New data release of GERDA Phase II: search for $0\nu\beta\beta$ decay of ^{76}Ge

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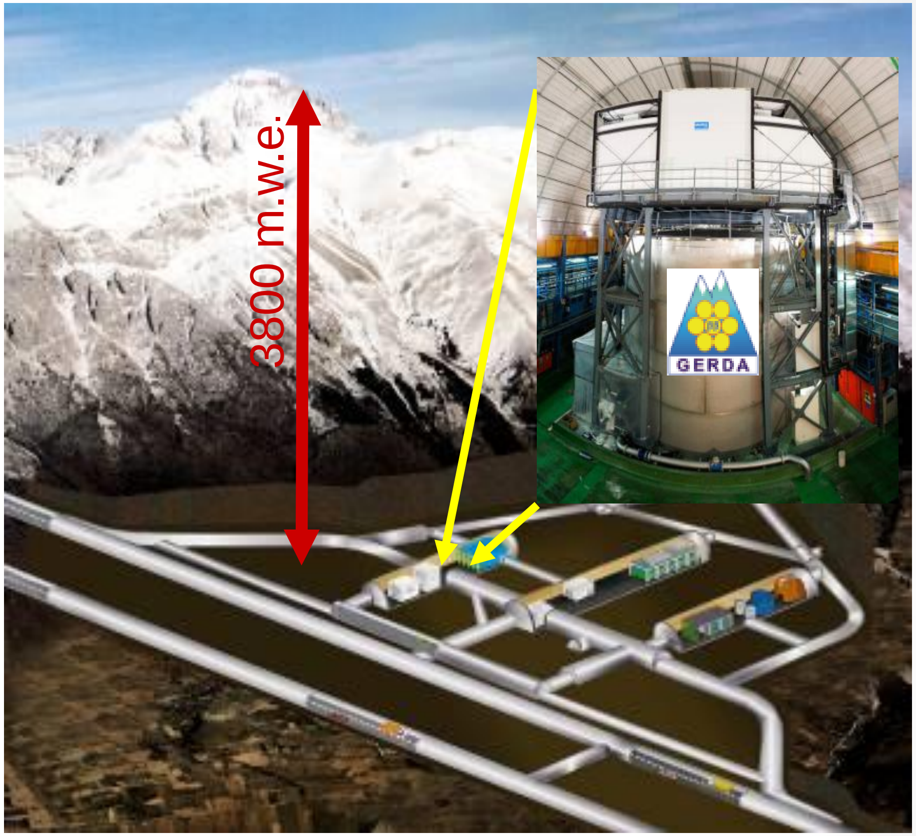
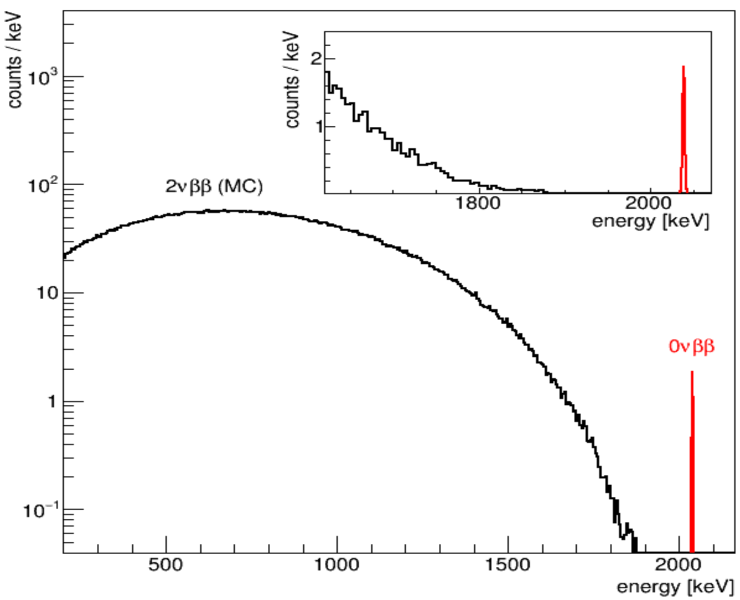
on behalf of the GERDA Collaboration

0νββ with GERDA

GERmanium Detector Array (INFN-LNGS, Italy) searches for 0ν2β decay in ^{76}Ge using HPGe detectors enriched in ^{76}Ge

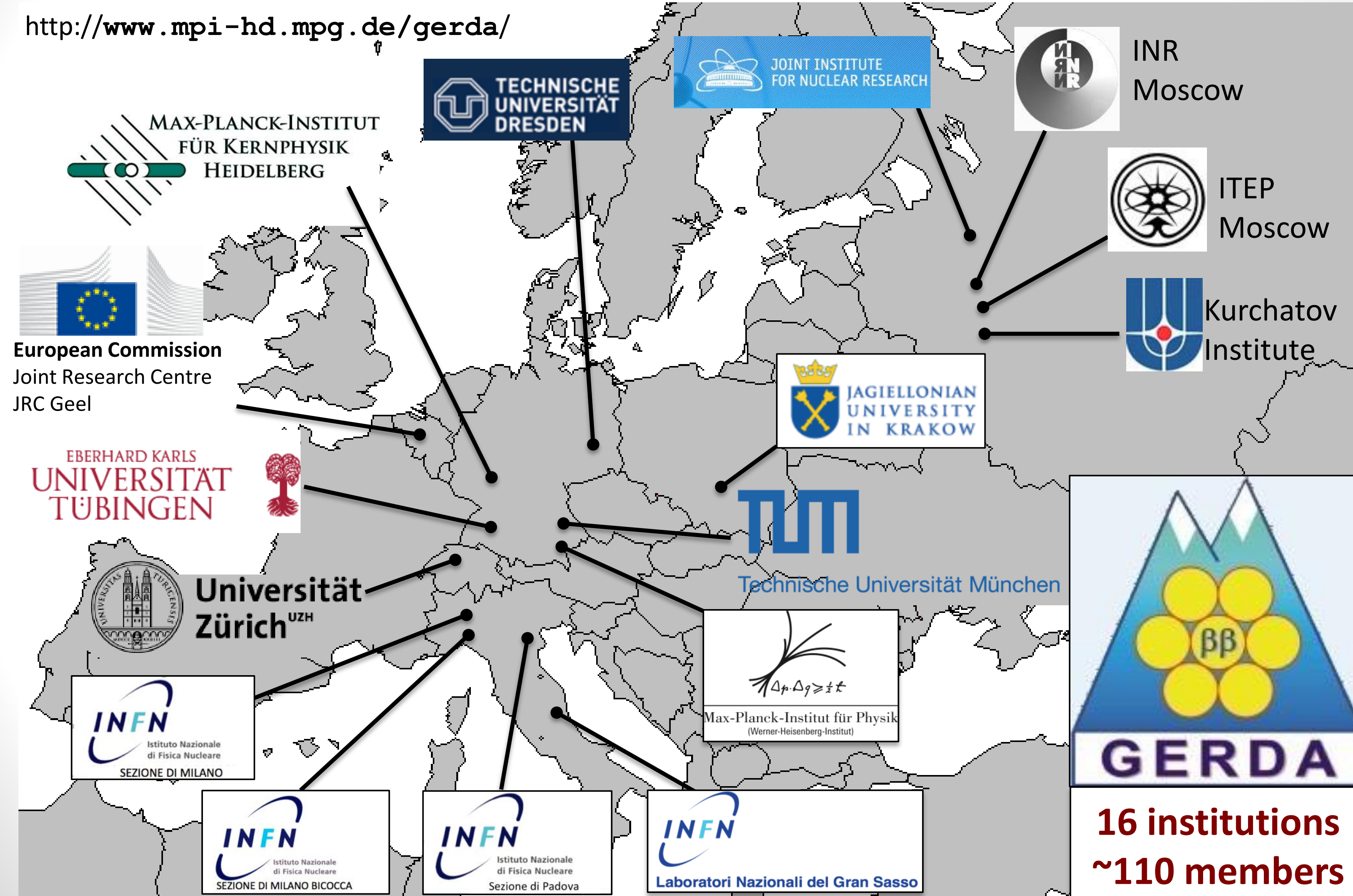




$Q_{\beta\beta}$-value = **2039 keV** in ^{76}Ge
Energy resolution <4 keV FWHM
→ important for discovery

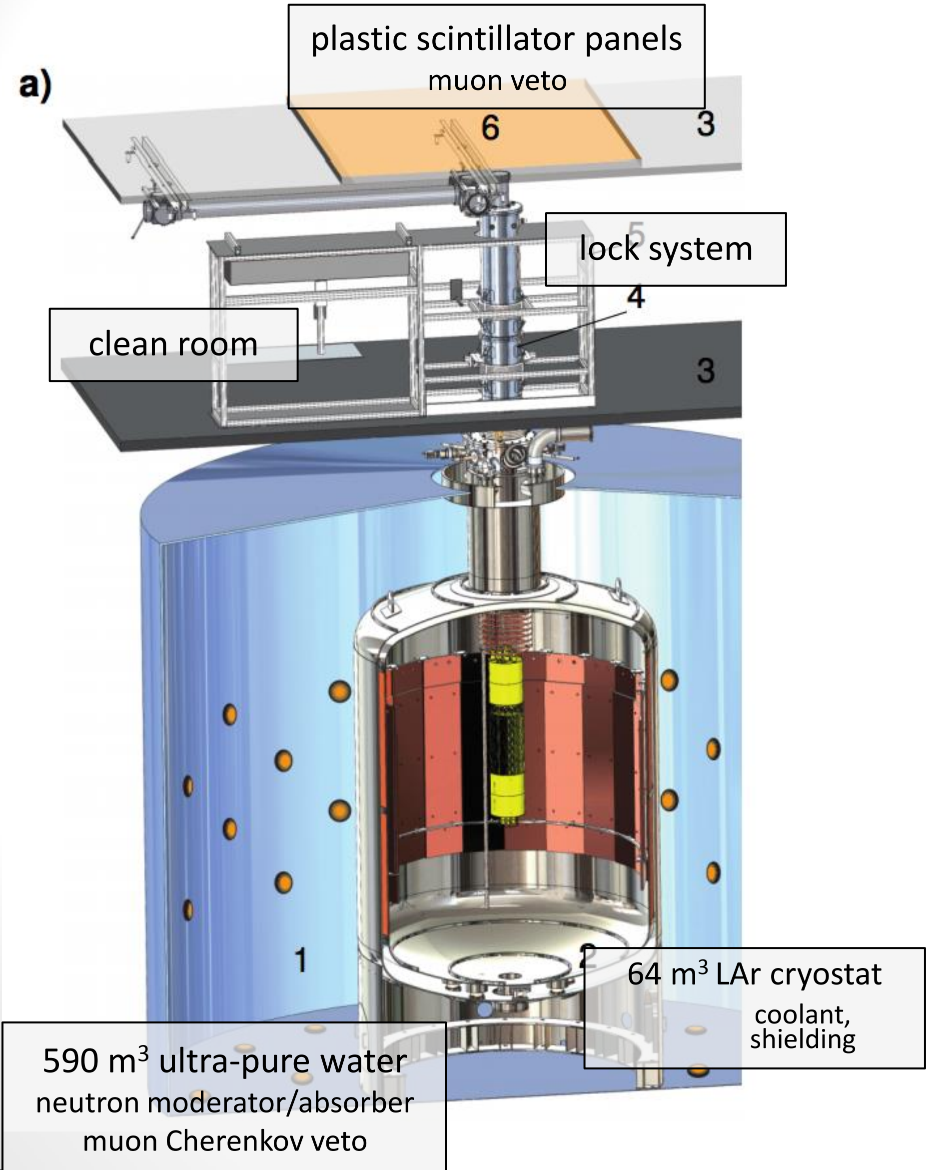
The GERDA Collaboration

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

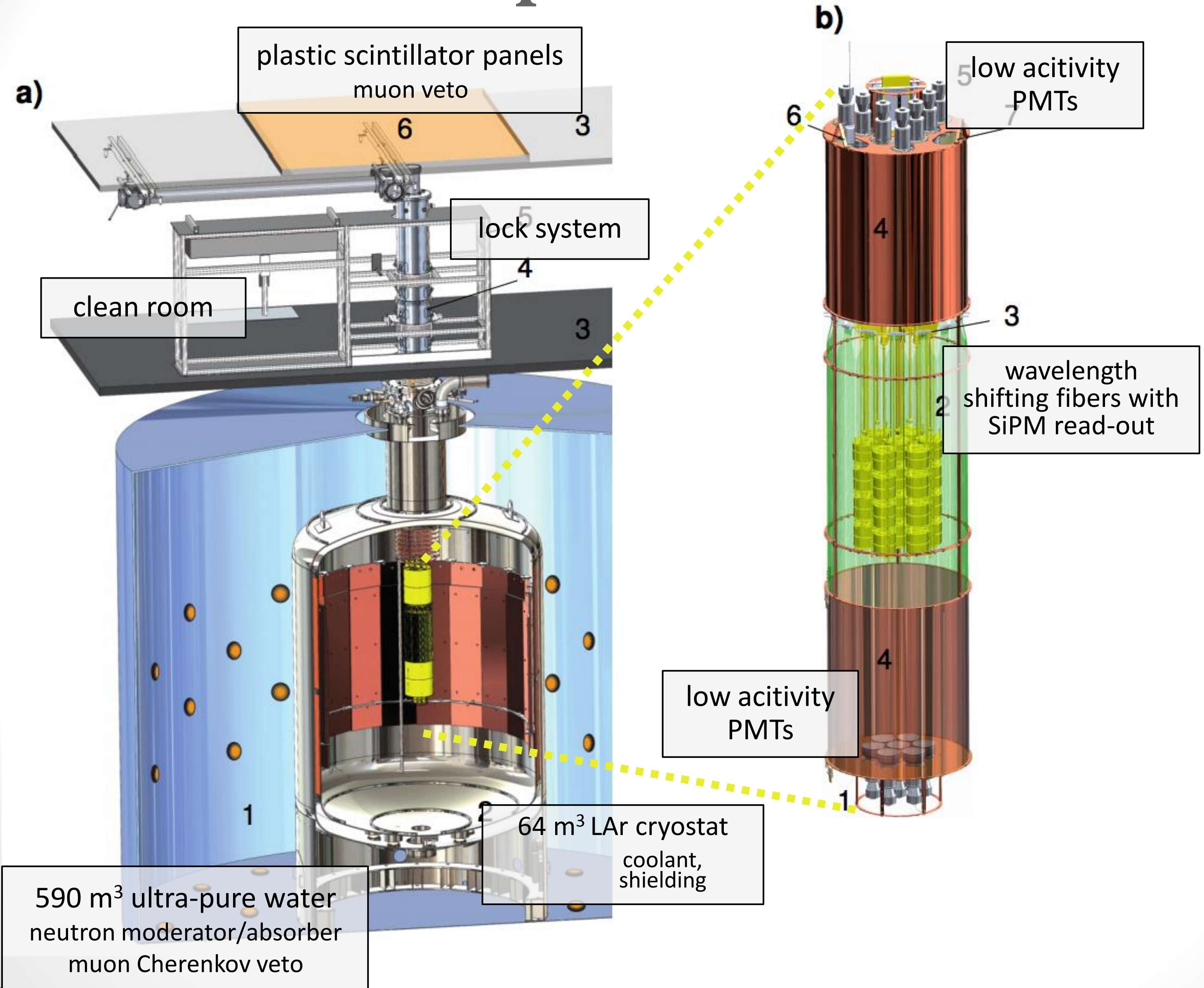


16 institutions
~110 members

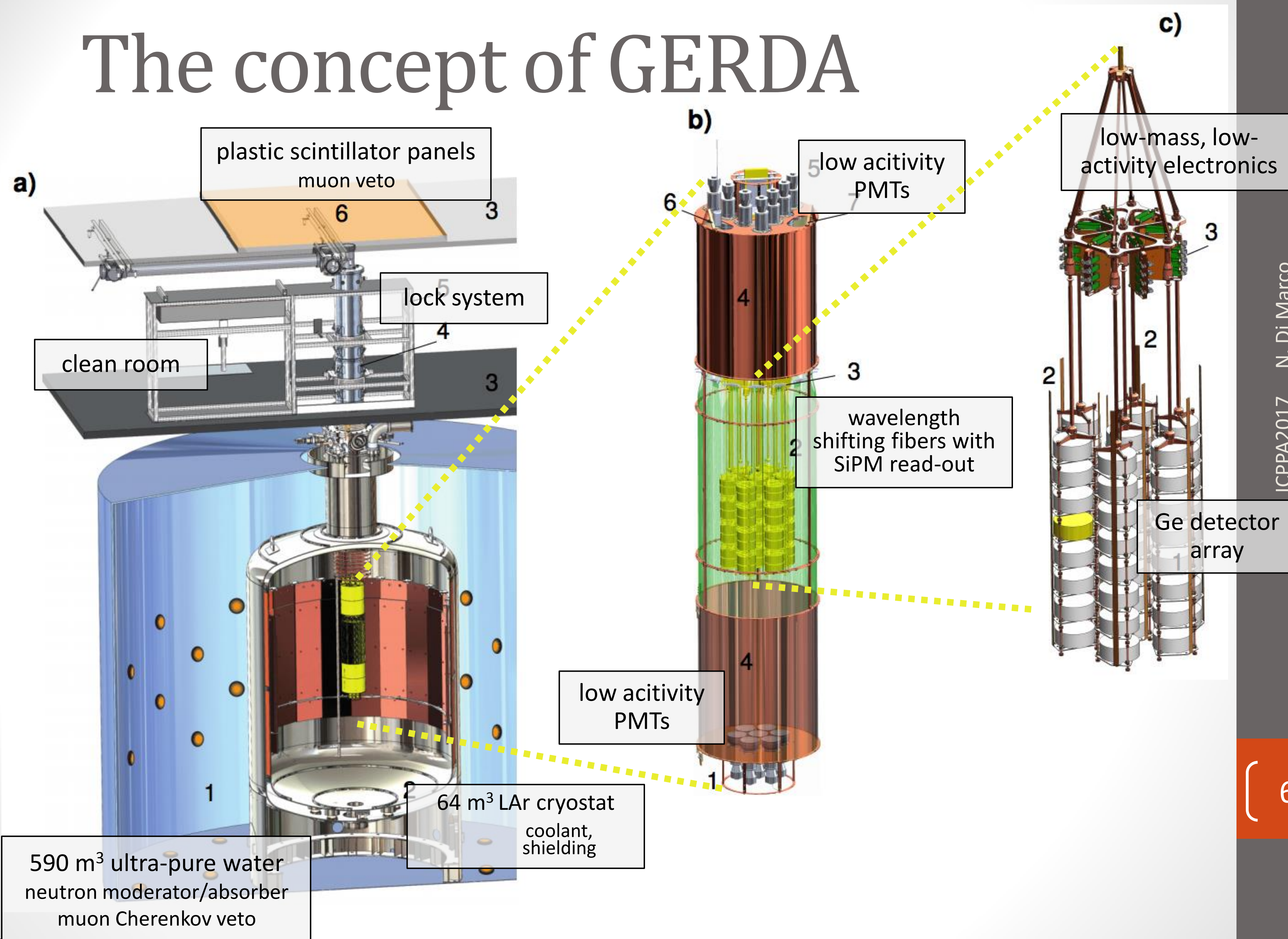
The concept of GERDA



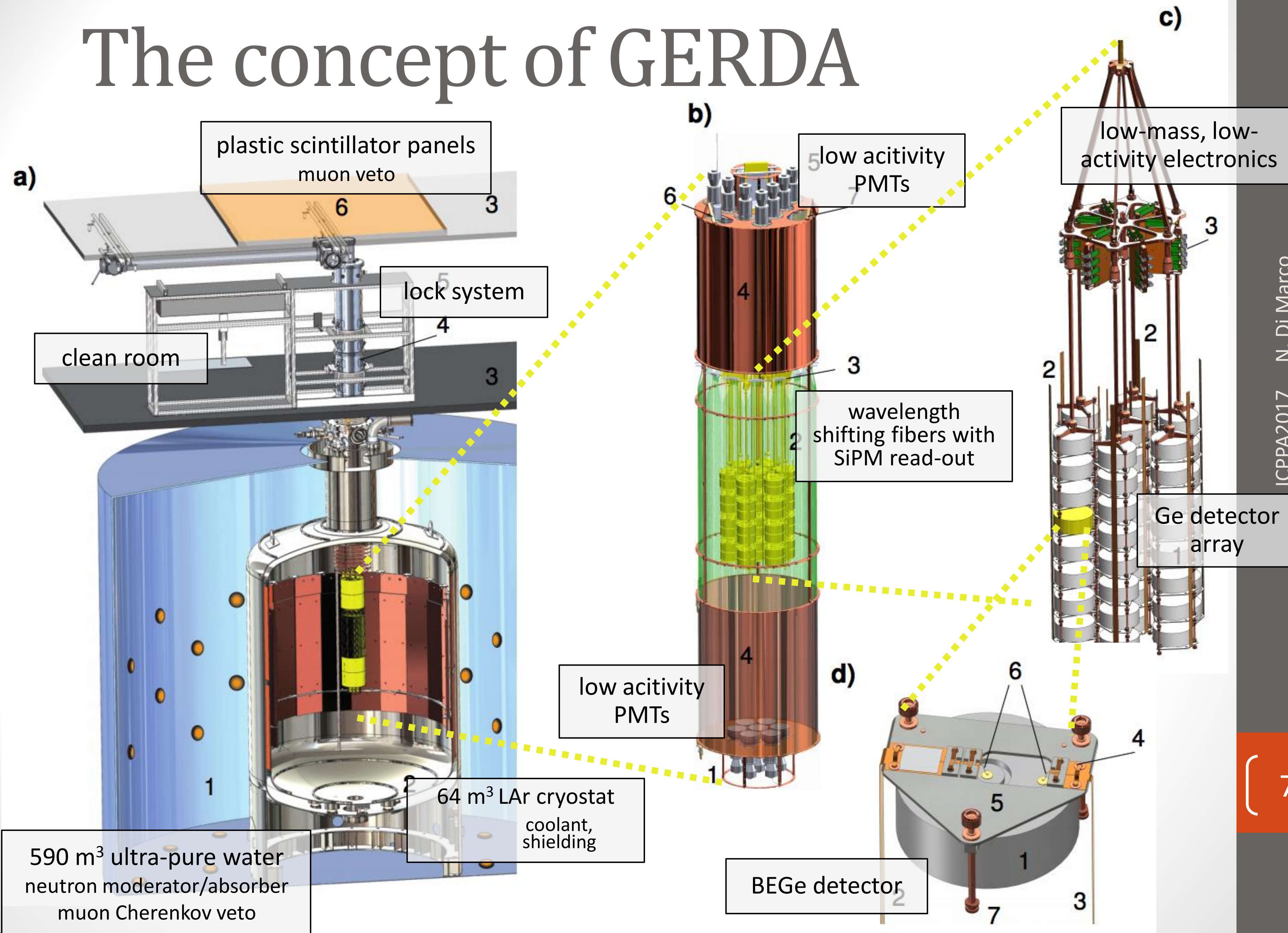
The concept of GERDA



The concept of GERDA



The concept of GERDA



DAQ strategy and phases

Phase I (Nov 2011- May 2013):

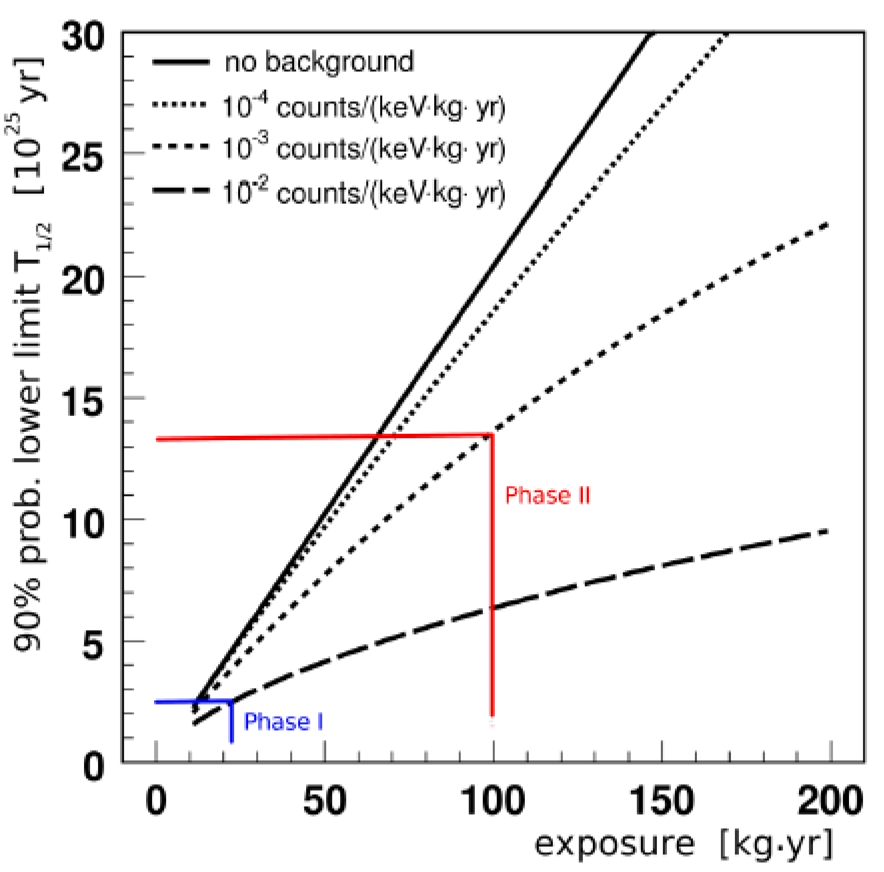
- Completed
- Use refurbished HdM and IGEX (18 kg) (+new BEGe Phase II detectors)
- BI ≈ 0.01 cts / (keV kg yr)
- No LAr readout (passive shield)
- Accumulated exposure **21 kg yr**

Phase II (Dec 2015- ongoing):

- Add new ^{enr}BEGe detectors (20 kg)
- BI ≈ 0.001 cts / (keV kg yr)
- Goal: 100 kg yr
- First data release Jun 2016 (about 11 kg yr)
- Results on *Nature 544 (2017) 47*

General strategy

- Blind analysis strategy
- Events at $Q_{\beta\beta}$ ± 25 keV in the blinding box
- Open box when all cuts finalized



Phys. Rev. Lett. 111 (2013) 122503
Nature 544 (2017) 47

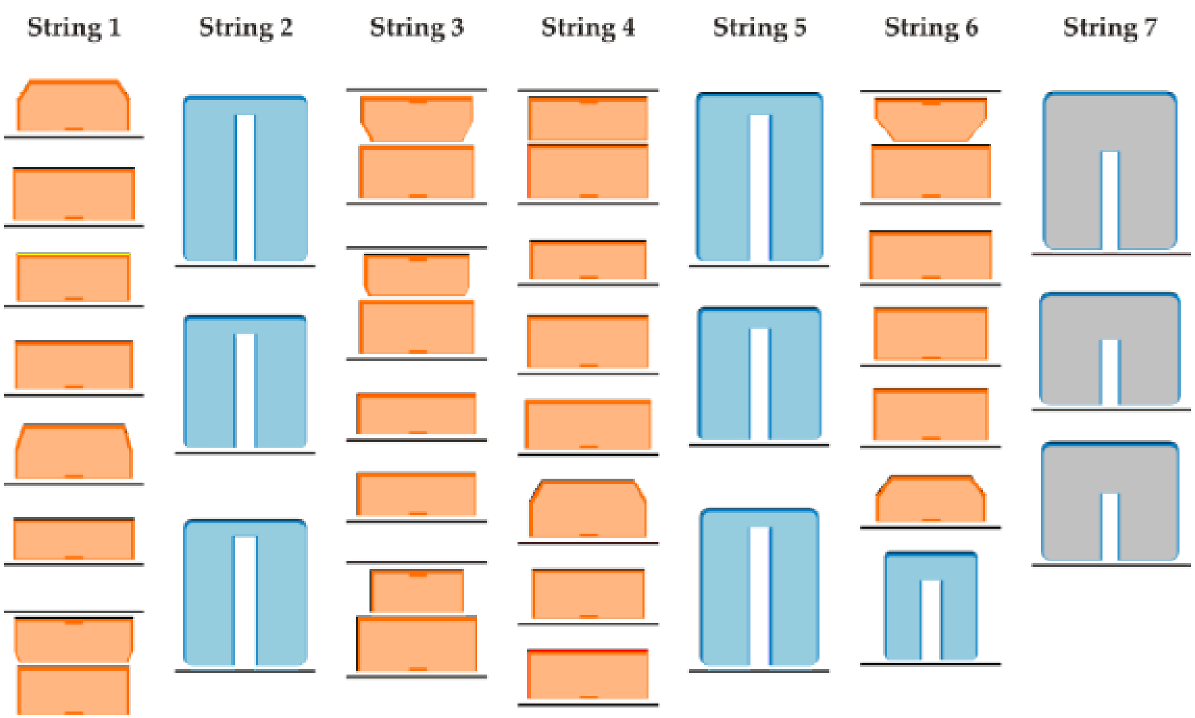
Phase II array

Deployed in December 2015

- 40 channels
- 30 ^{enr}BEGe (20 kg)
- 7 ^{enr}Coax (16 kg)
- 3 ^{nat}Coax (8 kg)

36 kg of enriched (87%) detectors

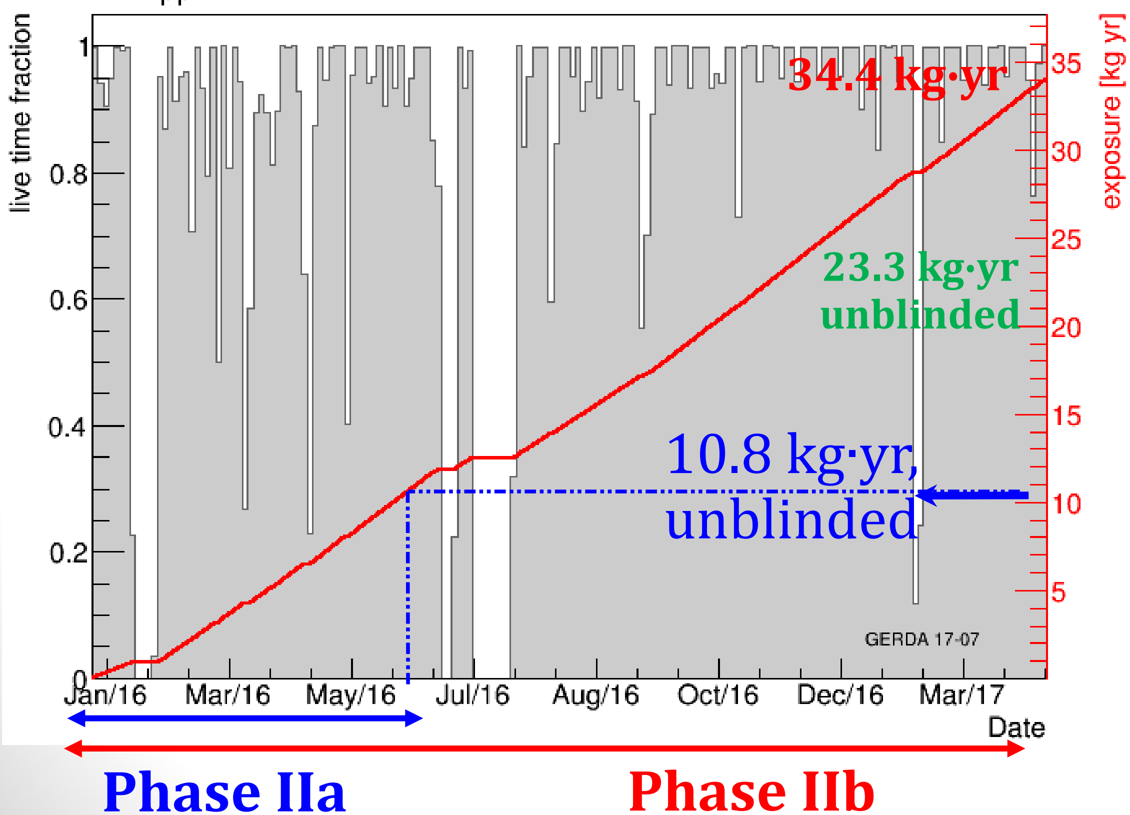
Current status: 3 diodes lost (burnout JFET)



Current data taking

Data taking in progress

- Phase II exposure increased by **x3** with respect to Nature paper (**Phase IIa**)
- Valid exposure accumulated **34.4 kg·yr** (18.2 BEGe + 16.2 Coax) up to Apr 15th (**Phase IIb**)
- A few more kg·yr already in the bag (Apr-Sept) with blinded box of ± 25keV around $Q_{\beta\beta}$



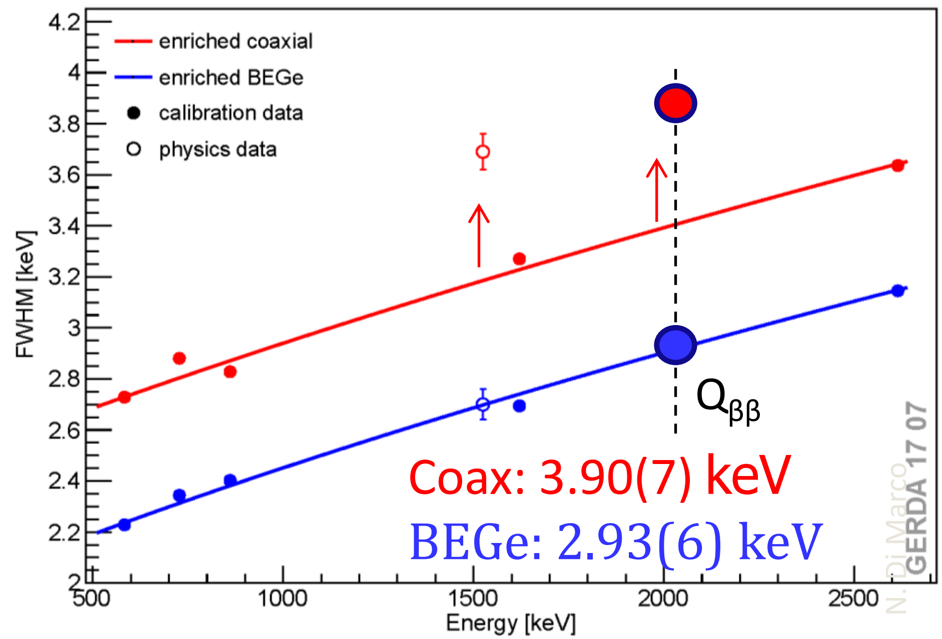
June 2017 unblinding

- Box opened for the BEGe dataset only (12.4 kg yr)
- ^{enr}Coax data (11.2 kg yr) still in the box
  - PSD does not reject a particular class of background events (α from the groove)
  - Work in progress in order to improve the PSD
- Total unblinded exposure: **23.3 kg yr** from **Phase II**

Energy Calibration

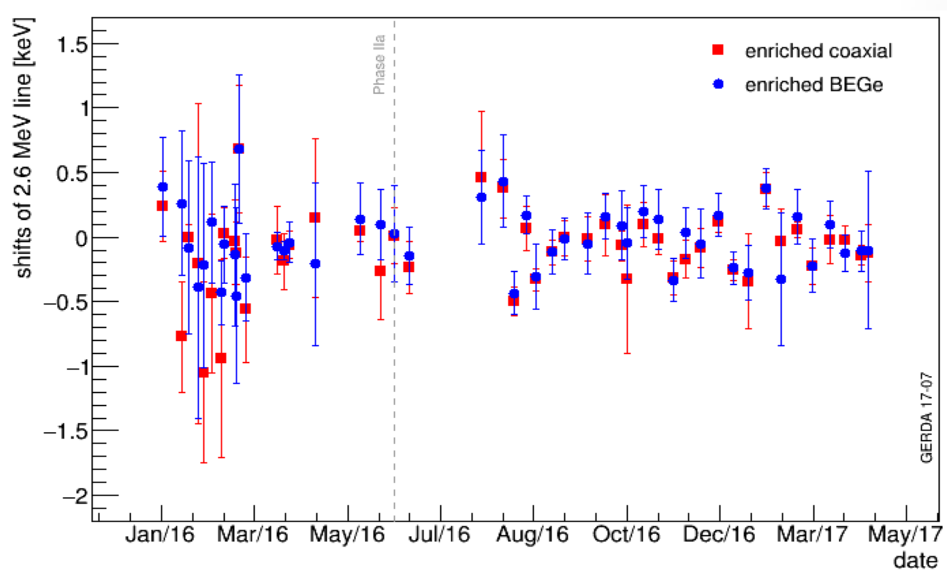
Energy scale

- Offline, using optimized ZAC filter
  Eur. Phys. J. C 75 (2015) 255
- Weekly calibrations with ^{228}Th sources
- Stability monitored online with Test Pulses, injected every 20 s

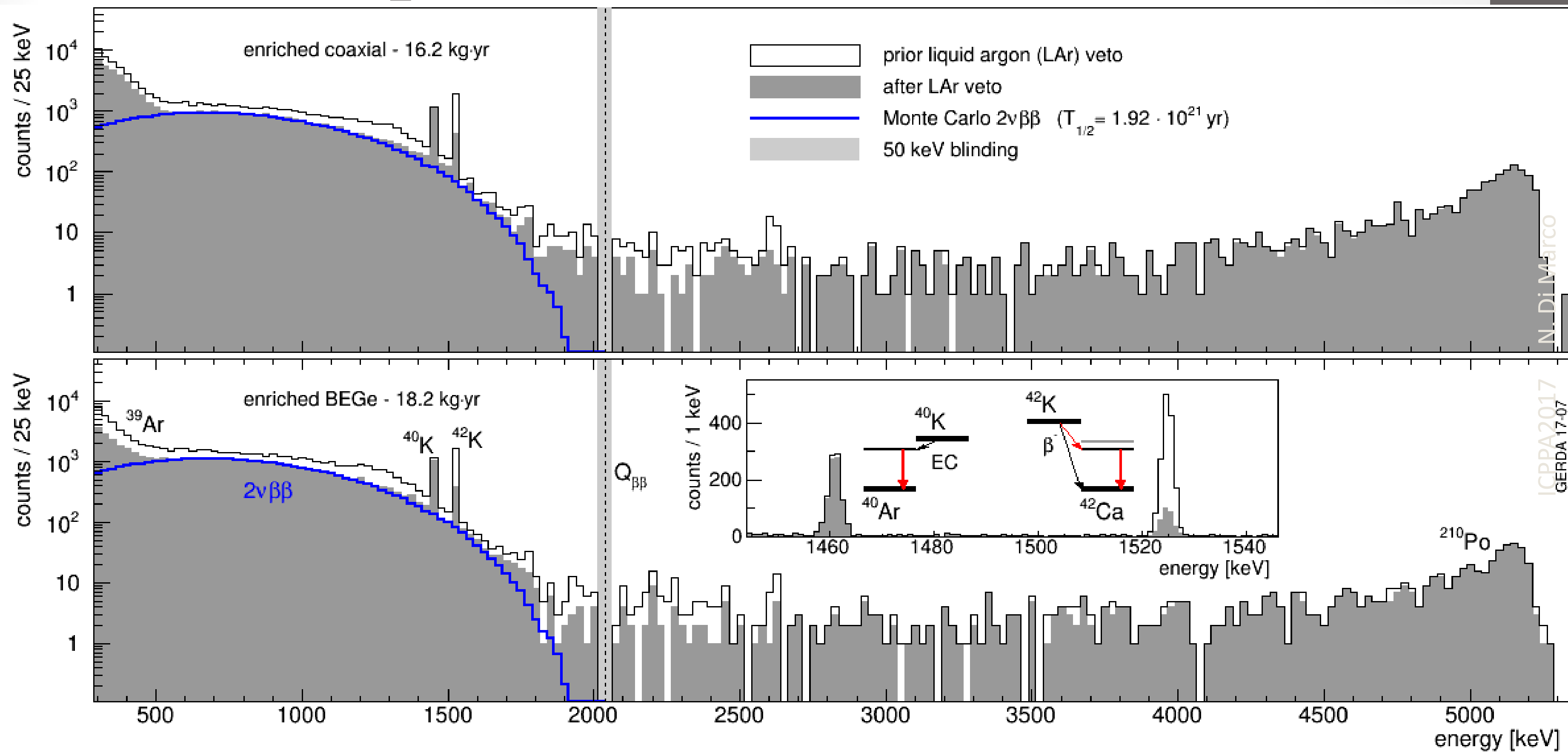


Energy resolution

- Profile derived from ^{228}Th calibrations
- Correction (for coax) applied derived from the resolution of the ^{40}K and ^{42}K peaks in the physics data
- Accounts for **instabilities** during the long-term data taking

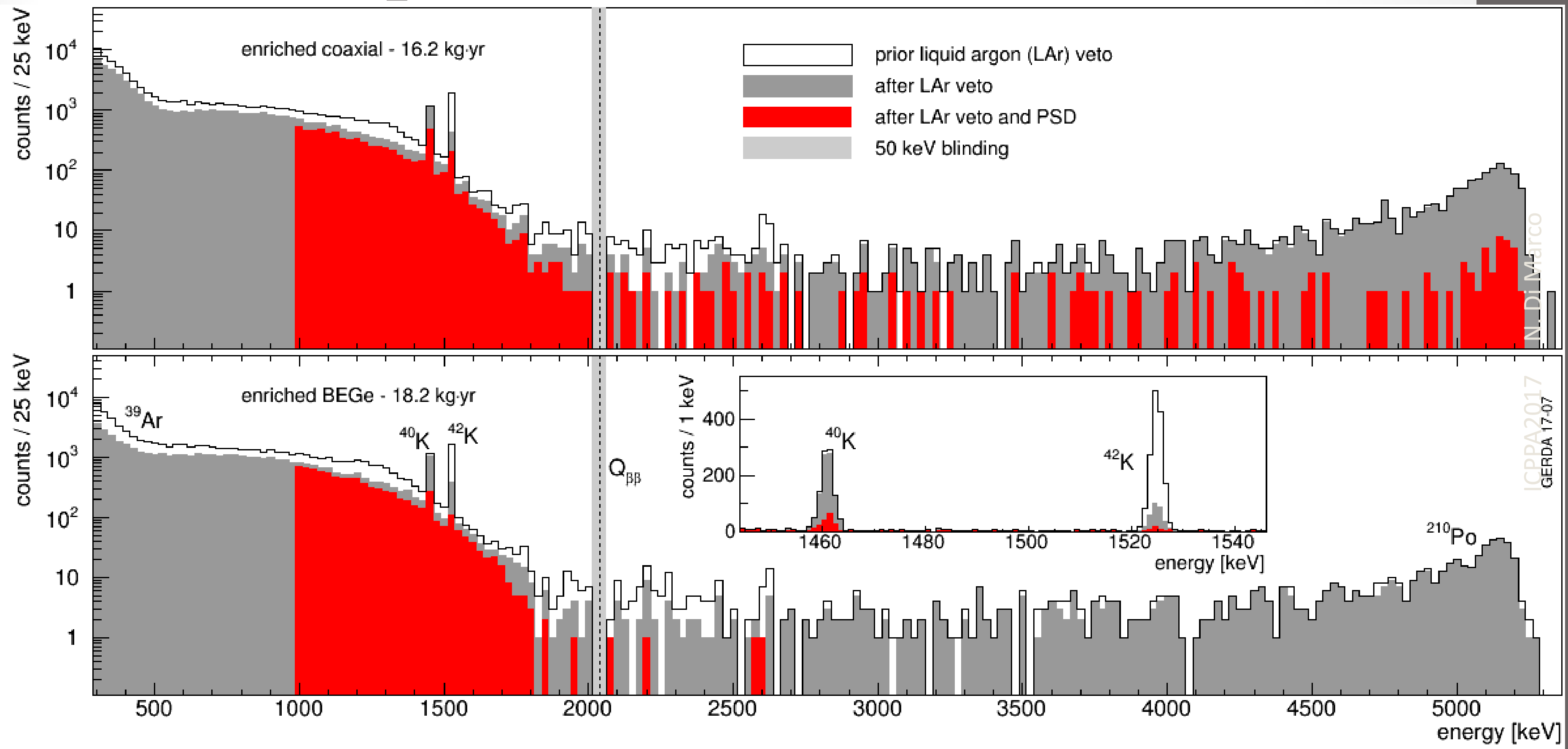


GERDA spectra



- Most prominent features: ^{39}Ar β (< 500 keV), 2νββ, ^{42}K and ^{40}K γ-rays, α

GERDA spectra

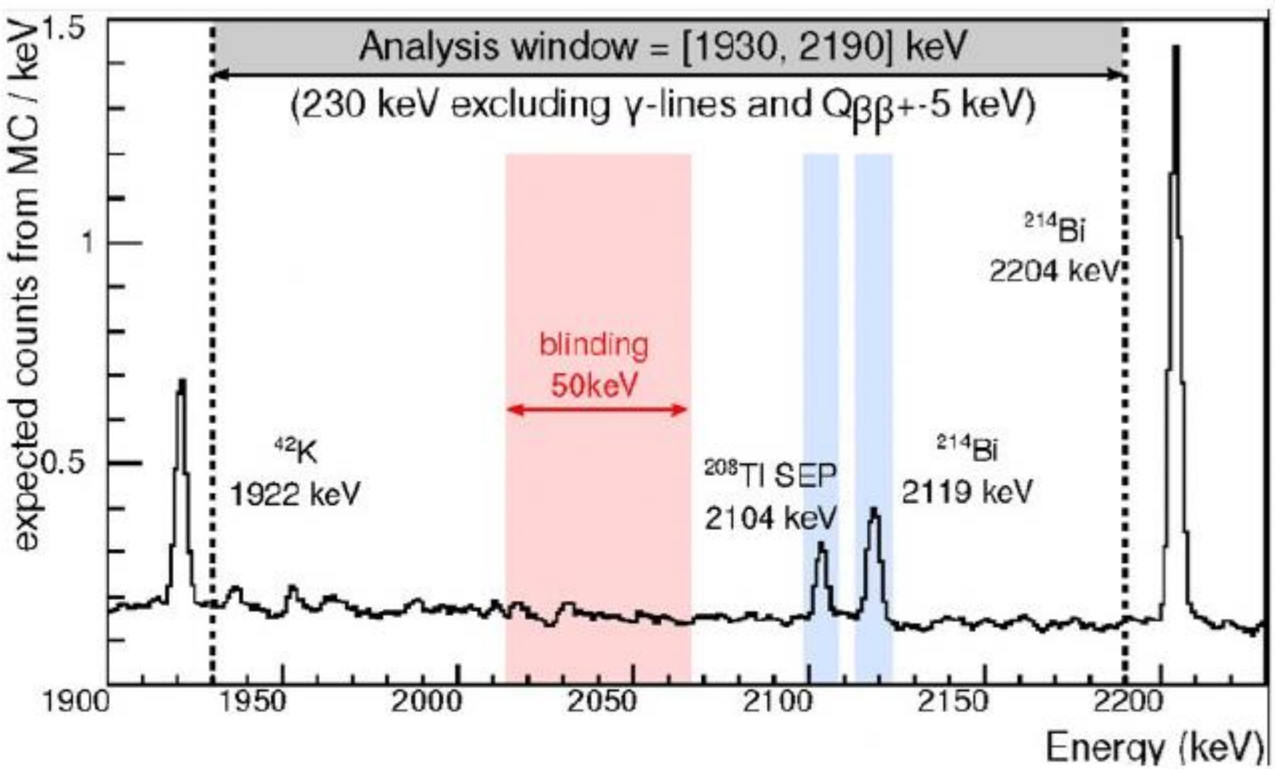


- Most prominent features: ^{39}Ar β (< 500 keV), 2νββ, ^{42}K and ^{40}K γ-rays, α
- PSD clears completely the α region
- LAr and PSD **complementary**
- Final background at $Q_{\beta\beta}$ O(10^{-3} cts/(keV kg yr))
- PSD for coaxials to be further optimized (groove α) → background will decrease

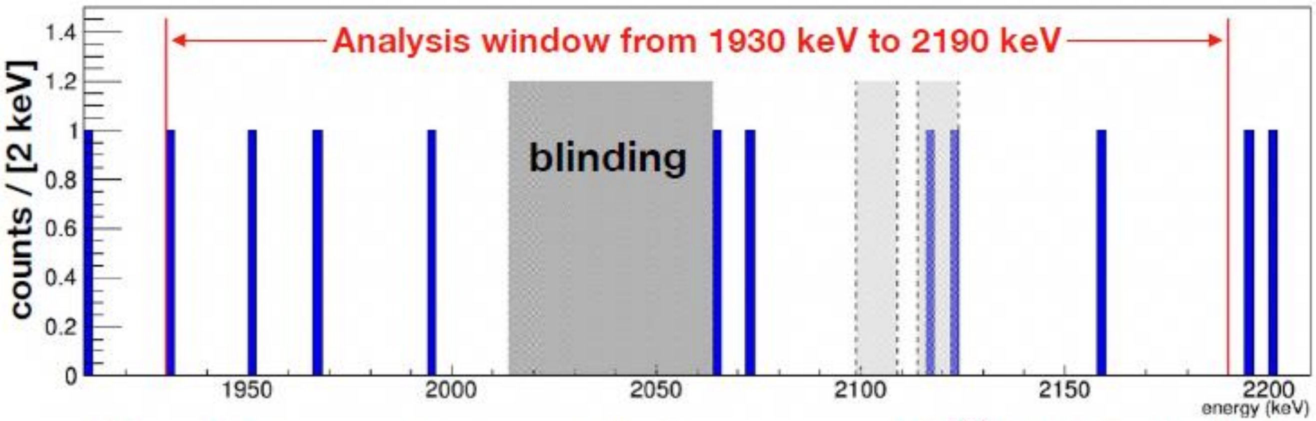
Background model

The background model (MC) , made considering the spectrum before LAr and PSD cuts confirms the background **is flat** around the ROI and inside the blinding window as in PhaseI

- The expected spectrum is roughly composed by: ~ 30% of events from α, 30% e- from 42K and 30% of 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

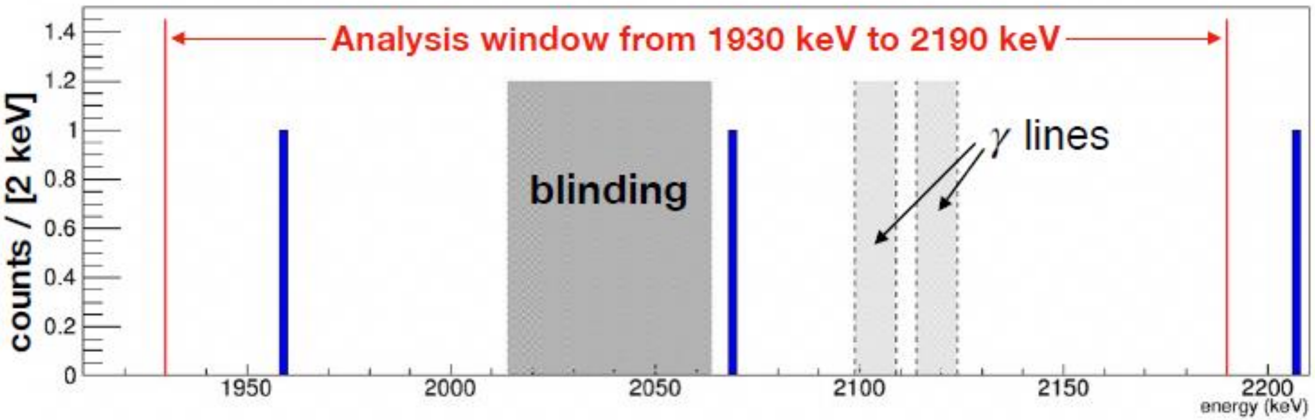


Spectra in the ROI



^{enr}Coax
16.2 kg · yr (after all cuts)

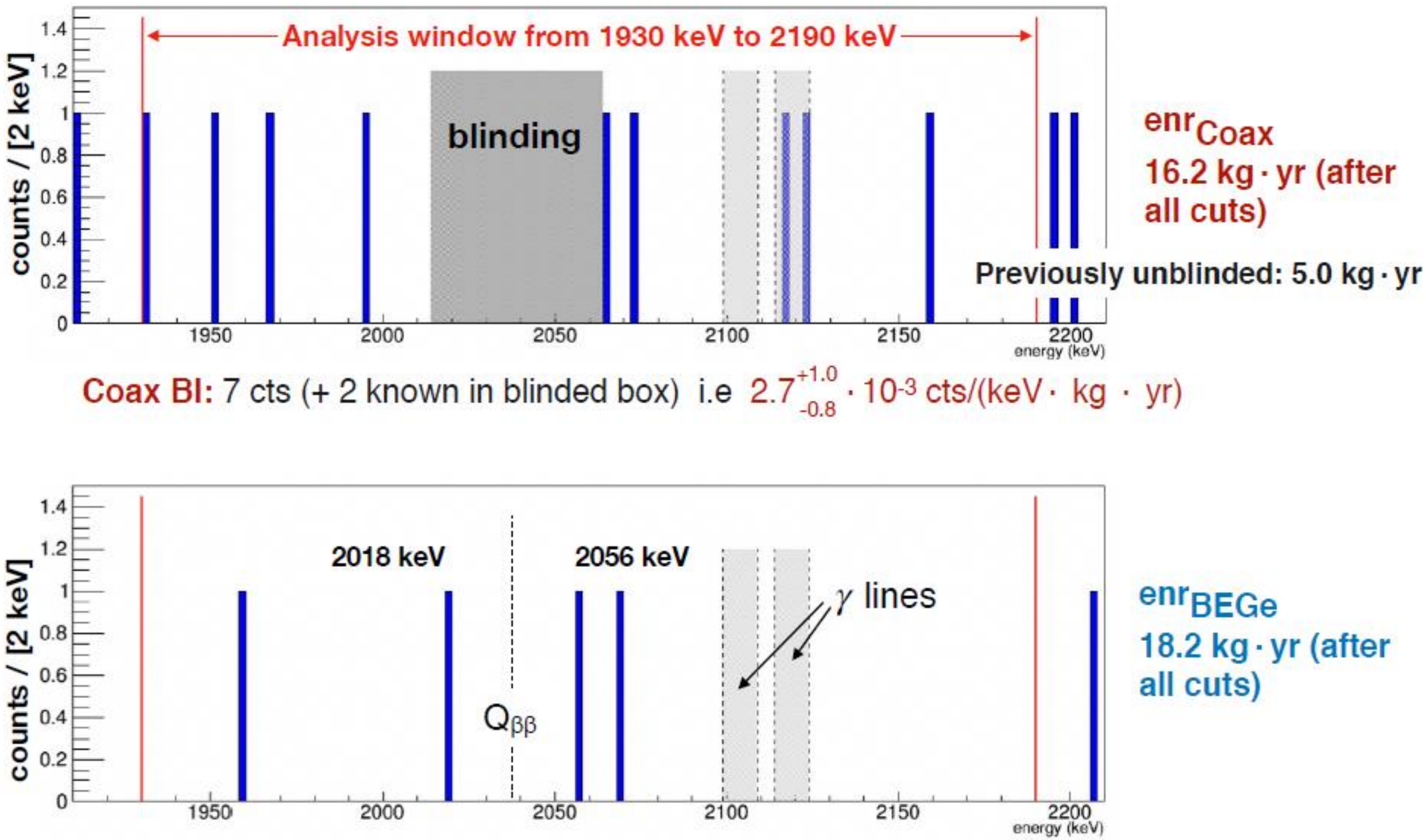
Coax BI: 7 cts (+ 2 known in blinded box) i.e $2.7^{+1.0}_{-0.8} \cdot 10^{-3}$ cts/(keV · kg · yr)



^{enr}BEGe
18.2 kg · yr (after all cuts)

BEGe BI: 2 cts i.e $0.5^{+0.5}_{-0.3} \cdot 10^{-3}$ cts/(keV · kg · yr)

Spectra in the ROI



enrCoax
16.2 kg · yr (after all cuts)

Coax BI: 7 cts (+ 2 known in blinded box) i.e $2.7^{+1.0}_{-0.8} \cdot 10^{-3}$ cts/(keV · kg · yr)

enrBEGe
18.2 kg · yr (after all cuts)

BEGe BI: 2 cts + 2 new (>10σ from $Q_{\beta\beta}$) i.e $1.0^{+0.6}_{-0.4} \cdot 10^{-3}$ cts/(keV · kg · yr)

Statistical analysis

- **Frequentist (preliminary results):**

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

$T^{0\nu}_{1/2} > 8.0\cdot10^{25}$ **yr @ 90% C.L.**

It was $5.3\cdot10^{25}$ yr in Phase Iia

Median Sensitivity (NO Signal)

$T^{0\nu}_{1/2} > 5.8\cdot10^{25}$ **yr @ 90% C.L.**

30% of MC realizations yield limit stronger than data

- upper limit on $m_{\beta\beta} < 0.12 - 0.27$ **eV**

- **Bayesian (preliminary results):**

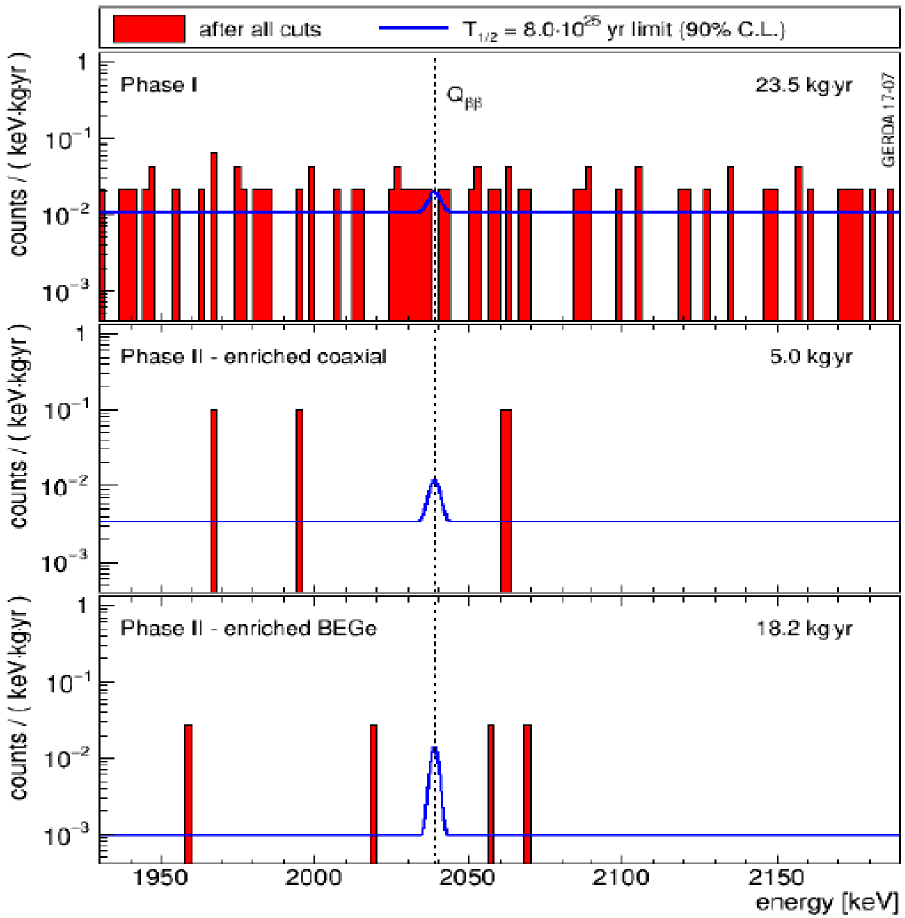
$T^{0\nu}_{1/2} > 5.1\cdot10^{25}$ **yr @ 90% C.I.**

Median Sensitivity:

$T^{0\nu}_{1/2} > 4.5\cdot10^{25}$ **yr @ 90% C.I.**

	Exposure (kg·yr)
Phase I (4 sets)	23.5
Phase II – coax	5.0
Phase II – BeGe	5.8+12.4 = 18.2

Tot = 46.7 kg· yr



Conclusions

- GERDA is running smoothly and with high efficiency
- We have collected more than 35 kg·yr of really good data: **i.e. more than 1/3 of Phase II exposure (100 kg·yr)**
- With the present release we have obtained:
  - ✓ Limit on $T_{1/2}^{0\nu} > 8.0 \cdot 10^{25}$ yr (90% CL)
  - ✓ Median Sensitivity: $5.8 \cdot 10^{25}$ yr (better than KamLandZen)
  - ✓ **BI(^{enr}Coax):** $2.7^{+1.0}_{-0.8} \cdot 10^{-3}$ cts/(keV· kg · yr)
  - ✓ **BI(^{enr}BEGe):** $1.0^{+0.6}_{-0.4} \cdot 10^{-3}$ cts/(keV ·kg · yr)
  - ✓ $m_{\beta\beta} < 0.12 – 0.27$ eV
- With more data we confirm to have reached our background index goal
- Lowest bkg (~10x) in ROI w.r.t experiments using other isotopes
- <1 bkg within 1*FWHM at 100 kg*yr: first background-free experiment in the field
- Next year we are ready to break the wall of 10^{26} yr in median sensitivity
- **This result suggests future Ge experiments with 200 kg and beyond (LEGEND)**

LEGEND experiment

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

219 members, **48** institutions, **16** countries

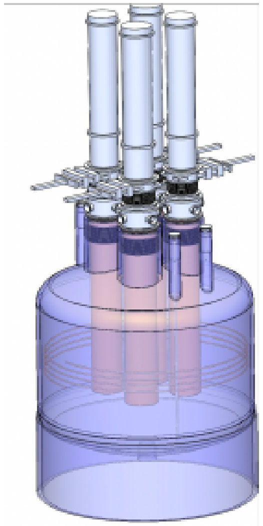
Collaboration in starting phase

2 Cospokespersons:
S. Elliott, S. Schönert

Aim of LEGEND

"The collaboration aims to develop a phased Ge76 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 experiment phases



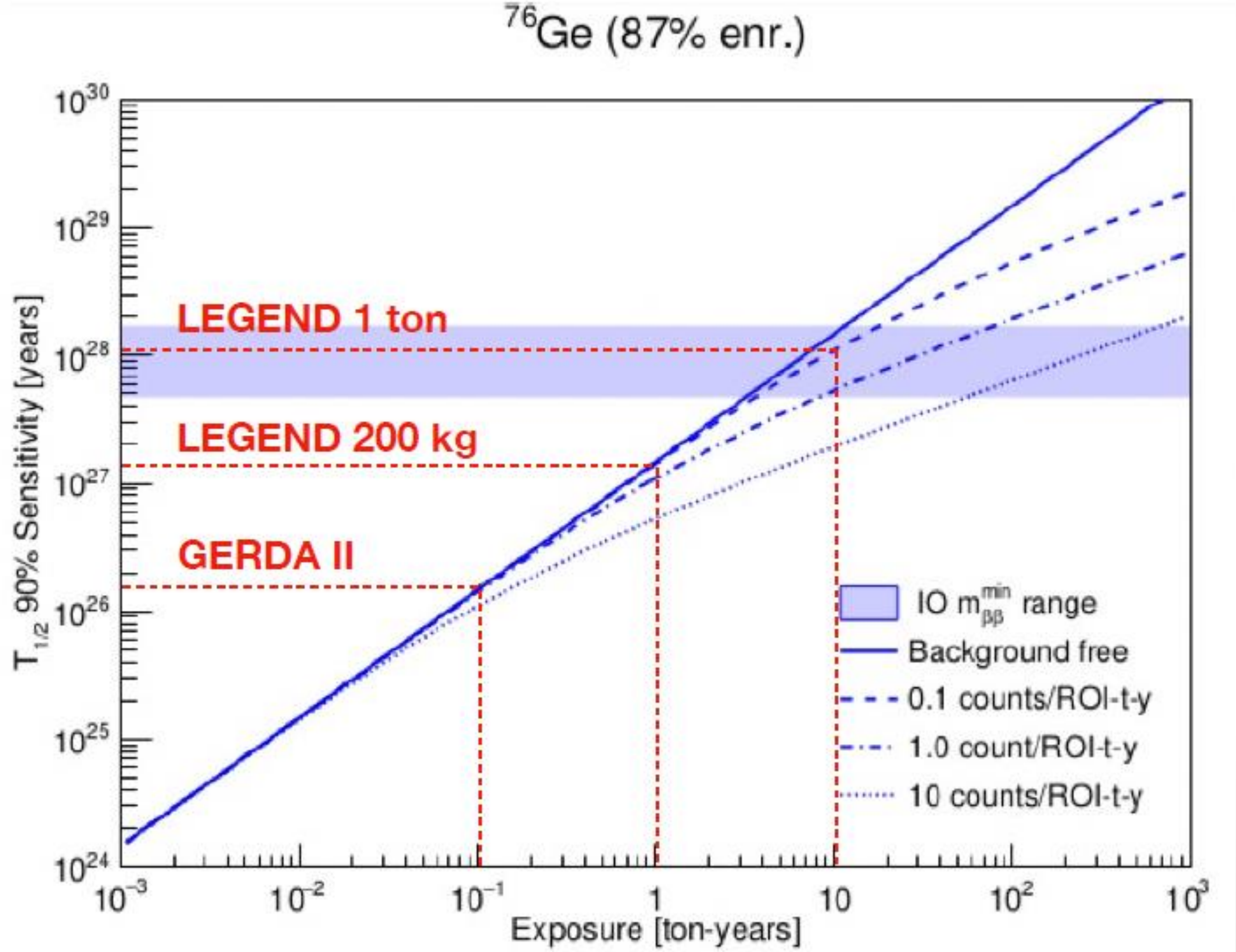
Phase I

- upgrade of existing GERDA infrastructure @ LNGS up to 200 kg
- Reduction of BI down to 0.6 counts /(FWMH t y) i.e a factor 5 w.r.t GERDA Phase II
- 35 kg from GERDA + 30 kg from Majorana exp + 20 kg from the GERDA Phase II upgrade + the rest to be purchased
- Start by 2021

Phase II

- up to 1000 kg (towards successive steps)
- reduction of BI to 0.1 counts /(FWMH t y) i.e a factor 30 w.r.t GERDA Phase II
- location to be defined
- timeline connected with the U.S DOE selection program

LEGEND performances



BACKUP

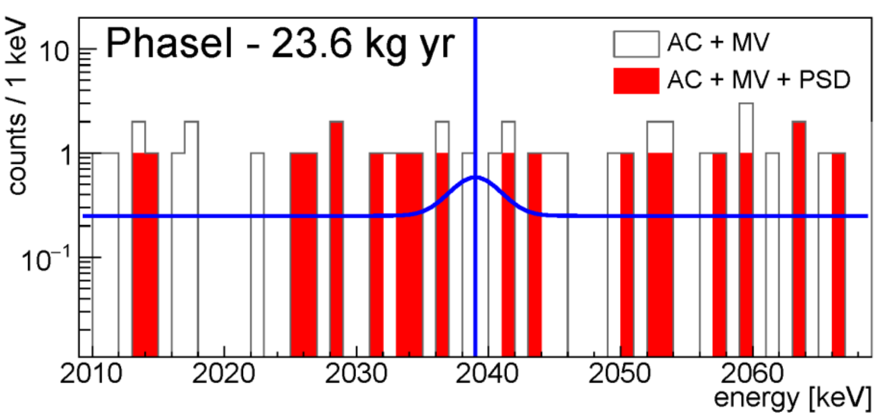
ARTICLE
Nature 544 (2017) 47
doi:10.1038/nature21717

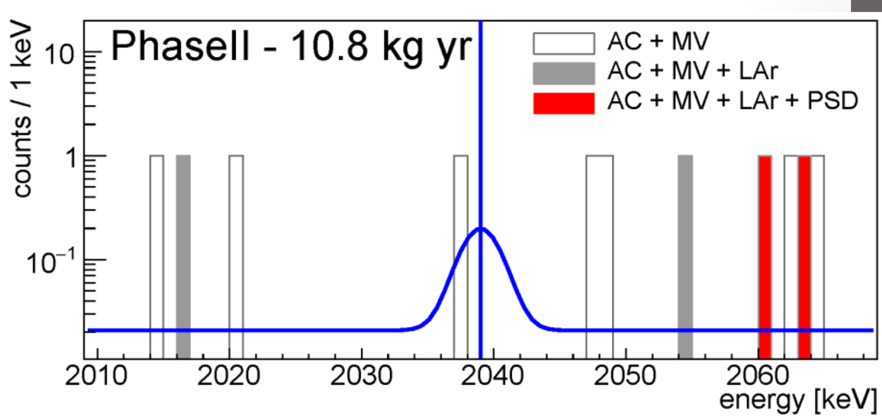
Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA

The GERDA Collaboration*

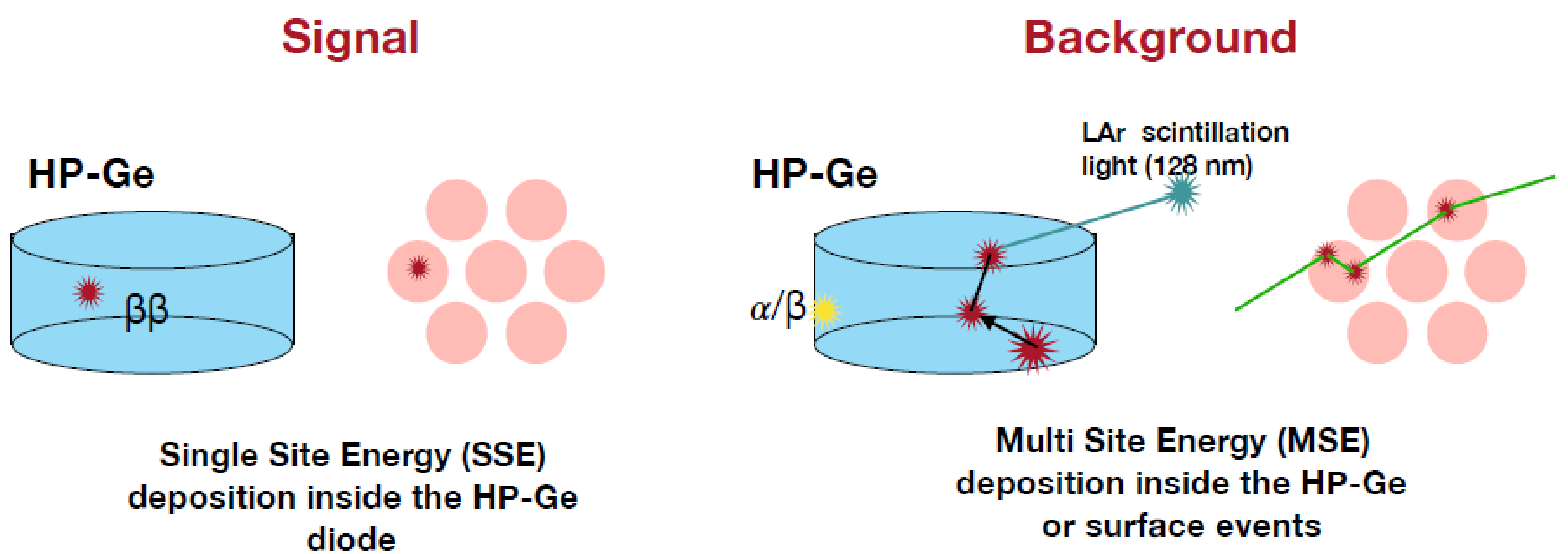
Previous Phase II results

- New limit on ^{76}Ge $T_{1/2}$ (Phase I+II)
  - **$T_{1/2}$ > 5.3·10^{25} yr @ 90% CL** (median sensitivity 4.0·10^{25} yr)
- **Background < 1 cts** for the full **design exposure**
  - Coax: **$3.5^{+2.1}_{-1.5}$ ·10^{-3}** cts/(keV·kg·yr), FWHM: 4.0(2) keV
  - BEGe: **7^{+11}_{-5} ·10^{-4}** cts/(keV·kg·yr), FWHM: 3.0(2) keV
- Bck/ε = 3.5 cts/(FWHM ton yr) [BEGe]



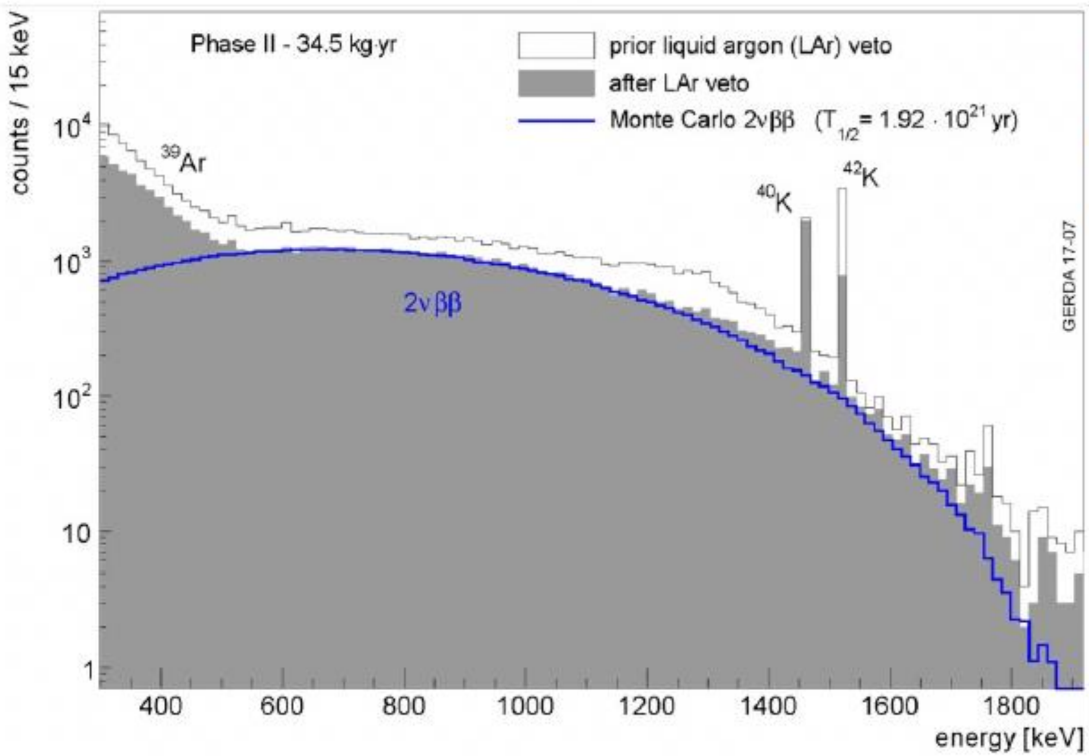


Background reduction



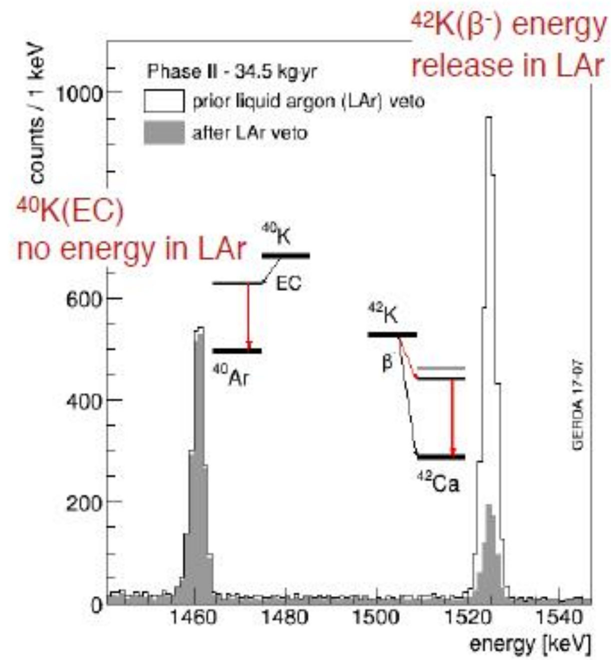
- Anticoincidence with the muon veto: **MV**
- Anticoincidence between detectors (cuts multi site): **AC**
- Active veto using LAr scintillation: **LAr Veto**
- Pulse shape discrimination: **PSD**

LAr veto background suppression



γ-lines from:

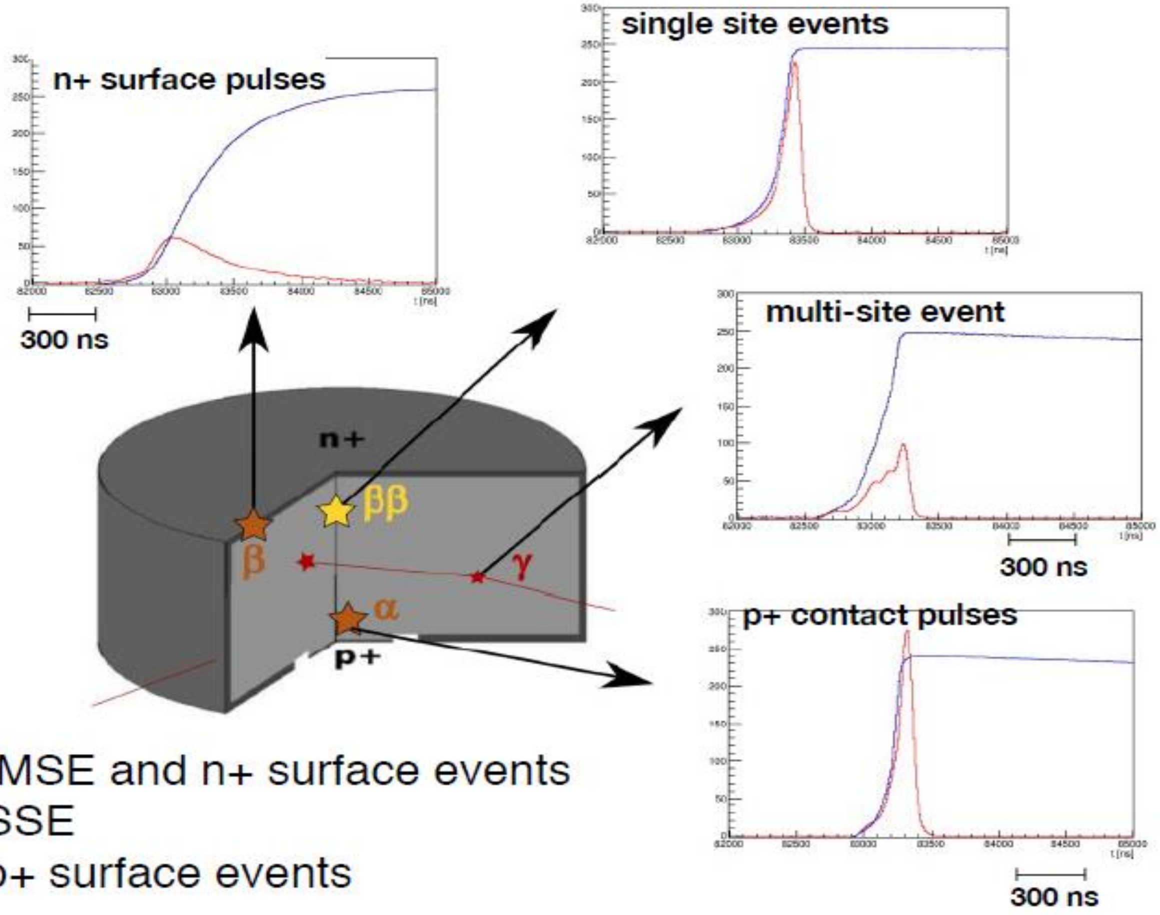
- $^{40}K \longrightarrow {}^{40}Ar + \gamma$ (1.4 MeV) [EC]
- $^{42}K \longrightarrow {}^{42}Ca + \gamma$ (1.5 MeV) + e^- (up to 2 MeV)



- $^{40}K/^{42}K$ Compton continuum fully suppressed
- LAr veto generates 2.3% dead time
- $T^{2\nu}_{1/2} = 1.92 \cdot 10^{21}$ yr taken from GERDA Phase I

Pulse Shape Discrimination: BEGe

Event classification using the Current/Energy ratio, i.e. A/E variable



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

Statistical analysis

dataset	exposure [kg·yr]	FWHM [keV]	ϵ	BI [10^{-3}cts/(kevkgyr)]
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI silver	1.3	4.3(1)	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}
PIIa coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PIIb BEGe	**18.2**	**2.9(1)**	**0.60(2)**	$\mathbf{1.0^{+0.6}_{-0.4}}$

GERDA
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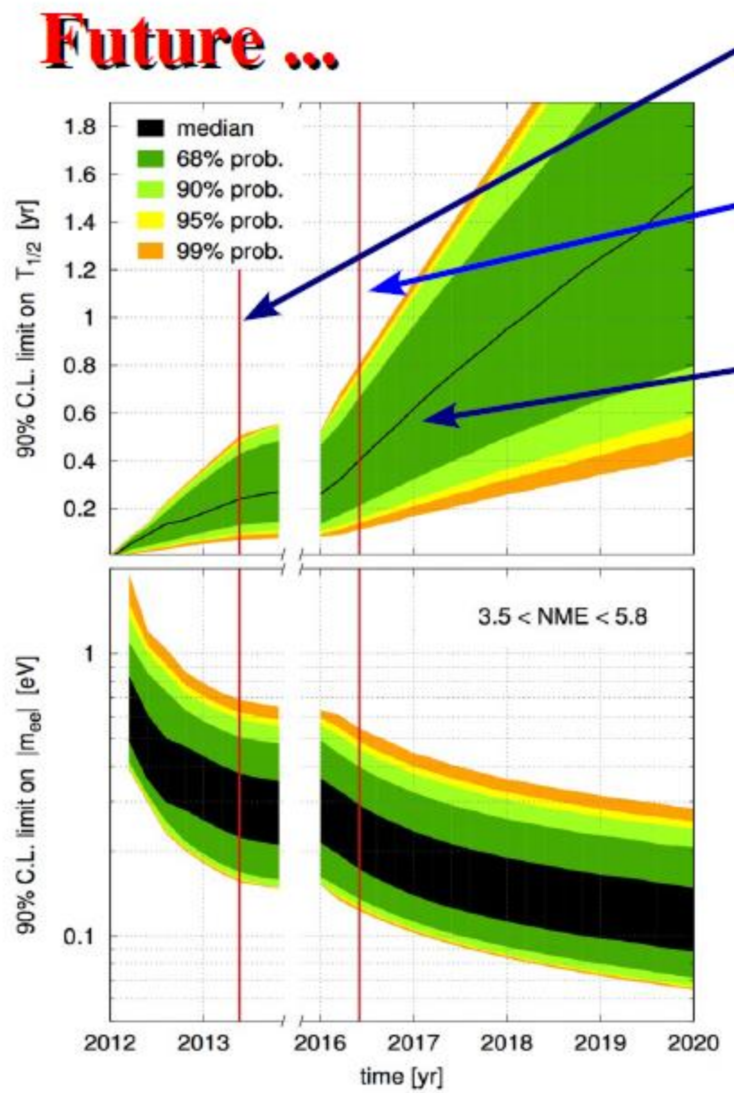
Total exposure 46.7 kg

Combined unbinned maximum likelihood fit (flat background + gaussian signal) of the 6 spectra:

- **Frequentist**: test statistics and method as in Cowan et al., EPJC 71 (2011)1554 (2 side test statistics)
- **Bayesian**: flat prior on $1/T_{1/2}^{0\nu}$ between 0 and 10^{-24} yr^{-1}
- Systematic uncertainties folded as pull terms or by Monte Carlo

Next steps



- **Phase I:** (23.5 kg·yr)
  - Sensitivity: **$2.4 \cdot 10^{25}$ yr**
  - Limit: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% CL)
- **Phase II a**: (Phase I + **10.8 kg·yr**)
  - Sensitivity: **$4.0 \cdot 10^{25}$ yr**
  - Limit: $T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr (90% CL)
- **This release** (Phase IIa + **12.4 kg·yr**)
  - Sensitivity: **$5.8 \cdot 10^{25}$ yr**
  - Limit: $T^{0\nu}_{1/2} > 8.0 \cdot 10^{25}$ yr (90% CL)
- Already available:
  - **11.2 kg·yr** of validated coax data
  - **~5 kg·yr** of data (Coax & BEGe) taken after Apr 15th
- The sensitivity of **10^{26} yr** will be reached in the middle of **2018**
- Final goals:
  - 100 kg·yr @ BI = 10^{-3} cts/(keV·kg·yr)
  - Sensitivity: **$1.3 \cdot 10^{26}$ yr**
  - Discovery potential up to **10^{26} yr** (*50% prob. chance for a 3σ* signal)