Neutrinos

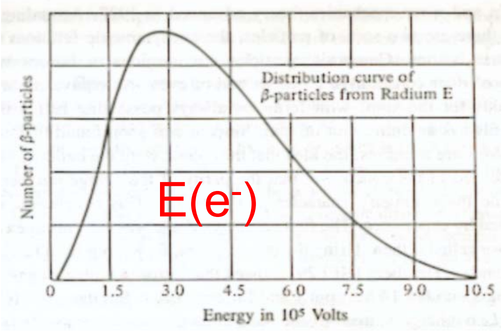
Walter Toki
Colorado State University
August 4, 2014

1. History of Neutrinos
2. Properties of Neutrinos
3. Why neutrinos are important to study
4. T2K neutrino experiment (CSU group's research)
    1. Construction and results
5. Future neutrino experiment called, LBNE

BRIEF HISTORY of the Neutrino

- 1927 , electron energy spectrum of radiative decays of radium E have continuous energy distribution

$$^{210}_{83}Bi \rightarrow ^{210}_{84}Po + e^{-} + (\overline{\nu}_e)?$$



- Energy does not seem to be conserved?
  - N. Bohr explains this due to Quantum Mechanic effect of energy uncertainty
  - 1930, W. Pauli explains as emission of neutral very light particle
  - E. Fermi names particle Neutrino (Italian neutral+bambino)

- 1956, Reines and Cowan experimentally detect anti-neutrino particles produced from Savannah reactor
  - Anti-neutrino produced in reactor $n \rightarrow p + e^{-} + \overline{\nu}_e$
  - Detected in liquid scintillator via $p + \overline{\nu}_e \rightarrow n + e^{+}$

- 1962 two types of neutrinos observed ν_e and ν_μ.
  - Neutrino from $p + e^{-} \rightarrow n + \nu_{(e)}$
  - Are different from neutrinos in $p + \mu^{-} \rightarrow n + \nu_{(\mu)}$

- 1998 Super Kamiokande Expt finds decisive evidence for neutrino oscillations

Properties of Neutrinos

- Neutral particles with very tiny mass; lightest <2 eV whereas proton mass 938 MeV. So neutrinos travel nearly at the speed of light c.

- Spin ½ particle (just like electron) and are classified as neutral Leptons which only interact via weak interactions

- So far observed THREE types or flavors of neutrinos; electron, muon, tau,

- Neutrinos can shape shift or “oscillate” between different neutrino flavors.

- Neutrinos observed in nature have spin pointing opposite to direction of motion (called left handed) and anti-neutrinos have is spin parallel to the direction of motion. This violates conservation of parity.

- Neutrinos interact VERY WEAKLY with matter such as proton/neutron, cross section at E_ν=1 GeV is 10^{-38} cm^2 so if a neutrino travels in water (density 1g/cm^3) it will travel $6.023 \times 10^{23}/10^{-38} \sim 10^{14}$ cm = 620 million miles before interacting whereas a 1 GeV pion will travel ~10cm.

- Neutrinos are the most abundant particles in the universe. The sun produces 10^{11} neutrinos per cm^2 at the surface of the earth. But due to the weak interaction of the neutrinos, a human being may expect to have 1 neutrino interaction per 72 years.

Why are neutrinos important?

• Quark and Leptons are the fundamental particles of matter. Neutrinos are ½ of the known leptons (other leptons are $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$)

• Neutrino interactions may explain why universe has matter and little anti-matter. This is a fundamental mystery.

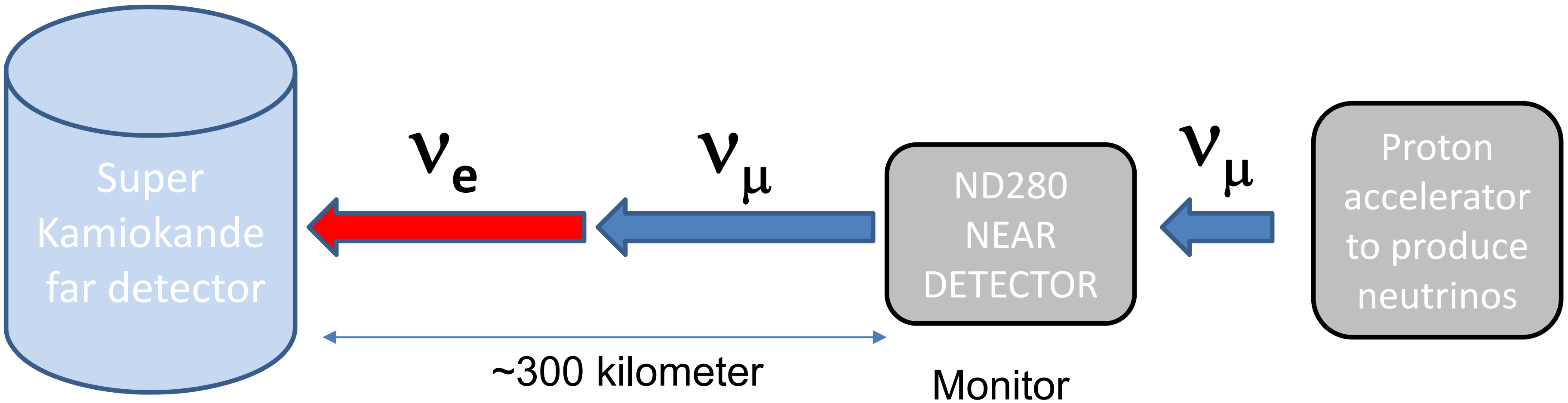
• Neutrinos will have practical applications in the next 50 years.

  - Analogous to electromagnetic waves (aka photons) in Maxwell's eqns in 1862. No one including Maxwell dreamed of future applications; radio (1901), TV (1941), radar(1939). Note these needed technical advances; vacuum tube, klystrons
  - The Standard Model was published 1967, so we can expect many future applications in communications to come.
  - recent application is nuclear reactor monitoring.

T2K Expt; aimed to measure the probability of the $\nu_\mu \rightarrow \nu_e$ after the neutrino travels hundreds of miles underground

Schematic Idea

Giant tank of water
Lined with phototubes



Super
Kamiokande
far detector

ν_e

ν_μ

ND280
NEAR
DETECTOR

ν_μ

Proton
accelerator
to produce
neutrinos

~300 kilometer

Detect electron
Type neutrinos in
reaction

$$\nu_e + n \rightarrow p + e^-$$

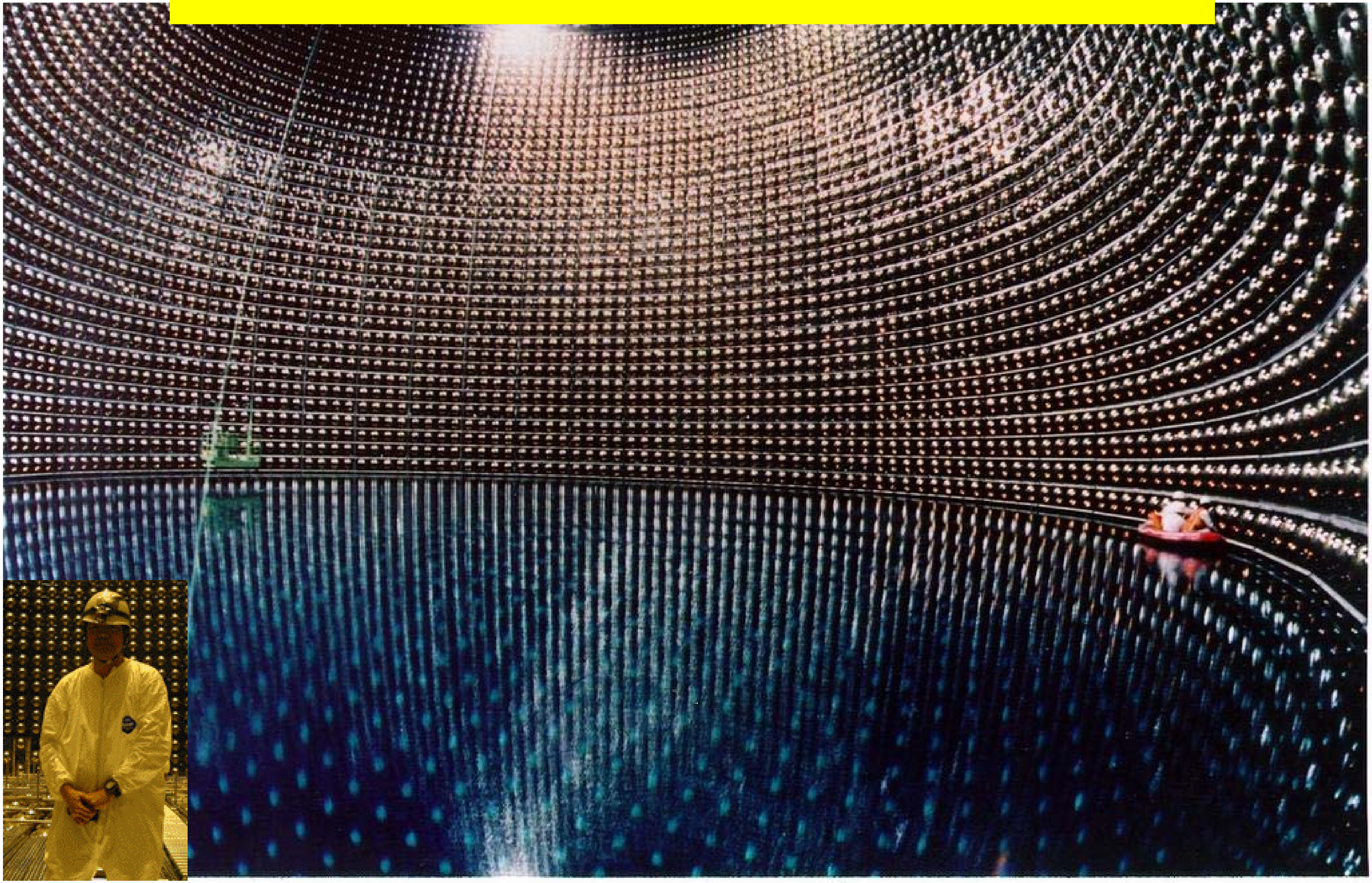
Monitor
Neutrino
beam

Tokai-to-Kamioka (T2K) experiment

$$\left|\left\langle \nu_e \middle| \nu_\mu(t) \right\rangle\right|^2 = \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2 L}{2E_\nu}\right)$$

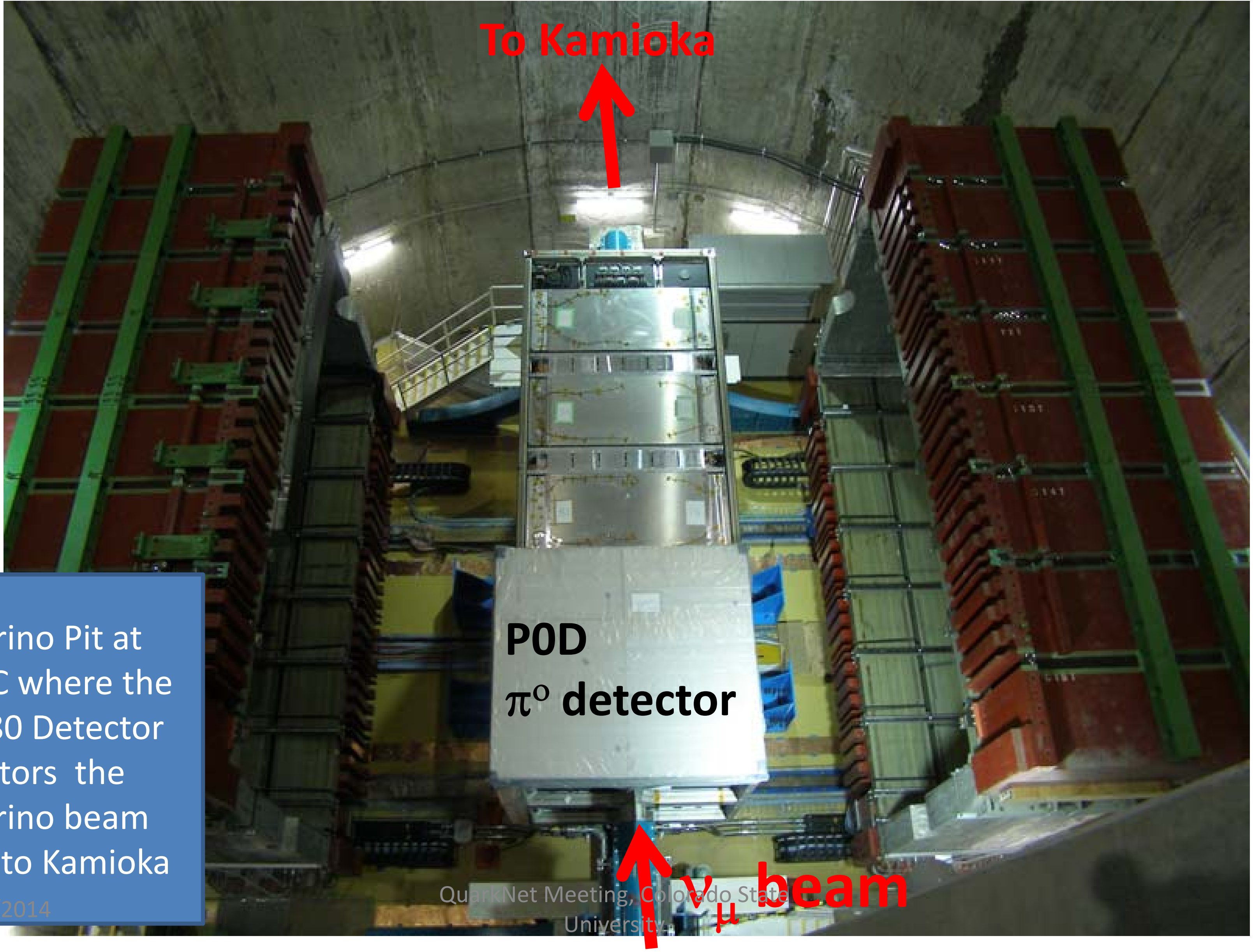
$$L = 295km,\ \ \Delta m^2 = 2.3\times 10^{-3} eV^2, E_\nu \approx 0.6GeV,\ \ \sin^2 2\theta_{13} = ?$$

SUPER KAMIOKANDE Detector



Underground tank of 50,000 tons of water lined with 11,000 phototubes

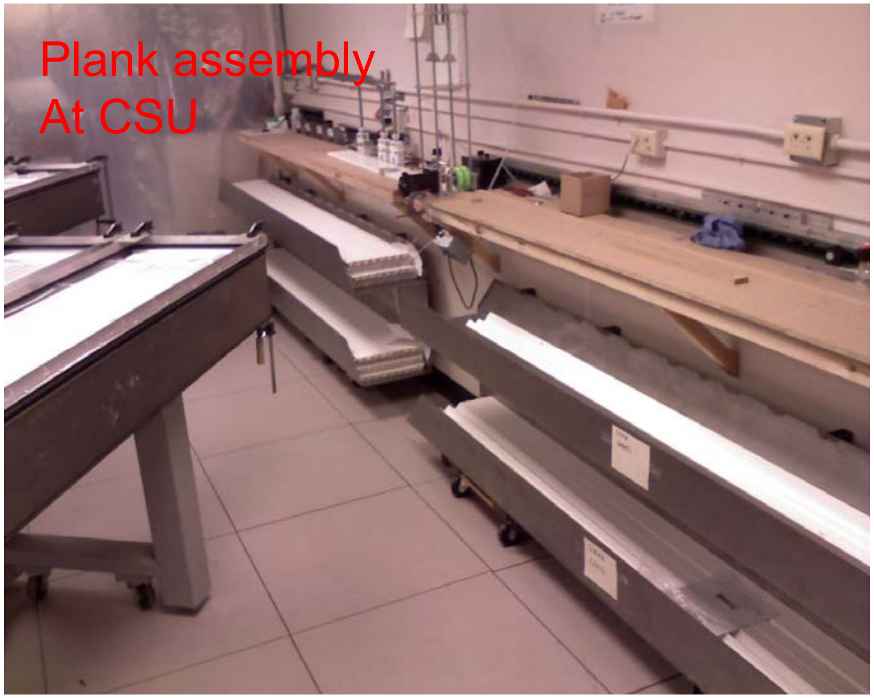
ND280 Detector (down stream det. 280m) at JPARC in front of the neutrino beam target



Neutrino Pit at JPARC where the ND280 Detector Monitors the Neutrino beam sent to Kamioka

CONSTRUCTION OF THE P0D DETECTOR (2008)

Scintillator bar
Assembly at CSU



Plank assembly
At CSU

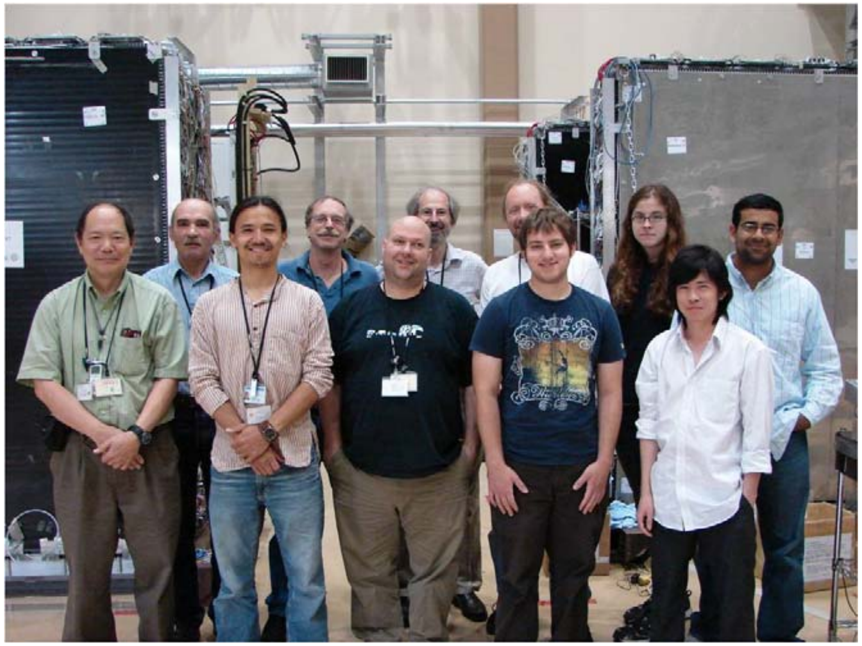
P0D assembly
At SBU

SuperP0D assembly
At SBU

P0D detector arrival & checkout at JPARC in JAPAN (2009)

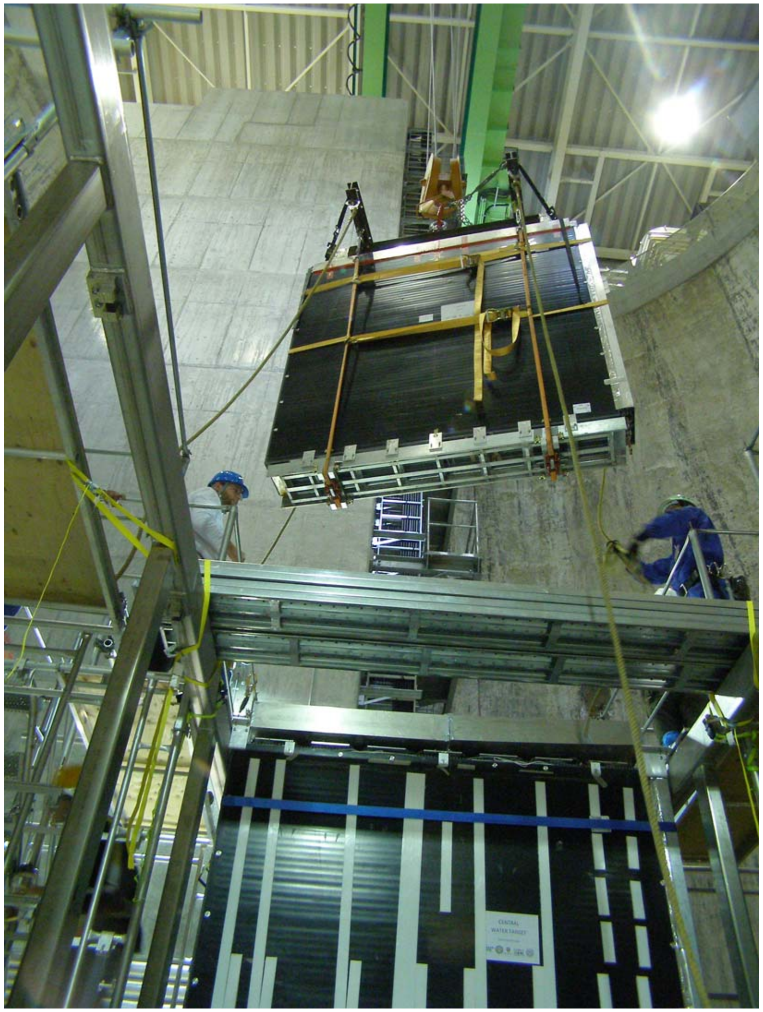
Detector ARRIVAL at JPARC
in April 2009

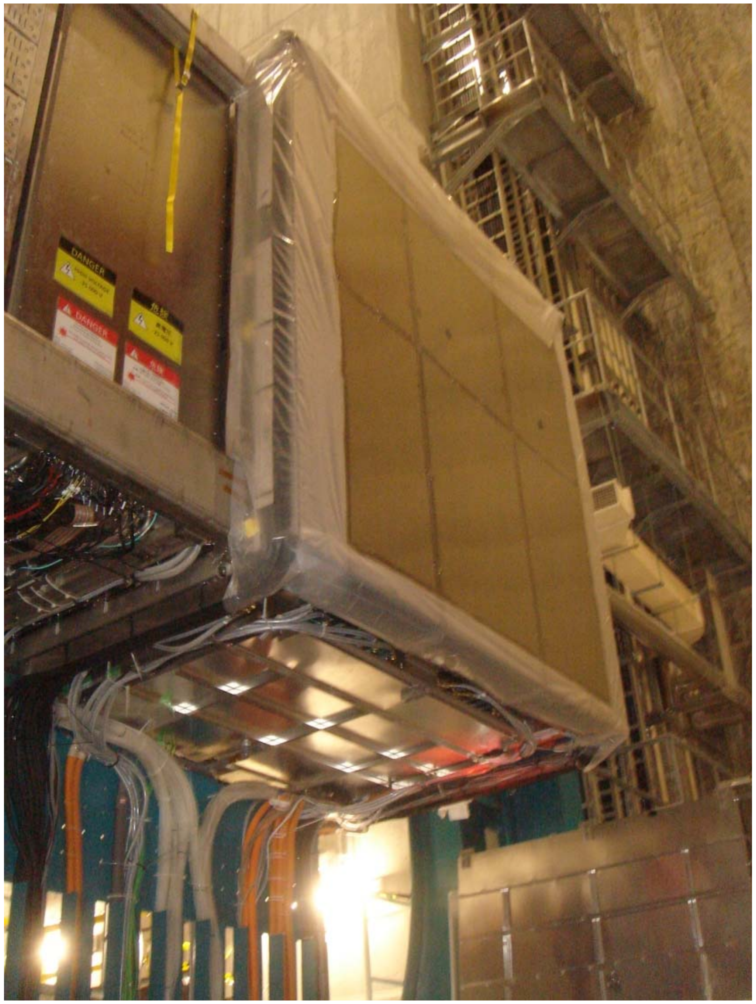
CREW at JPARC to checkout Det.



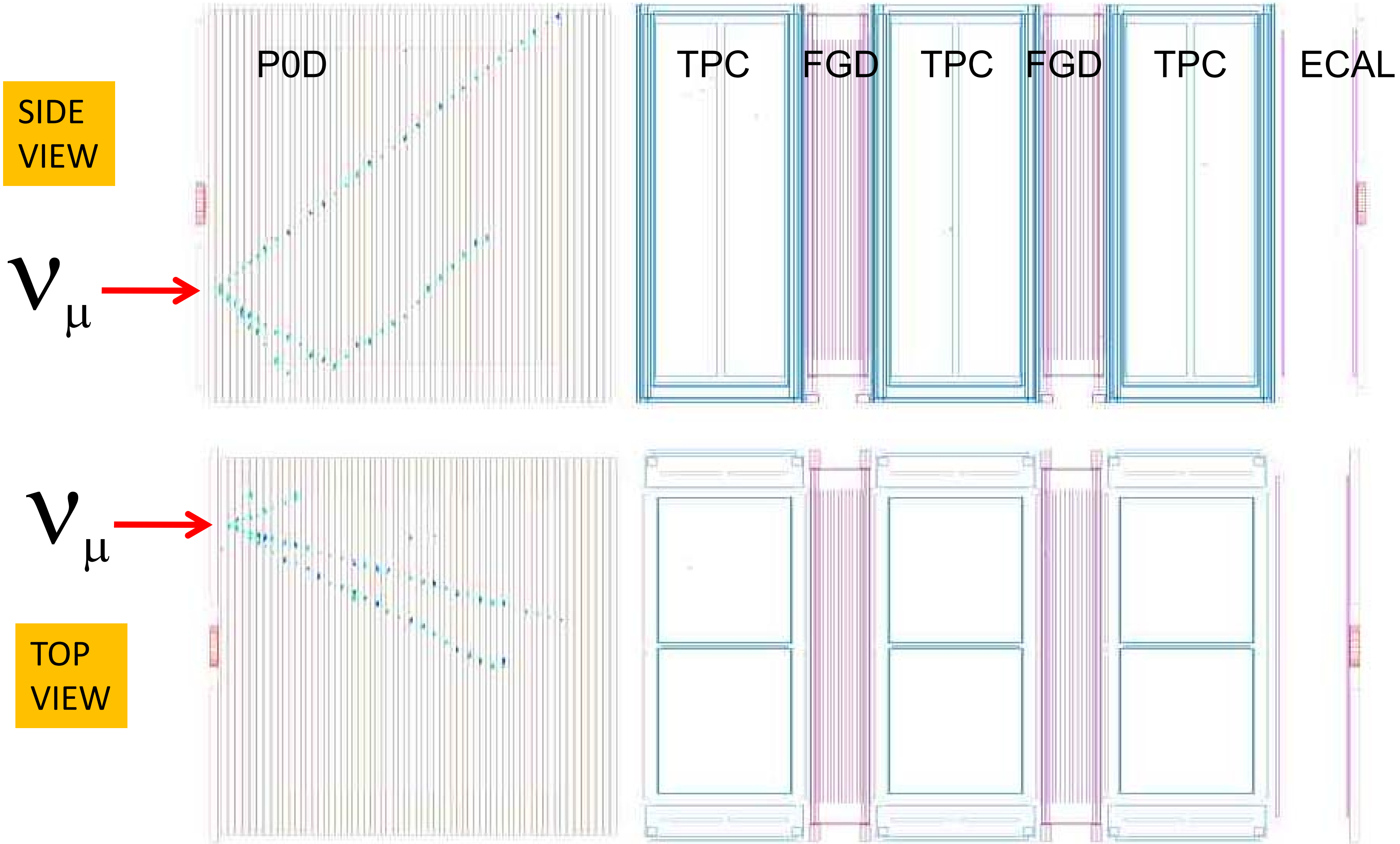
Collaboration members from CSU, SBU, U Rochester, and U Pittsburgh (CSU Prof's Toki, Buchanan, Wilson)

P0D INSTALLATION at neutrino pit in JAPAN

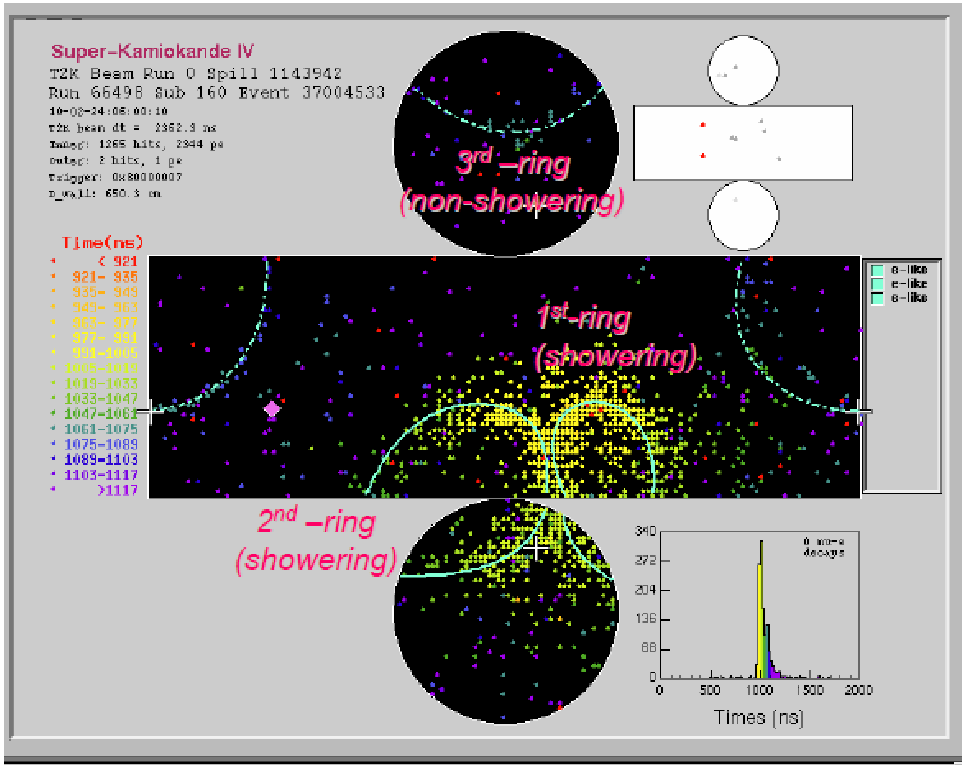

P0D detector sections lowered
Into the ND280 detector

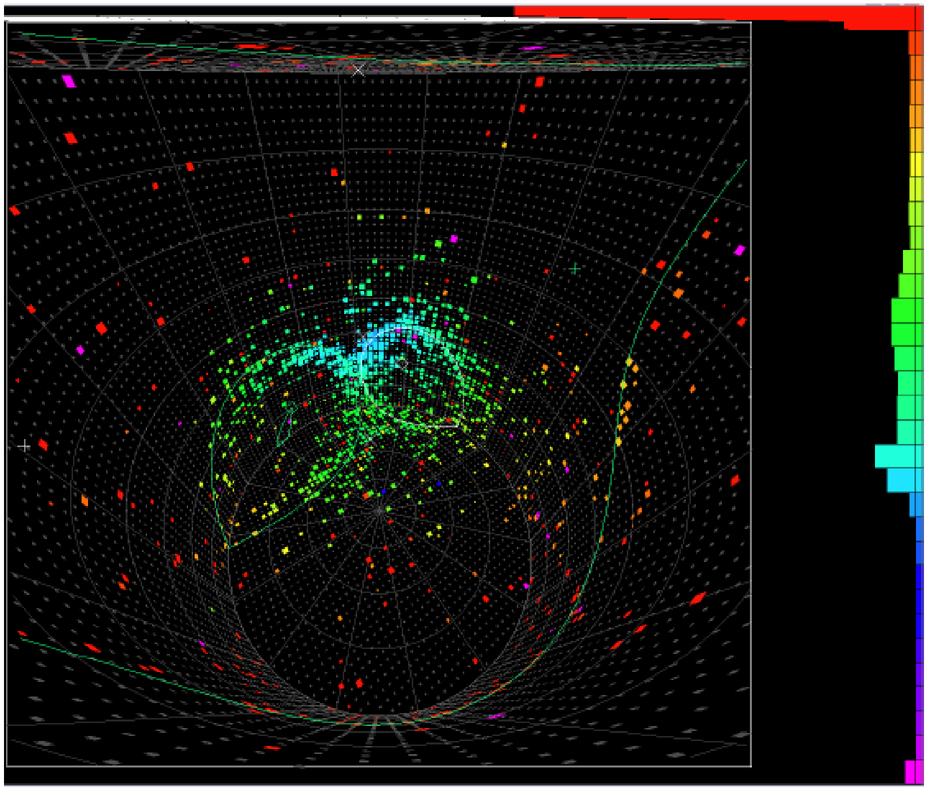

P0D detector side view

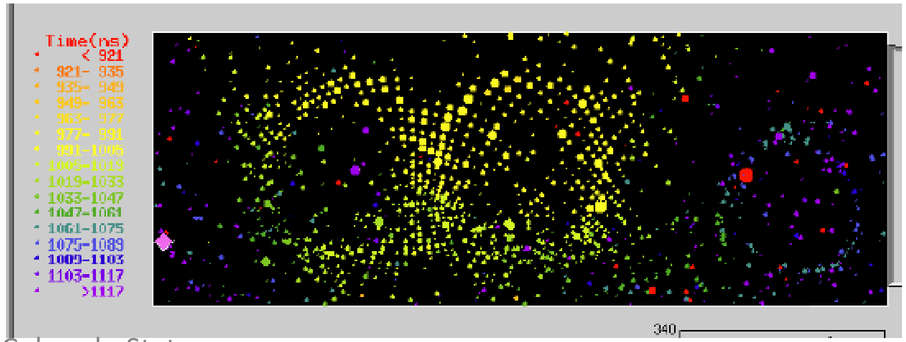
CANDIDATE NEUTRINO EVENT in P0D Detector



First event candidate at Super-K







1st ring + 2nd ring

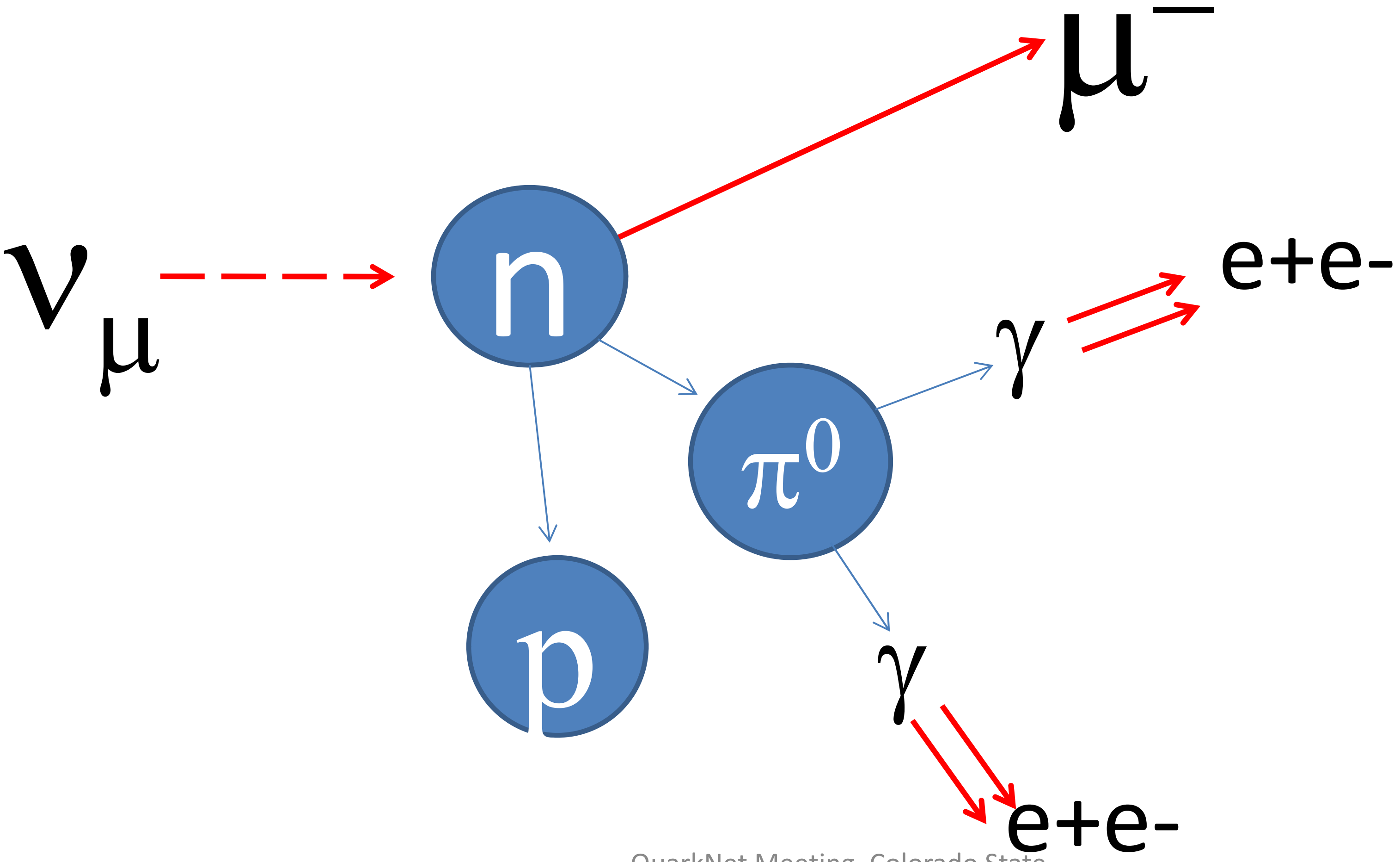
Invariant mass : 133.8 MeV/c^2

(close to π^0 mass)

momentum : 148.3 MeV/c

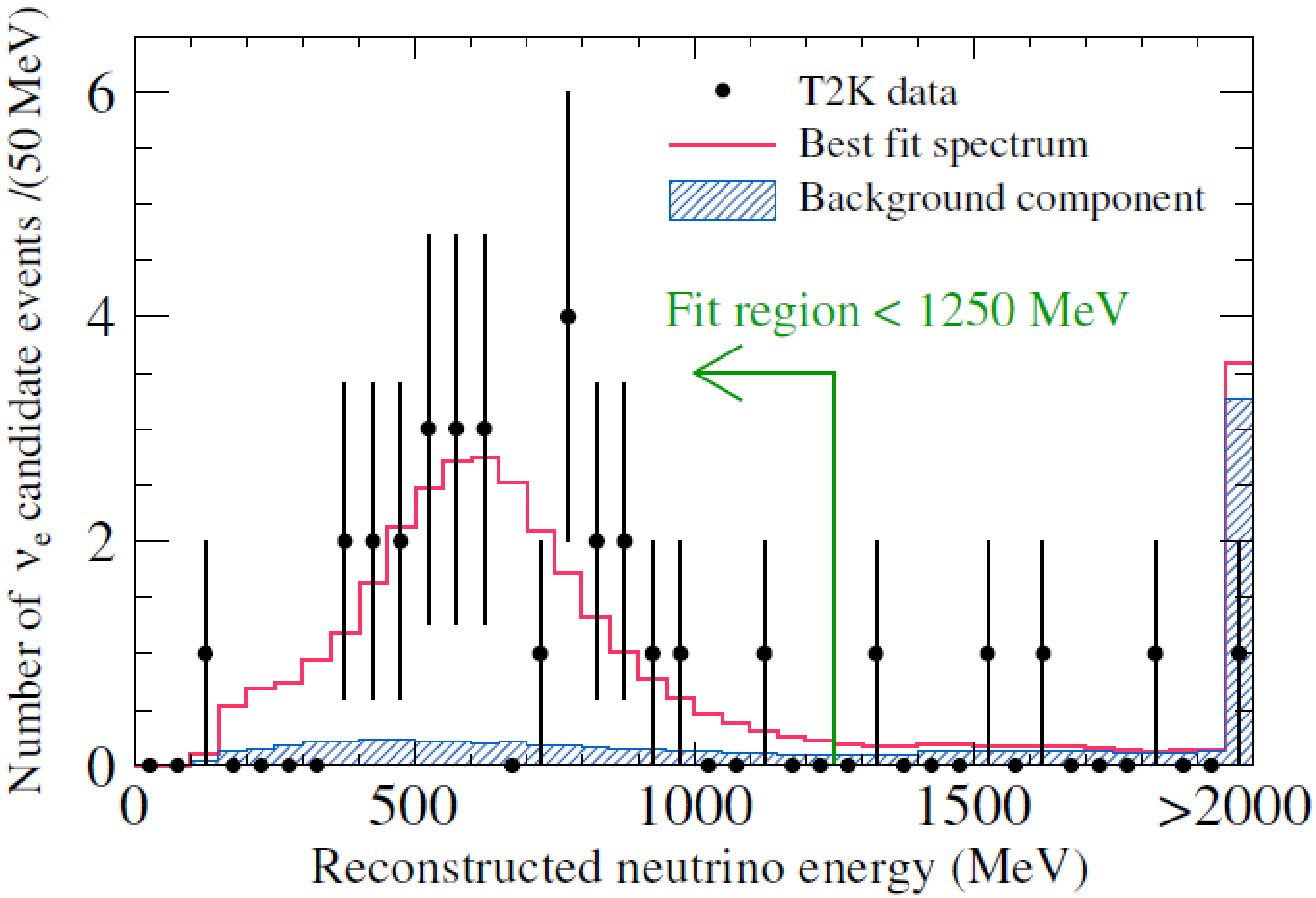
MOST LIKELY EVENT TOPOLOGY

$$\nu_\mu + n \rightarrow \mu^- + p + \pi^0,\ \ \pi^0 \rightarrow \gamma\gamma$$

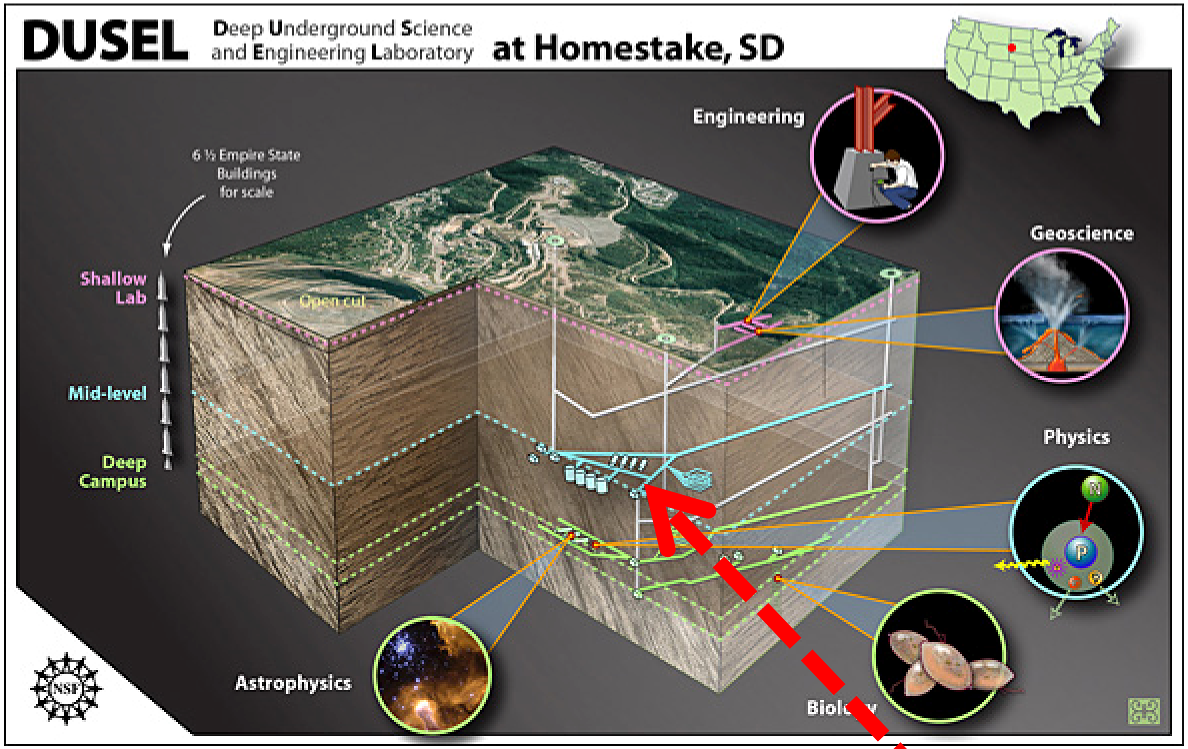


T2K Evidence for Neutrino Oscillations $\nu_\mu \rightarrow \nu_e$

Electron type neutrino energy distribution at Super Kamiokande



28 event candidates observed by October 2013.
Determines neutrino mixing parameter $\theta_{13} \approx 11$ deg.
Published in Physical Review Letters.



FUTURE PROJECT; LONG BASELINE NEUTRINO EXPERIMENTS (LBNE)
Now being proposed and planned.
(Bob Wilson)

ν_μ

Send a neutrino beam from Fermi National Accelerator Lab (near Chicago) to the Homestake Mine Underground lab called DUSEL in South Dakota

BACKUP slides

- The neutrinos we observe in nature are produced and detected as flavor neutrinos in 3 types; electron, muon, and tau neutrino flavors

- These flavor neutrinos are linear combinations of mass eigenstates, ν_1, ν_2, and ν_3.

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- The neutrino flavor wave function will oscillate between the 3 states With tiny masses m_1, m_2, and m_3.

$$|\nu_\mu(t)\rangle = U_{\mu 1}\exp\left(-im_1^2 t\right)|\nu_1\rangle + U_{\mu 2}\exp\left(-im_2^2 t\right)|\nu_2\rangle + U_{\mu 3}\exp\left(-im_3^2 t\right)|\nu_3\rangle$$

$$\left|\langle\nu_\mu|\nu_\mu(t)\rangle\right|^2 = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{2E}\right)$$

$$\left|\langle\nu_e|\nu_\mu(t)\rangle\right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{2E}\right)$$

⇐ We aim to measure the probability of the $\nu_\mu \rightarrow \nu_e$ after the neutrino travels hundreds of miles underground