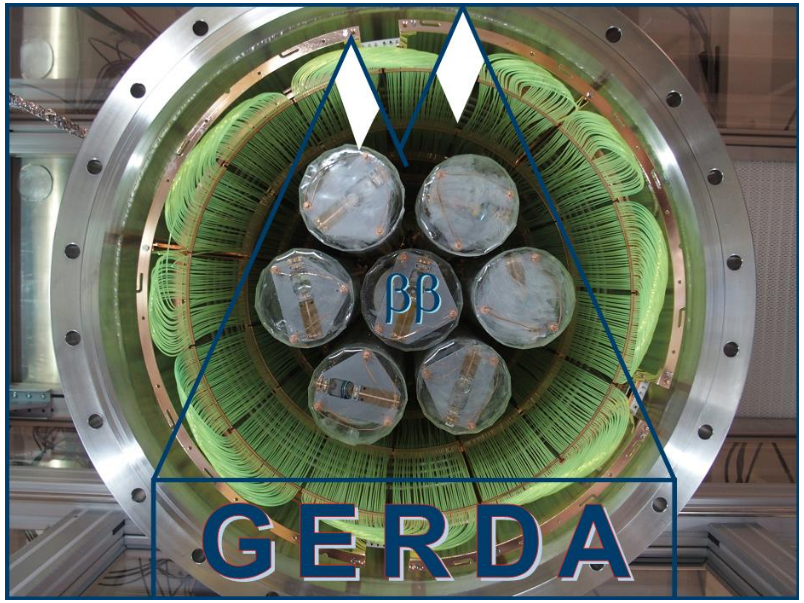
GERDA (LEGEND) project:
Searching for neutrinoless double beta decay of Ge

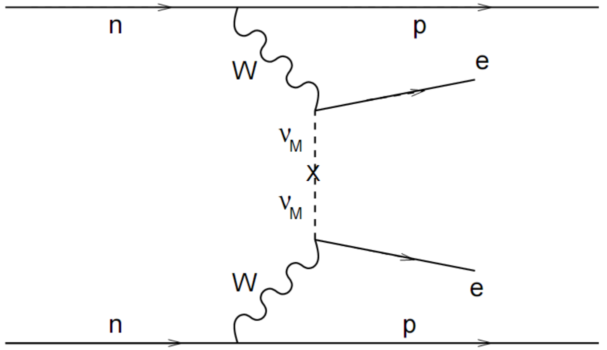


Konstantin Gusev

PACs Joint Session | 21 January 2021

Search for 0νββ-decay
Why and how?

0νββ



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

New Physics!

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

Access to ν mass scale

Experimental sensitivity:

- **Zero** background:

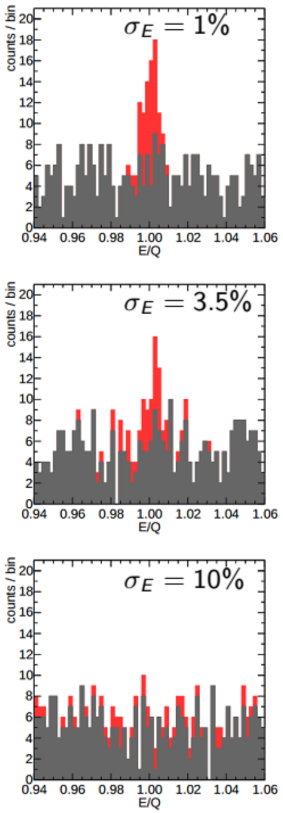
$$T^{0\nu}_{1/2} \propto M\,t$$

- Non-zero background:

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

Isotope	$G^{0\nu}$ (10^{-14}yr)	Q(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
! Resolution remains essential

Search for 0νββ-decay

What about mass?

Effective Majorana neutrino mass contributes in the decay rate:

Phase space factor

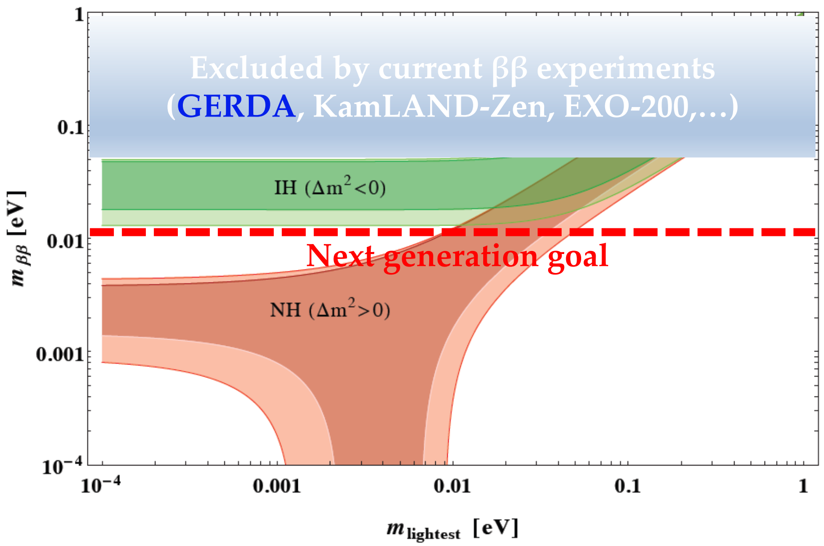
Effective Majorana neutrino mass

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

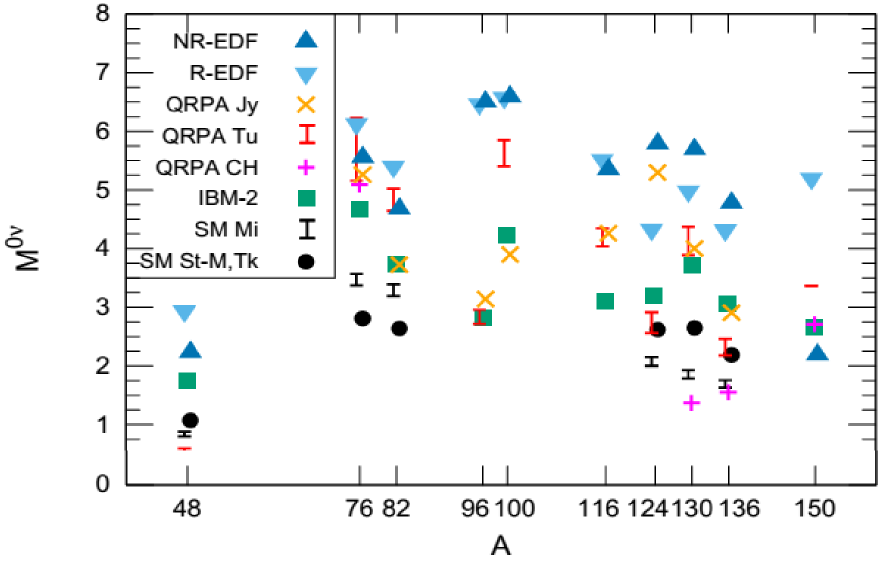
0νββ decay rate

Matrix element (NME)

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



NMEs for different isotopes/models

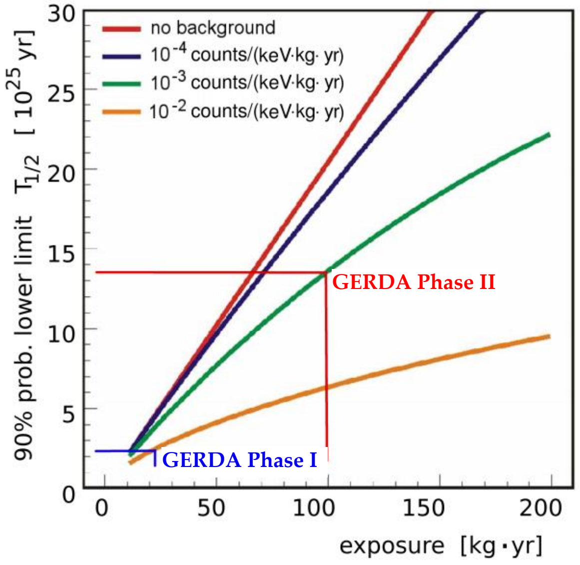


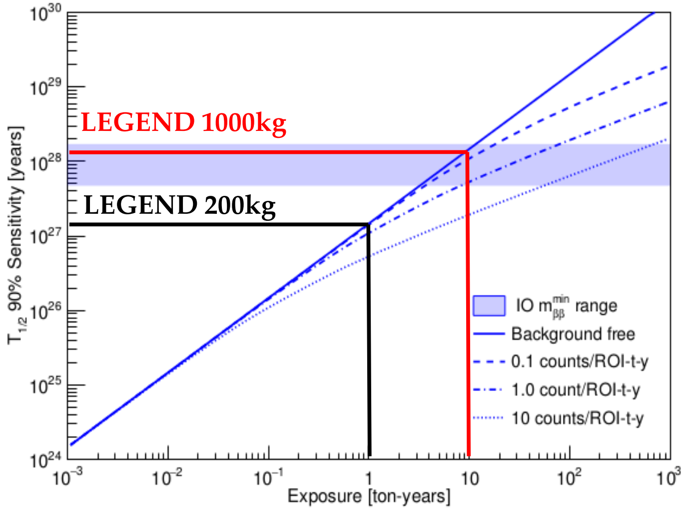
! No preferred isotope from Nuclear Physics (G*M)

GERDA/LEGEND phased approach

HPGe detectors enriched in ^{76}**Ge**

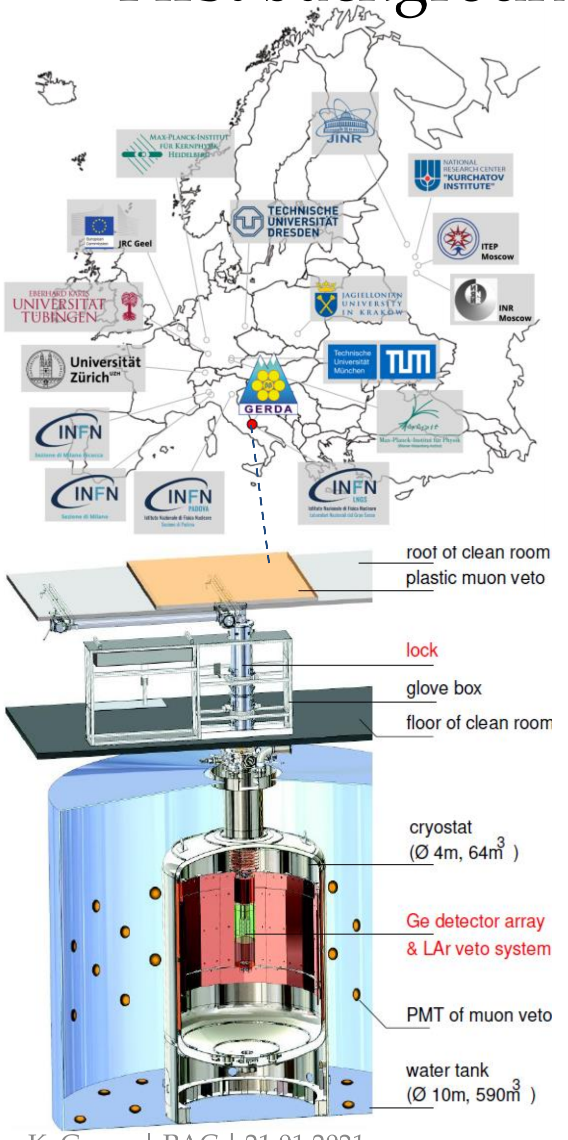
- ✓ very good energy resolution
  ~0.1% at $Q_{\beta\beta}$
- ✓ high detection efficiency
  source = detector
- ✓ “background-free” regime of data taking
  - ✓ deep underground location
    (LNGS, Italy, 3500 m.w.e)
  - ✓ careful assay of materials
  - ✓ passive and active shields
  - ✓ **bare Ge** detectors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





GERDA results

First background free $0\nu\beta\beta$ search



- ✓ GERDA successfully finished data taking in Dec 2019
- ✓ Full data set analyzed in 2020

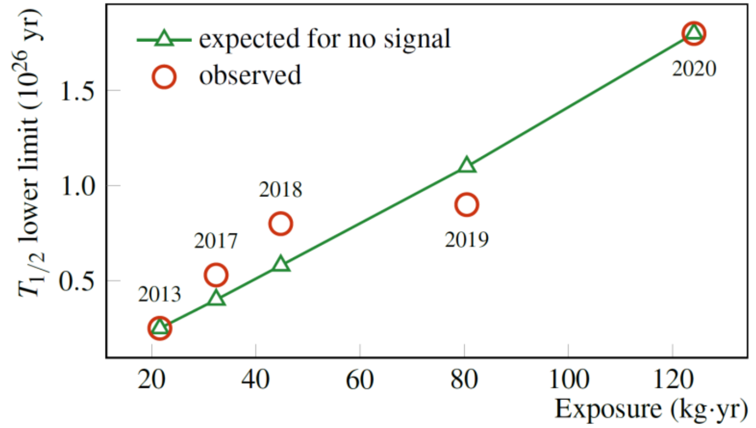
- ✓ **103.7 kg yr** of ^{76}Ge exposure collected in **Phase II** (**127.2** kg yr with Phase I)

- ✓ All design goals are **surpassed!**

GERDA Phase II	**goals**	**achievements**
background	~ 10^{-3} cts/(keV kg yr)	$\mathbf{5.2^{+1.6}_{-1.3} \times 10^{-4}}$ cts/(keV kg yr)
exposure	≥ 100 kg yr	**103.7** kg yr
sensitivity	$T^{0\nu}_{1/2} \geq 10^{26}$ yr	$\mathbf{T^{0\nu}_{1/2} > 1.8 \times 10^{26}}$ **yr**

- ✓ GERDA achieved world best half-life limit!

$$\mathbf{T^{0\nu}_{1/2} > 1.8 \times 10^{26}\ yr}\ (90\%\ CL)$$



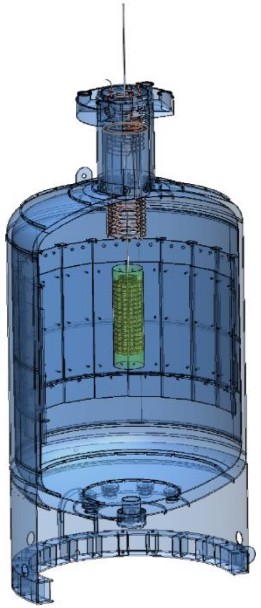
- ✓ Linear increase of sensitivity vs exposure is proven!
- ✓ Bright future for the next step:

LEGEND

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

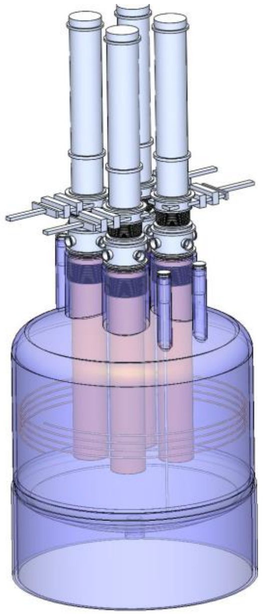
LEGEND mission:
"The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life significantly close to **10^{28}** years, using existing resources as appropriate to expedite physics results."



First stage (LEGEND-200):

- ✓ Existing **GERDA** infrastructure large enough for 200 kg of enriched detectors
- ✓ 14 strings arranged on maximum diameter of 550 mm
- ✓ Number of readout channels will increase substantially
  - ✓ raise clean room roof
  - ✓ new lock
  - ✓ new cabling
  - ✓ new detector suspension
- ✓ Detectors
  - ✓ BEGe's from GERDA
  - ✓ PPC's from Majorana (successfully tested in LAr)
  - ✓ new ICPC detectors (baseline 1.5 kg each)

Background goal: ~ 0.6 cts/(FWHM t yr)



Subsequent stages (LEGEND-1000):

- ✓ 1000 kg (staged)
- ✓ **Combine best** ideas from MAJORANA, GERDA, others
- ✓ **Baseline design**: **Ge** detectors in **LAr**
  - LAr detector volume separated by thin Cu from main cryostat volume
  - use depleted LAr in inner detector volumes
- Investigating alternatives
- ✓ **Profit from** experience with **LEGEND-200**

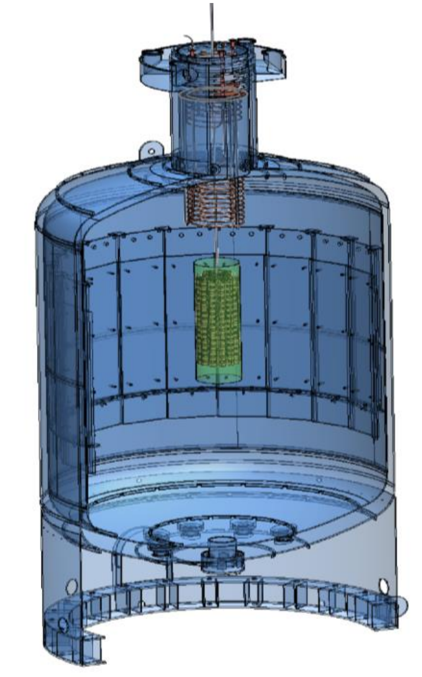
Background goal < 0.1 cnt/(FWHM t yr)

LEGEND:
the best from **GERDA** and **MAJORANA**

GERDA

- ✓ LAr veto
- ✓ Low-A shield, no Pb

GERDA achieved the lowest background index:
5×10^{-4} cts/(keV kg yr)
LEGEND-200 needs only ~ 3x better



Both

- ✓ Clean fabrication techniques
- ✓ Control of surface exposure
- ✓ Development of large point-contact detectors
- ✓ Best BI and FWHM in 0νββ field

MAJORANA

- ✓ Radiopurity of nearby parts (FETs, cables, Cu)
- ✓ Low noise FE improves PSD
- ✓ Low energy threshold

MAJORANA achieved best energy resolution:
2.5 keV FWHM at Q_{bb}

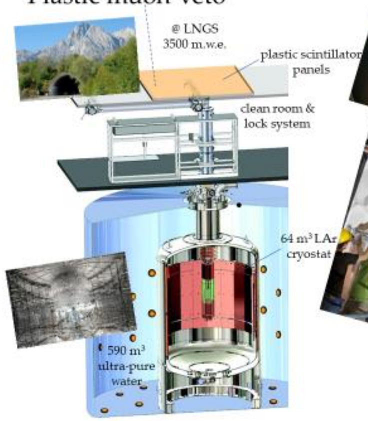
In fact, this LEGEND-200 goal is similar to the best of the GERDA detectors

GERDA (LEGEND) & **JINR**

Contributions

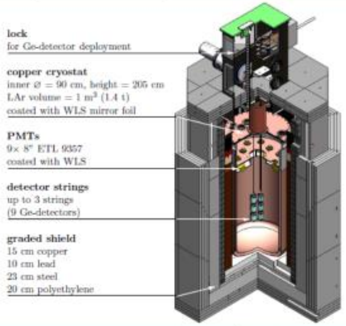
GERDA
Bare detectors

GERDA
Plastic muon veto



GERDA
LArGe test facility

Большая часть исследований по разработке аргонового вето и методик подавления фона от радиоактивного ^{42}Ar была выполнена при непосредственном участии сотрудников ОИЯИ с помощью низкофоновой тестовой установки LArGe



Для детального изучения фона от ^{42}Ar, был искусственно произведен ^{42}Ar и добавлен в жидкий аргон криостата LArGe. Были разработаны и протестированы различные способы подавления фона от ^{42}Ar.

GERDA collaboration, Eur. Phys. J. C 78 (2018) 388

GERDA Collaboration

March 25, 2019

Collaboration Management

spokesperson:	Riccardo Brugnera
co-spokesperson:	Bernhard Schwingenheuer
chair of collaboration board:	Josef Jochum
chair of speakers bureau:	Bela Majorovits
chair of editorial board:	Karl-Tasso Knöpfle
analysis coordinator:	Matteo Agostini
technical coordinator:	Konstantin Gusev
GLIMOS/RAE:	Marco Balata

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

Editorial Board: P. Grabmayr, R. Hiller, K.T. Knöpfle, A. Smolnikov, A. Zsigmond; (ex officio: R.Brugnera, B. Schwingenheuer) ➡ mail to EB

Speakers Bureau: L. Baudis, J. Jochum, A. Lubashevsky, B. Majorovits, F. Salamida; (ex officio: R.Brugnera, B. Schwingenheuer) ➡ mail to SB

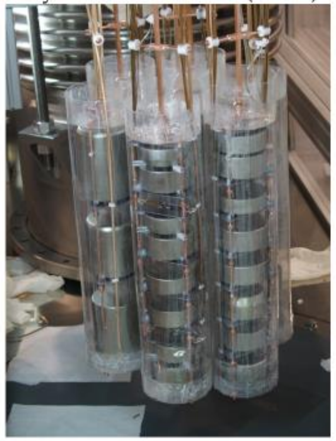
Groups and Principal Investigators

INFN Gran Sasso, GSSI:	M. Laubenstein
Cracow:	M. Wojcik
TU Dresden:	K. Zuber
JINR Dubna:	K. Gusev
Geel:	M. Hult
MPIK-Heidelberg:	W. Hofmann
	M. Lindner
Milano Bicocca & INFN:	E. Bellotti
INR Moscow:	L. Bezrukov
ITEP Moscow:	I. Kirpichnikov
Kurtchatov Moscow:	K. Gusev
MPI-P Munich:	A. Caldwell
TU Munich:	S. Schönert
Padova University & INFN:	R. Brugnera
EKUT Tübingen:	J. Jochum
U. Zürich:	L. Baudis

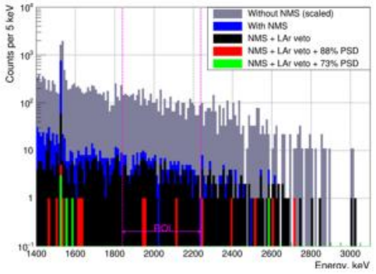
Task Groups and Leaders

TG1:	modification &test of existing diodes	S.Schönert
TG2:	design &production of new Ge diodes	A. Caldwell
TG3:	front end electronics	C. Cattadori/V. D'Andrea
TG4:	cryostat & cryogenic infrastructure	B. Schwingenheuer
TG5:	clean room & lock system	B. Majorovits
TG6:	water tank & water plants	C. Cattadori
TG7:	muon veto	J. Jochum/A.-K.Schütz/D.Zinatulina
TG8:	infrastructure & logistics	M. Junker
TG9:	DAQ &online software	B. Schwingenheuer/R.Brugnera
TG10:	simulation& background studies	L. Pandola/L. Pertoldi
TG11:	material screening	J. Schreiner/G. Zuzel
TG12:	energy calibration	L. Baudis/R. Hiller
TG13:	data reduction & analysis software	M. Agostini/C. Wiesinger
TG14:	LArGe	H. Simgen/S. Schönert
TG15:	detector integration, operation & maintenance	K. Gusev
TG16:	pulse shape analysis	Y. Kermaidic/A. Zsigmond

GERDA
Nylon mini-shroud (NMS)



- Разработанный NMS обладает хорошей радиоактивной чистотой, стабилен в жидком аргоне, улучшает работу аргонового вето и позволяет в комбинации с PSD уменьшить уровень фона в области интереса более чем в 1000 раз.
- NMS были успешно применены в GERDA. Новые улучшенные версии NMS будут специально приготовлены в чистой комнате ОИЯИ для эксперимента LEGEND.



A. Lubashevskiy et al., Eur. Phys. J. C 78 (2018) 15

GERDA **Phase II**
Upgrade 2018

GERDA (LEGEND) & **JINR**
Contributions

- ✓ ~ 15 kg of enriched ^{76}Ge
- ✓ Management and leadership of all operations with bare germanium detectors in all GERDA Phases
- ✓ Design, production, testing and installation of plastic muon veto system
- ✓ Crucial involvement in the development of liquid argon instrumentation:
  - ➢ R&D of argon scintillations registration principles
  - ➢ Design and production of the initial GERDA Phase II LAr veto system (2015)
- ✓ Design and production of modified LAr veto for GERDA upgrade in 2018 (together with TUM group)
- ✓ R&D and realization of original method of mitigation of ^{42}Ar background – nylon mini-shrouds (NMS)
- ✓ Participation in the development of PSD methods for germanium detectors
- ✓ Involvement in physics analysis

Responsibilities of **JINR** group members within the management structure of the **GERDA** collaboration	
K.Gusev	technical coordinator of the GERDA experiment; leader of detectors integration, operation & maintenance task group
A.Smolnikov	member of Editorial Board
A.Lubashevskiy	member of Speakers Bureau
D.Zinatulina	co-leader of muon veto task group

GERDA (LEGEND) & **JINR**

People

Name	Status	Project role	FTE
K.N.Gusev	PI	Project Leader (Ge detectors, active veto systems)	0.6
A.V.Lubashevskiy	senior researcher	Deputy Leader (analysis, ultrapure materials, Ge detectors)	0.3
N.S.Rumyantseva	researcher	Deputy Leader (Ge detectors, analysis)	0.4
V.B.Brudanin	senior researcher	Participant (^{76}Ge procurement, ultrapure materials)	0.1
M.V.Fomina	researcher	Participant (active veto systems)	0.2
S.A.Evseev	engineer	Participant (Ge detectors)	0.1
D.V.Filosofov	senior researcher	Participant (ultrapure materials)	0.1
L.Grubchin	senior researcher	Participant (Ge detectors)	0.1
Yu.B.Gurov	senior researcher	Participant (Ge detectors)	0.2
Zh.H.Hushvaktov	researcher	Participant (ultrapure materials)	0.2
I.I.Kamnev	technician	Participant (active veto systems)	0.2
A.A.Klimenko	senior researcher	Participant (analysis)	0.7
F.Mamedov	senior researcher	Participant (ultrapure materials, analysis)	0.2
I.B.Nemchenok	senior researcher	Participant (ultrapure materials, active veto systems)	0.2
A.V.Rakhimov	technician	Participant (ultrapure materials)	0.1
S.V.Rozov	senior researcher	Participant (Ge detectors)	0.1
V.G.Sandukovsky	senior researcher	Participant (Ge detectors)	0.5
K.V.Shakhov	researcher	Participant (ultrapure materials)	0.1
E.A.Shevchik	senior engineer	Participant (active veto systems)	0.3
Yu.A.Shitov	senior researcher	Participant (analysis)	0.1
A.A.Smolnikov	senior researcher	Participant (active veto systems, ultrapure materials, analysis)	0.7
S.I.Vasilev	senior researcher	Participant (active veto systems, analysis)	1.0
V.P.Volnikh	technician	Participant (technical support)	0.1
E.A.Yakushev	senior researcher	Participant (Ge detectors, analysis)	0.1
I.V.Zhitnikov	researcher	Participant (analysis)	0.1
			Total FTE = 6.8

GERDA (LEGEND) & **JINR**
Plans

2021-2022:
- Dismounting the plastic muon veto on top of the GERDA clean room; decision whether it is needed for LEGEND-200
- Finalizing the design, production and installation of LEGEND-200 LAr veto (joint JINR+TUM team)
- Production of NMSs for first LEGEND strings in the clean room at DLNP JINR, then integration at LNGS
- Completion of the design of string movement system in the LEGEND glove box, procurement and installation on-site
- Leadership in integration of the first strings of the LEGEND experiment
- Continuation of work on the conceptual design of LEGEND-1000 (Ge detectors, new materials, background mitigation methods, …)
- Continuation of the analysis of the GERDA data set (new limits on exotic decay modes)

2022-2023:
- Production of NMSs for all LEGEND-200 strings and mounting them in the experiment
- Leadership the integration of the full LEGEND-200 array
- Start analyzing of first LEGEND data, integration of JINR analysis team in the LEGEND-200 analysis group
- Continuation of work on the design of LEGEND-1000

2023-2024:
- Keeping the leading role in LEGEND detector operation and maintenance, analyzing detector stability and performance
- Management of adding of new detectors strings in the center of the LEGEND-200 array if the collaboration will decide to do so
- Continuation of the analysis of LEGEND-200 data (strong involvement in the publication activity)
- Continuation of work on ^{42}Ar and other background mitigation techniques, providing new solutions for LEGEND-1000
- Finalizing LEGEND-1000 LAr veto design
- Providing to the collaboration our developments in new detector types and low background materials

GERDA (LEGEND) & **JINR**

Financing

Form No. 26

Schedule proposal and resources required for the implementation of the Project GERDA (LEGEND)

		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. R&D of ultrapure materials 2. Procurement of ^{76}Ge detectors 3. R&D of active veto systems 4. R&D on Ge detectors 5. R&D of ^{42}Ar/^{42}K background mitigation	30 150 30 140 30	10 50 10 60 10	10 50 10 20 10	10 50 10 60 10
Expenditures		Construction/repair of premises				
Expenditures		Materials: 1. Enriched ^{76}Ge 2. Scintillating and clean materials 3. Chemicals for Ge detectors	 150 45 6	 50 15 2	 50 15 2	 50 15 2
Required resources	Standard hour	Resources of – Laboratory design bureau; – JINR Experimental Workshop; – Laboratory experimental facilities division; – accelerator; – computer. Operating costs.	 300 600	 100 200	 100 200	 100 200
Financing sources	Budgetary resources	Budget expenditures including foreign-currency resources.	581	207	167	207
Financing sources	External resources	Contributions by collaborators. Grants. Contributions by sponsors. Contracts. Other financial resources, etc.	30	10	10	10

Form No. 29

Estimated expenditures for the Project GERDA (LEGEND): searching for neutrinoless double beta decay of Ge-76

	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	100	100	100
5.	Experimental Workshop	standard hour	200	200	200
6.	Materials	201 k$	67	67	67
7.	Equipment	380 k$	140	100	140
8.	Construction/repair of premises	k$			
9.	Payments for agreement-based research	k$			
10.	Travel allowance, including:	150 k$			
	a) non-rouble zone countries		30	30	30
	b) rouble zone countries				
	c) protocol-based		20	20	20
	Total direct expenses	737	259	219	259

Taking into account the total FTE of the Project, about 115600US$ or 7398400₽ per year is needed for salaries. **Estimation** based on 2020 data and includes spending on technical personnel not listed in the project. 1US$ equal to 64₽ assumed in the estimation.

GERDA (LEGEND) & **JINR**

Publications, theses and talks (since the last approval)

1. «Upgrade for Phase II of the GERDA Experiment», Eur. Phys. J. C 78 (2018) 388.
2. «Mitigation of $^{42}Ar/^{42}K$ background for the GERDA Phase II experiment», Eur. Phys. J. C 78 (2018) 15.
3. «Improved Limit on Neutrinoless Double-β Decay of ^{76}Ge from GERDA Phase II», Phys. Rev. Lett. 120 (2018) 132503.
4. «Characterization of 30 ^{76}Ge enriched Broad Energy Ge detectors for GERDA Phase II», Eur. Phys. J. C. 79 11 (2019) 978.
5. «Probing Majorana neutrinos with double-β decay», Science 365 (2019) 1445.
6. «Modeling of GERDA Phase II data», Journal of High Energy Physics 03 (2020) 139.
7. «First Search for Bosonic Superweakly Interacting Massive Particles with Masses up to 1 MeV/c2 with GERDA», Phys. Rev. Lett. 125 (2020) 011801.
8. «Final Results of GERDA on the Search for Neutrinoless Double-β Decay», Phys. Rev. Lett. 125 (2020) 252502.

PhD:

2 Project members D.Zinatulina and M.Shirchenko graduated in 2019

2 Project members expected to complete their theses within 2 years:

- ✓ N.Rumyantseva, «Investigation of novel background suppression methods in double beta decay experiments» (preliminary)
- ✓ E.Shevchik, «Investigation of active background rejection by using cryogenic liquids» (preliminary)

GERDA (LEGEND) & **JINR**

Publications, theses and talks (since the last approval)

Invited plenary talks:

- ✓ Neutrino Oscillation Workshop 2018 (**NOW 2018**), September 9-16, 2018, Brindisi, Italy, «Neutrinoless double beta decay: Experimental challenges», *K. Gusev*
- ✓ 12th Matrix Elements for the Double beta decay Experiments meeting (**MEDEX'19**), May 27-31, 2019, Prague, Czech Republic «GERDA searches for 0νββ and other ββ decay modes of 76Ge», *A. Smolnikov*

Parallel talks:

- 68^{th} Conference on nuclear spectroscopy and atomic nucleus structure (**Nucleus 2018**), July 1-6, 2018, Voronezh, Russia, «New results of the search for neutrinoless double beta decay from GERDA Phase II», *N. Rumyantseva*
- 27^{th} International Workshop on Weak interactions and Neutrinos (**WIN2019**), June 3-8 2019, Bari, Italy, «Status of the search for neutrinoless double-beta decay with GERDA», *A. Lubashevskiy*
- 69^{th} Conference on nuclear spectroscopy and atomic nucleus structure (**Nucleus 2019**), July 1-5, 2019, Dubna, Russia, «Upgrade of the GERDA Phase II experiment», *E. Shevchik*
- The 27^{th} International Nuclear Physics Conference (**INPC 2019**), July 29 – August 2 2019, Glasgow, UK, «Latest results from the first background free search for neutrinoless double beta decay – GERDA Phase II», *K. Gusev*
- 8^{th} International Conference on New Frontiers in Physics (**ICNFP 2019**), August 21-29 2019, Crete, Greece, «Status of the GERDA Phase II experiment», *N. Rumyantseva*
- 40^{th} International Conference on High Energy Physics (**ICHEP 2020**), July 28 – August 6 2020, Prague (virtual conference), «Results of the GERDA Phase II experiment», *K. Gusev*

GERDA (LEGEND) & **JINR**

SWOT (LEGEND-200)

Strengths	Weaknesses
• Best energy resolution • Extremely low background • Existing infrastructure and design of main components (detector holders, electronics, LAr veto) • Availability of most personnel who managed and performed GERDA final integration in 2015 as well as GERDA Phase II modification in 2018	• Possibility to not reach background-free conditions
Opportunities	**Threats**
• **Well-established technology of detector fabrication** • **Secured funding for new detectors production**	• **Continuation of travel restrictions due to pandemic** • **High failure rate of new detector production**

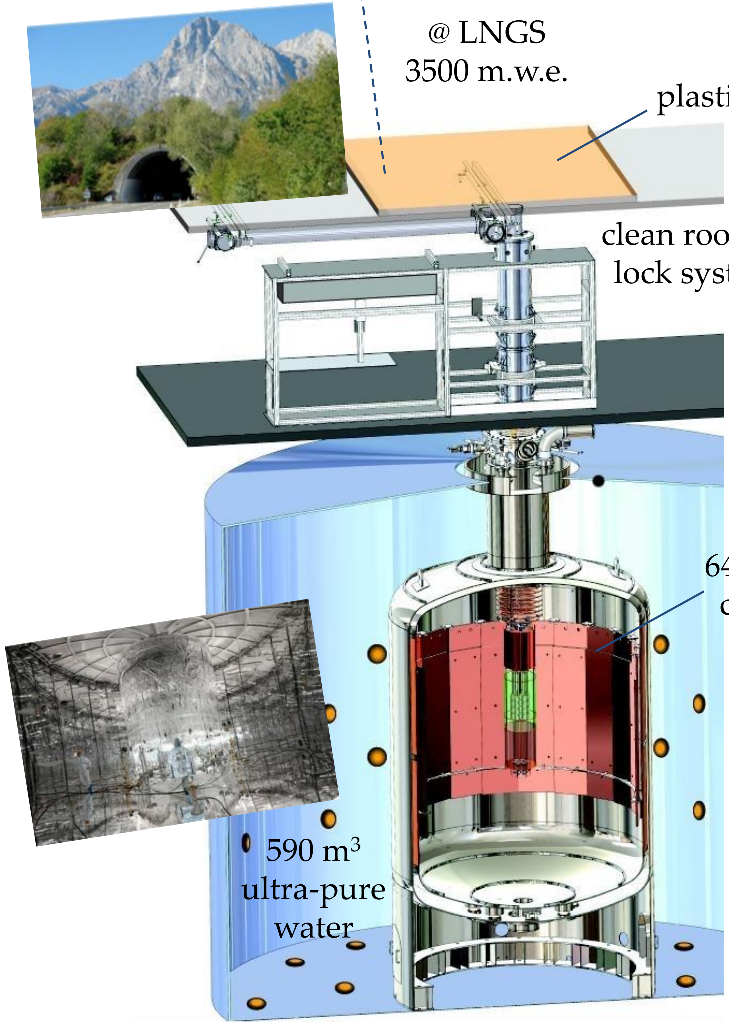
Additional slides

GERDA (LEGEND-200)

Location

GERDA & JINR

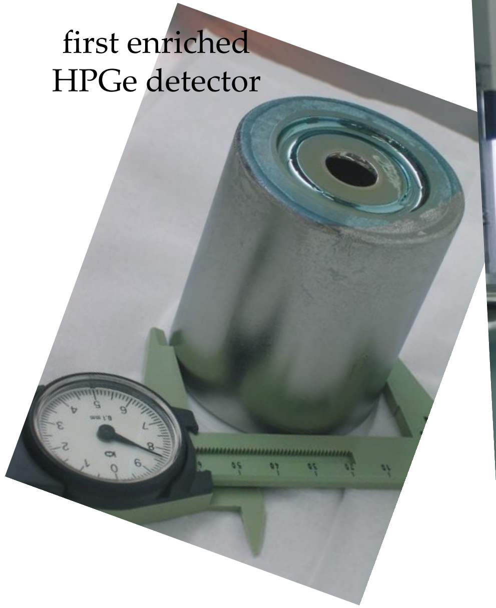
Plastic muon veto



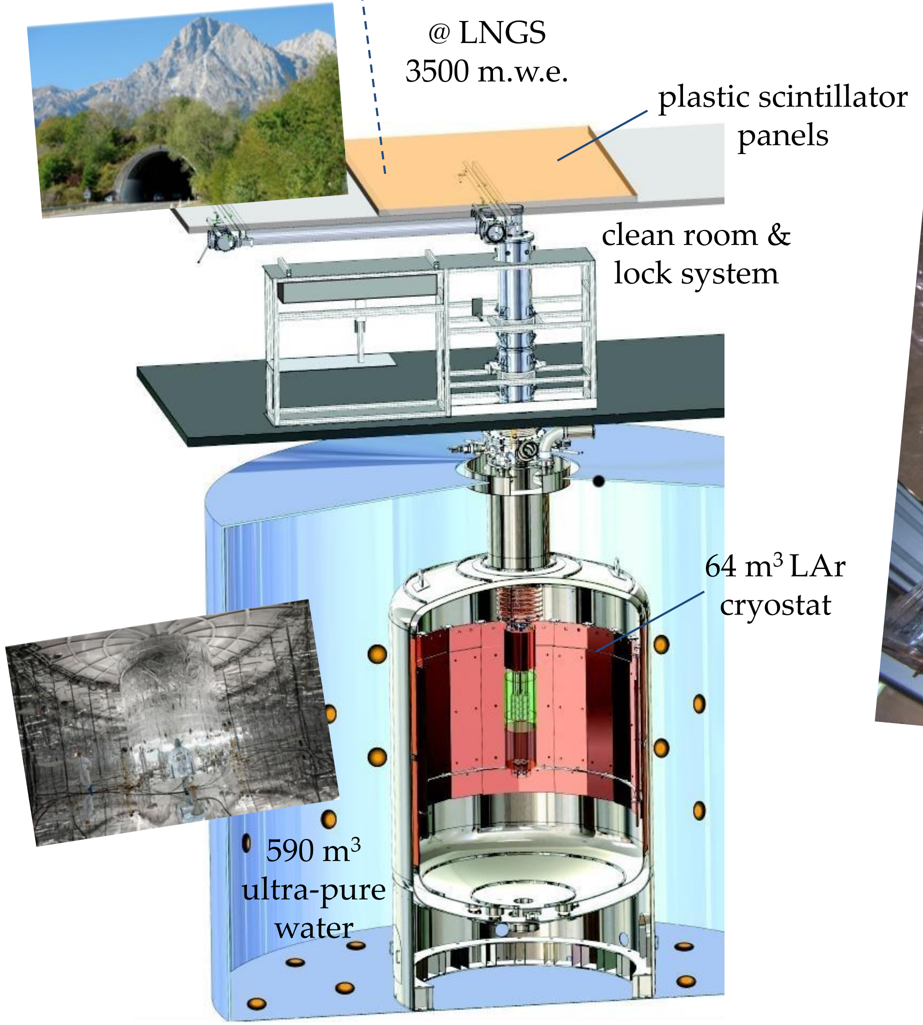
GERDA & **JINR**

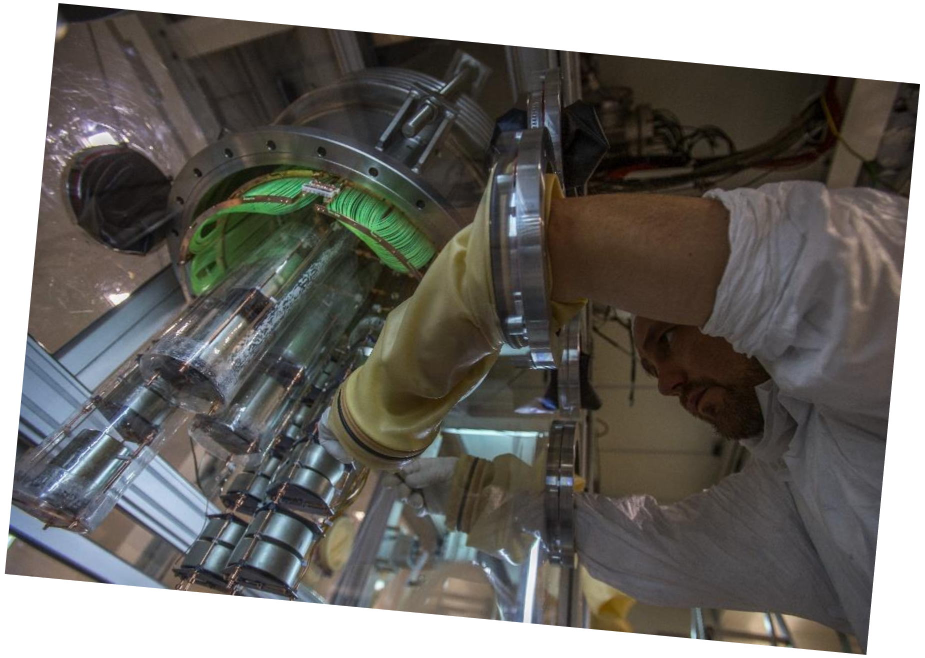
Bare detectors operations

first enriched
HPGe detector



GERDA & **JINR**
Bare detector operations

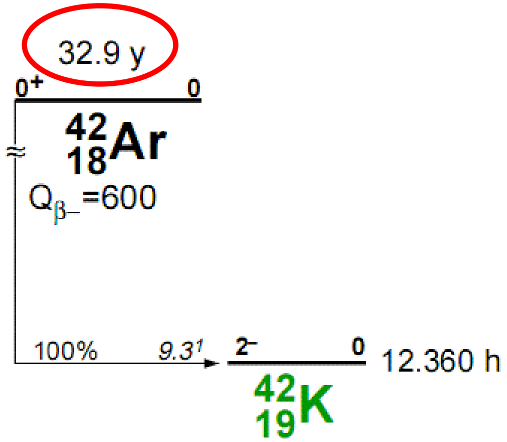


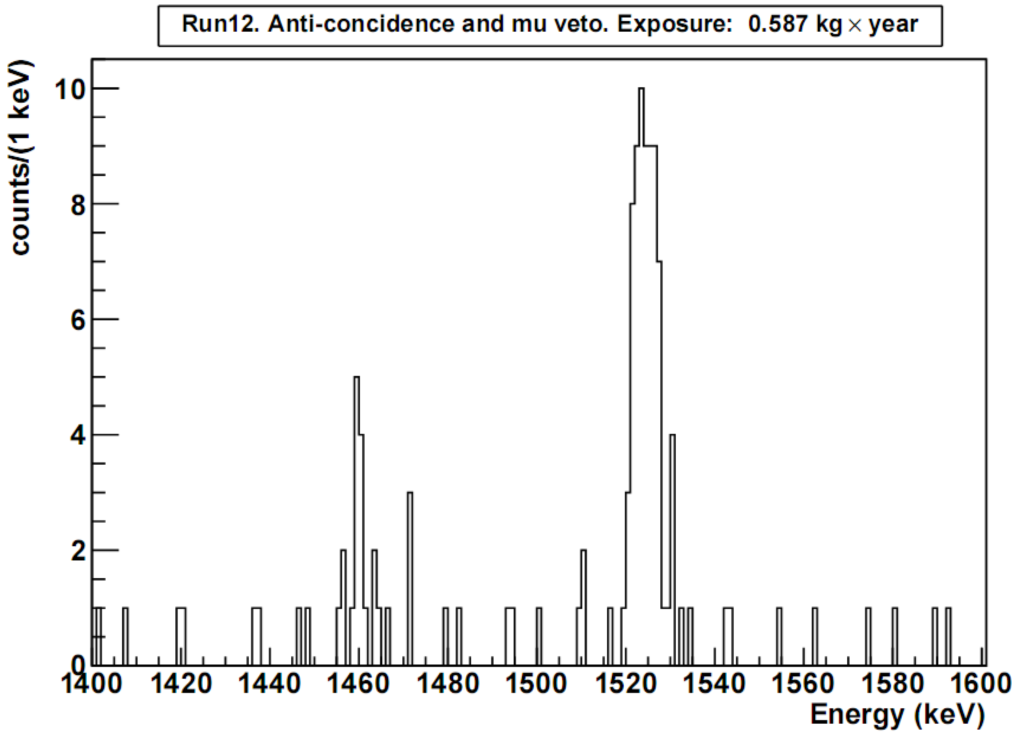


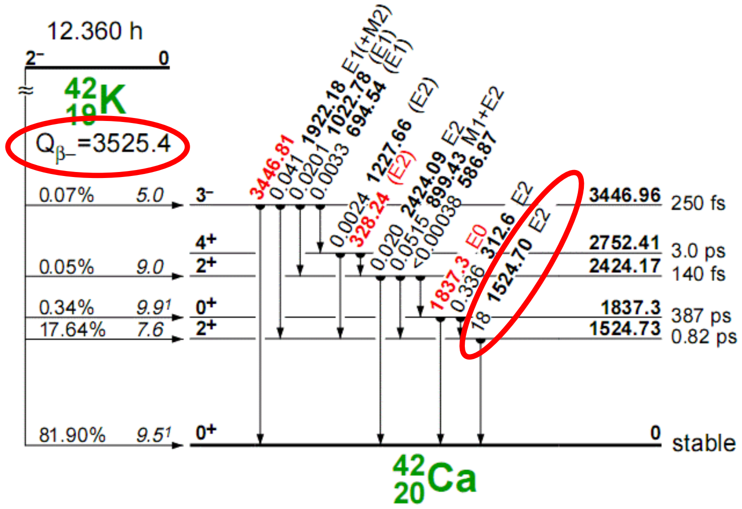
GERDA & JINR

^{42}Ar background mitigation

In GERDA Phase I a higher (compared with expectations) background from ^{42}K was found. ^{42}K is beta-decay isotope with the endpoint of 3.5 MeV. It's coming from ^{42}Ar in liquid argon around bare Ge detectors. First measurements, investigations and development of the suppression methods have been done in the LArGe low background test facility (next slide).





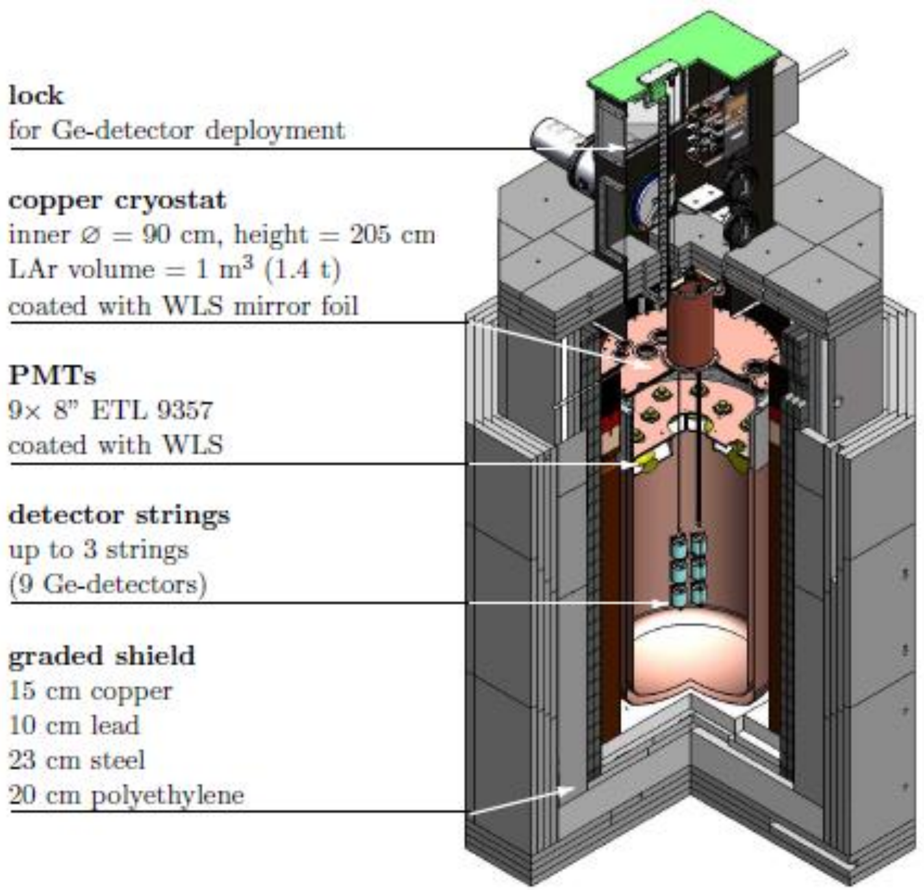


^{42}Ar background is one of the most dangerous in for GERDA and LEGEND!

GERDA & **JINR**

LArGe test facility

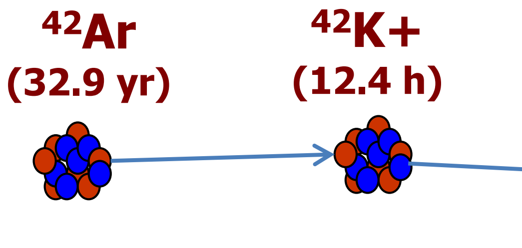
Design, creation and maintenance of low background **LArGe** test facility as well as R&D for LAr veto and ^{42}Ar mitigation in this setup have been done with crucial participation of **JINR** specialists!

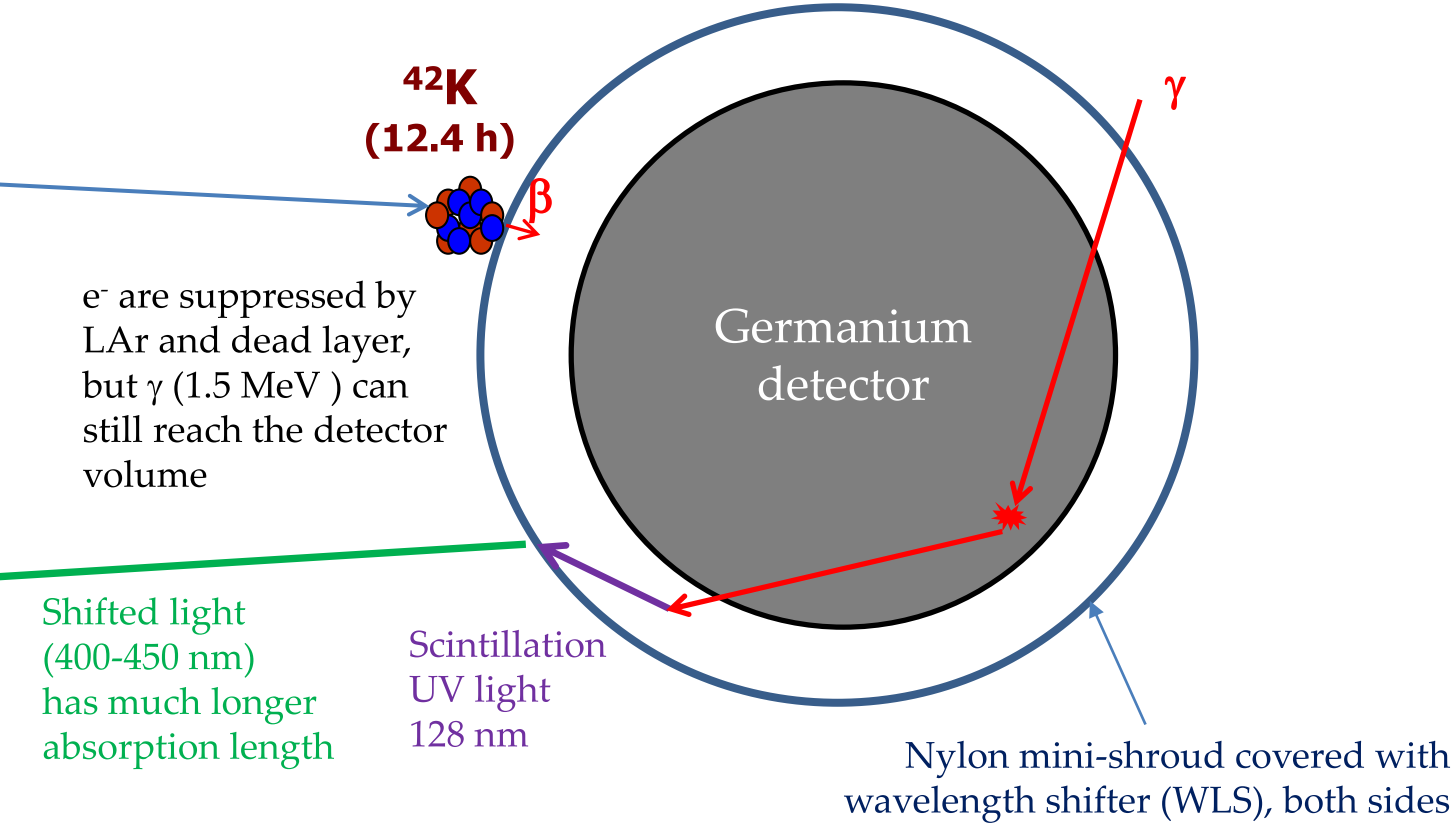


GERDA & **JINR**

^{42}Ar background mitigation – nylon mini-shroud (NMS) concept

Background from ^{42}Ar can be suppressed by a mini-shroud made of ultrapure nylon foil. It creates mechanical barrier which stops the drift of ^{42}K atoms towards the detector surface → dangerous betas from ^{42}K captured on the mini-shroud surface suppressed by LAr and dead layer of Ge detectors. However nylon is not transparent for the far UV light → nylon surface had to be covered with wavelength shifter (based on TPB).





Detection by LAr veto

GERDA (LEGEND) & **JINR**

^{42}Ar background mitigation – NMS

The NMS for GERDA Phase II were made from nylon. Nylon pieces were covered by WLS and formed to NMS with a clean glue.

- Very clean material used
- Low mass design
- Robust, good for handling, flexible and easy to shape
- Suitable for cryogenic usage
- Shift and transport light which can be detected

A. Lubashevskiy et al., Eur. Phys. J. C 78 (2018) 15

→ Worked well in GERDA Phase II

→ Modified versions of NMS are going to be produced by our team in the clean room at DLNP JINR and installed in LEGEND-200

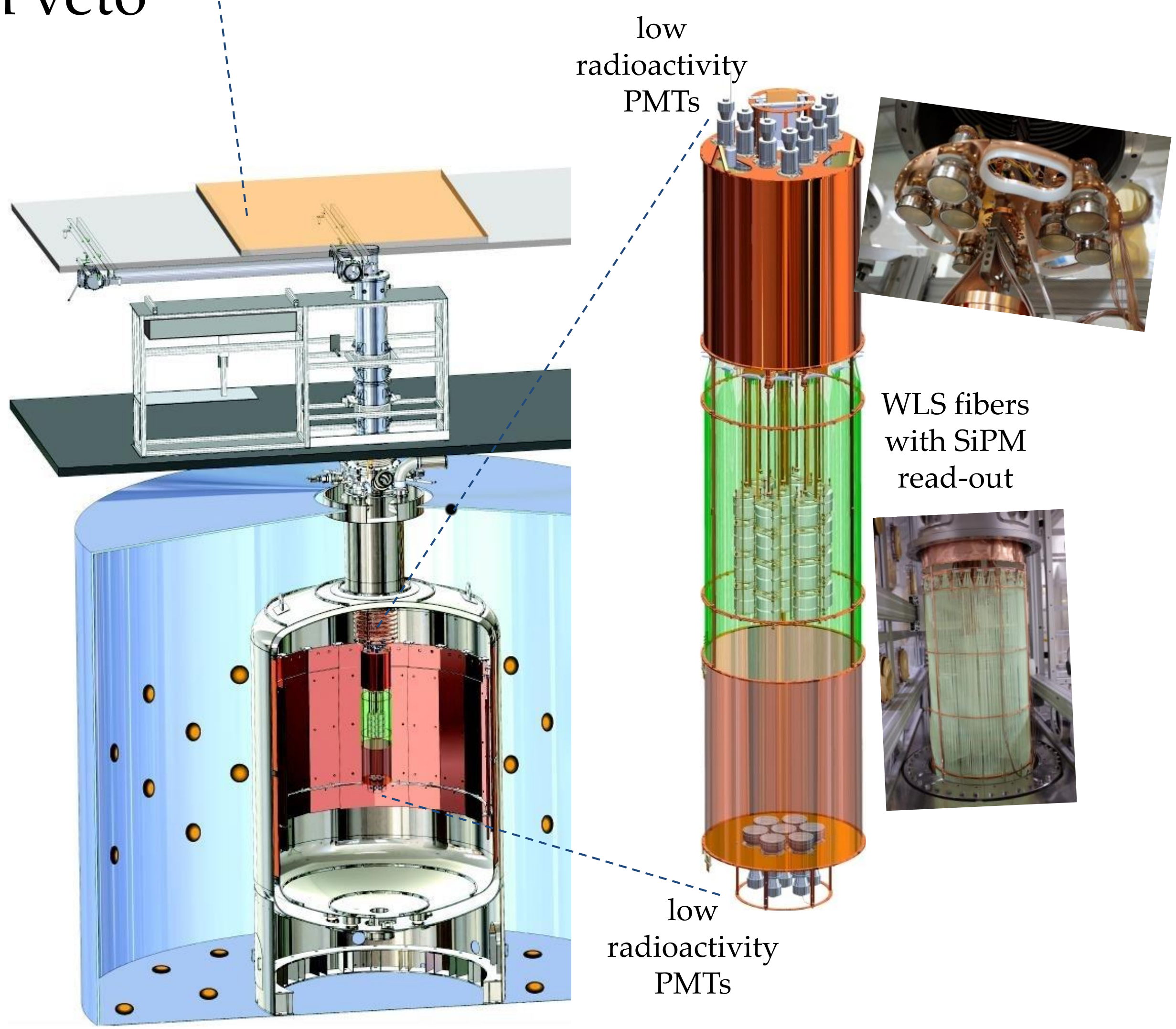
Table 5 Radioactive impurities of the components of one nylon mini-shroud (MS) from ICPMS measurements. Uncertainties are estimated to be about 30%

Component	U (ppt)	Th (ppt)	K (ppb)	Mass (g)
TPB	10	9	65	
Polystyrene	< 5	10	100	
Glue	< 10	< 10	900	
Nylon	< 10	< 15	–	27.6
Nylon coated	11	18	< 25	
Nylon glued	38	39	1200	
MS finished	6.1 μBq	2.6 μBq	242 μBq	28.1

Will be significantly improved for LEGEND-200!

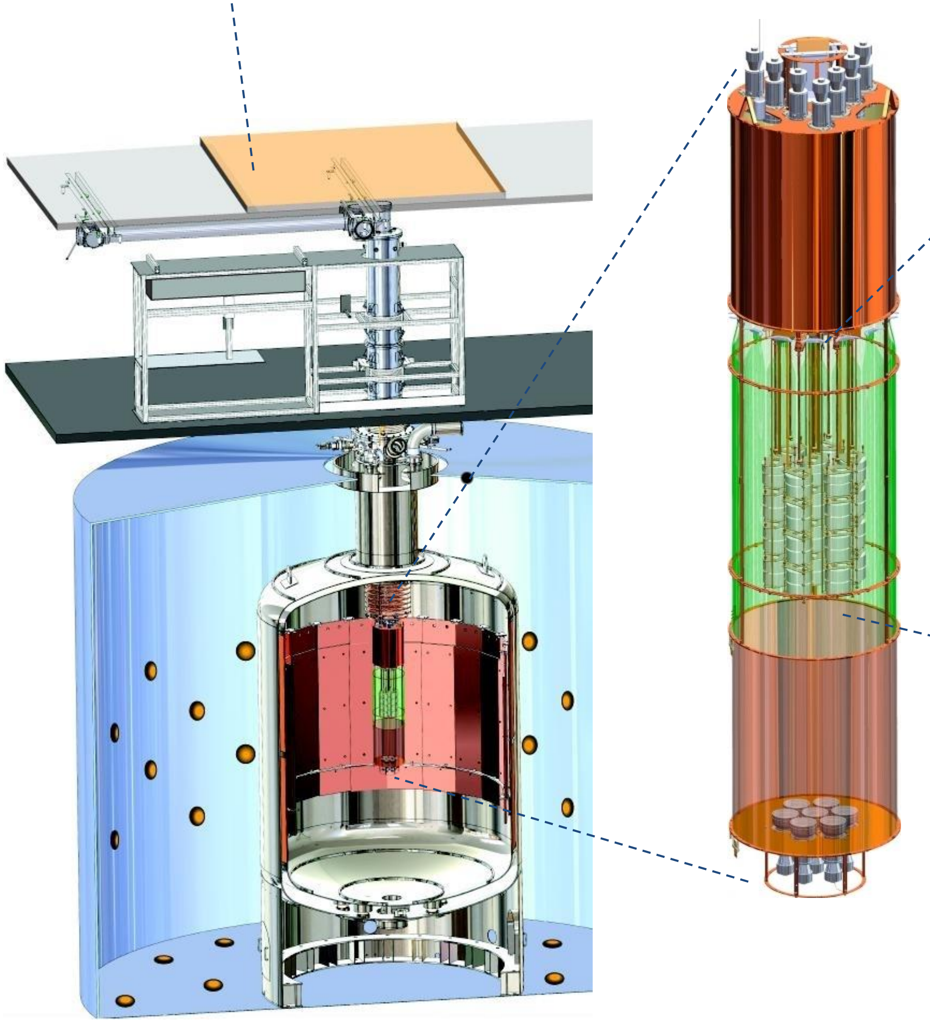
GERDA & **JINR**

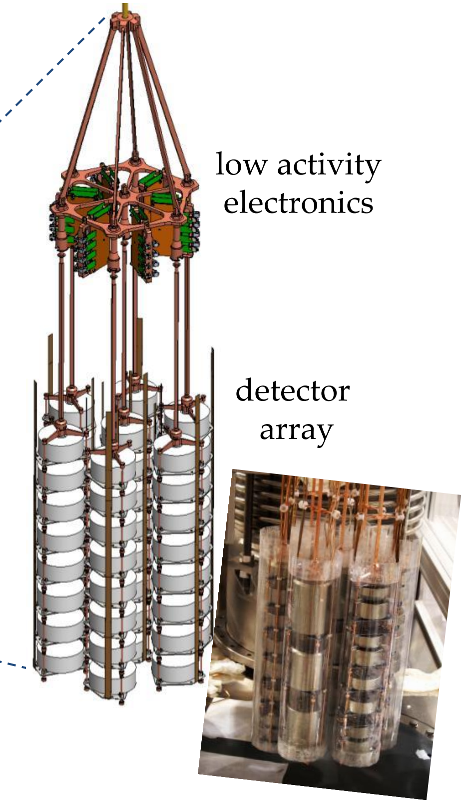
Liquid argon veto



GERDA & **JINR**

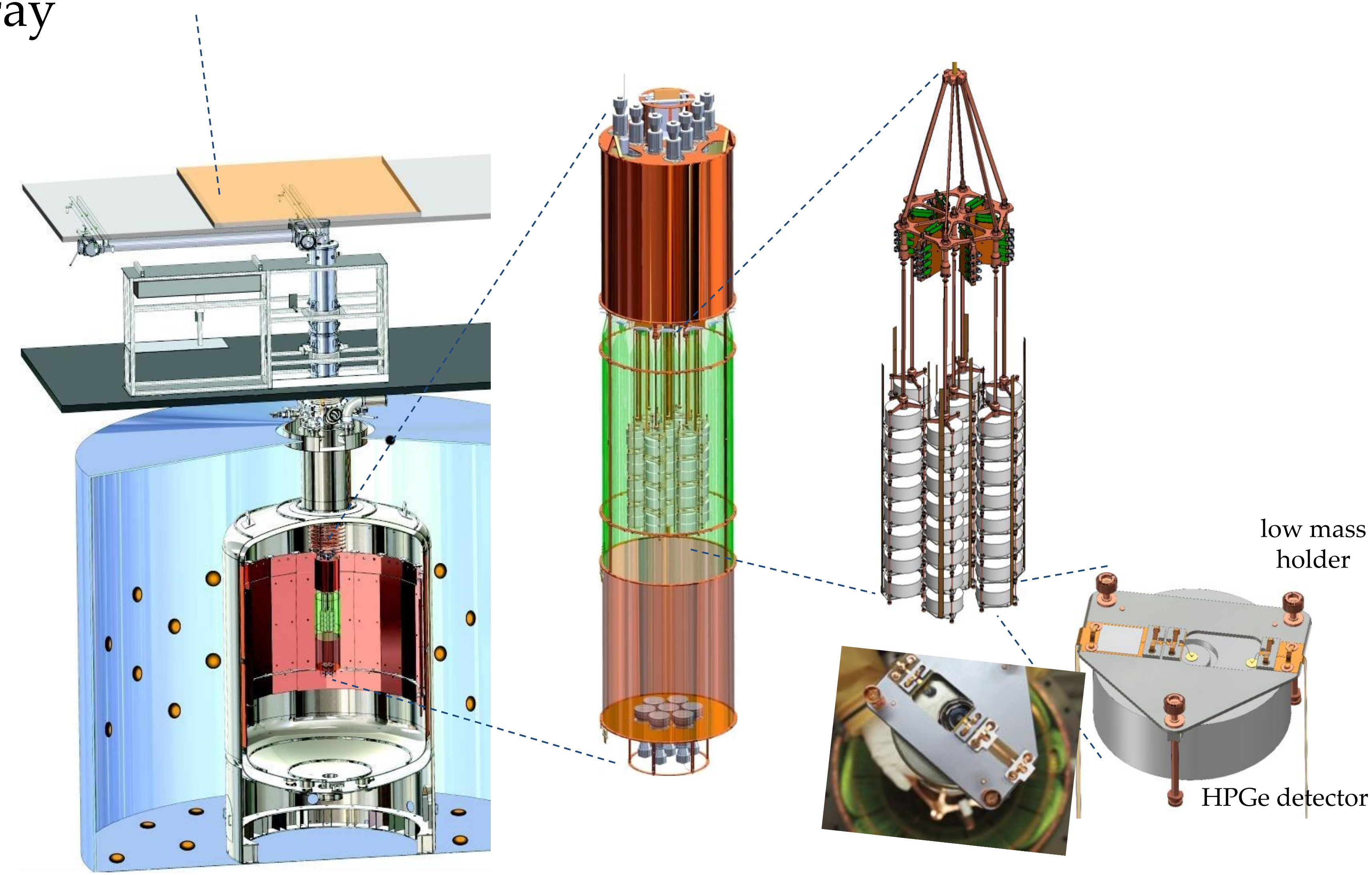
Detector array





GERDA & **JINR**

Detector array



GERDA & **JINR**

Detector array

Phase II:

- 7 enriched coaxial **(15.6 kg)**
- 30 enriched BEGe **(20.0 kg)**
- 3 natural coaxial (7.6 kg)

Phase II+:

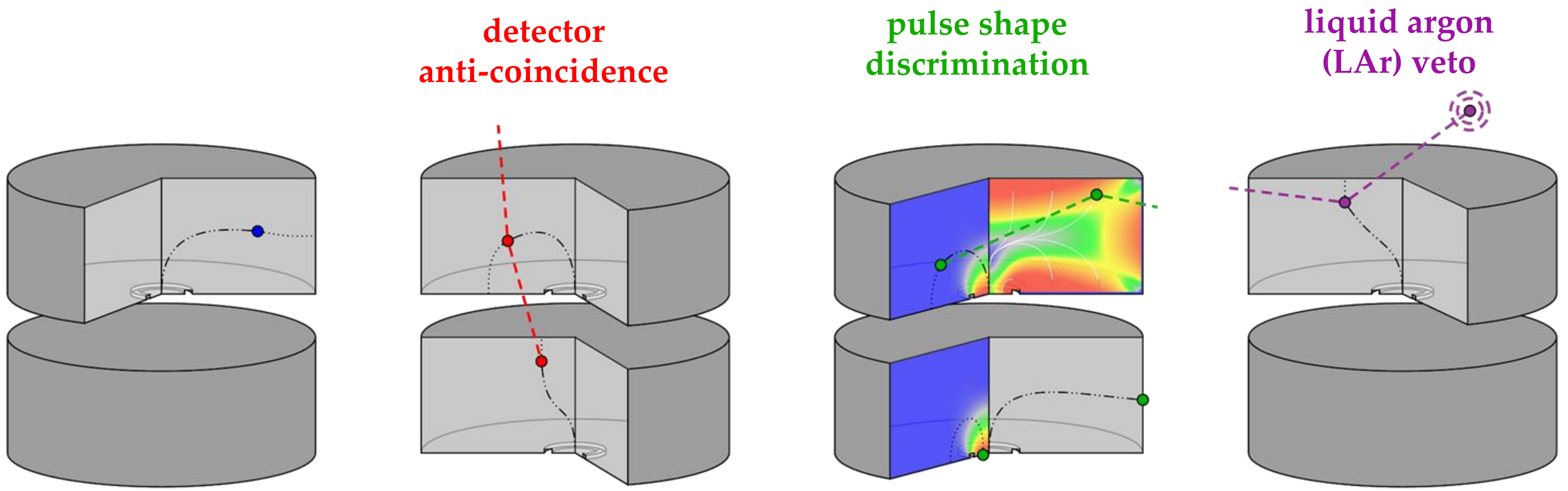
+ 5 enriched inverted coaxial (9.5 kg)
- 3 natural coaxial (7.6 kg)
+ **new LAr veto** instrumentation
+ cleaner materials

(upgrade performed in Spring-Summer 2018)

GERDA Phase II goals	
background	~ 10^{-3} cts/(keV kg yr)
exposure	≥ 100 kg yr
sensitivity	$T_{1/2}^{0\nu} \geq 10^{26}$ yr

GERDA & **JINR**

Background rejection

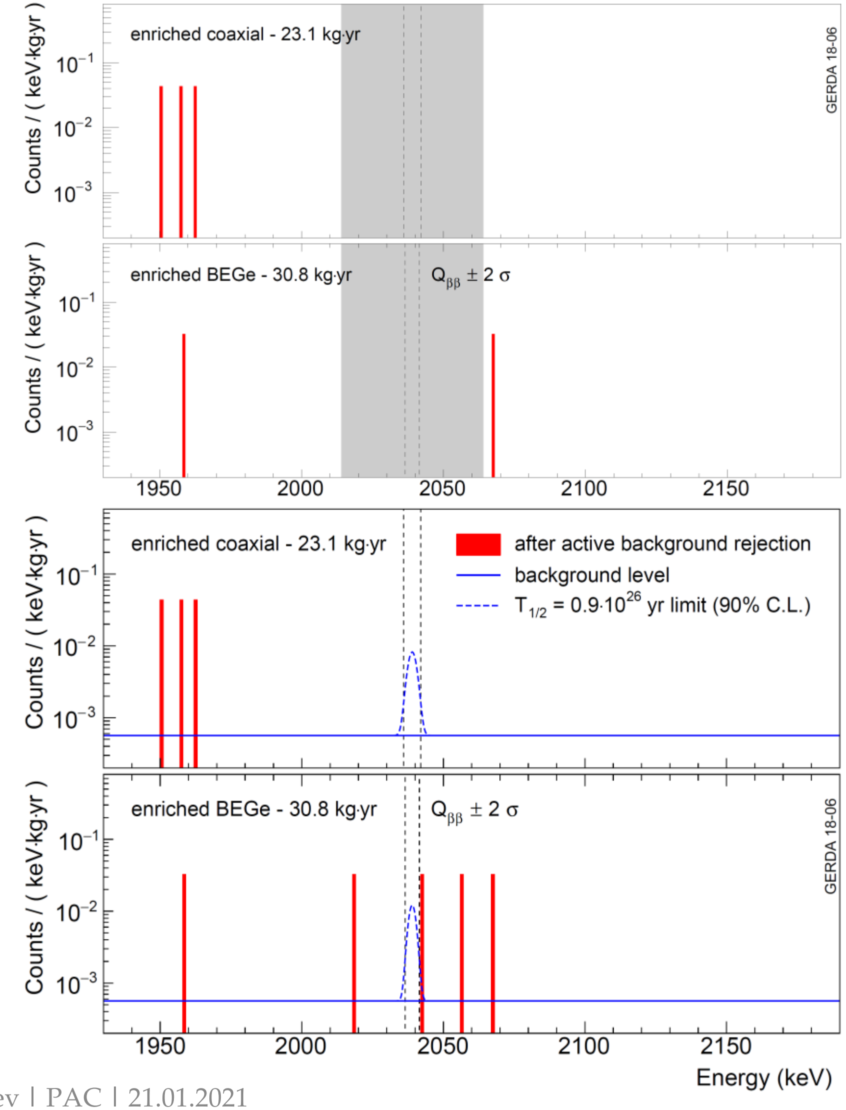


Point like (single site) **ββ** topology versus:

- **multi-detector** interactions
- **multi-site/surface** interactions
- **coincidence with energy deposition** in liquid argon

GERDA **Phase II**

Achievements up to 2019



Unique background indices achieved:

- ✓ Coax: $\mathbf{5.7^{+4.1}_{-2.6} \times 10^{-4}}$ cts/(keV·kg·yr)
- ✓ BEGe: $\mathbf{5.6^{+3.4}_{-2.4} \times 10^{-4}}$ cts/(keV·kg·yr)

***best** in the field when normalized to FWHM!*

GERDA Phase II limits @ 2019:

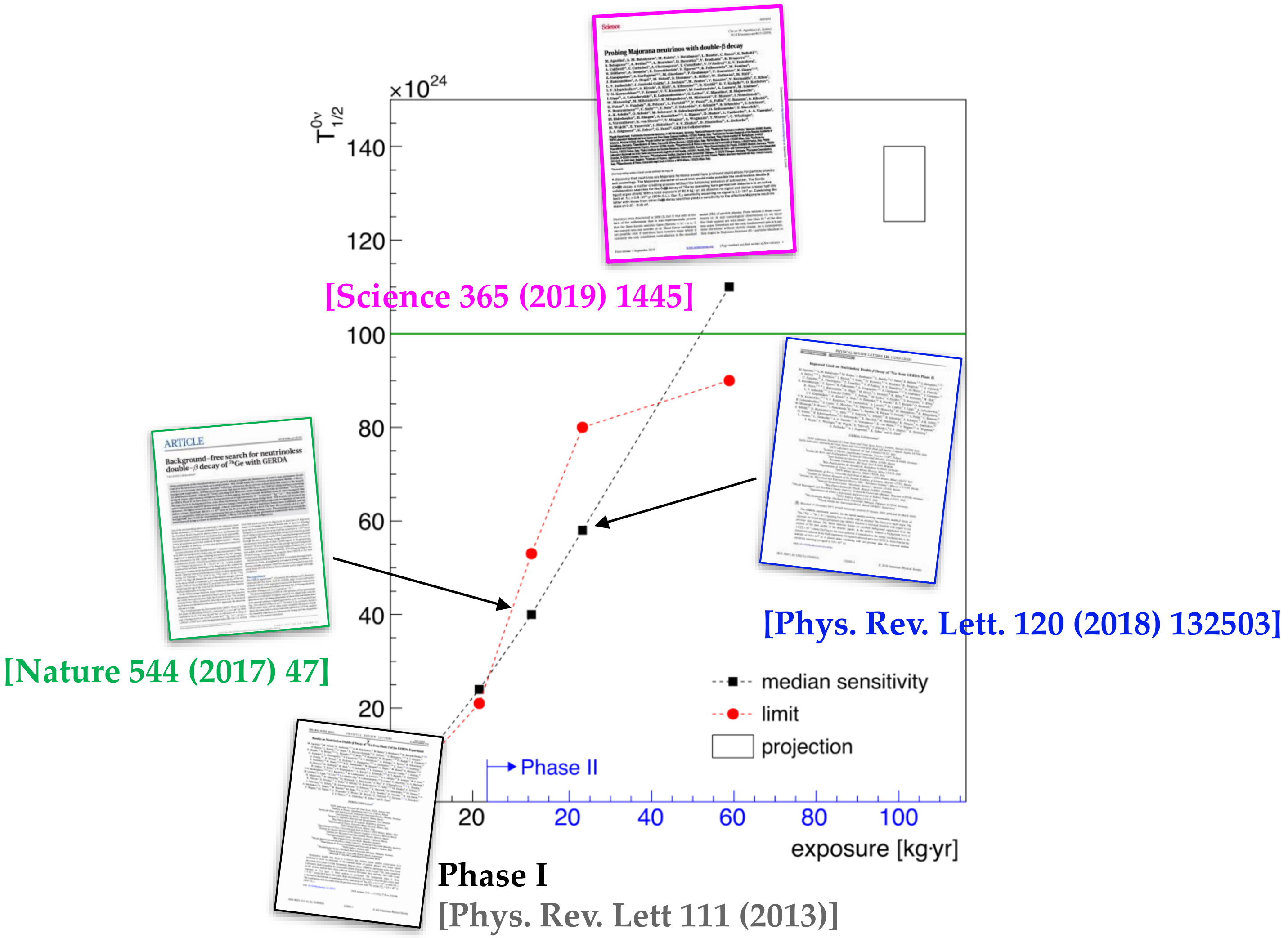
- ✓ Median sensitivity for limit setting:
  $\mathbf{1.1 \times 10^{26}}$ **yr** (world best!)
- ✓ Best fit → no signal
  $\boldsymbol{T^{0\nu}_{1/2} > 0.9 \times 10^{26}}$ **yr** (90% CL)

GERDA Phase II goals

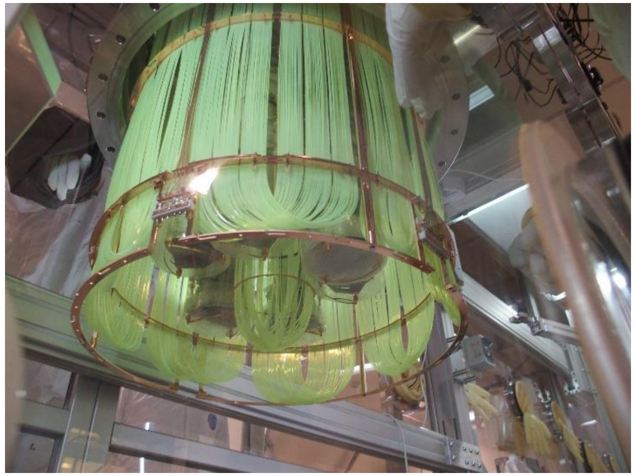
background	~ 10^{-3} cts/(keV kg yr)	✓
exposure	≥ 100 kg yr	
sensitivity	$T^{0\nu}_{1/2} \geq 10^{26}$ yr	✓

GERDA **Phase II**

Achievements up to 2019

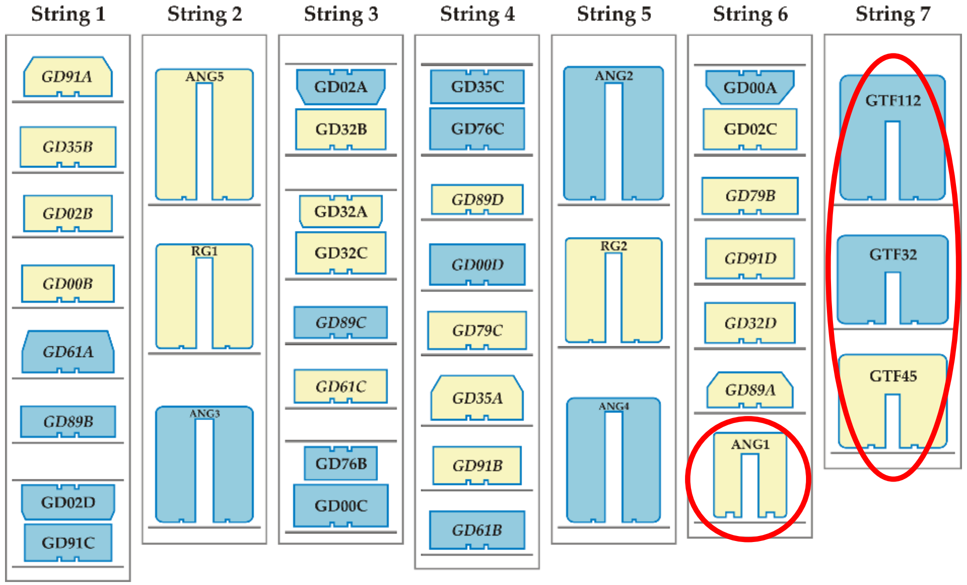


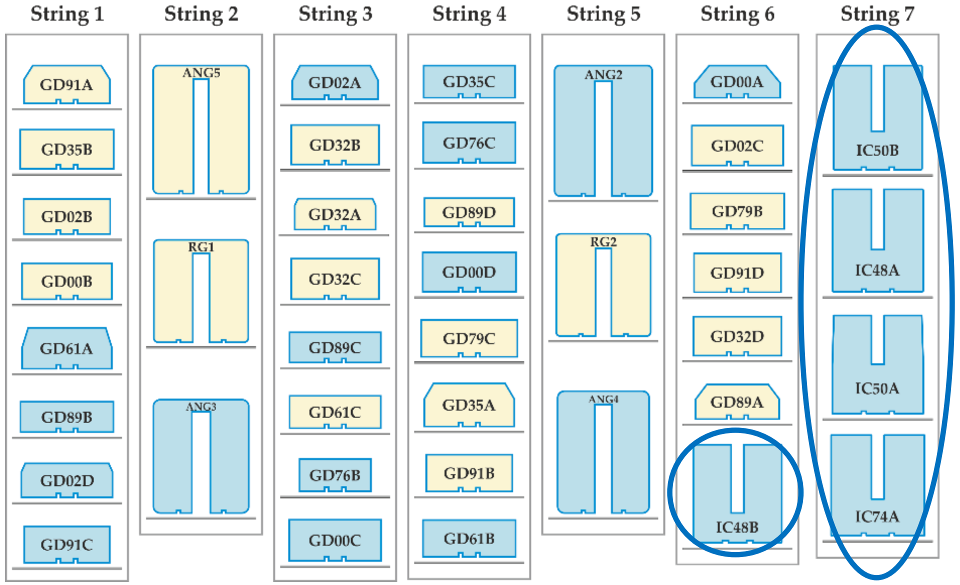
GERDA & JINR
Upgrade 2018



Upgrade of the GERDA experiment aimed to:

- ✓ Test the novel detectors + increase the mass of ^{76}Ge
- ✓ Show the possibility to improve the background index
  - ✓ Exchange all cables by new ones with better radiopurity
  - ✓ Replace old LAr veto by improved version
- ✓ Repair broken JFETs and electronic channels
- ✓ Prove the robustness and reproducibility of the GERDA approach





GERDA & **JINR**

Successful Upgrade 2018

- **New LAr veto**:
  - ✓ new fiber curtain (improved light collection) + central module to read out hidden Ar volume

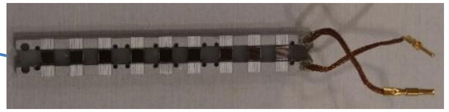
Old curtain

810 fiber ends, 90 SiPMs

New curtain

1215 fiber ends, 135 SiPMs

New readout



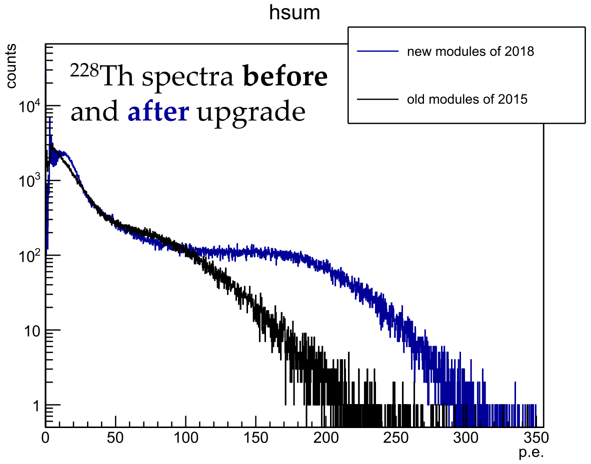
9 SiPMs mounted on fused synthetic quartz substrate

Central module

Designed

Produced

Installed

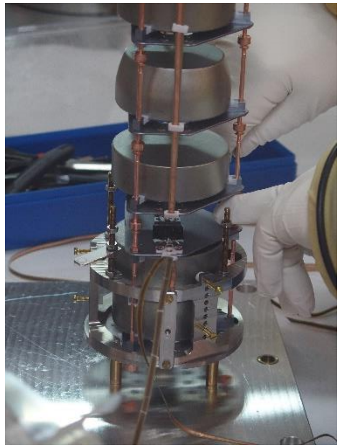


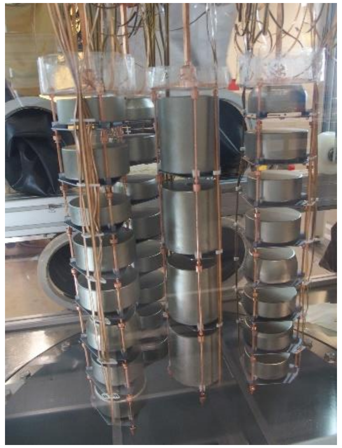
New LAr veto system was designed, produced, tested and installed by common TUM & **JINR** team

GERDA & **JINR**

Successful Upgrade 2018

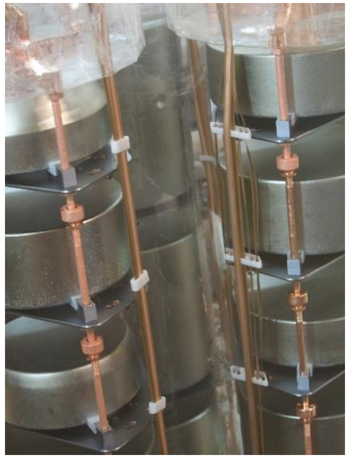
- ✓ All detectors were dismounted from the strings and holders, bonded with new cables and mounted back



- ✓ Broken electronic channels repaired and protective diodes installed

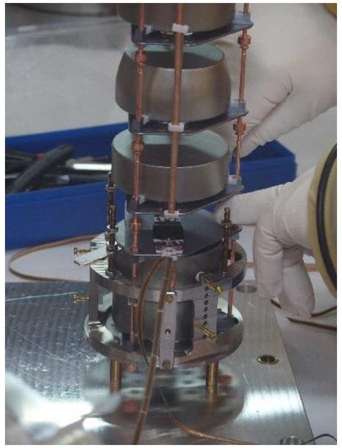
- ✓ New signal cable routing to reduce the cross-talk and improve resolution

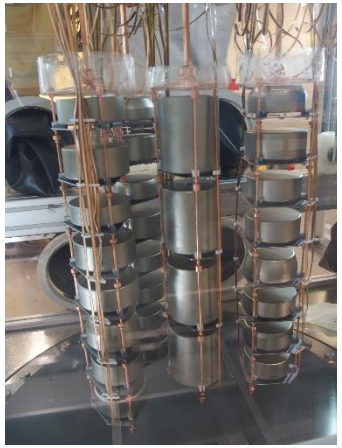


GERDA & **JINR**

Successful Upgrade 2018

- ✓ All detectors were dismounted from the strings and holders, bonded with new cables and mounted back

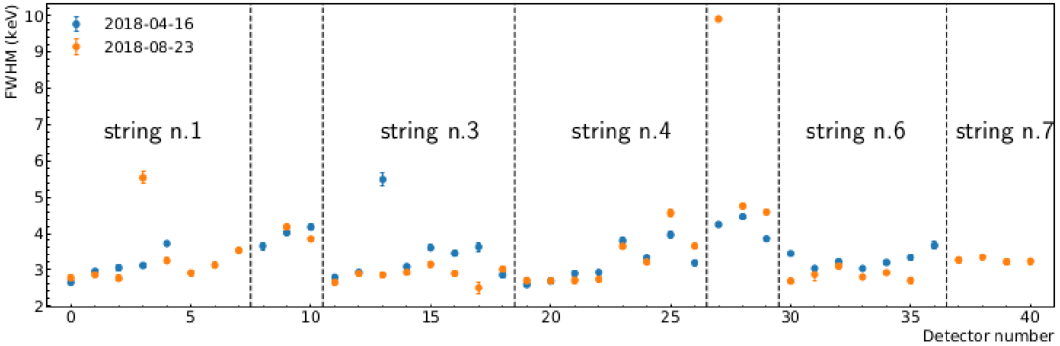





- ✓ Broken electronic channels repaired and protective diodes installed

- ✓ New signal cable routing to reduce the cross-talk and improve resolution

➡ **It helps!**

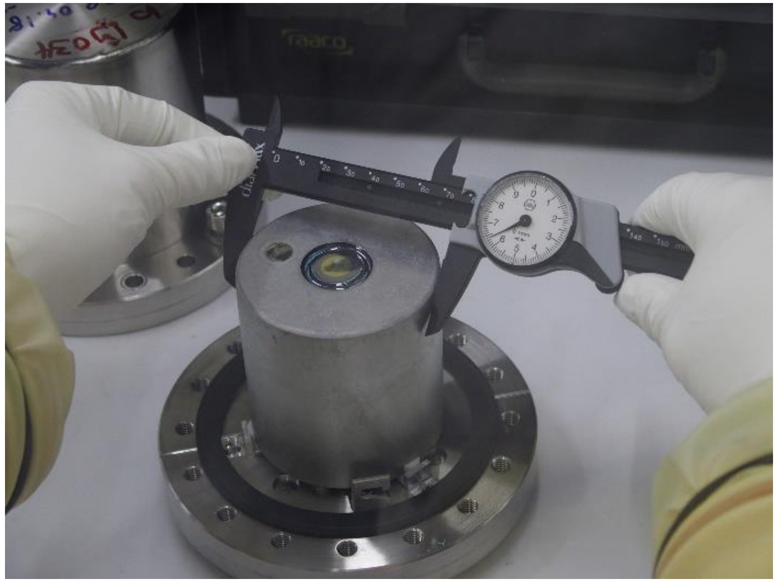


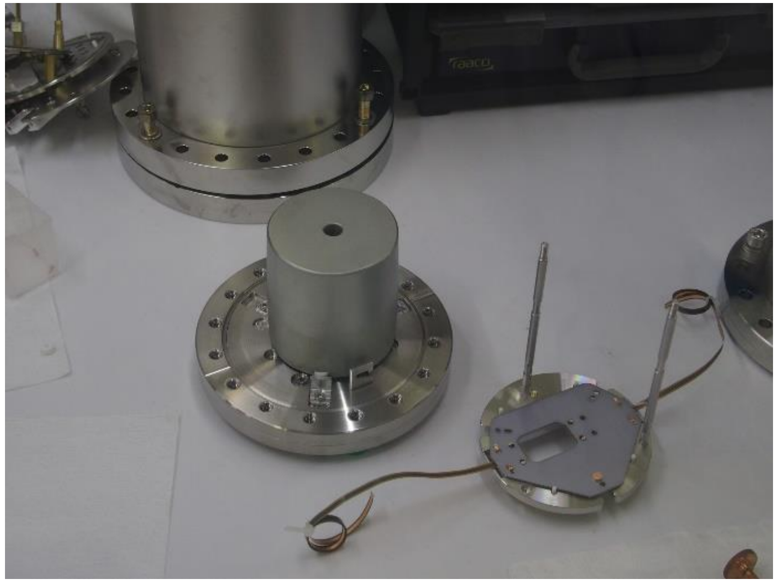
A/E resolution also improved for most channels!

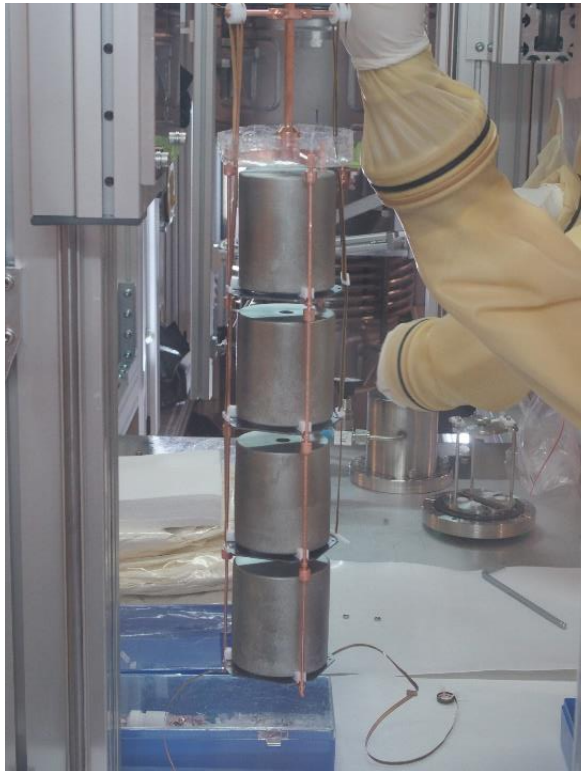
GERDA & **JINR**

Successful Upgrade 2018

- ✓ Installation of 5 novel **inverted coaxial detectors** made from ^{76}**Ge**







Results of upgrade 2018:

- ✓ Entire upgrade operation lasted ~5 weeks in April/May + 1 week in July
  - ✓ Performed by **JINR** + MPIK + TUM + INFN team
- ✓ All electronic channels worked
- ✓ No deterioration of detectors leakage current after upgrade
- ✓ New fiber shroud and central fiber module worked
- ✓ Energy resolutions improved
- ✓ Novel ^{76}Ge detectors installed

GERDA & **JINR**

Management structure

GERDA Collaboration

March 25, 2019

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

Collaboration Management

spokesperson:	Riccardo Brugnera
co-spokesperson:	Bernhard Schwingenheuer
chair of collaboration board:	Josef Jochum
chair of speakers bureau:	Bela Majorovits
chair of editorial board:	Karl-Tasso Knöpfle
analysis coordinator:	Matteo Agostini
technical coordinator:	Konstantin Gusev
GLIMOS/RAE:	Marco Balata

Editorial Board: P. Grabmayr, R. Hiller, K.T. Knöpfle, A. Smolnikov, A. Zsigmond; (ex officio: R.Brugnera, B. Schwingenheuer) ➡ mail to EB

Speakers Bureau: L. Baudis, J. Jochum, A. Lubashevsky, B. Majorovits, F. Salamida; (ex officio: R.Brugnera, B. Schwingenheuer) ➡ mail to SB

Groups and Principal Investigators

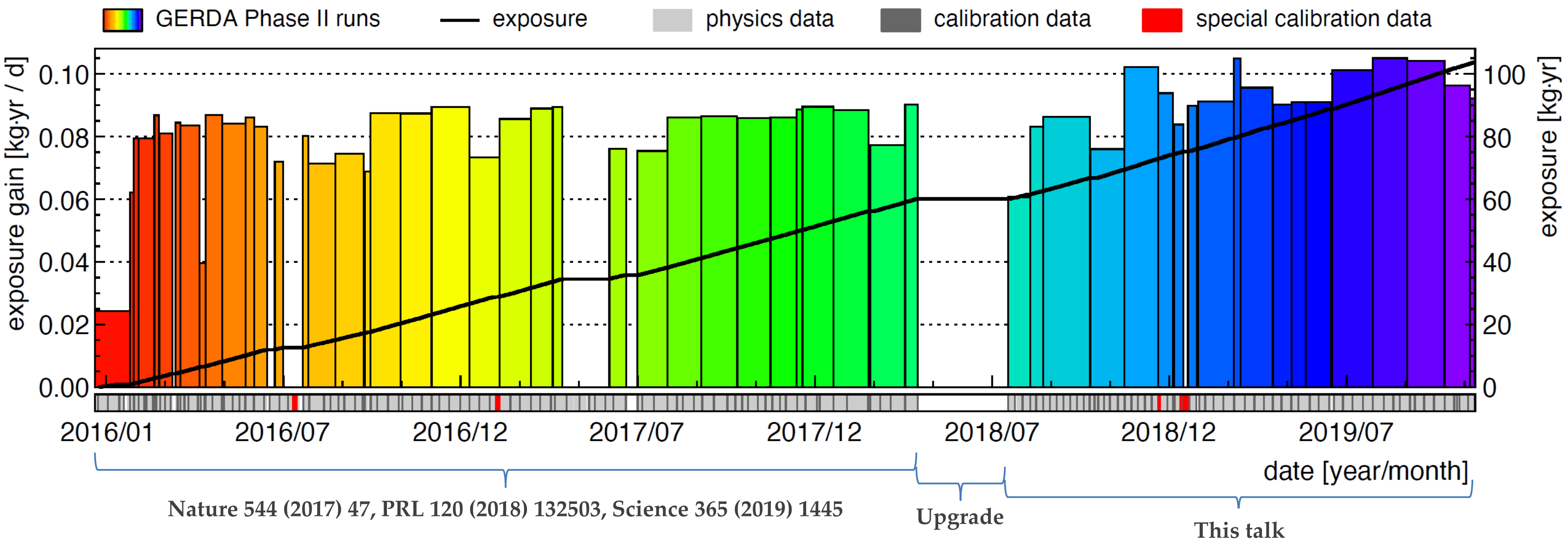
INFN Gran Sasso, GSSI:	M. Laubenstein
Cracow:	M. Wojcik
TU Dresden:	K. Zuber
JINR Dubna:	K. Gusev
Geel:	M. Hult
MPIK-Heidelberg:	W. Hofmann
	M. Lindner
Milano Bicocca & INFN:	E. Bellotti
INR Moscow:	L. Bezrukov
ITEP Moscow:	I. Kirpichnikov
Kurtchatov Moscow:	K. Gusev
MPI-P Munich:	A. Caldwell
TU Munich:	S. Schönert
Padova University & INFN:	R. Brugnera
EKUT Tübingen:	J. Jochum
U. Zürich:	L. Baudis

Task Groups and Leaders

TG1:	modification &test of existing diodes	S.Schönert
TG2:	design &production of new Ge diodes	A. Caldwell
TG3:	front end electronics	C. Cattadori/V. D`Andrea
TG4:	cryostat & cryogenic infrastructure	B. Schwingenheuer
TG5:	clean room & lock system	B. Majorovits
TG6:	water tank & water plants	C. Cattadori
TG7:	muon veto	J. Jochum/A.-K.Schütz/D.Zinatulina
TG8:	infrastructure & logistics	M. Junker
TG9:	DAQ &online software	B. Schwingenheuer/R.Brugnera
TG10:	simulation& background studies	L. Pandola/L. Pertoldi
TG11:	material screening	J. Schreiner/G. Zuzel
TG12:	energy calibration	L. Baudis/R. Hiller
TG13:	data reduction & analysis software	M. Agostini/C. Wiesinger
TG14:	LArGe	H. Simgen/S. Schönert
TG15:	detector integration, operation & maintenance	K. Gusev
TG16:	pulse shape analysis	Y. Kermaidic/A. Zsigmond

GERDA Results

Data taking



- Phase II duty cycle (including upgrade period): **87.7%**

✓ **103.7 kg yr** (**127.2** kg yr with Phase I)

✓ Full data set analyzed

GERDA Results

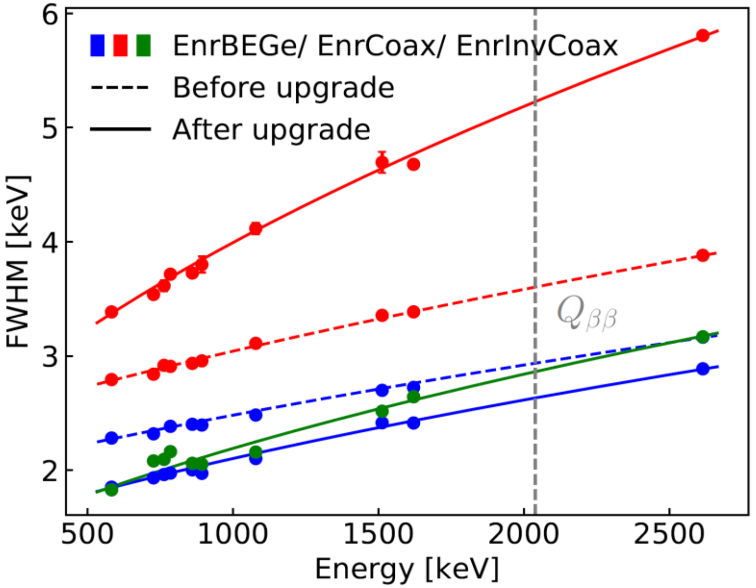
Performance

- ✓ Weekly calibrations with ^{228}Th source
- ✓ IC detectors perform similar to BEGe (mass ~ 3x)

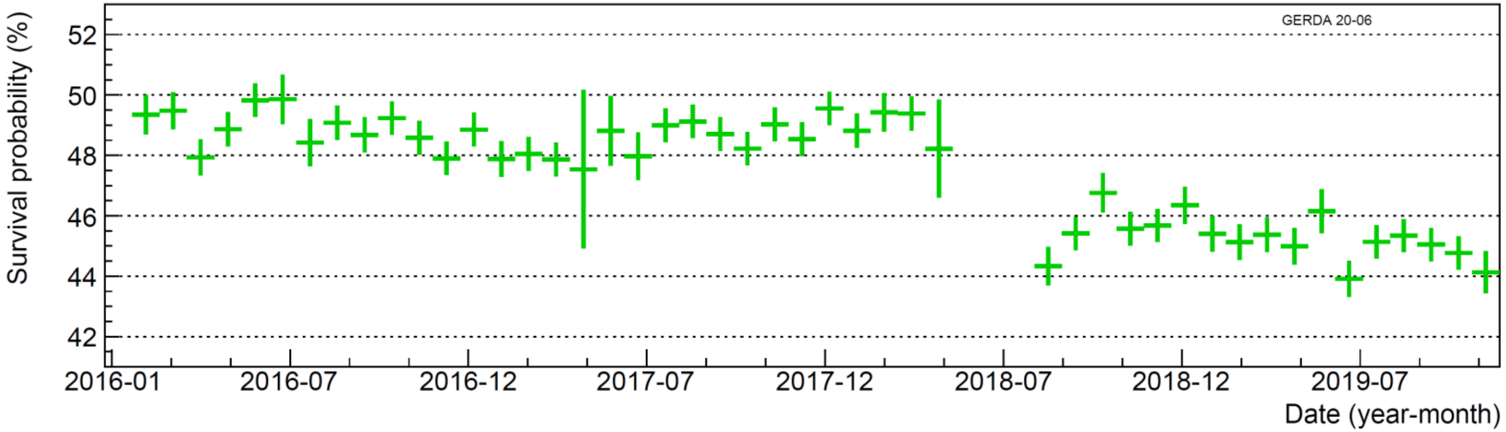
FWHM @ $Q_{\beta\beta}$ (keV):

	BEGe	Coax	IC
Before upgrade	2.9 ± 0.3	3.6 ± 0.3	
After upgrade	2.6 ± 0.2*	5.2 ± 1.9**	2.9 ± 0.1

* – improved due to new cable routing
** – dominated by one detector with the leakage current

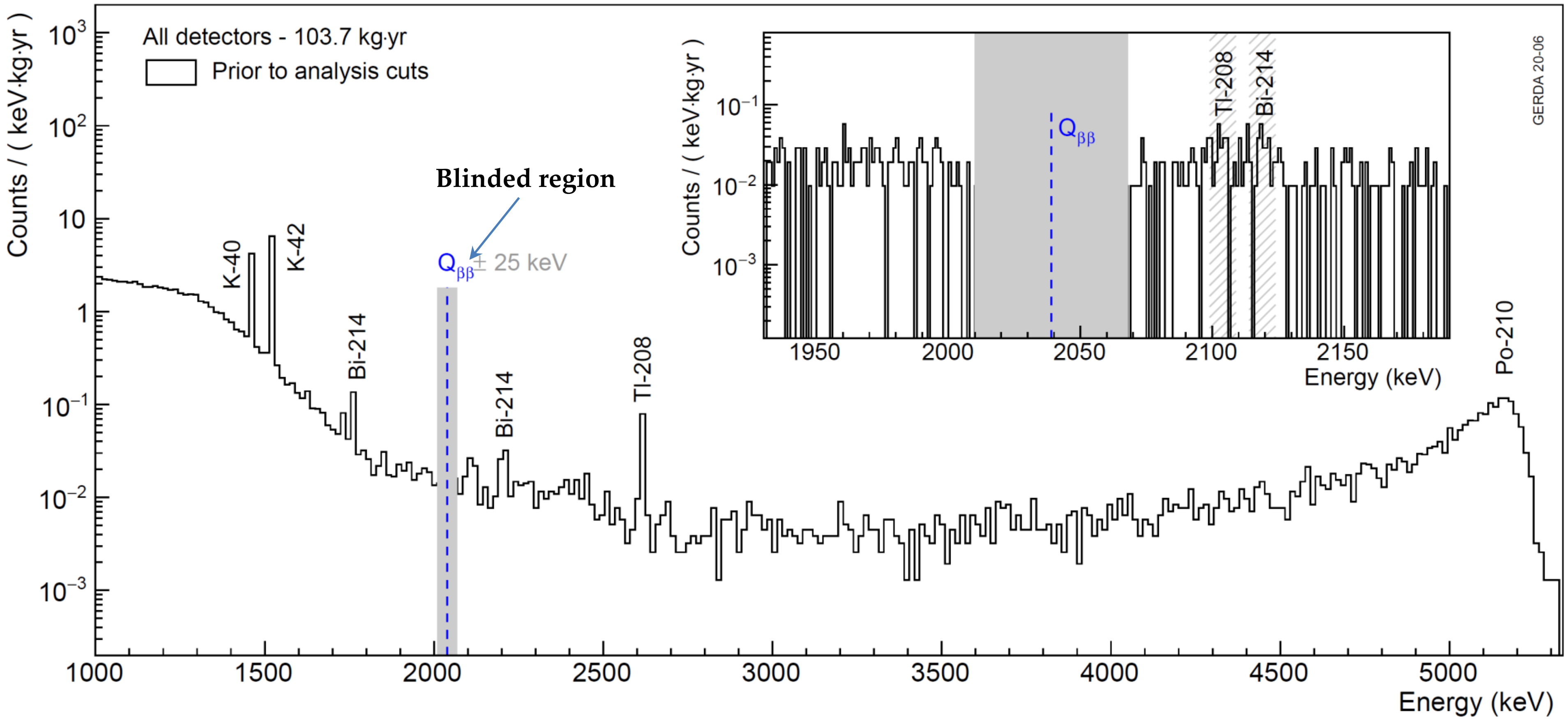


✓ Improved performance of the LAr veto after upgrade



GERDA Results

Physics spectrum – full data set!

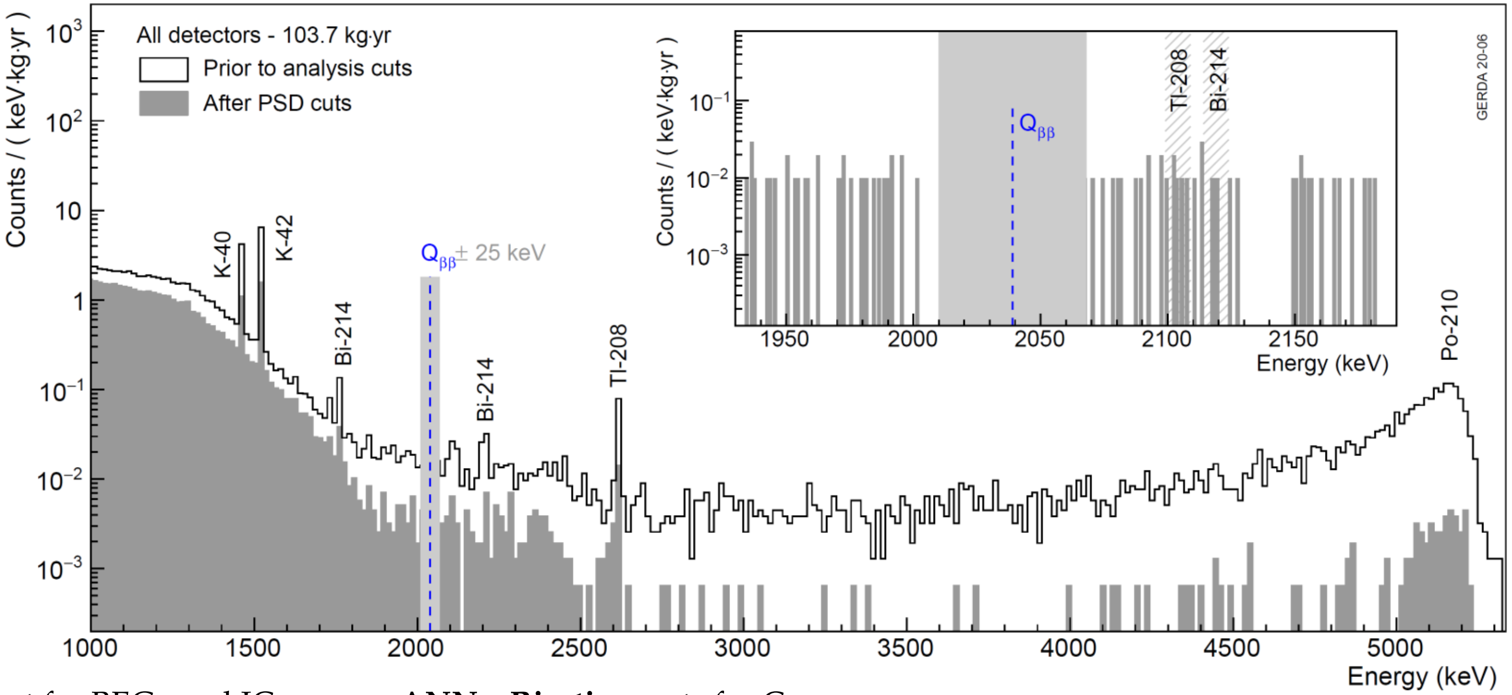


- ✓ Data quality, muon veto and anticoincidence cuts applied
- ✓ BI in the analysis window [1930-2190] keV **before** active cuts:

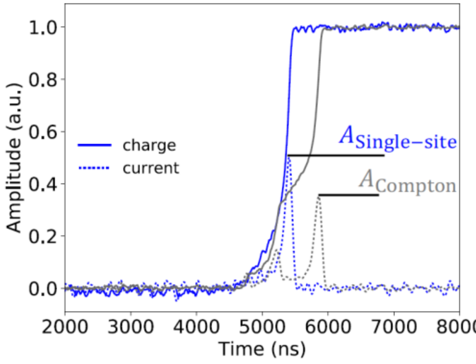
$$BI = 143^{+9}_{-8} \times 10^{-4} cts/(keV \times kg \times yr)$$

GERDA Results

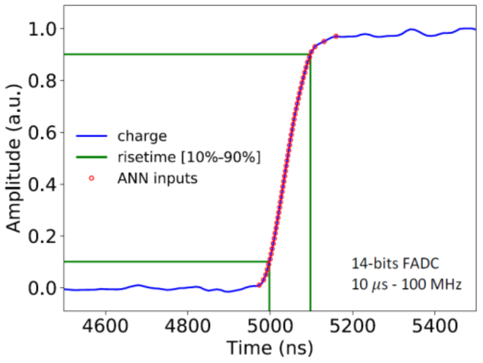
Physics spectrum after pulse shape discrimination (PSD)



A/E cut for BEGe and IC



ANN + Risetime cuts for Coax

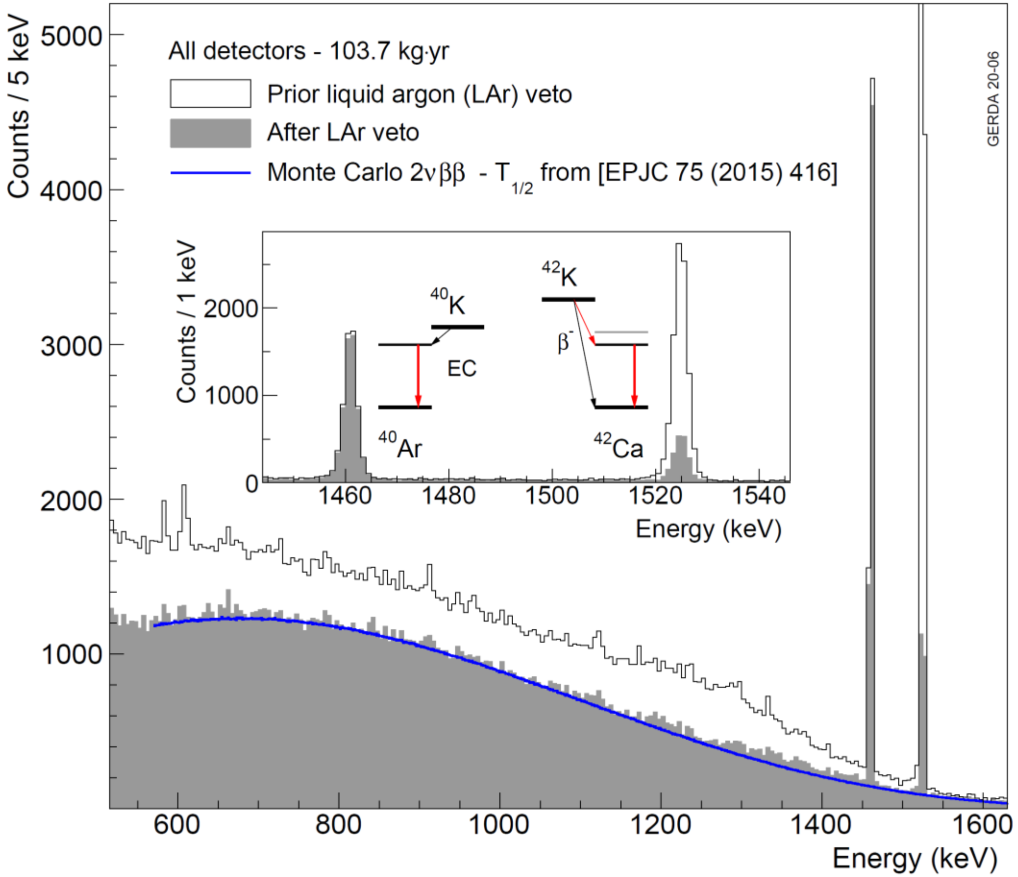


$0\nu\beta\beta$ decay signal efficiency:

- $\epsilon_{\mathbf{PSD}}^{\mathbf{BEGe}} = (\mathbf{88.7} \pm \mathbf{3.2})\%$
- $\epsilon_{\mathbf{PSD}}^{\mathbf{IC}} = (\mathbf{90.0} \pm \mathbf{1.7})\%$
- $\epsilon_{\mathbf{PSD}}^{\mathbf{Coax}} = (\mathbf{68.9} \pm \mathbf{3.1})\%$

GERDA Results

Physics spectrum after liquid argon (LAr) veto



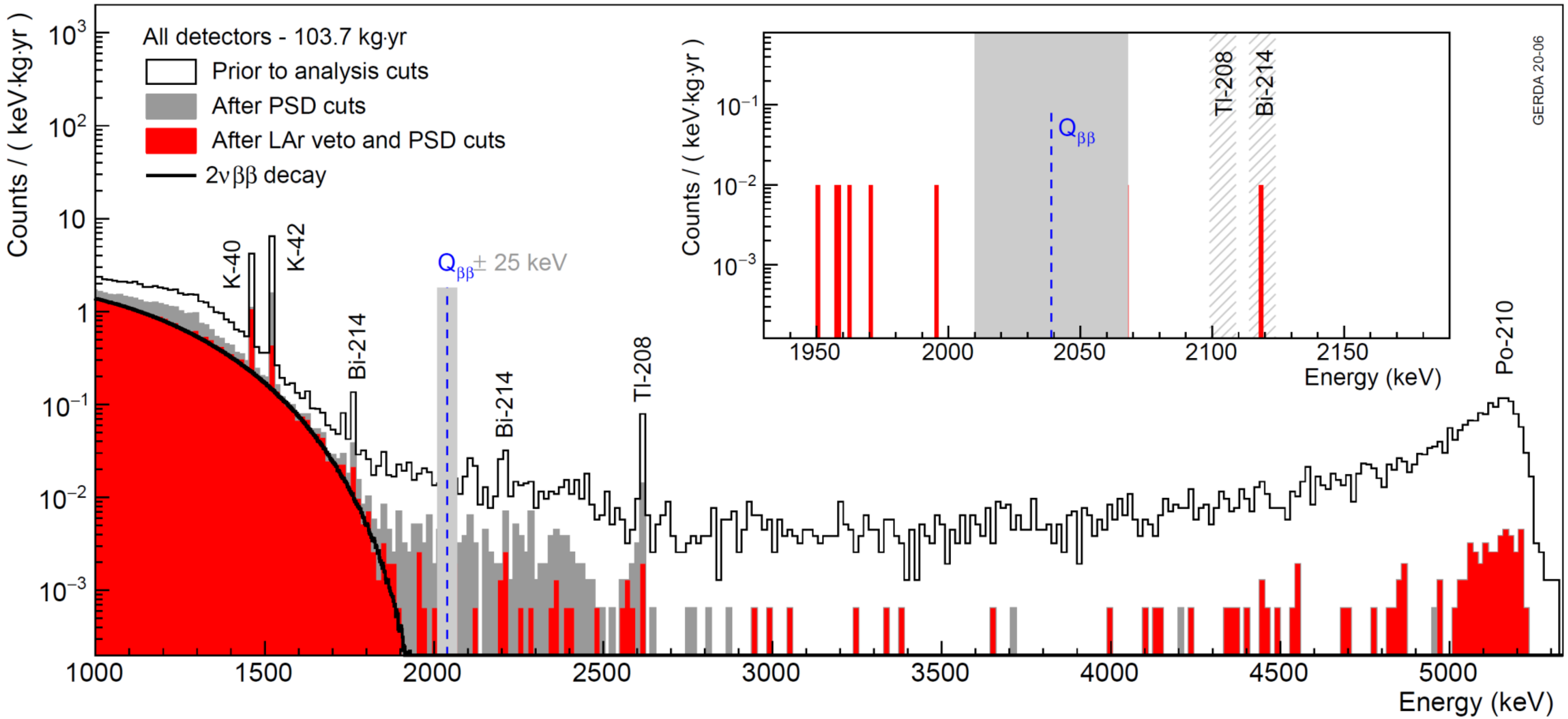
- ✓ Practically pure 2νββ spectrum after LAr veto cut < 1400 keV
- ✓ Strong suppression of ^{42}K line

$0\nu\beta\beta$ decay signal efficiency:

$$\epsilon_{\mathbf{LAr}} = (\mathbf{97.9} \pm \mathbf{0.1})\%$$

GERDA Results

Final spectrum



- ✓ Great complementarity between LAr and PSD cuts!
- ✓ BI in the analysis window [1930-2190] keV **after** active cuts:

$$\mathrm{BI} = \mathbf{5.2^{+1.6}_{-1.3} \times 10^{-4}} \mathrm{cts/(keV \times kg \times yr)}$$

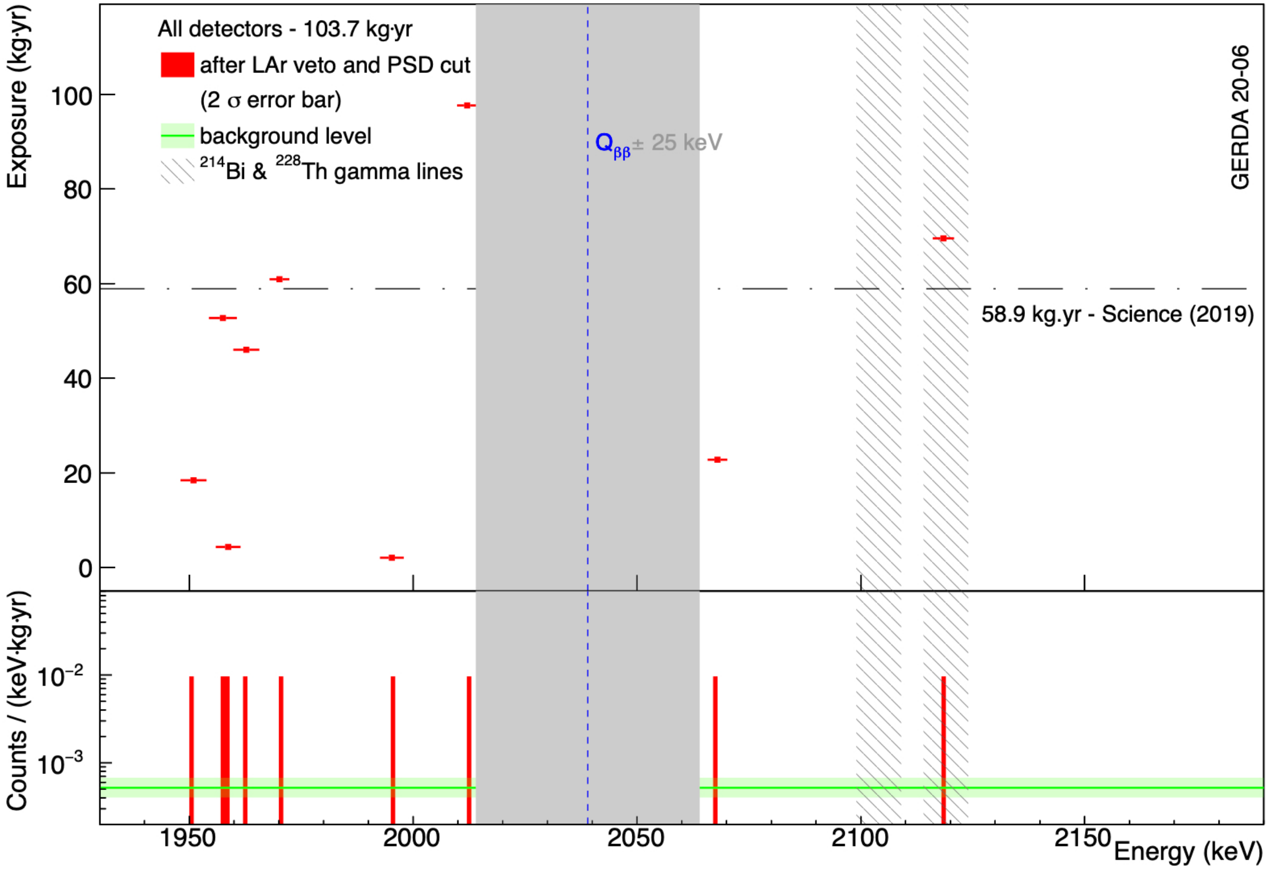
GERDA Results

Physics spectrum in the analysis window

Still blinded…

Dec 2019

Dec 2015



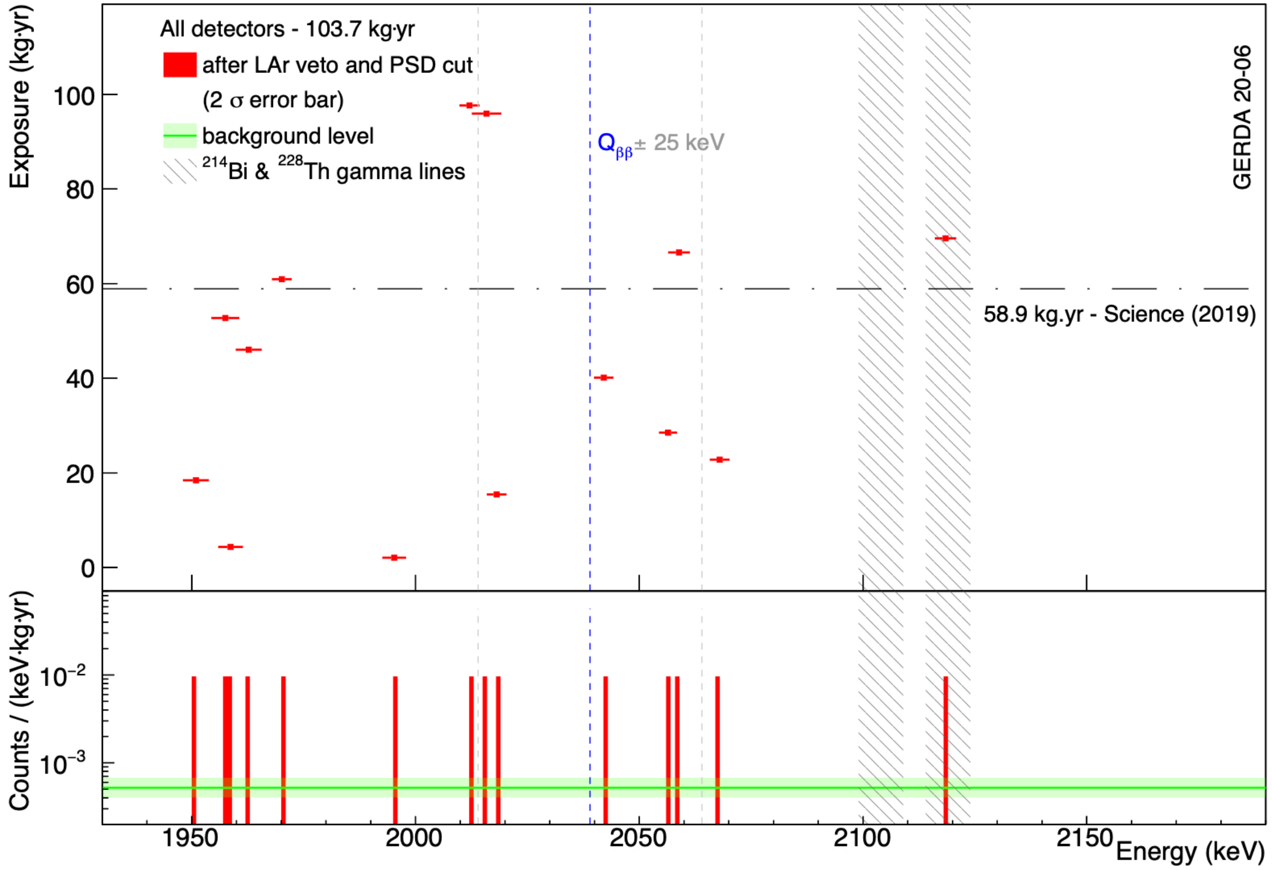
GERDA Results

Physics spectrum in the analysis window

Finally unblinded!

Dec 2019

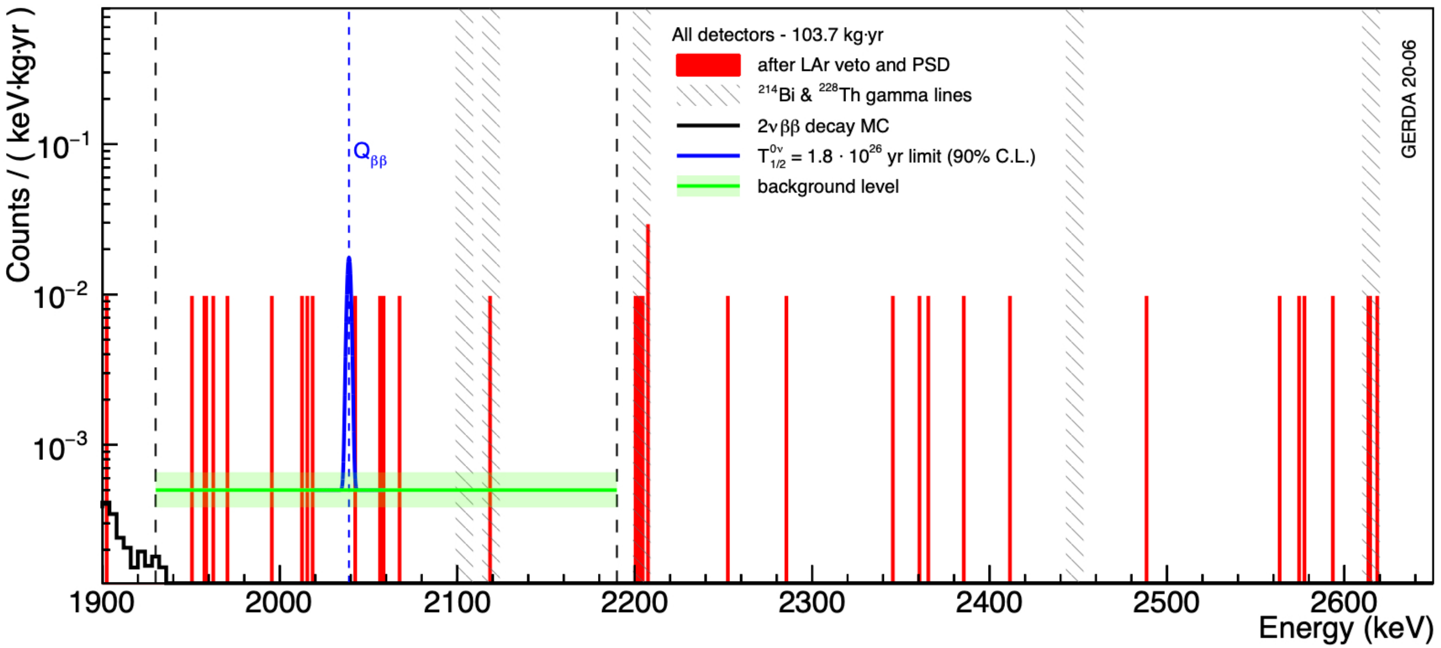
Dec 2015



- ✓ 2 new counts since the last data release
- ✓ **No** counts @ $Q_{\beta\beta}$ ± FWHM

GERDA

Final results



Frequentist analysis*:

- ✓ Median sensitivity for limit setting: $\mathbf{1.8 \times 10^{26}}$ **yr** (90% CL)
- ✓ Best fit → no signal

$\boldsymbol{T^{0\nu}_{1/2} > 1.8 \times 10^{26}}$ **yr** (90% CL)

Bayesian analysis*:

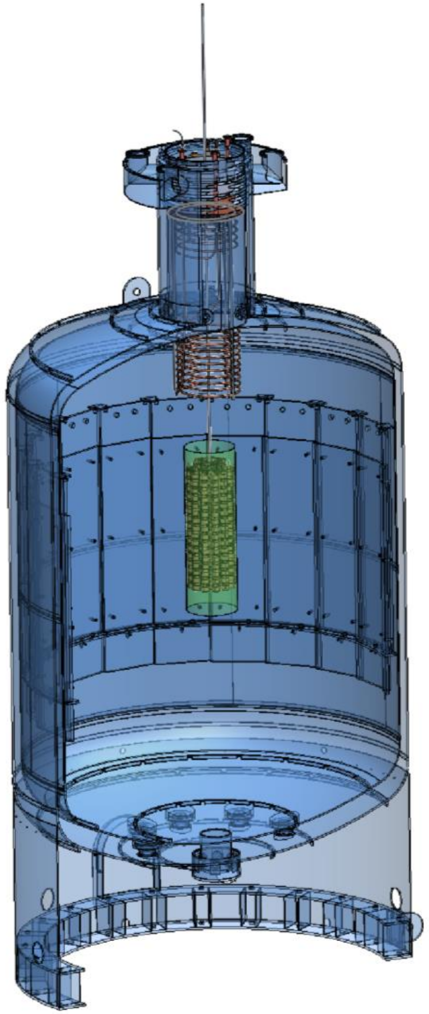
- ✓ Median sensitivity for limit setting: 1.4×10^{26} yr (90% CI)

$T^{0\nu}_{1/2} > 1.4 \times 10^{26}$ yr (90% CI)

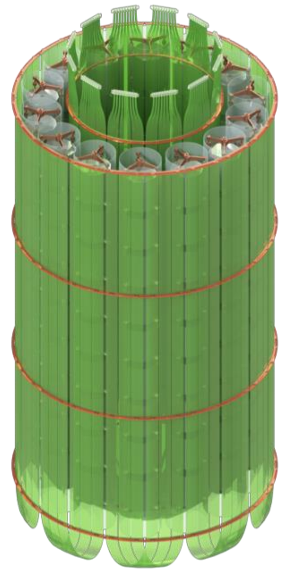
* – statistical treatment details in **Nature 544 (2017) 47**

LEGEND-200 & **JINR**

200 kg in GERDA setup



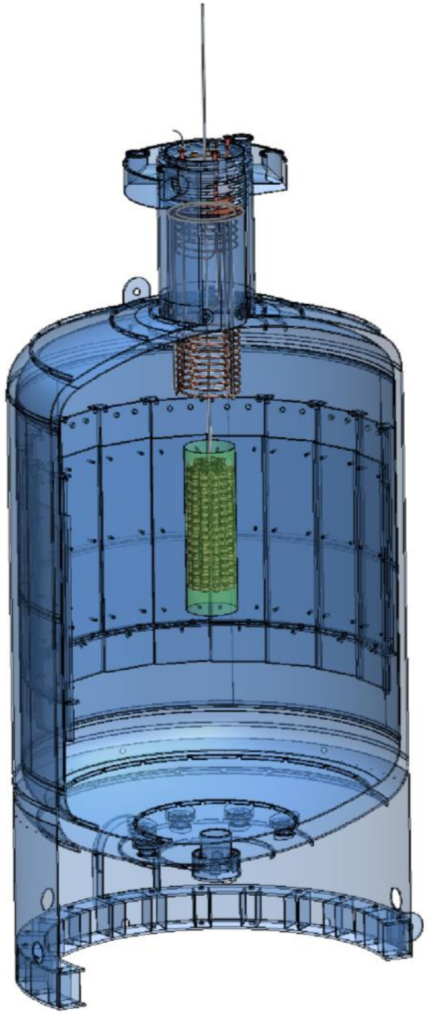
- ✓ Reuse existing GERDA infrastructure at LNGS
- ✓ Modifications of internal cryostat piping so can accommodate up to 200 kg of detectors
- ✓ Improvements
  - Use some larger Ge detectors
  - improve LAr scintillator light collection
  - lower mass, cleaner cables
  - lower noise electronics
- ✓ Estimate background improvement by ~ x3 over GERDA/MAJORANA (goal 0.6 cnt /(FWMH t yr)):
  - intrinsic : including $^{68}Ge/^{60}Co$ all OK
  - external Th/U: cleaner materials
  - surface events : α & β rejection via PSD
  - ^{42}Ar : better suppression & mitigation
  - muon induced : OK



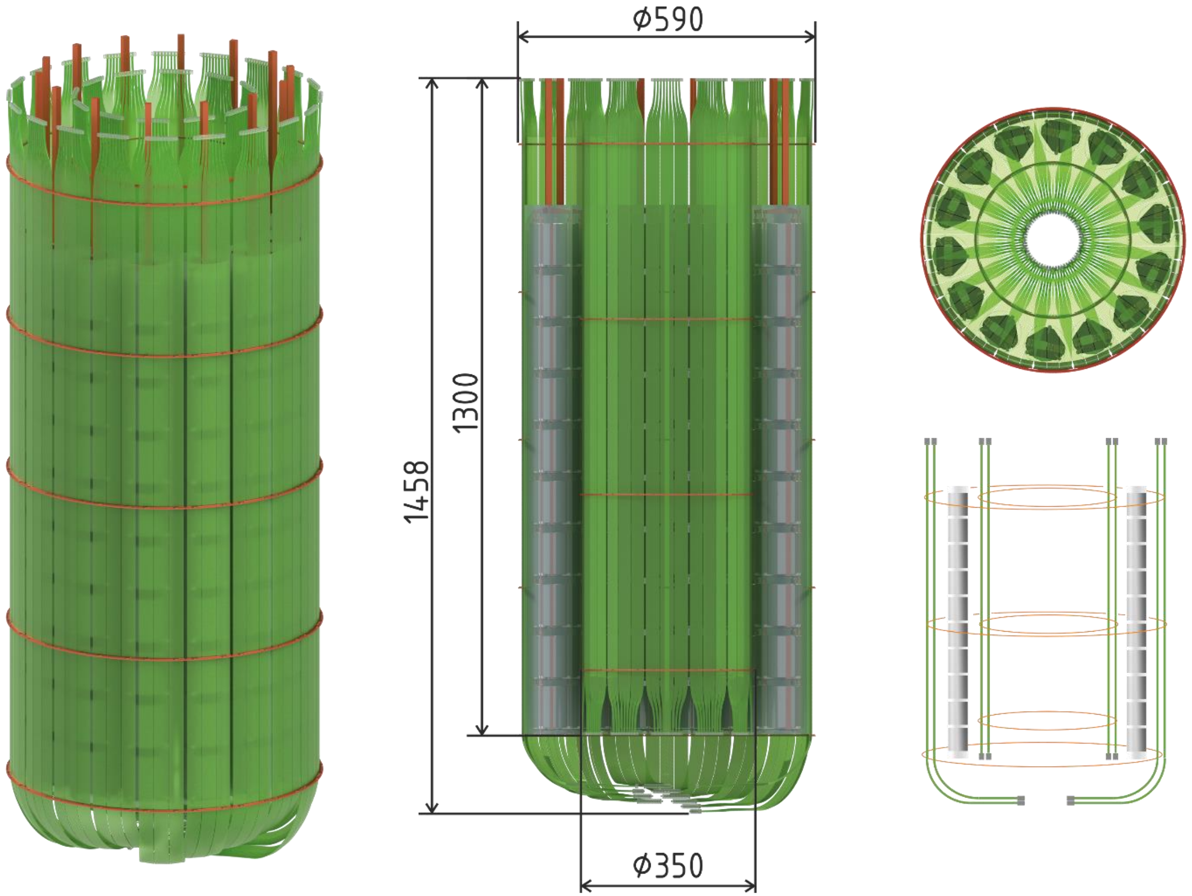
LEGEND-200 LAr veto design
(Picture of E. Shevchik (DLNP JINR))

LEGEND-200 & **JINR**

200 kg in GERDA setup



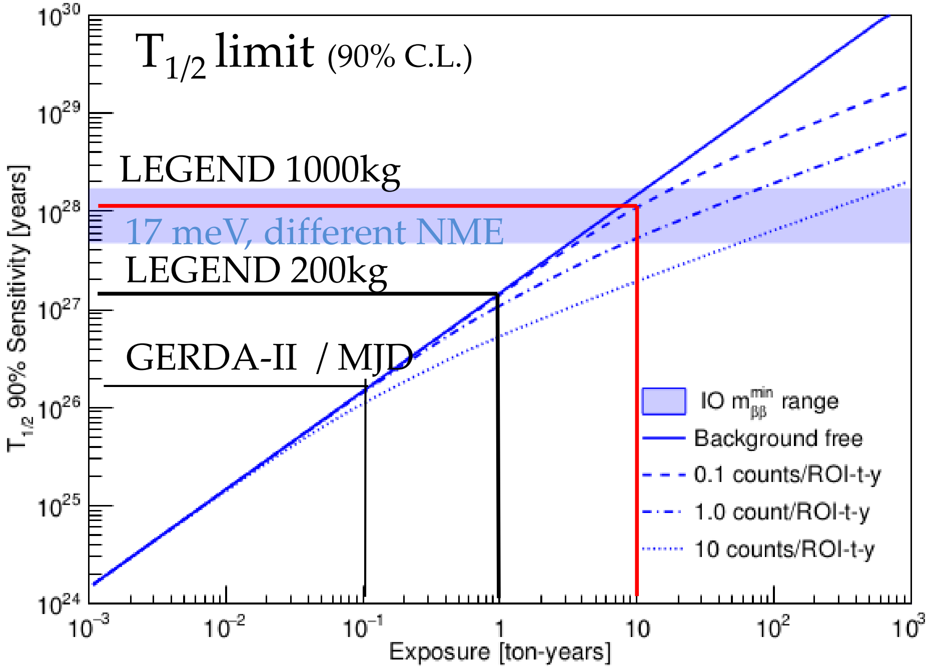
LEGEND-200 LAr veto design

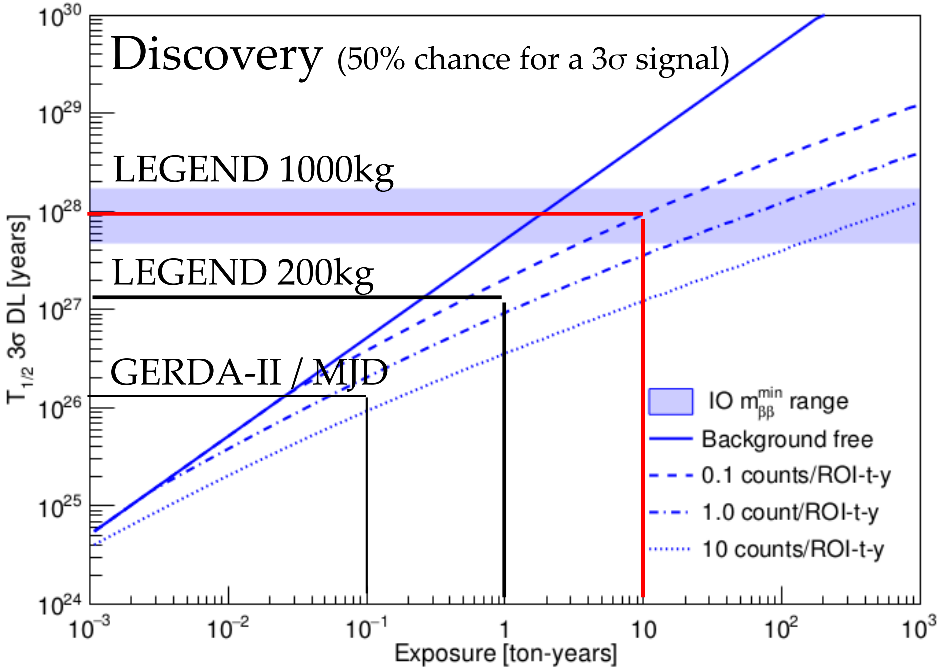


(Picture of E. Shevchik)

LEGEND-200

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)

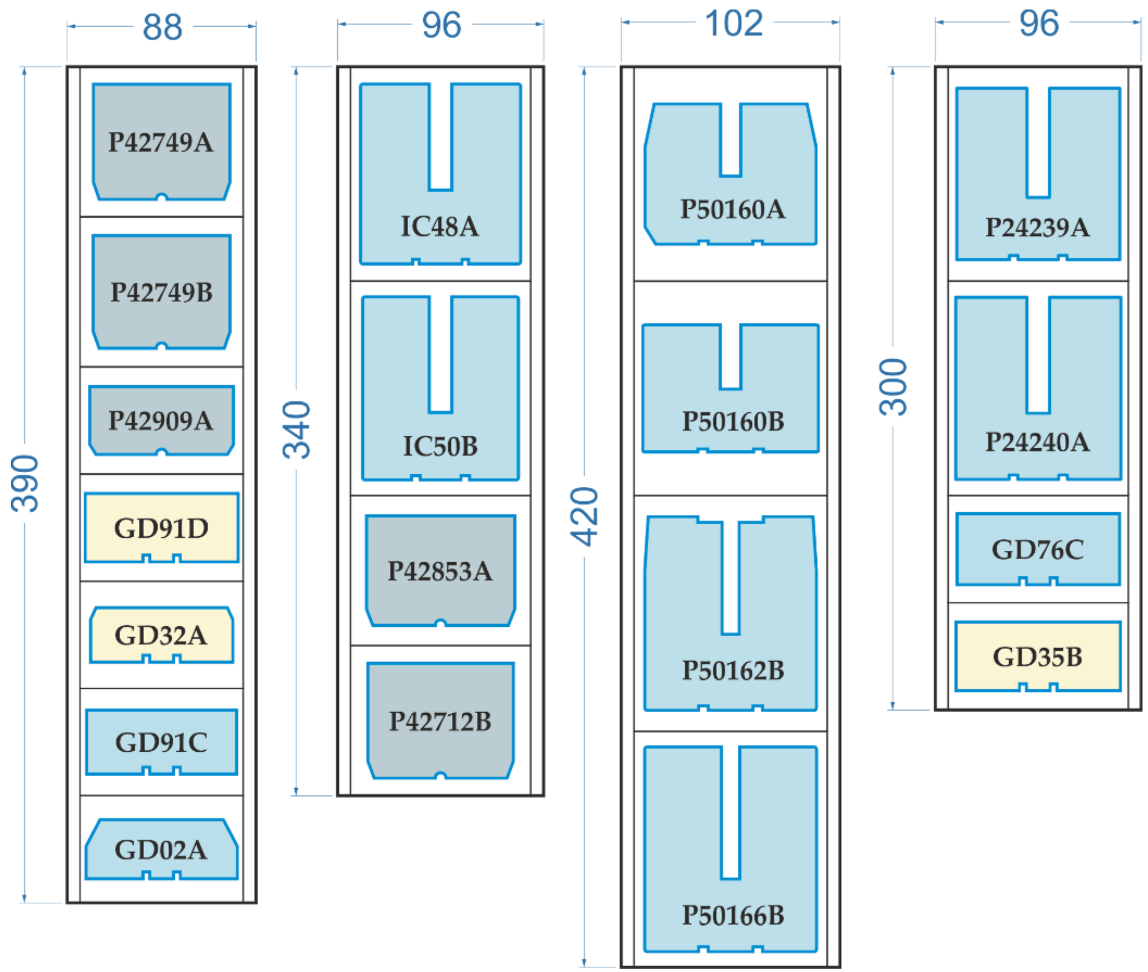
N.B.: background-free operation is a prerequisite for a discovery

PGT (Post GERDA Test) – 2020

Real integration test for LEGEND-200

Goals and hardware:

- test as many final components as possible
- low background to study e.g. alpha on PPC
- 19 detectors (enriched) (total mass ~ 25 kg):
    - 5 PPC from Majorana
    - 2 IC (inverted coax) from ORTEC,
    - 4 IC from Canberra,
    - 2 IC from GERDA
    - 6 BEGe from GERDA
- 3 nylon mini-shrouds
- check leakage current, bkg without nylon MS, …
- final detector support and final electronics (using GERDA coax cables)
    - ✓ tested before at TUM
- LAr veto (from GERDA)
- calibration system (from GERDA)
- DAQ (new + GERDA)
- analysis chain



✓ Prepared and started in early 2020 with the leading role of JINR specialists…