INSS 2018

Mainz, May 27, 2018

Atmospheric neutrino oscillations

Takaaki Kajita

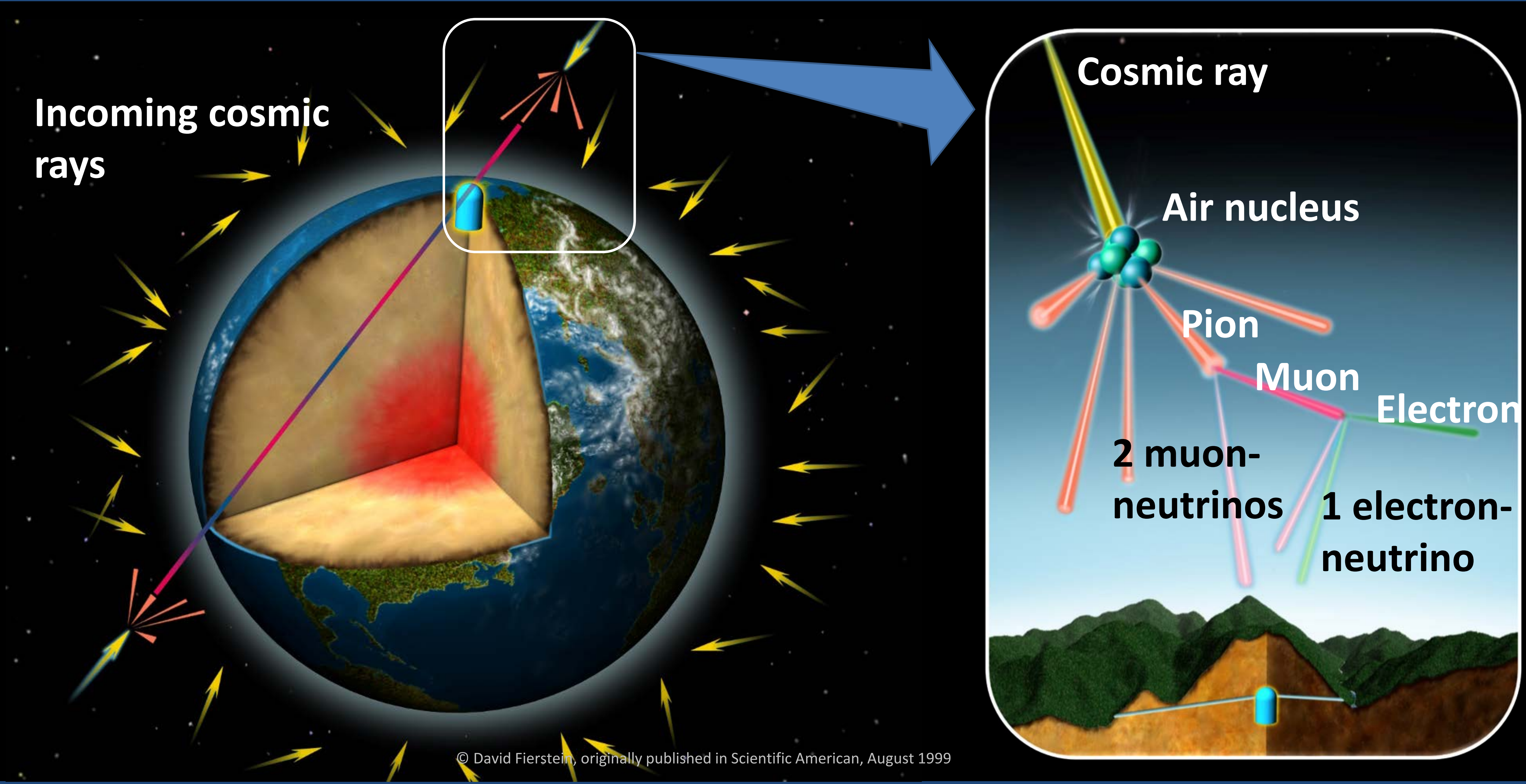
Institute for Cosmic Ray Research, The Univ. of Tokyo

Outline

- *Introduction: atmospheric neutrinos and the early days*
- *Kamiokande*
- *Atmospheric neutrino deficit*
- *Super-Kamioande*
- *Discovery of neutrino oscillations*
- *Neutrino oscillation studies*
- *Future neutrino oscillation experiments*
- *Summary*

Introduction: atmospheric neutrinos and the early days

Atmospheric neutrinos



Discovery of atmospheric neutrinos (1965)

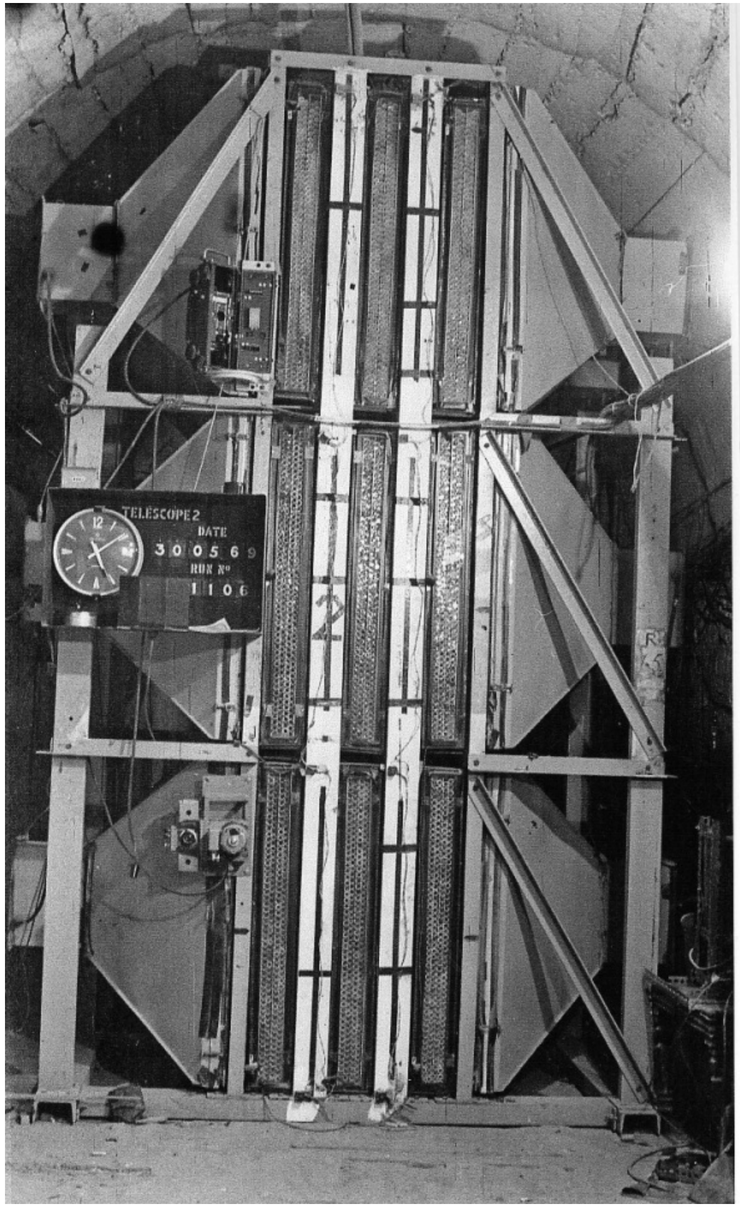
In 1965, atmospheric neutrinos were observed for the first time by detectors located very deep underground.

←In South Africa
F. Reines et al., PRL 15, 429 (1965)

→ In India
C.V. Achar et al., PL 18, 196 (1965)

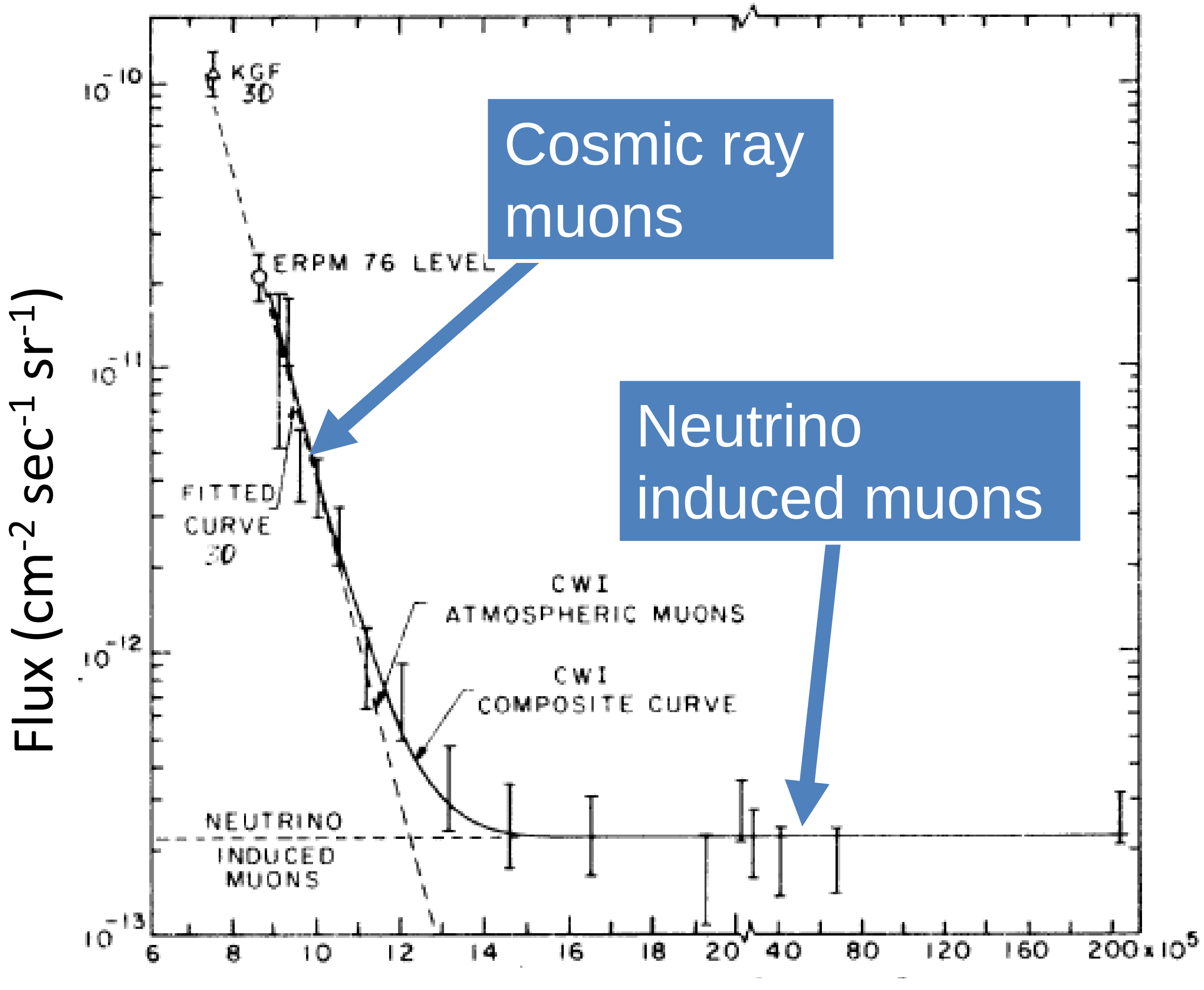
Photo by H.Sbel

Photo by N. Mondal

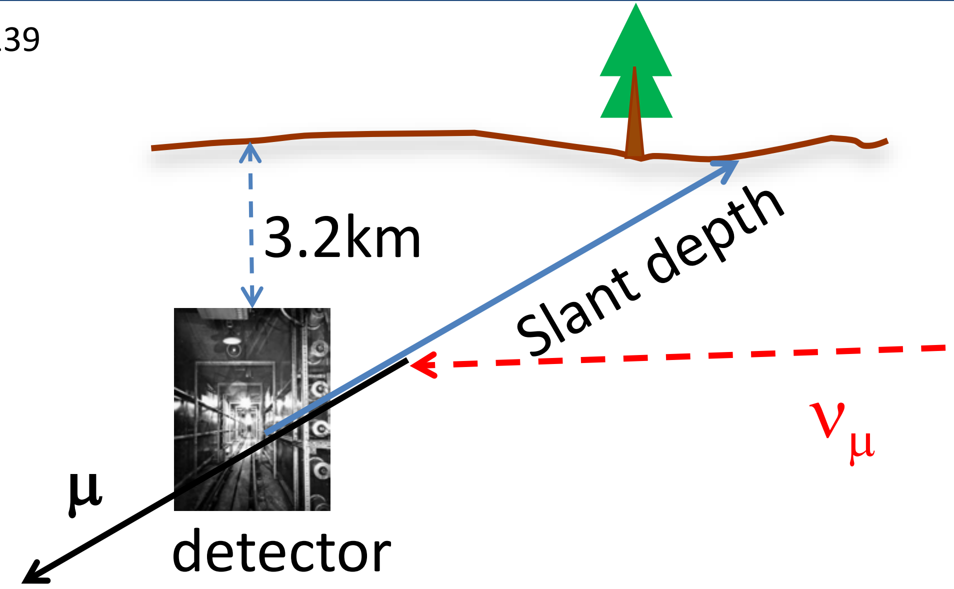


Slant depth distribution (from the South Africa experiment 1978)

M.F.Crouch et al., PRD 18 (1978) 2239



Slant depth ($h=h_v\cos^{-1}\theta$, m.w.e.)

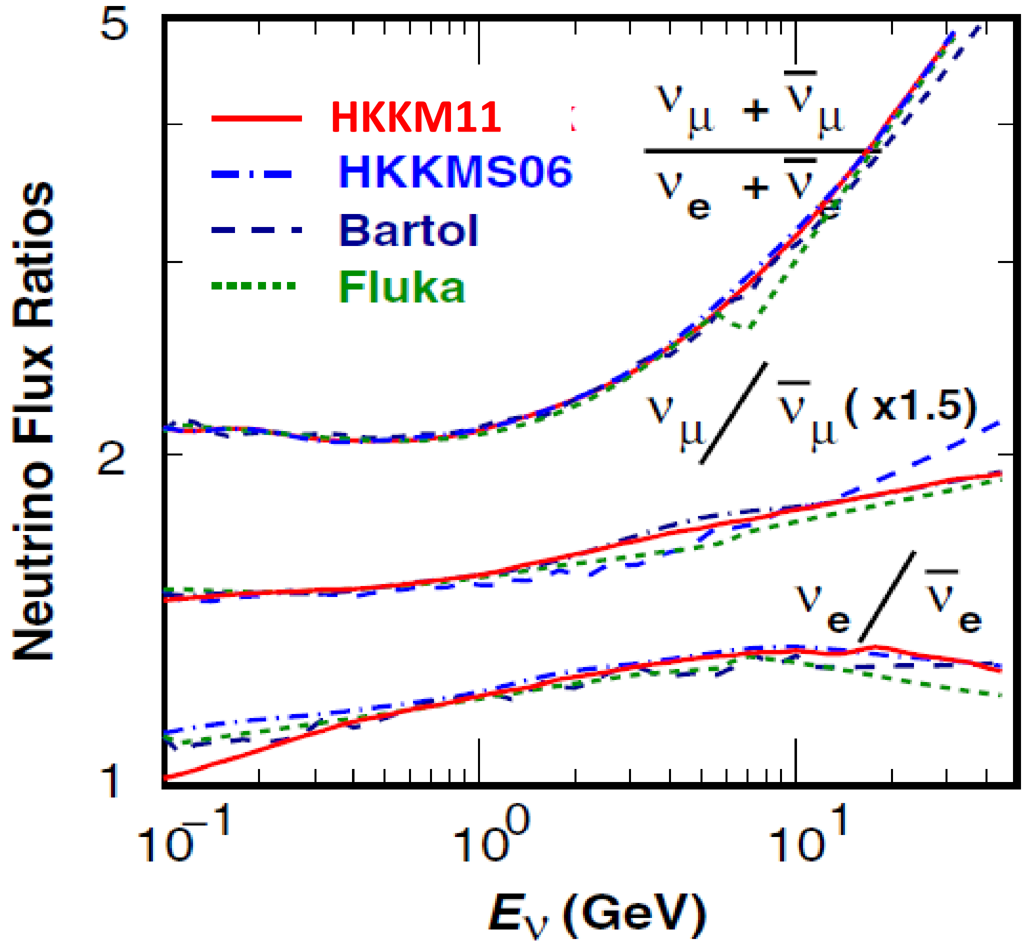


Paper conclusion:

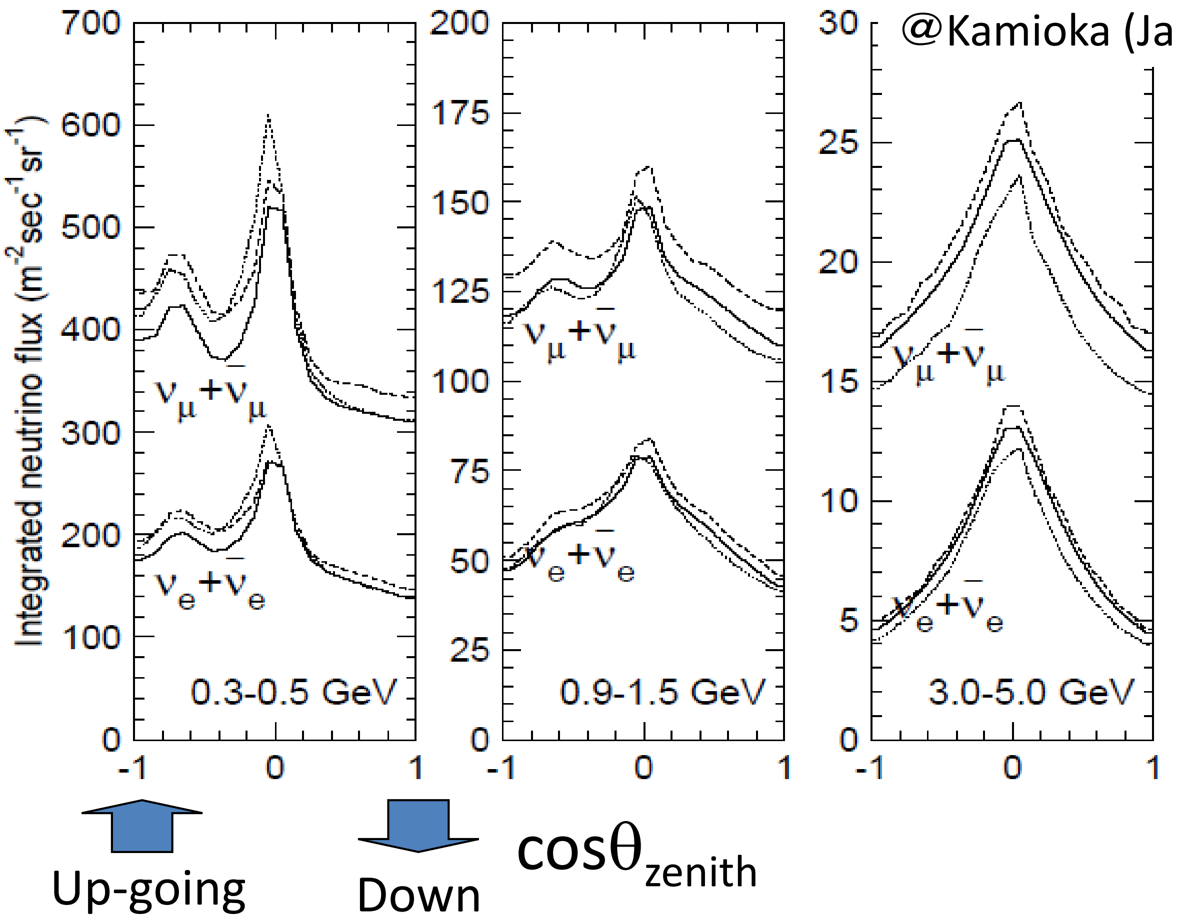
We conclude that there is fair agreement between the total observed and expected neutrino induced muon flux, i.e., Flux (predicted)/ Flux (observed) =1.6+/-0.4. The uncertainty arises from the neutrino fluxes (+/-30% ….)

Some feature of the atmospheric neutrino flux

M. Honda et al., PRD 83, 123001 (2011)



@Kamioka (Japan)



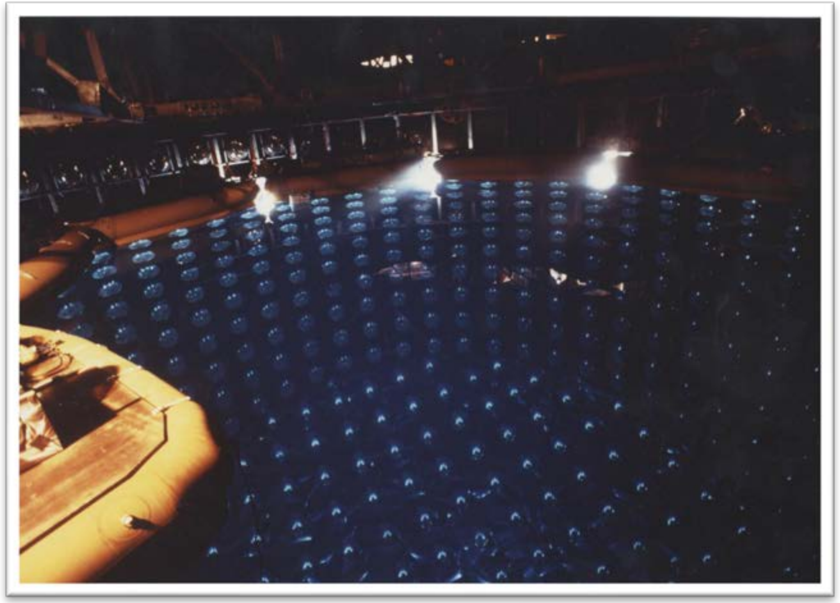
ν_μ/ν_e flux ratio is accurately calculated (~2% or better).

Up/down flux ratio is very close to 1.0 and accurately calculated (1% or better) above a few GeV.

Kamiokande

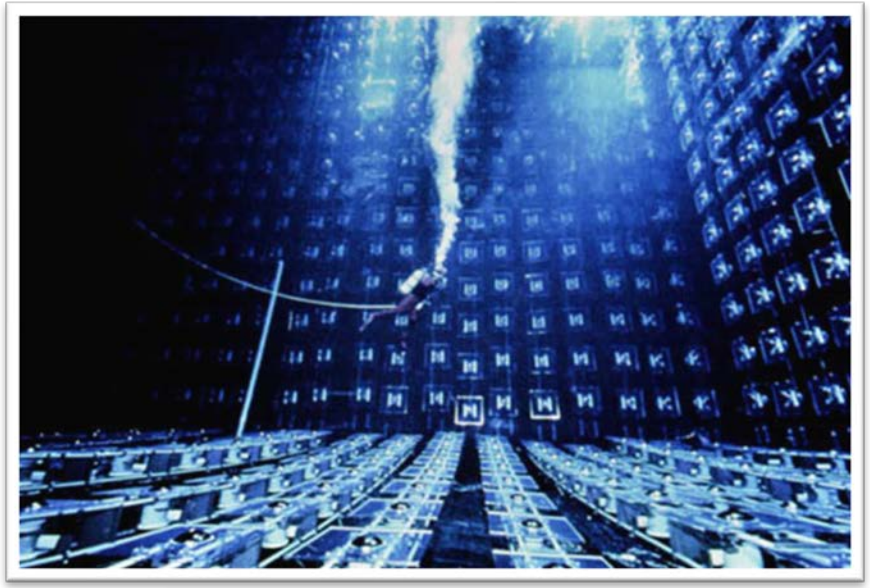
Proton decay experiments (1980's)

Grand Unified Theories
(in the 1970's)
➔ $\tau_p = 10^{30\pm2}$ years

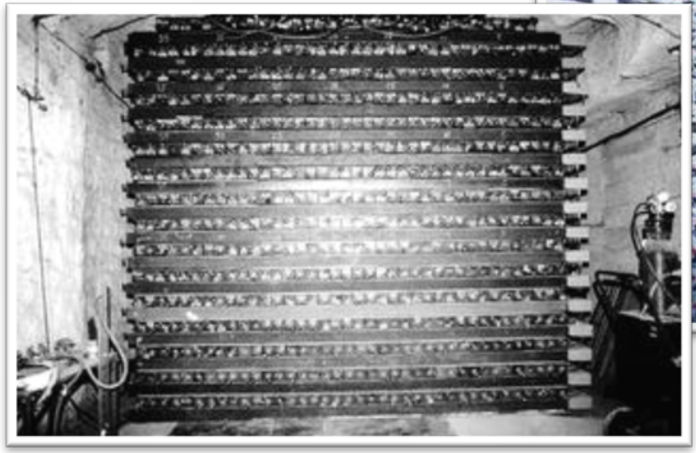


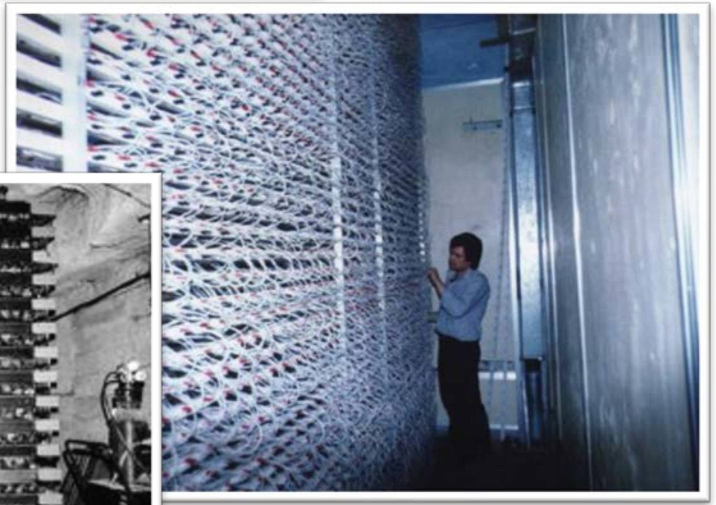
Kamiokande
(1000ton)

IMB
(3300ton)



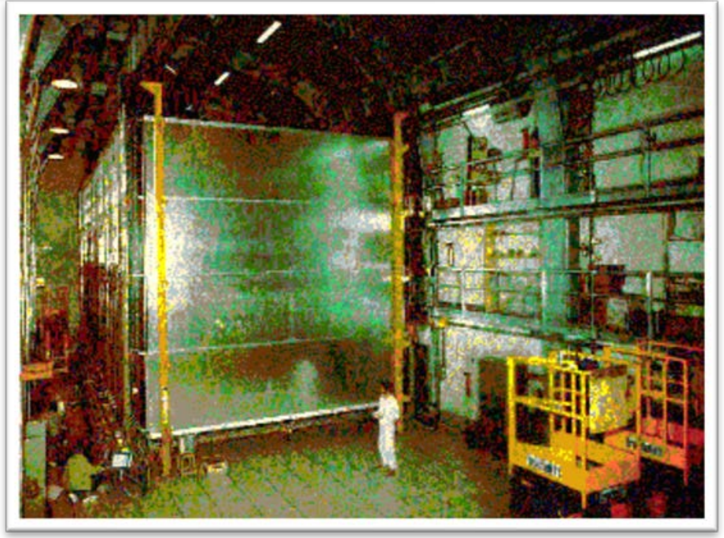
KGF (100ton)





NUSEX (130ton)

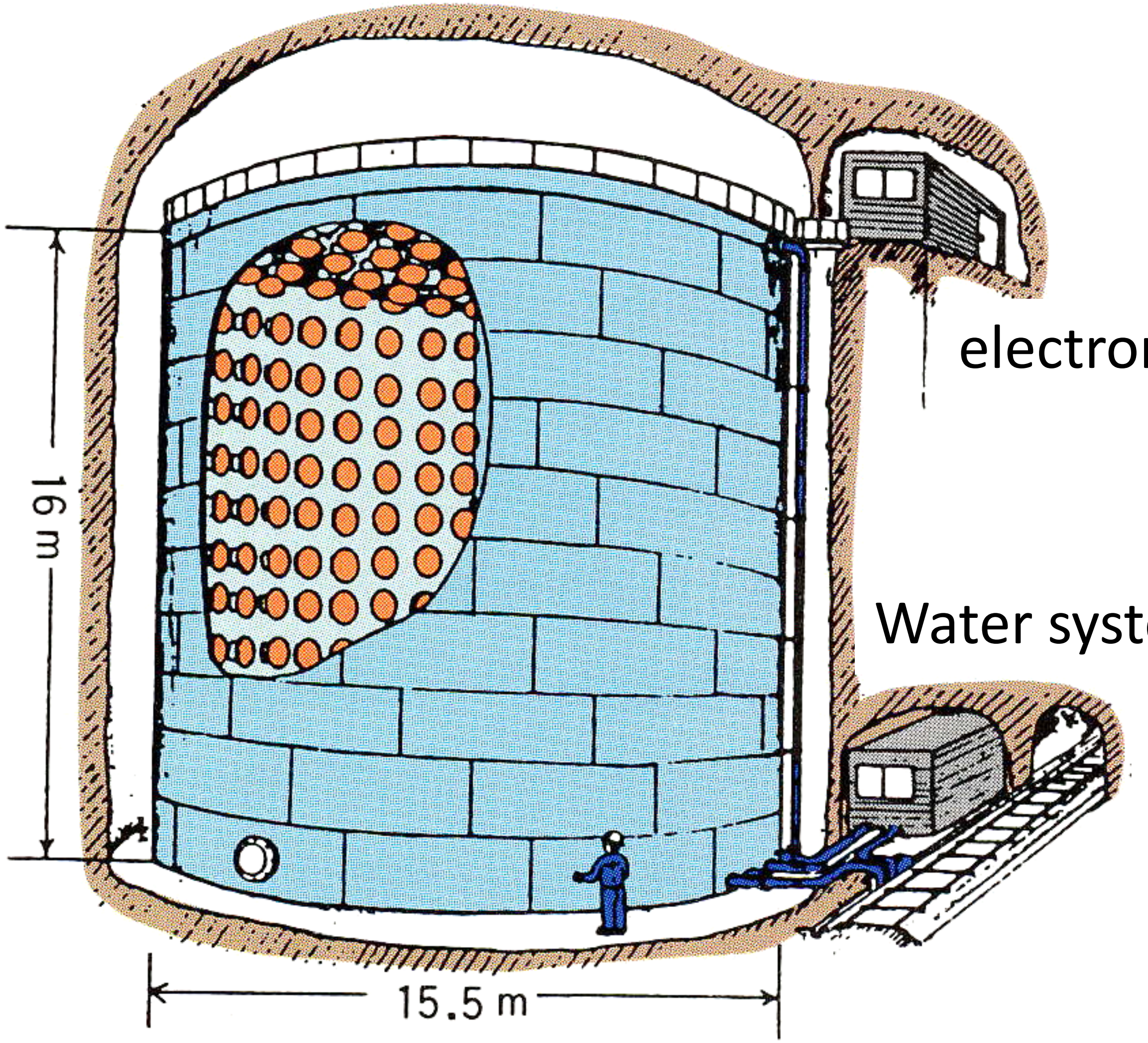
These experiments observed many contained atmospheric neutrino events (background for proton decay).

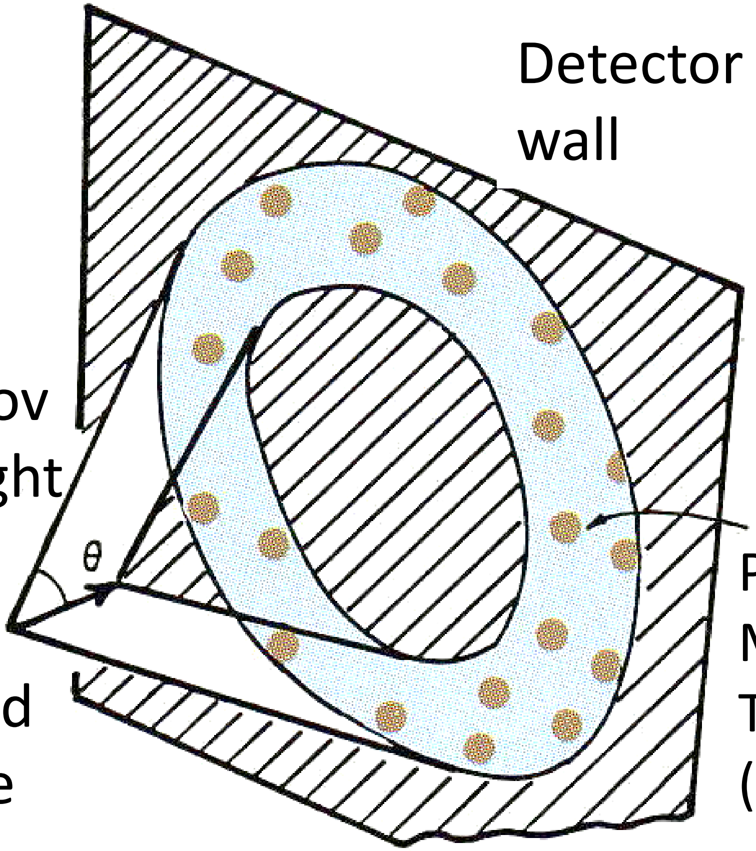


Frejus (700ton)

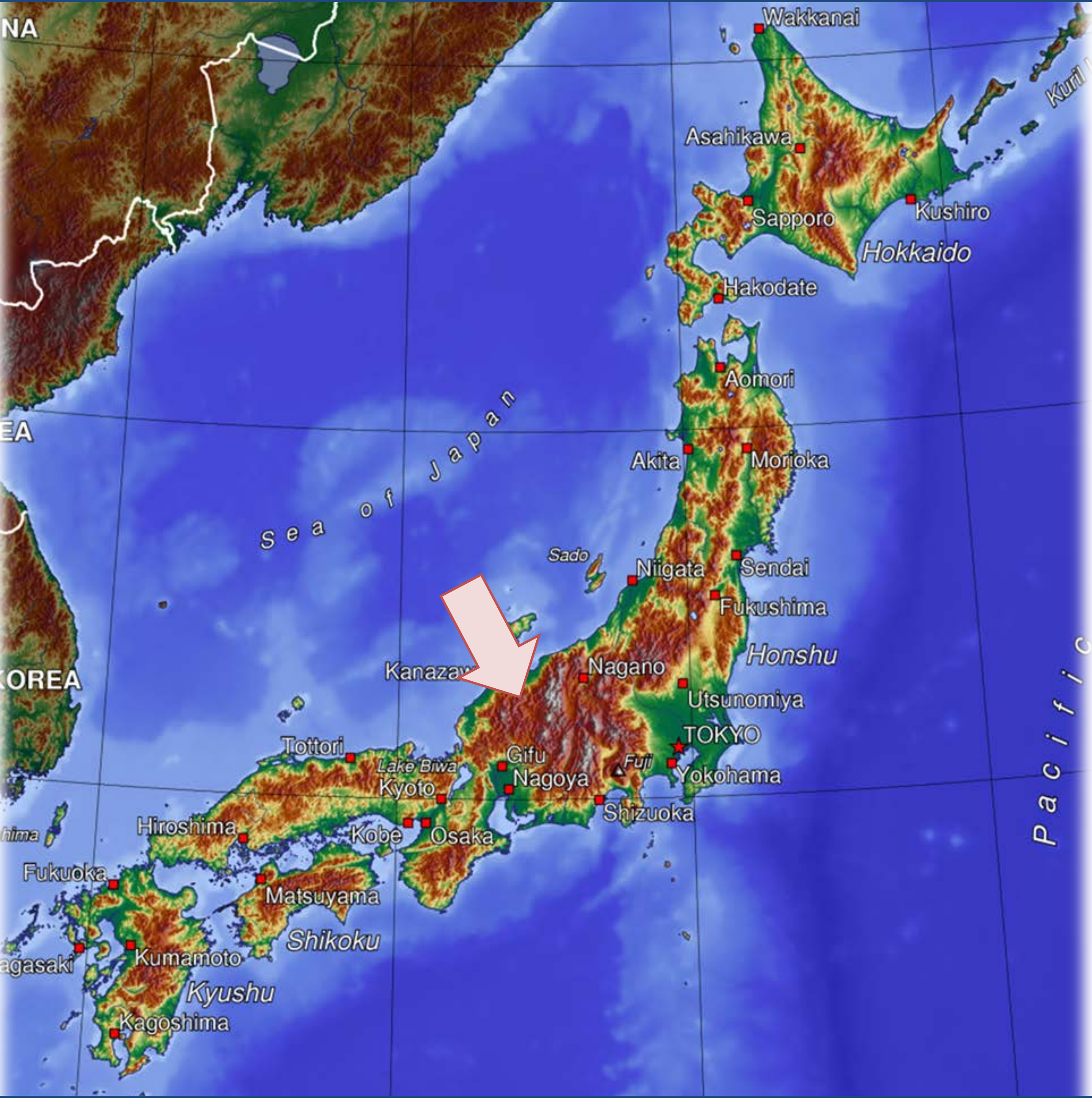
Kamioka Nucleon Decay Experiment (Kamiokande)

Kamiokande (3000 ton water Cherenkov detector)





Where is Kamiokande?



March 1996

Kamiokande construction team (Spring 1983)

Going into the mine (Spring 1983)

Going into the mine

Constructing the Kamiokande detector (Spring 1983)

Credit: ???
Maybe NHK or
Some other
TV company

Atmospheric neutrino deficit

Fewer muon decays than expected

Because atmospheric neutrinos are the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions. It was noted that the fraction of muon-decay signal was smaller than expected.

IMB

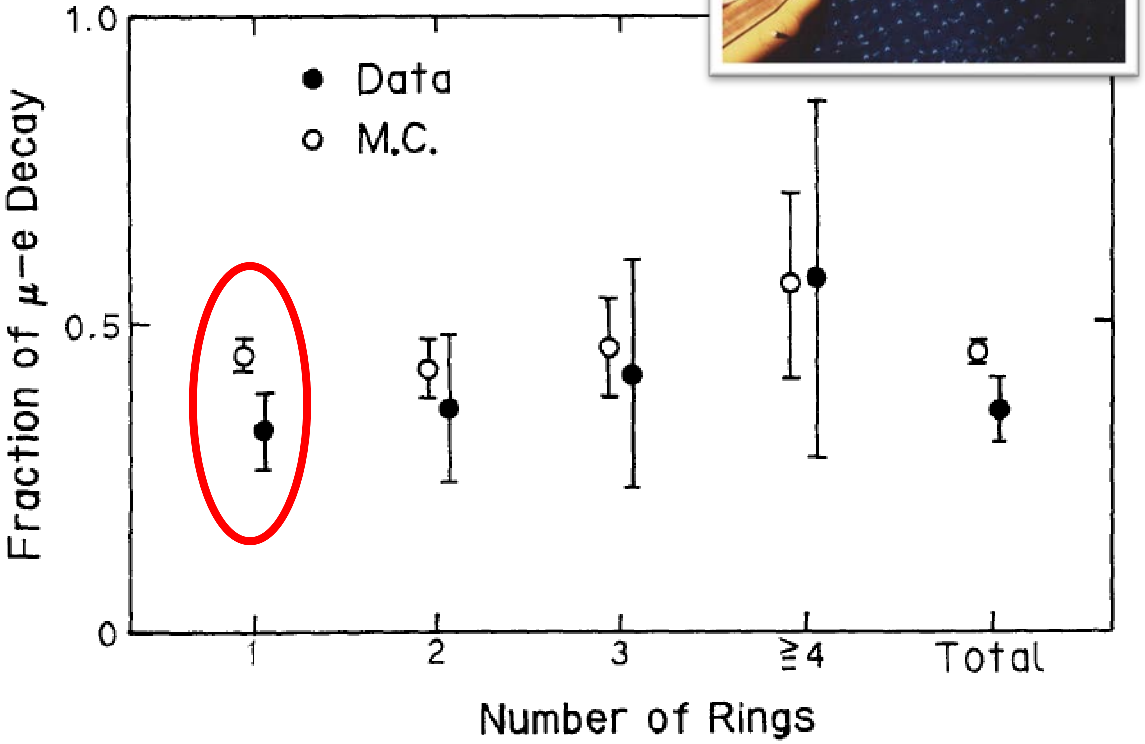
IMB, PRL 57, 1986 (1986)

VOLUME 57, PHYSICAL RE

well not only globally but also in small regions. The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

Kamiokande

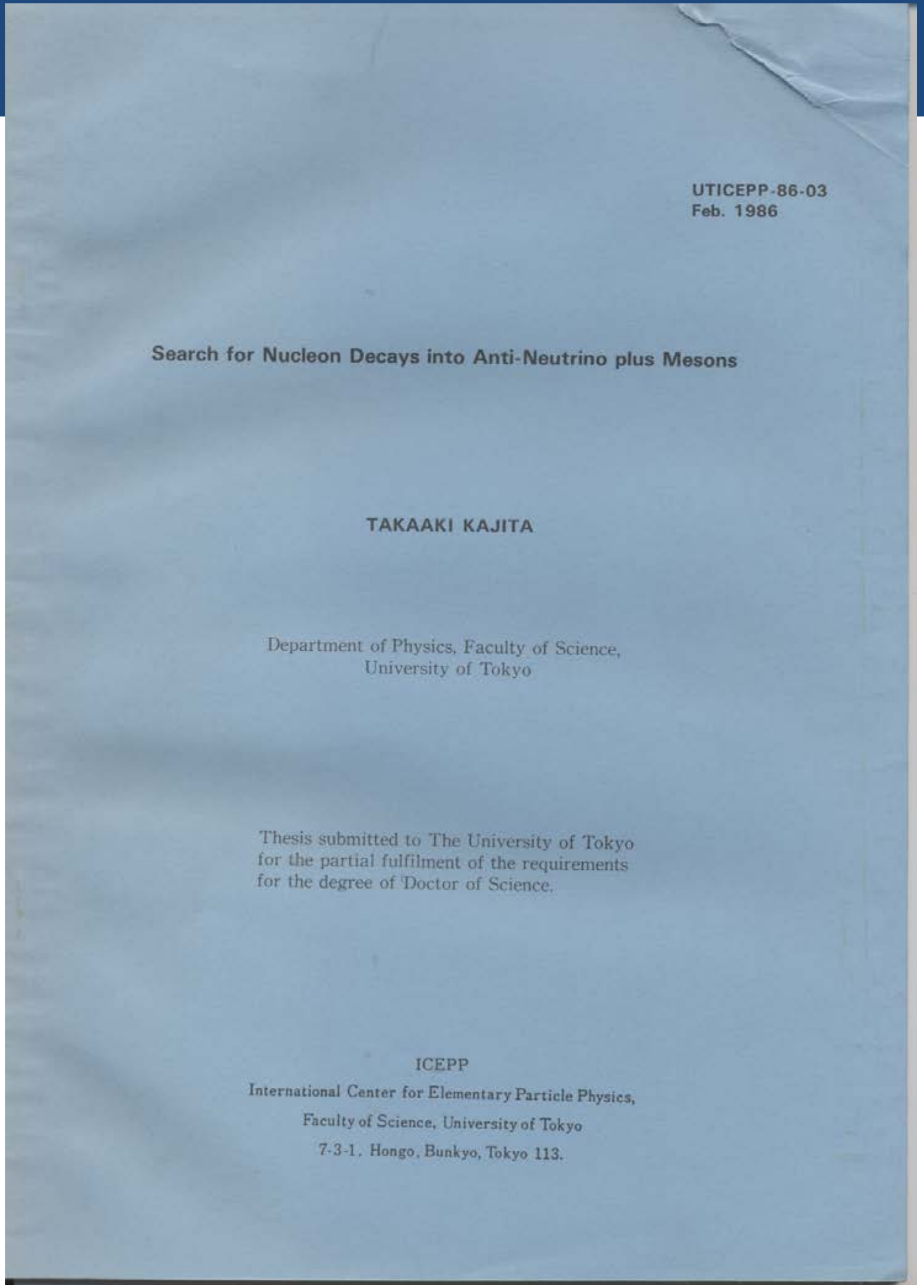
Kamiokande, J.Phys.Soc.Jpn 55, 3786 (1986)



Thesis (1986)

- I received PhD in March 1986 based on a search for proton decay.
- Of course, I did not find any evidence for proton decays…

- I felt that the analysis software, including the particle identification (electron-like or muon-like, PID), was not good enough to extract all the information that Kamiokande recorded.
- Therefore, as soon as I submitted my thesis, I started a work to improve the software.



UTICEPP-86-03
Feb. 1986

Search for Nucleon Decays into Anti-Neutrino plus Mesons

TAKAAKI KAJITA

Department of Physics, Faculty of Science,
University of Tokyo

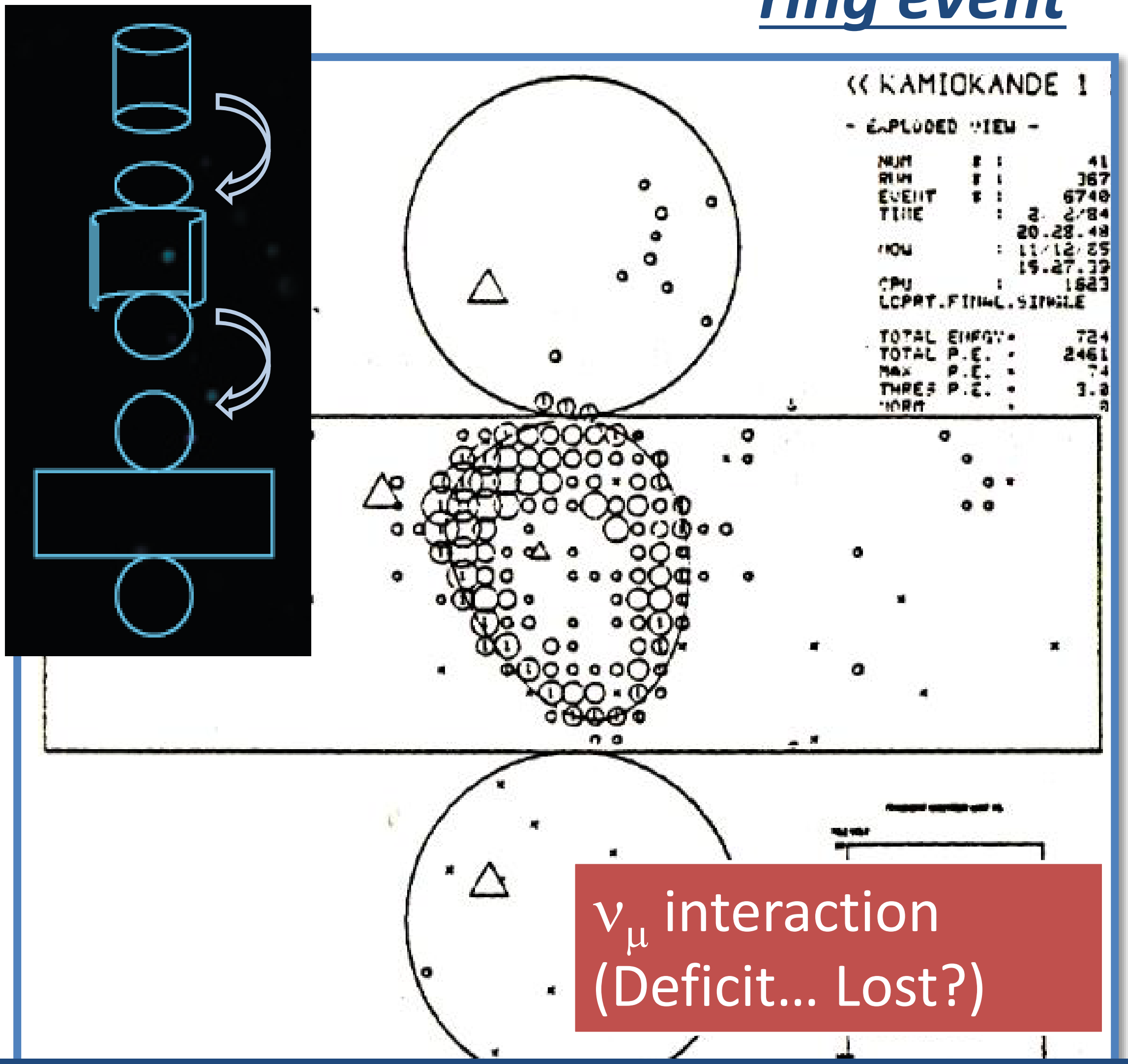
Thesis submitted to The University of Tokyo
for the partial fulfilment of the requirements
for the degree of Doctor of Science.

ICEPP
International Center for Elementary Particle Physics,
Faculty of Science, University of Tokyo
7-3-1, Hongo, Bunkyo, Tokyo 113.

1986…

- We developed particle identification software to know if a Cherenkov ring is produced by an electron (ν_e interaction) or a muon (ν_μ interaction).
- Of course, we did various tests of the software. As a final test, the neutrino flavor (ν_e or ν_μ) was studied for the atmospheric neutrino events. It was found that the number of ν_μ events was much fewer than expected.
- We thought that it is very likely that there were some mistakes somewhere in the data analysis, or maybe somewhere else.
- We started various studies to find mistakes.

Kamiokande's single-Cherenkov ring event



Atmospheric ν_μ deficit (1988)

After about one year of studies, we concluded that the ν_μ deficit cannot be due to any major problem in the data analysis nor the simulation.

K. Hirata et al, Phys.Lett.B 205 (1988) 416.

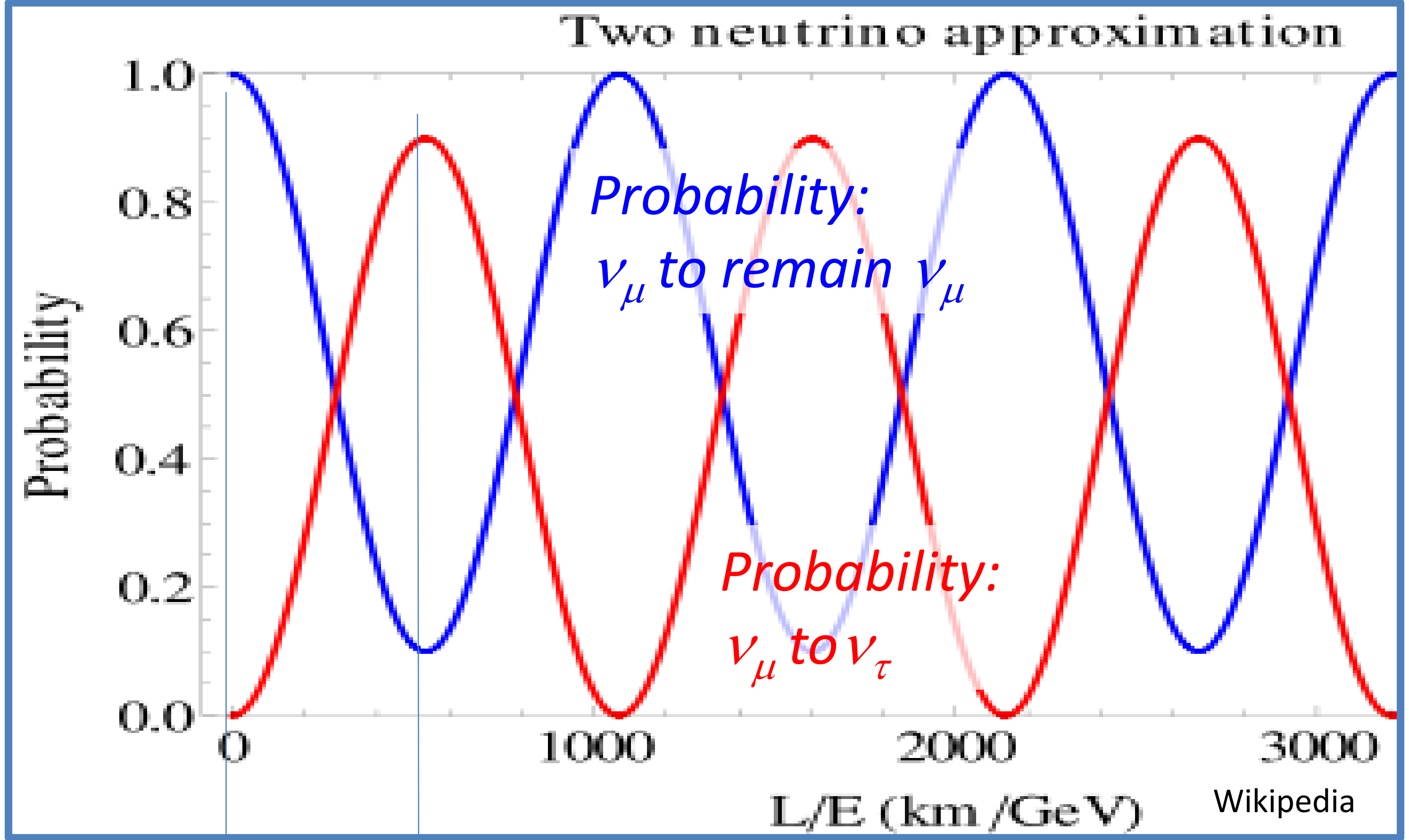
	Data	Monte Carlo prediction
electron-like (mostly ν_e interactions)	93	88.5
muon-like (mostly ν_μ interactions)	85	144.0

People showed interest in this paper, although most of them were rather skeptical.

What I thought: Although we had no clear idea what was the cause of the deficit, I was most excited with the data. I enjoyed to find out the cause of the deficit. I changed my research from the proton decay searches to neutrino studies.

Neutrino oscillations (in the vacuum)

If neutrinos have masses, neutrinos change their type (flavor) from one type (flavor) to the other. For example, ν_μ could oscillate to ν_τ.



Wikipedia

__Theoretically predicted by;__

S. Sakata, Z. Maki, M. Nakagawa

arXiv:0910.1657

B. Pontecorvo

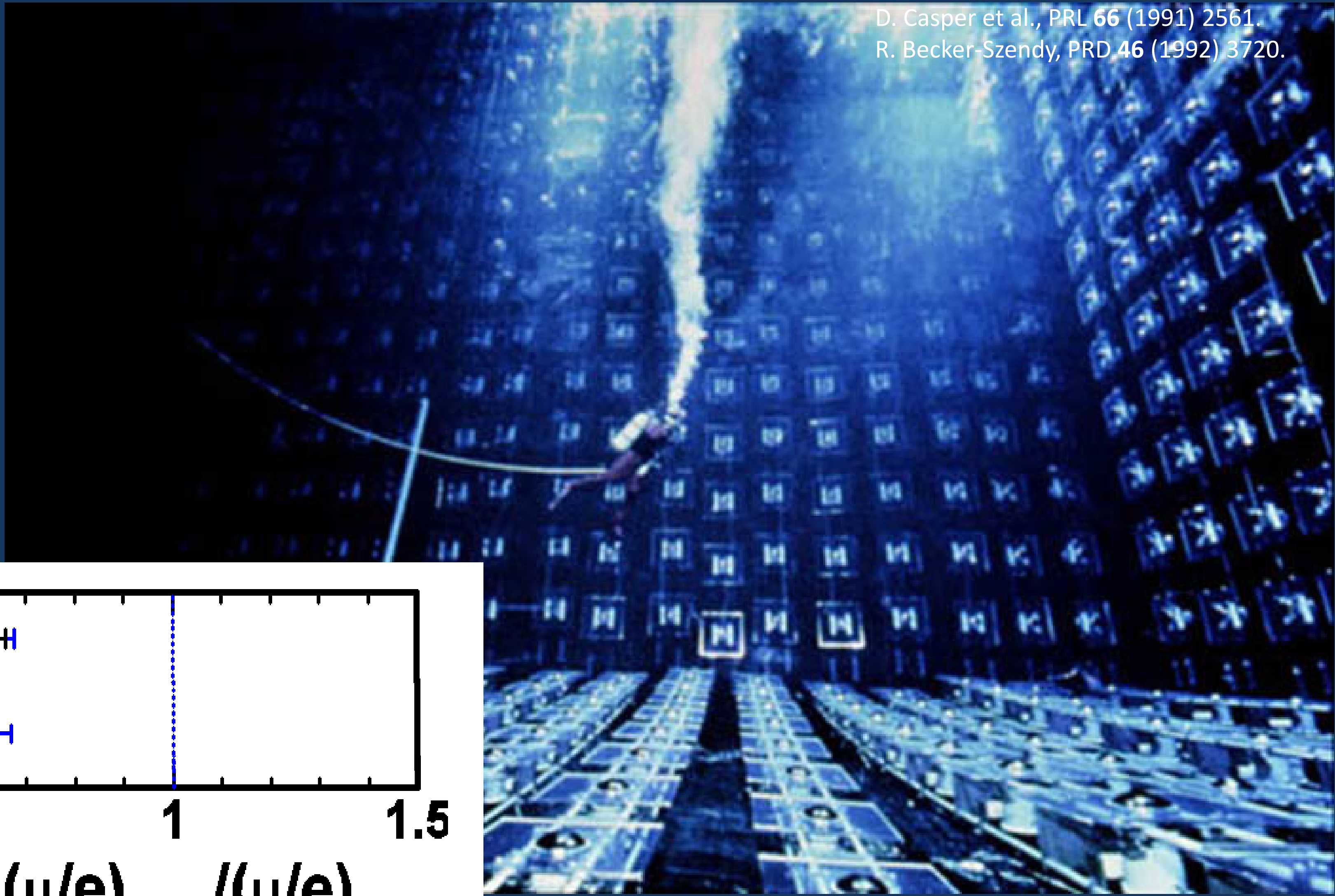
L is the neutrino flight length (km),

E is the neutrino energy (GeV).

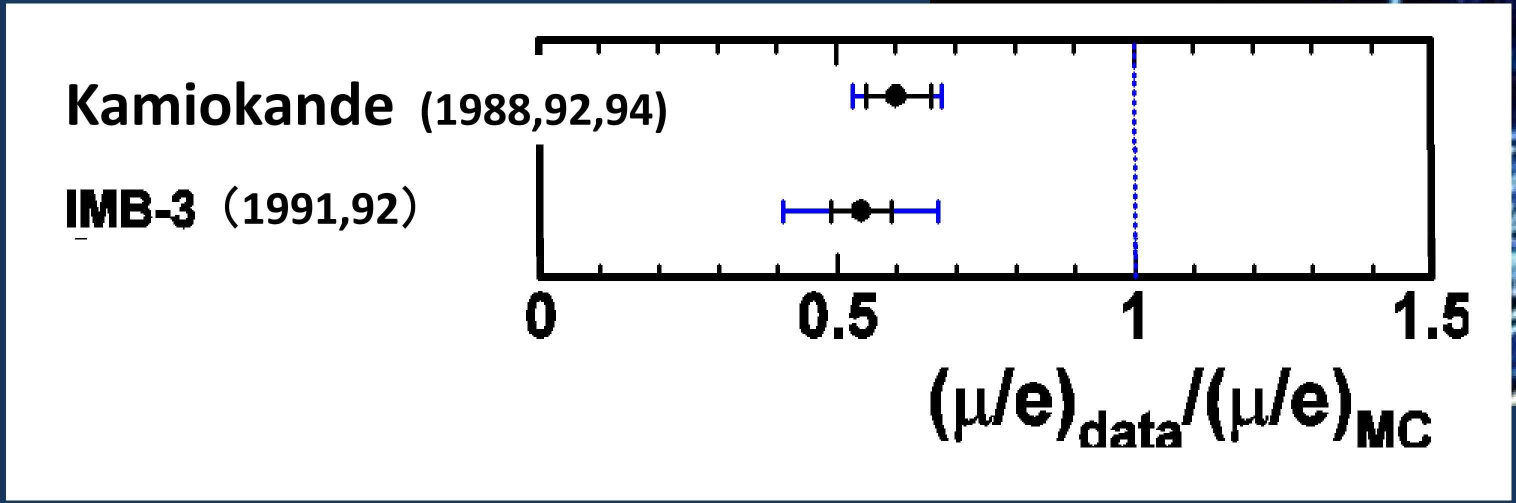
If neutrino mass is smaller, the oscillation length (L/E) gets longer.

Results from IMB on the ν_μ deficit

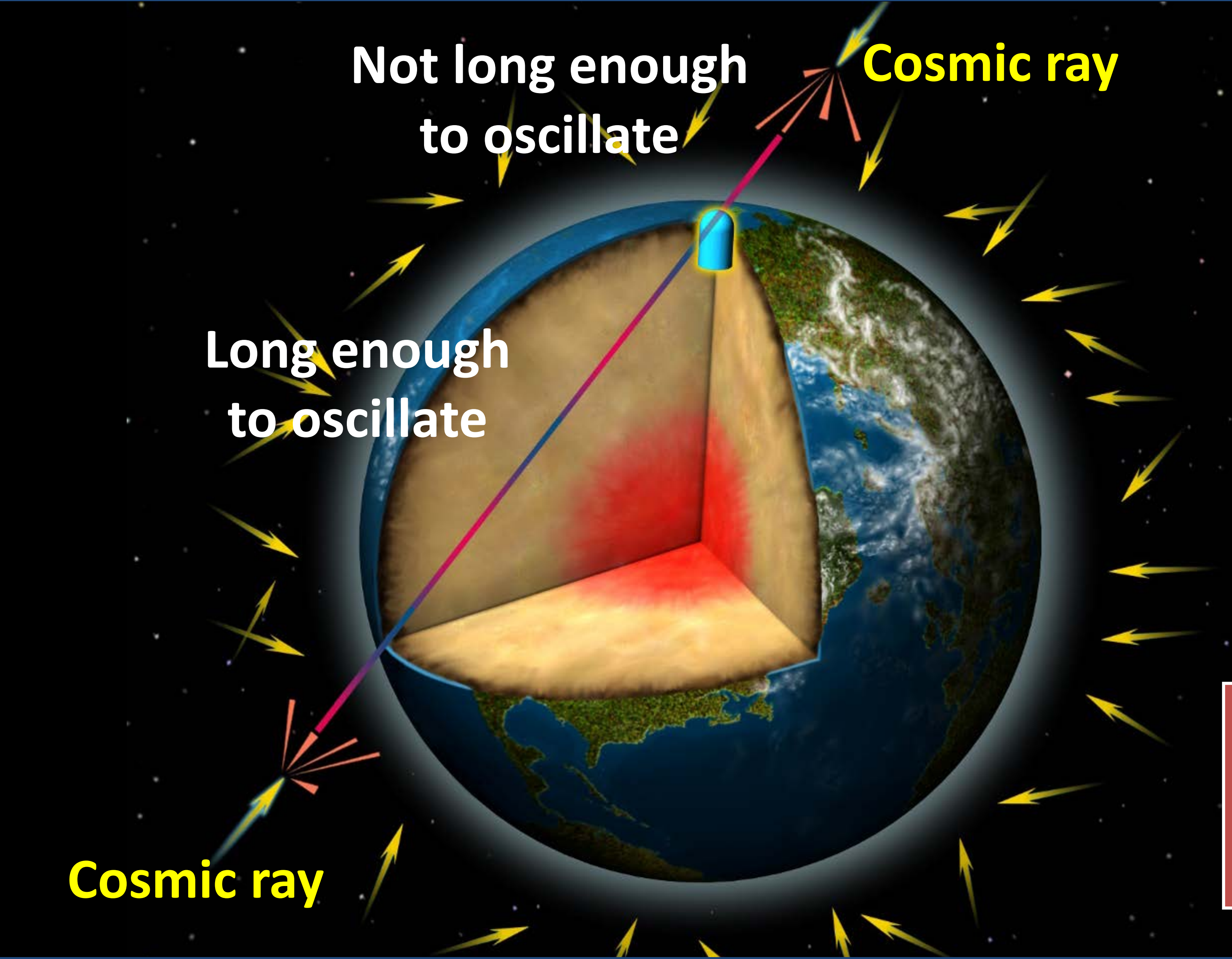
IMB experiment, which was another large water Cherenkov detector, also reported the deficit of ν_μ events in 1991 and 1992.



D. Casper et al., PRL **66** (1991) 2561.
R. Becker-Szendy, PRD **46** (1992) 3720.

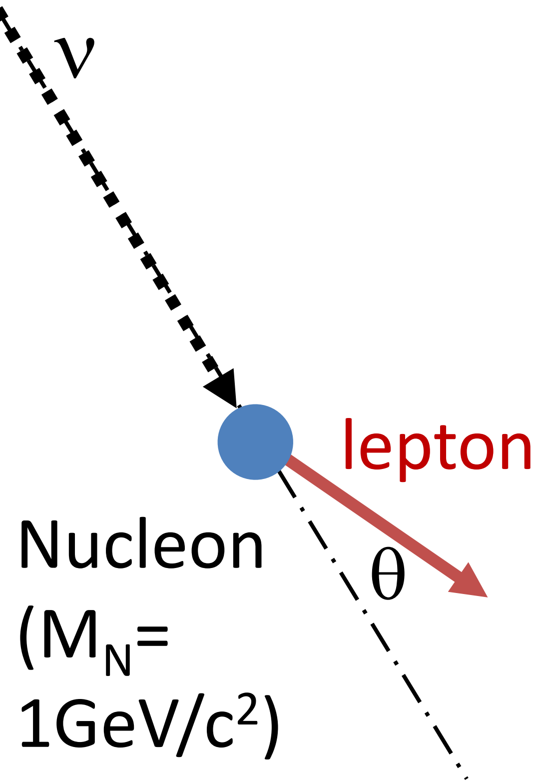


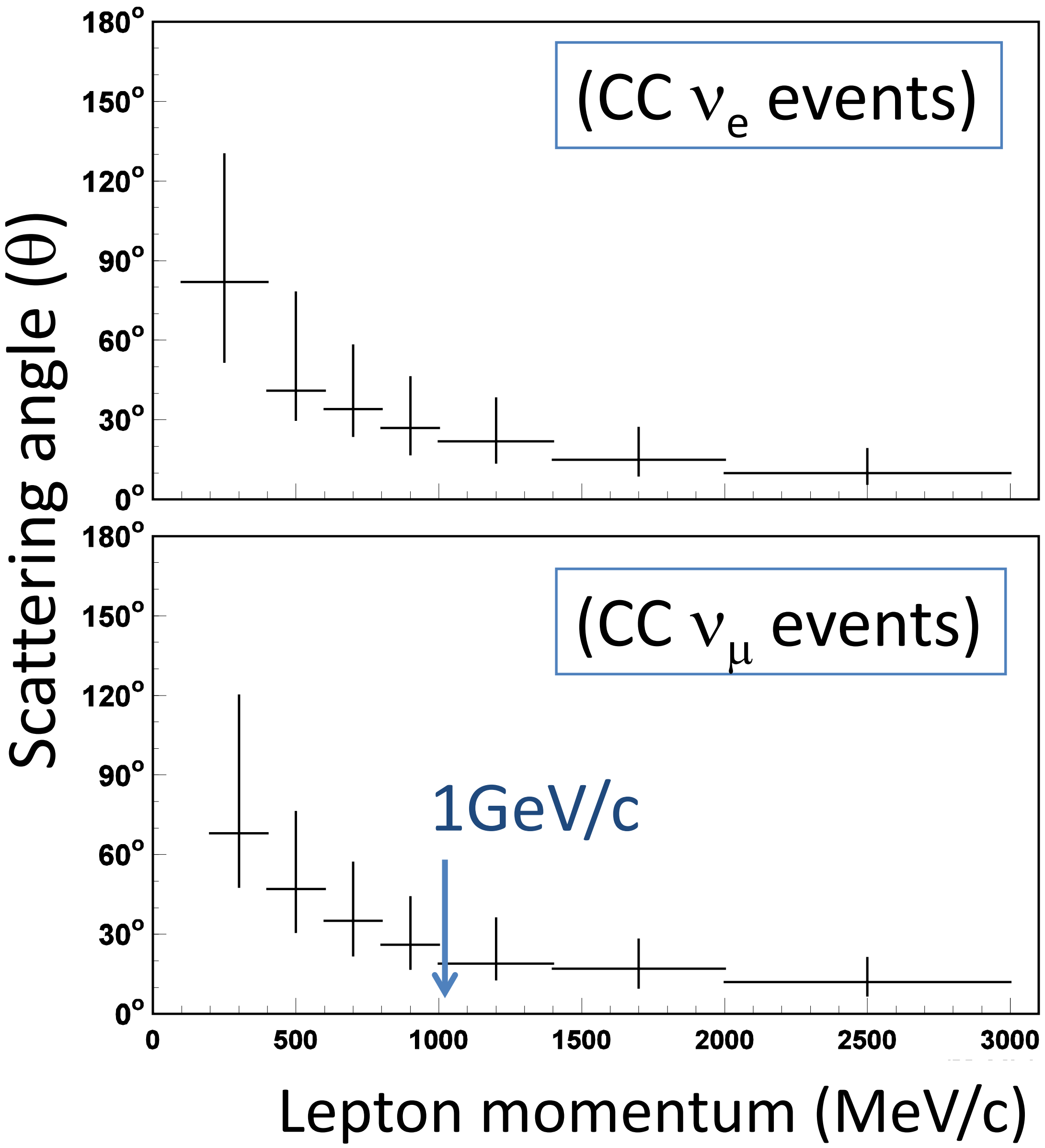
What will happen if the ν_μ deficit is due to neutrino oscillations



We should observe the up vs. down asymmetry of the atmospheric ν_μ's!

Angular correlation



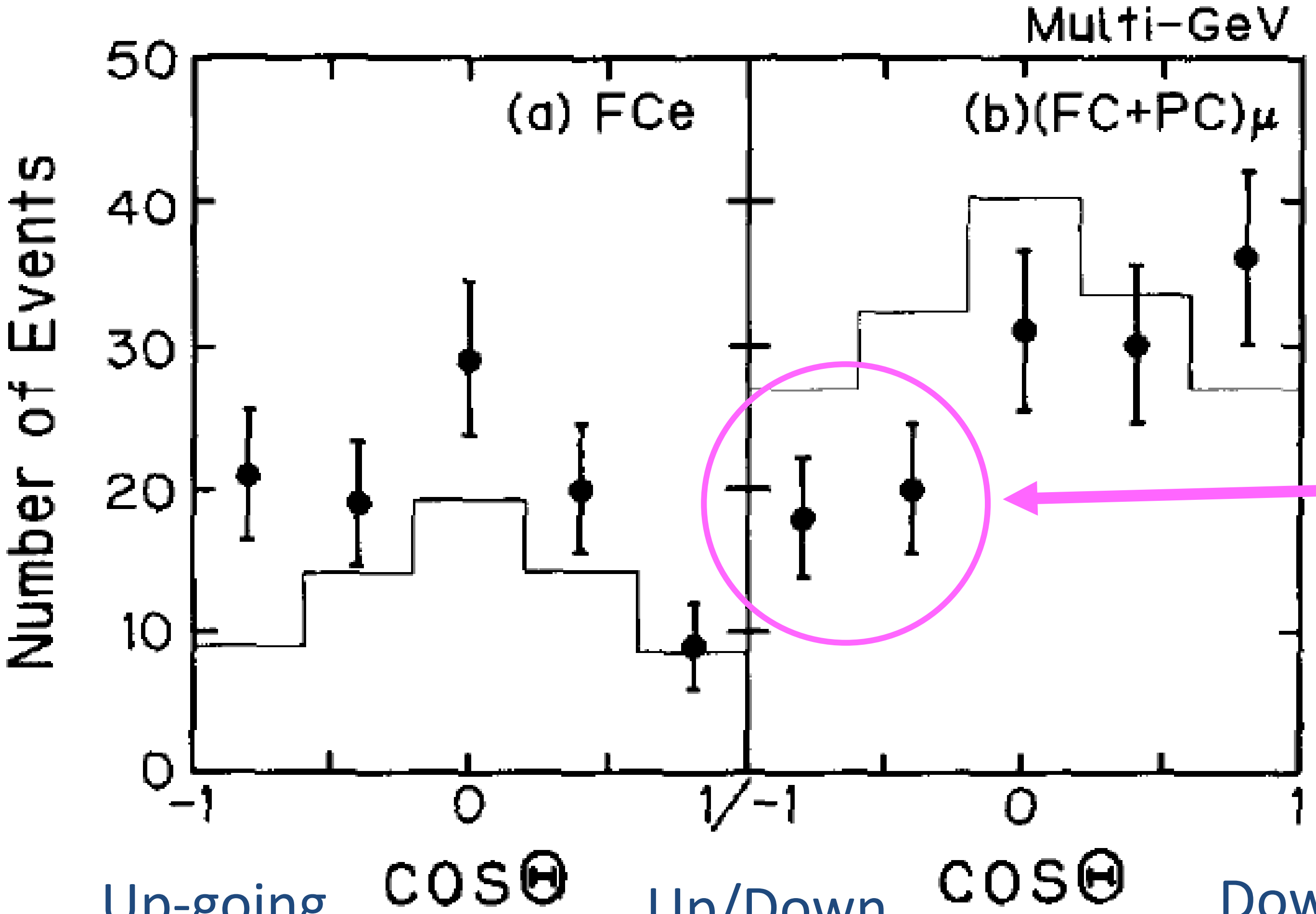


- ✓ We thought that we should study multi-GeV neutrino events.
- ✓ Therefore we started the data reduction work for partially-contained multi-GeV neutrino events, ~1 week after the submission of the 1988 paper.
- ➢ Kamiokande was not large enough. It took almost 6 years to get some meaningful results.

Zenith angle distribution for multi-GeV events (Kamiokande, 1994)

multi-GeV events

Kamiokande PLB 335, 237 (1994)



Up-going Up/Down Down

Deficit of upward-going μ-like events

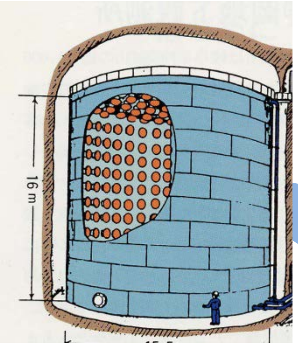
$$\frac{Up}{Down} = 1.38^{+0.39}_{-0.30}$$

$$\frac{Up}{Down} = 0.58^{+0.13}_{-0.11}\ (2.9\sigma)$$

The statistics were not high enough to conclude …
Much higher statics required (= much larger detector required)

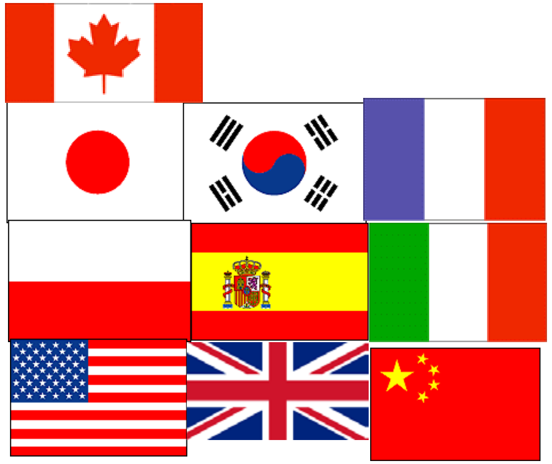
Super-Kamiokande

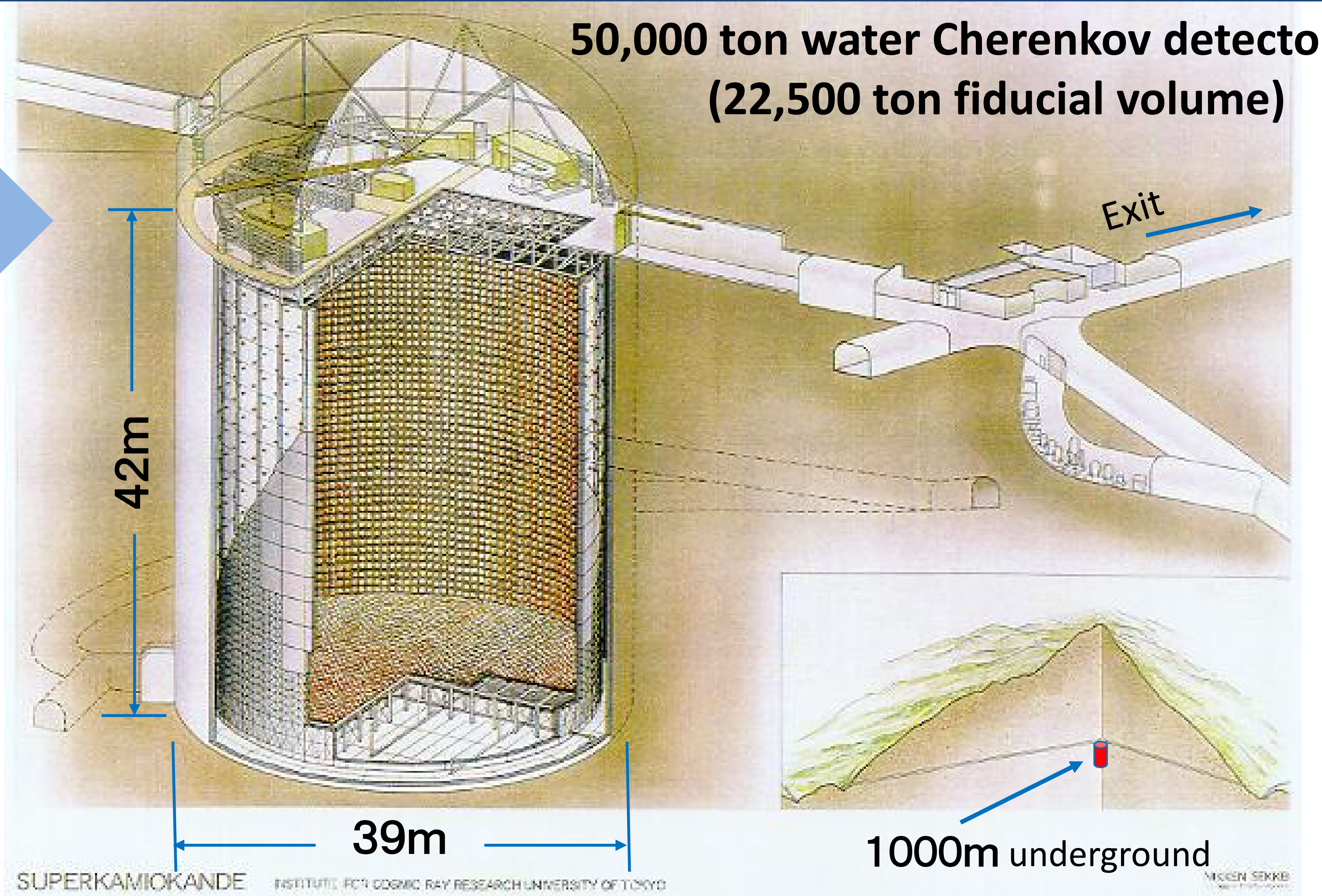
Super-Kamiokande detector



~20 times larger mass

~160 collaborators





Initial idea of Super-Kamiokande

KEK Report 84-12
September 1984
H

PROCEEDINGS OF

WORKSHOP ON GRAND UNIFIED THEORIES

AND COSMOLOGY

KEK, Tsukuba, Japan
December, 7-10, 1983

Edited by

K. ODAKA and A. SUGAMOTO

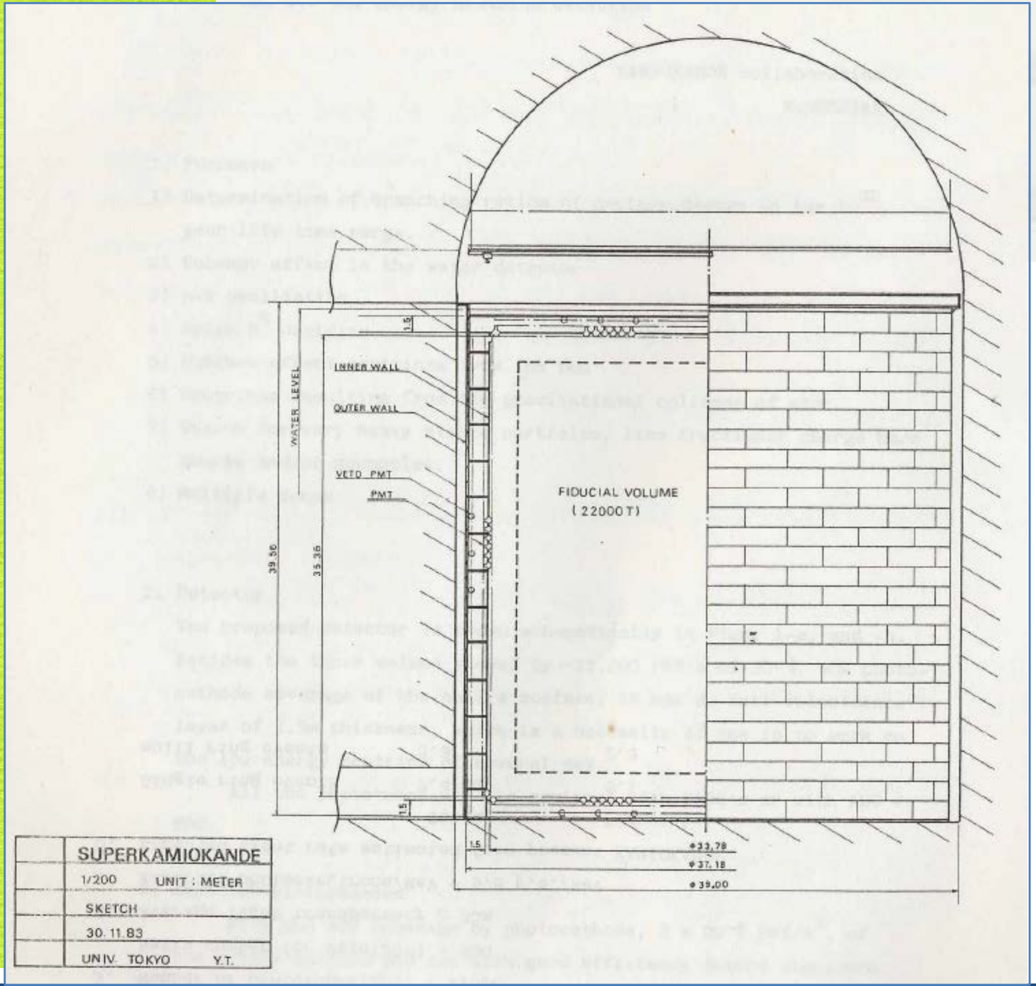
32 Kton Water Cerenkov Detector(JACK)

A proposal for detailed studies of nucleon decays

and for low energy neutrino detection

KAMIOKANDE collaboration

M.KOSHIBA



In the fall of 1983, Prof. Koshiba recognized that solar neutrinos can be detected in Kamiokande. At the same time, he proposed Super-Kamiokande to study solar neutrinos in detail (and to search for p-decays).

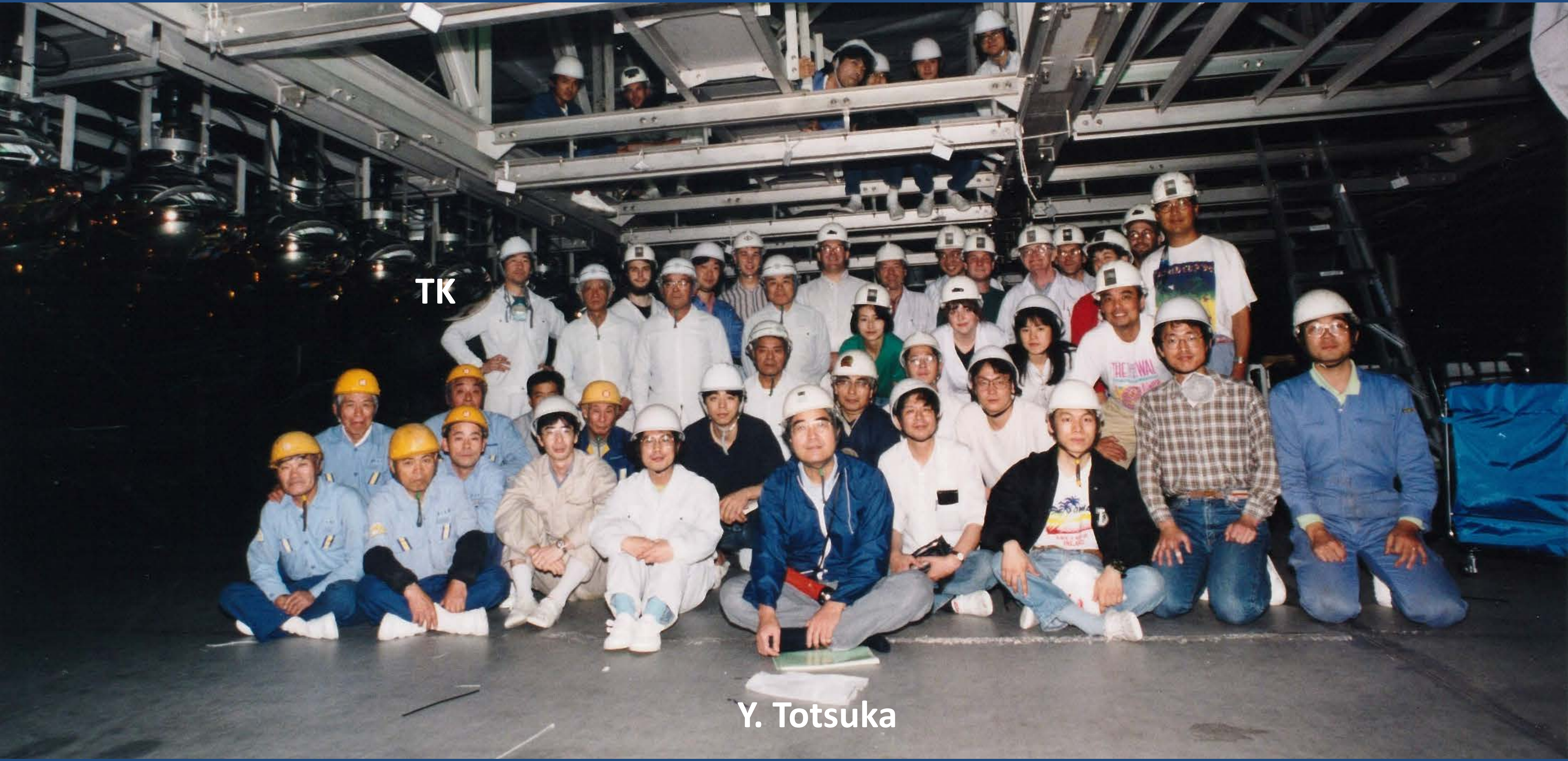
Beginning of the Super-Kamiokande collaboration between Japan and USA

@ Institute for Cosmic Ray Research, 1992

Excavation (1994)

The underground cavity of about 58m high was excavated.

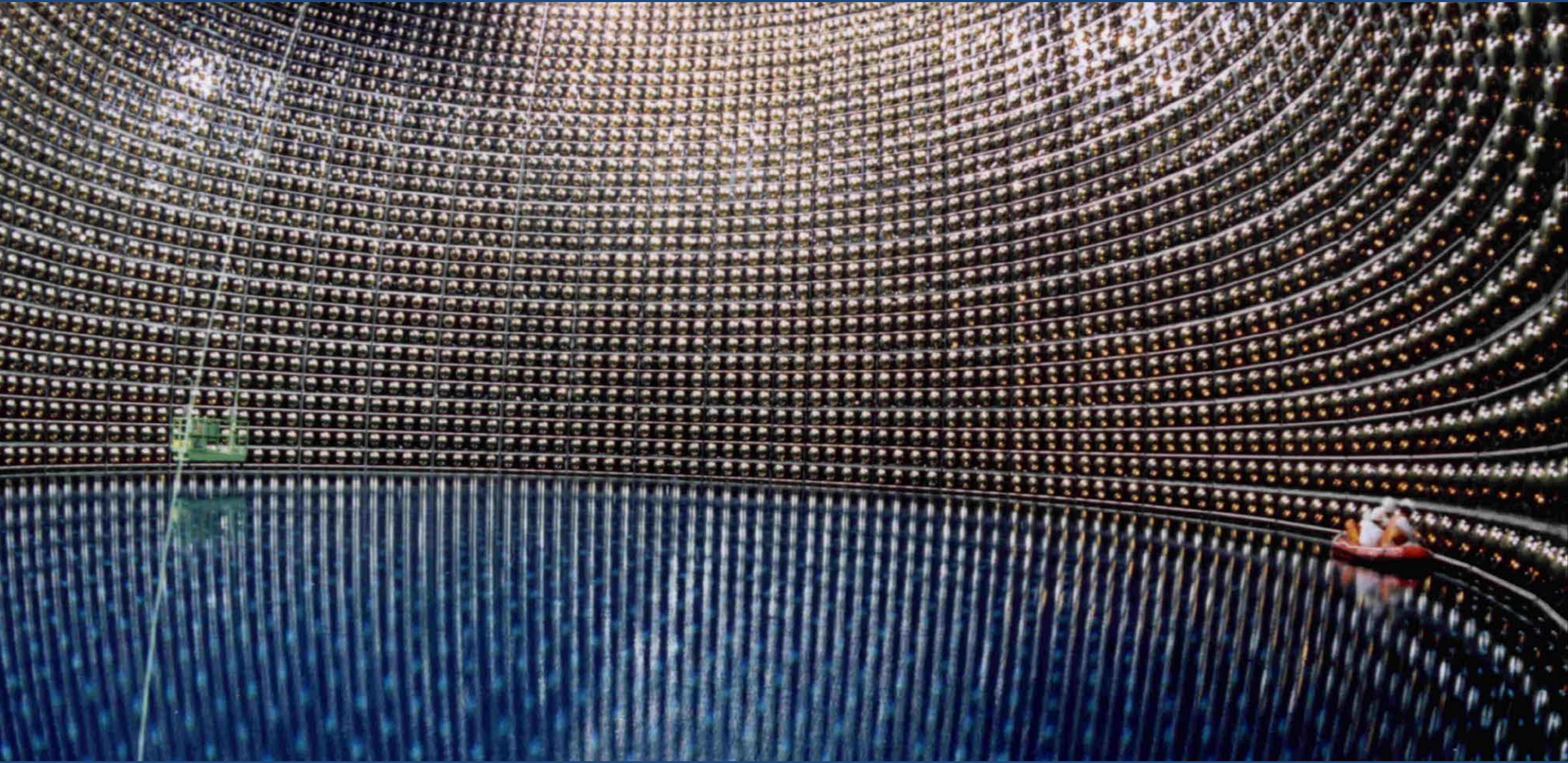
Constructing the Super-Kamiokande detector (spring 1995)



Constructing the Super-Kamiokande detector (Aug. 1995)

Filling water in Super-Kamiokande

Jan. 1996

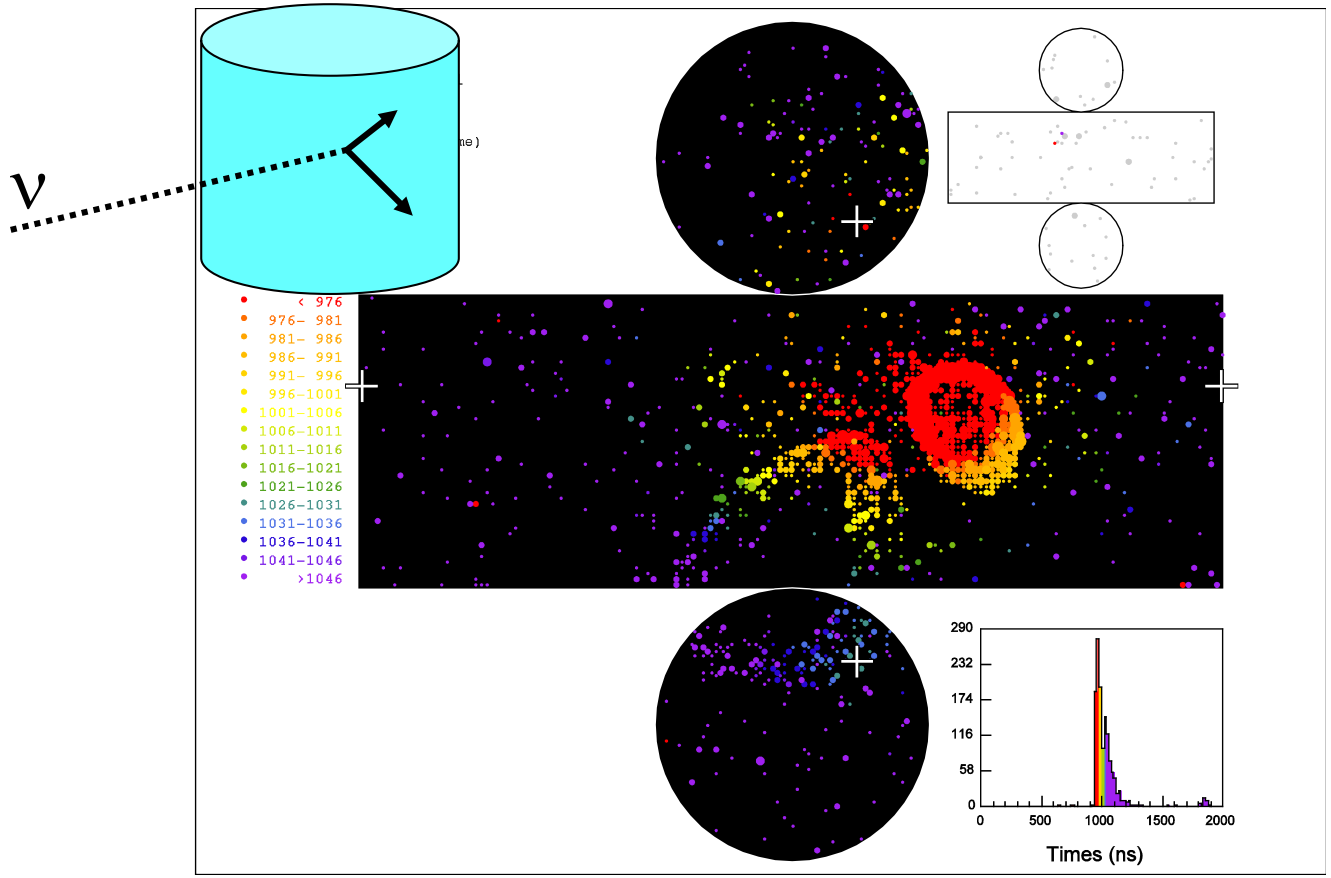


Discovery of neutrino oscillations

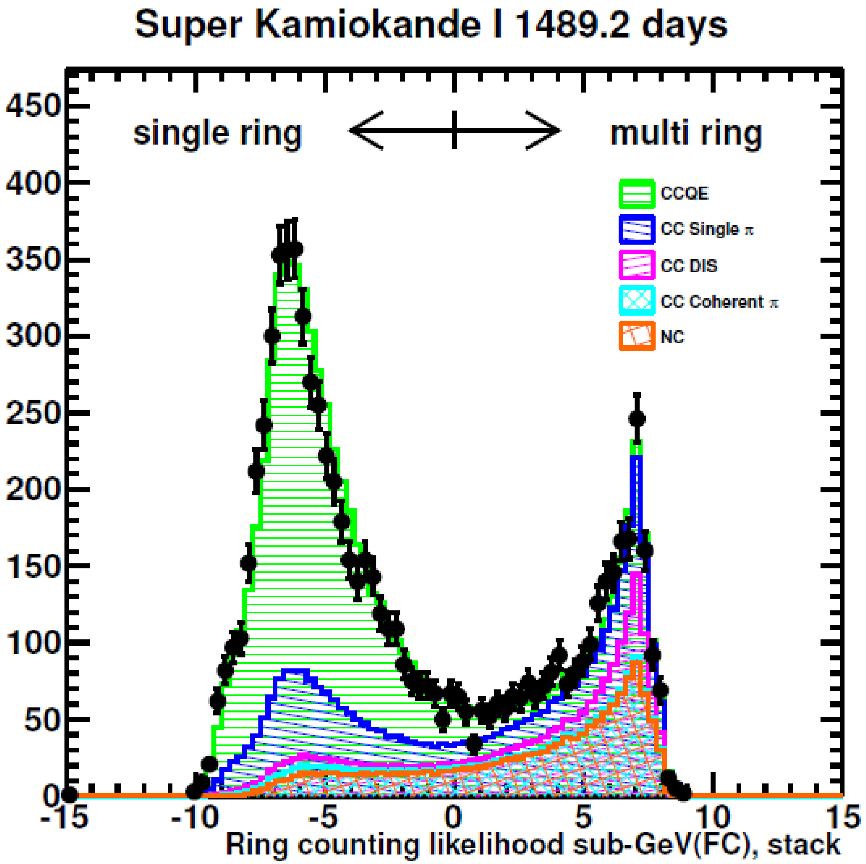
Fully automated analysis

- One of the limitation of the Kamiokande's analysis was the necessity of the event scanning for all data and Monte Carlo events, due to no satisfactory ring identification software.

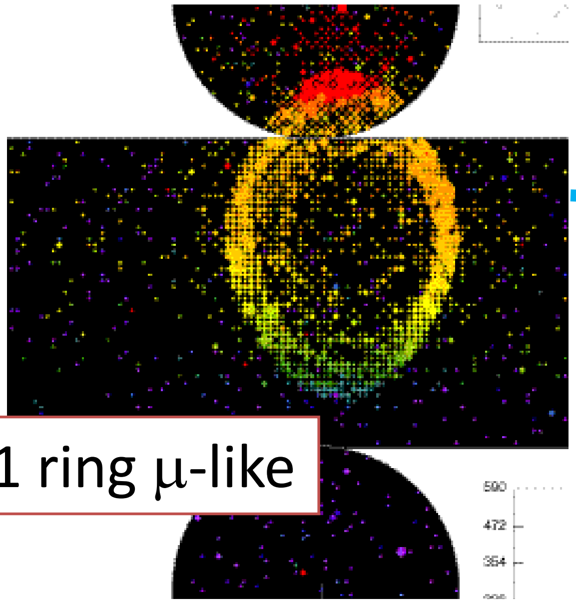
Multi Cherenkov ring event

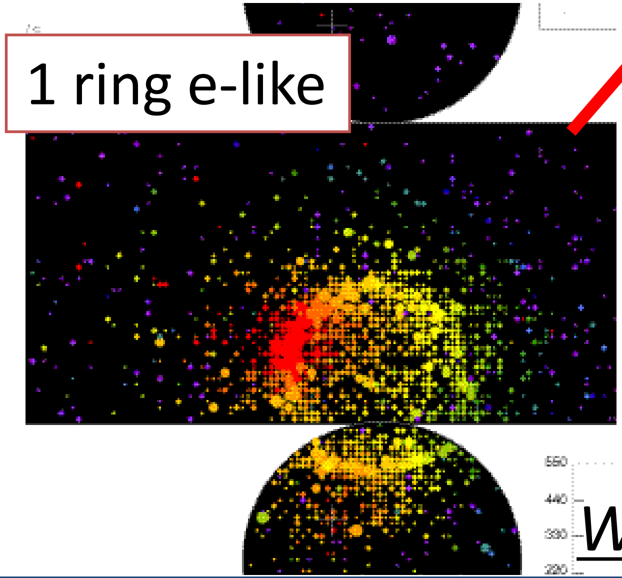


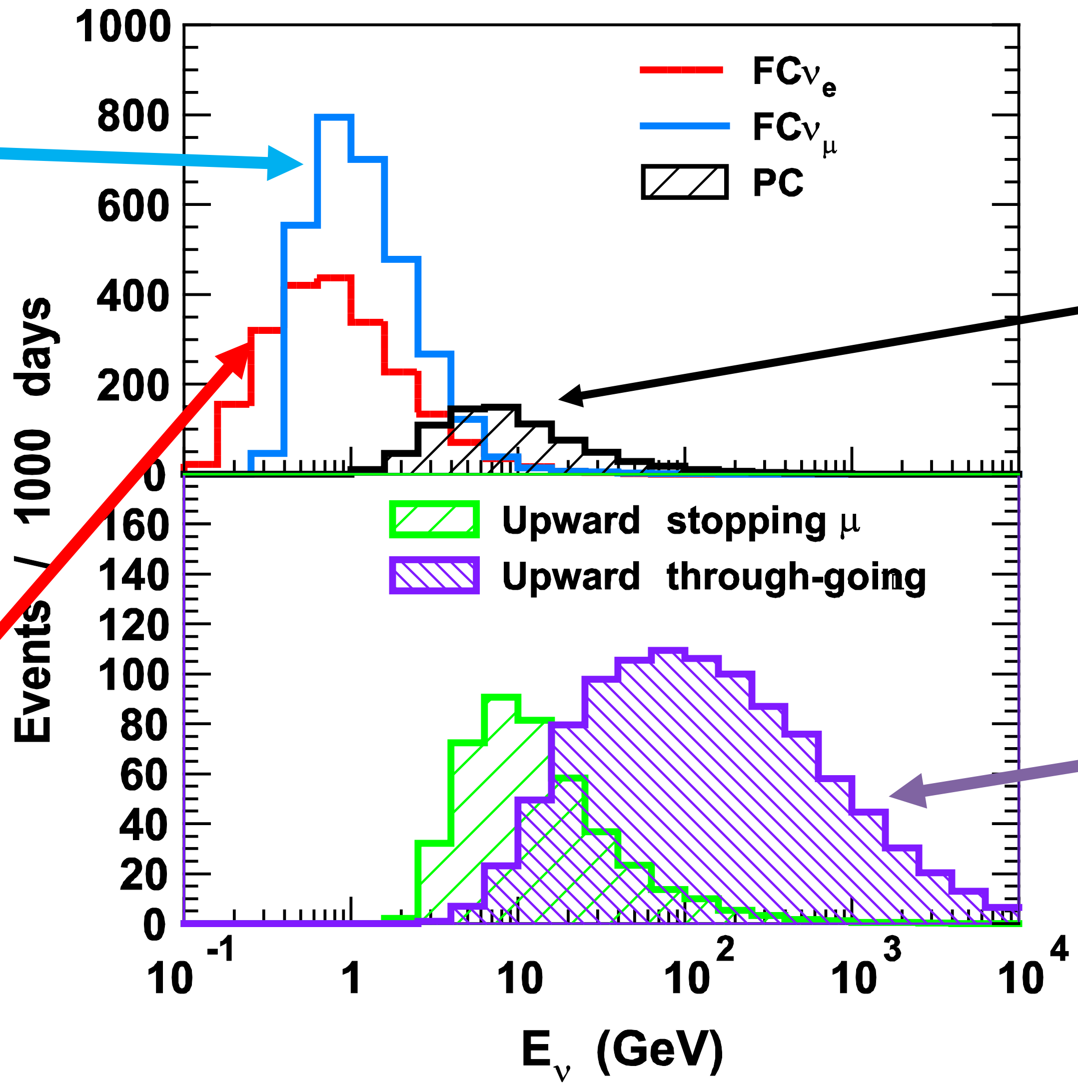
Hough transformation
+ maximum likelihood

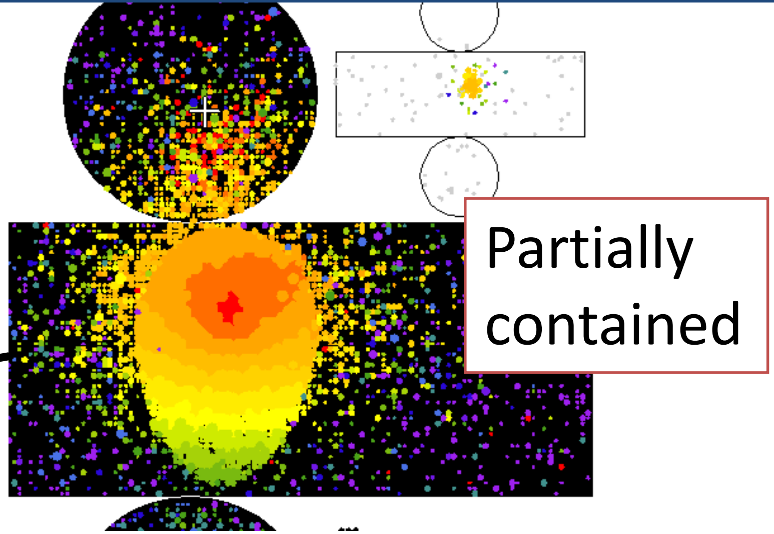


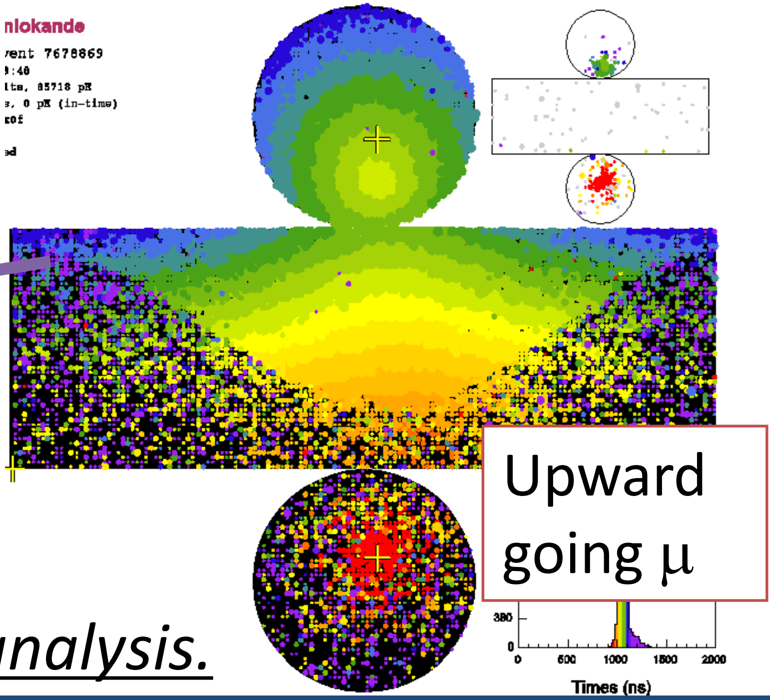
Event type and neutrino energy







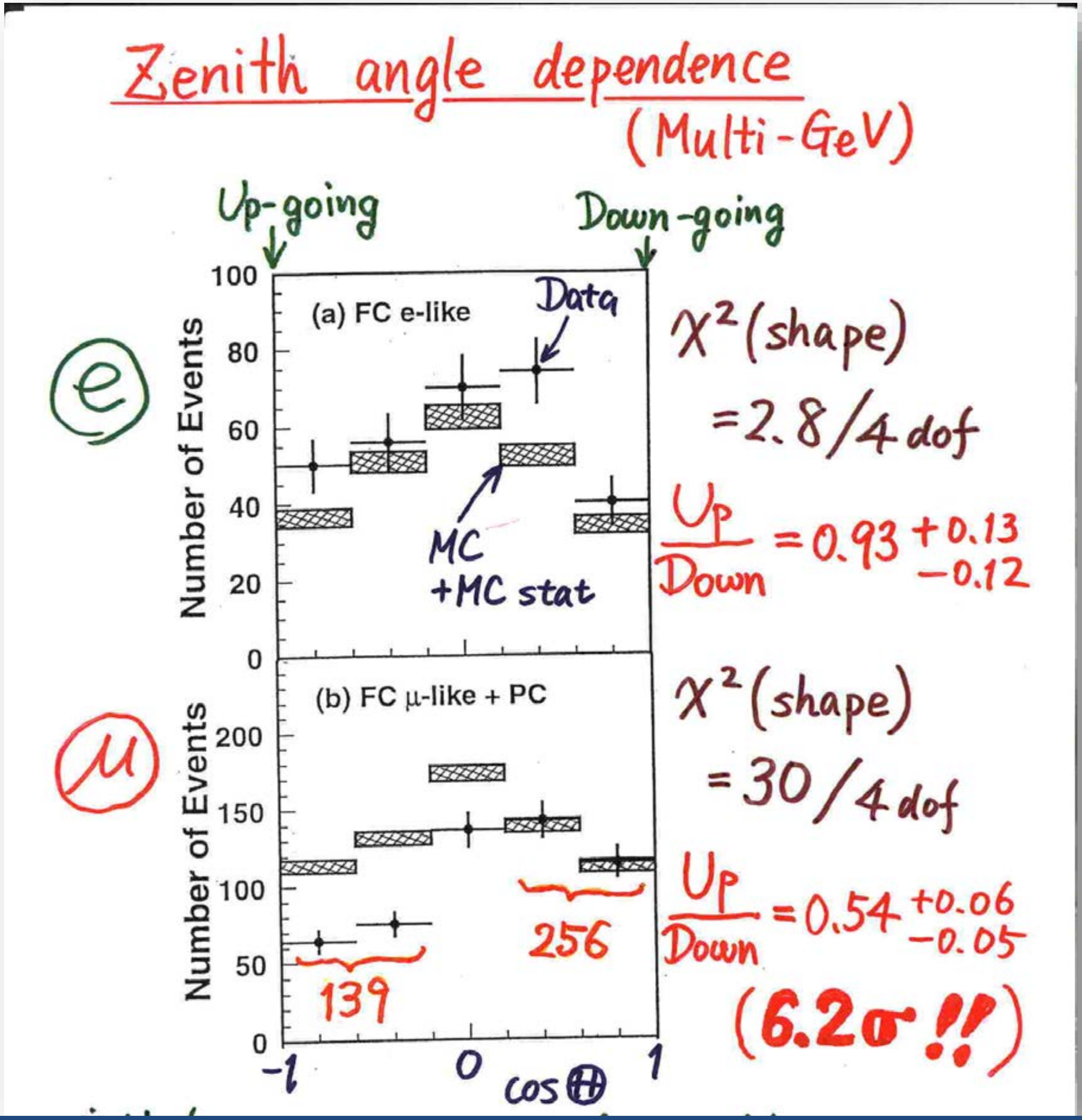


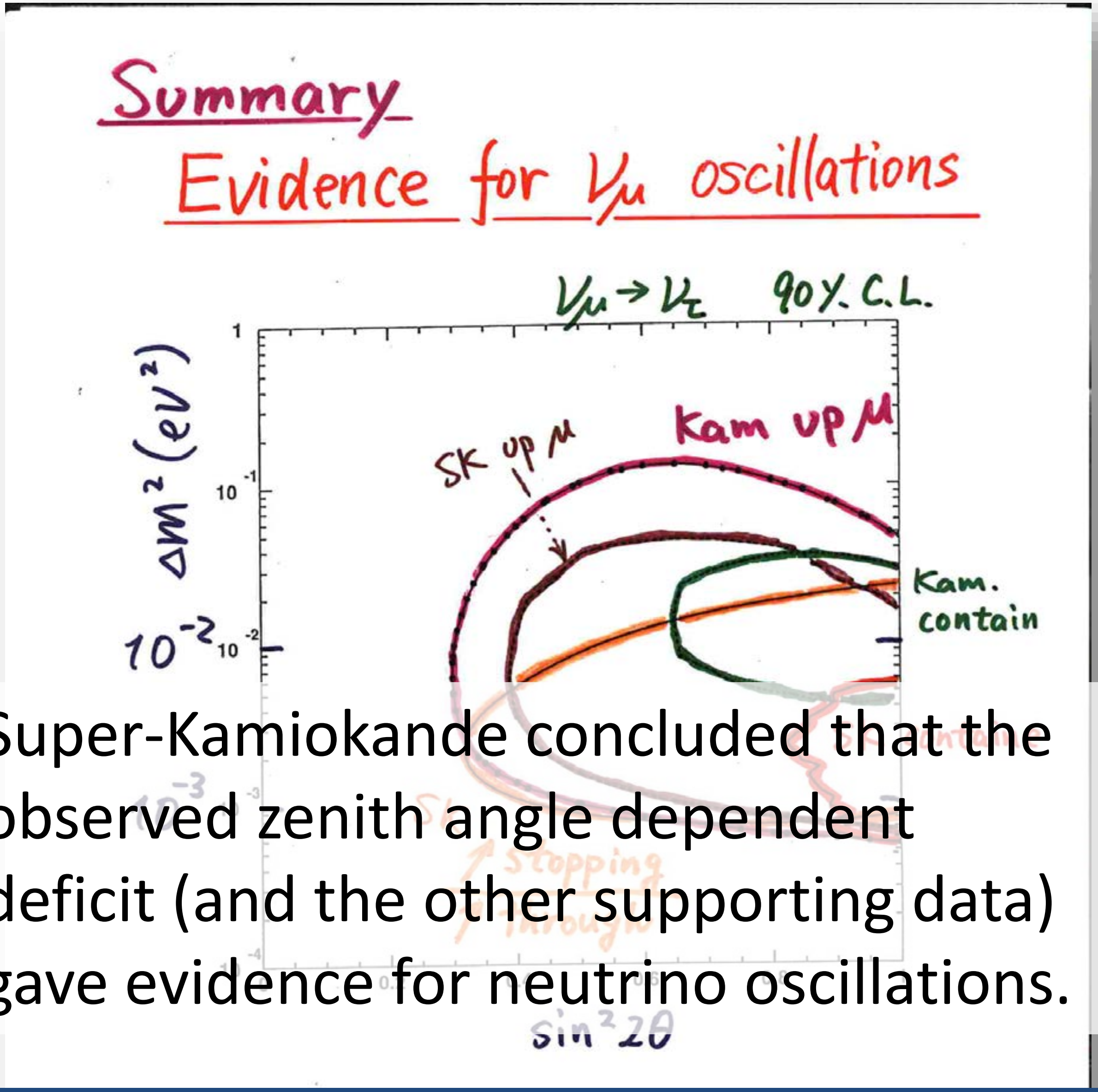


We decided to use all these events in the analysis.

Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

Y. Fukuda et al., PRL 81 (1998) 1562





Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

President Clinton's talk at MIT's 1998 Commencement

Wikimedia Commons

June 5, 1998

REMARKS BY THE PRESIDENT AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1998 COMMENCEMENT

. . . . .

Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.

. . . . .

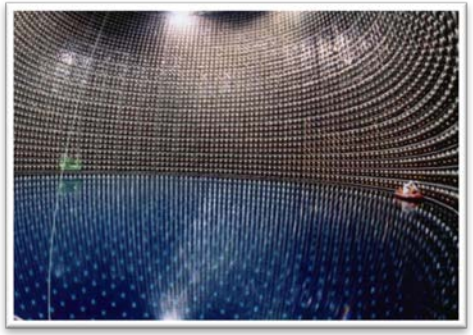
The larger issue is that these kinds of findings have implications that are not limited to the laboratory. They affect the whole of society -- not only our economy, but our very view of life, our understanding of our relations with others, and our place in time.

Neutrino oscillation studies

Studies of $\nu_\mu \rightarrow \nu_\tau$ oscillations

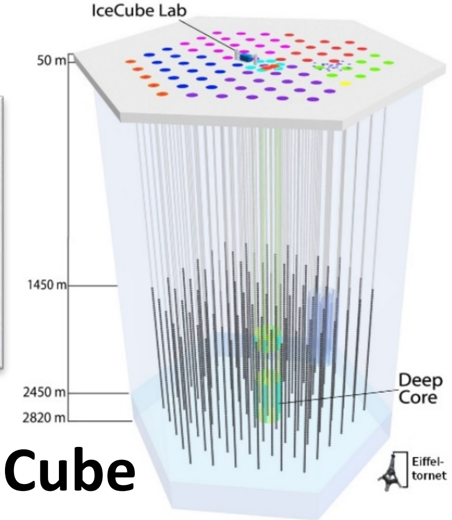
Atmospheric neutrinos

Super-K



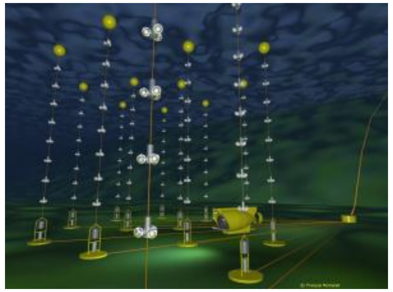
MACRO

Soudan-2



IceCube

ANTARES

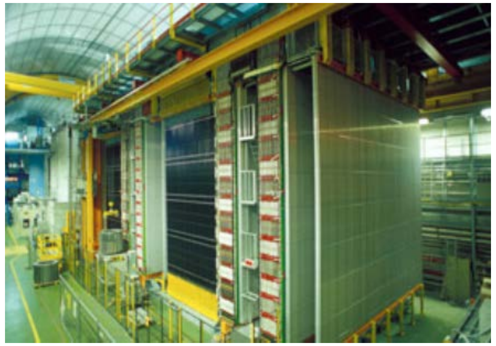


Accelerator based long baseline experiments

K2K

T2K

OPERA

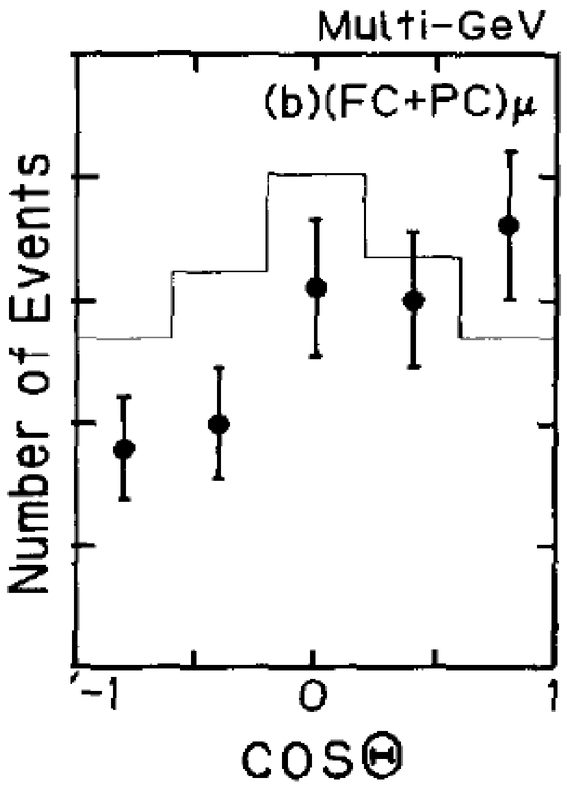


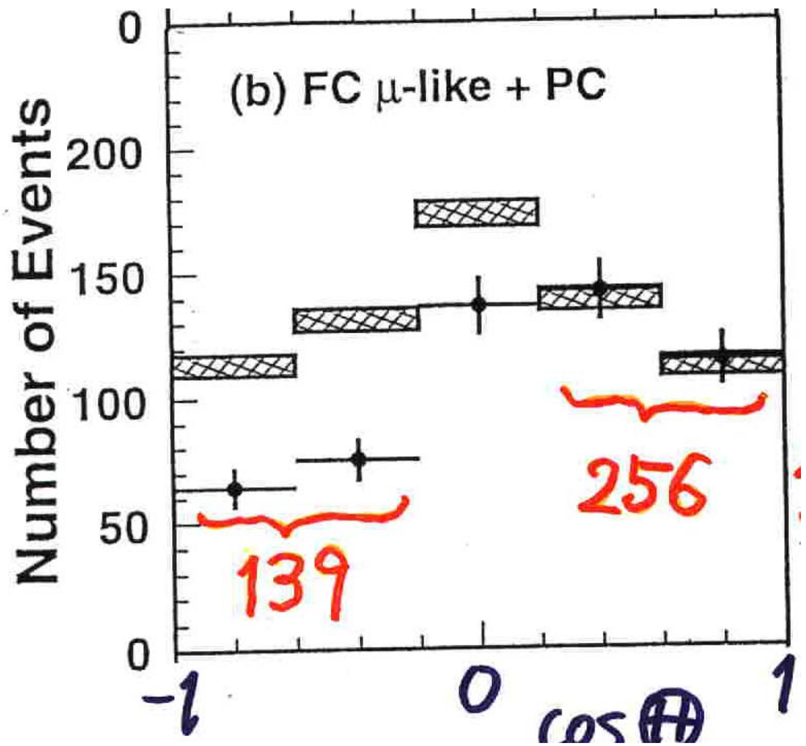
MINOS

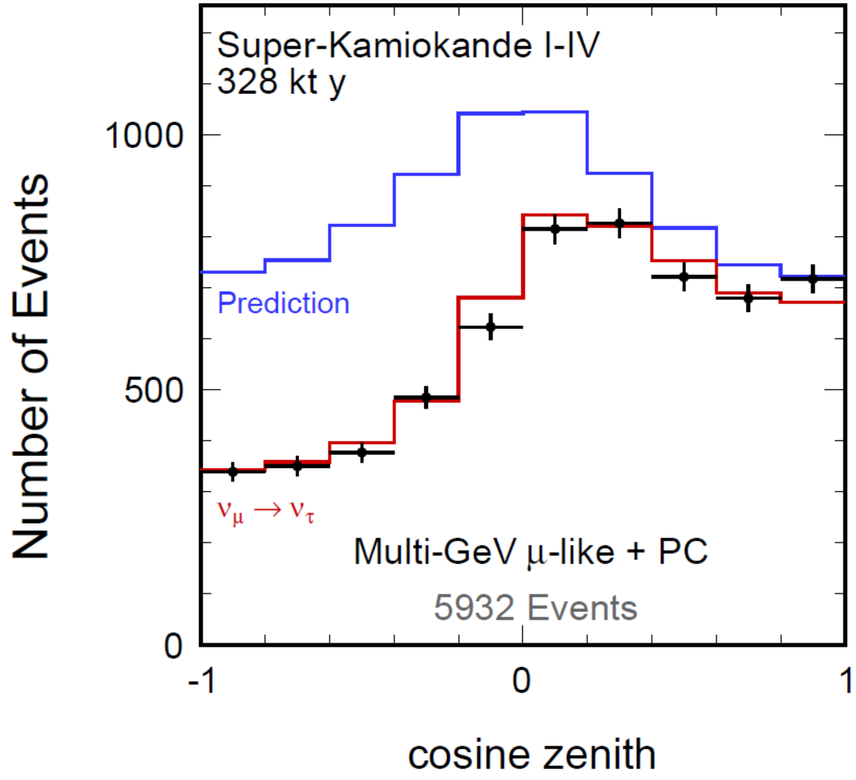
NOvA

Data updates

Kamiokande (1994) → Super-K @Neutrino98 → Super-K (2016)





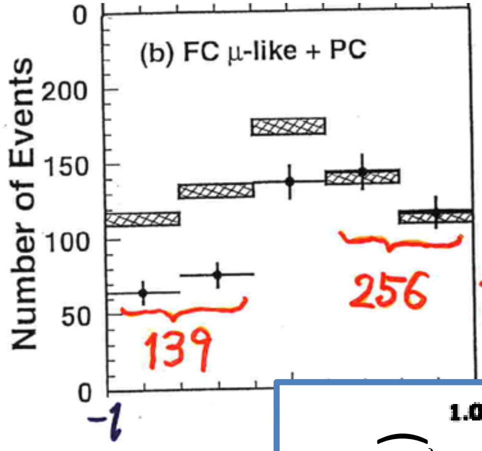


Number of events plotted:

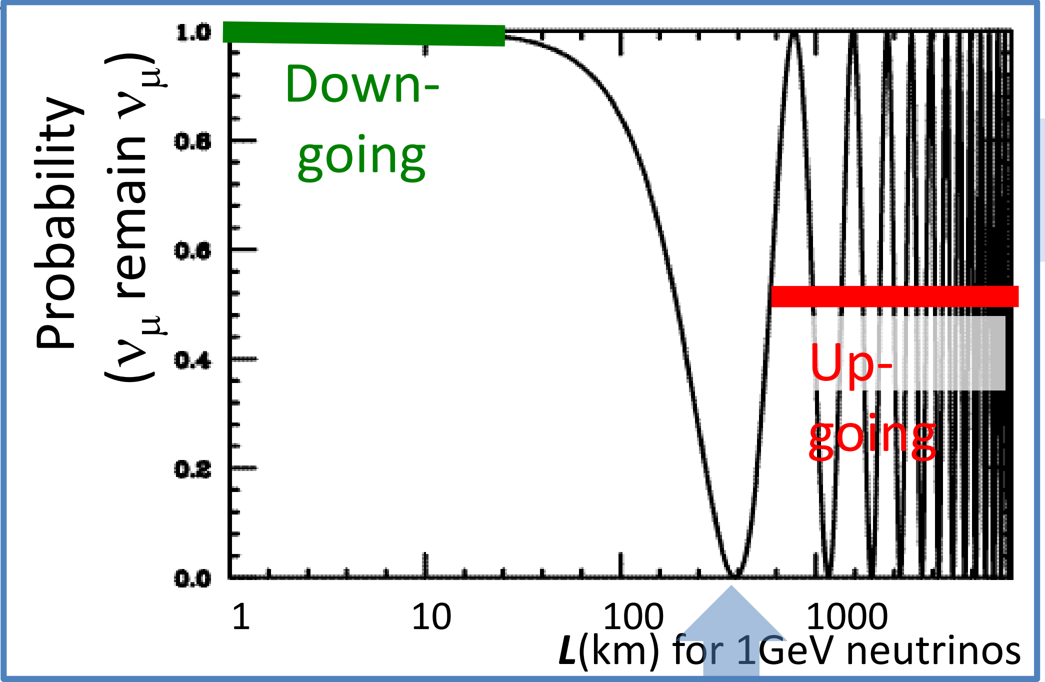
135 events → 531 events → 5932 events

Detailed studies of oscillations!

Really oscillations !

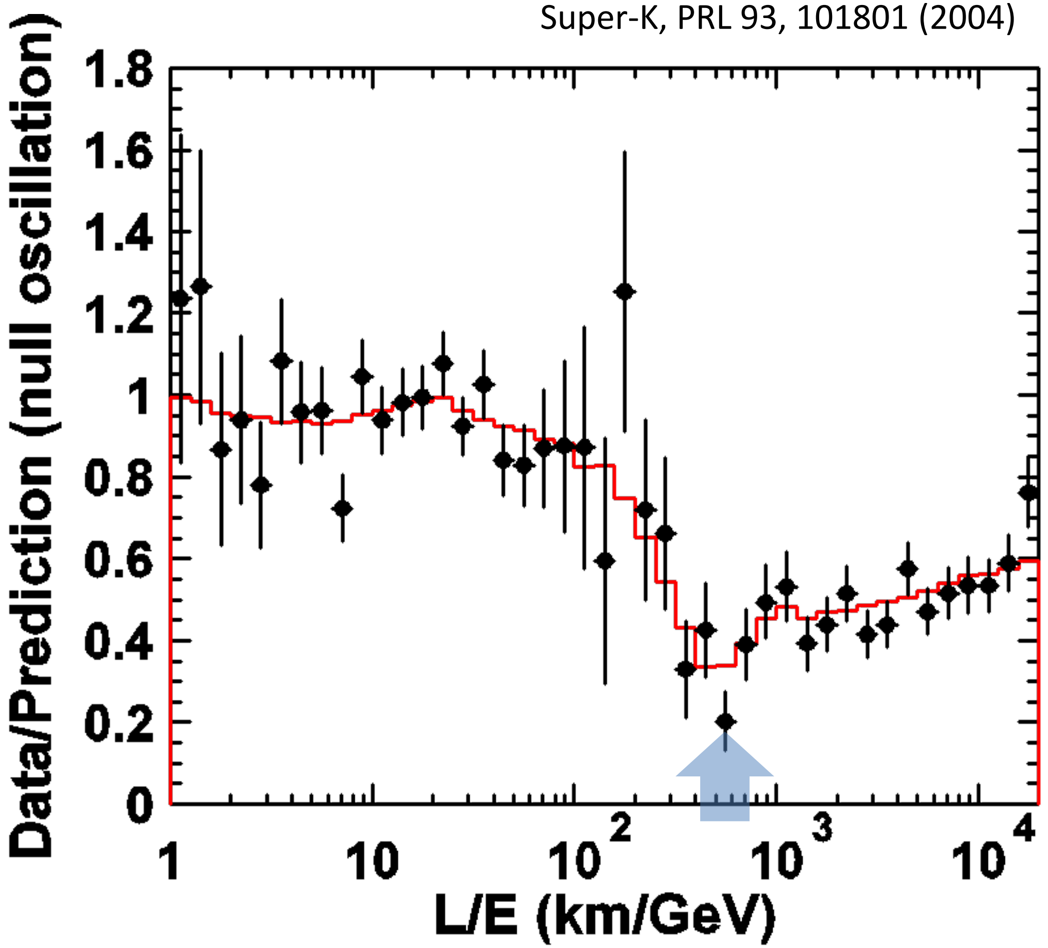


It was very nice to see that approximately half of the long traveling ν_μ's disappear. However, we wanted to really confirm neutrino "oscillations".



We wanted to observe this dip to confirm neutrino "oscillations".

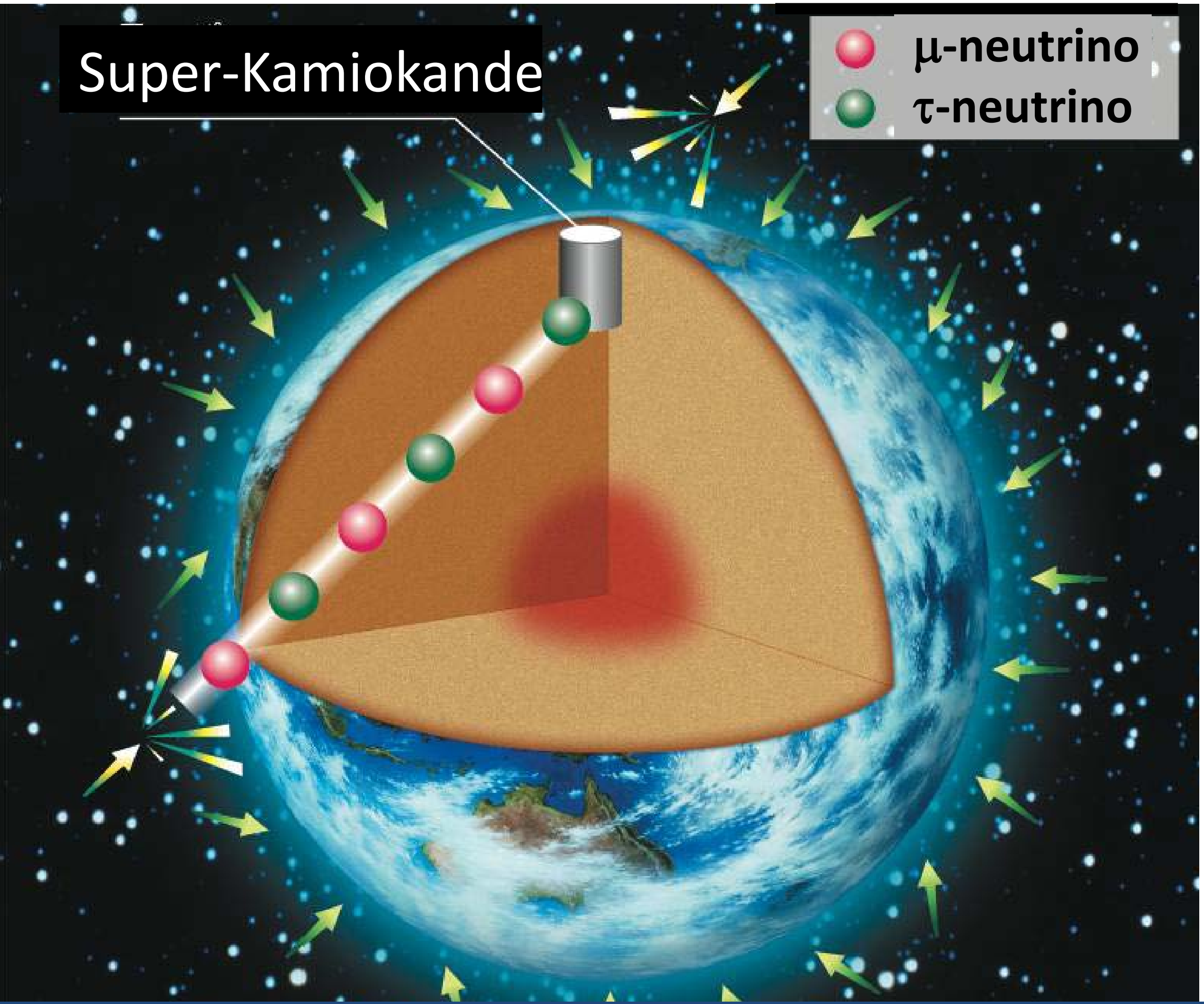
Super-K, PRL 93, 101801 (2004)

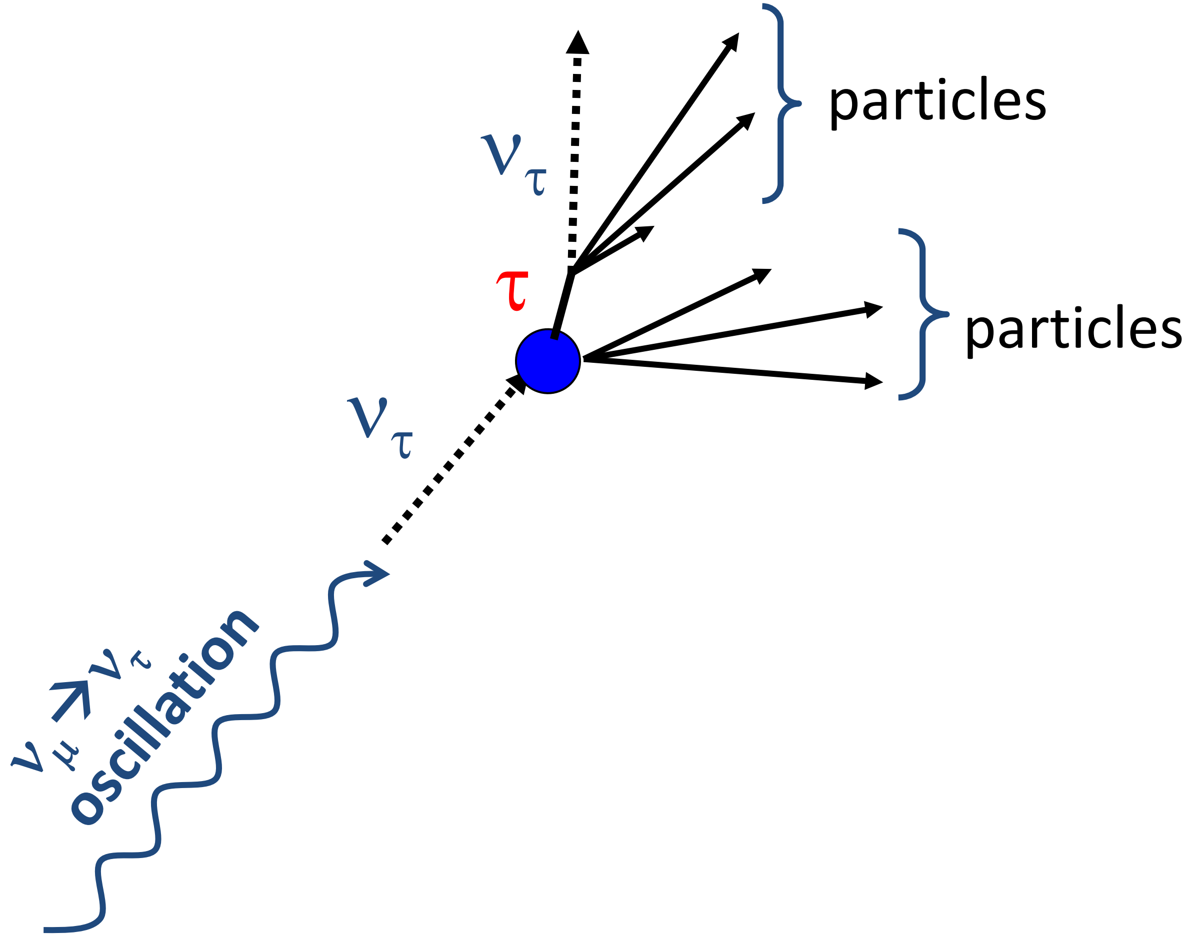


A dip is seen at L/E~500km/GeV.
➔ *Really oscillations (2004) !!*

tau neutrino appearance?

If the oscillations are between ν_μ and ν_τ, one should be able to observe ν_τ interactions.



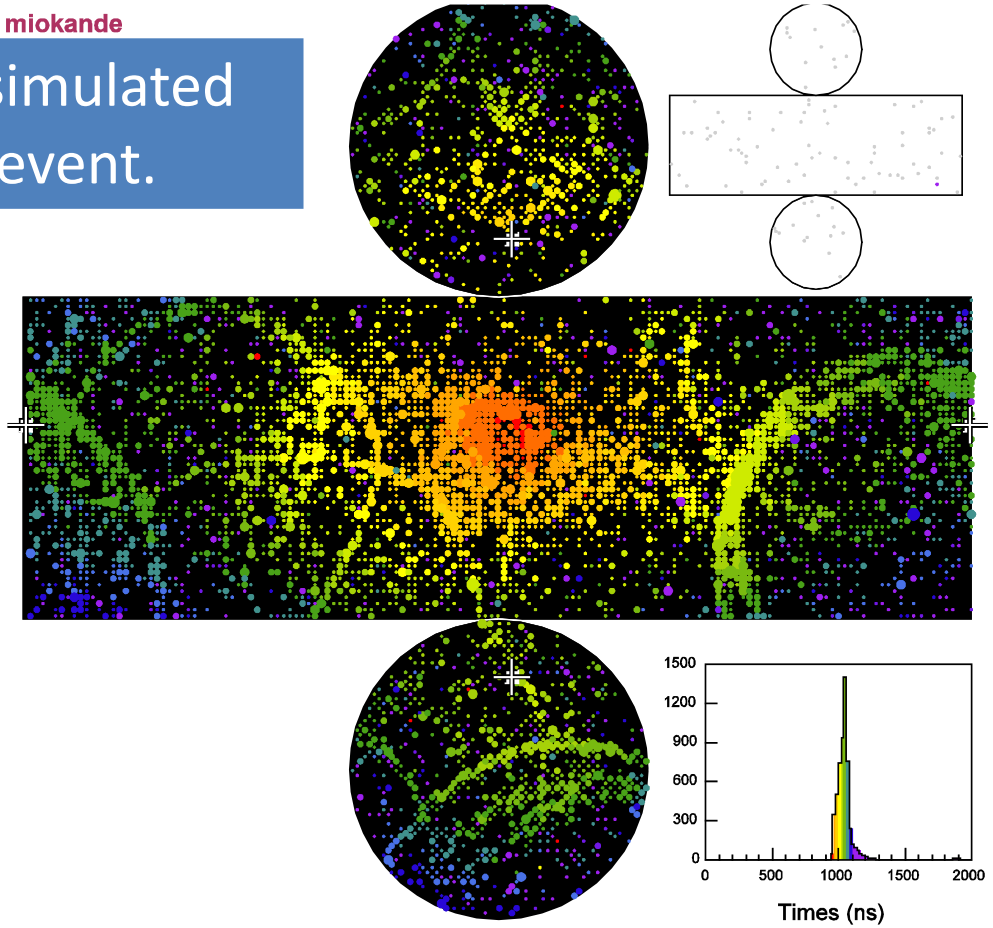


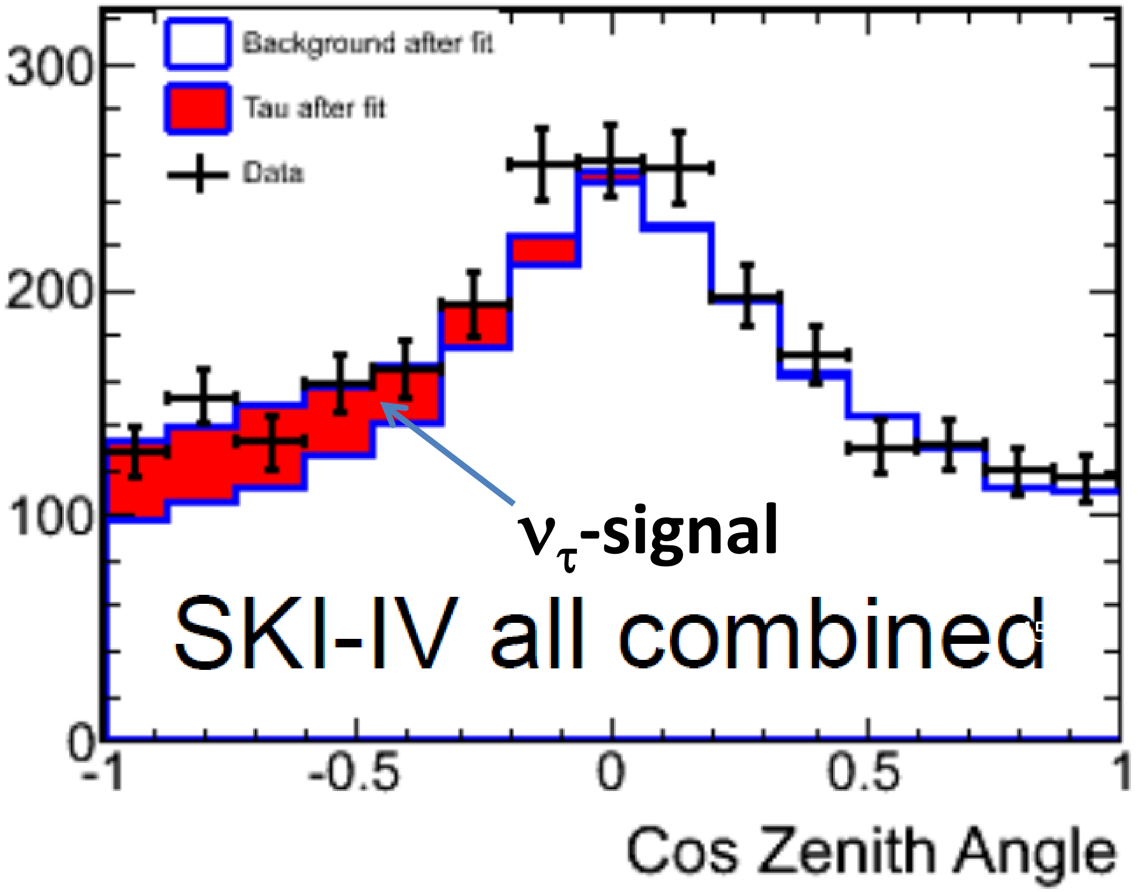
Detecting tau neutrinos

SK@Neutrino 2016,
See also, SK PRL 110(, 181802 (2013), SK PRL 97, 171801 (2006)

miokande

A simulated ν_τ event.





It is not possible for Super-K to identify ν_τ events by an event by event bases. ➔ Statistical analysis knowing that ν_τ's are upward-going only.

τ-appearance at 4.6σ

(consistent with OPERA)

Neutrino oscillation studies

$\nu_\mu \rightarrow \nu_\tau$ oscillations (Δm_{23}, θ_{23})

Atmospheric: Super-K, Soudan-2, MACRO IceCube/Deepcore, …

LBL: K2K, MINOS, OPERA, T2K, NOvA, …

$\nu_e \rightarrow (\nu_\mu+\nu_\tau)$ oscillations (Δm_{12}, θ_{12})

Solar: SNO, Super-K, Borexino, …

Reactor: KamLAND

θ_{13} experiments

LBL: MINOS, T2K, NOvA, …

Reactor: Daya Bay, Reno, Double Chooz

Status (before Neutrino 2016)

Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$

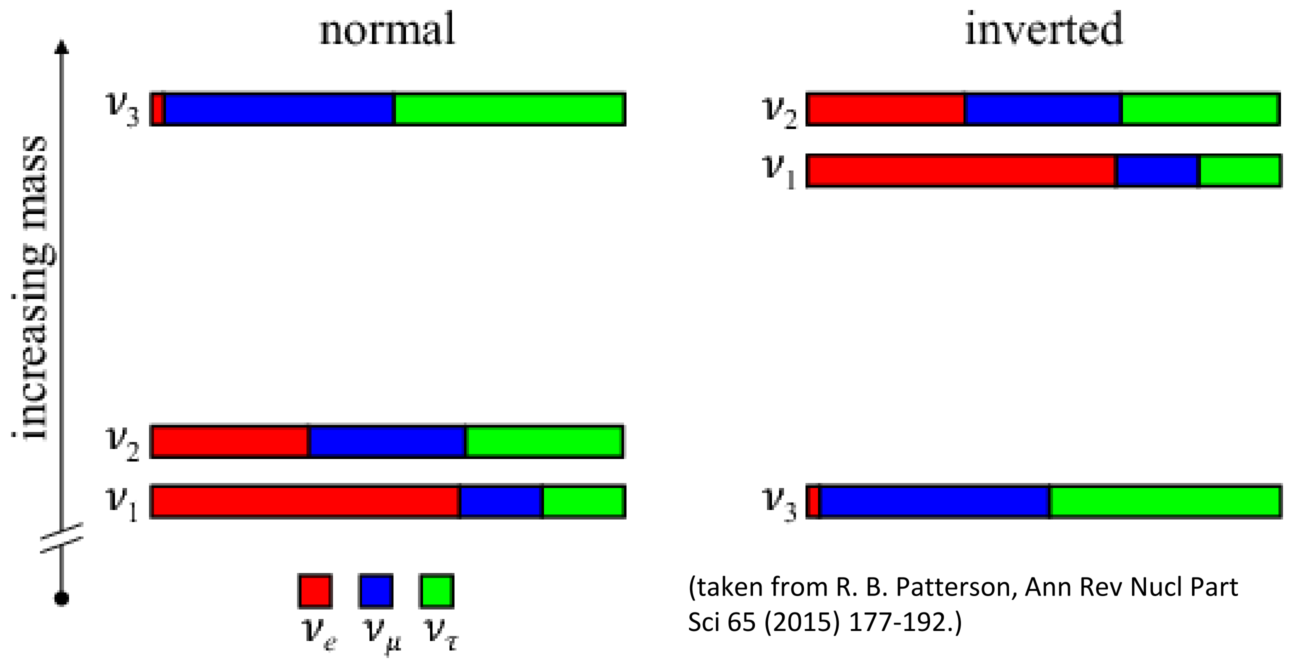
K. Nakamura and S.T. Petcov, "14. Neutrino mass, mixing and oscillations"

Basic structure for 3 flavor oscillations has been understood!

Future neutrino oscillation experiments

Agenda for the future neutrino measurements

Neutrino mass hierarchy?



(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

Absolute neutrino mass?

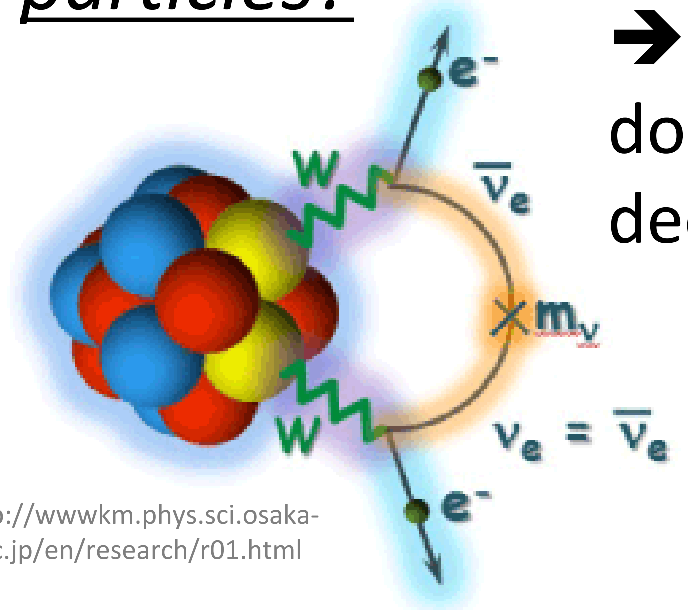
Beyond the 3 flavor framework? (Sterile neutrinos?)

CP violation?

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \ ?$$

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?

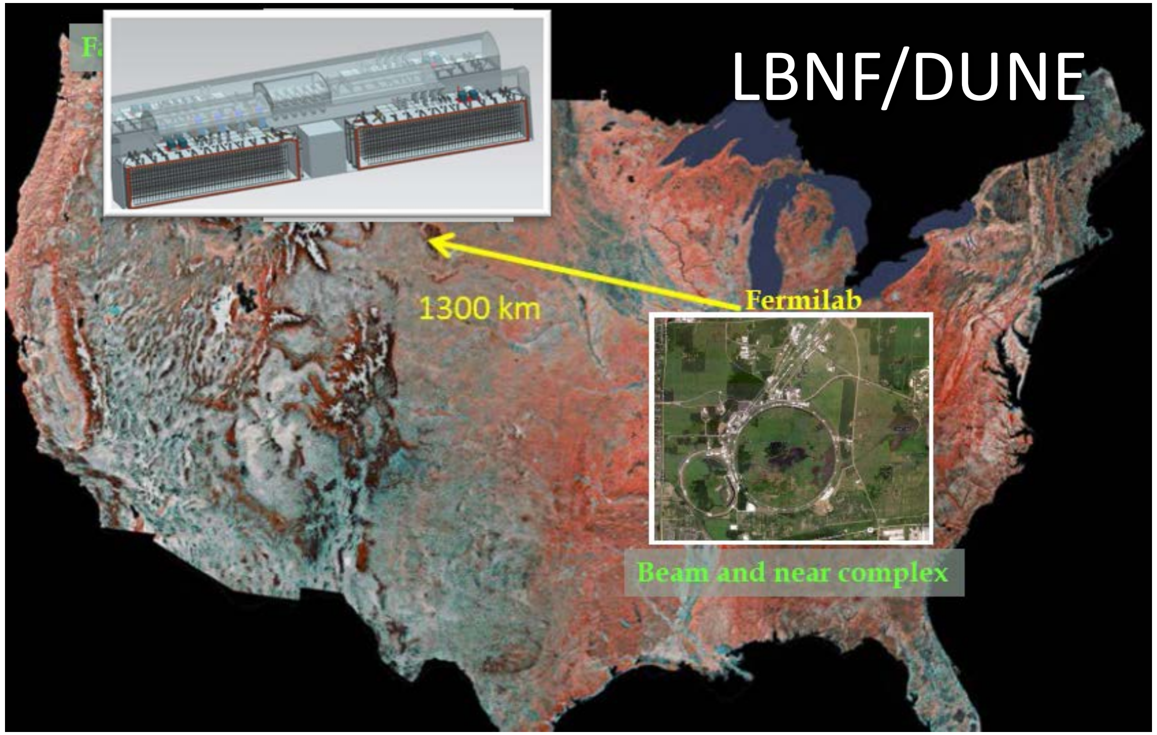


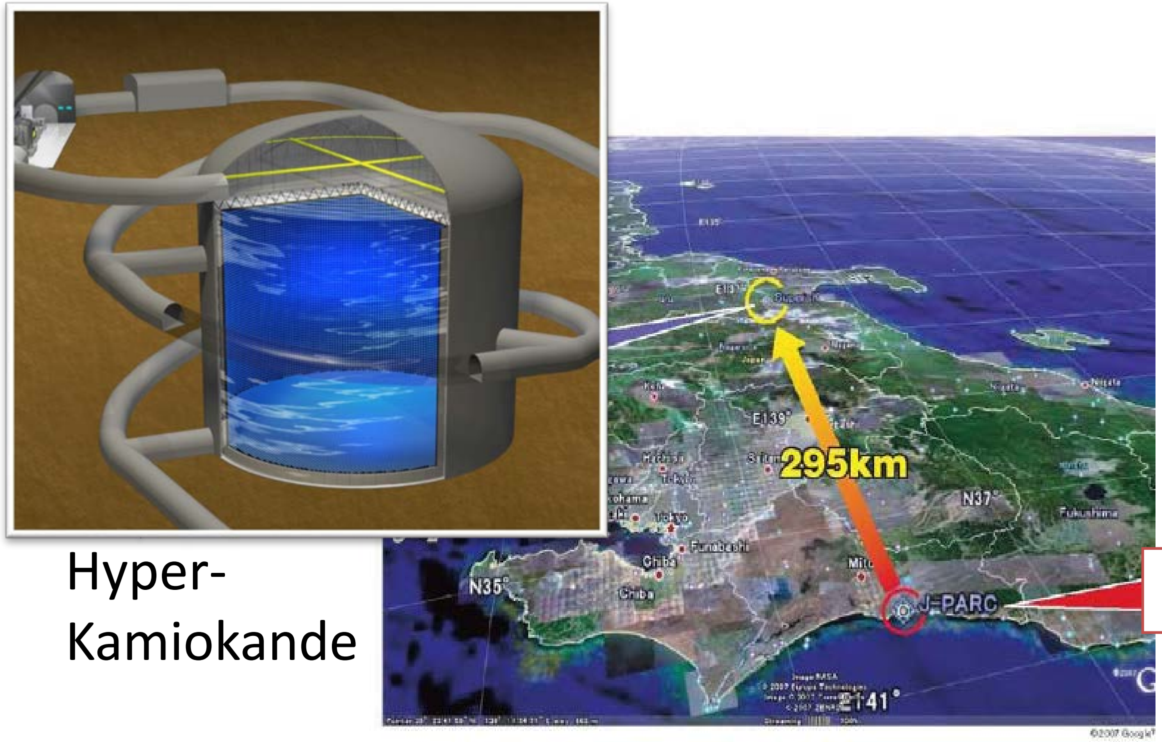
http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

➔ Neutrinoless double beta decay

Next generation neutrino oscillation experiments

- ✓ We would like to observe if oscillation of neutrinos and those of anti-neutrinos are different. If observed, it might be the first step to understand the origin of the matter in the Universe.
- ✓ It is not easy to observe this effect. We need the next generation long base line experiments with much higher performance neutrino detectors.





Hyper-Kamiokande

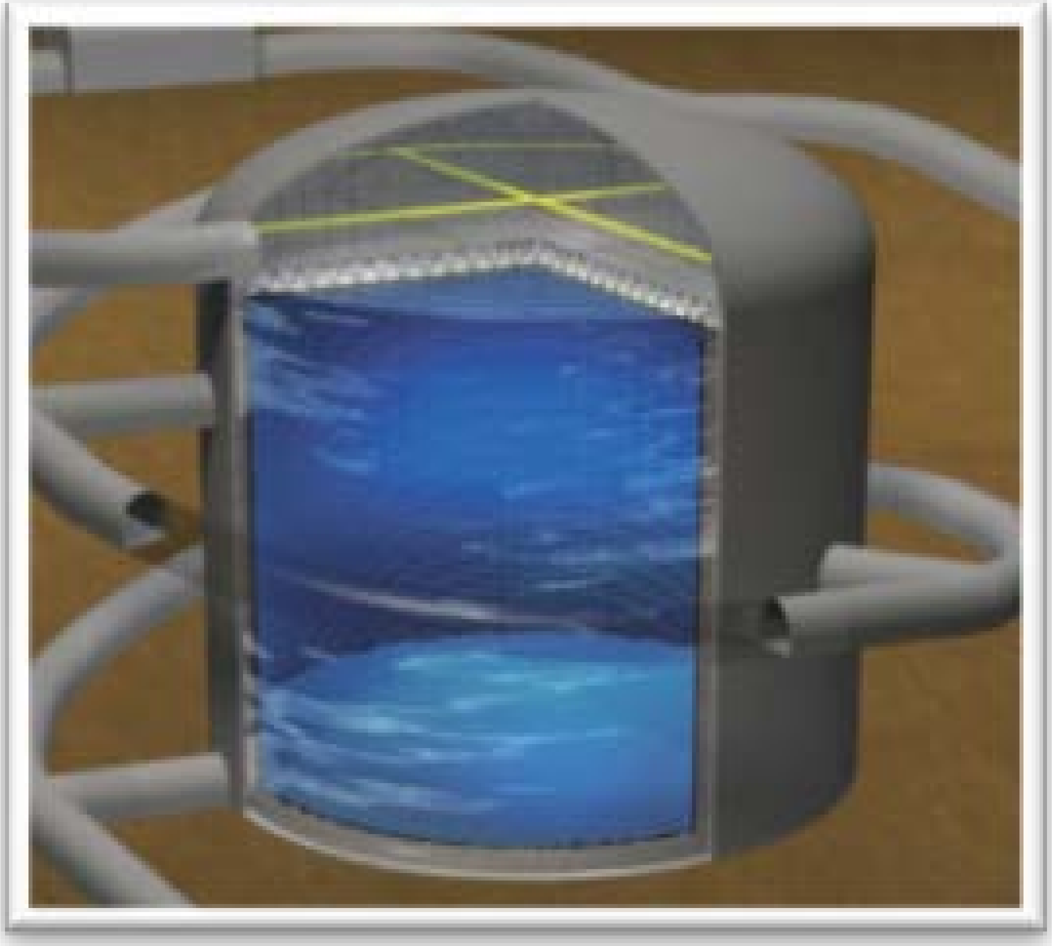
J-PARC

Hyper-K

- ✓ Hyper-K detector will be used to study:
  - ✓ Neutrino oscillations (accelerator, atmospheric and solar neutrinos)
  - ✓ Proton decays
  - ✓ Supernova neutrino burst
  - ✓ Past supernova neutrinos
  - ✓ ….

<u>*Status*</u>

- ✓ Hyper-K has been selected as one of the 7 large scientific projects in the Roadmap of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2017.
- ✓ We are waiting for the project approval by the Japanese government…



- ◆ Φ 74 meters and H 60 meters.
- ◆ The total and fiducial volumes are 0.26 and 0.19 M tons, respectively.

Summary

- “Proton decay experiments” in the 1980’s observed many contained atmospheric neutrino events, and discovered the atmospheric ν_μ deficit unexpectedly.
- In 1998, Super-Kamiokande discovered neutrino oscillations, which shows that neutrinos have mass.
- Since then, various experiments, including solar neutrino experiments, have studied neutrino oscillations.
- The discovery of non-zero neutrino mass opened a window to study physics beyond the Standard Model of particle physics. Neutrinos with small mass might also be the key to understand the fundamental questions of the Universe.