KIT Center Elementary Particle
and Astroparticle Physics (KCETA),
Dec 19, 2013

Julius Wess

Atmosphreic Neutrino Oscillations

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outline

- Introduction: Kamiokande - the starting point of my research -
- Discovery of neutrino oscillations: History
- Discovery of neutrino oscillations
- Recent result and a remark on the future
- Summary

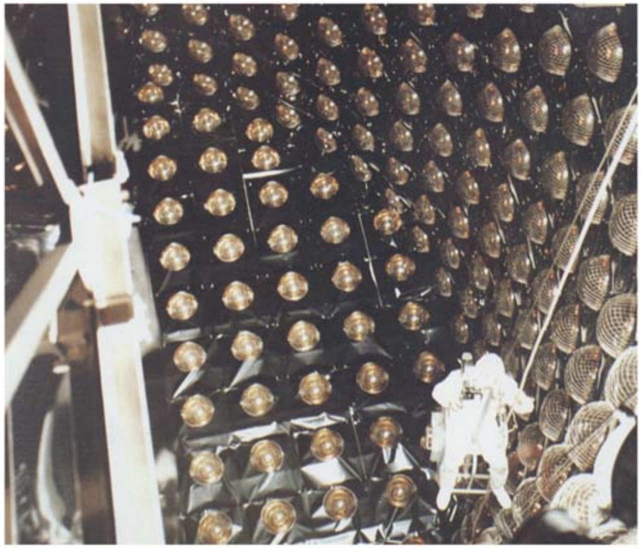
(No introduction to neutrino oscillation and related physics… Sorry for this.)

Introduction:

Kamiokande
- the starting point of my research –

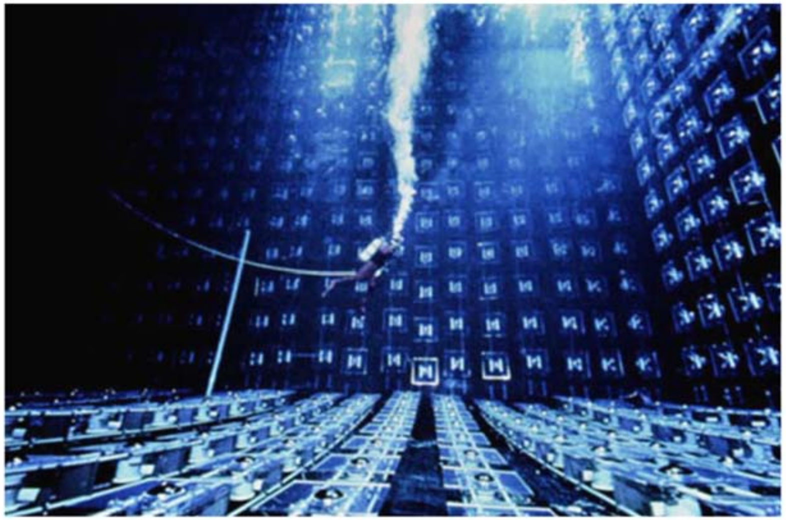
Proton decay experiments (1980's)

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



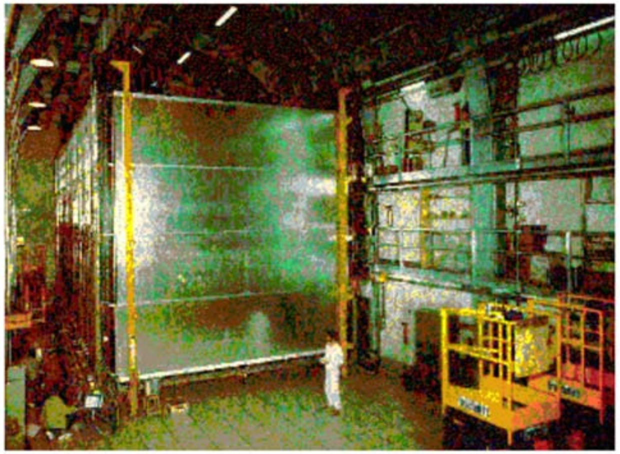
Kamiokande
(1000ton)

IMB
(3300ton)



NUSEX
(130ton)

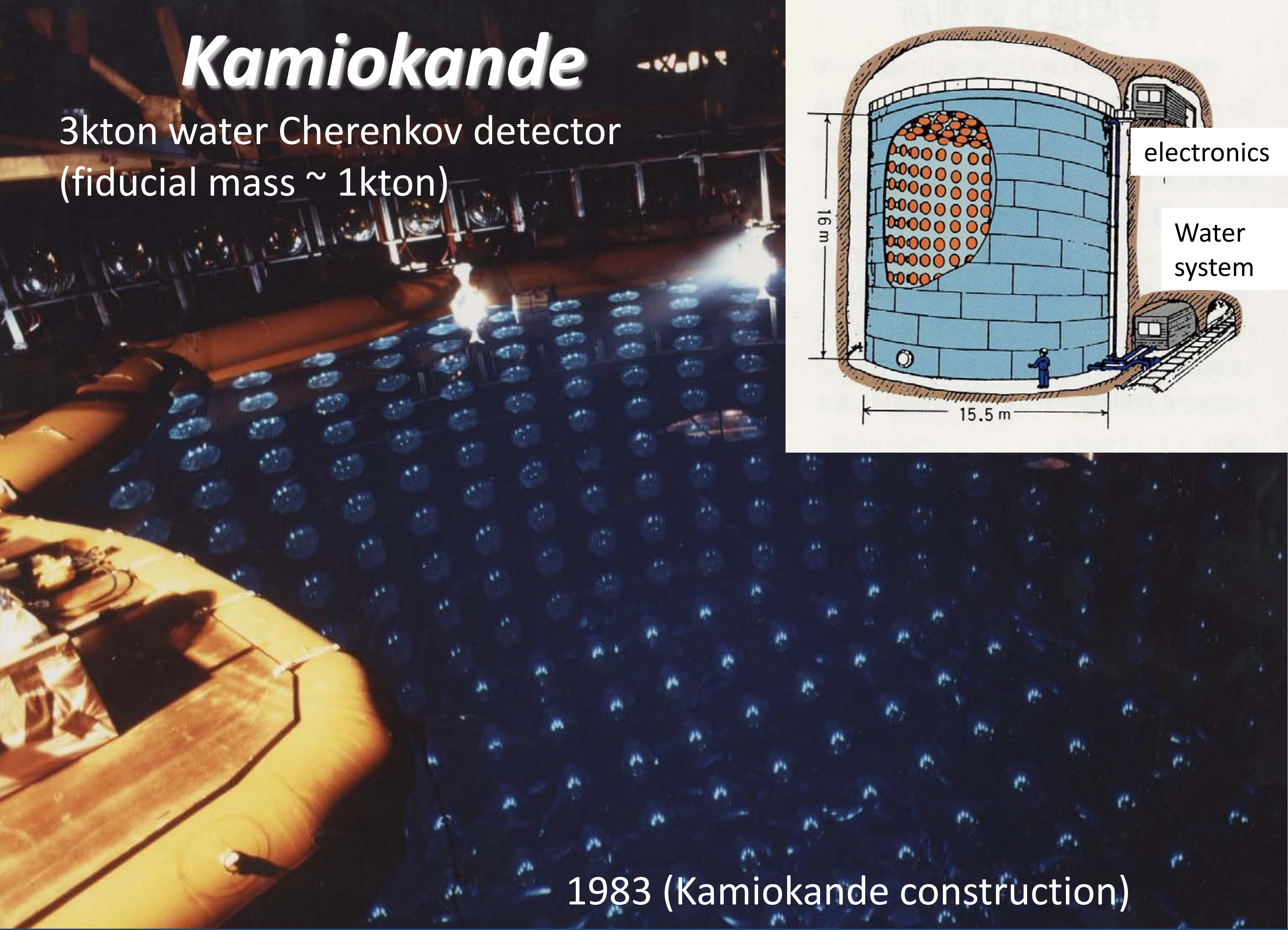
Frejus
(700ton)



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

Kamiokande

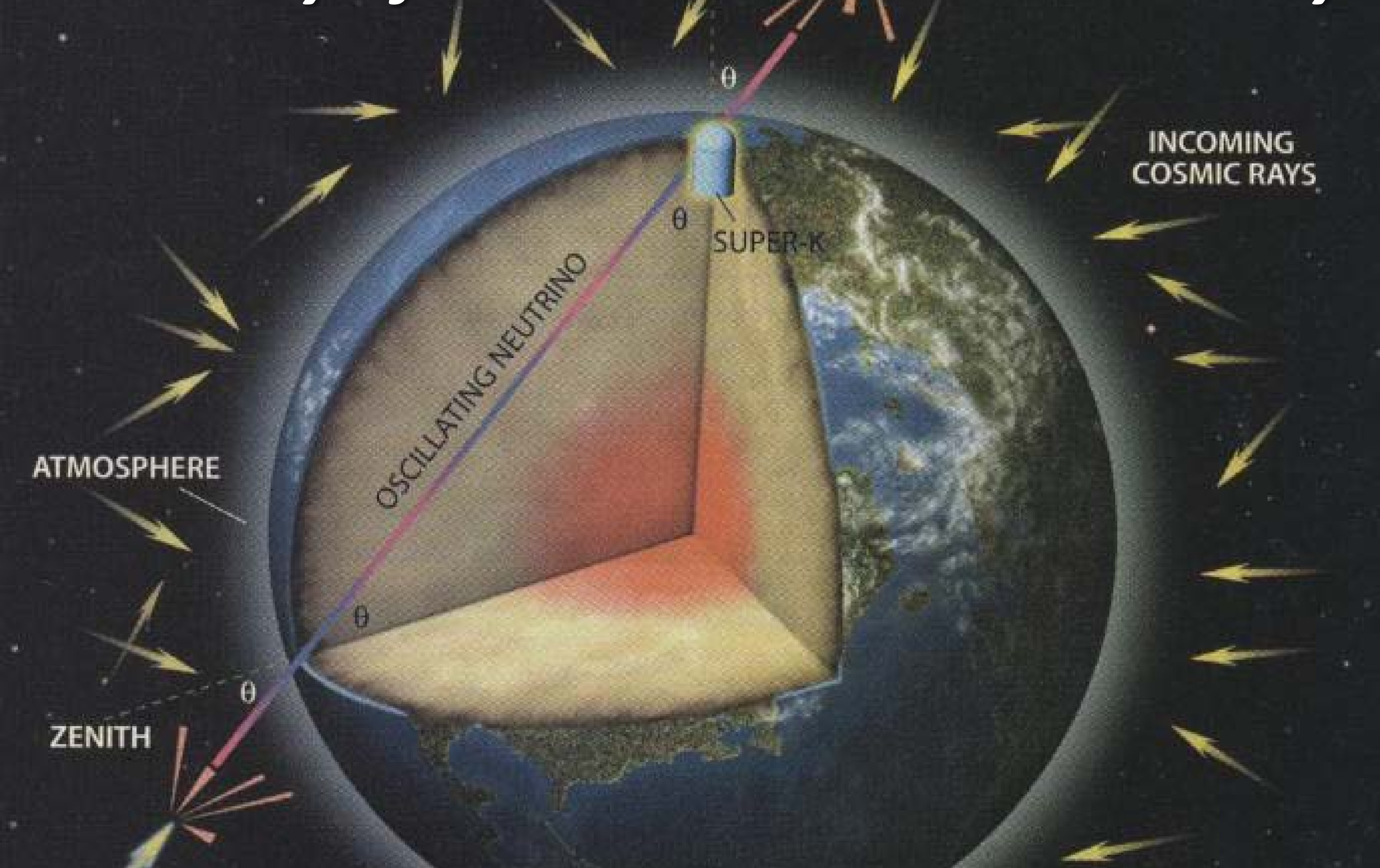
3kton water Cherenkov detector
(fiducial mass ~ 1kton)



1983 (Kamiokande construction)

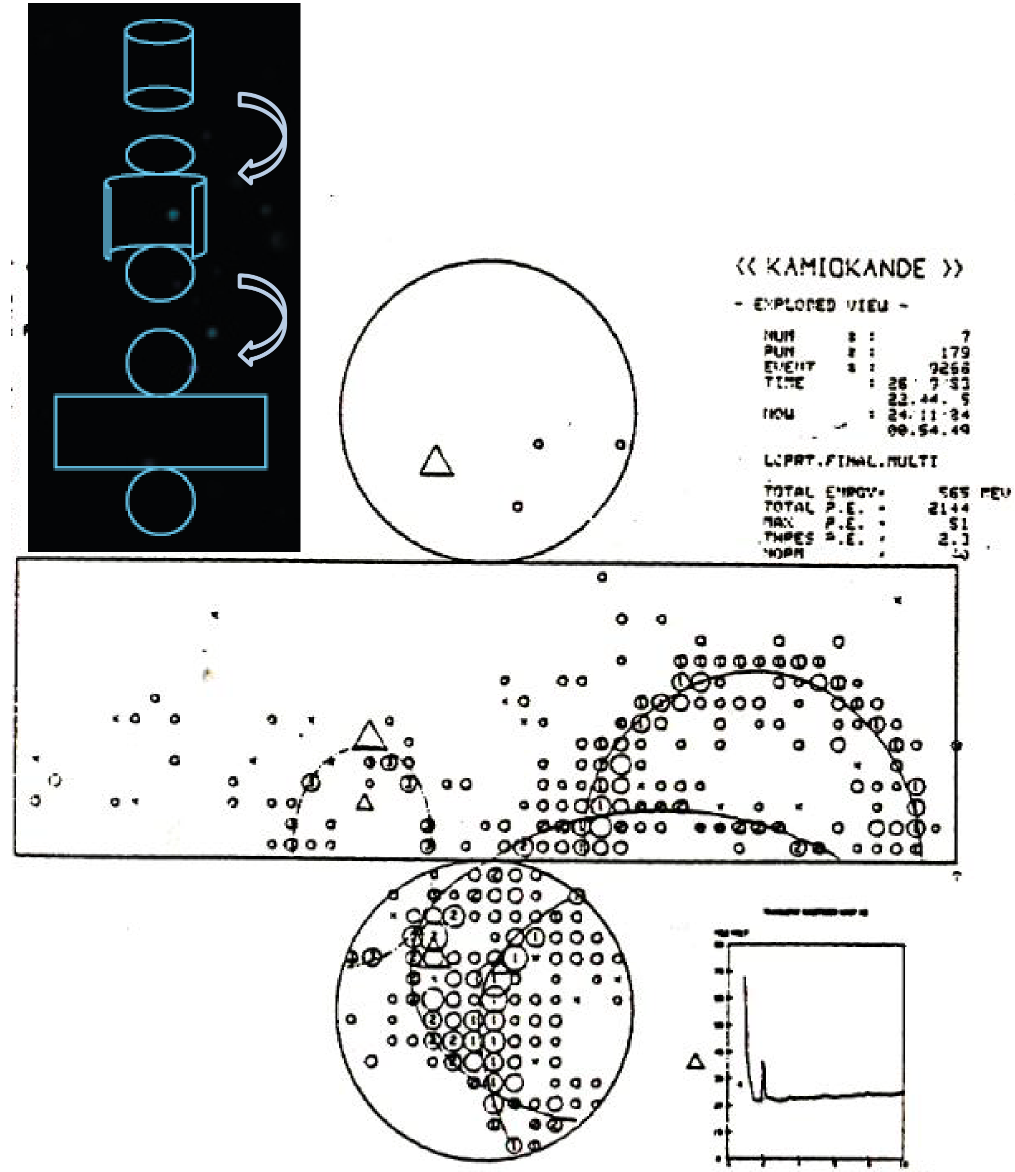
Kamiokande construction team (Spring 1983)

Discovery of neutrino oscillations: History



Particle Identification

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.

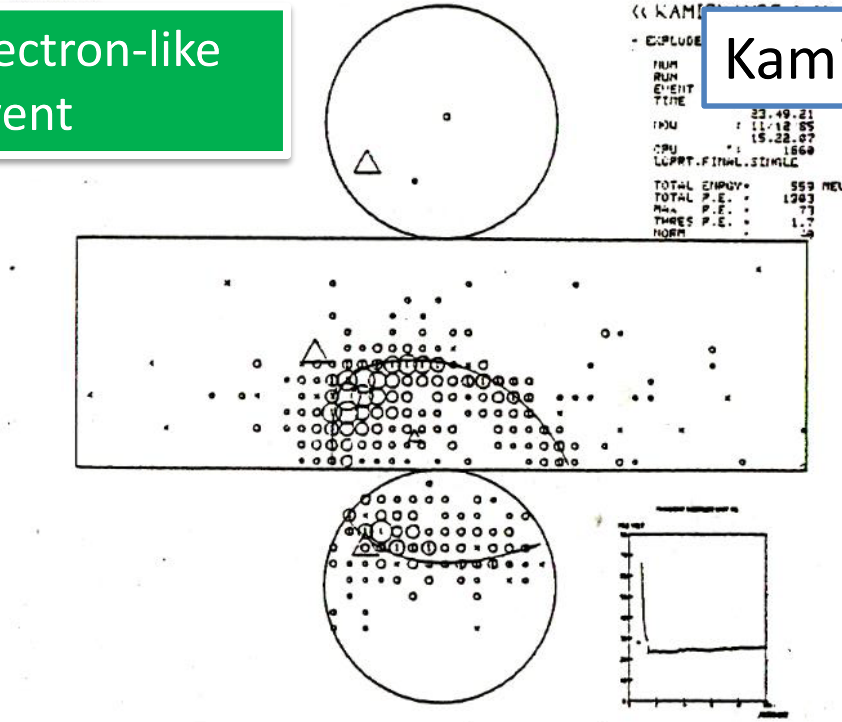


The simplest application of the PID was on single Cherenkov-ring events….

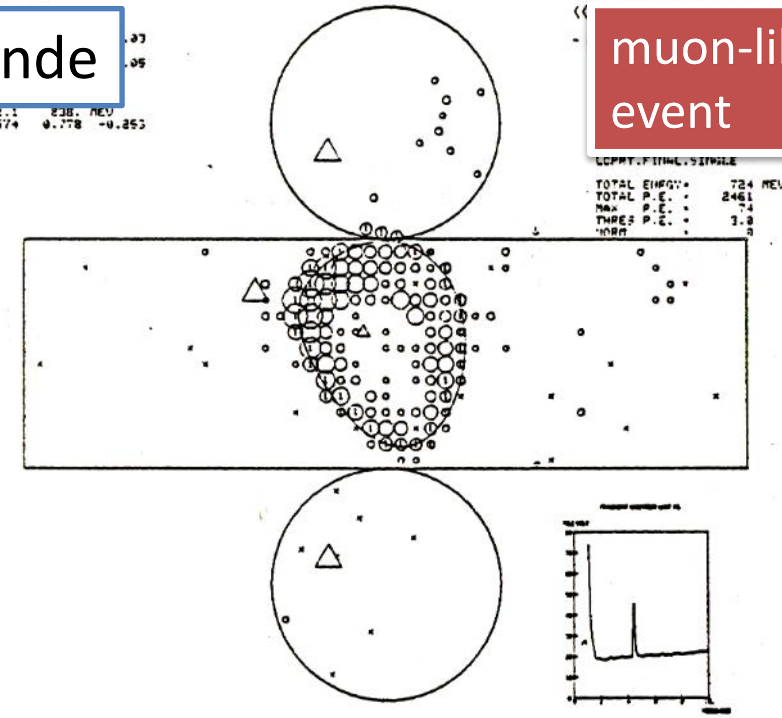
Particle identification: electron or muon ?

Kamiokande

electron-like event



muon-like event

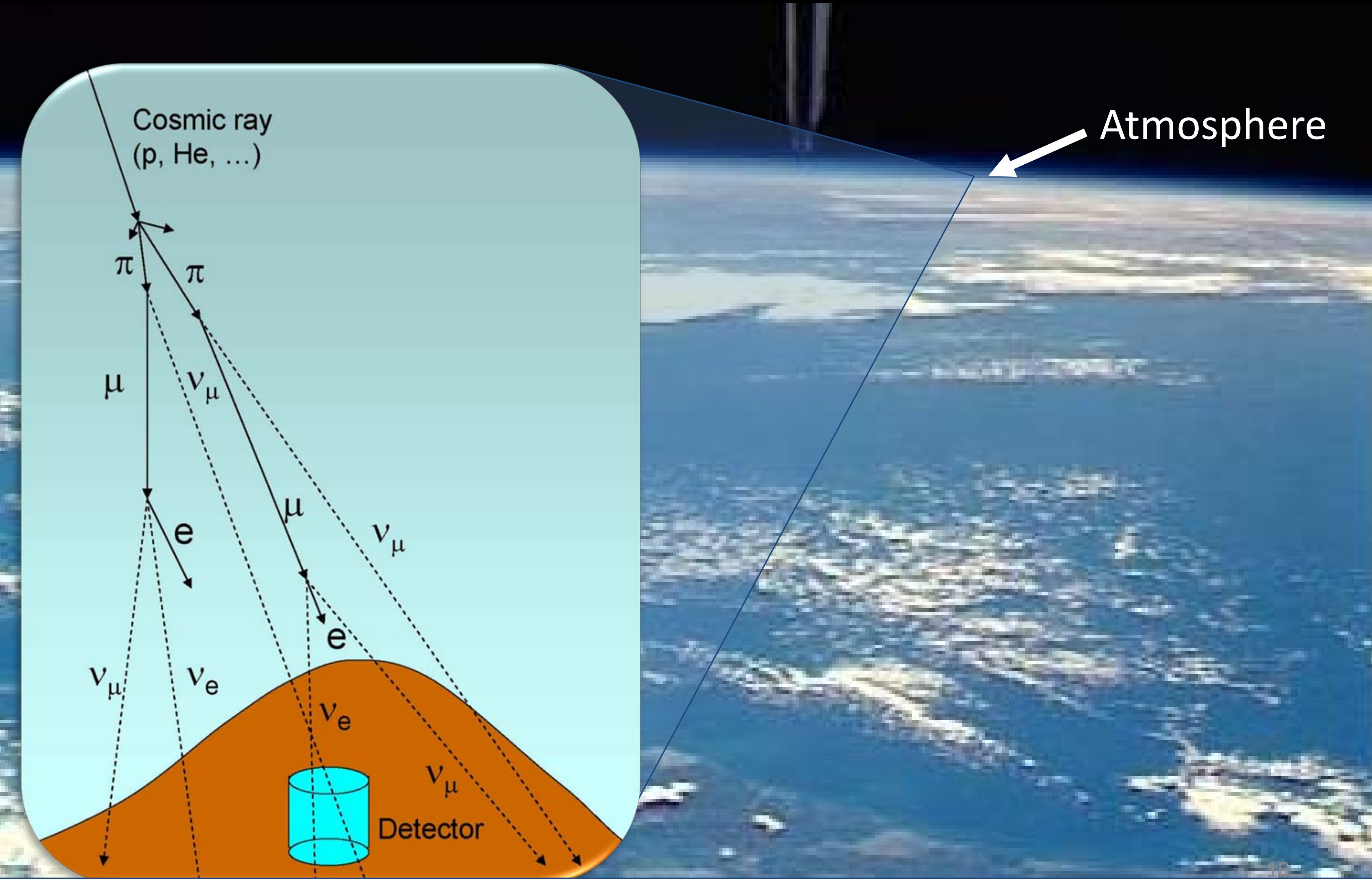


e: electromagnetic shower, multiple Coulomb scattering

μ: propagate almost straightly, loose energy by ionization loss

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

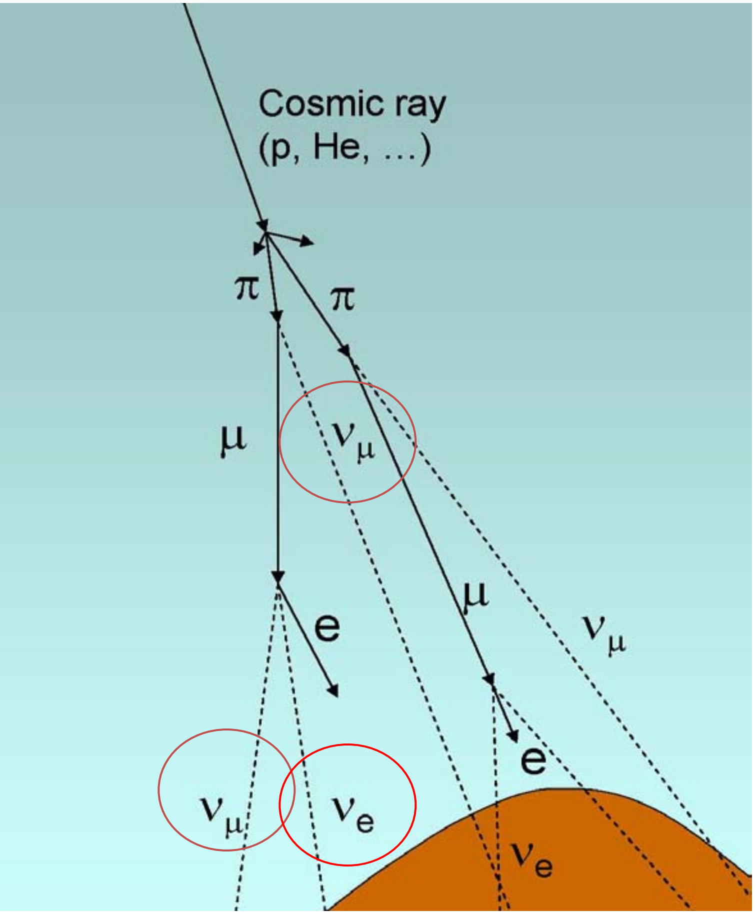
Production of atmospheric neutrinos

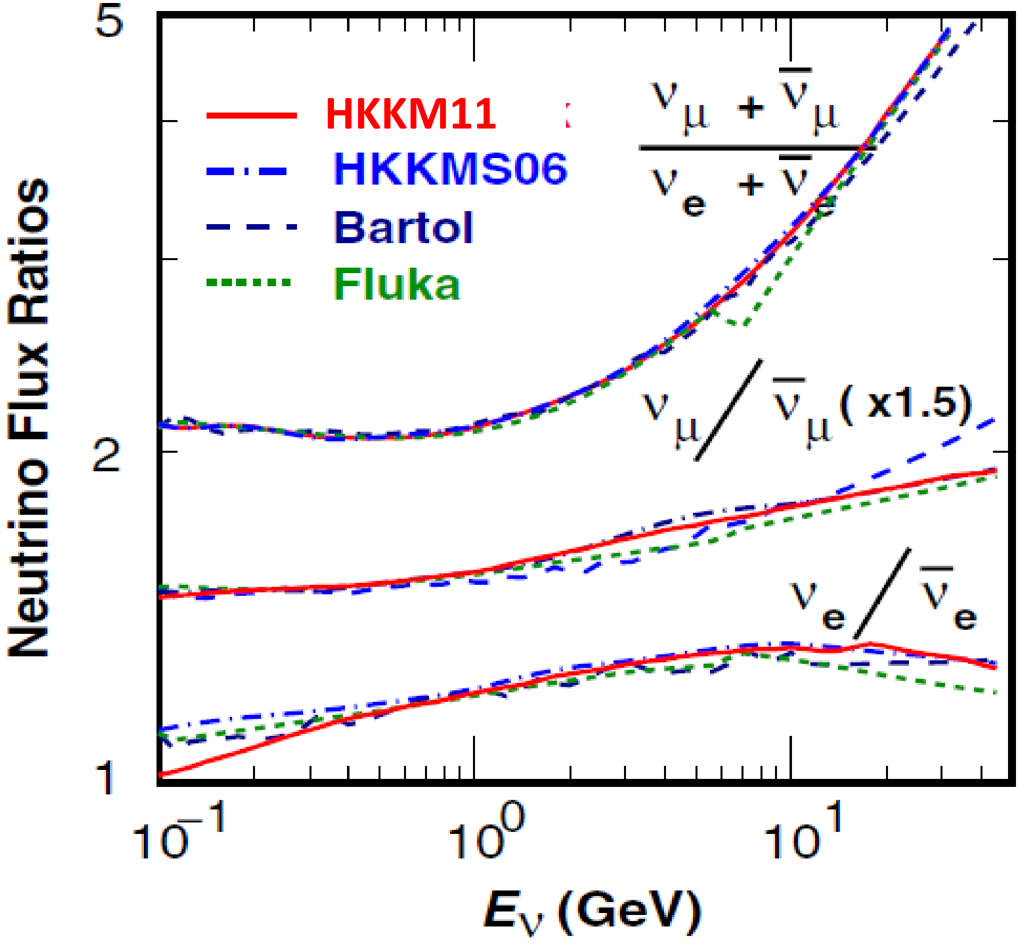


ν_μ over ν_e ratio of the beam

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

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





✓ 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.

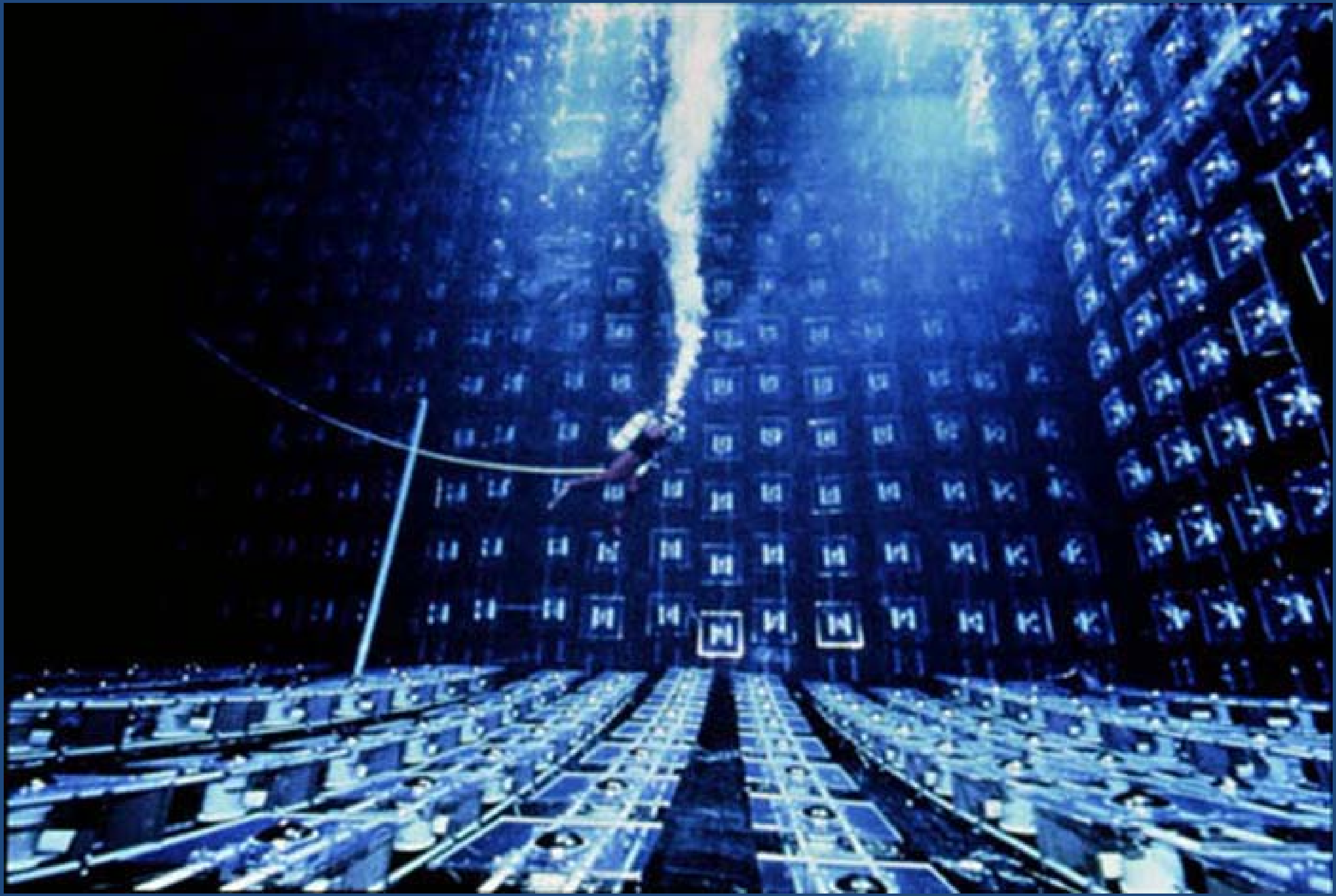
Kamiokande

2.87 kton・year

	Data	MC 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."

First supporting result on small μ/e

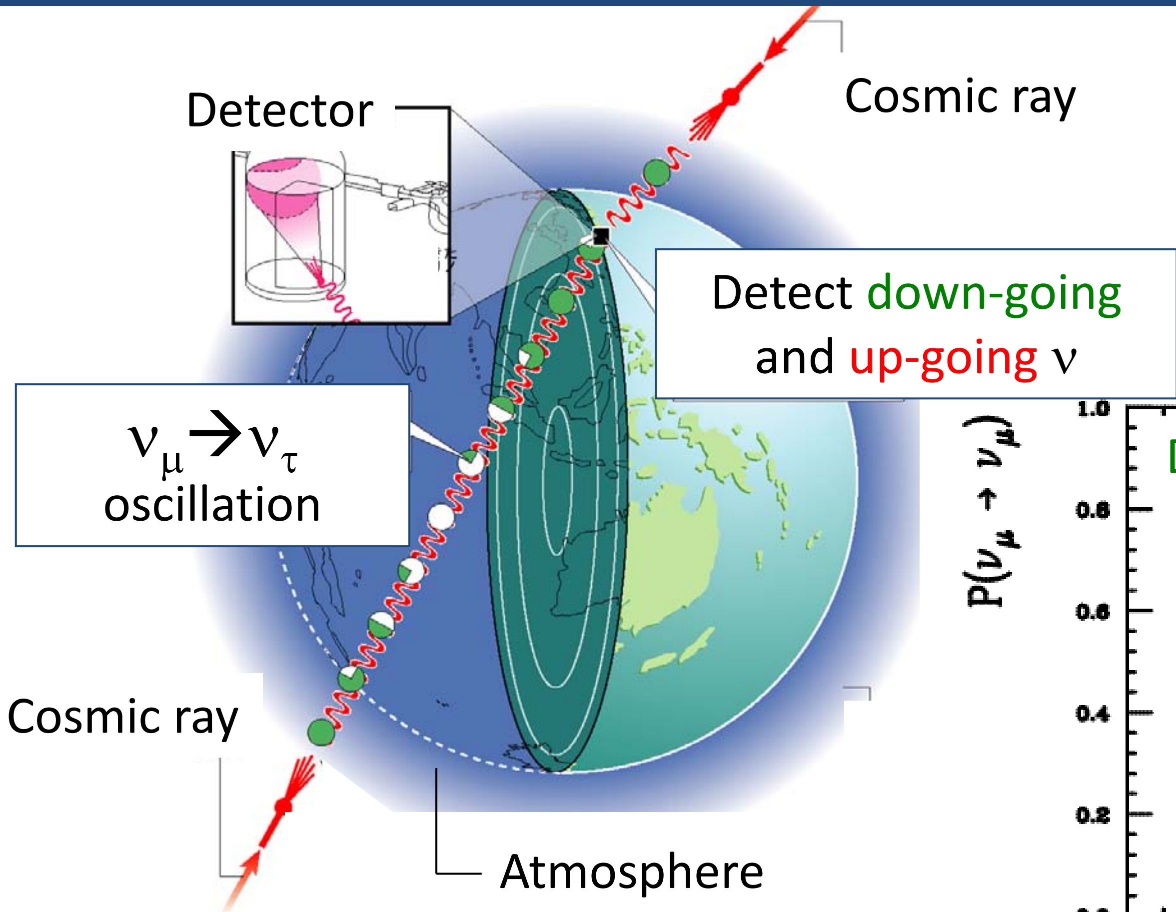


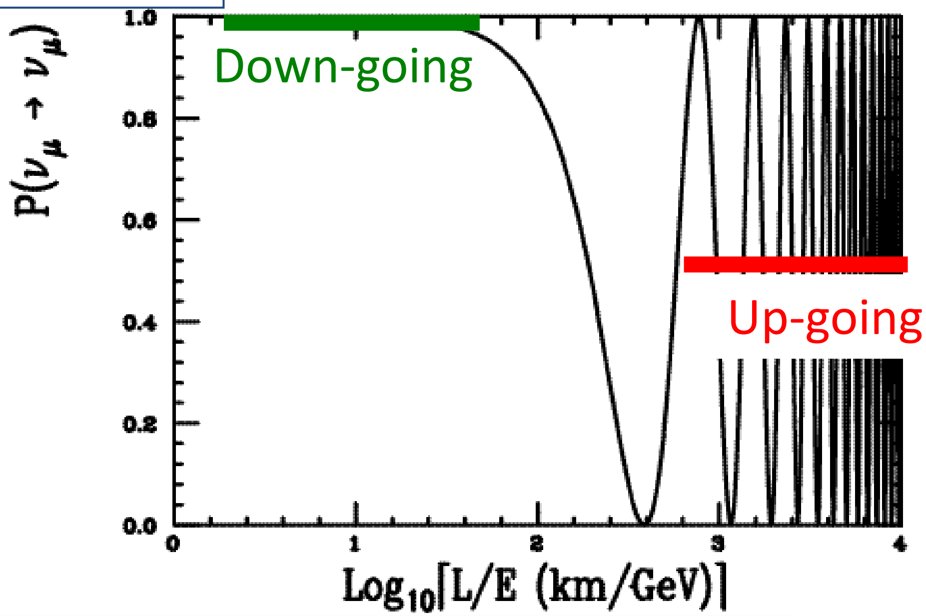
IMB experiment also reported smaller (μ/e) in 1991 and 1992.

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?

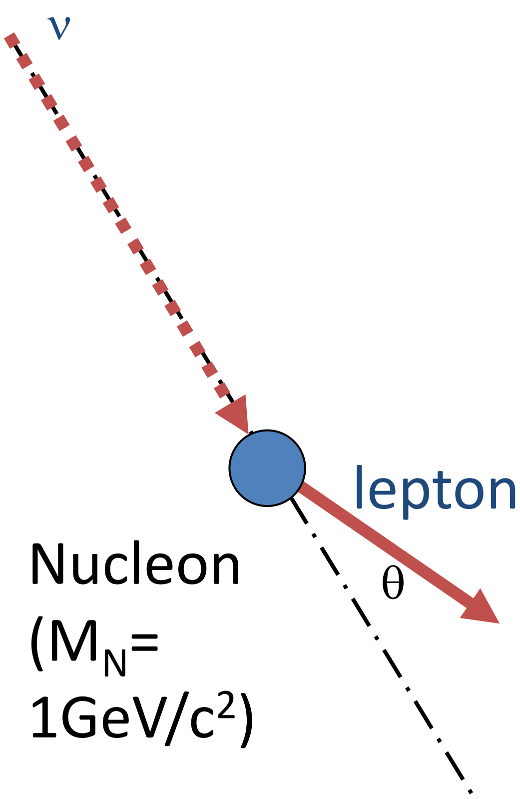
What will happen if the moun deficit is due to neutrino oscillations

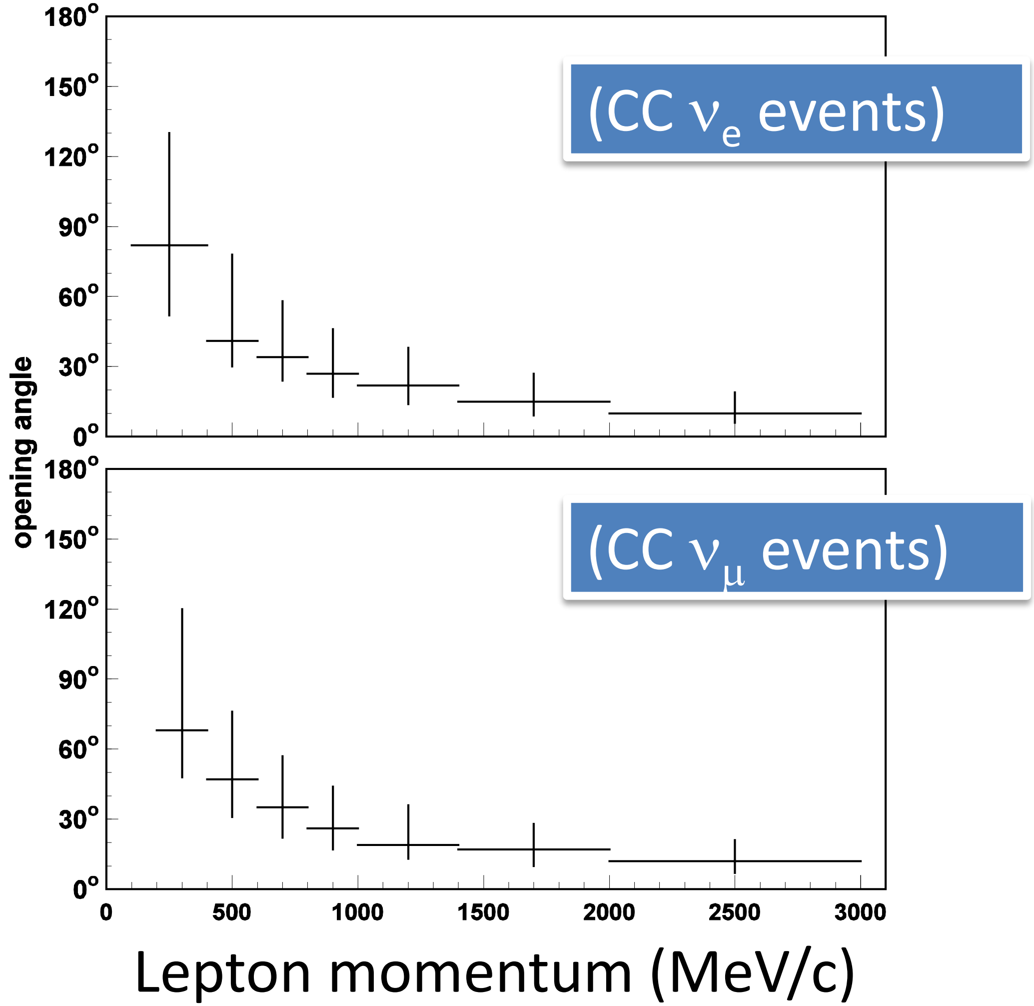




One should observe a deficit of upward going ν_μ's (=muons) !

Angular correlation

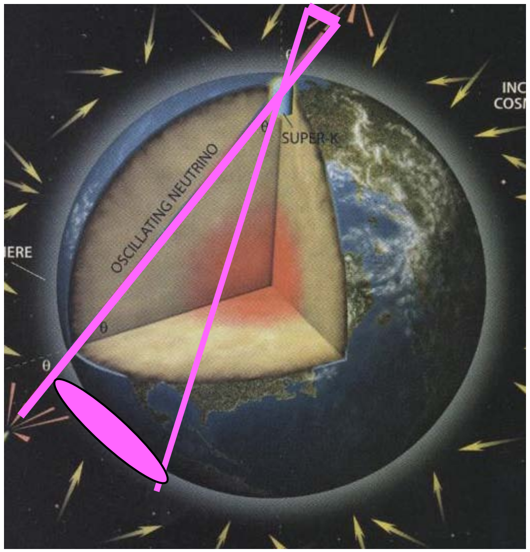




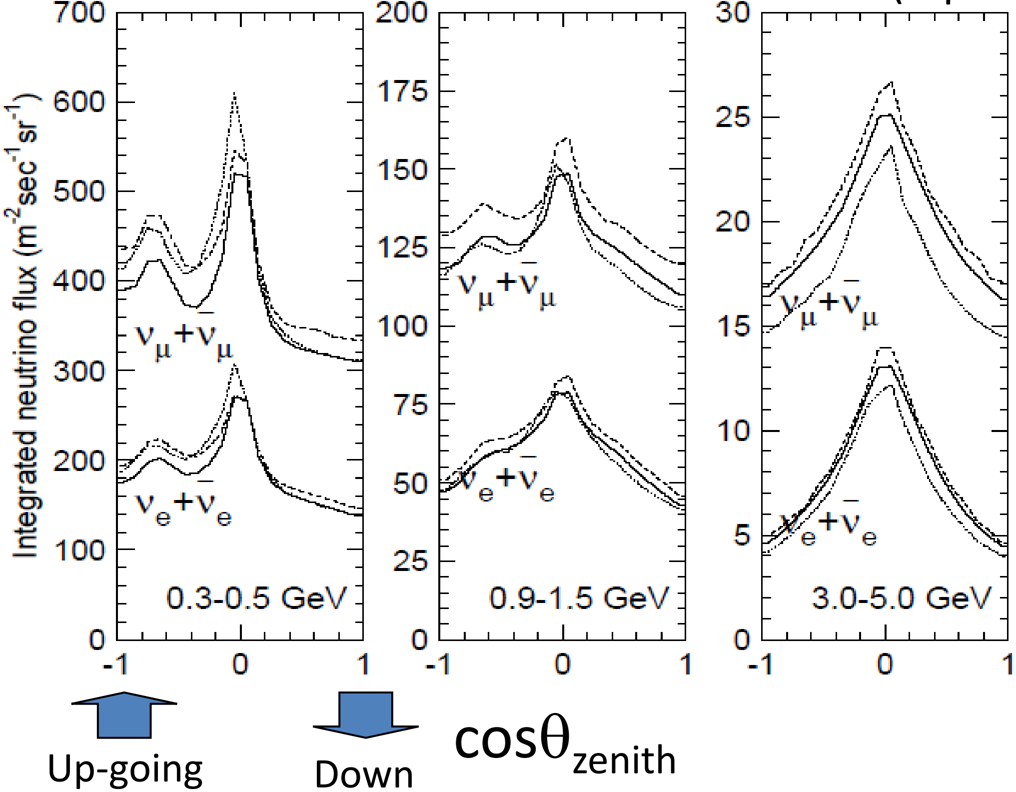
Events with their energy larger than ~1GeV need to be observed to study the zenith angle dependence

Some features of the beam (2)

Zenith angle



@Kamioka (Japan)

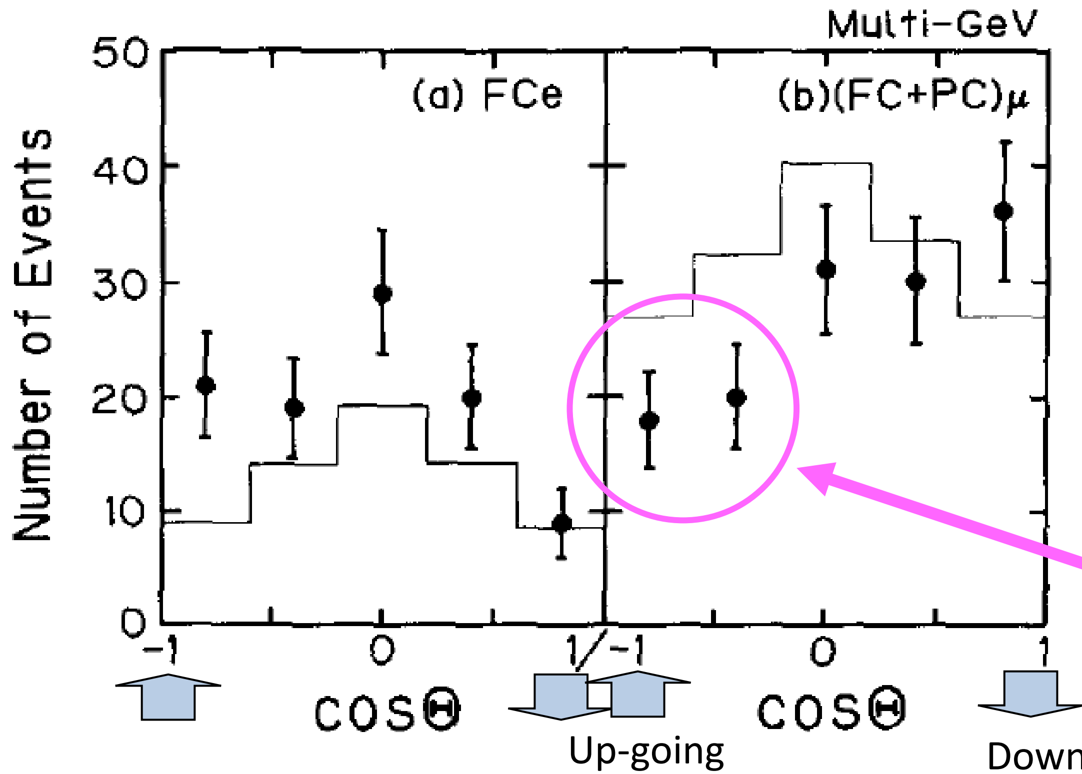


Up/down flux ratio is very close to 1.0 and accurately calculated (1% or better) above a few GeV.

Zenith angle distribution for multi-GeV events (1994)

multi-GeV events

Kamiokande PLB 335, 237 (1994)



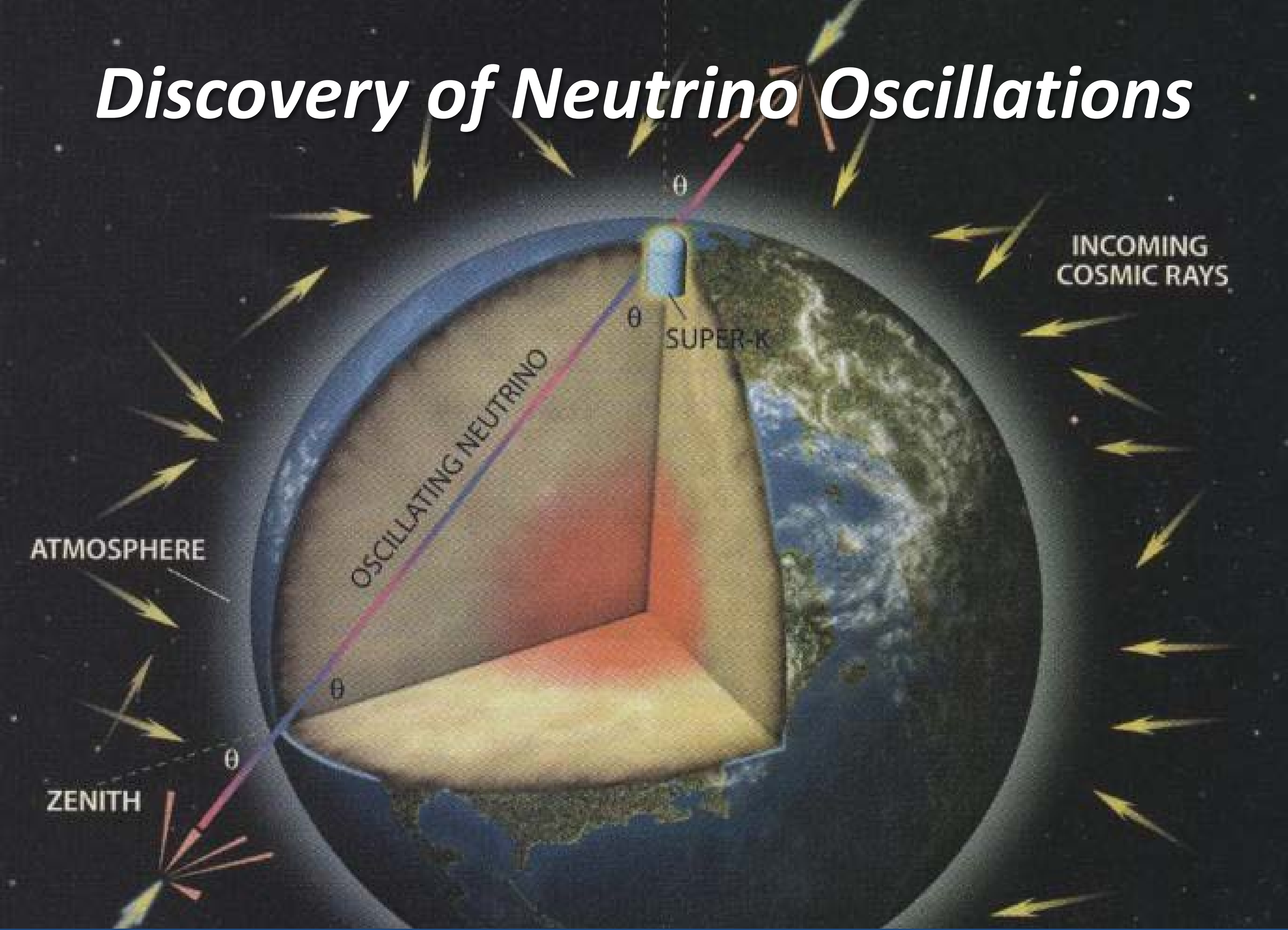
Deficit of upward-going μ-like events

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

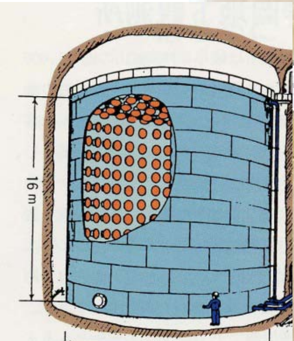
$$\frac{Up}{Down} = 0.58^{+0.13}_{-0.11} \;\; (2.9\sigma)$$

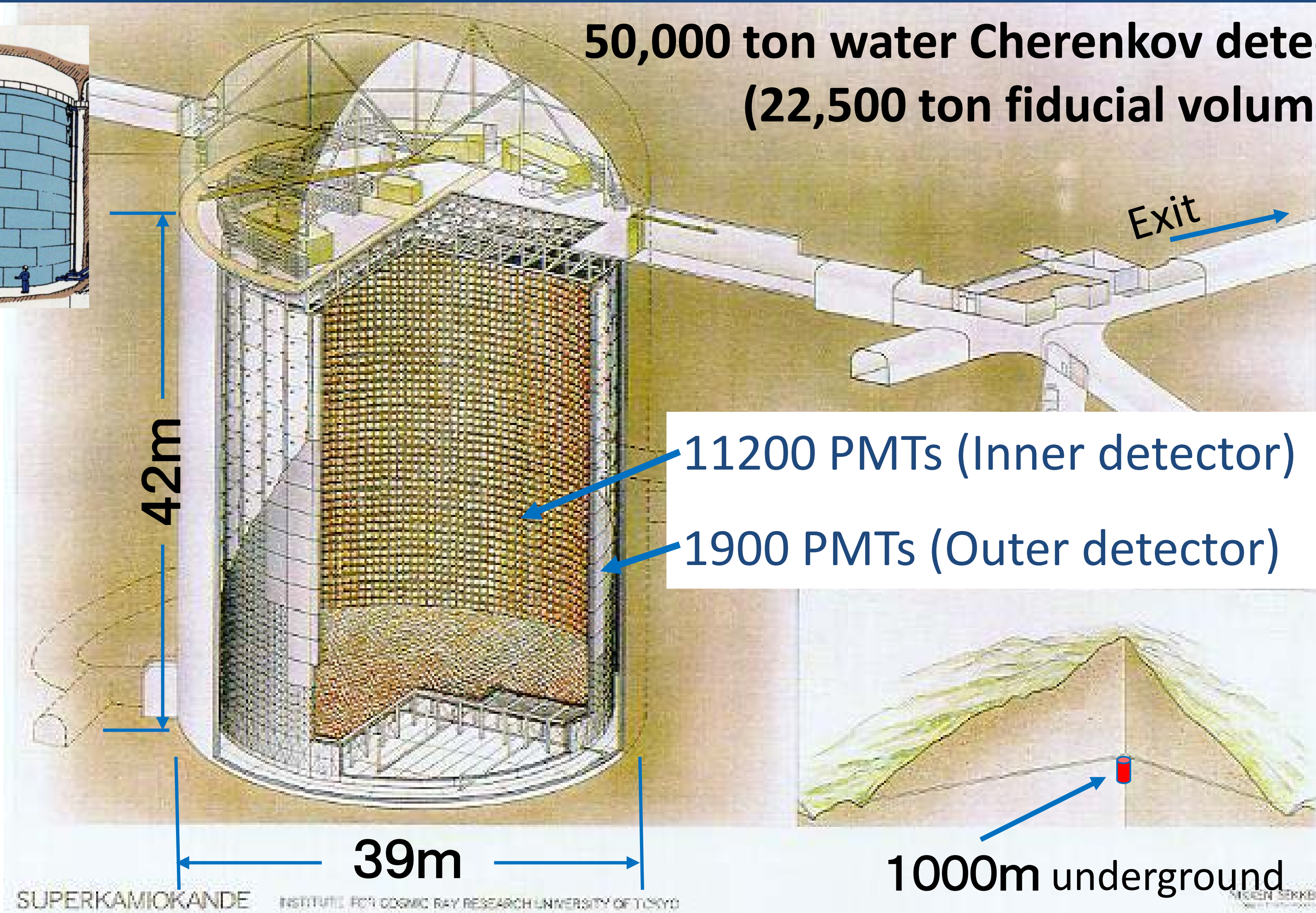
Not high enough statistics to conclude …
Much higher statics required (= much larger detector required)

Discovery of Neutrino Oscillations



Super-Kamiokade detector





50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)

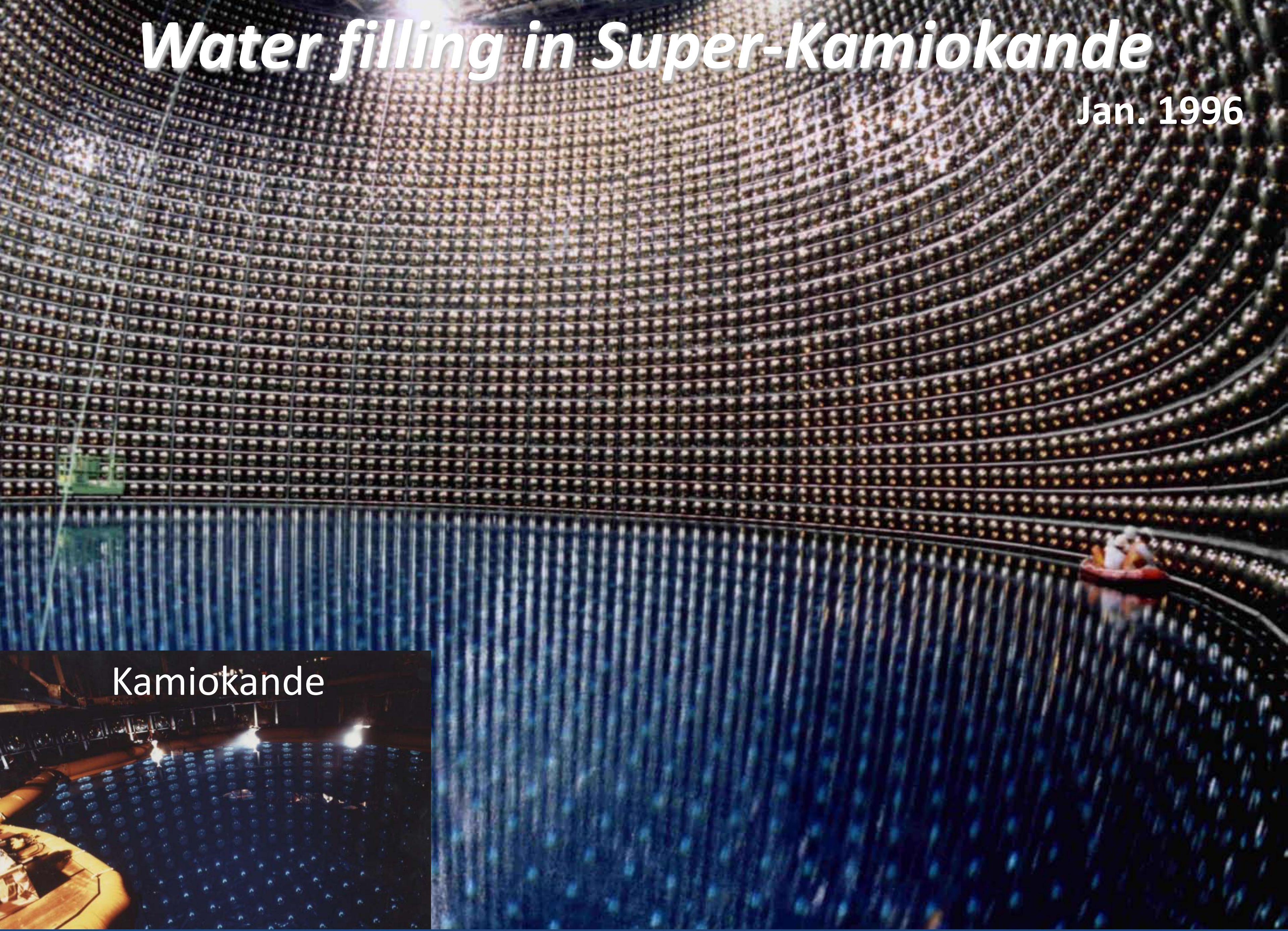
11200 PMTs (Inner detector)

1900 PMTs (Outer detector)

1000m underground

Water filling in Super-Kamiokande

Jan. 1996

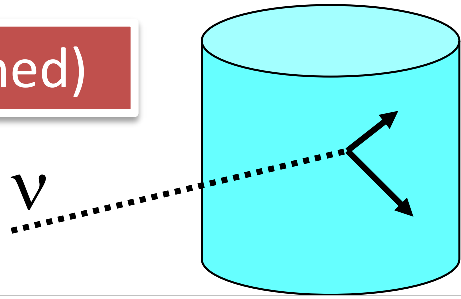


Super-K detector construction

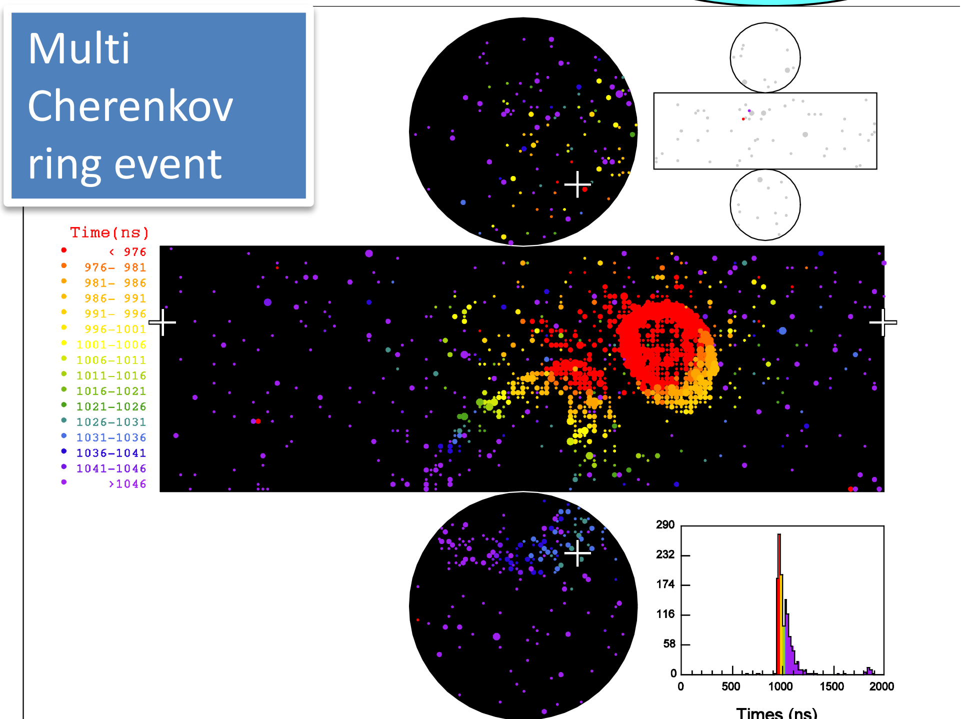
Fully automated analysis

▪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.

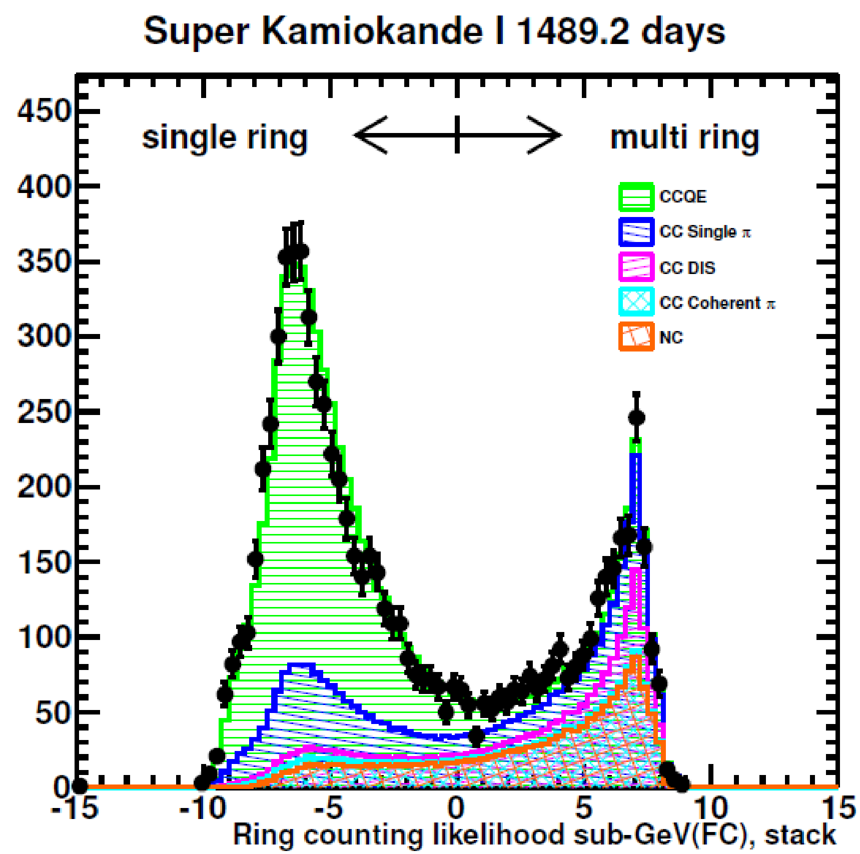
FC (fully contained)



Multi Cherenkov ring event



Hough transformation
+ maximum likelihood



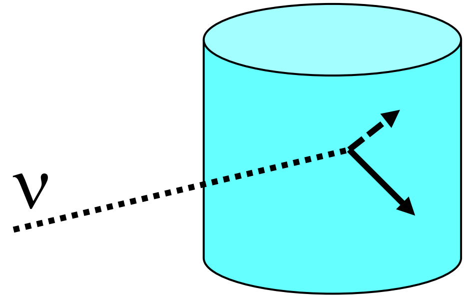
Various types of atmospheric ν events (1)

FC (fully contained)

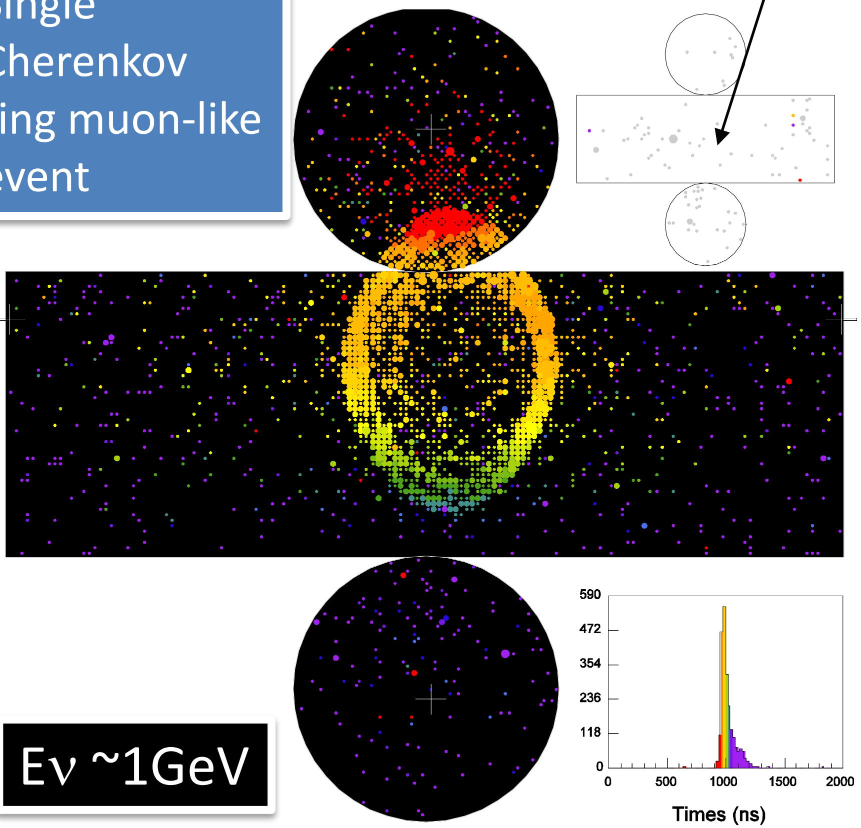
Color: timing

Size: pulse height

Outer detector (no signal)

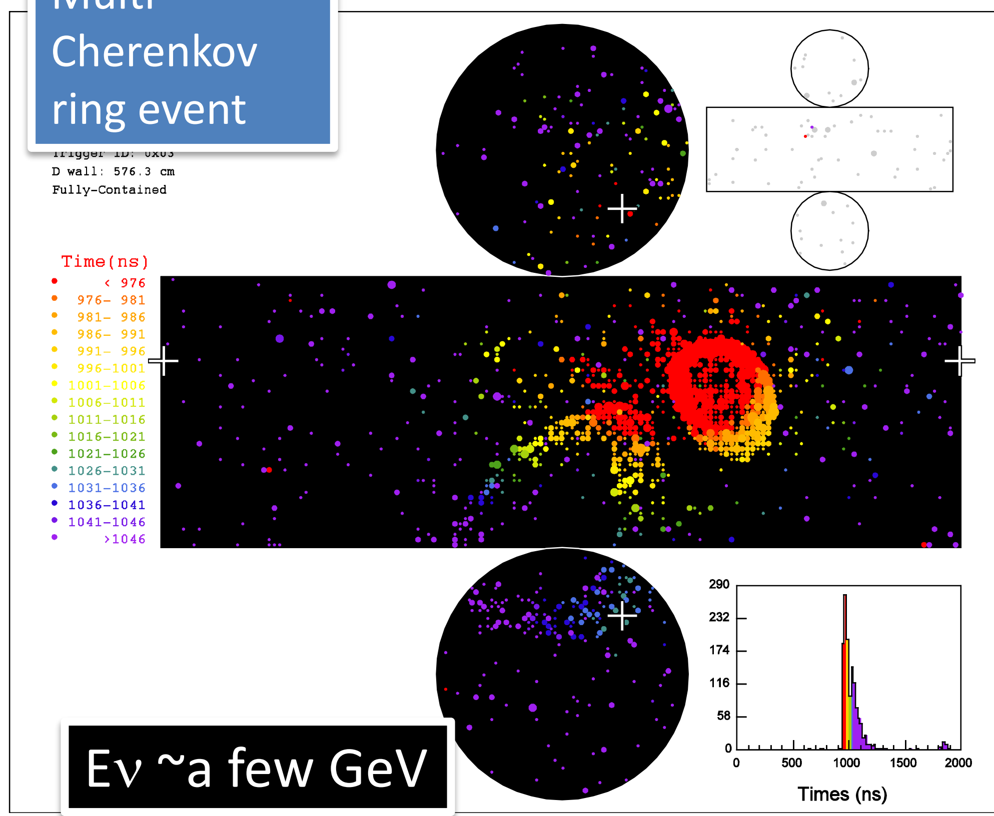


Single Cherenkov ring muon-like event



Eν ~1GeV

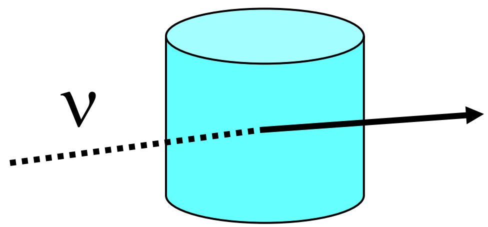
Multi Cherenkov ring event



Eν ~a few GeV

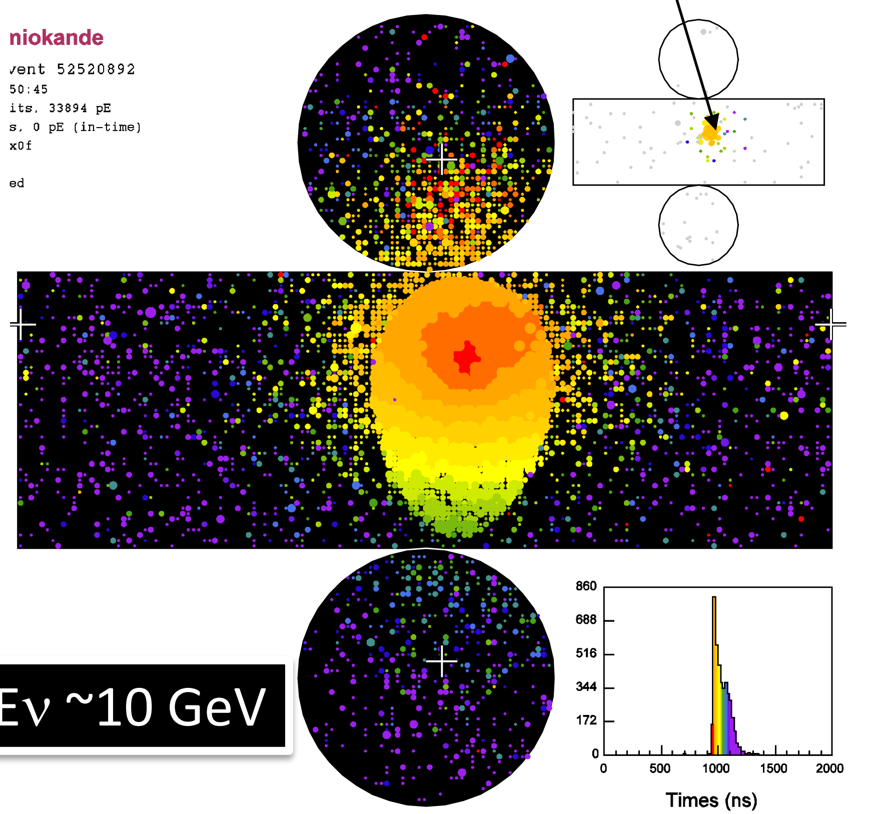
Various types of atmospheric ν events (3)

PC (partially contained)



- 97% CC ν_μ

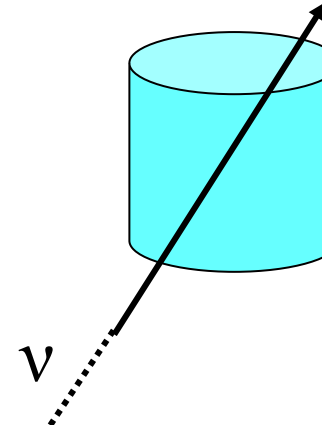
Signal in the outer detector

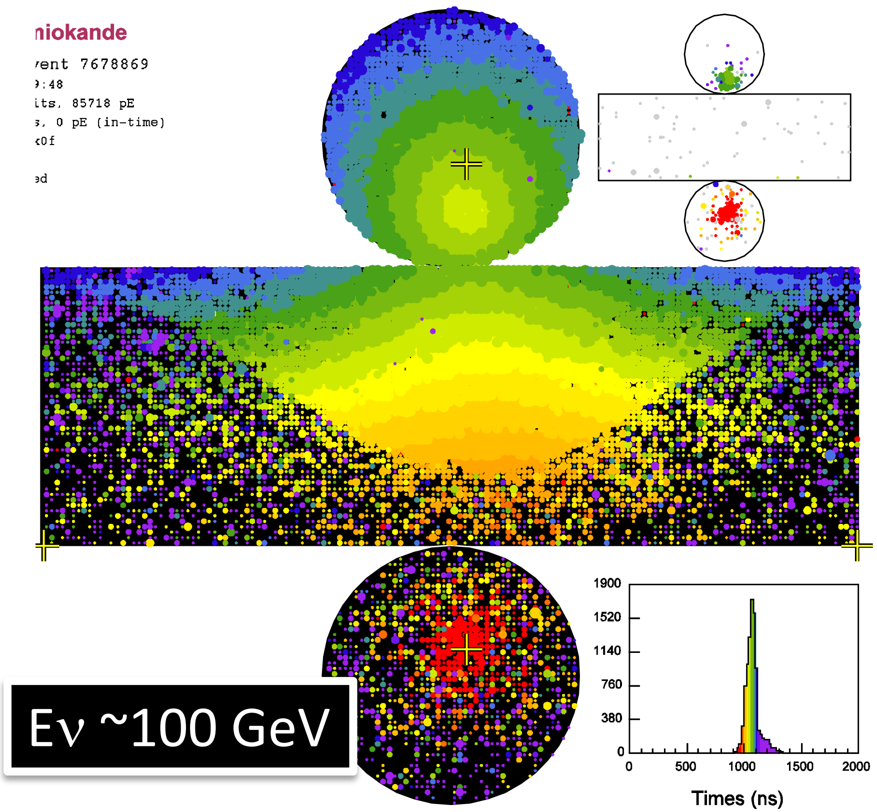


Eν ~10 GeV

Upward going muon

- almost pure CC ν_μ

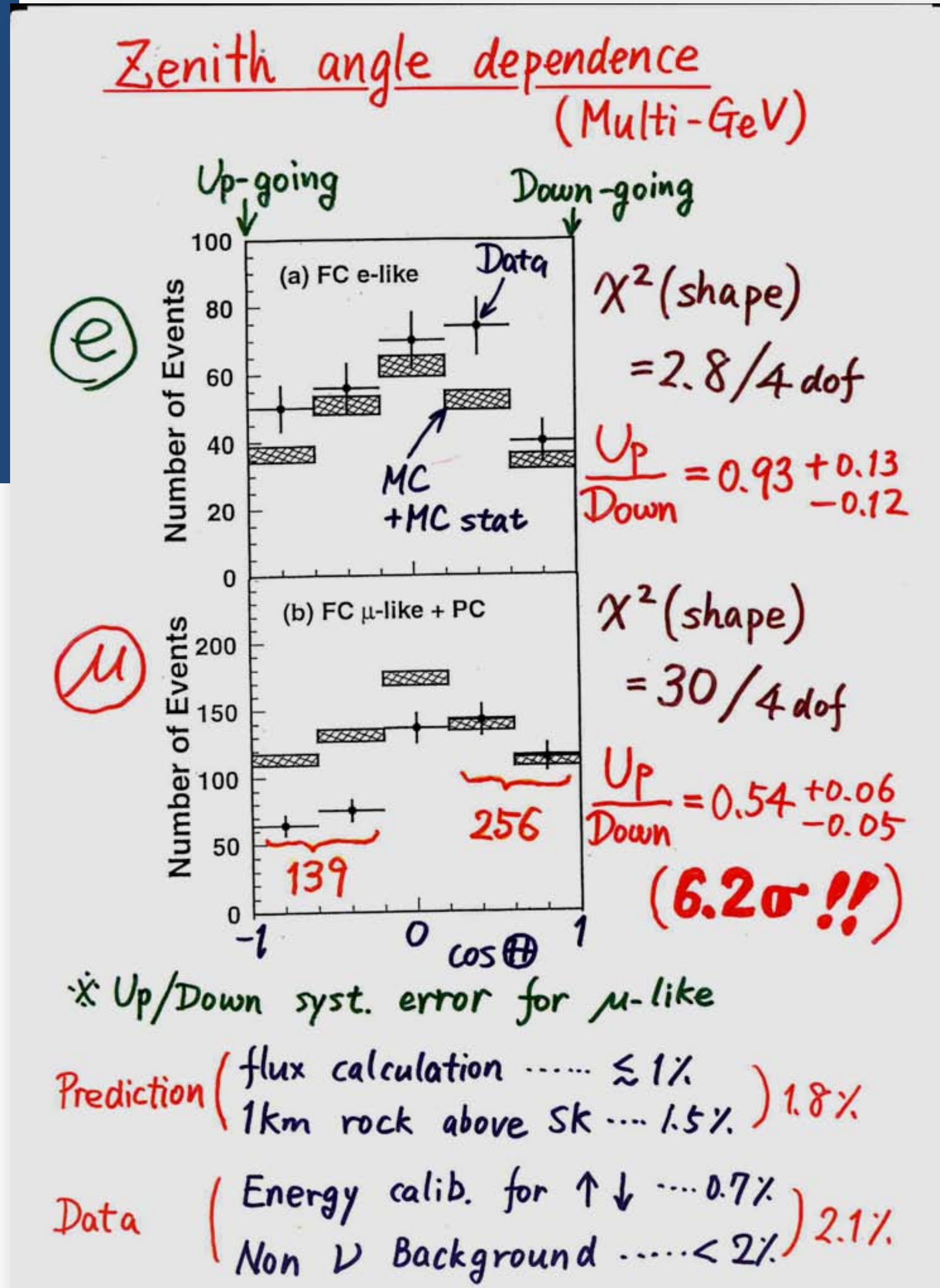




Eν ~100 GeV

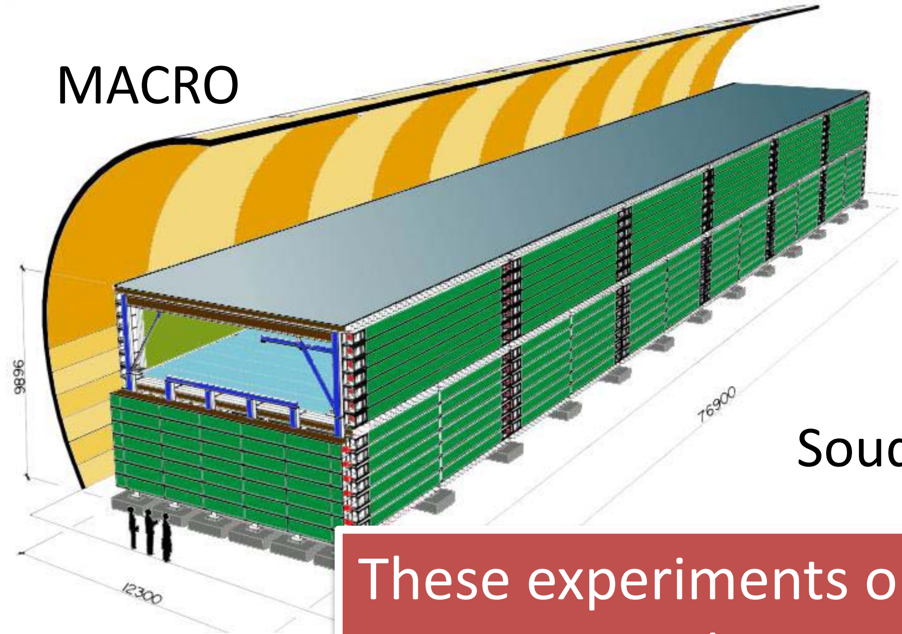
Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

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

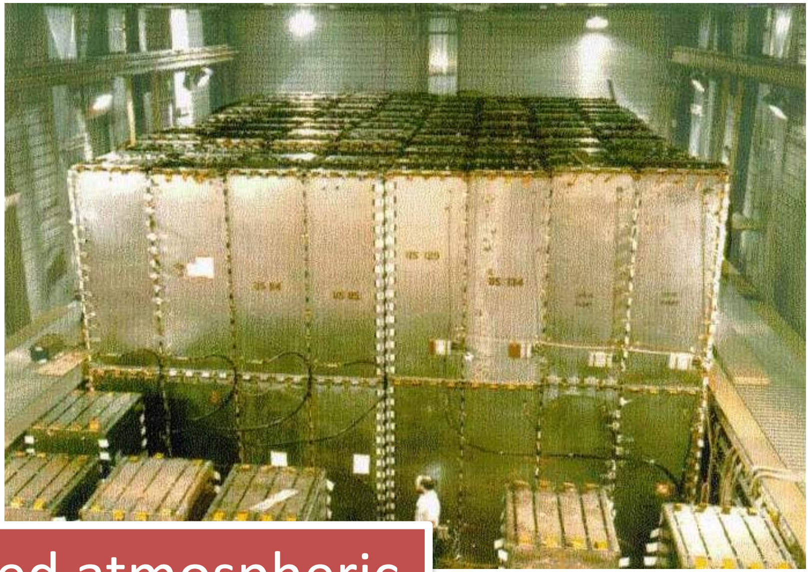


Results from the other atmospheric neutrino experiments

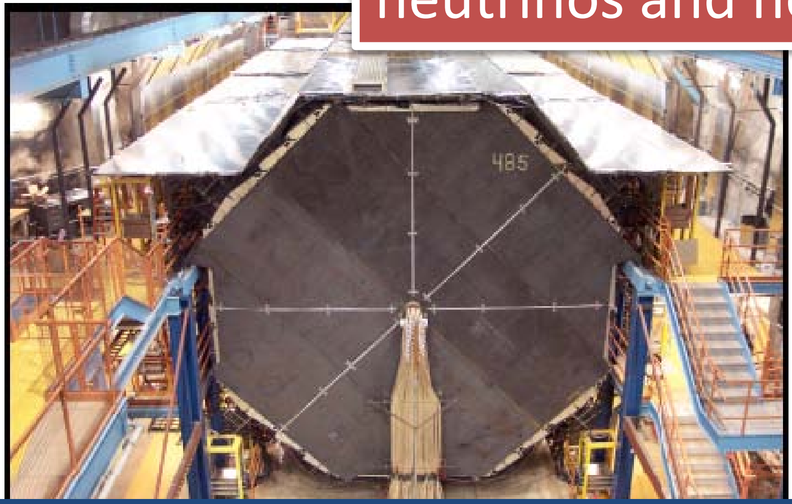
MACRO



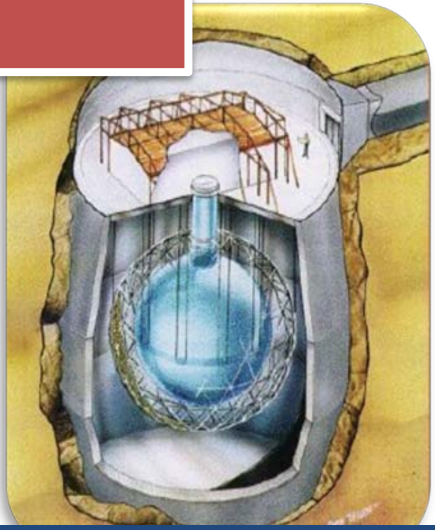
Soudan-2



These experiments observed atmospheric neutrinos and neutrino oscillations

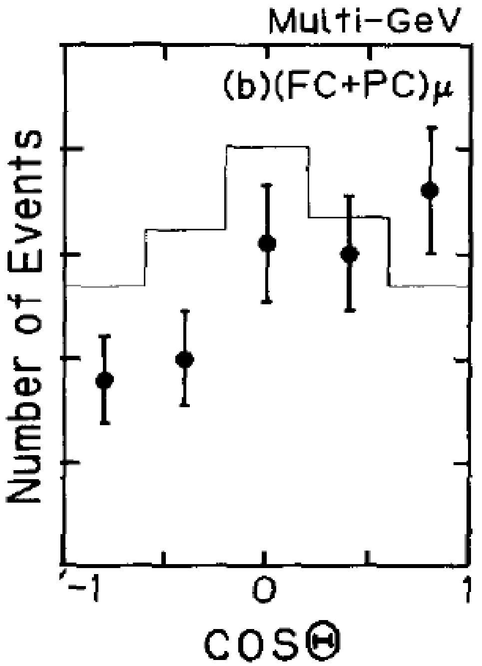


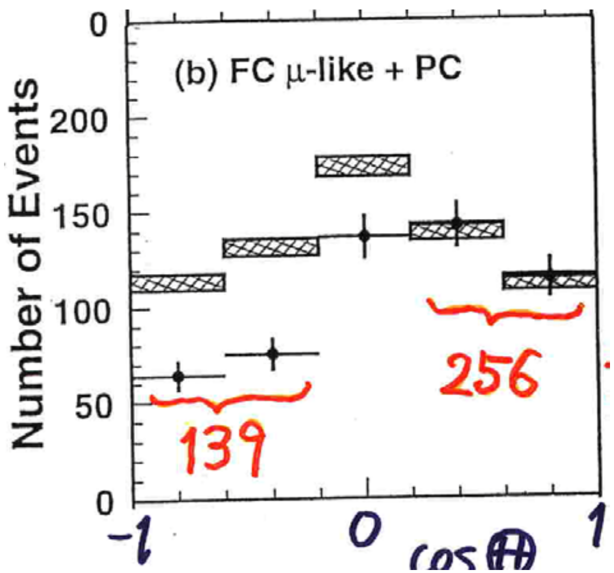
←MINOS / SNO→
(Atmospheric neutrinos)

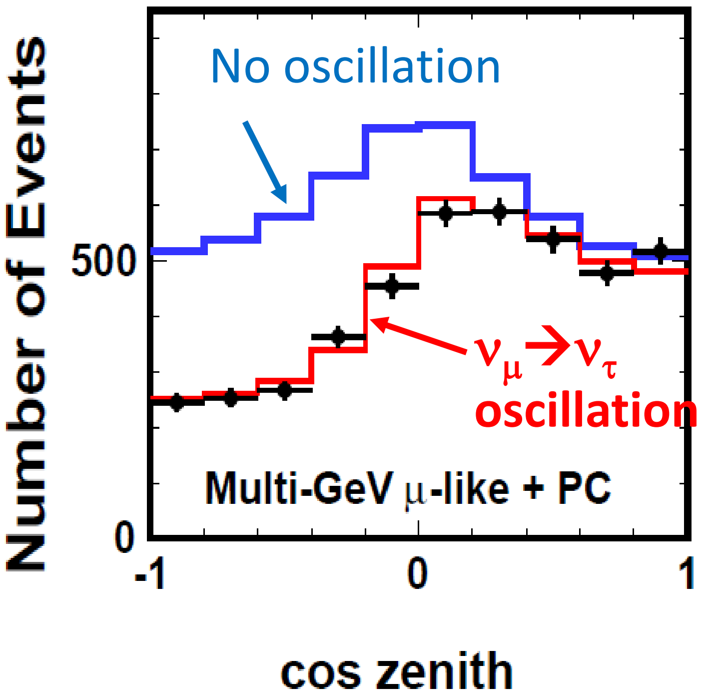


Data updates

Kamiokande (1994) → Super-K @Neutrino98 → Super-K @Neutrino 2012







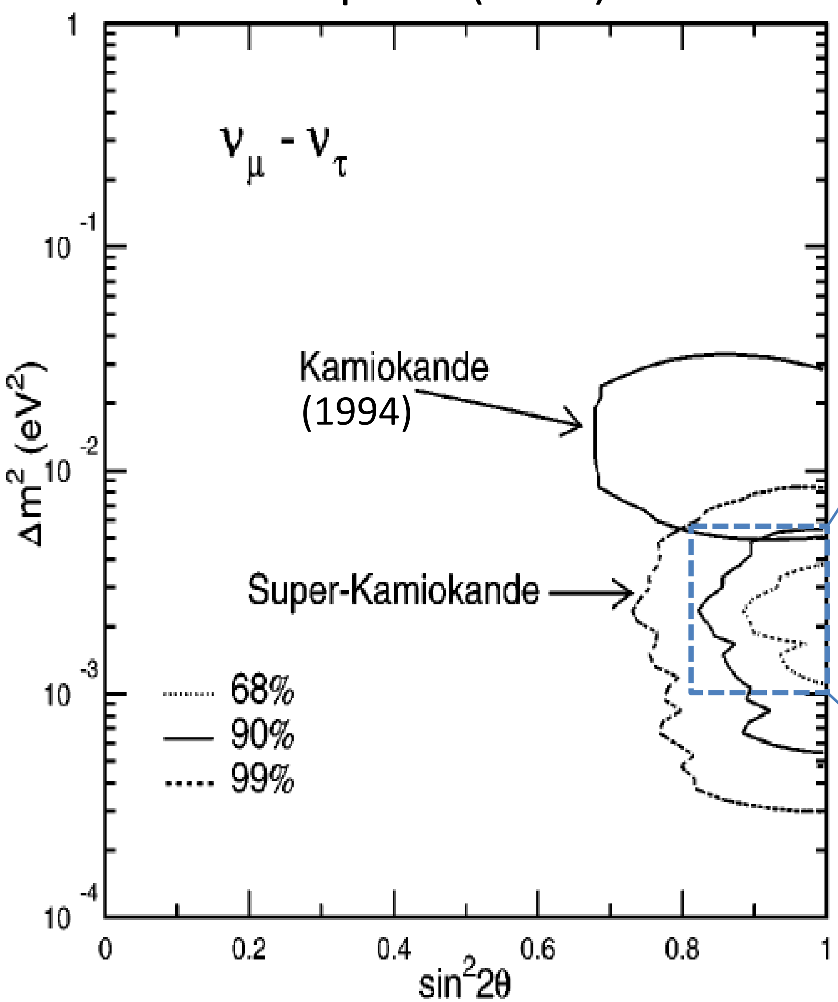
Number of events plotted:

<u>135 events</u> <u>531 events</u> <u>~4276 events</u>

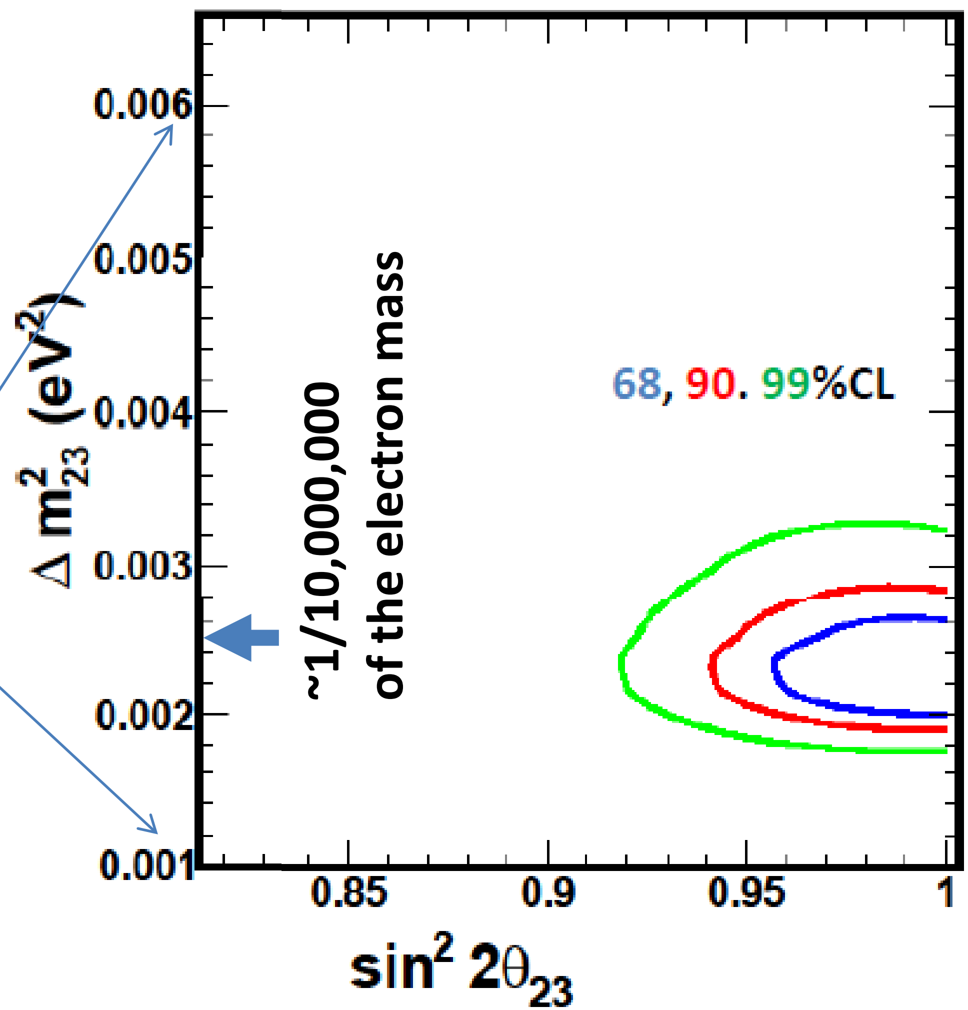
$\nu_\mu \rightarrow \nu_\tau$ allowed parameter region

Y. Itow (SK) nu2012

Super-K (1998)

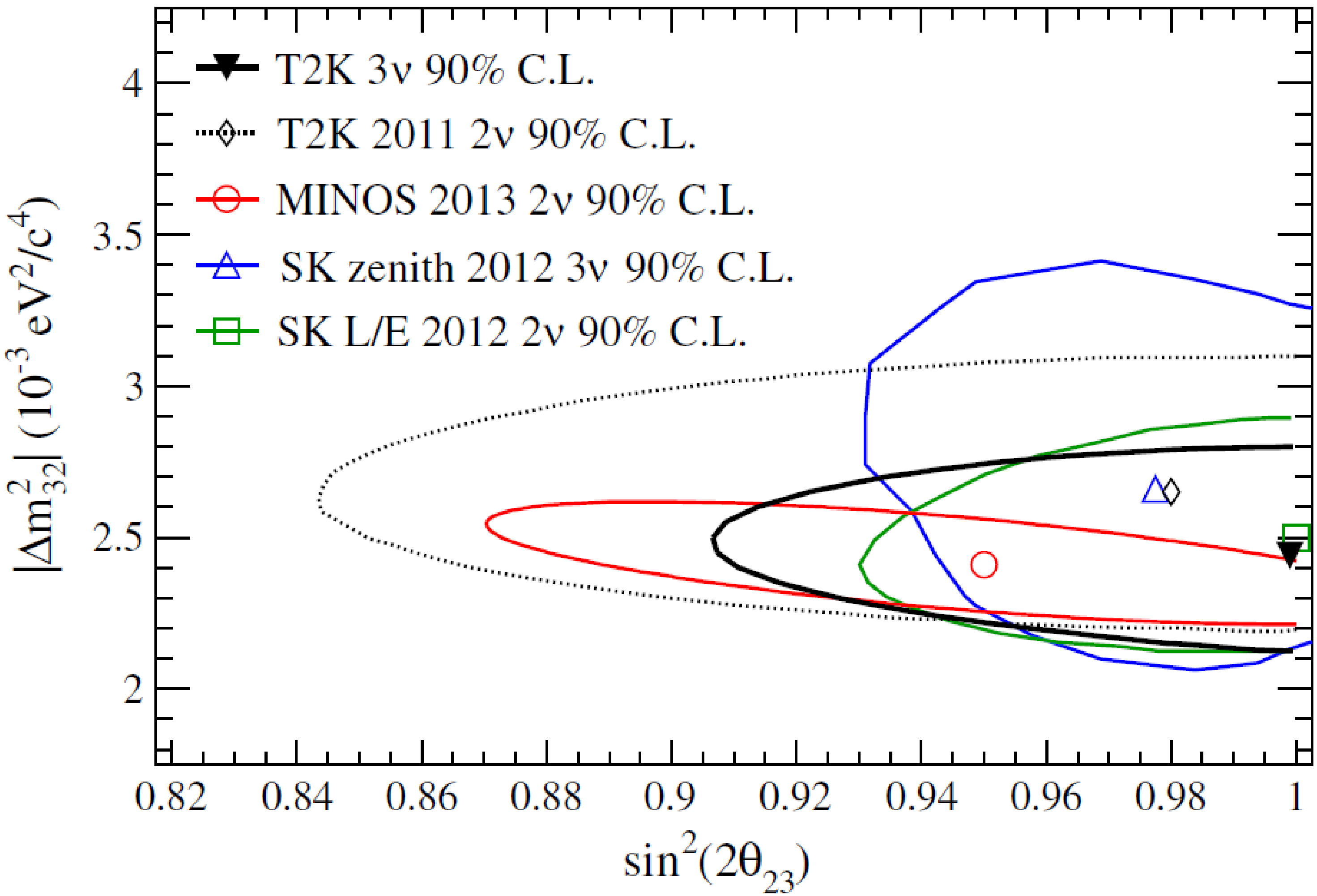


Super-K (2012)



Allowed parameter regions from present experiments

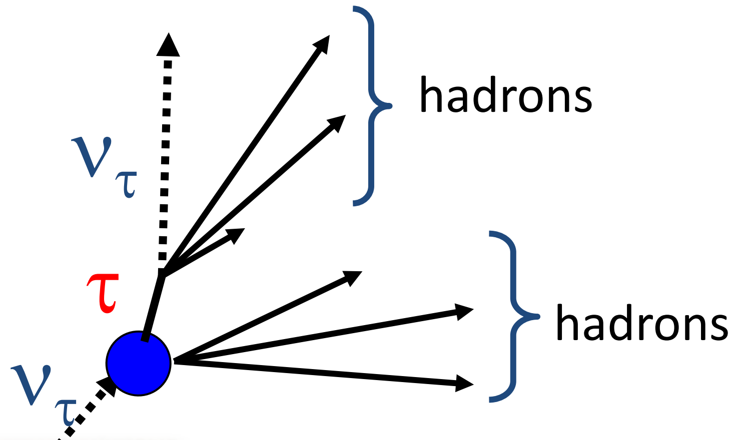
T2K collab. PRL 111, 211803 (2013)

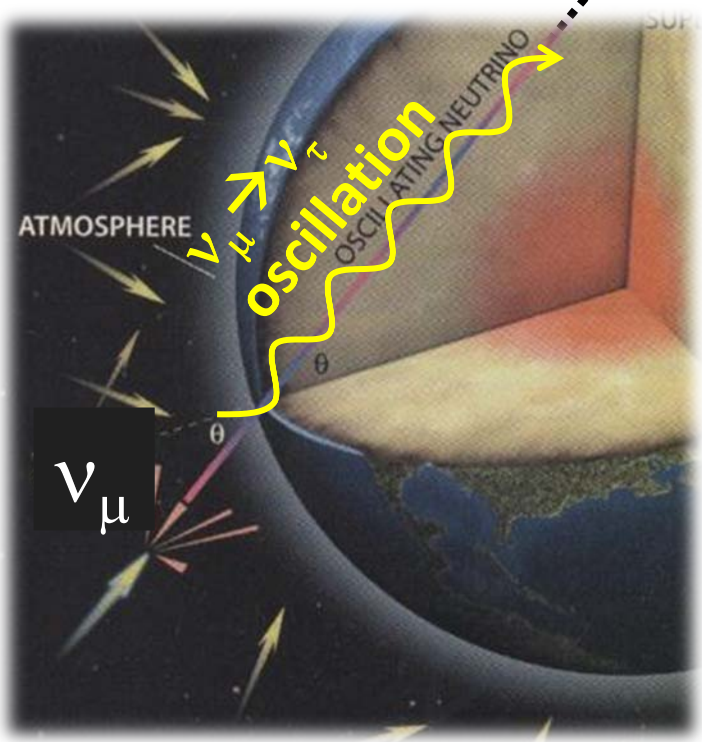


Resent result and a remark on the future

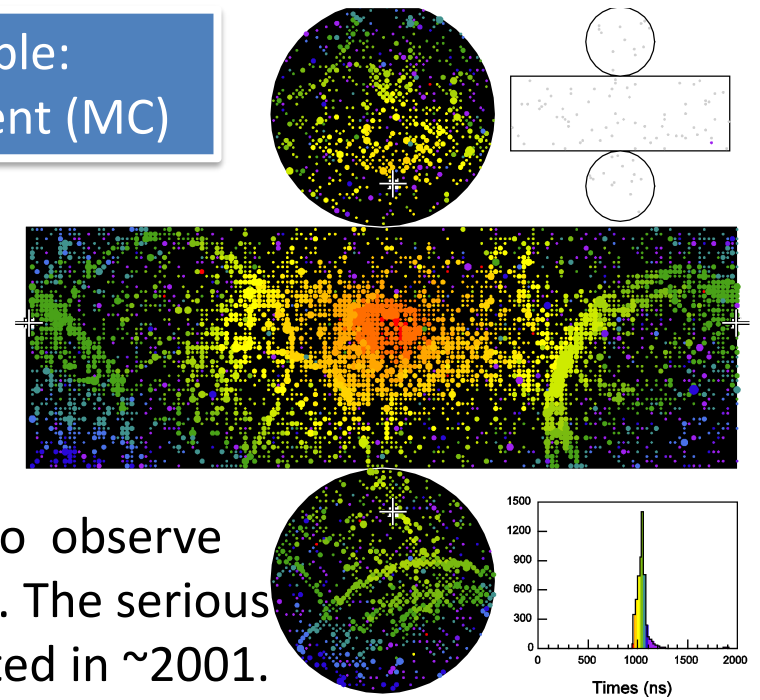
Detecting CC ν_τ events

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





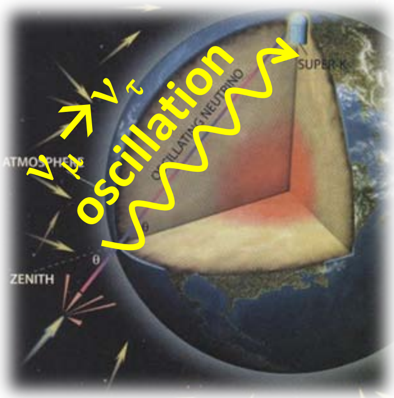
Example:
ν_τ event (MC)

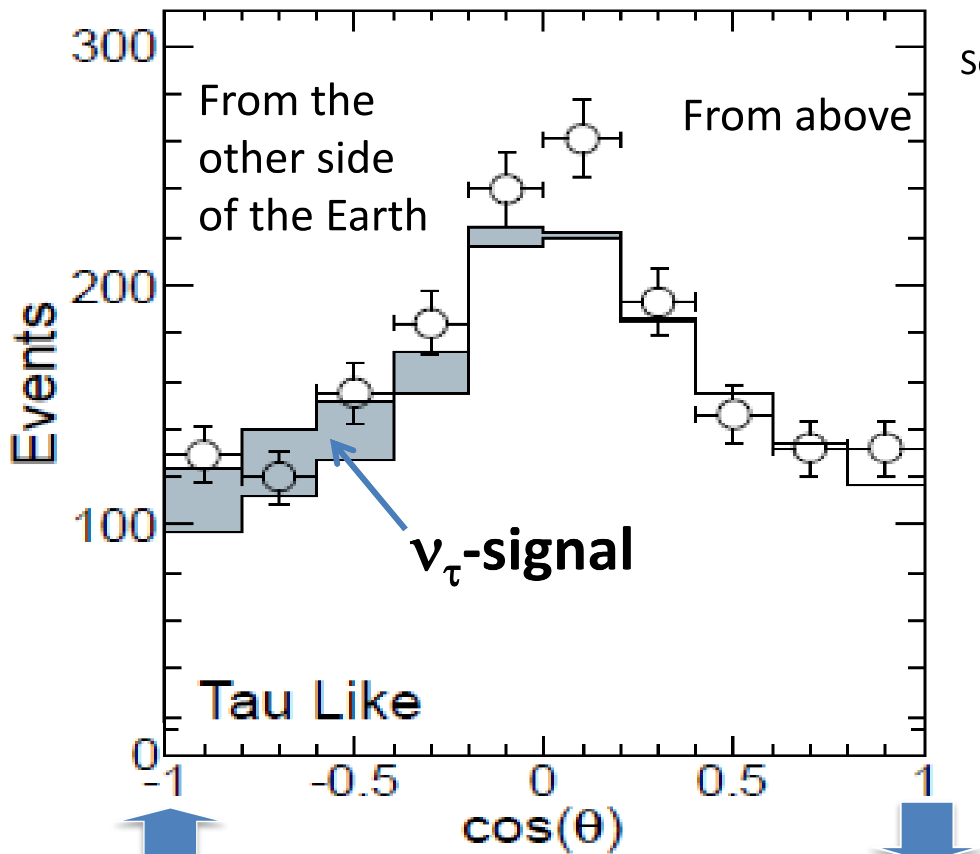


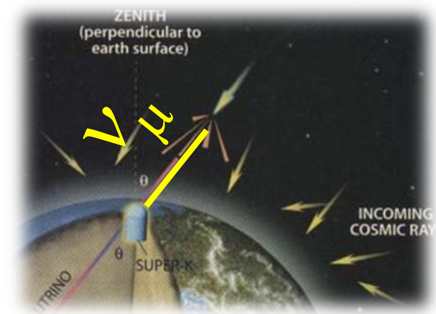
We wanted to observe these events. The serious analysis started in ~2001.

Zenith angle distribution and fit results

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







Up-going

Down-going

τ-appearance signal at 3.8σ

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

Future

- Now we know the values of 3 mixing angles and 2 Δm^2's based on results from various neutrino oscillation experiments.
- However, there are still unknowns of fundamental importance:

✓ Is the 3rd neutrino mass state really the heaviest (or the lightest)? → ➢ Atmospheric neutrinos, Long baseline neutrino oscillation experiments, …

✓ What are the absolute neutrino masses? → ➢ KATRIN, ….

✓ Are neutrinos and anti-neutrinos fundamentally the same particle? → ➢ Double beta experiments, …

✓ Are the oscillation of neutrinos and anti-neutrinos identical? → ➢ Long baseline neutrino oscillation experiments, …

✓ And possibly much more… → ➢ *New idea (Your idea)!*

Summary

- Unexpected muon-neutrino deficit in the atmospheric neutrino flux was observed in Kamiokande "accidentally" (1988).
- After that, Kamiokande and subsequently Super-Kamiokande tried to understand the cause of the deficit.
- I think it was lucky that Super-Kamiokande got a strong evidence for atmospheric neutrino oscillations in only 10 years (1998).
- I feel that I have been extremely lucky, because I have been involved in 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 Grand Unification.
- 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.

Thank you very much for your attention!