Study of neutrino oscillations with JUNO and Daya Bay experiments. 2018-2020

N. Anfimov, T. Antoshkina, D. Biaré, S. Biktemerova, I. Butorov, A. Chukanov, A. Chuvashova, S. Dmitrievsky, D. Fedoseev, K. Fomenko, A. Formozov, M. Gonchar, O. Gorchakov, Yu. Gornushkin, V. Gromov, N. Kolganov, D. Korablyev, A.Krasnoperov, N. Morozov, D. Naumov, E. Naumova, I. Nemchenok, A. Olshevskiy, T. Rezinko, A. Rybnikov, A. Sadovsky, A. Selyunin, O. Smirnov, S. Sokolov, A. Sotnikov, M. Strizh, K. Treskov

DLNP JINR

- Tasks
- Staff
- Age

9. Requested resources
    - Total
    - Costs
    - Visits

10. Daya Bay JINR Report. 2015-2017

11. JUNO JINR Report. 2015-2017

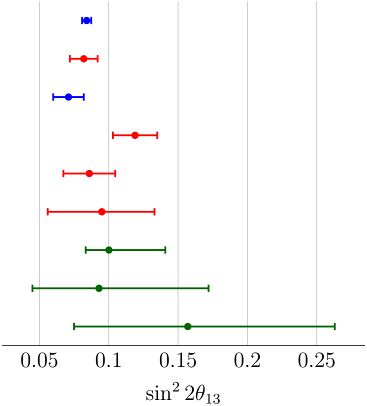
12. Answers to referees reports
    - Review by A.Eriditato
    - Review by M. Hnatic

- **Mass hierarchy.**
  - $m_3 > m_1$ or $m_3 < m_1$.
  - accelerator (NOVA, T2HK, DUNE), atmospheric (PINGU/ORCA, INO) and reactor neutrinos (JUNO, RENO-50)
- **CP violation.**
  - $\delta =?$
  - T2HK, NOVA and DUNE
- **Mixing matrix unitarity.**
  - $VV^\dagger \stackrel{?}{=} 1$
  - Do sterile neutrinos exist?
  - A long list of experimental proposals on the market.
- **Dirac vs. Majorana**
  - $\nu \stackrel{?}{=} \bar{\nu}$
  - GERDA, CUORE, KamLand-Zen, EXO, SuperNEMO

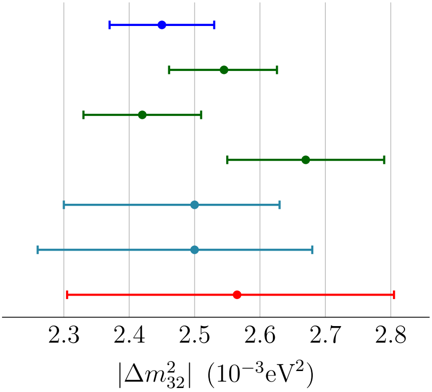
Project	ν source	Detector	Goal	Challenges
NOVA	LBL (810 km)	14 kt tracking calorimeter	2σ (2020)	Parameter degeneracy
JUNO	Reactor (53 km)	20 kt LS	$(3-4)\sigma$ (2026)	Energy resolution
PINGU/ORCA	Atmosphere	(1-10) Mt of ice	$(3-5)\sigma$ (unknown)	Energy resolution, systematics
INO	Atmosphere	50 kt magnetized calorimeter	3σ (2030)	Low statistics (10 years)
T2HK	LBL (295 km)	1Mt of water	3σ (2030)	Parameter degeneracy
DUNE	LBL (1300 km)	1kt of liquid argon	$(3-5)\sigma$ (2030)	Parameter degeneracy
Cosmology	Early Universe	CMB-S4 bolometers	4σ (>2023)	Dependence on cosmological models

Comparison of expected median sensitivities to neutrino mass hierarchy determination of various accelerator, atmospheric, reactor and cosmological experiments.

Experiment		Value
Daya Bay	nGd	0.0841 ± 0.0033
RENO	nGd	0.082 ± 0.010
Daya Bay	nH	0.071 ± 0.011
D-CHOOZ	nGd+nH	0.119 ± 0.016
RENO	nH	0.086 ± 0.019
D-CHOOZ	nH	$0.095^{+0.038}_{-0.039}$
T2K		$0.100^{+0.041}_{-0.017}$
NOνA	NH	$0.093^{+0.079}_{-0.048}$
	IH	$0.157^{+0.106}_{-0.082}$



Experiment	Value (10^{-3} eV^2)
Daya Bay	2.45 ± 0.08
T2K	$2.545^{+0.081}_{-0.084}$
MINOS	2.42 ± 0.09
NOνA	2.67 ± 0.12
Super-K	$2.50^{+0.13}_{-0.20}$
IceCube	$2.50^{+0.18}_{-0.24}$
RENO	$2.57^{+0.24}_{-0.26}$



BREAKTHROUGH PRIZE | FUNDAMENTAL PHYSICS

THE 2016 BREAKTHROUGH PRIZE IN FUNDAMENTAL PHYSICS IS AWARDED TO

Maxim Gonchar

AND COLLEAGUES AT DAYA BAY, KAMLAND, K2K & T2K,
SUDBURY NEUTRINO OBSERVATORY AND SUPER-KAMIOKANDE

For the fundamental discovery and exploration of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics.

NOVEMBER 8, 2015

Karl Johansson
Director
Breakthrough Prize Foundation

The Laureates from JINR are: M.O. Gonchar, Yu.A. Gornushkin, D.V. Naumov, I.B. Nemchenok, A.G. Olshevski (all from Daya Bay), E.A. Yakushev (KamLAND), V.A. Matveev and B.A. Popov (T2K).

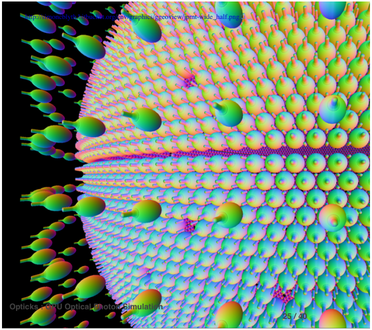

Daya Bay: Powerful reactor by mountains
4 x 20 tons target mass at far site
Far site (Hall 3)
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
900 m
Ling Ao Near site (Hall 2)
481 m from Ling Ao
526 m from Ling Ao II
Overburden: 112 m
465 m
Ling Ao-II NPP
2x2.9 GW
Water hall
810 m
Construction tunnel
Ling Ao
NPP, 2x2.9 GW
Liquid Scintillator hall
entrance
295 m
SAB
Daya Bay Near site (Hall 1)
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP, 2x2.9 GW
Total Tunnel length
~ 3000 m

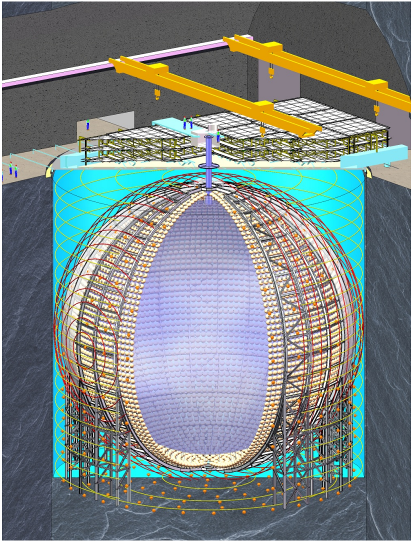
- Developed a Dubna IBD selection
- Estimated backgrounds to IBD candidates.
- Performed an oscillation analysis of Daya Bay data based on 1230 days of collected statistics.
  - official analysis of Daya Bay Collaboration
  - Paper Editors
- Wave packet impact on neutrino oscillations using the Daya Bay data.
  - Analysis
  - Paper writing
- The reactor antineutrino flux measurement
  - cross-check the official analysis
  - Review the Daya Bay paper.
- Conducted a research on measurement of reactor antineutrino energy spectra due to different isotopes.
  - Initial idea
  - Review the Daya Bay paper.

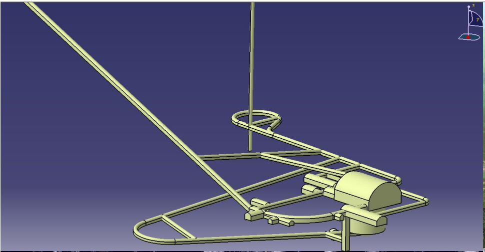
- Search for sterile neutrino.
    - Review analyses.
    - Paper writing.

- Vacuum survival oscillation probability P_{ee} does depend on neutrino mass ordering: $P_{\mathrm{ee}}^{\mathrm{NH}} \neq P_{\mathrm{ee}}^{\mathrm{IH}}$
- Optimization of sensitivity requres:
  - energy resolution $\sigma_E/E \leq 3\%/\sqrt{E}$,
  - optimal distance $L \approx 53$ km,
  - large mass of liquid scintillator $M = 20$ kt to ensure enough statistics $N_{\mathrm{IBD}} \approx 10^5$ in six years
  - maximize light collection efficiency: $N_{\mathrm{LPMT}} = 20000$ of 20" PMTs + $N_{\mathrm{SPMT}} = 25000$ of 3" PMTs, transparent LS
  - small background

- High QE PMT ($\sim$ 30%)
- Highly transparent LS
- Huge detector: 20 kt, ⌀34.5 m
- 20k 20″ PMTs
- 25k 3″ PMTs





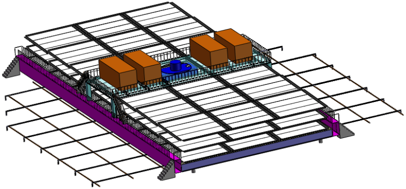


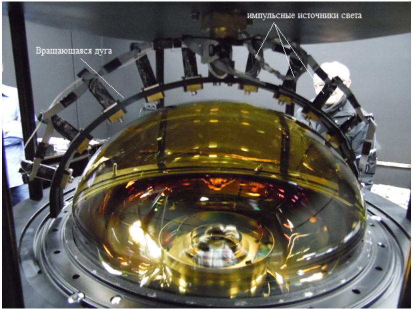
Progress: tunnel 1020 m/1340 m, shaft 485 m/611 m. To be completed in 2018.

- neutrino mass hierarchy determination with expected sensitivity corresponding to $(3-4)\sigma$,
- precision measurement of Δm^2_{21}, Δm^2_{32}, θ_{12} with accuracy better than 1%,
- possible observation of SuperNova neutrinos,
- detection of geo-neutrinos with a factor ten larger statistics than currently available,
- detection of diffuse SuperNova neutrinos,
- detection of solar neutrinos,
- detection of atmospheric neutrinos,
- study of sterile neutrino,
- indirect dark matter search,
- non-standard interaction study,
- probes of new physics.

Task	JINR	Start	End
Underground lab construction		2015.1.1	2019.6.30
Water pool cleaning and CD construction preparation		2019.7.1	2019.7.5
CD and water pull equipment installation		2019.7.6	2020.7.5
PMT base, HV and electronics prototypes ready	•	2017.3.1	2017.3.1
PMT base, HV and electronics design finalized	•	2018.4.30	2018.4.30
PMT base, HV and electronics production and aging tests	•	2018.5.1	2019.10.30
sPMT bidding		2017.1.1	2017.4.30
PMT mass production		2017.3.1	2019.6.30
PMT testing	•	2017.3.1	2020.1.31
PMT potting and testing		2018.10.1	2020.4.30
CD and VETO PMT installation		2019.10.1	2020.7.31
CD and water pool cleaning		2020.8.1	2020.8.31
Water pool cover is placed		2020.9.1	2020.9.7
TTS supporting structure installation	•	2020.9.8	2020.9.30
TTS installation	•	2020.10.1	2021.4.30
AD and VETO water filling		2020.9.8	2020.10.30
LS filling/commissioning		2020.11.1	2021.4.30
Test run	•	2021.5.1	2021.5.4

- Powering JUNO: PMT high voltage R&D
- Top Tracker: precise μ detector
- Earth Magnetic Field: PMT protection R&D
- PMT testing: brand new precise scanners + mass testing
- Liquid scintillator: purification methods and measurements
- Experiment sensitivity estimation
- MC and data analysis:
  - Hierarchy and oscillations
  - Solar and geo- neutrinos
  - Rare processes





- HV for 20 000 LPMT and 25 000 sPMT
  - Design, Production, Tests
- Top Tracker.
  - maintenance, installation, DAQ, design, production and delivery of mechanical support, and simulation and reconstruction software.
- PMT tests
  - Precision scanners, LED for containers, scanning techniques and acceptance criteria
- PMT protection against the EMF.
- Software development
  - Detector simulation
  - Reconstruction
  - Background
  - Statistical analysis (GNA)
  - Methodology for solar neutrinos

2018 I

1. Commissioning and installation of additional 2 scanning stations.
2. PMT testing
   - Naked PMT mass-testing by scanning and in the containers. Shifts on site
   - Potted PMT mass-testing. Shifts on site
   - Fine PMT studying with automatic scanning station
3. Start of HVU mass production and quality assurance tests
4. The Top Tracker DAQ software development
5. Prototyping and finalization of the Top Tracker mechanical support design
6. Top Tracker modules performance monitoring with cosmic muons
7. Simulation and reconstruction
   - Detector simulation and sensitivity estimation
   - Study of the PMT response impact on the oscillation analysis
   - IBD selection and background estimation methods
   - Muon tracking algorithms in the Top Tracker

2019 I

1. PMT testing
   - Naked PMT mass-testing by scanning and in the containers. Shifts on site
   - Potted PMT mass-testing. Shifts on site
   - Fine PMT studying with automatic scanning station
2. Finishing the HVU mass production and quality assurance tests
3. Fabrication of the Top Tracker mechanical support and shipment to JUNO
4. The Top Tracker DAQ software development
5. Top Tracker modules performance monitoring with cosmic muons
6. Simulation and reconstruction
   - Detector simulation and sensitivity estimation
   - Study of the PMT response impact on the oscillation analysis
   - IBD selection and background estimation methods
   - Muon tracking algorithms in the Top Tracker

2020 I

1. Potted PMT mass-testing. Shifts on site
2. Installation of PMTs to the JUNO detector. Shifts on site
3. Assembly and commissioning of the Top Tracker detector. Shifts at JUNO.
4. The Top Tracker DAQ software commissioning
5. Simulation and reconstruction
   - Detector simulation and sensitivity estimation
   - Study of the PMT response impact on the oscillation analysis
   - IBD selection and background estimation methods
   - Muon tracking algorithms in the Top Tracker

2018 I

1. Implementation of Daya Bay oscillation analysis within GNA framework
2. IBD selection of the complete dataset of Daya Bay phase I (2011-2017)
3. Background estimation
4. Oscillation analysis for the Phase I dataset
5. Detector energy response calibration
6. Remote and on-site shifts

2019 I

1. Implementation of combined oscillation analysis for the Daya Bay, Double CHOOZ and RENO experiments within GNA framework
2. Implementation of nH analysis of the Daya Bay data within dybOscar/GNA frameworks
3. Maintain and improve IBD selection and analysis techniques
4. Detector energy response calibration
5. Remote and on-site shifts

2020 I

1. IBD selection of the final dataset (2011-2020)
2. Background estimation
3. Final oscillation analysis of the complete Daya Bay data including both nGd and nH IBD selections
4. Update of the wave packet analysis based on the complete Daya Bay dataset
5. Collaborative work with Daya Bay, Double CHOOZ and RENO experiments towards combined oscillation analysis
6. Detector energy response calibration
7. Remote and on-site shifts

Conferences. Plenary talks I

1. D.Naumov. New Results from the Daya Bay Reactor Neutrino Experiment. Neutrino Telescopes, 13-17 March 2017, Venice, Italy;
2. D.Naumov. Latest Results from the Daya Bay Reactor Neutrino Experiment. New Trends in High-Energy Physics, 2-8 October 2016, Budva, Becici, Montenegro;
3. D.Naumov. Neutrino Physics with Nuclear Reactors. QUARKS-2016 19th International Seminar on High Energy Physics, Pushkin, Russia, 29 May - 4 June, 2016;
4. D.Naumov. Neutrino Physics with Nuclear Reactors. Международная Сессия-конференция Секции ядерной физики ОФН РАН, 12 - 15 апреля, 2016, ОИЯИ, Дубна;
5. D.Naumov. Neutrino Physics program at the JINR. 4th SOUTH AFRICA - JINR SYMPOSIUM. Few to Many Body Systems: Models and Methods and Applications, September 21-25, 2015, JINR Dubna, Moscow region, Russia;

Conferences. Plenary talks II

6. A.Olshevskiy. Accelerator Neutrino Physics. Международная Сессия-конференция Секции ядерной физики ОФН РАН, 12 - 15 апреля, 2016, ОИЯИ, Дубна;

Conferences. Talks at parallel sessions I

1. D.Naumov. Neutrino Oscillations in QFT with relativistic wave packets. Международная Сессия-конференция Секции ядерной физики ОФН РАН, 12 - 15 апреля, 2016, ОИЯИ, Дубна;
2. O.Smirnov. Geoneutrino studies with JUNO detector, International Workshop: Neutrino Research and Thermal Evolution of the Earth, October 25 – 27, 2016, Sendai, Japan;
3. Yu.Gornushkin. Status of the JUNO experiment. Международная Сессия-конференция Секции ядерной физики ОФН РАН, 12 - 15 апреля, 2016, ОИЯИ, Дубна;
4. M.Dolgareva, "Study of the neutrino decoherence effects in Daya Bay experiment". XIX International Scientific Conference of Young Scientists and Specialists. Dubna, 16-20 February, 2015.

Conferences. Talks at parallel sessions II

5. M.Dolgareva, “A study of the wave packets approach to the neutrino oscillations based on Daya Bay and KamLAND data”. XIX scientific conference of young scientists and specialists. Dubna, 14-18 March, 2016.
6. K.Treskov. Fast neutron background in the Daya Bay experiment. AYSS-2016, Dubna (winner of section), 14-18 March 2016.
7. T.Antoshkina. Studying of zonal characteristics of PMT. AYSS-2016, Dubna, 14-18 March 2016.
8. M.Gonchar, “Recent results from Daya Bay experiment”. International session-conference of the section of nuclear physics of PSD RAS. Dubna, 12-15 April, 2016.
9. M.Gonchar, "Oscillation analysis in Daya Bay experiment". XIX International Scientific Conference of Young Scientists and Specialists. Dubna, 16-20 February, 2015.

Conferences. Posters I

1. N.Anfimov. Testing methods for 20-inches PMTs of the JUNO experiment. INSTR-2017, Novosibirsk, Russia, 27 Feb - 3 Mar 2017.
2. T.Antoshkina. Optical simulation of PMT. The 2016 European School of High-Energy Physics (poster report), Norway, 15-28 June 2016.
3. T.Antoshkina. Optical simulation of PMT. 45th meeting of the PAC for Particle Physics in JINR (poster report), Dubna, 16-17 January 2017
4. T.Antoshkina. JUNO experiment. 44th meeting of the PAC for Particle Physics in JINR (poster report), Dubna, 14-15 December 2015
5. Yu.Gornushkin Background suppression in the JUNO experiment. 38th International Conference on High Energy Physics 3-10 August 2016, Chicago, USA (poster report);

Conferences. Posters II

6. K.Treskov. The usage of wave packet approach to neutrino oscillations in analysis of reactor and solar experiments, 44th meeting of the PAC for Particle Physics in JINR (poster report), Dubna, 14-15 December 2015
7. K.Treskov. Inverse beta-decay event selection and fast neutron background in the Daya Bay experiment. The 2016 European School of High-Energy Physics (poster report), Norway, 15-28 June 2016
8. K.Treskov. Inverse beta-decay event selection and fast neutron background in the Daya Bay experiment, 45th meeting of the PAC for Particle Physics in JINR (poster report), Dubna, 16-17 January 2017.
9. M.Gonchar, poster, "Oscillation analysis in Daya Bay experiment". 46th meeting of the PAC for Particle Physics. Dubna, 16-17 January, 2017.
10. M.Dolgareva, poster, "Study of decoherence effects in neutrino oscillations at Daya Bay". ICHEP 2016. Chicago, 3-10 August 2016.

JINR PACs I

1. M.Dolgareva, poster, "Study of decoherence effects in neutrino oscillations at Daya Bay". 46th meeting of the PAC for Particle Physics. Dubna, 16-17 January, 2017.
2. M.Gonchar, "JINR neutrino programme. Daya Bay and JUNO: precision measurements with reactor neutrinos". 46th meeting of the PAC for Particle Physics. Dubna, 16-17 January, 2017.
3. M.Gonchar, poster, "Oscillation analysis in Daya Bay experiment". Neutrino 2016. London 4-9 July, 2016.

Seminars I

1. D.Naumov. Измерение θ_{13}, Δm^2_{32} и ковариантная квантово-полевая теория нейтринных осцилляций, 07/02/2017 ПИЯФ, Гатчина, РФ;
2. D.Naumov. Ковариантная квантово-полевая теория нейтринных осцилляций, 09/11/2016 ИЯИ РАН, Москва, РФ;
3. D.Naumov. Измерение θ_{13}, Δm^2_{32} и ковариантная квантово-полевая теория нейтринных осцилляций, 03/11/2016 НИИЯФ ИГУ, Москва, РФ;
4. D.Naumov. Измерение θ_{13}, Δm^2_{32} и ковариантная квантово-полевая теория нейтринных осцилляций, 20/10/2016 ЛТФ ОИЯИ, Дубна, РФ;
5. A.Olshevskiy. The Scientific Heritage of Bruno Pontecorvo, The Triumph of Neutrino Oscillations. Seminar at Pisa, 13 October 2015.
6. M.Gonchar, "New results from the Daya Bay experiment". DLNP seminar. Dubna. 10 November 2016.

Seminars II

7. M.Gonchar, “Neutrino mass hierarchy measurement in JUNO”, seminar for students, Dubna, 11 February 2016.
8. M.Gonchar, „Измерение параметров смешивания нейтрино амплитуды осцилляций $\sin^2 2\theta_{13}$ и расщепления масс Δm^2_{32} в эксперименте Daya Bay“. DLNP seminar. Dubna, October, 2015

1. K. Treskov, specialist, 2015.
   „Нейтринные осцилляции в веществе и возможность экспериментального исследования декогеренции в солнечных экспериментах“.
2. M. Dolgareva, master, 2016.
   „Исследование эффектов декогерентности волновых пакетов в нейтринных осцилляциях на основе данных экспериментов KamLAND и Daya Bay“.
3. V. Sharov, bachelor, 2016.
   „Измерение характеристик крупногабаритных фотоэлектронных умножителей для эксперимента JUNO“. Moscow State University.
4. M. Gonchar, candidate, 2017.
   „Измерение угла смешивания θ_{13} и расщепления масс нейтрино Δm^2_{32} в эксперименте Daya Bay“.
5. D. Naumov, doctor, 2017.
   „Измерение θ_{13}, Δm^2_{32} и ковариантная квантово-полевая теория нейтринных осцилляций“.

[1] F. P. An *et al.* [Daya Bay Collaboration], "Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay", **Submitted to: Phys.Rev.Lett.** [arXiv:1704.01082 [hep-ex]].

[2] F. P. An *et al.* [Daya Bay Collaboration], "Measurement of electron antineutrino oscillation based on 1230 days of operation of the Daya Bay experiment", Phys. Rev. D **95**, no. 7, 072006 (2017)

[3] F. P. An *et al.* [Daya Bay Collaboration], "Study of the wave packet treatment of neutrino oscillation at Daya Bay", **Submitted to: Eur. J. Phys.**

[4] M. Dolgareva *et al.* [Daya Bay Collaboration], "Study of the wave packet treatment of neutrino oscillation at Daya Bay", PoS., T. ICHEP2016, 1081 (2016).

[5] F. P. An *et al.* [Daya Bay Collaboration], "Improved Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay", Chin. Phys. C **41**, no. 1, 013002 (2017)

[6] P. Adamson *et al.* [Daya Bay and MINOS Collaborations], "Limits on Active to Sterile Neutrino Oscillations from Disappearance Searches in the MINOS, Daya Bay, and Bugey-3 Experiments", Phys. Rev. Lett. **117**, no. 15, 151801 (2016)

[7] F. P. An *et al.* [Daya Bay Collaboration], "Improved Search for a Light Sterile Neutrino with the Full Configuration of the Daya Bay Experiment", Phys. Rev. Lett. **117**, no. 15, 151802 (2016)

[8] V. A. Bednyakov, D. V. Naumov and O. Y. Smirnov, "Neutrino physics and JINR", Phys. Usp. **59**, no. 3, 225 (2016).

[9] F. P. An *et al.* [Daya Bay Collaboration], "New measurement of θ_{13} via neutron capture on hydrogen at Daya Bay", **Phys. Rev. D** **93**, no. 7, 072011 (2016)

[10] F. P. An *et al.* [Daya Bay Collaboration], "Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay", **Phys. Rev. Lett.** **116**, no. 6, 061801 (2016)

[11] F. P. An *et al.* [Daya Bay Collaboration], "The Detector System of The Daya Bay Reactor Neutrino Experiment", **Nucl. Instrum. Meth. A** **811**, 133 (2016)

[12] F. An *et al.* [JUNO Collaboration], "Neutrino Physics with JUNO", **J. Phys. G** **43**, no. 3, 030401 (2016)

[13] D. V. Naumov, V. A. Naumov and D. S. Shkirmanov, "Inverse-square law violation and reactor antineutrino anomaly", **Phys. Part. Nucl.** **48**, no. 1, 12 (2017)

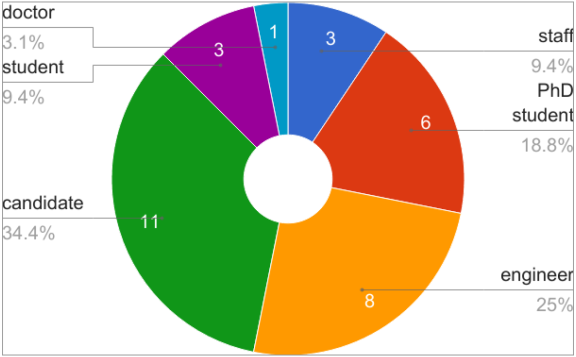
[14] F. P. An *et al.* [Daya Bay Collaboration], "New Measurement of Antineutrino Oscillation with the Full Detector Configuration at Daya Bay", **Phys. Rev. Lett.** **115**, no. 11, 111802 (2015)

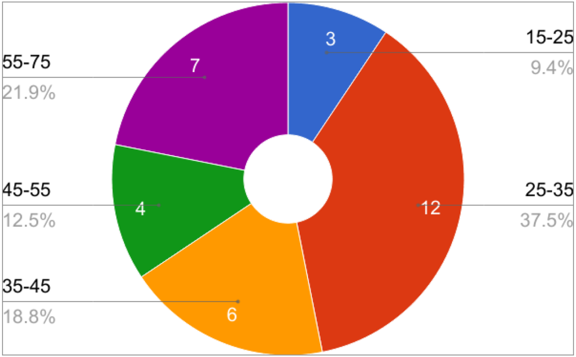
[15] Z. Djurcic *et al.* [JUNO Collaboration], "JUNO Conceptual Design Report", arXiv:1508.07166 [physics.ins-det].

		2018			2019			2020		
№	Name	DB	JUNO	**Sum**	DB	JUNO	**Sum**	DB	JUNO	**Sum**
1	N. Anfimov	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
2	T. Antoshkina	0	1	**1**	0	1	**1**	0	1	**1**
3	D. Biaré	0	1	**1**	0	1	**1**	0	1	**1**
4	S. Biktemerova	0	0.5	**0.5**	0	1	**1**	0	1	**1**
4	I. Butorov	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
6	A. Chukanov	0.5	0.5	**1**	0.4	0.6	**1**	0.3	0.7	**1**
7	A. Chuvashova	0	0.3	**0.3**	0	0.3	**0.3**	0	0.3	**0.3**
8	S. Dmitrievsky	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
9	D. Fedoseev	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
10	K. Fomenko	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
11	A. Formozov	0	0.8	**0.8**	0	1	**1**	0	1	**1**
12	M. Gonchar	0.7	0.3	**1**	0.5	0.5	**1**	0.5	0.5	**1**
13	O. Gorchakov	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
14	Yu. Gornushkin	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
15	V. Gromov	0	1	**1**	0	1	**1**	0	1	**1**
16	N. Kolganov	0	0.1	**0.1**	0	0.3	**0.3**	0	0.9	**0.9**
17	D. Korablyev	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
18	A. Krasnoperov	0	0.3	**0.3**	0	0.3	**0.3**	0	0.3	**0.3**

		2018			2019			2020		
№	Name	DB	JUNO	**Sum**	DB	JUNO	**Sum**	DB	JUNO	**Sum**
19	N. Morozov	0	0.2	**0.2**	0	0.2	**0.2**	0	0.2	**0.2**
20	D. Naumov	0.5	0.5	**1**	0.4	0.6	**1**	0.3	0.7	**1**
21	E. Naumova	1	0	**1**	0.8	0.2	**1**	0.7	0.3	**1**
22	I. Nemchenok	0.1	0.5	**0.6**	0.1	0.5	**0.6**	0.1	0.5	**0.6**
23	A. Olshevskiy	0.1	0.3	**0.4**	0.1	0.3	**0.4**	0.1	0.3	**0.4**
24	T. Rezinko	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
25	A. Rybnikov	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
26	A. Sadovsky	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
27	A. Selyunin	0	0.5	**0.5**	0	0.5	**0.5**	0	0.5	**0.5**
28	O. Smirnov	0	0.5	**0.5**	0	0.5	**0.6**	0	0.8	**0.8**
29	S. Sokolov	0	1	**1**	0	1	**1**	0	1	**1**
30	A. Sotnikov	0	0.3	**0.3**	0	0.3	**0.3**	0	0.3	**0.3**
31	M. Strizh	0.3	0	**0.3**	0.3	0	**0.3**	0.3	0	**0.3**
32	K. Treskov	0.6	0.4	**1**	0.5	0.5	**1**	0.3	0.7	**1**
	Sum FTE	3.8	15.5	**19.3**	3.1	17.1	**20.3**	2.6	18.5	**21.1**
	People	8	30	**32**	8	31	**32**	8	31	**32**
	FTE/person	0.48	0.52	**0.6**	0.39	0.55	**0.63**	0.33	0.6	**0.66**

Management	**D. Naumov**, M. Gonchar
PMT HV	A. Sadovsky, **A. Olshevskiy**
PMT response	**T.Antoshkina**, O. Gorchakov
PMT testing	**N. Anfimov**, D. Biaré (station), I. Butorov, D. Fedoseev, D. Korablyev, T. Rezinko, A. Rybnikov, A. Selyunin, S. Sokolov
Top Tracker	A. Chuvashova, D. Biaré, S. Dmitrievsky, **Yu. Gornushkin**, V. Gromov, A. Krasnoperov
PMT EMF shielding	K. Fomenko, **O. Smirnov**, A. Sotnikov
Detector EMF shielding	N. Morozov
LS	I. Nemchenok, A. Formozov (LS resolution MC)
Simulation and analysis	S. Biktemerova, A. Chukanov, **M. Gonchar**, N. Kolganov, **D. Naumov**, E. Naumova, M. Strizh, K. Treskov


doctor
3.1%
student
9.4%
candidate
34.4%
staff
9.4%
PhD
student
18.8%
engineer
25%
1
3
3
6
8
11


3
15-25
9.4%
55-75
21.9%
7
45-55
12.5%
4
25-35
37.5%
12
35-45
18.8%
6

HV system production, test and supply to JUNO	2 000
Design, production and delivery to JUNO of the TT mechanics	180
Equipment for PMT tests and data storage for test data	100
Prototyping of the EMF shielding	30
Daya Bay common fund contribution	180
Money for visits	500
Total	2 990 K$

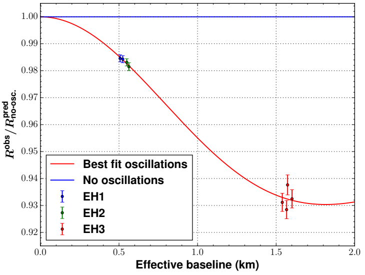
High Voltage	Components and PCB production		1000
	PCB and Unit assembly, sealing		500
	Testing		400
	Supply		100
	Total	20K units × 100 $	2000 K$
Top Tracker	Materials	140 tons × 0.68K$	95.0
	Production costs	140 tons × 0.48K$	67.5
	Transportation	7 containers x 2.5K$	17.5
	Total		180.0 K$

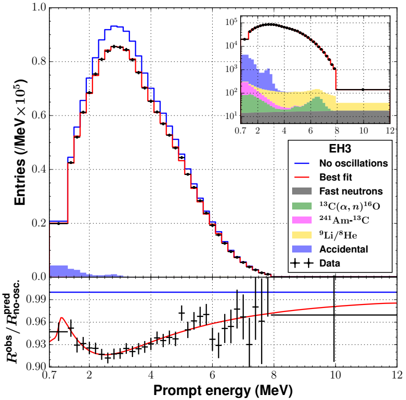
PMT testing	Materials		10
	Equipment		10
	Storage disks	$100\text{Tb}\times 2(\text{replicaiton})\times 3(\text{servers}) = 600$ Tb	25
	3 Data servers	on-site, IHEP, JINR	45
	2 Scanning Stations production + electronics	year 2018	10
	Total		100 K$
EMF shielding	Materials		9
	Work		12
	Equipment		9
	Total		30 K$

	Travels per year	Total	2018	2019	2020
JUNO	General Collaboration Meetings 2 meetings × 8 persons × 1week (1.5K$/week)	**72**	24	24	24
	Experts during PMT and electronics tests 14 men × months. (4K$/month)	**168**	56	56	56
	HV work 2 times × 2 men × 1week (1.5K$/week)	**18**	6	6	6
	EMF work 2 times × 2 men × 1week (1.5K$/week)	**18**	6	6	6
	TT monitoring 2 times × 2 men × 2 weeks (2K$/week)	**24**	8	8	8
	TT installation 15 men × months (3K$/month)	**45**	-	-	45
	Software work 2 times × 4 men × 2 weeks (2K$/week)	**48**	16	16	16
Daya Bay	General Collaboration Meetings 2 times × 3 men × 1 week (1.7K$/week)	**31**	11	10	10
	Shifts 8 weeks, 1.3K$/week	**31**	11	10	10
	Conferences, schools 6 men × visits (2.5K$/visit)	**45**	15	15	15
	Total	**500**	153	151	196

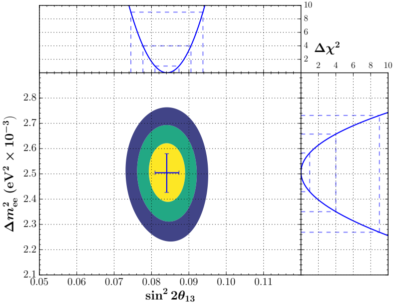
- Developed Dubna IBD selection method. IBD selection cuts are tuned optimizing the final uncertainty on oscillation parameters.
- An additional study of muon veto and multiplicity cuts concluded in their optimization.
- Estimated fast neutron background

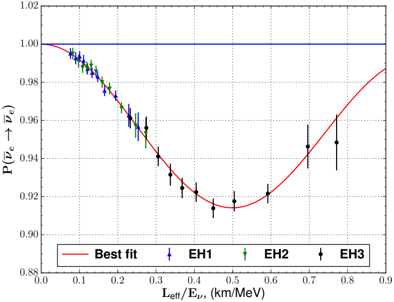
Far vs. near comparison





The observed **event rate deficit** and **relative spectrum distortion** are highly consistent with oscillation interpretation.





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

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

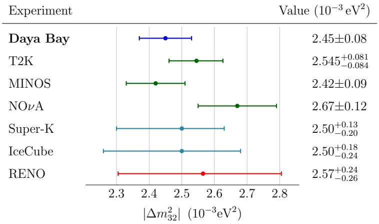
$$\chi^2/\mathrm{NDF} = 232.6/263$$

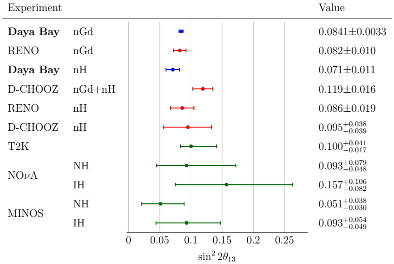
- Most precise $\sin^2 2\theta_{13}$ measurement. The non-zero value is excluded at $> 25\sigma$
- Most precise measurement of Δm^2_{ee}
- Normal Hierarchy:

$$\Delta m^2_{32} = (2.45 \pm 0.06(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})) \times 10^{-3}\ \mathrm{eV}^2$$

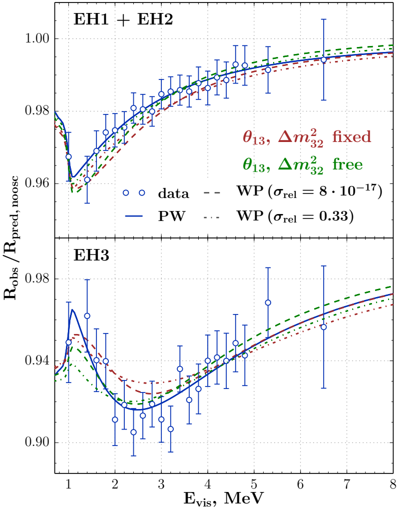
- Inverted Hierarchy:

$$\Delta m^2_{32} = (-2.56 \pm 0.06(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})) \times 10^{-3}\ \mathrm{eV}^2$$





- Plane-wave (PW) model of neutrino oscillations is not self-consistent
- A wave-packet (WP) model modifies the oscillation probability formula
- It depends on σ_p –effective dispersion of neutrino wave-packet and predicts suppression of oscillations:
  - at distances exceeding the **coherence length** $L^{coh} = \frac{L^{osc}}{\sqrt{2}\pi\sigma_{rel}}$, where $\sigma_{rel} = \sigma_p/p$.
  - if $\sigma_x \gg L^{osc}$, where $\sigma_x = 1/2\sigma_p$.



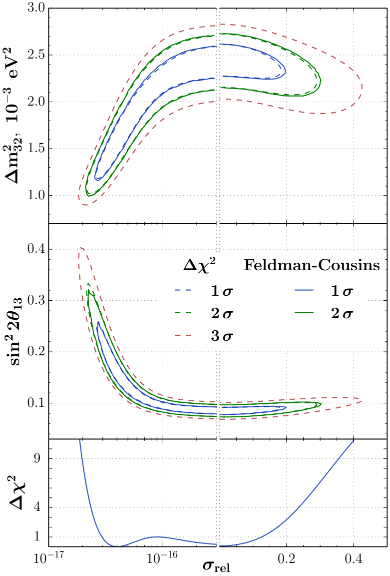
- The obtained limits read

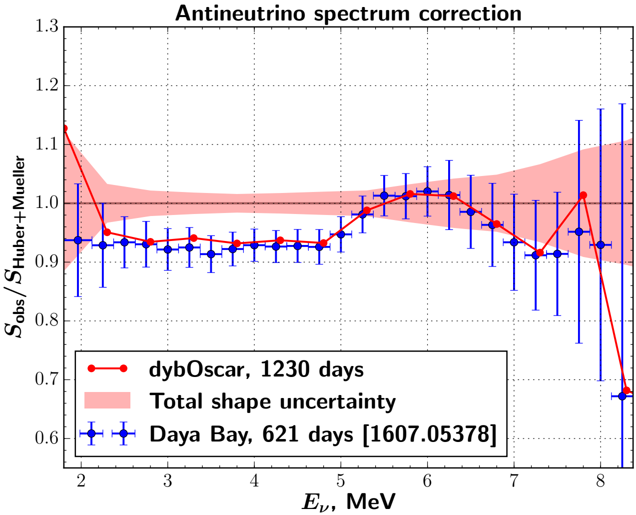
$$2.38 \cdot 10^{-17} < \sigma_{\text{rel}} < 0.23$$

- taking into account the reactor/detector sizes:

$$10^{-11}\ \text{cm} \lesssim \sigma_x \lesssim 2m.$$

- These results ensure unbiased measurement of $\sin^2 2\theta_{13}$ and Δm^2_{32} within the PW model





- Shape of reactor spectrum is fitted simultaneously with oscillation parameters. Good agreement with a dedicated analysis of the reactor spectrum.
- Correlation of oscillation and spectral parameters is negligible.

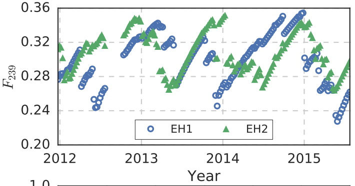
- A number density of IBD events reads

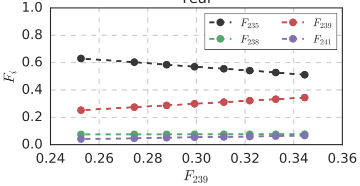
$$\frac{d^2 N_{\mathbf{IBD}}(E,t)}{dEdt} \propto \sigma_{\mathbf{IBD}}(E) \frac{W_{\mathbf{th}}(t)}{\overline{E}(t)} \sum_{i=1}^{4} f_i(t) S_i(E),$$

where $W_{\mathbf{th}}(t)$ – reactor power, $\overline{E}(t)$ – mean released energy per fission, $f_i(t)$ – fraction of fissions from isotope i, $\sigma_{\mathbf{IBD}}(E)$ – IBD cross-section. Main contributions to $\bar{\nu}_e$ production are due to ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu.

- For multiple reactors $f_i(t)$ is replaced by

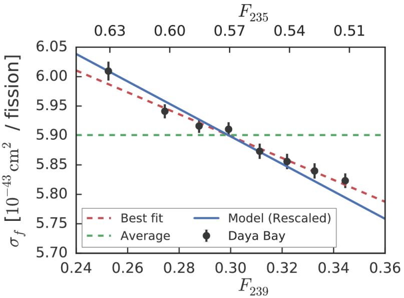
$$F_i(t) = \sum_r \frac{W^r_{\mathbf{th}}(t)\overline{P}^r_{\mathbf{ee}} f_i(t)}{L^2_r \overline{E}_r(t)} \Bigg/ \sum_r \frac{W^r_{\mathbf{th}}(t)\overline{P}^r_{\mathbf{ee}}}{L^2_r \overline{E}_r(t)} .$$



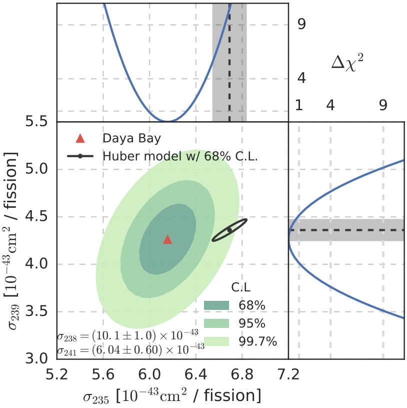


Time evolution of $W_{\mathbf{th}}(t)$, $\overline{E}(t)$, $F_i(t)$ can be seen as a dependence on F_i, for example, on F_{239}.

- Observed time evolution of IBD yield per fission σ_f ($> 10\sigma$).

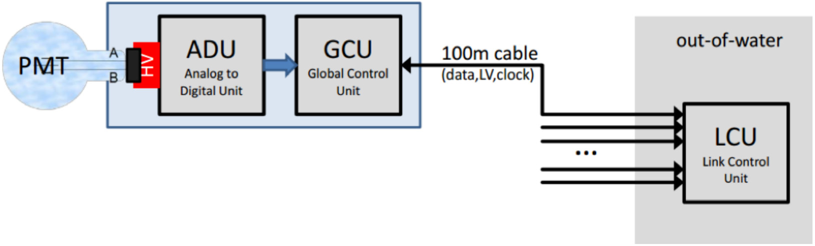


- Observed time evolution of IBD yield per fission σ_f ($> 10\sigma$).
- Measured ^{235}U and ^{239}Pu:
  - ^{239}Pu agrees with model.
  - ^{235}U disagrees with model.
- **Sterile neutrino hypothesis is unlikely to explain the reactor antineutrino anomaly.**



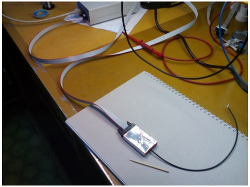
- $+24$V is converted into up to 3 kV in-place ($I_{\max} = 300\mu A$)
- The HV design driven the full electronics design
- Failure rate requirement to "channel": $< 1\%$ in 6y and $< 10\%$ in 20y.

Scheme BX



- $+24$V is converted into up to 3 kV in-place ($I_{\max} = 300\mu A$)
- The HV design driven the full electronics design
- Failure rate requirement to "channel": $< 1\%$ in 6y and $< 10\%$ in 20y.

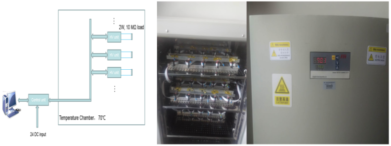
- Two companies: HVSYS (Dubna) and Marathon (Moscow)
- Both produced a first prototype (contracted by JINR)



- $+24$V is converted into up to 3 kV in-place ($I_{\max} = 300\mu A$)
- The HV design driven the full electronics design
- Failure rate requirement to "channel": $< 1\%$ in 6y and $< 10\%$ in 20y.

- Two companies: HVSYS (Dubna) and Marathon (Moscow)
- Both produced a first prototype (contracted by JINR)
- Accelerated life tests $\rightarrow$ optimizations

HV Units Acceleration Life Test



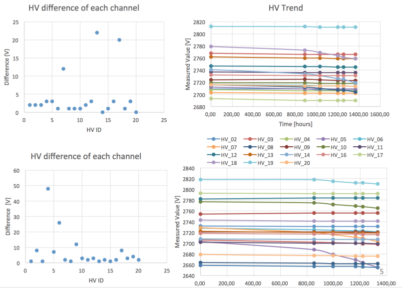
The structure | The inner | The outer

Integrated 7000 hours

- $+24$V is converted into up to 3 kV in-place ($I_{max} = 300\mu A$)
- The HV design driven the full electronics design
- Failure rate requirement to “channel”: $< 1\%$ in 6y and $< 10\%$ in 20y.

- Two companies: HVSYS (Dubna) and Marathon (Moscow)
- Both produced a first prototype (contracted by JINR)
- Accelerated life tests $\rightarrow$ optimizations

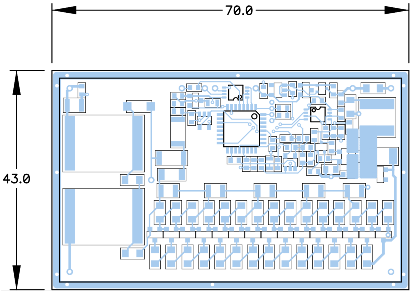
HV Units Drift observed



38 HVU alive. 5 show a drift of HV

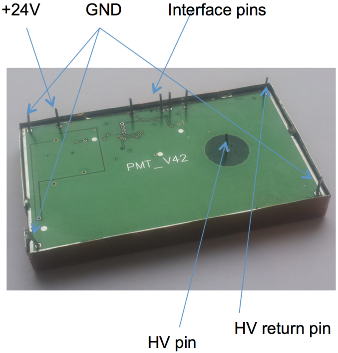
- $+24$V is converted into up to 3 kV in-place ($I_{\max} = 300\mu A$)
- The HV design driven the full electronics design
- Failure rate requirement to "channel": $< 1\%$ in 6y and $< 10\%$ in 20y.

- Two companies: HVSYS (Dubna) and Marathon (Moscow)
- Both produced a first prototype (contracted by JINR)
- Accelerated life tests $\rightarrow$ optimizations
- Second prototype (HVSYS+Marathon)



- $+24$V is converted into up to 3 kV in-place ($I_{\max} = 300\mu A$)
- The HV design driven the full electronics design
- Failure rate requirement to "channel": $< 1\%$ in 6y and $< 10\%$ in 20y.

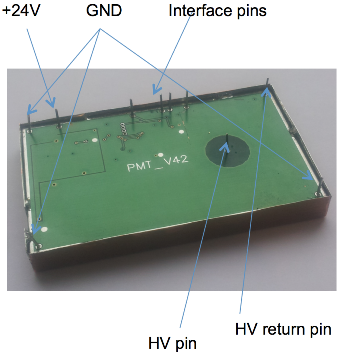
- Two companies: HVSYS (Dubna) and Marathon (Moscow)
- Both produced a first prototype (contracted by JINR)
- Accelerated life tests $\rightarrow$ optimizations
- Second prototype (HVSYS+Marathon)



200 HV units are being produced for further tests

- $+24$V is converted into up to 3 kV in-place ($I_{\max} = 300\mu A$)
- The HV design driven the full electronics design
- Failure rate requirement to "channel": $< 1\%$ in 6y and $< 10\%$ in 20y.

- Two companies: HVSYS (Dubna) and Marathon (Moscow)
- Both produced a first prototype (contracted by JINR)
- Accelerated life tests $\rightarrow$ optimizations
- Second prototype (HVSYS+Marathon)
- The goal: 100$/HVU (less than industrial) satisfying the strict requirements.



- Hamamatsu (Japan) R12860 20" PMT (5000) and NNVT (China) 20" MCP-PMT (15000).
- PDE (Photon Detection Efficiency)$> 24\%$ (at 425 nm),
- Gain $\simeq 10^7$,
- Dark rate < 50 kcps,
- Peak-to-Valley ratio > 2.5 etc.
- PDE PC surface inhomogeneity $< 15\%$.

JINR

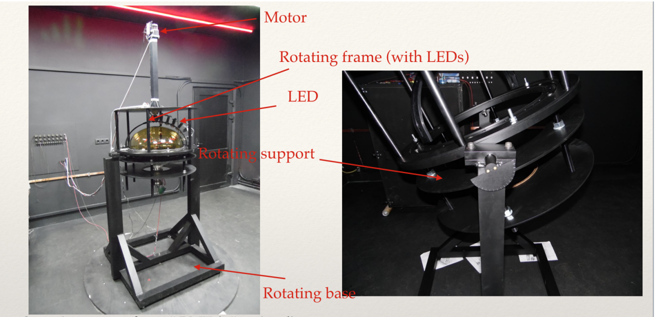
- constructed a laboratory with dark room and EMF compensation

JINR

- constructed a laboratory with dark room and EMF compensation

JINR

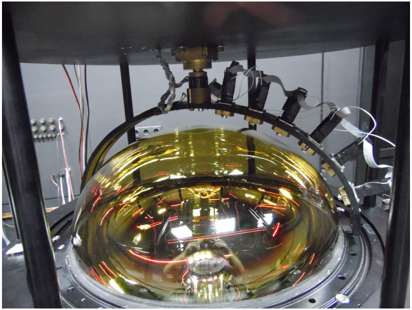
- constructed a laboratory with dark room and EMF compensation
- developed a brand-new PMT scanner

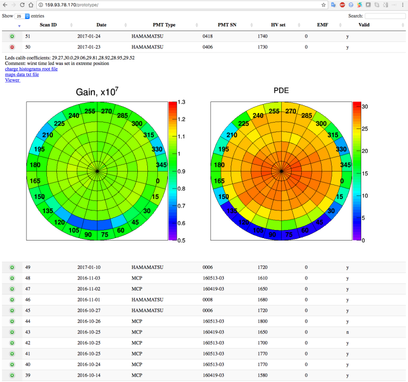


Scanning system for 20″ PMT (8″ optional)

JINR

- constructed a laboratory with dark room and EMF compensation
- developed a brand-new PMT scanner
- will deliver onsite 4 scanners with software (three already built)

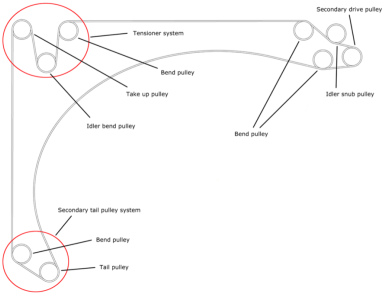


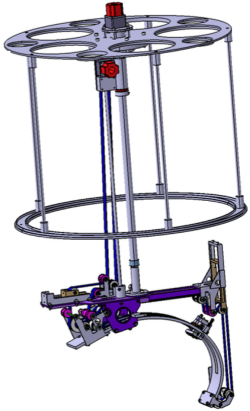


Scan ID	Date	PMT Type	PMT SN	HV set	EMF	Valid
51	2017-01-24	HAMAMATSU	0418	1740	0	y
50	2017-01-23	HAMAMATSU	0406	1730	0	y
49	2017-01-10	HAMAMATSU	0006	1720	0	y
48	2016-11-03	MCP	160513-03	1610	0	y
47	2016-11-02	MCP	160419-03	1650	0	y
46	2016-11-01	HAMAMATSU	0008	1680	0	y
45	2016-10-27	HAMAMATSU	0006	1720	0	y
44	2016-10-26	MCP	160513-03	1800	0	y
43	2016-10-25	MCP	160419-03	1650	0	n
42	2016-10-25	MCP	160513-03	1700	0	y
41	2016-10-25	MCP	160513-03	1770	0	y
40	2016-10-24	MCP	160513-03	1770	0	y
39	2016-10-14	MCP	160419-03	1580	0	y

JINR

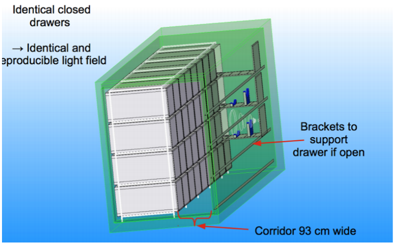
- constructed a laboratory with dark room and EMF compensation
- developed a brand-new PMT scanner
- will deliver onsite 4 scanners with software (three already built)
- developed a new type of scanner with single LED

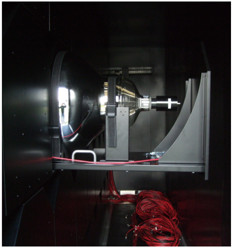




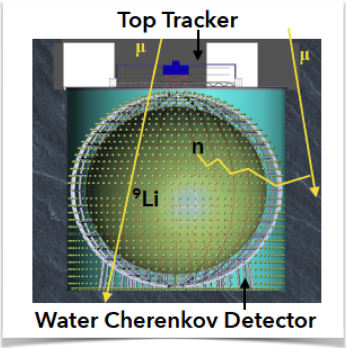
- Four containers with 36 drawers → mass testing of PMT
- JINR will supply 150 LED

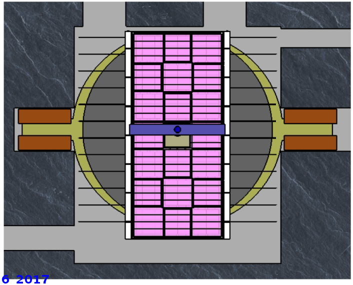
- JINR provides a help in setting up the integral measurements
- JINR develops a method matching integral and differential measurements





Main issue: $^{9}Li/^{8}He$ background.



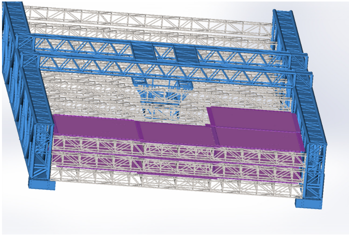


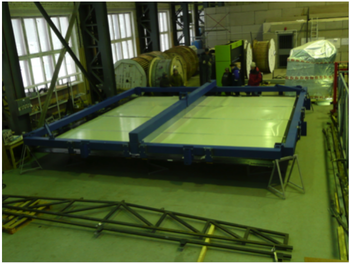
JINR is responsible for

- the design, fabrication and construction of the mechanical support of the TT detector;
- monitoring of performance of the TT modules during the period of their storage;

JINR takes part

- in development of the data acquisition system software;
- in the offline software development for the analysis of the TT data.





JINR is responsible for

- the design, fabrication and construction of the mechanical support of the TT detector;
- monitoring of performance of the TT modules during the period of their storage;

JINR takes part

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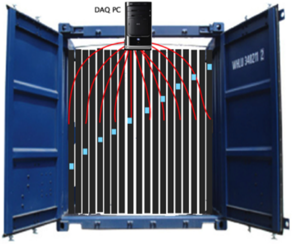

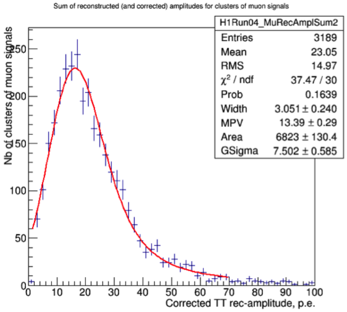

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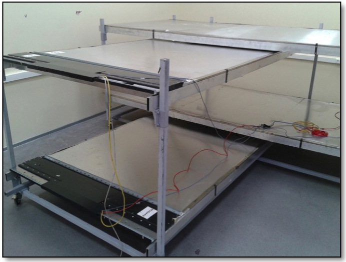
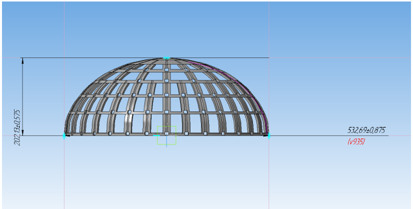
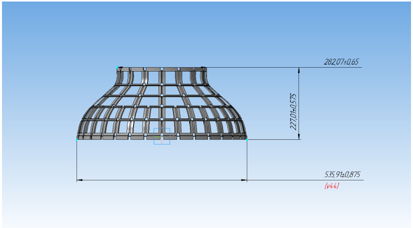


The cosmic ray telescope made of the TT modules at JINR for the DAQ software development.

- Collection efficiency of a large PMT is significantly degraded in a magnetic field
- We in JINR are working on a design of the protection

- Performed calculations of Helmholtz coils needed to screen EMF of CD (2D and 3D)
- Design and test a μ-metal cage
- Design and test various templates using amorphous and nanocrystalline materials



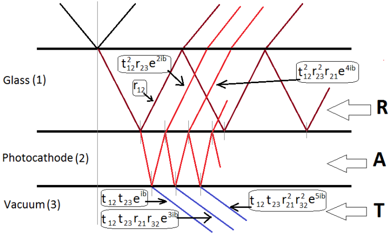


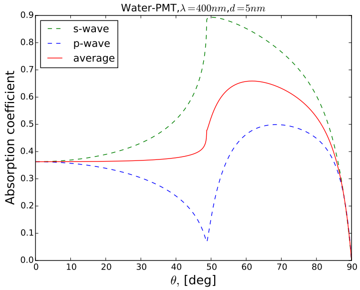
JINR team develops

- Global Neutrino Analysis Framework (GNA): statistical data analyses of neutrino experiments.

The following studies are performed:

- Impact of ^{9}Li/^{8}He background on mass hierarchy determination (GNA).
- Impact of ^{14}C contamination in liquid scintillator on mass hierarchy determination (GNA).
- Simulation of optical properties of photomultiplier in various media





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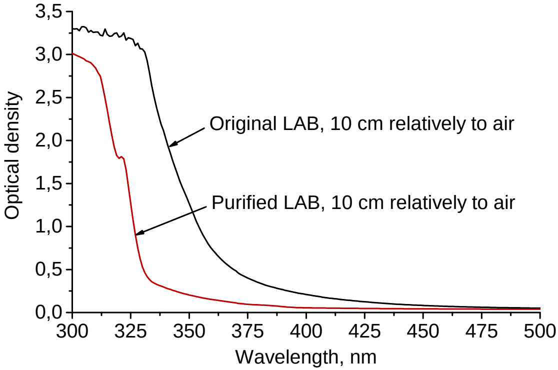
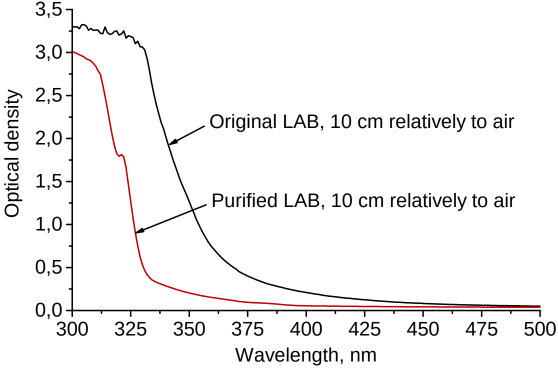


- Liquid scintillator of JUNO will be based on Linear alkylbenzene (LAB)
- The main problem: insufficient transparency of LAB.
- Based on various studies we proposed a purification method based on charcoal.
- Scintillation additive: 2,5-dipxenyloxazole (PPO) was purified and the light output of LS was measured (+6%).



- “The effort on Daya-Bay should be reduced correspondingly to the ramping up of the JUNO activities. The participation should be concentrated on the work of PhD students, in the position of writing excellent theses on data analysis such to include original physics results.”
  This is our plan also reflected in FTE migration from Daya Bay to JUNO.
- “The JUNO physics case should be carefully monitored by JINR management in relation to the international competition in view of the potential cancellation of the Taishan NPP cores, that would lead to a longer data taking period (7.5 years) needed to achieve the aimed at goals on the mass hierarchy determination.”
  Agreed.
- “The work on the JUNO PMT system must have first priority: this is the flagship hardware contribution from JINR.”
  This is the first priority.

- "The scientific contributions from JINR researchers have been so far very good in terms of presentations to conferences and number of published papers. However, an effort must be paid concerning the education and training of students. Only 3 PhD theses were completed so far. This is reflected in the average age of the group (40 years) and in the presence of only 3 bachelor and 6 PhD students out of 32 group members."
  We acknowledge this observation and will pay an additional attention to hire more students.
- "As mentioned above, the JINR group is large. One should make sure that the impact to the experiment be proportionally high. The referee sees that there are several cases where only a marginal contribution is expected for the future years by group members."
  The core of the group is very active and plays a leading role in the experiment. Several colleagues could devote a smaller fraction of their time due to involvement in other projects. This is reflected in FTE. Their contribution is however important enough.

- "As far as the financial resources, the referee would like to have a better clarification of the requested funds for the major effort on the HV: the level of detail on the estimates is lower that for the other subprojects, despite the quantitative relevance. "
  - **We estimate 20 000 channels worth to 2M$.**
  - **There is no commercial analogue of all functionalities for such a system. Existing HV units are by 2-3 times more expensive.**
  - **We are looking for components with higher reliability. The final price will be determined with a tender.**
  - **In case of higher price the JUNO Collaboration will cover the over-budget.**
- "The request for travel money seems to be excessive, also taking into account the overlap between Daya-Bay and JUNO. The referee is puzzled by the coincidence that the estimate for the needed travel money adds up to exactly 500 k$."
  This is a magic due to roundoff.

- "The weaknesses and potential risks of this project are not presented (for example, an increase of prices). Consequently, there are no prepared strategies how to handle the risk scenarios".
  Thanks for pointing this out. The project presented to PAC contains now the SWOT analysis.
- "LNP, some members of which are the project proponents, is a key participant in other important neutrino experiments such as Baikal experiment and experiment in the Kalinin atomic plant. What is the benefit in participating in another big project, what will be the synergistic effect in this triad participation and what will be the added value for JINR being international organization?"
  - **The main benefit is an important and exciting scientific program of Daya Bay and JUNO experiments which can not achieved in other experiments.**
  - **The mass hierarchy determination is a hard topic. It is safer to use several independent techniques like reactor and accelerator experiments to make a reliable measurement.**

- **The JINR Neutrino Program is a comprehensive multi-thread investigation of neutrino physics.**

- “Young scientists from JINR member states other than the Russian Federation are not included in this project. Are project proponents planning some activity to attract young scientists and engineers from the JINR member states?”
  We agree with a great importance of this remark. The Slovak group by Prof. F. Simkovich now joined our proposal.