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Aligarh Muslim Univ.

Neutrino Oscillations: discovery, status and prospect

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

Outline

- Introduction:
  - What are neutrinos?
  - atmospheric neutrinos
- Discovery of neutrino oscillations
- Status of neutrino oscillation studies
- Future
- Summary

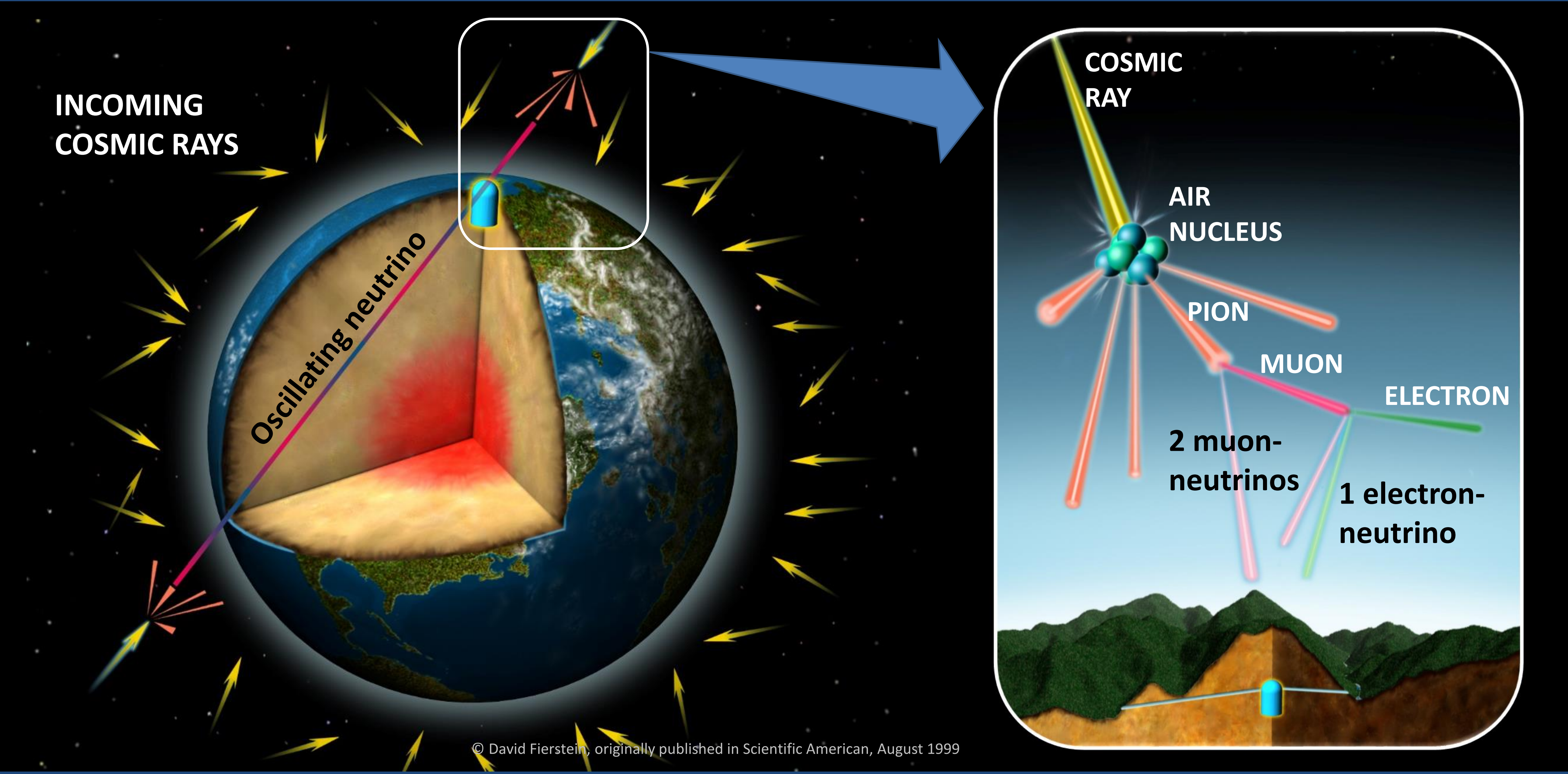
(apology: This talk is biased to atmospheric neutrino oscillations)

Introduction

What are neutrinos?

- Neutrinos;
  - are elementary particles like electrons and quarks,
  - have no electric charge,
  - have, like the other particles, 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,
  - can, however, interact with matter very rarely. A ν_μ interaction produces a muon. A ν_e interaction produces an electron.
- In the very successful Standard Model of particle physics, neutrinos are assumed to have no mass.

Atmospheric neutrinos



Discovery of atmospheric neutrinos (1965)

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

←In South Africa

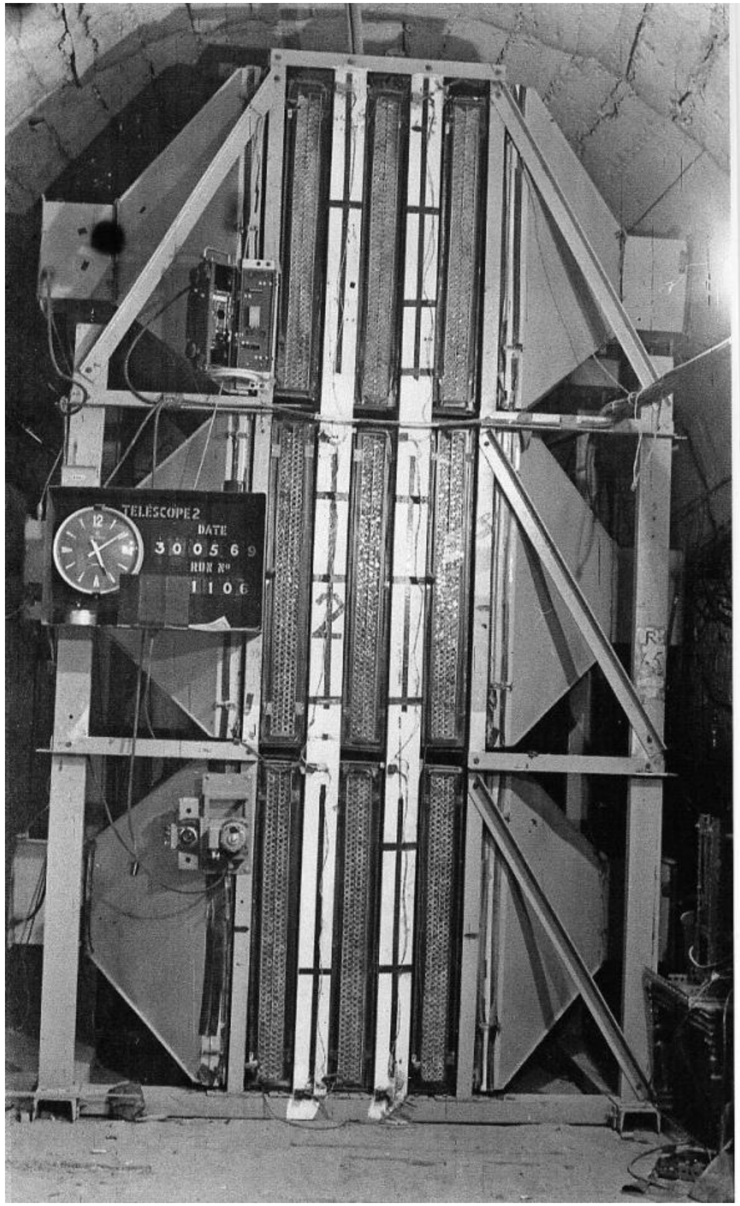
F. Reines et al., PRL 15, 429 (1965)

→ In India

C.V. Achar et al., PL 18, 196 (1965)

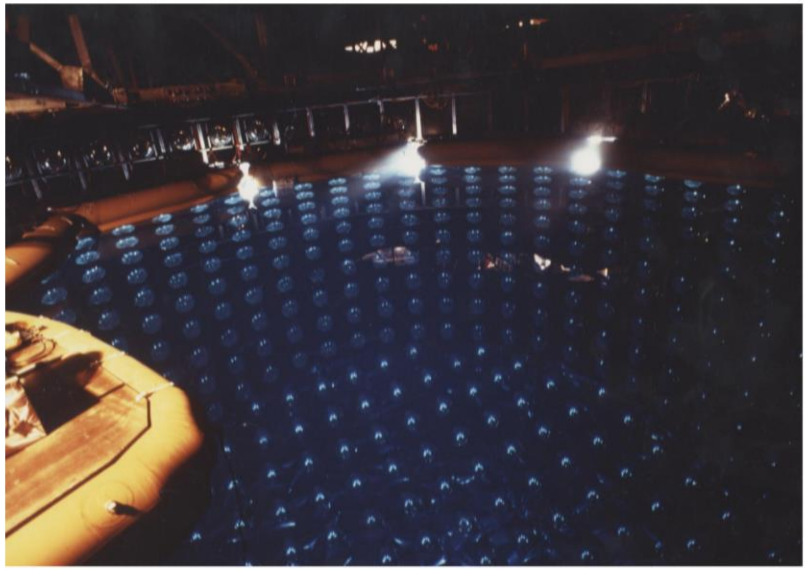
Photo by H.Sbel

Photo by N. Mondal



Discovery of neutrino oscillations

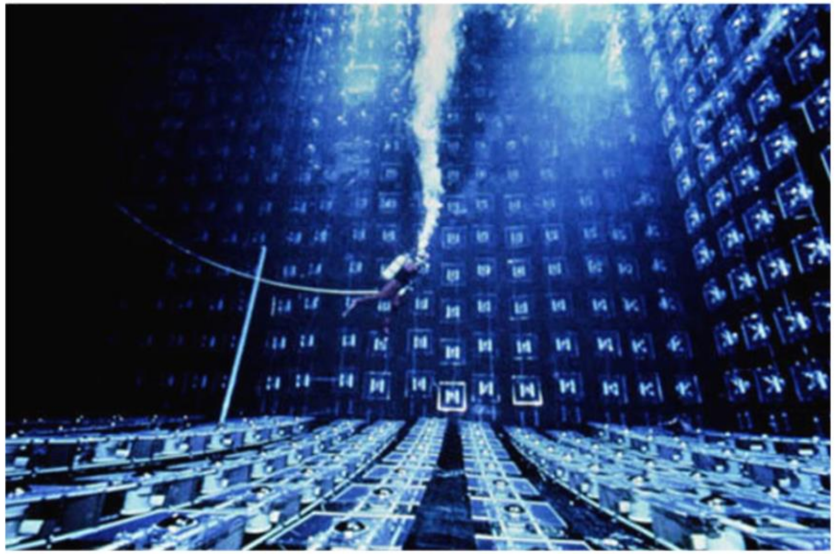
Proton decay experiments (1980's)



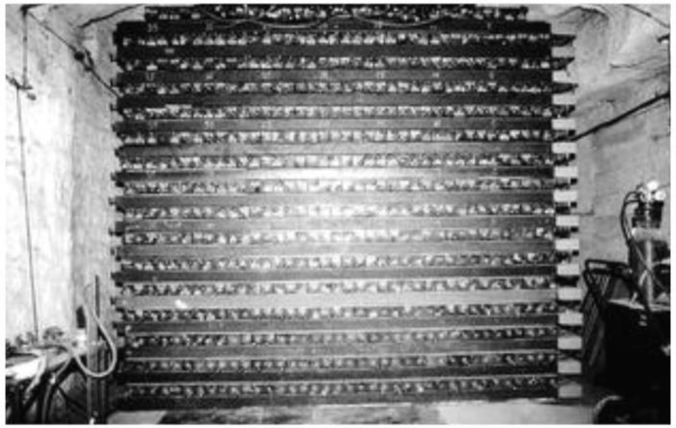
Grand Unified Theories
(in the 1970's)
➔ $\tau_p = 10^{30\pm2}$ years

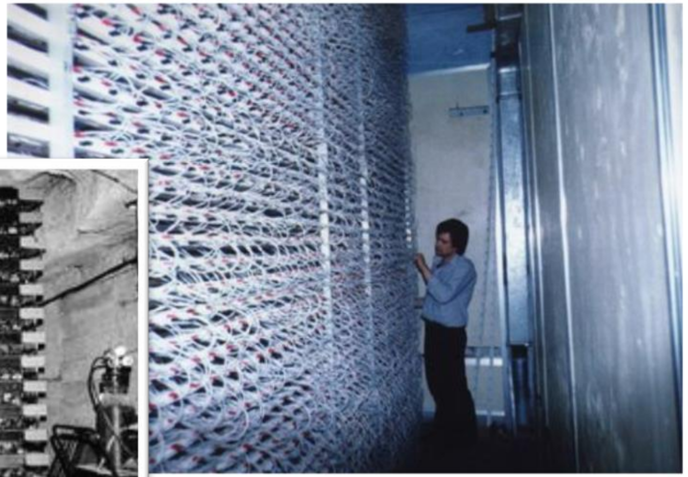
Kamiokande
(1000ton)

IMB
(3300ton)



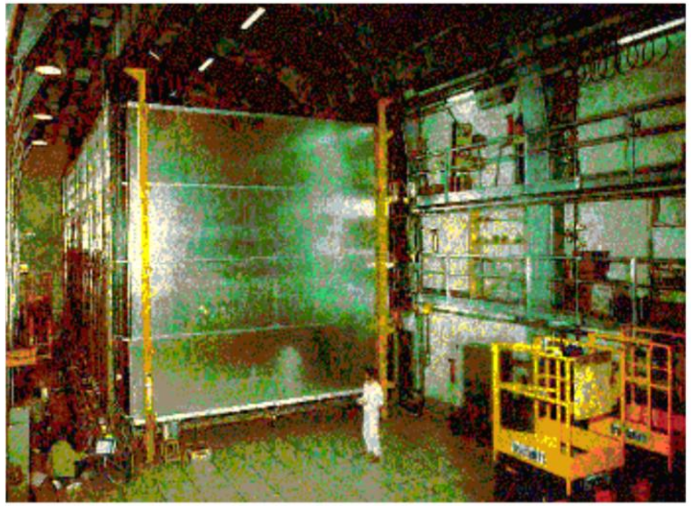
KGF (100tons)





NUSEX (130ton)

These experiments observed many contained atmospheric neutrino events (background for proton decay).



Frejus (700ton)

Constructing the Kamiokande detector (Spring 1983)

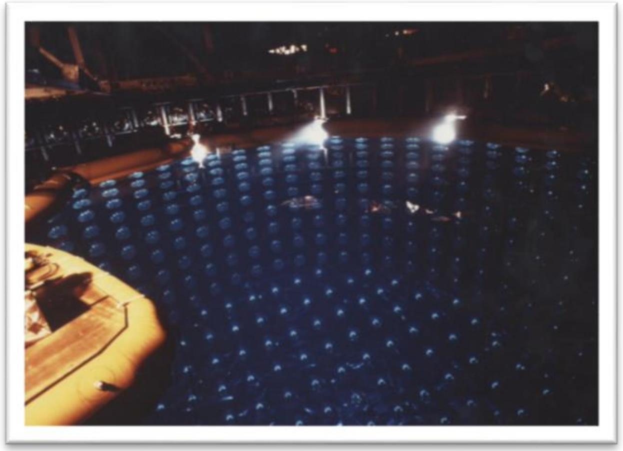
Y. Totsuka

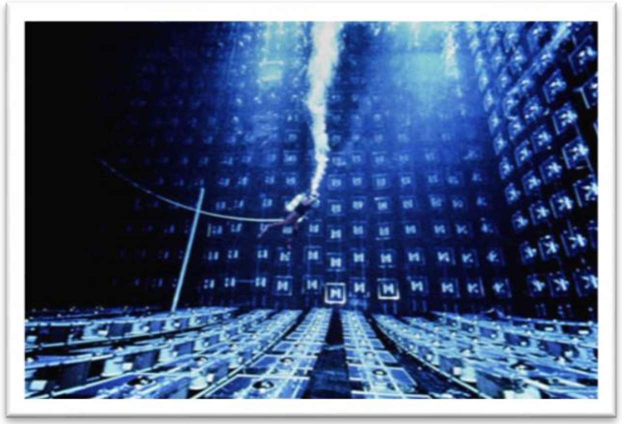
M. Koshiba
(2002 Nobel Prize)

T. Kifune

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

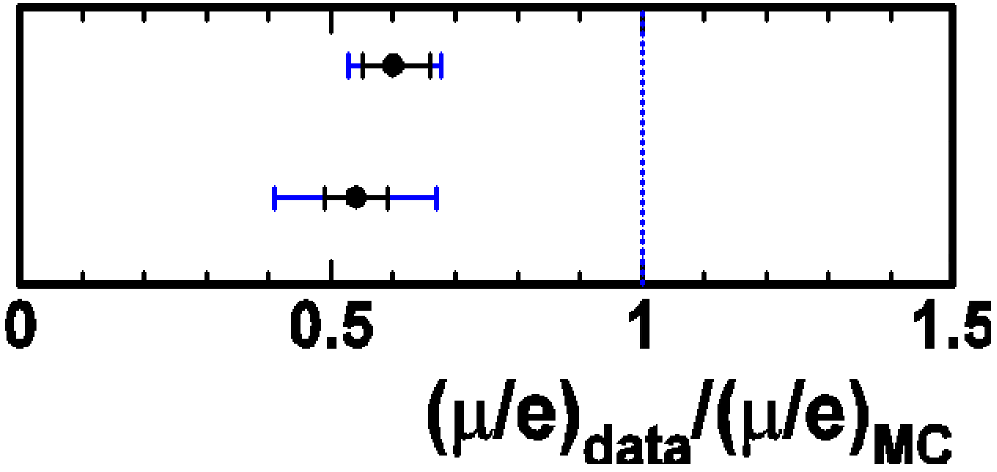
Because atmospheric neutrinos are the most serious background to the proton decay searches, it was necessary to understand and reduce the atmospheric neutrino background. During these studies, a significant deficit of atmospheric muon-neutrino events was found….





Kamiokande (1988, 92, 94)

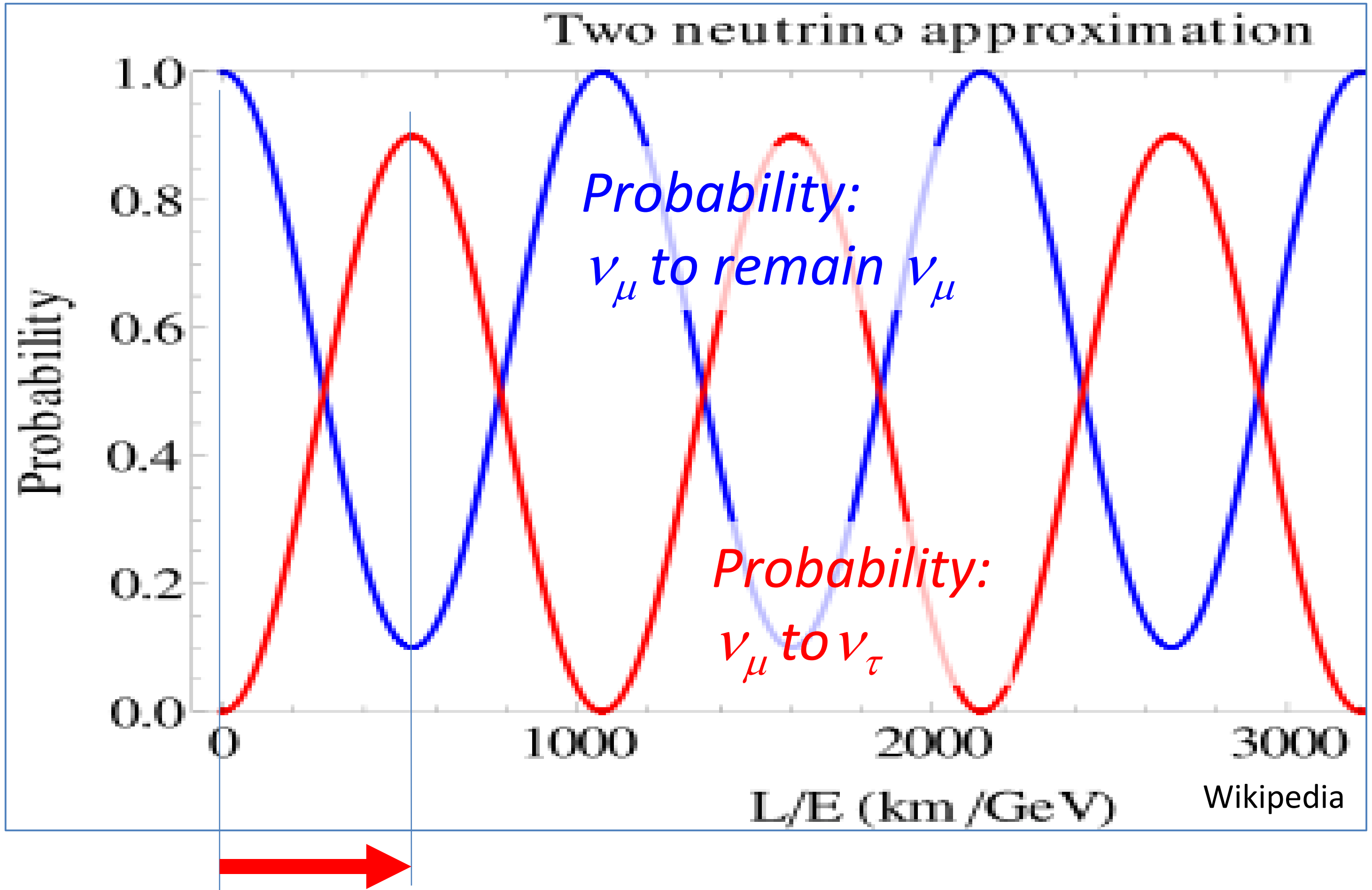
IMB (1991, 92)



It was suspected that 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.



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

Theoretically predicted by;

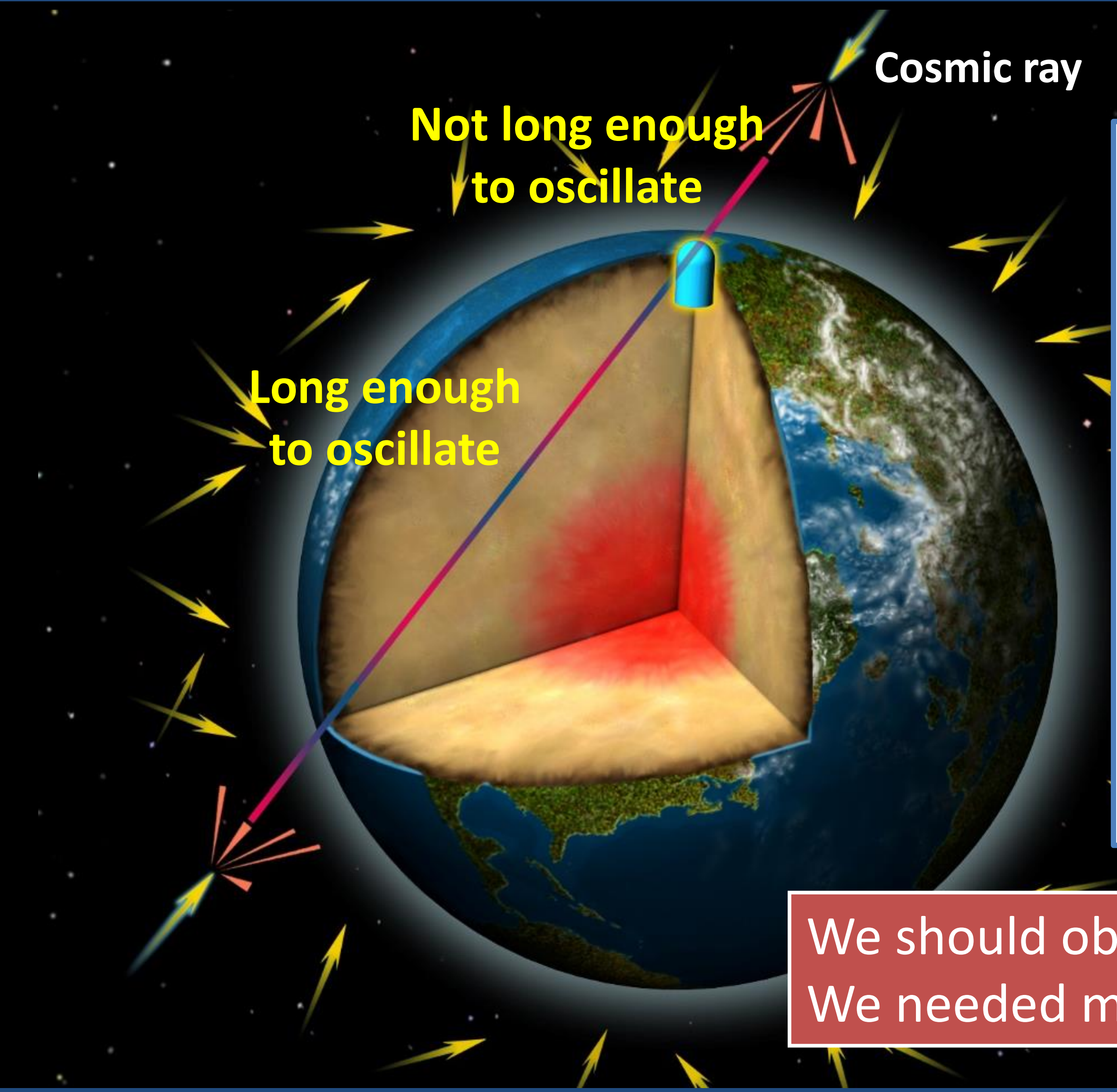
S. Sakata, Z. Maki, M. Nakagawa

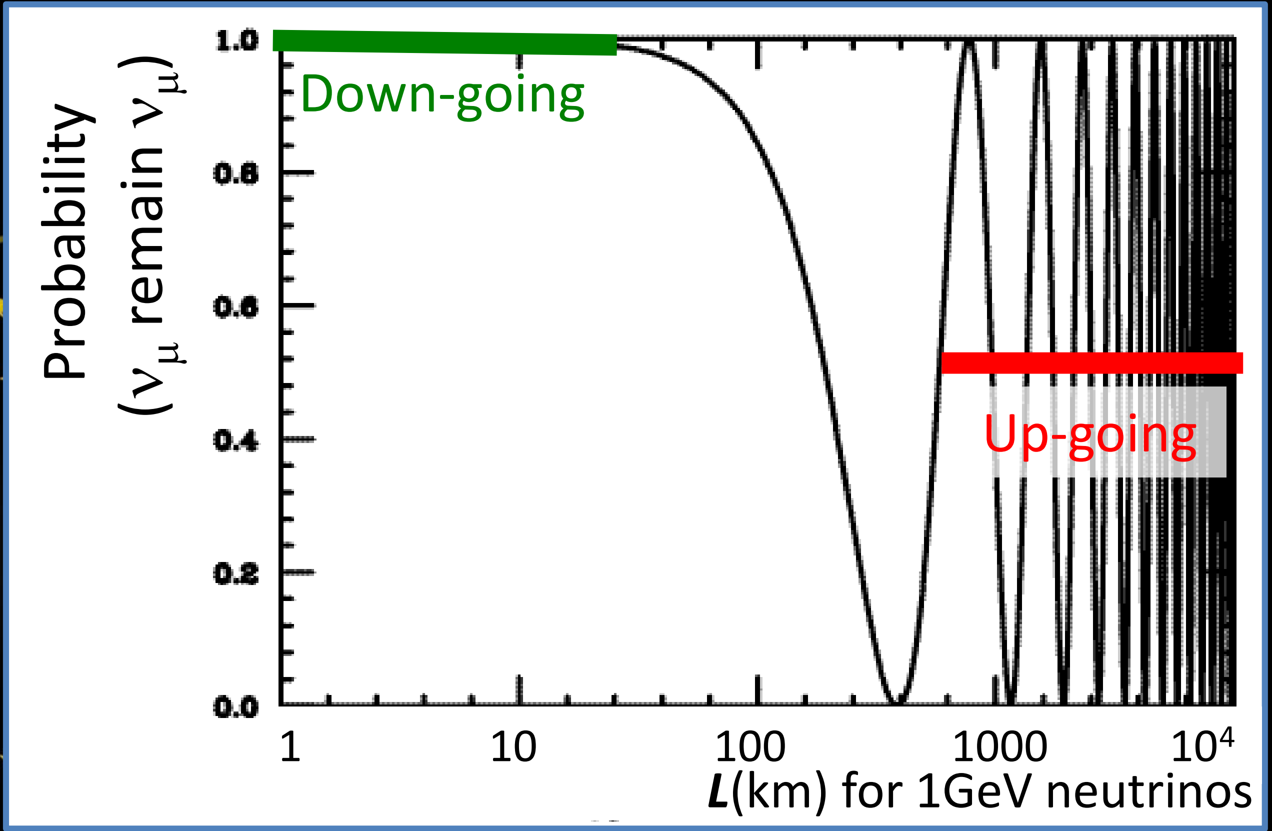
arXiv:0910.1657

B. Pontecorvo

L is the neutrino flight length (km),
E is the neutrino energy (GeV).

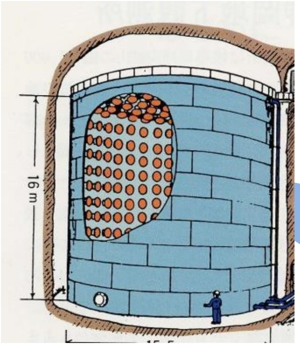
What will happen if the ν_μ deficit is due to neutrino oscillations





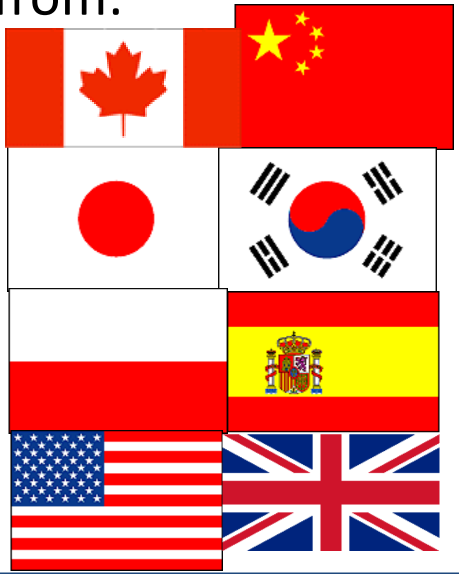
We should observe a deficit of upward going ν_μ's!
We needed much larger detector. ➔ Super-Kamiokande

Super-Kamiokande detector

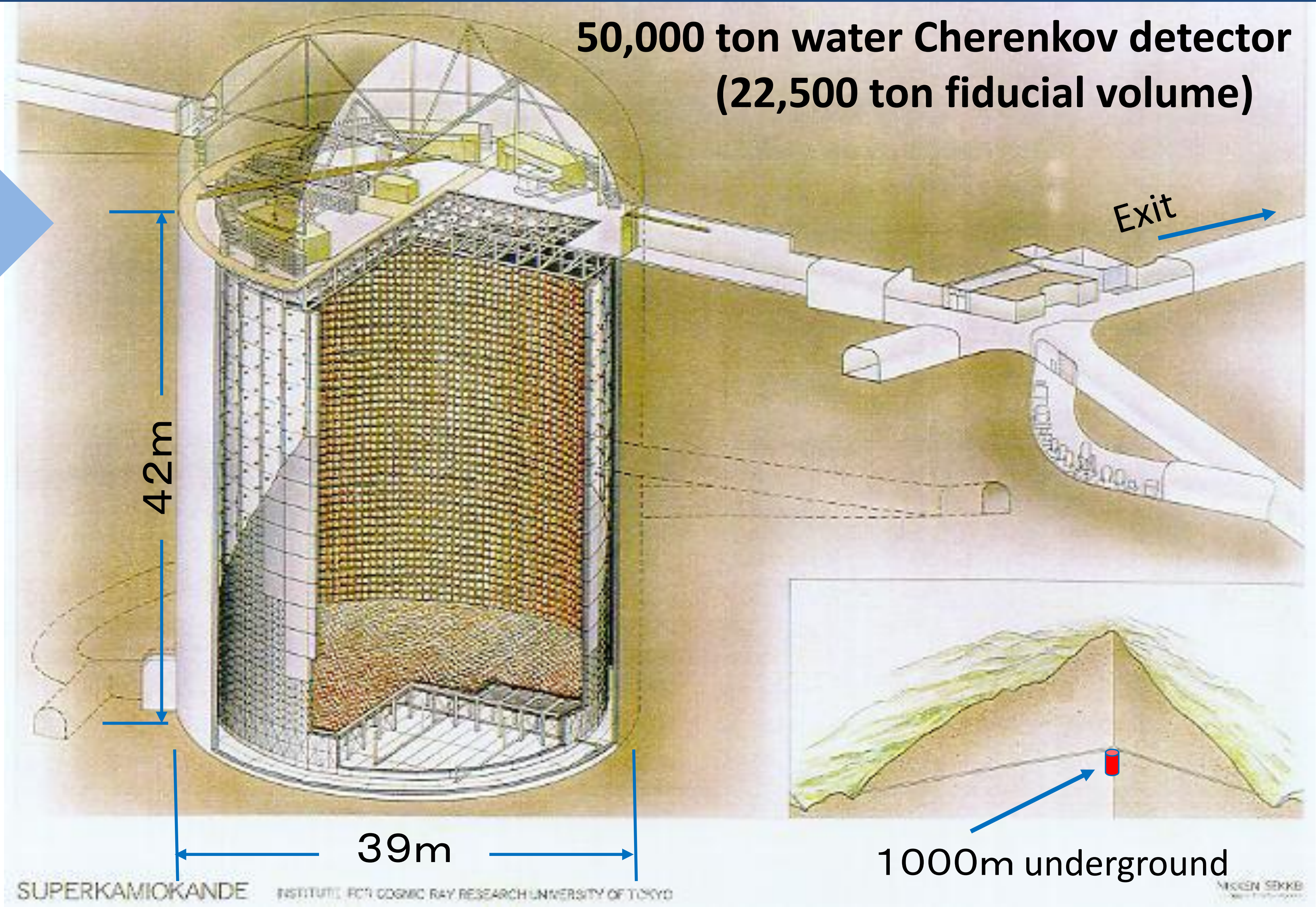


More than 20
times larger mass

~140 collaborators
from:

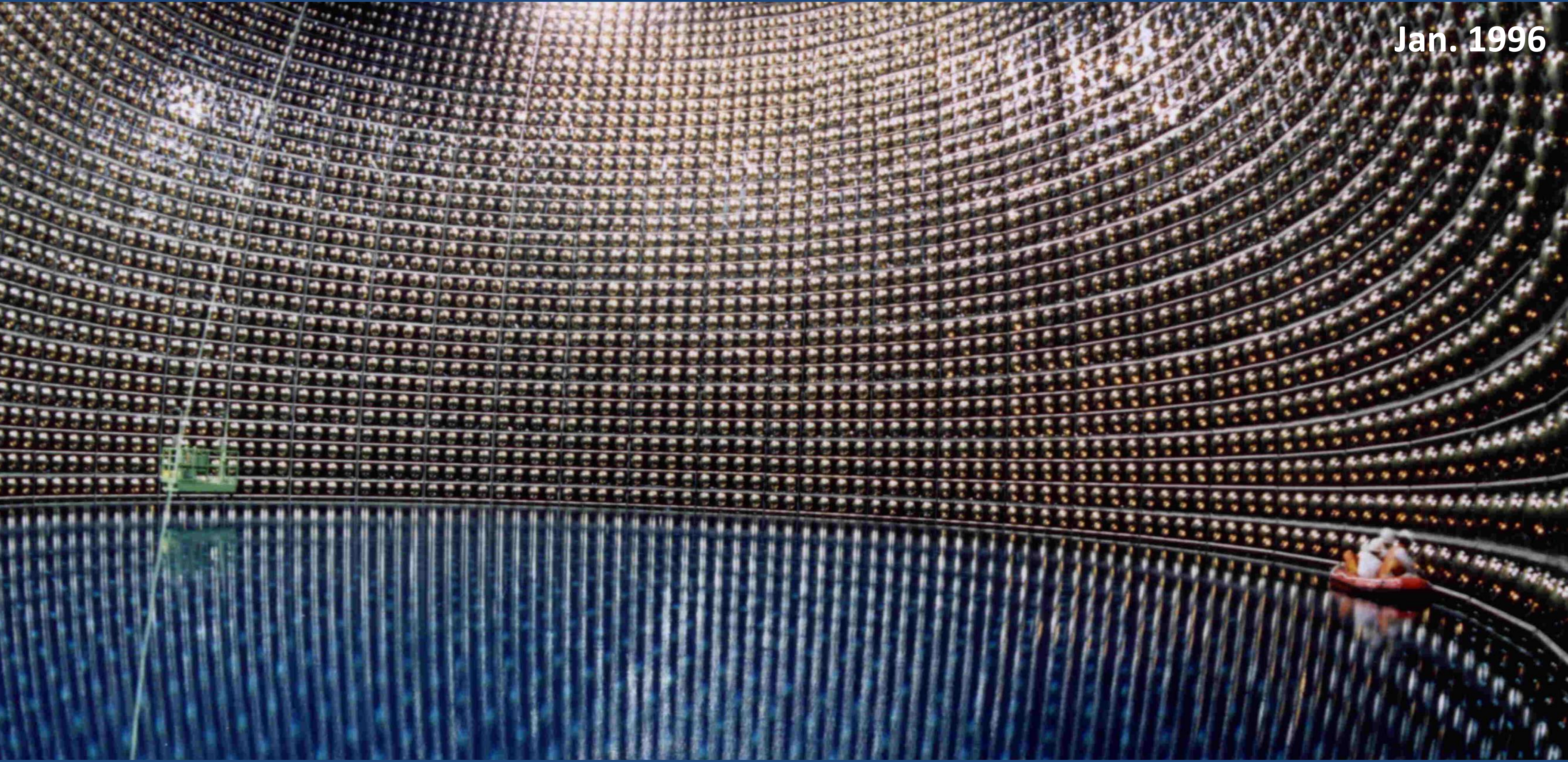


50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)

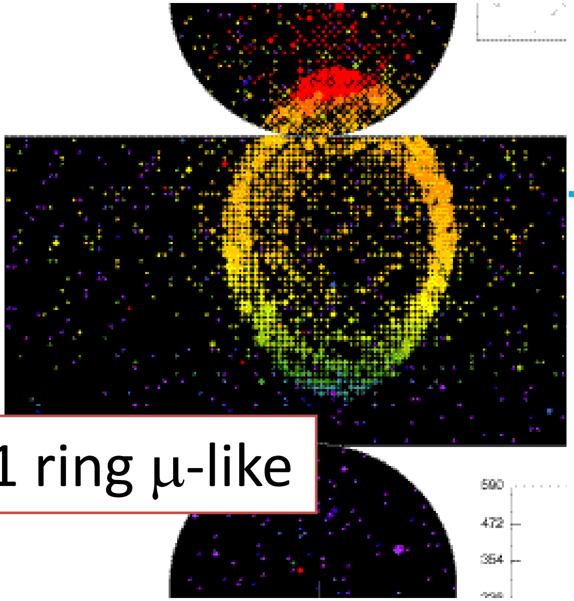


Constructing the Super-Kamiokande detector (spring 1995)

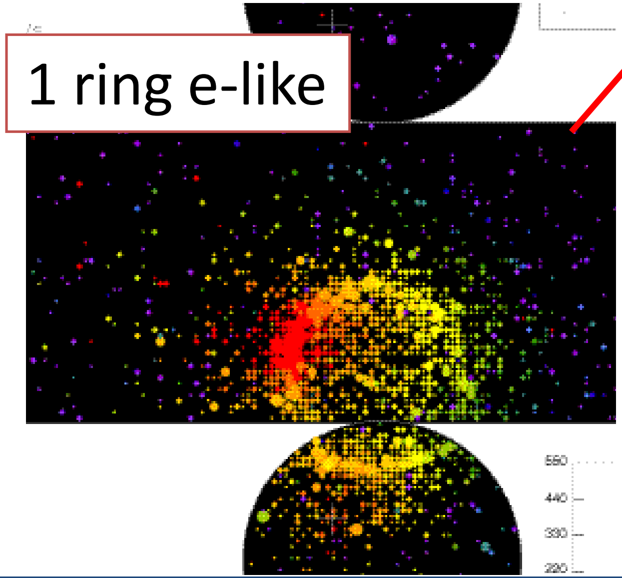
Filling water in Super-Kamiokande



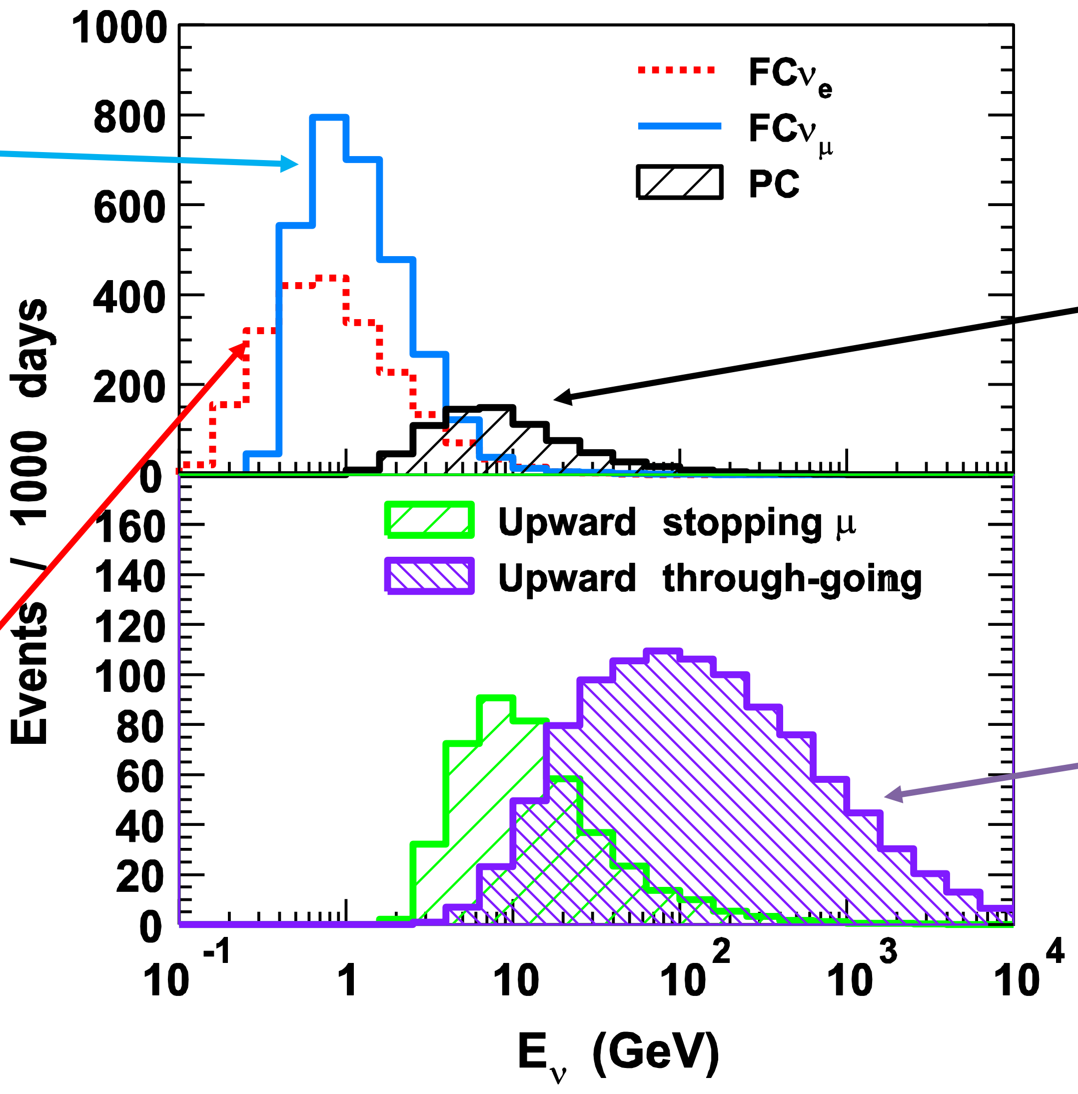
Event type and neutrino energy

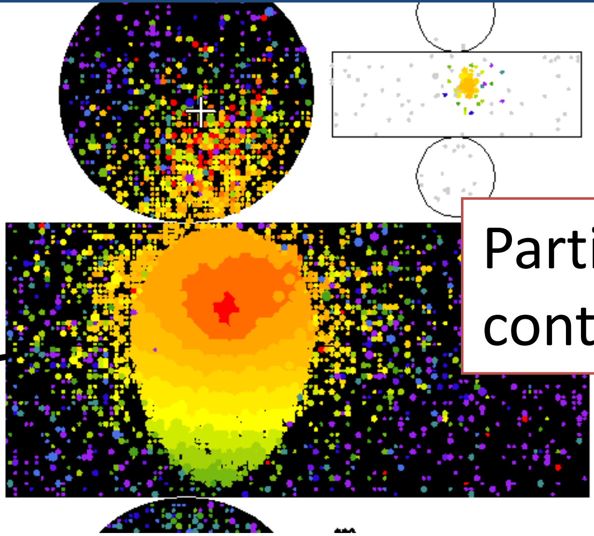


1 ring μ-like

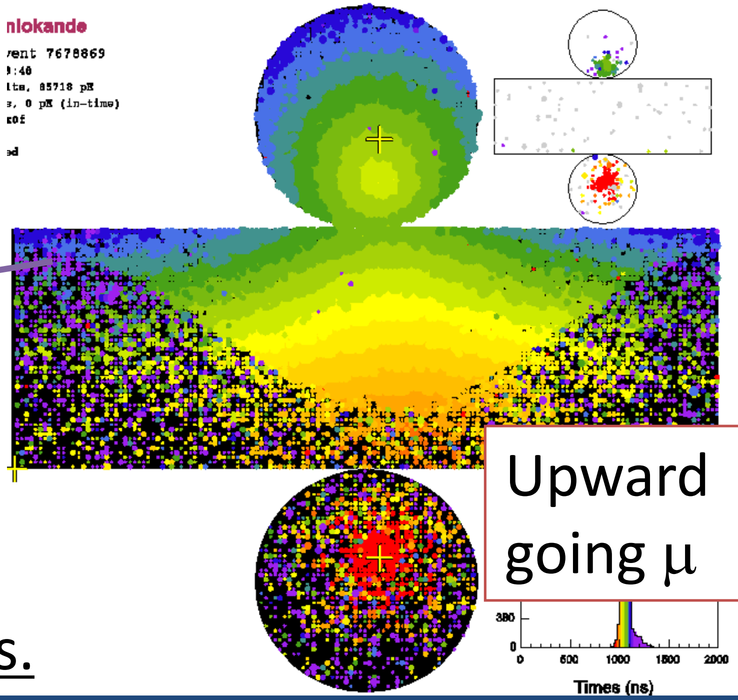


1 ring e-like





Partially contained

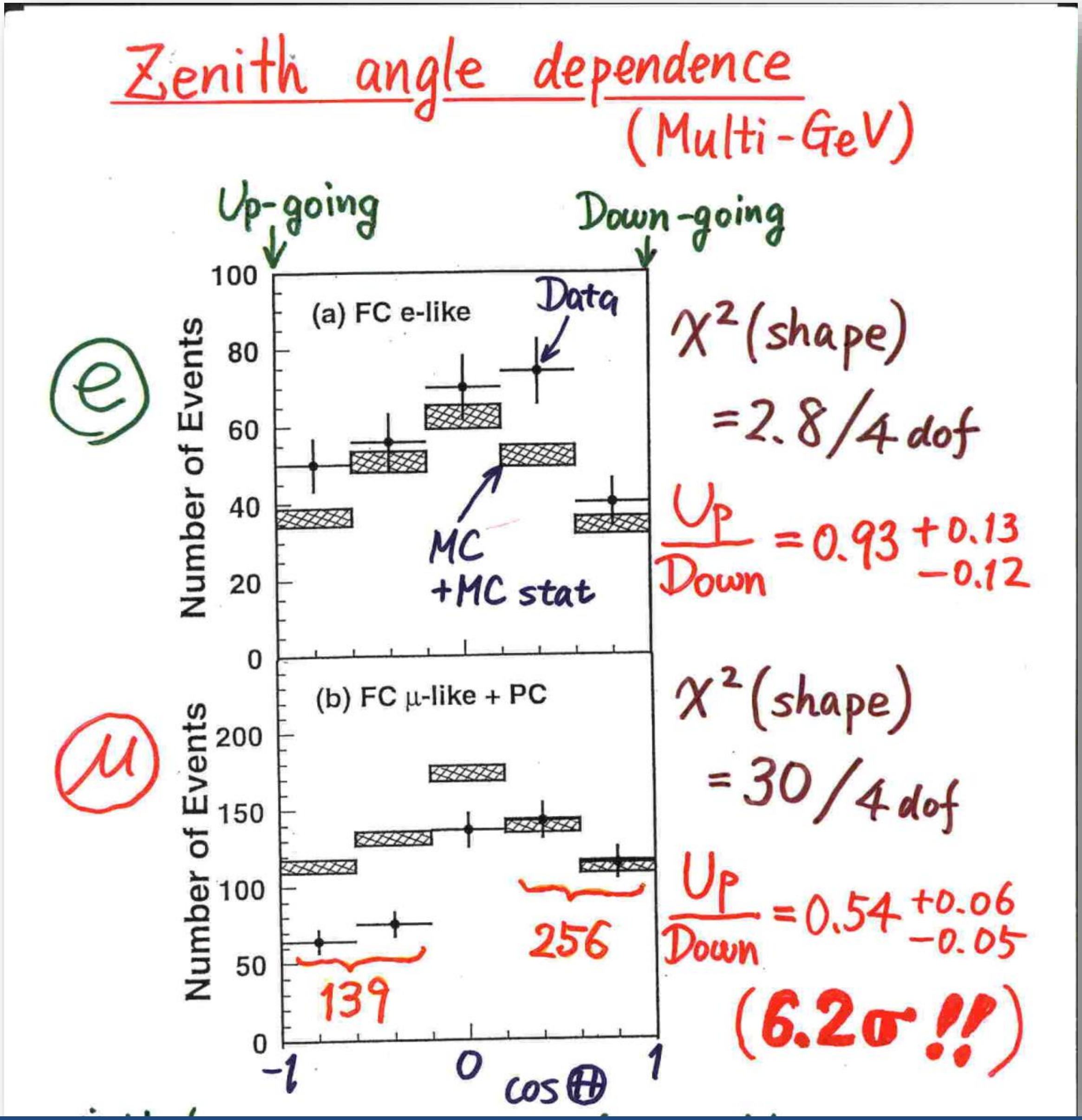


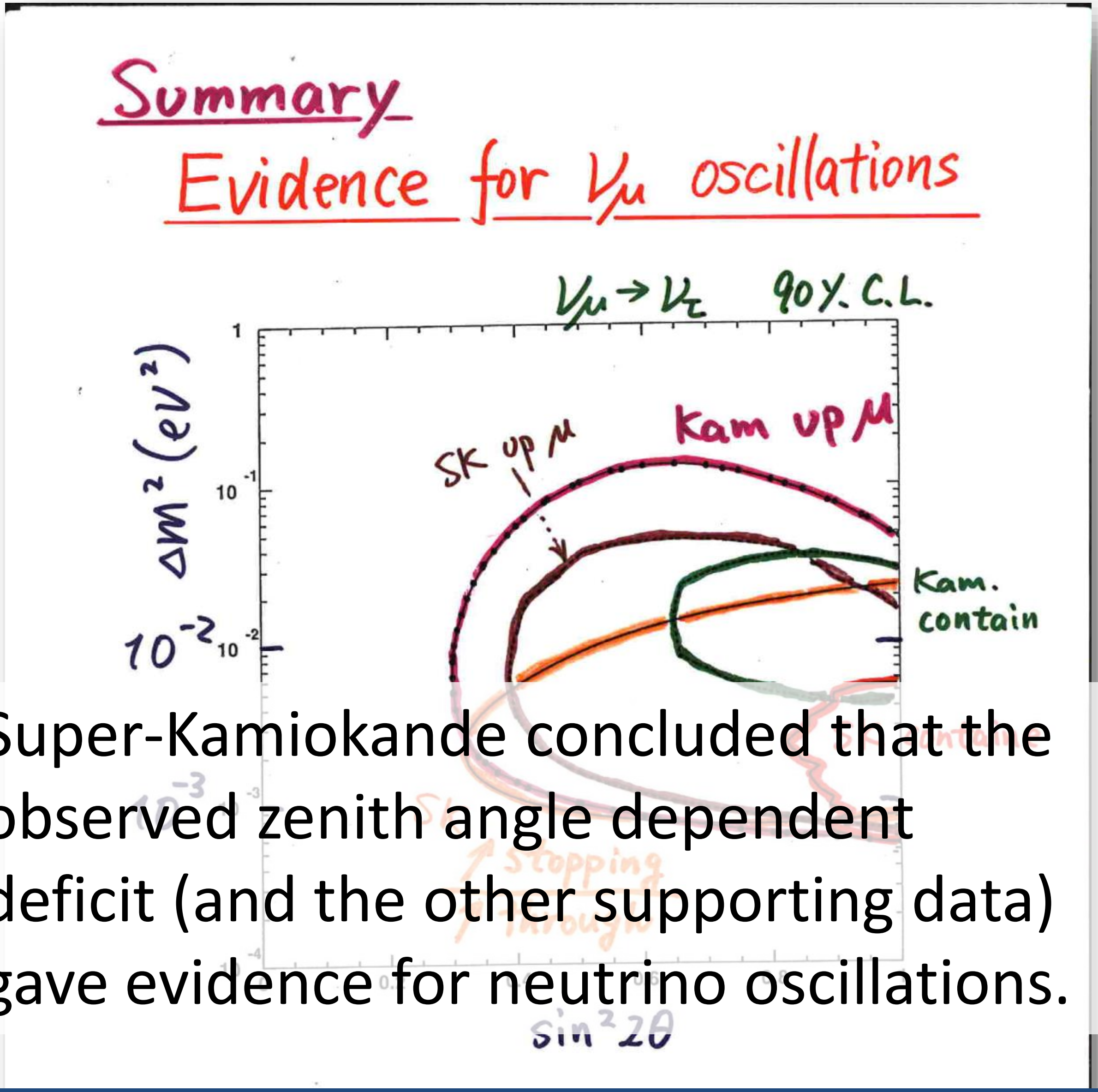
Upward going μ

All these events are used in the analysis.

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

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

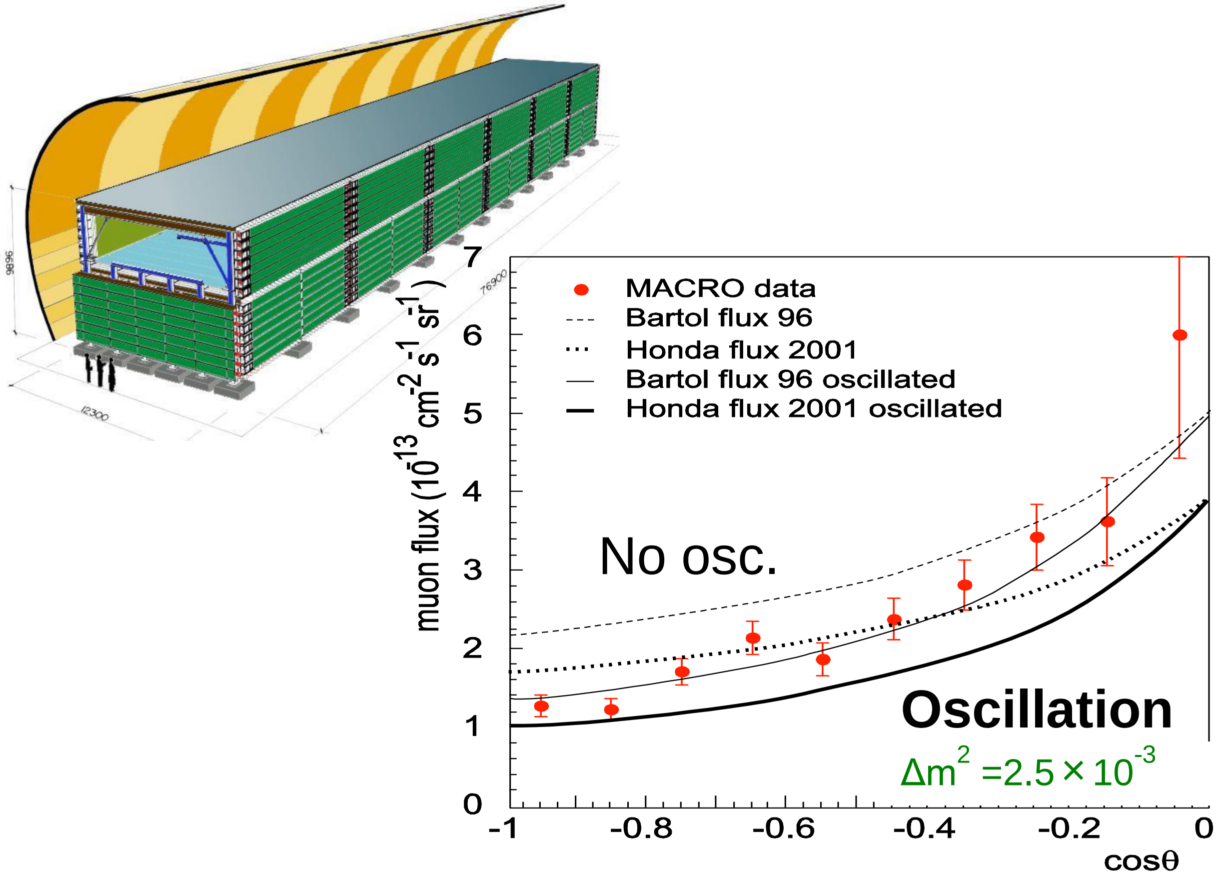




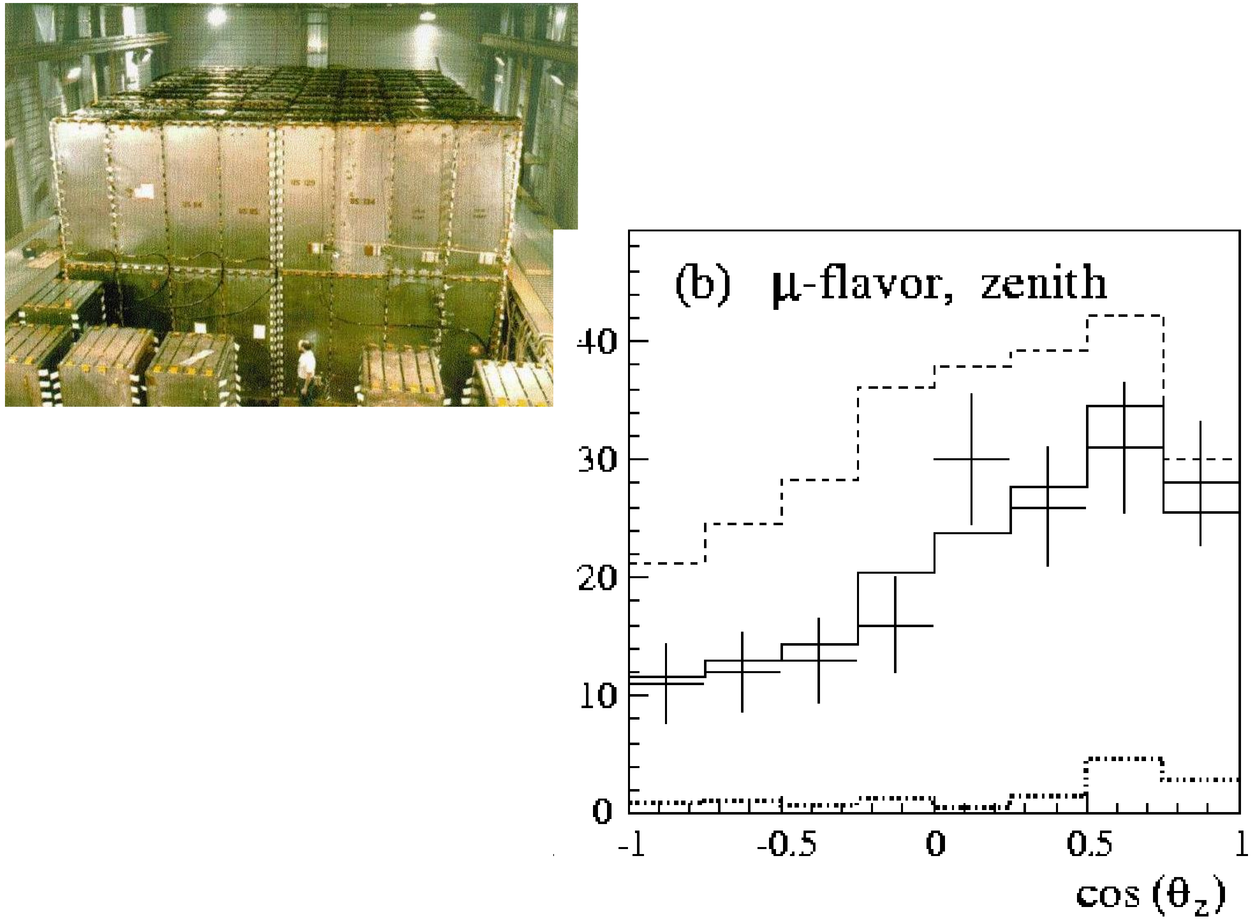
Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Results from the other atmospheric neutrino experiments

MACRO



Soudan-2



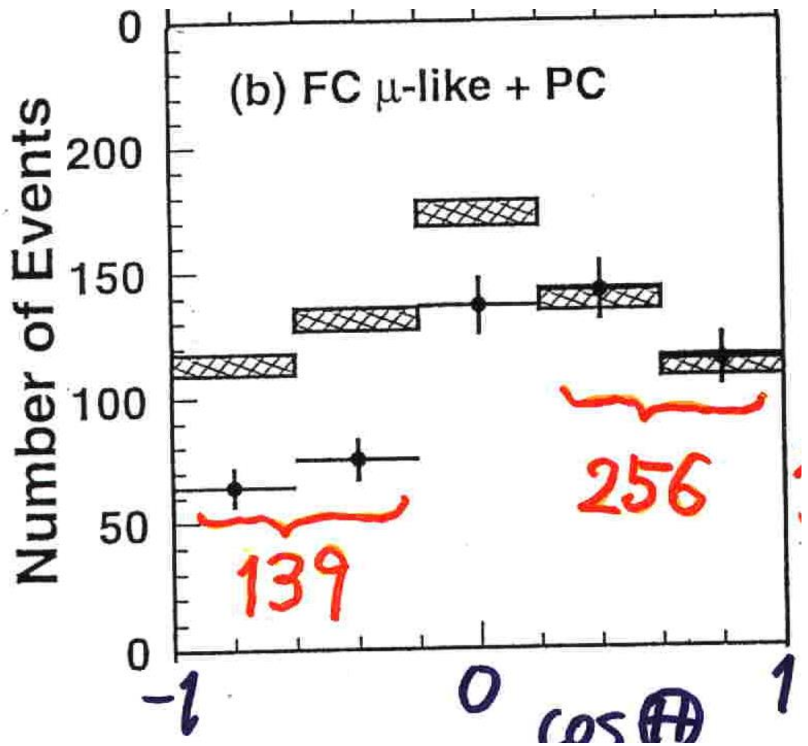
<u>These experiments observed atmospheric neutrinos and confirmed neutrino oscillations.</u>

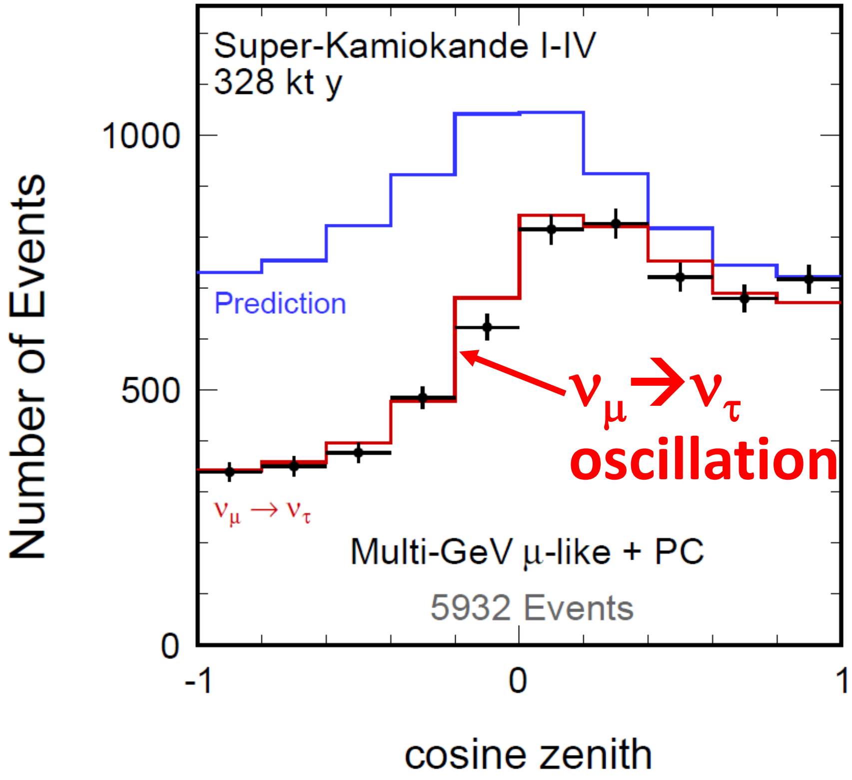
(Accelerator based LBL experiments also have confirmed and studied oscillations.)

Status of neutrino oscillation studies

Data updates

Super-K @Neutrino98 → Super-K (2016)





Number of events plotted:

531 events → 5932 events

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

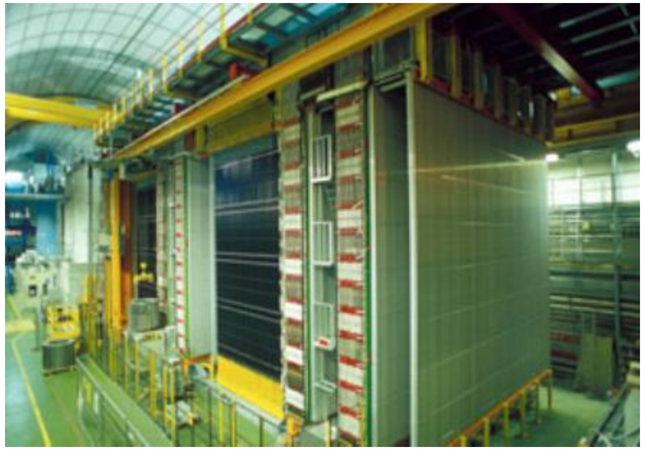
Neutrino oscillation studies

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

K2K

MINOS (USA)

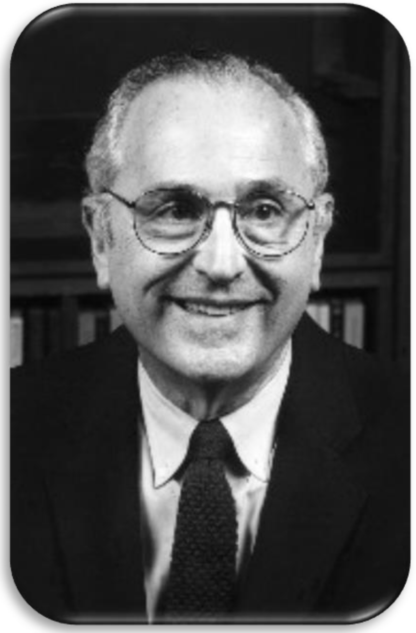
OPERA



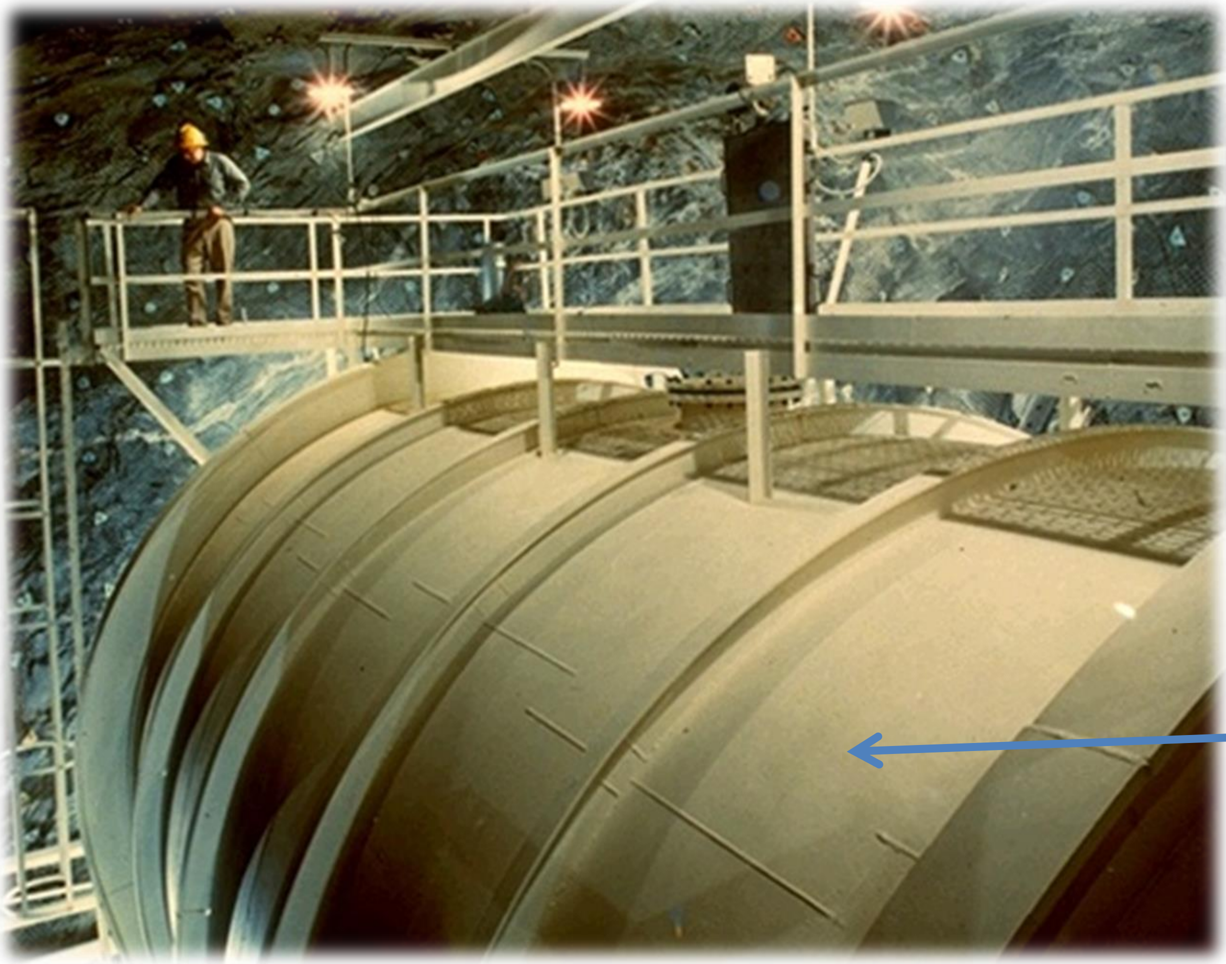
T2K

NOvA

Solar neutrino problem



J. N. Bahcall

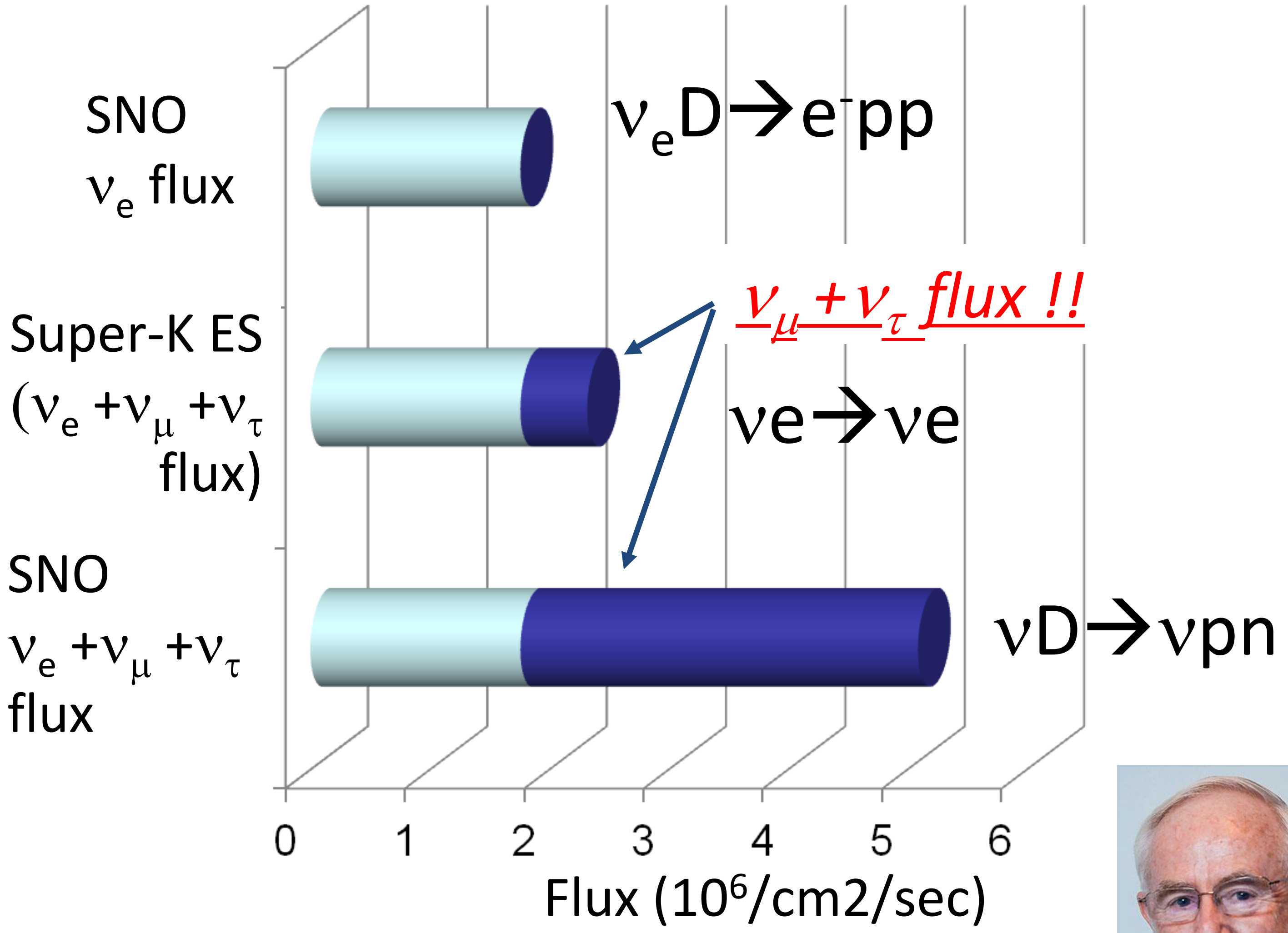


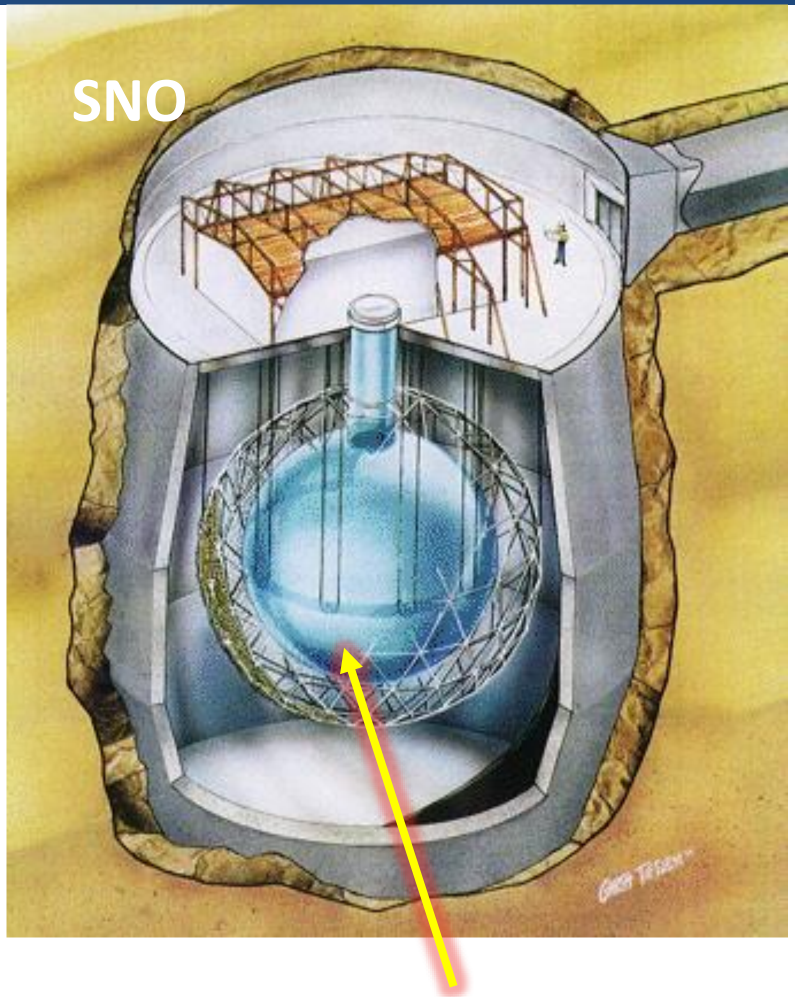
600ton
C_2Cl_4

R. Davis Jr.

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)





1000 ton of heavy water (D_2O)

Neutrino oscillation: electron neutrinos to the other neutrinos.

Art McDonald

Discovery of the third neutrino oscillations (2011-2012)

Accelerator based long baseline neutrino oscillation experiments

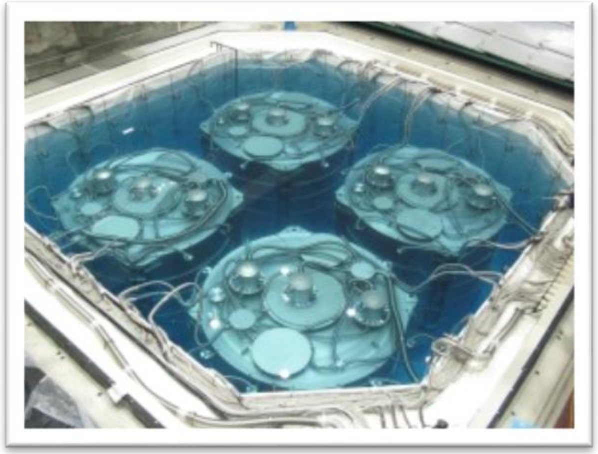
T2K (Japan)

MINOS (USA)

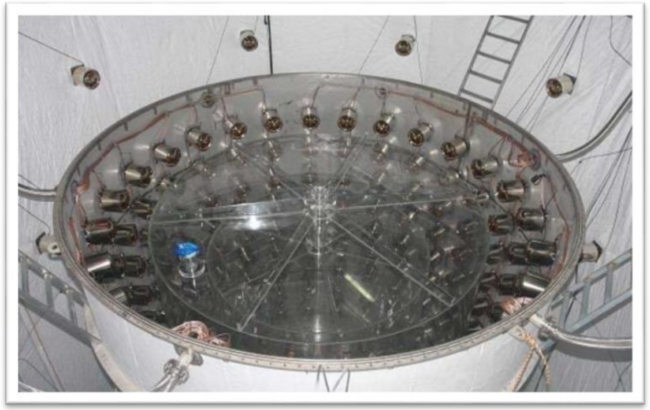
NOνA (USA)

Reactor based (short baseline) neutrino oscillation experiments

Daya Bay (China)

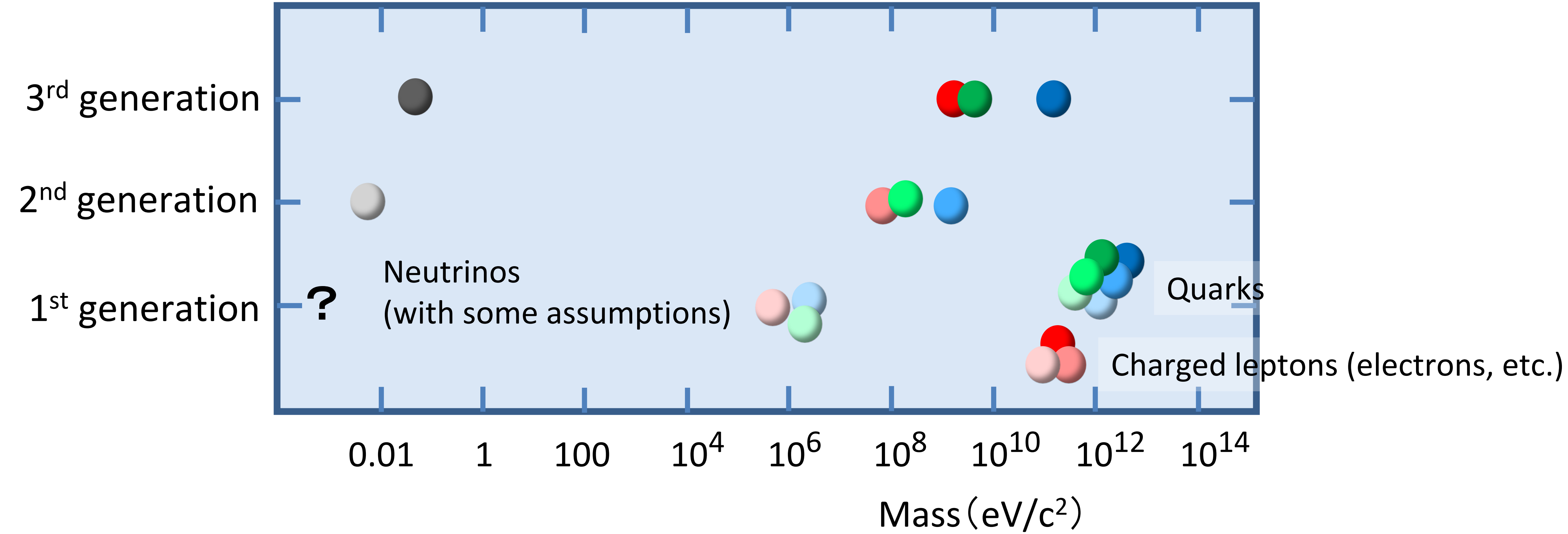


RENO (Korea)



Double Chooz (France)

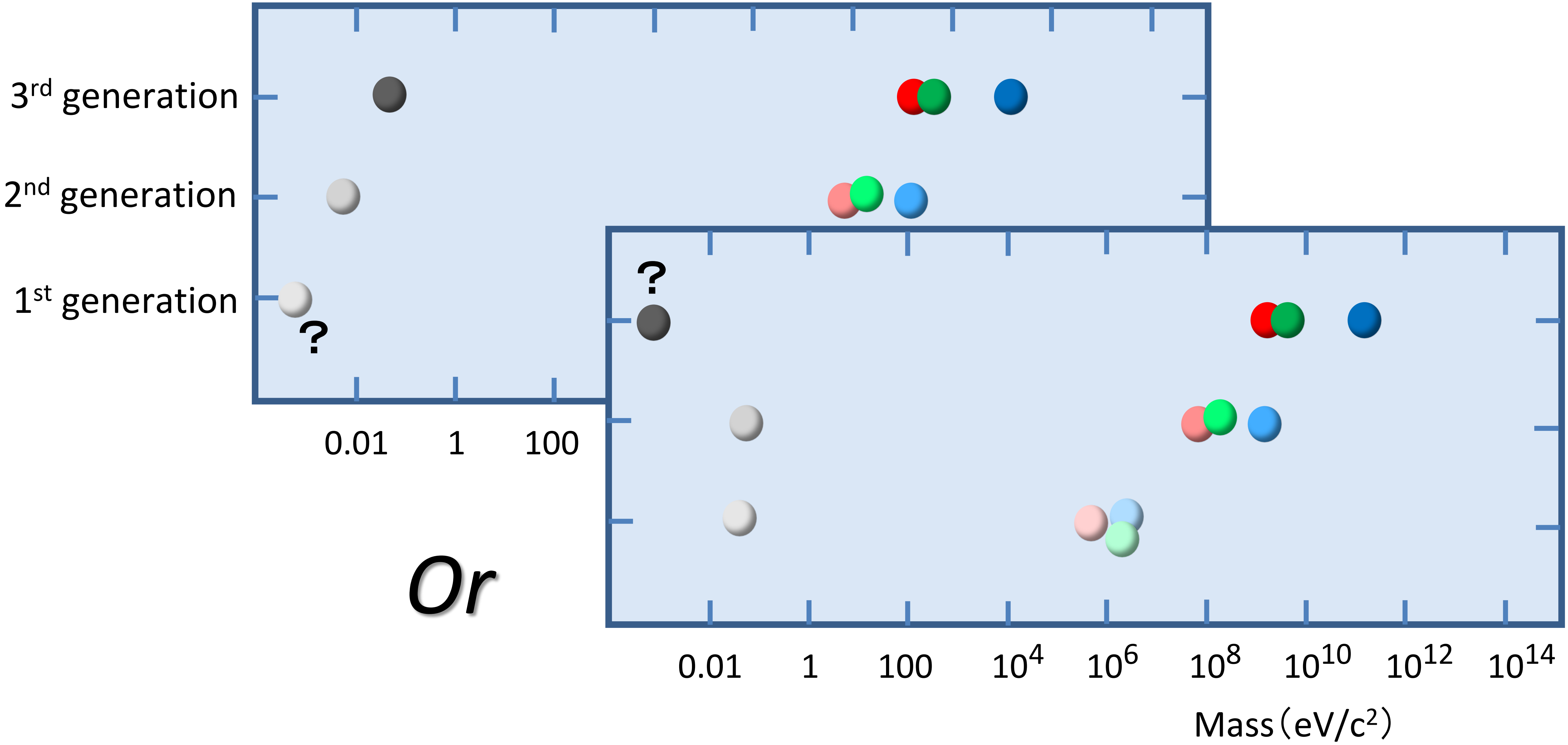
What have we learned?
Why are neutrinos important?



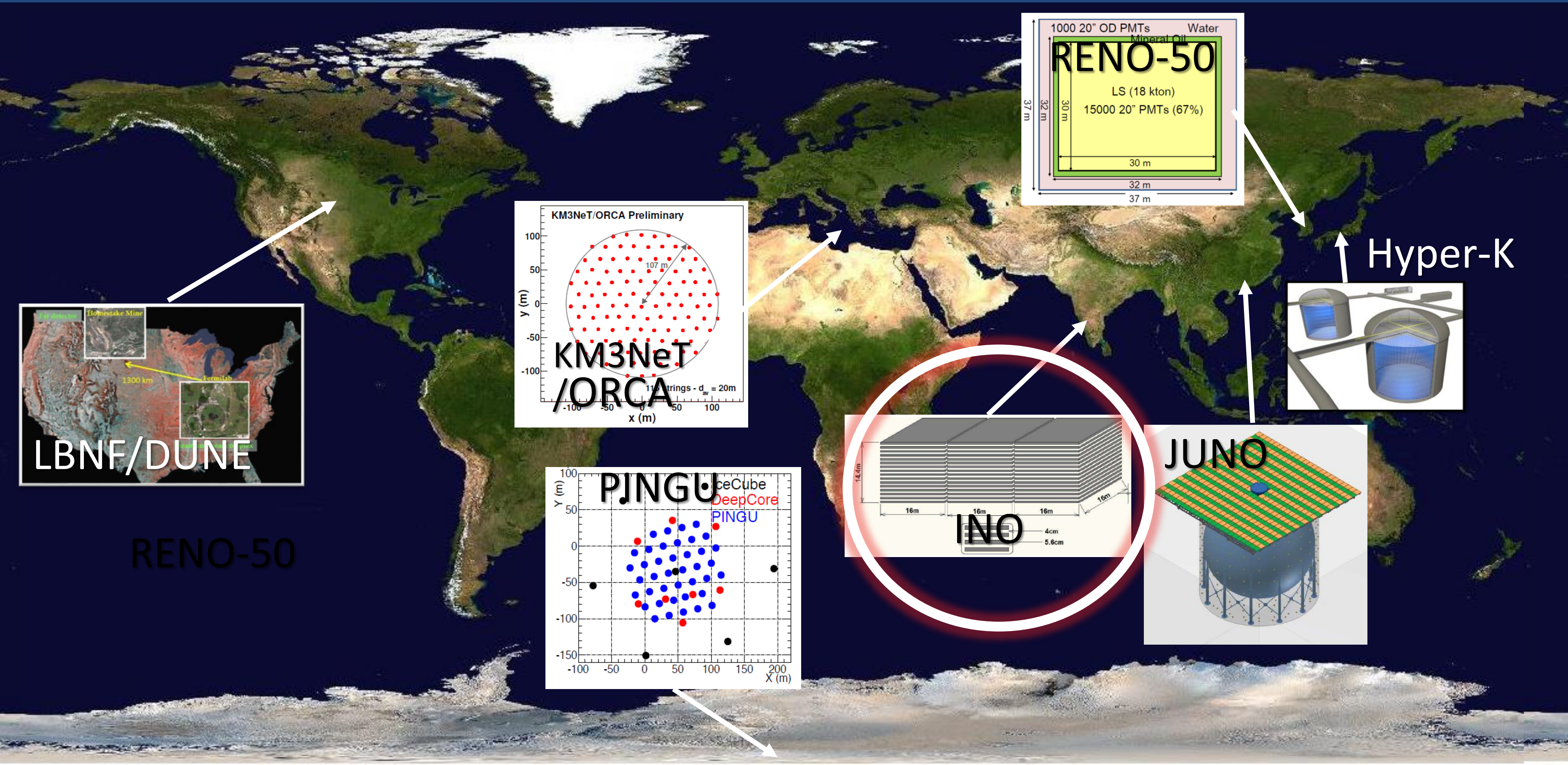
The neutrino masses are approximately (or more than) 10 billion (10 orders of magnitude) smaller than the corresponding masses of quarks and charged leptons!
We believe this is the key to understand the nature at the smallest and the largest scales.

Future

Neutrino mass



Future experiments that will tell us the order of the neutrino masses



Comment: Importance of "Interactions of neutrinos and hadrons"

- Neutrino oscillation experiments are very important.
- Now neutrino oscillation experiments enter into the precision measurement stage.
- In order to get the most from these experiments, we have to understand the "Interactions of neutrinos and hadrons" much better than before.

➔ This meeting !

Summary

- About 50 years ago, atmospheric neutrinos was observed for the first time.
- “Proton decay experiments” in the 1980’s observed many contained atmospheric neutrino events, and discovered the atmospheric ν_μ deficit.
- In 1998, Super-Kamiokande discovered neutrino oscillations, which shows that neutrinos have mass.
- Since then, various experiments, including solar neutrino experiments, have studied neutrino oscillations.
- The discovery of non-zero neutrino masses opened a window to study physics beyond the Standard Model of particle physics.
- There are still many things to be observed in neutrinos. Atmospheric neutrino experiments are likely to continue contributing to neutrino studies.
  ➔ I am looking forward the contribution of ICAL-INO.

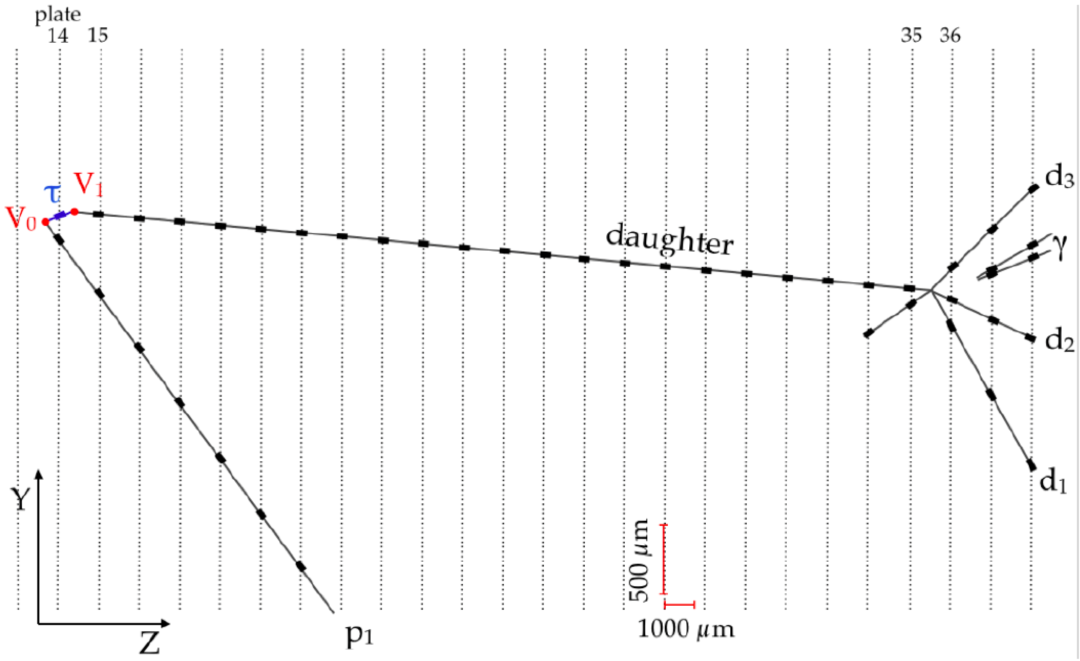
Back up

Some highlights (ν_τ appearance)

OPERA

5 tau-neutrino candidates observed.
Expected BG = 0.25 evens. (5.1σ)

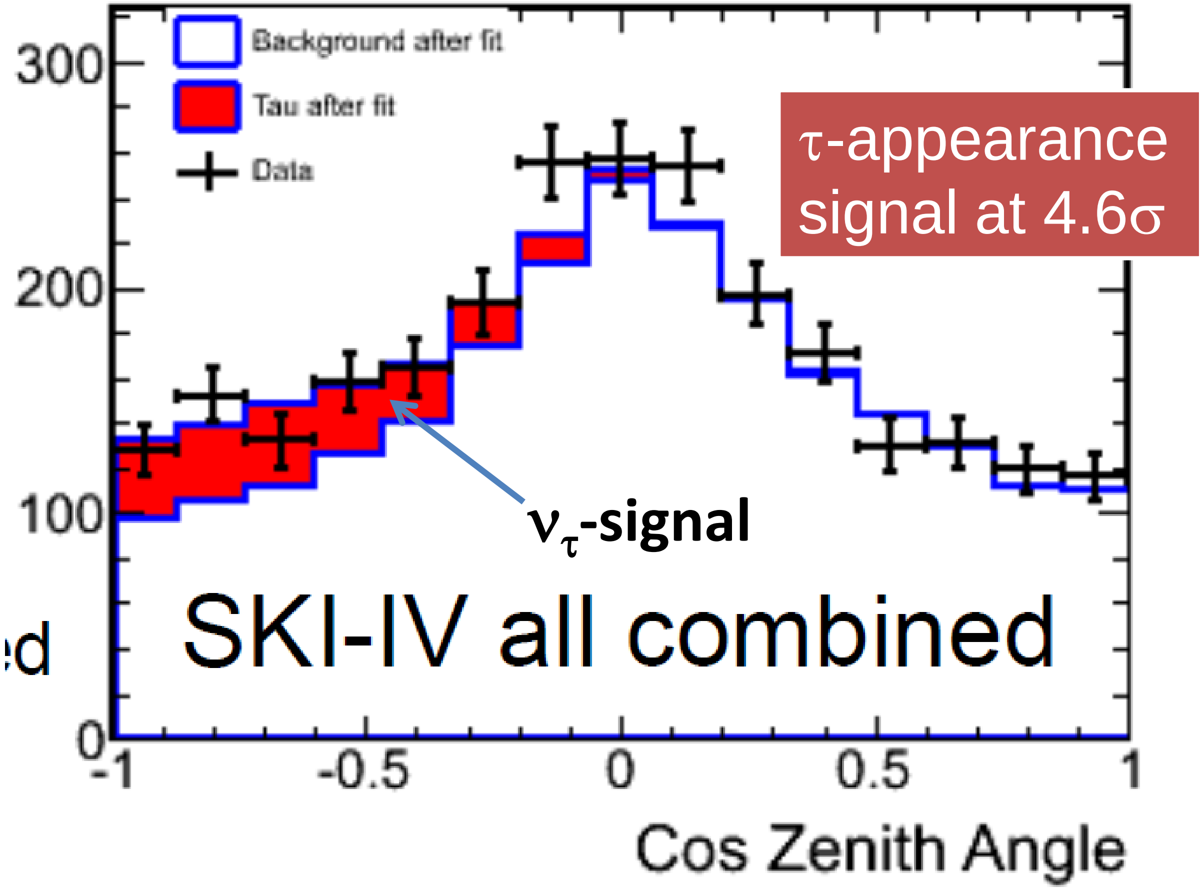
OPERA PRL 115 (2015) 121602



The fifth candidate event

Super-Kamiokande

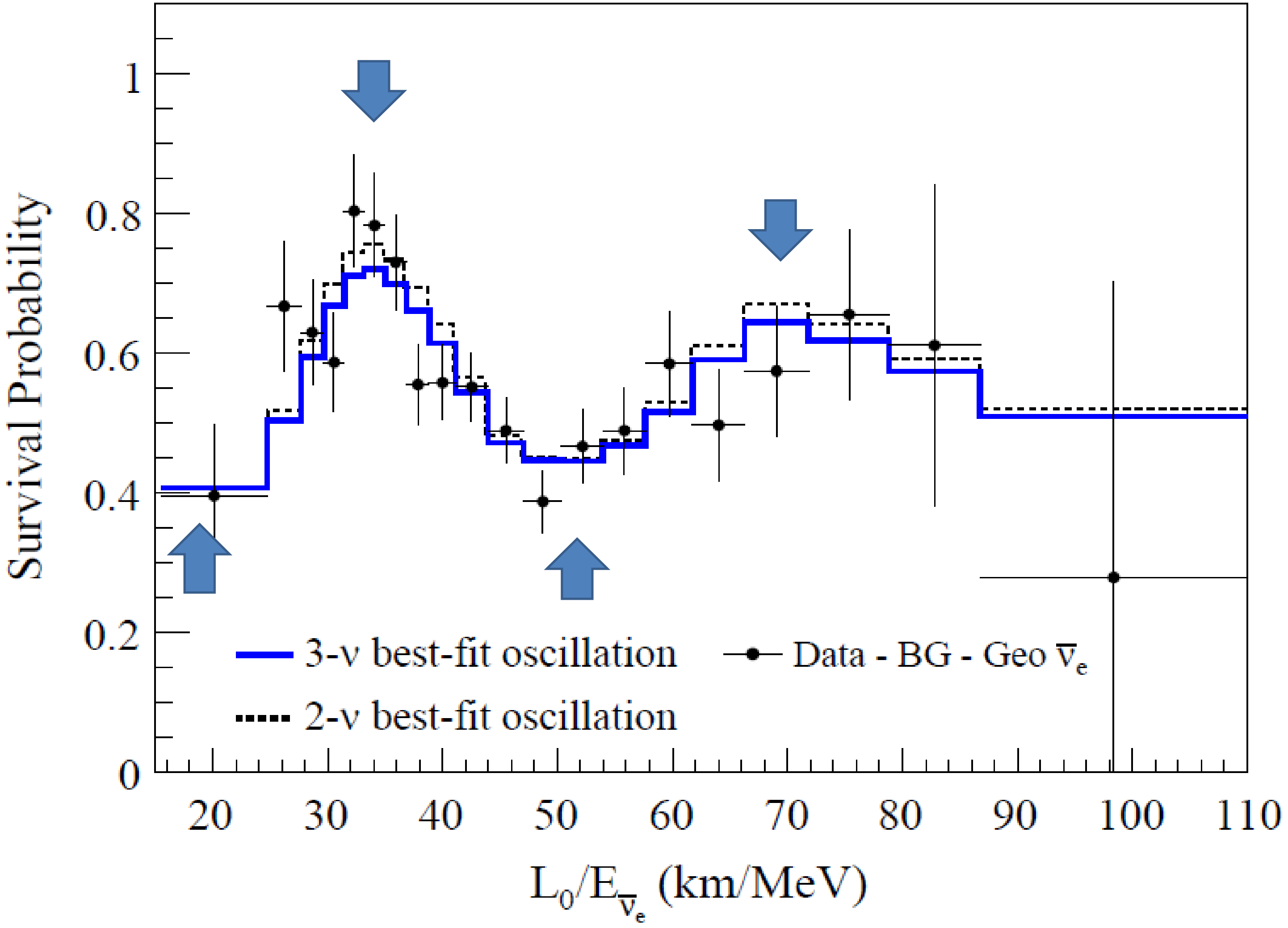
Super-K (S.Moriyama) @nu2016
See also, SK PRL 110(2013)181802



Really neutrino oscillations !

KamLAND observed neutrinos from nuclear power stations.

KamLAND, PRD 83, 052002 (2011)



KamLAND