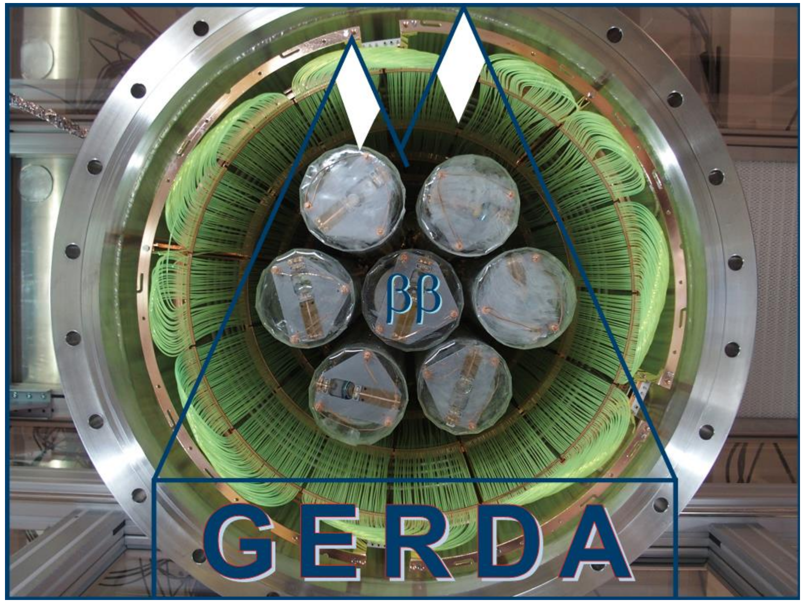
Проект GERDA (LEGEND):
поиск безнейтринного двойного бета распада ^{76}Ge

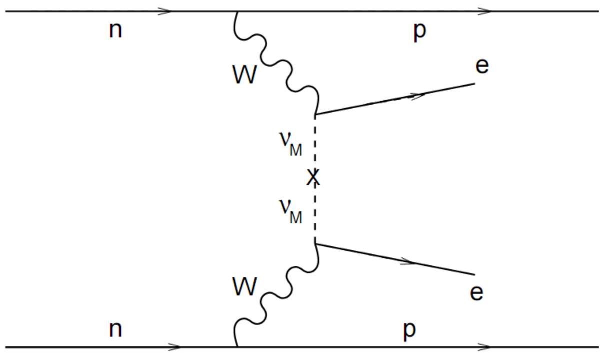


Константин Гусев

НТС ЛЯП ОИЯИ | 05 Ноября 2020

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:

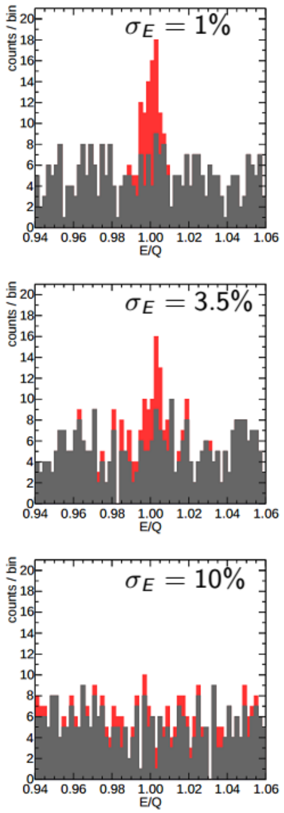
$$T_{1/2}^{0\nu} \propto M\,t$$

- Non-zero background:

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

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

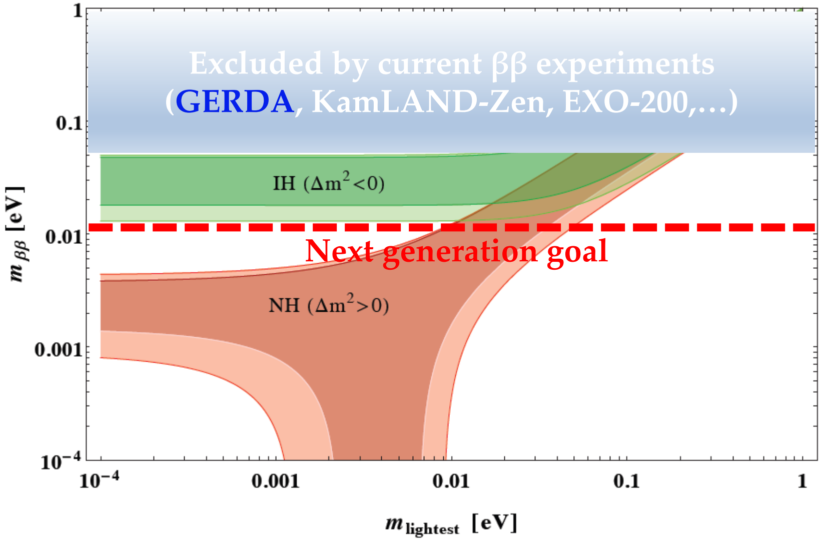
Effective Majorana neutrino mass

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

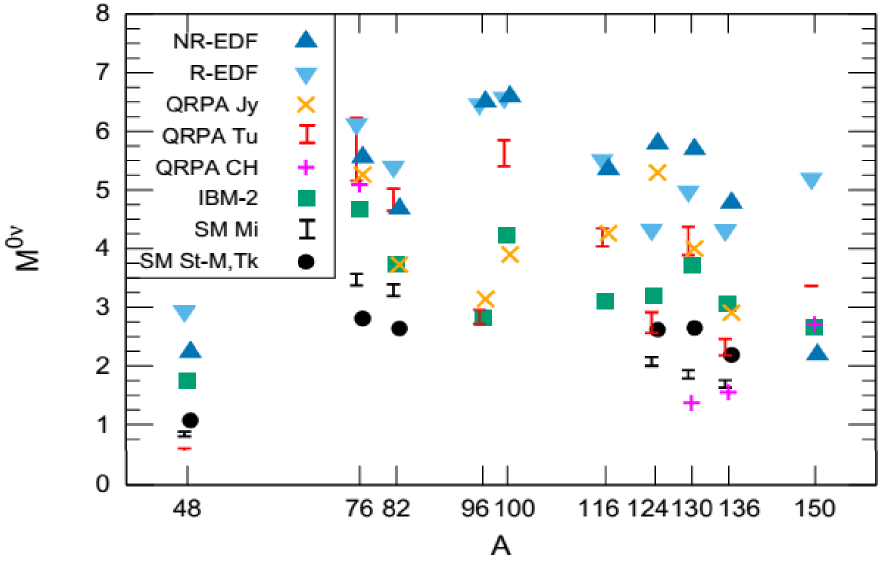
0νββ decay rate

Matrix element (NME)

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



NMEs for different isotopes/models

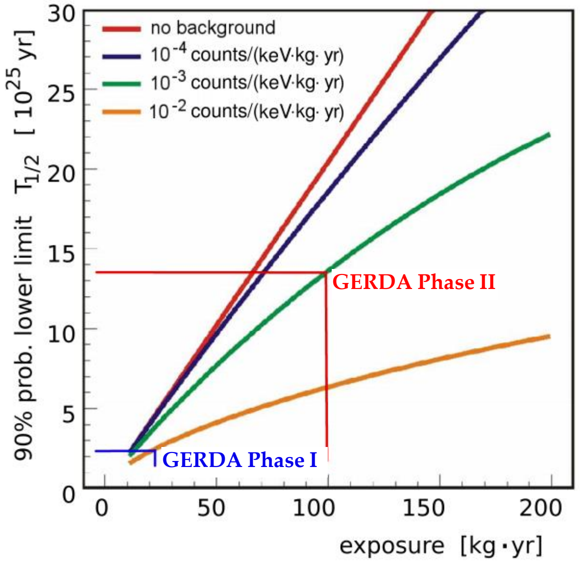


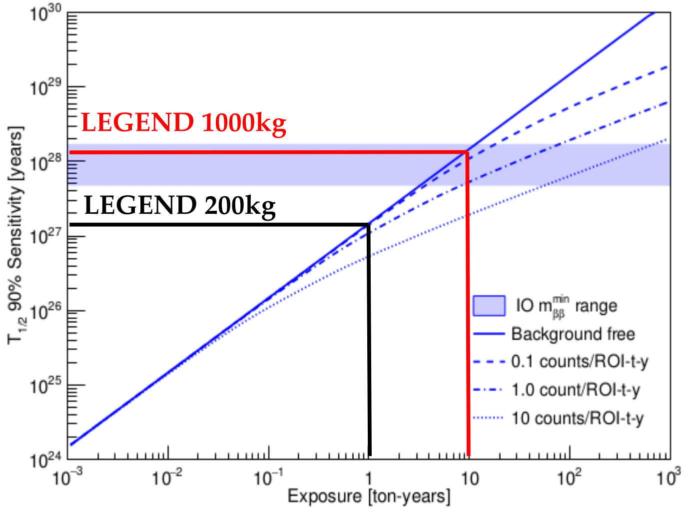
! No preferred isotope from Nuclear Physics (G*M)

GERDA/LEGEND phased approach

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

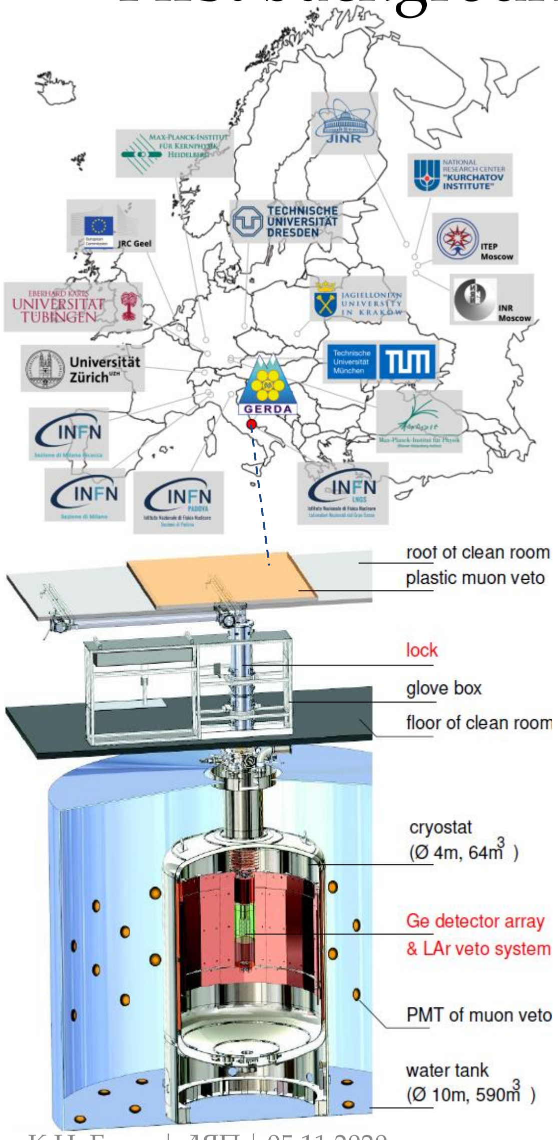
- ✓ very good energy resolution
  ~0.1% at $Q_{\beta\beta}$
- ✓ high detection efficiency
  source = detector
- ✓ "background-free" regime of data taking
  - ✓ deep underground location
    (LNGS, Italy, 3500 m.w.e)
  - ✓ careful assay of materials
  - ✓ passive and active shields
  - ✓ **bare Ge detectors**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





GERDA results

First background free 0νββ 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!**

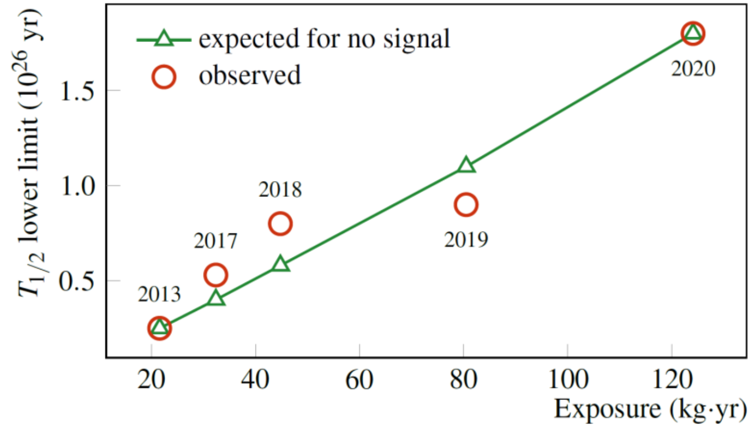
GERDA Phase II	**goals**	**achievements**
background	~ 10^{-3} cts/(keV kg yr)	$5.2^{+1.6}_{-1.3} \times 10^{-4}$ cts/(keV kg yr)
exposure	≥ 100 kg yr	**103.7** kg yr
sensitivity	$T^{0\nu}_{1/2} \geq 10^{26}$ yr	$T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ yr

- ✓ GERDA achieved world best half-life limit!

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

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

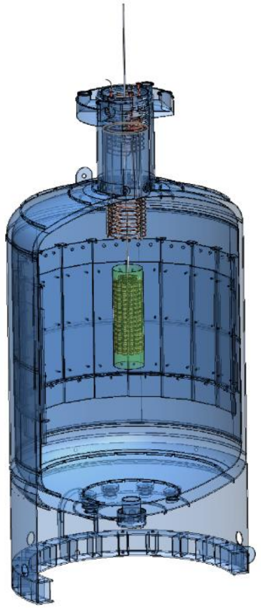
LEGEND



LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

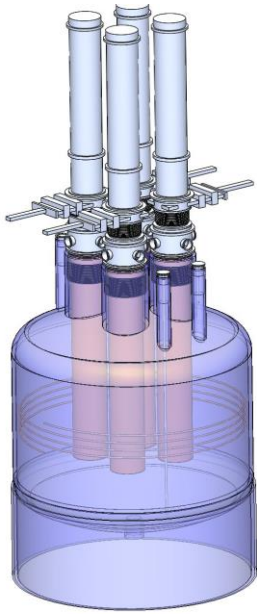
LEGEND mission:
"The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life significantly close to **10^{28}** years, using existing resources as appropriate to expedite physics results."



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)

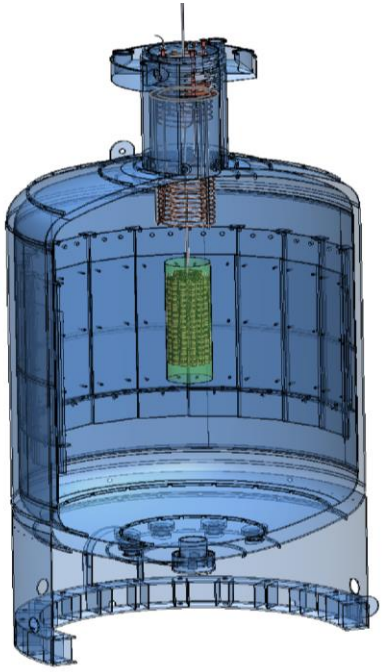


Subsequent stages (LEGEND-1000):

- ✓ 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 $0\nu\beta\beta$ field

MAJORANA

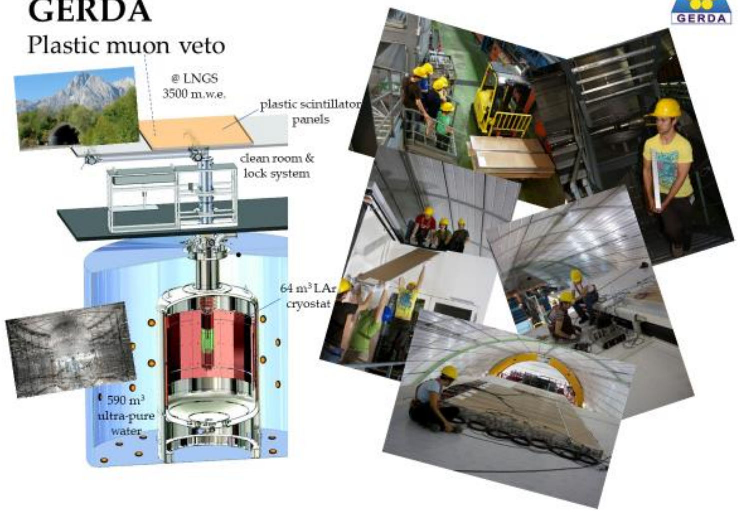
- ✓ Radiopurity of nearby parts (FETs, cables, Cu)
- ✓ Low noise FE improves PSD
- ✓ Low energy threshold

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**

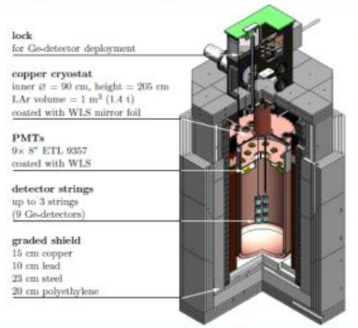
GERDA
Plastic muon veto



GERDA
Bare detectors

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

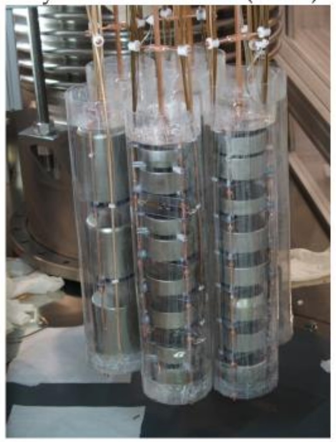


M. Agostini et al., Eur. Phys. J. C 75 (2015) 506

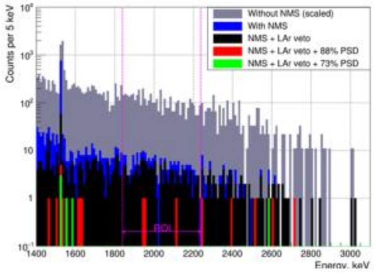
Для детального изучения фона от ^{42}Ar, был искусственно произведен ^{42}Ar и добавлен в жидкий аргон криостата LArGe. Были разработаны и протестированы различные способы подавления фона от ^{42}Ar.

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

GERDA
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 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
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TU Dresden:	K. Zuber
JINR Dubna:	K. Gusev
Geel:	M. Hult
MPIK-Heidelberg:	W. Hofmann
	M. Lindner
Milano Bicocca & INFN:	E. Bellotti
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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 (LEGEND) & **JINR**

- ✓ В отделе НЭОЯСиРХ ЛЯП было разработана, произведена, установлена и запущена система пластикового мюонного вето.
- ✓ Наши ученые внесли очень заметный вклад как в разработку и тестирование принципов регистрации сцинтилляций аргона, так и в непосредственное создание в 2015 году первой системы активного аргонового вето, успешно примененной в эксперименте.
- ✓ В 2018 году специалисты ЛЯП ОИЯИ, совместно с коллегами из Мюнхенского университета, разработали, изготовили и установили в GERDA модифицированную систему аргонового вето с улучшенной эффективностью сбора света.
- ✓ Сотрудниками ОИЯИ была разработана оригинальная методика по подавлению доминирующего фона от ^{42}Ar. Специально изготовленные сверхнизкофоновые нейлоновые кожухи со спектросмещающим покрытием, смонтированные вокруг германиевых детекторов, позволяют значительно снижать этот фон.
- ✓ Физики нашего института участвовали в анализе полученных данных.
- ✓ Сотрудники ОИЯИ непосредственно отвечали за все операции с открытыми обогащенными германиевыми детекторами, начиная с демонстрации их работоспособности в криогенной жидкости в самом начале проекта и заканчивая инсталляцией (и деинсталляцией) всех детекторов в установку GERDA в обеих фазах эксперимента.

GERDA (LEGEND) & **JINR**

People

- K.N.Gusev – Project Leader (technical coordination of the GERDA experiment, project coordination at JINR, Ge detectors, active veto systems), 0.6 FTE
- A.V.Lubashevskiy – Deputy Leader (analysis coordination, ultrapure materials, Ge detectors), 0.3 FTE.
- N.S.Rumyantseva – Deputy Leader (Ge detectors, analysis), 0.4 FTE
- V.B.Brudanin – Participant (^{76}Ge procurement, ultrapure materials), 0.1 FTE
- M.V.Fomina – Participant (active veto systems), 0.2 FTE
- S.A.Evseev – Participant (Ge detectors), 0.1 FTE
- D.V.Filosofov – Participant (ultrapure materials), 0.1 FTE
- L.Grubchin – Participant (Ge detectors), 0.1 FTE
- Yu.B.Gurov – Participant (Ge detectors), 0.2 FTE
- Zh.H.Hushvaktov – Participant (ultrapure materials), 0.2 FTE
- I.I.Kamnev – Participant (active veto systems), 0.2 FTE
- A.A.Klimenko – Participant (analysis), 0.7 FTE
- F.Mamedov – Participant (ultrapure materials, analysis), 0.2 FTE
- I.B.Nemchenok – Participant (ultrapure materials, active veto systems), 0.2 FTE
- A.V.Rakhimov – Participant (ultrapure materials), 0.1 FTE
- S.V.Rozov – Participant (Ge detectors), 0.1 FTE
- V.G.Sandukovsky – Participant (Ge detectors), 0.5 FTE
- K.V.Shakhov – Participant (ultrapure materials), 0.1 FTE
- E.A.Shevchik – Participant (active veto systems), 0.3 FTE
- Yu.A.Shitov – Participant (analysis), 0.1 FTE
- A.A.Smolnikov – Participant (active veto systems, ultrapure materials, analysis), 0.7 FTE
- S.I.Vasilev – Participant (active veto systems, analysis), 1.0 FTE
- V.P.Volnikh – Participant (technical support), 0.1 FTE
- E.A.Yakushev – Participant (Ge detectors, analysis), 0.1 FTE
- I.V.Zhitnikov – Participant (analysis), 0.1 FTE

Total FTE: 6.8

GERDA (LEGEND) & **JINR**

Plans

2021-2022:

Modification of GERDA cryostat for LEGEND-200. Integration of the first strings and start data taking of the LEGEND experiment. Working on the conceptual design of LEGEND-1000.

2022-2023:

Taking data in LEGEND-200. Finalizing the array by adding the rest of the enriched Ge detectors. Publication of the first results of LEGEND-200. Preparation of the LEGEND-1000 (procurement of enriched ^{76}Ge, production and testing of new Ge detectors, R&D of low background materials and electronics).

2023-2024:

Taking data in LEGEND-200. Adding the new detectors strings in the center of the LEGEND-200 array. Publication of improved results of LEGEND-200. Completion the design of LEGEND-1000. Continuation of preparation of the LEGEND-1000 (procurement of enriched ^{76}Ge, production and testing of new Ge detectors, R&D of low background materials and electronics).

GERDA (LEGEND) & **JINR**

Financing (forms № 26 and № 29)

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	30	10	10	10
		2. Procurement of ^{76}Ge detectors	150	50	50	50
		3. R&D of active veto systems	30	10	10	10
		4. R&D on Ge detectors	140	60	20	60
		5. R&D of $^{42}Ar/^{42}K$ background mitigation	30	10	10	10
		Construction/repair of premises				
		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
	External resources	Contributions by collaborators. Grants. Contributions by sponsors. Contracts. Other financial resources, etc.	30	10	10	10

	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

GERDA (LEGEND) & **JINR**

Publications and talks

1. «Upgrade for Phase II of the GERDA Experiment», Eur. Phys. J. C 78 (2018) 388.
2. «LArGe: active background suppression using argon scintillation for the Gerda 0νββ-experiment», Eur. Phys. J. C 75 (2015) 506.
3. «Mitigation of $^{42}Ar/^{42}K$ background for the GERDA Phase II experiment», Eur. Phys. J. C 78 (2018) 15.
4. «The GERDA experiment for the search of 0νββ decay in ^{76}Ge», Eur. Phys. J. C 73 (2013) 2330.
5. «Results on Neutrinoless Double-β Decay of ^{76}Ge from Phase I of the GERDA Experiment», Phys. Rev. Lett 111 (2013) 122503.
6. «Pulse shape discrimination for GERDA Phase I data», Eur. Phys. J. C 73 (2013) 2583.
7. «The background in the 0νββ experiment GERDA», Eur. Phys. J. C 74 (2014) 2764.
8. «Results on ββ decay with emission of two neutrinos or Majorons in ^{76}Ge from GERDA Phase I», Eur. Phys. J. C 75 (2015) 416.
9. «2νββ decay of ^{76}Ge into excited states with GERDA Phase I», J. Phys. G: Nucl. Part. Phys. 42 (2015) 115201.
10. «The performance of the Muon Veto of the GERDA experiment», EPJC 76 (2016) 298.
11. «Flux modulations seen by the muon veto of the GERDA experiment», Astroparticle Physics 84 (2016) 29.
12. «Limit on the radiative neutrinoless double electron capture of ^{36}Ar from GERDA Phase I», Eur. Phys. J. C 76 (2016) 652.
13. «Limits on uranium and thorium bulk content in GERDA Phase I detectors», Astroparticle Physics 91 (2017) 15.
14. «Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA», Nature 544 (2017) 47.
15. «The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND)», AIP Conference Proceedings 1894 (2017) 020027.
16. «Improved Limit on Neutrinoless Double-β Decay of ^{76}Ge from GERDA Phase II», Phys. Rev. Lett. 120 (2018) 132503.
17. «Characterization of 30 ^{76}Ge enriched Broad Energy Ge detectors for GERDA Phase II», Eur. Phys. J. C. 79 11 (2019) 978.
18. «Probing Majorana neutrinos with double-β decay», Science 365 (2019) 1445.
19. «Modeling of GERDA Phase II data», Journal of High Energy Physics 03 (2020) 139.
20. «First Search for Bosonic Superweakly Interacting Massive Particles with Masses up to 1 MeV/c2 with GERDA», Phys. Rev. Lett. 125 (2020) 011801.
21. «Final Results of GERDA on the Search for Neutrinoless Double-β Decay», submitted to Physical Review Letters, arXiv: 2009.06079.

GERDA (LEGEND) & **JINR**

Publications and talks

22. «Status of the GERDA experiment: on the way to Phase II», K.Gusev at TAUP 2015, Torino, Italy
23. «Status of preparations for the Phase II of the GERDA experiment aimed for the 0νββ decay search», A.Lubashevskiy at PATRAS 2015, Zaragoza, Spain.
24. «First results from Phase II of the GERDA experiment», K.Gusev at INPC 2016, Adelaide, Australia.
25. «Neutrinoless double beta decay: First results of GERDA Phase II and the status of other experiments», A.Lubashevskiy at PASCOS 2016, Quy Nhon, Vietnam.
26. «Double Beta Decay Experiments», K.Gusev at ICSSNP 2016, Dubna, Russia.
27. «Double beta decay experiments and neutrino mass investigation: Past, Present and Future», A.Smolnikov at QUARKS 2016, Pushkin, Russia.
28. «From Baksan to worldwide experiments searching for neutrinoless double beta decay», A.Smolnikov at ICSSNP 2017, Nalchik, Russia.
29. «Neutrinoless double beta decay search with the "background free" GERDA experiment», A.Lubashevskiy at ICSSNP 2017, Nalchik, Russia.
30. «GERDA: first background free search for neutrinoless double beta decay», K.Gusev at ICNFP 2017, Crete, Greece.
31. «LEGEND: new opportunity to discover the neutrinoless double beta decay», K.Gusev at ICNFP 2017, Crete, Greece.
32. «Neutrinoless double beta decay: Experimental challenges», K.Gusev at NOW 2018, Brindisi, Italy.
33. «Fifty Years of Searching for Neutrinoless Double Beta Decay with Ge Detectors», A.Smolnikov at History of Neutrinos, Paris, France.
34. «New results of the search for neutrinoless double beta decay from GERDA Phase II», N.Rumyantseva at Nucleus 2018, Voronezh, Russia.
35. «GERDA searches for 0νββ and other ββ decay modes of ^{76}Ge», A.Smolnikov at MEDEX 19, Prague, Czech Republic.
36. «Status of the search for neutrinoless double-beta decay with GERDA», A.Lubashevskiy at WIN 2019, Bari, Italy.
37. «Upgrade of the GERDA Phase II experiment», E.Shevchik at Nucleus 2019, Dubna, Russia.
38. «Latest results from the first background free search for neutrinoless double beta decay – GERDA Phase II», K.Gusev at INPC 2019, Glasgow, UK.
39. «Status of the GERDA Phase II experiment», N.Rumyantseva at ICNFP 2019, Crete, Greece.
40. «Results of the GERDA Phase II experiment», K.Gusev at ICHEP 2020, Prague (virtual conference).