NOvA/DUNE Project

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for the NOvA/DUNE JINR team

21 June, JINR PAC

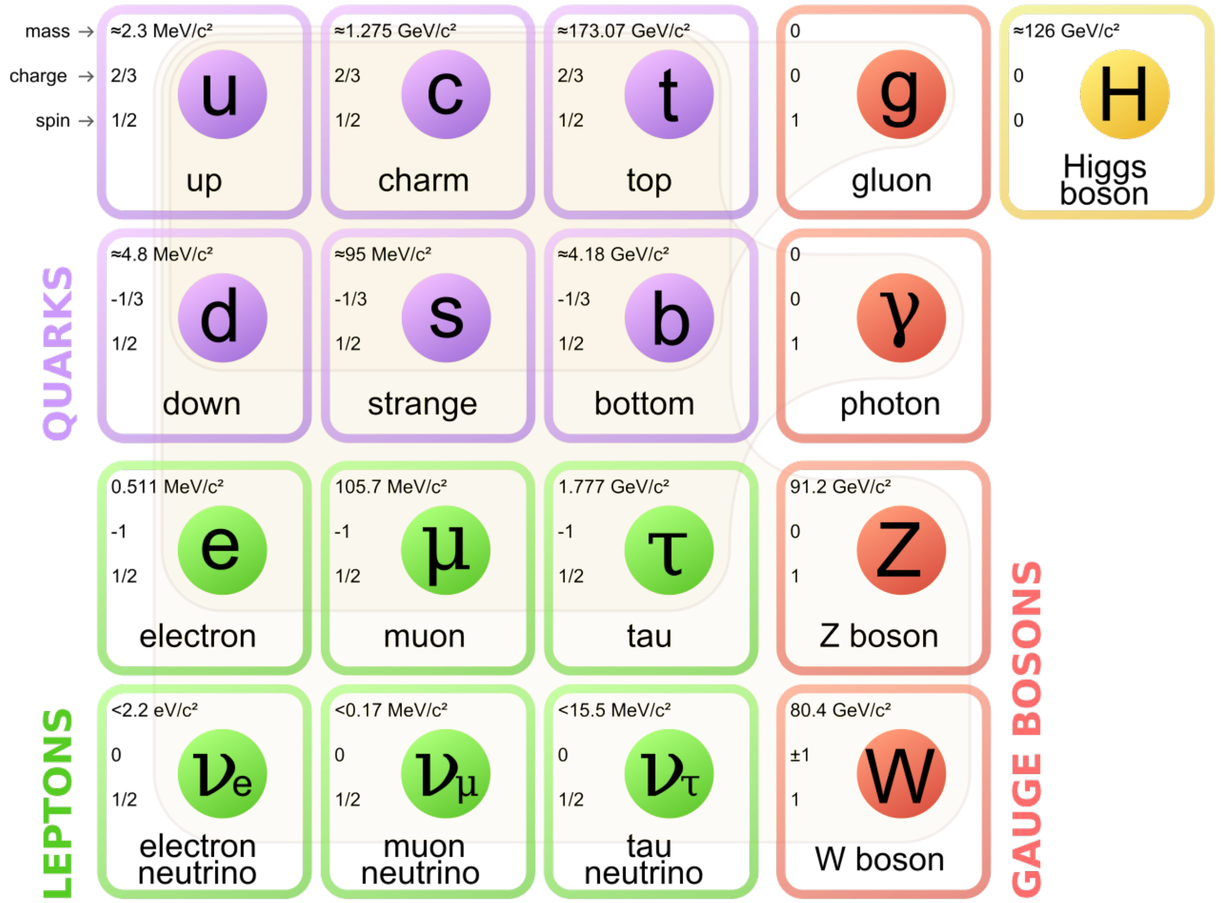
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Neutrino physics

- Standard Model particle.
- Small but non zero mass.
- Neutrino interactions conserve flavor.
- Interact only via weak (and gravity) force.

Modern hot topics:

- search for sterile neutrinos,
- measurement of absolute neutrino masses,
- search for neutrinoless double beta-decay (are neutrinos Dirac or Majorana particles),
- detection of relic neutrinos,
- study of neutrino oscillations,
- detection of high energy astrophysical neutrinos and spotting their sources,
- ...



Three-flavor neutrino oscillations

ATMOSPHERIC ACCELERATOR | SHORT BASELINE REACTOR ACCELERATOR | SOLAR LONG BASELINE REACTOR

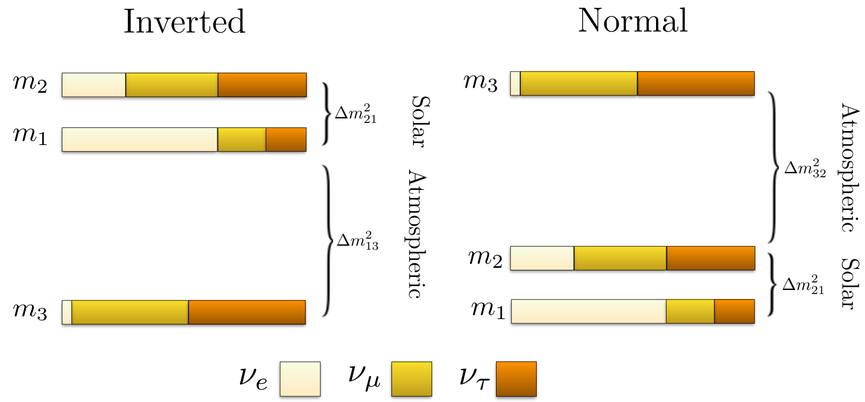
$$\left| \begin{matrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12}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

Oscillation parameters and how precisely do we know them:

$\theta_{12} \approx 34^\circ$ (4.2%)
$\theta_{23} \approx 49^\circ$ (5.2%)
$\theta_{13} \approx 9^\circ$ (3.1%)
$\Delta m^2_{21} \approx 7.4 \times 10^{-5}$ eV^2 (2.2%)
$\Delta m^2_{32} \approx +2.5 \times 10^{-3}$ eV^2 (1.2%)

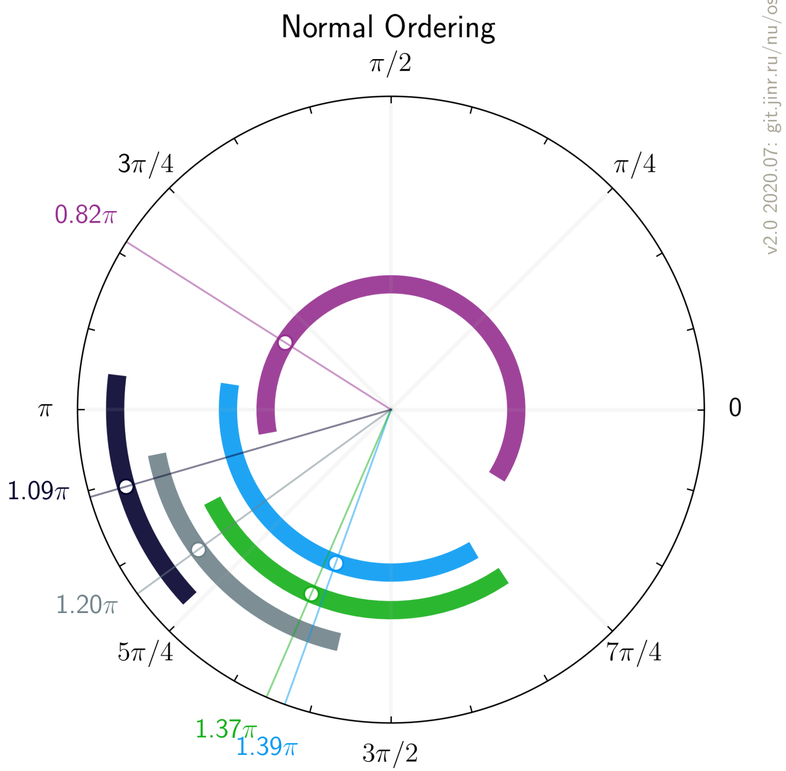
Open questions:

- Is θ_{23} 45°? (possible ν_μ and ν_τ symmetry in ν_3)
- Is there CP violation in lepton sector? (matter-antimatter asymmetry of the Universe (leptogenisis)



- Neutrino mass hierarchy (ordering) is Normal or Inverted? (neutrinoless double beta-decay searches, supernova simulations, relic neutrinos searches, absolute ν mass measurements etc)

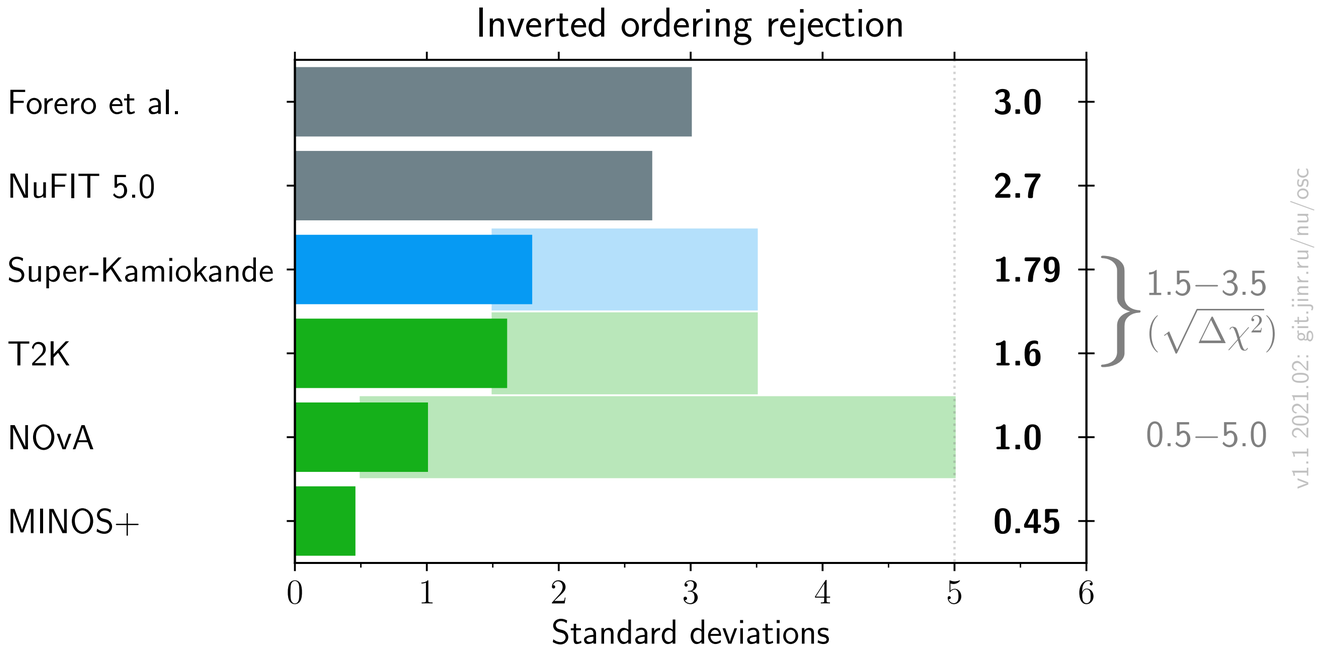
Current status and future prospects



v2.0 2020.07: git.jinr.ru/nu/osc

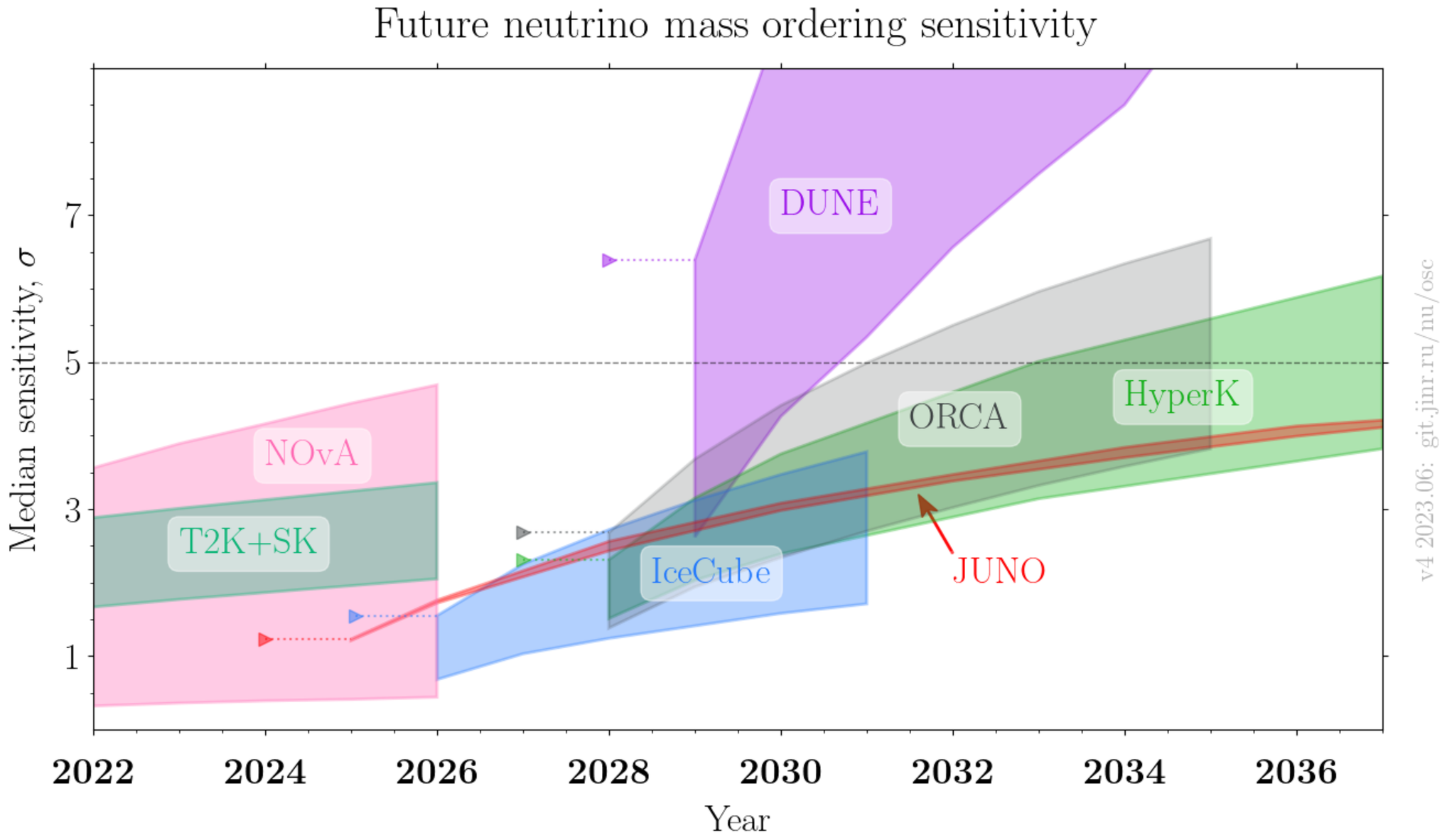
Experiment	δ_{CP}, π
NuFIT 5.0	$1.09^{+0.15}_{-0.13}$
Forero et al.	$1.20^{+0.23}_{-0.14}$
T2K	$1.37^{+0.32}_{-0.22}$
Super-Kamiokande	$1.39^{+0.28}_{-0.44}$
NOvA	$0.82^{+0.24}_{-1.00}$

- Recent results of NOvA and T2K showed tension in preferred values of δ_{CP}.
  - Significance is small ($<2\sigma$), both experiments will keep running.
  - NOvA-T2K joint analysis is under preparation.
- After finishing NOvA, T2K and Super-Kamiokande the only experiments that can measure δ_{CP} will be DUNE and Hyper-Kamiokande.



v1.1 2021.02: git.jinr.ru/nu/osc

Future prospects



The NOvA experiment

The NuMI Off-Axis ν_e Appearance Experiment

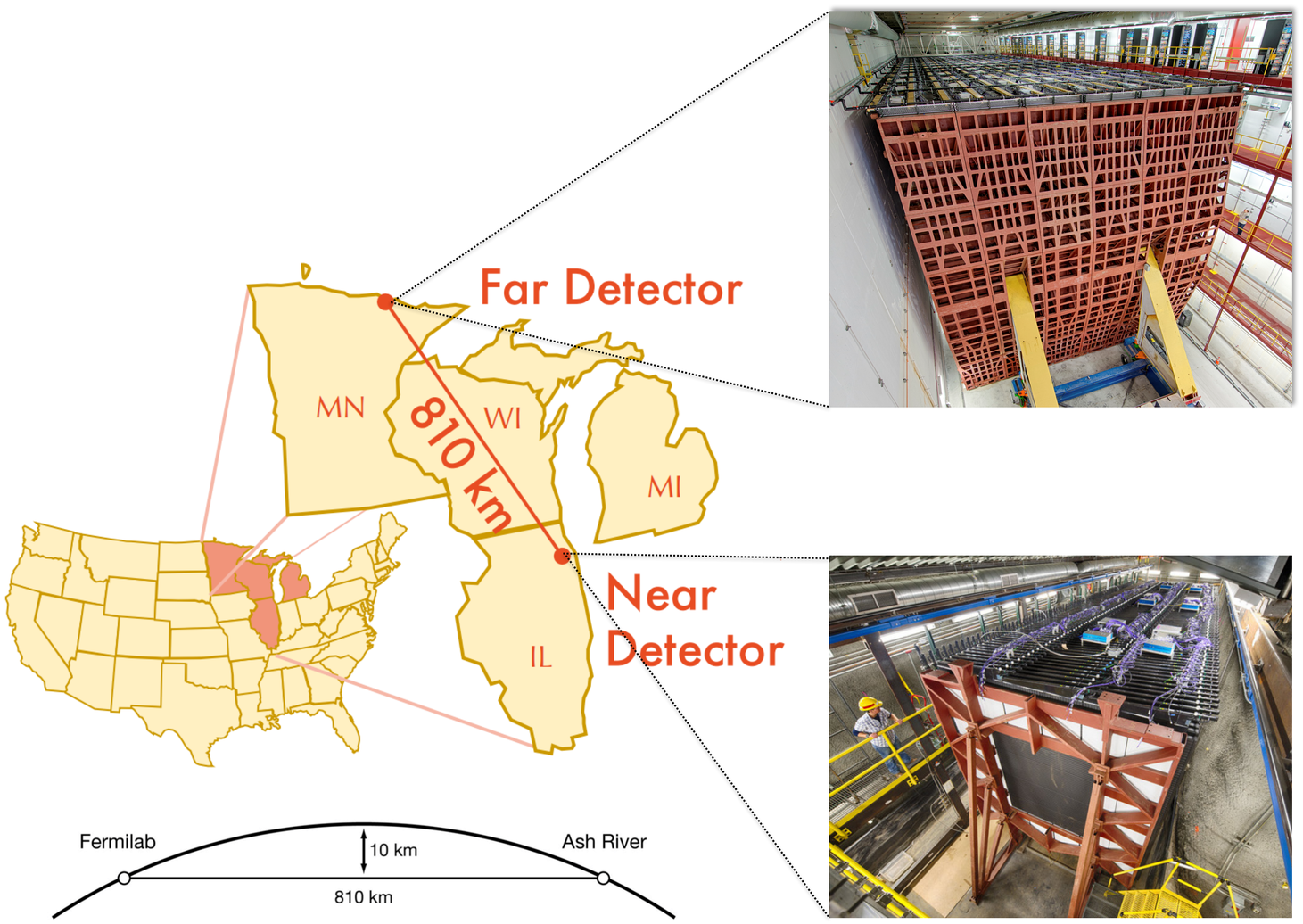
Experiment goals:

Using $\nu_\mu \to \nu_\mu$ $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
- Precise measurement Δm^2_{32}
- Mixing angle θ_{23}

Using $\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e)$
- Neutrino mass hierarchy
- CP violating phase
- Mixing angle θ_{23}

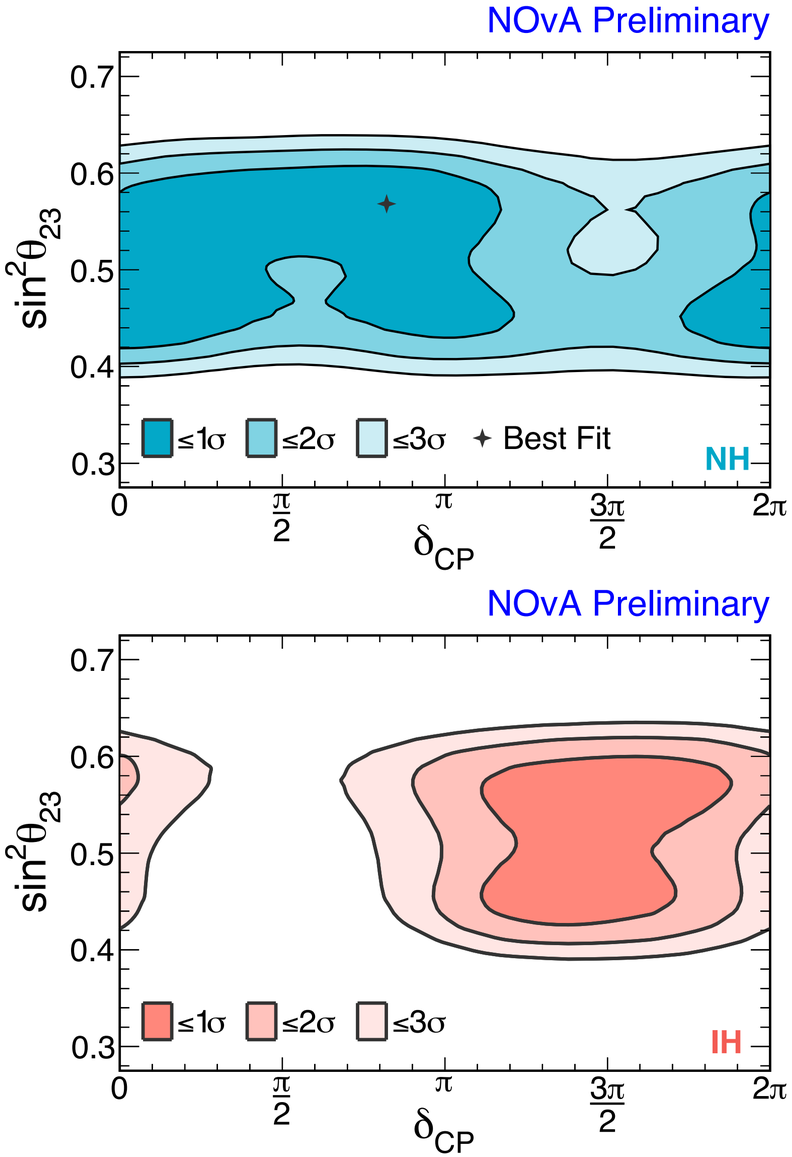
Long-baseline,
beam from Fermilab,
two detectors sit at
14 mrad off-axis

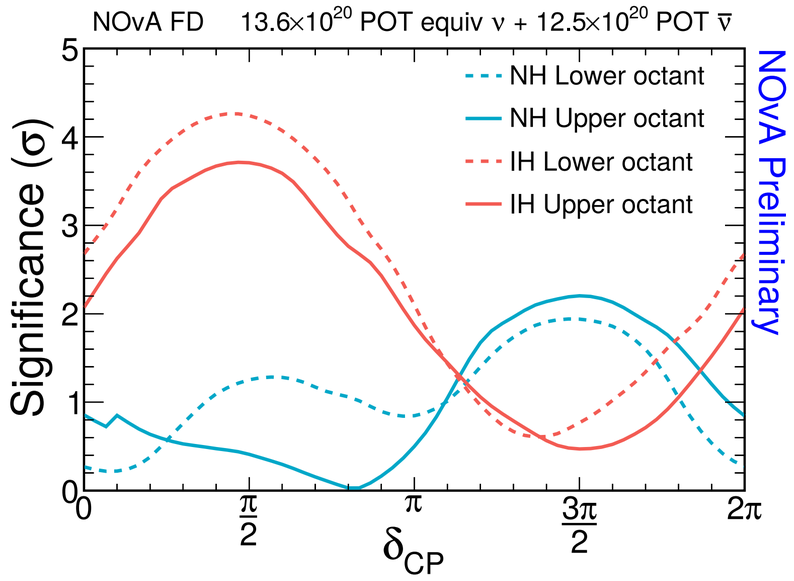
JINR joined NOvA in 2014

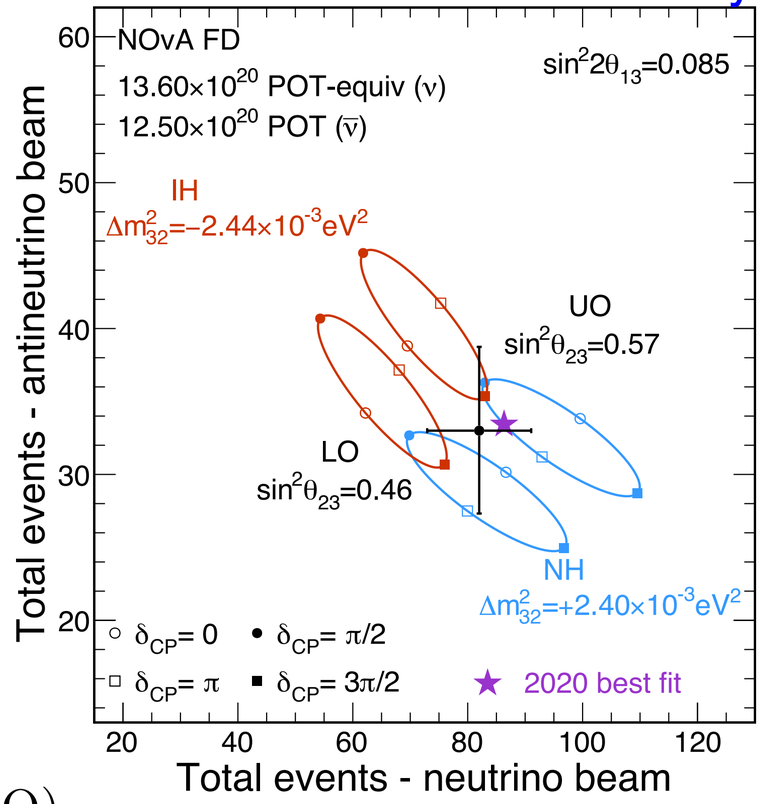


200 collaborators from 40 institutions and over 7 countries

Oscillation results: joint $\nu_\mu + \nu_e$ fit







✳ Best fit:

$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$$

$$\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\ \text{eV}^2\ \text{(NO)}$$

$$\delta_{CP} = 0.82\pi.$$

✳Disfavor NO, $\delta = 3\pi/2$ at $\sim 2\sigma$.

✳Exclude IO, $\delta = \pi/2$ at $> 3\sigma$.

Phys.Rev.D 106 (2022) 3, 032004

No strong asymmetry in the rates of ν_e and $\bar{\nu}_e$ appearance.

NOvA FUTURE

Currently running with neutrino beam.

- ✳ Plan is to run 50:50% $\nu : \bar{\nu}$;
- ✳ NOvA is expected to run until 2026 inclusively.

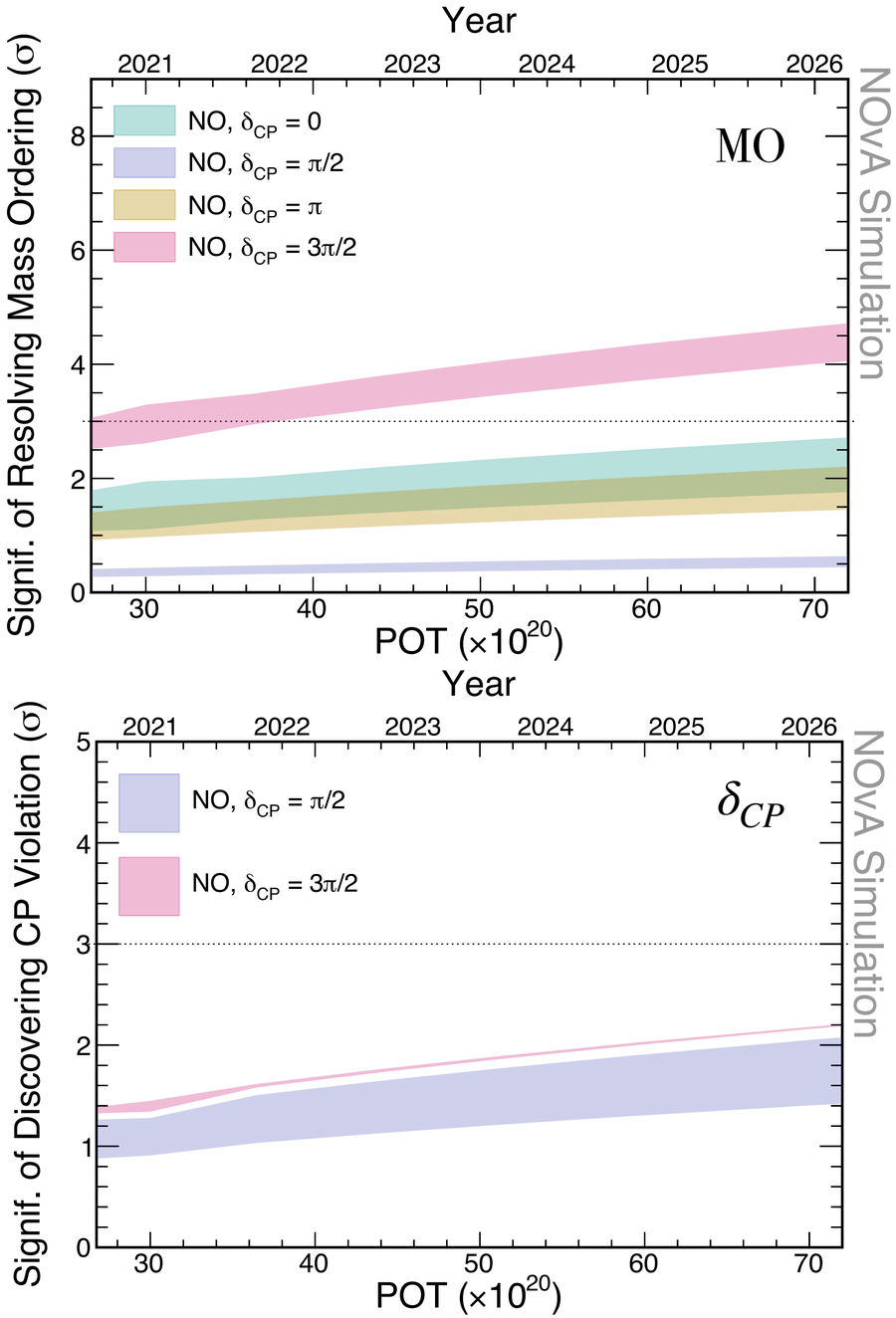
With current analysis, expect:

- ✳ potential 3-4σ sensitivity to hierarchy with favorable parameters;
- ✳ possible 2σ sensitivity to CP violation.

Note: sensitivity depends strongly on the true values in nature.

Expected improvements for upcoming analyses:

- ✳ accelerator → $\nu/\bar{\nu}$ beam intensity;
- ✳ test beam → improved det. response model.



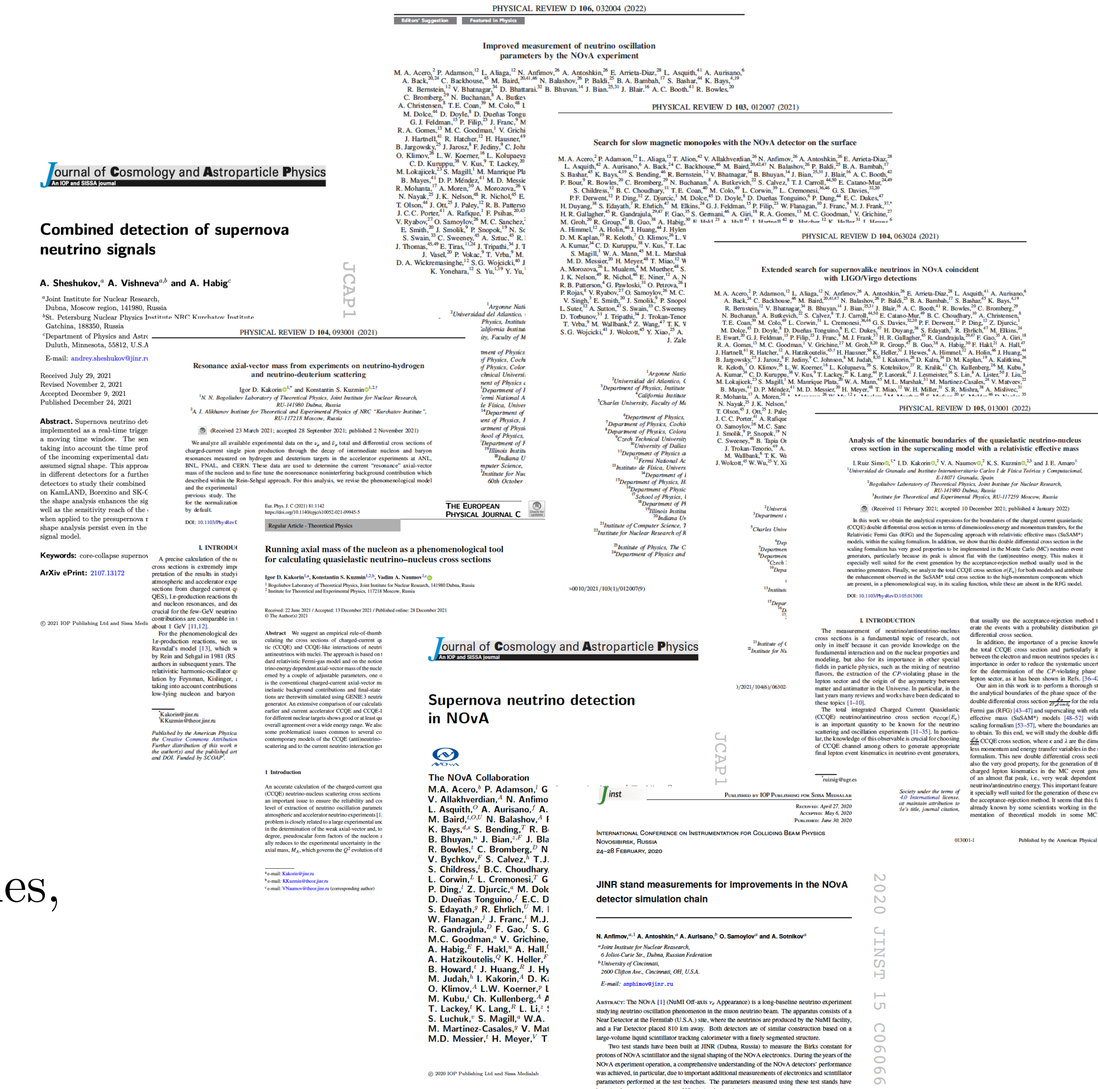
JINR CONTRIBUTION TO NOvA

PHYSICS

- Three-flavour oscillation analysis,
  - including NOvA-T2K joint analysis effort,
- supernova neutrino trigger and analysis development,
- magnetic monopole search,
- high-energy muon spectra,
- east-west asymmetry in muon spectra,
- theory of neutrino interactions.

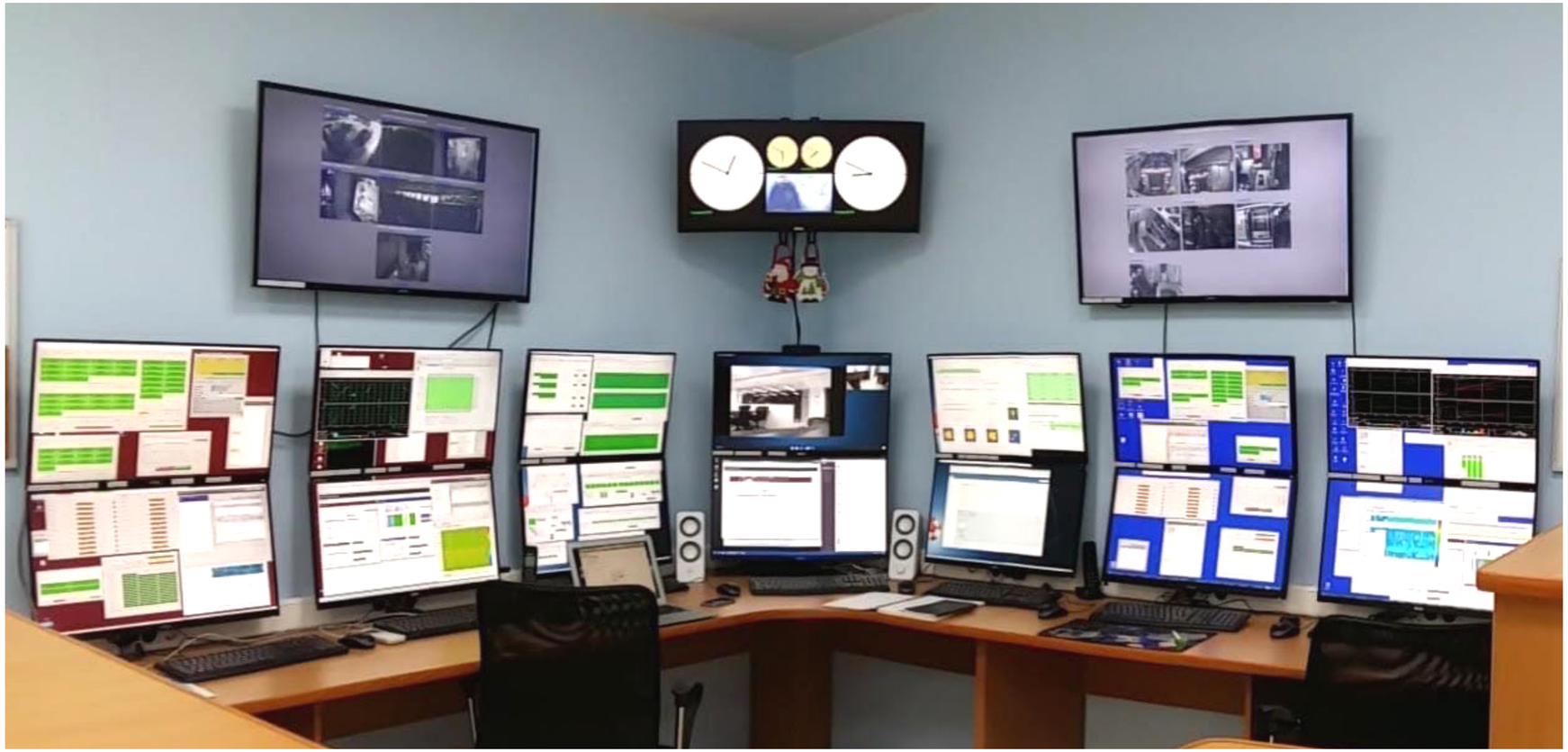
DETECTOR RELATED

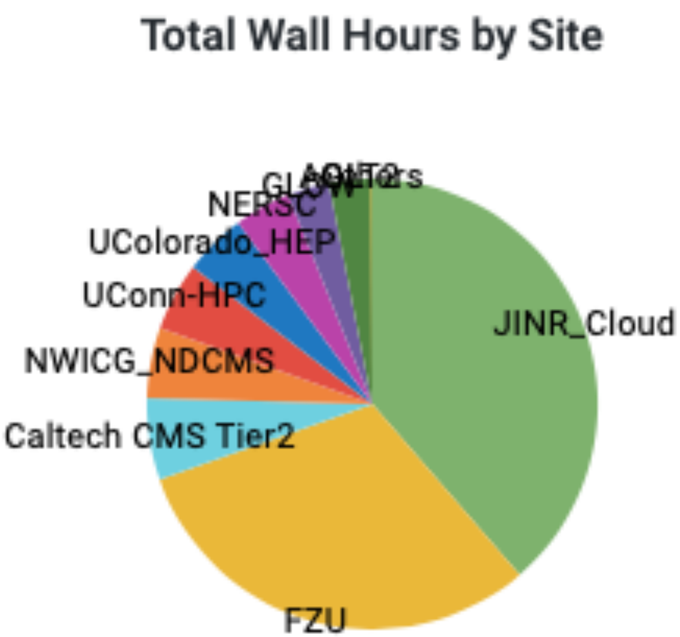
- Test bench for measurement of NOvA scintillator properties,
- test bench with detector electronics.



(not full list of papers)

NOvA's infrastructure at JINR

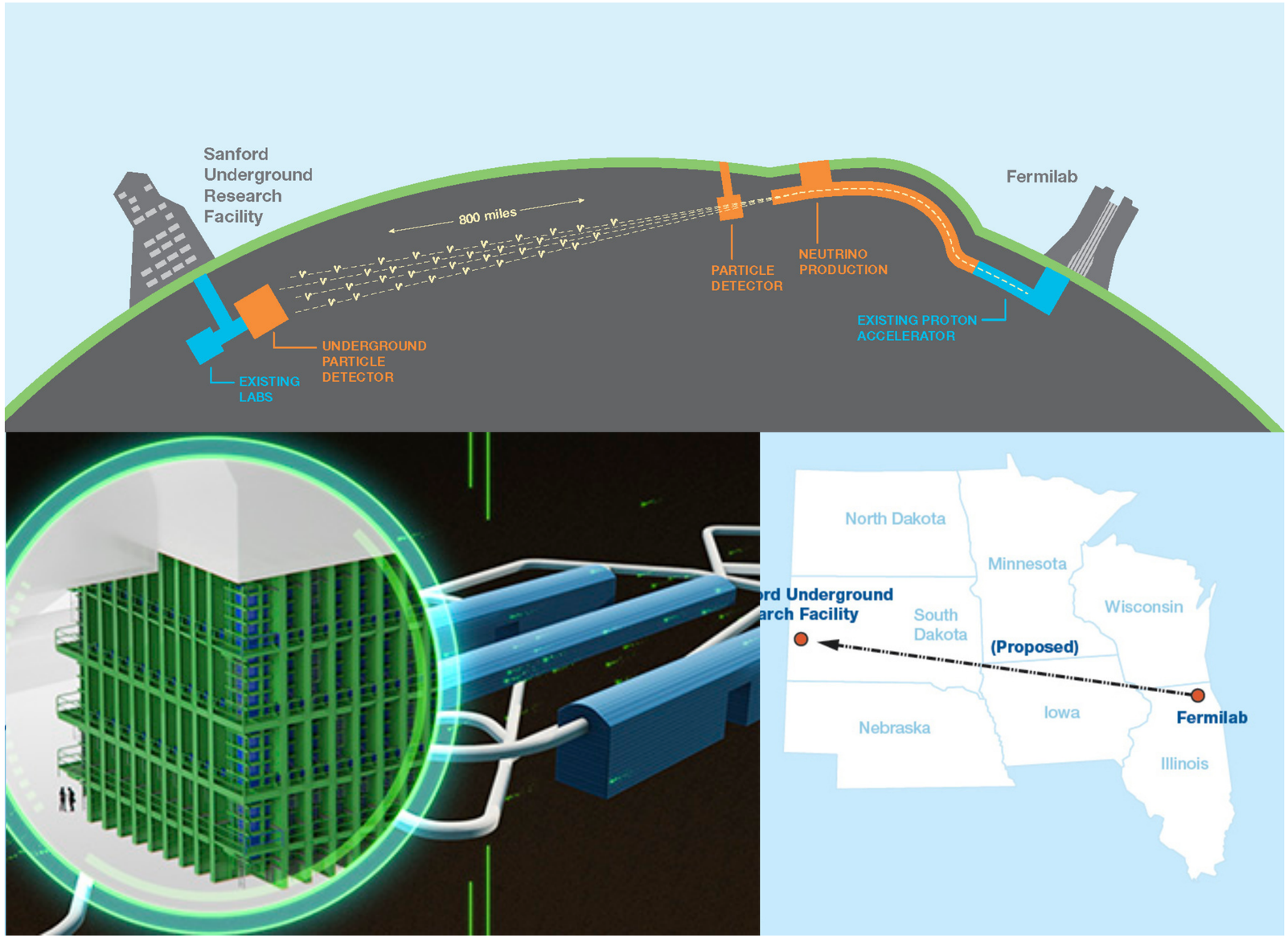




✳ Computing: 1k CPU and 90 Tb storage (group needs + experiment production jobs).

✳ Remote Operation Center (ROC Dubna) for experiment running and taking shifts from JINR.

The DUNE experiment



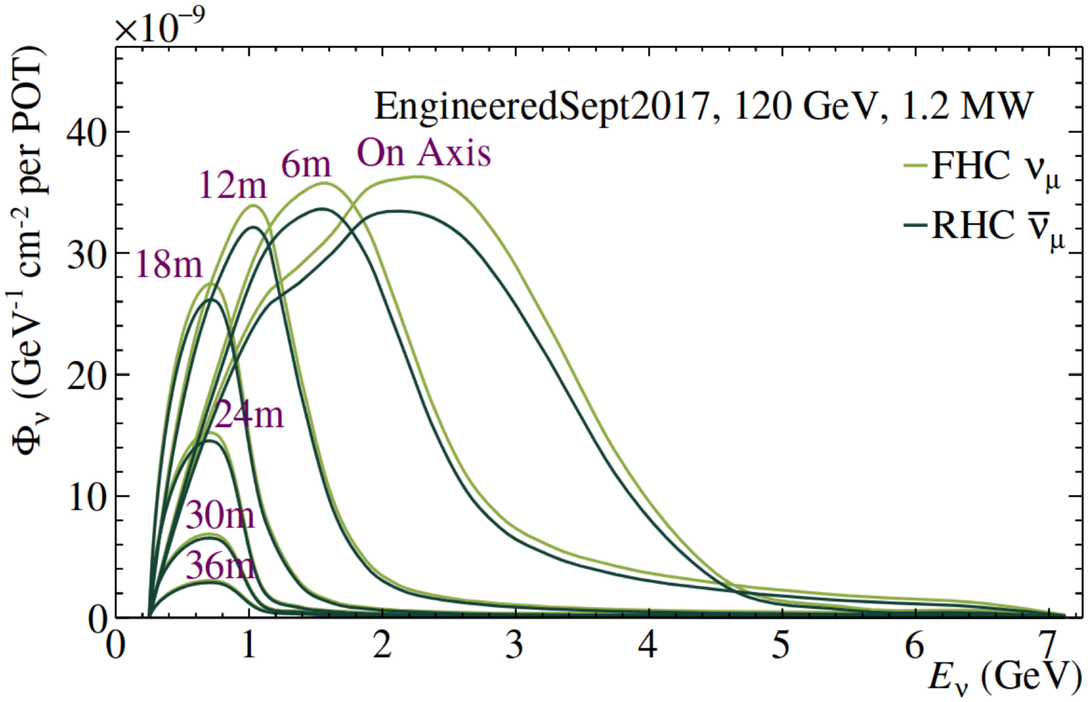
- 1400 collaborators from ~200 institutions and over 30 countries.

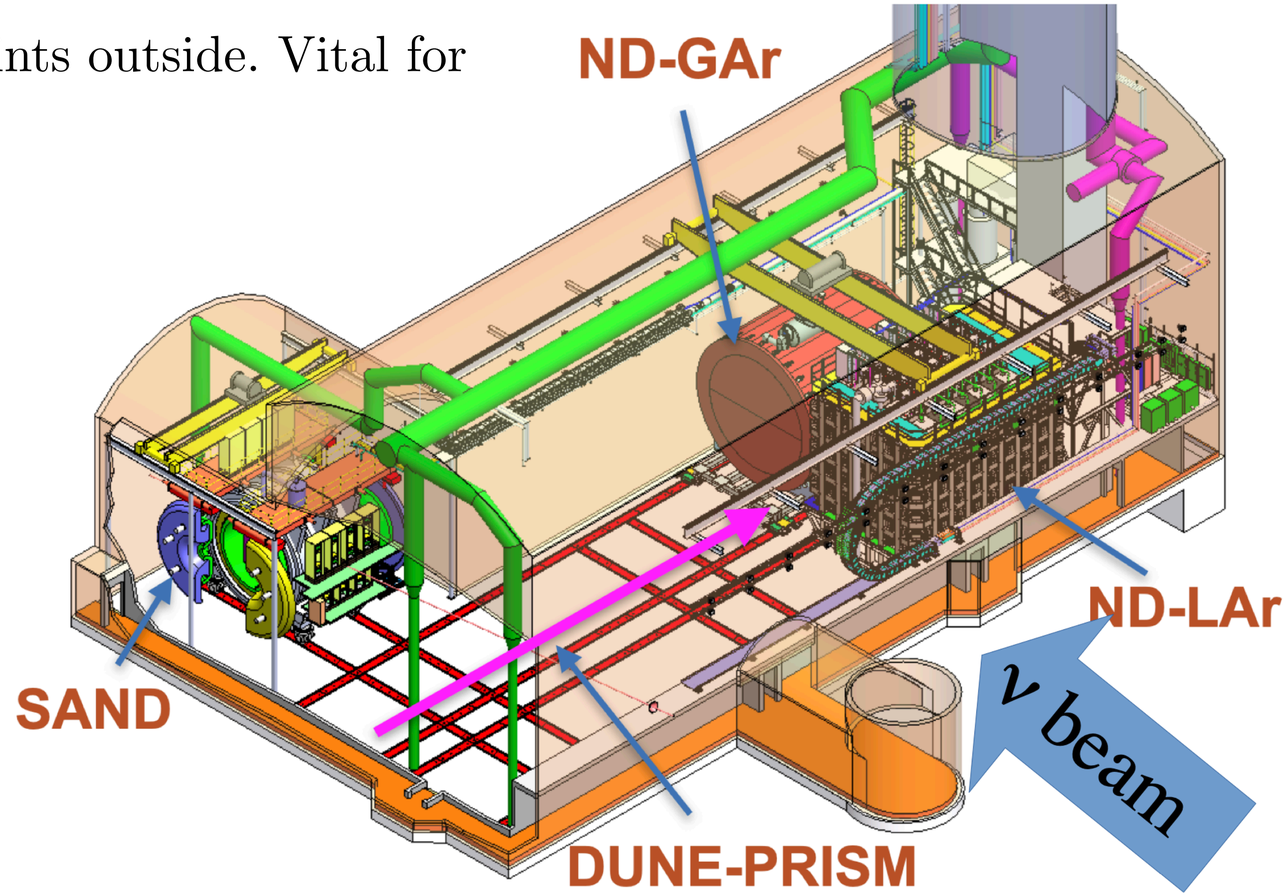
- DUNE will start ”in late 2020s” (this is official statement).
- Baseline 1300 km,
- δ_{CP} sensitivity, MO and all PMNS parameters.

- On-axis experiment;
- E at peak ~2.5 GeV;
- 70 kt FD LArTPC with single/dual phase under consideration;
- Start with 1.2 MW proton beam at 60-120 GeV (10^{20} POT/ year),
- up to 2.4 MW beam power by ~2035.

Near Detector complex

- ND complex with three detectors to scan the beam in the best possible way:
  - NDLAr
  - NDGAr (TMS at the beginning)
  - SAND
- Spend half of year on axis and half at several points outside. Vital for systematics control (DUNE-PRISM).





JINR contribution to DUNE

Detector related R&D

✳ NDLAr - light collection module development.
✳ SAND - straw-tube for STT tracker.

Physics based on previous experience

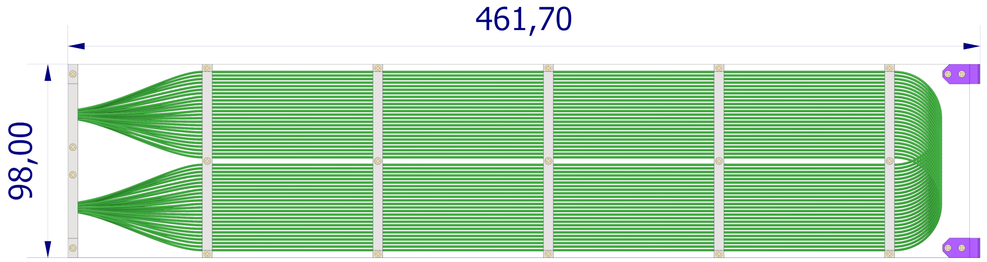
✳ Reconstruction in SAND, resonance and strange particles, beam monitoring.
✳ Physics with 2x2 prototype: cross sections, charged particle multiplicity etc
✳ Oscillation physics, DUNE-PRISM
✳ Transfer of NOvA exotics analyses

Computing

✳ 1k CPU (shared w/ NOvA), 0.7Pb storage + 0.5k CPU and 0.8Pb storage in the next three years

JINR CONTRIBUTION: NDLAr

JINR is working on complete light readout system (modules, Front-End electronics (preamplifiers), ADC, power supply system, signal/power lines, DAQ and Slow Control)

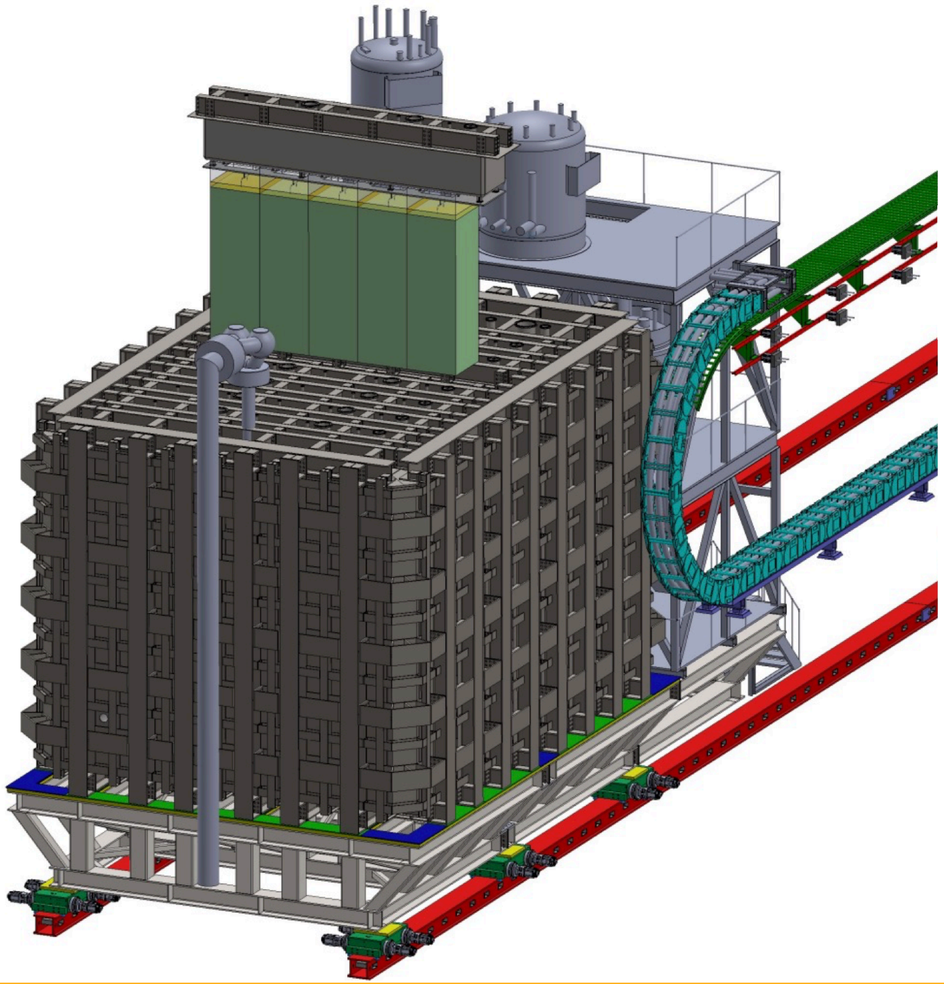


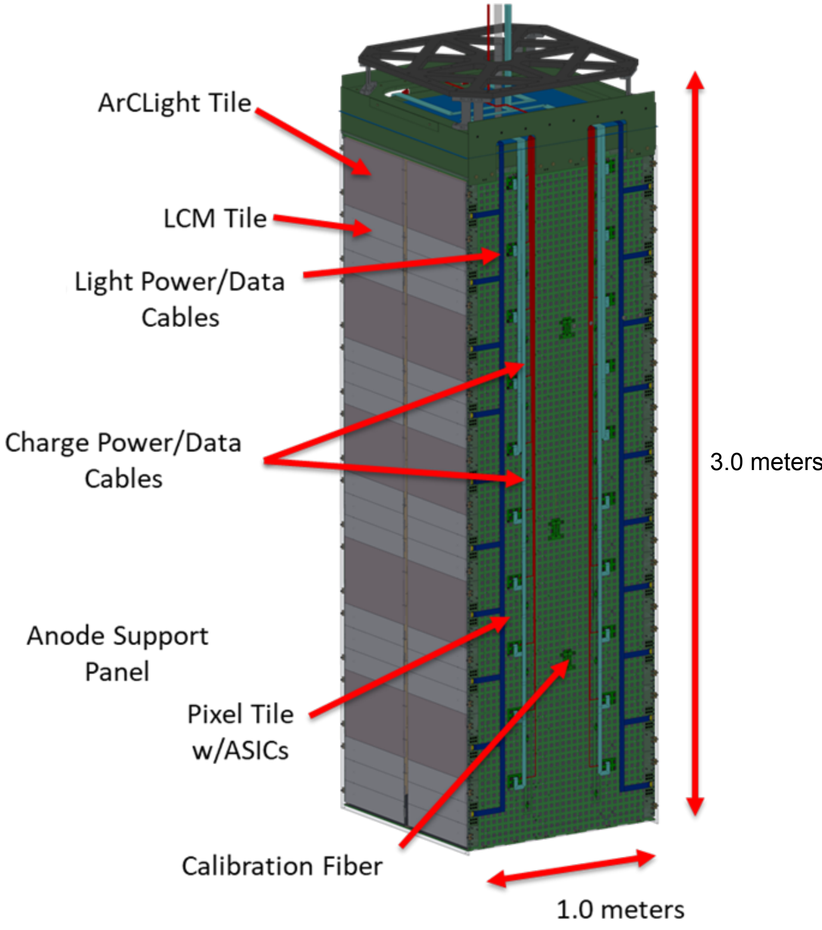
Tasks for this system:

- Provide t0-trigger for track correction
- Resolve pile-ups and associate tracks in time
- Assign detached energy events (~ns)

Prototypes:

- 2x2 at Fermilab with ν beam (2023-2024),
- full scale module (2024-2025).





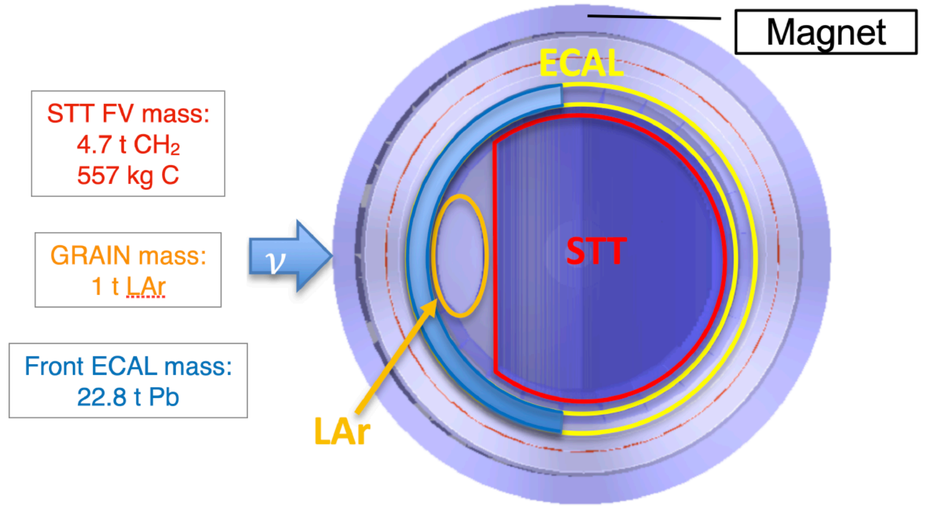
JINR CONTRIBUTION: SAND

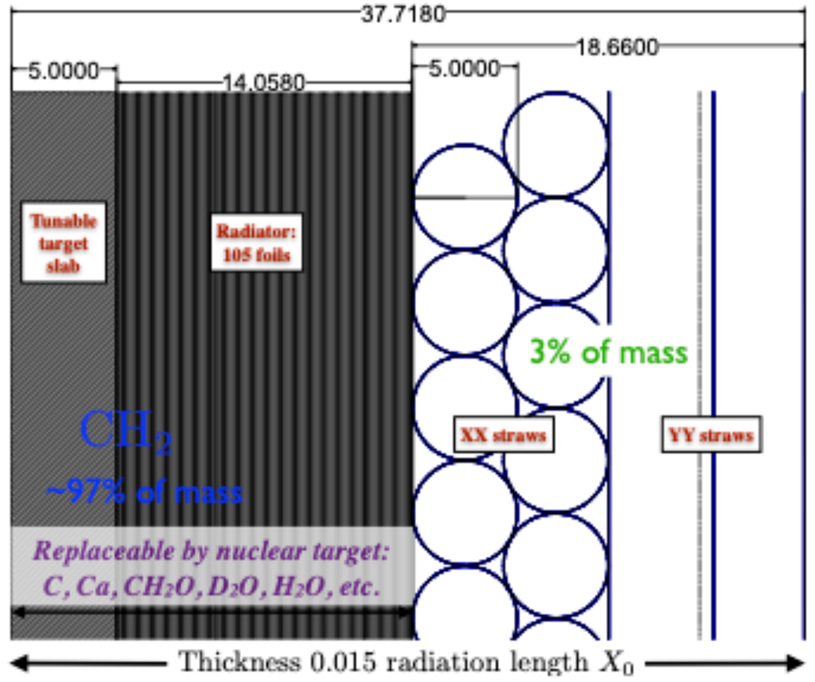
The primary goals of SAND:

- ✳ continuous monitoring of the event rates, beam profiles and spectra over time;
- ✳ precision in-situ flux measurements of all neutrino flavors initially present in the beam;
- ✳ constraining systematics from nuclear effects and related smearing

JINR group plans for 2023-2026:

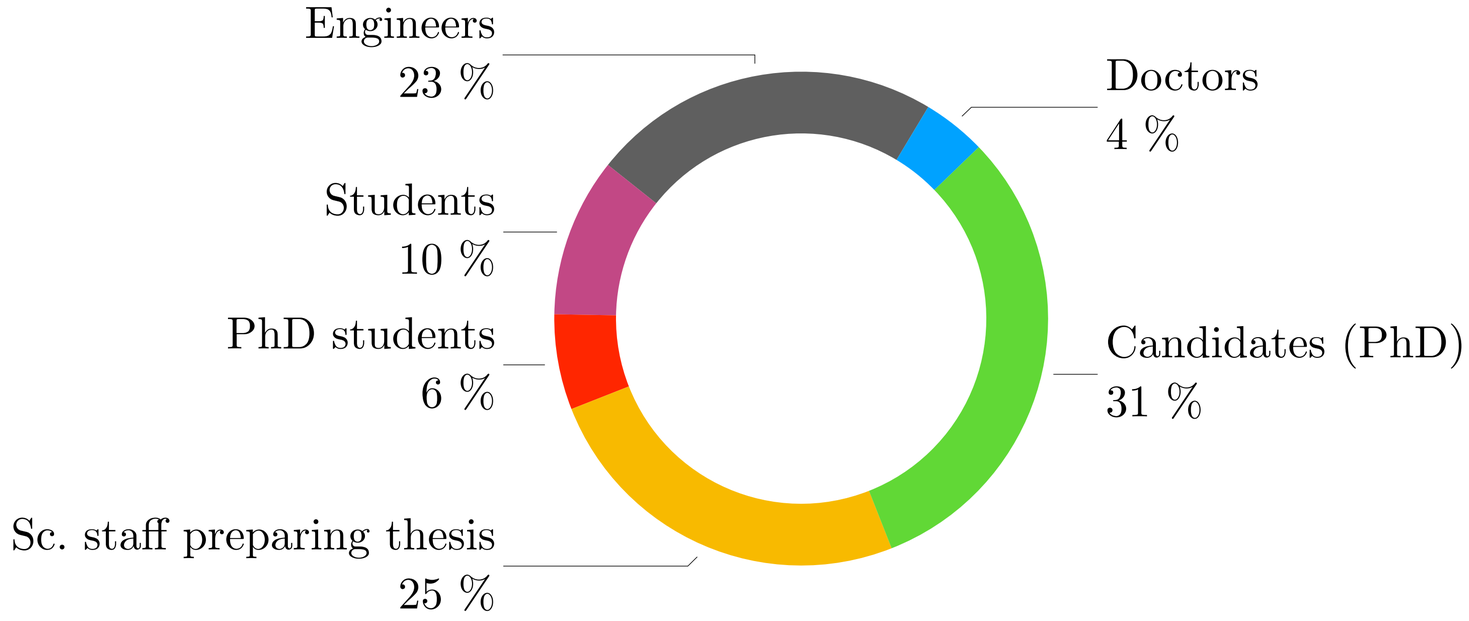
- ✳ 2023-2026: development of FE readout electronics including ASIC revision, testbeam exposure of small 0.35 m x 0.35 m prototypes at CERN to evaluate the performance of different FE readout options/prototypes
- ✳ 2024: assembly and test of full size prototype with one dimension of 4 m.

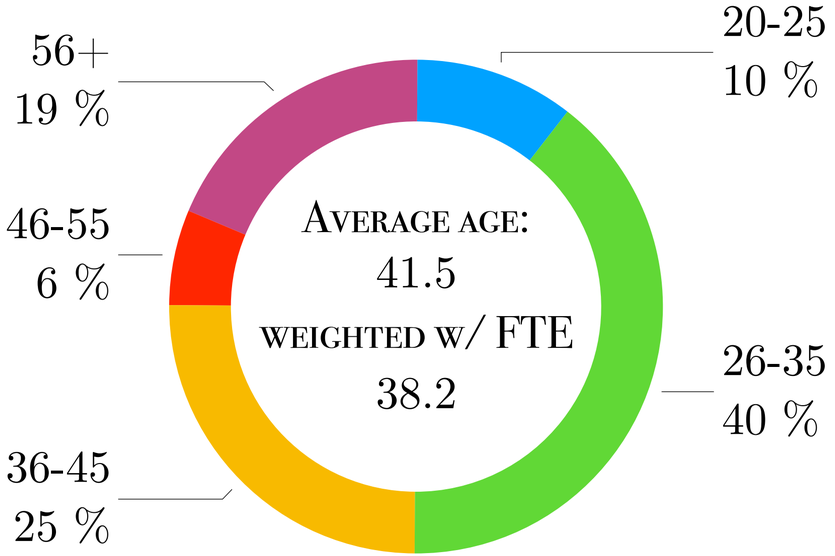




Project details: personnel & statistics

- 48 people from DLNP, VBLHEP, BLTP, MLIT with total FTE = 27.0 (0.56 FTE per group member)
- 5 management positions in NOvA and DUNE:
  - DUNE's light readout NDLAr (L3 manager),
  - NOvA's exotics co-convener,
  - NOvA's production co-convener,
  - NOvA's three-flavor analysis code review taskforce leader,
  - NOvA's executive committee member.





Project details: thesis, publications, reports

Over the last three years:

- 8 student's diploma were defended, 3 PhD thesis.

- JINR group members contributed significantly to 8 collaboration papers and, in addition, published 17 papers on NOvA/DUNE topics with small author list.
  - 15 papers in Q1-Q2 journals,
  - largest paper citations value is 116 (+ ∼50 per year).

- Conference presentations: 31
  - Posters: 6
  - Talks at parallel sessions: 21
  - Plenary talks: 4

- Internal collaboration talks: dozens per year from every actively working group member.

Project details: resources

Expenditures, resources, funding sources	Cost (thousands of US dollars)	Cost/Resources, distribution by years		
		1st year	2nd year	3rd year
International cooperation	540	180	180	180
Materials	350	130	110	110
Equipment and Third-party company services	140	60	40	40
Commissioning	30	10	10	10
R&D contracts with other research organizations	100	30	40	30
Software purchasing	60	20	20	20
Design/construction				
Service costs (planned in case of direct project affiliation)				
Resources required (standard-hours)				
Workshop and Design bureau	150	50	50	50
accelerator/installation				
reactor etc				
Budgetary resources				
JINR Budget	1220	430	400	390
Extra budgetary (supplementary estimates)				
Contributions by partners				
Funds under contracts with customers				
Other sources of funding				

Summary

✳ Neutrino physics is very exciting and rapidly developing area of high energy physics, with a good chance on fundamental discoveries. We have just entered a precision era for many directions.

✳ JINR has a long tradition and expertise of studying the wide scope of neutrino physics subjects, including oscillations that were proposed in Dubna.

✳ NOvA is a current experiment that will take data until 2026. It is producing interesting physics with JINR very noticeable participation in different analyses and detector studies. All contribution has been doing on existed JINR infrastructure.

✳ DUNE is a future neutrino mega-science project, next worldwide flagship that can finalize fundamental oscillation parameters measurement. The JINR involvement in both detector R&D and physics is very appreciated due to huge expertise in corresponding areas.

✳The NOvA/DUNE project is proposed to be extended for 2024-2026 to continue the JINR successful participation in NOvA and prepare for the future research in this area.

OVERFLOW SLIDES

	Helpful	Harmful
Internal	**STRENGTHS** ▸ Already fully operational NOvA experiment ▸ Approved NOvA running until 2026 and changeover to DUNE ▸ Tested and confirmed DUNE ND-LAr modules approach (approved at PDR level) ▸ JINR responsibility for two major subsystems in DUNE ND (Light detection, Straw-tracker) ▸ Rich non-oscillation program	**WEAKNESSES** ▸ Systematic error sources depending on unknown cross-sections and detector features ▸ Late DUNE start >2031 ▸ Restrictions for Russian fellows to enter DOE laboratories ▸ Export/Import restrictions in the Russian Federation.
External	**OPPORTUNITIES** ▸ Supernova burst, new physics existence ▸ Systematic errors reduction due to new measurements or theory improvement ▸ Development of new methods and technologies ▸ World's best management standards	**THREATS** ▸ Major accident with detectors or beam hardware ▸ Unexpected change of Fermilab plans due to significant budget cuts ▸ Major changes in the world situation

Computing resources	**Distribution by year**		
	1st year	2nd year	3rd year
Data storage (TB) - EOS - Tapes	1 PB (Cloud)	1.3 PB (Cloud)	1.5 PB (Cloud)
Tier 1 (CPU core hours)	0	0	0
Tier 2 (CPU core hours)	0	0	0
SC Govorun (CPU core hours) - CPU - GPU	0	0	0
Clouds (CPU cores)	1000	1250	1500

No	Category of personnel	Full name	Division	Position	Amount of FTE
1.	research scientists	Alexander Olshevsky	DLNP	Head of Department, Project leader	0.6
2.	research scientists	Nikolay Anfimov	DLNP	Head of sector (deputy)	0.5
3.	research scientists	Oleg Samoylov	DLNP	Head of sector (deputy)	0.8
4.	research scientists	Temur Enik	VBLHEP	Head of group	0.3
5.	research scientists	Sergey Movchan	VBLHEP	Head of sector	0.3
6.	research scientists	Georgy Kekelidze	VBLHEP	Head of sector	0.2
7.	research scientists	Artem Chukanov	DLNP	Senior researcher, PhD	0.5
8.	research scientists	Vyacheslav Tchalyshev	DLNP	Senior Researcher, PhD	0.5
9.	research scientists	Anastasia Bolshakova	DLNP	Researcher, PhD	0.5
10.	research scientists	Liudmila Kolupaeva	DLNP	Researcher, PhD	1.0
11.	research scientists	Alexander Antoshkin	DLNP	Researcher	0.9
12.	research scientists	Oleg Klimov	DLNP	Researcher	1.0
13.	research scientists	Olga Petrova	DLNP	Researcher	1.0
14.	research scientists	Arseniy Rybnikov	DLNP	Researcher	0.3
15.	research scientists	Alexander Selyunin	DLNP	Researcher	0.7
16.	research scientists	Vladislav Sharov	DLNP	Researcher	0.4
17.	research scientists	Andrey Sheshukov	DLNP	Researcher	0.8
18.	research scientists	Dmitry Shkirmanov	DLNP	Researcher	1.0
19.	research scientists	Svetlana Vasina	DLNP	Researcher	0.5
20.	engineers	Vasily Gromov	DLNP	Leading engineer	0.5
21.	engineers	Sergei Sokolov	DLNP	Senior engineer	0.6
22.	engineers	Vladimir Kozhukalov	DLNP	Engineer	1.0
23.	engineers	Ksenia Kuznetsova	DLNP	Engineer	0.5
24.	engineers	Dmitry Fedoseev	DLNP	Electronics engineer (1st class)	0.5

25.	engineers	Alexey Chetverikov	DLNP	Electronics engineer (2nd class)	0.5
26.	engineers	Albert Sotnikov	DLNP	Electronics engineer (1st class)	0.2
27.	PhD student	Anastasia Kalitkina	DLNP	Engineer (Associated)	1.0
28.	PhD student	Anna Morozova	DLNP	Engineer (Associated)	1.0
29.	Master student	Yuriy Ivaneev	DLNP	Associated	1.0
30.	Master student	Alexandra Ivanova	DLNP	Senior Laboratory Assistant (Associated)	1.0
31.	Master student	Anna Stepanova	DLNP	Senior Laboratory Assistant (Associated)	1.0
32.	Bachelor student	Petr Lensky	DLNP	Associated	1.0
33.	research scientists	Aleksander Kolesnikov	DLNP	Researcher	0.2
34.	research scientists	Aliaksei Paulau	DLNP	Researcher	0.1
35.	research scientists	Dosbol Baygarashev	VBLHEP	Researcher	0.2
36.	research scientists	Kirill Salamatin	VBLHEP	Researcher, PhD	0.2
37.	research scientists	Yerzan Mukhamedzha nov	VBLHEP	Researcher, PhD	0.2
38.	research scientists	Yury Kovalev	VBLHEP	Researcher, PhD	0.4
39.	engineers	Evgenya Vasilieva	VBLHEP	Engineer	0.2
40.	engineers	Nikolay Azorsky	VBLHEP	Engineer	0.2
41.	engineers	Vitaly Bautin	VBLHEP	Electronics engineer	0.2
42.	PhD student	Ismail Kambar	VBLHEP	Engineer (Associated)	0.2
43.	research scientists	Igor Kakorin	BLTP	Researcher, PhD	1.0
44.	research scientists	Konstantin Kuzmin	BLTP	Researcher, PhD	0.5
45.	research scientists	Victor Matveev	BLTP	Scientific Leader of JINR, Academician of RAS	0.1
46.	research scientists	Vadim Naumov	BLTP	Researcher, PhD	0.5
47.	engineers	Nikita Balashov	MLIT	Senior engineer	0.2
48.	Master student	Nikita Shirokov	DLNP	Associated	1.0
	Total:				**27.0**