Neutrinos, Astrophysics and Dark Matter at JINR

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Joint session of the PAC for Particle Physics and the PAC for Nuclear Physics

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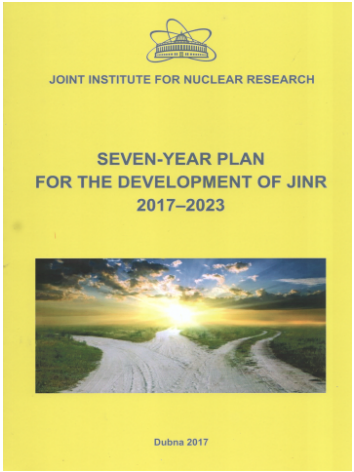
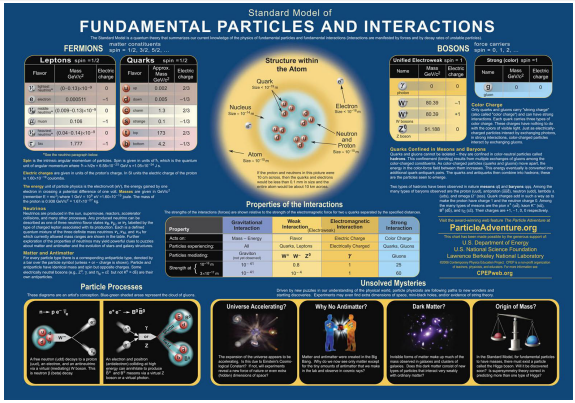
Just remind that →

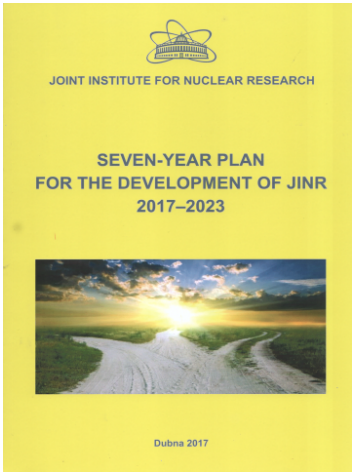


The strategic goal of particle physics and astrophysics is formation of a new unified physical view of our World without "problems" of the Standard Model,



which is nevertheless an outstanding achievement of Humankind!

The ways to reach the main goal of particle physics and astrophysics:



"Towards a new theory of elementary particles (a new physical picture of the World), the following sources of information are considered nowadays as most crucial:

1. Direct search for New Physics at Large Hadron Collider (supersymmetry, decays of the Higgs boson, extra dimensions, new types of state of matter, new particles and interactions, etc.)
2. Neutrino physics and astrophysics, (as the most intriguing and rapidly developing field of modern particle physics)
3. Cosmology, explanation of nature of Dark Matter and Dark Energy
4. Indirect search for New Physics mainly by means of precision studies of very rare transformations of hadrons and leptons with violating (flavor) symmetry of generations
5. *Being not directly connected with a New Physics the Hadron Structure is still very important and unique source for understanding of the QCD.*"

Neutrinos, Dark Matter, Astrophysics and Charged lepton flavor violation are below ... at JINR

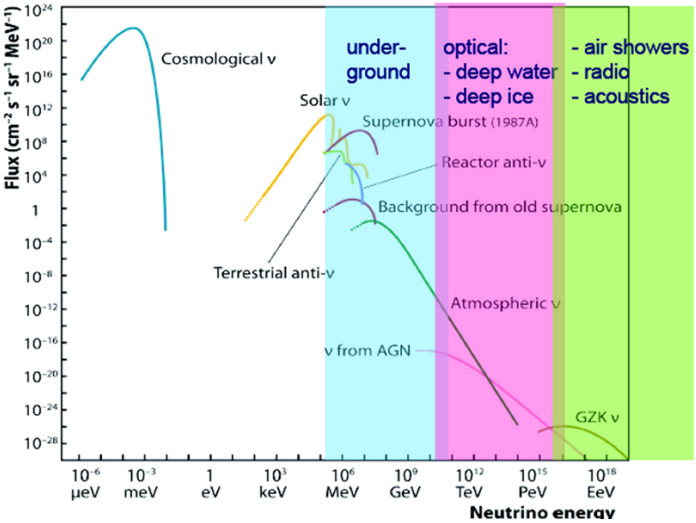
”Neutrino is a gift of Nature”



These ”gifts” are everywhere over space, time and wide energy spectrum ...

Variation of energy spectrum of known neutrinos is 24 orders of magnitude. The flux variation is also huge!

Sources	Flux, c^{-1}/sm^2	Energy, eV	Cross section, bn
Big Bang	10^{14}	10^{-4}	$< 10^{-32}$
Extra-Galactic	10^{-12}	10^{20}	10^{-4}
Galactic	10^{-10}	10^{15}	10^{-8}
Super Novae	10^{12}	10^{7}	10^{-16}
Solar	10^{10}	10^{6}	10^{-17}
Terrestrial	10^{6}	10^{4}	10^{-21}
Atmospheric	10^{2}	$10^{7\div13}$	$10^{-(16\div11)}$
Reactor	10^{13}	10^{6}	10^{-18}
Accelerator	10^{7}	10^{11}	10^{-13}



Today we know that neutrino —

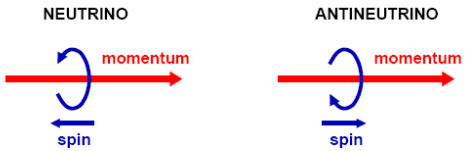
- is a fermion (has spin $s = 1/2$)
- does not participate in strong interaction (QCD neutral)
- does not participate in electromagnetic interaction (electrically neutral)
- takes part in weak interaction (if "active")
- undergoes gravity (if massive) ...
- Neutrino momentum $\vec{p}$ is always anti-parellel to neutrino spin $\vec{s}$!
- The key point is:



One has only left-haded neutrinos ν_L. There are no right-handed neutrinos ν_R !

Left-handed Doublets:

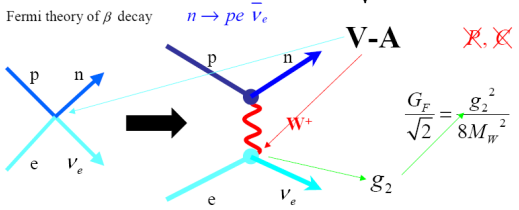
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

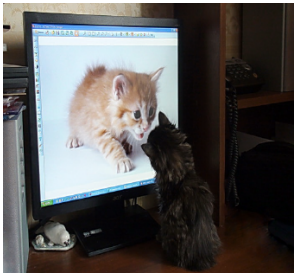


The point pushed forward the Standard Model!

The Higgs mechanism for elementary particle mass generation is inevitable only due to the point,
– that the Standard Model strongly respects the $SU(2)_L \times U(1)$ gauge symmetry, or
in other words, due to maximal Parity violation, or V–A structure of weak interaction, or
– masslessness of neutrinos ($m_\nu \equiv 0$), or full absence of the right-handed neutrinos ν_R.

$$L = \frac{G_F}{\sqrt{2}}\left[\bar{u}_n \gamma^\sigma (1-\gamma_5) u_p\right]\underbrace{\left[\bar{u}_{\nu_e} \gamma_\sigma (1-\gamma_5) u_e\right]}$$





The point is the core of the Standard Model!

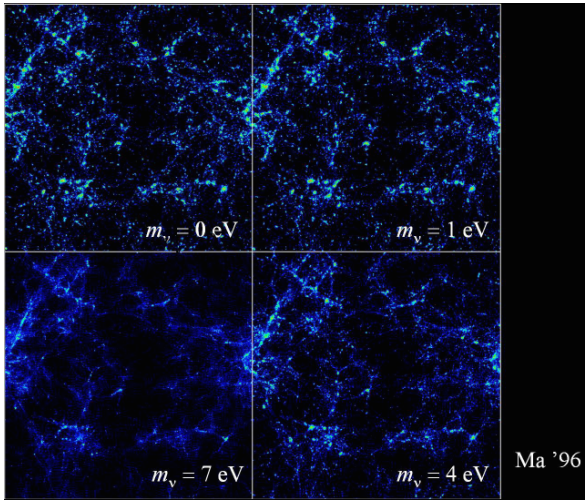
Neutrino oscillations prove the non-zero mass scale of neutrinos (one neutrino has $m_\nu > 0$).

$$\Delta m^2_{21} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\text{eV}^2,$$

Say: $$|\Delta m^2_{31}| = 2.43^{+0.06}_{-0.10} \times 10^{-3}\text{eV}^2,$$

$$0 < \sum_i m_i < 0.66 \text{ eV}.$$

The large-scale-structure (galaxy clusters) formation in the early Universe was very sensitive to the neutrino mass scale. It strongly prefers $m_\nu > 0$.



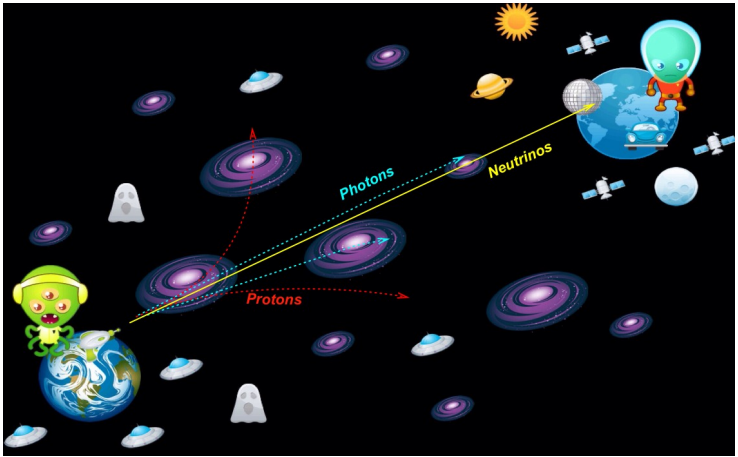
The point has limited the Standard Model ... and opens a way beyond!

Due to new sources and new detectors available the neutrinos have become unique messengers of unknown information (through huge space-time and very dense matter). Furthermore, the neutrinos will be soon a hot topic for super-high energy accelerator physics (looking for New Physics).

There is no other way to know what is going on inside the Sun, Earth, SN, core of nuclear plant, or in a far corner of the Cosmos. Only Neutrinos can probe scales from 10^{-33} to 10^{28}cm.

Only a ν-signal sent by a distant alien has a chance to reach us.

Because they interact very weakly. The weakness is now the power!



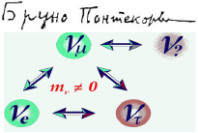
B. Pontecorvo and M.Markov have made the neutrino history in Dubna ...





1→ About 60 years ago the idea of neutrino oscillation was born in Dubna!

Bruno Pontecorvo said: *"The oscillations are very simple trick: 1–2–3 and … all OK!"*



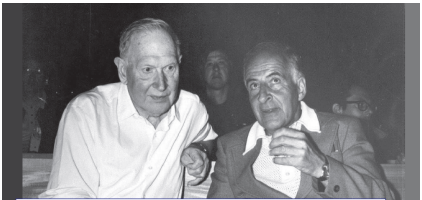
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Weak eigenstates | Atmospheric | CP phase | Sub-dominant θ_{13} oscillations | Solar | Mass eigenstates

$c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

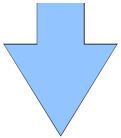
2→ The key idea of neutrino astrophysics was found in Dubna too.

M.A.Markov had proposed for the first time to define incoming directions of a cosmic ray charged particle in water by means of its Cherenkov radiation. The first realization of this idea was the Baikal neutrino telescope NT-200. This is foundation of the IceCude success of today!



M.Markov, 1960:
„We propose to install detectors to determine the direction of charged particles deep in a lake or in the sea and with the help of Cherenkov radiation" Proc. 1960 ICHEP, Rochester, p. 578.

By high fundamental level, world outlook importance, number of unresolved problems and huge potential of unexpected discoveries the Neutrino Physics and Astrophysics — among undisputed leaders in modern physics *(Russian Academy of Science. 2012)*



The amazing Neutrinos are in Dubna

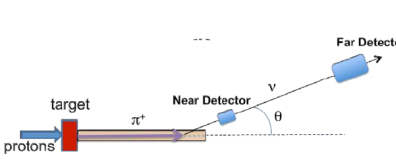
Study of Neutrino Oscillations (JINR topic 1099)

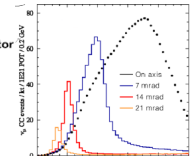
NOvA (accelerator) and JUNO (reactor)
are the best neutrino oscillation projects.

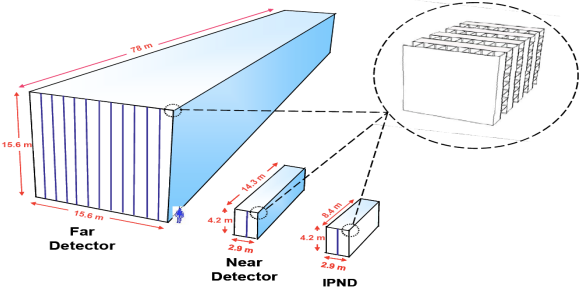
BOREXino is a unique solar neutrino project.

NOvA (NuMI Off-Axis ν_e Appearance) — a new generation accelerator long baseline experiment to study $\nu_\mu \to \nu_e$ oscillations.







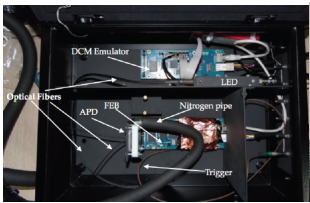


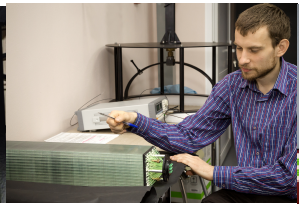
The goal is to precisely measure the neutrino mixing matrix, the neutrino mass hierarchy and CP violation effects in leptons. The NOvA apparatus consists of a Near Detector on the Fermilab site where the ν_μ-s are produced, and a Far Detector 810 km distant, both of similar construction and both situated 14 mrad off-axes to the ν beam. The Far Detector (14 kton) and Near Detector (220 ton) filled with liquid scintillator have been taking data since 2014, and a number of important measurements have been performed.

The JINR group (13.8 FTE) in NOvA has contributed significantly to the NOvA results.

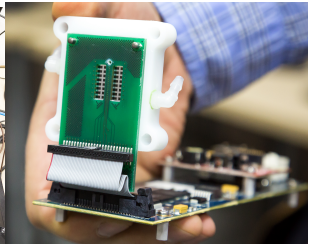
Dedicated infrastructure for NOvA experiment was created at JINR.

→ The NOvA electronics test bench was set up at DLNP and provided important measurements of electronics parameters used for simulation and calibration.









→ Another test stand was constructed at JINR to measure properties of the NOvA liquid scintillator, mainly to determine Birk's coefficient, which defines the response of scintillator to passage of slow protons.

→ The Remote Operation Center (ROC-Dubna) was put into operation in 2015, giving the possibility to fully participate in the data taking and quality monitoring.



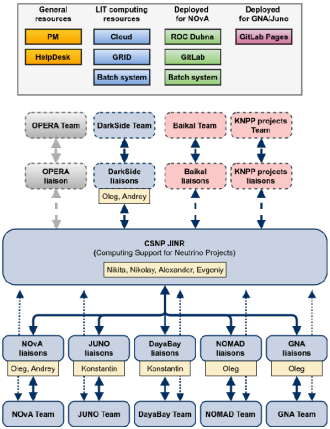
→ JINR computer infrastructure on the basis of GRID-Cloud technologies was developed. It is efficiently used for the home-based running of jobs and is a part of the NOvA distributed computing resources system for the use at peak loads.

NOvA Computing at JINR is at a highest level!

JINR Neutrino Programme already uses most advanced computer resources and facilities (Clouds, Grid, etc) initially oriented to the highest level LHC experiments ATLAS and CMS.

Modern LIT-based computer infrastucture for NOvA was created:

– Tested and installed DLNP-local computers use the NOvA computer software
– Universal Virtual Machines with NOvA software are implemented into LIT Cloud-infrastructure
— The Cloud was integrated into OSG (Open Science Grid) to perform simulation of neutrino events (NOvA production). The system was tested with another FNAL experiment Mu2e (CLFV search). It is under developing and can be scaleable
– Disc storage and data-cache for NOvA are under configuration and testing
– Tier-2 JINR infrastucture was integrated into OSG «NOvA production»
– There are plans for future enhancement of the NOvA computer resources at JINR.

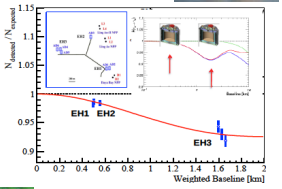


The goal of JINR-NOvA team evolution is the DUNE experiment.

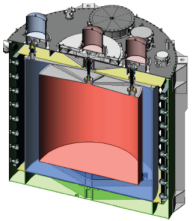
The reactor antineutrino experiment Daya Bay (China) with near and far identical detectors



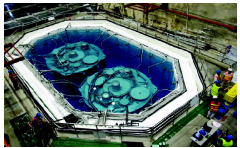
The main goal of the Daya Bay experiment is measurement of neutrino mixing angle θ_{13} via observation of the reactor $\bar{\nu}_e$ flux deficit on the far site (detectors) in comparison to the $\bar{\nu}$ flux in the near site (detectors). Apparent deficit of number of $\bar{\nu}$'s in the far detectors lead to discovery of new type of oscillations due to $\theta_{13} \neq 0$.



The $\bar{\nu}$ detector utilized a 3-zone scintillator structure. The inner one was the target filled with 20 tons of LS, doped by 0.1% of gadolinium. Next one was filled with 21 tons of undoped LS used to catch γs. The outer one was filled with 37 tons of mineral oil used as shield against the radiation. 192 8-inch PMT collected the light emitted in LS.



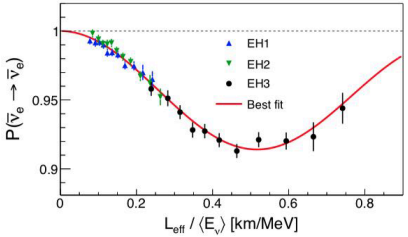




JINR in Daya Bay: 1) Development of the LS, suitable for the large-scale Daya Bay experiment. 2) PPO (2,5-diphenyloxazole) production for the LS (1.5 tons) and delivery to Daya Bay. 3) Suggestion of a new method of tagging fast neutron events based on Flash ADC signals. 4) Development of dedicated software package for the oscillation analyses. 5) With the package 3-ν rate+shape oscillation analysis and search for sterile neutrinos, etc

With the discovery and precise measurement of a non-zero θ_{13} mixing angle the neutrino physics has entered a new era of tackling the problems of neutrino mass hierarchy and lepton CP violation. The Daya Bay experiment has first announced the 5σ discovery and has now the most precise measurement as well.

The JINR contribution to the data analysis is significant and is recognized by the collaboration. The most precise measurement of the oscillation parameters θ_{13} and Δm^2_{32} is based on the analysis of the JINR group (Phys. Rev. D95 (2017) 072006). The most precise measurement of L/E oscillation dependence was obtained →

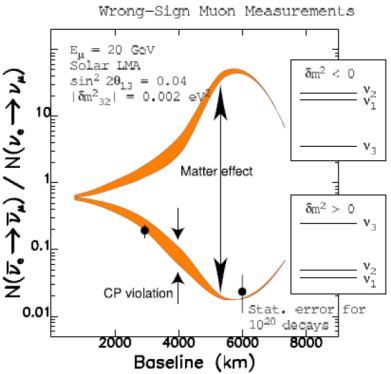




Due to precise measurements of the θ_{13} the Daya Bay Collaboration have received prestigious *Breakthrough prize in Fundamental Physics 2016*. DLNP laureates are M.Gonchar, Yu.Gornushkin, D.Naumov, I.Nemchenok, A.Olshevski (Daya Bay), E.Yakushev (KamLAND) and B.Popov (T2K).

From Daya Bay → JUNO to fix ν mass hierarchy, CP, SN, etc.





The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment

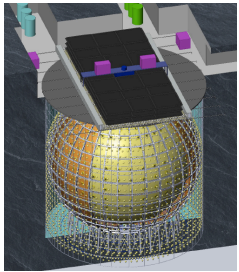


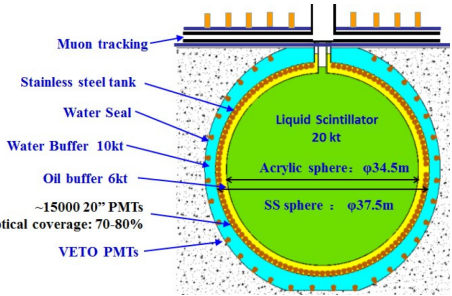
The main goal of JUNO is determination of neutrino mass hierarchy and precise measurements of oscillation parameters by detecting reactor $\bar{\nu}$ from Yangjiang and Taishan Nuclear Power Plants with a 20k-ton liquid scintillator detector of unprecedented 3% energy resolution at 700-m deep underground.

Improvement to be: For Δm^2_{21} from 3% $\rightarrow$ 0.6%; For $\sin^2\theta_{12}$ from 6% $\rightarrow$ 0.7%; For Δm^2_{32} 5% $\rightarrow$ 0.6%; For $\sin^2\theta_{13}$ 4% $\rightarrow$ 1.5%.

Some other research topics are:
Geoneutrinos (10 more statistics); diffuse SN, solar, atmospheric, sterile neutrinos; p-decay via $p \rightarrow K\nu$; indirect dark matter and new physics search, etc.

JUNO would be able to detect 5000 SN neutrinos in less than 10 sececons for a SN event 10 kpc away (our Galaxy).





The JUNO project is now in the construction stage.

The JINR group has a number of important contributions including:

— R&D and production of high voltage units for 20 000 PMTs 20-inch in diameter and 25 000 PMTs 3-inch in diameter.

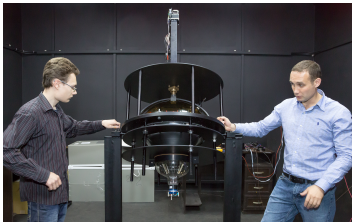
— R&D and production of the precision muon Top Tracker based on the plastic scintillator technology.

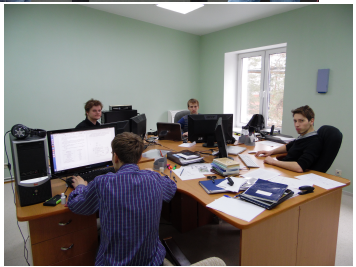
— Development of methods for individual and mass testing of PMTs.

— Detector simulation, reconstruction, events selection and background determination.

— Development of methods and software for the data analysis. The DLNP group will take part in the oscillation data analysis in the JUNO experiment based on best experience from Daya Bay.

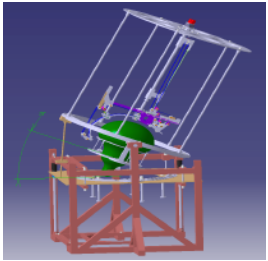
JINR team (12.6 FTE) has a lot to do in the JUNO project!





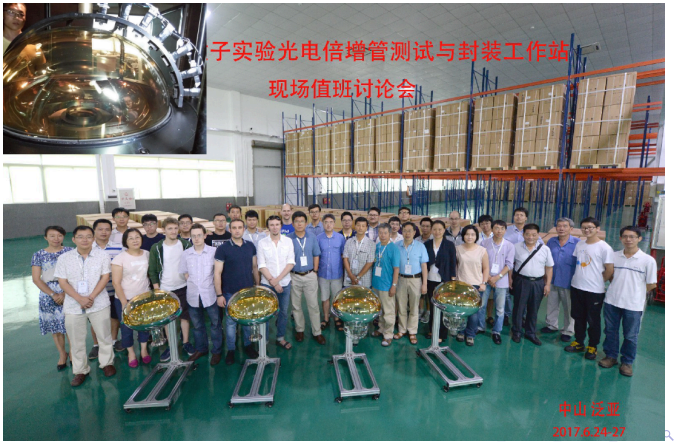
An example: A special scanner-device was designed at DLNP for usage in the JUNO Collaboration

The scanner allowed one to perform measurements of PMT integral and zone (at different photocathode points) parameters: photon detection efficiency, gain, dark noise rate, the single electron response performance, the transit time spectrum (evaluating the amount of pre-pulse due to the production of photoelectrons directly on the dynodes system and the transit time spread) and the after-pulse probability at the tens of microseconds time scale, etc.





"Large photocathode 20-inch PMT testing methods for the JUNO experiment." N. Anfimov for the JUNO Collaboration, 1705.05012. JINST 12 (2017) C06017.

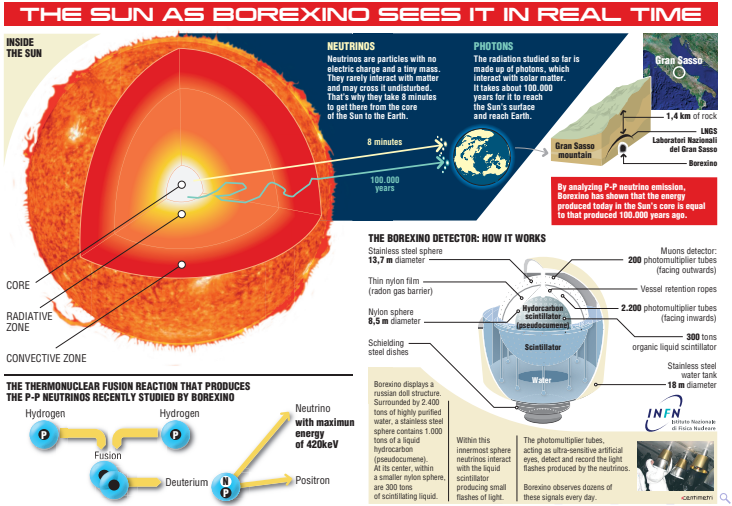


The BORon solar neutrino EXperiment, BOREXino, at the Gran Sasso Underground Laboratory (Italy).



First observation of geoneutrino, study of natural radioactivity of the Earth, measurement of ^{7}Be solar neutrino flux, first direct pep solar neutrino measurement, test of seasonal and diurnal variations of the solar neutrino flux ... were obtained with significant contribution of JINR team (3.75 FTE, to the detector running and data analysis, but withOUT any hardware contribution).

In 2014 the solar neutrino flux from the pp-reaction was measured with the detector Borexino in real time. *G.Bellini, et al, (Borexino Collaboration), Nature, vol. 512 (2014) 383.*
JINR team made strong contribution as well.



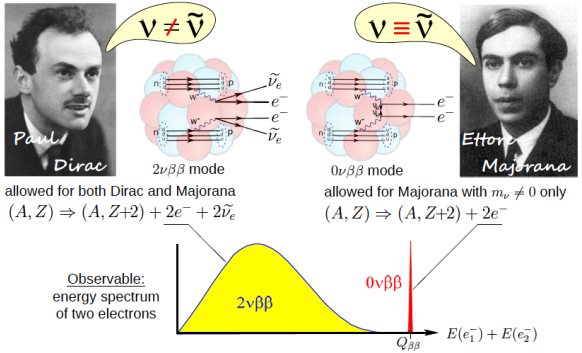
Non-accelerator physics and astrophysics (JINR 1100)

The $0\nu\beta\beta$-search with unique pair of SuperNEMO and GERDA.

The KNP-Plant is a unique antineutrino infrastructure →

GEMMA/νGeN and DANSS are on the best track ...

The neutrinoless nuclear double beta decay ($0\nu\beta\beta$) is a most direct way to check the Nature of neutrino. It violates the total lepton number conservation law by 2 units and is possible only if the neutrino is a Majorana particle ($\nu \equiv \bar{\nu}$) with non-zero effective mass.



Probability of $0\nu\beta\beta$-decay is given by $W = G_{0\nu} \left|\mathcal{M}_{0\nu}\right|^2 \langle m_\nu \rangle^2$, where $G_{0\nu} \sim Q^5_{\beta\beta}$ is a phase space factor and $\mathcal{M}_{0\nu}$ is the nuclear matrix element.

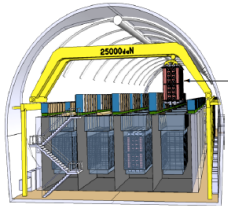
An observation of $0\nu\beta\beta$-decay would allow determination of the absolute neutrino mass scale — $\langle m_\nu \rangle$.

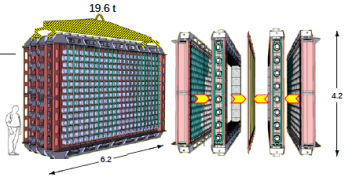
Two-neutrino double beta decay ($2\nu\beta\beta$) is an allowed, very rare weak interaction process. The study of $2\nu\beta\beta$-rate is very important. It constitutes the main background for the $0\nu\beta\beta$-decay signal, and provides one with a valuable input for the nuclear structure $\mathcal{M}_{0\nu}$ theoretical calculations.

JINR participates in both different modes of the $0\nu\beta\beta$-experiments:
SuperNEMO (when $\beta\beta$-detector $\neq$ $\beta\beta$-source) and GERDA (when $\beta\beta$-detector $=$ $\beta\beta$-source).

Search for neutrinoless double beta decay with experiment SuperNEMO in the Modane Undeground Laboratory (France, Frejus tunnel) at 4800 m w.e.

SuperNEMO can measure individual electron tracks, vertices, energies and time of flight (full kinematics and topology of an event). The background rejection is based on identification of γ-rays, α-particles, and distinguishing e^- from e^+ with a magnetic field. The $\beta\beta$-source separation from the detector allows several different isotopes to be studied.





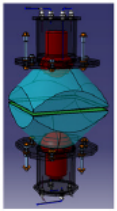
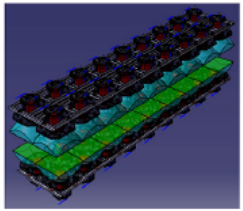
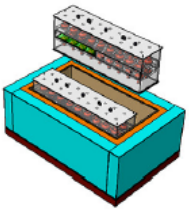
Parameter	NEMO-3	SuperNEMO
Isotope and its mass	^{100}Mo, 7 kg	^{150}Nd or ^{82}Se, 100 - 200 kg
Efficiency	8%	~30%
Energy resolution (FWHM)	8% @ 3 MeV	4% @ 3 MeV
Internal ^{208}Tl contamination in $\beta\beta$ foil	$< 20\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
Internal ^{214}Bi contamination in $\beta\beta$ foil	$< 300\ \mu$Bq/kg	$< 10\ \mu$Bq/kg (if ^{82}Se)
Internal Radon contamination in tracker	~ 5 - 6 mBq/m^3	< 0.1 mBq/m^3
$T_{1/2}(0\nu\beta\beta)$ sensitivity	$> 1 \times 10^{24}$ y	$> 2 \times 10^{26}$ y
$\langle m_\nu \rangle$ sensitivity	$\leq$ (310 - 790) meV	$\leq$ (30 - 100) meV

The expected improvement in performance.

SuperNEMO will consist of 20 independent modules. Each module contains 5-7 kg of a thin foil surrounded by a gas tracking chamber followed by calorimeter walls. The tracking contains more than 2000 wire drift chambers operating in the Geiger mode. The calorimeter is divided into 1000 blocks which cover most of the detector outer area and are read out by low-background PMT. The main candidate isotopes are ^{82}Se, ^{150}Nd and ^{48}Ca.

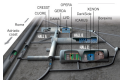
JINR team (5.3 FTE) has 25 yr experience of work in the NEMO–SuperNEMO projects with main responsibilities:

– Radiochemical purification of isotopes and production of radioactive mono-isotopes
– Development and construction of the calorimeter and veto systems based on plastic scintillators
– Software development, simulations, and data analysis
– Manufacturing of signal and High-Voltage cables for the tracker, cabling, testing and tuning
– Acquisition, creation and maintenance of equipment for low-background measurements: Ge, radon, neutron detectors in LSM
– R&D, construction of ultra low-background BiPo-3 spectrometer (below) to measure radiopurity of $\beta\beta$-source foils, etc.

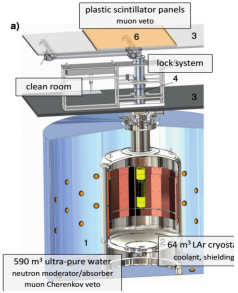




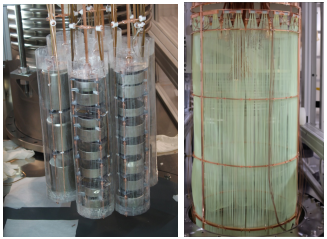

JINR plans in SuperNEMO are: Calibration of the Demonstrator (ready in 2018), creation of it's neutron shielding, data collection, data analysis, background assessment and control, first results (upto 2021). Continuation of R&D on enrichment of other isotopes: ^{150}Nd, ^{96}Zr, ^{48}Ca. Improvement of the cleaning procedure for ^{82}Se, etc.

GERmanium Detector Array (GERDA) to search for neutrinoless double beta decay in ^{76}Ge at the Gran-Sasso Undeground Laboratory

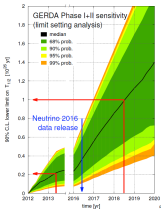


There is a very intriguing claim on observation of the $0\nu\beta\beta$ decay in ^{76}Ge (6.4σ) by Prof. H.V.Klapdor-Kleingrothaus (Heidelberg-Moscow experiment). Only GERDA is able to test directly the claim. In $0\nu\beta\beta$-search with Ge $\beta\beta$-detector matches $\beta\beta$-source. The GERDA has an array of 40 Ge detectors, mounted in low-mass supports and immersed in a cryostat filled with liquid argon, which serves as a cooling and shield against external backgrounds. The cryostat is inside a water tank of 10 m in diameter.



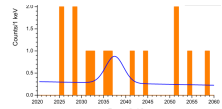


Array of Ge-detectors, Argon Vero system





The signature of ^{76}Ge $0\nu\beta\beta$ decay is a peak at decay Q-value $= 2039.061 \pm 0.007$keV.

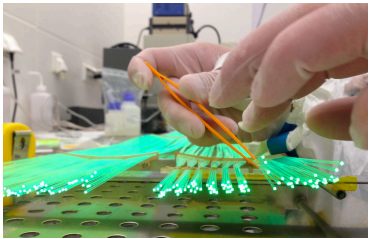


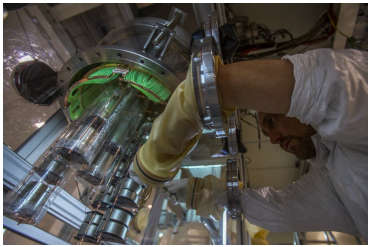
H.V. Klapdor-Kleingrothaus:
$T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31})10^{25}$yr.

The GERDA have been working in the stable mode since 2016. The best achieved background index was 10^{-3} counts/(keV kg year). The best limit from both Phases is $T^{0\nu}_{1/2} > 8.0 \times 10^{25}$ yr.

The JINR team (7.5 FTE) plays significant role in the GERDA experiment:

– JINR was responsible for design, production, testing and installation of the plastic muon veto system.
– JINR specialists participated heavily in the development of LAr instrumentation (veto and the central fiber module).
– A tool for suppression of dominant ^{42}Ar background for Phase II was developed, produced, tested and installed by the team.
– JINR played the important role in the development of methods of pulse shape discrimination for HPGe used in Phase II.
– JINR was responsible for test, mount and commission of the GERDA core — arrays of bare HPGe in both Phases.
– JINR provided 8 kg of enriched ^{76}Ge for the GERDA projects.

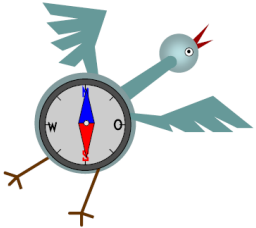


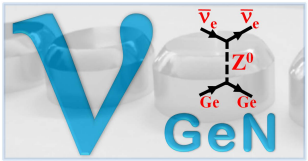


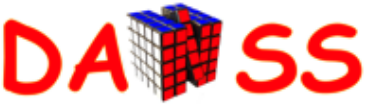


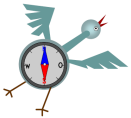
The GERDA experiment will reach the designed exposure in the end of 2019. Then the GERDA infrastructure will be modified to adopt up to 200 kg of Ge detectors of LEGEND project (will start in 2021). The JINR group will participate in all stages of the LEGEND experiment.

Neutrino Physics at the Kalinin Nuclear Power Plant







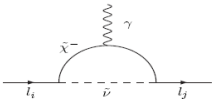


Investigation of neutrino properties with the low-background Ge spectrometer GEMMA-III (**G**ermanium **E**xperiment Searching for **M**agnetic **M**oment of **A**ntineutrino) at the Kalinin Nuclear Power Plant



The goal is to measure the neutrino magnetic moment, by studying the $\bar{\nu}_e$ scattering in HPGe detectors located close to a reactor. It could prove non-zero electromagnetic properties of neutrinos and is very important for astrophysics.

In the Standard Model (diagonal μ_{ii}^{ν} and transition μ_{ij}^{ν}) magnetic moments are proportional to the (Dirac) neutrino mass and are very small $\mu_\nu = 10^{-19}(m_\nu/1\ \text{eV})\mu_\text{B}$. If neutrinos are Majorana, $\mu_{ii}^{\nu} \equiv 0$, but still $\mu_{ij}^{\nu} \neq 0$. Beyond SM (SUSY) the Majorana neutrino (transition) magnetic moment(s) could be at a level of $10^{-12}\mu_\text{B}$ (present sensitivity region).

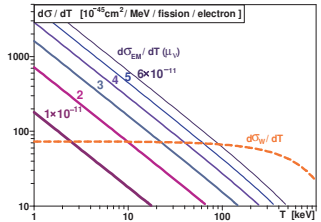


An observation of $\mu_{ij}^{\nu} > 10^{-14}\mu_\text{B}$ would be an evidence of New Physics and would indicate the Majorana nature of neutrino(s).

The ν-e differential cross section is a sum of weak ($d\sigma^W/dT$) and electromagnetic ($d\sigma^{EM}/dT$) terms. These cross sections averaged over the typical $\bar{\nu}$-reactor spectrum are functions of the electron recoil energy. At low recoil energy ($T \ll E_\nu$) $d\sigma^W/dT$ becomes almost constant while $d\sigma^{EM}/dT$ increases as T^{-1}.

The lower a detector energy threshold is the more considerable increase in the μ^ν-effect with respect to the weak irreducible background can be obtained.

$\rightarrow$ GEMMA-III sensitivity is expected at a level of $5 \times 10^{-12}\mu_\text{B}$.



Experiment at KNPP aimed at Detection of Coherent **N**eutrino–**Ge** **N**ucleus Elastic Scattering (νGeN). *It is a clear JINR proposal.*



Why observation of the Coherent Neutrino Nucleus Scattering (CNNS) is important?

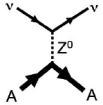
$\rightarrow$ One believes the CNNS is very important in the early Universe, crucial for SN evolution, sensitive probe of new physics

$\rightarrow$ Due to NC, an observation of ν-oscillations (disappearence) with CNNS could be an evidence for sterile neutrino(s)

$\rightarrow$ Interactions of solar neutrinos through CNNS will be an irreducible background for direct DM observation.

$\rightarrow$ Due to the CNNS one can significantly reduce the size and mass of a neutrino detector, which would help to develop neutrino based applied research (non-intrusive monitoring of nuclear reactors, etc).

Detection of neutrinos (with E_ν <50 MeV) via coherent scattering off a nucleus $\nu A \rightarrow \nu A$ is a challenge. The CNNS is a neutral-current process, its cross section is enhanced by the number of nuclear target neutrons squared: $\frac{d\sigma}{d\cos\theta} \simeq \frac{G_F^2}{16\pi^2} E_\nu^2 (1+\cos\theta) N^2 F^2(q^2)$, where $F(q^2) \propto \exp^{-R^2 q^2}$ is an elastic nuclear form-factor, which vanishes the coherent effect with increase of momentum transfer q vs A-radius R.



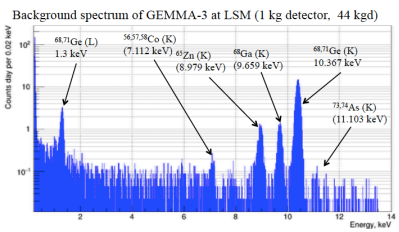
The only measurable CNNS-signature is recoil energy $E_R = \frac{q^2}{2m_p A}$, which is very small ($E_R < 1$ keV for Ge).

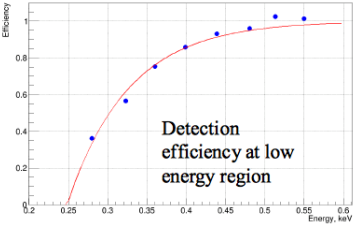
Due to uniquness of HPGe detectors together with unique $\bar{\nu}$-flux the νGeN has good chances to observe for the first time the coherent neutrino-nucleus scattering in the true low-energy domain.

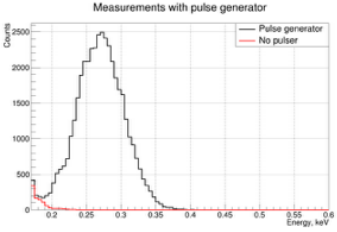
GEMMA+νGeN — the JINR "twin" experiments for measurements of neutrino properties with low-background germanium spectrometers at KNPP

A study (in 2018) of 1st detector (1 kg) done at LSM (EDELWEISS-I shield) and at JINR revealed that:

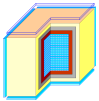
1) the energy resolution is 78.0(3) eV with pulse generator, and 117(4) eV for 1.3 keV L-cosmogenic line of ^{68,71}Ge;
2) data taking is possible from the energy threshold below of 200 eV;
3) one has extremely low sensitivity to microphone noise (important for work at KNPP).







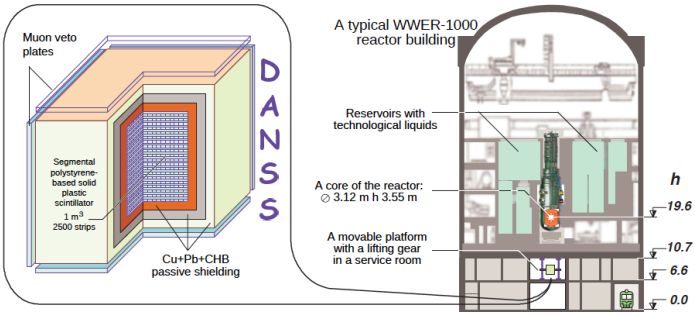
– All tests at JINR are finished and the setup is re-integrated under the reactor. First results are expected in the middle of 2019.
– After first detection of the CNNS the detectors will be used to study the CNNS in detail.
– Further development will be connected with new HPGe detectors with increased mass (up to 10 kg in total).



Detector of the Reactor **A**nti**N**eutrino based on **S**olid **S**cintillator — DANSS.
Direct registration of the $\bar{\nu}$ with highly segmented movable polystyrene-based detector

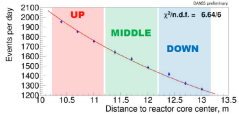


The aim is a relatively small (1 m^3) $\bar{\nu}$–detector that does not contain any aggressive, cryogenic or other dangerous liquids in big amount and can be safely installed close to the core of an industrial power reactor. With high $\bar{\nu}$ flux it can detect about 5000 $\bar{\nu}$/day with $S/B \sim 40$, and measure $\bar{\nu}$ energy spectrum.



DANSS (due to precise $E_{\bar{\nu}}$-measurement, 3D-info about events) can be used for applied and fundamental goals: on-line monitoring of a reactor, fuel composition diagnostics (^{235}U/^{239}Pu) and tomography, search for short-range ν-oscillation and sterile ν's, etc.

DANSS-lifting is a key feature:

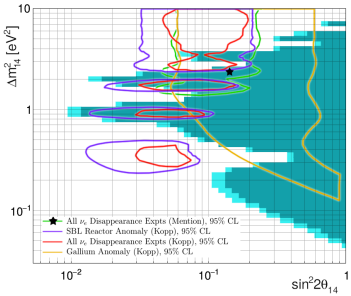


Detector of AntiNeutrino based on Solid state Scintillator: *Reactor monitoring and search for short-range neutrino oscillations — JINST 11 (2016) no.11, P11011; 1606.02896*

Detector of the Reactor AntiNeutrino based on Solid Scintillator (DANSS) → Phys.Lett. B787 (2018) 56-63:

– DANSS is taking data since Apr 2016 (data available for analysis – since Oct 2016)
– 4910 IBD events/day are detected in the closest DANSS-core position
– Background estimation is 133 μ-induced events/day (2.7% for Up position)
– A large fraction of the allowed sterile oscillation parameters region is excluded in a model-independent way.
– The Reactor antineutrino anomaly (RAA) point ($\Delta m^2 = 2.3$ eV^2, $\sin^2 2\theta = 0.14$) is excluded at the 5σ level
– The best point at ($\Delta m^2 = 1.4$ eV^2, $\sin^2 2\theta = 0.05$) has 2.8σ significance
– DANSS performs data taking, and relevant analyses are under way ... → up to 2021

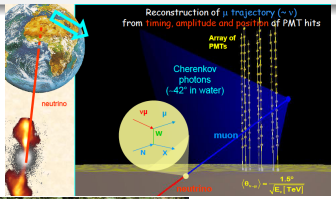
In the Figure are given: CL exclusion area in Δm^2_{14}–$\sin^2 2\theta_{14}$. The shaded area represents DANSS analysis. Curves show allowed regions from neutrino disappearance experiments, and the star is the best point from the RAA and GA fits.





Gigaton Volume Neutrino Detector at Lake Baikal

A couple of years ago IceCube saw nothing, and GVD on Baikal was almost not needed. Today the IceCube sees galactic neutrinos, but not very good. The GVD on Baikal is urgently needed! It is a long-term project with a clear and strong prospects. Its discoveries are waiting for us (V.Rubakov, 16.12.2013).

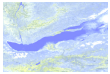


A very new stage of the Baikal project was started in 2014!

25.09.2014: The JINR Scientific Council recommends the JINR Directorate to support the implementation of the JINR Neutrino Program (Baikal-GVD) with about $5M per year.



BAIKAL-GVD. Deep underwater muon and neutrino detector at Lake Baikal



The next generation neutrino telescope, BAIKAL–Gigaton Volume Detector, is aimed at studying astrophysical neutrino fluxes and mapping the high-energy neutrino sky in the Southern Hemisphere including the region of the Galactic center.

Other topics include:

— Search for neutrinos from point-like sources,

— Neutrinos from GRB and AGN,

— Diffuse flux of HE-neutrinos,

— Atmospheric ν-s oscillations, mass hierarchy, etc

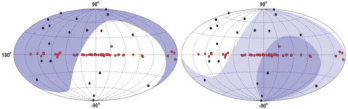
— Neutrinos from DM annihilation in the Sun and the Earth,

— Non-SM neutrino interactions,

— Magnetic monopoles, Q-balls, etc,

— Global ν Network,

— IceCube PeV-νs?

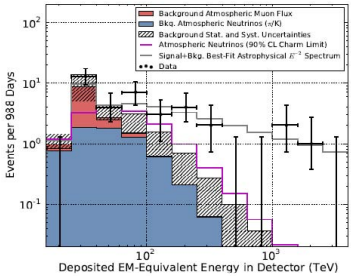


October 15, 2013. München. MoU signing

From left to right: Christian Spiering, Maarten de Jong, Tyce DeYoung, Zhan.-Arys Djilkibaev, Juan-Jose Hernandez-Rey, Paschal Coyle, Olga Botner, Uli Katz.

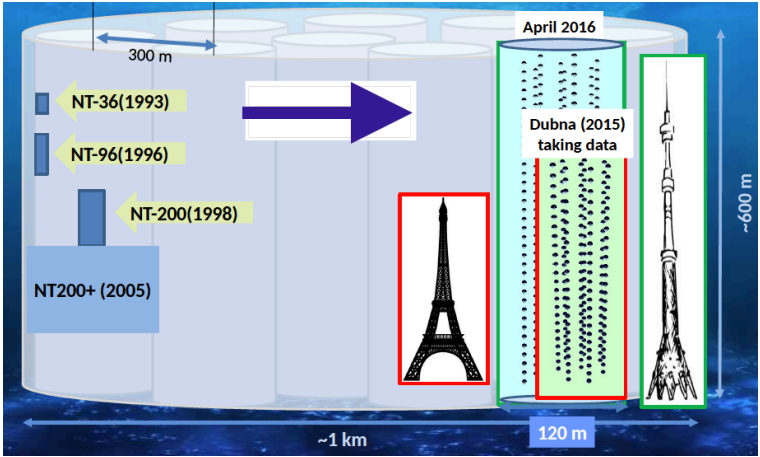
IceCube, KM3Net, Baikal-GVD jointed into Global Neutrino Network

IceCube (left) and Baikal-GVD (right) are complementary to cover the all neutrino Sky.



IceCube sees (extra)galactic neutrinos, but not very good. The key parameter of the BAIKAL-GVD is angular resolution, which should be much better than 1°!

2016 was the key year for the Baikal-project development.

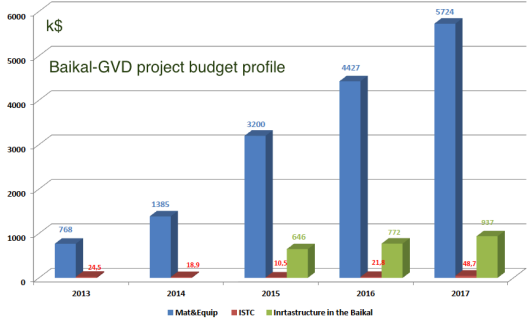




In 2 years a great step was taken by JINR to the full-scale Baikal-cluster. One can compare this huge progress with previous 20 years of the project development (very important in fact).

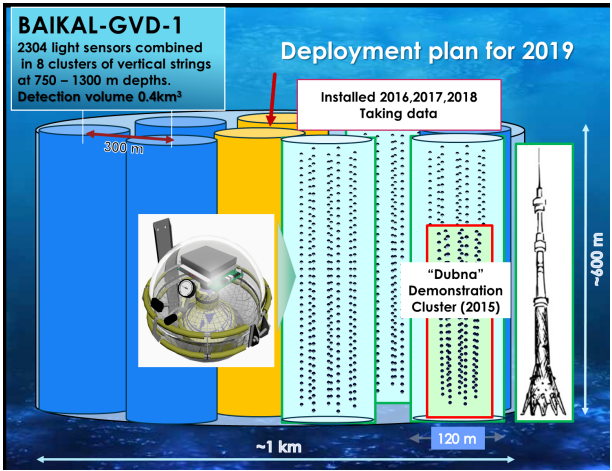
Mass production and testing of optical modules were organized in Dubna.

Baikal-GVD JINR budget in 2013–2018.



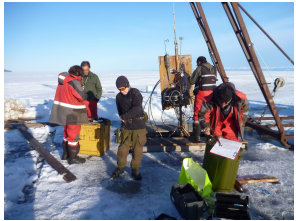
The JINR Directorate has approved this budget increase, and guaranteed the Baikal-GVD progress

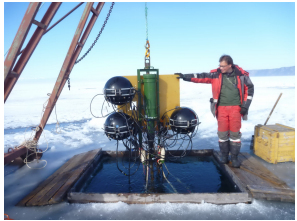
It looks like all things are going well and we will manage to be in time ...



Configuration	2015	2016	2017	2018
The number of OMs	192	288	576	864
Geometric sizes, m	Ø80×345	Ø120×525	2×Ø120×525	3×Ø120×525
GVD Effective Volume	0.03 km3	0.05 km3	0.1 km3	0.15 km3

JINR team in Baikal-GVD is:
I.Belolaptikov, E.Sushenok, R.Dvornicky, N.Gorshkov, M.Kolbin, K.Konishev, A.Korobchenko, M.Kruglov, V.Nazari, T.Orazgali, E.Pliskovski, V.Rushay, B.Shaybonov, A.Svistunov (1.0), A.Doroshenko, K.Golubkov, M.Milenin, A.Panfilov, D.Petukhov, G.Safronov (0.5), P.Antonov, E.Khramov, S.Sinegovski (0.3), V.Brudanin (0.2) = 17.1 FTE (8.3 FTE 2015).



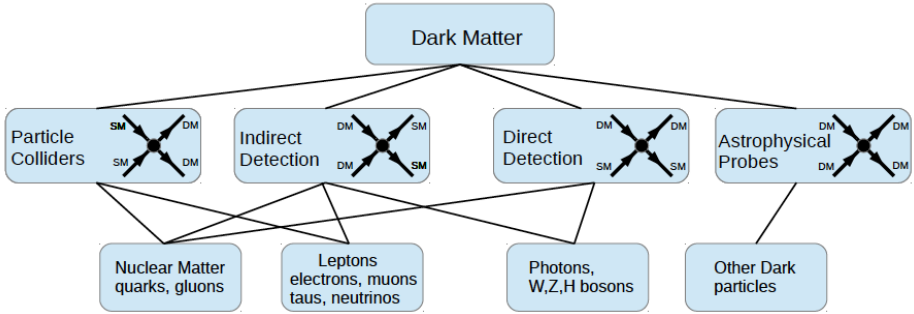


Installation of the 1st GVD-cluster DUBNA

The team participates in all major steps of the project:
1) Assembly, test and study of OMs (the main detection units). Only at JINR one has facility for testing and calibration of OMs; 2) Preparing elements of basic construction of the detector; 3) Computing and data taking shore part of the DAQ system and clusters synchronization; 4) All network structure, access and security service at the site; 5) Remote control and monitoring of the detector; 6) On-line and simulation software support and development; 7) Data analysis frame support and development, data transfer from the site, collecting raw data, support data bank in JINR. JINR is the data center of the Baikal-GVD project; 8) Primary data analysis and monitoring; MC production; reconstruction of track events, events selection, etc.

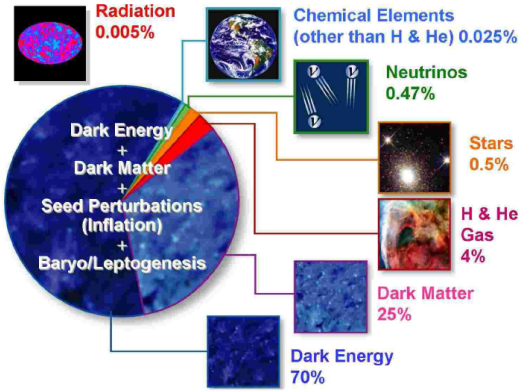
The JINR team plan ($\equiv$ the Collaboration one) is to assemble elements of the detector and deploy 2 clusters (2X288 OMs) per year. To improve reliability of equipment, JINR creates a full-scale testing facility, which will allow for long-time test of the equipment in a whole architecture (cluster). The facility will allow one to optimize the OMs production line for rate up to 900 OM per year and to prepare an extra cluster for long-time testing. JINR will extend computing resources for disk space and computing power for analysis and MC sumulation.

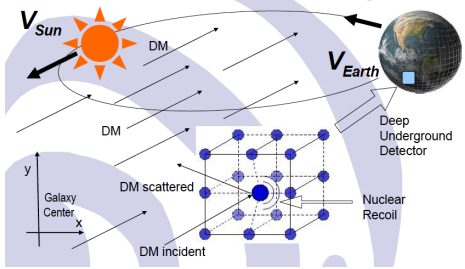
Dark Matter search in Dubna

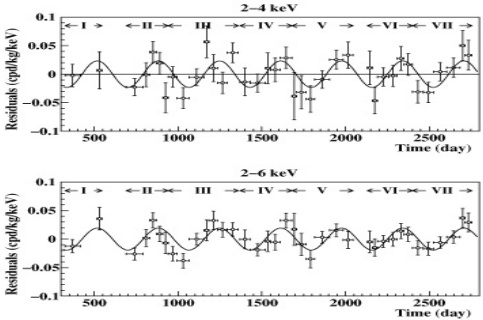


Formation of the Universe from the Big Bang requires non-gravitational interaction (very-very weak?) between the dark and ordinary matter → Weakly Interacting Massive Particle (WIMP) is a prime candidate for the relic Dark Matter.

Only Direct DM detection can prove the WIMP is true Dark Matter





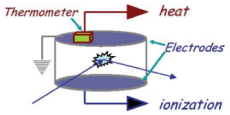


Direct Dark Matter detection idea:

One looks for tiny nucleus recoils due to WIMP interactions with target material. Next, one extracts some positive signature from the recoil spectra to prove true DM nature of the interactions. Annual modulation of the spectra is the only available DM signature: seen only by DAMA/LIBRA →

EDELWEISS-LT — Direct low-mass WIMP searches with HPGe Semiconductor Bolometers at LSM Underground Laboratory (4800 m.w.e.)

The EDELWEISS searches for direct evidence of Dark Matter (DM) particles through their scattering off Ge nuclei within cryogenic Ge bolometers (20 mK) with simultaneous measurement of phonon and ionization signals. Comparison of these signals gives very efficient event-by-event discrimination between nuclear recoils (induced by DM and n scattering) and background electrons.



Completed EDELWEISS-III used 800-grams FID (Fully Inter-Digitized) detectors with a significantly increased (for the annual modulation signature) fiducial volume →

EDELWEISS-III detectors have an excellent background rejection performance, *the best in the World*, but not competitive with large Ar/Xe DM detectors above 6 GeV/c^2.





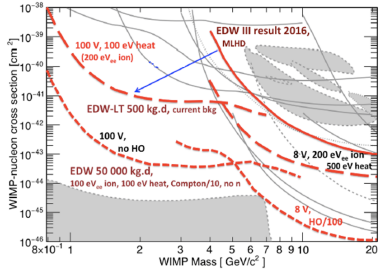
The Collaboration runs EDELWEISS-LT aimed at "light" WIMPs, Axion-like particles in the energy region inaccessible by the large Ar/Xe DM detectors. At the R&D stage a number of interesting results was already obtained: arXiv:1901.03588

Dubna team (6 FTE) participates in all stages of the EDELWEISS project:
– Assembly and commissioning of each new stage of the experiment;
– Data taking (including daily routine procedures, as well as regular and special calibration runs);
– Low background study and development of methods of neutron and radon detection;
– R&D of new low energy threshold HPGe detectors, Detector simulations, data acquisition and data analysis;
– At JINR an equipment for radon-emanation study and new less-radioactive components will be developed.





JINR R&D of EDELWEISS detectors, holders, supports



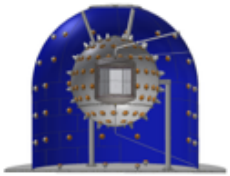
Current (EDWIII 2016) and expected limits (EDW50000 kgd).

The JINR group in parallel uses EDELWEISS LSM infrastructure for R&D of semiconductor detectors with ultra-low energy thresholds and selection of less-radioactive materials. This is a basis for domestic GEMMA/νGeN experiments and for R&D.

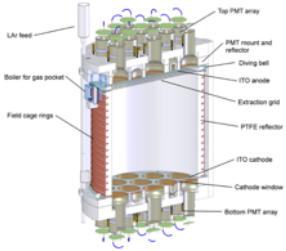
DarkSide — Dark Matter search experiment using low radioactivity argon (low ^{39}Ar) at the Gran-Sasso Underground Laboratory (3400 m.w.e.)



DarkSide-50 (50 kg prototype 2-phase Argon TPC) runs in the tank of the CTF (Borexino prototype). Important results are obtained in 2017, including the best limits for low mass DM particles: 100 GeV (100 GeV, 10 TeV) are 2×10^{-44} (8.6×10^{-44}, 8.0×10^{-43}) cm^2.

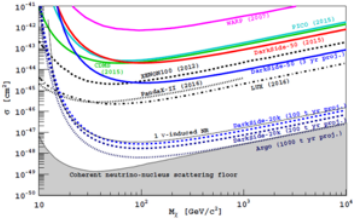


JINR (Borexino team, 3.75 FTE) was involved in the project from the beginning. Dubna group activities are: analysis of the ^{39}Ar data from DS-50, Seasonal variation search with DS-50, Testing of the muon veto PMTs, Development of the Geant-based platform for muon-veto simulations, MC tuning of the DS20k configuration, Neutron veto design and SiPM modeling for DS20k, etc



DarkSide Collaboration plans a new G2 experiment (DS20k) with 20 tonnes of Ar-filled TPC.

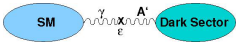
There is agreement with ArDM(LSC), DS50(LNGS), DEAP3600 and MiniCLEAN (SNOlab) to join efforts to carry out DS20k as a single G2 experiment: Global Argon Dark Matter Collaboration (GADMC).



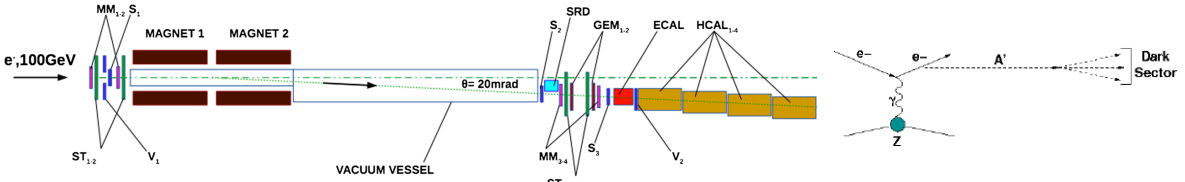
JINR will take part in the seasonal variation search in the DS-50 data and study of the ^{39}Ar spectrum.

NA64 — Search for dark sectors in missing energy events at the CERN SPS

Besides Standard-Model World one has some Hidden Sector which interacts with SM-World via some Dark Force exchange. The most popular mediator is a massive vector boson (Dark Photon, arXiv:1311.0029). One searches for the the Dark Photon (or axion-like particle).

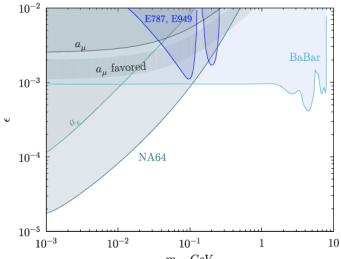


The NA64 is a fixed-target experiment at the CERN SPS utilizing the active beam dump combined with the missing energy approach to search for invisible decays of Dark Photon (A'), invisible decays of $K_{S,L}$-mesons and hadron as well as μ-interactions resulting in invisible final states due to production of new penetrating particles.

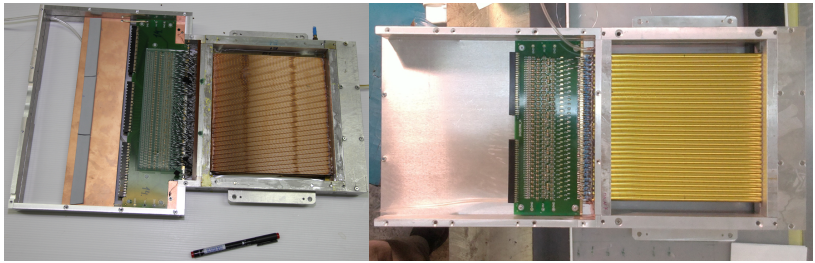


Phys.Rev. D.97 072002 (2018): *The NA64 setup (left) to search for $A' \rightarrow$ invisible decays of the bremsstrahlung A's produced in the reaction $eZ \rightarrow eZA'$ (right) of 100 GeV e^- incident on the active ECAL target.*

JINR group (4.7 FTE) in NA64 is responsible for the tracking system: coordinate detectors based on the thin-wall drift tubes (straw tubes).



The NA64 exclusion region in the $(m_{A'}, \epsilon)$ plane.

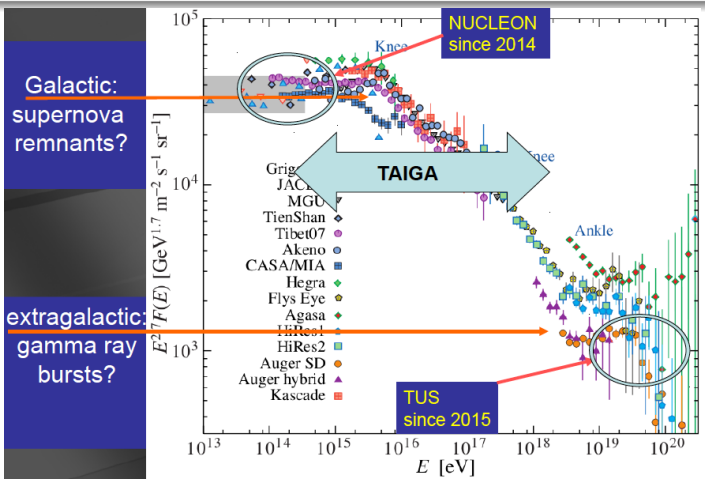


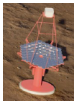
600 6mm-straw-tubes [right] (6 frames of chambers) and 800 2mm-straw-tubes [left] (8 frames of chambers) were manufactured at JINR; all chambers were assembled, equipped and tested. On-line monitoring and visualization for the chambers, decoding and data acquisition software were prepared.

JINR participated in NA64 data taking and was responsible for the straw tube chambers.

JINR group plans to install all JINR equipment in experimental zone at SPS H4 channel in 2019. JINR team plans R&D on new large area straw-tube chambers and R&D with cosmic and ion-sources aimed at the improvement of the chambers, tests of electronics and DAQ modernization. JINR will participation in data analysis, MC simulation, reconstruction and preparation of the proposal for the 2nd stage of the experiment.

Dubna Astroparticle Physics — TAIGA, TUS, NUCLEON

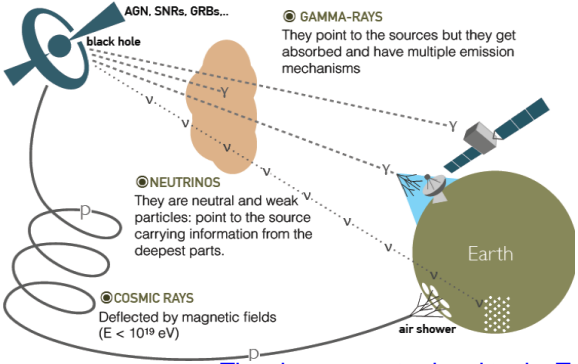




TAIGA — **T**unka **A**dvanced **I**nstrument for cosmic rays and **G**amma **A**stronomy (*Russia, Germany, Italy, Romania, ...*)



To understand the work of Cosmic Accelerators, detections of cosmic rays, γ–rays and neutrinos are needed.



The main topics of the TAIGA array:

Multi-TeV γ-ray astronomy: search for galactic sources of particles up to PeV-energies, VHE spectra measurement of known sources (where do they stop?), diffuse emission measurement from the galactic plane and local supercluster.

Charged cosmic ray study of the energy spectrum and mass composition in 10^{14}–10^{16}eV with high statistics.

Particle physics study includes: axion/photon conversion, hidden photon/photon oscillations, Lorentz invariance violation, pp and pA cross-section measurement, search for quark-gluon plasma, indirect search for dark matter particles ...

The observatory is placed in the Tunka Valley (50 km from Lake Baikal).

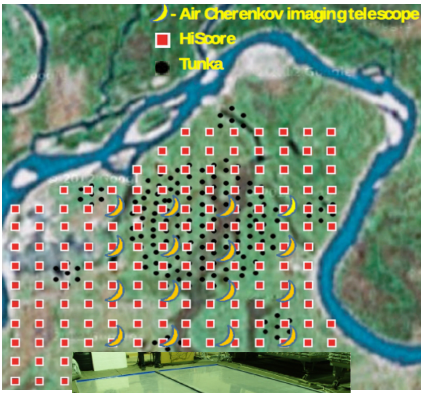
TAIGA hybrid array will be made of:
500 wide-angle optical stations,
16 Imaging Air Cherenkov Telescopes,
Net of muon detectors:

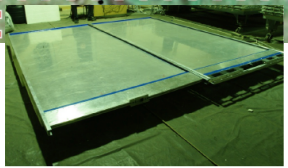


Non-imaging wide-angle optical stations (HiSCORE)



Net of imaging detectors, mirrors 8 m^2

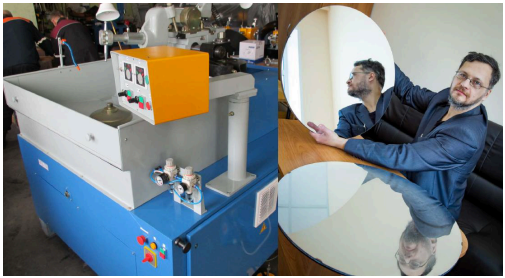


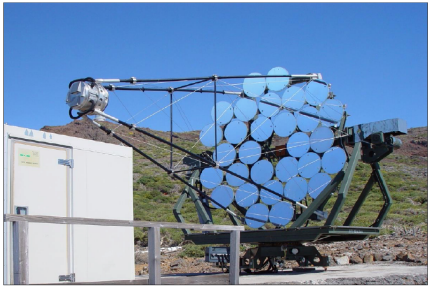


Muon detectors, sensitive area 2000 m^2

Core position and direction of an EAS will be measured by HiSCORE stations.
Background suppression is the goal of individual IACTs.
The hybrid array of HiSCORE + Imaging detectors give superior background suppression.

JINR team (7.4 FTE) full responsibility is the Imaging Air Cherenkov Telescope (IACT) design, mechanics manufacturing and tests. Two IACTs were produced up to 2018. JINR is responsible for 1200 PMTs tests and calibration for IACTs. JINR team participates in shifts at Tunka area, MC simulation and physical analysis.







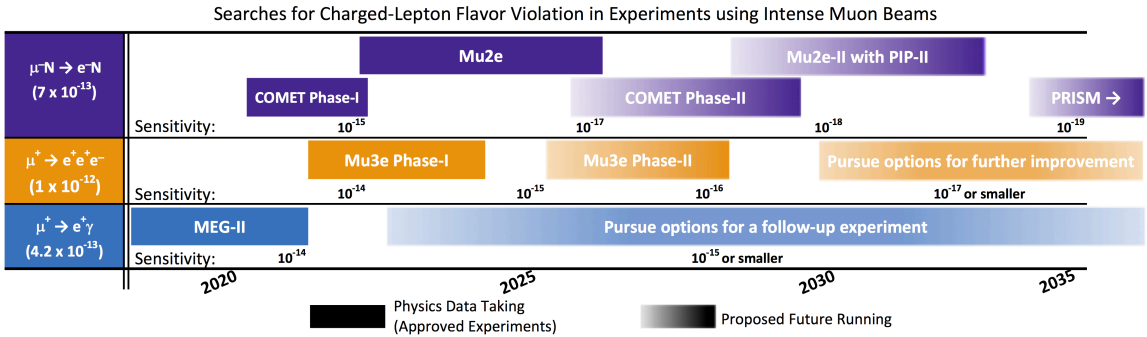
The 2nd IACT at DLNP

→ The 3rd IACT will be redesigned including experience of operation in Siberia and delivered to Tunka in August 2019.

→ R&D of focusing mirror facets production was started in JINR. With a polishing machine the first facet prototypes were fabricated by the bending glass technology. For IACT-3 30-35 mirror facets will be produced.

→ In 2019 the Collaboration plans to increase the area of TAIGA-HiSCORE to 1 km^2, deploy two new IACTs and 200 m^2 of new muon detectors. After that it will be possible to start realization the TAIGA scientific program.

Charged Lepton Flavour Violation search with muon beams in Dubna: Mu2e, COMET, $\mu \to e\gamma$, g–2

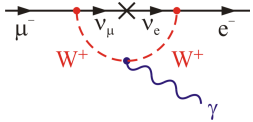


Due to non-zero neutrino Pontecorvo-Maki-Nakagawa-Sakata mixing matrix: ν-oscillations "guarantee" neutrinoless transitions between generations of charged leptons:

$$\mu \to e\gamma,\ \mu \to 3e,\ \mu N \to eN,\ \tau \to \mu\gamma,\ H \to \mu\tau ...$$

However, exceptionally small neutrino masses completely close the feasibility of such processes in the Standard Model ($\sim 10^{-50}$).

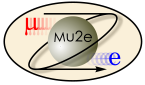
$$|V| = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{pmatrix} 0.84 \pm 0.01 & 0.54 \pm 0.02 & 0.05 \pm 0.05 \\ 0.38 \pm 0.06 & 0.60 \pm 0.06 & 0.70 \pm 0.06 \\ 0.38 \pm 0.06 & 0.60 \pm 0.06 & 0.70 \pm 0.06 \end{pmatrix} \end{array}$$



Therefore search for flavor transitions among leptons (unlike quarks) is a most clear probe of many New Physics models at unique energy scales (up to 10^5 TeV).

DLNP participates in preparation for high-sensitivity search for Charged Lepton Flavor Violation in $\mu N \to eN$ via measuring the ratio of the conversion rate to the ordinary μ-capture rate: $R_{\mu e} = \dfrac{\Gamma(\mu^- \mathrm{Al} \to e^- \mathrm{Al})}{\Gamma(\mu^- \mathrm{Al} \to \nu_\mu \mathrm{Mg})}$.

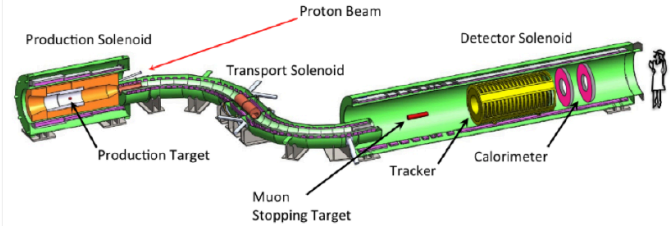
It is very exciting, if one could measure muon-to-positron conversion, because it is a direct analog to the famous neutrinoless double beta decay ($0\nu\beta\beta$) and "measures" muon-to-electron transition effective neutrino mass (which is sensitive to absolute neutrino mass scale): $\langle m_\nu \rangle_{\mu e} = V_{e1} V_{\mu 1} m_1 + V_{e2} V_{\mu 2} m_2 + V_{e3} V_{\mu 3} m_3$.



Search for Charged Lepton Flavor Violating neutrinoless conversion of a muon to an electron in the field of a nucleus at FNAL



The goal of the Mu2e experiment is a process with charged lepton number violation when a muon coherently transforms into an electron in a nucleus $\mu^- N \to e^- N$. The first phase of the experiment will be held with the Al target in 2020–2023. The sensitivity expected in 2023 is 6×10^{-17} (10,000 times better then in SINDRUM-II).



The beam line begins by colliding protons onto a production target to produce low momentum pions. The resulting πs are either transported through a decay volume or directly stopped inside the target, and their decay μs are collected. It requires low momentum muons (50 MeV/c), in order to stop them in thin targets at the center of the setup. To reach the target sensitivities requires high-intensity μ-s (10^8 μ/s).

The detector must precisely determine the energy, momentum, and timing of particles originating from the muon stopping target.

The Mu2e Project achieved a significant milestone in 2016 (July 14) when deputy director for science programs in the DOE (Pat Dehmer) approved Critical Decision 3, which authorizes start of full construction.



DLNP (13.3 FTE) conducted R&D on the choice of the scintillation crystal and EM calorimeter veto system, participated in data simulation, creation and testing of the detector systems. A method for increasing the light yield from scintillation strips was developed. Beam tests of Cosmic Ray Veto (CRV) counter prototypes were fulfilled.

Radiation hardness tests of the scintillator strips and filler samples at the IBR-2 facility were performed. Technology of the CRV 4-layers module assembly was developed→





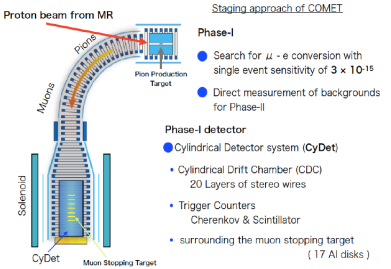
JINR plans in Mu2e experiment are:

– Participation in production and test (with radioactive sources and muons) of the CRV modules.
– Creation of a system for parallel filling of the fiber holes with synthetic low molecular weight rubber (SKTN) for several discounters simultaneously. Filling the discounters for all long CRV modules (about 7 meters). *Dubna is responsible for this task.*
– Creation test bench and performing tests of all Mu2e EMC-preamplifiers at Dubna.
– Performing neutron radiation hardness tests of preamplifiers at JINR IBR-2.
– R&D with BaF2 crystals which are planning to be used in the second stage of the Mu2e experiment.
– Participation in the Mu2e detector assembly, tests and commissioning.

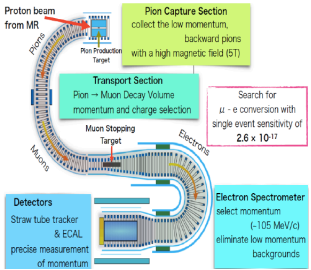
COMET (COherent Muon to Electron Transition) — search for neutrino-less conversion of muons to electrons in a nucleus at J-PARC (Japan)

The COMET will look for $\mu^- + (A, Z) \to e^- + (A, Z)$ conversion with the same accuracy (10^{-17}) as the Mu2e experiment (with another setup). Independent observations of the process are very important.

Phase - I



Phase - II



The goals of Phase-I are:

– Direct measurement of the p-beam extinction and other potential background sources for the full COMET experiment with actual beam line;

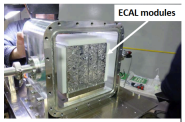
– Search for $\mu \to e$ conversion with sensitivity of $3 \cdot 10^{-15}$ (200 times better the current best SINDRUM-II limit).

The goals of Phase-II (unapproved yet) are:

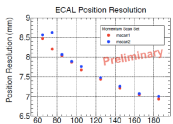
$\to$ Creation of a full beam line, use of higher beam intensity, modifications of the detector configuration from CDC to the Straw tracker and ECAL. The 8 GeV proton beam power will increase from 3.2 kW (Phase-I) to 56 kW (Phase-II). These modifications and experience (Phase-I) will make possible to reach sensitivity of $3 \cdot 10^{-17}$.

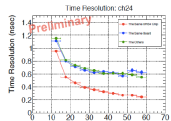
JINR (20.5 FTE) contributes to R&D and construction of two basic COMET detector systems: the Electromagnetic CALorimeter (ECAL) and Straw tracker detector.

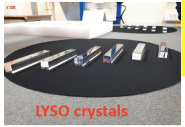
Straw-Ecal prototypes combine test (March 2017) (1.3 GeV electron cyclotron), Japan



Prototype (8x8, 64) of calorimeter



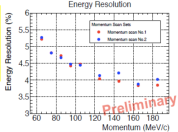




The ECAL beam test results for 105 MeV electron

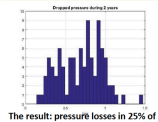
- Position resolution – 7.6 mm
- Time resolution – 0.4 ns
- Energy resolution (σ/E) - 4.2%

- 2400 LYSO crystals
- 20 x 20 x 120 mm³
- readout → 10 x 10 mm² APD

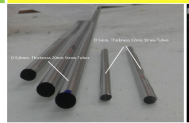


Testing about 2,700 straw tubes for Phase I in Japan

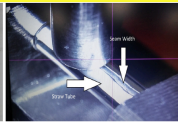
First R&D: 5 mm diameter straw tubes made of 12 mic aluminized mylar at JINR-DLNP for COMET



The result: pressure losses in 25% of 9.8 mm tubes during 2 years

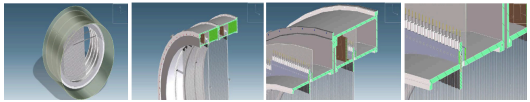


Comparison of 9.8 mm and 5 mm straw tubes



Straw Tube ultrasonic welding process

Engineering design work



JINR → ECAL:
R&D of LYSO crystals based calorimeter;
LYSO crystals parameters investigation;
Certification of the LYSO crystals; etc

JINR → Straw tracking (for Phase I):
Straw tubes design and production (∼2700), preliminary tests, checking of properties. Simulation of straw tracker; Study of gas mixtures properties; Study of the temperature and time dependence of the straw tubes.

In 2018 a new manufacturing area for straw-tube R&D and production was created at DLNP.

JINR plans are: R&D of a new type of the LYSO crystals (ECAL); check the Straw Tubes in Japan before installation, preparation for assembly; R&D on the straw-tube at DLNP; the straw-tube simulation, etc.

Priorities within the Neutrino Programme and the related topics:

1. Baikal-GVD
2. JUNO
3. GEMMA, νGeN, DANSS (KNPP)
4. NOvA, Daya Bay, EDELWEISS, SuperNEMO, GERDA
5. Mu2e, COMET $\rightarrow$ *to join in one powerful JINR CLFV-topic...*
6. BOREXino, TAIGA, NA64, g–2
7. DarkSide, TUS, NUCLEON, MEG, etc

Conclusion

- All main projects of the JINR Neutrino Programme (Baikal-GVD, JUNO, DANSS, GEMMA, νGeN, NOvA, EDELWEISS, SuperNEMO, GERDA, Mu2e, COMET) are of highest scientific importance
- JINR is on the main stream of modern particle physics (Neutrinos, Astrophysics, Dark Matter, CLFV, ...)
- JINR has clear future on the stream due to many young scientists strongly involved.







Thank you very much!

Conclusion

- All main projects of the JINR Neutrino Programme (Baikal-GVD, JUNO, DANSS, GEMMA, νGeN, NOvA, EDELWEISS, SuperNEMO, GERDA, Mu2e, COMET) are of highest scientific importance
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Thank you very much!

Extra Slide Collection

There is a special interest in the (anti)neutrino experiment νGeN !

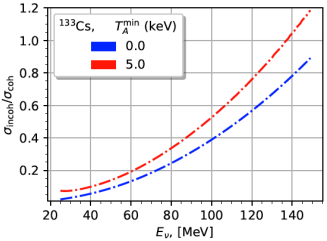
The first experimental evidence for CNNS was reported in 2017 by the COHERENT Collaboration. CsI[Na] scintillator was exposed by pulses of neutrinos with energies of tens of MeV produced by the Spallation Neutron Source at the Oak Ridge National Laboratory. But at these E_ν the momentum transfer q is large enough to break the coherence condition $qR \ll 1$. Energy deposits observed by COHERENT correspond to $1 < qR < 2.7$ and the elastic cross-section should be suppressed. Furthermore, the COHERENT threshold is 5 keV (for Gs). At higher energies, but still in the regime where the nucleus conserves its integrity, the elastic cross-section vanishes and the νA interaction probability must be determined by inelastic interactions. The corresponding cross section should be given by a sum of elastic and inelastic cross sections.

Question: What has COHERENT really seen? What are the coherency and the incoherency in elastic νA scattering?

Answer: in Phys. Rev. by V.Bednyakov and D.Naumov — a broken tail of CNNS...

Ratios incoh/coh for νA-scattering as a function of E_ν, $T_A^{\min}$ (detection threshold) are $\rightarrow$

"The coherent and incoherent regimes appear due to elastic and inelastic processes, when all possible initial and final states are taken into account. The coherent and incoherent cross-sections are driven by $|F^2_{p/n}|$ and $(1 - |F^2_{p/n}|)$ factors, providing a smooth transition between them. For ^{133}Cs and $E_\nu \simeq 40$ MeV the incoherent cross-section is about 15% of the coherent one. The incoherent processes being a relatively small "background" to the coherent ones provide an important clue if γs released by excited nucleus are detected. Detection of both signals due to nuclear recoil and excitation γs is a sensitive instrument in studies of nuclear structure and signs of new physics".



Ergo: It is very important to observe true CNNS — *where incoherence is suppressed very significantly* $\rightarrow$

The goal for the νGeN experiment with its very low energy threshold!

The DLNP principles of participation in an international experiment:

– The experiment must be of highest scientific importance

– Contribution of the DLNP must be crucial, even if not the biggest one (the Flerov's principle)

– Something important must remain in the DLNP from this participation (equipment, workshops, highly skilled personnel, experience, ideas, image)

– The youth generation should be involved in the experiment (as indicator of relevance, as a guarantee of future development, as a way of training highly qualified personnel, etc)

The Nature of Neutrinos is a central problem of elementary particle physics and astrophysics.

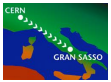
By the Nature we mean properties of neutrinos, which determine the specificity of their interaction with the matter — masses, the character of their transformation into each other (mixing), how many different types of neutrinos, Dirac or Majorana they are, if they have electromagnetic properties, as well as their natural sources (cosmic origin).

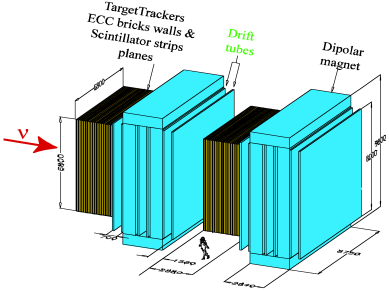
This is really the key, interdisciplinary problem which connects the entire elementary particle physics, cosmology and astrophysics.

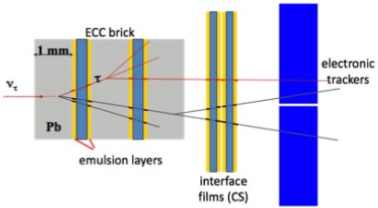
By high fundamental level, world outlook importance, number of unresolved problems and huge potential of unexpected discoveries the Neutrino Physics and Astrophysics — among undisputed leaders (*Russian Academy of Science. 2012*).

To solve its specific problems, neutrino physics requires unique equipment never known before. Its development gives rise to utterly new, equally unique technologies, materials, and instruments, which in turn are in demand in other fields of science and in everyday life.

The OPERA goal — observation of $\nu_\mu \to \nu_\tau$ oscillation via registration of ν_τ appearance in ν_μ beam from CERN (17 GeV, 732 km, 1400 m underground in the Gran Sasso Lab).

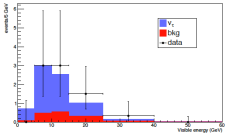






Emulsion Cloud Chamber (ECC) detector had a modular structure made of a sandwich of passive material plates interspaced with emulsion layers (bricks). Wall made of 3264 bricks and 2 planes of electronic Target Tracker comprised a module. Two supermodules were made of a target section which is a sequence of 31 modules, and of downstream muon spectrometer.

OPERA data taking was completed and the result on the discovery of muon to tau neutrino oscillation was already published. Final OPERA result is (1804.04912.pdf; 1811.00095.pdf): 10 observed events with expected background of 2 events. It allowed OPERA to improve the significance of muon to tau neutrino oscillation observation in appearance mode to 6.1 sigma. In addition, an estimate of the tau neutrino CC cross section was performed with the OPERA data.



NEUTRINOS

OPERA concludes on tau appearance

The OPERA experiment, located at the Gran Sasso Laboratory of the Italian National Institute for Nuclear Physics (INFN), was designed to conclusively prove that muon-neutrinos can oscillate into tau-neutrinos by studying beams of muons sent from CERN 730 km away.

In a paper published on 22 May, describing the very final results of the experiment on neutrino oscillations, the OPERA collaboration has reported the observation of a total of 10 candidate events for a muon-to tau-neutrino conversion. This result demonstrates unambiguously that muons morph into tau neutrinos on their way from CERN to Gran Sasso.

The OPERA collaboration observed the first tau-neutrino event (evidence of muon-neutrino oscillation) in 2010, followed by four additional events reported between 2012 and 2015. A new analysis strategy applied to the full data sample collected between 2008 and 2012 led to the new total of 10 candidate events, with an extremely high level of significance. "We also report the first direct observation of the tau-neutrino lepton number, the parameter that discriminates neutrinos from antineutrinos," says Giovanni de Lellis, OPERA spokesperson. "It is extremely gratifying to see today that our legacy results largely exceed the level of confidence we had envisaged in the experiment proposal."

Beyond its contribution to neutrino physics, OPERA pioneered the use of large-scale emulsion films with fully automated and high-speed readout technologies with submicrometre accuracy. These technologies are now used in a wide range of other scientific areas, from dark-matter searches to investigations of volcanoes, and from the optimisation of hadron therapy for cancer treatment to the exploration of secret chambers in the Great Pyramid. The OPERA collaboration has also made its data public through the CERN open data portal, allowing researchers outside the collaboration to conduct novel research and offering tools such as a visualiser to help adapt the datasets for educational use.

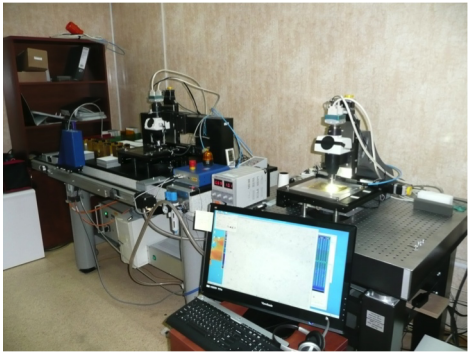


The OPERA detector (left) and an event display showing a muon-to-tau neutrino conversion (right).

Further reading

OPERA Collaboration 2018 *Phys. Rev. Lett.* **120** 211801.

JINR group has contributed significantly to scintillator strip production and the Target Tracker detector construction (modules and detector assembly and calibration), operation (brick finding task software) data taking and to the physics analysis of the OPERA data.



JINR team today is S.Vasina, E.Sitnikova (1.0), Yu. Gornushkin, S. Dmitrievsky (0.5), A.Sotnikov (0.2) with annual budget about 13k$ (activity under 1099)

JINR created the scanning lab equipped with two automatic scanning stations and performed the OPERA emulsion data analysis. Software for finding brick with the neutrino vertex was developed at JINR.

← JINR emulsion scanning station for emulsion processing.

JINR has proposed the improved method of the neutrino event time registration which allowed to perform correct measurement of the neutrino velocity after the hardware bug elimination, etc.

JINR made principal contribution in the $\nu_\mu \rightarrow \nu_e$ analysis and preparation of the publications.

The BORon solar neutrino EXperiment, BOREXino, at the Gran Sasso underground laboratory (since 1992, Italy).



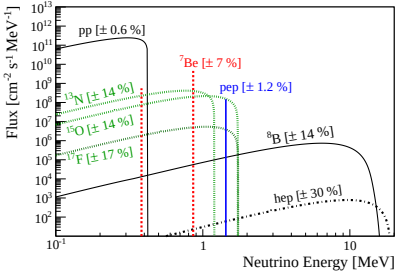
The first stage goal of Borexino experiment — solar ^{7}Be ν-flux measurement with 5% precision was achieved in 2011.

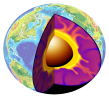
To reduce main contaminants in the sub-MeV range repurification was completed in 2011–2013.

At the second stage, with the high radiopurity Borexino can perform new investigations:

Solar Neutrino study, solar models discrimination.
— Improvement of ^{7}Be neutrino flux measurement (3%)
— pp-neutrino flux measurement with 10% precision
— pep neutrino measurement with better precision (>3σ)
— ^{8}B neutrino measurement with 4-fold statistics (10%)
— measurement (or limits) on the CNO neutrino flux.
Search for non-standard interactions of neutrino.
Search for dark matter with modified Borexino-CTF.
Supernova neutrino detection, etc

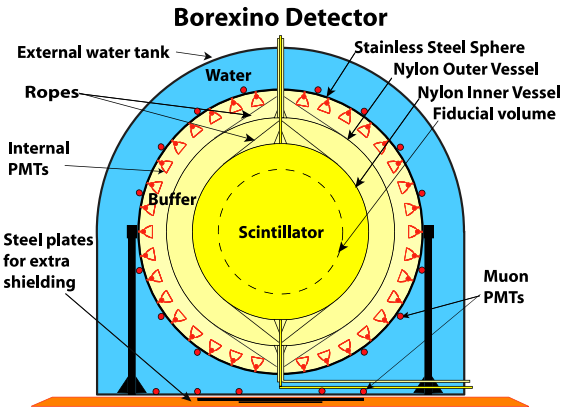
There are no competing projects existing at the moment.

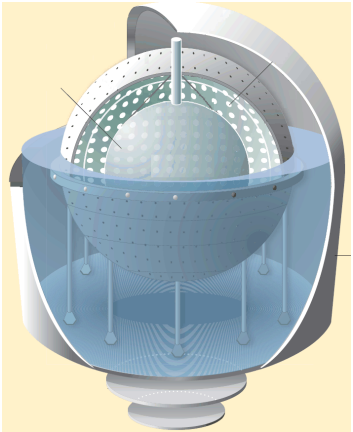




Geoneutrino flux measurement with higher statistics.

The detector is located deep underground (3800 m of water equivalent) in the Hall C of the Laboratori Nazionali del Gran Sasso (Italy), where the muon flux is suppressed by a factor of 10^6.





Borexino uses 278 t of HP liquid organic scintillator to register νe-scattering with 200 keV threshold. The base of the dome-like structure is 18 m in diameter. The scintillation light is collected by 2212 PMTs. The Borexino has an excellent energy resolution (at 662 keV is 44 keV or, 6.6%) for its size, due to the high light yield of 500 p.e./MeV/2000 PMT.

First observation of geoneutrino (10 events), study of natural radioactivity of the Earth, measurement of ^{7}Be solar neutrino flux with 5%-precision, first direct pep solar neutrino measurement, test of seasonal and diurnal variations of the solar neutrino flux, etc — were obtained with significant contribution of JINR team to the detector running and data analysis (with no hardware contribution).

JINR team is A.Vishneva (1.0), O.Smirnov (0.75), K.Fomenko, M.Gromov, A.Formozov (0.5), A.Sotnikov (0.4) = FTE 3.65. Former O.Zaimidoroga and D.Korablev.
— Annual budget is 24k$ (JINR, 1099)



JINR team participated in:

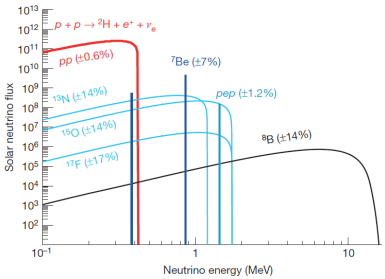
– Data acquisition system for the prototype detector (CTF),
– Preparation of the PMT test facility and tests of 2200 PMTs,
– R&D of the automated system for controlled setting of the PMT HV,
– Tests of the μ-metal magnetic shielding for the CTF and Borexino,
– R&D of the PMT charge and timing calibration techniques,
– Participation in the Borexino cabling and PMT cleaning,
– Data taking shifts with the CTF and the Borexino data taking period,
– Data analysis: Be-7 flux, antineutrino fluxes (geo and limits on the solar neutrino fluxes), seasonal variations, limits on the effective neutrino magnetic moment, pp-neutrino flux, rare processes, etc.

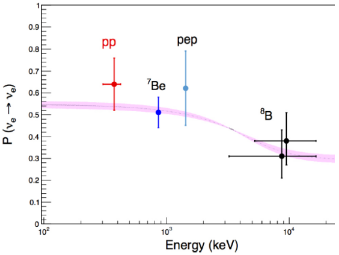
JINR team plans are:

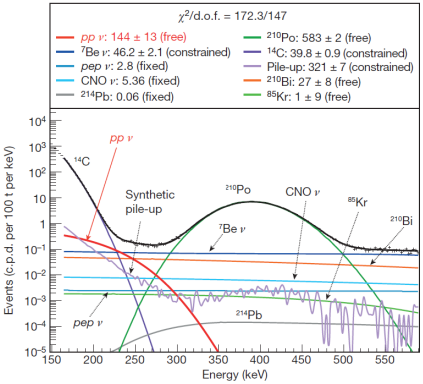
1) A paper about non-standard neutrino interactions, 2) Joint analysis of the Phase I and Phase II data with a goal of 7-8% for the pp-neutrino flux measurement, 3) CNO and geo-neutrino analysis of the extended set of data.

In 2014 the solar neutrino flux from the pp-reaction was measured with the detector Borexino in real time. *G.Bellini, et al, (Borexino Collaboration), "Neutrinos from the primary proton–proton fusion process in the Sun", Nature, vol. 512 (2014) 383.*

JINR has strongly contributed!





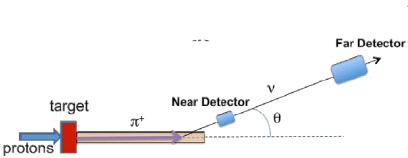


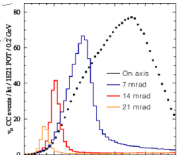
The pp-neutrino events were observed previously in the radiochemical (integrating) experiments (SAGE, GALLEX/GNO), which accounted for 1/2 of the total counts. It was not possible to extract the pure pp-neutrinos without other data.

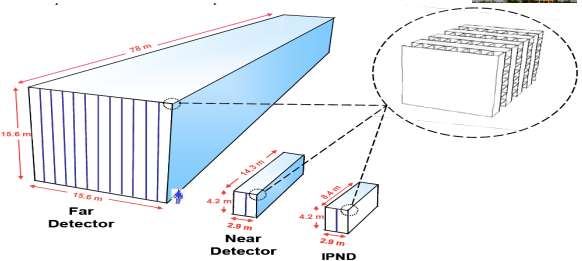
The accuracy of pp-neutrino flux measurement was about 10 %. The result confirms the stationarity of the Sun on the timescale of the hundreds of thousands of years: ν's give a picture of the energy release in the present, solar luminosity corresponds to the energy release in the distant past, the photons from the center of the Sun reach the surface due to the slow diffusion process, which occupies hundreds of thousands of years.

NOvA (NuMI Off-Axis ν_e Appearance) — a new generation accelerator long baseline experiment to study $\nu_\mu \rightarrow \nu_e$ oscillations.









The goal is to precisely measure the neutrino mixing matrix, the neutrino mass hierarchy and CP violation effects in leptons. The NOvA apparatus consists of a Near Detector on the Fermilab site where the ν_μ-s are produced, and a Far Detector 810 km distant, both of similar construction and both situated 14 mrad off-axes to the ν beam. The Far Detector (14 kton) and Near Detector (220 ton) filled with liquid scintillator have been taking data since 2014, and a number of important measurements have been performed on the basis of statistics collected so far.

At present NOvA is closely approaching the 2σ level of excluding Inverse Hierarchy for all values of CP violation parameter. Continuing the data taking, and altering neutrino and antineutrino beams, NOvA can largely improve its sensitivity.

The JINR group in NOvA has contributed significantly to the NOvA results.



— JINR team today: V. Allakhverdian, V. Amvrosov, A.Antoshkin, A.Kalitkina, L.Kolupaeva, C.Kullenberg, M.Petropavlova, O.Petrova (1.0), O.Samoylov, A.Sheshukov (0.7), A.Olchevsky, O.Klimov (0.5), N.Anphimov, N.Balashov, V.Naumov, E.Kuznetsov (0.3), A.Sotnikov (0.2), A.Baranov, S.Bilenky, A.Dolbilov, K.Kuzmin, V.Matveev (0.1) =13.8 FTE.

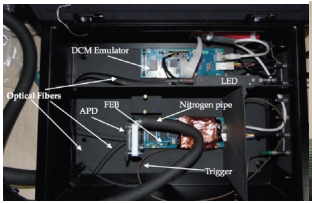
— Annual budget is 130k$ (JINR 1099)

– Members of the JINR group are deeply involved in physical analyses, in particular: the basic oscillation analysis (ν_μ disappearance, ν_e appearance), Supernova and slow monopole searches, Cosmic Ray and measurements in the Near Detector. They are also involved in the development of simulation and analysis software, and are serving as a Detector Simulation conveners, Offline and DAQ Software Release Managers, DAQ, DDT and ROC experts, etc.

– The JINR team plans to extend its involvement in the NOvA data taking and analyses. Maintenance of ROC-Dubna and the hardware test bench facility are planned, as well as a further increase of the NOvA computing power at JINR to cope with the large amount of data, and the continuation of the aforementioned analyses.

Dedicated infrastructure for NOvA experiment was created at JINR.

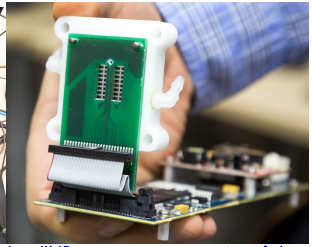
→ The NOvA electronics test bench was set up at DLNP and provided important measurements of electronics parameters used for simulation and calibration.





→ Another test stand was constructed at JINR to measure properties of the liquid NOvA scintillator, mainly to determine Birk's coefficient, which defines the response of scintillator to passage of slow protons.



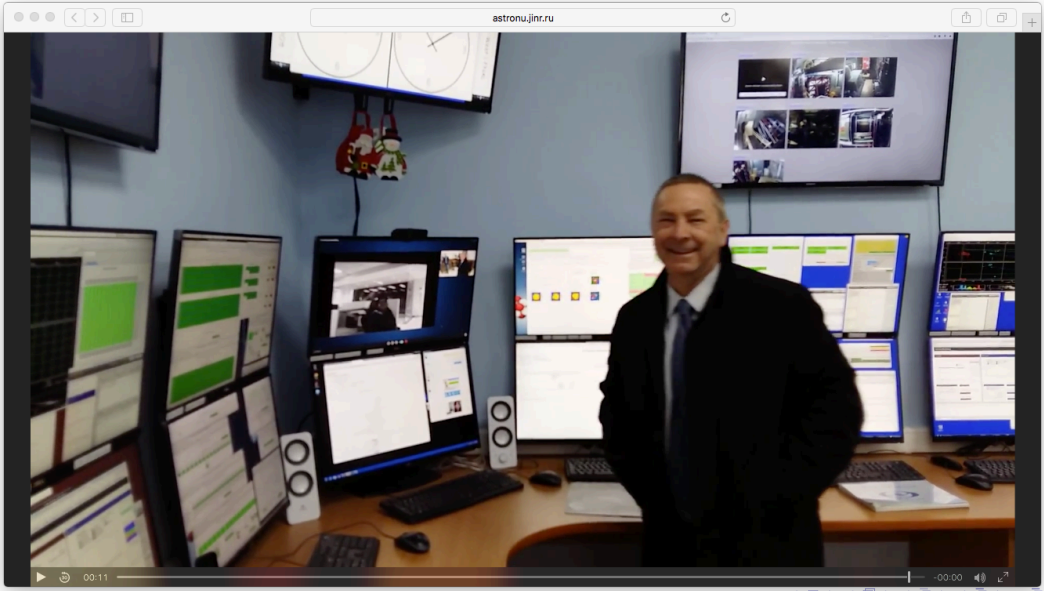


→ The Remote Operation Center (ROC-Dubna) was put into operation in 2015, giving the possibility to fully participate in the data taking and quality monitoring.



→ JINR computer infrastructure on the basis of GRID-Cloud technologies was developed. It is efficiently used for the home-based running of jobs and is a part of the NOvA distributed computing resources system for the use at peak loads.

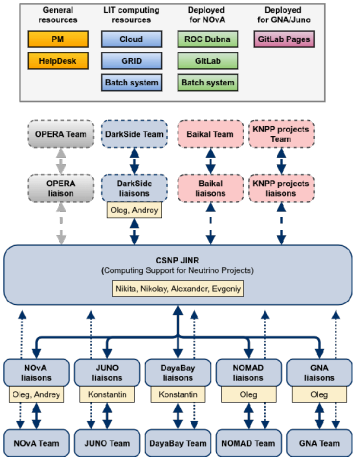
Nigel Lockyer has used NOvA-ROC to communicate with his FNAL people



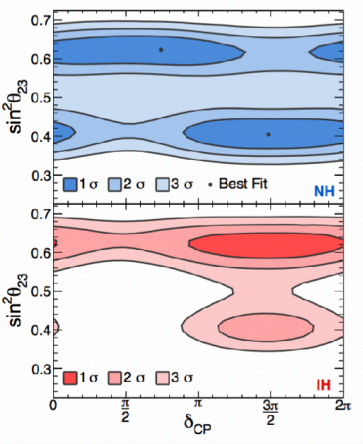
Modern LIT-based computer infrastucture for NOvA:

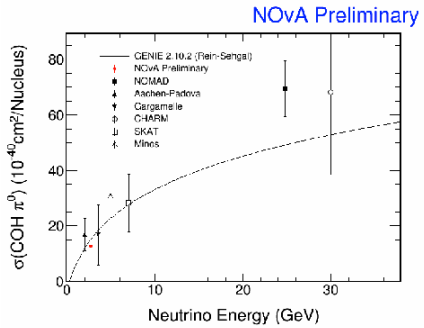
– Tested and installed DLNP local computers to use the NOvA computer software;
– Universal Virtual Machines with NOvA software are implemented into JINR-LIT cloud-infrastructure,
— The Cloud was integrated into OSG (Open Science Grid) to perform simulation neutrino events (NOvA production). The systems were tested with another FNAL experiment — mu2e. – The system is under developing and can be scaleable.
– Disc storage and data-cache for NOvA are under configuration and testing;
– Tier-2 JINR infrastucture was integrated into OSG «NOvA production»,
– There are plans for future enhancement of the NOvA computer resources at JINR.

JINR Neutrino Program already uses most advanced computer resources and facilities (Clouds, Grid, etc) initially oriented to the highest level LHC experiments ATLAS and CMS.



With collected statistics of NuMI 6.05×10^{20} POT:
– one expected 473 ± 30 ν_μ events without oscillations.
– Observed numbers of 78 ν_μ and 33 ν_e events strongly confirmed the oscillations.
– Совместный анализ gave some preference to direct neutrino mass hierarhy and excluded inverse hierarhy at 3σ with $\delta_{CP} = \frac{\pi}{2}$.





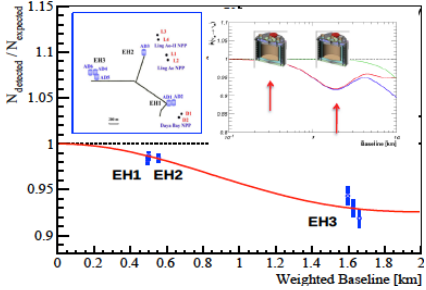
– New ν-interaction cross sections are measured with near NOvA Detector via coherent and semi-inclusive π^0 production in CC channel.
– Search for sterile neutrinos in NC π^0 production was complided.

Recent NOvA papers are:
Phys.Rev. D96 (2017) no.7, 072006 (sterile neutrino); Phys.Rev.Lett. 118 (2017) no.23, 231801 (combined $\nu_e + \nu_\mu$ study); Phys.Rev.Lett. 118 (2017) no.15, 151802 (ν_μ dissapearence).

The reactor antineutrino experiment Daya Bay (China) with near and far identical detectors.

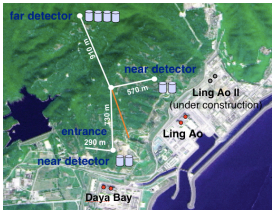


— The main goal of the Daya Bay experiment is measurement of neutrino mixing angle θ_{13} via observation of the reactor $\bar{\nu}_e$ flux deficit on the far site (detectors) in comparison to the $\bar{\nu}$ flux in the near site (detectors).
— In 2012 using 6 antineutrino detectors the experiment has discovered that $\theta_{13} \neq 0$ with statistical significance higher than 7σ and measured the value of $\sin^2 2\theta_{13} (= 0.089 \pm 0.010)$ with highest precision in the world.
Other targets of the experiment include:
— measurement of neutrino squared mass difference Δm^2_{ee}, — measurement of the $\bar{\nu}$-flux (normalization and shape),
— sterile neutrino search,
— oscillation analysis based on hydrogen capture of recoil neutron from IBD reaction $\bar{\nu}_e + p \rightarrow n + e^+$,
— oscillation analysis using 8 antineutrino detectors, and SuperNovae νs detection.

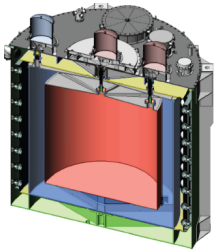


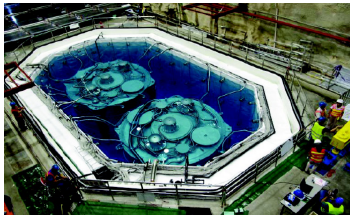
Reactor antineutrinos are recorded by near and far identical detectors. Apparent deficit of number of antineutrinos in the far detectors lead to discovery of new type of oscillations due to $\theta_{13} \neq 0$.

Electron $\bar{\nu}_e$ were detected via the inverse β-decay ($\bar{\nu}_e p \rightarrow e^+ n$). The e^+ almost immediately released its energy and annihilated with e^- (prompt signal, with 1.02÷10 MeV). The neutron was thermalized in about 28μs and was captured by a Gd nucleus, which then emited several γs with a total energy of 8 MeV (delayed signal).



The "geometry" of Daya Bay layout.





The $\bar{\nu}$ detector utilized a 3-zone scintillator structure (3 concentric cylindrical volumes). The innermost volume was the target: 3.1×3.1 m acrylic vessel, filled with 20 t of LS, doped by 0.1% of gadolinium. Next volume (4×4 m) was filled with 21 t of undoped LS used to catch γs and was located in a steel vessel of 5×5 m. The outermost volume was filled with 37 t of mineral oil used as shield against the radiation. 192 8-inch PMT collected the light emitted in LS.

JINR in Daya Bay: 1) Development of the LS, suitable for the large-scale Daya Bay experiment. 2) PPO (2,5-diphenyloxazole) production for the LS (1.5 tons) and delivery to Daya Bay. 3) Suggestion of a new method of tagging fast neutron events based on Flash ADC signals. 4) Development of dedicated software package for the oscillation analyses. 5) With the package 3-ν rate+shape oscillation analysis and search for sterile neutrinos, etc

New Daya Bay oscillation result

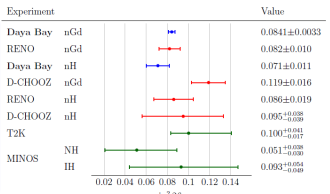
New measurement

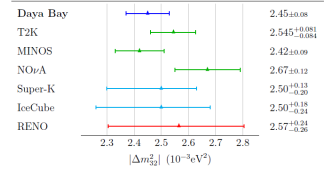
- Based on >2.5M events:

$$\sin^2 2\theta_{13} = 8.41 \pm 0.27\ (\text{stat}) \pm 0.19\ (\text{syst}) \times 10^{-2}$$

$$|\Delta m^2_{ee}| = 2.50 \pm 0.06\ (\text{stat}) \pm 0.06\ (\text{syst}) \times 10^{-3}\ \text{eV}^2$$

- Most precise $\sin^2 2\theta_{13}$ measurement.
- Daya Bay Δm^2_{32} accuracy is comparable with accuracy of the accelerator experiments.





Dubna group contribution

- **JINR result is official now.**
- IBD selection: K. Treskov, A. Chukanov
- Fast neutron selection: K. Treskov
- Osc. analysis: M. Gonchar, D. Naumov
- Candidate thesis: M. Gonchar
- Doctor thesis: D. Naumov

arXiv:1610.04802, PRD

2016 Daya Bay results

Dubna group contribution

- Neutrino wave packet (WP) size: $\sigma_x > 10^{-11}$ cm.
  - Theory: D. Naumov, V. Naumov.
  - Analysis: M. Dolgareva, M. Gonchar.
  - Analysis (FC): D. Taychenachev.
  - Analysis (solar): K. Treskov.

Other important results

- Independent nH rate-only analysis based on 621 days of data is consistent with nGd

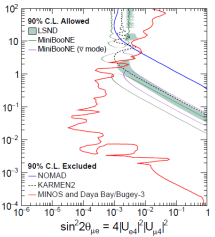
$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

and is the world's third precision measurement.

- Reactor antineutrino flux ~5% deficit.
- Spectral distortion around 5–6 MeV: global (local) significance 2.9σ (4.4σ).
- Stringent limits for sterile neutrinos for

$$2 \cdot 10^{-4}\ \text{eV}^2 < \Delta m^2_{41} \lesssim 2\ \text{eV}^2$$

  - based on combined Bugey+Daya Bay+MINOS analysis.
  - excludes most of the LSND anomaly.



New publications:

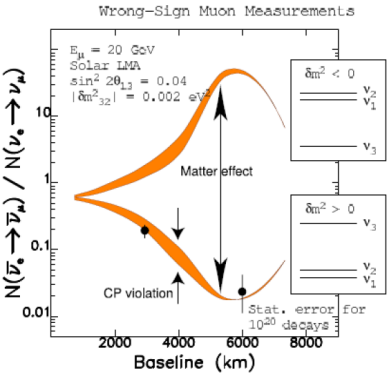
Osc. (nH)	1603.03549 PRD
Sterile	1607.01174 PRL
Sterile+	1607.01177 PRL
Reactor	1607.05378 CPC
WP	1608.01661 PRD
Osc. (nGd)	1610.04802 PRD

JINR current group: Naumova E.A. (0.8), Naumov D.V., Gonchar M.O., Treskov K.A. (0.5), Chukanov A.V. (0.4), Dolzhikov D.A., Zavadsky V.S., Selivanov D.A., Fatkina A.I. (0.2).

The group has developed GNA (Global Neutrino Analysis) — a new tool for fitting comprehensive numerical models with large number of parameters. The application scope of GNA includes: Daya Bay, JUNO, TAO (JUNO near detector), NOvA, PROSPECT and others, as well as the possibility of combination of several analyses with proper systematics treatment.

From Daya Bay → JUNO to fix ν mass hierarchy, CP, SN, etc.





The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment



The main goal is determination of neutrino mass hierarchy and precise measurements of oscillation parameters by detecting reactor $\bar{\nu}$ from Yangjiang and Taishan Nuclear Power Plants with a 20k-ton liquid scintillator detector of unprecedented 3% energy resolution (at 1 MeV) at 700-meter deep underground.

The neutrinos mix via the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_2\end{pmatrix}$$

$\sin^2\theta_{12}=0.307^{+0.018}_{-0.016}$ $\quad \Delta m^2_{21}=7.54^{+0.26}_{-0.22}\times10^{-5}\text{eV}^2$

$\sin^2\theta_{23}=0.386^{+0.024}_{-0.021}$ $\quad |\Delta m^2_{31}|=2.43^{+0.06}_{-0.10}\times10^{-3}\text{eV}^2$

$\sin^2\theta_{13}=0.024^{+0.0025}_{-0.0025}$ $\quad m_e<2.05$ eV; $\sum_i m_i<0.66$ eV

Mass hierarchy:

$m_3>m_1$ or $m_3<m_1$?

Expected precision improvement by JUNO is

For Δm^2_{21} from 3% $\rightarrow$ 0.6%; For $\sin^2\theta_{12}$ from 6% $\rightarrow$ 0.7%.
For Δm^2_{32} from 5% $\rightarrow$ 0.6%; For $\sin^2\theta_{13}$ from 4% $\rightarrow$ 1.5%.

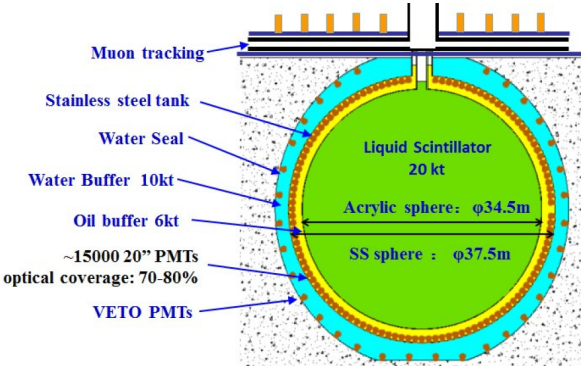
Other topics are: Geoneutrinos (a factor of 10 more statistics); diffuse supernova, solar, atmospheric, sterile neutrinos; p-decay $p\rightarrow K\nu$; indirect dark matter search; probe of new physics via non-standard ν interaction.

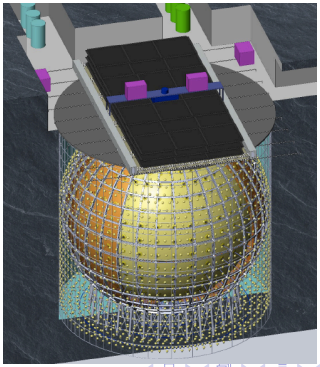
JUNO would be able to detect about 5000 Supernova neutrinos in less than 10 seconds for an SN event 10 kpc away (our Galaxy). This is a unique feature of JUNO due to channels: $\bar{\nu}_e p \rightarrow n e^+$ (3000 events); $\bar{\nu}_e {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B}^* ({}^{12}\mathrm{N}^*) e^+$ (10-100 events); $\nu_x {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N}^* \nu_x$ (600 events) $\nu_x p \rightarrow \nu_x p$ and $\nu_x + e^- \rightarrow \nu_x e^-$ (3000 events).

To reach the goals, one has to fulfil the main requirements:

→ Large scale detector (20 kt of liquid scintillator) with energy resolution not worse than 3% at 1 MeV;

→ The optimal baseline is 52 km, baselines to 2 reactor complexes equal to each other within 200 m.

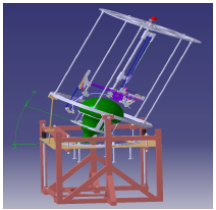


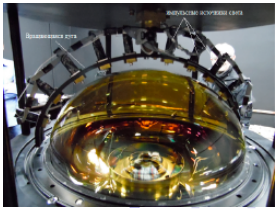


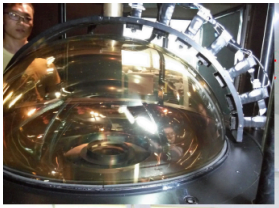
1. Study of JUNO sensitivity to the mass hierarchy measurement
2. Development of simulation and reconstruction software for the experiment
3. Estimation of reconstruction accuracy of the visible energy and interaction position
4. Simulation of various detector design options, Estimation and modeling of backgrounds
5. Liquid Scintillator studies
6. Study of PMT sensitivity to (protection against) the Earth magnetic field
7. Feasibility study of Top Muon Veto detector based on OPERA Target Tracker detector
8. Development and tests of high voltage system for JUNO PMT
9. Software development for the global analysis of ν oscillations with primary goal of combining reactor and accelerator neutrino data to measure the mass hierarchy
10. 2014: DLNP facility construction dedicated to comprehensive characterization of PMT:

A special scanner-device was designed →

It allowed one to perform measurements of PMT integral and zone (at different photocathode points) parameters: photon detection efficiency, gain, dark noise rate, the single electron response performance, the transit time spectrum (evaluating the amount of pre-pulse due to the production of photoelectrons directly on the dynodes system and the transit time spread) and the after-pulse probability at the tens of microseconds time scale, etc.





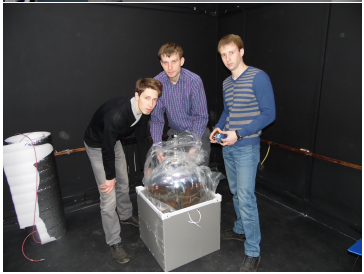


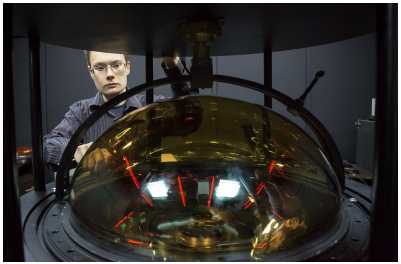
Large photocathode 20-inch PMT testing methods for the JUNO experiment. (N. Anfimov for the JUNO Collaboration), 1705.05012. JINST 12 (2017) no.06, C06017.

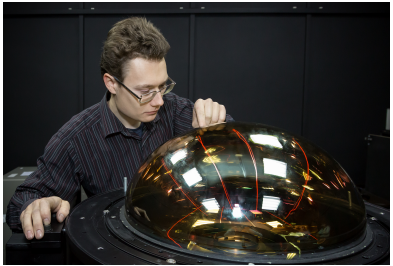


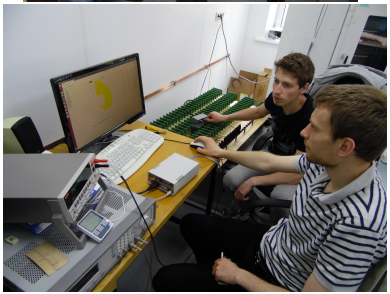













— **JINR people:** T.Antoshkina (1.0), V. Gromov, A.Sadovsky (0.8), A. Chukanov (0.6), D.Naumov, M.Gonchar, A.Olshevski, Yu.Gornushkin, S.Biktemerova, K.Treskov, I.Butorov, A.Rybnikov, A.Selyunin, S.Dmitrievsky, S.Sokolov, V.Sharov (0.5), D.Fedoseev (0.4), N.Anfimov, O.Gorchakov (0.3), O.Smirnov, I.Nemchenok, A.Krasnoperov (0.25), E.Naumova, D.Selivanov, A.Fatkina, D.Korablev, K.Kuznetsova, A.Sotnikov, Z.Sadygov (0.2) = 12.55 FTE.

— **Annual budget** is about 1.4M$ (JINR, 1099)

The JUNO project is now in the construction stage.

The JINR group has a number of important contributions including:

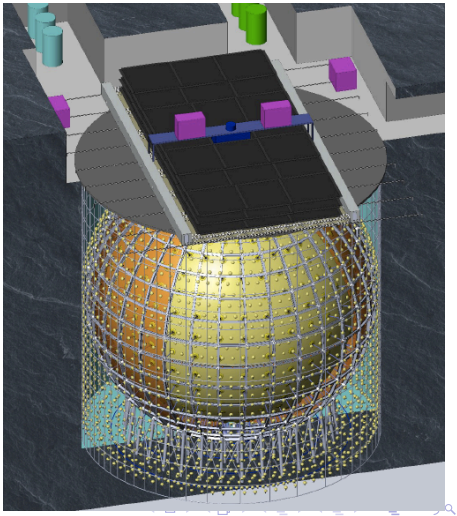
— *R&D and production of high voltage units for 20 000 PMTs 20-inch in diameter and 25 000 PMTs 3-inch in diameter.*

— *R&D and production of the precision muon Top Tracker based on the plastic scintillator technology.*

— *Development of methods for individual and mass testing of PMTs.*

— *Detector simulation, reconstruction, events selection and background determination.*

— *Development of methods and software for the data analysis. The DLNP group will take part in the oscillation data analysis in the JUNO experiment based on our best experience from Daya Bay.*



DLNP has a lot to do in the JUNO project!

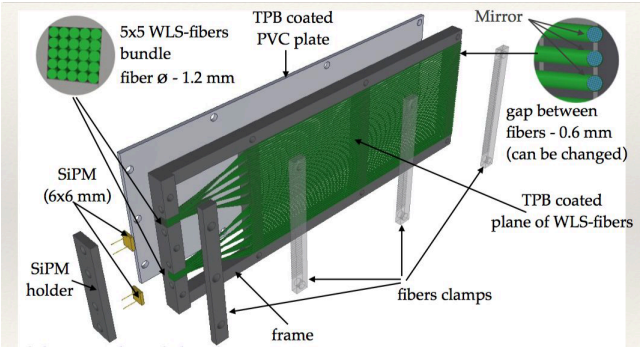
New ideas beyond the 7-year Plan: JUNO → DUNE

DLNP R&D activity on photo-detectors allowed the JINR group to be fully prepared for the tasks in future projects.

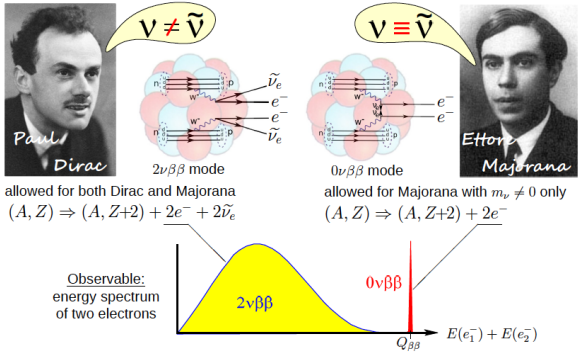
In particular, for the JUNO project this resulted in the development of the scanning station for PMT acceptance tests.

In addition, the feasibility study for the JINR participation in the DUNE project has started recently. In this study DLNP develops an option of scintillation light detection in liquid argon for DUNE near detector.

A scheme of the 1st light collection prototype is give →



The neutrinoless nuclear double beta decay ($0\nu\beta\beta$) is a most direct way to check the Nature of neutrino. It violates the total lepton number conservation law by 2 units and is possible only if the neutrino is a Majorana particle ($\nu \equiv \bar{\nu}$) with nonzero effective mass.



Probability of $0\nu\beta\beta$-decay is given by $W = G_{0\nu} \left|\mathcal{M}_{0\nu}\right|^2 \langle m_\nu \rangle^2$, where $G_{0\nu} \sim Q^5_{\beta\beta}$ is a phase space factor and $\mathcal{M}_{0\nu}$ is the nuclear matrix element.

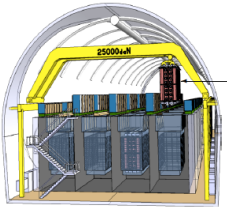
An observation of $0\nu\beta\beta$-decay would allow determination of the absolute neutrino mass scale — $\langle m_\nu \rangle$.

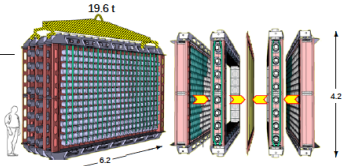
Two-neutrino double beta decay ($2\nu\beta\beta$) is an allowed, very rare weak interaction process. The study of $2\nu\beta\beta$-rate is very important. It constitutes the main background for the $0\nu\beta\beta$-decay signal, and provides one with a valuable input for the nuclear structure $\mathcal{M}_{0\nu}$ theoretical calculations.

JINR participates in both very different modes of the $0\nu\beta\beta$-experiments:
SuperNEMO (when $\beta\beta$-detector $\neq$ $\beta\beta$-source) and GERDA (when $\beta\beta$-detector $=$ $\beta\beta$-source).

Search for neutrinoless double beta decay with experiment SuperNEMO in the Modane Undeground Laboratory (France, Frejus tunnel) at 4800 m w.e.

SuperNEMO will measure individual electron tracks, vertices, energies and time of flight (full kinematics and topology of an event). The background rejection is based on identification of γ-rays, α-particles, and distinguishing e^- from e^+ with a magnetic field. The $\beta\beta$-decay source separation from the detector allows several different isotopes to be studied.



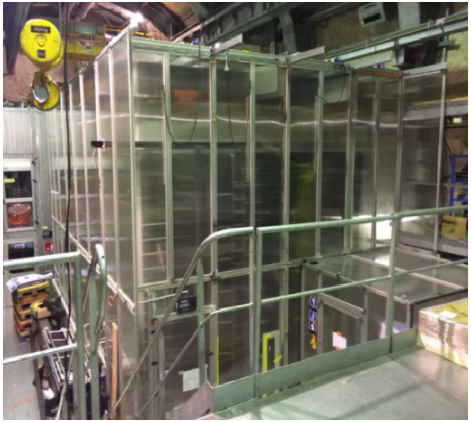


Parameter	NEMO-3	SuperNEMO
Isotope and its mass	^{100}Mo, 7 kg	^{150}Nd or ^{82}Se, 100 - 200 kg
Efficiency	8%	~30%
Energy resolution (FWHM)	8% @ 3 MeV	4% @ 3 MeV
Internal ^{208}Tl contamination in $\beta\beta$ foil	< 20 μBq/kg	< 2 μBq/kg
Internal ^{214}Bi contamination in $\beta\beta$ foil	< 300 μBq/kg	< 10 μBq/kg (if ^{82}Se)
Internal Radon contamination in tracker	~ 5 - 6 mBq/m^3	< 0.1 mBq/m^3
$T_{1/2}(0\nu\beta\beta)$ sensitivity	$> 1 \times 10^{24}$ y	$> 2 \times 10^{26}$ y
$\langle m_\nu \rangle$ sensitivity	$\leq$ (310 - 790) meV	$\leq$ (30 - 100) meV

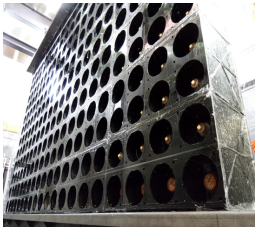
The expected improvement in performance.

SuperNEMO consists of 20 independent modules. Each module contains 5-7 kg of a thin ample foil surrounded by a gas tracking chamber followed by calorimeter walls. The tracking contains more than 2000 wire drift chambers operating in the Geiger mode and arranged in 9 layers parallel to the foil. The calorimeter is divided into 1000 blocks which cover most of the detector outer area and are read out by low background PMT. The main candidate isotopes are ^{82}Se, ^{150}Nd and ^{48}Ca.

SuperNEMO-Demonstrator is the first real-scale SuperNEMO unit with 7 kg of ^{82}Se



The Demonstrator was officially put into operation (7.11.2017) and was aimed to reach expected background suppression.





Calorimeter and its optical module





Tracker constractions



DLNP clear room for ^{82}Se purification

The JINR contribution into the NEMO project is very important:

— MC simulation of the SuperNEMO detector design, performance evaluation

— Development of tracking software, $\beta\beta$-event selection criteria, background estimations, databases, data acquisition, slow control system, and data analysis software

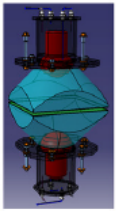
— Development and construction of the calorimeter and veto systems based on plastic scintillators

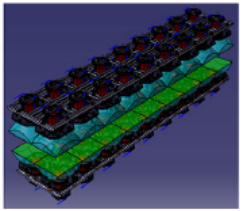
— Development of the calibration and monitoring system on the basis of JINR radioactive sources

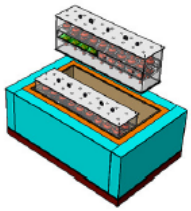
— Conduction of low background measurements screening radioactive purity of enriched $\beta\beta$-decay sources and structural materials for the Demonstrator with a big JINR HPGe-detector (600 cm^3)

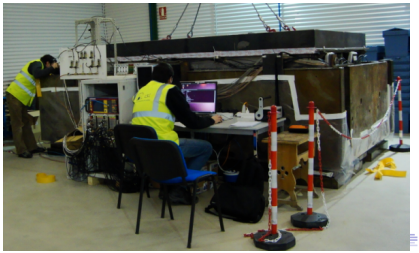
— Creation of the electromagnetic source of mono-energetic electrons for quality control of plastic scintillators

— Development and construction of the ultra low-background BiPo-3 spectrometer (in figures below) aimed to measure radiopurity of $\beta\beta$-decay source foils, etc.







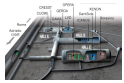


The JINR team is O.Kochetov, V.Tretyak, V. Timkin (0.9), G.Marinov, Yu.Shitov (0.5), N.Mirzaev (0.4), D.Karaivanov, A.Rahimov (0.35), D.Filosofov, A.Salamatin, I.Kamnev, O.Vagina (0.3), A.Smolnikov, A.Klimenko, I.Nemchenok (0.2), V.Brudanin, V.Egorov (0.1) = 5.2 FTE. 2019 budget is 63 k$ (JINR 1100).

This team has 25 yr experience of work in the NEMO–SuperNEMO projects with main responsibilities:
– Radiochemical purification of isotopes and production of radioactive mono-isotopes.
– Calorimeter and VETO R&D and productions.
– Software development, simulations, and data analysis.
– Manufacturing of signal and HV cables for the tracker, cabling, testing and tuning.
– Acquisition, creation and maintenance of equipment for low-background measurements: germanium, radon, neutron detectors in LSM.

JINR plans in SuperNEMO are:
Calibration of the Demonstrator (2019, after completion of its assembly), creation of a neutron shielding of it. Further calibrations and data collection in the full configuration of the Demonstrator.
Further data taking, data analysis, background assessment and control, publication of first results (upto 2021).
Continuation of the R&D program on the methods of enrichment of other isotopes: ^{150}Nd, ^{96}Zr, ^{48}Ca.
Improvement of the cleaning procedure for ^{82}Se.

GERmanium Detector Array (GERDA) to search for neutrinoless double beta decay in ^{76}Ge at the Gran-Sasso Undeground Laboratory



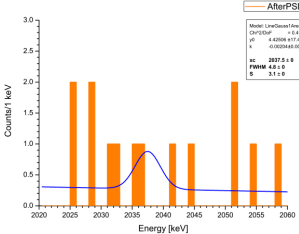
Prof. H.V.Klapdor-Kleingrothaus (Heidelberg-Moscow experiment) published a claim on observation of the $0\nu\beta\beta$ decay in ^{76}Ge (6.4 σ CL). The claim was very intriguing and has to be verified directly with ^{76}Ge. Only GERDA is able to test directly the claim.

A $0\nu\beta\beta$ experiment with Ge relies on the idea that $\beta\beta$-detector $=$ $\beta\beta$-source.

— The goal of the GERDA Phase-I stage (finished in 2013) was to scrutinize the claim with a total exposure of 21 kg yr. No indication of a peak at $Q_{\beta\beta}$ was found. GERDA did not support the claim of $0\nu\beta\beta$ decay in ^{76}Ge. The limit was $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$y (90% CL).

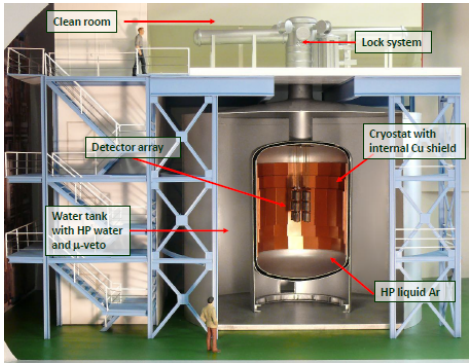
— Phase-II is aimed at exploring $T^{0\nu}_{1/2} > 10^{26}$ yr, with 100 kg yr of exposure and a background index 10^{-3} counts/(keV kg yr). To reach such a background level the GERDA is going to operate 30 extra detectors (20 kg of ^{76}Ge) with a new electrode geometry (BEGe detectors), providing superior pulse shape discrimination. New devices were installed (to identify energy depositions) in the liquid argon surrounding the detector array, through the detection of the induced LAr scintillation light. In coincidence with a Ge detector signal they can be used as anti-Compton or anticoincidence veto.

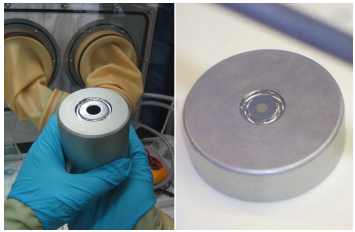
The signature of $0\nu\beta\beta$ decay in ^{76}Ge is a peak at the Q-value of the decay (2039.061 ± 0.007 keV).



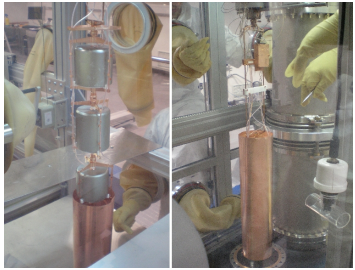
H.V. Klapdor-Kleingrothaus:
$T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr.

The GERDA experiment is located at the Laboratori Nazionali del Gran Sasso (Italy). The setup has an array of Ge detectors, mounted in low-mass supports and immersed in a 64 m^3 cryostat filled with liquid argon. The LAr serves as a cooling medium and shield against external backgrounds. The cryostat is located inside a water tank of 10 m in diameter.



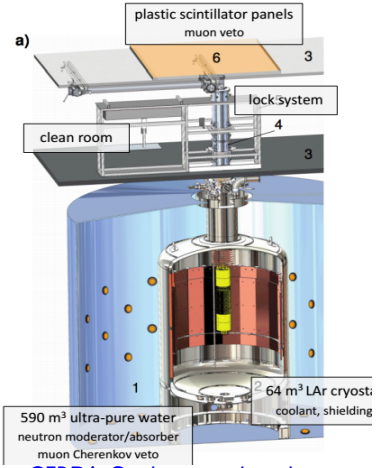


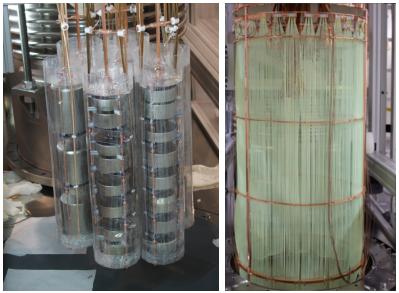
A semi-coaxial Phase I (Left) and BEGe Phase II (Right) detectors.



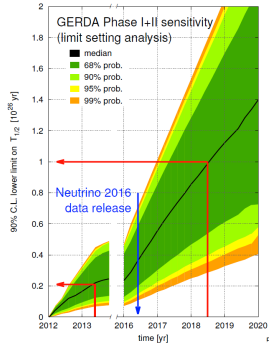
A string of 3 ^{enr}Ge detectors.

In Phase II, 7 strings of the detectors were installed (30 new BEGe + 7 semi-coaxial from Phase I, about 35 kg of ^{enr}Ge) in ultralow-background holders made from intrinsically pure monocrystalline silicon. Entirely new electronics will provide better energy resolution and PSD capability. The LAr instrumentation will be implemented in the GERDA cryostat in order to detect the scintillation light of Ar as an additional background rejection tool.





Array of Ge-detectors, Argon Vero system



ARTICLE

Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA

Forty GERDA Ge detectors have been working in the stable mode since 2016 in LAr, which cools and shields them actively and passively. The best achieved background index was 10^{-3} counts/(keV kg year). The new best limit from both Phases is $T^{0\nu}_{1/2} > 8.0 \times 10^{25}$ yr. People claim it is the first backgroundless experimental search.

JINR team is K.Gusev, S.Nepochatich (1.0), A.Smolnikov, D.Borowicz (0.8), N.Rumyantseva (0.7), A.Klimenko, V.Sandukovsky (0.5), A.Lubashevskiy, D.Zinatulina (0.4), M.Shirchenko (0.3), M.Fomina, I.Nemchenok, E.Shevchik, I.Zhitnikov (0.2), V.Brudanin, V.Egorov, O.Kochetov (0,1) = 7.5 FTE. 2019 budget is 274k$ (JINR, 1100).

The team plays significant role in the GERDA experiment:

– JINR was responsible for design, production, testing and installation of the plastic muon veto system on top of the GERDA cryostat. This veto will also be used for LEGEND-200.

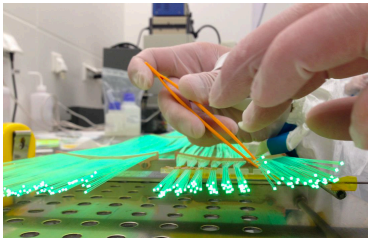
– JINR specialists participated heavily in the development of LAr instrumentation (veto and the central fiber module).

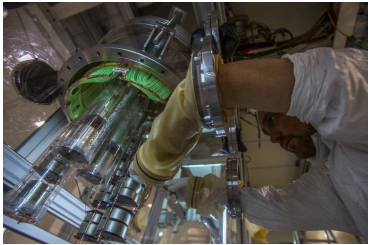
– A special tool for suppression of dominant 42Ar background for GERDA Phase II (nylon mini-shrouds covered by wavelength shifter) has been developed, produced, tested and installed by the team.

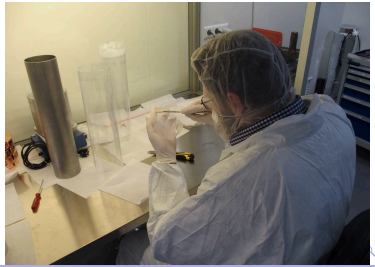
– JINR played the important role in the development of methods of pulse shape discrimination for HPGe used in Phase II.

– JINR was responsible for test, mount and commission of the GERDA core — arrays of bare HPGe in both Phases.

– JINR is providing 8 kg of enriched 76Ge for the GERDA and LEGEND projects.







The GERDA experiment is going to reach the designed exposure in the end of 2019. Then the GERDA infrastructure will be modified to adopt up to 200 kg of Ge detectors in the first phase of LEGEND project. The plan is to start the data taking in LEGEND-200 in 2021. The JINR group will participate in all stages LEGEND experiment.

– JINR will participate in completion of the GERDA data analysis and in simulation of the LEGEND project.

– Due to gained experience in Ge operation, JINR group will further keep the leading role in this activity.

JINR specialists will be strongly involved in the GERDA array dismounting, which will be organized by JINR people. The JINR group is going to participate in the procurement, testing and installation of new enriched Ge detectors for LEGEND-200.

– JINR people are joining the R&D and realization of new active liquid argon veto system for LEGEND experiment.

– JINR team will dismount (GERDA) and mount back (LEGEND) the plastic muon veto system.

– JINR group in LEGEND-200 will be partly or fully responsible for:

The R&D and production of nylon mini-shrouds (tool needed for suppression of dominant 42Ar background); The design and procurement of the new glove box for the operation with enriched Ge detectors; The design of the detector holders and strings. We plan to use for 3D printing machines at JINR to produce some parts of a detector holder. That opens very fast and effective way to find all possible design flaws and probably to produce ultra-clean holders.

— New test facility at JINR in the recently made clean room for Ge detector testing and nylon mini-shroud production is under design. This facility will include:

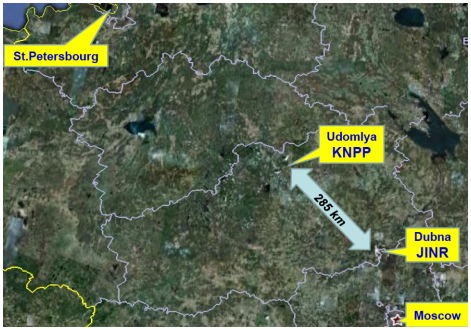
A wide neck cryostat connected to the Ni-flushed glove box to perform all detector and mini-shroud handling in the ultra-clean environment; a stand for nylon mini-shroud production; a deep access bonding machine to provide good quality and low mass contacts to Ge detectors; etc.

”A neutrino interdisciplinary laboratory at the

Kalinin Nuclear Power Plant

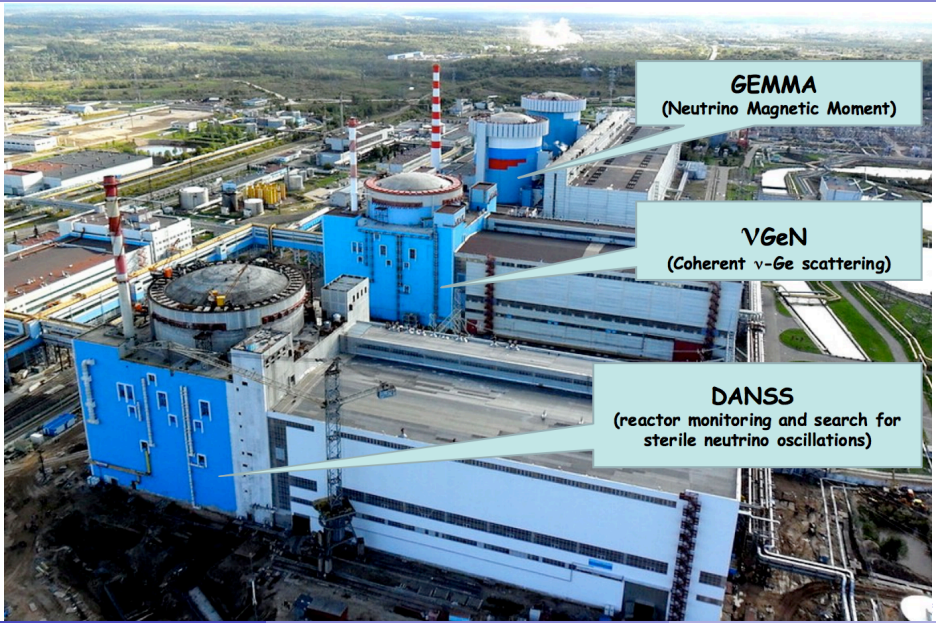
could be the Next Russian mega-project”...

(A decision of the RAS Scientific Council “Neutrino Physics and Neutrino Astrophysics”, 26.06.2012)





In the middle of the road between Dubna and Udomlya


GEMMA
(Neutrino Magnetic Moment)
VGeN
(Coherent ν-Ge scattering)
DANSS
(reactor monitoring and search for sterile neutrino oscillations)

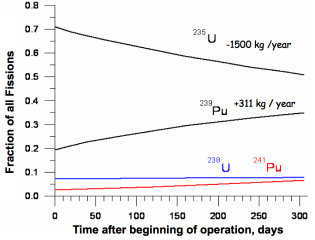
The RAS Scientific Council stresses (26.06.2012) that …

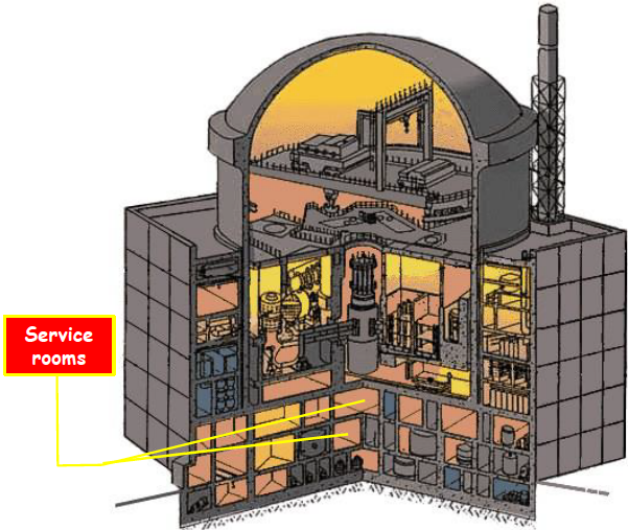
"Special attention should be paid to the unique opportunity to accomplish a new *modern neutrino interdisciplinary project* in Russia at the Kalinin Nuclear Power Plant. This modern neutrino laboratory will really allow Russia to be the world leader, both in fundamental research on reactor antineutrinos and in applied research for nuclear energy industry and safety of nuclear reactors."

Kalinin Nuclear Power Plant is a standard 3GW$_{th}$ (WWER-1000) water-moderated and water-cooled Power reactor.
→ Core diameter 3.12 m, height 3.5 m.
→ Fuel is 66 ton of ^{238}U (96.7%) and ^{235}U (3.3–5%).
→ Operation 320 days (to be increased). Fuel recharge 50 days.
1500 kg of ^{235}U is burned out → 311 kg of ^{239}Pu is produced which changes ($\sim$10%) the flux and E-spectrum of $\bar{\nu}$'s emitted.
→ Full KNPP flux is about 10^{21} antineutrinos per sec into 4π.

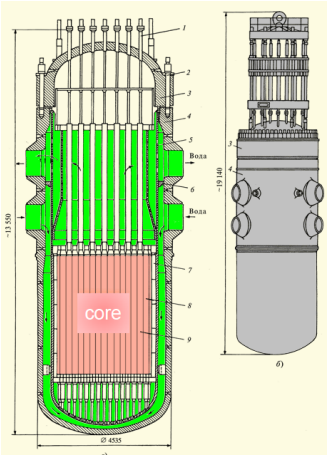
Unique flux, 5×10^{13} anti-neutrinos per sec and cm^2, is available at 10 m from the core!



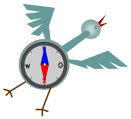




There are several Service rooms under the core of the industrial WWEP-1000 reactor available for (our) scientific research.



The "interior" of WWEP-1000.
Water: T_{out} = 324 C, P = 160 atm, T_{in} = 289 C.
Core: h = 3.50 m, d = 3.12 m. Fuel: 66 t.



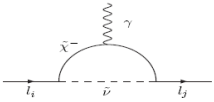
Investigation of neutrino properties with the low-background Ge spectrometer GEMMA-III (**G**ermanium **E**xperiment Searching for **M**agnetic **M**oment of **A**ntineutrino) at the Kalinin Nuclear Power Plant



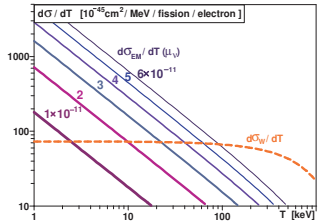
The goal of this project is to measure the neutrino magnetic moment, by studying the $\bar{\nu}$-electron scattering in HPGe detectors located close to a nuclear reactor of KNPP. It could prove non-zero electromagnetic neutrino properties, and is very important for restriction of astrophysical models.

In the Standard Model (diagonal μ^{ν}_{ii} and transition μ^{ν}_{ij}) magnetic moments of neutrinos are proportional to the (Dirac) neutrino mass and are very small $\mu_\nu = 10^{-19}(m_\nu/1\text{ eV})\mu_B$. If neutrinos are Majorana, their $\mu^{\nu}_{ii} \equiv 0$, but still $\mu^{\nu}_{ij} \neq 0$.

In SM extensions (SYSY, etc) the Majorana neutrino (transition) magnetic moment(s) could be at a level of $10^{-10\div12}\mu_B$ (present sensitivity region). It follows also from general considerations that for the Dirac neutrinos $\mu_\nu < 10^{-14}\mu_B$.



An observation of $\mu^{\nu}_{ij} > 10^{-14}\mu_B$ would be an evidence of New Physics and would indicate the Majorana nature of neutrino(s).

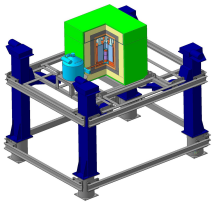


The ν-e differential cross section is a sum of weak ($d\sigma^W/dT$) and electromagnetic ($d\sigma^{EM}/dT$) terms. These cross sections averaged over the typical $\bar{\nu}$-reactor spectrum are functions of the electron recoil energy. At low recoil energy ($T \ll E_\nu$) $d\sigma^W/dT$ becomes almost constant while $d\sigma^{EM}/dT$ increases as T^{-1}.

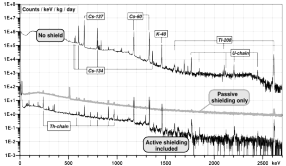
The lower the detector energy threshold is the more considerable increase in the μ_ν-effect with respect to the weak irreducible contribution-background can be obtained.

$\rightarrow$ One expected GEMMA-III sensitivity at a level of $6 \times 10^{-12}\mu_B$.

The GEMMA setup (2 detectors of 3 kg each) is placed inside a cup-shaped NaI crystal with 14 cm thick walls surrounded by 5 cm of electrolytic copper and 15 cm of lead. Being located 10 m below the center of the core of reactor N3 the Setup is well shielded against the hadronic component of cosmic rays by the reactor body and technological equipment (70 mwe). Enormous flux of $5.4 \times 10^{13}/\mathrm{cm}^2/\mathrm{s}$ $\bar{\nu}$-s is also available. The γ-background conditions are much better (by a factor of 10 vs N2).



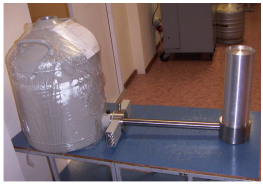
Cosmic μ-component is reduced by a factor of 10(3) at $20^\circ(80^\circ)$ with respect to vertical line. Nevertheless, a part of residual muons are captured in the shielding and produce neutrons that scatter in the detector and raise the low energy background. To suppress it the spectrometer is covered with additional plastic scintillator plates which produce relatively long μ-veto signals.

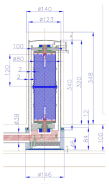


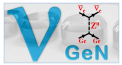
Effectiveness of passive and active shieldings

The detector is movable due to a special lifting mechanism that can vary the distance between the detector and the center of the reactor core from 10 to 12 m. It allows on-line variation of the $\bar{\nu}$-flux and thus suppresses the main systematic errors caused by the possible long-term instability and uncertainties of background.

A special U-type low-background cryostat (left) is used to improve the passive shielding and to reduce the external background in the region of interest down to $0.5 \div 1.0$ keV·kg·day^{-1}. Special care is taken to improve antimicrophonic and electric shielding. The energy threshold is reduced from 2.8 to 1.5 keV.







Experiment at KNPP aimed at Detection of Coherent **N**eutrino–**Ge N**ucleus Elastic Scattering (νGeN). *It is a clear JINR proposal.*



Why observation of the Coherent Neutrino Nucleus Scattering (CNNS) is important?

→ One believes the CNNS is very important in the early Universe, crucial for SN evolution, sensitive probe of new physics.

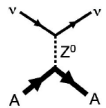
→ Due to NC, an observation of ν-oscillations with CNNS could be an evidence for sterile neutrino(s).

→ Due to the CNNS one can significantly reduce the size and mass of a neutrino detector, which would help to develop neutrino based applied research (non-intrusive monitoring of nuclear reactors, etc).

→ CNNS is very crucial for a next generation of DM search. Interactions of solar neutrinos through CNNS will be an irreducable background for direct DM observation, etc.

An experiment that will be able to detect low-energy events of CNNS will be a breakthrough in neutrino physics.

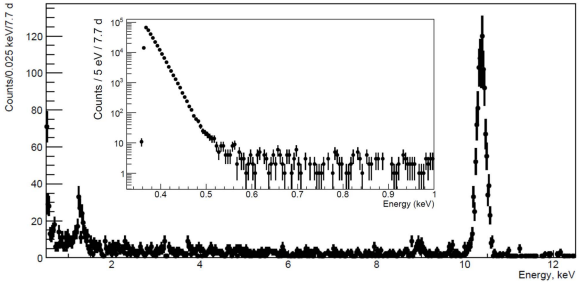
Detection of neutrinos (with $E_\nu < 50$ MeV) via coherent scattering off a nuclear target $\nu A \rightarrow \nu A$ is a challenge in modern physics. In the Standard Model the CNNS is a neutral-current process, which cross section is enhanced strongly being proportional to the number of nuclear target neutrons squared: $\frac{d\sigma}{d\cos\theta} \simeq \frac{G_F^2}{16\pi^2} E_\nu^2 (1+\cos\theta) N^2 F^2(q^2)$, where $F(q^2) \propto \exp^{-R^2 q^2}$ is an elastic nuclear form-factor, which vanishes the coherent effect with increase of momentum transfer q vs A-radius R.



The only measurable CNNS-signature is a recoil energy $E_R = \frac{q^2}{2m_p A}$, which is very small ($E_R < 1$ keV for Ge).

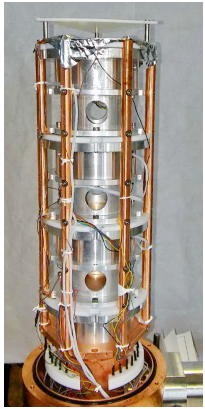
Due to uniquness of JINR HPGe detectors together with unique $\bar{\nu}$-flux at the KNPP the νGeN has good chances to observe for the first time the coherent neutrino-nucleus scattering in the true low-energy domain.

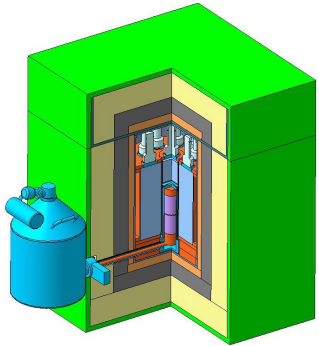
In 2016–2018 a new type of detector with point contacts was used. It allows an ultralow effective threshold 300 eV. Several detectors with total mass 5 kg give an opportunity to reach the sensitivity $\mu_\nu \simeq 5 \div 10 \times 10^{-12}\mu_B$. For the νGeN setup (with 4 HPGe low-energy-threshold-of-300 eV detectors, 450 grams each) placed 10 m away from the center of the reactor core up to 10 of events of the CNNS in Ge are expected for detection per day.



The low energy spectrum for one νGeN detector. For 1.3 keV line the energy resolution (FWHM) is 170 ± 20 eV.

Photo of the νGeN internal part that includes 4 HPGe detectors $\rightarrow$

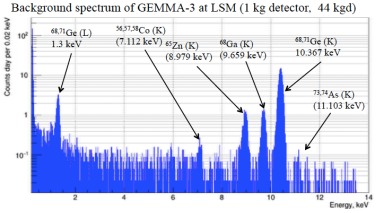


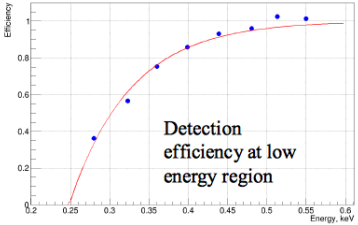


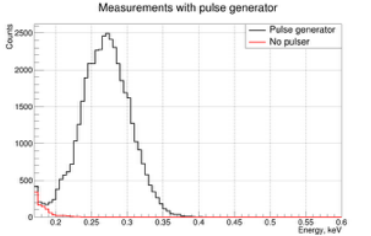
The νGeN setup (green is active μ-veto system, yellow is passive neutron shield (polyethylene), gray is lead shield, orange is copper shield, blue is NaI(Tl) active anti-compton system).

GEMMA and νGeN — JINR "twin" experiments for measurements of neutrino properties with low-background germanium spectrometers at KNPP

A test of 1st detector (1 kg), performed in 2018 at LSM, revealed that: 1) the energy resolution (FWHM) is 78.0(3) eV with pulse generator, and 117(4) eV for 1.3 keV L-cosmogenic line of 68,71Ge; 2) data taking is possible from the energy threshold below of 200 eV; 3) one has extremely low sensitivity to microphone noise (important for successful implementation at KNPP).



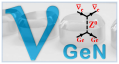


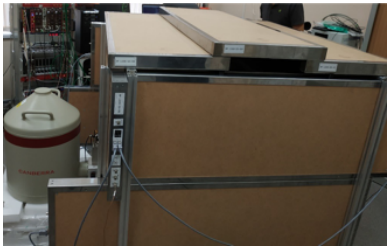


All tests at JINR are finished and the setup is re-integrated at the experimental hall under the reactor of KNPP. First results from GEMMA-III are expected at first half of 2019. After first detection of the CNNS the detectors will be used studying of the CNNE in detail. Further development will be connected with new HPGe detectors with increased mass (up to 10 kg in total).



GEMMA and νGeN — JINR "twin" experiments for measurements of neutrino properties with low-background germanium spectrometers at KNPP

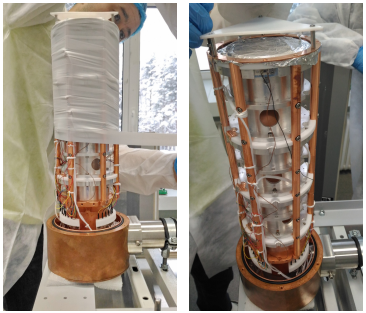




Tests of experimental setup at JINR.

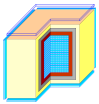
Passive shielding assembly under KNPP reactor →





Work with the GEMMA detectors at Dubna.

Joint GEMMA and νGeN team is D.Medvedev, D.Ponovarev, I.Rozova (1.0) Z.Kalaninova (0.8), A.Lubashevskiy, V.Sandukovsky, S.Rozov (0.5), V.Egorov , M.Fomina, M.Shirchenko, E.Yakushev (0.3), V.Brudanin, V.Belov,, I.Zhitnikov, D.Zinatulina (0.2) = 7.2 FTE, with 2019 budget is about 194k$ (JINR, 1100).

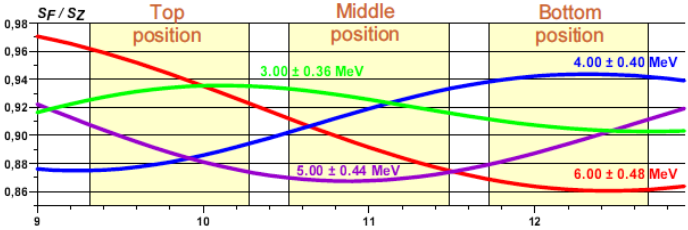


Detector of the Reactor **A**nti**N**eutrino based on **S**olid **S**cintillator — DANSS.
Direct registration of the reactor $\bar{\nu}$ with highly segmented movable polystyrene-based detector



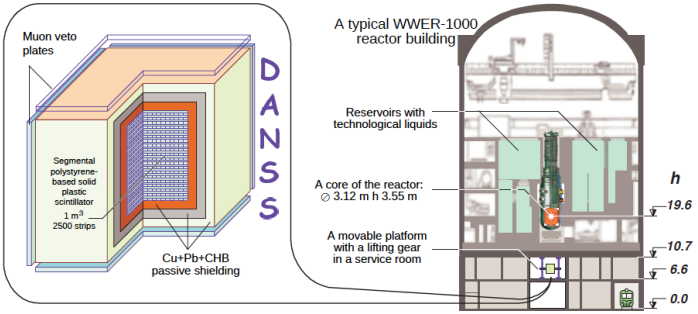
The aim is a relatively small (1 m^3) $\bar{\nu}$–detector that does not contain any aggressive, cryogenic or other dangerous liquids in big amount and can be safely installed close to the core of an industrial power reactor. With high $\bar{\nu}$ flux it can detect about 10,000 $\bar{\nu}$/day with $S/B \sim 100$, and measure $\bar{\nu}$ energy spectrum.

DANSS (due to precise measurement of $E_{\bar{\nu}}$) can be used for many applied and fundamental goals: on-line monitoring of a reactor, fuel composition diagnostics (^{235}U/^{239}Pu) and tomography, search for short-range ν-oscillation and sterile ν's, etc. In particular, by varying the core-detector distance (9.8–12.2 m) the detector will be able to check the "reactor neutrino anomaly" (of short-range neutrino oscillation to a sterile state). With 1-year measurement, the expected sensitivity to the oscillation parameters could reach $\sin^2 2\theta \sim 5 \times 10^{-3}$ with $\Delta m^2 \in 0.02 \div 5.0$ eV^2.



Each curve corresponds to the ν-oscillation with given energy and represents the relative deviation of the detector counting rate from the $1/L^2$-rule. Moving the detector to a top, middle and bottom position will be possible to observe the shown deviation of few percent.

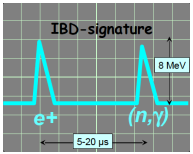
This strategy is the most free of systematic errors, because it does not require theoretical calculation of the spectrum shape and does not depend on the fuel composition. It increases sensitivity by a factor of 3.

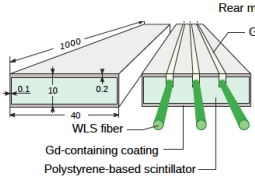


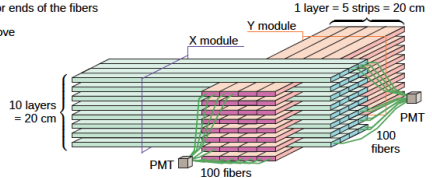
The DANSS detector consists of a highly segmented plastic scintillator (1 m^3), surrounded with a composite shield of copper, lead and borated polyethylene (CHB), and vetoed against cosmic μs with external scintillator plates. Its very close location to the core of a reactor allows extremely high $\bar{\nu}$-flux and provides very good shielding against cosmic rays (50 mwe) which completely removes fast cosmic neutrons and suppresses μ-component by a factor of 6. High segmentation of the plastic scintillator allows background suppression down to a 1% level.

The basic element of DANSS is a polystyrene-based extruded scintillator strip ($1{\times}4{\times}100$ cm^3) with a thin Gd-containing surface coating, which is a light reflector and an (n,γ)-converter. Each set of 50 parallel strips are combined into a module. The whole detector (2500 strips) is a structure of 50 intercrossing modules. Each module is viewed by a compact PTM, etc.

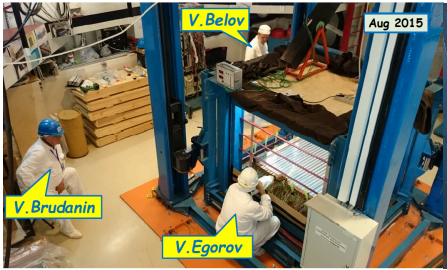
Inverse β-decay ($\bar{\nu}_e p \rightarrow e^+ n$) is used to detect $\bar{\nu}$-s. The energy threshold is 1.8 MeV, and most of the $\bar{\nu}_e$-energy is transferred to the e^+.



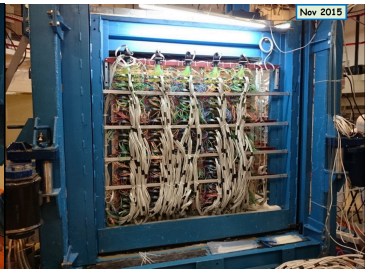




This e^+ deposits its energy within a short range (few cm) and annihilates into two 511-keV γ-s — the 1st (prompt) energy deposition. The second (delayed) deposition is due detection of the neutron. Initial energy of the neutron is only few keV. After some traveling in the plastic scintillator it is captured by gadolinium (^{157}Gd or ^{155}Gd) with a very high cross-section. As a result, a cascade of γ-rays is emitted with a total energy of about 8 MeV.


V.Belov
Aug 2015
V.Brudanin
V.Egorov


Sep 2015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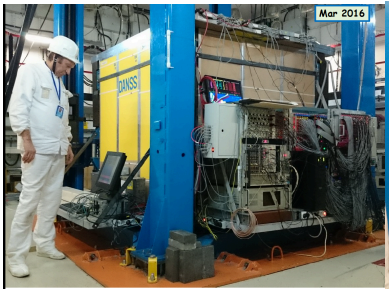
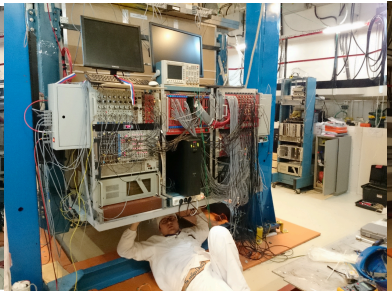
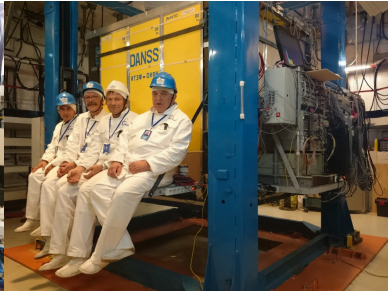
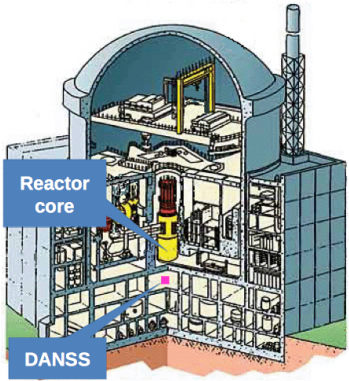

Mar 2016
DANSS




DANSS

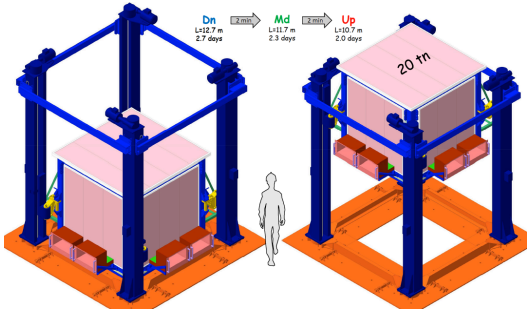
DANSS

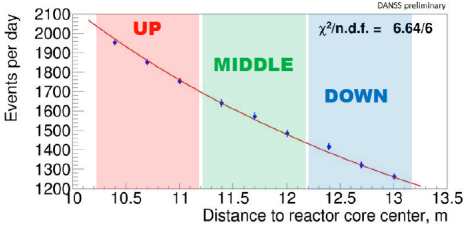
Detector of AntiNeutrino based on Solid state Scintillator: *Reactor monitoring and search for short-range neutrino oscillations — JINST 11 (2016) no.11, P11011; arXiv:1606.02896*



– Segmented XY plastic scintillator (1 m^3 =1.1 t) close to the core of the KNPP reactor 4
– Overburden 50 m w.e. (reactor cauldron, cooling pond, concrete)
– 3D-information about each event
– IBD count rate $\sim$ 4000 $\bar{\nu}$/day with Signal/BG $\sim$ 40
– Lifting platform $\rightarrow$ distance is varied on-line (10.7$\rightarrow$12.7 m) within 5 min each 2-3 days
– Evolution of the $\bar{\nu}$ flux and spectrum with distance $\rightarrow$ model-independent analysis

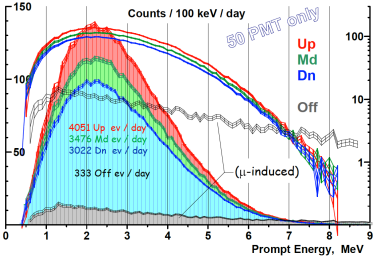
Lifting the DANSS is a key feature:



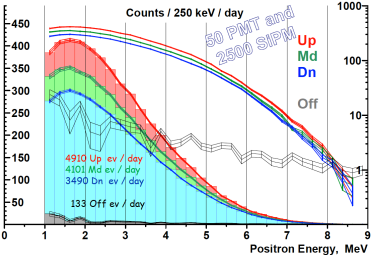


IBD total rate as function of distance.

An example of energy spectra (partial segmentation)



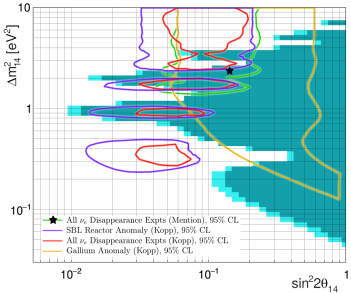
An example of energy spectra (full segmentation)

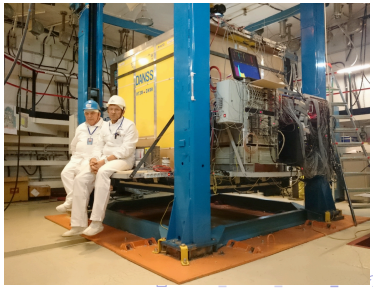


Detector of the Reactor AntiNeutrino based on Solid Scintillator (DANSS) Phys.Lett. B787 (2018) 56-63:

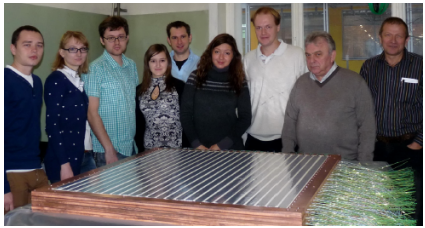
1) DANSS is taking data since Apr 2016 (data available for analysis – since Oct 2016)
2) 4910 IBD events/day are detected in the closest DANSS-core position
3) Background estimation is 133 μ-induced events/day (2.7% for Up position)
4) Spectrum dependence on the fuel composition within the campaign is clearly visible and agrees with HM-prediction
5) A large fraction of the allowed sterile oscillation parameters region is excluded in a model-independent way. The Reactor antineutrino anomaly (RAA) point ($\Delta m^2 = 2.3$ eV^2, $\sin^2 2\theta = 0.14$) is excluded at the 5σ level
6) The best point at ($\Delta m^2 = 1.4$ eV^2, $\sin^2 2\theta = 0.05$) has 2.8σ significance
7) DANSS performs data taking, and relevant analyses are under way ...

In the Figure are given: CL exclusion area in Δm^2_{14}–$\sin^2 2\theta_{14}$. The shaded area represents DANSS analysis. Curves show allowed regions from neutrino disappearance experiments, and the star is the best point from the RAA and GA fits.





— JINR team is V.Egorov, V.Belov, M.Fomina, S.Kazartcev, A.Kuznetsov, I.Zhitnikov (1.0), M.Shirchenko, Yu.Shitov, I.Rozova, D.Zinatulina (0.5), D.Medvedev, N.Rumyantseva,Ye.Shevchik, (0.3), V.Brudanin, Z.Hons, Z.Kalaninova, A.Lubashevskiy, D.Ponomarev, V.Sandukovsky, S.Rozov, E.Yakushev (0.1), with 2019 budget is about 260k$ (JINR, 1101)



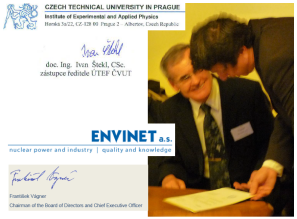
JINR plays a leading role in the Project:

Most work was performed in Dubna by the JINR staff: design and creation of the entire mechanical structure (detector strips with WLS fibers, passive and active shielding, lifting system), light extraction system, PMT front-end electronics, data acquisition system, design and creation of the prototype (DANSSino) and test measurements with it. ITEP is responsible for managing with SiPM (front-end electronics and data taking).

In the next project period (years 2019-2021) the JINR group will work in following directions:

Perform neutrino diagnostics of the reactor (measure E_ν-spectrum as a function of the campaign time) with the DANSS spectrometer. Create two new neutrino detectors S^3 (S-cube) and start it to operation. Depending on the situation, take more active part in upgrade of the Neutrino4 detector. Continue searching for short-range neutrino oscillations (measure E_ν-spectrum as a function of the distance) with the existing DANSS spectrometer and with a new detector being under creation now within the Neutrino4/Neutrino6 project.

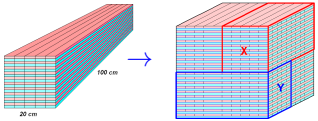
The S^3-detector (next version of DANSSino) was under construction in order to test another signal extraction and another basic element — the improved scintillator plate made by ENVINET (Czech Republic). Together with the Institute of Experimental and Applied Physics, CTU in Prague.







The edge effects reduce efficiency from 72% to 10–15%. Therefore



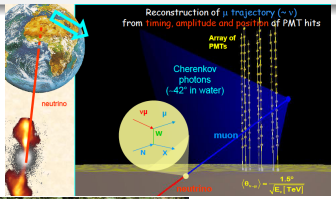
The S^3 (active volume 64 liters) will work at Temelin NPP and will see 400 $\bar{\nu}$/day with negligible backgrounds.



By optimizing the chemical composition of the scintillator the energy resolution was improved by an extra factor of 2. Optimal 2% PTP admixture was found by JINR request.

Gigaton Volume Neutrino Detector at Lake Baikal

A couple of years ago IceCube saw nothing, and GVD on Baikal was almost not needed. Today the IceCube sees galactic neutrinos, but not very good. The GVD on Baikal is urgently needed! It is a long-term project with a clear and strong prospects. Its discoveries are waiting for us (V.Rubakov, 16.12.2013).

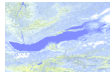


A very new stage of the Baikal project was started in 2014:

25.09.2014: The JINR Scientific Council recommends the JINR Directorate to support the implementation of the JINR Neutrino Program (Baikal-GVD) with $5M per year.



BAIKAL-GVD. Deep underwater muon and neutrino detector at Lake Baikal



The next generation neutrino telescope, BAIKAL–Gigaton Volume Detector, is aimed at studying astrophysical neutrino fluxes and mapping the high-energy neutrino sky in the Southern Hemisphere including the region of the Galactic center.

Other topics include:

— Search for neutrinos from point-like sources,

— Neutrinos from GRB and AGN,

— Diffuse flux of HE-neutrinos,

— Atmospheric ν-s oscillations, mass hierarchy, etc

— Neutrinos from DM annihilation in the Sun and the Earth,

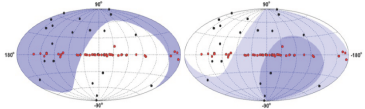
— Non-SM neutrino interactions,

— Magnetic monopoles, Q-balls, etc,

— Global ν Network,

— CERN-to-GVD LBL ν-beam?

— IceCube PeV-νs?



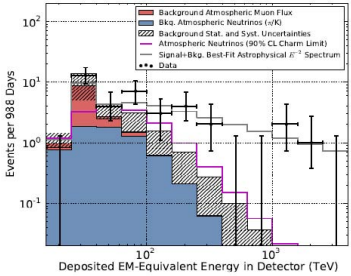


October 15, 2013. München. MoU signing.

From left to right: **Christian Spiering, Maarten de Jong, Tyce DeYoung, Zhan.-Arys Djilkibaev, Juan-Jose Hernandez-Rey, Paschal Coyle, Olga Botner, Uli Katz.**

IceCube, KM3Net, Baikal-GVD jointed into Global Neutrino Network, extremely important project !

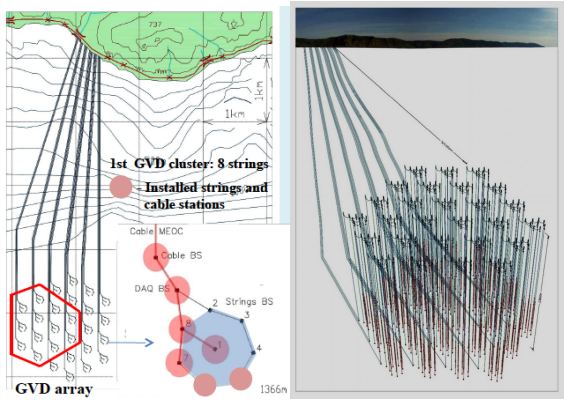
IceCube (left) and Baikal-GVD (right) are complementary to cover the all neutrino Sky.

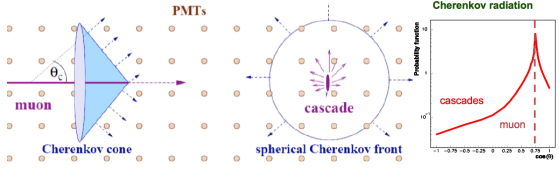


IceCube sees (extra)galactic neutrinos, but not very good. The key parameter of the BAIKAL-GVD is angular resolution, which should be much better than 1°!

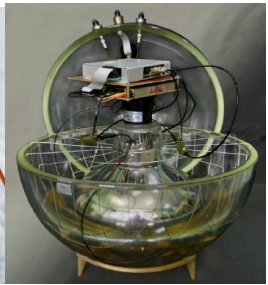
General Requirements: 1) km^3-scale 3D-array of photo sensors, 2) flexible structure allowing an upgrade and/or rearrangement of the main building blocks (clusters), 3) high sensitivity and resolution of neutrino energy, direction and neutrino flavor content.

Detection principles for muon tracks (left) and cascades (right) in underwater detectors. The Cherenkov light emission by cascades is peaked at the Cherenkov angle θ_c with respect to the cascade axis but has a wide distribution covering the full solid angle.



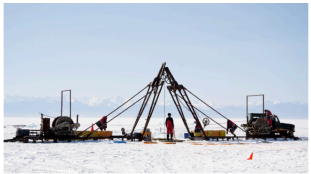








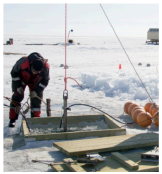














New data-taking center at the site was installed in 2016.





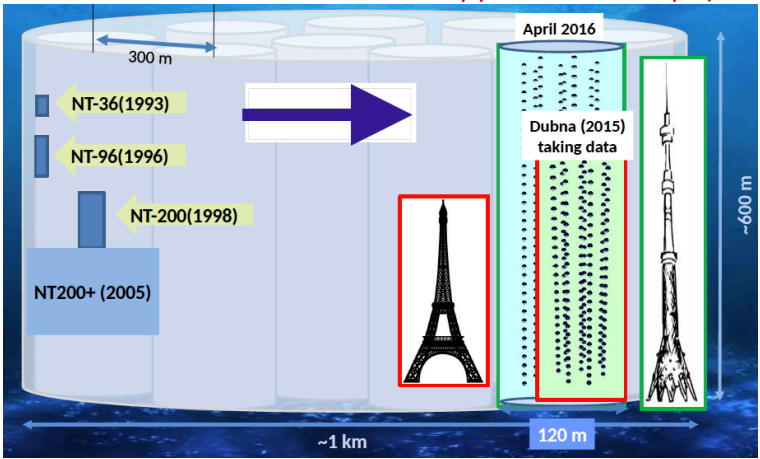
The building in Baikalsk was prepared for test-lab and store for optical modules of the next stages of the detector.





New facility for long-term tests and production line of OMs for the next detector extensions were started in Dubna.

2016 was the key year for the Baikal-project development.



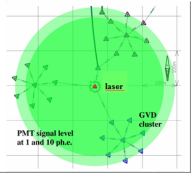


In 2 years a great step was taken by JINR to the full-scale Baikal-cluster. One can compare this huge progress with previous 20 years of the project development (very important in fact).

Mass production and testing of optical modules were organized in Dubna.





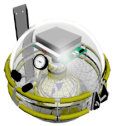


The main purposes of the deep-water pulsed Laser are inter-cluster calibration and cascade emulations. The Laser has the wavelength 532 nm, pulse energy 0.37 mJ (10^{15} photons) and flash duration about 1 ns, etc

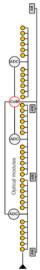


Warm well-equipped storages for OMs before traveling to Baikal.

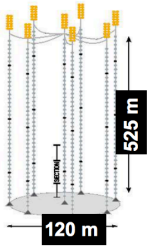
Baikal-GVD (phase 1, 2020)



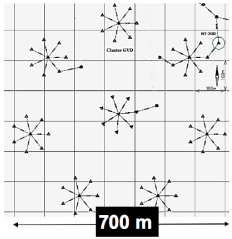
Optical Module



String (contains 36 OMs)



Cluster (contains 8 strings)



Baikal-GVD-1 (contains 8 clusters)

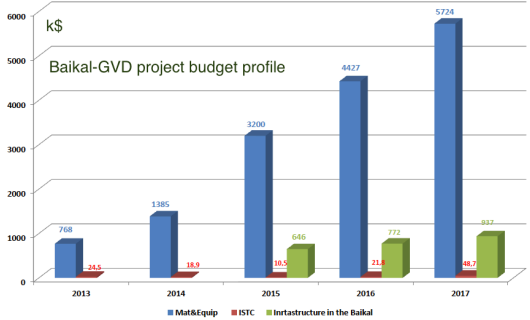
	GVD-1
Total Optical Modules	2304
Number of Clusters (8 Strings)	8
Location Depths	750 – 1275 m
Effective Volume (E > 100 TeV)	0.4 km^3

Baikal-GVD directional resolution

For Cascades – about 3°

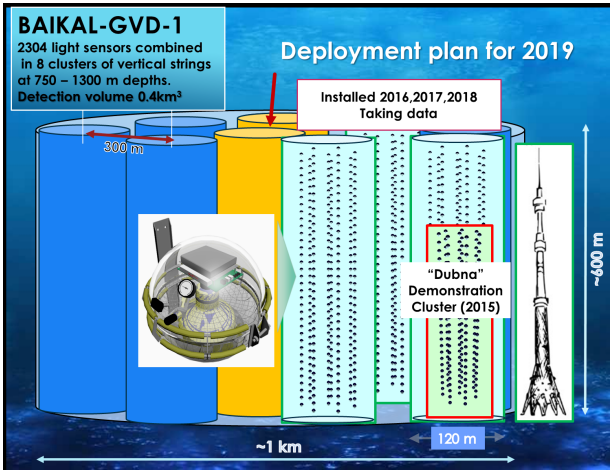
For Muons – 0.25° - 0.5°

Baikal-GVD JINR budget in 2013–2018.



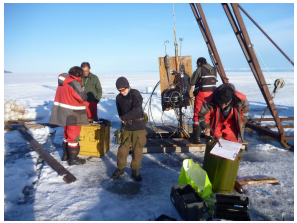
The JINR Directorate has approved this budget increase, and guaranteed the Baikal-GVD progress

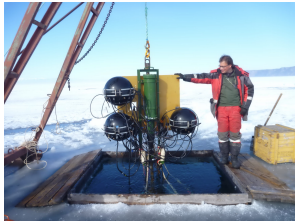
It looks like all things are going well and we will manage to be in time ...



Configuration	2015	2016	2017	2018
The number of OMs	192	288	576	864
Geometric sizes, m	Ø80×345	Ø120×525	2×Ø120×525	3×Ø120×525
GVD Effective Volume	0.03 km3	0.05 km3	0.1 km3	0.15 km3

Baikal-JINR team is:
I.Belolaptikov, E.Sushenok, R.Dvornicky, N.Gorshkov, M.Kolbin, K.Konishev, A. Korobchenko, M. Kruglov, V.Nazari, T.Orazgali, E.Pliskovski, V. Rushay, B. Shaybonov, A. Svistunov (1.0), A.Doroshenko, K.Golubkov, M.Milenin, A.Panfilov, D.Petukhov, G.Safronov (0.5), P.Antonov, E.Khramov, S.Sinegovski (0.3), V.Brudanin (0.2) = 17.1 FTE (8.3 FTE 2015).
Annual budget = 7M$ (JINR 1100).





Installation of the 1st GVD-cluster DUBNA

The team participates in all major steps of the project:
1) Assembly, test and study of OMs — the main detection units. Only at JINR one has facility for testing and calibration of OMs; 2) Preparing elements of basic construction of the detector; 3) Computing and data taking shore part of the DAQ system and clusters synchronization; 4) All network structure, access and security service at the site; 5) Remote control and monitoring of the detector; 6) On-line and simulation software support and development; 7) Data analysis frame support and development, data transfer from the site, collecting raw data, support data bank in JINR. JINR is the data center of the Baikal-GVD project; 8) Primary data analysis and monitoring; MC production; Reconstruction of track events, events selection, etc.

The JINR plan (≡ the Collaboration plan) is to assemble elements of the detector and deploy 2 clusters (2X288 OMs) per year. Furthermore: To improve reliability of equipment, JINR will create a full-scale testing facility, which will allow for long-time test of the equipment in a whole architecture (cluster). The facility will allow one to optimize the OMs production line for rate up to 900 OM per year and to prepare an extra cluster for long-time testing. JINR will extend computing resources for disk space and computing power for analysis and MC.

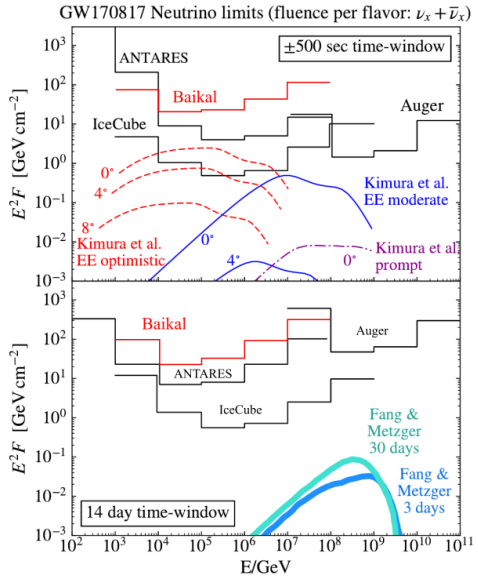
One of Baikal-GVD results in 2018:

On August 17, 2017, a gravitational wave signal, GW170817, from a binary neutron star merger has been recorded by the Advanced LIGO and Advanced Virgo observatories.

No significant neutrino signal was observed.

Figure caption →

Upper limits (at 90 % CL) on the neutrino spectral fluence from GW170817 during a ± 500 s window centered on the GW trigger time (top panel), and a 14-day window following the GW trigger (bottom panel). For each experiment, limits are calculated separately for each energy decade, assuming a spectral fluence $F(E) = F_{\rm up} \times [E/\mathrm{GeV}]^{-2}$ in that decade only.



Deep LSM-underground WIMPs

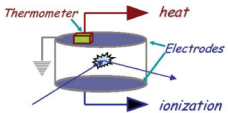




How many Dark Matter WIMPs one has in two cups of good underground coffee?

EDELWEISS-LT — Direct low-mass WIMP searches with HPGe Semiconductor Bolometers at LSM Underground Laboratory

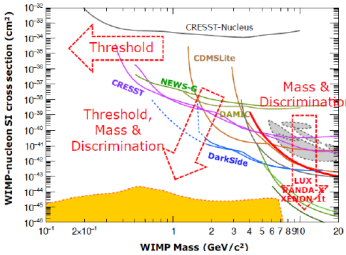
The EDELWEISS searches for direct evidence of Dark Matter (DM) particles through their scattering off Ge nuclei within cryogenic Ge bolometers (20 mK) with simultaneous measurement of phonon and ionization signals. Comparison of these signals gives very efficient event-by-event discrimination between nuclear recoils (induced by DM and n scattering) and background electrons.



Completed EDELWEISS-III used 800-grams FID (Fully Inter-Digitized) detectors with a significantly increased fiducial volume →

EDELWEISS-III detectors have an excellent background rejection performance, the best in the world, but not competitive with large Ar/Xe DM detectors above 6 GeV/c^2.

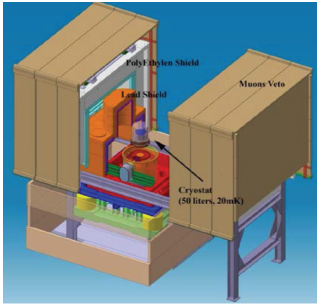


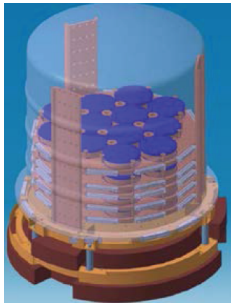


Thus, the Experiment is moving to EDELWEISS-LT, aimed at search for "light" WIMPs, Axion-like particles in the energy region inaccessible by the large Ar/Xe DM detectors.

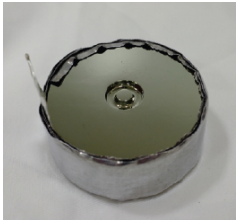
Already in 2018 at the current R&D stage of EDELWEISS-LT a number of interesting results was obtained.

The heart of EDELWEISS is the ^{3}He-^{4}He dilution cryostat with HPGe bollometeres. The setup is located in LSM, in the Frejus tunnel connecting France and Italy, under 1800 m of rock overburden (4700 m.w.e.). The resulting muon flux is 4 $\mu/m^2/day$ (10^6 times less than at see level), and the fast neutron flux is $\sim 10^{-6}$ cm^2/s.









The point contact detector wrapped in roman lead.

EDELWEISS shielding includes a surrounding of detectors by 20 cm of Pb, (include internal layer from archaeological roman lead), 50 cm of polyethylene and active μ-veto (100 m^2 of plastic scintillators). When the shields are closed the cryostat is supplied with 9 l/min flux of radon-free air. The shielded dilution cryostat is located in an air-tight and pressurized clean room of class 1000. To reduce microphone noise due to vibrations, the cryostat is located on a pneumatic suspension.

JINR made hardware:

– Highly sensitive radon detection system to continuous control of air at proximity to the EDELWEISS cryostat;

– Movable radon detector that is mainly used for control air quality of the radon-free air factory;

– Two low background thermal neutron detectors based on He-3 counters with low noise data acquisition chain. The detectors were used for accurate investigation of neutron field and its stability in the LSM underground laboratory as well inside of the EDELWEISS shields;

– Fast neutron detection setup based on 4 He-3 counters and moderator with the low noise data acquisition chain;

– R&D and use of a new thermal neutron detection system based on iodine containing scintillators;

– Low background alpha spectrometer with exchangeable silicon PIN alpha detector of high area;

– Elements of passive lead shield for EDELWEISS R&D cryostat;

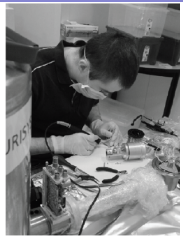
– Two HPGe spectrometers for selection of less-radioactive materials (this is part of LSM-JINR common infrastructure that is also used by other experiments with JINR participation);

– Low threshold HPGe detectors for DM search (EDWIGE branch of the EDELWEISS).

JINR made software:

– Being experts in low-energy electron spectroscopy JINR group developed a particle generator including all atomic processes in low energies (Auger, Coster Kronig transitions, X-rays) crucially important for background model at DM search region;

– JINR is fully responsible for data acquisition for radon/neutron/alpha detectors as well for data analysis from those detectors; as well as for data analysis accumulated with the EDWIGE (EDELWEISS-I shield HPGe detectors R&D) branch of the EDELWEISS.



As part of collaboration with less than 50 members Dubna team participates in all stages of the project:
— Assembly and commissioning of each new stage of the experiment
— Data taking (including daily routine procedures, as well as regular and special calibration runs)
— Low background study and development of methods of neutron and radon detection
— R&D of new low energy threshold HPGe detectors, Detector simulations, data acquisition and data analysis.
In JINR we also will develop equipment for radon-emanation study; In cooperation with radiochemistry sector new less-radioactive components will be developed (as, for example, soldering and flux).



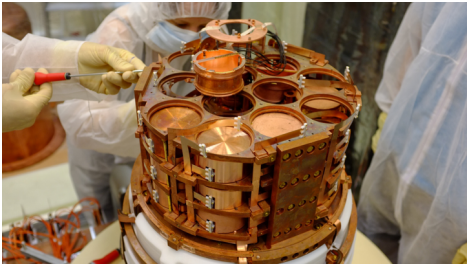
JINR R&D of EDELWEISS detectors, holders, supports

— JINR team: K.Shakhov (1.0), E.Yakushev, S.Rozov (0.7), D.Filosofov, N.Mirzaev, A.Rakhimov (0.3), D.Ponomarev, I.Rozova (0.5), A.Lubashevskiy, Z.Kalaninova, L.Perevoshchikov (0.2), V.Brudanin (0.1) = 5FTE.
— Annual budget is about 76k$ (JINR, 1100)

The JINR EDELWEISS group has an own agenda connected with using of the EDELWEISS infrastructure to R&D of classical semiconductor detectors with ultra-low energy thresholds and for selection of less-radioactive materials. This is one of the bases for current "home" experiments, as GEMMA/νGeN, as well is the base for further developments.

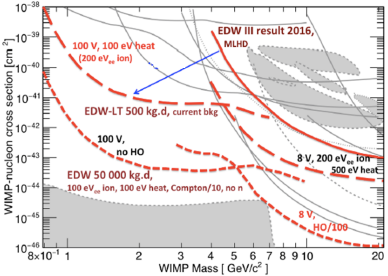
2017. Installation of EDELWEISS detectors S. Marnieros (France), D. Ponomarev, S. Rozov, E. Yakushev, etc



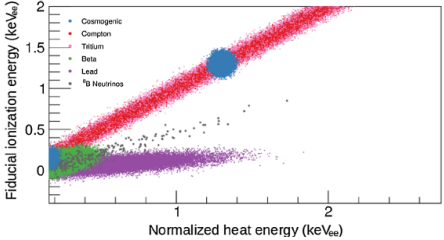




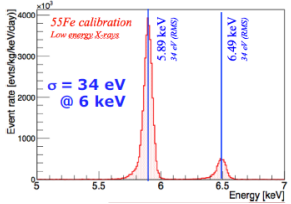




Current limits (EDW III 2016) and expected results of EDELWEISS-LT (EDW50000 kg.d) after background/resolution improvements.



Simulation (1000 kg yr) of ^{8}B coherent ν-nucleus scattering signal and backgrounds to be measured in EDELWEISS-LT



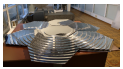
Energy resolution of a EDELWEISS unit.

Important to say the following:

— *Concerning the needs of Ge based DM direct searches with respect to huge Xe and Ar experiments* one has to stress that general complicity of experimental techniques combined with model-dependent interpretation of results makes multi-target/multi experimental technique approach to be the only reliable way for true DM detection.

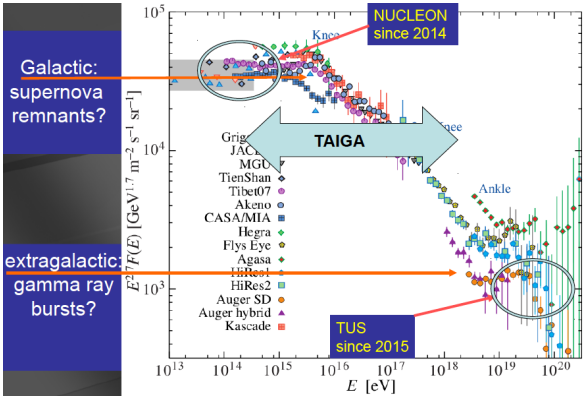
— To prove true DM observation one needs 1) a characteristic spectrum that depends on nuclear mass and spin; 2) an annual modulation in both the event rate and the recoil, 3) and Experiment-independent DM parameters.

→ Development of new Ge-based DM search experiment EDELWEISS-LT is highly valuable for direct DM searches.



Orbital TUS detector to study Ultra High Energy Cosmic Ray (UHECR) (including neutrino) Extensive Air Showers (EAS) from the space orbit.

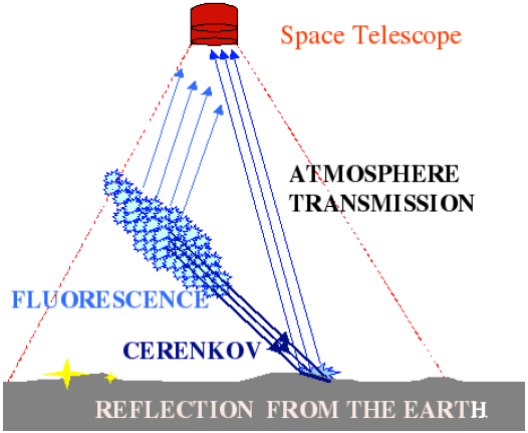


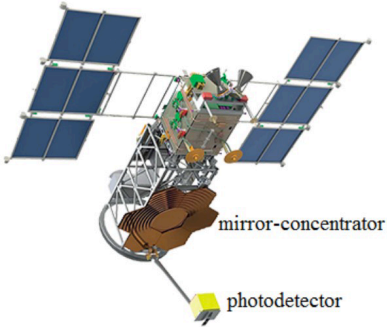


The TUS space experiment has been proposed to measure the energy spectrum, composition and angular distribution of the UHECR up to 10^{20} eV, and to study the region beyond the GZK cutoff. Existence of these particles is beyond the Standard Model of particle physics and is of great interest.

The study from the orbit is much more effective in comparison with the ground-based detectors. The existing world statistics is assumed to be increased by a factor of 2 during 3 years of the global data taking.

The fluorescent and Cherenkov radiation of the EAS generated by UHECR particles should be detected in the Earth's atmosphere on the night side of the orbit at altitudes 400–500 km. It will be possible to evaluate the EAS energy and arrival directions at energies $E > 7 \times 10^{19}$ eV that is beyond the GZK limit.

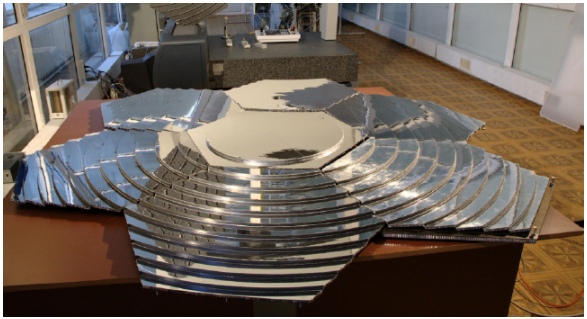


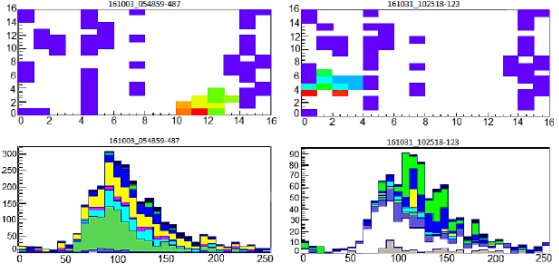


Mass	< 60 kg.
Power	65 W.
Data rate	200 Mbytes/day
1 EAS event	~128Kbytes
FOV	±4,5 degree.
Pixel:	10 mrad (5x5 km)
Mirror area	1,8 m^2.
Focal distance	1,5 m
Number of pixels	16x16 PMTs.

An important advantage of space detector is the possibility of taking data from different arrival directions of the sky with the same apparatus and with the same systematic uncertainties.

→ Design, fabrication and optical parameters measurements of the focusing Fresnel mirrors (above).
→ The software package was developed to simulate performance of the TUS detector (for the Fresnel mirror optical parameters, the light guide of the photo detector, and the front end and trigger electronics).
→ The software was developed to reconstruct EAS events. The TUS first EAS candidate is analysed (above).

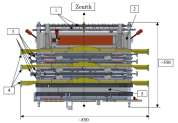




The 1st EAS candidates. Upper – images of events with hit pixels on the PMT matrix. Bottom – the amplitude variations of time for selected hit pixels.

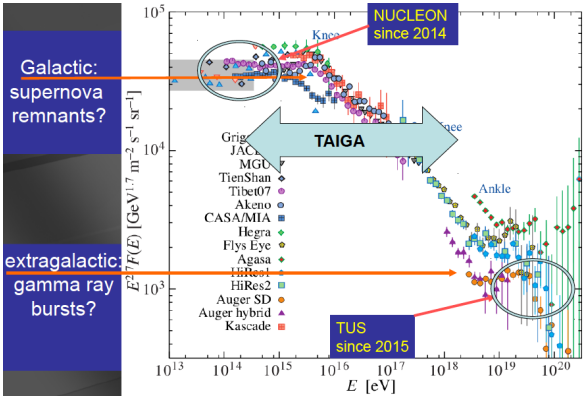
Duration within TAIGA project in JINR is 2015–2020.
JINR team: A. Grinyuk (50%), M. Lavrova (60%), L.Tkachev, U. Nurtaeva (20%), A. Tkachenko, V.Grebenyuk (10%)

JINR plans in TUS:
1. Calibration of TUS detector PMTs with flight data.
2. Search and physical analysis of EAS candidates.
3. Publish 2-3 papers in the refereed journals.



The NUCLEON Space Experiment (by Moscow University, JINR, MEPhi, SDB Automatika, Russia)



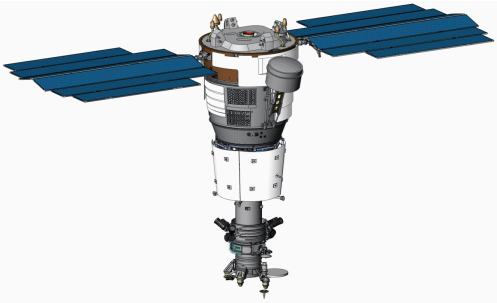


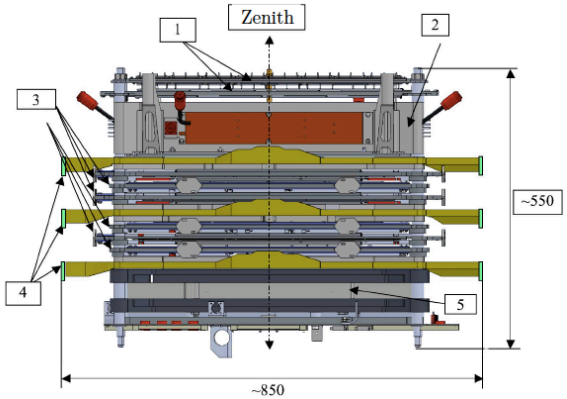
The NUCLEON satellite experiment is designed to investigate directly, above the atmosphere, the energy spectra of cosmic-ray nuclei and the chemical composition (Z=1-30) at energy range 0.1–1000 TeV.

The effective geometric factor is more than 0.2 m2sr for nuclei and 0.06 m2sr for electrons. The planned exposition time is more than 5 years.

In the end of 2014, the NUCLEON detector was launched into a sun-synchronous orbit with an average altitude of 475 km and an inclination of 97 degrees as an additional payload of the Russian satellite Resource-P 2.

The NUCLEON on the satellite. Weight is 360 kg; Power consumption 160 W. Transmit 10GB data/day.





NUCLEON: 1 – two pairs of planes of the charge measurements; 2 – a carbon target; 3 – six planes of the energy measurements (KLEM tracker); 4 – three double-layer planes of the scintillator trigger system; 5 – a small aperture calorimeter.

The primary energy is reconstructed by registration of spatial density of the secondary particles. The particles are generated by the first hadronic interaction in a carbon target. Then additional particles are produced in thin tungsten converter by electromagnetic and hadronic interactions. Thus it is possible to design relatively light CR-detectors with a large geometric factor.

The JINR responsibility was production of NUCLEON trigger system. Three trigger modules were produced and tested in assemble with other detectors at CERN SPS beam tests. JINR group was responsible for NUCLEON apparatus beam tests at SPS CERN for years (below).



Duration within TAIGA project is 2015–2020.

JINR team: U.Nurtaeva (80%), A.Pan (70%), A.Kalinin (50%), L.Tkachev, A.Tkachenko, V.Grebenyuk, S.Porokhovoy, A.Sadovsky (20%), N.Gorbunov, A.Rogov, M.Slunecka (10%)

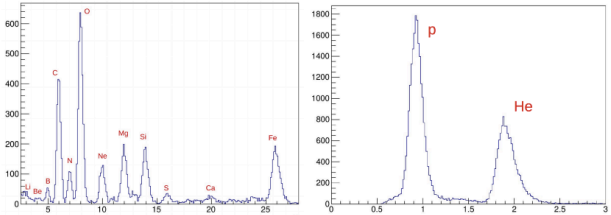
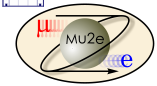


Figure 4. Charge distributions of the cosmic ray nuclei measured in the NUCLEON experiment.

Future: Participation in OLVE-HERO space project. The goal is CR measurement at 10^{12}–10^{16} eV will a large ionization-neutron 3D calorimeter of high granularity and geometric factor of 16 m^2sr.

The boron loading plastic scintillator detector prototype was designed and tested at CERN SPS with Pb (2016) and Xe (2017).

JINR group participates in data taking, developing of physical analysis programs, and in the new post NUCLEON-project preparation (prototype design, fabrication) and beam tests.

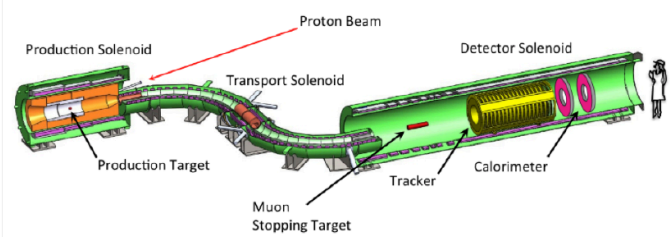


Search for Charged Lepton Flavor Violating neutrinoless conversion of a muon to an electron in the field of a nucleus at FNAL



The goal of the Mu2e experiment is a process with charged lepton number violation when a muon coherently transforms into an electron in a nucleus $\mu^- N \to e^- N$. The first phase of the experiment will be held with the Al target in 2020–2023. The sensitivity expected in 2023 is 6×10^{-17} (10,000 times better then in SINDRUM-II).

In the Standard Model this process is strongly ($\sim 10^{-50}$) suppressed due to tiny neutrino mass scale.



The beam line begins by colliding protons onto a production target to produce low momentum pions. The resulting πs are either transported through a decay volume or directly stopped inside the target, and their decay μs are collected. It requires low momentum muons (50 MeV/c), in order to stop them in thin targets at the center of the setup. To reach the target sensitivities requires high-intensity μ-s ($10^8 \mu/s$).

The detector must precisely determine the energy, momentum, and timing of particles originating from the muon stopping target.

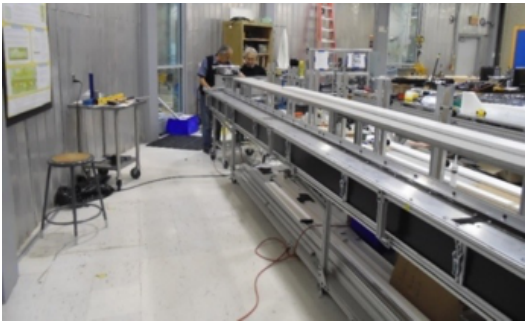
The Mu2e Project achieved a significant milestone in 2016 (July 14) when deputy director for science programs in the DOE (Pat Dehmer) approved Critical Decision 3, which authorizes start of full construction.





The Mu2e Entrance (left) and Mu2e Experimental area (right)

DLNP conducted R&D on the choice of the elements of the scintillation crystal and EM calorimeter veto system, participated in data simulation, creation and testing of the detector systems. A method for increasing the light yield from scintillation strips was developed. Beam tests of Cosmic Ray Veto (CRV) counter prototypes were fulfilled. Radiation hardness tests of the scintillator strips and filler samples at the IBR-2 facility were performed. Technology of the CRV 4-layers module assembly was developed.





In 2016–2017 JINR members were sent to the University of Virginia, USA, to launch mass production of CRV scintillation modules. They successfully develop a procedure of module assemble and created two pilot CRV modules with a length of 90 cm and prepared scintillation strip components for a 4.5-m-long module. They assembled a set of cathode strip chambers to be used for CRV modules.



JINR in Mu2e Electromagnetic calorimeter has done:
– Simulation of the EC calibration in situ.
– R&D with LYSO and CsI crystals as elements of the calorimeter. Tests of the calorimeter prototypes.
– Participation in the calorimeter preamplifiers design and tests at Frascati.
– Preparation of the stand at Dubna for tests of the whole set of preamplifiers.
– R&D with BaF2 crystals for 10 times higher beam intensity.

— JINR team: Artikov A.M., Chokheli D., Kharzheev Yu.N., Kolomoets V.I. (100), Atanov N.V., Baranov V.Yu., Vasilyev I.I. (90), Shalyugin A.N., Simonenko A.V. (80) Davydov Yu.I., Glagolev V.V., Khomutov N.V. (70), Budagov J.A., Krylov V.A., Suslov I.A., Usubov Z. (50), Kuchinsky N.A., Tereschenko V.V. (30), Baranov V.A., Demin D.L., Duginov V.N. (20).

— Duration of the Mu2e is 2015–2020.

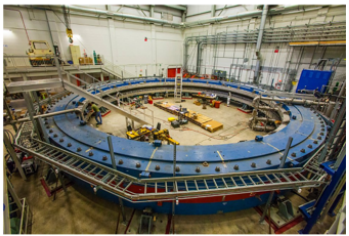
— Annual budget is about 240k$ (JINR, 1124).

JINR plans in Mu2e experiment are:

– Participation in the production of the CRV modules at Virginia University.
– Creation of a system for parallel filling of the fiber holes with synthetic low molecular weight rubber (SKTN) for several discounters simultaneously.
– Filling the discounters for all long CRV modules (about 7 meters) and probably for whole set of CRV modules if collaboration will decide it in 2019. Dubna is responsible for this task.
– Performing tests of the CRV modules with radioactive sources and muons.
– Participation in the CsI crystals QA (Quality Assurance) tests at CalTech before EM calorimeter assembly.
– Creation test bench and performing tests of all Mu2e EMC-preamplifiers at Dubna.
– Performing neutron radiation hardness tests of preamplifiers at JINR IBR-2.
– Evaluating the performance of Tracker panels at the University of Minnesota. Quality Assurance and Control of the Tracker panels (testing for leaks, holding high voltage, etc.)
– Continue R&D with BaF2 crystals which are planning to be used in the second stage of the Mu2e experiment.
– Continue simulation of the EM calorimeter calibration.
– Participation in the Mu2e detector assembly, tests and commissioning.

Muon anomalous magnetic moment can be calculated with great precision and will be measured with Fermilab muon beams in the Muon g–2 experiment. Comparison of the experimental data and the SM predictions will provide a reliable search for new physics. The difference between the measurement and the prediction at the moment $\Delta a_\mu = (255 \pm 80) \times 10^{-11}$ (3.2σ) is the key for NP in the TeV energy range. The accuracy of this measurement will be 4 times higher.

Ring at Fermilab



JINR (few FTE from Mu2e) contribution to the Muon g-2 experiment:

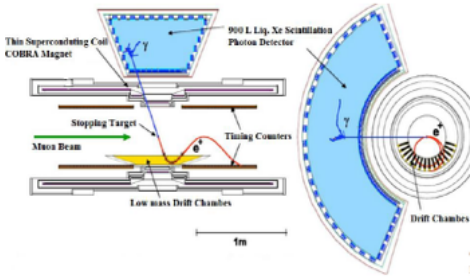
– Alarm system and web-interface software for experiment DAQ control was developed and used during the data taking run.
– Graphical Event Display application was developed to visualize online experimental events based on Geant4 geometry.
– R&D works for a tracker prototype based on cathode straw tubes.

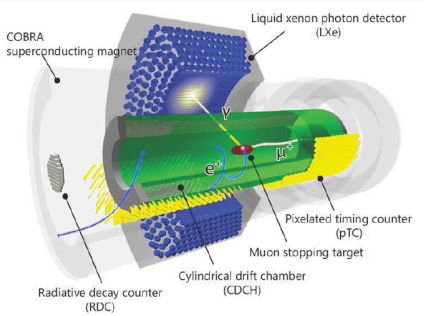
JINR plans in the Muon g-2 experiment :

– Development of new custom JavaScript web pages for the MIDAS ODB control.
– Participation in tuning and running of the DAQ system. Expert support of the MIDAS software during physics runs 2018–2020.
– Support and further development of the Event Display application.
– Participation in the run shifts during physics runs 2019–2020.
– Participation in the analysis of the experimental data.

DLNP (few FTE from Mu2e) helps to run the MEG experiment in PSI.

The upper limit on the decay probability $\mu^+ \to e^+ + \gamma$ according to data 2009–2013 is expected to be 5×10^{-13}. After a significant setup improvement new data taking is planned. On the basis of the data the sensitivity will be improved up to 5×10^{-14} in 2019.

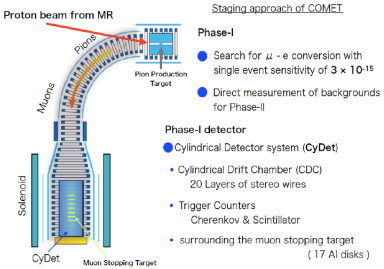




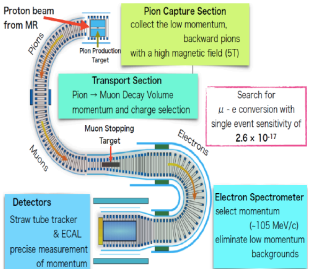
COMET (COherent Muon to Electron Transition) — search for neutrino-less conversion of muons to electrons in a nucleus at J-PARC (Japan)

The COMET will looks for $\mu^- + (A, Z) \to e^- + (A, Z)$ conversion with the same accuracy (10^{-17}) as the Mu2e experiment (with another setup). Independent observations of the process are very important.

Phase - I



Phase - II



The goals of Phase-I are:

– Direct measurement of the p-beam extinction and other potential background sources for the full COMET experiment with actual beam line;

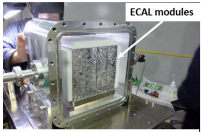
– Search for $\mu \to e$ conversion with sensitivity of $3 \cdot 10^{-15}$ (200 times better the current best SINDRUM-II limit).

The goals of Phase-II are:

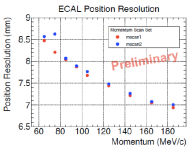
$\to$ Creation of a full beam line, use of higher beam intensity, modifications of the detector configuration from CDC to the Straw tracker and ECAL. The 8 GeV proton beam power will increase from 3.2 kW (Phase-I) to 56 kW (Phase-II). These modifications and experience (Phase-I) will make possible to reach sensitivity of $3 \cdot 10^{-17}$.

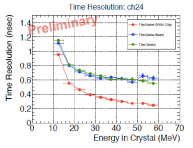
JINR contributes to R&D and construction of two basic COMET detector systems:
the Electromagnetic CALorimeter (ECAL) and Straw tracker detector.

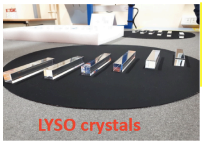
Straw-Ecal prototypes combine test (March 2017) (1.3 GeV electron cyclotron), Japan



Prototype (8x8, 64) of calorimeter



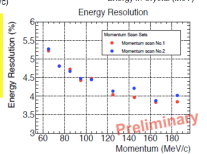




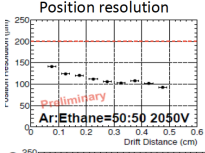
The ECAL beam test results for 105 MeV electron

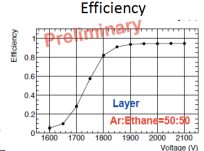
- Position resolution – 7.6 mm
- Time resolution – 0.4 ns
- Energy resolution (σ/E) - 4.2%

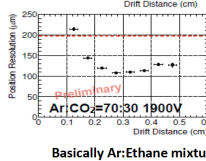
- 2400 LYSO crystals
- 20 x 20 x 120 mm^3
- readout → 10 x 10 mm^2 APD

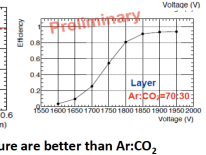


Straw-Ecal prototypes combine test (March 2017) (1.3 GeV electron cyclotron), Japan

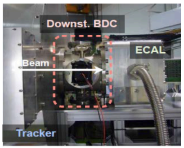


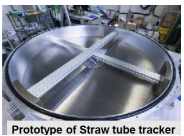






Basically Ar:Ethane mixture are better than Ar:CO_2





JINR → the ECAL :

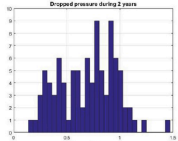
R&D of LYSO crystals based calorimeter;
LYSO crystals parameters investigation;
Measurements with calorimeter prototype;
Certification of the LYSO crystals; etc

JINR → the Straw tracking (for Phase I):

Straw tubes design and production (~2700), preliminary tests, checking of properties. Simulation of straw tracker;
Study of gas mixtures properties;
Study of the temperature and time dependence of the straw tubes.

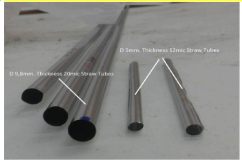
In 2018 new manufacturing area for straw-tube R&D and production (for Phase-II) was created at DLNP.

Testing about 2,700 straw tubes for Phase I in Japan

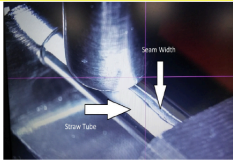


The result: pressure losses in 25% of 9.8 mm tubes during 2 years

First R&D: 5 mm diameter straw tubes made of 12 mic aluminized mylar at JINR-DLNP for COMET

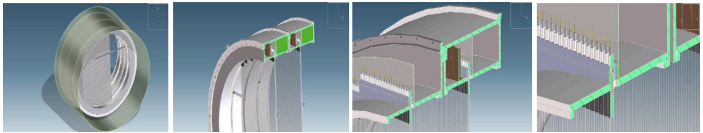


Comparison of 9.8 mm and 5 mm straw tubes



Straw Tube ultrasonic welding process

Engineering design work



— Duration of the COMET is 2015–2020.
— Annual budget is about 158k$ (JINR, 1134).

— JINR team: I.L.Evtoukhovitch, P.G.Evtoukhovitch, V.A.Kalinnikov, E.S.Kaneva, X.Khubashvili, M.D.Kravchenko, A.S.Moiseenko, A.V.Pavlov, B.M.Sabirov, N.Tsverava, E.P.Velicheva, A.D.Volkov (1.0), Z.Tsamalaidze (0.8), G. Adamov, D. Aznabayev, D. Baygarashev, V.N.Duginov, D. Goderidze, A.Issadikov (0.5), K.I.Gritsai, A.Khvedelidze, A.G.Samartsev (0.3), T.L.Enik, V.V.Elsha, G.A. Kozlov (0.2), S.N.Movchan, S.N.Shkarovskiy (0.1) = 20.5 FTE

– JINR plans in COMET ECAL: R&D of a new type of the LYSO (engineered) crystals; GEANT4 simulation of the ECAL and the certification of the crystals.

– JINR plans to check the Straw Tubes in Japan before installation: All tubes were pressurized for long-term storage. By design, straws should be released from pressure and cut from glued end-plugs with a length of 5 cm Mylar. After relaxation of the material, each tube should be checked by the following parameters: uniformity of the straw tube's cylindrical shape, uniform diameter over the entire length of the cylinder, mechanical damages, any detachment of aluminum from the Mylar surface. Preparing tubes for assembly.

– JINR will continue the straw-tube R&D at DLNP: It is planed to work on R&D straw tubes with a diameter of 5 mm from 12 μm of aluminized Mylar and their production. After complete preparation of the laboratory (clean room) the study and production of new type of straws will start. The clean room is already equipped with the tools and measurement stands. A new equipment allows us to control characteristics of all produced tubes with high accuracy. The production new type of straw tubes, testing, creation of straw tracker prototypes and beam-test in vacuum is planned.

– JINR goals in the straw-tube simulation are: To obtain drift lines in a 3-dimensional view and make changes in the algorithm for construction of isochronous drift lines taking into account the design features of the COMET experiment. To simulate the response of the straw tracker in ISEDUST.