Super-Kamiokande
(+K2K, T2K)

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The University of Tokyo

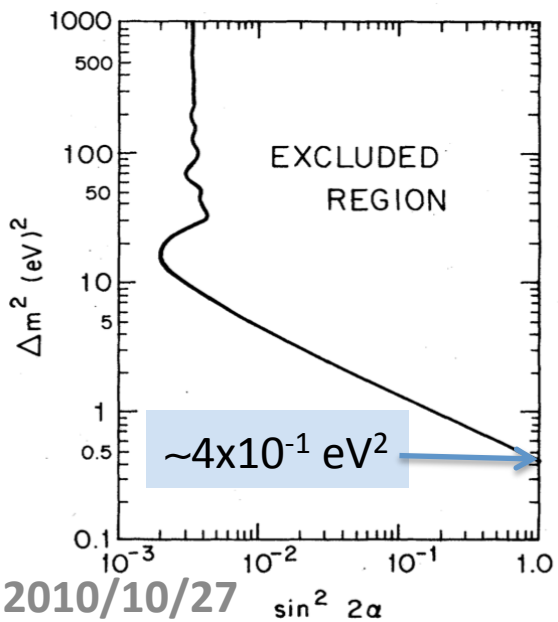
@30th Anniversary of US-Japan Cooperative Research Program,
On 20th of October, 2010, in Hawaii

(Personal) Introduction

1984
BNL E734
(US-Japan Cooperative RP)

YS analyzed and written
this oscillation paper
with Al Mann

$\nu_\mu \rightarrow \nu_e$ limit
L= 96m, $\langle E_\nu \rangle$=1.2 GeV



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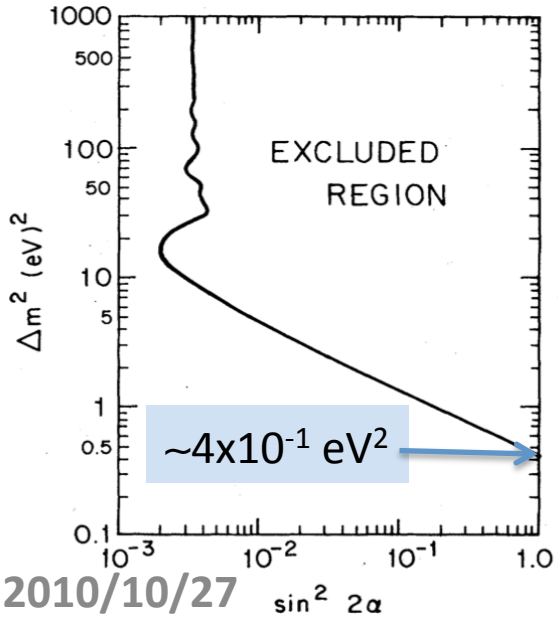
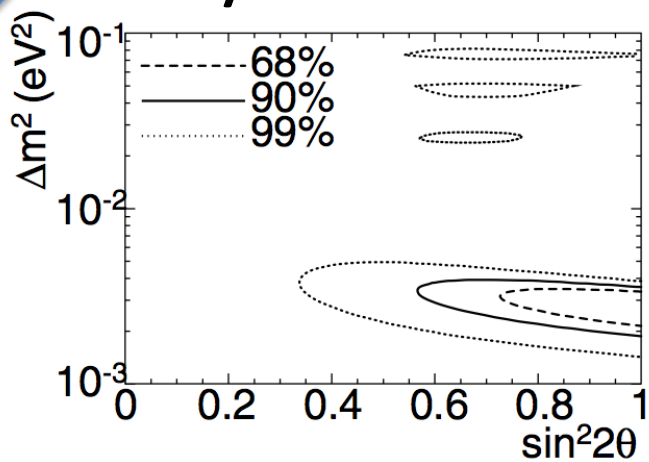


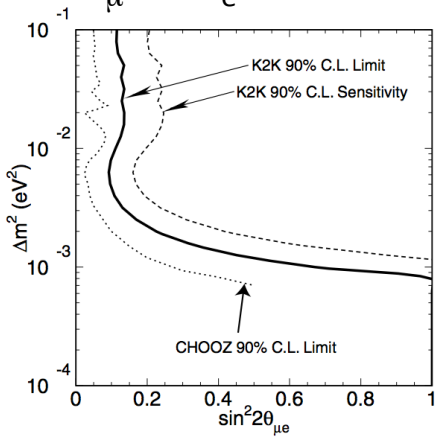
20 years

2004
K2K/SK



$\nu_\mu \rightarrow \nu_\mu$
L= 250km, $\langle E_\nu \rangle$=1.3 GeV

$\nu_\mu \rightarrow \nu_e$



~1000 times improvement

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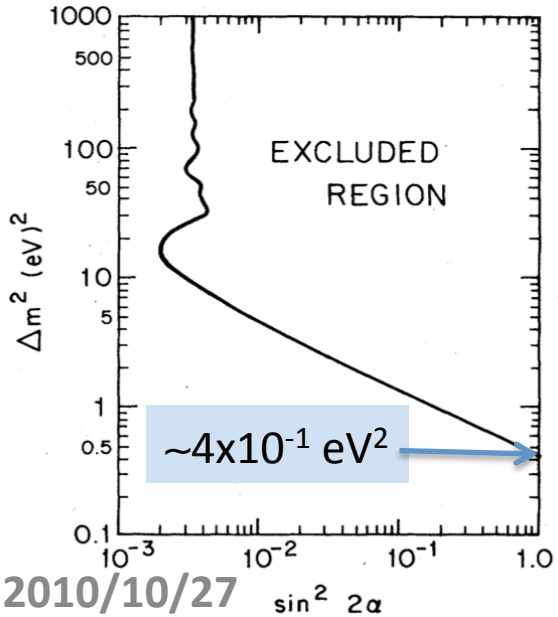
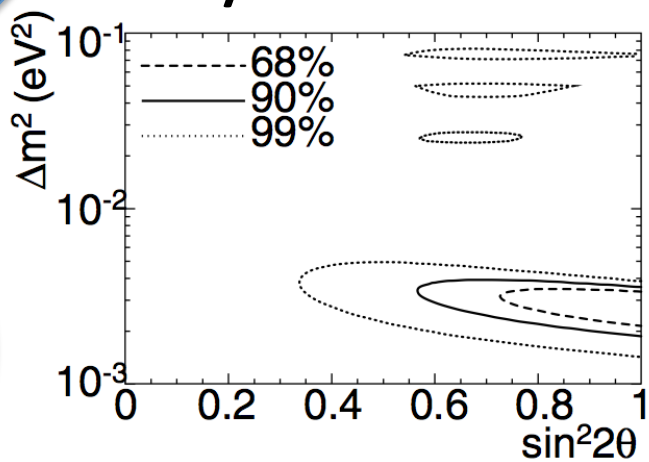


20 years

During the missing 20 yr, YS has been working mostly on Kamiokande and Super-Kamiokande

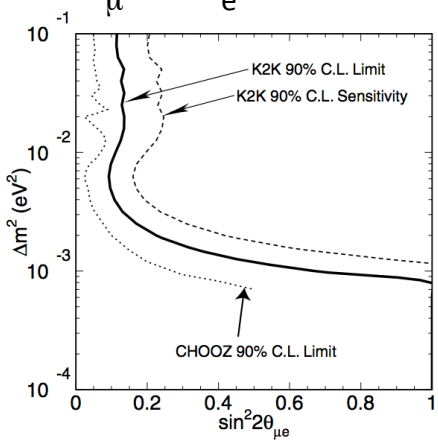
2004
K2K/SK



$\nu_\mu \rightarrow \nu_\mu$
L= 250km, $\langle E_\nu \rangle$=1.3 GeV

$\nu_\mu \rightarrow \nu_e$

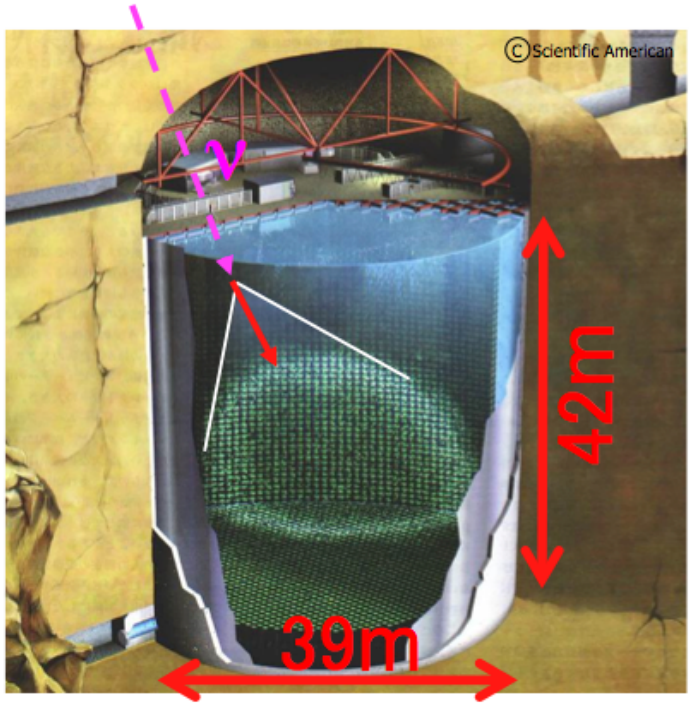
1000 times improvement



No body can predict experiments 20 years from now !

Super-Kamiokande

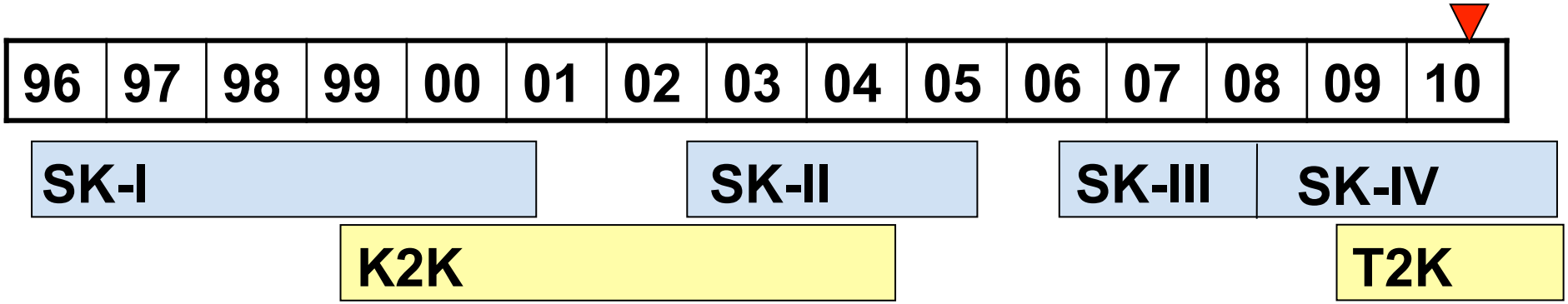
- Not a part of the US-Japan cooperative research program
- But a good example of successful US- Japan Collaboration



- 50,000 tons of Imaging Water Cherenkov Detector
  - Inner: 32,000 tons
    (Outer Vol: ~2.5 m thick)
  - Fid. Vol: 22,500 tons
- 11,146 PMTs (ID)
  - 50 cm in diameter
  - 40% coverage
- 1,885 PMTs (OD)
  - 20 cm in diameter
- 1,000 m underground

~130 Collaborators from 36 inst. (6 countries)

Brief history of Super-K



- 4 phases: SK-I, SK-II, SK-III, SK-IV
  - SK-I (11,146 PMTs (40% cov.))
    - April-1996 → June-2001
  - Accident (lost more than half of PMTs)
    - Nov-12, 2001
  - SK-II (5,182 PMTs (19% cov.))
    - Dec-2002 → Nov-2005
  - SK-III (11,129 PMTs (40% cov.))
    - July-2006 → Sept-2008
  - SK-IV (11,129 PMTs (40% cov., New Elec.))
    - Sept-2008 →
- K2K: March-1999 → Nov-2004
- T2K: April 2009 →

US Joined

- In 1992, US group joined the Super-Kamiokande experiment, one year after the start of the construction in 1991.
- Most of them were the former members of the IMB group who were the competitors of the Kamiokande experiment.
- Hank will discuss the international collaboration issues later

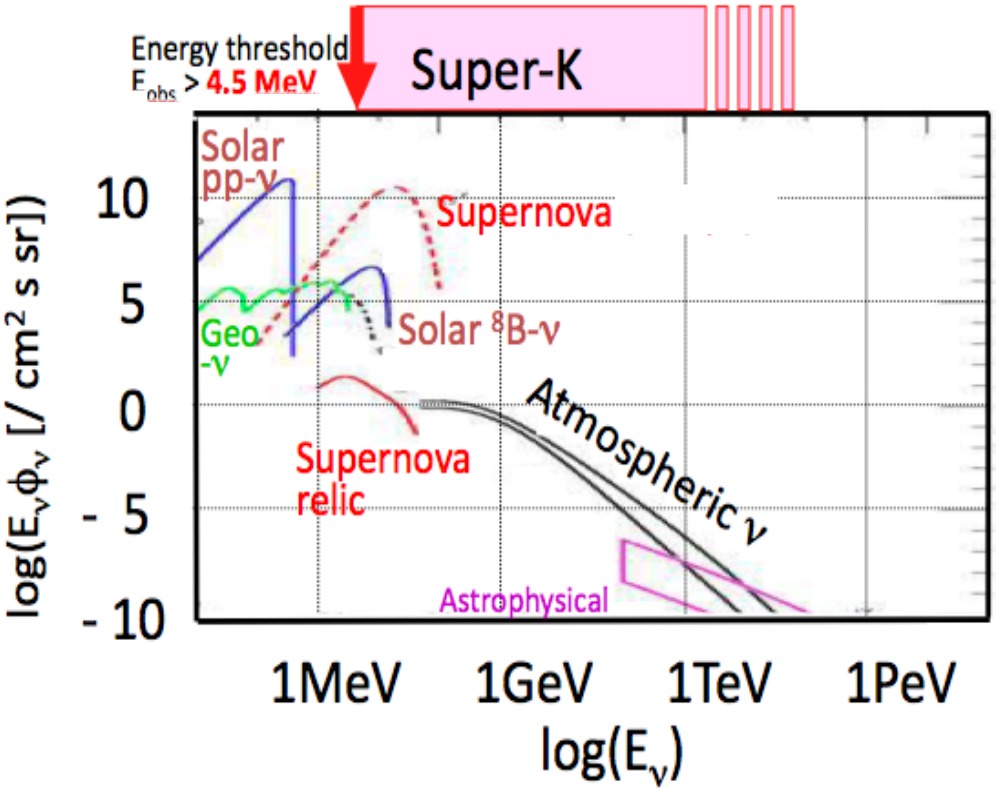
Hank Sobel *Yoji Totsuka*

- Budget JPN : US = 10 : 2
- Manpower JPN : US = 1 : 1

We thought that man power is also resources (Y. Totsuka's thoughts)

Physics Objectives

Multi-purpose detector covering wide energy range



- **Precise study of Atmospheric Neutrinos**
  > 10 events /day
- **Precise study of solar neutrinos**
  > 15 events /day
- **Look for neutrinos from supernovae**
  > 8,000 events for SN at 10kpc distance
- **Look for SN relic Neutrinos**

Discovery Neutrino Oscillation

Discovery Solar - ν Oscillation w/SNO

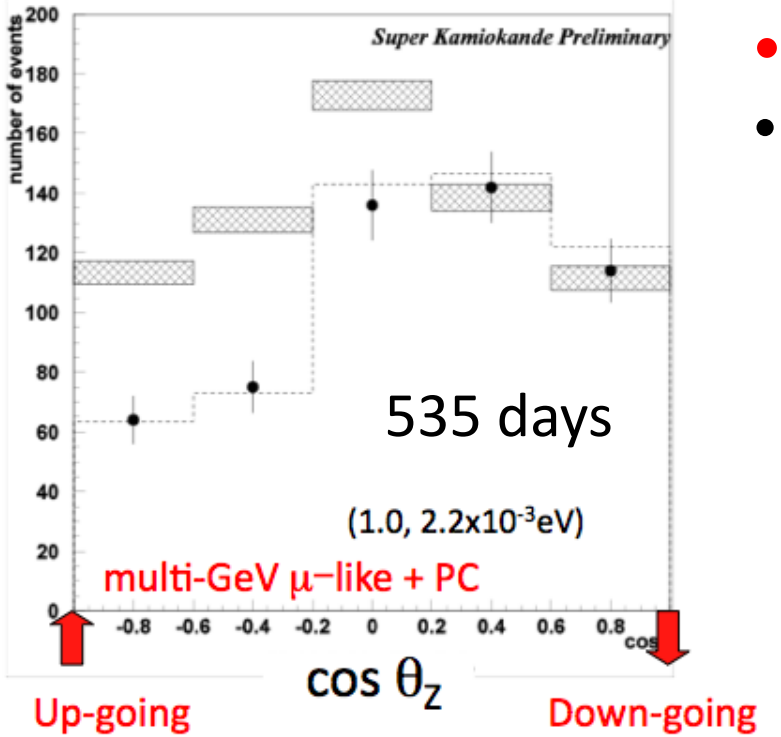
GadZOOKs

- **Look for Proton Decay**
  Up to **10^{33}~10^{34}** years

10^{34} yrs

- **Far Detector for Long baseline ν Oscillation Experiments**

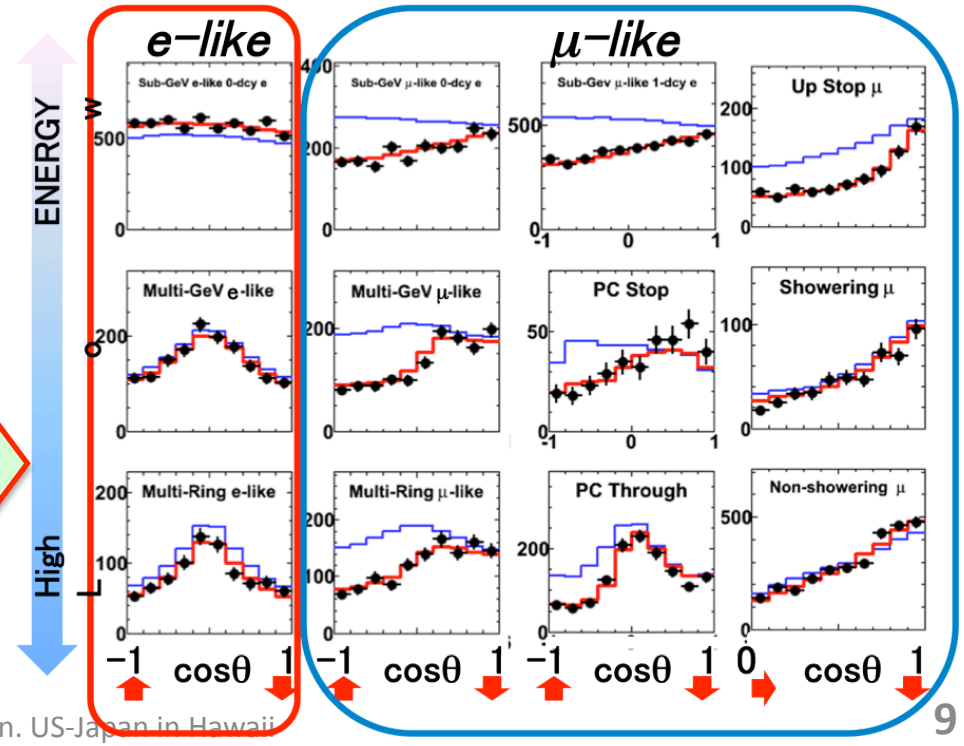
Discovery of Atmospheric ν Oscillation



- In 1998
- SK observed
  - Asymmetry of μ-like events in the zenith angle distributions

  ➔ Definitive evidence of the neutrino oscillation independent of the flux calculations

Latest SK results (SK-I,II,III combined)
–2806days (173ktyr) for FC+PC
  –24841 events
–3109days for up-μ
  –4238 event



Oscillation Parameters (3 flavor)

Normal Mass Hierarchy

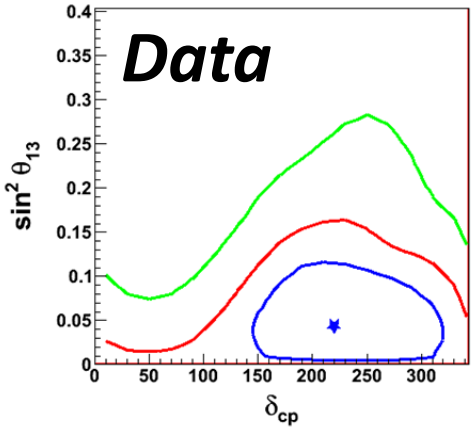
$$\Delta m^2_{23} = 2.11^{+0.43}_{-0.12}\ eV^2$$
$$\sin^2\theta_{23} = 0.525^{+0.072}_{-0.084}$$
$$\sin^2\theta_{13} < 0.066\ (90\%\ C.L.)$$

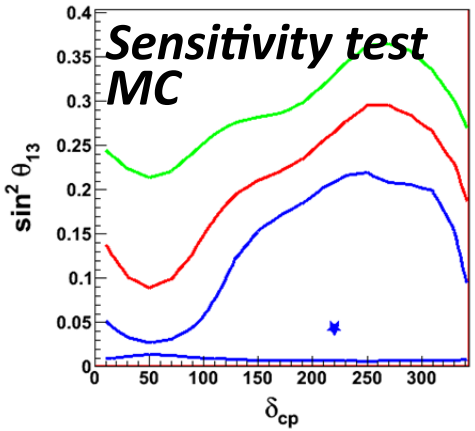
Inverted Mass Hierarchy

$$\Delta m^2_{23} = 2.51^{+0.13}_{-0.42}\ eV^2$$
$$\sin^2\theta_{23} = 0.575^{+0.048}_{-0.074}$$
$$\sin^2\theta_{13} < 0.122\ (90\%\ C.L.)$$

CP phase

Inverted Mass Hierarchy





- Best fit (IMH)
  - CP phase: 220°
  - $\sin^2\theta_{13}$: 0.044
- 1 σ level discussion
- Statistical fluctuation or may be something

➔Atm-ν sensitivity to CPV

K2K

First earth scale long baseline experiment

Confirmation of the atmospheric neutrino oscillation

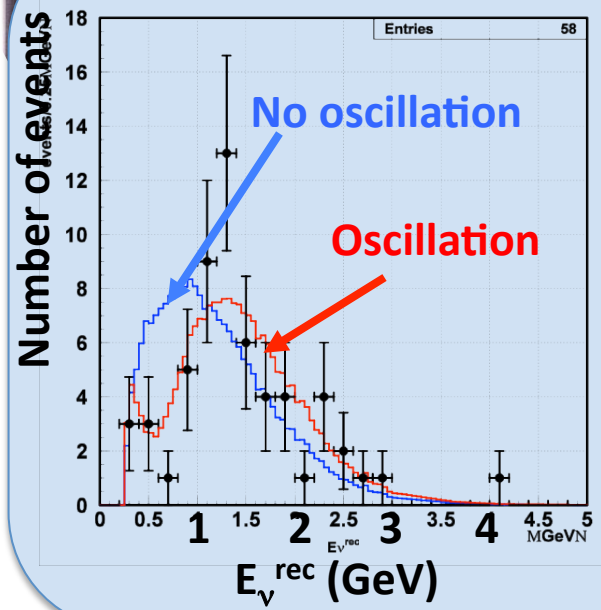
Total POT delivered

Jun.1999 – Nov.2004

completed

1.049×10^{20} POT

1R-μ spectrum shape



N_{obs}/N_{pred}

=112 ev/155.9 ev

=72% (~10% syst.)

$$prob. = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

L=250km (fixed), <Eν> ~ 1.3GeV

$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta = 1$

Expect ~70% survival

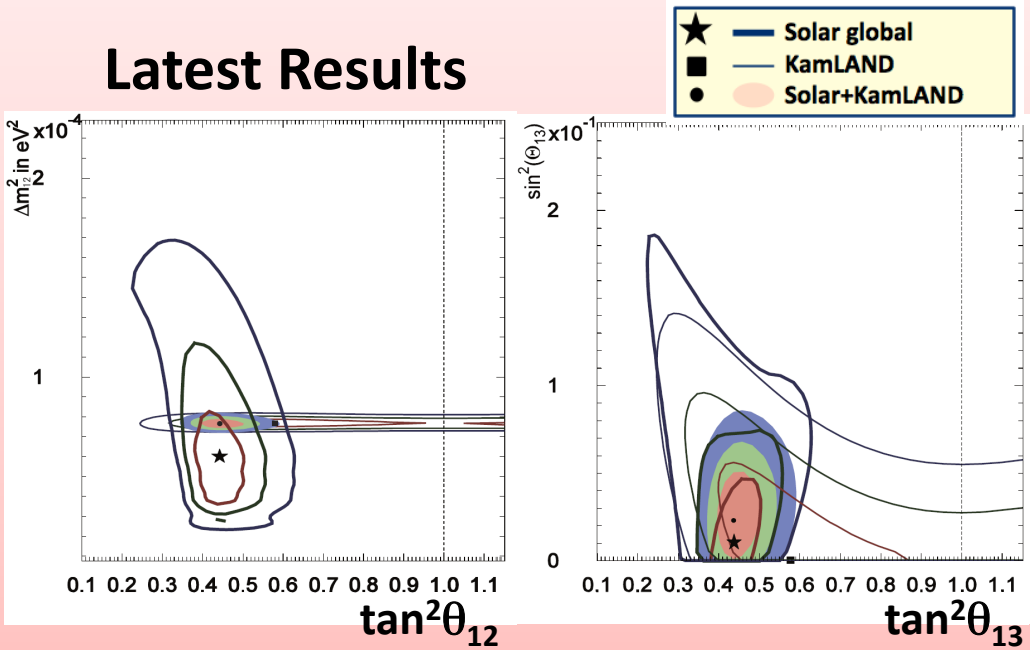
SK Solar Neutrino Oscillation

- SK 1258 days **ES flux**: PRL86 in **June 18, 2001** issue
  - $\nu + e \rightarrow \nu + e$ $2.35 \pm 0.02 \pm 0.08 \times 10^6\ cm^{-2}s^{-1}$
- SNO **CC results**: announcement in **June 18, 2001**
  - $\nu_e + d \rightarrow p + p + e^-$ $1.76 \pm 0.06 \pm 0.09 \times 10^6\ cm^{-2}s^{-1}$

→ Evidence of Neutrino Oscillation

SNO (ν_e) +SK (ν_e + (ν_μ + ν_τ)x0.15)
4.3 σ effect of the existence of non-electron neutrino components in solar neutrino on the earth

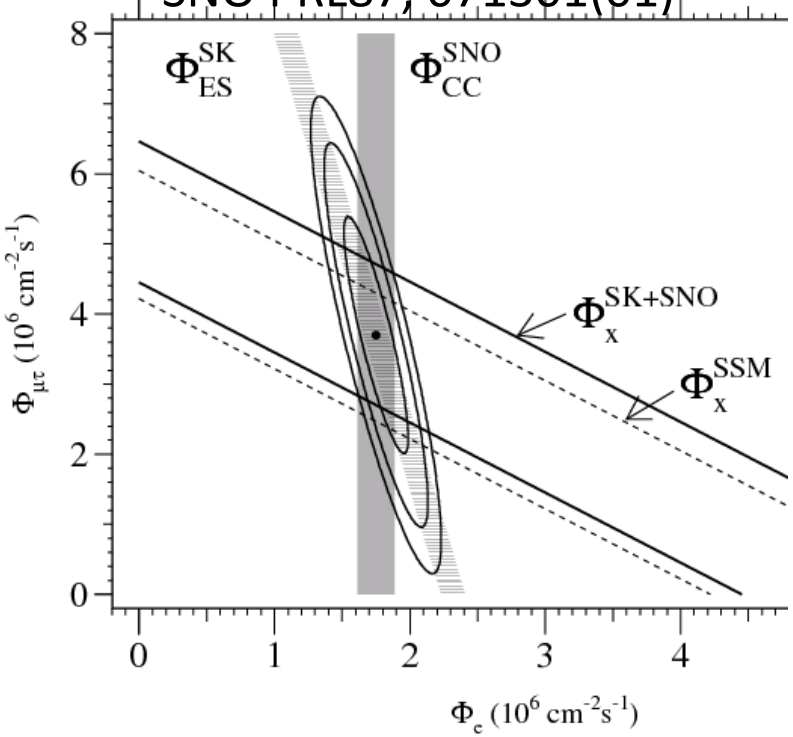
Latest Results



$\Delta m_{12}^2 = 7.7\times10^{-5}\ eV^2$
$\tan^2\theta_{12} = 0.44$
$\Phi_{B8} = 0.91\times \Phi_{B8,SSM}$

$\sin^2\theta_{13}=0.025^{+0.018}_{-0.016}$
(<0.059 @95%C.L.)

SNO PRL87, 071301(01)



What is missing

Octant of θ_{23}
Mass hierarchy
θ_{13}
CP-phase

Entire spectrum
Sub-dominant effects
θ_{13}

mixing: $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

flavor eigenstates

mass eigenstates

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

Atmospheric ν
Long baseline
(θ_{23}: maximal?)

Reactor
(θ_{13}: upper limit)
Not determined yet

Solar ν
Reactor
(θ_{12}: large)

- **θ_{13}**

➔ Long baseline neutrino oscillation experiment (T2K)

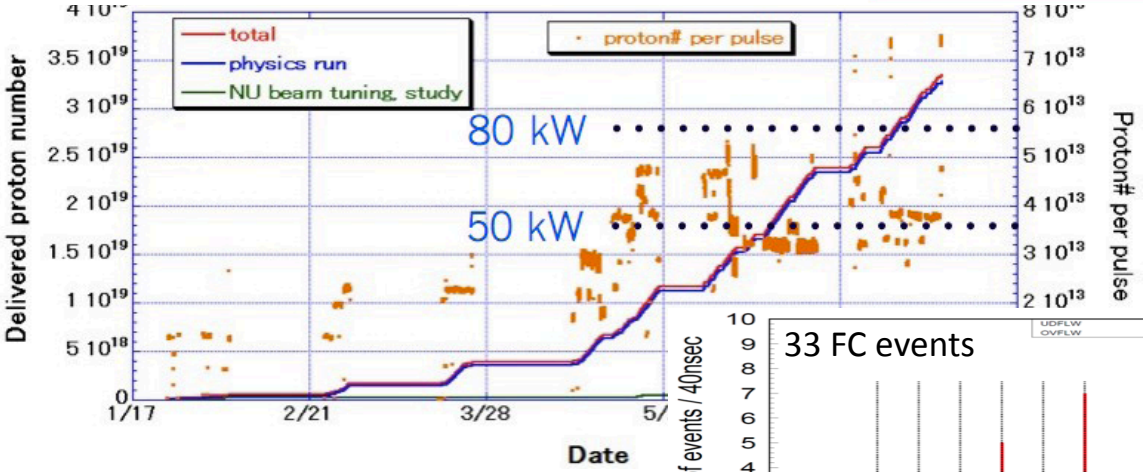
➔ May lead to a study on CP Violation

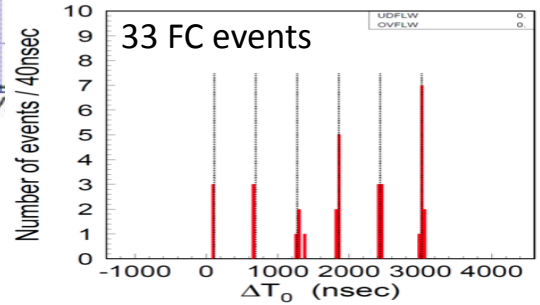
- **Supernova**
- **Proton Decay**

T2K

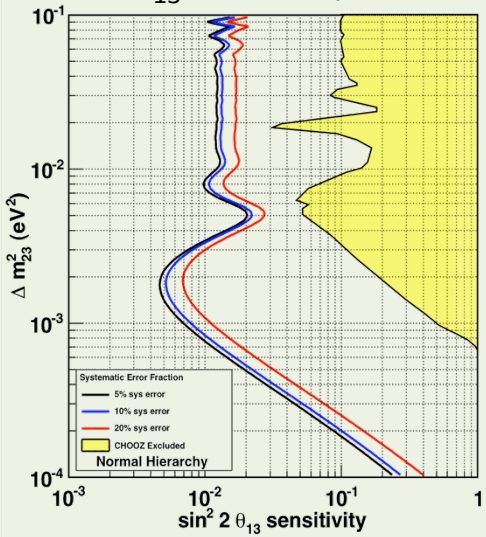
- Look for θ_{13}: very small mixing angle ($\nu_\mu \rightarrow \nu_e$ appearance)
  ➔ need statistics ➔ higher beam intensity (K2K x ~50)

First beam on target: April-23, 2009
First physics run
Jan-23 → Jun-26, 2010
< ~50kW>, 3.29x10^{19} POT



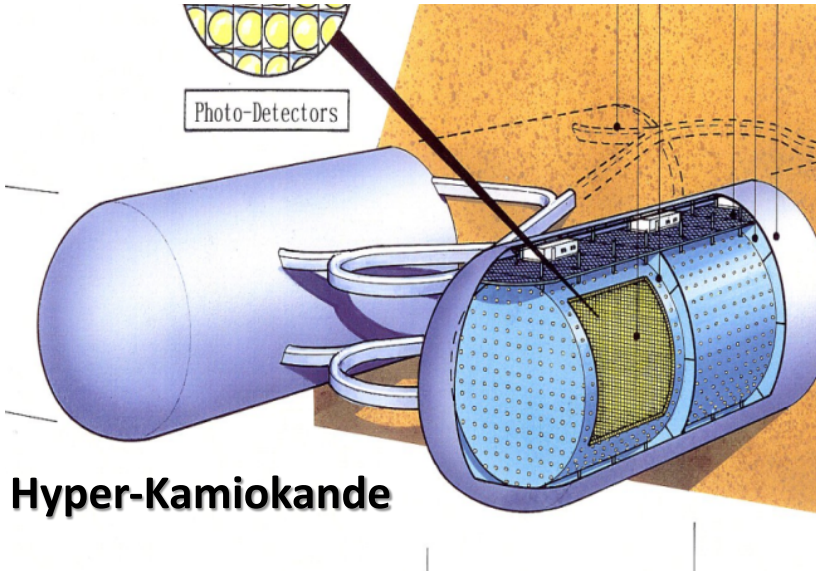


90 % C.L. Sensitivity
750 kW in 5 yrs
$\sin^2 2\theta_{13} < 0.008$ (90% C.L.)



$\Delta m^2_{23}=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$,
$\delta CP=0$, normal hierarchy

The mission may continue to the Next generation detectors, Hyper-Kamiokande and beyond



- Fiducial mass 540kt
  - ← 22.5 kton: SK (x20)
- Precise study on solar and atmospheric neutrinos

- Tie up with the accelerator neutrino beam (a few MW)
  - Study on CP Violation in neutrino sector
    - **Leads us to the origin of matter in the Universe**
- Supernova neutrinos
  - 200k neutrino events for SN at 8kpc
    - **250 ν_e from neutronization burst**
    - **θ_{13} sensitivity to $\sin^2\theta_{13}<10^{-4}$**
- Proton decay
  - 10^{35} yrs for $p \rightarrow e\pi^0$ mode
  - Step into the discovery region