Research in Non-accelerator neutrino physics and astrophysics and proposals for the Seven-Year Plan

Evgeny Yakushev

56th meeting of the PAC for Nuclear Physics

Dubna, 2023

The research theme: Non-accelerator neutrino physics and astrophysics

7 main projects:

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

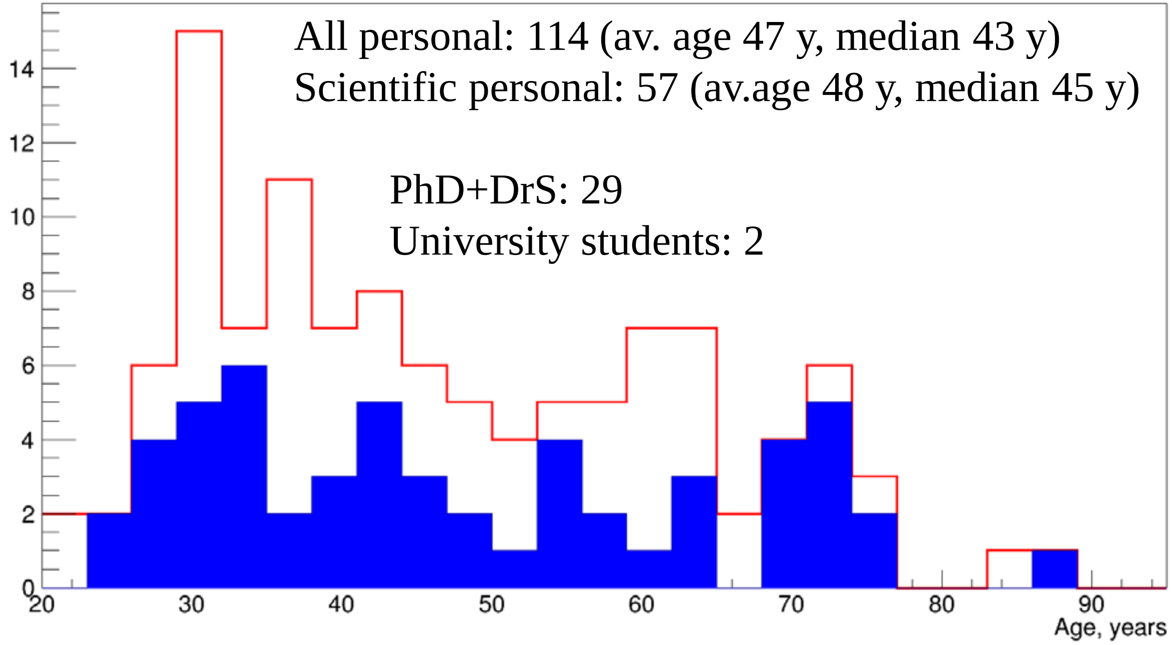
+ Activities

Partners: Azerbaijan, Bulgaria, Germany, Kazakhstan, Russia, Uzbekistan, Czech Republic, France, USA

Non-Accelerator Neutrino Physics and Astrophysics

Base: The Department of Nuclear Spectroscopy and Radiochemistry,
Dzhelepov Laboratory of Nuclear Problems

- 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, design generators for production of nuclear medical radionuclides [PET diagnostics, radiopharmaceuticals, etc];
- Investigation of hyperfine interactions using the method of perturbed angular correlations on probe nuclei in solid and liquid samples.

Places: JINR, Underground laboratories, Nuclear reactors, Lake Baikal

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.

In addition to the scientific personal involved in the theme, the following resources are available to carry out the scientific projects:

- the laboratory for the production and repair of semiconductor detectors

- laboratory for creation and production of scintillation materials for detectors

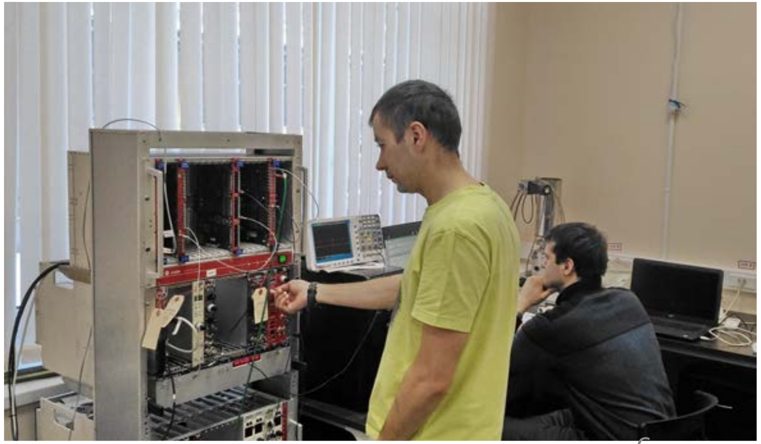
- radiochemical sector (creation of calibration radioactive sources, purification of materials designated for low-background measurements from their contamination by natural radioactivities, etc.)

- mechanical workshops

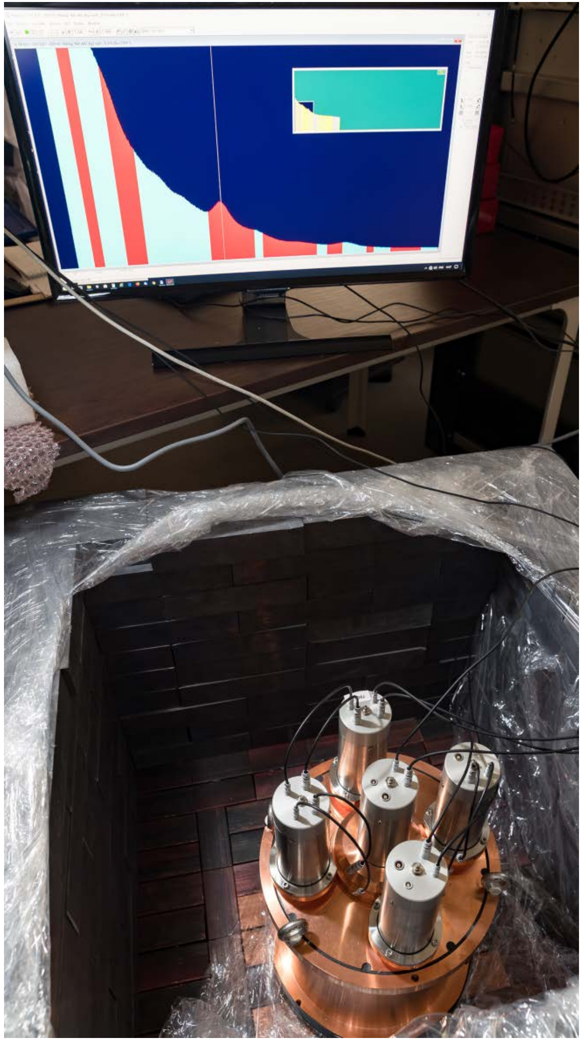
- a group of computer support

- a group of mass separators

Facilities for works/test/repair semiconductor detectors

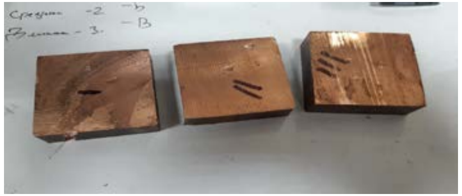


Infrastructure at JINR for detector R&D and tests



Low radioactive materials

Infrastructure at JINR for sample preparation and preliminary tests



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

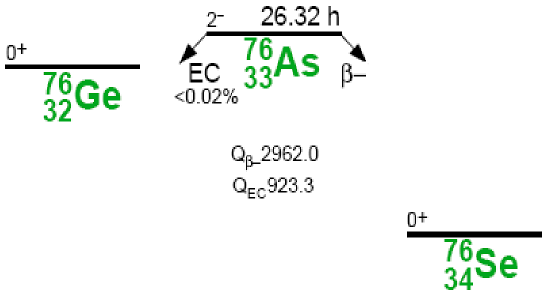
Low radioactive Flux (JINST 15 (05), T05004)

Radiochemistry clean rooms

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

We will be glad to have PAC members visit to our department

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

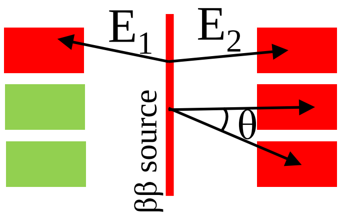
Method to study: nuclear spectrometry

Investigation 2β decay, search for 0ν2β

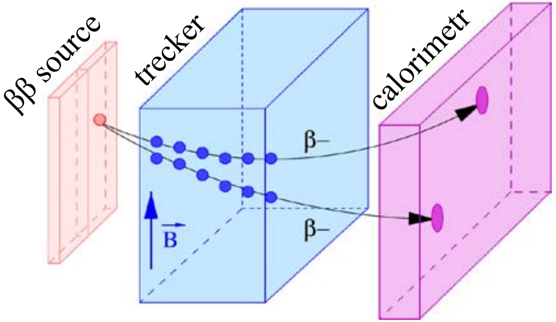
Two main approaches:

Track-calorimetric approach

Simple case



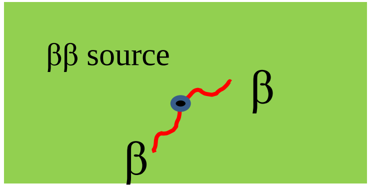
Improved experiment



- 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	$\mathbf{E_{0\nu2\beta}}$	**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



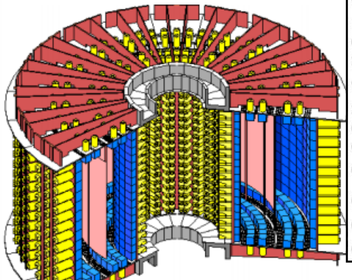
- Detector = source;
- Efficiency near 100%;
- Compactness = the possibility of highly effective application of additional active and passive methods of background control, minimization of the amount of materials used near the detectors (background reduction);
- Several detectors (or selection of a sensitive 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 (just started of data takin)

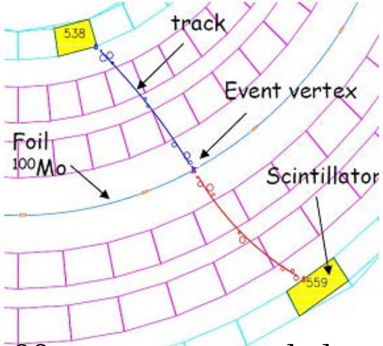
supernemo collaboration

$t_{1/2}(10^{21}$ 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	$0^+ \rightarrow 0^+_1$	Ge coinc.	14	BELLI	10
0.57	$^{+0.13}_{-0.09}$	±0.08	^{100}Mo	$0^+ \rightarrow 0^+_1$	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



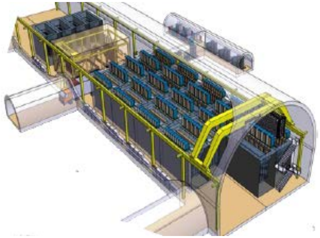
ββ event, as recorded by NEMO-3

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 :

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

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

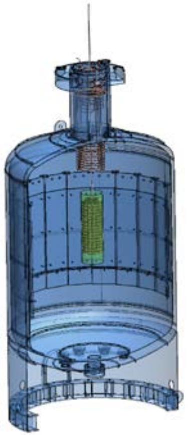
Demonstrator in the LSM

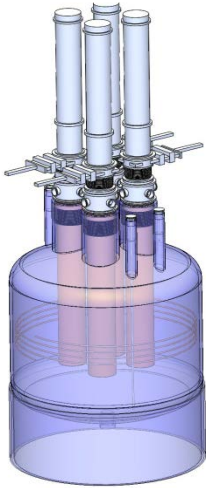
$0\nu\beta\beta$ search with HP^{76}Ge detectors immersed in liquid argon
GERDA – LEGEND

GERDA phase II	aim	result
Background	$\sim 10^{-3}$ 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	$\mathbf{T^{0\nu}_{1/2} > 1.8 \times 10^{26}}$ **yr**

LEGEND-200

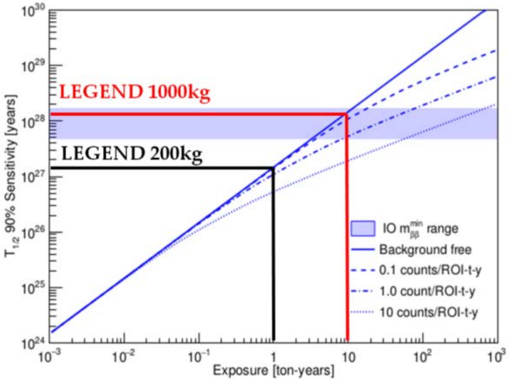
- ✓ First step to tone-scale ^{76}Ge exp.
- ✓ Improvements:
  - bigger mass of each of the detectors (in average)
  - improved LAr veto
  - less materials, new cables (less radioactive)
  - new electronics with lower noises
- ✓ Background improvement (estimate) : ~ x5 to GERDA
- ✓ 200 kg ^{76}Ge
- ✓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



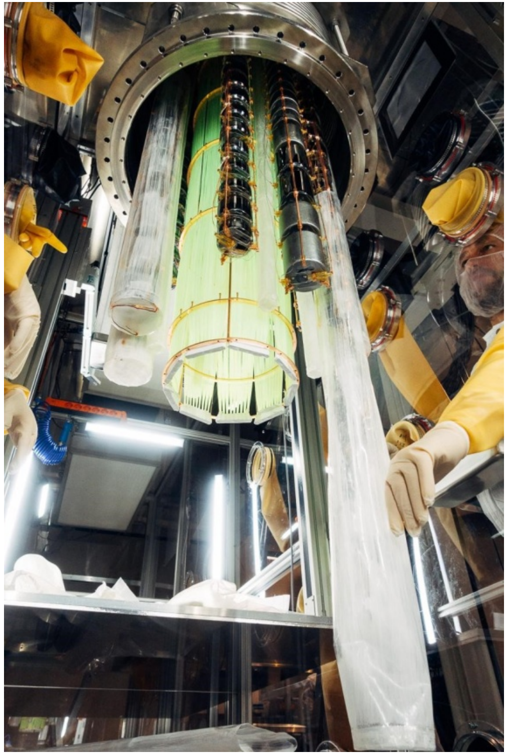


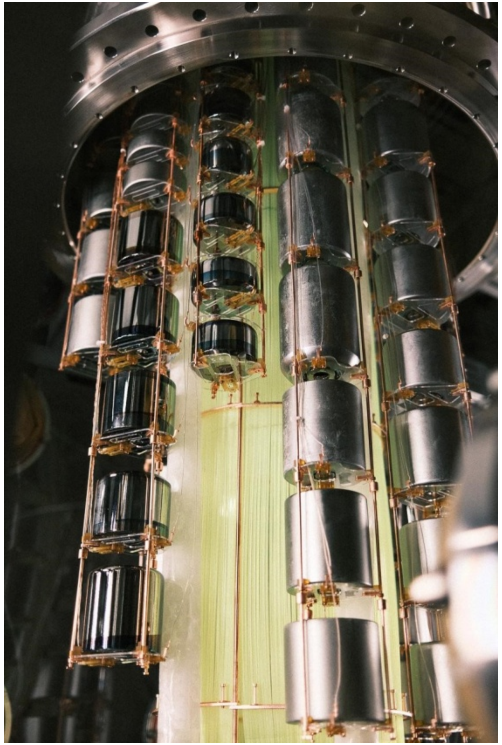
LEGEND-1000

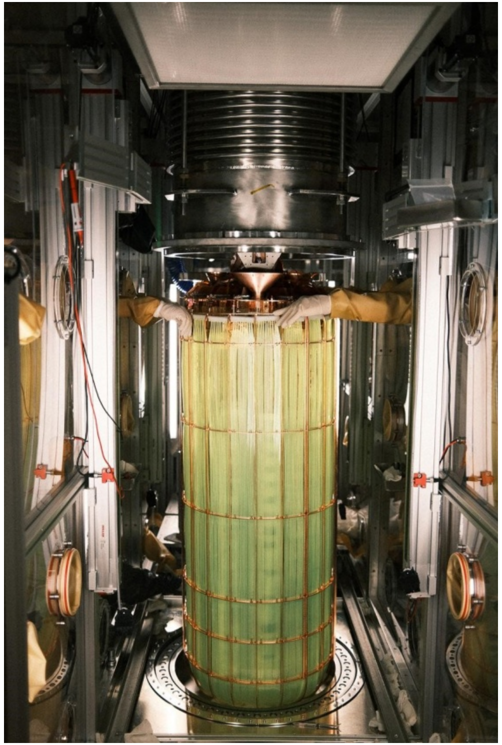
- ✓ New infrastructure and design (some developments for Majorana)
- ✓ Improvements based on LEGEND-200
- ✓ 1000 kg ^{76}Ge
- ✓ Target: $T_{1/2} \geq 10^{28}$ y



In the fall of 2022, the DLNP participated in the detectors installation. The active argon instrumentation system and all currently available Ge-76 detectors were re-installed. Now 101 germanium detectors are assembled in LEGEND and data collection has begun. The enriched Ge-76 isotope mass exceeded 100 kg for the first time. Now it is ~140 kg.







In 2023, when the remaining detectors are made, they will be added to the setup to reach the final Ge-76 mass of 200 kg. Then, after 5 years of data taking, the LEGEND-200 aims to reach the desired neutrinoless double beta decay sensitivity of 10^{27} years.

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

MONUMENT project (Measurement of ordinary muon capture (OMC) for verification of nuclear matrix elements of 2β-decays)

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.*

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

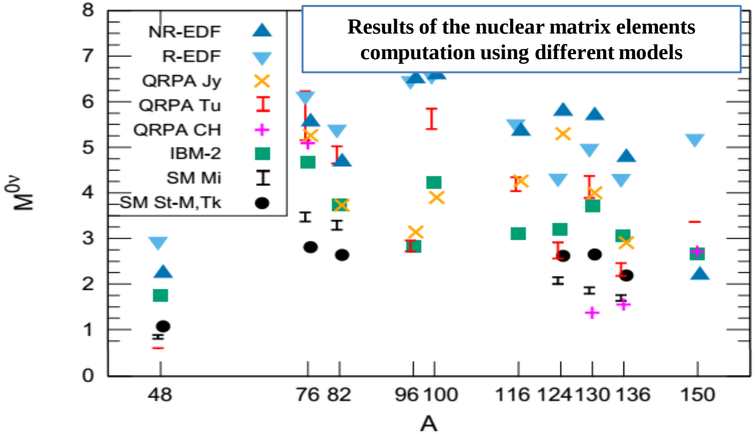
$\langle m_{\beta\beta}\rangle$ — Effective Majorana Mass

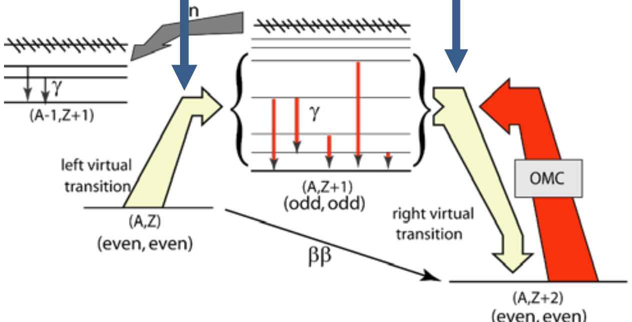
$M^{0\nu}$

Probability of the $0\nu\beta\beta$ process

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

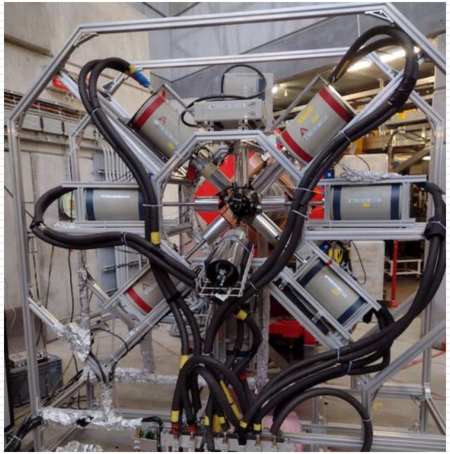
Nuclear Matrix Element (NME)

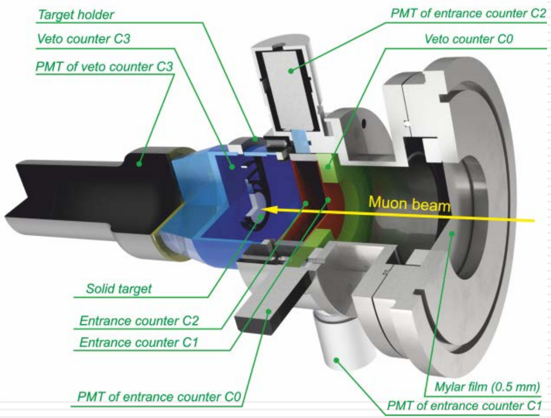


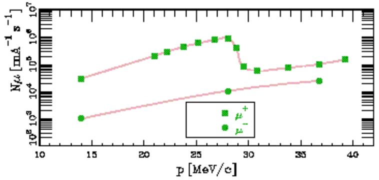


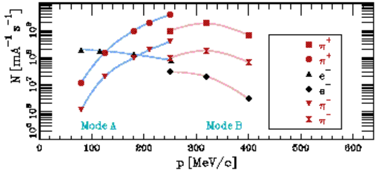
- In case of observed $0\nu\beta\beta$ decay the experimental results could help to improve NME calculations to define the effective Majorana neutrino mass
- **Right virtual transitions in DBD will be tested by Ordinary Muon Capture -> OMC and $0\nu\beta\beta$ operate in the q ≈ 100 MeV momentum-exchange region** – high-lying states will be populated
- **g_A – suppression probing -- via capture rates calculations**

Status of the MONUMENT project (2020-2022)









Purpose	OMC targets (enrichment)	Year/Status
experimental input for DBD NME calculations	^{76}Se (99.97%)	**2021** / analysis and publication
experimental input for DBD NME calculations	^{136}Ba (95.27%)	**2021** / analysis and publication
experimental input for astrophysics investigations with SN	^{100}Mo (97.3%)	**2022** / started data analysis
Nuclear spectroscopy, total cap. rates, yields	^{nat}Mo	**2022** / started data analysis
experimental input for DBD NME calculations	^{96}Mo (exp. 95.3%)	**2023** / in production
testing nuclear shell model (SM) calculations	^{56}Fe (exp. 99.9%)	**2023** / in preparation

➢ **OMC is the sensitive tool to probe properties of DBD process.** It is based on mature experimental technique successfully developed during many years, which demonstrates satisfactory agreement between experimental and theoretical data;

➢ **The unique information obtained at OMC provide a significant experimental contribution to the nuclear spectroscopy**, which is very actual in the nowadays;

➢**It is planned to continue the intensive multi-year research program** (at PSI beamline).

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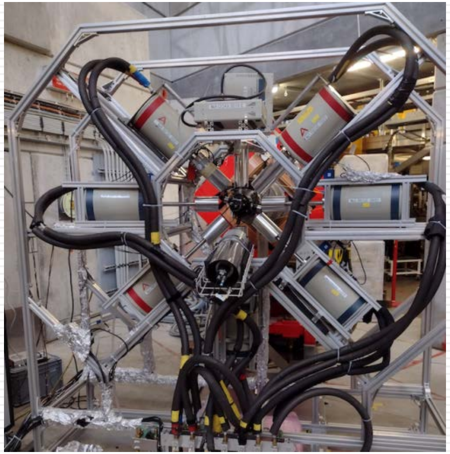

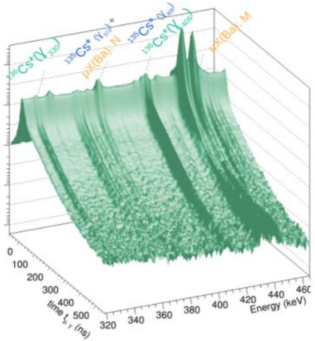

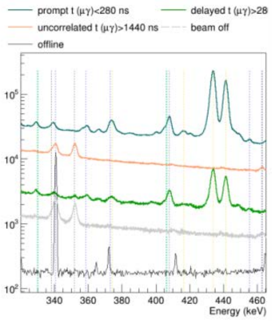

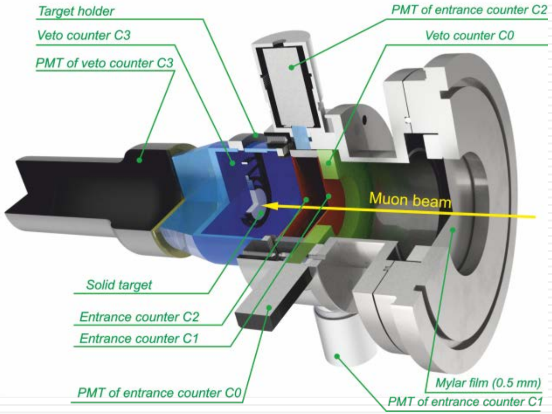

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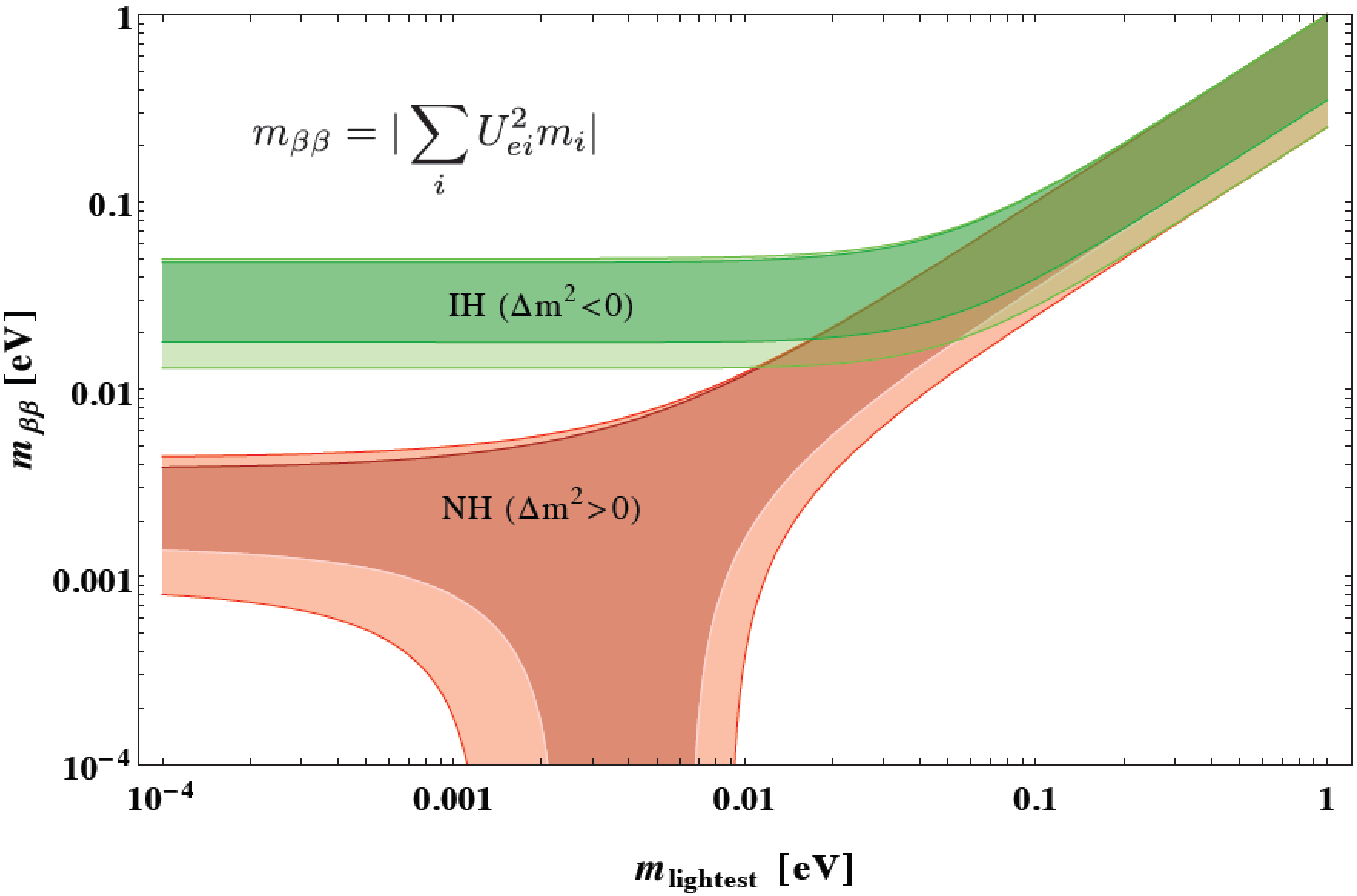


$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$
IH ($\Delta m^2 < 0$)
NH ($\Delta m^2 > 0$)
1
0.1
0.01
0.001
10^{-4}
10^{-4}
0.001
0.01
0.1
1
$m_{\beta\beta}$ [eV]
m_{lightest} [eV]

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

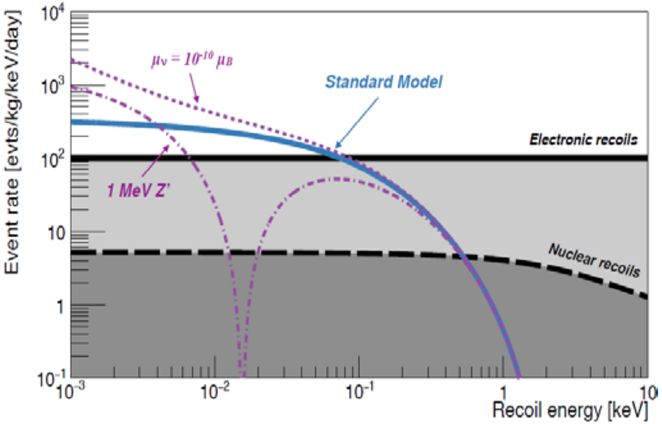
EDELWEISS: Direct search for Dark Matter, HPGe detectors at ~20 mK, low background environment in deep underground laboratory (LSM).

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

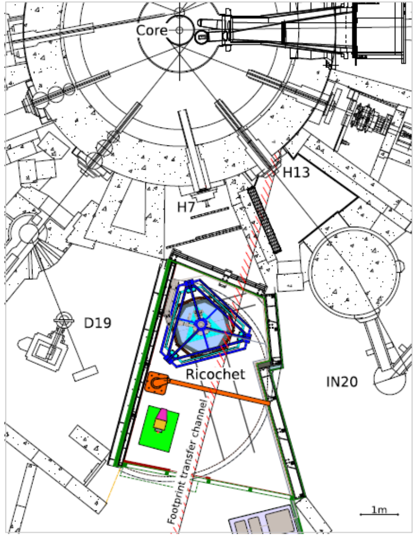
Thanks to the latest developments, the experiment remains competitive in the energy regions (low mass WIMPs, bosonic DM, etc, inaccessible to large Ar / Xe experiments.

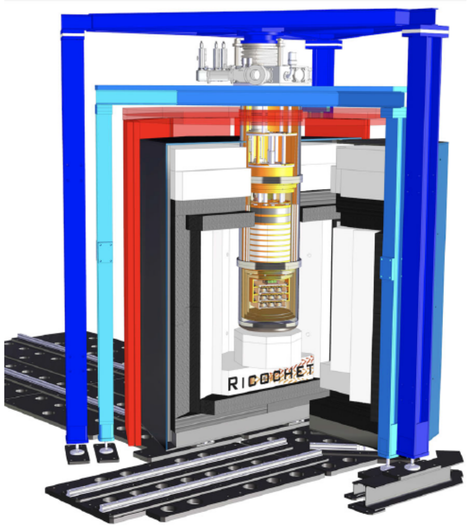
New detectors developed by EDELWEISS, have unique characteristics for detecting ultralow-energy nuclei recoils.

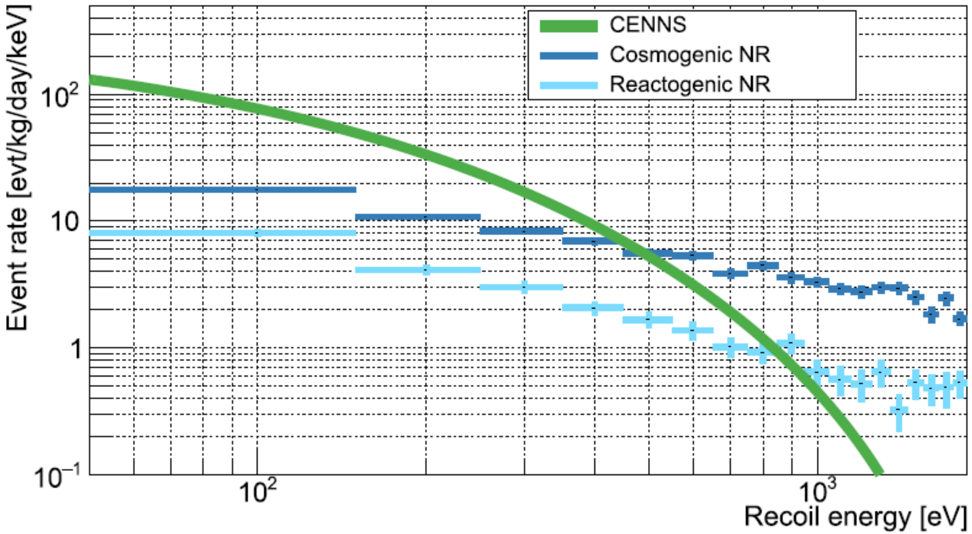
The same technology and detectors will be applied for precision measurements of CEνNS in the region of full coherency in the Ricochet experiment (reactor neutrinos). The main goal: precise (1% level) study of CEνNS, and target other New physics phenomena.



The experiment will deploy a kg-scale low-energy-threshold detector array combining Ge and Zn target crystals 8.8 m away from the 58MW research nuclear reactor core of the ILL



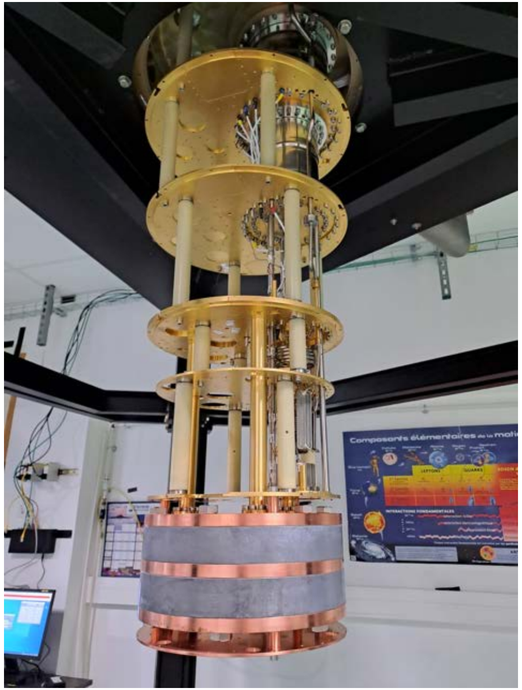


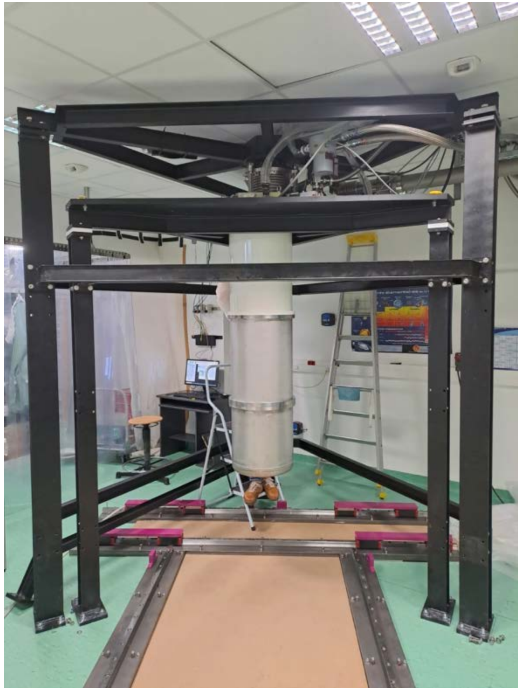


	Cosmogenic	Reactogenic	Total (MC)	CENNS (Ge/Zn)
Nuclear recoils [50 eV, 1 keV] (evts/day/kg)				
No shielding (I)	1554 ± 12	53853 ± 544	55407 ± 545	–
Passive shielding (II)	42 ± 3	2.4 ± 0.3	44 ± 3	–
Passive + μ-veto (III)	7 ± 2		9 ± 2	12.8 / 11.2

The Ricochet experiment should reach a statistical significance of 4.6 to 13.6 σ for the detection of CENNS after one reactor cycle

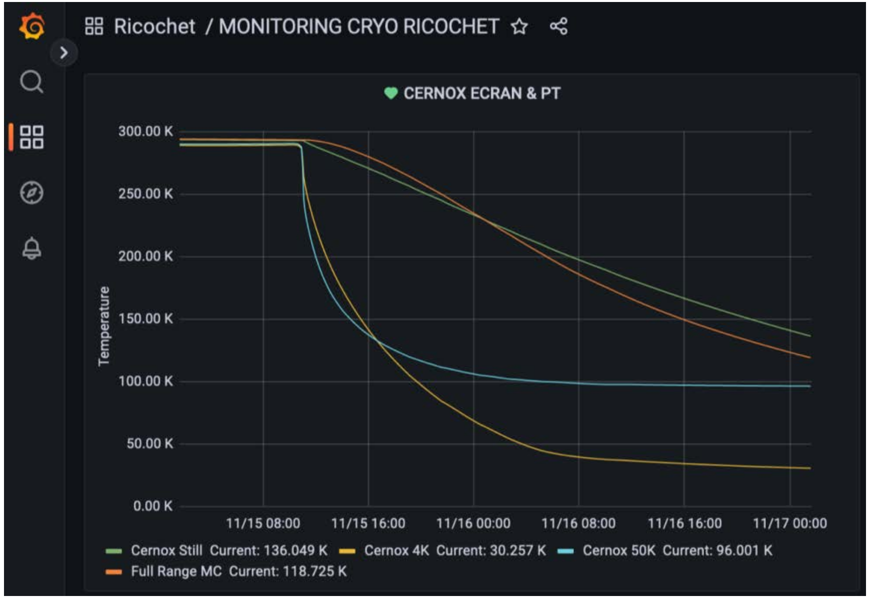
Dry, low-background, low-noise ^3He-^4He dilution cryostat produced in cooperation between JINR, IP2I and CryoConcept

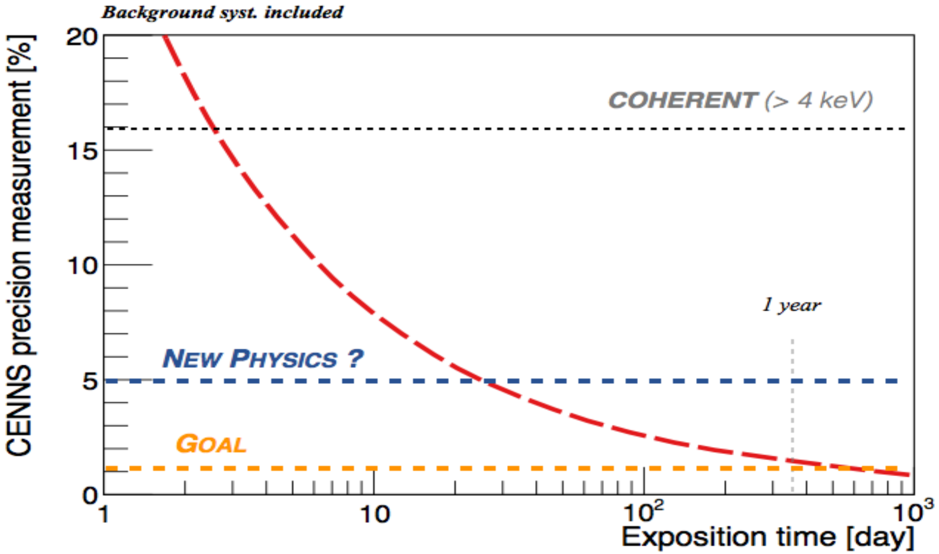




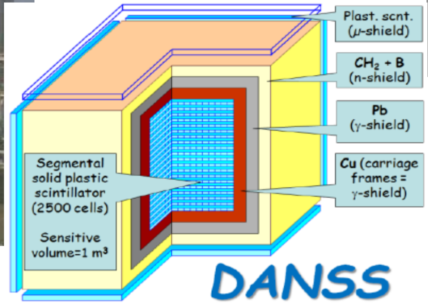
Our other involvement: muon veto, supplementary detectors, etc.

After some delay with the construction, the cryostat is now working and is ready to be installed at ILL !





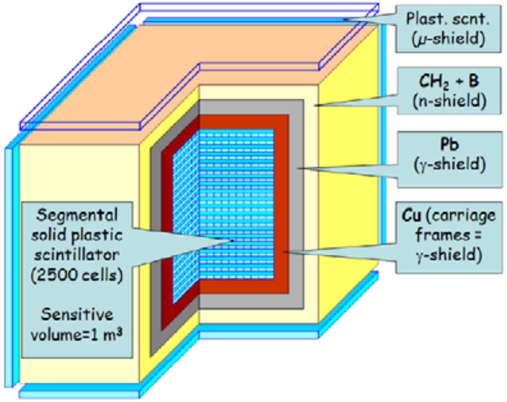
Our participation in experiments with world leading sensitivities to ultra-rare processes provides the solid base for home neutrino experiments



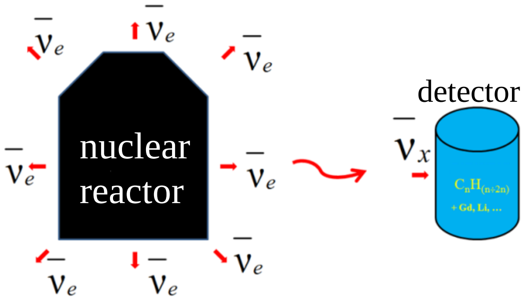
DANSS

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

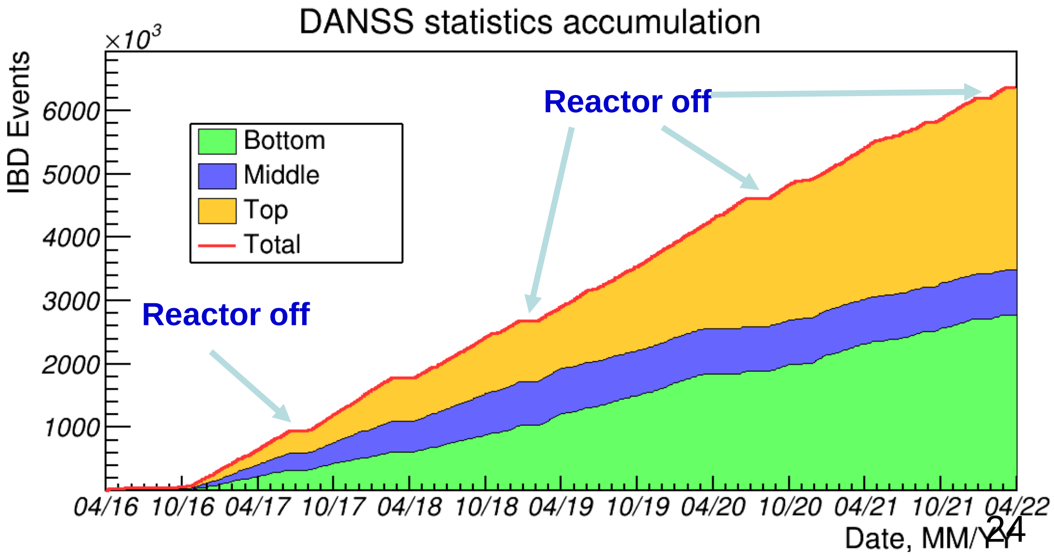
$$\bar{\nu}_e + p \rightarrow n + e^+$$



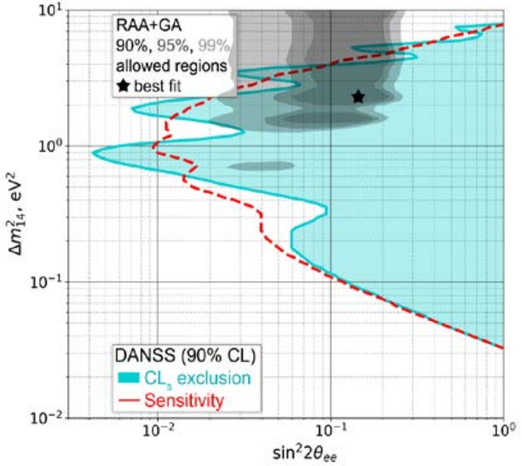
Compact (1 m^3) highly segmented (2500 plastic scintillator plates) neutrino spectrometer DANSS aims at searching for oscillations in sterile neutrinos, as well as monitoring with neutrinos the reactor power and the composition of nuclear fuel.



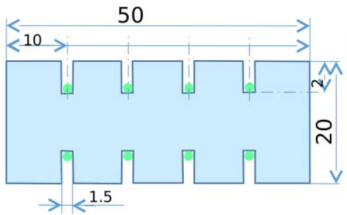
- DANSS is located under unit #4 KNPP (VVER-1000, 6 × 10^{20} $\bar{\nu}_e$ / sec);
- Shield from cosmic ~ 50 m.w.e.;
- Lifting platform: distance to reactor from 10.9 to 12.9 m;
- ~5000 events/day;
- World leading results between all reactor based experiments for sterile neutrino search;
- No indications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

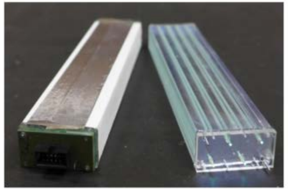


The most probable point of RAA is excluded at >5σ CL



New scintillator strips

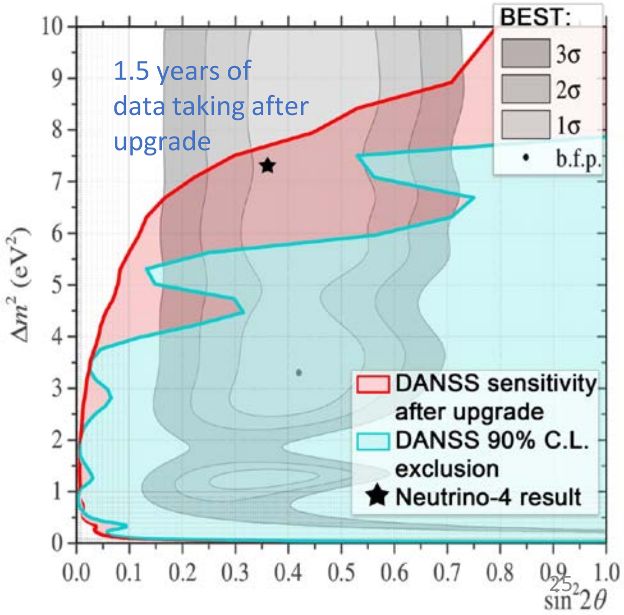




WLS fiber positions were optimized for better uniformity of response
New fast (4ns decay time) YS2 fiber will be used

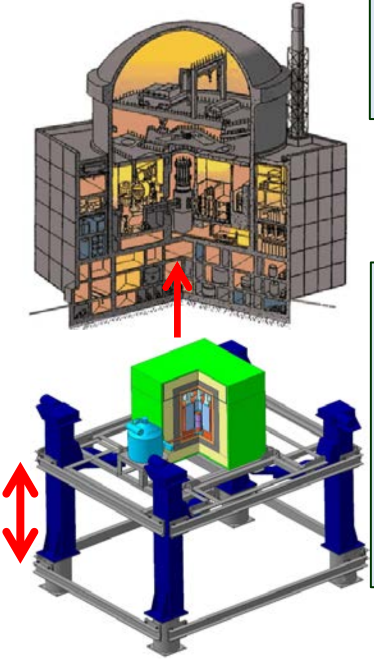
Upgrade to DANSS-2, the main goal is to reach the resolution **13%/√E** (now 34%/√E).

New geometry:
Strips: 2x5x120 cm,
2-side 4SiPM readout
Structure: 60 layers x 24 strips: 1.7 m^3
Setup uses <u>the same shielding and moving platform.</u>
Gd is in foils between layers.

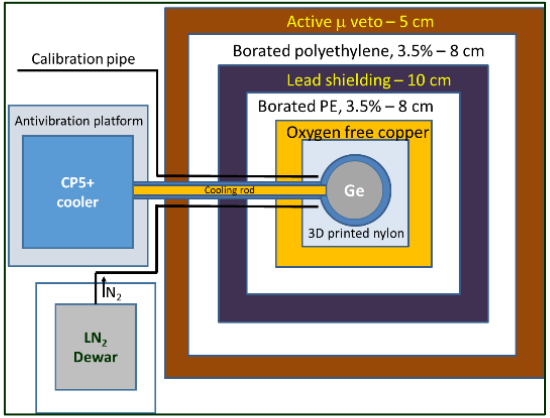


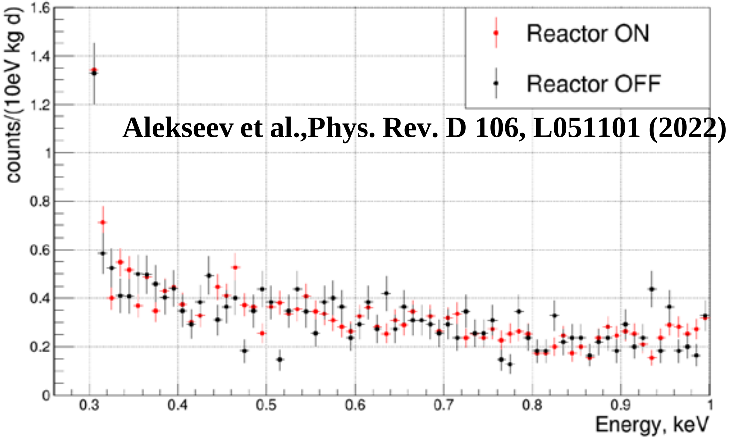
experiment at Kalinin nuclear power plant

- ✓ The νGeN project studies neutrino scattering at Kalinin Nuclear Power Plant (KNPP, Russia). Main interests: **coherent elastic neutrino-nucleus scattering** (**CEνNS**), the search for the **magnetic moment of neutrino (MMN)**, search for New Physics beyond the SM, and many other applications, including reactor monitoring.
- ✓ The experimental setup is constructed under reactor unit #3 of KNPP at a distance of **11.1-12.3 m** from the center of the **3.1 GW_{th}** core under enormous antineutrino flux **(4.4-3.6)×10^{13} ν/cm^2/s** at 50 m w.e. overburden.
- ✓ The low-threshold HP Ge detector with a mass of 1.4 kg is used to detect desired signals. The installation of setup started in 2019. Since that time we performed the data taking, several improvements were performed since that time.

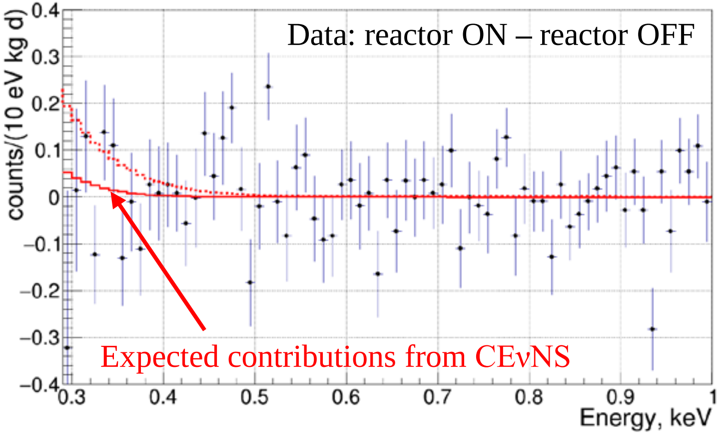


- ✓ The passive and active shielding covers detectors from all sides suppressing backgrounds.
- ✓ Active antivibration platform suppresses microphonic noises.
- ✓ Nitrogen flushing decrease background from radon.
- ✓ Movable platform (completed in 2022) allows to change the distance to the reactor, thus changing the ν flux.
- ✓ Special acquisition system was developed to suppress noise and achieve energy resolution of 101.6(5) eV (FWHM).





- ✓ No significant difference between regimes with reactor ON and OFF has been observed in first data taken in 2021. The new limit on the quenching parameter in germanium has been obtained (**k<0.26**).
- ✓ In 2021-2023 we continued data taking, until 2023 we accumulated raw data: reactor ON **928 kgd**, OFF: **175 kgd**. Similar statistics with improved threshold and background level at low energy suggests that we already reached a better sensitivity for the magnetic moment of neutrino than GEMMA collaboration (set up the current world best limit for MMN).
- ✓ The new measurements at a closer distance from the reactor (11.1 m instead of 12.2 m) with higher flux started in September 2022.
- ✓ New results with more statistics and optimized measurement modes are expected soon. Search for evidence of other effects in data are ongoing.



First results on CEνNS by νGeN

	Days	Counts per kgd
Reactor on	**94.50**	**2.32 ± 0.15**
Reactor off	**47.09**	**2.34 ± 0.21**
On-off	**-**	**< 0.4 (90% CL)**
CEνNS (expect)	**-**	**~ 0.058-0.66**

- ✓ The experiment mostly performed by JINR, more manpower needed.
- ✓ In 2022 the νGeN collaboration were extended by groups from CTU (Prague, Czech Republic) and LPI RAS (Moscow, Russia).
- ✓ The internal shielding and new better detectors are planned to be used to improve sensitivity of experiment.

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.

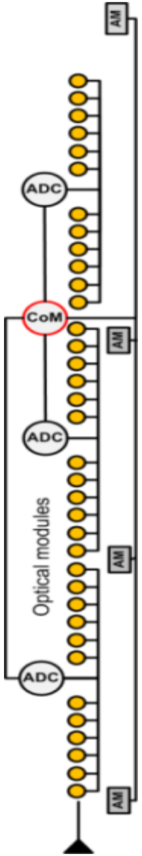
Now – building BAIKAL-GVD (**Gigaton Volume Detector)** has huge progress and will be continued

Physics:

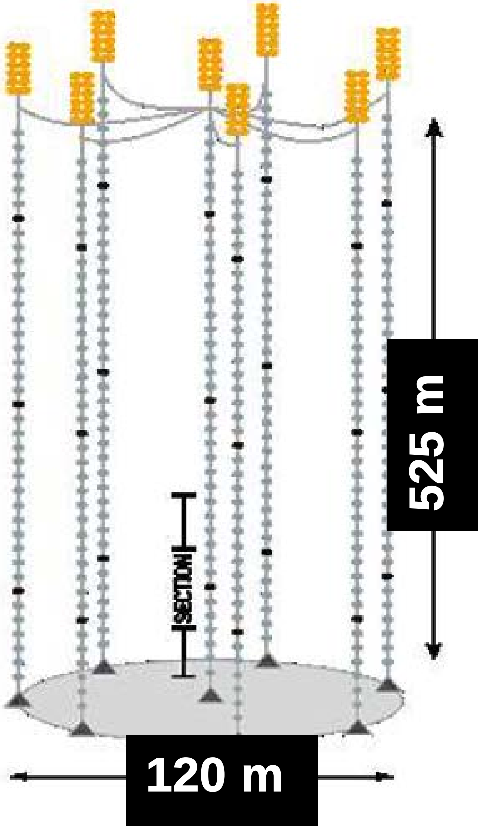
- Investigate Galactic and extragalactic neutrino “point sources”;
- Diffuse neutrino flux – energy spectrum, local and global anisotropy, flavor content;
- Indirect search for Dark Matter;
- Exotic particles – monopoles, Q-balls, nuclearites, …

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

Our staff is also important force to install the modules, commissioning, running, data taking and final analysis



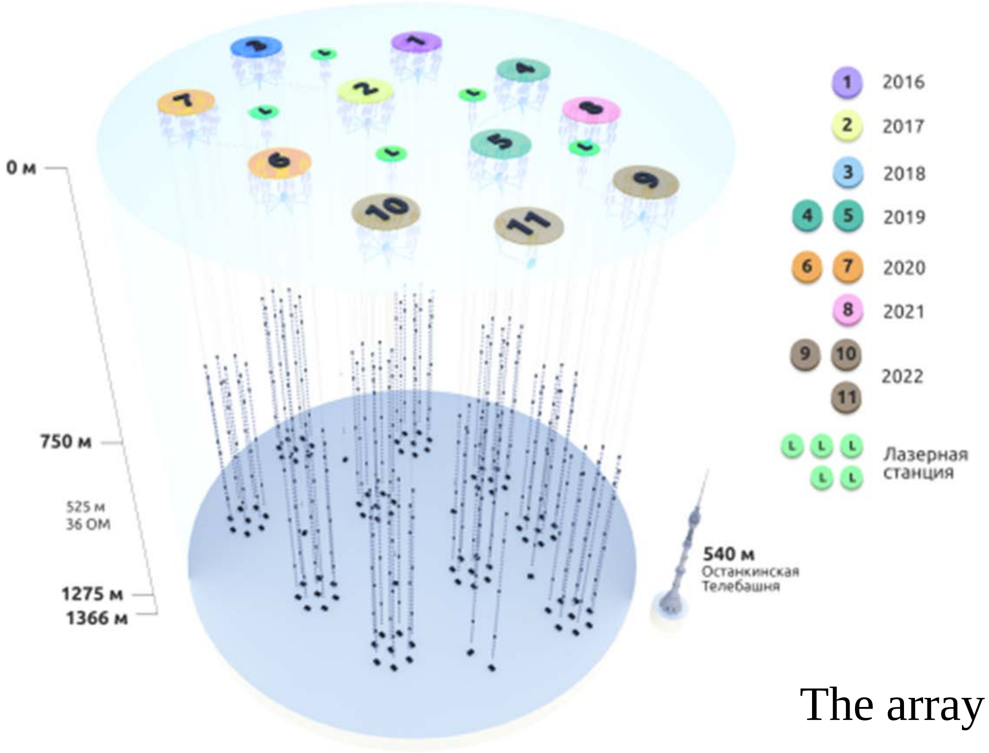
String: 36 OMs



Cluster: 8 strings

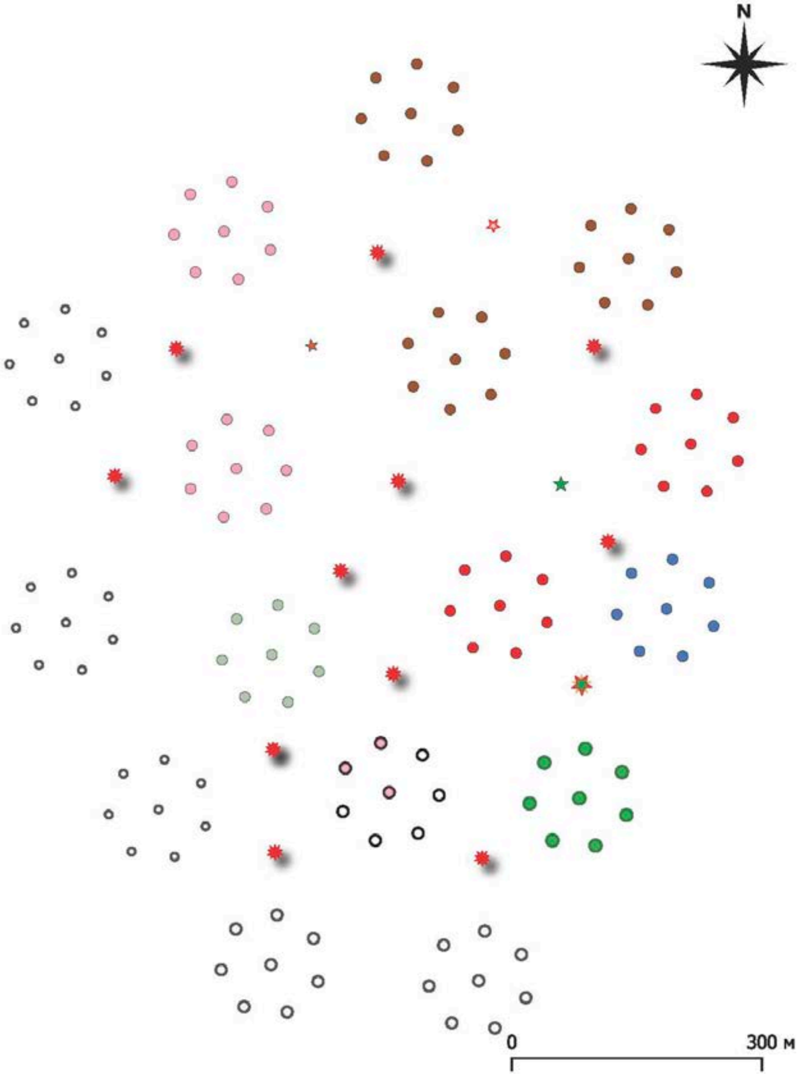
Baikal-GVD construction status

Status 2022: 10 clusters, 5 laser stations, experimental cluster prototype with new DAQ system



- About 700 optical modules are assembled for deployment in 2023.
- The collaboration is planning to install additional 2 new clusters in case a good external conditions (weather and ice).

The array contains 2916 optical modules.



Deployment schedule

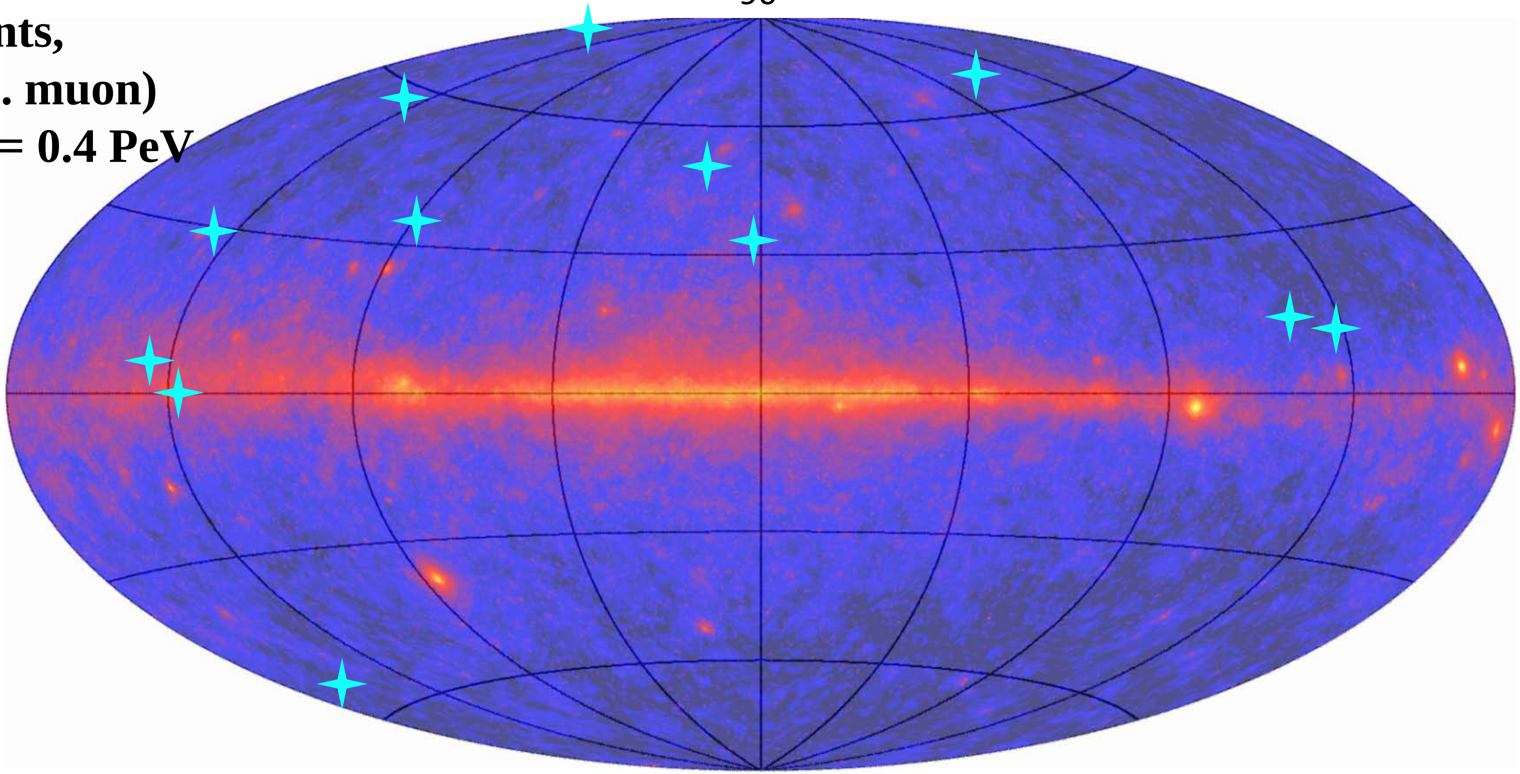
Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2916
2023	12	3564
2024	14	4212
2025	16	4860

Some Baikal-GVD cascade events >100 TeV

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

90^0

180^0



-180^0

-90^0

To improve the efficiency and to reflect real involvement of personal and resources we propose to reorganize the structure of the theme.

If supported, the new structure will have 4 main projects:

- **BAIKAL-GVD**

- **A short baseline reactor neutrino investigation (Ricochet, DANSS-2 and νGeN experiments)**

- **Nuclear spectrometry for search and investigation of rare phenomena (all double beta decay related experiments and activities, search for Dark Matter by nuclear spectrometry methods, etc)**

- **Radiochemistry plus spectroscopy for astrophysics and nuclear medicine**

Radiochemistry plus spectroscopy for astrophysics and nuclear medicine

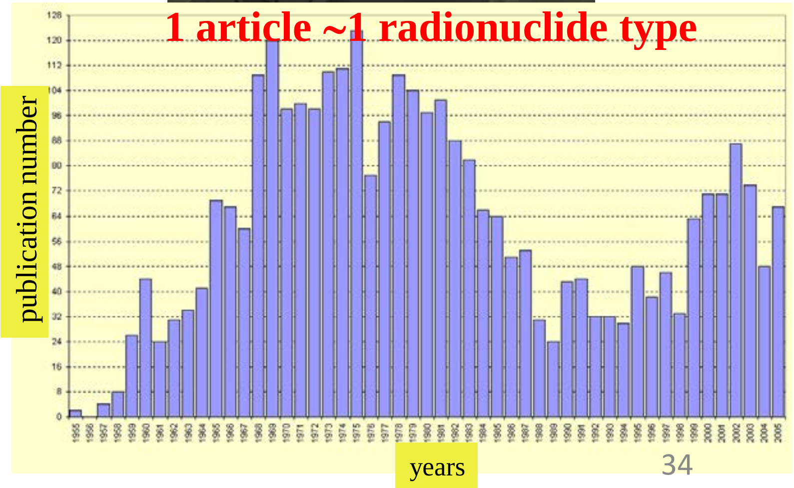
Huge accumulated experience since 1950: radiochemistry and spectroscopy / target irradiated on the DLNP Phasotron

- **The radiochemical experience in the production of radionuclides of almost all elements for spectroscopy + the sources preparation**

- **In cooperation with foreign colleagues, production methods of the most important radiopharmaceuticals for nuclear medicine were developed: ^{177}Lu, ^{90}Y, ^{211}At, etc.**

- **In recent years, the development of the production methods of the relevant radiopharmaceuticals for nuclear medicine has also continued. It can be highlighted: production method of ^{68}Ga radiopharmaceuticals for PET diagnostics from the $^{68}Ge \to {}^{68}Ga$ generator, the reverse-tandem scheme of the $^{44}Ti \to {}^{44}Sc$ generator, the development of the production methods of ^{225}Ac, etc.**

- **Low-background samples for research in the field of neutrino physics and the search for Dark Matter particles has been actively developed. For example, in order to search of $0\nu2\beta$, ^{82}Se purification was carried out and kilogram quantities of the elemental highly dispersed form with a unique low content of radioactive impurities were produced.**



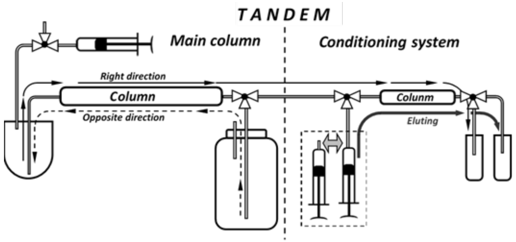
- *Study of sorption processes for various solution-sorbent systems as a chemical basis for methods of purification and analysis of low-background materials.*

- *Development of radionuclides production and analysis methods for various nuclear spectrometric and chemical tasks, including calibrations of low-background installations and various spectroscopic R&D. It is planned to create about 30 (50) generators with long-lived radionuclides using reverse-tandem schemes.*

- *Development of low-background samples production methods (^{82}Se, ^{96}Zr, shielding materials, solder, etc.) for astrophysical problems at a new ultra-low level of impurity content (μBq/kg for Th and U) through the use of countercurrent chromatography, low-boiling and other prepared or selected reagents, as well as selected and prepared reactor materials.*

- *Development of low-background samples analysis methods at an ultra-low sensitivity level (μBq/kg for Th and U) using ICP-MS and neutron activation analysis. To achieve this sensitivity level it is necessary to develop methods of the preliminary chemical concentration (separation) of impurities from materials.*

- **$^{172}Hf \rightarrow ^{172}Lu$**
- **$^{44}Ti \rightarrow ^{44}Sc$**
- **$^{32}Si \rightarrow ^{32}P$**
- **$^{60}Fe \rightarrow ^{60m}Co$**
- **$^{90}Sr \rightarrow ^{90}Y$**
- **$^{125}Sb \rightarrow ^{125m}Te$**
- **$^{137}Cs \rightarrow ^{137m}Ba$**
- **$^{194}Hg \rightarrow ^{194}Au$**
- **$^{243}Am \rightarrow ^{239}Np$**
- **Etc.**



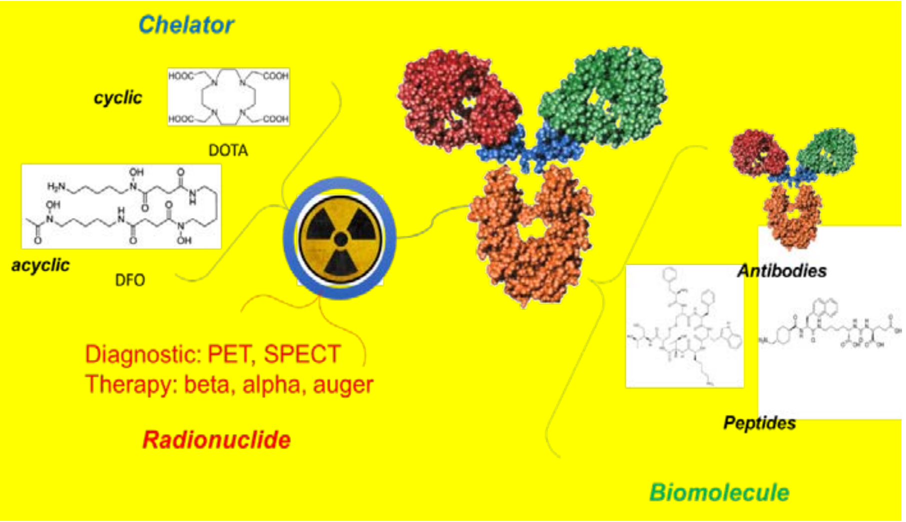
- *Study of sorption processes for various solution-sorbent systems as a chemical basis for methods of radiopreparations purification and radionuclide generators design for the radiopharmaceuticals production.*

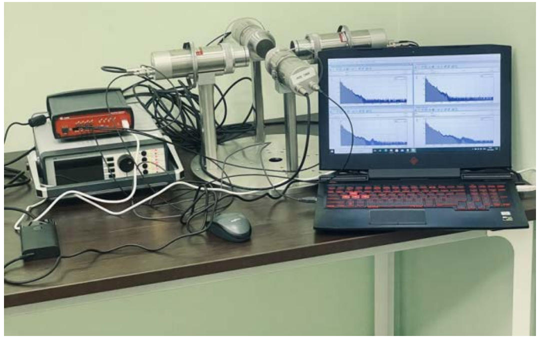
- *Development of methods of the radionuclides production and isolation from targets irradiated with protons, neutrons and gamma-rays (bremsstrahlung) for the radiopharmaceuticals production.*

- *To expand the nuclear medical radionuclides production possibilities, the development of a wide range of radionuclide generators ($^{44}Ti \rightarrow {}^{44}Sc$, $^{68}Ge \rightarrow {}^{68}Ga$, $^{90}Sr \rightarrow {}^{90}Y$, $^{238}U \rightarrow {}^{234}Th$, $^{237}Np \rightarrow {}^{233}Pa$, $^{229}Th \rightarrow {}^{225}Ac$, $^{227}Ac \rightarrow {}^{227}Th \rightarrow {}^{223}Ra$, $^{202}Pb \rightarrow {}^{202}Tl$, $^{194}Hg \rightarrow {}^{194}Au$, $^{32}Si \rightarrow {}^{32}P$, etc.) based on the reverse-tandem methods will continue. The 1-2 generators design possibility of significant activity for external users will be considered.*

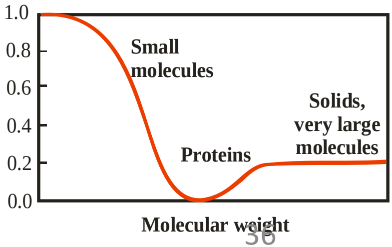
- *Development of methods for labeling radiopharmaceuticals with radionuclides.*

- *Application of nuclear spectrometric and radiochemical methods for the modern radiopharmaceuticals and their precursors study. The Perturbed Angular Correlation (PAC) method of Mössbauer spectroscopy will be used. It is also supposed to use electrophoresis methods in free electrolyte to determine the kinetic and thermodynamic constants of radiopharmaceuticals with radionuclides.*





Integral factor PAC



Summary of the major aims for new seven years plan:

• DANSS experiment: Checking the extended region of the phase space of oscillations into a sterile neutrino with reaching the signal region of the NEUTRINO-4 experiment; precision measurement of the spectrum of reactor antineutrinos; measuring the evolution of nuclear fuel.

• RICOCHET experiment: New physics with precision measurements of CEνNS at reactors.

• νGeN: Observation of coherent elastic neutrino-nuclear scattering with antineutrino from reactor, search for magnetic moment of neutrino up to the world leading levels.

• LEGEND: achievement the discovery sensitivity for neutrinoless double-beta decay at 10^{28} years.

• BAIKAL-GVD: Observation of ultra-high energy astrophysical neutrinos; identification of their sources and nature.

• Radiochemistry plus spectroscopy for astrophysics and nuclear medicine: Production and analysis methods of low background samples with purity level of μBq/kg for experiments of astrophysics and neutrino physics; production and analysis of novel radiopharmaceuticals; new types of radionuclide generators; investigation of new materials and mechanisms of local interactions of radioactive probe nuclei in substance.

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

- Participation in world leading experiments;

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

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

- 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

We propose to present the written projects for 2024-2028 yy during the next/summer 2023 PAC meeting

Only slides1-4, 10-31, 33, 34, 37, 38 will be shown during the PAC presentation

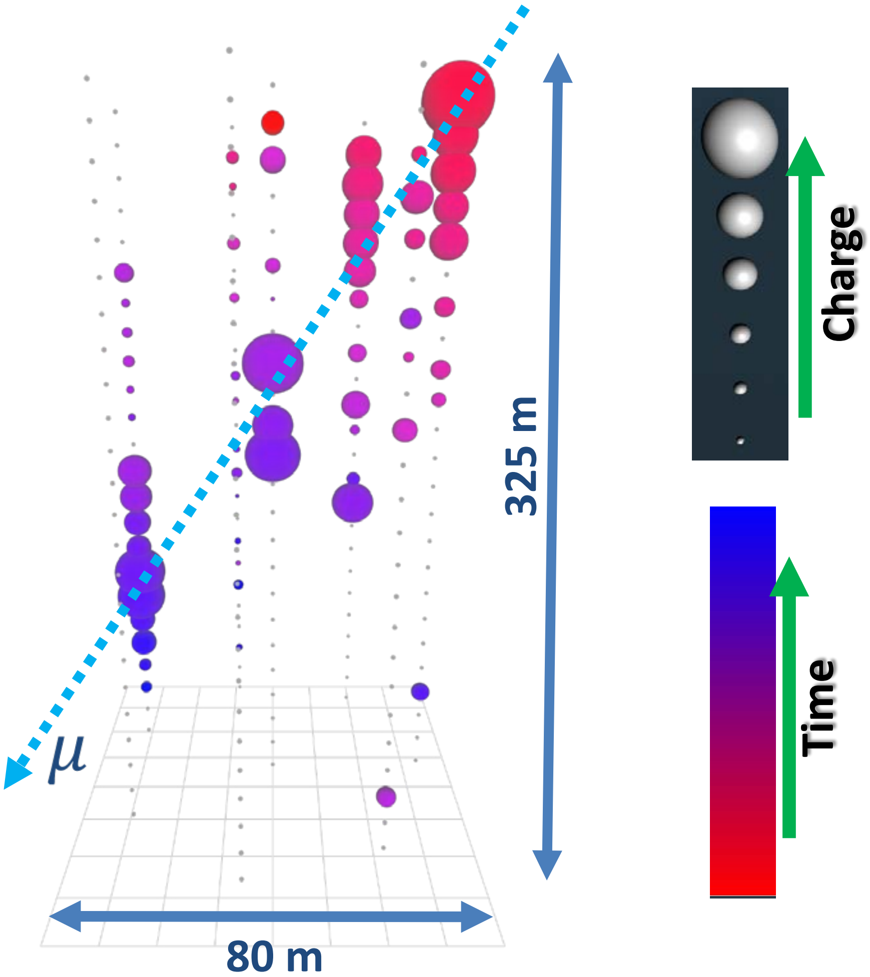
Additional slides

JINR
BAIKAL-GVD optical module assembly line

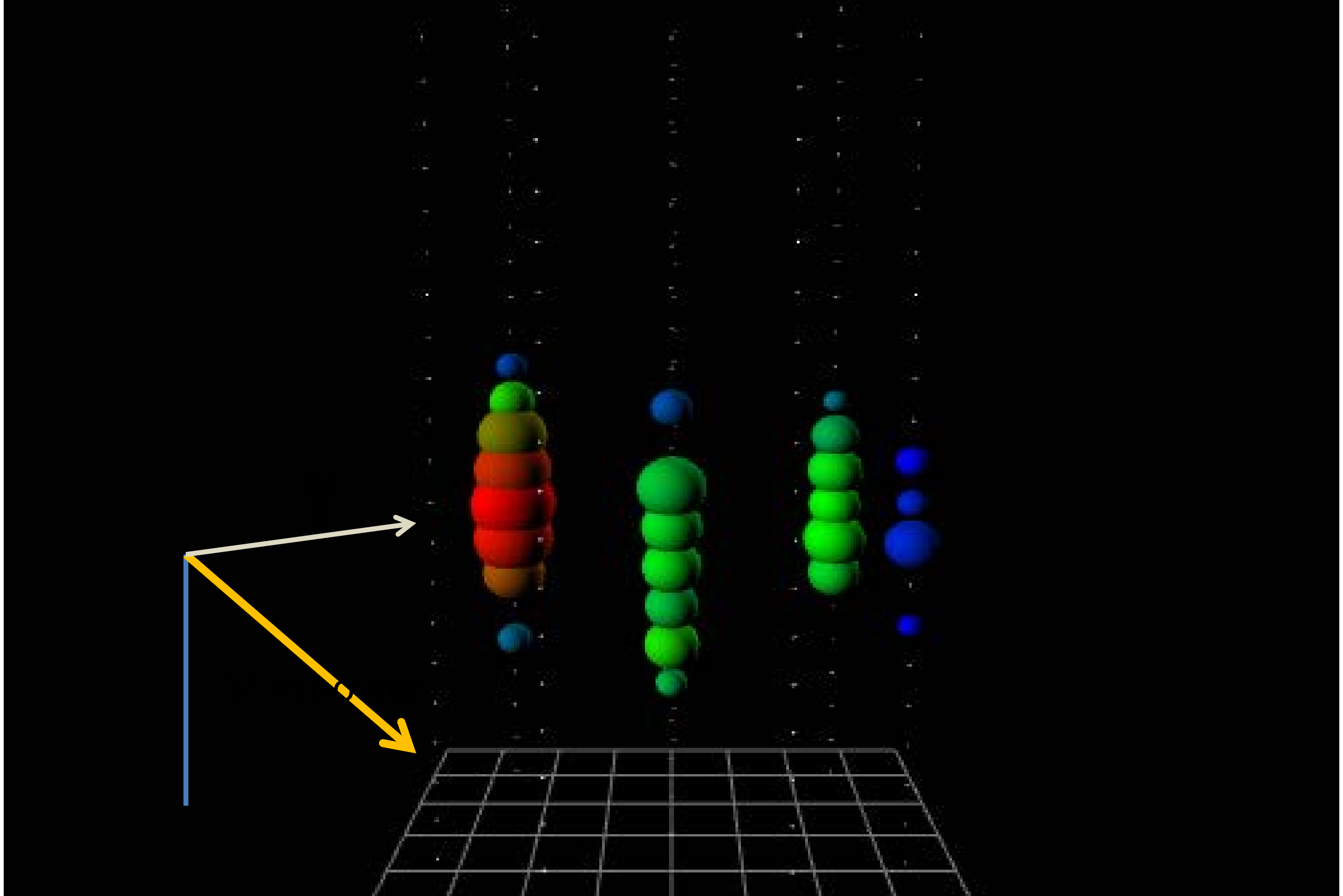
Assembly and tests 12 OM per day


20 48

An event in the BAIKAL-GVD



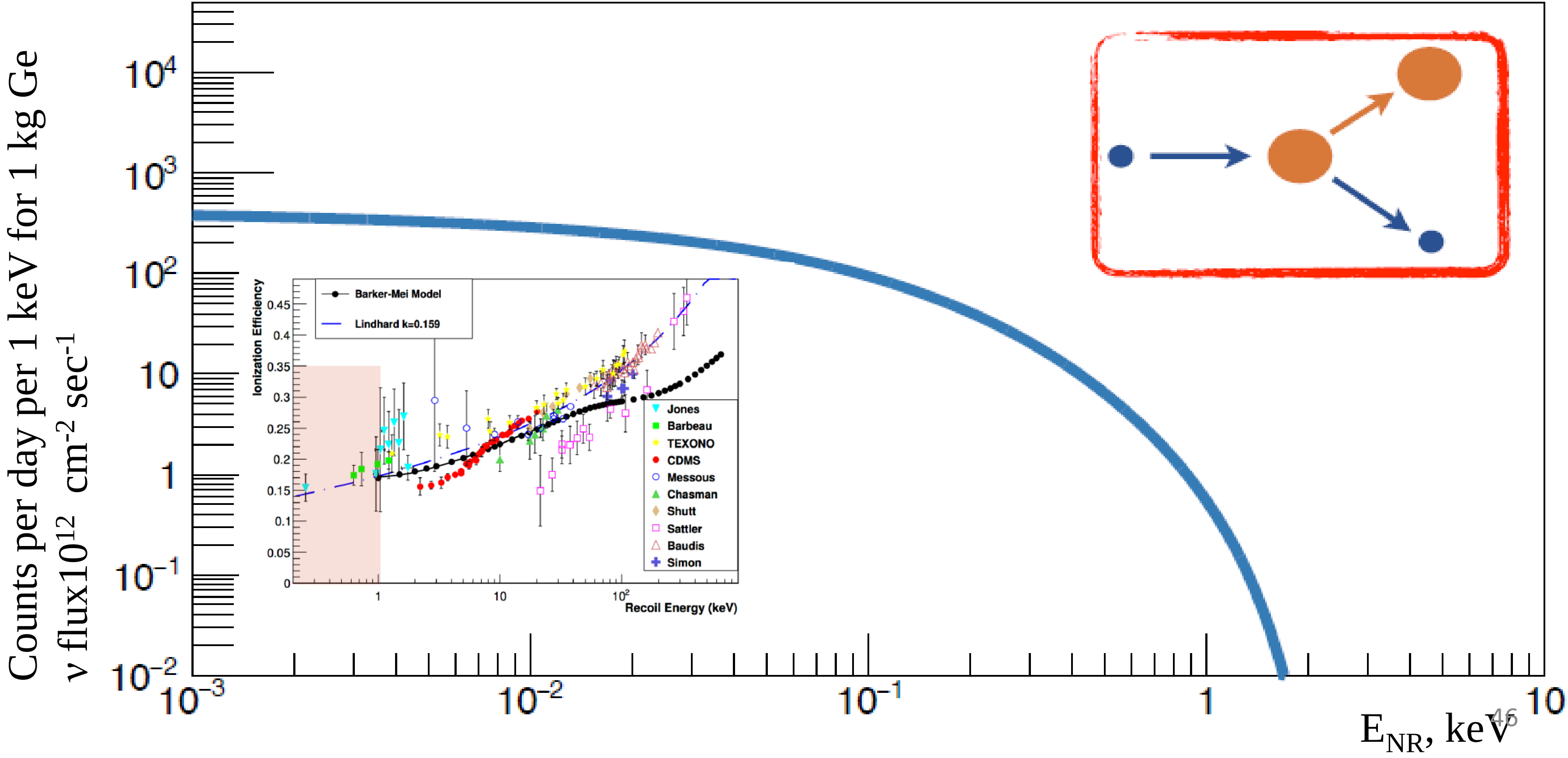
E = 158 TeV, θ = 59°, ρ = 73 m, z = -62 m



Coherent elastic neutrino-nucleus scattering (CEνNS)

The use of bolometers makes it possible to measure the energy of the nucleus directly (heat signal), in contrast to semiconductor detectors that measure ionization.

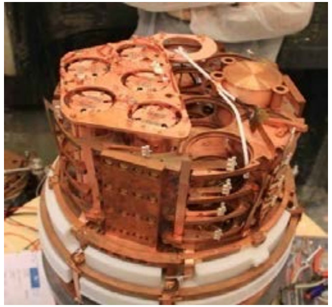
This it the way to the precision measurements.

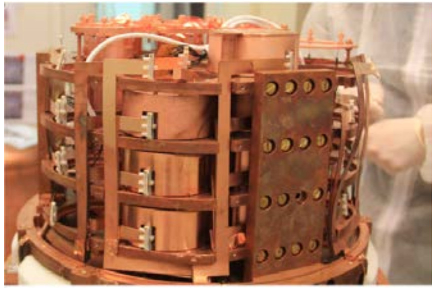


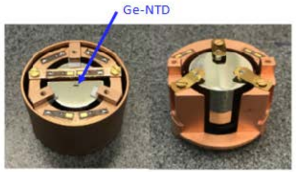
J. Billard *et al.*, JCAP 11 (2018) 016

The current phase results

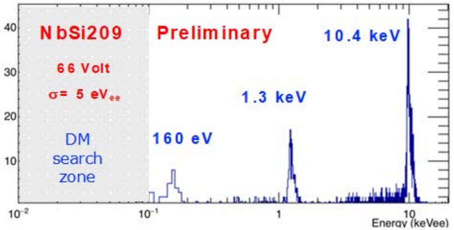
- Continuous data taking in the LSM underground laboratory from January 2019 – July 2020;
- Almost continuous data taking in the test dry cryostat in Lyon (R&D);
- 11 different Ge detectors;
  - Rest of the cryostat used for joint physics run with CUPID-Mo 0ν2β search
- Compare detector physics in 32 g, 200 g and 800 g detectors;
- Compare performance of NTD and NbSi-TES heat sensors;
- Obtaining near single-electron sensitivity on 33 and 200 g detectors: exploration of DM interactions with electrons and nuclei.
- Study of low-energy backgrounds in Ge detectors operated with large Neganov-Trofimov-Luke amplifications.



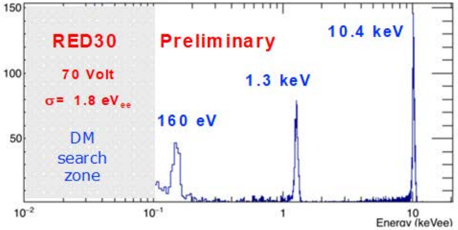




- NbSi209: 200g Ge with TES thermal sensor



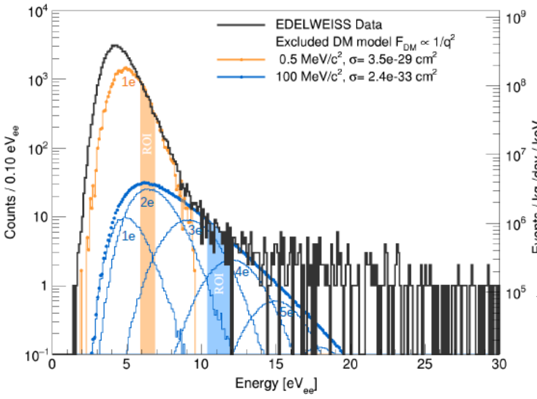
- RED30 : 33 g Ge Al electrodes, NTD thermal sensor



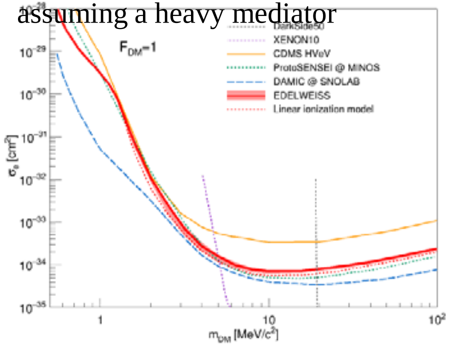
EDELWEISS has been able to obtain at the LSM run the lowest radioactive background levels below 10 keV in massive Ge detectors (~0.1 evt/kg/day/keV)

World leading results for DM search (a lot of data treatment is still in process)

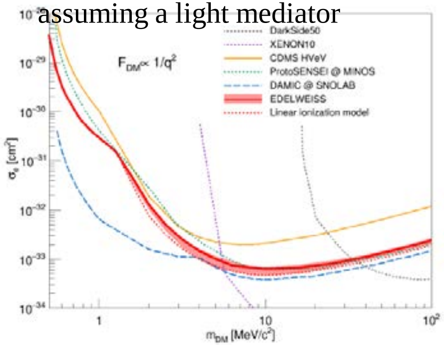
EDELWEISS results (PRL 125, 141301, 2020)



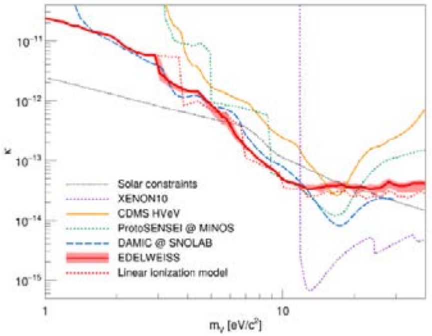
Scattering of DM particles on electrons assuming a heavy mediator



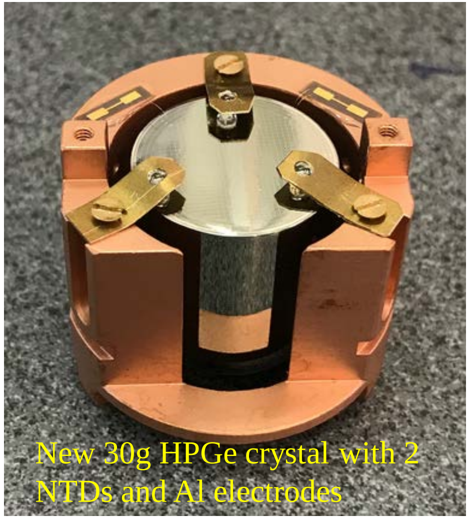
Scattering of DM particles on electrons assuming a light mediator



Kinetic mixing ***k*** of a dark photon



An unprecedented **charge resolution of 0.53 electron-hole pairs** (RMS) has been achieved using the Neganov-Trofimov-Luke internal amplification. We set the first Ge-based constraints on sub-MeV/c^2 DM particles interacting with electrons, as well as on dark photons down to 1 eV/c^2. These are competitive with other searches and demonstrate the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale electron signals.

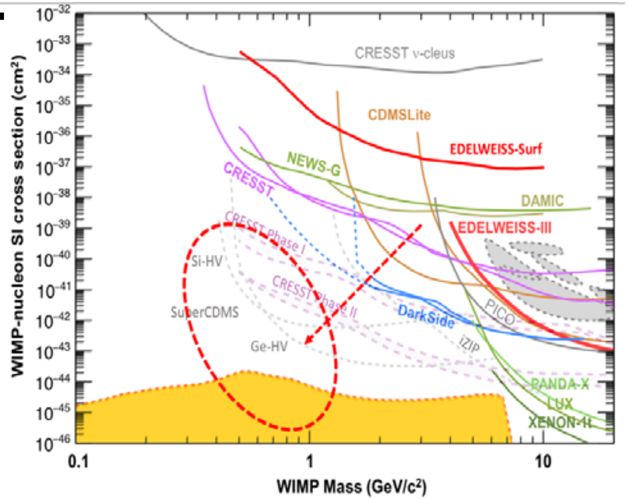


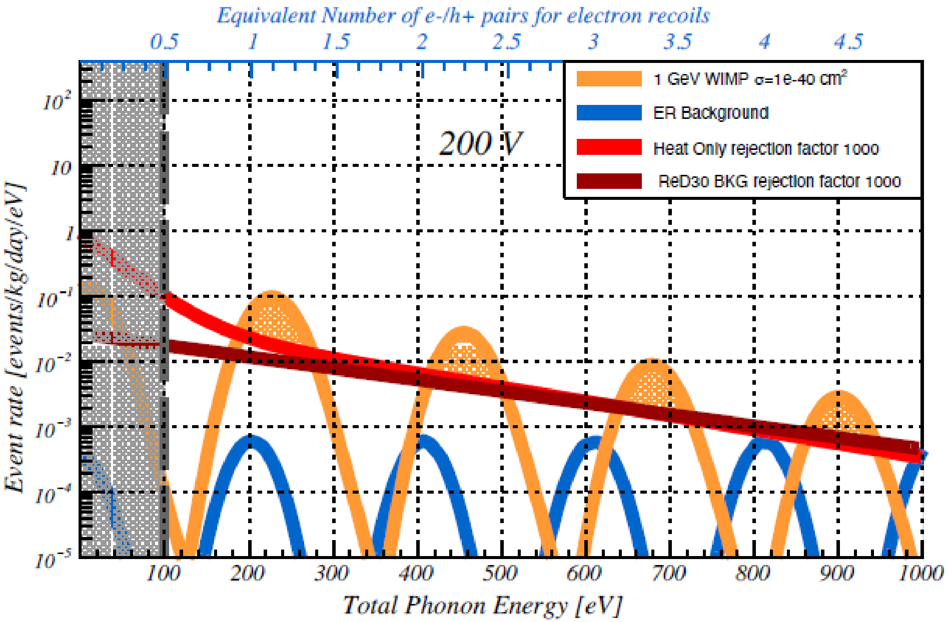
New 30g HPGe crystal with 2 NTDs and Al electrodes

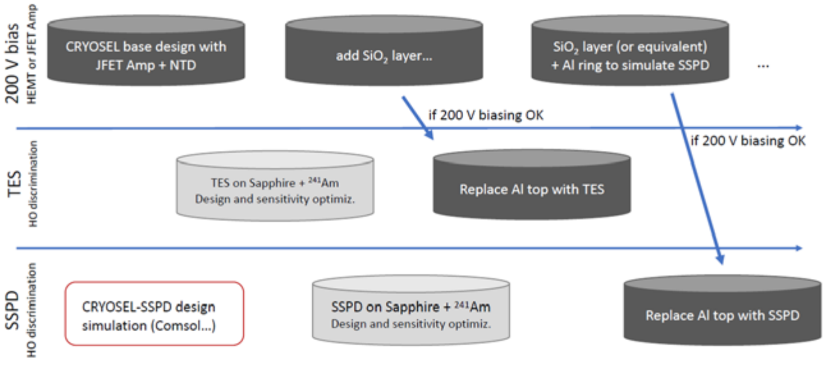
In new class of light DM models the interaction with normal matter comes from the coupling of a Dark Sector photon with the normal photon.

How to detect: DM-electron scattering

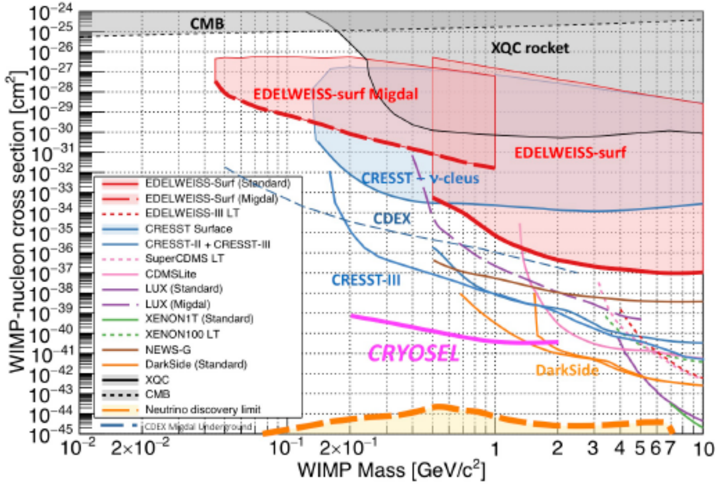
Theory predictions: complete coverage (10^{-40} cm^2) possible with 1 kg year exposure of a detector sensitive to the single electron in the absence of any background

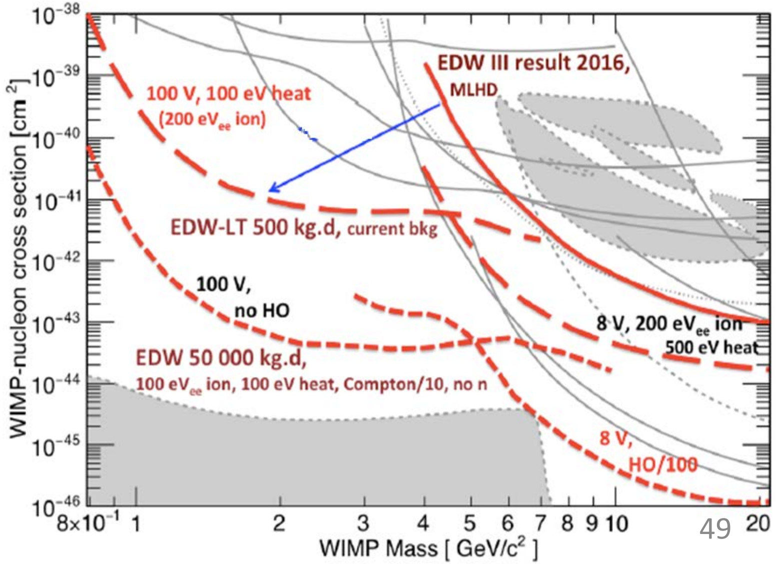






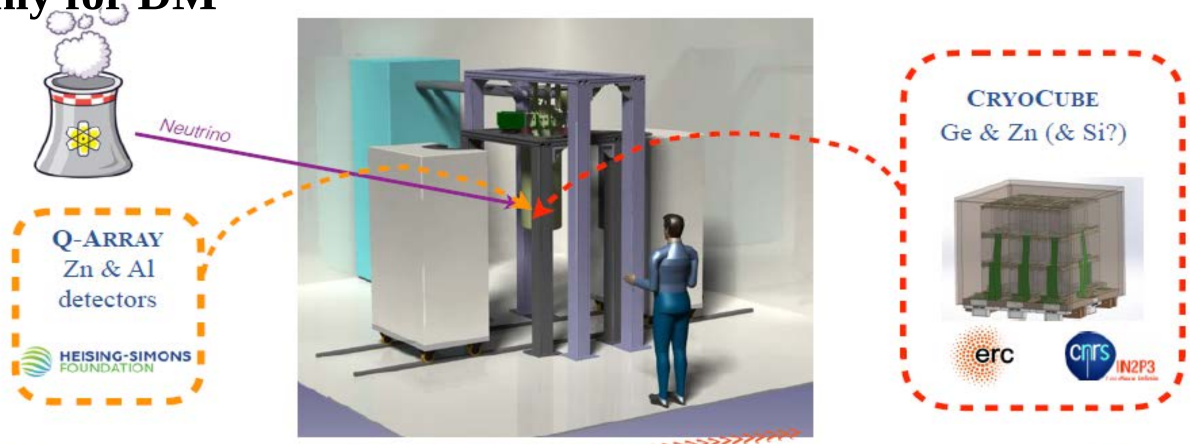
Lab and LSM physics runs to be planned upon R&D results





EDELWEISS bolometers - not only for DM

RICOCHET aims at building the ultra low-energy **CEνNS neutrino observatory** dedicated to physics beyond the Standard Model



50 eV energy threshold with a 10^3 background rejection down to the threshold

The first key feature of the RICOCHET program, compared to other planned or ongoing CEνNS projects, is to aim for a kg-scale experiment with significant background rejection down to the O(10) eV energy threshold.

The CRYOCUBE: a compact tabletop size setup

27 x 33 g detectors
8 x 8 x 8 cm^3
radio-pure infrared-tight copper box

Neutrino source

RICOCHET: first phase at ILL (Grenoble)

• 58 MW research reactor;
• Total neutrino flux: $1x10^{19}$ ν/sec;
• 20 events of CEνNS per day for RICOCHET (1 kg) for 7 m distance;
• 3-4 ON/OFF per year;
• Cosmic shield ~15 m.w.e.;
• STEREO data about neutrino spectrum and backgrounds.

STEREO Coll., JINST 2018