DLNP JINR Neutrino Program

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Dzhelepov Laboratory of Nuclear Problems

- 18 August 1946 Soviet government approved the proposal of Academician Igor Kurchatov to construct in USSR "the installation M".
- 14 December 1949 The 480 MeV synchrocyclotron started operation at the Hydrotechnical Laboratory in Dubna, the most powerful accelerator in the world.
- 26 March 1956 Laboratory of Nuclear Problems of JINR has been founded.

- DLNP these days: 618 people staff , 8 scientific departments
- Very welcome young scientists to join research projects. Possible diploma themes:

  https://dlnp.jinr.ru/education/

Dzhelepov Laboratory of Nuclear Problems

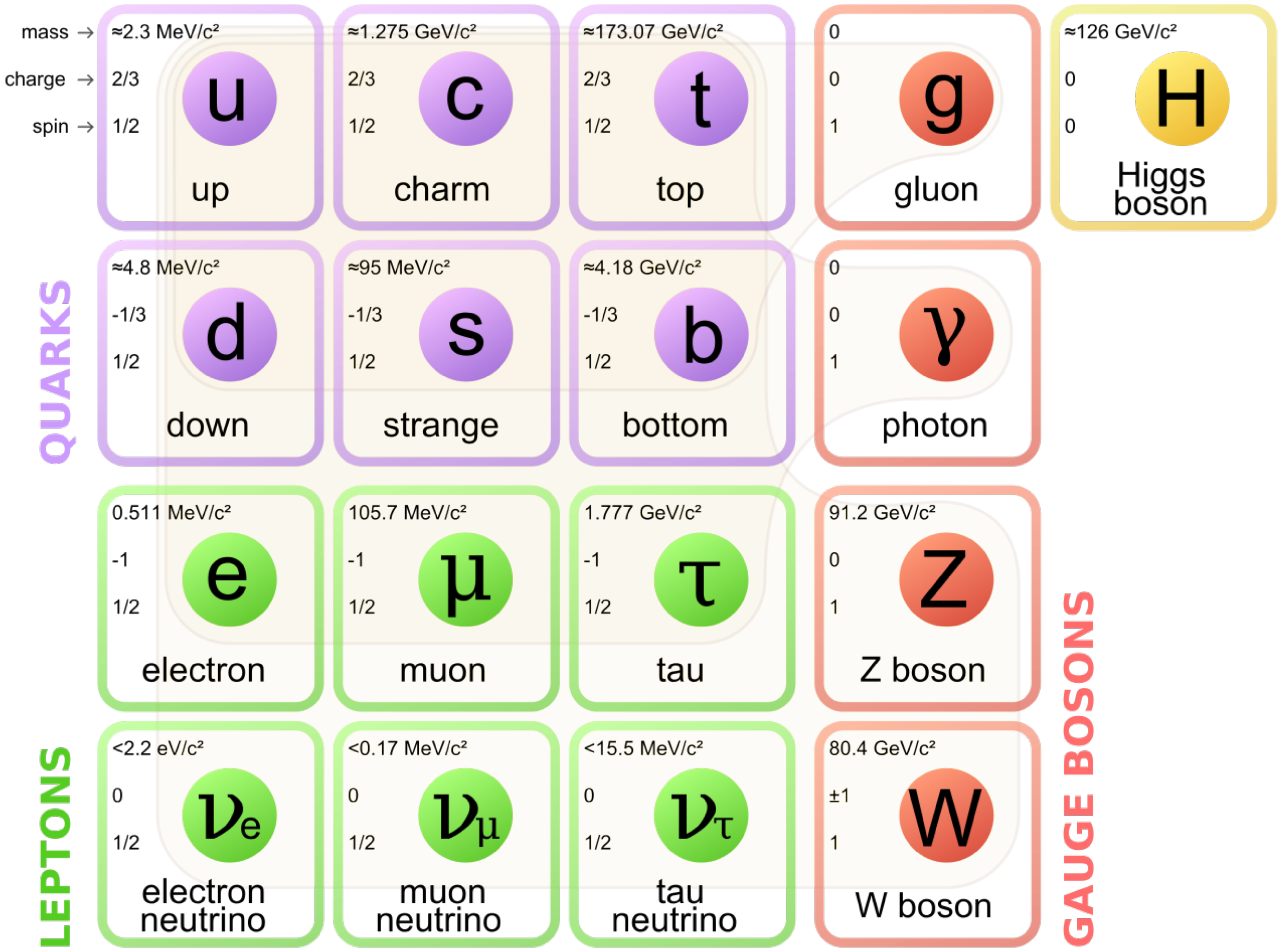
Scientific landscape

- Elementary particle physics and heavy ion HEP:
  - Neutrino physics
  - ATLAS @ LHC
  - BES III
  - COMPASS/AMBER
  - SPD @ NICA
- Nuclear physics:
  - Neutrino physics
  - Radiochemistry and spectroscopy
- Accelerator physics:
  - LINAC-200
  - MSC-230
- Low temperature physics

- Applied research:
  - Inclinometer
  - New detectors
  - Positron annihilation spectroscopy
  - Radiochemistry for nuclear medicine
- Life science

Prominent program that is impactful and well-known all over the world in both fundamental and applied sciences

Neutrino



Standard Model (SM) particle

✳Three flavors

✳Charge = 0, color = 0, spin = 1/2

✳So far considered to be Dirac particle

✳ Neutrino interactions conserve flavor

✳ Interact only via weak (and gravity) force

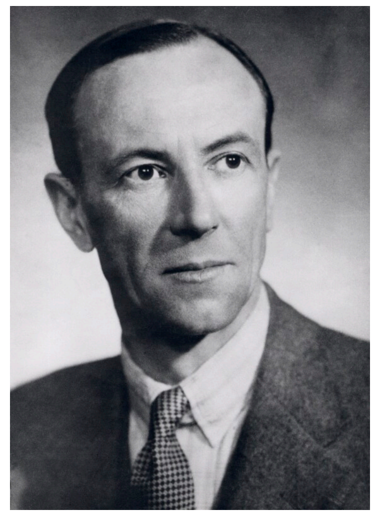
✳ Small but non zero mass

✳ Neutrinos mix → existence of neutrino oscillations

Oscillations is the only evidence of physics beyond SM that can be reproduced in lab.

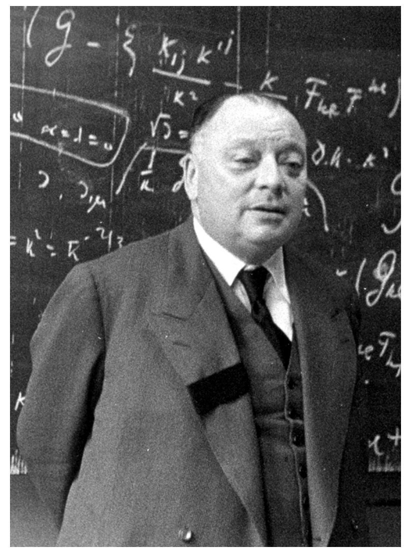
Super brief neutrino history

In one slide



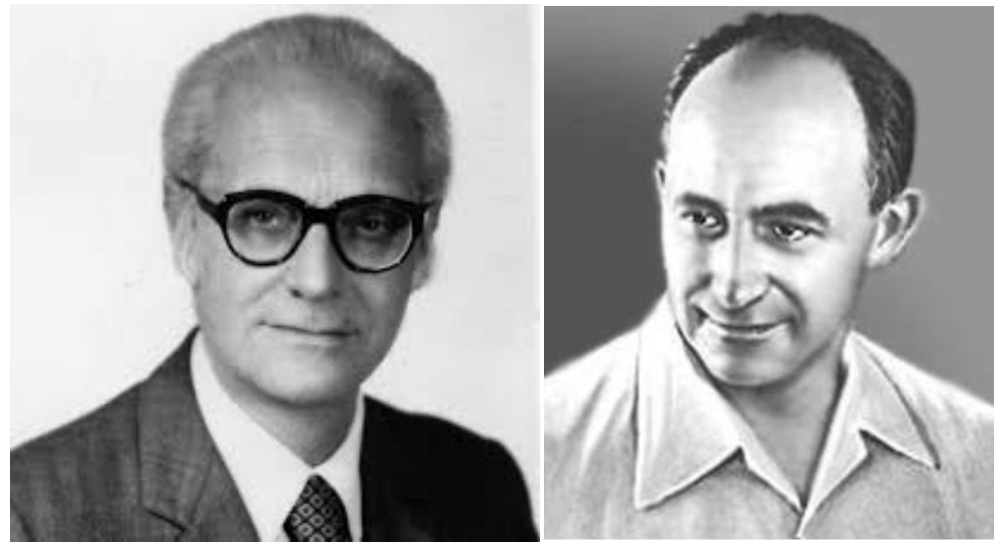
missed energy
in beta-decay

1914



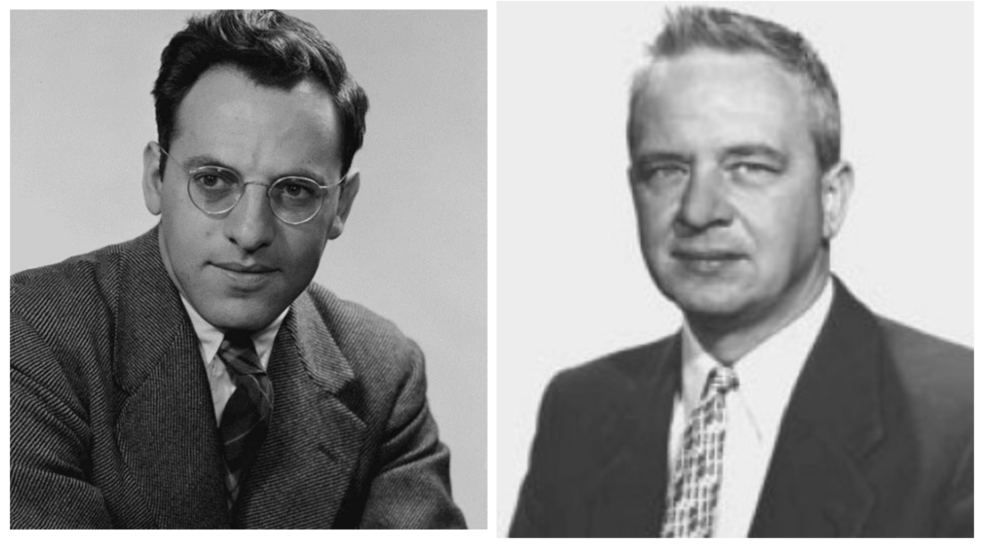
elusive particle
as a solution

1930



the name of neutrino

1933



(electron) neutrino
discovery

1956

Бруно Понтекорво

proposal of
neutrino oscillations
(and many other things)

1957

muon neutrino
discovery

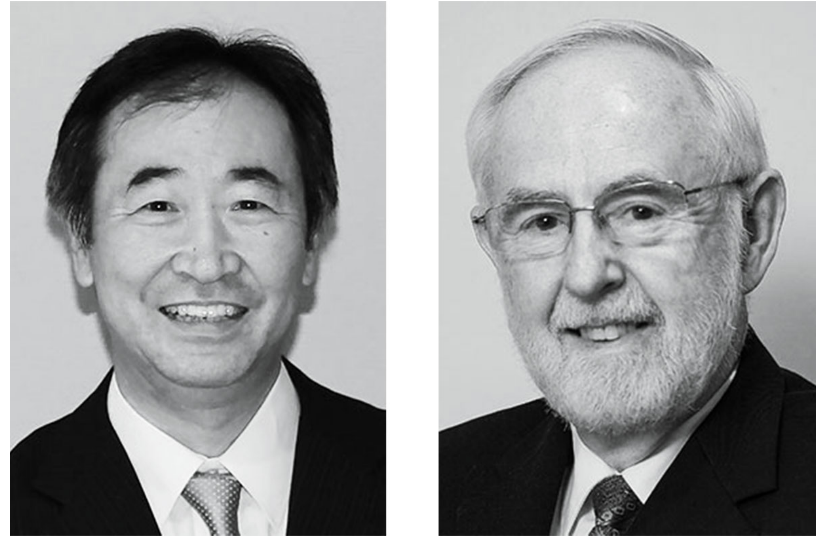
1962

first hint on
neutrino oscillations

1970 (- 1994)

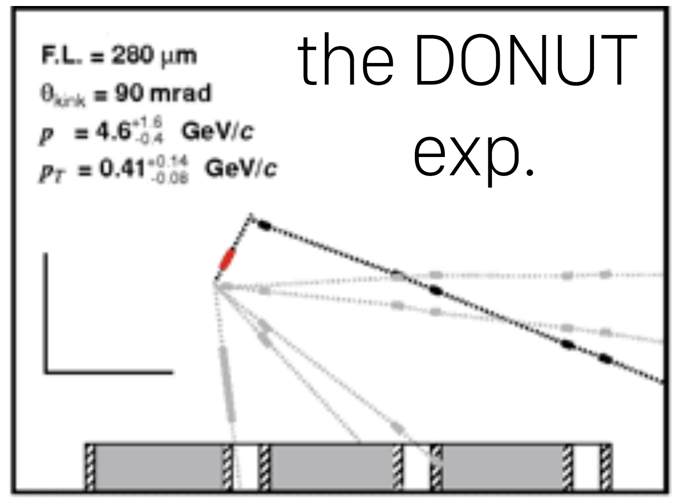
first supernova
neutrino registration

1987



discovery of neutrino
oscillations

1998 and 2002



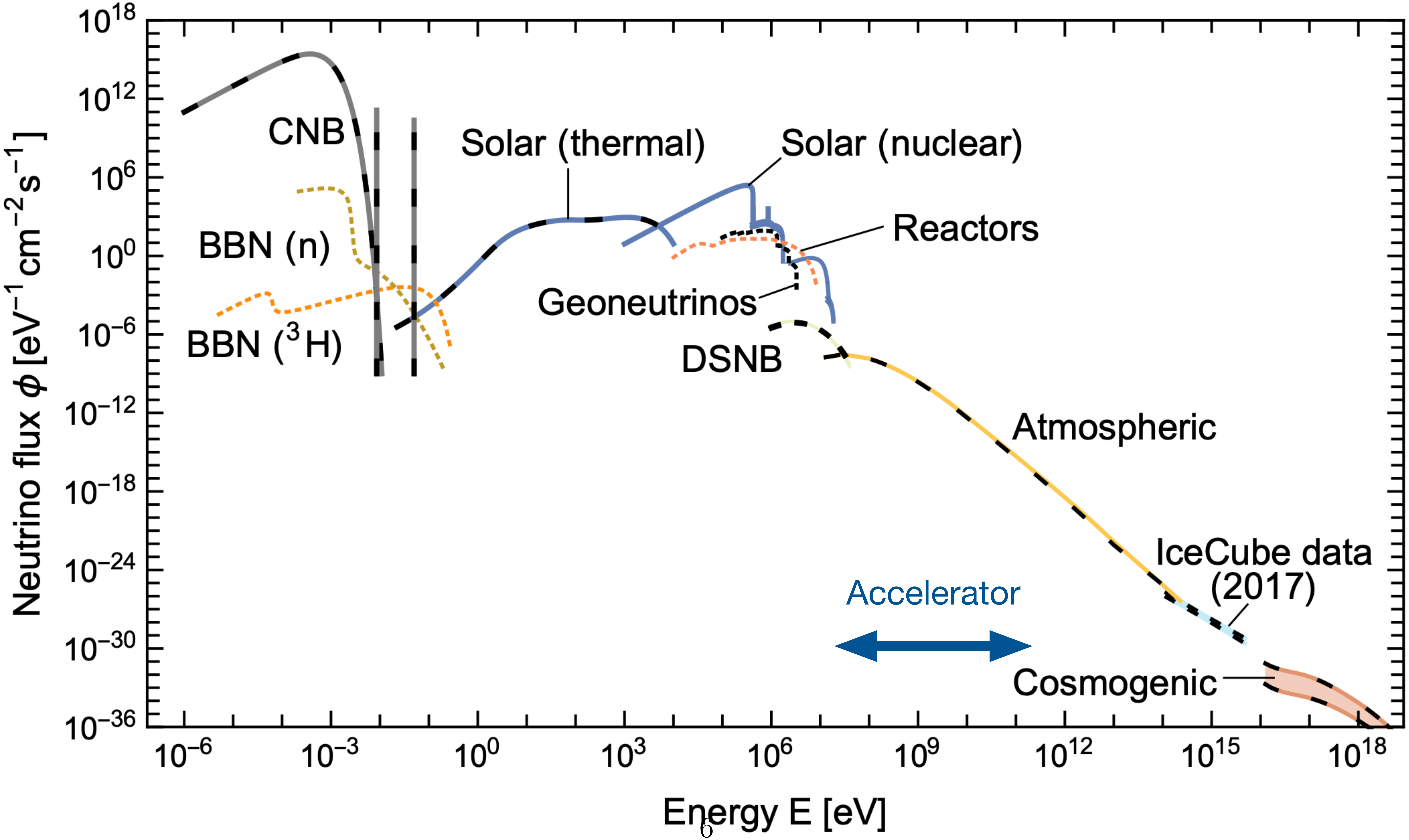
the DONUT exp.

tau neutrino
discovery

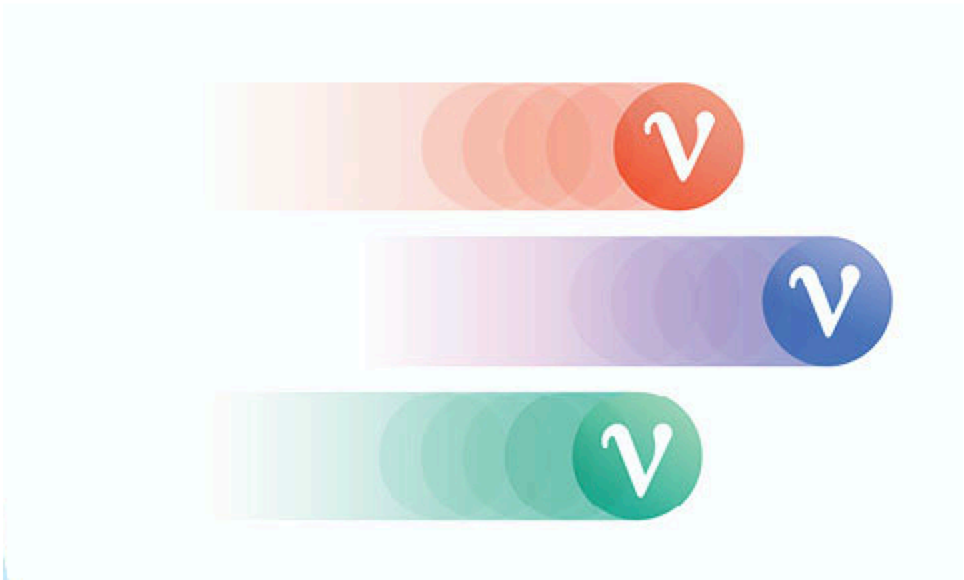
2000

N
O
W
A
D
A
Y
S

Neutrino sources



Modern neutrino physics



~Applied

Physics **with** neutrinos

- Solar
- Geo
- Reactor
- Atmospheric
- Supernova
- Astrophysical and cosmological

Fundamental

Physics **of** neutrinos:

- Study the properties:
  - Neutrino oscillations
  - Measurement of Absolute Masses
  - Neutrino interactions etc
- Search for BSM physics:
  - Neutrinoless double beta decay
  - Sterile neutrinos etc
- Search for relic neutrinos
- …

JINR neutrino program

Neutrino interactions: νGEN, Ricochet, DsTau, FASER

Three-flavor neutrino oscillations: JUNO, NOvA, T2K

Sterile neutrinos: DANSS

Neutrinoless double β-decay: LEGEND, SuperNEMO, MONUMENT, Zr-BNO, Se-LSM, TGV

Dark matter: DarkSide, SHiP

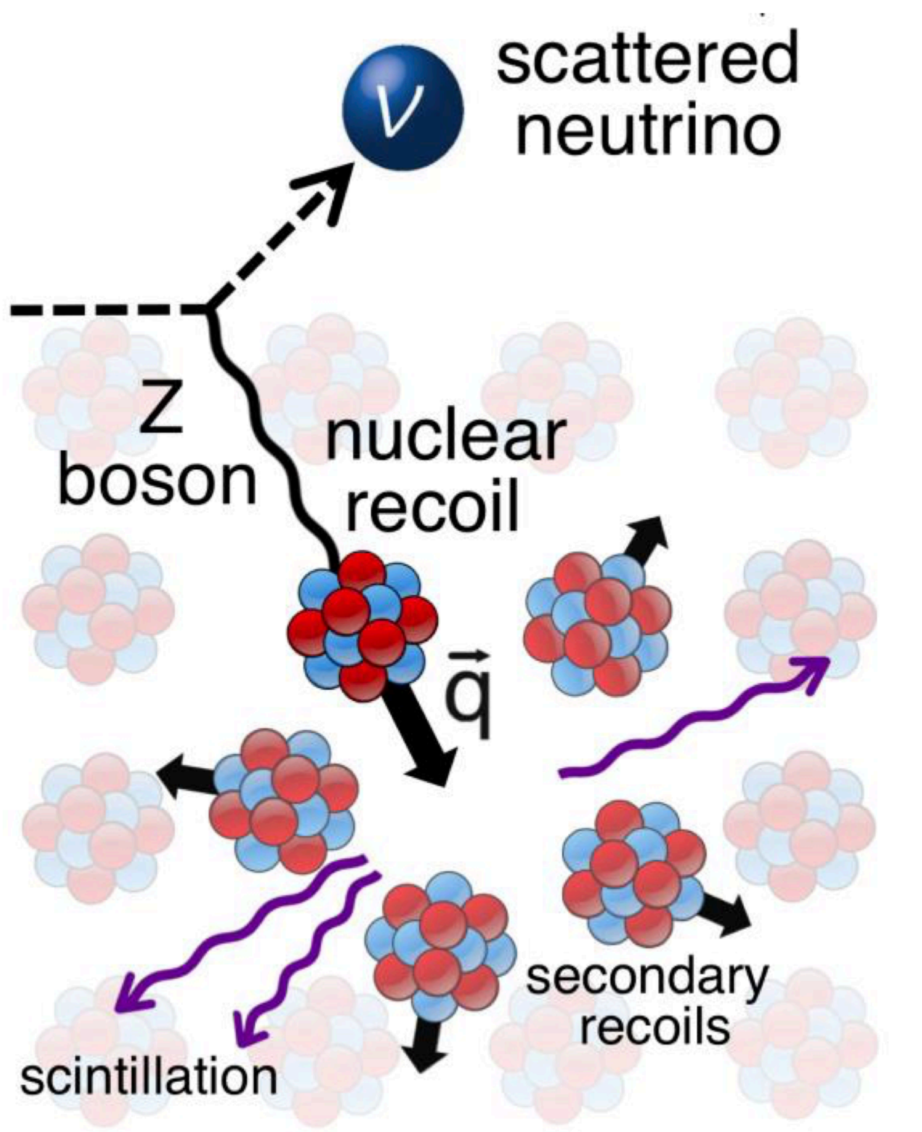
Sources of high energy γ: TAIGA

Astrophysical neutrino: Baikal-GVD

Theoretical support

JINR PTP

Coherent elastic νN scattering



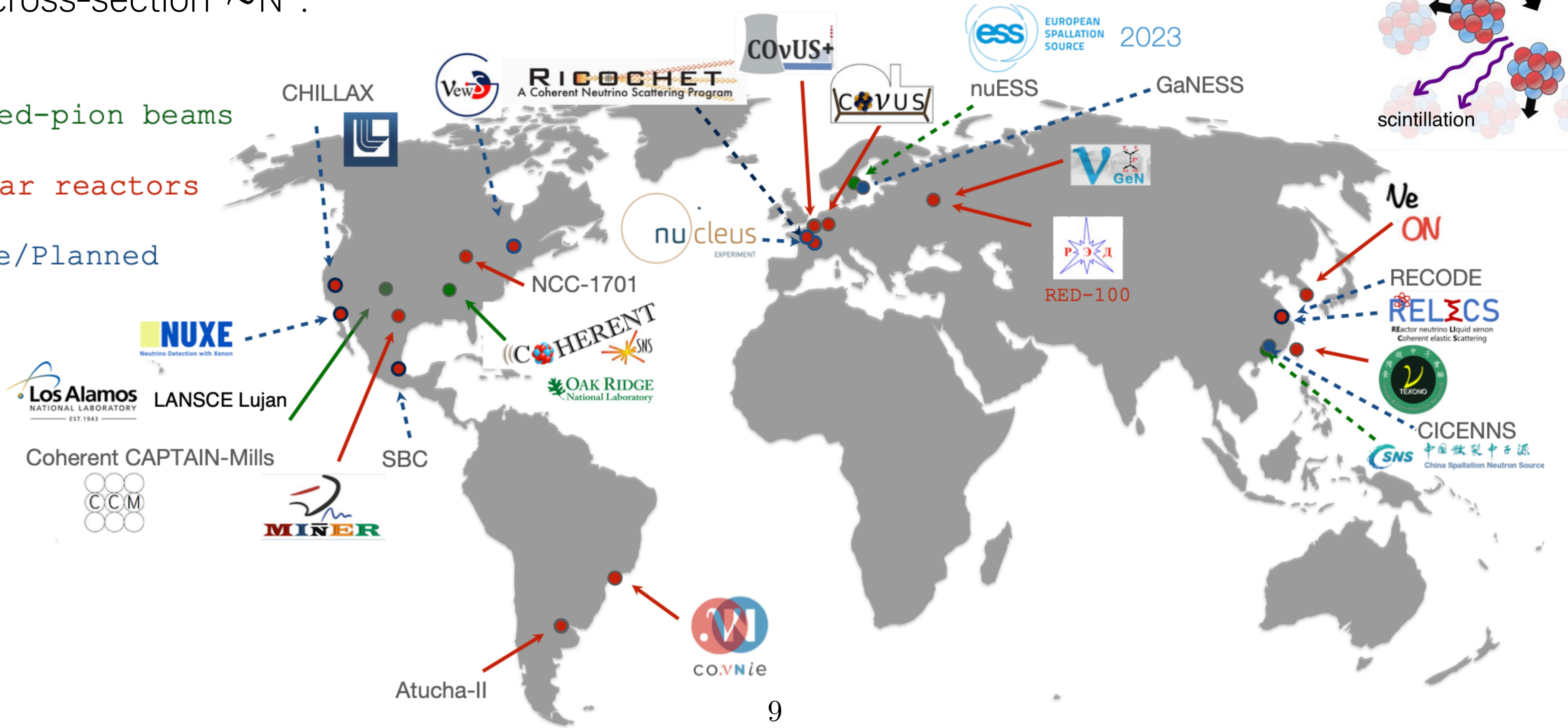
- ✳ Dominant process for $E_\nu < 50$ MeV.
- ✳ Cons: recoil energy ~keV.
  Pros: cross-section ~N^2.

Discovered by COHERENT in 2017

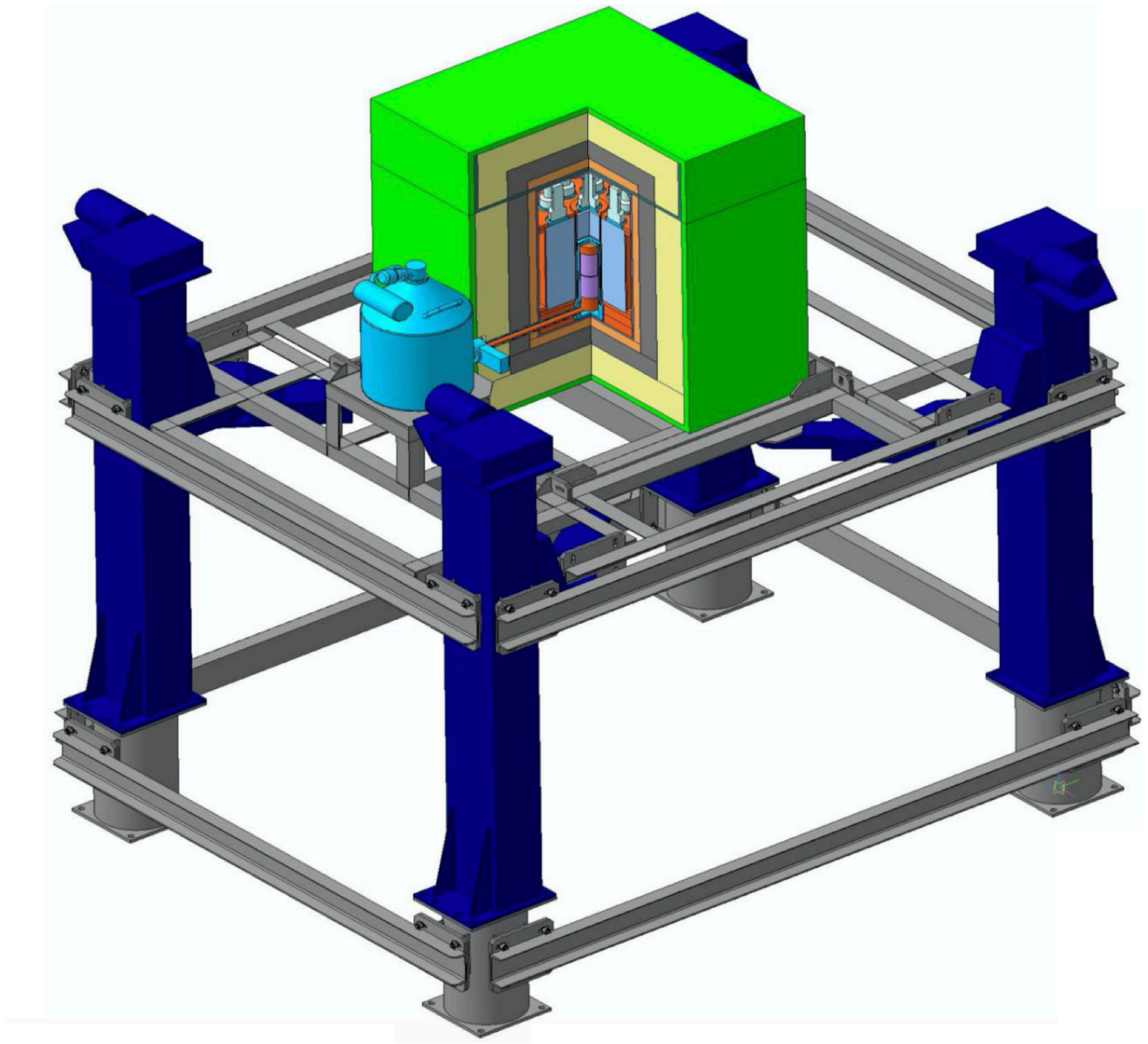
● Stopped-pion beams

● Nuclear reactors

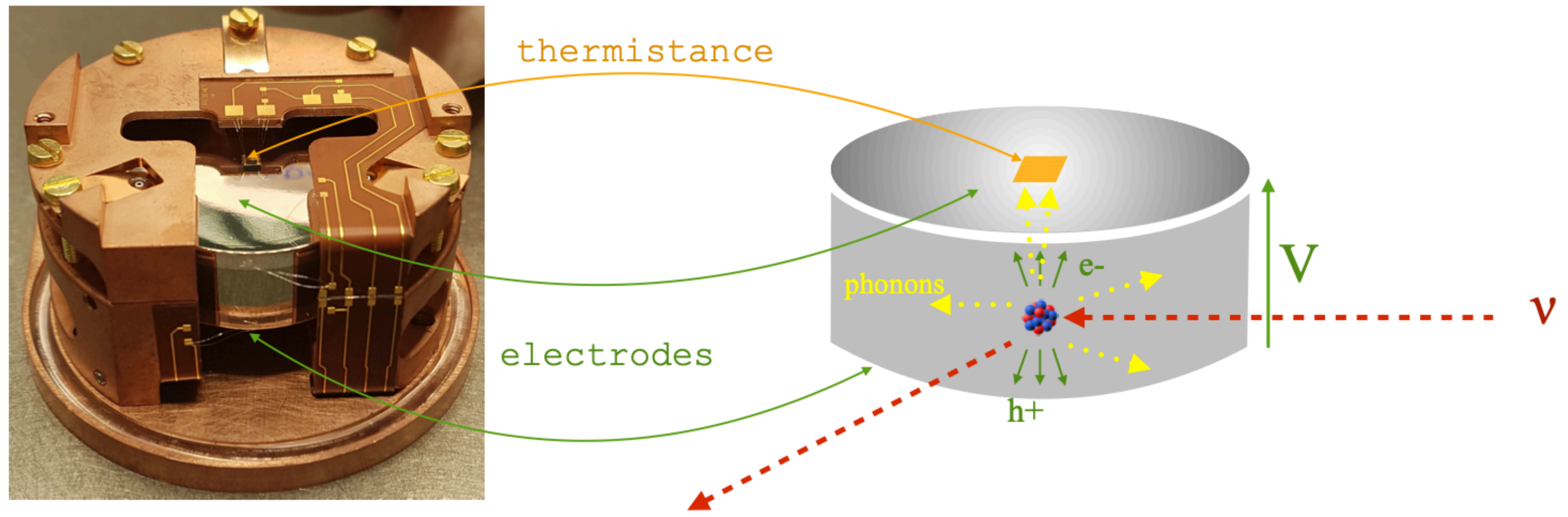
● Future/Planned



νGEN and Ricochet



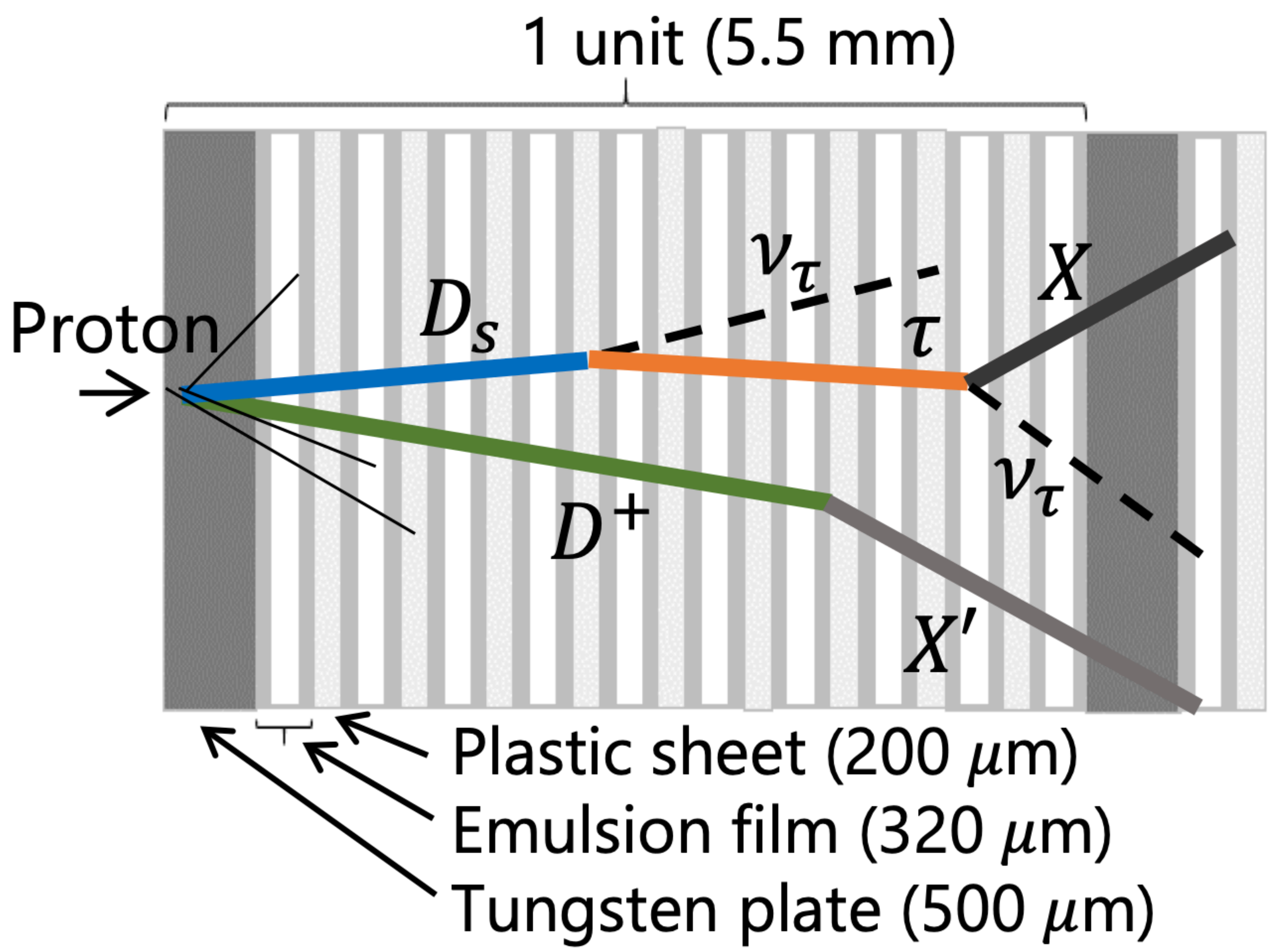
- ~15 running or planned experiments around the world. Among them are Ricochet (ILL) and νGEN (Russia).
- νGEN is a JINR domestic experiment at KNPP.
- Goals: detect area of full coherence (< 30 MeV); Standard Model test; a bkg for dark matter searches; $\bar{\nu}$ flux monitoring from NPP, neutrino magnetic moment measurements etc.
- νGEN features: huge neutrino flux, small bkg, moving platform.
- Measurements were already started, data taking and analysis are ongoing.
- Ricochet: detector was commissioned and data taking started in 2025
  - CryoCube, an array of germanium-based cryogenic detectors cooled to 10 millikelvin for simultaneous detection of ionisation and heat



DsTau and FASERnu

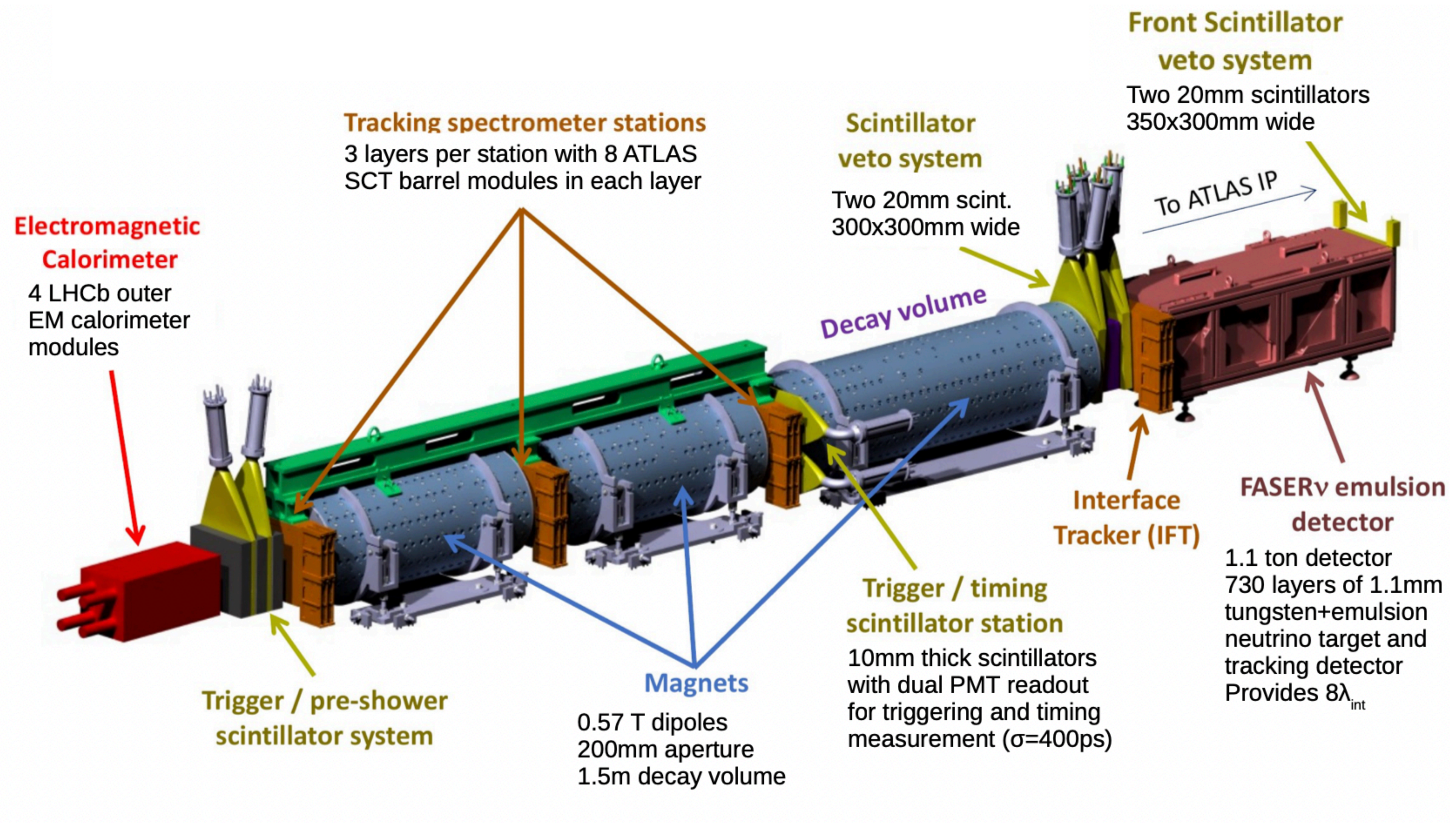
DsTau (NA65), SPS

- ✳ 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)



Neutrino oscillations and mixing

atmospheric
accelerator

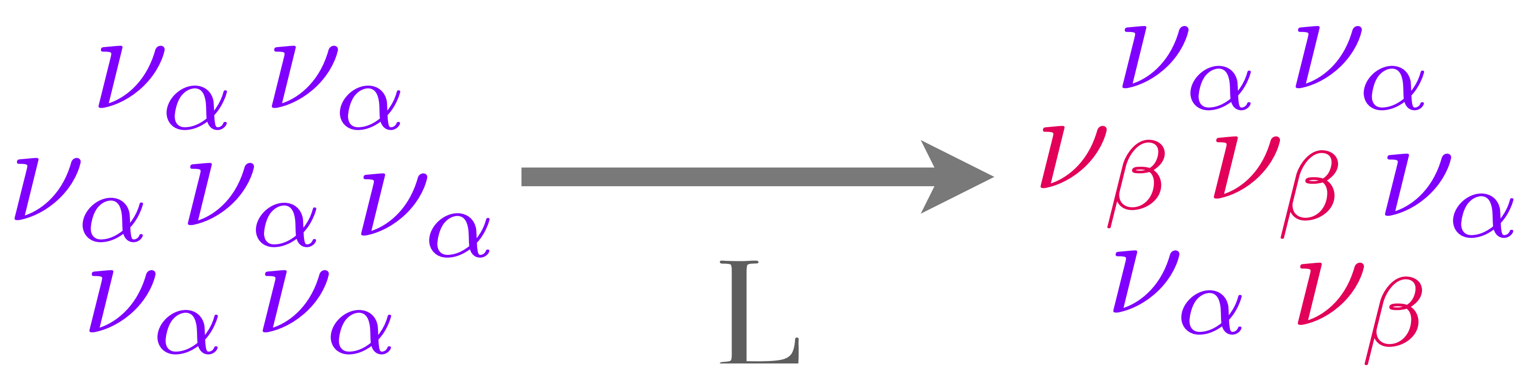
short baseline reactor
accelerator

solar
long baseline reactor

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

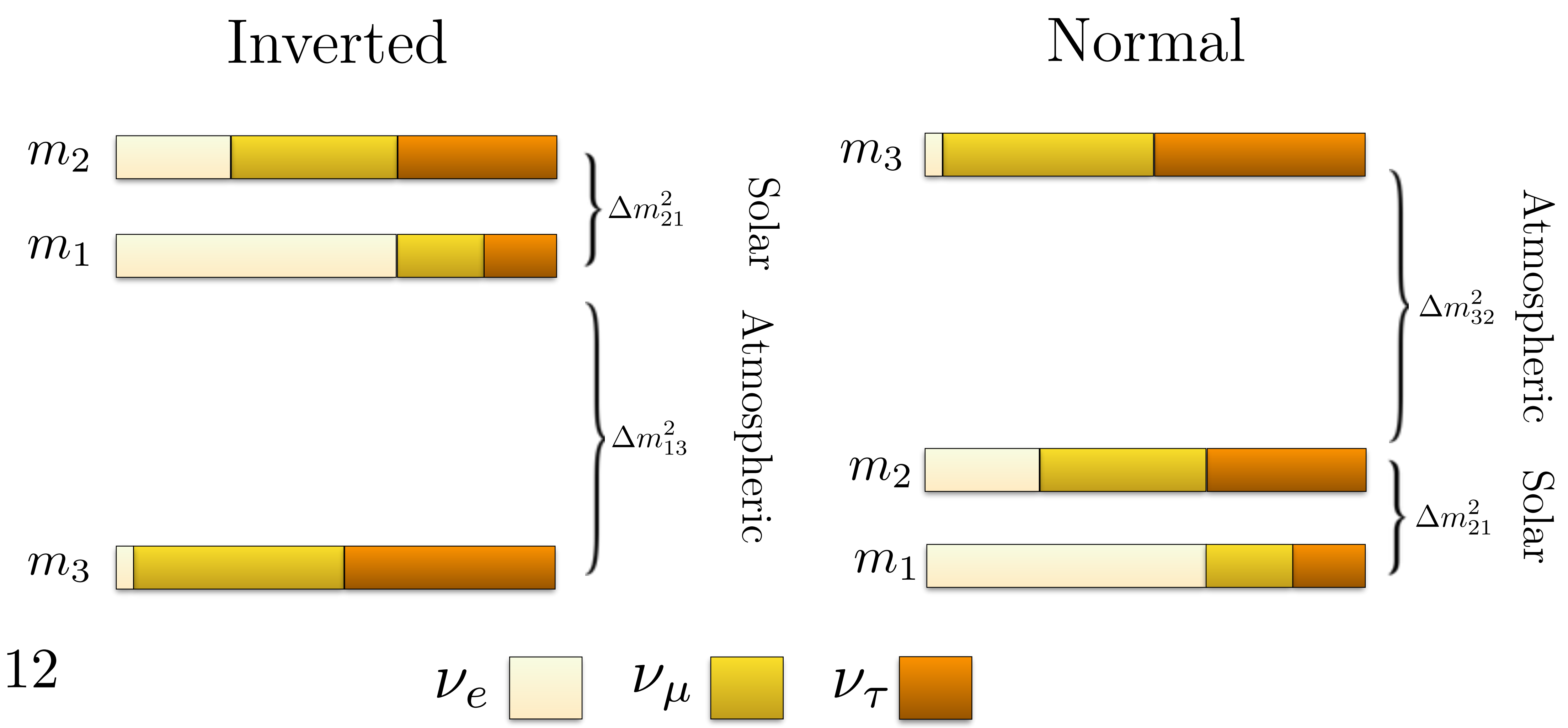
Oscillation parameters and how precisely do we know them:

$\theta_{12} \approx 34^\circ$ (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°?
Is there CP violation in lepton sector?
Neutrino mass hierarchy (ordering) is Normal or Inverted?



Motivation

Neutrino mass ordering

Mass hierarchy/ordering plays important role for:

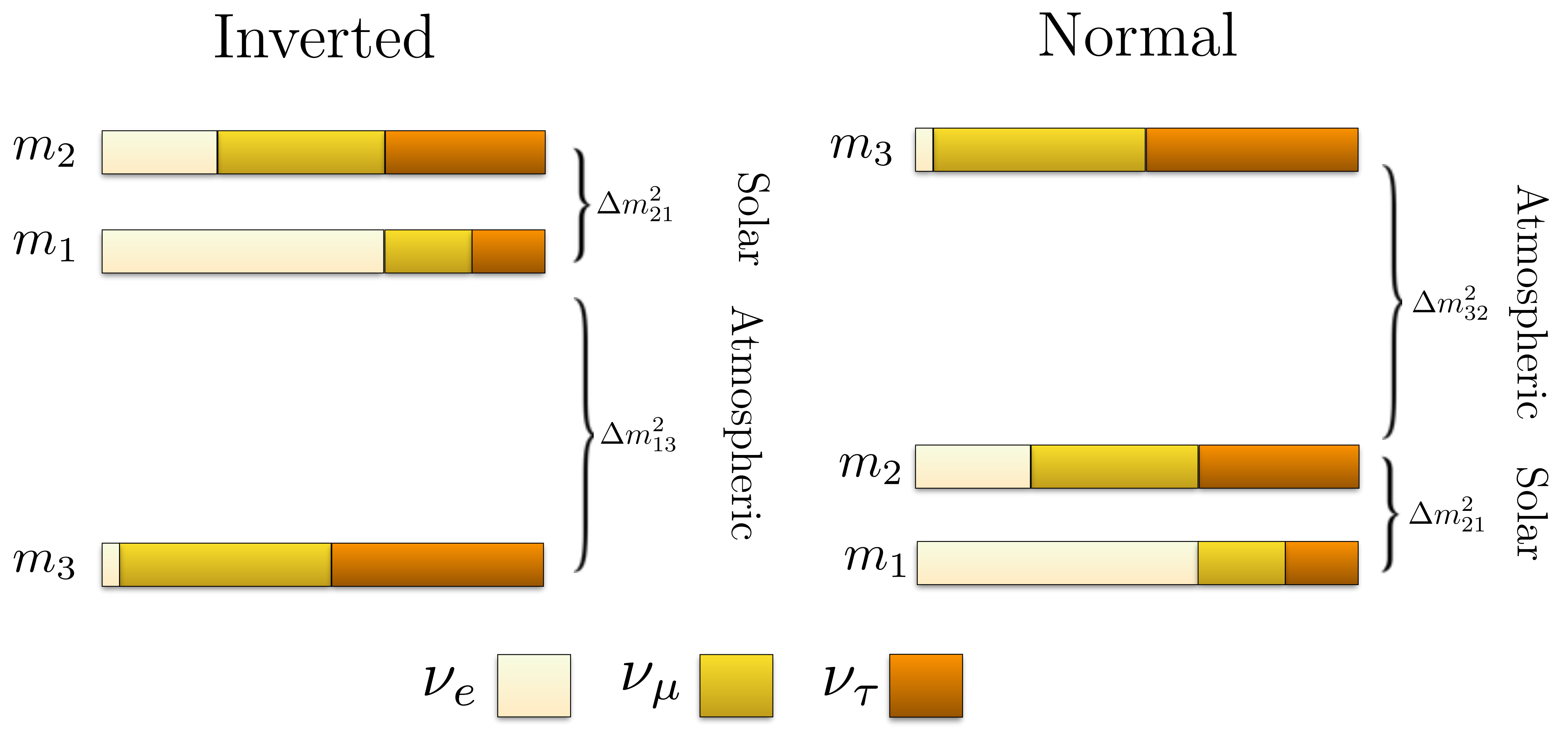
✳ neutrinoless double beta-decay searches,

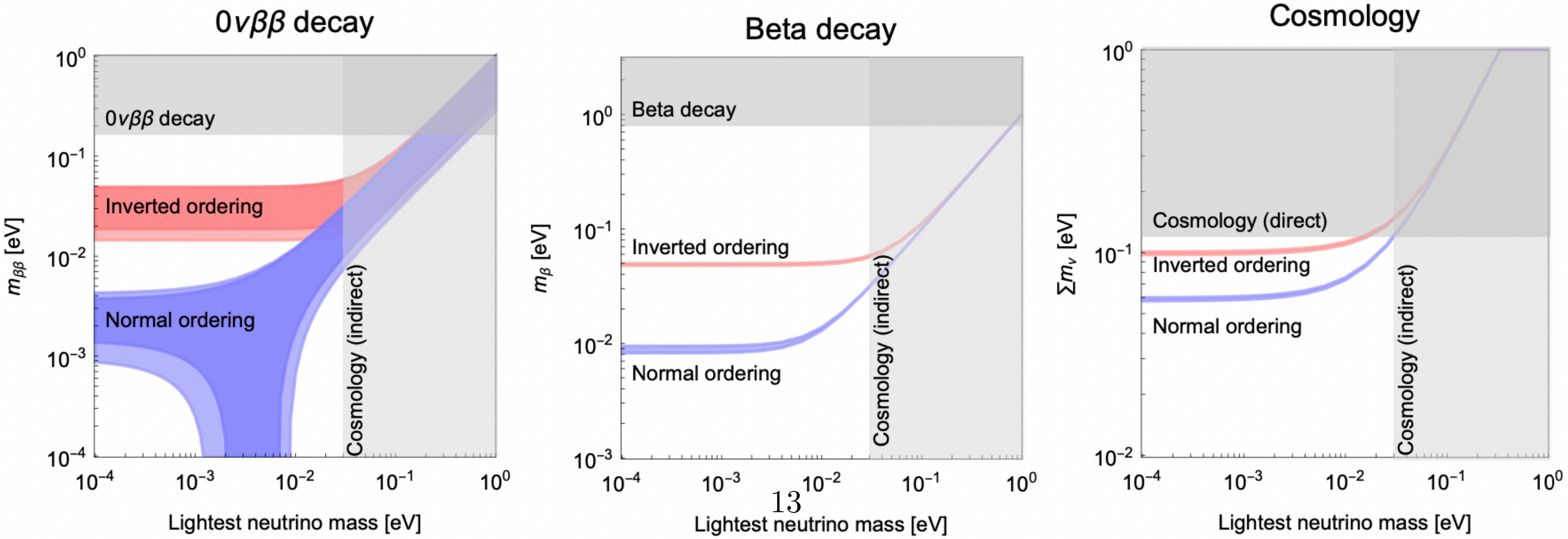
✳ supernova simulations,

✳ relic neutrinos searches,

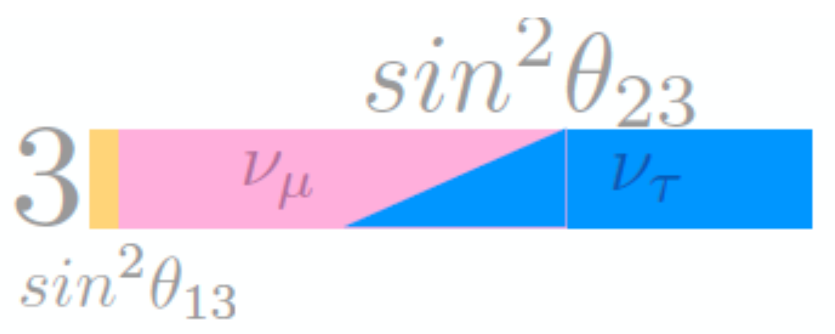
✳ absolute ν mass measurements etc.

So it affects everything connected with ν masses





Motivation



θ_{23} is responsible for possible ν_μ and ν_τ symmetry in ν_3

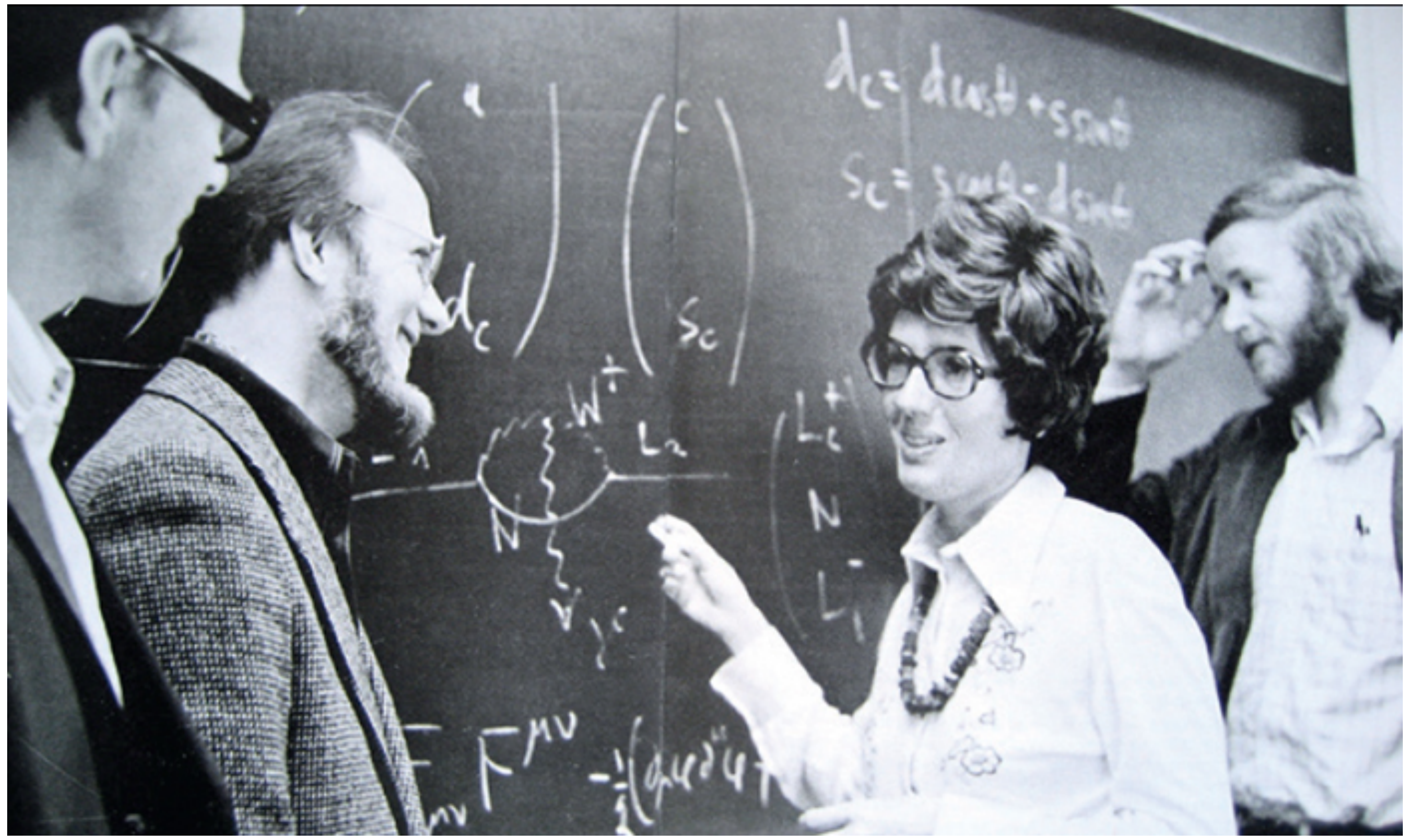
δ_{CP} may be connected with matter-antimatter asymmetry of the Universe (leptogenisis)

$$\frac{J_{\text{PMNS}}}{J_{\text{CKM}}} = \frac{3\times 10^{-2}}{3\times 10^{-5}} \sin(\delta_{\text{PMNS}})$$

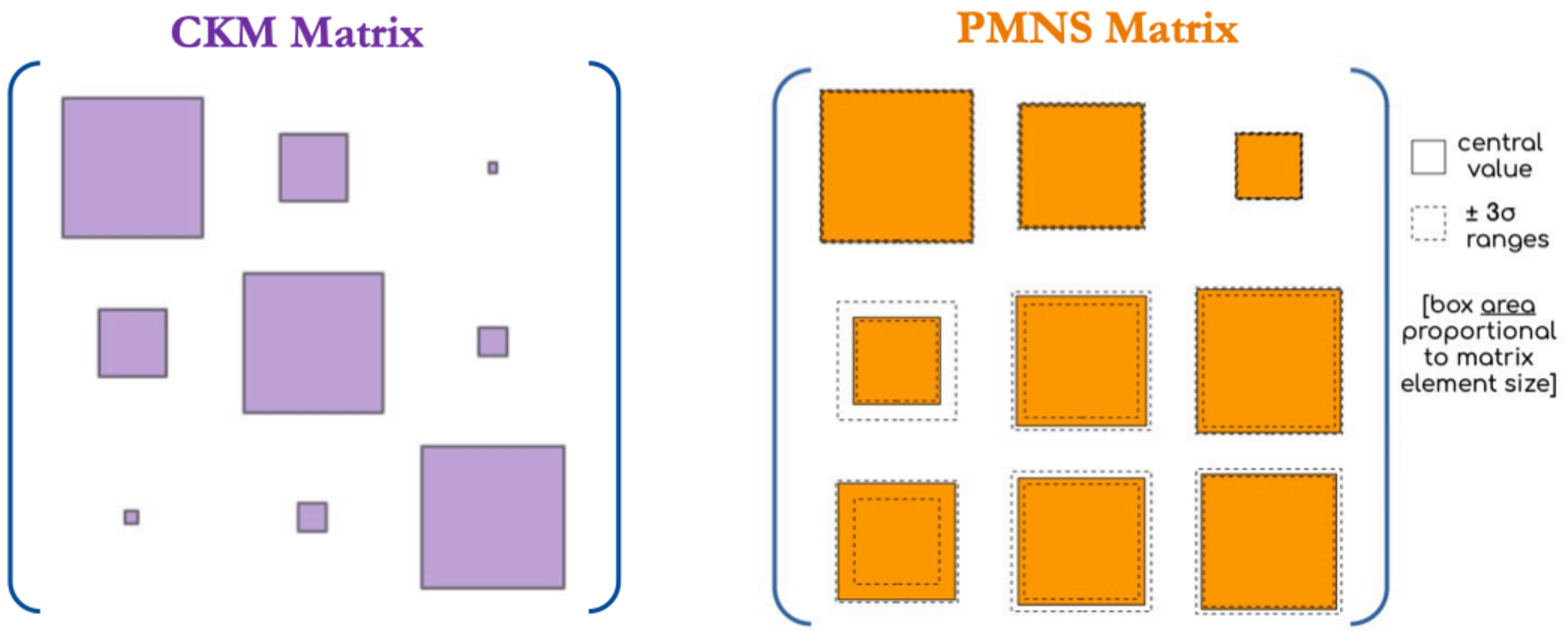
The very final goal of all these measurements is the creation of theory that can also explain the smallness of neutrino masses and mixing, and its unification with SM.

Neutrino parameters as test for theories (check sums).

Unitarity of mixing matrix.



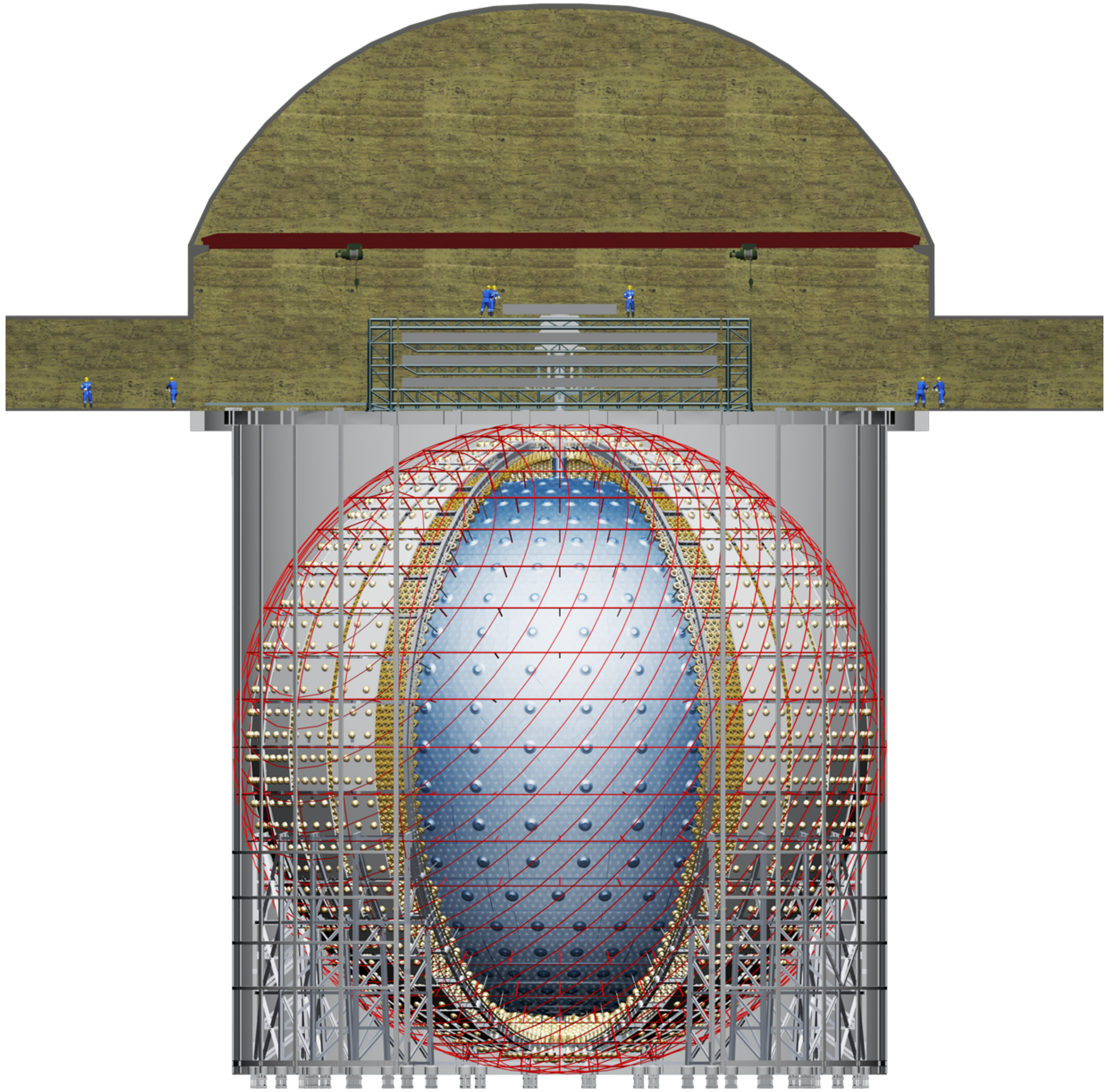
$$J \equiv s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta$$



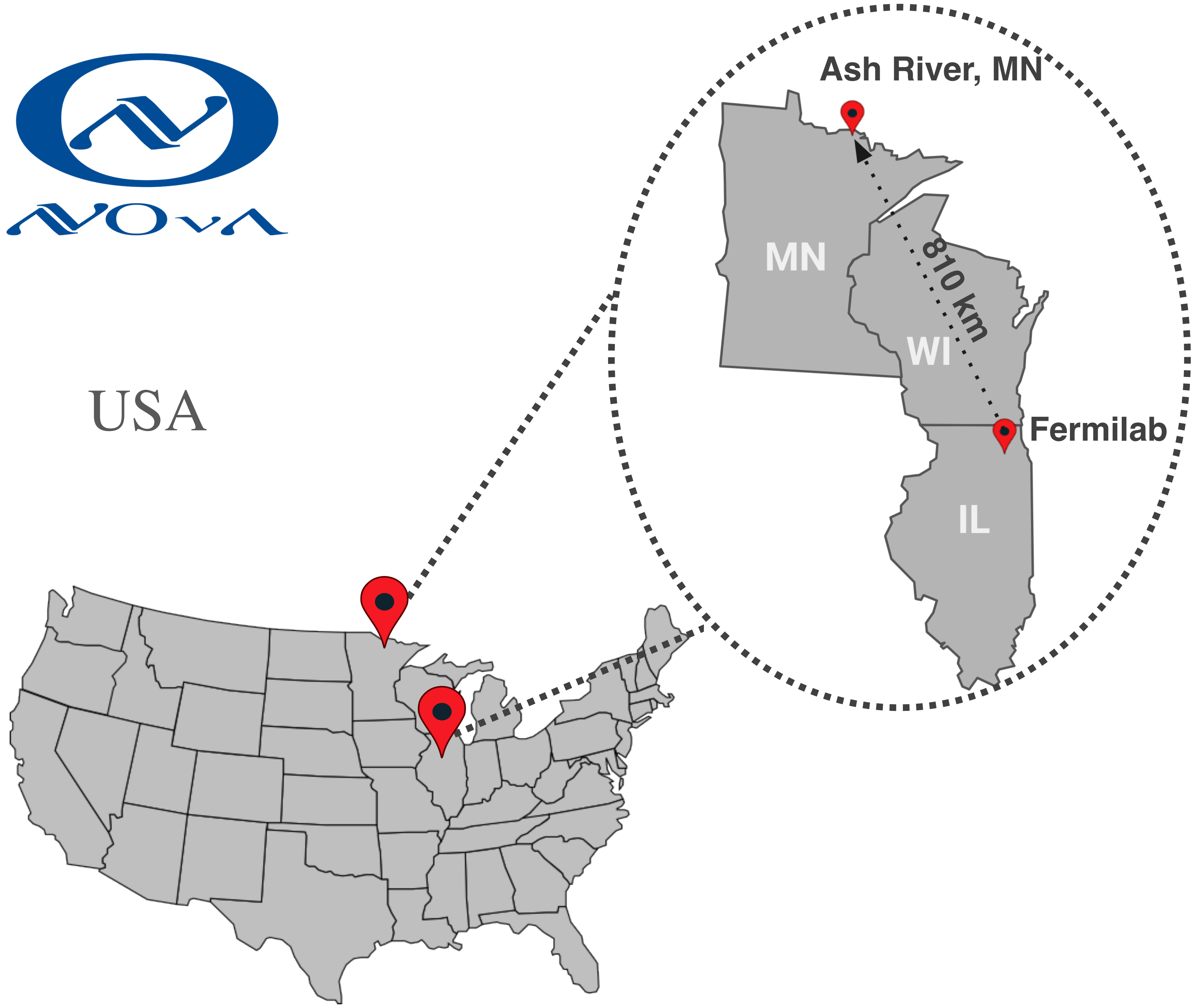
JUNO

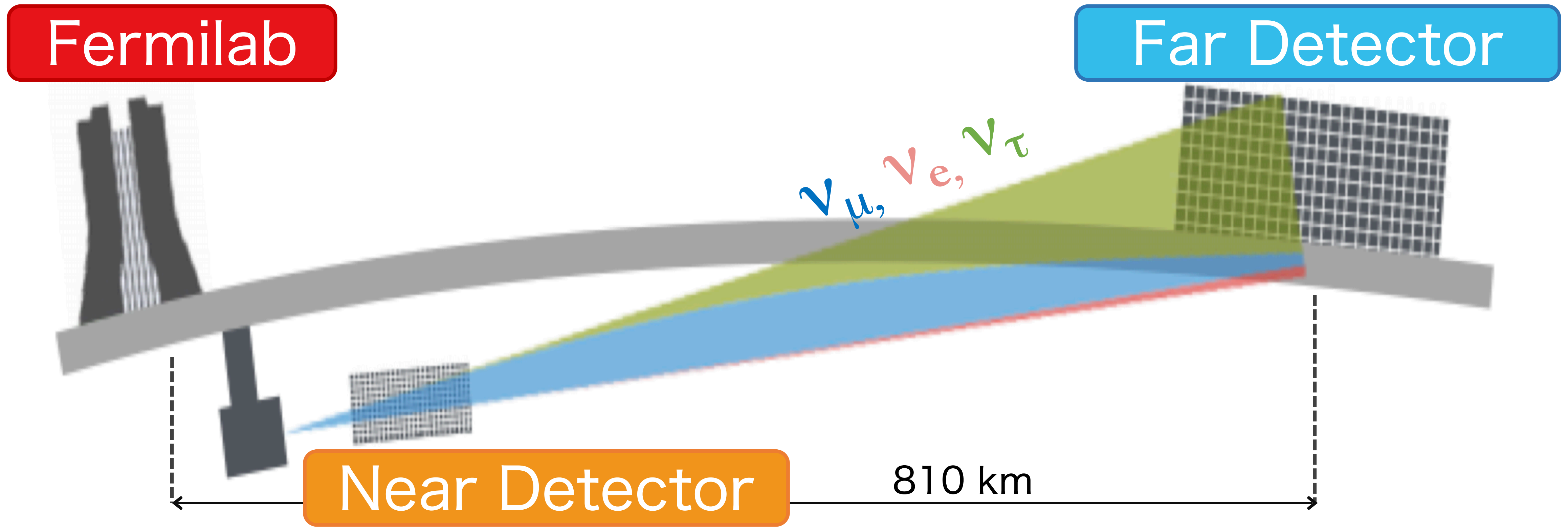
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \underbrace{\sin^2 2\theta_{13}\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E} + \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right)}_{\text{MEDIUM BASELINE}} - \underbrace{\sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}}_{\text{LONG BASELINE}}$$

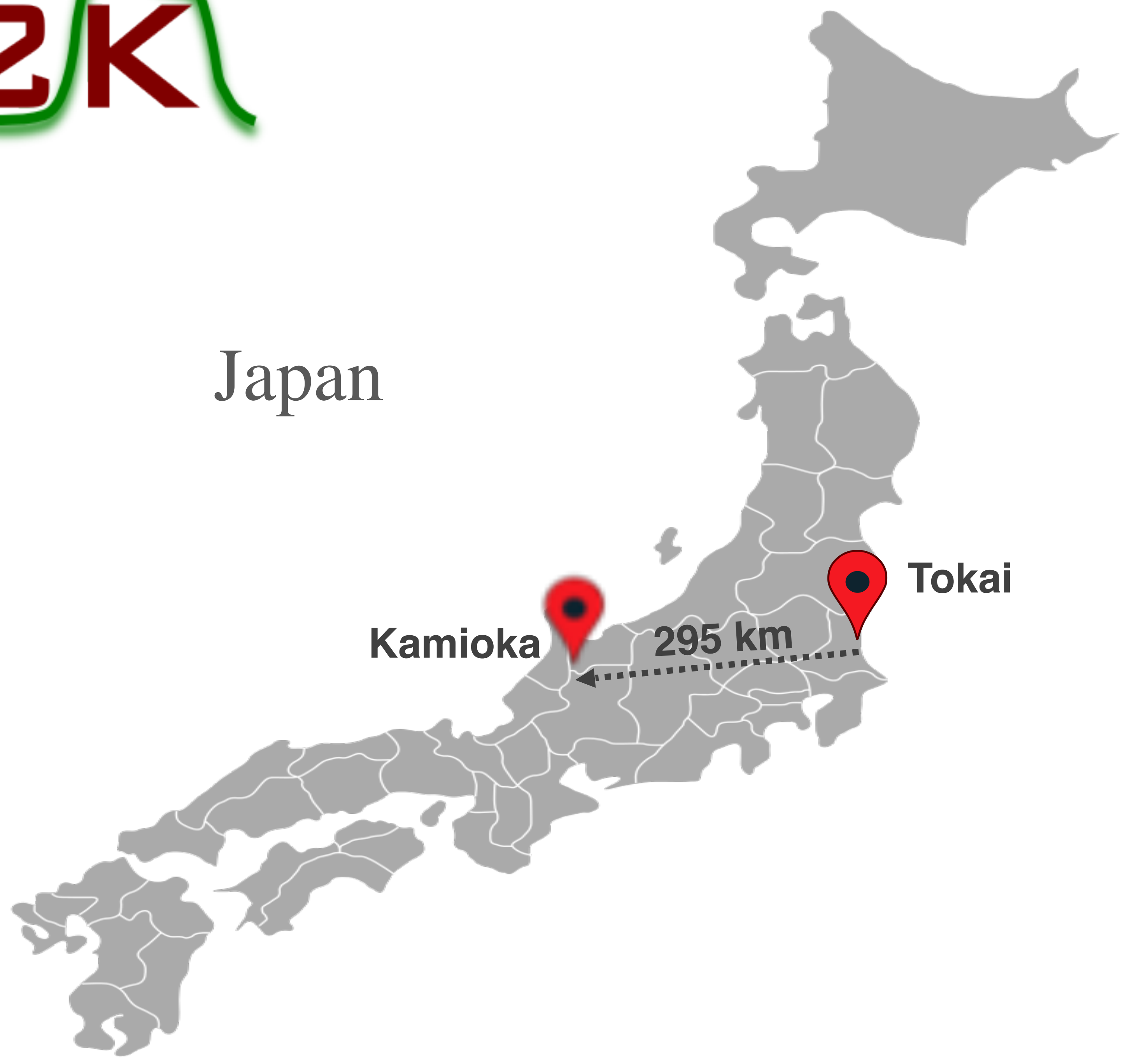
- ✴ An experiment in China that has started taking data in 2025
  - ✴ First results were already presented in the end of 2025
- ✴ Long baseline (53 km) → more sensitivity to Δm^2_{21} and θ_{12}, also Δm^2_{32} and mass hierarchy.
- ✴ Unique opportunity to measure Δm^2_{21} and θ_{12} with both solar and reactor neutrinos for cross check of SK+SNO vs. KamLAND tension.
- ✴20 kt LS detector, 26.6 GWth power → 45 IBD events/day.
- ✴ More opportunities: geo neutrinos, supernova, proton decay etc.

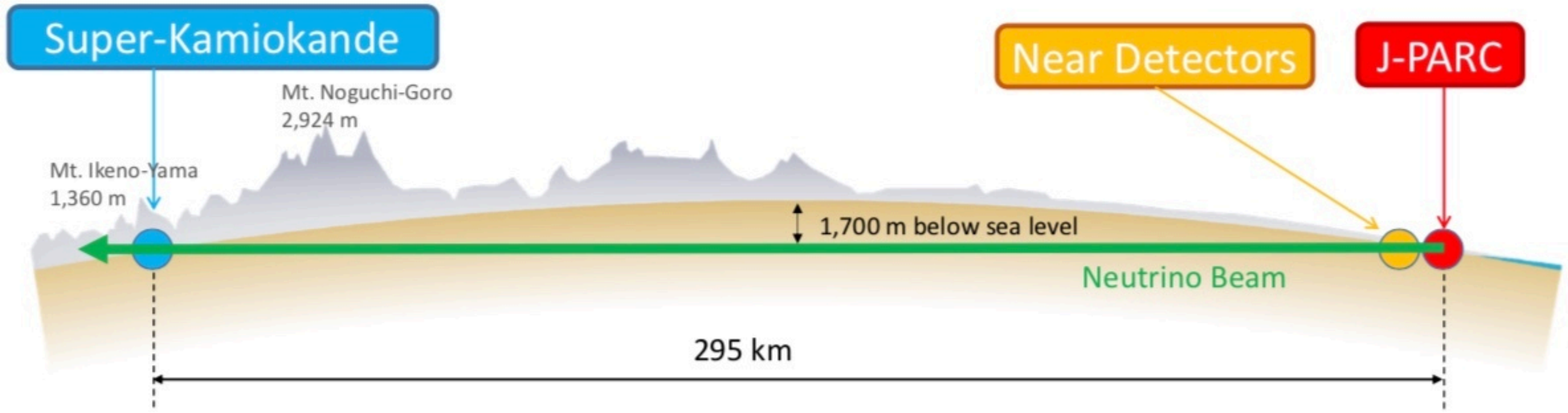


NOvA and T2K


USA
Ash River, MN
MN
810 km
WI
Fermilab
IL

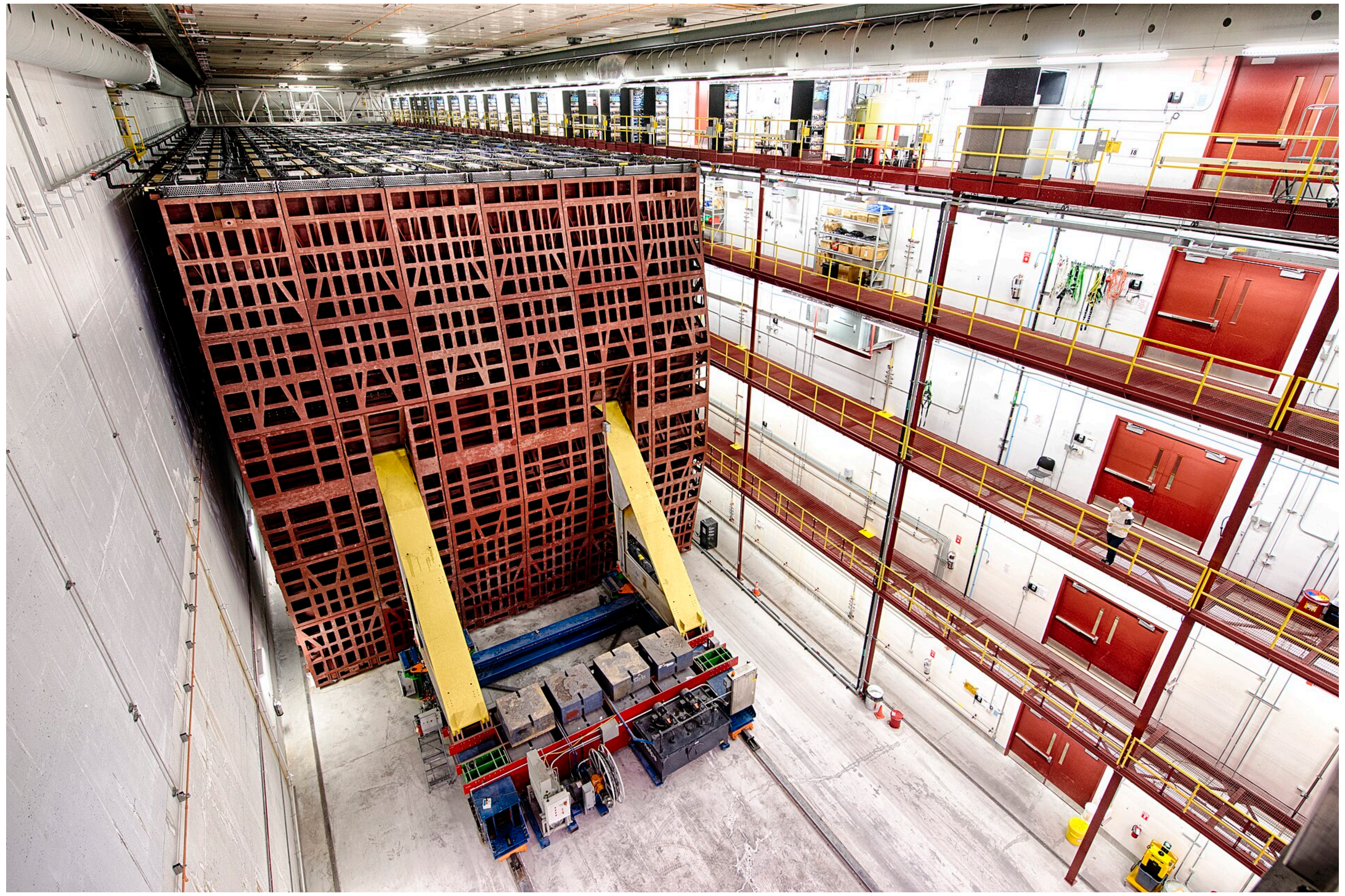

Fermilab
Far Detector
ν_μ, ν_e, ν_τ
Near Detector
810 km


Japan
Tokai
Kamioka
295 km

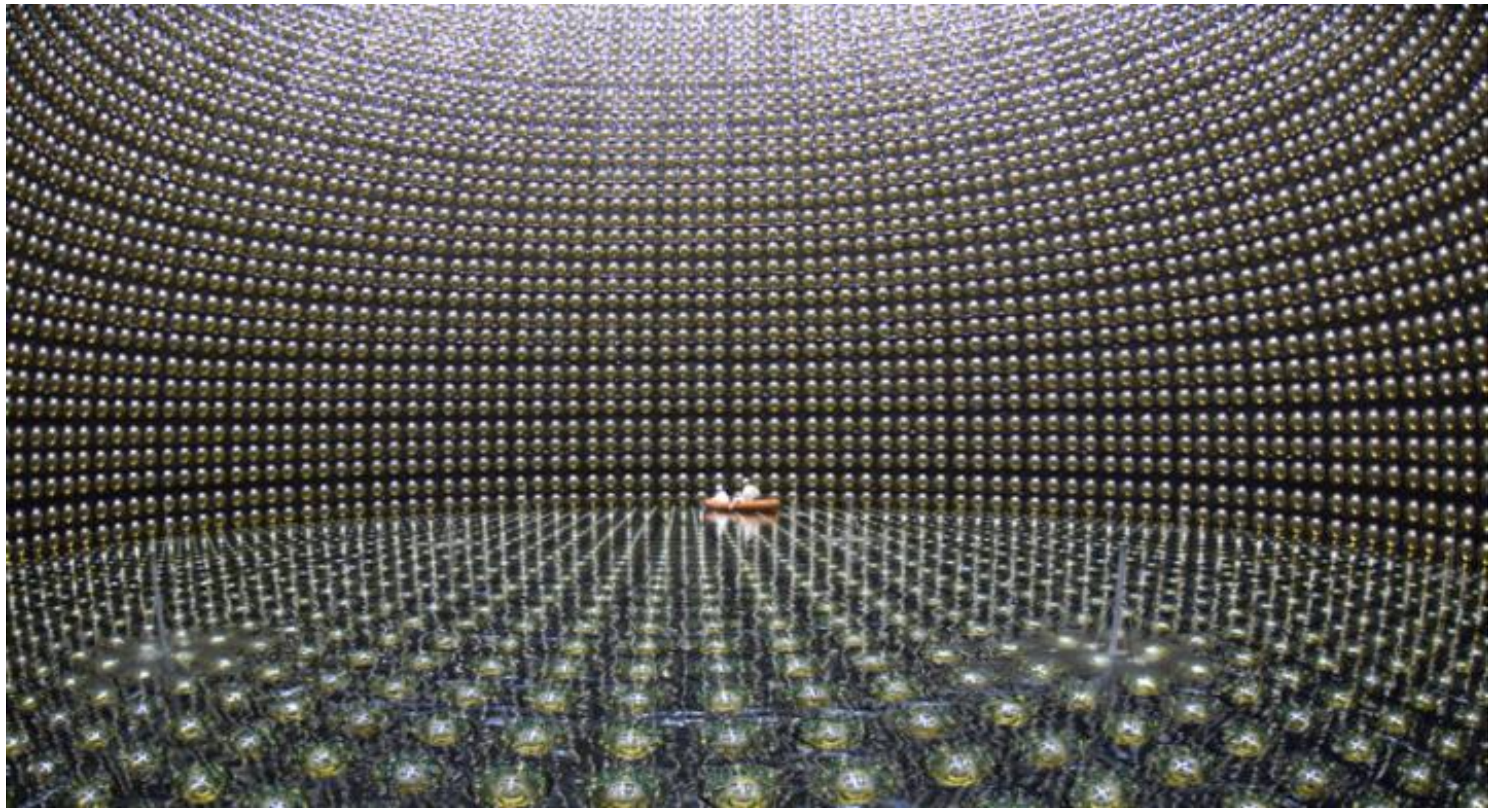

Super-Kamiokande
Mt. Noguchi-Goro
2,924 m
Mt. Ikeno-Yama
1,360 m
Near Detectors
J-PARC
1,700 m below sea level
Neutrino Beam
295 km

NOvA and T2K

NOvA far detector

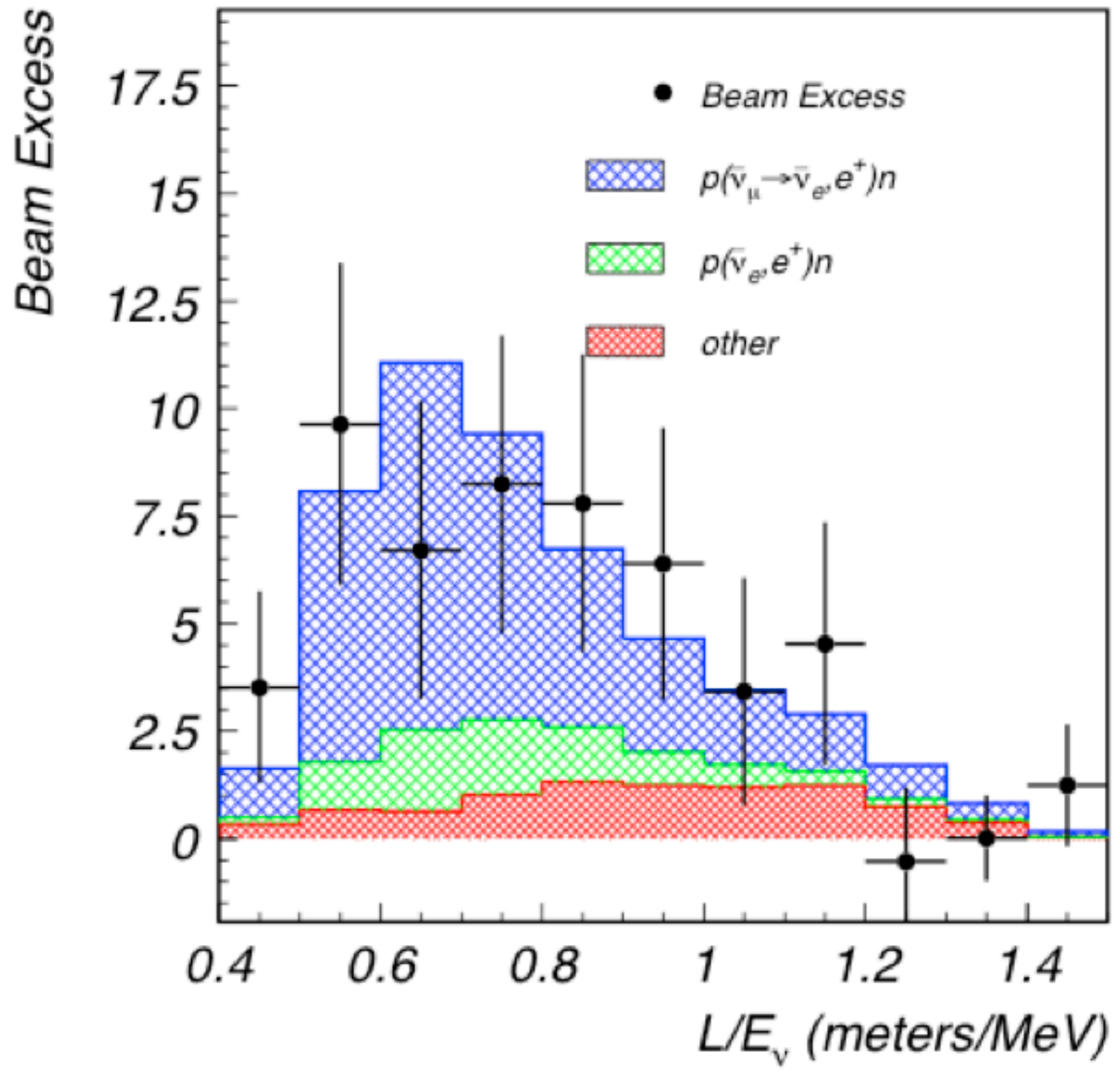


Famous Super-Kamiokande, far detector for T2K



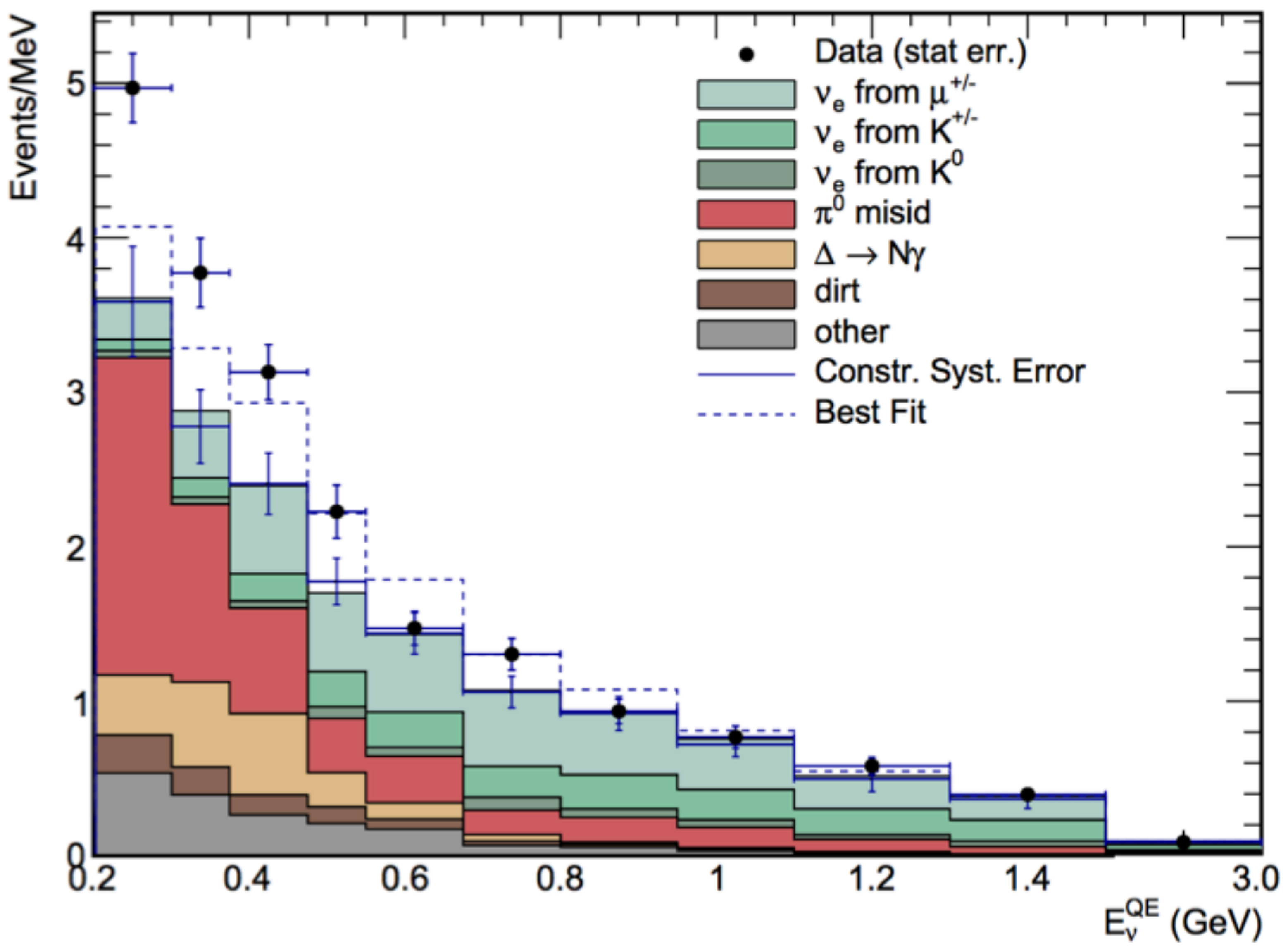
Sterile neutrino searches

Experimental origins

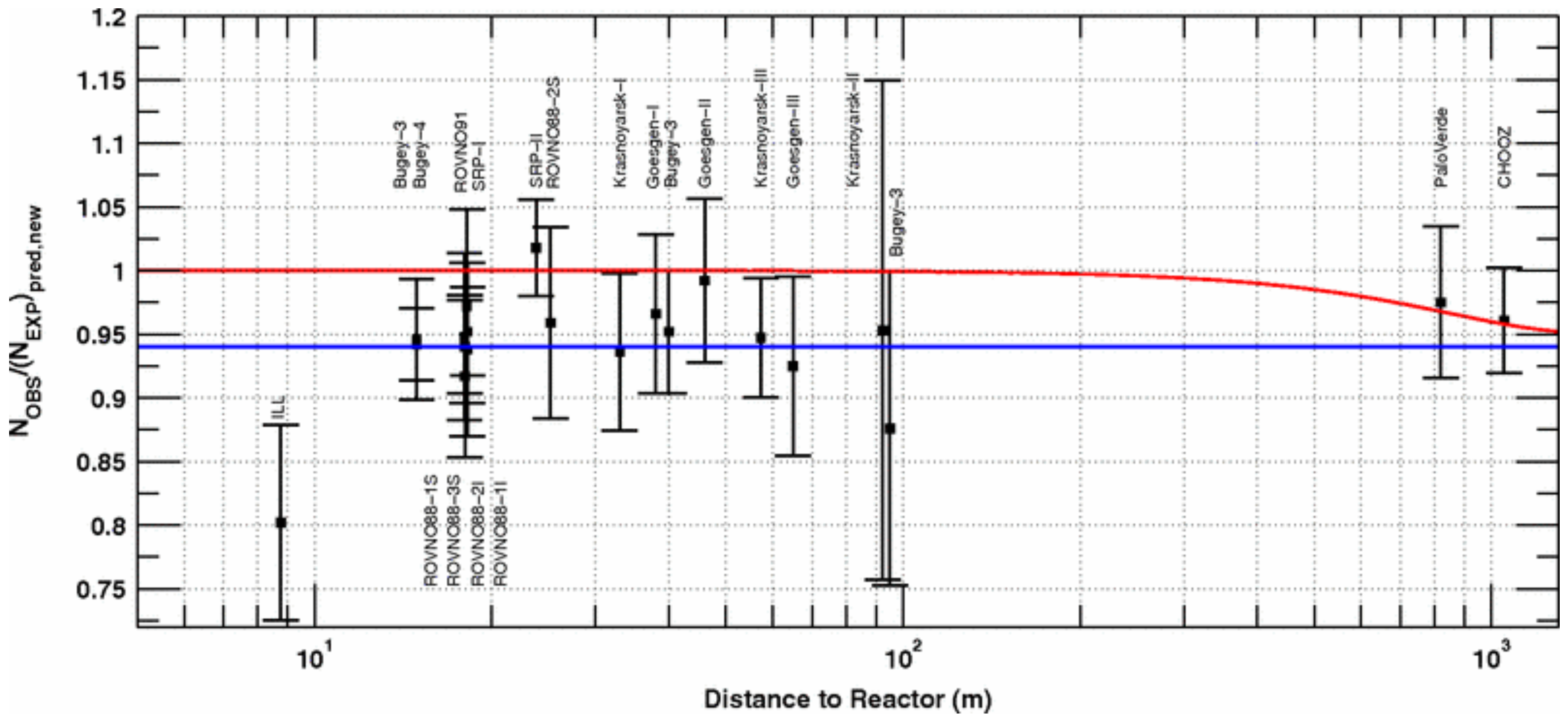


LSND detected $\bar{\nu}_e$'s with 3.8σ excess

MiniBooNE detected 4.8σ excess with ν_e's

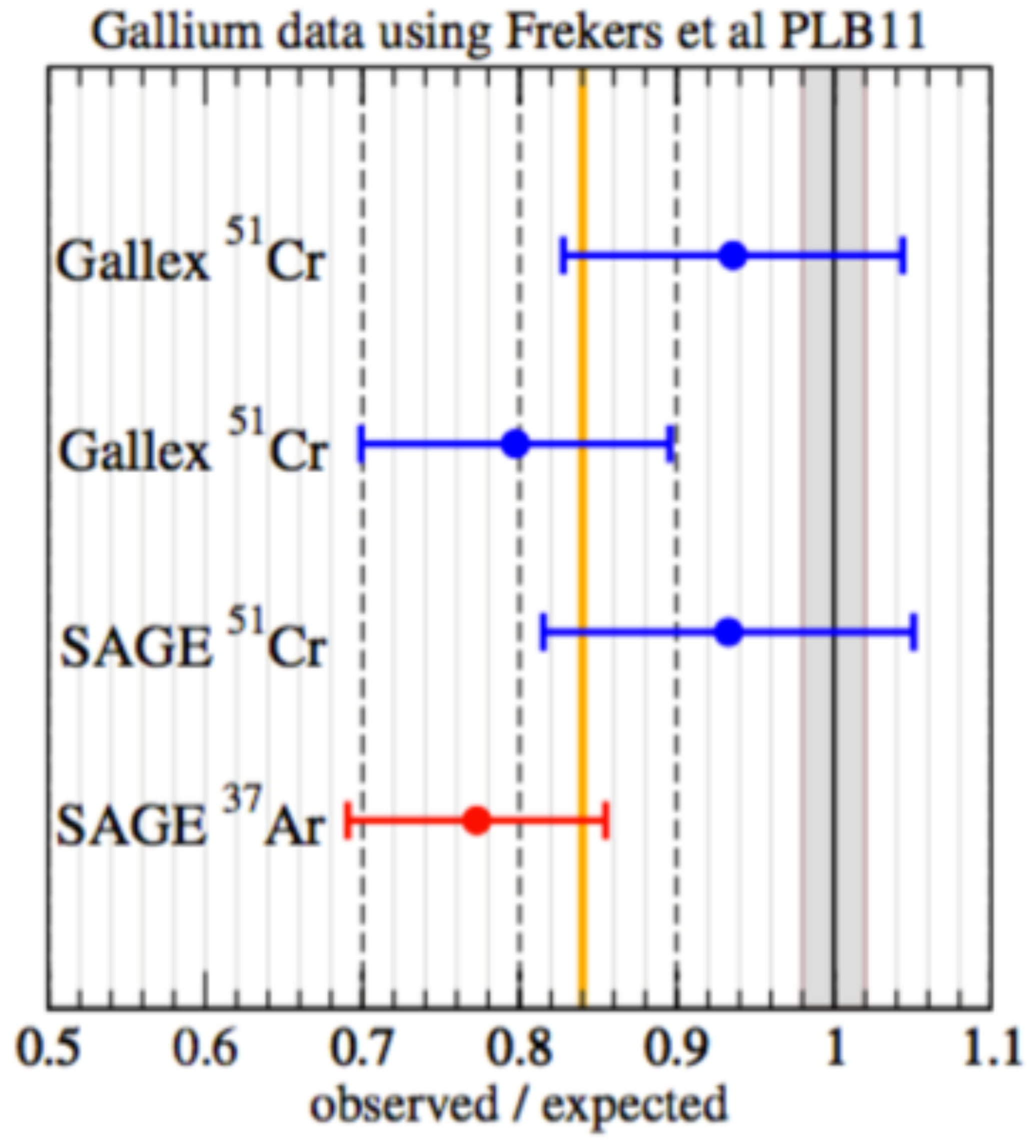


Absolute reactor $\bar{\nu}_e$ flux anomaly (RAA): 6% deficit (3σ)



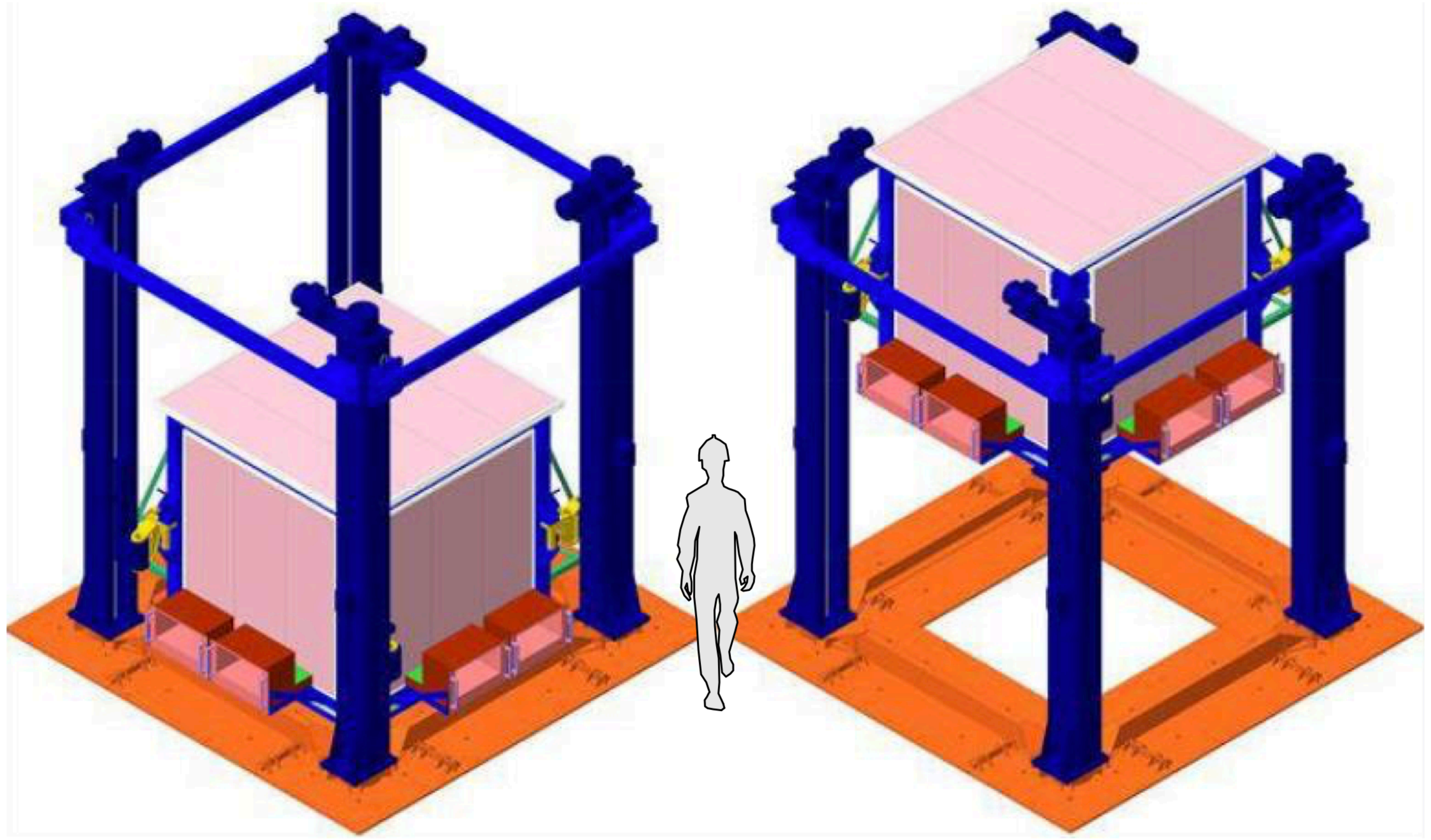
Neutrino-4 (3σ) and BEST (>5σ) also see anomalies.

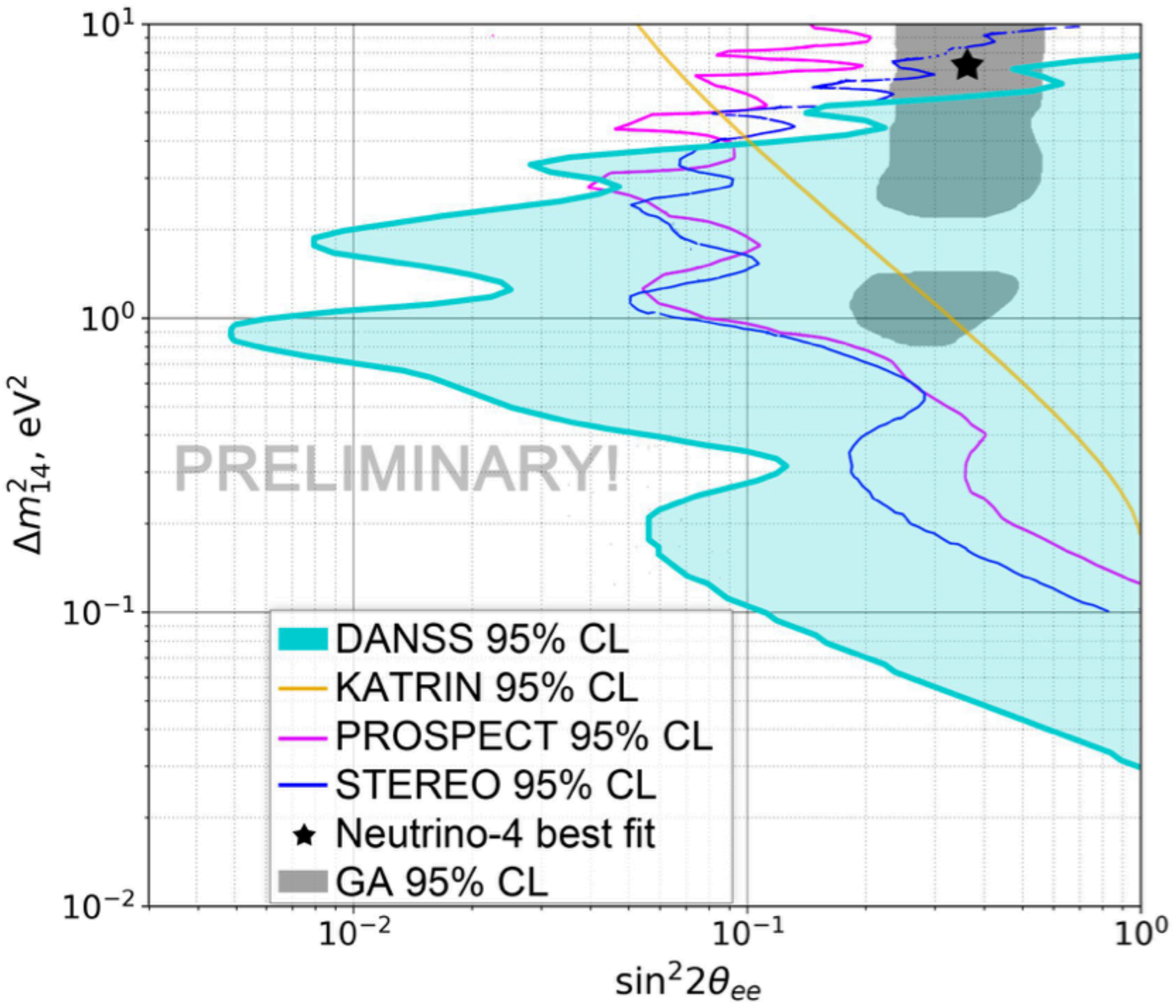
2.7σ deficit of ν_e's from intense electron capture calibration sources



DANSS

- JINR domestic experiment at KNPP.
- Data taking since 2016: collected the world's largest IBD event statistics
- Recent analysis using relative counting rates excludes a large and the most interesting fraction of sterile neutrino parameter space
- Currently: upgrade to check BEST и Neutrino – 4.
- More opportunities: reactor monitoring, measure high energy reactor antineutrino spectrum (study of bump and shoulder in spectra)



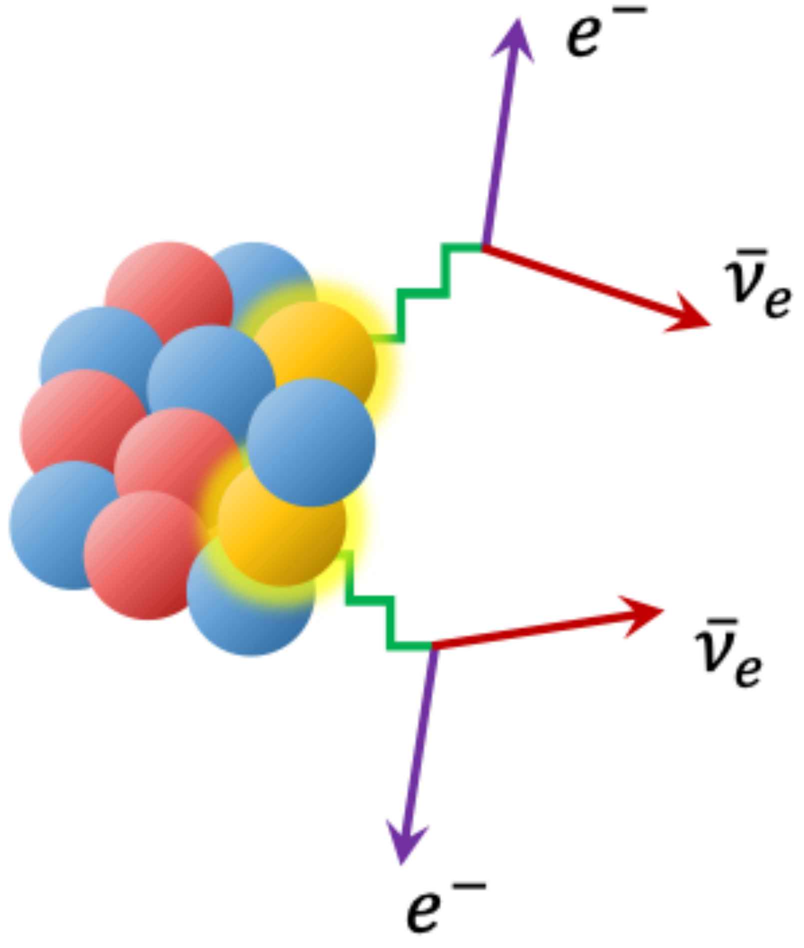


Neutrinoless double beta-decay

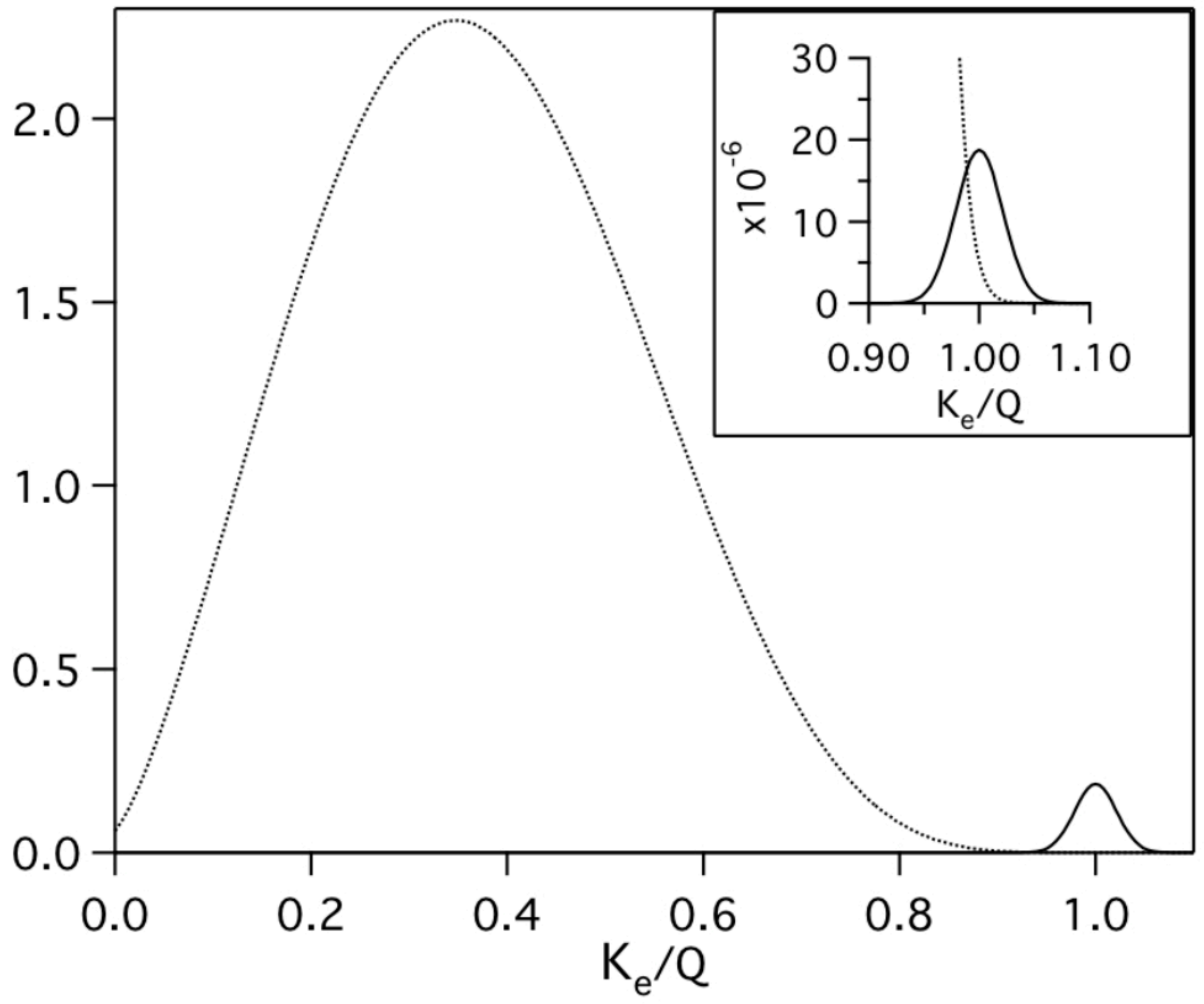
$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

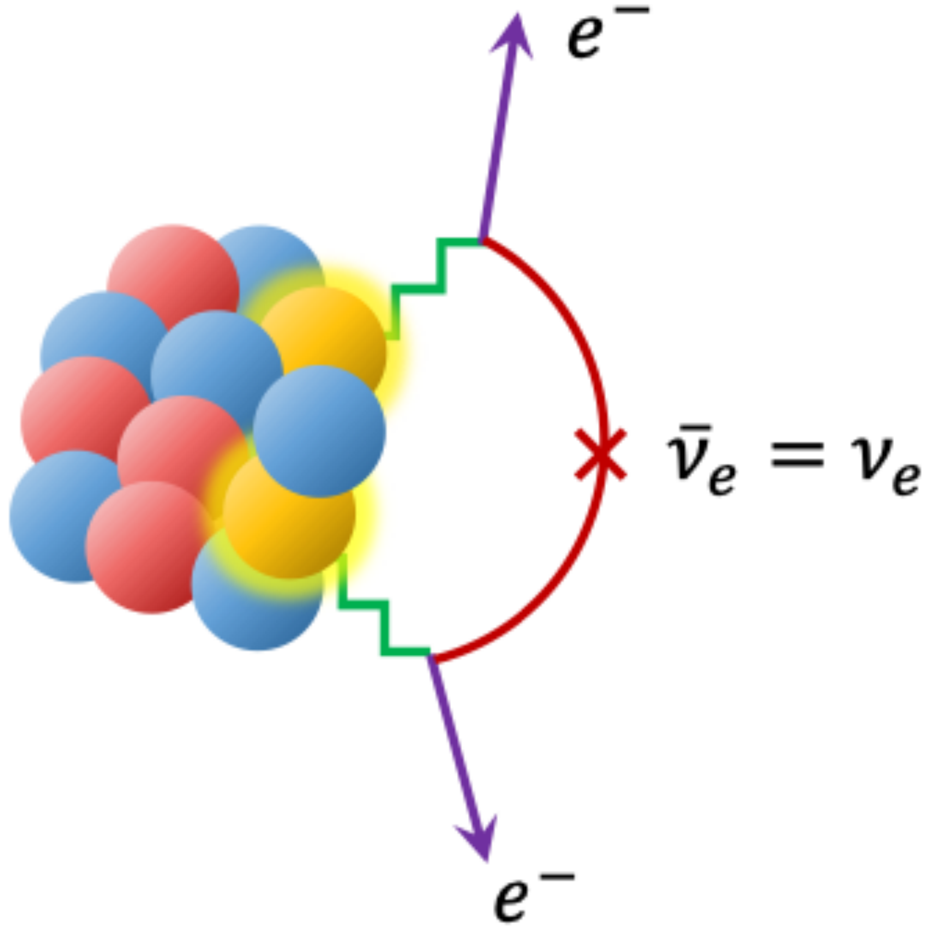
Answer the question whether neutrinos are Majorana particles.

Lepton number violation in weak processes can help to explain matter/antimatter asymmetry; smallness of neutrino masses.



$T_{1/2} \sim 10^{21}$ yrs





$T_{1/2} > 10^{25}$ yrs

Process is possible in isotopes that undergo SM-allowed $2\nu\beta\beta$ decay.

About 10 isotopes are considered in the experiments.

isotope mass

running time

detection efficiency

$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{m \cdot t}{B \cdot \sigma_E}}$$

bkg rate

energy resolution

nuclear matrix element (NME)

phase space factor

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$$

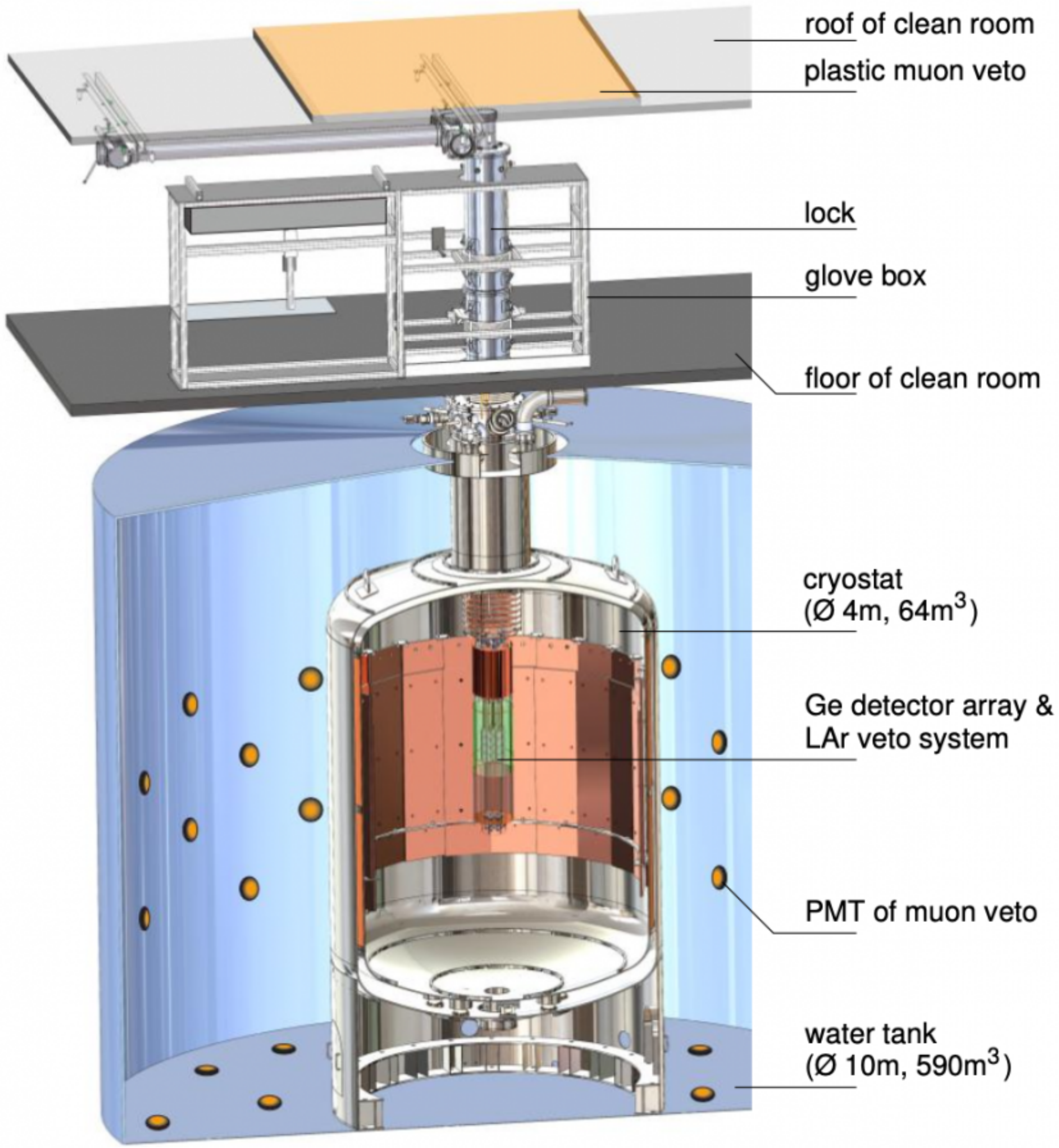
elements of PMNS matrix

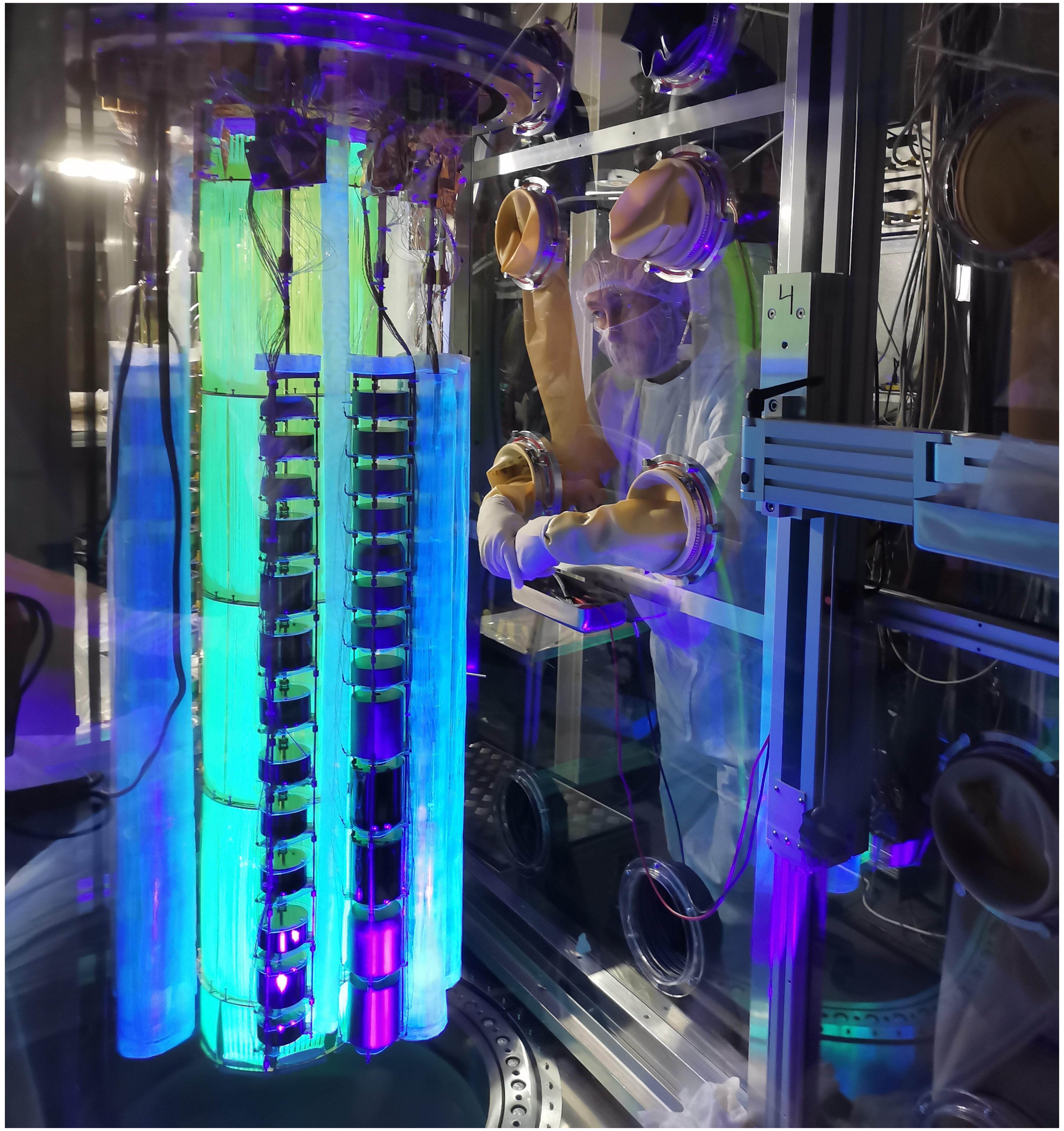
$$\langle m_{\beta\beta} \rangle^2 = | \sum_i U_{ei}^2 \, m_{\nu_i} |^2$$

Measure $T_{1/2} \rightarrow$ constraints for $\langle m_{\beta\beta} \rangle^2$

Neutrinoless double beta-decay

LEGEND

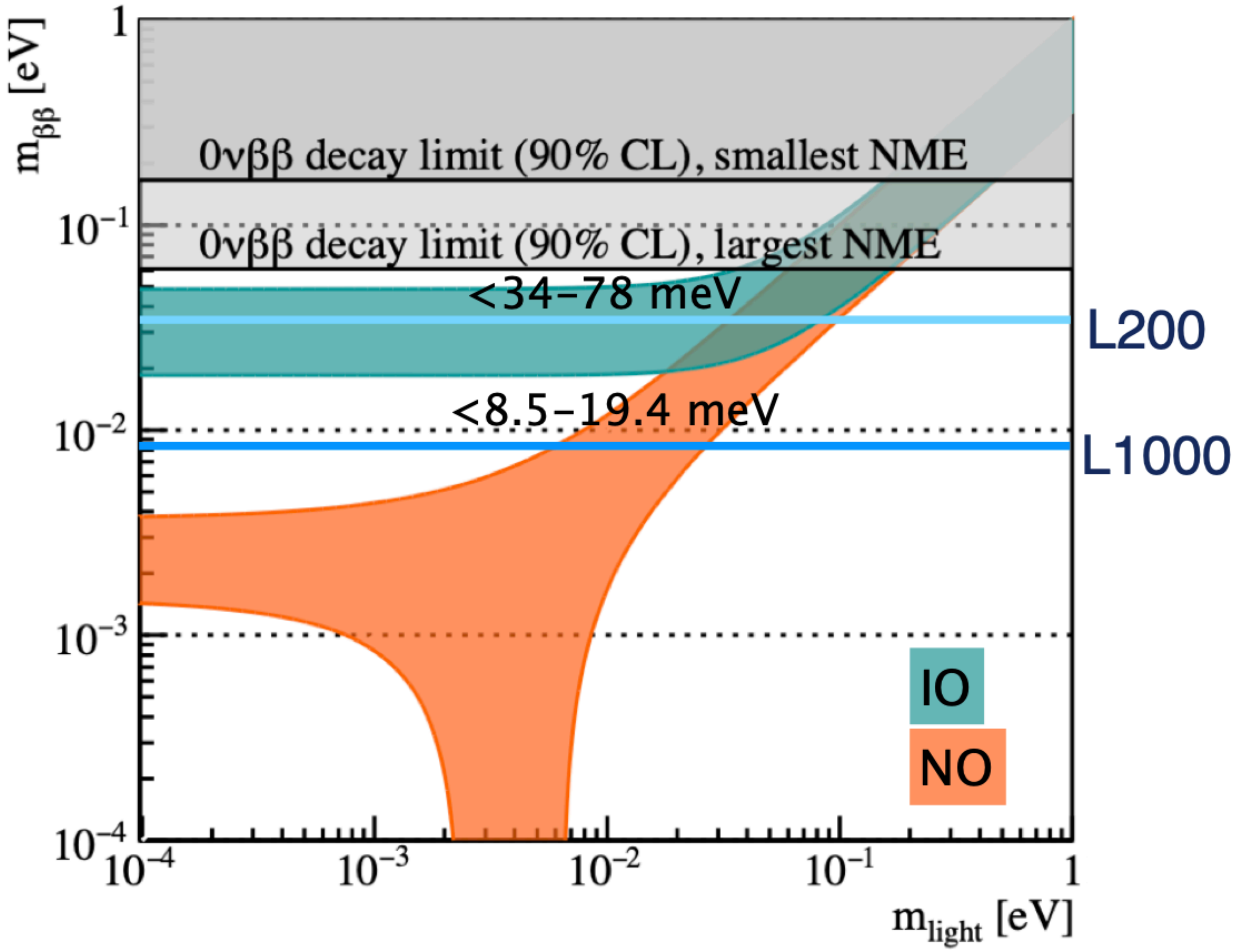




Neutrinoless double beta-decay

Recent results and physics at JINR

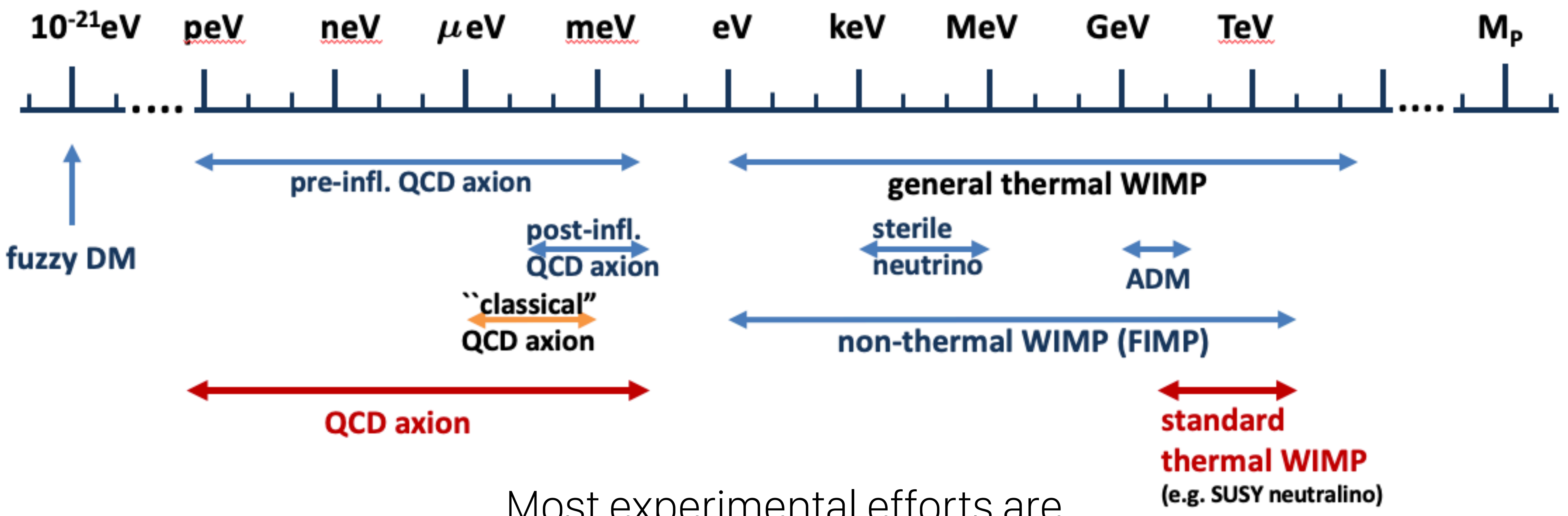
- The most precise restriction today is the one made by KamLAND-Zen 800
  $\langle m_{\beta\beta} \rangle$ < 28–122 meV
- SuperNEMO like NEMO-3 will have an ability to change the isotopes → a lot of unique measurements.
- First LEGEND-200 results: $\langle m_{\beta\beta} \rangle$ < 75–200 meV
- Near future experiment goal is IH area (sensitivity required $T_{1/2} \sim 10^{28}$ = 1 ton scale like LEGEND-1000).
- Complementary measurements:
  - MONUMENT: μ capture for several daughter nucleus for $0\nu\beta\beta$ decays
  - Zr-BNO (BNO) and Se-LSM (Modan): to study rare $2\nu\beta\beta$ decays



Dark matter

Intro

- ✴ Matter we know accounts only for 5% of the content of the universe!
- ✴ Dark matter interacts gravitationally – has a mass.
- ✴ Dark matter is essentially neutral and interacts very weakly w/ SM
- ✴ Nature: most likely a new particle Beyond the SM



Most experimental efforts are concentrated on these two

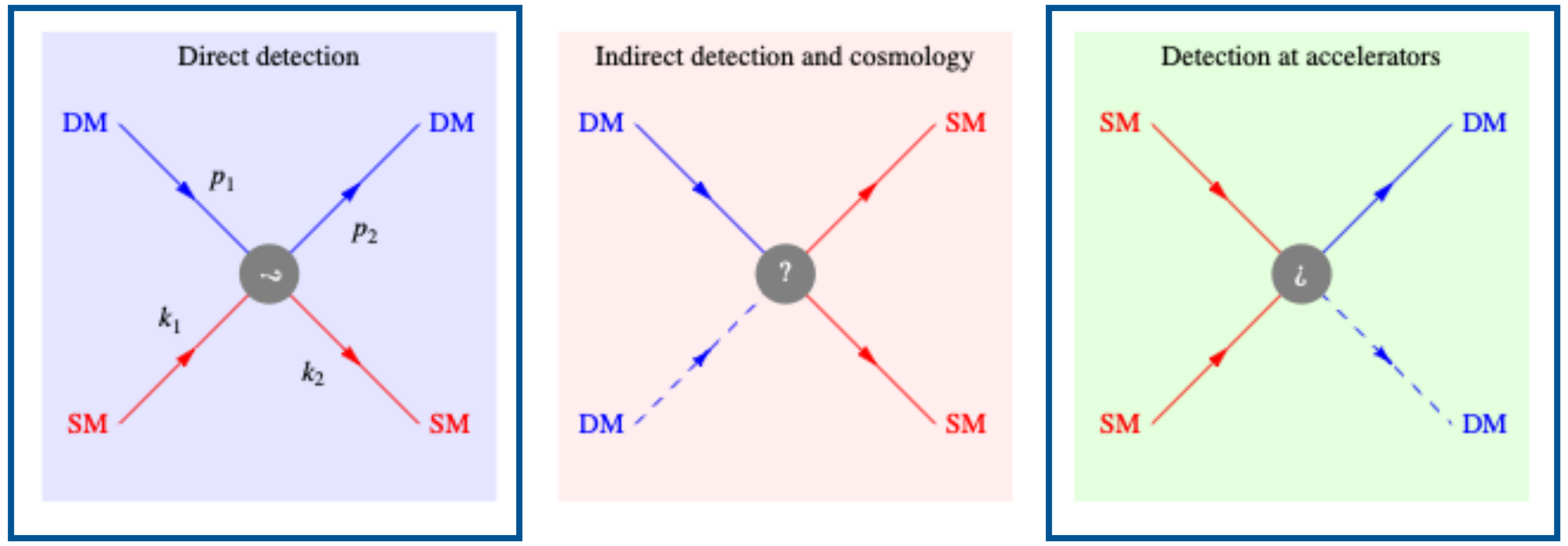
Dark matter

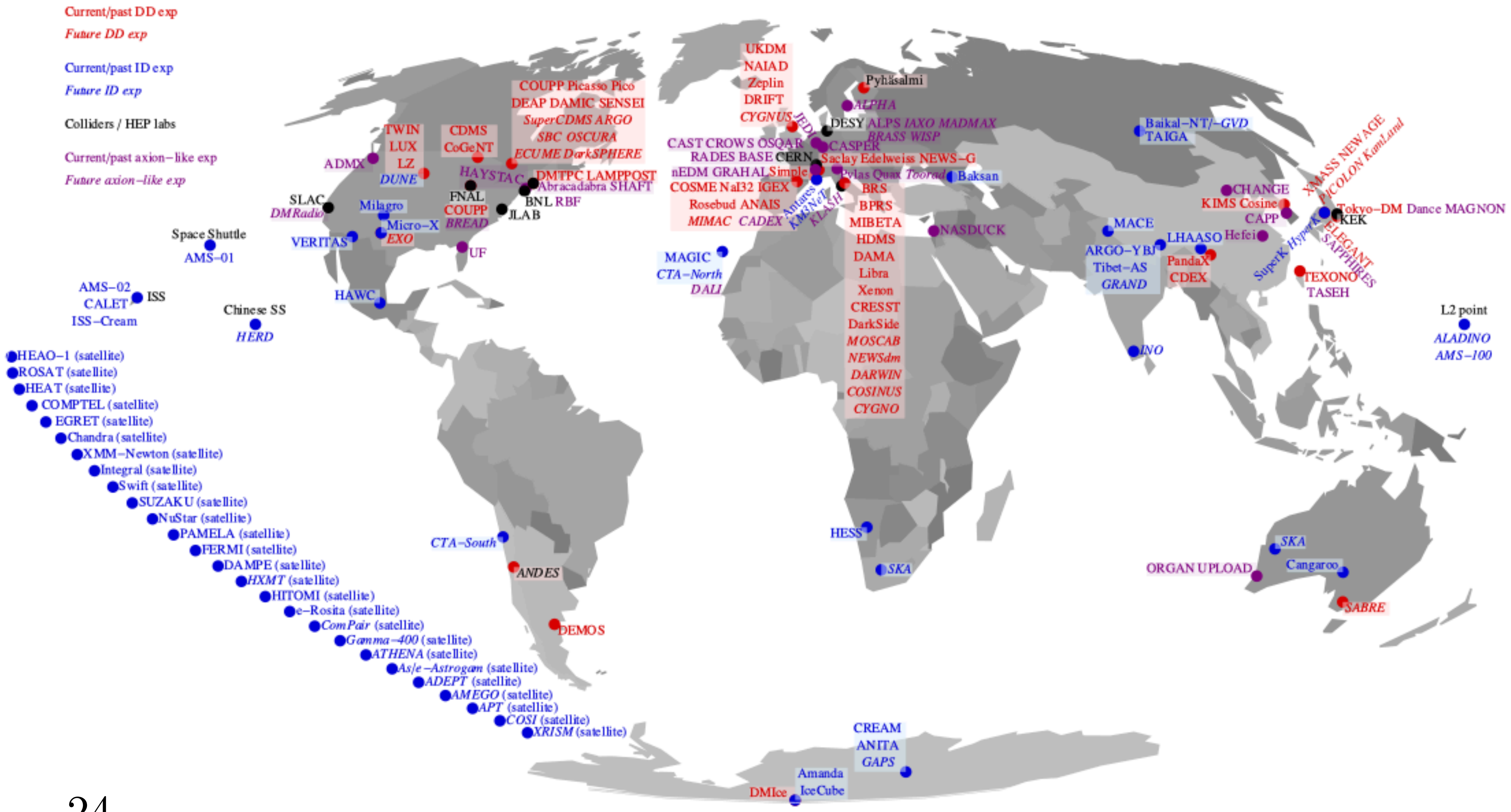
DarkSide and SHiP

- ✳ Detection of the energy deposited due to elastic scattering off target nuclei.
- ✳ Elastic scattering of a WIMP deposits small amount of energy into recoiling nucleus (~ few 10s of keV)
- ✳ The noble-gas TPC detector technology is highly promising: LAr (DarkSide) and LXe.
- ✳ SHiP is a fixed target accelerator experiment for ν physics and dark matter search; expected to start taking data in ~2035 at CERN

Like in DarkSide

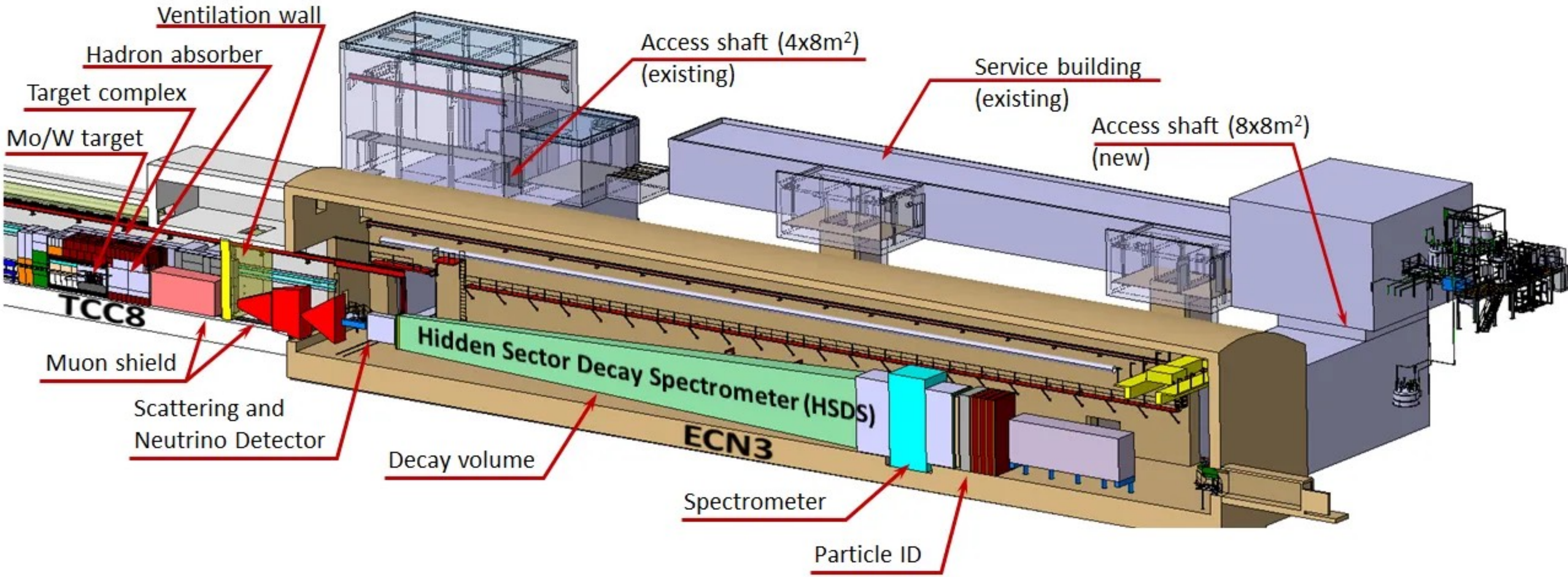
Like in SHiP



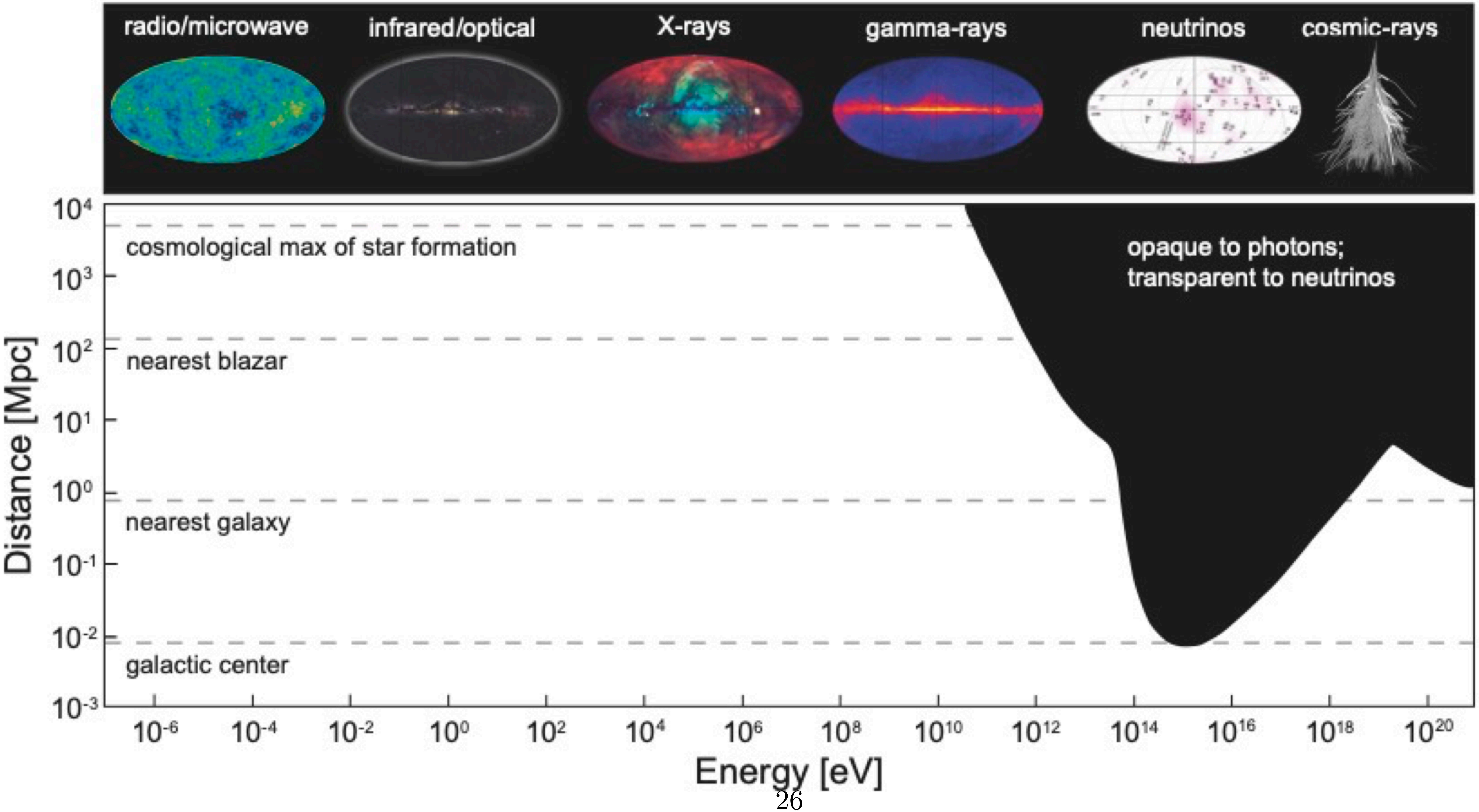


Dark matter

SHiP

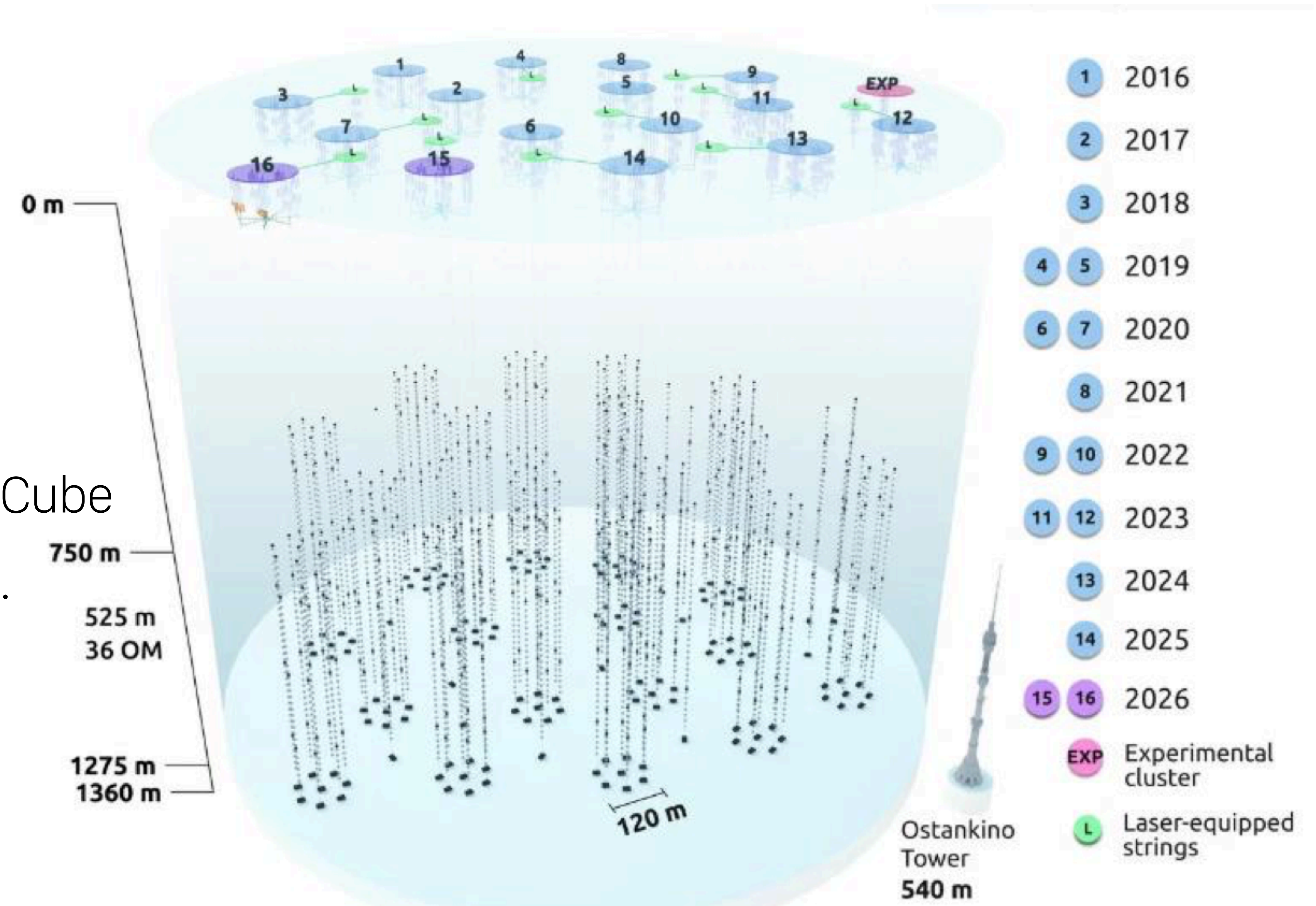


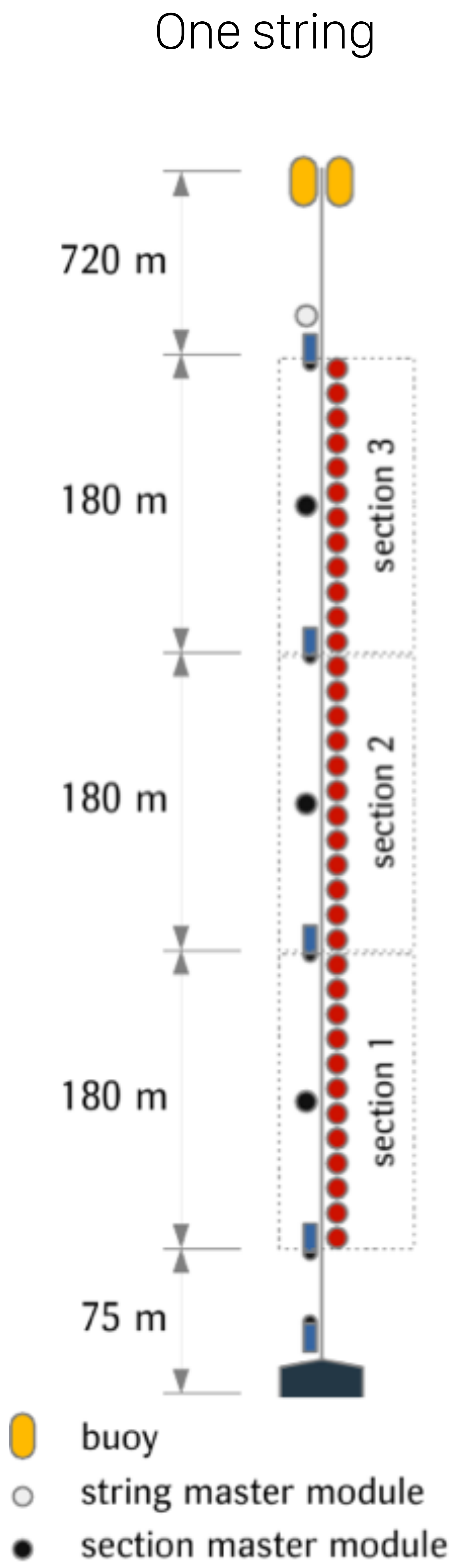
Astrophysical neutrinos



Baikal GVD

- ✳ Experiment in the Northern hemisphere at Baikal lake with strong JINR participation.
- ✳ Goal is to find sources of astrophysical neutrinos
- ✳ Planned volume ~1 km^3.
  - ✳ Currently installed 0.8 km^3.
- ✳ Advantages:
  - ✳ water instead of ice,
  - ✳ high angular resolution,
  - ✳ cheaper technology than IceCube
- ✳ Part of Global Neutrino Network.



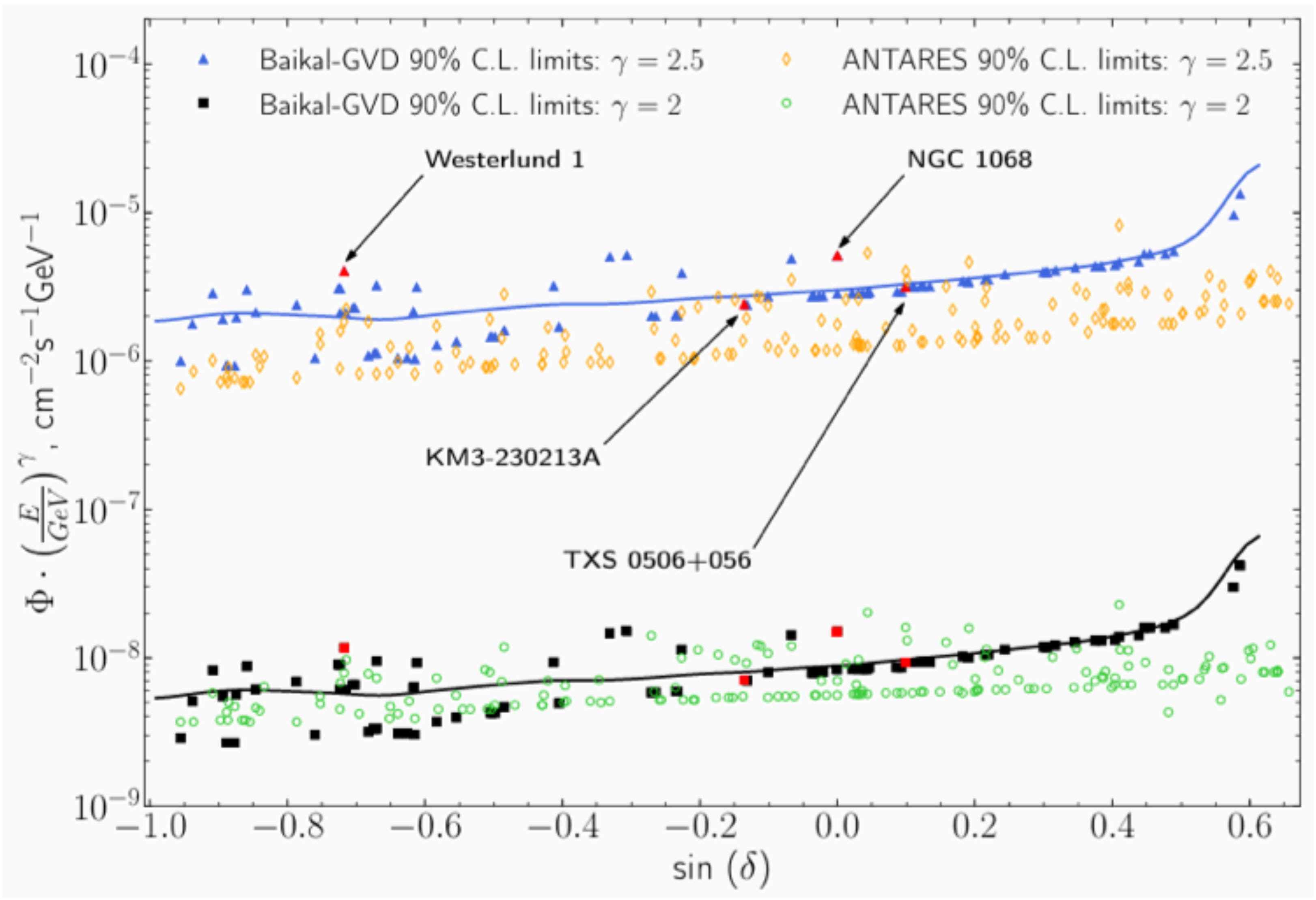


Baikal GVD

Baikal GVD

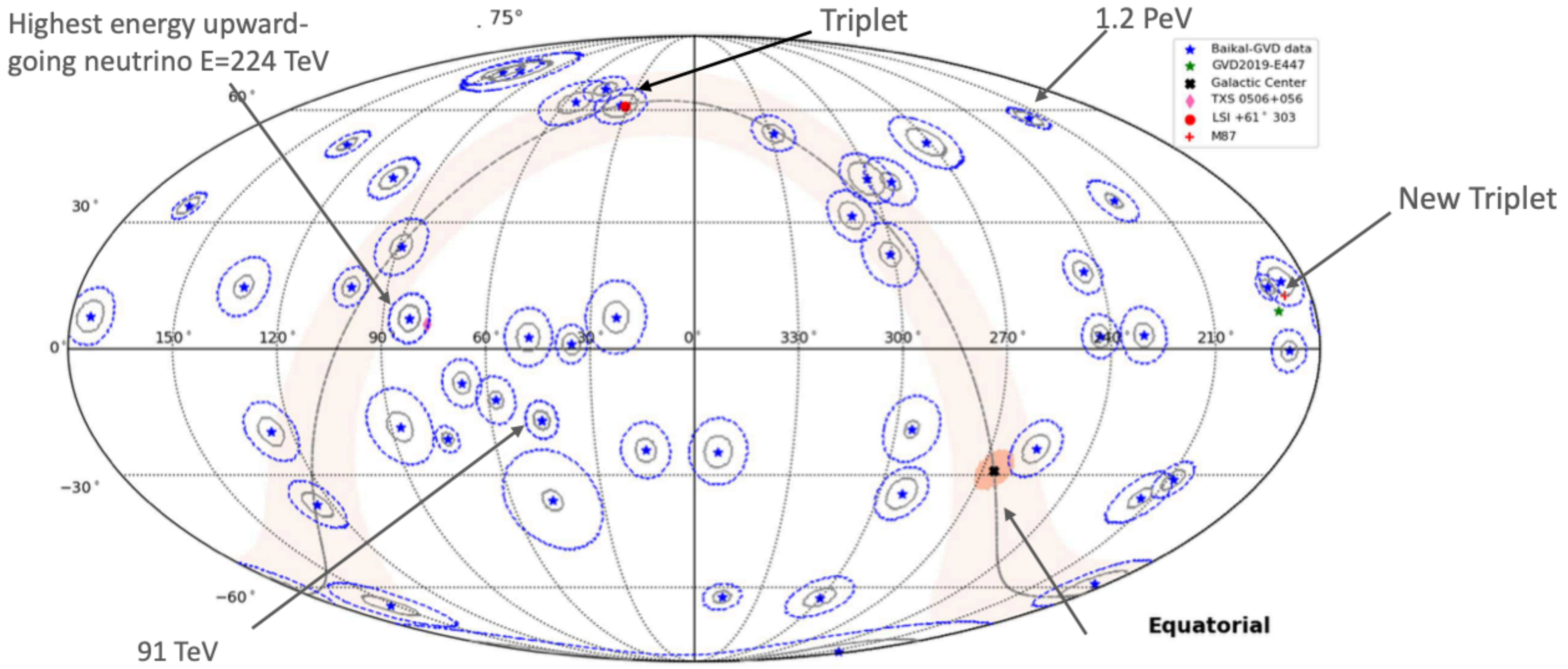
Current results

- ✳ As of 2021 Baikal-GVD is the largest neutrino telescope in the North at present.
- ✳ Baikal and ANTARES confirm the results obtained by IceCube.
- ✳ Possible upgrade to 30 km^3 detector is under consideration (Baikal-HUNT)



Point-like source search with tracks
Guided search over a list of 92 objects

New high-energy cascade sky map
Data from April 2018 to March 2024



Highest energy upward-going neutrino E=224 TeV

Triplet

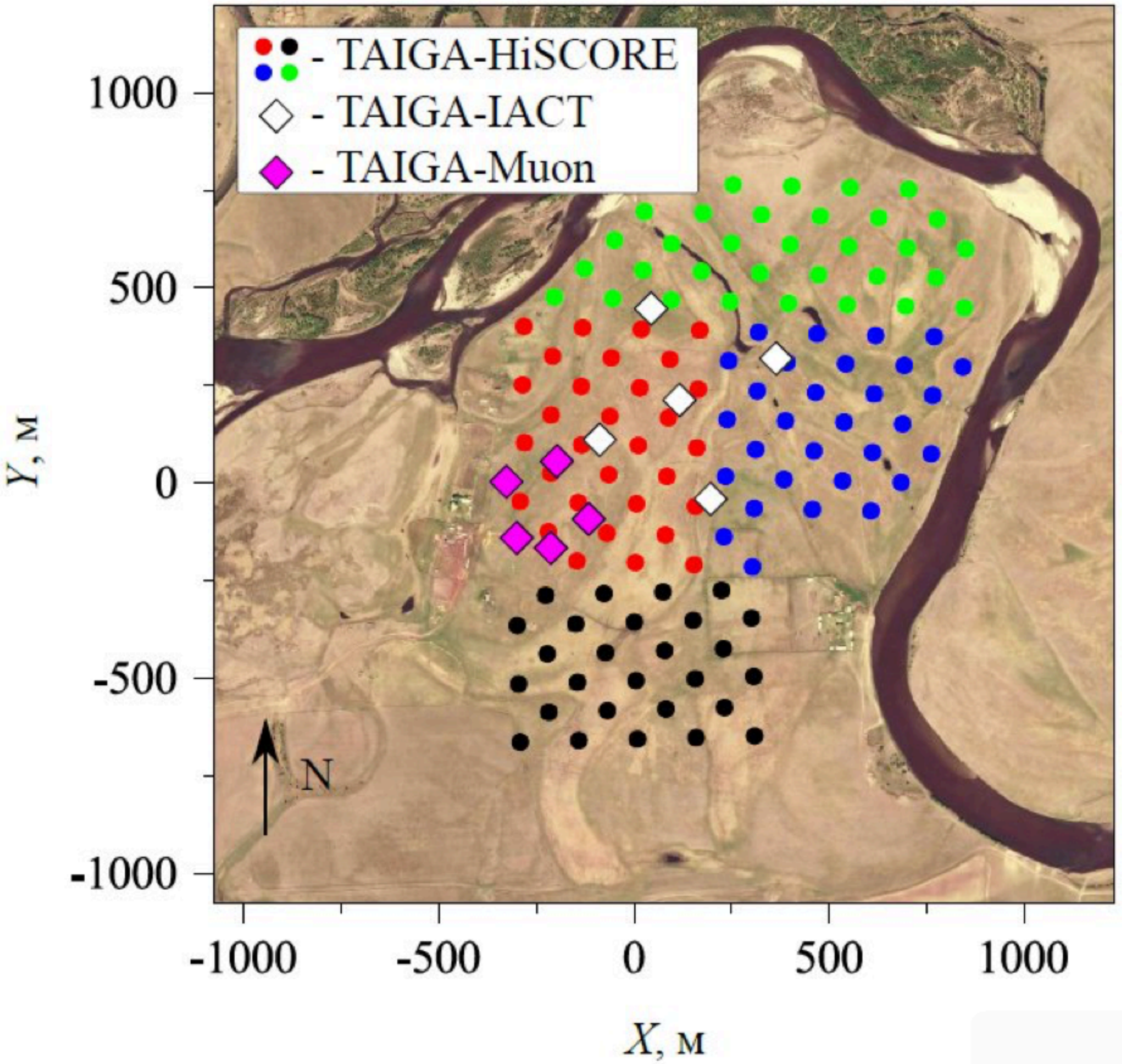
1.2 PeV

New Triplet

91 TeV

TAIGA

- ✳ Hybrid astrophysical complex for detecting high energy cosmic rays in order to study their flux and origin
  - ✳ CR physics in energy range $10^{14} - 10^{18}$ eV
  - ✳ Gamma astronomy in energy range > 10^{12} eV
- ✳ Consist of TAIGA-IACT atmospheric Cherenkov telescopes and wide-angle Cherenkov detectors TAIGA-HiSCORE



- ✳ Water Cherenkov pools are under construction
- ✳ Possibility of extending this project to 100 km^2 experiment is under consideration

Theory (at BLTP)

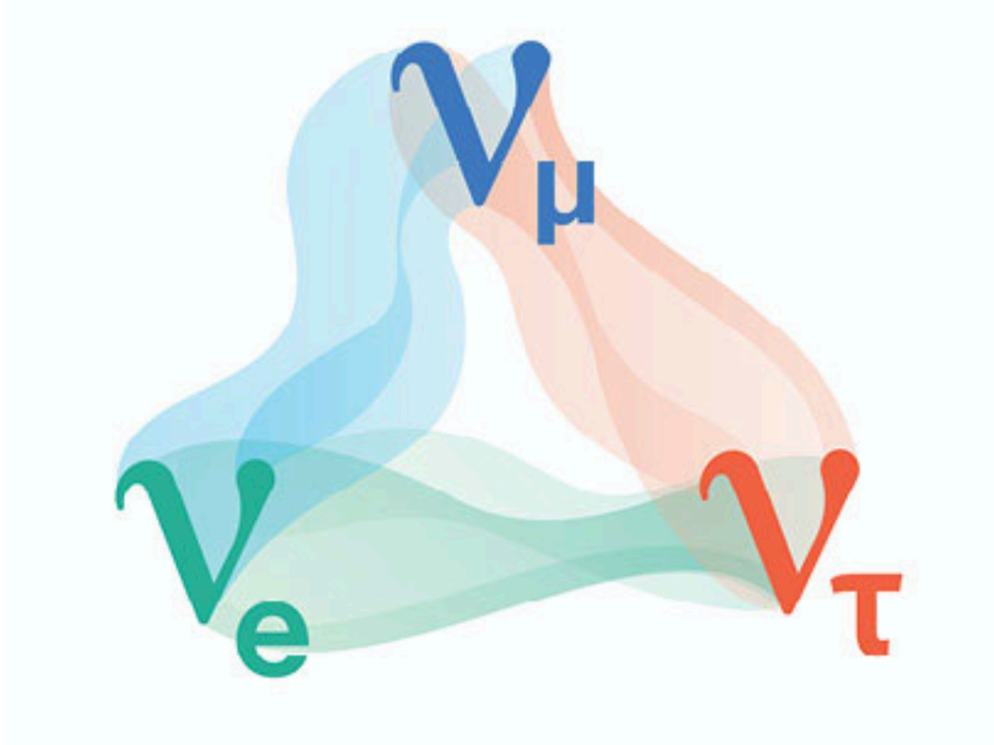
- Theoretical support to different experiments mentioned:
  - Neutrino-nucleus interactions, model tunes according to the modern experimental data.
  - QFT of neutrino oscillations.
  - NMEs calculations for $0\nu\beta\beta$ and $2\nu\beta\beta$.
  - Investigation of the corrections to the reactor antineutrino flux prediction (in context of reactor antineutrino anomaly).
- Schools for young scientists in neutrino physics:
  - annual Baikal school;
  - biennial Baksan School jointly with INR RAS;
  - biennial Pontecorvo Neutrino Physics school.

JINR possesses a unique prominent scientific school in neutrino physics founded by B. Pontecorvo and S.M. Bilenki who worked here.

Summary

- Very exciting time for many areas of neutrino physics.

- In the upcoming couple decades should get answers to many outstanding questions:
  - Precise knowledge of oscillation parameters and NMO.
  - Are there sterile neutrinos?
  - Is there a $0\nu\beta\beta$ decay?
  - What is the origin of ultra high energy astrophysical neutrinos?
  - etc



- To probe all of them new groundbreaking methods and detector techniques are needed (hardware and software) as well as a reduction of known systematics.

- If you're interested you're very welcome to join!