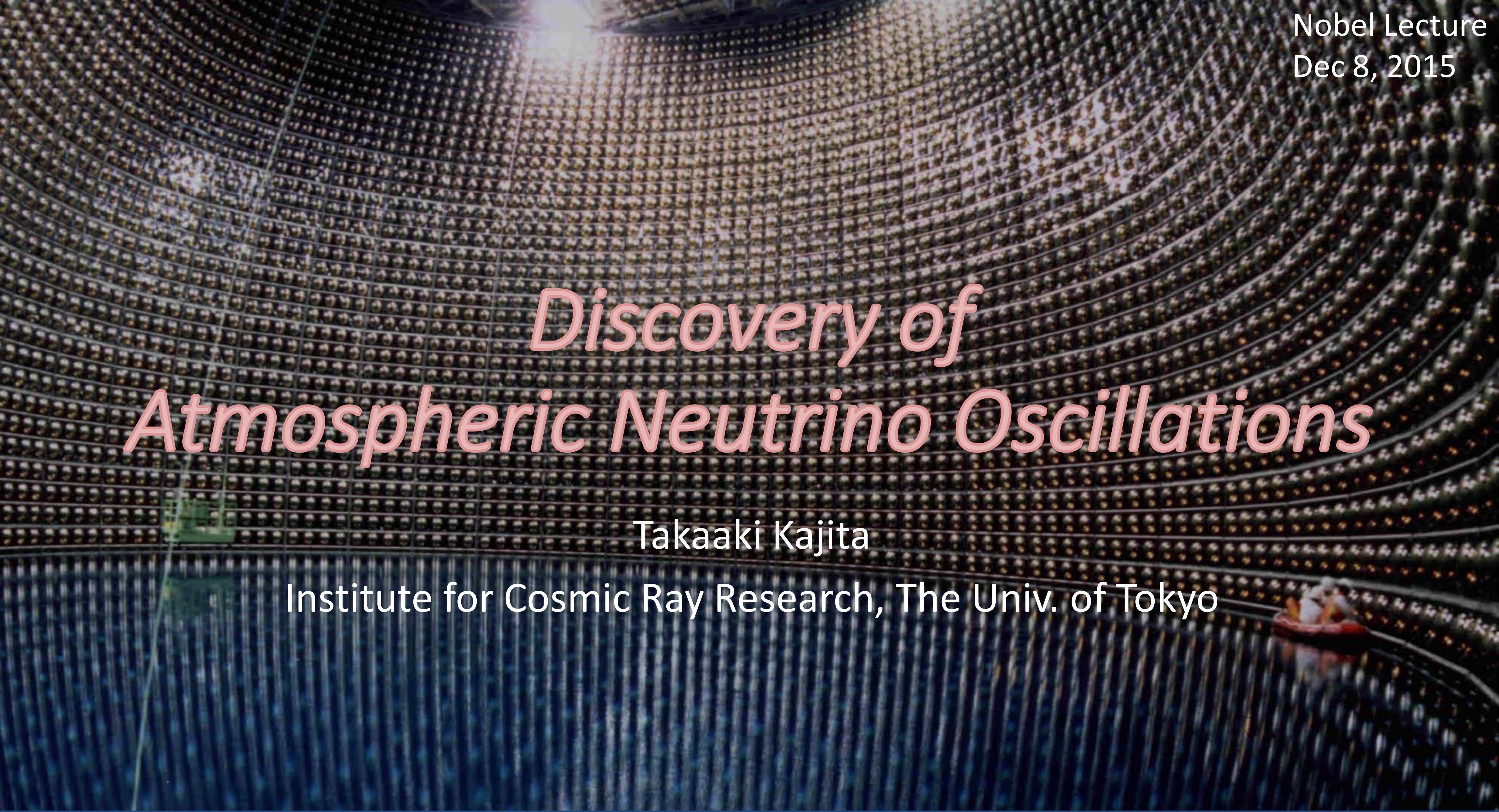


Nobel Lecture
Dec 8, 2015

Discovery of Atmospheric Neutrino Oscillations

Takaaki Kajita
Institute for Cosmic Ray Research, The Univ. of Tokyo

Outline

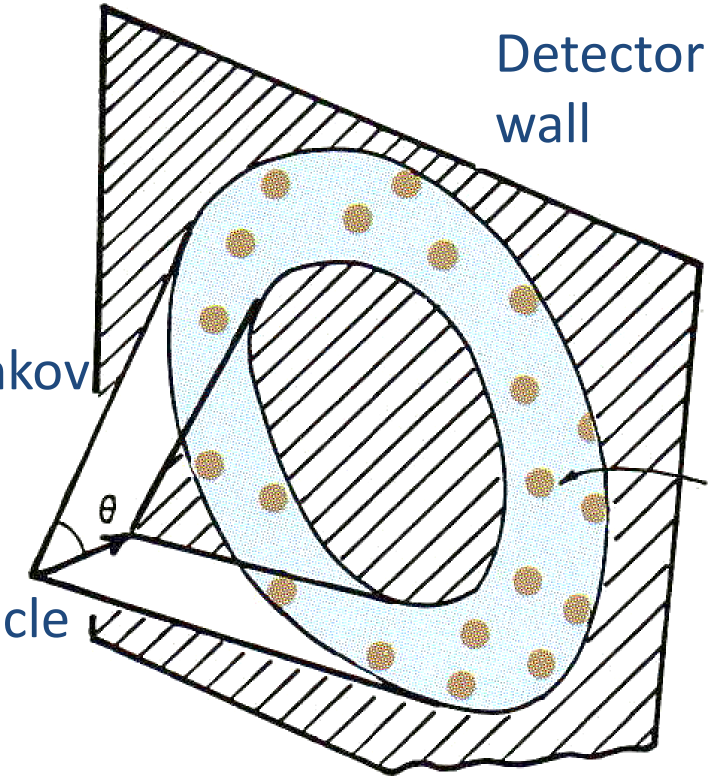
- Introduction: Kamiokande - the starting point -
- Atmospheric neutrino deficit
- Discovery of neutrino oscillations
- Recent results and the future
- Summary
- Acknowledgements

Introduction: Kamiokande - the starting point -

Kamioka Nucleon Decay Experiment (Kamiokande)

- ✓ In the late 1970's, new theories that unify Strong, Weak and Electromagnetic forces were proposed.
- ✓ These theories predicted that protons and neutrons (i.e., nucleons) should decay with the lifetime of about 10^{28} to 10^{32} years.
- ✓ Several proton decay experiments began in the early 1980's. One of them was the Kamiokande experiment.

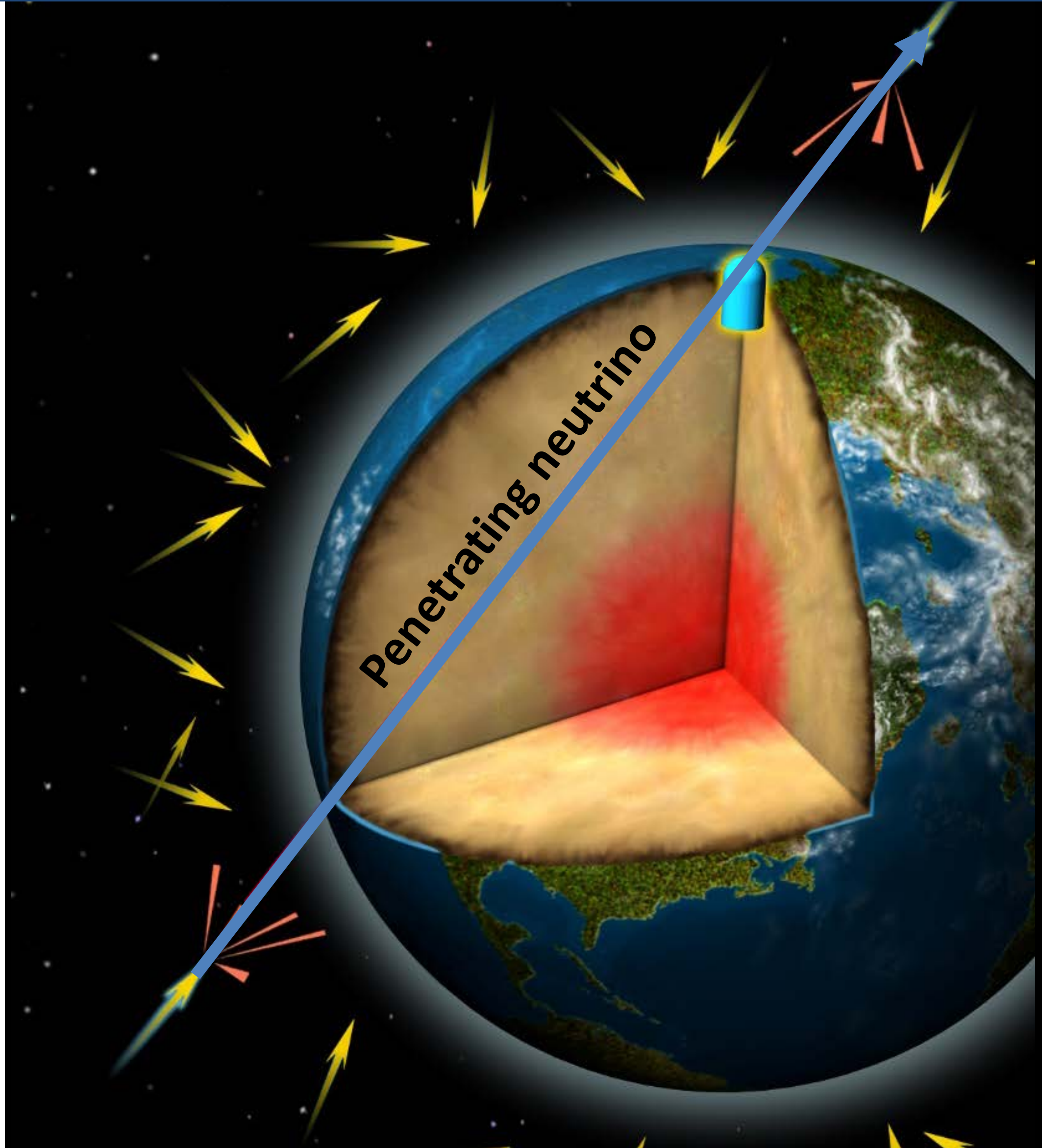
Kamiokande (1000 ton fiducial volume)



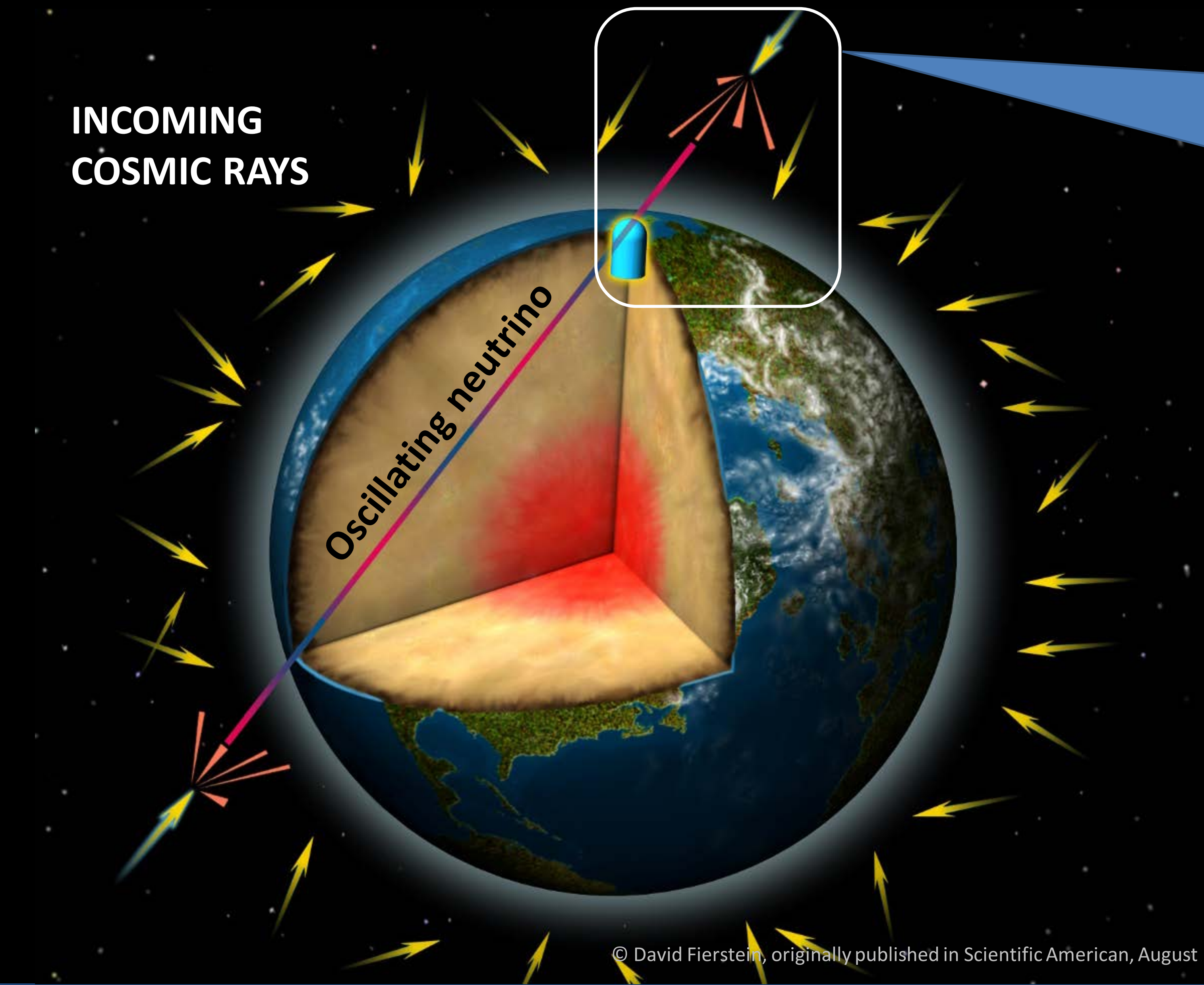
Kamiokande construction team (Spring 1983)

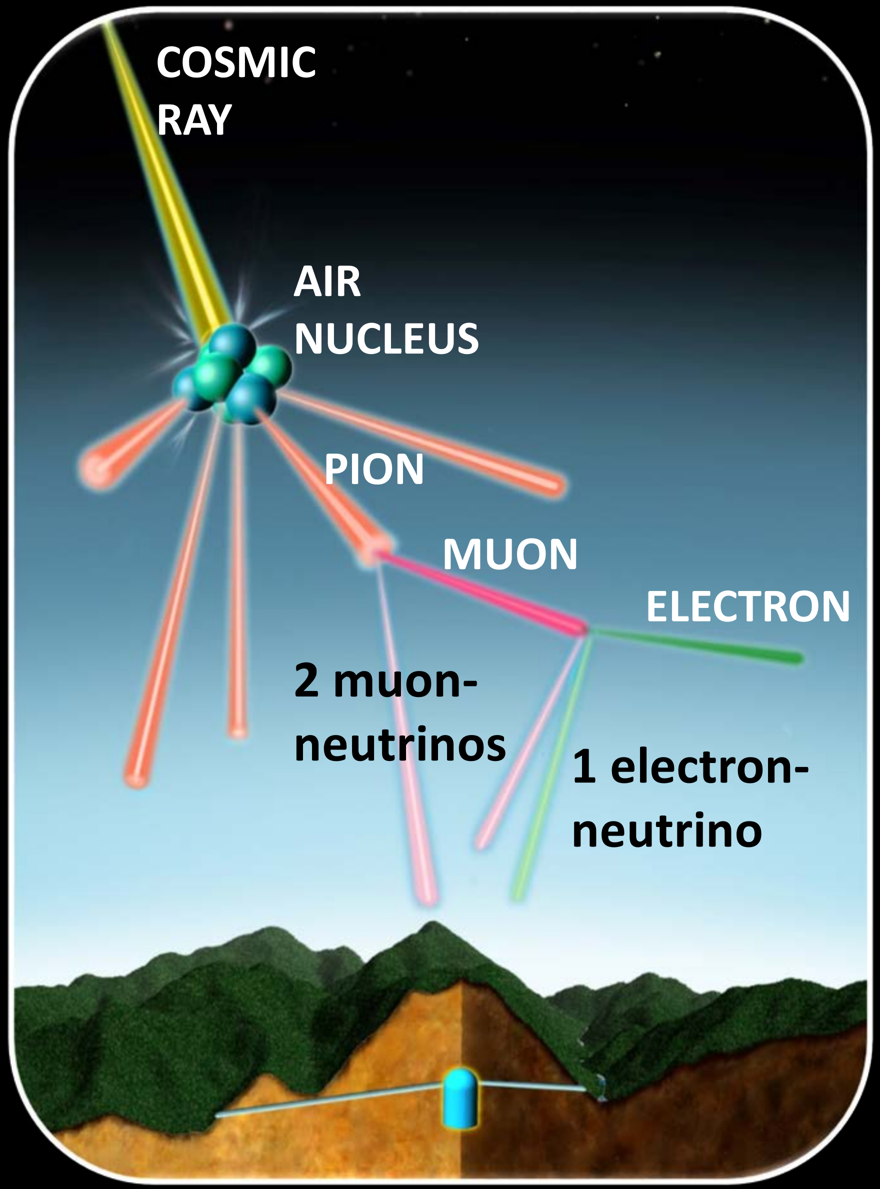
What are neutrinos?

- Neutrinos;
  - are fundamental particles like electrons and quarks,
  - have no electric charge,
  - have 3 types (flavors), namely electron-neutrinos (ν_e), muon-neutrinos (ν_μ) and tau-neutrinos (ν_τ),
  - are produced in various places, such as the Earth's atmosphere, the center of the Sun, ….
  - can easily penetrate through the Earth, the Sun…
  - can, however, interact with matter very rarely. A ν_μ produces a muon. A ν_e produces an electron.
- In the very successful Standard Model of particle physics, neutrinos are assumed to have no mass.
- However, physicists have been asking neutrinos really have no mass.



Atmospheric neutrino deficit

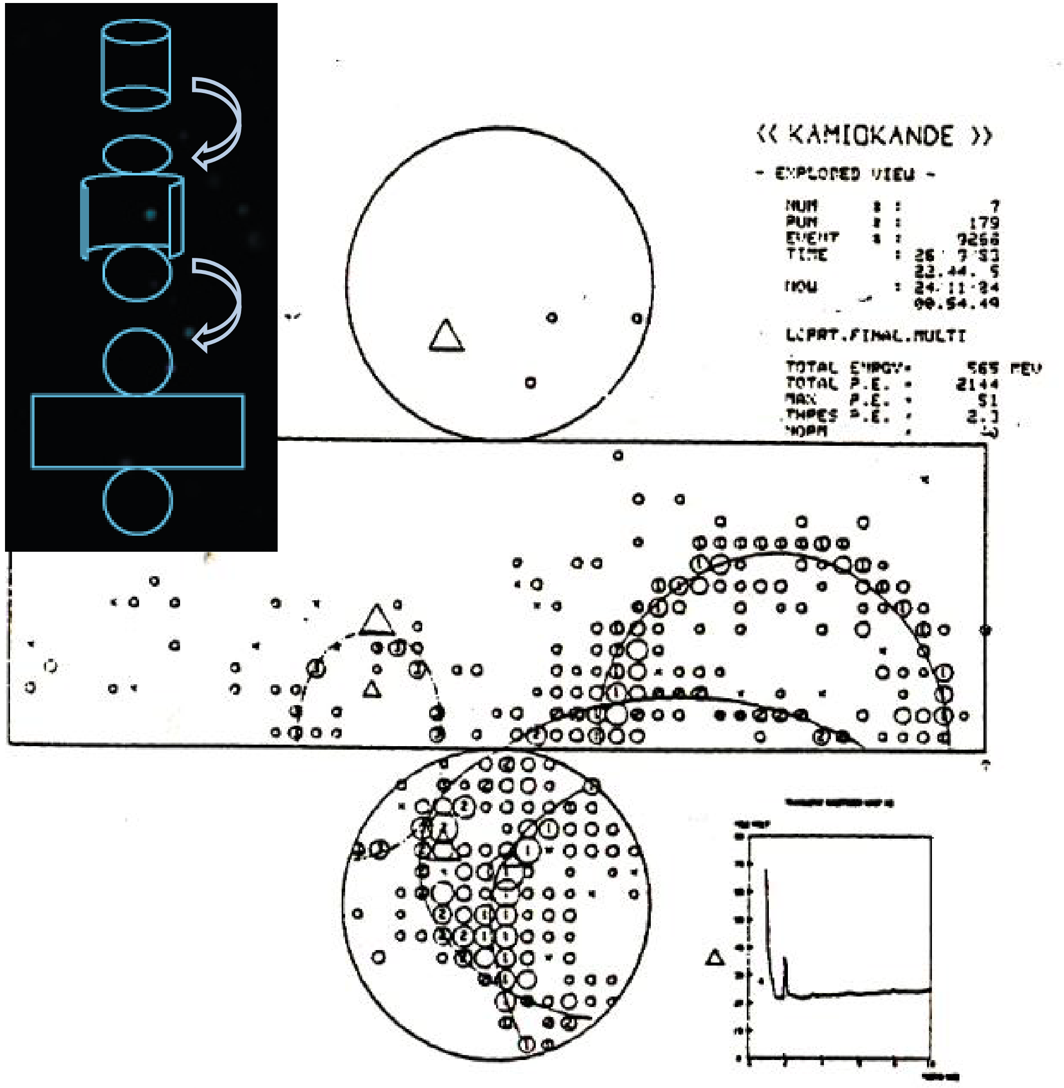




I got my PhD in March 1986 based on a search for proton decay. (I did not find any evidence for proton decay.)

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….

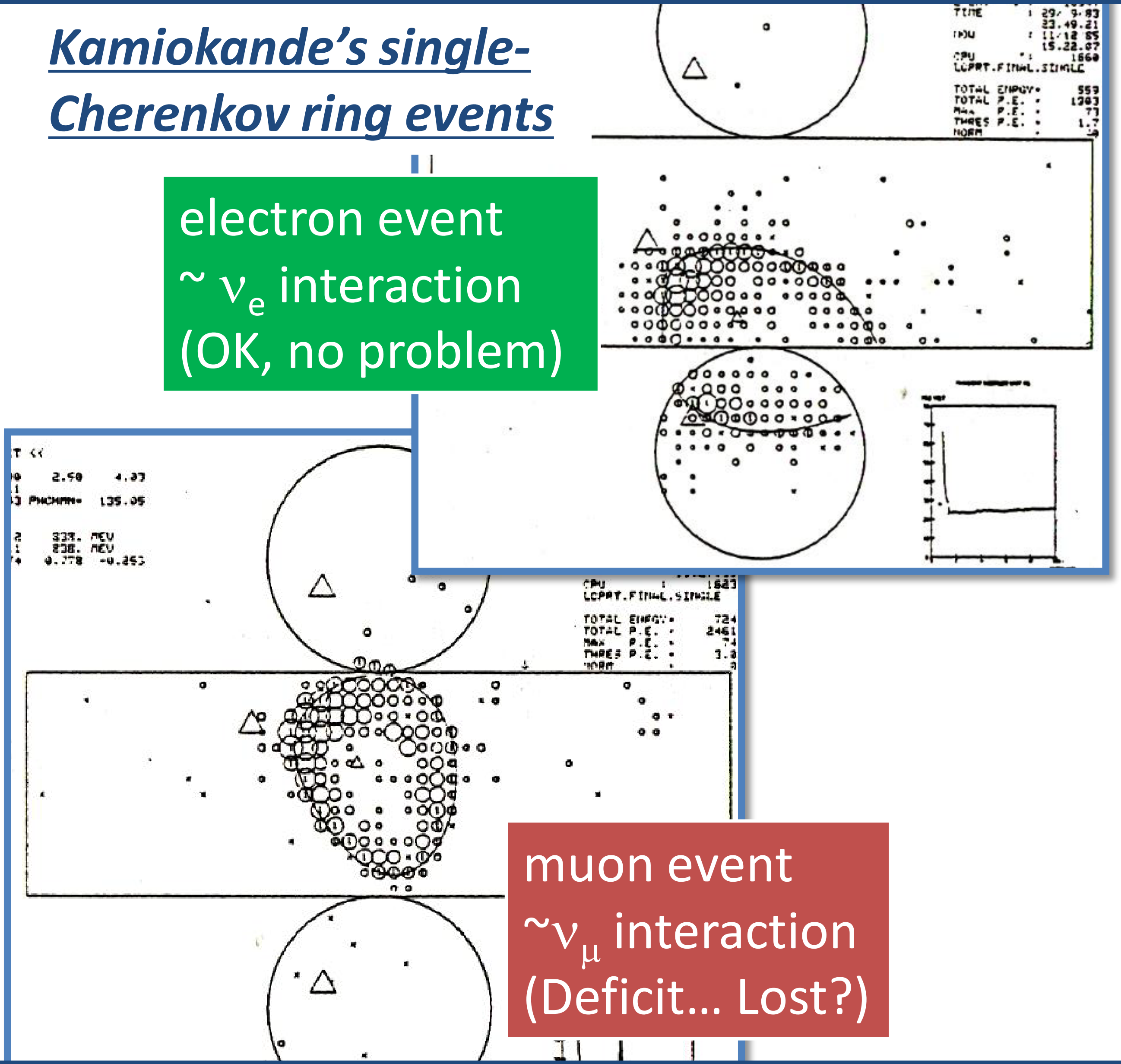


Multi-ring event observed in Kamiokande.

A strange result…

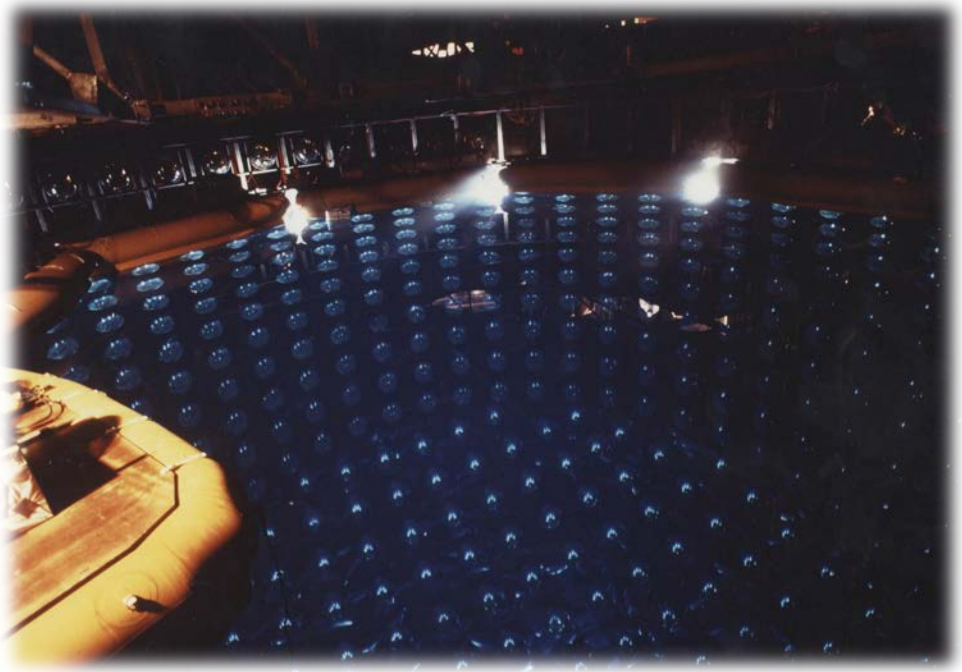
- The neutrino flavor was studied for the atmospheric neutrino events.
- The result was strange. The number of ν_μ events was much fewer than expected.
- At first, I thought that I made some serous mistake.
- In order to know where I made mistake, I decided to scan the real events. Immediately, I realized 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



Result on the ν_μ deficit (1988)

After more than 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.



Kamiokande

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

	Data	Prediction
ν_e events	93	88.5
ν_μ events	85	144.0

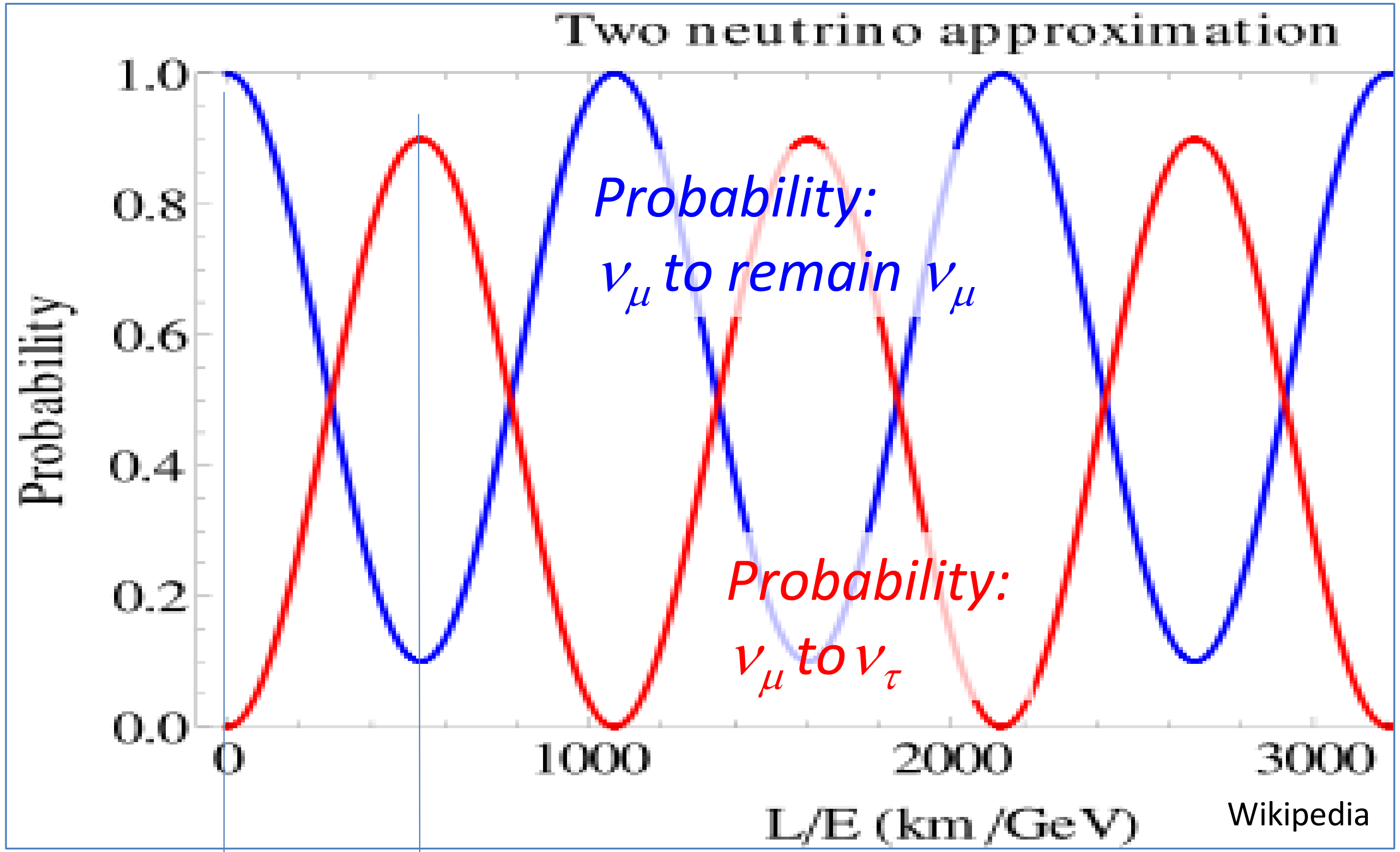
Paper conclusion: "We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data."

My personal memory:

I was most excited with the possibility of neutrino oscillations with large mixing angle. Namely, ν_μ 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 ν_μ and ν_τ.



Theoretically predicted by;

S. Sakata, Z. Maki, M. Nakagawa

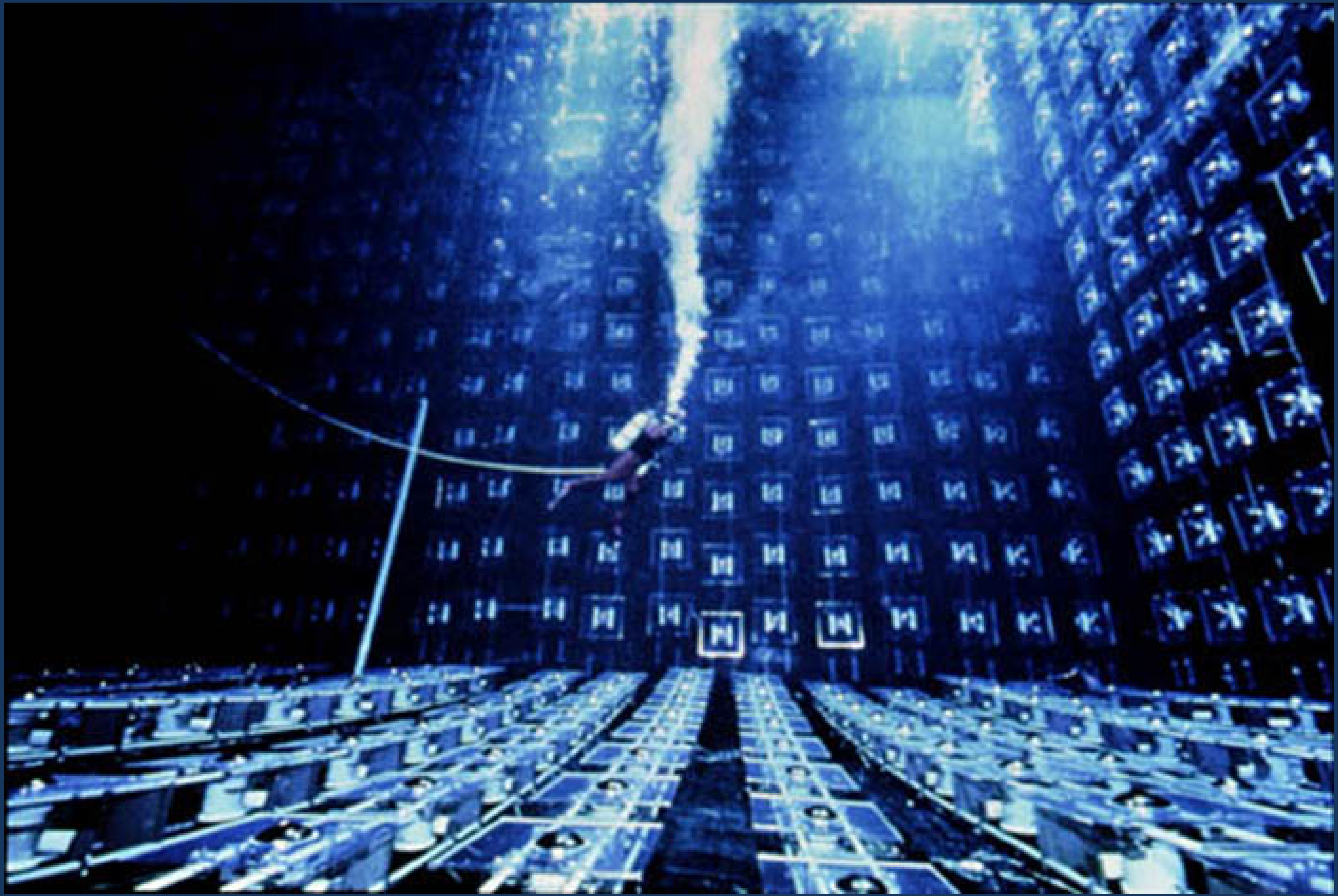
arXiv:0910.1657

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.

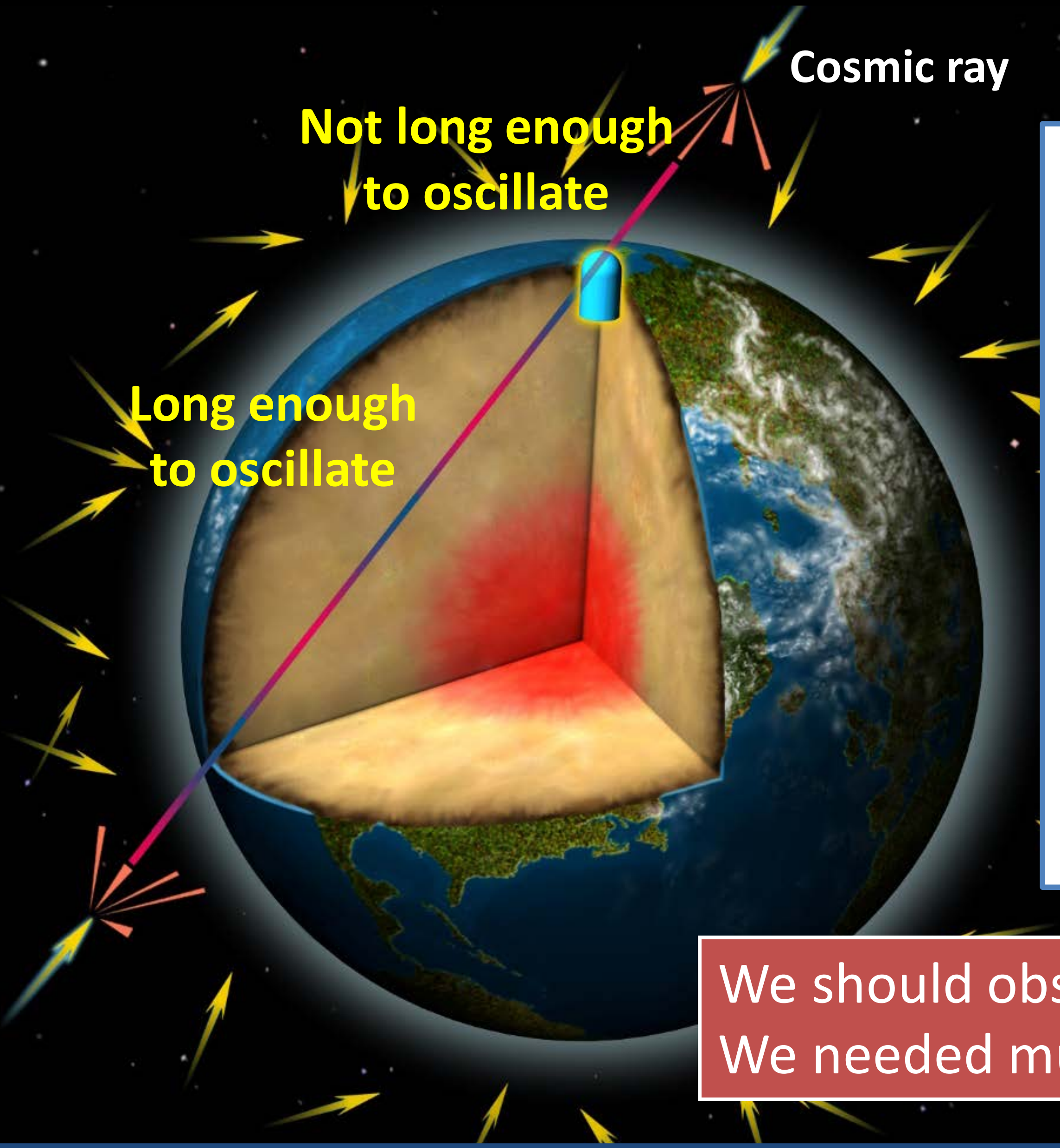
Results from IMB on the ν_μ deficit

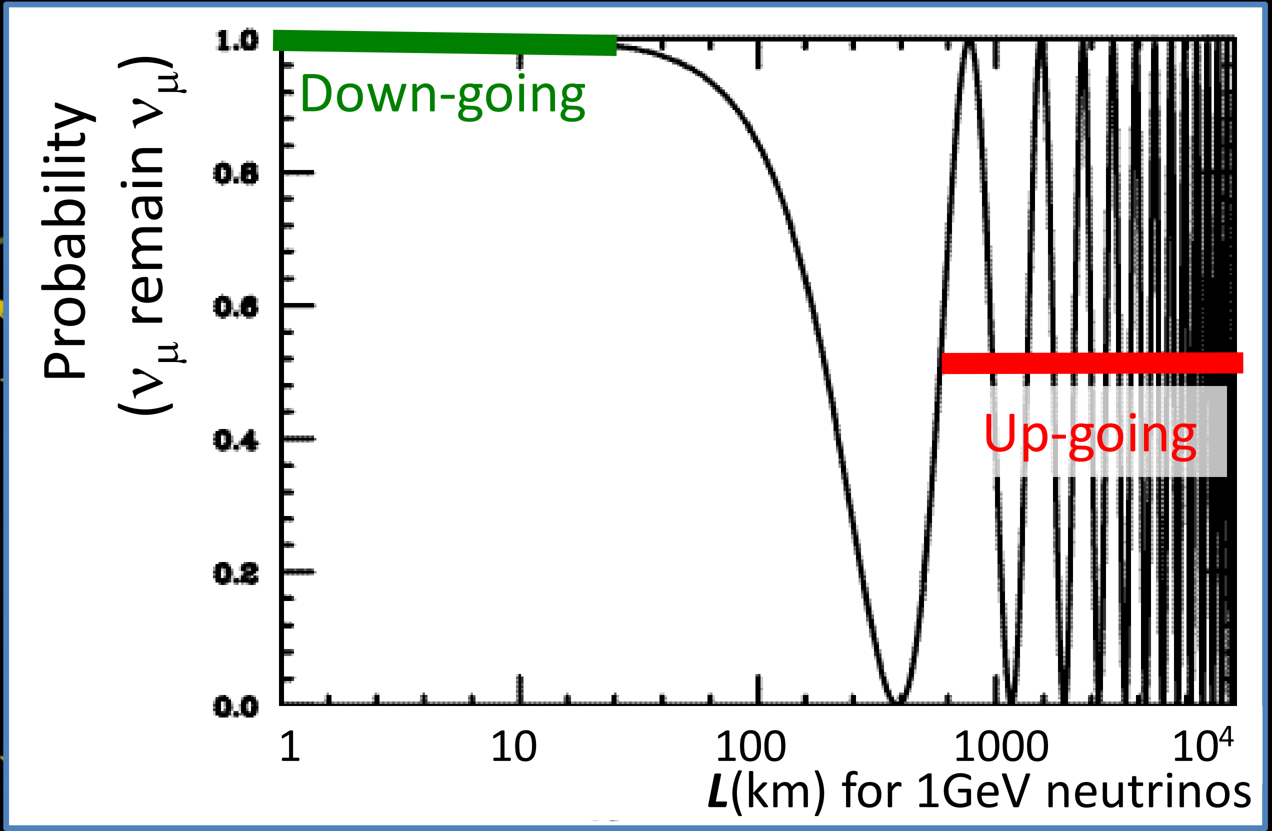


D. Casper et al., PRL **66** (1991) 2561.
R. Becker-Szendy, PRD **46** (1992) 3720.

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

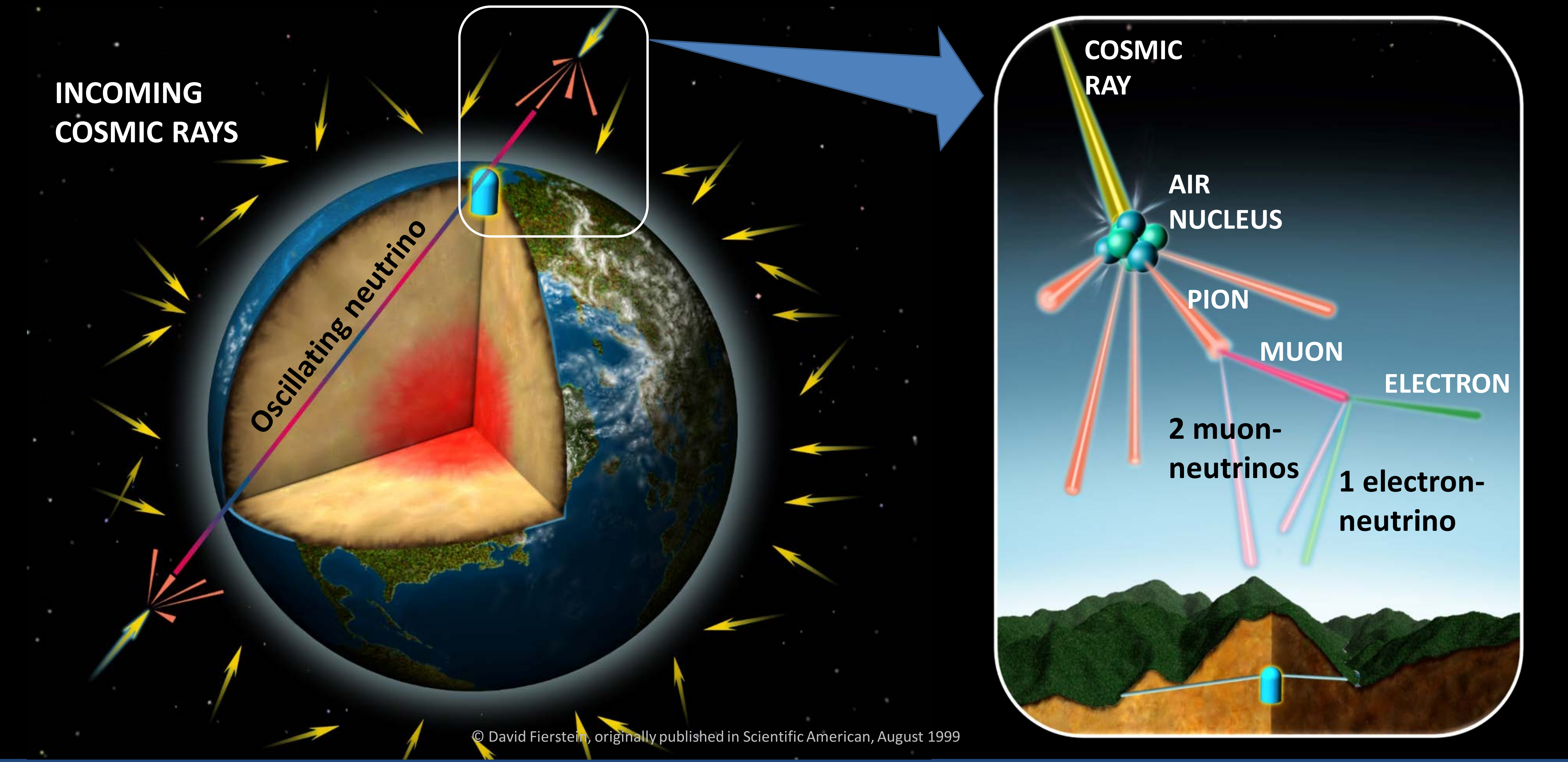
What will happen if the ν_μ deficit is due to neutrino oscillations



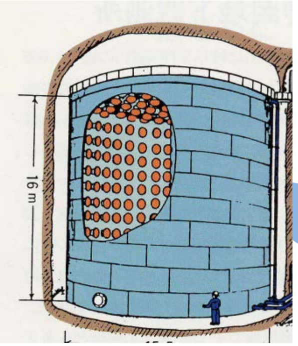


We should observe a deficit of upward going ν_μ's!
We needed much larger detector. ➔ Super-Kamiokande

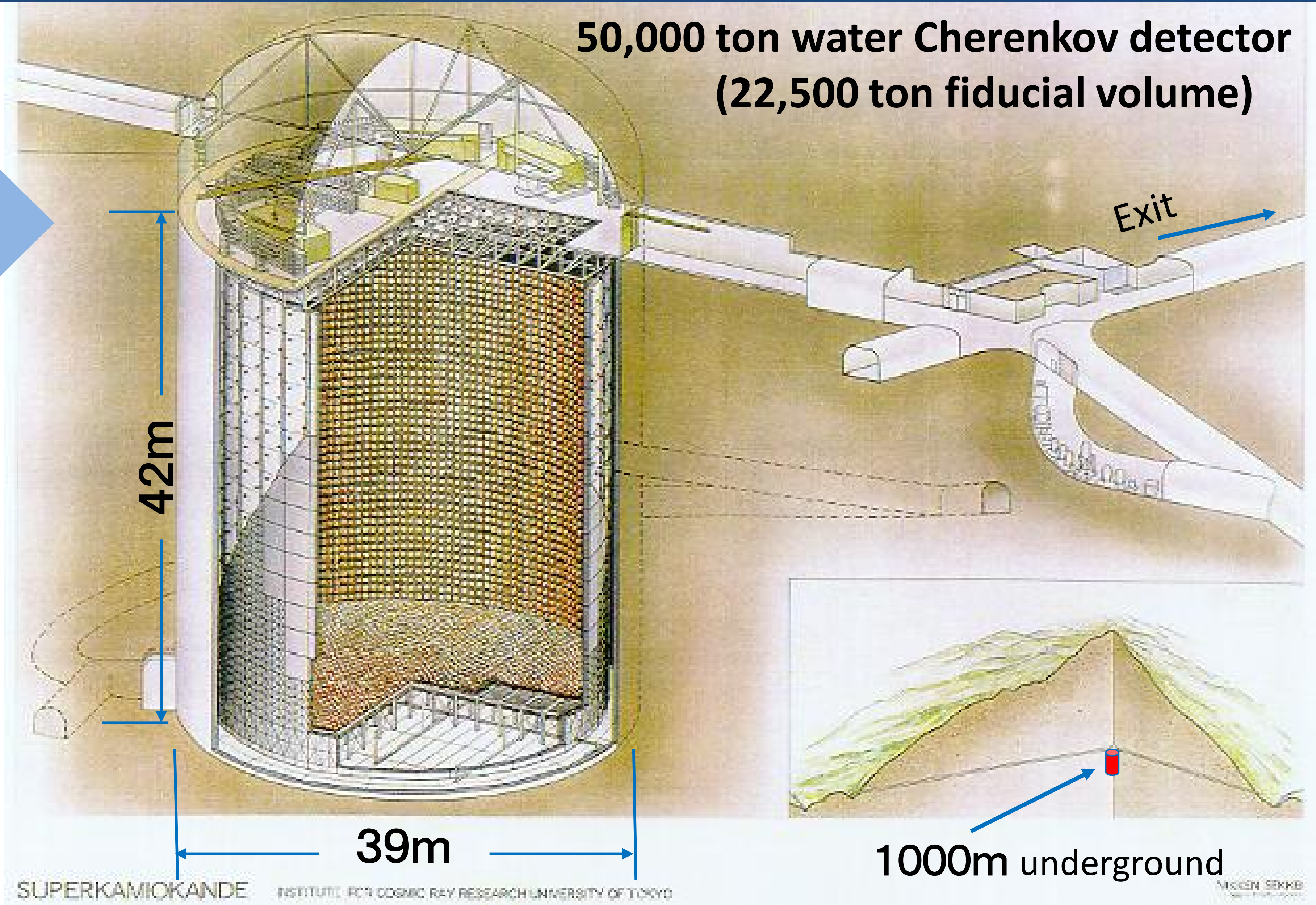
Discovery of neutrino oscillations



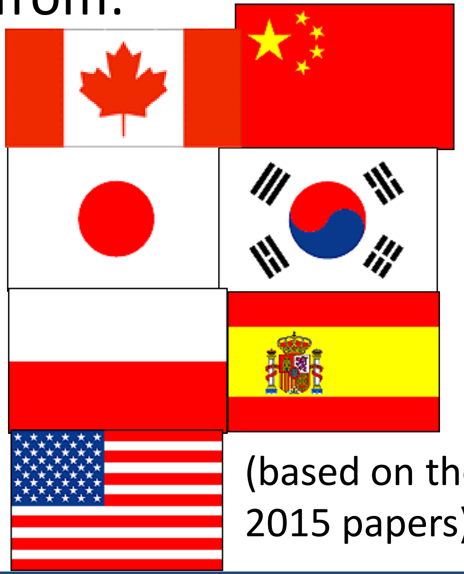
Super-Kamiokande detector



More than 20
times larger mass



~120 collaborators from:

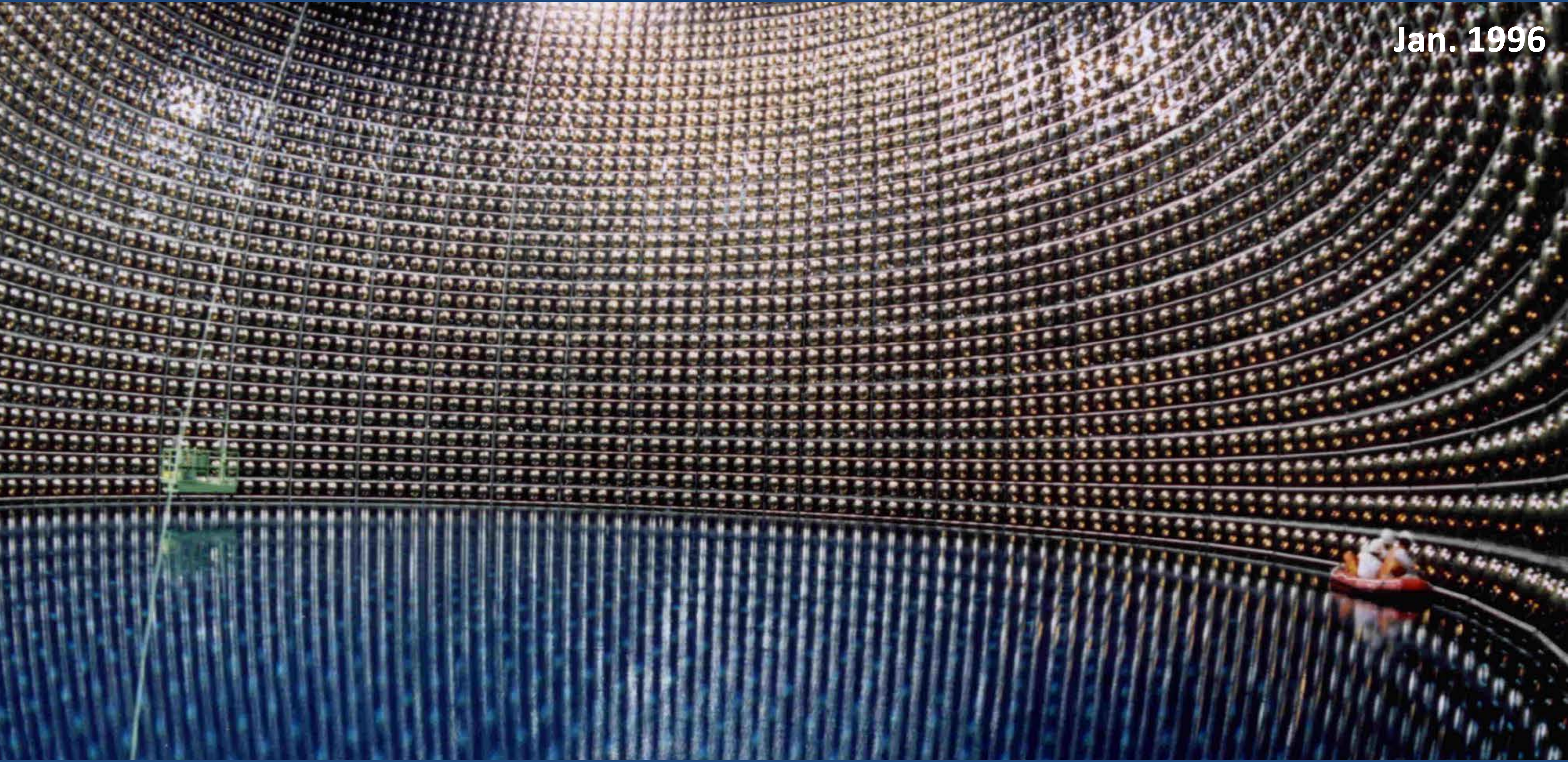


(based on the 2015 papers)

Beginning of the Super-Kamiokande collaboration between Japan and USA

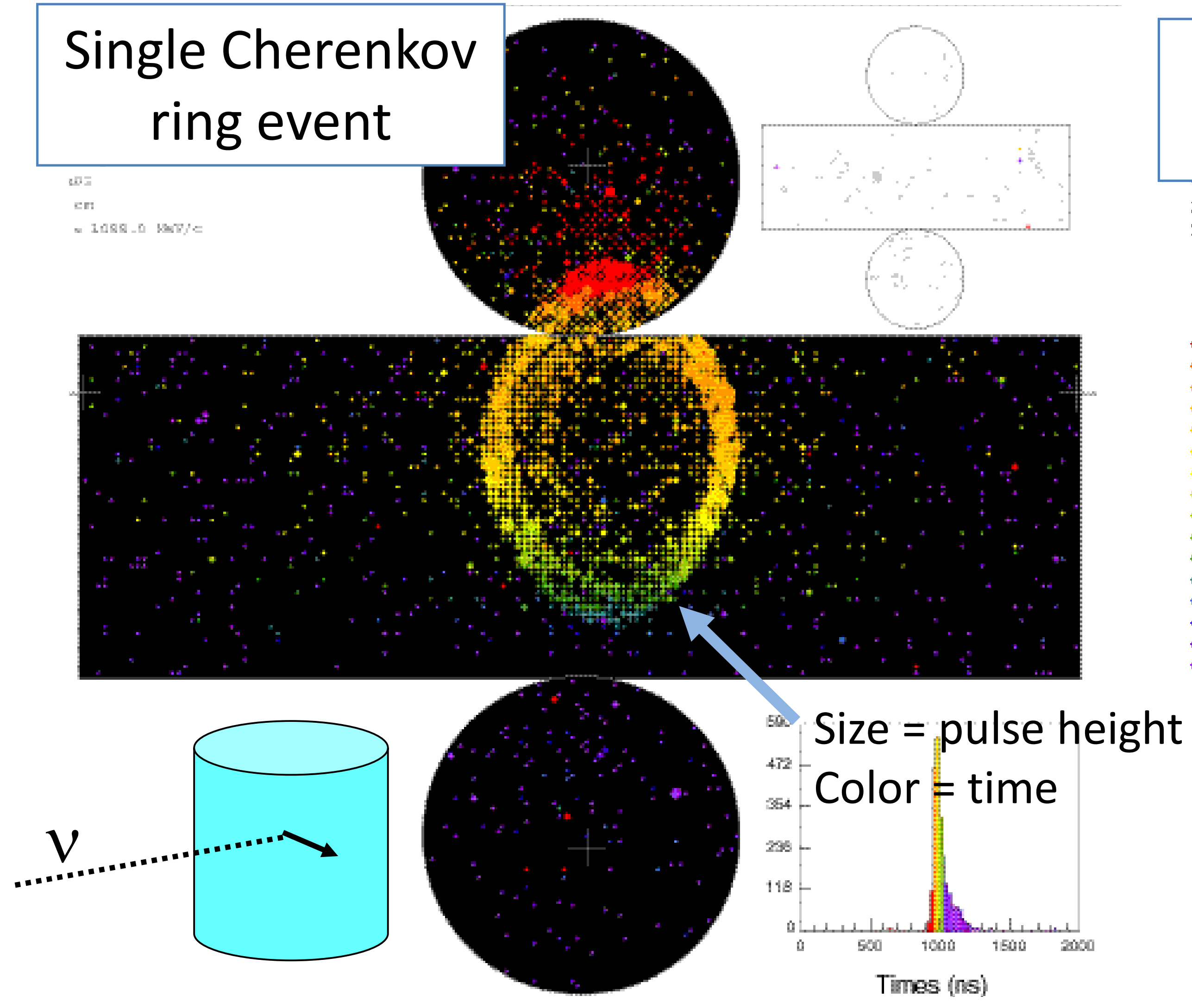
@ Institute for Cosmic Ray Research, (Probably) 1991 or 1992

Filling water in Super-Kamiokande

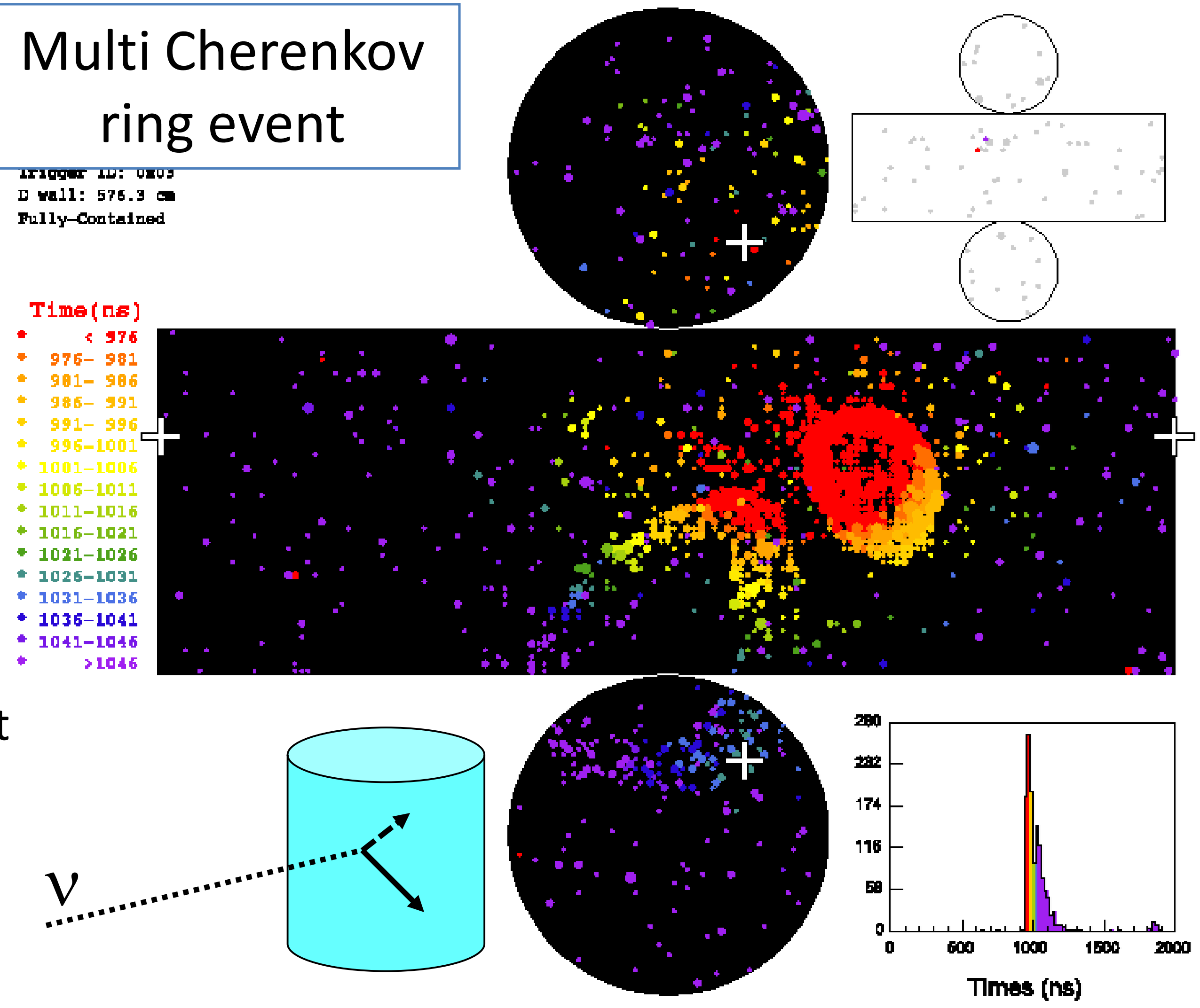


Atmospheric neutrino events observed in Super-K (1)

Single Cherenkov ring event

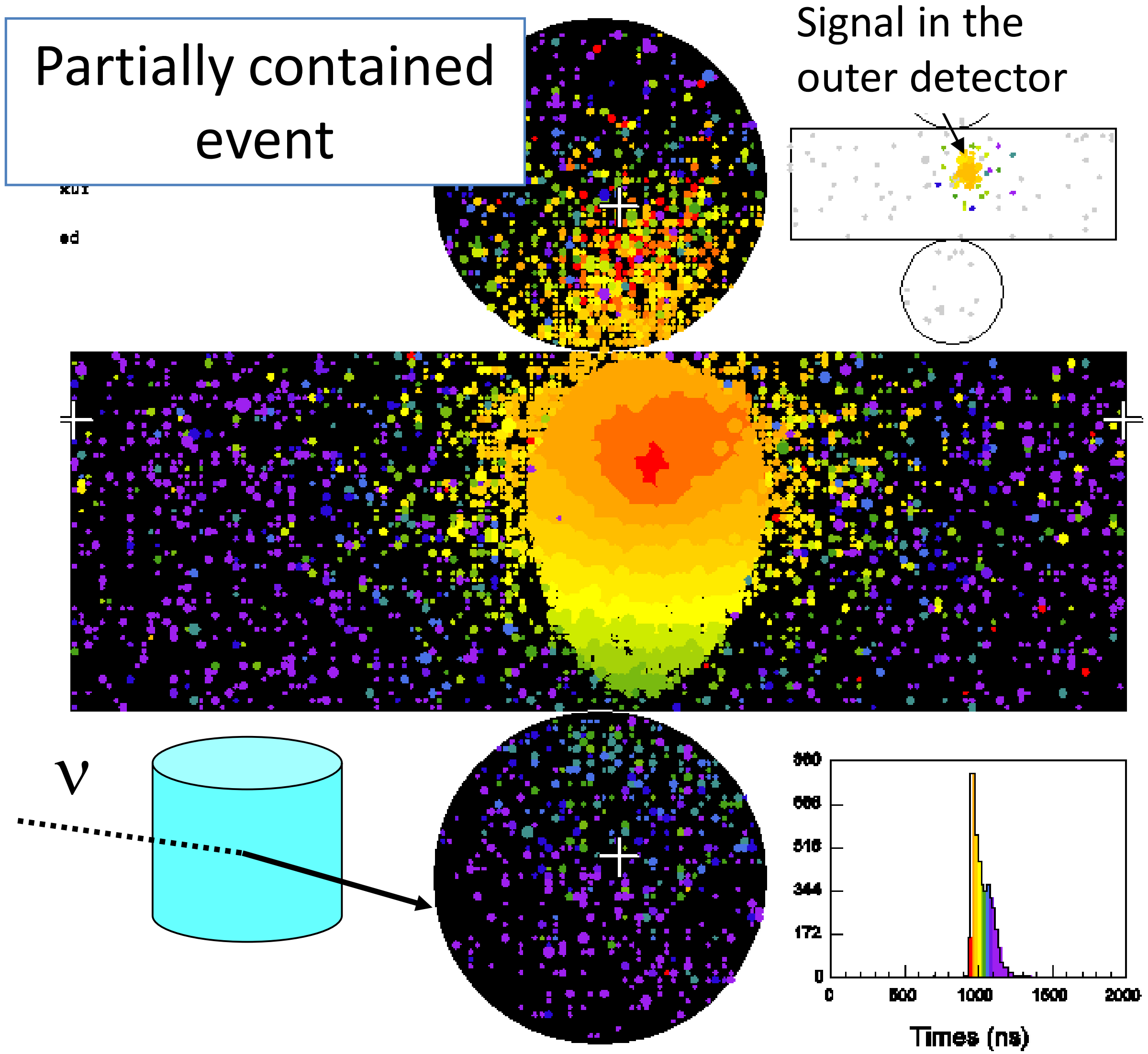


Multi Cherenkov ring event

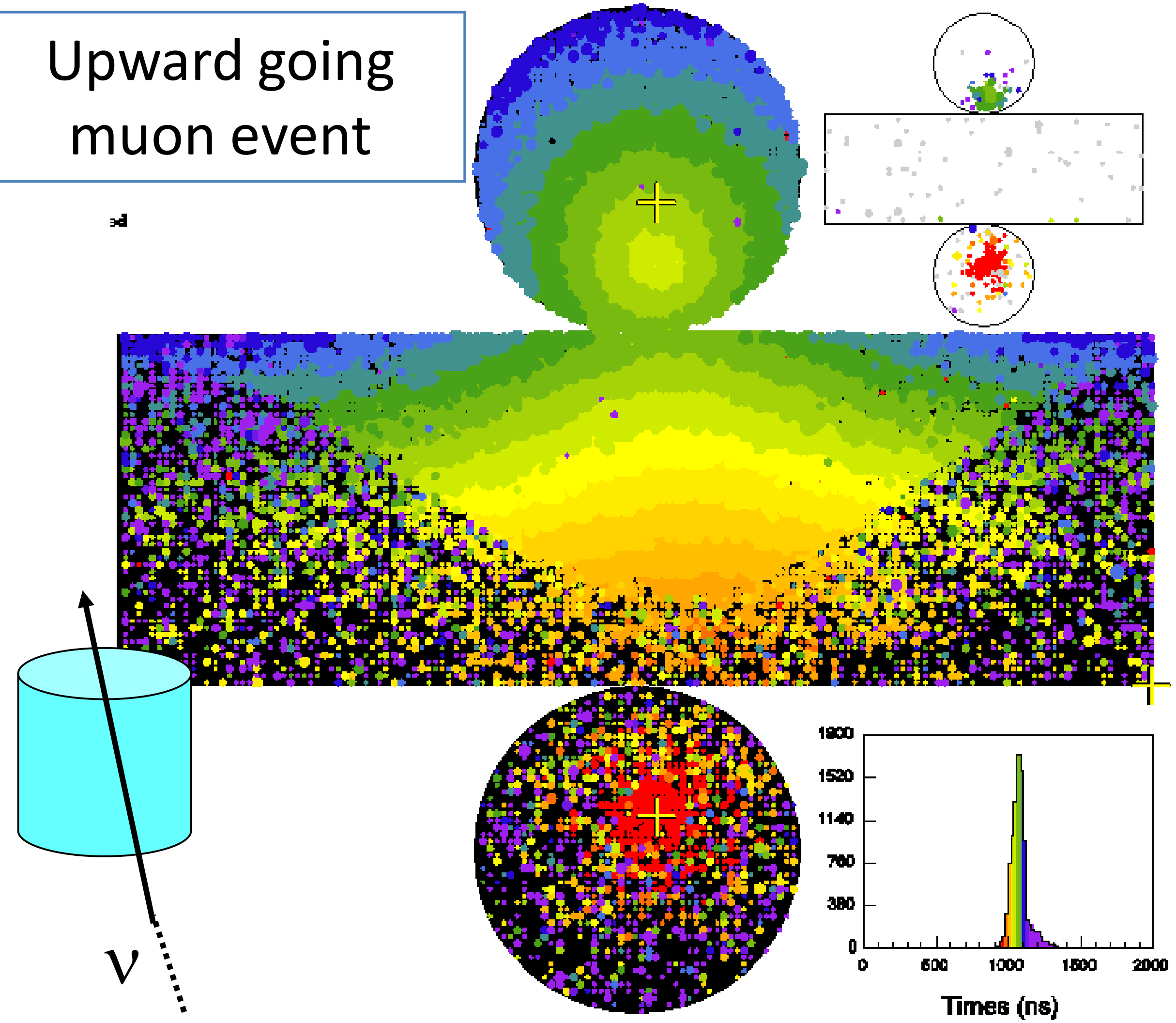


Atmospheric neutrino events observed in Super-K (2)

Partially contained event



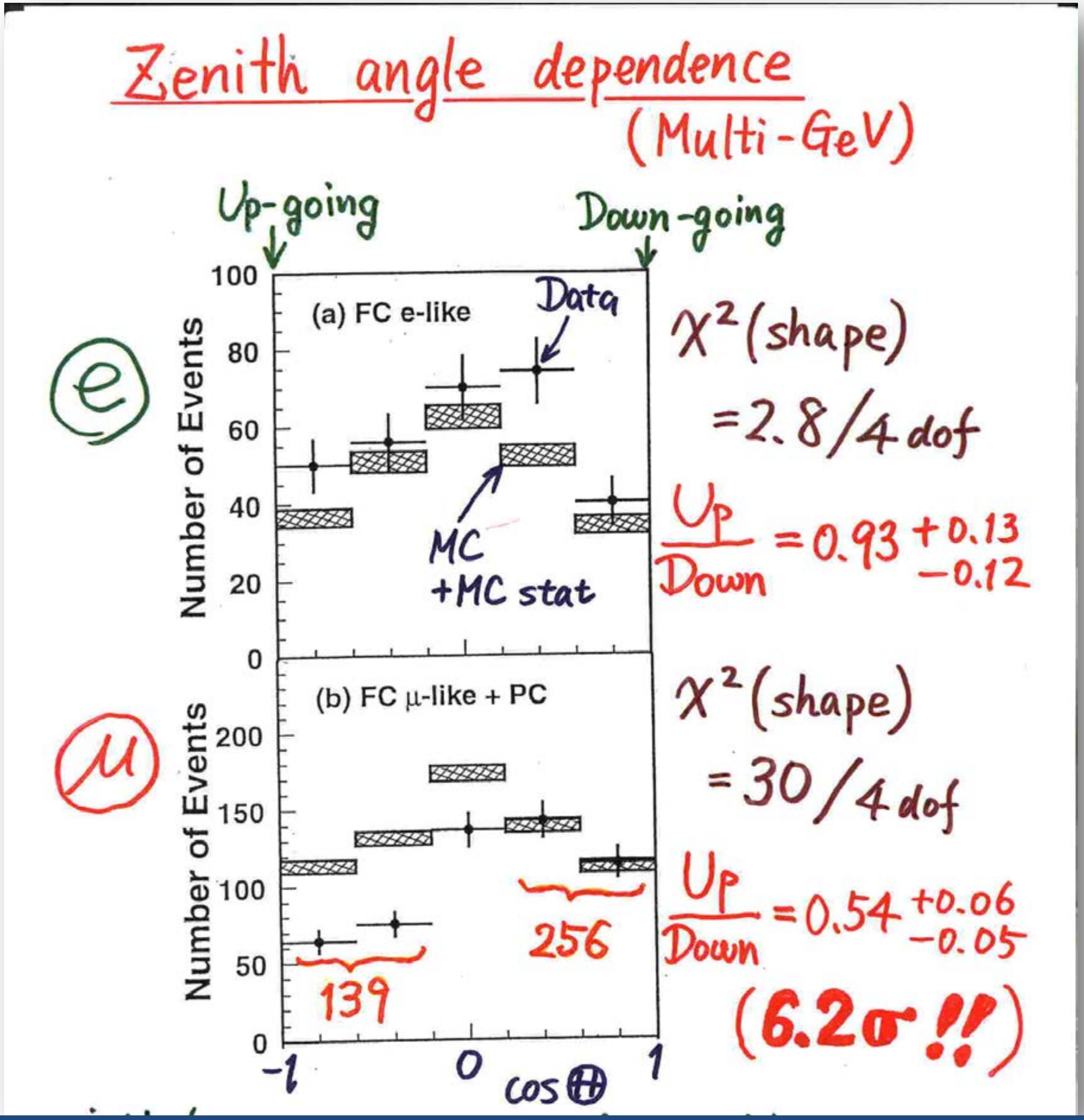
Upward going muon event

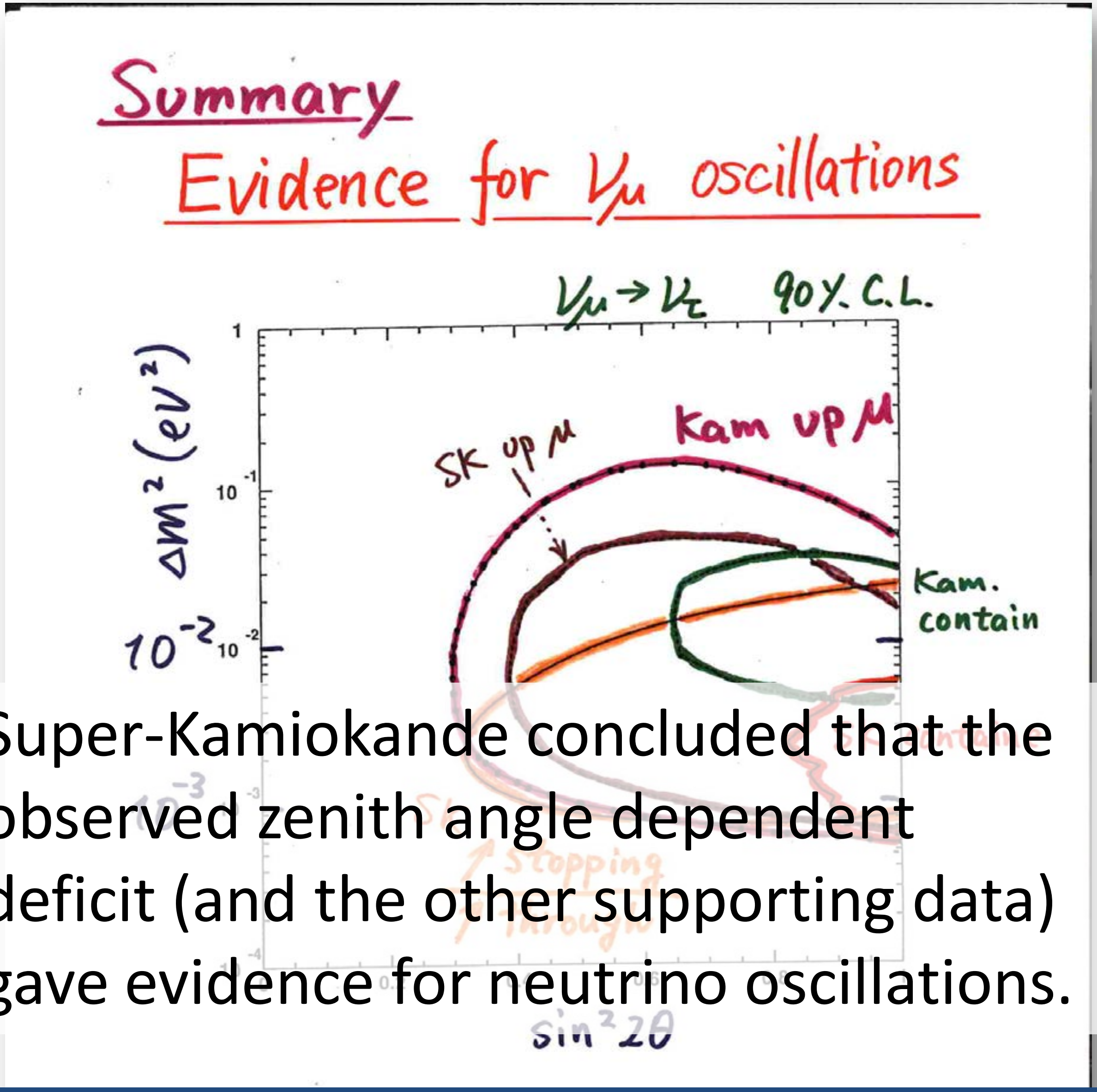


All these events are used in the analysis. ← ***Collaborative work of many (young) people!***

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

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

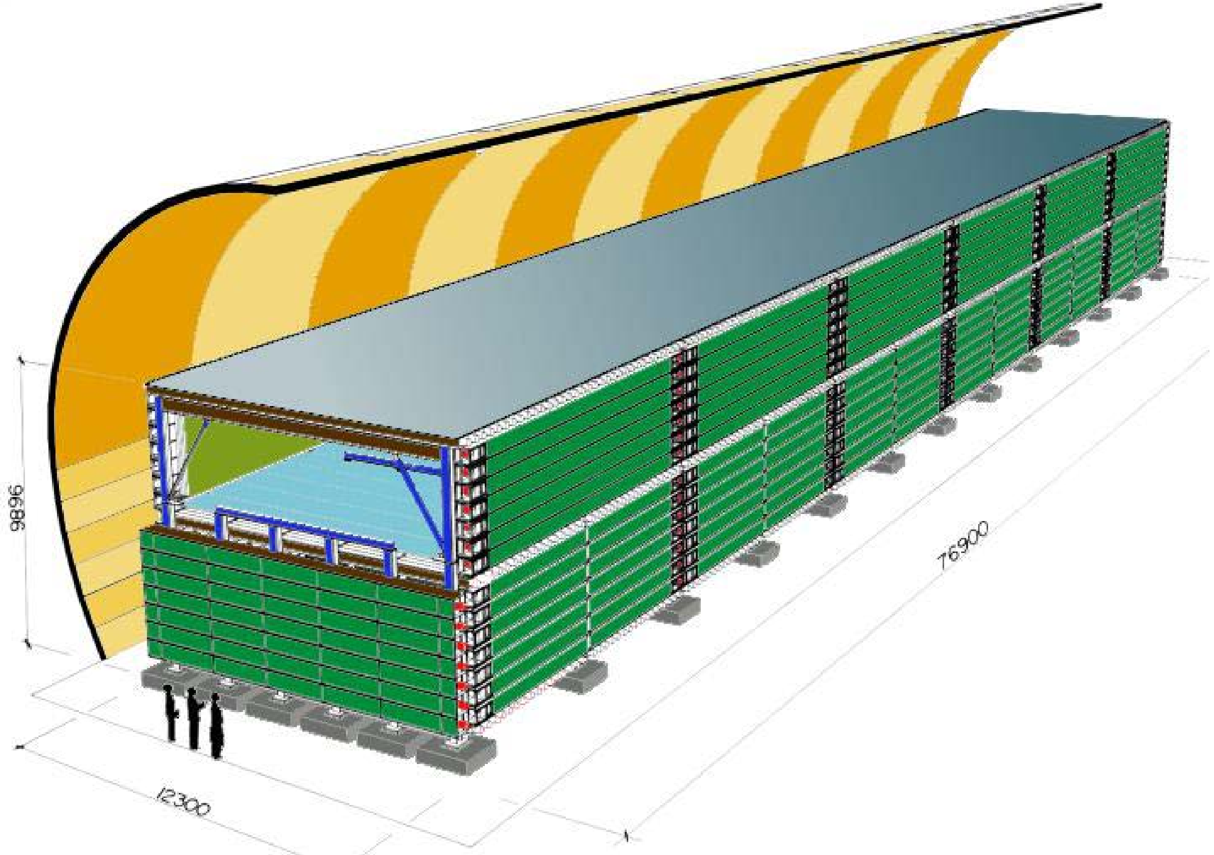




Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Results from the other atmospheric neutrino experiments

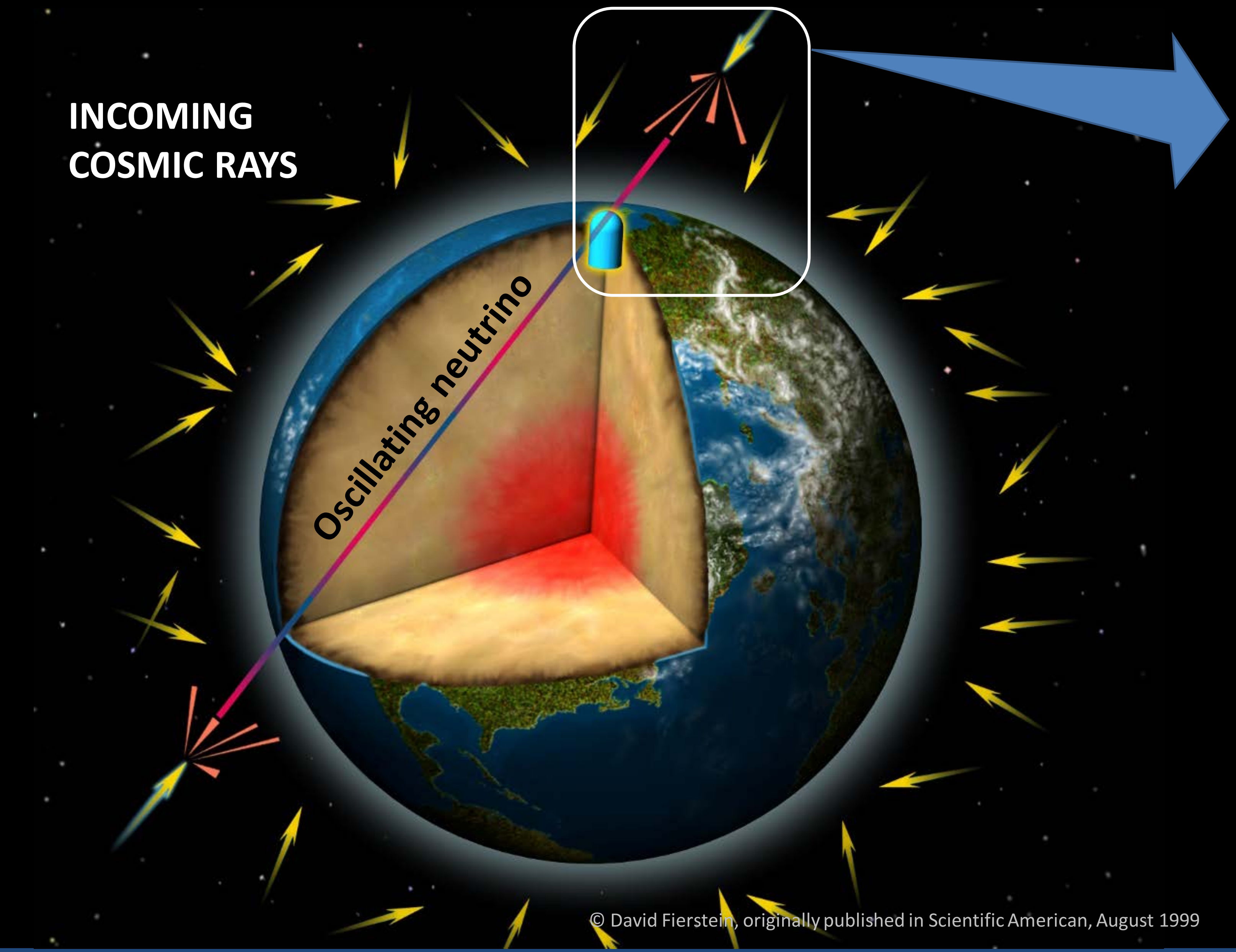
MACRO

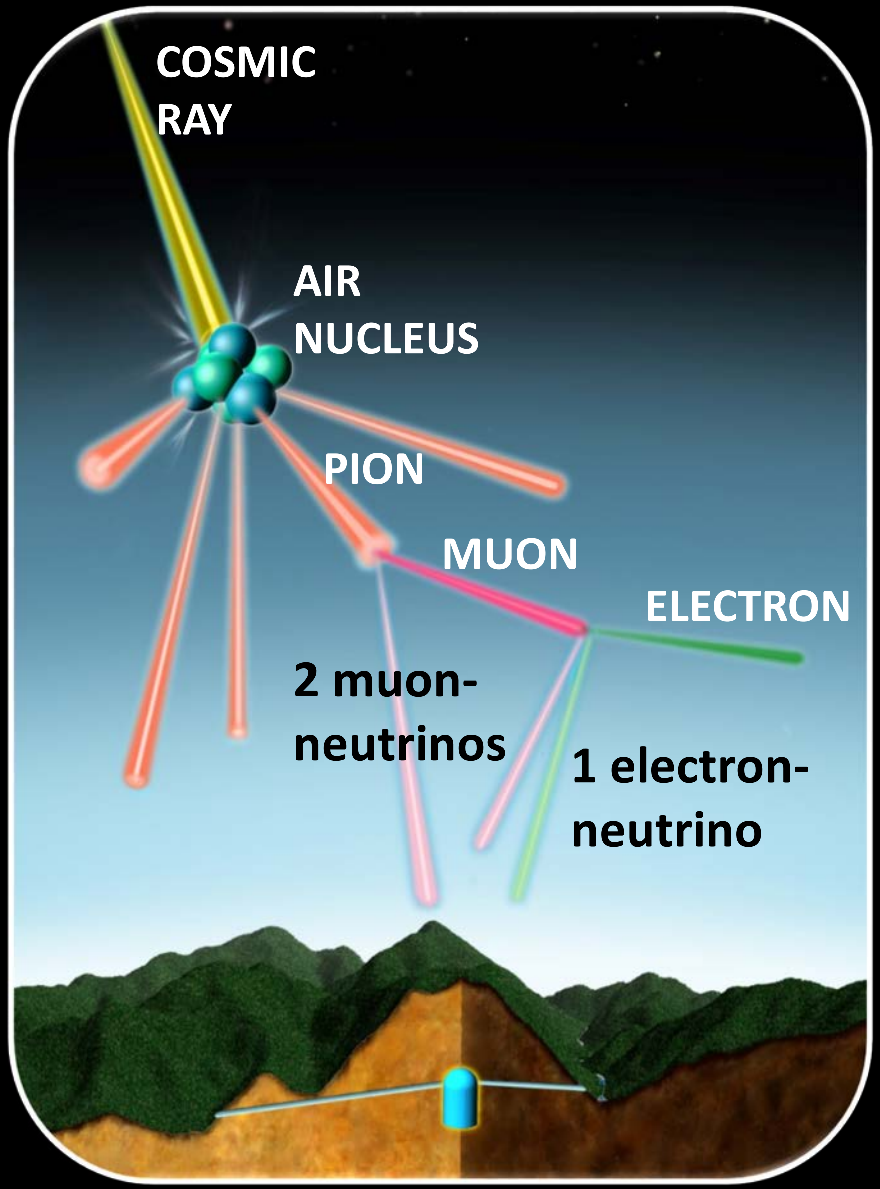


Soudan-2

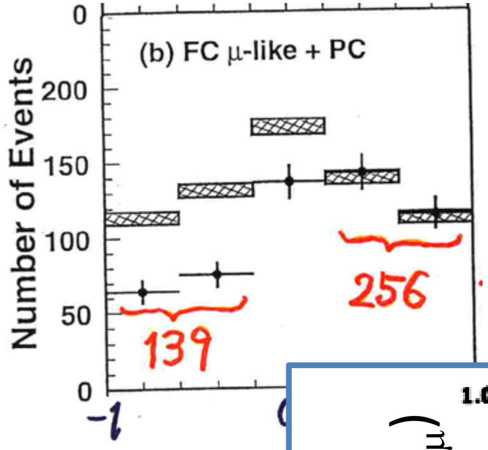
<u>These experiments observed atmospheric neutrinos and confirmed neutrino oscillations.</u>

Recent results and the future

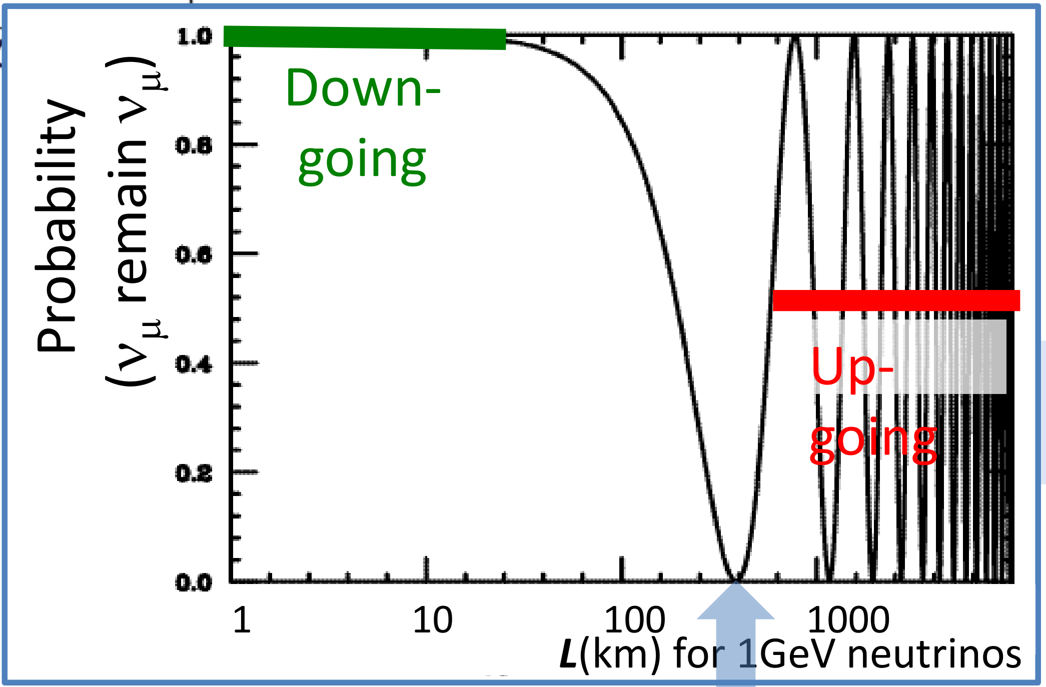


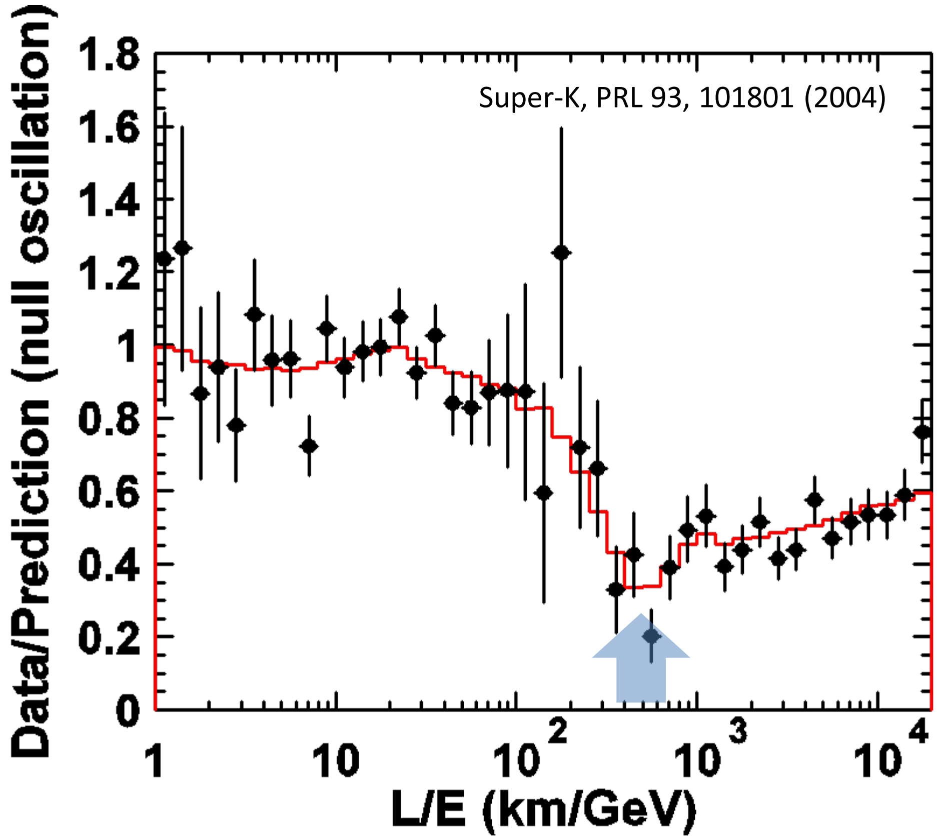


Really oscillations



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".





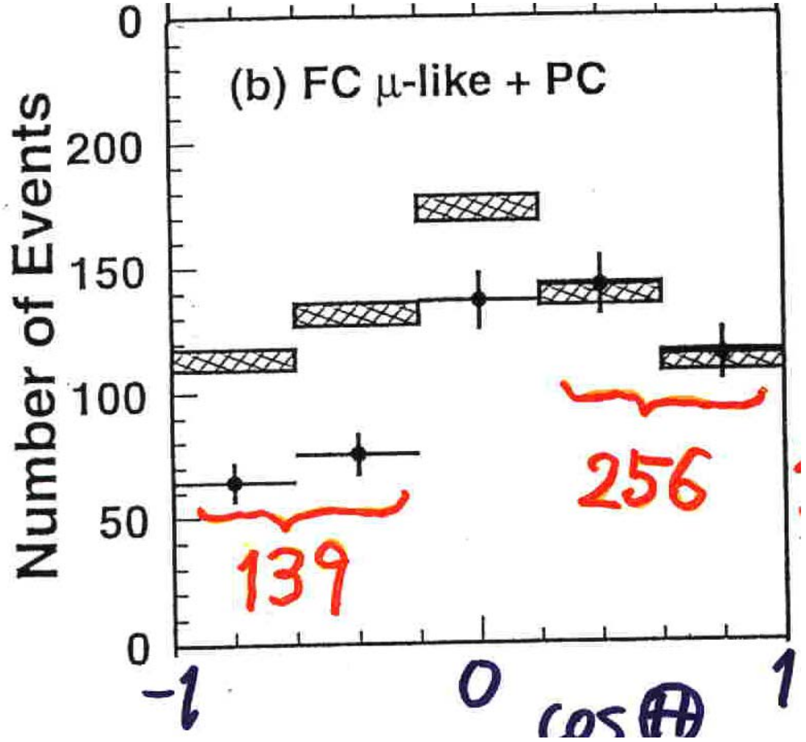
We wanted to observe this dip to confirm neutrino "oscillations".

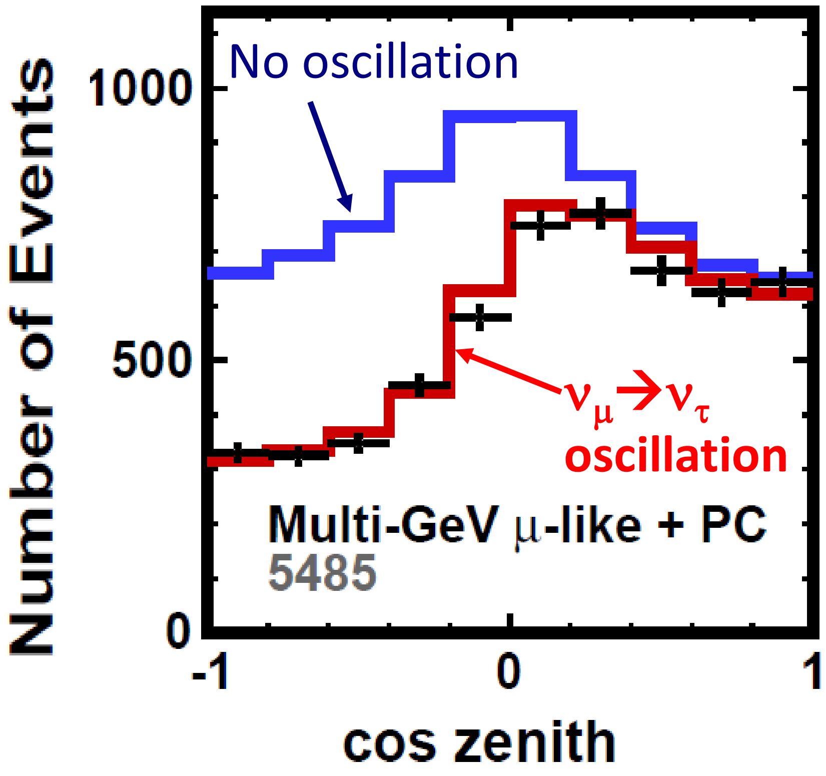
A dip is seen around L/E = 500 km/GeV.
➔ *Really oscillations (2004) !!*

Data updates and neutrino masses and mixing angles

Super-K @Neutrino98

Super-K (2015)





These data tell us;

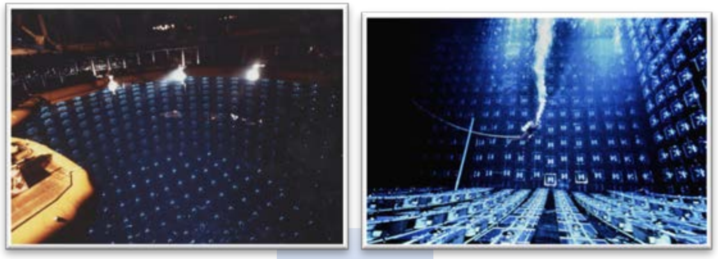
1. Heaviest neutrino mass is approximately **10,000,000** times smaller than the electron mass (which is the lightest particle except for neutrinos).
2. **ν_μ's oscillate maximally to ν_τ's**, which is really surprising. We want to understand why.

Number of events plotted:

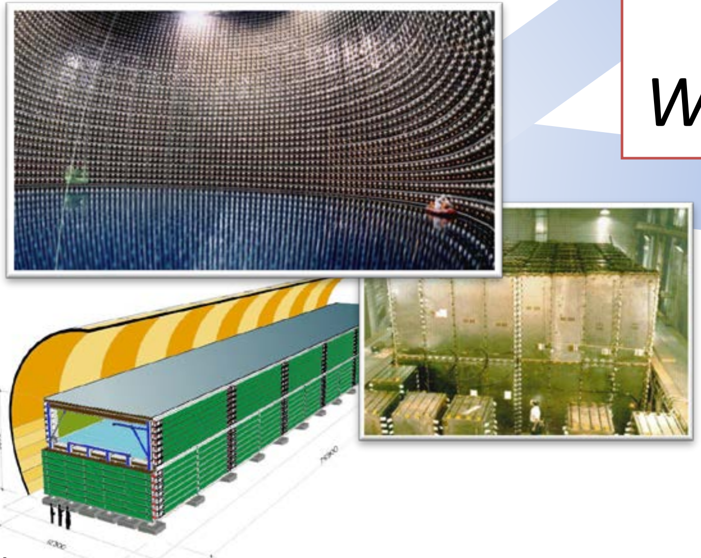
531 events → 5485 events

Neutrino oscillation experiments: Past, Present and Future

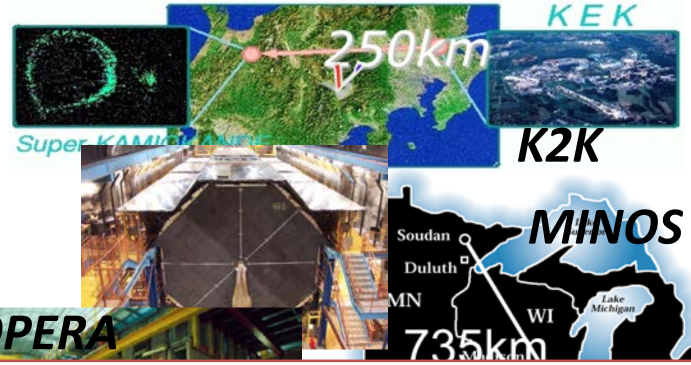
"Atmospheric ν_μ deficit" (around 1990)



"Discovery of neutrino oscillations" (1990's)

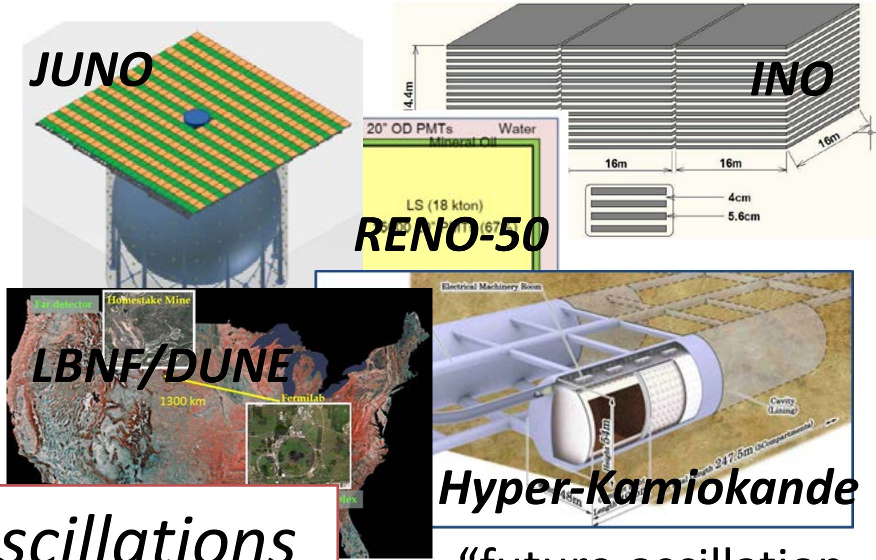


"Long-baseline neutrino oscillation experiments" (~2000's)

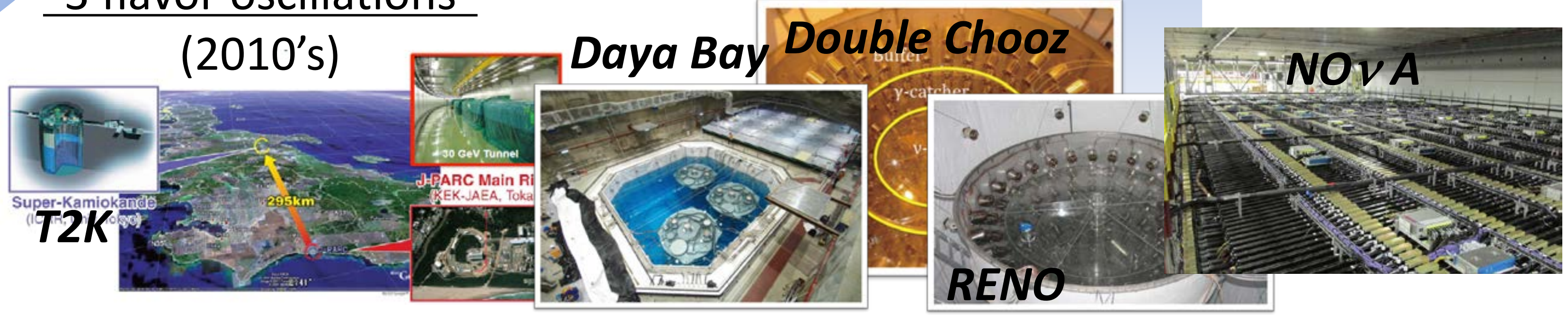


Our understanding on neutrino oscillations have been improving tremendously!
We still have to understand neutrinos more!

"future oscillation experiments" (2020's ?)



"3 flavor oscillations" (2010'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 Morihiro 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!