









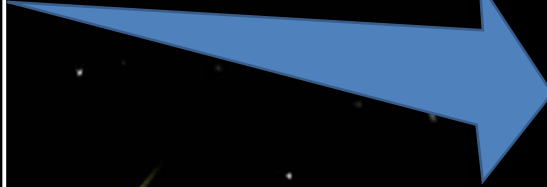
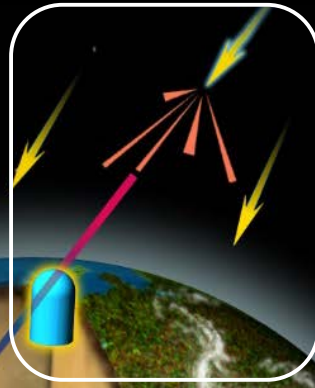




# Atmospheric neutrino deficit

INCOMING  
COSMIC RAYS

Oscillating neutrino



COSMIC  
RAY

AIR  
NUCLEUS

PION

MUON

ELECTRON

2 muon-  
neutrinos

1 electron-  
neutrino

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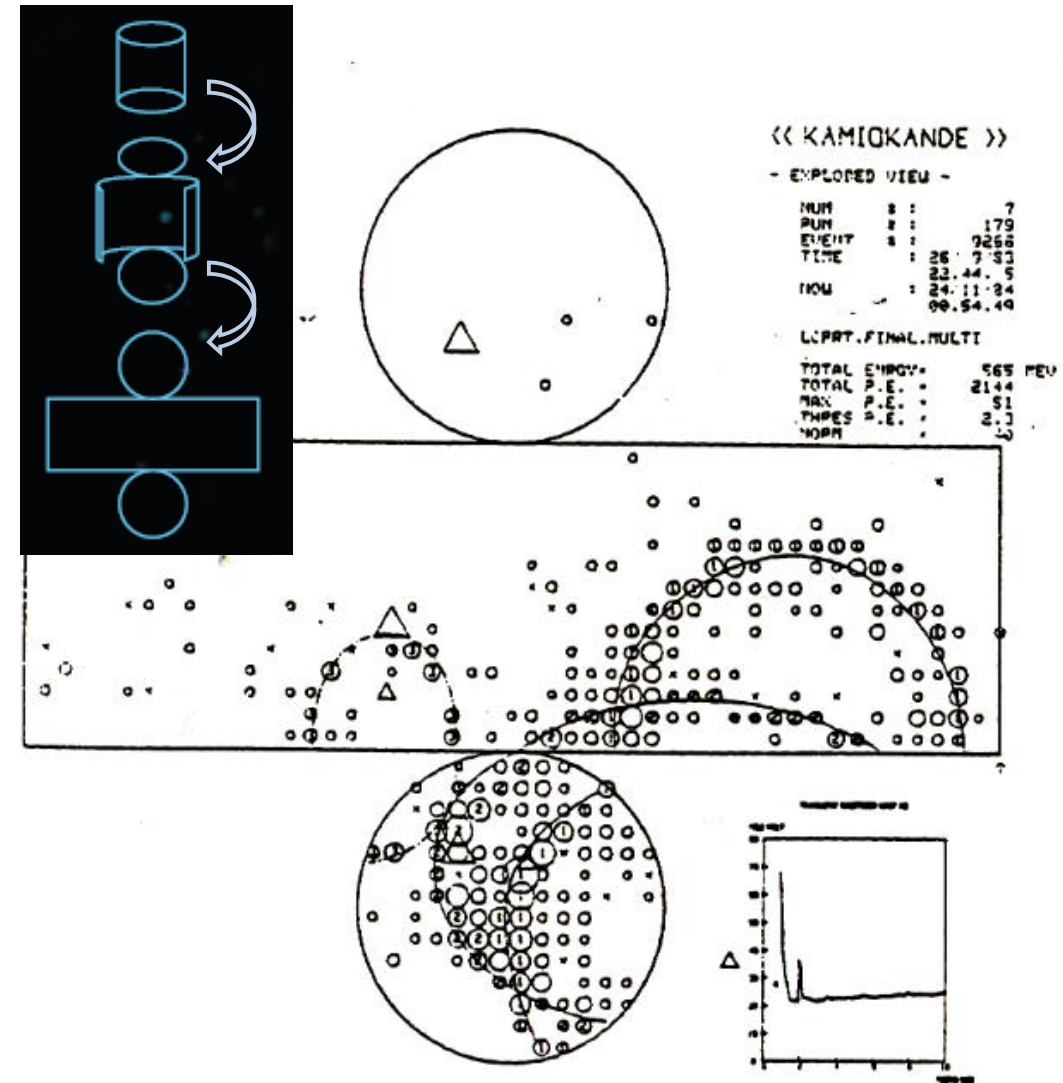
# 1986...

I got my PhD in March 1986 based on a search for proton decay. (I did not find any evidence for proton decay.)

I felt that the analysis software was not good enough to select the signal (proton decays) from the background (atmospheric neutrino interactions) most efficiently. Therefore, as soon as I submitted my thesis, I began to work to improve the software.

One of them was an analysis software to identify the particle type for multi Cherenkov-ring events. Namely, we wanted to know if each Cherenkov ring in a multi-ring event is produced by an electron or a muon.

The new software was applied to single Cherenkov-ring events, which were the easiest events to analyze....



Multi-ring event observed in Kamiokande.

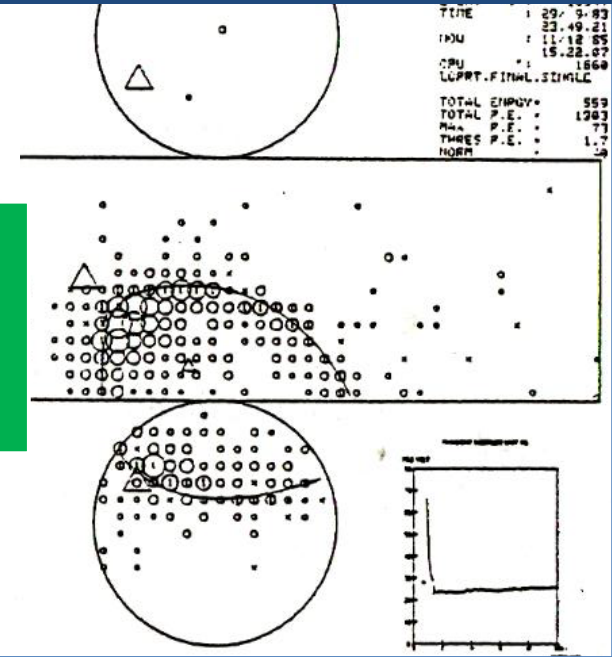


# A strange result...

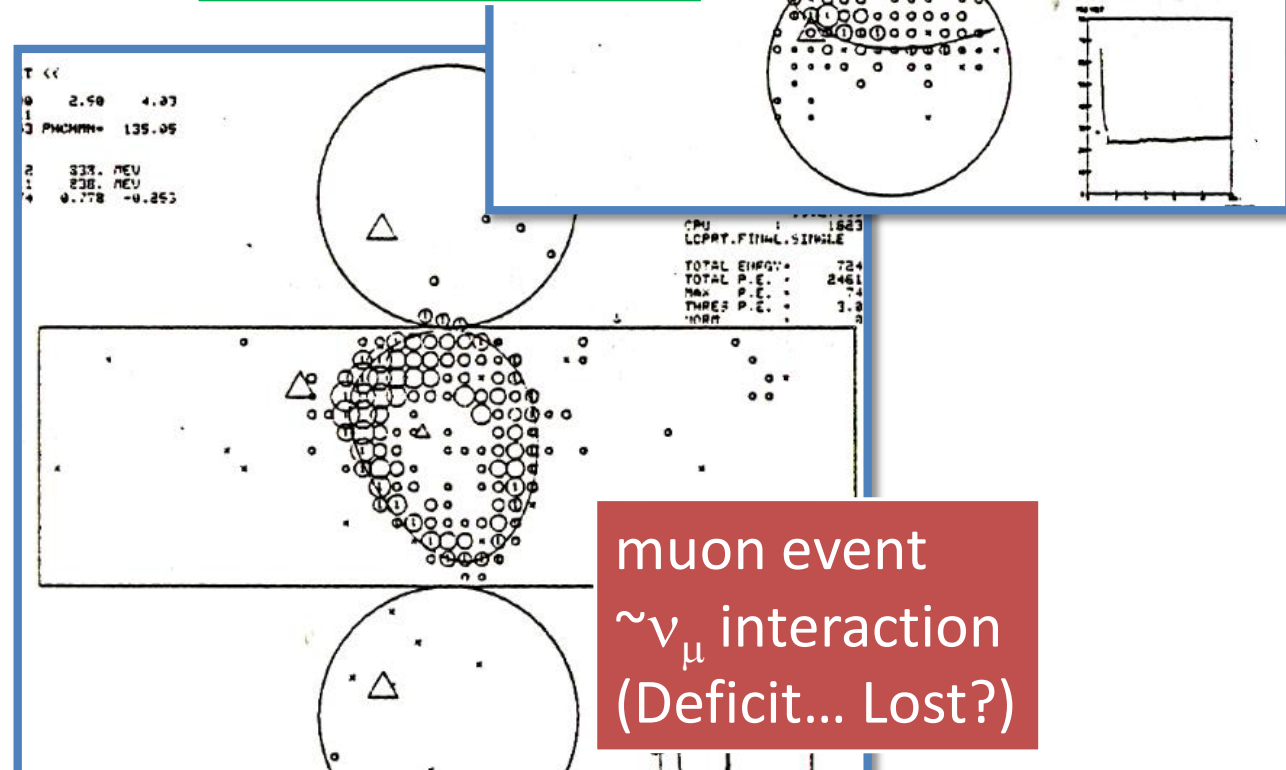
- The neutrino flavor was studied for the atmospheric neutrino events.
- The result was strange. The number of  $\nu_\mu$  events was much fewer than expected.
- At first, I thought that I made some serious mistake.
- In order to know where I made mistake, I decided to scan the real events. Immediately, I realized that the analysis software was right (!).
- I thought that it is very likely that there are some mistakes somewhere in the simulation, data reduction, and/or event reconstruction.
- We, mostly M. Takita and TK, started various studies to find mistakes in the late 1986.

## Kamiokande's single-Cherenkov ring events

electron event  
 $\sim \nu_e$  interaction  
(OK, no problem)



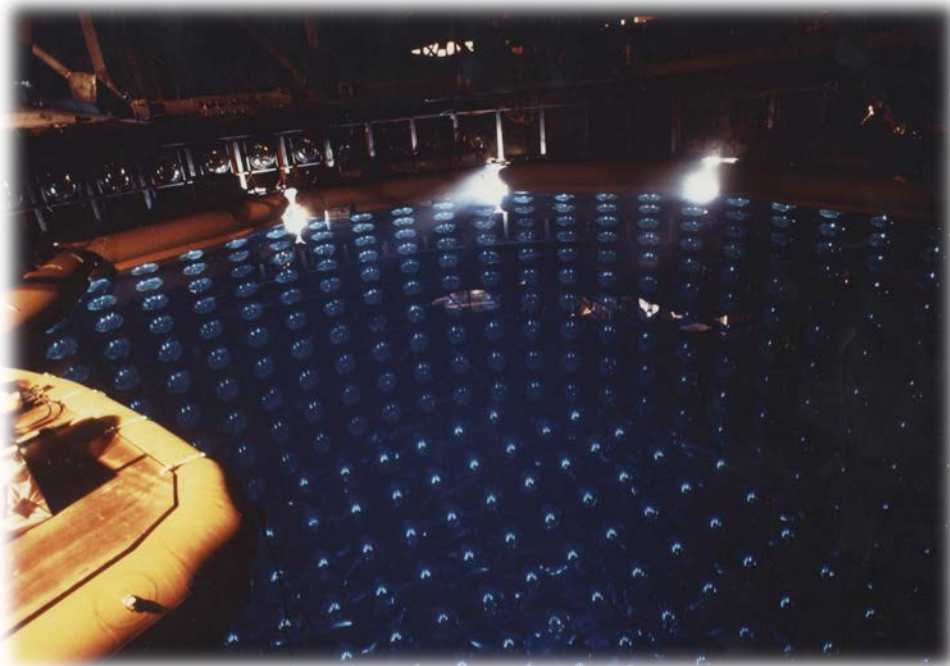
muon event  
 $\sim \nu_\mu$  interaction  
(Deficit... Lost?)



# Result on the $\nu_\mu$ deficit (1988)

After more than one year of studies, we concluded that the  $\nu_\mu$  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.



Kamiokande

	Data	Prediction
$\nu_e$ events	93	88.5
$\nu_\mu$ events	85	144.0

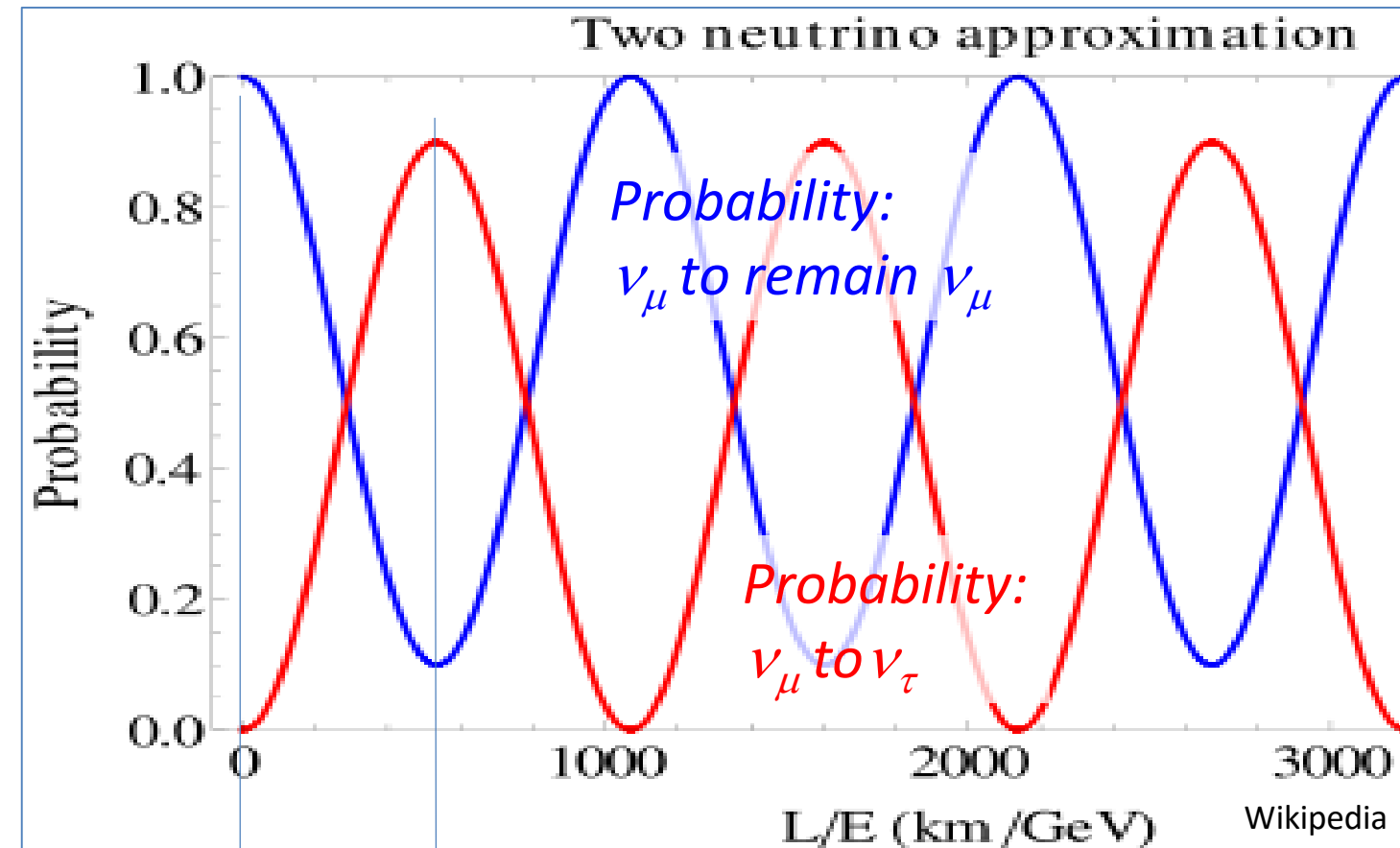
Paper conclusion: “We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics **such as neutrino oscillations might explain the data.**”

My personal memory:

I was most excited with the possibility of neutrino oscillations with large mixing angle. Namely,  $\nu_\mu$  seemed to oscillate maximally to the other neutrino type, which was not expected. This gave me the strong motivation to continue the study.

# Neutrino oscillations

If neutrinos have masses, neutrinos change their flavor (type) from one flavor (type) to the other. For example, oscillations could occur between  $\nu_\mu$  and  $\nu_\tau$ .



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.



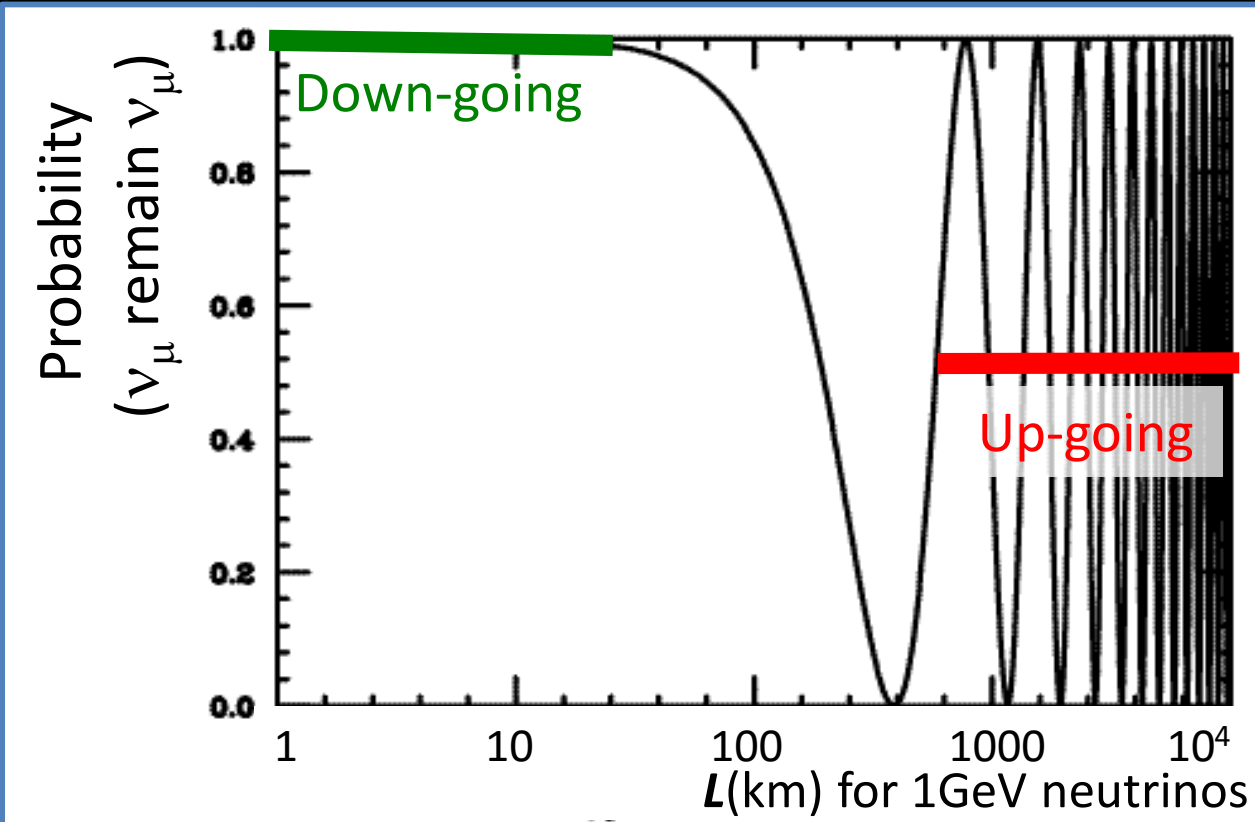
# Results from IMB on the $\nu_\mu$ deficit



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

IMB experiment, which was another large water Cherenkov detector, also reported the deficit of  $\nu_\mu$  events.

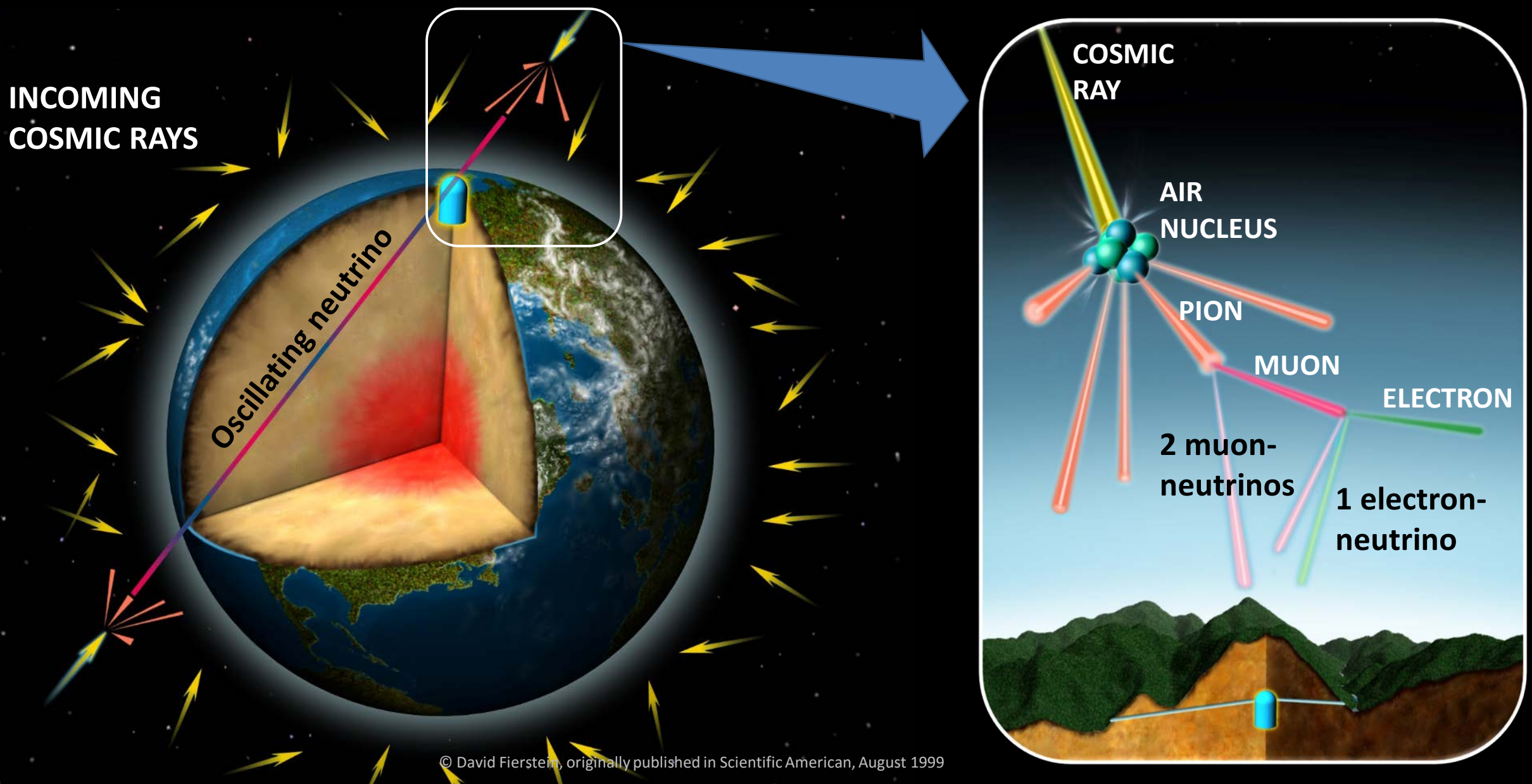
# What will happen if the $\nu_\mu$ deficit is due to neutrino oscillations



We should observe a deficit of upward going  $\nu_\mu$ 's!  
We needed much larger detector. → Super-Kamiokande

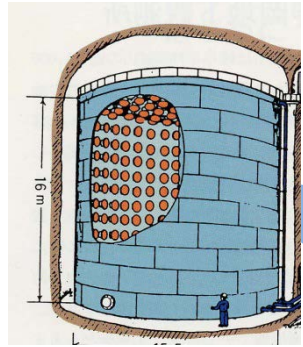


# Discovery of neutrino oscillations



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# Super-Kamiokande detector

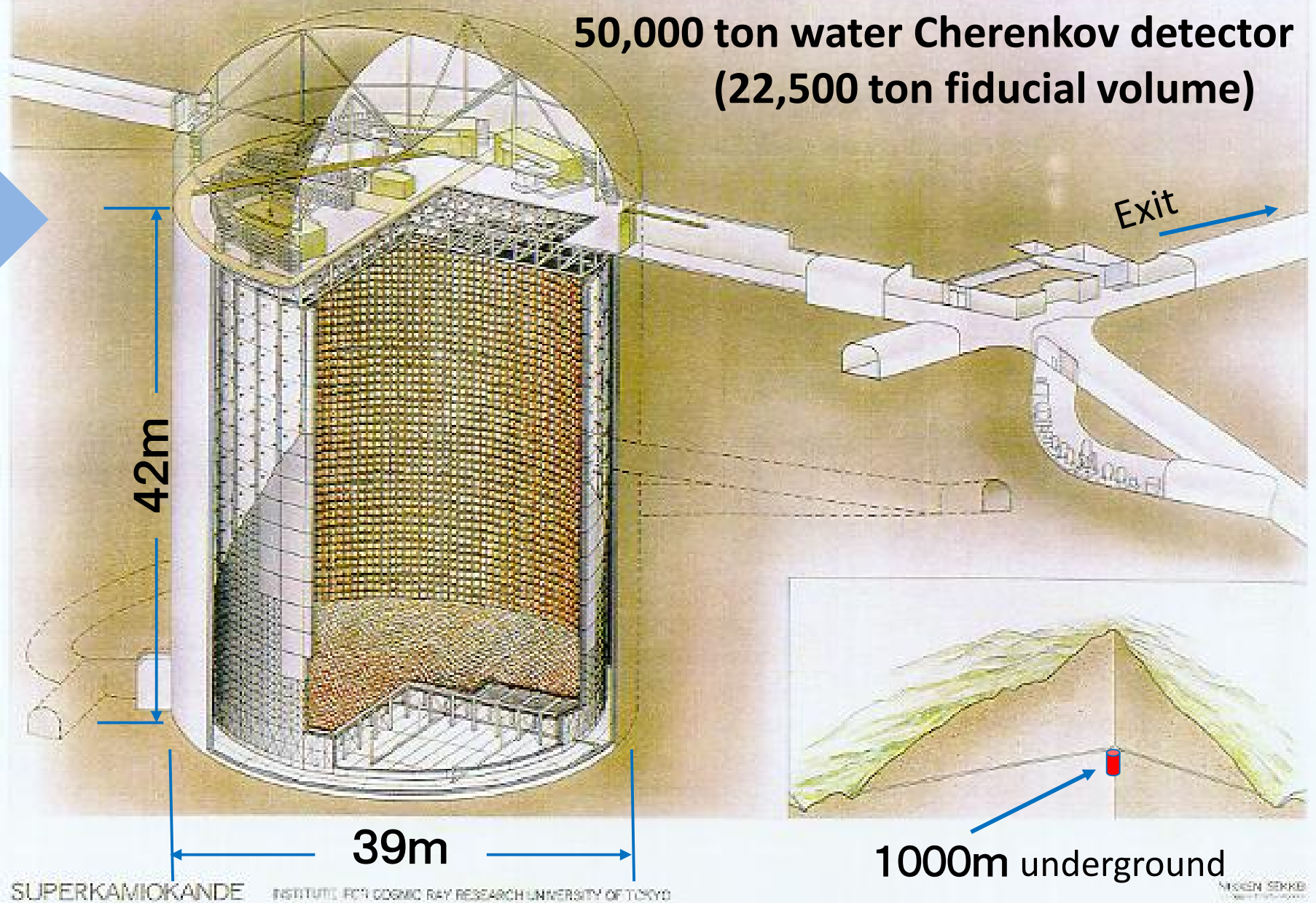


More than 20 times larger mass

~120 collaborators from:



(based on the 2015 papers)





# *Beginning of the Super-Kamiokande collaboration between Japan and USA*

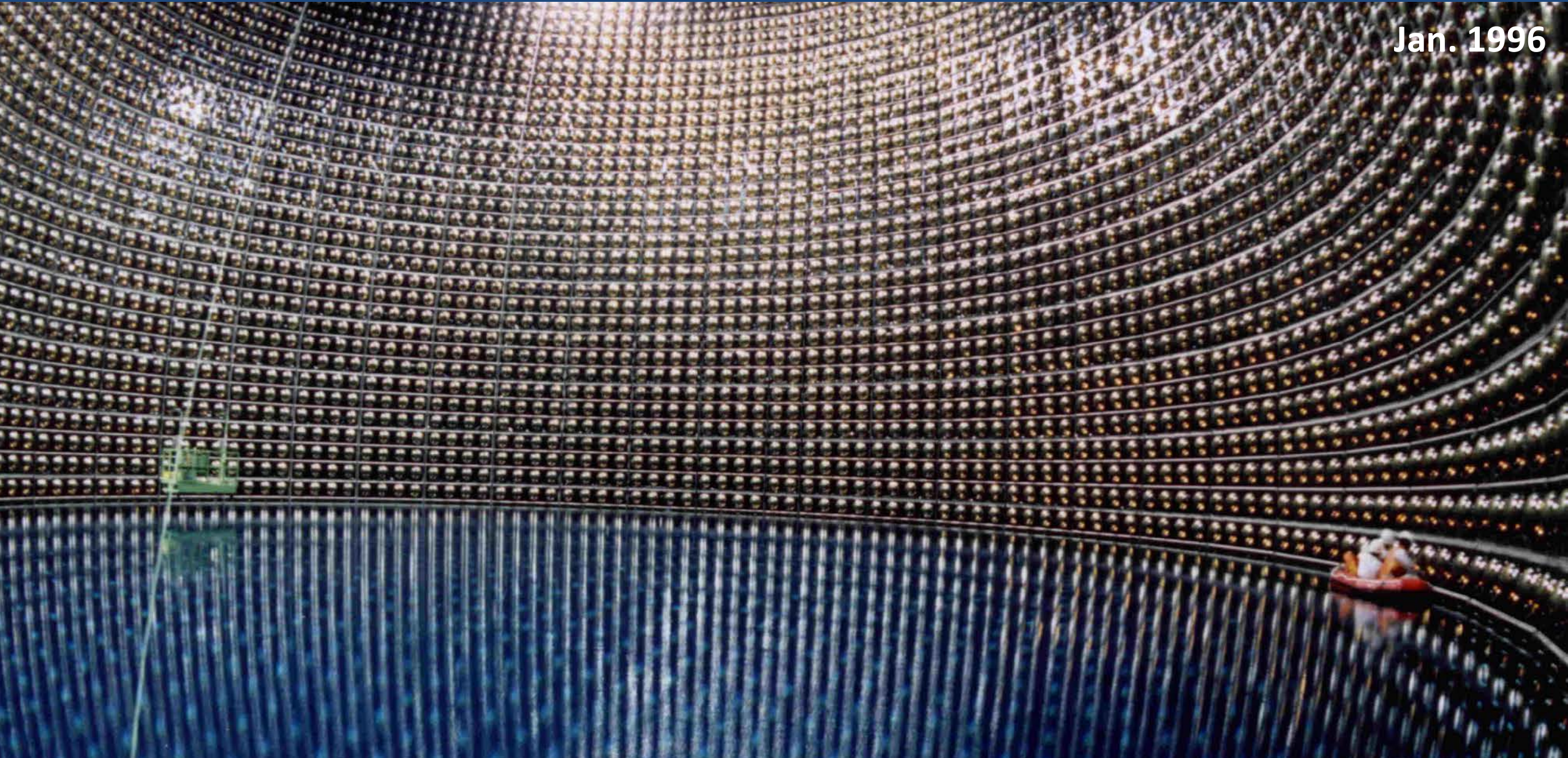


@ Institute for  
Cosmic Ray  
Research,  
(Probably) 1991  
or 1992



# Filling water in Super-Kamiokande

Jan. 1996

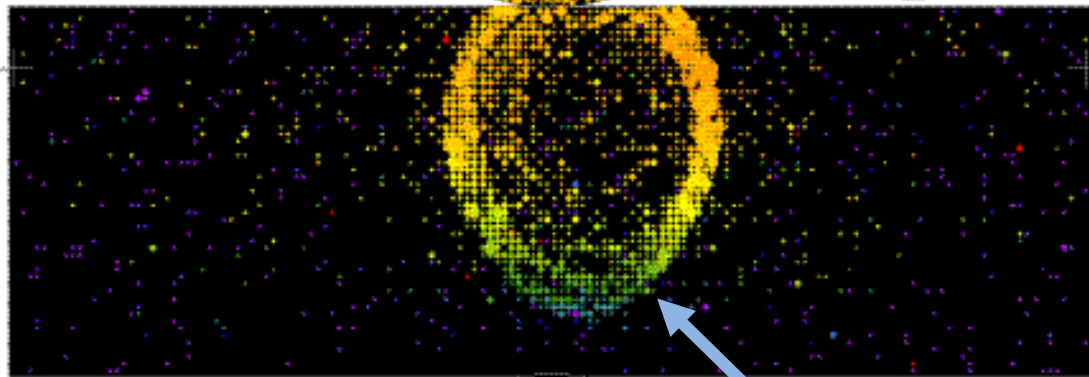
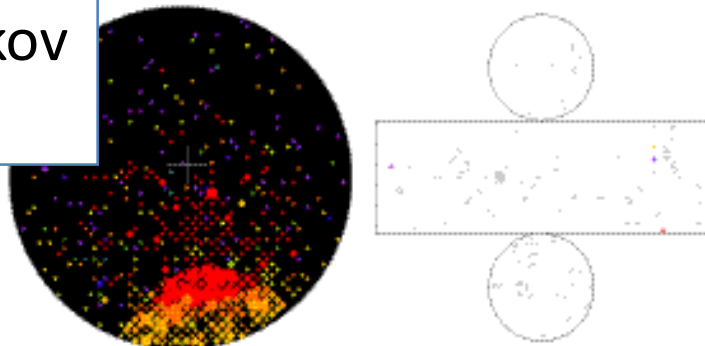




# Atmospheric neutrino events observed in Super-K (1)

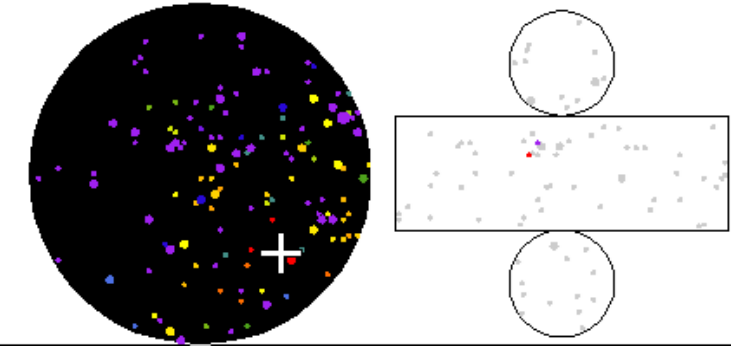
Single Cherenkov ring event

602  
cm  
1.058 ± 0.197/c



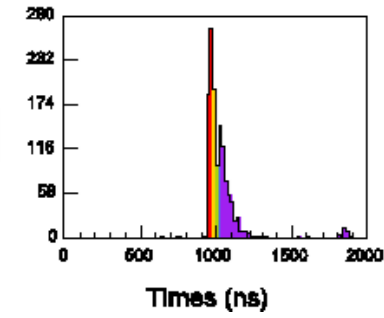
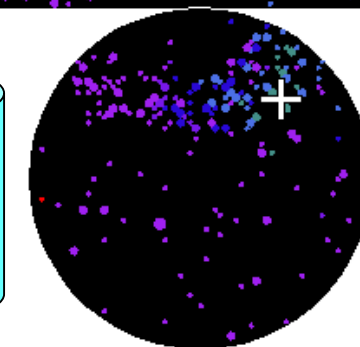
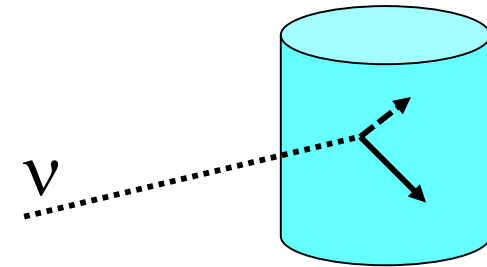
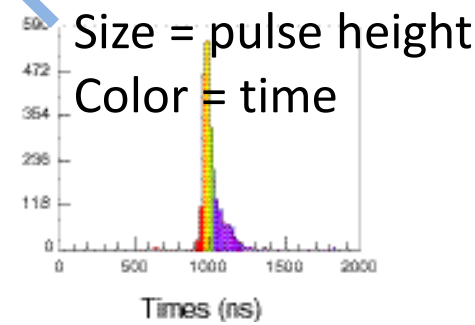
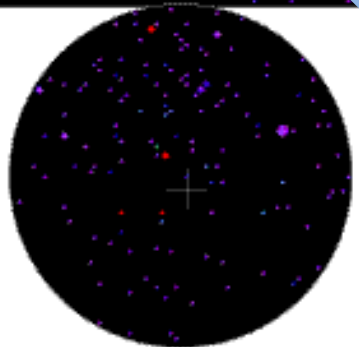
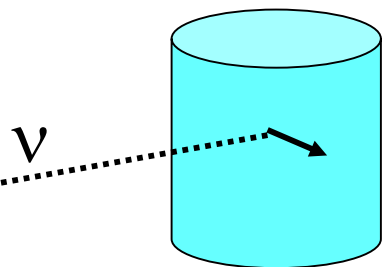
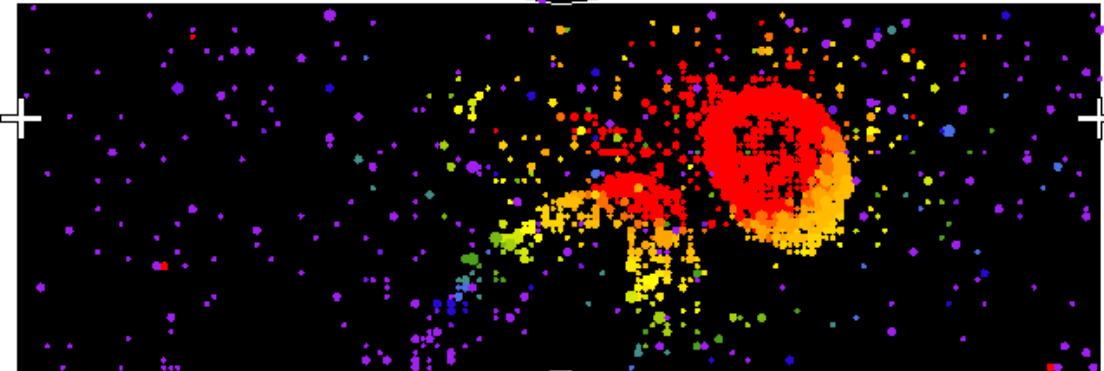
Multi Cherenkov ring event

Trigger ID: 0M05  
D wall: 576.3 cm  
Fully-Contained



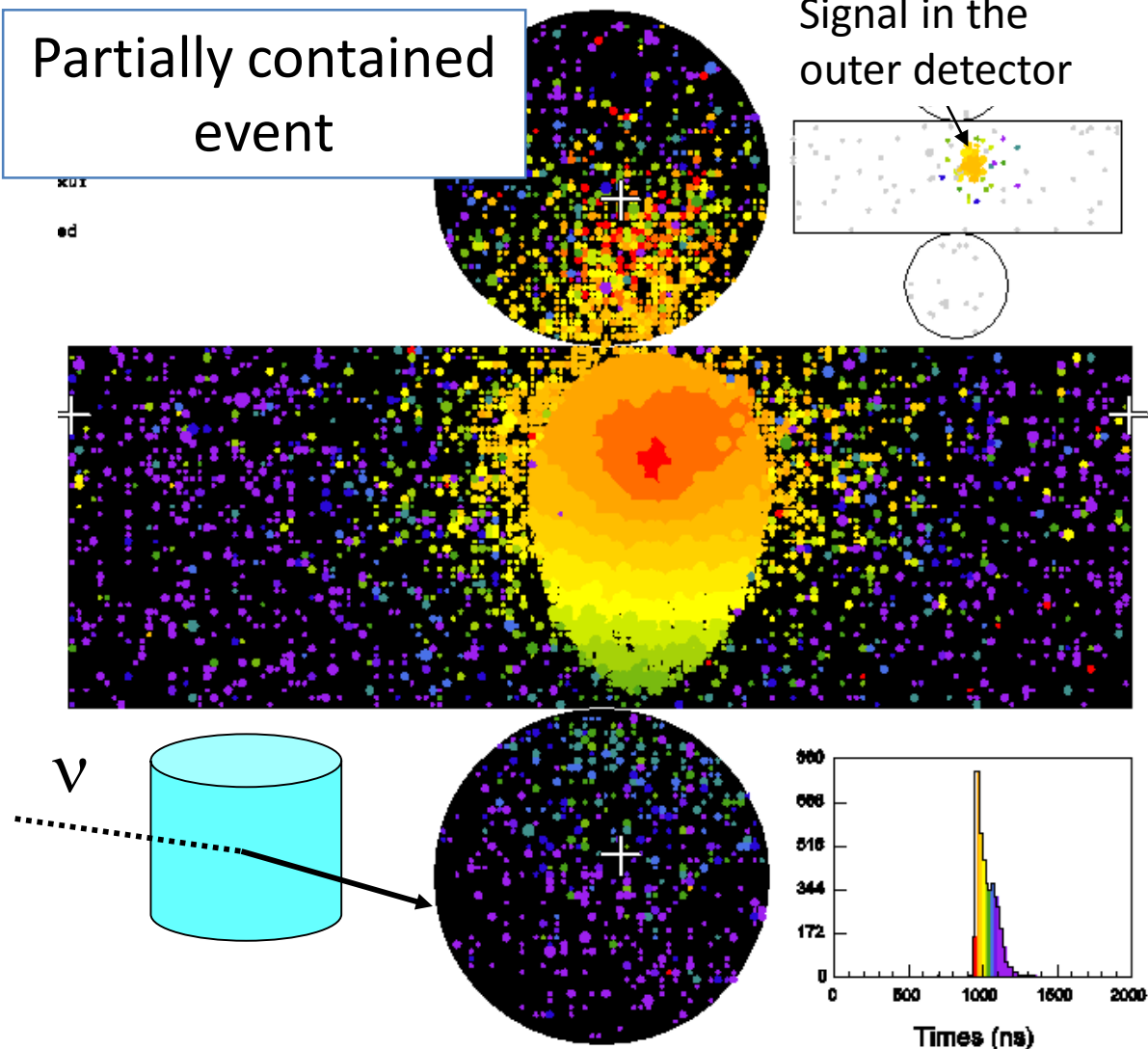
Time (ns)

- ★ < 976
- ★ 976- 981
- ★ 981- 986
- ★ 986- 991
- ★ 991- 996
- ★ 996-1001
- ★ 1001-1006
- ★ 1006-1011
- ★ 1011-1016
- ★ 1016-1021
- ★ 1021-1026
- ★ 1026-1031
- ★ 1031-1036
- ★ 1036-1041
- ★ 1041-1046
- ★ >1046

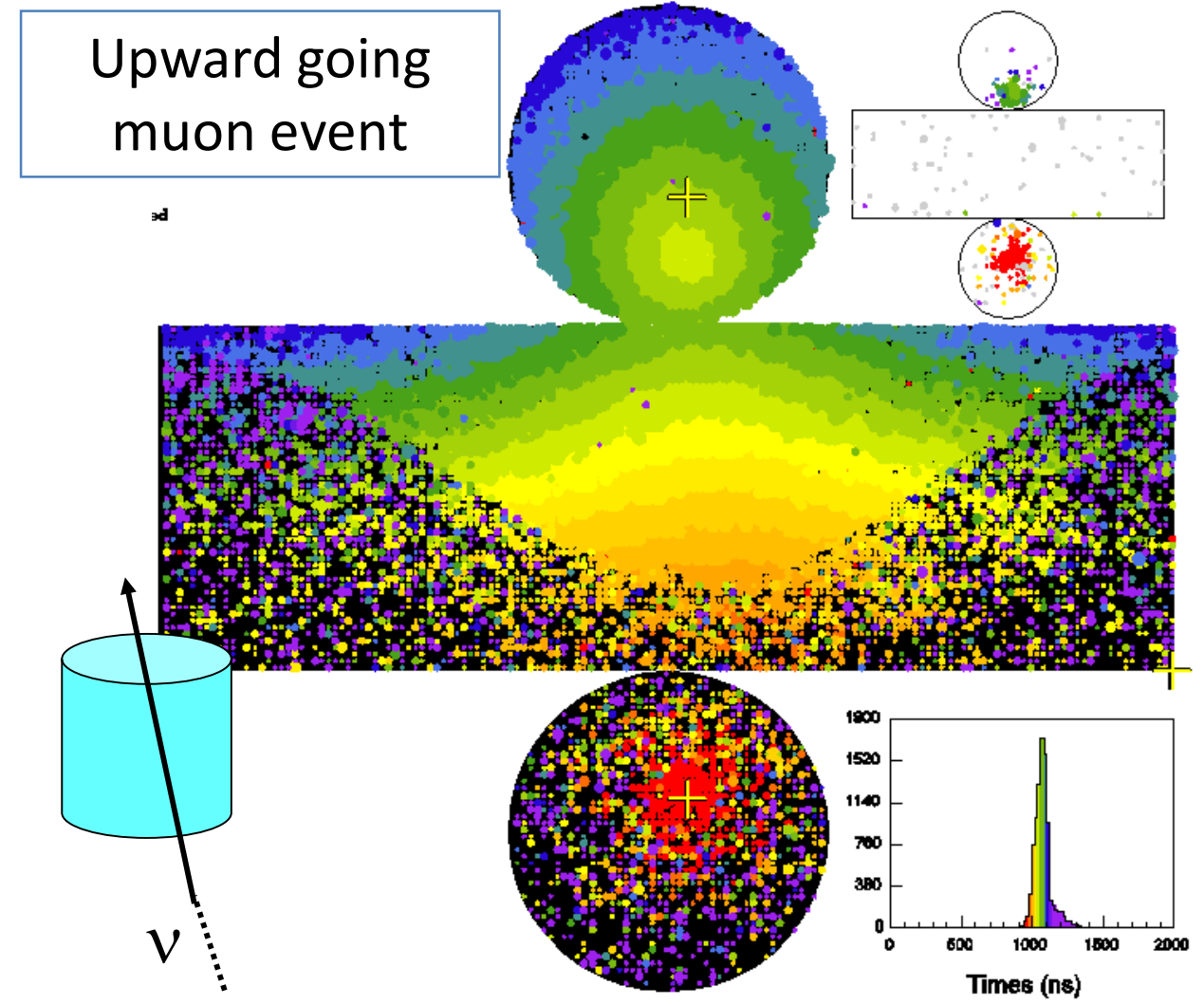


# Atmospheric neutrino events observed in Super-K (2)

Partially contained event



Upward going muon event

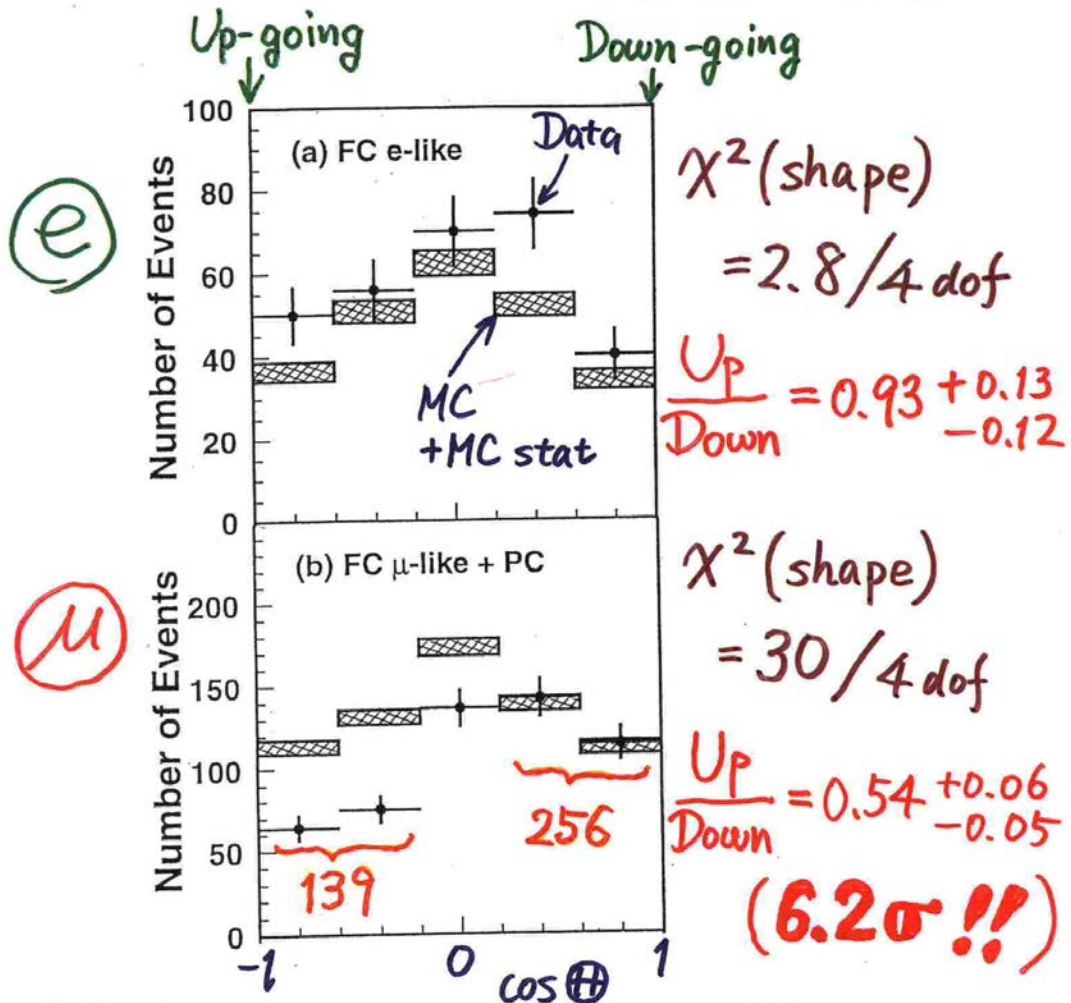


All these events are used in the analysis. ← ***Collaborative work of many (young) people!***

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

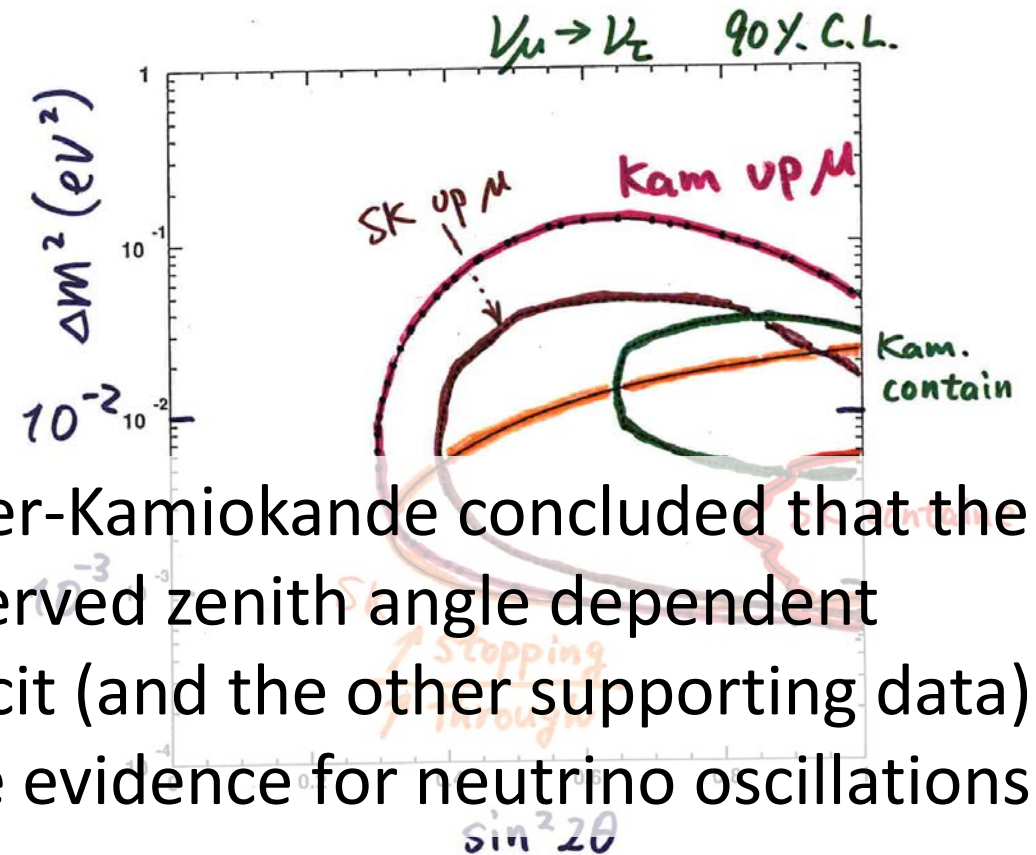
Y. Fukuda et al., PRL 81 (1998) 1562

## Zenith angle dependence (Multi-GeV)



## Summary

### Evidence for $\nu_\mu$ oscillations

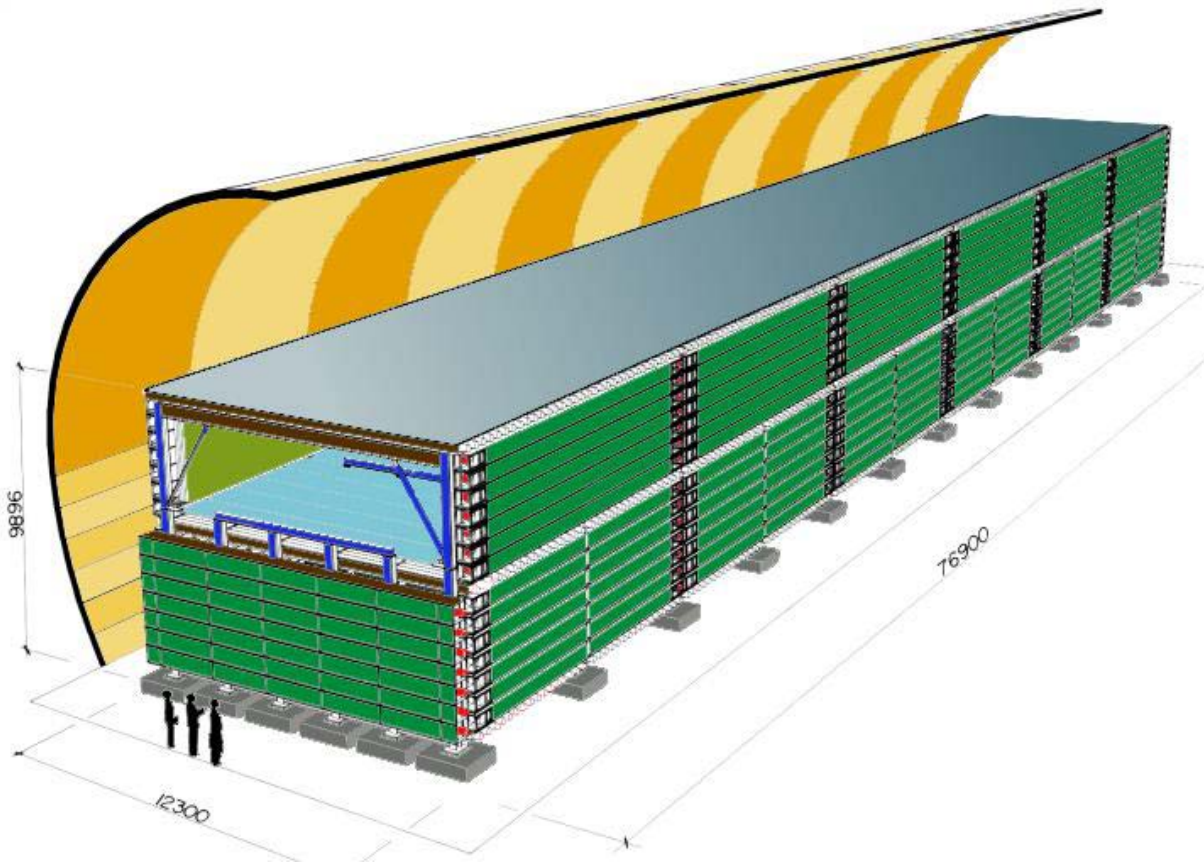


Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.



# Results from the other atmospheric neutrino experiments

MACRO



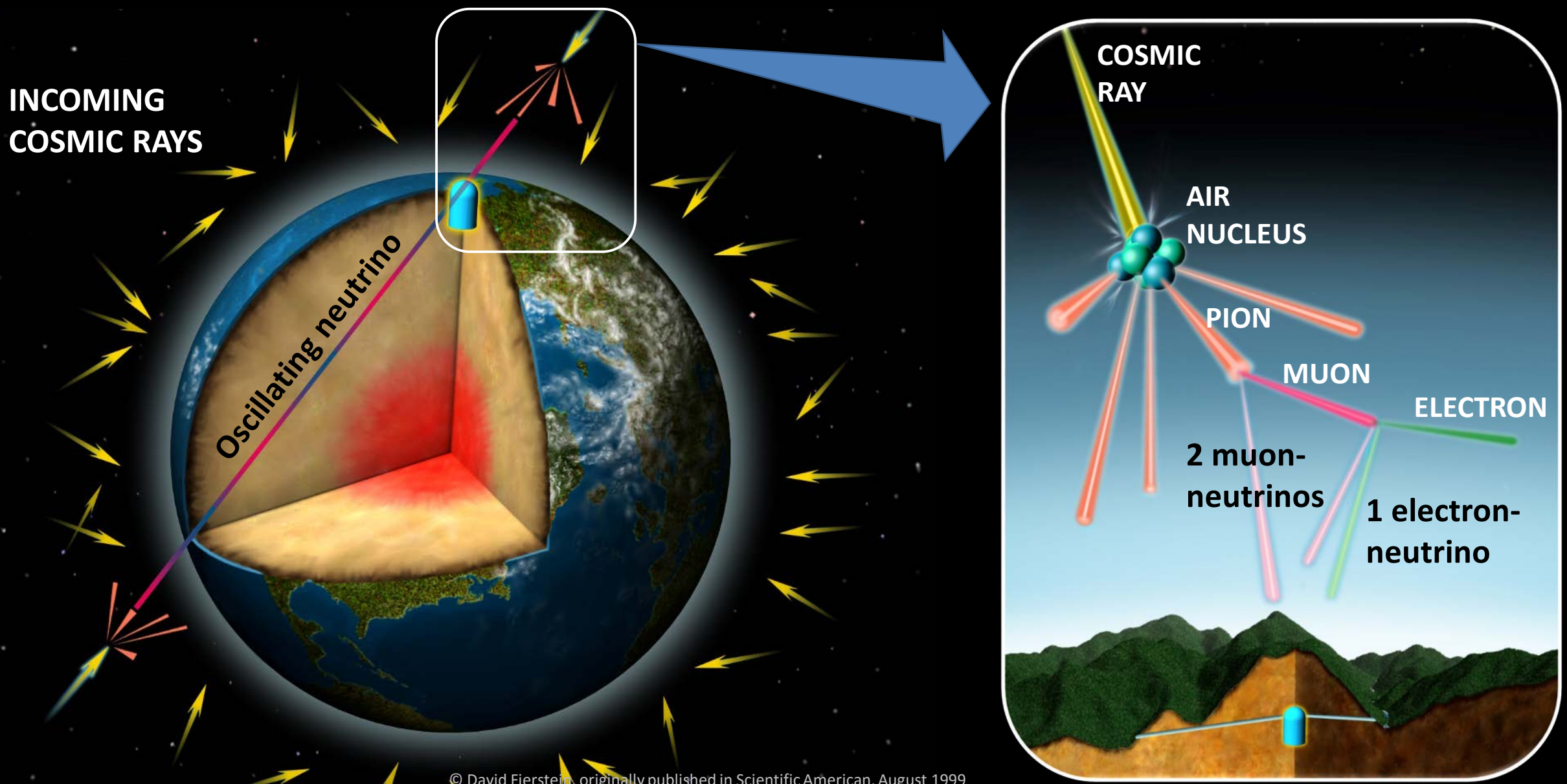
Soudan-2



These experiments observed atmospheric neutrinos and confirmed neutrino oscillations.

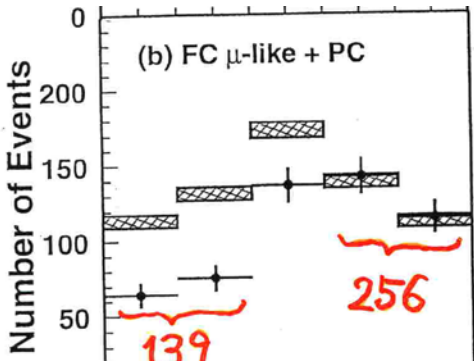


# Recent results and the future

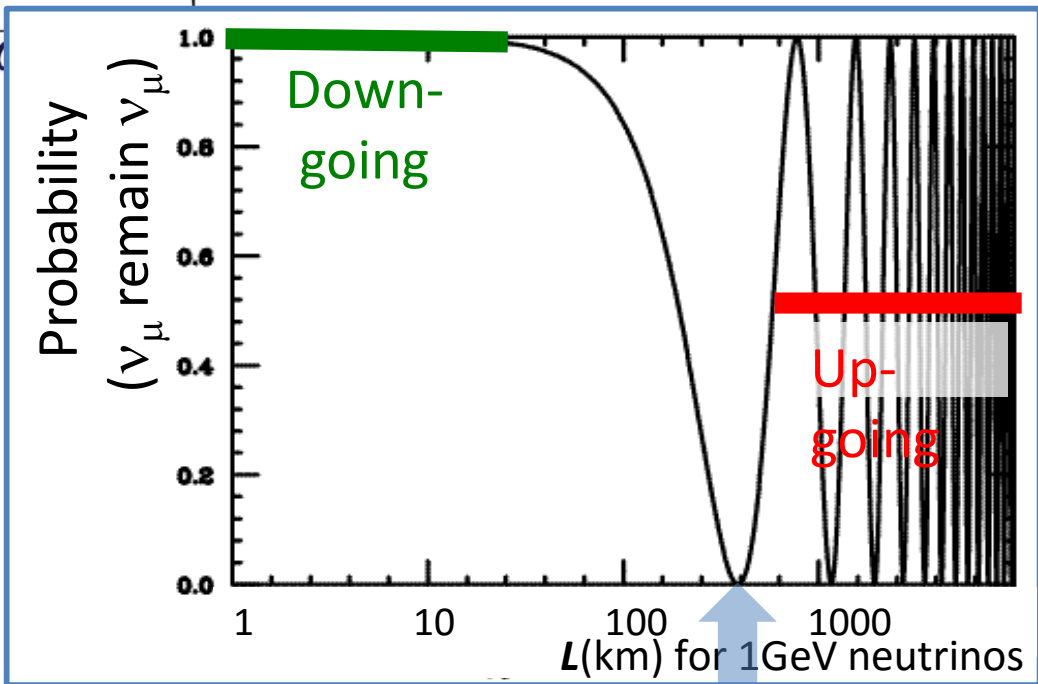


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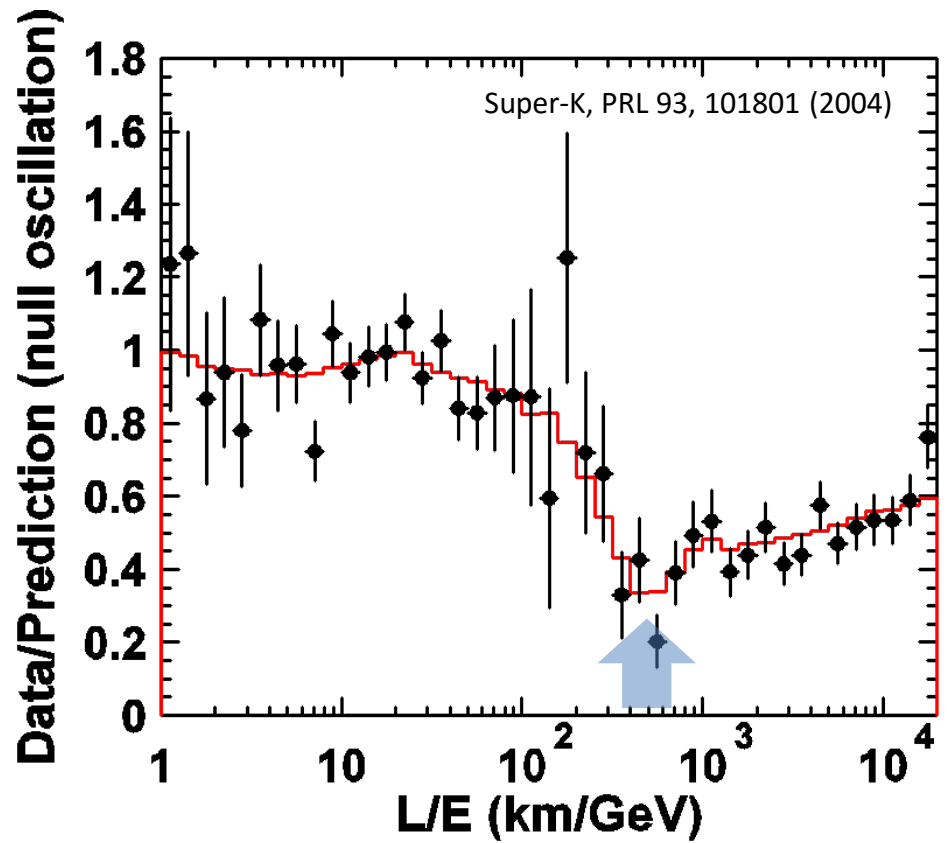
# Really oscillations



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



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

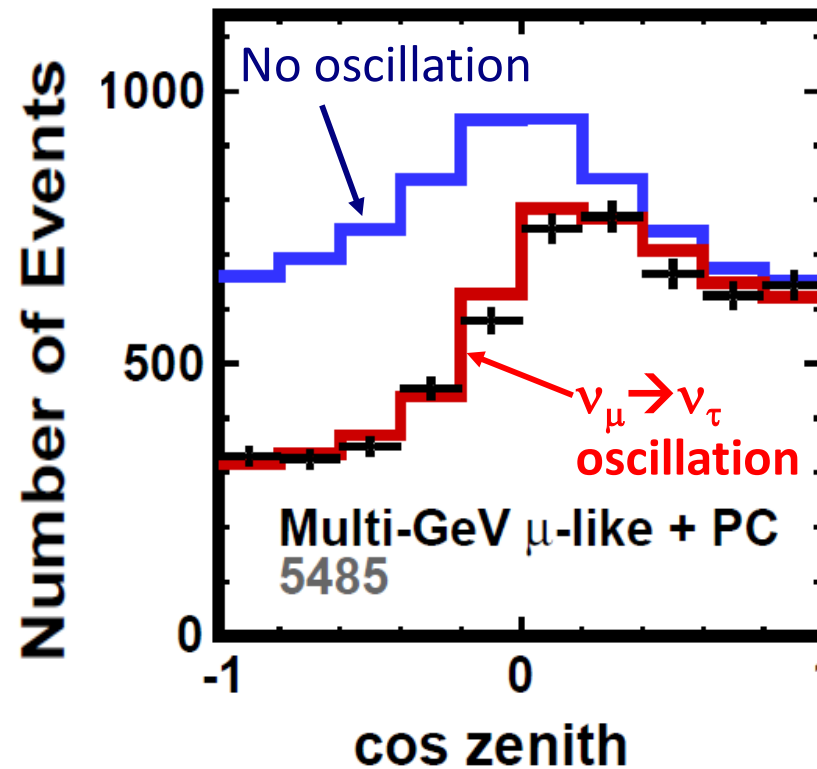
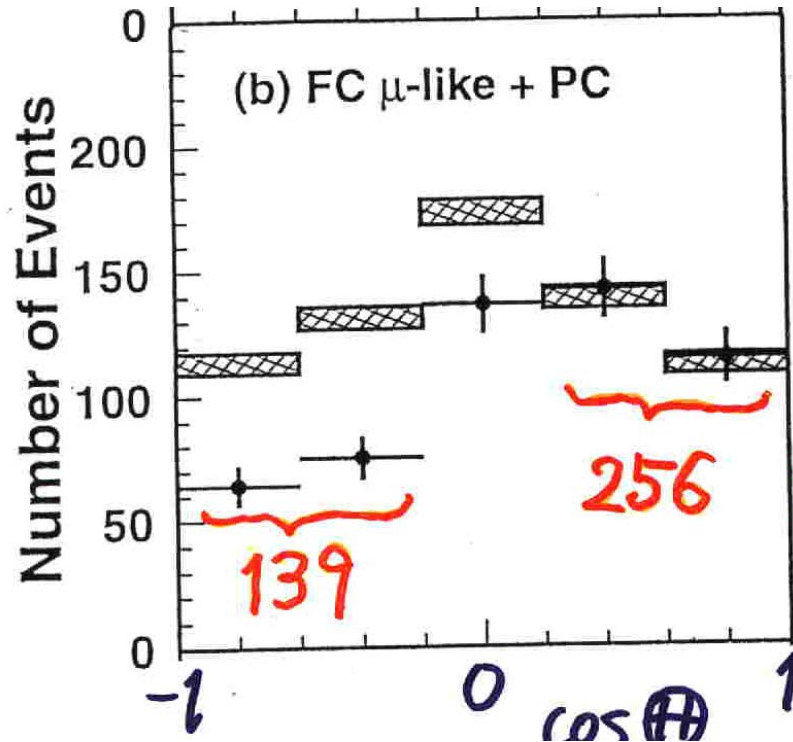


A dip is seen around  $L/E = 500$  km/GeV.  
→ Really oscillations (2004) !!

# Data updates and neutrino masses and mixing angles

Super-K @Neutrino98

Super-K (2015)



Number of events plotted:

531 events

5485 events

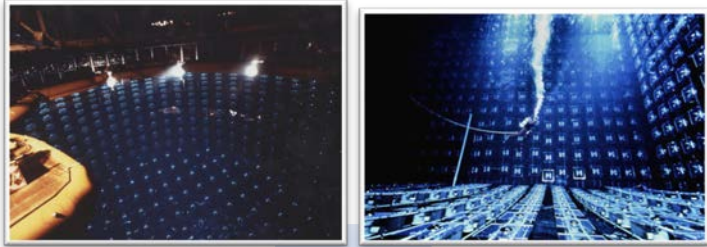
These data tell us;

1. Heaviest neutrino mass is approximately **10,000,000 times smaller** than the electron mass (which is the lightest particle except for neutrinos).
2.  **$\nu_\mu$ 's oscillate maximally to  $\nu_\tau$ 's**, which is really surprising. We want to understand why.

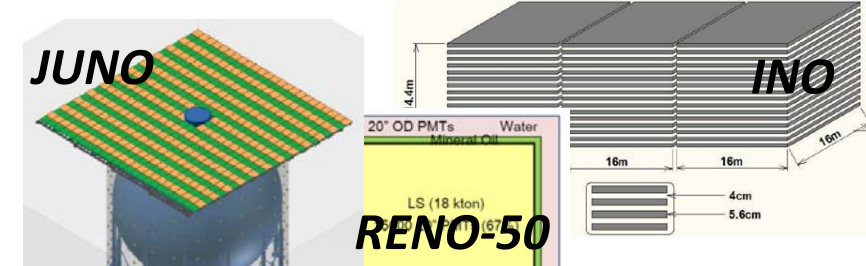
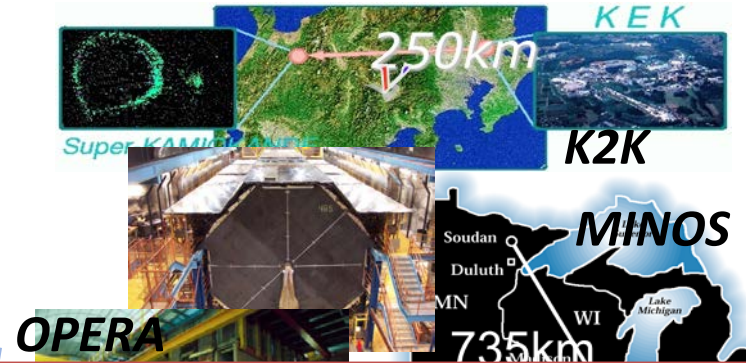


# Neutrino oscillation experiments: Past, Present and Future

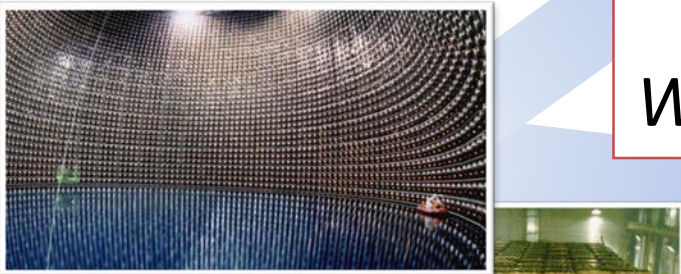
“Atmospheric  $\nu_\mu$  deficit”  
(around 1990)



“Long-baseline neutrino oscillation experiments” (~2000’s)

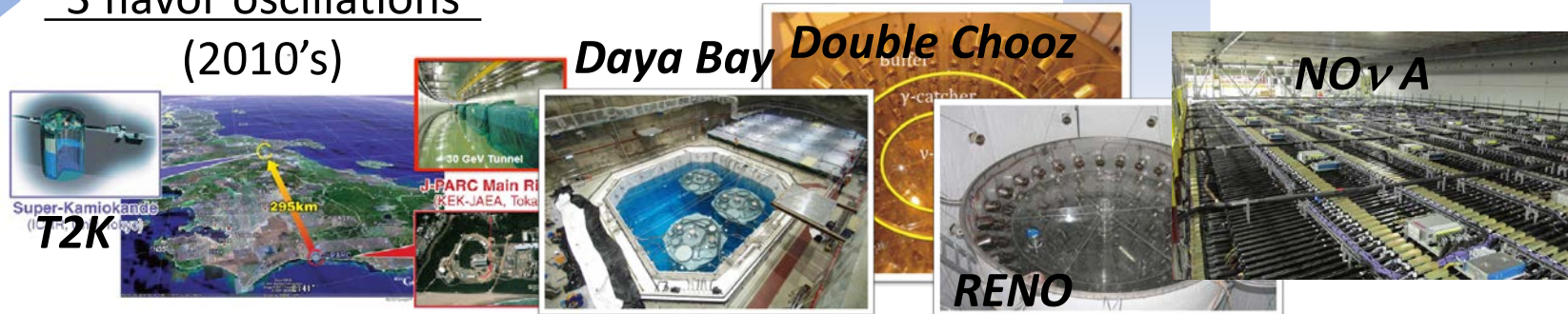


“Discovery of neutrino oscillations” (1990’s)

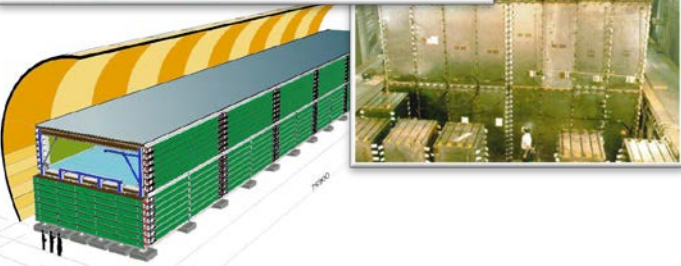


*Our understanding on neutrino oscillations have been improving tremendously!  
We still have to understand neutrinos more!*

“3 flavor oscillations”  
(2010’s)



“future oscillation experiments”  
(2020’s ?)



(These are not the complete list. Sorry... For the solar neutrino part, please see the presentation by Prof. Art McDonald.)

# Summary

- Unexpected muon-neutrino deficit in the atmospheric neutrino flux was observed in Kamiokande (1988).
- Subsequently, in 1998, Super-Kamiokande **discovered neutrino oscillations, which shows that neutrinos have mass.**
- 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 beyond the Standard Model of elementary particle physics, 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.



# Acknowledgements

I would like to thank collaborators of the Kamiokande and Super-Kamiokande experiments. In particular, I would like to thank Masatoshi Koshiba and Yoji Totsuka for their continuing support and encouragements of my research throughout my career. Ed Kearns worked with me on the analyses of atmospheric neutrinos in Super-Kamiokande for many years. Masato Takita and Kenji Kaneyuki worked with me in the Kamiokande analysis. Yoji Totsuka, Yoichiro Suzuki and Masayuki Nakahata have been leading the Super-Kamiokande experiment. Hank Sobel and Jim Stone have been leading the US effort of Super-Kamiokande. Kenzo Nakamura and Atsuto Suzuki played very important roles in the early stage of Super-Kamiokande. Hard work by young collaborators of Super-K was essential for the discovery.

Also, I would like to thank Morihiko Honda for the neutrino flux calculation.

Finally, Super-Kamiokande acknowledges MEXT, DOE, and Kamioka Mining and Smelting Company.



*Super-Kamiokande collaboration (End of 1998, at the top of the Super-Kamiokande tank)*

*Thank you very much for your attention!*