20th WCNDT 20th World Conference on Non-Destructive Testing
Songdo Convensia, Incheon, Korea, 27~31 May 2024

Neutrinos - key particles for our understanding of the smallest particles and the largest Universe -

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Abstract: Neutrinos are remarkably interesting particles. Neutrinos have three types, i.e., electron neutrinos, muon-neutrinos and tau-neutrinos. They have no electric charge, exceptionally
small mass and interact with matter very rarely. Because of the last nature, neutrinos can easily pass through even the Earth or the stars. One can study the interior of stars by detecting neutrinos from these stars, although the detection of neutrinos is difficult. More than 20 years ago, neutrinos were found to have tiny mass. I will discuss the studies of neutrinos focusing on our studies that have been carried out in Kamioka, Japan.

ACADEMIA NDT INTERNATIONAL RESEARCH DAY 2024
20th World Conference on Non-Destructive Testing (20th WCNDT)
Incheon, South Korea, May 29, 2024

Neutrinos

- key particles for understanding the smallest particles and the largest Universe -

Takaaki Kajita
Institute for Cosmic Ray Research, The University of Tokyo

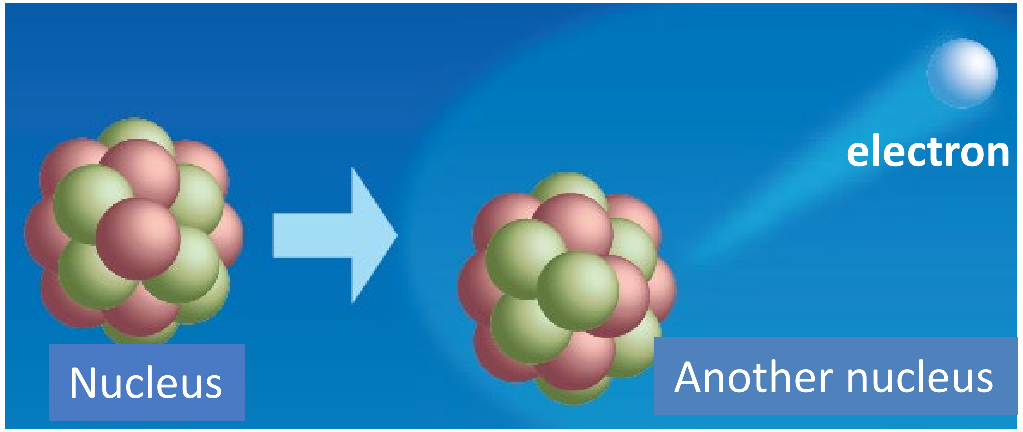
Outline

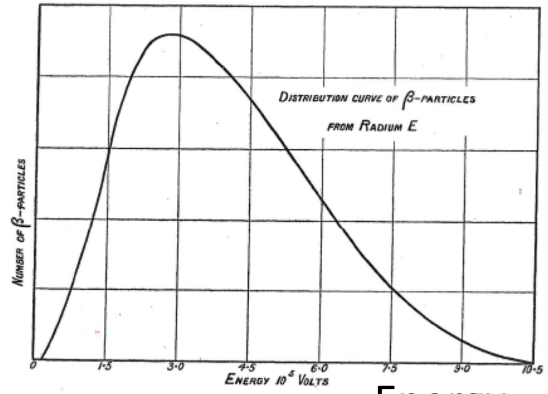
- *What are neutrinos?*
- *Solar and atmospheric neutrinos*
- *Kamiokande*
- *Super-Kamiokande and the discovery of neutrino oscillations*
- *Discovery of solar neutrino oscillations*
- *Neutrinos and a big mystery in the Universe*
- *Summary*

What are neutrinos ?

Birth of neutrino

In the early 20th century, physicists were puzzled with β-decays. Namely, the measured energy spectrum of β rays (electrons) were continuous rather than a unique value expected for 2 body decays.



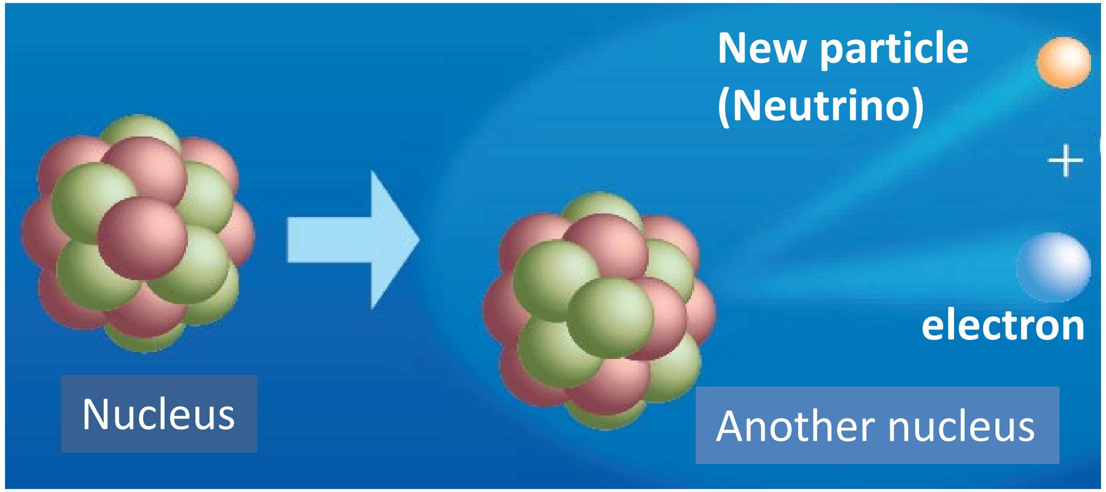


C.D. Ellis and W.A. Wooster, Proc. of the Royal Soc. (London) A117 (1927) 109-123.

(Wikipedia)

On Dec. 4, 1930, Wolfgang Pauli wrote a letter to “Dear radioactive ladies and gentlemen”.

He wrote “I have hit upon a desperate remedy to save … the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles …”.



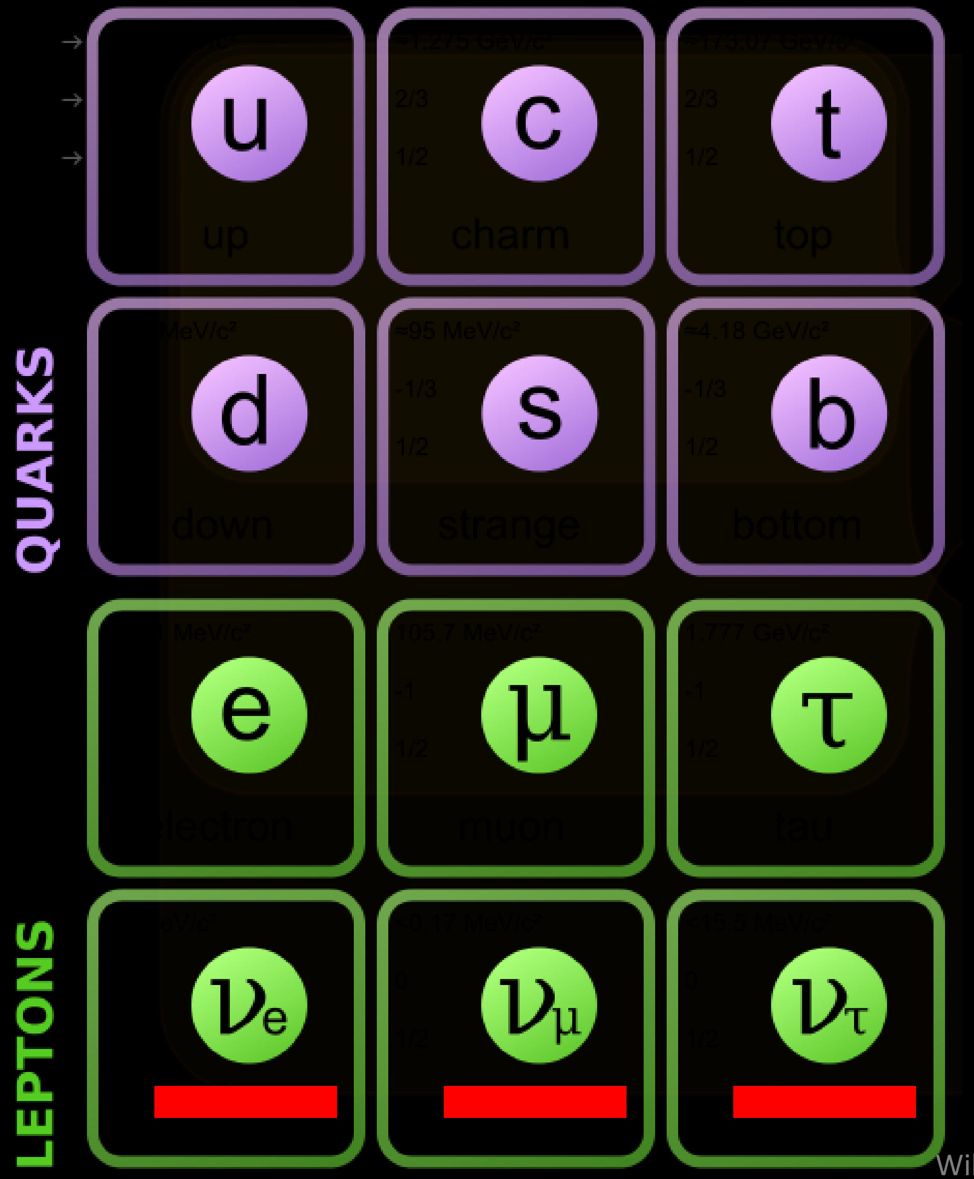
T. Kajita、Illume, Vol.16, No.2 (2004)

What are neutrinos

Neutrinos;

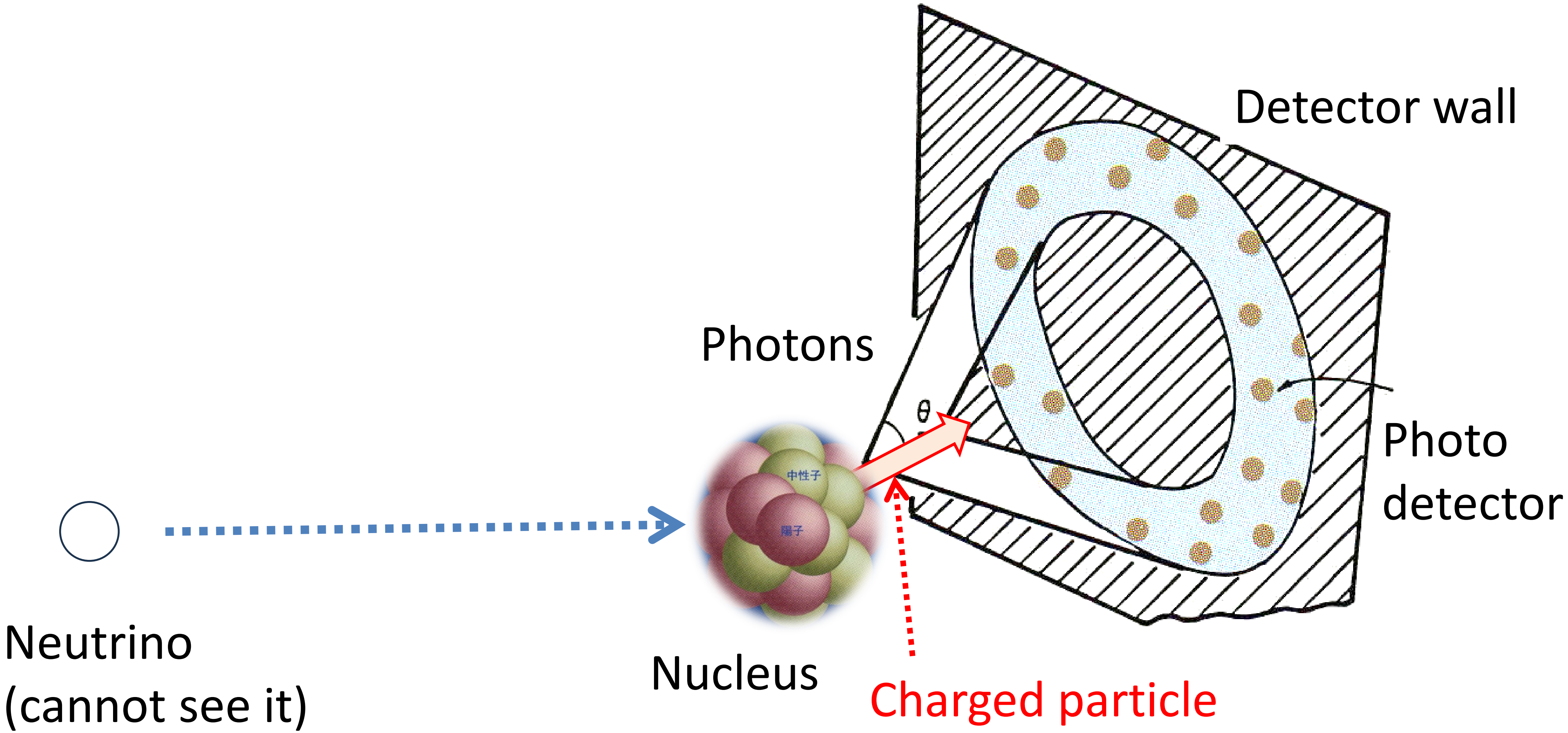
- ✓ are fundamental particles like electrons and quarks,
- ✓ are something like electrons without electric charge,
- ✓ can easily pass through even the Earth, but can interact with matter very rarely,
- ✓ have 3 types (flavors), namely electron-neutrinos (ν_e), muon-neutrinos (ν_μ) and tau-neutrinos (ν_τ),

  and
- ✓ have been assumed to have no mass.



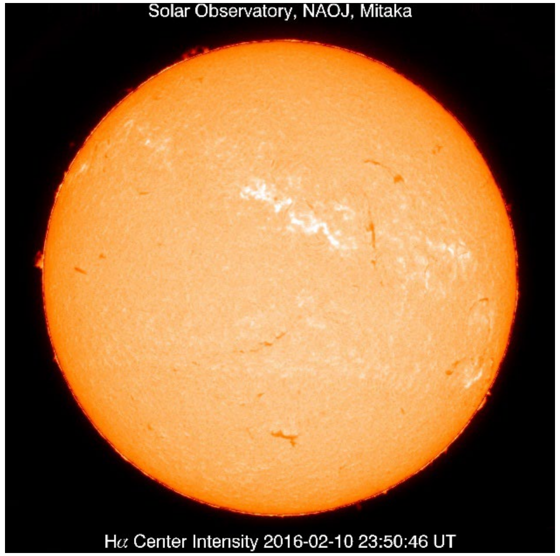
Wikipedia

How can we observe neutrinos ?



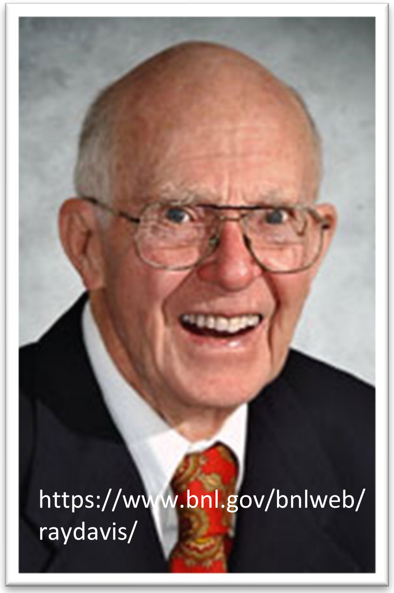
Solar and atmospheric neutrinos

Solar neutrinos



The Sun generates energy by nuclear fusion processes. Neutrinos are created by these processes. Therefore, the observation of solar neutrinos is very important to understand the energy generation mechanism in the Sun.

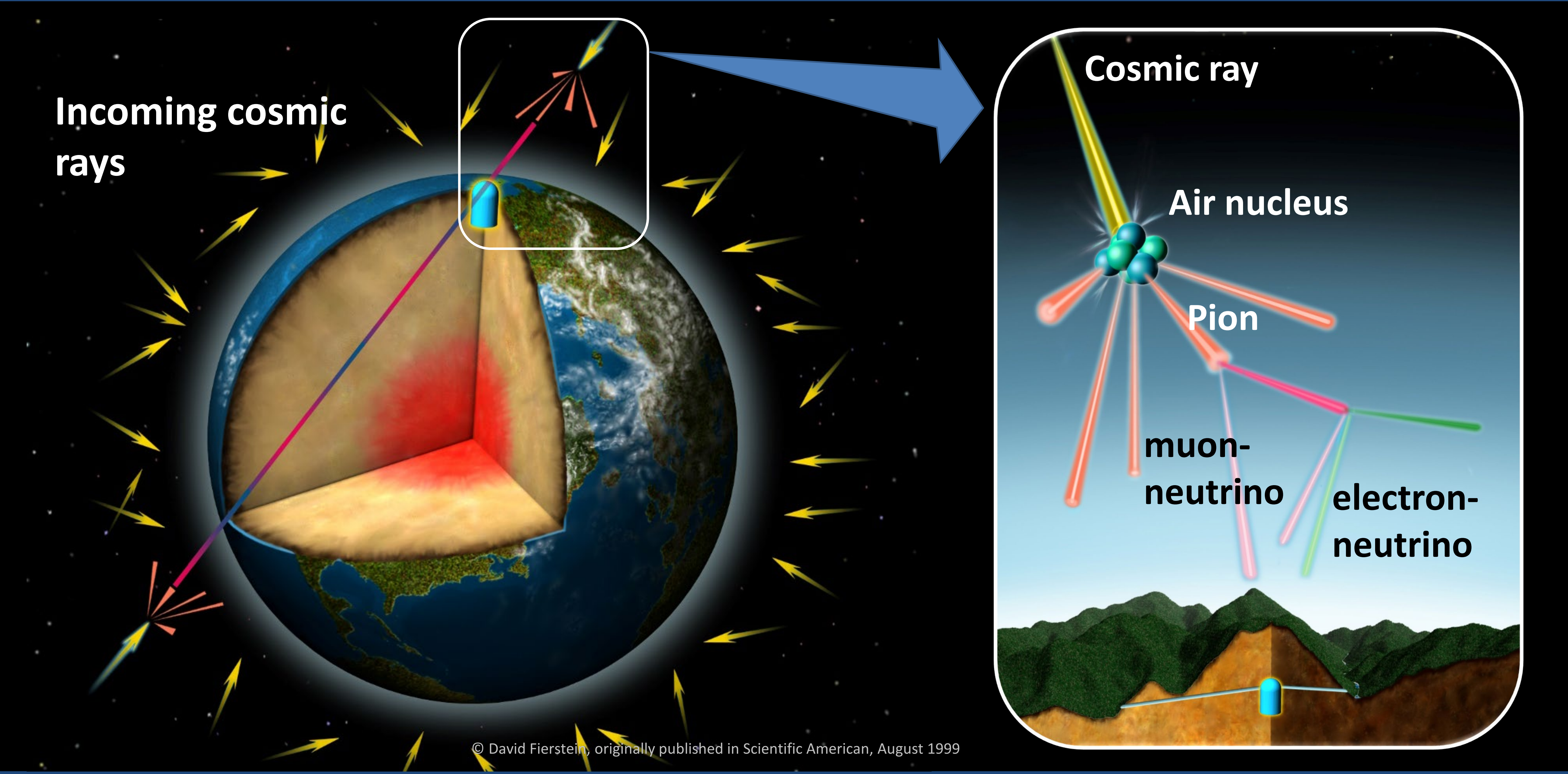
600ton C_2Cl_4



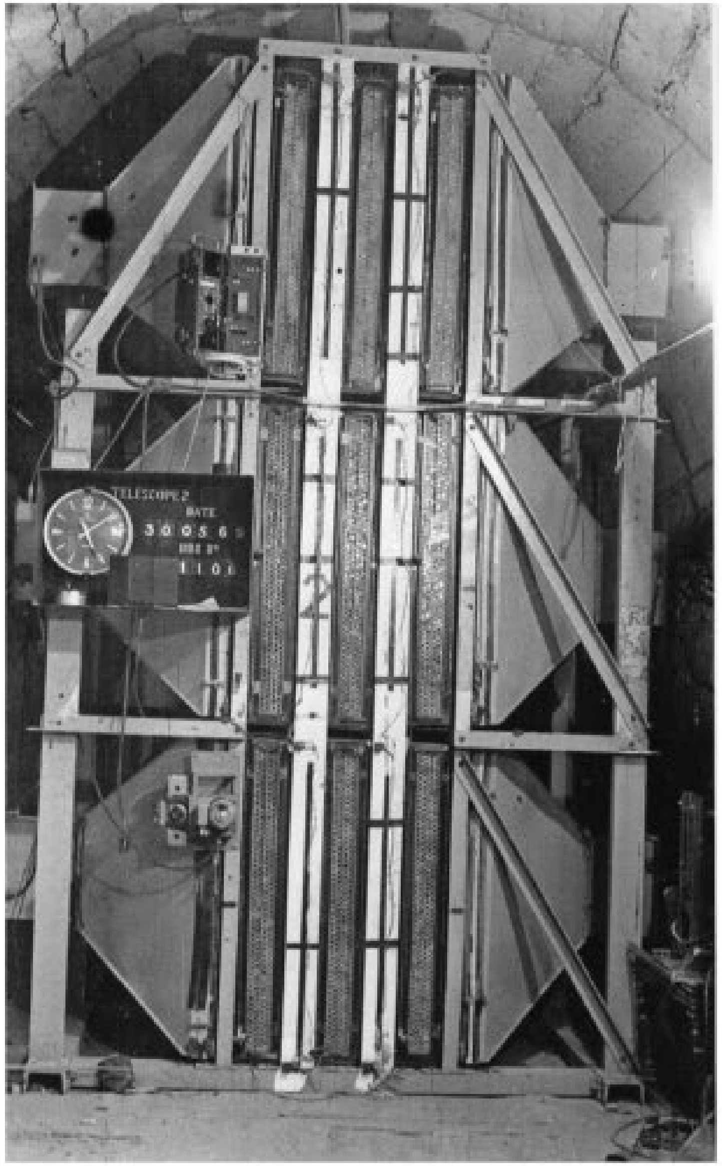
R. Davis Jr.

Pioneering Homestake experiment observed solar neutrinos for the first time (R. Davis Jr., D. S. Harmer and K. C. Hoffman PRL 20 (1968) 1205). However, the observed event rate was only about 1/3 of the prediction (since 1960's, solar neutrino problem).

Atmospheric neutrinos



Discovery of atmospheric neutrinos



In 1965, atmospheric neutrinos were observed for the first time by detectors located very deep underground.

← In India

C.V. Achar et al. (India-Japan-UK collaboration), PL 18, 196 (1965)

In South Africa →

F. Reines et al., PRL 15, 429 (1965)

Photo by N. Mondal

Photo by H.Sobel

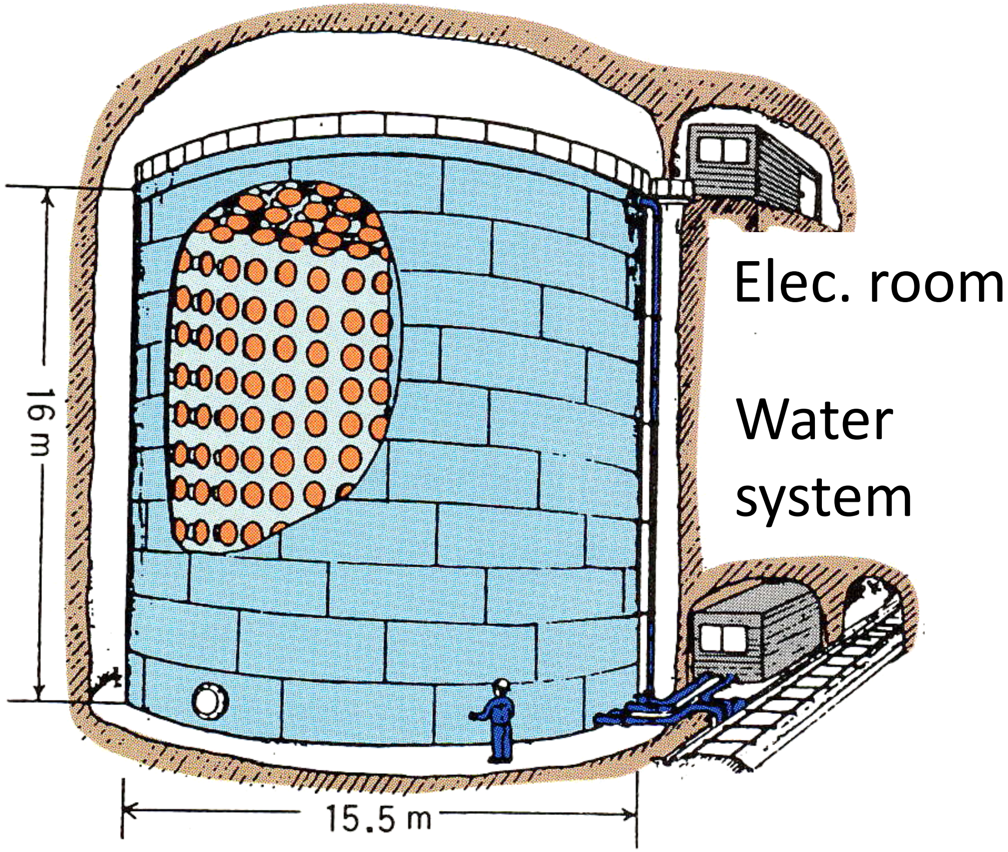
Kamioknade

Kamioka Nucleon Decay Experiment (Kamiokande)

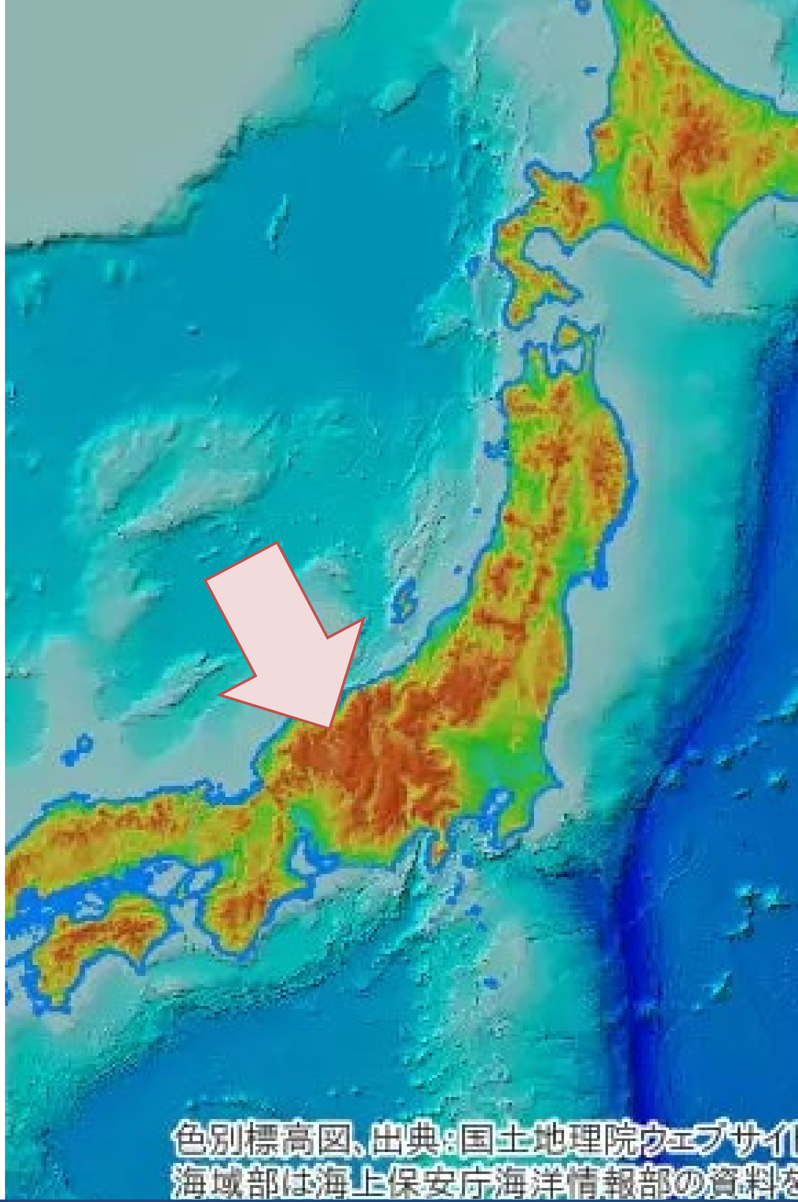
- ✓ In the 1970's, new theories of elementary particles predicted that protons should decay with the lifetime of about 10^{30} years.
- ✓ Several proton decay experiments began in the early 1980's. One of them was Kamiokande.

Kamiokande

(3000 ton water detector)



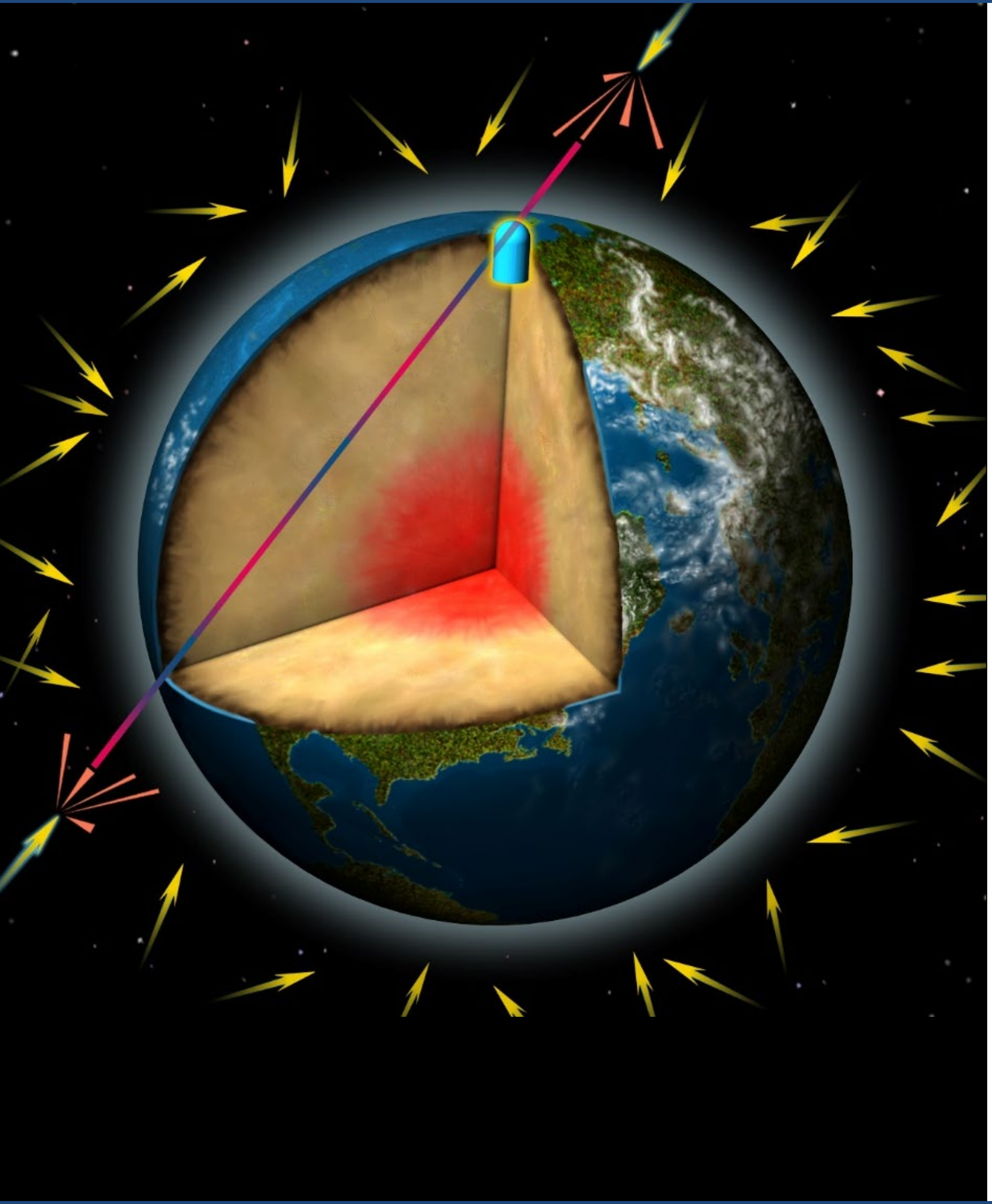
https://kids.gakken.co.jp/kagaku/nandemo/science220525/



I was fascinated by the concept of proton decay and participated in Kamiokande at the time I became a graduate course student (April 1981).

Construction of the Kamiokande detector (spring 1983)

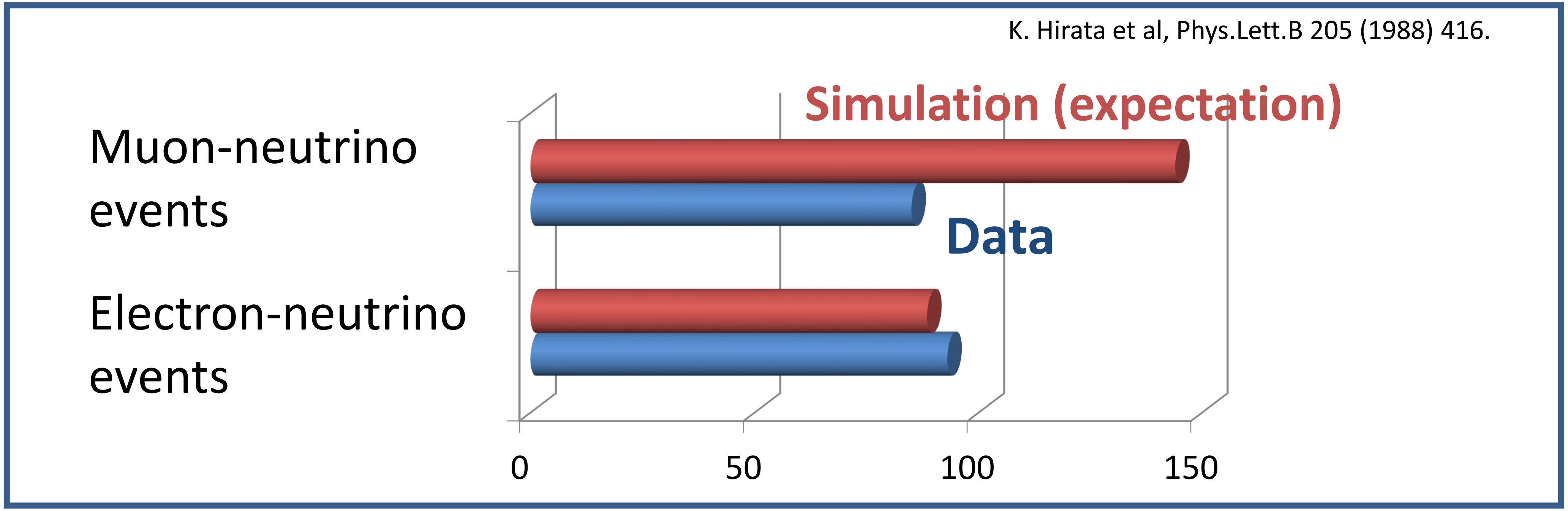
Atmospheric neutrinos: background for proton decay



- In 1986, there was still no evidence for proton decays. But we still wanted to observe proton decays.
- Therefore, we developed a new software to improve the proton decay searches by better separating proton decay signals from the neutrino background.
- As a test of the new software, the neutrino type (electron-neutrino or muon-neutrino) was studied for the atmospheric neutrino events. The number of muon-neutrino events was much fewer than expected.
- We thought that it is very likely that there were some mistakes somewhere in the new software. We started various studies to find mistakes.

Atmospheric ν_μ deficit (1988)

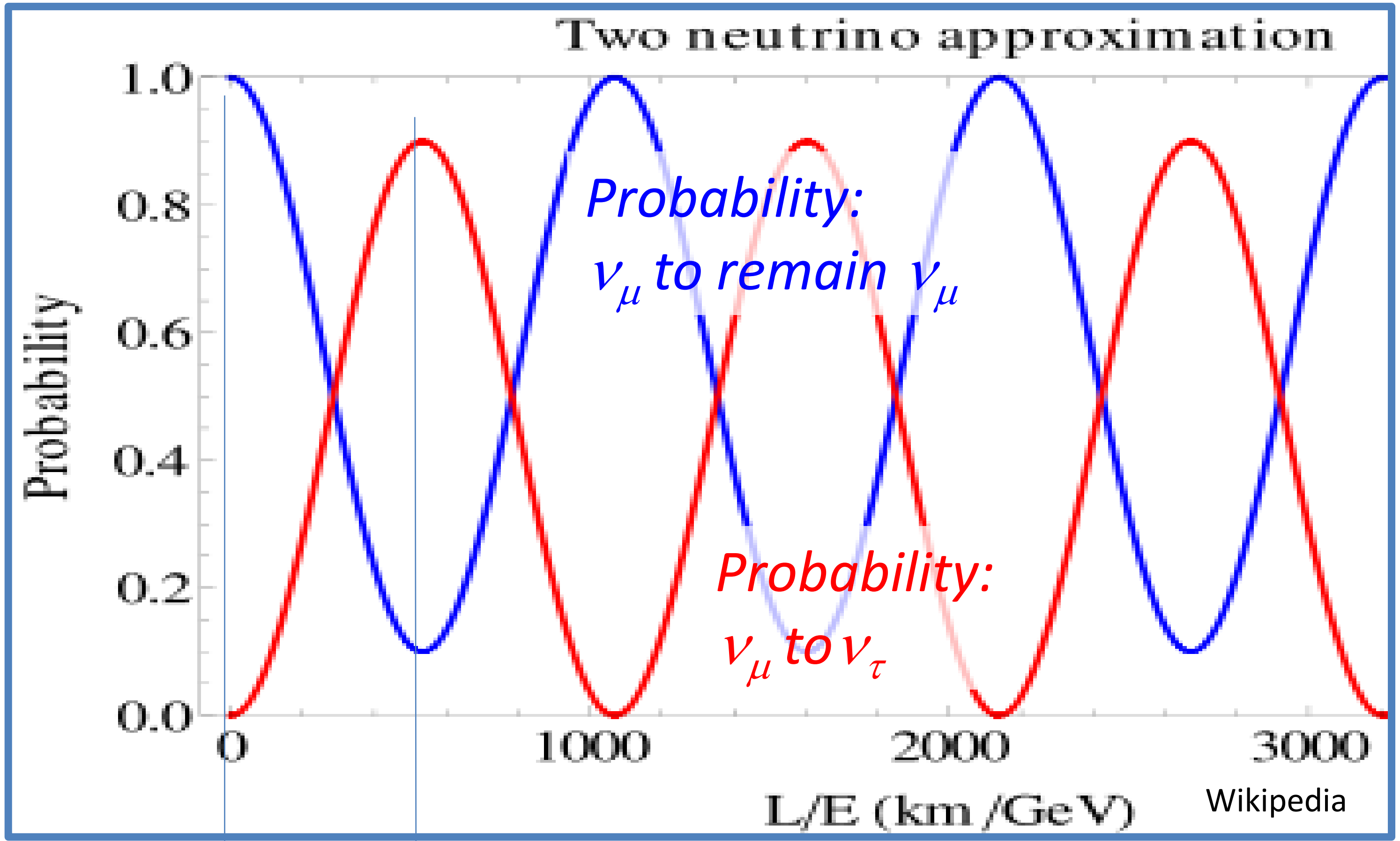
After about one year of studies, we concluded that the ν_μ deficit cannot be due to any major problem in the data analysis.



<u>*What I thought*</u>: Although we had no clear idea what was the cause of the deficit, I was most excited with the data. I changed my research completely from the proton decay searches to neutrino studies to know what are going on in neutrinos.

Neutrino oscillations (in the vacuum)

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



Theoretically predicted by;

S. Sakata, Z. Maki, M. Nakagawa

arXiv:0910.1657

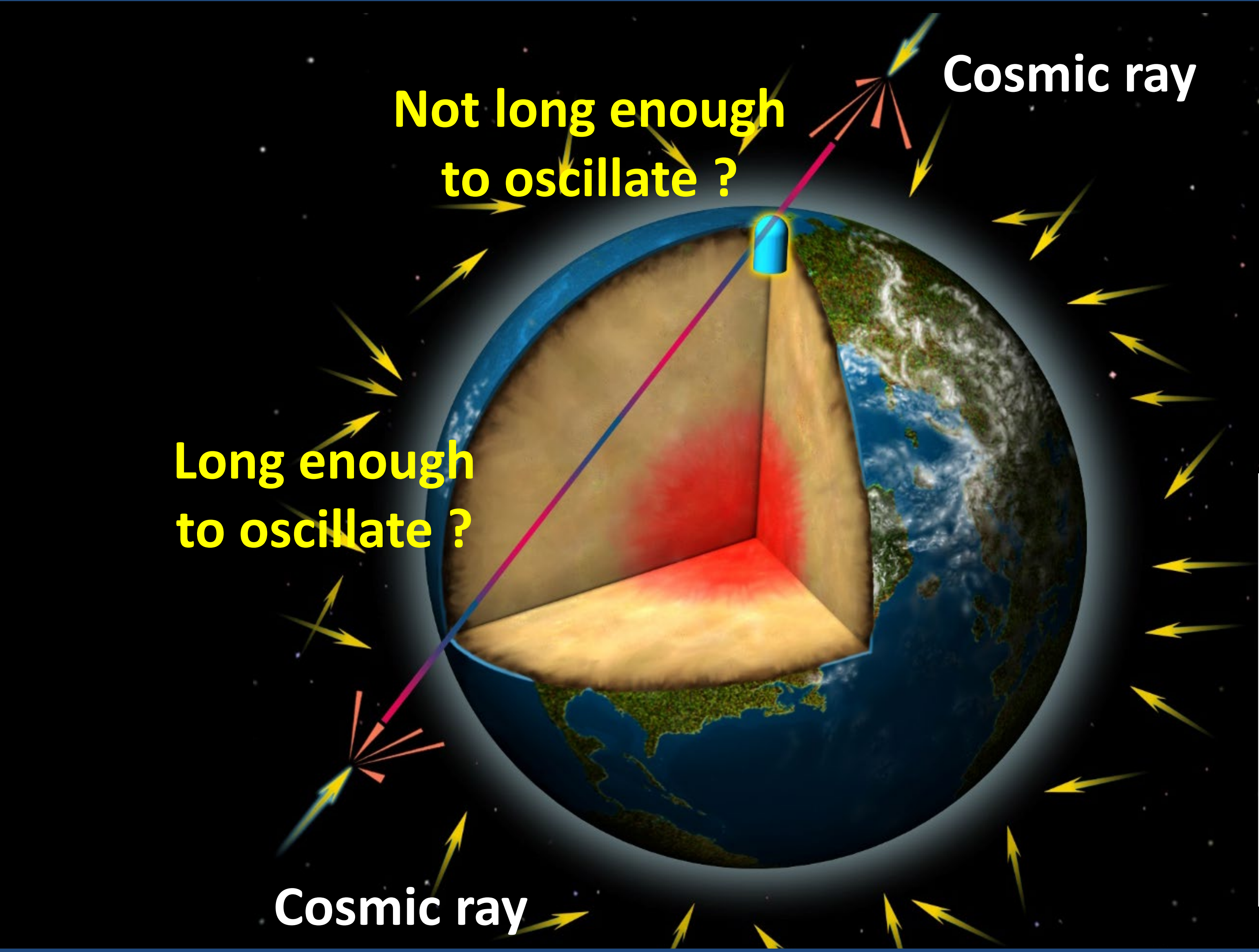
B. Pontecorvo

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.

What will happen if the muon-neutrino deficit is due to neutrino oscillations

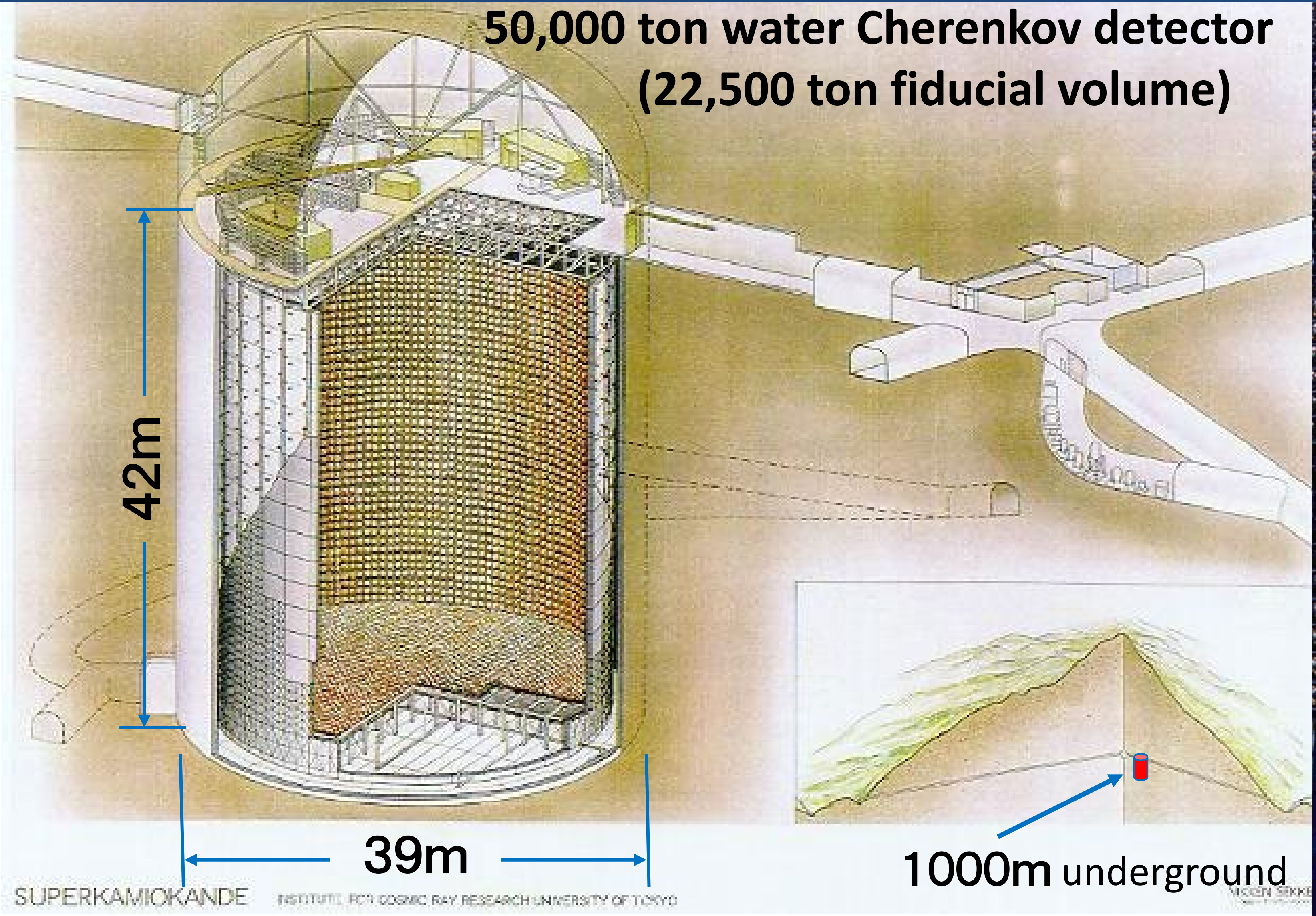


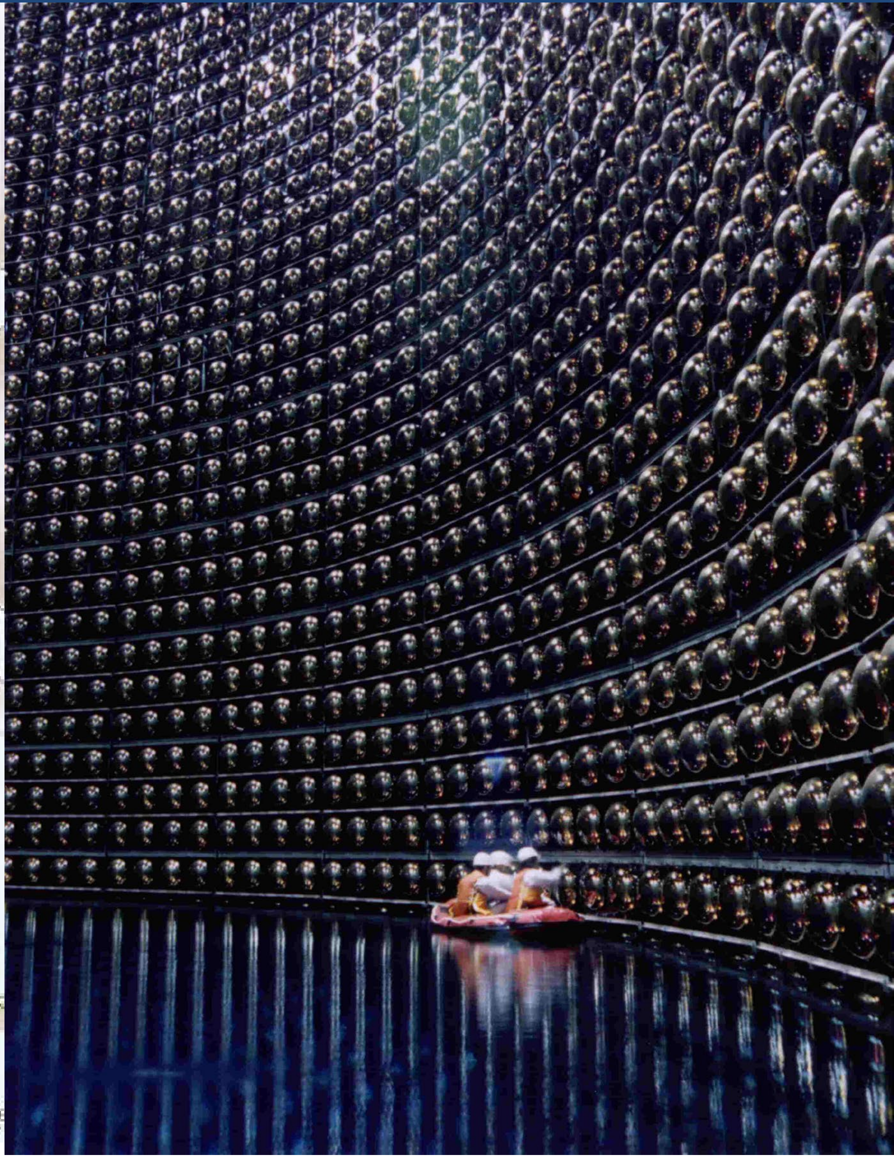
An asymmetry of the up- versus down-going flux of muon-neutrinos should be observed! However, Kamiokande was too small.
➔ Super-Kamiokande

Super-Kamiokande and the discovery of neutrino oscillations

Super-Kamiokande

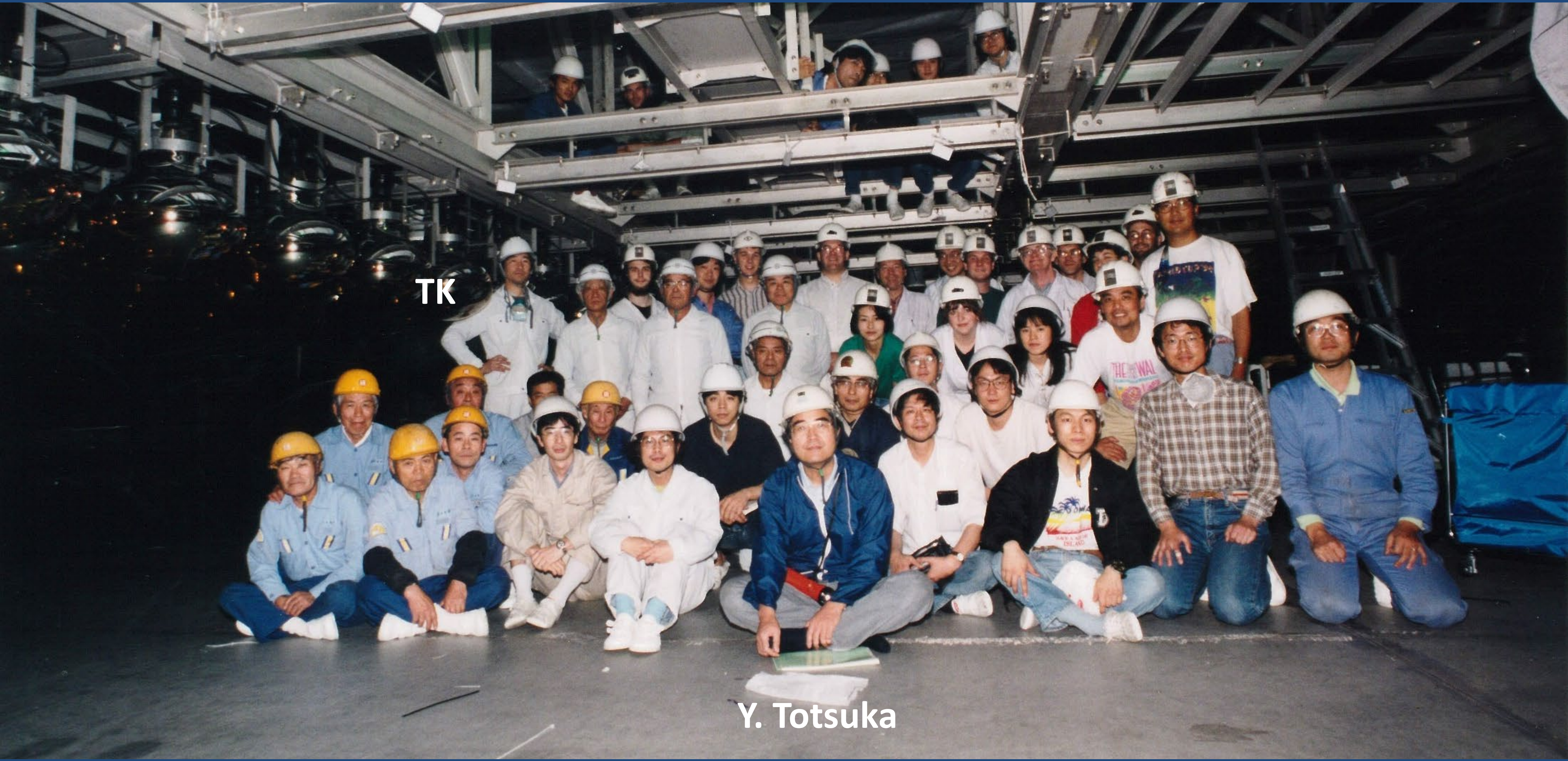
50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)





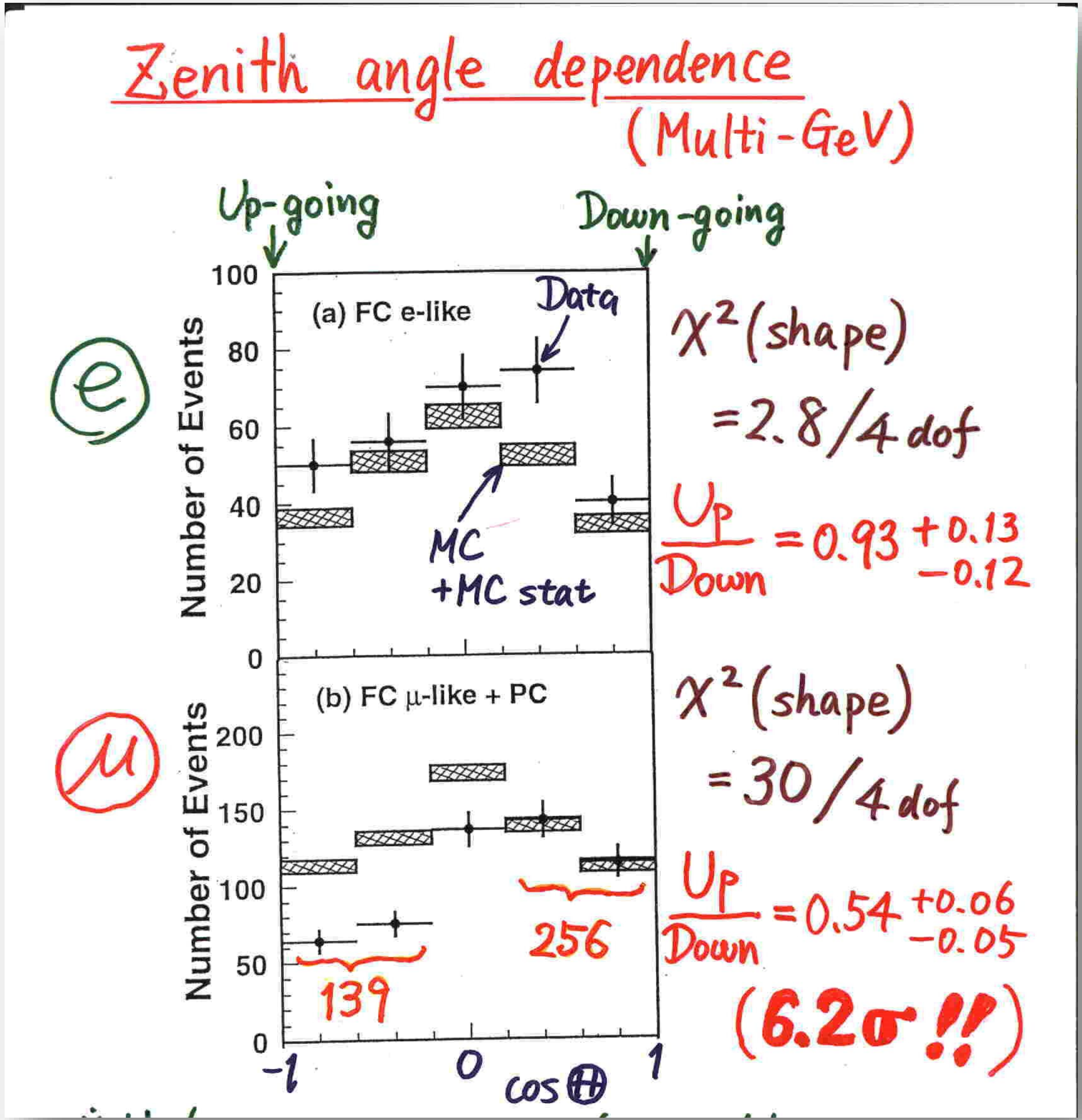
~230 collaborators

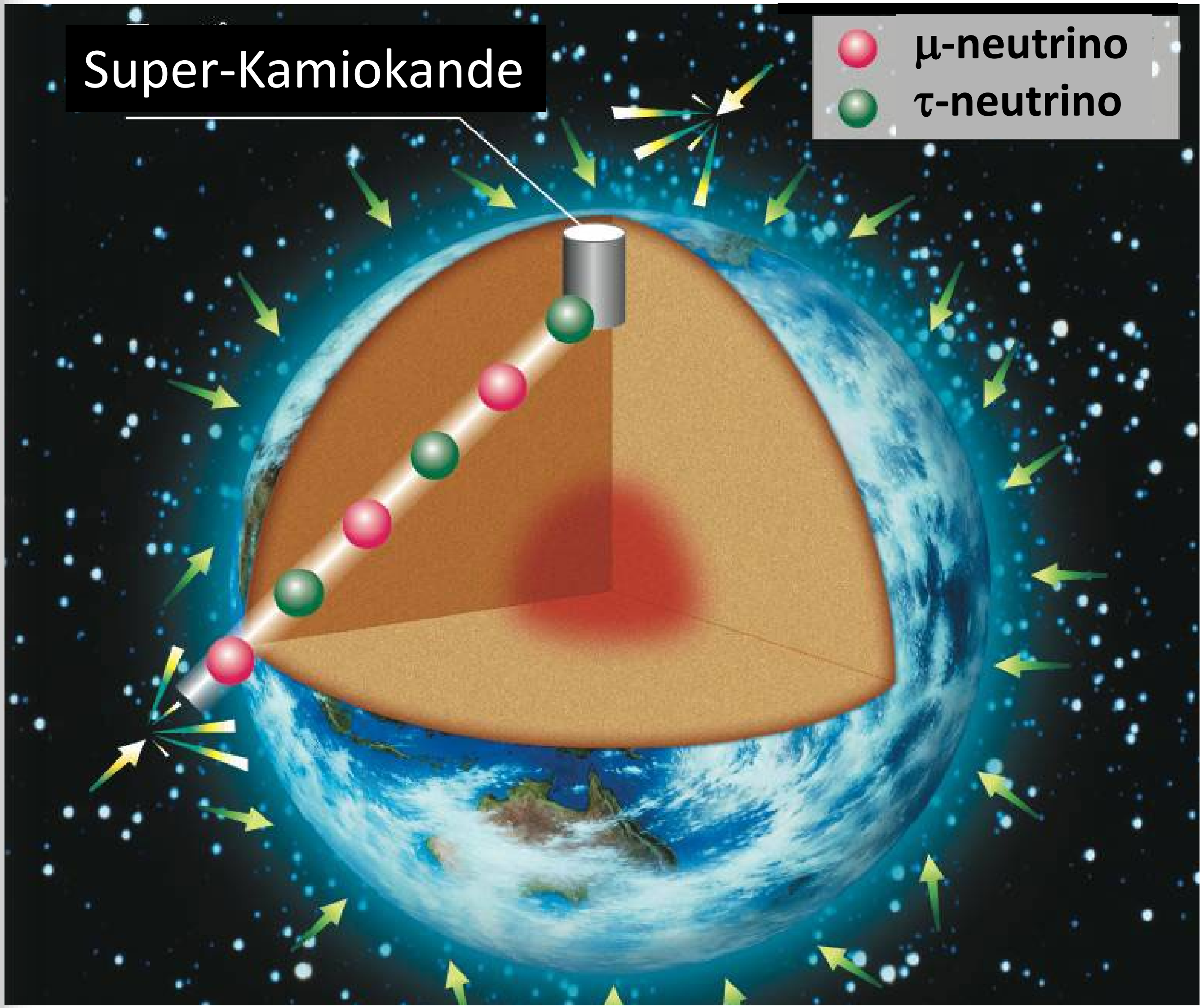
Constructing the Super-Kamiokande detector (spring 1995)



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

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





President Clinton's talk at MIT's 1998 Commencement

President William Jefferson Clinton—1998 MIT Commencement

https://www.youtube.com/watch?v=9LheUWrXUHU

Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.

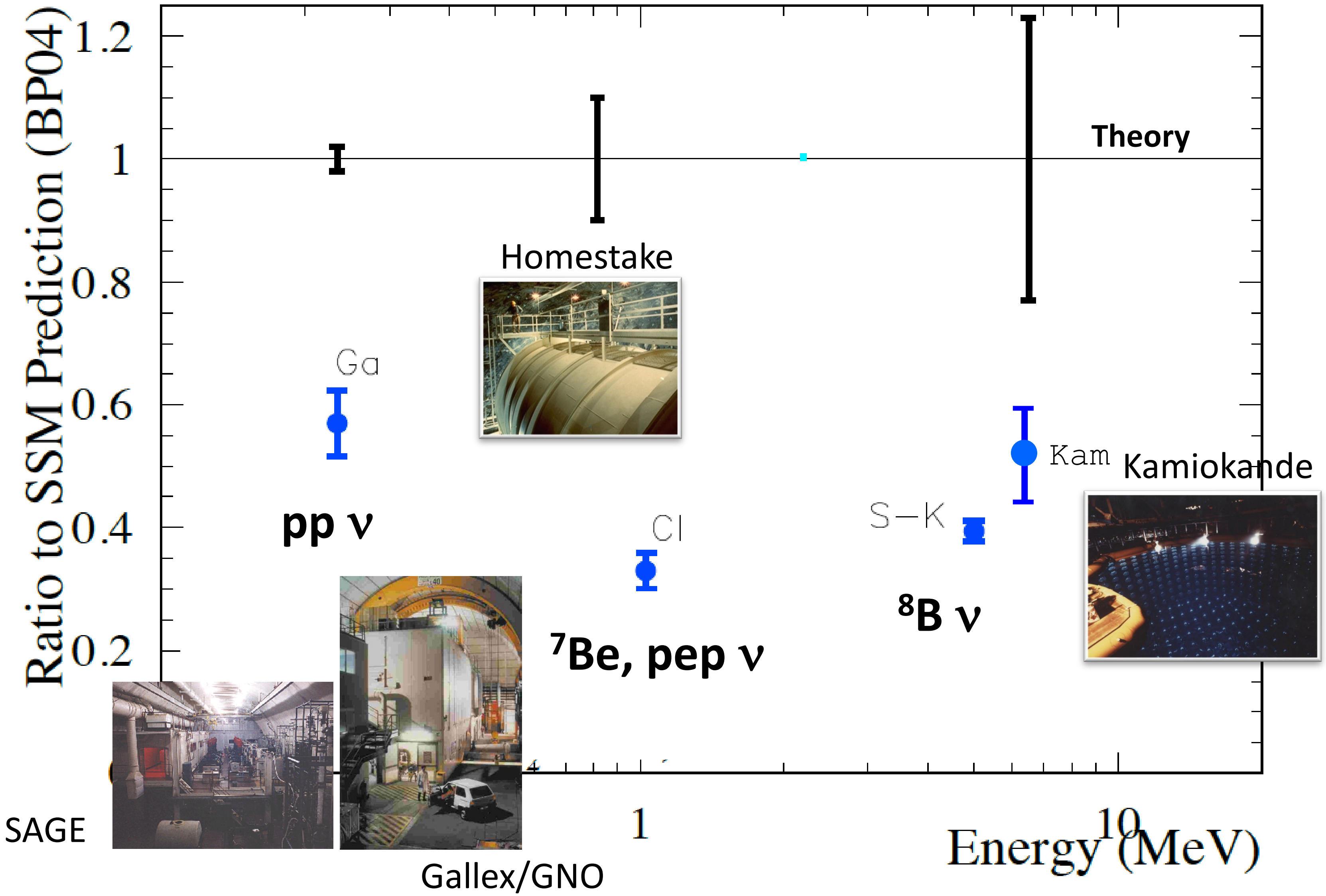
.....

The larger issue is that these kinds of findings have implications that are not limited to the laboratory. They affect the whole of society -- not only our economy, but our very view of life, our understanding of our relations with others, and our place in time.

Discovery of solar neutrino oscillations

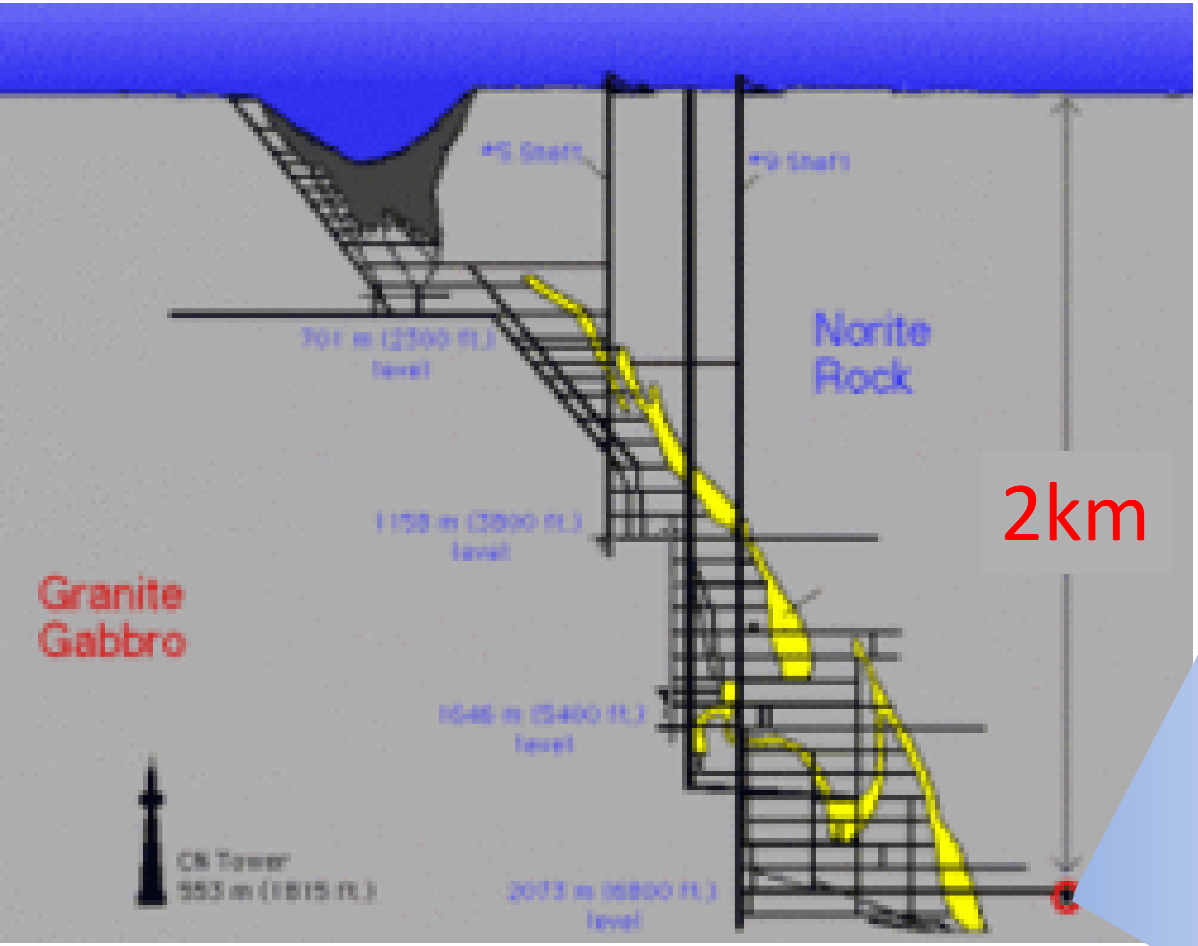
Solar neutrino problem

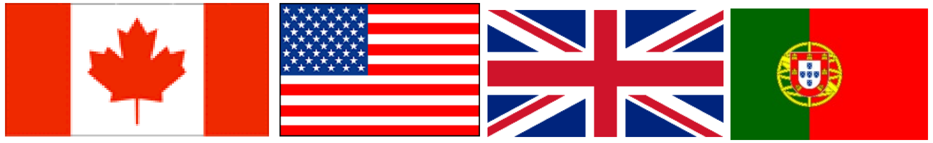
In the 20th century, several experiments observed solar neutrinos.



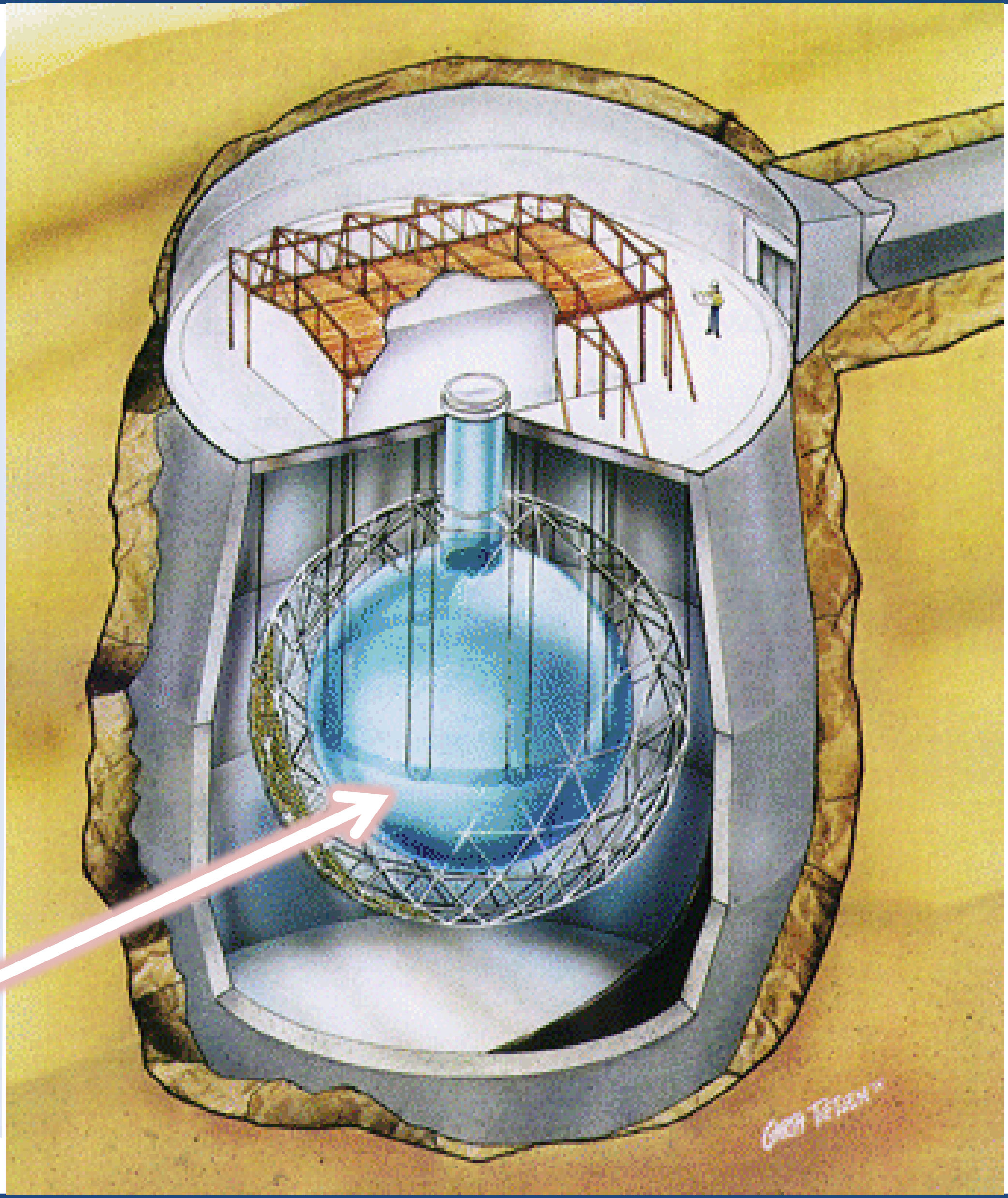
These solar neutrino experiments observed the deficit of solar neutrinos.
However, during the 20th century, it was not possible to understand the reason for the deficit.

SNO detector



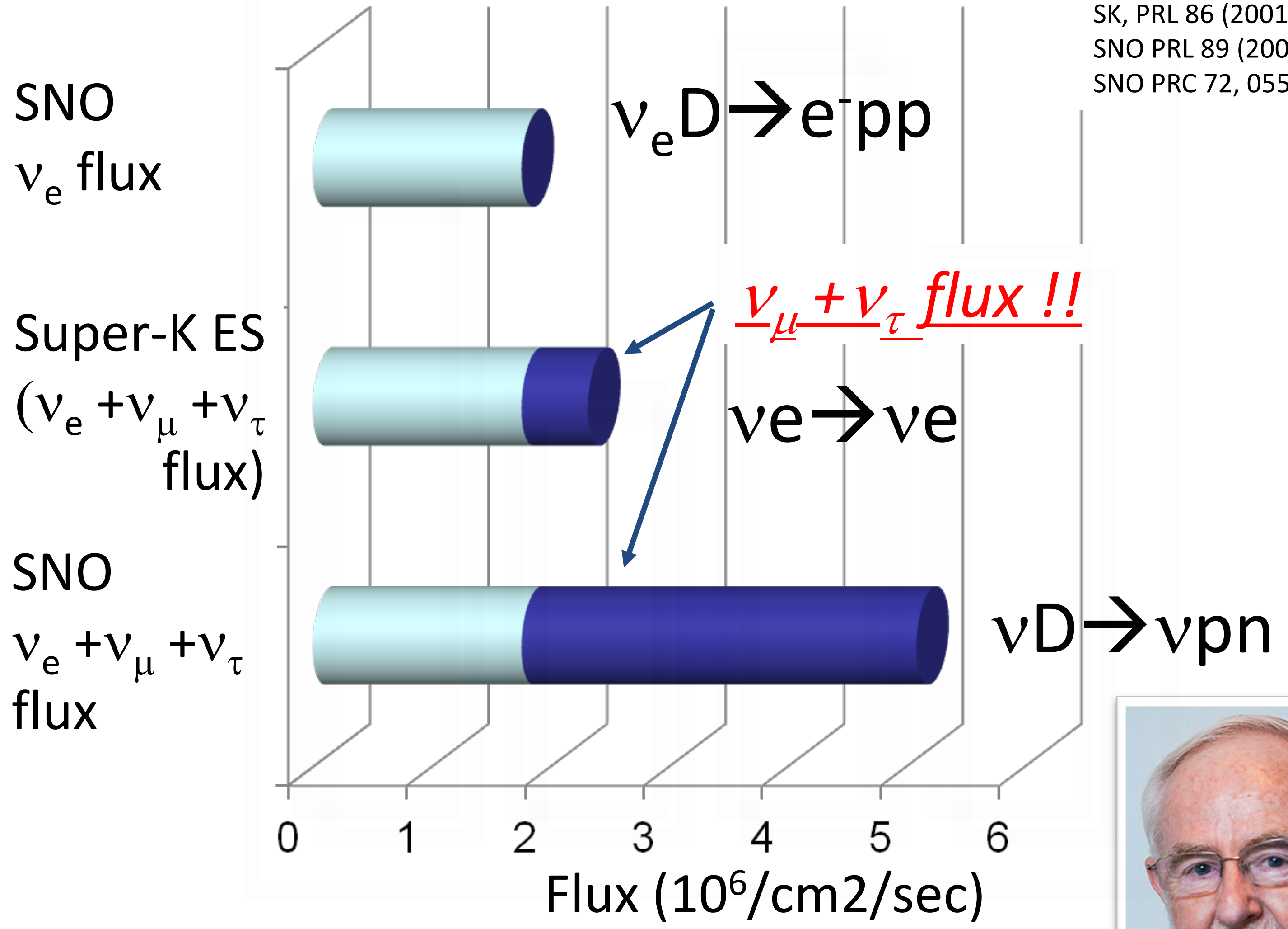


1000 ton of
heavy water (D_2O)

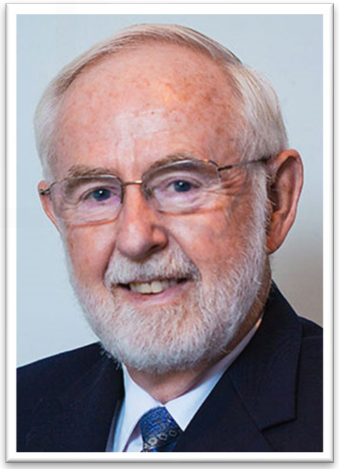


Solar neutrino oscillation (2001-2002)

SK, PRL 86 (2001) 5651
SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)

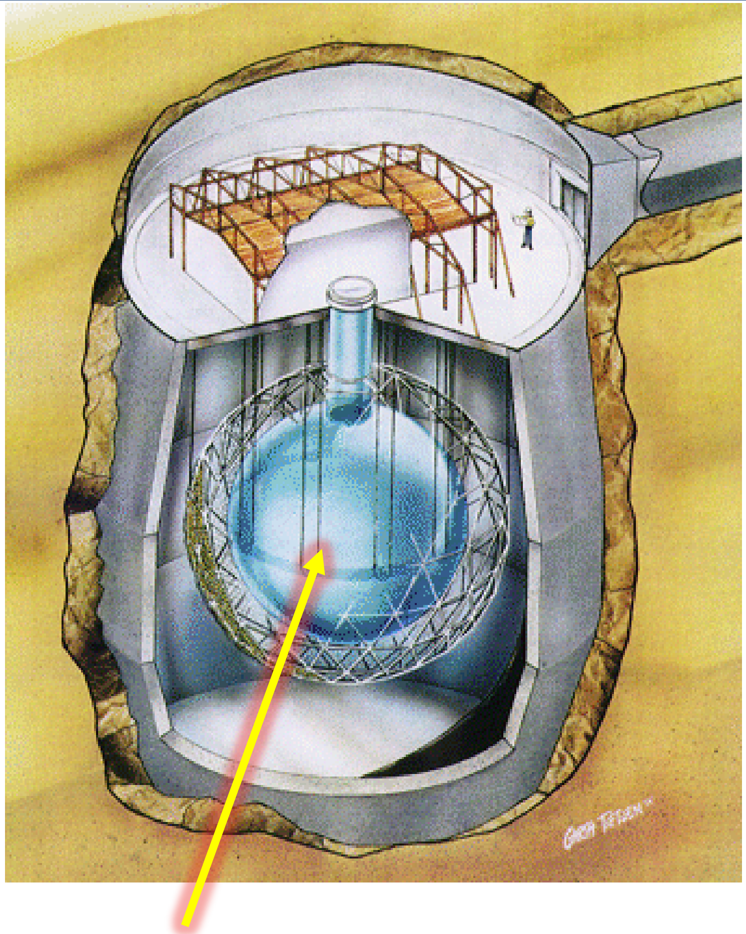


Neutrino oscillation: electron neutrinos to the other neutrinos.



Art McDonald

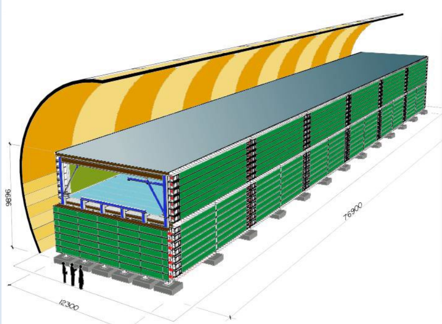
Photo: K. MacFarlane. Queen's University /SNOLAB

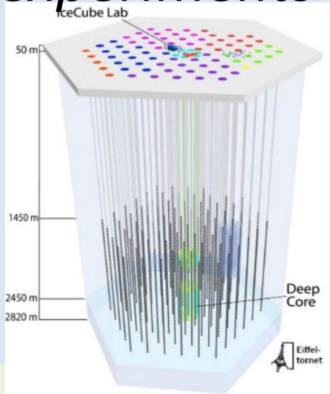


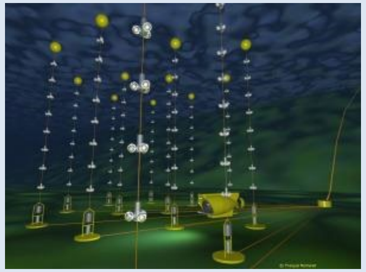
1000 ton of heavy water (D_2O)

Many exciting results in neutrino oscillations (partial list)

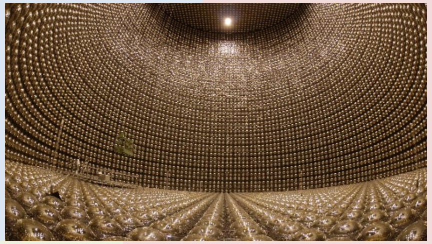
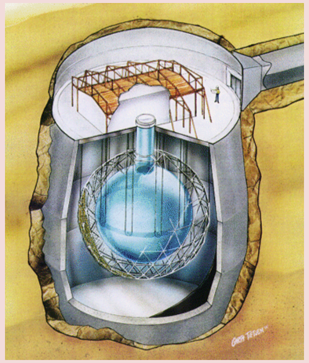
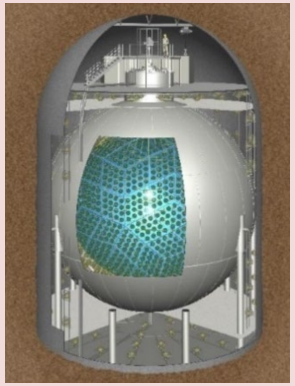
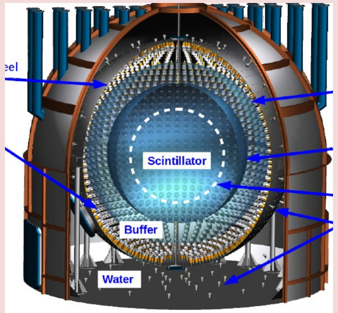
Atmospheric neutrino oscillation experiments



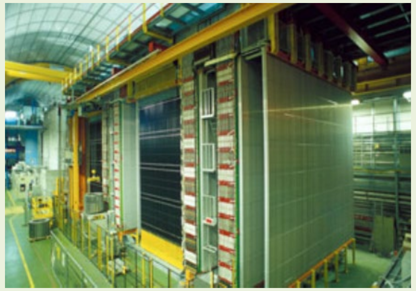




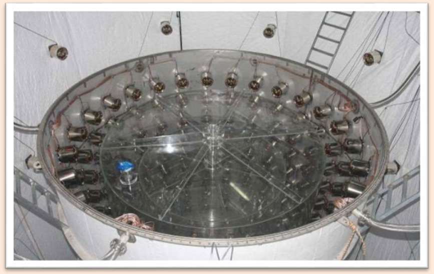
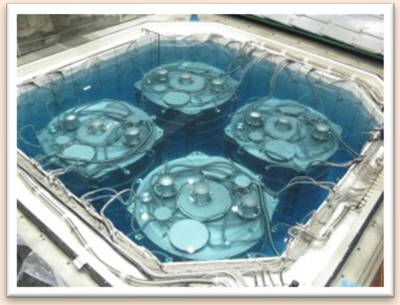
Solar neutrino oscillation experiments

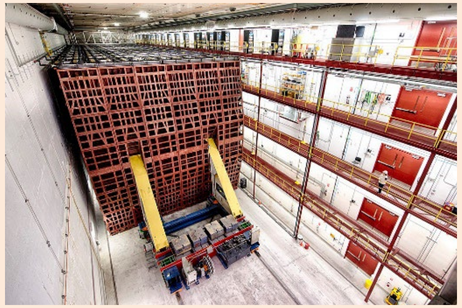





Accelerator based neutrino oscillation experiments



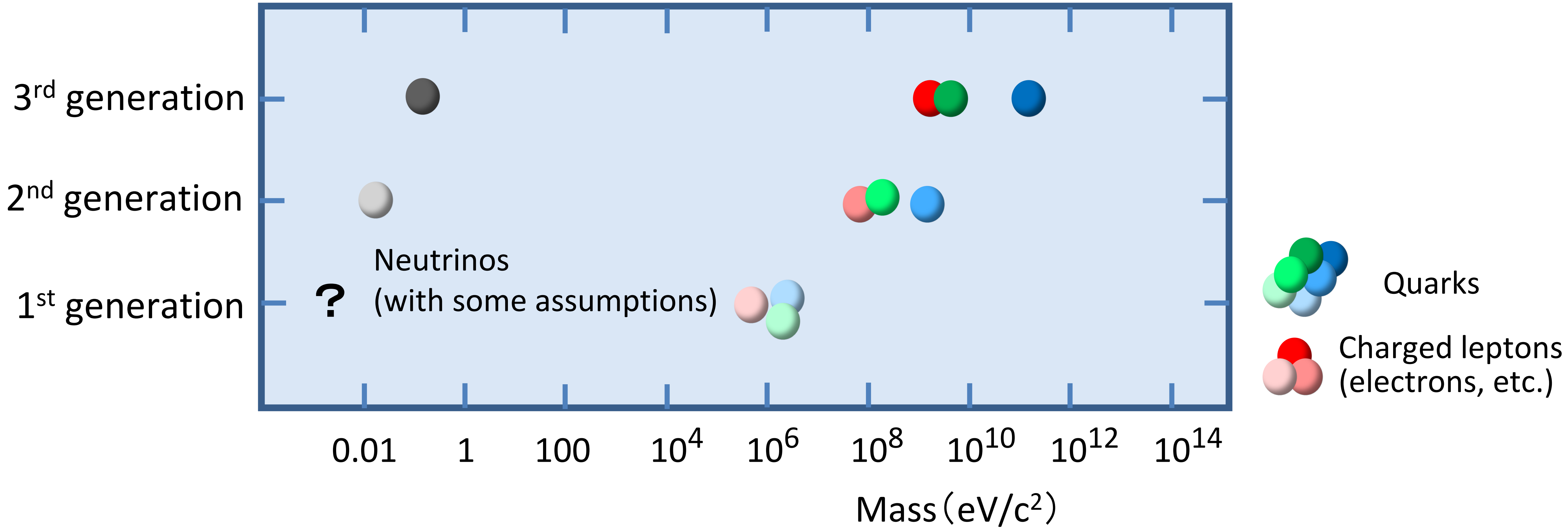
3 flavor(type) neutrino oscillation experiments



Neutrinos and a big mystery in the Universe

What have we learned?
Why are neutrinos important?

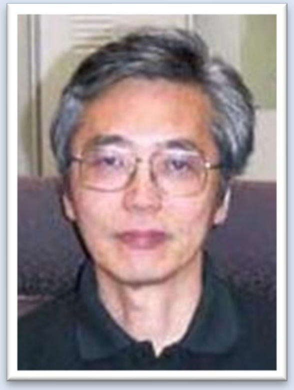


The neutrino mass is approximately (or more than) 10 billion times (10 orders of magnitude) smaller than the corresponding mass of quarks and charged leptons!
We believe this is the key to better understand elementary particles and the Universe.

A big mystery

Big Bang (very hot Universe) → Now

Number of protons (matter particles)	+	Number of anti-protons (anti-matter particles)	=	Number of protons (matter particles)
1,000,000,001		1,000,000,000		= 1



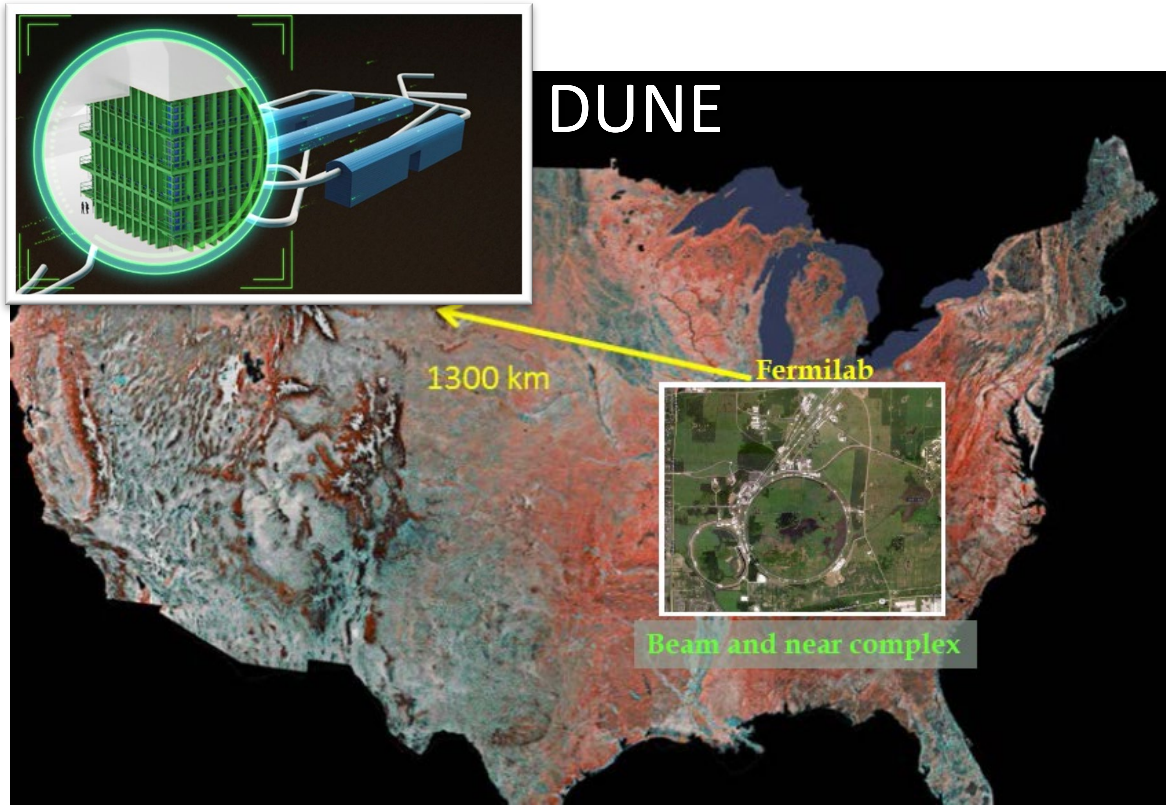
Neutrinos with very small mass might be the key to understand the big mystery of the matter in the Universe !

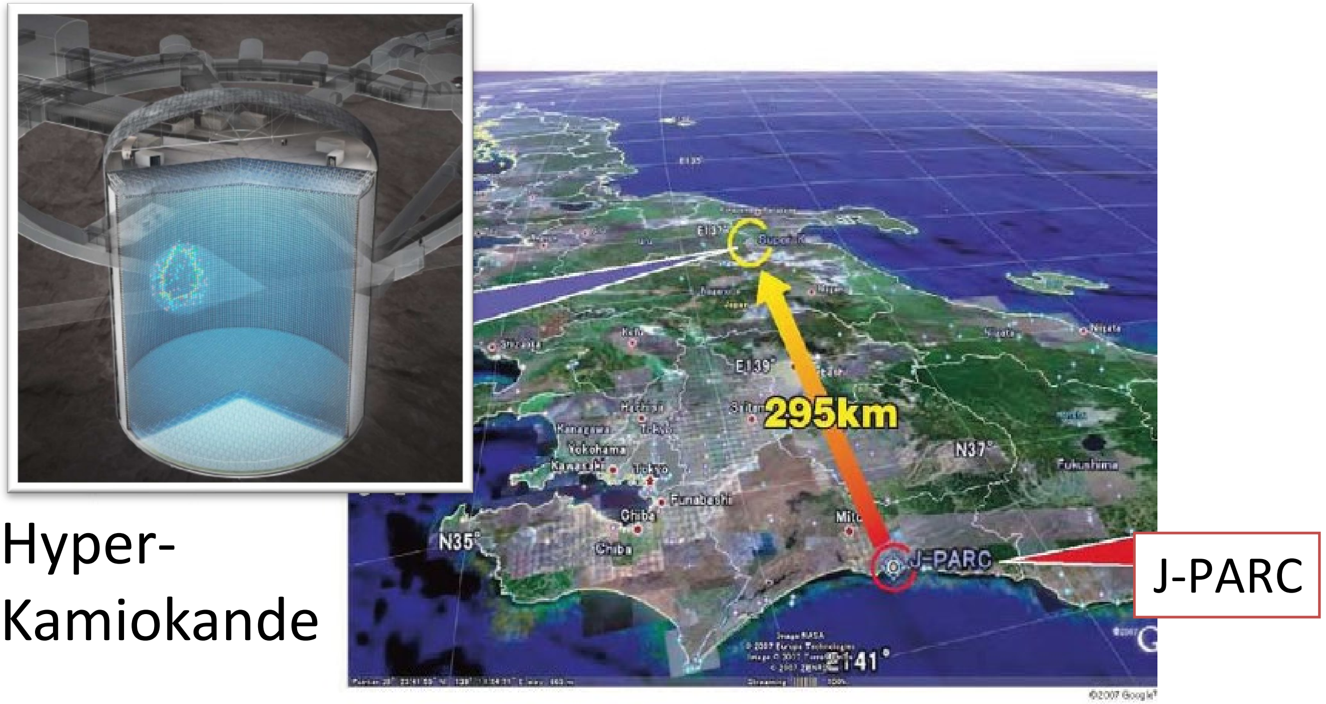
M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45-47

https://subarutelescope.org/jp/gallery/pressrelease/2015/06/22/173.html

Future

- ✓ We would like to know if neutrinos are related to the origin of the matter in the Universe.
- ✓ We would like to observe if neutrino oscillations of neutrinos and those of anti-neutrinos are different. ➔ We need the next generation neutrino experiments.





Hyper-Kamiokande

(Several other possibilities…)

Summary

- Neutrino oscillations were discovered by large underground detectors.
- The discovery of neutrino oscillations opened a window to study physics beyond the Standard Model of particle physics. Neutrinos with small mass might also be the key to understand the fundamental questions of the Universe.
- Neutrinos might be the key particles for the understanding of the smallest particles and the largest Universe.
- There are many unanswered questions in the Universe. I hope that these questions will be answered by the future research. I also hope that these future research will find unknown questions to date, which will be the key to understand the Universe better.