Project “Studying neutrino properties in accelerator experiments”

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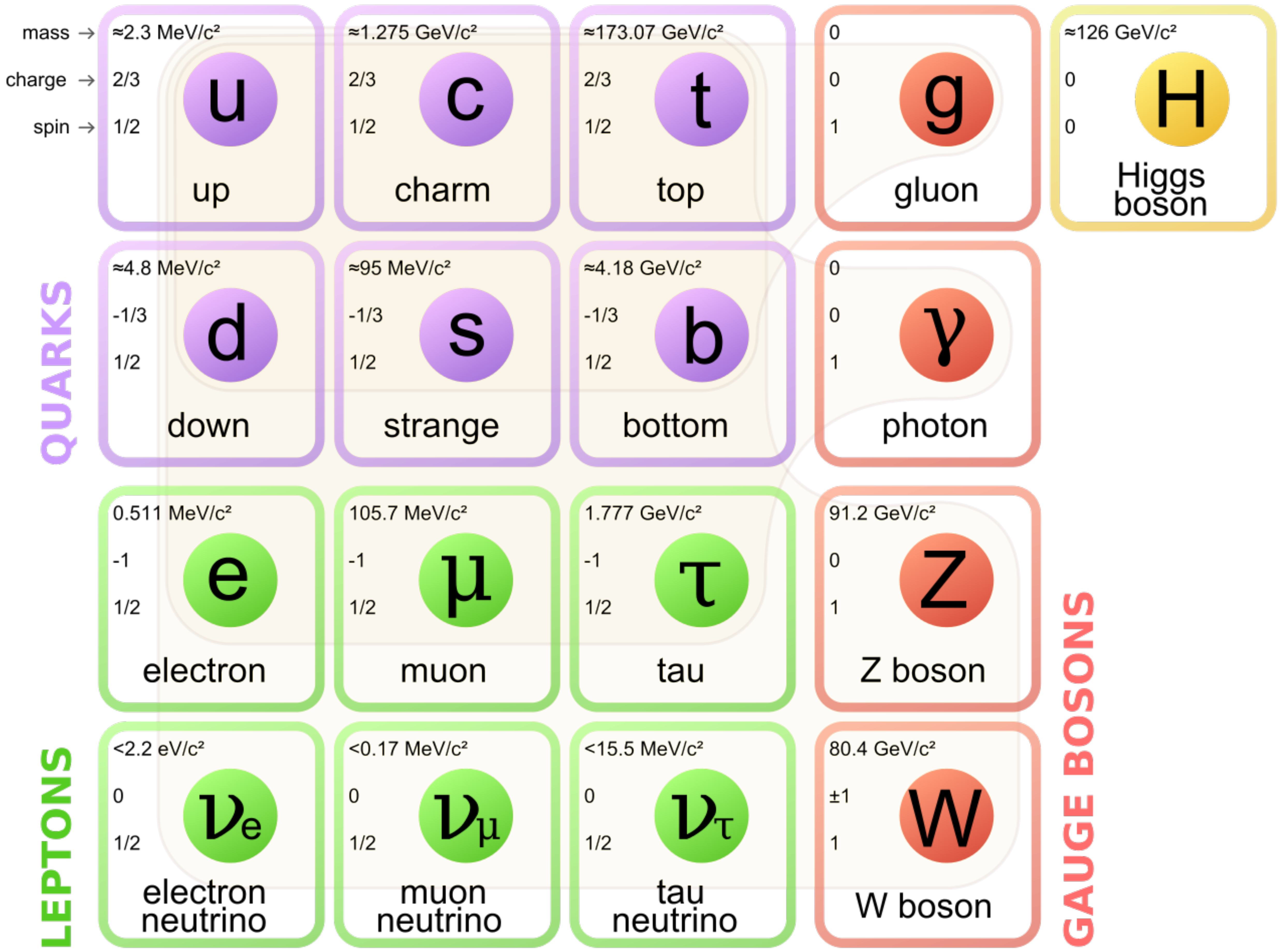
JINR PAC

Neutrino physics

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

Modern hot topics:

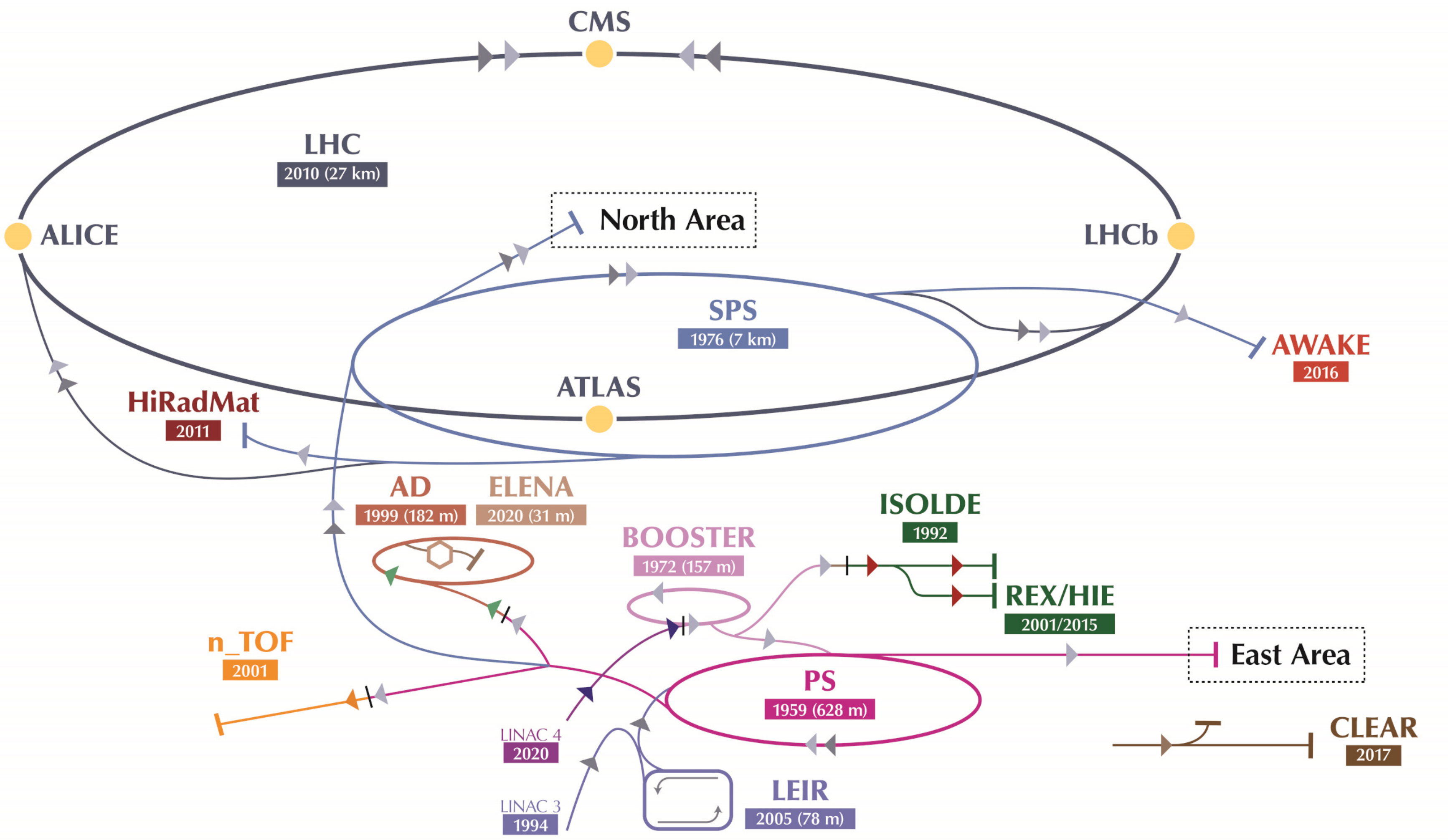
- Study neutrino properties, incl. three-flavor oscillation parameters;
- search for sterile neutrinos;
- measurement of absolute neutrino masses,
- search for neutrinoless double beta-decay (are neutrinos Dirac or Majorana particles);
- detection of relic neutrinos;
- detection of high energy astrophysical neutrinos and spotting their sources;
- ...



Accelerator neutrino beams

- ✴ Artificial source of particles
- ✴ Allows a good control of beam characteristics to emphasise sensitivity to target parameters
  - ✴ Focused and intense beam with timing information to reduce backgrounds
  - ✴ Can choose energy to work with and switch between neutrinos and antineutrinos (important for study of oscillations)

- ✴ NOvA and T2K work with decay in flight neutrinos (p beam and fixed target to produce the flux)
- ✴ FASER work with decay in flight neutrinos produced at ATLAS p+p collision point
- ✴ DsTau is a beam dump experiment



Neutrino oscillations and mixing

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:

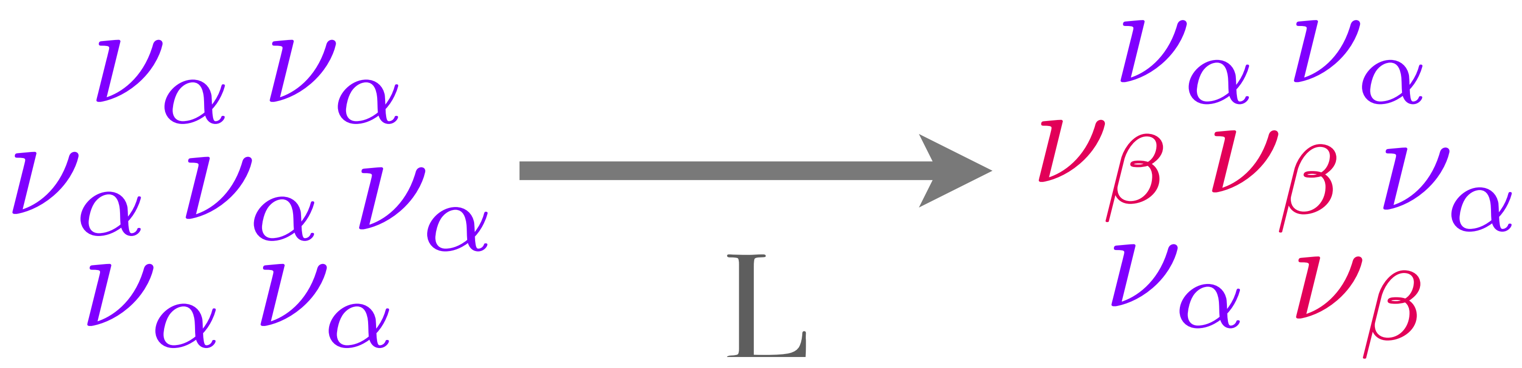
$\theta_{12} \approx 34^\circ$ (4.4%)

$\theta_{23} \approx 49^\circ$ (5.2%)

$\theta_{13} \approx 9^\circ$ (3.8%)

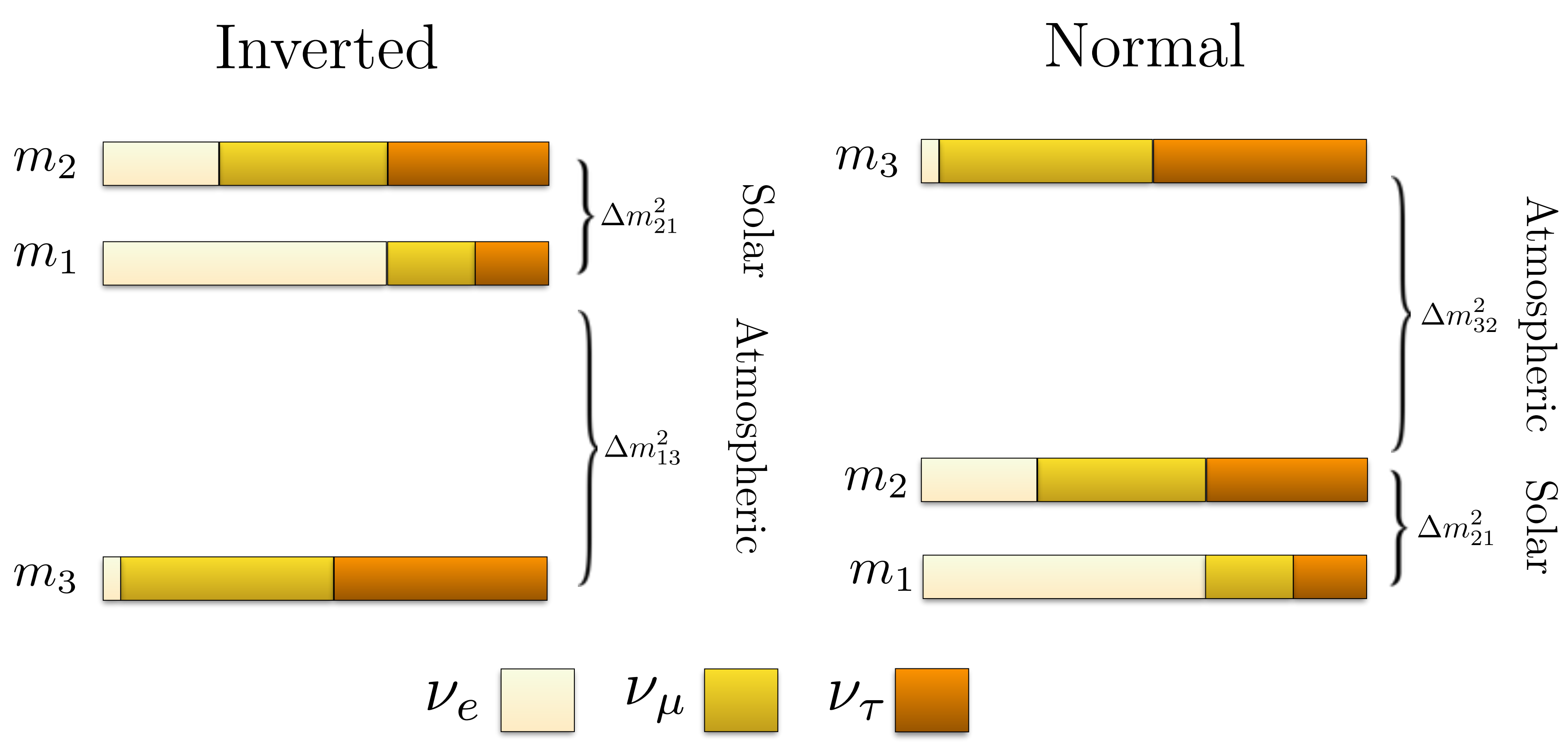
$\Delta m^2_{21} \approx 7.4 \times 10^{-5}\ \mathrm{eV}^2$ (2.2%)

$\Delta m^2_{32} \approx +2.5 \times 10^{-3}\ \mathrm{eV}^2$ (1.4%)



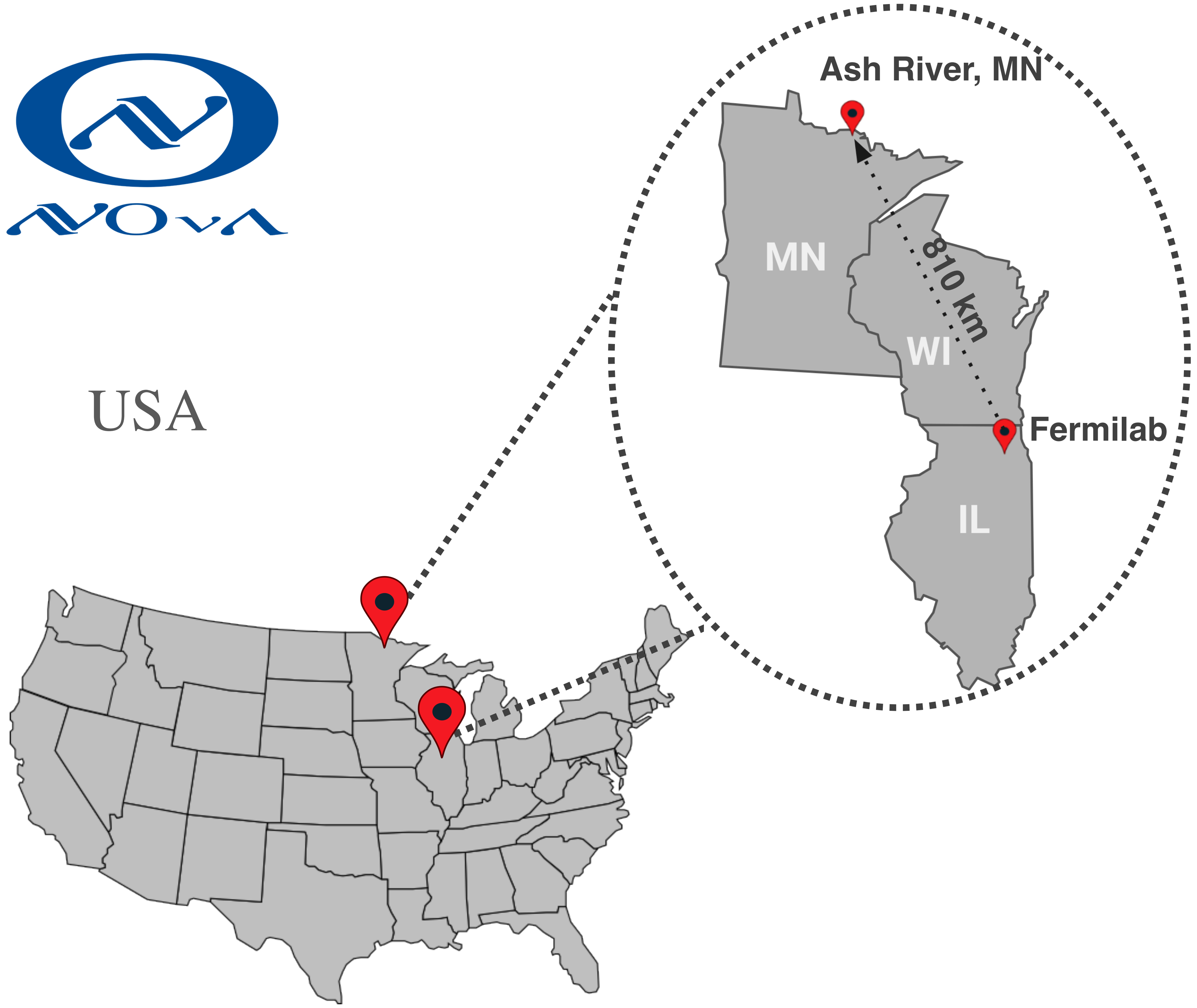
Open questions:

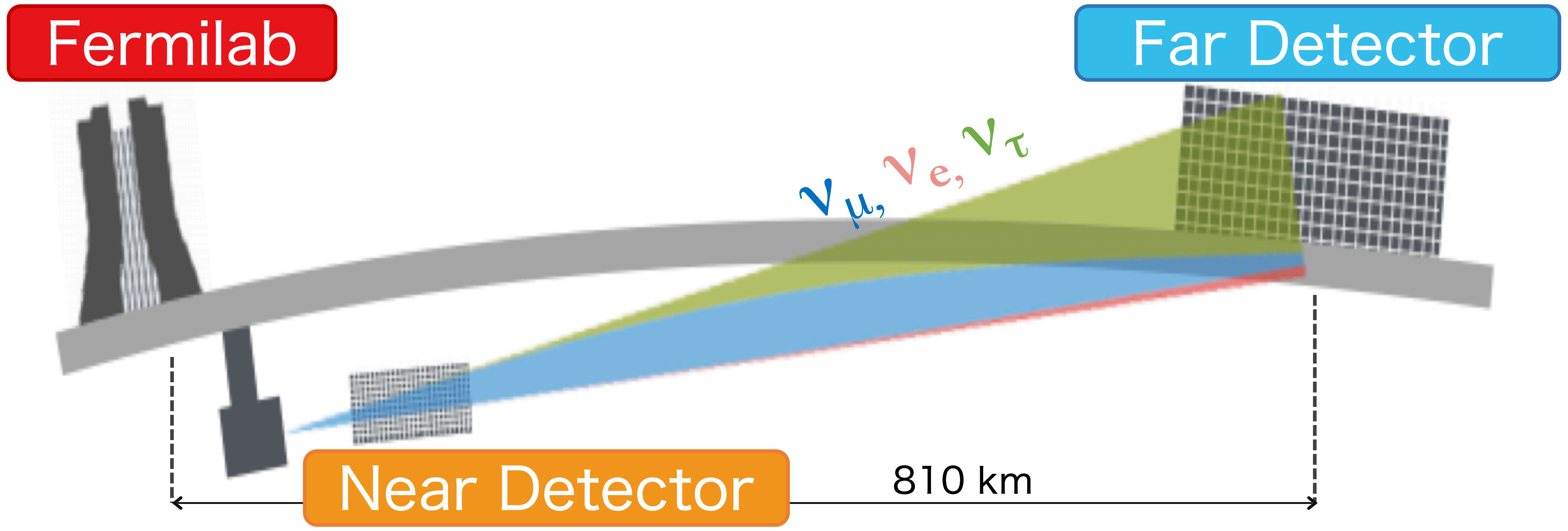
- ✳ Is θ_{23} 45°? (possible ν_μ and ν_τ symmetry in ν_3)
- ✳ Is there CP violation in lepton sector? (matter-antimatter asymmetry of the Universe (leptogenisis)
- ✳ Neutrino mass hierarchy (ordering) is Normal or Inverted? (neutrinoless double beta-decay searches, supernova simulations, relic neutrinos searches, absolute ν mass measurements etc)



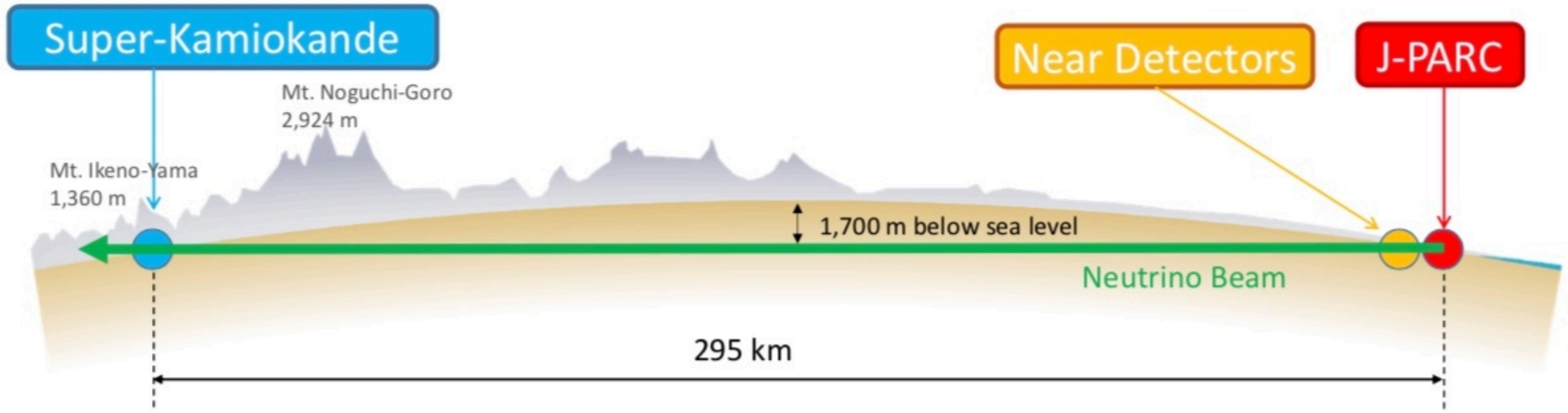
NOvA and T2K

USA





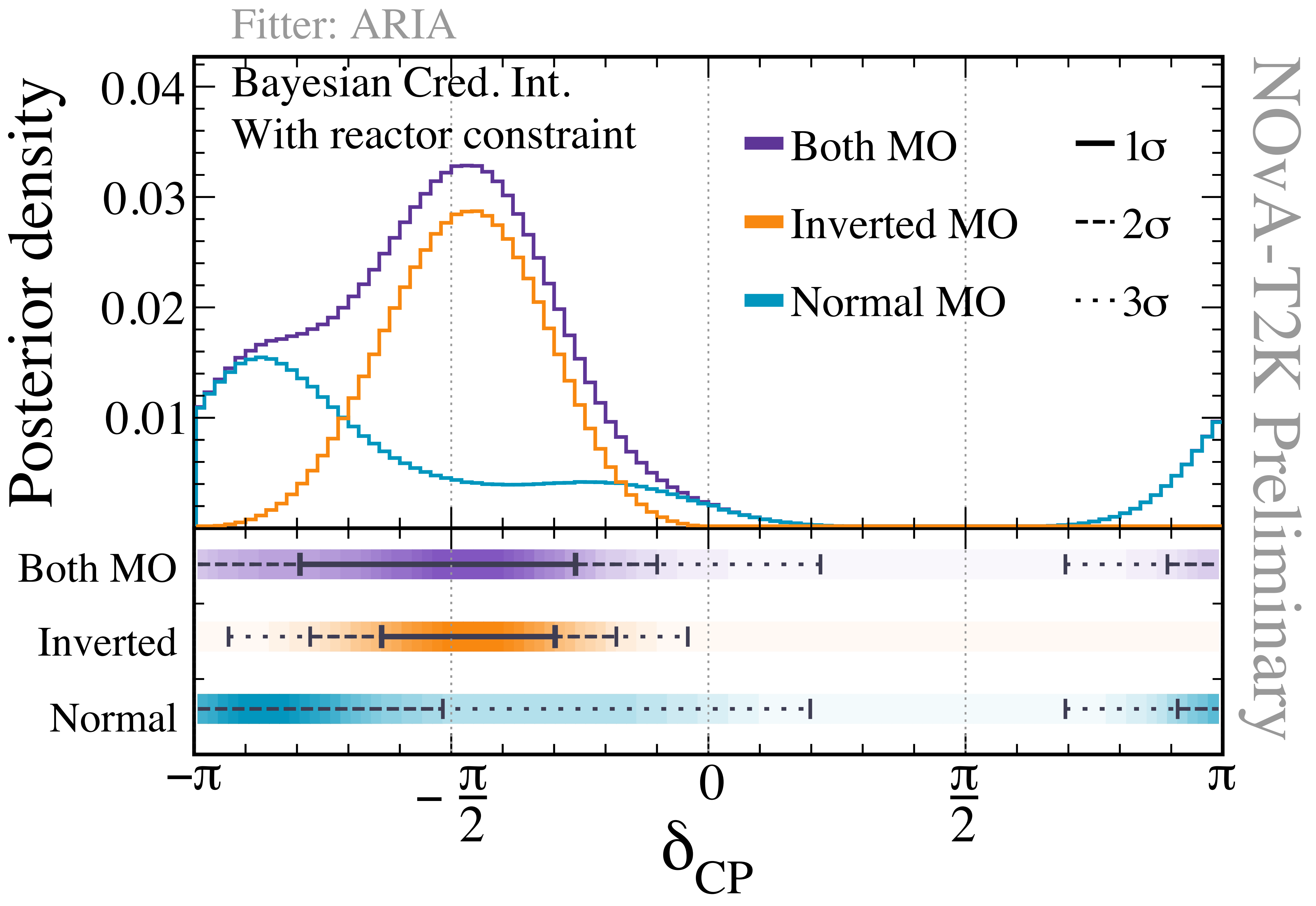
Japan



NOvA + T2K

Based on latest published analyses

- ✴ Full implementation of:
  - ✴ energy reconstruction and detector response;
  - ✴ detailed likelihood from each experiment;
  - ✴ consistent statistical inference across the full dimensionality.
- ✴ In-depth review of:
  - ✴ models, systematic uncertainties and possible correlations.
  - ✴ different analysis approaches driven by contrasting detector designs.
    - ✴ As a by-product: cross-check and review of each other analyses.
- ✴ Result:
  - ✴ More precise measurement of oscillation parameters if compare to individual results
    - ✴ Strong constraint on Δm^2_{32}, strongly favour CP violation in IO.
  - ✴ Firm foundation for further NOvA+T2K analyses



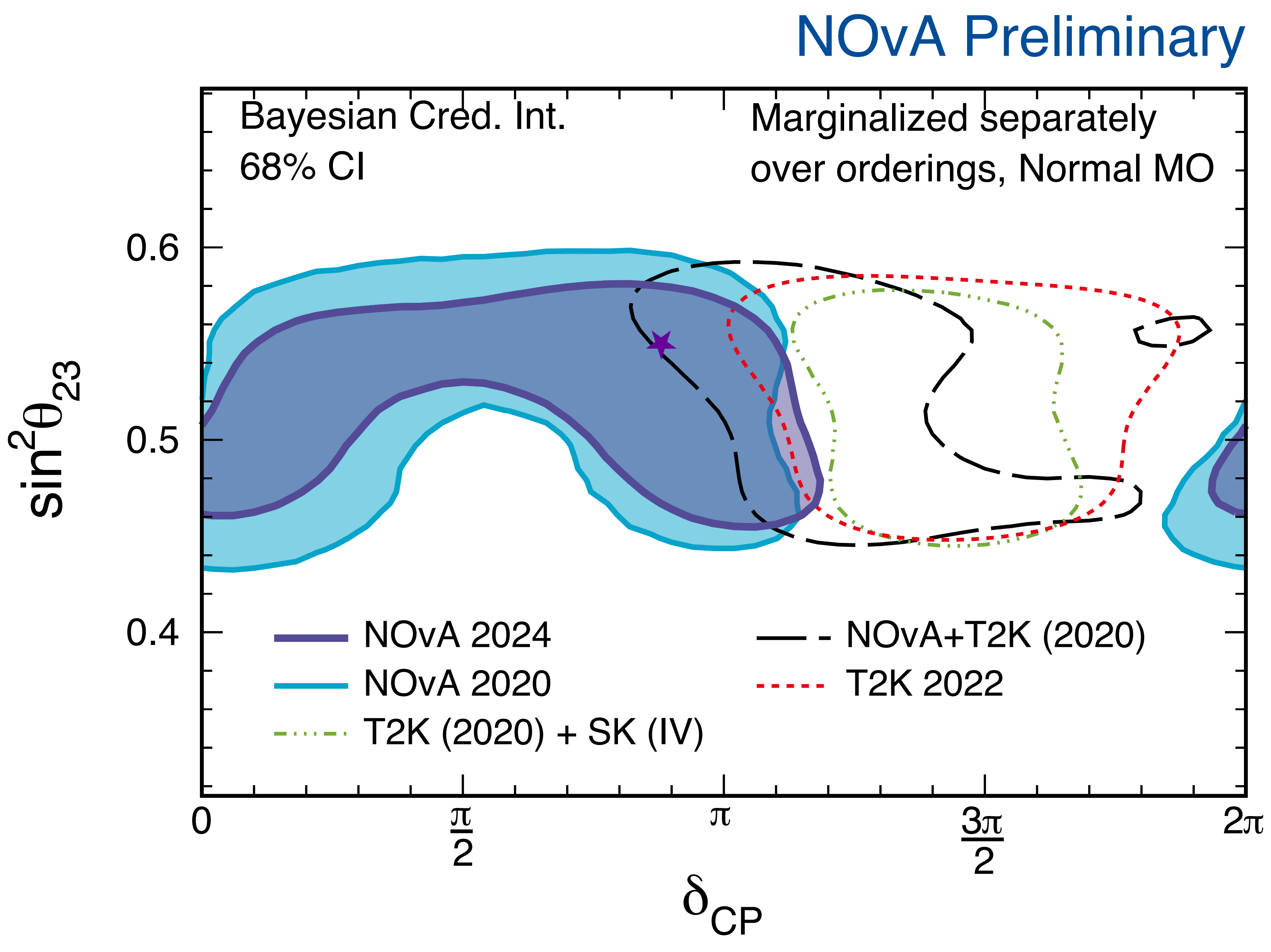
Publication prepared for Nature is under review by both collaborations

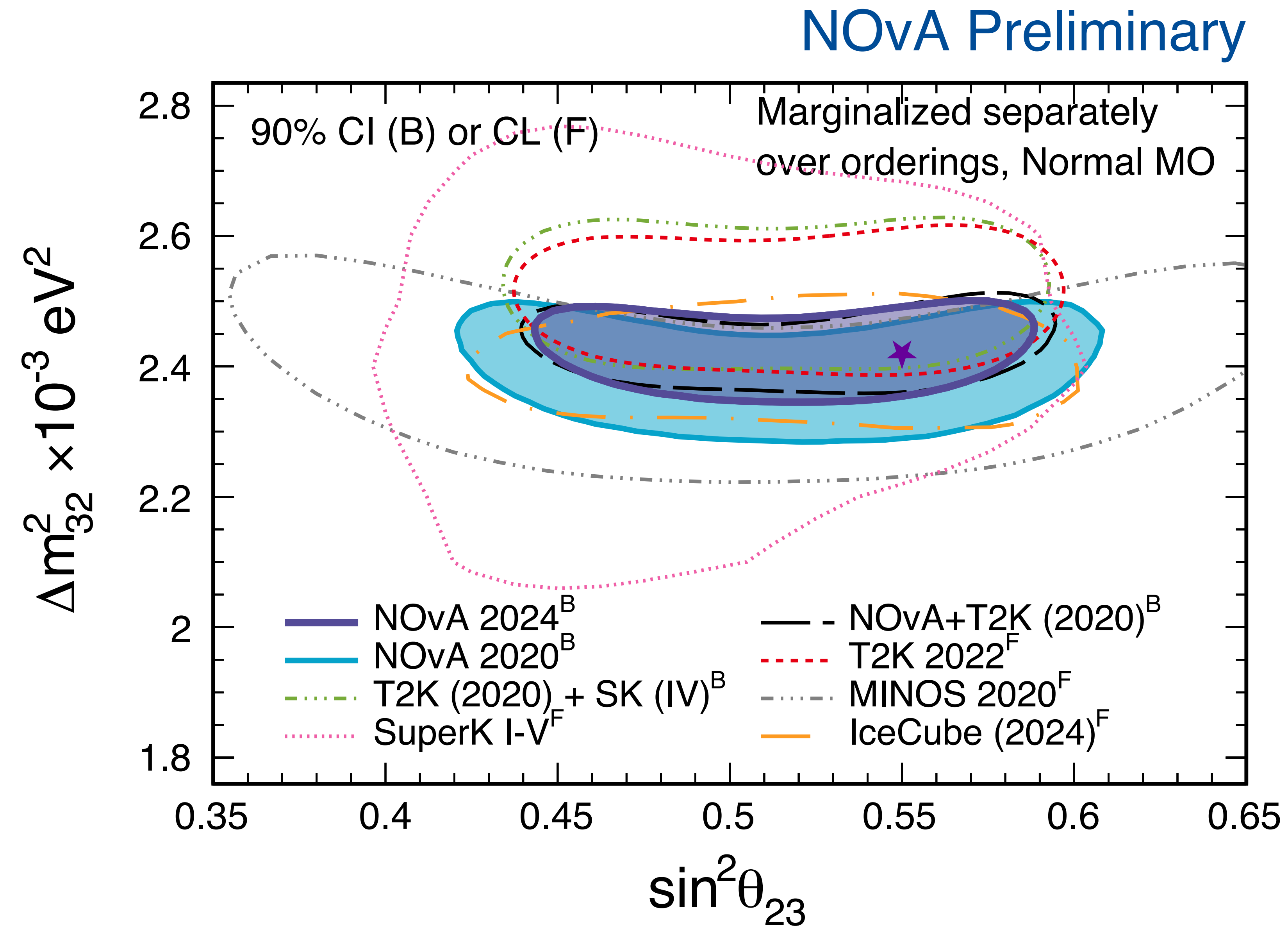
NOvA results

Recent 2024 results

- NOvA's first large update since 2020
  - Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data.
    - World's largest accelerator ν sample
  - Various remarkable updates to the analysis procedures.
- As a result:
  - Most precise single-experiment measurement of Δm^2_{32} (1.5%).
  - Results are consistent with previous analysis.
  - Data favours region where matter, CP violation effects are degenerate.
  - Reactor constraint on Δm^2_{32} enhances Normal Ordering preference.

Publication prepared for PRL is under review by paper review committee of the NOvA experiment





JINR contribution

NOvA

- Three-flavor oscillation analysis,
  - including NOvA-T2K joint analysis effort,
- supernova neutrino trigger and analysis development,
- magnetic monopole search,
- high-energy muon spectra,
- atmospheric neutrino oscillations,
- theory of neutrino interactions.

FTE: 10.5

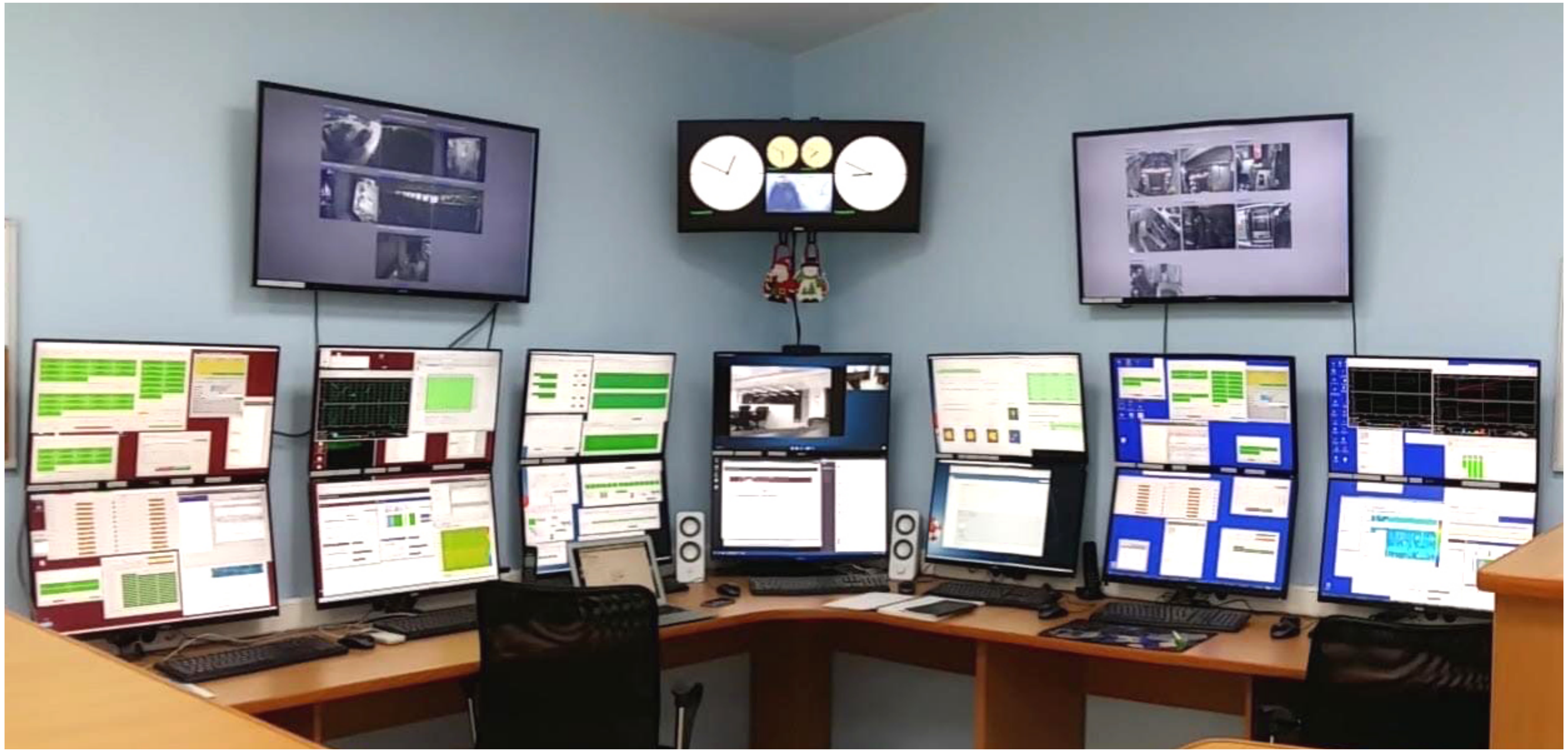
T2K:

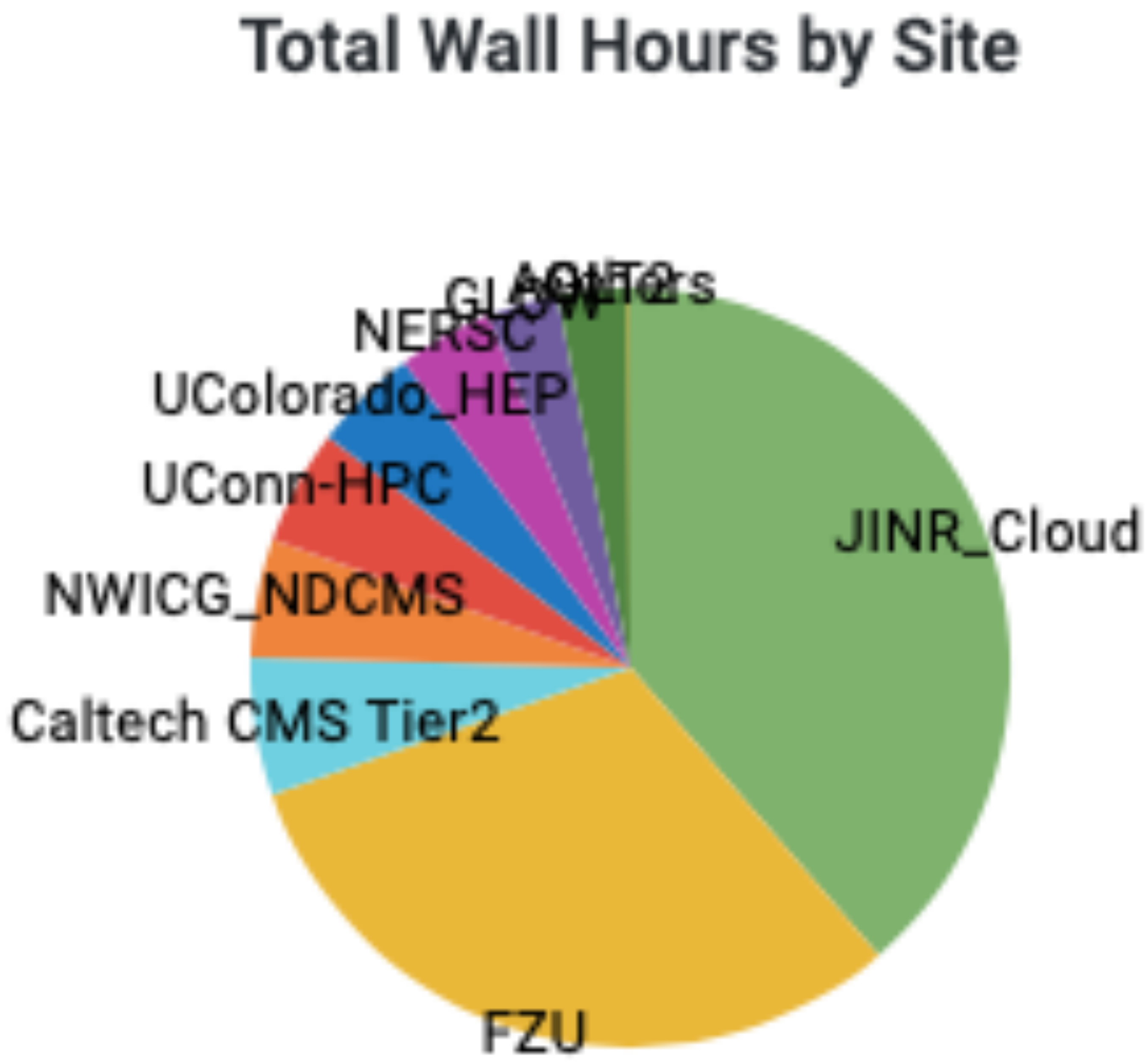
- Search for axion-like particles,
- systematic uncertainties evaluation,
- ND280 Machine Learning group,
- theory of neutrino interactions.

FTE: 6.7

For both experiments there was methodical contribution in the past

Infrastructure at JINR





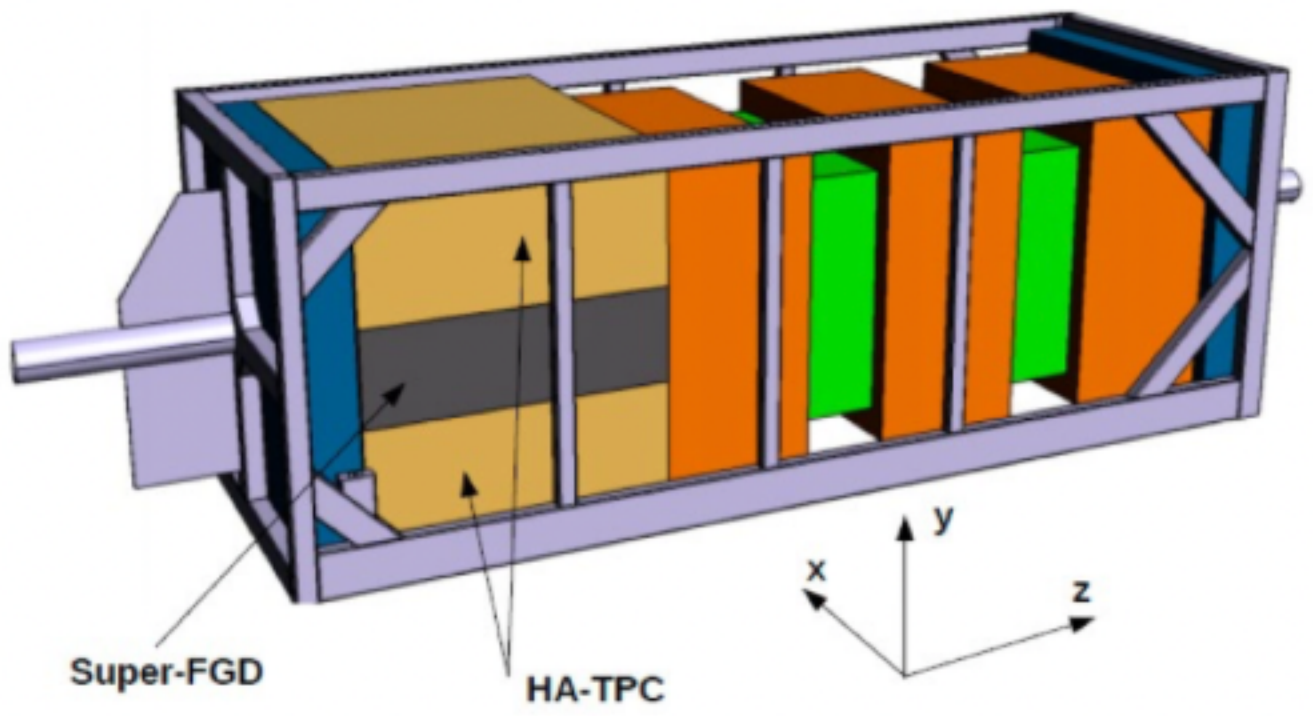
- Computing: 1k CPU and 3.8 PB storage (group needs + experiment production jobs).
- Remote Operation Center (ROC Dubna) for experiment running and taking shifts from JINR.

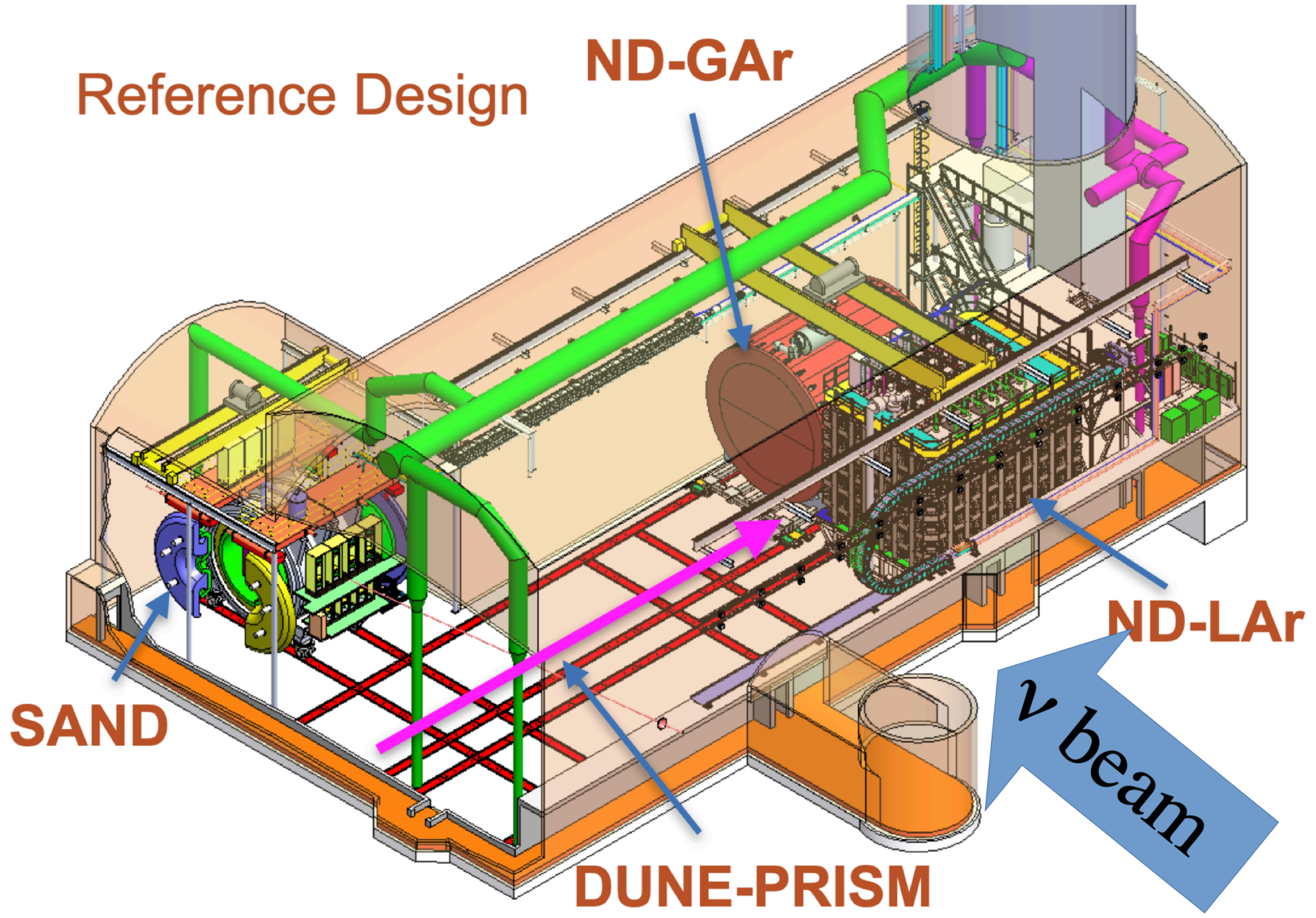
Future prospects in three-flavor oscillations

DUNE and HyperK

JINR already made methodical contribution to the experiments:

- ✳ HyperK:
  - ✳ SuperFGD optical studies and calibrations.
    - ✳ Result: detector is collecting data as phase II of T2K
- ✳ DUNE:
  - ✳NDLAr: complete light readout system (modules, Front-End electronics (preamplifiers), ADC, power supply system, signal/power lines, DAQ and Slow Control)
    - ✳Results: 2x2 prototype at Fermilab, full scale module
  - ✳SAND: straw-tubes's R&D studies at CERN to evaluate the performance of different FE readout options/prototypes



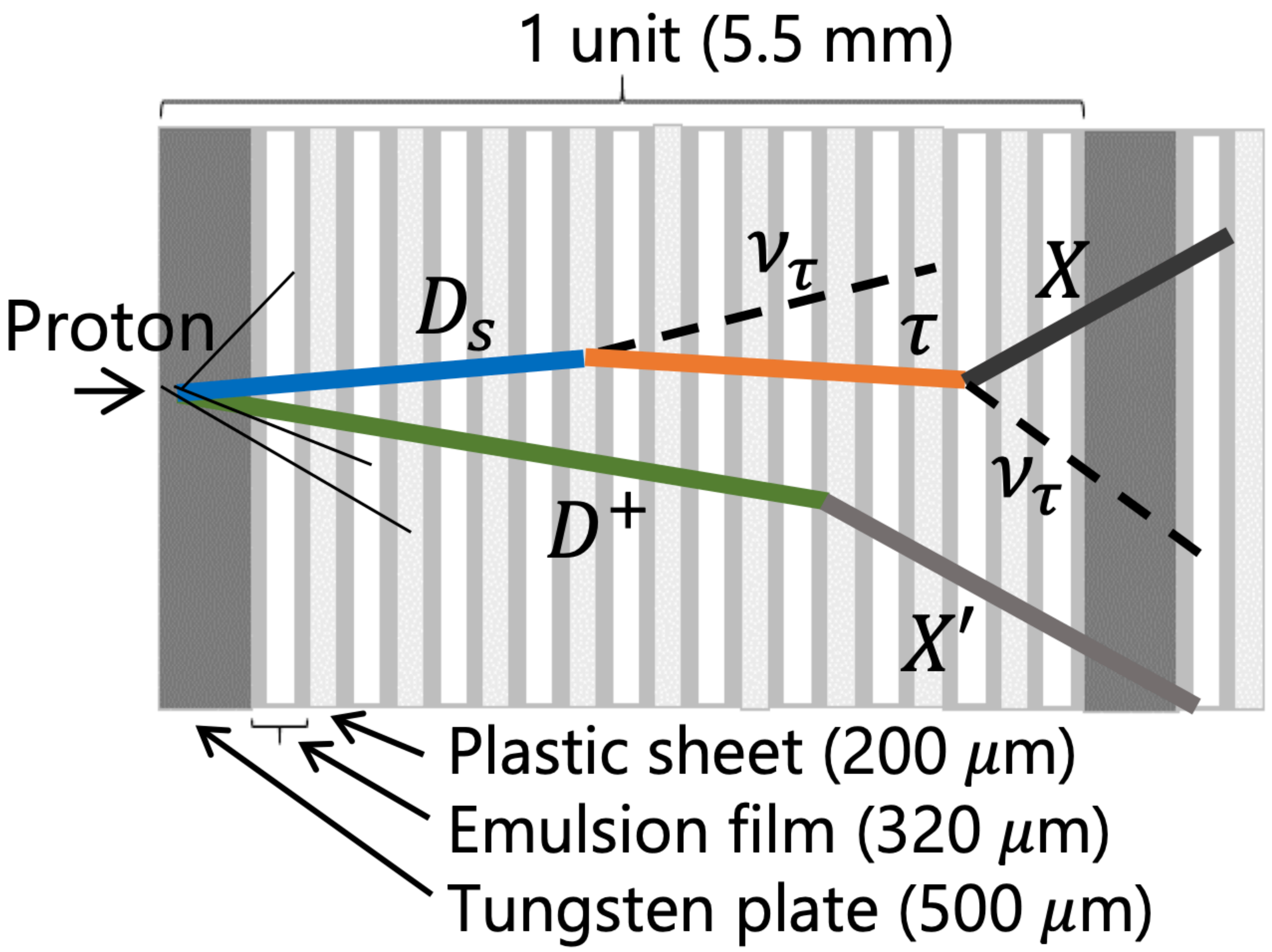


Official participation of JINR is not confirmed neither in DUNE nor in HyperK

DsTau and FASER

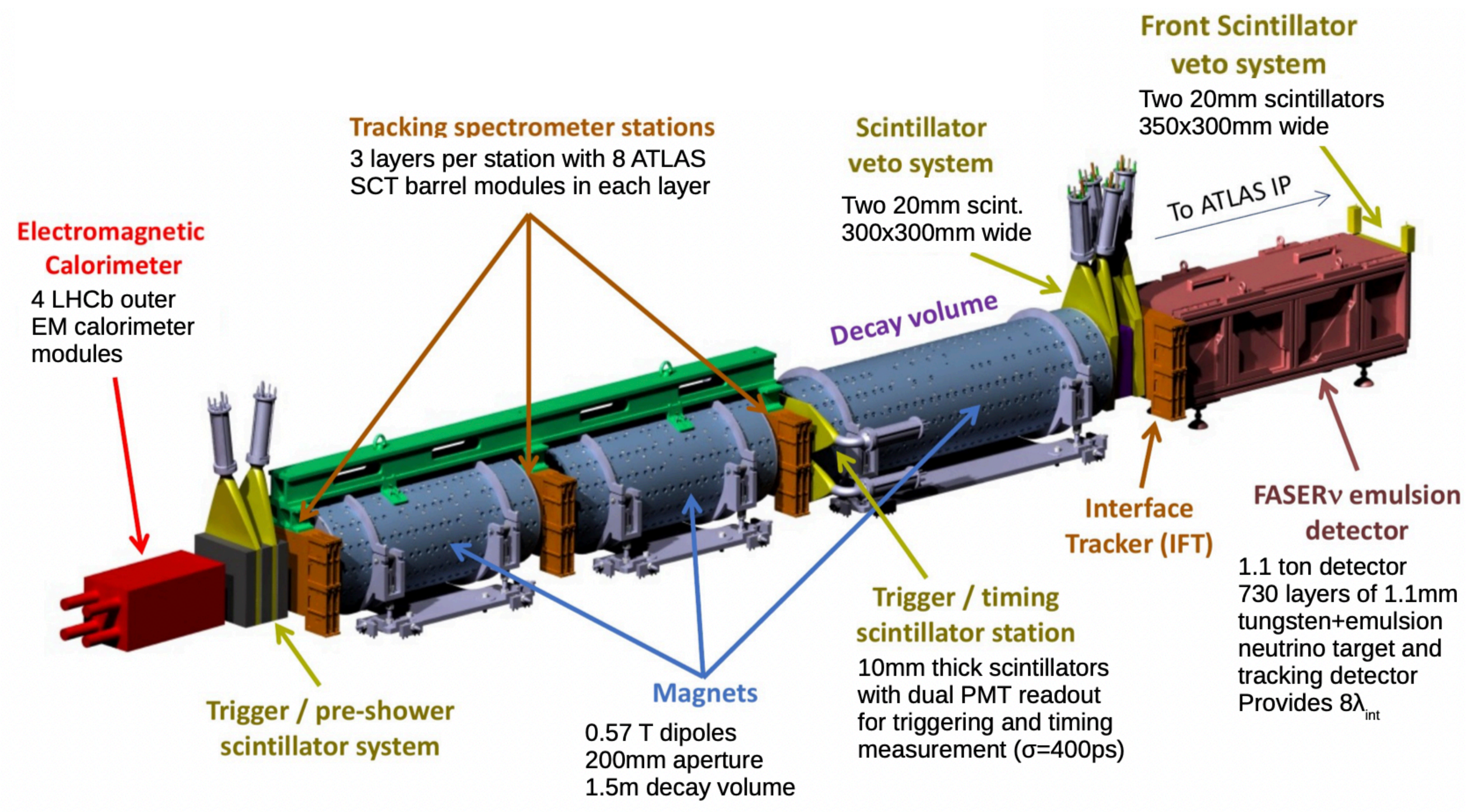
DsTau (NA65), SPS

- ✳ Main goal of DsTau is ν_τ production cross-section measurement (to be reduced to ~10%)
  - ✳ contribution to SHiP neutrino program, FASER and SND
  - ✳ huge systematics for ν_τ flux prediction.
- ✳ Emulsion detector (big experience of JINR group in this technology)



FASER(ν)

- ✳ Located 480m from ATLAS interaction point
- ✳ Designed to detect neutrinos and search of dark photons
- ✳ 100's GeV - few TeV scale energies
  - ✳ First ever ν cross-section measurements at these energies
  - ✳ Can measure all neutrino flavors → can increase the number of reconstructed ν_τ's in the world (so far ~dozen)



JINR contribution to FASER and DsTau

Physics

✳ Data collection and analysis (data simulation and distributed data mass processing responsibility)
✳ Development of new software for effective very high track density data analysis as well as the physics analysis.

Detector related

✳ R&D of electromagnetic calorimeter for FASER

FTE: 6.5

Complementarity and synergy

From the JINR contribution to these experiments point of view

NOvA and T2K:

- The presence of experts in the elements of NOvA and T2K data analysis at JINR can play a synergetic role even with ban on simultaneous participation in both experiments:
  - Three-flavor oscillations analysis
  - NOvA and T2K joint analysis (previously participation was on NOvA side)
  - Neutrino interaction cross-section model tuning for better understating the systematics and proper unification in analyses these models should be reviewed coherently in both experiments
  - Search for exotic objects and non-standard interactions

FASER and DsTau:

- Both experiments are aimed at studying various aspects of the production and interaction of tau neutrinos using the nuclear photoemulsion technique

FASER and T2K:

- SuperFGD technique is already used at T2K and also considered for the next upgrade of FASER, so, experience in detector operation and data analysis will be useful

DsTau and NOvA:

- Measured neutrino production cross-section is important for atmospheric neutrino and muon studies in NOvA

Project personnel

Theme: 1099
Project NOvA opened in 2014
Project T2K 2022-2023

✴ DLNP (43):

L. Kolupaeva, A. Olshevsky, Yu. Gornushkin, O. Samoylov, N. Anfimov, A. Sheshukov, V. Tchalyshev, A. Sadovsky, S. Dmitrievsky, I. Chirikov-Zorin, A. Antoshkin, A. Selyunin, A. Rybnikov, O. Klimov, A. Bolshakova, S. Vasina, D. Korablev, A. Kalitkina, A. Gridina, A. Stepanova, V. Sharov, A. Ivanova, D. Fedoseev, V. Gromov, S. Sokolov, V. Kozhukalov, A. Chetverikov, K. Kuznetsova, O. Geytota, A. Sotnikov, Yu. Davydov, V. Tereschenko, I. Suslov, V. Lyubushkin, V. Baranov, N. Khomutov, I. Zimin, I. Vasilyev, V. Kiseeva, O. Atanova, V. Glagolev, B. Popov, S. Tereschenko

✴ BLTP (6):

I. Kakorin, K. Kuzmin, G. Kozlov, V. Matveev, V. Naumov, D. Shkirmanov

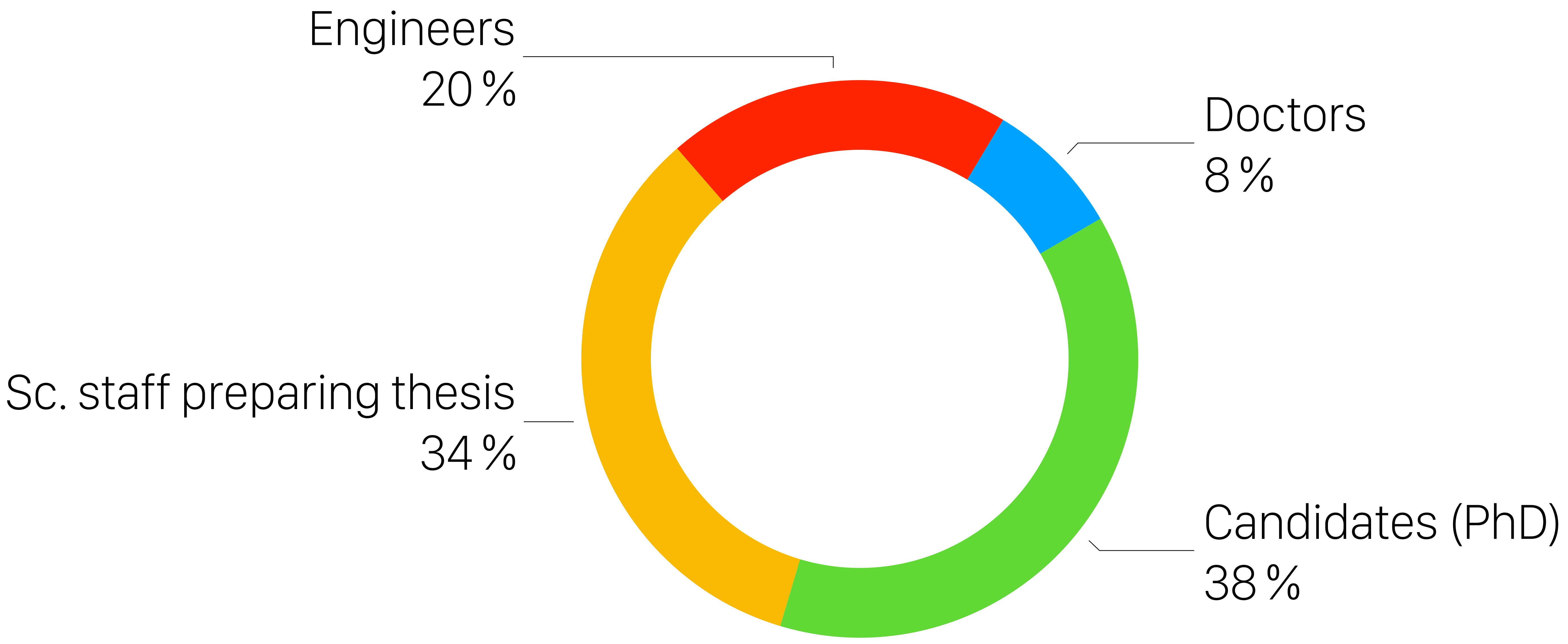
✴ MLIT (1):

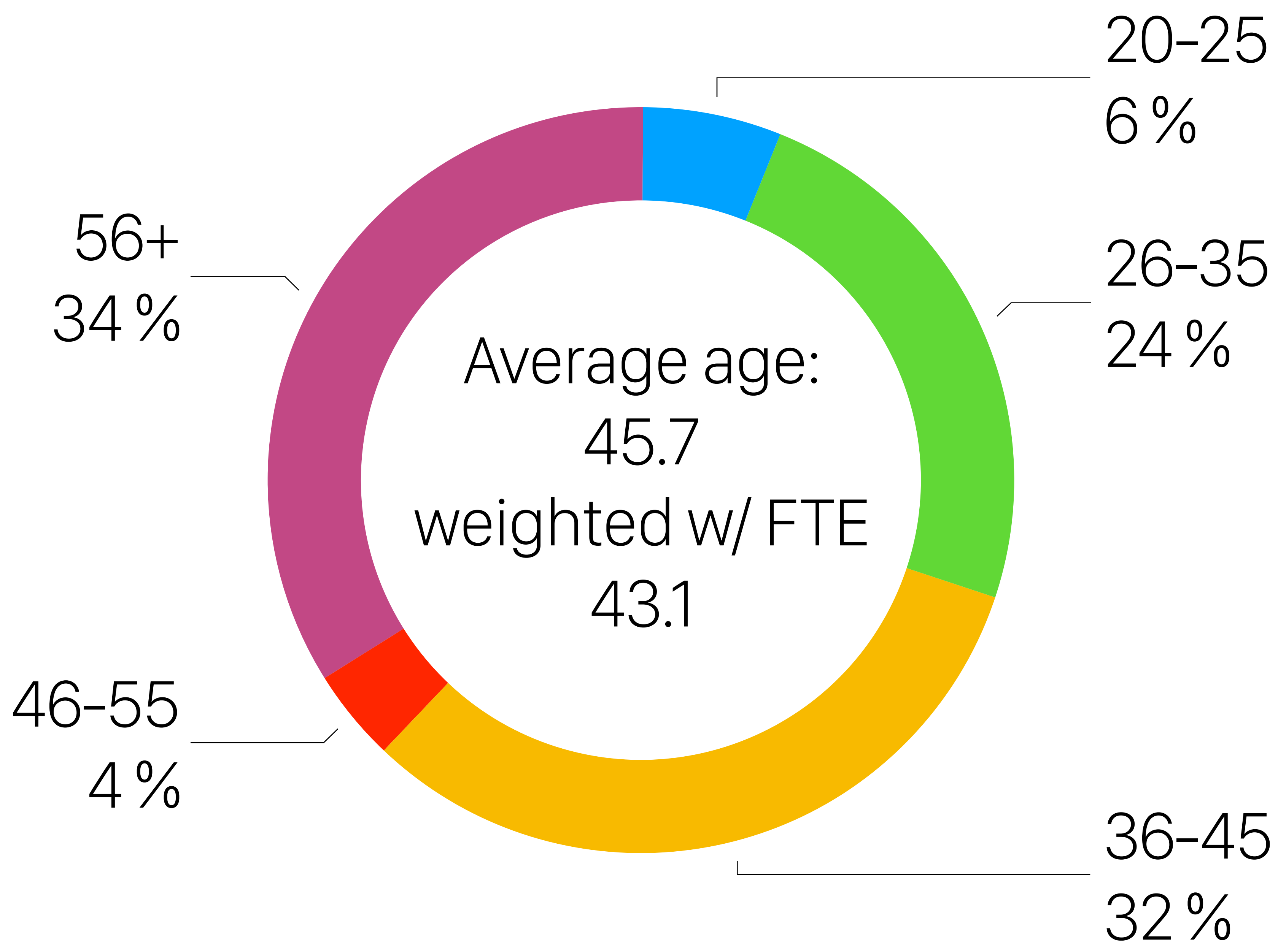
N. Balashov

In total: 50 people with FTE=23.7

Project personnel

- 3 PhD thesis were defended on NOvA, expect +2 in 2025-2026, several more at longer distance
- Management positions:
  - NOvA's exotics co-convener,
  - NOvA's three-flavor analysis co-convener,
  - DsTau collaboration board chair





Project resources

Expenditures, resources, funding sources	**Cost (thousands of US dollars)**	**Cost/Resources, distribution by years**		
		1st year	2nd year	3rd year
International cooperation	450	150	150	150
Materials	90	30	30	30
Equipment and Third-party company services	60	20	20	20
Commissioning				
R&D contracts with other research organizations	30	10	10	10
Software purchasing	30	10	10	10
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	660	220	220	220
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.

✳ Contemporary neutrino physics includes various searches beyond Standard Model phenomena as well as careful measurements of neutrino properties as intrinsic characteristics of this particle.

✳ This proposal aims to gather JINR participation in accelerator neutrino experiments into one project. This includes the present state-of-the-art: NOvA, T2K, DsTau and FASER experiments, in which different neutrino properties will be studied comprehensively: mass ordering, leptonic CP violation, lepton universality, neutrino interactions and others.

✳ Project is proposed to be opened for three years starting in 2026 to continue the JINR successful participation in all these experiments and prepare for the future research in this area.