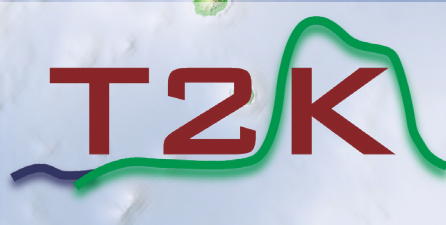


東海-神岡間長基線ニュートリノ振動実験

**T2K (Tokai-to-Kamioka)**

**long-baseline neutrino-oscillation  
experiment**



T2K group  
Institute of Particle and Nuclear Studies,  
High Energy Accelerator Research Organization (KEK)  
J-PARC center

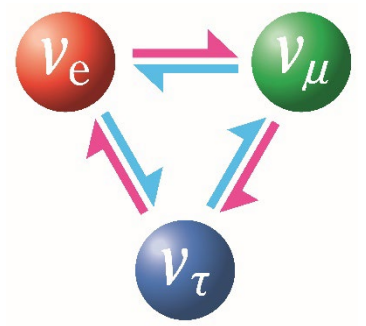
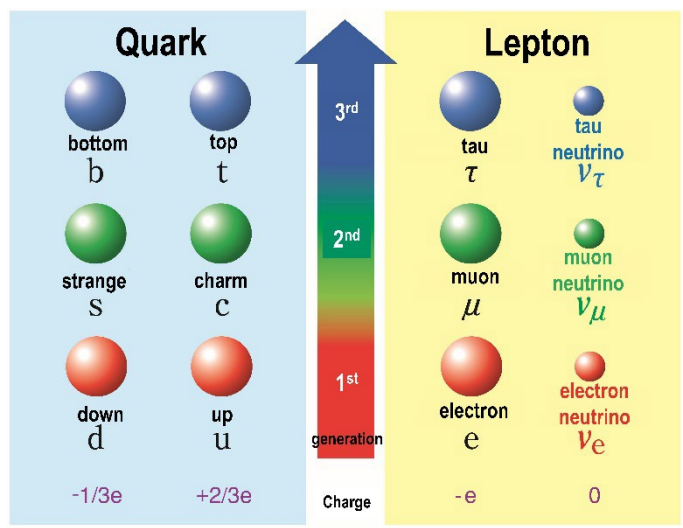
June 2026

# Neutrino Oscillation and long-baseline neutrino-oscillation experiments

## What are neutrinos?

Neutrinos are electrically neutral elementary particles with masses smaller than one millionth of those of quarks or electrons. There are three types (generations) of neutrinos: electron neutrinos ( $\nu_e$ ), muon neutrinos ( $\nu_\mu$ ), and tau neutrinos ( $\nu_\tau$ ). It is also known that each has its own corresponding antineutrino. Although neutrinos cannot be perceived directly, they certainly exist in enormous quantities all around us. In fact, hundreds of trillions of neutrinos emitted from the Sun pass through our bodies every second without any interaction.

There are three generations of each type of quark and lepton that make up nature.



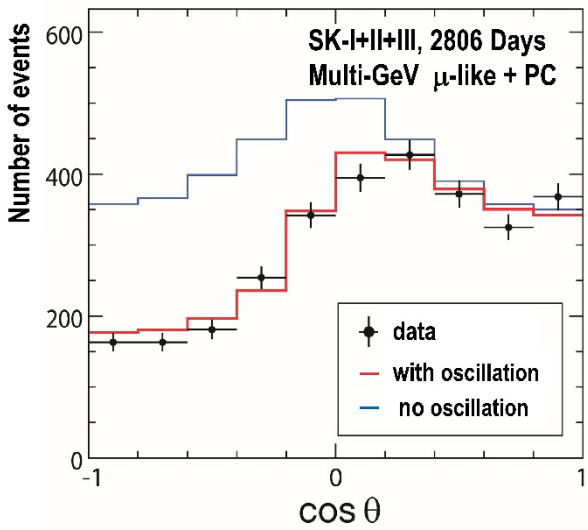
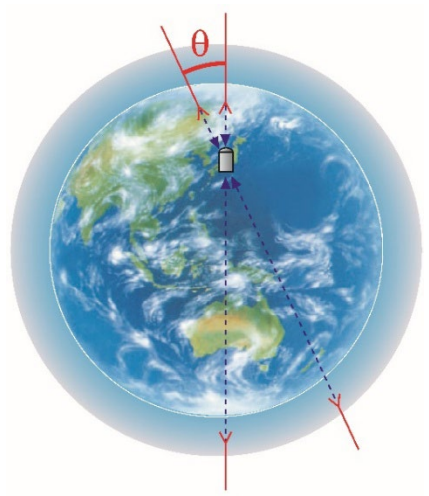
Schematic diagram of the neutrino oscillation between three generations

## What are neutrino oscillations?

Neutrino oscillation is the phenomenon in which the three generations of neutrinos swap places with each other while traveling. For example, even if a 100% pure muon neutrino beam is produced in an accelerator, a certain percentage will transform into tau neutrinos over a distance. As it travels further, it reverts to the original muon neutrino. This process repeats, hence the name neutrino oscillation. Neutrino oscillation is a phenomenon that occurs only when neutrinos have mass and when there is mixing between generations. Currently, neutrino oscillation is the only way to investigate the extremely small masses of neutrinos and the mixing between generations.

## Discovery of neutrino oscillation by Super-Kamiokande

The discovery of neutrino oscillation was announced by the Super-Kamiokande collaboration in June 1998. The zenith angle distribution of atmospheric neutrinos produced by cosmic rays interacting with the atmosphere was examined. Far fewer neutrinos were detected coming from the opposite side of the Earth than from directly overhead. This is believed to happen because some muon neutrinos oscillate into tau neutrinos along the way, and those cannot be observed. This became the world's first experimental proof that neutrinos have a small but finite mass.



## Neutrino oscillation experiment using an accelerator neutrino beam

Following the discovery of neutrino oscillations by Super-Kamiokande, neutrino oscillation experiments using neutrino beams began around the year 2000. These are long-baseline neutrino-oscillation experiments that observe neutrino beams produced by accelerators with detectors hundreds of kilometers away, studying neutrino oscillations during flight. We decided to create our own neutrino beam optimized for neutrino oscillation research, measure neutrinos immediately after production, and use neutrinos with well-known properties to study neutrino oscillations in detail.

### K2K (KEK-to-Kamioka) experiment

The world's first long-baseline neutrino oscillation experiment was the K2K experiment. A neutrino beam produced at the High Energy Accelerator Research Organization (KEK) in Tsukuba City, Ibaraki Prefecture, Japan, was directed into the 50,000-ton water Cherenkov detector, Super-Kamiokande, located 250 km away in Kamioka Town, Gifu Prefecture. The experiment ran from 1999 to 2004 and, for the first time, verified neutrino oscillation using human-made neutrinos, a phenomenon previously observed with atmospheric neutrinos.

### T2K (Tokai-to-Kamioka) experiment

The T2K experiment started in 2009 as the successor to the K2K experiment. A high-intensity neutrino beam is generated at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai Village, Ibaraki Prefecture, and is shot toward the Super-Kamiokande detector 295 km away. Further study of neutrino oscillation is anticipated.



## History of neutrino physics

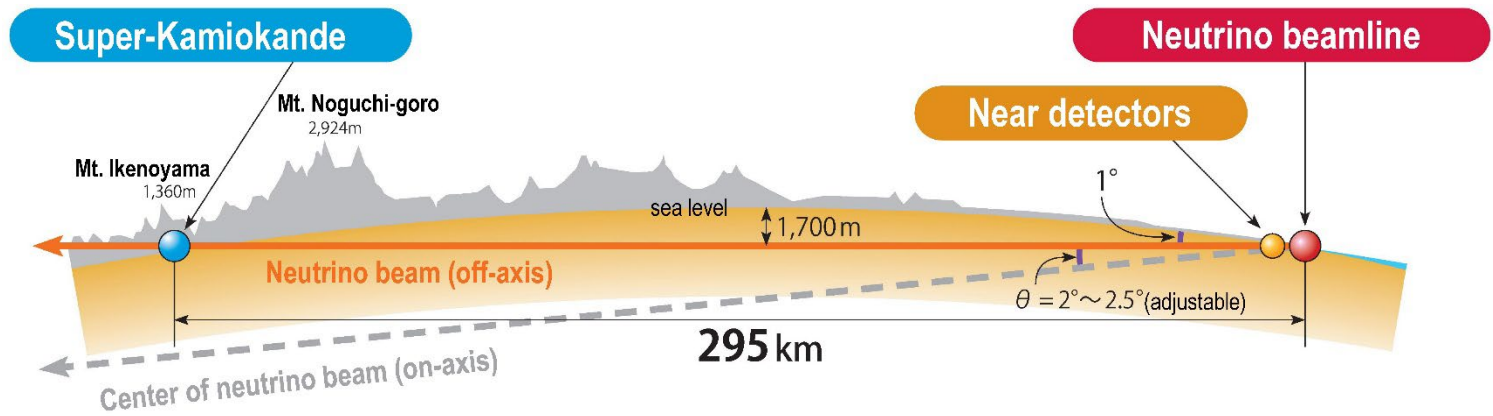
1930	Pauli predicted the existence of neutrino	2000	Discovery of tau neutrino by Niwa and DONUT collaboration
1956	Discovery of electron anti-neutrino by Reines, Cowan et al.	2001	Discovery of solar neutrino oscillation by Super-Kamiokande collaboration and SNO collaboration
1962	Discovery of muon neutrino by Lederman, Schwartz, Steinberger et al.	2002	Discovery of reactor anti-electron neutrino oscillation by Kamland collaboration
1962	Theoretical framework of neutrino oscillation by Make, Nakagawa and Sakata	2002	Koshihara and Davis won the Nobel Prize in Physics
1987	Discovery of neutrinos from Supernova SN1987A by Koshihara and Kamiokande-II collaboration	2004	Atmospheric neutrino oscillation was confirmed using artificial neutrino beam by K2K experiment
1991	Three generations of light neutrinos are established by LEP experiments	2013	Discovery of appearance of electron neutrino due to neutrino oscillation by T2K experiment
1998	Discovery of atmospheric neutrino oscillation by Totsuka, Kajita and Super-Kamiokande collaboration	2015	Kajita and McDonald won the Nobel Prize in Physics
1999	First detection of artificial neutrino beam in the K2K long-baseline neutrino oscillation experiment	2015	Nishikawa and K2K/T2K collaborations won the Breakthrough prize
		2016	The first evidence of CP violation was found by T2K experiment

The T2K international collaboration involves over 500 physicists from around the world. J-PARC is one of the international hubs for neutrino research.

# Overview of the T2K experiment

The T2K experiment consists of three components

- 1** Producing a neutrino beam in Tokai ----- Neutrino beamline
- 2** Observing neutrinos from the neutrino beam in Tokai ----- Near detectors
- 3** Observing neutrinos from the neutrino beam in Kamioka-- Super-Kamiokande



## Discovery of $\nu_{\mu} \rightarrow \nu_e$ oscillation by the T2K experiment

The probability of  $\nu_{\mu} \rightarrow \nu_e$  oscillations is much smaller than the probability of  $\nu_{\mu} \rightarrow \nu_{\tau}$  oscillations. The  $\nu_{\mu} \rightarrow \nu_e$  oscillations were not observed in neutrino oscillation experiments prior to T2K.

The T2K experiment started full-scale operation in 2010, employing the newly constructed J-PARC neutrino beamline, which can produce high-intensity neutrino beam.

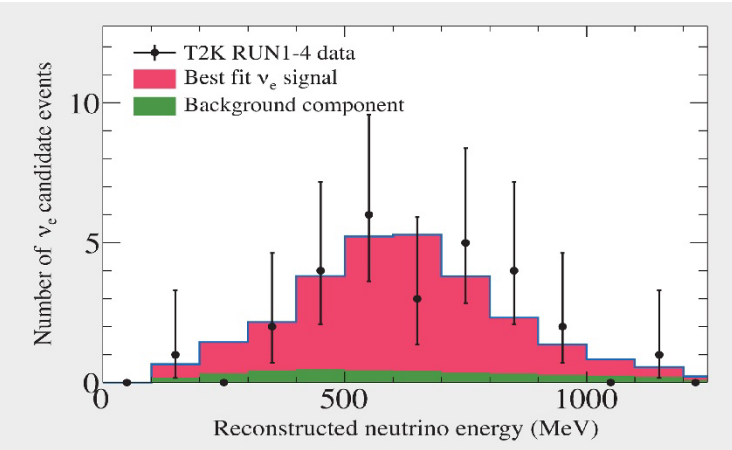
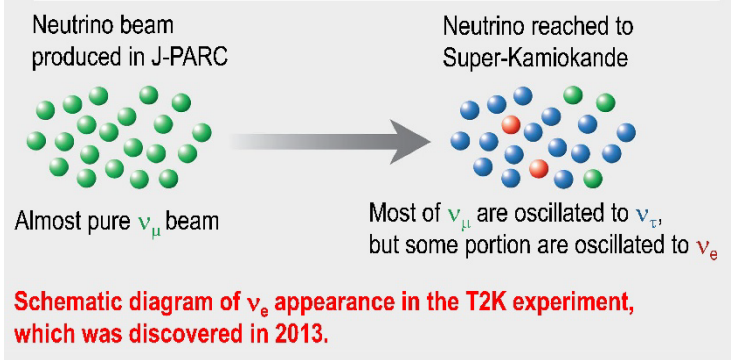
In July 2013, the T2K group announced the discovery of "electron neutrino appearance" which means  $\nu_{\mu}$  oscillated into  $\nu_e$  during the flight from Tokai to Kamioka.

The discovery of this new oscillation channel suggested that neutrino oscillations are a three-generation phenomenon. It was the beginning of a new era in neutrino oscillation research.

## CP violation in the neutrino sector

If neutrino oscillations violate CP symmetry, differences in oscillation probabilities between neutrinos and antineutrinos should occur.

After the discovery of the electron neutrino appearance, the T2K experiment set the examination of CP violation as its next major goal and started beam operation in antineutrino mode in 2014.

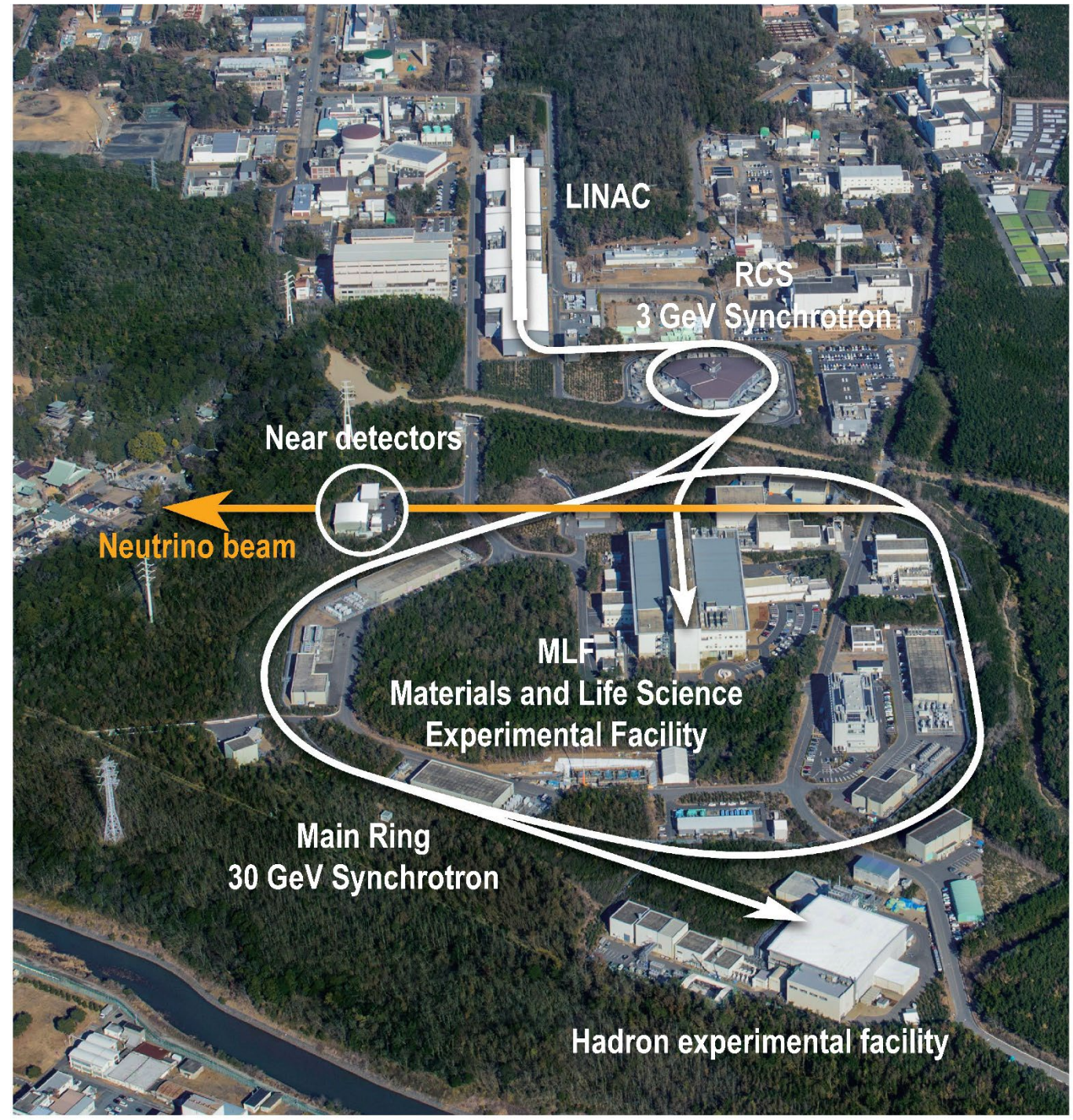


Energy distribution for the 28 observed  $\nu_e$  candidates. The data (black dots) are well reproduced by the combination of the expected  $\nu_e$  appearance signal (red) and the predicted background (green). The probability that this excess arises from statistical fluctuations of background events is less than one in a trillion.

## J-PARC (Japan Proton Accelerator Research Complex)

J-PARC (Japan Proton Accelerator Research Complex) is the name of the proton accelerators and associated user facilities constructed from 2001. It is a joint project organized by the High Energy Accelerator Research Organization (KEK) and the Japan Atomic Energy Agency (JAEA) in Tokai Village, Ibaraki Prefecture.

The neutrino beamline and near detectors of the T2K experiment are part of the J-PARC facilities. At J-PARC, protons are accelerated in a LINAC, then sent through a 3 GeV synchrotron (RCS) to the main ring (MR). The protons are kicked inward toward the Kamioka direction by an electromagnet called a kicker, then sent through the neutrino beamline. The first proton beam was injected into the neutrino beamline in 2009.

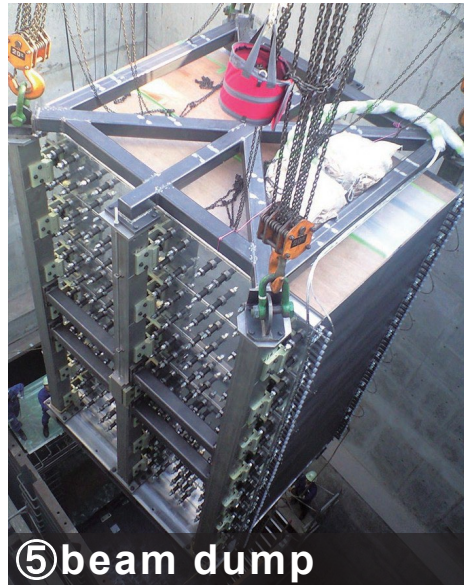


### Neutrino beamline



⑥ muon monitors

The muon monitors are devices that indirectly monitor the direction and stability of the neutrino beam by measuring muons produced together with neutrinos.



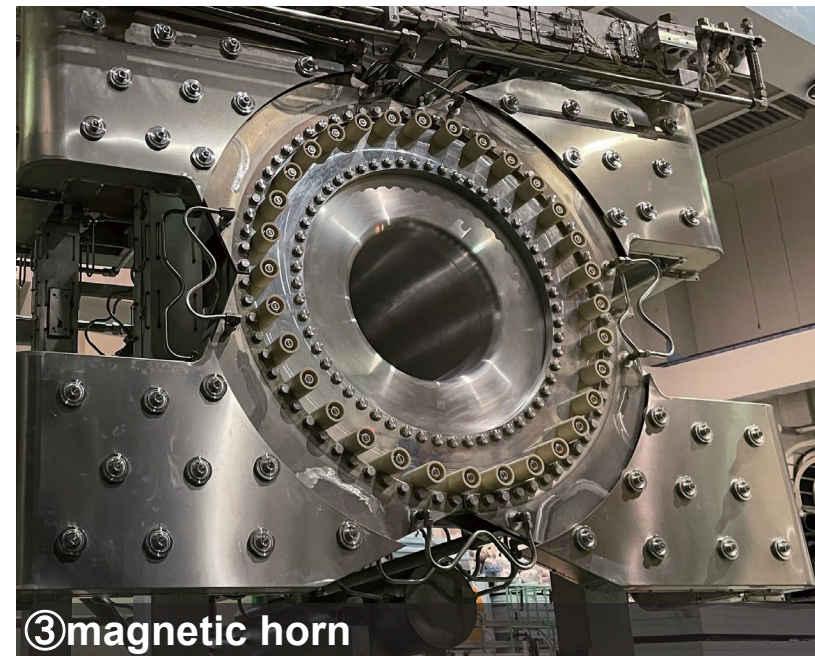
⑤ beam dump

A beam dump made of graphite blocks is installed downstream of the beamline. Particles other than neutrinos and muons are absorbed by this beam dump.



④ decay volume

The charged pions and kaons decay in the 100 m-long decay volume. Neutrinos are generated as decay products.



③ magnetic horn

The magnetic horns are devices that focus pions and kaons into the forward direction using a strong magnetic field generated by a 320 kA pulse current. Switching the direction of the current allows switching between the neutrino beam and the antineutrino beam.

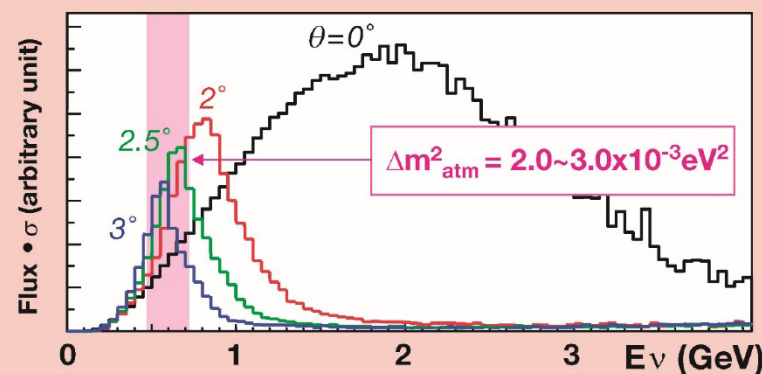


② target

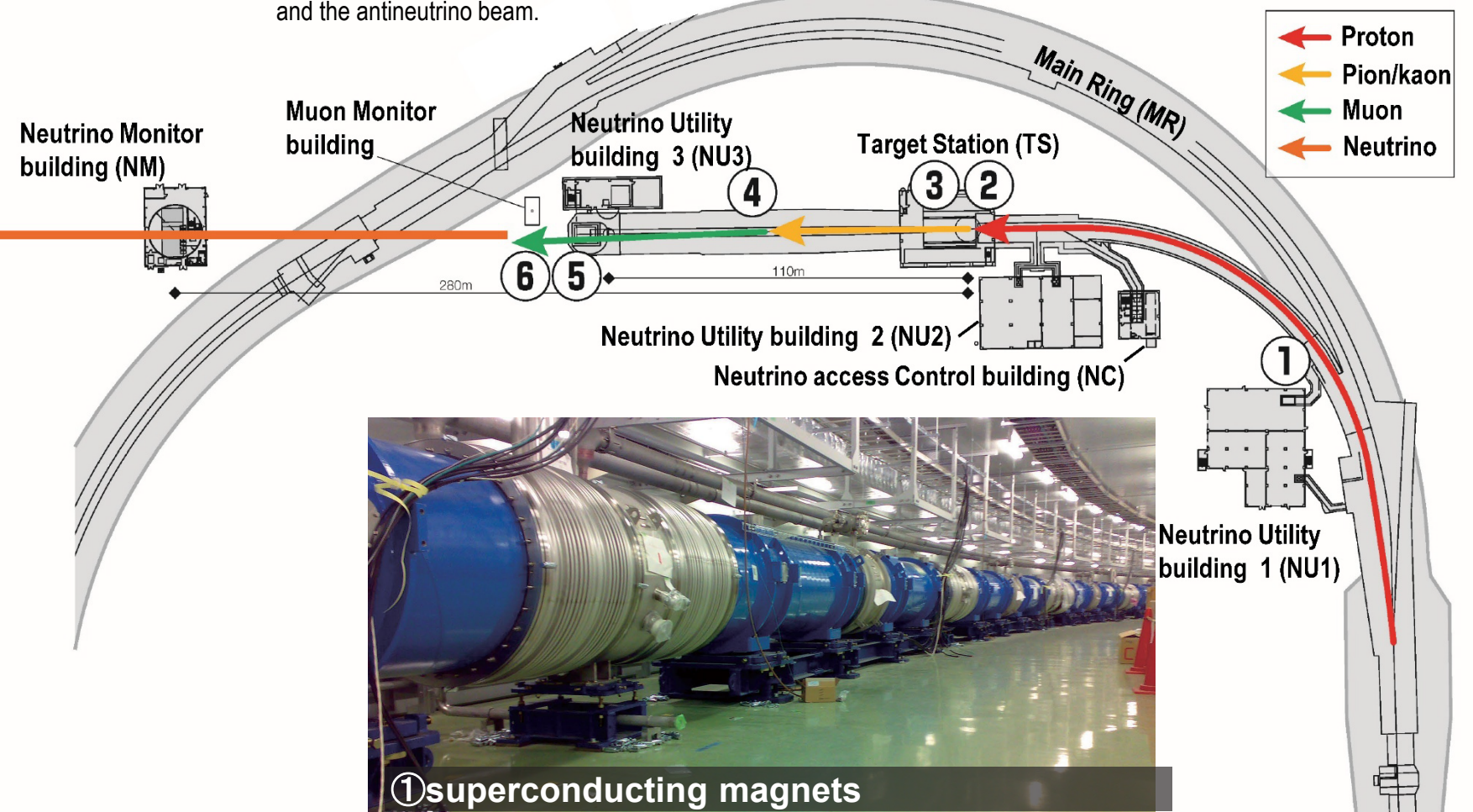
The proton beam injected into the target station collides with a graphite target installed inside the first magnetic horn. Pions and kaons are generated by hadronic interactions.

### To Super-Kamiokande, 295 km away

The neutrino beam generated at J-PARC has a spread. The energy of the neutrino beam is highest toward the center and decreases with angle from the center. The T2K experiment employs an “off-axis” configuration, designed so that the neutrino beam reaching Super-Kamiokande is offset by 2.5° from the beam center. The neutrinos observed at Super-Kamiokande will be low-energy neutrinos around 0.6 GeV, where neutrino oscillation probabilities are highest.



Energy distribution of the off-axis ( $\theta=2^\circ\sim 3^\circ$ ) and on-axis ( $\theta=0^\circ$ ) beam.



① superconducting magnets

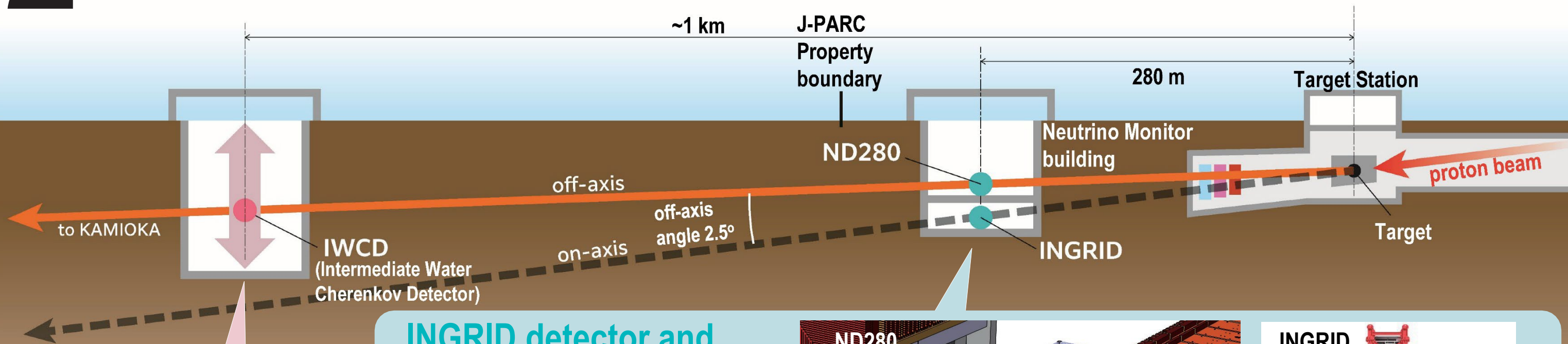
The proton beam extracted from the main ring is bent toward the Super-Kamiokande direction by the strong magnetic field of superconducting magnets aligned in the arc section.

# 2

## Observing neutrinos from the neutrino beam in Tokai

### Near detectors

In Tokai, several detectors have been installed or are under construction to observe neutrinos just after their production.



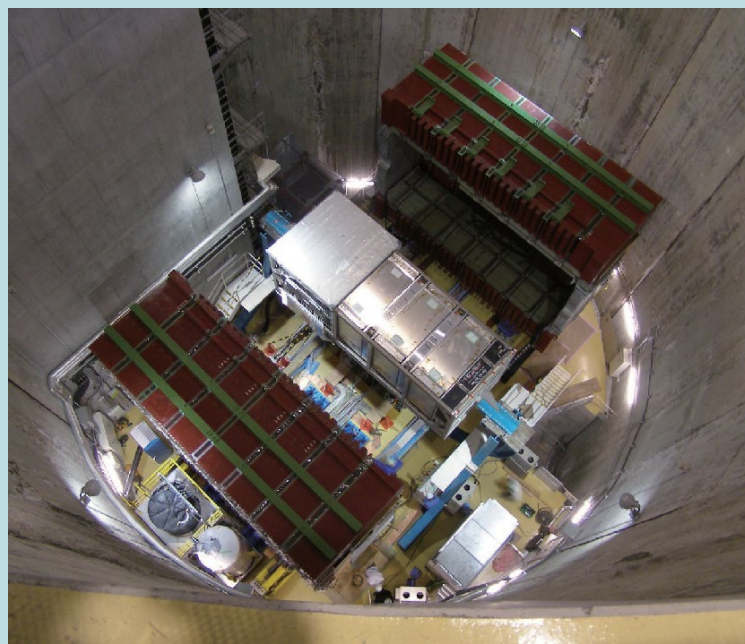
#### IWCD detector

The IWCD detector is planned for installation outside the J-PARC site, 1 km from the target, on the west side of National Route 245. The IWCD detector is a water Cherenkov detector using the same technology and geometry as the one in Kamioka. Therefore, direct comparison of the measurements is possible without considering any detector characteristics. Furthermore, the IWCD detector can measure neutrinos in directions ranging from  $1.5^\circ$  to  $4.0^\circ$  by moving vertically around the center of the Hyper-Kamiokande direction, which is  $2.5^\circ$  off-axis.

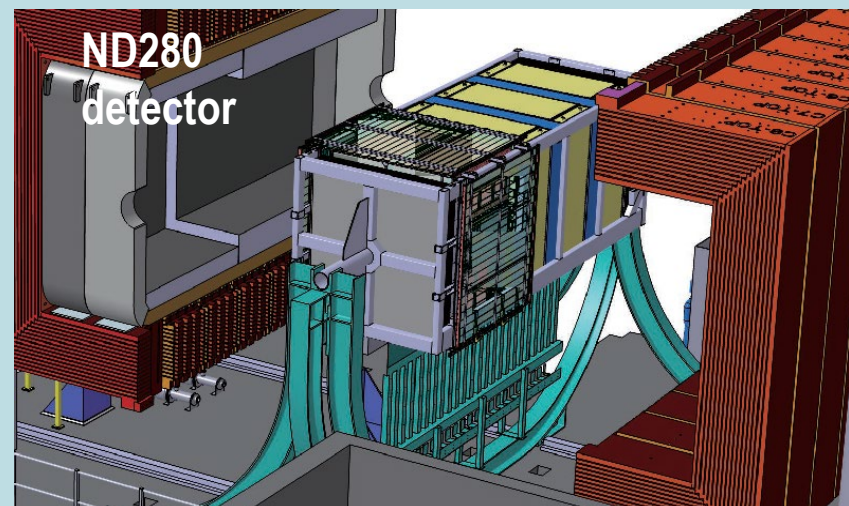


#### INGRID detector and ND280 detector

The near detectors at the J-PARC site are installed in an underground experimental hall (Neutrino Monitor Building) located 280 meters downstream of the target, at a depth of 33.5 meters and with a diameter of 17.5 meters. They consist of the INGRID detector positioned along the beam center and the ND280 detector positioned toward Kamioka.



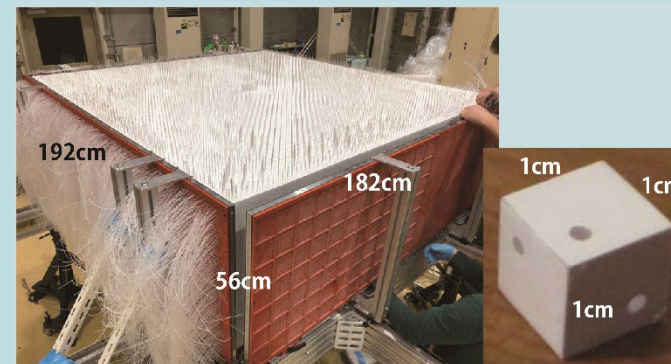
ND280 detector viewed from the ground floor of the Neutrino Monitor Building. For maintenance, the magnets surrounding the ND280 instrument are opened to the left and right, revealing the instrument's central section.



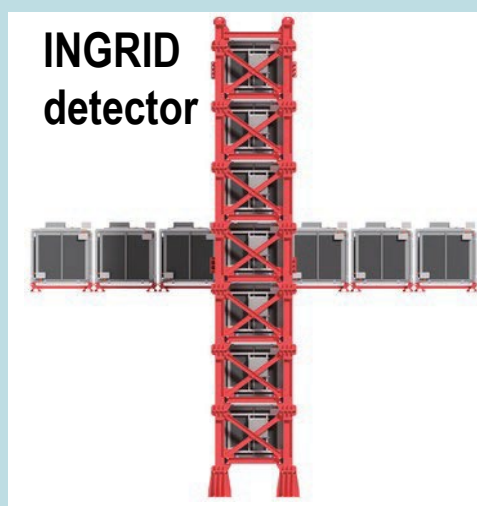
The ND280 detector measures the energy distribution of the neutrino beam and the fraction of electron neutrinos in the beam.

#### SuperFGD

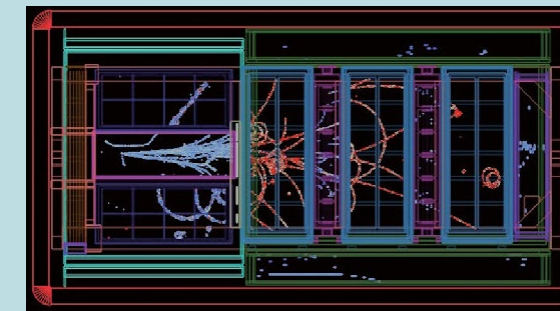
The core of the ND280 detector is a device named SuperFGD, installed in 2023. SuperFGD is a target and track detector consisting of approximately 2 million  $1\text{ cm}^3$  plastic scintillator cubes arranged in a grid of  $192 \times 182 \times 56$ . The scintillation light generated by charged particles in each cube is read out via fibers from three directions. SuperFGD is a massive target and an ideal neutrino detector capable of reconstructing particle tracks in three dimensions with 1 cm spatial resolution.



SuperFGD prior to installation and a single plastic scintillator cube



Schematic view of the INGRID detector. The black square section represents the neutrino detector.

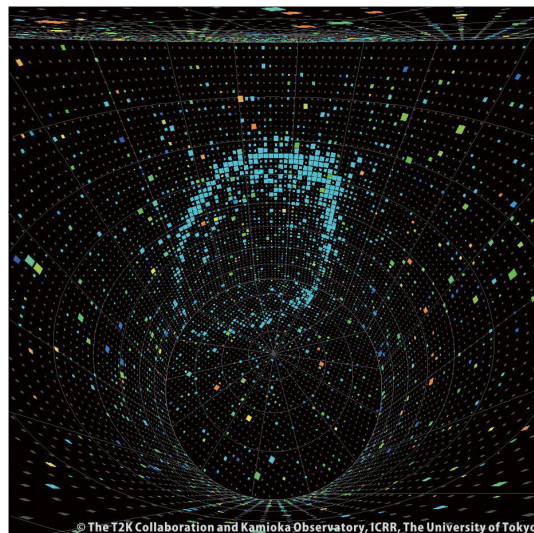


An event detected by the entire ND280 detector for a neutrino interaction occurring inside SuperFGD

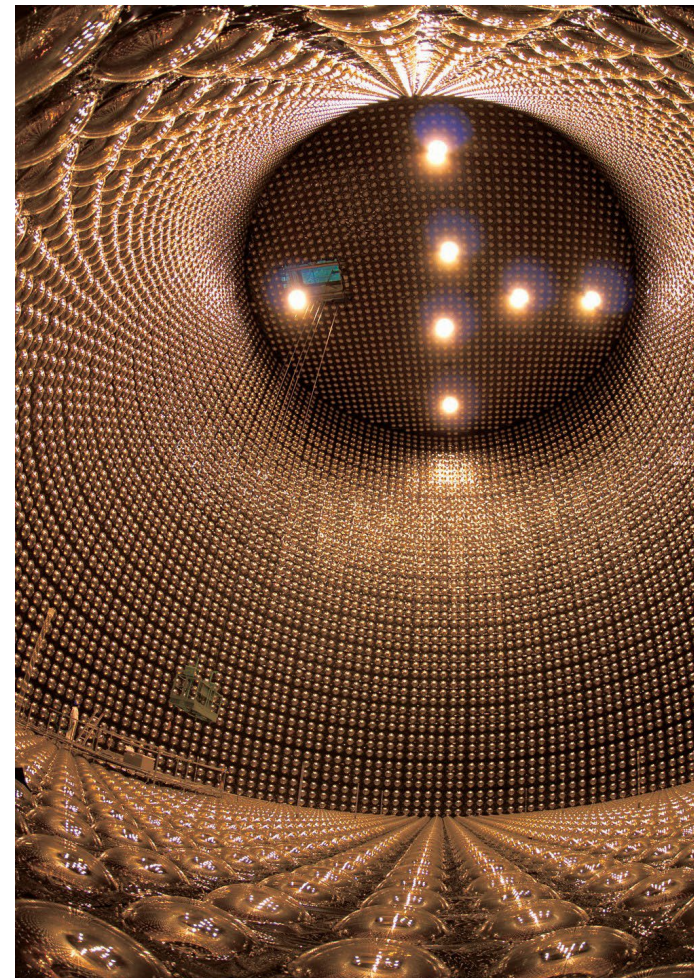
# 3 Observing neutrinos from the neutrino beam in Kamioka

## Super-Kamiokande

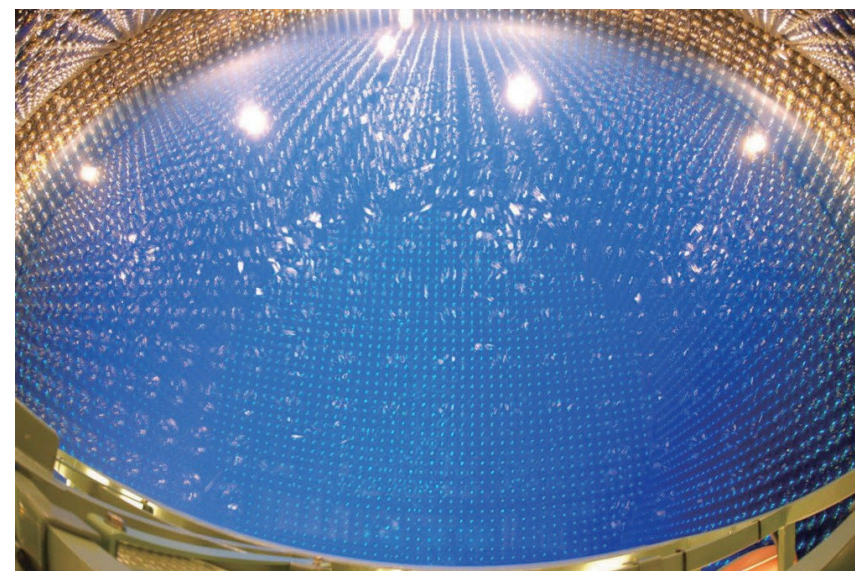
Super-Kamiokande is a large water Cherenkov neutrino detector by the Institute for Cosmic Ray Research, University of Tokyo, located 1,000 meters underground at the Kamioka Mine in Hida City, Gifu Prefecture. It started observations in April 1996 and continues to detect many kinds of neutrinos. The detector consists of a 39.3-meter-diameter, 41.4-meter-tall water tank containing 50,000 tons of pure water. It is equipped with 11,129 highly sensitive photodetectors (photomultiplier tubes). By detecting the faint Cherenkov light emitted when neutrinos rarely interact in the water, it can determine the type of neutrino, its direction of arrival, and its energy.



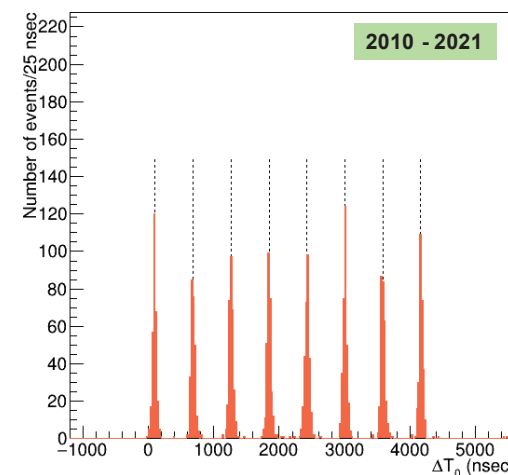
One of the candidates for the world's first observed electron neutrino appearance event by the T2K experiment



Super-Kamiokande without water



Super-Kamiokande filled with ultra-pure water for 90% of its volume



Time distribution of neutrino events. The 8-bunch structure of the neutrino beam can be confirmed.

## Hyper-Kamiokande (under construction)

Hyper-Kamiokande is the next-generation giant water Cherenkov detector in Kamioka. It is under construction 600 meters underground in Kamioka, northern Gifu Prefecture. It detects Cherenkov light generated in ultra-pure water within a tank measuring 68 meters in diameter and 71 meters in depth using approximately 40,000 photomultiplier tubes. These tubes offer approximately twice the sensitivity, resolution, and safety of those in Super-Kamiokande. The effective mass is equivalent to 8.4 times that of Super-Kamiokande. The Hyper-Kamiokande experiment also includes neutrino oscillation experiments using the neutrino beam from J-PARC. The experiment plan was approved in early 2020, and construction is underway for the start of experiments in 2028. As of end of 2025, about 650 researchers from 23 countries worldwide are participating.

**In progress!**

### Cavity and Tank

Tunnel excavation started in May 2021. Combining the dome and cylindrical sections creates a vast cavity measuring 69 meters in diameter and 94 meters in height, making it the world's largest underground artificial cavity. Excavation work was completed in July 2025. Following the subsequent tank fabrication work, installation of the photomultiplier tubes will start.

**In progress!**

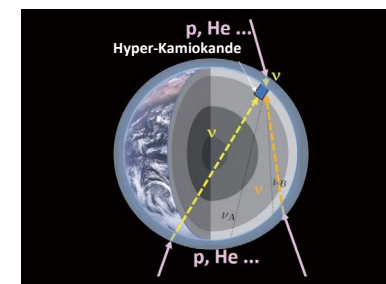
### Photomultiplier tube

An improved version of the 50 cm-diameter high-sensitivity photomultiplier tubes used in Super-Kamiokande (left photo) will be employed. Manufactured at an average rate of 5,000 tubes per year, they await installation in the tank. Approximately 20,000 photomultiplier tubes are scheduled for completion by 2026. A "compound-eye" light sensor with enhanced time resolution (right photo) has also been developed. Combining both is expected to improve detection accuracy.

## Physics in Hyper-Kamiokande

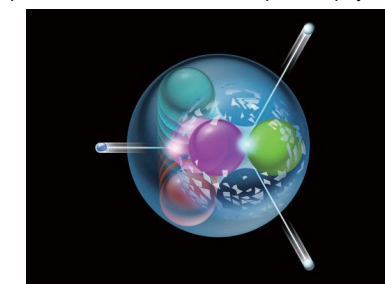
### Neutrino Oscillation

In addition to neutrino and antineutrino beams from J-PARC, we will comprehensively elucidate neutrino oscillations between the three generations using atmospheric neutrinos and solar neutrinos.



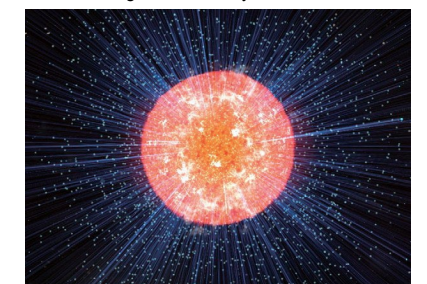
### Nucleon Decay

The Grand Unified Theory provides a unified explanation for the three interactions existing in nature, the strong interaction, the weak interaction, and the electromagnetic interaction. This theory predicts nucleon decay. We aim to discover the world's first nucleon decay and pioneer a new framework for particle physics.

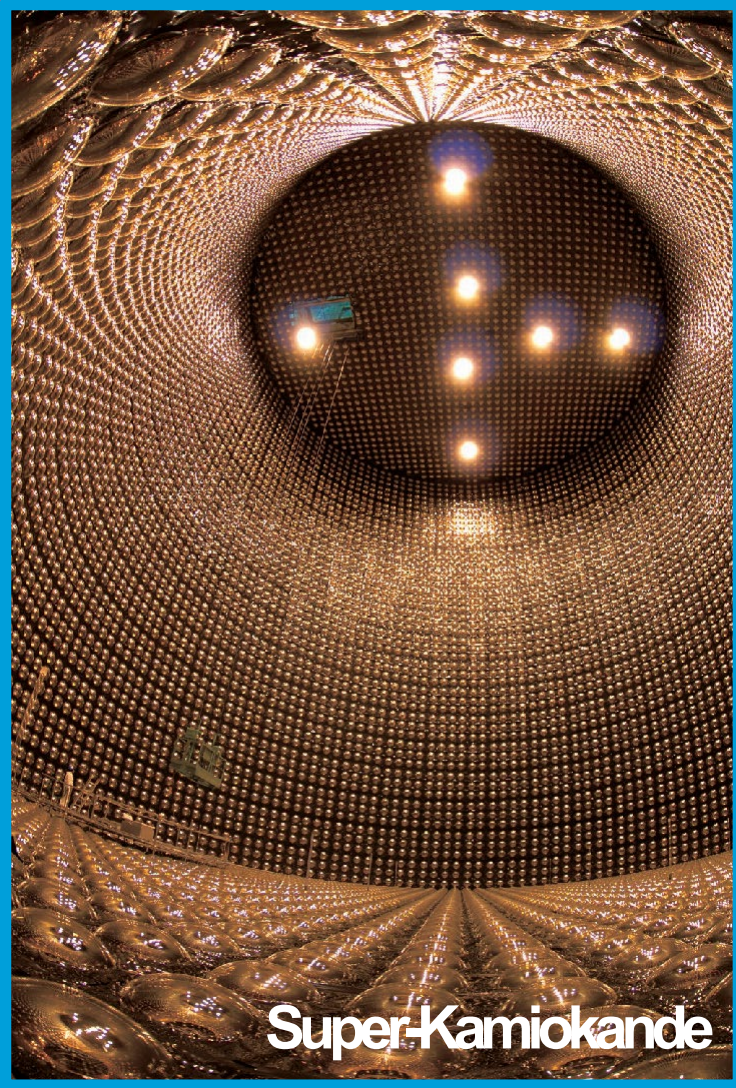


### Neutrino Astronomy

Observations of solar neutrinos, neutrinos from supernova explosions, neutrinos from past supernova explosions, and neutrinos from high-energy astrophysical sources such as neutron stars contribute to understanding the evolution and history of the universe and to advancing multi-messenger astronomy.



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Kamioka

Super-Kamiokande

This pamphlet and the latest results can be downloaded from the following links.

[https://j-parc.jp/documents/pdf/2026/T2K\\_202606\\_E-Low.pdf](https://j-parc.jp/documents/pdf/2026/T2K_202606_E-Low.pdf)

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