A lucky experience

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I thank JINR for the recognition of T2K contribution to the neutrino physics. I am honored to receive Bruno Pontecorvo prize.

The experiments have never been realized without efforts of many people. T2K and K2K collaborators (With the K2K experience, T2K could be realized) for their hard and innovative work.

Accelerator colleagues at J-PARC for the hard work to build and to operate new high power accelerator.

Pioneering Japanese high-energy physicists, whose hard efforts realized the first Japanese proton accelerator, which made it possible to build first neutrino beam in Japan twenty years later for K2K.

The late Prof. Y. Totsuka made every possible effort to advance both K2K and T2K from the very beginning as Spokesperson of Super Kamiokande and later as Director General of KEK.

Prof. H. Sugawara, former Director General of KEK, made long baseline experiments a reality in Japan by his firm decision and strong support.

Last but not least, I would thank my wife for the support.

T2K Collaboration

Canada, France, Italy, Korea, Poland, Russia, Spain Switzerland, UK, USA and Japan

Yoji Totsuka

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Many experiments contributed to show various aspects of neutrino oscillation since 1960's

- Deficiency of solar neutrino
  - Home-stake and many Radio-chemical experiments
- Flavor changes in solar neutrino
  - SNO showed components other than electron neutrino in solar neutrino
- Oscillation pattern in reactor neutrino with ~200km baseline
  - KAMLAND
- Atmospheric $\nu\mu$ disappearance
  - Kamiokande/Super-Kamiokande oscillation with earth scale baseline
- Oscillation pattern in GeV mu-neutrino beam
  - K2K, MINOS wide range measurements of disappearance

- Two oscillations (νe Δm^2_{sol}, $\nu\mu$ Δm^2_{atm})
  - Flavor changes between initial and final state neutrino
  - Oscillation pattern shows each flavor neutrino is a quantum mechanical superposition of different masses

The T2K Experiment

Sub-GeV ν_μ (anti-ν_μ) beam generated at J-PARC and detected at Super-Kamiokande with 295km baseline

Main modes of investigation

$\nu_\mu \rightarrow \nu x$ disappearance

$\nu_\mu \rightarrow \nu_e$

Anti-$\nu_\mu \rightarrow$anti-ν_e

- ν_e disappear also with Δm^2_{atm}
  - Daya-Bay, RENO, Double-CHOOZ
- $\nu_\mu \to \nu_e$ with Δm^2_{atm}
  - T2K
- $\nu_\mu \to \nu_\tau$ detected
  - OPERA

Can 3 generation scheme describe all modes of observed neutrino oscillation?

cij = cosθij, sij=sinθij

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{12}, θ_{23}, θ_{13} + δ (+2 Majorana phase)

Δm^2_{21}, Δm^2_{32}, ($\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$)

Mass Hierarchy (sign of Δm^2_{31}), θ_{23} octant ambiguity (θ_{23} >π/4 or <π/4) and CP-violation

First term dominates $P_{\mu e}$ with relatively large θ_{13}

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} + solar\ term \qquad (Reactor\ \bar{\nu}_e\ disapp.)$$

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{23} + second\ order \qquad (\nu_\mu\ disapp.\ in\ atm./accel.)$$

$$P_{\mu e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{31} \qquad (\nu_\mu \to \nu_e\ appearance)$$

$$\mp \delta_{CP} term \cdot \sin\Delta_{31}\left(\Delta m^2_{21}/\Delta m^2_{31}\right) + Matter\ effect\ S^2_{13}\left(\frac{(\pm A)L}{4E_\nu} + c\right)$$

$$+ solar$$

$$\delta_{CP} term = Jahlskog\ \ factor \cdot \sin\delta_{CP},$$

$$\Delta_{ij} = \Delta m^2_{ij} L / E_\nu,\ \ \Delta m^2_{ij} = m^2_i - m^2_j \quad A = 2VE_\nu / \Delta m^2_{31}$$

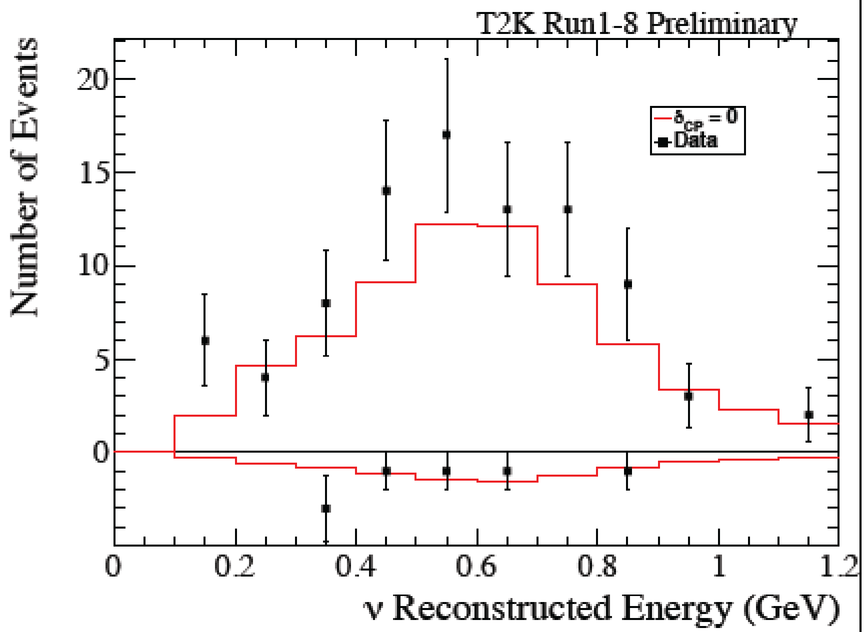
Near 1st maximum

$|\Delta m^2_{21}/\Delta m^2_{31}|$~0.03

Mark Hartz KEK Colloquium Aug.,2017

E-LIKE OBSERVATION VS. PREDICTION

- Compared to $\delta_{cp}=0$ prediction:
  - Excess in neutrino mode (top)
  - Deficit in antineutrino mode (bottom)



- All present observations of neutrino oscillation are consistent with the 3 generation scheme in first order
- T2K experiment continues improving its results. I expect young colleagues will make a big step forward in near future

Fundamental questions

- Origin of mass of quarks and leptons
  - Origin of many orders of magnitudes different masses
  - Relationship of flavor and mass

- Origin of matter dominated Universe
  - related to CP violation in lepton ?
    - Due to δ_{CP} , nothing else?

- Difficult questions to answer by experiments

BUT

- Sometimes, theoretical prejudice and analogy from known physics mislead

1980's Long / Short Baseline argument
A motivation of short baseline exp't

Critical mass density of Universe ~ 5000 eV/cm^3 (Flat curvature),
If Dark matter is due to neutrinos

	number density (/cm^3)	mass (eV)	mass density (eV/cm^3)
Nucleon	10^{-7}	10^9	100
Neutrino	100 / flavor	1~10	3~3000

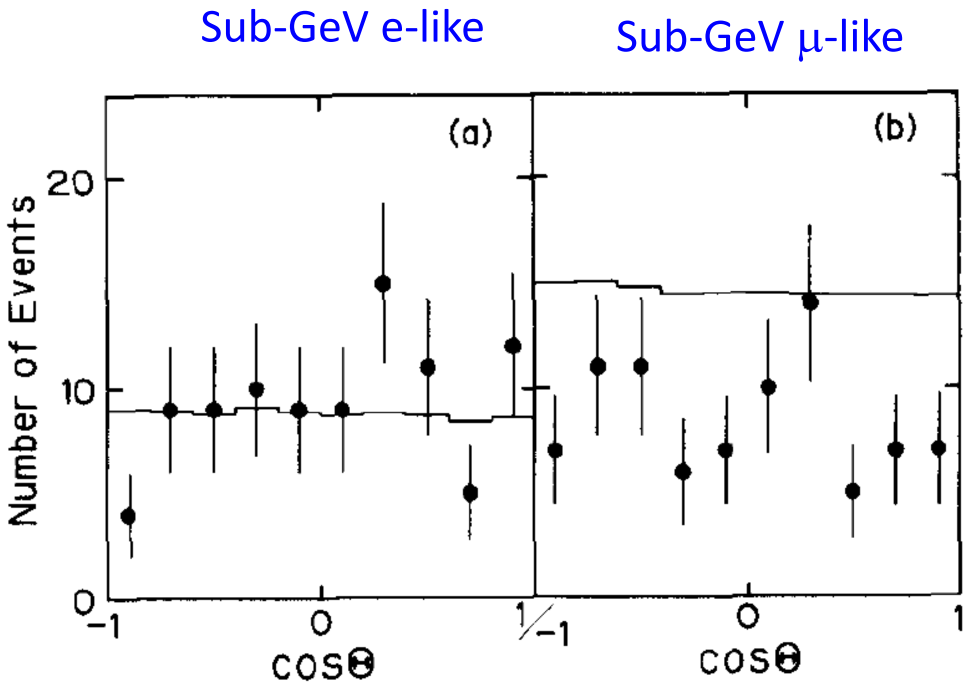
Short baseline look for small mixing

COBE and further developments

Unexpected New Δm^2 region

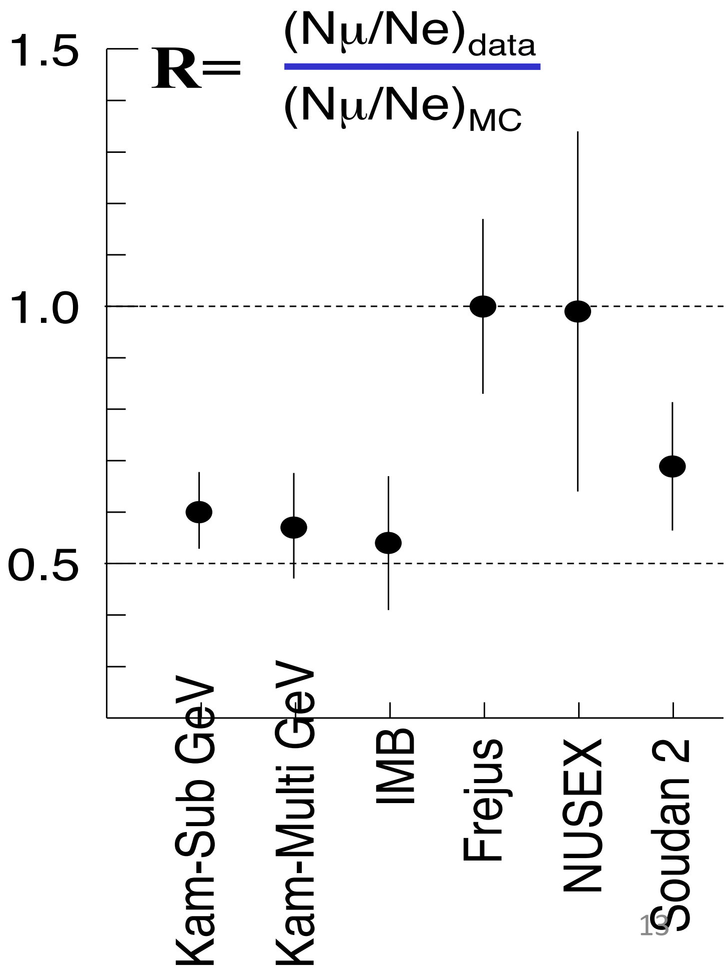
1988

KAMIOKANDE



Kamiokande collab:.
Phys. Lett. **B 205**, 416 (1988)

1992



- Exciting fundamental questions remain to be investigated （Mass, Flavor….)

- Unexpected phenomenon opened new roads in the past
  - New approach to a problem with quantitative studies with right conditions
  - With fresh brain
  - At the right time
  - If nature is friendly (lucky enough)