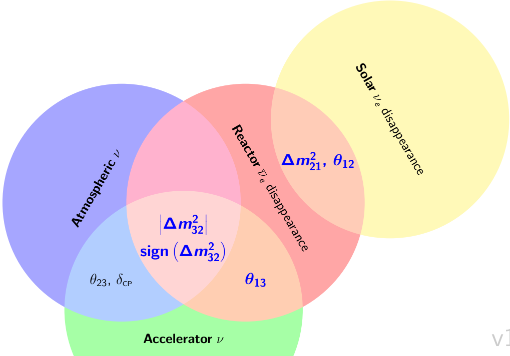
The JUNO Project

Dmitry Naumov for the JINR group

PAC JINR

June 29, 2020



v1.0

The project update: JUNO and Daya Bay

Daya Bay will stop by the end of 2020

Topic: 2010-2023

- 02-2-1099-2010/2023 Study of Neutrino Oscillations

Past: 2007—2017

- The Daya Bay Project

Present: 2018—2020

- The JUNO/Daya Bay Project

Future: 2021—2023

- The JUNO Project
- The Daya Bay activity

The project update: JUNO and Daya Bay

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Future: 2021—2023

- The JUNO Project
- The Daya Bay activity

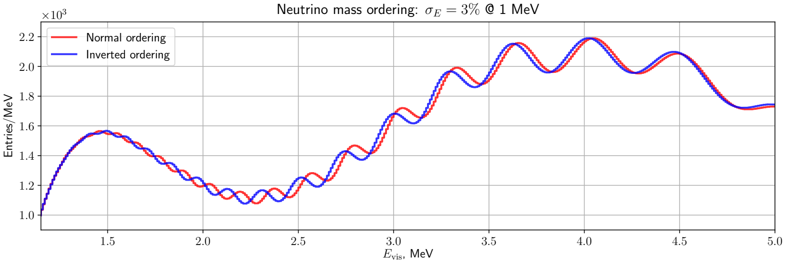
Our team

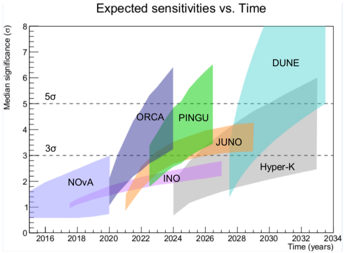
N. Anfimov, T. Antoshkina, S. Biktemerova, A. Bolshakova, I. Butorov, A. Chetverikov, A. Chukanov, S. Dmitrievsky, D. Dolzhikov, D. Fedoseev, M. Gonchar, Y. Gornushkin, M. Gromov, V. Gromov, D. Korablev, A. Krasnoperov, N. Kutovskiy, K. Kuznetsova, Y. Malyshkin, D. Naumov, E. Naumova, I. Nemchenok, A. Olshevskiy, A. Rybnikov, A. Sadovsky, D. Selivanov, A. Selyunin, V. Sharov, A. Shaydurova, V. Shutov, O. Smirnov, S. Sokolov, A. Sotnikov, M. Strizh, V. Tchalyshev, K. Treskov, N. Tsegelnik, V. Zavadskyi, O. Zaykina

39 from JINR

Summary

Sensitivity plot: KM3NeT@NOW2016 (outdated) | CDR: 1508.07166 | Physics: 1507.05613





- Mass hierarchy determination: $3-5\ \sigma$
- Measurement of ν mixing parameters: unc. $< 1\%$
- Probe PMNS matrix unitarity: $\sim$1% level
- Precision reactor $\overline{\nu}$ spectrum: $\sigma_E \sim 2\%$ at 1 MeV

- Supernovae ν and DSNB
- Solar and geo- ν
- Atmospheric ν
- Sterile ν and exotic searches
- Proton decay

JUNO SCHEDULE

Complete conceptual design. International collaboration established.

Bidding of detector components.

PMT mass production and testing.

End of civil construction. Electronics mass production.

Start of data taking

2014 2015 2016 2017 2018 2019 2020 2021 2022

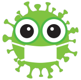
Start civil construction, PMT production line.

Start PMT mass production. First electronics prototypes.

Start PMT potting.

We are here

PMT installation. Detector and veto construction.



JINR group activities

JUNO and TAO: hardware

- PMT:
  - characterization
  - mass testing
  - HV for JUNO
- SiPM for TAO
  - purchase
  - acceptance studies
  - mass characterization
  - HV for TAO
- Top Tracker Support
- EMF shielding
- Computing

JUNO and TAO: software

- Sensitivity
- Vertex, energy, track reco.
- Machine learning
- Top Tracker DAQ

Analysis frameworks

- GNA

Daya Bay (recent)

- Oscillation analysis
- Wave packets
- IBD selection
- Sterile neutrino
- Neutrino directionality

JINR group plans: 2021–2023

- HV for JUNO LPMT and sPMT: assembly, tests, installation. Slow control
- Top Tracker: assembly, installation, commissioning. DAQ software. Slow control
- SiPM for TAO: purchase, mass test, hv units
- HV for TAO SiPM: R&D, production, software
- EMF protection for WP LPMTs: R&D, production
- Reconstruction of primary vertex, energy, muon track: include calibration, production
- Analysis: data analyses, combination with other experiments
- GNA: GPU support, automatic differentiation, development and support, data analyses

Publications 2018–2020 I

1. D.V.Naumov, V.A.Naumov, "Quantum Field Theory of Neutrino Oscillations",
   10.1134/S1063779620010050. Phys.Part.Nucl. 51 (2020) no.1, 1-106.
2. O.Smirnov, "Experimental aspects of geoneutrino detection: Status and perspectives",
   Progress in Particle and Nuclear Physics 109 (2019) 103712.
3. N.Anfimov, A.Rybnikov, and A.Sotnikov. "Optimization of the light intensity for photodetector calibration".
   Nucl. Instrum. Meth., A939:61 – 65, 2019.
4. A.Fatkina et al., "GNA: new framework for statistical data analysis".
   [arXiv:1903.05567 [cs.MS]]. EPJ Web Conf. 2014 (2019)
5. A.Fatkina et al., "CUDA Support in GNA Data Analysis Framework".
   [arXiv:1804.07682 [cs.DC]]. Computational Science and Its Applications Proc IV (2018).
6. N.Anfimov (JUNO). "Large photocathode 20-inch PMT testing methods for the JUNO experiment"
   JINST 12 (2017).

Publications 2018–2020 II

1. Daya Bay Collaboration, "Extraction of the ^{235}U and ^{239}Pu Antineutrino Spectra at Daya Bay", arXiv:1904.07812 [hep-ex]. Phys.Rev.Lett. 123 (2019) no.11, 111801.
2. Daya Bay Collaboration, "A high precision calibration of the nonlinear energy response at Daya Bay", arXiv:1902.08241 [physics.ins-det]. Nucl.Instrum.Meth. A940 (2019) 230-242.
3. Daya Bay Collaboration, "Measurement of the Electron Antineutrino Oscillation with 1958 Days of Operation at Daya Bay", arXiv:1809.02261 [hep-ex]. Phys.Rev.Lett. 121 (2018) no.24, 241805.
4. Daya Bay Collaboration, "Improved Measurement of the Reactor Antineutrino Flux at Daya Bay", arXiv:1808.10836 [hep-ex]. Phys.Rev. D100 (2019) no.5, 052004.

INSPIRE HEP Summary	Citeable	Published
Papers	16	11
Citations	125	121
Citations/paper (avg)	7.8	11

Theses

2017	candidate	**M. Gonchar**	The measurement of neutrino mixing angle θ_{13} and neutrino mass splitting Δm^2_{32} in the Daya Bay experiment.
2017	doctor	**D. Naumov**	Measurement θ_{13} and Δm^2_{32} of and quantum-field theory of neutrino oscillations.
2019	doctor	**I. Nemchenok**	Development and research of plastic and liquid scintillators for detectors of experiments in the field of neutrino physics.
Soon	candidate	**N. Anfimov**	Methods for the research of photodetectors and their application.
Soon	doctor	**O. Smirnov**	Study of the geo- and pp-chain solar neutrino fluxes with the Borexino detector.
...	candidate	**K. Treskov**	... oscillation analysis in Daya Bay

Students: 2018–2020

- ✓ Bachelors: 4 students
- ✓ Masters: 2 students
- ✓ Summer Student Program: 6 students

Staff I: average for 3 years

1	N. Anfimov	staff	0.4	PMT testing group leader
2	T. Antoshkina	PhD student	1	PMT optics response simulation. Formulation of requirements for PMT testing quality
3	S. Biktemerova	PhD student	1	sensitivity estimation, detector simulation, data analysis
4	A. Bolshakova	staff	1	PMT data analysis
5	I. Butorov	engineer	0.5	Designing and technical work PMT testing, analysis
6	A. Chetverikov	engineer	0.3	Designing and technical work PMT testing
7	A. Chukanov	candidate	0.7	Reconstruction, data analysis
8	S. Dmitrievsky	candidate	0.5	Simulation and software development for TT
9	D. Dolzhikov	student	0.33	Selection and analysis
10	D. Fedoseev	engineer	0.3	Designing and technical work
11	M. Gonchar	PhD student	1	sensitivity estimation, detector simulation, data analysis
12	Yu. Gornushkin	candidate	0.5	The TT project coordination
13	M. Gromov	candidate	0.5	Analysis, SuperNOVA
14	V. Gromov	engineer	0.5	Software development for TT/TAO JUNO
15	D. Korablev	staff	0.57	software development for PMT testing and TT, Long term-stability, PMT testing, Analysis

Staff II: average for 3 years

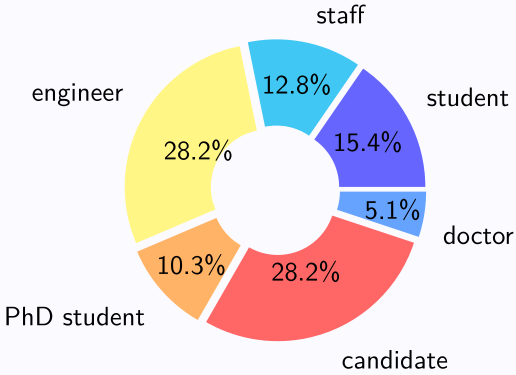
15	D. Korablev	staff	0.57	software development for PMT testing and TT, Long term-stability, PMT testing, Analysis
16	A. Krasnoperov	candidate	0.3	Software development for TT JUNO
17	N. Kutovskiy	candidate (**LIT**)	0.2	IT
18	K. Kuznetsova	engineer	0.3	SiPM testing, Analysis
19	Y. Malyshkin	candidate	0.5	Analysis, reconstruction
20	D. Naumov	doctor	0.6	project management. Reactor spectrum measurement. Oscillation analyses. Global analysis
21	E. Naumova	staff	1	Reactor spectrum measurement.
22	I. Nemchenok	candidate	0.5	Investigation of properties and stability of liquid scintillator
23	A. Olshevskiy	doctor	0.5	analysis preparation, HV and other JINR hardware activities coordination
24	A. Rybnikov	engineer	0.3	PMT testing, SiPM testing
25	A. Sadovsky	candidate	0.5	PMT HV R&D
26	D. Selivanov	student	0.13	Reconstruction
27	A. Selyunin	engineer	0.2	PMT testing

Staff III: average for 3 years

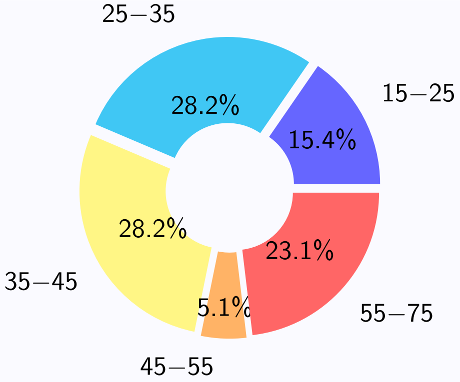
27	A. Selyunin	engineer	0.2	PMT testing
28	V. Sharov	engineer	0.5	PMT testing
29	A. Shaydurova	student	0.13	Neutrino oscillations in matter
30	V. Shutov	engineer	0.3	HV unit software and tests
31	O. Smirnov	candidate	0.6	PMTs magnetic shielding, energy resolution studies
32	S. Sokolov	engineer	0.5	Designing and technical work, PMT testing
33	A. Sotnikov	engineer	0.3	PMTs magnetic shielding, PMT tests
34	M. Strizh	student	0.13	reconstruction of neutrino directionality
35	V. Tchalyshev	candidate	0.5	SiPM testing, clean room support
36	K. Treskov	PhD student	1	sensitivity estimation, software development, data analysis
37	N. Tsegelnik	student (**LTF**)	0.5	fitting software
38	V. Zavadskyi	student	0.27	Oscillation Analysis
39	O. Zaykina	staff	1	Reconstruction
	Total FTE		19.87	
	Avg. people		38	Mostly DLNP
	FTE/person		0.52	

Staff summary: 2021–2023

Status distribution



Age distribution



Total FTE	19.87
Avg. people	38
FTE/person	0.52

JUNO Expenditures 2018–2020

	HV Units	TOP Tracker	PMT Scanning	JUNO Computing	TAO	Total
JINR contribution, USD	**2M**	(in-kind) 0.8M + 0.2M	2 stations +personnel on site	**2M**	**1.5M**	6.5M
Payment status	100%	80%	Secured	50%	66.6%	74%
In progress, USD		0.2M		1M	0.5M	**1.7M**

Form 26

	Item			Total	2021	2022	2023
Equipment, k$	1. JUNO	maintenance		**1000**	—	500	500
	2. SiPM для TAO	purchase and tests		**500**	300	200	—
	3. Top Tracker Support	production, assembly, installation		200	200	—	—
	4. HV	assembly, installation, tests		200	200	—	—
	5. Computing Infrastructure	servers, disks, tape		**500**	300	100	100
	Total			**2400**	1000	800	600
	Other	launch, shifts, analysis, meetings, conferences	k$	**800**	300	250	250
Source	Budget		k$	**3200**	1300	1050	850
	Extra	funds		30	10	10	10

Form 29

№	Item, k$		Total	2021	2022	2023
1.	Accelerator		—	—	—	—
2.	Computer		—	—	—	—
3.	Design bureau (DLNP)	*working hours*	*2100*	*700*	*700*	*700*
4.	Experimental Workshop (JINR)		*2400*	*800*	*800*	*800*
5.	Computers, connection		30	10	10	10
6.	Materials		**900**	500	300	100
7.	Equipment		**1440**	480	480	480
8.	R&D		30	10	10	10
9.	Missions		**800**	300	250	250
	Total		**3200**	**1300**	**1050**	**850**

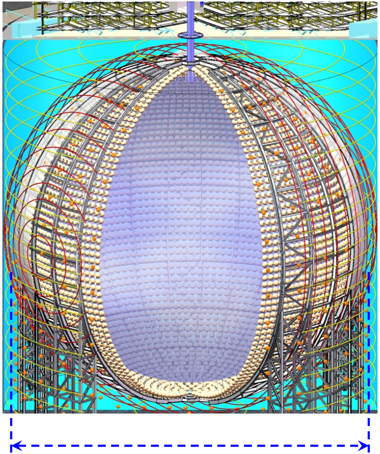
SWOT analysis

	Helpful	Harmful
Internal	**Strengths**	**Weaknesses**
	✓ Neutrino hierarchy determination	✗ Failure to achieve 3% energy resolution
	✓ Method different from other experiments	✗ Insufficient detector/structure integrity
	✓ Precision measurement of 3 oscillation parameters	✗ Insufficient electronics/HV reliability
	✓ Precision measurement of 3 PMNS elements (+DB)	✗ Delay with detector installation
	✓ Geo-neutrinos measurement	
	✓ Solar, atmospheric ν, proton decay, etc.	
External	**Opportunities**	**Threats**
	▪ Supernova burst	✗ Underground collapse and flooding
	▪ Diffuse Supernova background ν	
	▪ New physics	

Thank you for your attention!

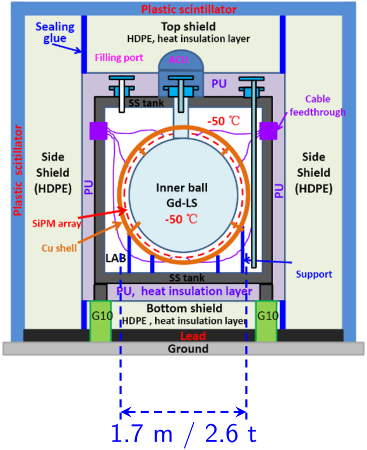
Spare slides:

Antineutrino Detectors (AD)



	Daya Bay	JUNO
Attention	Uncorr. ε unc.	**Energy resolution**
Method	Identical ADs 3 zones	**Light collection**
Scintillator	GdLS/LS	**LS**
PMTs	192 8"	**18k 20"** **+26k 3"**
Coverage, %	12	**78**
Light col. p.e./MeV	160	~~1200~~ **1350**
σ_E at 1 MeV, %	8.7	**3**
Detectors	4/4 far/near	**1**
Thermal power, GW	17.4	~~35.8~~ **26.6**
Baseline	0.5 km–2 km	**52 km**
IBD/day/AD	75/635 far/near	~~60~~ **45**

Antineutrino Detectors (AD)



	Daya Bay	**TAO**	JUNO
Attention	Uncorr. ε unc.	**Energy resolution**	
Method	Identical ADs 3 zones	**Light collection** **Dark noise**	
Scintillator	GdLS/LS	**GdLS** **@ -50°C**	LS
PMTs	192 8"	**SiPM** **1.5M 5 mm**	18k 20" +26k 3"
Coverage, %	12	**94**	78
Light col. p.e./MeV	160	**4500**	~~1200~~ 1350
σ_E at 1 MeV, %	8.7	**2**	3
Detectors	4/4 far/near	**1**	1
Thermal power, GW	17.4	**4.6**	~~35.8~~ 26.6
Baseline	0.5 km—2 km	**30 m**	52 km
IBD/day/AD	75/635 far/near	**2000**	~~60~~ 45

Neutrino physics at JUNO I

- Neutrino mass ordering (NMO)
  - 3σ NMO sensitivity within ~~6~~ 8 years.
  - 4σ with Δm^2_{32} input from accelerator experiments.
  - $> 5\sigma$ combined analysis with IceCube within 3–7 years or PINGU in 2 years.
  - Combination with accelerator experiments — promising.

JUNO, IceCUBE, PINGU, arXiv:1911.06745

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Physics with TAO

- Precision reactor $\overline{\nu}_e$ spectra:
  - Total spectrum.
  - $^{235}\mathrm{U}/^{239}\mathrm{Pu}$ spectra.
- Search for sterile neutrino.

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- Neutrino oscillation parameters measurement
  - ~ 20 oscillation cycles in a single experiment.
  - Expected precision for $\Delta m^2_{32/21}$ and $\sin^2 2\theta_{12} < 0.7\%$.
  - $\sin^2 2\theta_{13}$ precision 15%. (Daya Bay: $< 3\%$).
  - Test U_{PMNS} unitarity on $< 1\%$ level $\hookrightarrow$ similar to quark sector.

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  - Test U_{PMNS} unitarity on $< 1\%$ level $\hookrightarrow$ similar to quark sector.
- Atmospheric neutrinos ▶
  - Measure θ_{23} with 6° precision.
  - Complimentary NMO sensitivity.

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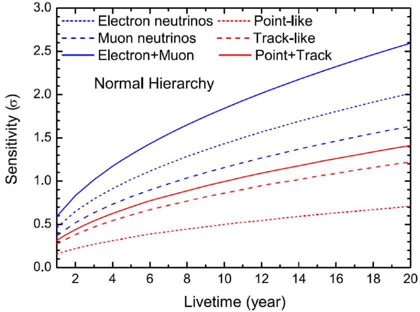

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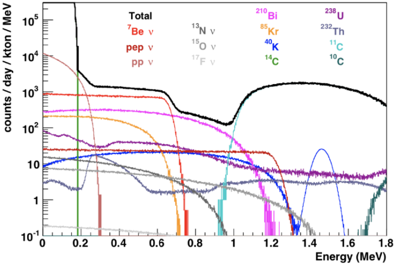
Neutrino physics at JUNO II

- Solar neutrino ▶
  - 1000 ^{7}Be and 10 ^{8}B neutrino interactions per day.



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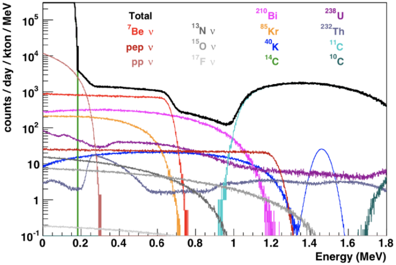
- SuperNOVA
  - Sensitivity: flavor content, energy spectrum, time evolution.
  - 10k events (5k via IBD) for SN @ 10kpc.
- Diffuse SuperNOVA background (DSNB)
  - 3σ sensitivity in 10 years or strongest constraint.



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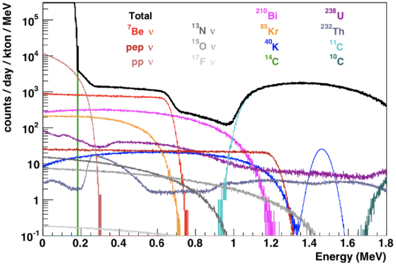

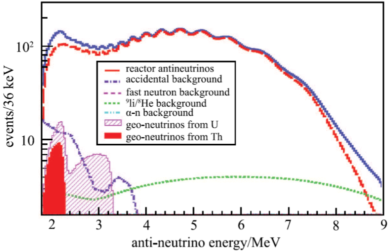

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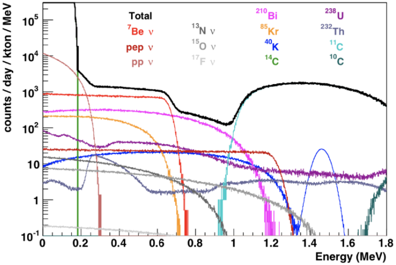
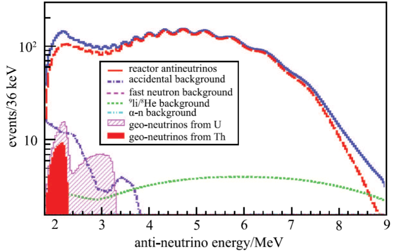
- Proton decay
  - Competitive sensitivity via $p \to \overline{\nu} + K^{+}$.
  - Triple coincidence signal.

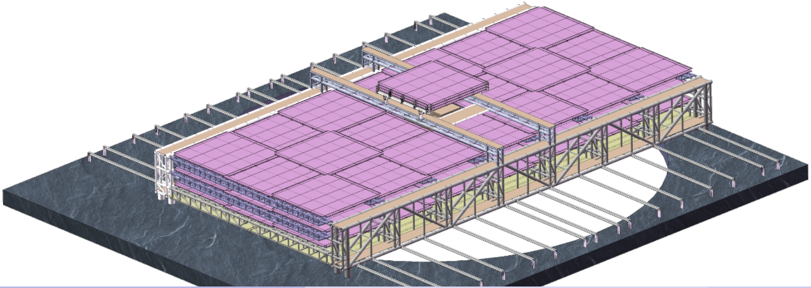




Veto: Top muon Tracker (TT)

Motivation

- Precision muon tracking: 0.2°/0.5°
- Layered plastic scintillator detector
- Partial coverage: ∼63%
- 3 layers x 21 "walls" x 8 modules
- Wall: 7x7 m^2, 1 t / Layer: ∼1000 m^2



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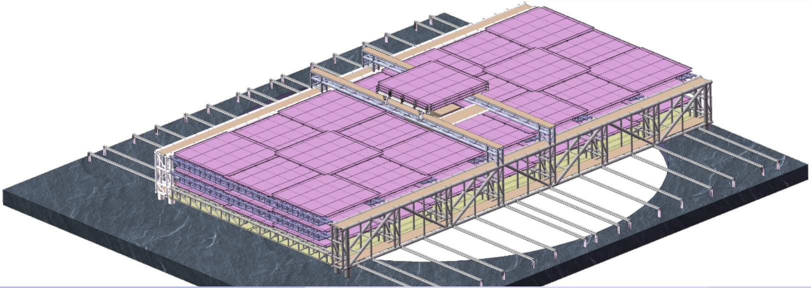
Status: JINR

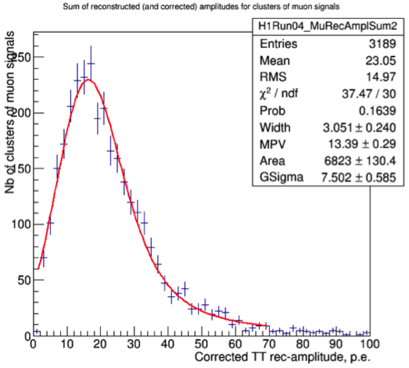
- Mechanical support structure R&D, prototyping and validation: done
- Assembly procedure, tools: done, reviewed
- Bidding: done
- Manufacturing (140 t): 2021
- Assembly on site: 2021.09→2022.03

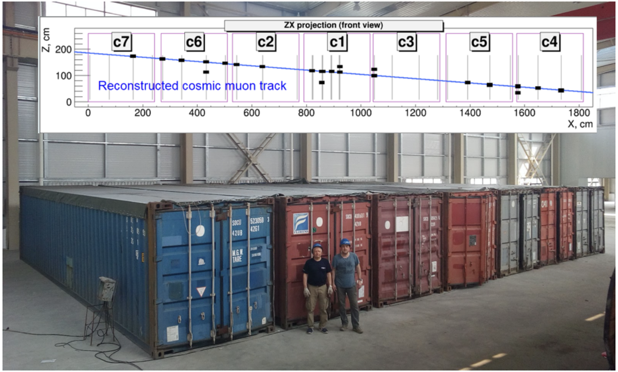


TT: plastic scintillator monitoring

Plastic scintillator for TT

- Re-used OPERA Target Tracker
- ✓ Delivered on-site and stored in 7 containers
- ✓ Active DAQ to study aging





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Plastic scintillator for TT

- Re-used OPERA Target Tracker
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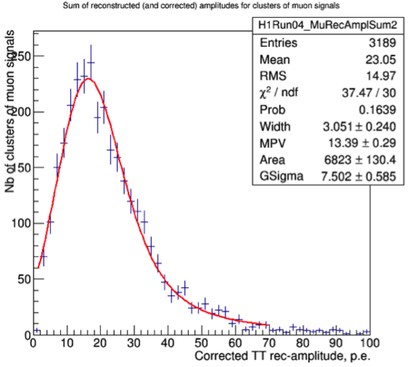
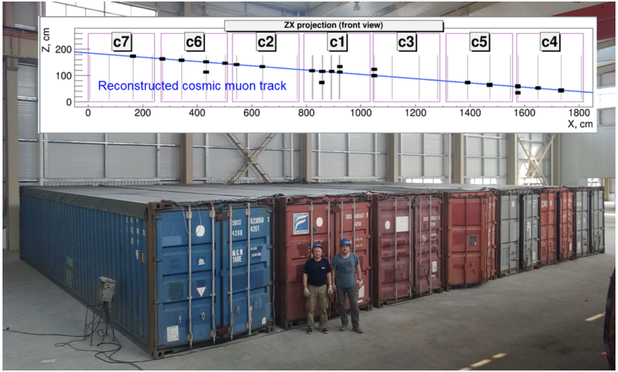
JINR

- ✓ Mobile DAQ and software (storage): operating
- DAQ software for TT: in progress



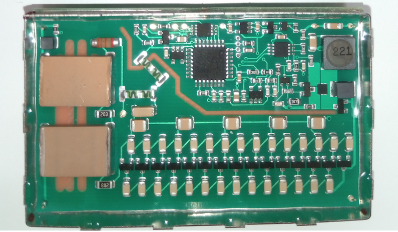


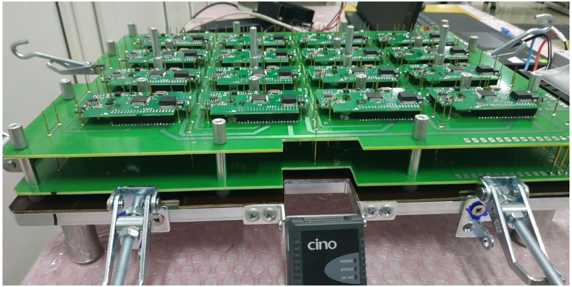
HV UNITS

High Voltage supply provided by JINR

- ∼18'000 large PMTs — central detector
- ∼ 2'000 large PMTs — veto
- ∼25'600 small PMTs — central detector
- ∼**25'000** underwater HV units — required

  1 unit per 8 sPMTs





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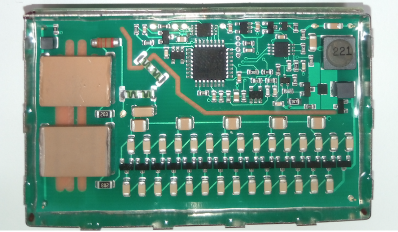
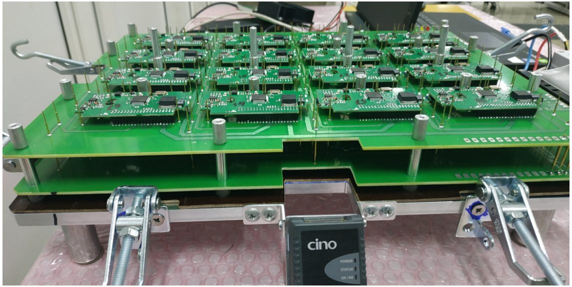
Status

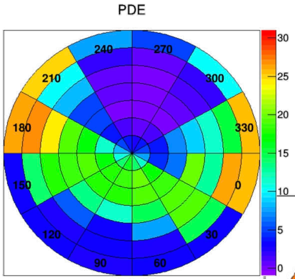
✓ R&D, prototyping
✓ Testing: materials, ageing, thermo cycling
✓ Factory setup, procedures: Shenzhen
✓ Test batch: 500 items
- Production via single batch: → 2020



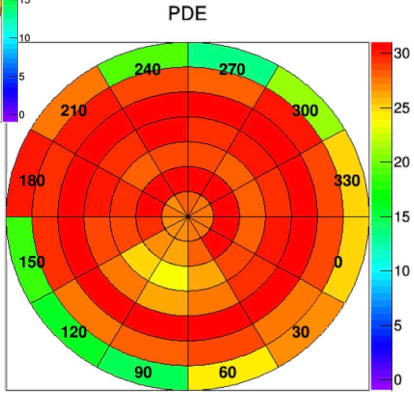


PMT Scanning

- ✓ 3 Scanning stations produced @JINR:
  - 1 in DLNP / 2 in China
  - All in individual dark rooms
  - Dedicated software
- ✓ Scanning: 3-4 PMTs/day
- ✓ ~ 2500 PMTs scanned
- ✓ Maintain database, web accessible
- ✓ Study Earth Magnetic Field impact ▸
- Complementary to mass testing

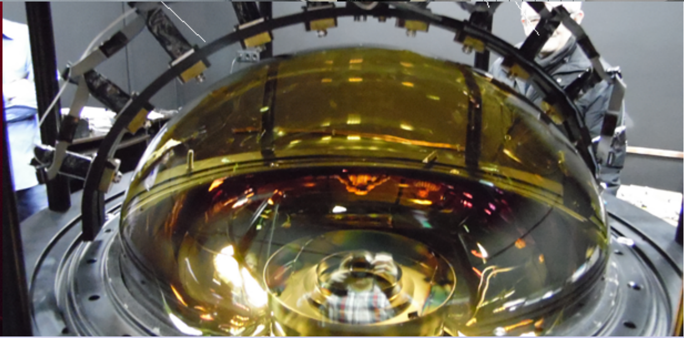


◂ Magnetic field: 42 μT



Magnetic field: compensated ▸

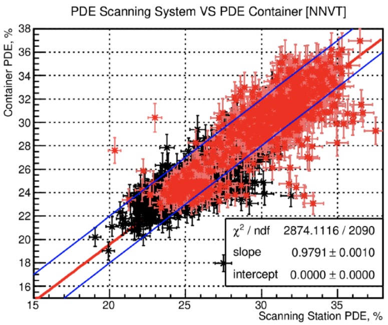
JINR PMT testing laboratory



Mass PMT Testing

Scanning and mass testing

- ✓ Almost 17k PMTs tested
- ✗ ∼3% rejected
- ✓ 3'110 PMTs tested after potting
- ✓ Complementary and consistent performance



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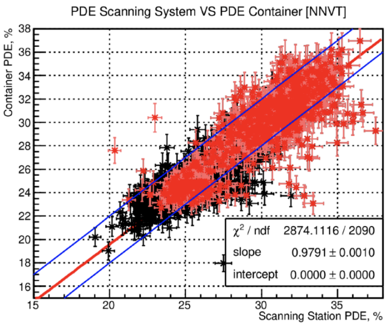
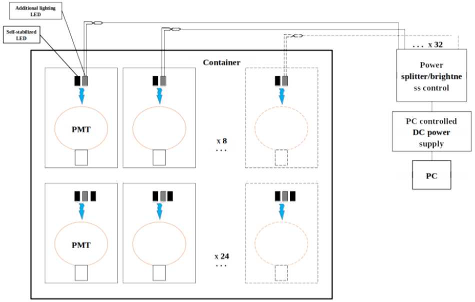
Long term stability

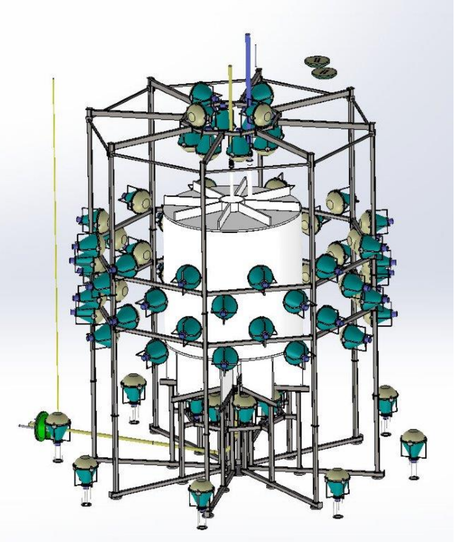
- ✓ 1 container equipped by JINR
- ✓ Operating since February 2020
- ▪ 32 PMTs for 1 year
- ✓ DAQ software by JINR group





OSIRIS: PMT protection vs. Earth Magnetic Field

- Online Scintillator Internal Radioactivity Investigation System
- 76 20" PMTs: 64 detector + 12 veto
- Individual EMF protection: Metglas+Al cones:
  - detector: carbon fiber composite
  - veto: fiberglass composite
- EMF reduction factor: x2 $\parallel$ and x10 $\perp$



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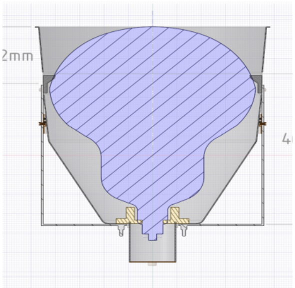

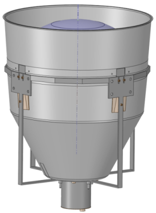

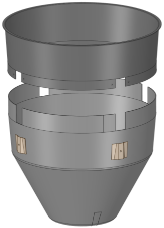

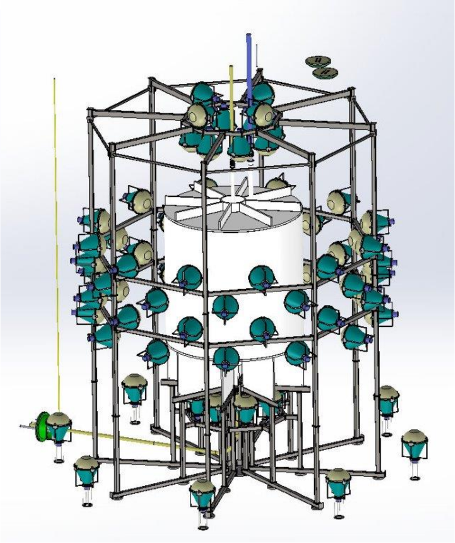

Prototypes and radioactivity balance

- 3 prototypes produced
- White coating for additional light collection ►
- Table: carbon fiber option
- Fiberglass: more radioactive, but acceptable

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Material	U, ppb	Fraction Th, ppb	K, ppm	U	Mass, µg Th	^{40}K
AMAG-170 (0.2 mm)	3	<5	0.84	4.7	<7.8	0.154
Epoxy	<0.1	0.9	0.78	<0.12	0.11	0.1
Carbon fiber	1	<6	15	0.25	<4.9	1.4
Gelcoat white	7	7	4.33	2.5	2.5	0.2
Cu foil	<0.3	<0.2	<0.127	<0.024	0.016	<0.001
Al foil	170	26	<0.96	15.3	2.4	<0.01
Total				22.8	<18	1.9
PMT glass	400	400	60	3600	3600	63

TAO — Taishan Antineutrino Observatory

Objective

- Precision antineutrino spectrum measurement
- High statistics, no oscillations
- Unprecedented precision: $\sigma_E \sim 2\%$ at 1 MeV

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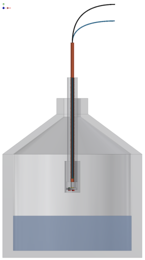
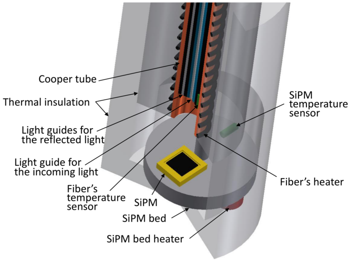
✓ TAO CDR preparation

- SiPM mass characterization





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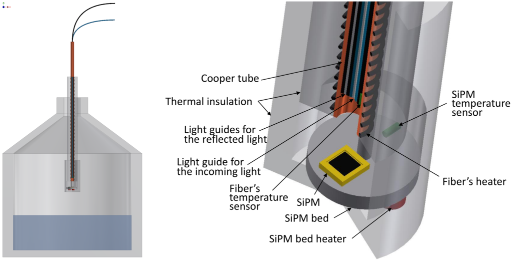
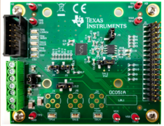
- SiPM high voltage supply
- 2/3 SiPM purchase funding: 1.5M$



a) - Custom made HV unit by JINR



b) - DAC81416EVM by TI

Computing: LIT&DLNP

Total requirements before 2040 (JINR)

- 4000 cores / 4 PB disk / 40 PB tape + 4 PB disk cache
- To store complete copy of JUNO data

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CPU and storage

✓ Current: 300 cores / 25 TB (dCache) + 500 TB (EOS)

- New: HP servers with 2880 cores with increased RAM 16 GB ▸
  - ✓ purchased and delivered in 2019, installed recently
  - ▸ to be powered
  - ▸ Part of Neutrino Computing Platform: shared, quota

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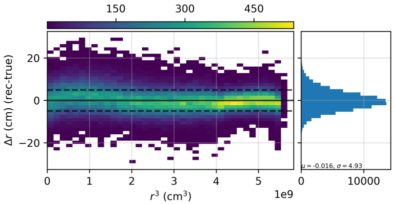
Network and GRID

✓ GRID: CVMFS repository / Secondary VOMS server: deployed

✓ Network [Gbps]: 2x100 (local) / 3x100 (wide) / 2x10 ($\leftrightarrow$ China)

JUNO Reconstruction at JINR: progress



Neural Networks: vertex/energy reco ▸

- ✓ Exceptional speed, industry support
- ✓ Consistent with traditional methods
- ✗ Long training
- TODO: develop calibration methods
- Sphere projection? or Graph Neural Networks
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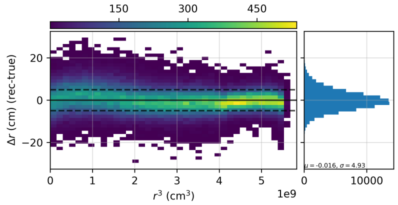
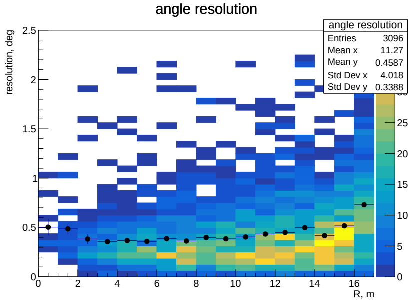


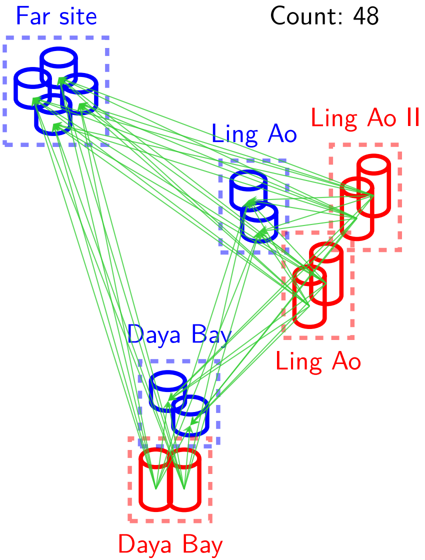
Muon track reconstruction ▸

- For background rejection: $^{8}\mathrm{He}/^{9}\mathrm{Li}$, fast-$n$
- ✓ Decomposition into spherical functions
- ✓ Single tracks, muon bundles
- ✓ Precision: 0.5° and 10 cm



Why GNA: Day Bay experiment

Count: 48



$$\vec{N}^d = \vec{B}^d + \left(\prod_m C_m\right) \times$$

$$\times \sum_t \dots \sum_r \dots \int \int^{\rightarrow} \dots \sum_i \dots \sum_c P_c(L_r^d, \dots) \dots$$

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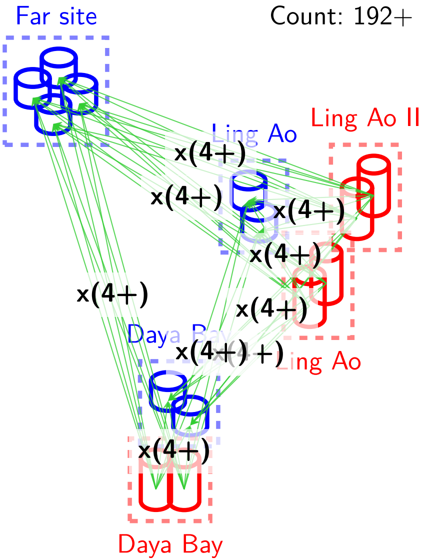

Requirements

- Efficient scalable models, lots of parameters
  - Laziness, caching
  - Flexibility
  - Portability (GPU)
- Long term support and compatibility
  - Readability, hand-over-ability
  - Minimize boilerplate code

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GNA: JUNO/Daya Bay implementation

- GNA framework — scalable high performance fitting.

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  iav[d]|
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    sum[r]|
     baselineweight[r,d]*
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  jacobian(enu(), ee(), ctheta())
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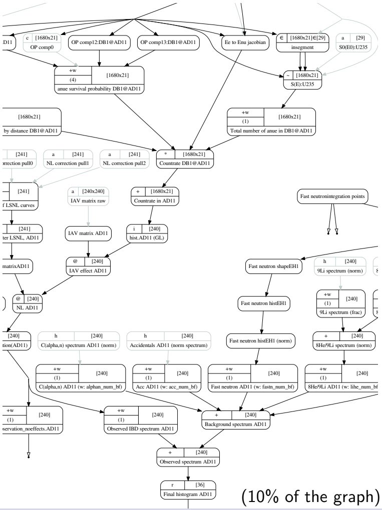

http://gna.pages.jinr.ru/gna/gallery.html

(10% of the graph)

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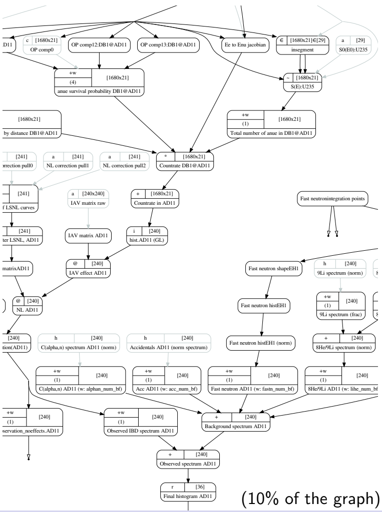

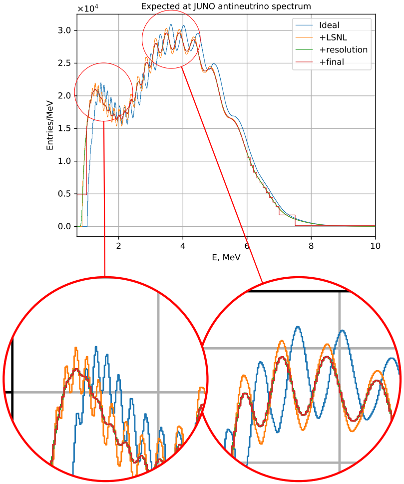

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Plans

- GPU support
- TensorFlow support?
- Documentation, tutorial, etc.