The JUNO Project

Dmitry Naumov

Dzhelepov Laboratory for Nuclear Problems

PAC for Particle Physics, June 21, 2023

Contents

The project

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

- Daya Bay Project: 2007–2017. Data taking: 2011–2020.
- JUNO Project since 2018.

The project

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

- Daya Bay Project: 2007–2017. Data taking: 2011–2020.
- JUNO Project since 2018.

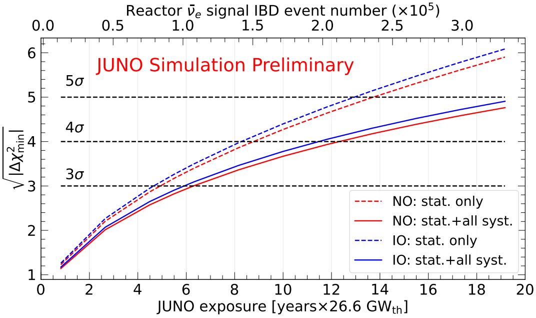
Our team

N. Anfimov, T. Antoshkina, N. Balashov, S. Biktemerova, A. Bolshakova, 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, D. Naumov, E. Naumova, I. Nemchenok, A. Olshevsky, A. Rybnikov, A. Sadovsky, A. Selyunin, V. Sharov, V. Shutov, O. Smirnov, S. Sokolov, A. Sotnikov, V. Tchalyshev, N. Tsegelnik, V. Zavadskiy

39 experts from DLNP/MLIT/BLTP: 15.9 FTE + 5 students

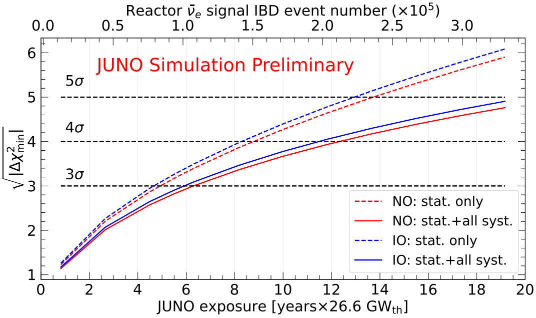
Physics programme

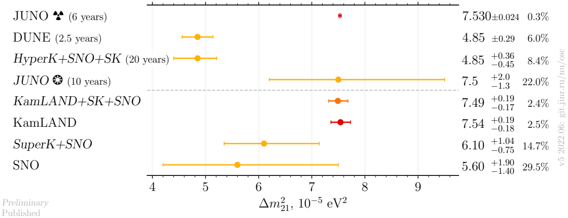
- Reactor $\overline{\nu}_e$ at 52.5 km (JUNO):
  - Neutrino mass ordering: 3σ in 6 years (alone)
    $4-5\sigma$ (combined)



Physics programme

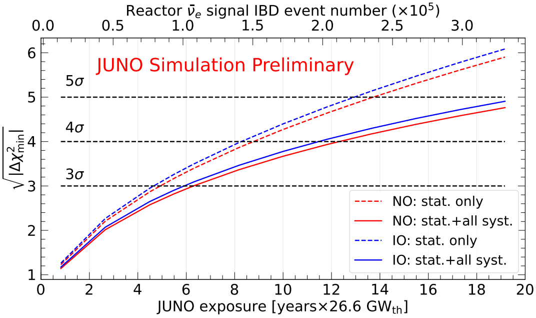
- Reactor $\overline{\nu}_e$ at 52.5 km (JUNO):
  - Neutrino mass ordering: 3σ in 6 years (alone)
    $4-5\sigma$ (combined)
  - Oscillation parameters: 0.2% – 0.5%
    for Δm^2_{31}, Δm^2_{21}, $\sin^2 2\theta_{13}$.

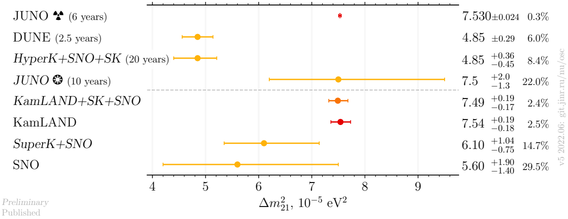




Physics programme

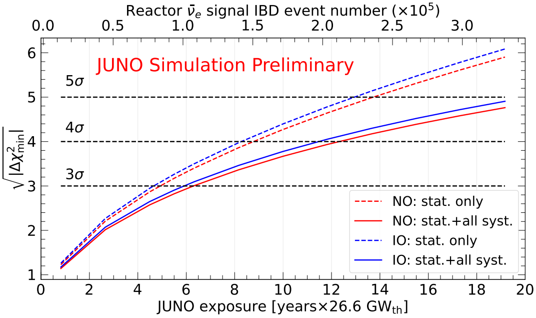
- Reactor $\overline{\nu}_e$ at 52.5 km (JUNO):
  - Neutrino mass ordering: 3σ in 6 years (alone)
    $4-5\sigma$ (combined)
  - Oscillation parameters: $0.2\% - 0.5\%$
    for Δm^2_{31}, Δm^2_{21}, $\sin^2 2\theta_{13}$.
- Reactor $\overline{\nu}_e$ at 30 m (TAO):
  - Reactor $\overline{\nu}_e$ spectrum with 1% stat. uncertainty
    and $\sigma = 2\%$ energy resolution at 1 MeV.
  - Competitive sterile neutrino sensitivity.

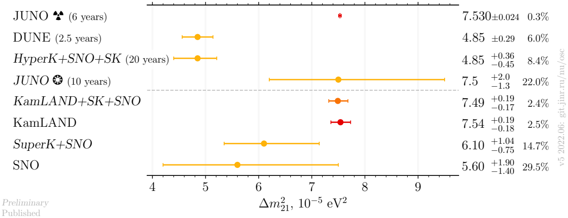




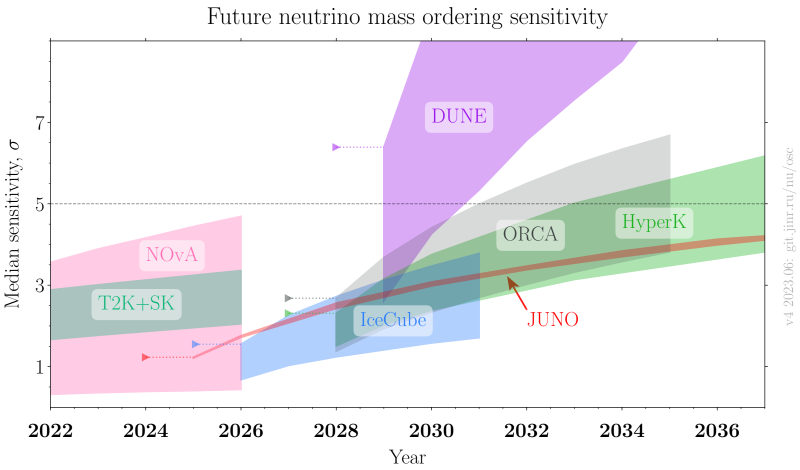
Physics programme

- Reactor $\overline{\nu}_e$ at 52.5 km (JUNO):
  - Neutrino mass ordering: 3σ in 6 years (alone)
    $4-5\sigma$ (combined)
  - Oscillation parameters: $0.2\% - 0.5\%$
    for Δm^2_{31}, Δm^2_{21}, $\sin^2 2\theta_{13}$.
- Reactor $\overline{\nu}_e$ at 30 m (TAO):
  - Reactor $\overline{\nu}_e$ spectrum with 1% stat. uncertainty
    and $\sigma = 2\%$ energy resolution at 1 MeV.
  - Competitive sterile neutrino sensitivity.
- Other sources:
  - Solar neutrinos from ^{7}Be, pep, CNO and ^{8}B.
  - Atmospheric $\nu_\mu/\overline{\nu}_\mu$ and $\nu_e/\overline{\nu}_e$.
  - SuperNova neutrinos and Diffuse SuperNova Neutrino Background.
  - Geo-neutrinos.
  - Proton decay.





JUNO sensitivity



Competitive and complementary senstivitity to NMO.

JUNO SCHEDULE

Complete conceptual design. International collaboration established.

2014

2015

Start civil construction, PMT production line.

Bidding of detector components.

2016

2017

Start PMT mass production. First electronics prototypes.

PMT mass production and testing.

2018

2019

Start PMT potting.

End of civil construction. PMT testing. Electronics mass production.

2020

2021

Underground lab preparation. Electronics mass production.

OSIRIS assembly. Water pool preparation. Stainless steel structure assembly.

2022

We are here

2023

Acrylic vessel assembly. PMT installation. Detector and veto construction. TAO assembly.

Detector completion!

2024

JINR contribution: detector

Current contributions

PMTs	• SiPM		1	M$
Power Supply	• High Voltage for PMTs, R&D, production costs		2	M$
	• Power Supply for SiPM R&D		0.5	M$
Top Tracker muon veto	• previously, Opera Target Tracker	(in-kind)	0.8	M$
	• support structure R&D		0.2	M$
PMT studies	• Scanning stations R&D, production	}	0.5	M$
	• Large PMT characterization	}		
	• Large PMT mass testing, long term testing	}		
	• SiPM acceptance, mass testing	}		
PMT protection	• against Earth Magnetic Field: R&D, prototypes	}		
Computing	• Extended memory CPU servers (3000 cores)		2	M$
			7	M$

- HV design, proposed by JINR has driven the design of electronics and DAQ.

JINR contribution: computing

Data centers

- Dubna is expected to be one of the data storage and data processing centers
- Data rate: 3 PB/year
- Memorandum of Understanding for computing is signed by JINR
- IHEP is able to facilitate construction of high speed channel on Chinese side

JINR contribution: computing

Data centers

- Dubna is expected to be one of the data storage and data processing centers
- Data rate: 3 PB/year
- Memorandum of Understanding for computing is signed by JINR
- IHEP is able to facilitate construction of high speed channel on Chinese side

Resources requirements, from MoU

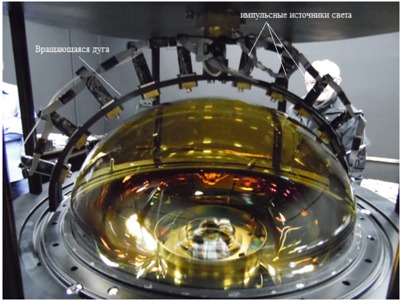
JINR	Planned to be pledged*				
	2023	2024	2025	2026	2027
Tape (PB)	5	5	5	5	5
Disk (PB)	5	5	5	5	5
CPU	36	36	30	20	10

*numbers are *not* cumulative

Large photomultipliers

Individual tests (lead by Nikolay Anfimov)

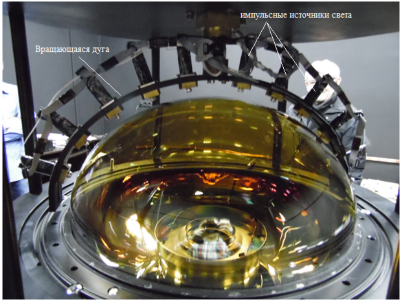
- 4000 large PMTs studied in scanning stations, developed by JINR
- JINR staff tests PMTs on site before installation.



Large photomultipliers

Individual tests (lead by Nikolay Anfimov)

- 4000 large PMTs studied in scanning stations, developed by JINR
- JINR staff tests PMTs on site before installation.



Long term container testing (Denis Korablev)

- 36 LPMTs were studied for 580 days with accelerated aging applied.

✓ Stable performance.

Large photomultipliers

Individual tests (lead by Nikolay Anfimov)

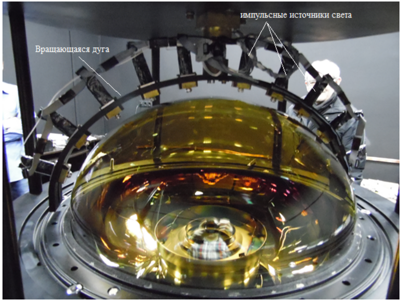
- 4000 large PMTs studied in scanning stations, developed by JINR
- JINR staff tests PMTs on site before installation.

Long term container testing (Denis Korablev)

- 36 LPMTs were studied for 580 days with accelerated aging applied.
- ✓ Stable performance.

HV production (lead by Alexander Olshevskiy)

- 25000 HV cells produced in 2021.
- +10% of HV cells produced in 2022



Silicon photomultipliers

Mass-testing (lead by Arseny Rybnikov)

- A station for mass testing of SiPM was designed, assembled and commissioned at IHEP.
- A few hundreds of SiPM tiles already scanned.

Silicon photomultipliers

Mass-testing (lead by Arseny Rybnikov)

- A station for mass testing of SiPM was designed, assembled and commissioned at IHEP.
- A few hundreds of SiPM tiles already scanned.

Power supply (lead by Nikolay Anfimov)

- Power Supply for SiPM designed.
- All electronic components delivered.
- Marathon people will help to manage production.
- A test batch of 5 units produced at IHEP for tests and calibration.

Top Tracker and Computing

TT assembly (lead by Yury Gornushkin)

- Produced stainless steel structure for the Top Tracker.
- Developed assembly and installation instructions.

Top Tracker and Computing

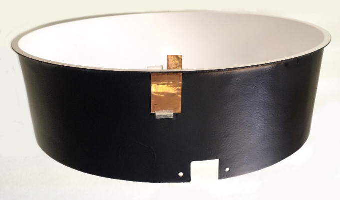
TT assembly (lead by Yury Gornushkin)

- Produced stainless steel structure for the Top Tracker.
- Developed assembly and installation instructions.

Protection against Earth Magnetic Field

(lead by Oleg Smirnov)

- Designed and produced 76 innovative magnetic shielding screens for the LPMTs of the OSIRIS detectors.



Top Tracker and Computing

TT assembly (lead by Yury Gornushkin)

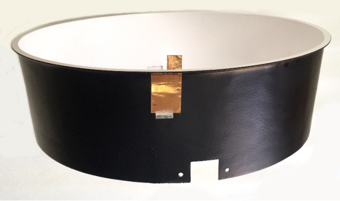
- Produced stainless steel structure for the Top Tracker.
- Developed assembly and installation instructions.

Protection against Earth Magnetic Field (lead by Oleg Smirnov)

- Designed and produced 76 innovative magnetic shielding screens for the LPMTs of the OSIRIS detectors.

Computing (lead by Nikolay Kutovsky)

- At least 2000 CPUs provided for the GRID infrastructure
  - up to 3000 CPUs available
  - 15 GB RAM per CPU
  - Processed almost 50% of JUNO jobs in total.



Analysis

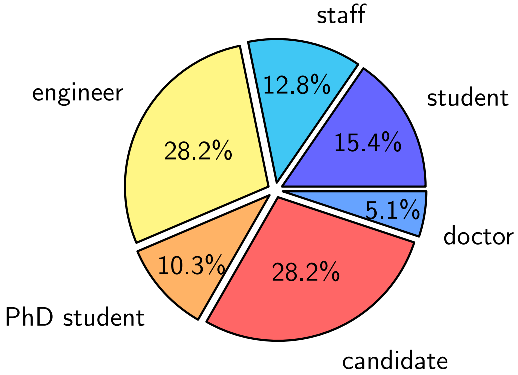
- fitter (including GNA) development (lead by Maxim Gonchar)
- Sensitivity to Neutrino Mass Ordering (Maxim Gonchar)
  - NMO sensitivity analysis finally approved. Paper is ready for the review.
- ML reconstruction of energy (Arsenii Gavrikov, Yury Malyshkin)
  - NN and BDT energy reco based on aggregated features.
- PMT optical model (Tatiana Antoshkina)
  - Full theoretical description of the optical processes on the PMT glass boundaries.
- Muon track reconstruction with spherical functions (Artem Chukanov)

JINR group plans: 2024–2026

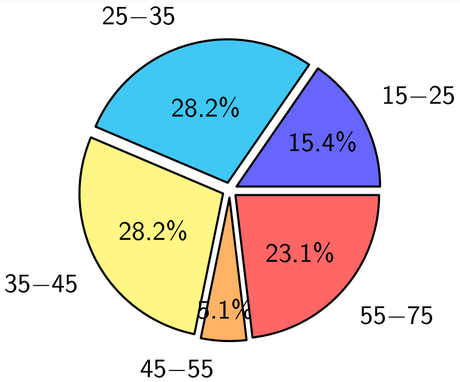
• Reconstruction	muon tracks and electromagnetic showers.
• Veto Top Tracker	assembly, installation, commissioning. DAQ software. Slow control. First physics results.
• Large PMTs	tests with HV units, installation.
• Central detector	Filling and running.
• SiPM for TAO	testing, installation. Production and commissioning of the power system.
• TAO	Filling and running.
• Analysis	First measurements of neutrino oscillation parameters. First constraints on the parameters of the sterile neutrino.

Staff summary: 2021–2023

Status distribution



Age distribution



Publications 2021–2023 I

Summary

- 25 publications total
- 12 publications by (with contribution) of JINR stuff

List

1. Abuselme A.,..., Gonchar M.,..., Malyshkin Yu. et al., Sub-percent precision measurement of neutrino oscillation parameters with JUNO, e-Print: 2204.13249 [hep-ex], Published in: Chin.Phys.C 46 (2022) 12, 123001
2. JUNO Collaboration, JUNO physics and detector, e-Print: 2104.02565 [hep-ex], Published in: Prog.Part.Nucl.Phys. 123 (2022), 103927
3. An F.P.,..., Dolzhikov D.,..., Gonchar M.,..., Naumov D.,..., Olshevkiy A.,..., Treskov K.,..., Zavadskyi V. et al., Precision measurement of reactor antineutrino oscillation at kilometer-scale baselines by Daya Bay, e-Print: 2211.14988 [hep-ex], submitted to PRL.
4. Angel Abusleme,..., Dmitrievsky S.,..., Gornushkin Yu.,..., Korablev D. et al., The JUNO experiment Top Tracker, e-Print: 2303.05172 [hep-ex], to be submitted.

Publications 2021–2023 II

List

1. Arsenii Gavrikov, Yury Malyshkin, Fedor Ratnikov (Higher Sch. of Economics, Moscow and Dubna, JINR), Energy reconstruction for large liquid scintillator detectors with machine learning techniques: aggregated features approach, e-Print: 2206.09040 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 11, 1021, Eur.Phys.J.C 82 (2022), 1021
2. Xu H.,..., Anfimov N.,..., Gromov M.,..., Rybnikov A. et al., Calibration strategy of the JUNO-TAO experiment, e-Print: 2204.03256 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 12, 1112
3. Bieger L.,..., Gromov M.,..., Smirnov O. et al., Potential for a precision measurement of solar pp neutrinos in the Serappis experiment, e-Print: 2109.10782 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 9, 779
4. Qian Z.,..., Gavrikov A.,..., Gonchar M.,..., Malyshkin Yu.,..., Treskov K. et al., Vertex and energy reconstruction in JUNO with machine learning methods, e-Print: 2101.04839 [physics.ins-det], Published in: Nucl.Instrum.Meth.A 1010 (2021), 165527
5. O. Smirnov, D. Korablev, A. Sotnikov et al., Magnetic shielding for large photoelectron multipliers for the OSIRIS facility of the JUNO detector, e-Print: 2212.02562 [physics.ins-det], submitted to JINST.

Publications 2021–2023 III

List

1. A. Stepanova (Dubna, JINR), M. Gonchar (Dubna, JINR), L. Kolupaeva (Dubna, JINR), K. Treskov (Dubna, JINR), Deep Underground Neutrino Experiment DUNE—Calculation of Sensitivity to the Measurement of Oscillation Parameters, Published in: Phys.Part.Nucl.Lett. 19 (2022) 5, 505-508
2. Rybnikov, A.V., Anfimov, N.V., Fedoseev, D.V. et al. Optical Fiber Splitter for Photodetector Testing. Phys. Part. Nuclei Lett. 19, 797–802 (2022). https://doi.org/10.1134/S1547477122060255
3. Abusleme, A.,..., Anfimov N,. et al. Mass testing and characterization of 20-inch PMTs for JUNO. Eur. Phys. J. C 82, 1168 (2022). https://doi.org/10.1140/epjc/s10052-022-11002-8

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.
2021	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	**V. Zavadskyi**	... Sterile neutrino search in Daya Bay and JUNO
...	candidate	**D. Dolzhikov**	... Oscillation analysis in JUNO

Finance: form 26

	Item		Total	2021	2022	2023
Expeditures, k$	1. International cooperation		**750**	250	250	250
	2. Materials		**280**	100	100	80
	3. Equipment, third-party company services		**150**	50	50	50
	4. R&D contracts with other research organizations		**60**	20	20	20
	5. Software purchase		**60**	20	20	20
	JINR budget	k$	1300	440	440	420
	Workshop and design	standard hours	**150**	50	50	50

SWOT analysis

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

Conclusions

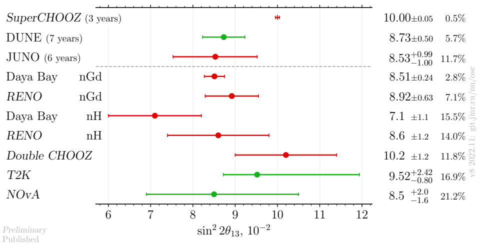
- JUNO detector assembly status reaches 50% completion.
- JINR staff occupies leading positions in the JUNO hierarchy.
- JUNO will provide the leading precision in measuring neutrino oscillation parameters.
- JUNO is a multipurpose detector with a wide range of physics possibilities.

Thank you for your attention!

Spare slides:

Daya Bay oscillation result

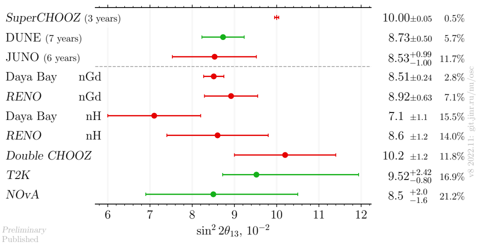
- Original goal: measure unknown $\sin^2 2\theta_{13}$ value down to 0.01.



Daya Bay oscillation result

nH, 621 days, arXiv:1603.03549, PRD

nGd, full dataset of 3158 days, arXiv:2211.14988



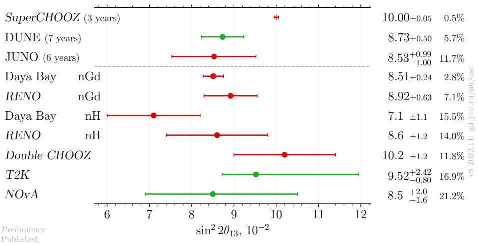
- Original goal: measure unknown $\sin^2 2\theta_{13}$ value down to 0.01.
- Most precise $\sin^2 2\theta_{13}$ measurement.
- $\sin^2 2\theta_{13} = 0$ is excluded at almost 35σ.
- nH $\sin^2 2\theta_{13}$ measurement has world's third precision.

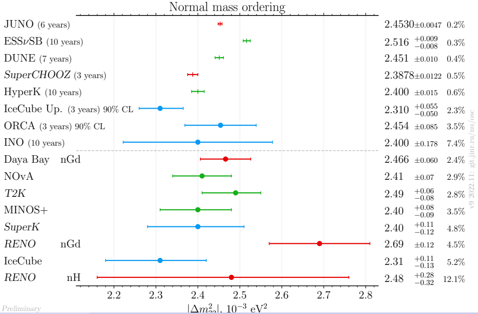
Daya Bay oscillation result

nH, 621 days, arXiv:1603.03549, PRD

nGd, full dataset of 3158 days, arXiv:2211.14988

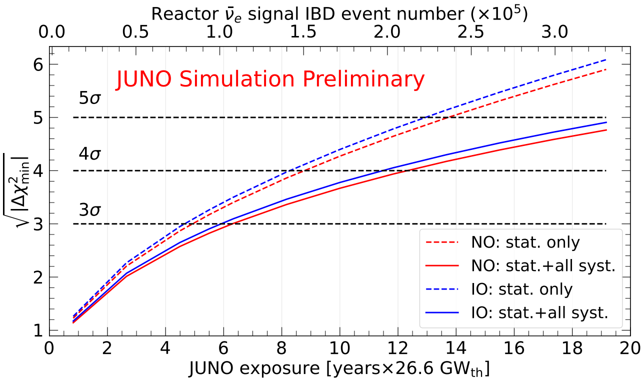
- Original goal: measure unknown $\sin^2 2\theta_{13}$ value down to 0.01.
- Most precise $\sin^2 2\theta_{13}$ measurement.
- $\sin^2 2\theta_{13} = 0$ is excluded at almost 35σ.
- nH $\sin^2 2\theta_{13}$ measurement has world's third precision.
- First world's measurement of Δm^2_{32}.
- Δm^2_{32} is consistent with and complementary to accelerator measurements.
- Negligible correlation between $\sin^2 2\theta_{13}$ and Δm^2_{32}.





Physics

Sensitivity to Neutrino Mass Ordering



✓ JUNO+TAO, 6 years×26.6 GW exposure: $\sim 3\sigma$

✓ +1% external constrain on Δm^2_{32}: $> 4\sigma$

✓ combined with accelerator/atmospheric experiment: $> 5\sigma$

↪ sensitivity boost due to tension for wrong ordering

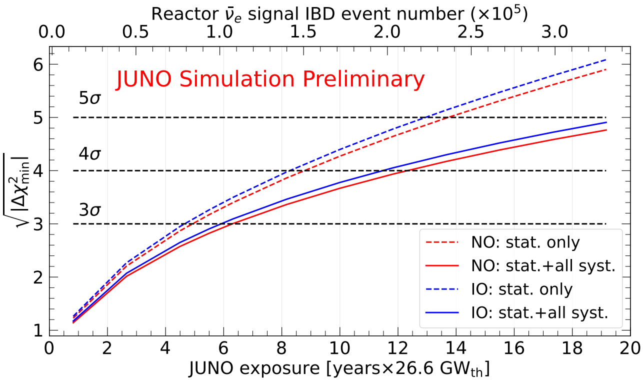
Signal and background

- Inverse beta decay: $\overline{\nu}_e + p \to e^+ + n$
  ↪ double coincidence
- Signal: 47 $\overline{\nu}_e$/day, backgrounds: 9%

▸ Extra

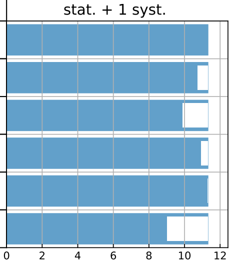
[2008.11280], JUNO+IceCube [1911.06745]

Sensitivity to Neutrino Mass Ordering



Impact of systematics:

	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



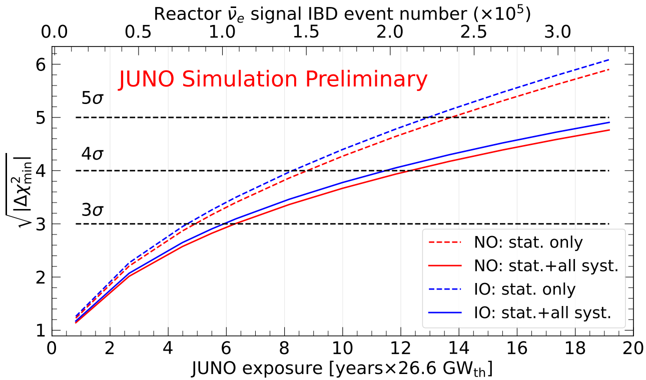
JUNO Simulation Preliminary

- ✓ JUNO+TAO, 6 years×26.6 GW exposure: $\sim 3\sigma$
- ✓ +1% external constrain on Δm^2_{32}: $> 4\sigma$
- ✓ combined with accelerator/atmospheric experiment: $> 5\sigma$
  ↪ sensitivity boost due to tension for wrong ordering

▸ Extra

[2008.11280], JUNO+IceCube [1911.06745]

Sensitivity to Neutrino Mass Ordering



✓ JUNO+TAO, 6 years×26.6 GW exposure: $\sim 3\sigma$

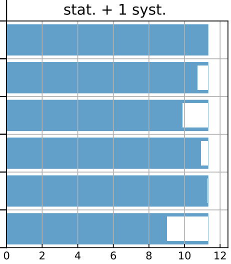
✓ +1% external constrain on Δm^2_{32}: $> 4\sigma$

✓ combined with accelerator/atmospheric experiment: $> 5\sigma$

↪ sensitivity boost due to tension for wrong ordering

Impact of systematics:

	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



JUNO Simulation Preliminary

- Paper draft under collaboration review.
- Combination of reactor and atmospheric channels within JUNO is investigated.

▸ Extra [2008.11280], JUNO+IceCube [1911.06745]

JUNO and neutrino oscillation parameters

[2204.13249]

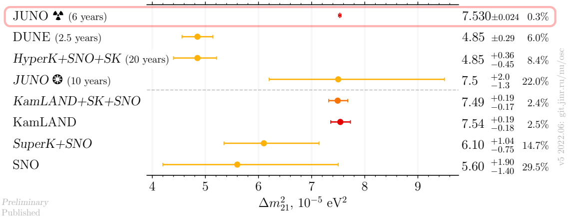
- Percent precision for $\Delta m^2_{21}/\Delta m^2_{31}$: 100 days
- Few permille level for $\Delta m^2_{21}/\Delta m^2_{31}/\sin^2 2\theta_{12}$: 6 years

✓ Order of magnitude improvement over existing constraints.

JUNO AND NEUTRINO OSCILLATION PARAMETERS

[2204.13249]

- Percent precision for $\Delta m^2_{21}/\Delta m^2_{31}$: 100 days
- Few permille level for $\Delta m^2_{21}/\Delta m^2_{31}/\sin^2 2\theta_{12}$: 6 years



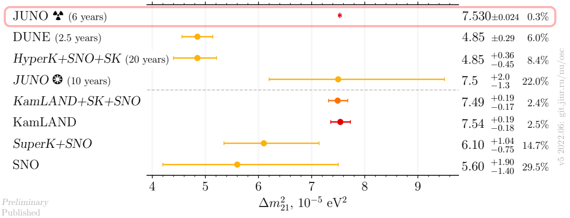
✓ Order of magnitude improvement over existing constraints.

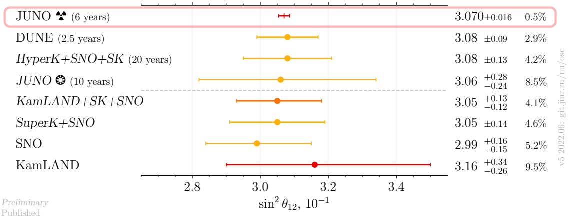
JUNO AND NEUTRINO OSCILLATION PARAMETERS

[2204.13249]

- Percent precision for $\Delta m^2_{21}/\Delta m^2_{31}$: 100 days
- Few permille level for $\Delta m^2_{21}/\Delta m^2_{31}/\sin^2 2\theta_{12}$: 6 years

✓ Order of magnitude improvement over existing constraints.



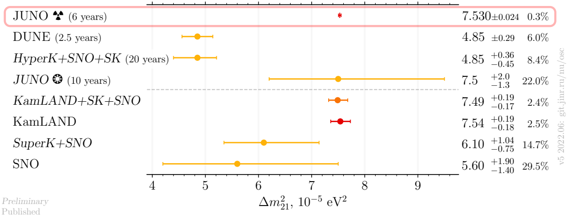


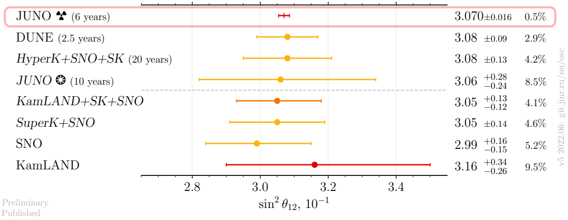
JUNO and neutrino oscillation parameters

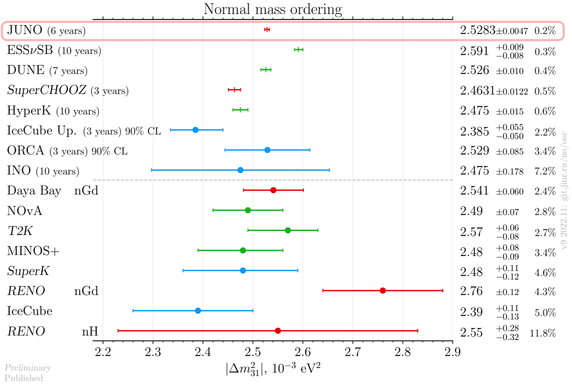
[2204.13249]

- Percent precision for $\Delta m^2_{21}/\Delta m^2_{31}$: 100 days
- Few permille level for $\Delta m^2_{21}/\Delta m^2_{31}/\sin^2 2\theta_{12}$: 6 years

✓ Order of magnitude improvement over existing constraints.

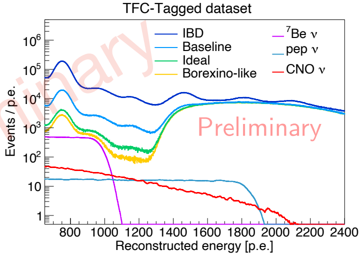






✓ Almost no correlation between measured parameters.

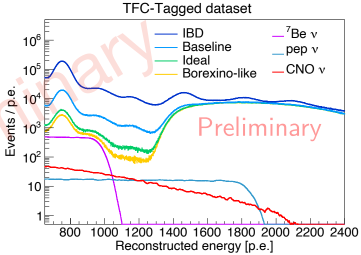
Intermediate energy solar neutrinos: ^{7}Be, pep, CNO

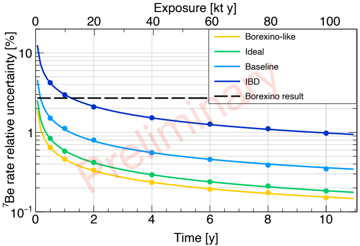


Detection

- Signal: ν_e elastic scattering off e^-
- Expected rate:
  - ^{7}Be — $\sim$ 130 ES/day
  - pep — $\sim$ 17 ES/day
  - CNO — $\sim$ 16 ES/day
- Limiting factors: LS purity, cosmic ray related background
- Baseline ^{238}U/^{232}Th contamination: 10^{-16} g/g

Intermediate energy solar neutrinos: ^{7}Be, pep, CNO

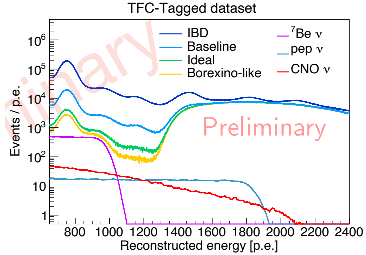




Detection

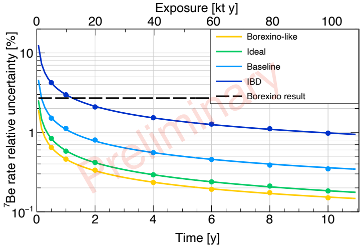
- Signal: ν_e elastic scattering off e^-
- Expected rate:
  - ^{7}Be ~ 130 ES/day
  - pep ~ 17 ES/day
  - CNO ~ 16 ES/day
- Limiting factors: LS purity, cosmic ray related background
- Baseline ^{238}U/^{232}Th contamination: 10^{-16} g/g

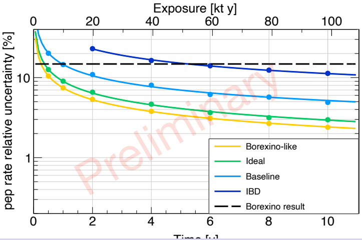
Intermediate energy solar neutrinos: ^{7}Be, pep, CNO



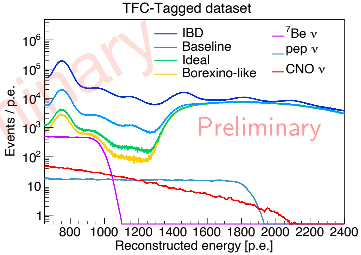
Detection

- Signal: ν_e elastic scattering off e^-
- Expected rate:
  - ^{7}Be ∼ 130 ES/day
  - pep ∼ 17 ES/day
  - CNO ∼ 16 ES/day
- Limiting factors: LS purity, cosmic ray related background
- Baseline ^{238}U/^{232}Th contamination: 10^{-16} g/g



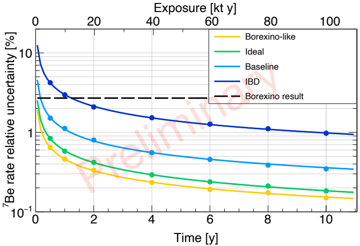


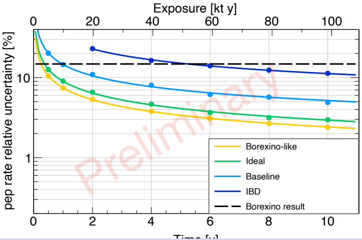
Intermediate energy solar neutrinos: ^{7}Be, pep, CNO

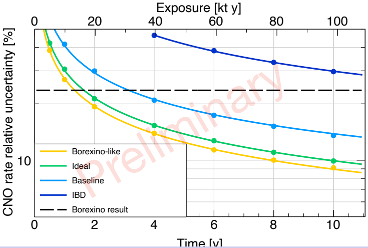


Detection

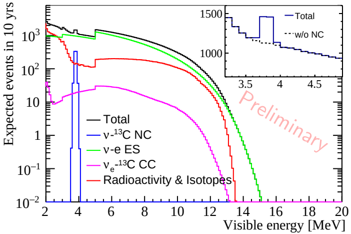
- Signal: ν_e elastic scattering off e^-
- Expected rate:
  - ^{7}Be ∼ 130 ES/day
  - pep ∼ 17 ES/day
  - CNO ∼ 16 ES/day
- Limiting factors: LS purity, cosmic ray related background
- Baseline ^{238}U/^{232}Th contamination: 10^{-16} g/g

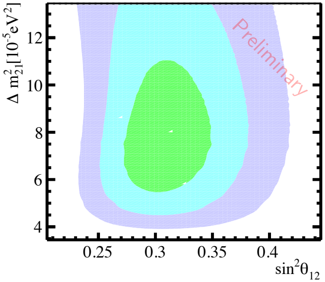






Oscillation physics with solar ^{8}B ν_e



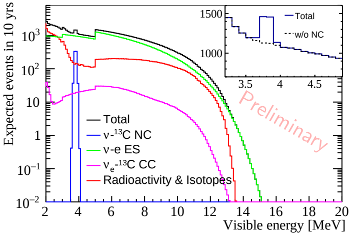


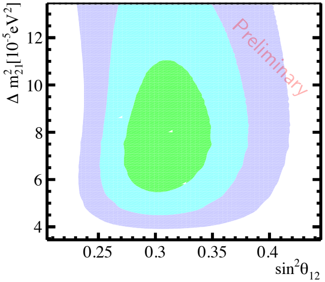
Oscillations

- ^{8}B ν_e are sensitive to the matter effect: Day/Night asymmetry

Extra

Oscillation physics with solar ^{8}B ν_e





Oscillations

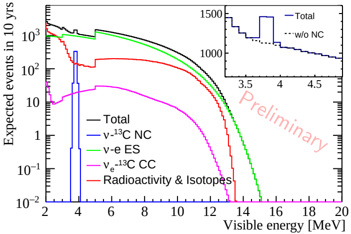
- ^{8}B ν_e are sensitive to the matter effect: Day/Night asymmetry

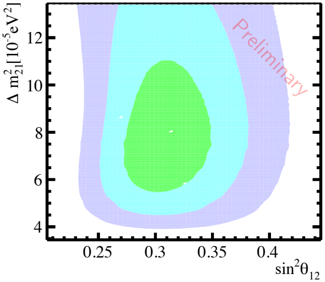
Detection

- Elastic scattering off e^- $\sim$16 ν_e/day
- Neutral current on ^{13}C $\sim$73.8 ν_e/year
- Charged current on ^{13}C $\sim$64.7 ν_e/year
- Limiting factors: LS purity, cosmic ray related background
- Baseline $^{238}U/^{232}Th$ contamination: 10^{-16} g/g

Extra

Oscillation physics with solar ^{8}B ν_e





Oscillations

- ^{8}B ν_e are sensitive to the matter effect: Day/Night asymmetry

Detection

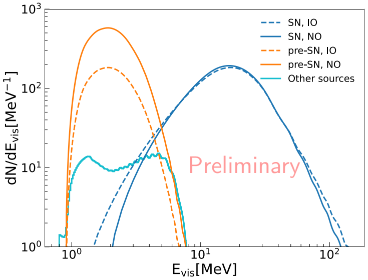
- Elastic scattering off e^- $\sim$16 ν_e/day
- Neutral current on ^{13}C $\sim$73.8 ν_e/year
- Charged current on ^{13}C $\sim$64.7 ν_e/year
- Limiting factors: LS purity, cosmic ray related background
- Baseline ^{238}U/^{232}Th contamination: 10^{-16} g/g

Data and analysis

- Events binned vs zenith angle $\cos\theta_z$ and ν_e energy
- 5%, $\sim$ 9% and $\sim$ 22% sensitivity to ^{8}B flux, $\sin^2 2\theta_{12}$ and Δm^2_{21}.

Extra

Core collapse SuperNova explosion

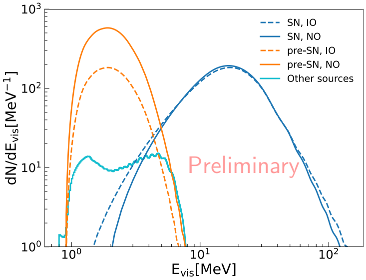


- Expect a few SuperNova explosions per century
- $\sim 10^4$ events in 10 s

On the plot

- SN @10 kpc
- pre-SN @0.2 kpc
- Reactor IBD background

Core collapse SuperNova explosion



On the plot

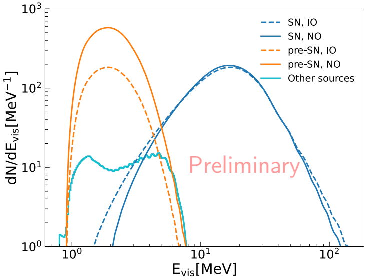
- SN @10 kpc
- pre-SN @0.2 kpc
- Reactor IBD background

- Expect a few SuperNova explosions per century
- $\sim 10^4$ events in 10 s

Detection

- Dedicated trigger: 100 keV threshold
- Expected statistics:
  - 5000 IBD
  - 2000 ES off proton
  - 300 ES off electron
  - 300 ν^{12}C NC
  - 200 ν^{12}C CC
  - Negligible background

Core collapse SuperNova explosion



On the plot

- SN @10 kpc
- pre-SN @0.2 kpc
- Reactor IBD background

- Expect a few SuperNova explosions per century
- $\sim 10^4$ events in 10 s

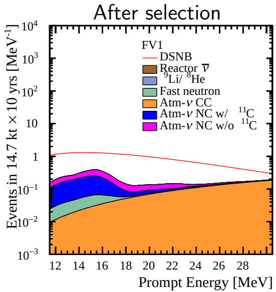
Detection

- Dedicated trigger: 100 keV threshold

Goals

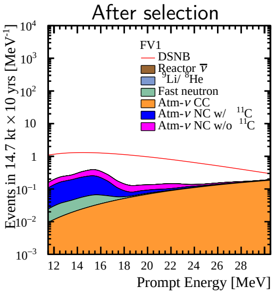
- Measure: flavor content, time evolution, flux, energy spectrum
- Study: stellar parameters, SN physics, late stage stellar evolution
- Constrain $m_\nu < (0.83 \pm 0.24)$ eV @90% CL @10 kpc [1412.7418]
- Multi-messenger trigger

Diffuse SuperNova neutrino background



[2205.08830]

Diffuse SuperNova neutrino background



DSNB

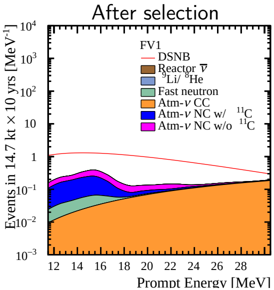
- Integrated signal of all the SuperNova explosions in the universe
- Not yet observed

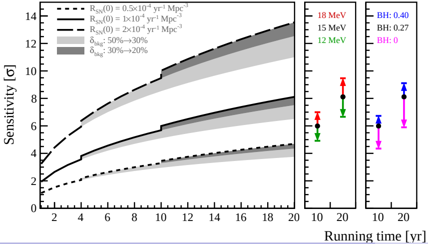
Detection

- Signal: inverse beta decay
- Expected rate: 2–4 $\overline{\nu}_e$/year
- Energies: E>12 MeV, above reactor IBD

[2205.08830]

Diffuse SuperNova neutrino background





DSNB

- Integrated signal of all the SuperNova explosions in the universe
- Not yet observed

Detection

- Signal: inverse beta decay
- Expected rate: 2–4 $\overline{\nu}_e$/year
- Energies: E>12 MeV, above reactor IBD

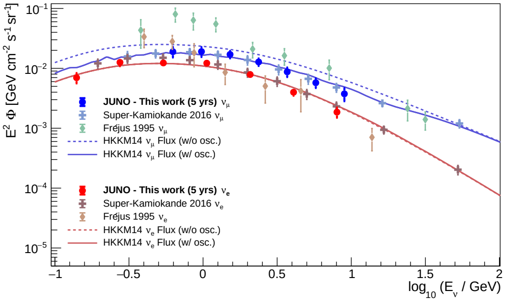
Discovery potential

- 5σ in 10 years
- 3σ in 3 years

[2205.08830]

Oscillation physics with atmospheric $\nu_\mu/\overline{\nu}_\mu$

[2103.09908][2104.02565]

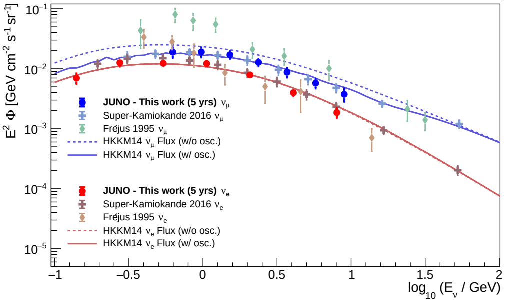


Oscillations

- Matter effect: θ_z dependence

Oscillation physics with atmospheric $\nu_\mu/\overline{\nu}_\mu$

[2103.09908][2104.02565]



Oscillations

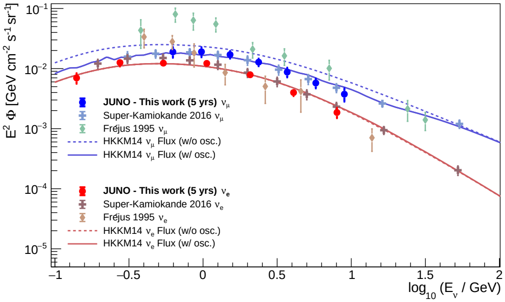
- Matter effect: θ_z dependence

Detection

- Primary channel: $\nu_\mu/\overline{\nu}_\mu$ CC
- Expected statistics, 200 kton-years: 1233/1035 events
- Limiting factors: angular resolution / PID purity

Oscillation physics with atmospheric $\nu_\mu/\overline{\nu}_\mu$

[2103.09908][2104.02565]



Oscillations

- Matter effect: θ_z dependence

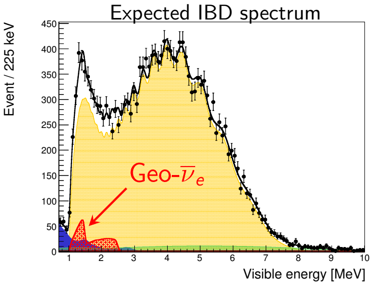
Detection

- Primary channel: $\nu_\mu/\overline{\nu}_\mu$ CC
- Expected statistics, 200 kton-years: 1233/1035 events
- Limiting factors: angular resolution / PID purity

Data and analysis

- Events binned vs zenith angle $\cos\theta_z$ (fine) and ν energy (coarse)
- $\sim 1\sigma$ sensitivity to ordering in 10 years
- Potential: combination with reactor analysis

Geo-neutrinos

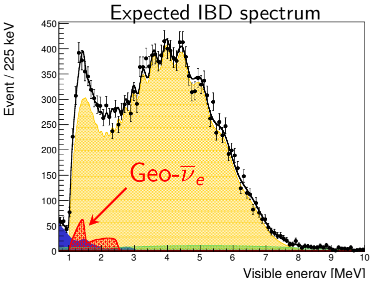


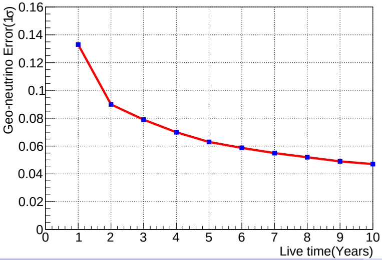
Source: ^{238}U/^{232}Th from Earth's crust and mantle

- $^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\overline{\nu}_e$
- $^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\overline{\nu}_e$
- there is also ^{40}K, which is below IBD threshold of 1.8 MeV
- 500 km of crust around JUNO contributes > 50% of signal
- Local geological studies: [1901.01945] [1903.11871]

[2104.02565]

Geo-neutrinos





Source: ^{238}U/^{232}Th from Earth's crust and mantle

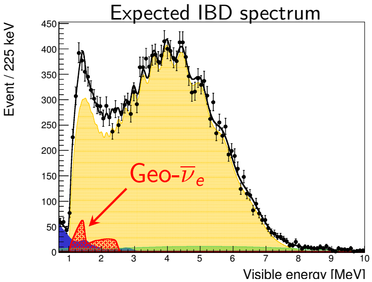
- 500 km of crust around JUNO contributes > 50% of signal
- Local geological studies: [1901.01945] [1903.11871]

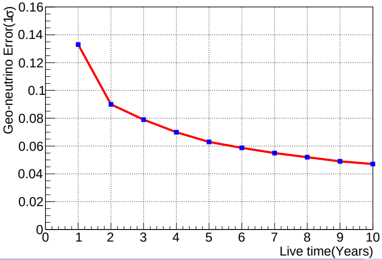
Data

- KamLAND: 175 $\overline{\nu}_e$ in 8 years [2205.14934]
- Borexino: 53 $\overline{\nu}_e$ in 9 years [1909.02257]
- JUNO: 400 $\overline{\nu}_e$/year (40 TNU/year)

[2104.02565]

Geo-neutrinos





Source: ^{238}U/^{232}Th from Earth's crust and mantle

- 500 km of crust around JUNO contributes > 50% of signal
- Local geological studies: [1901.01945] [1903.11871]

Data

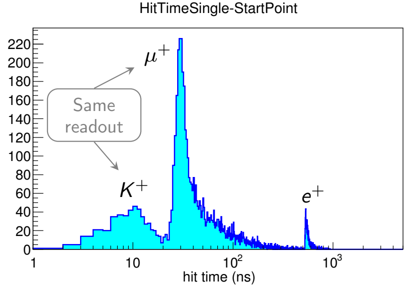
- KamLAND: 175 $\overline{\nu}_e$ in 8 years [2205.14934]
- Borexino: 53 $\overline{\nu}_e$ in 9 years [1909.02257]
- JUNO: 400 $\overline{\nu}_e$/year (40 TNU/year)

Goals

- 5% geo-$\overline{\nu}_e$ measurement in 10 years
- Measure: Th/U mass ratio
- Study: radiogenic heat production

[2104.02565]

Proton decay

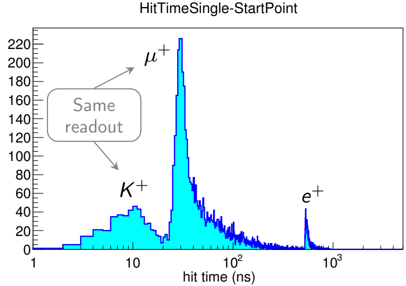


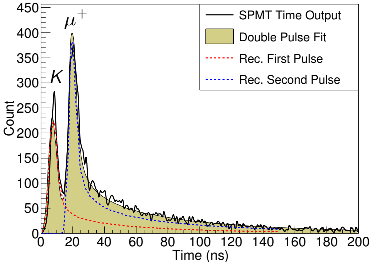
Signature

- $p \to \nu + K^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ GUT
- $p \to \nu + \pi^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ SUSY
- $p \to \mu^+ \mu^+ \mu^-$ under investigation

[2104.02565]

Proton decay





Signature

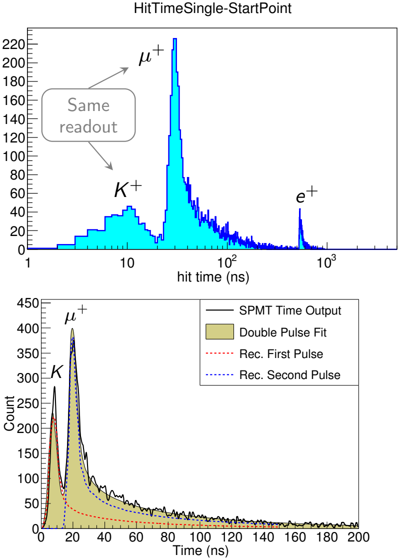
- $p \to \nu + K^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ GUT
- $p \to \nu + \pi^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ SUSY
- $p \to \mu^+\mu^+\mu^-$ under investigation

Data

- Signal: three-fold coincidence
- Backgrounds: atmospheric neutrinos, cosmic muons

[2104.02565]

Proton decay



Signature

- $p \to \nu + K^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ GUT
- $p \to \nu + \pi^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ SUSY
- $p \to \mu^+\mu^+\mu^-$ under investigation

Data

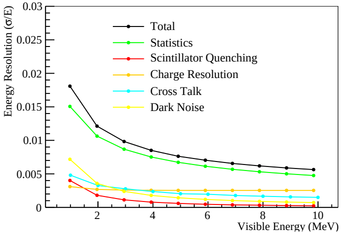
- Signal: three-fold coincidence
- Backgrounds: atmospheric neutrinos, cosmic muons

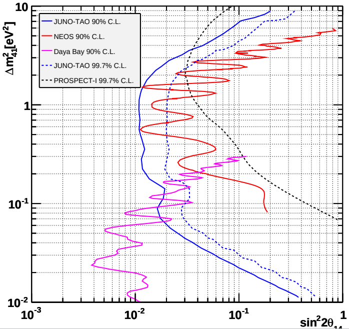
Sensitivity

- 8.34×10^{33} years 90% CL in 10 years

[2104.02565]

Sterile neutrino search with TAO



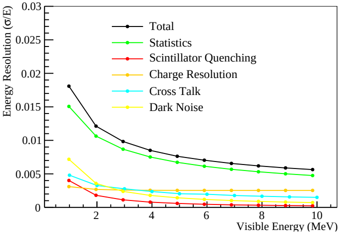


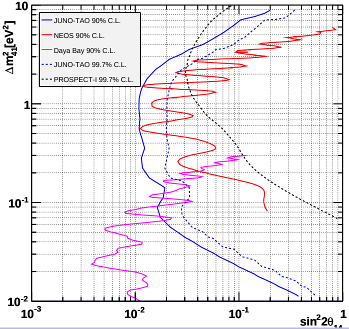
Primary goal

TAO CDR [2005.08745]

- Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

Sterile neutrino search with TAO





Primary goal

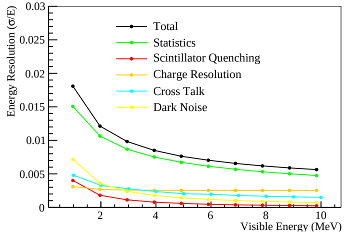
TAO CDR [2005.08745]

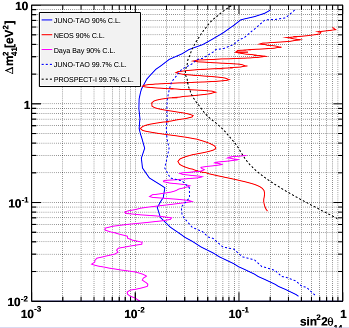
- Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

Oscillations: reactor at 30 m

- Relevant range: $0.5\,\mathrm{eV}^2 \lesssim \Delta m^2_{41} \lesssim 5\,\mathrm{eV}^2$
- ∼large L counterbalanced with high energy resolution

Sterile neutrino search with TAO





Primary goal

TAO CDR [2005.08745]

- Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

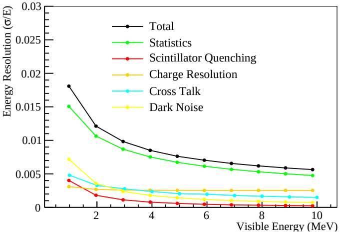
Oscillations: reactor at 30 m

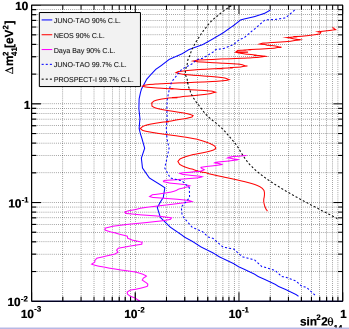
- Relevant range: $0.5\,\mathrm{eV}^2 \lesssim \Delta m^2_{41} \lesssim 5\,\mathrm{eV}^2$
- ∼large L counterbalanced with high energy resolution

Detection

- Inverse beta decay with nGd tag
- Expected rate: $\sim 2000\ \overline{\nu}_e/\mathrm{day}$

Sterile neutrino search with TAO





TAO CDR [2005.08745]

Primary goal

- Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

Oscillations: reactor at 30 m

- Relevant range: $0.5\,\text{eV}^2 \lesssim \Delta m^2_{41} \lesssim 5\,\text{eV}^2$
- $\sim$large L counterbalanced with high energy resolution

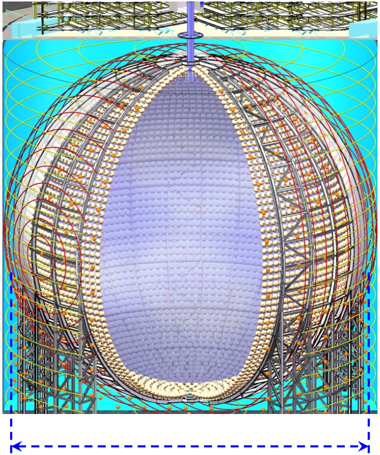
Detection

- Inverse beta decay with nGd tag
- Expected rate: $\sim 2000\ \overline{\nu}_e$/day

Data and analysis

- Events, finely binned vs energy
- Simultaneous fit: TAO's 4 virtual subdetectors
- Probe Neutrino-4 best-fit: Δm^2_{41}=7.25 eV^2, $\sin^2 2\theta_{14}$=0.26

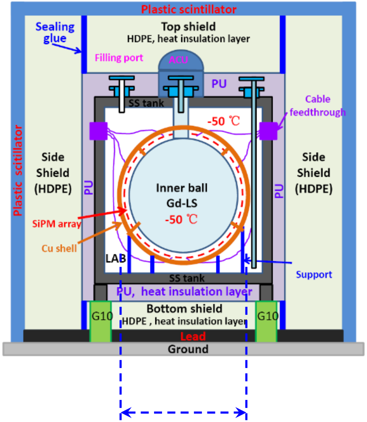
Antineutrino Detectors (AD)



35 m / 20 **kt** LS

	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)



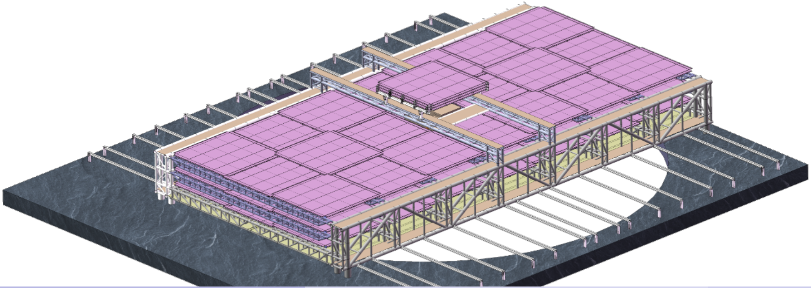
1.7 m / 2.6 t GdLS

	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

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



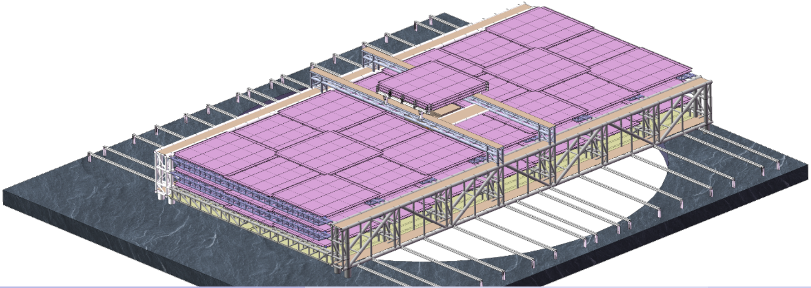
Veto: Top muon Tracker (TT)

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

Status: JINR

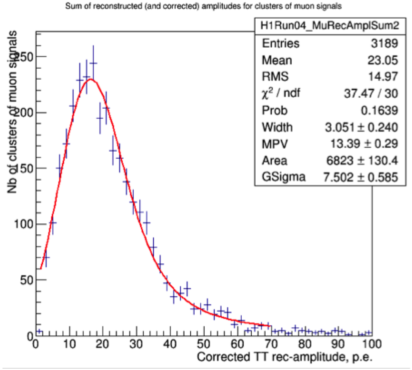
- Mechanical support structure R&D, prototyping and validation: done
- Assembly procedure, tools: done, reviewed
- Bidding: done
- Manufacturing (140 t): 2021
- Assembly on site: 2021.09→2022.03

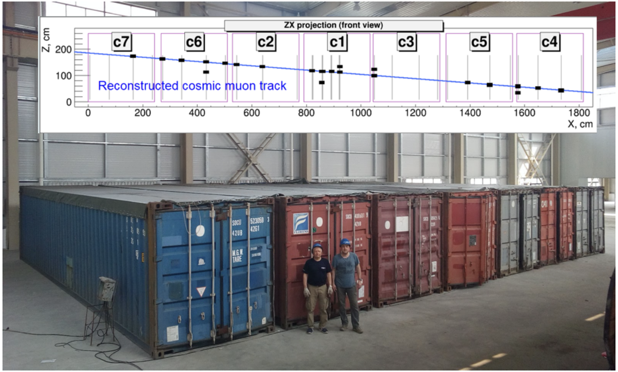


TT: PLASTIC SCINTILLATOR MONITORING

Plastic scintillator for TT

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

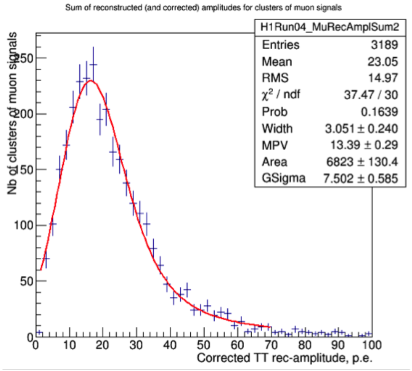




TT: plastic scintillator monitoring

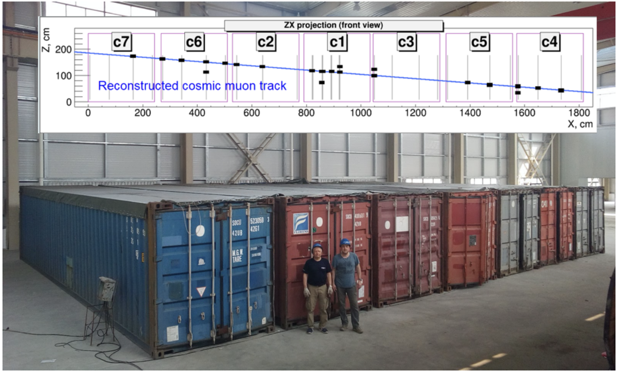
Plastic scintillator for TT

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



JINR

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

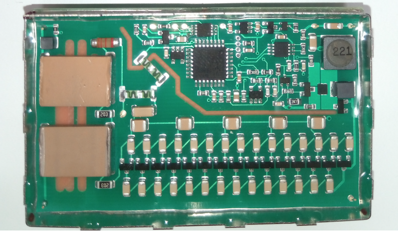


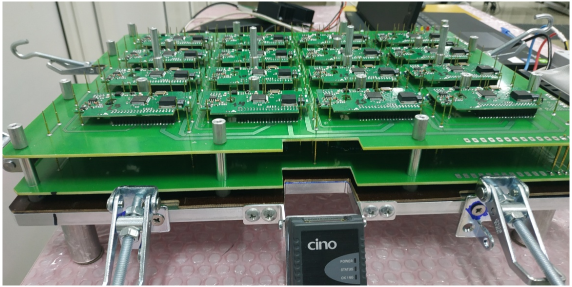
HV UNITS

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



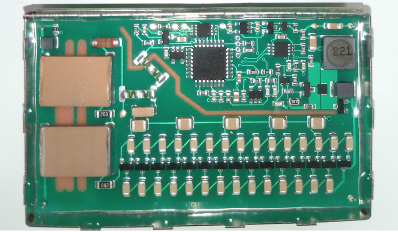


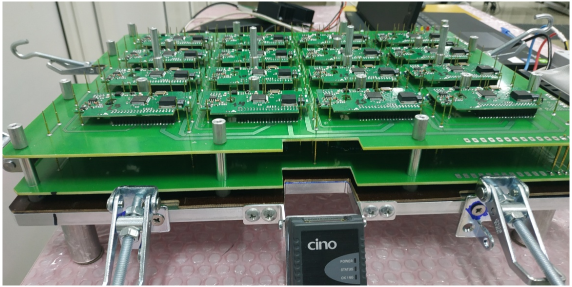
HV UNITS

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



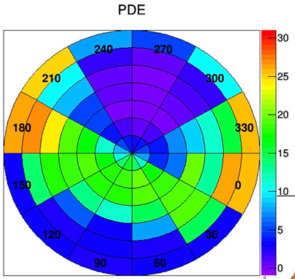


Status

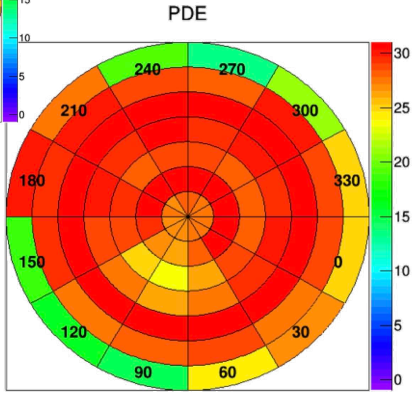
- ✓ R&D, prototyping
- ✓ Testing: materials, ageing, thermo cycling
- ✓ Factory setup, procedures: Shenzhen
- ✓ Test batch: 500 items
- Production via single batch: → 2020

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

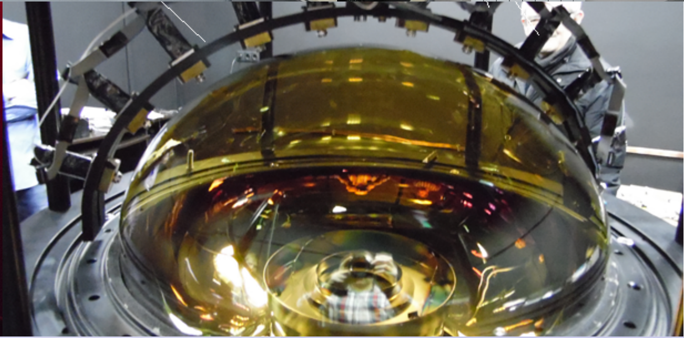


◀ Magnetic field: 42 μT



Magnetic field: compensated ▶

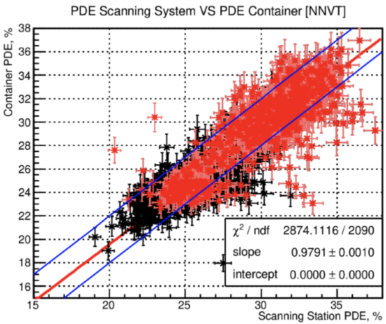
JINR PMT testing laboratory



Mass PMT Testing

Scanning and mass testing

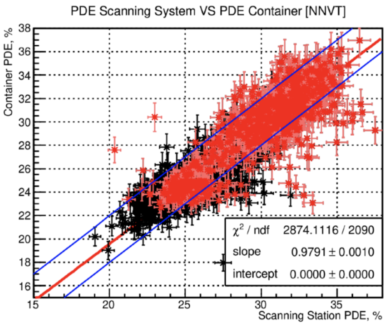
- ✓ Almost 17k PMTs tested
- ✗ ∼3% rejected
- ✓ 3'110 PMTs tested after potting
- ✓ Complementary and consistent performance



Mass PMT Testing

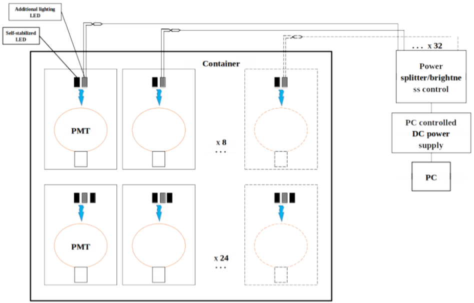
Scanning and mass testing

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



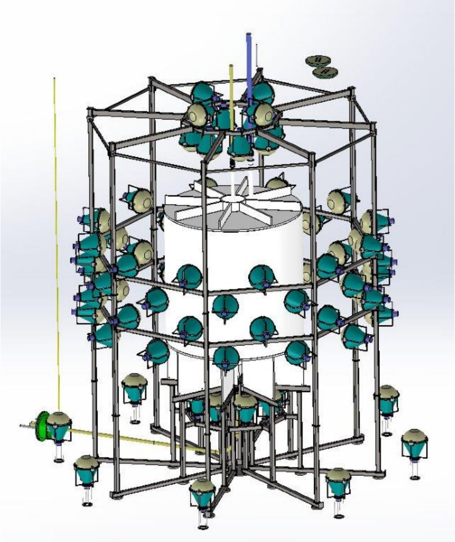
Long term stability

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



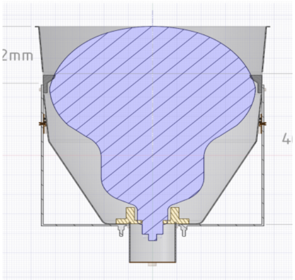
OSIRIS: PMT protection vs. Earth Magnetic Field

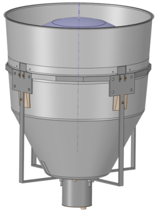
- Online Scintillator Internal Radioactivity Investigation System
- 76 20" PMTs: 64 detector + 12 veto
- Individual EMF protection: Metglas+Al cones:
  - detector: carbon fiber composite
  - veto: fiberglass composite
- EMF reduction factor: x2 $\parallel$ and x10 $\perp$

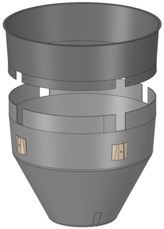


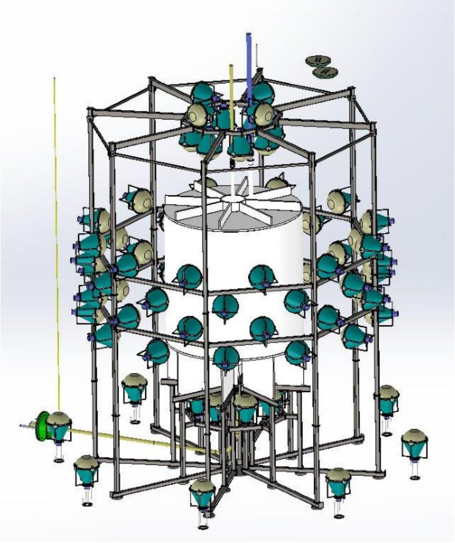
OSIRIS: PMT protection vs. Earth Magnetic Field

- 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 $\perp$









Prototypes and radioactivity balance

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

Prototypes and radioactivity balance

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



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

TAO — Taishan Antineutrino Observatory

Objective

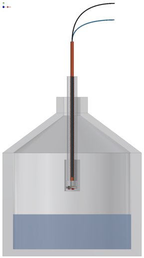
- Precision antineutrino spectrum measurement
- High statistics, no oscillations
- Unprecedented precision: $\sigma_E \sim 2\%$ at 1 MeV

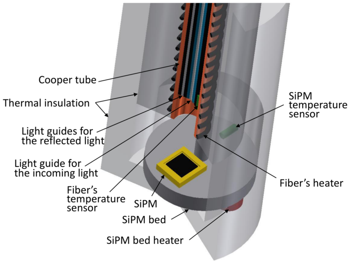
JINR contribution

✓ SiPM acceptance studies at −50 °C

✓ TAO CDR preparation

- SiPM mass characterization





TAO — Taishan Antineutrino Observatory

Objective

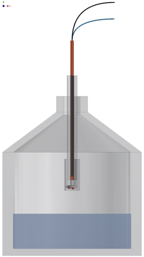
- Precision antineutrino spectrum measurement
- High statistics, no oscillations
- Unprecedented precision: $\sigma_E \sim 2\%$ at 1 MeV

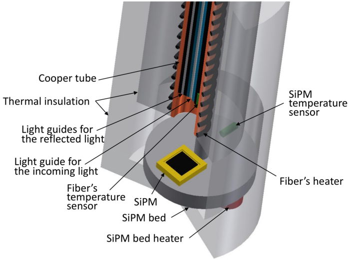
JINR contribution

✓ SiPM acceptance studies at −50 °C

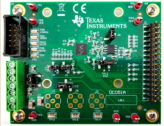
✓ TAO CDR preparation

- SiPM mass characterization
- 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

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

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

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

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

Network and GRID

✓ GRID: CVMFS repository / Secondary VOMS server: deployed

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