June 2, 2022,
Public talk (online),
Neutrino 2022, Virtual Seoul

Oscillating Neutrinos - a key to understanding the Universe

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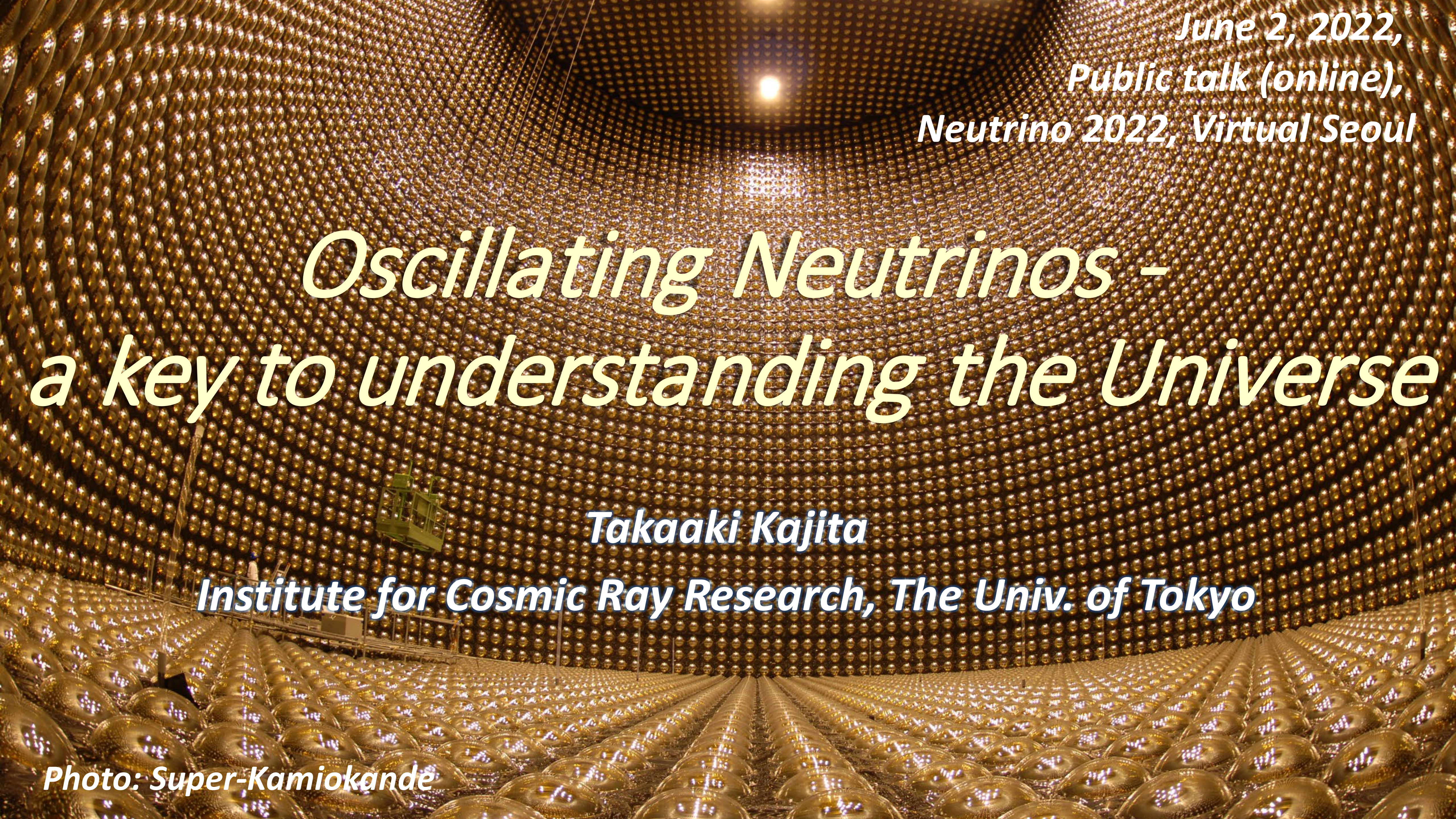


Photo: Super-Kamiokande

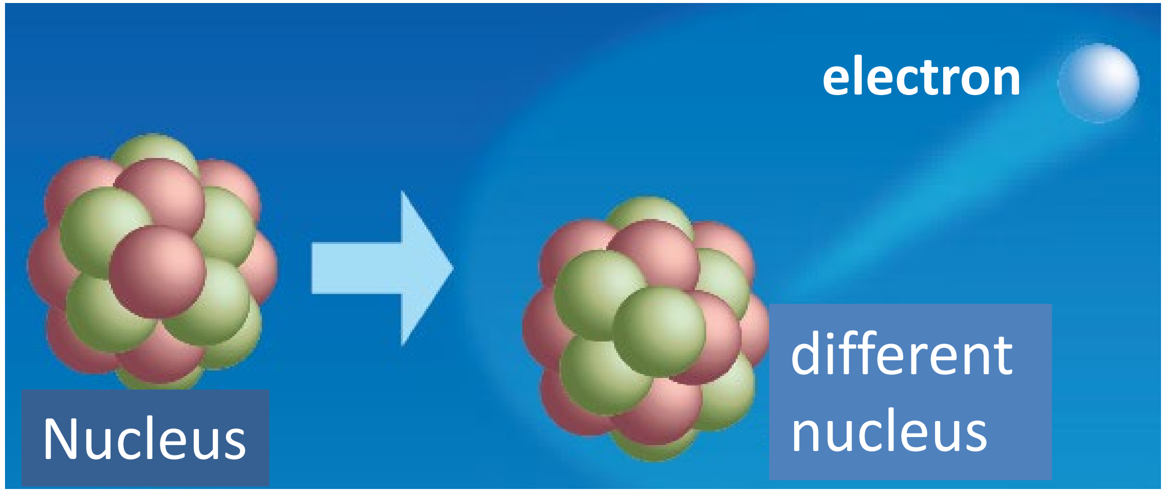
Outline

- *Introduction*
- *Early days*
- *Discovery of neutrino oscillations*
- *Solar neutrino oscillations*
- *Oscillating neutrinos and the Universe*
- *Summary*

Introduction

Initial hint for neutrinos

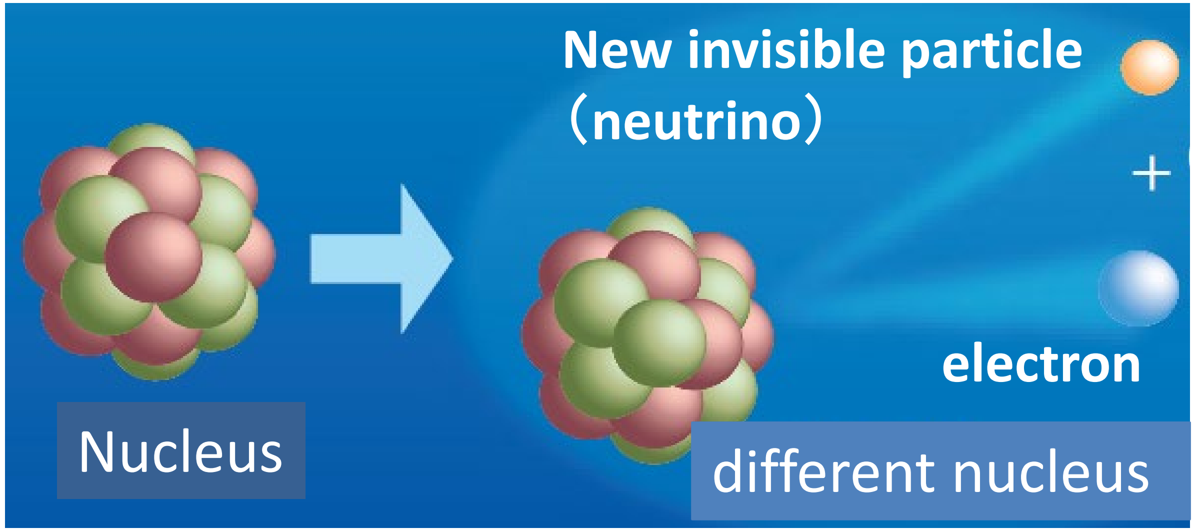
Nuclear β decay (a nucleus change to a different nucleus by emitting an electron)



In this case, the energy of the electron should be unique. But the observations suggested various or continuous electron energies….

(1930, W. Pauli)

(Wikipedia)

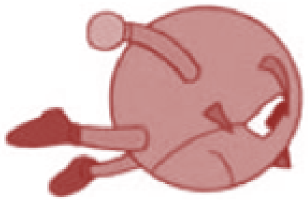


Credit : 梶田隆章「ニュートリノ振動」をとらえる、イリューム, Vol.16, No.2 第32号(2004)

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, like the other particles, 3 types (flavors), namely electron-neutrinos (ν_e), muon-neutrinos (ν_μ) and **tau-neutrinos (ν_τ),**



Electron-neutrino

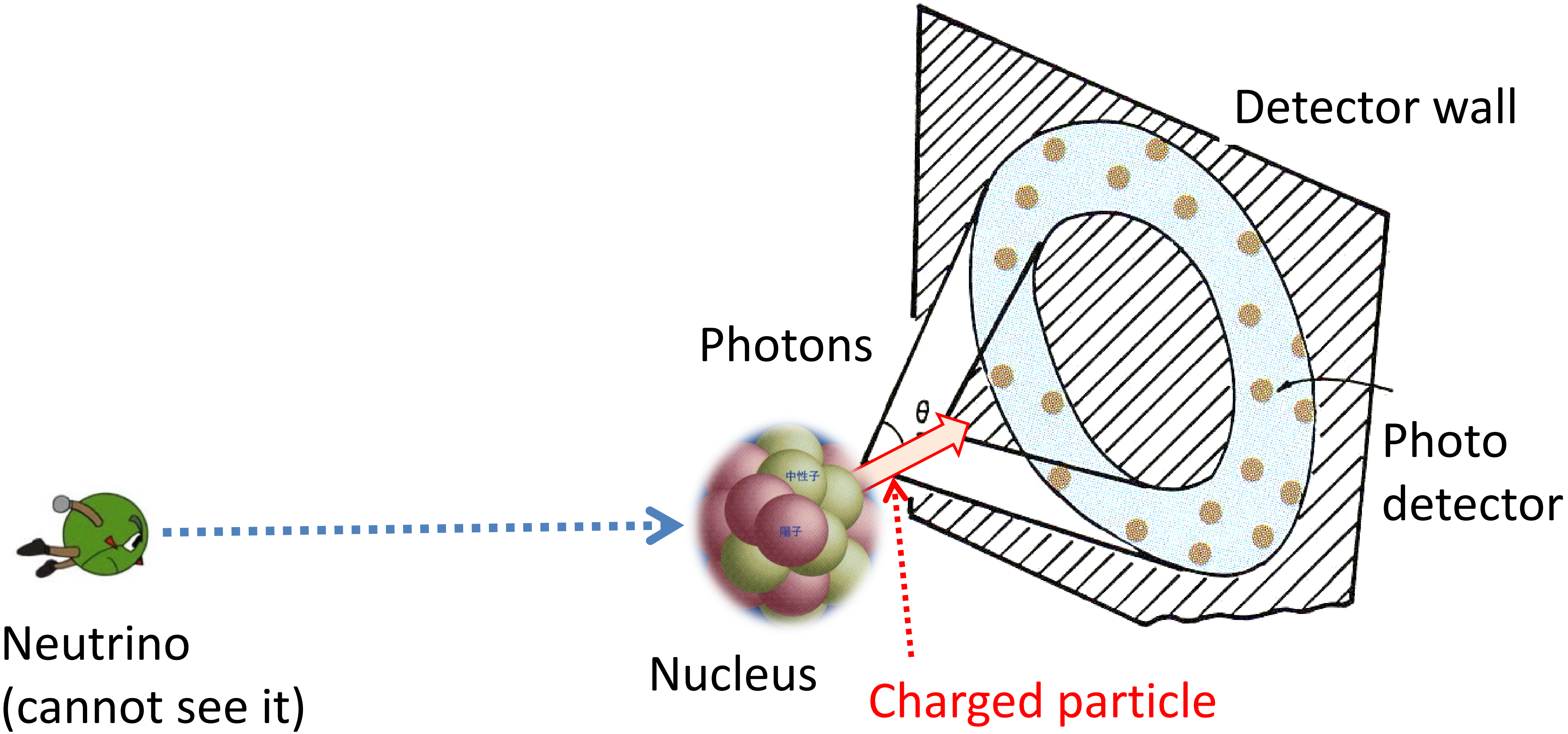
Muon-neutrino
(or mu-neutrino)

Tau-neutrino

http://dchooz.titech.jp.hep.net/nu_oscillation.html
(slightly modified)

- ✓ have been assumed to have no mass.

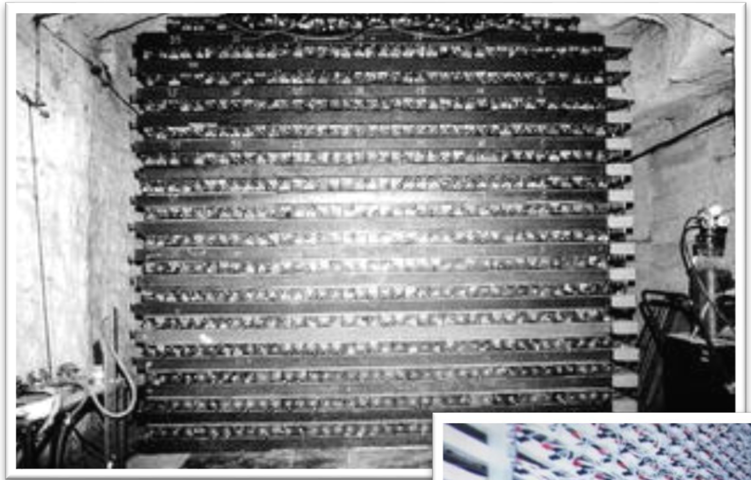
How can we detect neutrinos ?



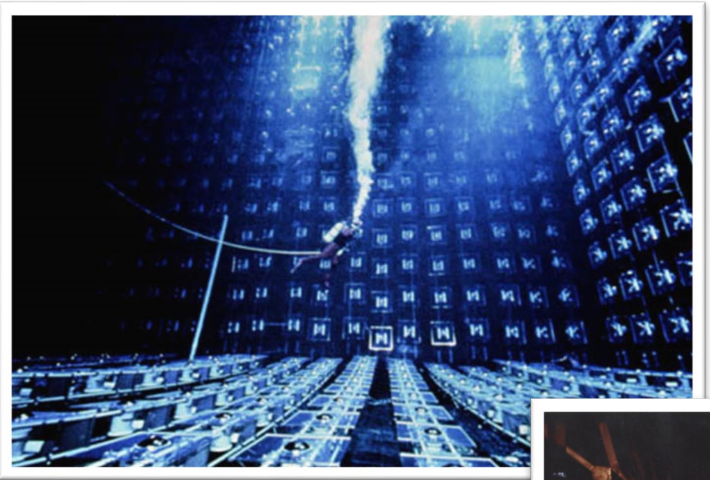
Early days

Proton decay experiments

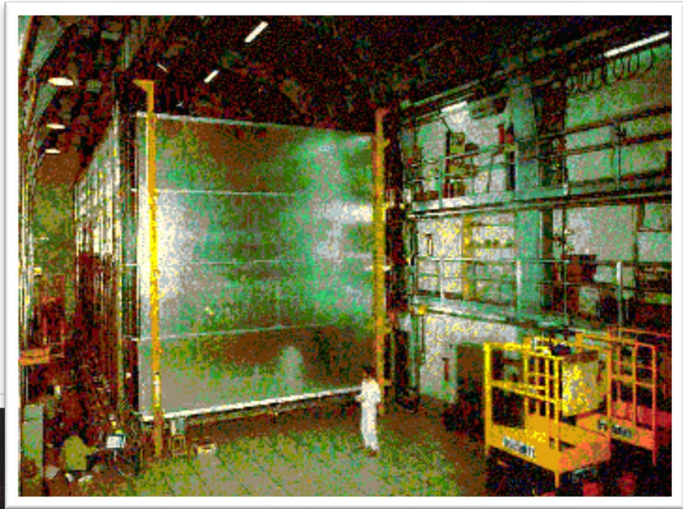
- ✓ In the 1970's, new theories of elementary particles predicted that protons should decay with the lifetime of about 10^{30} years.
- ✓ Several proton decay experiments began in the early 1980's.



KGF (India)

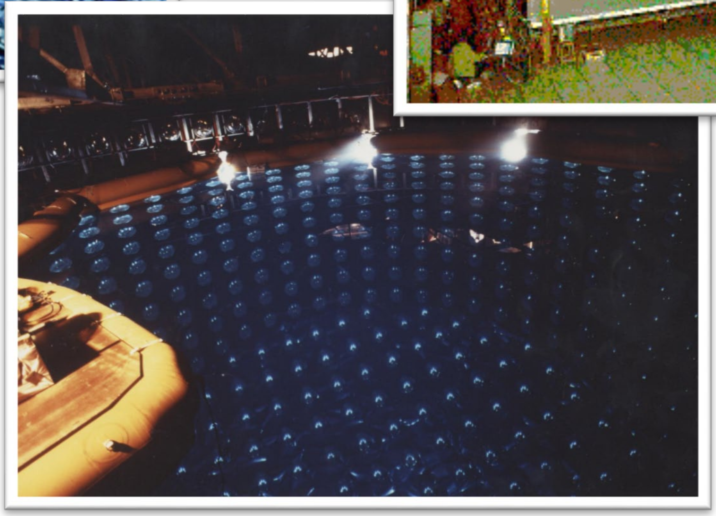


IMB (USA)



Frejus (Europe)

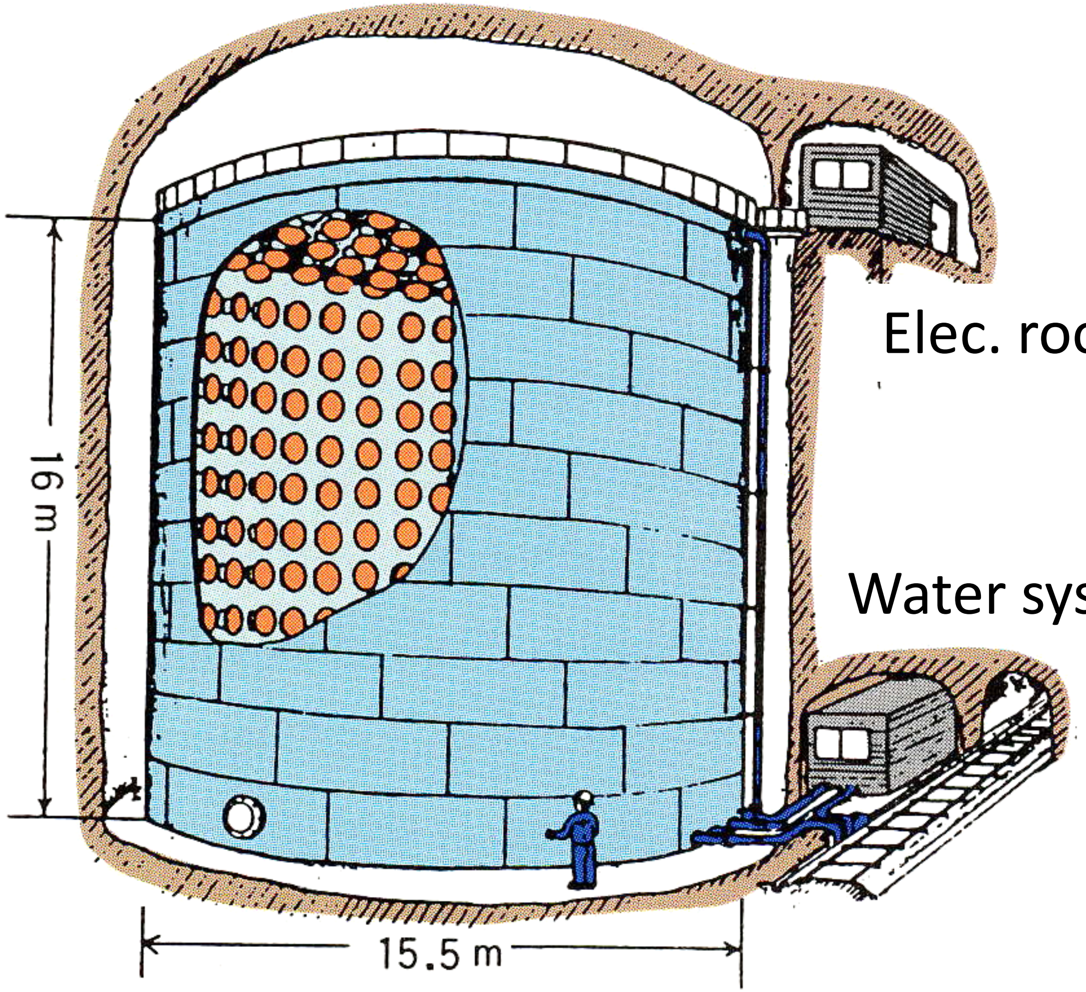
NUSEX (Europe)

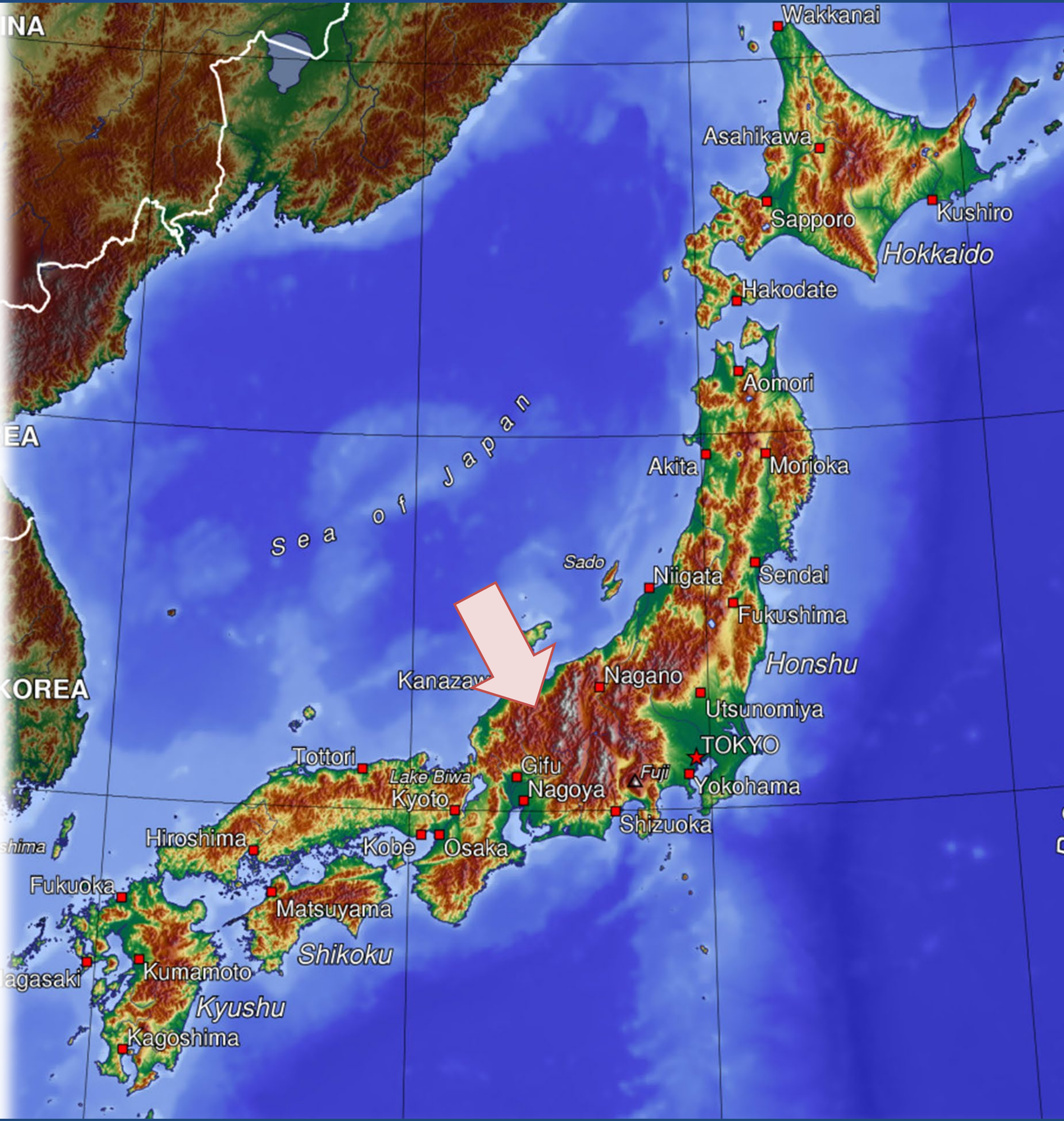


Kamiokande (Japan)

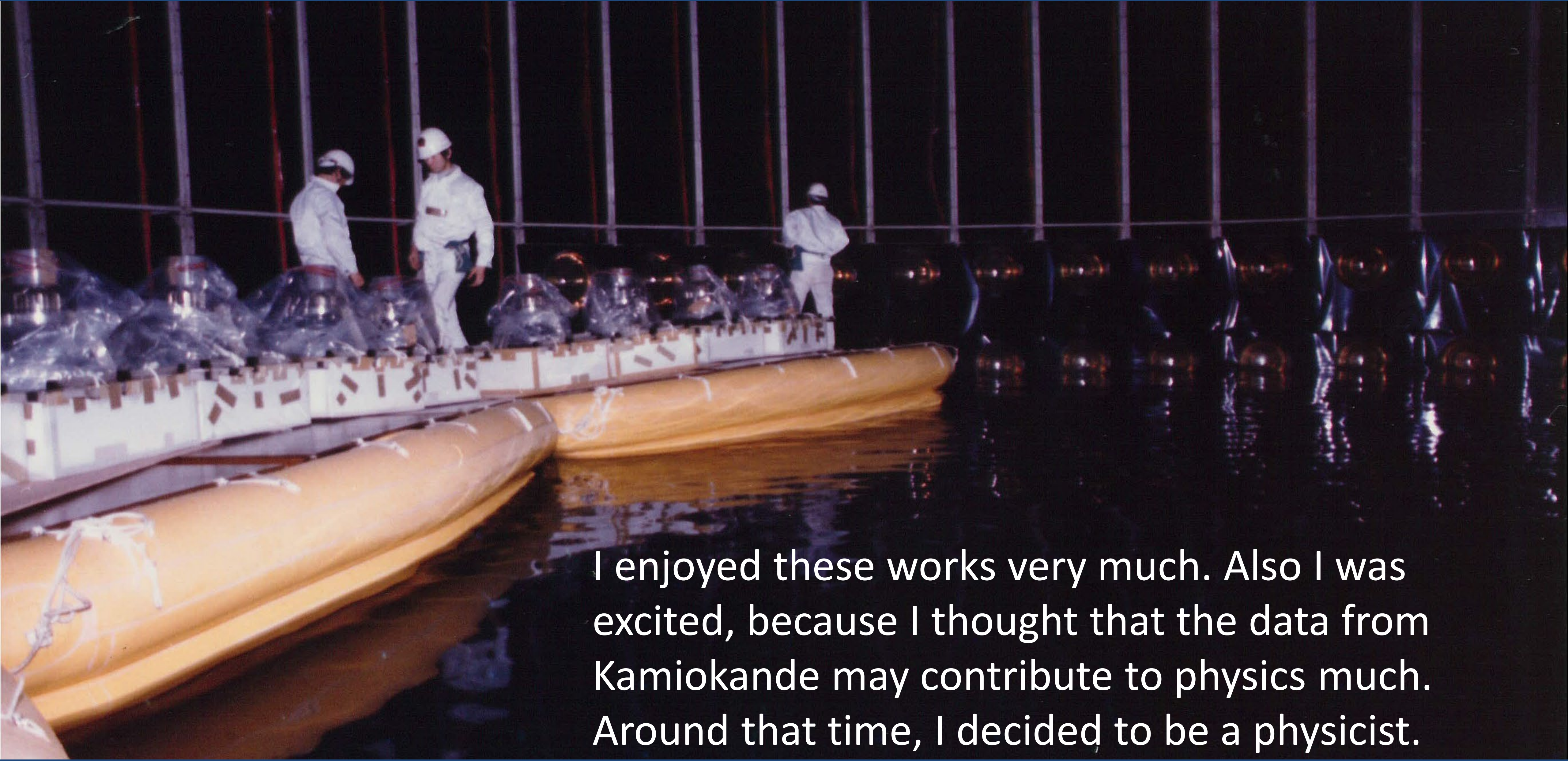
Kamiokande

- ✓ One of these experiments was Kamiokande (3000 ton water).



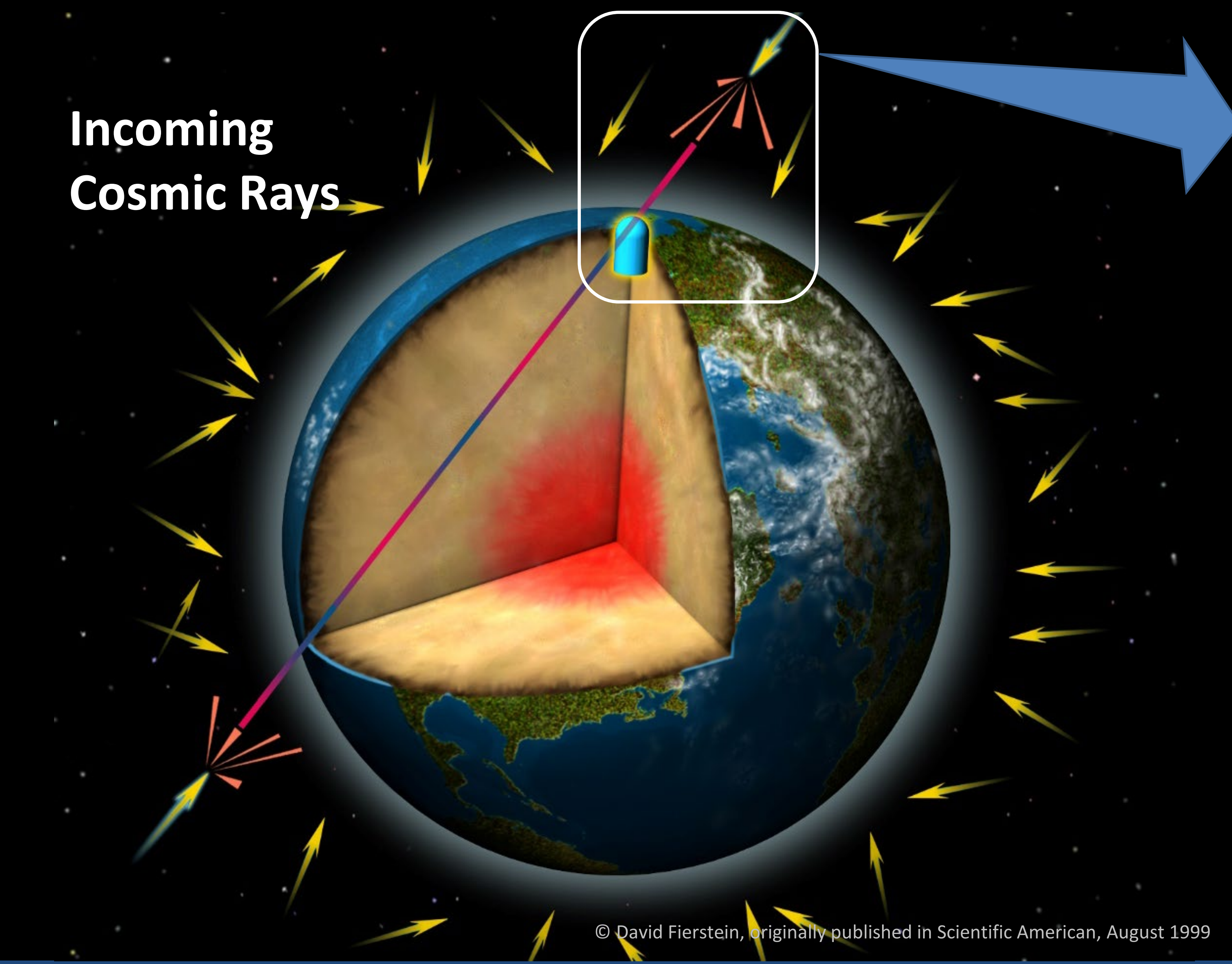


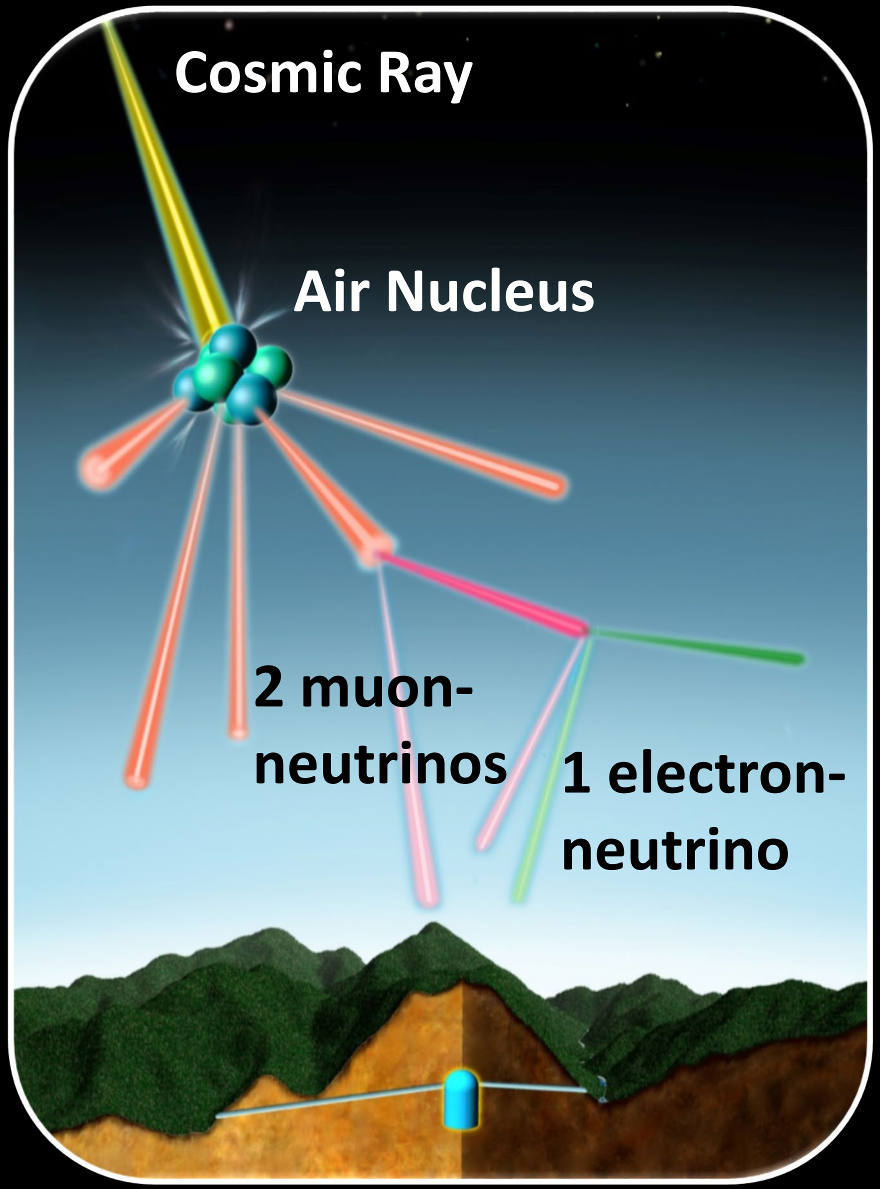
Construction of the Kamiokande detector (spring 1983)



I enjoyed these works very much. Also I was excited, because I thought that the data from Kamiokande may contribute to physics much. Around that time, I decided to be a physicist.

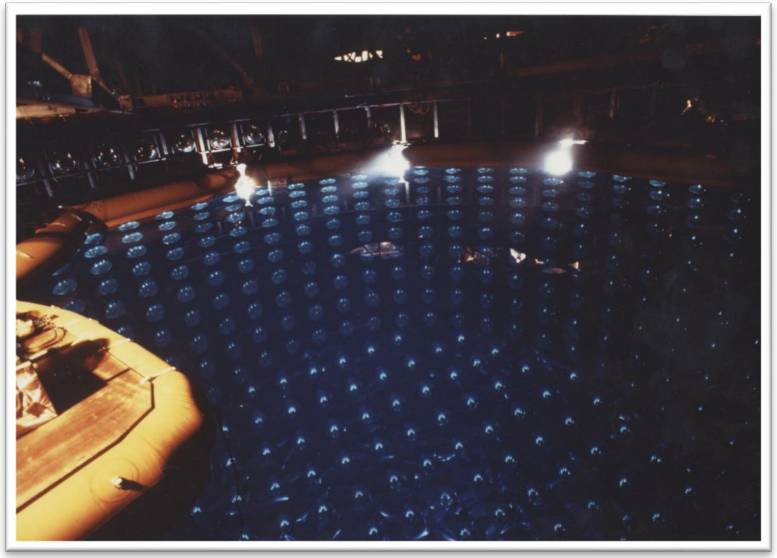
Atmospheric neutrinos



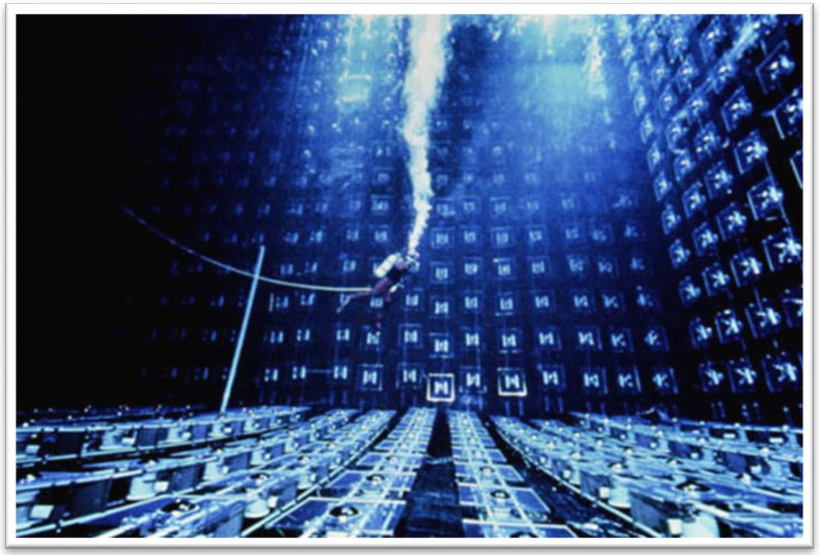


Atmospheric neutrino deficit (1980's to 90's)

- ✓ Proton decay experiments in the 1980's observed many atmospheric neutrino events.
- ✓ Because atmospheric neutrinos were the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions.
- ✓ During these studies, a significant deficit of atmospheric mu-neutrino events was observed.



Kamiokande



IMB

<u>My personal memory</u>: Although we had no clear idea what was the cause of the deficit, I was most excited with the data. I thought that the data indicated something new. As a scientist, it was the most exciting time. I decided to concentrate on this topic.

Neutrino oscillations

If neutrinos have mass, neutrinos change their type from one type to the other. For example, a **mu-neutrino** may change the type to a **tau-neutrino**.

http://dchooz.titech.jp.hep.net/nu_oscillation.html (slightly modified)

mu-neutrino tau-neutrino mu-neutrino tau-neutrino

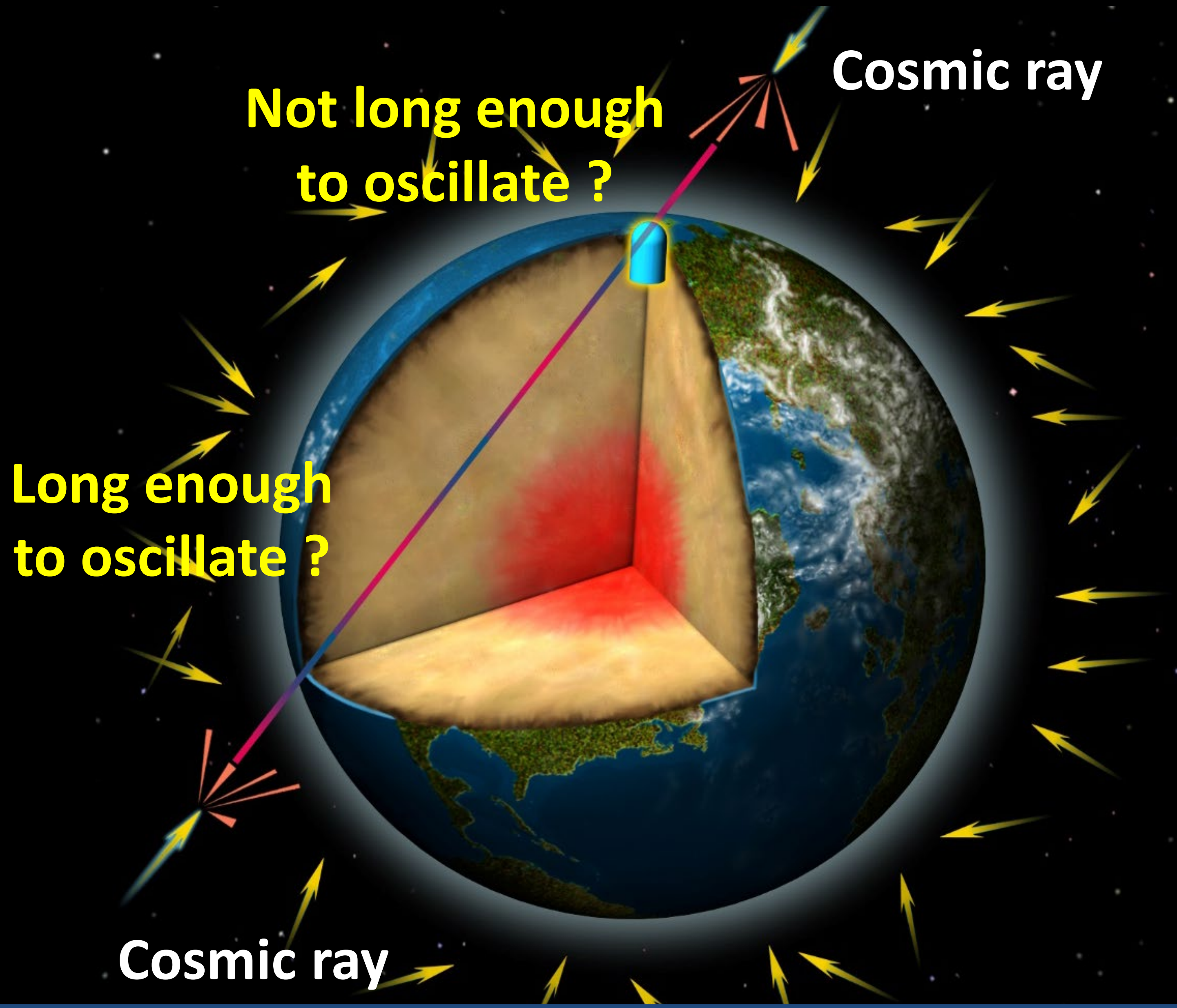
Neutrino oscillations were predicted more than 50 years ago by Maki, Nakagawa, Sakata, and by Pontecorvo.

S. Sakata, Z. Maki, M. Nakagawa

arXiv:0910.1657

B. Pontecorvo

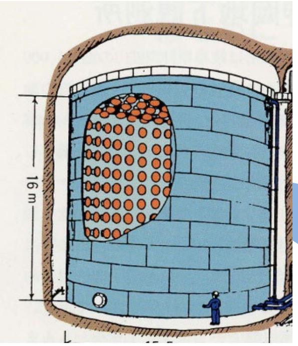
What will happen if the deficit is due to neutrino oscillations



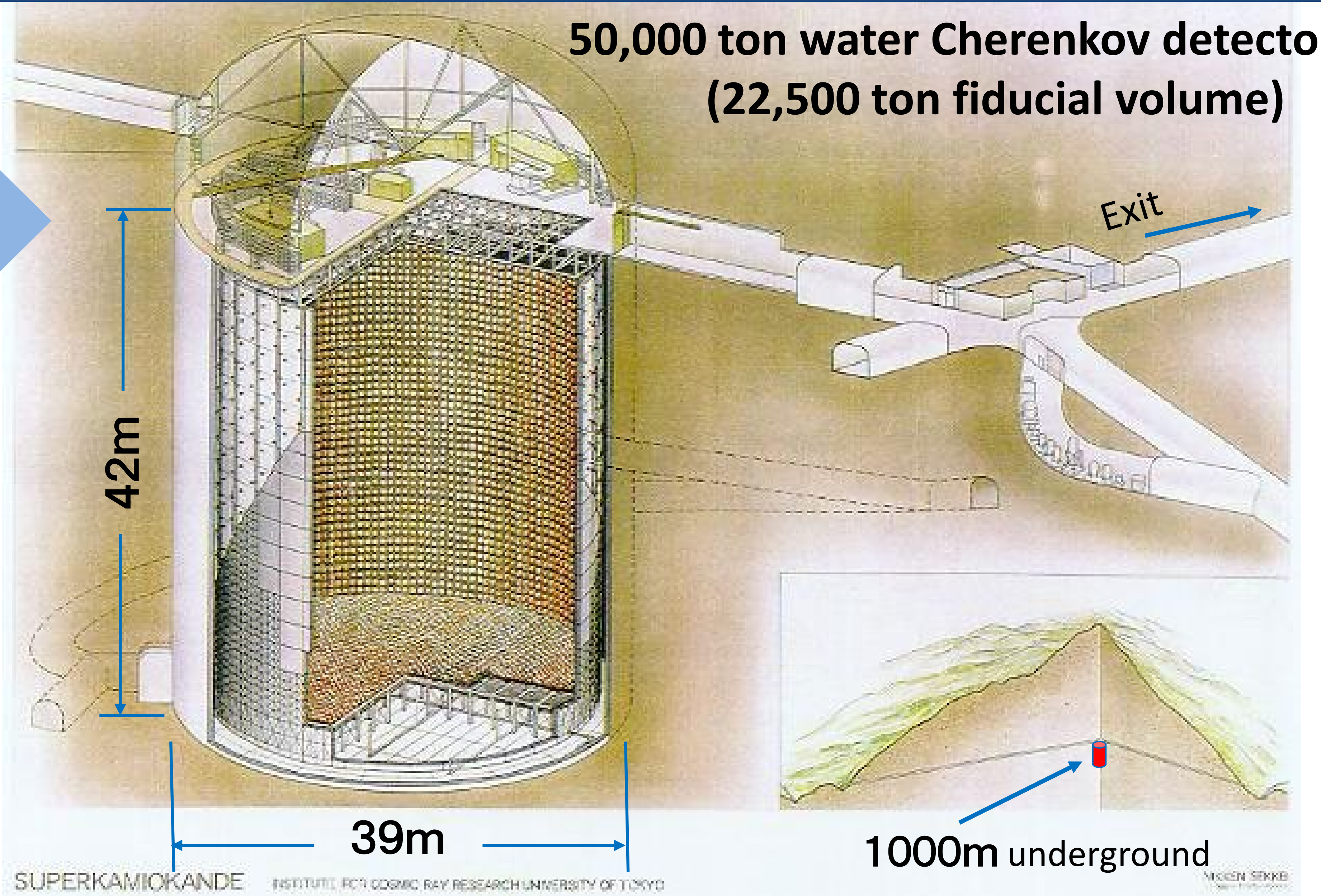
An asymmetry of the up- versus down-going flux of muon-neutrinos should be observed! However, Kamiokande was too small.
➔ Super-Kamiokande

Discovery of neutrino oscillations

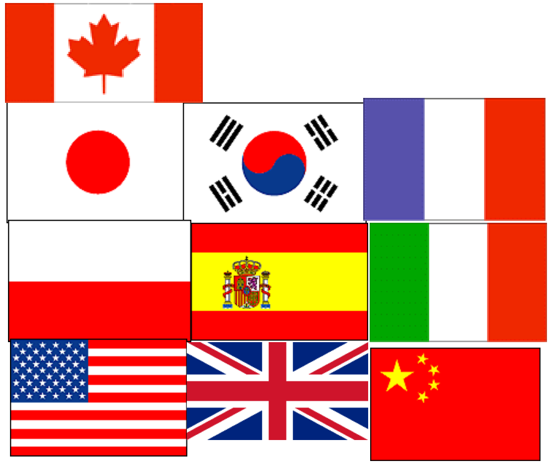
Super-Kamiokande detector



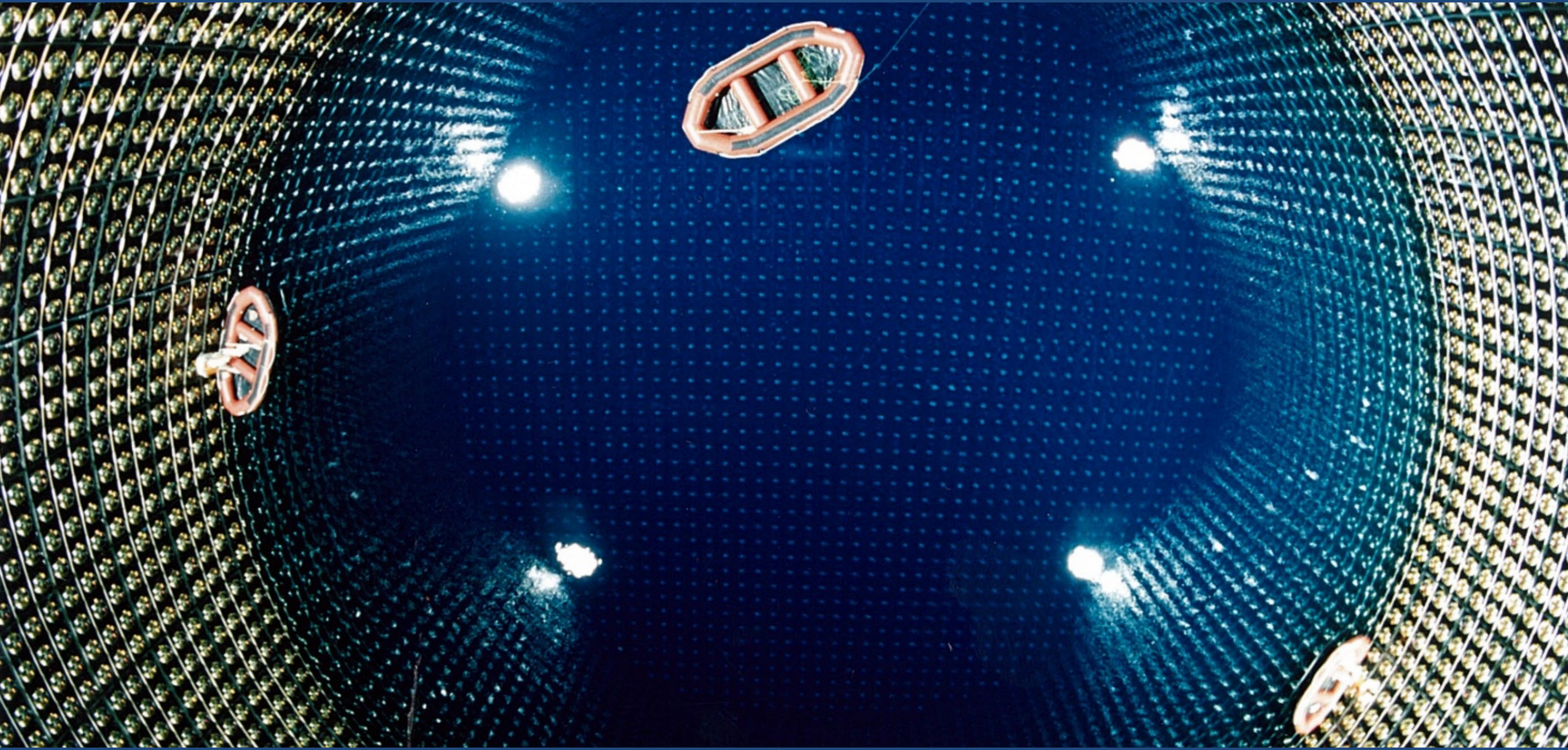
~20 times
larger mass



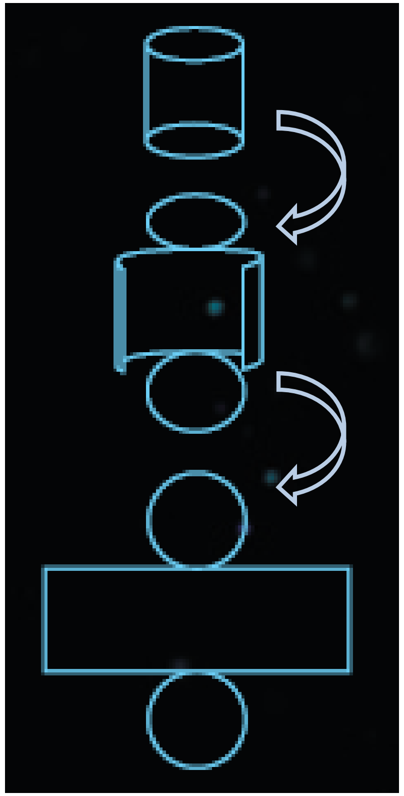
~200 collaborators

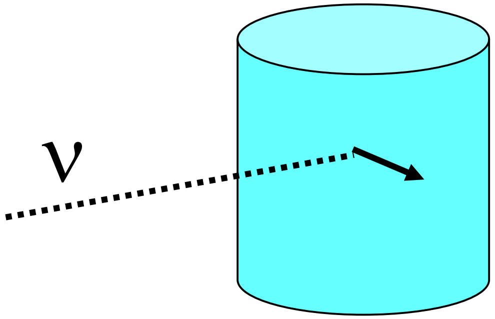


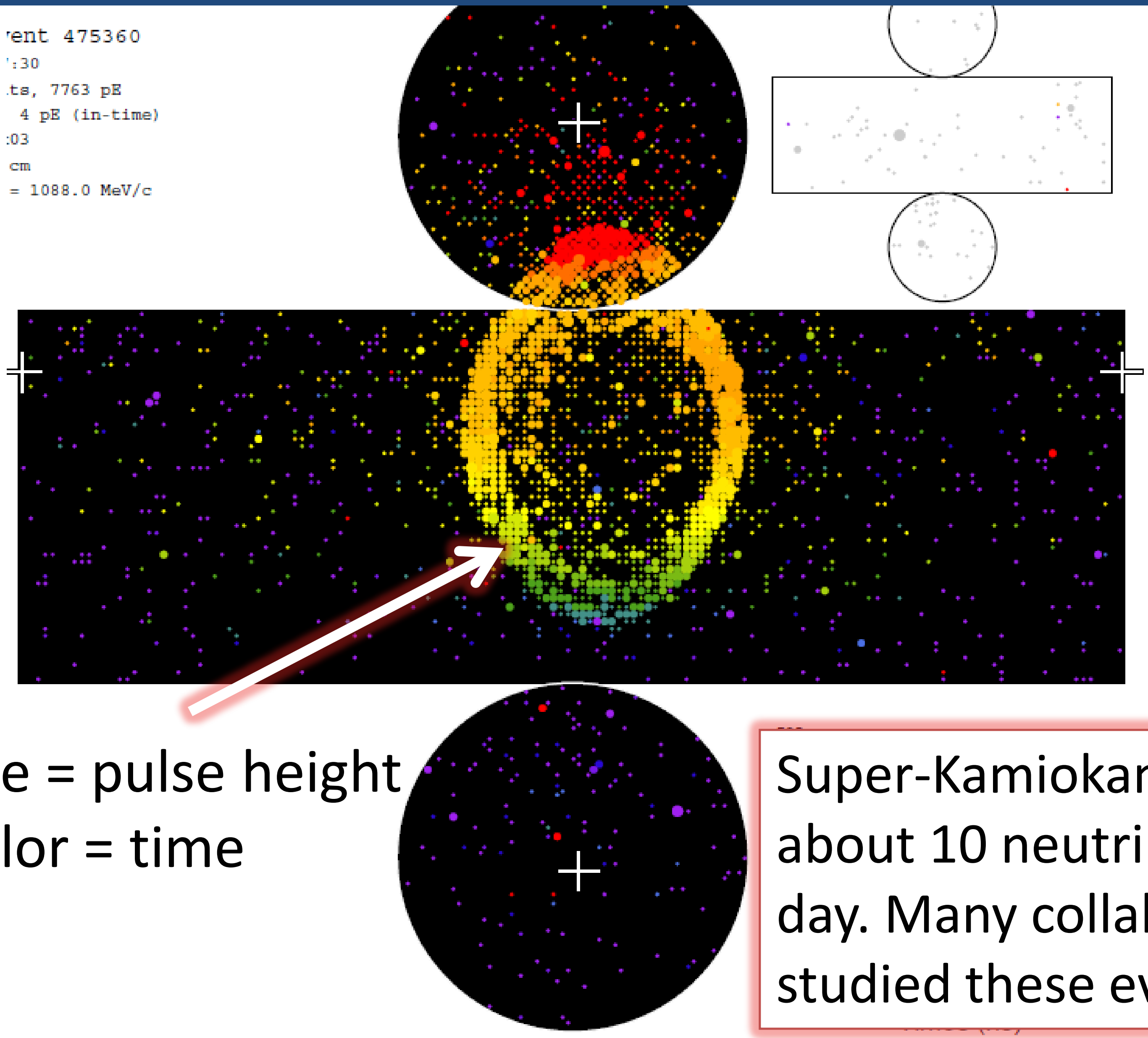
Filling water in Super-Kamiokande (Jan. 1996)



Atmospheric neutrino events observed in Super-K





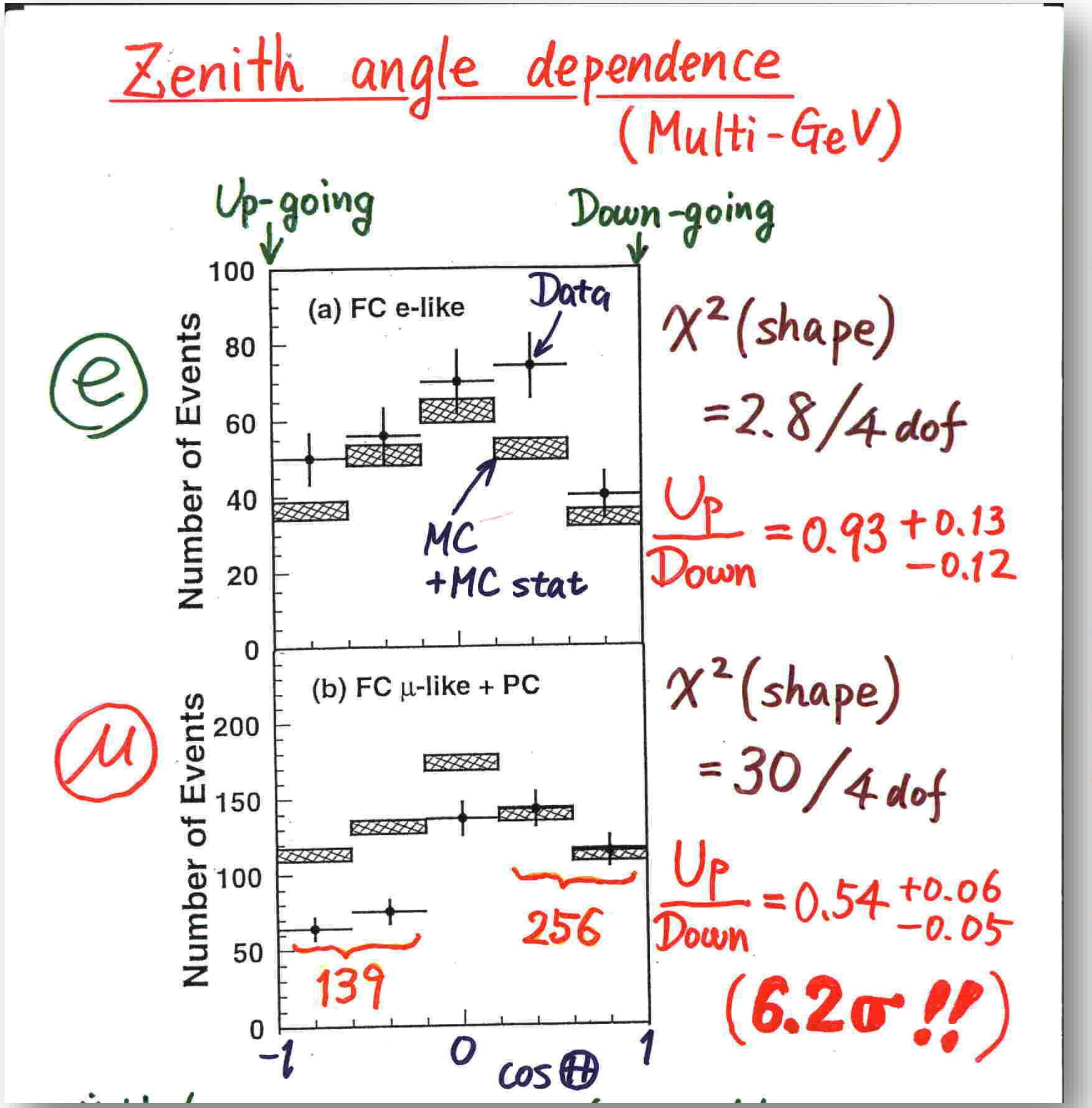


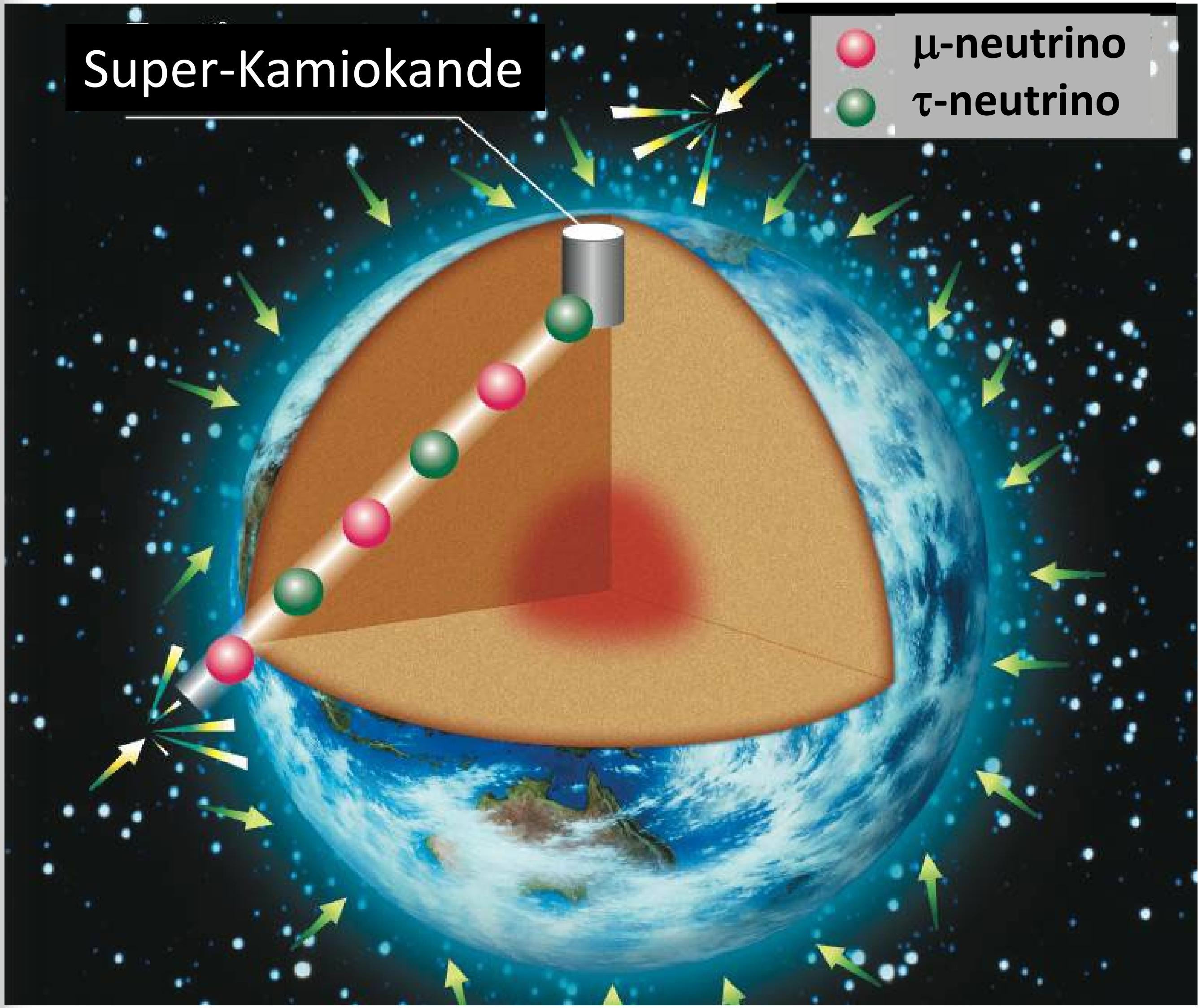
Size = pulse height
Color = time

Super-Kamiokande observes about 10 neutrino events in a day. Many collaborators studied these events as a team.

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

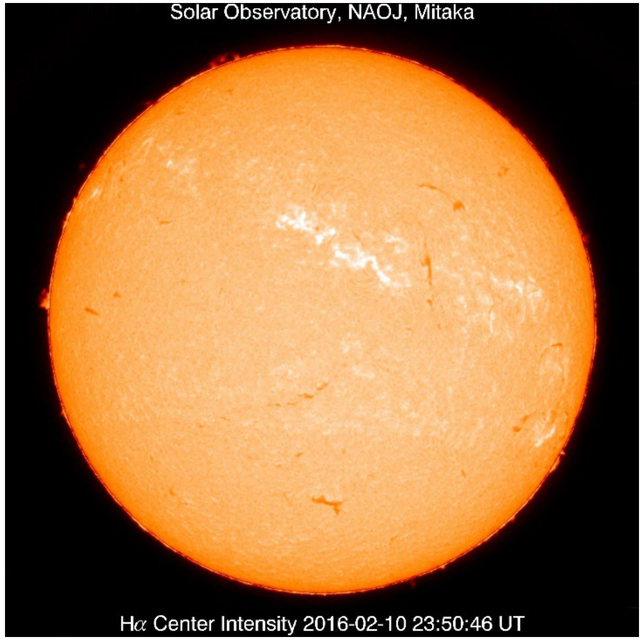
Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.

. . . . .

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.

Solar neutrino oscillations

Solar neutrino problem



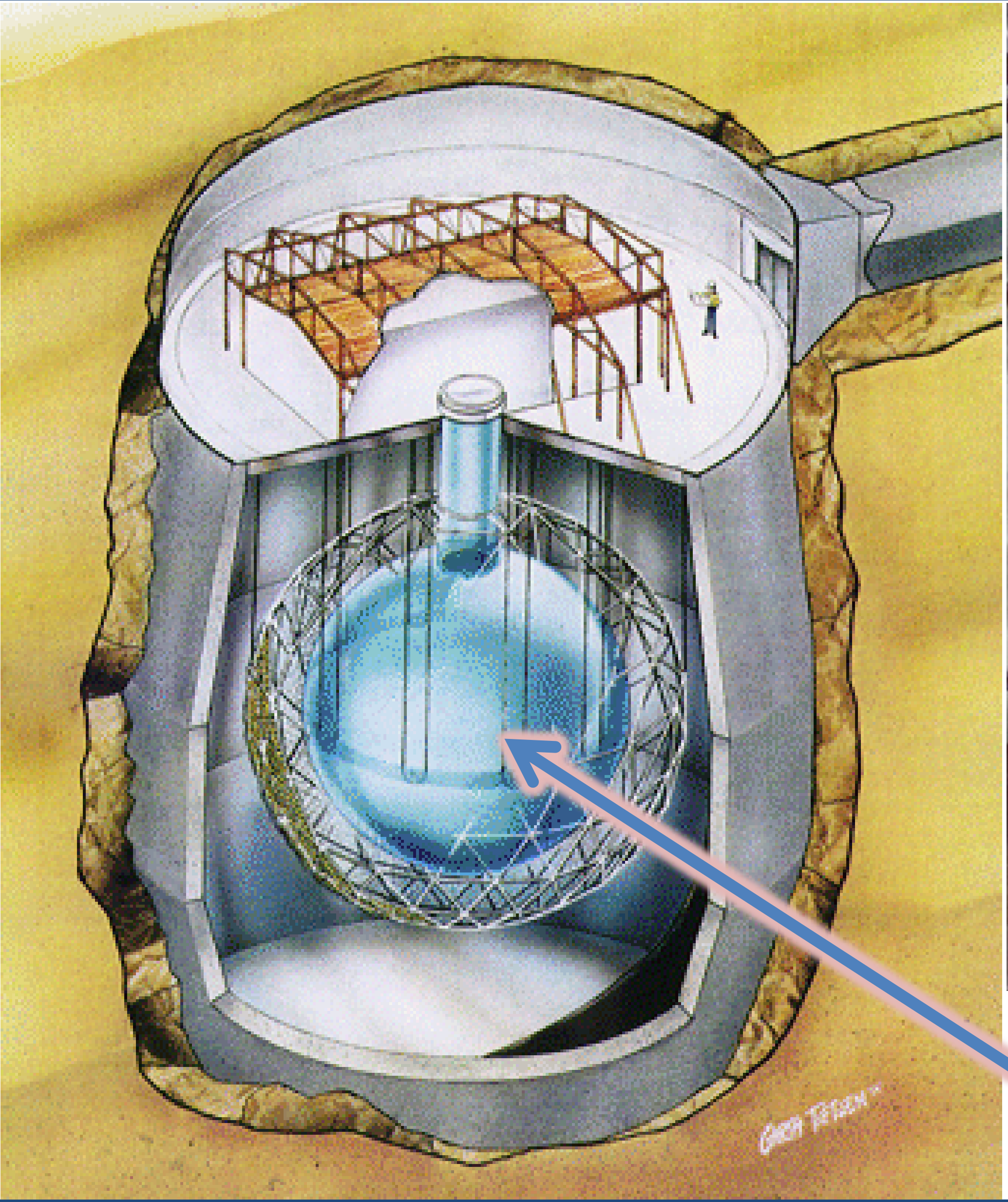
The Sun generates energy by nuclear fusion processes. During these processes, many neutrinos are generated.

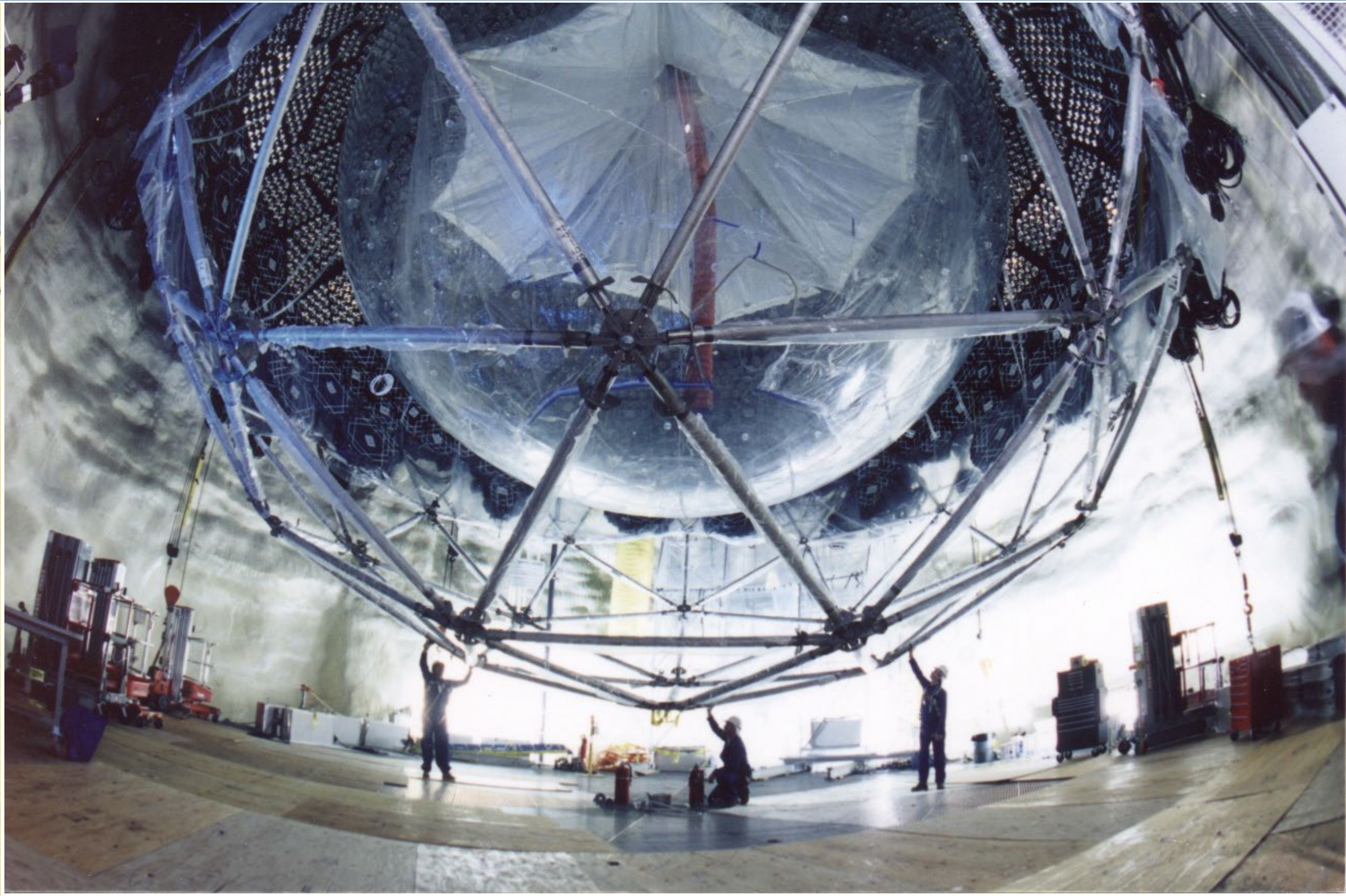
600ton C_2Cl_4

R. Davis Jr.

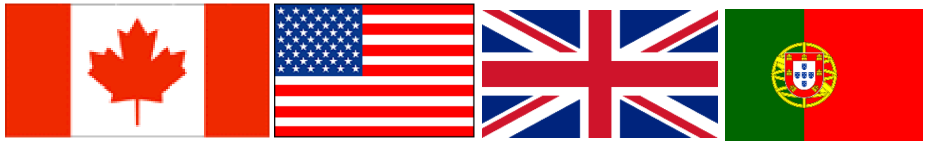
More than 50 years ago, the Homestake experiment observed solar neutrinos for the first time. However, the observed event rate was only about 1/3 of the prediction.

SNO detector



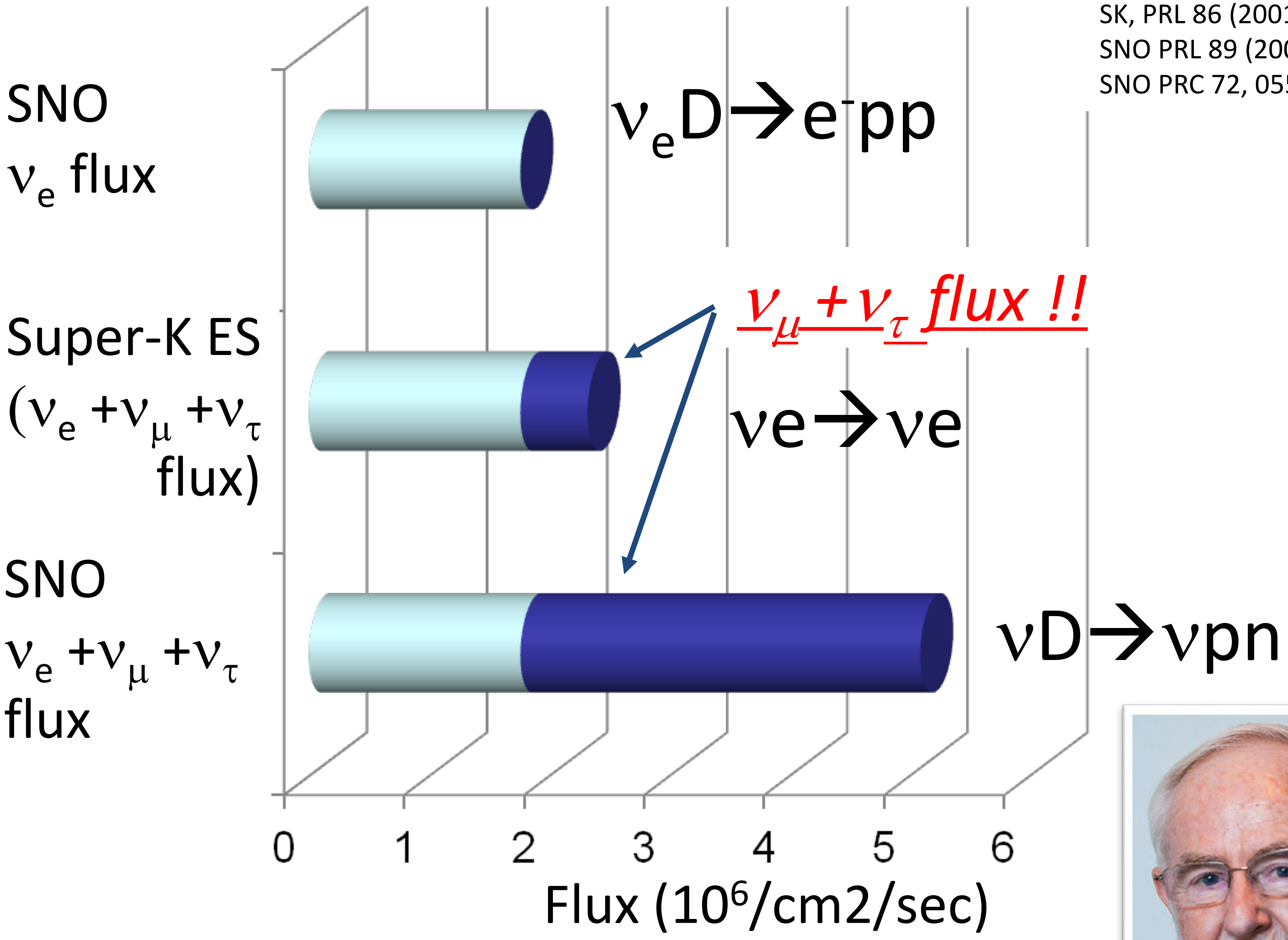


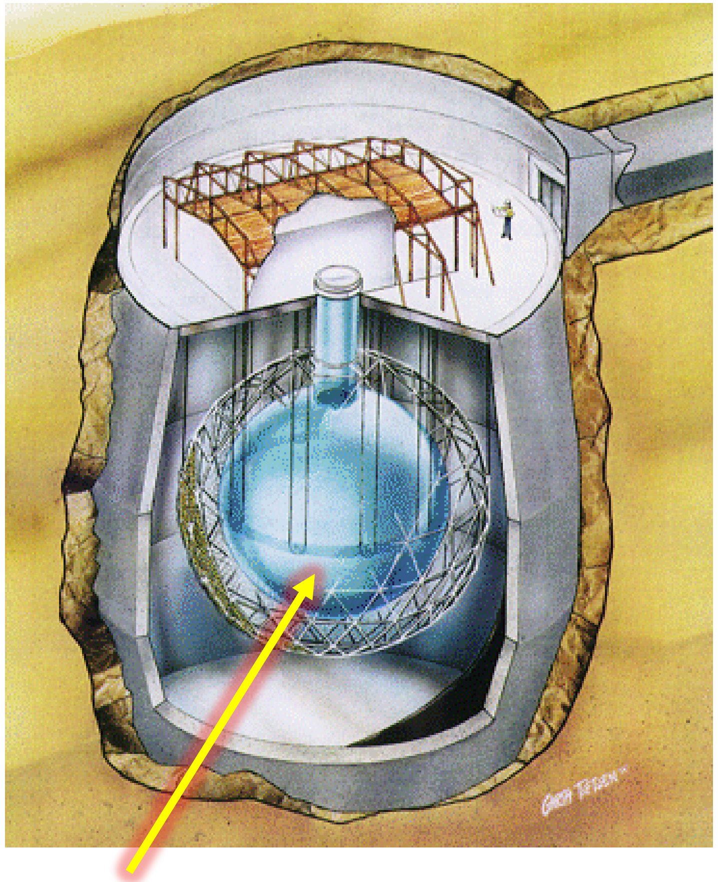
1000 tons of
heavy water (D_2O)



Solar neutrino oscillation (2001-2002)

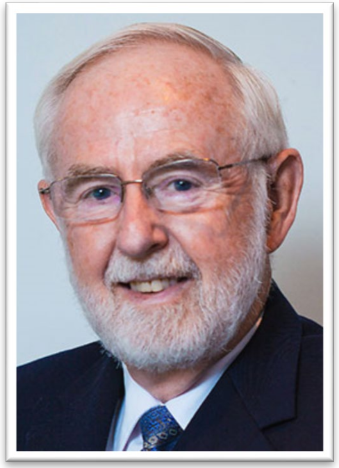
SK, PRL 86 (2001) 5651
SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)





1000 tons of heavy water (D_2O)

Neutrino oscillation: electron neutrinos to the other neutrinos.

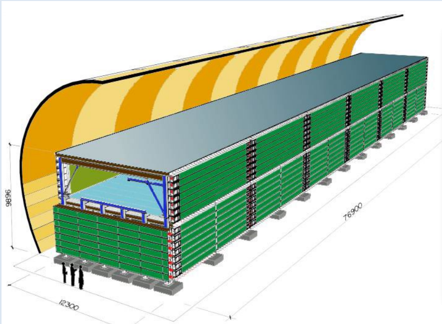


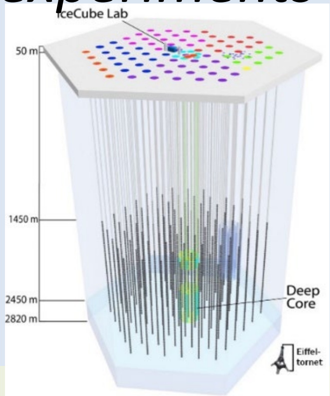
Art McDonald (Nobel Prize 2015)

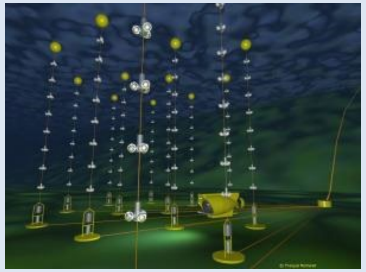
Photo: K. MacFarlane. Queen's University /SNOLAB

Many exciting results in neutrino oscillations (partial list)

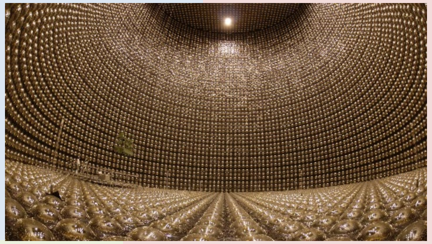
Atmospheric neutrino oscillation experiments

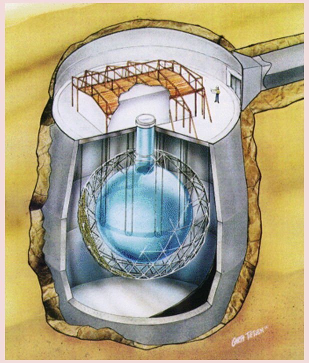


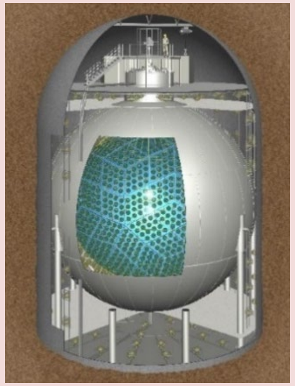


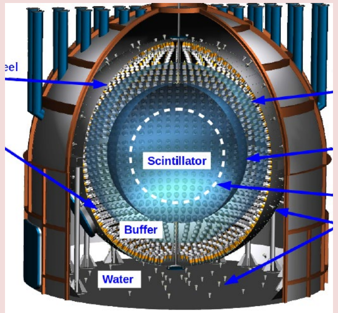


Solar neutrino oscillation experiments

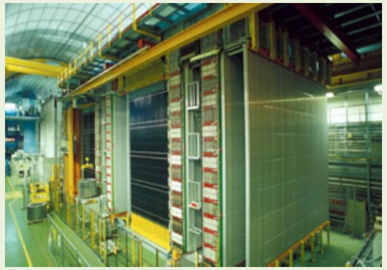






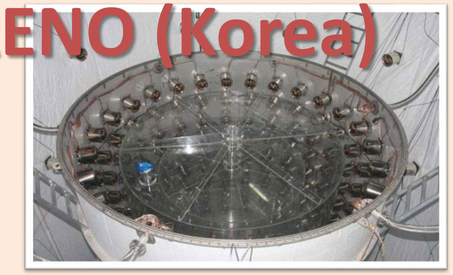


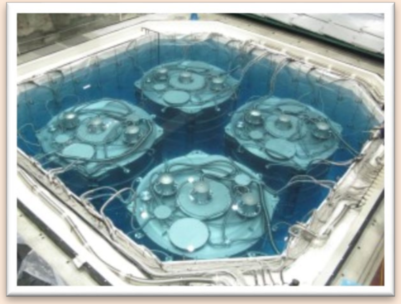
Accelerator based neutrino oscillation experiments

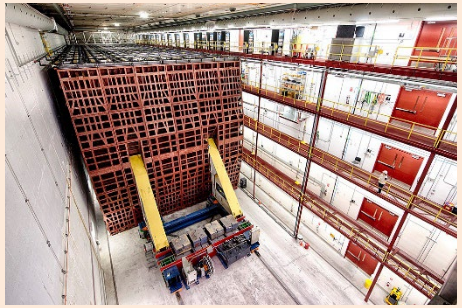


3 flavor(type) neutrino oscillation experiments

RENO (Korea)

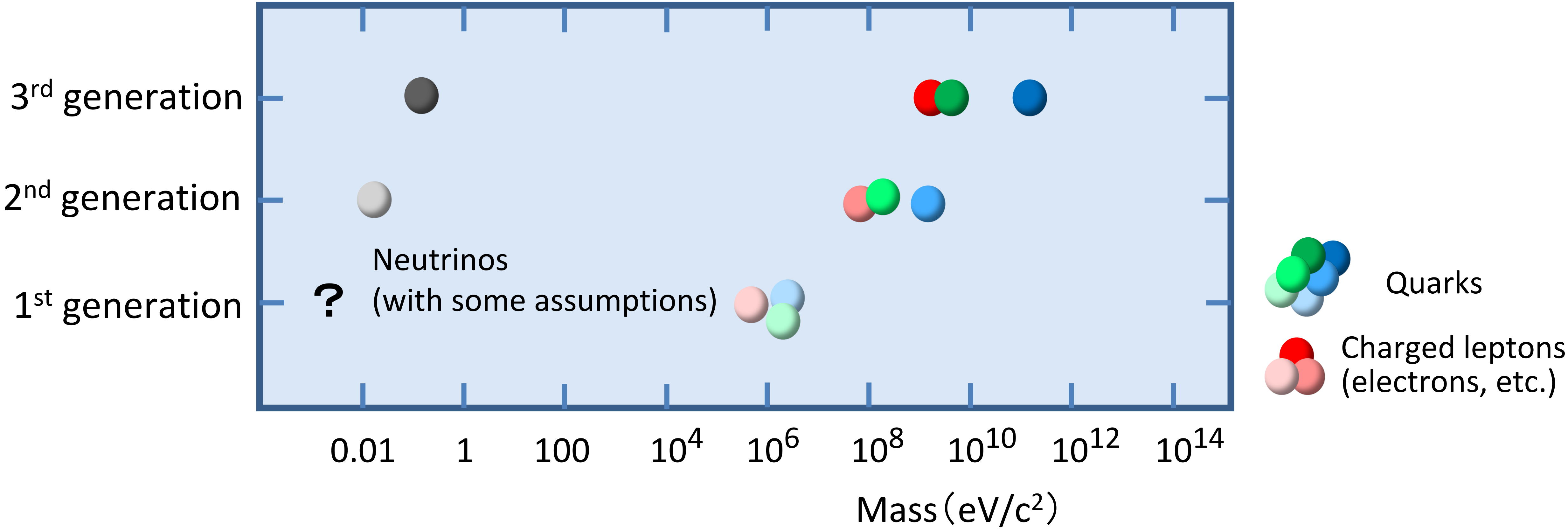






Oscillating neutrinos and the Universe

What have we learned?
Why are neutrinos important?



The neutrino mass is approximately (or more than) 10 billion (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

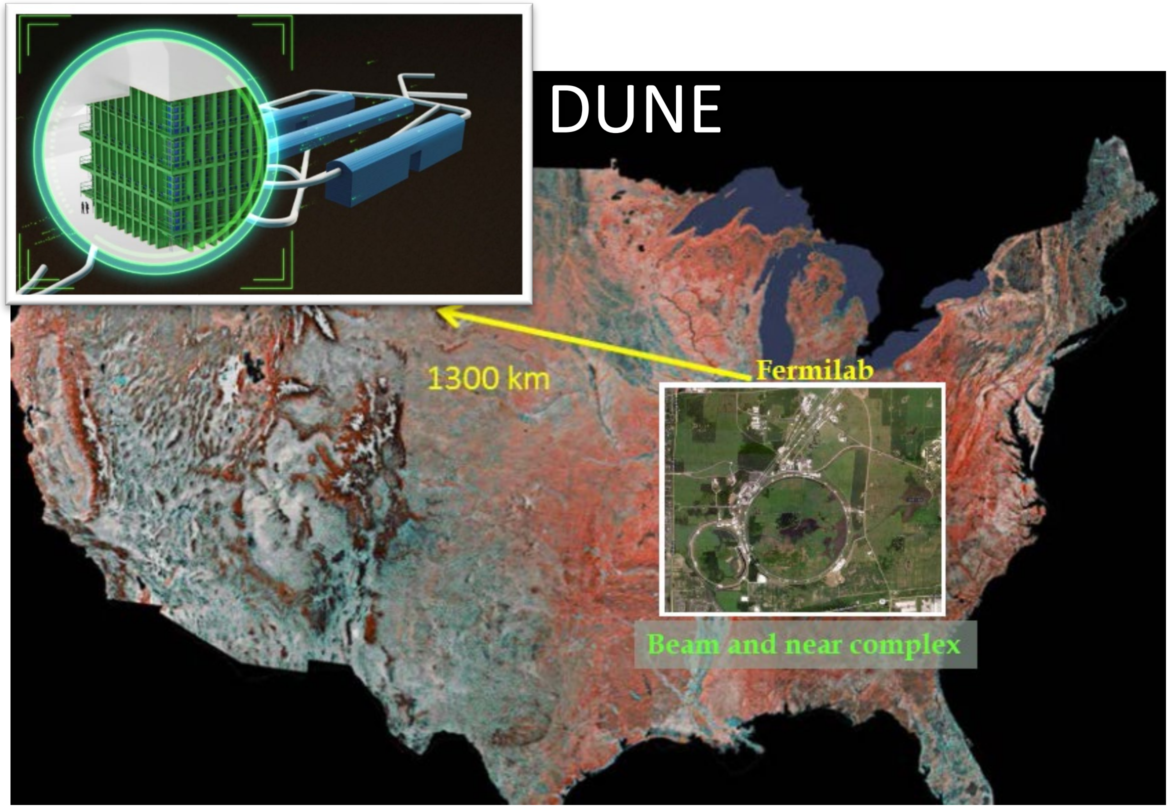
Number of protons (matter particles)	+	Number of anti-protons (anti-matter particles)	=	Number of protons (matter particles)
1,000,000,001		1,000,000,000		= 1

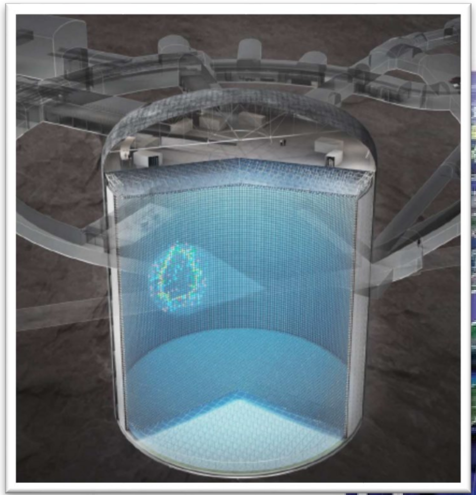
Neutrinos with very small mass might be the key to understand the big mystery of the matter in the Universe !

Perseus Cluster (Abell426)
Photo by Y.Nakagawa, 2007

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 long baseline experiments with much higher performance neutrino detectors.





Hyper-Kamiokande

J-PARC

(Several other possibilities…)

Summary

- Neutrinos are very interesting particles.
- Neutrino oscillations were discovered by the Super-Kamiokande and SNO experiments.
- The discovery of non-zero neutrino mass 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 will continue to be interesting!
- (I feel that I was very fortunate. I had very good advisors, colleagues and was involved in very good scientific projects.)

Science is really interesting!

I hope that many of the audience today decide to do science.