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Neutrinos

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

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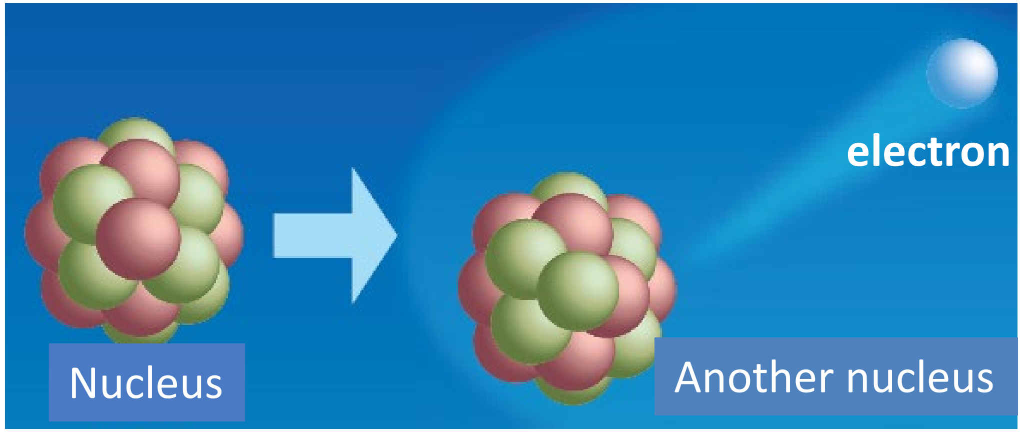
Outline

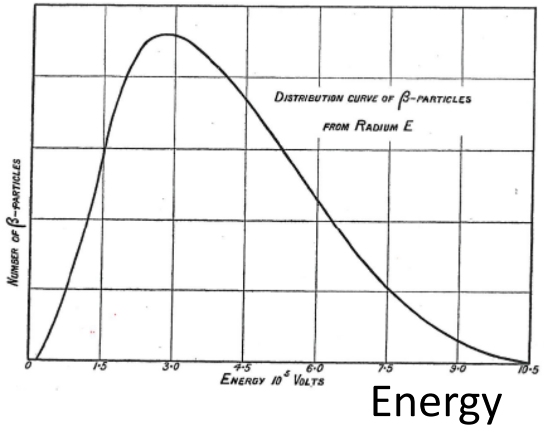
- *What are neutrinos*
- *Neutrino problems*
- *Discovery of neutrino oscillations*
- *Discovery of solar neutrino oscillations*
- *Discovery of the third neutrino oscillations*
- *Neutrinos: remaining questions and mysteries*
- *Summary*

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.

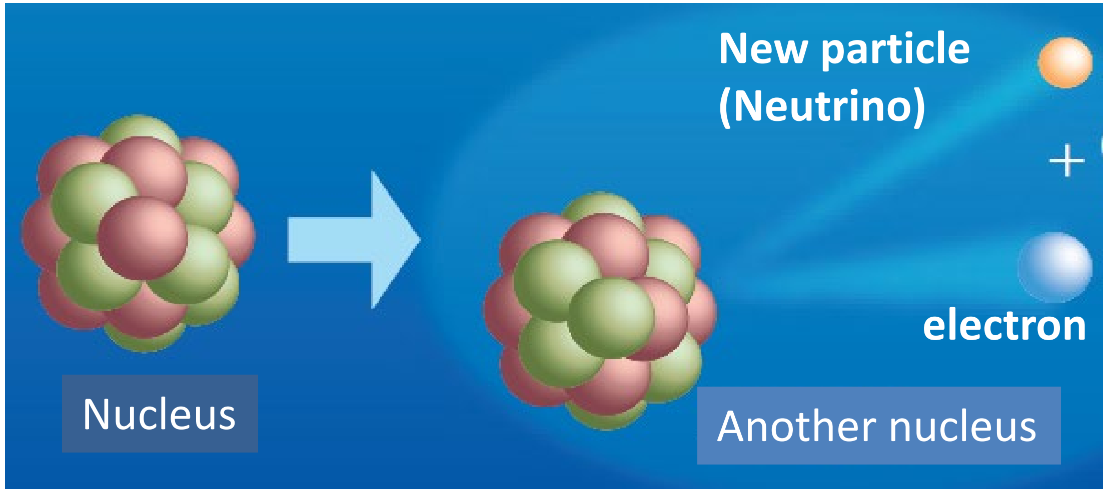




C.D. Ellis and W.A. Wooster, Proc. of the Royal Soc. (London) A117 (1927) 109-123.

(Wikipedia)

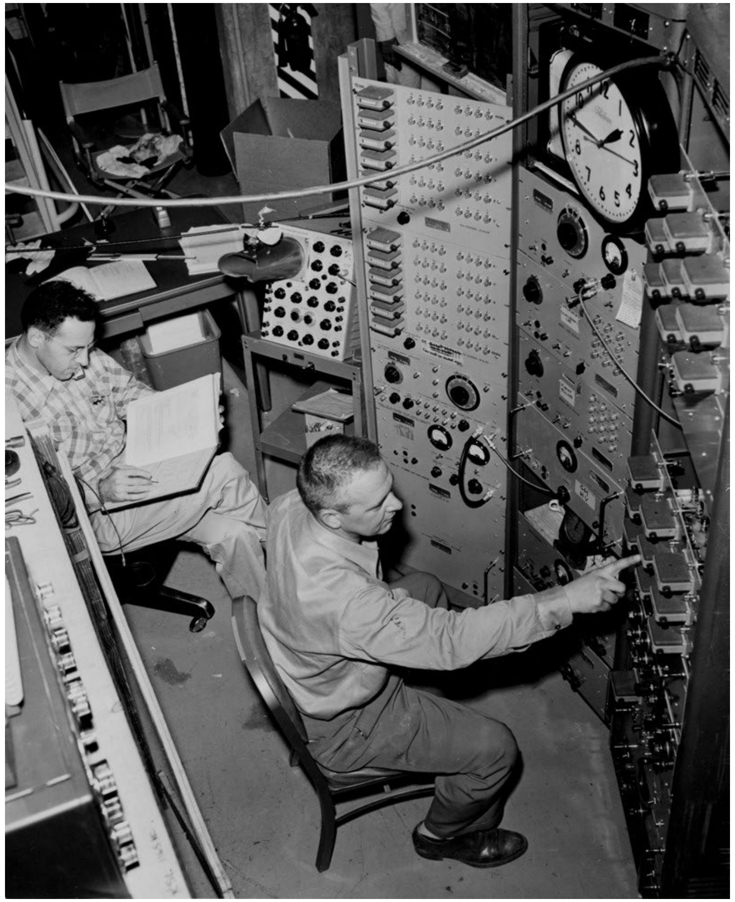
On Dec. 4, 1930, Wolfgang Pauli wrote a letter to "Dear radioactive ladies and gentlemen".



T. Kajita、Illume, Vol.16, No.2 (2004)

Discovery of neutrinos

- ✓ In 1956, Frederick Reines and Clyde Cowan observed interactions of (anti-electron) neutrinos that were generated by a nuclear power plant.
- ✓ In 1962, muon-neutrinos were discovered by observing neutrinos produced by an accelerator.



Nobel Prize in Physics 1995 to Frederick Reines.

Frederick Reines (left) and Clyde Cowan, at the controls of the Savannah River experiment (1956) (Wikipedia)

Nobel Prize in Physics 1988 to Jack Steinberger, Melvin Schwartz, and Leon Lederman.
(https://www.bnl.gov/newsroom/news.php?a=217621)

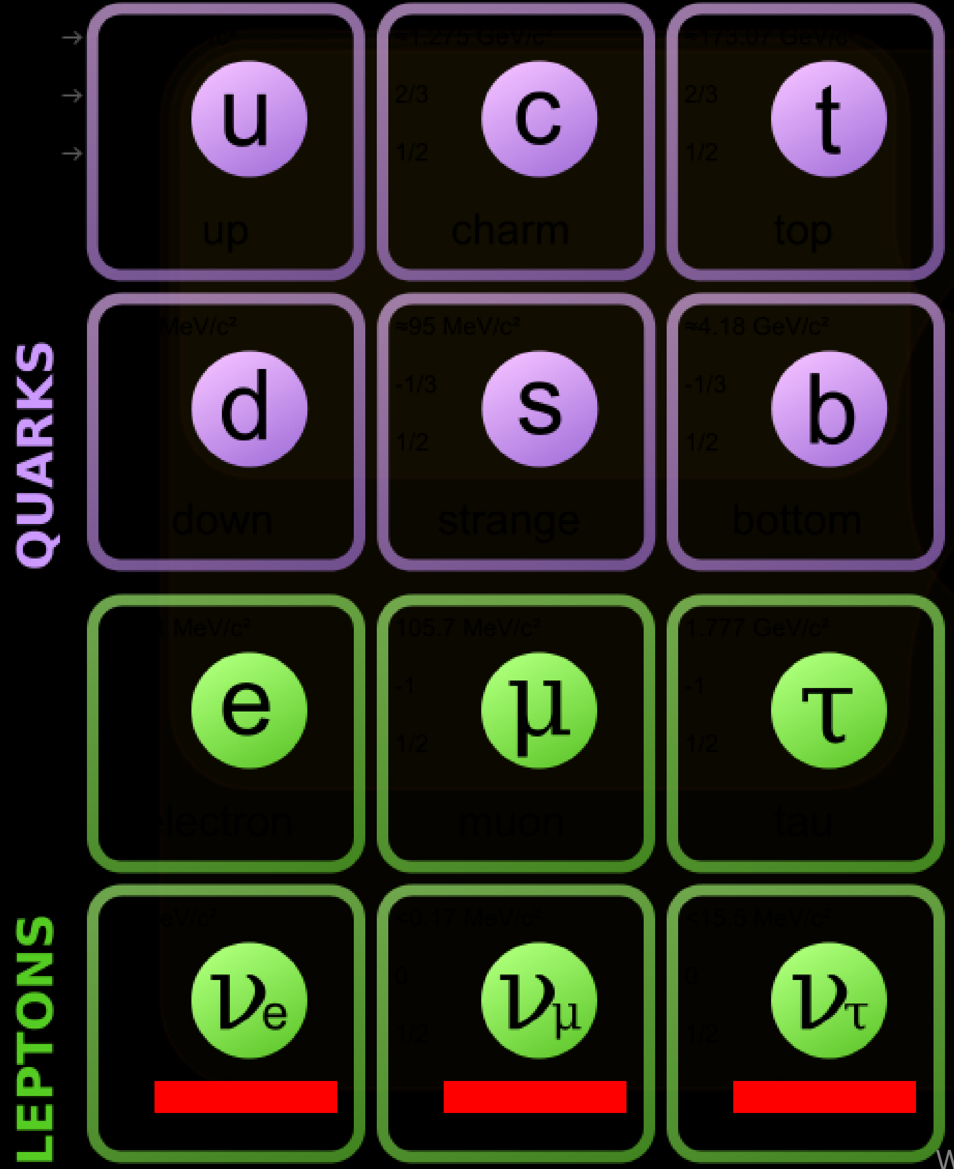
- ✓ (In 2000, tau-neutrinos were observed for the first time.)

What are neutrinos

Neutrinos;

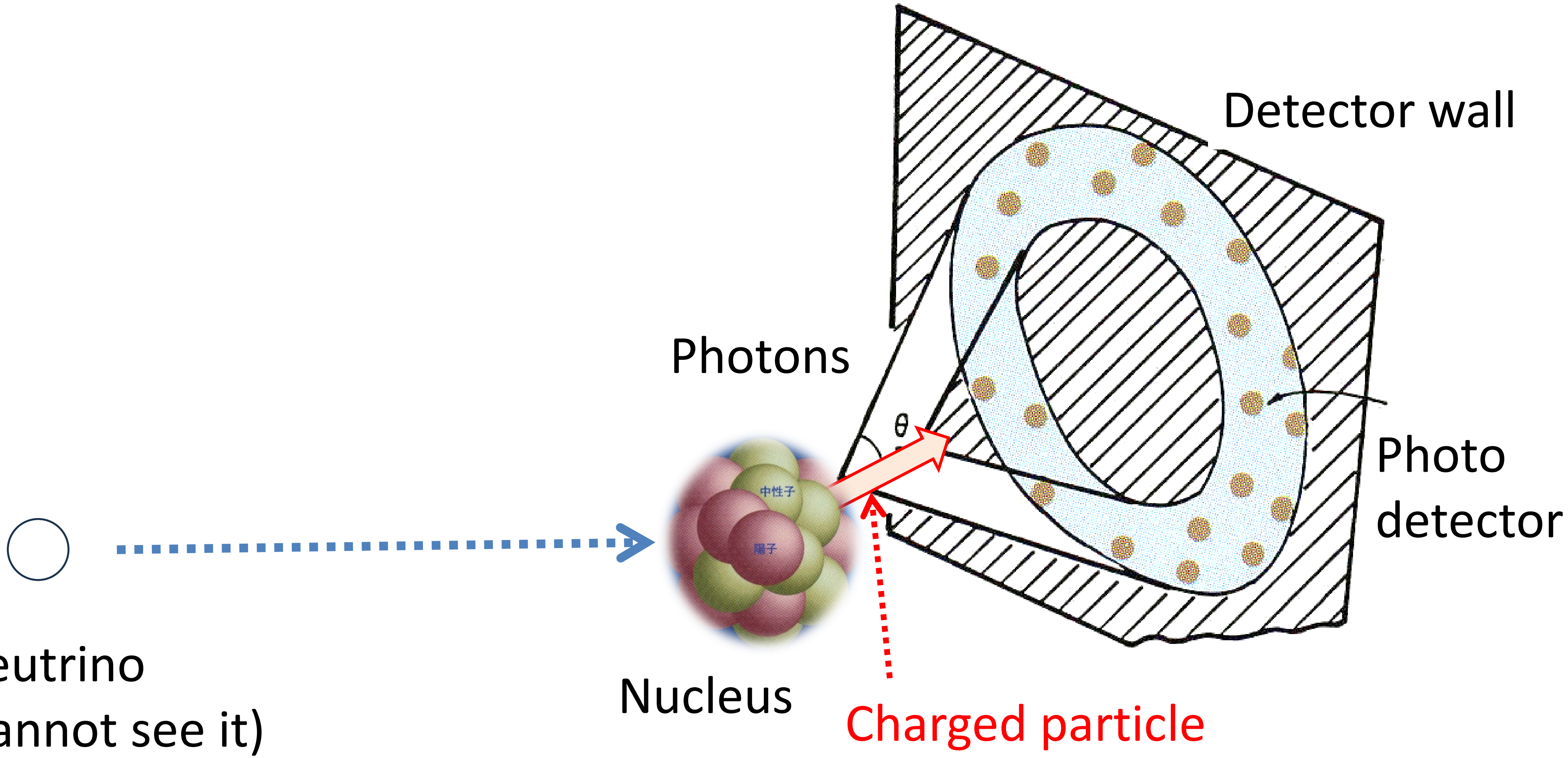
- ✓ are fundamental particles like electrons and quarks,
- ✓ are something like electrons without electric charge,
- ✓ can easily pass through even the Earth, but can interact with matter very rarely,
- ✓ have 3 types (flavors), namely electron-neutrinos (ν_e), muon-neutrinos (ν_μ) and tau-neutrinos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

  and
- ✓ have been assumed to have no mass.



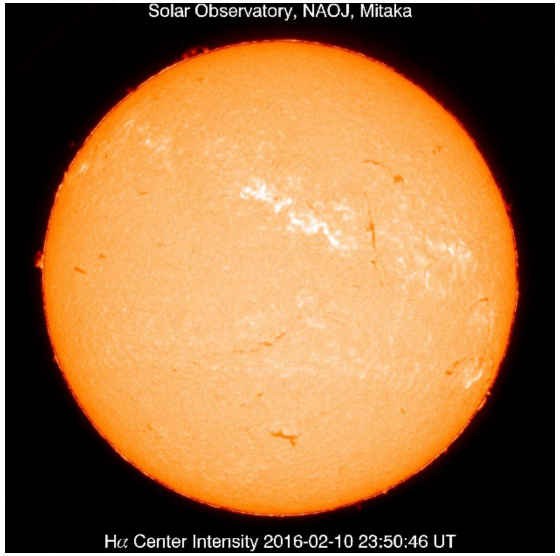
Wikipedia

How can we observe neutrinos ?



Neutrino problems

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

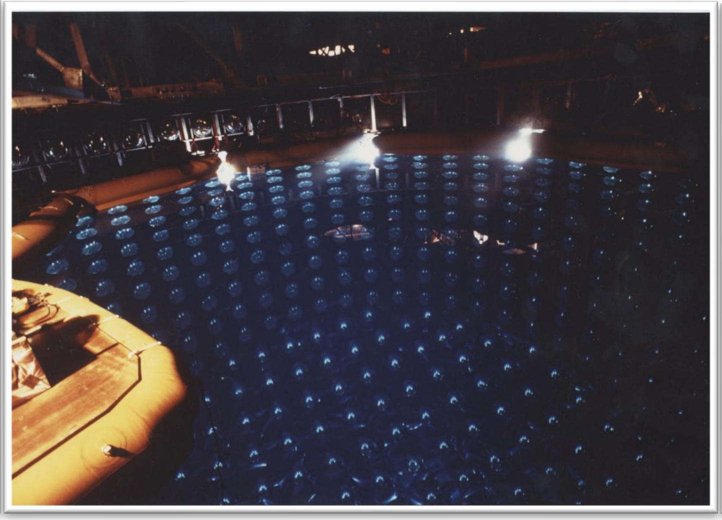
R. Davis Jr.
(Nobel Prize in Physics 2002)

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 end of the 1960's, "solar neutrino problem").

Solar neutrino problem

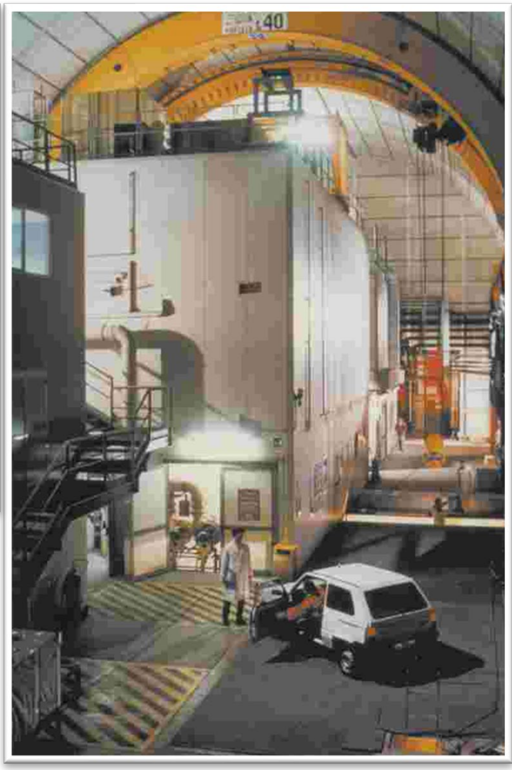
In the 20th century, several experiments observed solar neutrinos.

Homestake



Kamiokande

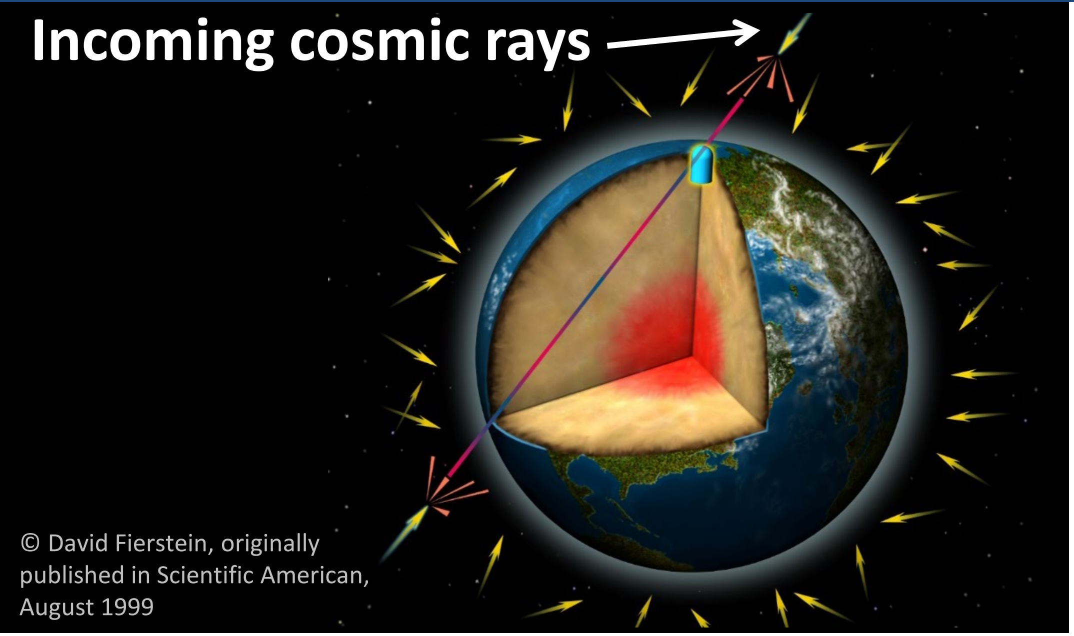
SAGE

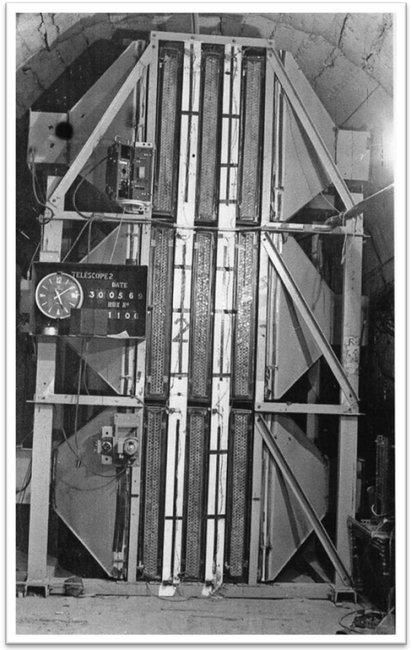


Gallex/GNO

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.

Atmospheric neutrinos



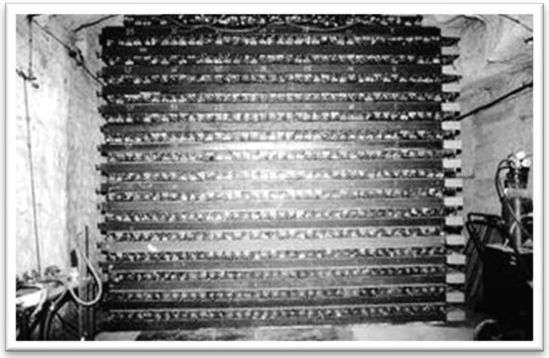


In 1965, atmospheric neutrinos were observed for the first time by detectors located extremely deep underground, one in India (left) and one in in South Africa (right).

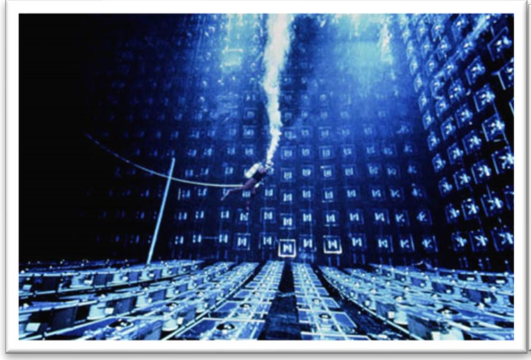
Photo by N. Mondal

Photo by H.Sobel

In the 1970's, newly proposed Grand Unified Theories predicted that protons should decay with the lifetime of about 10^{30} years. ➔ Several proton decay experiments began in the early 1980's.

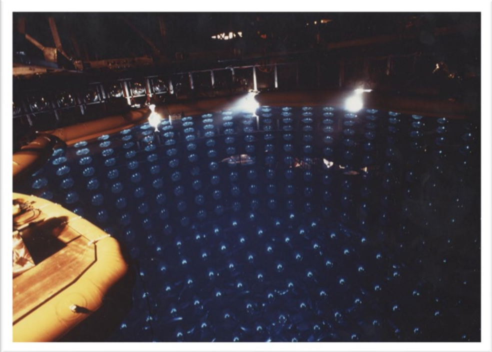


KGF

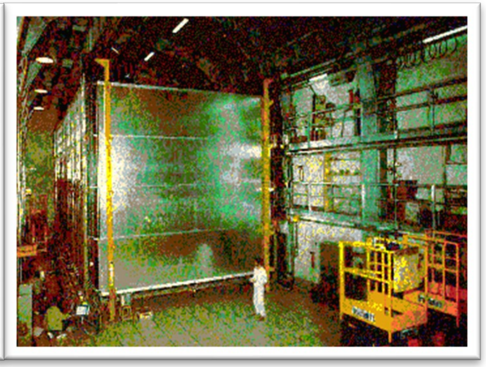


IMB

NUSEX



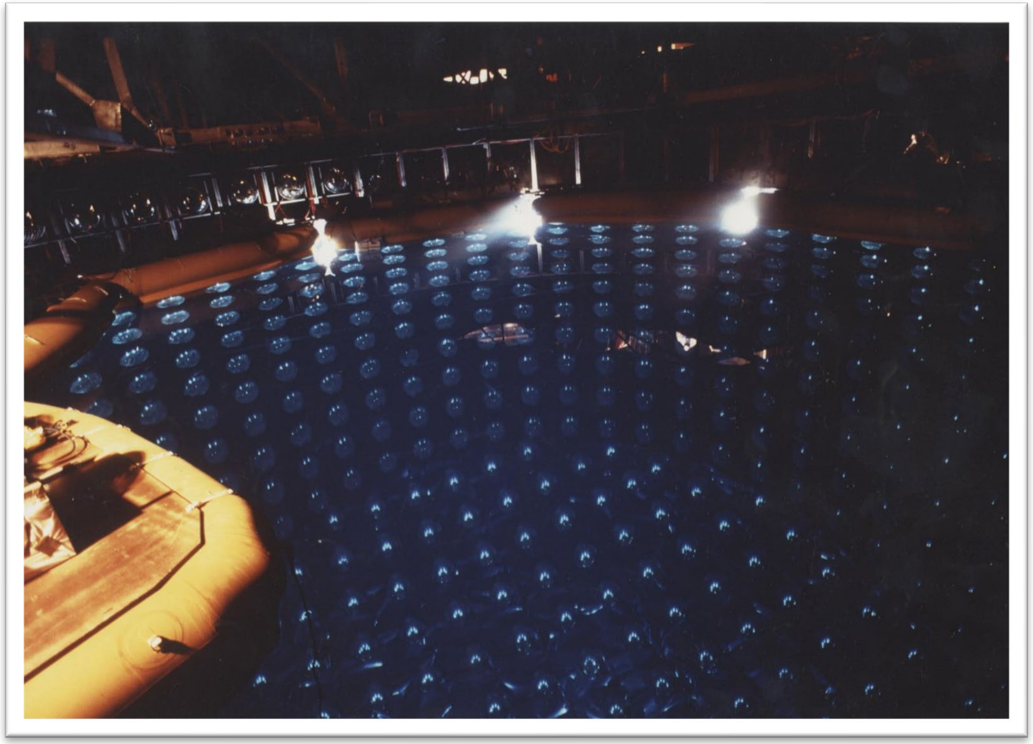
Kamiokande



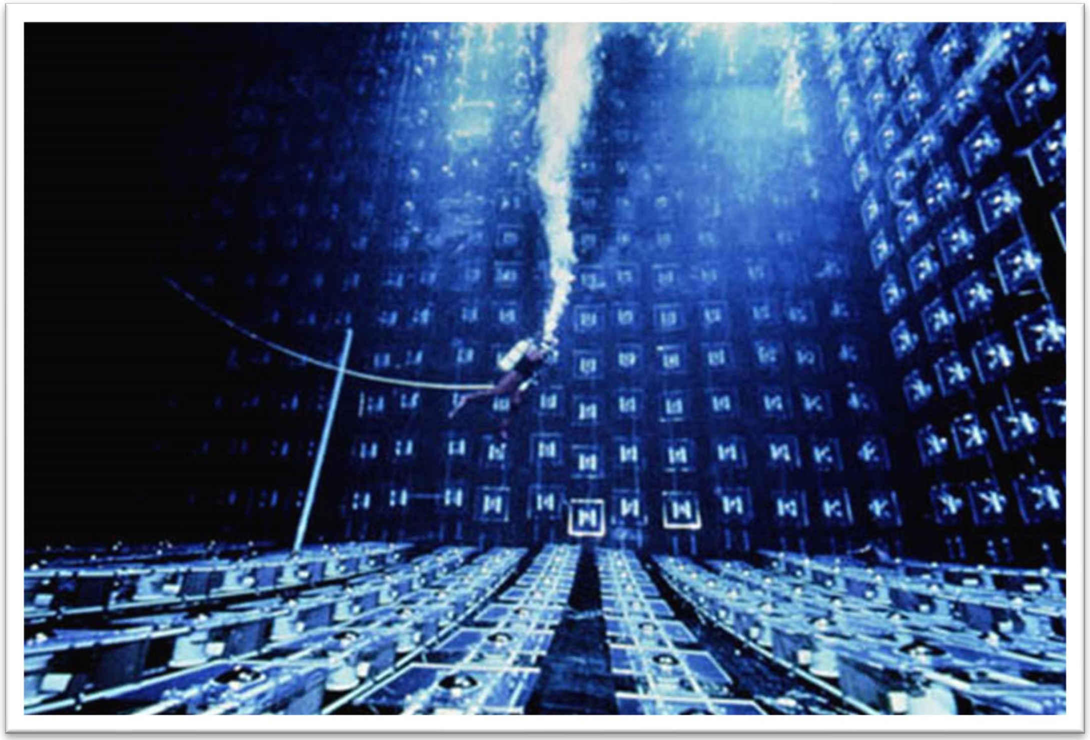
Frejus

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

- ✓ Proton decay experiments in the 1980's observed many atmospheric neutrino events.
- ✓ Because atmospheric neutrinos are 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 ν_μ events was observed.



Kamiokande



IMB

Neutrino oscillations

If neutrinos have mass, neutrinos change their flavor (type) from one flavor (type) to the other. For example, a mu-neutrino may oscillate 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 also by Pontecorvo.

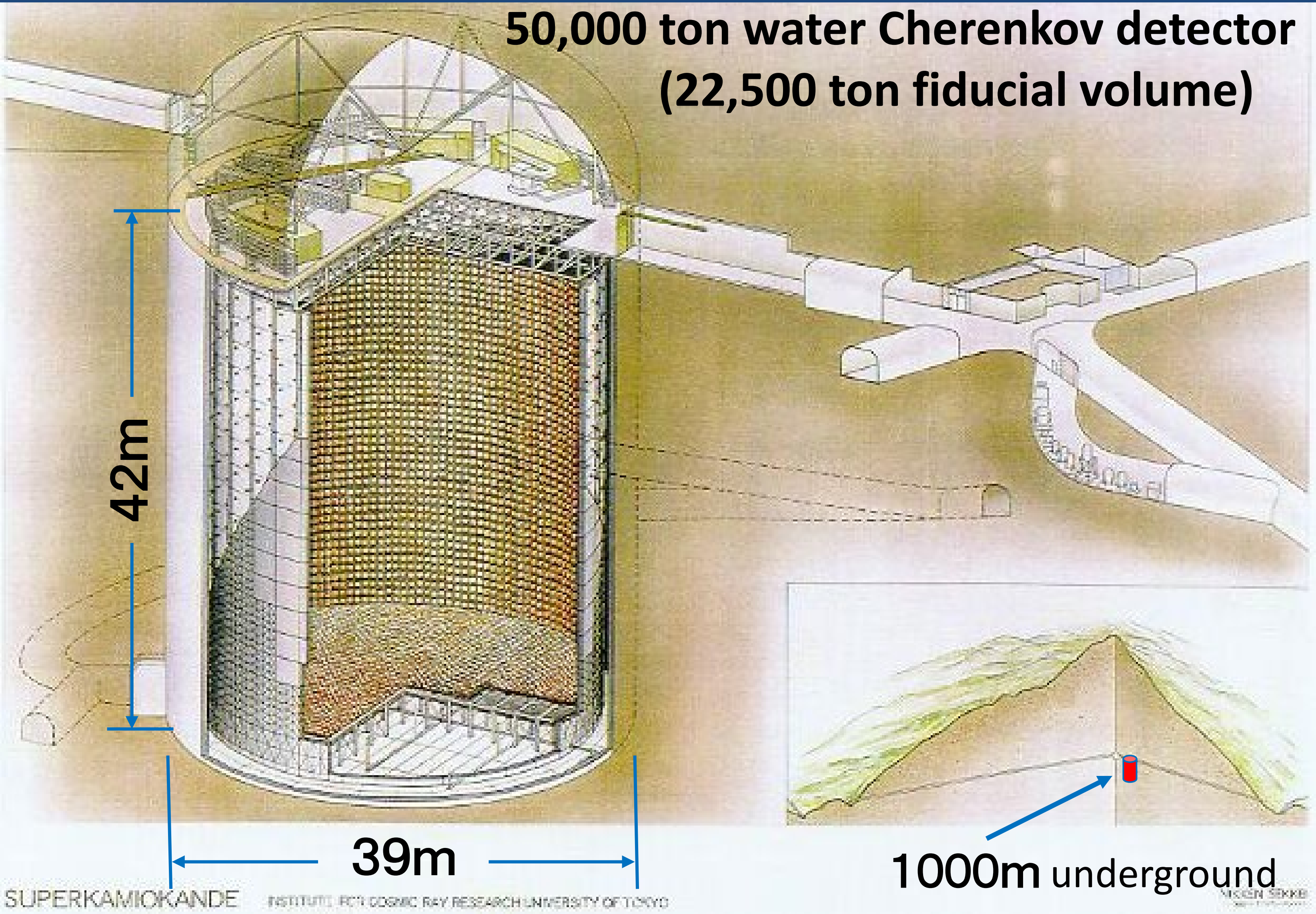
S. Sakata,
Z. Maki,
M. Nakagawa

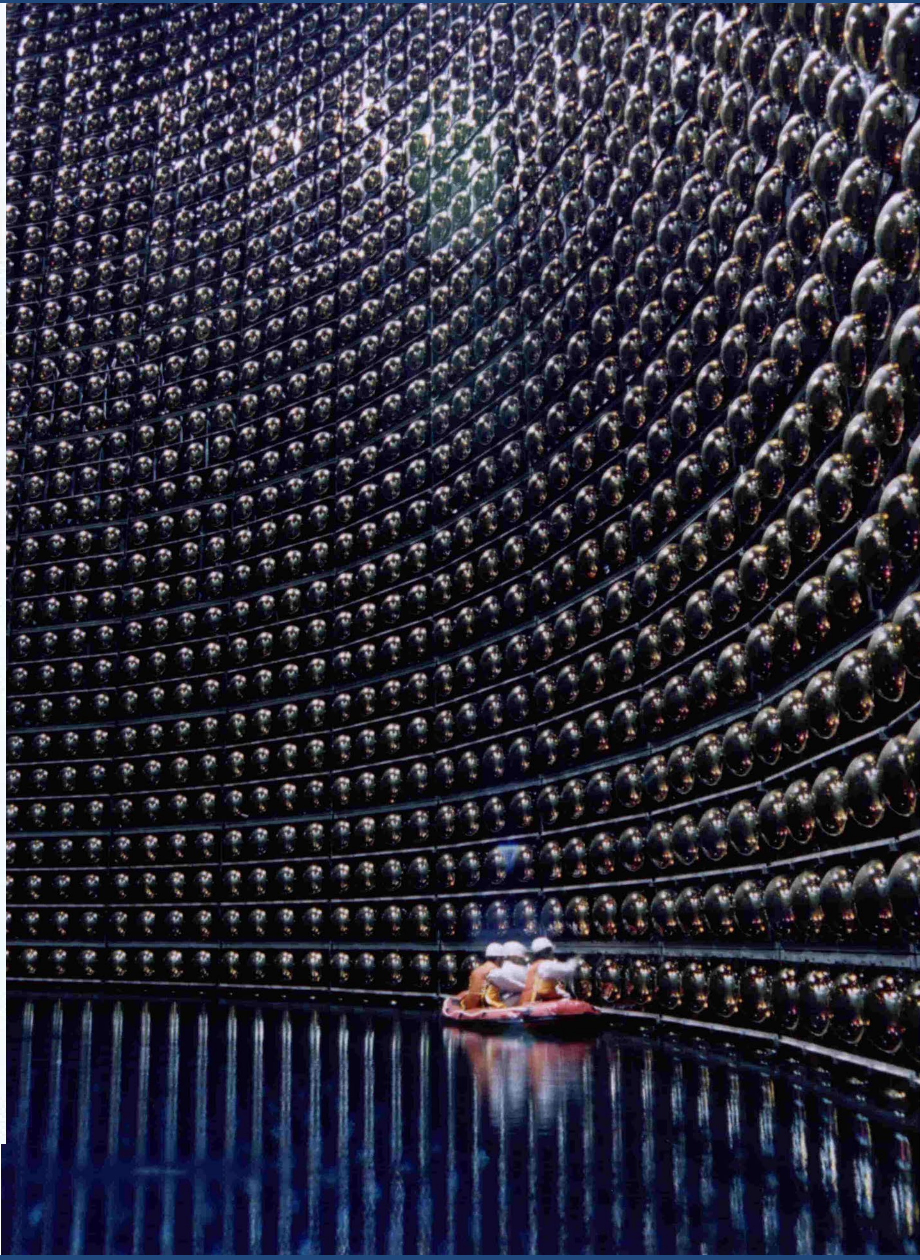
arXiv:0910.1657

B. Pontecorvo

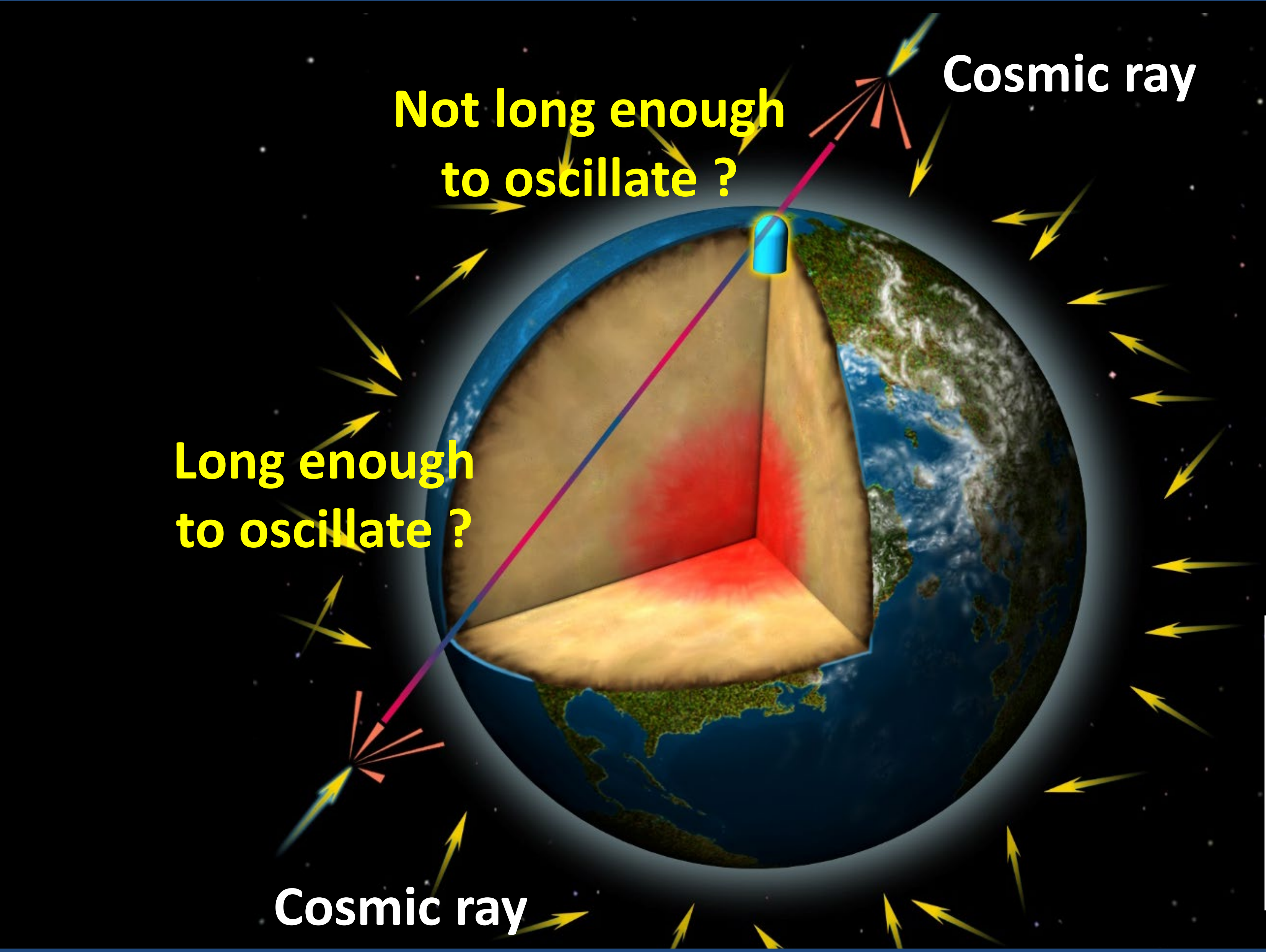
Discovery of neutrino oscillations

Super-Kamiokande





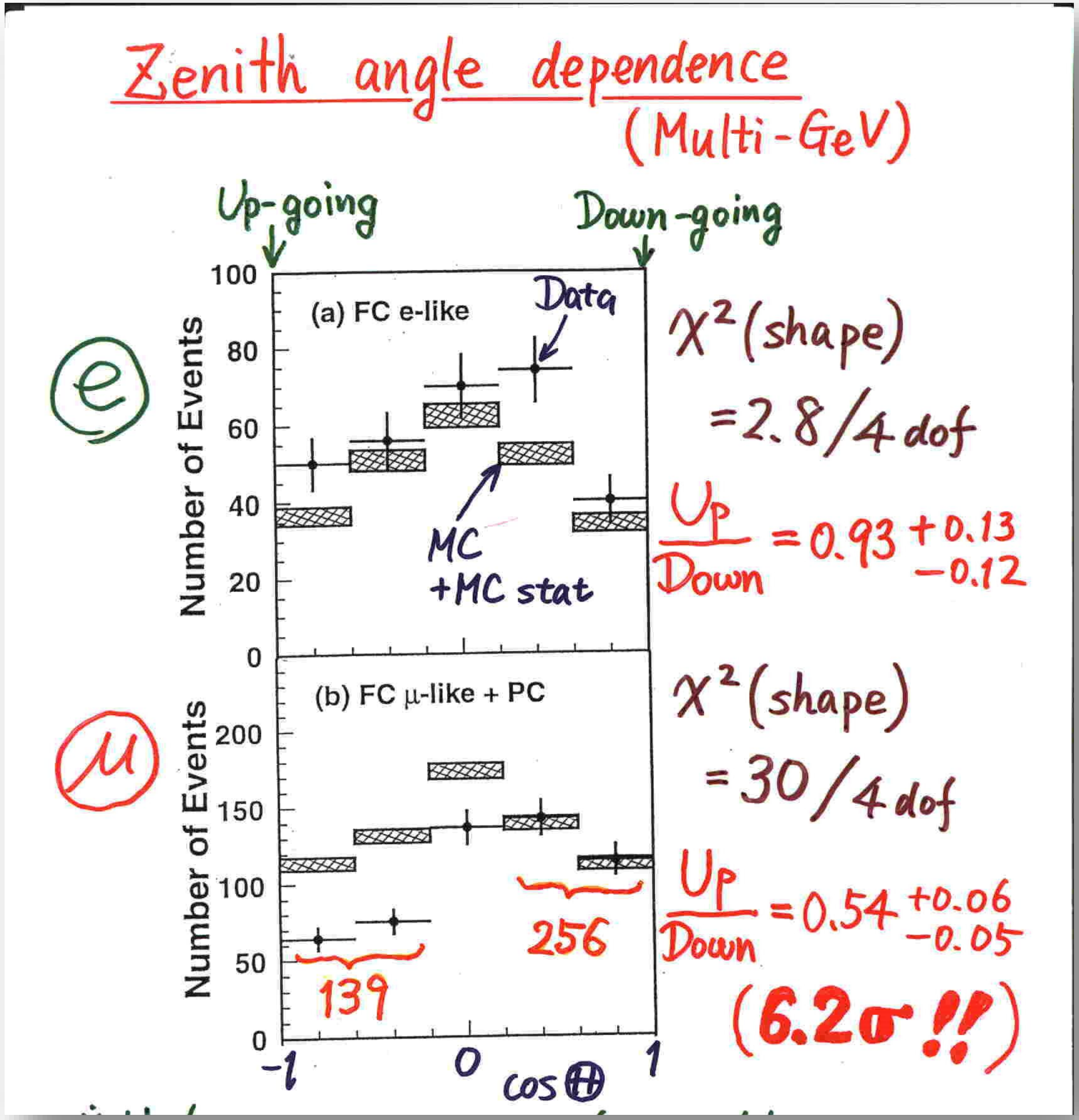
What will happen if the muon-neutrino deficit is due to neutrino oscillations

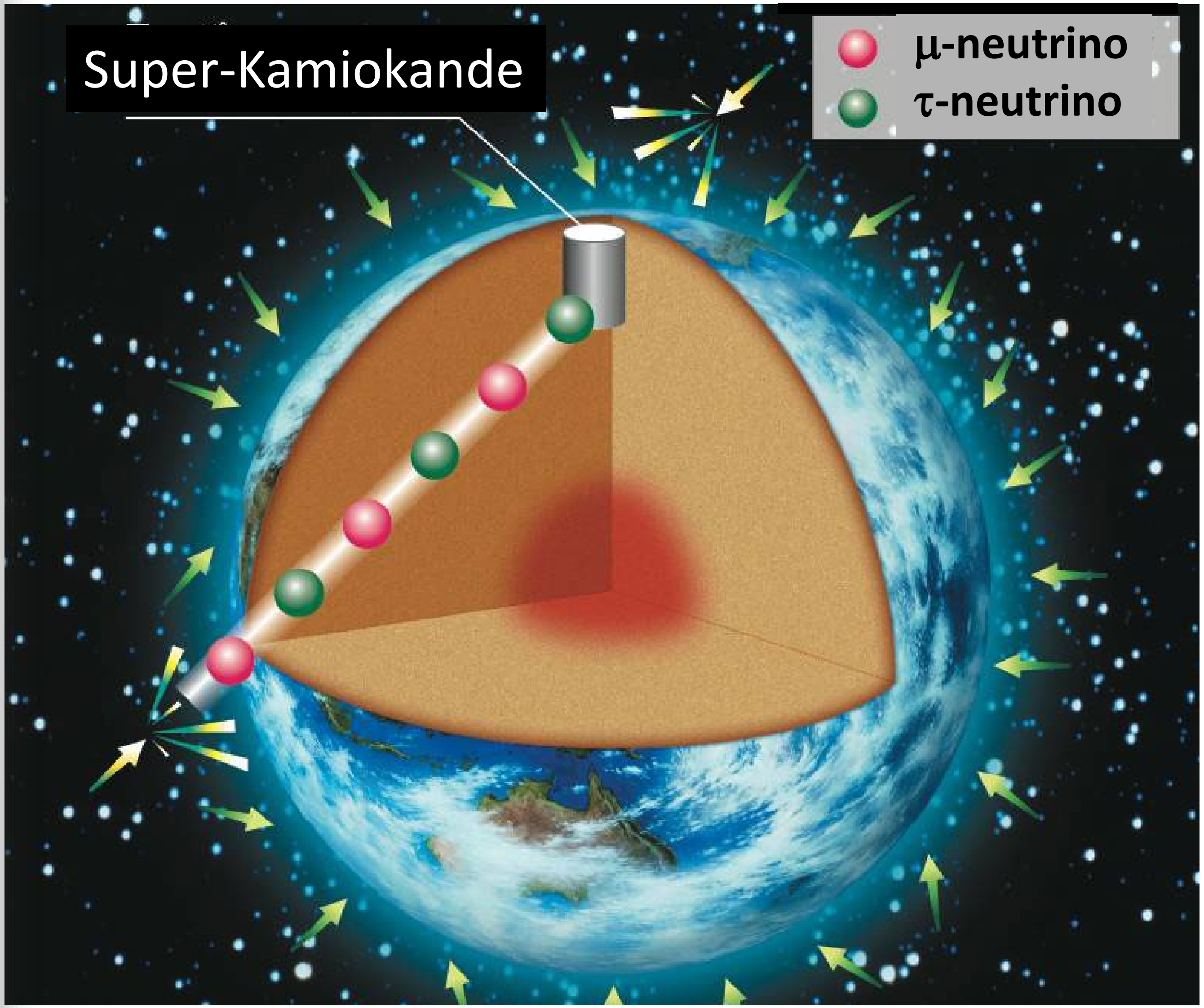


An asymmetry of the up- versus down-going flux of muon-neutrinos should be observed!

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.

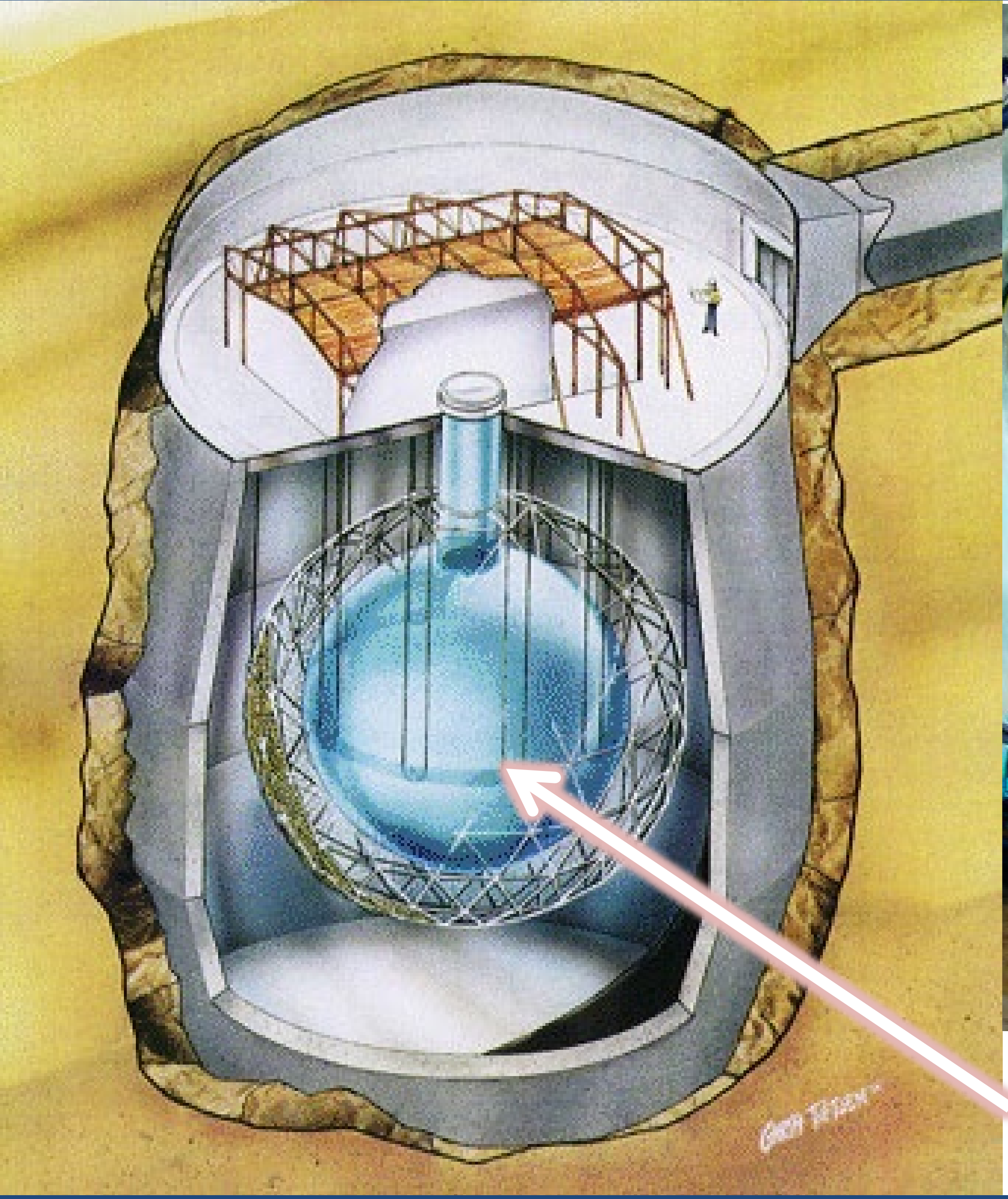
Discovery of solar neutrino oscillations

Initial idea

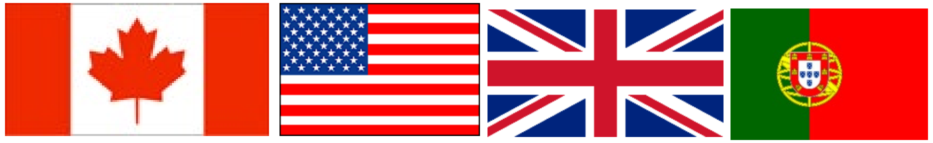
- People were puzzled with the solar neutrino data. (Some people argued that solar model might not be accurate. Some people discussed that, maybe, neutrinos oscillate. But there was no conclusion.)
- Then in 1985, there was a great idea: If we measure the electron-neutrino flux and the total (electron + muon + tau) neutrino flux,
  and if the electron-neutrino flux is smaller than the total (electron + muon + tau) neutrino flux
  ➔ muon neutrinos + tau neutrinos from the Sun
  ➔ neutrino oscillations
- For this purpose, solar neutrino experiment with heavy water (D_2O) was proposed.

Herbert Chen, PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

SNO detector

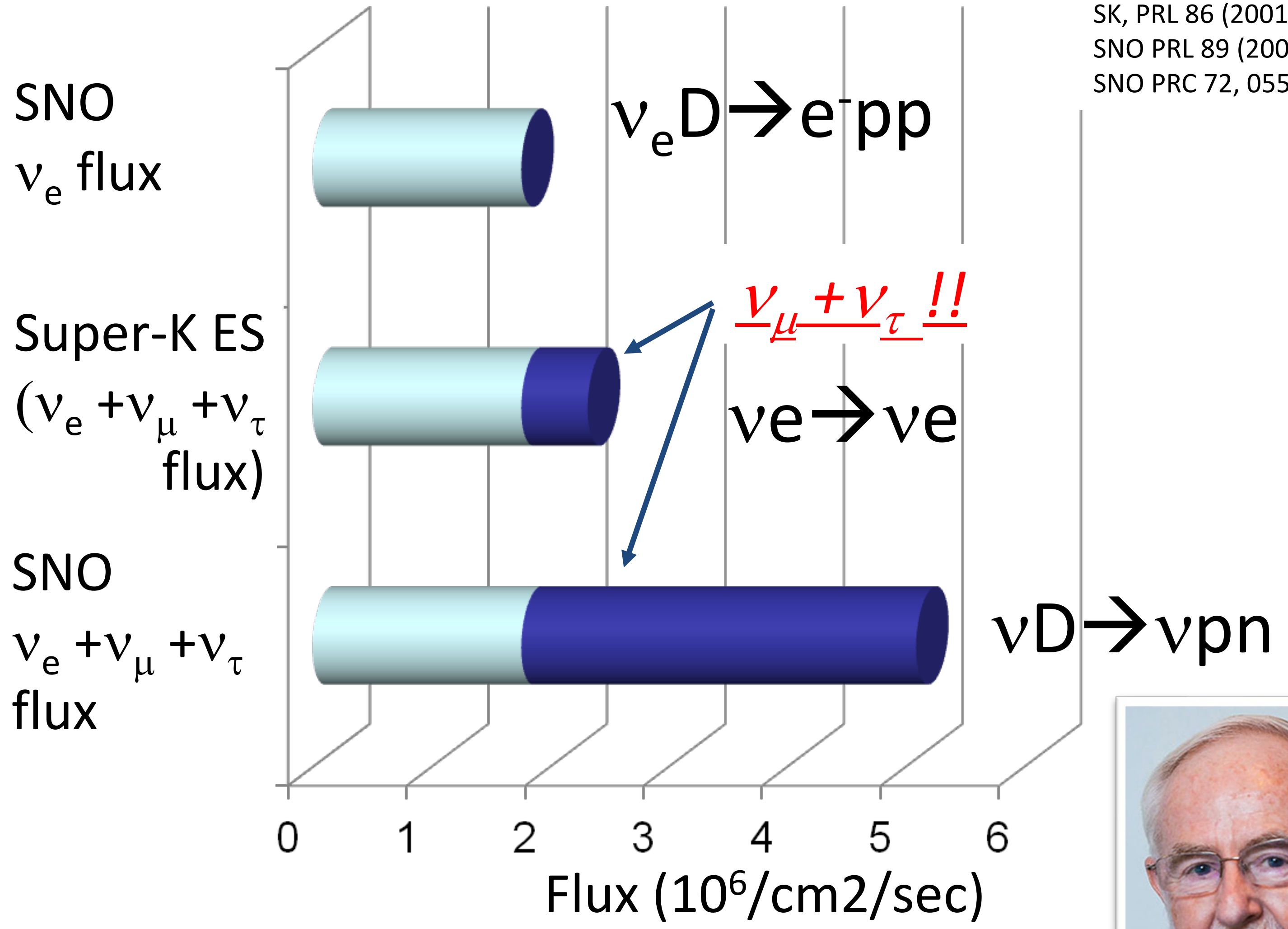


1000 ton of heavy water (D_2O)

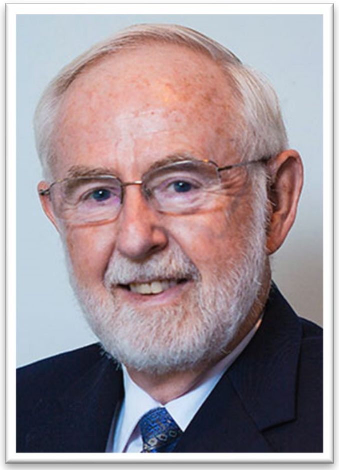


Solar neutrino oscillation (2001-2002)

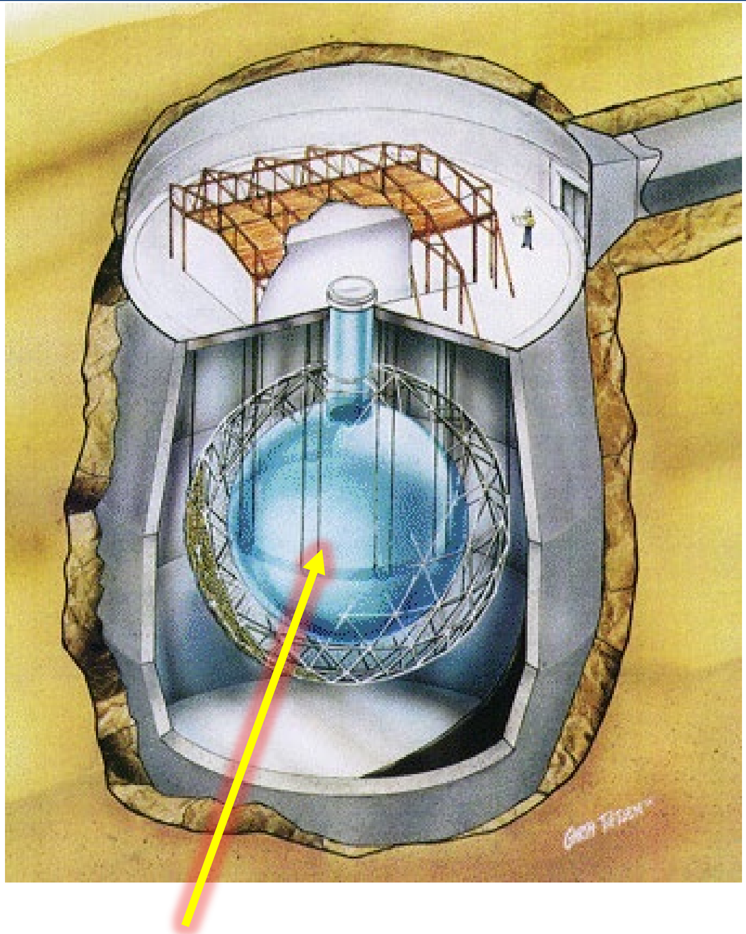
SK, PRL 86 (2001) 5651
SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)



Solar neutrino oscillation (2001-2002):
electron neutrinos to the other neutrinos.



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



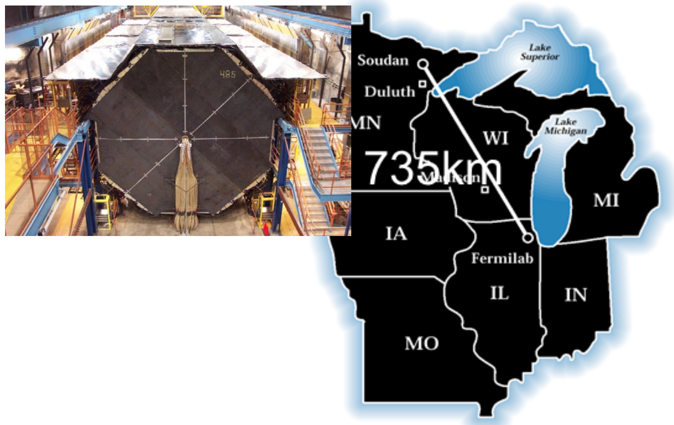
1000 ton of heavy water (D_2O)

Discovery of the third neutrino oscillations

Experiments for the third neutrino oscillations

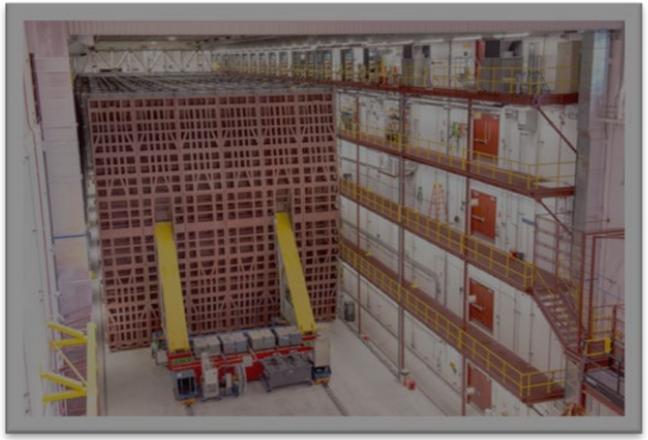
Accelerator based long baseline neutrino oscillation experiments

MINOS



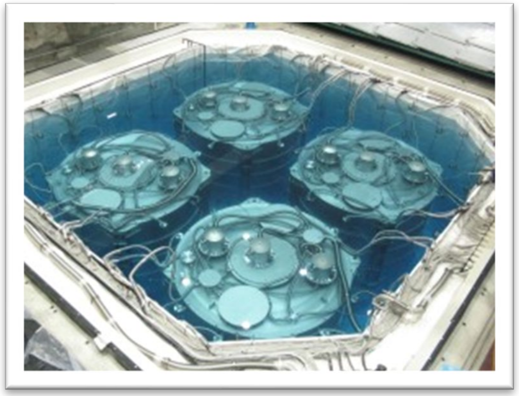
T2K

NOνA *(came slightly late)*



Reactor based (short baseline, 1-2 km) neutrino oscillation experiments

Daya Bay



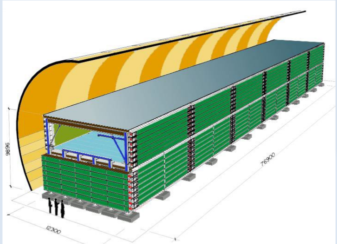
RENO

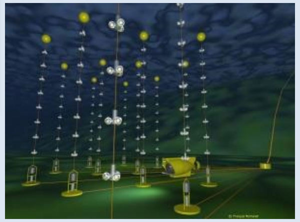
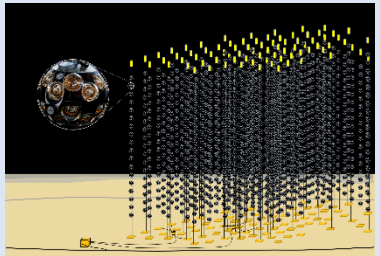
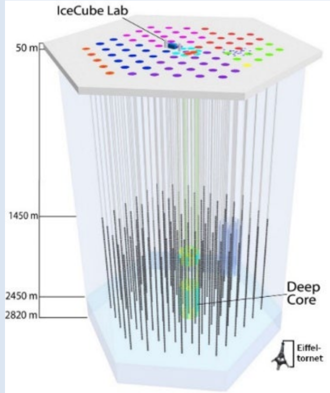
Double Chooz

The basic structure for 3 flavor neutrino oscillations has been understood!

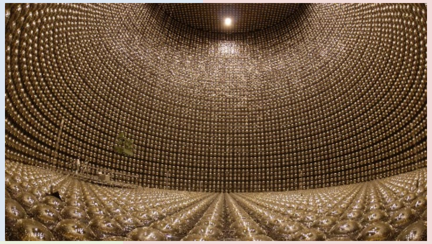
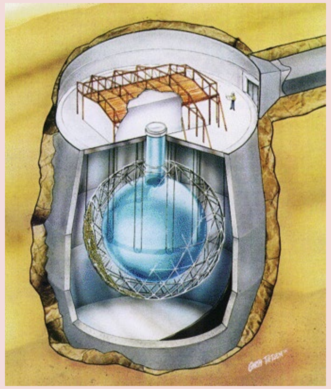
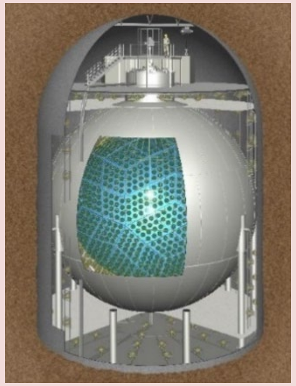
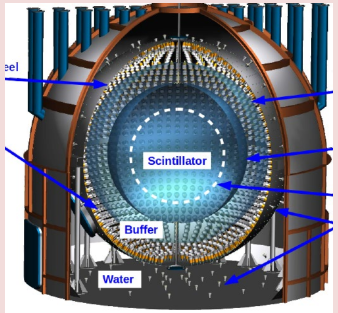
Many exciting results in neutrino oscillations (partial list)

Atmospheric neutrino oscillation experiments

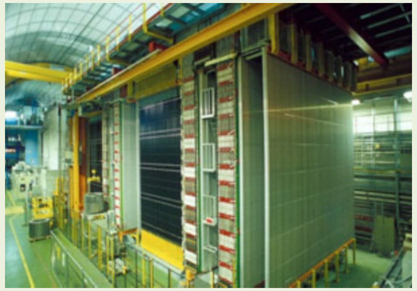


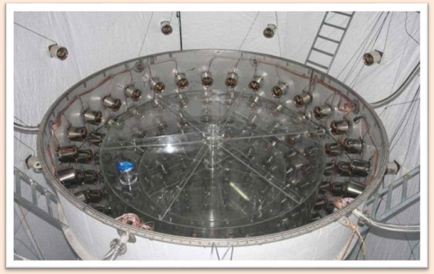
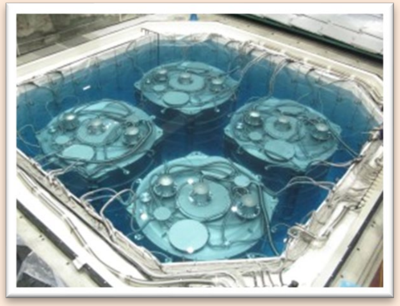
Solar neutrino oscillation experiments

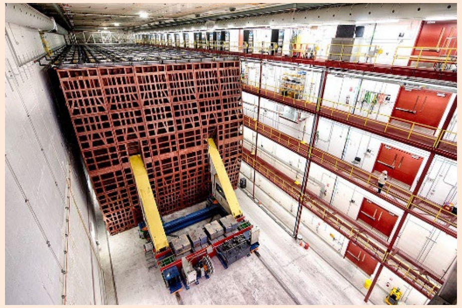





Accelerator based neutrino oscillation experiments



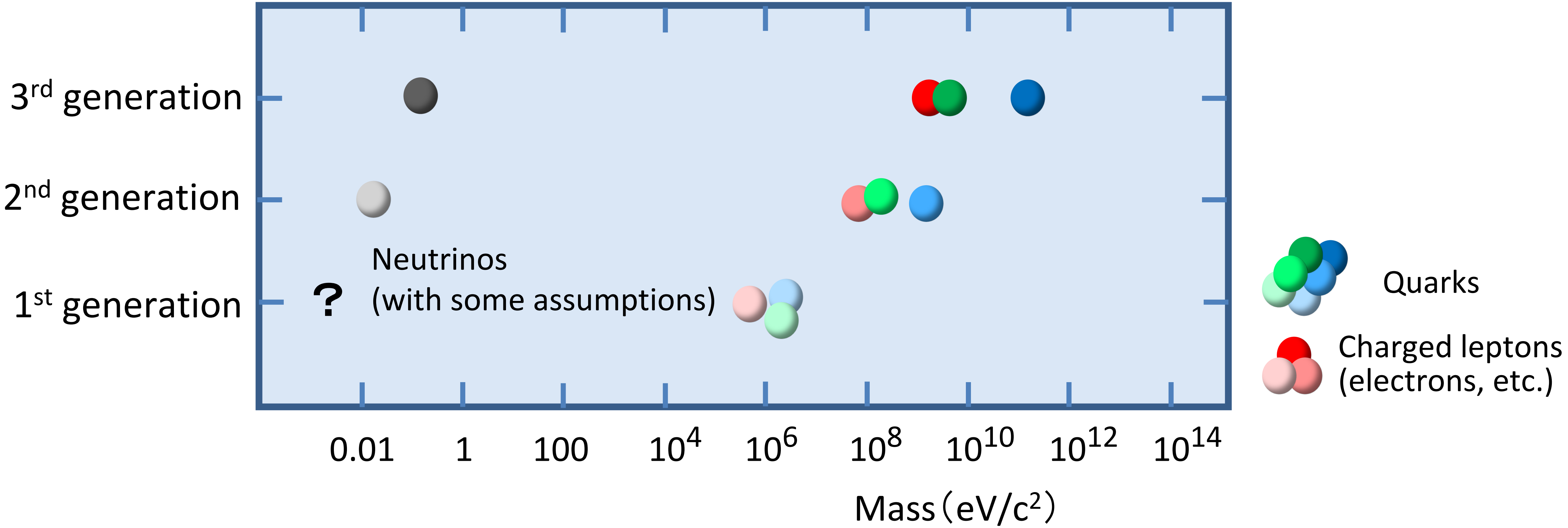
3 flavor(type) neutrino oscillation experiments



Neutrinos: remaining questions and mysteries

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

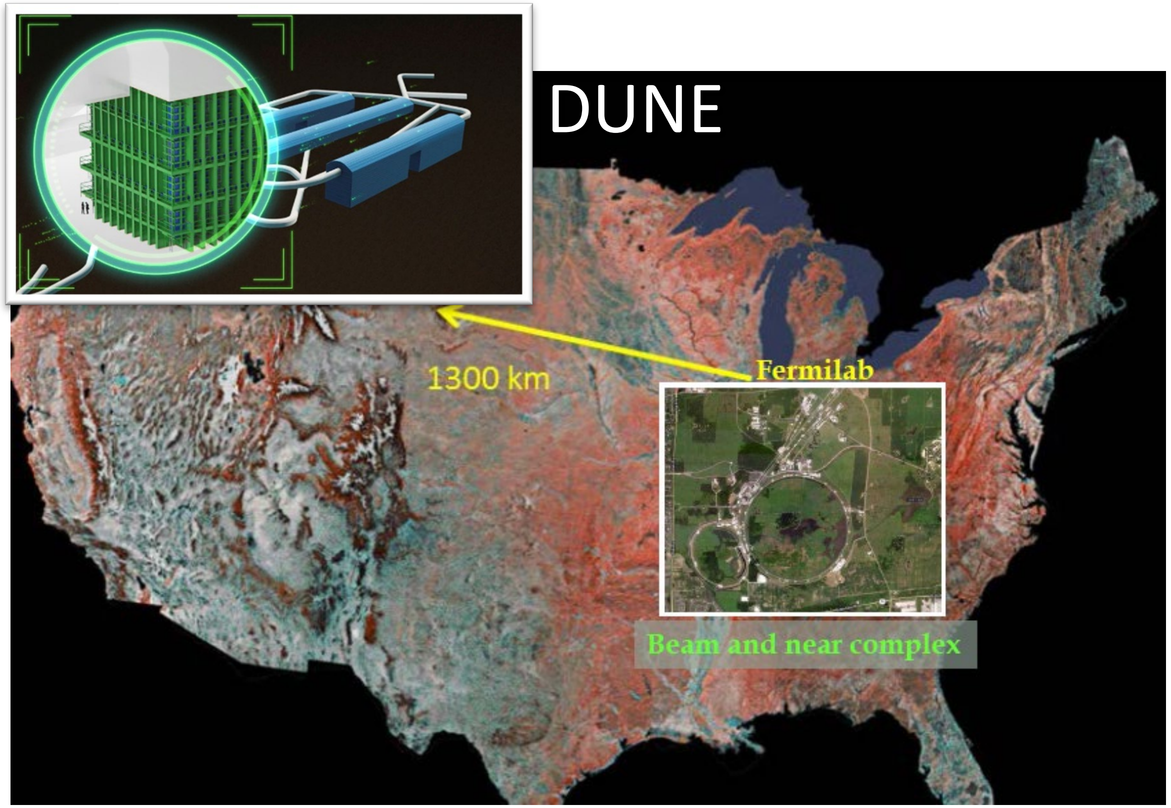
Neutrinos with very small mass might be the key to understand the big mystery of the matter in the Universe !

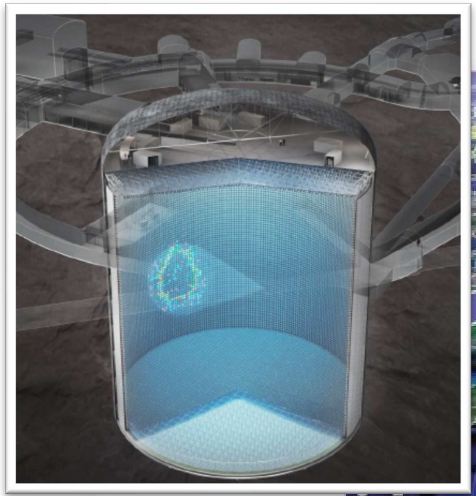
M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45-47

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

Future experiments: DUNE and Hyper-Kamiokande

- ✓ 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.



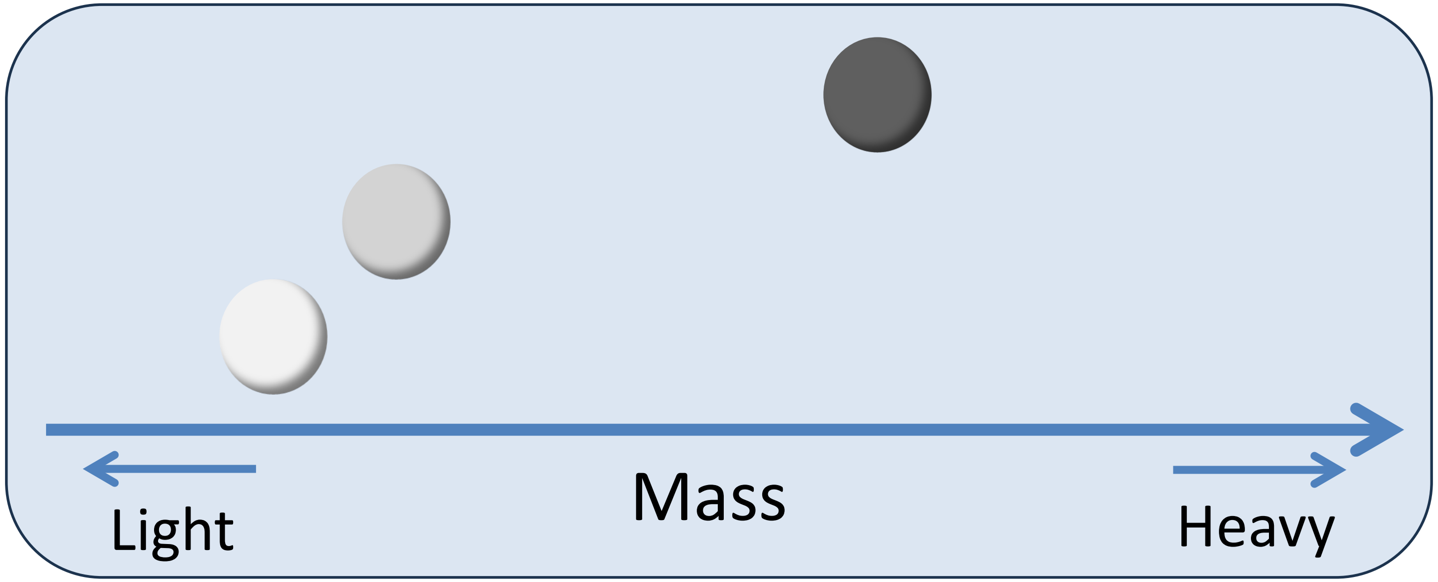


Hyper-Kamiokande

(Several other possibilities…)

Do we really understand the neutrino mass?

- We know that there are 3 neutrino masses.
- We usually assume that the third neutrino mass (●) is the heaviest.
- But is this assumption correct?



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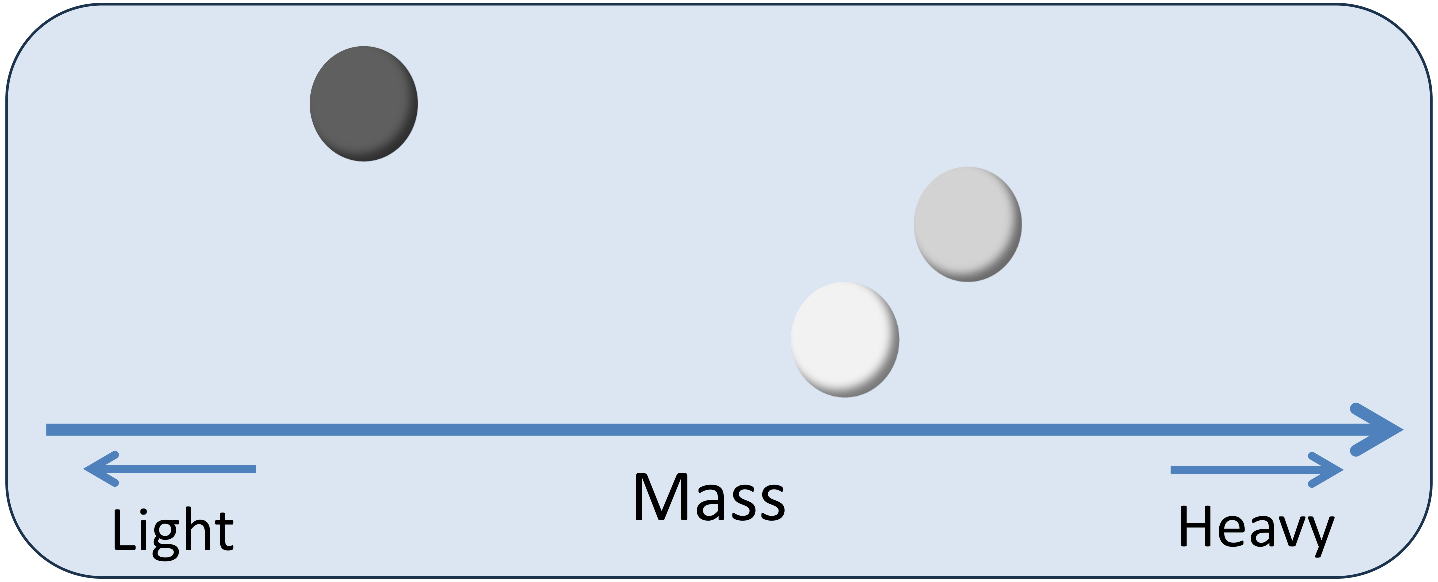
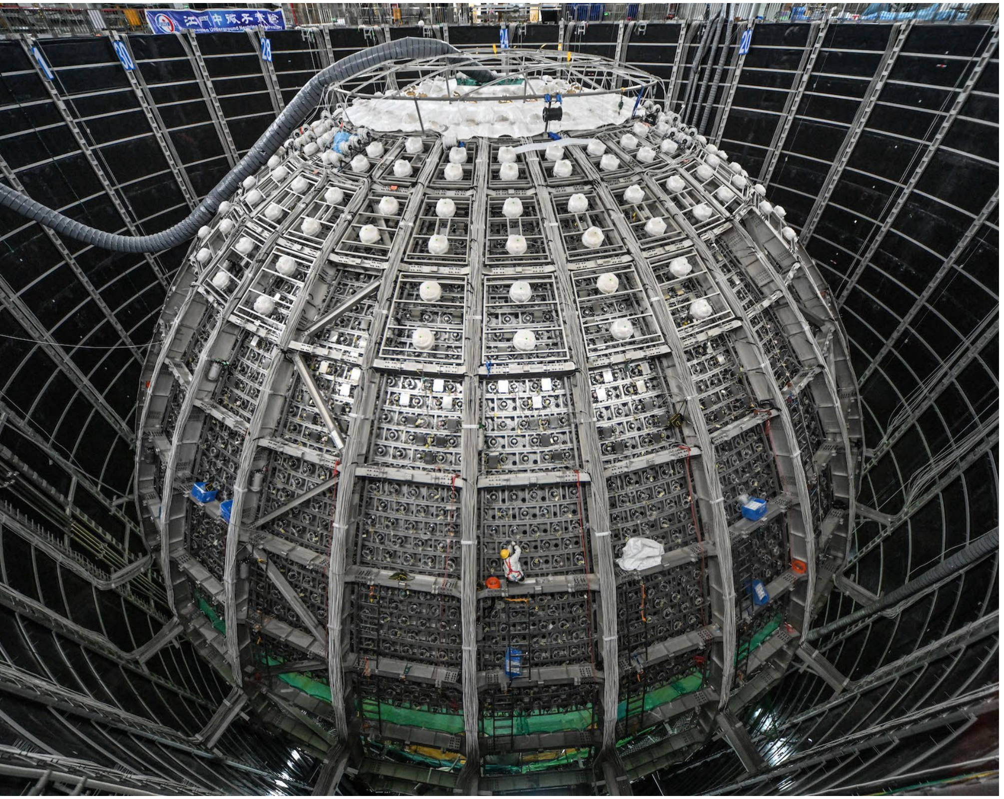


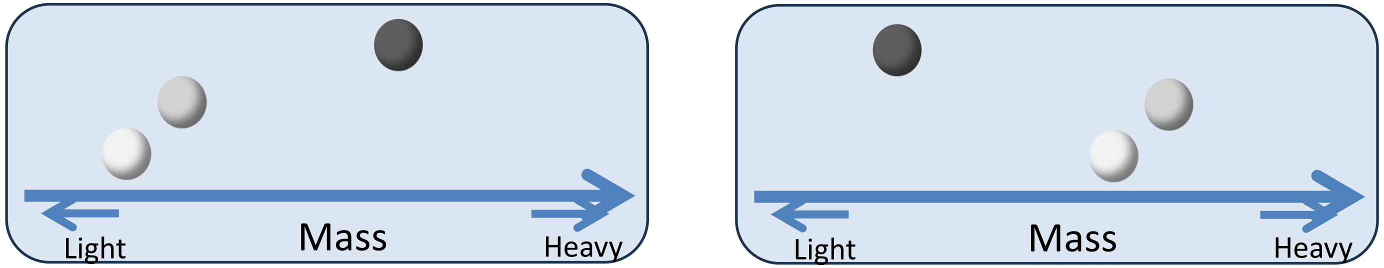
✓ The present data tell us that we do not know if the third neutrino mass is really the heaviest.

✓ We need the next generation, neutrino oscillation experiments.

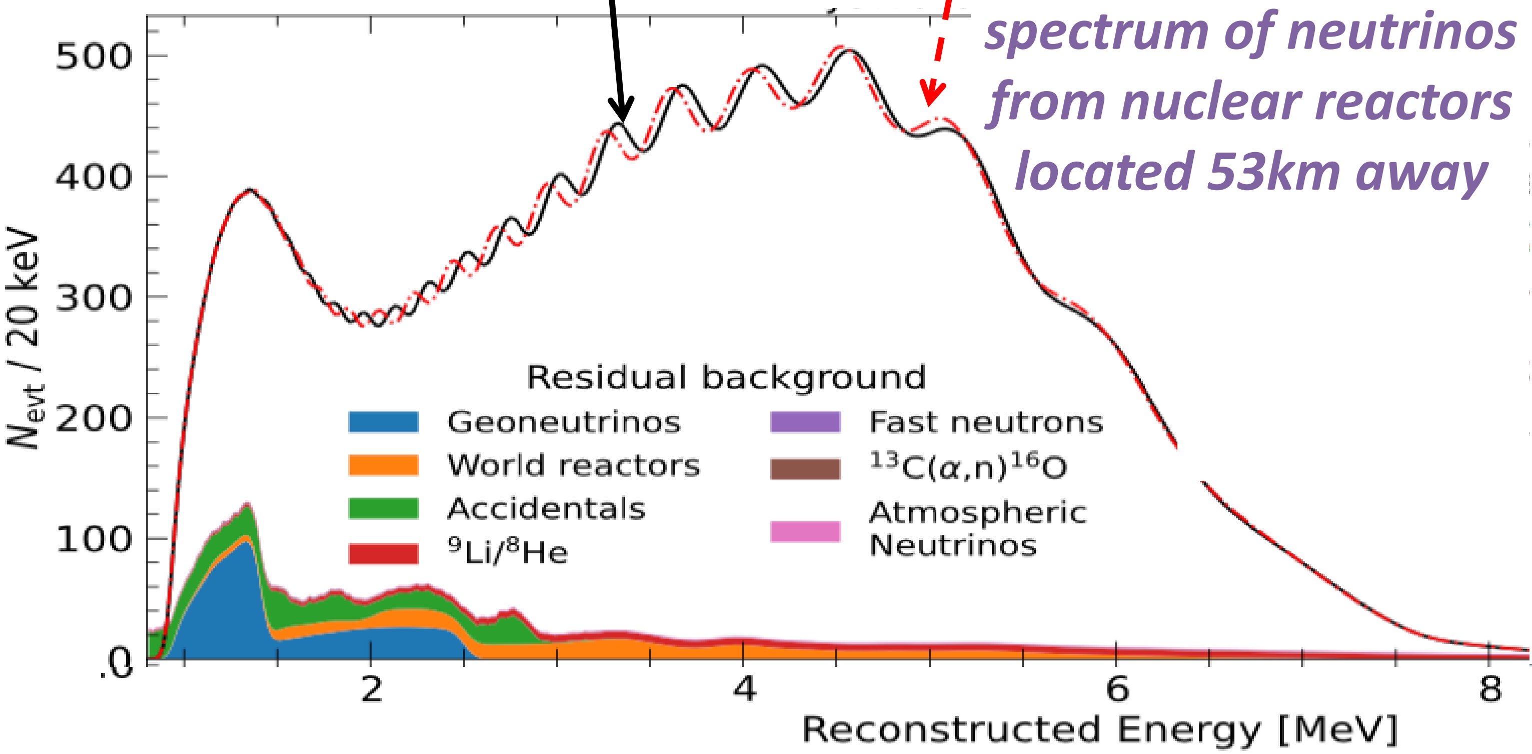
Jun Cao, Neutrino2024
Marco Grassi, NNN2023



JUNO detector (world largest (20kton) liquid scintillator detector, located “near” Haikou)

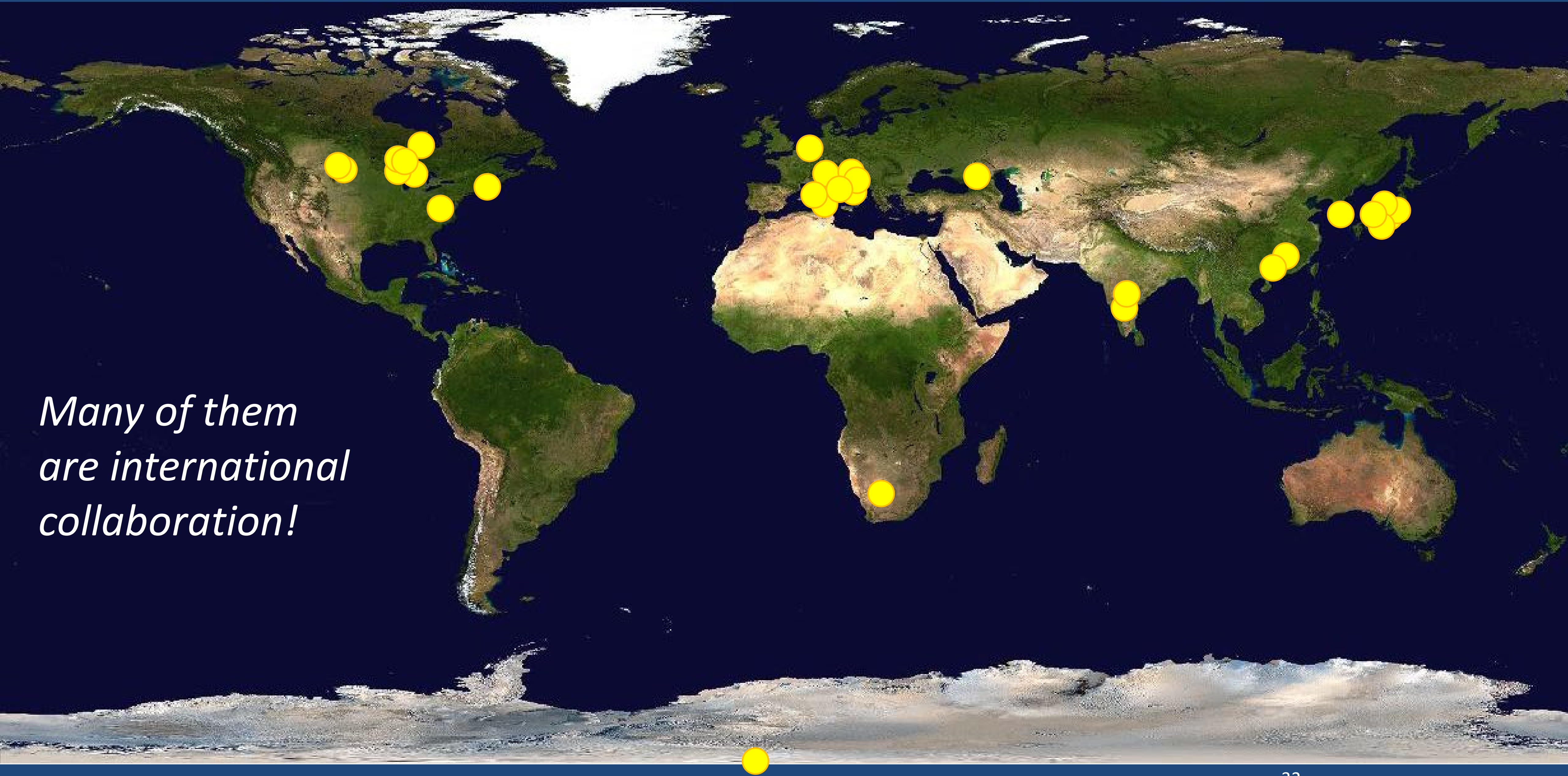


Expected energy spectrum of neutrinos from nuclear reactors located 53km away



Detector will be filled with liquid scintillator next year (2025)!

Global effort!



Many of them are international collaboration!

Summary

- Neutrinos have been playing very important roles in understanding the laws of nature.
- Neutrinos are likely to continue playing very important roles in understanding the smallest particles and the largest Universe.
- Study of neutrinos, or study of physics in general, is a global effort!