Discovery of Neutrino Oscillations

The legacy of Bruno Pontecorvo

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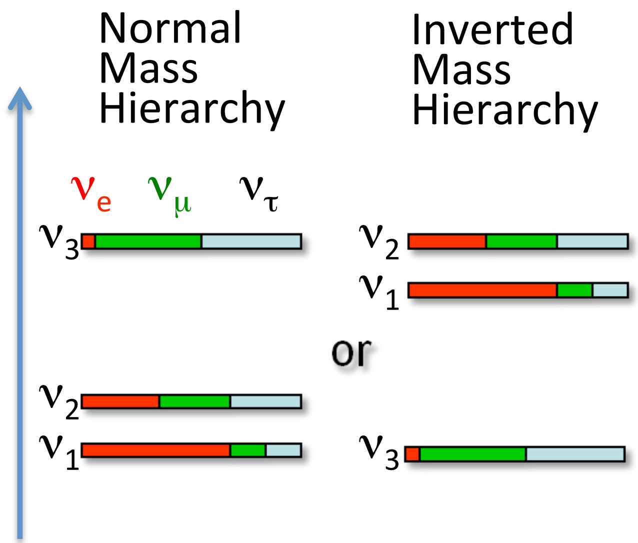
2013
The centenary of the birth of B. Pontecorvo

- 15 years after the discovery of the neutrino oscillation in 1998.
- I am very pleased to have been a witness of the saga for the discovery of the neutrino oscillations
  - both atmospheric and solar neutrino oscillations, and θ_{13} thorough the study in Super-Kamiokande
- Bruno's legacy, 'neutrino oscillation' has been proved to exist.
- The story will continue to the future including the attractive subjects on
  - CP Violation in the lepton sector, origin of the matter in the Universe and so on

Early indications from experiments

- If we look back, it had arisen from two mysteries
  - Solar neutrino problem in late 1960's (Homestake)
  - Atmospheric neutrino anomaly in 1988 (Kamiokande)
- Very luckily (we <u>now</u> know), oscillations through θ_{23} (atmospheric) and θ_{12} (solar) are almost decoupled since
  - θ_{13} is small ($\sin^2 2\theta_{13} \sim 0.1$) and
  - Δm_{23}^2 ($\sim 2.4\text{x}10^{-3}\text{eV}^2$) >> Δm_{12}^2 ($\sim 7.6\text{x}10^{-5}\text{eV}^2$)

Neutrino Oscillation



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

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

SK /K2K(SK)

Reactor ShortBL
($\sin^2\theta_{13}$~0.025,
δ_{CP} ?)

T2K(SK)

Solar ν
Reactor LBL
(θ_{12}: large)

SNO+SK /KL

- Solar and atmospheric ν oscillations were able to be treated and studied separately at 1st approximation

Difficult to resolve the problems

But unluckily,

- For solar neutrinos: $\Delta m_{12}^2 \sim 7.6\text{x}10^{-5}\text{eV}^2$
  - Reactor experiments with < 100 m baseline in 1970's-80's were not able to reach the sensitivity to test solar ν problem:

    $$\Delta m^2 \sim E/L \sim 5\ \text{MeV}/100\text{m} = 5\text{x}10^{-2}\ \text{eV}^2$$
  - We could not get any help from the reactor experiments at that time
- Later (in 2003) the long baseline reactor experiment with the baseline of ~200 km could confirm the solar neutrino oscillations (KamLAND):

  $$\Delta m^2 \sim E/L \sim 5\ \text{MeV}/200\text{km} = 3 \text{ x } 10^{-5}\ \text{eV}$$

Difficult to resolve the problems

But unluckily,

- For atmospheric neutrinos: $\Delta m_{23}^2 \sim 2.4\mathrm{x}10^{-3}\mathrm{eV}^2$
  - Accelerator long baseline experiments in 80's (baselines were ~laboratory scale < 1 km) were not able to reach the sensitivity to test atmospheric ν anomaly:

$$\Delta m^2 \sim E/L \sim 1\ \mathrm{GeV}/1\ \mathrm{km} \sim 1\ \mathrm{eV}^2$$

  - We could not get any help from the accelerator oscillation experiments in 80's
- Later (in 2003) the long baseline accelerator experiments could confirm the atmospheric neutrino oscillations (K2K):

$$\Delta m^2 \sim E/L \sim 0.5\mathrm{GeV}/200\mathrm{km} = 3 \times 10^{-3}\ \mathrm{eV}^2$$

Difficult to resolve the problems

- The solar neutrino problem and the atmospheric neutrino anomaly were in a similar situation.
- Therefore we must 'establish' the atmospheric anomaly and the solar neutrino problem as neutrino oscillations by themselves (no help from experiments using man-made neutrinos)
- In order to do that, it is necessary to have an evidence which does not depend on the 'flux calculations'

Difficult to resolve the problems

- Convincing evidence was obtained:
  - for atmospheric ν oscillation
    - by observing an asymmetry in the zenith angle distribution or an up-down asymmetry
  - for solar neutrinos
    - by making a direct comparison of two measurements "ν_e only" measurement vs "$\nu_e + \nu_X$" measurement
- It took us very long time to really reach the conclusions

Atmospheric Neutrinos

- There is an interesting early discussion by B. Pontecorvo and S. M. Bilenky

  Physics Report 41(1978)225-261

LEPTON MIXING AND NEUTRINO OSCILLATIONS

S.M. BILENKY and B. PONTECORVO

Joint Institute for Nuclear Research, Dubna, USSR "survival" of the cosine term is that the effective source dimension r must be smaller than the oscillation length

$$r \lesssim L. \tag{81}$$

Since $r \simeq 10^{-3} R$, the inequality (81) is comparable, in essence, with the inequality (80). Thus we conclude that the condition of coherence (79) does not impose any conditions supplementary to the condition (81).

5.8. *Oscillations and cosmic neutrinos*

The phenomena of neutrino oscillations, if it does take place, could be of importance in cosmic ray neutrino* experiments. Let us give a few examples.

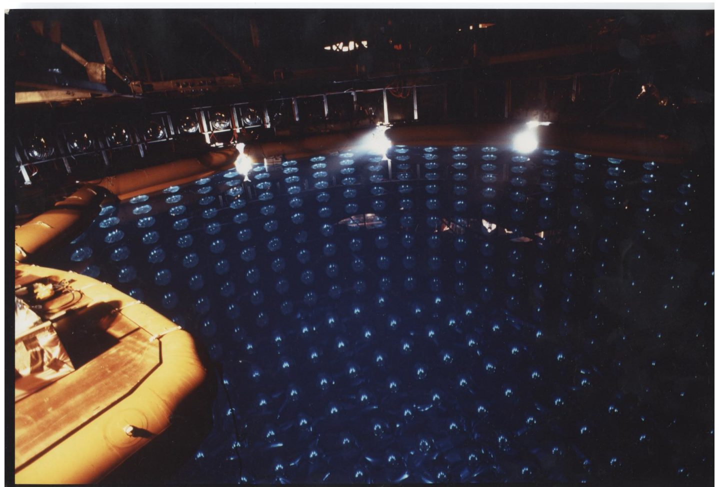
1) At the underground Neutrino Observatory of the Institute for Nuclear Research Academy of Sciences of the USSR an experiment is being prepared [43], in which there will be detected high energy muon neutrinos emitted by mesons, which are produced in collisions of cosmic ray protons with nitrogen and oxygen nuclei in the atmosphere. The energy spectra and other properties of those neutrinos have been calculated and the results are given in ref. [44]. High energy muons produced by ν_μ's interacting with nuclei in the Earth will be detected by 8 hodoscope plane systems (every one of which has an area of 1500 m^2) of organic scintillators. The scintillator systems are in coincidence, the logic giving information on the muon trajectory and also establishing whether the detected muon has come either from "above" or from "below" (in the last case it is produced by a muon neutrino impinging upon the Earth opposite face and passing through the Earth). The average neutrino momentum in such experiments is 5–10 GeV, and the distance from the neutrino source to the detector is $R \simeq 10^4$ km for neutrinos coming from the Earth opposite face. Making use of formula (66) it is possible to test the neutrino mixing hypothesis by comparing the measured and "expected" ν_μ intensities. The sensitivity of those experiments for testing neutrino mixing is, in principle, quite high [43], the value of $M^2_{\min}$ (see the definition (60)) being $M^2_{\min} \simeq 10^{-3}$ (eV)^2. Thus, these experiments have a sensitivity intermediate between that of the experiments wherein artificial (reactor, accelerator) neutrinos are used and that of the investigations wherein solar neutrinos are used. However, the statistical accuracy which can

Atmospheric Neutrinos

- The atmospheric neutrino anomaly came later (in 1988) than the solar neutrino problem
- But resolved earlier (in 1998) than the solar neutrino problem
- Took us about 10 years to resolve the problem

Early Indication

- Atmospheric Neutrinos were the background for proton decay search in large detectors in 80's.
- 3000 ton Water Cherenkov detector, Kamiokande, observed fewer μ-like events in atmospheric ν interactions than expected.

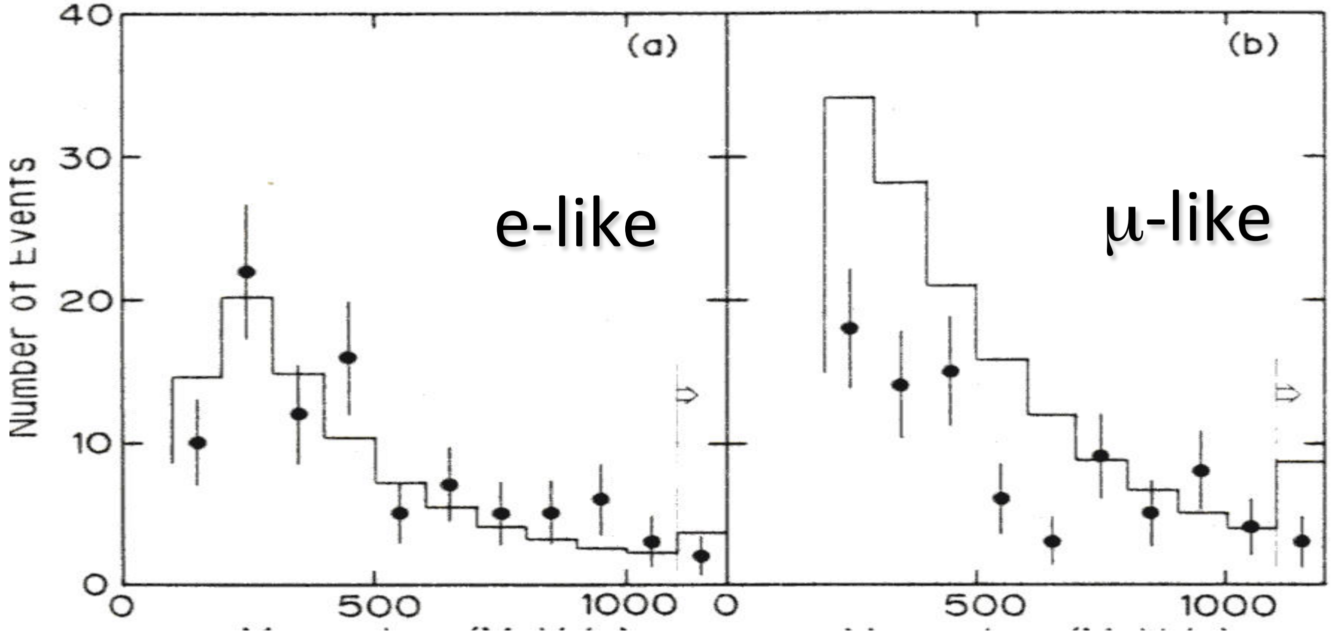


Kamiokande

- Water Cherenkov Detector
- 3000 ton inner mass
- 2140 ton fiducial mass for atm-ν analysis
- 1000 50cmϕ photomultiplier tubes

Early Indication in 1988

- ***R= (Obs./MC)μ-like = 59±7% (stat.)***



Momentum (MeV/c)

- This was the first indication of the atmospheric neutrino anomaly.

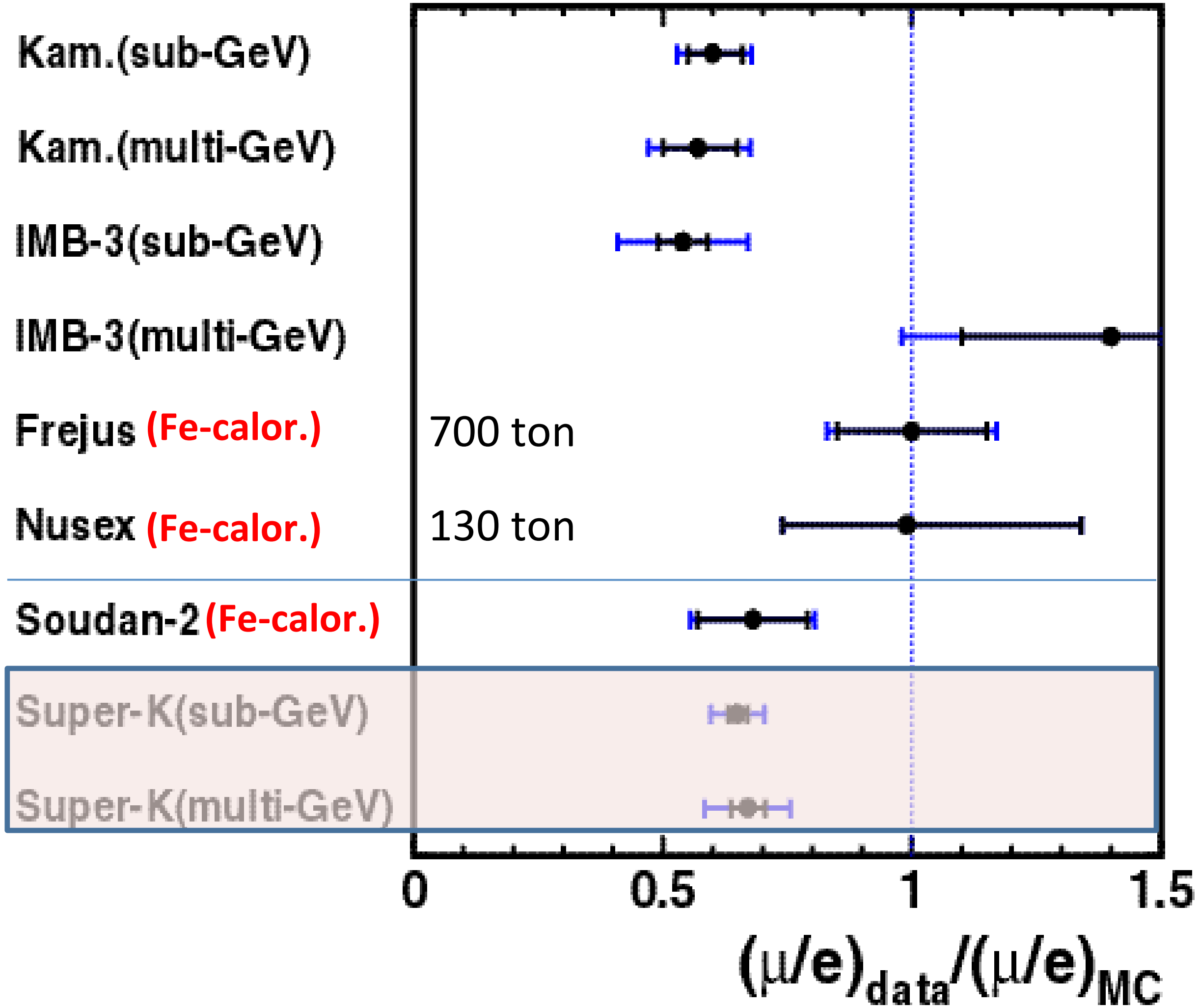
Kamiokande result

- Why this observation was not widely accepted as a neutrino oscillation?
- Probably the reasons were the followings
  1. Results strongly depend upon the atmospheric neutrino flux calculations
  2. There were large uncertainties in the flux calculations
     - Primary cosmic ray flux, primary interactions, secondary particles productions, decays, earth's magnetic fields, modulations, parameters for atmosphere,………
  3. Another important issue was that theorists did not believe 'large mixing'. This was the prejudice that mixing must be small like quark mixing.

Further Confusions in early 90's

- In late 80's and early 90's when Kamiokande presented the neutrino anomaly, there were other experiments giving results inconsistent with Kamokande results.
- Especially two experiments using Fe calorimeter provided no deficits
- There was an argument about possible systematics between Water Cherenkov and Fe calorimeter, but this problem was solved in 1997 by another Fe calorimeter experiment, Soudan-2 which provided consistent results with Kamiokande

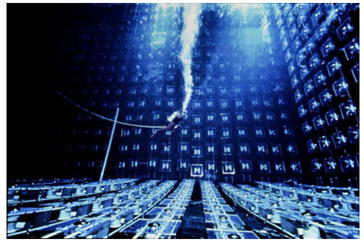
R measurement in 90's

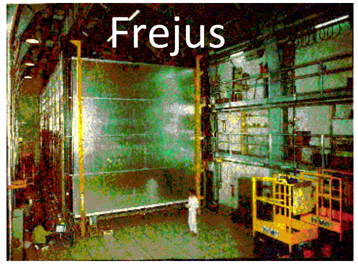


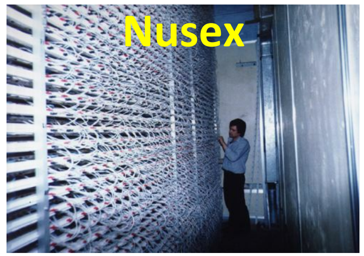
1988

1992

1997



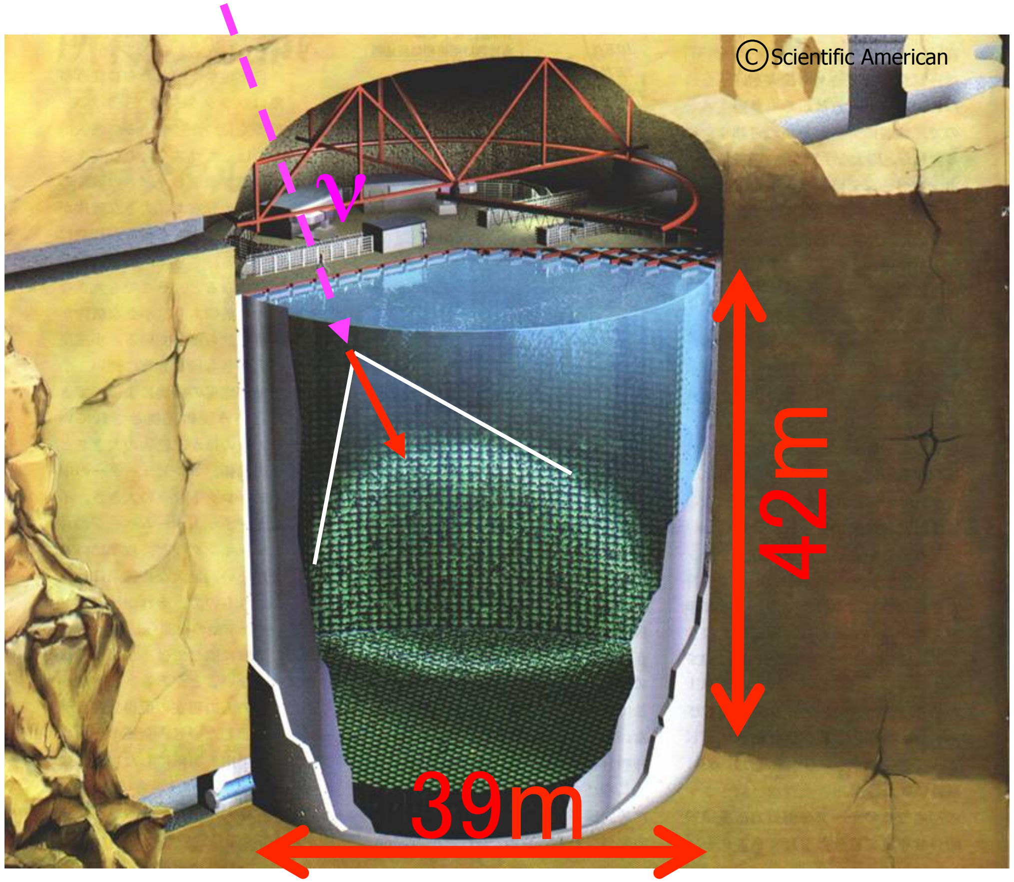




In early 90's, there are some confusion among the data

- While preparing this talk, I am very much curious about whether Bruno Pontecorvo believed that the atmospheric anomaly in late 80’s arose from a neutrino oscillation or not.

Super-Kamiokande

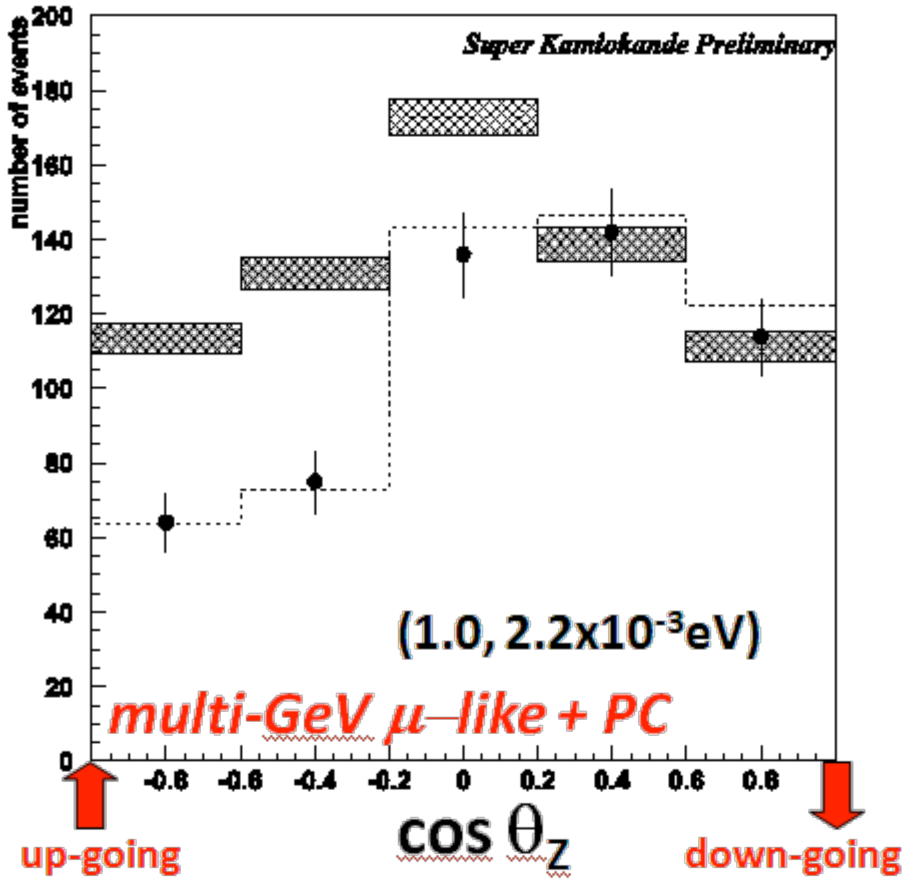


11,146 PMTs (ID)
50 cm in diameter
40% coverage

1,885 PMTs (OD)
20 cm in diameter

- Break through came from Super-Kamiokande
- Super-K is a 50,000 tons Water Cherenkov detector, started to take data in 1996
- Fiducial mass is more than 10 time of Kamiokande for the atmospheric neutrino analysis. It accumulates about 10 atmospheric neutrino events per day.

Discovery of Atmospheric ν Oscillation



- June 1998, two years after the start of SK,
  - we have obtained a definitive evidence of a neutrino oscillation.
  - we found an asymmetry in a zenith angle distribution where we observed deficits of up-going ν_μ
- The results were essentially independent of the flux calculations
- This was the discovery of Neutrino Oscillation

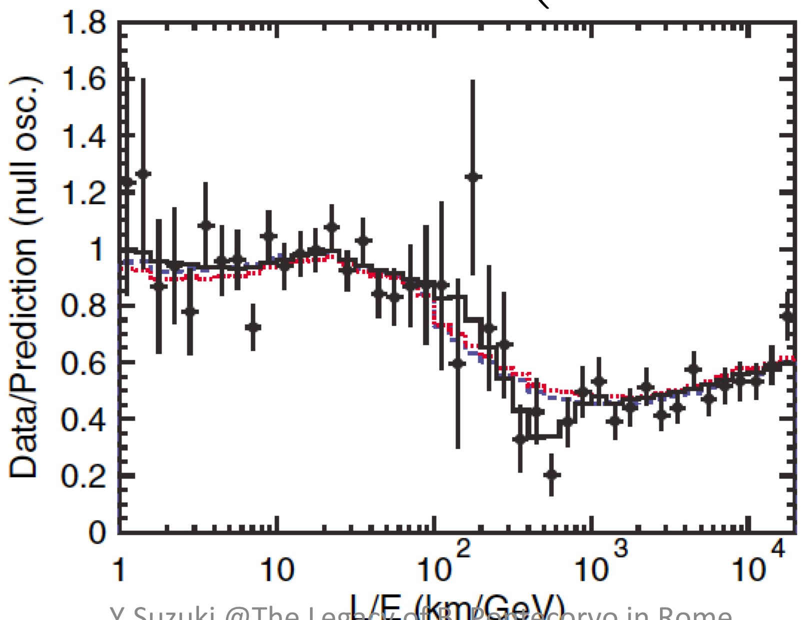
$\Delta\chi^2$ = 69.8 for no oscillation

Evidence for the atmospheric neutrino oscillation

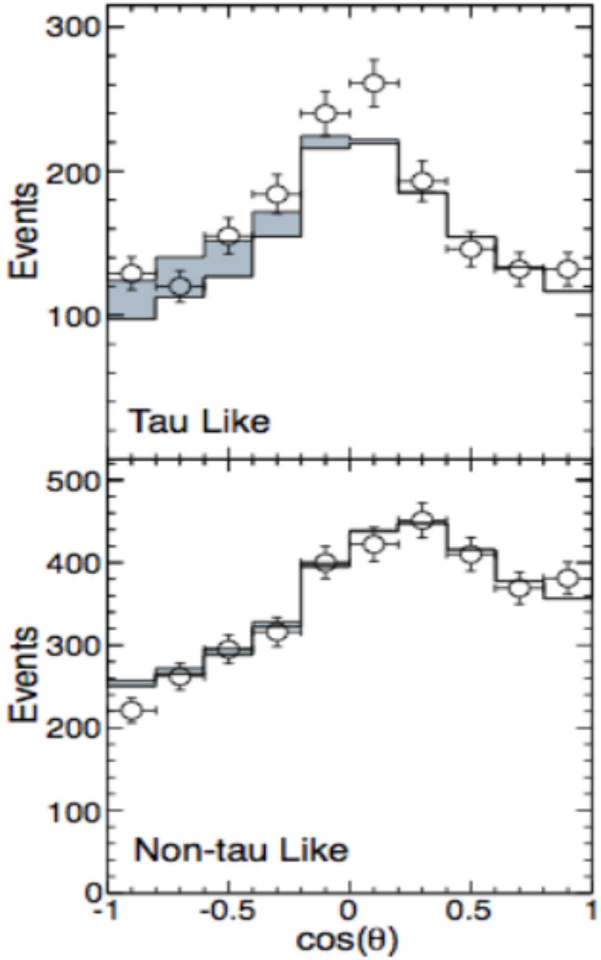
After the discovery

- In 2004, oscillatory pattern was observed in the L/E plot (SK)

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2(\mathrm{eV}^2)\frac{\mathrm{L(km)}}{\mathrm{E(GeV)}}\right)$$

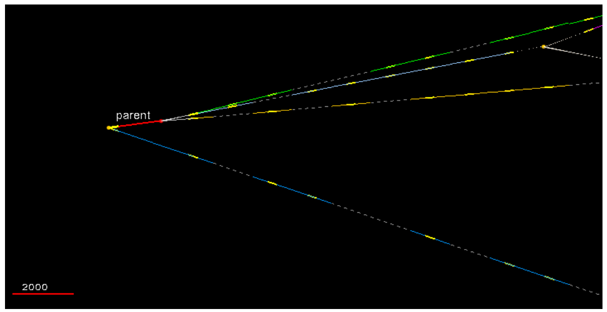


Evidence for the atmospheric neutrino oscillation



After the discovery

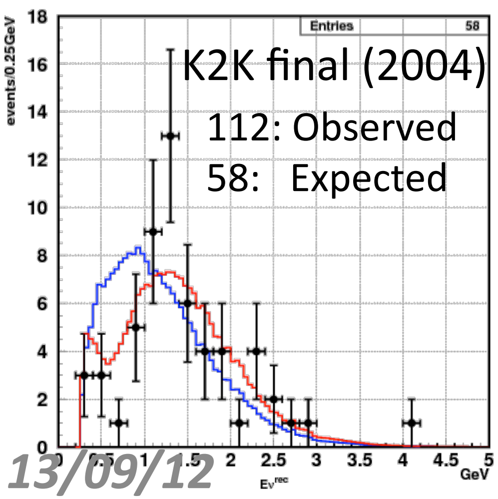
- In 2013, ν_τ appearance was identified by statistical analysis:
  - 3.8 σ effect
  - a proof of $\nu_\mu \rightarrow \nu_\tau$ oscillation (SK)
- Direct detection of tau appearance by OPERA (CERN to Gran Sasso).
  - They observed 3 tau events by 2013 (by emulsion chamber)

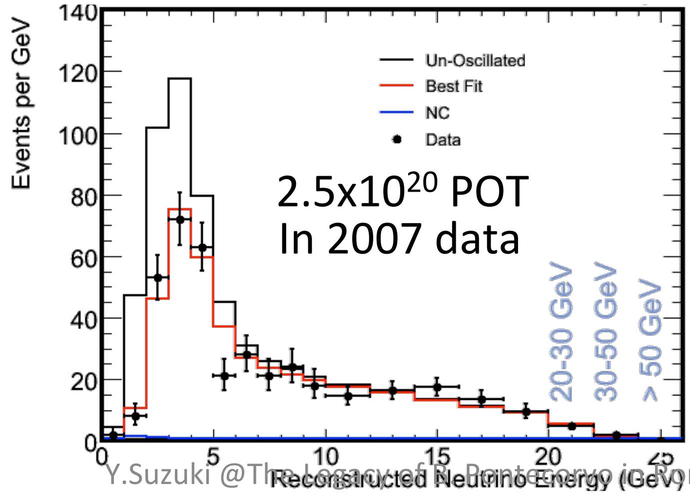


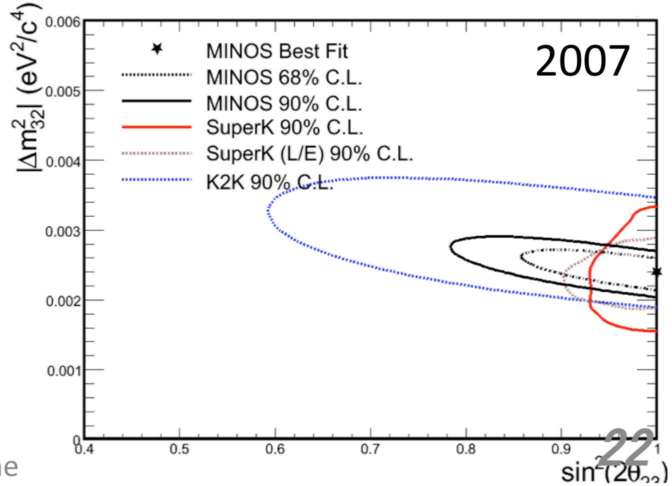
2nd ν_τ candidate $\tau \rightarrow$ 3h
June 2012

Confirmation of the atmospheric neutrino oscillation

- There were accelerator long baseline neutrino oscillation experiments in early 2000's
  - K2K(KEK to Kamioka): baseline~250 km & E_ν=1.4 GeV
  - MINOS(Fermilab to Soudan): baseline 735 km & E_ν = a few GeV (Wide band)
- **K2K and MINOS** confirmed the atmospheric neutrino oscillation by man-made neutrinos

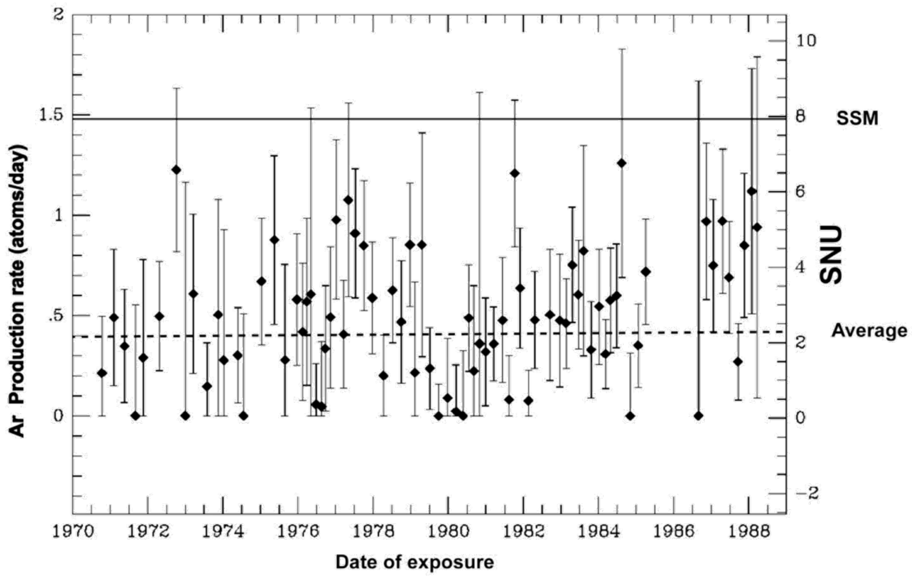






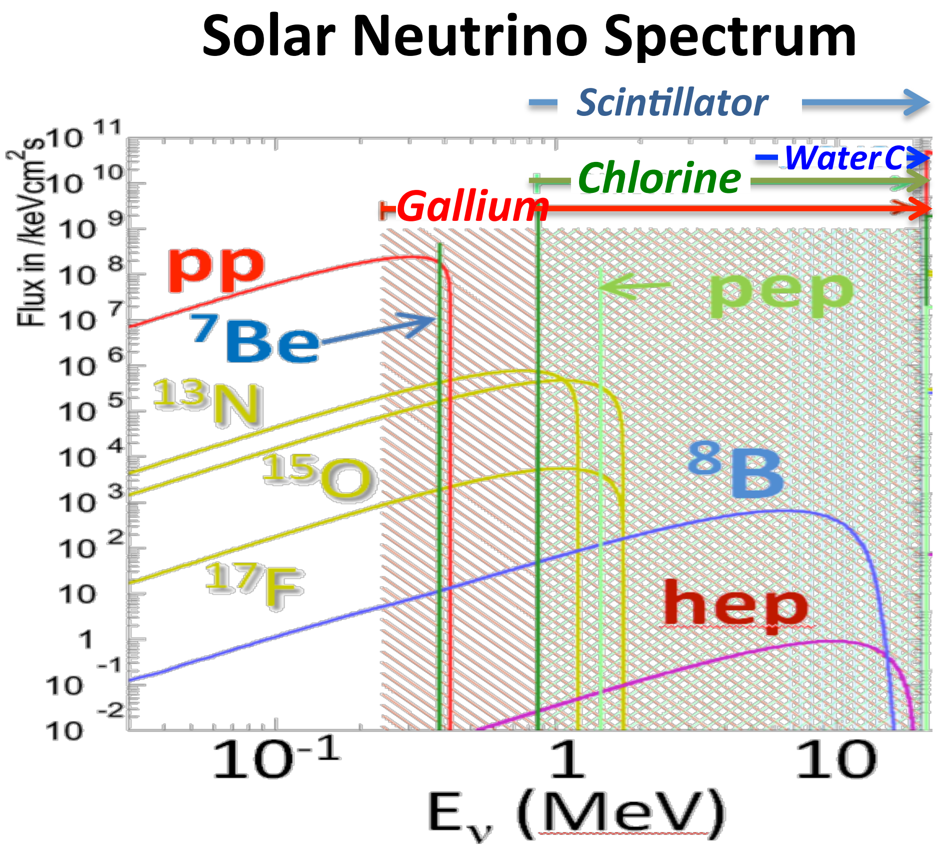
Solar neutrino problem

- Solar neutrino problem was indicated first in late 60's ~ early 70's by a radio-chemical experiment (a legacy of B. Pontecorvo) of $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$, in the Homestake gold mine led by R. Davis.



- But took us about 40 years to resolve the problem

Solar Neutrino Spectrum



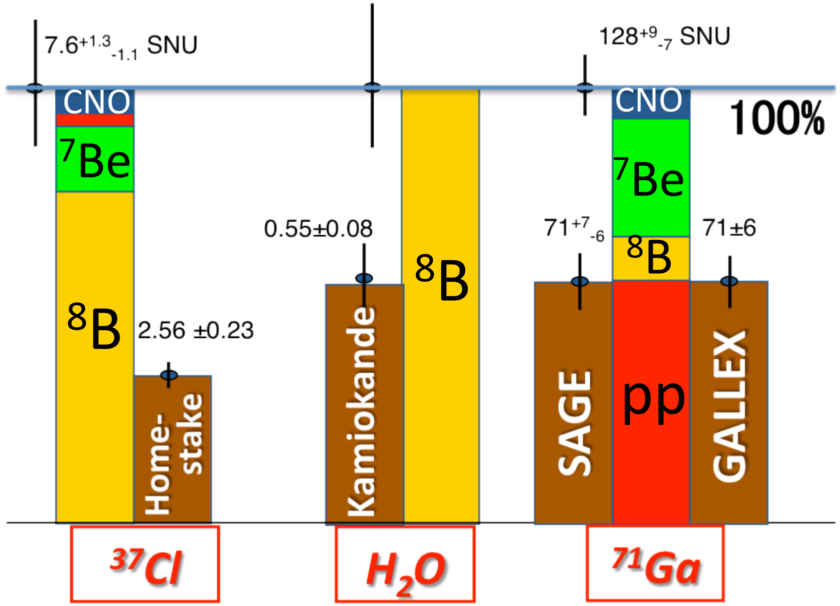
- **In pp-chain, there are 5 nuclear reactions to produce neutrinos**

1. $p+p \rightarrow d+e^{+}+\nu_e$ (E_{max}<0.42 MeV)
2. $e^{-}+{}^{7}Be \rightarrow {}^{7}Li+\nu_e$ (0.86, 0.38)
3. $p+e^{-}+p \rightarrow d+\nu_e$ (1.44)
4. $p+{}^{7}Be \rightarrow {}^{8}B+\gamma$
   ${}^{8}B \rightarrow {}^{8}Be+e^{+}+\nu_e$ (E_{max}<15)
5. ${}^{3}He+p \rightarrow {}^{4}He+e^{+}+\nu_e$ (E_{max}<18.8)

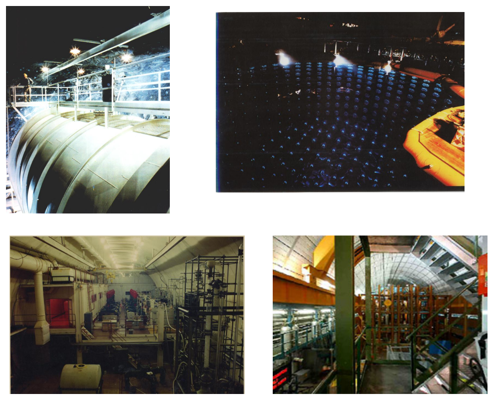
- **Solar neutrino experiments have different energy thresholds**

1. Cl: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^{-}$ (E_{th}>0.81)
2. Ga: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^{-}$ (E_{th}>0.23)
3. Water/Heavy Water:
   $\nu + e \rightarrow \nu + e$ (> 3~5)
   $\nu_e + d \rightarrow p + p + e$
   $\nu + d \rightarrow p + n + \nu$
4. Scintillator:
   $\nu + e \rightarrow \nu + e$ (> 0.8(${}^{7}Be$), >3(${}^{8}B$))

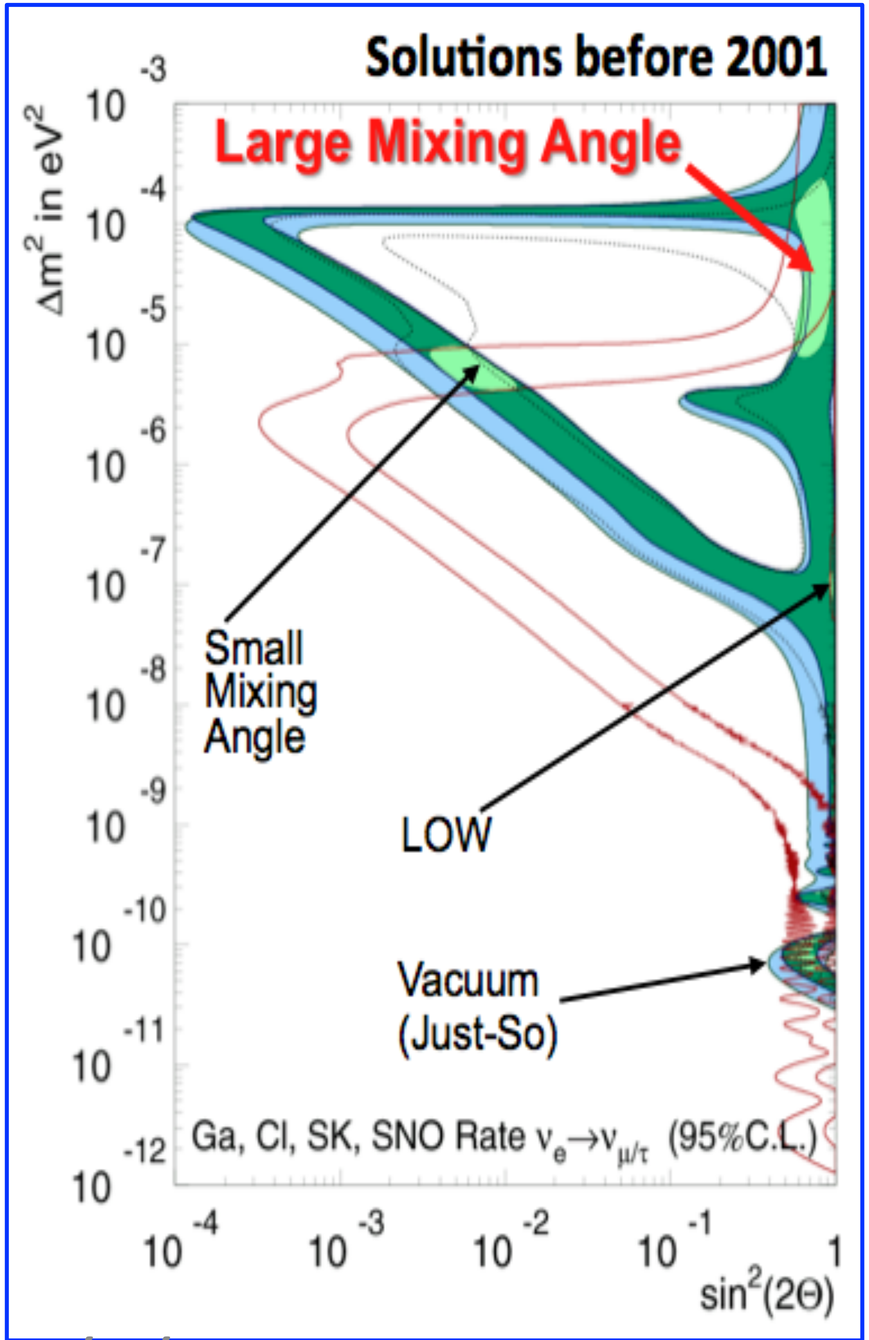
In early 90's



- In early 90's, there were four solar neutrino experiments covering wide rage of energy.
  - Homestake experiment (Cl)
    - First solar neutrino experiment
  - Kamiokande (Water Ch)
    - Directionality
  - Sage/Gallex experiments
    - Sensitive to pp-neutrinos



- All the experiments showed deficits of solar neutrinos.



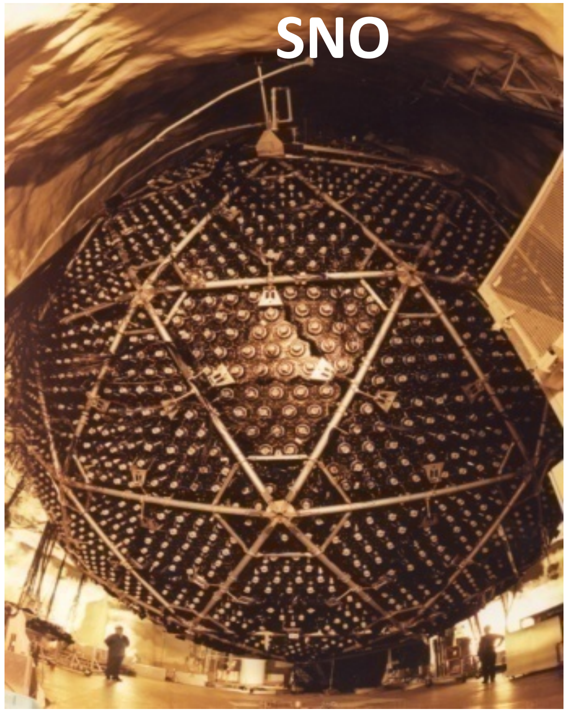
Four solutions

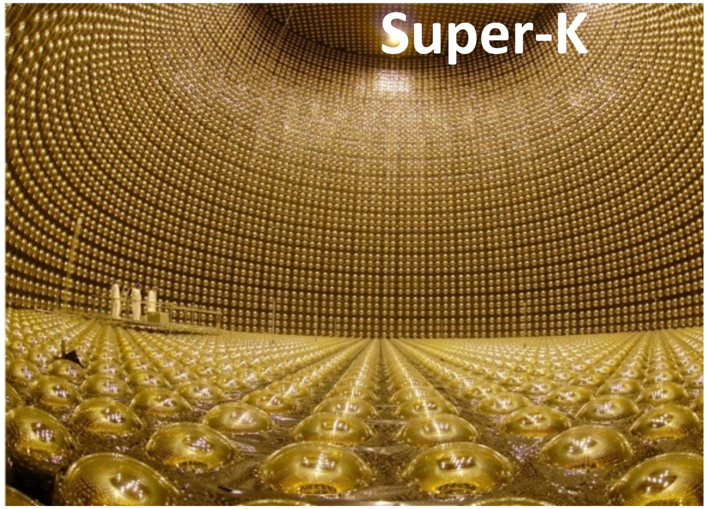
- Four different parameter (Δm^2, $\sin^2 2\theta$) regions were allowed by combining the results of all the solar neutrino experiments
  - Large mixing angle solution
  - Small mixing angle solution
  - LOW solution
  - Vacuum Solution
- But the results depend upon the flux calculations by the standard solar models

➔ No convincing/compelling evidence for solar neutrino oscillations yet.

Super-Kamiokande and SNO

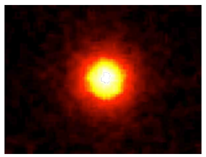
- The definitive evidence for the solar neutrino oscillation arose from Super-Kamiokande and SNO experiments

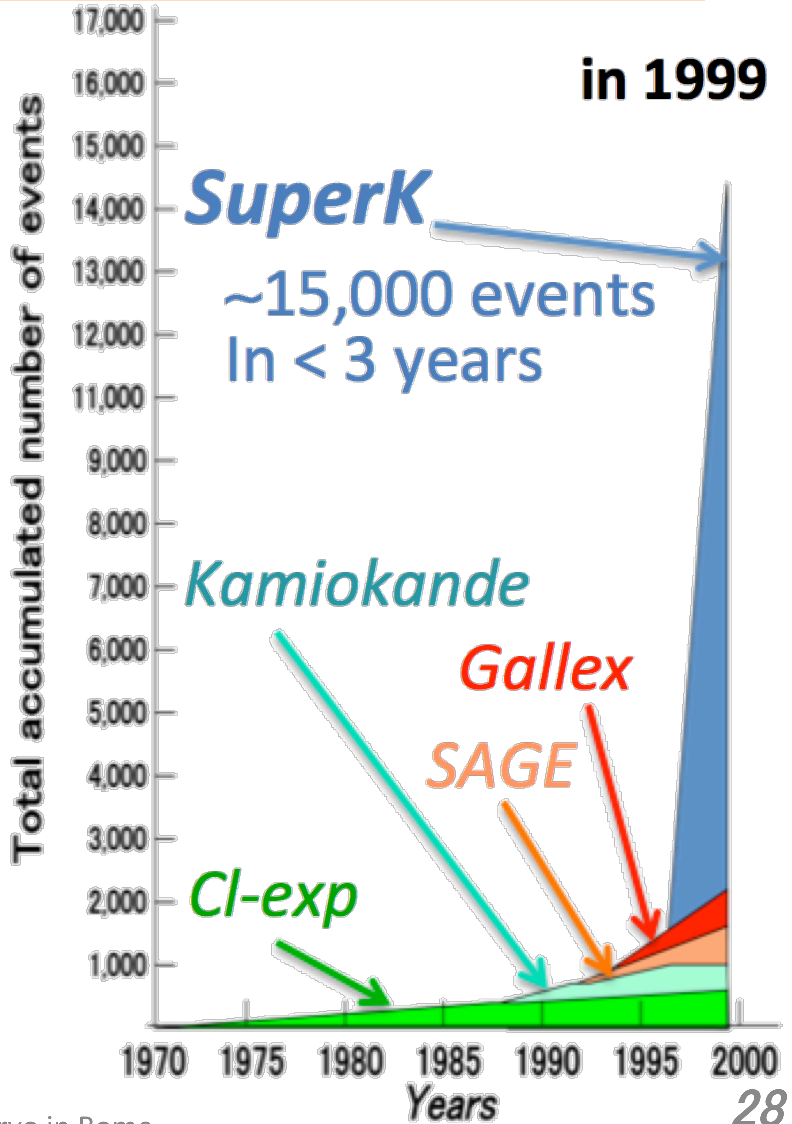


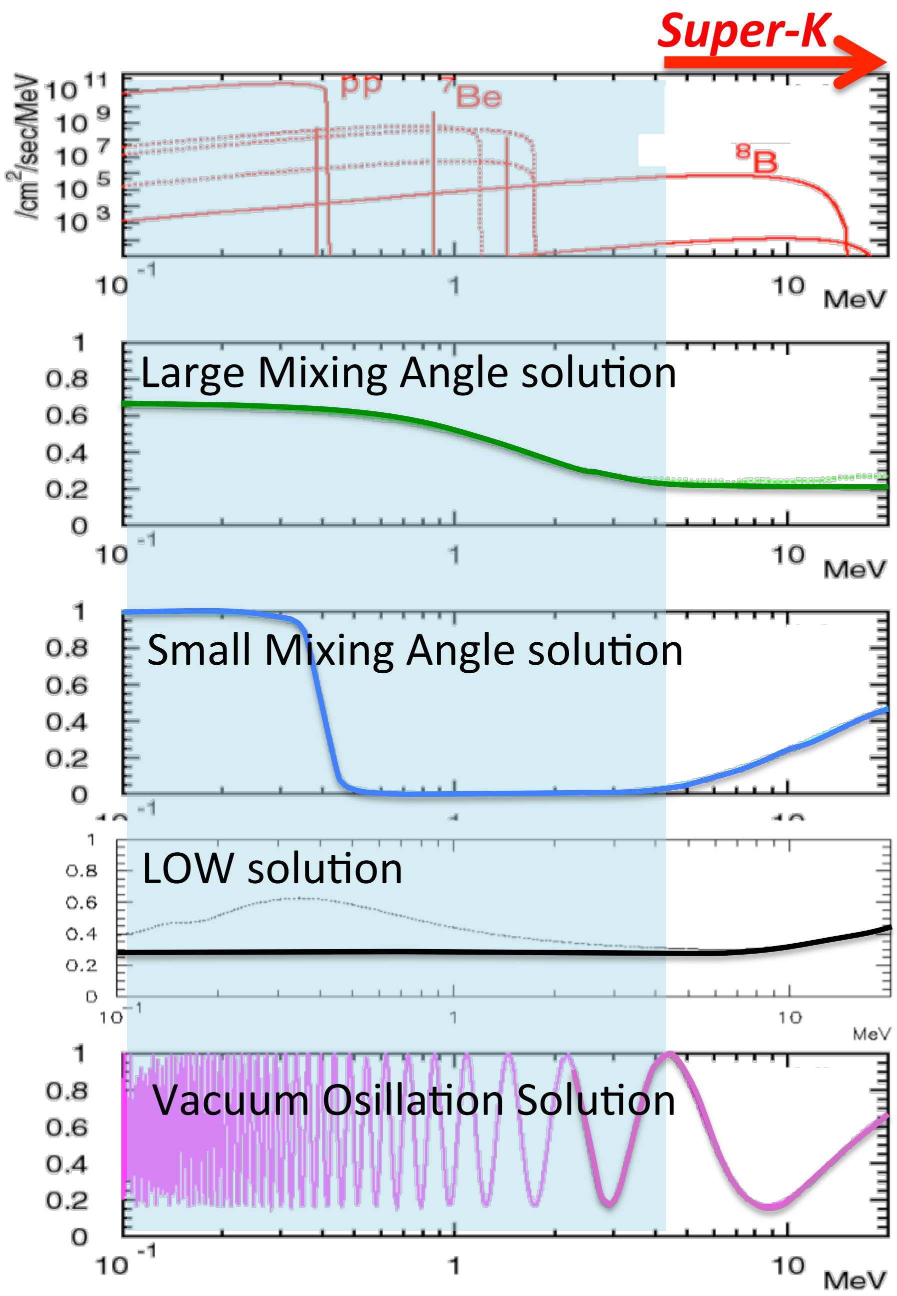


Solar ν in Super-Kamiokande

- SK has measured solar ν with very high statistics ($\nu+e \rightarrow \nu+e$)
  - ~ 15 events/day
  - ~ *60,000 ev. for the last 17 years*
  - – provide a precise flux [$\nu_e+0.15(\nu_\mu+\nu_\tau)$] measurement
- Recoil electron energy
  - – determine energy spectrum
- Time
  - – see the effects of day/night, seasonal variation
- Directionality
  - – identify the signal from the sun
  - – reduce backgrounds





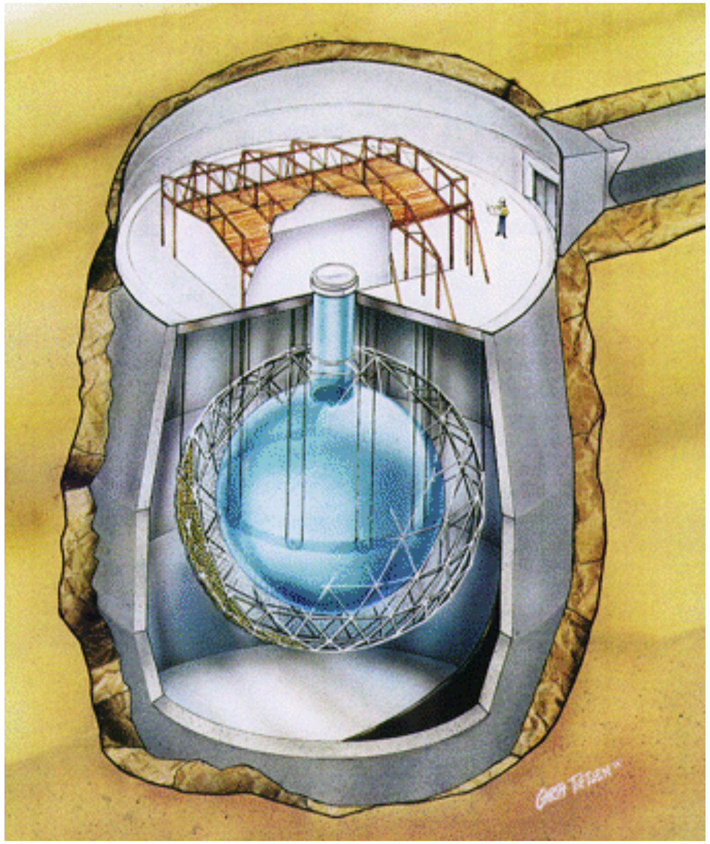


Aim of the SK solar ν measurement

Looking for 'smoking gun' evidence

- LMA
  - No spectrum distortion
  - Small Day/Night in HE
- SMA
  - Spectrum distortion
- LOW
  - Spectrum distortion
  - Large Day/Night in LE
- Vacuum
  - Spectrum distortion
  - Seasonal variation

SNO



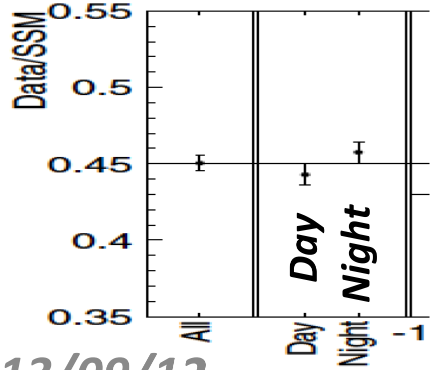
- 1000 ton D_2O
- 2092 m underground
- SNO measures
  - Elastic scattering
    - $\nu + e \rightarrow \nu + e$
  - Charged Current (CC)
    - $\nu_e + d \rightarrow p + p + e-$
    - Sensitive only to ν_e
  - Neutral Current (NC)
    - $\nu_x + d \rightarrow \nu_x + p + n$
    - Phase 1: $n + d \rightarrow T + 6.25$ MeV γ
    - Phase 2: $n + {}^{35}Cl \rightarrow {}^{36}Cl + 8.6$MeV $\sum\gamma$
    - Phase 3: $n + {}^{3}He$ counter
    - Sensitive to all kind of neutrinos
- Smoking Gun of SNO is NC

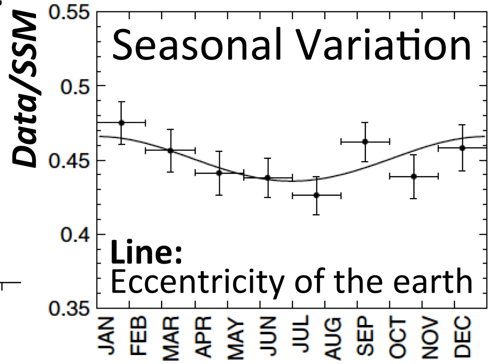
Comparison of CC and NC gives a definitive and compelling evidence for solar neutrino oscillation

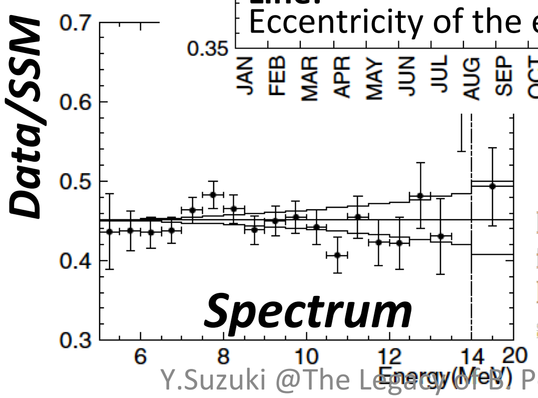
SK Publication of 1258 days of data

Two papers in PRL on 18th June 2001 issue

1. Precise flux measurement:
   – Solar ^{8}B and hep Neutrino Measurements
2. Oscillation Analysis:
   – No strong spectrum distortion
   – Small day /night
   – No seasonal
   ➔ LMA preferred







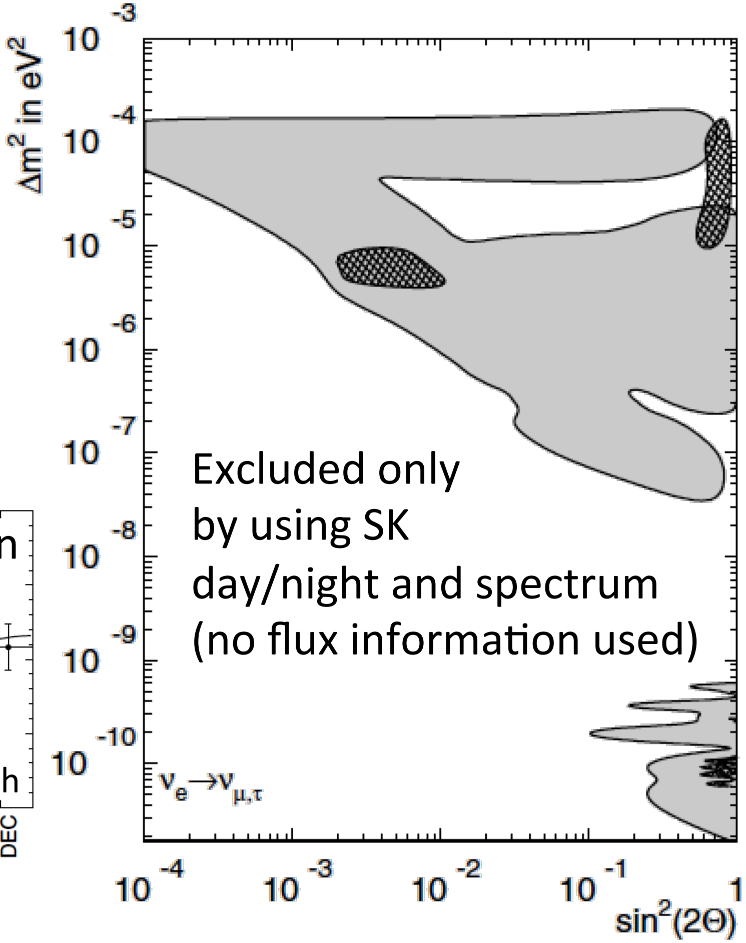
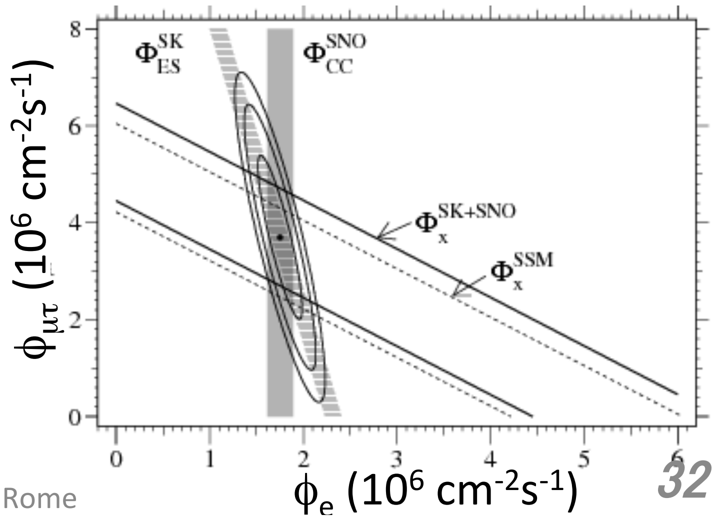


FIG. 3. Exclusion area for two-flavor oscillation $\nu_e \leftrightarrow \nu_\mu/\nu_\tau$ from a day/night spectrum analysis. As in Fig. 1, the cross-hatched area is allowed at 95% C.L. by the combined flux analysis.

Evidence on 18th June, 2001

- **18-June-2001: SNO announced the discovery of Solar Neutrino Oscillation**
  (*SNO+Super-Kamiokande (just published data)*)
  - **SNO: charged current →ν_e** 35%
  - **SK: Electron Scattering →ν_e+0.15(ν_μ+ν_τ)** 46.5%
- Found there are non-electron neutrino components in the solar neutrinos measured on the earth **3.3 σ**



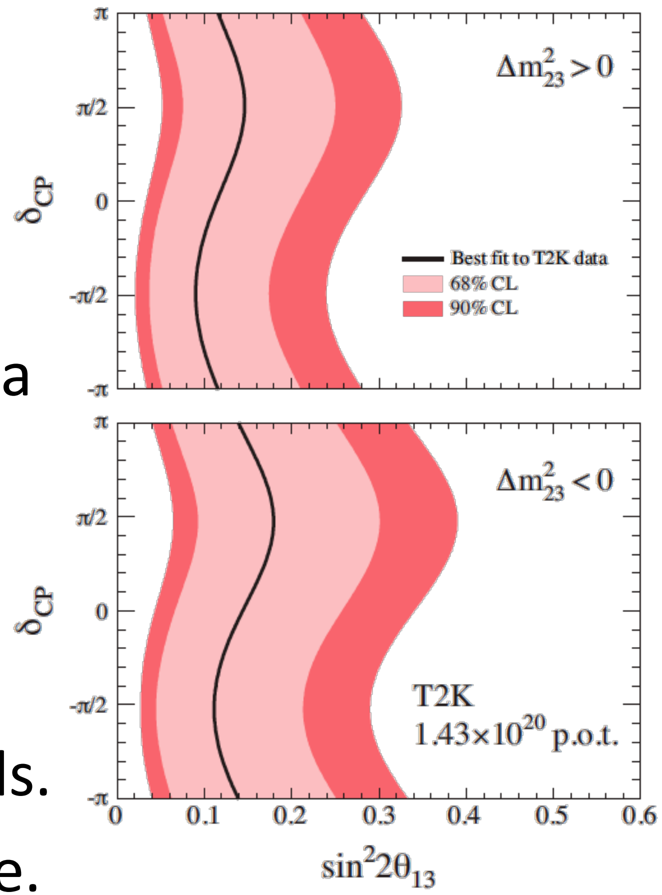
- Flux measurement have played crucial role
- 5 months later, SK had an accident and SK were out of business for 2 years

Confirmation of the Solar neutrino oscillation

- SNO neutral current measurements
  - SNO has provided first neutral current measurement in 2002 by identify the neutron by detecting MeV gammas from n + d $\rightarrow$t + 6.25 MeV γ reaction. Direct comparison of CC and NC gave 5.3 σ effect for the neutrino oscillation.
  - Later years, SNO used Cl and ^{3}He neutron counters to enhance NC measurements
- KamLAND (KL)
  - KL is a long baseline, <L> ~ 180 km, reactor neutrino experiment with a sensitivity of E/L ~ 5/180,000 ~ 3 x 10^{-5} eV^2
  - In 2003, KL found the reactor $\bar{\nu}_e$ disappearance of 61% consistent with the solar LMA oscillation parameters (99.95% C.L.)

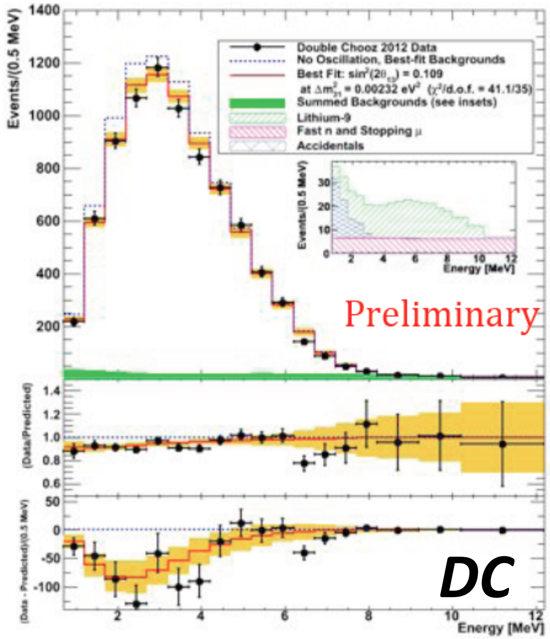
θ_{13}

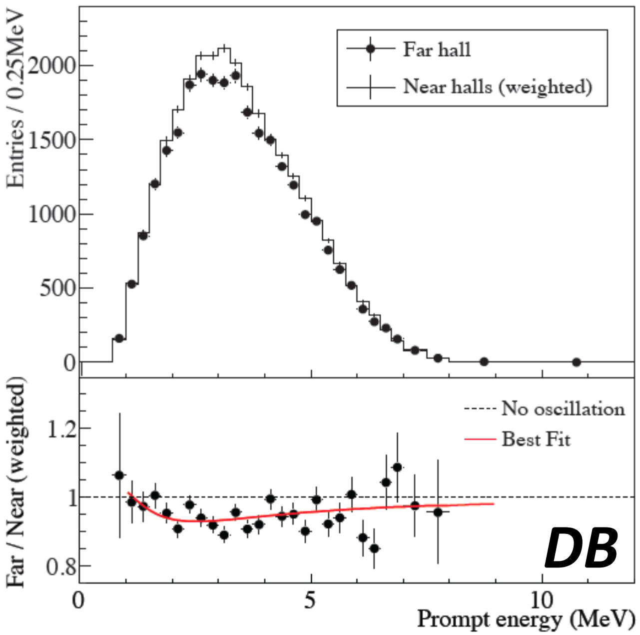
- Before 2011, θ_{13} was the last missing angle and believed to be small.
- In 2011, T2K, which was a long baseline neutrino oscillation experiment to shoot neutrinos from JPARC proton synchrotron in Japan to Super-Kamiokande, 295 km at a distance to look for $\nu_\mu \rightarrow \nu_e$ appearance with the average neutrino energy of 0.7 GeV, has first shown an indication of non-zero θ_{13} where 6 e-like events were observed with 1.5 ± 0.3 (syst.) backgrounds.
- This provides ***2.5 σ*** effect of ν_e appearance.

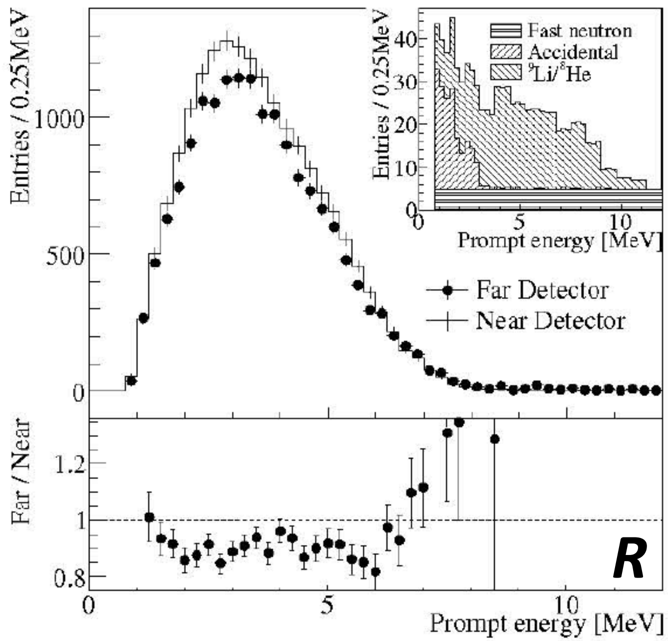


θ_{13}

- In 2012 reactor experiments have provided the evidence of ν_e disappearance and have determined the value of θ_{13} at ~10% level
  - $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$ Double CHOOZ
  - $\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$ Daya Bay **7.7σ effect**
  - $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$ RENO







10% level measurements ➔ 5% in future

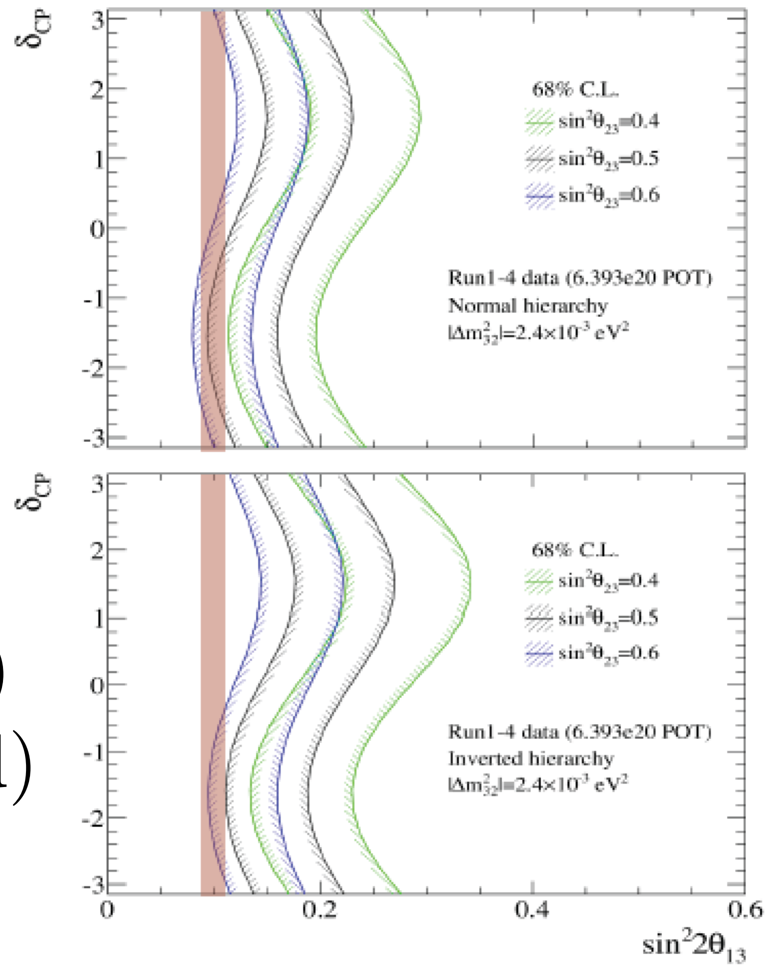
θ_{13}

- In 2013: 7.5 σ evidence of $\nu_\mu \rightarrow \nu_e$ appearance was obtained by T2K
- T2K observed 28 electron events with 4.64±0.53 backgrounds

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034} \text{ (Normal)}$$
$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040} \text{ (Inverted)}$$

(for $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$\sin^2\theta_{23}$ = 0.4, 0.5, 0.6



From the discovery to the precision measurement

- All the mixing angles and mass differences are now determined by many experiments precisely $\lesssim O(10\%)$

${\Delta m_{12}}^2$	$= 7.58^{+0.21}_{-0.20} \times 10^{-5} eV^2$	$(\sim 2.8\%\ @\Delta\chi^2 = 1)$	$[KamLAND]$
$\sin^2\theta_{12}$	$= 0.310^{+0.014}_{-0.014}$	$(\sim 4.5\%\ @\Delta\chi^2 = 1)$	[all solar experiments]
${\Delta m_{23}}^2$	$= 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$	$(\sim 4.2\%\ @\Delta\chi^2 = 1)$	$[MINOS]$
$\sin^2\theta_{23}$	$= 0.575^{+0.038}_{-0.075}$	$(\sim 13\%\ @\Delta\chi^2 = 1)$	[Super-Kamiokande 3ν for Inv.MH]
$\sin^2\theta_{13}$	$= 0.0223 \pm 0.0028$	$(\sim 13\%\ @\Delta\chi^2 = 1)$	[Daya Bay]

Conclusions

- In 2013, 100 years after the birth of B. Pontecorvo and 15 years after the discovery of the neutrino oscillation, we now knows all the mixing angles and mass differences precisely
- Bruno's Legacy has been proved to be true, now new horizon of neutrino oscillation has opened up.
- We will determine mass hierarchy, octant of θ_{23} and CP phase in near future
- In conjunction with the determination of Majorana nature of neutrinos, the future study of neutrino oscillation (especially CP phase) may be able to explain the origin of the matter of the Universe.