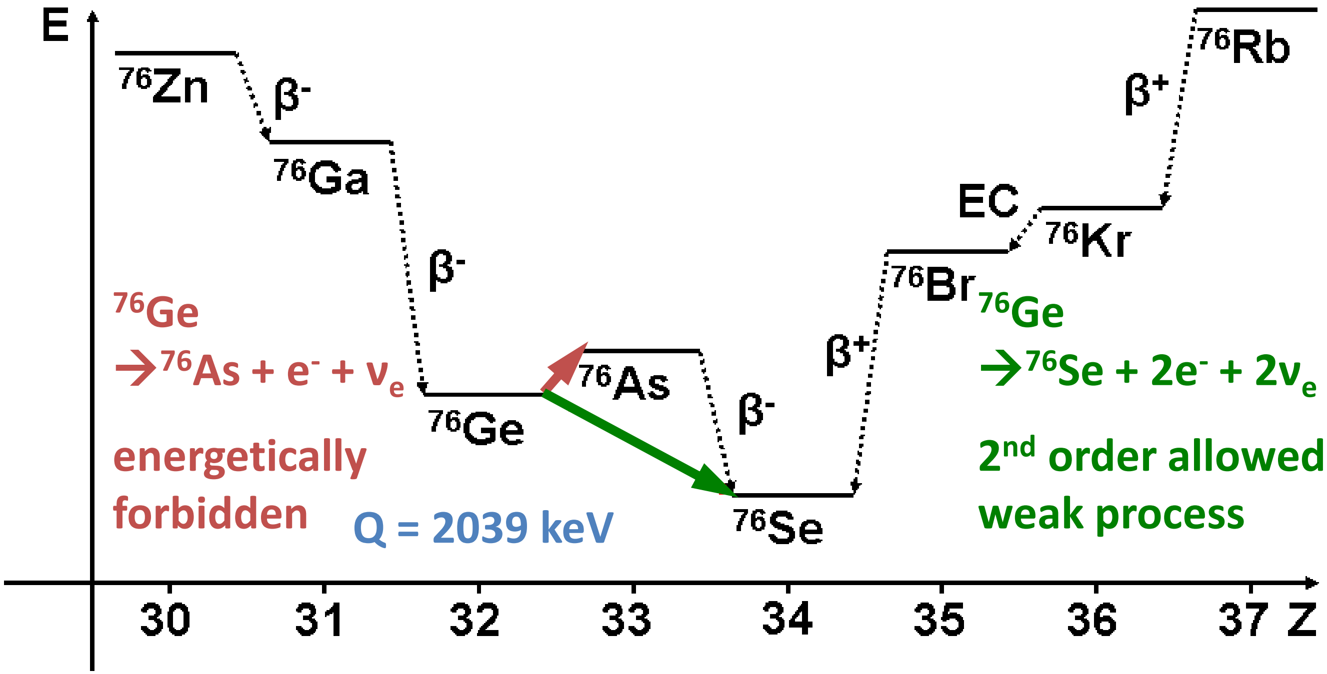
GERDA:
first background free search for neutrinoless double beta decay

Konstantin Gusev
for the GERDA collaboration

ICNFP 2017
August 2017 – Crete – Greece

Short intro in 0νββ-decay

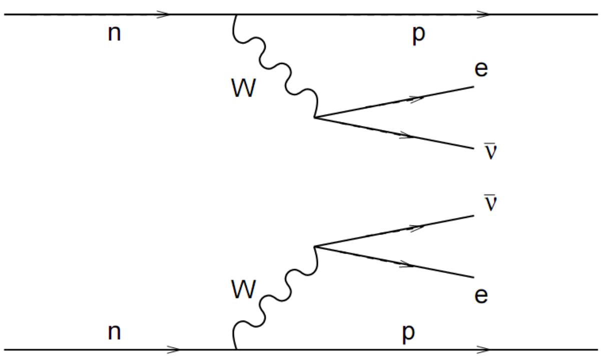


- ✓ In 1936 Maria Göppert-Mayer noted, that in some even-even nuclei the single β-decay is energetically forbidden whereas the simultaneous but independent β-decay of two nucleons (so-called double beta decay) is allowed

Short intro

Why (0ν)ββ-decay?

2νββ

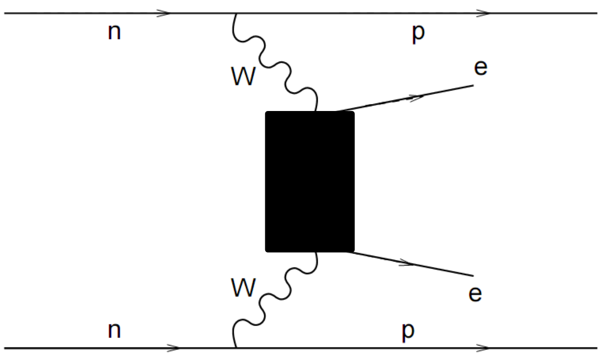


- violates lepton number? **NO**
- forbidden in SM? **NO**

- but half life is 10^{10} longer than the age of the universe, however already observed!

^{76}Ge: $T_{1/2}^{2\nu} = 1.92 \times 10^{21}\mathrm{yr}$

0νββ



- violates lepton number? **YES!**
- forbidden in SM? **YES!**

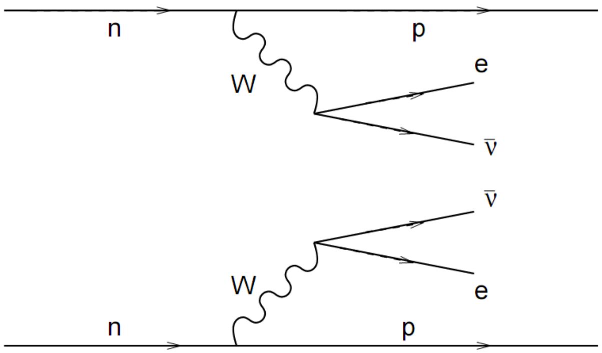
New Physics!

- **ν** has **Majorana** mass component

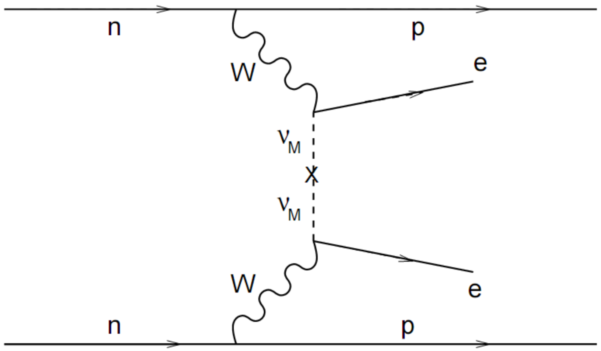
Short intro

Why (0ν)ββ-decay?

2νββ



0νββ



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- violates lepton number? **YES!**
- forbidden in SM? **YES!**

New Physics!

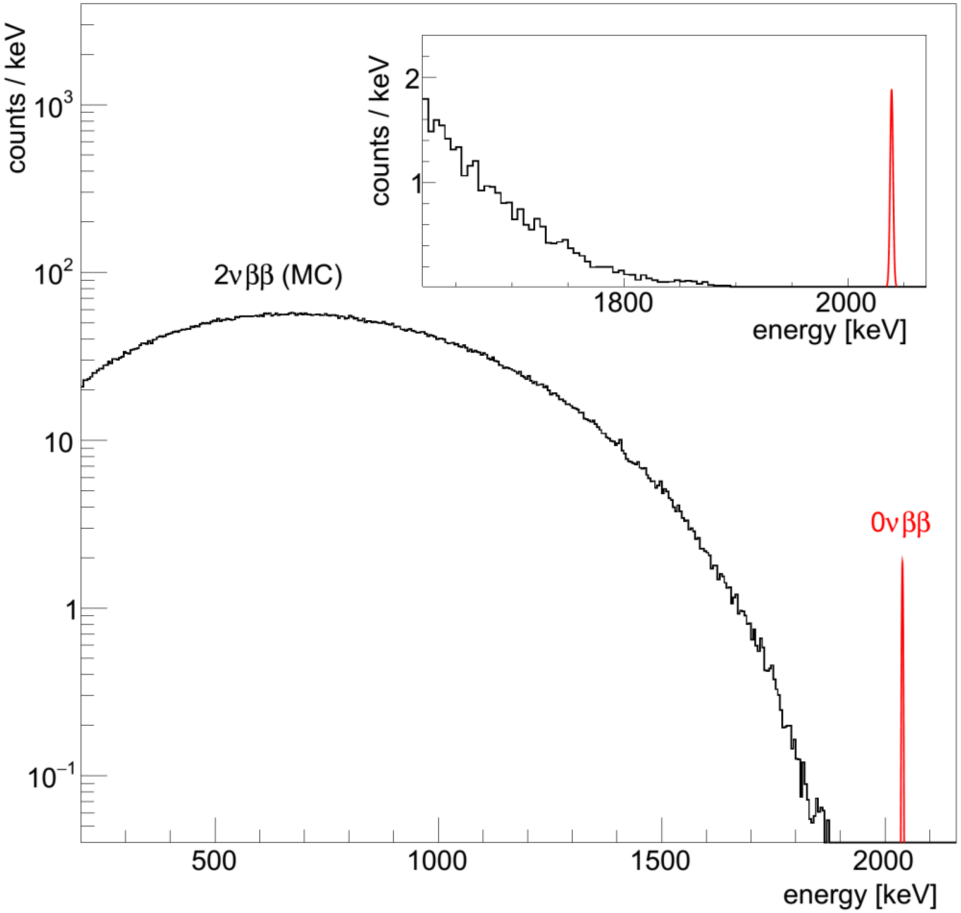
- **ν** has **Majorana** mass component
- **IF** light neutrino exchange

Access to ν mass scale

Short intro

What are we measuring?

Summed electron spectrum (^{76}Ge):



0νββ:

Sharp peak at Q-value of the decay

$T_{1/2}^{0\nu} > 10^{25}\mathrm{yr}$

2νββ:

Continuous spectrum

$T_{1/2}^{2\nu} \sim 10^{21}\mathrm{yr}$

↳ **Background for 0νββ**

⇓

Energy resolution essential

Short intro

What about mass?

Effective Majorana neutrino mass contributes in the decay rate:

Phase space factor

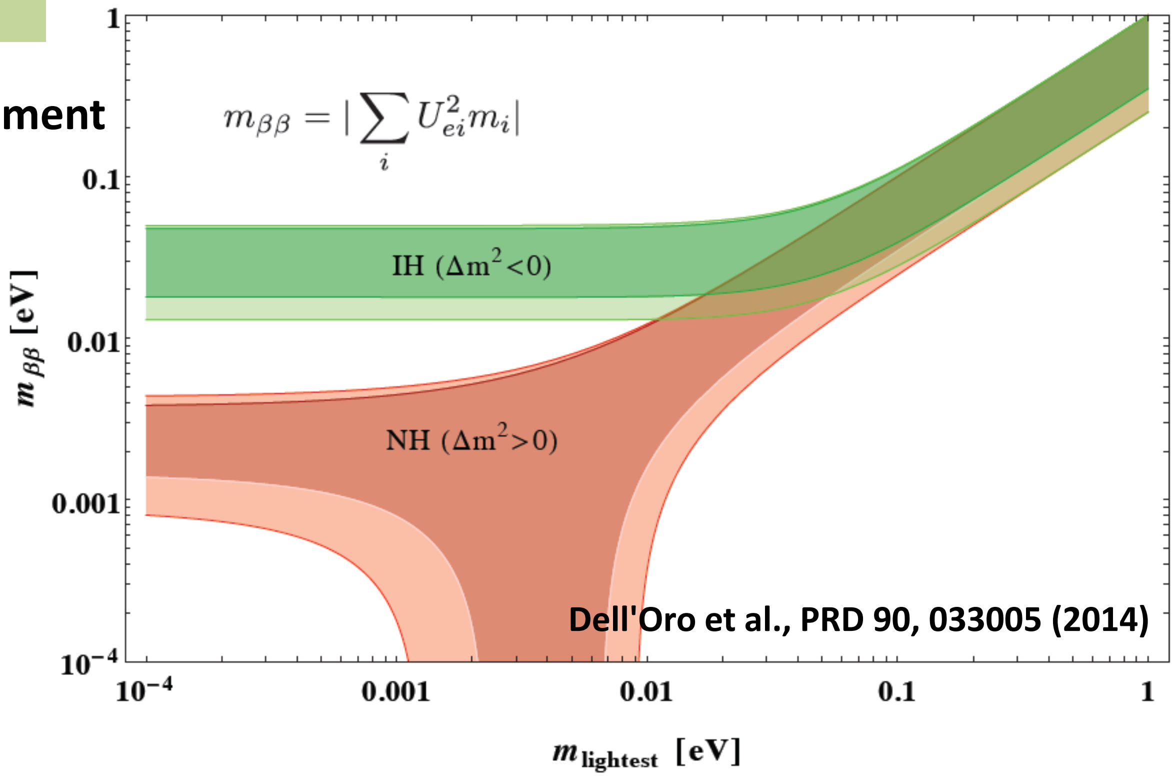
Effective Majorana neutrino mass

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

0νββ decay rate

Matrix element (NME)

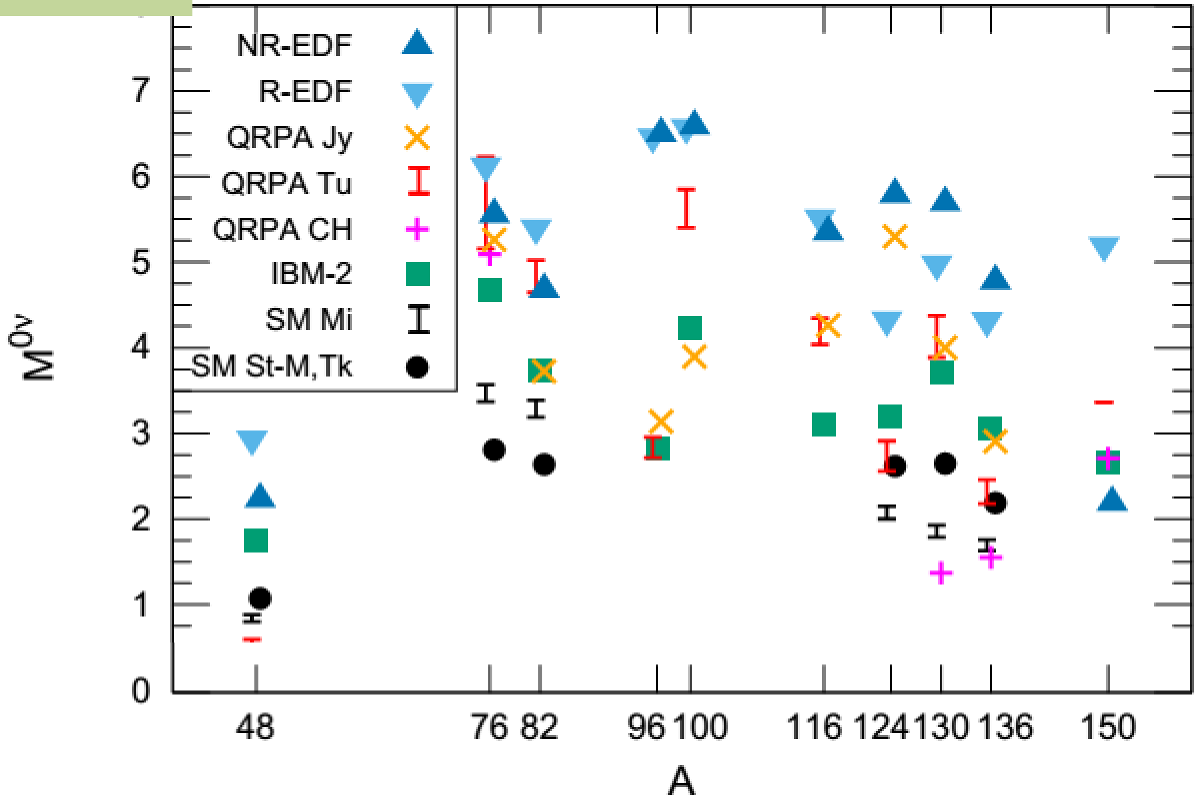
$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 \, m_i \right|$$



Short intro

NME

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$



Engel & Menéndez
arXiv: 1610.06548v2

- ✓ No preferred isotope from Nuclear Physics (G*M)

Short intro

How to measure?

Experimental sensitivity:

- **Zero** background:

$$T_{1/2}^{0\nu} \propto M\, t$$

- Non-zero background:

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M\, t}{\Delta E\; BI}}$$

$M\, t$ – exposure (kg yr)

ΔE – energy resolution (keV)

BI – background index (counts/keV kg yr)

Isotope	$G^{0\nu}$ (10^{-14}yr)	$Q(\text{keV})$	Nat. ab. (%)
^{48}Ca	6.3	4273.7	0.187
^{76}Ge	0.63	2039.1	7.8
^{82}Se	2.7	2995.5	9.2
^{100}Mo	4.4	3035.0	9.6
^{130}Te	4.1	2530.3	34.5
^{136}Xe	4.3	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

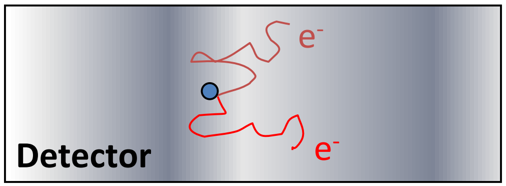
enrichment required except for ^{130}Te, not (yet) possible for all, costs differ

✓ Target mass and detector efficiency as high as possible

✓ "**Zero-background**" to have linear increase of sensitivity vs exposure

Short intro
Two experimental approaches

Source = Detector



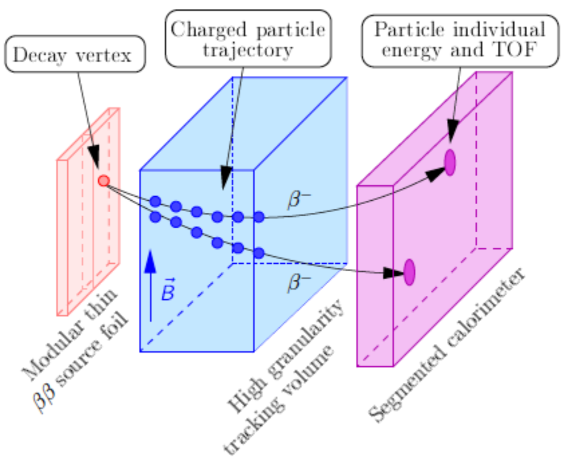
GERDA, Majorana, CUORE, EXO, Kamland-Zen, …

+ High detection efficiency
+ Large target mass possible

± Reconstruction of event topologies

– Restricted number of isotopes

Source ≠ Detector



SuperNEMO

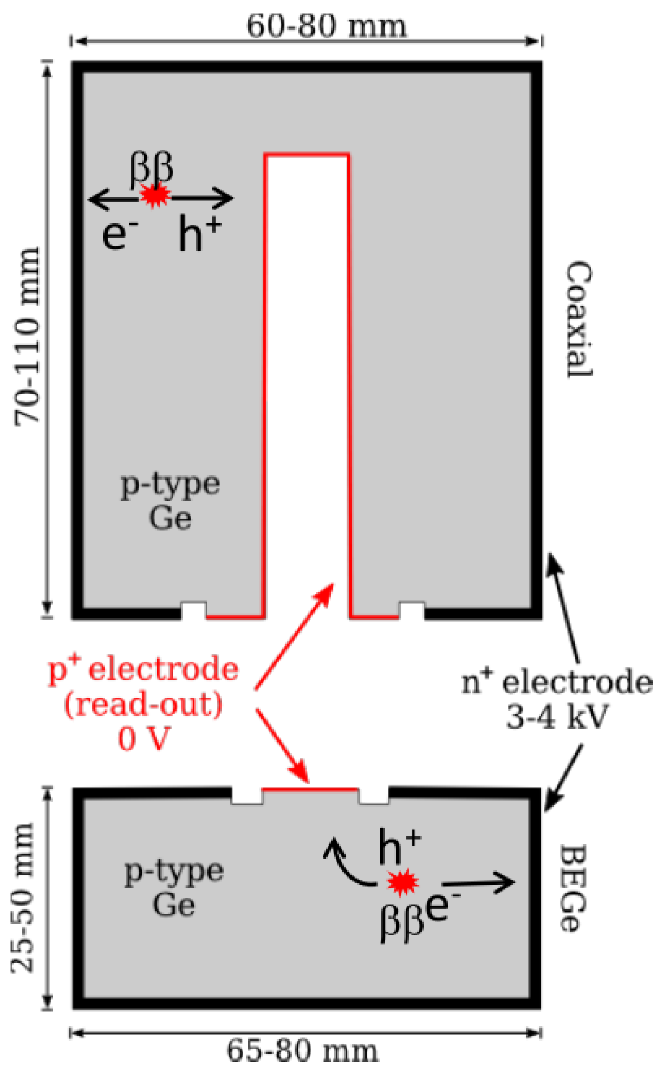
+ Reconstruction of event topologies
+ Coincidence scheme
→ zero background
+ No restriction on isotopes

– Difficult to obtain large masses

More about $0\nu\beta\beta$ searches on Aug 26th & ICNFP17 in B. Schwingenheuer's talk

GERDA approach

HPGe detectors enriched in ^{76}Ge



- ✓ detector-grade germanium is high-purity material
  - ⇒ low background
- ✓ established detector technology
  - ⇒ industrial support
- ✓ very good energy resolution
  - ~0.1% at $Q_{\beta\beta}$
- ✓ high detection efficiency
  - source = detector

GERDA approach

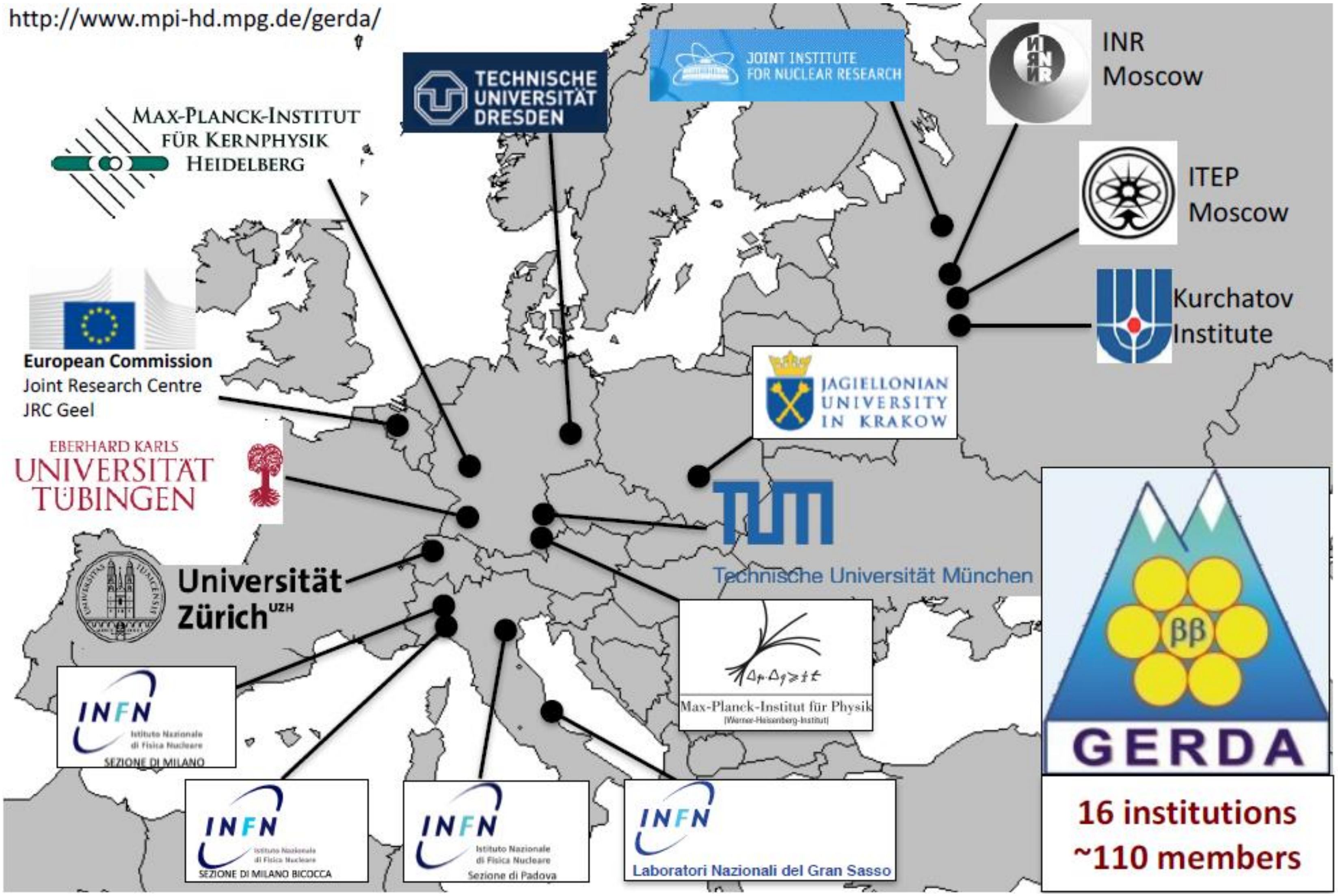
enriched HPGe detectors in cryogenic liquid

- ✓ detector-grade germanium is high-purity material
  ⇒ low background
- ✓ established detector technology
  ⇒ industrial support
- ✓ very good energy resolution
  ~0.1% at $Q_{\beta\beta}$
- ✓ high detection efficiency
  source = detector
- ✓ **bare** detectors in liquid argon

GERDA

the Collaboration

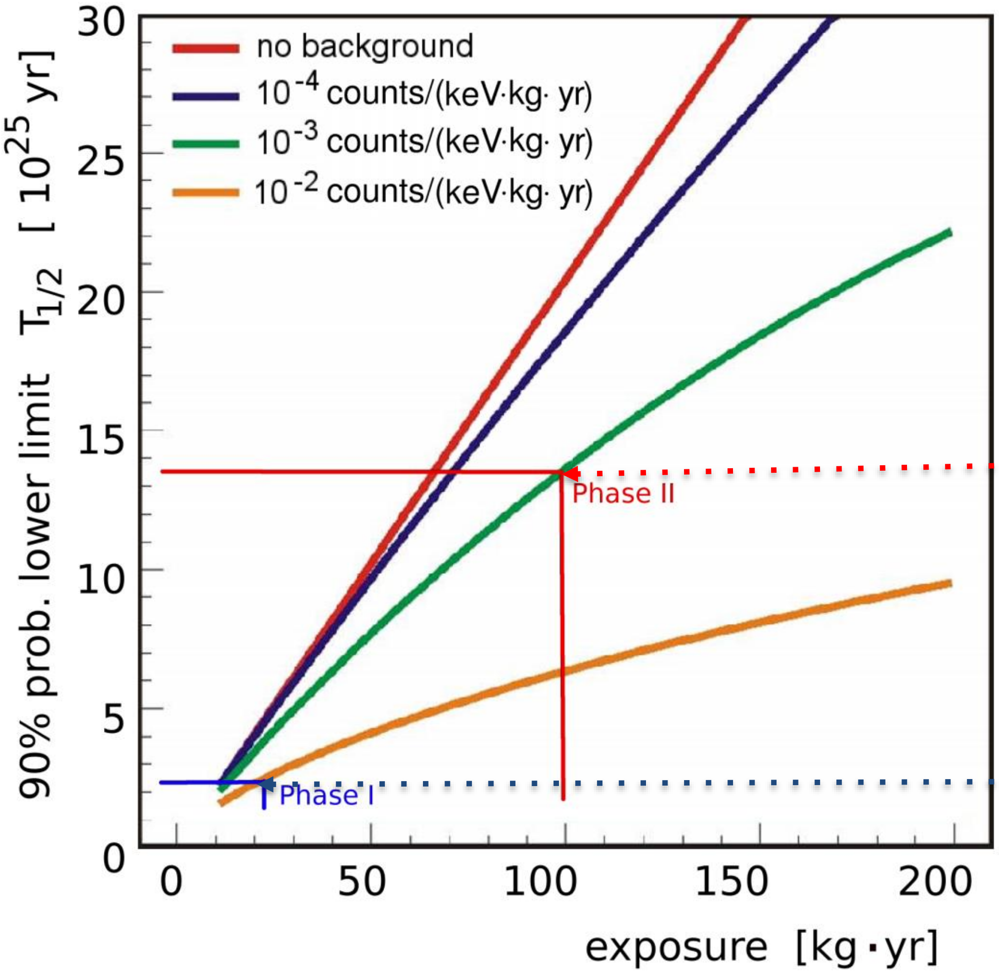
http://www.mpi-hd.mpg.de/gerda/



GERDA
the Collaboration

GERDA

Sensitivity



Phase II (Dec 2015 – ongoing):

Add new BEGe detectors (20 kg)

BI ≈ 0.001 cts / (keV kg yr)

Sensitivity after 100 kg yr

Phase I (Nov 2011 – May 2013):

Use refurbished HdM & IGEX (18 kg)

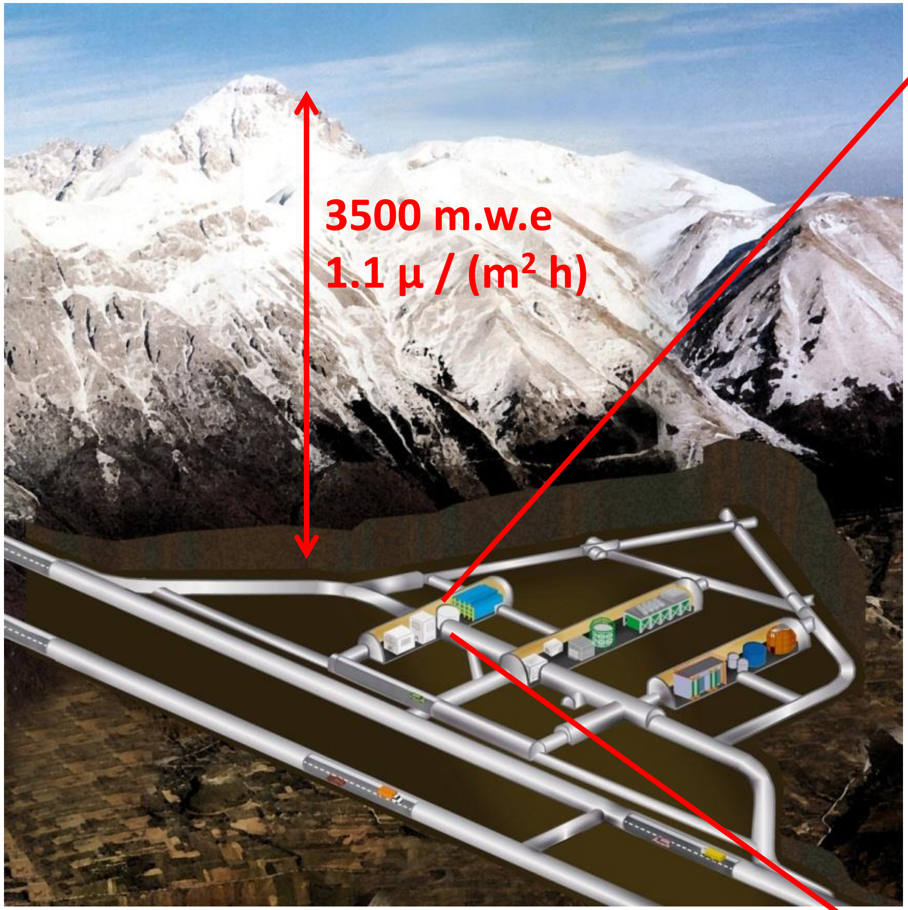
BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr

$$T^{0\nu}_{1/2} > 2.1 \times 10^{25}\ \text{yr}\ (90\%\ \text{CL})$$

(PRL 111 (2013) 122503)

GERDA
location

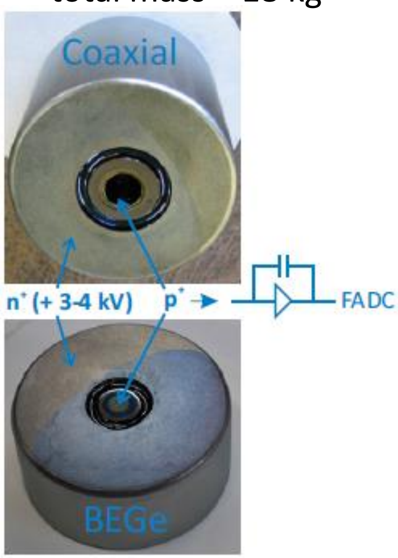


✓ deep underground – Hall A of **LNGS**, Italy

GERmanium **D**etector **A**rray

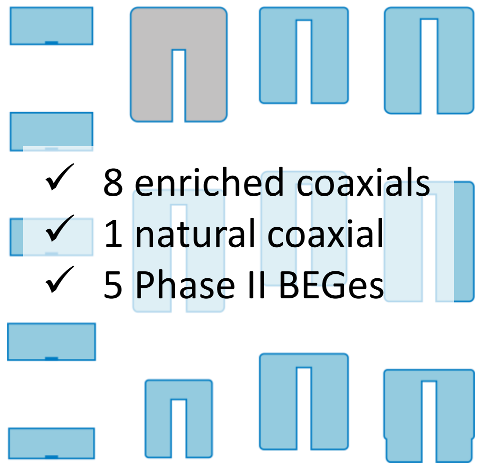
HPGe detectors

Coaxials:
- from HdM and IGEX
- reprocessed by Canberra
- total mass ~ 18 kg



BEGes:
- novel Ge detectors
- produced by Canberra
- total mass ~ 20 kg
- better **PSD** and **FWHM**

Phase I



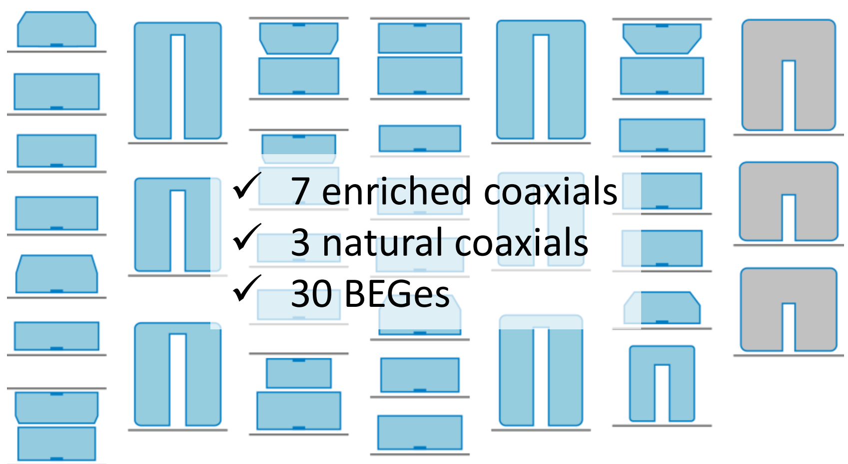
- ✓ 8 enriched coaxials
- ✓ 1 natural coaxial
- ✓ 5 Phase II BEGes

! **Bare Ge** detectors in **LAr** – **first** time ever

! Pulse shape discrimination (**PSD**)
+ **active** veto (in Phase II)

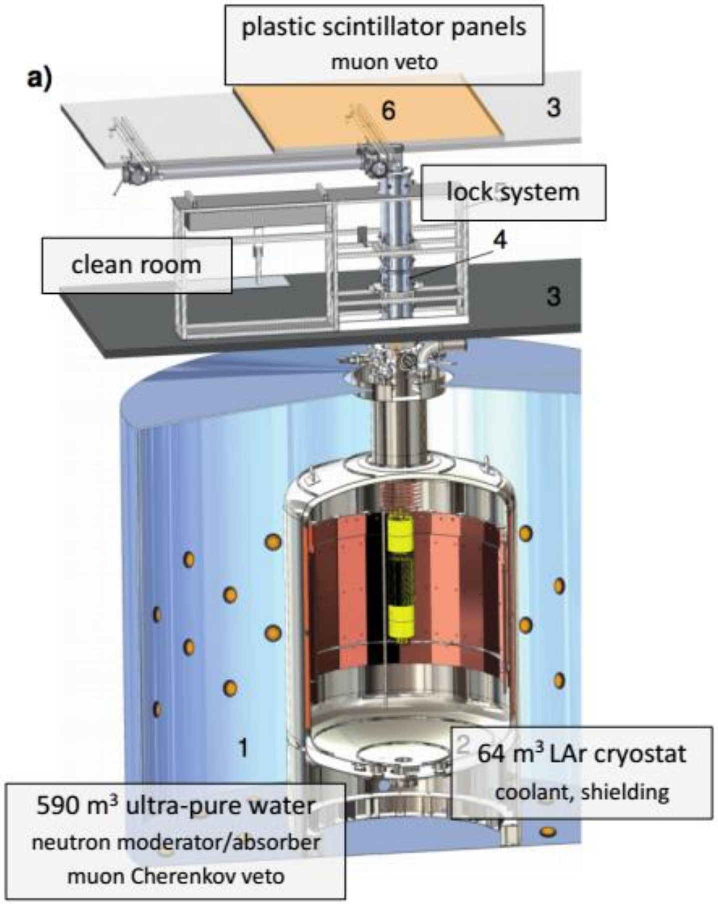
! **Blind analysis** – **first** time in the field

Phase II



- ✓ 7 enriched coaxials
- ✓ 3 natural coaxials
- ✓ 30 BEGes

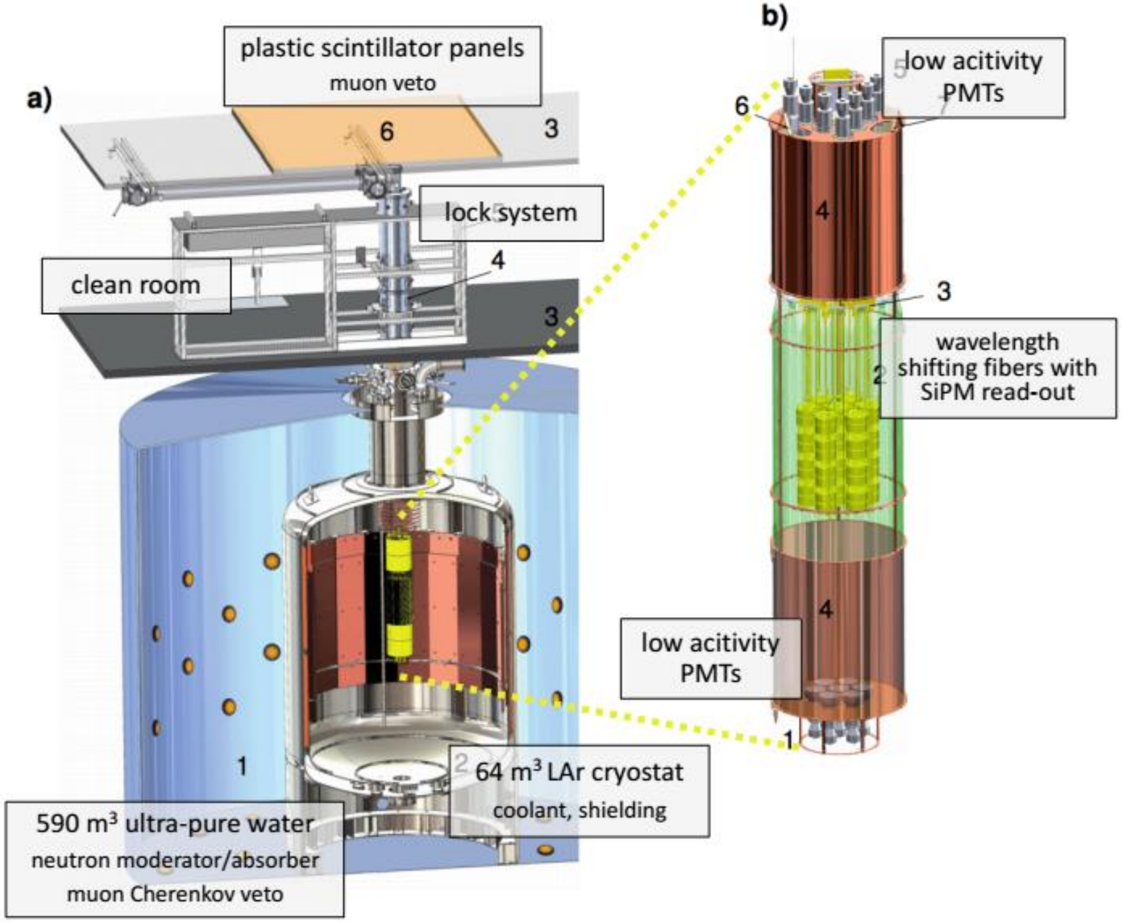
GERDA
Design



a) overview

GERDA

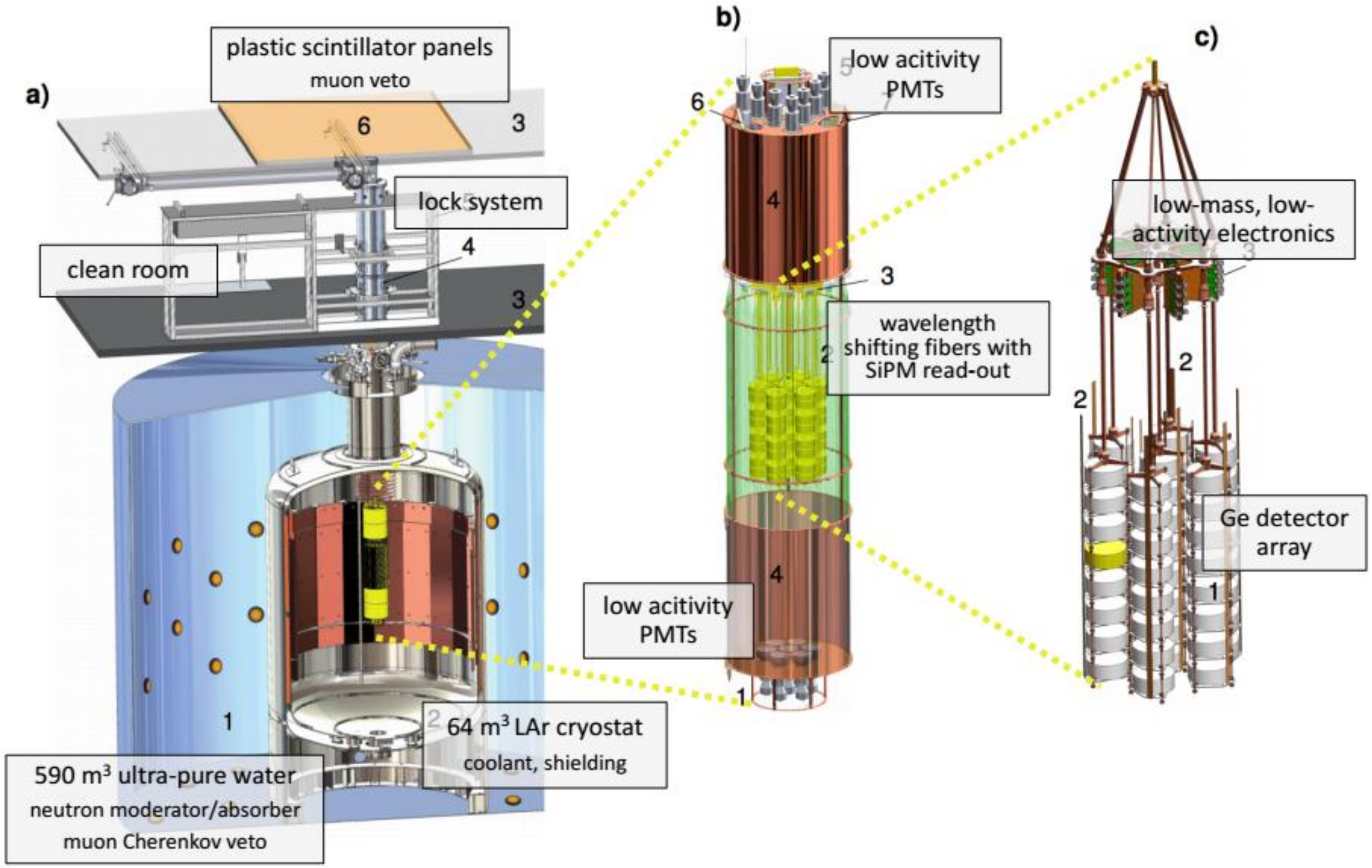
Design



a) overview

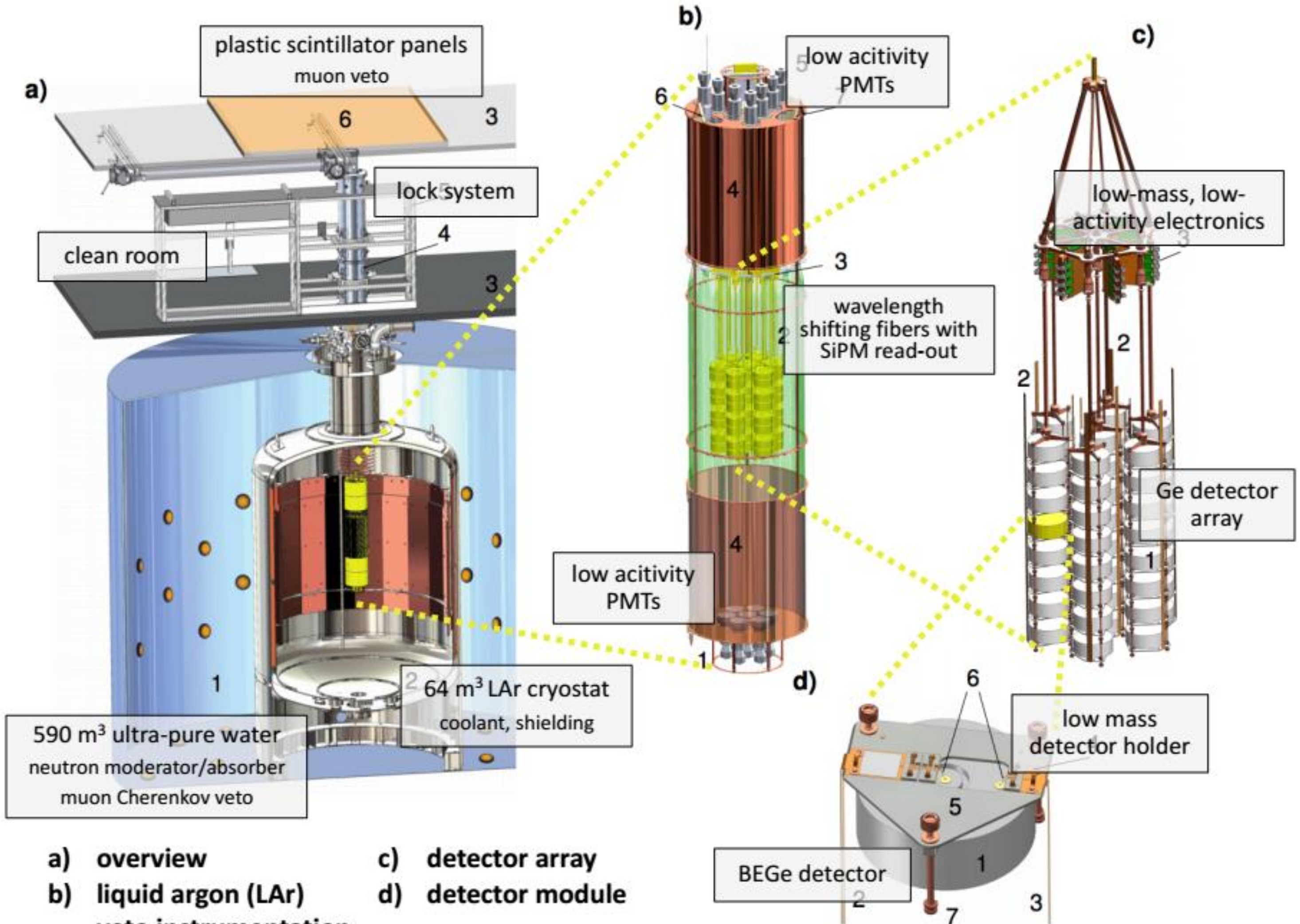
b) liquid argon (LAr) veto instrumentation

GERDA
Design



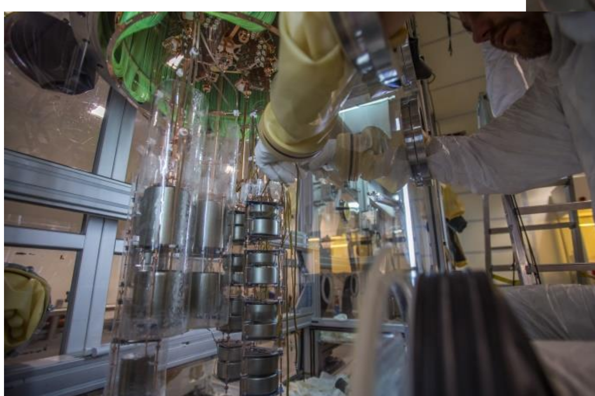
a) overview
b) liquid argon (LAr) veto instrumentation
c) detector array

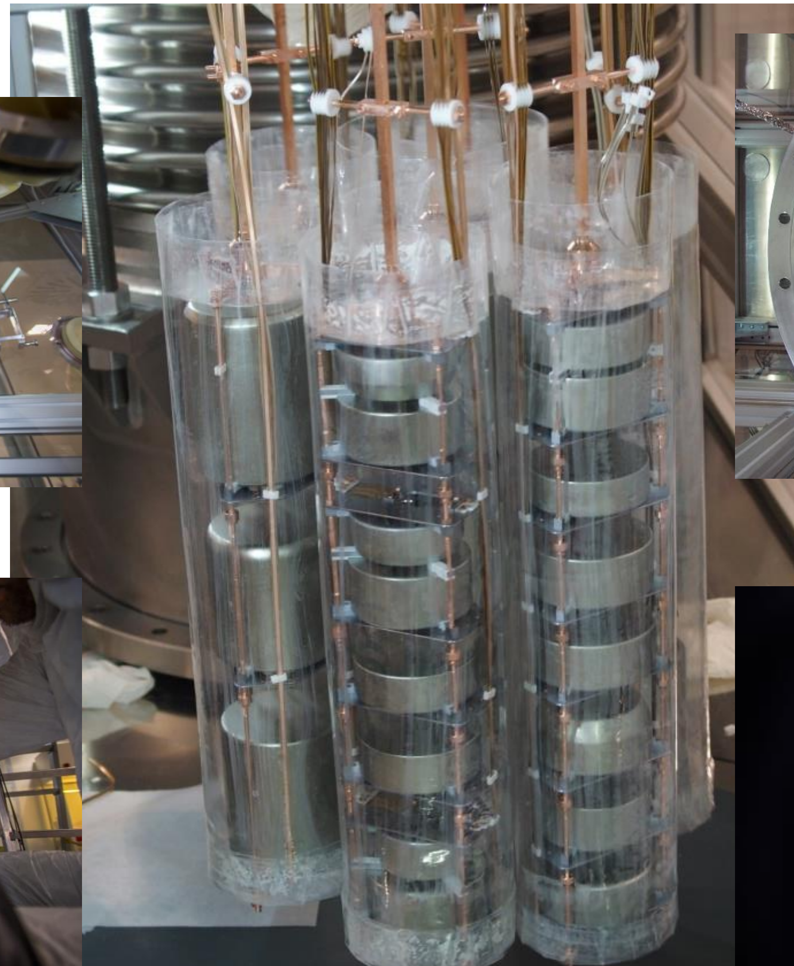
GERDA
Design



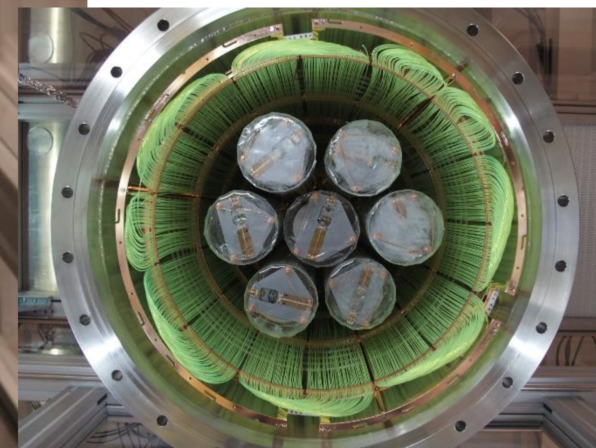
a) overview
b) liquid argon (LAr) veto instrumentation
c) detector array
d) detector module

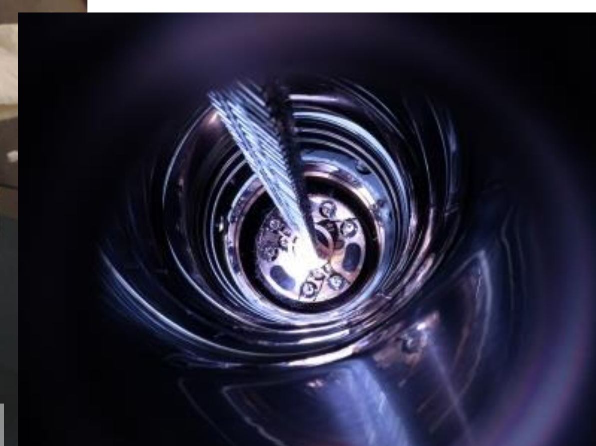
GERDA Phase II
Final integration (Dec 2015)





All 40 channels working!!!





GERDA Phase II
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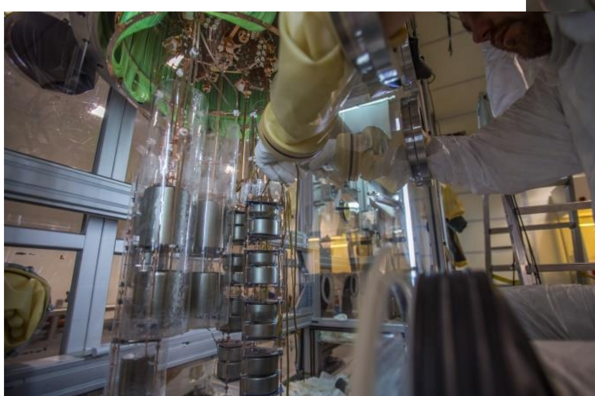
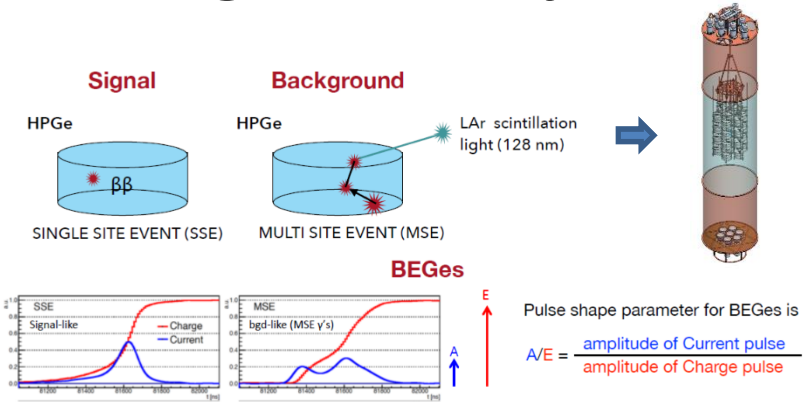
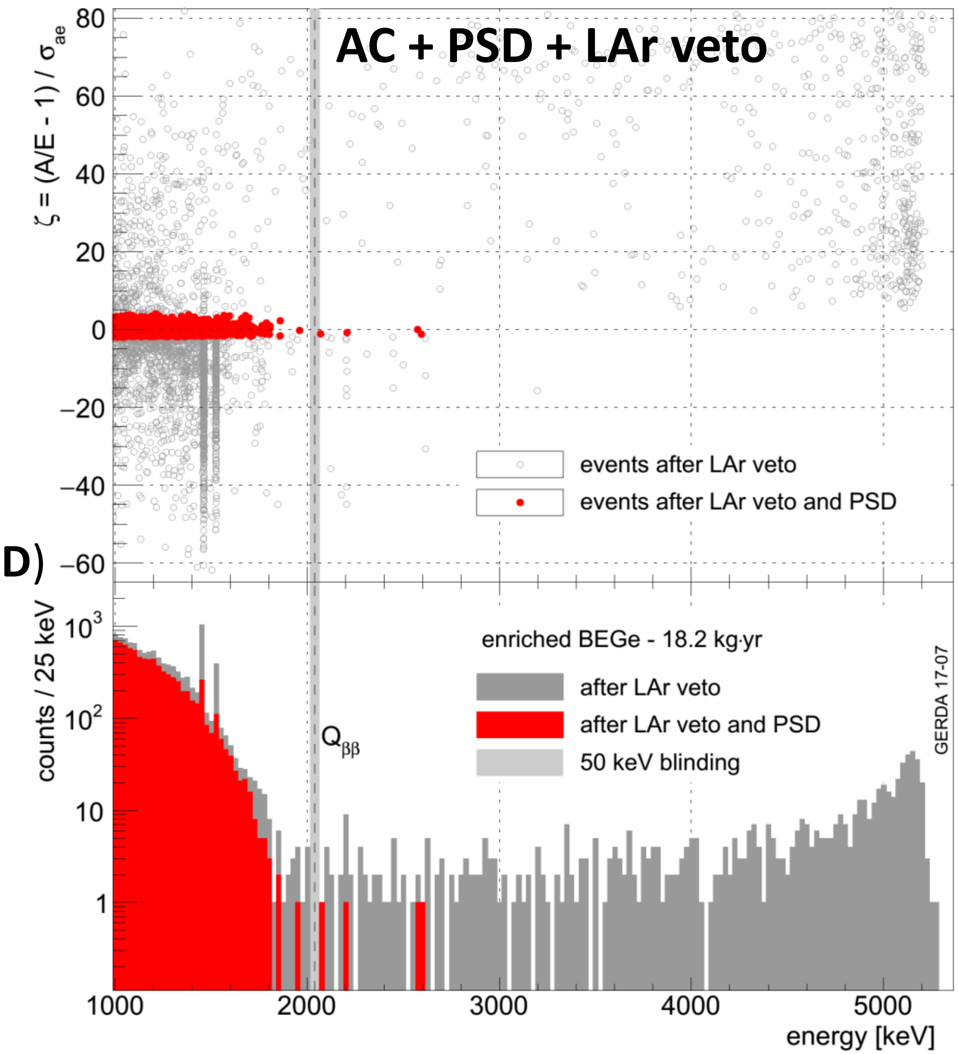


GERDA
Background rejection





Background:

Multi-site energy deposition:

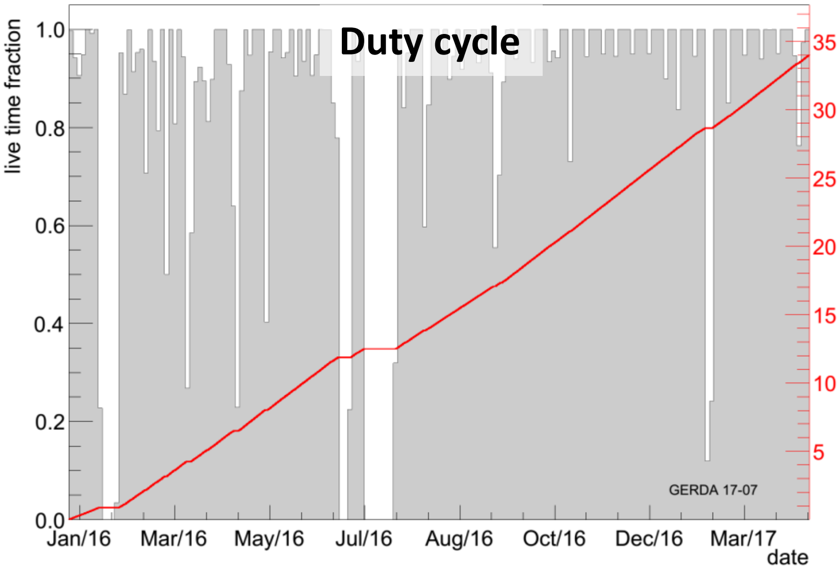
- 1 HPGe – Pulse Shape Discrimination (**PSD**)
- > 1 HPGe – anti-coincidence (**AC**)
- HPGe + LAr – **LAr veto**

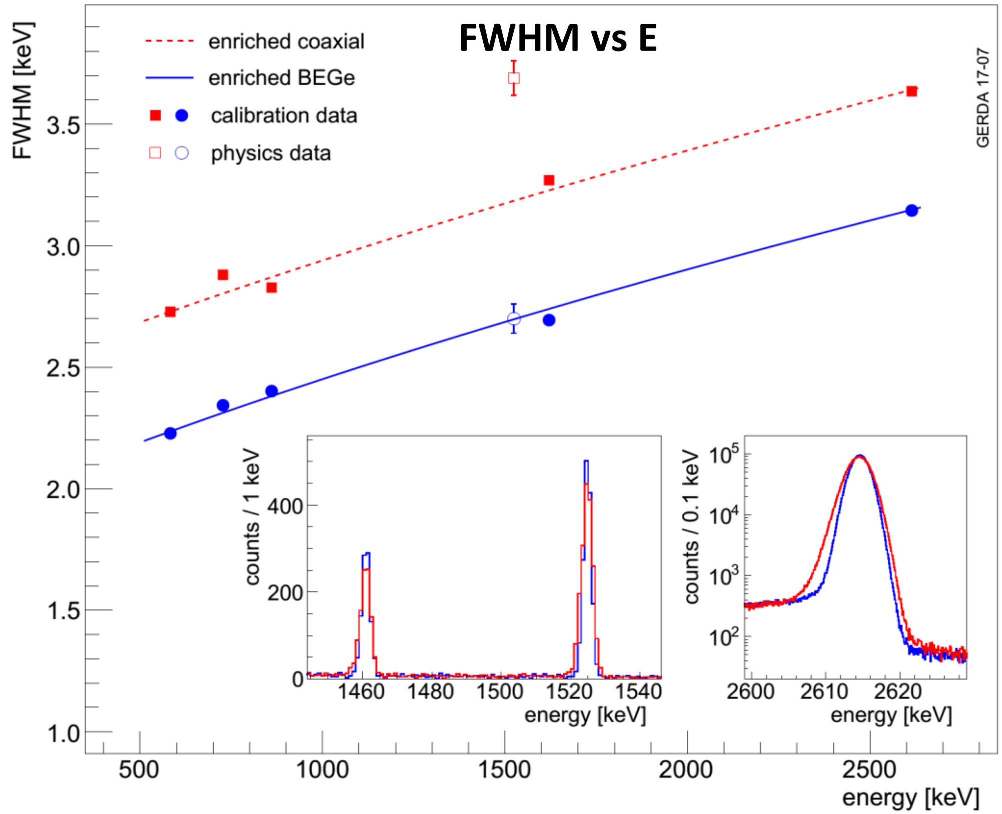
Surface events – **PSD**

✓ PSD and LAr **complementary**

✓ **All α**-s cut by **PSD!**

GERDA
Performance





- Dec 2015 to April 2017, **93%** duty cycle
- Weekly calibrations with ^{228}Th sources
- Energy reconstruction with ZAC filter

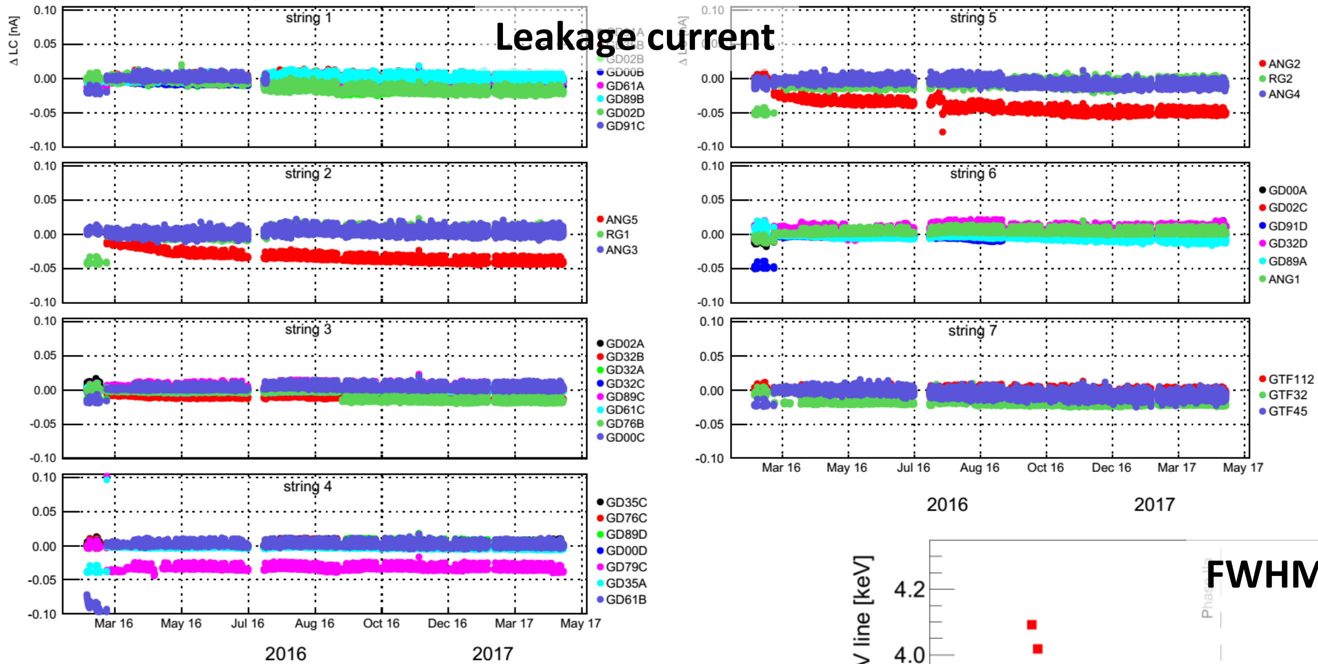
  (Eur. Phys. J. C 75 (2015) 255)
- Final resolution corrected for $^{40/42}$K lines in physics data

FWHM at $Q_{\beta\beta}$:
Coaxial: **3.90**(7) keV
BEGe: **2.93**(6) keV

GERDA

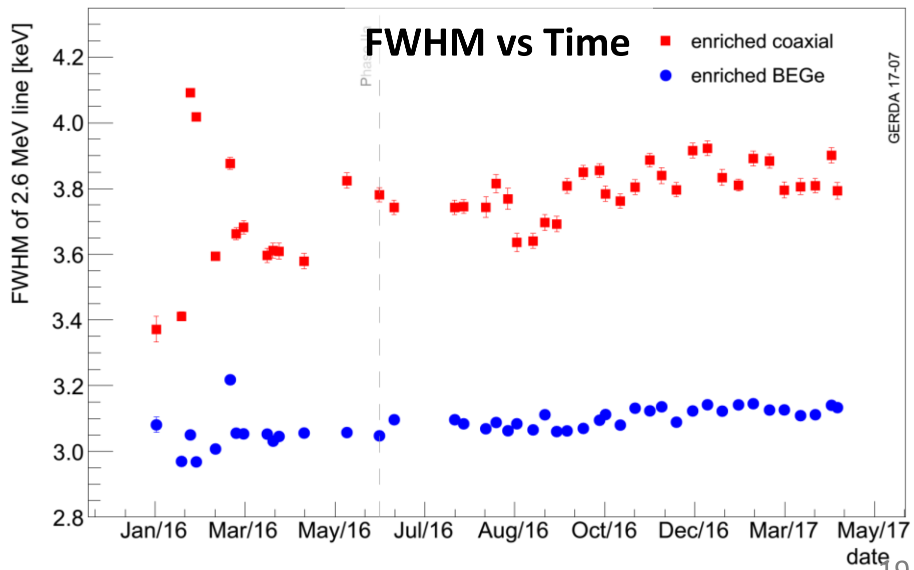
Performance

Leakage current



- ✓ Leakage current of detectors – no increase
- ✓ LAr veto performance – stays unchanged
- ✓ FWHM of HPGe diodes – stable

FWHM vs Time



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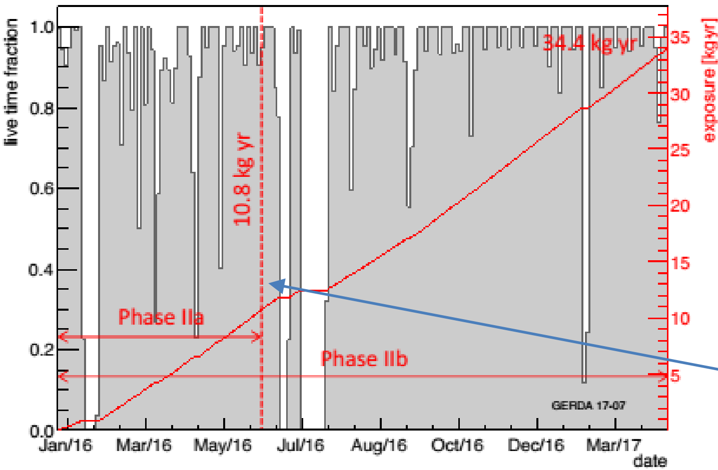
Previous Phase II results (Phase IIa)



Phase IIa exposure:
Coaxials: 5 kg yr
BEGe: 5.8 kg yr

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*

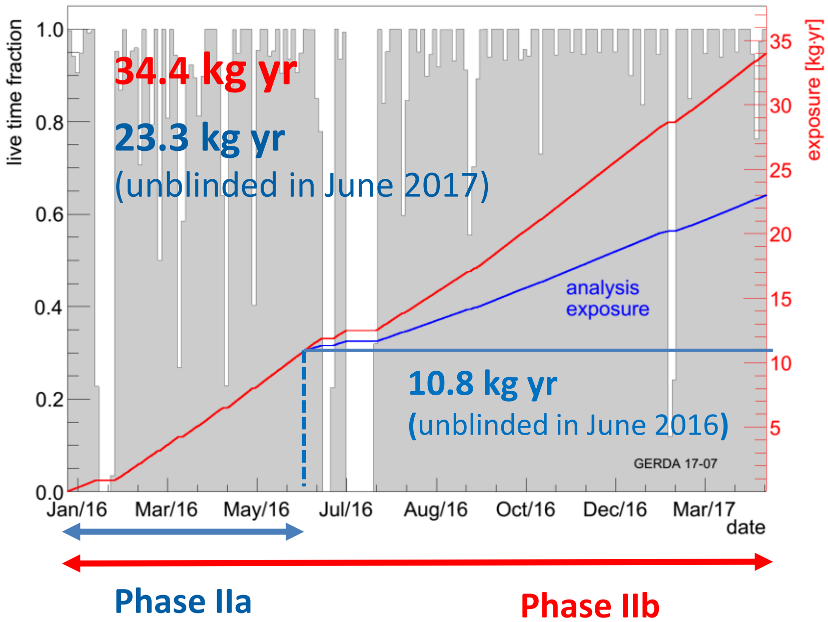
- New $T_{1/2}^{0\nu\beta\beta}$ limit from Phase I & Phase IIa data:
  - ✓ Sensitivity: $T_{1/2}^{0\nu} > 4 \times 10^{25}$yr (90% CL)
  - ✓ Limit: $T_{1/2}^{0\nu} > 5.3 \times 10^{25}$yr (90% CL)
- Background index (BI) for BEGe: $0.7^{+1.1}_{-0.5} \times 10^{-3}$cts/(keV kg yr)

< 1 count in ROI up to design exposure (100 kg yr)

background free!

GERDA

Current data taking



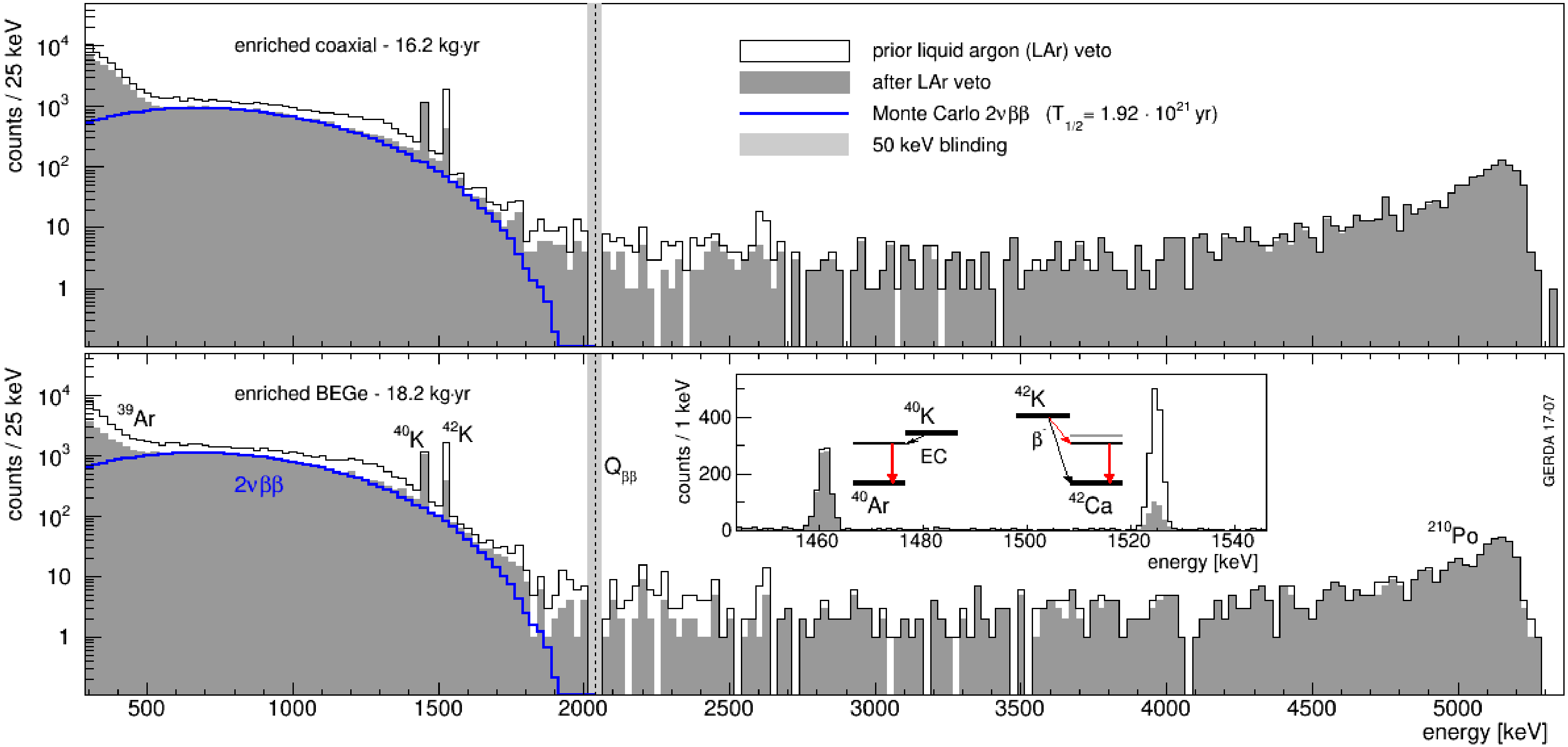
- Data taking is ongoing
  - Phase II exposure increased by **x3** with respect to Nature paper (**Phase IIa**)
  - **Valid** exposure accumulated **34.4 kg yr** up to Apr 15th (**Phase IIb**)
    - 18.2 kg·yr of BEGe data
    - 16.2 kg·yr of Coaxial data
  - A few more kg·yr already available (Apr-Aug)

- Only **BEGe** dataset unblinded (**12.4 kg yr**)
- New coaxial data (11.2 kg yr) still blinded:
  - **Background** similar to Phase IIa
  - Can be **improved further** by better rejection of **α**-s from the **groove**
  - Work on better α cut is ongoing
- Total unblinded exposure: **23.3 kg yr**

GERDA

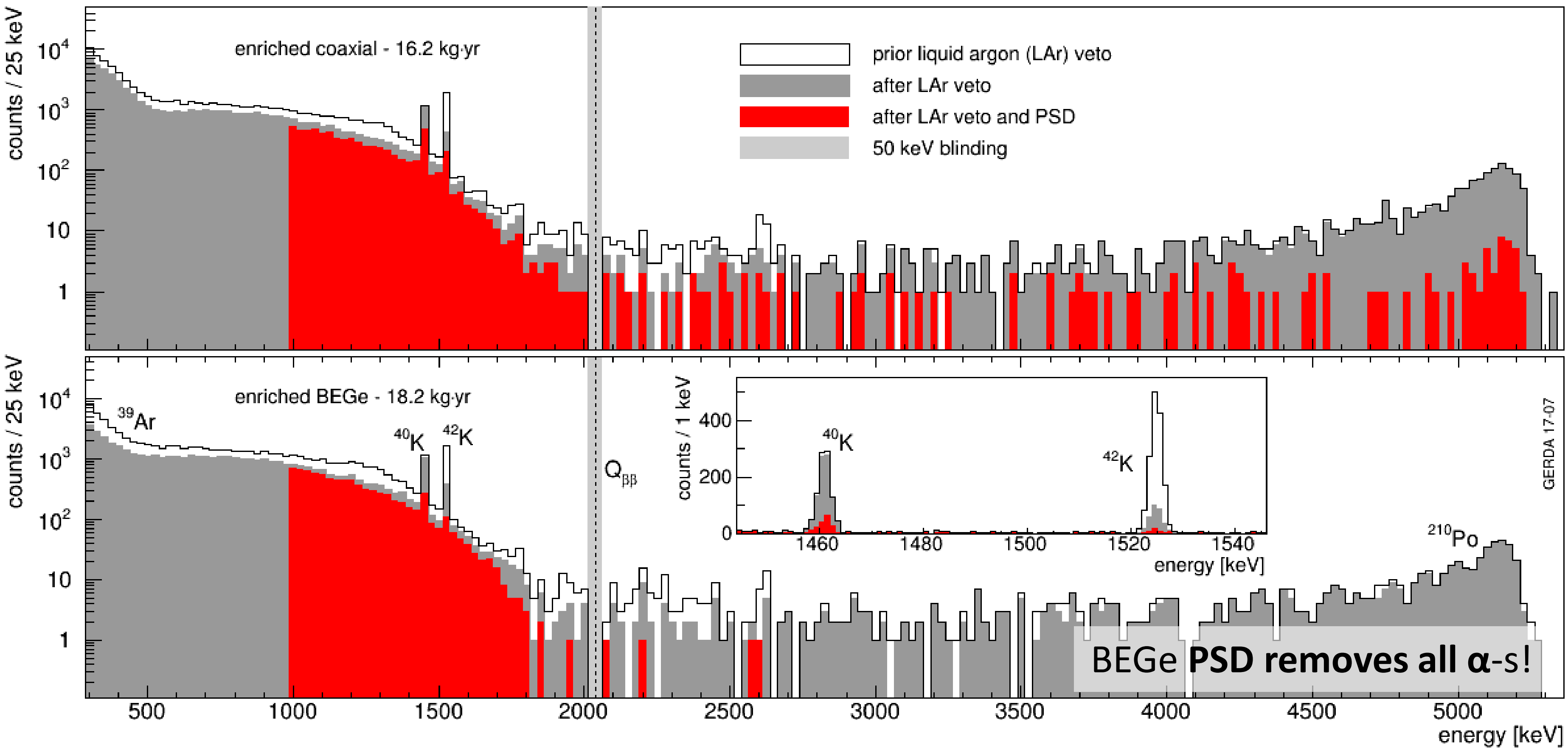
Spectra

After LAr veto:



GERDA
Spectra

After LAr veto + PSD:



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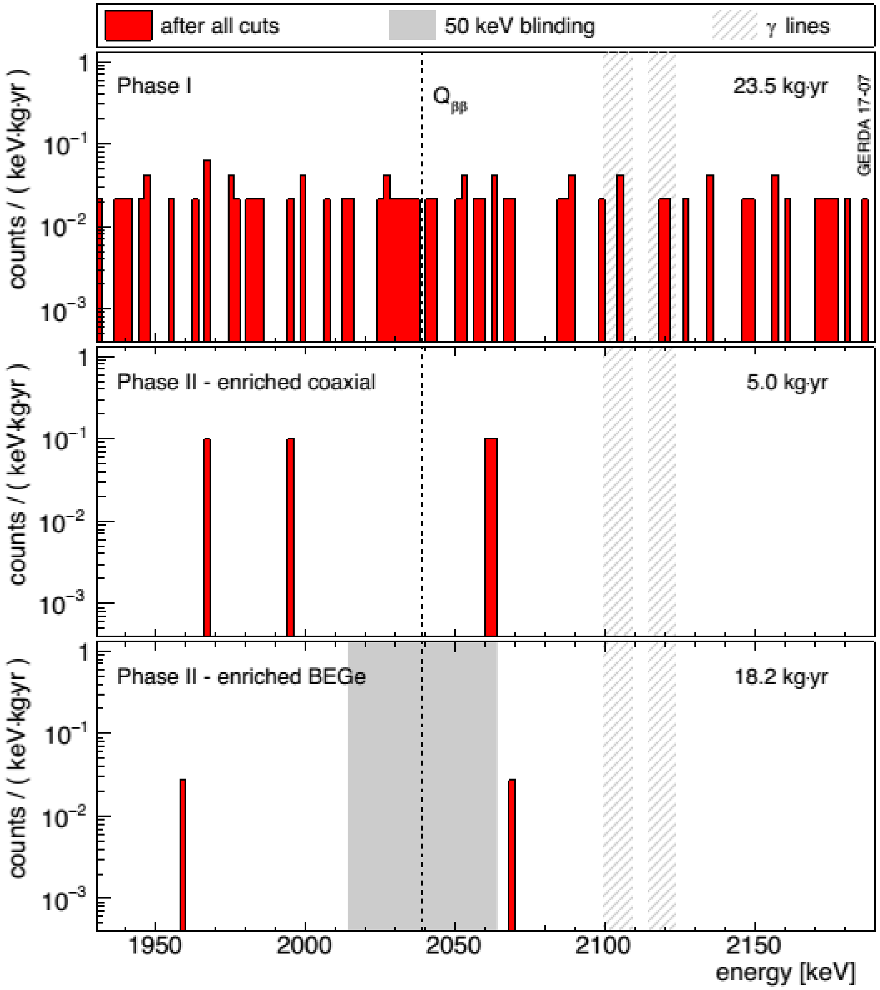
New unblinding (Cracow, 30th of June 2017)



BEGe dataset (18.2 kg yr)

	Counts in ROI	BI at $Q_{\beta\beta}$ x 10^{-3} cts/ (keV kg yr)
Before	2	$0.5^{+0.5}_{-0.3}$

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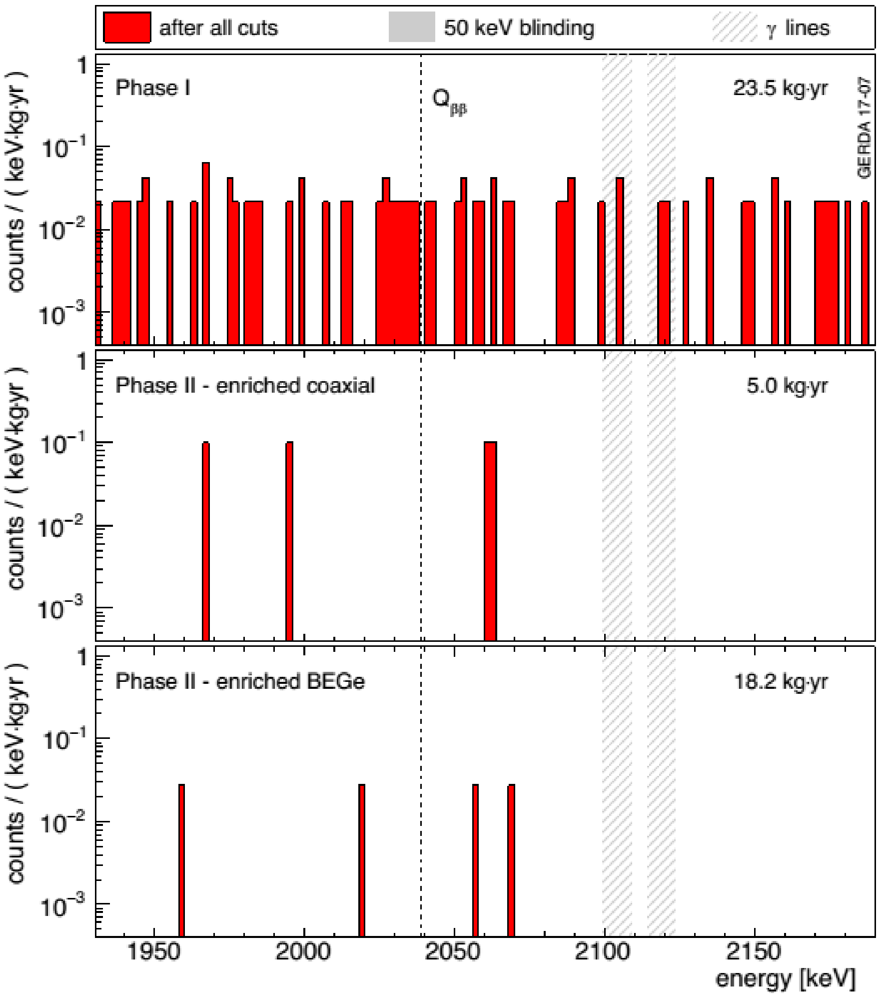
New unblinding

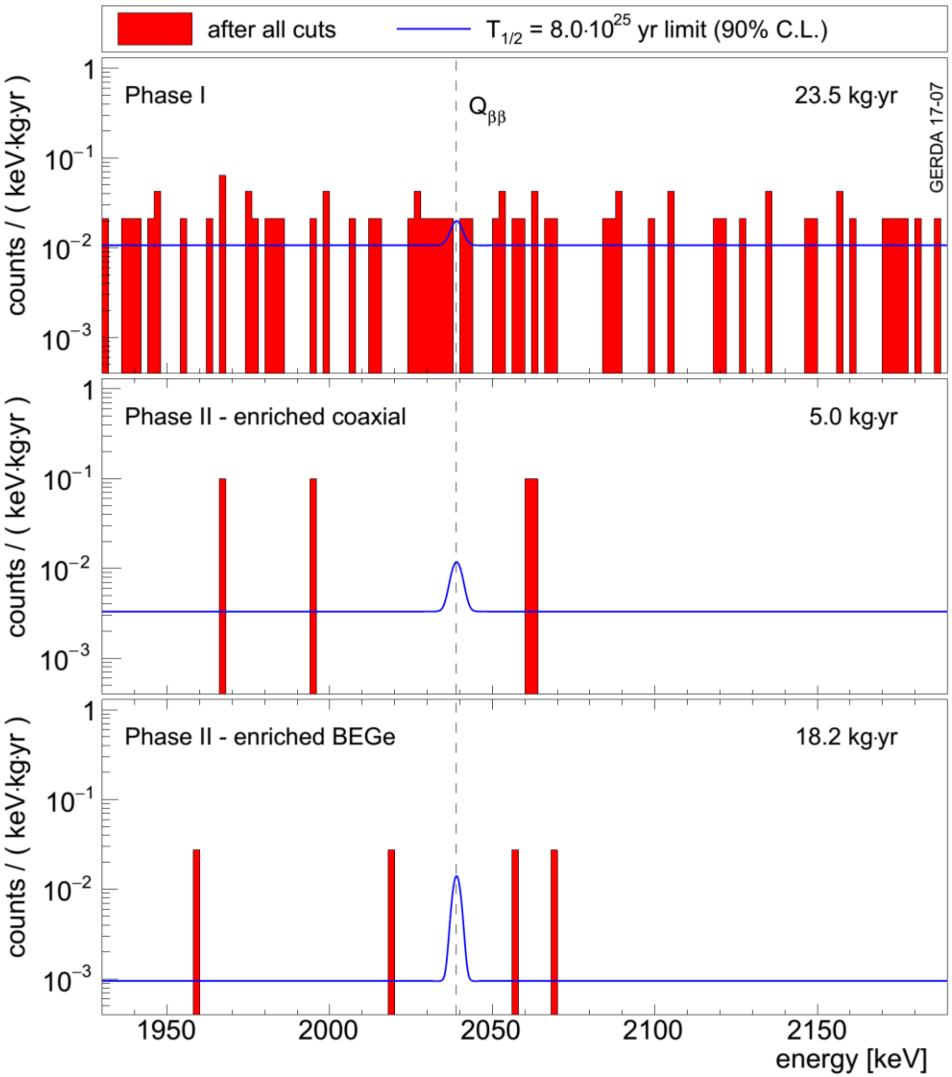


BEGe dataset (18.2 kg yr)

	Counts in ROI	BI at $Q_{\beta\beta}$ x 10^{-3} cts/ (keV kg yr)
Before	2	$0.5^{+0.5}_{-0.3}$
After	4	$1.0^{+0.6}_{-0.4}$

GERDA

New result



Full exposure (46.7 kg yr)

	Exposure (kg yr)
Phase I (4 sets)	23.5
Phase IIa – coaxials	5.0
Phase IIb – BeGe	5.8 + 12.4 = 18.2

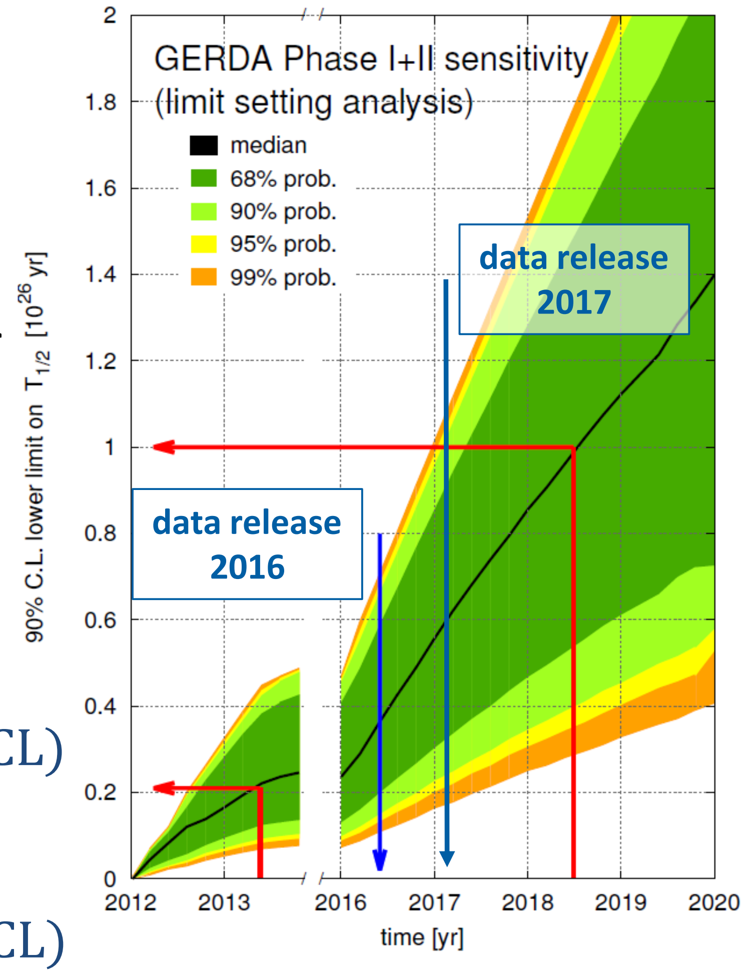
	Profile likelihood 2-side test stat.	Bayesian flat prior on cts
0νββ cts best fit value (cts)	0	0
$T_{1/2}^{0\nu\beta\beta}$ lower limit ($\times 10^{25}$yr)	**> 8.0 (90% CL)**	> 5.1 (90% CL)
$T_{1/2}^{0\nu\beta\beta}$ median sensitivity ($\times 10^{25}$yr)	**5.8 (90% CL)**	4.5 (90% CL)

Best in 0νββ field!

GERDA

First background free 0νββ search

- Phase II is successfully taking data since December 2015
- Background design goal reached:
  - ✓ BI in ROI for BEGe ~ **10^{-3}** counts/(keV kg yr)
  - ! best BI in ROI ever achieved!
- GERDA will stay background free up to 100 kg yr
- Sensitivity goal (~ 10^{26} yr):
  - ✓ should be reached in 2018
- New $T_{1/2}^{0\nu\beta\beta}$ limit from Phase I & Phase II data:
  - ✓ Sensitivity: $T_{1/2}^{0\nu} > 5.8 \times 10^{25}\text{yr (90\% CL)}$
    (best in the field)
  - ✓ Limit: $T_{1/2}^{0\nu} > 8.0 \times 10^{25}\text{yr (90\% CL)}$

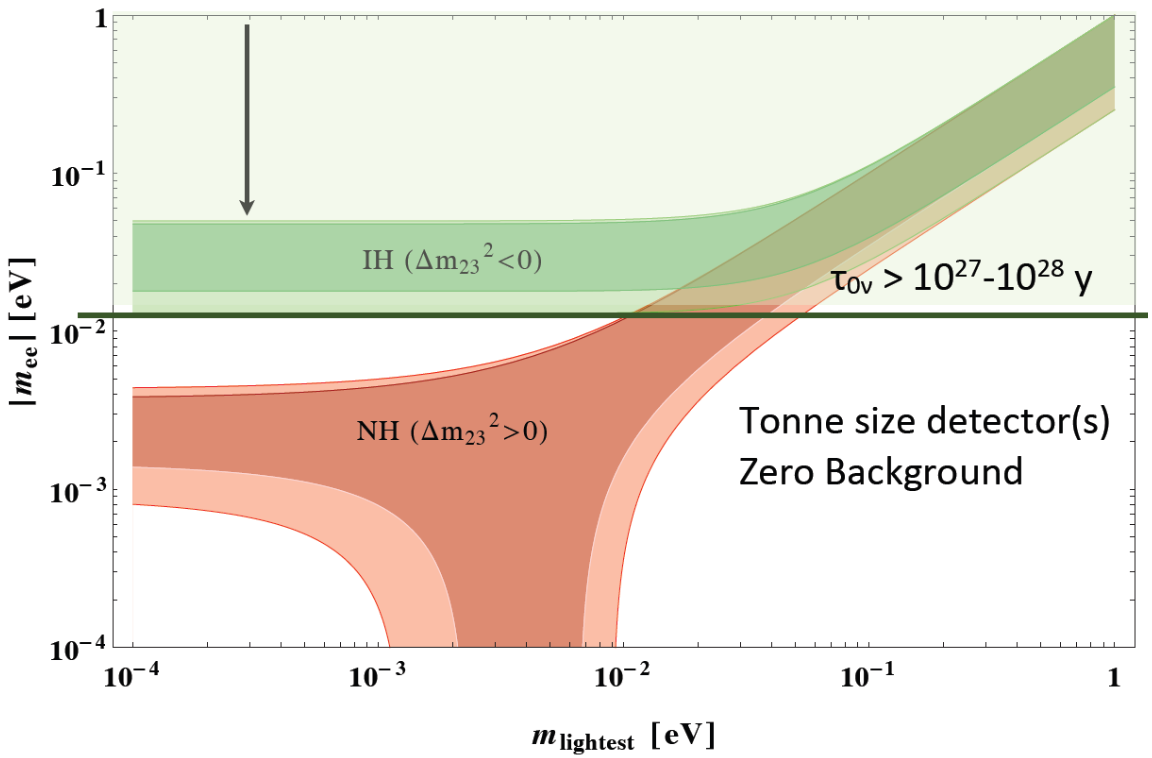


Beyond GERDA

LEGEND project

LEGEND (Large Enriched Germanium Experiment for Neutrinoless ββ Decay):

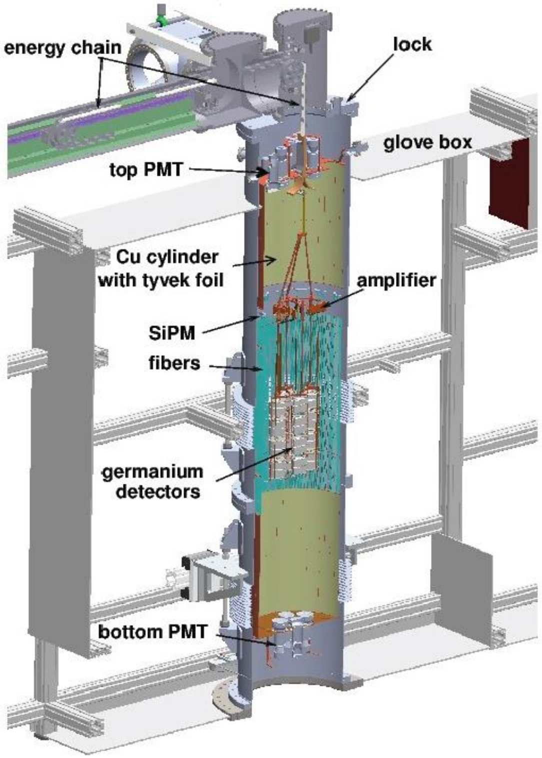
- ✓ Collaboration formed in Oct 2016
- ✓ First stage with 200 kg of ^{76}Ge in modified GERDA cryostat at LNGS

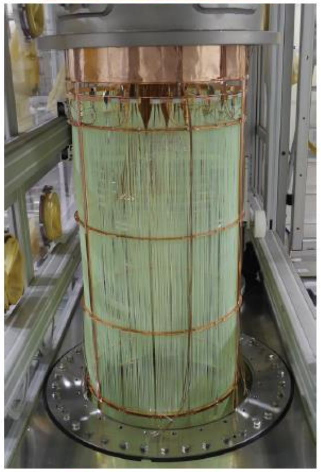


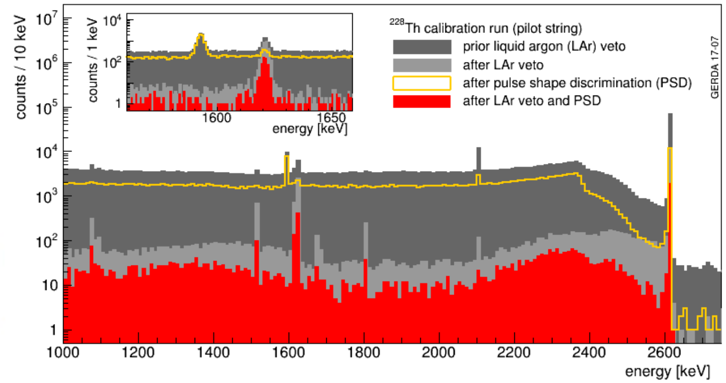
More about LEGEND in my talk on Aug 29th & ICNFP17

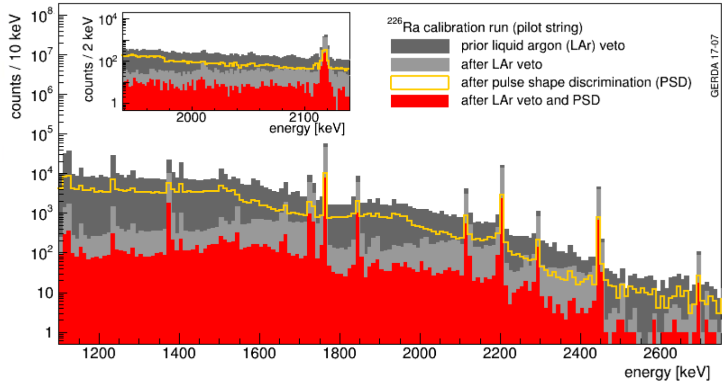
Additional slides

Phase II upgrade
LAr veto



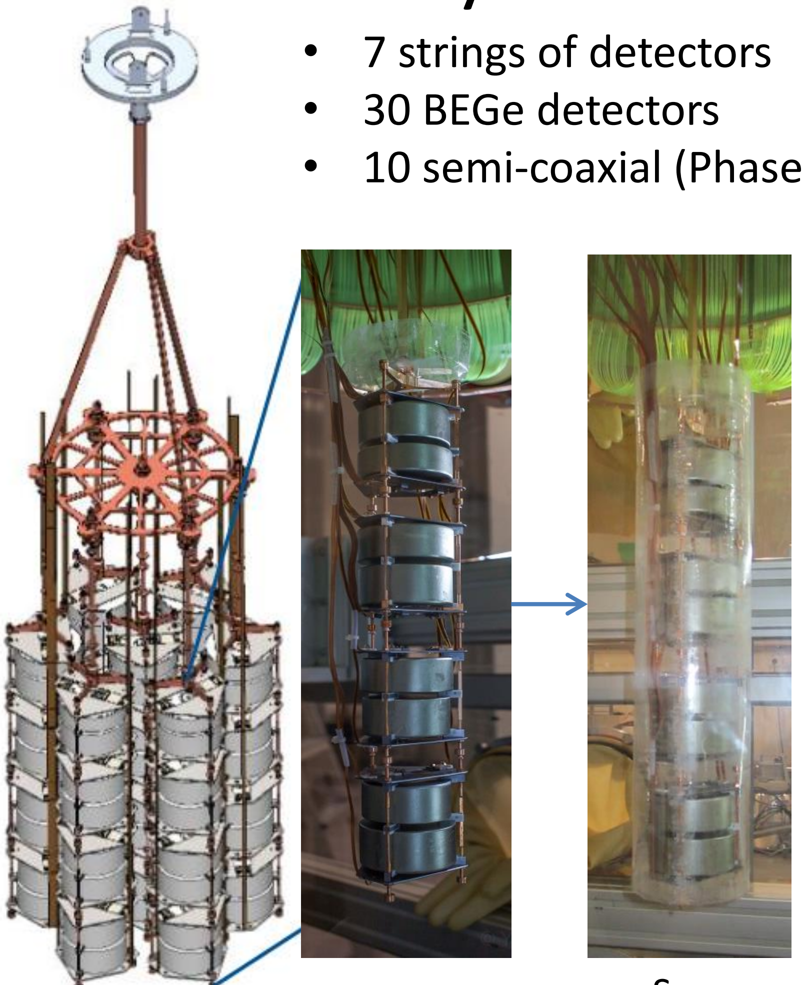






- ✓ works well
- ✓ suppression factors depend on isotope, location and detector configuration

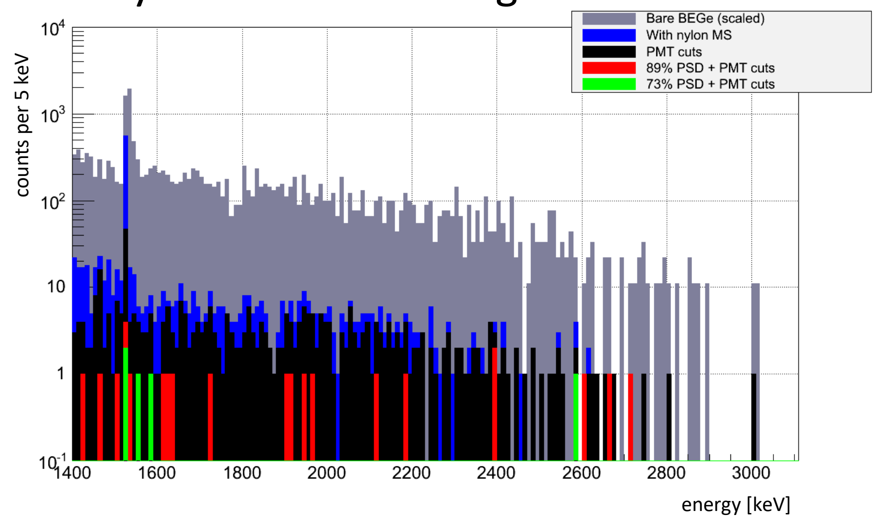
Phase II
detector array



- 7 strings of detectors
- 30 BEGe detectors
- 10 semi-coaxial (Phase I) detectors: 7 enriched + 3 non-enriched

✓ Dense packing of detectors allows better anti-coincidence cut

✓ Each string enclosed by transparent nylon mini-shroud against ^{42}K-ions:



Suppression factor > 1000 for ^{42}K bkg has been demonstrated in LArGe test facility (nylon mini-shroud + PSD + LAr veto)