14th Patras Workshop on Axions, WIMPs and WISPs
Hamburg, 18 - 22 June 2018

Riccardo Brugnera
Padova University and INFN

on behalf of the
GERDA Collaboration

Searching for neutrinoless double-beta decay with GERDA

Outline:

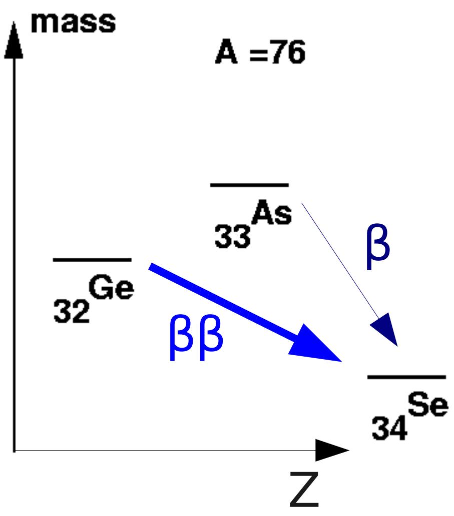
- Double Beta Decay
- GERDA design
- Results from Phase II
- Results from other experiments

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

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

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

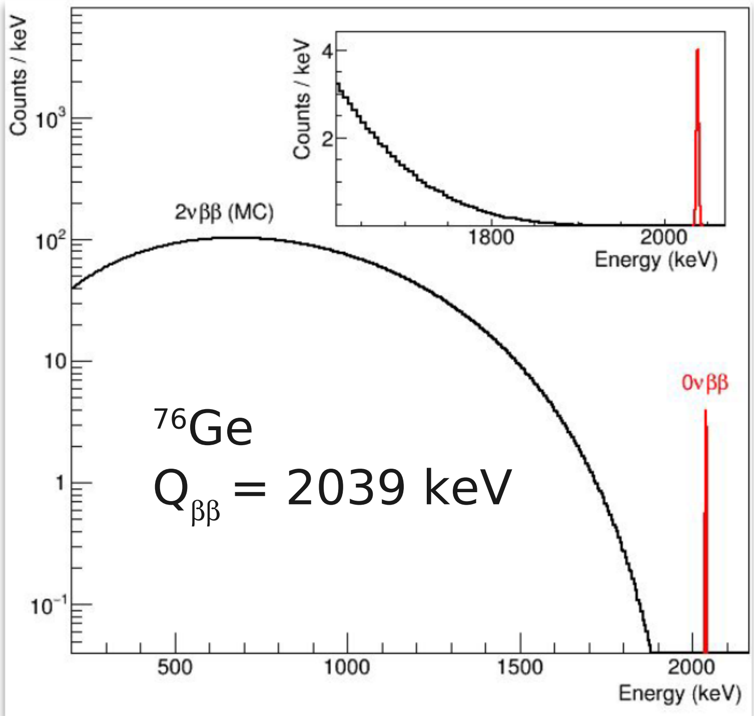
^{76}Ge: $T_{1/2} \sim 10^{21}$ yrs



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

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

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



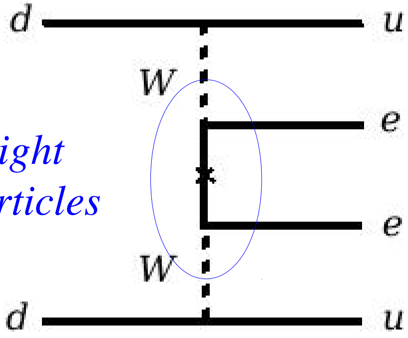
^{76}Ge

$Q_{\beta\beta}$ = 2039 keV

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

- would establish ***lepton number violation*** $\Delta L = 2$
- more ***physics beyond standard model***
- 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***

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

nuclear matrix element

phase space factor

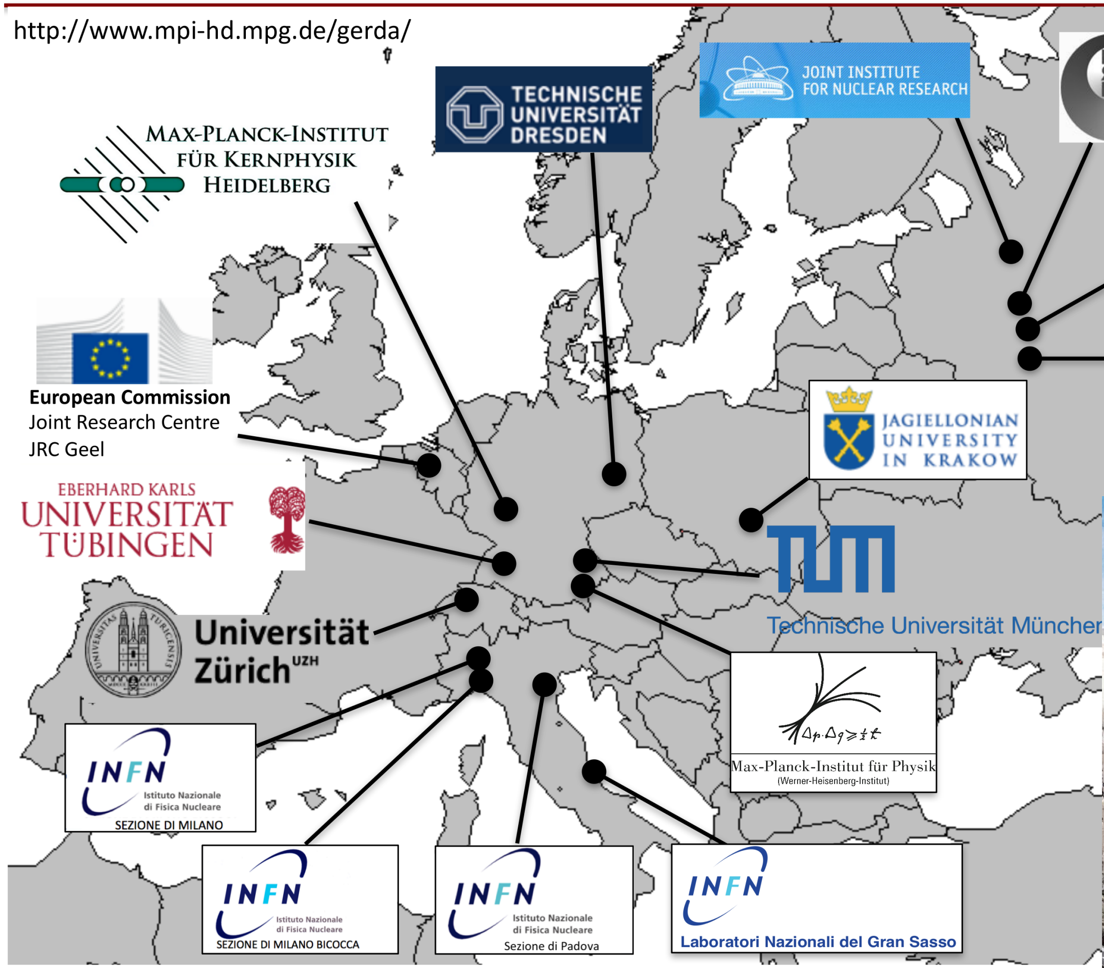
$$\langle m_\nu\rangle = \left|\sum_i U^2_{ei} m_i\right|$$

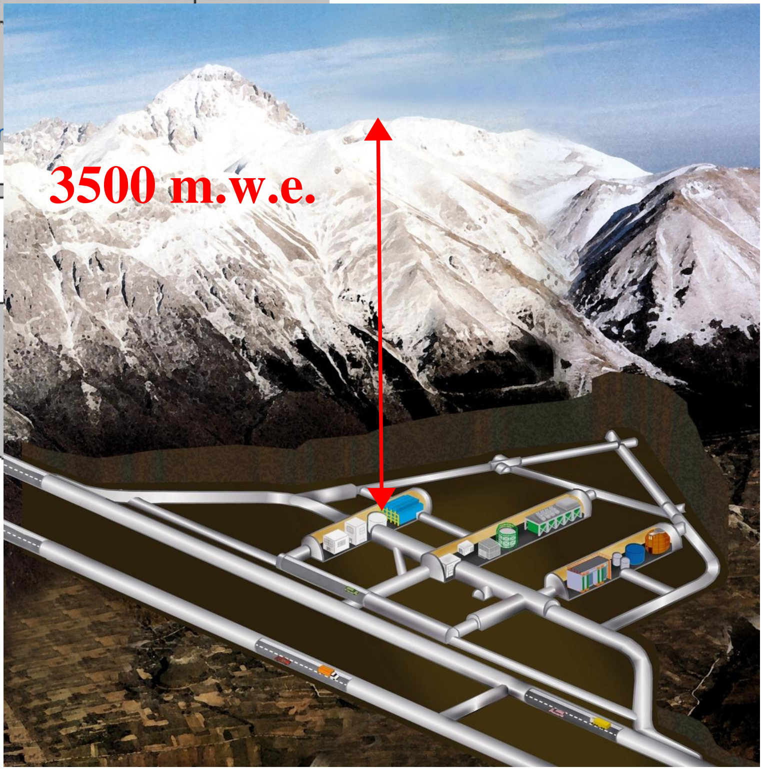
effective Majorana neutrino mass

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

The GERDA Collaboration

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

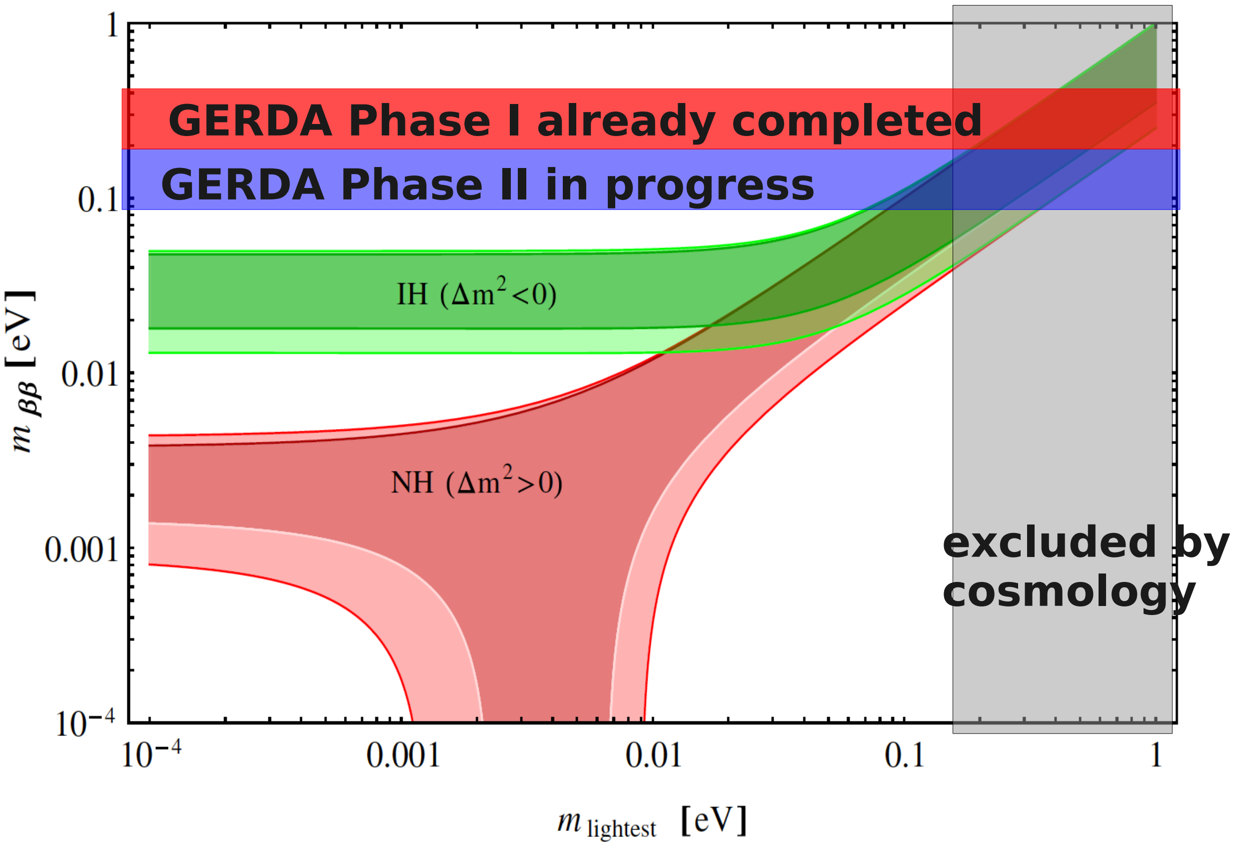




The experiment is located at the **INFN Laboratori Nazionali del Gran Sasso**, Italy below a rock overburden of ~ 3500 m water equivalent

GERDA physics goal

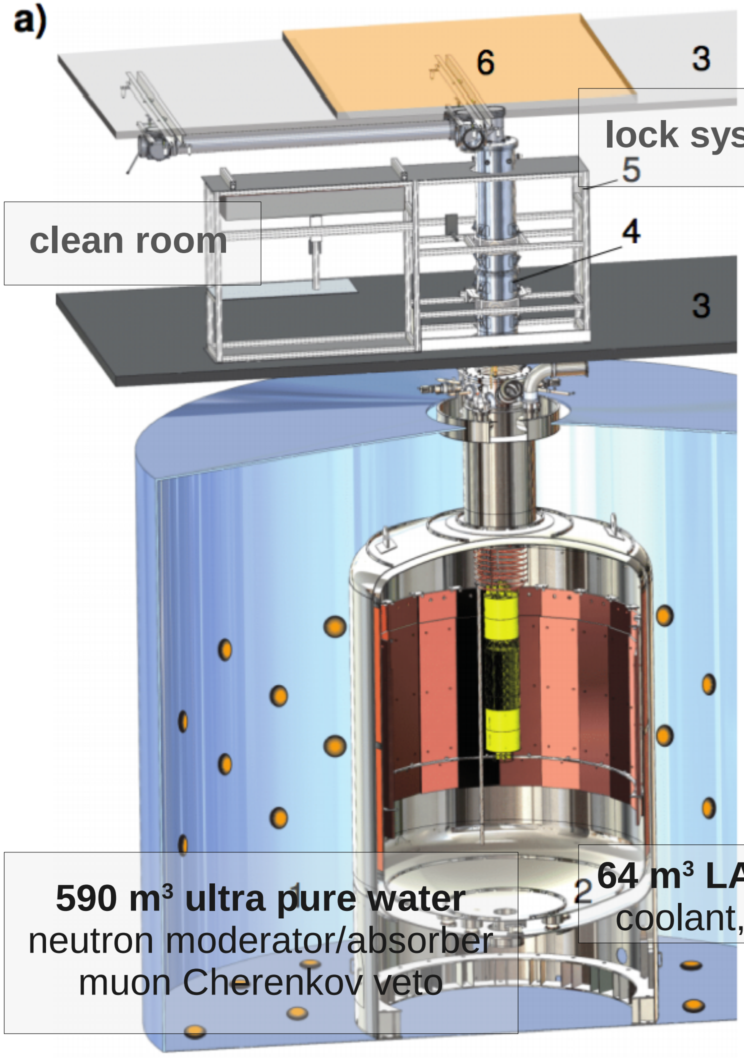
S. Dell'Oro, S. Marcocci, F. Vissani, PRD 90 (2014)



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

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

Phase I: Eur. Phys. C 73 (2013) 2330
Phase II: Eur. Phys. C 78 (2018) 388
Nature 544 (2017) 47



plastic scintillator panels
muon veto

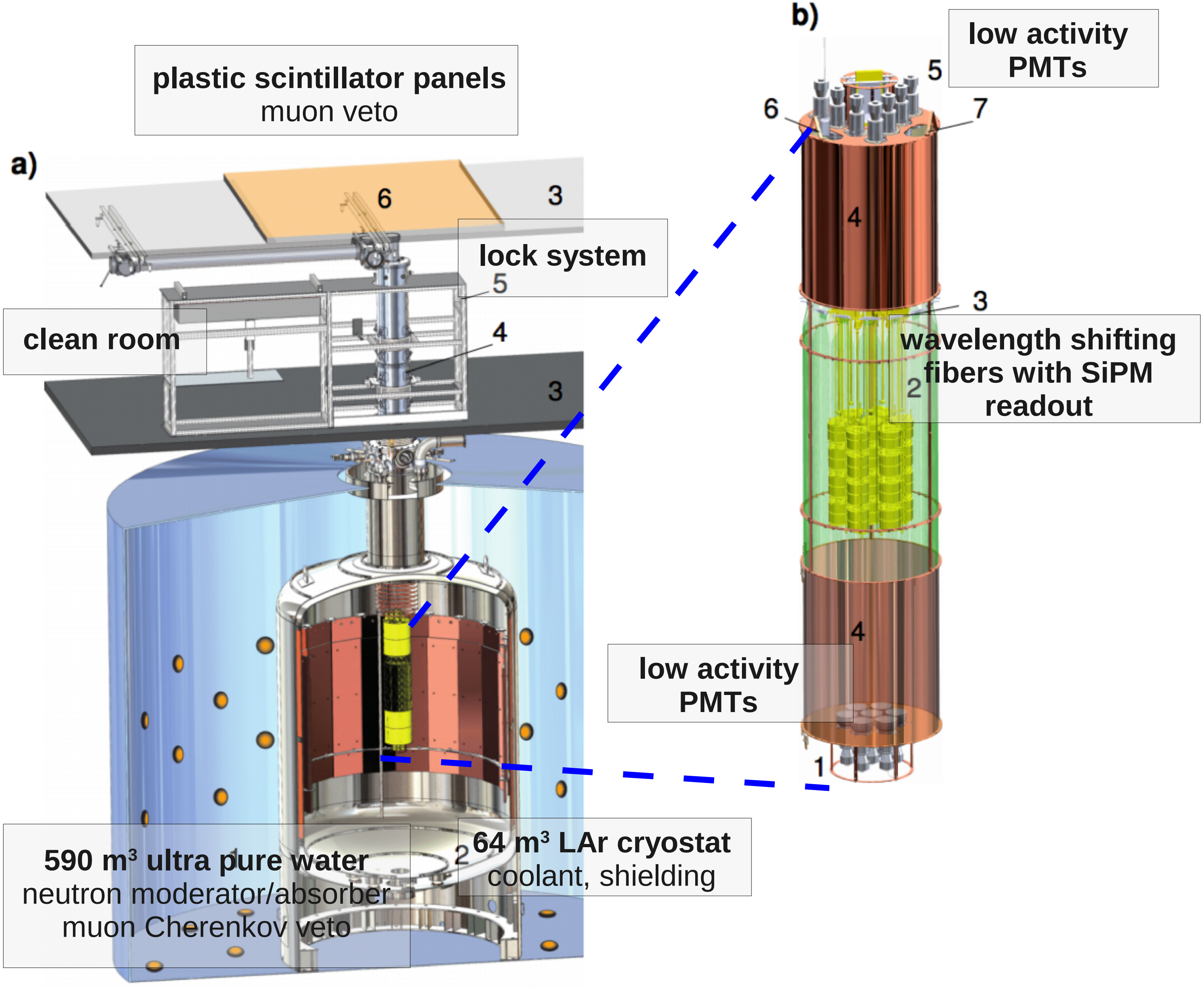
lock system

clean room

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

64 m³ LAr cryostat
coolant, shielding

a) overview



plastic scintillator panels
muon veto

lock system

clean room

low activity
PMTs

wavelength shifting
fibers with SiPM
readout

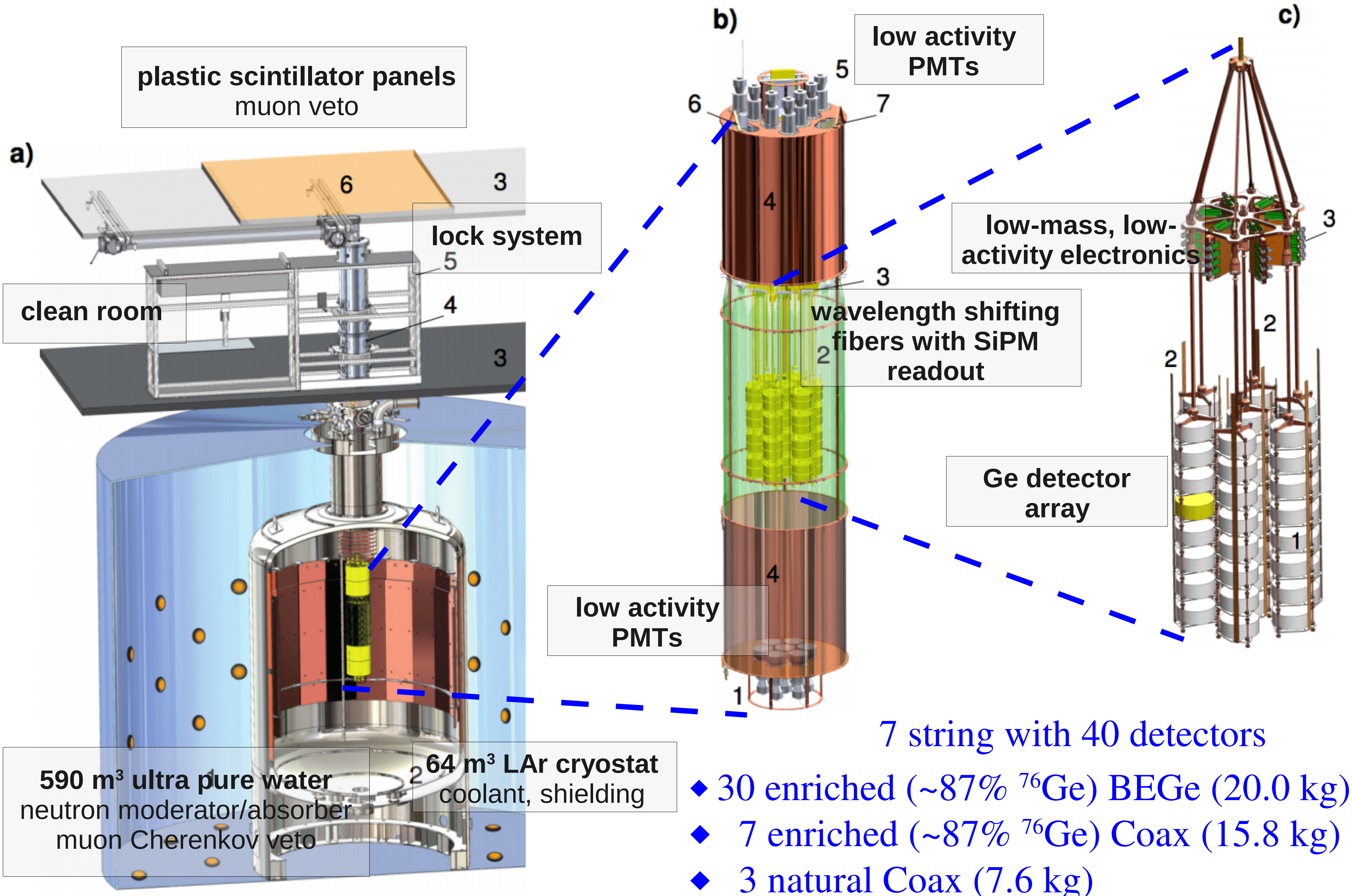
low activity
PMTs

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

64 m³ LAr cryostat
coolant, shielding

a) overview

b) liquid argon (LAr)
veto instrumentation



plastic scintillator panels
muon veto

lock system

clean room

590 m³ ultra pure water
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64 m³ LAr cryostat
coolant, shielding

low activity PMTs

wavelength shifting fibers with SiPM readout

low activity PMTs

low-mass, low-activity electronics

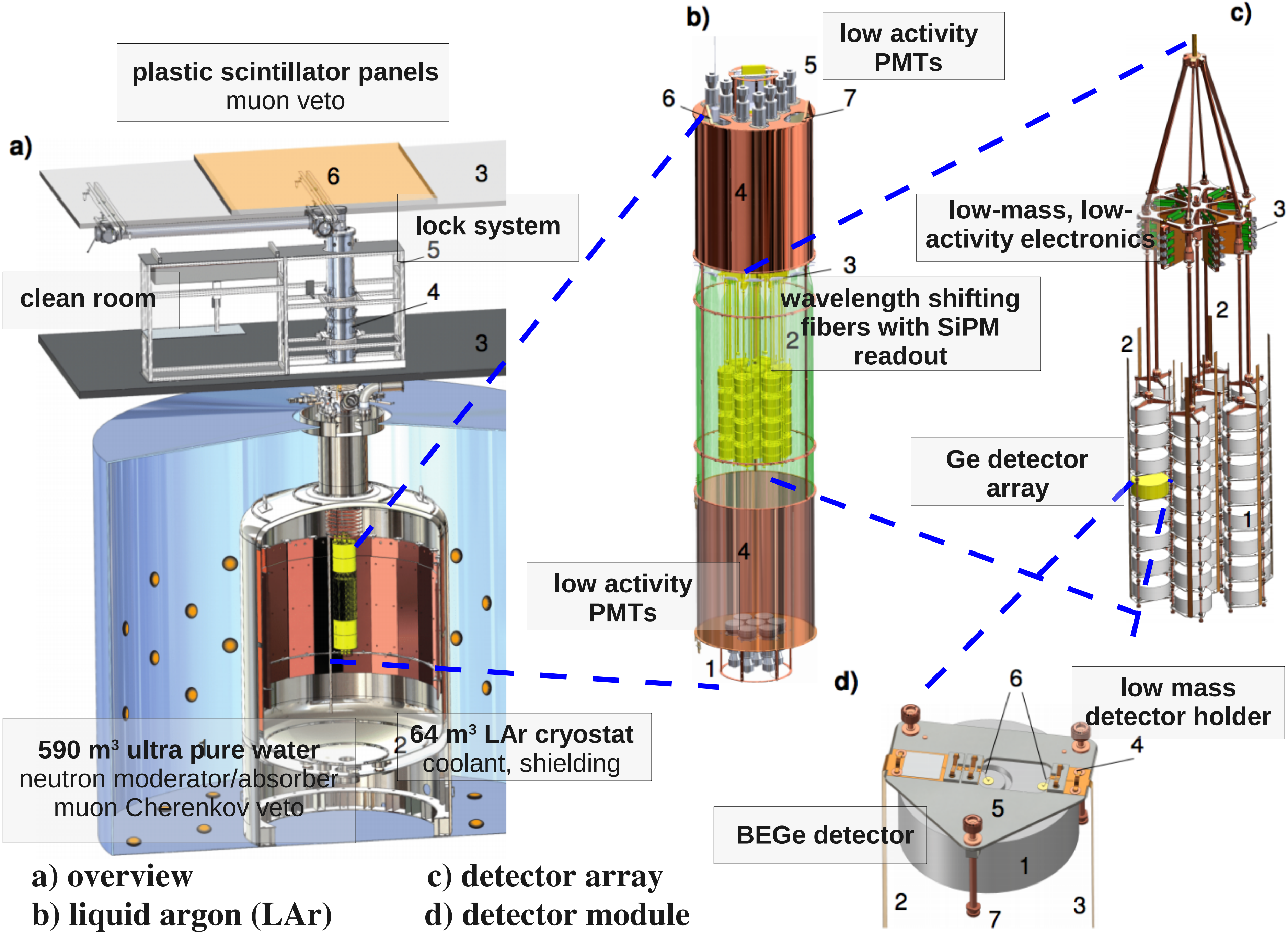
Ge detector array

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

7 string with 40 detectors

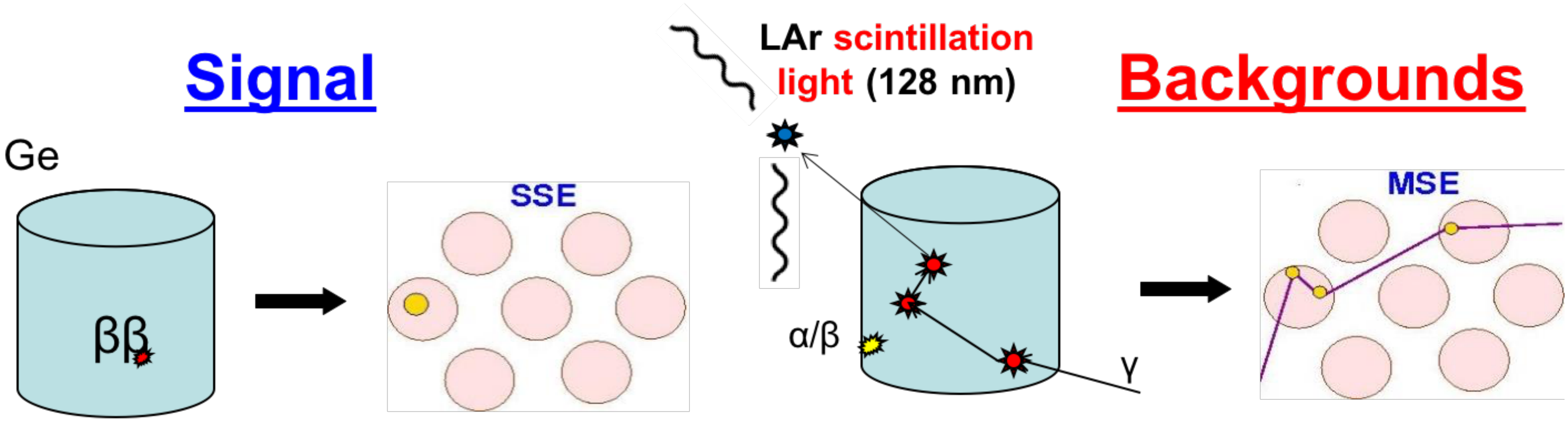
- 30 enriched (~87% ^{76}Ge) BEGe (20.0 kg)
- 7 enriched (~87% ^{76}Ge) Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

→ **35.8 kg of enr detectors**



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

Background reduction tools

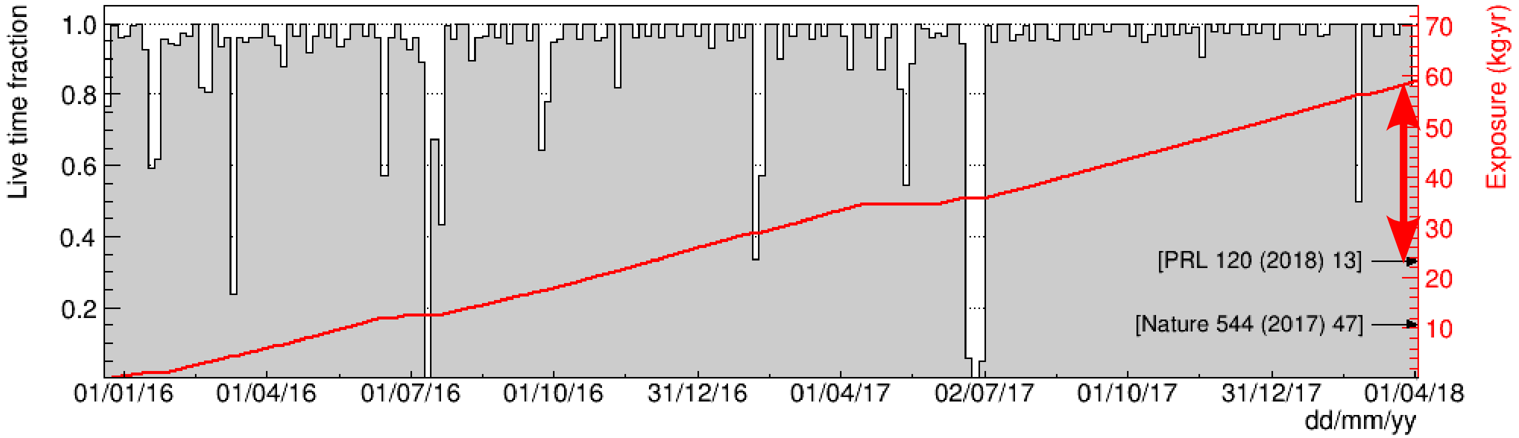


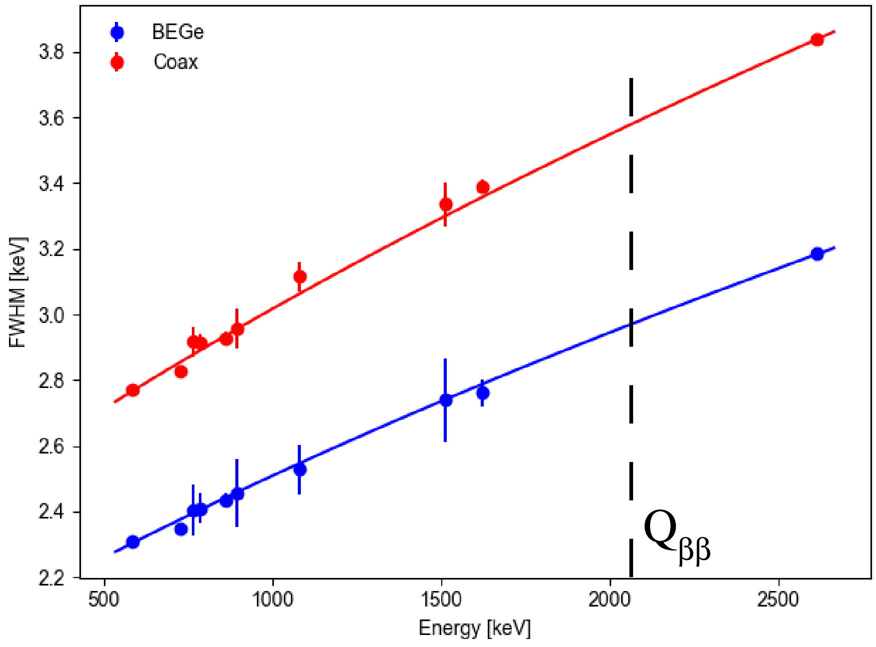
Point-like (single-site) energy deposition inside one HP-Ge diode

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)

Status of Phase II data-taking





Data taking:

- ◆ new data release: **35.7 kg·yr** BEGe and Coax data
- ◆ **58.9 kg·yr** exposure for the entire Phase II

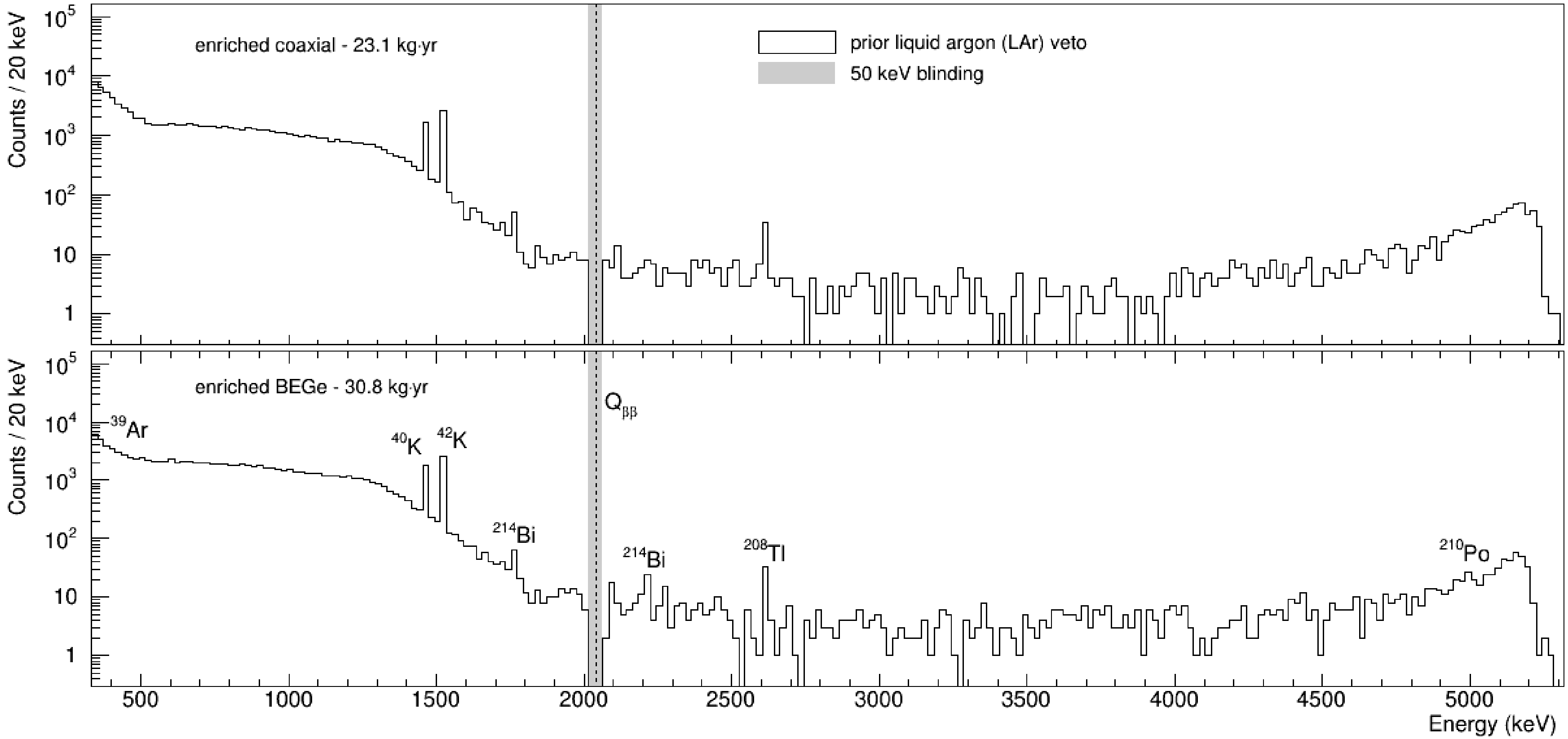
Energy calibration:

- ◆ weekly ^{228}Th calibrations
- ◆ comparison with γ lines in physics data
- ◆ stability between calibration: every 20 s pulser injected into FE

@$Q_{\beta\beta}$: FWHM(**Coax**) = **3.6 ± 0.1** keV

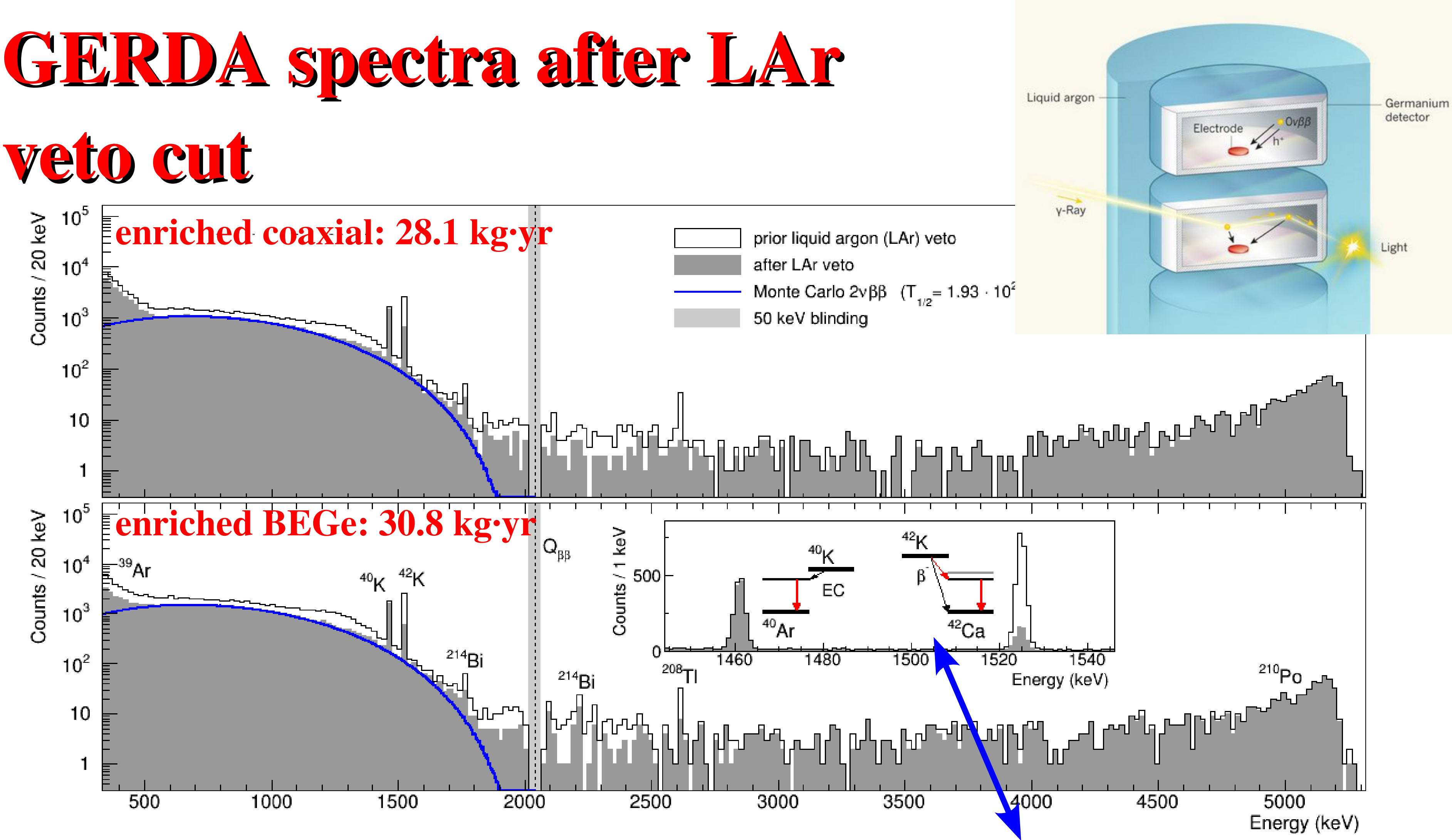
@$Q_{\beta\beta}$: FWHM(**BEGe**) = **3.0 ± 0.1** keV

Phase II GERDA spectra



- Spectra after **energy calibration**, **quality cuts**, **Muon Veto cut** and **AntiCoincidence cut**
- Most prominent feature: ^{39}Ar β (< 500 keV), 2νββ, ^{42}K and ^{40}K γ lines, α in the high energy part of the spectrum
- **Blinded Analysis**: events with energy $Q_{\beta\beta}$ ± 25 keV not processed until all analysis cuts finalized

GERDA spectra after LAr veto cut



- $^{40}K/^{42}K$ 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:

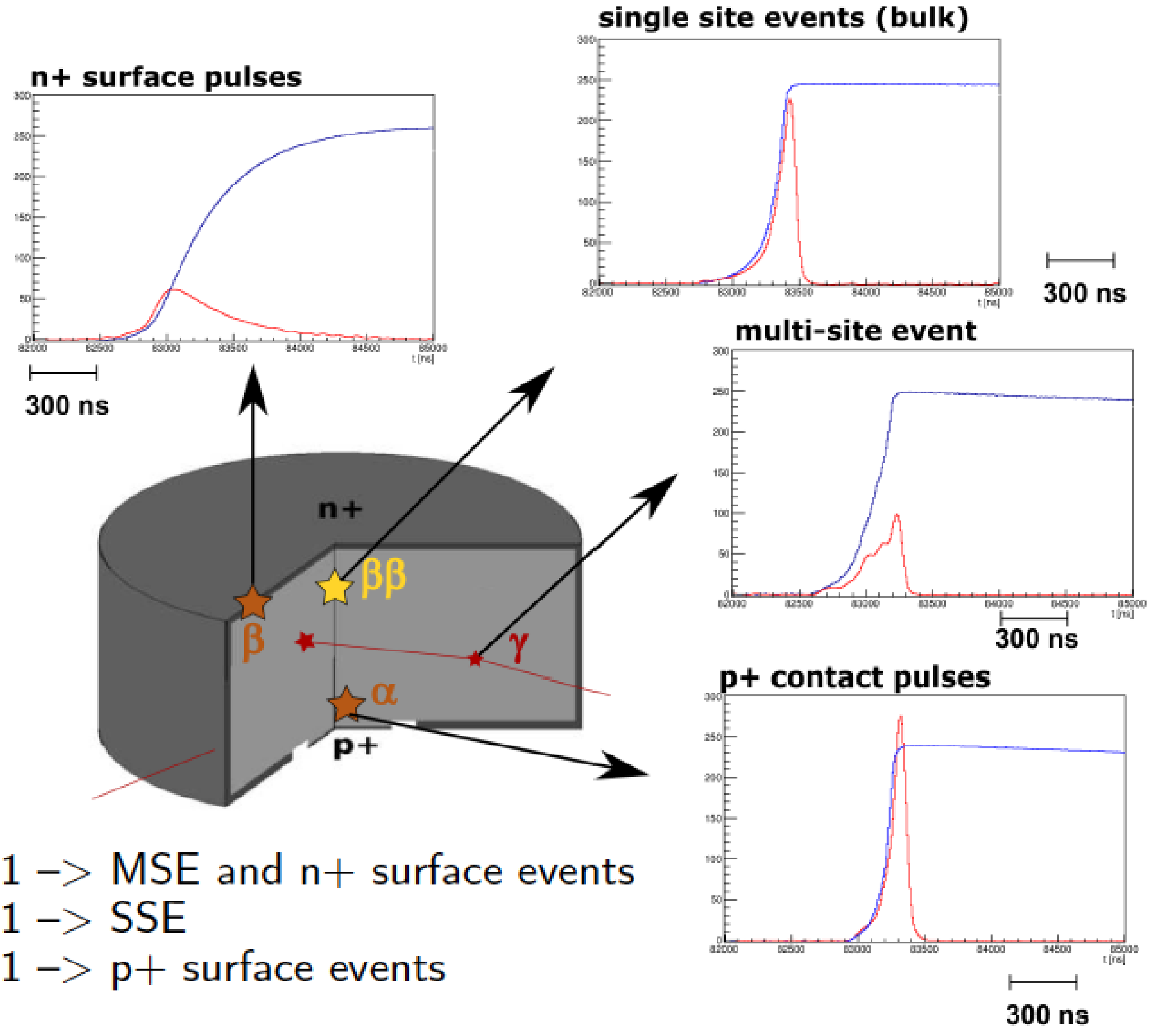
$^{40}K \rightarrow {}^{40}Ar + \gamma$ (1.4 MeV) [EC]

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

+ e- (up to 2 MeV)

Pulse Shape Discrimination: BEGe

- Event 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

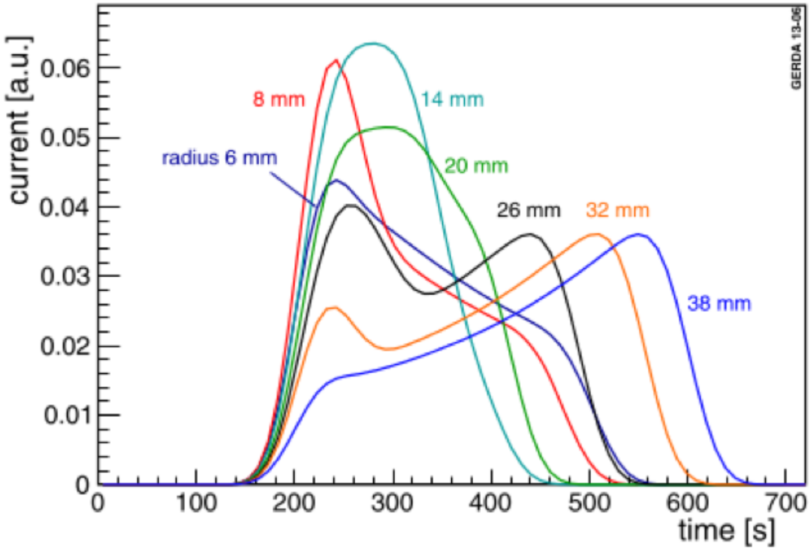
Pulse Shape Discrimination: Coax

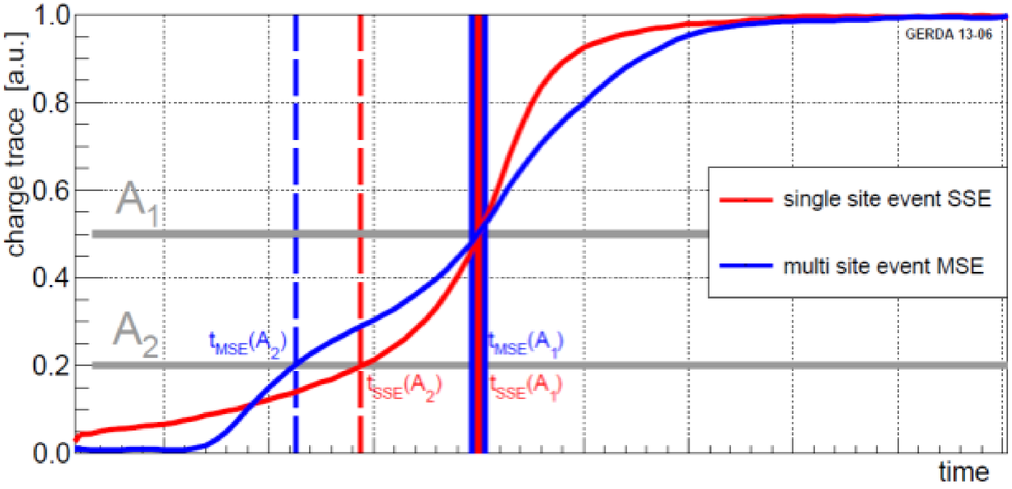
- PSD for Coax detectors less effective than for BEGes

- **MSE suppression**: Artificial Neural Network (**ANN**) using as input variables the times when the charge pulse reaches 1, 3, 5, … 99% of the full height

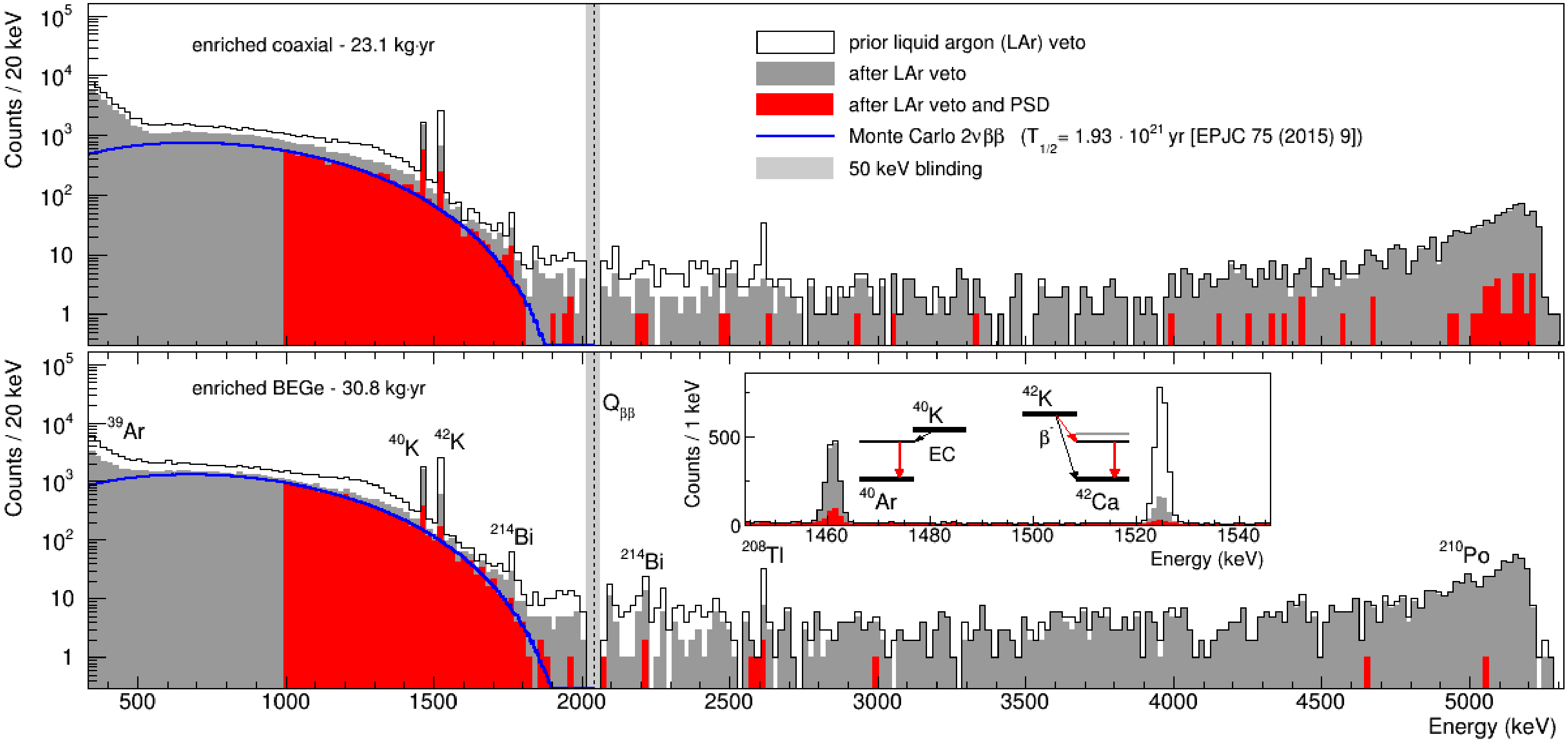
- **α events suppression**: based on their fast rise time.

Current Pulses for SSE



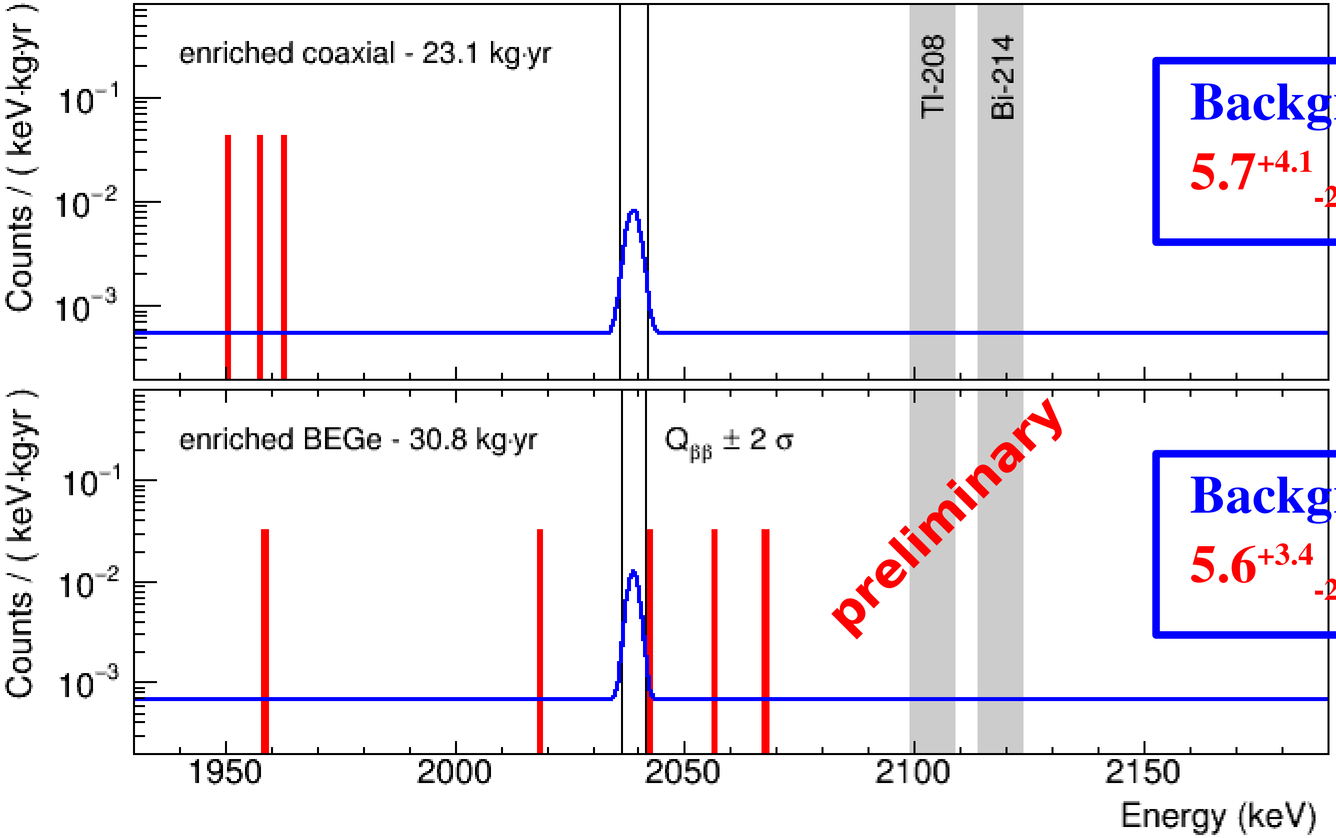


GERDA spectra after LAr cut + PSD cut



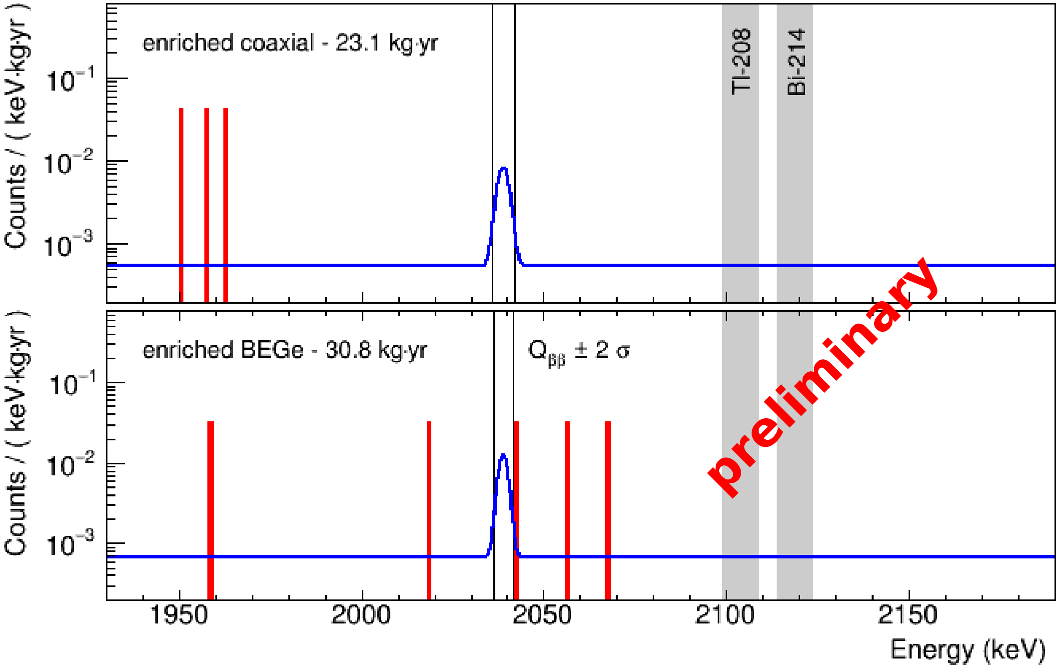
- ➢ LAr and PSD highly effective cuts

Spectra in the ROI



Background Index:
$5.7^{+4.1}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)

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



Statistical Analysis

- **Frequentist (preliminary results):**

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

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

  Median Sensitivity (NO Signal)

  $T^{0\nu}_{1/2} > 1.1 \cdot 10^{26}$ 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):**

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

  Median Sensitivity:

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

  59% of MC realizations yield limit stronger than data

- Bayes factor: $P(H_1)/P(H_0) = 0.054$

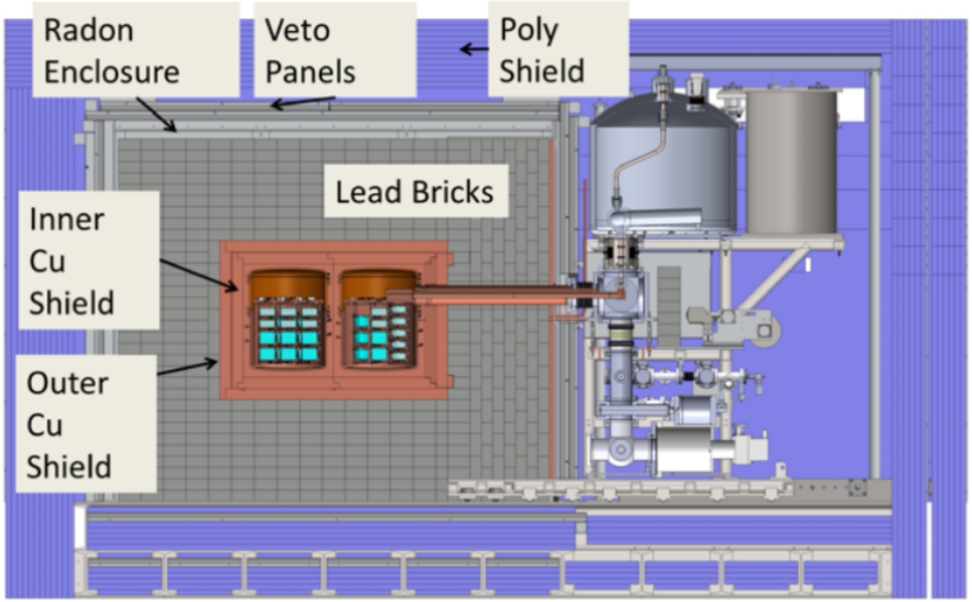
  where:

  H_1:signal+background hypothesis

  H_0: background-only hypothesis

Other experiments

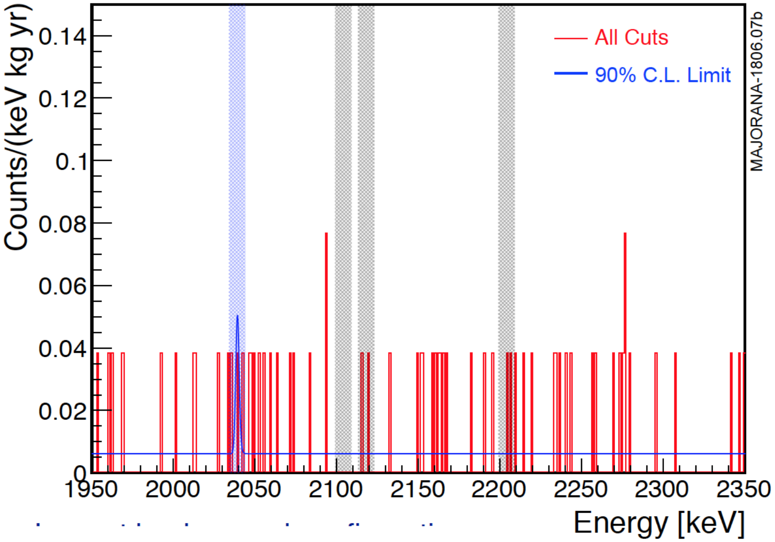
MAJORANA DEMONSTRATOR



operating at the Sanford Underground Facility (USA), 4300 m.w.e.

29.7 kg of enriched (88%) **^{76}Ge** detectors

compact shield: low-background passive Cu and Pb shield with muon veto



New data release shown at Neutrino 2018

exposure: 26 kg·yr

FWHM($Q_{\beta\beta}$=2039 keV) = 2.5 keV

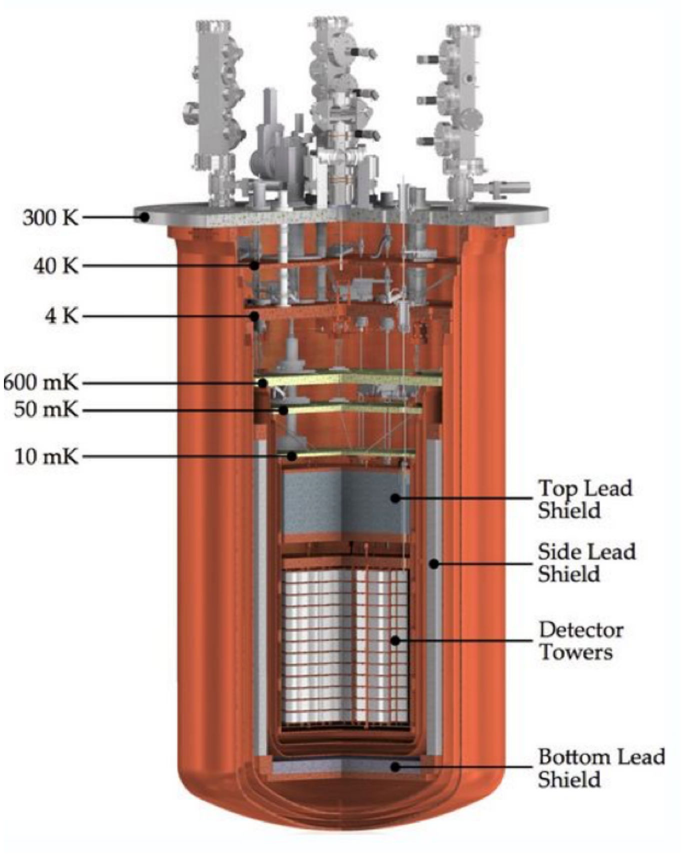
BI: $(4.7 \pm 0.8)\cdot 10^{-3}$ cts/(keV·kg·yr)

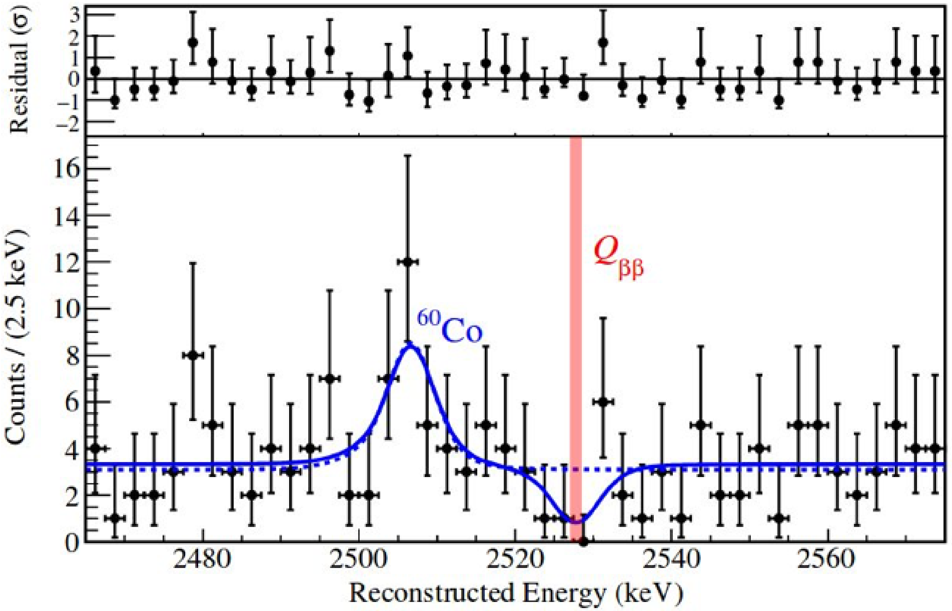
lower limit: **$T^{0\nu}_{1/2} > 2.7\cdot 10^{25}$ yr (90% CL)**

median sensitivity: **$4.8\cdot 10^{25}$ yr (90% CL)**

$m_{ee} < 200 - 433$ meV

CUORE





operating at LNGS (Italy), 3500 m.w.e.

988 $^{nat}\mathbf{TeO_2}$ bolometers

active mass: 742 kg

isotope mass: 206 kg ^{130}Te

TeO_2 exposure: 86.3 kg·yr

FWHM($Q_{\beta\beta}$= 2528 keV)= 7.7 ± 0.5 keV

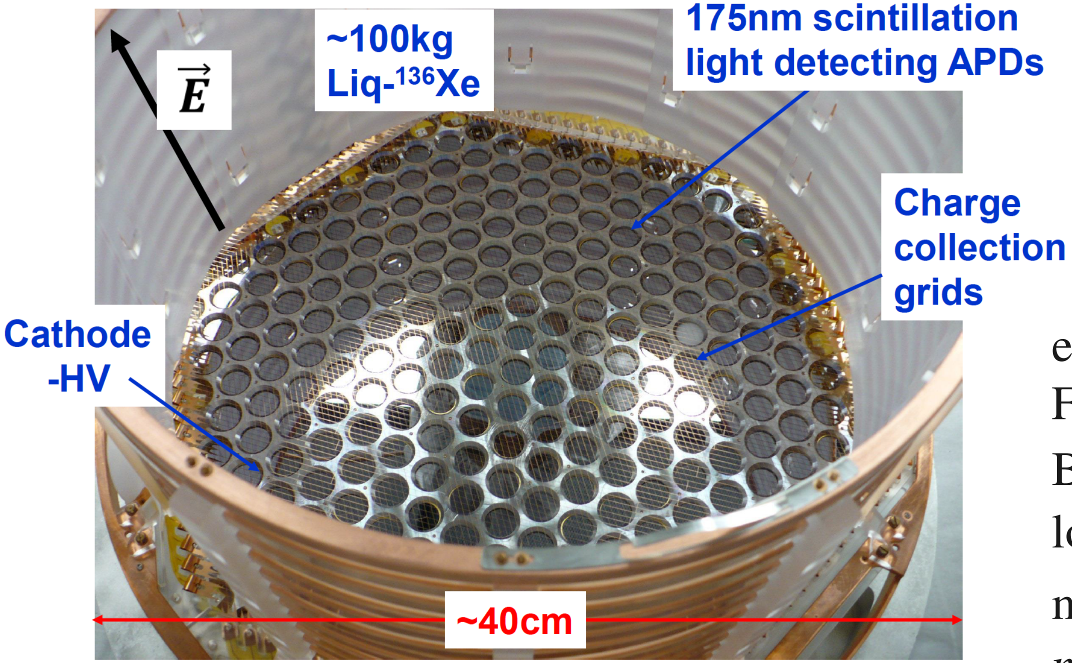
BI: (14 ± 2)$\cdot 10^{-3}$ cts/(keV·kg·yr)

lower limit: **$T^{0\nu}_{1/2} > 1.5\cdot 10^{25}$ yr (90% CL)**

median sensitivity: **$0.7\cdot 10^{25}$ yr (90% CL)**

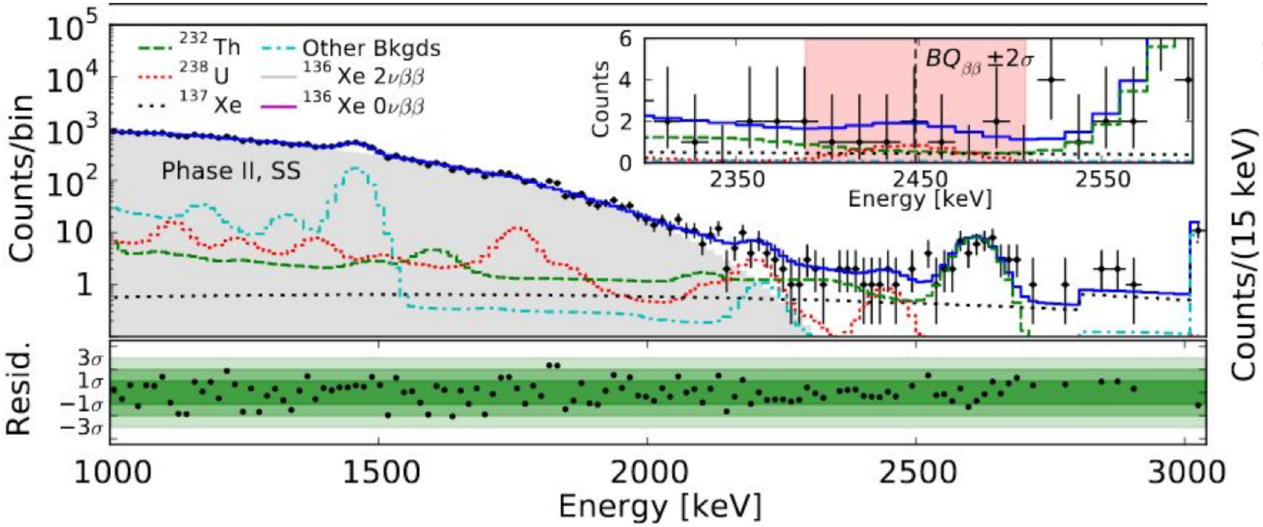
m_{ee} < 110 - 520 meV

EXO-200

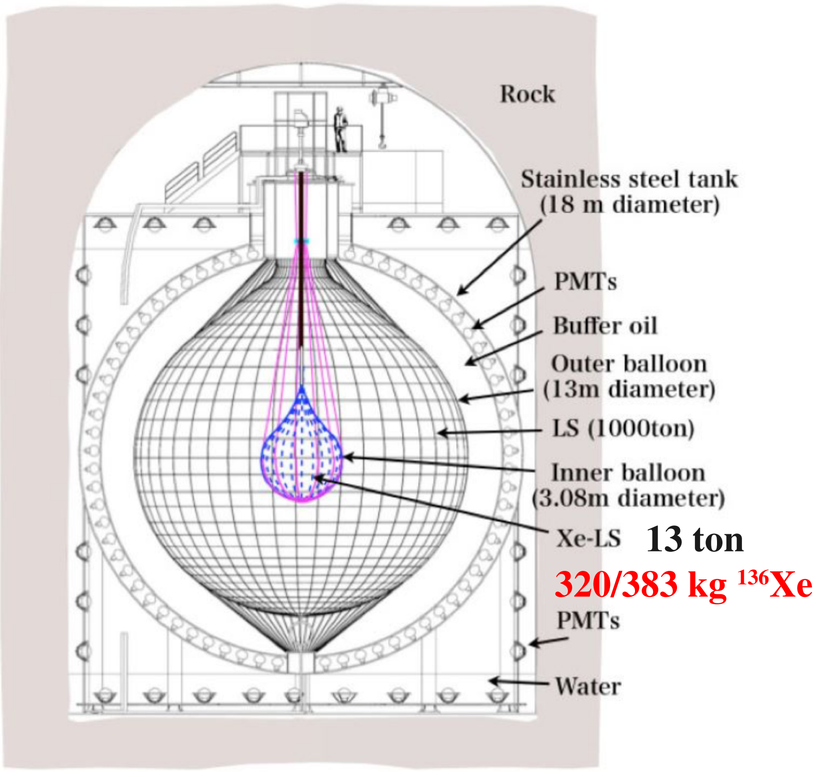


operating at WIPP, Carlsbad, NM (USA), 1624 m.w.e.
cylindrical single phase TPC filled with 200 kg of liquid Xe enriched to 80.6% in **^{136}Xe**

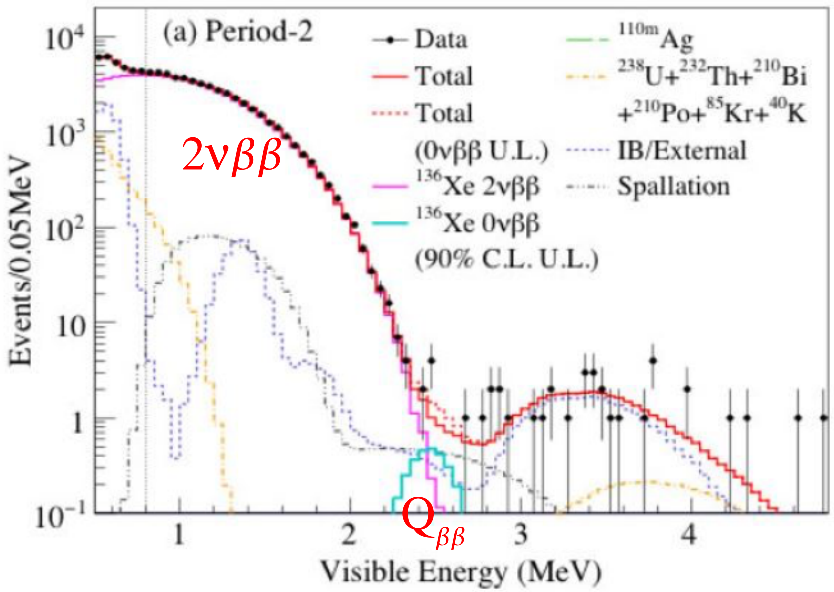
exposure: 177.6 kg·yr
FWHM($Q_{\beta\beta}$= 2458 keV) = 71 keV
BI: $(1.5 \pm 0.3)\cdot 10^{-3}$ cts/(keV·kg·yr)
lower limit: **$T^{0\nu}_{1/2} > 1.8\cdot 10^{25}$ yr (90% CL)**
median sensitivity: **$3.8\cdot 10^{25}$ yr**
$m_{ee} < 147 - 398$ meV



KamLAND-Zen



operating at Kamioka, Japan, 2700 m.w.e.
^{136}**Xe** (3%) loaded scintillator (90% enrichment)



exposure: 593.5 kg·yr

FWHM($Q_{\beta\beta}$= 2458 keV) ≈ 270 keV

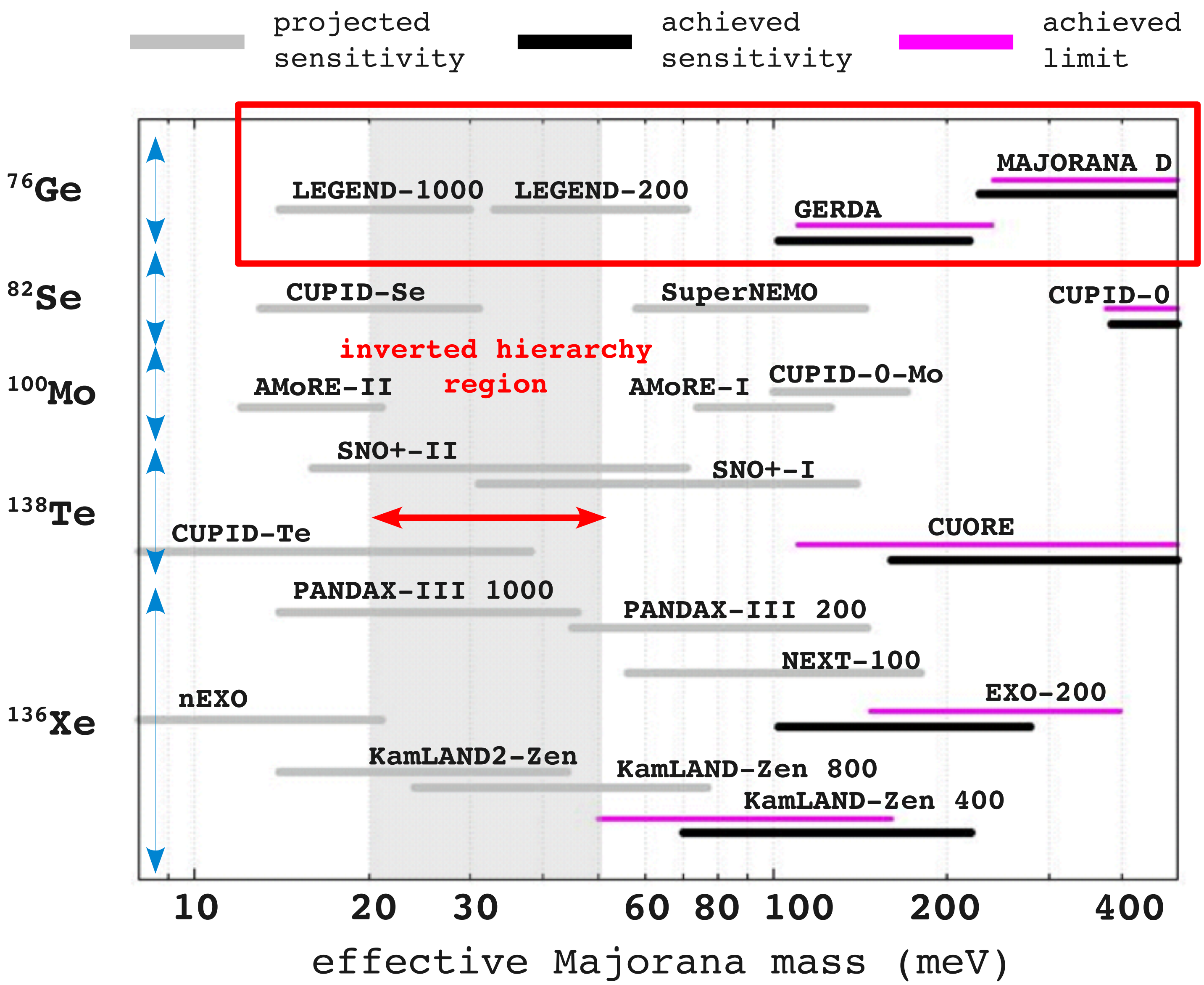
BI ≈ $0.4 \cdot 10^{-3}$ cts/(keV·kg·yr)

lower limit: **$T^{0\nu}_{1/2} > 10.7 \cdot 10^{25}$ yr (90% CL)**

median sensitivity: **$5.6 \cdot 10^{25}$ yr**

$m_{ee} < 61 - 165$ meV

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

Conclusions

- **GERDA Phase II** has worked **smoothly** and with **high efficiency since** December 2015
- We have collected ~ **59 kg·yr** of really good data
- With the present data release we have obtained:
  - Limit on **$T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% CL)**
  - Median Sensitivity: **$1.1 \cdot 10^{26}$ yr** (*the best in the world!*)
  - BI(^{enr}Coax): **$5.7^{+4.1}_{-2.4} \cdot 10^{-4}$ cts/(keV· kg · yr)**

    BI(^{enr}BEGe): **$5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV ·kg · yr)**
  - **$m_{ee} < 0.11 – 0.25$ eV**

preliminary

- **Lowest bkg** (~10x) in ROI respect to experiments using other isotopes
- **Best median sensitivity** respect to all other experiments
- Promising future for a Ge experiment with 200 kg (**LEGEND-200**) and beyond (**LEGEND-1000**)