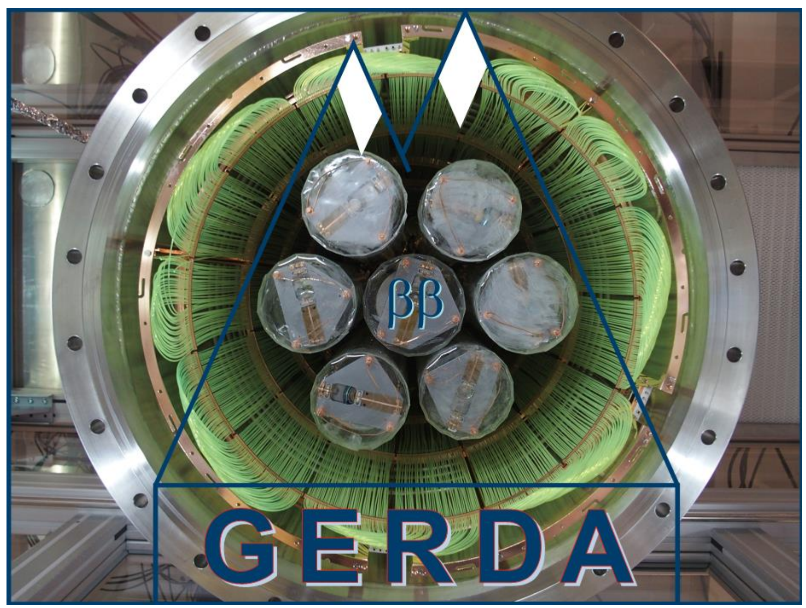
JOINT INSTITUTE FOR NUCLEAR RESEARCH

GERDA

GERDA (“G&M”) Project: Searching for neutrinoless double beta decay of ^{76}Ge

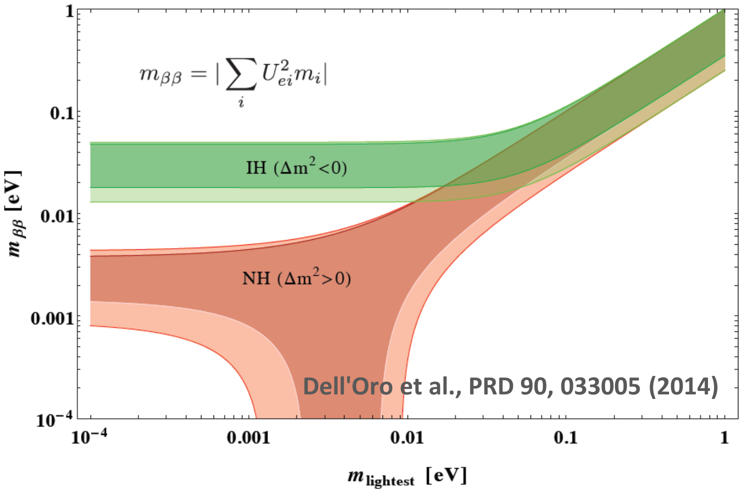


Konstantin Gusev

PAC for Nuclear Physics 47th meeting| 17 January 2018

0νββ-decay

- violates lepton number ↔ forbidden in the SM
- only if ν has Majorana mass component or other new ΔL = 2 operators exist



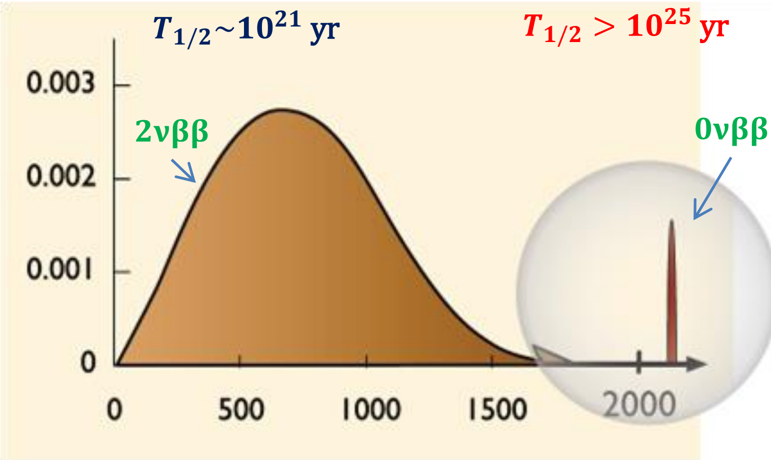
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

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

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

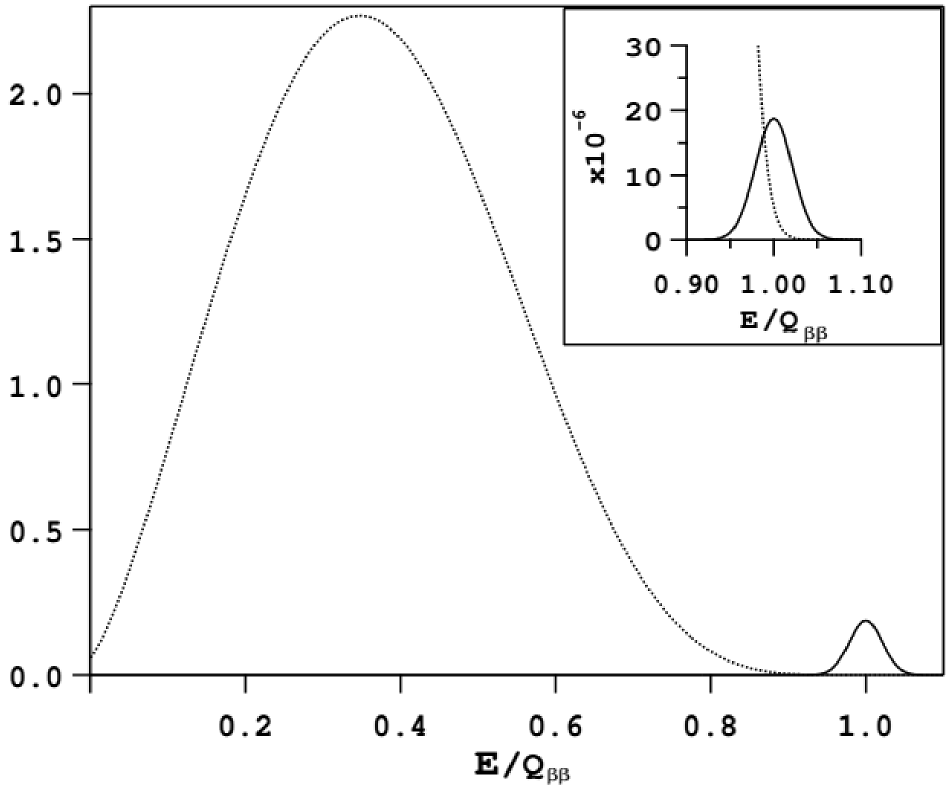
$M\,t$ - exposure (kg yr)
ΔE - energy resolution (keV)
BI - background index (counts/keV kg yr)

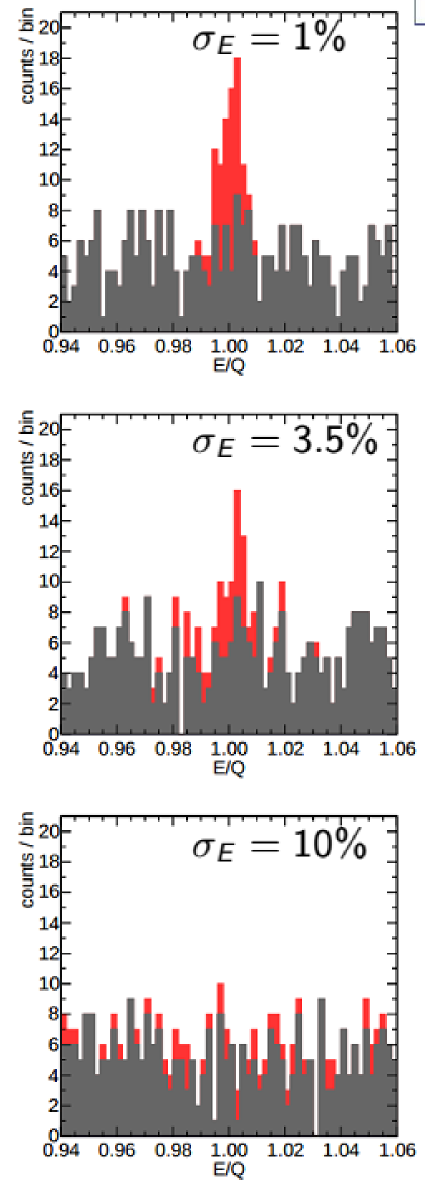
- ✓ No preferred isotope from Nuclear Physics (G*M)
- ✓ Target mass and detector efficiency as high as possible
- ✓ “Zero-background” regime if possible
- ✓ Resolution remains essential due to 2νββ



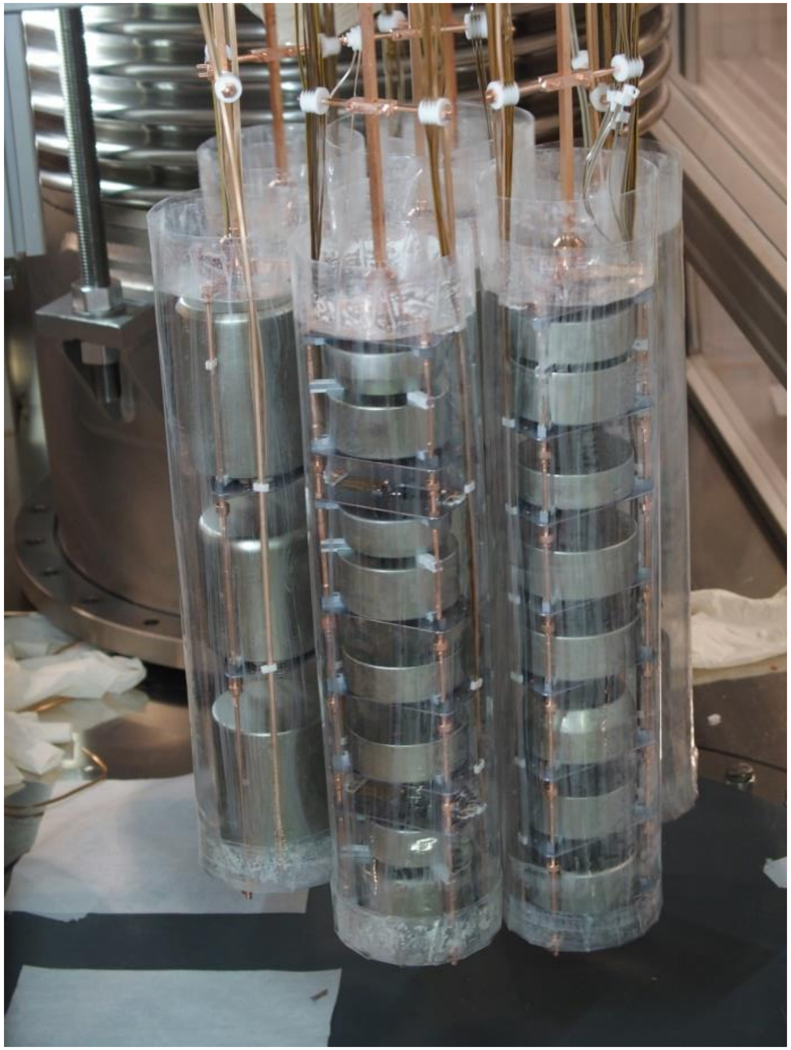
0νββ-decay

✓ Resolution remains essential due to 2νββ



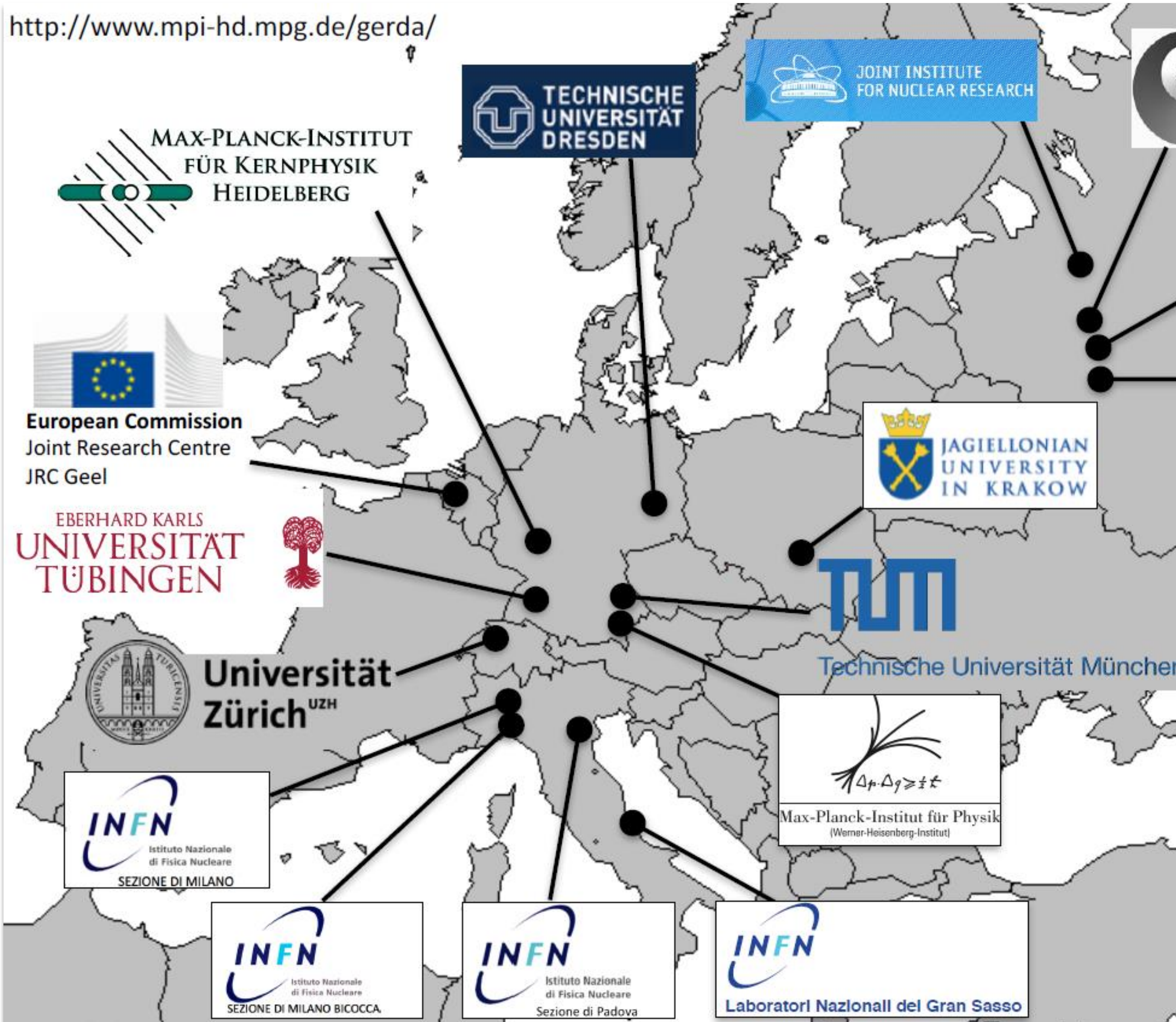


GERmanium **D**etector **A**rray
Approach



- ✓ Ge detectors enriched in ^{76}Ge
- ✓ very good energy resolution
  ~0.1% at $Q_{\beta\beta}$
- ✓ high detection efficiency
  source = detector
- ✓ Ultra low background
  - ✓ deep underground location
    (LNGS, Italy, 3500 m.w.e)
  - ✓ careful assay of materials
  - ✓ passive and active shields
  - ✓ **bare Ge** detectors in liquid argon (LAr)
    first time ever!
  - ✓ pulse shape discrimination (**PSD**)
    + **active** LAr veto (in Phase II)

GERDA Collaboration



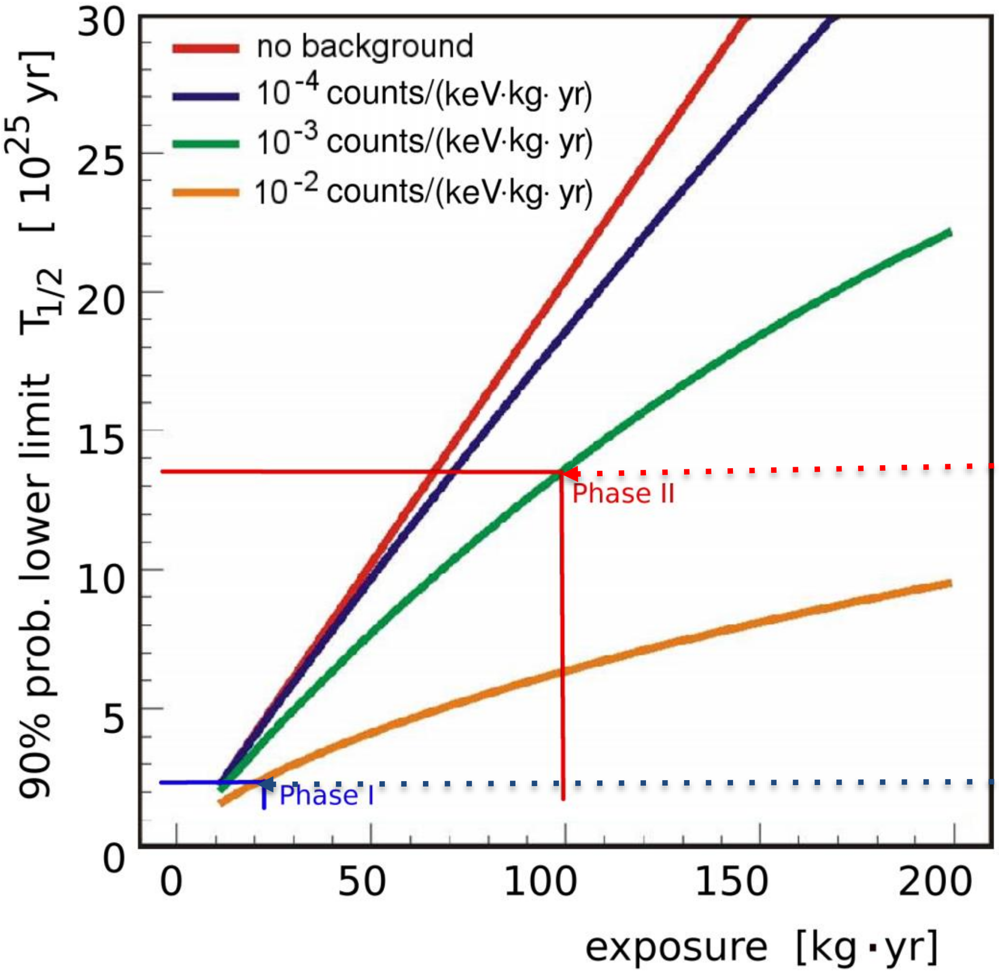
Project Members from JINR:
V.Brudanin, D.Borowicz, M.Fomina, V.Egorov, A.Klimenko, O.Kochetov, I.Nemchenok, N.Rumyantseva, V.Sandukovsky, E.Shevchik, M.Shirchenko, A.Smolnikov, I.Zhitnikov

Team leader:
K. Gusev

Deputy leaders:
A.Lubashevskiy
D.Zinatulina

GERDA

Phases and sensitivity



<u>Phase II (Dec 2015 – ongoing):</u>

Add new BEGe detectors (20 kg)

BI ≈ 0.001 cts / (keV kg yr)

Sensitivity after 100 kg yr

<u>Phase I (Nov 2011 – May 2013):</u>

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

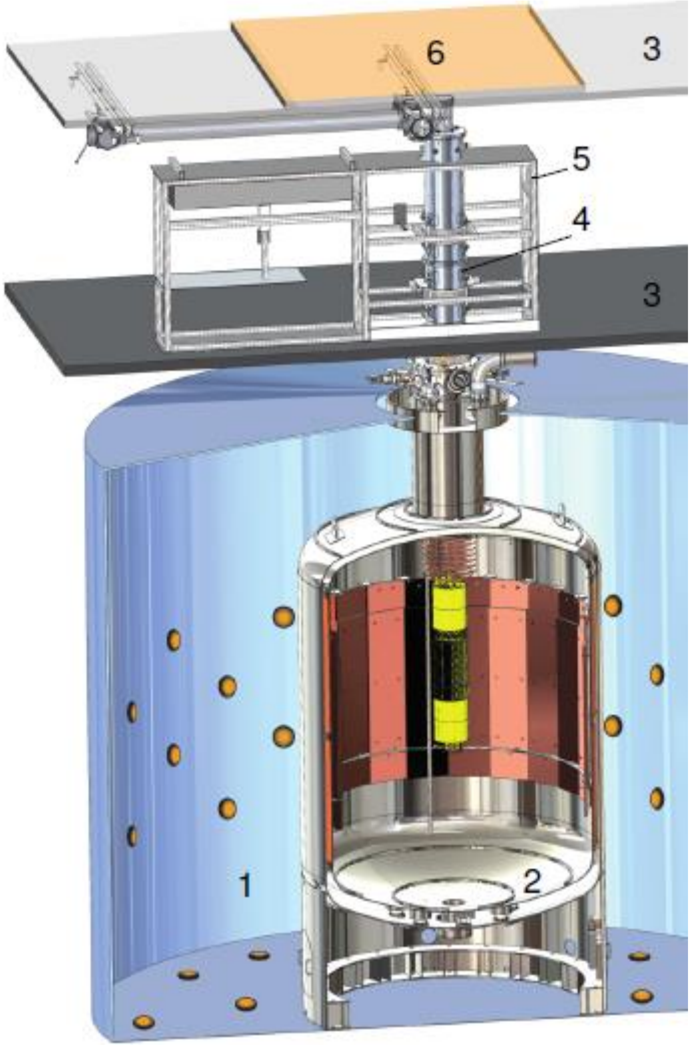
Sensitivity after 20 kg yr

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

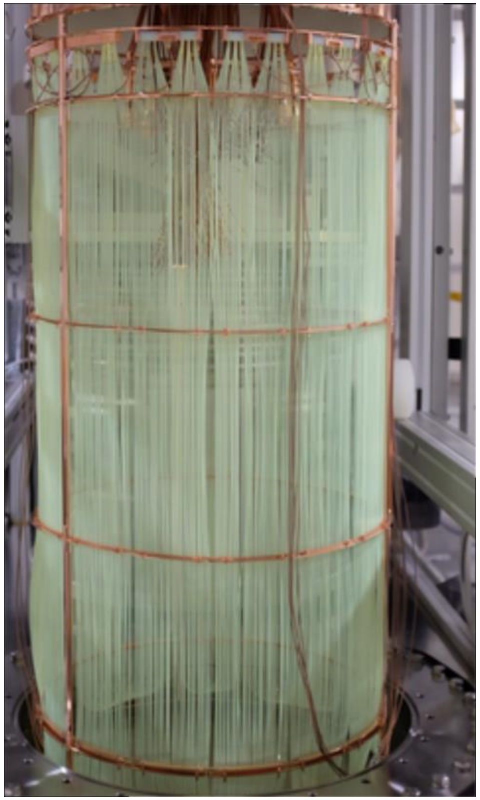
(PRL 111 (2013) 122503)

GERDA Phase II

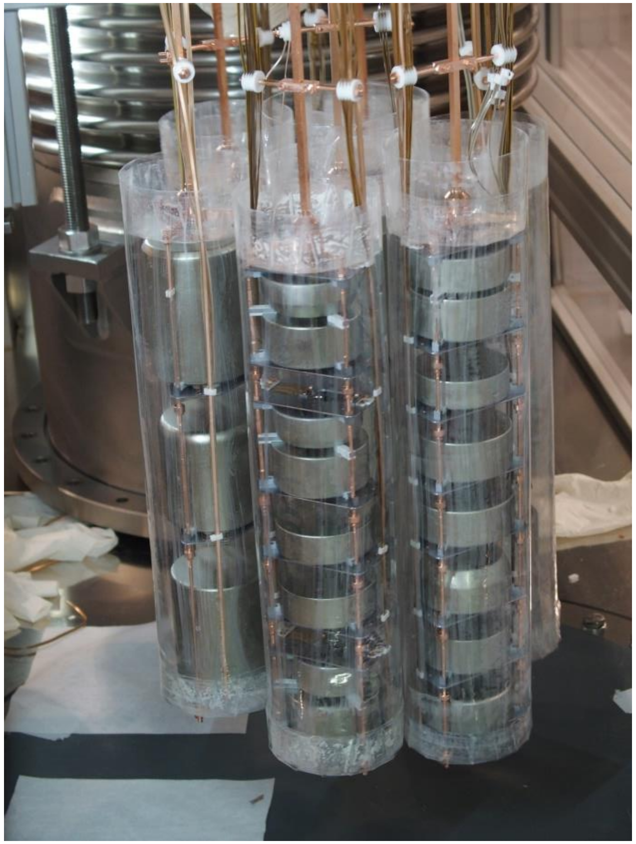
Started in December 2015



LAr veto



HPGe detectors array



All 40 detectors and LAr veto work

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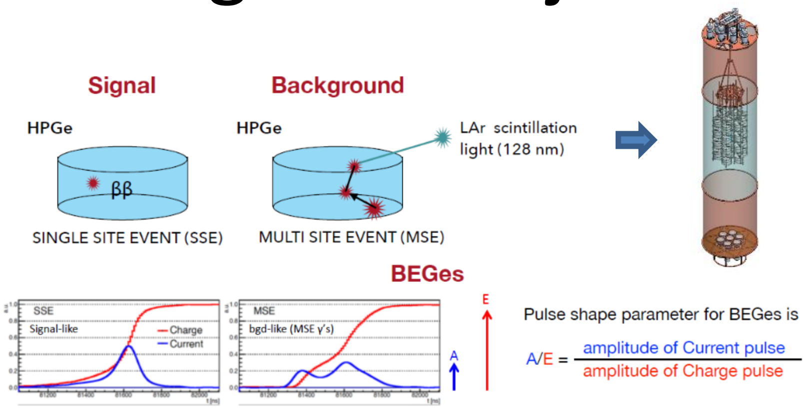
Background rejection

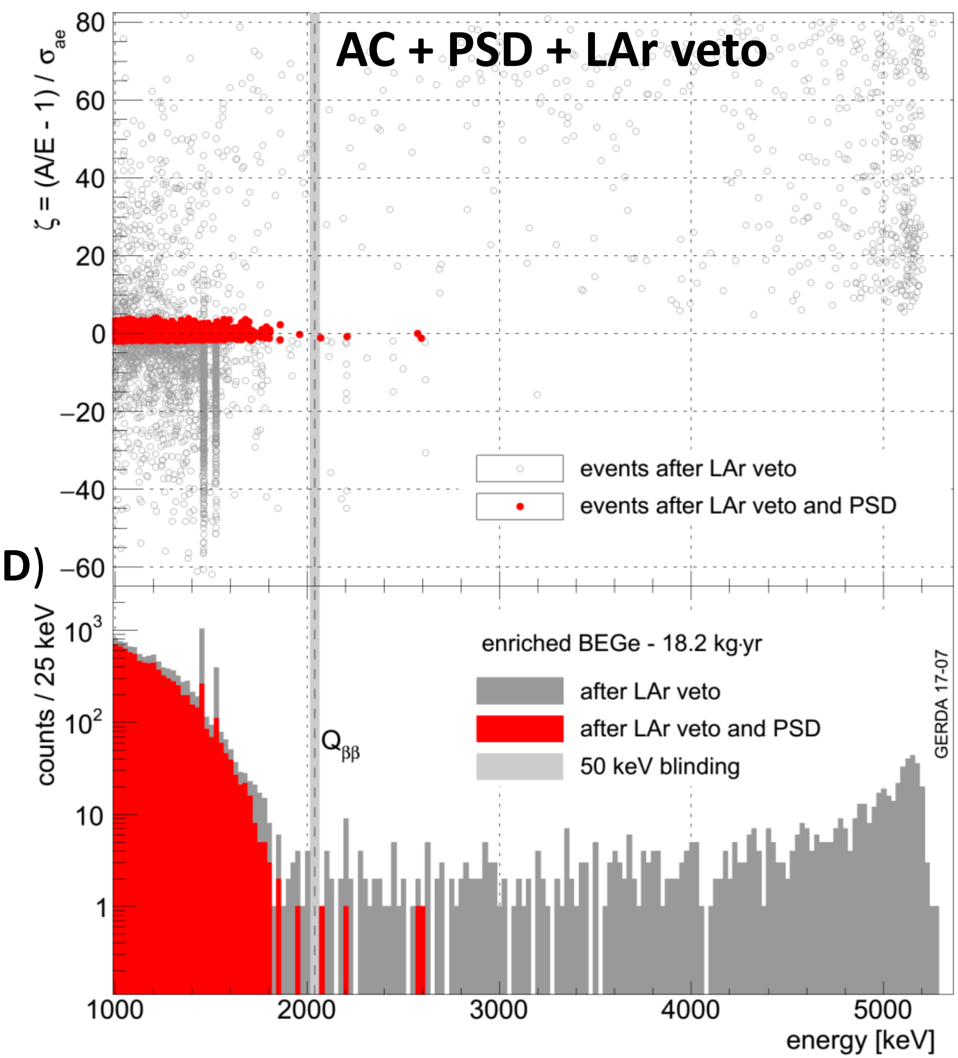


Background:

Multi-site energy deposition:

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

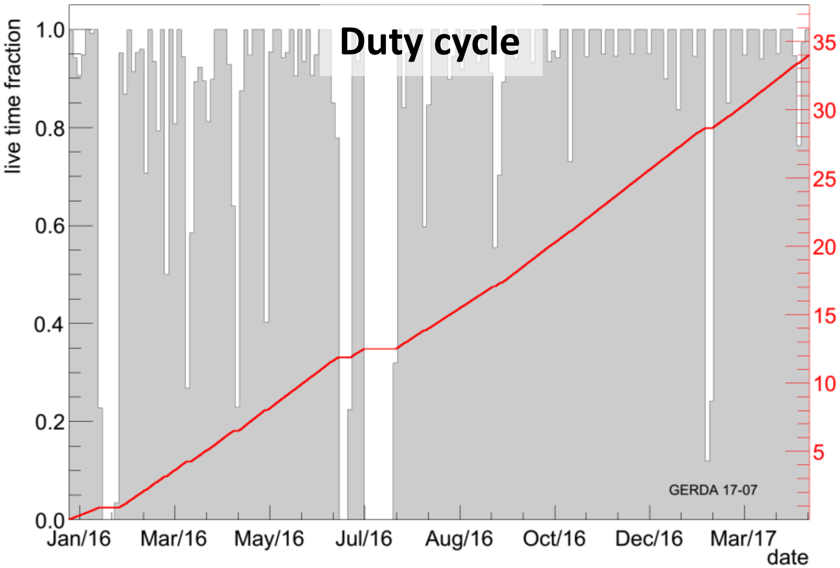
Surface events – **PSD**

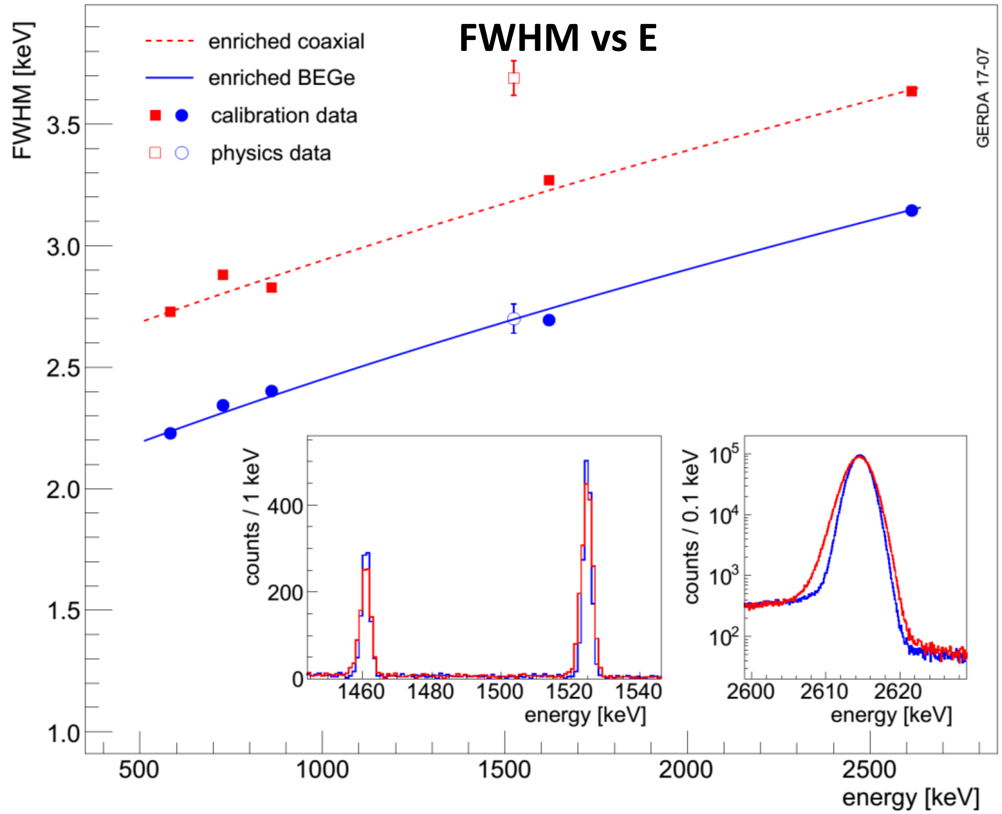


✓ PSD and LAr **complementary**

✓ **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

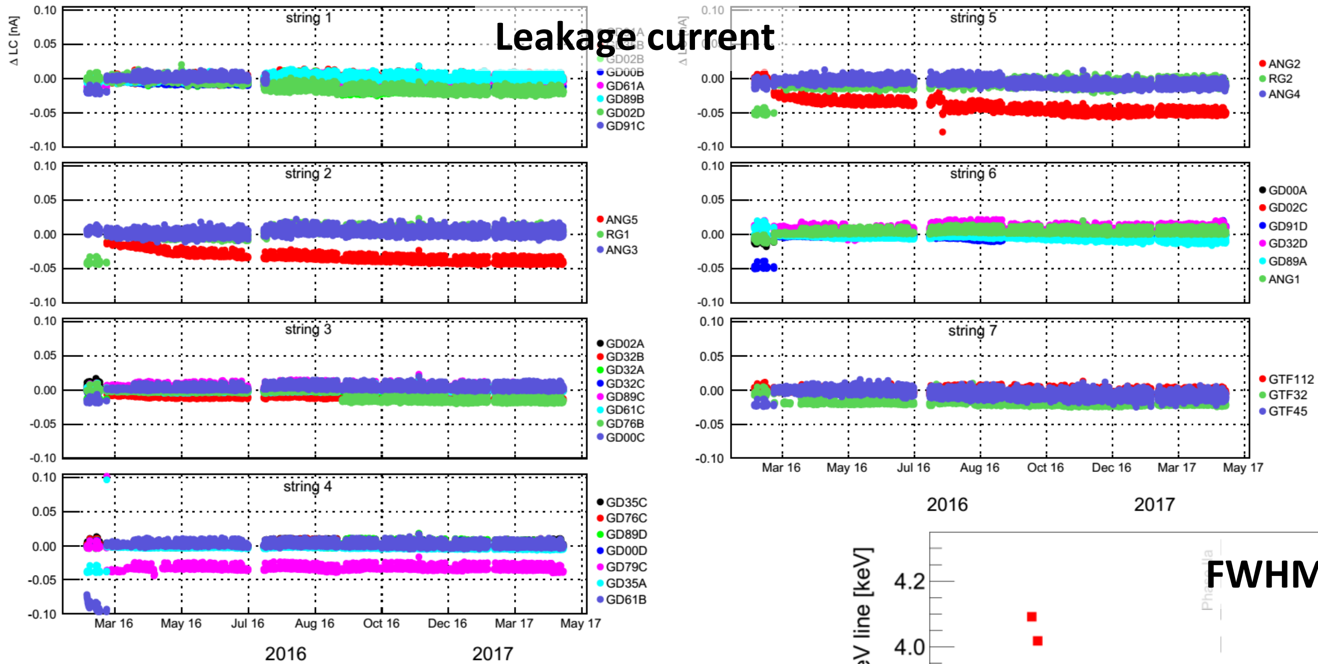
FWHM at $Q_{\beta\beta}$:

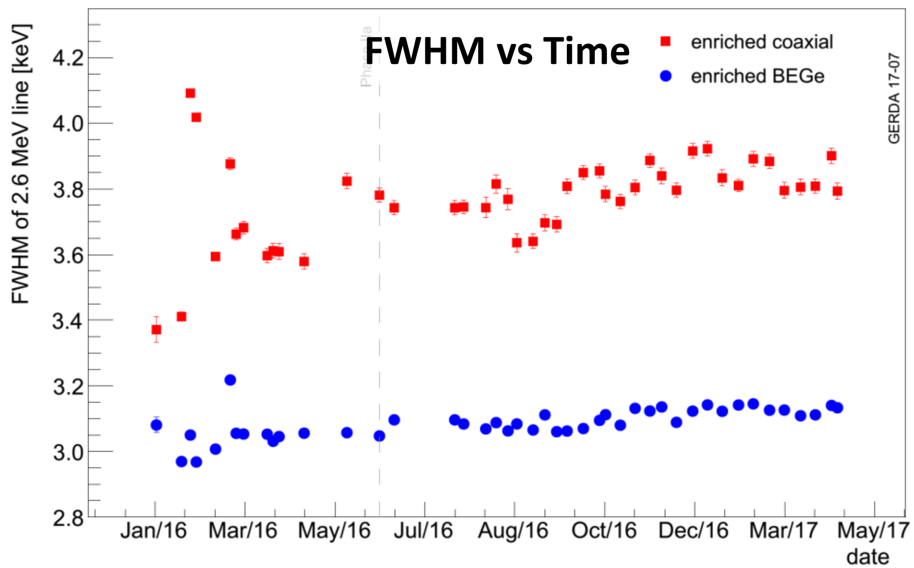
Coaxial: **3.90**(7) keV

BEGe: **2.93**(6) keV

GERDA

Performance

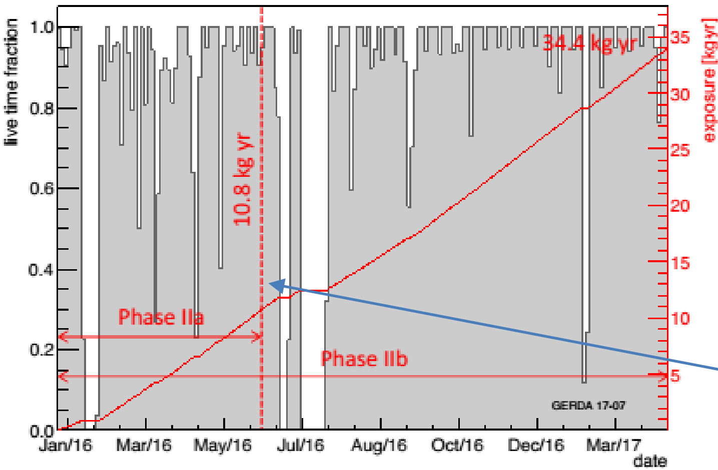




- ✓ Leakage current of detectors – no increase
- ✓ LAr veto performance – stays unchanged
- ✓ FWHM of HPGe diodes – stable

GERDA

Phase II 2016 results



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*

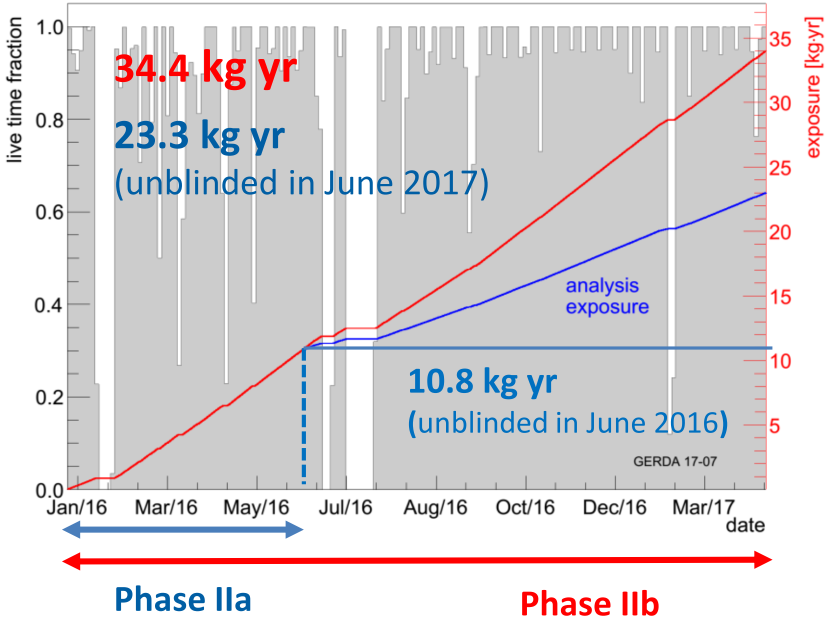
- New $T_{1/2}^{0\nu\beta\beta}$ limit from Phase I & Phase IIa data:
  - ✓ Sensitivity: $T_{1/2}^{0\nu} > 4 \times 10^{25}$yr (90% CL)
  - ✓ Limit: $T_{1/2}^{0\nu} > 5.3 \times 10^{25}$yr (90% CL)
- Background index (BI) for BEGe: $0.7^{+1.1}_{-0.5} \times 10^{-3}$cts/(keV kg yr)

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

background free!

GERDA

Data taking status 2017

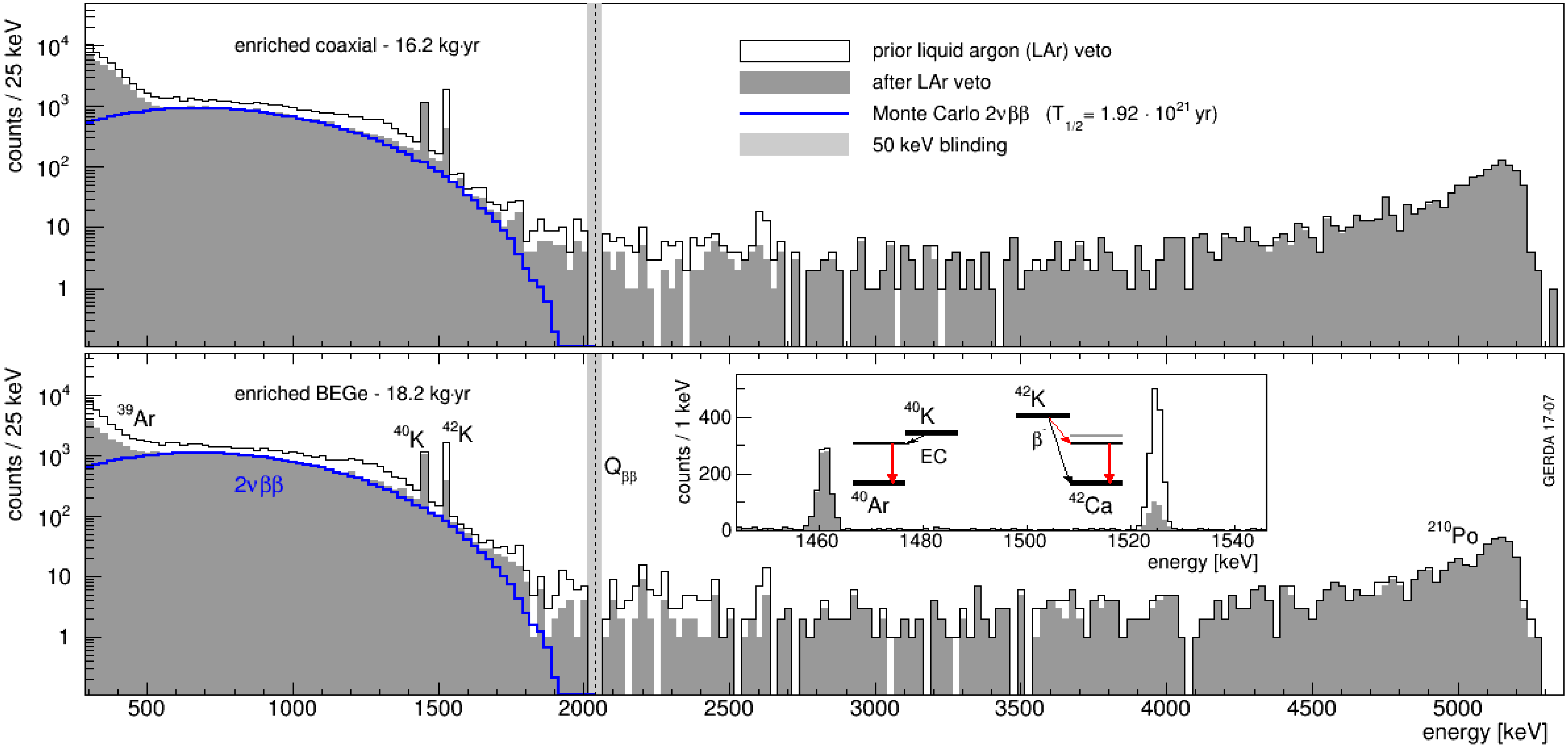


- Data taking is ongoing
  - Phase II exposure increased by **x3** with respect to Nature paper (**Phase IIa**)
  - **Valid** exposure accumulated **34.4 kg yr** up to Apr 15th (**Phase IIb**)
    - 18.2 kg·yr of BEGe data
    - 16.2 kg·yr of Coaxial data
  - About 12 more kg·yr already available (Apr-Dec)

- Only **BEGe** dataset unblinded (**12.4 kg yr**)
- BI for **BEGe** confirmed with 3-fold exposure: $1.0^{+0.6}_{-0.4} \times 10^{-3}$cts/(keV 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**

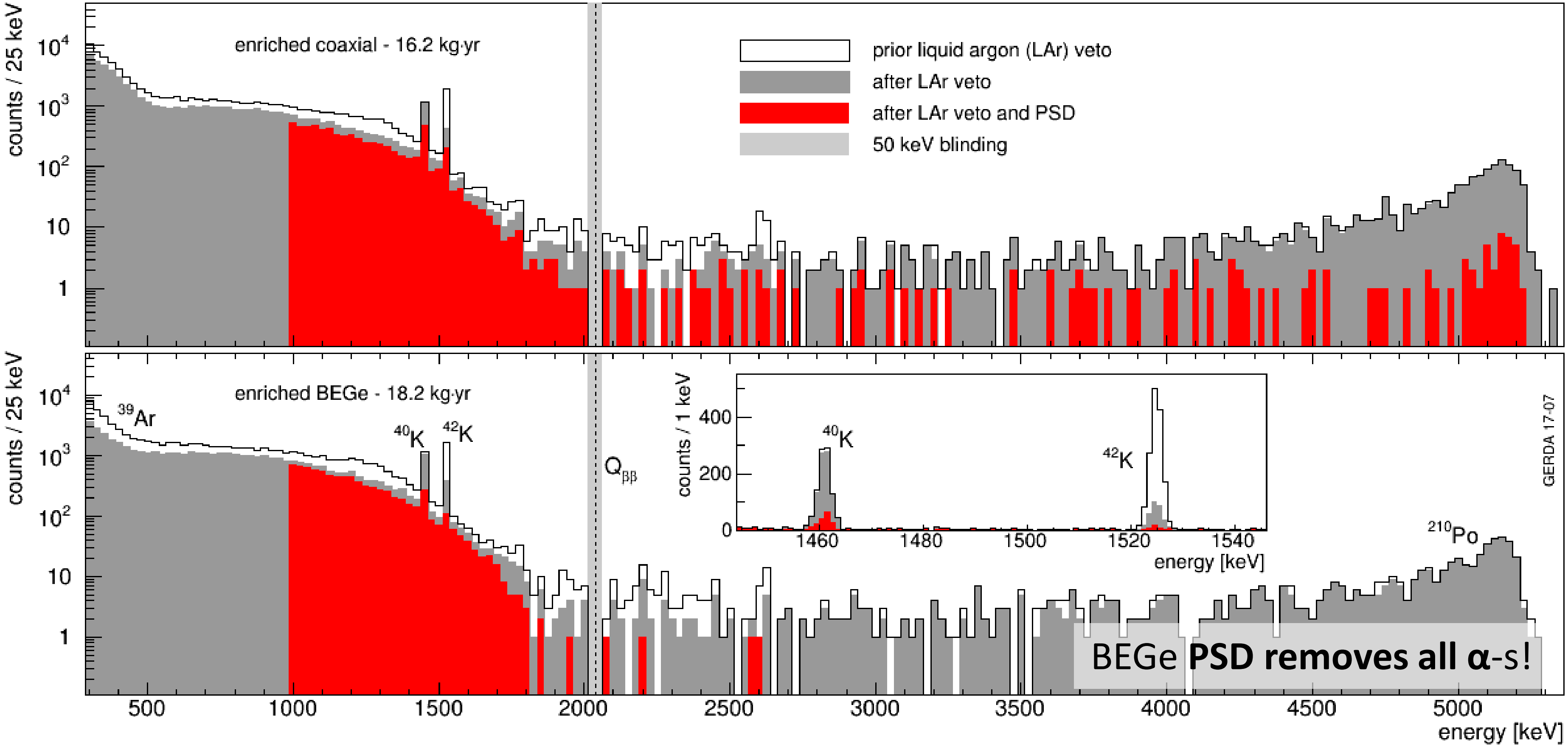
GERDA
Spectra 2017

After LAr veto:



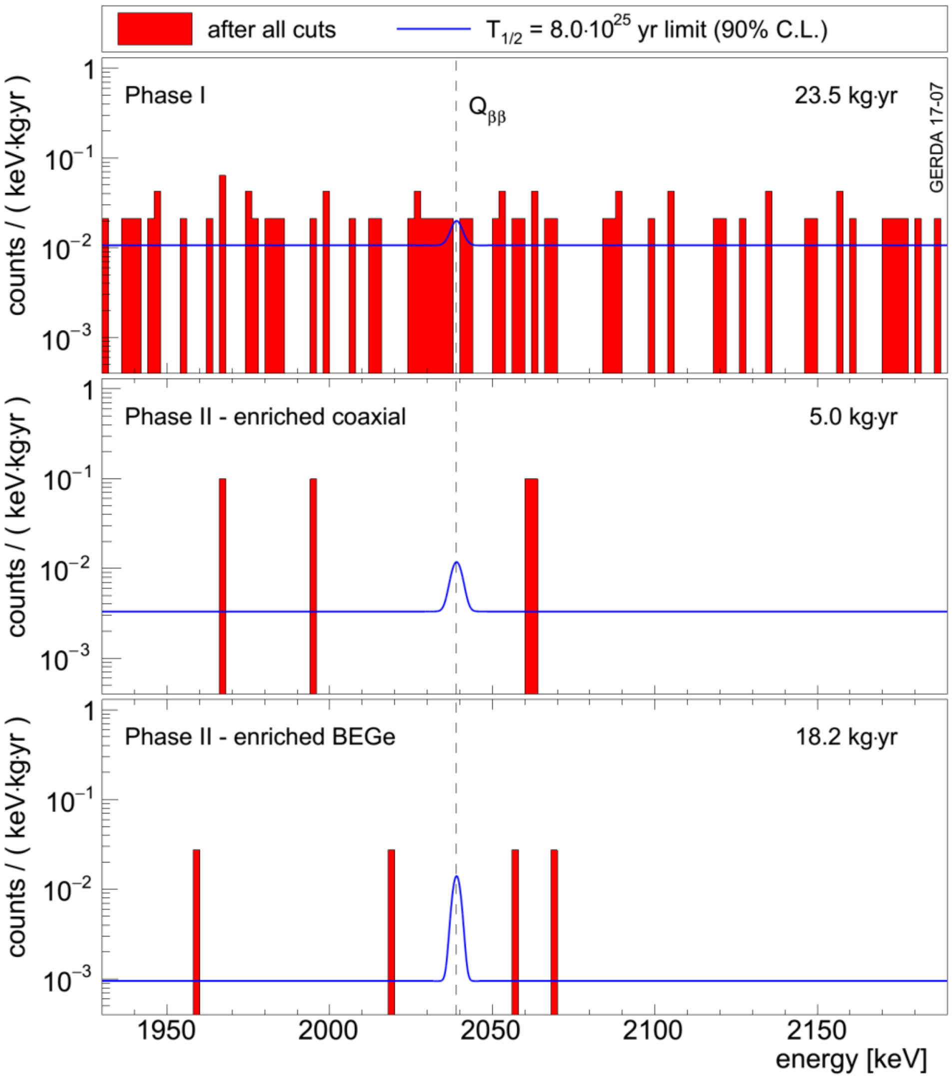
GERDA
Spectra 2017

After LAr veto + PSD:



GERDA

Phase II 2017 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

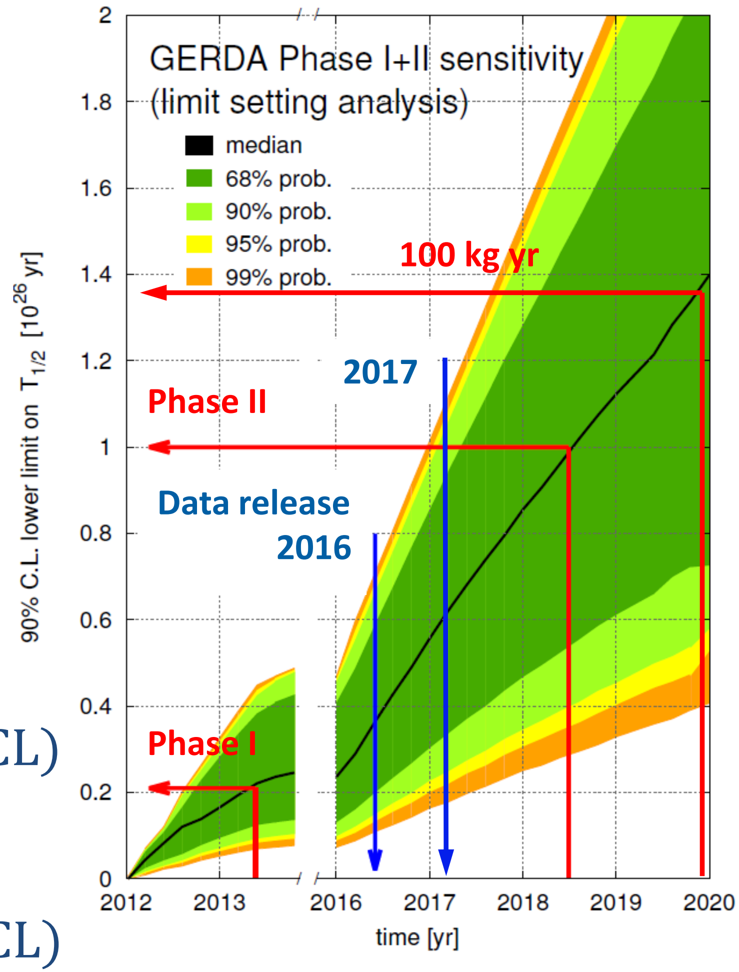
- Phase II is successfully taking data since December 2015

- 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: $T_{1/2}^{0\nu} > 5.8 \times 10^{25} \text{yr (90\% CL)}$

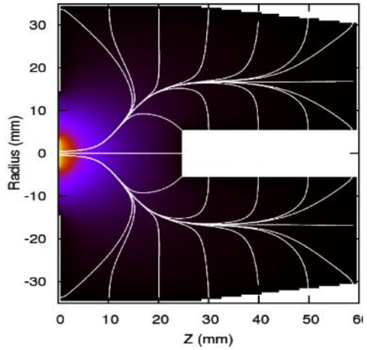
    (best in the 0vββ field)
  - ✓ Limit: $T_{1/2}^{0\nu} > 8.0 \times 10^{25} \text{yr (90\% CL)}$



GERDA

Next steps: possible upgrade

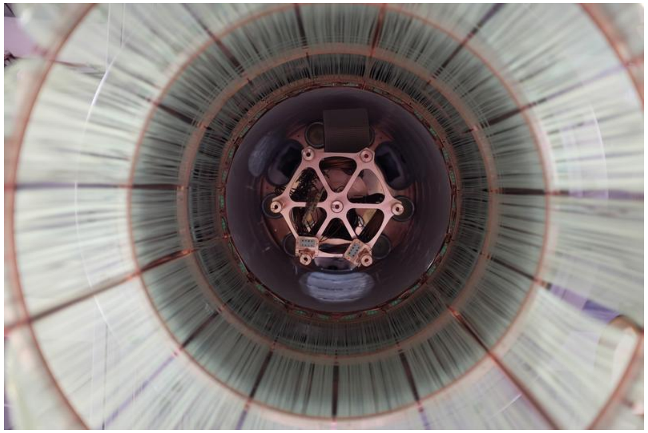
- **New detectors:**
  - ✓ Novel inverted coaxial detector (massive as coaxial and PSD as BEGe)
  - ✓ Enriched material procured
  - ✓ Detectors production ongoing
  - ✓ Significant financial support from **JINR**



Nylon mini-shrouds (MS)
✓**JINR** responsibility

Improved LAr veto:
✓Production ongoing
✓Common TUM and **JINR** effort

Cables:
✓New cables (cleaner) are ready



All detectors have to be completely **dismounted**
Existing detectors, new detectors, new cables, nylon MSs, new LAr veto needs to be **integrated** and data taking has to be **restarted** ~ few months of work

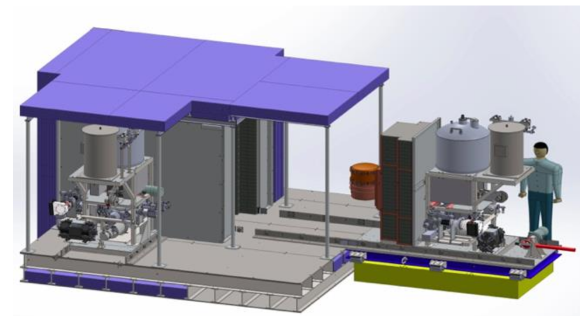
Upgrade process will be **organized** by **JINR** team

G&M

GERDA & Majorana

GERDA

Majorana Demonstrator (MJD)



- Bare Ge-diodes array in LAr
- Shield: high-purity LAr/ H_2O

Phase I: 17 kg (HdM/IGEX)*
Phase II: **38 kg ^{76}Ge**

- Arrays of Ge-diodes in high purity electroformed Cu cryostats
- Shield: Pb, electroformed Cu

30 kg ^{76}Ge

LEGEND: 200 kg and 1000 kg ^{76}Ge

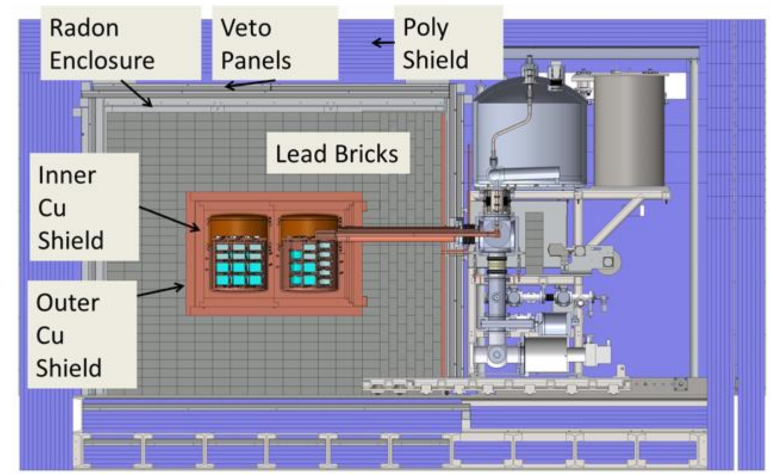
* – completed

G&M

Majorana Demonstrator status

First results from Modules 1 and 2 in-shield

- ✓ Exposure: 1.39 kg yr
- ✓ Background index of 1.8 x 10^{-3} cnt/(keV kg yr)
- ✓ Analysis cuts are still being optimized
- ✓ 10x more exposure in hand – analysis ongoing



- The ^{76}Ge enriched point contact detectors developed by MAJORANA
  - ✓ best energy resolution (2.4 keV FWHM at 2039 keV) of any ββ-decay experiment.
  - ✓ provide excellent pulse shape discrimination reduction of backgrounds.
  - ✓ at low energies have sub-keV energy thresholds and excellent resolution allowing the DEMONSTRATOR to perform sensitive tests in this region for physics beyond the standard model (*PRL **118**, 161801 (2017)*).
- The DEMONSTRATOR's initial backgrounds and the GERDA Phase II backgrounds are the **lowest backgrounds** in the region of interest (ROI) achieved to date of **all** current or previous **0νββ** experiments.

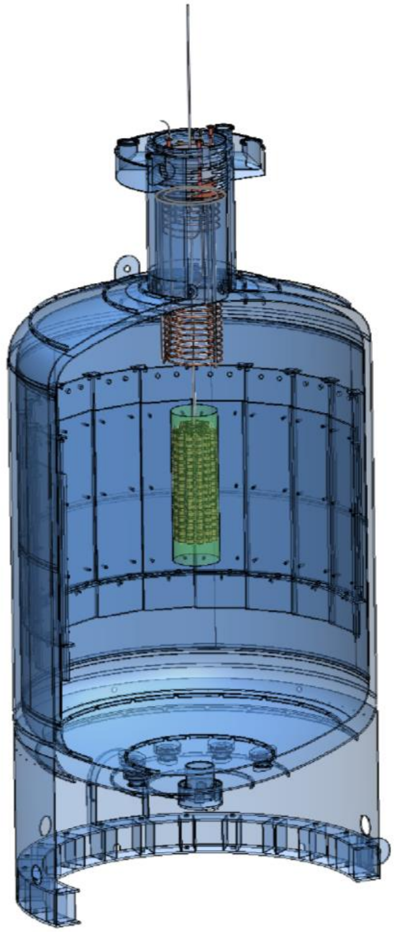
G&M future → LEGEND

Large **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay

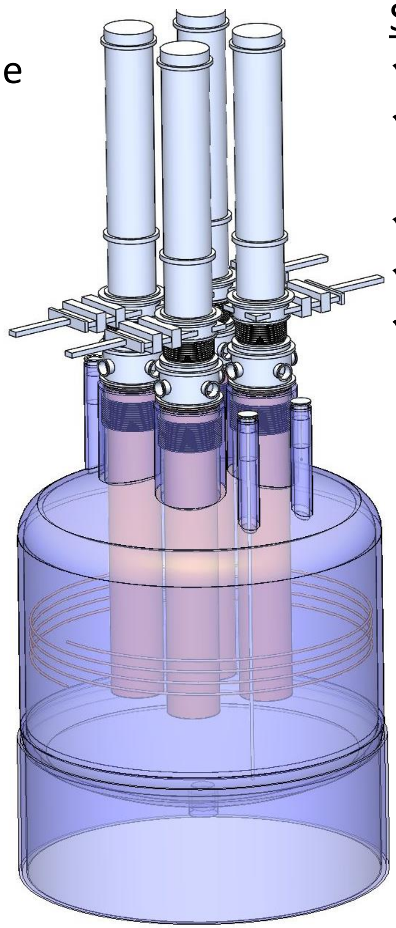
LEGEND mission:
"The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life significantly close to **10^{28}** years, using existing resources as appropriate to expedite physics results."

G&M future → LEGEND

Large **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay



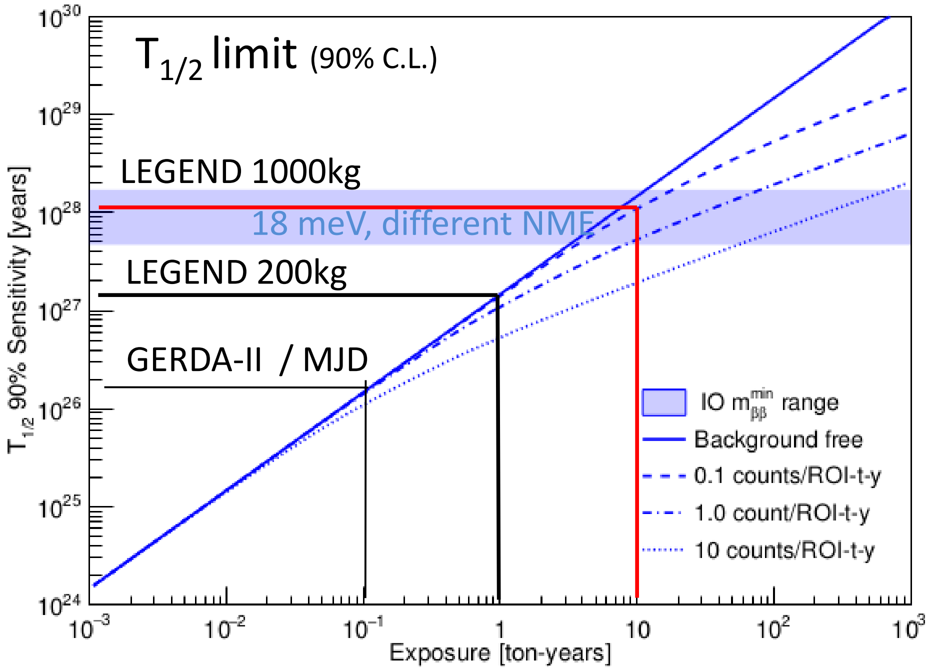
First stage:
- ✓ (up to) 200 kg in upgrade of existing GERDA infrastructure at LNGS
- ✓ bkg reduction by factor 3-5 w.r.t GERDA
- ✓ Sensitivity **10^{27}** yr

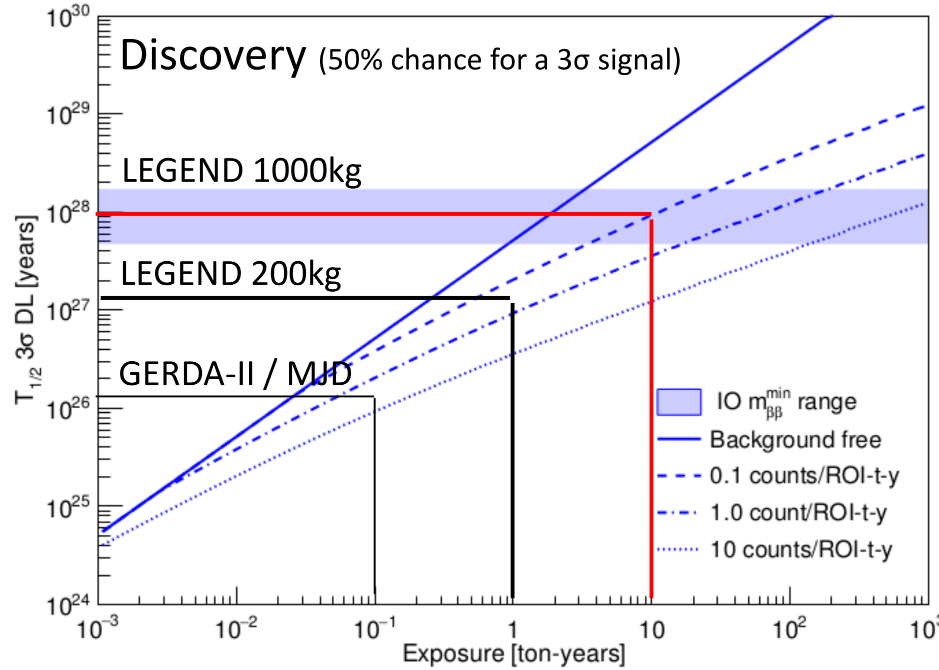


Subsequent stages:
- ✓ 1000 kg (staged)
- ✓ timeline connected to DOE down select process
- ✓ bkg factor 30 w.r.t GERDA
- ✓ Location tbd
- ✓ Sensitivity **10^{28}** yr

G&M future → LEGEND

Sensitivity





- ✓ $T_{1/2}$ unknown, BSM → 'around corner'
- ✓ background reduction in steps → phased approach

- ✓ inputs: 60% efficiency (GERDA number)
- ✓ Background: GERDA/MJD ~ 3 cts/(FWHM t yr)
  200 kg ~ 0.6 cts/(FWHM t yr)
  1000 kg ~ 0.1 cts/(FWHM t yr)

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

Project
GERDA (“G&M”) → LEGEND

- ✓ Ultimate Goal: exposure of 10 t yr; background of 0.1 cnt / FWHM t yr.
- ✓ GERDA & Majorana are taking data in the “background free” regime.
- ✓ LEGEND is selecting the best technologies from GERDA and Majorana as well as contributions from other groups and experiments.
- ✓ Taking a **phased, stepwise implementation**; *e.g.* 200 → 500 → 1000 kg.
- ✓ Preparations for LEGEND 200 are underway. Possible start at the end of 2020.
- ✓ Baseline design for LEGEND 1000 established.
- ✓ Thanks to excellent energy resolution ^{76}Ge has a discovery potential at a half-life close to 10^{27} (LEGEND-200) and 10^{28} (LEGEND-1000) years respectively.

GERDA (“G&M”) at JINR Plans

2018-2019:
The upgrade of the GERDA experiment by adding novel enriched detectors and exchanging of the existing liquid argon veto by improved version. Achieving of design sensitivity of 10^{26} years.

2019-2020:
Reaching of planned GERDA exposure of 100 kg yr. Preparation of the first phase of next generation experiment LEGEND (procurement of enriched ^{76}Ge, production and testing of new Ge detectors, R&D of low background materials and electronics).

2020-2021:
Completion of the GERDA experiment, publication of results. Modification of GERDA cryostat for LEGEND Phase I. Integration and start data taking of the LEGEND experiment.

GERDA publications

1. «The GERDA experiment for the search of 0νββ decay in ^{76}Ge», EPJC 73 (2013) 2330.
2. «Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment», PRL 111 (2013) 122503.
3. «Pulse shape discrimination for GERDA Phase I data», EPJC 73 (2013) 2583.
4. «The background in the 0νββ experiment GERDA», EPJC 74 (2014) 2764.
5. «Results on ββ decay with emission of two neutrinos or Majorons in ^{76}Ge from GERDA Phase I», EPJC 75 (2015) 416.
6. «2νββ decay of ^{76}Ge into excited states with GERDA Phase I», J. Phys. G: Nucl. Part. Phys. 42 (2015) 115201.
7. «LArGe: active background suppression using argon scintillation for the GERDA 0νββ-experiment», EPJC 75 (2015) 506.
8. «The performance of the Muon Veto of the GERDA experiment», EPJC 76 (2016) 298.
9. «Flux modulations seen by the muon veto of the GERDA experiment», Astrop. Phys. 84 (2016) 29.
10. «Limits on uranium and thorium bulk content in GERDA Phase I detectors», Astrop. Phys. 91 (2017) 15.
11. «Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA», **Nature** 544 (2017) 47.
12. «Mitigation of ^{42}Ar/^{42}K background for the GERDA Phase II experiment», submitted to EPJC.
13. «Upgrade for Phase IIa of the GERDA Experiment», submitted to EPJC.
14. «Improved limit on neutrinoless double beta decay of ^{76}Ge from GERDA Phase II», submitted to PRL.

Additional slides

JINR in GERDA

JINR in GERDA management:
K. Gusev – technical coordinator
A. Smolnikov – member of Editorial Board
A. Lubashevskiy – member of Speakers Bureau

GERDA (“G&M”) at JINR
People

Name	Status	Responsibilities	FTE
K. Gusev	Project leader	Project coordination, Ge detectors, ultrapure materials	1.0
A. Lubashevskiy	Deputy leader	Data analysis, Ge detectors, ultrapure materials	0.4
D. Zinatulina	Deputy leader	Muon veto, Ge detectors	0.5
V. Brudanin	Participant	Head of the department, ^{76}Ge procurement	0.1
D. Borowicz	Participant	Ge detectors	0.8
V. Egorov	Participant	Active veto systems	0.1
M. Fomina	Participant	Active veto systems	0.2
A. Klimenko	Participant	Analysis	0.5
O. Kochetov	Participant	Ultrapure materials, active veto systems	0.1
I. Nemchenok	Participant	Ultrapure materials, active veto systems	0.2
S. Nepochatich	Participant	Analysis, Ge detectors	1.0
N. Rumyantseva	Participant	Analysis, Ge detectors	0.7
V. Sandukovsky	Participant	Ge detectors	0.5
E. Shevchik	Participant	Active veto systems	0.2
M. Shirchenko	Participant	Active veto systems, Ge detectors	0.3
A. Smolnikov	Participant	Active veto systems, ultrapure materials, analysis	0.8
I. Zhitnikov	Participant	Active veto systems, Ge detectors	0.2
In total			**7.6**

GERDA ("G&M") at JINR
Financing (form N 26)

Expenditures, resources, financing sources			Costs (k$) Resource requirements	Proposals of the Laboratory on the distribution of finances and resources		
				1st year	2nd year	3rd year
Expenditures		1. Production of the test stand for Ge detectors	40	30	10	
		2. R&D of ultrapure materials	30	10	10	10
		3. Procurement of ^{76}Ge detectors	150	50	50	50
		4. R&D of low background electronics	30	10	10	10
		5. R&D of active veto systems	30	10	10	10
		6. Procurement of prototype detectors	60	60		
		Construction/repair of premises				
		Materials:				
		1. Enriched ^{76}Ge	150	50	50	50
		2. Scintillating materials	30	20	7	3
		3. Chemicals for Ge detectors	5	2	2	1
Required resources	Standard hour	Resources of – Laboratory design bureau; – JINR Experimental Workshop; – Laboratory experimental facilities division; – accelerator; – computer. Operating costs.				
Financing sources	Budgetary resources	Budget expenditures including foreign-currency resources.	621	274	181	166
	External resources	Contributions by collaborators. Grants. Contributions by sponsors. Contracts. Other financial resources, etc.	30	10	10	10

GERDA ("G&M") at JINR Financing (form N 29)

	Expenditure items	Full cost	1st year	2nd year	3rd year
	Direct expenses for the Project				
1.	Accelerator, reactor	h			
2.	Computers	h			
3.	Computer connection	6 k$	2	2	2
4.	Design bureau	standard hour			
5.	Experimental Workshop	standard hour			
6.	Materials	185 k$	72	59	54
7.	Equipment	340 k$	170	90	80
8.	Construction/repair of premises	k$			
9.	Payments for agreement-based research	k$			
10.	Travel allowance, including: a) non-rouble zone countries b) rouble zone countries c) protocol-based	90 k$	30	30	30
	Total direct expenses	621	274	181	166

Comparison experiments

		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cnt/t yr FWHM]	$T_{1/2}$ limit sensitivity [10^{25} yr] after 4 yr	worst m_{ee} limit [meV] (lowest NME, g_A unquenched)	
Gerda II	Ge	35/27	3	5	15	190	running
MajoranaD	Ge	30/24	3	5	15	190	
EXO-200	Xe	170/80	88	220	6	240	
Kamland-Z	Xe	383/88 750/??	250	90 ?	6 50	240 85	design
Cuore	Te	600/206	5	230	9	210	
NEXT-100	Xe	100/80	17	30	6	240	
SNO+	Te	2340/260	190	60	17	160	
nEXO	Xe	5000/4300	58	5	600	24	future
Ge-200	Ge	200/155	3	1	100	75	
Ge-1000	Ge	1000/780	3	0.2	1000	24	

* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

[&] kg of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

Note: values are design numbers except for GERDA, EXO-200 and Kamland-Zen