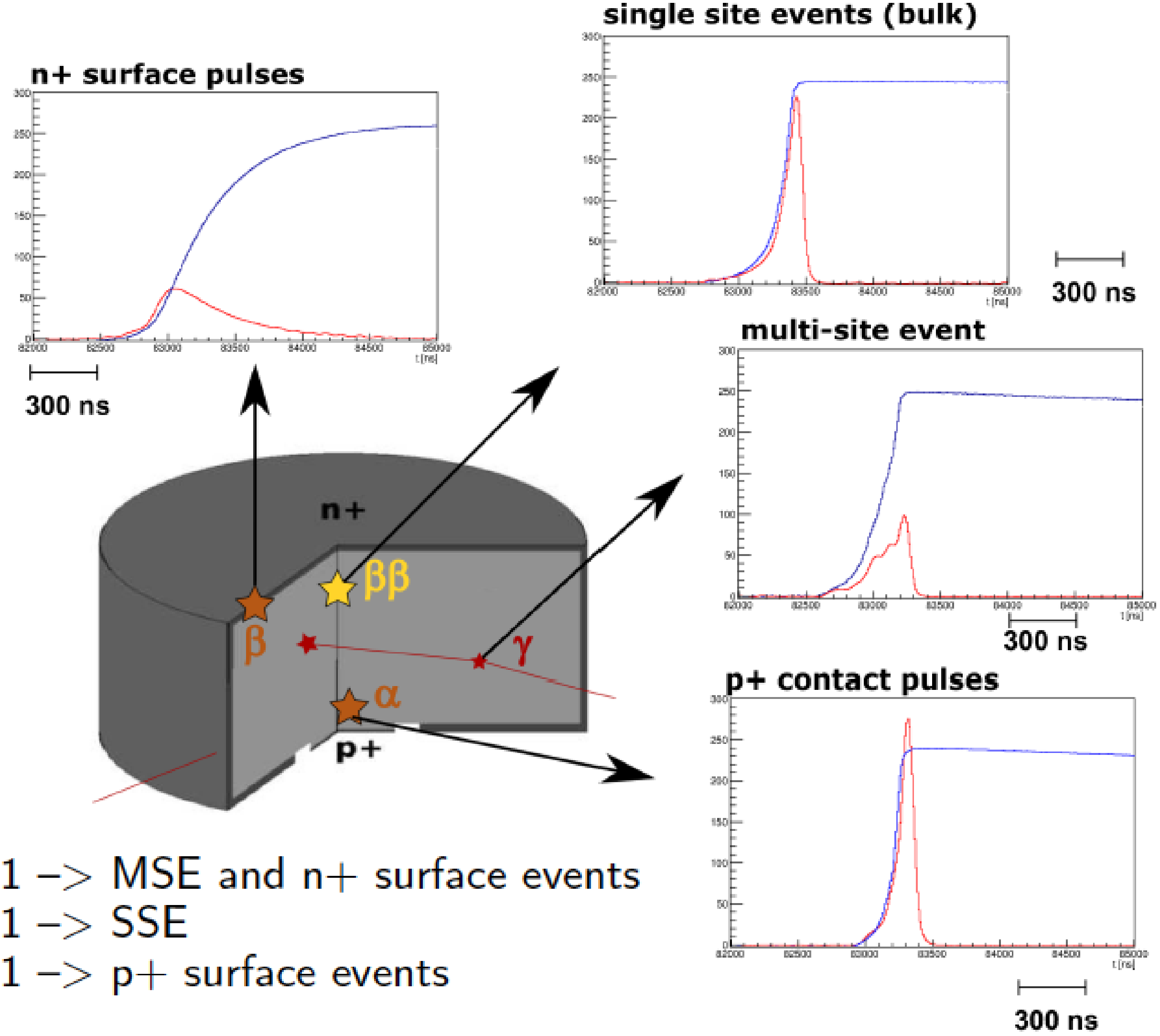






Pulse Shape Discrimination: BEGe

- Event classification using the ratio: Current/Energy i.e. **A/E** variable

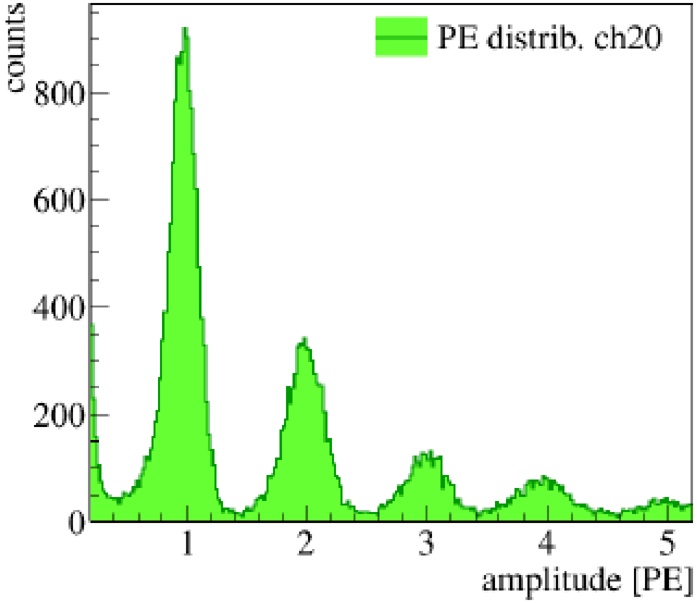


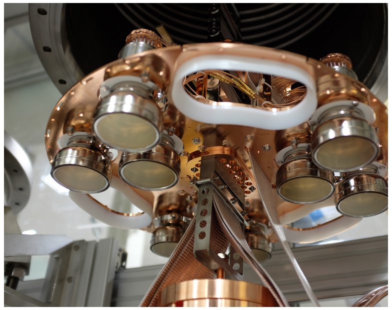
A/E<1 –> MSE and n+ surface events
A/E~1 –> SSE
A/E>1 –> p+ surface events

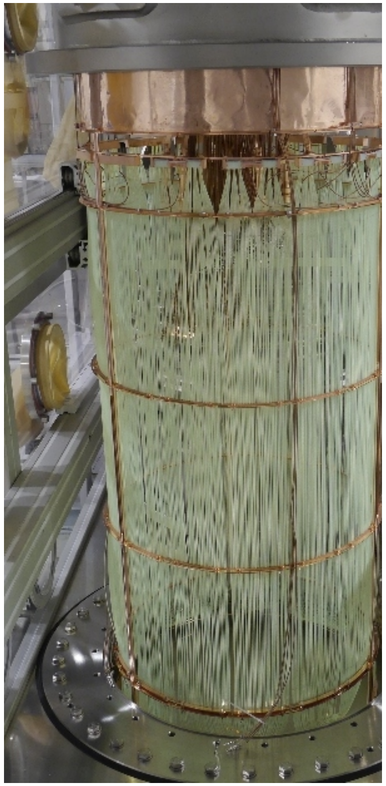
Phase II: LAr scintillation light veto

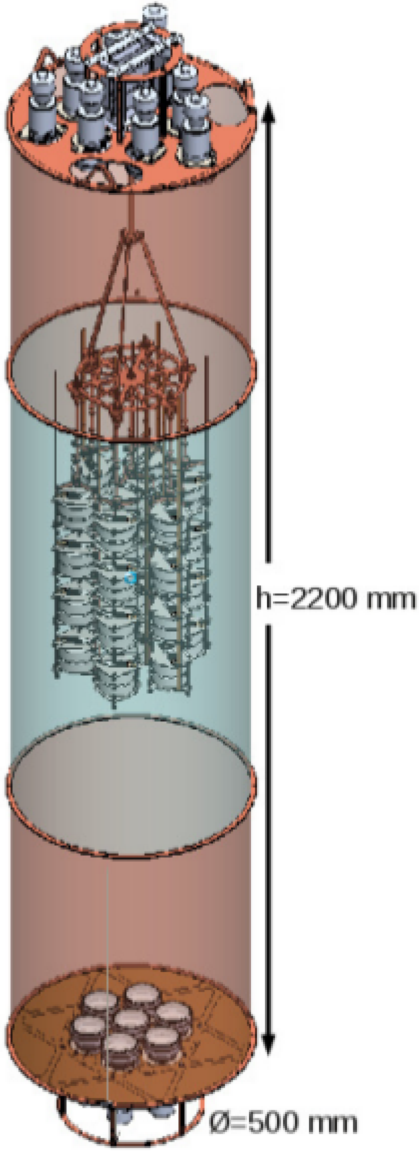
Hybrid veto system

- 16 PMTs (9 top / 7 bottom)
- 800m fibers coated with WLS + 90 SiPMs
- nylon mini-shroud around each string coated with WLS





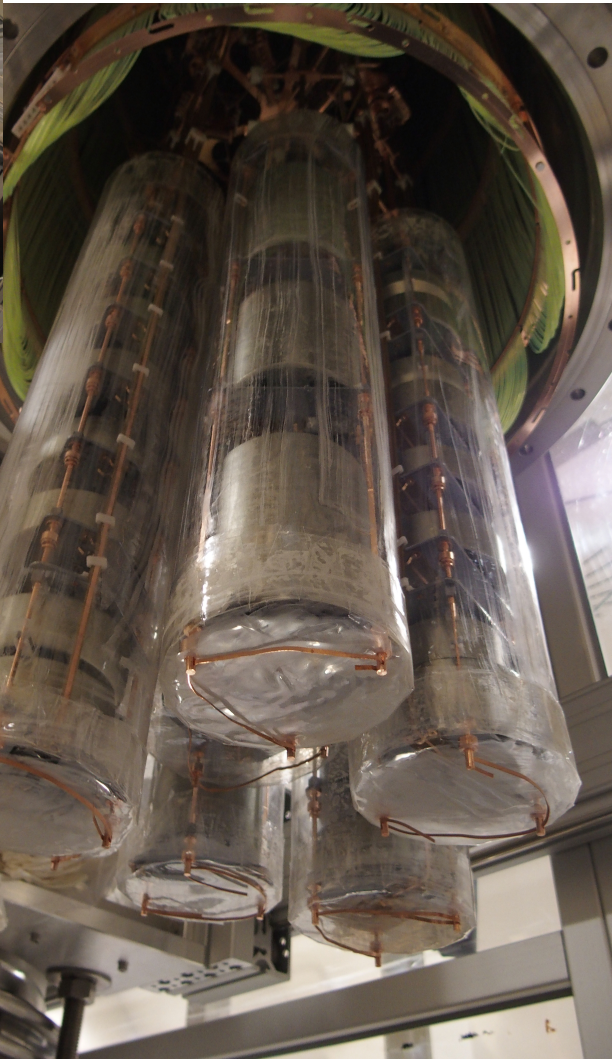


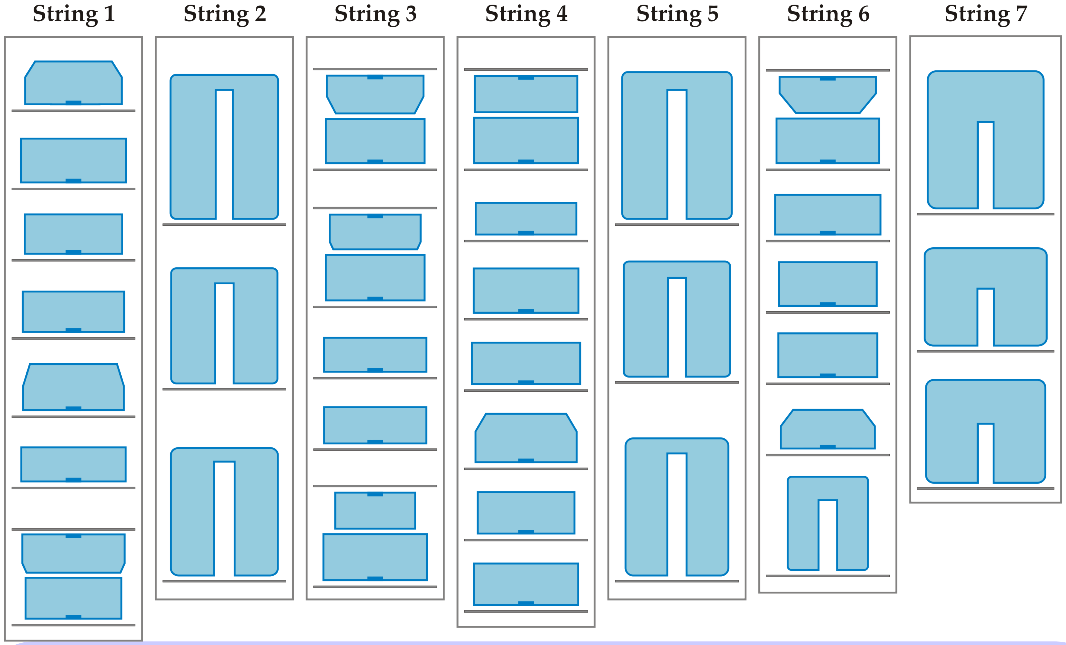


Phase II array configuration

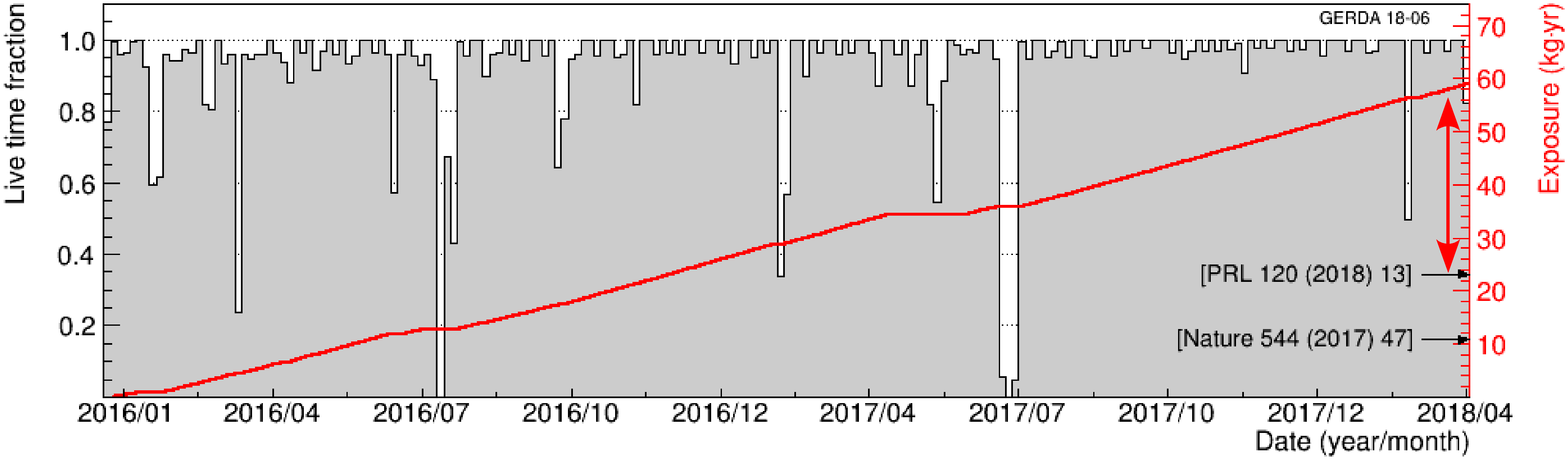
- Deployed in Dec. 2015
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

⇒ **35.8 kg of enr. detectors**





Status of Phase II data-taking

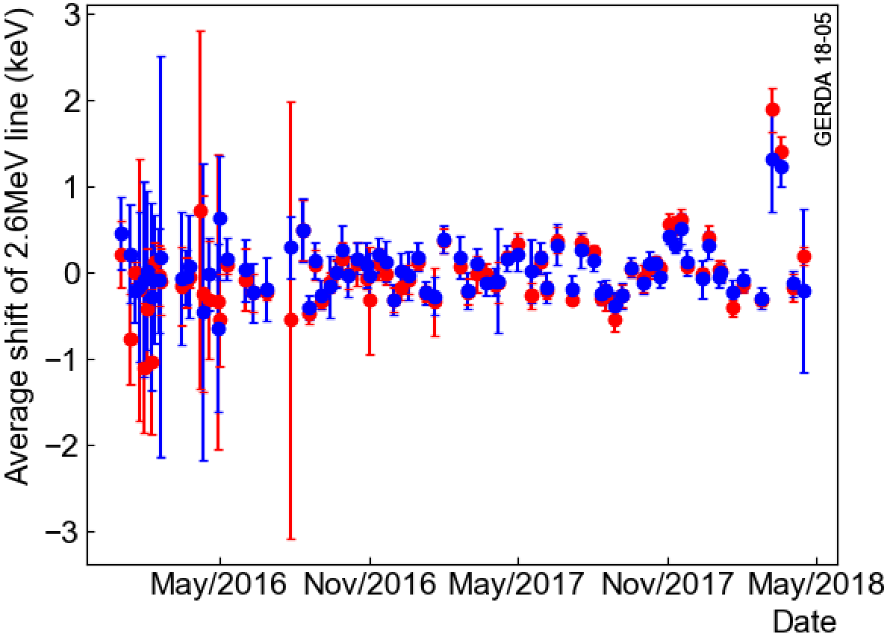


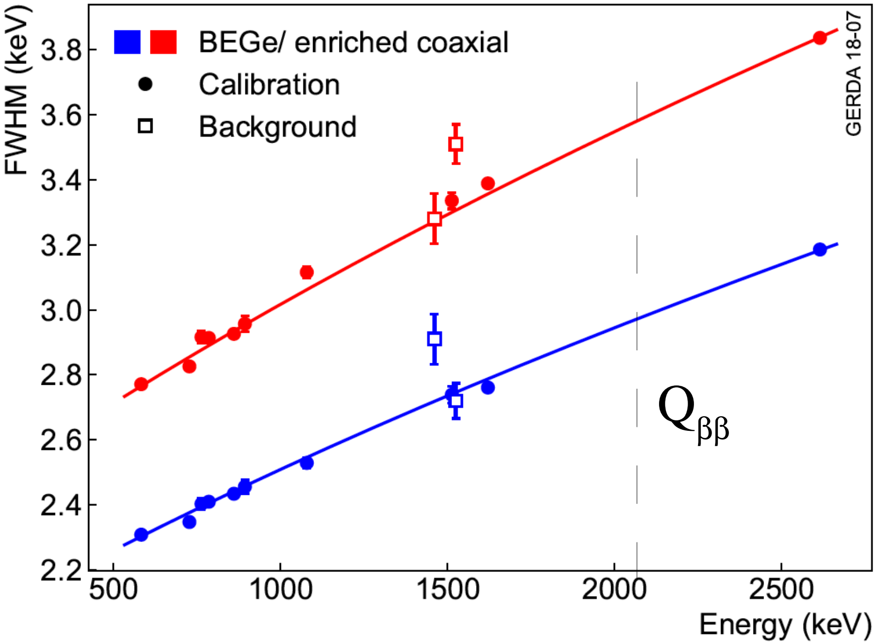
Data taking:

- ◆ new data release this year: **35.7 kg·yr** BEGe and Coax data
- ◆ **58.9 kg·yr** exposure for the entire Phase II
- ◆Total exposure analyzed: **23.5** (Phase I) + **58.9** (Phase II) **= 82.4 kg·yr**
- ◆ blinded box of ± 25keV around $Q_{\beta\beta}$

Energy scale and resolution

- weekly ^{238}Th calibrations
- comparison with ^{42}K, ^{40}K peaks in physics data
- energy reconstructed with “zero area cusp” filter **[EPJC 75 (2015) 255]**
- energy scale monitored with pulser
- ≤ 1 keV changes between successive



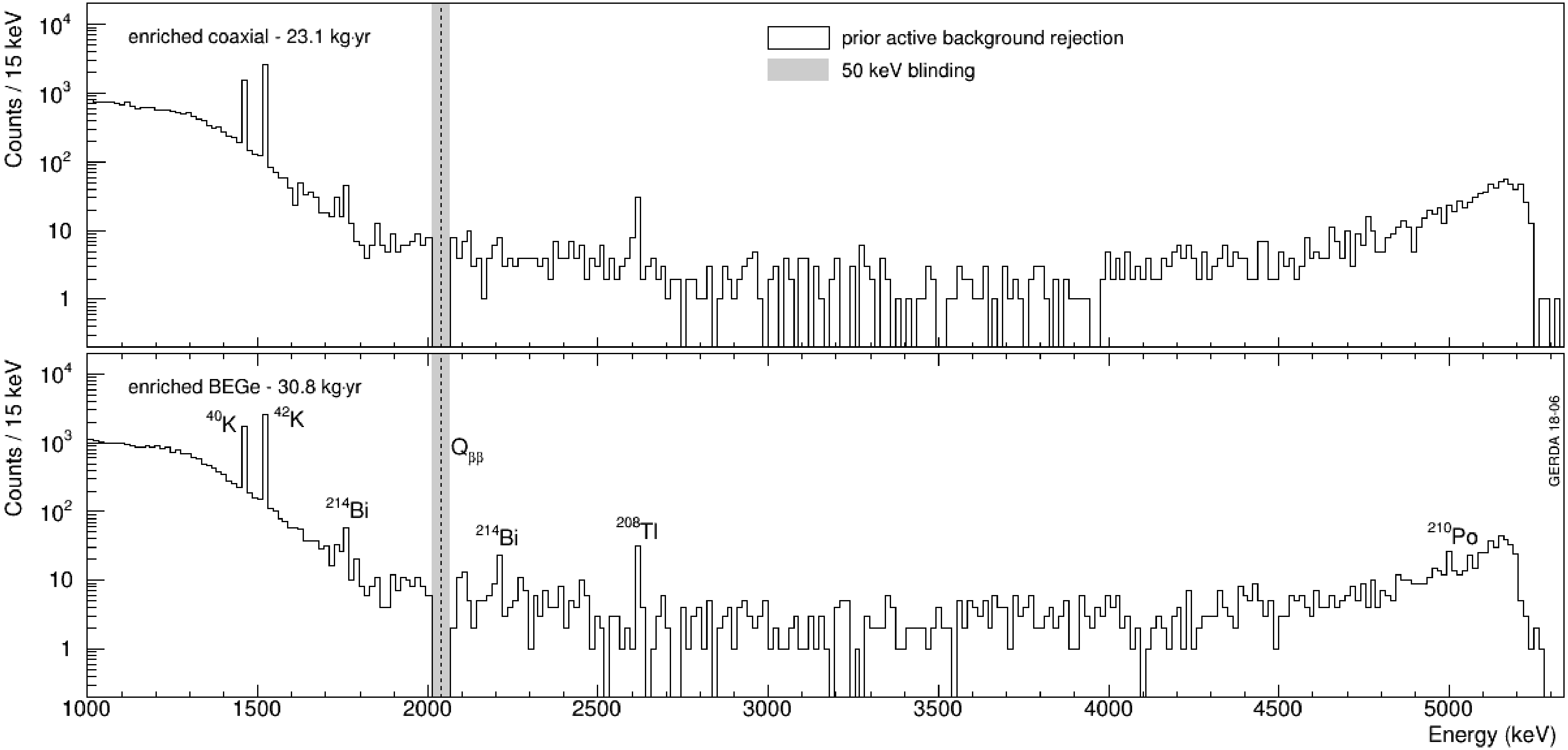


- data removed from $0\nu\beta\beta$ analysis if energy scale uncertain

Performance on full physics data set

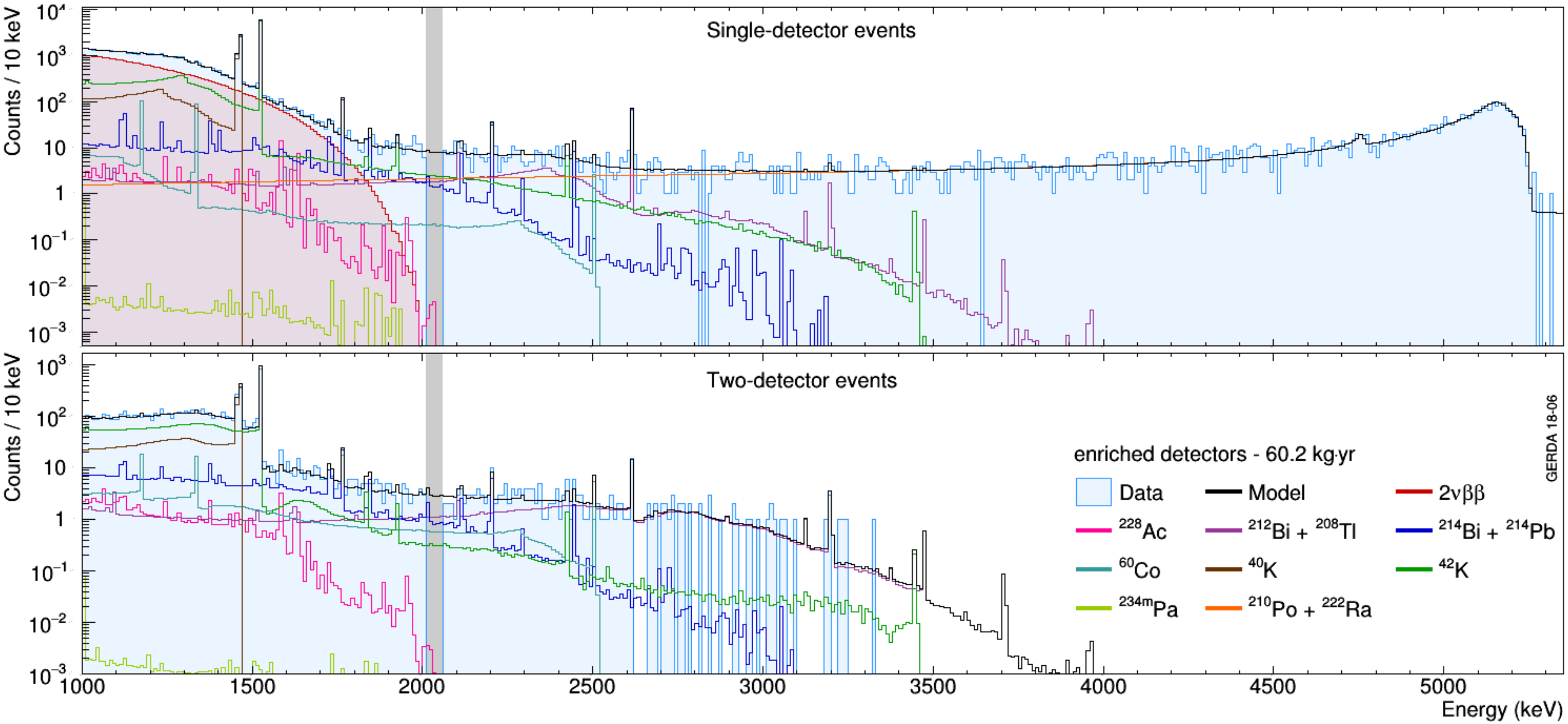
dataset	energy resolution (FWHM at $Q_{\beta\beta}$)
coaxial	**3.6 (1) keV**
BEGe	**3.0 (1) keV**

Phase II GERDA spectra



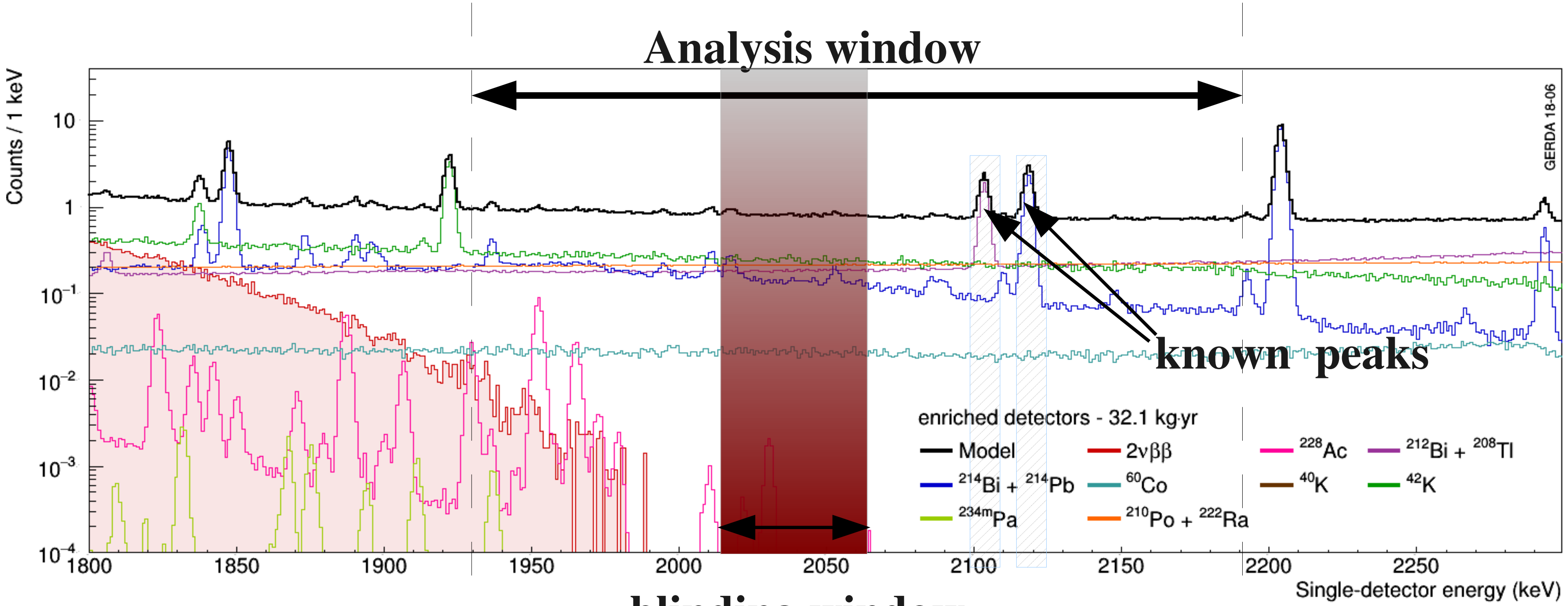
- Spectra after **quality cuts**, **Muon Veto cut** and **AntiCoincidence cut**
- Most prominent feature: 2νββ, ^{42}K and ^{40}K γ lines, α in the high energy part of the spectrum

Background model for Phase II data



- full GERDA experimental setup is reproduced in a GEANT4 framework
- bkg contaminations: 2νββ in the enriched detectors , ^{42}K in LAr, ^{40}K, ^{232}Th, ^{238}U decay chains, ^{60}Co in detector holders, cables, electronic components, LAr instrumentation …
- PDFs built from the MC output and used later in the fits
- Runtime ON/OFF detectors and run livetimes are taken into account
- Both anti-coincidence and coincidence spectra simultaneously taken into account
- Bayesian statistical analysis fits
- Known inventory screening used as priors

Background Model: Predictions



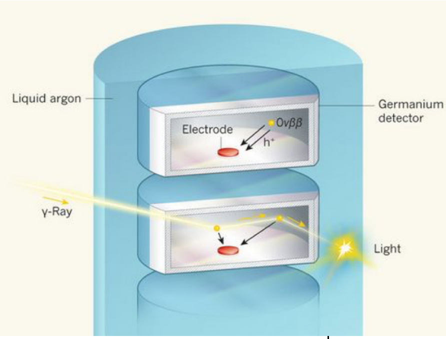
Analysis window

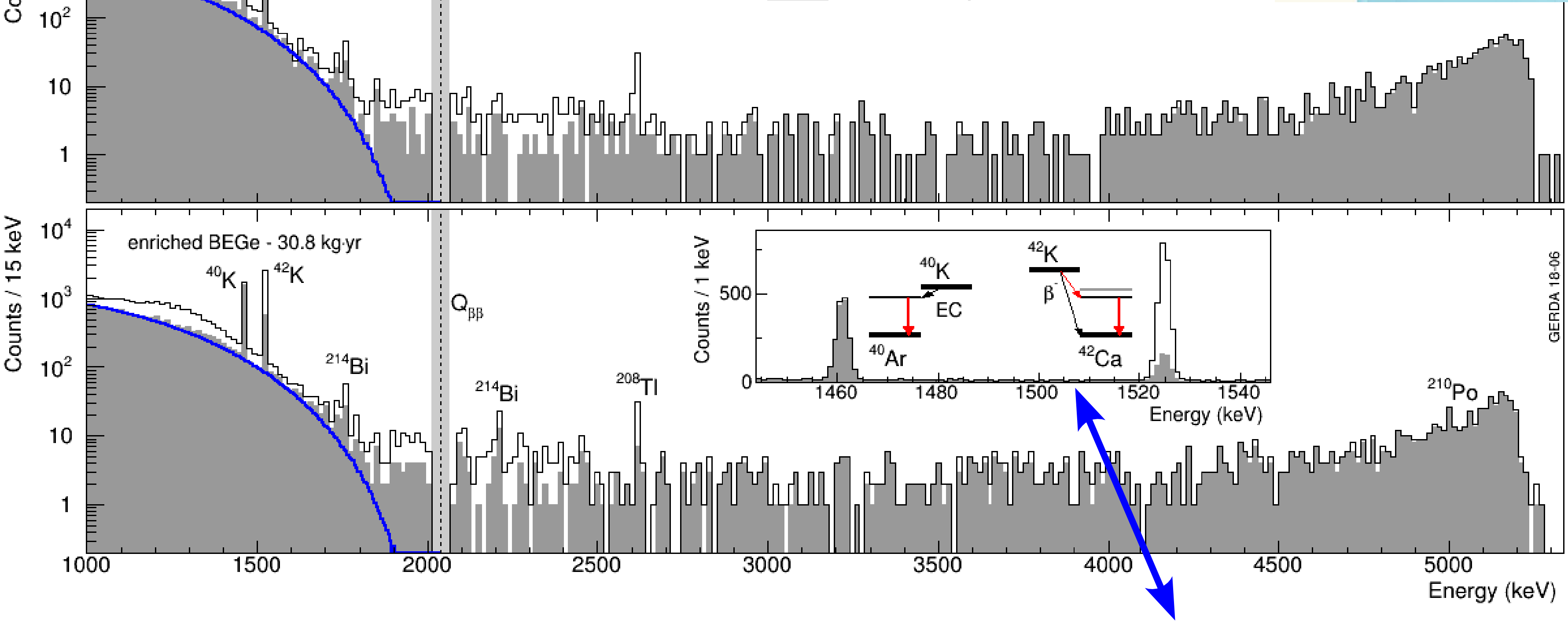
known peaks

blinding window

- ➢The background model confirms the **flatness of the background around the ROI** and in the analysis window as in Phase I
- ➢The expected spectrum is roughly composed in almost equal percentage of : events from α, e^- from ^{42}K and γ coming from ^{212}Bi + ^{208}Tl and ^{214}Bi + ^{214}Pb as in Phase I
- ➢Use the same **analysis window** as in Phase I
  - ●1930 – 2190 keV excluding the interval 2104 ±5 keV and 2119 ±5 keV of known peaks

LAr veto background suppression





- ^{40}K/^{42}K Compton continuum mostly suppressed
- $T^{2\nu}_{1/2} = 1.9 \cdot 10^{21}$ yr taken from Phase I

[EPJC 75 (2015) 416]

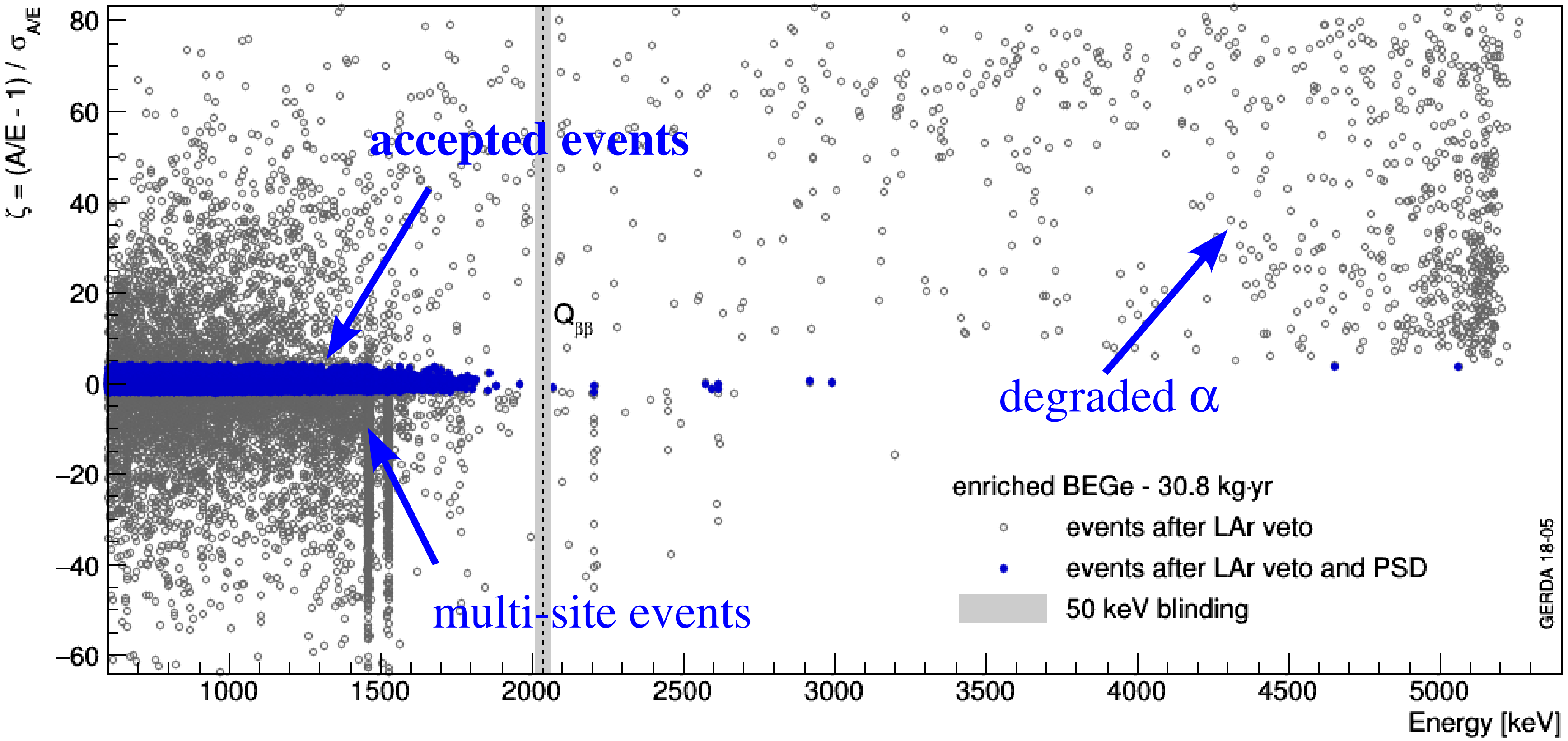
γ-lines from:

$^{40}K \rightarrow {}^{40}Ar + \gamma$ (1.4 MeV) [EC]

$^{42}K \rightarrow {}^{42}Ca + \gamma$ (1.5 MeV)

+ e- (up to 2 MeV)

Pulse Shape Discrimination: BEGe



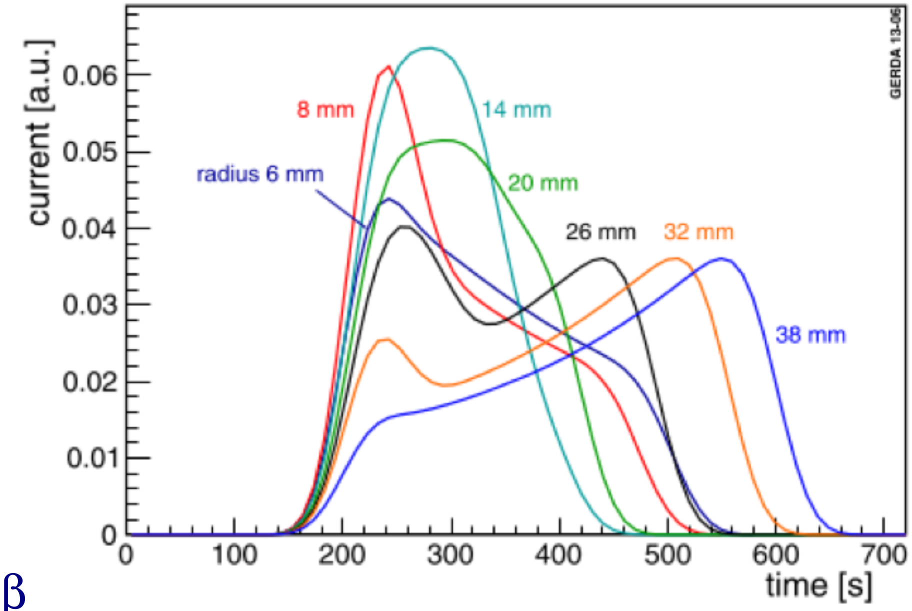
- ➢Event-by-event selection
- ➢Acceptance for 0νββ events: **(87.6 ± 2.5)%**
  - ◆ estimated from ^{208}Tl DEP
  - ◆ double checked at low energy with 2νββ events (after LAr cut): (85.4 ± 1.9)%

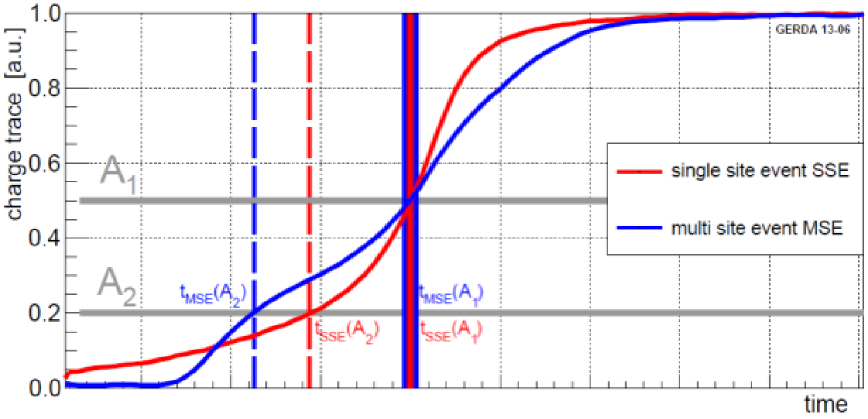
A/E method

Pulse Shape Discrimination: Coax

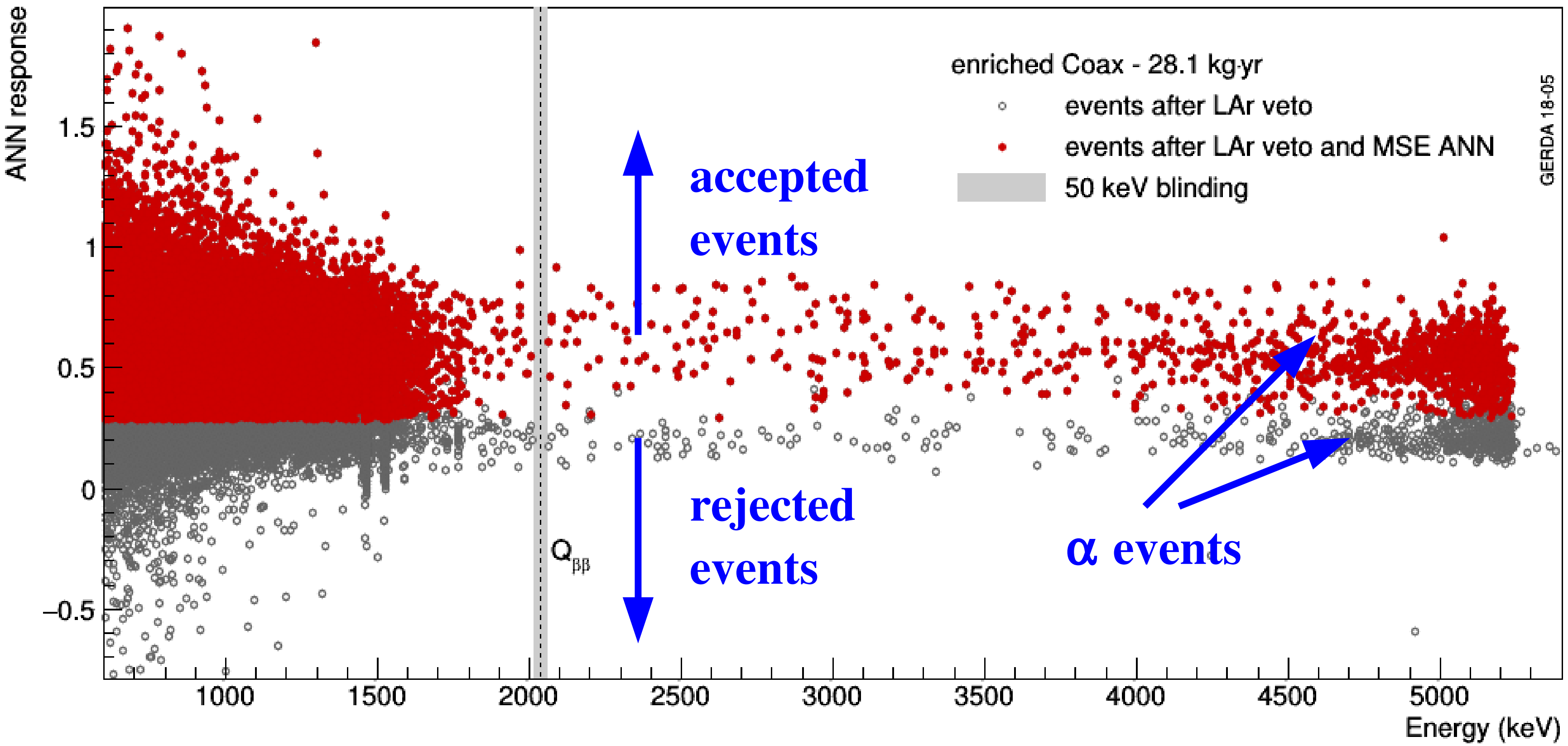
- PSD for Coax detectors less effective than for BEGes
- Artificial Neural Network (ANN) as in Phase I:
  - Trained on signal (SSE): ^{208}Tl (2614 keV) DEP at 1592 keV
  - Background (MSE): ^{212}Bi @ 1620 keV γ-line
  - Acceptance for 0νββ events (**84±5**)%
    - Double check with Compton edge and 2νββ events
    - MC simulation of waveforms

Current Pulses for SSE





Pulse Shape Discrimination: Coax



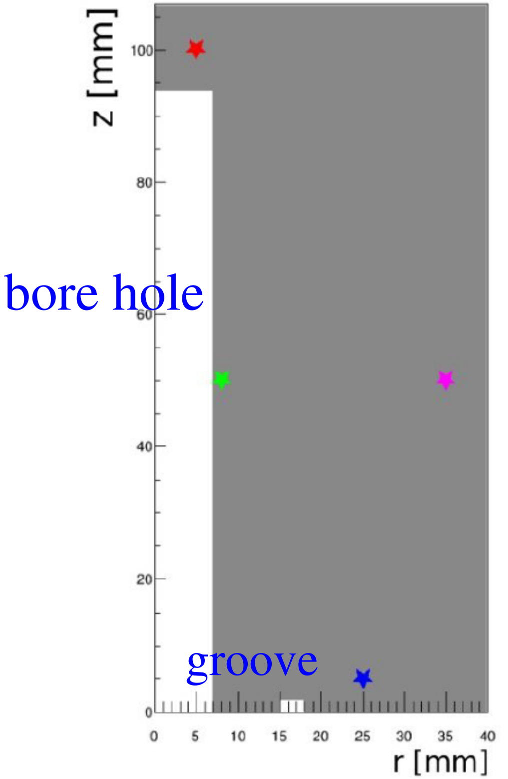
- Acceptance for 0νββ events (**84 ± 5**)%
  - MC simulation of waveforms
  - Double check with 2νββ events

ANN method for MSEs

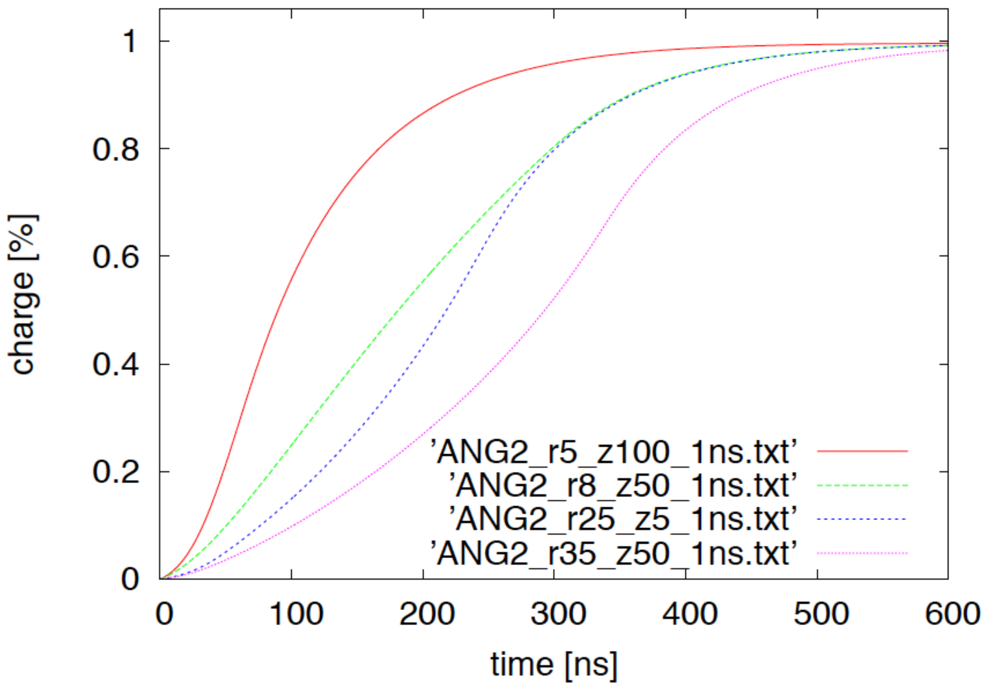
Pulse Shape Discrimination: Coax

- New rejection method for **α events** based on their (fast) **rise time**

coaxial detector

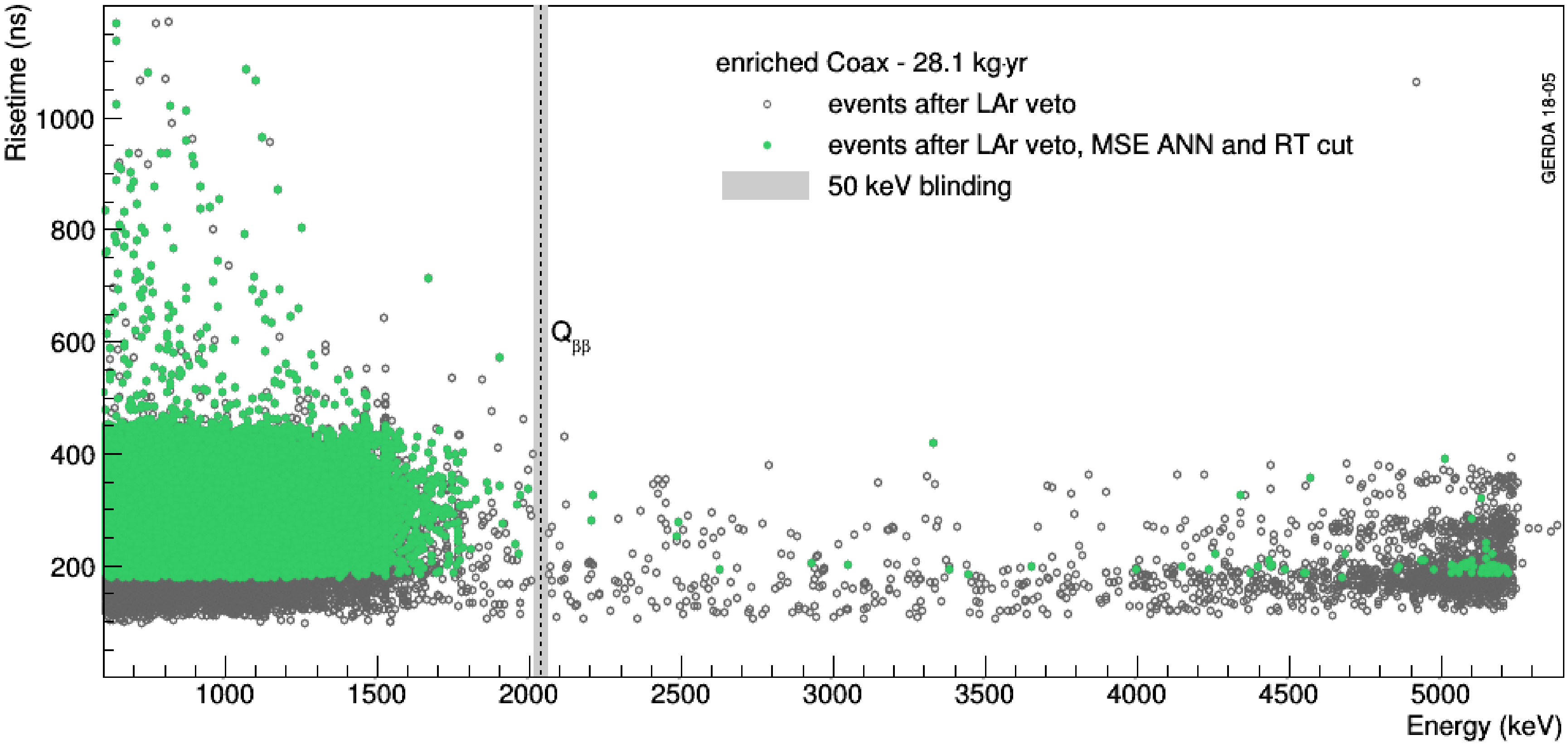


MC simulation



- Events with **rise time** (10%-90% of the rising part the pulse) faster than 180-220 ns (depending on specific detector) are rejected as **α events**

Pulse Shape Discrimination: Coax

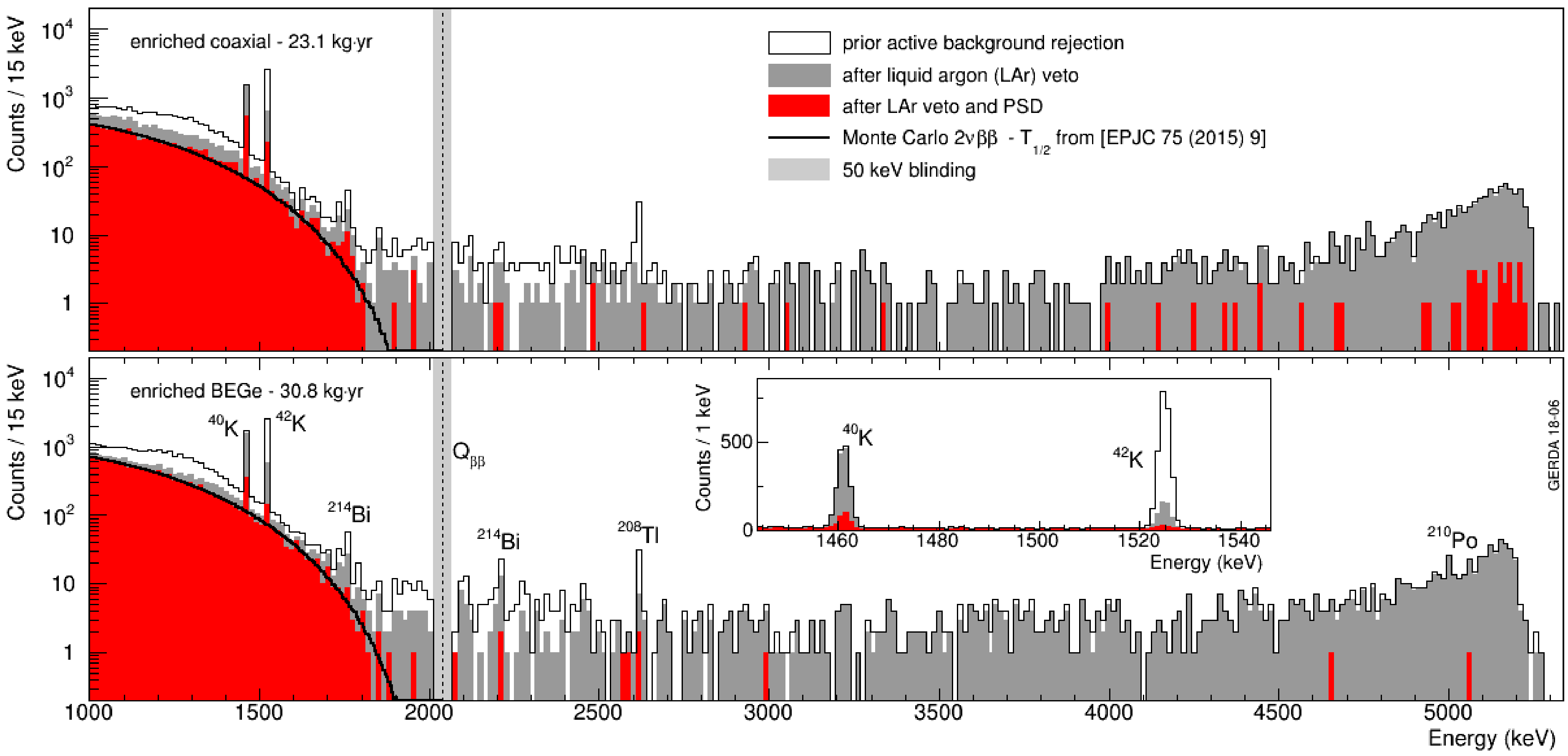


RT method

for α events

- **RT Acceptance** for 0νββ events (**85 ± 1**)%
  - estimated from 2νββ events
- **Total acceptance** (ANN and RT) for 0νββ events : (**71 ± 4**)%

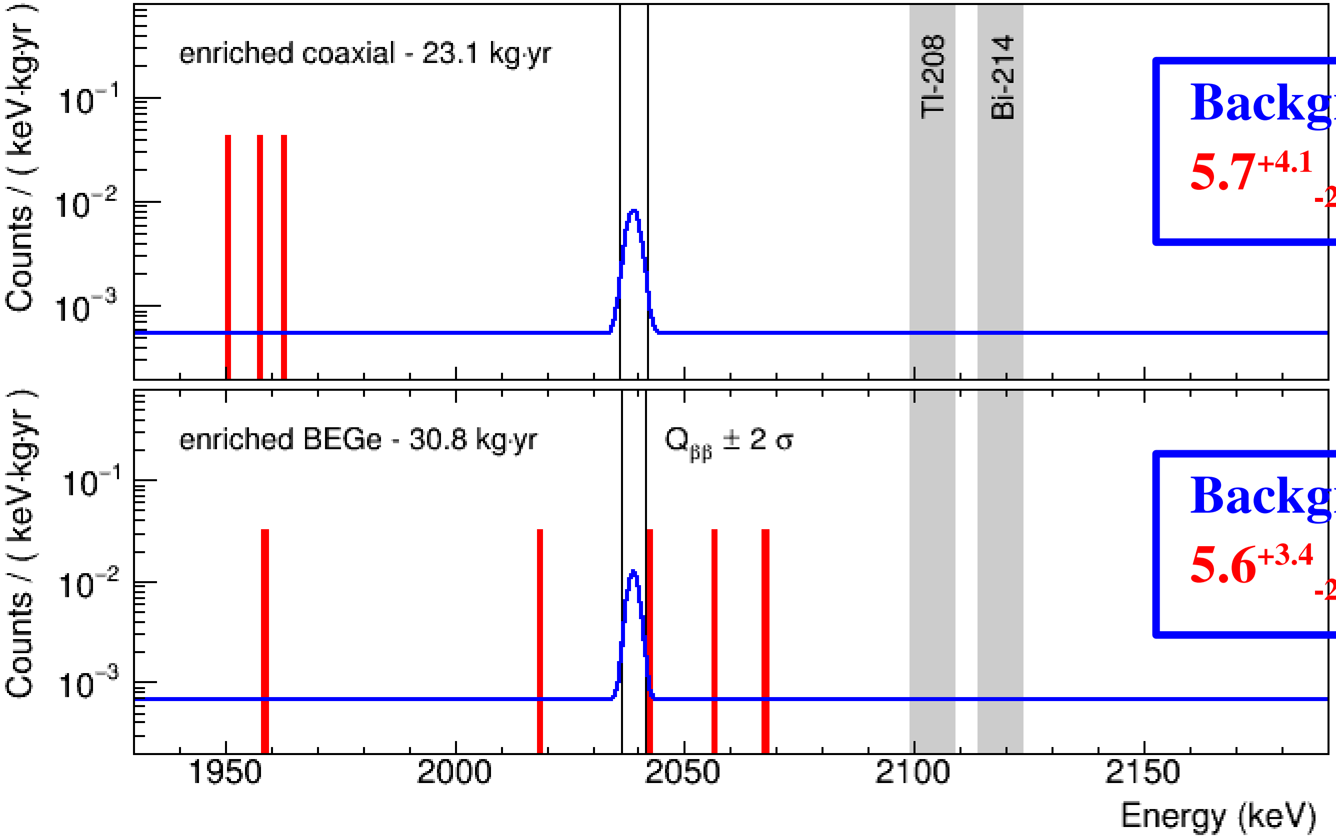
GERDA spectra after LAr cut + PSD cut



- LAr and PSD highly effective cuts

Spectra in the ROI

Analysis window

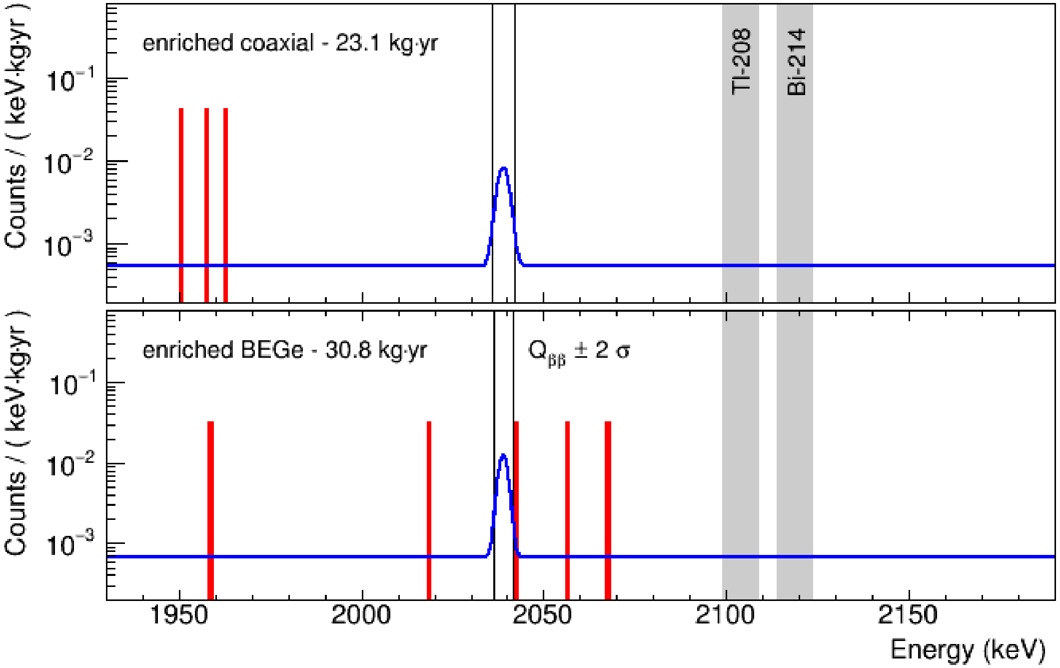


Background Index:
$5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)

Background Index:
$5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)

- **Lowest bkg in the ROI respect to all experiments using other isotope**

Statistical Analysis



- **Frequentist (preliminary results):**

  Best fit $N^{0\nu} = 0$

  $\boldsymbol{T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}}$ **yr @ 90% C.L.**

  Median Sensitivity (NO Signal)

  $\boldsymbol{T^{0\nu}_{1/2} > 1.1 \cdot 10^{26}}$ **yr @ 90% C.L.**

  63% of MC realizations yield limit stronger than data

- upper limit on

  $m_{\beta\beta} < 0.11 – 0.25$ eV

- **Bayesian (preliminary results):**

  $\boldsymbol{T^{0\nu}_{1/2} > 0.8 \cdot 10^{26}}$ **yr @ 90% C.I.**

  Median Sensitivity:

  $\boldsymbol{T^{0\nu}_{1/2} > 0.8 \cdot 10^{26}}$ **yr @ 90% C.I.**

  59% of MC realizations yield limit stronger than data

GERDA: the end

- At the end of 2019 GERDA will have collected: **100 kg·yr** of exposure @ **BI = 10^{-3} cts/(keV·kg·yr)**
- **Sensitivity**: **1.4·10^{26} yr**
- **Discovery potential up to 10^{26} yr** (*50% prob. chance for a 3σ signal*)

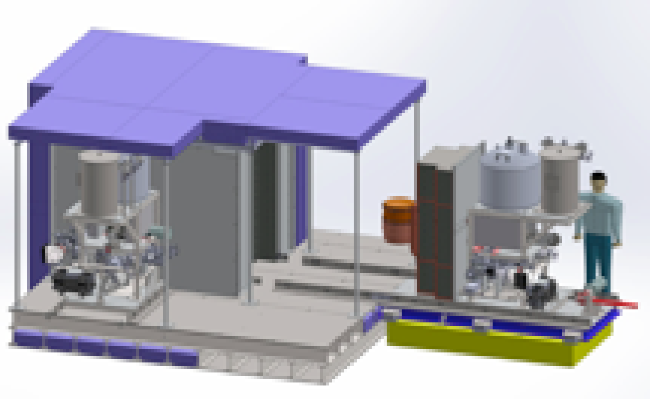
What next ?

The ^{76}Ge experiments: GERDA & MJD

GERDA

- Bare ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon/H_2O
- Phase I: 17 kg (HdM/IGEX)
- Phase II: 35.8 kg enriched in ^{76}Ge

MAJORANA-DEMONSTRATOR (MJD)



- Arrays of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper/lead
- 30 kg enriched in ^{76}Ge

➢ **Physics goals**: degenerate mass range

➢ **Technology**: study of backgrounds and exp. techniques

◆ exchange of knowledge & technologies (e.g. MaGe MC)

◆ intention to merge for future large scale ^{76}Ge experiment selecting the best technologies tested in GERDA & MJD

Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay - LEGEND

250 members, 51 institutions, 16 countries

Collaboration formed in October 2016

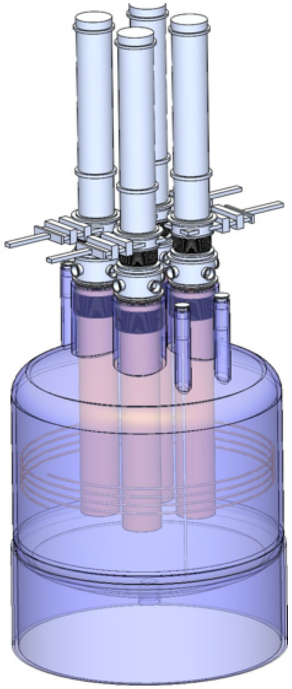
LEGEND mission:

“The collaboration aims to develop a phased Ge-76 based double beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results”

LEGEND: a staged approach

First Stage:

- upgrade of the existing infrastructure of GERDA up to 200 kg
- reduction of the BI of a factor 3-5 w.r.t. GERDA Phase II
- to reach 200 kg: 35 kg from GERDA + 30 kg from MJD. The remaining has to be bought.

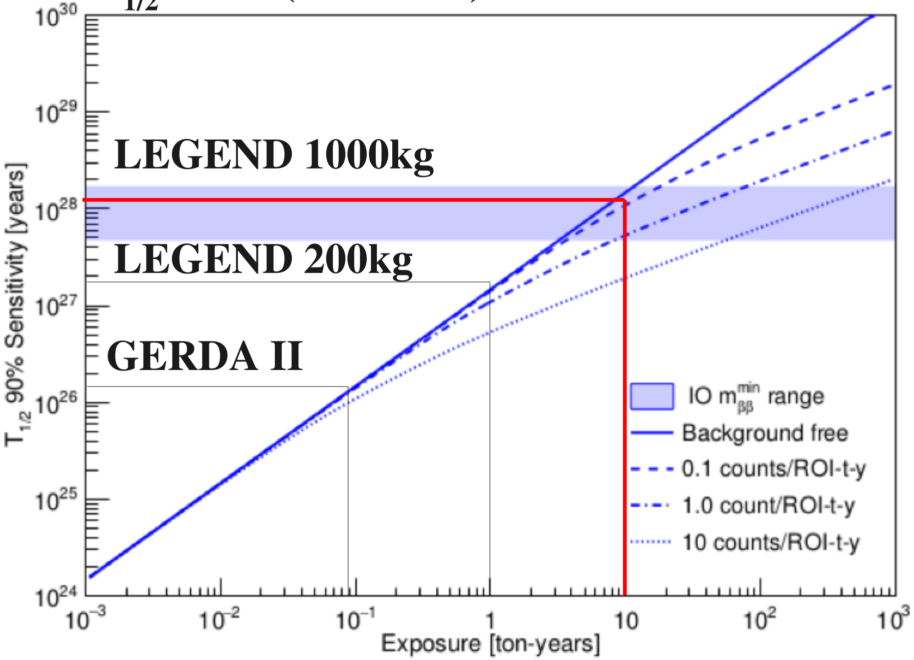


Further Stages:

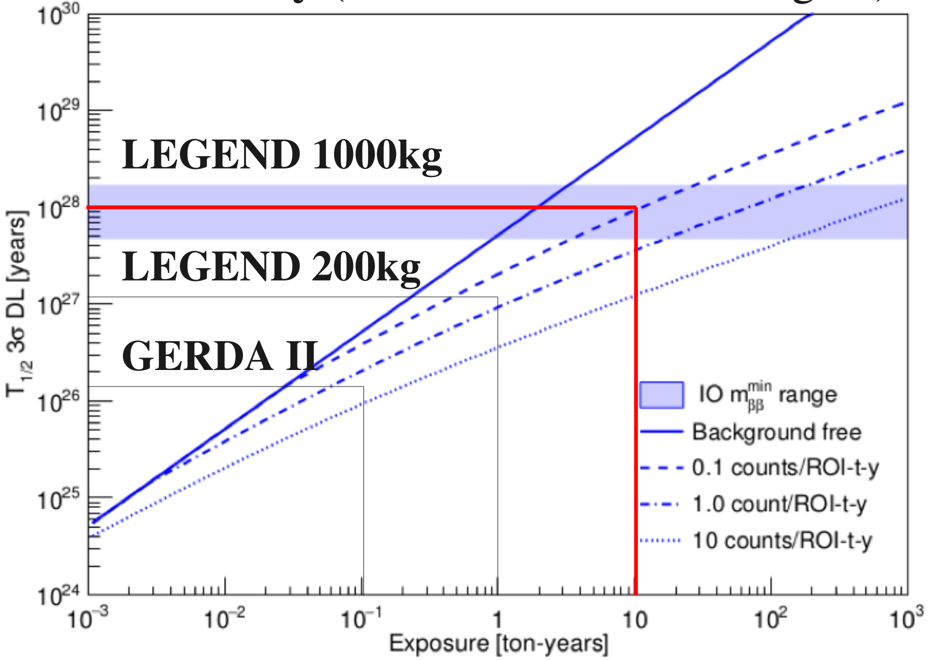
- 1000 kg (staged)
- timeline connected to DOE down selection process
- Background reduction of a factor 30 w.r.t. GERDA
- Location to be defined
- Required depth (Ge-77m) under investigation. LNGS could be a solution

LEGEND: sensitivities for limit setting and discovery

$T_{1/2}$ limit (90% CL)



Discovery (50% chance for a 3σ signal)



Plots details:

- 60% efficiency (including: isotopic fraction, active volume fraction, analysis cuts)
- GERDA II: 3 counts/(ROI·ton·yr)
- LEGEND-200: 0.6 counts/(ROI·ton·yr)
- LEGEND-1000: 0.1 counts/(ROI·ton·yr)

N.B.: **background-free condition is a prerequisite for a discovery**

Next step: LEGEND-200 @ LNGS

- Cryostat neck inner diameter enlarged to 610 mm
- **Larger Ge detectors with BEGe/PPC-like performances**
- Improve **LAr optical purity** (light yield, attenuation length)
- **Improve LAr light detection (readout also between strings)**
- Background **reduction by a factor 3-5** w.r.t. GERDA Phase II
- GERDA Phase II will continue the data taking **until 2019**
- **LEGEND-200 will start 1.5 years later**
- Fully funded

GERDA upgrade (1)

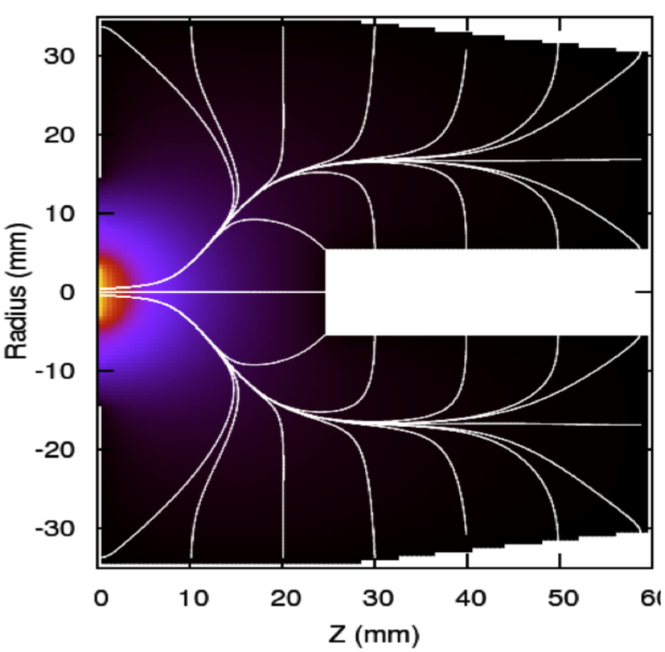
- In **Spring 2018** made an upgrade of the apparatus
- Main aim: **help the transition** from **GERDA** to **LEGEND-200**

Work done:

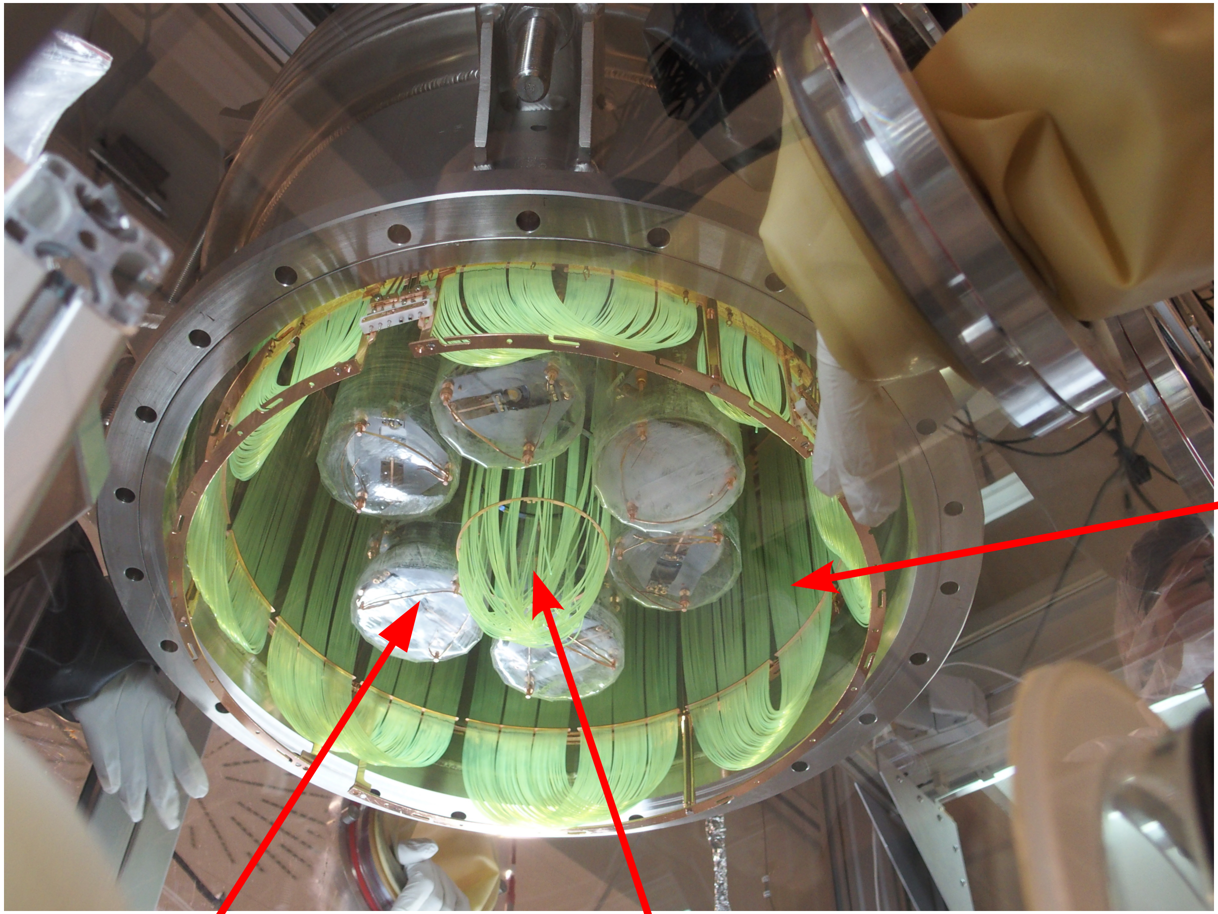
- **new enriched inverted coaxial detectors (9.5 kg)** in place of the natural coaxial detectors. (but 1 enriched coaxial subtracted, so the increase in mass is of ~ **8.5 kg**).
- **new fiber curtain** with a factor 2 increase in light yield + **new fiber curtain around the central string**
- **repairs** of some broken JFET + some holders modification (from single to double configuration)
- installation of **protecting diodes** in the FE cards
- **exchange of the HV and signal cables** with cables having lower radioactivity budget + **re-routing of the HV and signal cables**

GERDA upgrade (2)

- **5 Inverted-coaxial point contact (ICPC) detector** (total mass: 9.5 kg)
- Same **energy resolution** and similar **PSD** properties of the BEGe detectors
- But **higher masses (~1.8 kg)** than those of BEGe (~0.7 kg)
- Then less cables, less FE channels ⟶ **less background** ⟶ **better BI**
- **These are the detectors much probably chosen for LEGEND-200**



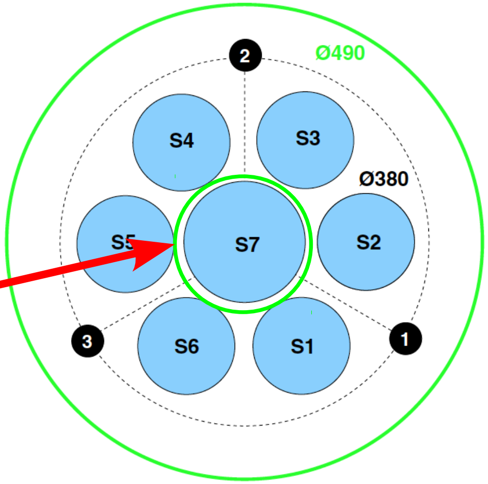
Gerda upgrade (3)



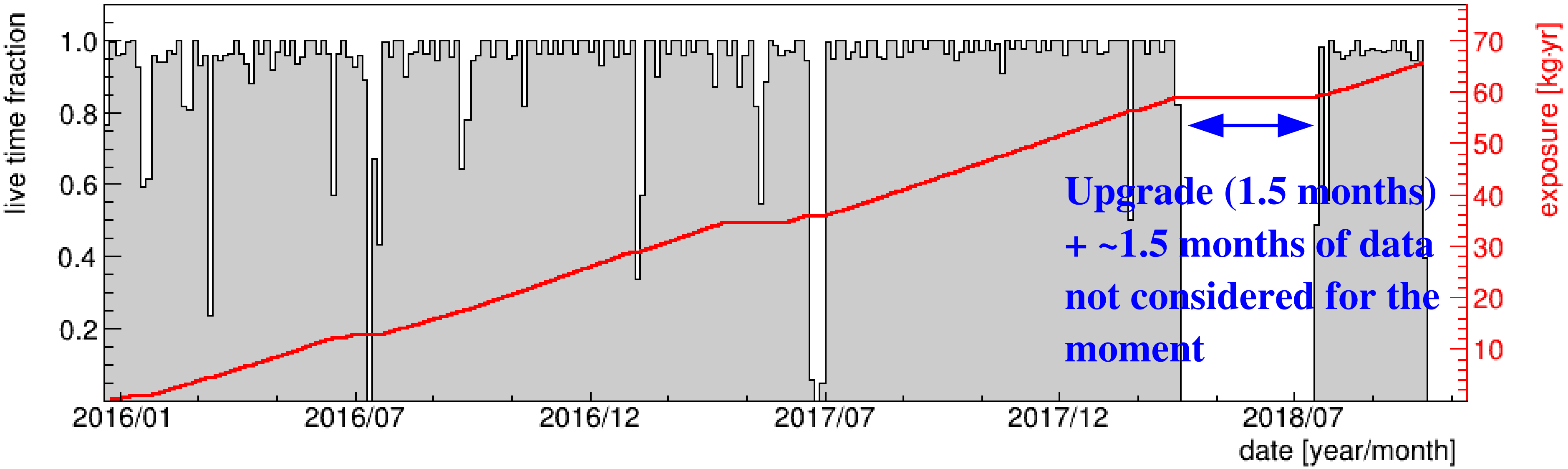
fiber shroud

detectors string

central fiber shroud



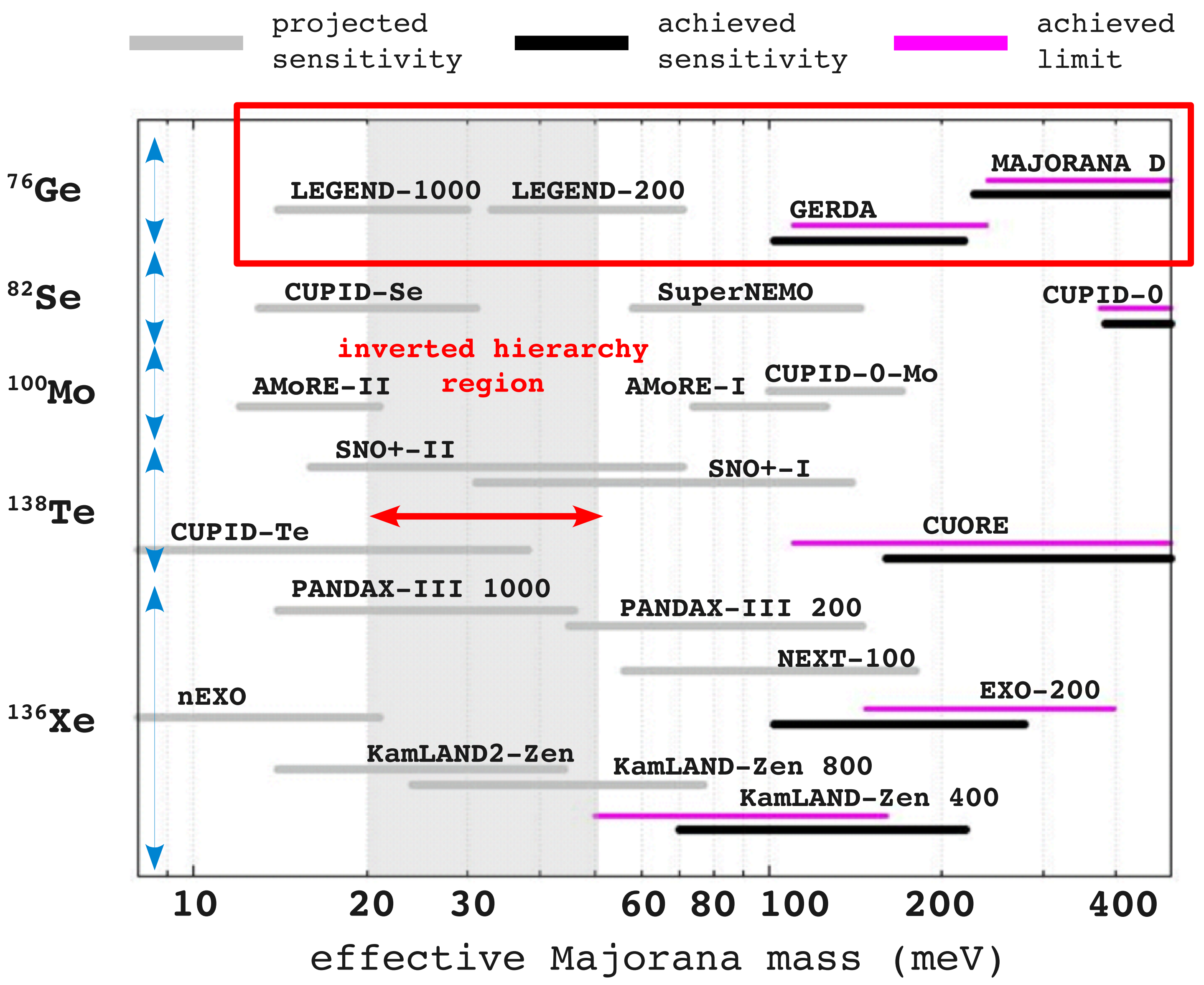
Restart of the data taking



Upgrade (1.5 months) + ~1.5 months of data not considered for the moment

- Data taking resumed immediately after the end of the upgrade works
- First runs are not taken into account, for the moment.
- From 18/07/2018 data taking sufficiently stable.
- Live time fraction: 95.2 %
- But various detectors are not working well and are used in anticoincidence mode (of which **1 Inverted Coax**)
- We hope to improve the situation
- In any case the rate **kg·yr/day** is now slightly better than before the upgrade

Present status and future perspectives for m_{ee}



LEGEND Collab.
already formed

LEGEND-200
will start at LNGS
in 2021:
200 kg of ^{enr}Ge
detectors in the
GERDA setup

Summary

- Believing in the existence of $0\nu2\beta$ is a prejudice, but I bet it exists
- Neutrinos are shy, but kind (e.g. LMA, θ_{13}, δ_{CP}): discovery may be around the corner
- Lepton number conservation is not experimentally proved
    - The $0\nu2\beta$ is the main way to look for $\Delta L = 2$
    - Could help to explain matter/antimatter asymmetry
- $0\nu2\beta$ only way to determine the neutrino nature
- GERDA has demonstrated that Ge detectors
    - are based on a **well-known technology**
    - have the **best energy resolution**
    - have the **lowest background in the ROI**
    - have the **best sensitivity**
    - allow a **flat background around the ROI**
- **LEGEND** towards 200 kg and 1000 kg Ge **formed in October 2016**
- **LEGEND-200** working hard to take data in the **middle of 2021**