Neutrino physics and detectors
From Kamiokande to T2K

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XIV ICFA School On Instrumentation
In Elementary Particle Physics
La Habana, Cuba

This lecture

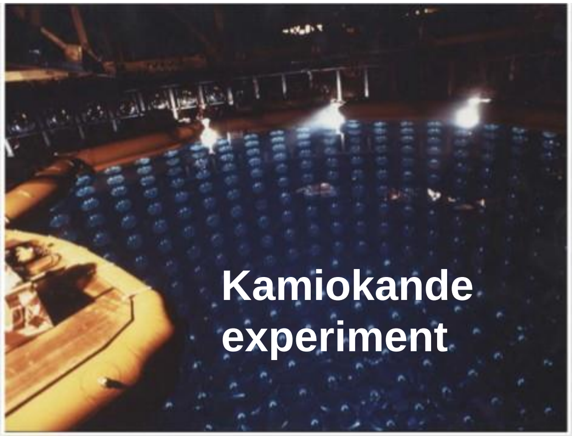
- **I was nominated as the lecturer of "Neutrino physics and detectors". Organizers of the ICFA school looked my previous lecture and asked me to give a similar lecture in this school.**

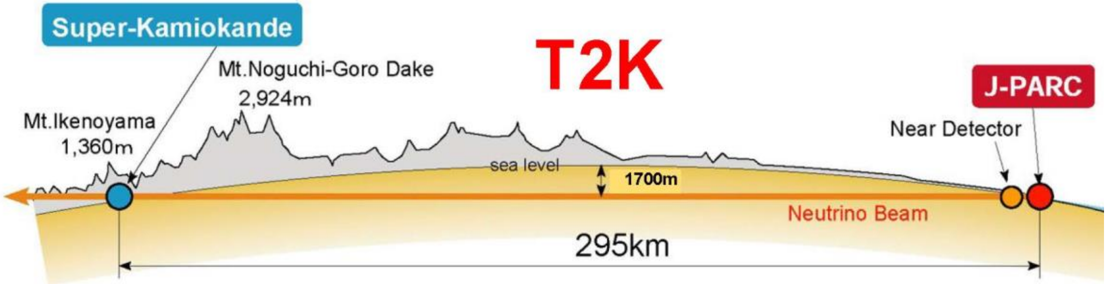
- **The title of my previous lecture was "From Kamiokande to T2K". It was given at "Vietnam school on Neutrino" in July 2017. The lecture was 90 minutes/day x 3 days = 270 minutes.**

- **The lecture in this school is 120 minutes short version of my lecture in Vietnam. If you have an interest, please visit the longer version:**
  https://www.dropbox.com/s/0qrujalpo8sonv3/Oyama-Lecture-1-2-3.ppt?dl=0
  or
  http://www-nu.kek.jp/~oyama/VSoN2017.oyama.ppt

About myself / About my lecture

From 1984, I have participated in following experiments.





I would like to present a review of these Kamioka-related experiments.


84 10.

History of Discoveries by neutrino experiments

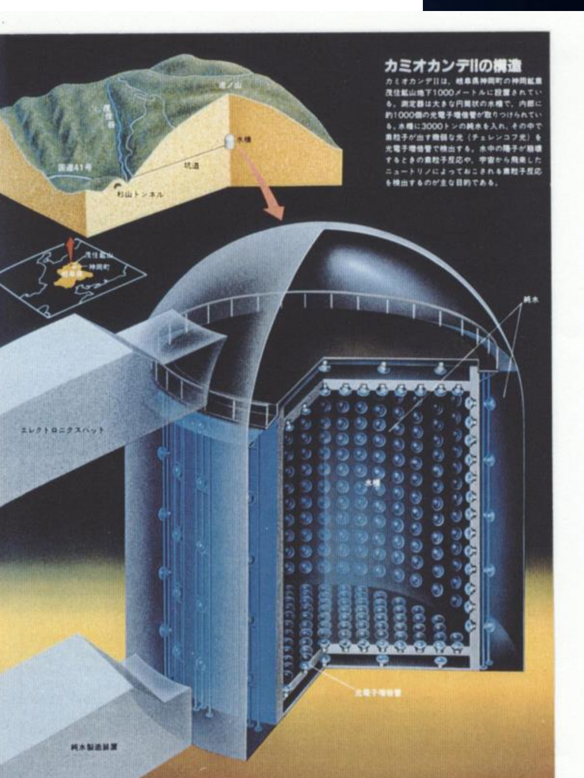
1956 Reines and Cowan discovered anti-electron neutrino from a reactor (N)
1962 Muon neutrino beam experiment by L.Lederman et al (N)
1965 KGF observed atmospheric neutrino
1968 Homestake experiment claimed solar neutrino deficit (N)
1973 Neutral Current interaction was discovered by Gargamelle
1987 Kamiokande and IMB detected neutrinos from supernova SN1987A (N)
1988 Kamiokande claimed atmospheric muon neutrino deficit
1989 Kamiokande confirmed the solar neutrino deficit
1998 Super-Kamiokande observed atmospheric neutrino oscillation (N)
1998 Super-Kamiokande confirmed solar neutrino deficit
2000 DONUT observed tau neutrino
2001 SNO confirmed solar neutrino oscillation by neutral current measurement (N)
2002 Kamland observed deficit of reactor neutrinos
2004 K2K confirmed atmospheric neutrino oscillation by artificial neutrino beam
2006 Completely independent confirmation of ν_μ-ν_τ oscillation by MINOS
2011 First indication of non-zero θ_{13} by T2K
2012 Non-zero θ_{13} was confirmed by 3 reactor experiments
2013 Evidence of non-zero θ_{13} by T2K
2015 Hints toward negative δ_{CP} by T2K
2015 Discovery of ν_τ signal from ν_μ-ν_τ oscillation by OPERA

Main topics of my lecture, and will be presented precisely.
Related to main topics, and will be mentioned briefly.

Kamiokande(1983-1996)

- A large water Cherenkov detector constructed at 1000 m (2400 meter water equivalent) underground in Kamioka mine, Japan.

- 3000 tons of pure water are viewed by 1000 20-inchΦ PMTs.



Kamioka Nucleon Decay Experiment

- To search for nucleon decay, huge number of nucleons must be 'viewed'.

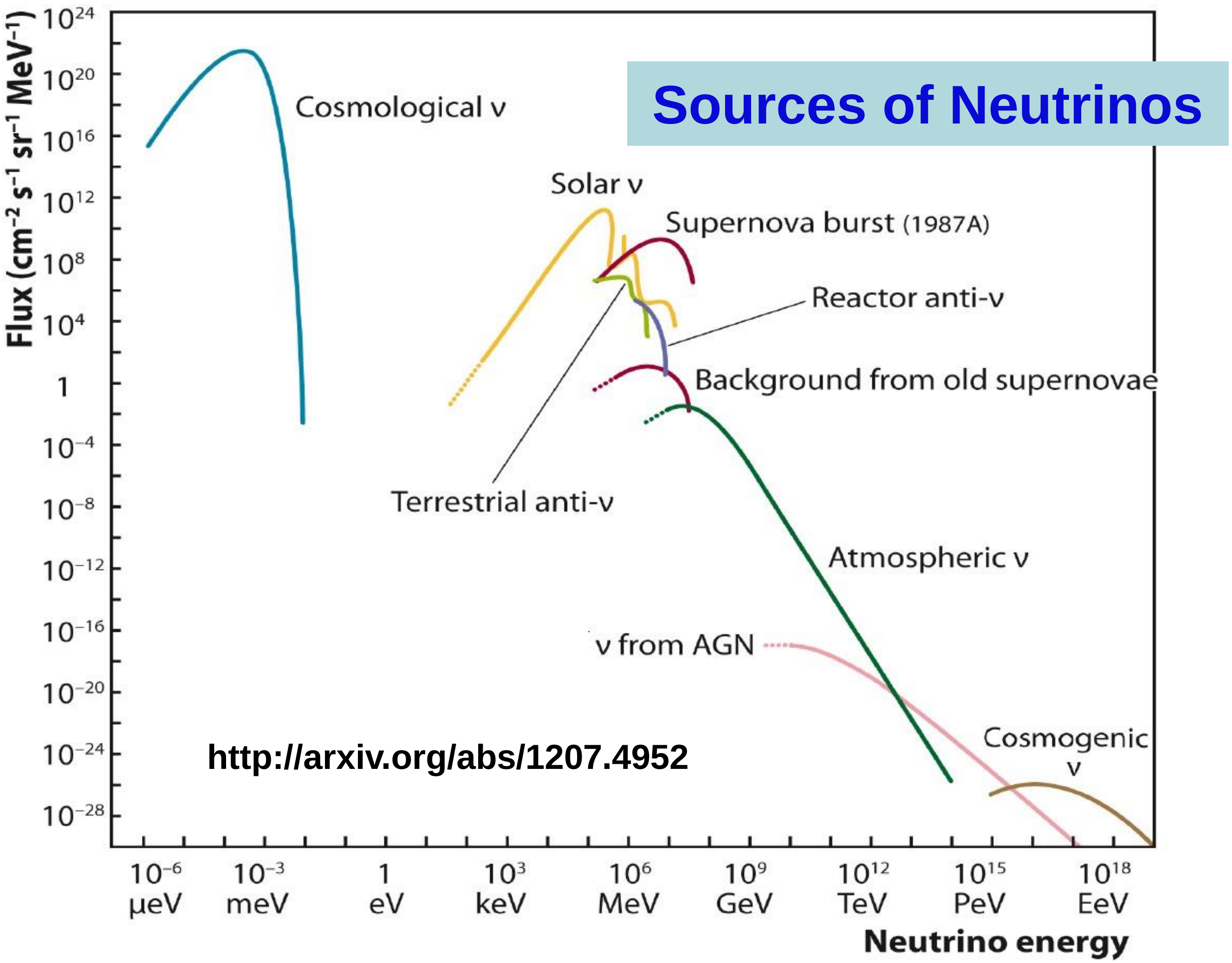
- Water Cherenkov detectors are one of best solutions for nucleon decay search.

1. Water is very cheap and transparent.
2. Assume that nominal size of the detector is R. The volume is in proportional to R^3, but number of photo sensor on the wall is in proportional to R^2. It is effectively cheaper for larger detector.

- In February 1979, the first unofficial proposal of Kamiokande was presented.
- In December 1980, the design of 20-inchΦ photomultiplier tube (PMT) was fixed.
- In July 1983, the experiment started, but no nucleon decay was found.

“Kamioka Nucleon Decay Experiment” to “Kamioka Neutrino Detection Experiment”

- After successful exclusions of most of Grand Unified Theories….., main subjects became Solar Neutrinos and Atmospheric Neutrinos.



Solar neutrino and Atmospheric neutrino

Solar Neutrino

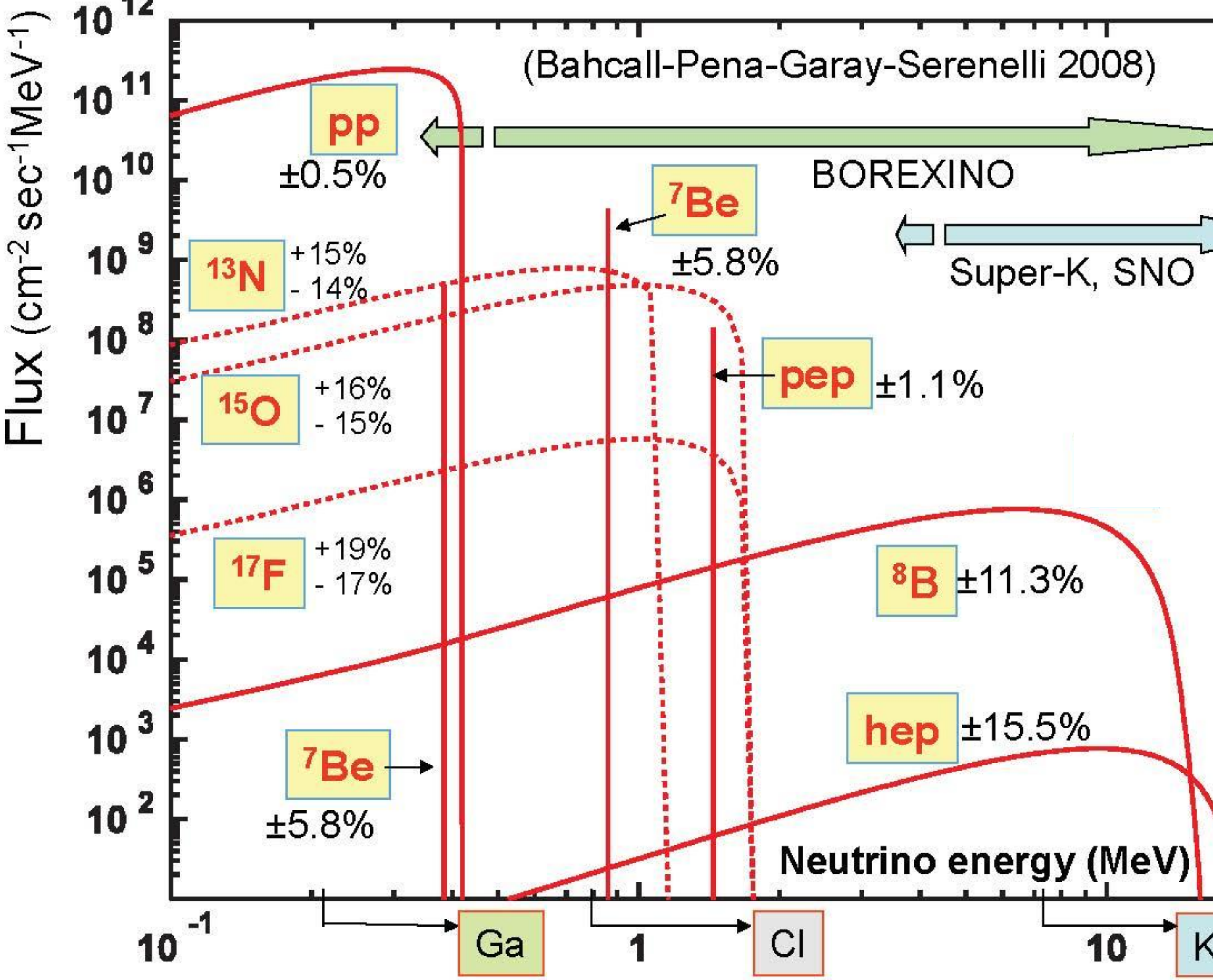
- **E~10 MeV energy range. ("Low energy" in Kamioka terminology)**
- **Energies of supernova neutrinos are also in this range.**
  Reactor neutrinos have slightly smaller energy.
- **ν_e-ν_μ oscillation was studied with these neutrinos.**
- **Solar neutrino is in the field of nuclear physics and astronomy. We were not familiar to these fields. We have started from "nuclear decay" (instead of nucleon decay) and "definition of celestial coordinate"**
- **Once our detector was constructed, we must consider what physics can be done with our own detector. We must keep studying nearby research field!**

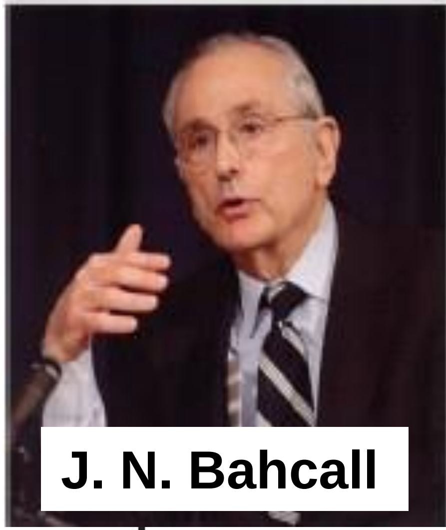
Atmospheric neutrino

- **E~1 GeV energy range. ("ATMPD" in Kamioka terminology)**
- **Accelerator neutrino beam have similar energies.**
  Nucleon decays are also in this energy range (if exist).
- **ν_μ-ν_τ oscillation was studied using neutrinos in this energy range**

Energy spectrum of solar neutrinos

Standard Solar Model (SSM)

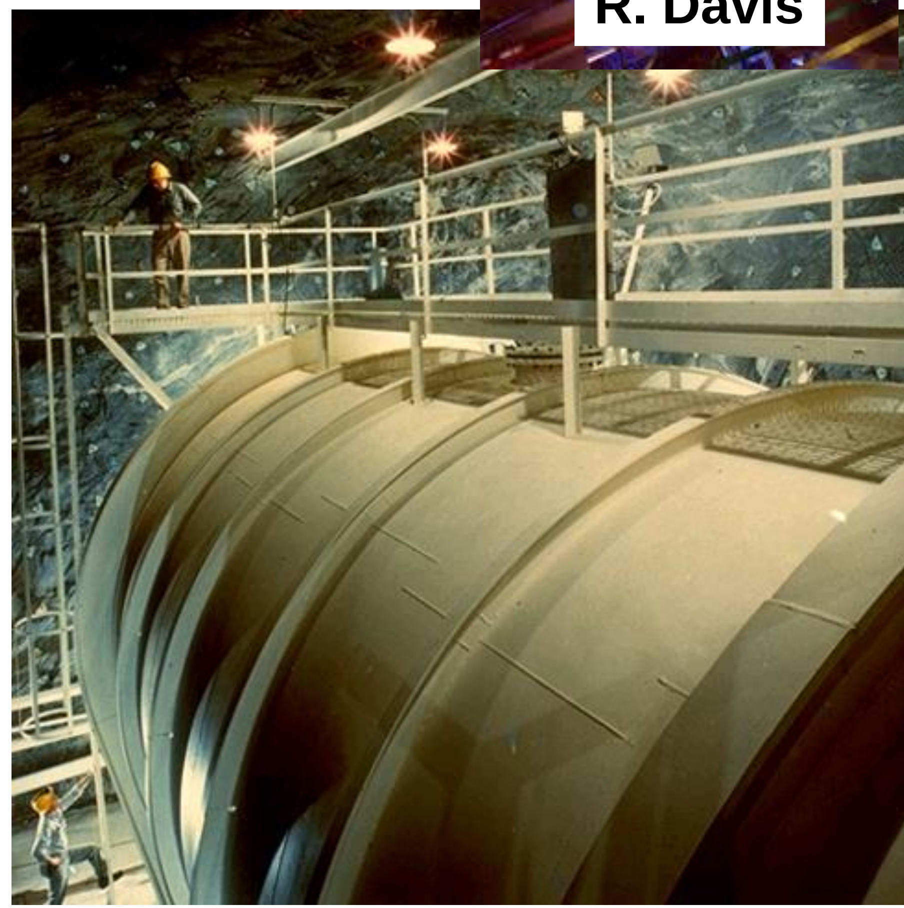




J. N. Bahcall

Homestake Chlorine Experiment

- The pioneer solar neutrino experiment conducted by Raymond Davis. The experiment started in 1967.
- 615 tons of fluid C_2Cl_4 are stored in a tank chamber at 1480m underground in Homestake lead mine, South Dakota.
- From $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$ reaction, ^{37}Ar are accumulated. The energy threshold of the reaction is 0.814 MeV, and the production rate is ~0.5 ^{37}Ar/day. Sensitive to ^{7}Be solar neutrinos.
- ^{37}Ar atoms are extracted by bubbling helium gas through tank every few weeks. Number of ^{37}Ar decays ($\tau_{1/2}$ = 35 days) are counted in a low-background environment.

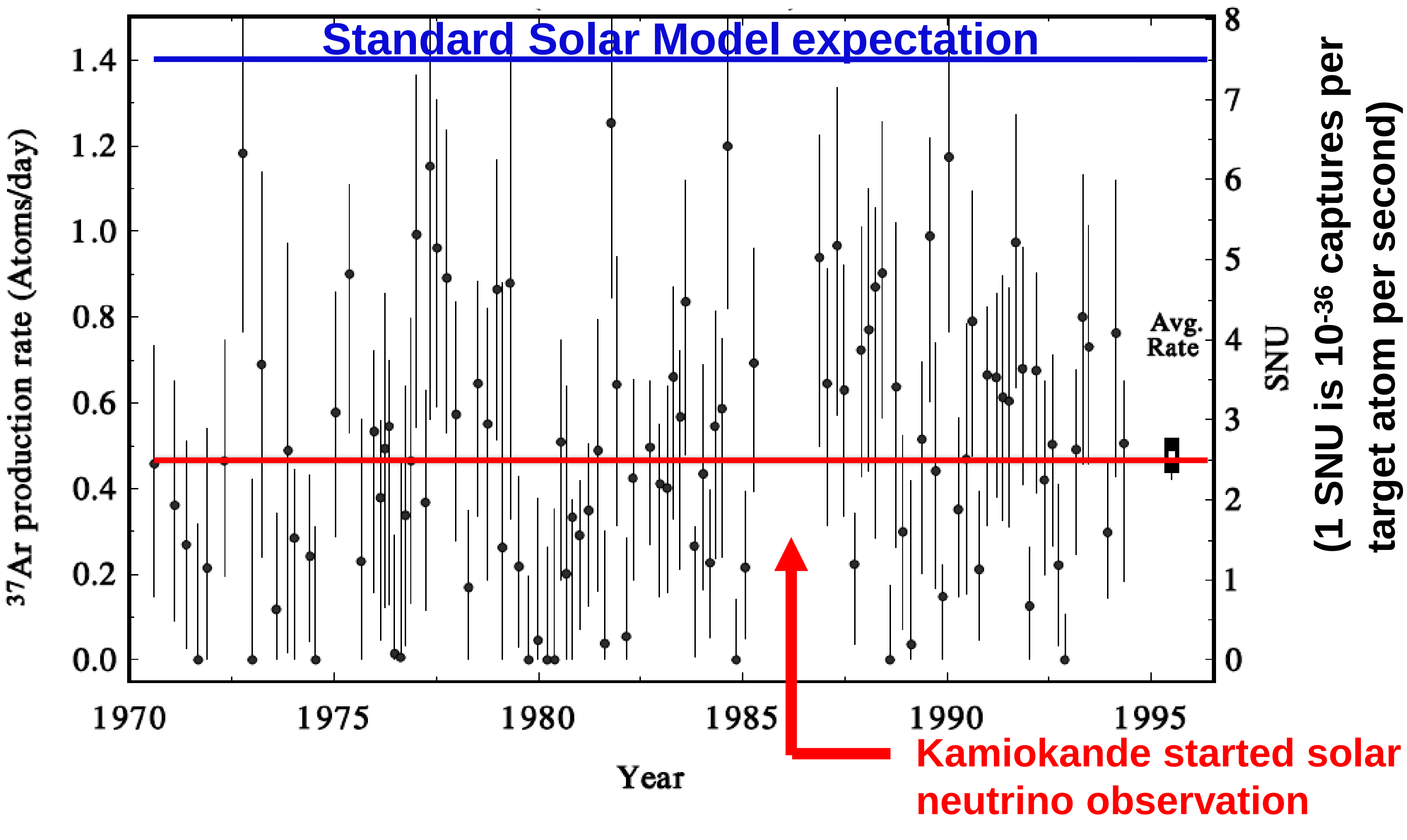


Results from Homestake experiment

- The number of solar neutrino events measured by Homestake experiment is about 1/3 of the Standard Solar Model prediction. The first result was published in 1968. R. Davis et al., Phys. Rev. Lett. 20, 1205(1968)

- **Is it an evidence of neutrino oscillation ?**

~25 years of data
2200 solar neutrinos



Solar neutrino oscillation?

Homestake experiment claimed solar neutrinos deficit for over 15 years until middle of 1980s. However, we did not consider the result seriously.

SSM calculation

- **Total neutrino flux seems to be certainly robust.**
  It can be directly evaluated from the solar luminosity.
- **However, Homestake experiment does not measure pp neutrino.**
  Other neutrino components are small fractions and not robust.
  It strongly depend on core temperature, chemical composition, cross sections, opacity of the Sun, etc.

We cannot believe the calculation !

Homestake experiment

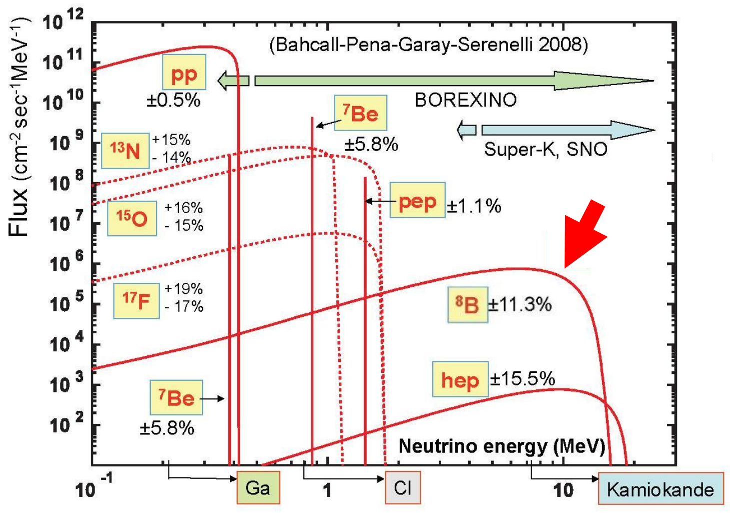
- **Experiments in ~1MeV energy range are not territory of high energy physicists. R. Davis was not a physicist, but a chemist.**
- **Radiochemical method is not common technology for high energy physicists. Most of our experiments are "counter experiments".**

We cannot imagine the experiment !

No experiment followed Homestake.

Solar neutrinos in water Cherenkov detector

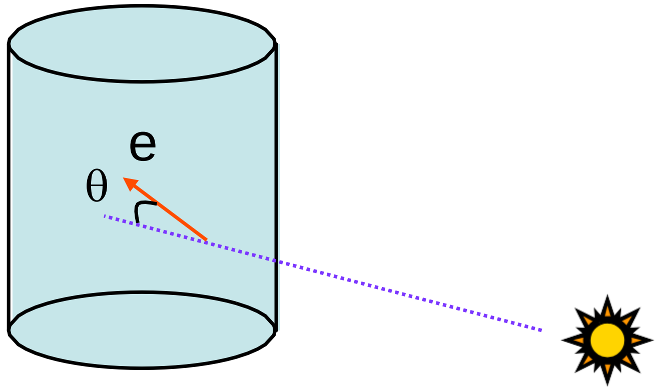
- In water Cherenkov detector, only ^{8}B neutrinos whose nominal energy is ~8 MeV can be detected.



- Elastic scattering between neutrinos and orbital electrons are employed.

$$\nu_e + e \rightarrow \nu_e + e$$

Recoil electrons keep energy and directional information of initial neutrinos



- Interactions with hydrogen and oxygen nuclei do not occur because the energy of solar neutrinos are too low.

Kamiokande-II

- When Kamiokande experiment started, the trigger threshold of the detector was ~29 MeV. This threshold was low enough to detect nucleon decay mode $p \to \nu K^+ (\mu^+ \nu)$, which records the smallest energy deposit in the detector.

- To detector ^{8}B solar neutrinos, the trigger threshold of the detector should be reduced to be around ~8 MeV.

- In addition to the trigger threshold, background events in the low energy range should be reduced.

- From fall 1984 to end of 1986, many detector upgrade to observe ^{8}B solar neutrinos were done. They are:
  1. Removal of radioactive sources in water
  2. Construction of anticounter
  3. Installation of New electronics

- After these upgrade, namely, Kamiokande-II started in early 1987.

Removal of radioactive sources in water

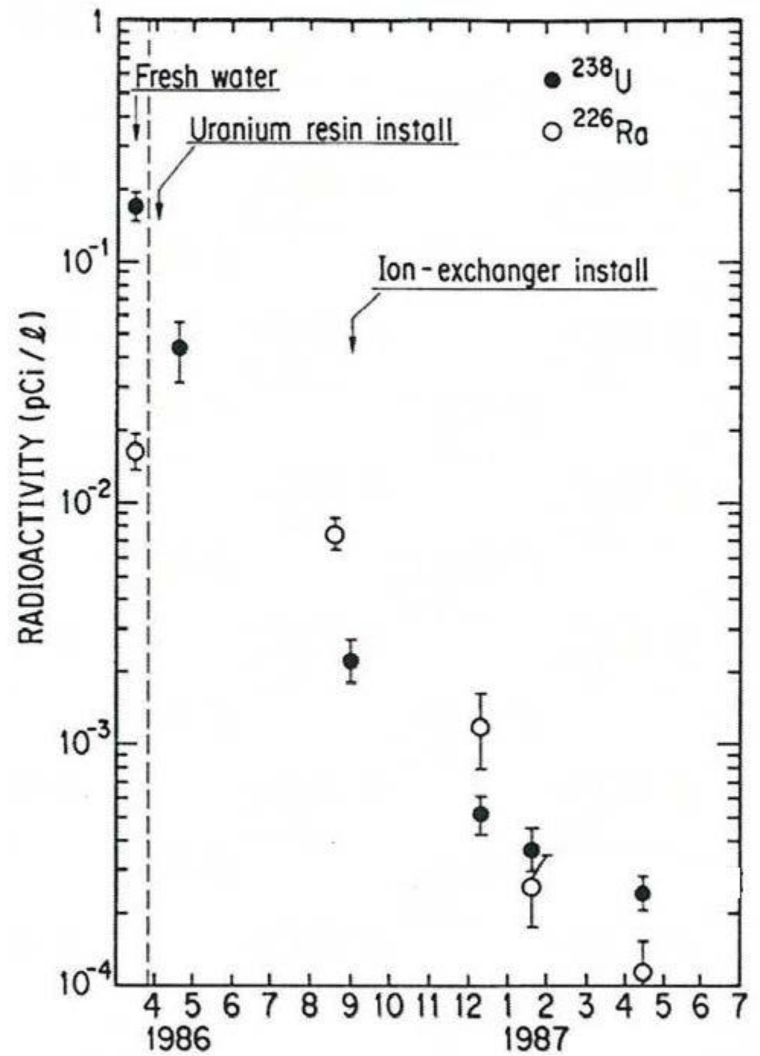
- The most serious background were the β-decay products in Uranium-Radium series. Note that nominal energy of them are < several MeV.

- Fresh water from the mine contains large concentration of Radon. Supplying the fresh water was stopped and closed circulation mode was employed. A Radon-free water generation system was also installed.

- In the water circulation system, Uranium resin and Ion-exchanger were added.

- To prevent contact of water and Radon-rich mine air, an air-tight ceiling on the top of the tank were made. Other components in the water circulation system were also made air-tighten.

- Finally, the radioactivity was reduced by 3 orders of magnitudes.

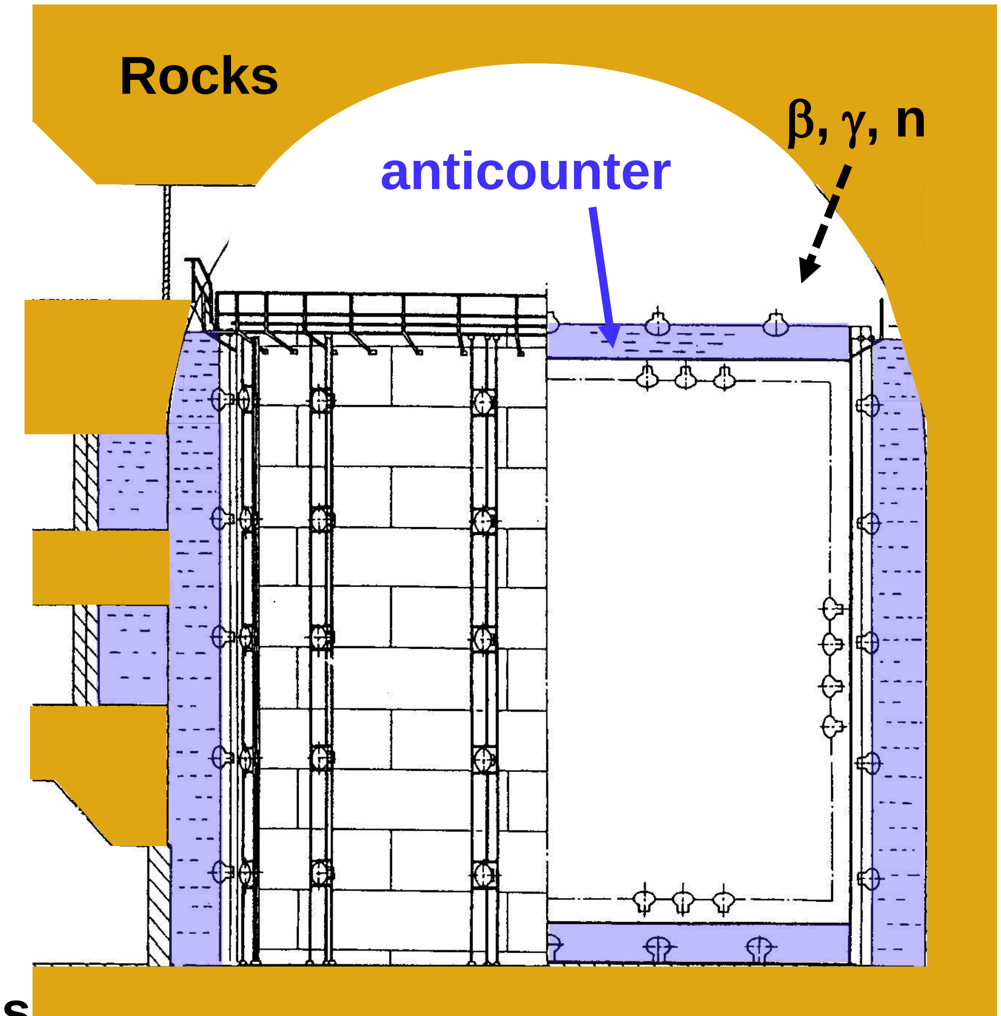


Anticounter

- **The anticounter layer surrounding the inner detector were newly constructed until fall 1985.**
  It was also water Cherenkov detector with >1.4 m water thickness and 123 20-inchΦ PMTs.

- **The main purpose of the anticounter layer is to identify entering/exiting charged particles such as cosmic ray muons.**

- **The anticounter water layer effectively absorb radio activities from surrounding rocks and air.**



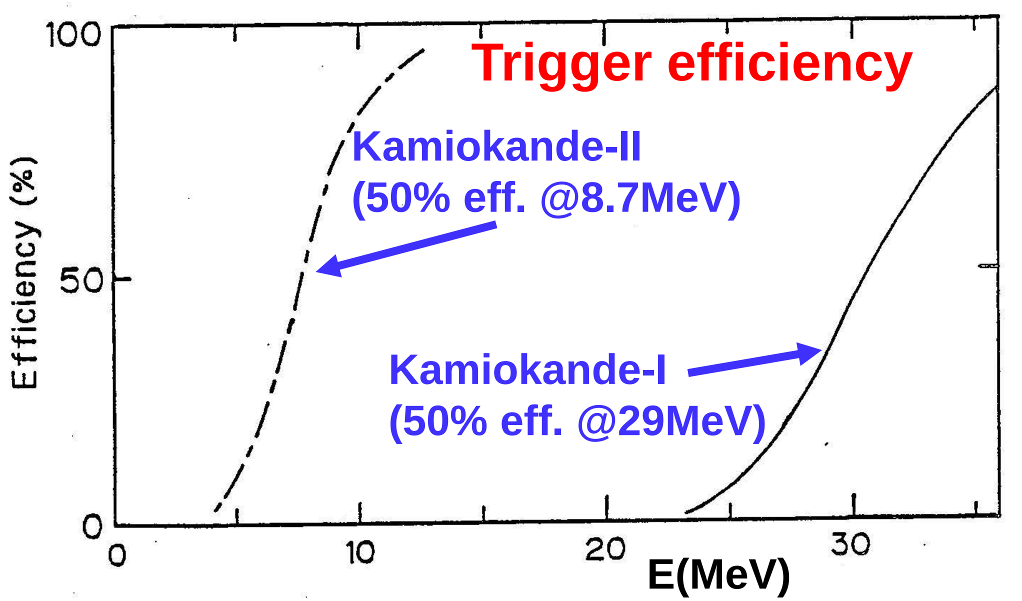
New electronics

- **University of Pennsylvania group joined the experiment and installed new readout electronics in summer 1986.**

Design of the new electronics

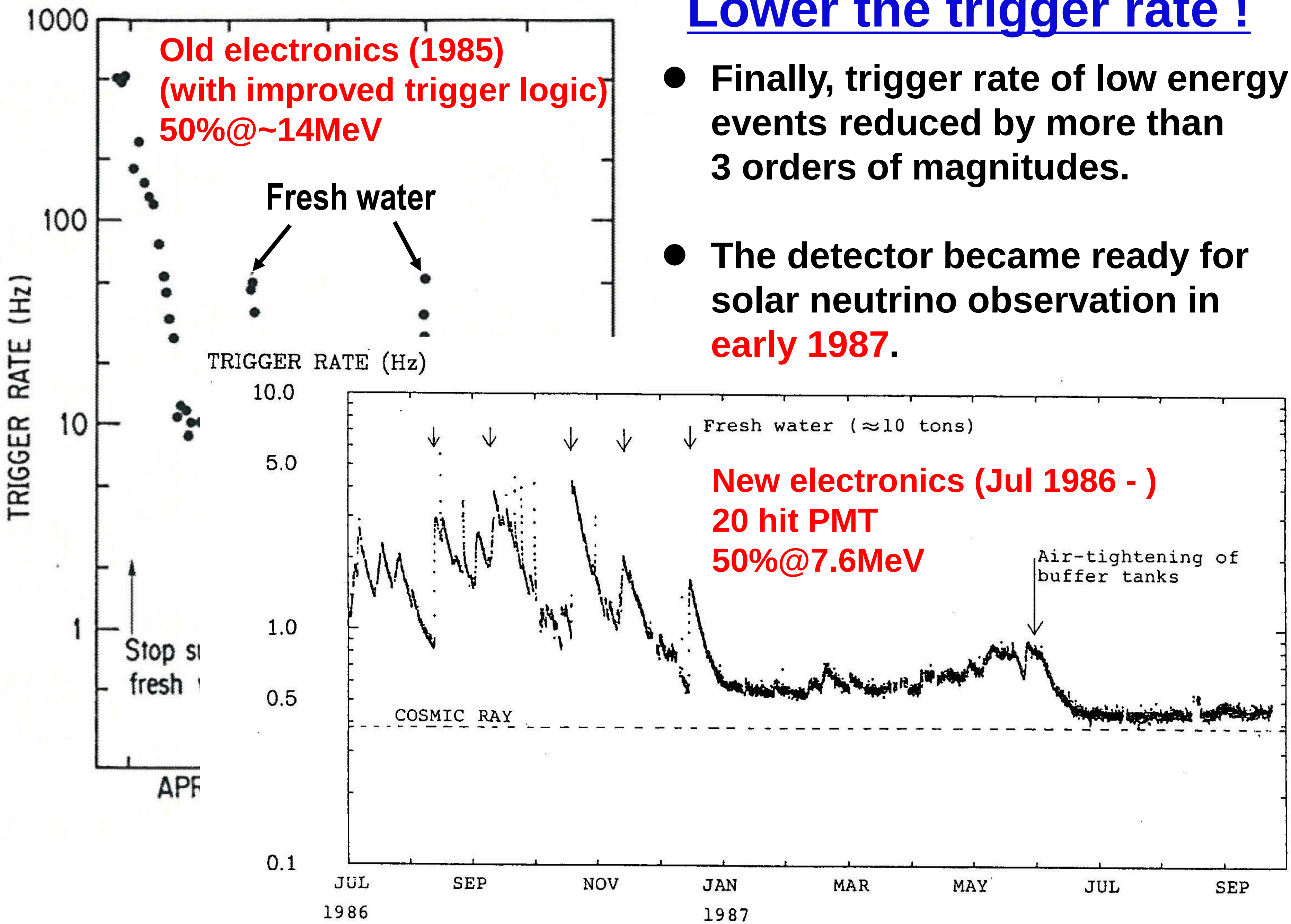
> - **Charge and timing information of PMTs are digitized in PMT by PMT basis.**
> - **Discriminator is also in PMT by PMT basis.**
>   **"Number of hit PMT" signal is made from sum of the discriminator outputs, and used for the trigger logic.**

- **The new electronics was operated with the condition $N_{hit} \geqq 20$, which corresponds to 7.6MeV energy threshold.**



Lower the trigger rate !

- Finally, trigger rate of low energy events reduced by more than 3 orders of magnitudes.
- The detector became ready for solar neutrino observation in early 1987.



Observation of solar neutrinos in Kamiokande-II

- The **first real-time**, **directional** neutrino signal from the direction of the Sun.

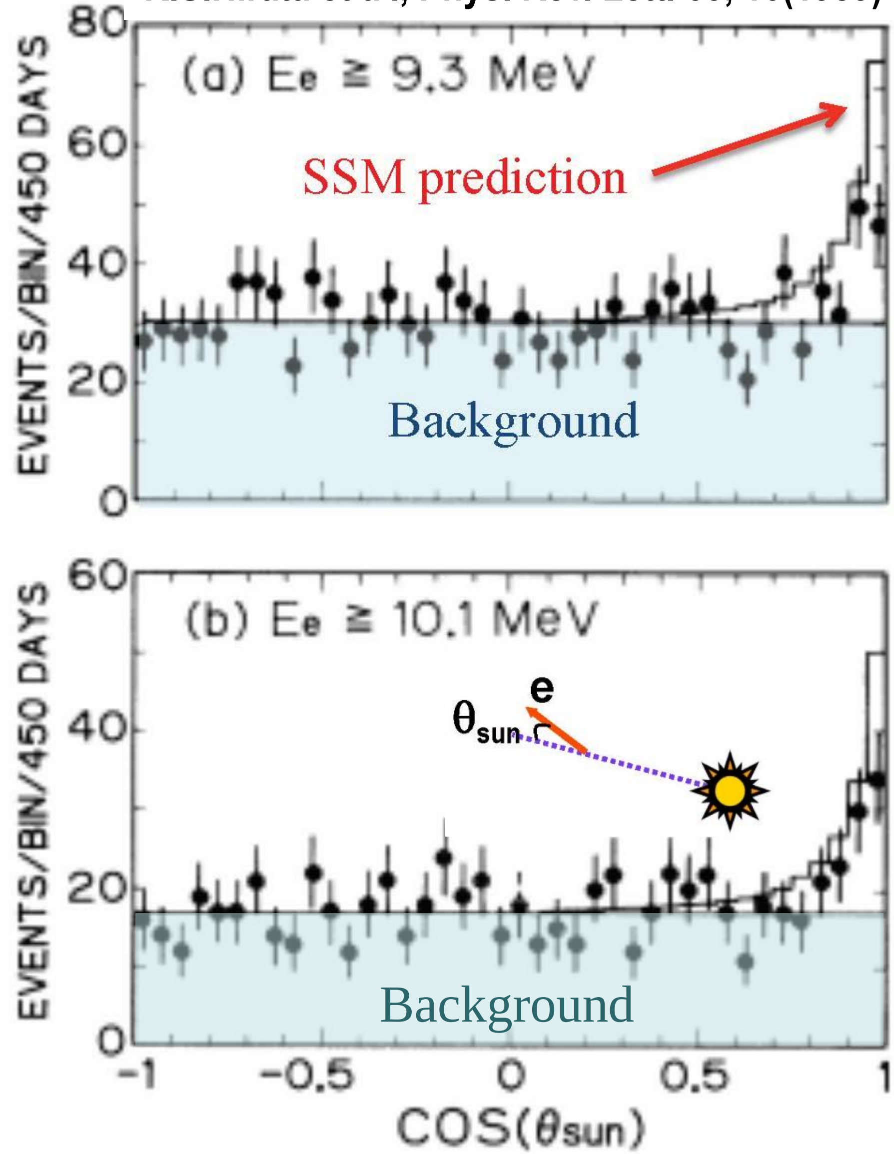
- The observed neutrino flux is
  0.46 ± 0.13(stat.) ± 0.08(sys.)
  of SSM prediction.

- The observation is certainly smaller than the SSM prediction. However, the discrepancy is not consistent with Homestake.

  Homestake : ~ 1/3 of SSM
  Kamiokande-II : ~ 1/2 of SSM

- After Kamiokande-II observation, measurements with different energy threshold became key issue for other new experiments.

K.S.Hirata et al., Phys. Rev. Lett. 63, 16(1989)

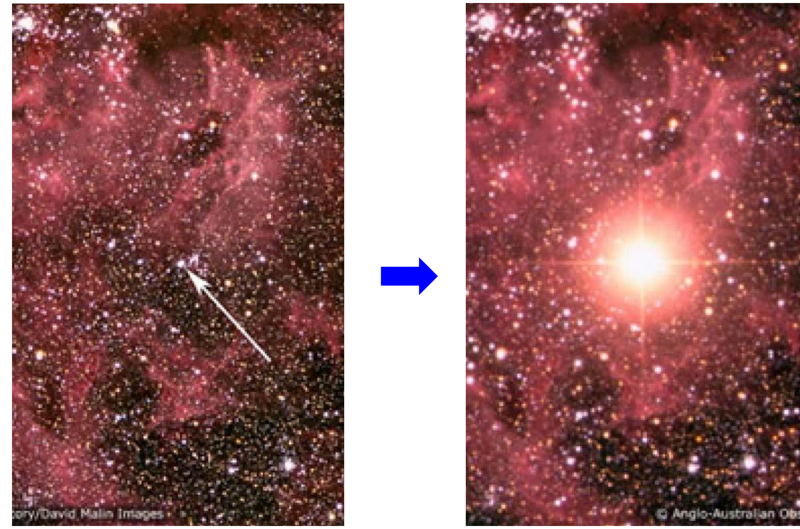


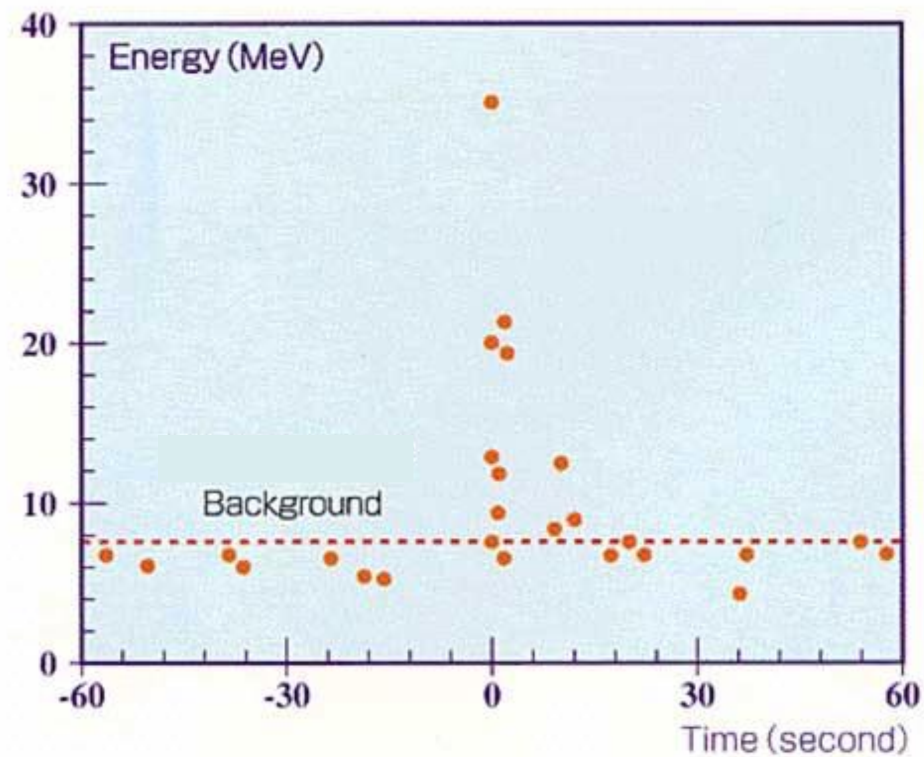
SN1987A

- **In Kamiokande, observation of solar neutrinos has been started from early January 1987. The detector was ready for observation of low energy neutrinos.**

- **In February 25, 1987, we received a news of a supernova explosion in Large Magellanic Cloud, which is only 160k light-year away from our solar system.**

- **Kamiokande immediately analyzed the data, and found a clear 11 neutrino events in 13 seconds from February 23, 07:35:35UT (±1min).**





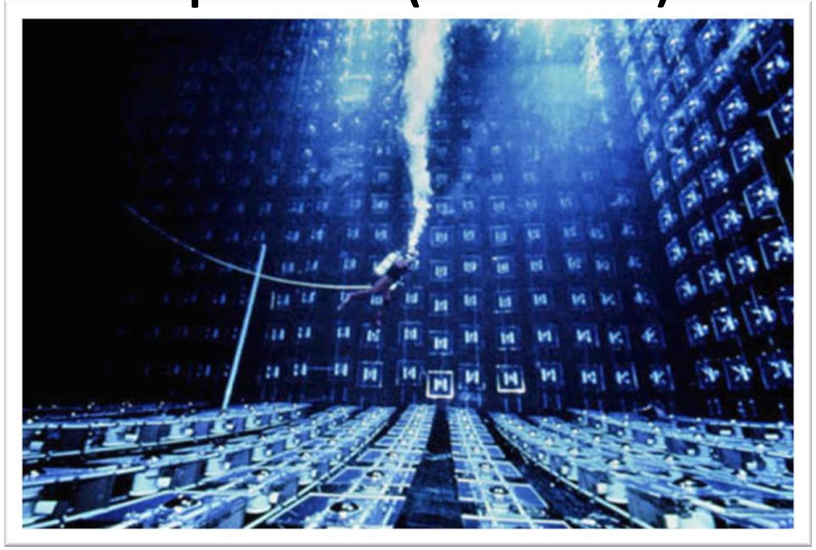
Confirmation by IMB

- After hearing observation of Kamiokande, the IMB group found neutrino events in Kamiokande event time.
  They found 8 neutrino events with energies between 20 MeV to 40 MeV during 6 seconds.
  The Kamiokande result was certainly confirmed.

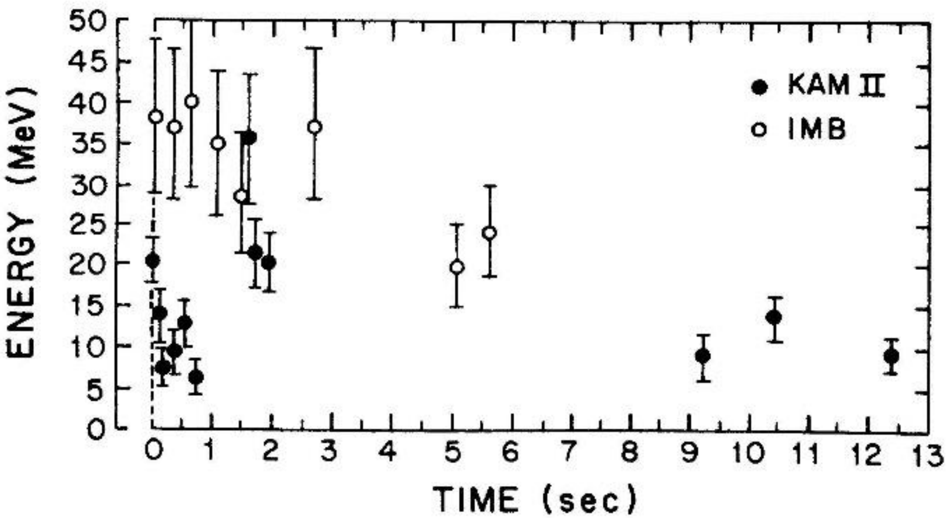
R.M.Bionta et al., Phys.Rev.Lett. 58,1494(1987)

- IMB physicists searched for neutrino events in > 100MeV energy range?
  Kamiokande members in Univ. of Tokyo well knew the neutrino energy range because they kept close communication with theoretical astrophysics group in the University.
  Communication with theorists is important.

IMB experiment (1982-1991)



A water Cherenkov detector at 1570 m.w.e. in the Morton Salt Mine, Ohio.
8 kt of water is viewed by 2048 8-inchΦ PMTs. Fiducial volume is 3.3 kt.



Some words by Koshiba

- **“Measurements of arrival time and arrival direction of signals are essentially important in astronomy. If such information is missing, it is difficult to claim astronomy. Observation of neutrinos from SN1987A by Kamiokande was the birth of neutrino astronomy.”**

  - **The title of second Kamiokande paper on solar neutrino became “Results from One Thousand Days of Real-Time, Directional Solar- Neutrino Data”.**

- **“Just after the start of Kamiokande-II, neutrinos from SN1987A passed through our detector. It is said that Koshiba is an extremely lucky person. However, I would like to emphasize that 6 billions of people had equal opportunity to detect the Supernova neutrinos. Only our group prepared for it.”**

He strongly appealed that he is the founder of neutrino astronomy, and his achievement was not unexpected good luck.

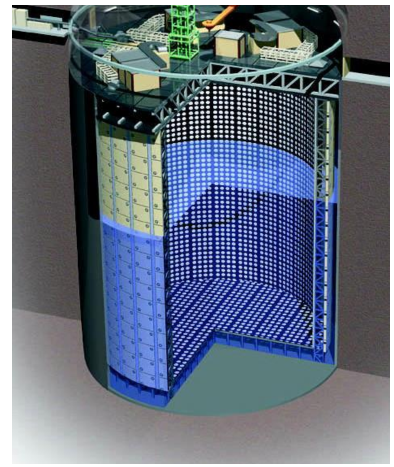
Nobel Prize

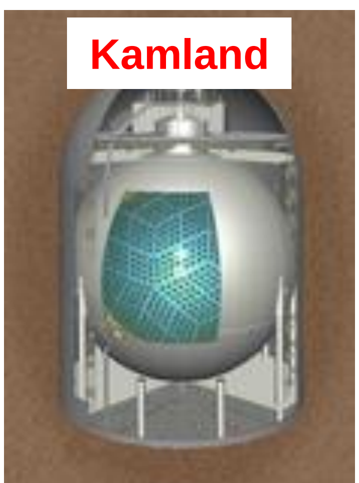
- **Masatoshi Koshiba shared the Nobel Prize in Physics for 2002 with Raymond Davis Jr. The reason of the award is "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"**

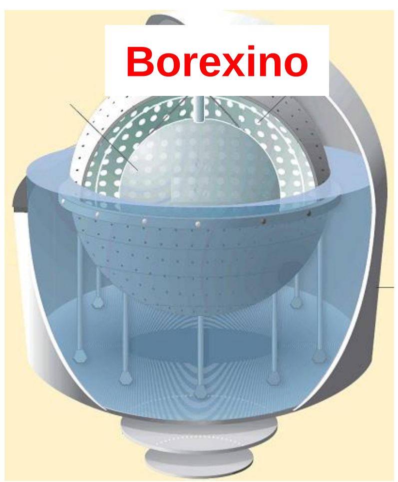
Solar neutrino/Reactor neutrino experiments

- **Solar neutrino observation became an active research subject, and many solar/reactor experiments followed.**

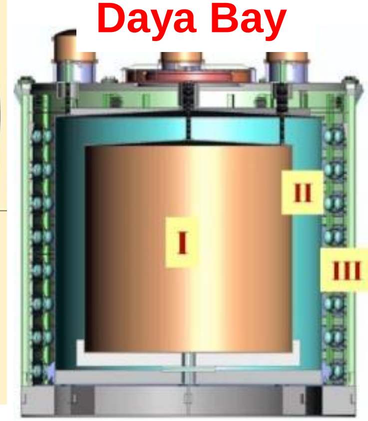
Super-Kamiokande



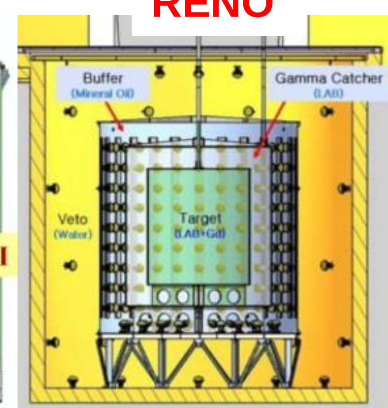




Daya Bay



RENO

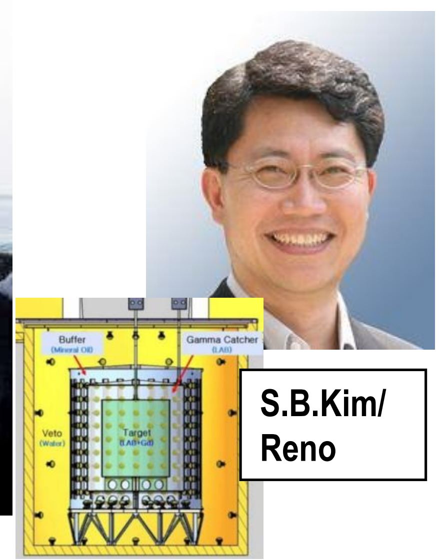


Double Chooz

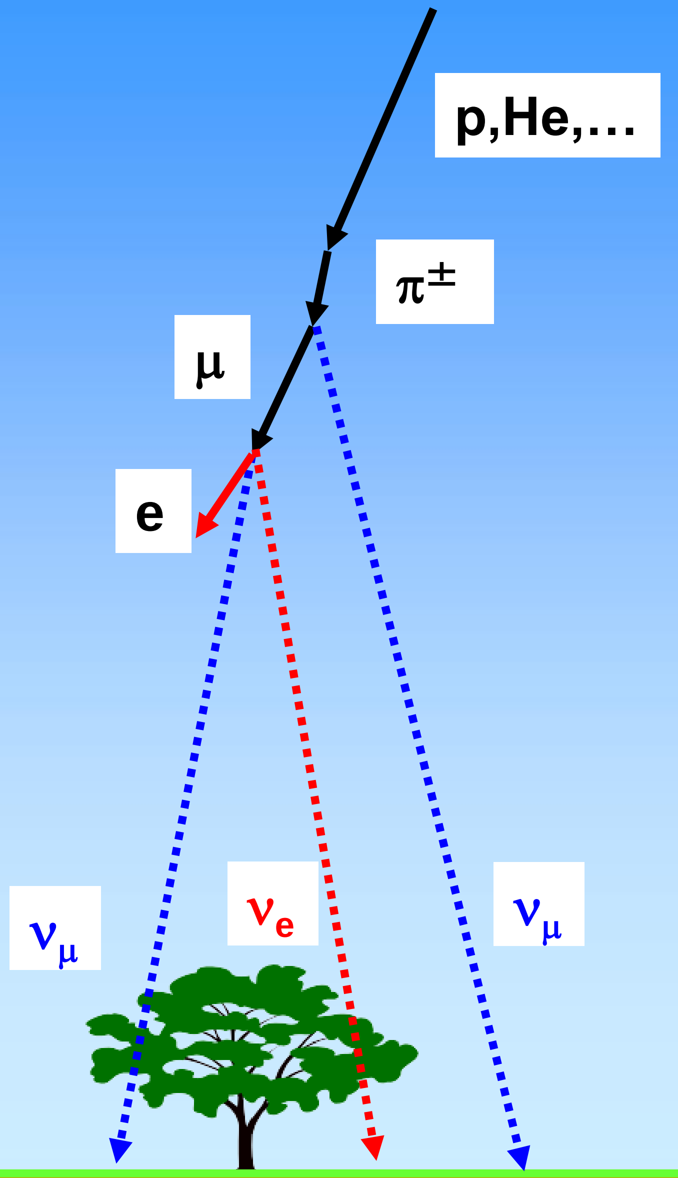
Solar neutrino/Reactor neutrino experiments

- **Kamiokande-II became a historical prototype for some of other solar/reactor neutrino detectors. Liquid (water, heavy water or liquid scintillator) as target material are stored in a large tank, and viewed by large diameter PMTs. The inner detector is surrounded by 4π anticounter.**

- **Members of Kamiokande-II became leaders in other experiments:**
  - Spokespersons of Super-Kamiokande, Kamland and Reno were members of Kamiokande-II.
  - University of Pennsylvania group joined SNO experiment and designed the SNO electronics. The co-spokesperson of the SNO experiment were a member of Kamiokande-II.



Atmospheric neutrinos

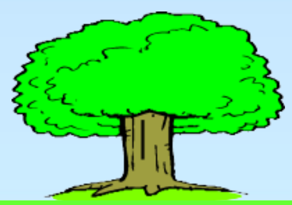


Primary cosmic rays (p, He,…) collide with upper atmosphere and neutrinos are produced.

$$\pi \rightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_e + \nu_\mu$$

$\nu_e : \nu_\mu \sim 1 : 2$

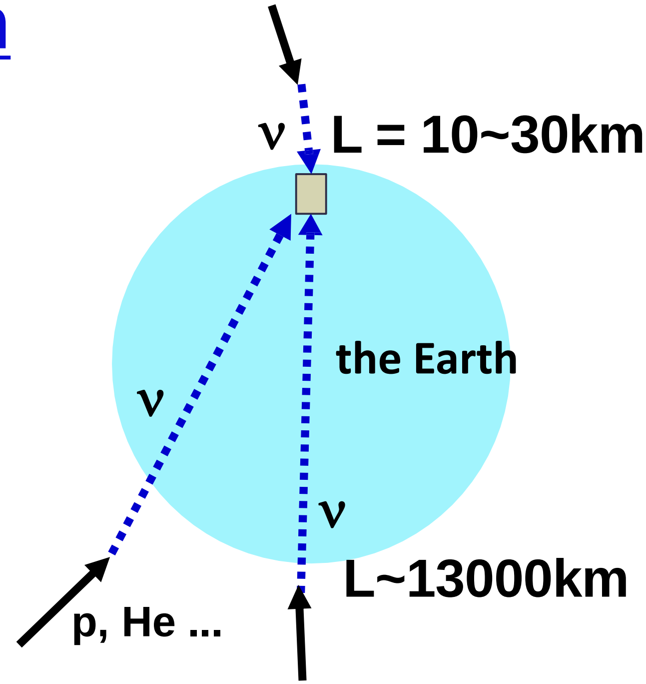
Particles and anti-particles are not distinguished unless needed. For example, π -> $\mu + \nu_\mu$ means π^+ -> $\mu^+ + \nu_\mu$ and π^- -> $\mu^- + \bar{\nu}_\mu$.

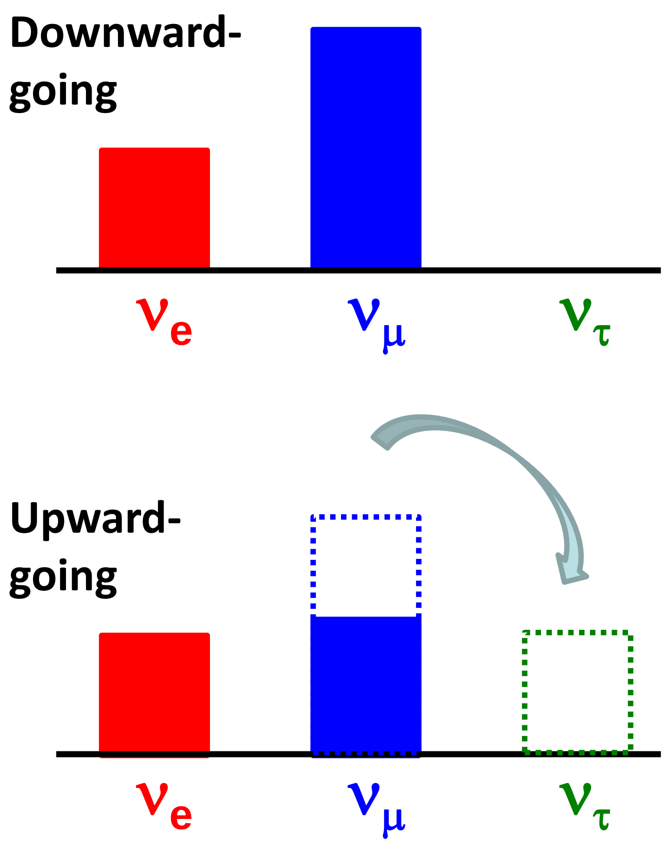


Atmospheric neutrino oscillation

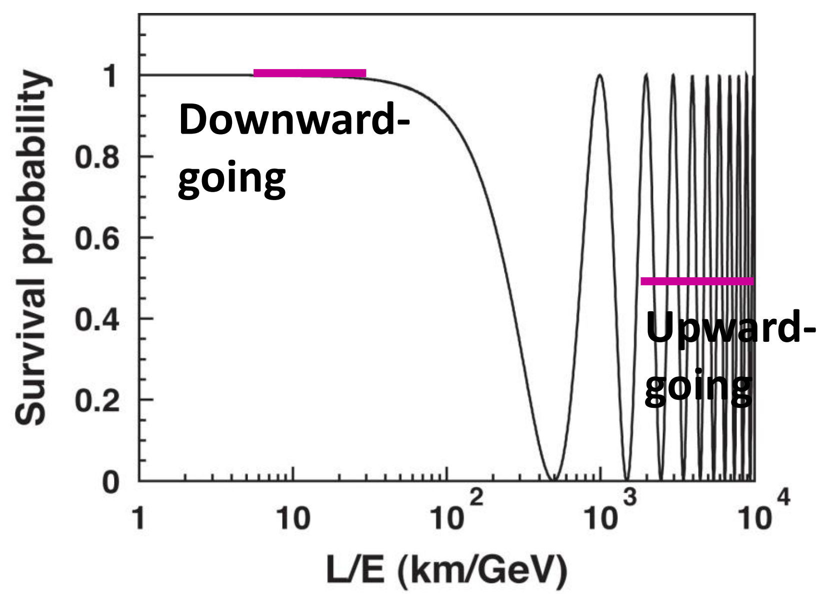
- Number of upward-going ν_μ is significantly smaller than expectation. Numbers of downward-going neutrinos and upward-going ν_e agree with expectations.

- Neutrino oscillation from ν_μ to ν_τ can explain the ν_μ deficit.





$P(\nu_\mu\text{->}\nu_\mu) = 1\text{-}\sin^2 2\theta \sin^2(\Delta m^2 L/4E)$



“Experimental study of the atmospheric neutrino flux”

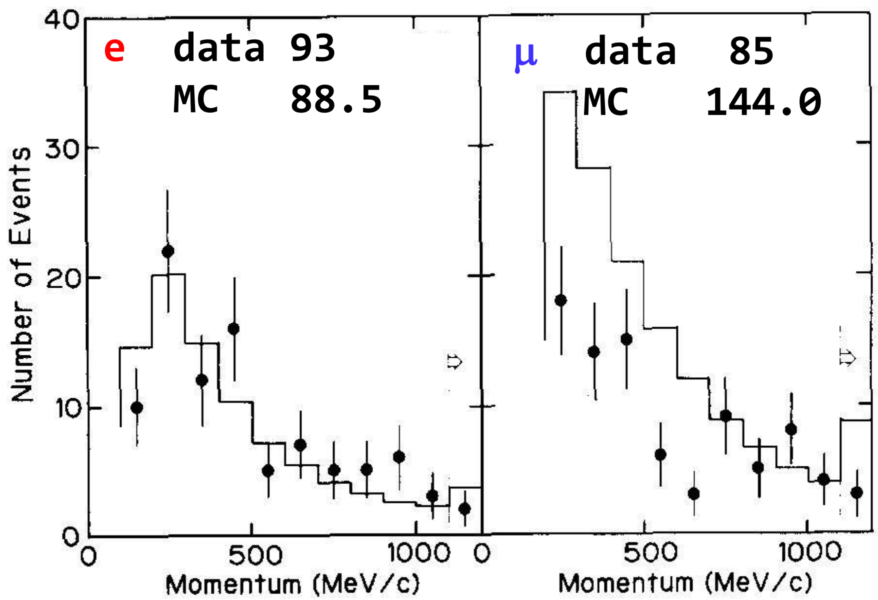
The first Kamiokande paper : K.S.Hirata et al.. Phys. Lett B205. 416(1988)

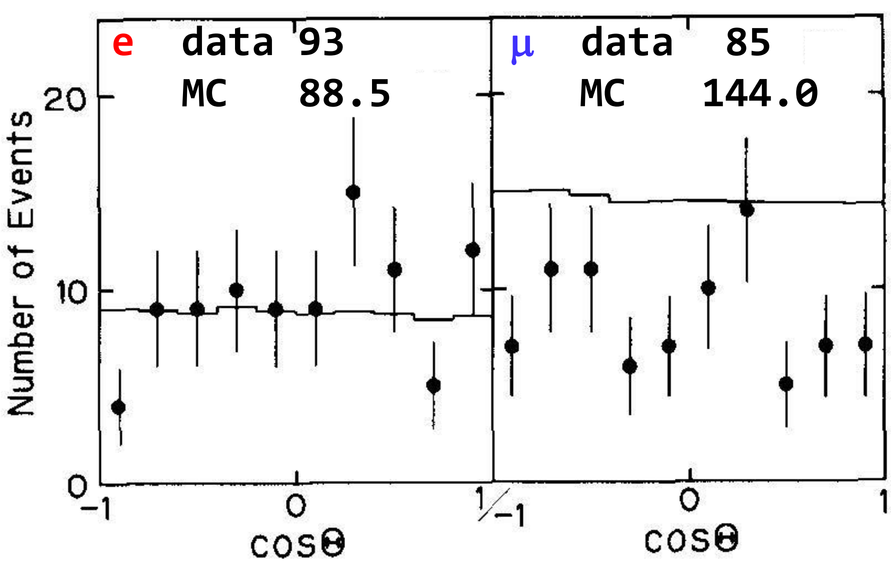
2.87 kt·yr data

	data	MC
Single ring e-like	93	88.5
Single ring μ-like	85	144.0
Multi ring	87	86.2
total	265	318.7

- e-like : good agreement
  μ-like : data/MC = 59±7% (stat)

- “We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data.”





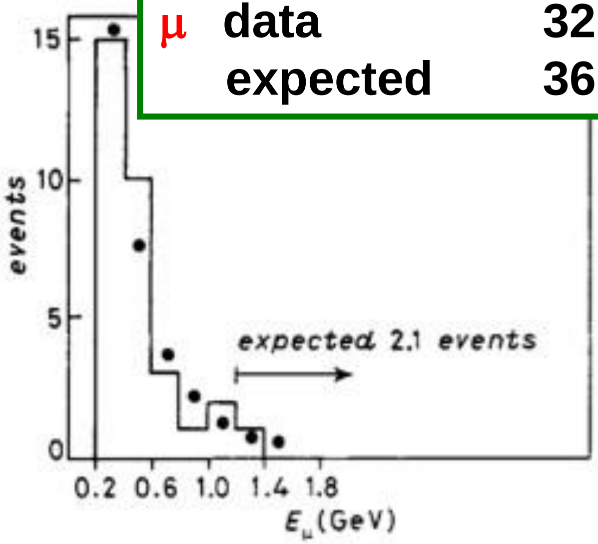
NUSEX experiment (1982-1988)

- The NUSEX detector is a digital tracking calorimeter of **3.5m x 3.5m x 3.5m**, located in Mont Blanc tunnel at 4800 m.w.e. underground.

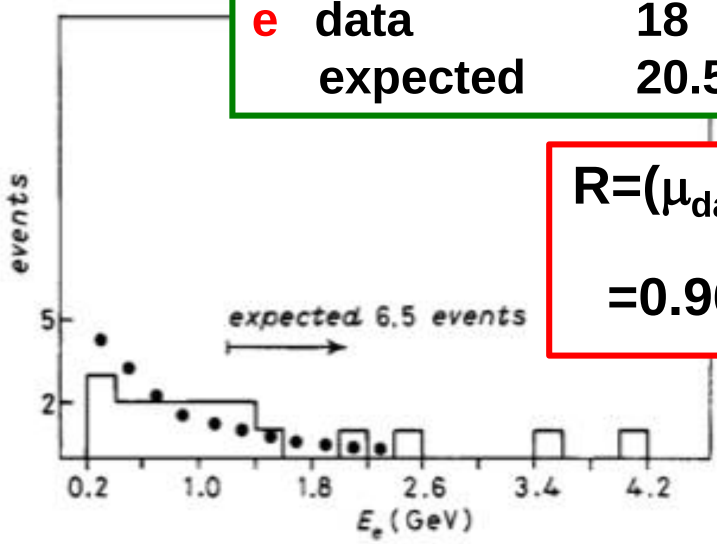
- It is a sandwich of 134 horizontal **iron plates** of 1.0 cm thickness, and layers of plastic **streamer tubes** 3.5 m long and of (9 x 9) mm^2 cross-section.
The total active mass is **150 ton**.

- From **740 ton・yr** of exposure, **data agree with Monte Carlo expectation**.

μ	data	32
	expected	36.8



e	data	18
	expected	20.5



$$R=(\mu_{data}/\mu_{MC})/(e_{data}/e_{MC}) = 0.96^{+0.32}_{-0.28}$$

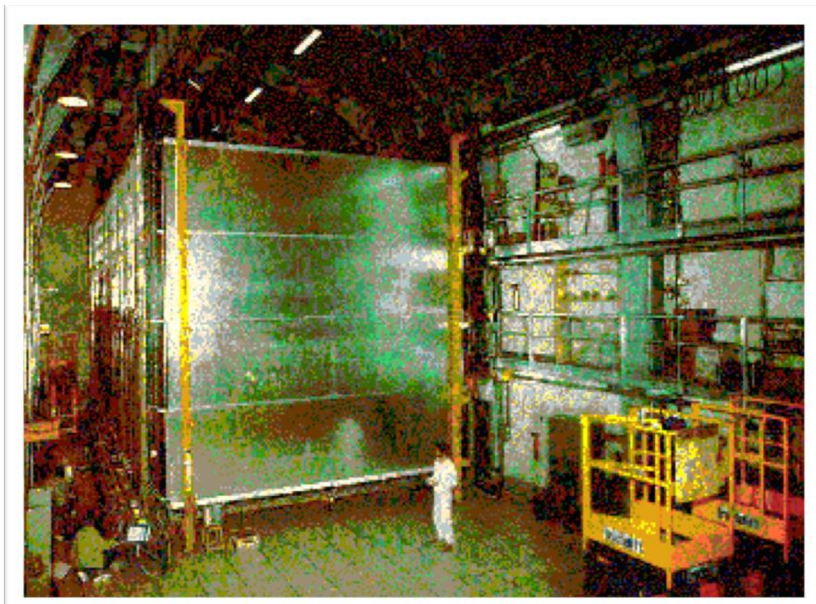
M. Aglietta et al., Europhys. Lett. 8 (7), 611 (1989)

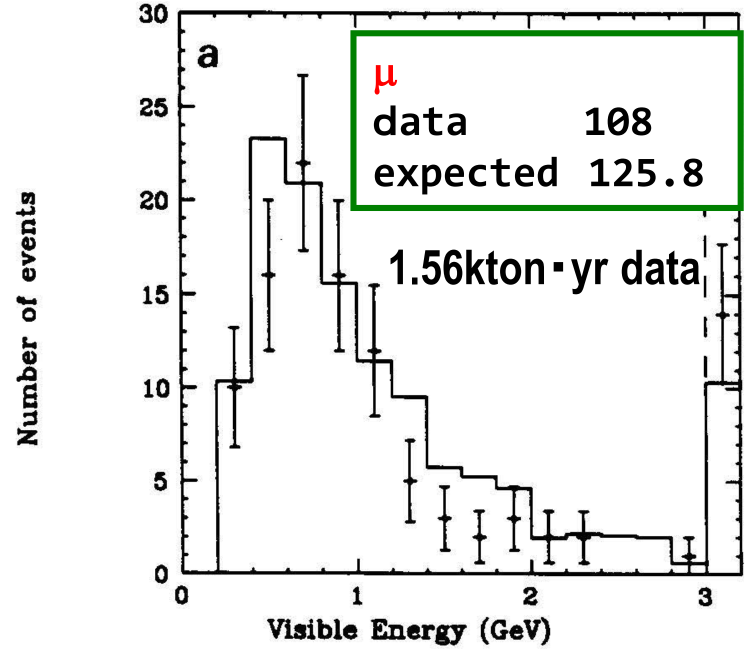
Frejus experiment (1984-1988)

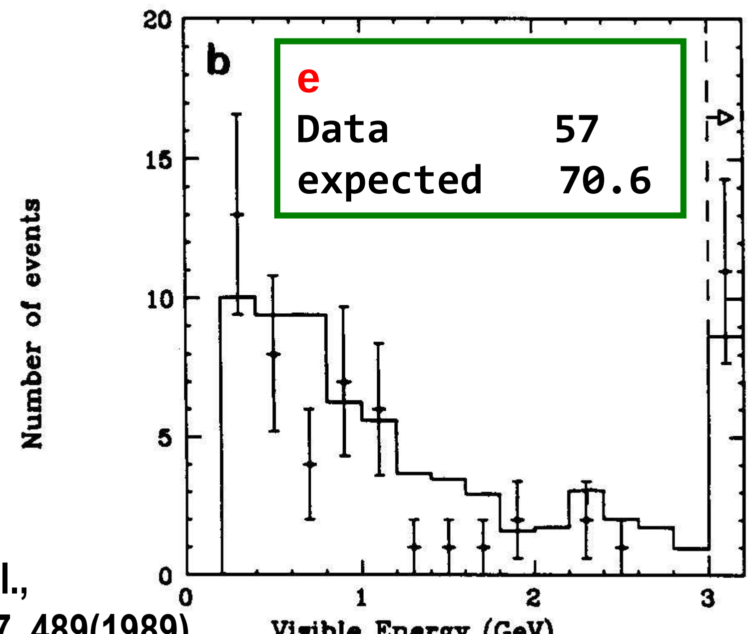
- The Frejus detector is located in the Frejus highway tunnel connecting France and Italy. The rock coverage is 1780m.

- It consists of 912 flash chamber planes and 113 Geiger tube planes. A flash chamber plane is made of a sandwich of 3 mm thick iron plates and 5 mm thick plane of plastic flash tubes. The fiducial mass is 554 tons.

- “Good agreement is obtained between the data and the simulation within statistics.”







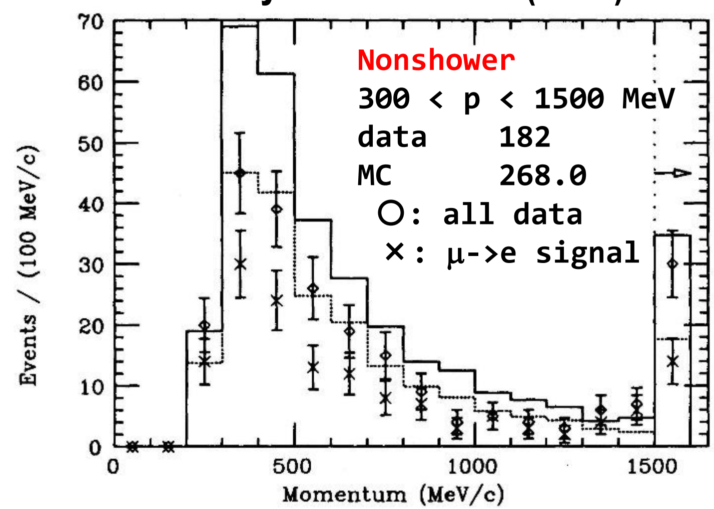
Ch. Berger et al.,
Phys. Lett B227, 489(1989)

IMB-3 experiment

- Data from 851 days of IMB-3 experiment are analyzed.
  A total of 935 contained atmospheric neutrino events are accumulated from 7.7 kton·yr of exposure.

R.Becker-Szendy, et al
PhysRevD.46.3720(1992)

	data	Monte Carlo
Nonshowering (ν_μ-like single ring)	182	268.0
Showering (ν_e-like single ring)	352	257.3

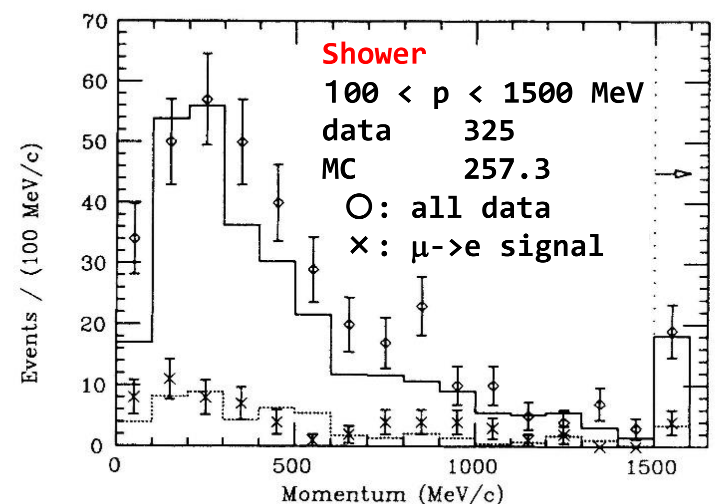


- The fraction of nonshowering events is

  Data: $0.36 \pm 0.02(\text{stat}) \pm 0.02(\text{syst})$
  MC: $0.51 \pm 0.01(\text{stat}) \pm 0.05(\text{syst})$

  The discrepancy is 2.6σ.

- Alternative analysis employing μ->e decay signal also shows a similar discrepancy.

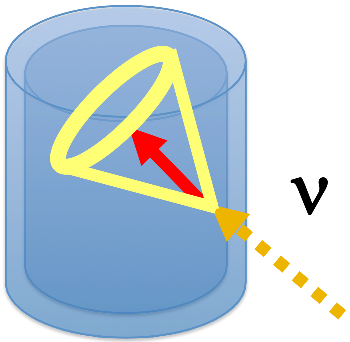


"Atmospheric ν_μ/ν_e ratio in the multi-GeV energy range"

The third Kamiokande paper : **K.S.Hirata et al., Phys. Lett. B335, 237(1994)**

- **Atmospheric neutrino analysis was extended to higher (multi-GeV) energy range. In addition to fully contained events with E_{vis} > 1.33 GeV, partially contained events are included.**
  Analysis for the sub-GeV neutrinos was also updated.

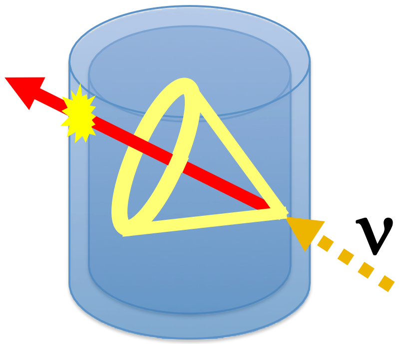
			data	M.C.
Sub-GeV (7.7 kt·yr, 690 events)		e-like	248	227.6
		μ-like	234	356.8
Multi-GeV	Fully-contained (8.2 kt·yr,195 events)	e-like	98	66.5
		μ-like	31	37.8
	Partially-contained (6.0 kt·yr,118 events)	e-like	---	-----
		μ-like	104	124.4



- **In the multi-GeV energy range,**

$$R=(\mu/e)_{data}/(\mu/e)_{MC} = 0.57\ ^{+0.08}_{-0.07}\ (stat.) \pm 0.07(syst.)$$

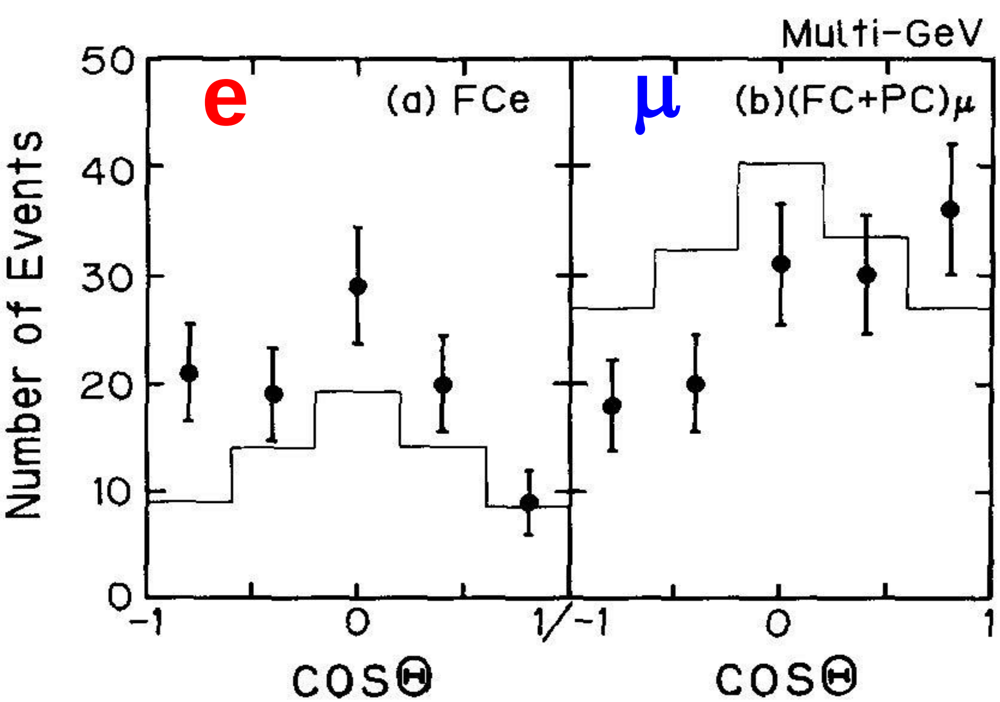
The result shows a small ν_μ/ν_e ratio, and is consistent with sub-GeV energy range.

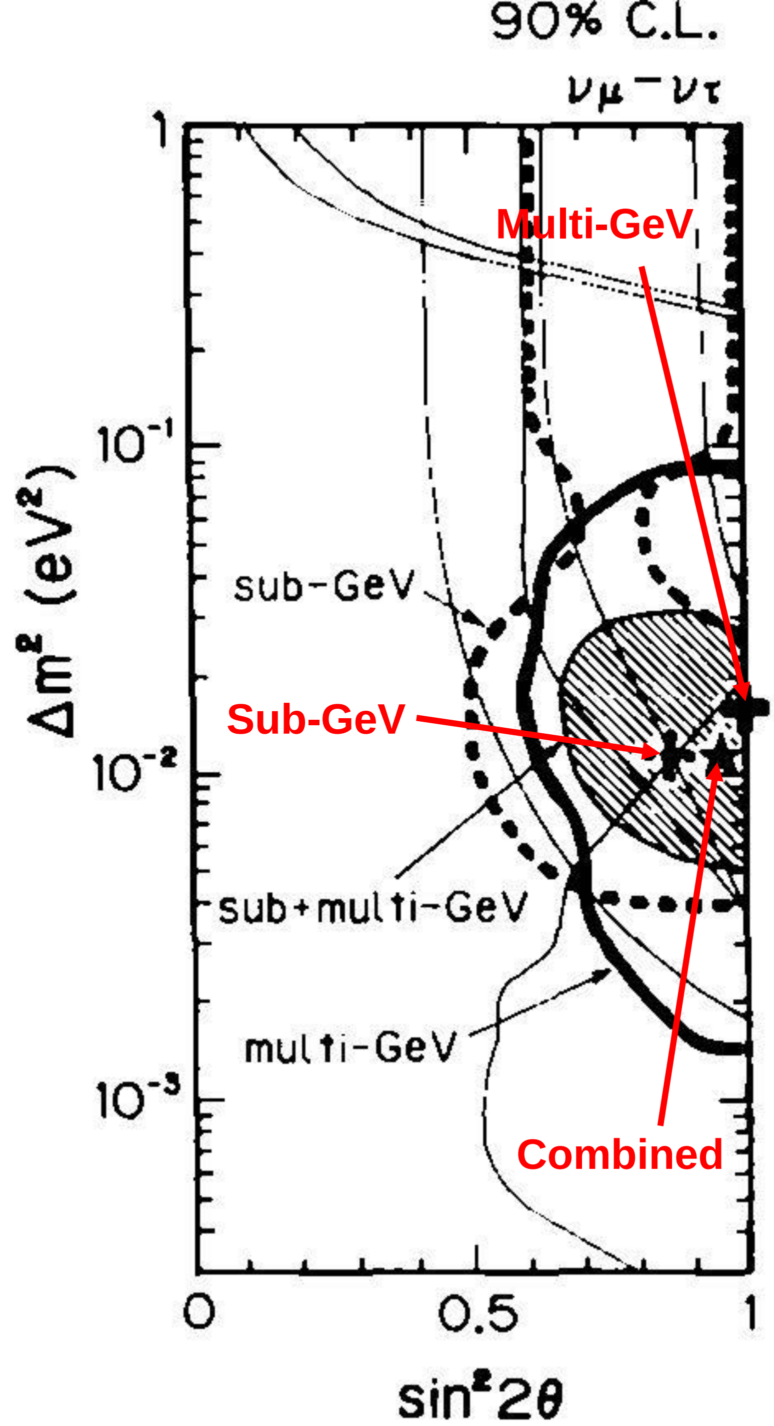


"Atmospheric …… multi-GeV energy range"(continued)

- **Zenith angle distribution of multi-GeV muon neutrino events shows clear up/down asymmetry.**

- **Sub-GeV and Multi-GeV results are consistent with each other.**
  Strict constraints for oscillation parameters are obtained.





Atmospheric neutrino oscillation in early 1990s

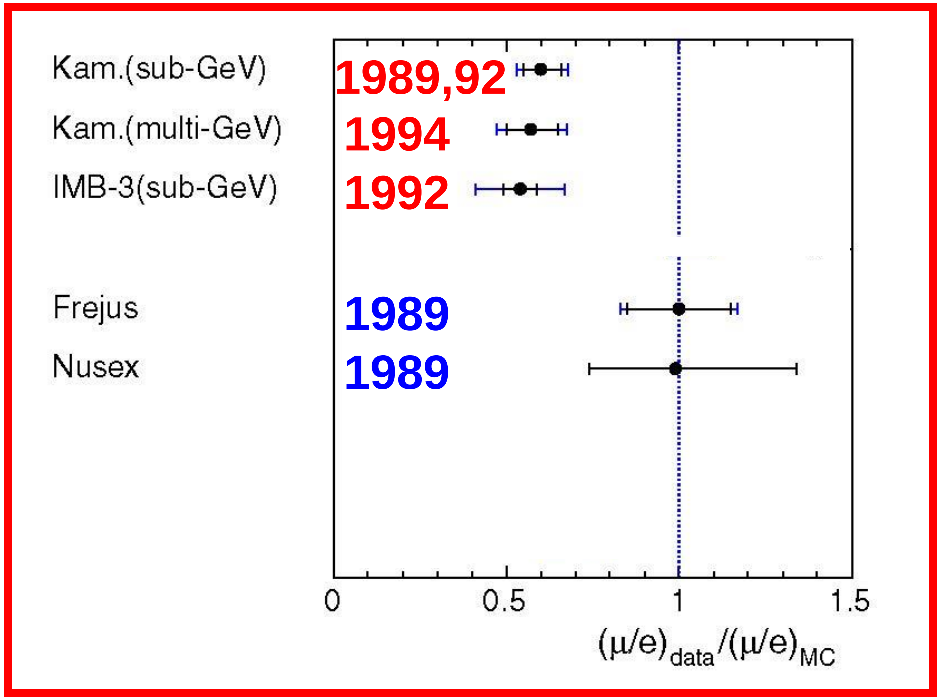
- In the first result, the statistics was poor, and the up/down asymmetry was not clear. The straightforward impression was "Number of muon neutrino events is slightly small..."

- Some of the experiment reported negative results. Kamiokande results are not widely believed.

- To claim "Neutrino Oscillation" was big and risky challenge. If it is not true, all Kamiokande members will loose their confidence as high energy physicists. We hesitated to use word "neutrino oscillations". We frequently used "muon neutrino deficit" or "atmospheric neutrino anomaly", instead.

From a review article "Atmospheric Neutrinos" by T. Kajita New Journal of Physics 6, 194(2004)

Water Cherenkov
Tracker



Atmospheric neutrinos really oscillate??

- **An episode around 1992 in Kamioka. Conversation between Prof. Y. Totsuka and myself when drinking.**

Stressful working days in Kamioka mine. Conversations occasionally become radical when drinking.

drunken font

Y.O Totsuka-sensei, please tell me honestly !
Do you really believe atmospheric neutrino oscillation ?

Y.T Um.............., probably, it is not true. It might be our mistake.

Next morning

Y.T. Please do not spread what I said yesterday night.
Make sure that it is a secret!

hangover font

- **Around 1992, even the spokesperson could not believe our own result. Why we could not?**

Toward confirmation of ν_μ-ν_τ oscillation

- **To claim neutrino oscillations, there are some problem to be solved.**

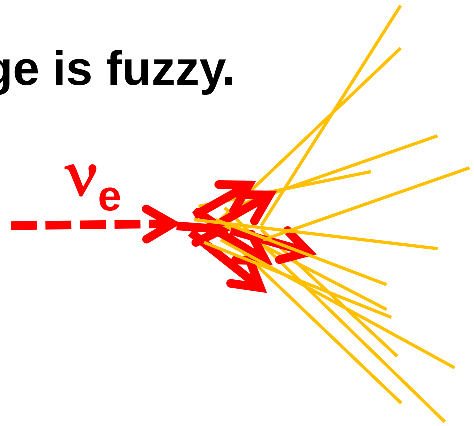
1. **The capability of e/μ particle identification is suspicious.**
2. **Statistics is definitely poor. Much more data is needed.**
3. **Large uncertainty of atmospheric neutrino flux.**
4. **Negative results by other experiments.**

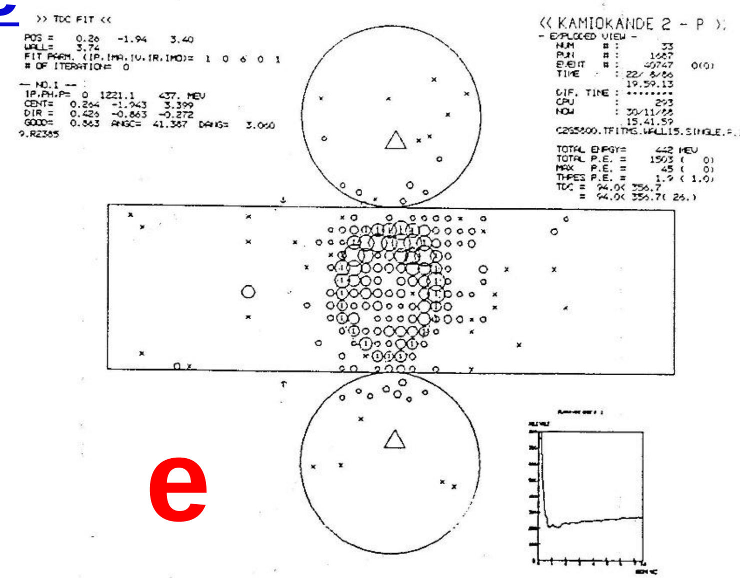
- **First 3 suspicious points should be experimentally examined one by one. Such examinations were started after the observation of muon neutrino deficit in Kamiokande.**
- **For the 4th point, negative results were given by all tracking type detectors. However, it was beyond what we can do.**

e/μ identification in Kamiokande

$\nu_e \rightarrow e$

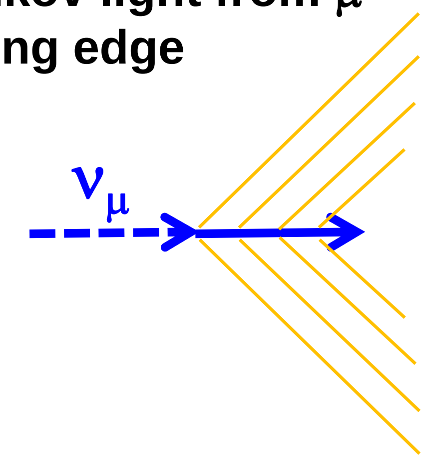
Cherenkov light from electromagnetic shower. Electrons and positrons are heavily scattered.
Cherenkov ring edge is fuzzy.

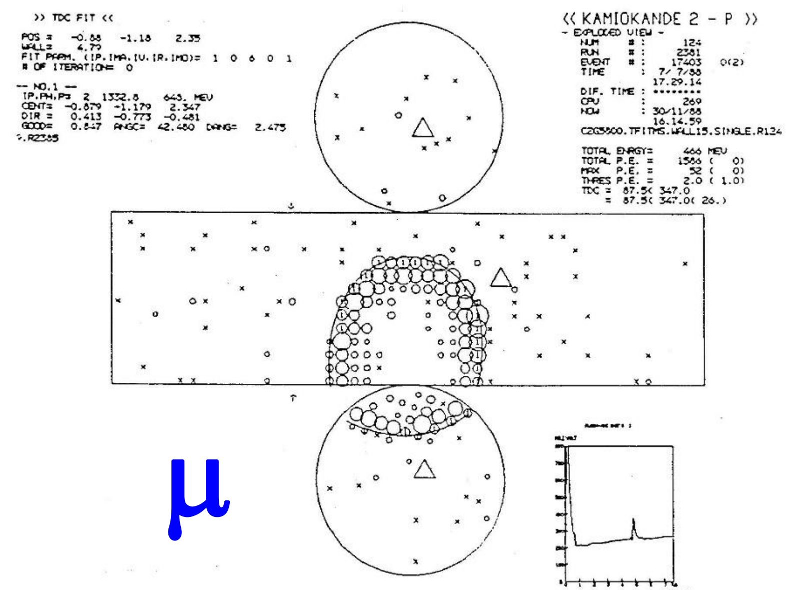




$\nu_\mu \rightarrow \mu$

Only direct Cherenkov light from μ
Clear Cherenkov ring edge





e/μ misidentification probability is less than 1 %.

Beam Test for the e/μ identification

- Only two water Cherenkov detectors, Kamiokande and IMB, claimed atmospheric muon neutrino deficit.
  Tracking type detectors, NUSEX and Frejus, could not find the anomaly.

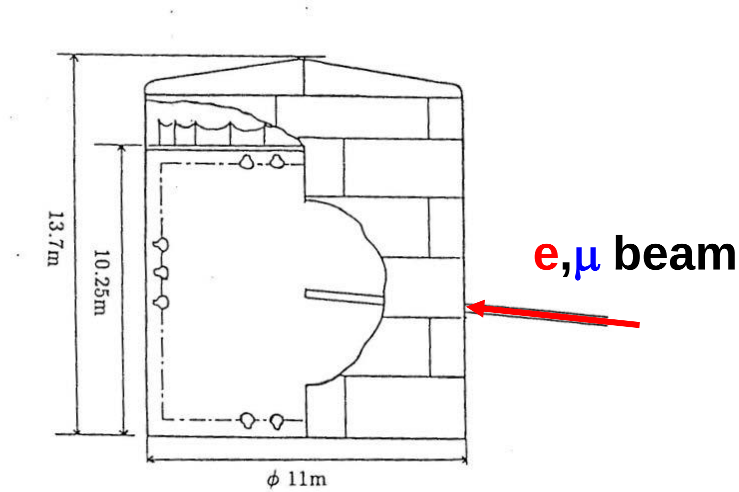
- Is it a problem of water Cherenkov detectors ?
  The e/μ identification of water Cherenkov detector has been examined only by Monte Carlo events.
  The e/μ identification capability are certainly critical issue to be examined.

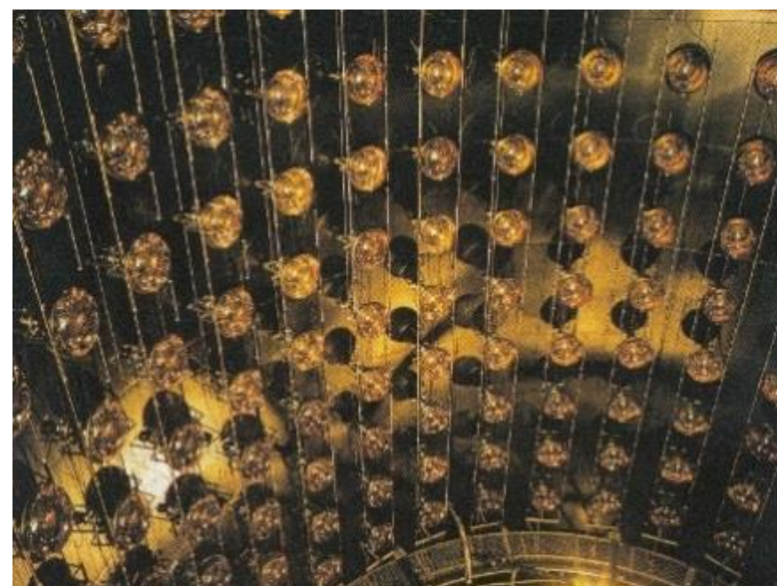
- To verify the particle identification capability, a "beam test" was planned.

→ **E261A experiment**

KEK Proton Synchrotron E261A (1992-1994)

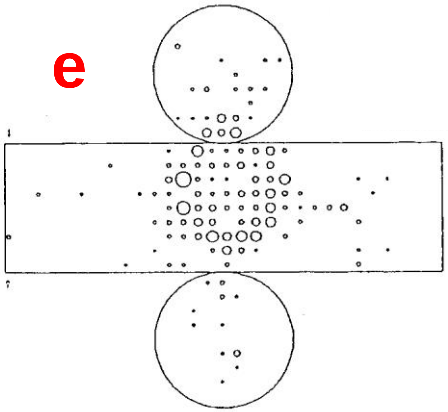
- **1kt water Cherenkov detector was built in KEK North counter hall. Electrons and muons from 12 GeV proton Synchrotron were injected.**

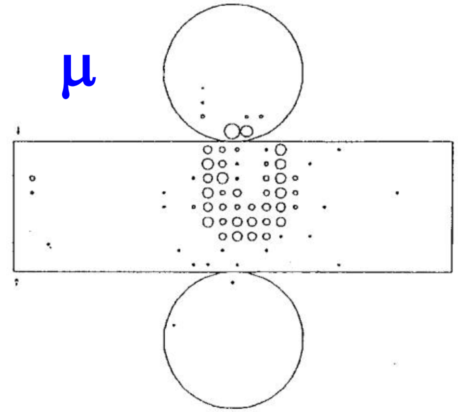




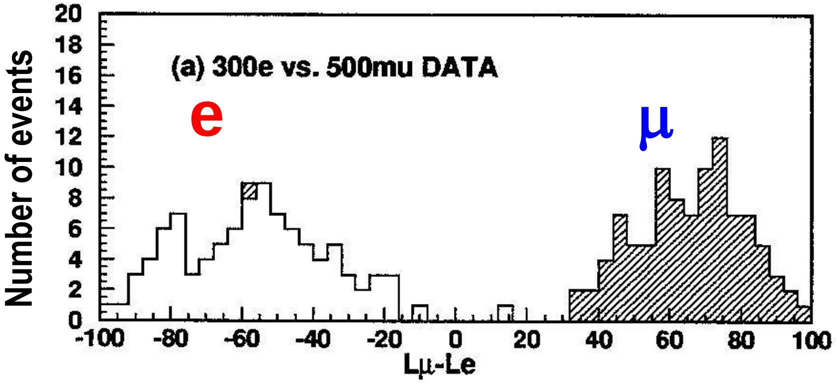
Beam test for the particle identification

- Fuzzy edge for e event and clear edge for μ event are confirmed.

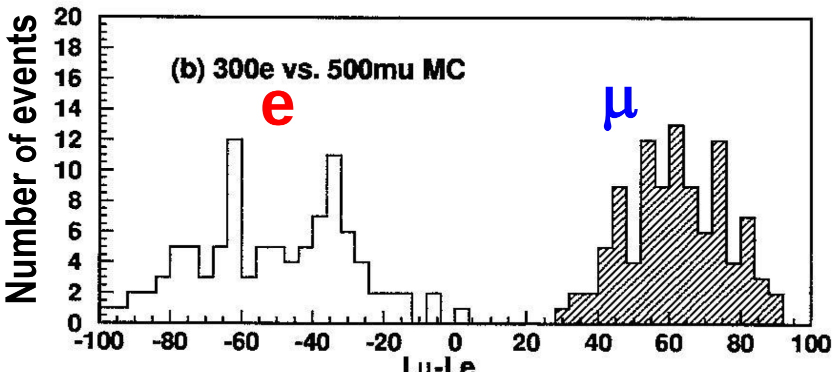




- e-likelihood (L_e) and μ-likelihood (L_μ) are calculated. From a comparison between L_e and L_μ, particle id are judged.



- The algorithm clearly separate e beam events and μ beam events.

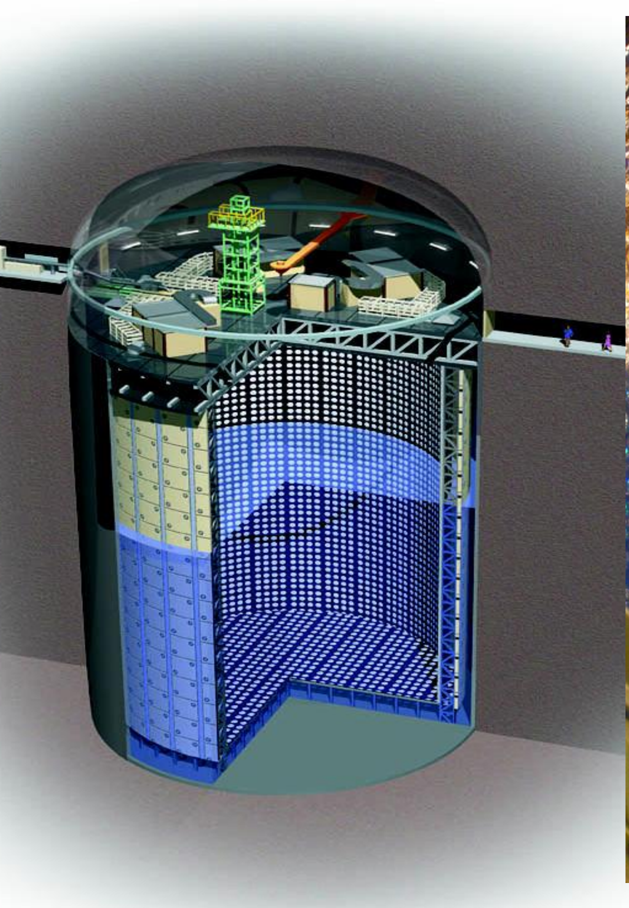


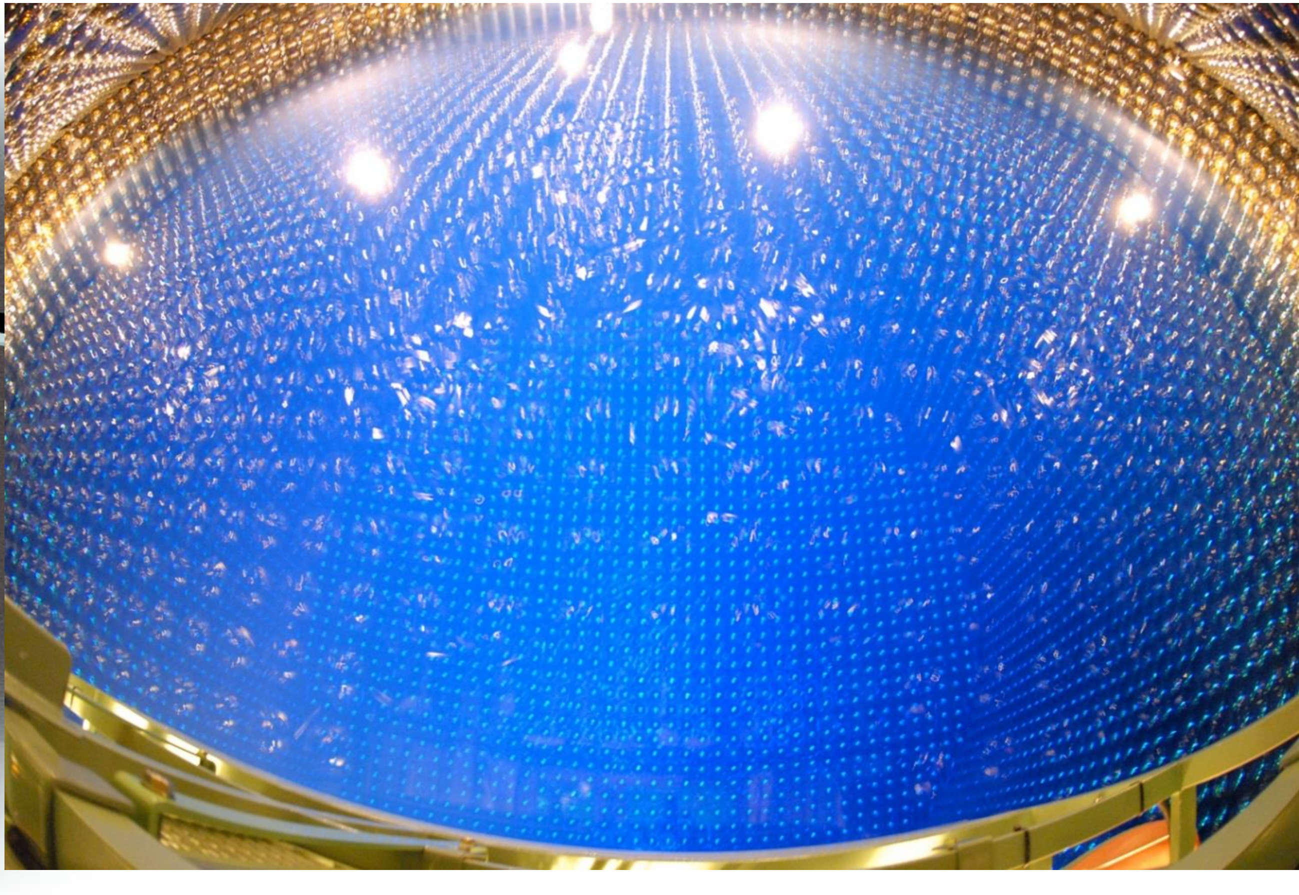
- It was experimentally verified that the e/μ identification capability is better than 99%.

S.Kasuga et al., Phys. Lett. B374,238(1996)

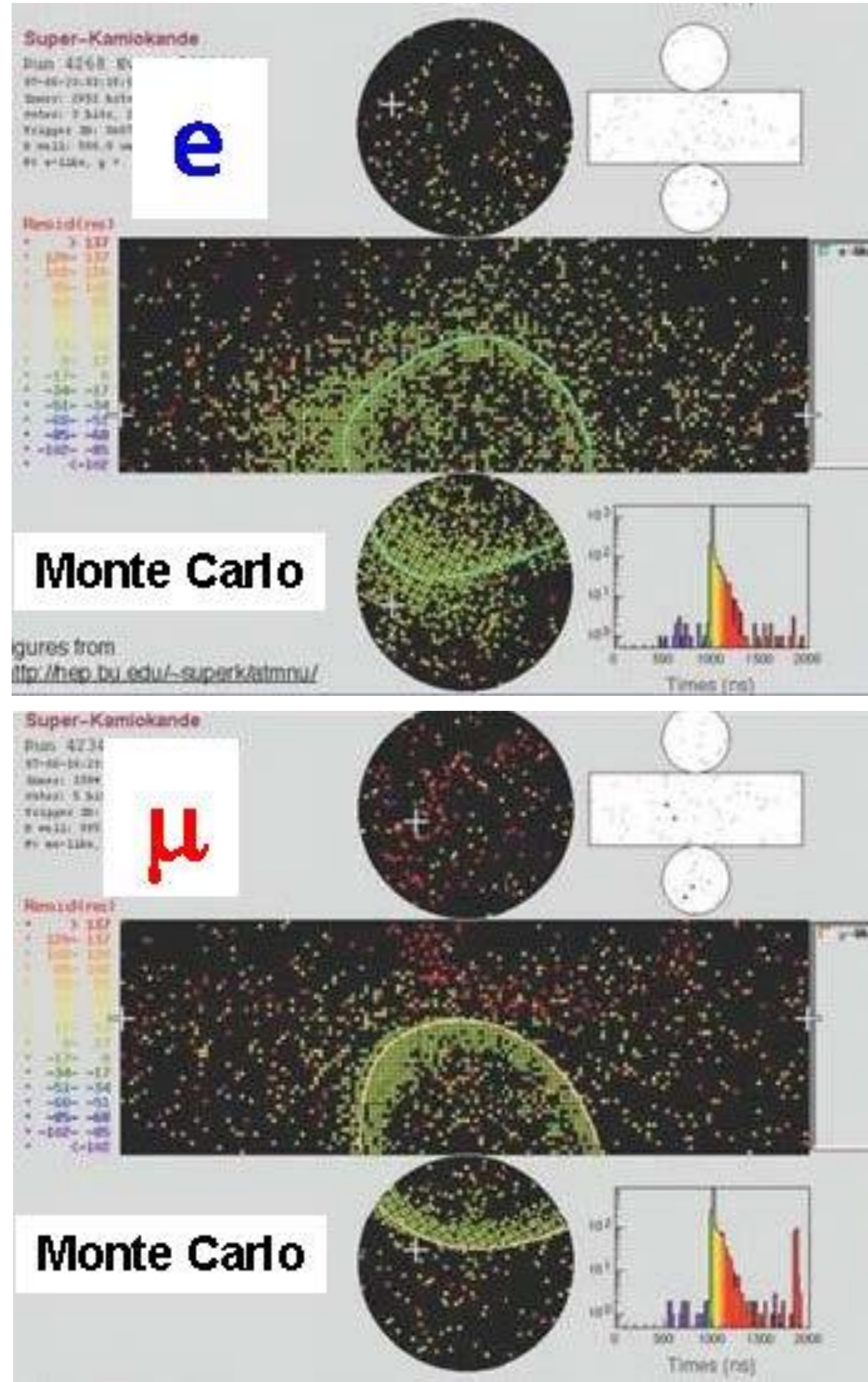
Super-Kamiokande (1996 -)

- **50 kt water Cherenkov detector with 11146 20-inch Φ PMTs. The fiducial volume is 22.5 kt.**
- **Located at 1000 m underground in Kamioka mine, Japan**
- **Operation since April 1996.**



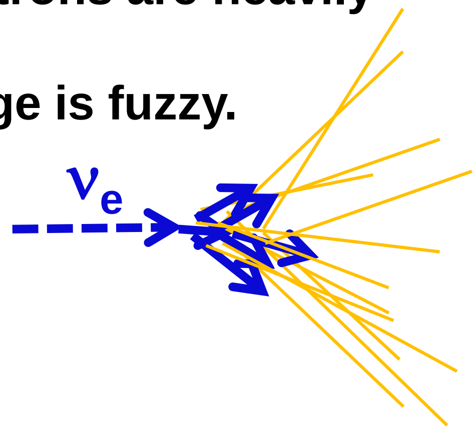


e/μ identification in Super-Kamiokande



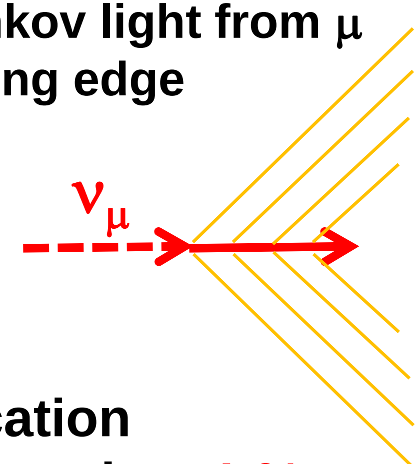
$\nu_e \rightarrow e$

Cherenkov light from e-m shower.
Electrons and positrons are heavily scattered.
Cherenkov ring edge is fuzzy.



$\nu_\mu \rightarrow \mu$

Only direct Cherenkov light from μ
Clear Cherenkov ring edge



- e/μ misidentification probability is less than 1 %.

Improvements of atmospheric neutrino analysis

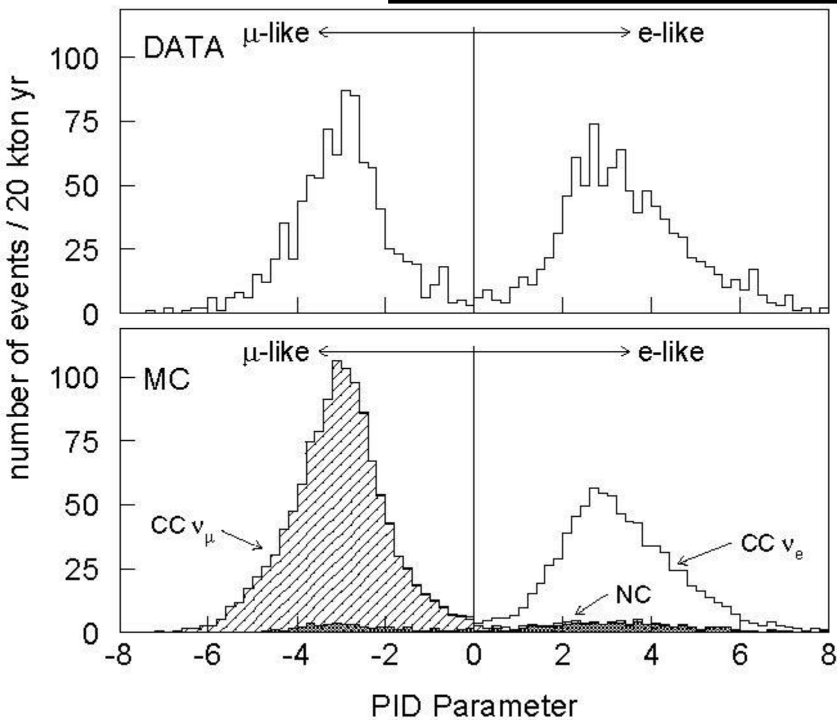
In Kamiokande

- **Event reconstructions were based on visual scan. The visual scan might be a cause of biases in the analysis.**
- **I was a poor scanner and the results of the reconstruction were different from other scanners.** **Kajita-san told me "You're fired!"**

In Super-Kamiokande

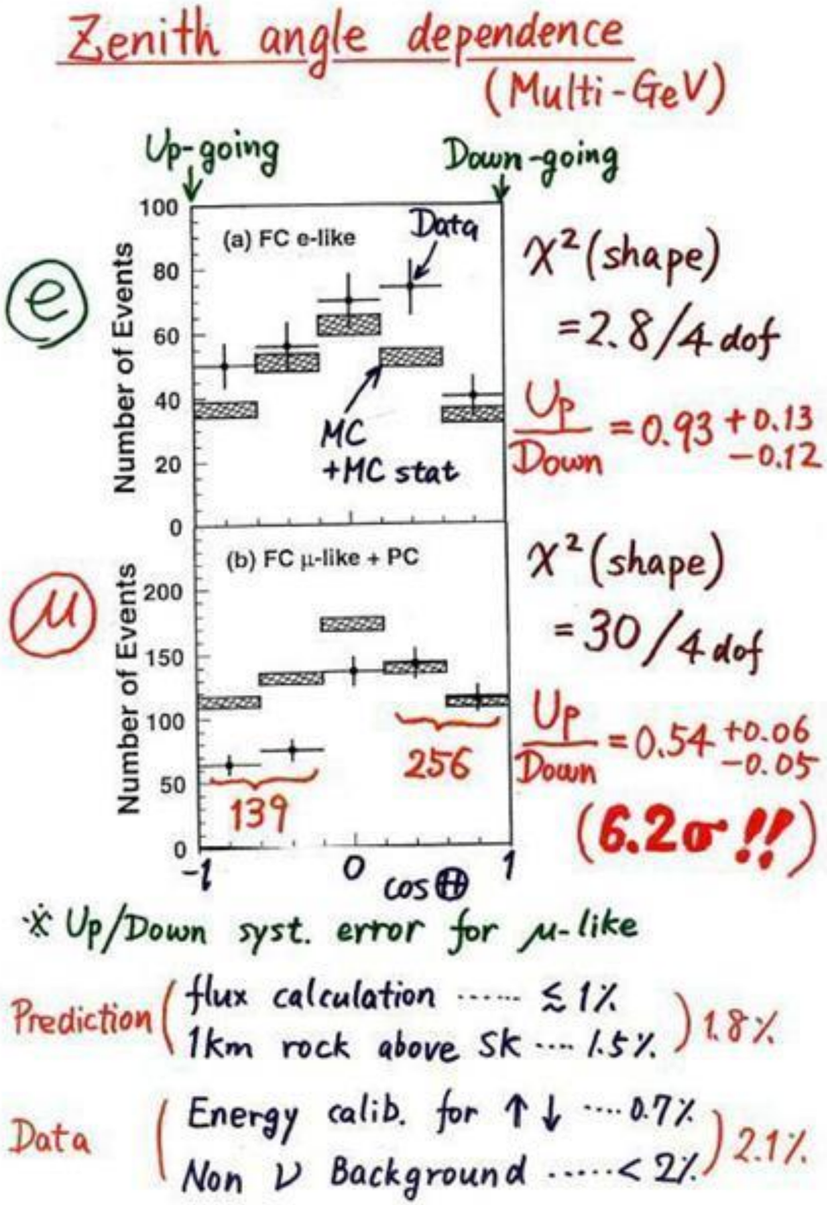
- **Number of events is much larger than Kamiokande. Visual scan was impossible any more.**
- **Automatic analysis tools were developed. They are;**
  1)Automatic vertex reconstruction
  2)Automatic ring counting
  3)Ring separation
  4)Determination of particle direction
- **Particle identification program were applied to the result of automatic reconstruction.**

Y.Fukuda et al.,
Phys. Lett. B433, 9 (1998)



Discovery of atmospheric neutrino oscillation in Super-Kamiokande

- At NEUTRINO 1998 Conference in Takayama, discovery of ν_μ-ν_τ oscillation was reported by Prof. T. Kajita, on behalf of Super-Kamiokande collaboration.

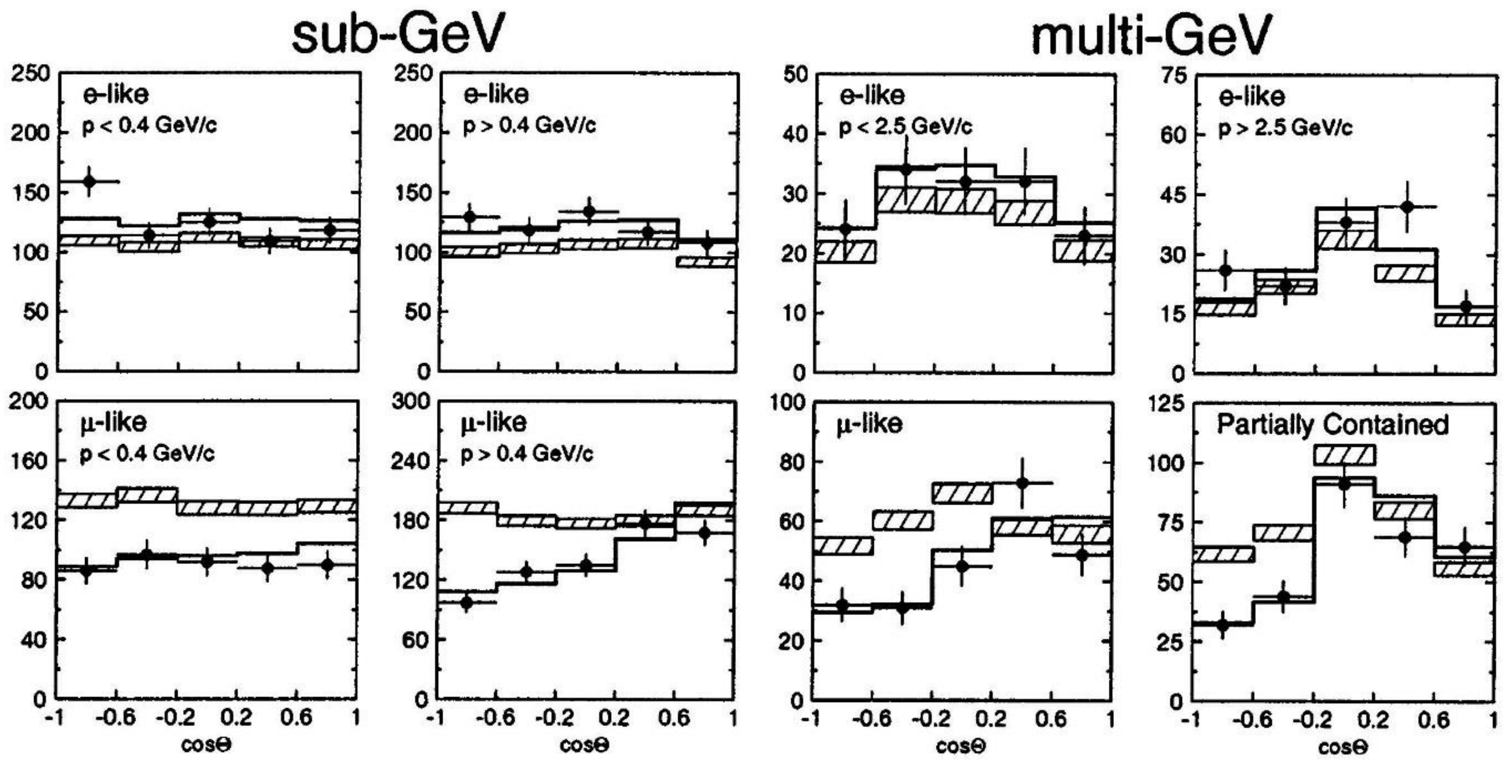


"Evidence for Oscillation of Atmospheric Neutrinos"

Y. Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998)

- **Immediately after NEUTRINO 1998, the results are published. A total of 4654 atmospheric neutrino events are employed which are accumulated in 535 days, corresponding to 33.0 kt・yr.**

- **Number of electron neutrinos well agrees with expectation, but number of muon neutrinos is clearly smaller than the expectation. Significant zenith angle distributions are also found.**



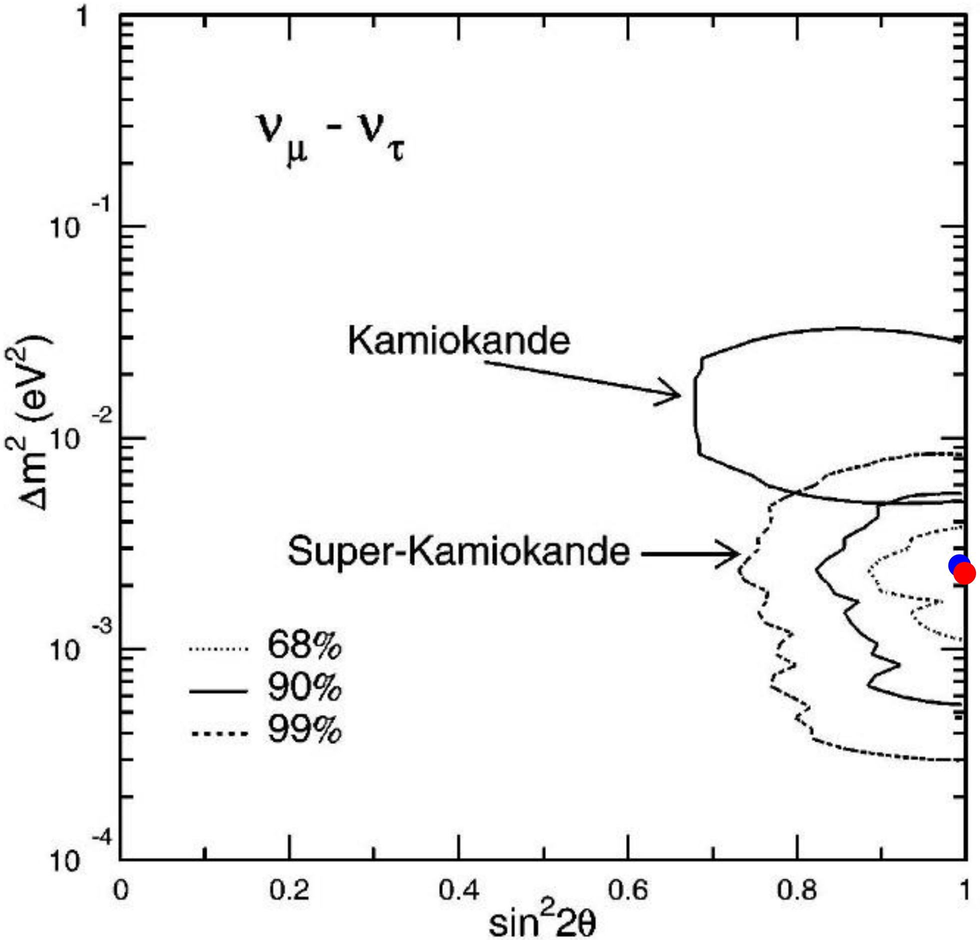
“Evidence for Oscillation of Atmospheric Neutrinos”

- The data are consistent with two-flavor ν_μ- ν_τ oscillations with

  $\sin^2 2\theta > 0.82$
  and
  $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ eV^2

  at 90% confidence level.

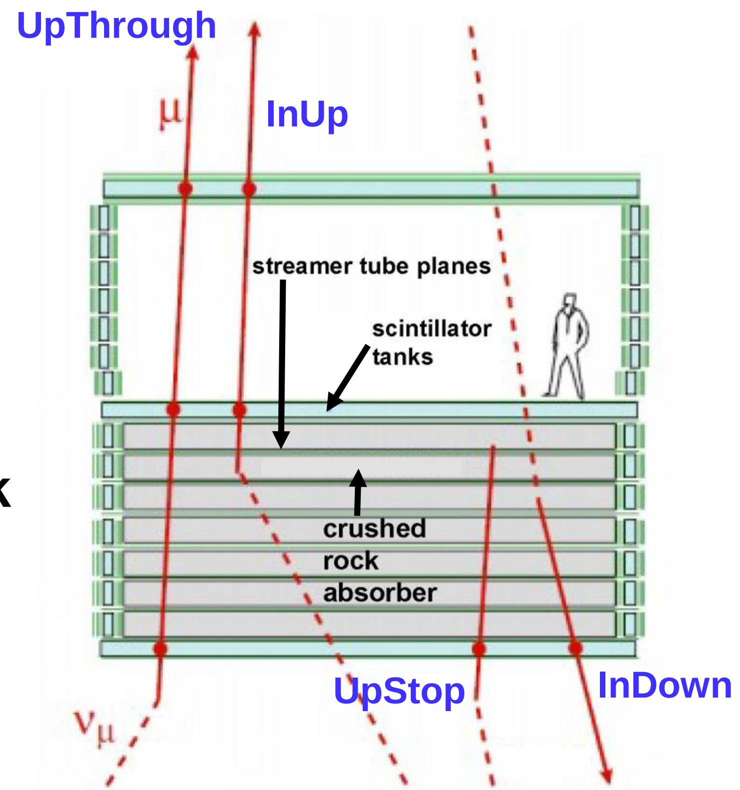
- The best fit parameters are
  $\Delta m^2 = 2.2 \times 10^{-3}$eV^2
  $\sin^2 2\theta = 1.0$.
  It agree with the numbers in PDG2017(NH),
  $\Delta m^2 = 2.45 \times 10^{-3}$eV^2
  $\sin^2\theta = 0.51$.



The results are inconsistent with the Kamiokande data. Do not ask me why. Ask Kajita-san !

- 17 years later, this paper became a “Nobel Prize paper”.

MACRO experiment (1989-2000)



- The MACRO detector is a large rectangular box of 76.6 m x 12 m x 9.3 m. It was located at 3150 m.w.e. underground in Gran Sasso Laboratory, Italy.

- The experiment is optimized for muon track measurement.

- Streamer tubes provides track information of the muons with angular resolution between 0.2^{o} and 1^{o}, depending on the track length.

- Liquid scintillator planes records arrival time of particles. The nominal time resolution is 500 ps.
  The time difference between two separate planes provides the travel direction of muons.

MACRO results

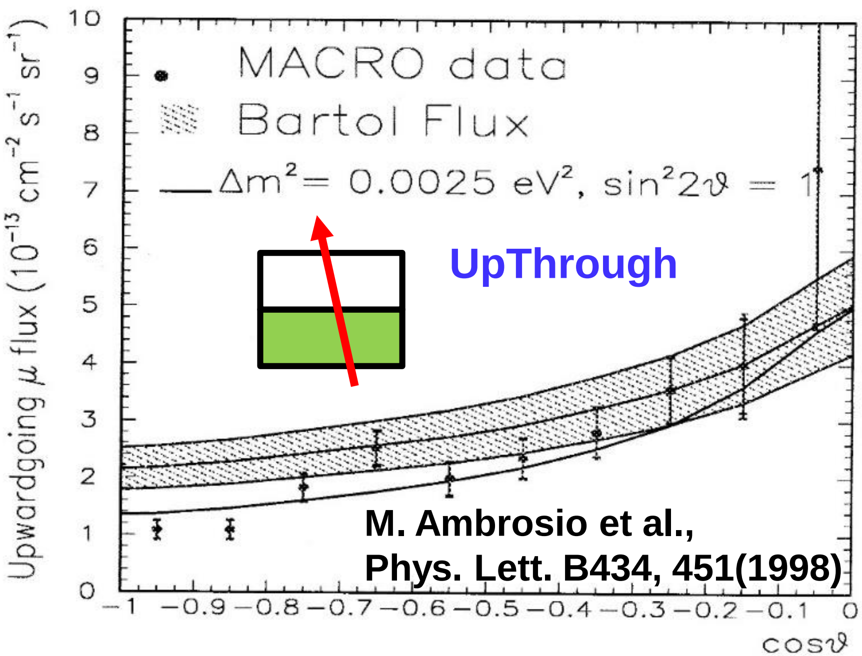
- The muon neutrino deficit was reported in 1998. From 1989 to 1997, 451 UpThough events were found where MC expectation was 612.

- $R = (\mu)_{data}/(\mu)_{MC}$ was calculated to be

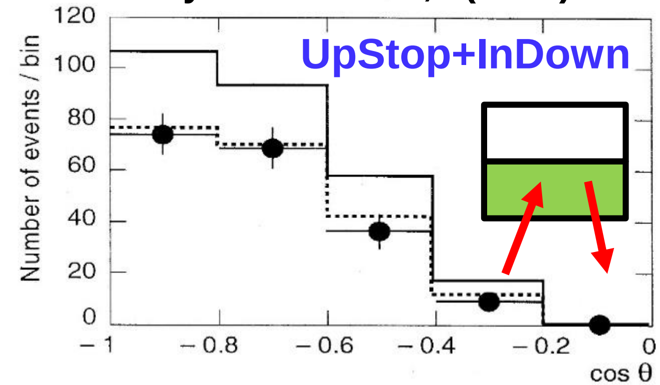
$$R = 0.74 \pm 0.036(\text{stat.}) \pm 0.046(\text{syst.}) \pm 0.13(\text{theor.})$$

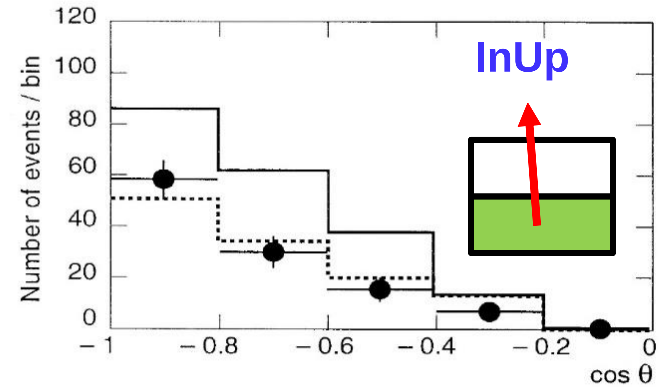
"The observed zenith distribution for $-1.0 \leqq \cos\theta \leqq -0.1$ does not fit well with the no oscillation expectation,"

- In 2000, observation of muon neutrino deficit in UpStop+InDown and InUP events followed.



M. Ambrosio et al.,
Phys. Lett. B478, 5(2000)





Soudan-2 experiment (1989-2001)

- Fine-grained iron tracking calorimeter with a honeycomb geometry. The fiducial mass was 770 ton.

- The detector was located at a depth of 2070 m.w.e underground in Soudan mine, Minnesota.

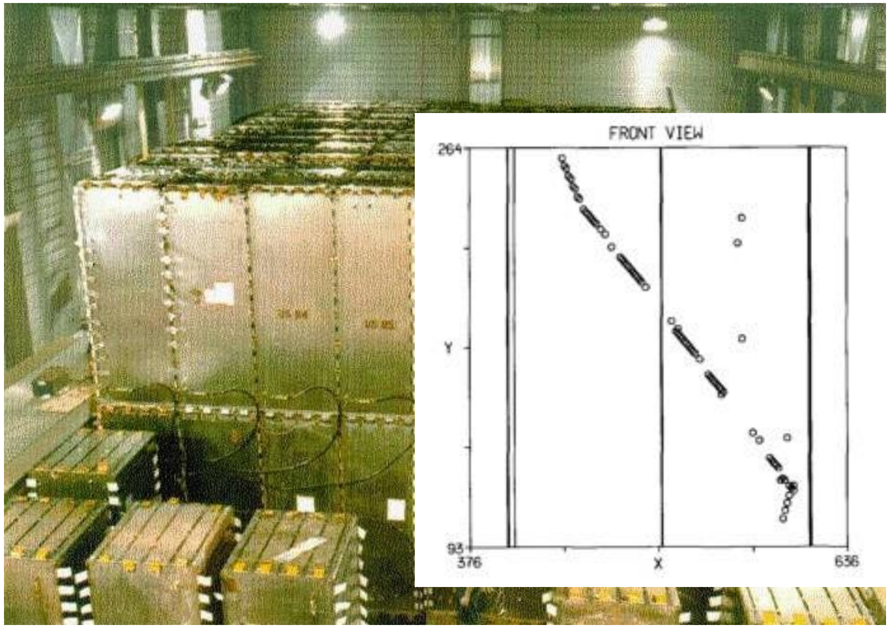
- $R=(\mu/e)_{data}/(\mu/e)_{MC}$ were;

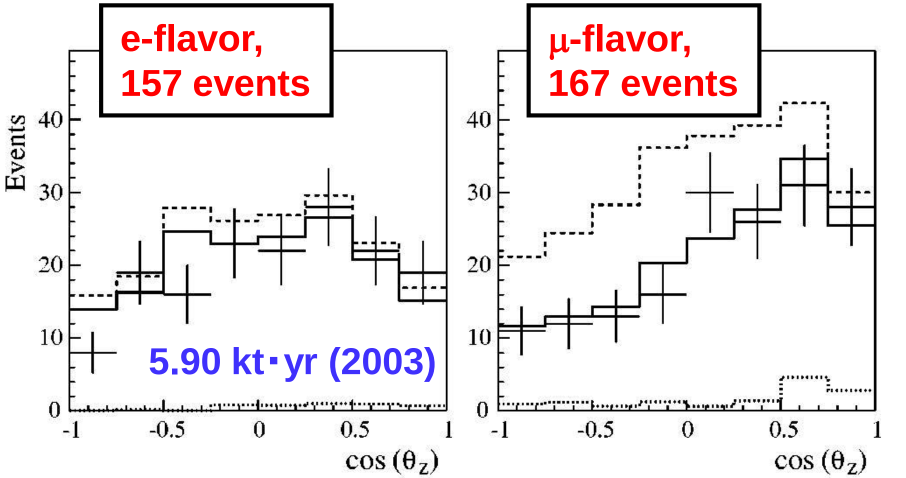
$R = 0.72 \pm 0.19(stat.)^{+0.05}_{-0.07}(syst.)$
1.52 kt･yr (1997)

$R = 0.64 \pm 0.11(stat.) \pm 0.06(syst.)$
3.9 kt･yr (1999)

$R = 0.69 \pm 0.10(stat.) \pm 0.06(syst.)$
5.90 kt･yr (2003)

- The muon neutrino deficit was confirmed in the 1999 paper.





W.W.M.Allison et al., Phys. Lett. B391,491(1997)
W.W.M.Allison et al., Phys. Lett. B449,137(1999)
M.Sanchez et al., Phys. Rev. D 68, 113004 (2003)

Toward confirmation of ν_μ-ν_τ oscillation (~1999)

In early 1990s

1. ~~The capability of e/μ particle identification is suspicious.~~
2. ~~Statistics is definitely poor. Much more data is needed.~~
3. Large uncertainty of atmospheric neutrino flux.
4. ~~Negative results by other experiments.~~

- **Particle identification problem was settled by E261A experiment.**
- **Enough statistics of data were accumulated by Super-Kamiokande.**
- **Two tracking type detectors claimed the atmospheric muon neutrino deficit. However, it was just after the observation by Super-Kamiokande. Their statistics were quite poor to claim "neutrino oscillation" by a single experiment.**
- **They completely forgot that claiming neutrino oscillation is quite risky! Their announcement was "Do not miss the bus".**

or, in Japanese famous phrase,

「赤信号みんなで渡れば恐くない!」

"If everyone crosses against the red light, there's nothing to be afraid of."

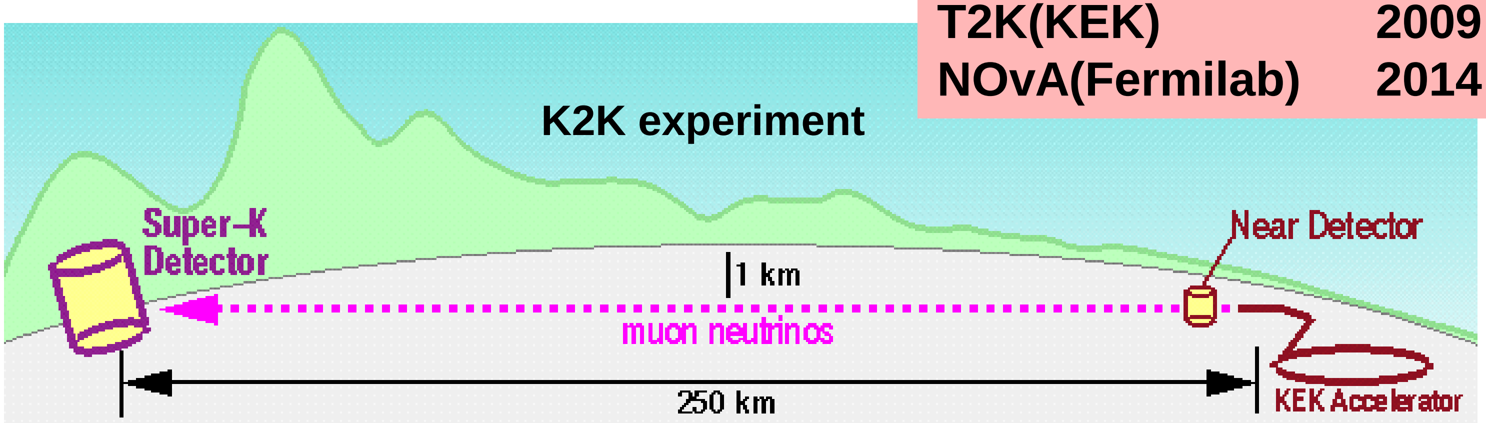
From “atmospheric neutrino” to “neutrino beam”

- **Atmospheric neutrino flux has inevitable large uncertainties.**
- **High energy physicists strongly hope to examine neutrino oscillations using neutrino beam. Artificial neutrino beam can be controlled and the neutrino flux can be measured by physicist directly.**

Long-baseline Neutrino-oscillation experiments

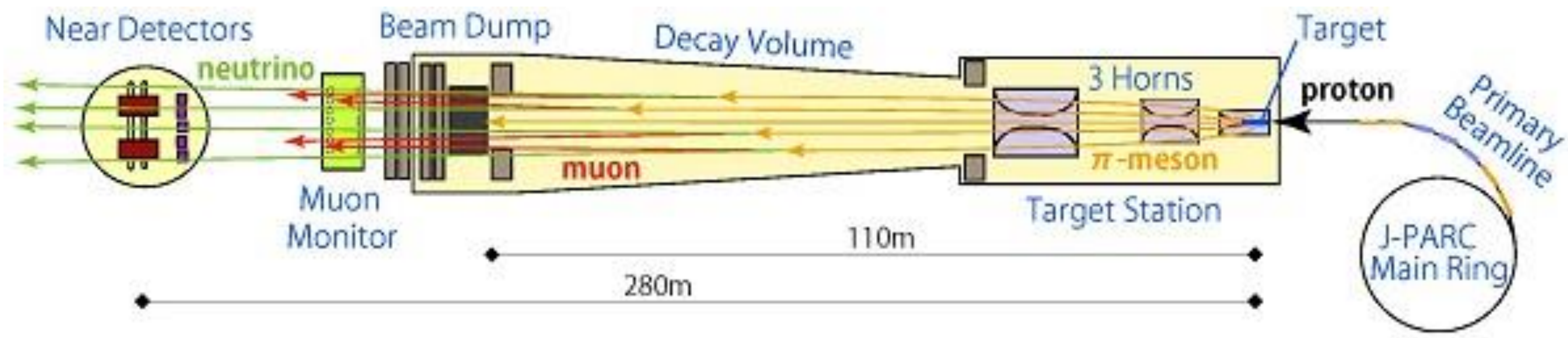
- **The first experiment was K2K (KEK to Kamioka) experiment started in 1999.**

K2K (KEK)	1999 - 2004
MINOS(Fermilab)	2005 -
T2K(KEK)	2009 -
NOvA(Fermilab)	2014 -



- **20th century was an epoch of natural neutrino experiments.**
  atmospheric neutrino, solar neutrino, supernova neutrino
  21st century is an epoch of artificial neutrino experiments.
  neutrino beam, reactor neutrino

Atmospheric neutrino(AN) vs Neutrino beam(NB)(1)



① **Calculation of neutrino flux**

(AN) Flux of primary proton beam has large uncertainty. Geomagnetic field and atmospheric temperature should be also taken into account.

(NB) Primary proton beam is well controlled, and has fixed energy and direction. Geometry of the beam line including target, magnetic horn, decay volume, beam dump are completely known.

② **Near detector**

(AN) We cannot make near detectors.

(NB) We can construct near detector at hundreds meters downstream of the target. We can accurately measure energy spectrum and components of the neutrino beam just after the neutrino production.

Atmospheric neutrino(AN) vs Neutrino beam(NB)(2)

③ Neutrino oscillation probability in event by event basis

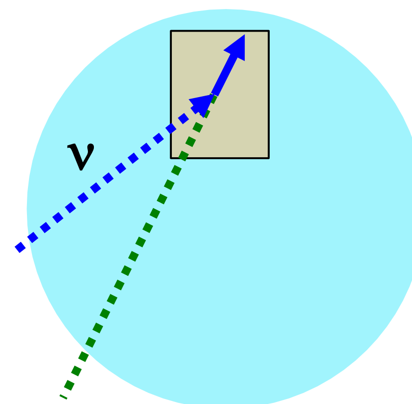
Neutrino oscillation probability is written as

$$P(\nu_\mu\text{->}\nu_x) = \sin^2 2\theta \sin^2(\Delta m^2 L/4E)$$

（L is neutrino travel distance, E is neutrino energy）

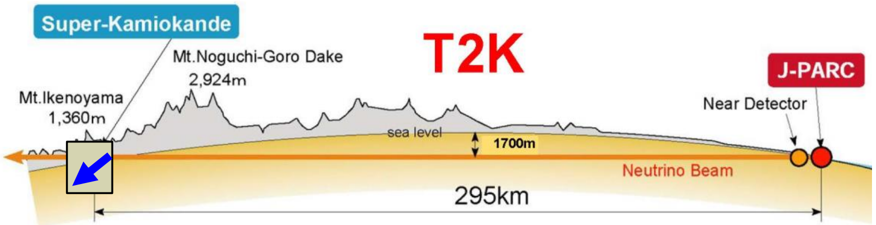
Measurement of neutrino travel distance and neutrino energy is essential

(AN) The true neutrino travel direction in unknown. The travel direction of charged lepton must be used instead. Accordingly, approximate neutrino travel distance must be used. Also neutrino energy must be estimated from muon/electron energy.



(NB) Neutrino travel distance is the distance of the baseline. Unlike atmospheric neutrinos, we have one additional information; scattering angle between the neutrino and the muon. The neutrino energy can be calculated from the muon energy and the opening angle from the neutrino direction.

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu \cos\theta_{\mu\text{-}\nu}}$$



Atmospheric neutrino(AN) vs Neutrino beam(NB)(3)

④ **Neutrino energy spectrum**

(AN) Cannot be changed

(NB) Can be changed. In T2K experiment, peak energy of the neutrino beam is adjusted to the oscillation maximum by **off-axis beam**.

⑤ ν_e/ν_μ **ratio**

(AN) ~1/2

(NB) order of ~1/100

④,⑤,⑥ are important features of the T2K experiment and will be discussed later.

⑥ **Neutrino beam and antineutrino beam**

(AN) Cannot be changed

(NB) Can be changed by switching current direction of magnetic horns

Budget and manpower

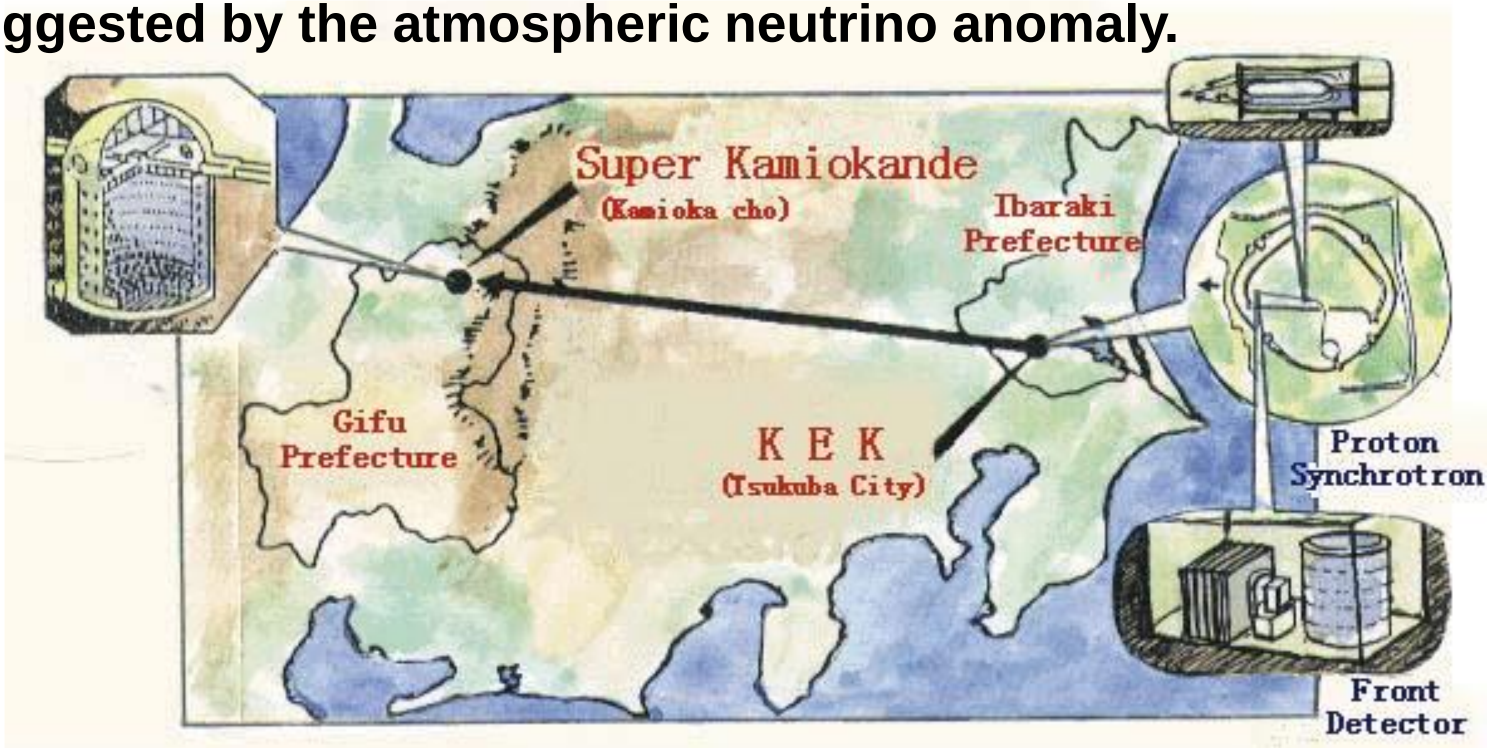
(AN) Free of charge, no manpower

(NB) Huge budget and enormous manpower are required for construction and operation. Stressful daily life of physicists.

**From scientific point of view, neutrino beam has many advantages.
However, neutrino oscillation was discovered with atmospheric neutrinos.
The winner in the history is atmospheric neutrinos.**

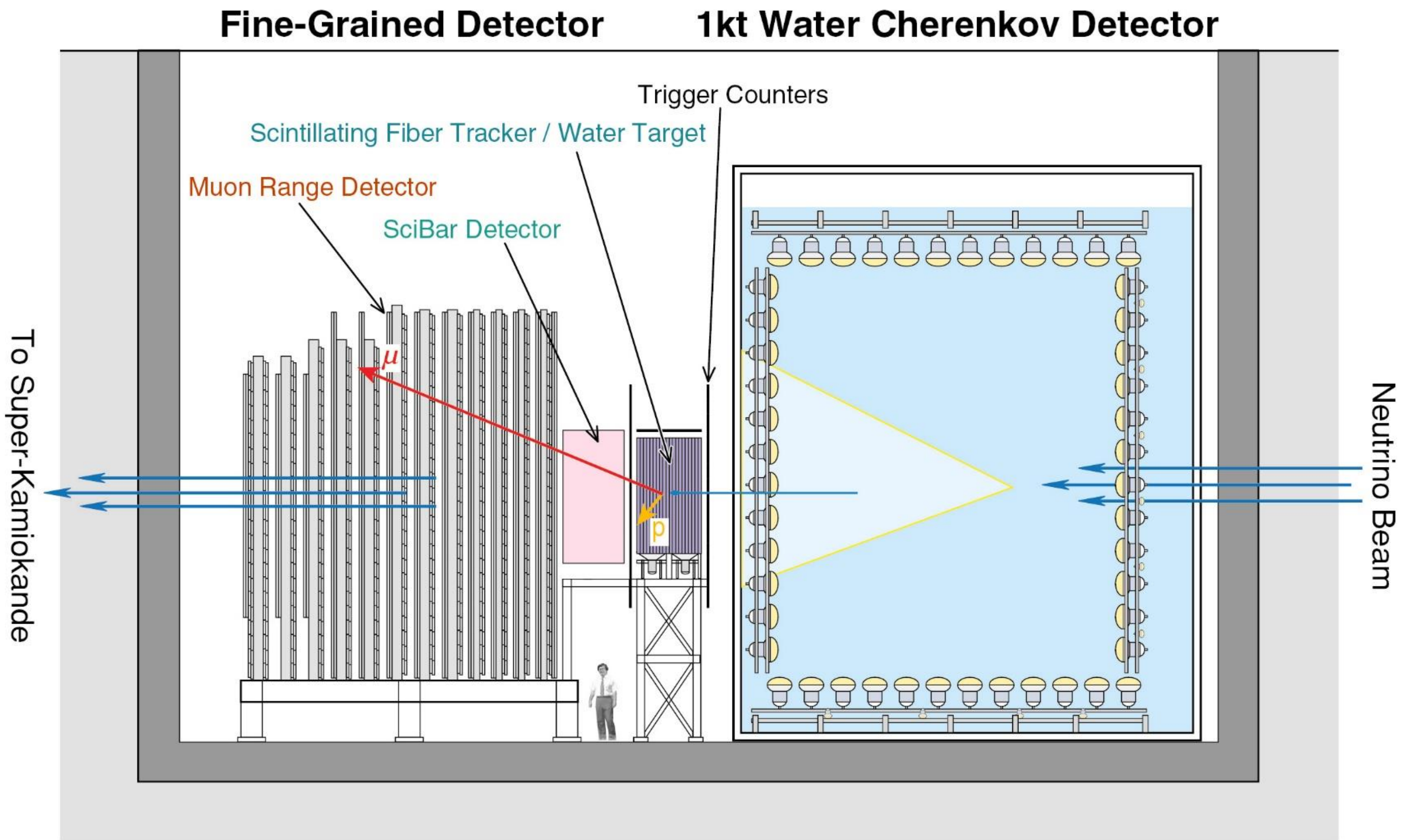
K2K experiment

- **First long-baseline neutrino oscillation experiment (1999-2004)**
- **Confirmation of ν_μ-ν_τ oscillation reported by Super-Kamiokande using artificial neutrino beam.**
- **Muon neutrino beam generated at KEK is shot toward the Super-Kamiokande detector, which is 250km away from KEK**
- **Search for neutrino oscillations in the parameter region $\Delta m^2_{32} > 2\times 10^{-3}$ eV^2 is possible. It covers the parameter regions suggested by the atmospheric neutrino anomaly.**




K2K neutrino beamline in KEK
TRISTAN RING
(B-factory)
12GeV PS
Primary Beam-line
P
12GeV/c proton beam
1.1μsec beam duration
2.2sec accelerator cycle
Al Target
Intensity 5~6x10^12 ppp
Total ~10^20 p.o.t.
Decay Volume
(200m)
π+ -> μ+ + νμ
Muon Pit
Near Detectors
νμ
To Kamioka

K2K Near Detectors at 300m from the target



(a)1kt water Cherenkov detector (1kt)

An 1/50 miniature of SK detector. Direct comparison with SK data

(b)Fine-Grained Detector (FGD)

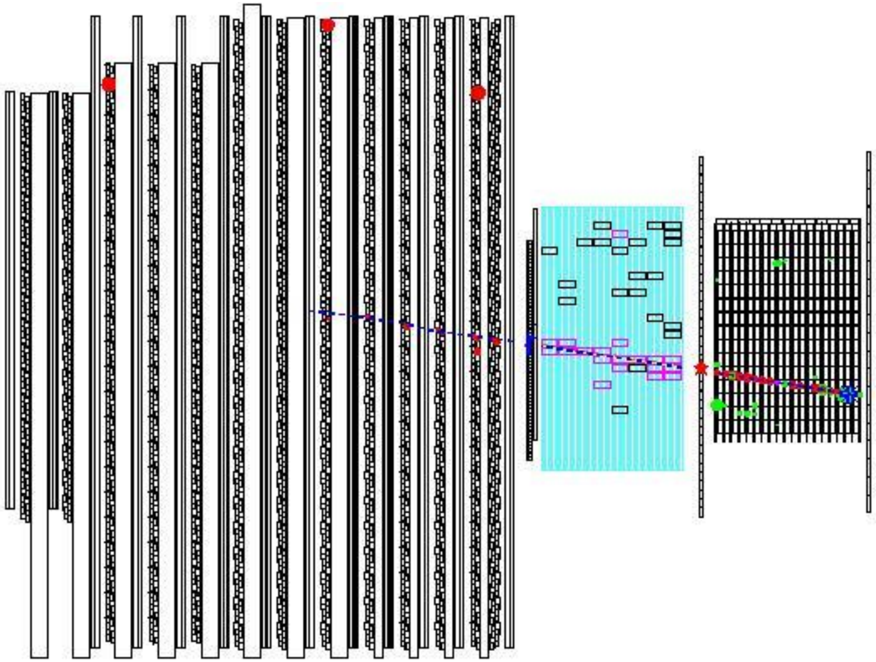
Consists of 4 detector elements.

Precise measurement of neutrino beam property.

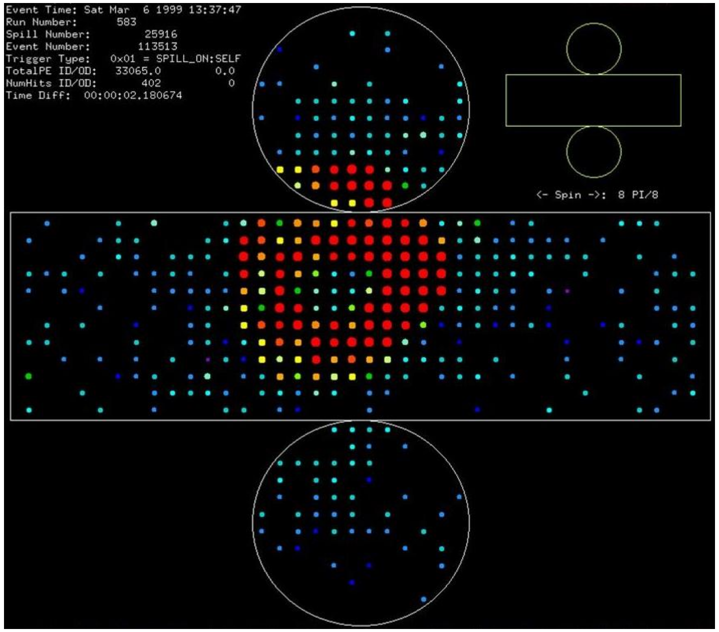
Study of the Neutrino beam in the Near Detectors

- **Data recorded in the Near Detectors are used to study properties of the neutrino beam.**

Fine-Grained detector



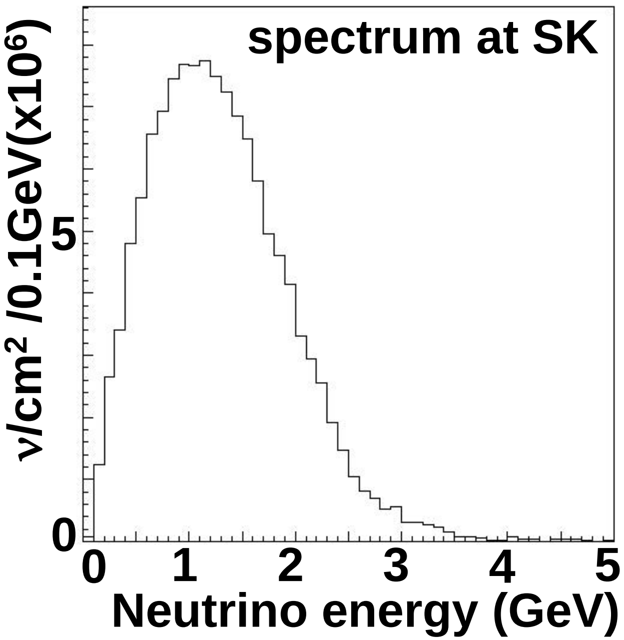
1kt detector

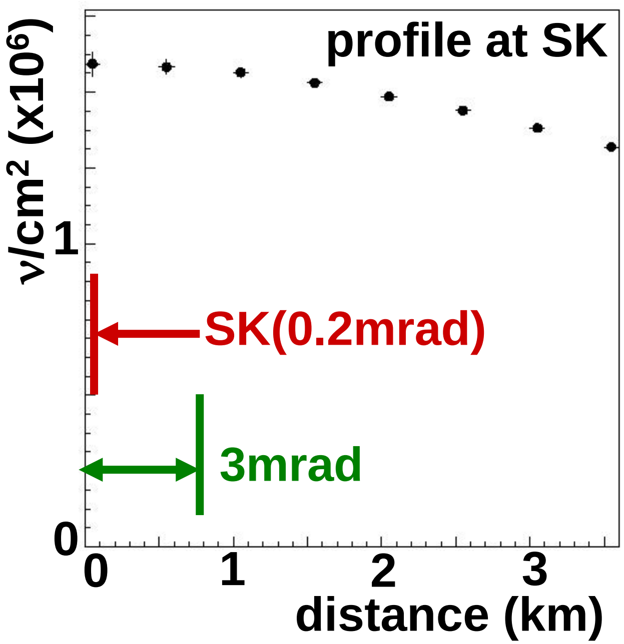


- **The beam direction, stability of the beam intensity, energy spectrum, ν_e/ν_μ ratio well agree with expectations.**
- **The excellent agreements between data and expectations in KEK site ensure the reliability of the expected beam at SK site.**

Property of the neutrino beam

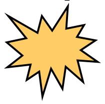
- The mean energy is ~1.3 GeV and the peak energy is about ~1.0 GeV.
- Almost pure muon neutrino beam. ν_e/ν_μ ratio is ~1%.
- The direction of the beam is adjusted within 1mrad.
- Nearly the same energy spectrum and flux within 3 mrad.
  It covers the size of SK; ~50m/250km = 0.2mrad.
- Neutrino flux at SK (250km downstream) is $1.3\times10^6 \nu/cm^2$ for 10^{20}p.o.t.,
  and ~170 events are expected in the 22.5kton of fiducial volume
  in the case of null oscillation.





Summary of data-taking in K2K

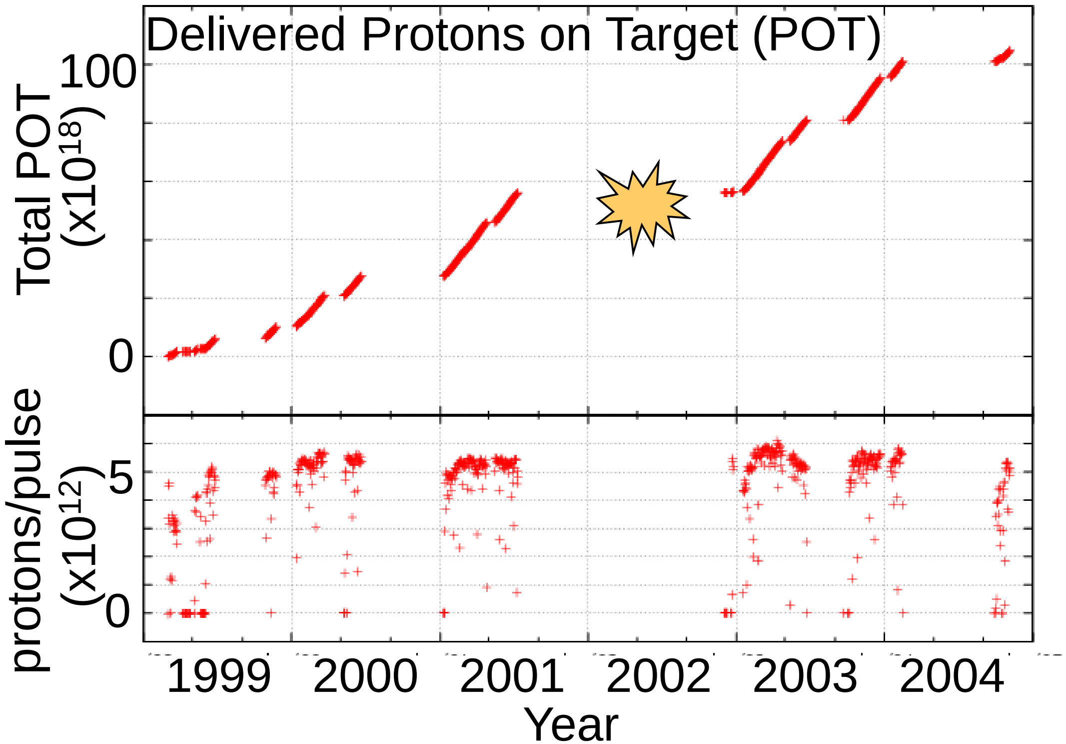
- **First neutrino beam:** **January 27, 1999**
- **Physics run:** **Jun 4, 1999 – Jul 12, 2001 (K2K-I)**



Super-Kamiokande accident

Jan 17, 2003 – Nov 6, 2004 (K2K-II)

- **Total physics run:** **442.8 days (233.7+209.1)**
- **Total spill numbers:** **17.4×10^6 spill**
- **Total POT for analysis:** **92.2×10^{18} p.o.t. (47.9×10^{18} + 44.3×10^{18})**

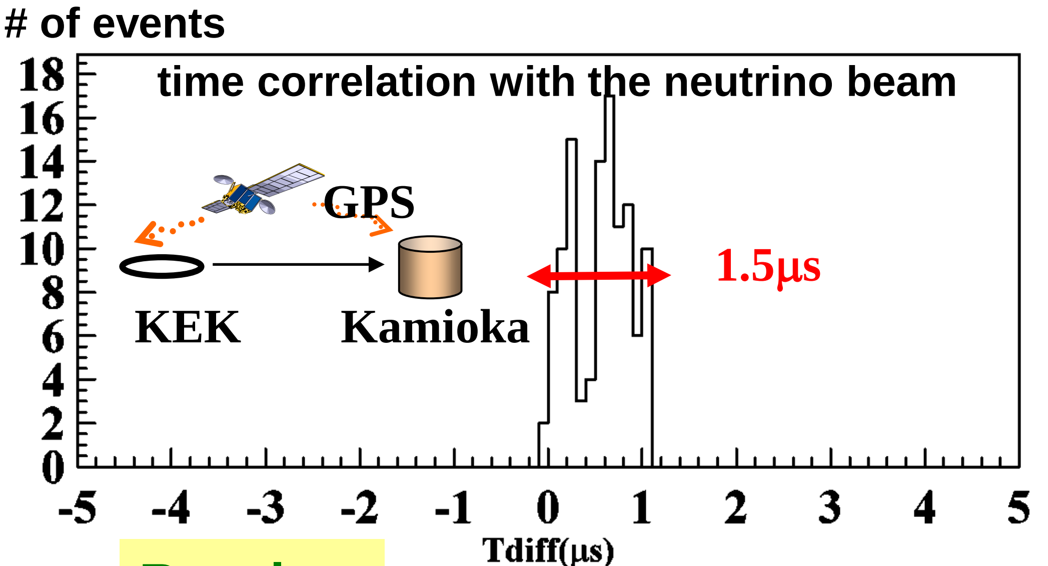


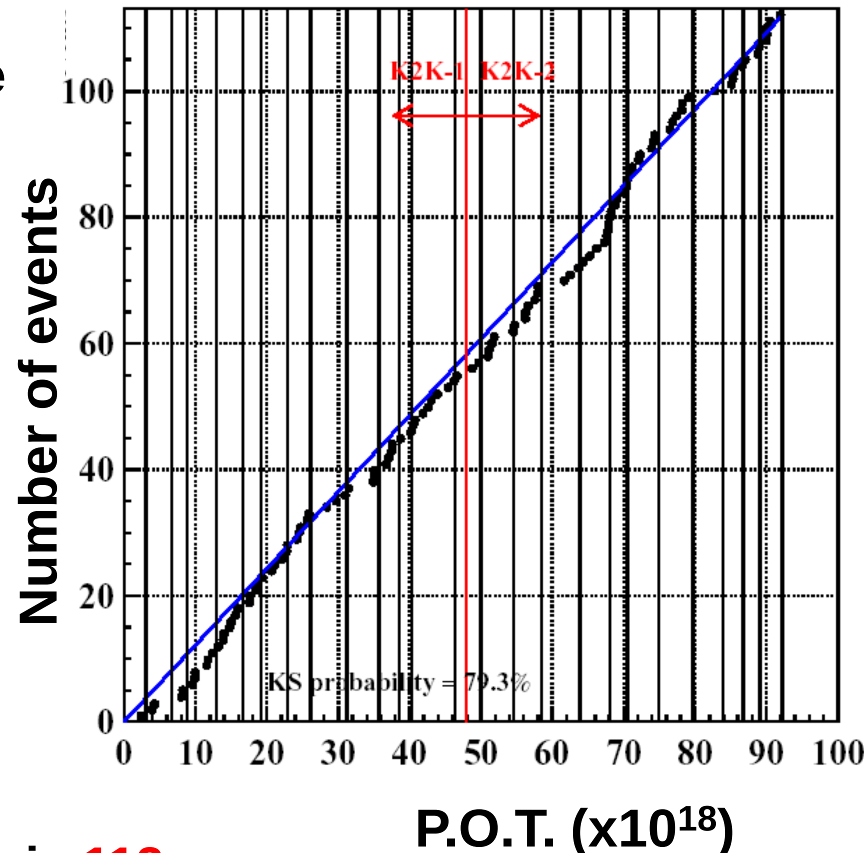
Neutrino events in Super-Kamiokande

Selection

- E_{vis} > 30 MeV and no signal in the outer detector
- Events within 1.5μsec time window are selected because neutrino beam width is 1.1μsec and accuracy of the absolute time determination by GPS is 0.2μsec.

History of event accumulation

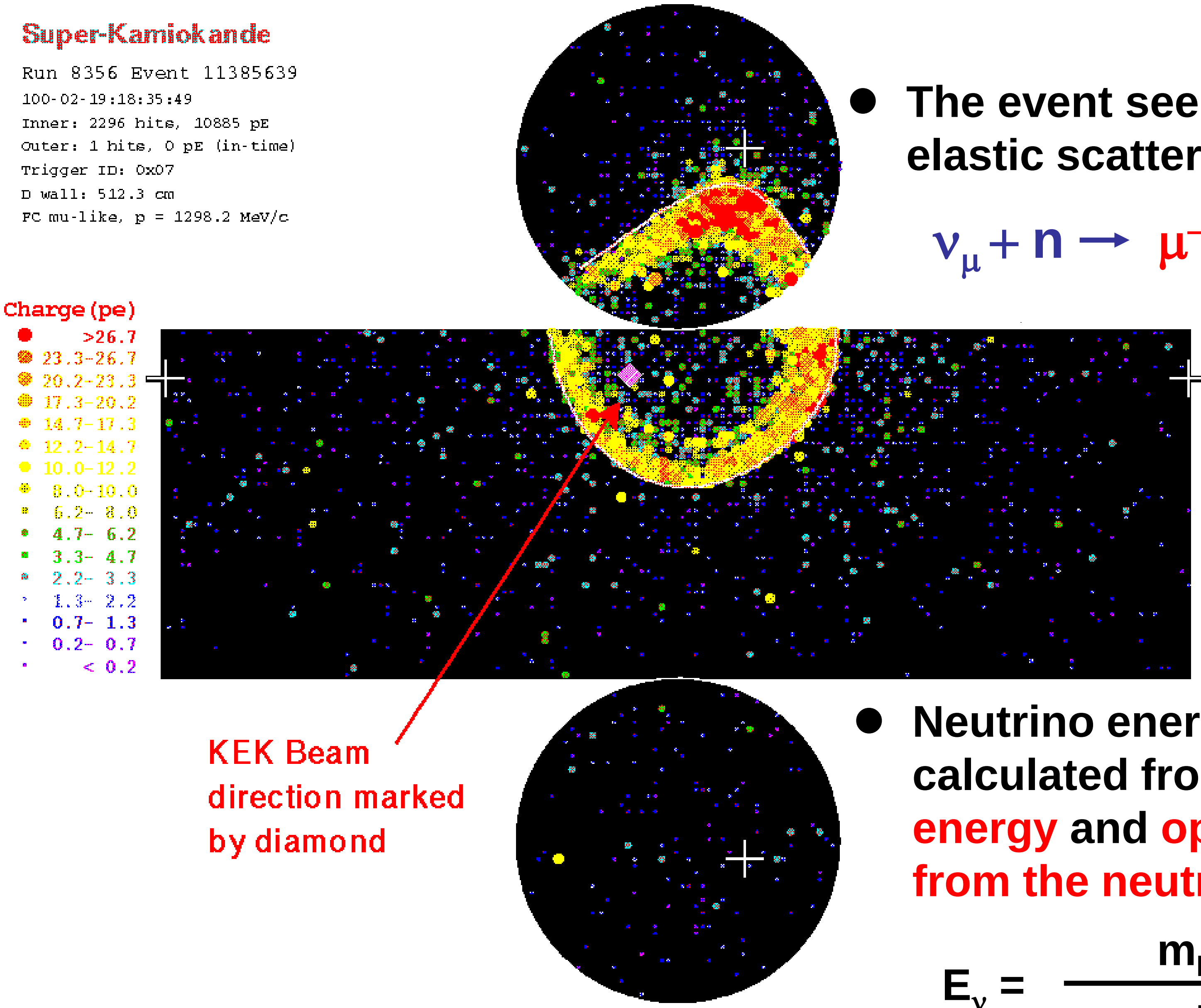




Results

- Number of events in the fiducial volume is 112.
  Expected atmospheric neutrino background is 2.5×10^{-3} events.
- The rate of the neutrino events is uniform.

A typical K2K neutrino event in Super-Kamiokande



- The event seems to be quasi-elastic scattering interaction;

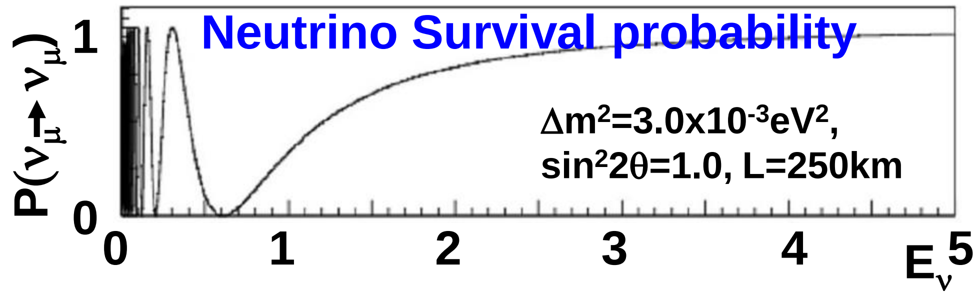
$$\nu_\mu + n \rightarrow \mu^- + p$$

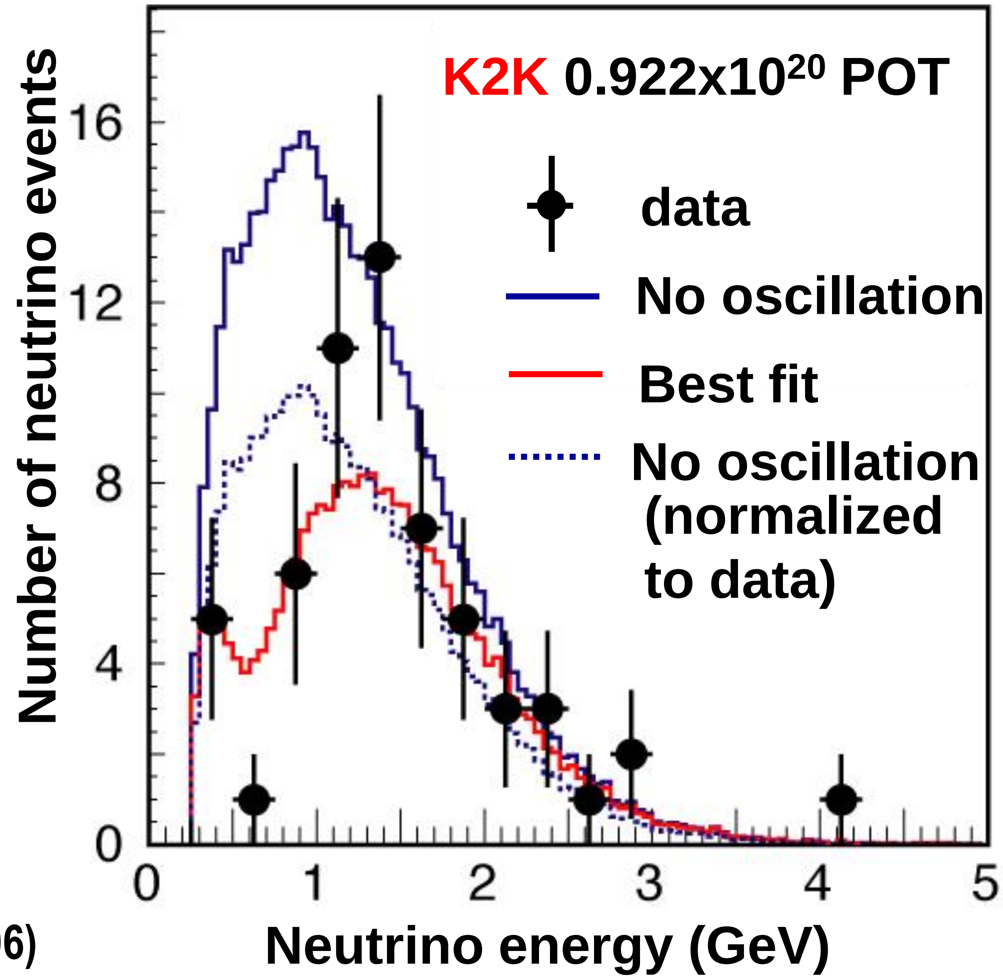
- Neutrino energy can be calculated from muon energy and opening angle from the neutrino direction.

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu \cos\theta_{\mu\text{-}\nu}}$$

ν_μ-ν_τ oscillation analysis for K2K data

- We observed 112 neutrino events where the expectation is $158.1^{+9.2}_{-8.6}$. Number of neutrino events is considerably smaller than expectation.
- Neutrino energy distribution is calculated from 58 single ring μ-like events. The result shows a clear distortion in 0.5-1.0 GeV range. It reflects energy dependence of neutrino survival probability.
- If null oscillation is assumed, such poor agreements happen with a probability of 0.0015%(4.3σ).

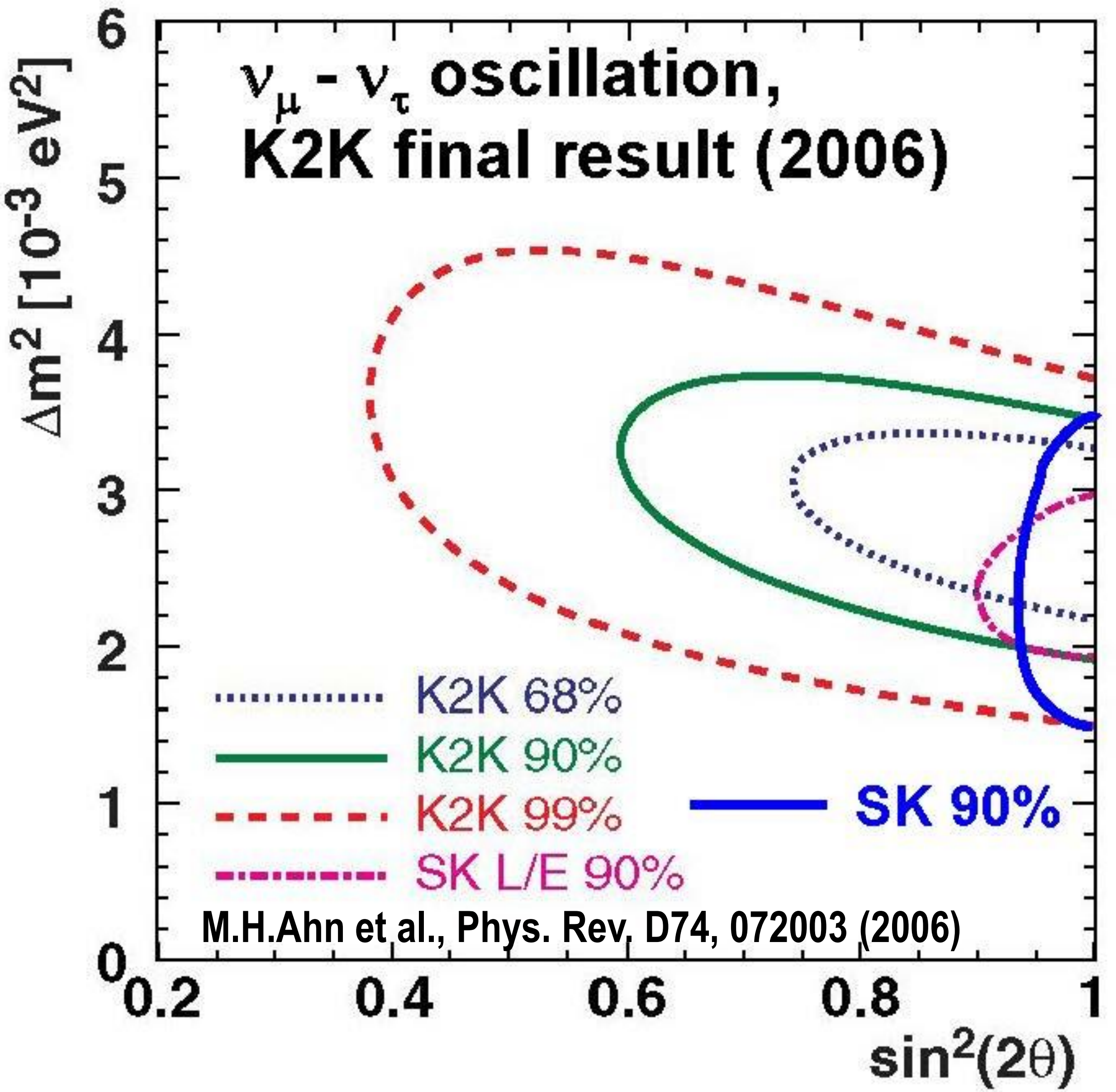




M.H.Ahn et al., Phys. Rev. D74, 072003 (2006)

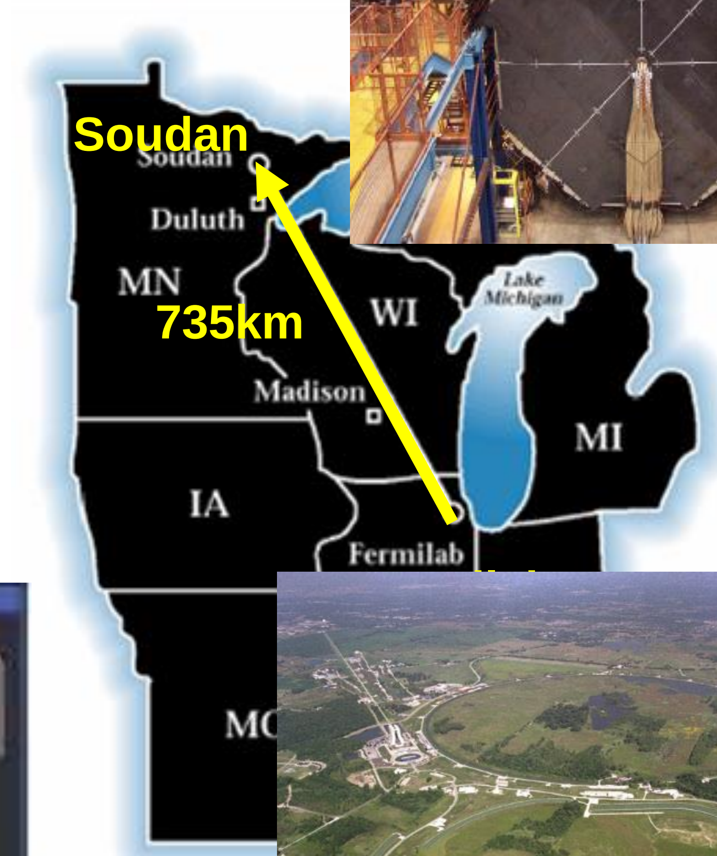
Constraints on ν_μ-ν_τ oscillation

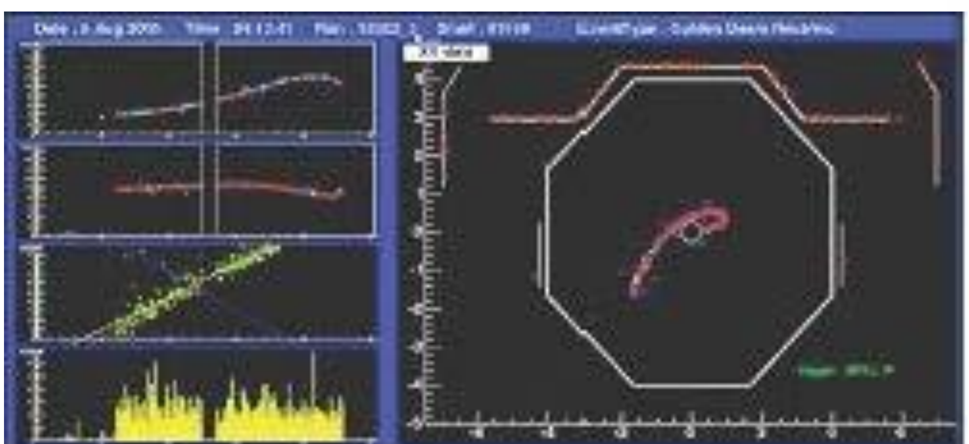
- The best fit parameters
  Δm^2 = $2.8 \times 10^{-3} eV^2$
  $\sin^2 2\theta$ = 1.0
- For $\sin^2 2\theta = 1.0$, $\Delta m^2 = (1.9\sim3.5) \times 10^{-3} eV^2$ at 90% C.L.
- The constraints agree with atmospheric neutrino results from Super-Kamiokande.
- This is the first confirmation of ν_μ-ν_τ oscillation by an artificial neutrino beam.



MINOS experiment (2005 -)

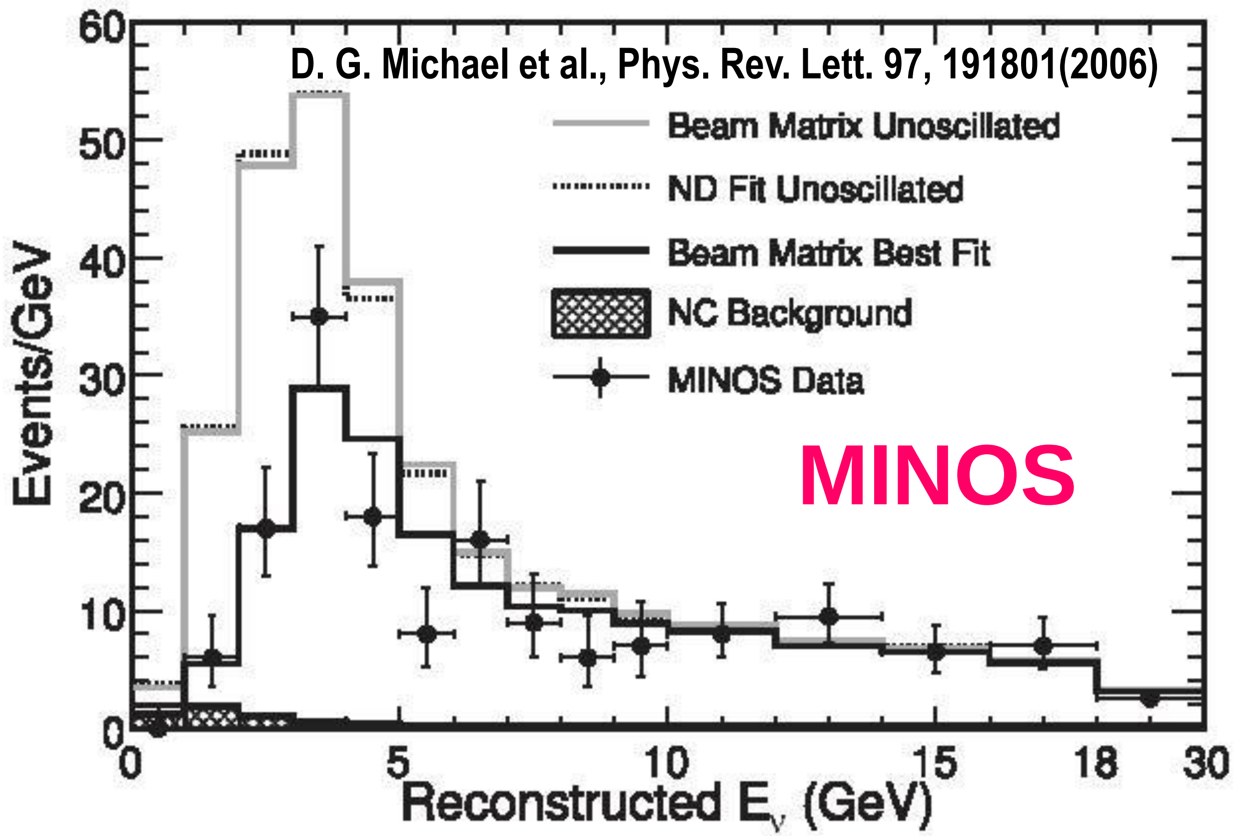
- **Long-baseline neutrino-oscillation experiment using FNAL 120 GeV Main Injector (NuMI) and far detector in Soudan Mine, 735 km away.**
- **The far detector is a "sandwich" of iron plate of 2.54 cm thickness and scintillator of 1.00 cm thickness. The total volume is 5.4 kton. They are in 1.3 Tesla of magnetic field.**
- **A 0.98 ton near detector of similar design is also constructed in FNAL.**





Muon neutrino disappearance by MINOS

- **MINOS experiment published the first result of muon neutrino disappearance in 2006.**
- **From 1.27 x 10^{20} POT data, 215 muon neutrino events are found, where 336±14 events are expected if no-oscillation is assumed.**
- **An distortion of the energy spectrum which is a strong indication of neutrino oscillation is also found.**



Constraints on ν_μ-ν_τ oscillation from MINOS

- The data are consistent with ν_μ disappearance via oscillations with

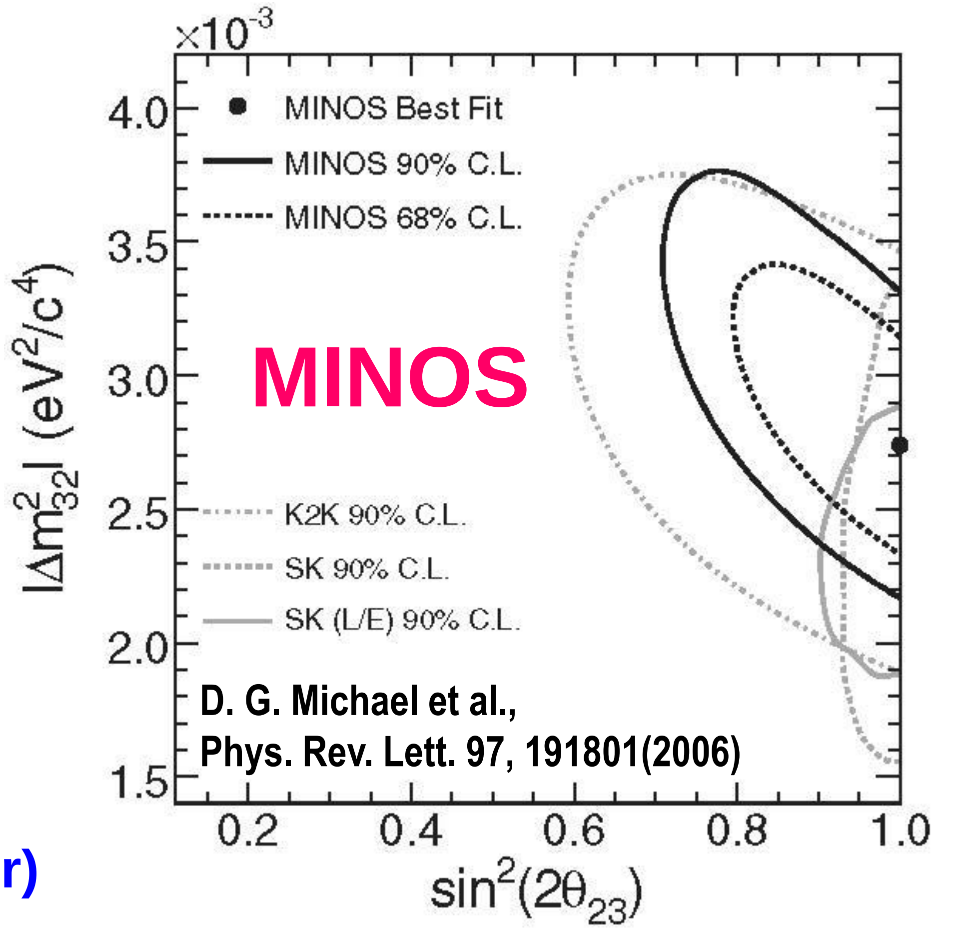
$|\Delta m^2_{32}|$ = $(2.74 {}^{+0.44}_{-0.27})\times 10^{-3}$ eV^2

and

$\sin^2 2\theta_{23} > 0.87$ (68%C.L.).

- The result is consistent with SK and K2K.
- This is the first perfectly-independent and convincing confirmation of the ν_μ- ν_τ neutrino oscillation discovered by Super-Kamiokande.

-beam (atmospheric/accelerator)
-detector (Water Cherenkov/tracker)
-collaboration



Nobel Prize

- **Takaaki Kajita (Super-Kamiokande collaboration) shared the Nobel Prize in Physics for 2015 with Arthur B. McDonald (SNO collaboration). The reason of the award is "for the discovery of neutrino oscillations, which shows that neutrinos have mass"**

Status of neutrino oscillations in the middle of 2000s

- The **neutrino mixing between ν_μ and ν_τ** (between 2nd and 3rd generation) was discovered with atmospheric neutrinos by **Super-Kamiokande** in 1998.

- The ν_μ-ν_τ oscillation was confirmed with artificial neutrino beam by **K2K** experiment in 2004.

- The ν_μ-ν_τ oscillation was also confirmed with **MINOS** experiment in 2006. It was the first perfectly-independent confirmation of the Super-Kamiokande results.

- Around 2000, the **neutrino mixing between ν_e and ν_μ** (between 1st and 2nd generation) was established with solar/reactor neutrinos. There were contributions from **Homestake**, **Kamiokande**, **Super-Kamiokande**, **SNO** and **Kamland**. (This is out of scope of my lecture)

- Experimental study of neutrino oscillations moved to new phase: **Three flavor oscillation**.

From 2 flavor oscillation to 3 flavor oscillation

- **Study on neutrino oscillations was extended to three flavor oscillations.**
  If 3 flavor oscillation is assumed, the flavor eigenstates are mixtures of the mass eigenstates, and the correlation can be written as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

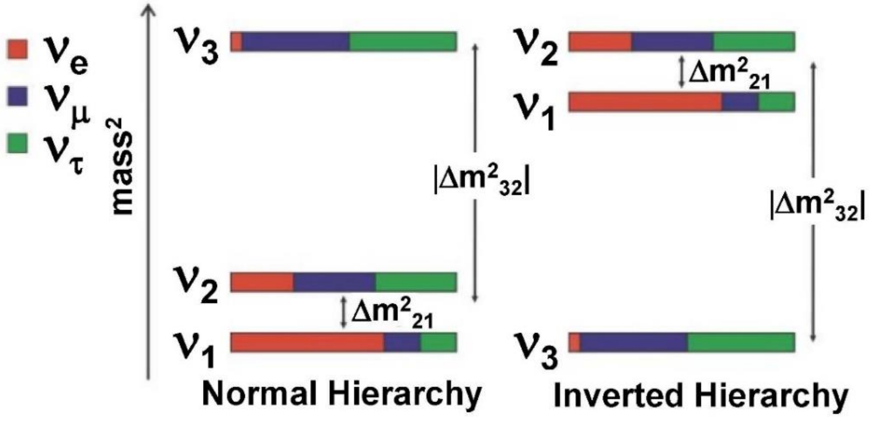
- **The equation has 6 parameters.**

  2 square mass differences (Δm^2_{21}, Δm^2_{32}),
  3 mixing angles (θ_{12},θ_{23},θ_{13})
  1 CP violation phase, δ_{CP}.

  $\Delta m^2_{ij} = m^2_i - m^2_j$

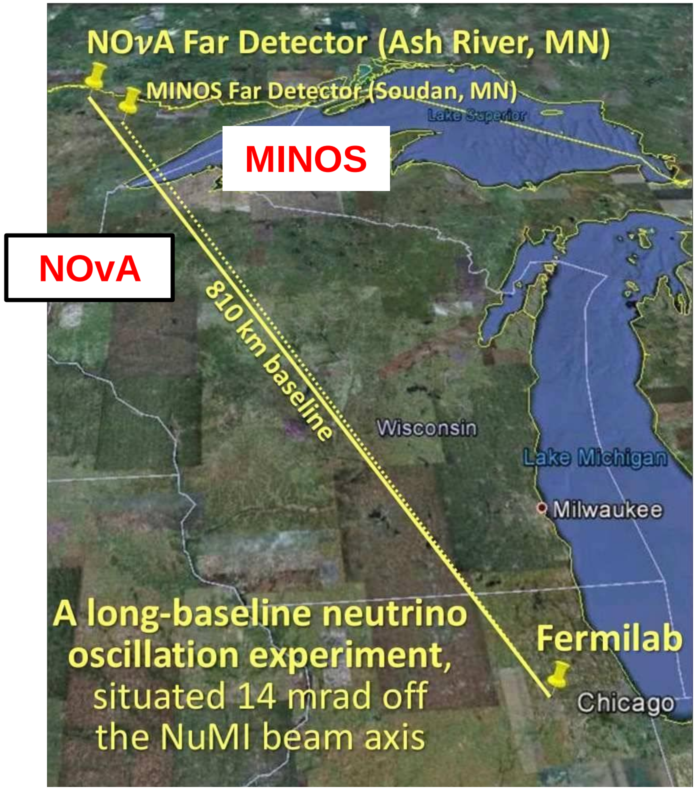
- **Δm^2_{21}, θ_{12}, Δm^2_{32}, θ_{23} were already well studied. θ_{13} and δ_{CP}, which appear in mixing between 1st and 3rd generations, became the main topics.**

- **Mass hierarchy, which is sign of $\Delta m^2_{32} \sim \Delta m^2_{31}$, is another unknown parameter within our scope.**



Experiments for θ_{13} and δ_{CP} measurementsmets

- **Two long-baseline neutrino beam experiments (T2K and NOvA) and three reactor neutrino experiments (Daya Bay, Reno, Double Chooz) were newly proposed. MINOS was in operation.**



Reactor experiments and long-baseline experiments

- In **reactor experiments**, $\sin^2 2\theta_{13}$ can be examined from disappearance of $\bar{\nu}_e$.

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{32} L/4E_\nu)$$

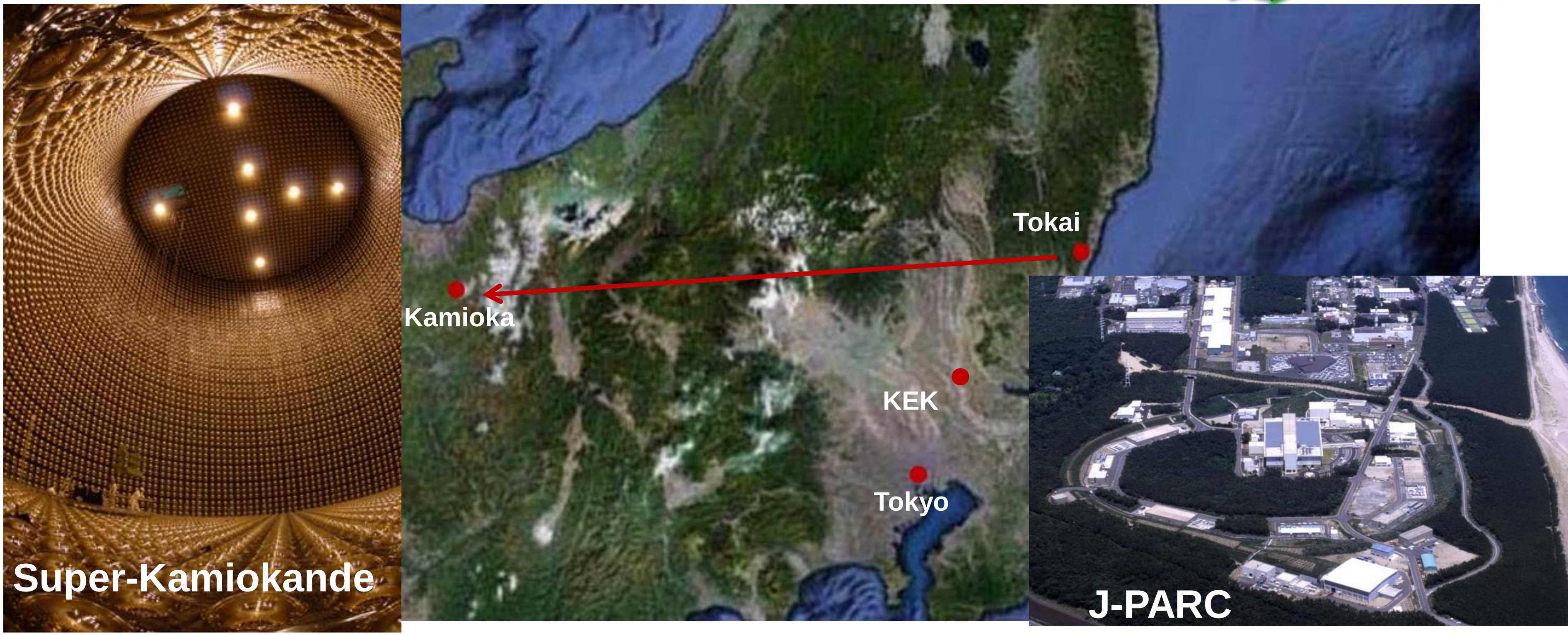
- In **long-baseline experiments**, $\sin^2 2\theta_{13}$ can be studied by appearance of ν_e and $\bar{\nu}_e$. The oscillation probability also includes CP-violation phase, and mass hierarchy as correction terms.

$$\begin{aligned} P(\nu_\mu \to \nu_e) \approx\ & \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)\left(1 + \frac{4\sqrt{2} G_F n_e E}{\Delta m^2_{31}}(1 - 2\sin^2\theta_{13})\right) \\ \mp\ & \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta_{\rm CP} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) \end{aligned}$$

- for neutrino, + for anti-neutrino

- Two different types of experiments provide independent measurements of $\sin^2 2\theta_{13}$. In addition, studies of δ_{CP} and mass hierarchy might be possible from the combination of two types of experiments.

T2K experiment



- Second generation long-baseline neutrino-oscillation experiment; from Tokai to Kamioka. The experiment started in 2009.
- High intensity almost pure ν_μ beam from J-PARC is shot toward the Super-Kamiokande detector 295 km away.

Features of the T2K experiment

- High intensity primary proton beam. The primary goal of T2K was "~78 x 10^{20} POT data by ~750 kW beam in 5 years". It is about ~100 times larger than K2K which accumulated ~1×10^{20} POT data with 5kW beam.

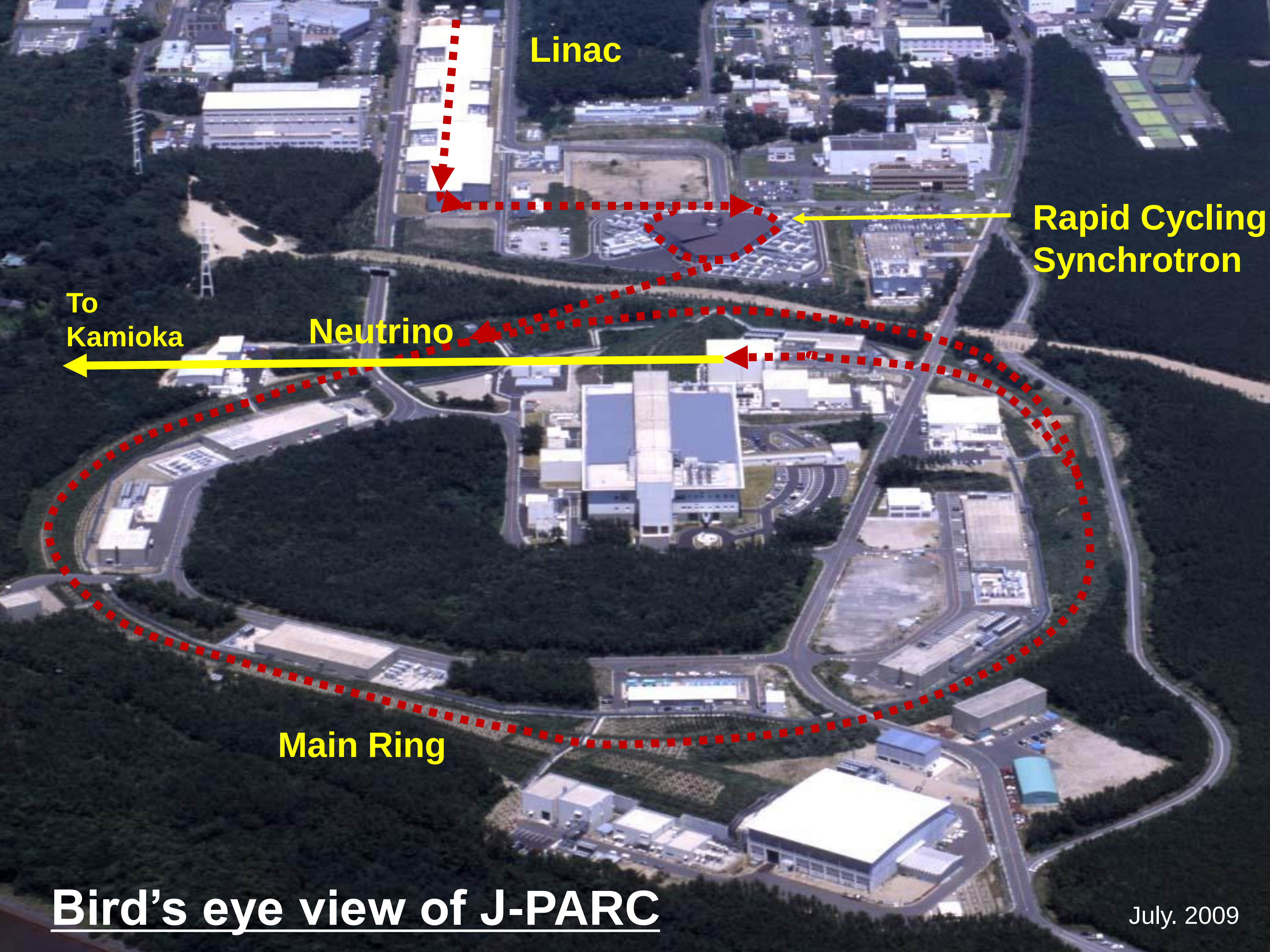
Advantage of the T2K neutrino beam

④ **Neutrino energy spectrum**
(AN) Cannot be changed
(NB) Can be changed. In T2K experiment, peak energy of the neutrino beam is adjusted to the oscillation maximum by off-axis beam.

⑤ **ν_e/ν_μ ratio**
(AN) ~1/2
(NB) order of ~1/100

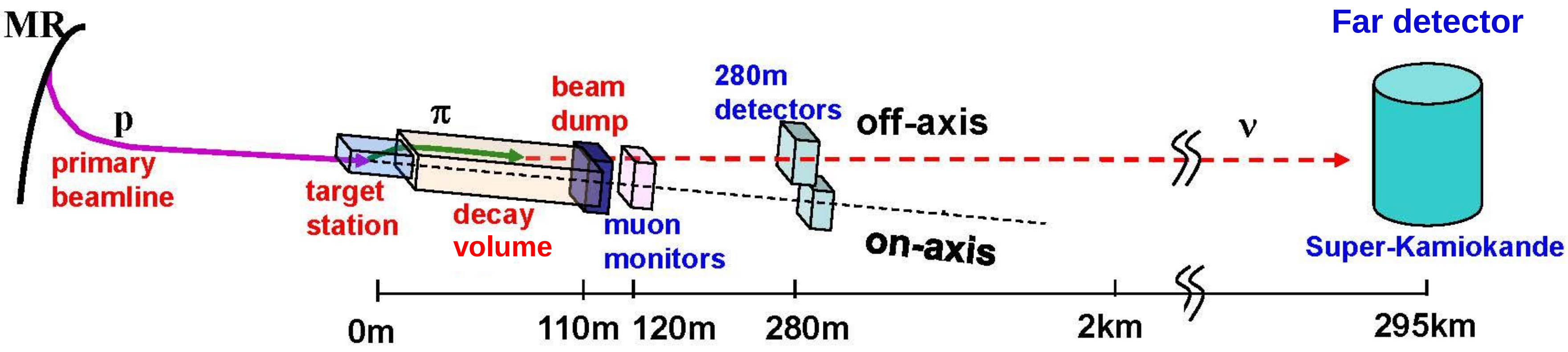
⑥ **Neutrino beam and antineutrino beam**
(AN) Cannot be changed
(NB) Can be changed by switching current direction of magnetic horns

- Discoveries of finite θ_{13} and δ_{CP} by ν_e appearance is the main goal. In addition, precise measurement of Δm^2_{32} and $\sin^2 2\theta_{23}$ is possible by ν_μ disappearance.



Bird’s eye view of J-PARC

T2K Beam line and Detectors



Beamline

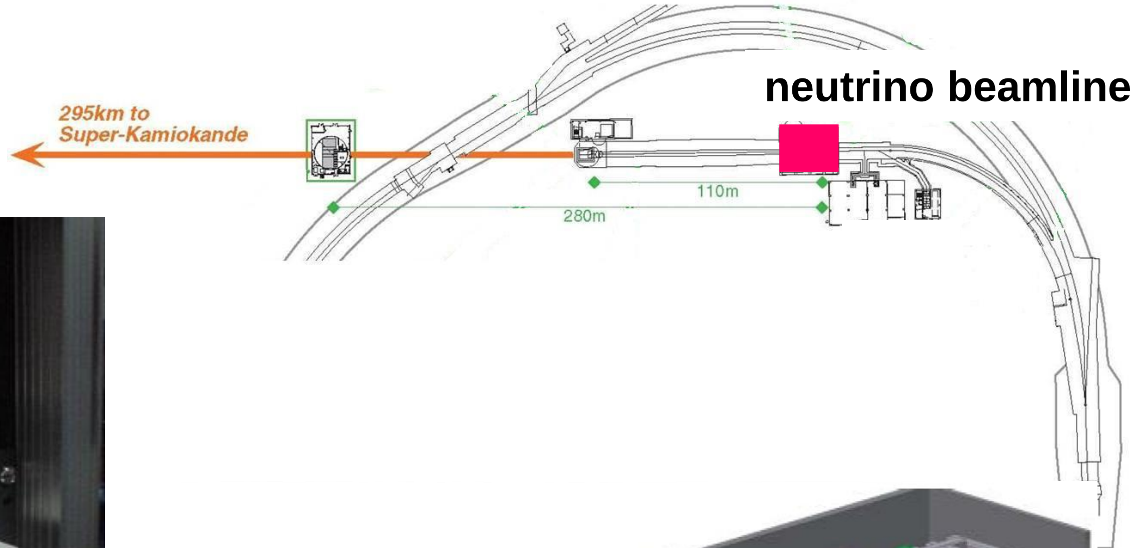
- Primary beamline
- Target station
- Decay Volume
- Beam dump @ ~110 m downstream

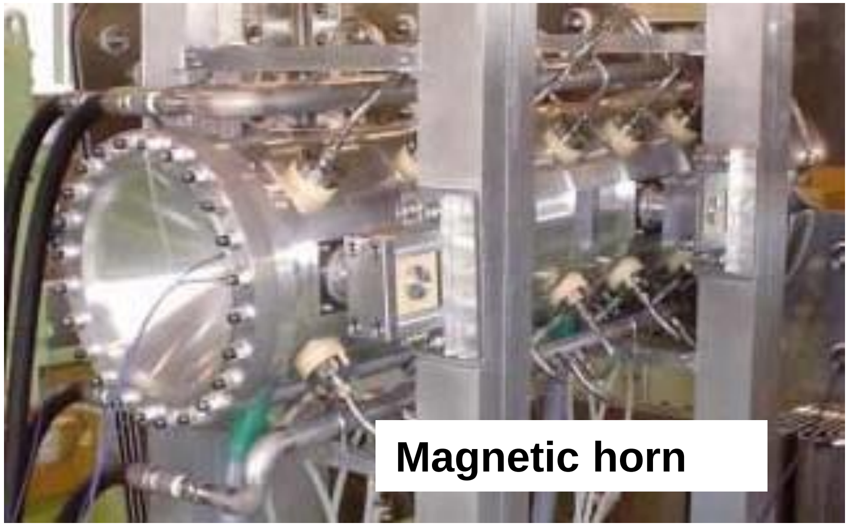
Detectors

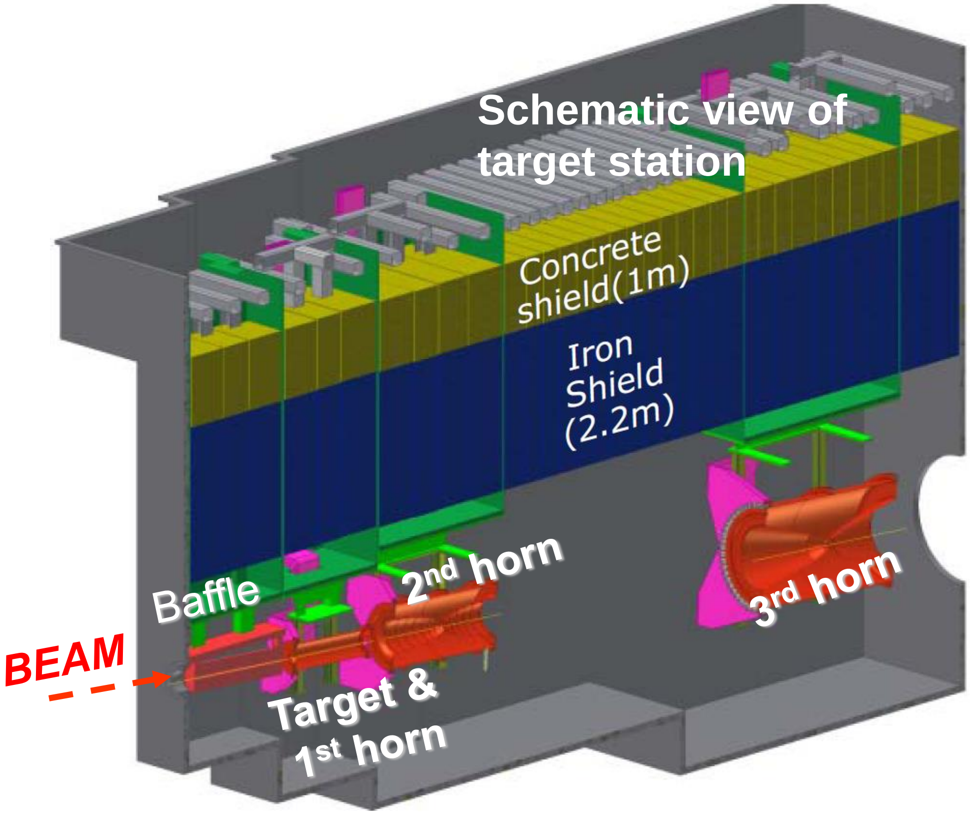
- Muon monitors@ ~120 m downstream
- Near detectors@ ~280 m downstream.
- Far detector@ 295 km downstream (Super-Kamiokande)

Off-axis beam : the center of the beam direction is adjusted to be 2.5^{o} off from the SK direction.

Target Station



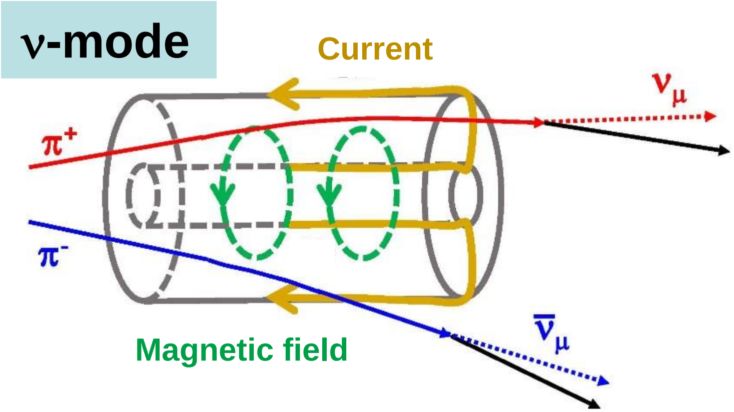


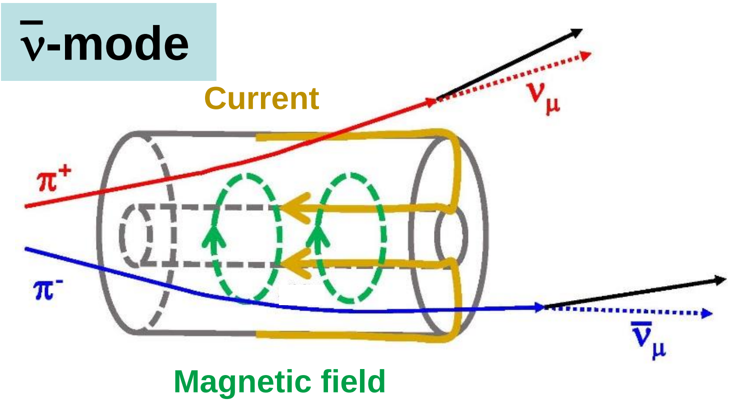


Magnetic horn

- Magnetic horn is **focus/defocus** device installed just downstream of the target. High (**~250kA**) current generate magnetic field, and direction of π's are changed.
- In ν-mode, π^+ is focused and π^- is defocused. Accordingly, ν-rich beam is generated in the forward direction.
- In $\bar{\nu}$-mode, π^- is focused, and π^+ is defocused. $\bar{\nu}$-rich beam is generated in the forward direction.
- Neutrino flux at SK is enhanced by factor **~10** (total) and **~16** (at ~0.6GeV).
- Neutrino components in each mode:

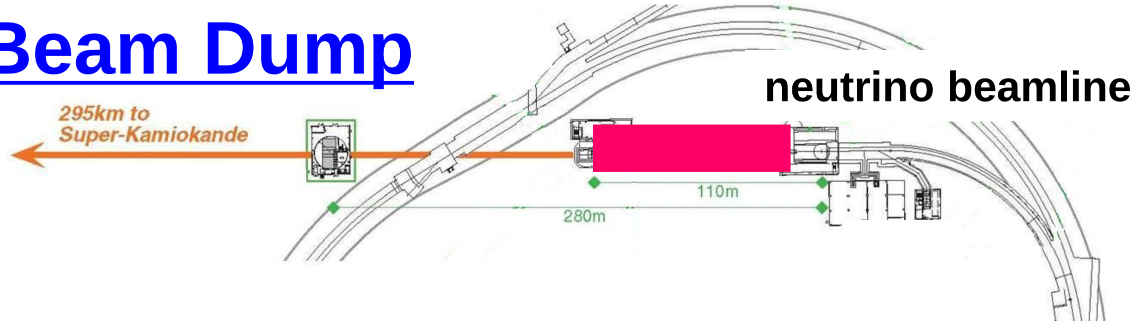
	ν_μ	$\bar{\nu}_\mu$	$\nu_e+\bar{\nu}_e$
ν-mode	~97%	~2%	~1%
$\bar{\nu}$-mode	~2%	~97%	~1%



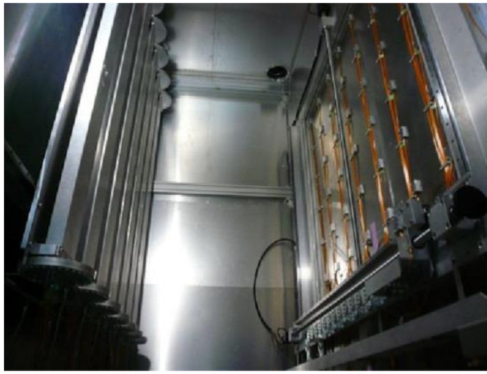


Decay Volume and Beam Dump

neutrino beamline

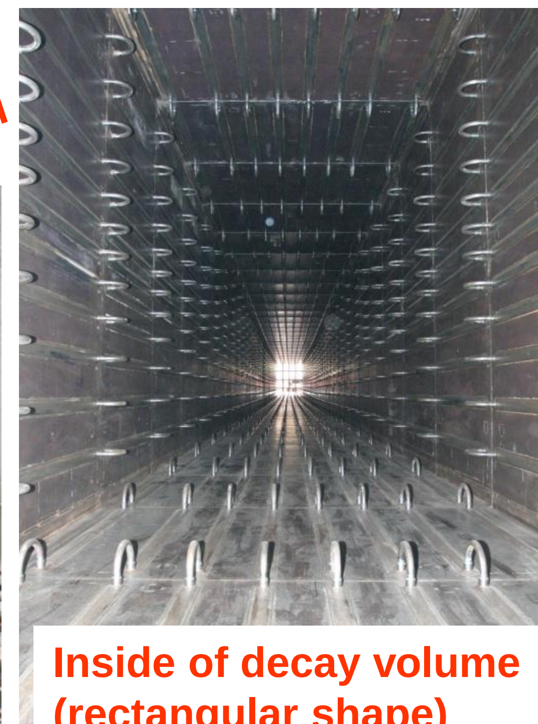


Muon monitors in Muon Pit



Beam Dump
(installation)

Installation of decay volume



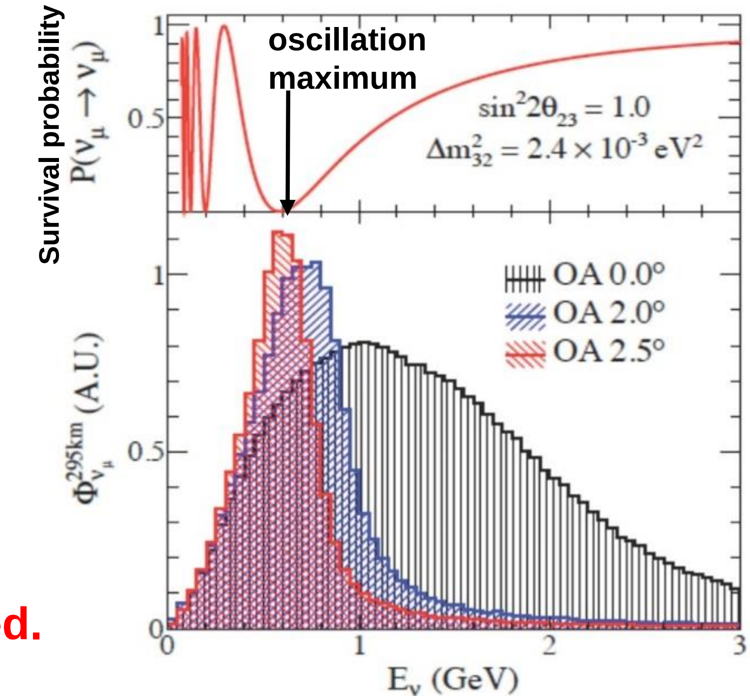
Inside of decay volume
(rectangular shape)

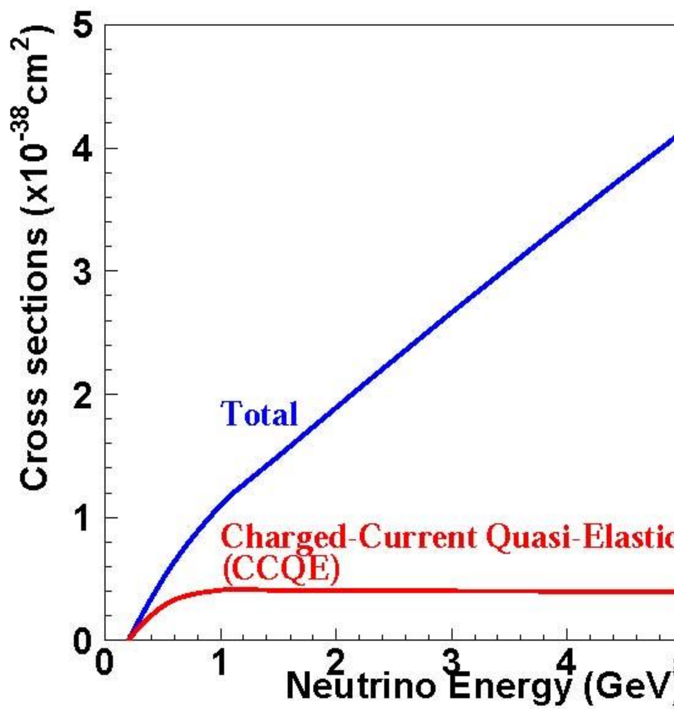
Off-axis beam

The center of the beam direction is adjusted to be 2.5° off from the SK direction.
Neutrino energy spectrum becomes quasi-monochromatic. The peak energy is ~0.6 GeV.

Merits of the off-axis beam are:

- The neutrino energy peak agrees with the oscillation maximum.
- High energy (> 1 GeV) neutrinos are suppressed.
  - Neutrino energy spectrum is calculated from CCQE events; ν_μ + n ⇢ μ + p. Fraction of CCQE events is small in high energy range and some of non-CCQE events are serious background for the CCQE selection.
  - Neutral Current (NC) π^0 events are background for the ν_e appearance search. NCπ^0 events are reduced by the suppression of high energy neutrinos.
- Water Cherenkov detector has better performance for single charged particle events.

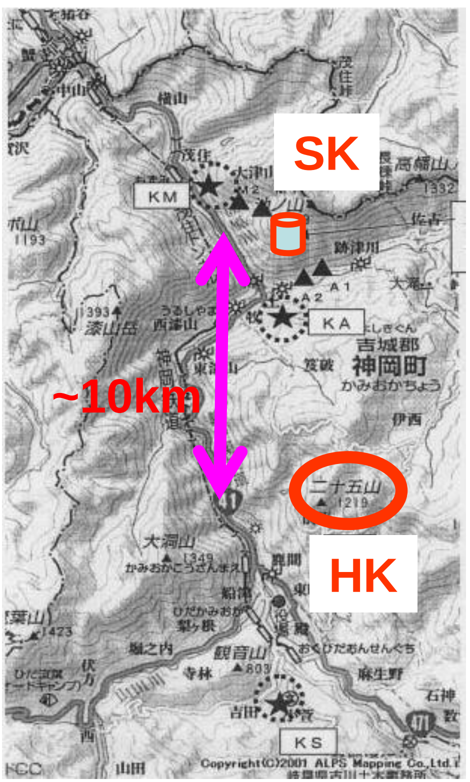


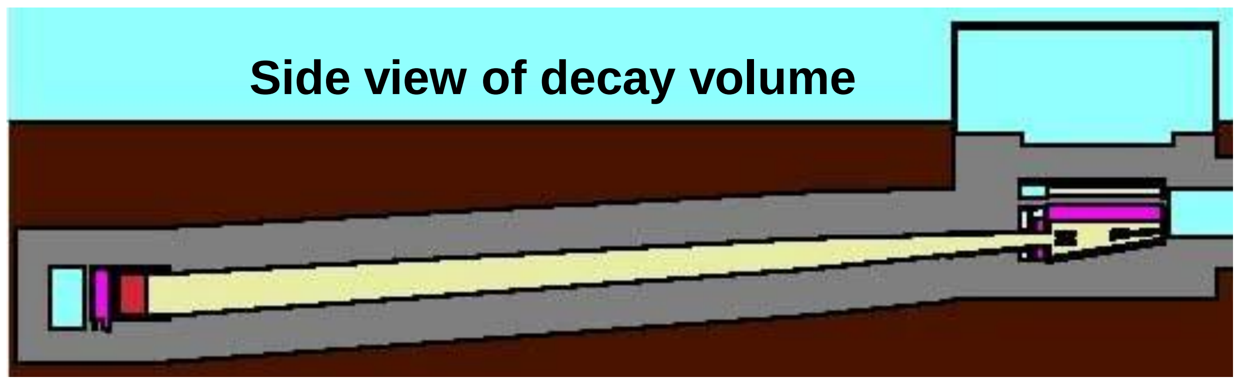


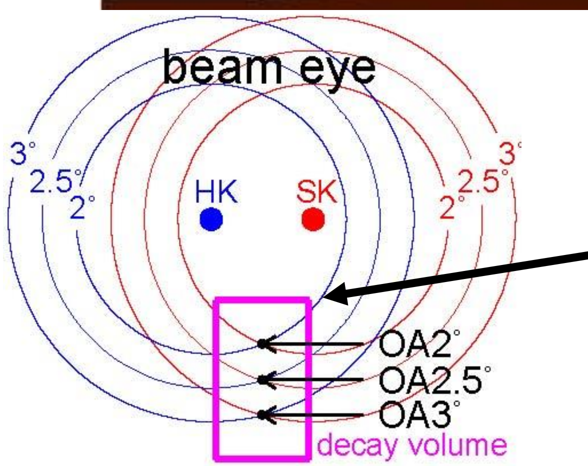
Beam direction and shape of the decay volume

- When the construction of the beam line started around ~2002, the best off-axis angle was unknown. The beam direction must be able to adjusted to 2º ~ 3º off both from SK and HK (HK will be 10km away from SK).
- The cross section of the decay volume is rectangular, and the height of the volume is larger in downstream. Keep a tunability of the beam direction and wait other experiments.

Map in Kamioka

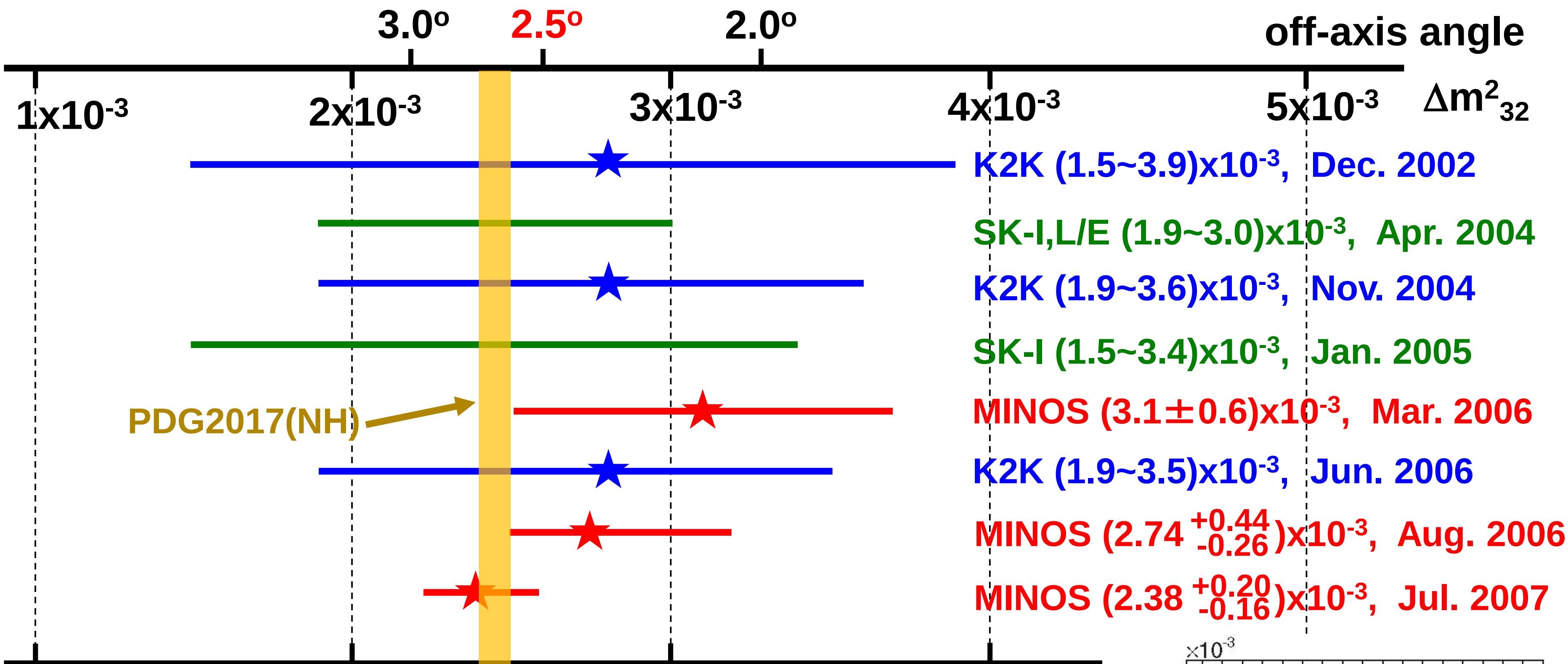




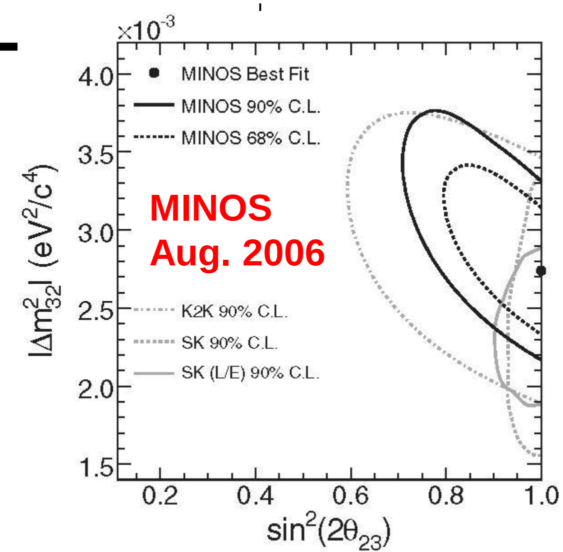


Cross section of decay volume

History of Δm^2_{32} and off-axis angle



MINOS reports 1σ error and SK/K2K present 90% region.

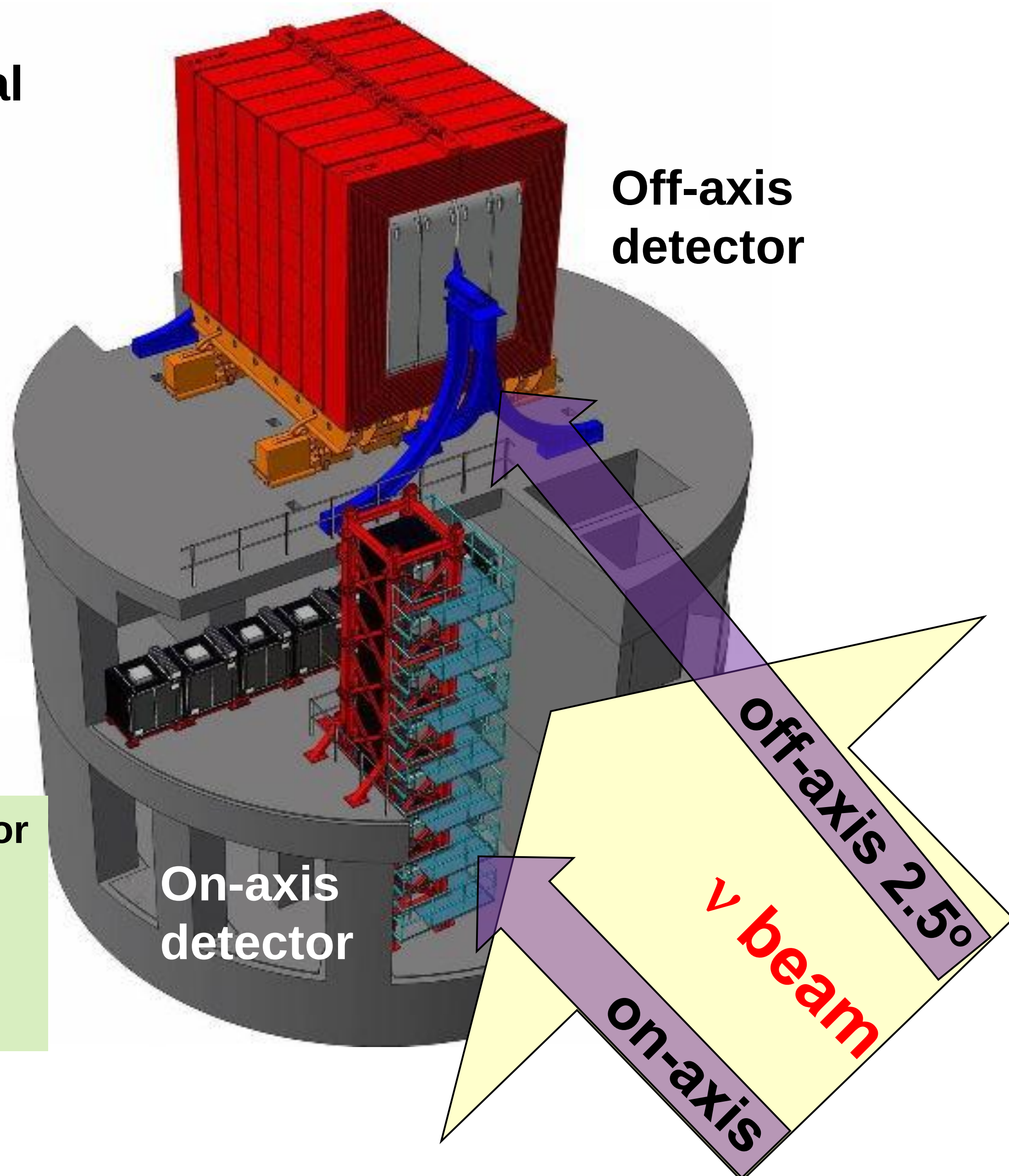


- Possible off-axis angle was designed to be 2° ~ 3° by the K2K result in 2002.
- After the MINOS result was published in August 2006, the T2K collaboration decided to start the experiment with off-axis 2.5°.

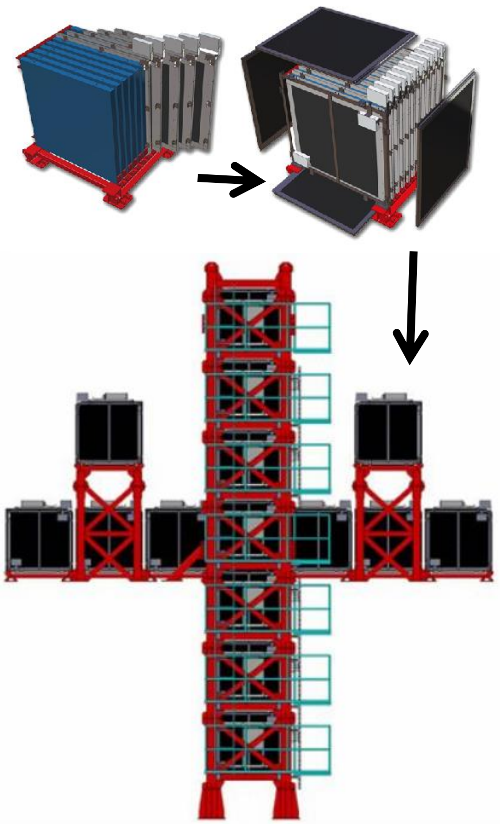
Near Detectors at 280m downstream

- The detectors were made in the underground experimental hall, 33.5m depth and 17.5m diameter.
  It is located at 280m downstream from the target.
- Two detectors were installed; they are On-axis Detector in the direction of the neutrino beam center, and Off-axis detector in the direction of Super-Kamiokande.

Unlike K2K, a water Cherenkov detector can not be used in T2K near detector.
-Event rate is too high.
-Neutrino energy is high and muons escape from an 1kt tank.

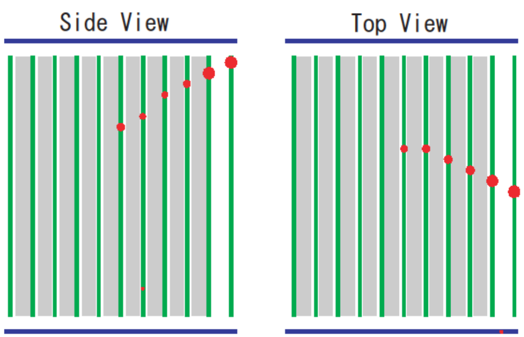


On-axis detector (INGRID)

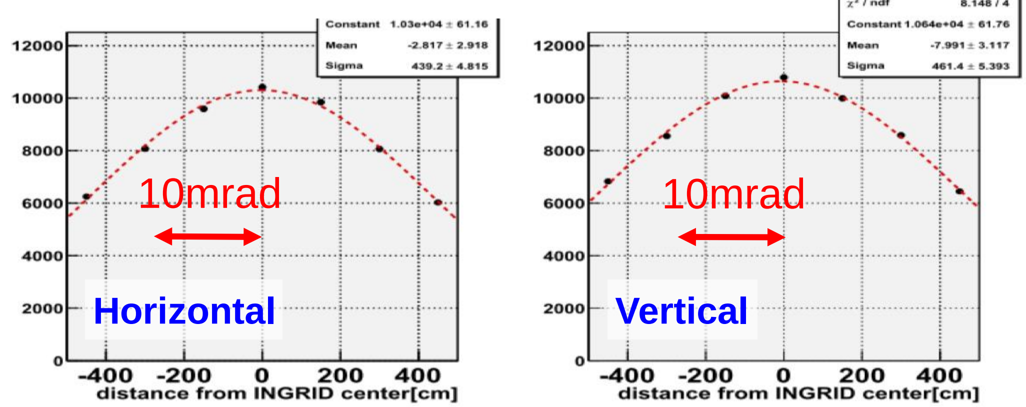


- Consists of 16 modules; 7 horizontal, 7 vertical, and 2 off-diagonal. Each module is 1m x 1m x 1m cube.
- Each module is "sandwich" of 11 scintillator layers and 10 iron layers. They are surrounded by 4 veto planes.
- The neutrino beam center is obtained from horizontal/vertical distribution of the neutrino event rate. The nominal accuracy is ~0.1 mrad.

INGRID event view

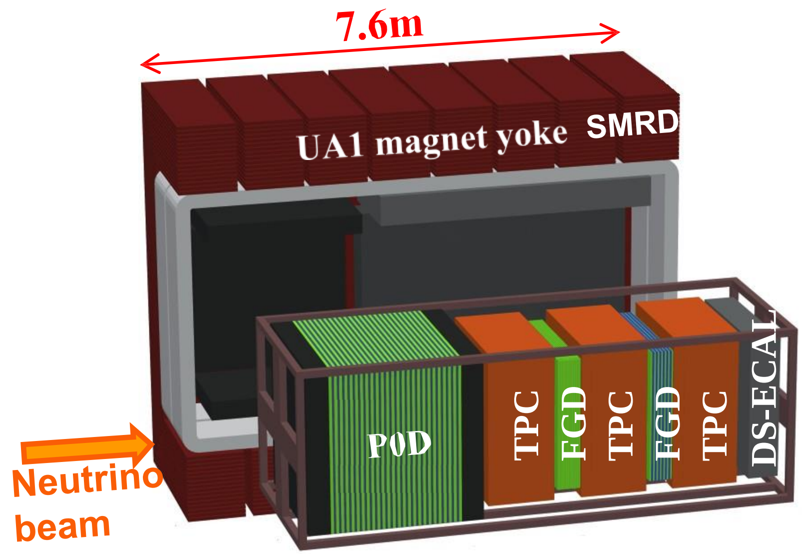


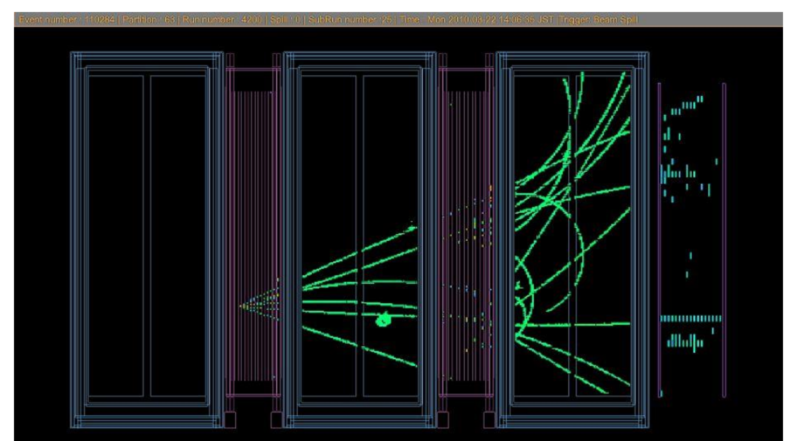
Number of event distribution



Off-axis detector (ND280)

- ND280 is made from several components.
- 2 FGDs (Fine-Grained Detectors) consist of scintillator bars and one has water as a target material.
- 3 gas-filled TPCs (Time Projection Chambers) track charged particles.
- All components are in 0.2 T of magnetic field. The magnets were previously used in UA1 and NOMAD.
- Charged particles are deflected by the magnetic field. The curvature of the track recorded by TPC are used to determine the momentum of the particles.
- Neutrino flux as well as neutrino interactions can be studied from the reconstructed track information.
- Other components are P0D (π^0 detector), ECAL(Electromagnetic CALorimeter) and SMRD(Side Muon Range Detector).

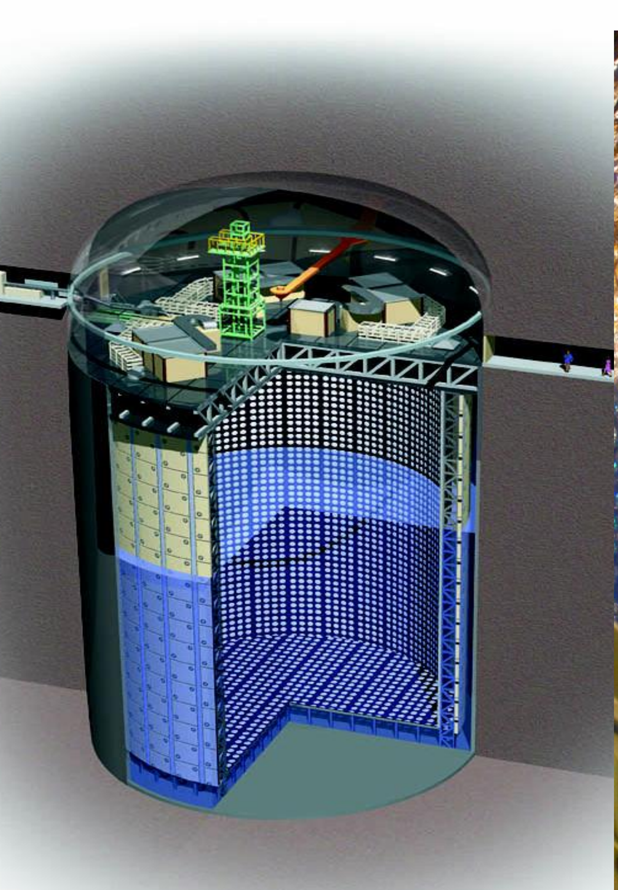


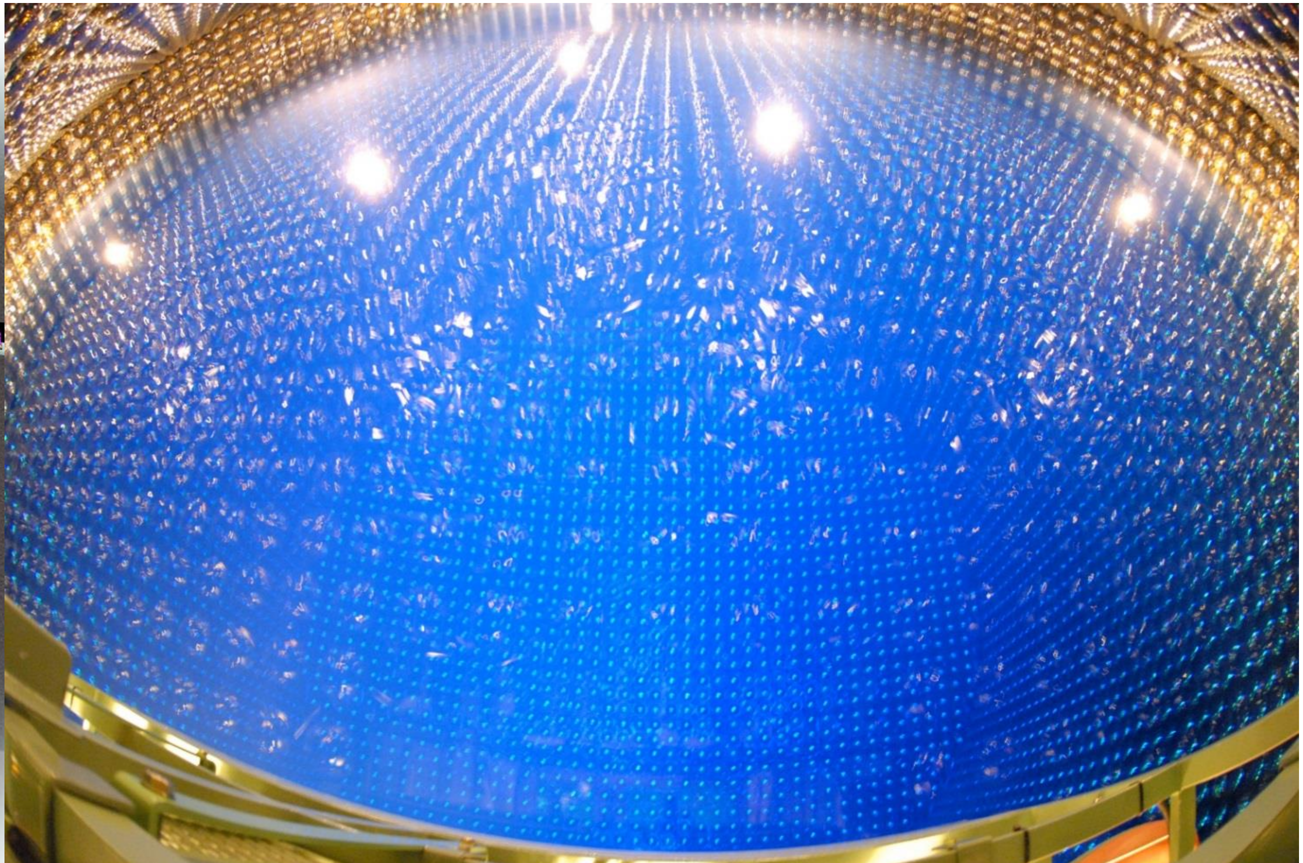


Far detector : Super-Kamiokande (SK)

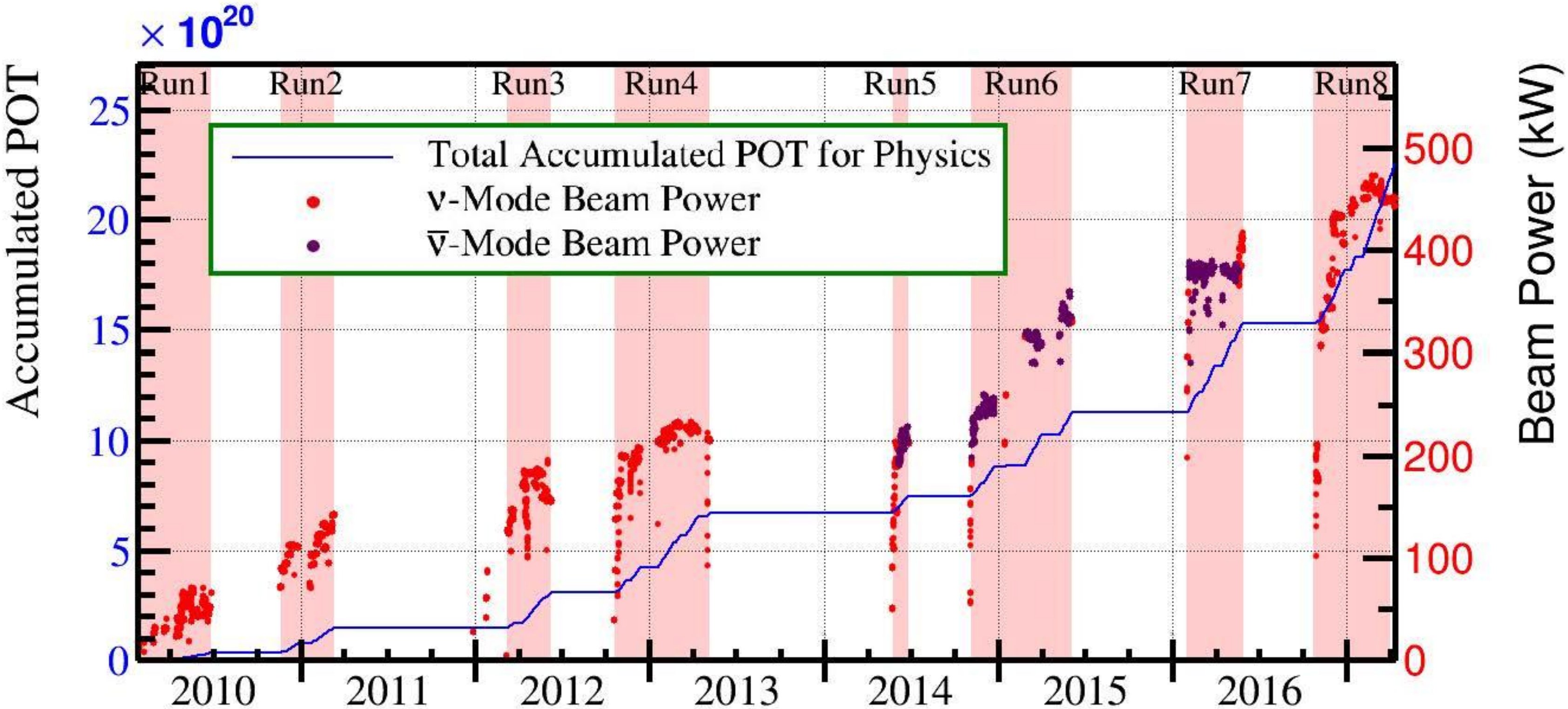
- **50kt water Cherenkov detector. The fiducial volume of the inner detector is 22.5 kton, and is viewed by 11129 20-inch diameter PMTs. Outer water layer surrounding the inner volume is viewed by 1885 8-inch diameter PMTs.**

- **Located at 1000 m underground in Kamioka mine, Japan. The distance from the J-PARC is 295 km.**





History of the T2K neutrino beam



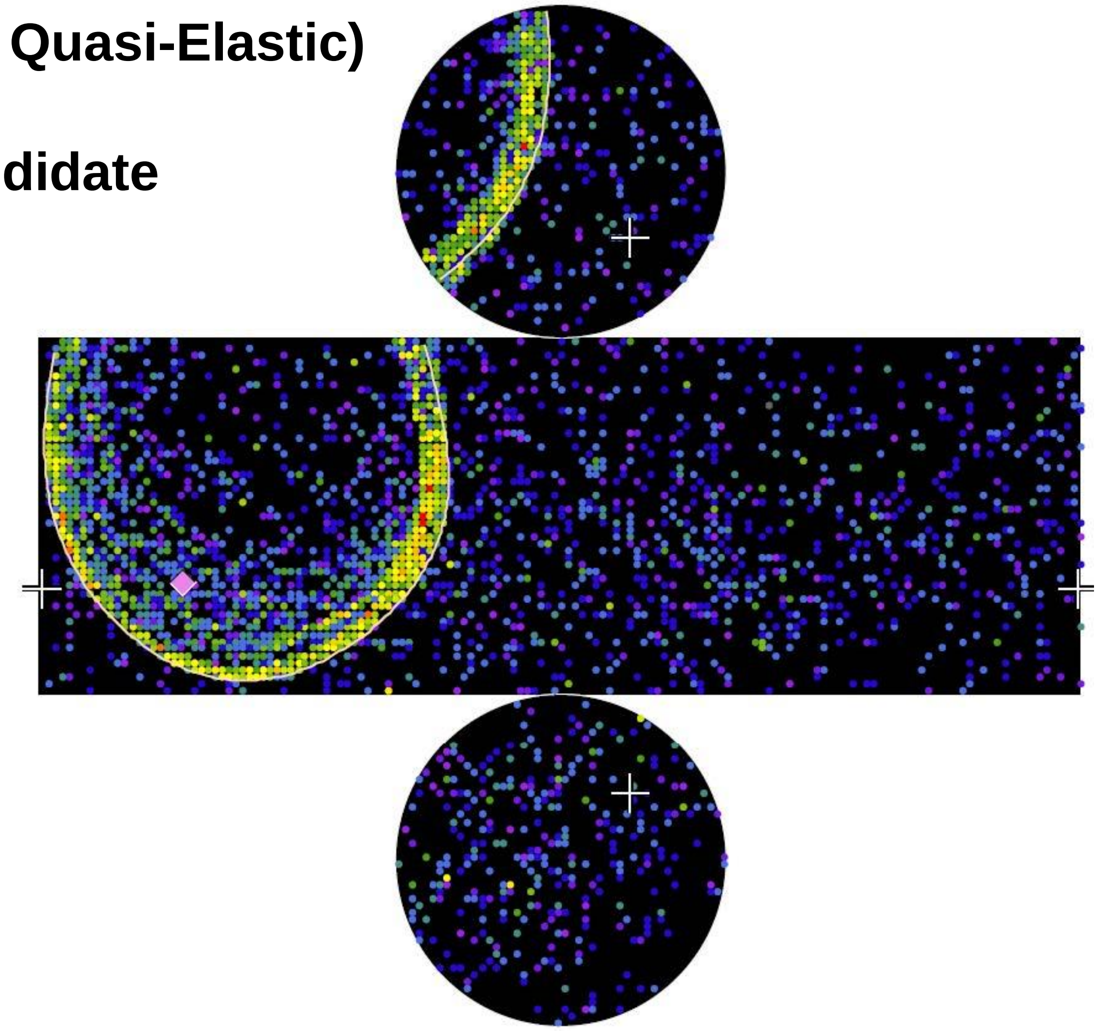
- **The maximum beam power achieved is ~470kW. (still far from 750kW)**

Period	Beam	POT
Jan.2010 - May 2013	ν-mode	$7.57 \times 10^{20}(\nu)$ and $7.53 \times 10^{20}(\bar{\nu})$
Jun.2014 - May 2016	ν̄-mode(+ν-mode)	
Oct.2016 - Apr.2017	ν-mode	$7.26 \times 10^{20}(\nu)$
Total		22.36×10^{20}

ν_μ disappearance analysis

CCQE (Charged Current Quasi-Elastic)

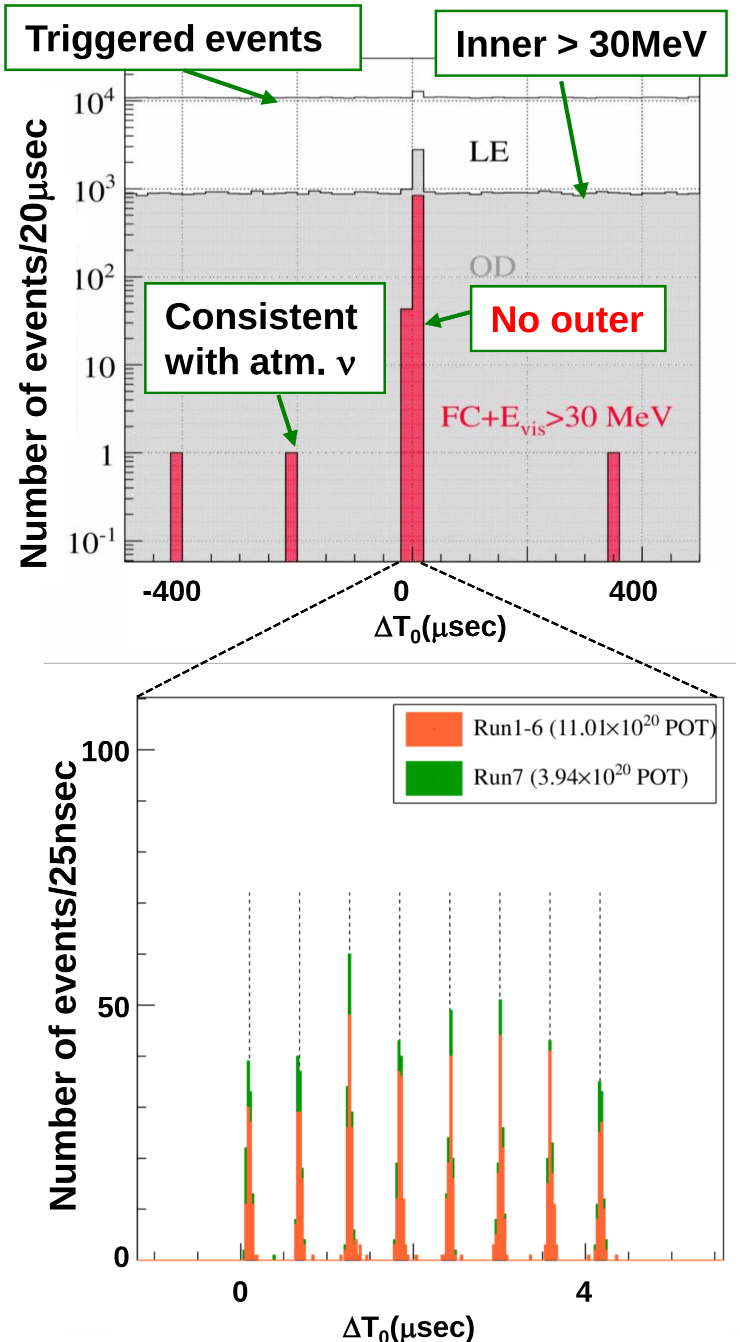
$\nu_\mu + n \rightarrow \mu^- + p$ **candidate**



Super-Kamiokande Event Selection

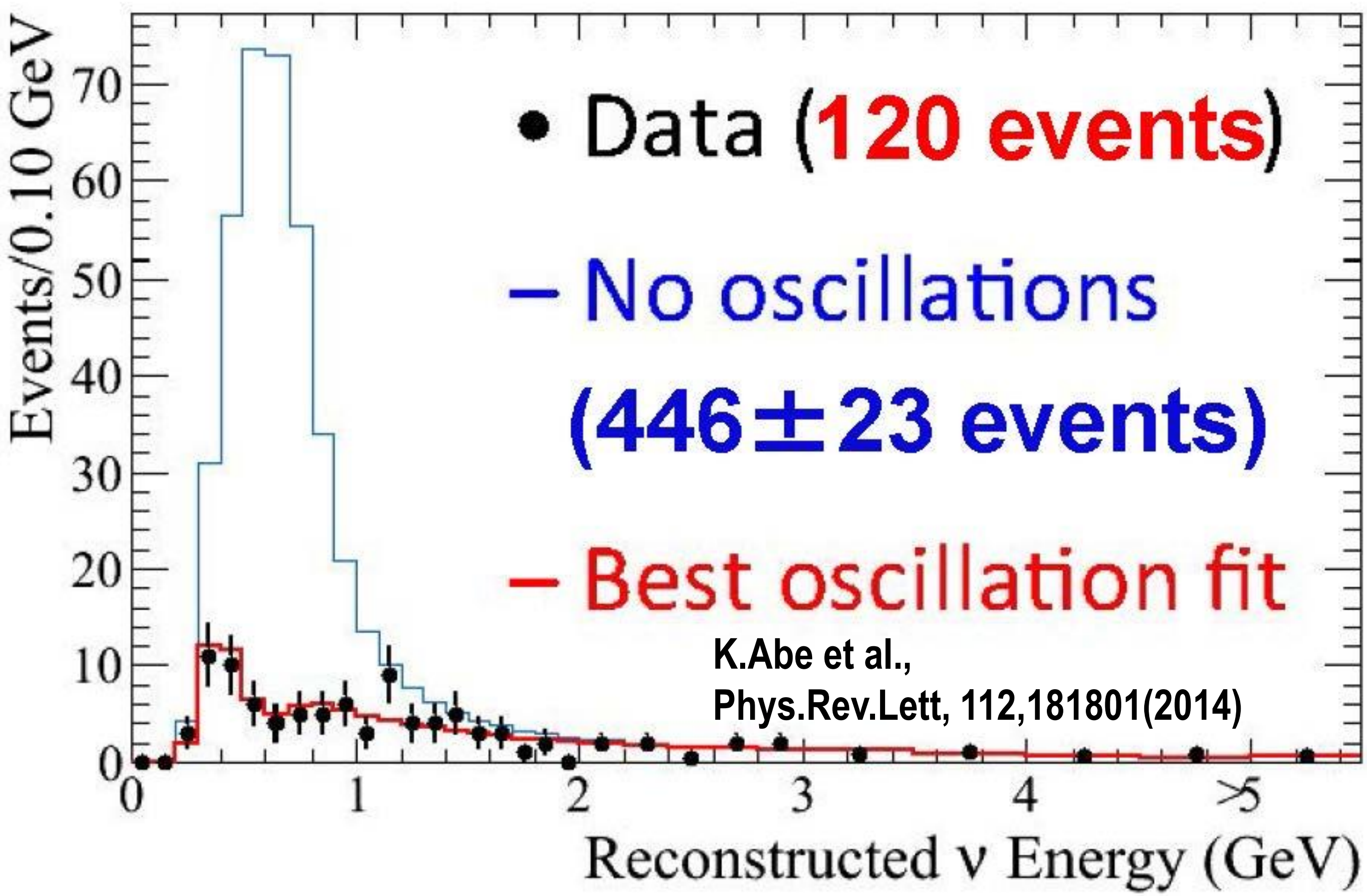
Event Selection Criteria

1. **Total energy deposit in the inner detector is larger than 30 MeV equivalent.**
2. **No outer detector activity**
3. **The event time agrees with ~5 μsec beam period in 2.48 sec accelerator cycle.**
   (8 bunch structure can be found.)
4. **1 Ring events**
   → e/μ particle identification is applied

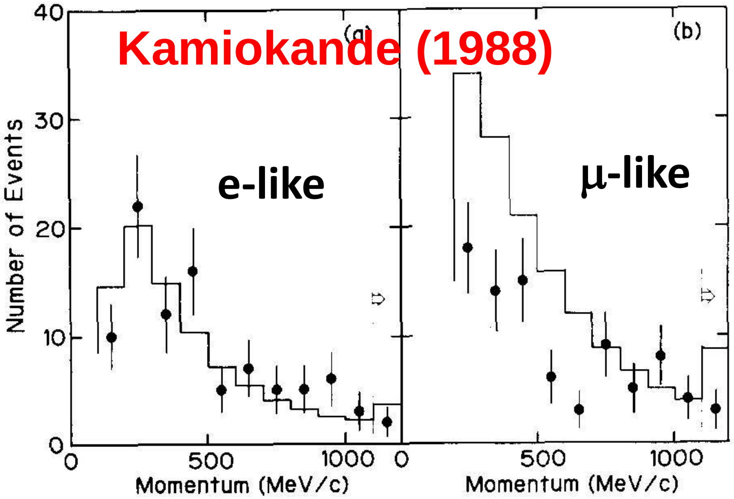


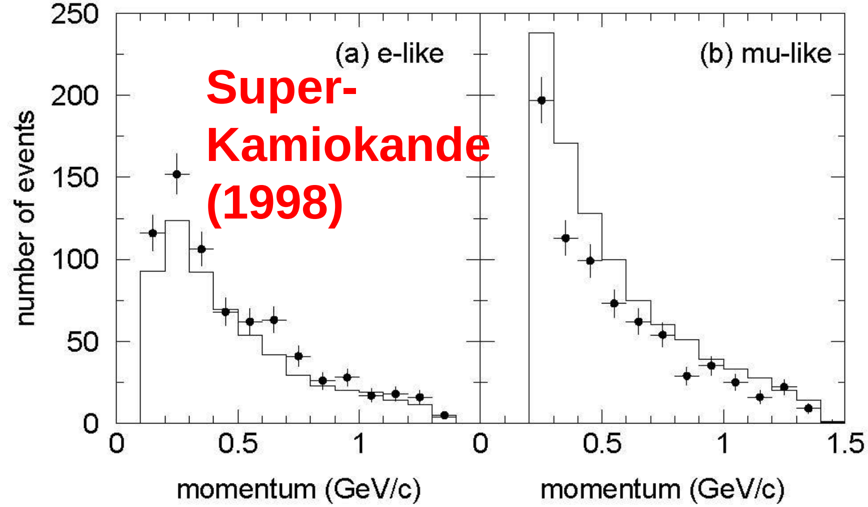
Results of ν_μ disappearance

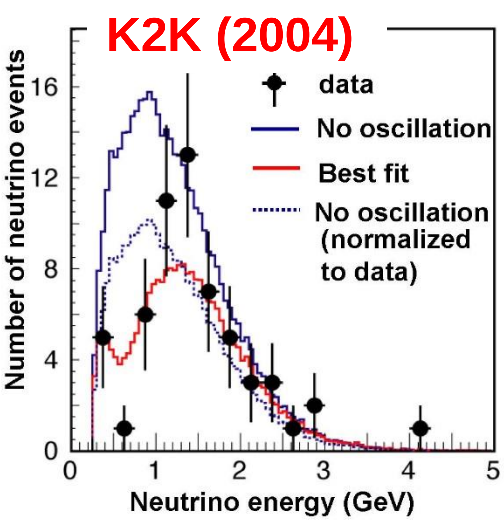
- **6.57 x 10^{20} POT data, which were accumulated between January 2010 and May 2013, were used.**
- **120 muon neutrino events are observed where 446±23 events are expected in the case of no oscillation. Distortion of the energy spectrum is also obvious.**

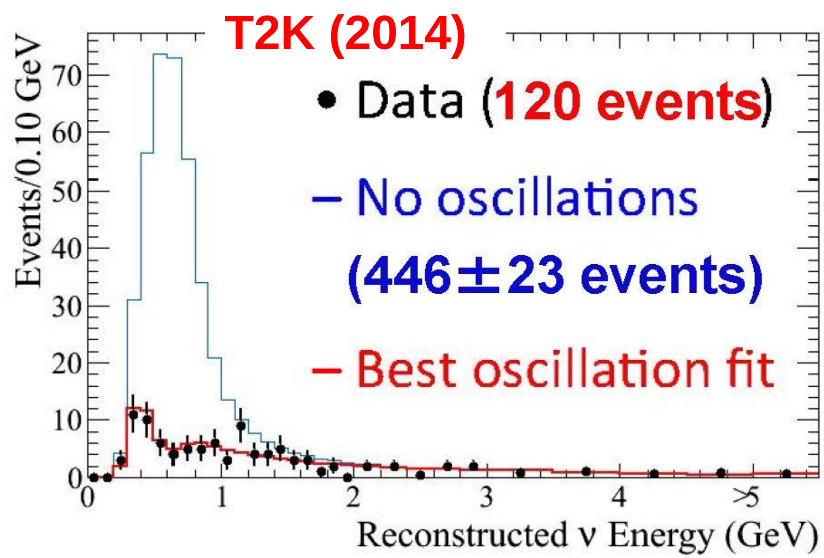


History of “muon neutrino deficit”









- Progress in a quarter of a century is very impressive.

Constraints on oscillation parameters in $\sin^2\theta_{23} - \Delta m^2_{32}$ plane

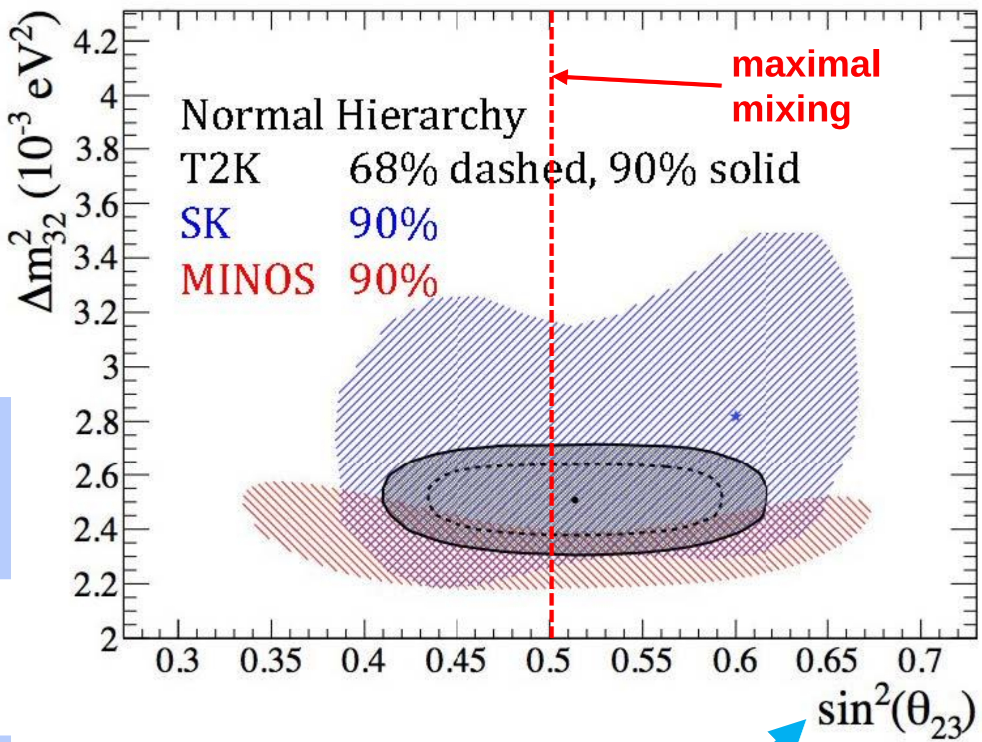
- **Constraints on oscillation parameters in $\sin^2\theta_{23} - \Delta m^2_{32}$ plane was obtained.**
- **Best-fit oscillation parameters are calculated to be**

$$\Delta m^2_{32} = (2.51 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

for normal hierarchy, and

$$\Delta m^2_{13} = (2.48 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.511 \pm 0.055$$

for inverted hierarchy.

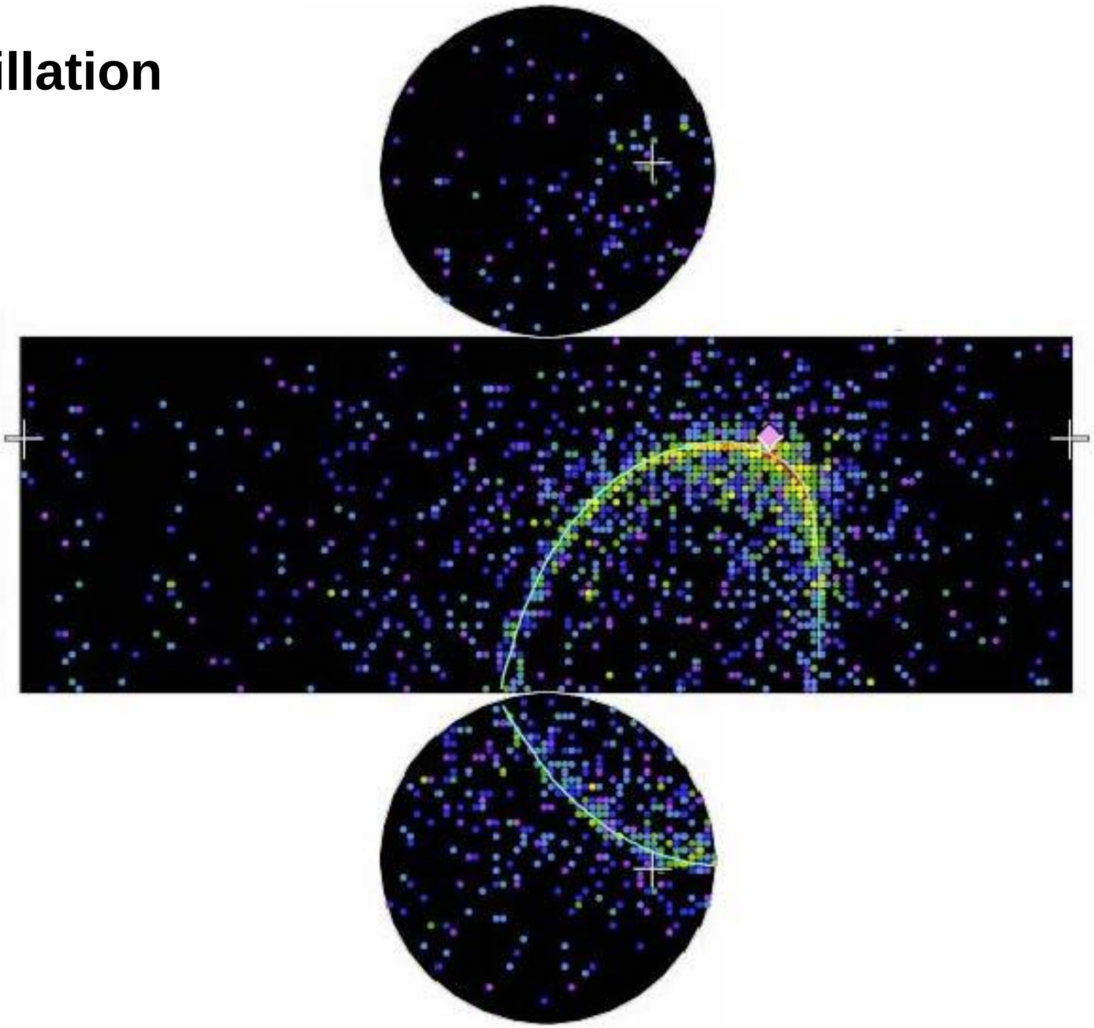


In the framework of the ν_μ-ν_τ 2 flavor oscillation, only $\sin^2 2\theta_{23}$ appears in the oscillation probabilities. Since $\sin^2\theta_{23}$ term appears in 3 flavor oscillation, $\sin^2\theta_{23}$ is used as horizontal axis instead of $\sin^2 2\theta_{23}$.

- **These results were most stringent constraints for $\sin^2\theta_{23}$ in 2014.**

ν_e appearance analysis

Possible $\nu_\mu \longrightarrow \nu_e$ oscillation candidate



Let me address ν_e/ν_μ ratio

ν_e/ν_μ ratio
(AN) ~1/2
(NB) order of ~1/100

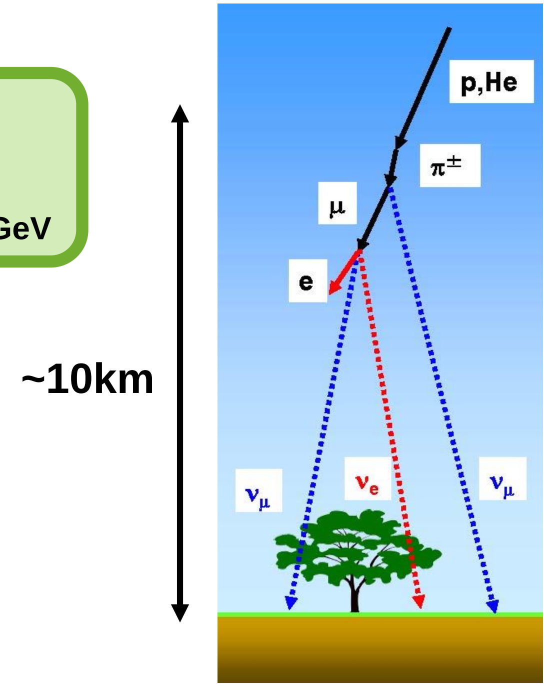
ν_e appearance search with atmospheric neutrinos

- Distance between π production point and the ground (which is "beam dump") is ~10km. Because of this long distance, most of muons decay, and additional ν_e and ν_μ are produced.

$$\pi \rightarrow \mu + \nu_\mu$$
$$\quad \mu \rightarrow e + \nu_e + \nu_\mu$$

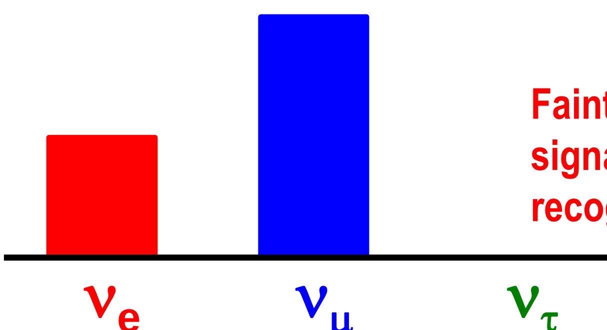
$d = (E/m) \cdot \tau \cdot c$
$d_\pi \sim$ 56m
$d_\mu \sim$ 6200m for E ~ 1GeV

Accordingly, ν_e/ν_μ is about 1/2.



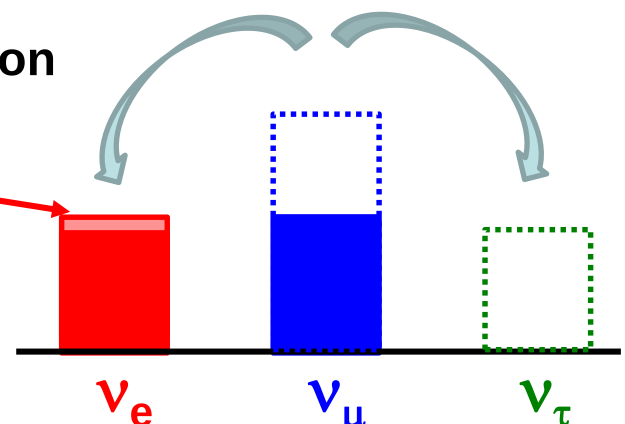
- Because of large number of original ν_e, faint oscillation signal cannot be recognized.

Before oscillation



After oscillation

Faint oscillation signal cannot be recognized.

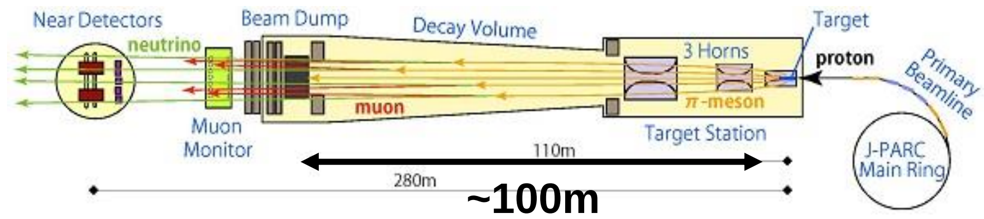


ν_e appearance search with neutrino beam

- Distance between π production point (target) and the beam dump is ~100 m. Most of muons are absorbed in the beam dump. Additional neutrinos are not produced.

$\pi \rightarrow \mu + \nu_\mu$

μ → Absorbed in beam dump

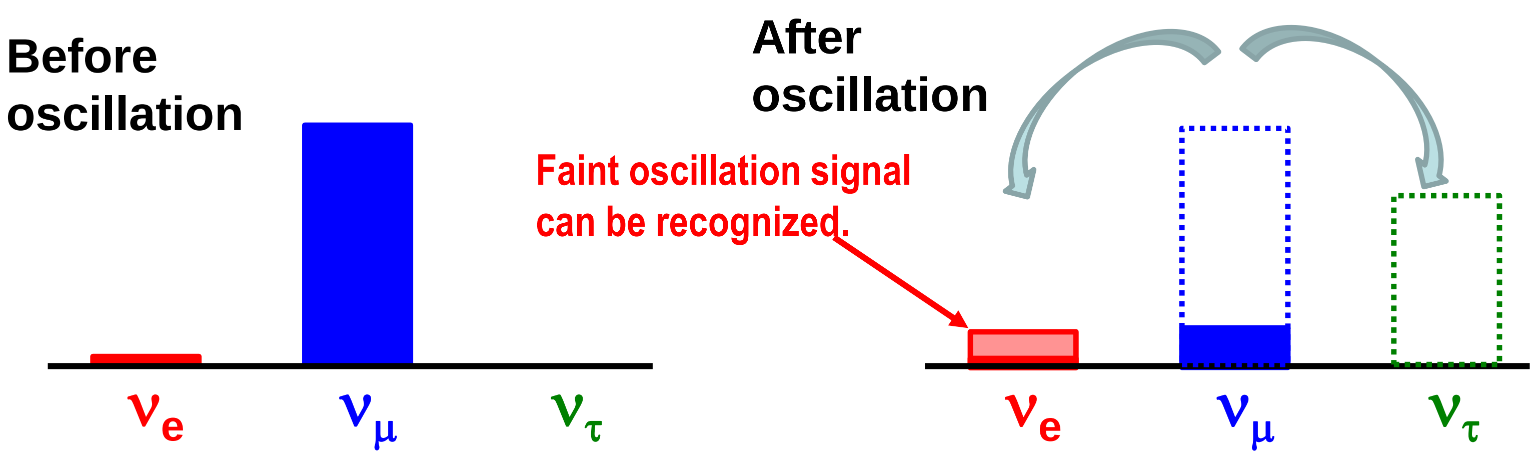


$d = (E/m) \cdot \tau \cdot c$

$d_\pi \sim$ 56m

$d_\mu \sim$ 6200m for E ~ 1GeV

- Accordingly, ν_e/ν_μ is order of ~1/100.
- Since number of original ν_e is quite small, faint ν_μ->ν_e appearance signal can be recognized. (From the experiment, it was found that ~5% of disappeared ν_μ goes not to ν_τ but to ν_e.)

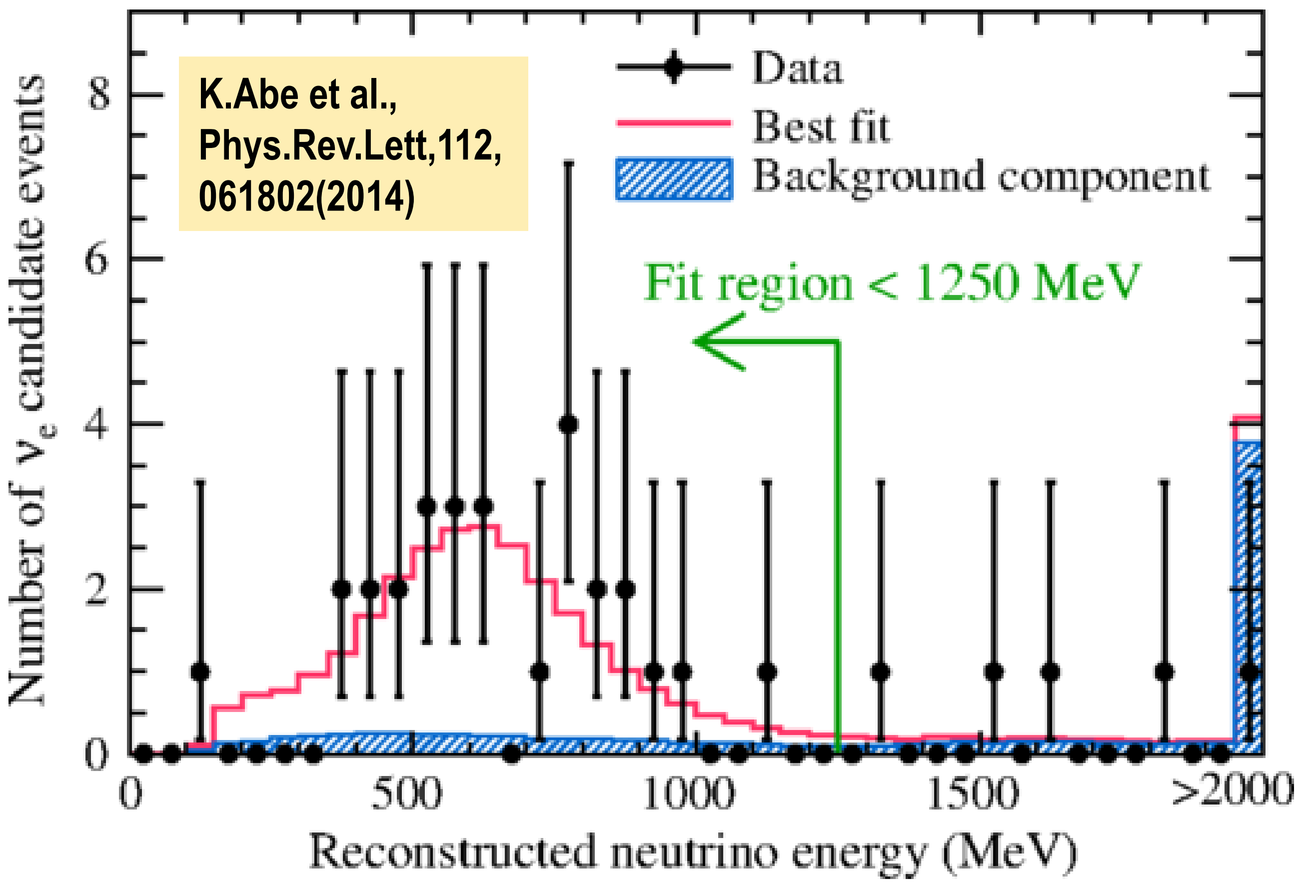


Results of ν_e appearance

- **6.57 x 10^20 POT data were employed. The period of the data is the same as the ν_μ disappearance analysis.**

- **Where expectation for no oscillation is 4.9±0.6(sys.) events, 28 events are found. The signal is 7.3σ and it is certainly discovery of neutrino oscillation from ν_μ to ν_e and also discovery of finite θ_{13}.**

- **This is the most successful achievement by T2K experiment so far.**



Results of ν_e appearance analysis

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$
$$\mp \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta_{CP}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

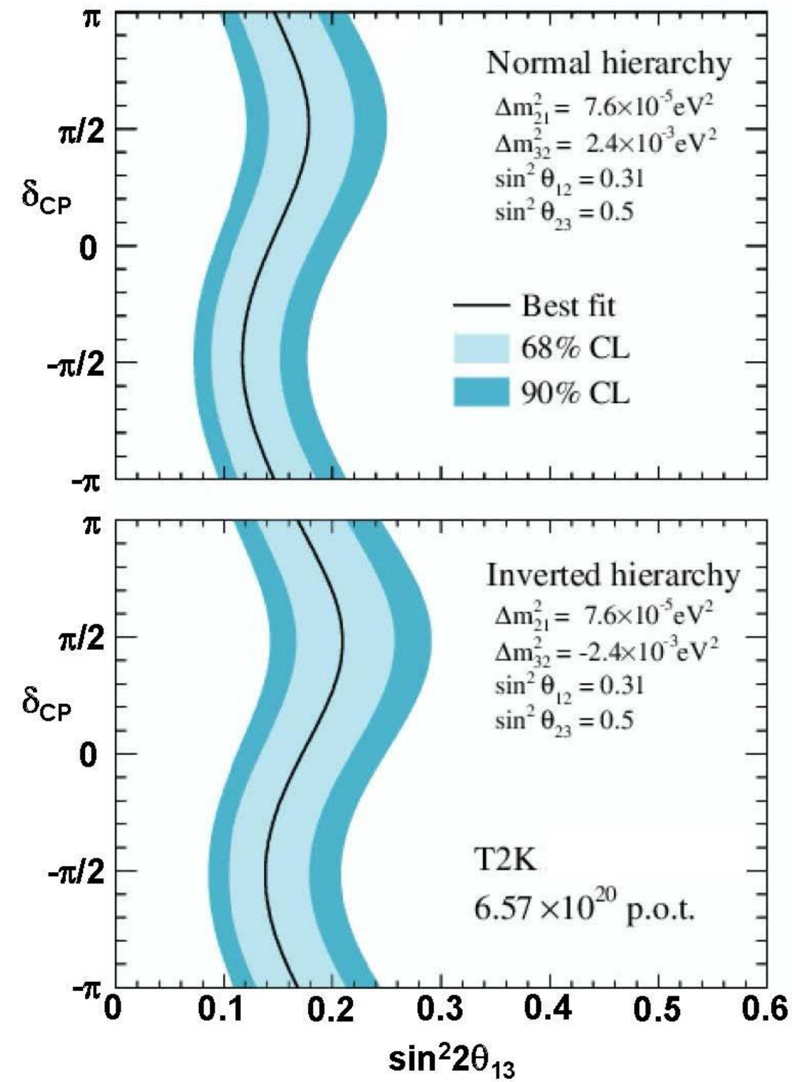
- **The 90% C.L. region in $\sin^2 2\theta_{13} - \delta_{CP}$ plane is obtained.**
- **When $\delta_{CP} = 0$ is assumed, The 68% C.L. intervals for $\sin^2 2\theta_{13}$ are**

$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$

for normal hierarchy, and

$\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$

for inverted hierarchy.



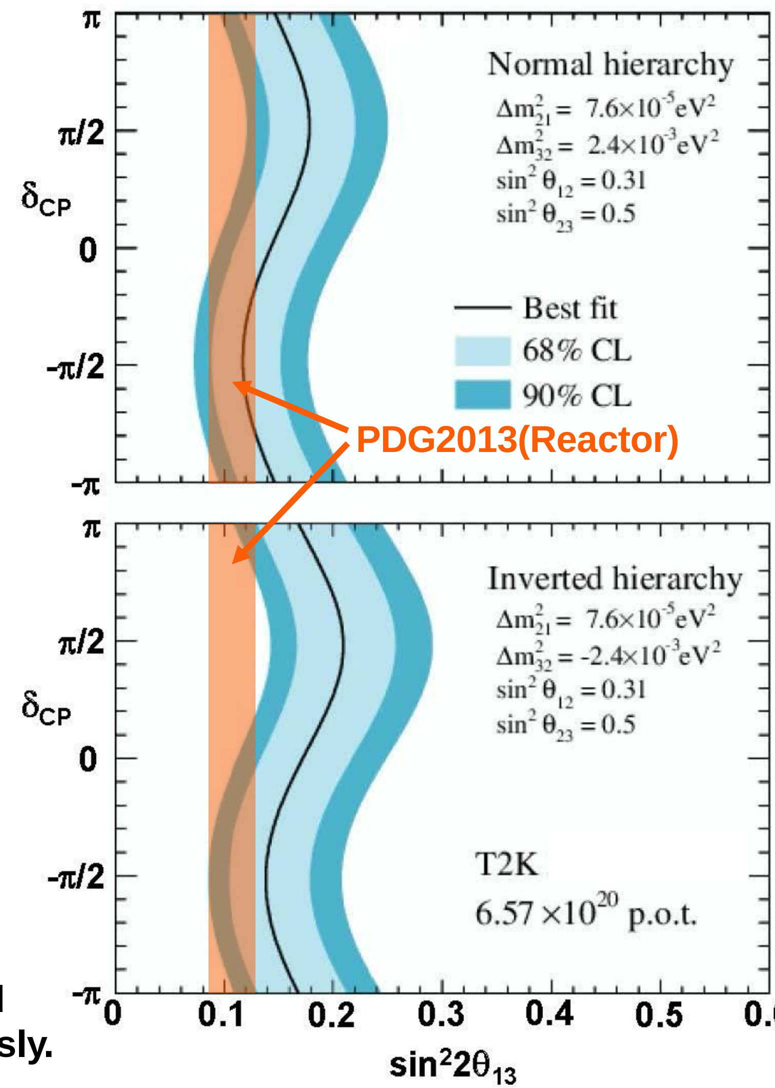
Combined with reactor constraints

- The T2K results are combined with constraints from reactor experiments (Daya Bay, Reno and Double Chooz);
  $\sin^2 2\theta_{13} = 0.095 \pm 0.010$ (PDG2013).
- It seems that negative δ_{CP} with normal hierarchy is favored.
- From more complicated and exhaustive statistical analysis*,

$$0.459 < \delta_{CP} < 2.592 \quad \text{(NH)}$$
and
$$-0.251 < \delta_{CP} < 3.427 \quad \text{(IH)}$$

are excluded with 90% C.L.

- The results are hints towards $\delta_{CP} \sim -\pi/2$ and normal hierarchy.

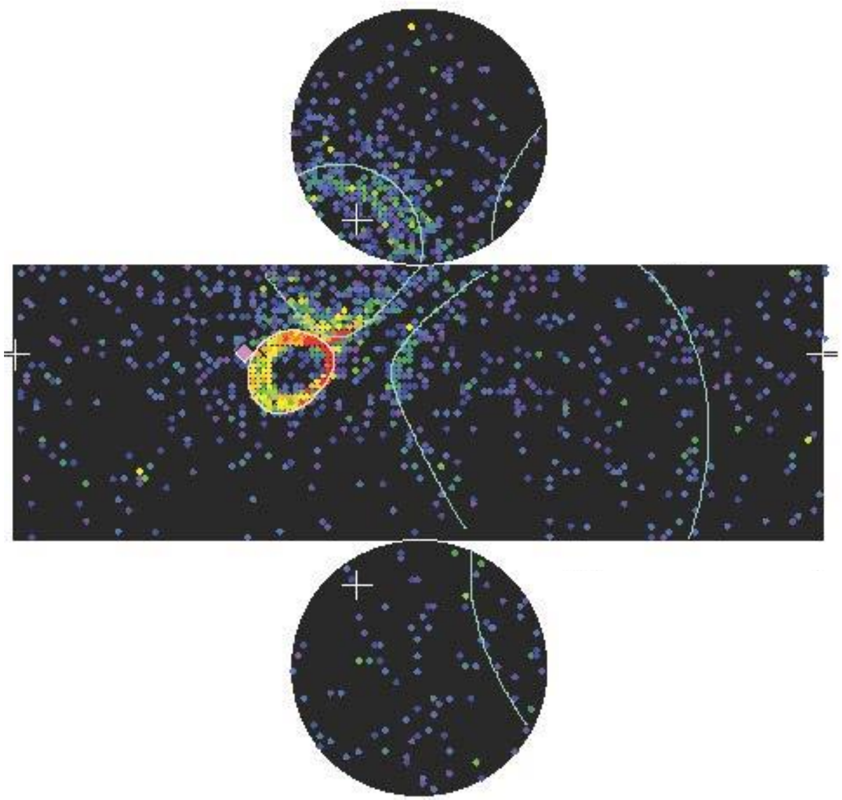


*ν_μ disappearance and ν_e appearance are combined, and 4 parameters (δ_{CP}, θ_{13}, θ_{23}, Δm^2_{32}) are fitted simultaneously.

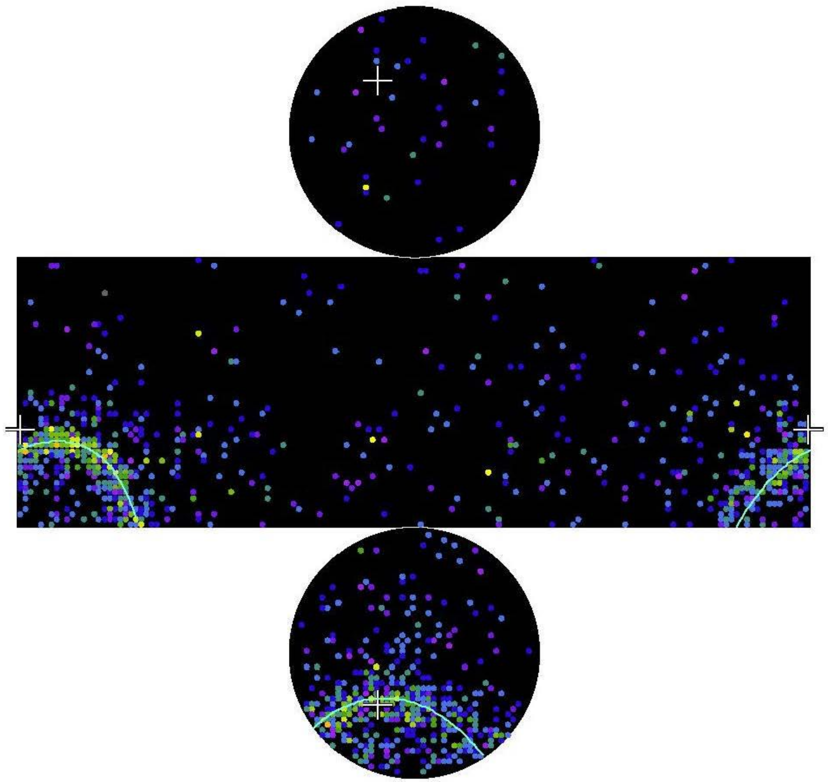
ν_e and $\bar{\nu}_e$ appearance analysis

- "History" is finished, and **the latest results** are presented from here! They were made public in August 2017.

The first neutrino event in $\bar{\nu}$-mode beam recorded on June-8-2014



Possible $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation candidate



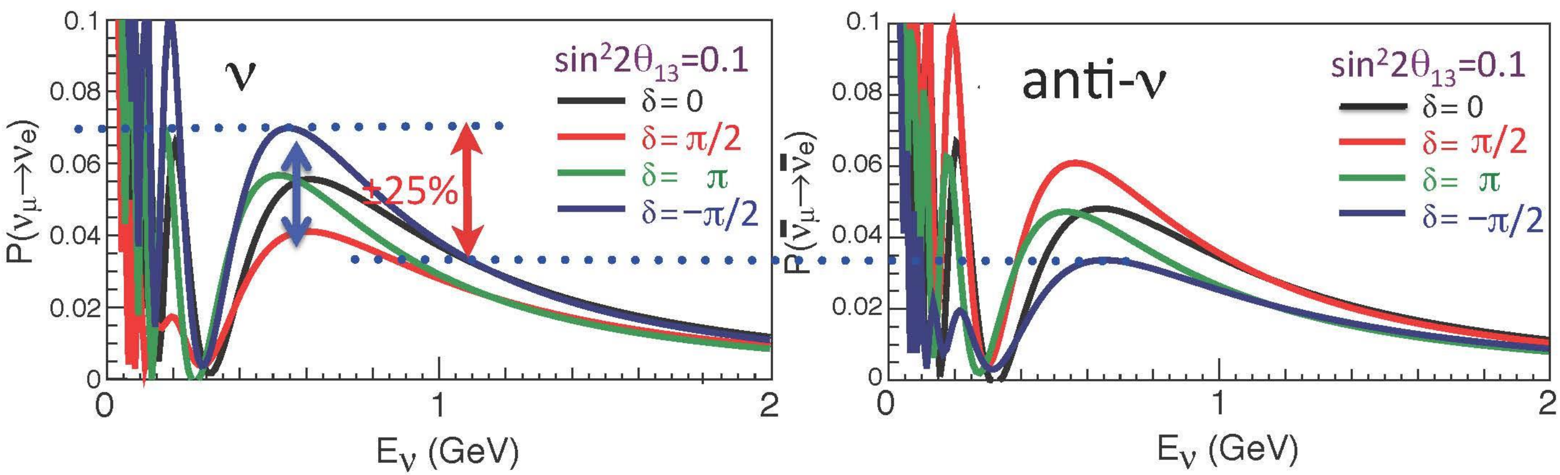
ν_e appearance and $\bar{\nu}_e$ appearance

- **The probability of ν_e appearance can be written as**

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$
$$\mp \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta_{\mathrm{CP}}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

- for neutrino, + for anti-neutrino

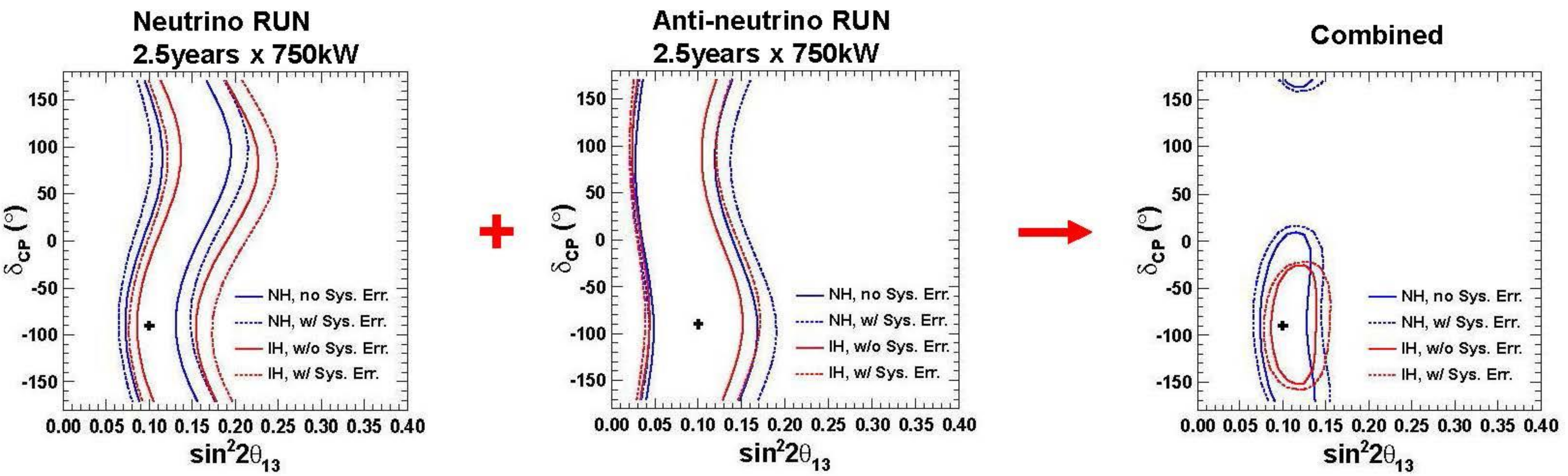
- **The sign of δ_{CP} term is reversed in anti-neutrino oscillation. If the anti-neutrino oscillation probability is larger (smaller) than the neutrino oscillation probability, it might be an evidence of positive (negative) δ_{CP} .**



Why do we need anti-neutrino beam for δ_{CP} ?

- **T2K collaboration are planning to assign 50% of the beam time to the anti-neutrino run. Future sensitivity studies are :**

"Neutrino Oscillation Physics Potential of the T2K Experiment", T2K collaboration, Prog. Theor. Exp. Phys. 043C01(2015)

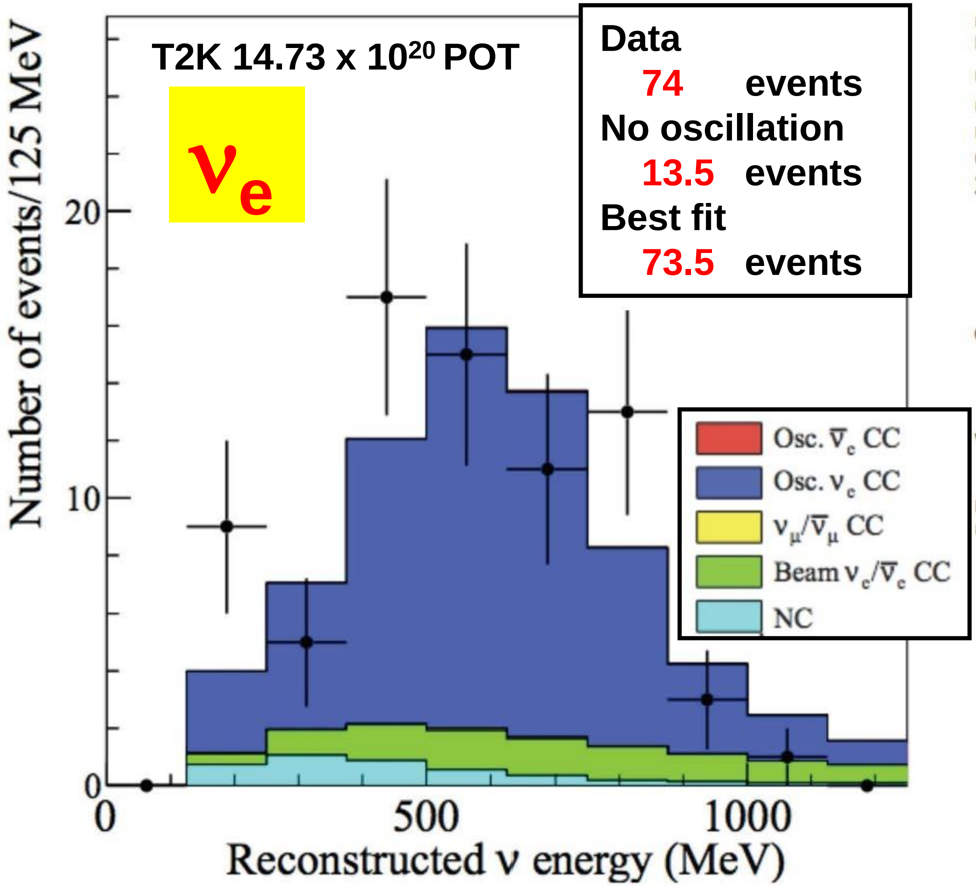


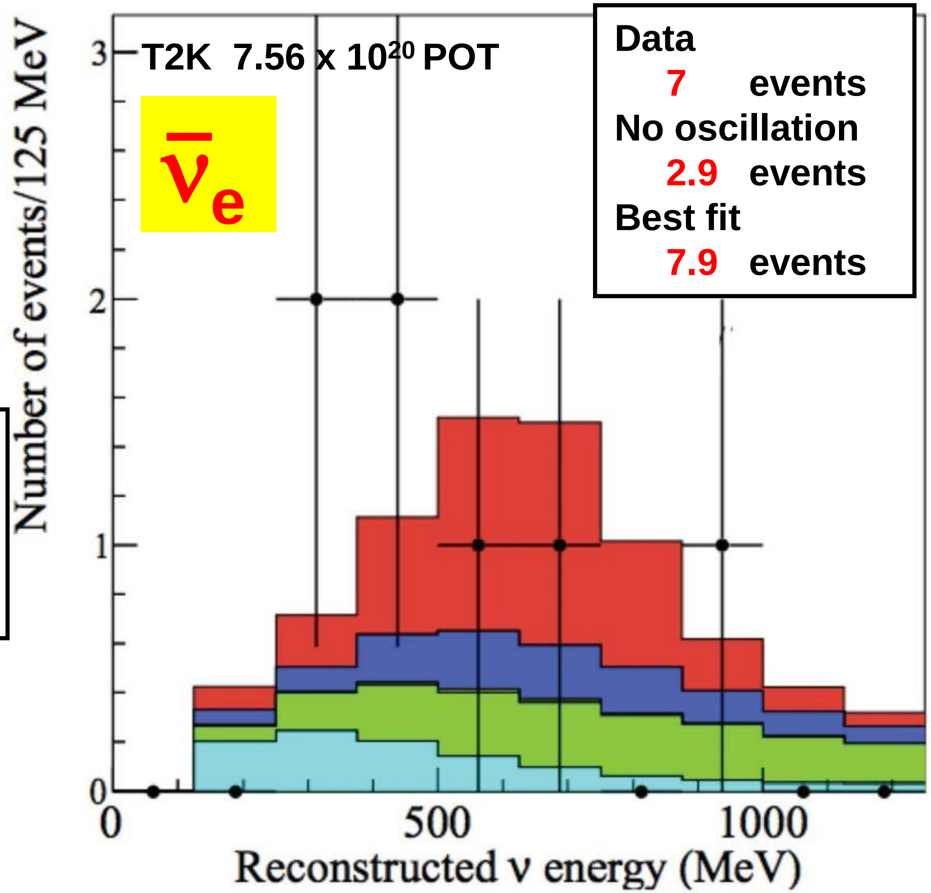
- **By combining neutrino and anti-neutrino results, constraints on δ_{CP} range can be obtained by a single experiment without help of reactor results.**

Results of ν_e and $\bar{\nu}_e$ appearance

Preliminary results in Summer 2017, update of K.Abe et al., Phys.Rev.Lett, 118,151801(2017)

- For ν_e appearance, 74 events are found where expectation for no oscillation is 13.5. It is certainly ν_e appearance signal.
- For $\bar{\nu}_e$ appearance, 7 events are found where expectation for no oscillation is 2.9. Obviously more statistics is needed.





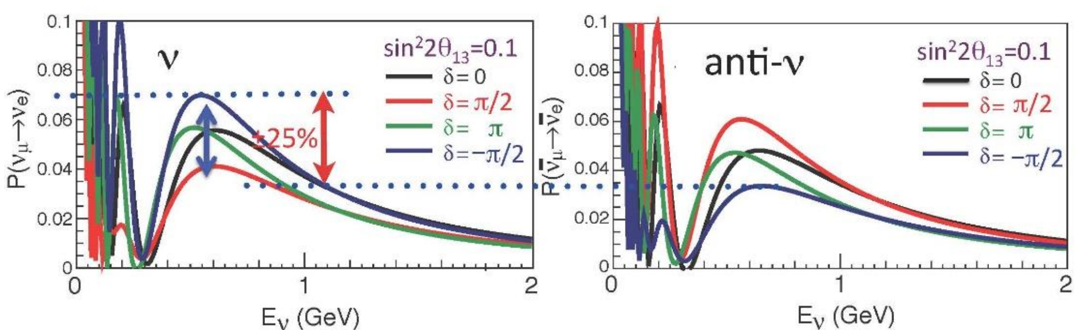
Number of $\nu_e/\bar{\nu}_e$ events and expectations

- Number of ν_e and $\bar{\nu}_e$ events are compared with expectations with various δ_{cp} values.

hierarchy	ν_e/ν_e	Data	Expected			
			$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$
Normal	ν_e(CCQE)	74	73.5	61.4	49.9	61.9
	ν_e(CC1π)	15	6.9	6.0	4.9	5.8
	$\bar{\nu}_e$(CCQE)	8	7.9	9.0	10.0	8.9

ν_e(CC1π) event sample is also employed to improve statistics

- Let me remind you that….

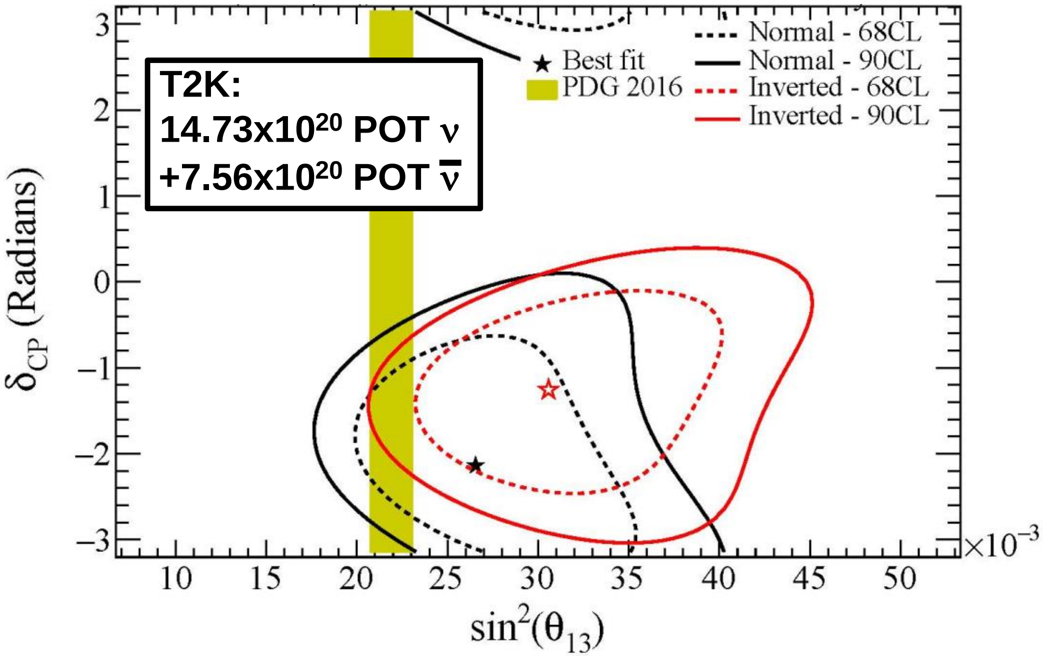


If the $\bar{\nu}$ oscillation probability is smaller than the ν oscillation probability, it might be a evidence of negative δ_{CP} .

- Clearly, normal hierarchy with δ_{cp} ~ $-\pi/2$ gives the best agreement.

Constraints on $\sin^2\theta_{13} - \delta_{cp}$ plane

- Constraints on $\sin^2\theta_{13} - \delta_{cp}$ plane are calculated. Constraints from reactor experiments given by PDG2016 are also shown. Note that T2K can give a constraints on δ_{CP} by a single experiment.



- The best fit δ_{cp} is $\delta_{cp} = -1.83$ with normal hierarchy. It is almost $-\pi/2(=-1.57)$.

- The 2σ C.L. allowed intervals are

$-2.98 < \delta_{CP} < -0.60$ (NH) and $-1.54 < \delta_{CP} < -1.19$ (IH)

The CP-conserving values, $\delta_{cp} = 0$ and $\delta_{cp} = \pi$, fall outside 2σ C.L. intervals.

- **Hints towards $\delta_{CP} \sim -\pi/2$ and normal hierarchy.**

Summary of Neutrino oscillations in 2017

- Δm^2_{21} and θ_{12} were determined by solar/reactor neutrino experiments.

  $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.307 \pm 0.013$ $\theta_{12} \sim 33^{\circ}$

- $|\Delta m^2_{32}|$ and θ_{23} were studied by atmospheric/long-baseline experiments.

  $|\Delta m^2_{32}| = (2.45 \pm 0.05) \times 10^{-3}\, \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.51 \pm 0.04$ for normal hierarchy

  $\theta_{23} \sim 45^{\circ}$

  $|\Delta m^2_{32}| = (2.52 \pm 0.05) \times 10^{-3}\, \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.50 \pm 0.04$ for inverted hierarchy

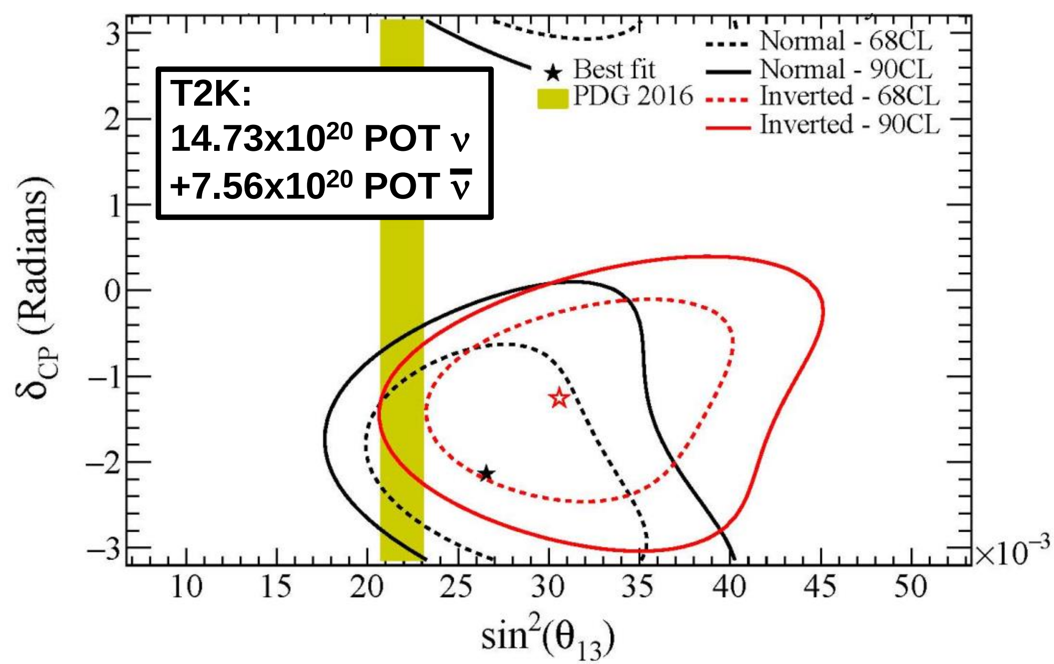
- θ_{13} was studied by long-baseline/reactor experiments.

  $\sin^2\theta_{13} = 0.0210 \pm 0.0011$

PDG2017

- At present, the CP violation phase δ_{CP}, and mass hierarchy, sign of Δm^2_{32} are still unknown.

- The first hints towards $\delta_{CP} \sim -\pi/2$ and normal hierarchy are obtained.



History of Discoveries by neutrino experiments

1956 Reines and Cowan discovered anti-electron neutrino from a reactor (N)
1962 Muon neutrino beam experiment by L.Lederman et al (N)
1965 KGF observed atmospheric neutrino
1968 Homestake experiment claimed solar neutrino deficit (N)
1973 Neutral Current interaction was discovered by Gargamelle
1987 Kamiokande and IMB detected neutrinos from supernova SN1987A (N)
1988 Kamiokande claimed atmospheric muon neutrino deficit
1989 Kamiokande confirmed the solar neutrino deficit
1998 Super-Kamiokande observed atmospheric neutrino oscillation (N)
1998 Super-Kamiokande confirmed solar neutrino deficit
2000 DONUT observed tau neutrino
2001 SNO confirmed solar neutrino oscillation by neutral current measurement (N)
2002 Kamland observed deficit of reactor neutrinos
2004 K2K confirmed atmospheric neutrino oscillation by artificial neutrino beam
2006 Completely independent confirmation of ν_μ-ν_τ oscillation by MINOS
2011 First indication of non-zero θ_{13} by T2K
2012 Non-zero θ_{13} was confirmed by 3 reactor experiments
2013 Evidence of non-zero θ_{13} by T2K
2015 Hints toward negative δ_{CP} by T2K
2015 Discovery of ν_τ signal from ν_μ-ν_τ oscillation by OPERA

Main topics of my lecture, and will be presented precisely.
Related to main topics, and will be mentioned briefly.

Summary

- Neutrino physics made great progress in recent several decades guided by many experiments.

- Experiments in Kamioka contributed to the progress significantly.

Appendix:
The birth of Kamiokande

This is not a physics session, but a kind of business session…..

Introduction

- Kamiokande (1983 - 1996) was the first Nobel Prize experiment outside of Europe and America in the field of high energy physics.

- Kamiokande was small manpower / small budget experiment.
  In the first Kamiokande paper in 1985, only 12 authors. They are
  7 staffs (about 5 Full Time Equivalent) and 5 graduate students.

- The initial budget for the experiment was 5 Oku-yen and additional running cost was about 1 Oku-yen/year. It was quite small budget.
  (1 Oku-yen ~ 0.5 Million US dollars in early 1980s.)

- Reporting why Kamiokande experiment succeeded with small manpower / small budget will be very instructive.

Search for Nucleon Decay into Charged Lepton+Mesons

Katsushi ARISAKA, Takaaki KAJITA, Masatoshi KOSHIBA,
Masayuki NAKAHATA, Yuichi OYAMA, Atsuto SUZUKI,
Masato TAKITA, Yoji TOTSUKA, Tadashi KIFUNE,†
Teruhiro SUDA,† Kasuke TAKAHASHI†† and Kazumasa MIYANO†††

Department of Physics and ICEPP, University of Tokyo, Tokyo 113
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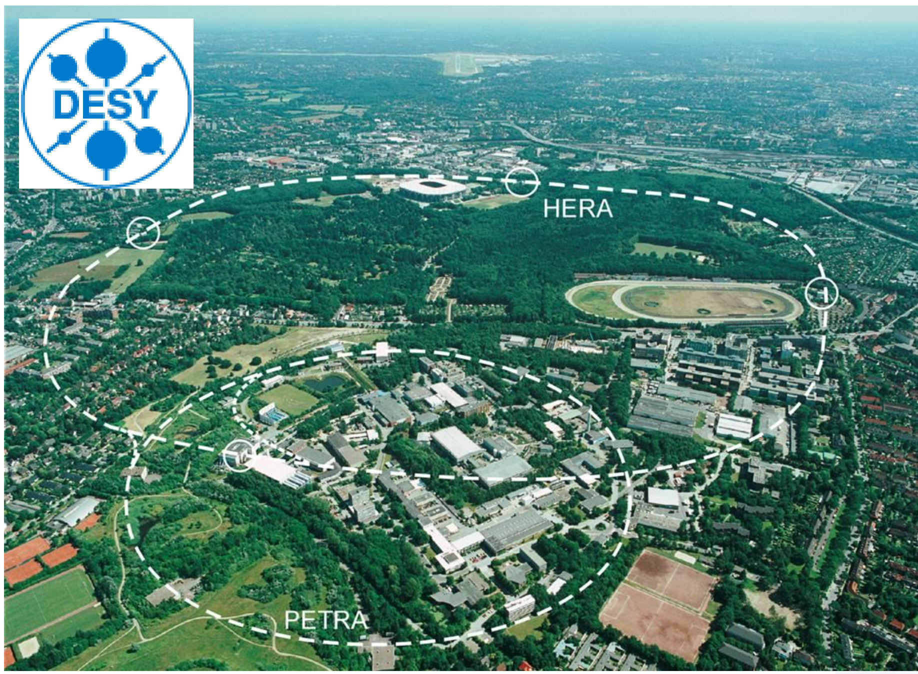
††KEK, National Laboratory for High Energy Physics, Ibaraki 305
†††Department of Physics, University of Niigata, Niigata 950–21

(Received July 19, 1985)

Before Kamiokande experiment…..

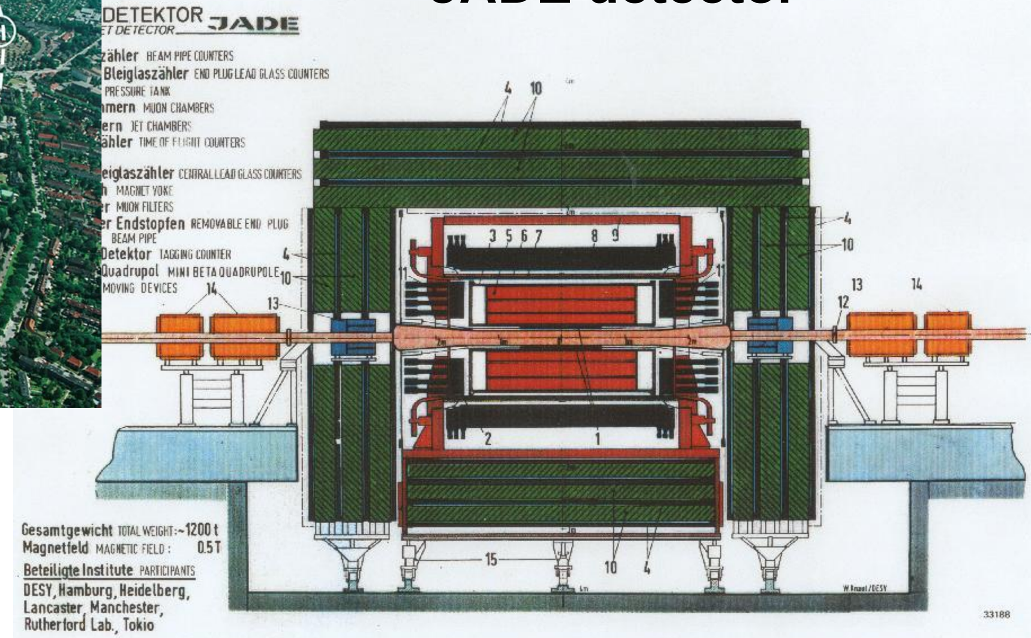
- Before Kamiokande experiment, Koshiba's group in department of physics, University of Tokyo participated in JADE Experiment (1977-1986) in PETRA Ring in DESY, Hamburg.

- Kamiokande was the second and local experiment of the group.
  It was planned just after the JADE experiment started successfully.



PETRA Ring in DESY

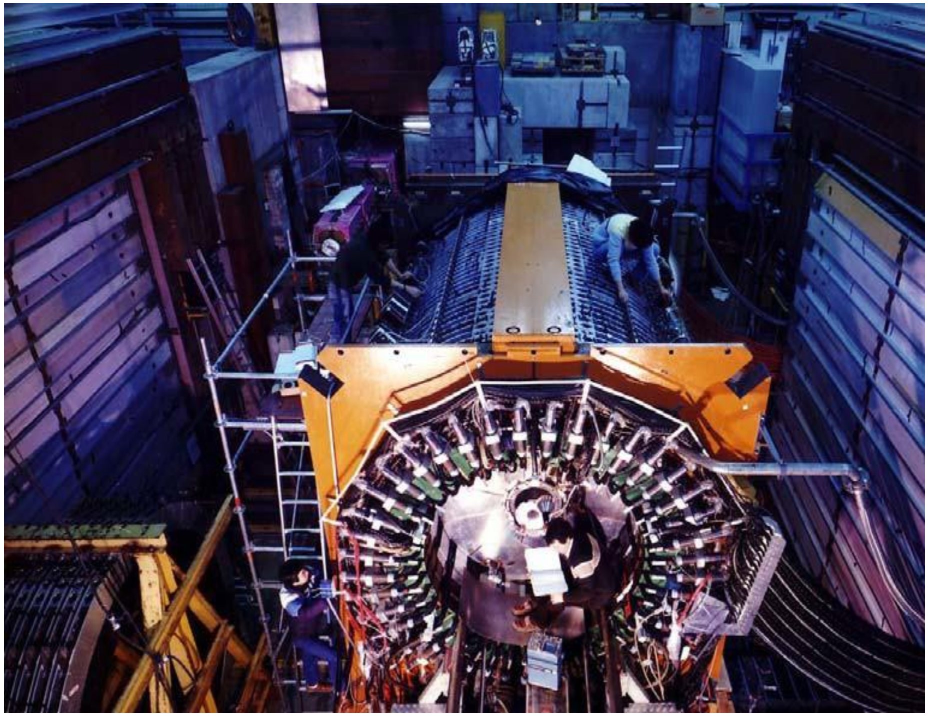
JADE detector



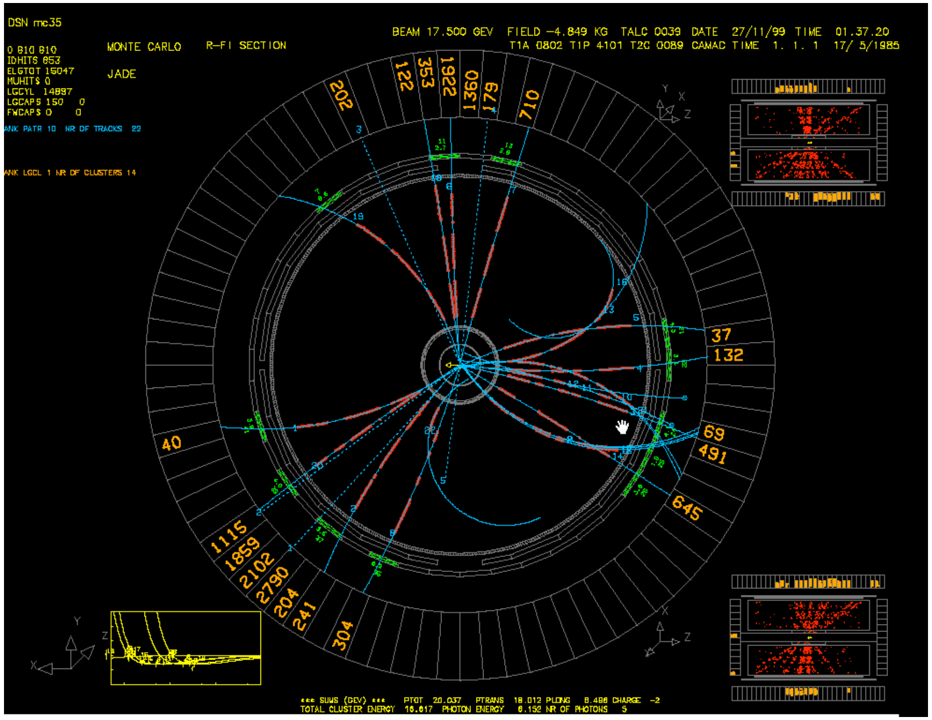
JADE experiment

- JApan Deutschland England collaboration.
- The main purpose of the experiment was observation of heavier new quarks. Unfortunately, it was not succeeded.
- Instead, 3 jet events which directly show existence of gluons were discovered together with other 3 experiments in PETRA.

JADE detector



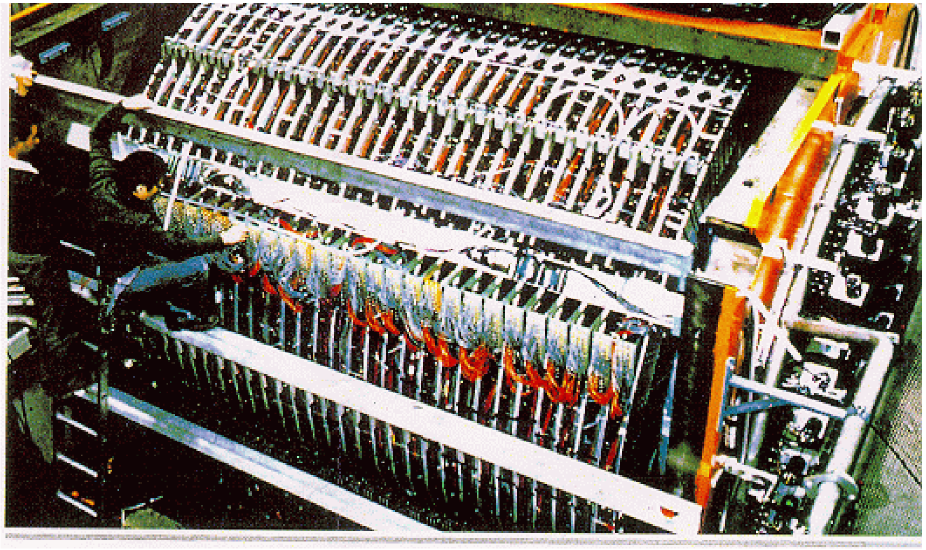
gluon event



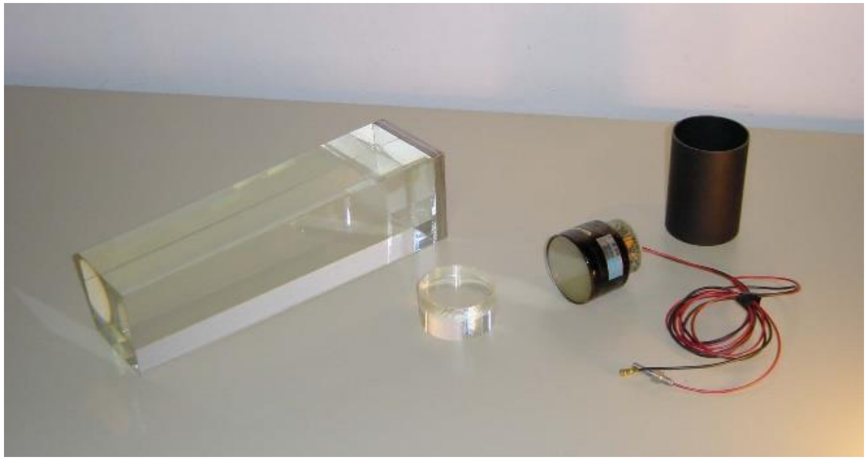
Lead glass counter and photomultiplier tubes (PMT)

- In JADE experiment, Koshiba's group took charge of lead glass counters. It is a calorimeter to measure energy of electro-magnetic showers. Basically, it consists of a total of 2712 photomultiplier tubes (PMTs) and lead glasses.

Assembling JADE Lead glass counter



Lead glass and PMT for OPAL experiment
(sorry! I could not find that of JADE)



- At that time, the leading company of the PMTs was Philips in Nederland. PMTs made by Philips and made by Hamamatsu were compared and obviously Philips PMTs were much much better than Hamamatsu PMTs.

Hamamatsu PMTs !

- Koshiba decided to use Hamamatsu PMTs although all other collaborators strongly opposed it. Koshiba said
  "Our research budget is funded by the Japanese government. For the critical and high-technology component of the detector, we must purchase Japanese products as much as possible.“

- Hamamatsu developed new PMTs for JADE lead glass counters with cooperation of Japanese JADE members. Hamamatsu accumulated experience in the design of PMTs thanks to Koshiba's decision.

- It was real “first step” for the Kamiokande experiment.

Hamamatsu R594 PMT
for JADE experiment

Development of 20-inchΦ PMT

- When the planning of Kamiokande experiment started around 1979, IMB group have already started similar project independently in USA.

- The IMB detector is larger and the start of the experiment is earlier. It seems there is no advantage in Kamiokande.

	IMB	Kamiokande
Total (Fiducial) Volume	8000 ton (3300 ton)	3000 ton (1000 ton)
Start	1982	1983
PMTs (size x number)	8 inchΦ x 2048	20 inchΦ x 1000

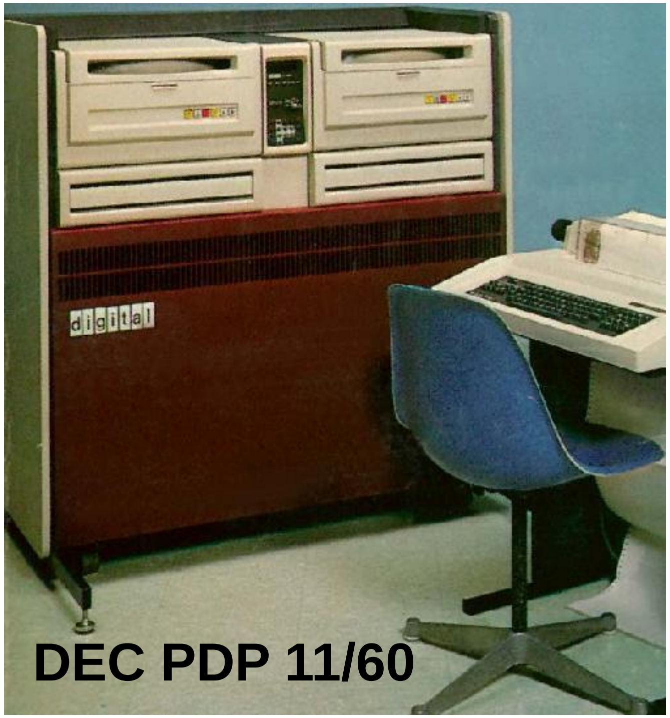
- "Ask Hamamatsu to make new PMTs which have large diameter. They cannot reject my request. They succeeded as a PMT company after we selected Hamamatsu PMTs for JADE experiment!"

- 20-inchΦ PMTs were developed, and precise measurement became possible with large photo collection.
It led to the success of the experiment.

Use property of JADE experiment !

- The tank including PMT support structure was designed and constructed by Mitsui Engineering and Shipbuilding Co.,Ltd.
  The company also designed structure of the JADE lead glass counter. The group had enough experience of communication with the company.

- DEC PDP 11/60 was used as on-line data-taking computer. The group asked how to use it to a JADE member since PDP 11 series was used in JADE.



DEC PDP 11/60

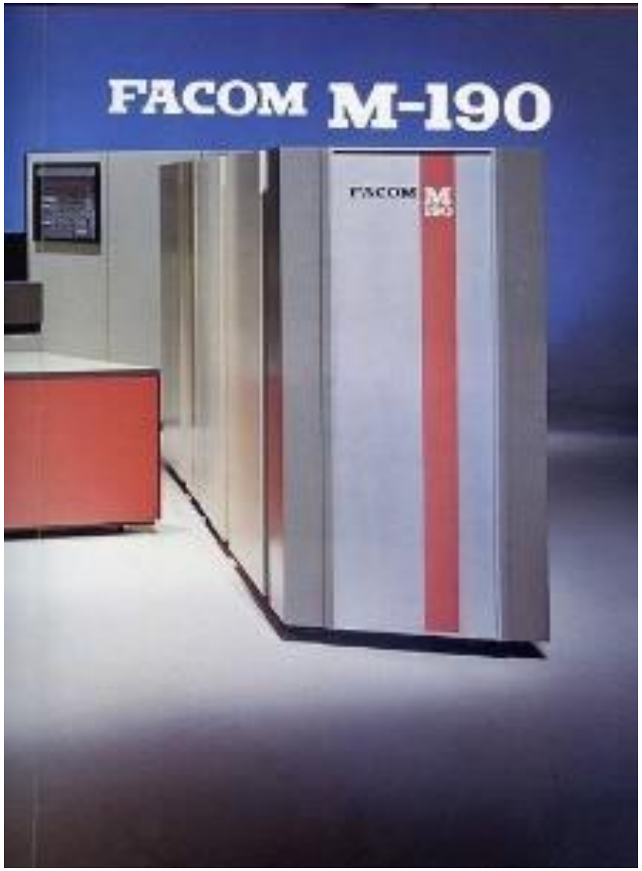
- For readout electronics, high voltage power supplies and distributors, ready-made electronics were purchased. For some of the component, second-hand modules were used.

Use property of JADE experiment !

- For off-line analysis computer, an IBM-type mainframe computer, FACOM M-190 for JADE experiment was used without any charge. Kamiokande members were just USERS of the computer, and did not care any maintenance and management.

- In the analysis computer, all utility software for JADE experiment were used. They include data structure or event display.

- For Monte Carlo simulation program, lead glasses were replaced with water, and only geometry was changed.



To summarize, Kamiokande borrow (or steal) almost everything from JADE experiment. In that sense, Kamiokande is (JADE)' at the first stage. That is one reason why Kamiokande started with small manpower and small budget.

What young physicists from emerging countries can learn from Kamiokande experience?

- In future, you will form high energy experimental groups in your own countries, and will join large international collaborations in foreign countries. Keep in mind following…….

For critical and high-technology components of the detector, purchase your own national products.
It would contribute to technology upgrade of your national companies, and would be the "first step" of your future experiments.

You should consider to imitate a detector component and start your own experiment in your own country. You can borrow (or steal) every property/experience/technology/software/hardware/manpower from your international collaboration.

Thank you !