Non-Accelerator Neutrino Physics and Astrophysics

7 main projects:

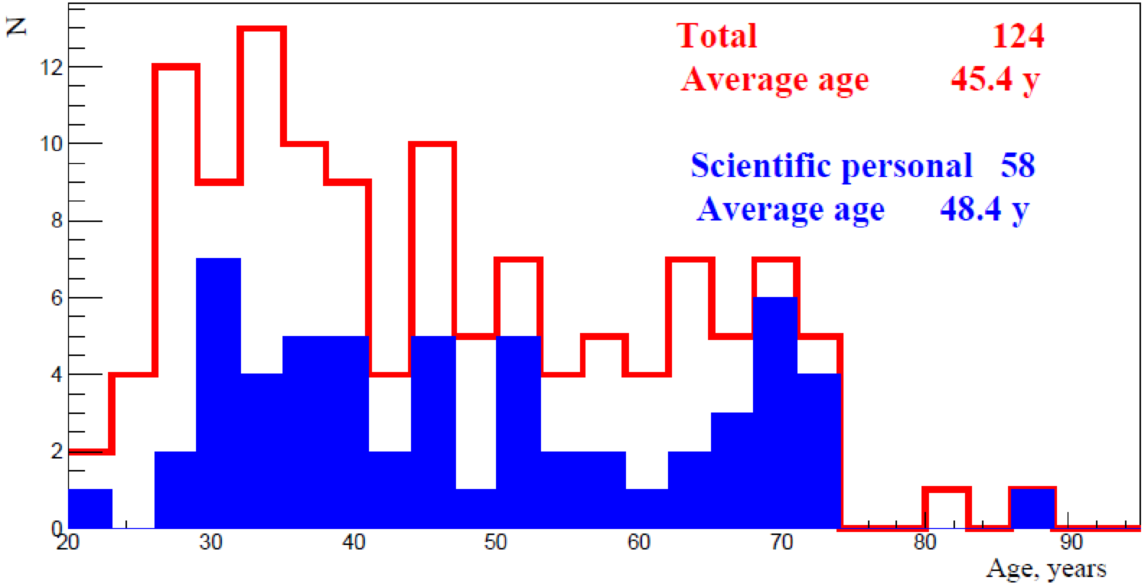
- **SuperNEMO,**
- **GERDA (Legend),**
- **Monument,**
- **EDELWEISS/Ricochet,**
- **GEMMA(νGeN),**
- **DANSS,**
- **BAIKAL-GVD**

Partners: Azerbaijan, Bulgaria, Germany, Kazakhstan, Poland, Russia, Slovakia, Uzbekistan, Czech Republic, Great Britain, Finland, France

Non-Accelerator Neutrino Physics and Astrophysics

Base: The Department of Nuclear Spectroscopy and Radiochemistry, DLNP

- 50-years experience in high-precision nuclear spectroscopy using semiconductor, scintillator and other types of detectors;
- 30-years experience of rare processes studies in different underground environments;
- 15-years experience with neutrino experiments on nuclear reactors;
- Participation in the BAIKAL neutrino program for 20+ years



The department has the knowledge, personnel and capabilities to create world-class facilities, conduct measurements with them and obtain world-leading results

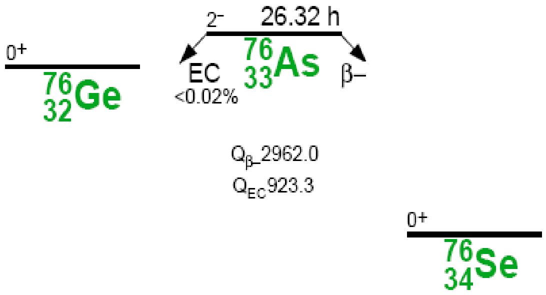
Scientific directions :

- Double beta decay, clarification of the neutrino nature Majorana or Dirac;
- Nuclear matrix elements for 2β-decays;
- Fundamental neutrino properties (magnetic moment, mixture with a sterile state, coherent scattering on nuclear);
- Monitoring of nuclear reactors with neutrino detectors;
- Direct and indirect search for Dark Matter;
- Investigation of galactic and extragalactic neutrino sources;
- Spectrometry of nuclei far from stability;
- Study of atomic processes accompanying radioactive decay;
- Development and implementation of methods for separation of macro-quantities of a substance from impurities, synthesis of materials from ultrapure precursors;
- Investigation of hyperfine interactions using the method of perturbed angular correlations on probe nuclei in solid and liquid samples.

Experiments conducted in: DLNP, underground laboratories, KNPP, lake Bikal

The main task of the theme: Using nuclear spectrometry methods to study various processes that are interesting at the present stage of the development of science, including and with focus to rare processes.

Connection between neutrino physics and astrophysics (on example of neutrinoless Double Beta Decay)



In the Standard Model this process cannot occur without neutrinos

Observation at any level would imply:

- Lepton number L is not conserved
- Neutrinos have *Majorana masses* — masses with a different origin than the quark and charged lepton masses
- Neutrinos are their own antiparticles

Observation of 0νββ would make more plausible:

- The See-Saw model of the origin of neutrino mass
- Leptogenesis, an outgrowth of the See-Saw, which may be the origin of the baryon-antibaryon asymmetry of the Universe

General opinion of the particle physics community:

A non-zero signal for 0νββ would be a tremendously important discovery

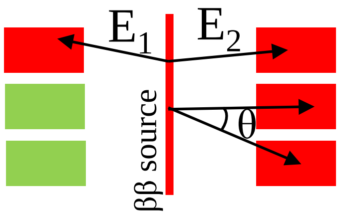
Method to study: nuclear spectrometry

Investigation 2β decay, search for 0ν2β

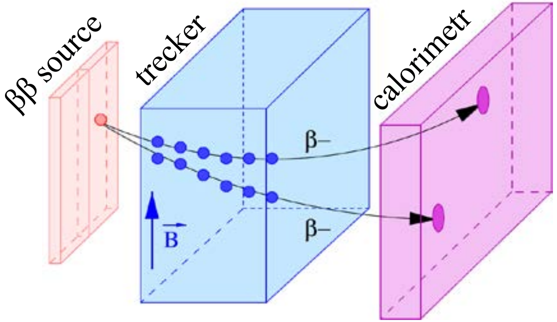
Two main approaches:

Track-calorimetric approach

Simple case



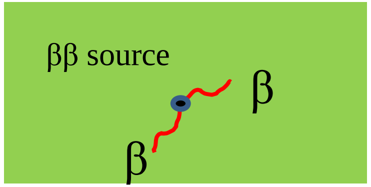
Improved experiment



- Full information about event (energy of each electrons, particle identification, track reconstruction, angular distribution);
- Sensitive to non standard modes of 0ν2β decays;
- Possibility to measure several (almost any) isotopes in one detector;
- Unique information about 2ν2β.

Isotop	$E_{0\nu2\beta}$	abudance %
^{48}Ca	4273.7	0.187
^{76}Ge	2039.1	7.8
^{82}Se	2995.5	9.2
^{100}Mo	3035.0	9.6
^{130}Te	2530.3	34.5
^{136}Xe	2461.9	8.9
^{150}Nd	3367.3	5.6

Calorimetric approach



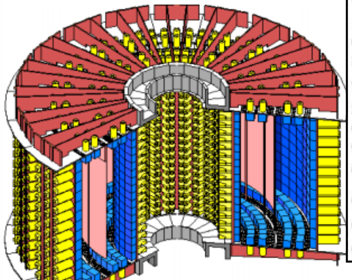
- Detector = source;
- Efficiency near 100%;
- Compactness = the possibility of highly effective application of additional active and passive methods of background control, minimization of the amount of materials used near the detectors (background reduction);
- Several detectors (or selection of a sensitive volume) = systematics, homogeneity;
- Selection of events (PSD, two measurement channels, no multiplicity (if several detectors …);
- Achieving higher mass and low background (i.e. better result for 0ν2β decay) with low cost.

From NEMO3 to SuperNEMO through the Demonstrator phase (start of data takin- 2021)

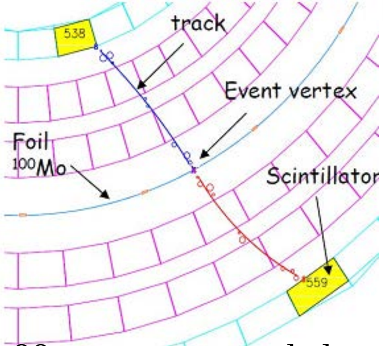
supernemo collaboration

$t_{1/2}(10^{21}$ yr)			ISOTOPE	TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
> 0.87			^{134}Xe		EXO-200	[1] ALBERT	17C
0.82	±0.02	±0.06	^{130}Te		CUORE-0	[2] ALDUINO	17
0.00690	±0.00015	±0.00037	^{100}Mo		CUPID	[3] ARMENGAUD	17
0.0274	±0.0004	±0.0018	^{116}Cd		NEMO-3	[4] ARNOLD	17
0.064	$^{+0.007}_{-0.006}$	$^{+0.012}_{-0.009}$	^{48}Ca		NEMO-3	[5] ARNOLD	16
0.00934	±0.00022	$^{+0.00062}_{-0.00060}$	^{150}Nd		NEMO-3	[6] ARNOLD	16A
1.926	±0.094		^{76}Ge		GERDA	[7] AGOSTINI	15A
0.00693	±0.00004		^{100}Mo		NEMO-3	[8] ARNOLD	15
2.165	±0.016	±0.059	^{136}Xe		EXO-200	[9] ALBERT	14
9.2	$^{+5.5}_{-2.6}$	±1.3	^{78}Kr		BAKSAN	[10] GAVRILYAK	13
2.38	±0.02	±0.14	^{136}Xe		KamLAND-Zen	[11] GANDO	12A
0.7	±0.09	±0.11	^{130}Te		NEMO-3	[12] ARNOLD	11
0.0235	±0.0014	±0.0016	^{96}Zr		NEMO-3	[13] ARGYRIADES	10
0.69	$^{+0.10}_{-0.08}$	±0.07	^{100}Mo	$0^+ \to 0^+_1$	Ge coinc.	[14] BELLI	10
0.57	$^{+0.13}_{-0.09}$	±0.08	^{100}Mo	$0^+ \to 0^+_1$	NEMO-3	[15] ARNOLD	07
0.096	±0.003	±0.010	^{82}Se		NEMO-3	[16] ARNOLD	05A
0.029	$^{+0.004}_{-0.003}$		^{116}Cd		$^{116}CdWO_4$ scint.	[17] DANEVICH	03

	NEMO3	SuperNEMO
Isotope	Mo-100	Se-82 (Nd-150)
Efficiency	18%	30%
Energy resolution for 3 MeV elevtrons	8% (FWHM)	4% (FWHM)
Backgrounds		Reduced by factor 10



NEMO-3



ββ event, as recorded by NEMO-3

Demonstrator Module (2.5 year run)

17.5 kg×yr initial exposure :

$$T^{0\nu}_{1/2} > 5.9 \times 10^{24} \text{ yr}$$

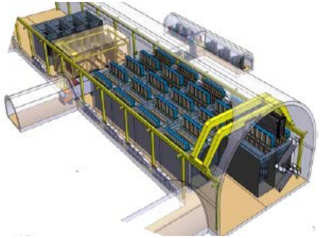
$$\langle m_\nu \rangle < 0.20 - 0.55 \text{ eV}$$

Full SuperNEMO

500 kg×yr :

$$T^{0\nu}_{1/2} > 10^{26} \text{ yr}$$

$$\langle m_\nu \rangle < 40 - 110 \text{ meV}$$



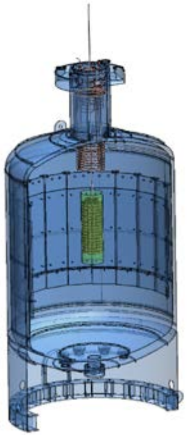
Demonstrator in the LSM

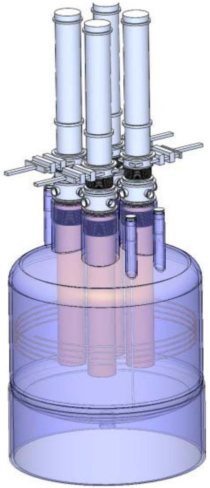
0νββ search with HP^{76}Ge detectors immersed in liquid argon
GERDA – LEGEND

GERDA phase II	aim	result
Background	~ 10^{-3} cts/(keV kg yr)	$5.2^{+1.6}_{-1.3} \times 10^{-4}$ cts/(keV kg yr)
Statistic accumulated	≥ 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

LEGEND-200

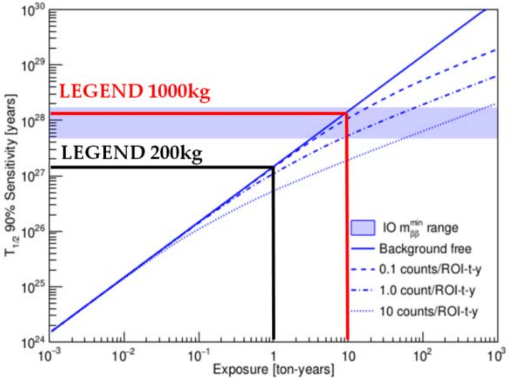
- ✓ First step to tone-scale ^{76}Ge exp.
- ✓ Improvements:
  - bigger mass of each of the detectors (in average)
  - improved LAr veto
  - less materials, new cables (less radioactive)
  - new electronics with lower noises
- ✓ Background improvement (estimate) : ~ x5 to GERDA
- ✓ 200 kg ^{76}Ge
- ✓ Target: $T_{1/2} \geq 10^{27}$ y





LEGEND-1000

- ✓ New infrastructure and design (some developments for Majorana)
- ✓ Improvements based on LEGEND-200
- ✓ 1000 kg ^{76}Ge
- ✓ Target: $T_{1/2} \geq 10^{28}$ y



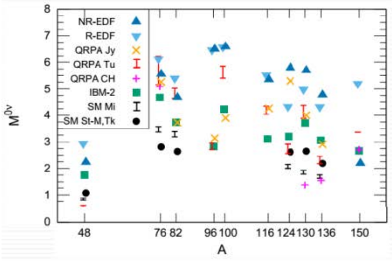
From half-life to neutrino mass:
the key information is in nuclear matrix elements

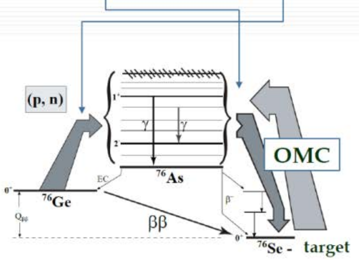
$$\frac{1}{T_{1/2}^{0\nu}} \propto \left|\sum_i U_{ei}^2 m_i\right|^2 G^{0\nu} \left|\langle A,Z+2|S|A,Z\rangle\right|^2$$

$\langle m_{\beta\beta}\rangle$ $\qquad M^{0\nu}$

$$\langle A,Z+2|S|A,Z\rangle \propto \sum_n \langle Z+2|\hat{H}|Z+1,n\rangle\langle Z+1,n|\hat{H}|Z\rangle$$

APPEC-2019, Recommendation 6: *The computation of nuclear matrix elements is challenging and currently is affected by an uncertainty which is typically quantified in a factor of 2-3... An enhanced effort is required and a stronger interactions between the particle physics and nuclear community would be highly beneficial. Dedicated experiments may be required.*



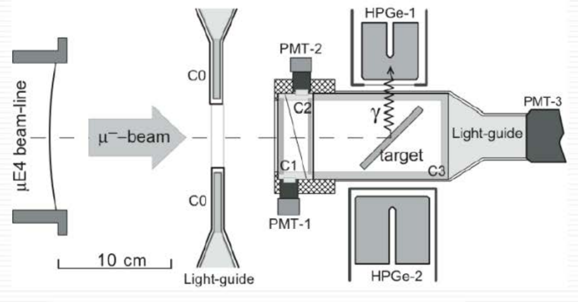


We are investigating this problem in the framework of the new MONUMENT project (Measurement of ordinary muon capture (OMC) for verification of nuclear matrix elements of 2β-decays)

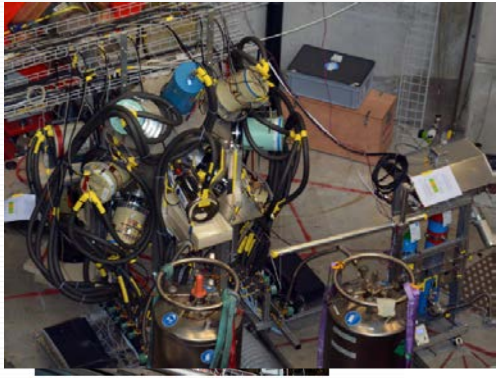
JOINT INSTITUTE FOR NUCLEAR RESEARCH

Measurement set-up

PAUL SCHERRER INSTITUT PSI

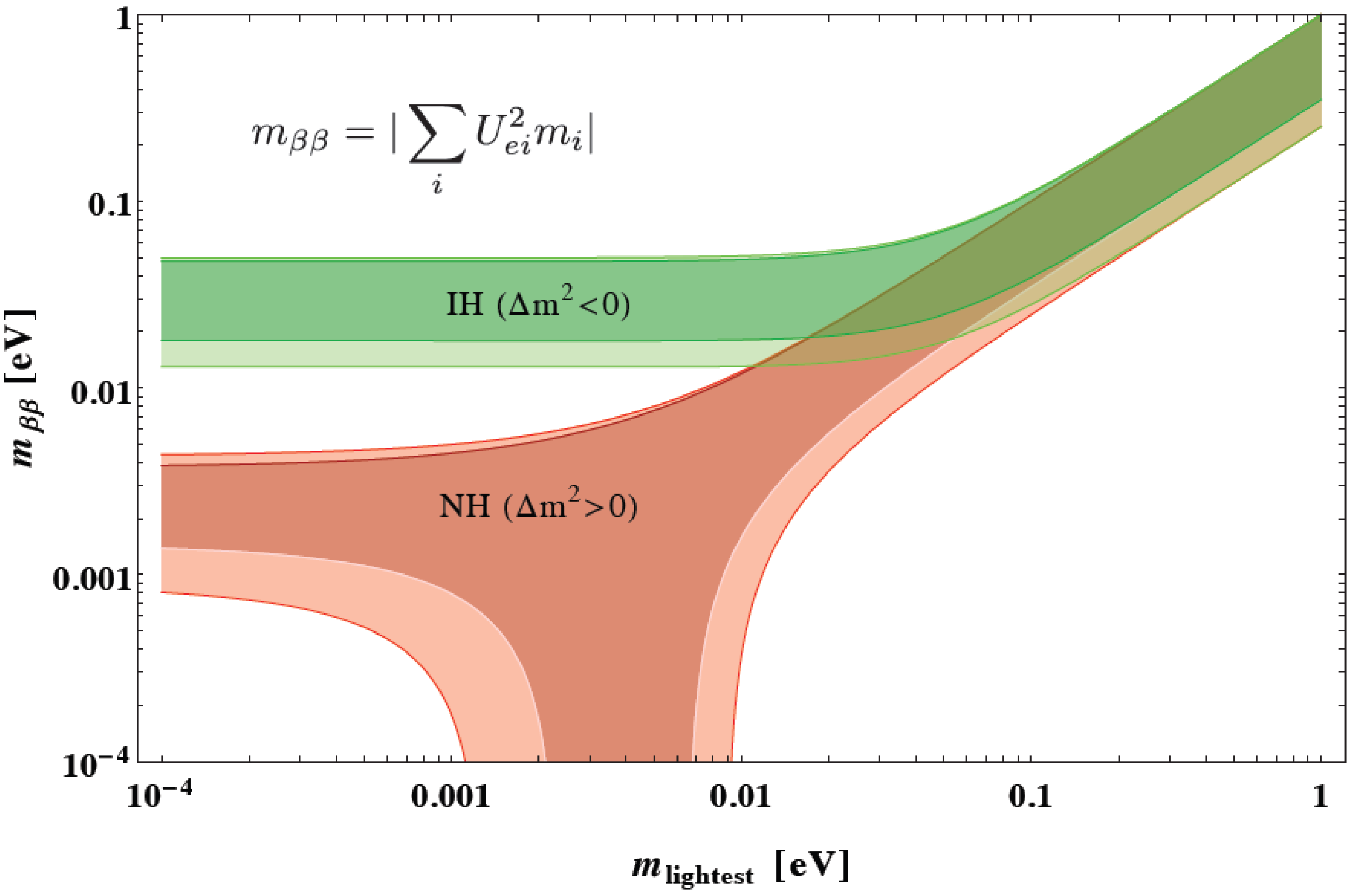


$$\mu_{stop} = \overline{C0} \wedge C1 \wedge C2 \wedge \overline{C3}$$



From 2021 to 2023 plans are to measure OMC for ^{136}Ba, ^{76}Se and ^{96}Mo isotopes. OMC for ^{136}Ba and ^{76}Se are most important for 0ν2β experiments – ^{136}Xe - nEXO, KamLAND2-Zen, NEXT, DARWIN and PandaX-III – and ^{76}Ge – LEGEND.

In addition, we are going to measure and obtain results for OMC in ^{40}Ca, ^{56}Fe, ^{32}S and ^{100}Mo isotopes. These results are important for the experimental verification of theoretical calculations and may also be useful for astrophysics.



$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$
IH ($\Delta m^2 < 0$)
NH ($\Delta m^2 > 0$)
$m_{\beta\beta}$ [eV]
m_{lightest} [eV]
1
0.1
0.01
0.001
10^{-4}
10^{-4}
0.001
0.01
0.1
1

EDELWEISS/RICOCHET: Joint project for Direct Dark Matter search and precision study of CEνNS with new cryogenic detectors

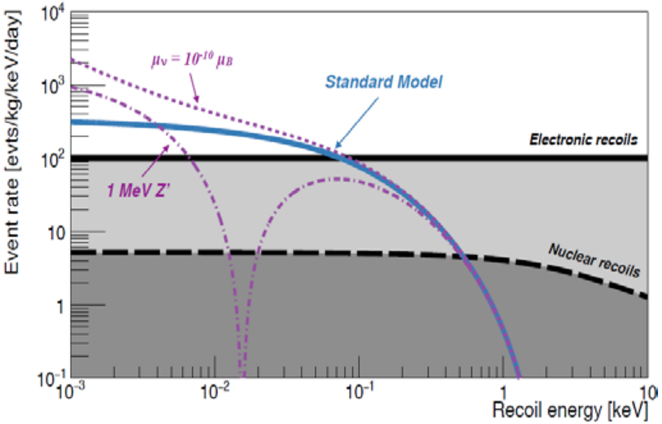
EDELWEISS: Direct search for Dark Matter, HPGe detectors at ~20 mK, low background environment in deep underground laboratory (LSM).

For the last 25 years EDELWEISS has been the leading experiment in the direct detection of Dark Matter with HPGe bolometer detectors.

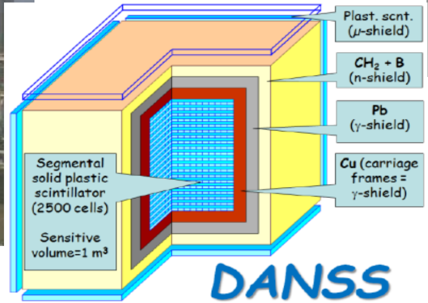
Thanks to the latest developments, the experiment remains competitive in the energy regions (low mass WIMPs, bosonic DM, etc, inaccessible to large Ar / Xe experiments.

New detectors developed by EDELWEISS, have unique characteristics for detecting ultralow-energy nuclei recoils.

The same technology and detectors will be applied for precision measurements of CEνNS in the region of full coherency in the Ricochet experiment (reactor neutrinos). The main goal: precise (1% level) study of CEνNS, and target other New physics phenomena.



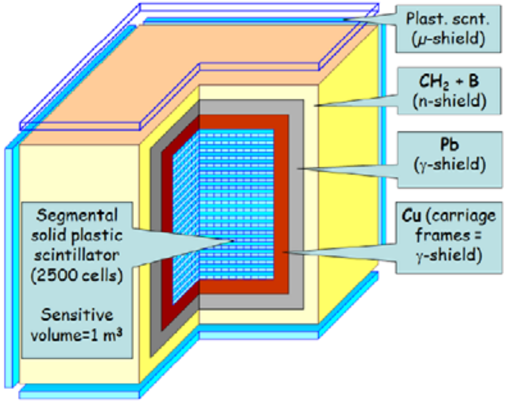
Our participation in experiments with world leading sensitivities to ultra-rare processes provides the solid base for home neutrino experiments



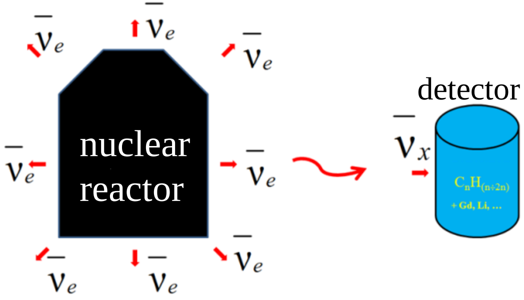
DANSS

Investigations of reactor antineutrinos at the KNPP with an inverse beta decay detector

$$\bar{\nu}_e + p \rightarrow n + e^+$$



Compact (1 m^3) highly segmented (2500 plastic scintillator plates) neutrino spectrometer DANSS aims at searching for oscillations in sterile neutrinos, as well as monitoring with neutrinos the reactor power and the composition of nuclear fuel.

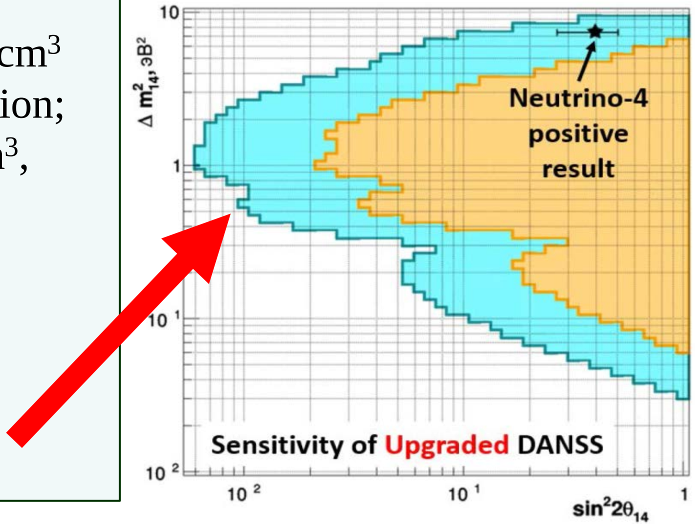


- DANSS is located under unit #4 KNPP (VVER-1000, 6 × 10^{20} $\bar{\nu}_e$ / sec);
- Shield from cosmic ~ 50 m.w.e.;
- Lifting platform: distance to reactor from 10.9 to 12.9 m;
- During 4 years 4 000 000 reactor antineutrinos were detected (~5000 events/day);
- World leading results between all reactor based experiments for sterile neutrino search;
- No indications on a significant level for sterile neutrino were found

From DANSS to DANSS2:

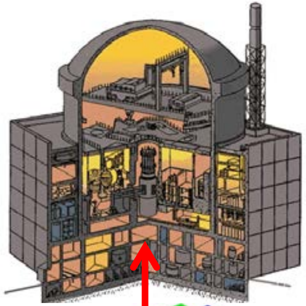
- ✓ New scintillators 2x5x120 cm^3 with two sided light collection;
- ✓ 60 layers x 24 plates: 1,7 m^3, same shields and lifting platform;
- ✓ Gd: foils between layers.

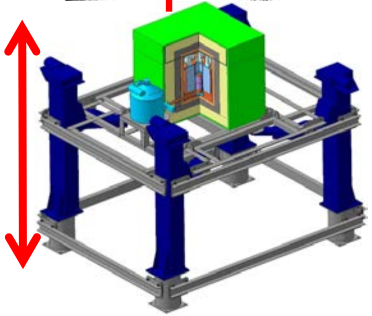
Target: the energy resolution: 34%/√E → 15% /√E

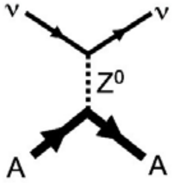


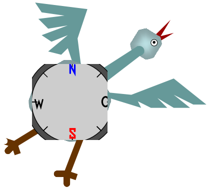
experiment at KNPP

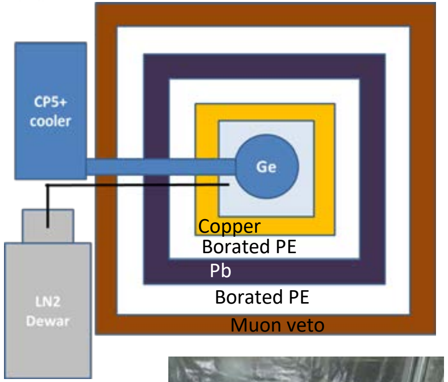
The νGEN / GEMMA projects are aimed at investigating the fundamental properties of neutrinos. In particular, it search coherent elastic neutrino-nucleus scattering and the magnetic moment of the neutrino. The experimental facility is being built under the reactor of the Kalinin NPP, located 285 km from Dubna. The experiment uses the latest HPGe detectors with an ultra low energy thresholds.











From GEMMA-I to νGEN:

- ✓ Threshold: 2 keV → **200 eV**
- ✓ Flux: $2.6 \cdot 10^{13}$ ν/(s·cм^2) → **$5 \cdot 10^{13}$ ν/(s·cм^2) (new place, lifting platform!)**
- ✓ HPGe: 1.5 kg → 5.5 kg
- ✓ $\mu_\nu < 2.9 \cdot 10^{-11} \mu_B \rightarrow \mu_\nu < (5\text{-}9) \cdot 10^{-12} \mu_B$ (after several years of data taking)

North hemisphere biggest neutrino detector BAIKAL-GVD

Neutrino telescopes brings an important information complementary to the traditional optic and radio telescopes.

Main principle : determination of direction and energy of charged particles (appearing as result of neutrino interaction) with the help of Cherenkov radiation

Baikal project: From 1980 tests and R&D, started in 1993.

Now – building BAIKAL-GVD (**Gigaton Volume Detector)** has huge progress and will be continued

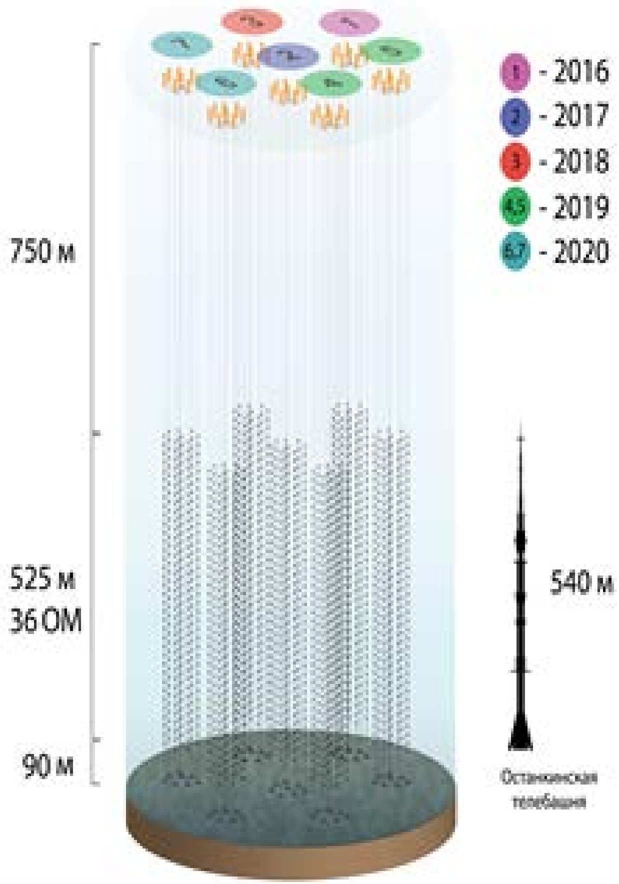
Physics:

- Investigate Galactic and extragalactic neutrino “point sources”;
- Diffuse neutrino flux – energy spectrum, local and global anisotropy, flavor content;
- Indirect search for Dark Matter;
- Exotic particles – monopoles, Q-balls, nuclearites, …

DLNP created facilities to produce and tests optical modules (the main element of BAIKAL-GVD)

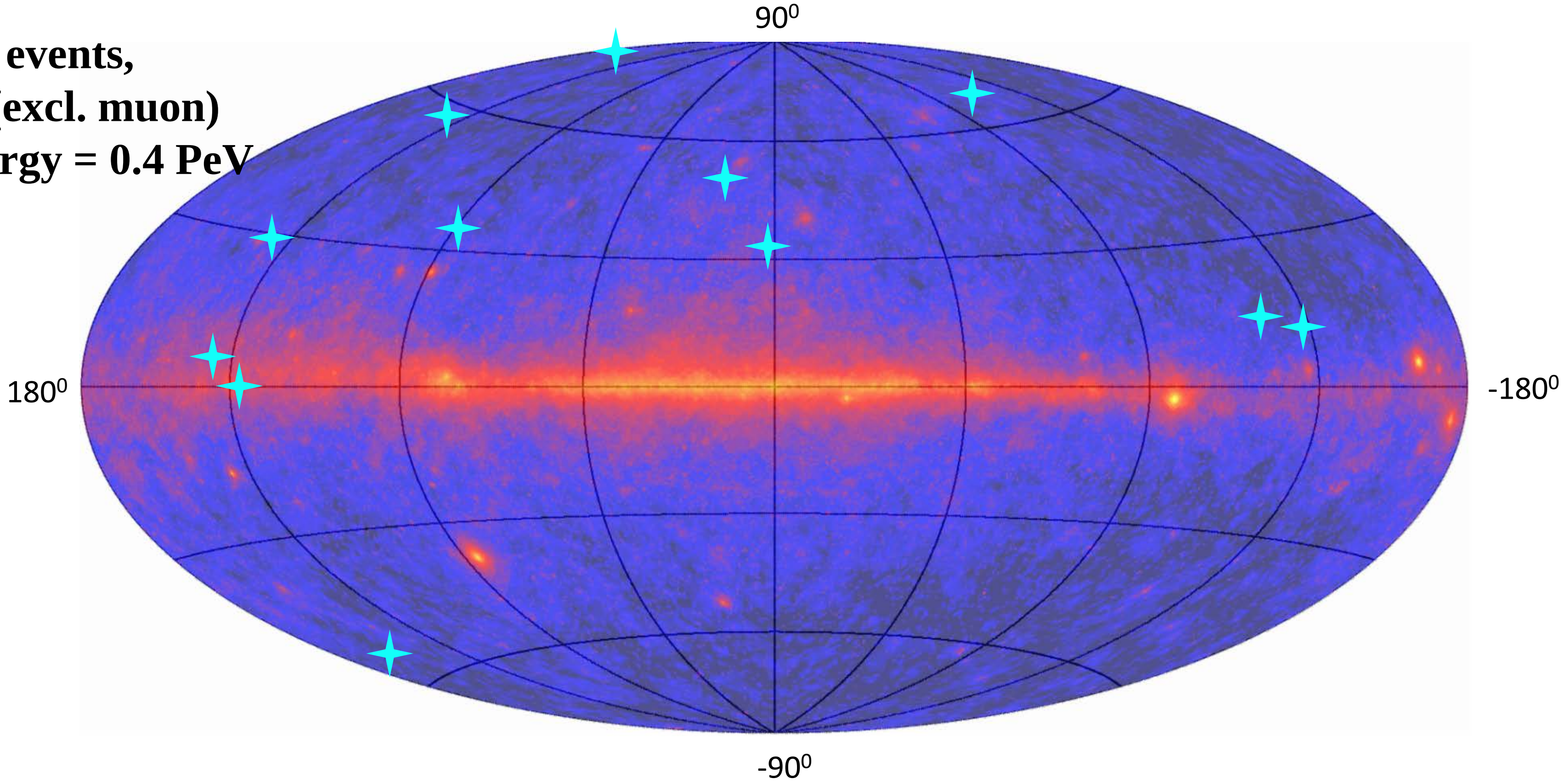
7 clusters – each of them with 288 OMs arranged at eight vertical strings

Now: effective volume for high energy cascade events about 0.35 km³

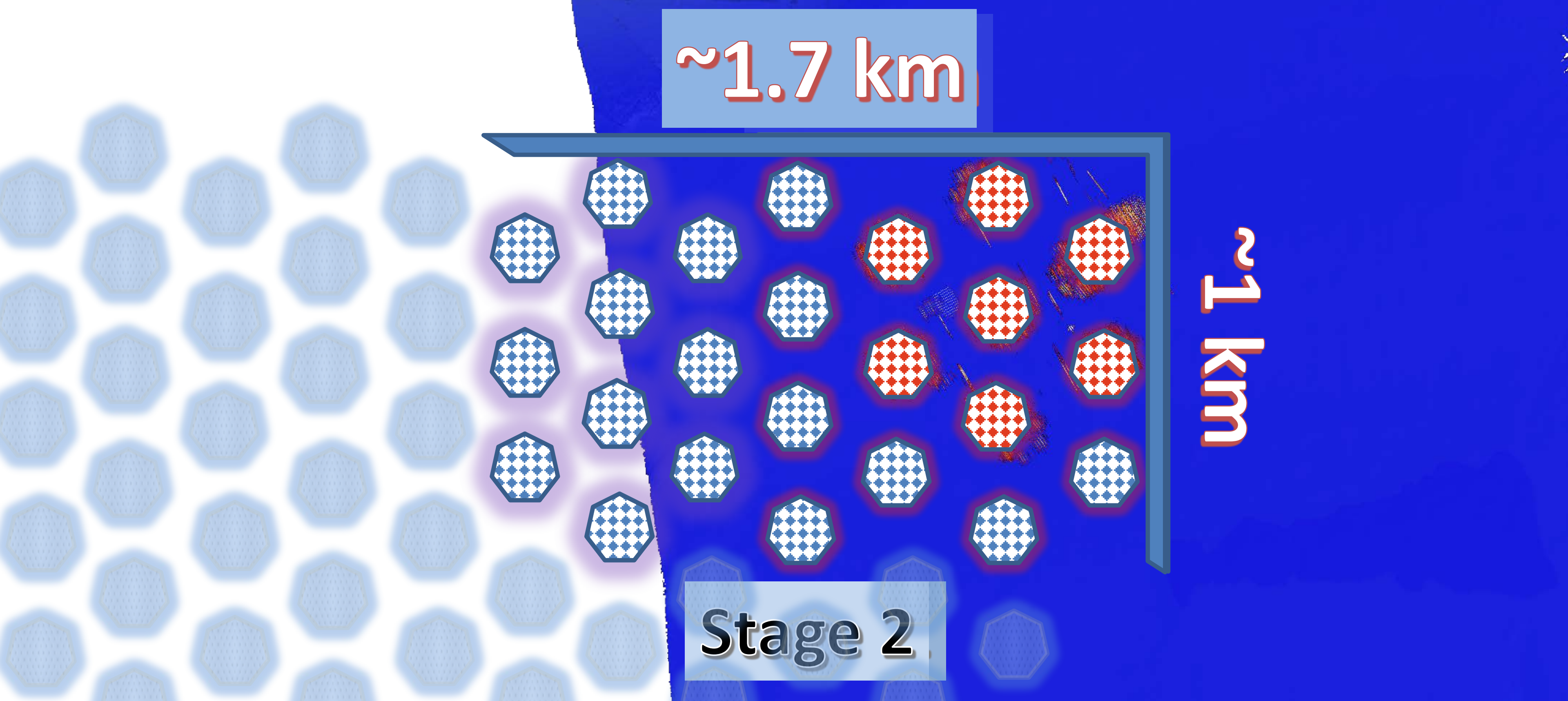


Baikal-GVD 2016,2018,2019 cascade events >100 TeV

12 events,
NC, CC (excl. muon)
Max. energy = 0.4 PeV



Status Baikal-GVD 2020



1) Comprehensive scientific program reflecting name of the theme “Non-accelerator neutrino physics and astrophysics”

2) Participation in world leading experiments

3) Brings modern know-how and culture of experiment for “home” projects;

4)Creation of infrastructure at JINR to ensure current and future projects at a modern level;

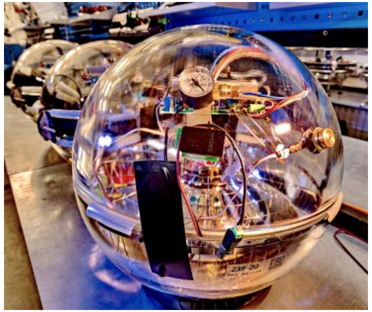
5) In average 25 publications per year (plus many conference proceedings, preprints, etc).

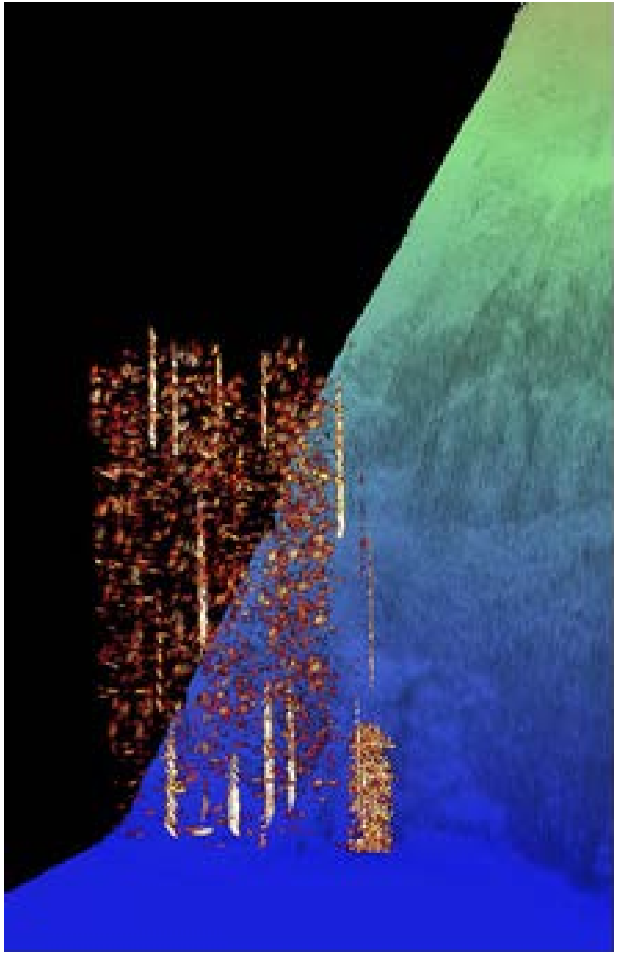
We would like to ask the Programme Advisory Committee to support our researches conducted in frame of the theme and to support continuation of all individual projects BAIKAL-GVD, DANSS, EDELWEISS-RICOCHET, GERDA (LEGEND), MONUMENT, νGeN (GEMMA) and SuperNEMO

№№	Activities	Total cost	Costs per years (thousand USD)		
			1st year	2nd year	3rd year
1.	Project GERDA (Legend)	**737**	259	219	259
2.	Project SuperNEMO	**436**	322	57	57
3.	Project EDELWEISS (Ricochet)	**411**	162	122	127
4.	Project DANSS	**716**	252	227	237
5.	Project νGeN	**467**	189	54	224
6.	Project BAIKAL-GVD	**21000**	7000	7000	7000
7.	Project MONUMENT	**318**	133	65	120
8.	Activity: Investigation of 2K2ν and 2K0ν decays of 106Cd with the TGV spectrometer	**45**	15	15	15
9.	Activity: Investigation of spectra of low-energy electrons after radioactive decays to obtain data for atomic and nuclear physics and for nuclear medicine. Investigation of decays of rear-earth radionuclides and structure of their excited states	**60**	20	20	20
10.	Activity: Radiochemical support of irradiation of targets, separation of radionuclides from them by radiochemistry and mass separation methods, preparation of ionizing radiation sources for physical research at DLNP; chemical, radiochemical and mass separator support of low-background measurements for neutrino physics	**60**	20	20	20
11.	Development of methods for the separation of elements (radiochemistry and mass separation); development of methods for obtaining radioisotopes for nuclear medicine and the synthesis of radiopharmaceuticals based on them; development and manufacture of micro sources for cancer brachytherapy; study of thephysicochemical properties of condensed matter using the method of perturbed angular correlations of nuclear radiation	**100**	50	30	20
12.	Development and production of low-energy-threshold HPGe detectors. Development and production of special types of Si and Ge detectors for low background measurements. Development and production of plastic scintillators for low-background spectrometers, neutron detectors, and cosmic muon detection.	**110**	30	50	30
	Total	**24460**	**8452**	**7879**	**8129**

2016	2017	2018	2019	2020
1 cluster	**2 clusters**	**3 clusters**	**5 clusters**	**7 clusters**

2021	2022	2023
8-9 clusters	10 clusters	12 clusters





From JINR Seven-Year Plan 2017-2023

Financing schedule for the BAIKAL-GVD project for 2017–2023 (k$)

	2017	2018	2019	2020	2021	2022	2023	Total
PMTs Hamamatsu R7081-100	2 100.0	2 100.0	2 100.0	2 100.0	2 100.0	2 100.0	2 100.0	**14 700.0**
Glass pressure holdings with connectors	1 000.0	1 000.0	1 000.0	1 000.0	1 000.0	1 000.0	1 000.0	**7 000.0**
Electronics and computing	1 100.0	1 250.0	1 400.0	1 400.0	1 400.0	1 400.0	1 400.0	**9 350.0**
Underwater connection cables	500.0	500.0	700.0	700.0	700.0	700.0	700.0	**4 500.0**
Infrastructure and transport (shore computer center, labs, living buildings, vehicles for winter work)	800.0	800.0	800.0	800.0	800.0	800.0	800.0	**5 600.0**
Total	**5 500.0**	**5 650.0**	**6 000.0**	**6 000.0**	**6 000.0**	**6 000.0**	**6 000.0**	**41 150.0**

From the current BAIKAL-GVD project (upgraded numbers based on real spending during first years)

Form № 29

Estimate of expenditures for the project BAIKAL-GVD, Deep underwater muon and neutrino detector on Lake Baikal

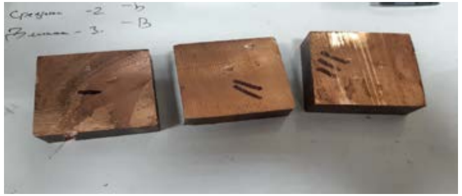
#	Designation for outlays	Full cost	1st year	2nd year	3rd year
	Direct expenses for the project				
1.	Networking	30.0K US$	10.0	10.0	10.0
2	DLNP workshop	3300 h.	1100	1100	1100
3.	JINR workshop	6000 h.	2000	2000	2000
4.	Materials	14280.0K US$	4760.0	4760.0	4760.0
5.	Equipment	6300.0K US$	2100.0	2100.0	2100.0
6.	R&D on a contract base	210.0K US$	70.0	70.0	70.0
7.	Travel expenses	180.0K US$	60.0	60.0	60.0
	Total	**21000.0K US$**	**7000.0K$**	**7000.0K$**	**7000.0K$**

Supplementary materials

Facilities

Photos of the clean room built in JINR for Se and Nd purification
On the right: Purifications of Se is in process

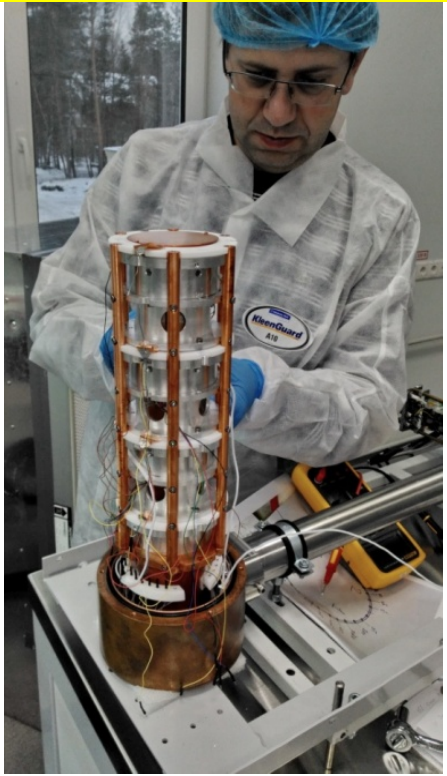
Low radioactive materials
Infrastructure at JINR for sample preparation and preliminary tests




Solder (60% of Sn and 40% of archPb – (Talanta 192)


Low radioactive Flux (JINST 15 (05), T05004)

Facilities for works/test/repair semiconductor detectors



Infrastructure at JINR for detector R&D and tests