National Taiwan University
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Atmospheric Neutrino Studies and Neutrino Oscillation

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Outline

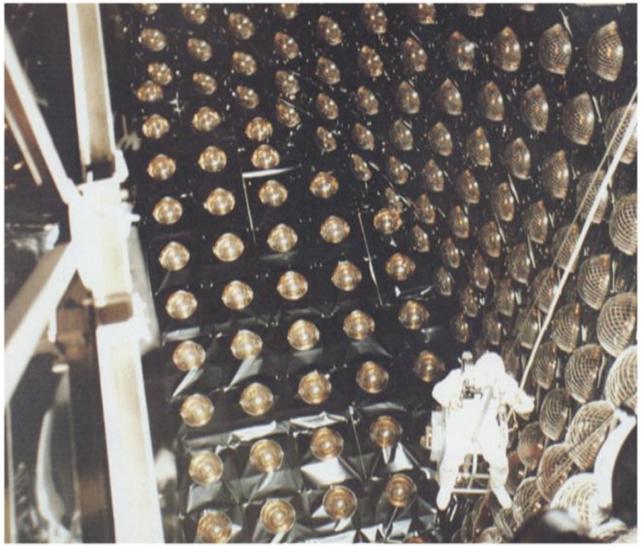
- Introduction: Kamiokande - the starting point of my research -
- Discovery of neutrino oscillations: History
- Discovery of neutrino oscillations
- Recent results
- Future
  - Appendix
- Summary

Introduction:

Kamiokande
- the starting point of my research –

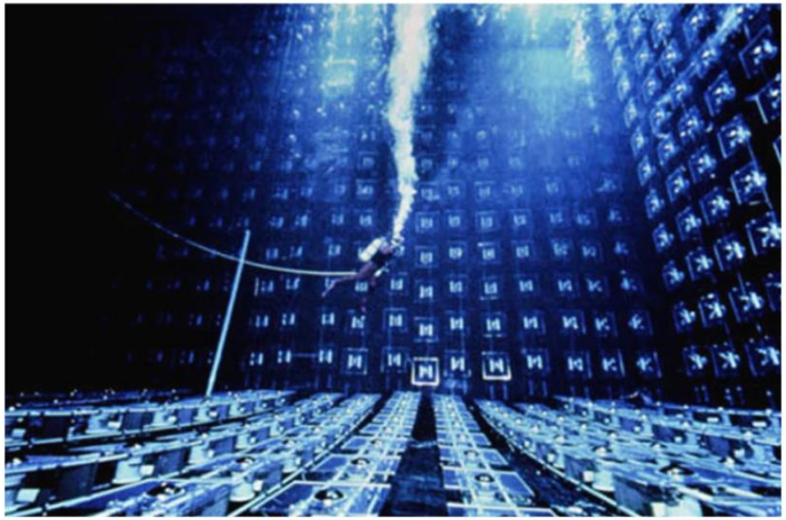
Proton decay experiments (1980's)

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



Kamiokande (1000ton)

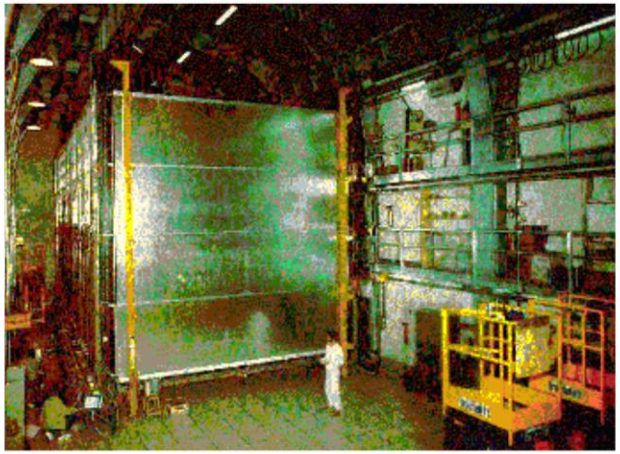
IMB (3300ton)



NUSEX (130ton)

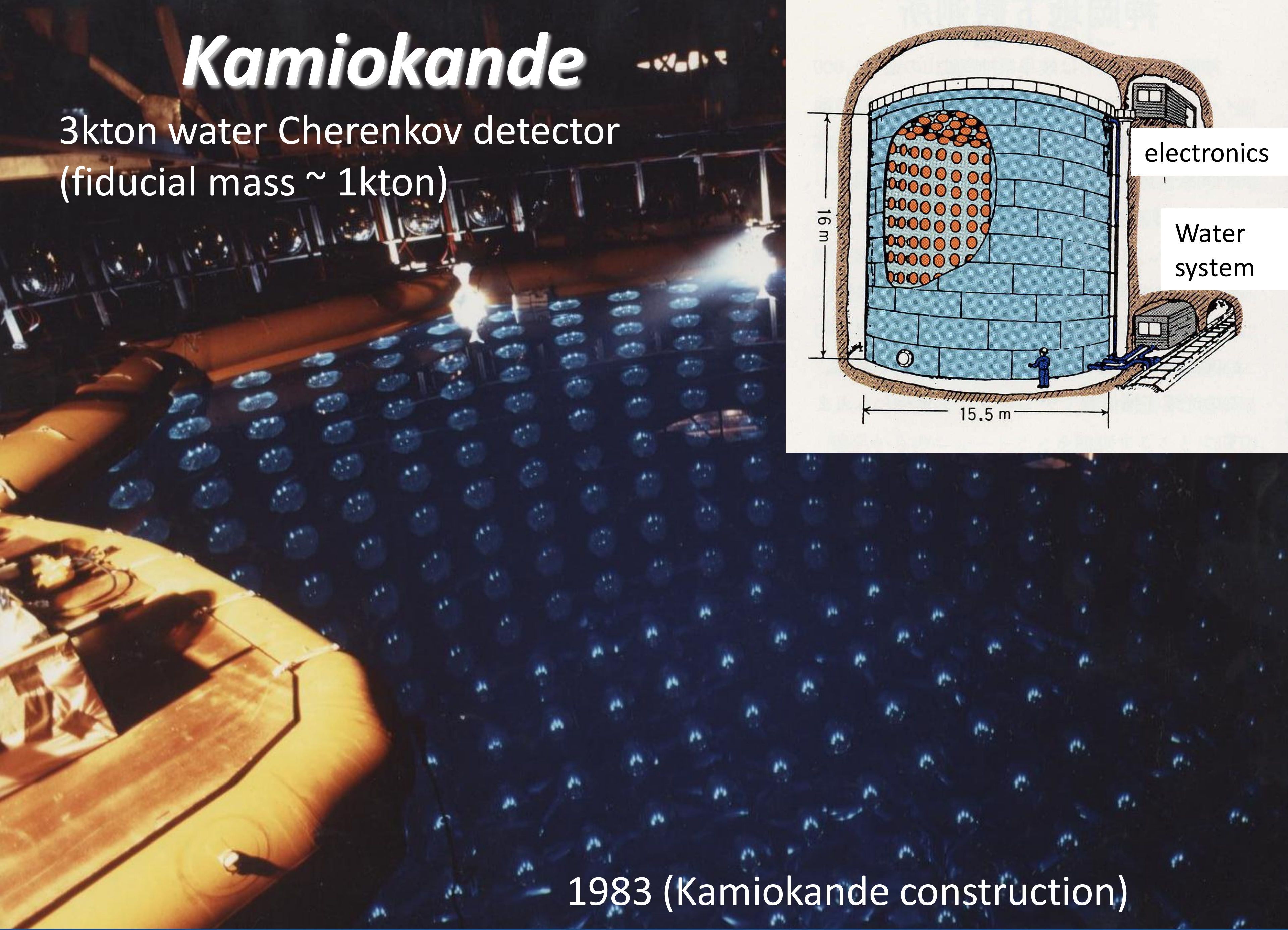
Frejus (700ton)

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



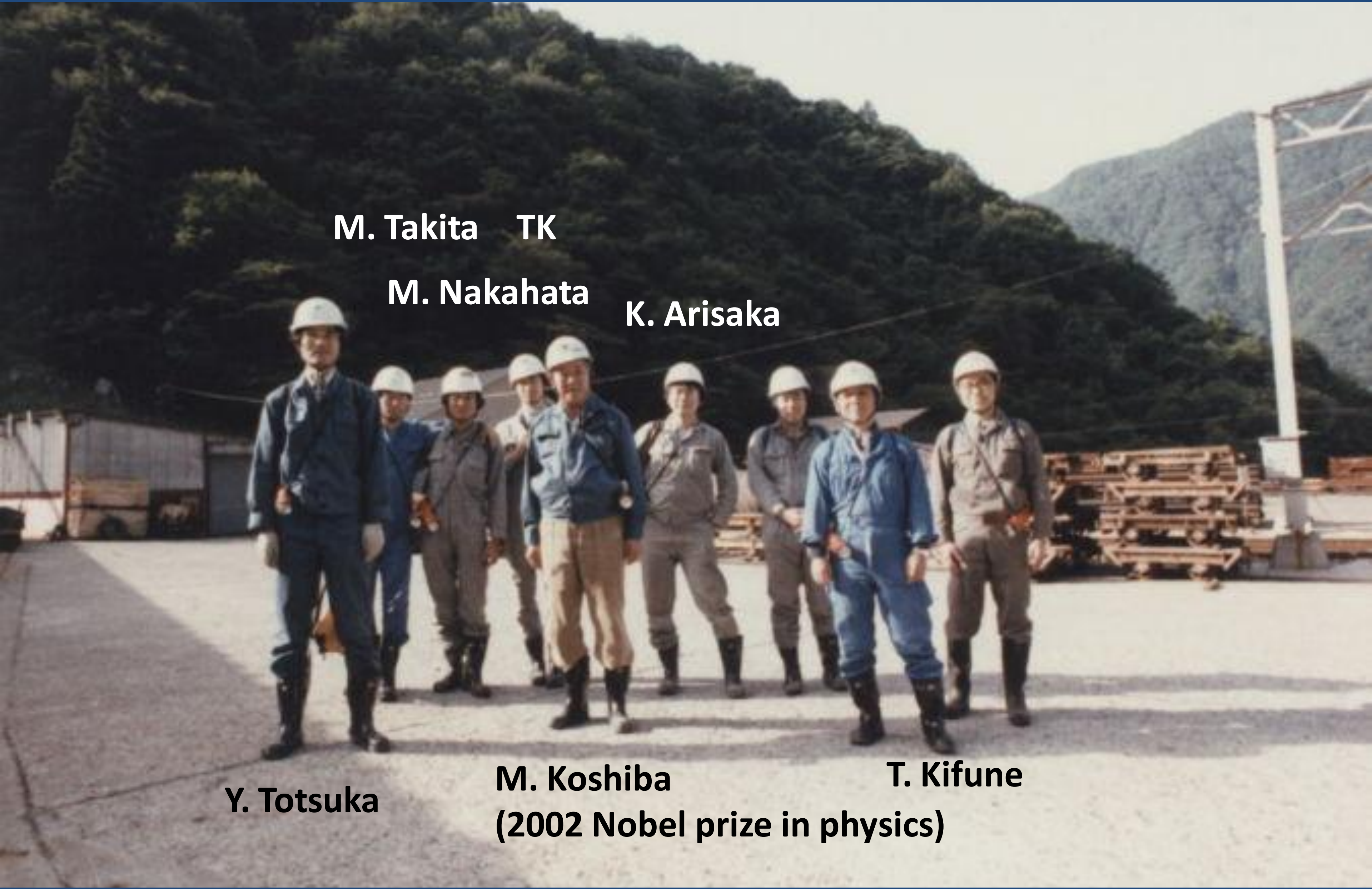
Kamiokande

3kton water Cherenkov detector
(fiducial mass ~ 1kton)

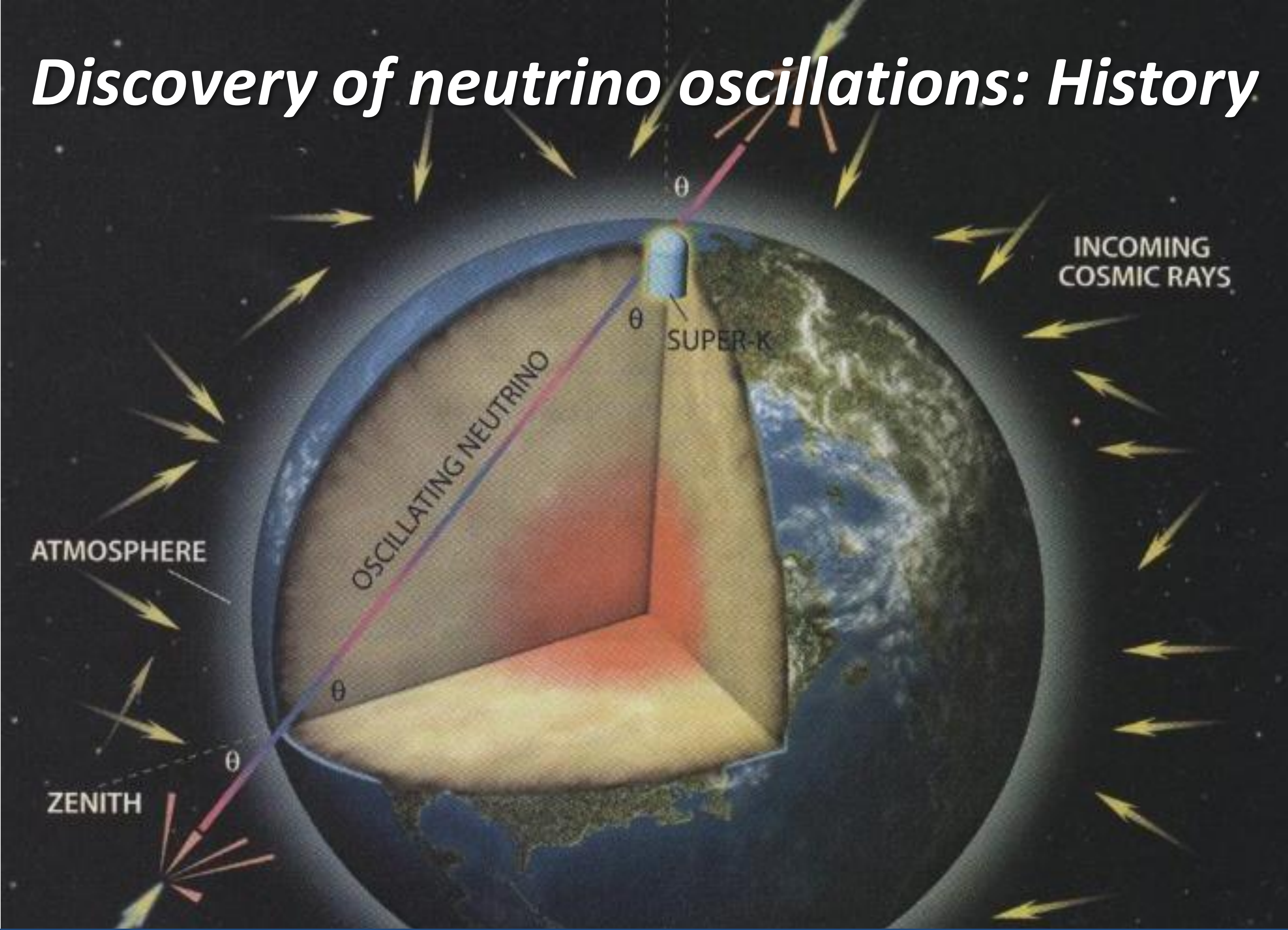


1983 (Kamiokande construction)

Kamiokande construction team (Spring 1983)



Discovery of neutrino oscillations: History

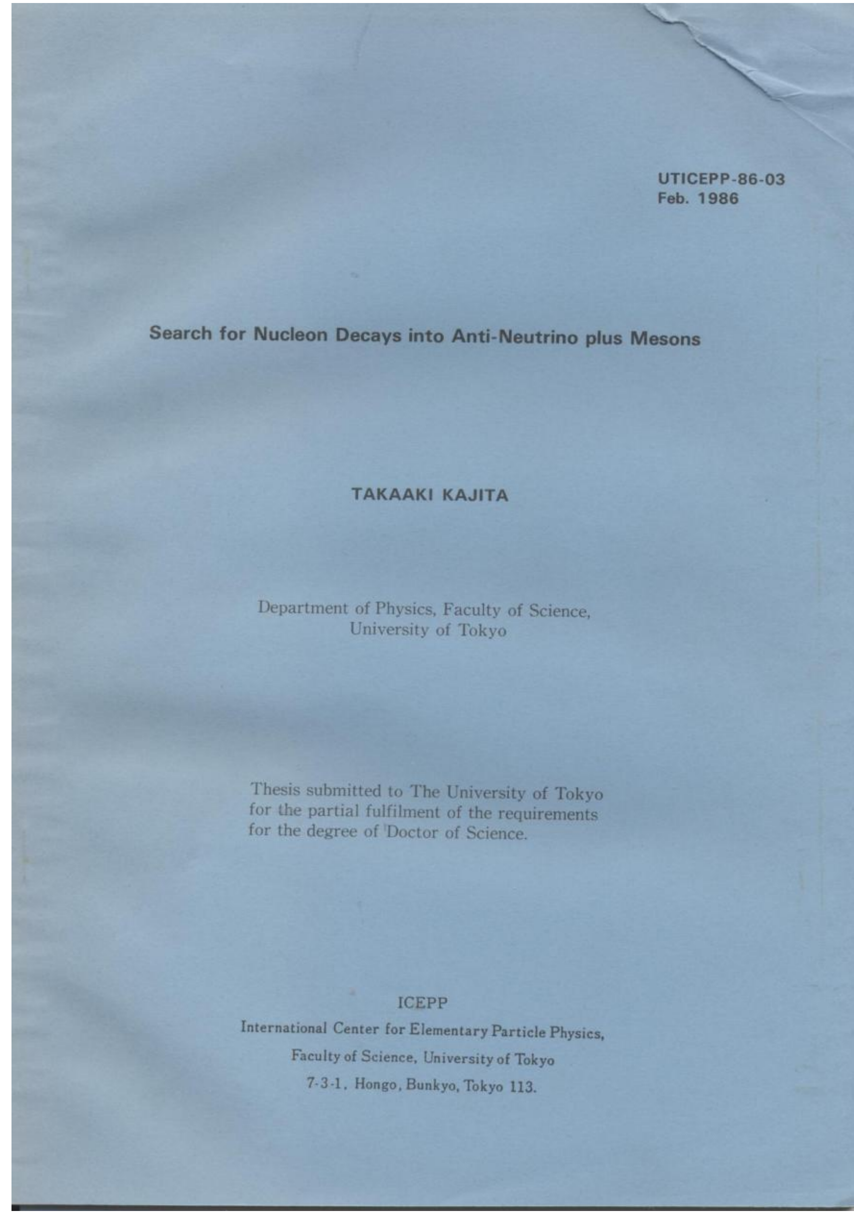


Thesis (1986)

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

I felt that the analysis software, including the particle identification (electron-like or muon-like, PID) for the multi Cherenkov-ring events, was not good enough to extract all the information that Kamiokande recorded.

Therefore, as soon as I submitted my thesis, I started a work (i.e., my personal project) to improve the software.



UTICEPP-86-03
Feb. 1986

Search for Nucleon Decays into Anti-Neutrino plus Mesons

TAKAAKI KAJITA

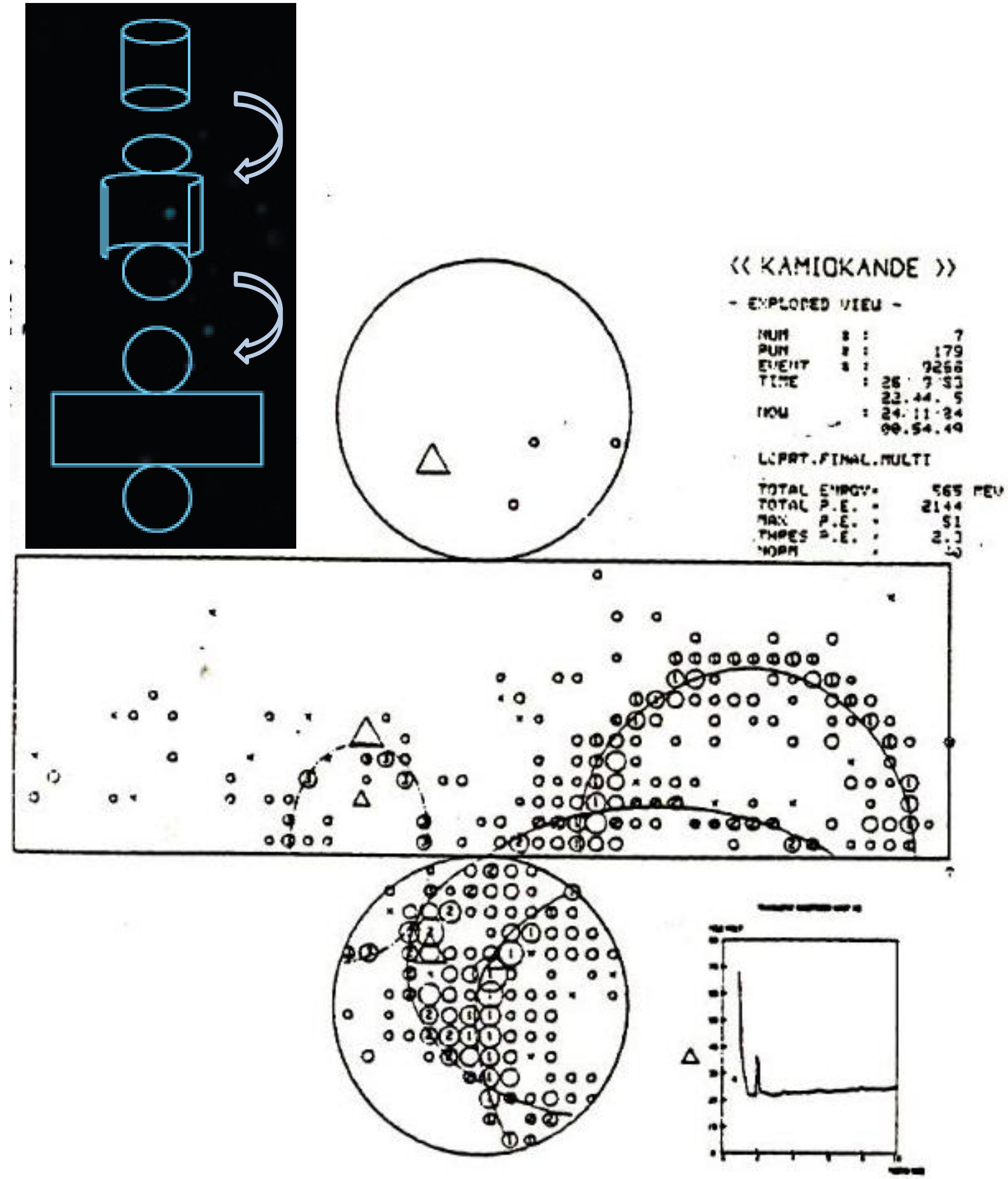
Department of Physics, Faculty of Science,
University of Tokyo

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.

Particle Identification

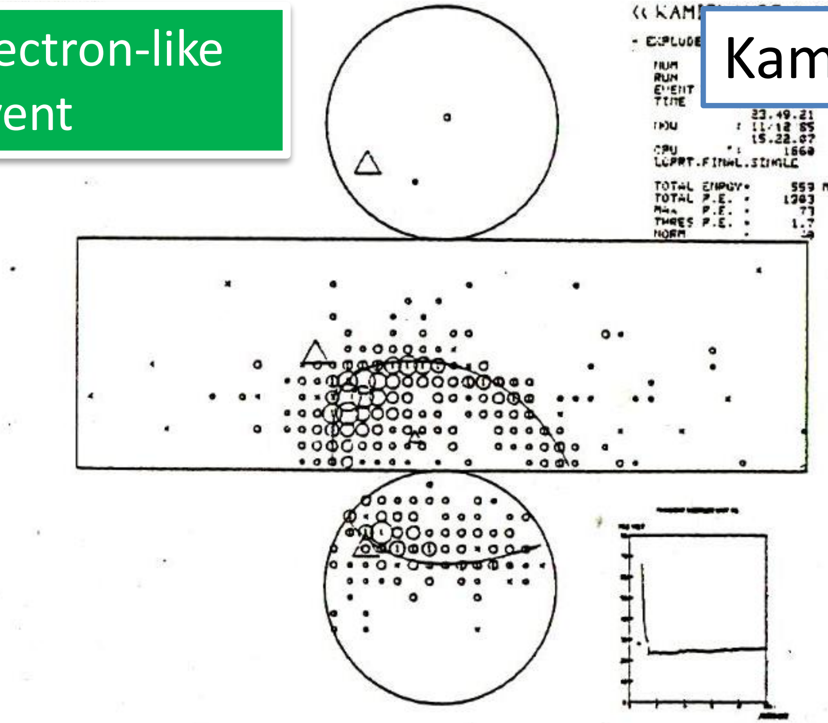
One of them was a new particle identification (PID) software for multi Cherenkov-ring events. Namely, I designed that the PID can identify if a Cherenkov ring of a multi Cherenkov-ring event is a non-showering (muon-like) or showering (electron-like) whenever possible.



The simplest application of the PID was on single Cherenkov-ring events….

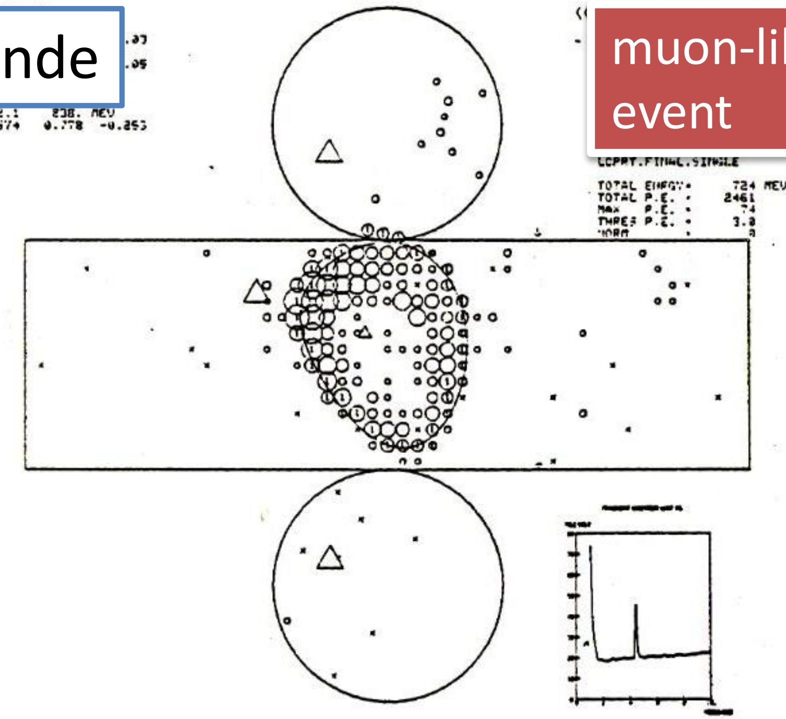
Particle identification (PID): electron or muon ?

electron-like event



Kamiokande

muon-like event



e: electromagnetic shower, multiple Coulomb scattering

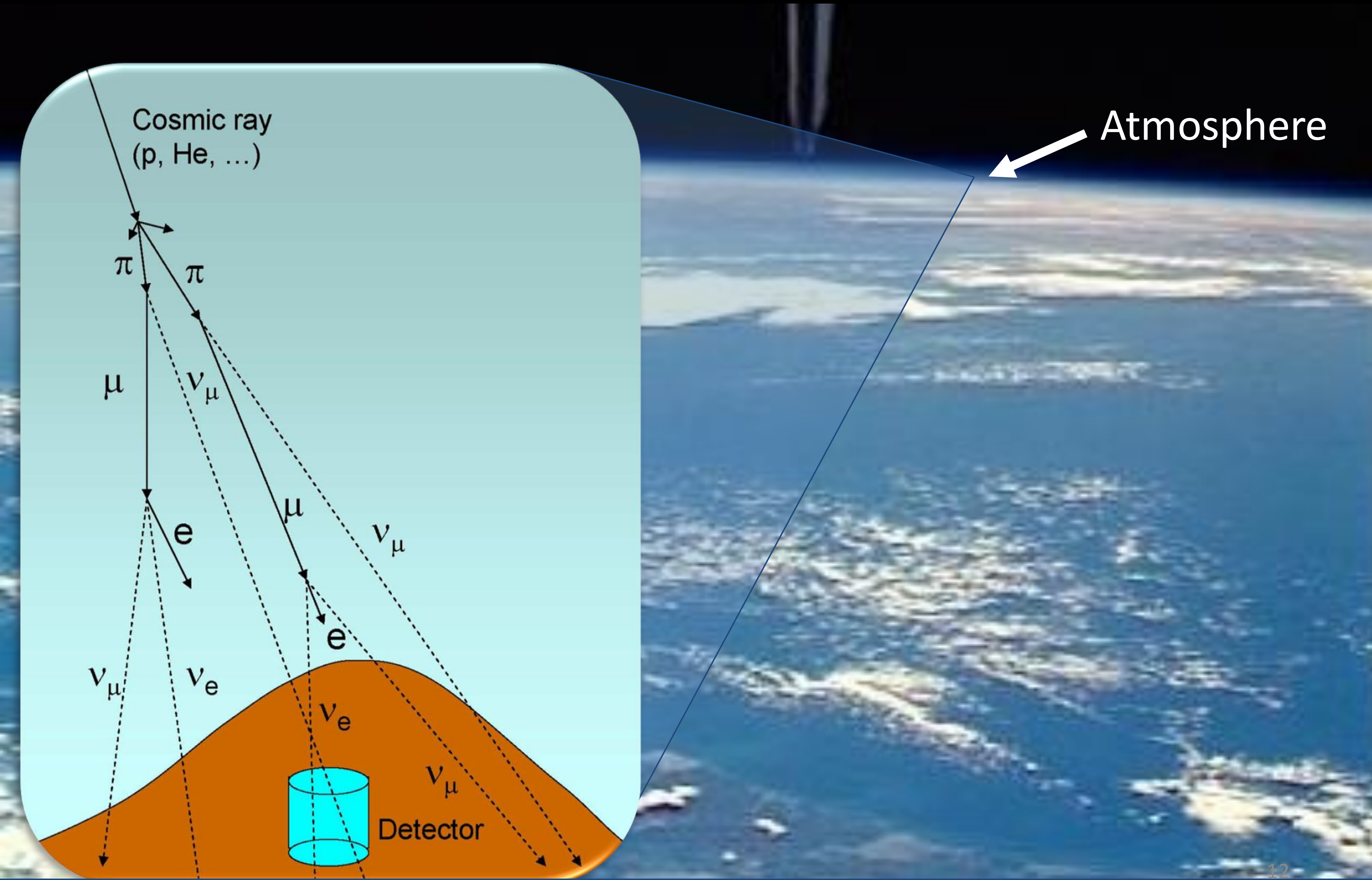
μ: propagate almost straightly, loose energy by ionization loss

Particle types are identified using the difference in the event pattern (maximum likelihood method)

A strange result…

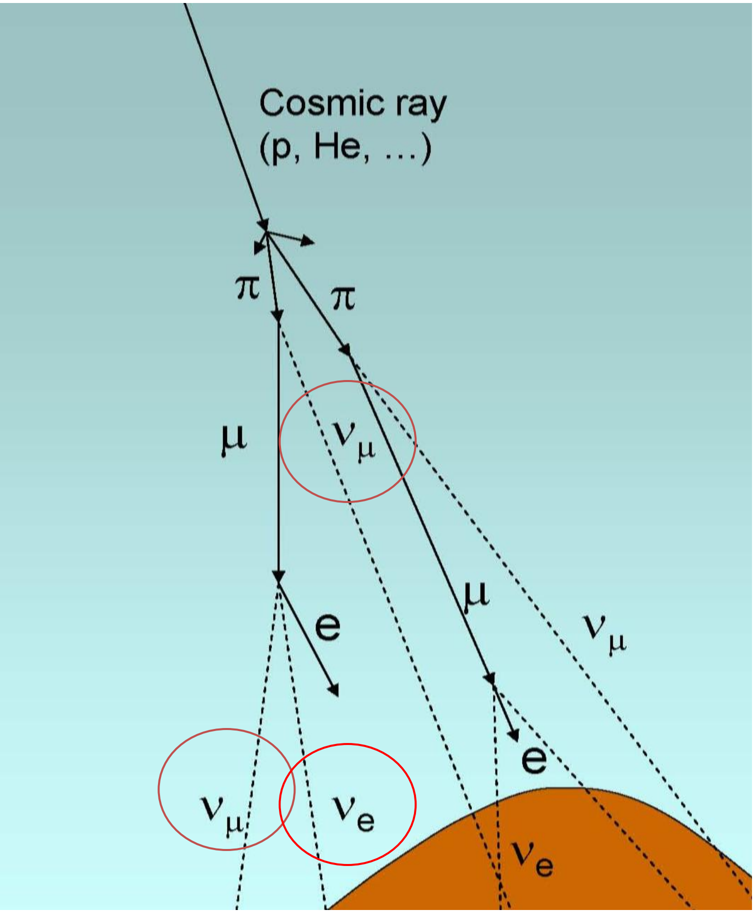
- The PID was applied to the atmospheric neutrino Monte Carlo simulation events. It worked well for them.
- Then, the new PID was applied to the real atmospheric neutrino events.
- The result was strange. The number of μ-like events was much fewer than expected.
- At first, I thought that our Monte Carlo simulation might be too simple and the “Monte Carlo detector” simulation did not reproduce the “real detector”.
- I wanted to identify what is different between the real events and the Monte Carlo simulation. I decided to scan the real events.
- Immediately, I found that the PID results for the data were correct! (I had a strong confidence with my eye, since I already scanned many, many Monte Carlo and data events, since the beginning of the Kamiokande experiments in 1983.)
- Something might be happening in neutrinos. However, I thought that it is much more likely that I made some mistake somewhere in the Monte Carlo simulation, data reduction, and/or event reconstruction….
- We started various studies in late 1986.

Production of atmospheric neutrinos

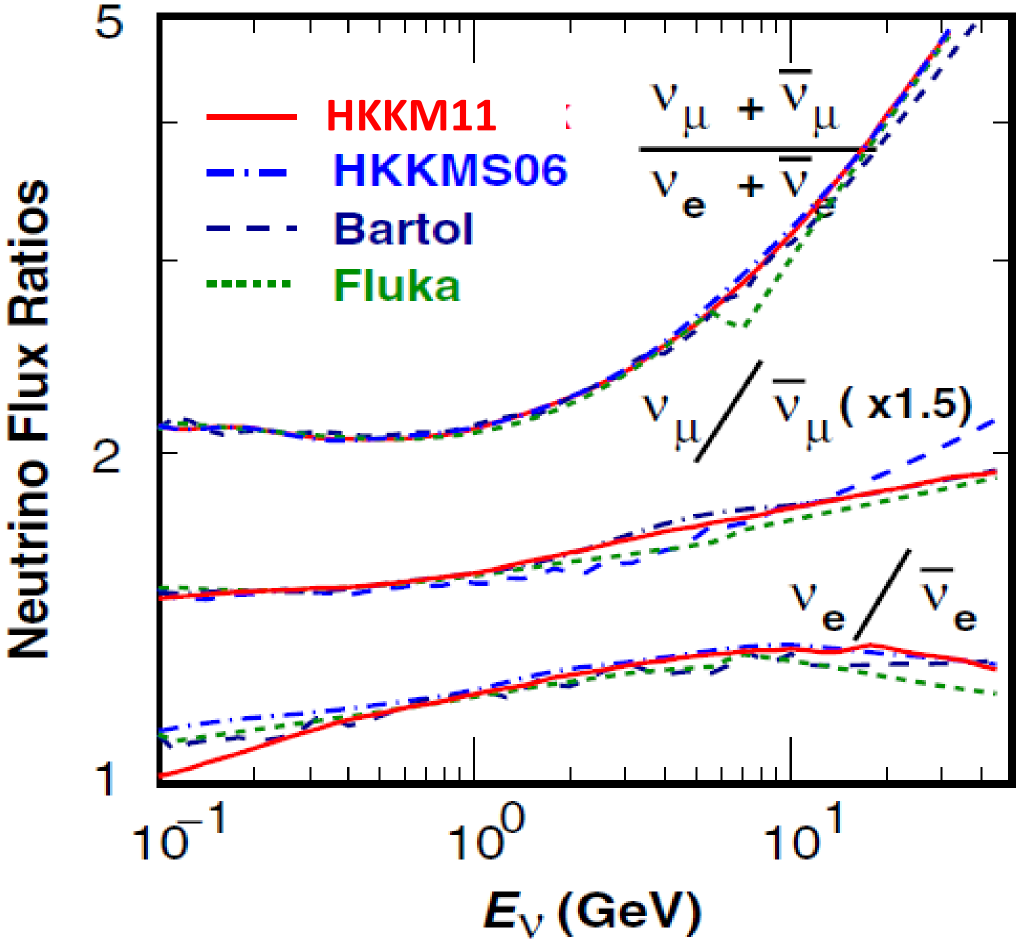


ν_μ over ν_e ratio of the beam

$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$



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

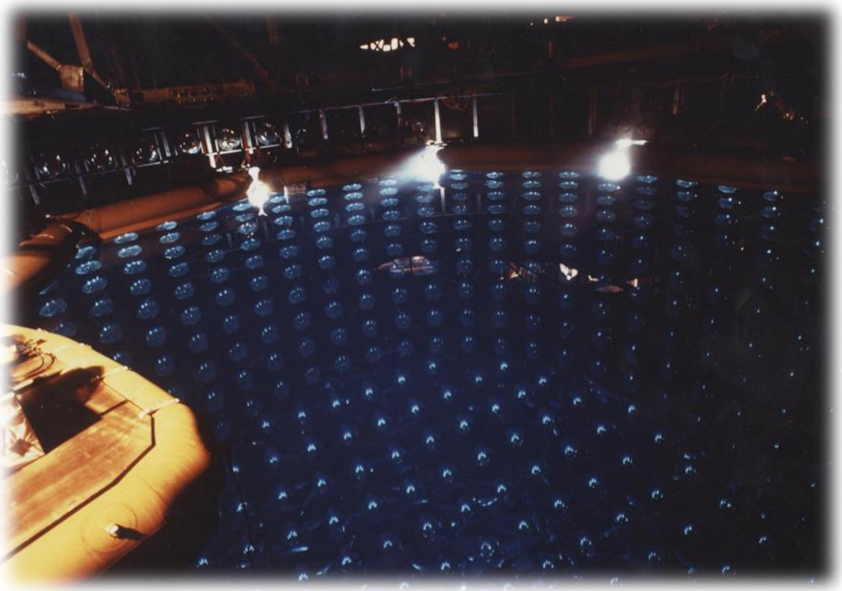


✓ ν_μ/ν_e ratio is calculated to an accuracy of about 2% below ～5GeV.

First result on the μ/e ratio (1988)

After more than 1 year of studies, we concluded that the muon deficit cannot be due to any major problem in the data analysis nor in the Monte Carlo simulation.

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



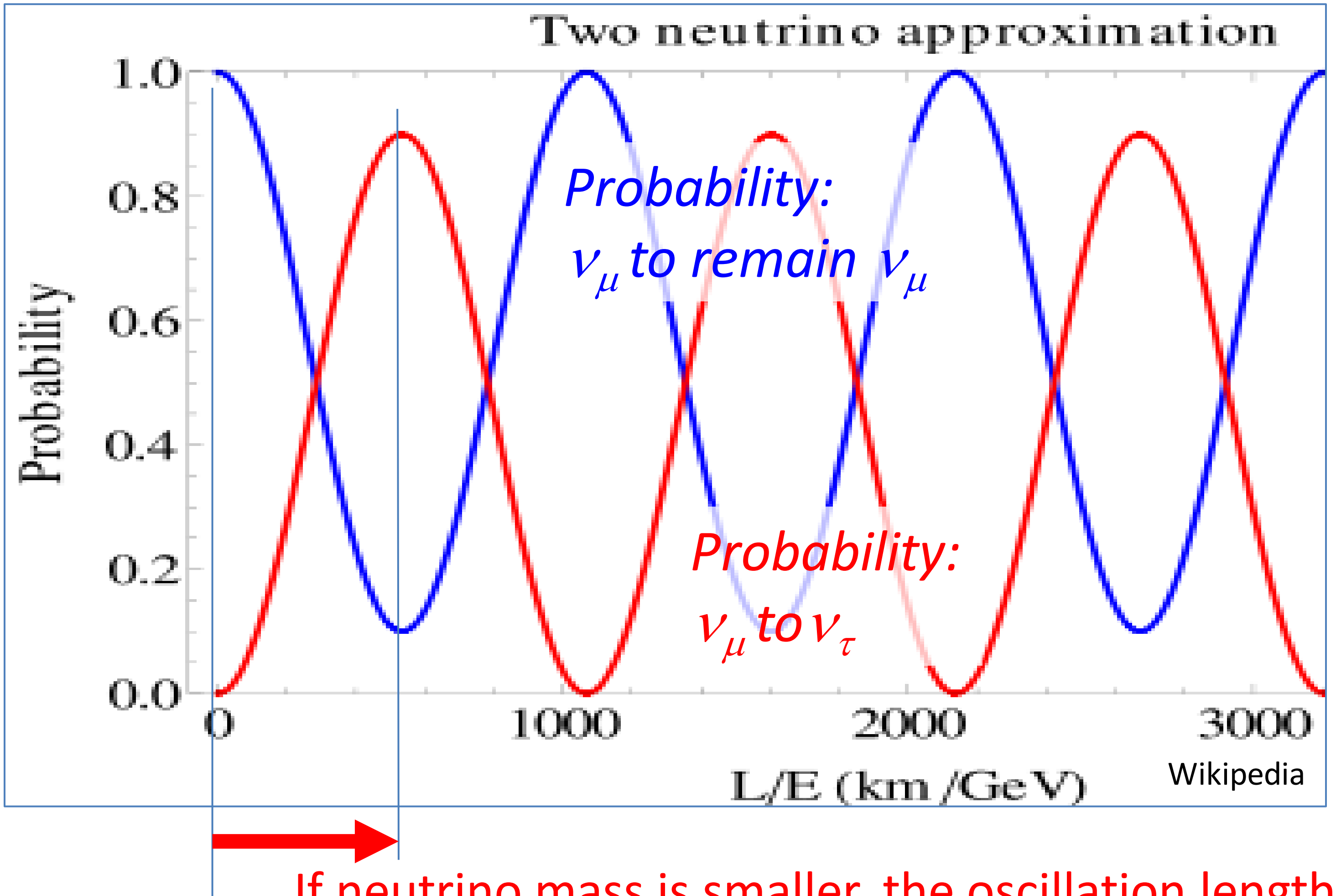
Kamiokande

	Data	Prediction
e-like (~CC ν_e)	93	88.5
μ-like (~CC ν_μ)	85	144.0

Paper conclusion: "We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccoundted-for physics such as neutrino oscillations might explain the data."

Neutrino oscillations

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



Maki, Nakagawa, Sakata 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 small μ/e

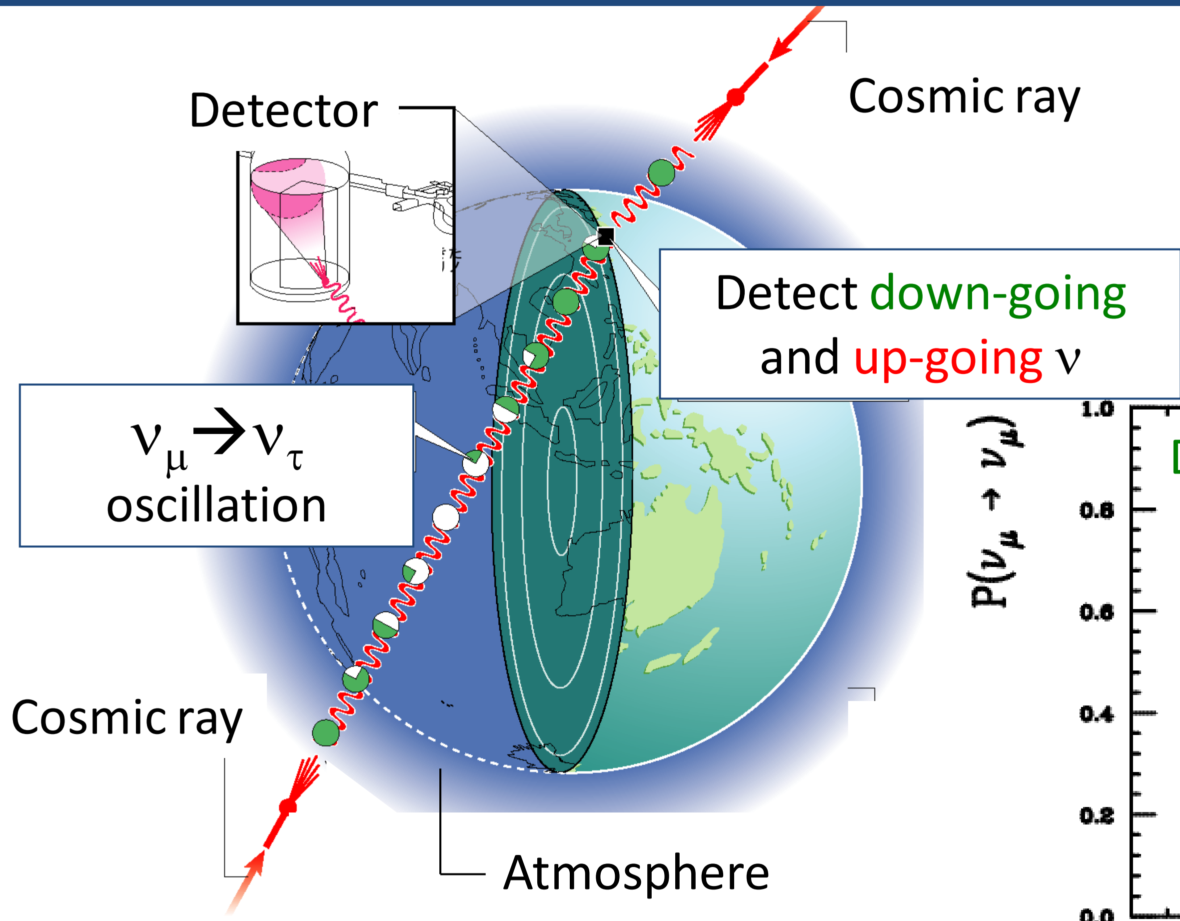
D. Casper et al., PRL **66** (1991) 2561.
R. Becker-Szendy, PRD **46** (1992) 3720.

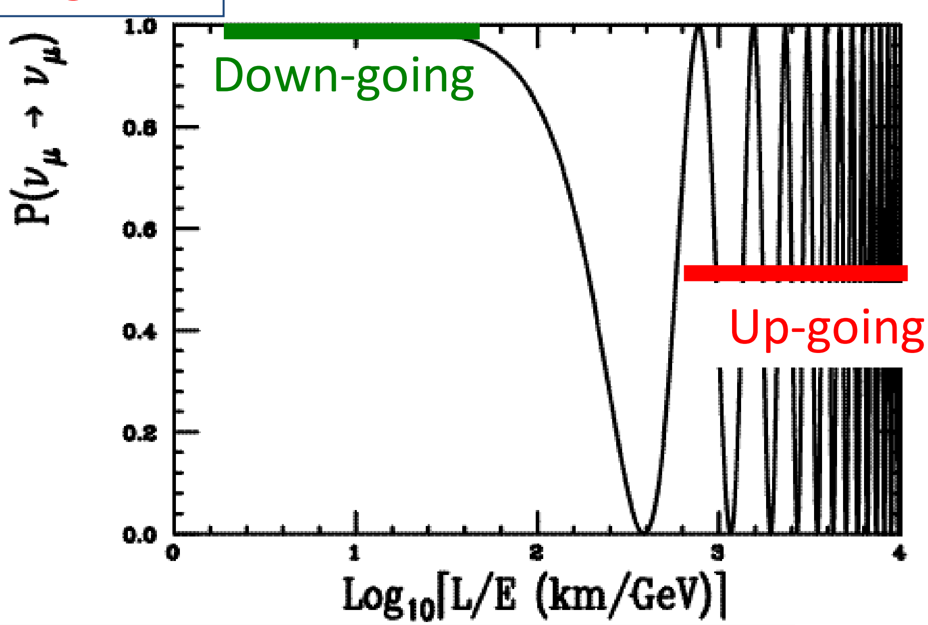
IMB experiment, which was another large water Ch. detector also reported smaller (μ/e) in 1991 and 1992.

After the first result on the μ/e ratio …

- Although it was clear that the small μ/e ratio implied something unexpected, the physics behind this result was unknown. (We recognized that neutrino oscillation was a possibility as we wrote in the paper.)
  - Was the result due to neutrino oscillations?
  - If so, $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$?
  - Some other physics?

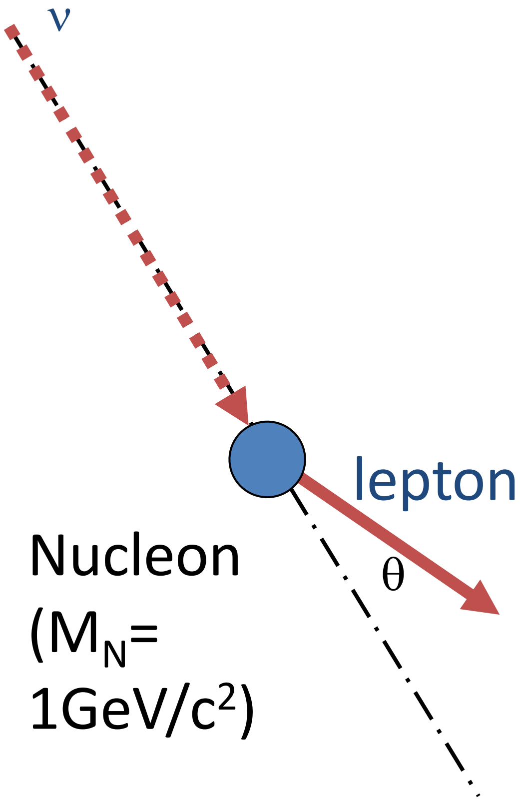
What will happen if the moun deficit is due to neutrino oscillations



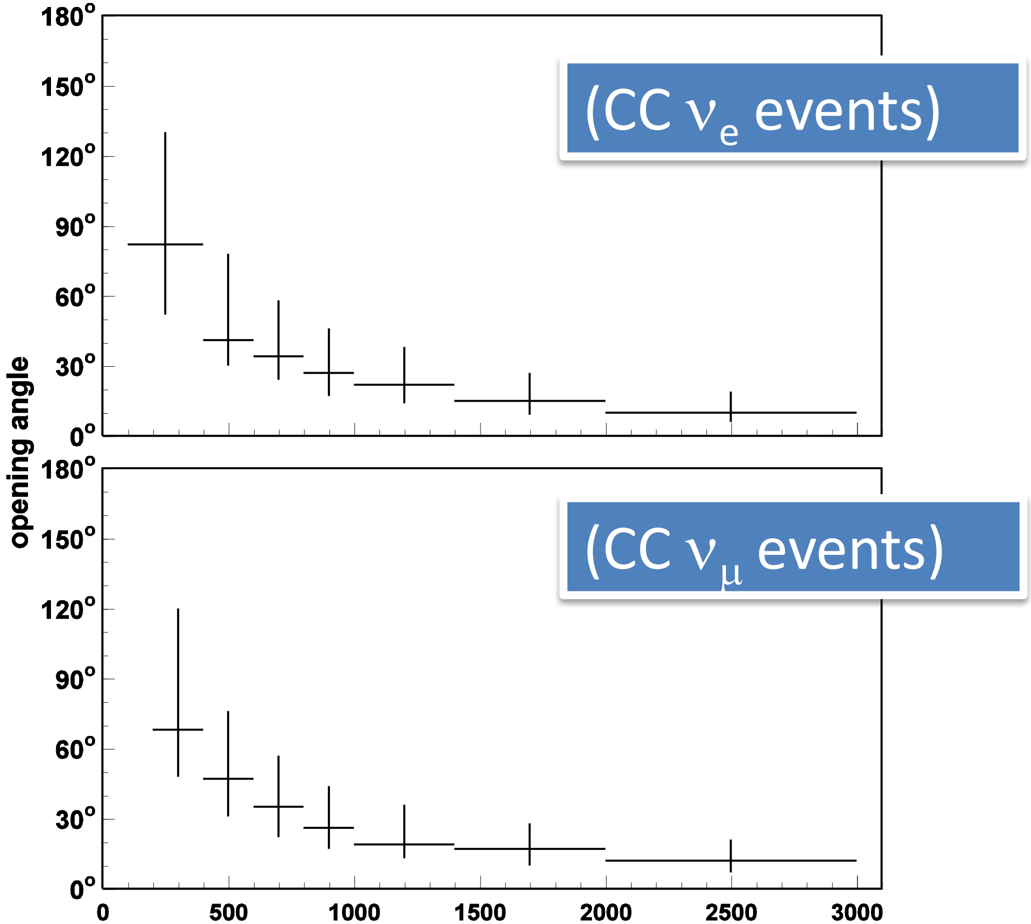


One should observe a deficit of upward going ν_μ's (=muons) !

Angular correlation



Nucleon
(M_N=
1GeV/c^2)

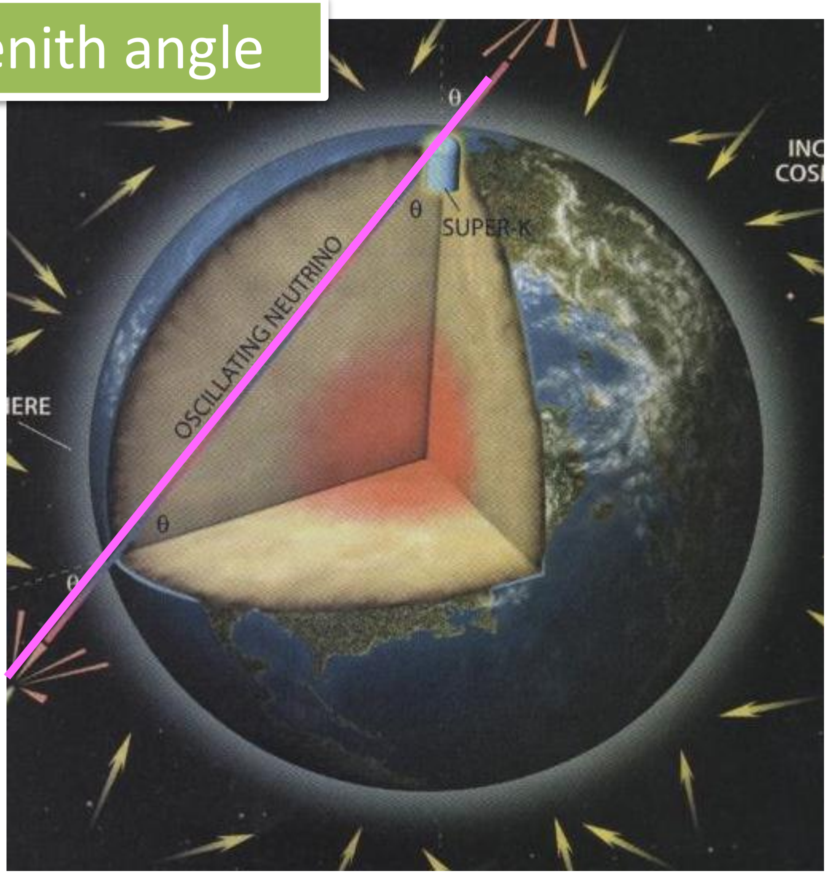


Lepton momentum (MeV/c)

Events with their energy larger than ~1GeV need to be observed to study the zenith angle dependence

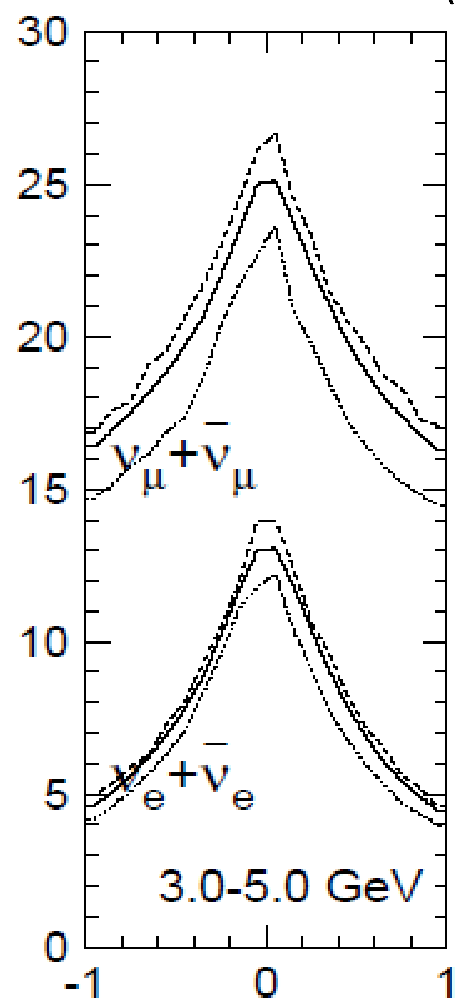
Some features of the beam (2)

Zenith angle



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

@Kamioka (Japan)



Up-going $\cos\theta_{zenith}$ Down

After the first result on the μ/e ratio …

- Although it was clear that the small μ/e ratio implied something unexpected, the physics behind this result was unknown. (We recognized that neutrino oscillation was a possibility as we wrote in the paper.)
  - Was the result due to neutrino oscillations?
  - If so, $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$?
  - Some other physics?

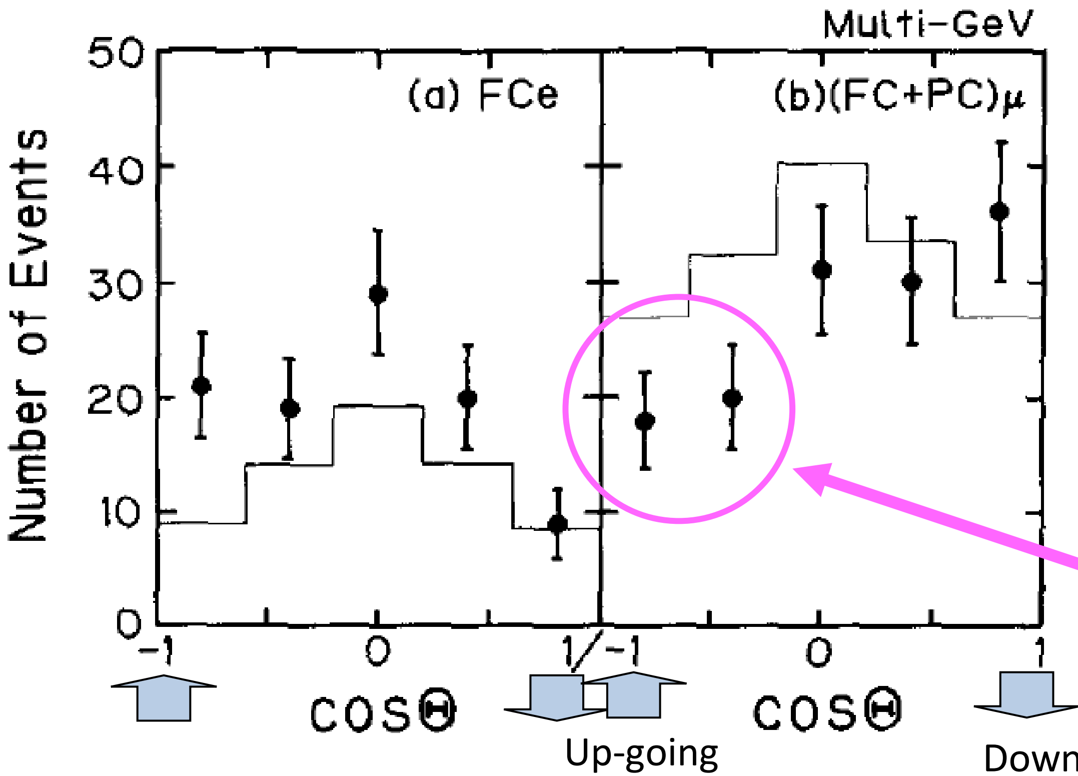
- We thought that we should study multi-GeV neutrino events.
- Therefore we started the data reduction work for partially-contained multi-GeV neutrino events, ~1 week after the submission of the 1988 paper.

➢ Kamiokande was not big enough. It took almost 6 years to get some meaningful results.

Zenith angle distribution for multi-GeV events (1994)

multi-GeV events

Kamiokande PLB 335, 237 (1994)



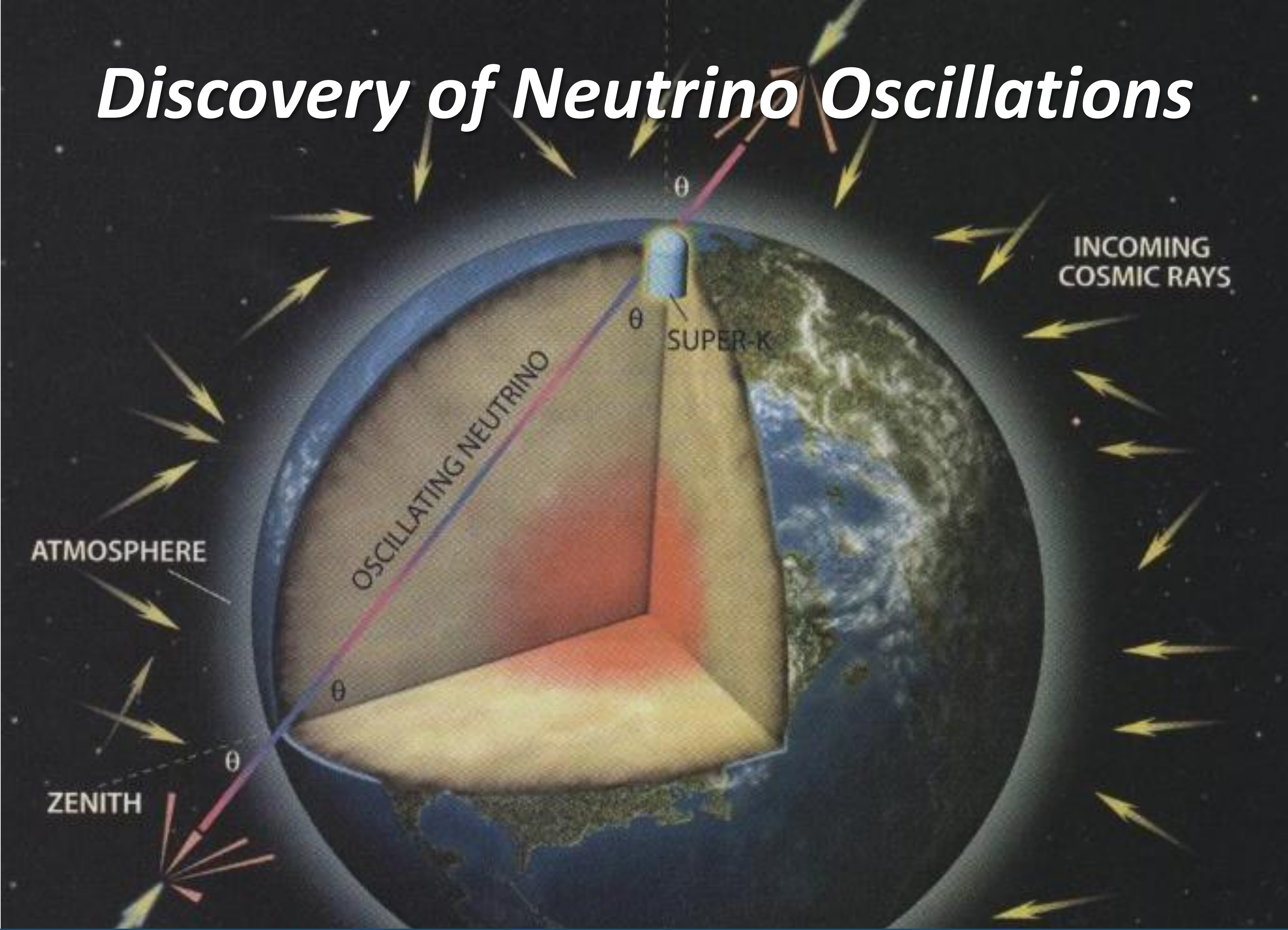
Deficit of upward-going μ-like events

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

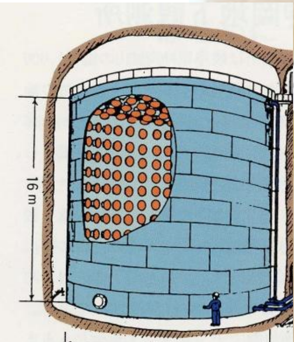
$$\frac{Up}{Down} = 0.58^{+0.13}_{-0.11} \ (2.9\sigma)$$

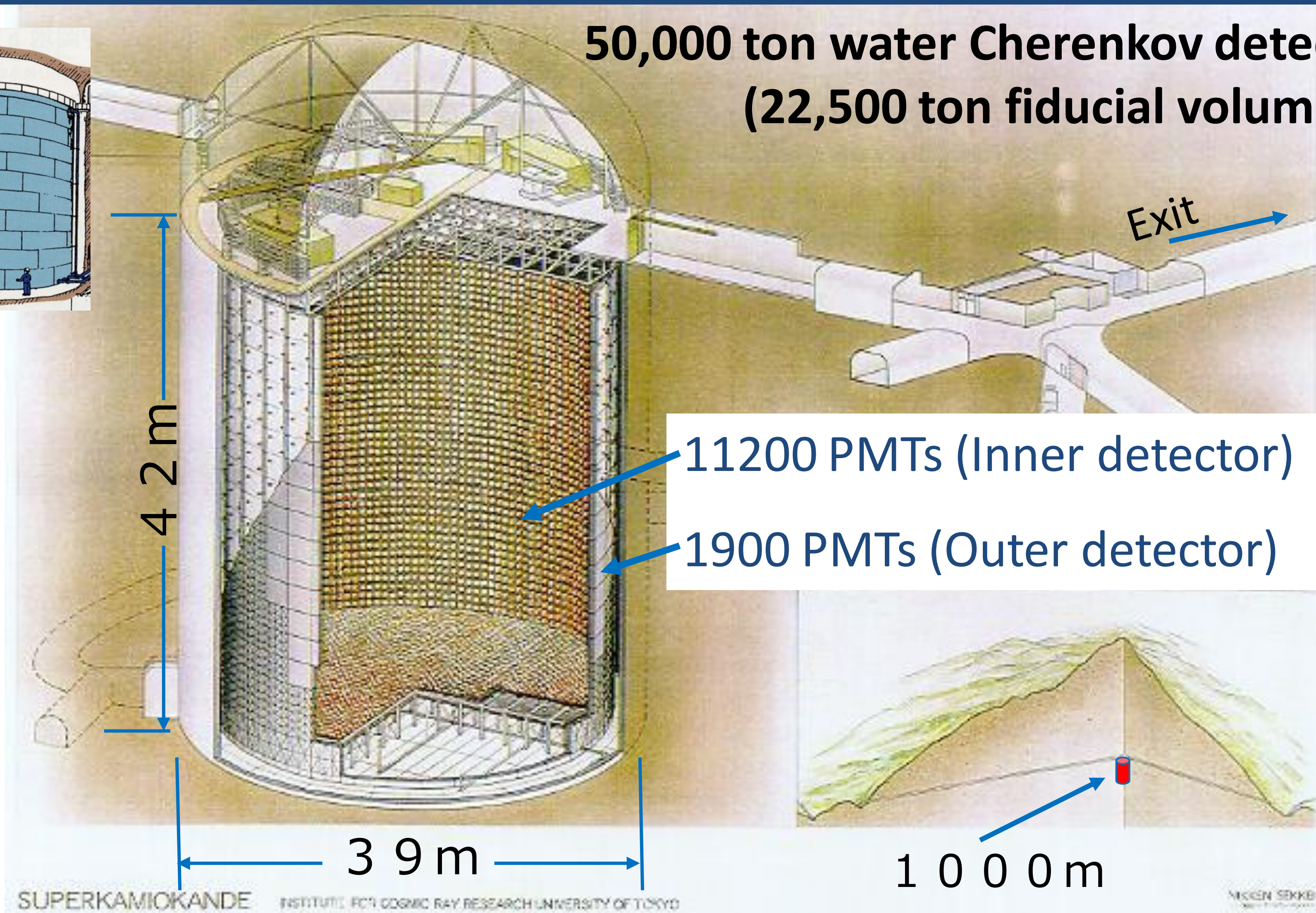
Not high enough statistics to conclude …
Much higher statics required (= much larger detector required)

Discovery of Neutrino Oscillations



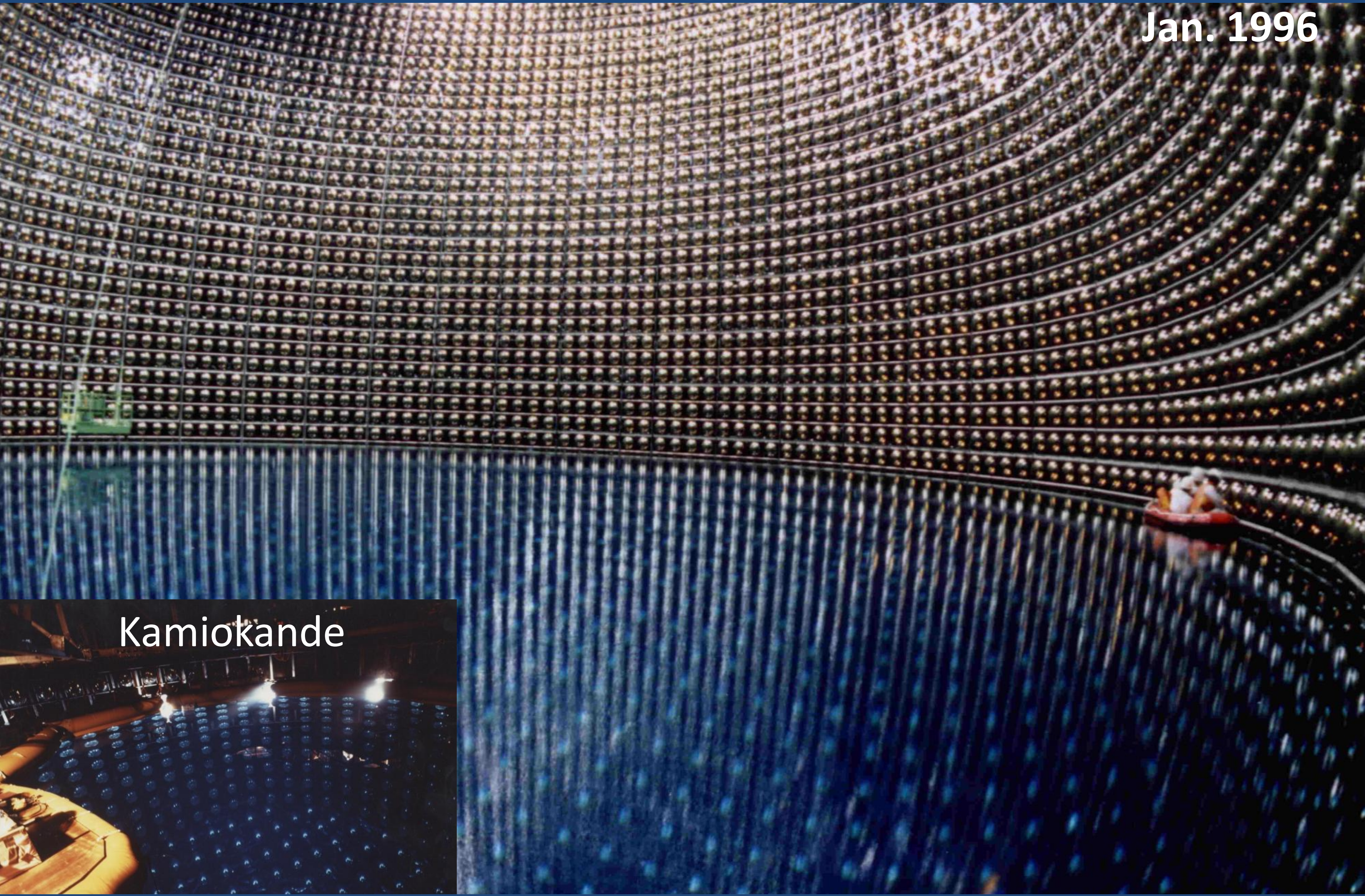
Super-Kamiokade detector





Beginning of the Super-Kamiokade collaboration between USA and Japan

Water filling in Super-Kamiokande

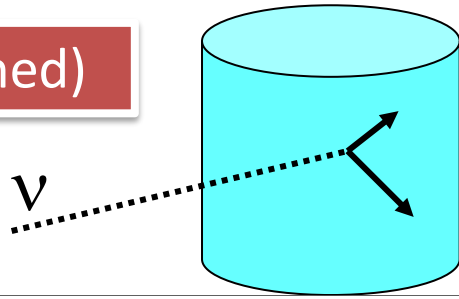


Super-K detector construction

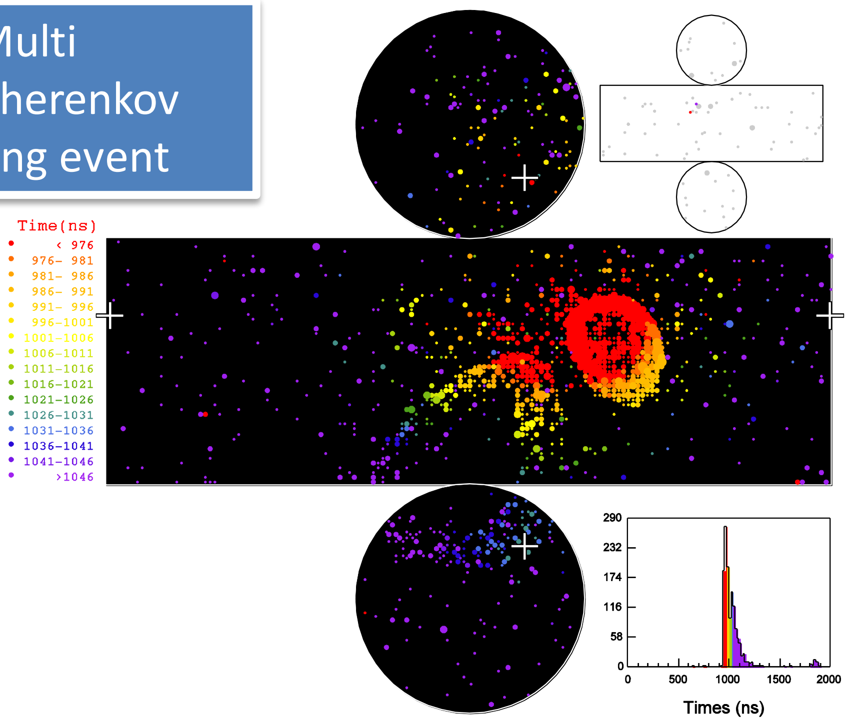
Fully automated analysis

・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.

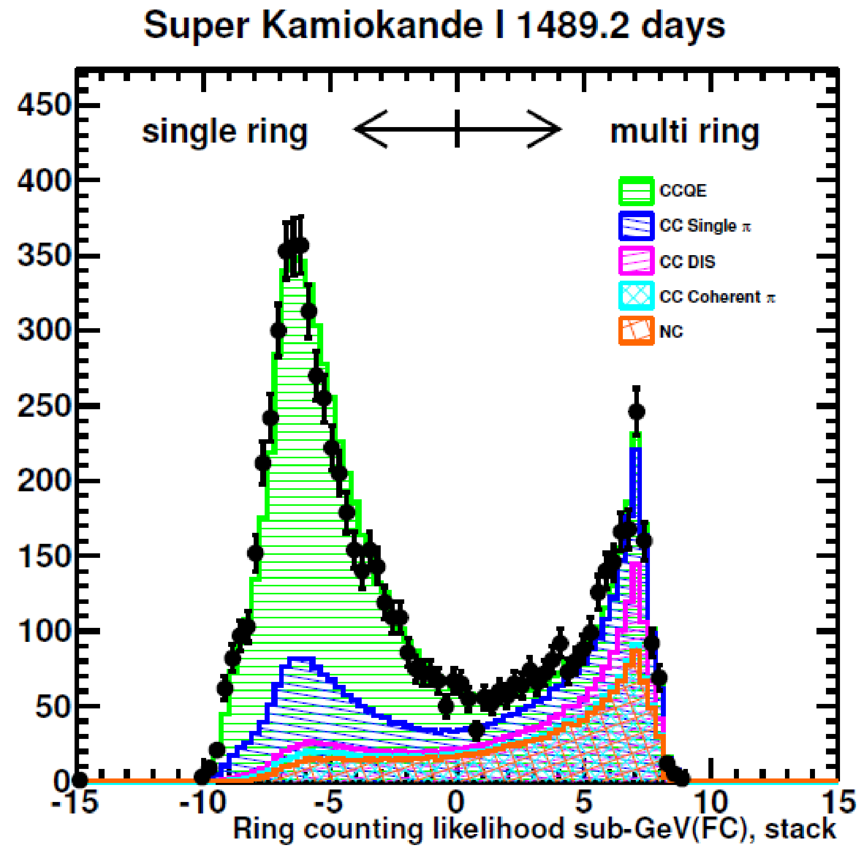
FC (fully contained)



Multi Cherenkov ring event



Hough transformation + maximum likelihood



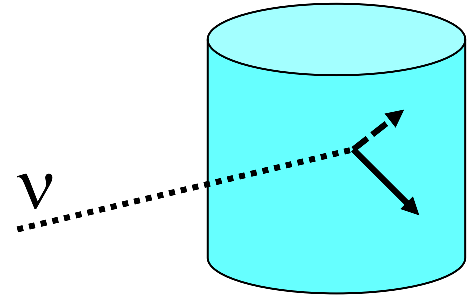
Various types of atmospheric ν events (1)

FC (fully contained)

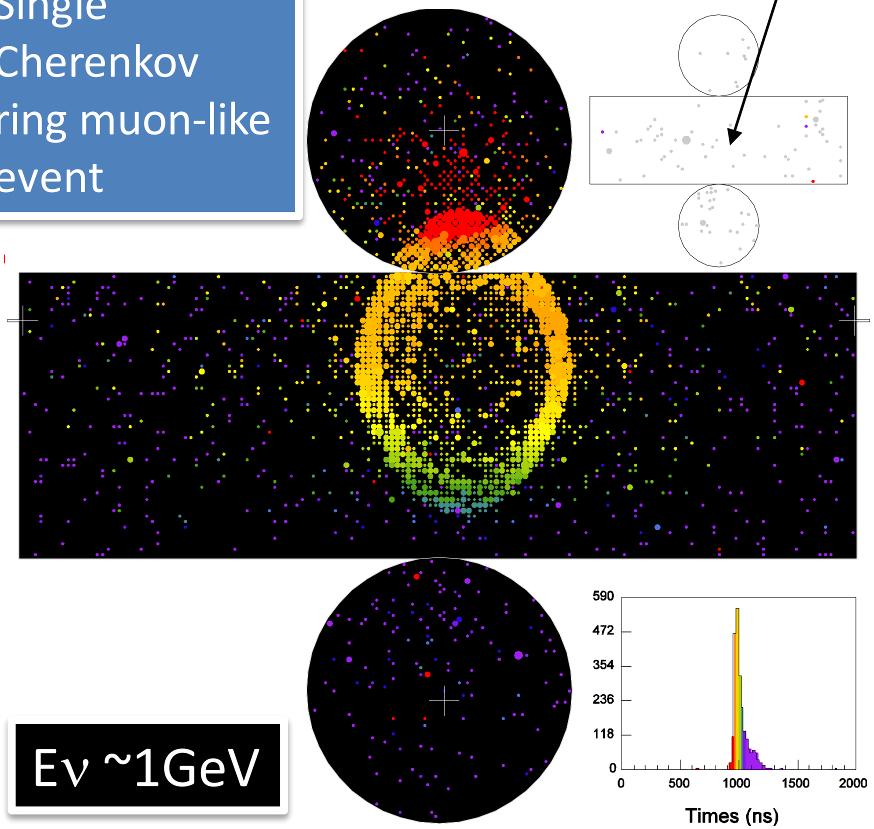
Color: timing

Size: pulse height

Outer detector (no signal)

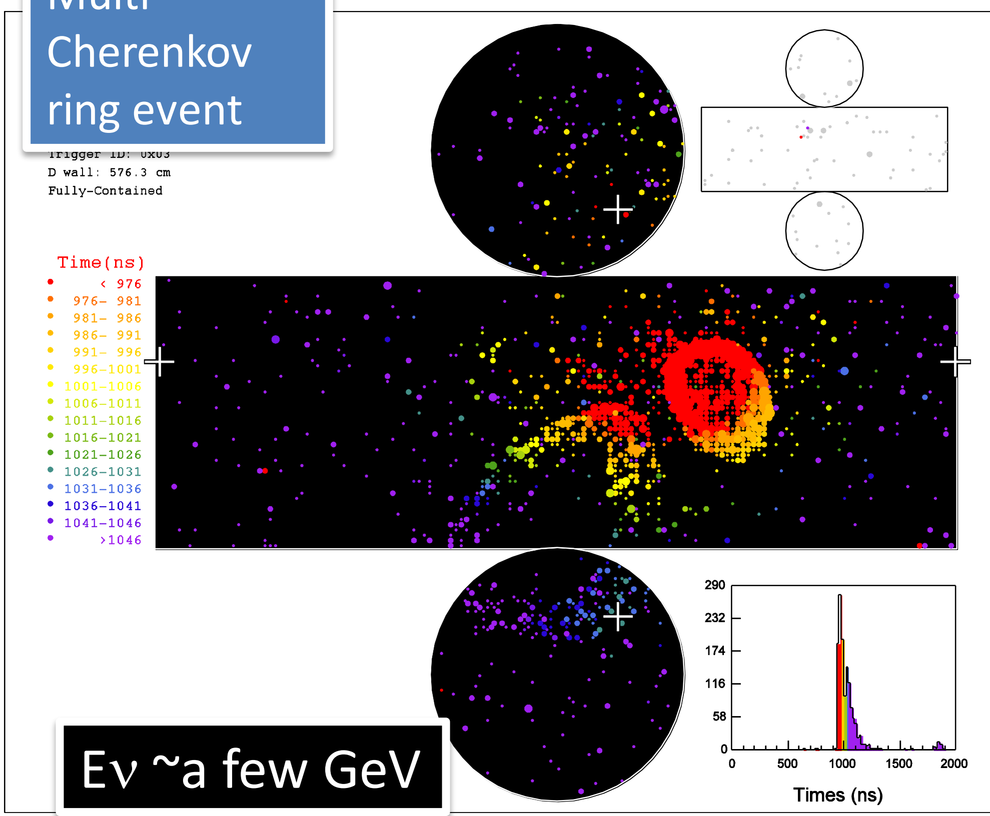


Single Cherenkov ring muon-like event



Eν ~1GeV

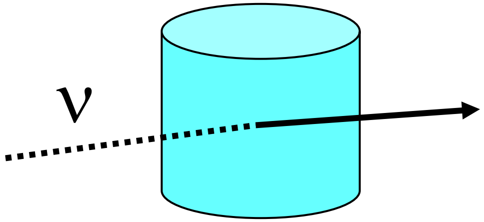
Multi Cherenkov ring event



Eν ~a few GeV

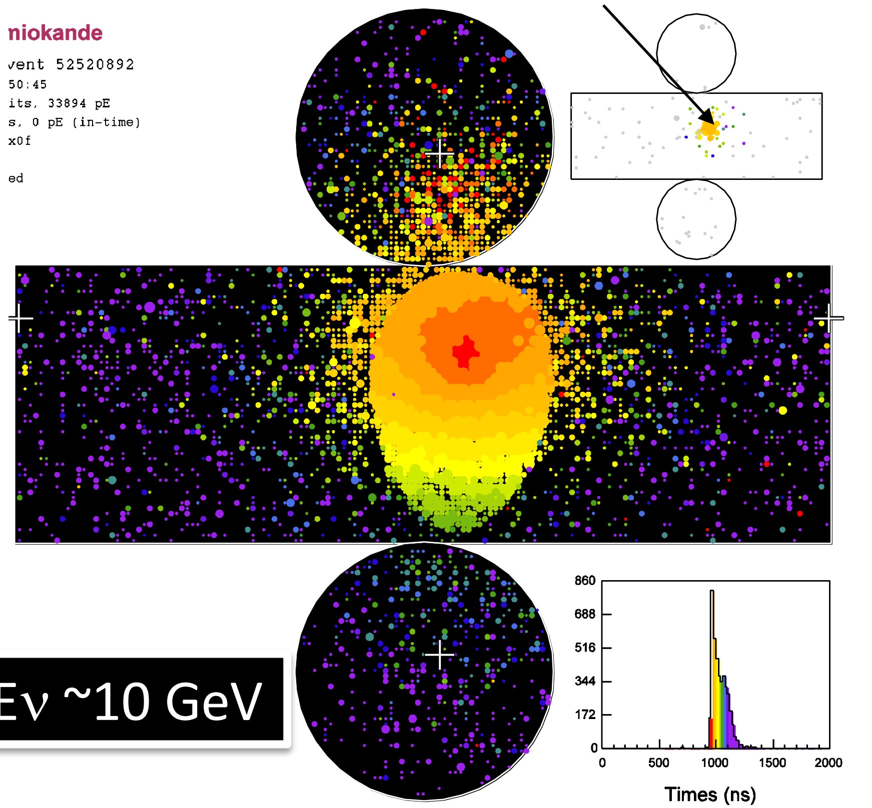
Various types of atmospheric ν events (3)

PC (partially contained)



- 97% CC ν_μ

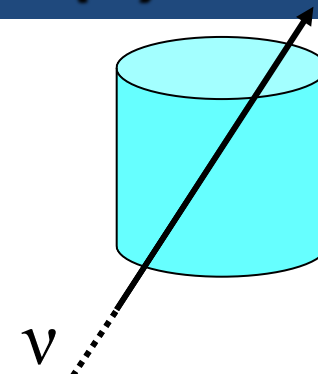
Signal in the outer detector

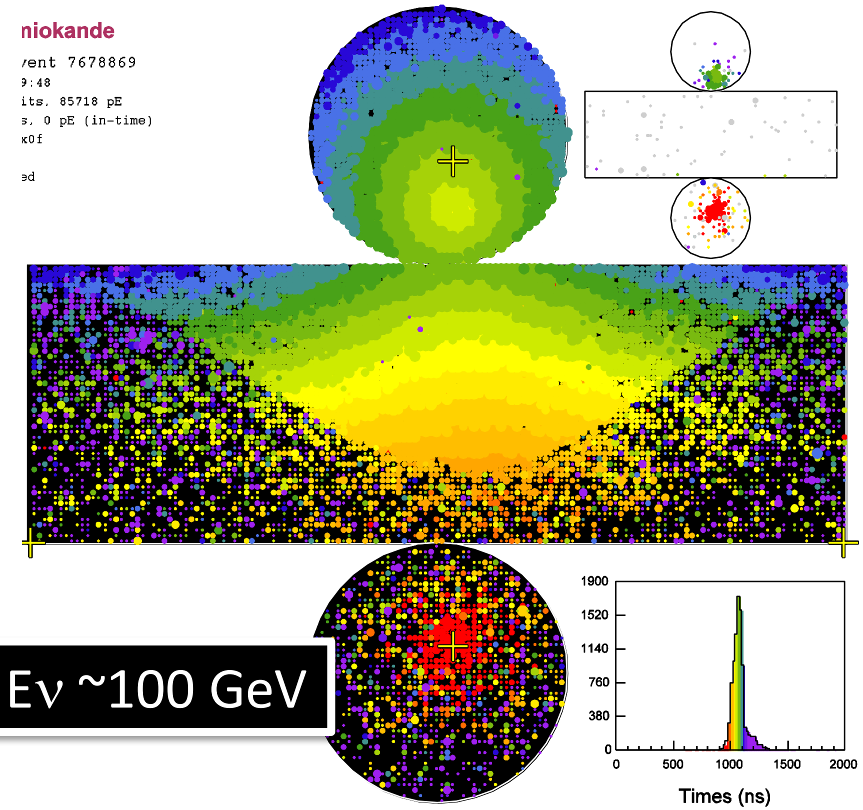


Eν ~10 GeV

Upward going muon

- almost pure CC ν_μ



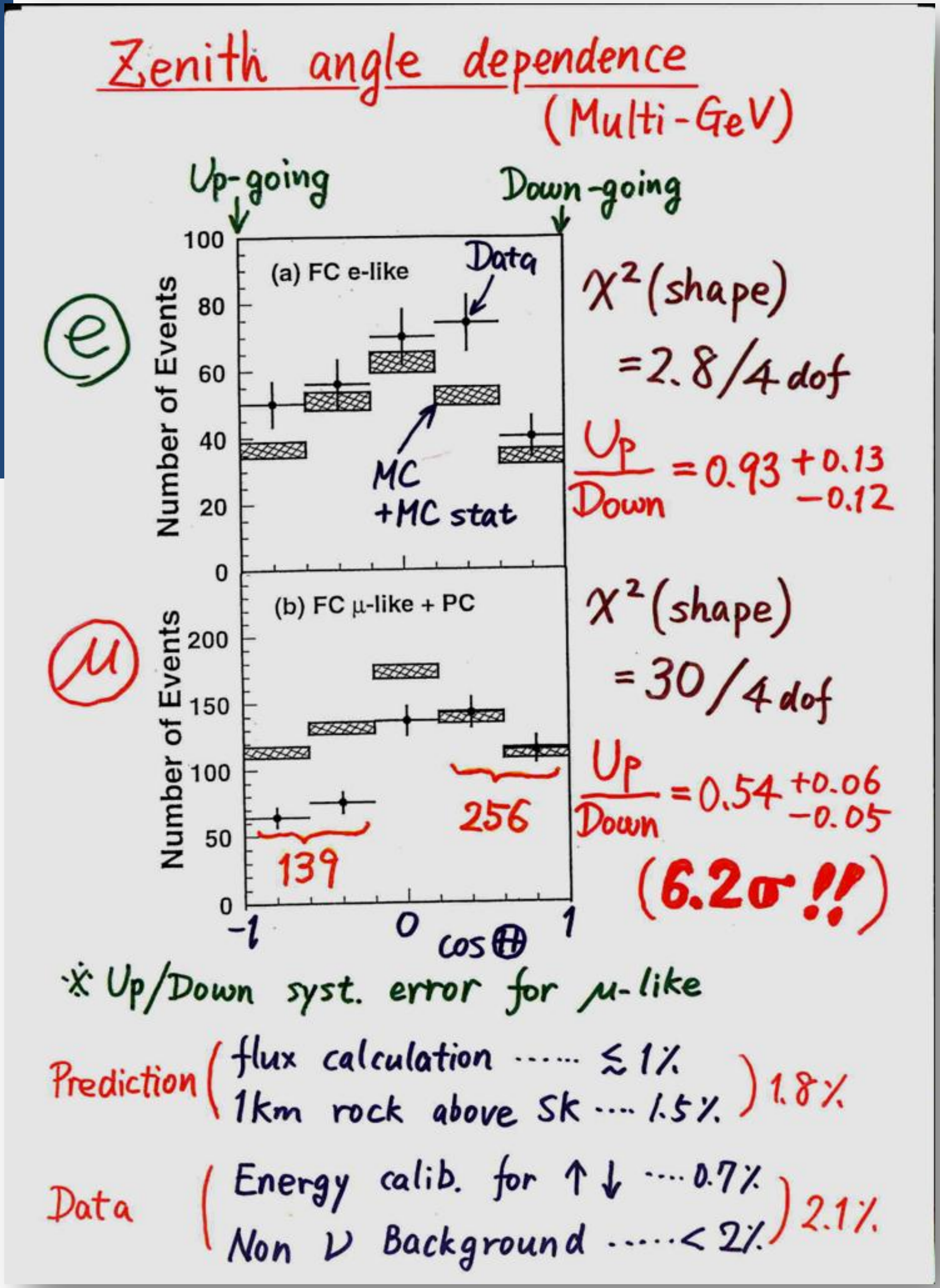


Eν ~100 GeV

All these events are used in the analysis. ← ***Collaborative work of many (young) people!***

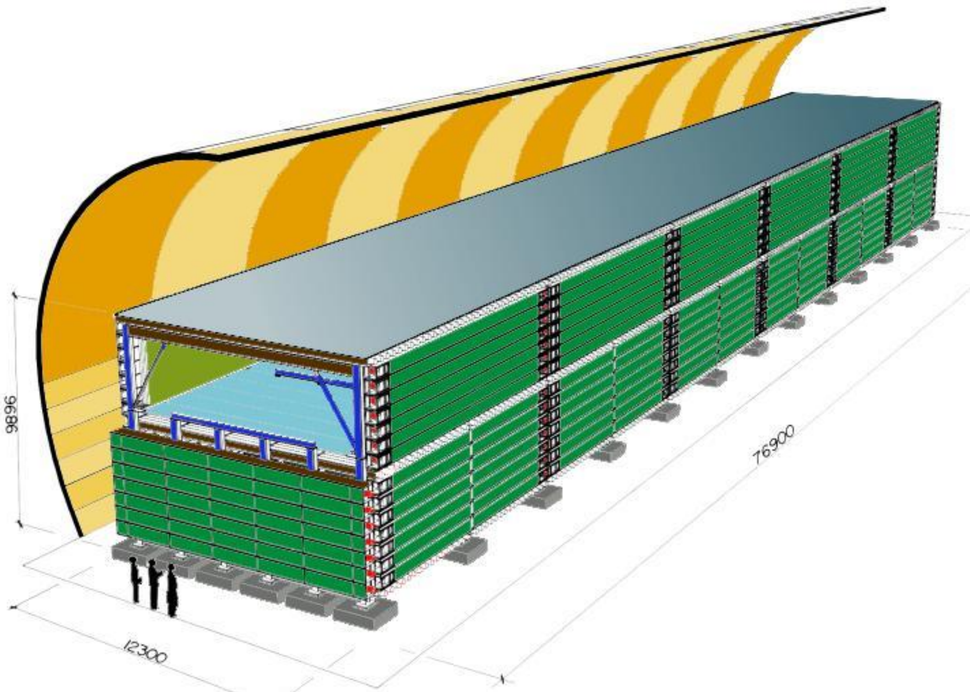
Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

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



Results from the other atmospheric neutrino experiments

MACRO



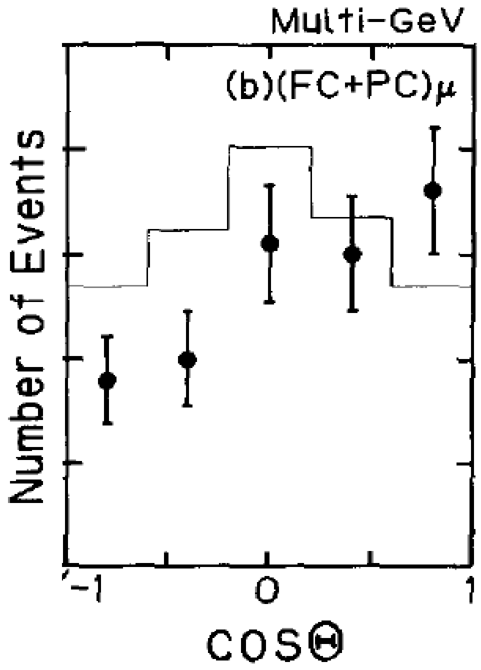
Soudan-2

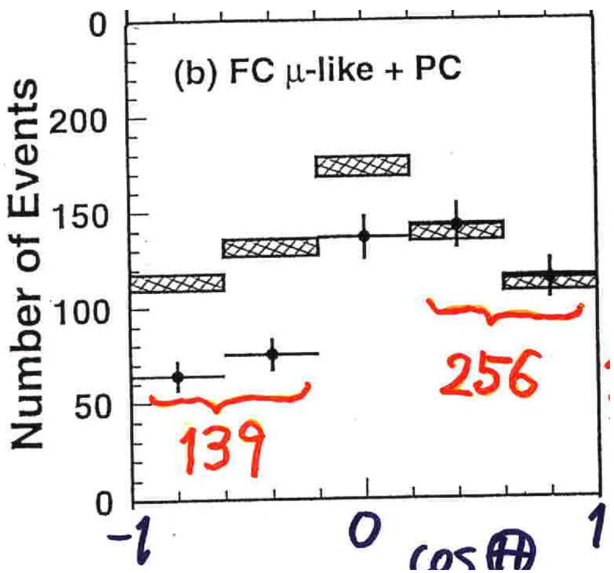
These experiments observed atmospheric neutrinos and confirmed neutrino oscillations

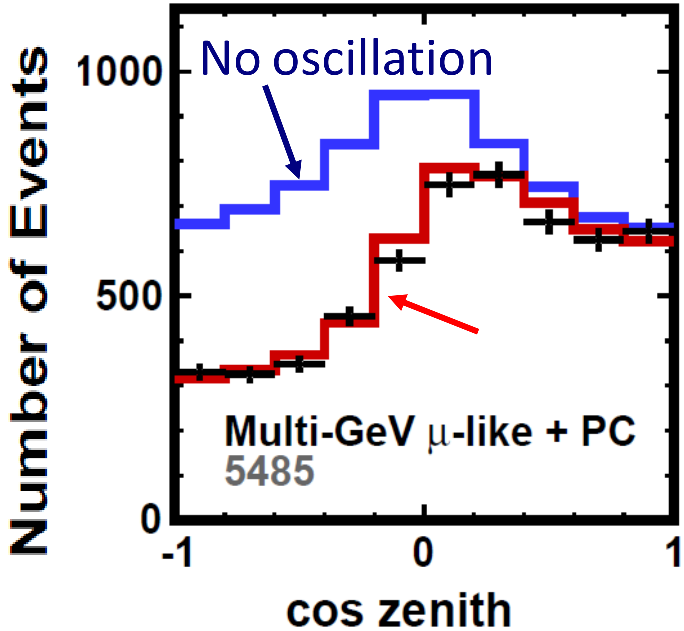
Resent results

Data updates

Kamiokande (1994) → Super-K @Neutrino98 → Super-K (2015)







Number of events plotted:

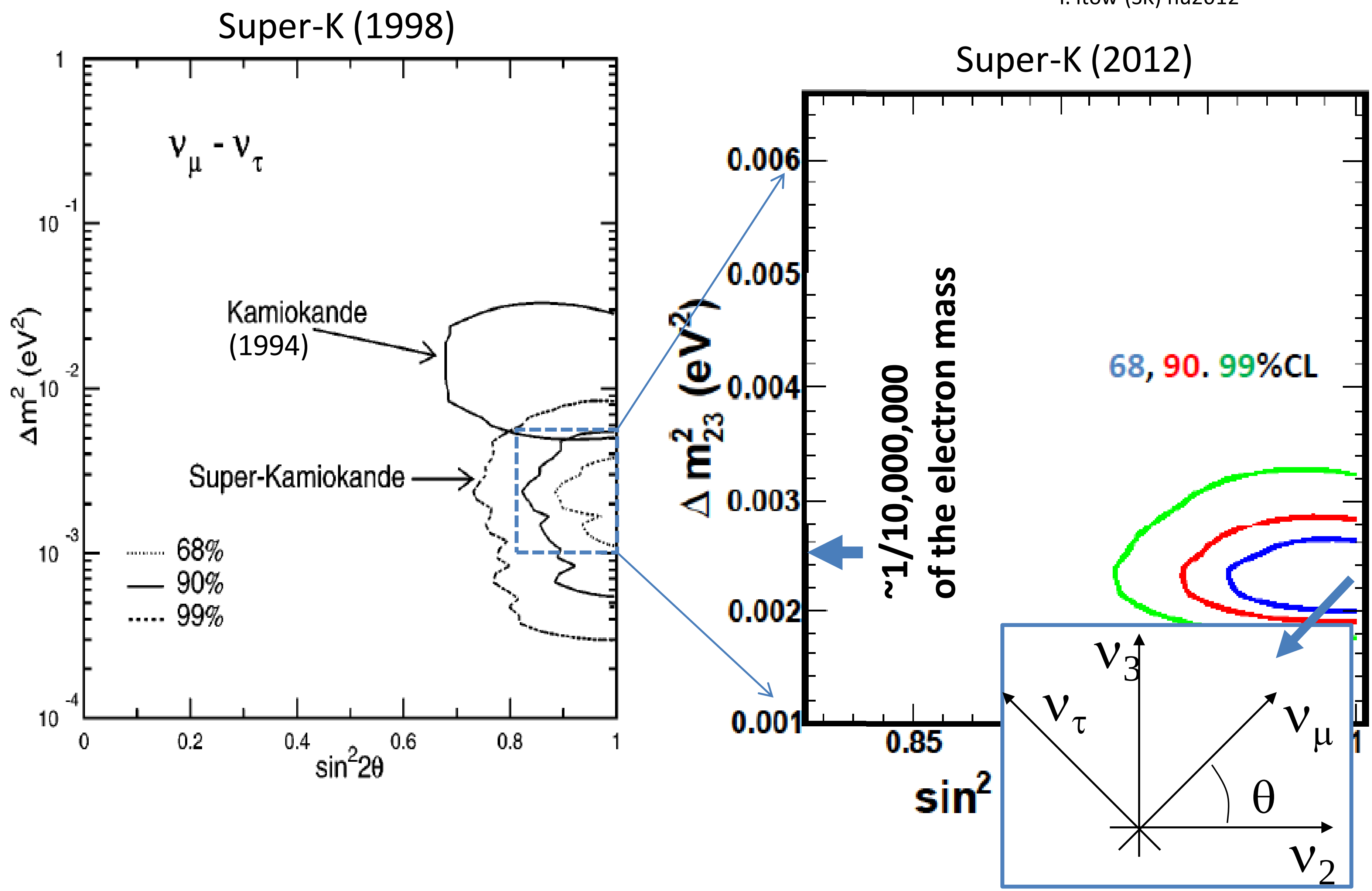
135 events

531 events

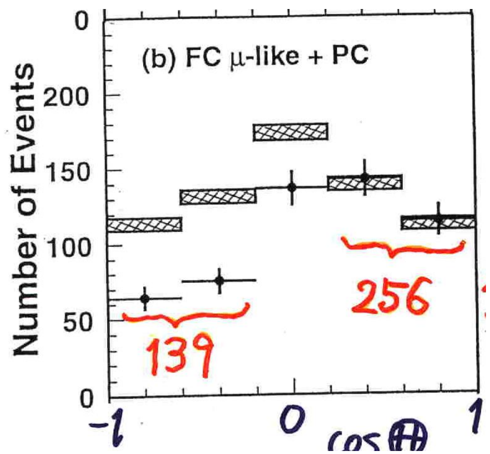
5485 events

$\nu_\mu \rightarrow \nu_\tau$ allowed parameter region

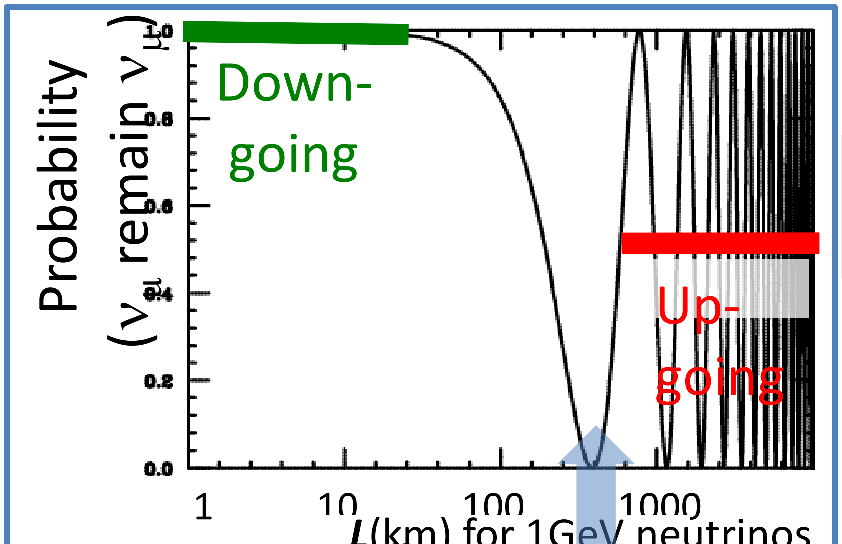
Y. Itow (SK) nu2012

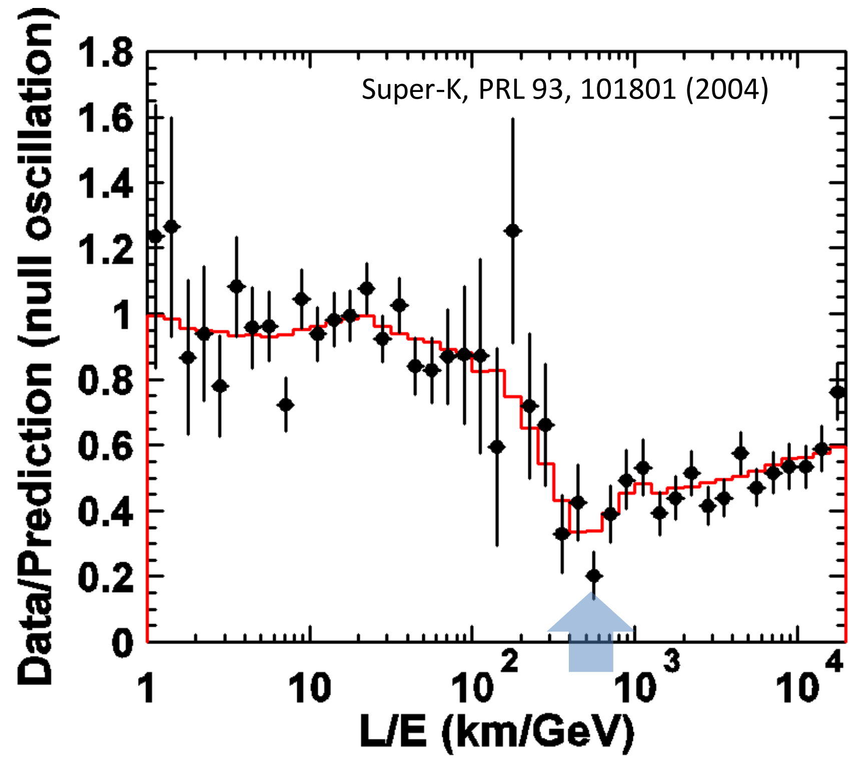


Really oscillations



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".



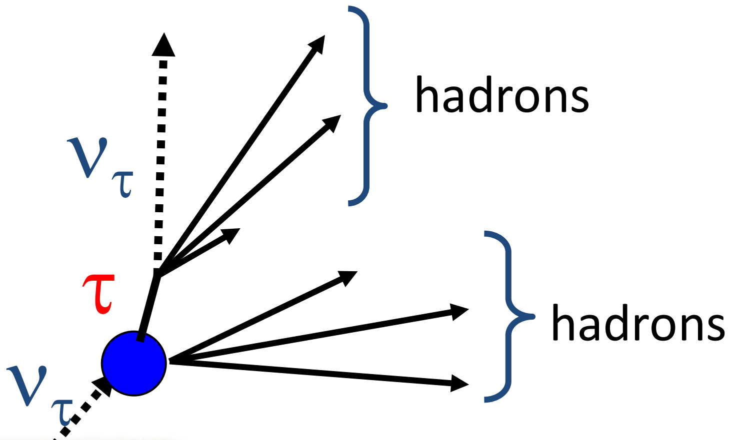


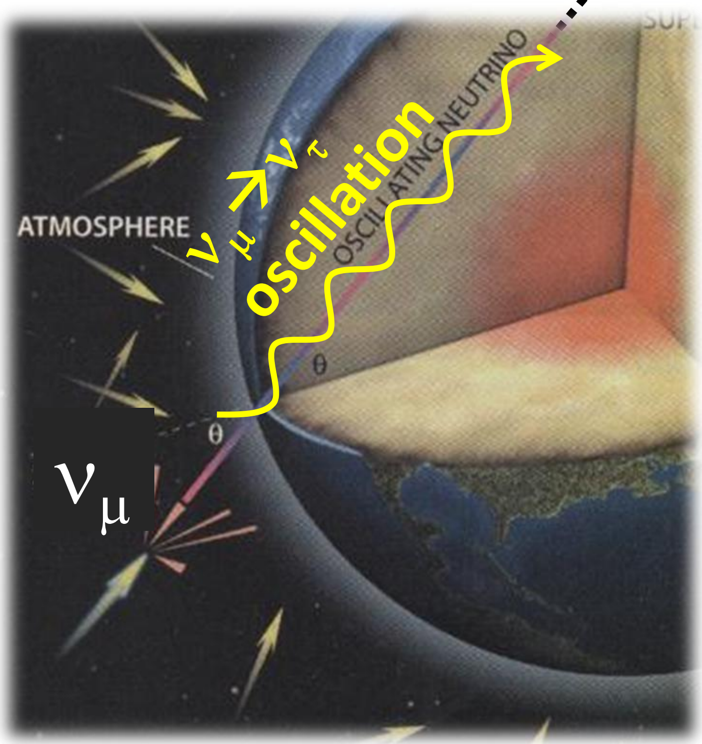
We wanted to observe this dip to confirm neutrino "oscillations".

A dip is seen around L/E = 500 km/GeV. ➔ *Really oscillations !!*

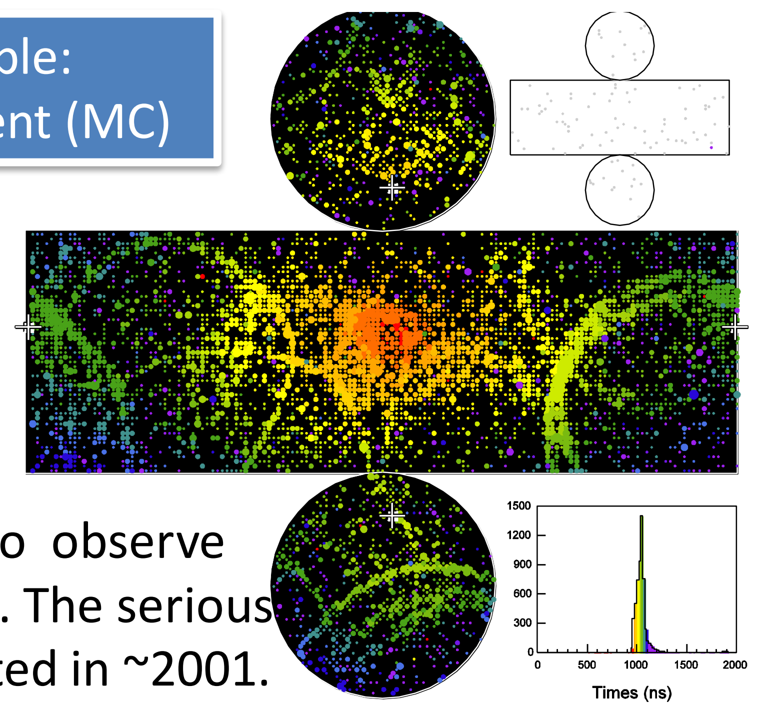
Detecting CC ν_τ events

If the oscillations are $\nu_\mu \rightarrow \nu_\tau$, we should observe ν_τ interactions





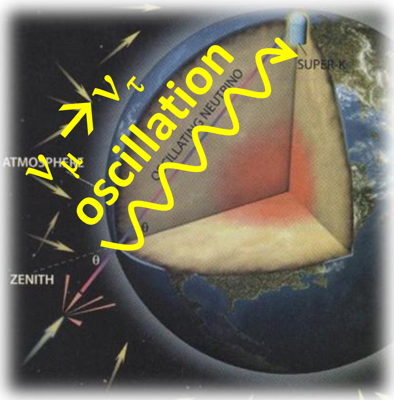
Example:
ν_τ event (MC)

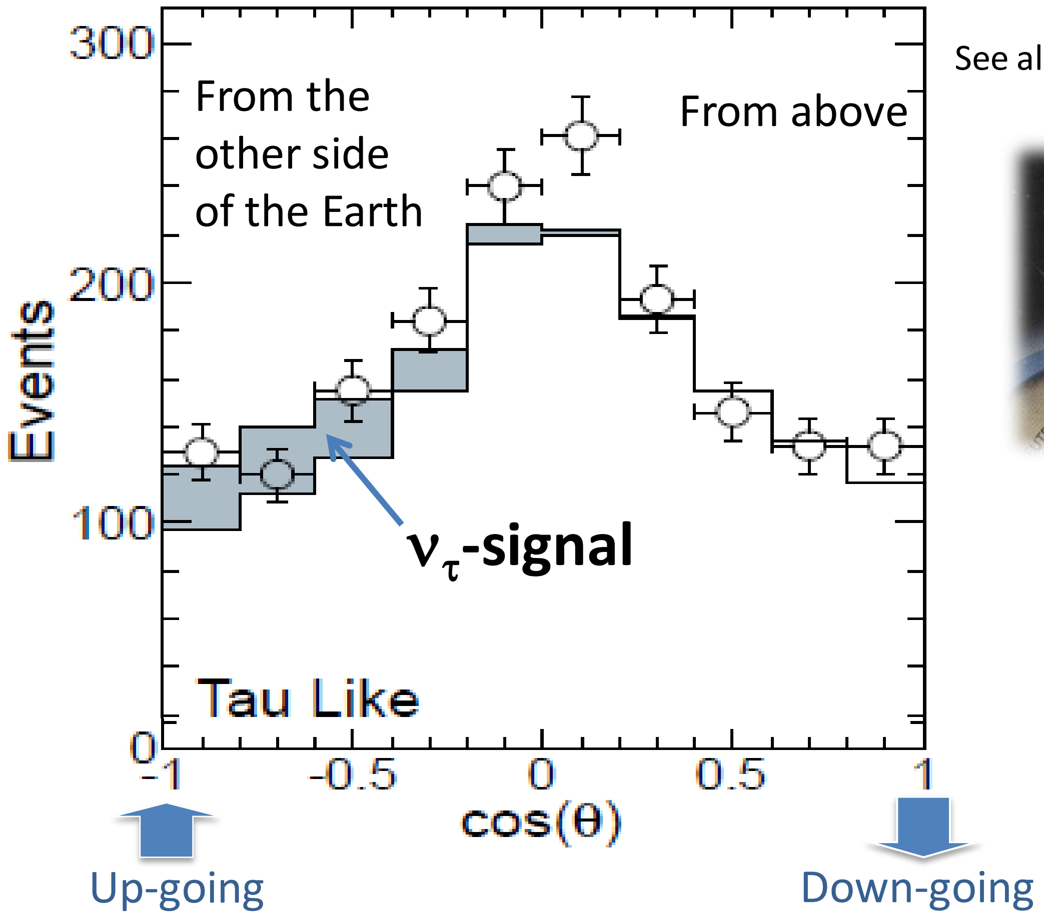


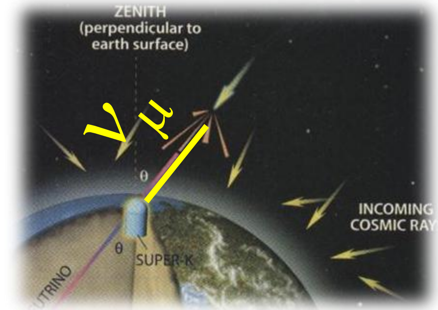
We wanted to observe these events. The serious analysis started in ~2001.

Zenith angle distribution and fit results

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







τ-appearance signal at 3.8σ

Fitted number of τ events	180.1±44.3(stat) +17.8 / -15.2(syst)
Expected number of τ events	120.2+34.2/-34.8(syst)

Future

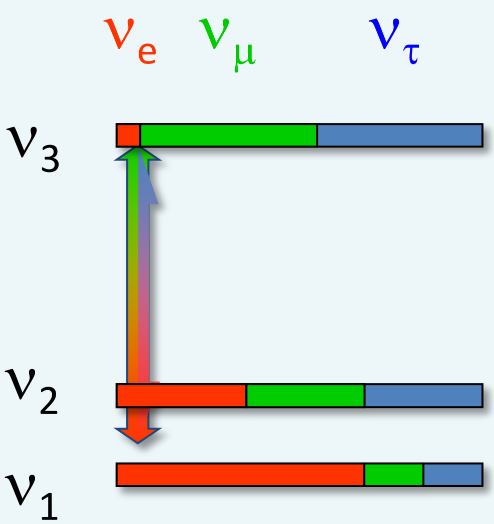
Present status:
2 flavors to 3 flavors: summary

arXiv: 1209.3023v3

parameters	3σ range	
$\sin^2\theta_{12}$	0.267 – 0.344	Solar (SNO, Super-K etc), KamLAND
$\sin^2\theta_{23}$	0.342 – 0.667	Atmospheric (Super-K etc), Long baseline (MINOS, T2K etc)
$\sin^2\theta_{13}$	0.0156 – 0.0299	Long baseline (T2K, MINOS, etc), Reactor (Daya Bay, RENO, D-Chooz)
Δm_{12}^2	(7.00 – 8.09) $\times 10^{-5}$ eV^2	Solar (SNO, Super-K etc), KamLAND
$\lvert\Delta m_{13 \text{ or } 23}^2\rvert$	(2.24 – 2.70) $\times 10^{-3}$ eV^2	Long baseline (MINOS, T2K etc) and Atmospheric (Super-K)

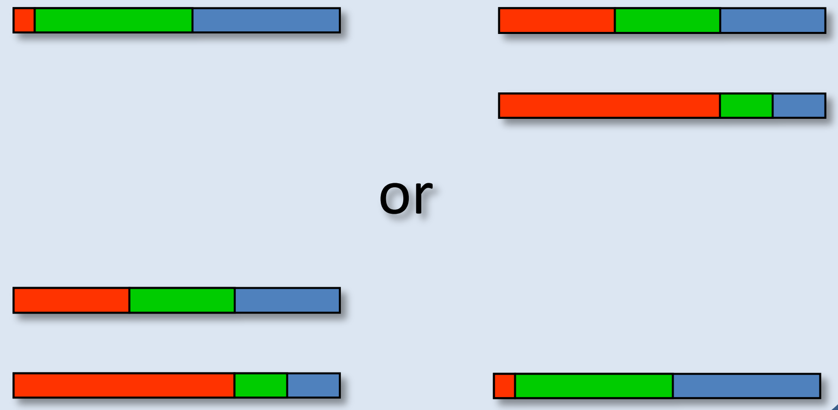
Unknowns

θ_{13}



θ_{13} is not very small

Mass hierarchy ?



Is the mass pattern of neutrinos similar to those of quarks and charged leptons?

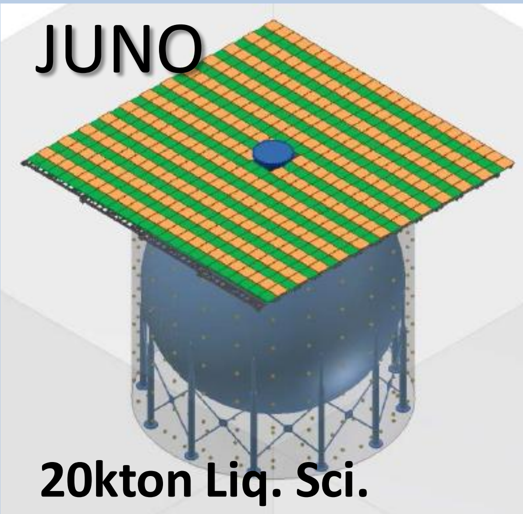
CP violation ?

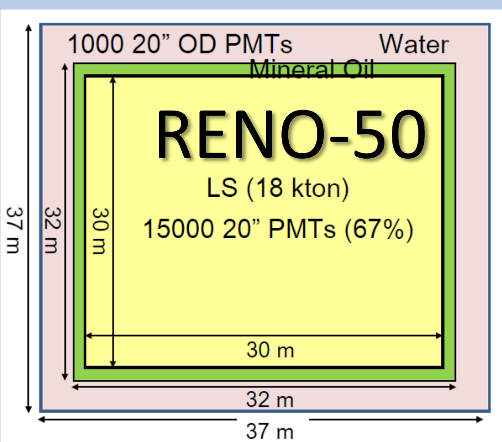
$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \ ?$$

Baryon asymmetry of the Universe?

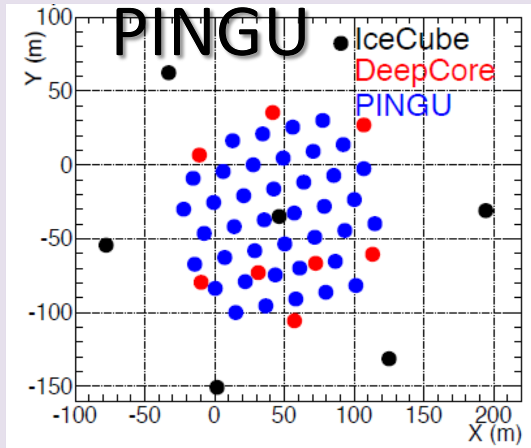
Future experiments

Reactor exp's

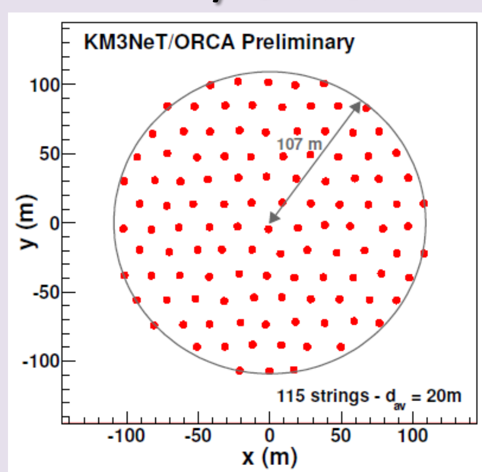


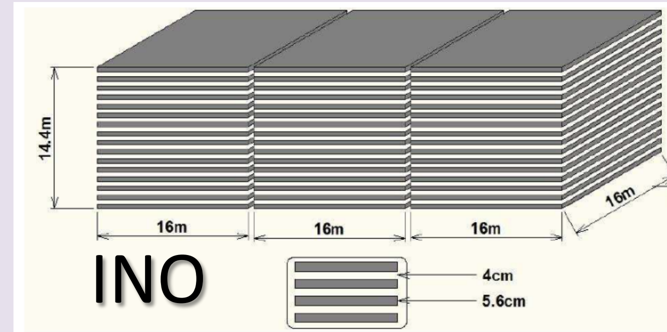


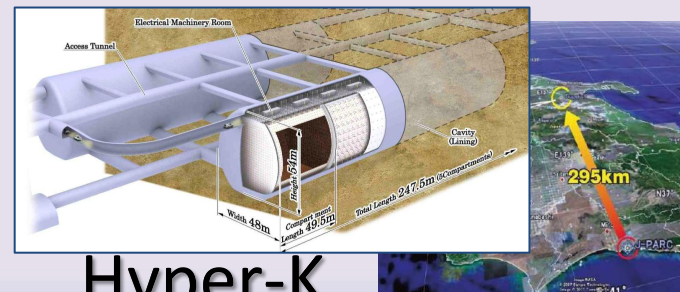
Atmospheric ν exp's



KM3NeT/ORCA

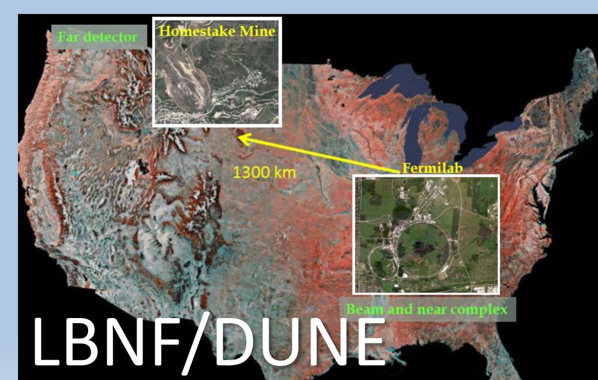






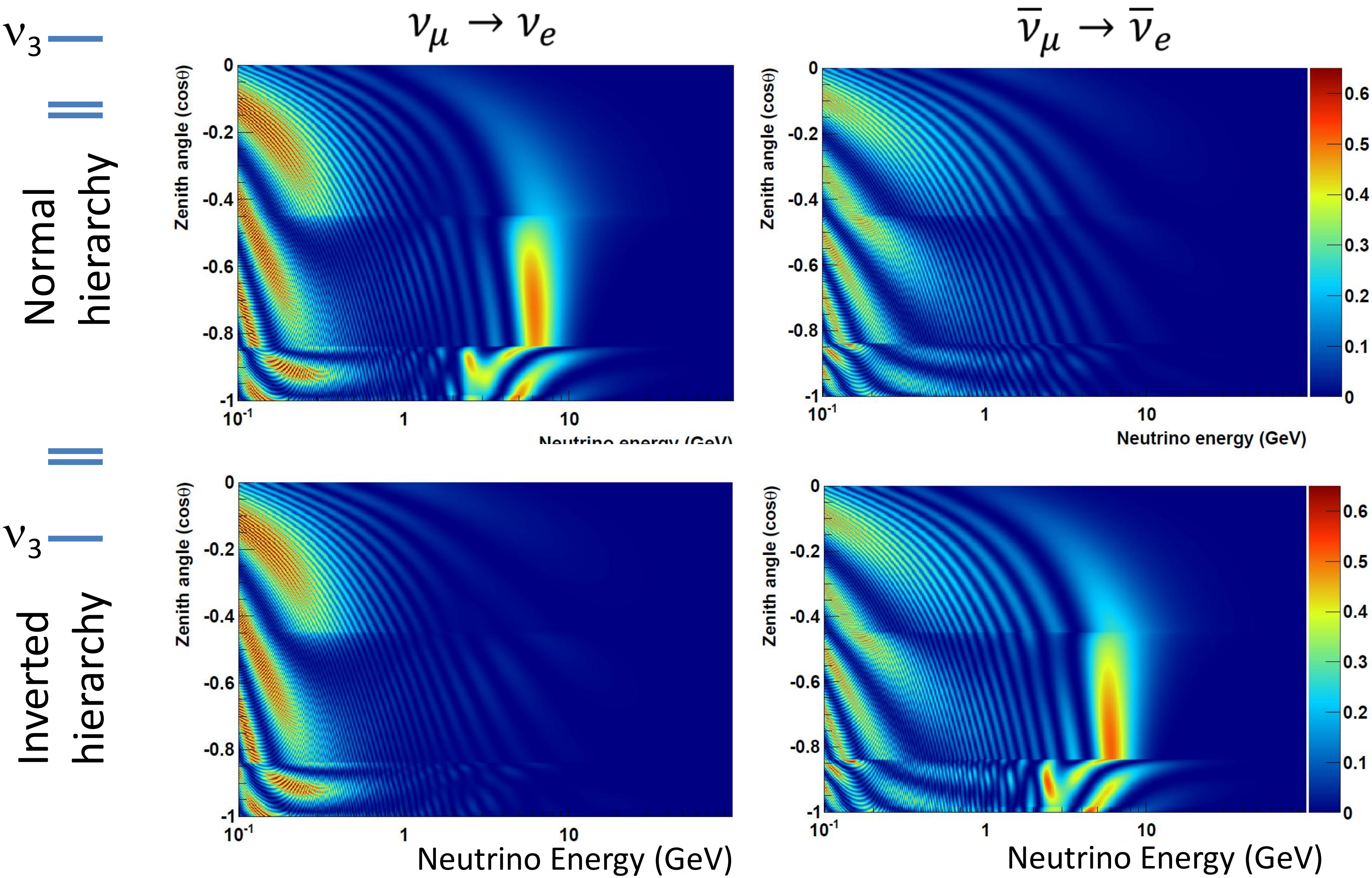
Hyper-K

LBL ν exp's



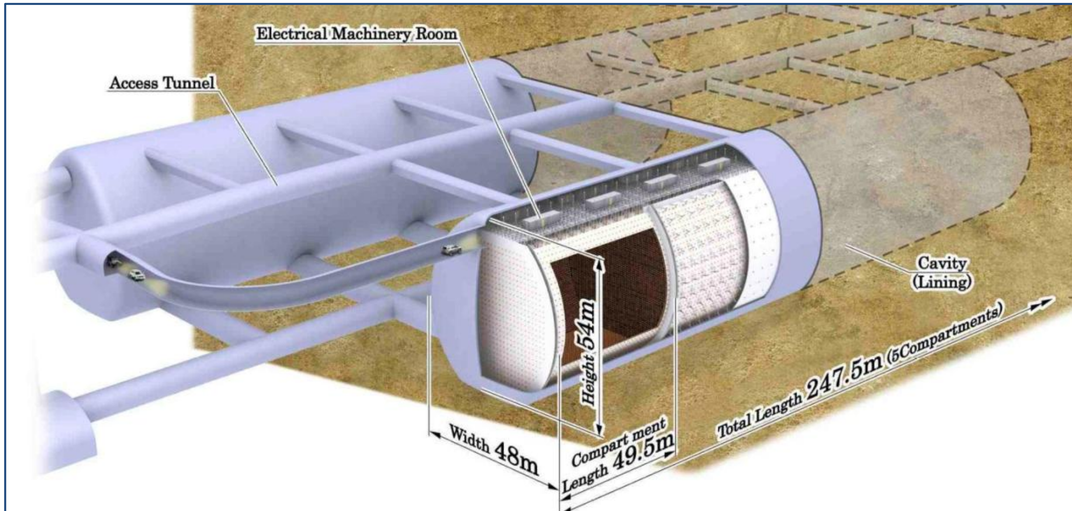
Atmospheric Neutrino Oscillations

Oscillation probabilities



Hyper-Kamiokande

Hyper-K, PTEP (2015)



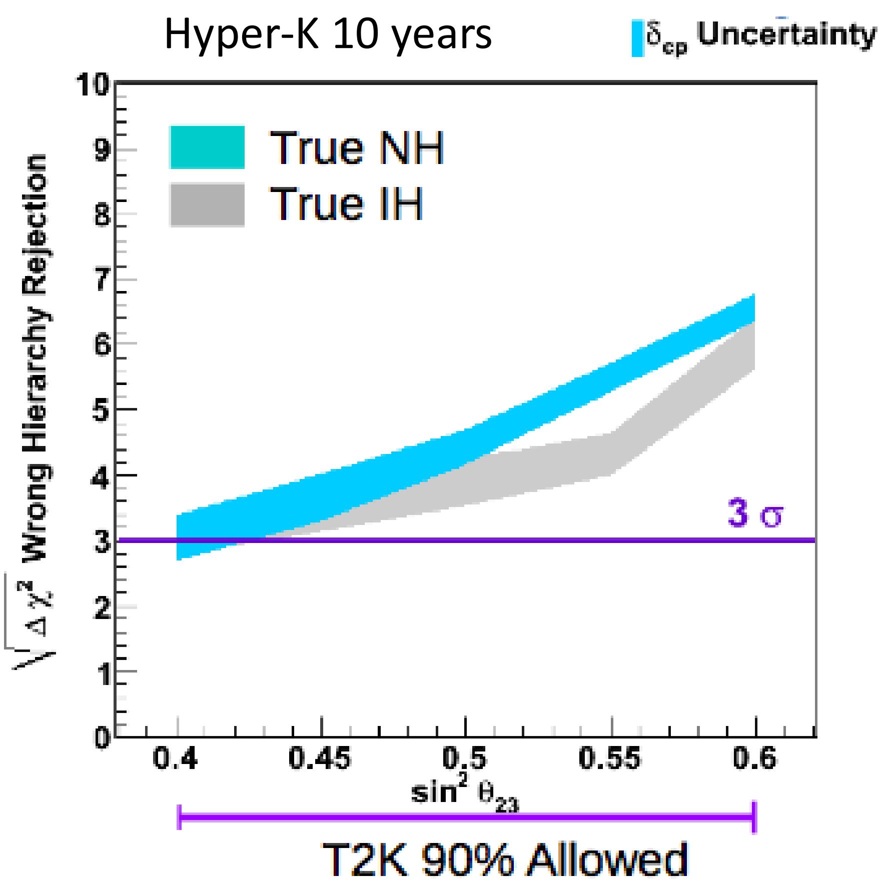
- Cavity : 48m(W) x 54m(H) x 250m(L) x 2
- Water volume :
  - Total : 0.496x2 = 0.99 Mton
  - Fiducial volume = 0.56 Mton (25x SK)
- Photo-detectors :
  - ID : ~99,000 20” PMTs, 20% photo-coverage
  - OD : ~25,000 8” PMTs, same coverage as SK

•750 kW (assumed)

2.5 degree off-axis beam from J-PARC
295km baseline length
and
Atmospheric neutrinos

Hyper-K's sensitivity to mass hierarchy

MH determination with Atmospheric neutrinos



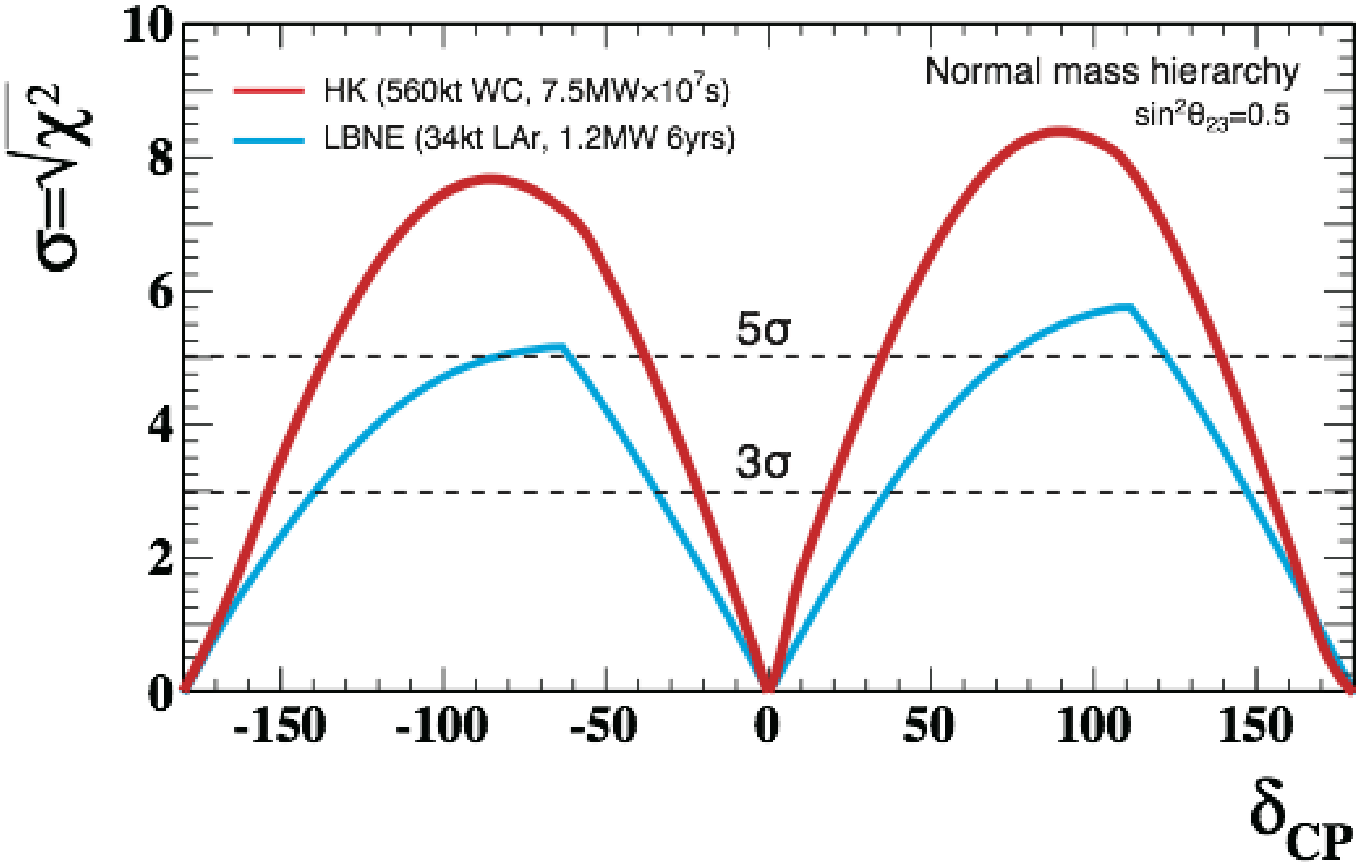
Hyper-Kamiokande status and plan

- proto-collaboration has been formed
- 240 people from 13 countries
- R&D funds have been granted in several countries
- Selected as one of the 25 top priority future projects by Science Council of Japan in 2014
- But was not included in the MEXT (Japanese funding agency) roadmap in 2014 → must wait for the next round (2017)
- If the construction begins in 2018, experiment ~2025

CP violation (LBNF/DUNE and J-PARC/Hyper-Kamiokande)

CP violation sensitivity (MH assumed to be known)

Plot by M. Shiozawa
K. Abe et al., arXiv: 1502.05199
M.Thomson, 2nd International meeting for Large Neutrino Infrastructure, April 2015



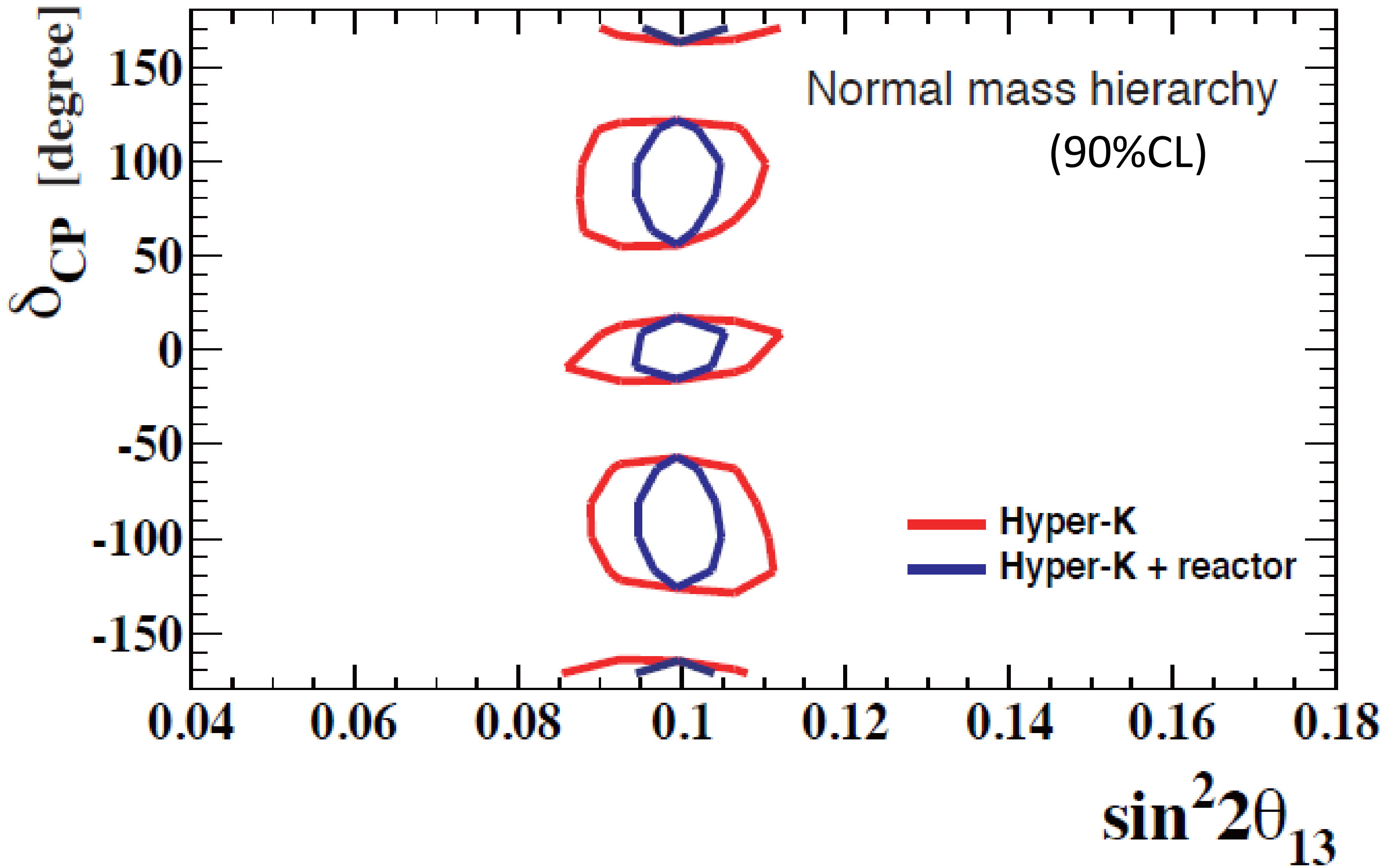
Hyper-K slightly better due to larger statistics

CP phase measurement

K. Abe et al., arXiv: 1502.05199

Measurement of δ_{CP}
(MH assumed to be known)

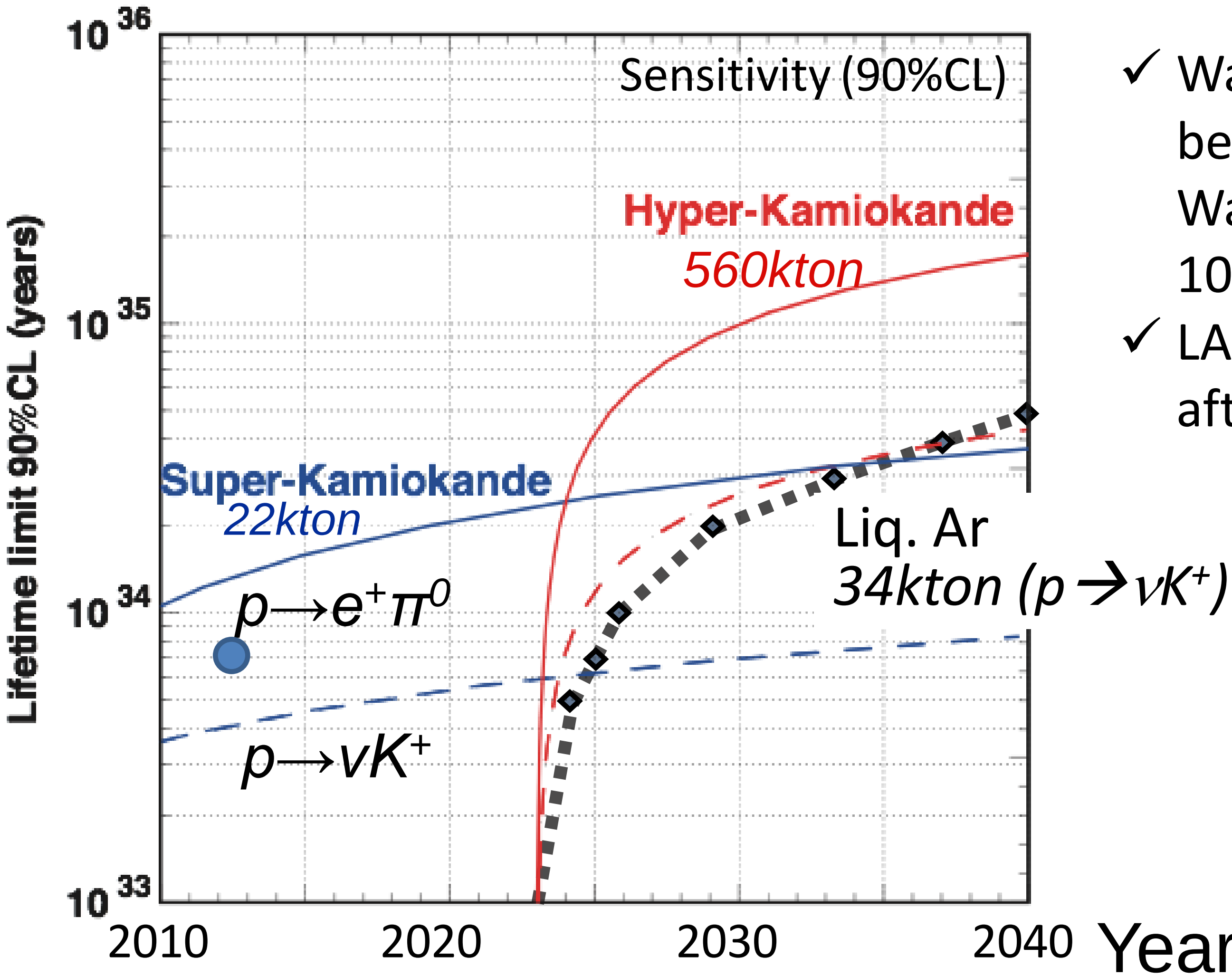
Hyper-Kamiokande



Appendix: coming back to the "signal"

Proton decays: estimated limit

About 35 years ago, proton decay experiments began to search for proton decays with the lifetime of ~10^{30} years…



- ✓ Water Ch. much better for $p \rightarrow e\pi^0$. Water Ch. can reach 10^{35} years.
- ✓ LAr better for $p \rightarrow \nu K^+$ after many years….

Summary

- Unexpected muon-neutrino deficit in the atmospheric neutrino flux was observed in Kamiokande (1988).
- Subsequently, Super-Kamiokande discovered atmospheric neutrino oscillations (1998).
- I feel that I have been extremely lucky, because I have been involved in the excitement of this discovery from the beginning.
- The discovery of non-zero neutrino masses opened a window to study physics at a very high energy scale, probably that of the Grand Unification of elementary particle interactions.
- There are still many things to be observed in neutrinos. Further studies of neutrinos might give us fundamental information for the understanding of the nature, such as the origin of the matter in the Universe.