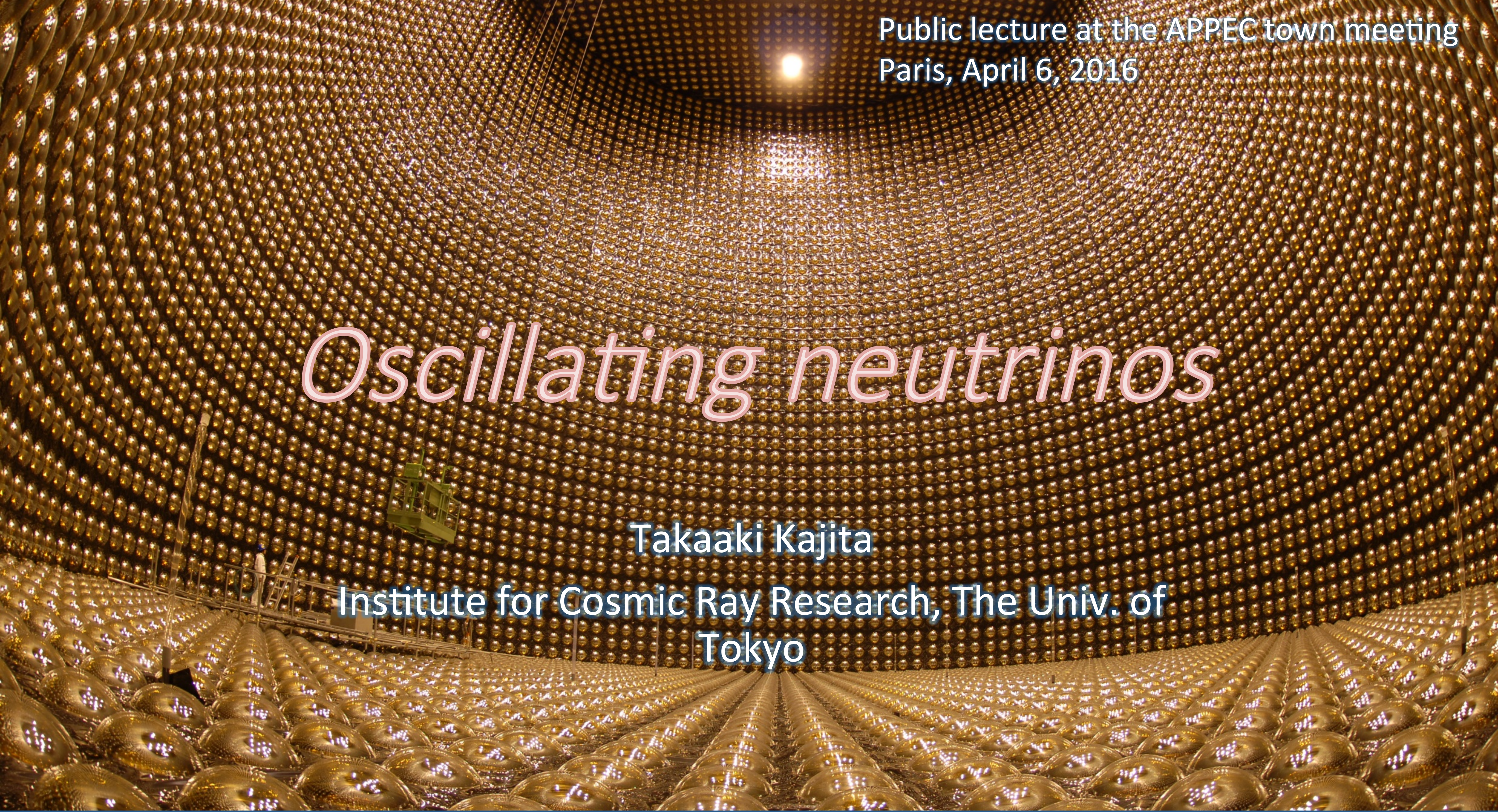


Public lecture at the APPEC town meeting
Paris, April 6, 2016

Oscillating neutrinos

Takaaki Kajita

Institute for Cosmic Ray Research, The Univ. of Tokyo

Outline

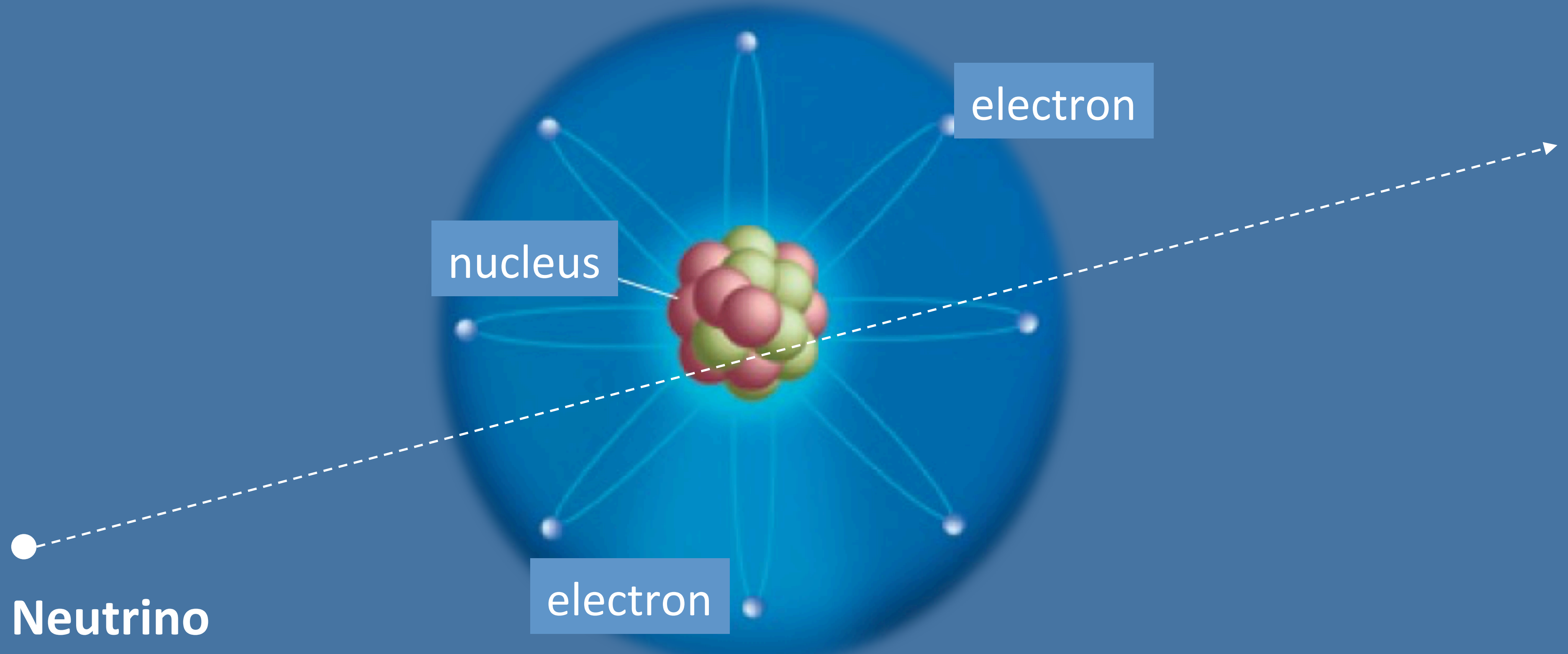
- Introduction: What are neutrinos?
- Atmospheric neutrino deficit
- Discovery of neutrino oscillations
- Present status of neutrino oscillations
- The future
- Summary

Introduction: What are neutrinos?

What are neutrinos?

Neutrinos;

- ✓ are fundamental particles like electrons and quarks,
- ✓ are like electrons without electric charge,
- ✓ have been assume to have no mass.



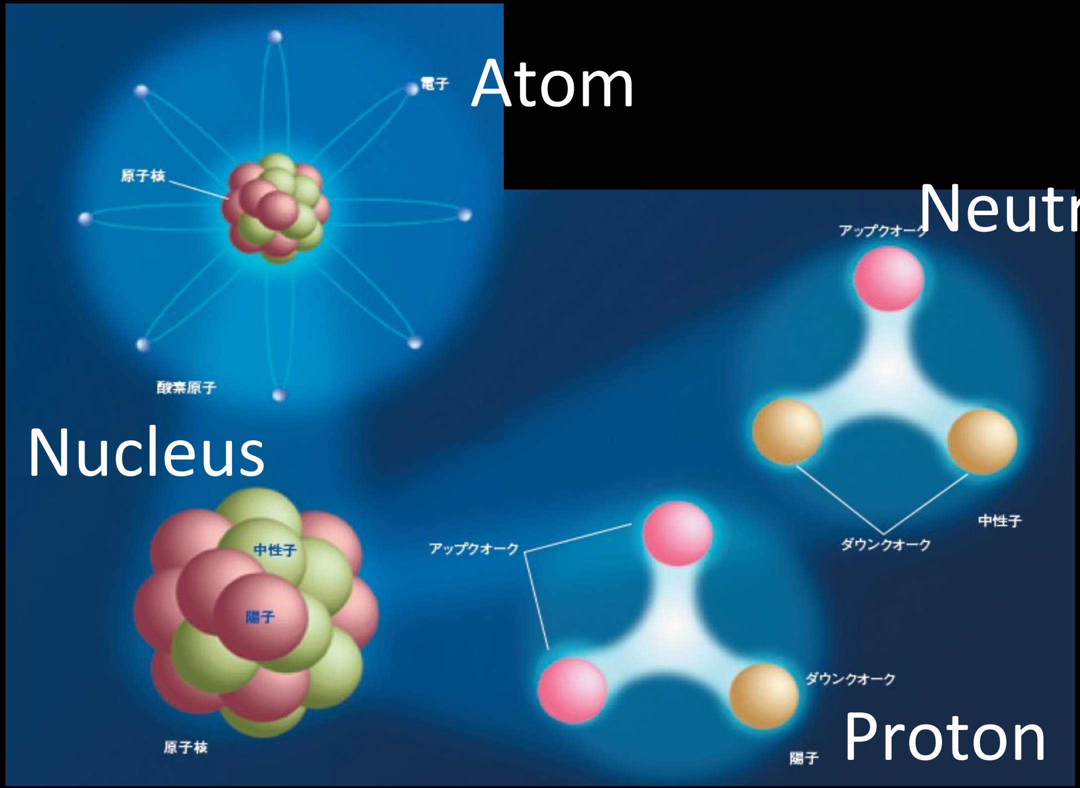
Neutrinos can easily penetrate through the Earth…

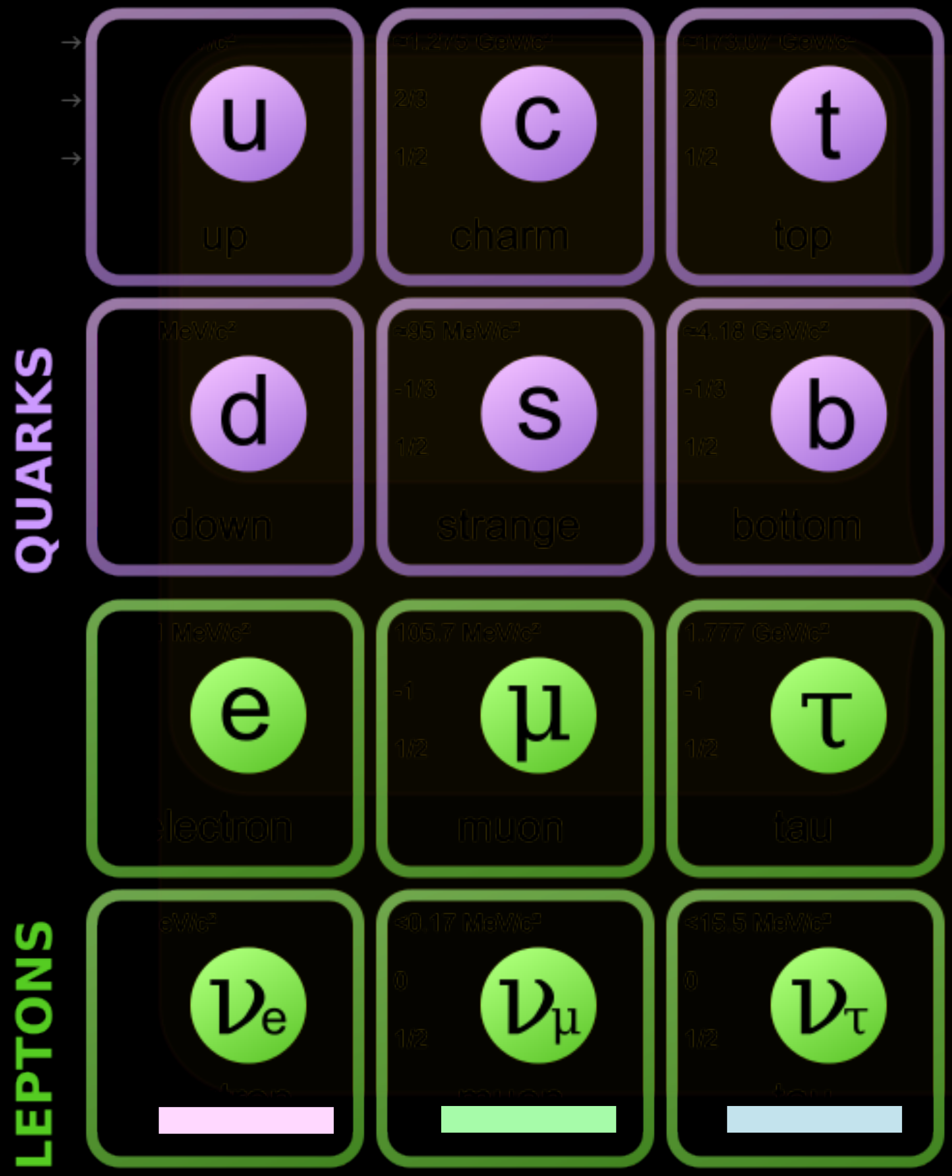
Neutrinos with the energy relevant to today's talk can penetrate through 10,000 Earths.

However, they sometime interact with matter.

Picture : NASA

3 types (flavors) of neutrinos



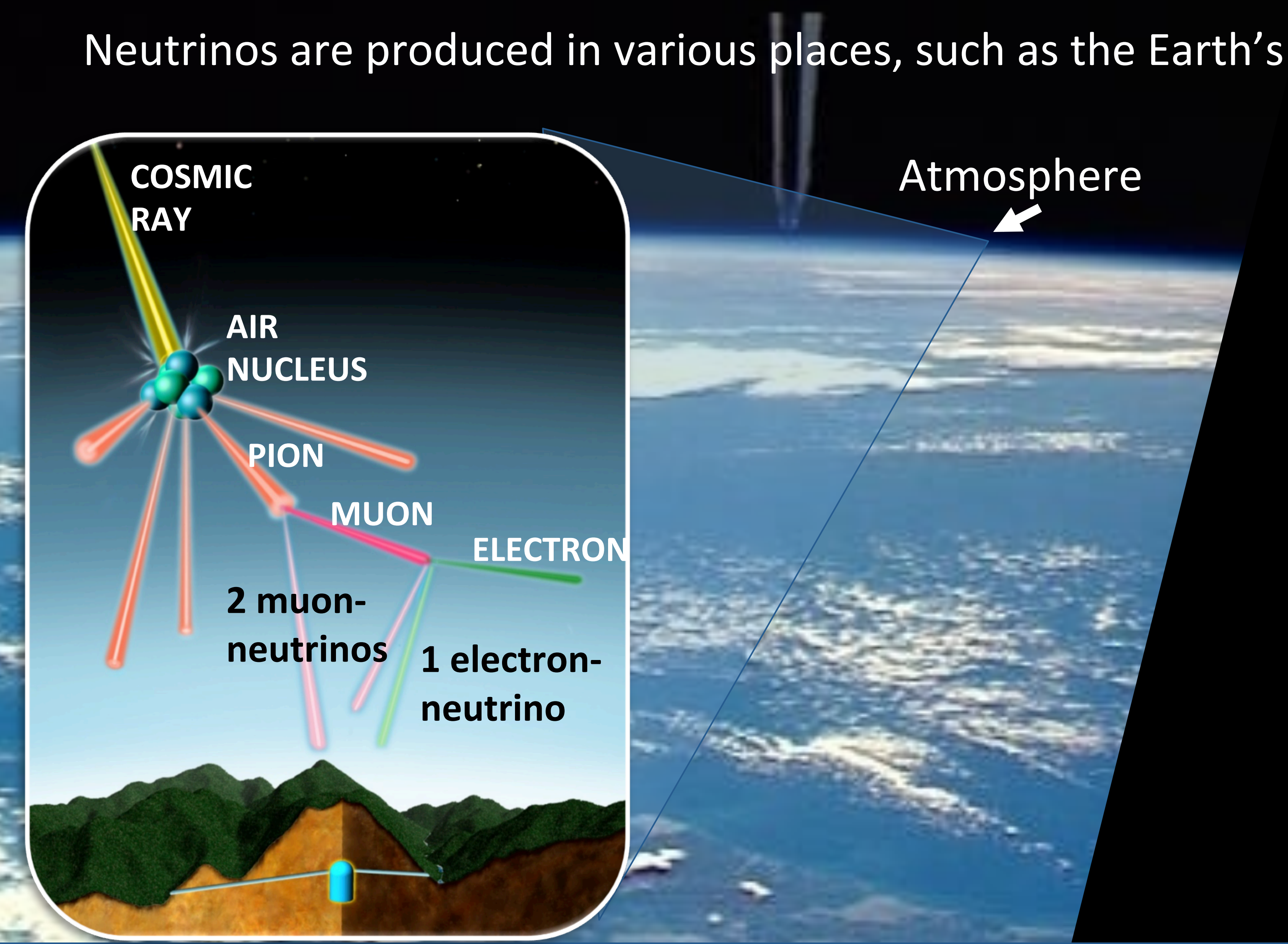


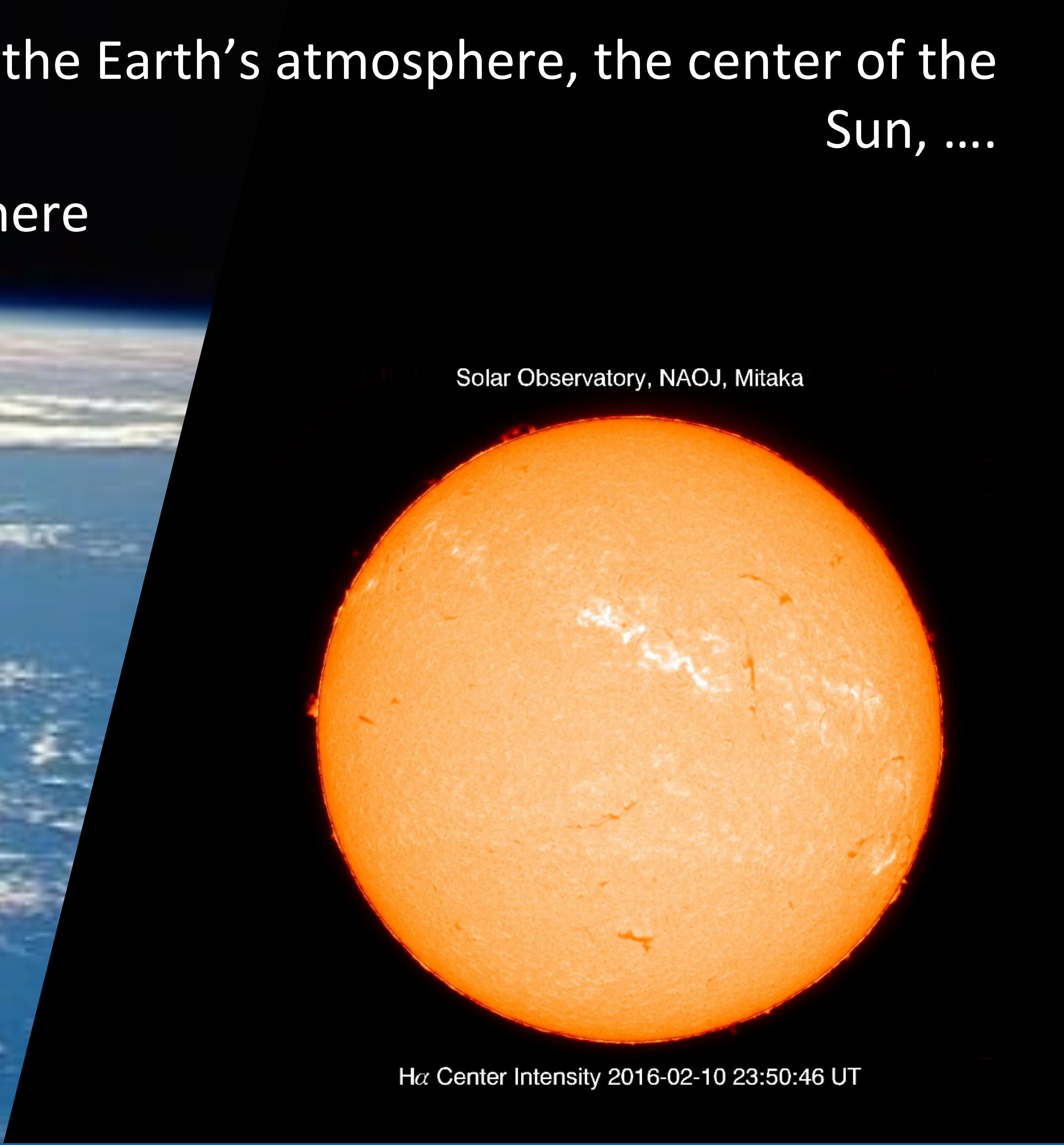
Wikipedia

Quarks and leptons are the most fundamental particles that constitute the matter.
Neutrinos are one of the leptons.
Neutrinos have 3 types (flavors): electron-neutrinos, muon-neutrinos and tau-neutrinos.

Production of neutrinos

Neutrinos are produced in various places, such as the Earth's atmosphere, the center of the Sun, ….

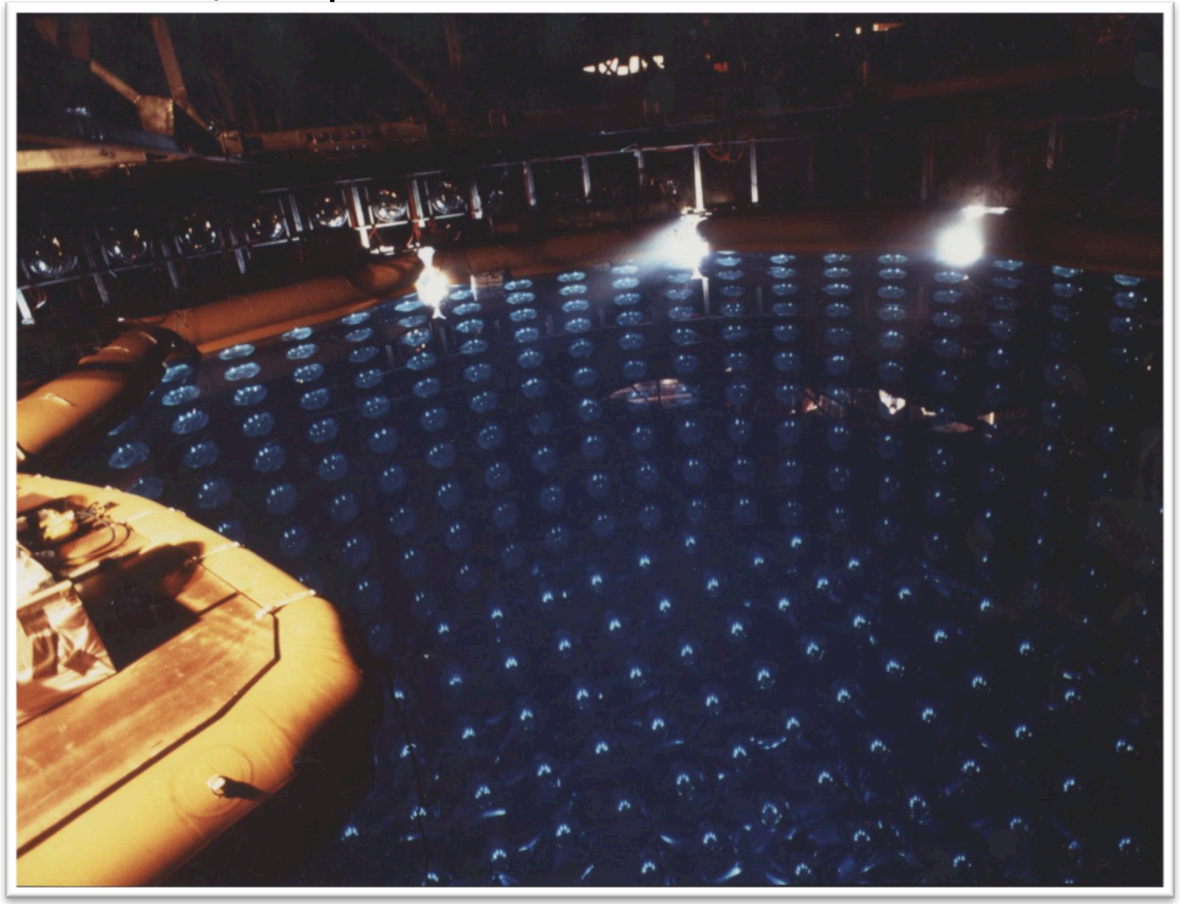




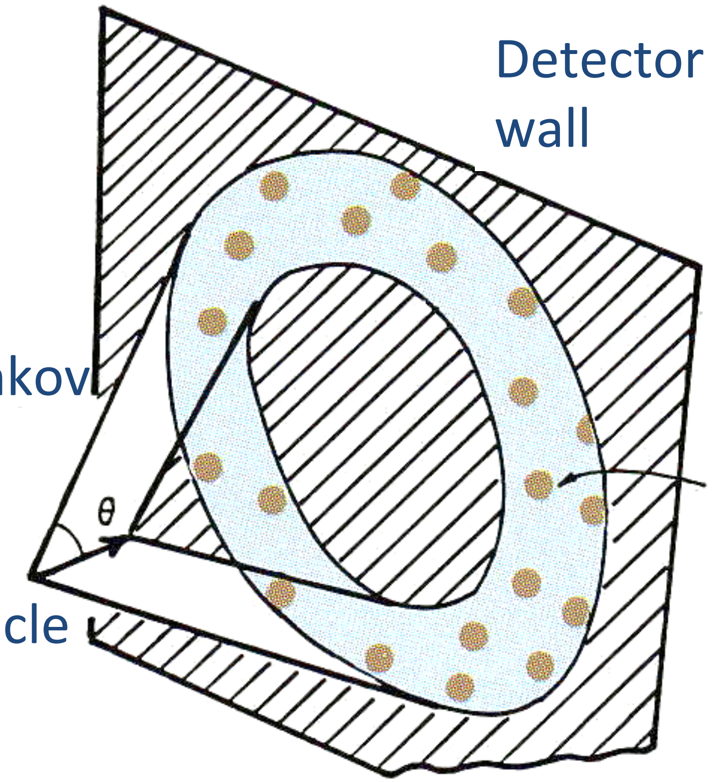
Atmospheric neutrino deficit

Kamioka Nucleon Decay Experiment (Kamiokande)

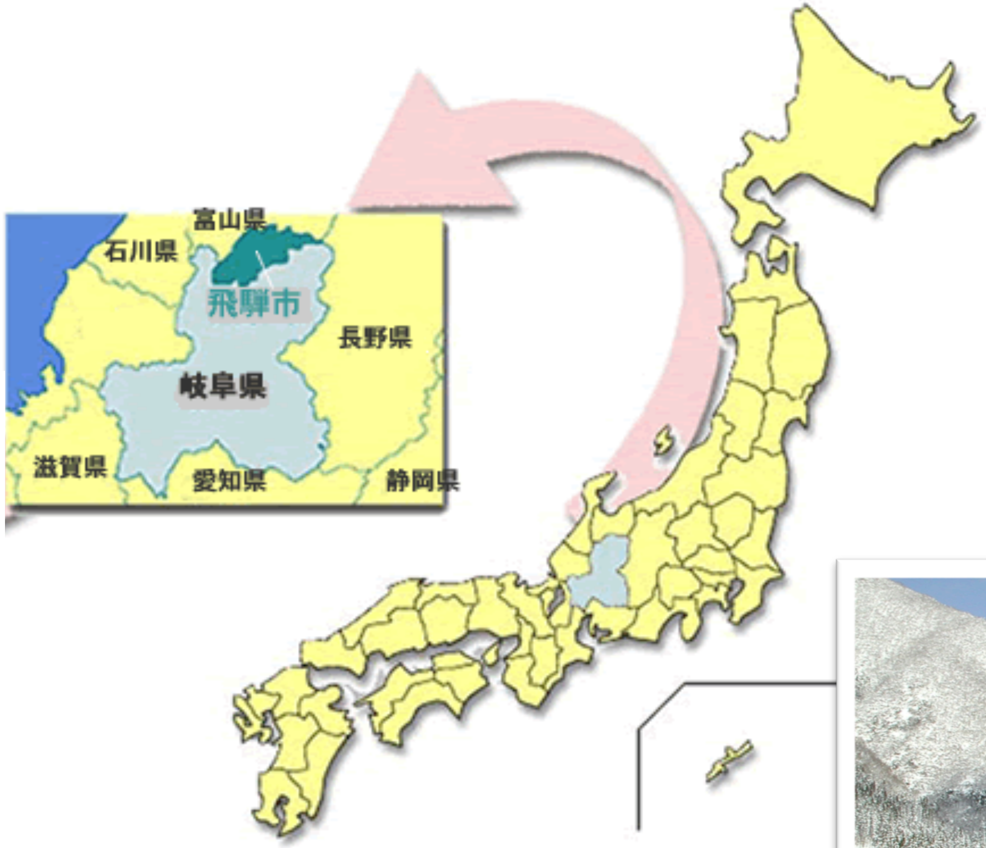
- ✓ In the late 1970's, new theories that unify Strong, Weak and Electromagnetic forces were proposed.
- ✓ These theories predicted that protons and neutrons (i.e., nucleons) should decay with the lifetime of about 10^{28} to 10^{32} years.
- ✓ Several proton decay experiments began in the early 1980's.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

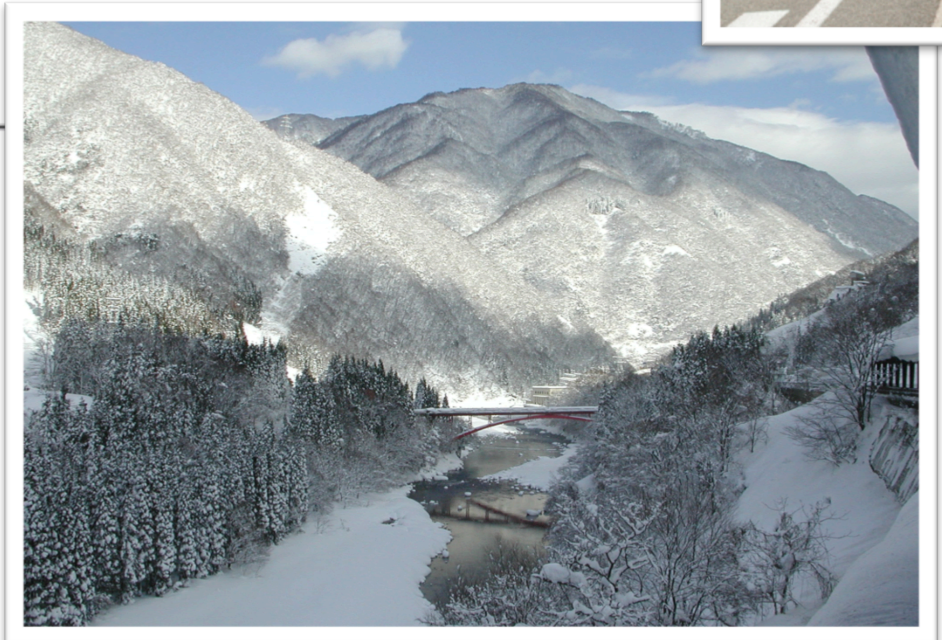


Kamiokande (1000 ton fiducial volume)



Where is Kamioka?

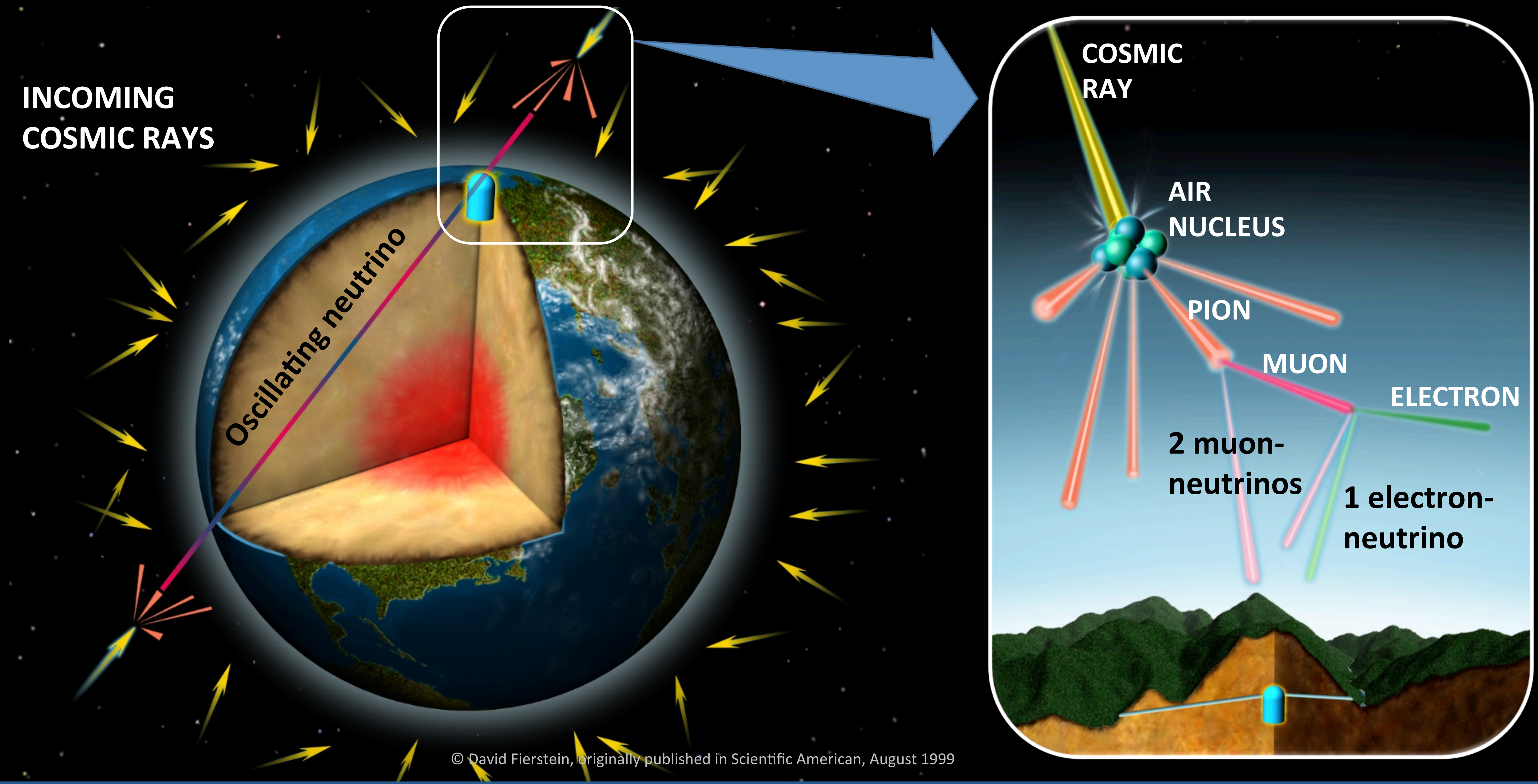




Kamiokande construction team (Spring 1983)

Constructing the Kamiokande detector (Spring 1983)

Atmospheric neutrinos



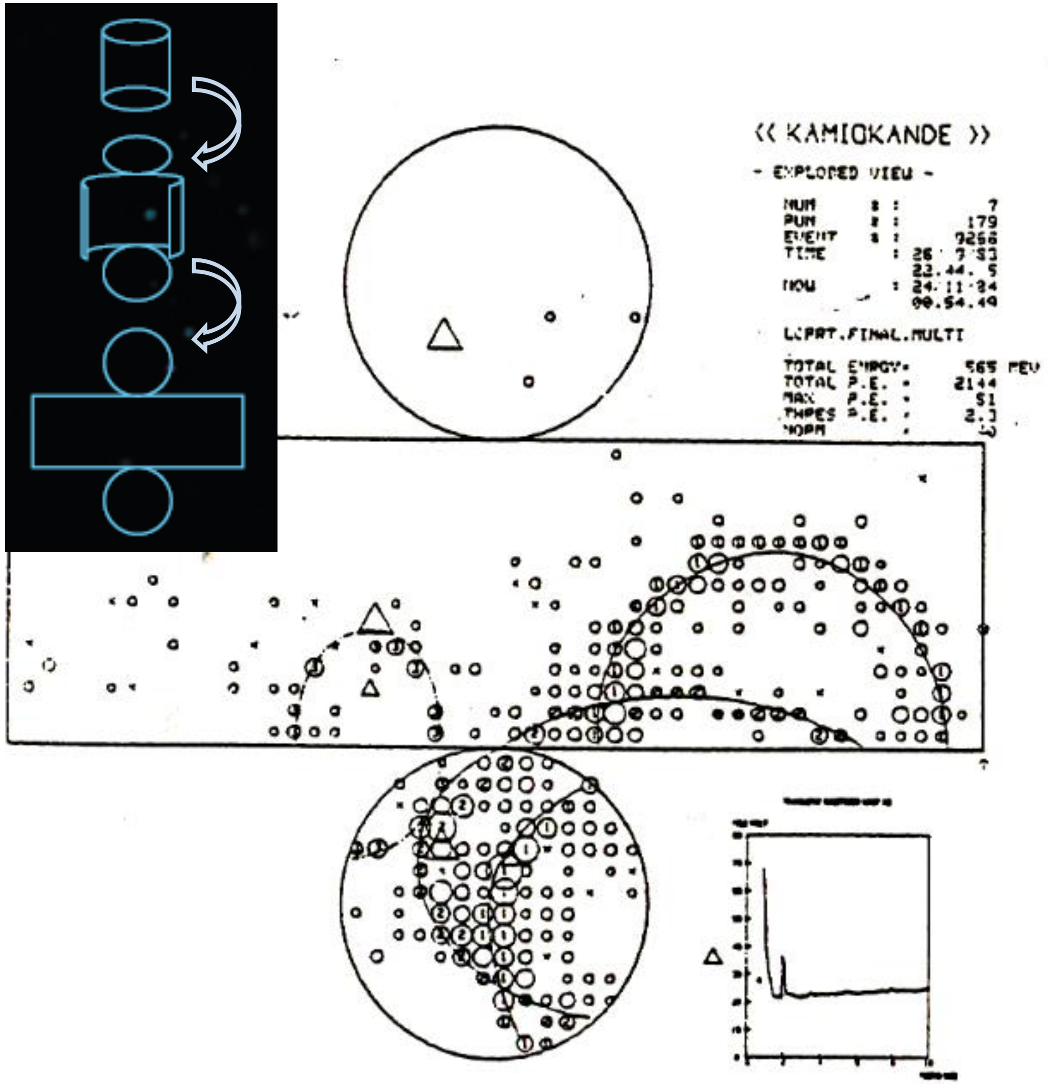
1986...

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.

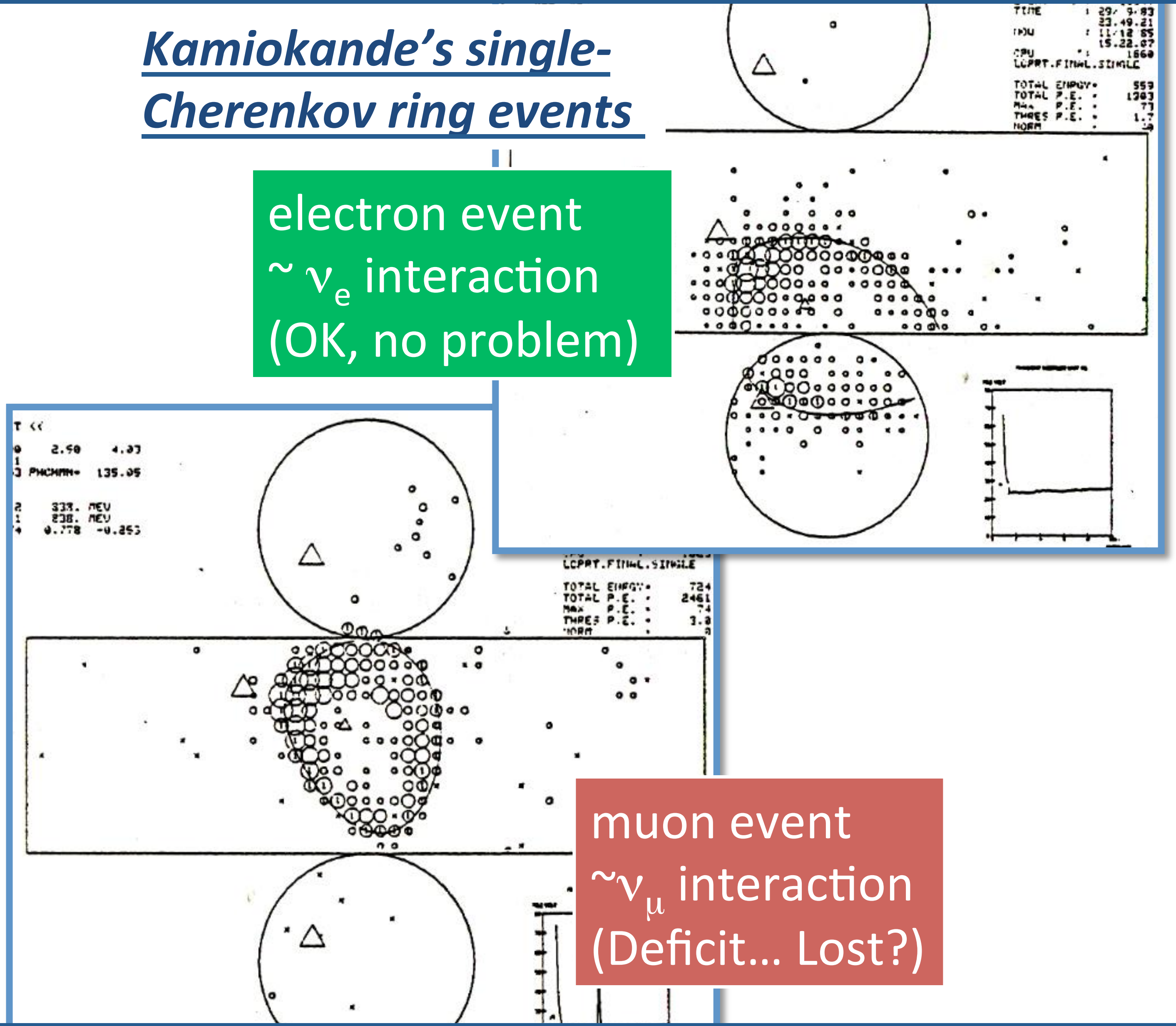
The new software was applied to single Cherenkov-ring events, which were the easiest events to analyze....



Multi-ring event observed in Kamiokande.

A strange result…

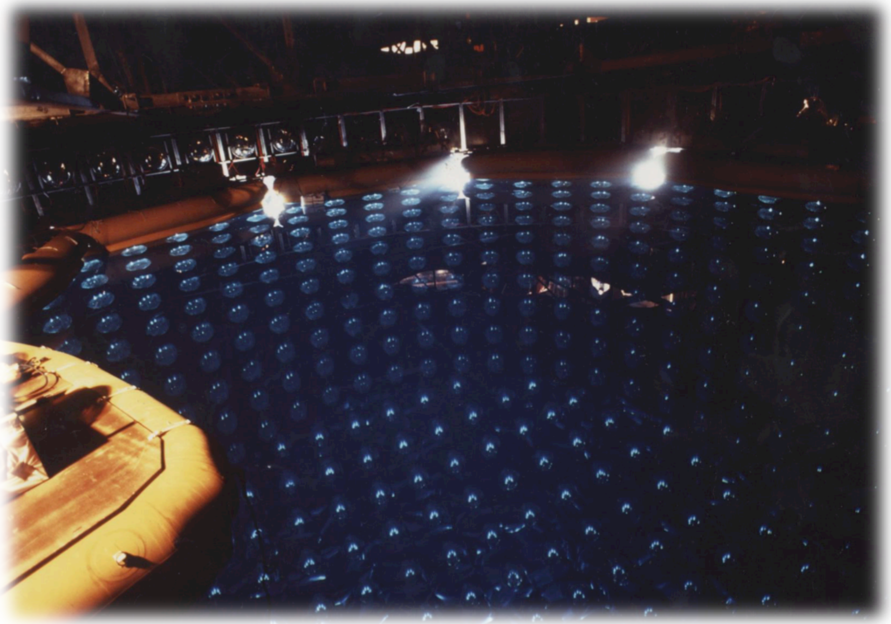
- The neutrino flavor was studied for the atmospheric neutrino events.
- The result was strange. The number of ν_μ events was much fewer than expected.
- I thought that it is very likely that there are some mistakes somewhere in the simulation, data reduction, and/or event reconstruction.
- We started various studies to find mistakes in the late 1986.



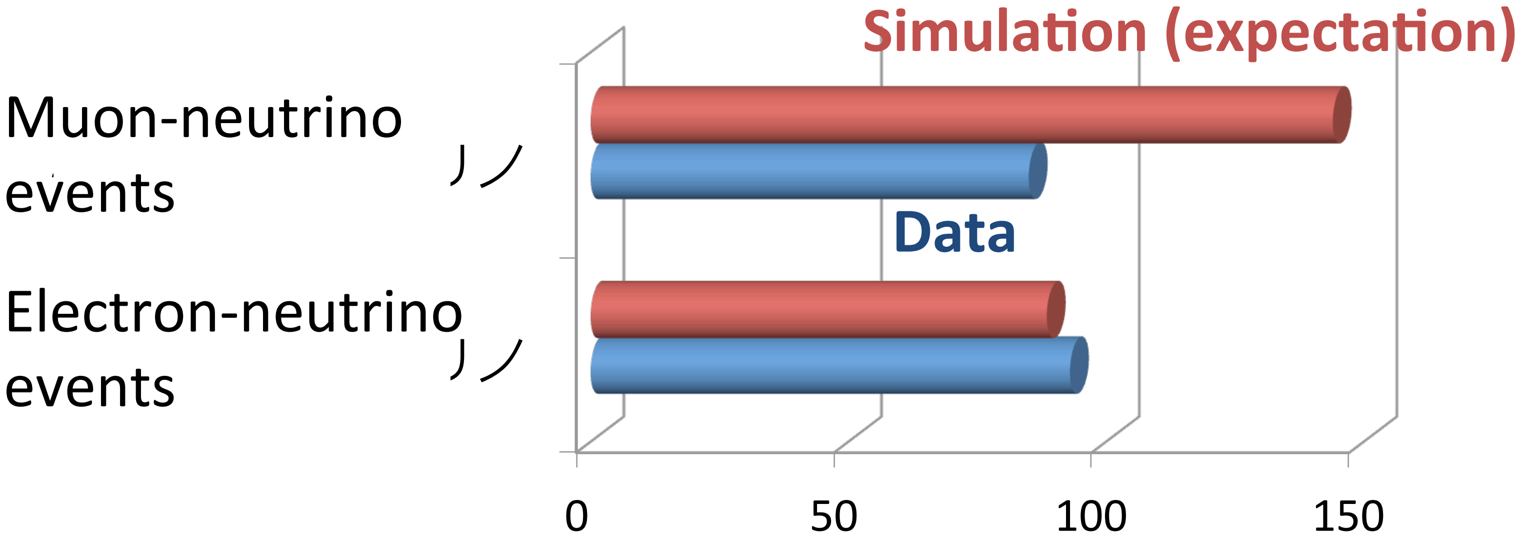
Result on the ν_μ deficit (1988)

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.

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



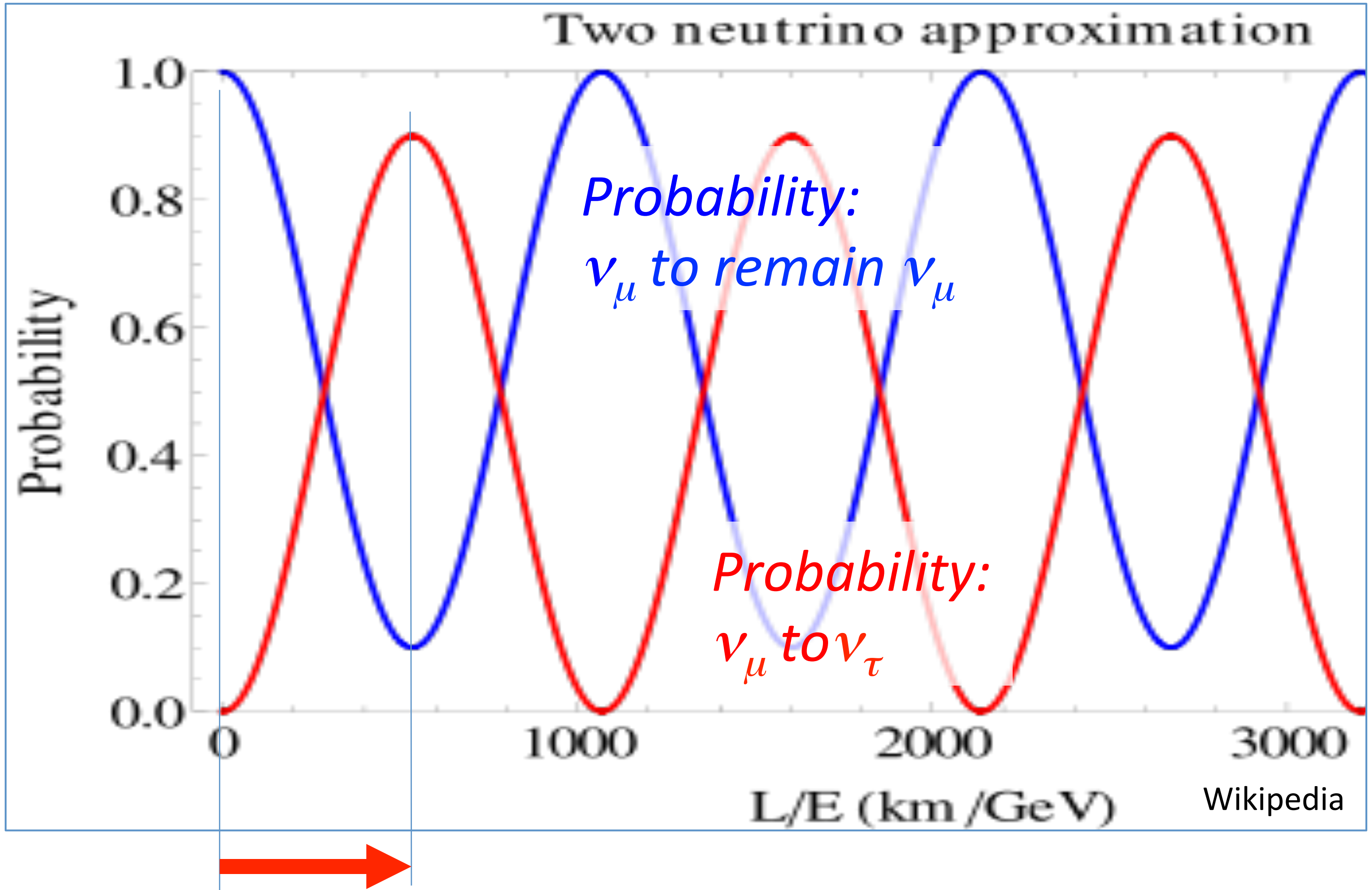
Kamiokande



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.”

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.



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).

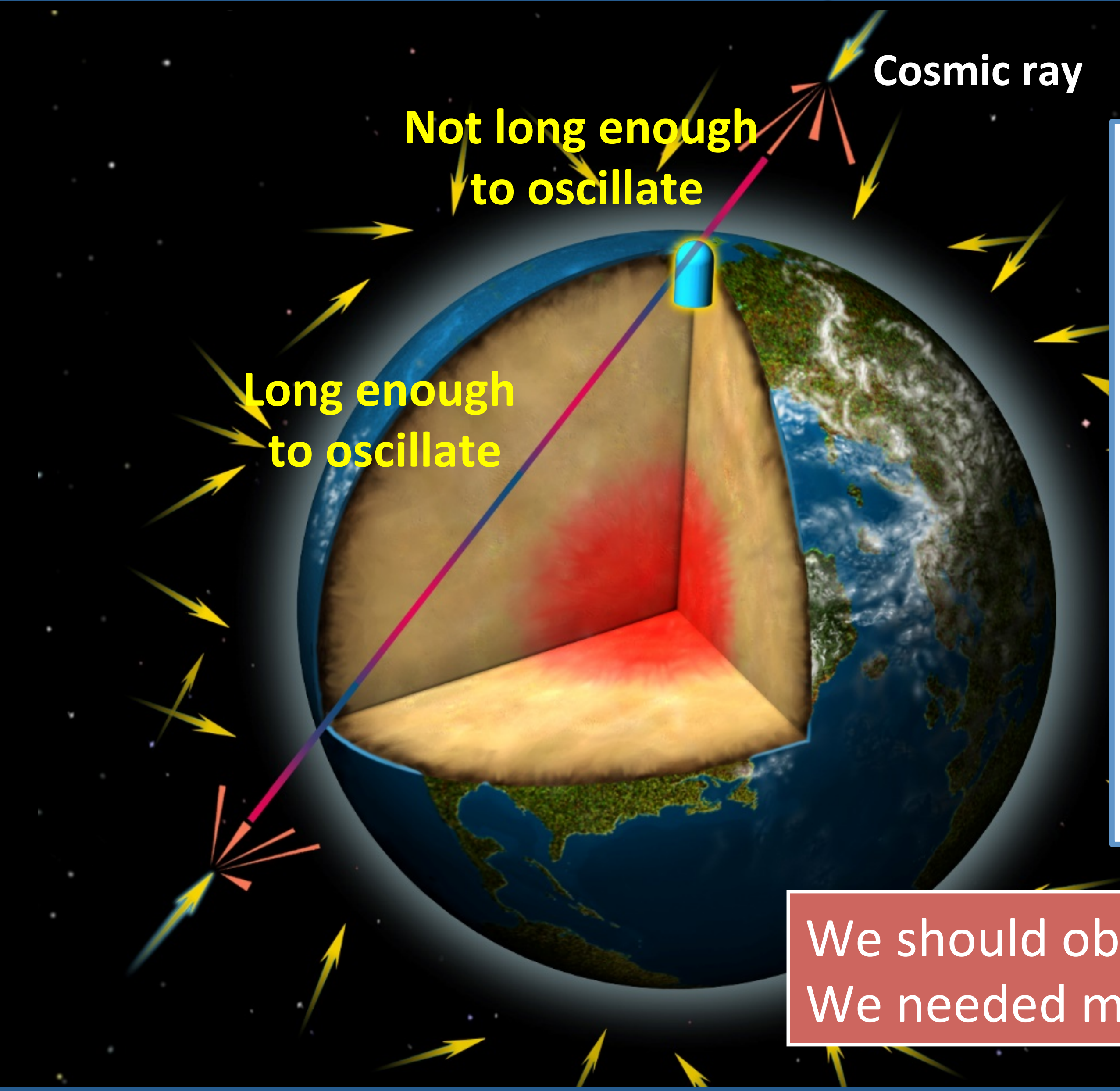
If neutrino mass is smaller, the oscillation length (L/E) gets longer.

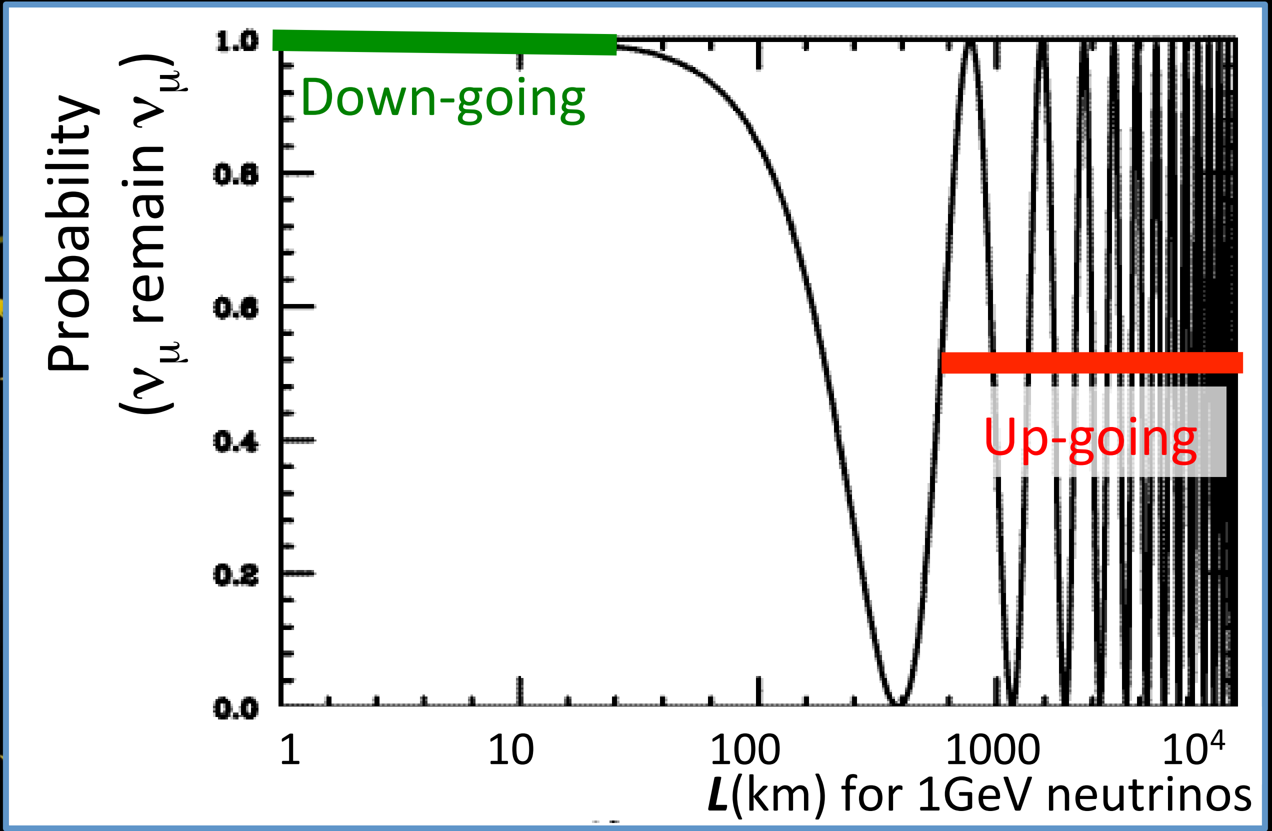
Results from IMB on the ν_μ deficit

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

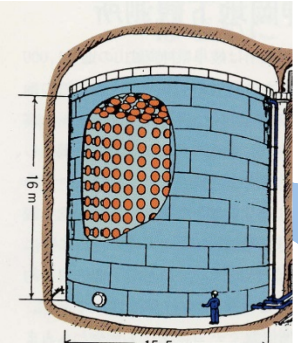




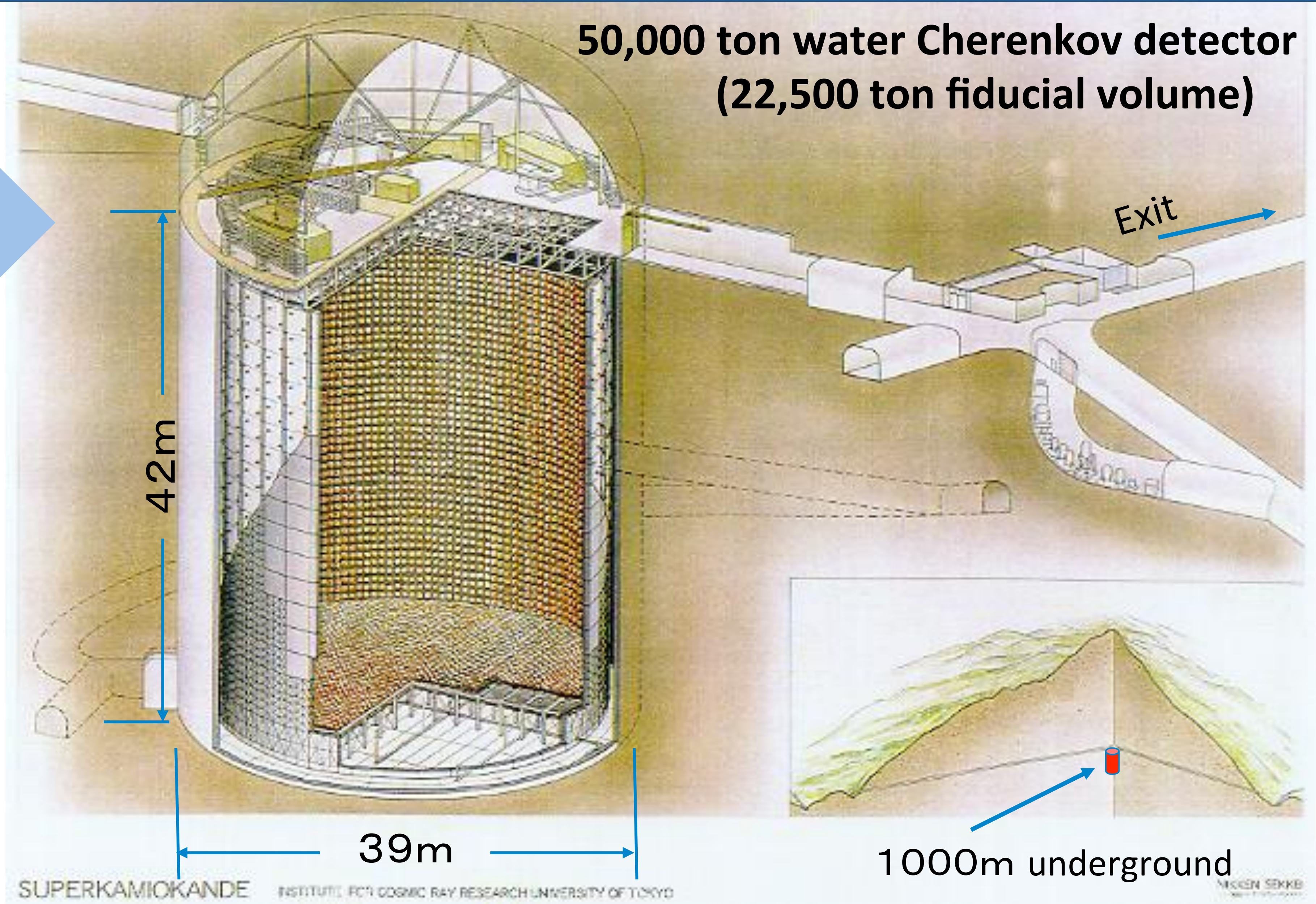
We should observe a deficit of upward going ν_μ's!
We needed much larger detector. ➔ Super-Kamiokande

Discovery of neutrino oscillations

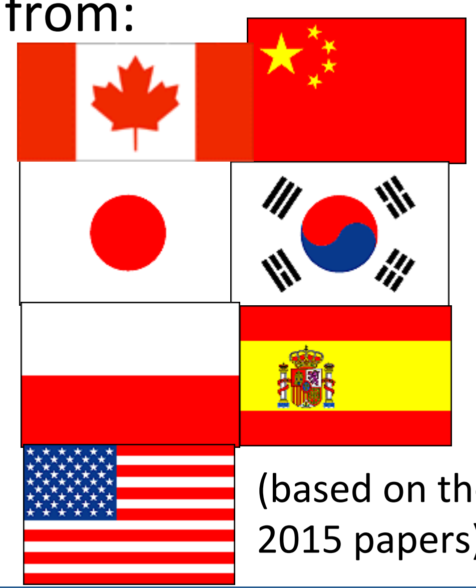
Super-Kamiokande detector



More than 20
times larger mass



~120 collaborators
from:

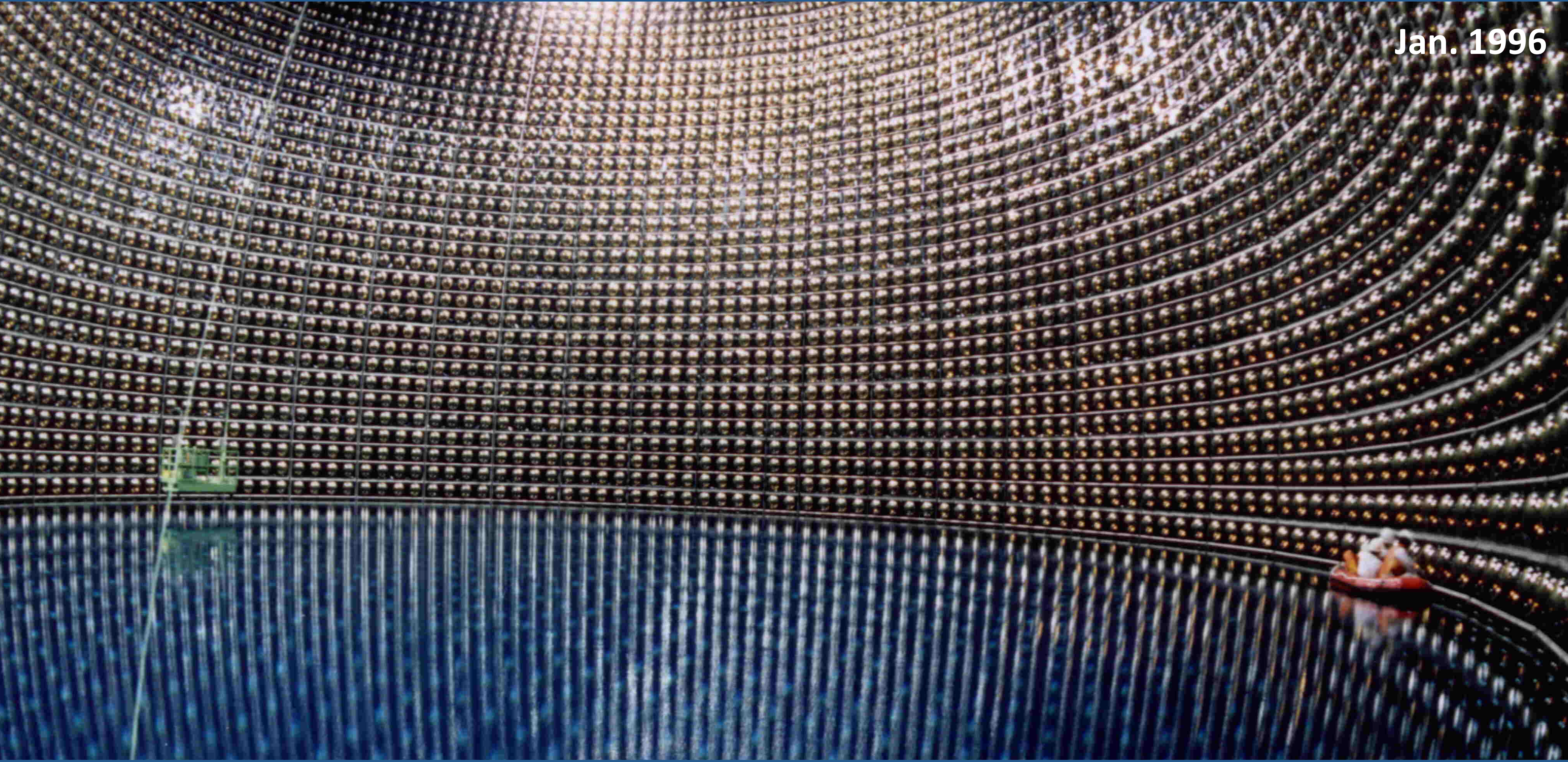


(based on the
2015 papers)

Constructing the Super-Kamiokande detector (spring 1995)

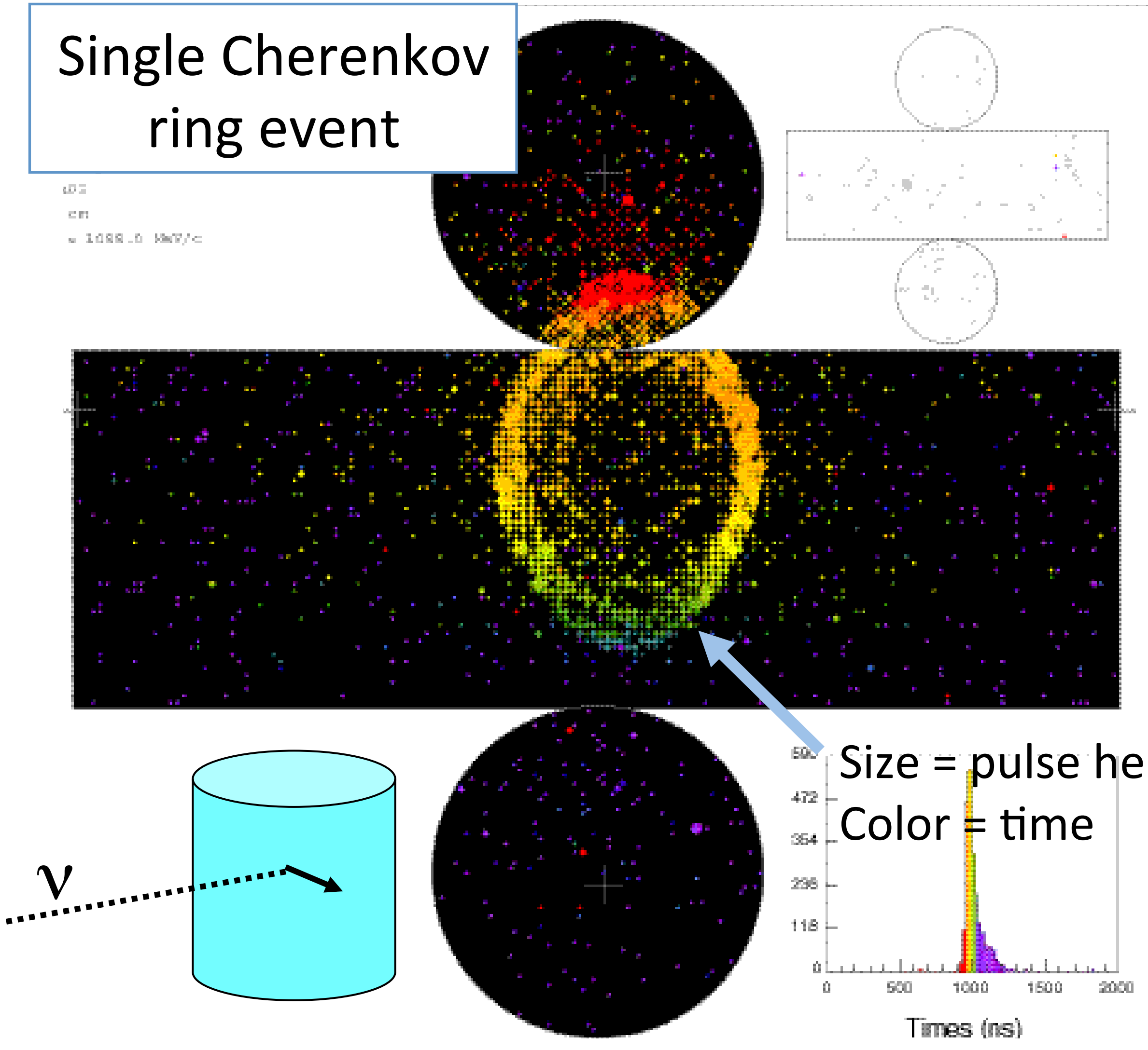
Y. Totsuka

Filling water in Super-Kamiokande



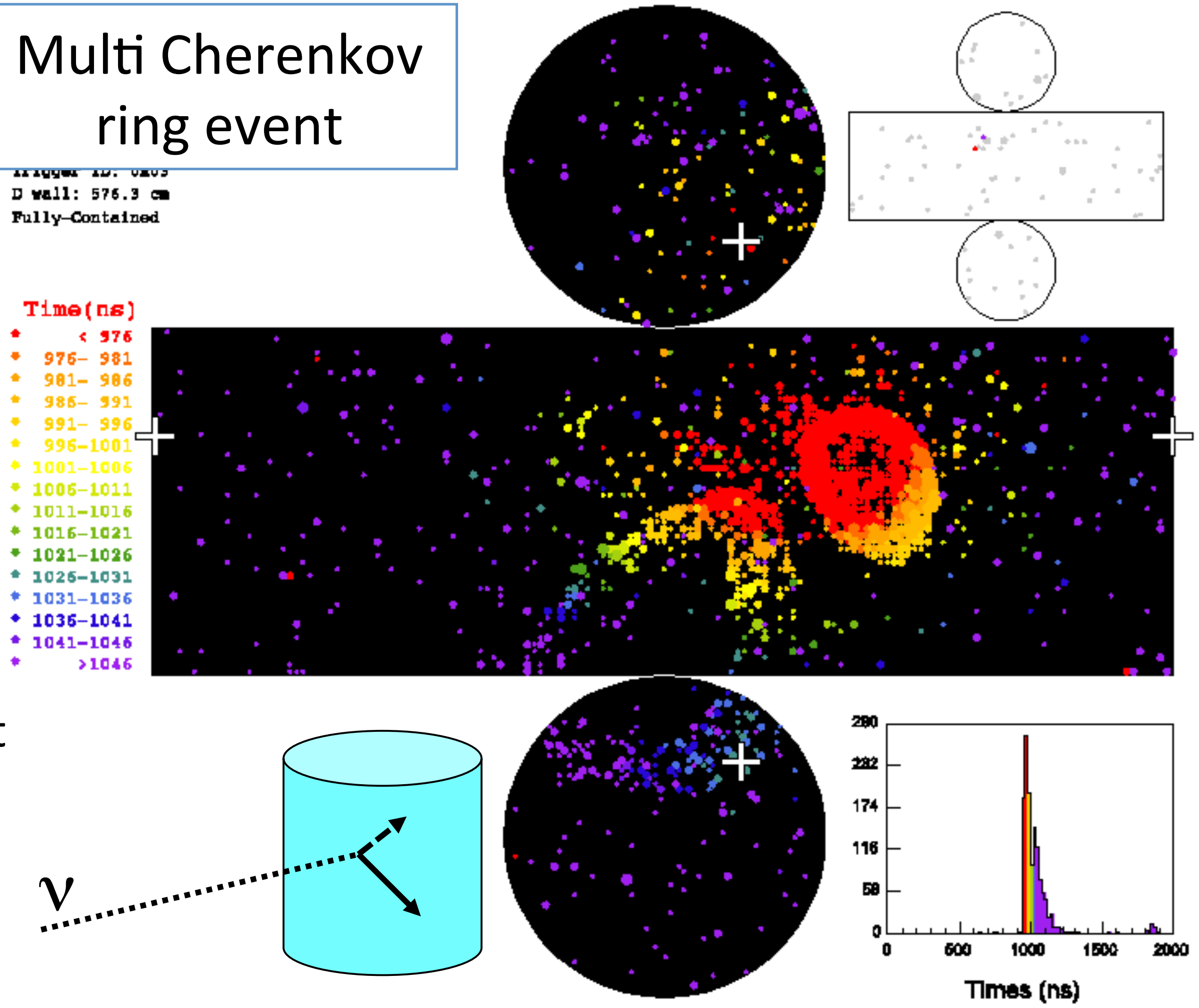
Atmospheric neutrino events observed in Super-K (1)

Single Cherenkov ring event

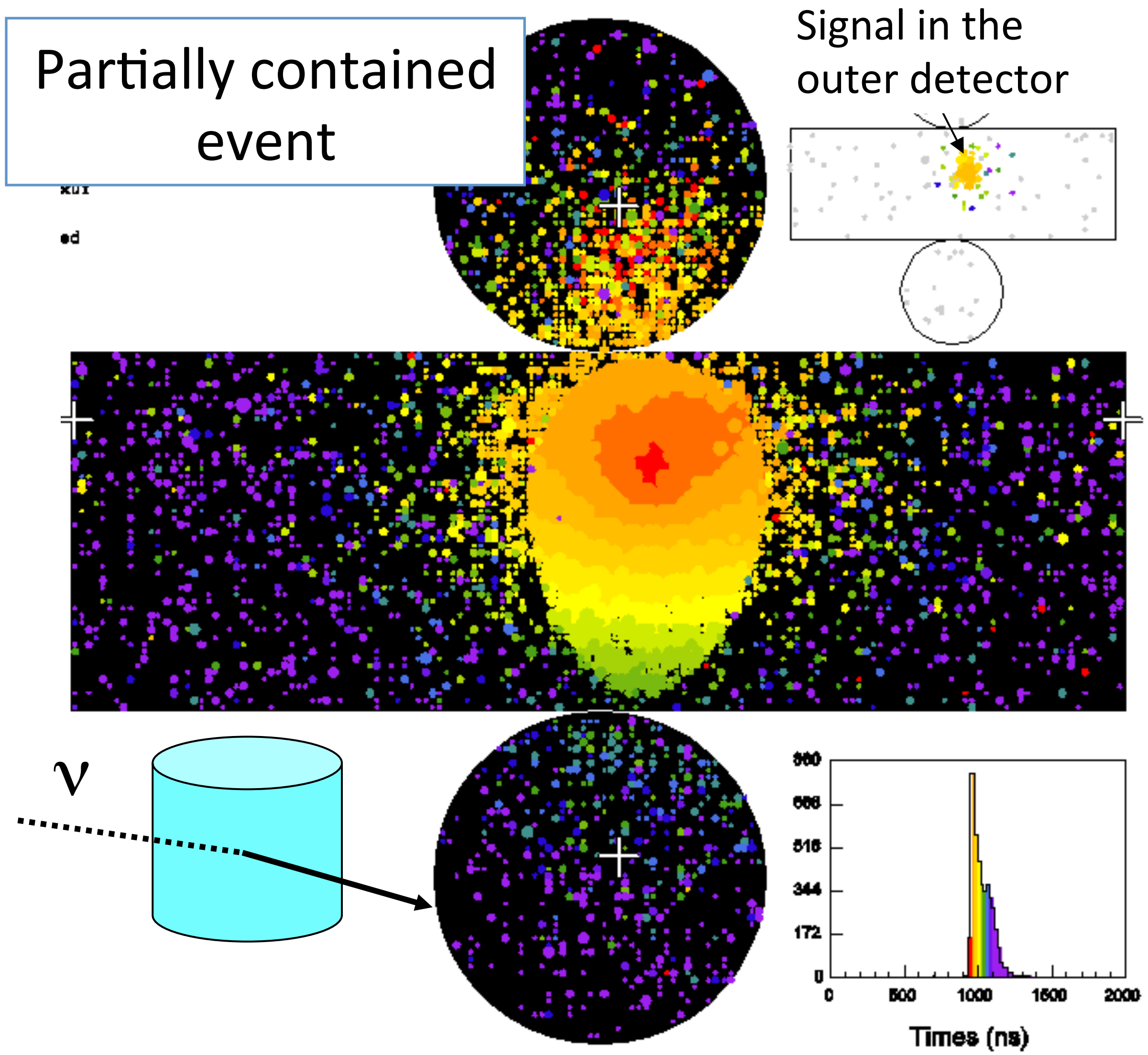


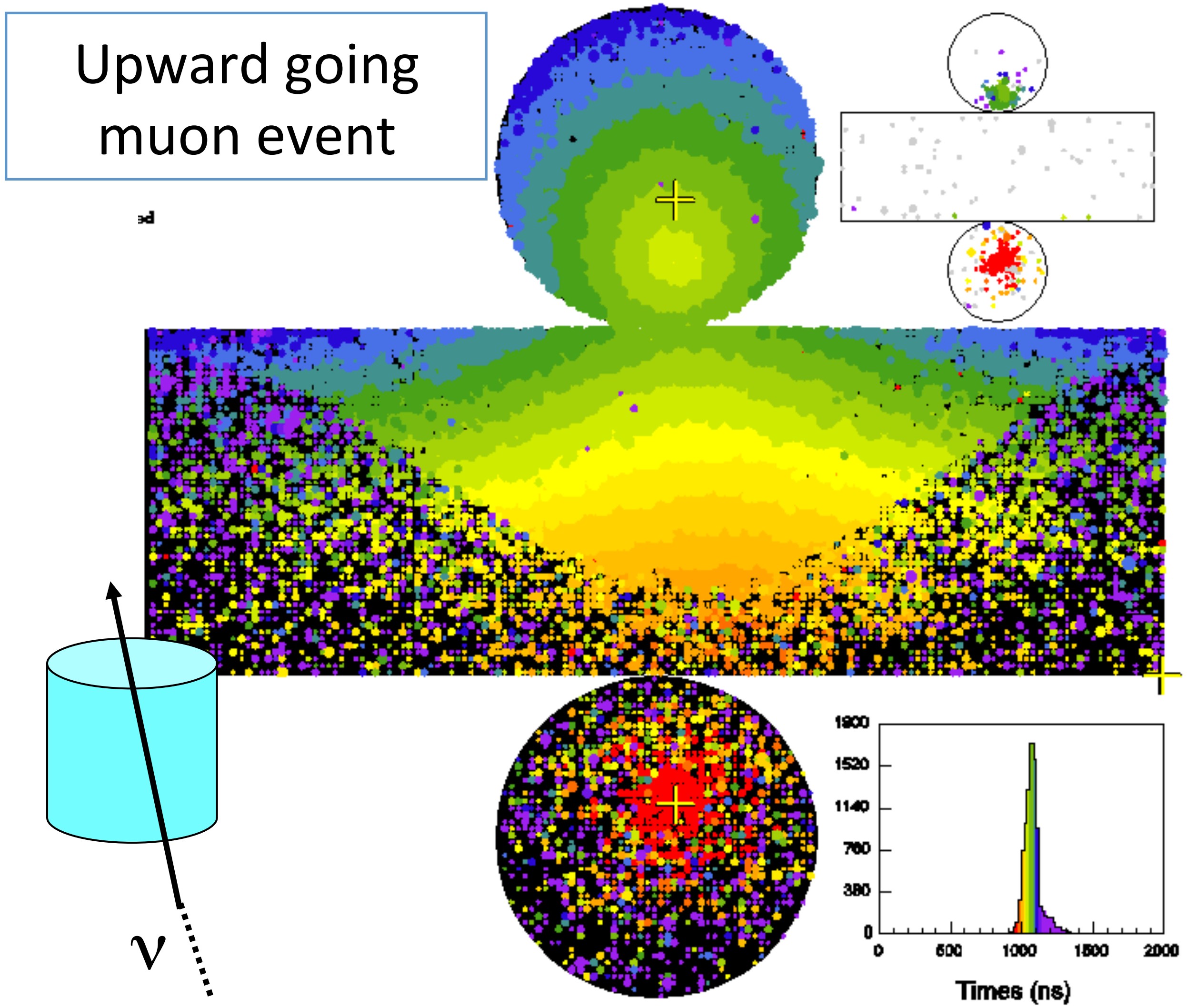
Size = pulse height
Color = time

Multi Cherenkov ring event



Atmospheric neutrino events observed in Super-K (2)

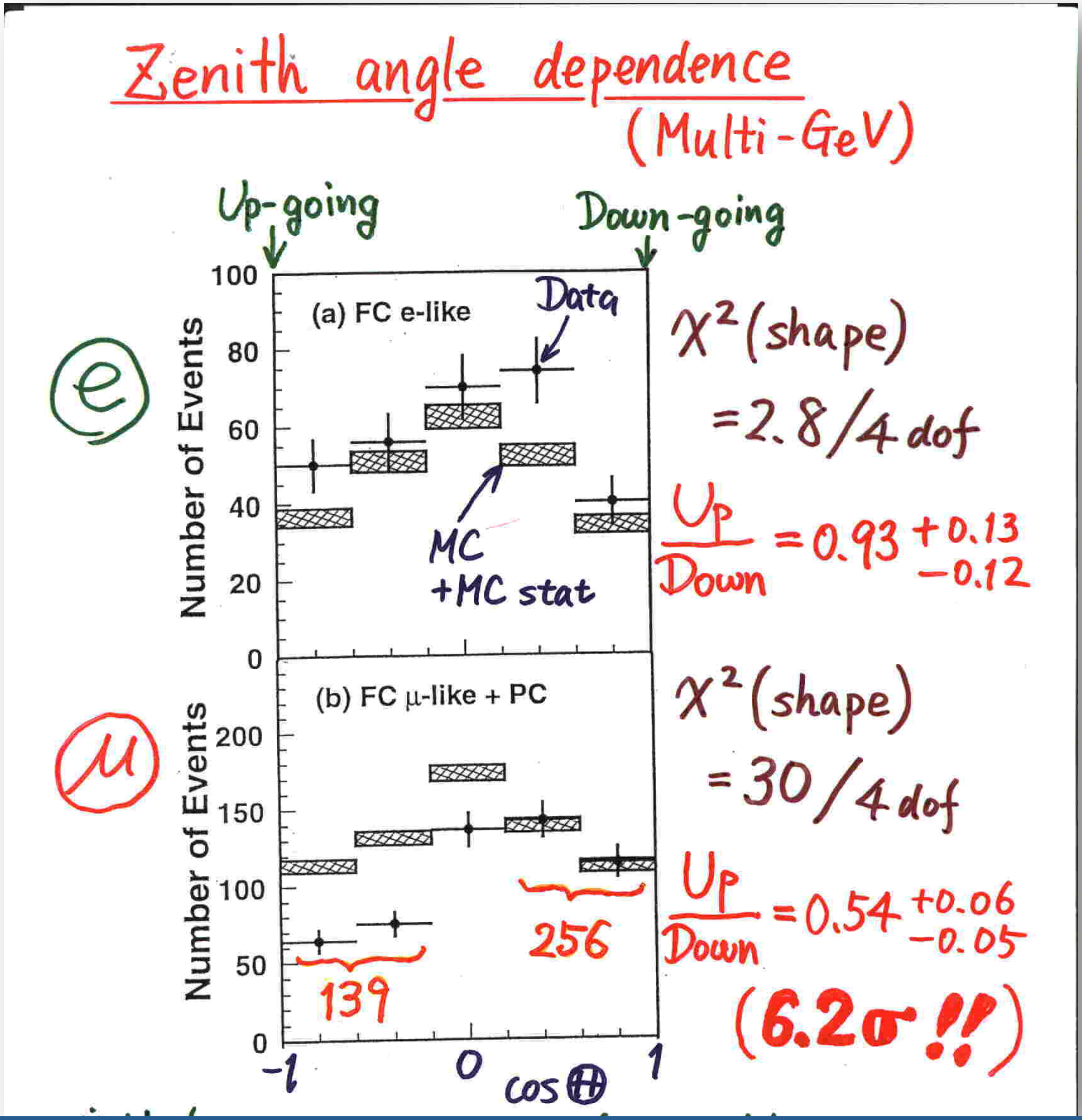


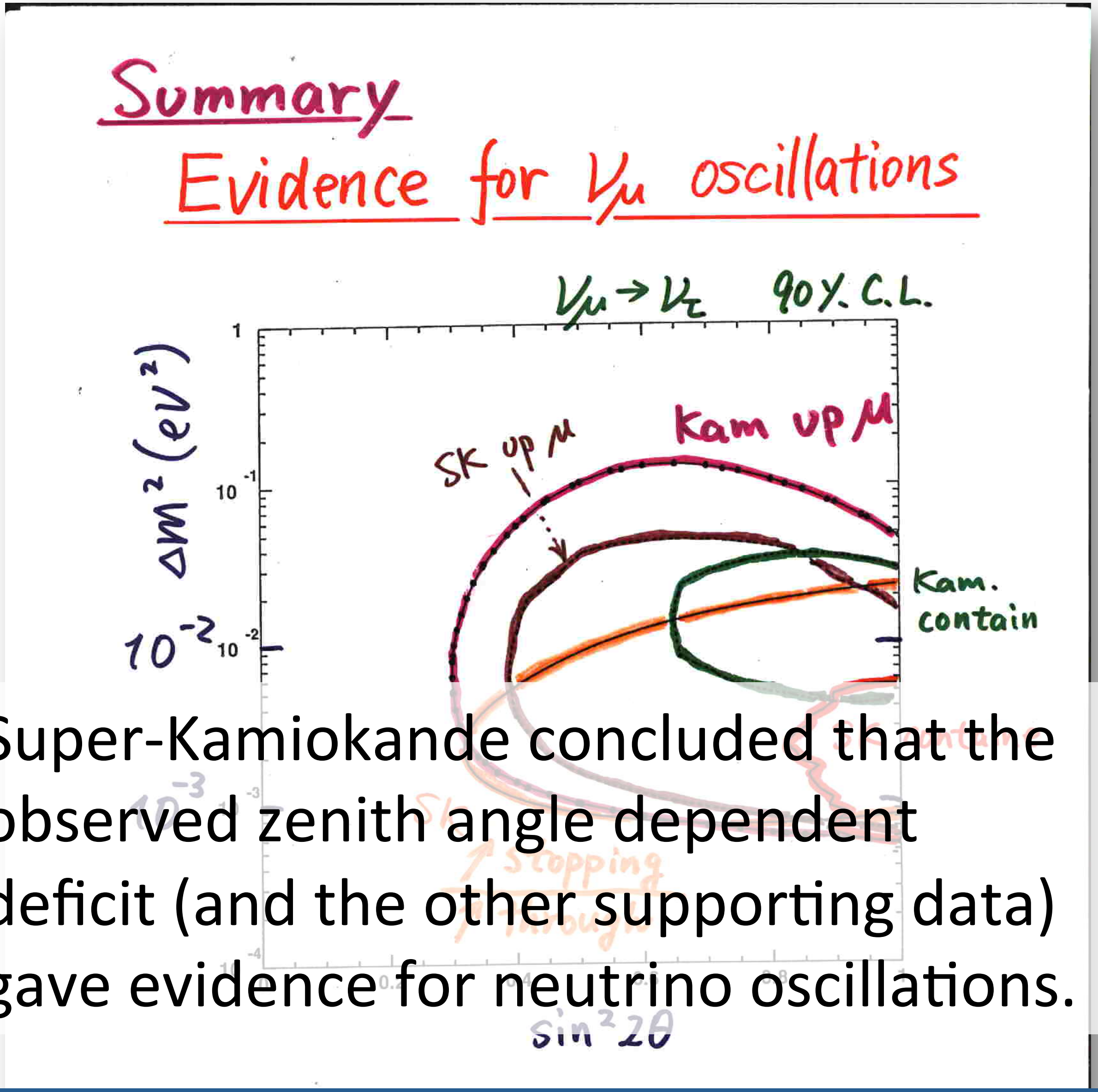


All these events are used in the analysis. ← ***Collaborative work of many (young) people!***

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

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

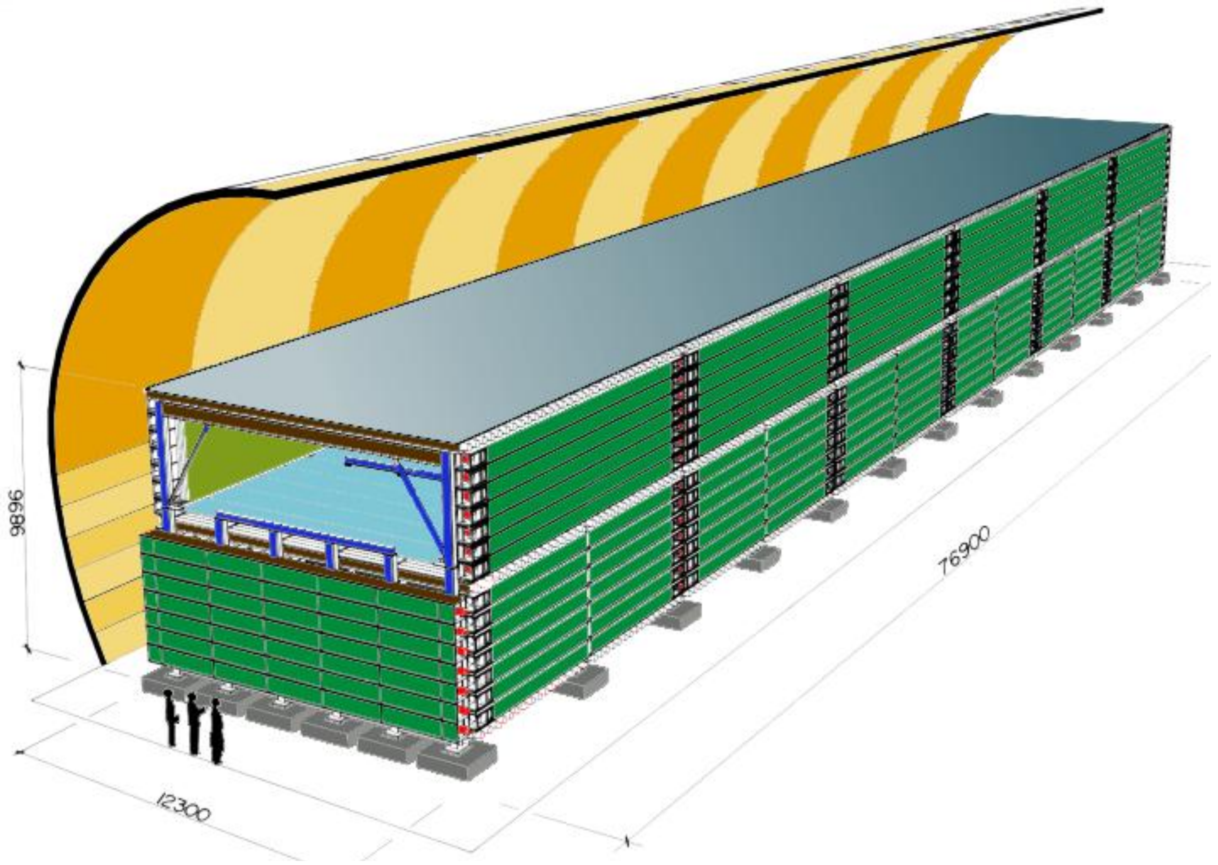




Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Results from the other atmospheric neutrino experiments

MACRO

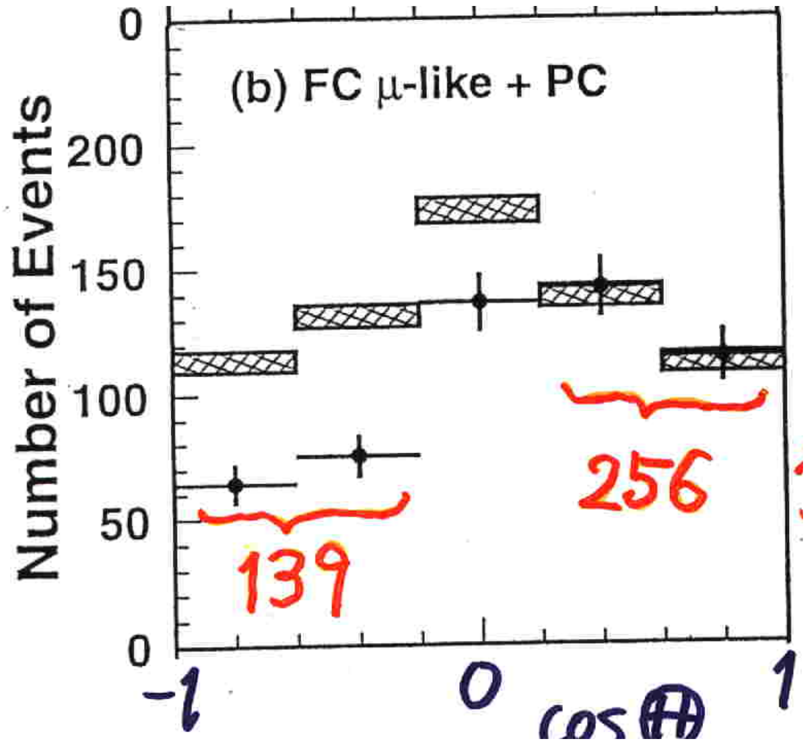


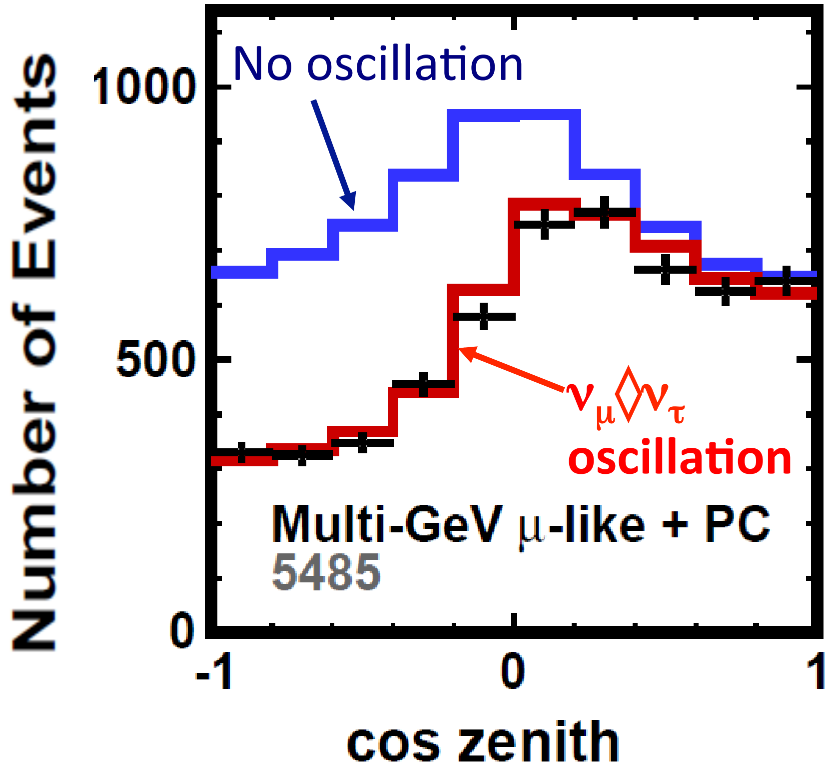
Soudan-2

These experiments observed atmospheric neutrinos and confirmed neutrino oscillations.

Data updates and neutrino masses and mixing angles

Super-K @Neutrino98 → Super-K (2015)





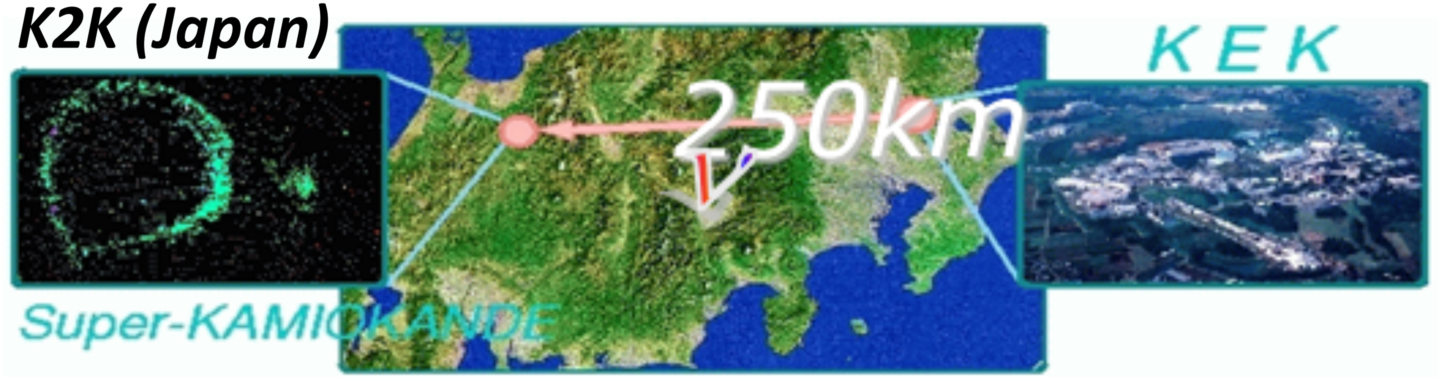
Number of events plotted: 531 events → 5485 events

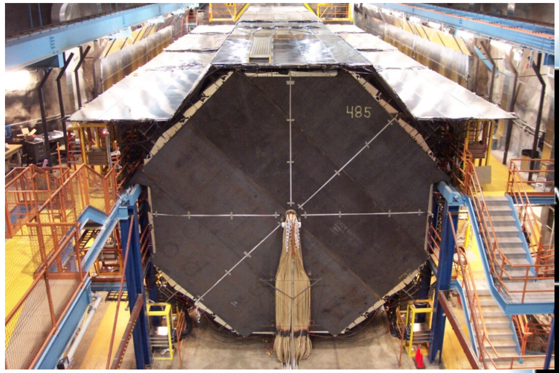
Various studies of neutrino oscillations have been carried out with these data!

Neutrino oscillation studies

In addition to atmospheric neutrino experiments, various accelerator based long baseline neutrino oscillation experiments have been studying neutrino oscillations.

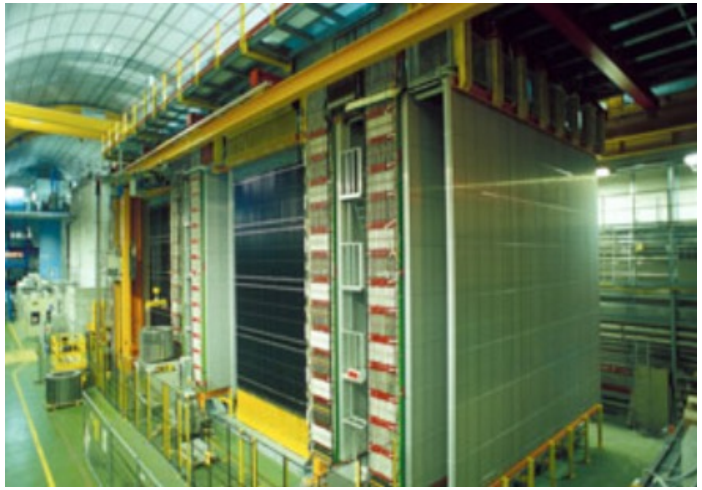
K2K (Japan)





MINOS (USA)

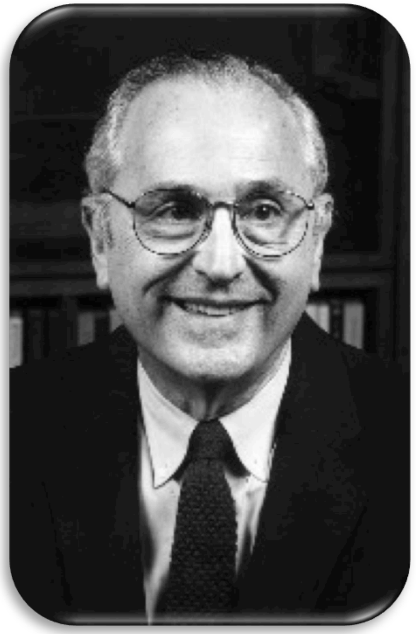
OPERA (Europe)



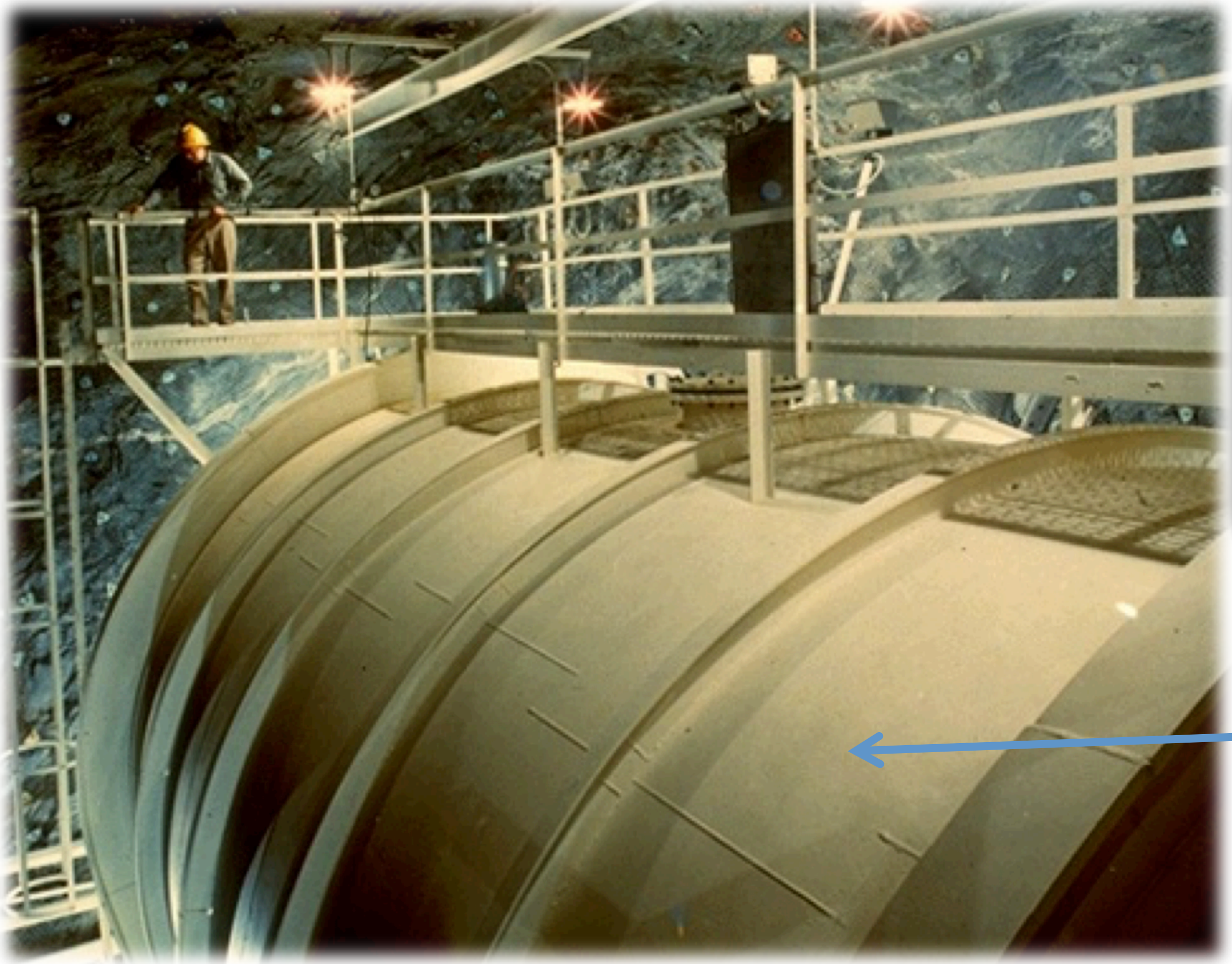
T2K (Japan)

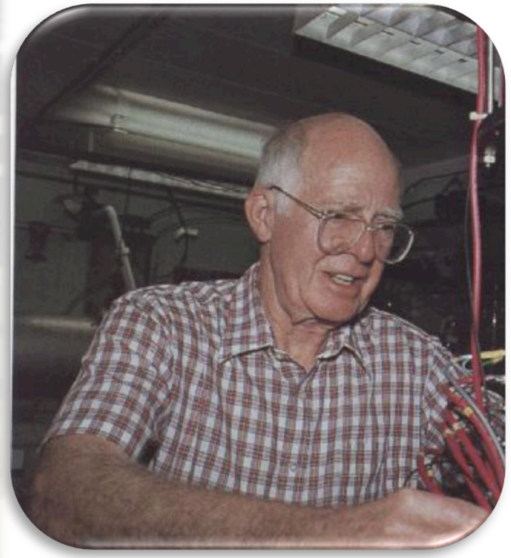
Present status of neutrino oscillations

Solar neutrino problem



J. N. Bahcall



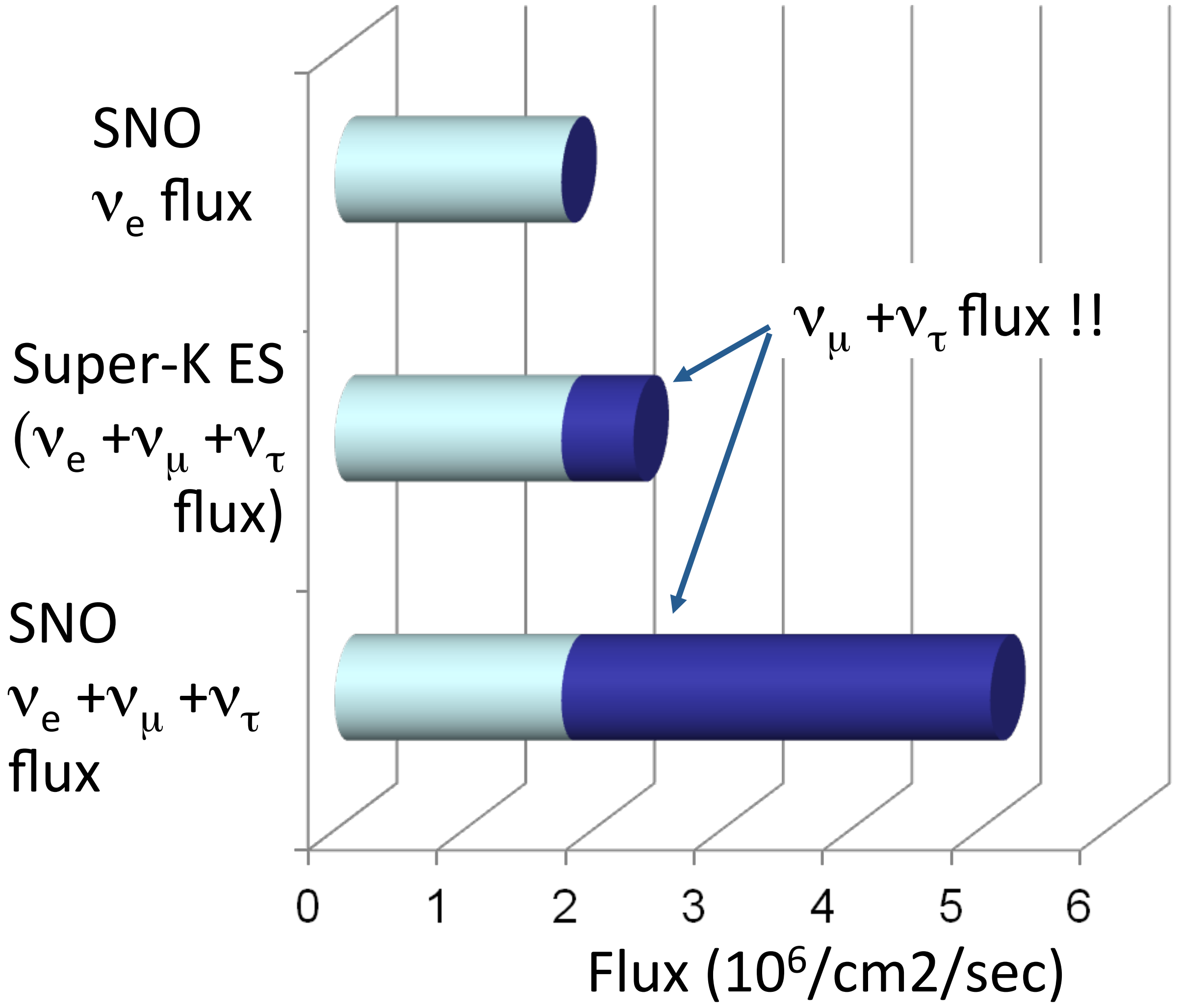


R. Davis Jr.

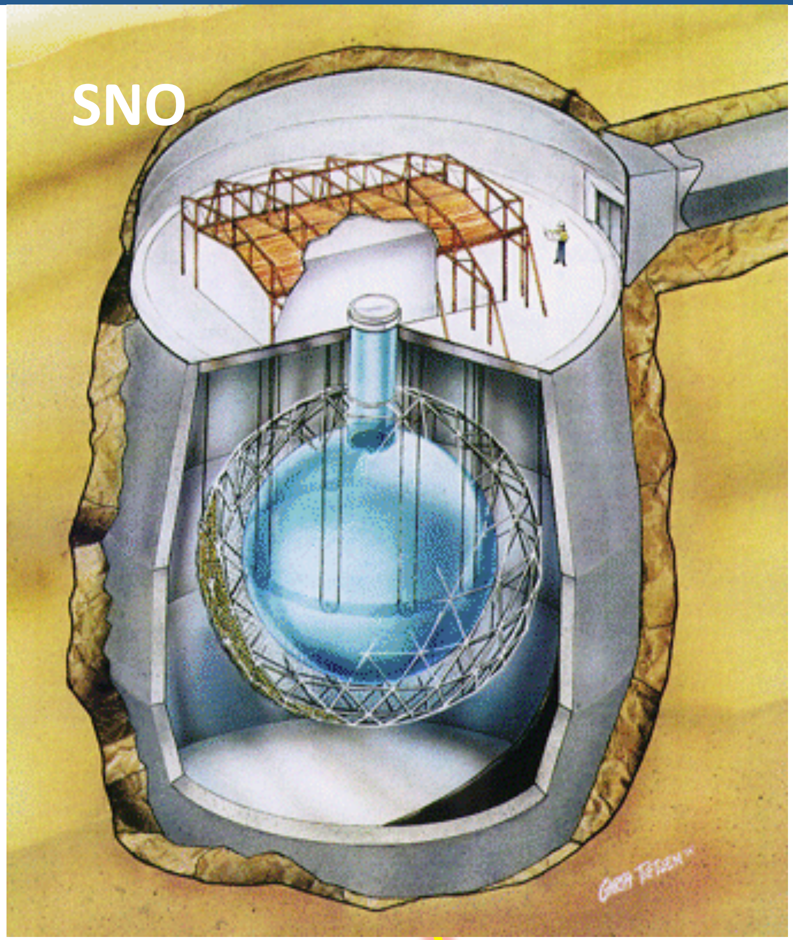
600ton
C_2Cl_4

Pioneering Homestake solar neutrino experiment observed only about 1/3 of the predicted solar neutrinos (1960's).
This problem was confirmed by the subsequent experiments in the 1980's and 90's.

Solving the solar neutrino problem (2001-2002)



Neutrino oscillation: electron neutrinos to the other neutrinos.

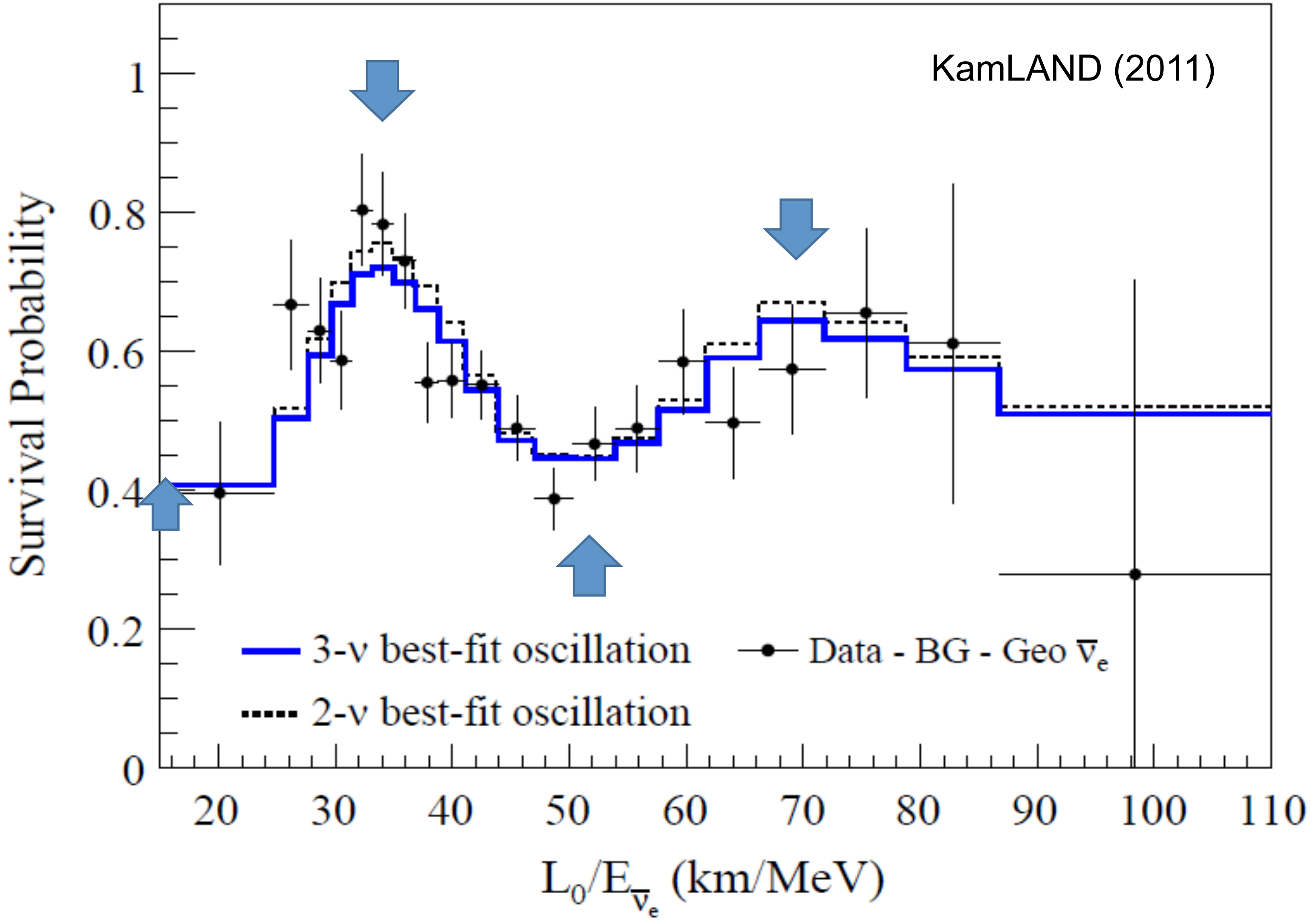


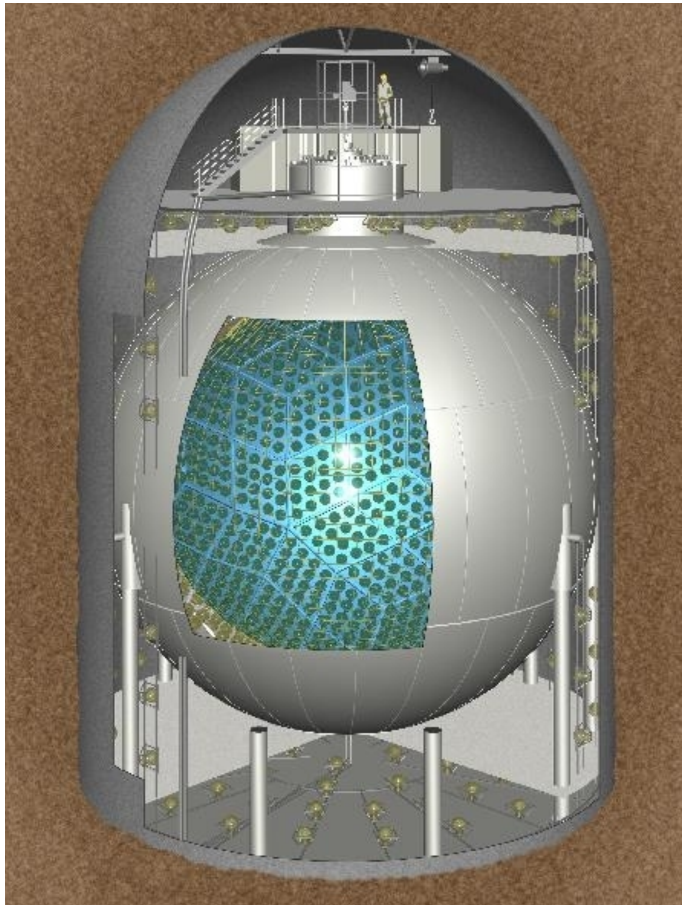
1000 ton of heavy water (D_2O)

Art McDonald

Really neutrino oscillations !

KamLAND observed neutrinos from nuclear power stations.





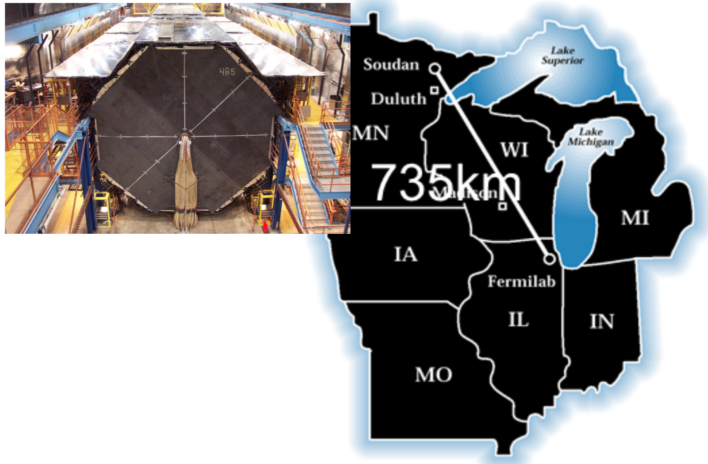
KamLAND

Discovery of the third neutrino oscillations (2011-2012)

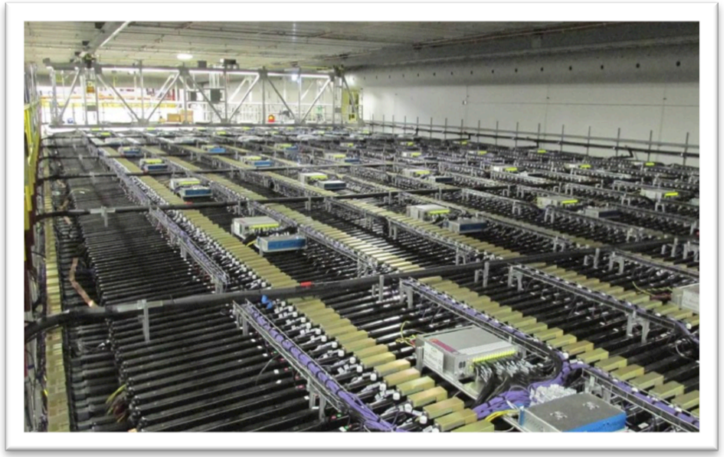
Accelerator based long baseline neutrino oscillation experiments

T2K (Japan)

MINOS (USA)

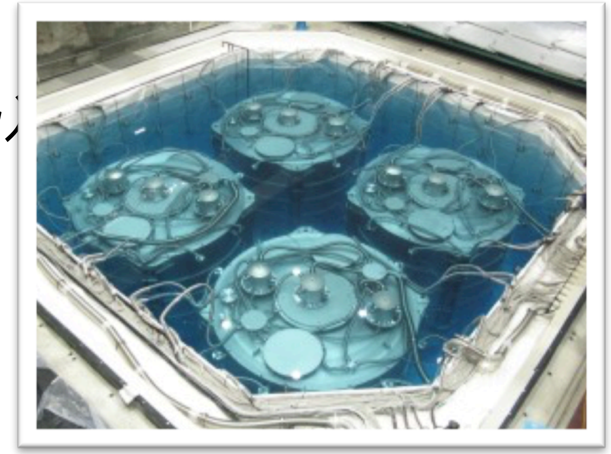


NOν A (USA)

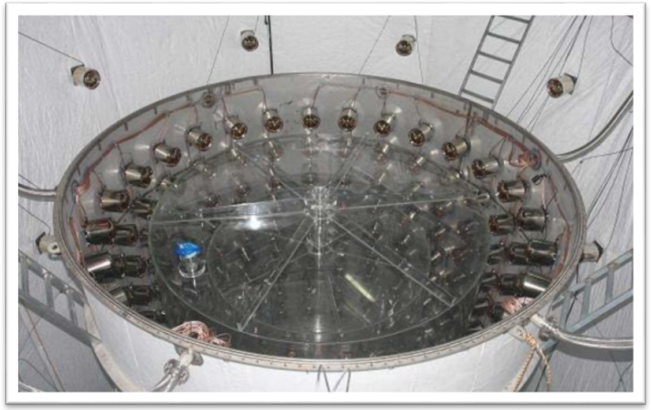


Reactor based (short baseline) neutrino oscillation experiments

Daya Bay (China)

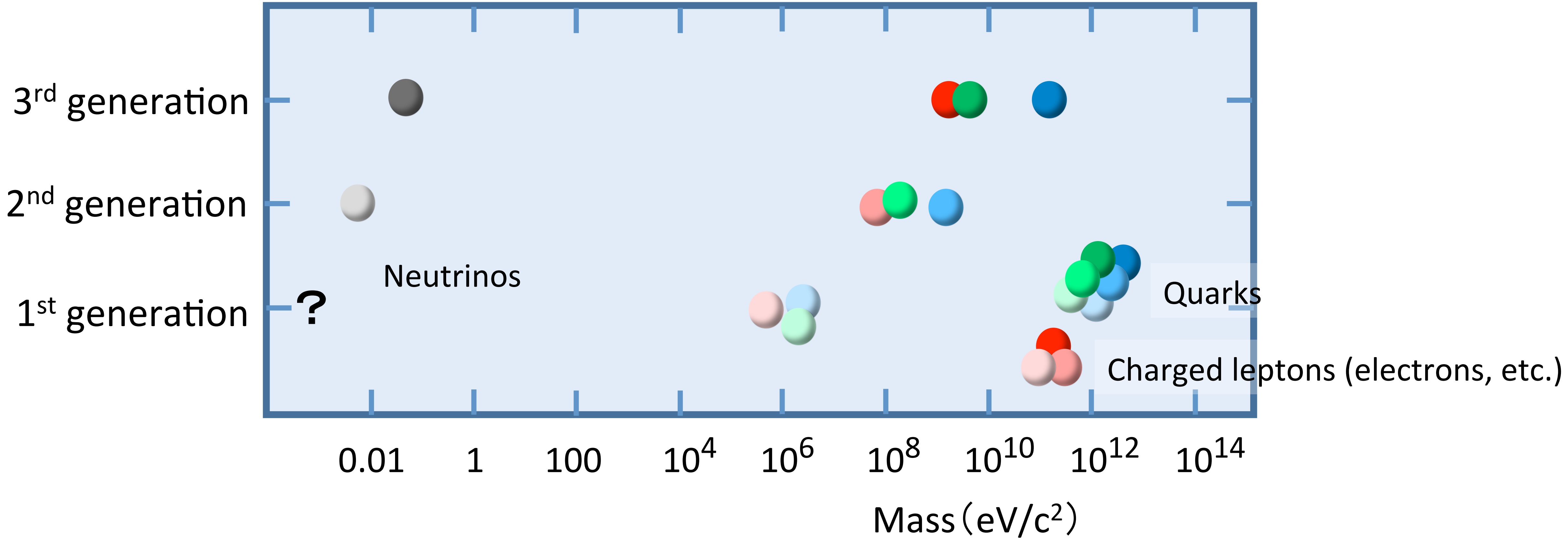


RENO (Korea)



Double Chooz (Fr

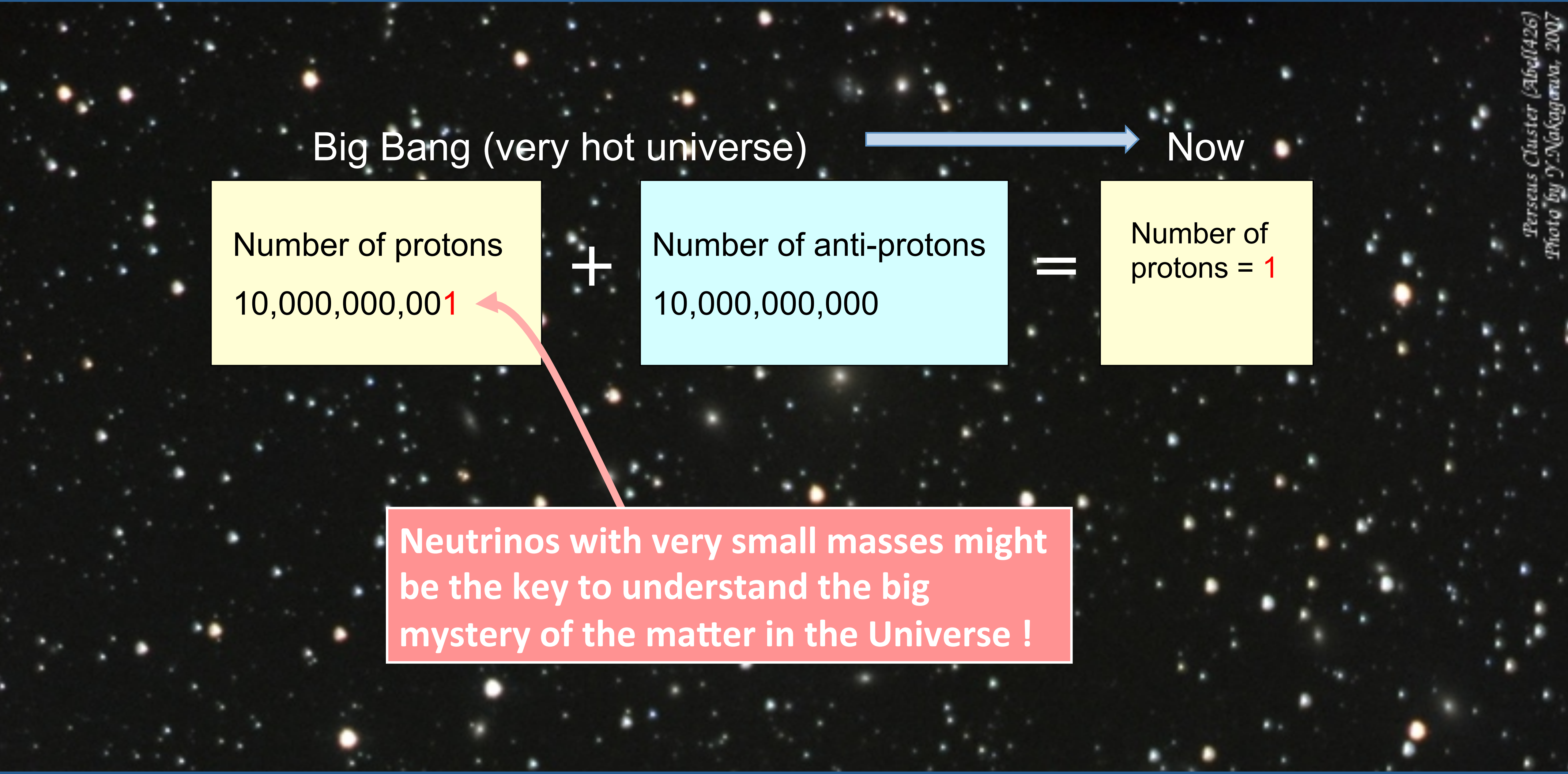
What have we learned?
Why are neutrinos important?



The neutrino masses are approximately (o more than) 10 billion (10 orders of magnitude) smaller than the corresponding masses of quarks and charged leptons!
We believe this is the key to understand the nature at the smallest and the largest scales.

The future

A big mystery



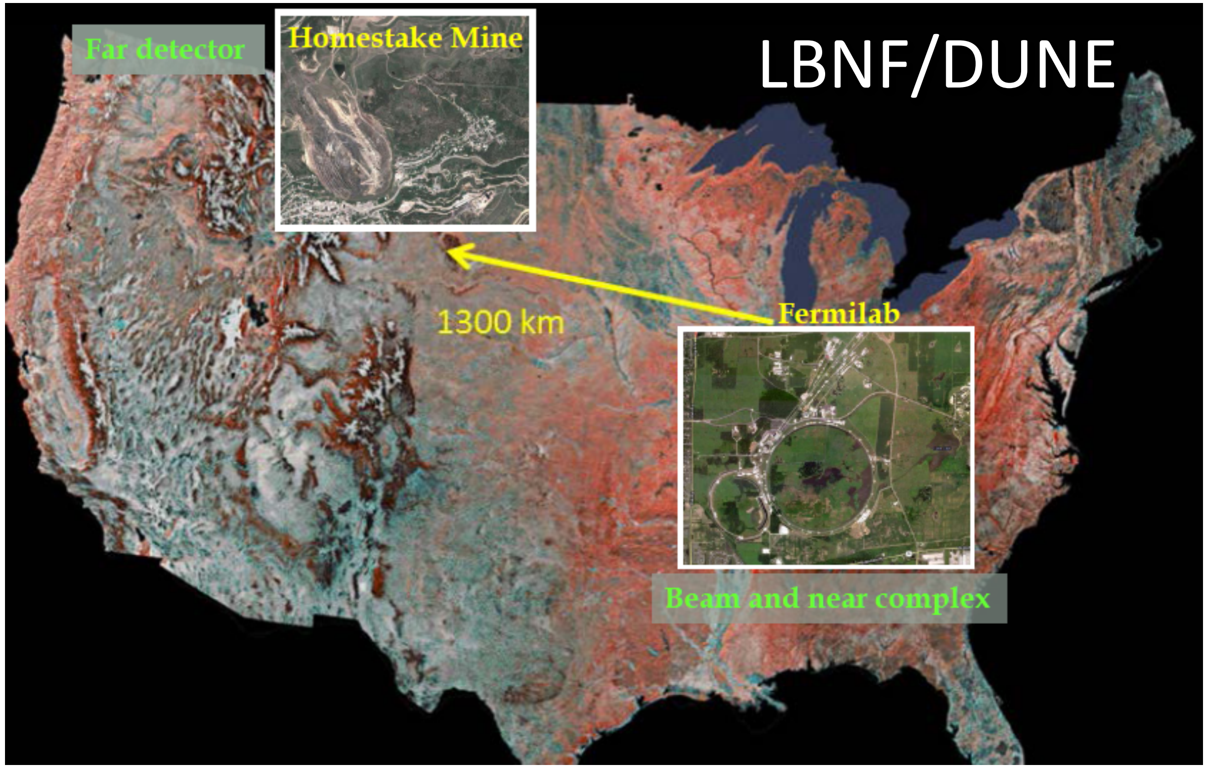
Big Bang (very hot universe) → Now

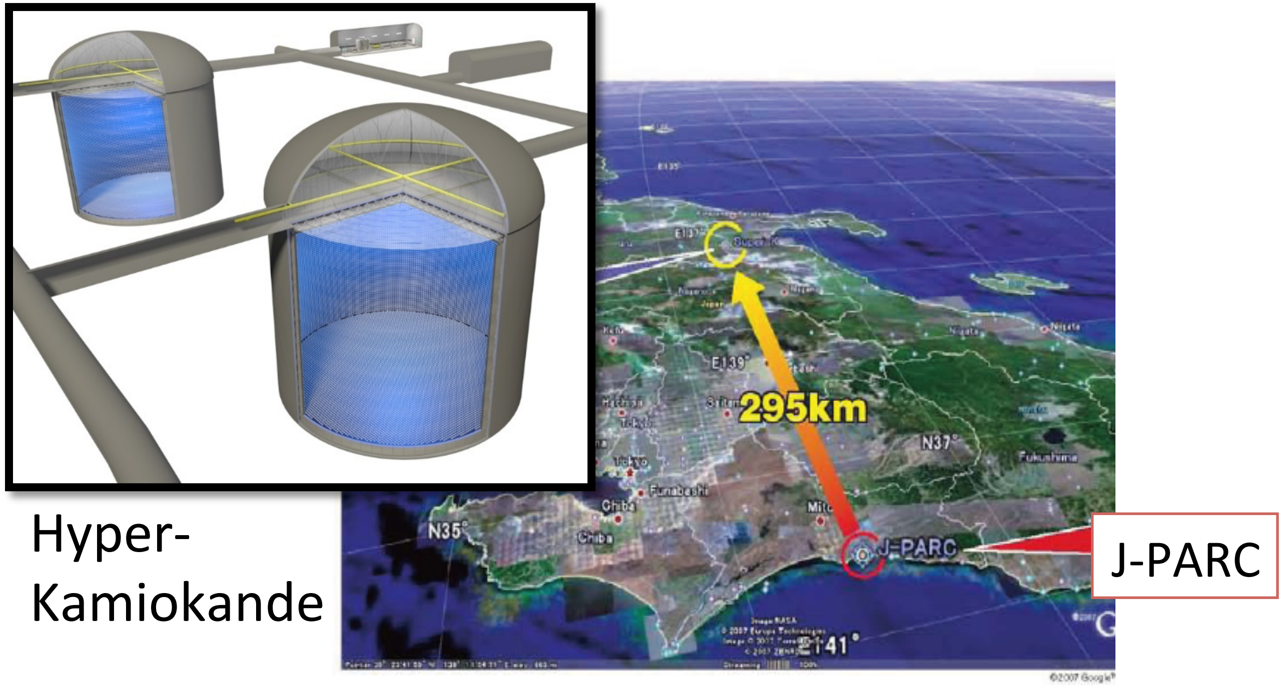
Number of protons	+	Number of anti-protons	=	Number of protons = 1
10,000,000,001		10,000,000,000		

Neutrinos with very small masses might be the key to understand the big mystery of the matter in the Universe !

How shall we understand this mystery?

- ✓ This mystery needs to be understood based on neutrino oscillation experiments.
- ✓ In more detail, we would like to observe if neutrino oscillations of neutrinos and those of anti-neutrinos are different.
- ✓ This is a difficult experiment. We need the next generation long base line experiments with much high performance neutrino detectors (please see below).





Hyper-Kamiokande

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.
- Since then, various experiments have revealed the nature of neutrinos.
- 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.

Thank you very much for your attention!