CP symmetry test with neutrinos

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- Neutrino oscillation
- CP symmetry test with neutrino
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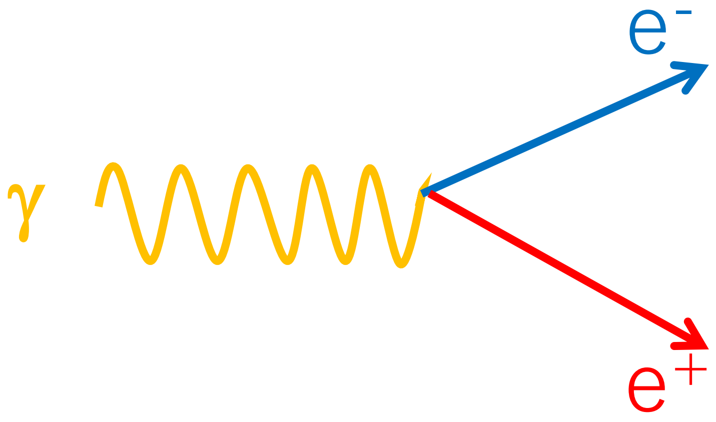
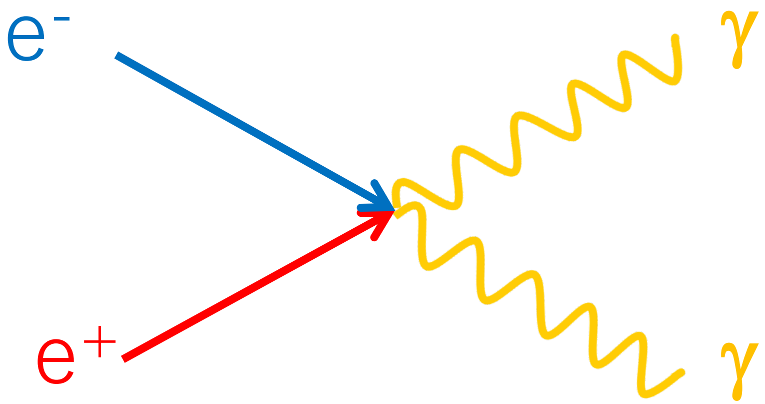
- Summary

Anti-matter

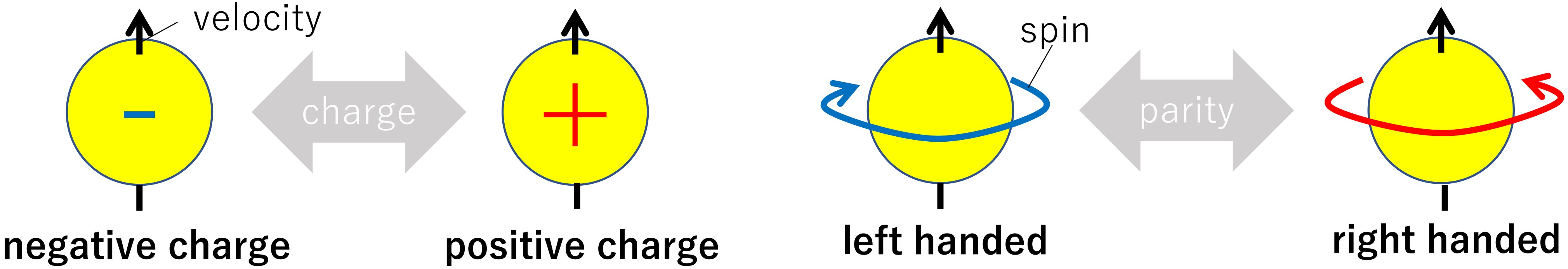
- **Quarks and leptons** have their **anti-matter** counterparts which have **almost** same characters but opposite charges.
  - Electron (e^-) ⇔ Positron (e^+)
  - Quark (q) ⇔ Anti-quark ($\bar{q}$)
  - Neutrino (ν) ⇔ Anti-neutrino ($\bar{\nu}$)
- **Pair creation** and **Annihilation**
  - Matter and its anti-matter are created/annihilated in pairs from/into **energy (= photons)**.



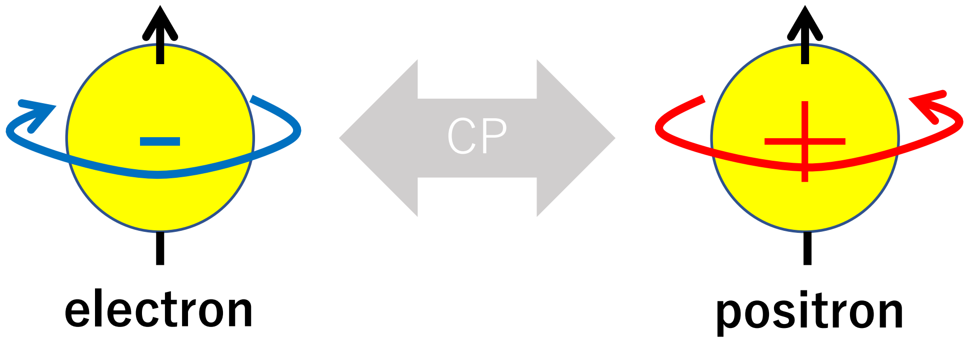


CP symmetry

- CP transformation
  - Charge conjugation + Parity reversal

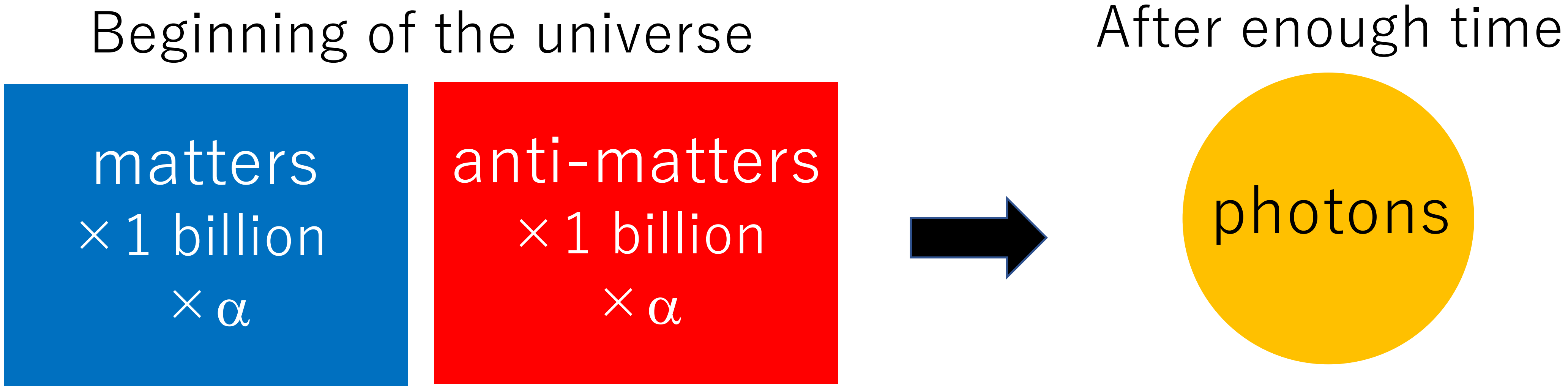


- Matter and its anti-matter are related by CP transformation.
  - CP violation means the laws of the physics are not the same for matter and anti-matter.



Mystery of the universe

- The universe started with the Bing Bang (= huge energy).
  - Same amount of matters and anti-matters were produced in **pair creation** at that time.
  - If enough time has passed, all the matters and the anti-matters are converted into photons in **annihilation**.



Beginning of the universe

matters
×1 billion
×α

anti-matters
×1 billion
×α

After enough time

photons

Mystery of the universe

- Current universe (13.8 billion years after the Big Bang).
  - Photons and matters are dominated, but no anti-matter exists.
  - **1/1000000000** imbalance between matters and anti-matters (= CP violation) is required.
    - Quarks violate the CP symmetry, but 7 digits short.
    - **<u>Test the CP symmetry in neutrinos!</u>**

Beginning of the universe

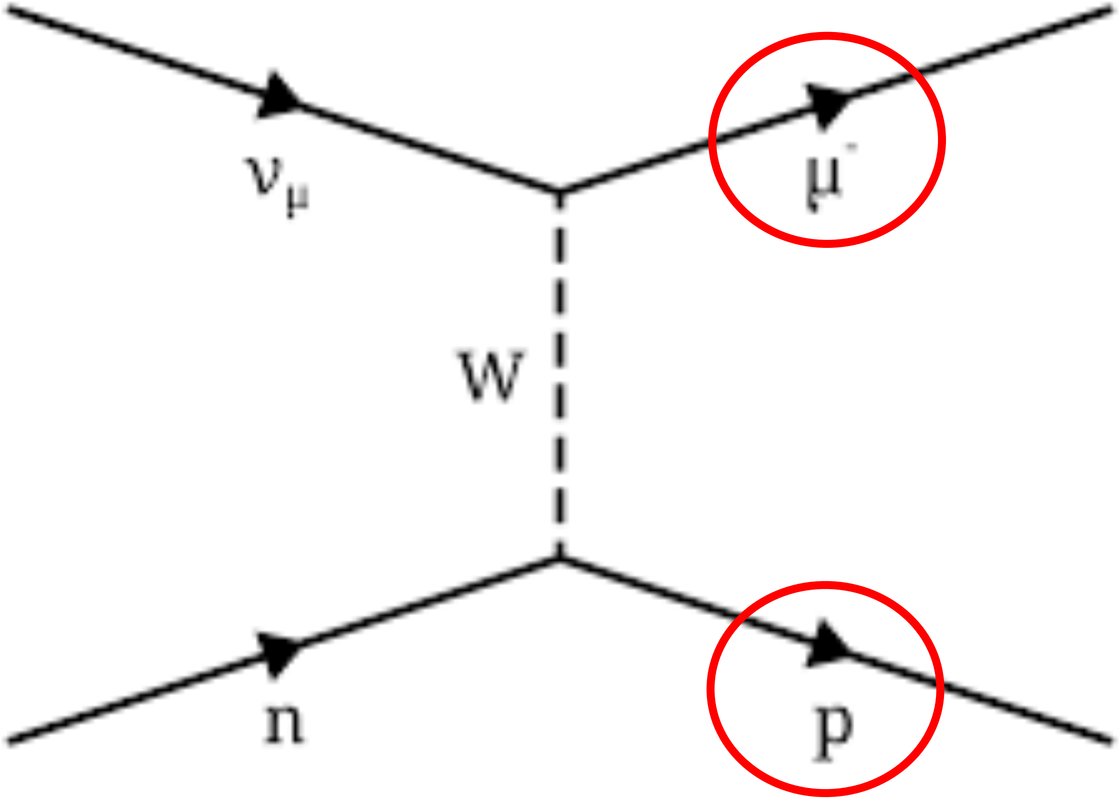
The current universe

Neutrinos

- 3 flavors (ν_e, ν_μ, ν_τ) and their anti-matters (ν_e, ν_μ, ν_τ)
- No charge
- **Very light** but non-zero **mass** ($< 10^{-5}\ m_e$)
- **Weak interaction** only, so it is called ghost particle.
- Flavor eigenstates (ν_e, ν_μ, ν_τ) and mass eigenstates (ν_1, ν_2, ν_3) are mixing.
- The universe is full of neutrinos.
  - photons ~ $400/cm^3$
  - **neutrinos ~$300/cm^3$**
  - proton/neutron ~ $0.000001/cm^3$

How to detect neutrinos

- Observe charged particles generated in the weak interactions.



Neutrino oscillation

- Neutrino is produced in one of flavor eigenstates (ν_e, ν_μ, ν_τ).
- Then, it travels in superposition of mass eigenstates (ν_1, ν_2, ν_3).

$$|\nu_l(t)>=\sum_{i=1}^{3}\boxed{U_{li}}e^{-iE_it}|\nu_i>$$

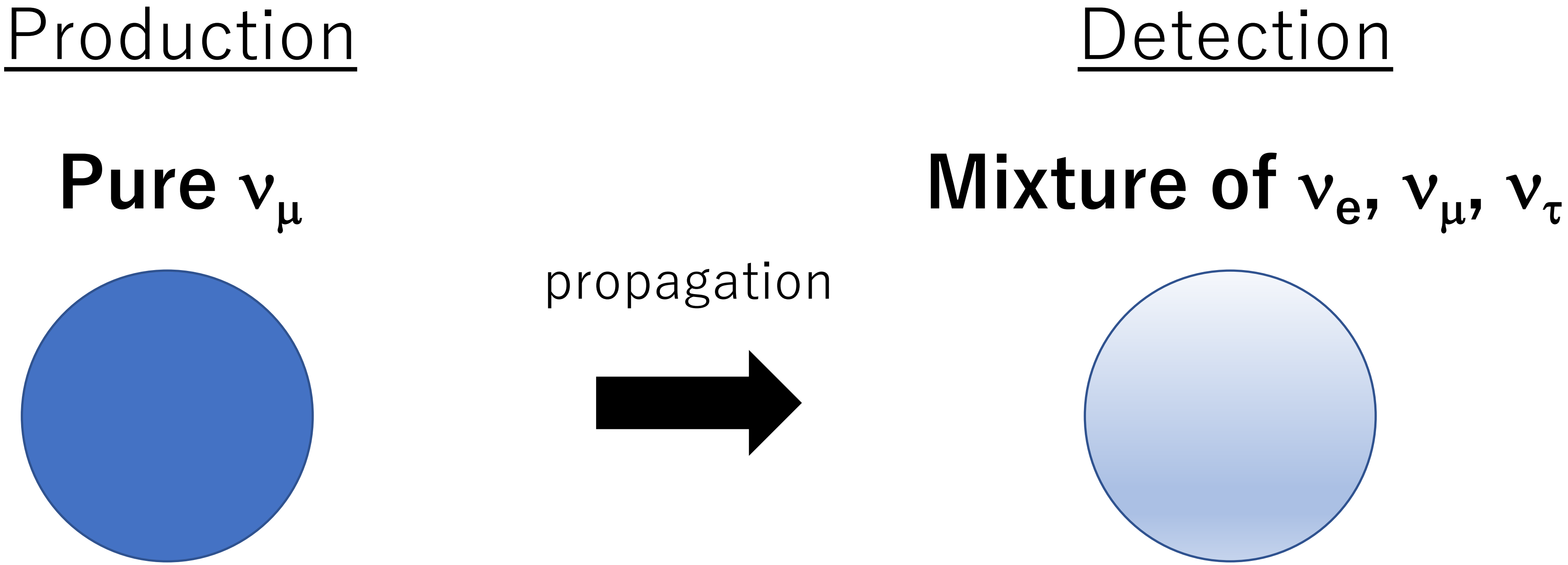
mixing matrix

$$E_i = p + \frac{m_i^2}{2p}$$

- Relative phases of the mass eigenstates change due to their mass differences, and it results different mixture of flavor eigenstates.

Neutrino oscillation!

Neutrino oscillation



Production

Pure ν_μ

propagation

Detection

Mixture of ν_e, ν_μ, ν_τ

Neutrino oscillation

Mixing matrix:

$$U_{li} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- 2 flavor case (for simplicity)

Appearance probability

$$P(\nu_e \to \nu_\mu; t) = P(\nu_\mu \to \nu_e; t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$\Delta m^2 \equiv m_2^2 - m_1^2$: mass difference

θ : mixing angle

measure

$L (= t)$: flight length

E : neutrino energy

control

$$C_{ij} = \cos\theta_{ij}, \ \ S_{ij} = \sin\theta_{ij}$$

Neutrino oscillation

- 3 flavor case

Pontecorvo-Maki-Nakagawa-Sakata (**PMNS**) mixing matrix:

$$U_{li} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Acc./Atmospheric ν Reactor ν & Acc. ν Solar ν

$\sin^2\theta_{23} = 0.512^{+0.019}_{-0.022}$ $\sin^2\theta_{13} = (2.18 \pm 0.07) \times 10^{-2}$ $\sin^2\theta_{12} = 0.307^{+0.013}_{-0.022}$

(Normal hierarchy, octant I)

<u>3 × 3 unitary matrix → 1 complex phase</u>

δ_{CP} : CP violation phase ($\delta_{CP} \rightarrow -\delta_{CP}$ for anti-ν)

Long-baseline accelerator neutrino oscillation experiments

$$\nu_\mu \to \nu_e ; t \quad \Longleftrightarrow \quad \overline{\nu}_\mu \to \overline{\nu}_e ; t$$

CP transformation

δ_{CP}

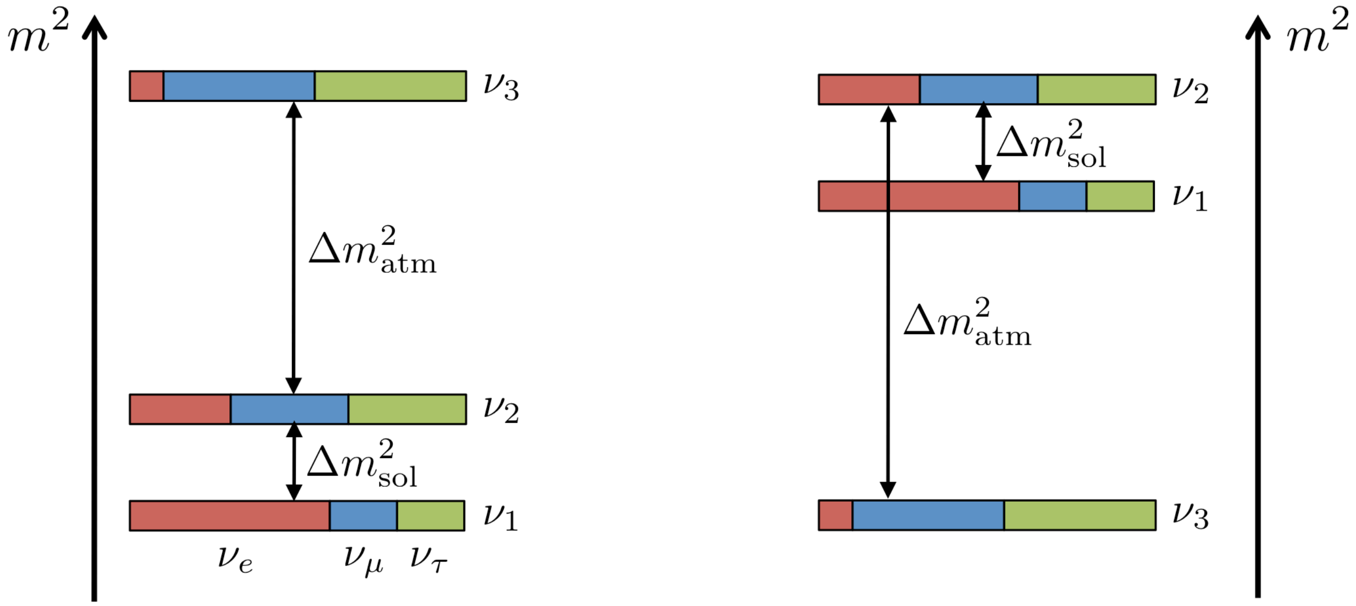
1. **Produce** $\nu_\mu / \overline{\nu}_\mu$ beams with accelerators.
2. **Detect** the beams at far detectors at distances of ~300-800 km.
3. **Compare** $P(\nu_\mu \to \nu_e ; t)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e ; t)$.

If $P(\nu_\mu \to \nu_e ; t) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e ; t)$ ➡ $\delta_{CP} \neq 0$, **CP violation**

If ν travels in vacuum, that’s it.
But, another effect exists.

Mass hierarchy

- Sign of Δm^2_{32} is not know.



normal hierarchy (NH)

inverted hierarchy (IH)

$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} eV^2$$

normal hierarchy (NH)

$$\Delta m^2_{32} = (2.444 \pm 0.034) \times 10^{-3} eV^2$$

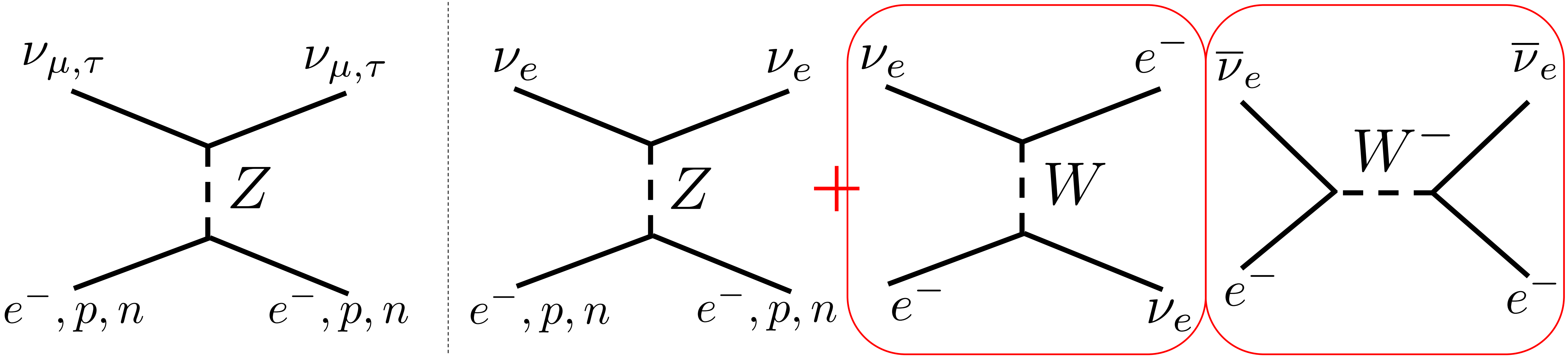
inverted hierarchy (IH)

$$\Delta m^2_{32} = (-2.53 \pm 0.05) \times 10^{-3} eV^2$$

Matter effect in neutrino oscillation

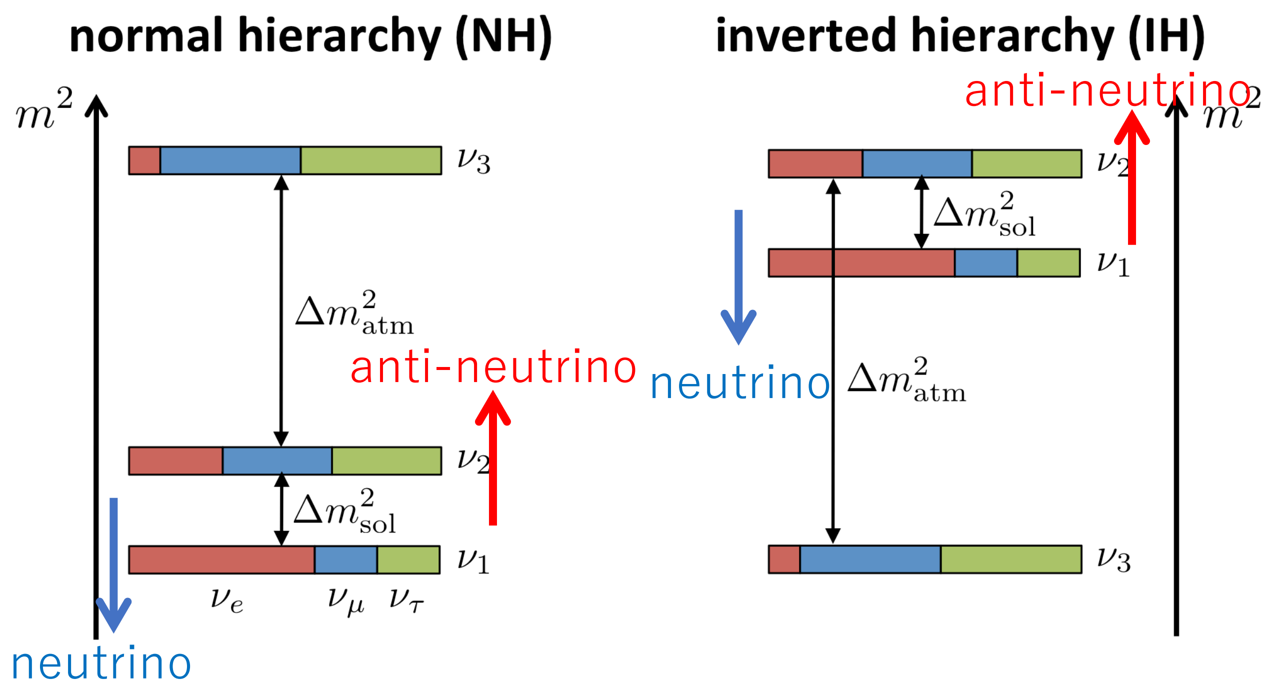
muon, tau neutrinos

electron neutrinos



- CC interactions occur only ν_e and $\overline{\nu}_e$.
- Relative masses of $\nu_e/\overline{\nu}_e$ to $\nu_{\mu,\tau}/\overline{\nu}_{\mu,\tau}$ change.

Matter effect in neutrino oscillation



Matter effect reduce mass of ν_e and increase mass of $\overline{\nu}_e$.

Neutrino:
Matter effect increase. Δm^2_{23} for normal hierarchy and reduce Δm^2_{23} for inverted hierarchy.

Anti-neutrino:
Matter effect reduce Δm^2_{23} for normal hierarchy and increase Δm^2_{23} for inverted hierarchy.

Larger matter effect = greater sensitivity to the **mass ordering determination**.

Matter effect in neutrino oscillation

Effective Hamiltonian: $H = \frac{1}{2E}\left(UMU^\dagger + A\right)$

U : PMNS mixing matrix

$$A = \begin{pmatrix} A_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$A_{CC} = 2\sqrt{2}E_\nu G_F N_e$$

($A_{CC} \rightarrow -A_{CC}$ for $\overline{\nu}_e$)

$$M = \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}$$

G_F : Fermi coupling constant

N_e : electron density

Neutrino oscillation in matter

$C_{ij} = \cos\theta_{ij},\ \ S_{ij} = \sin\theta_{ij}$

$\Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu$

- 3 flavor case

$$\boxed{\delta \to -\delta \quad \text{and} \quad A_{CC} \to -A_{CC} \quad \text{for} \quad \overline{\nu}}$$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e; t) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \ \sin^2\Delta_{31} && \textbf{Leading } (\theta_{13}) \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \ \cos\Delta_{32} \ \sin\Delta_{31} \ \sin\Delta_{21} && \textbf{CPC} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \ \sin\delta \ \sin\Delta_{32} \ \sin\Delta_{31} \ \sin\Delta_{21} && \textbf{CPV} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \ \sin^2\Delta_{21} && \textbf{Solar} \\
& \left.\begin{aligned}
& -8C_{13}^2 S_{13}^2 S_{23}^2 \frac{A_{CC} L}{4E_\nu} (1 - 2S_{13}^2) \cos\Delta_{32} \ \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{A_{CC}}{\delta m^2_{31}} (1 - 2S_{13}^2) \ \sin^2\Delta_{31}
\end{aligned}\right\} && \textbf{Matter}
\end{aligned}
$$

$A_{CC} = 2\sqrt{2} E_\nu G_F N_e \rightarrow$ Matter effect is proportional to E_ν (and L).

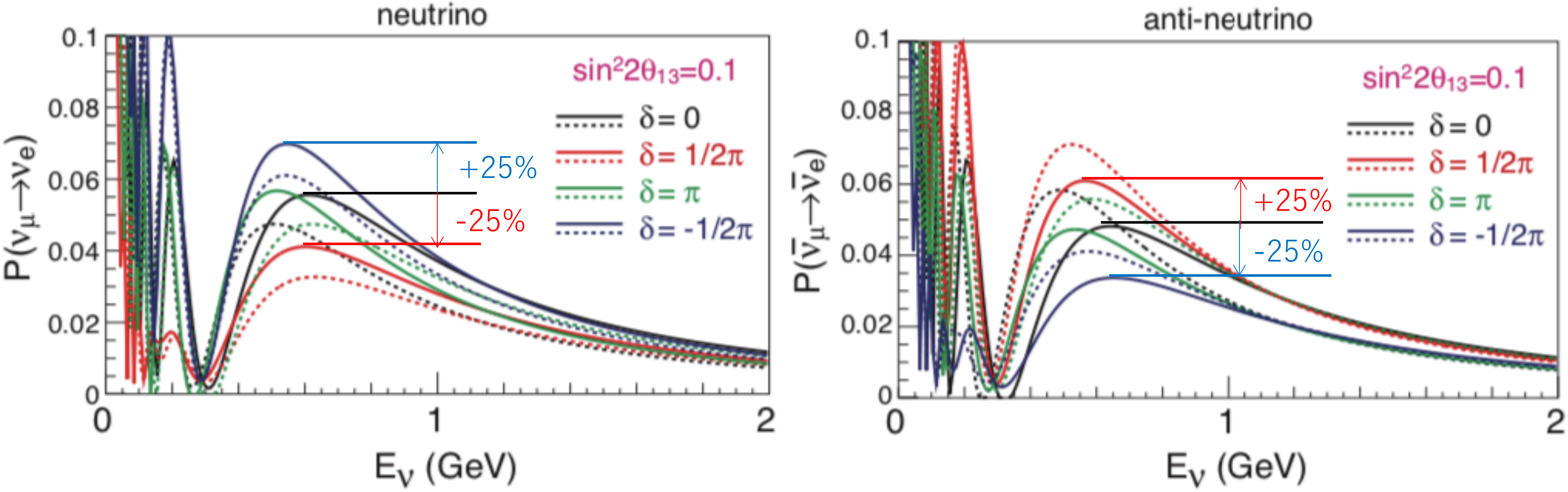
* Formula from “Letter of Intent: The Hyper-Kamiokande Experiment”, arXiv:1109.3262 [hep-ex]

Neutrino oscillation in matter

$$L = 295 \text{ km}$$
$$sin^2 2\theta_{13} = 0.1$$
$$\rho = 2.6\text{g/cm}^3$$

- 3 flavor case

Solid line: normal mass hierarchy
Dashed line: inverted mass hierarchy



* Figures from “Letter of Intent: The Hyper-Kamiokande Experiment”, arXiv:1109.3262 [hep-ex]

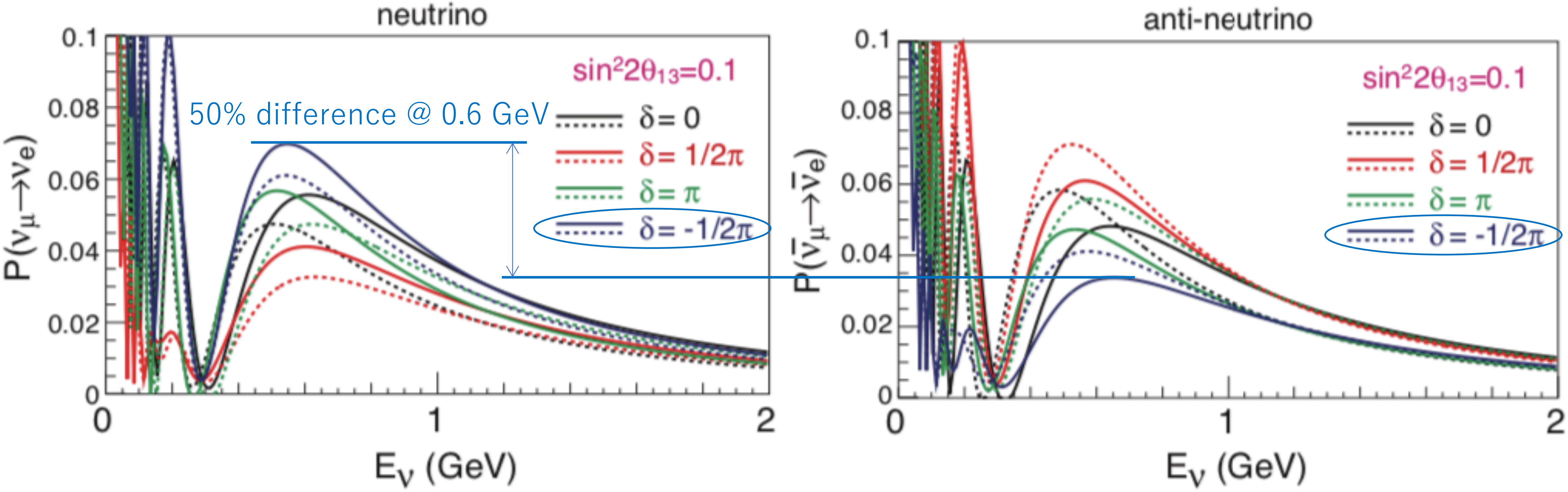
Neutrino oscillation in matter

$$L = 295 \text{ km}$$
$$sin^2 2\theta_{13} = 0.1$$
$$\rho = 2.6 \text{g/cm}^3$$

- 3 flavor case

If $\delta = -1/2\pi$ and normal mass hierarchy,

Solid line: normal mass hierarchy
Dashed line: inverted mass hierarchy



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Neutrino oscillation in matter

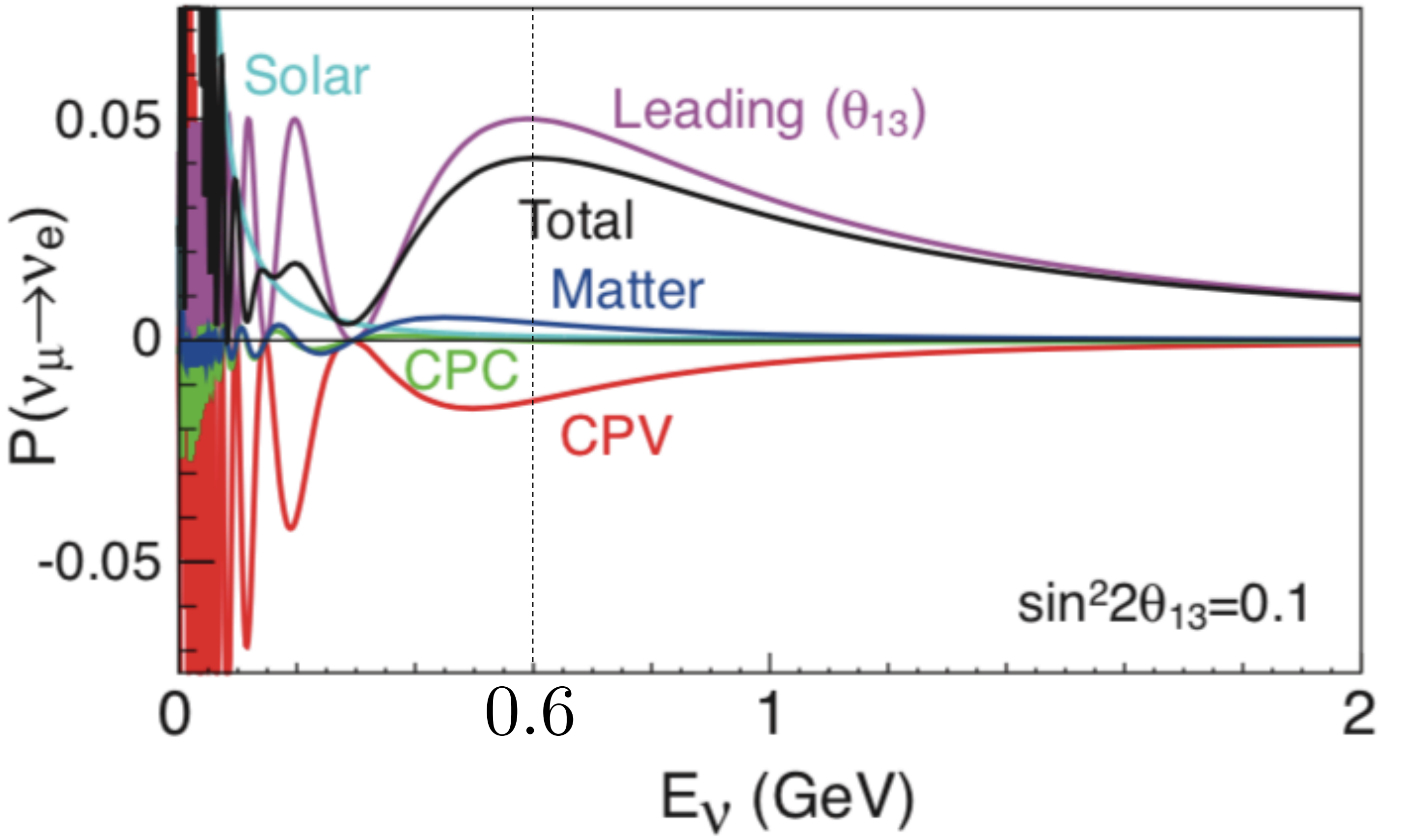
$L = 295\ \mathrm{km}$

$sin^2 2\theta_{13} = 0.1$

$\rho = 2.6\mathrm{g/cm}^3$

Normal mass hierarchy

- 3 flavor case



CPV = - 28% of Leading

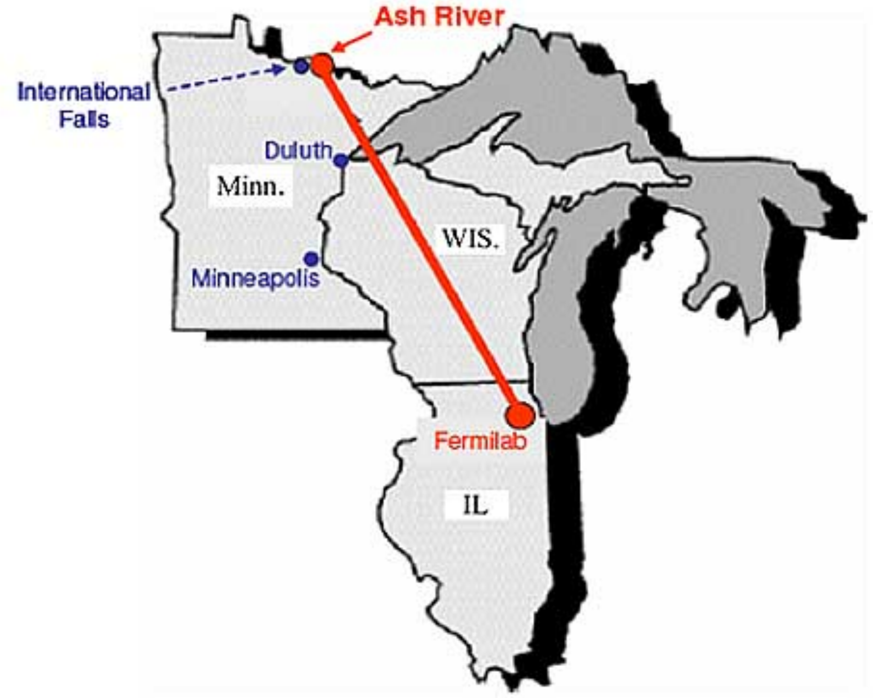
Matter = 8% of Leading

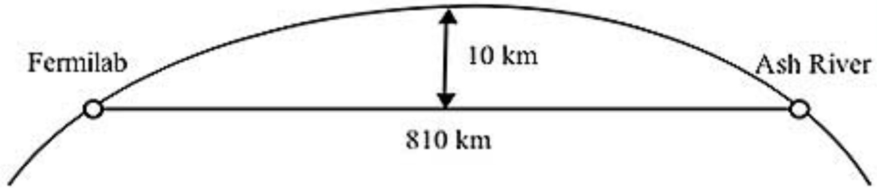
@ $E_\nu = 0.6\mathrm{GeV}$

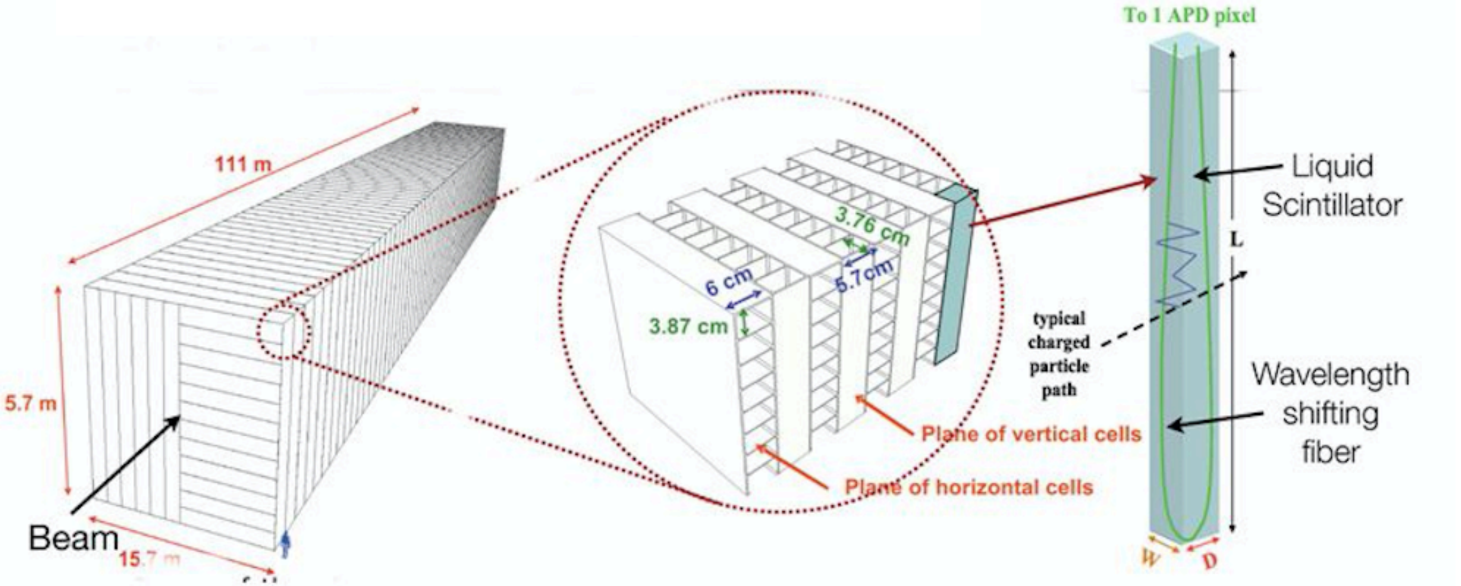
* Figures from “Letter of Intent: The Hyper-Kamiokande Experiment”, arXiv:1109.3262 [hep-ex]

Long-baseline accelerator neutrino oscillation experiments, T2K

Long-baseline accelerator neutrino oscillation experiments, NOνA







T2K and NOνA

- General features of T2K and NOνA
  - High-quality ν_μ ($\overline{\nu}_\mu$) beam.
    - **Small** ν_e ($\overline{\nu}_e$) **contamination**.
    - Intense and **narrow-band** beam.
    - Peak E_ν tuned for oscillation maximum.
    - Reduce BG from high energy tail.
  - **Statistical error** > Systematic error in CP symmetry test now.
    - We need more beam.
    - We need larger far detector.

T2K and NOνA

- Comparison of T2K and NOνA
  - Peak E_ν~0.6GeV (T2K) and ~ 2GeV (NOνA)
  - Baseline L = 295 km (T2K) and 810 km (NOνA)
    - **NOνA** has much larger matter effect than T2K, so it **has greater sensitivity to the mass ordering determination**.
    - **T2K can measure CP violation effect more purely**.
  - Far detector
    - T2K: Water Cherenkov detector (50 kton total mass)
    - NOνA: Segmented liquid scintillator bars (14 kton total mass)
      - Same physics, but different detection technologies.
      - This is a good thing!

The T2K collaboration

~500 members, 64 Institutes, 12 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U of Science
Yokohama National U.

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
ETH Zurich
U. Bern
U. Geneva

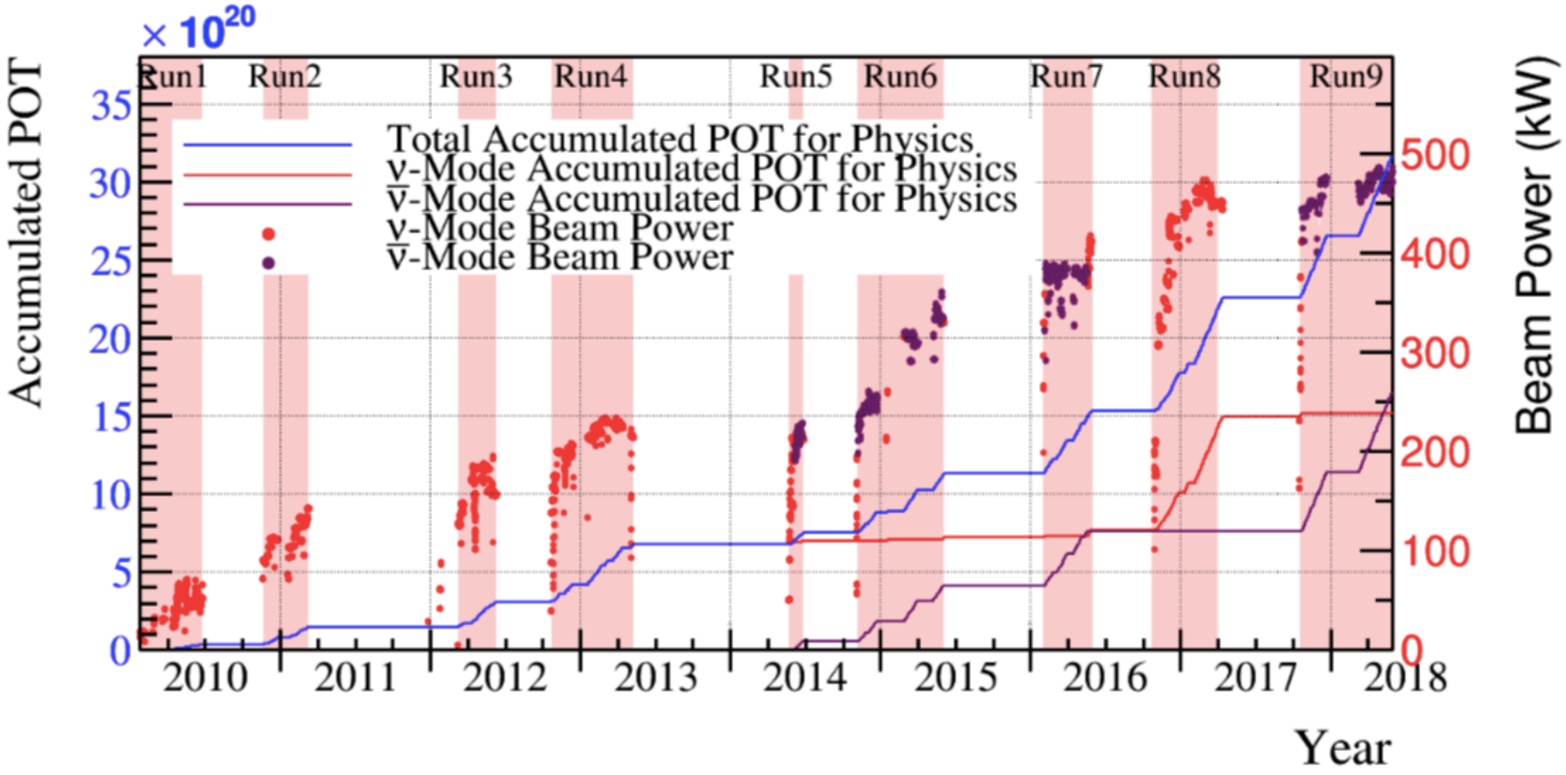
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
IFIRSE
IOP, VAST

T2K data

- Jan. 20, 2010 ~ May 31, 2018
  - ν beam: 1.49×10^{21} POT
  - $\overline{\nu}$ beam: 1.63×10^{21} POT
  - 40% of the total approved T2K POT (7.8×10^{21} POT)



CP symmetry test in T2K

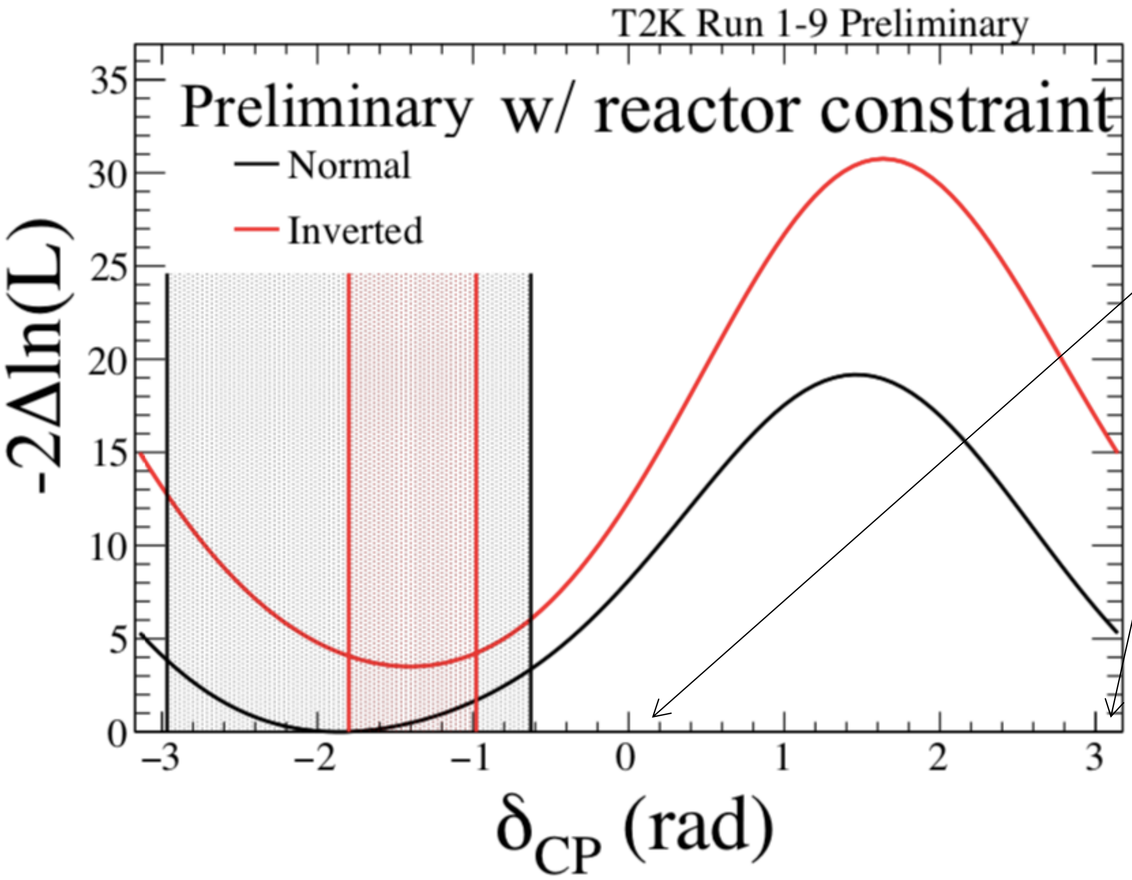
- Observed events at the far detector, Super-K

	Observed	δ=-π/2	δ=0	δ=+π/2	δ=π
ν_e in ν beam	75	74.4	62.2	50.6	62.7
ν_e w/ $1\pi^+$ in ν beam	15	7.0	6.1	4.9	5.9
$\overline{\nu}_e$ in $\overline{\nu}$ beam	15	17.1	19.4	21.7	19.3

T2K data prefer $\delta_{CP} = -\pi/2$:
maximize ν_e appearance and minimize $\overline{\nu}_e$ appearance.

CP symmetry test in T2K

T2K data prefer values of $\delta_{CP} \sim -\pi/2$ mostly driven by the large number of events observed in ν_e-like sample in neutrino beam.

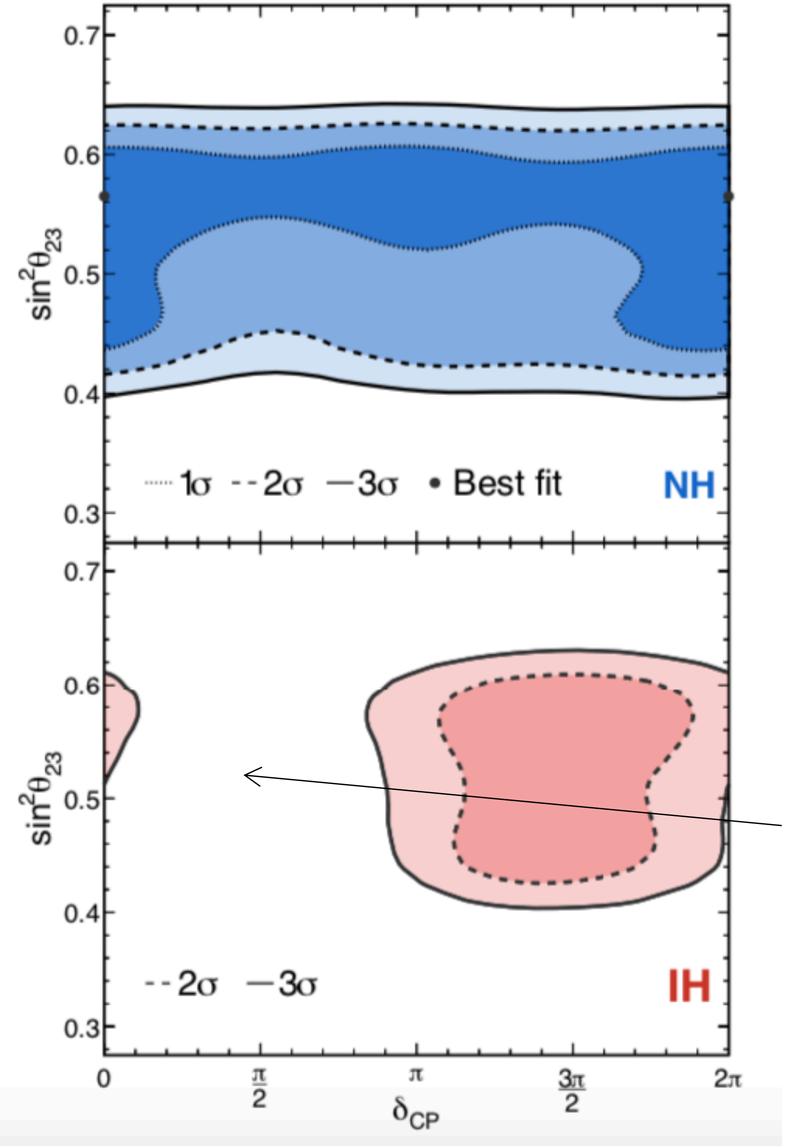


CP symmetry, $\delta_{CP} = 0, \pi$, is excluded w/ 2σ.

C.L.	Normal hierarchy	Inverted hierarchy
68%	[-2.51, -1.26]	-
90%	[-2.80, -0.84]	-
2s	[-2.97, -0.63]	[-1.78, -0.98]

CP symmetry test in NOνA (recently updated)

14 June 2019, arXiv: 1906.04907v2 [hep-ex]



Data: ~ Feb. 26, 2019

ν beam: 0.885×10^{21} POT

$\overline{\nu}$ beam: 1.233×10^{21} POT

Normal mass hierarchy is preferred with **1.9 σ** significance.

Most values near $\delta_{CP} = \pi/2$ in the inverted mass hierarchy are excluded by more than 3σ.

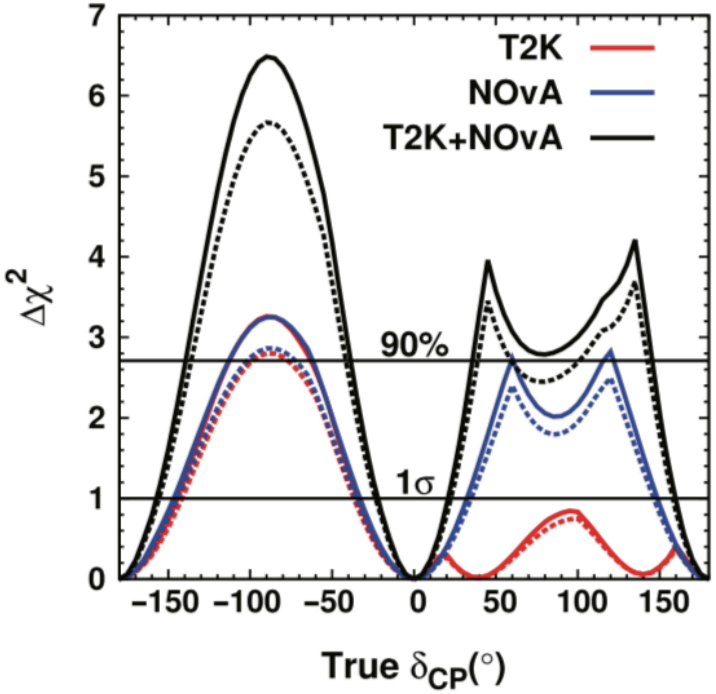
Future prospects

T2K and NOνA

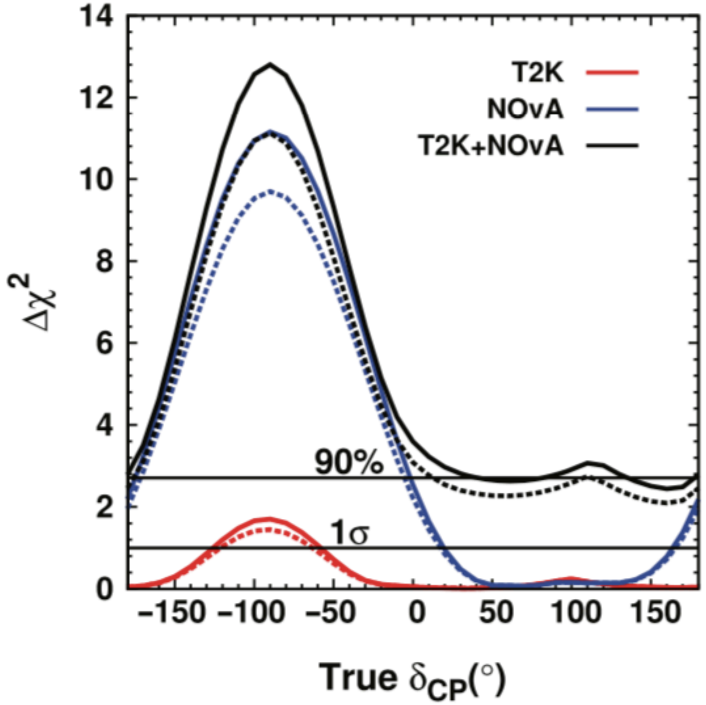
- Healthy competition/complementarity between T2K and NOνA.
  - **Joint analysis plans** in the works.
  - Sensitivity studies of T2K/NOνA joint analyses

    DOI: 10.1093/ptep/ptv031, arXiv preprint: 1409.7469.

Rejecting $\sin\delta_{CP} = 0$



Determining mass hierarchy



Normal mass hierarchy

Solid line: Stat. error only
Dashed line: with Sys. error

T2K

ν beam: 3.9×10^{21} POT
$\overline{\nu}$ beam: 3.9×10^{21} POT

NOνA

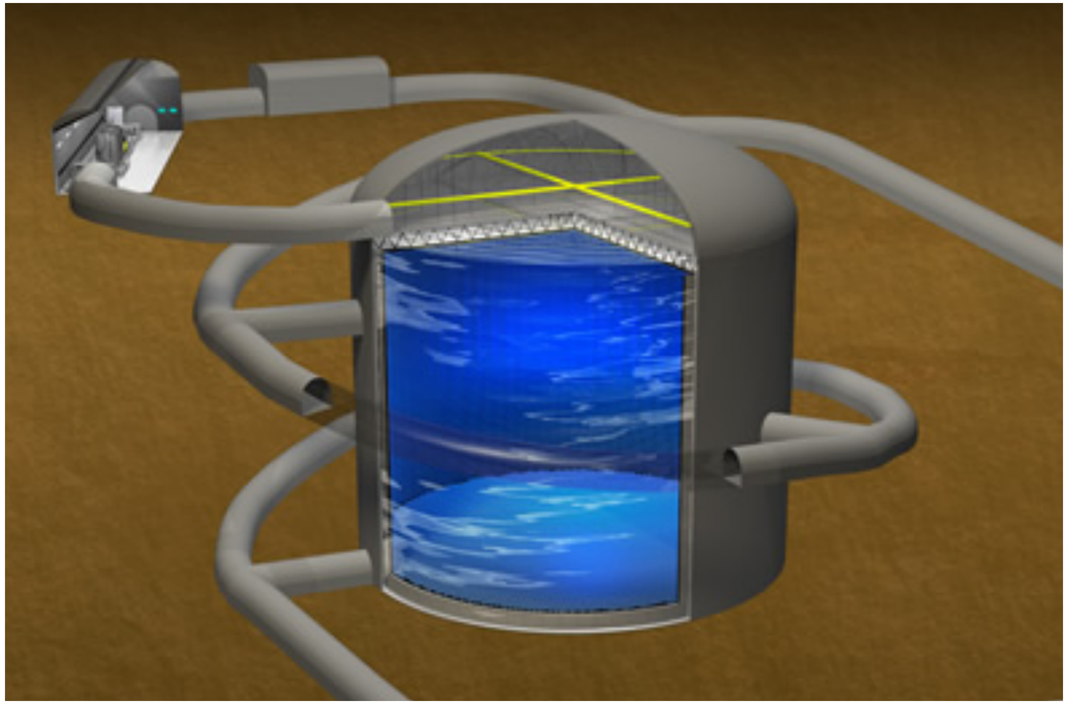
ν beam: 1.8×10^{21} POT
$\overline{\nu}$ beam: 1.8×10^{21} POT

Strategy

- Smaller statistical error
  - Larger far detector
  - Higher intensity beam
- Smaller systematic error
  - Near detector upgrade

Larger far detector

Hyper-K

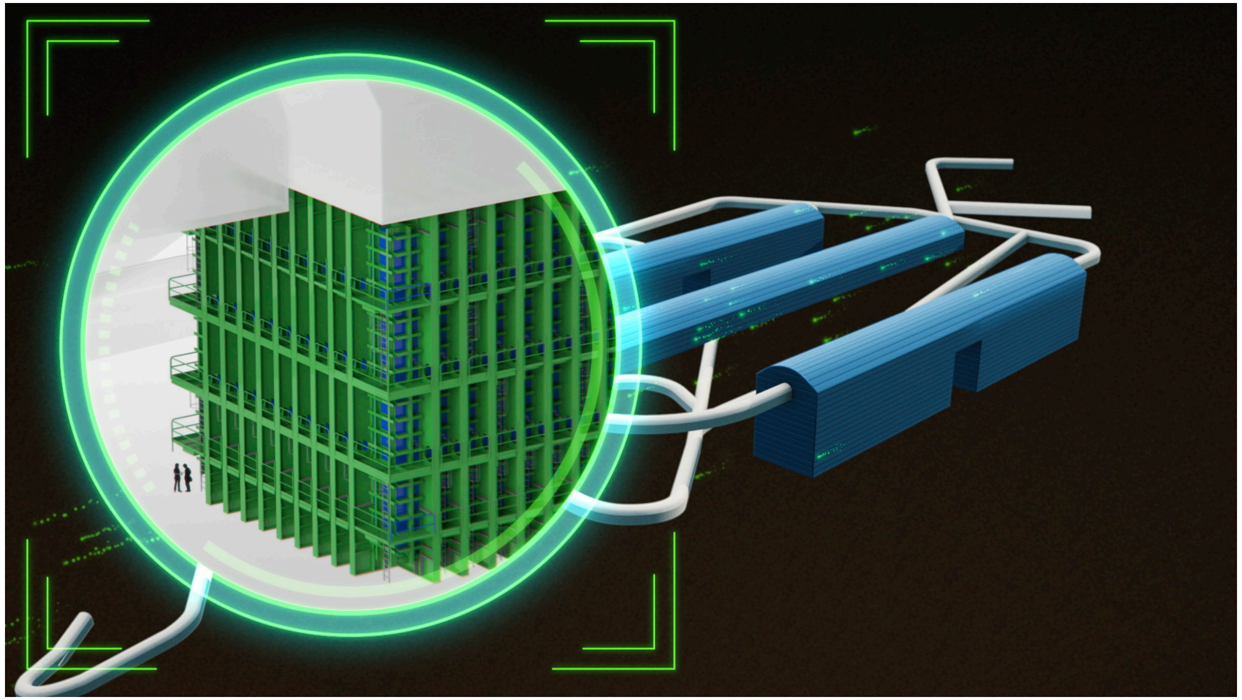


Fiducial mass: 190 kton

→ ~10 times of Super-K

Construction starts in 2020!

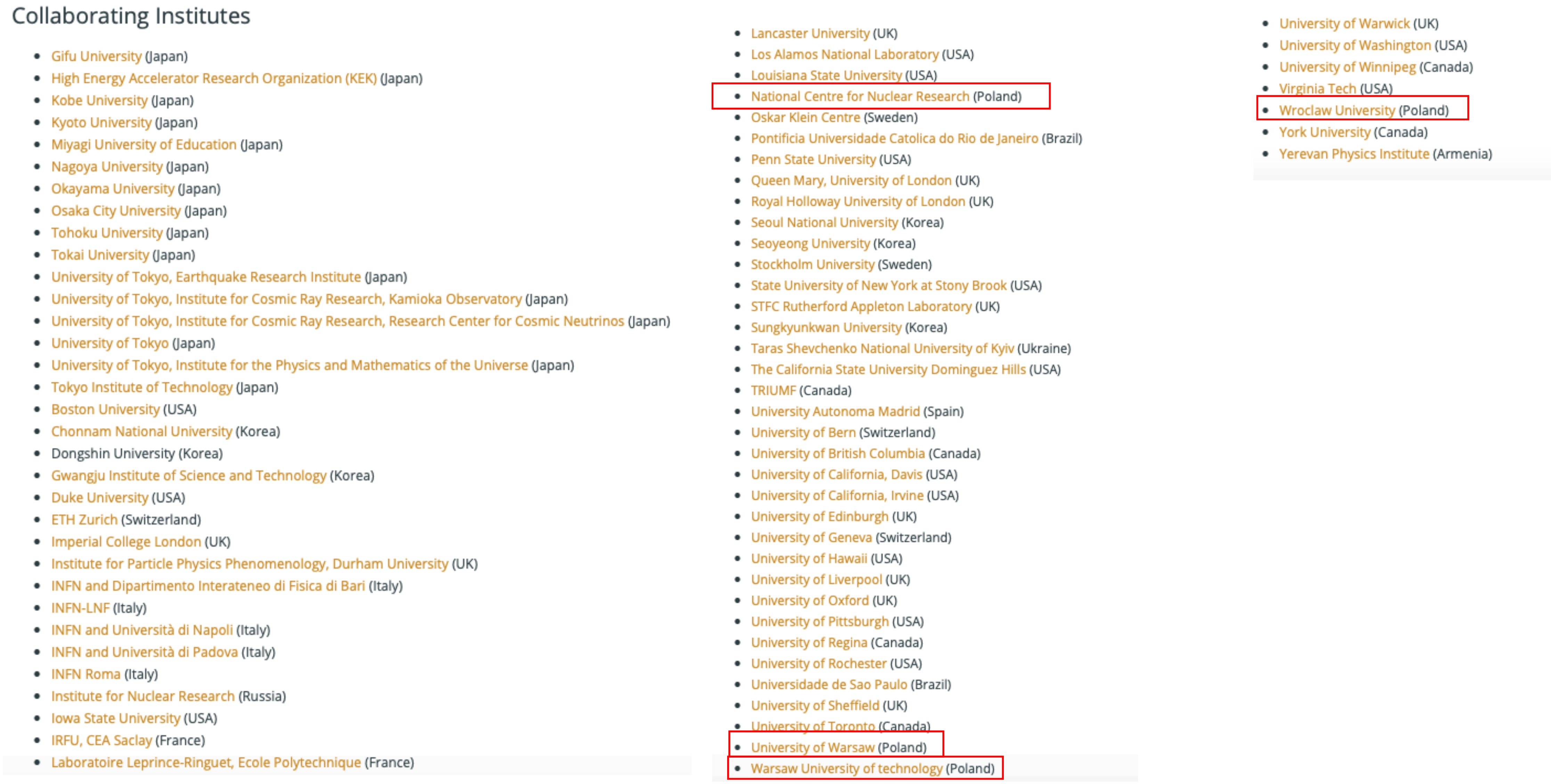
DUNE



Fiducial mass: 40 kton

Under construction!

Hyper-K collaboration



Collaborating Institutes

- Gifu University (Japan)
- High Energy Accelerator Research Organization (KEK) (Japan)
- Kobe University (Japan)
- Kyoto University (Japan)
- Miyagi University of Education (Japan)
- Nagoya University (Japan)
- Okayama University (Japan)
- Osaka City University (Japan)
- Tohoku University (Japan)
- Tokai University (Japan)
- University of Tokyo, Earthquake Research Institute (Japan)
- University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory (Japan)
- University of Tokyo, Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos (Japan)
- University of Tokyo (Japan)
- University of Tokyo, Institute for the Physics and Mathematics of the Universe (Japan)
- Tokyo Institute of Technology (Japan)
- Boston University (USA)
- Chonnam National University (Korea)
- Dongshin University (Korea)
- Gwangju Institute of Science and Technology (Korea)
- Duke University (USA)
- ETH Zurich (Switzerland)
- Imperial College London (UK)
- Institute for Particle Physics Phenomenology, Durham University (UK)
- INFN and Dipartimento Interateneo di Fisica di Bari (Italy)
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- INFN and Università di Padova (Italy)
- INFN Roma (Italy)
- Institute for Nuclear Research (Russia)
- Iowa State University (USA)
- IRFU, CEA Saclay (France)
- Laboratoire Leprince-Ringuet, Ecole Polytechnique (France)
- Lancaster University (UK)
- Los Alamos National Laboratory (USA)
- Louisiana State University (USA)
- National Centre for Nuclear Research (Poland)
- Oskar Klein Centre (Sweden)
- Pontificia Universidade Catolica do Rio de Janeiro (Brazil)
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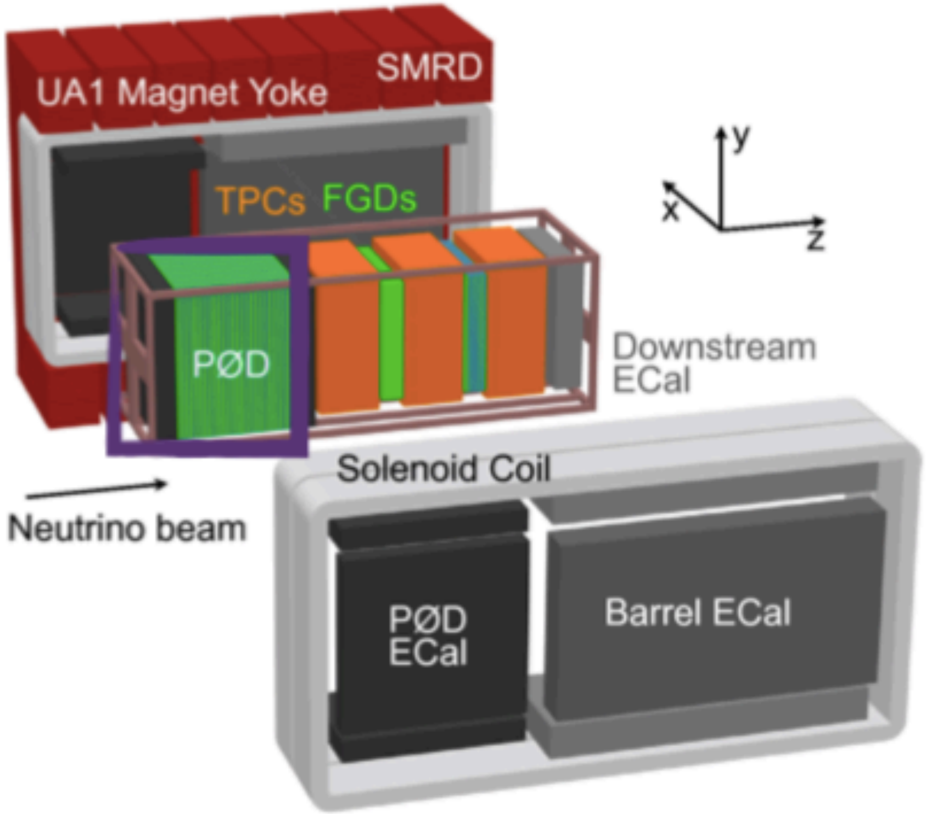
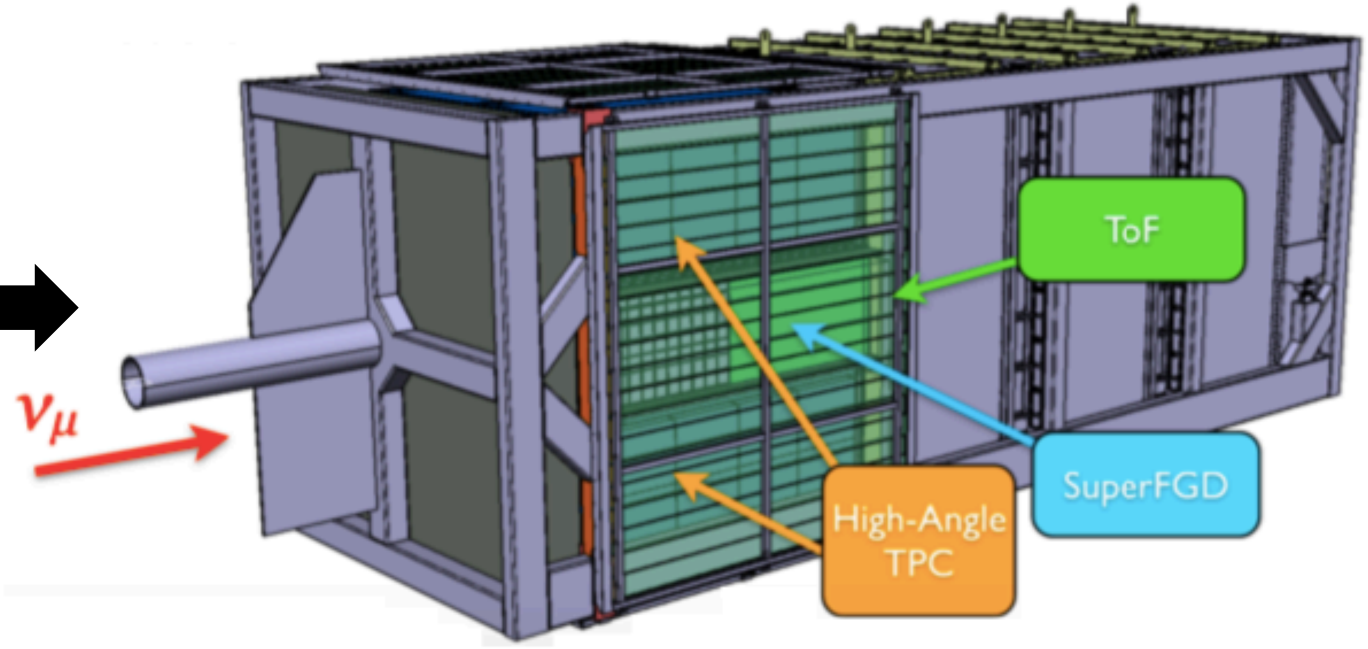
- Universidade de Sao Paulo (Brazil)
- University of Sheffield (UK)
- University of Toronto (Canada)
- University of Warsaw (Poland)
- Warsaw University of technology (Poland)
- University of Warwick (UK)
- University of Washington (USA)
- University of Winnipeg (Canada)
- Virginia Tech (USA)
- Wroclaw University (Poland)
- York University (Canada)
- Yerevan Physics Institute (Armenia)

T2K near detector upgrade

Plan to install in 2021.





- Higher efficiency in the “high angle” region.
- Lowe threshold for protons.

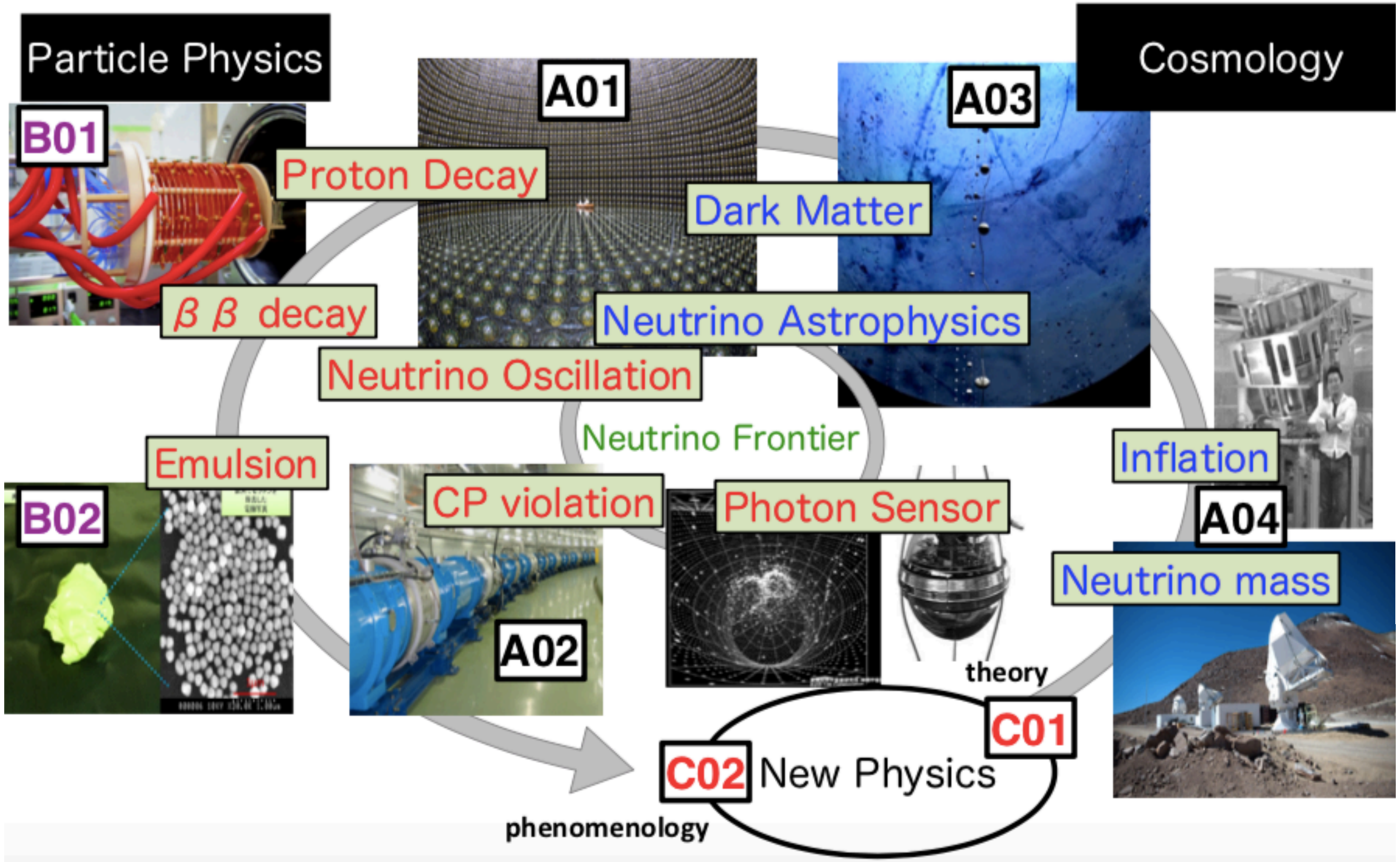
Research project in Japan

Exploration of Particle Physics and Cosmology with Neutrinos

2018.7〜2023.3 (A01-04, B01-02, C01-02)

https://www-he.scphys.kyoto-u.ac.jp/nucosmos/

With neutrinos, our research integrates particle physics, nuclear physics, cosmic rays, and cosmology.



Summary

- T2K
  - **CP symmetry**, $\delta_{CP} = 0, \pi$ is **excluded with** 2σ **significance**.
- NOνA
  - **Normal mass hierarchy** is preferred with 1.9σ significance.
- Future
  - Smaller statistical error
    - Larger far detectors: **Hyper-K** and **DUNE**
    - **Higher intensity beam**
  - Smaller systematic error
    - **Near detector upgrade**

Dziękuję

Backup

Matter effect in neutrino oscillation

- 2 flavor case (for simplicity)

$$P(\nu_e \to \nu_\mu; t) = P(\nu_\mu \to \nu_e; t) = \sin^2 2\theta_M \sin^2 \left(\frac{\Delta m_M^2 L}{4E} \right)$$

matter effect

$$\Delta m_M^2 = \xi \times \Delta m^2 \qquad \sin 2\theta_M = \frac{\sin 2\theta}{\xi}$$

$$\xi = \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \frac{A_{CC}}{\Delta m^2} \right)^2}$$

$A_{CC} = 2\sqrt{2} E_\nu G_F N_e$ ($A_{CC} \to -A_{CC}$ for $\overline{\nu}_e$)

G_F : Fermi coupling constant N_e :electron density