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THE T2K EXPERIMENT

NEUTRINO OSCILLATIONS

- **Neutrino oscillations is a phenomenon in which a neutrino changes its flavor** (electron, muon or tau) as it propagates through space.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad \begin{aligned} c_{ij} &\equiv \cos\theta_{ij} \\ s_{ij} &\equiv \sin\theta_{ij} \end{aligned}$$

- **Neutrino oscillations in the $\nu_\mu \rightarrow \nu_\mu$ disappearance channel refer to the reduction in the number of muon neutrinos** observed after propagation over a long distance.

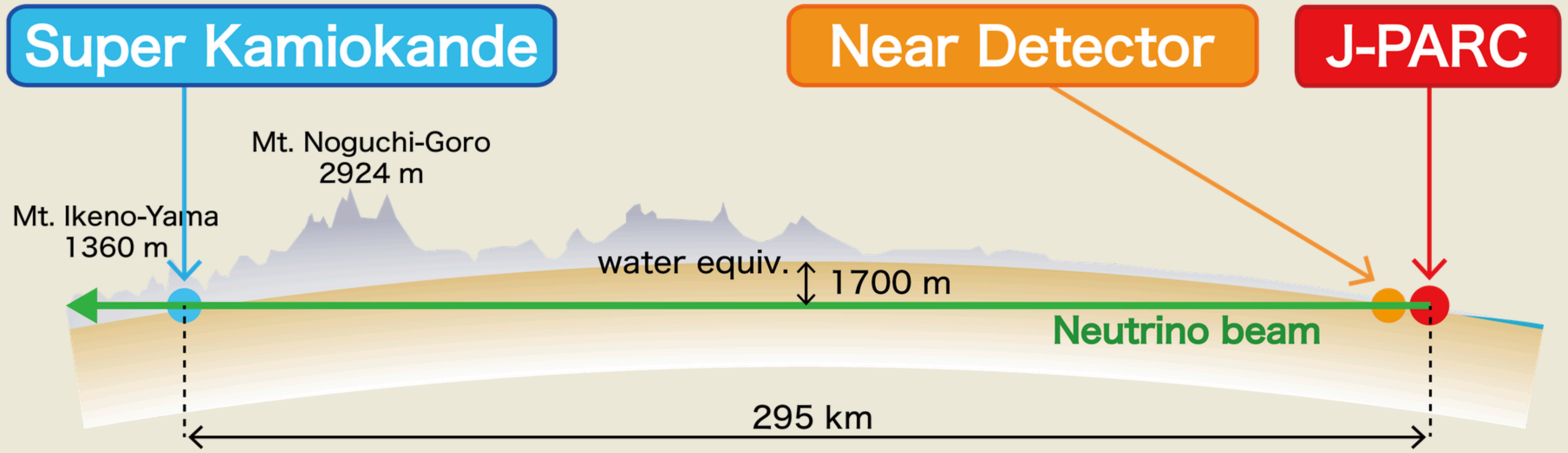
$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\frac{\Delta m^2_{32} L}{E_\nu}\right)$$

- **In the $\nu_\mu \rightarrow \nu_e$ appearance channel, electron neutrinos are observed in a beam** that was originally composed mainly of muon neutrinos.

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\frac{\Delta m^2_{32} L}{E}\right) \mp \left(1.27\frac{\Delta m^2_{21} L}{E}\right) 8J_{CP}\sin^2\left(1.27\frac{\Delta m^2_{32} L}{E}\right)$$

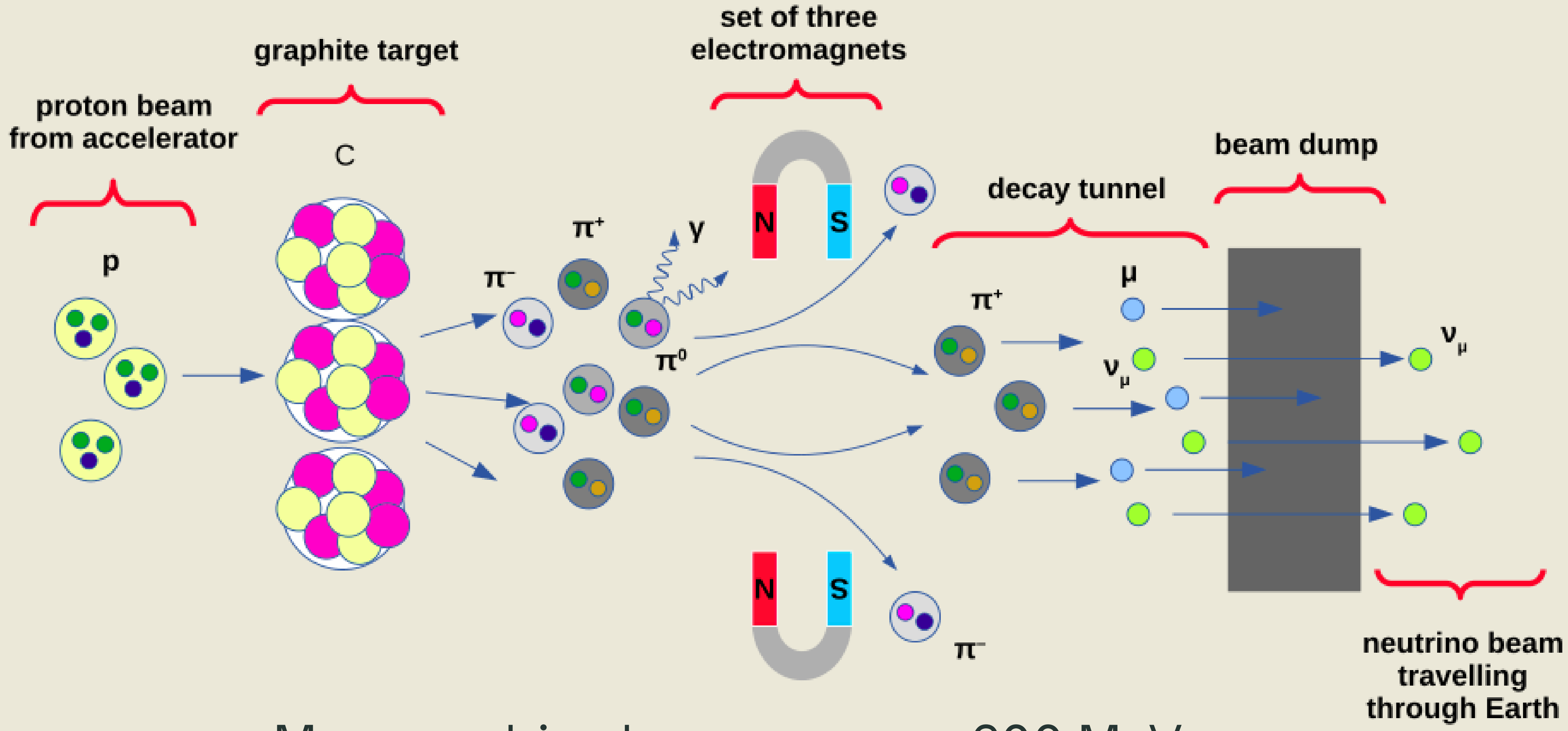
$$J_{CP} = \frac{1}{8}\cos(\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin(\delta_{CP})$$

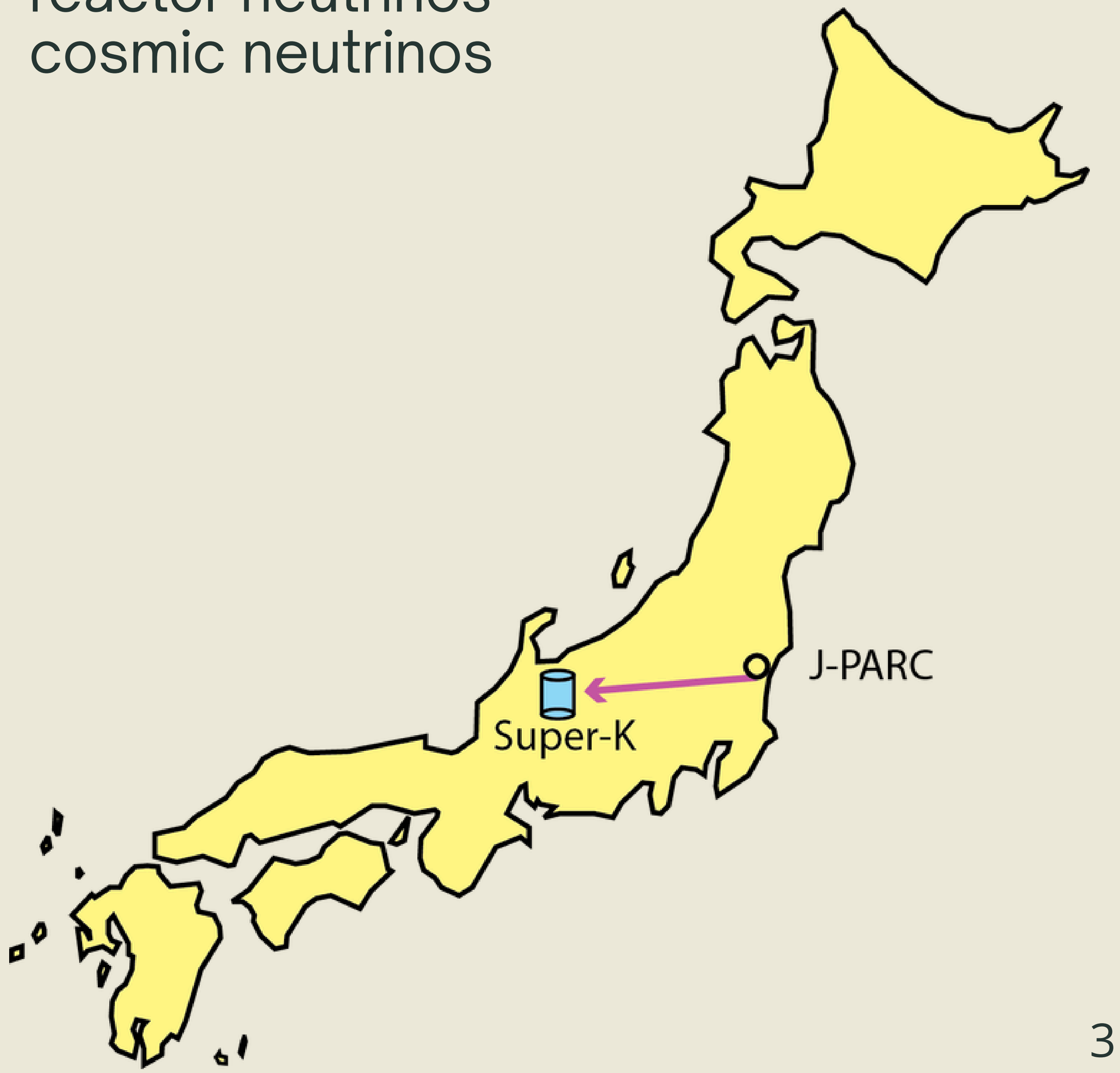
BEAMLINE



Neutrino sources include:

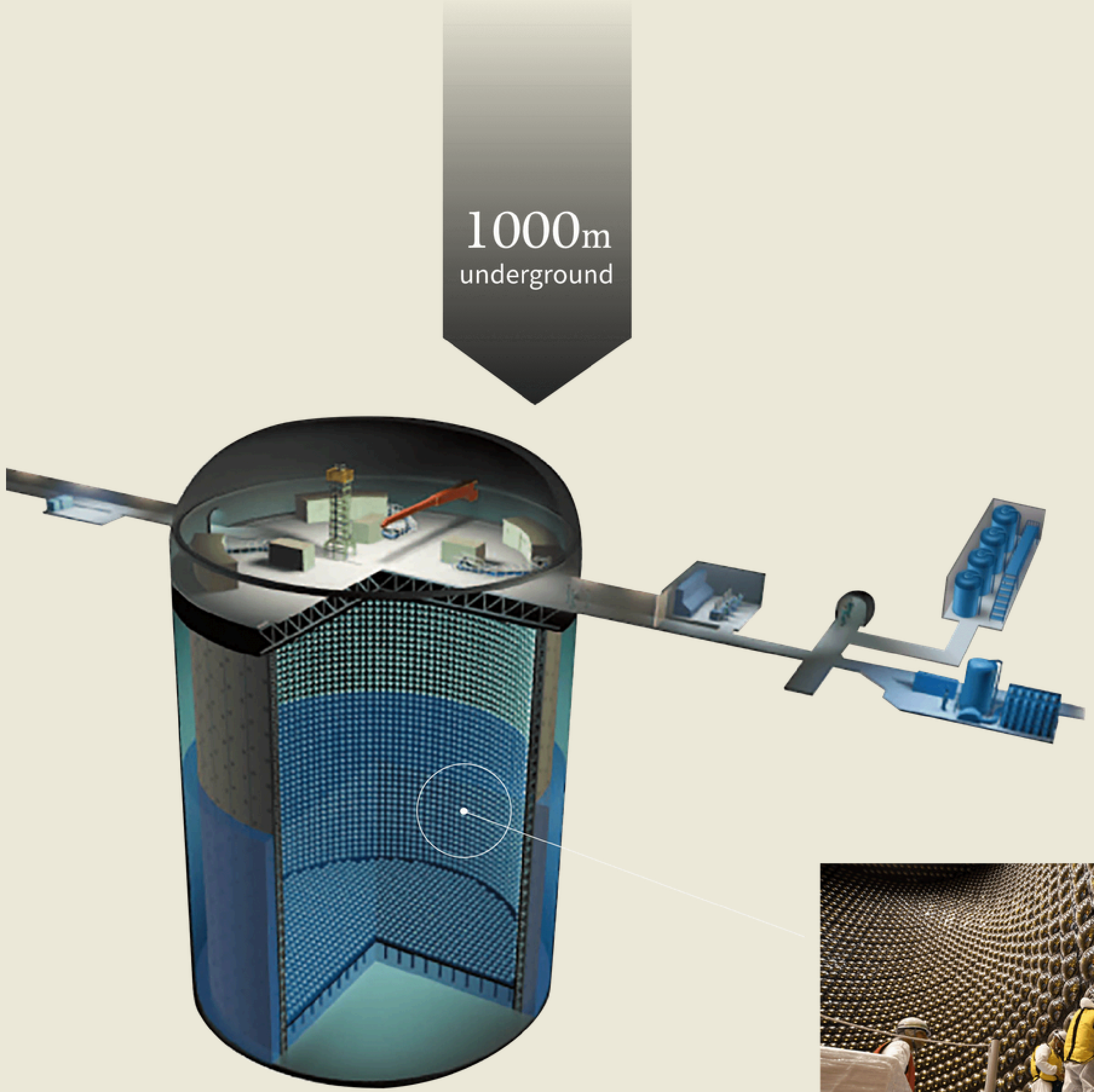
- **accelerator (beam) neutrinos** (T2K's object of interest)
- atmospheric neutrinos
- solar neutrinos
- supernova neutrinos
- reactor neutrinos
- cosmic neutrinos



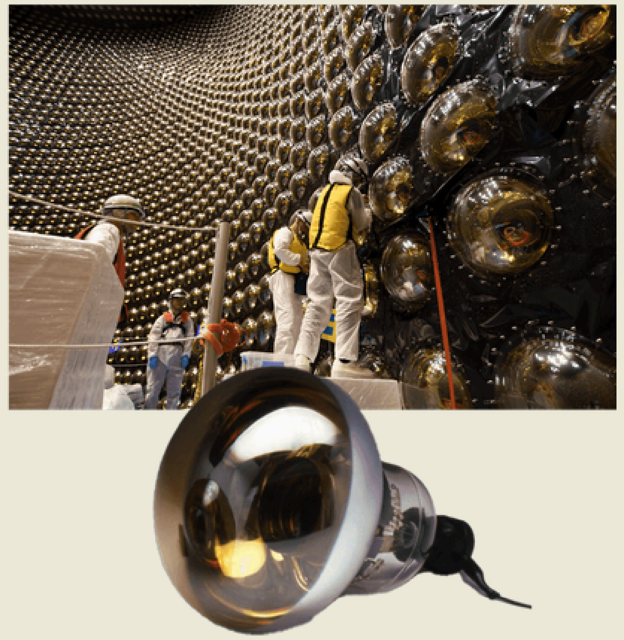


Mean neutrino beam energy ~600 MeV

FAR DETECTOR

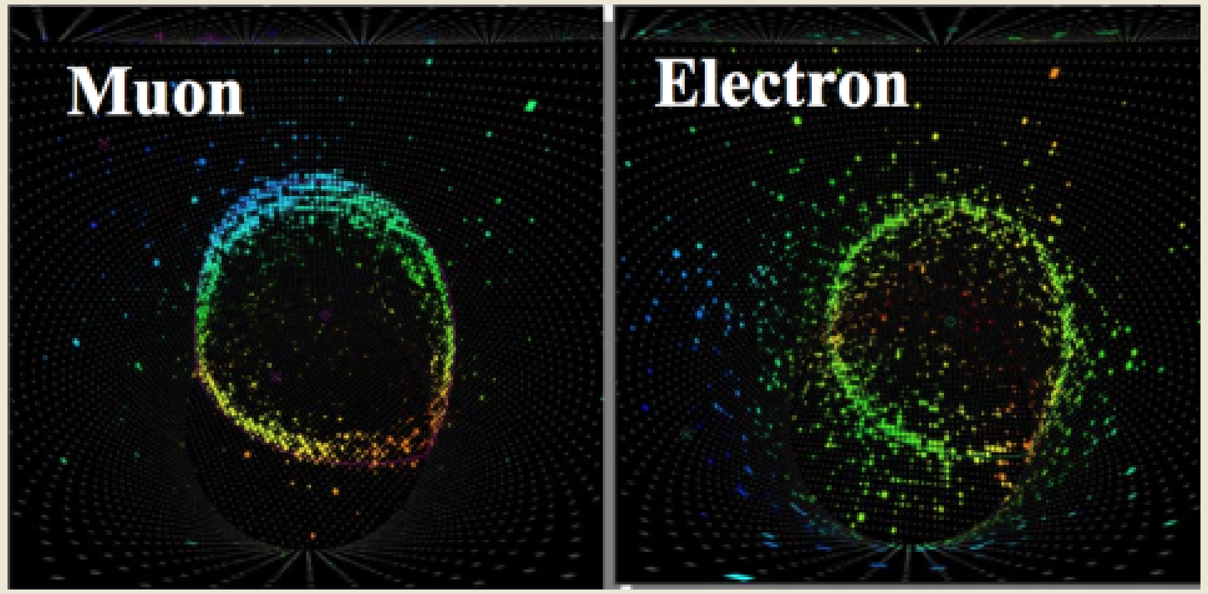


50 ktons of ultra-pure (later it became Gd-doped) water



11K photomultipliers

- **Neutrino interactions can produce a charged lepton, which leads to Cherenkov light** being detected as rings in the Super-Kamiokande detector.
- **The ring pattern** (which tends to be sharp for muons, fuzzy for electrons, due to their mass differences) **forms the basis for particle identification.**



At T2K's mean beam energy, CCQE interactions dominate.

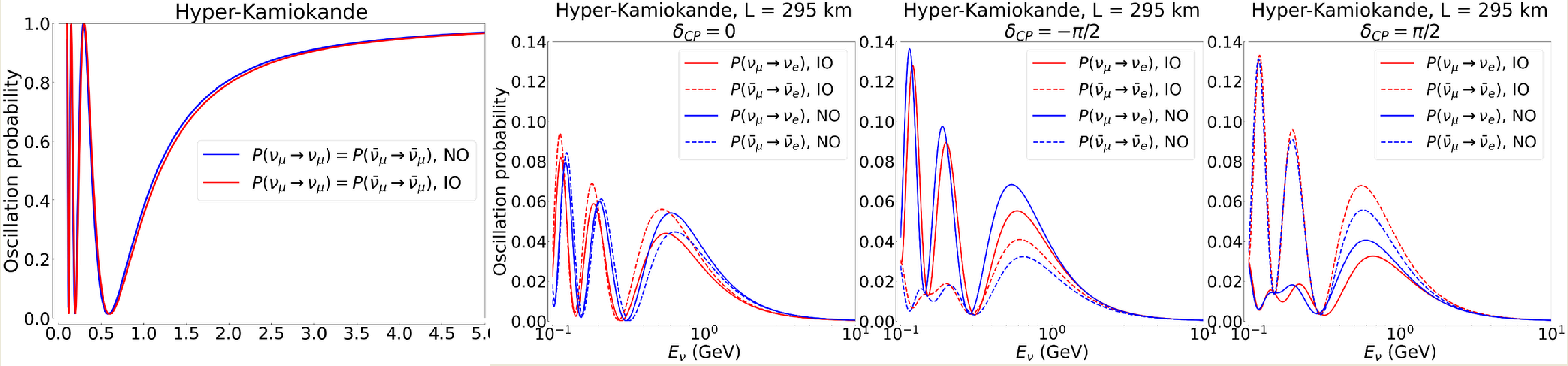
$$\nu_\mu + n \rightarrow \mu^- + p \qquad \nu_e + n \rightarrow e^- + p$$
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n \qquad \bar{\nu}_e + p \rightarrow e^+ + n$$

SUMMARY+FUTURE

- **The goal of the T2K experiment is to study neutrino oscillations** by comparing the properties of a neutrino beam near the source and after traveling a long distance.
- Key unknowns: CP violation phase, mass ordering: inversed (IO) or normal (NO).
- Next-generation water Cherenkov detector **Hyper-Kamiokande is under construction**! An analogous experiment called T2HK will follow the studies.

From PDG Live

Three-neutrino mixing parameters	
$\sin^2\theta_{12}$	0.307 ± 0.012
Δm^2_{21}	$(7.50 \pm 0.19) \times 10^{-5}$ eV^2
$\sin^2\theta_{23}$	$0.534^{+0.015}_{-0.019}$
Δm^2_{32}, IO	$(-2.527 \pm 0.034) \times 10^{-3}$ eV^2
Δm^2_{32}, NO	$(2.451 \pm 0.026) \times 10^{-3}$ eV^2
δ_{CP}	$1.21^{+0.19}_{-0.22}$ π rad



Oscillation probabilities as functions of energy for Hyper-Kamiokande