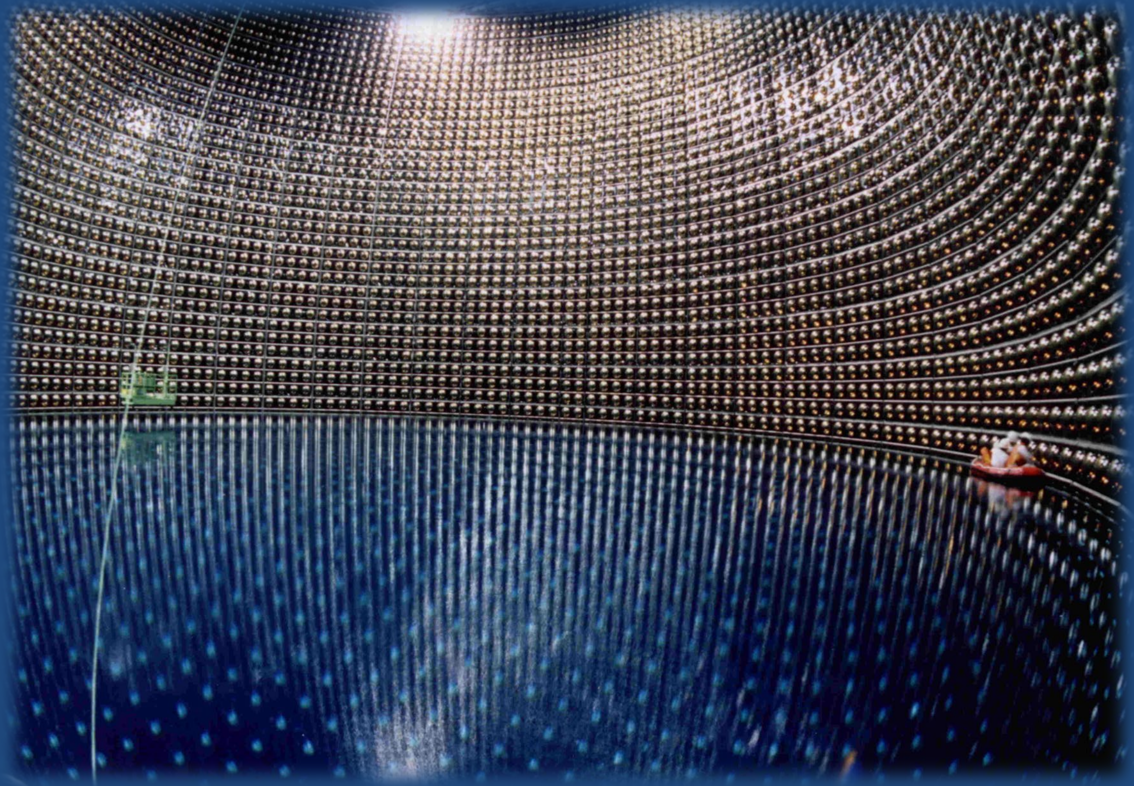
GGI, Florence, Italy, June 27, 2024

Path to Discovery: Neutrino Oscillations



Takaaki Kajita

Institute for Cosmic Ray Research, The Univ. of Tokyo

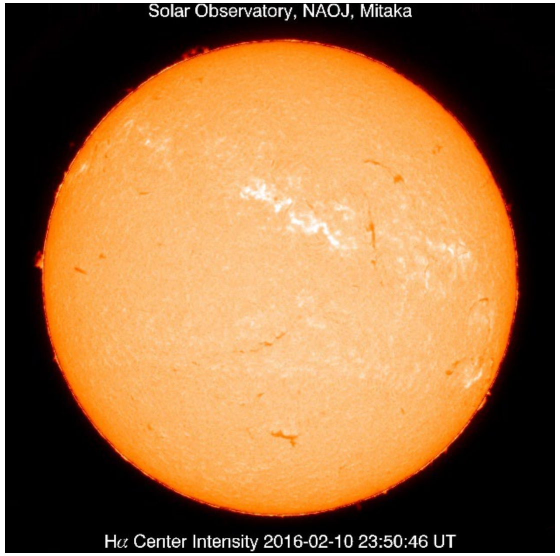
Outline

- Early days
- Discovery of neutrino oscillations
  - Atmospheric neutrino oscillations
  - Solar neutrino oscillations
  - The third oscillation channel
- Status and future
- Summary

Many thanks to Art McDonald for various information related to SNO

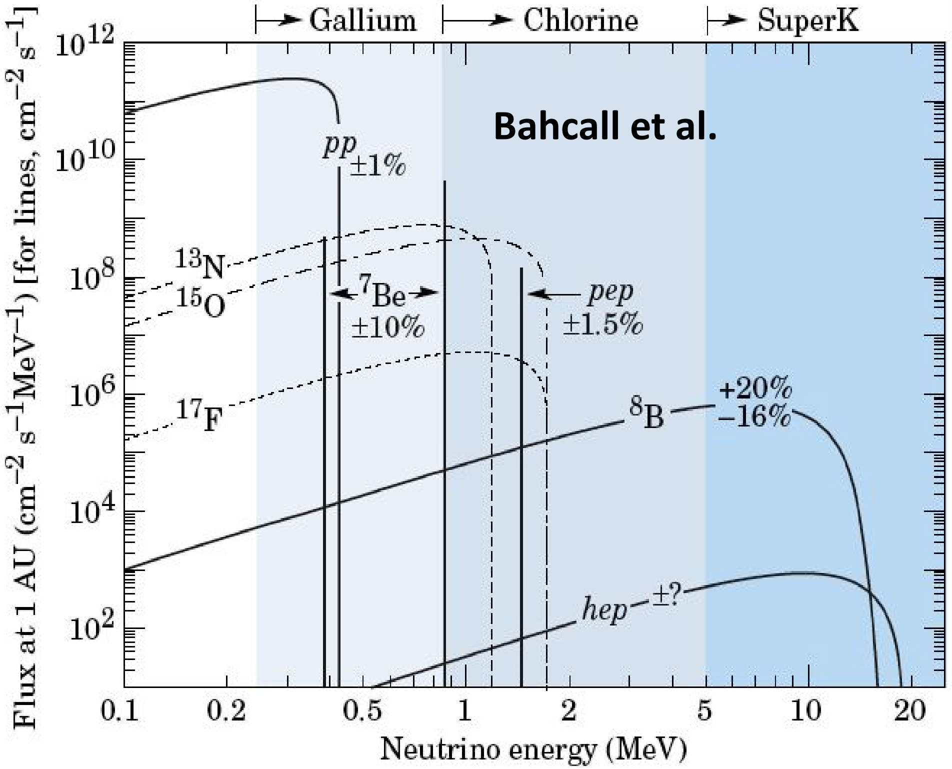
Early days

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.

Energy spectrum: Solar neutrinos

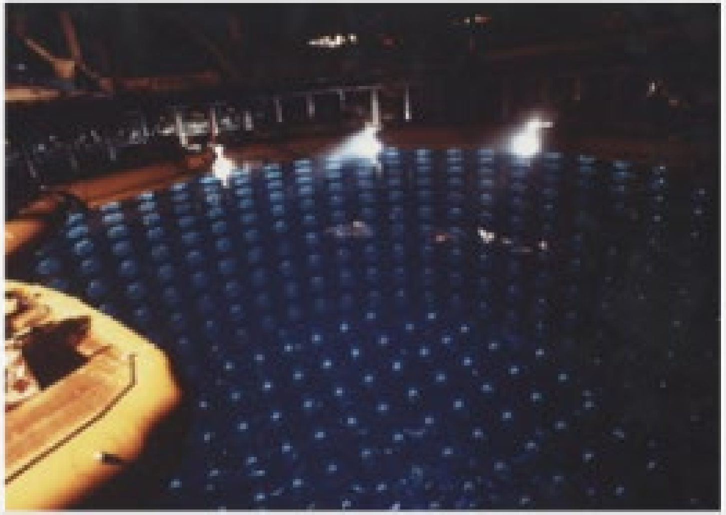


600ton C_2Cl_4

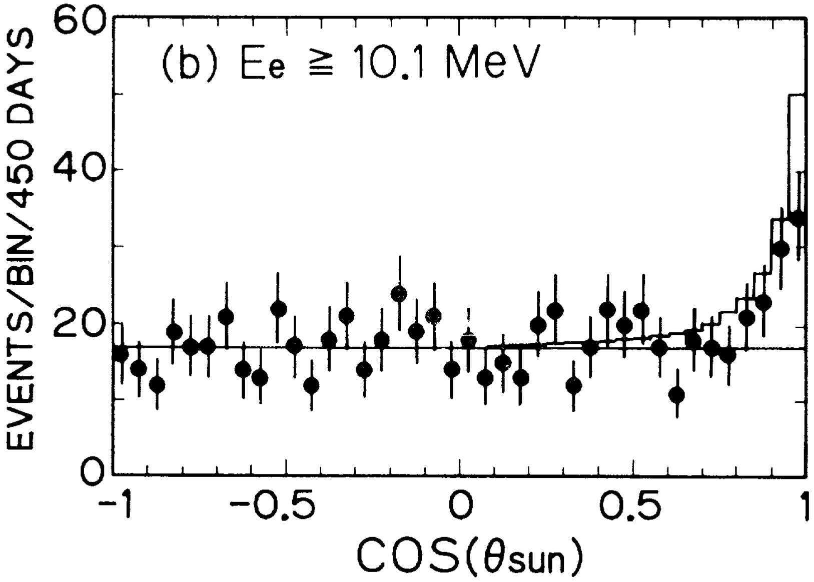
The pioneering Homestake experiment observed solar neutrinos for the first time (R. Davis Jr., D. S. Harmer and K. C. Hoffman PRL 20 (1968) 1205). However, the observed event rate was only about 1/3 of the prediction.

Subsequent solar neutrino experiments

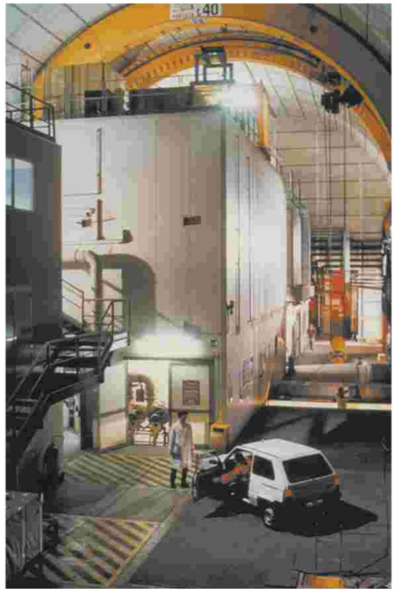
Kamiokande (water)

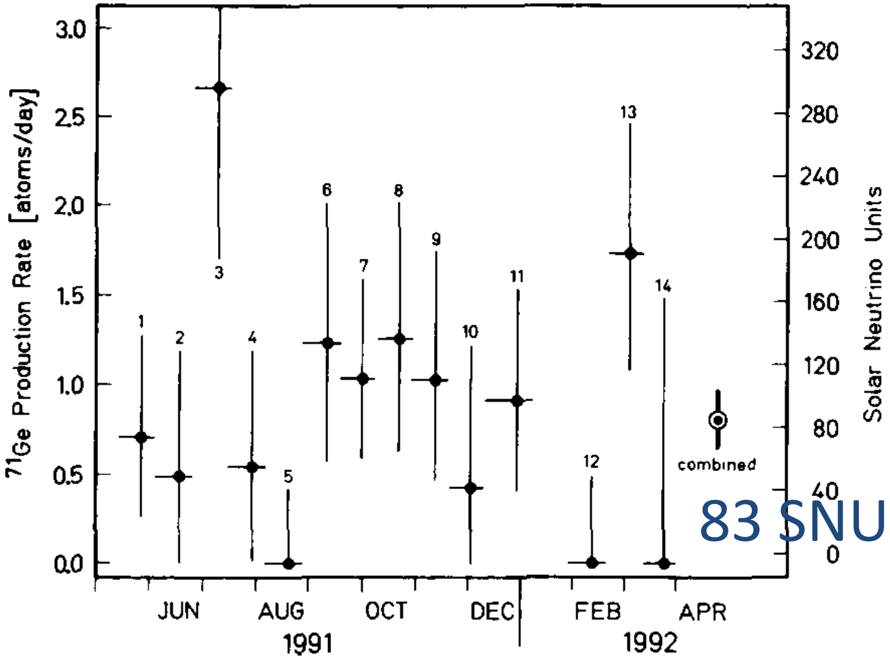


K. S. Hirata et al., PRL 61 (1989) 16.



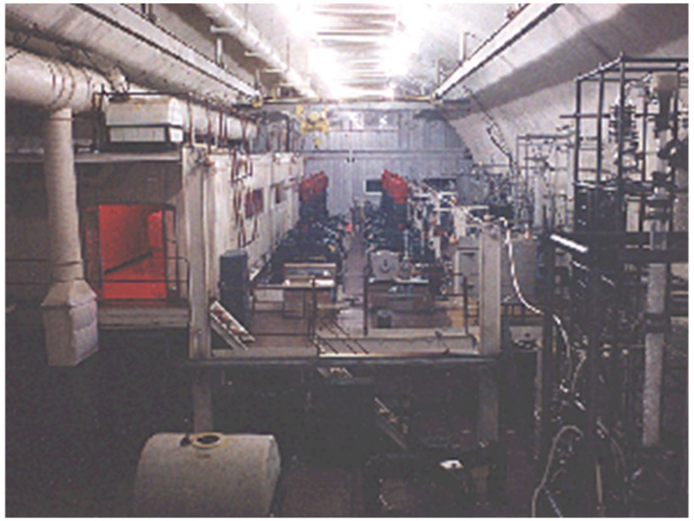
Gallex/GNO (Gallium)





83 SNU

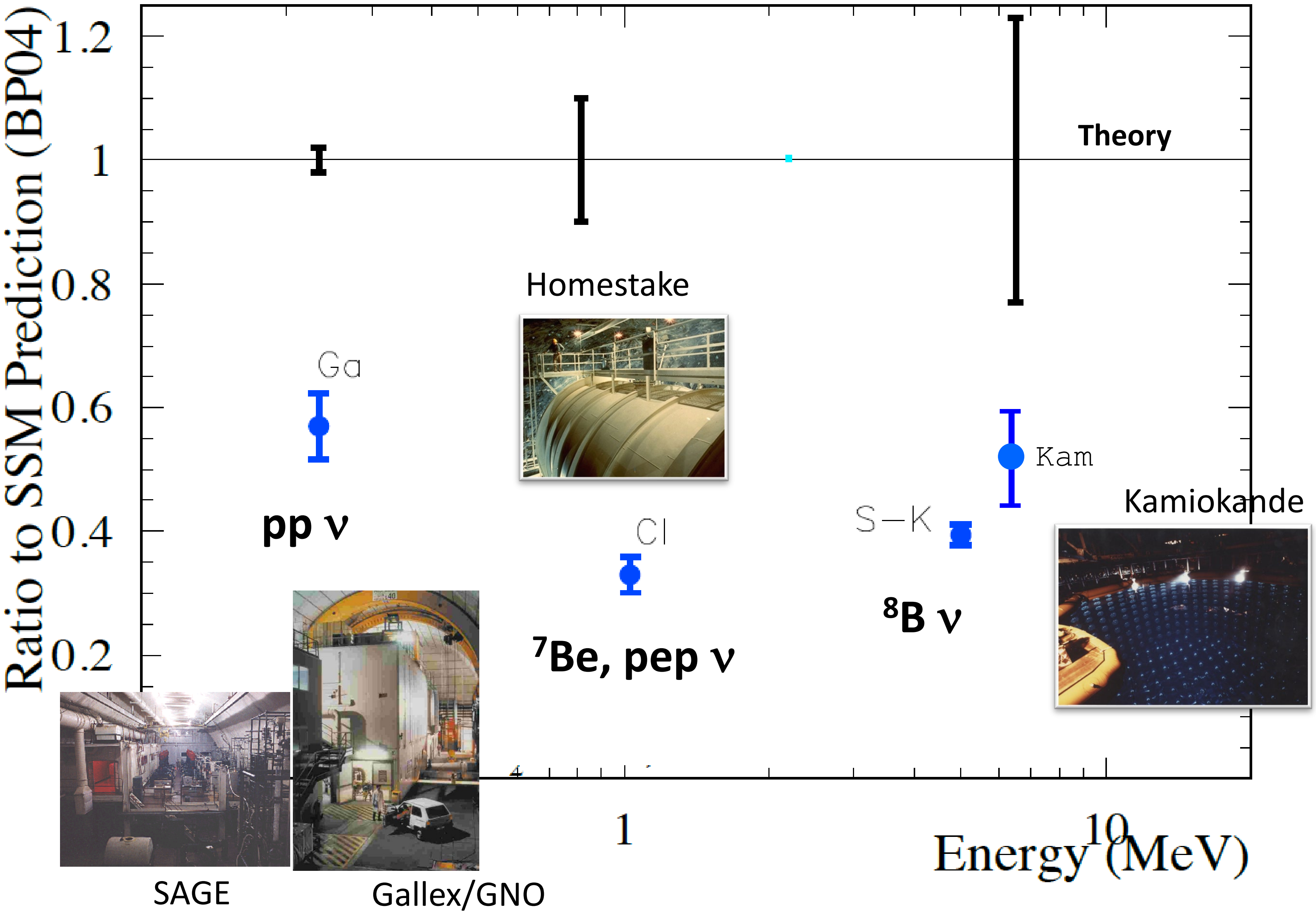
SAGE (Gallium)



A. I. Abazov et al., PRL 67 (1991) 3332.

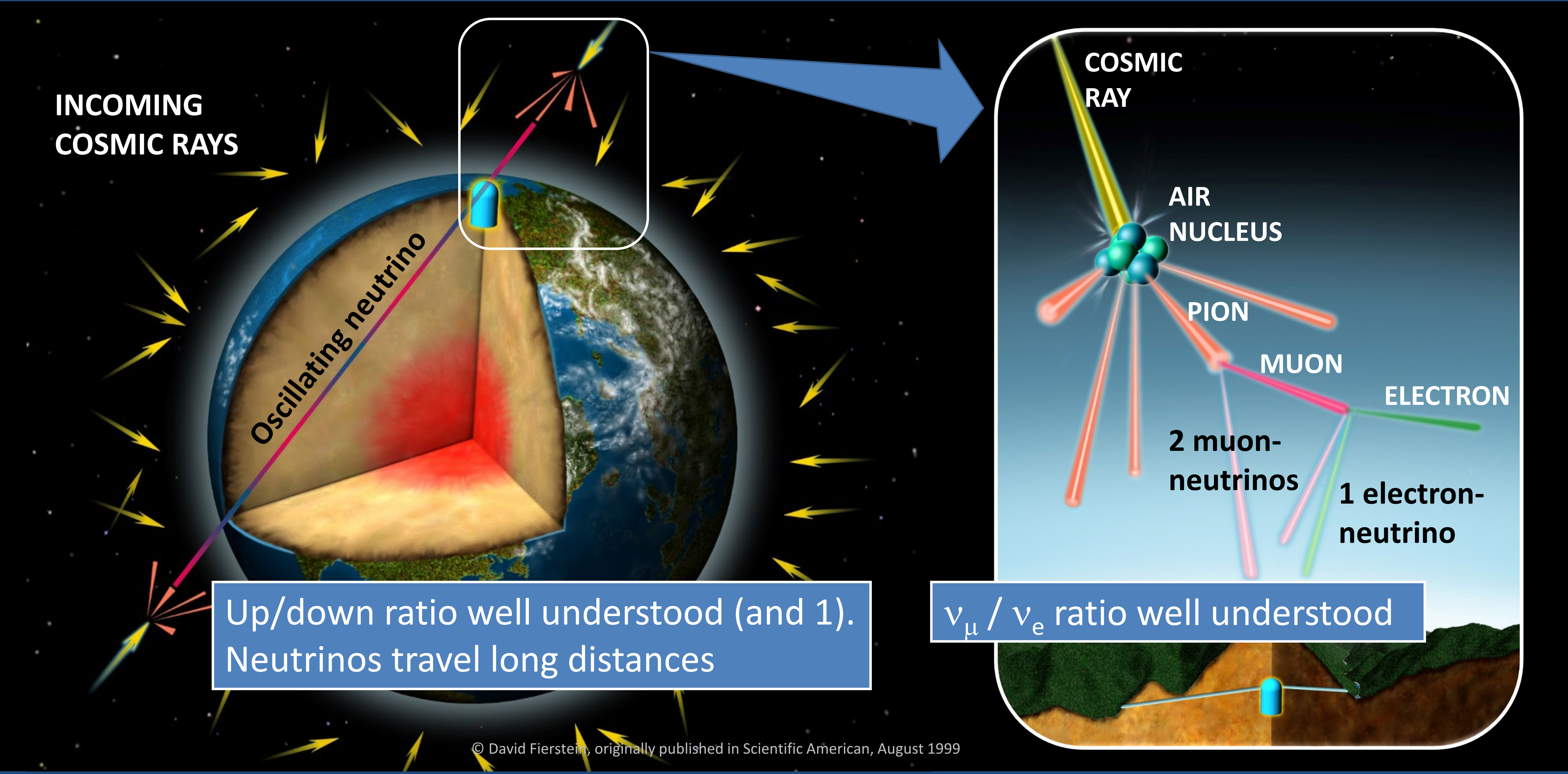
SAGE: "we observed the capture rate to be 20 +15/-20(stat) +/- 32(syst) solar neutrino units (SNU), resulting in a limit of less than 79 SNU (90% C.L.). This is to be compared with 132 SNU predicted by the standard solar model."

Solar neutrino problem



In the 20th century, several experiments observed solar neutrinos.
These solar neutrino experiments observed the deficit of solar neutrinos.

Atmospheric neutrinos

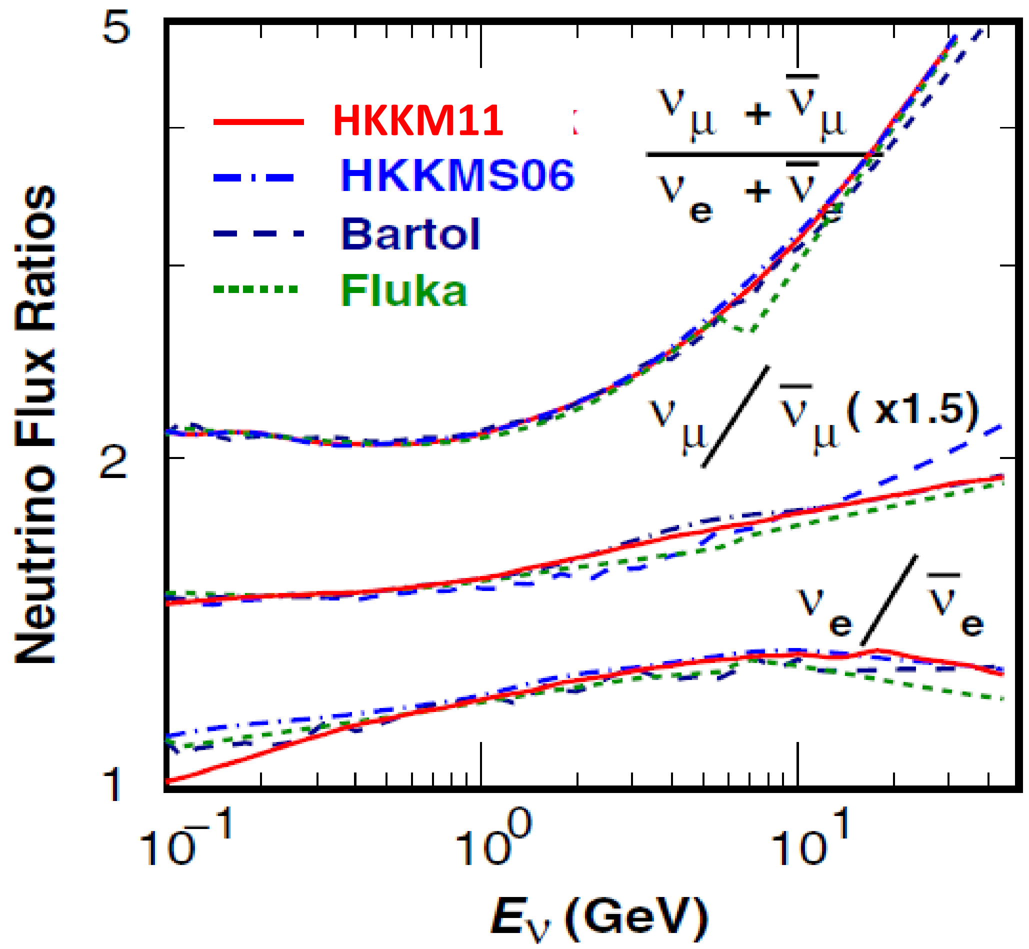


Up/down ratio well understood (and 1).
Neutrinos travel long distances

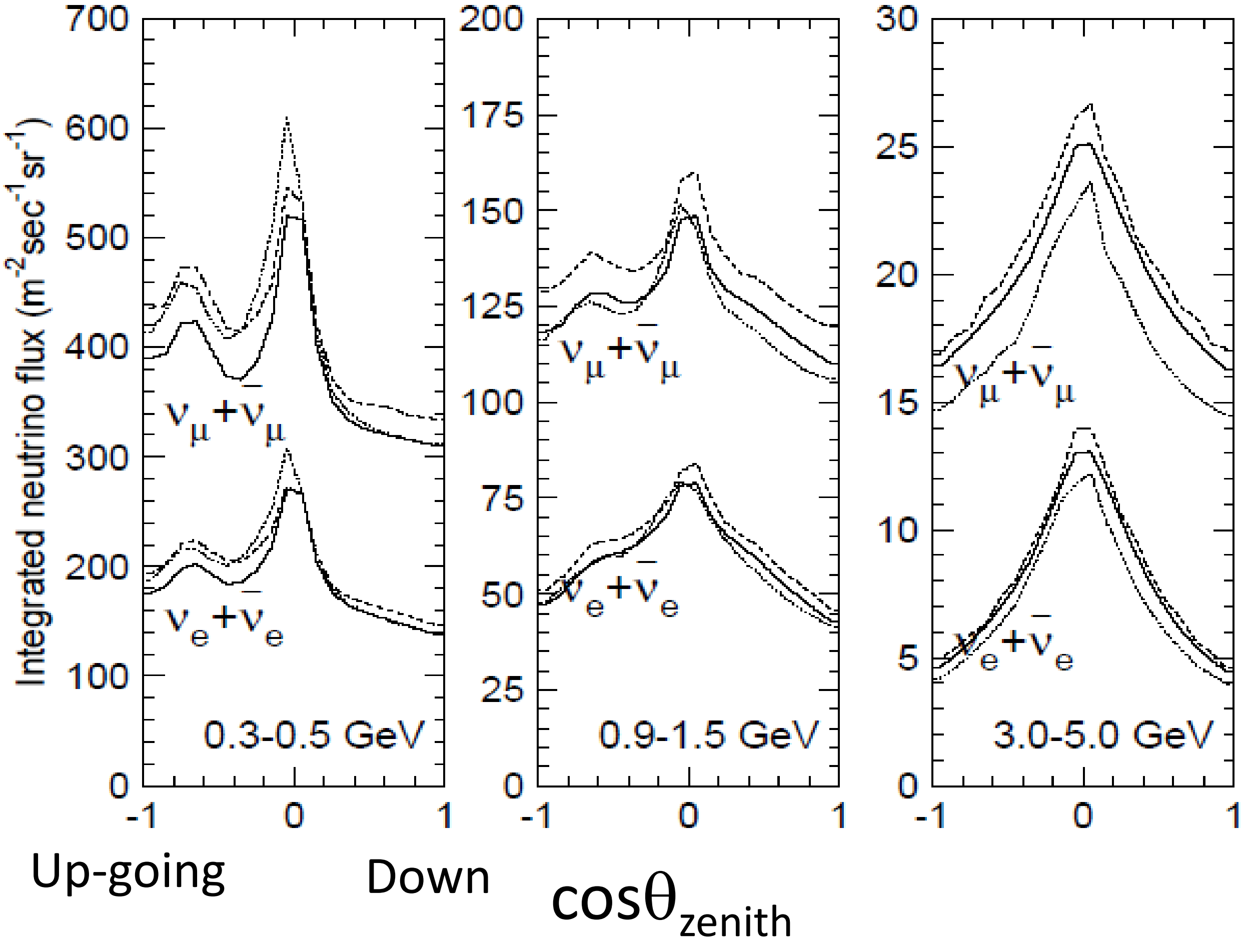
ν_μ / ν_e ratio well understood

Key features of the atmospheric neutrino beam

M. Honda et al., PRD 83, 123001 (2011)



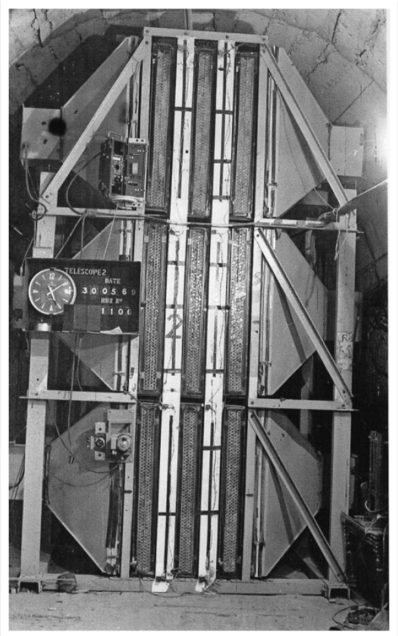
@Kamioka (Japan)



ν_μ/ν_e ratio is calculated to an accuracy of about 2% below ～5GeV.

Up/down flux ratio is very close to 1.0 and accurately calculated (1% or better) above a few GeV.

Observation of atmospheric neutrinos

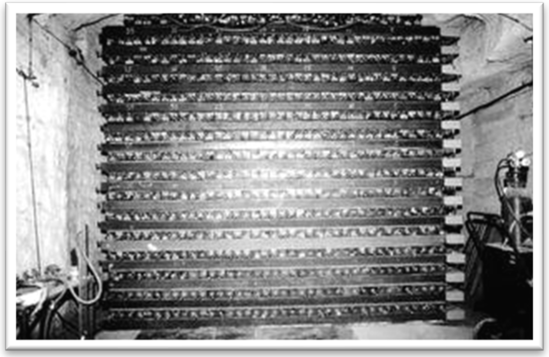


In 1965, atmospheric neutrinos were observed for the first time by detectors located extremely deep underground, one in India (left) and one in in South Africa (right).

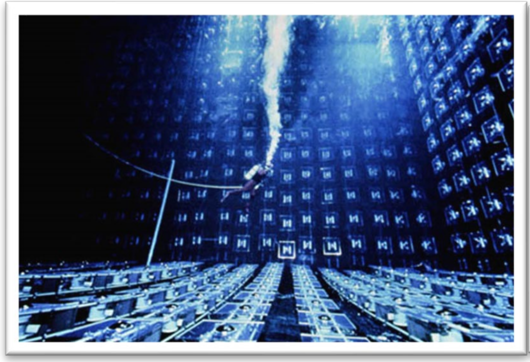
Photo by N. Mondal

Photo by H.Sobel

In the 1970's, Grand Unified Theories predicted the proton decays. ➔ Several proton decay experiments began in the early 1980's. Atmospheric neutrinos were the BG for the proton decay.

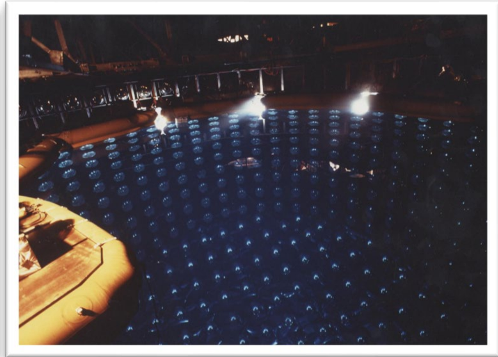


KGF

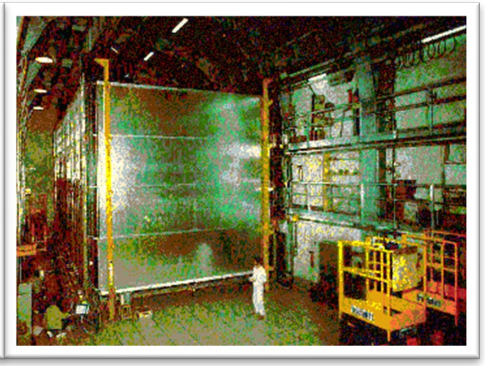


IMB

NUSEX



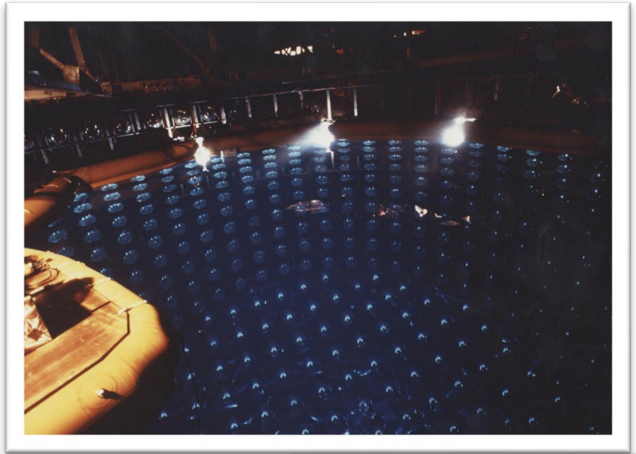
Kamiokande

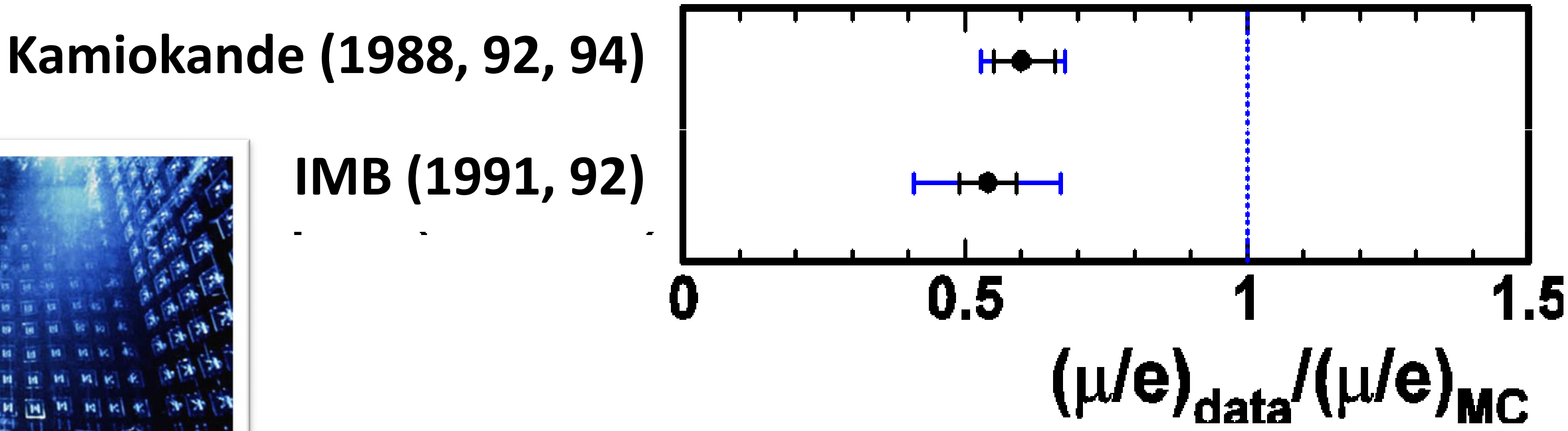


Frejus

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

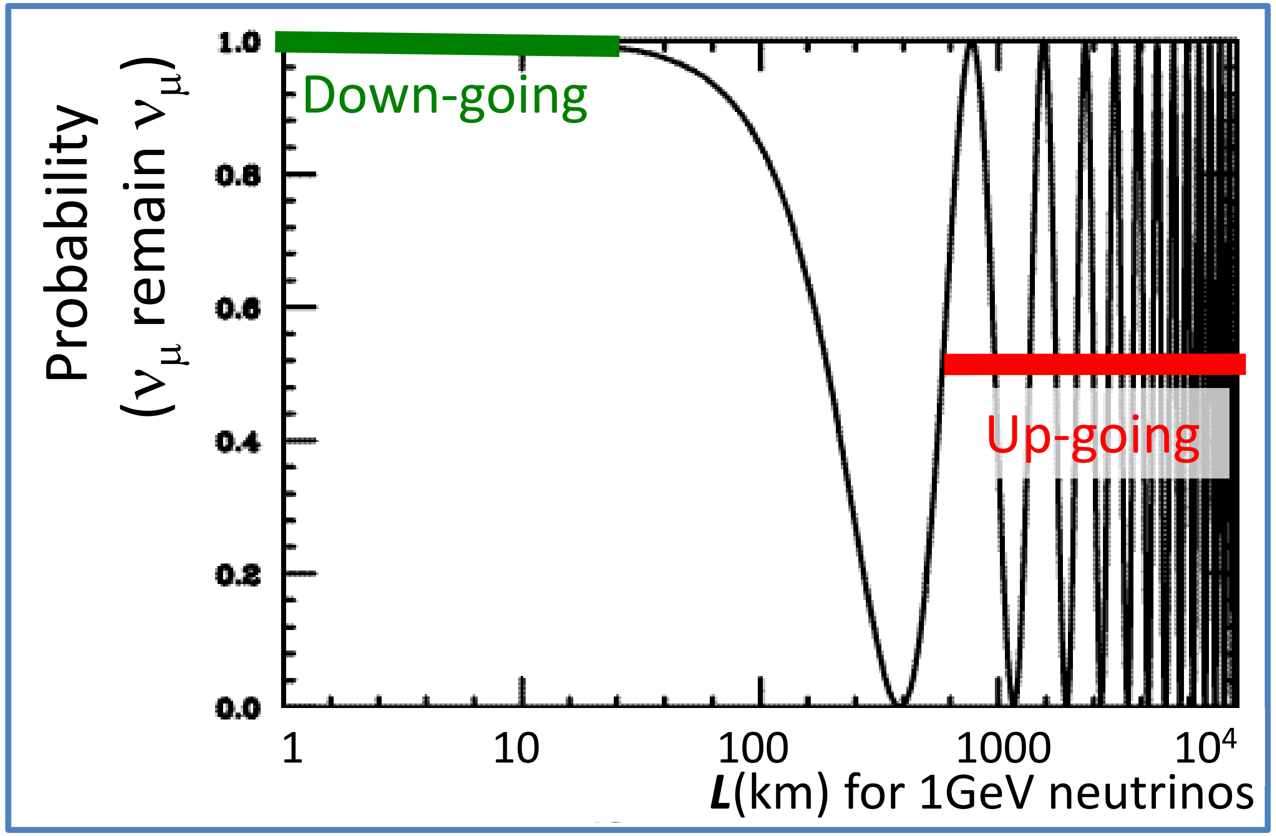
- ✓ Proton decay experiments in the 1980's observed many atmospheric neutrino events.
- ✓ Because atmospheric neutrinos are the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions.
- ✓ During these studies, a significant deficit of atmospheric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

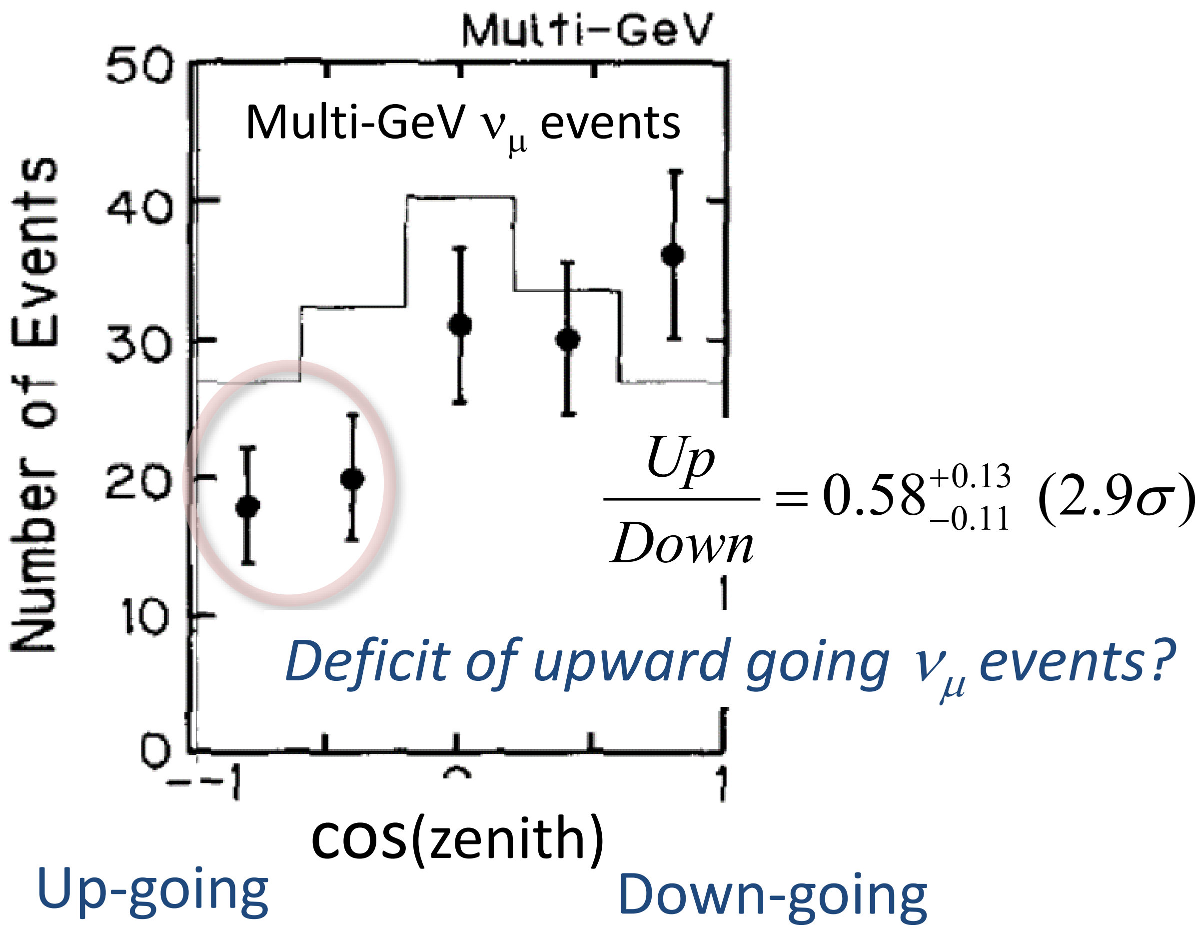




Zenith angle distribution from Kamiokande (1994)

Kamiokande Phys. Lett. B 335, 237 (1994)





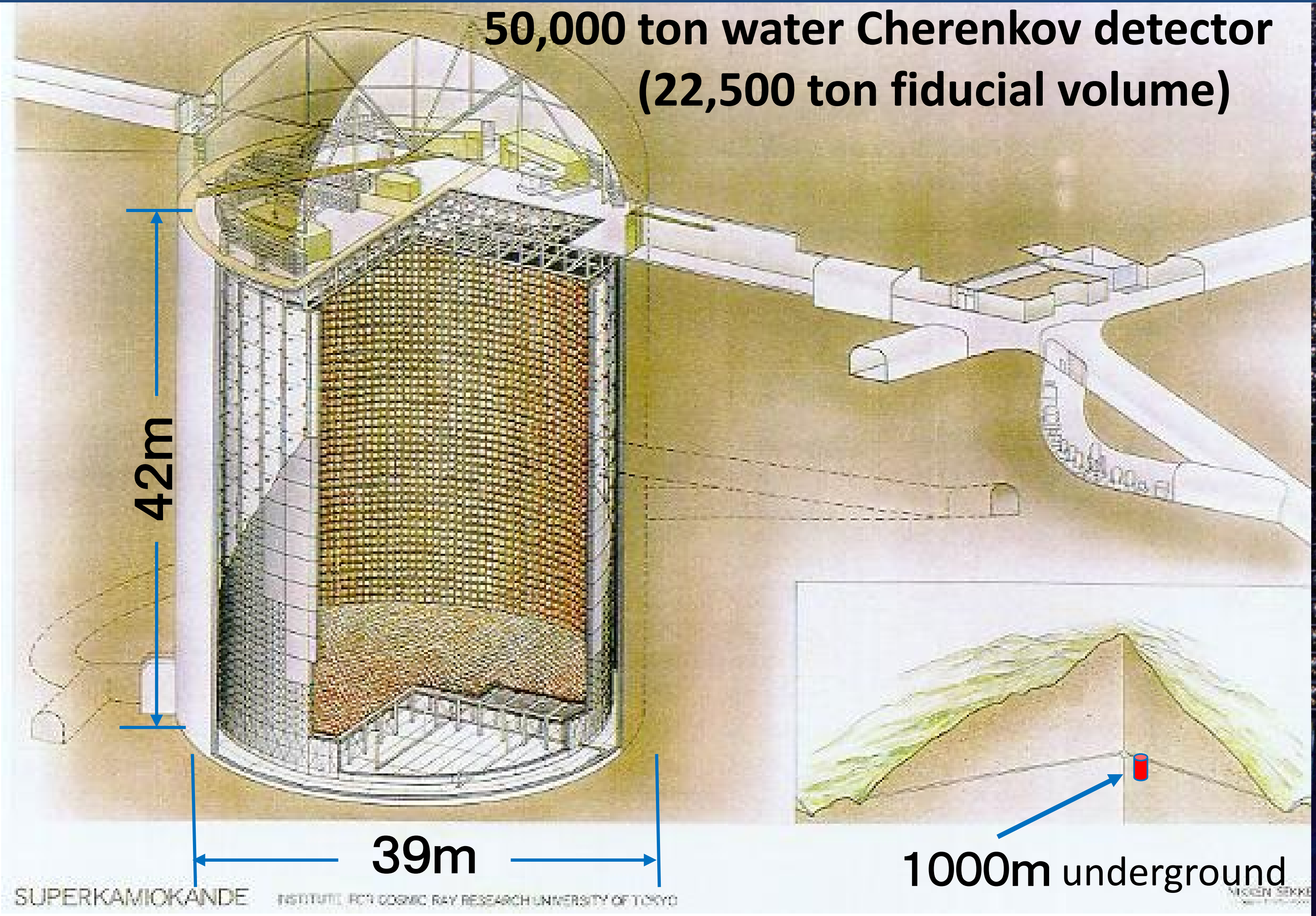
Deficit of upward going ν_μ events?

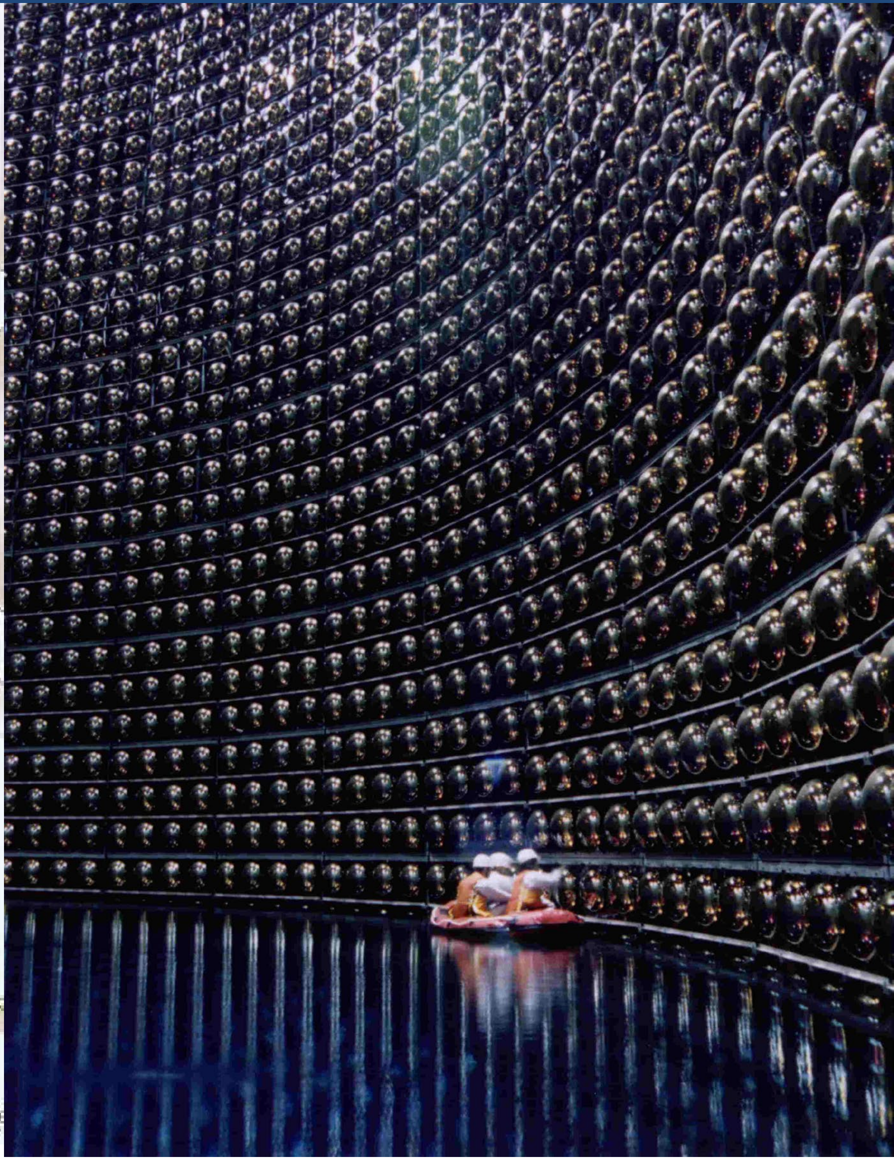
The data suggested something interesting. But the statistics of the data are not large enough. Much larger detector needed. ➔ Super-Kamiokande

Discovery of neutrino oscillations:

- Atmospheric neutrino oscillations

Super-Kamiokande



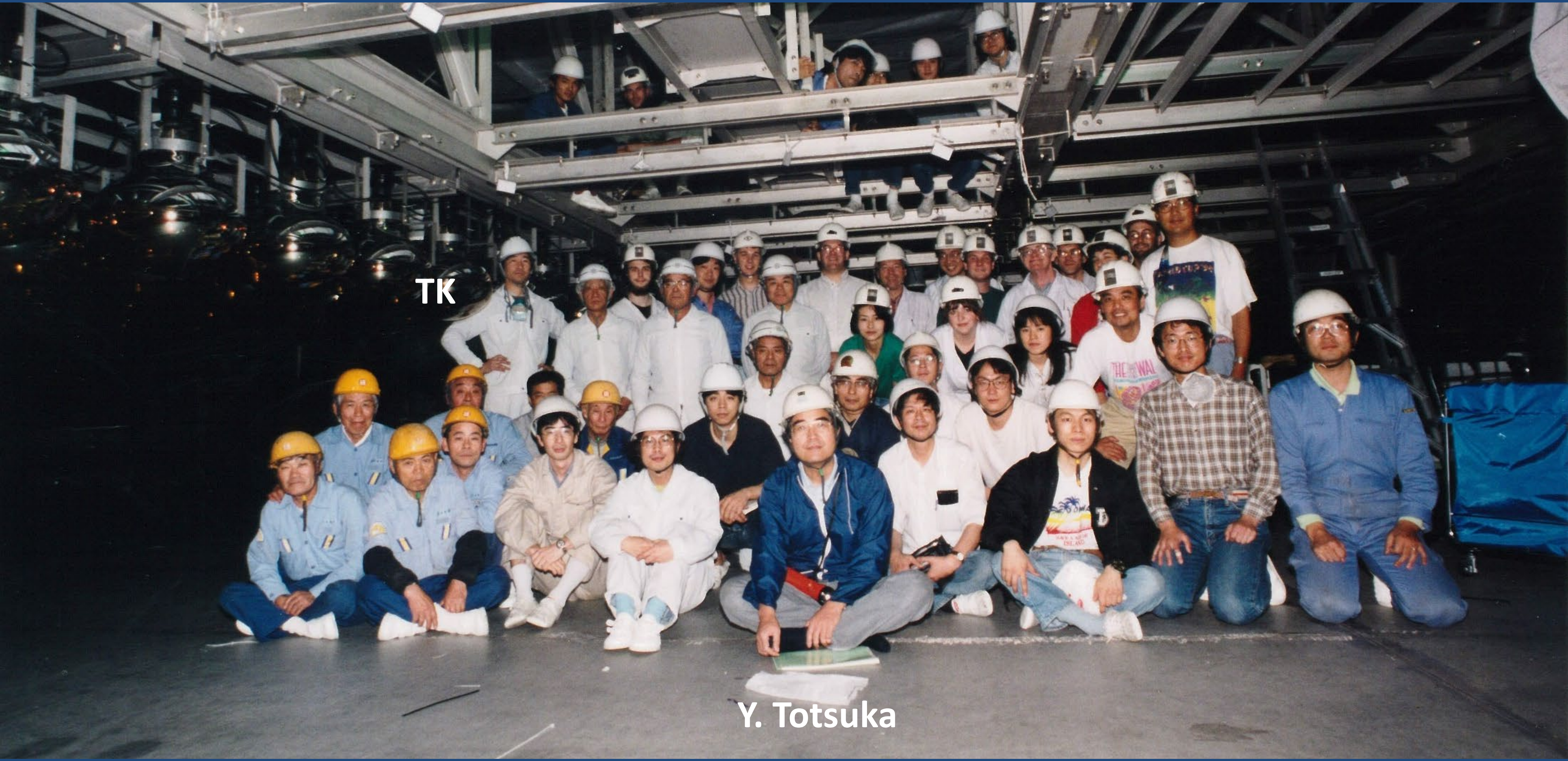


~230 collaborators

Beginning of the Super-Kamiokande collaboration between Japan and USA

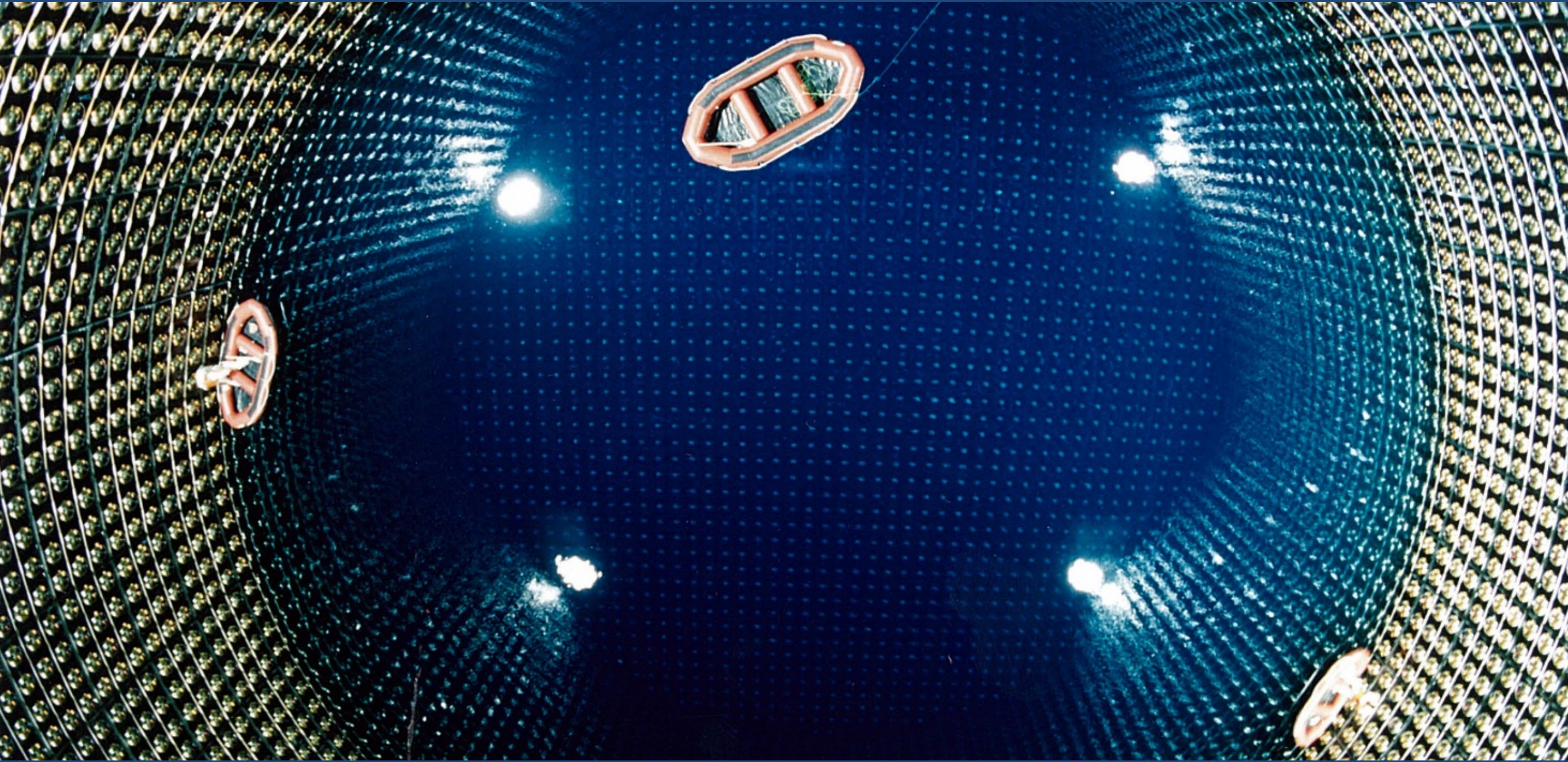
@ Institute for Cosmic Ray Research, 1992

Constructing the Super-Kamiokande detector (spring 1995)

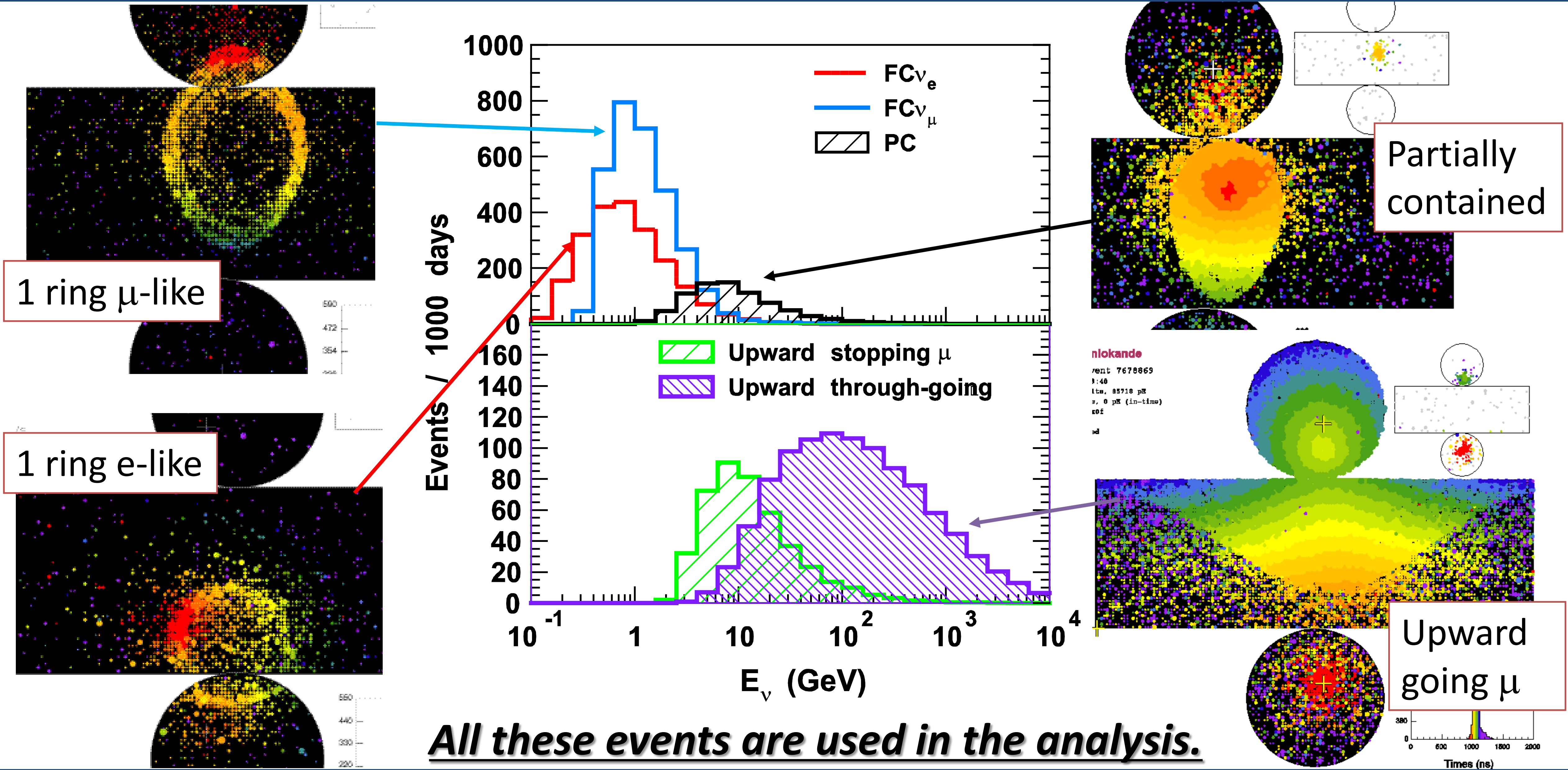


Filling water in Super-Kamiokande

Jan. 1996

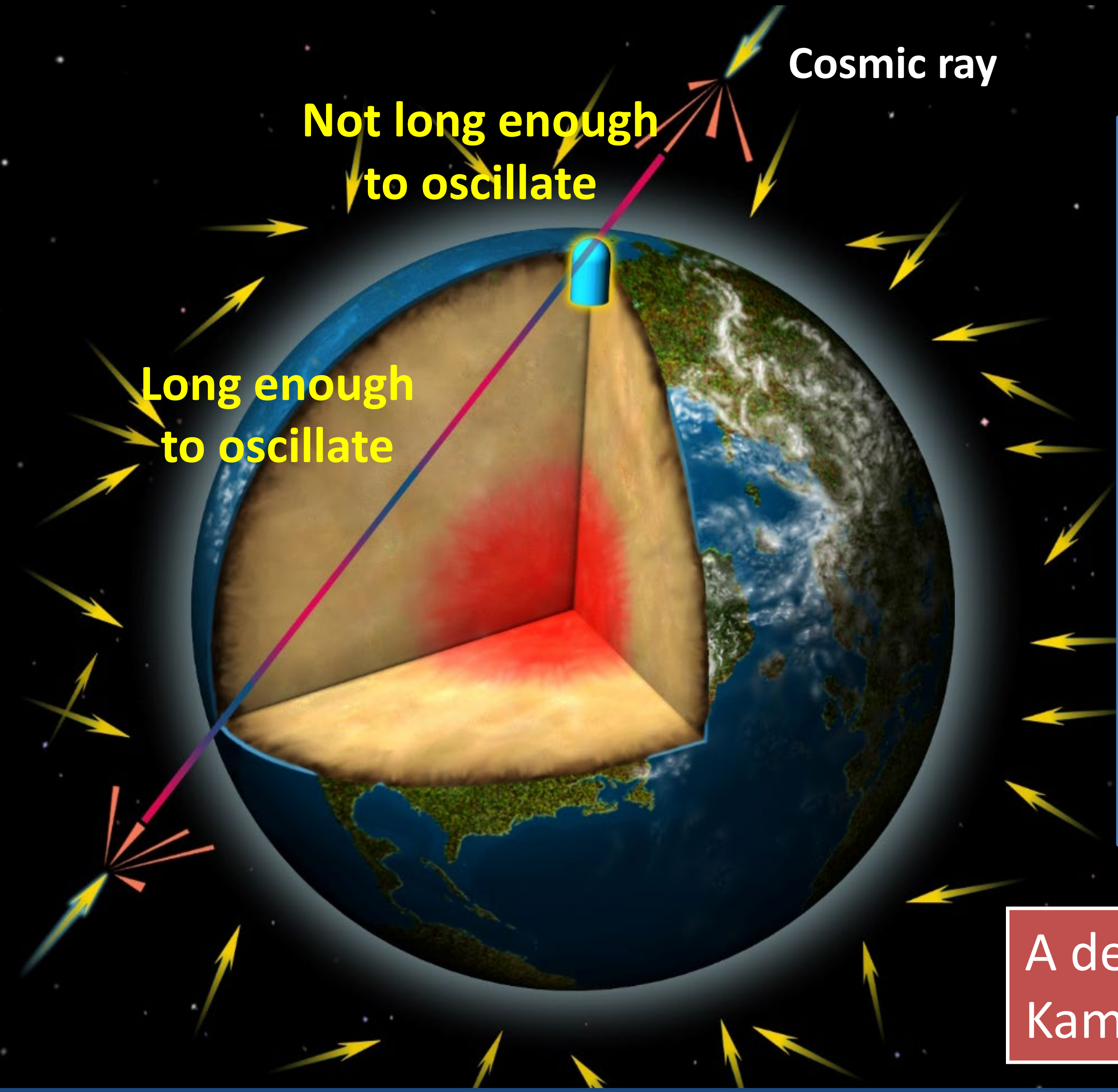


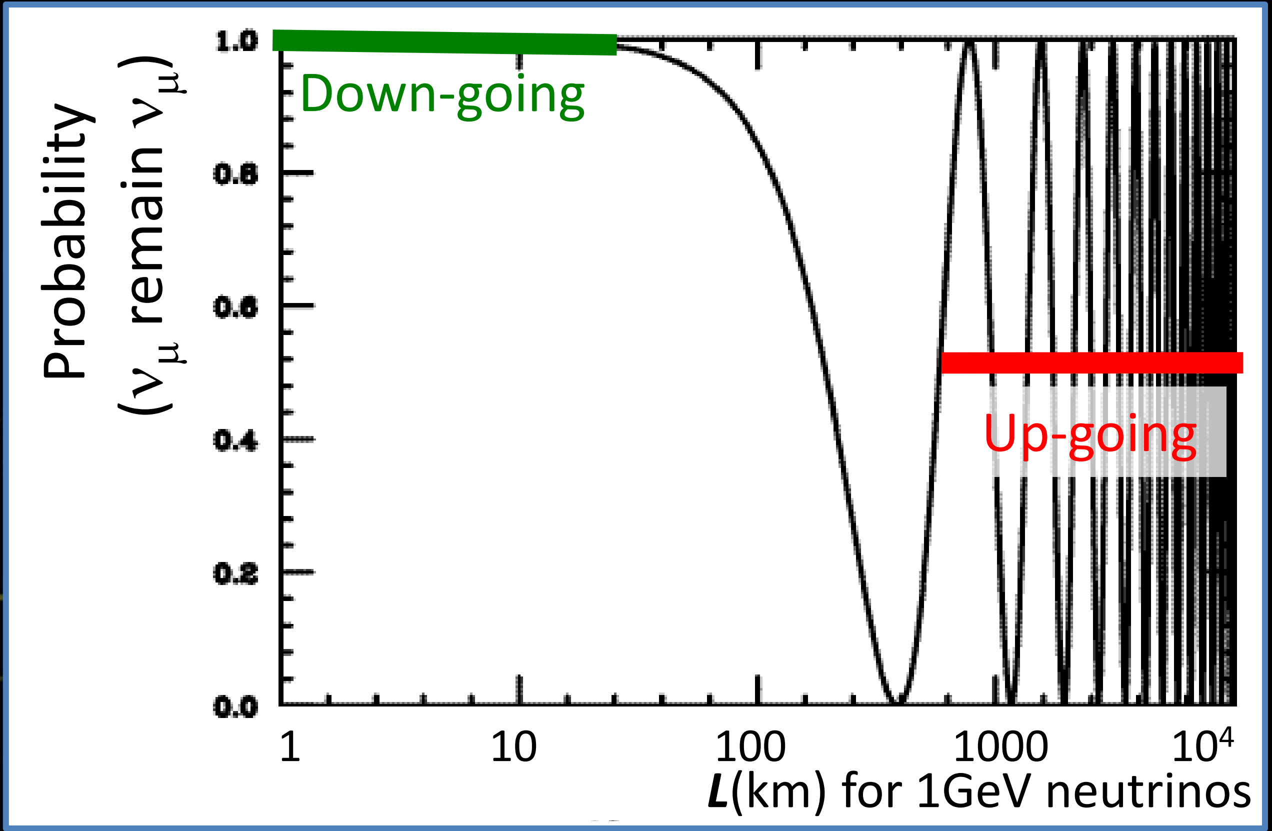
Event type and neutrino energy



All these events are used in the analysis.

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

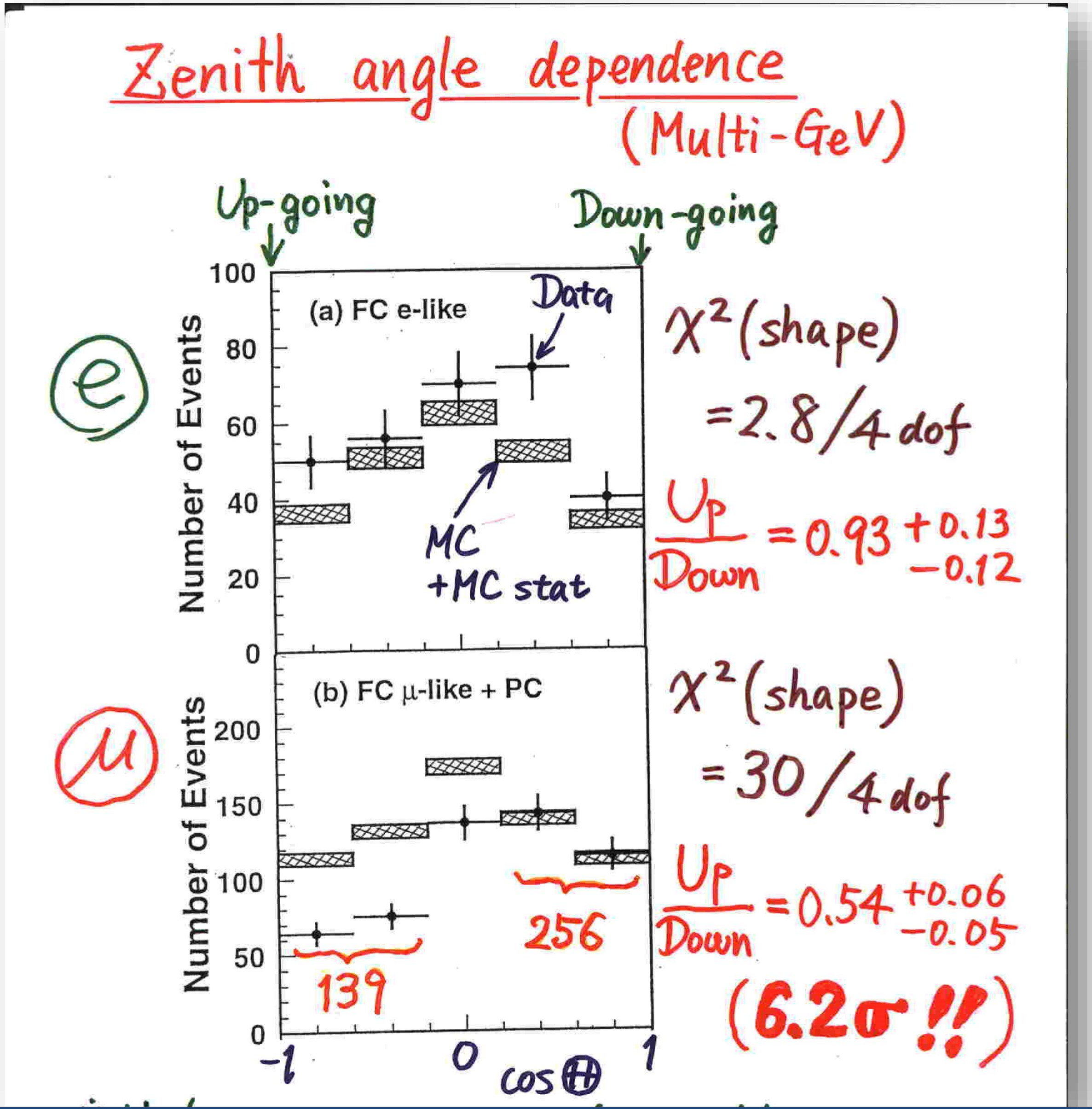


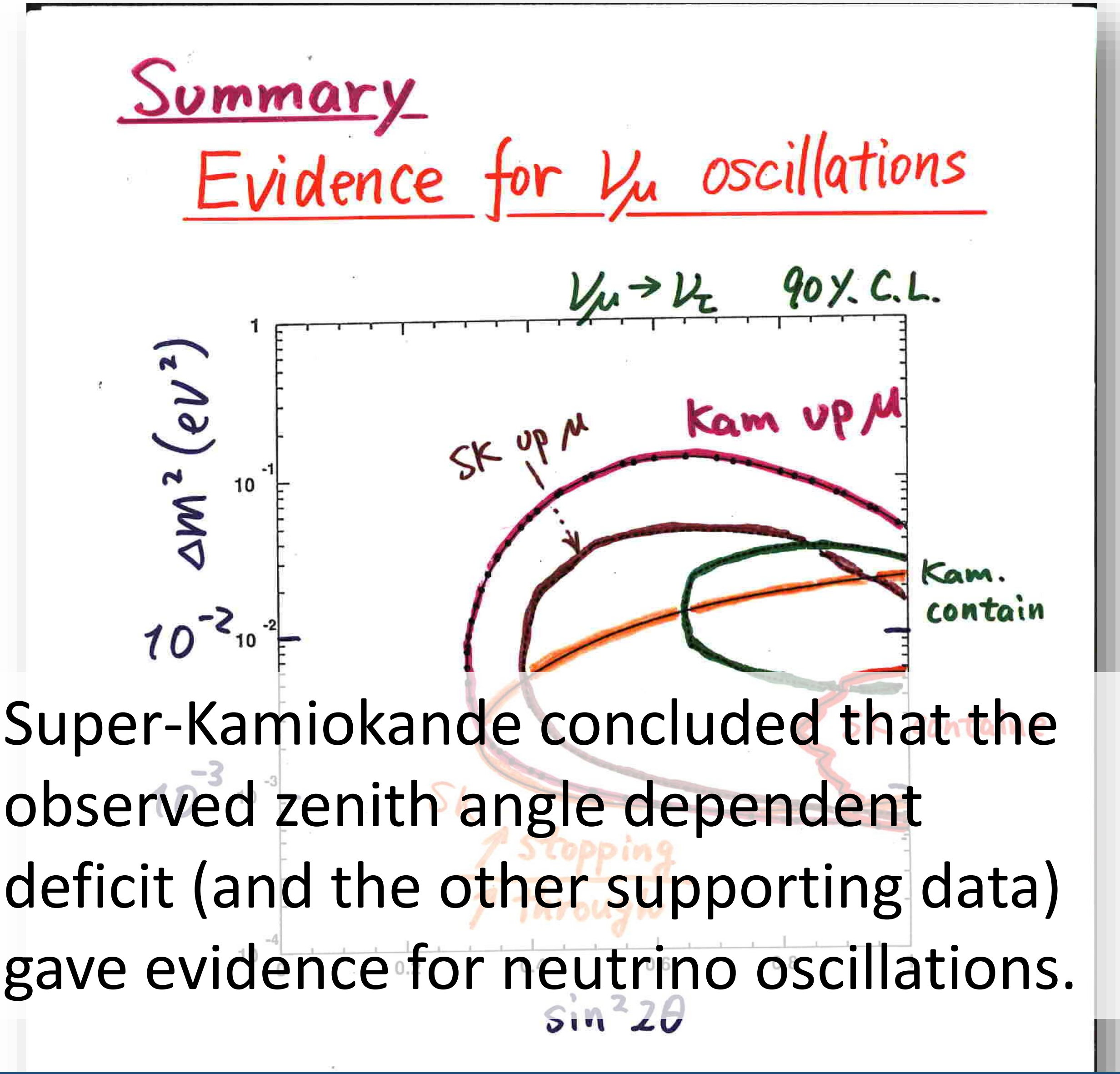


A deficit of upward going ν_μ's should be observed!
Kamiokande was too small. ➔ Super-Kamiokande

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

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

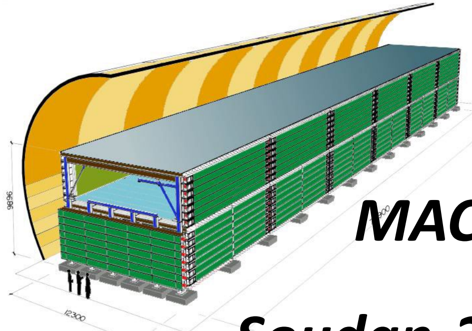




Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Neutrino oscillation studies

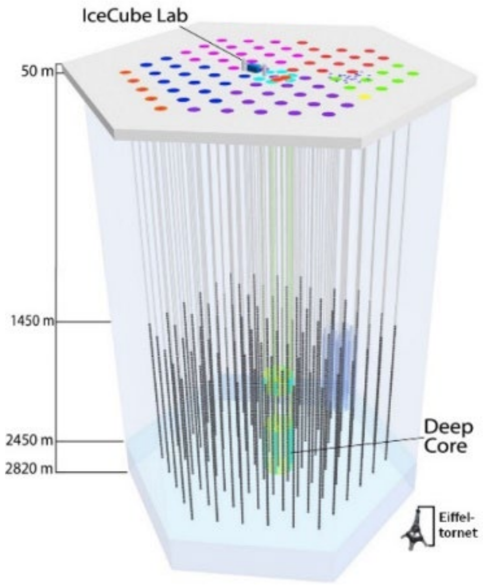
Various atmospheric neutrino and accelerator based long baseline neutrino oscillation experiment have been studying neutrino oscillations in detail.



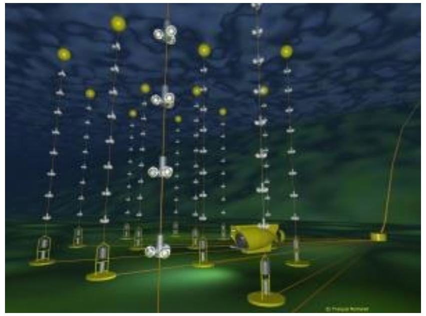
MACRO

Soudan-2

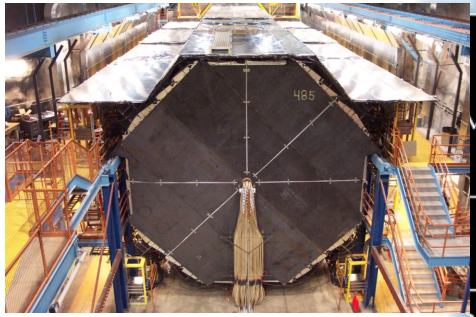
K2K



IceCube



ANTARES



MINOS

OPERA

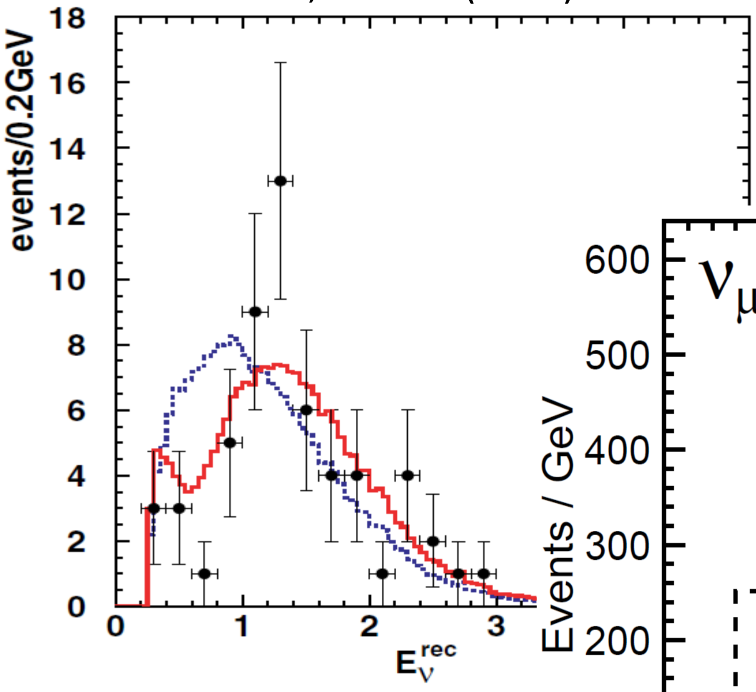
T2K

NOvA

ν_μ disappearance studies (accelerator experiments)

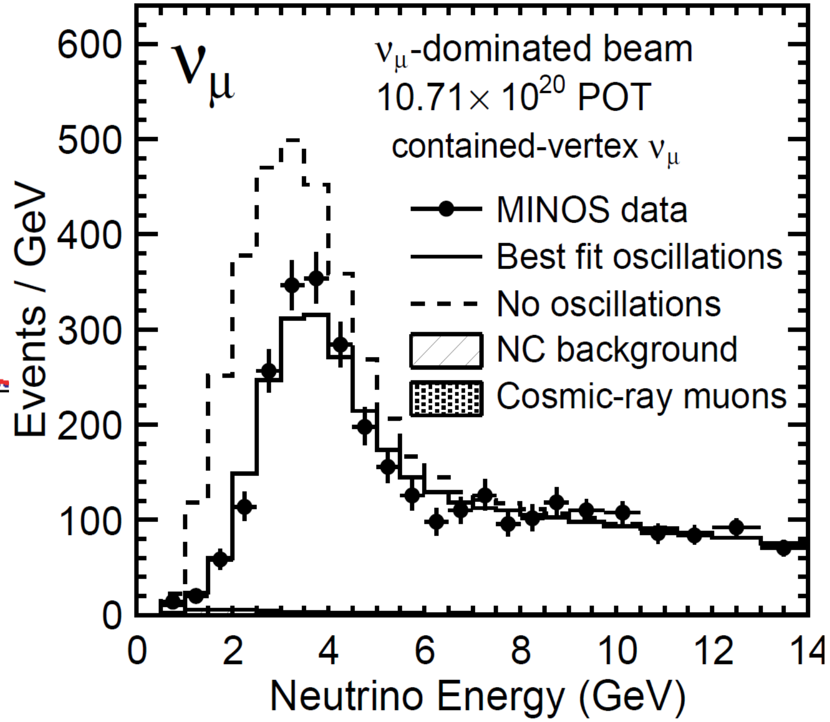
K2K

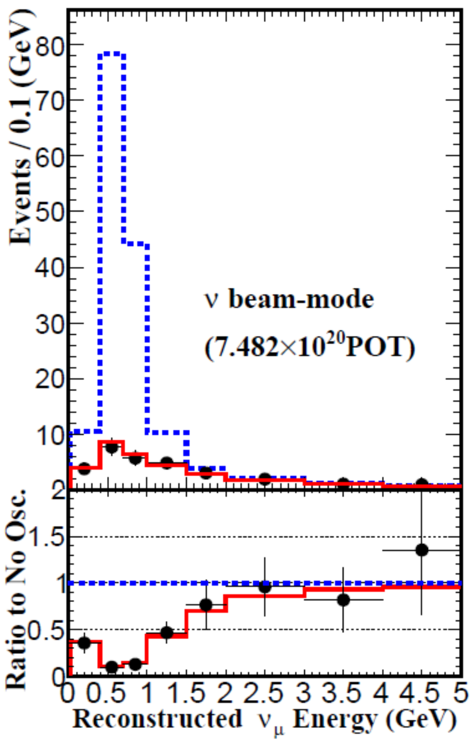
K2K, PRD 74 (2006) 072003



MINOS

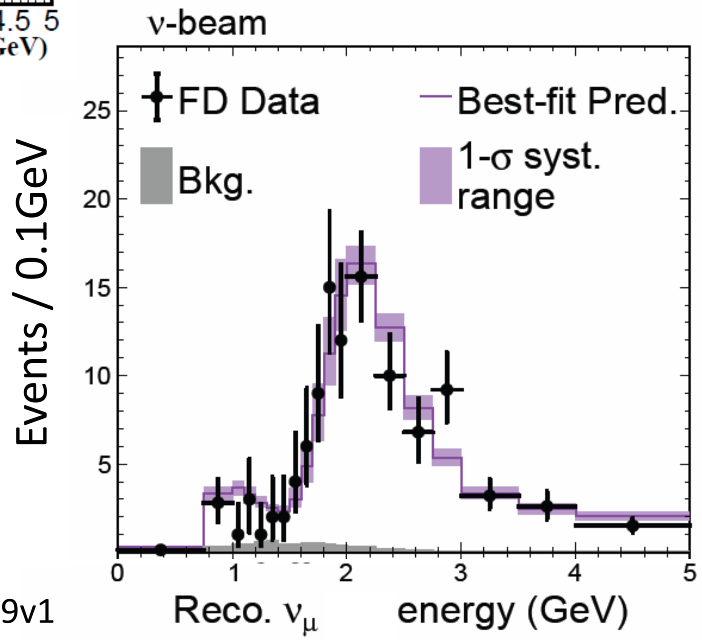
MINOS PRL 110 (2013) 251801





T2K

T2K, Phys.Rev.D 96 (2017) 1, 011102



NOvA

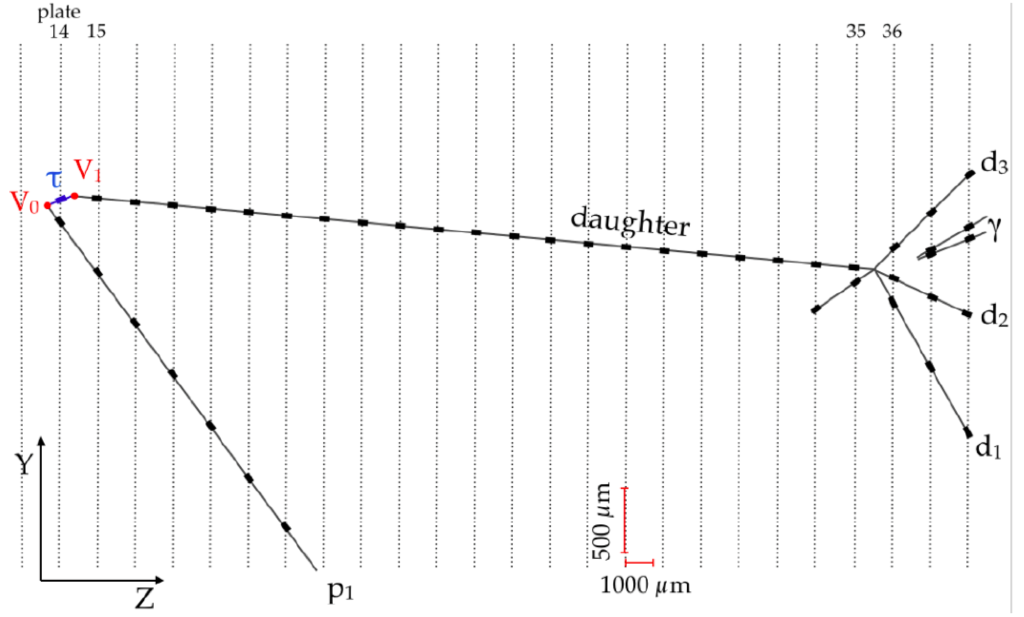
NOvA, arXiv:2108.08219v1

ν_τ appearance

OPERA

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

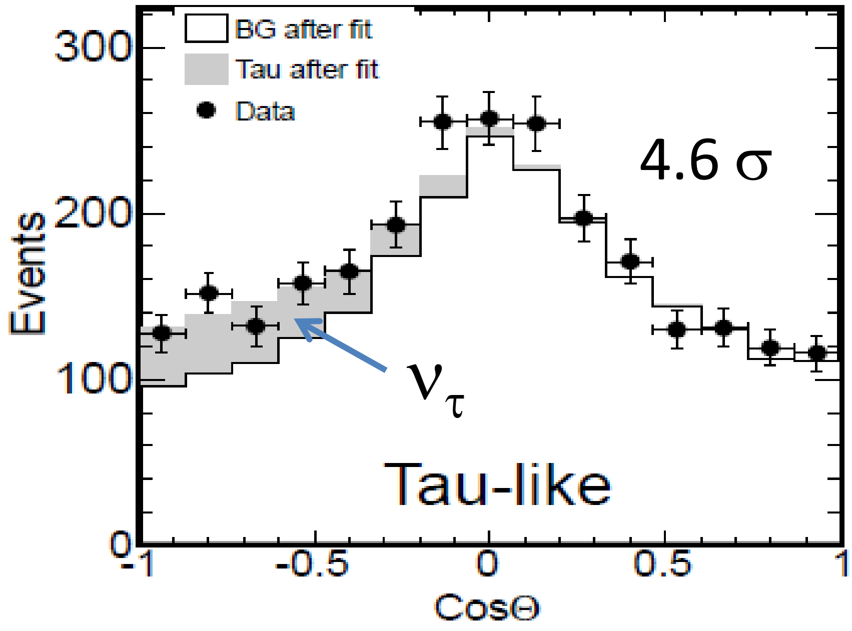
OPERA PRL 115 (2015) 121602



The fifth candidate event

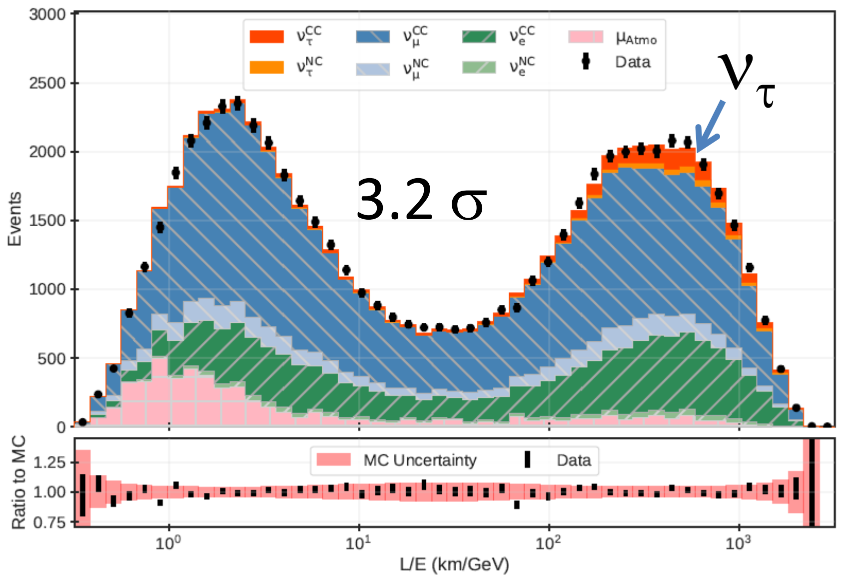
Super-Kamiokande

Super-K,
PRD 98 (2018) 5, 052006



IceCube

IceCube,
PRD 99 (2019) 3, 032007

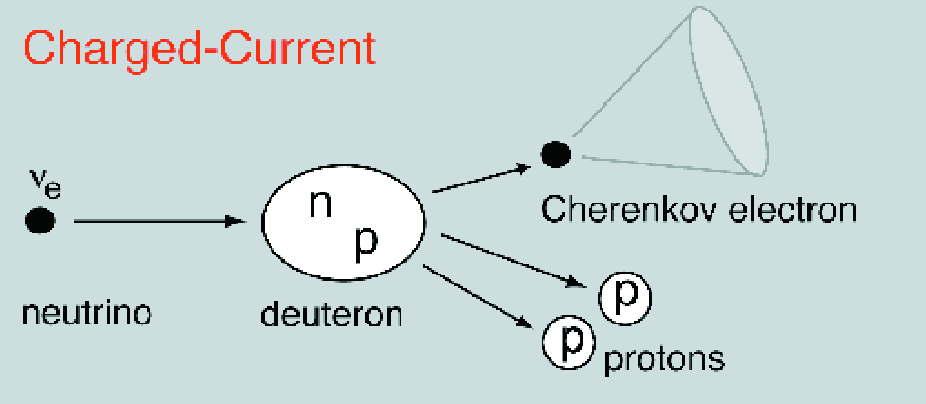


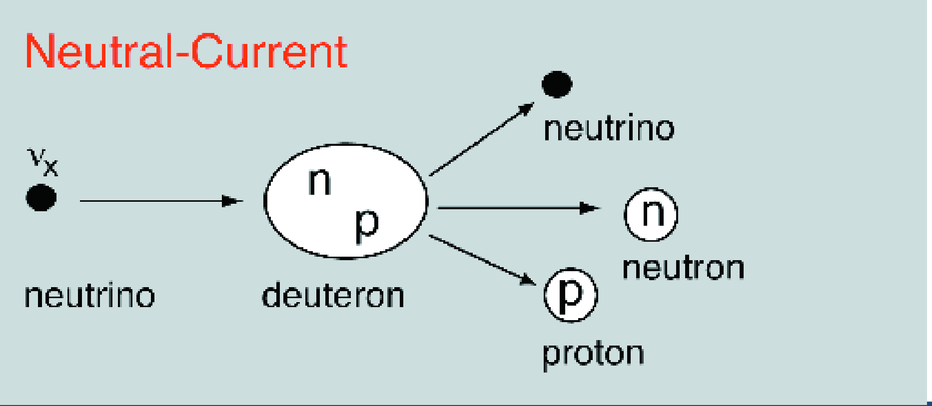
Discovery of neutrino oscillations:
- Solar neutrino oscillations

Unique signatures of heavy water (D_2O) experiments

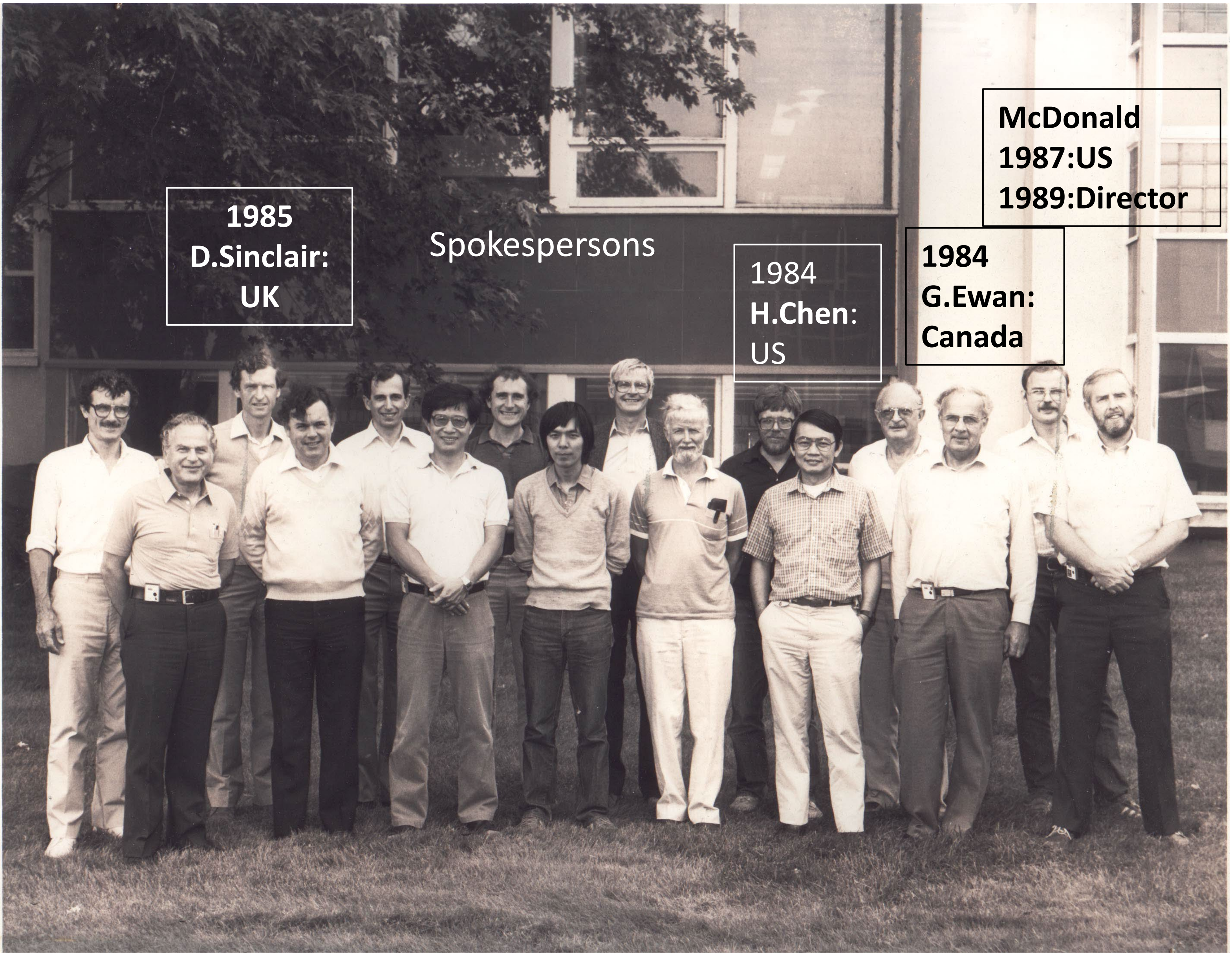
Herbert Chen, PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.





SNO Collaboration Meeting, Chalk River, 1986

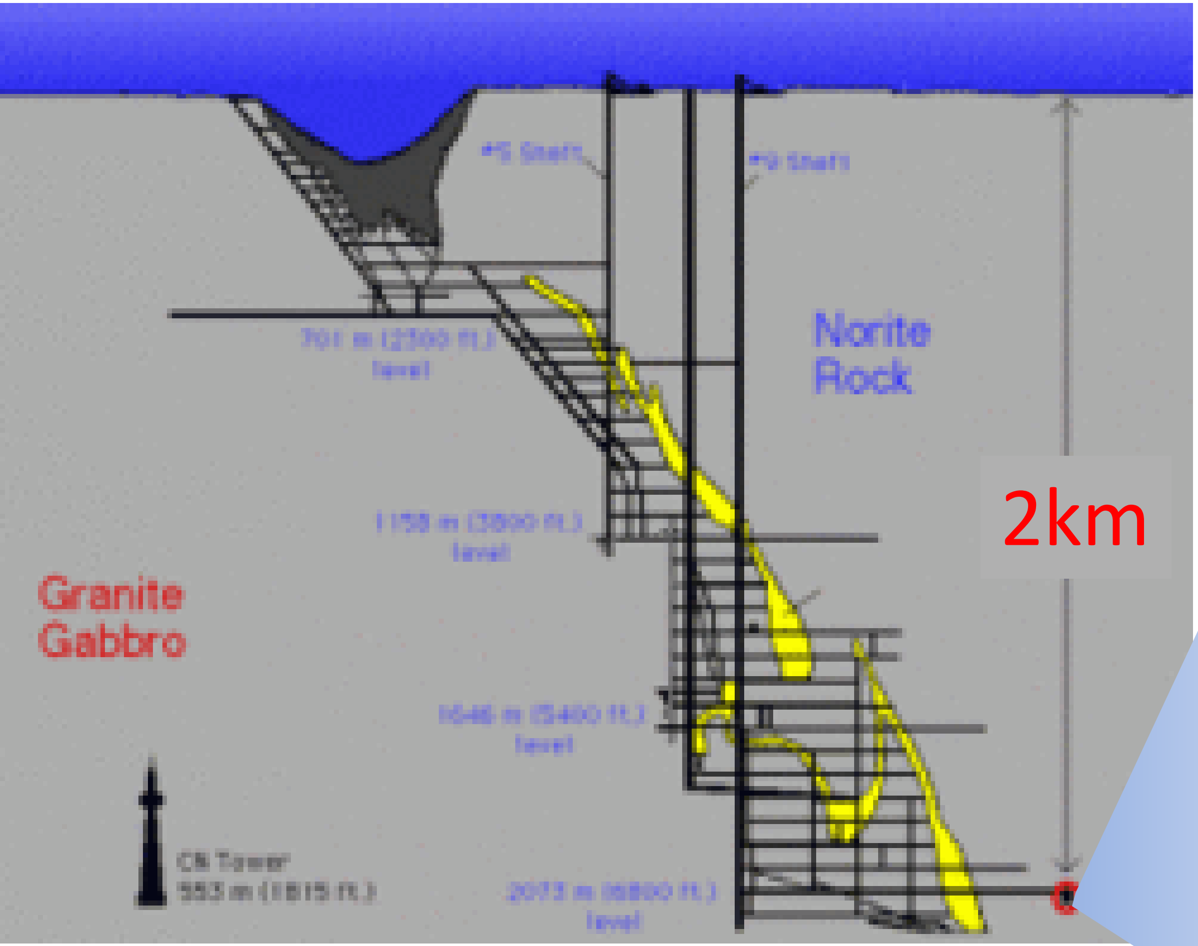


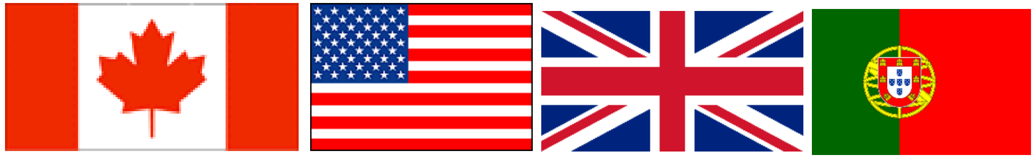
Art McDonald, talk at Neutrino 2016

PROPOSAL TO BUILD A NEUTRINO OBSERVATORY IN SUDBURY, CANADA

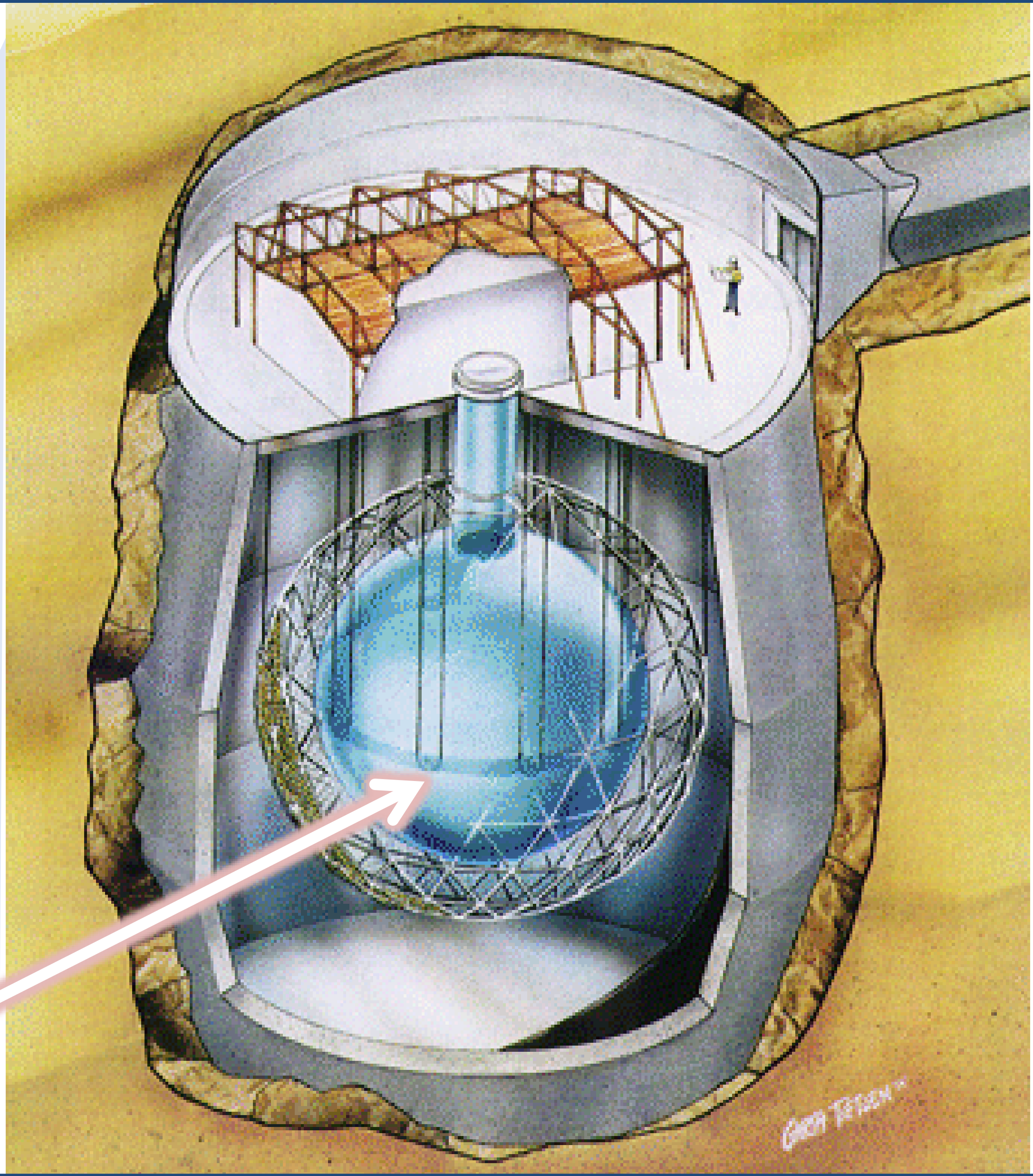
D. Sinclair, A.L. Carter, D. Kessler, E.D. Earle, P. Jagam, J.J. Simpson, R.C. Allen, H.H. Chen, P.J. Doe, E.D. Hallman, W.F. Davidson, A.B. McDonald, R.S. Storey, G.T. Ewan, H.-B. Mak, B.C. Robertson Il Nuovo Cimento C9, 308 (1986)

SNO detector





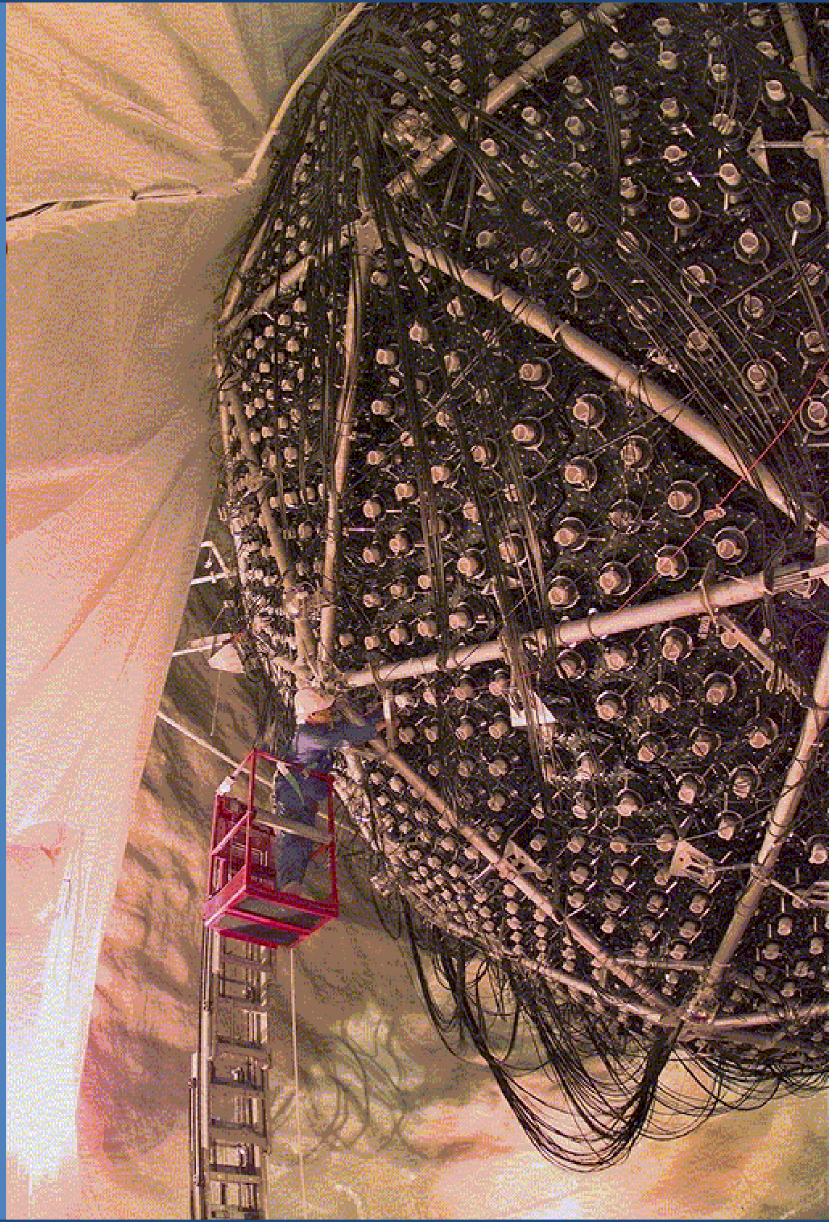
1000 ton of
heavy water



Constructing the SNO detector

One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions.

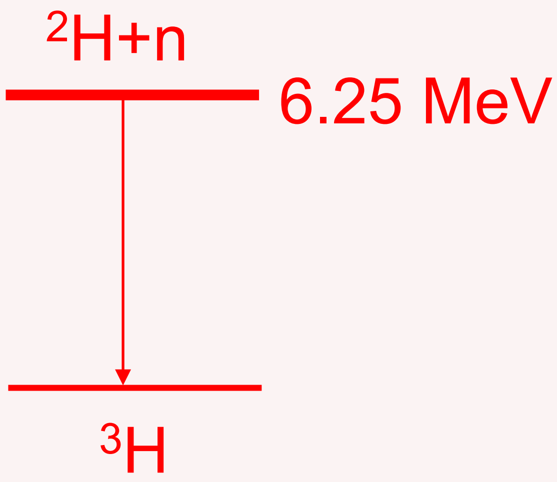
Filled with pure and heavy water in April 1999.



3 neutron detection methods (for $\nu\, d \rightarrow \nu\, p\, n$ measurement)

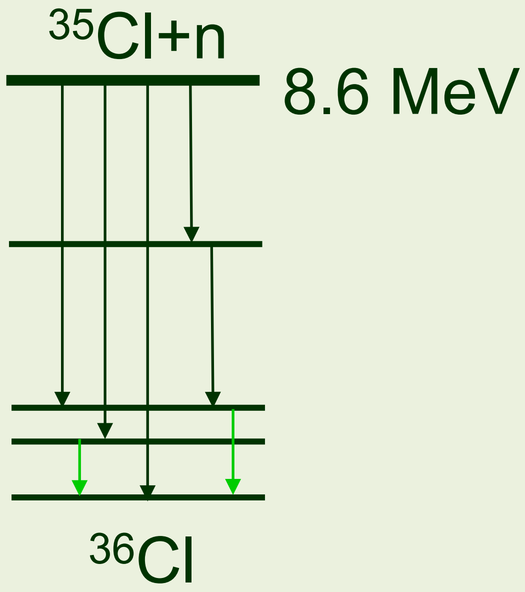
Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^{2}H(n, \gamma)^{3}H$
Eff. ~14.4%



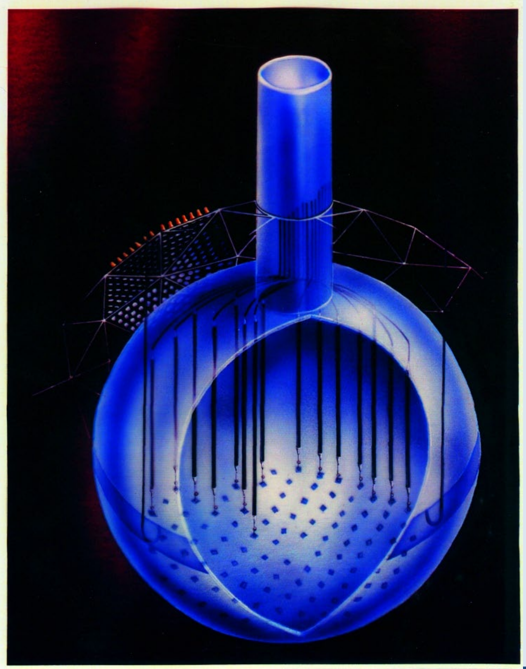
Phase II (salt)
July 01 - Sep. 03

2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Eff. ~40%

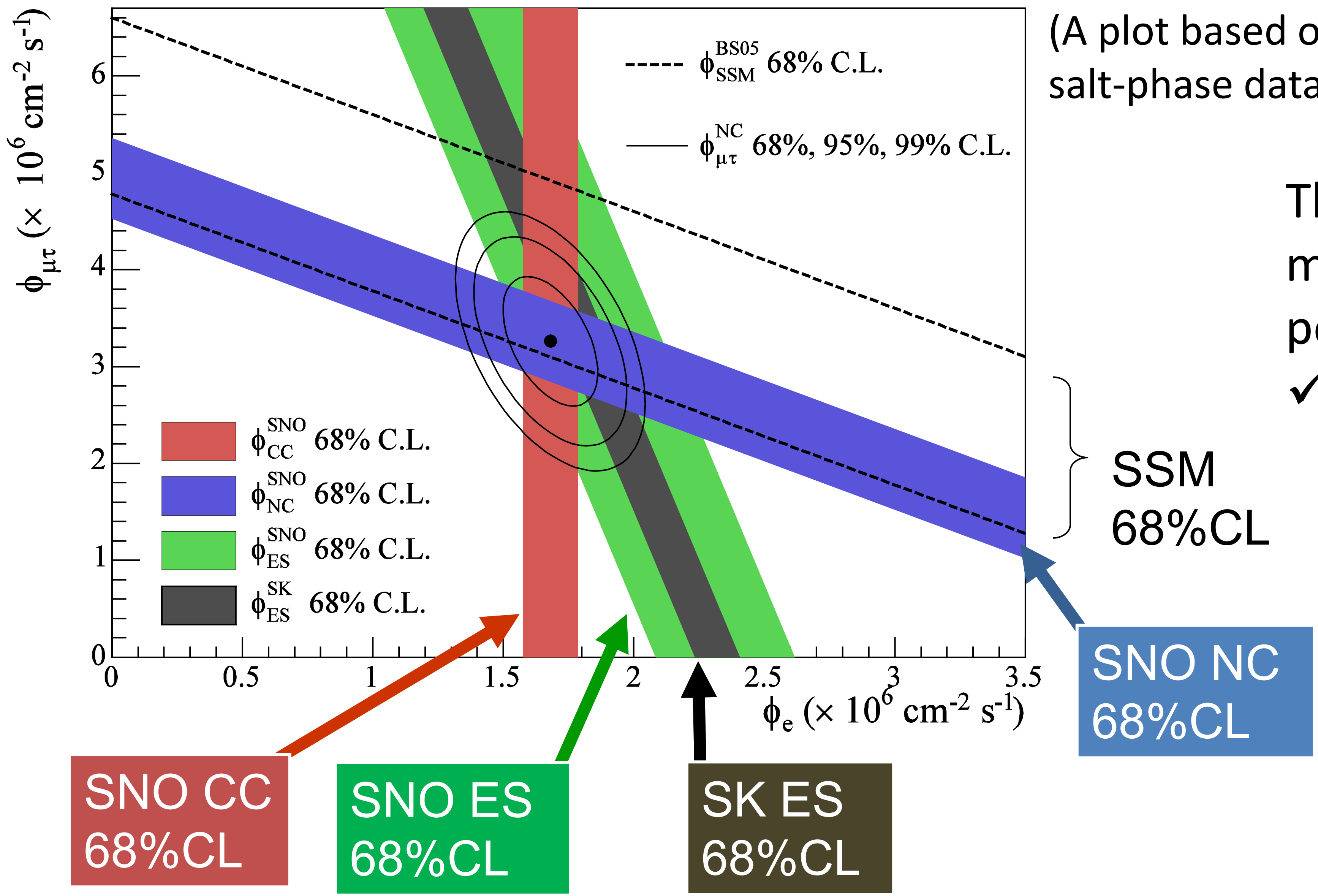


Phase III (^{3}He)
Nov. 04-Dec. 06

400 m of proportional counters
$^{3}He(n, p)^{3}H$
Effc. ~ 30% capture



Evidence for solar neutrino oscillations



(A plot based on the salt-phase data)

SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)

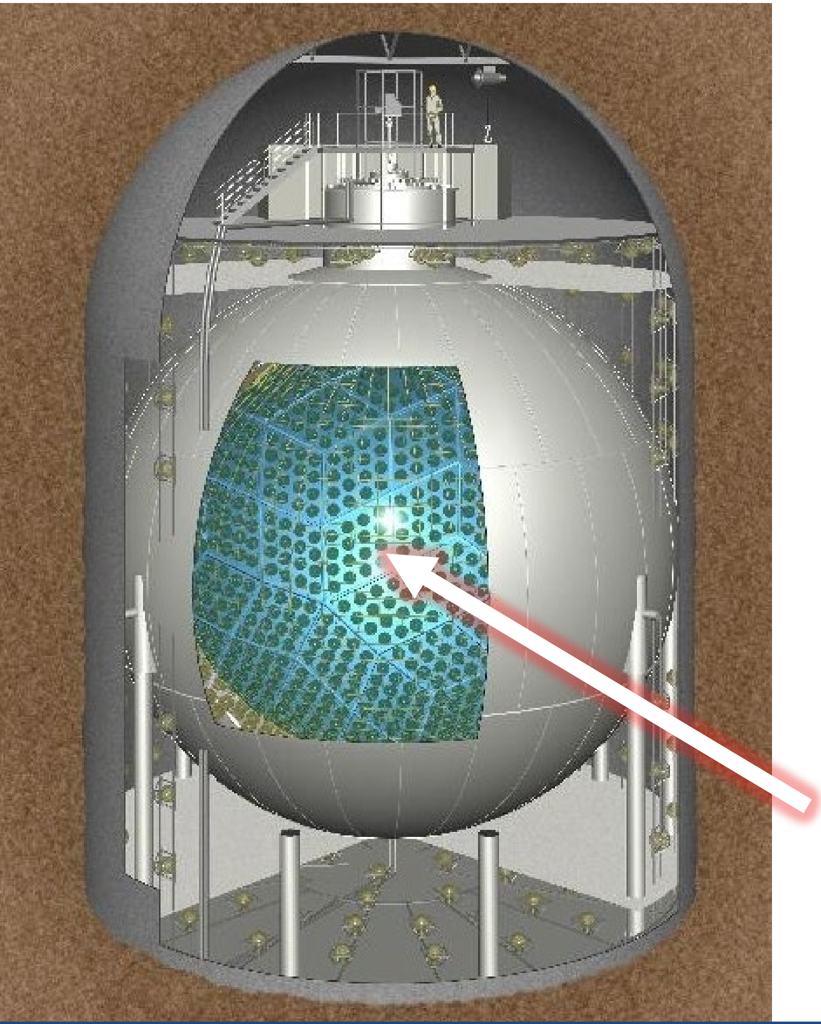
Three (or four) different measurements intersect at a point.

✓ *Evidence for (ν_μ+ν_τ) flux*

(Results from the 3 phases of the SNO experiment were consistent.)

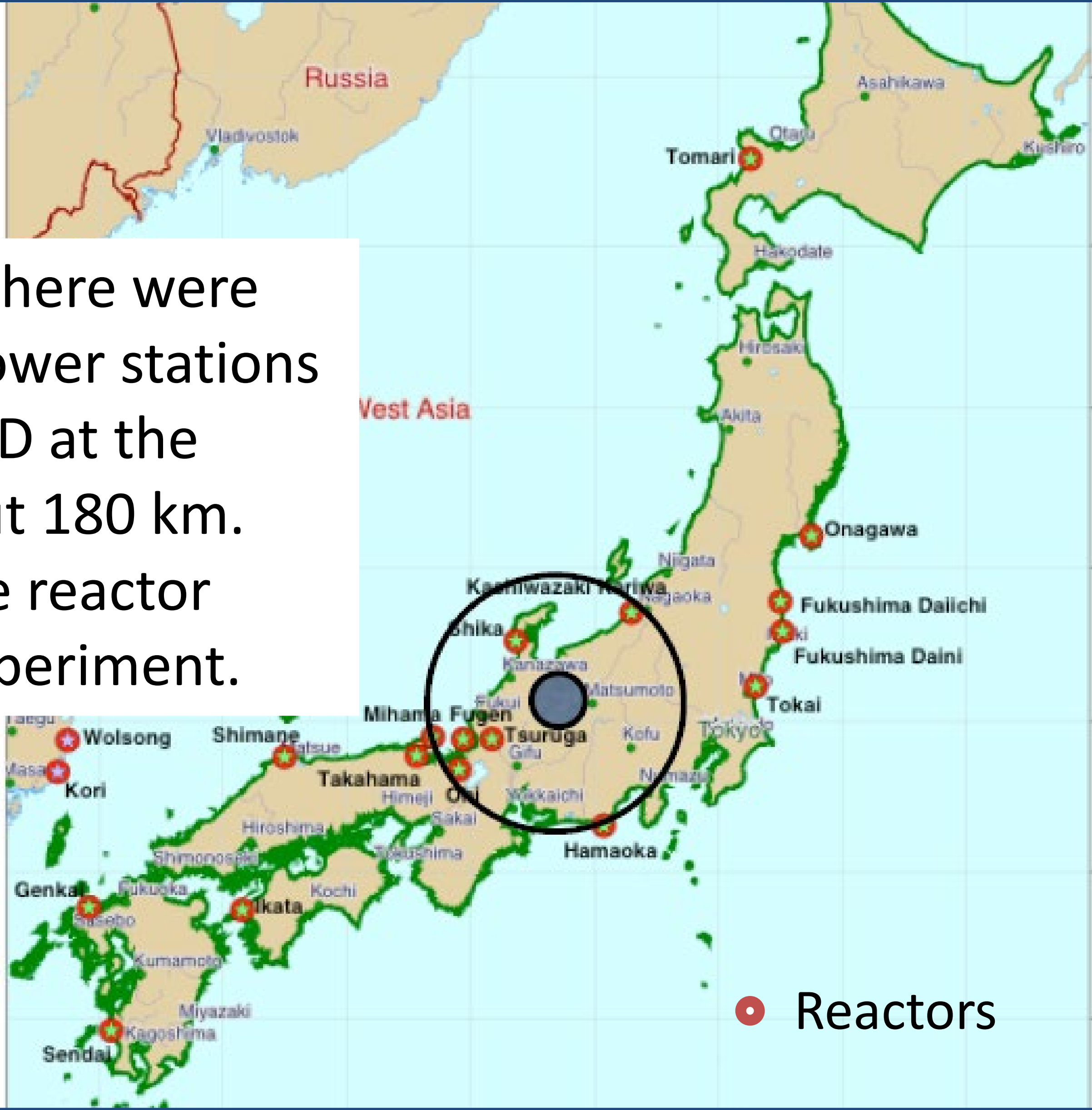
KamLAND

KamLAND is a 1kton liquid scintillator detector constructed at the location of Kamiokande.



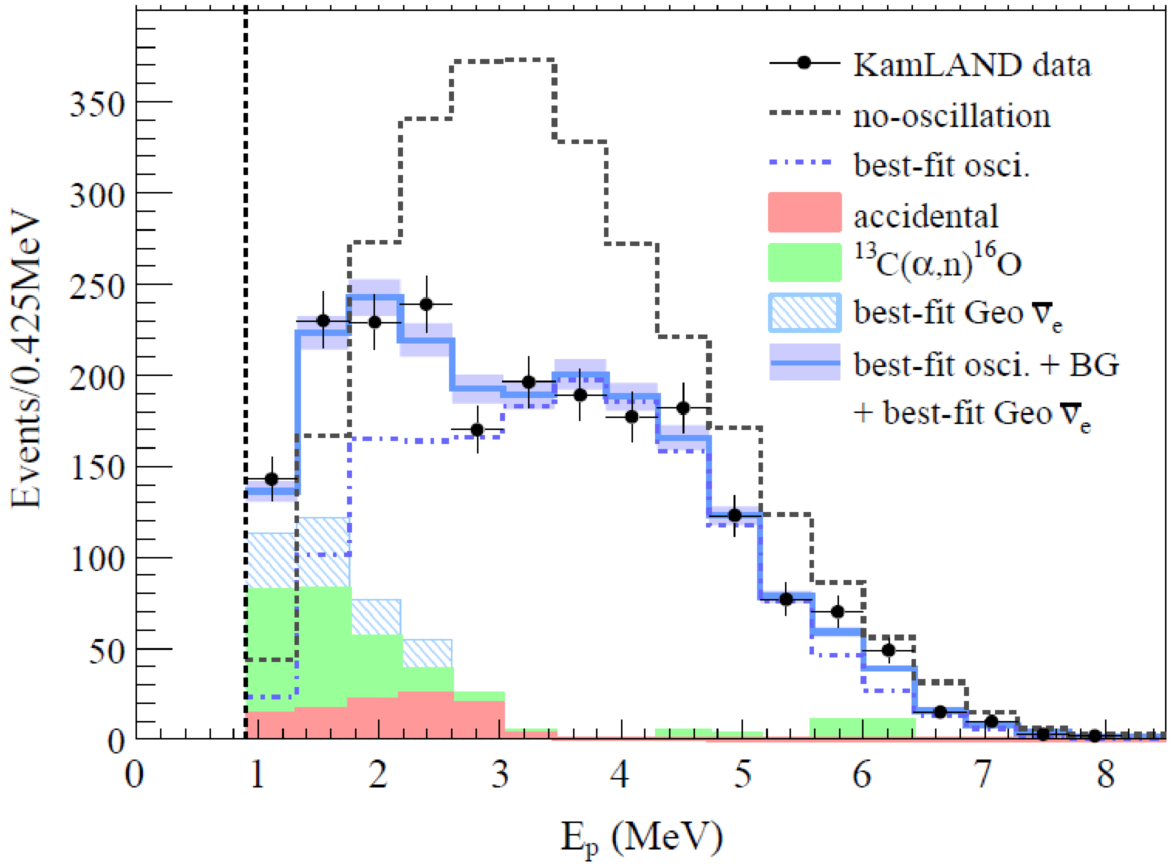
1kton liq. scintillator

In early 2000’s, there were many nuclear power stations around KamLAND at the distance of about 180 km.
➔ Long baseline reactor neutrino osc. experiment.



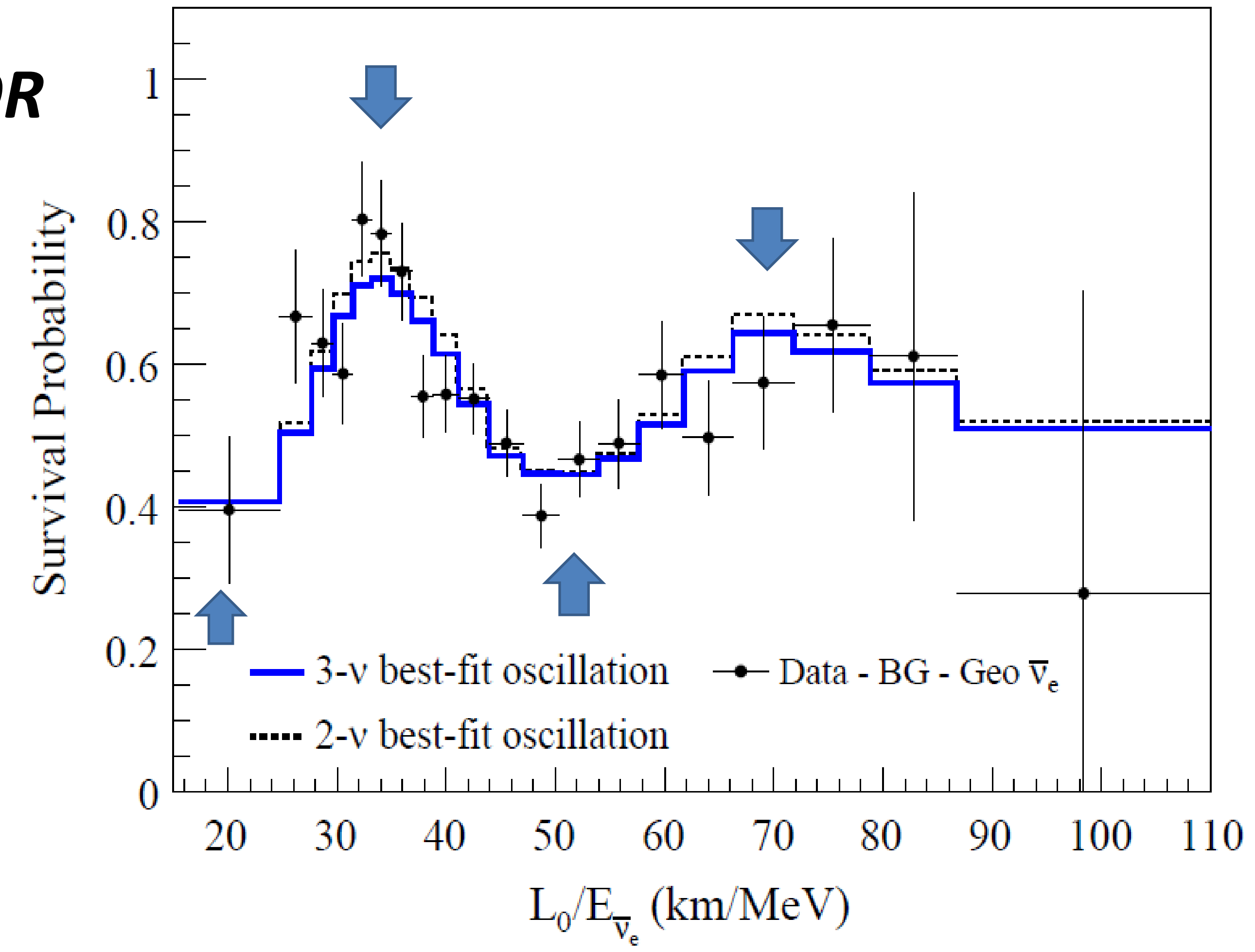
Really neutrino oscillations !

KamLAND PRD 83 (2011) 052002



Energy spectrum of neutrinos from nuclear power stations observed in KamLAND.

OR



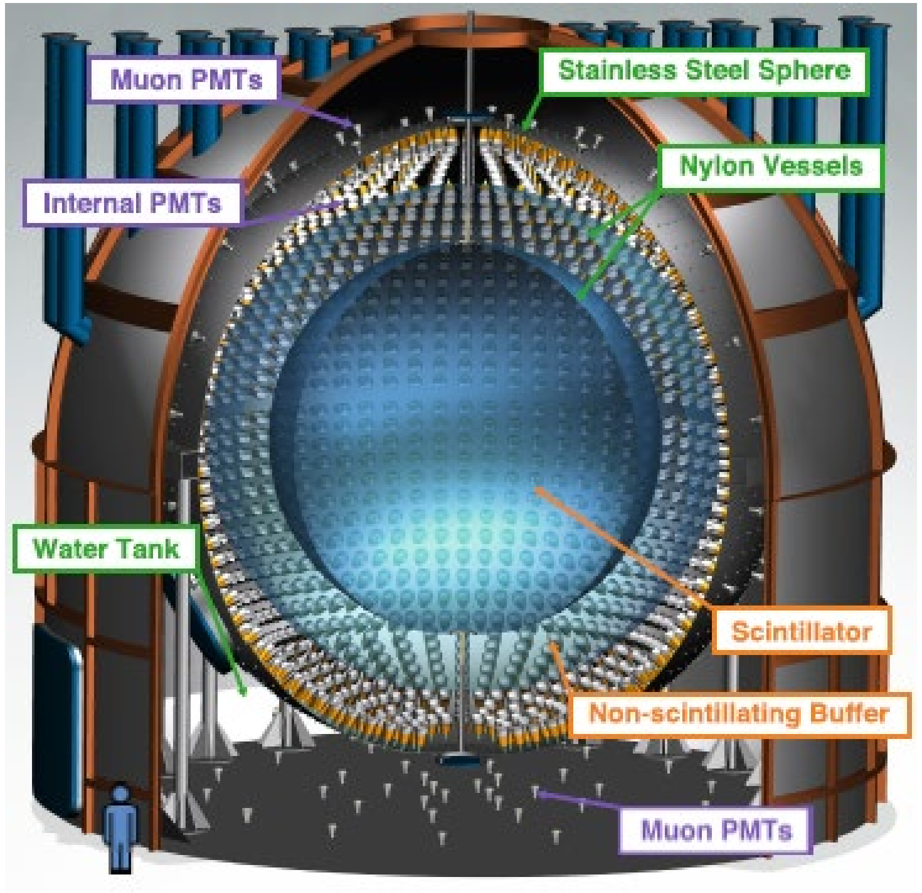
Really neutrino oscillations!

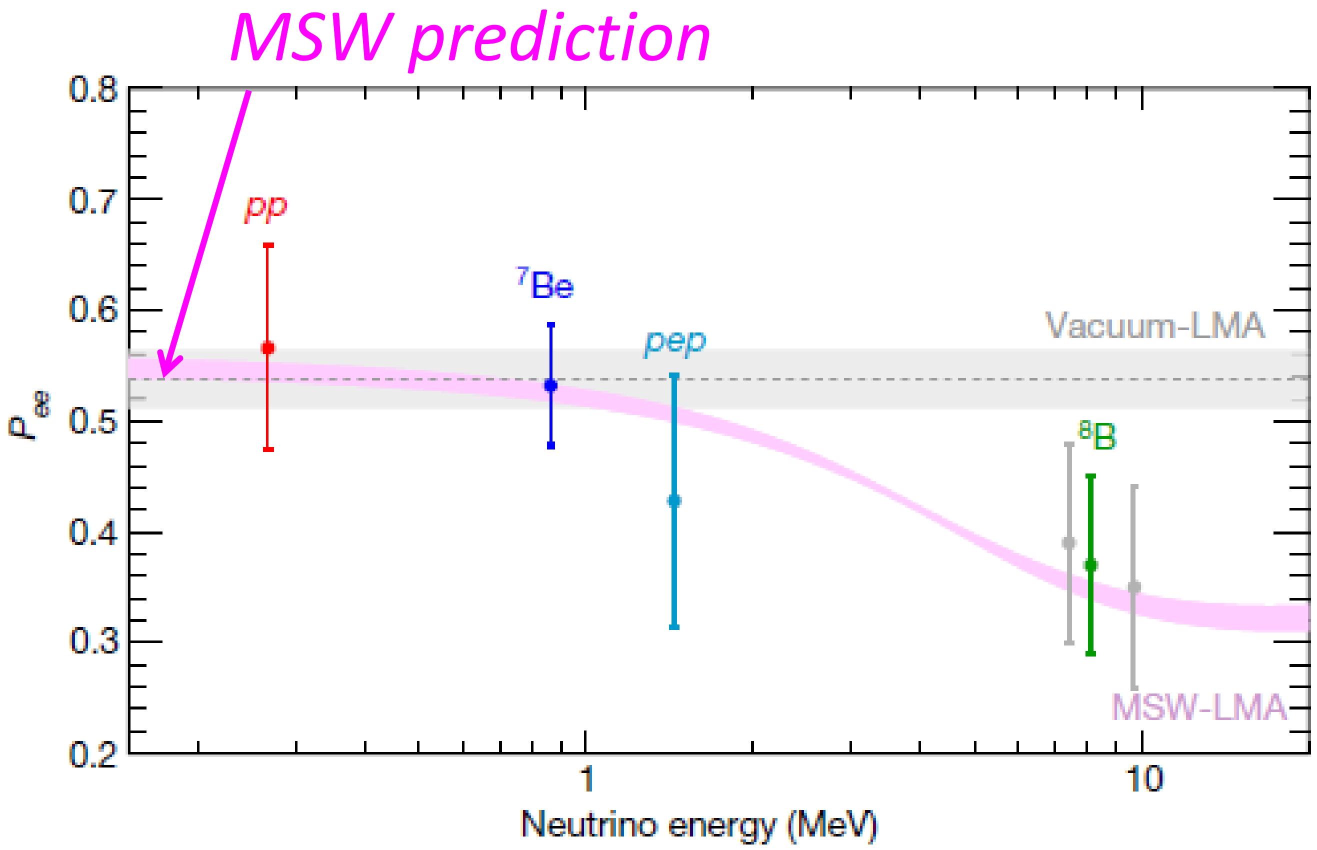
Consistent with MSW (Energy dependence)

Borexino

Designed to measure sub-MeV solar neutrinos

Borexino, PRL 101, 091302 (2008), PRD 82 (2010) 033006, PRL 108, 051302 (2012), Nature 512, 383 (2014), PRD 89, 112007 (2014), Nature 562 (2018) 7728, 505-510



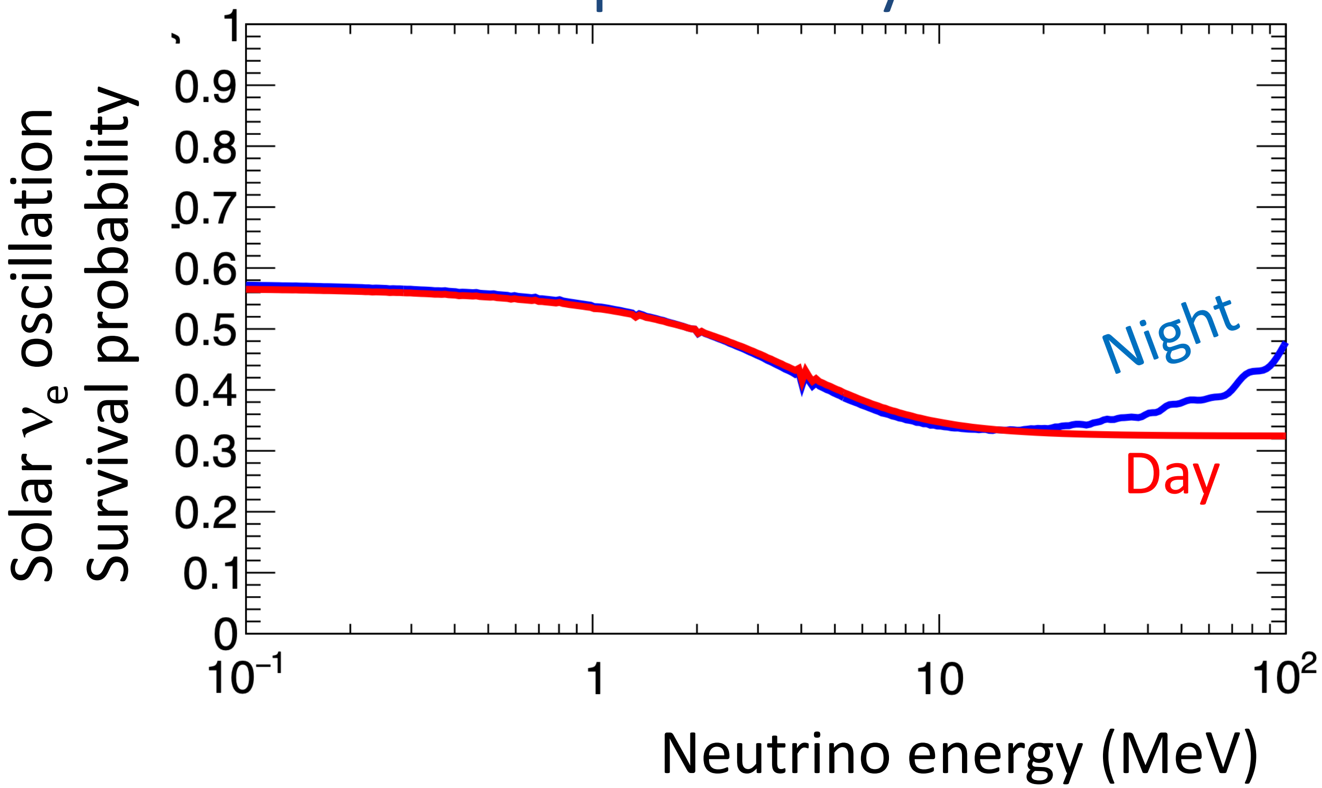


- ✓ *The data are consistent with the MSW prediction!*
- ✓ *Also, observation of CNO neutrinos (Nature 587 (2020) 577-582) !*

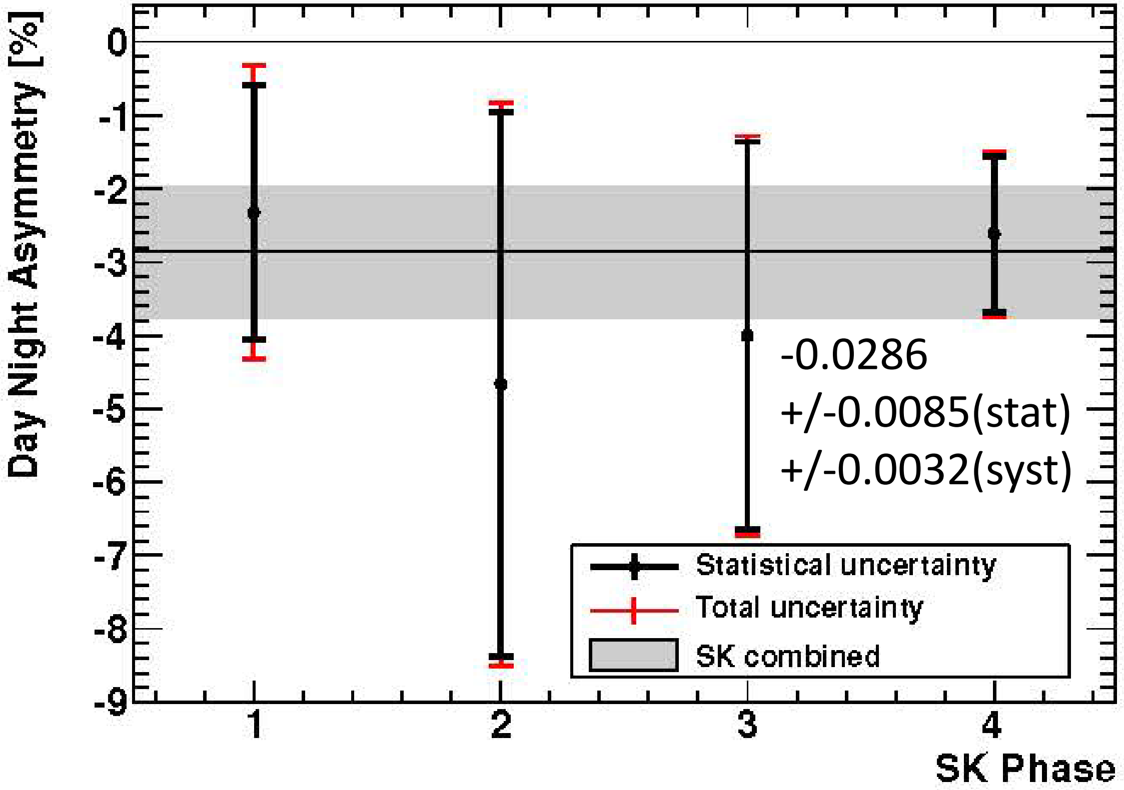
Consistent with MSW (Day-Night effect)

Due to the matter effect in the Earth, we expect that the night-time solar ν_e flux is slightly higher than the day-time flux.

Predicted solar neutrino oscillation probability



Super-K arXiv:2312.12907



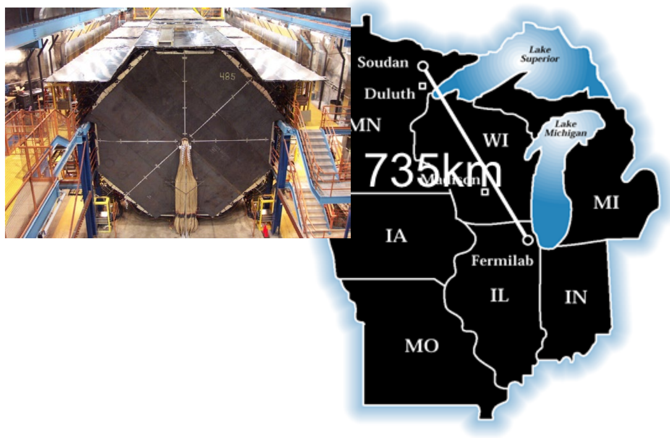
3σ evidence for day-night effect!

Discovery of neutrino oscillations:
- The third oscillation channel

Experiments for the third neutrino oscillations

Accelerator based long baseline neutrino oscillation experiments

MINOS

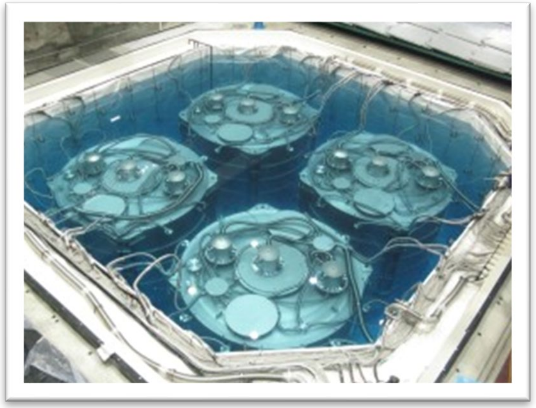


T2K

NOνA *(came slightly late)*

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

Daya Bay



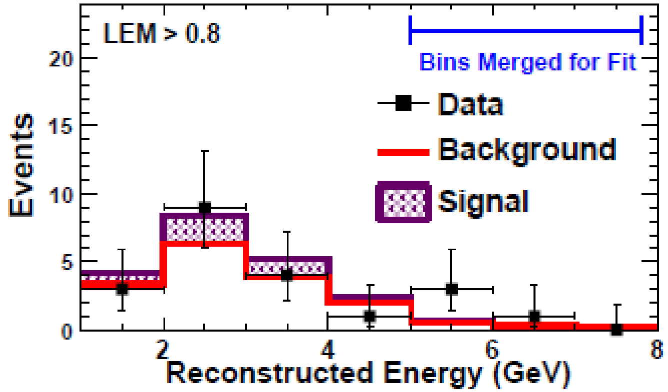
RENO

Double Chooz

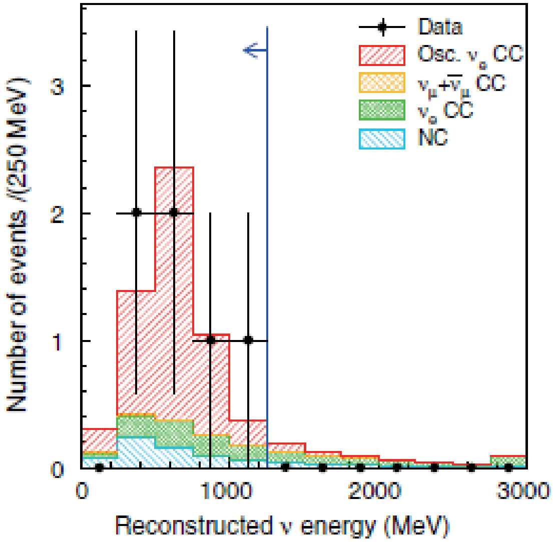
Discovery of the third neutrino oscillations (2011-2012)

Accelerator based ν_e appearance experiments

MINOS PRL 107 (2011) 181802



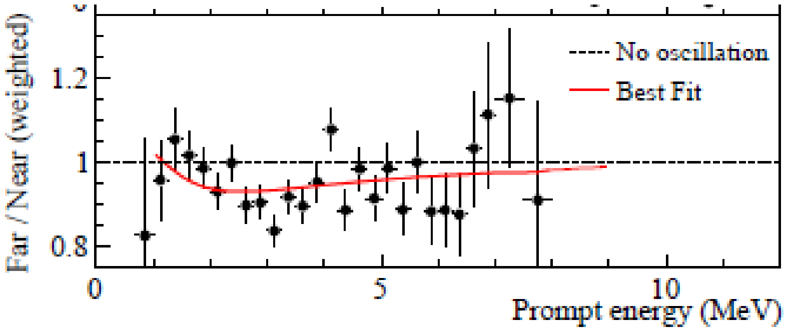
T2K
PRL 107 (2011) 041801



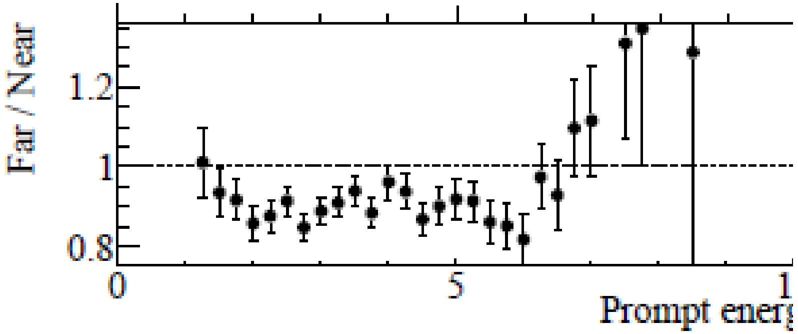
Note: these data are those in 2011-2012. The updated data are much better (including those from NOvA).

Reactor based anti-ν_e disappearance experiments

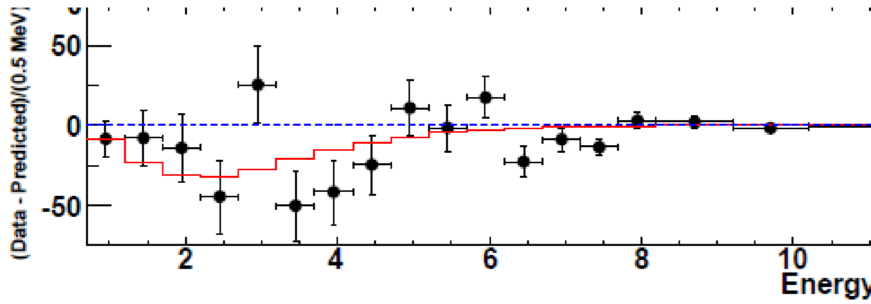
Daya Bay PRL 108 (2012) 171803



RENO PRL 108 (2012) 191802



Double Chooz PRL 108 (2012) 131801

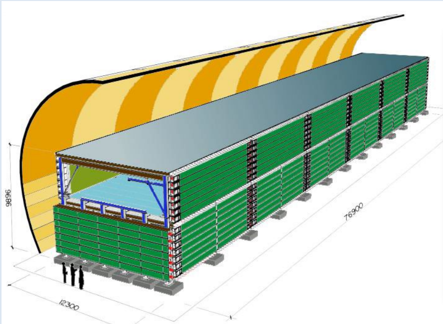


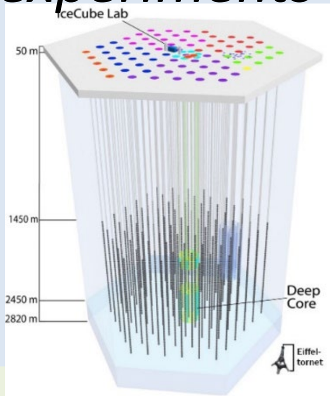
The basic structure for 3 flavor neutrino oscillations has been understood!

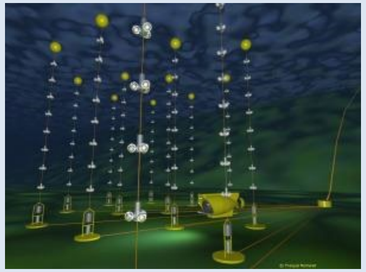
Status and future

Many exciting results in neutrino oscillations (partial list)

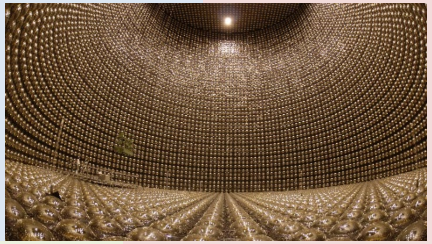
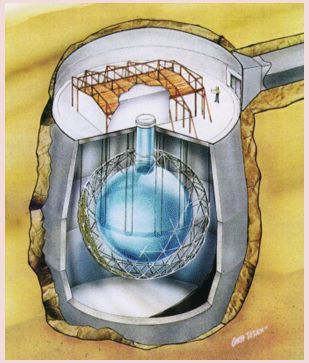
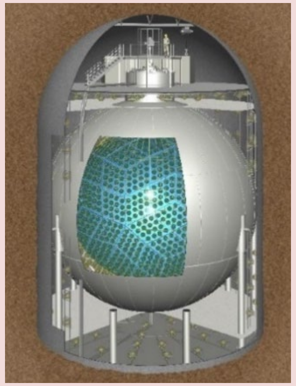
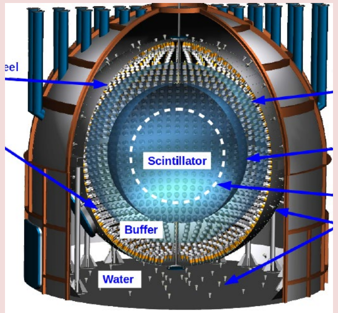
Atmospheric neutrino oscillation experiments



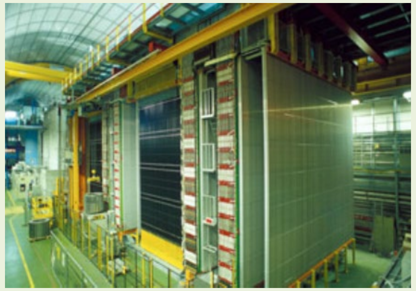




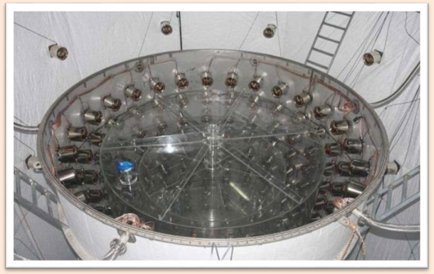
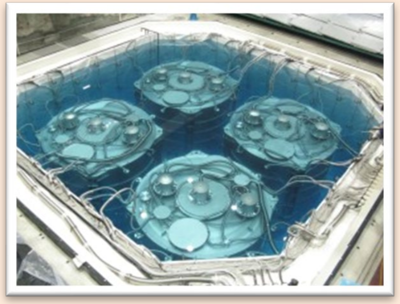
Solar neutrino oscillation experiments

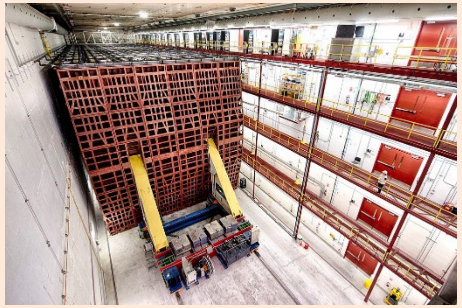





Accelerator based neutrino oscillation experiments



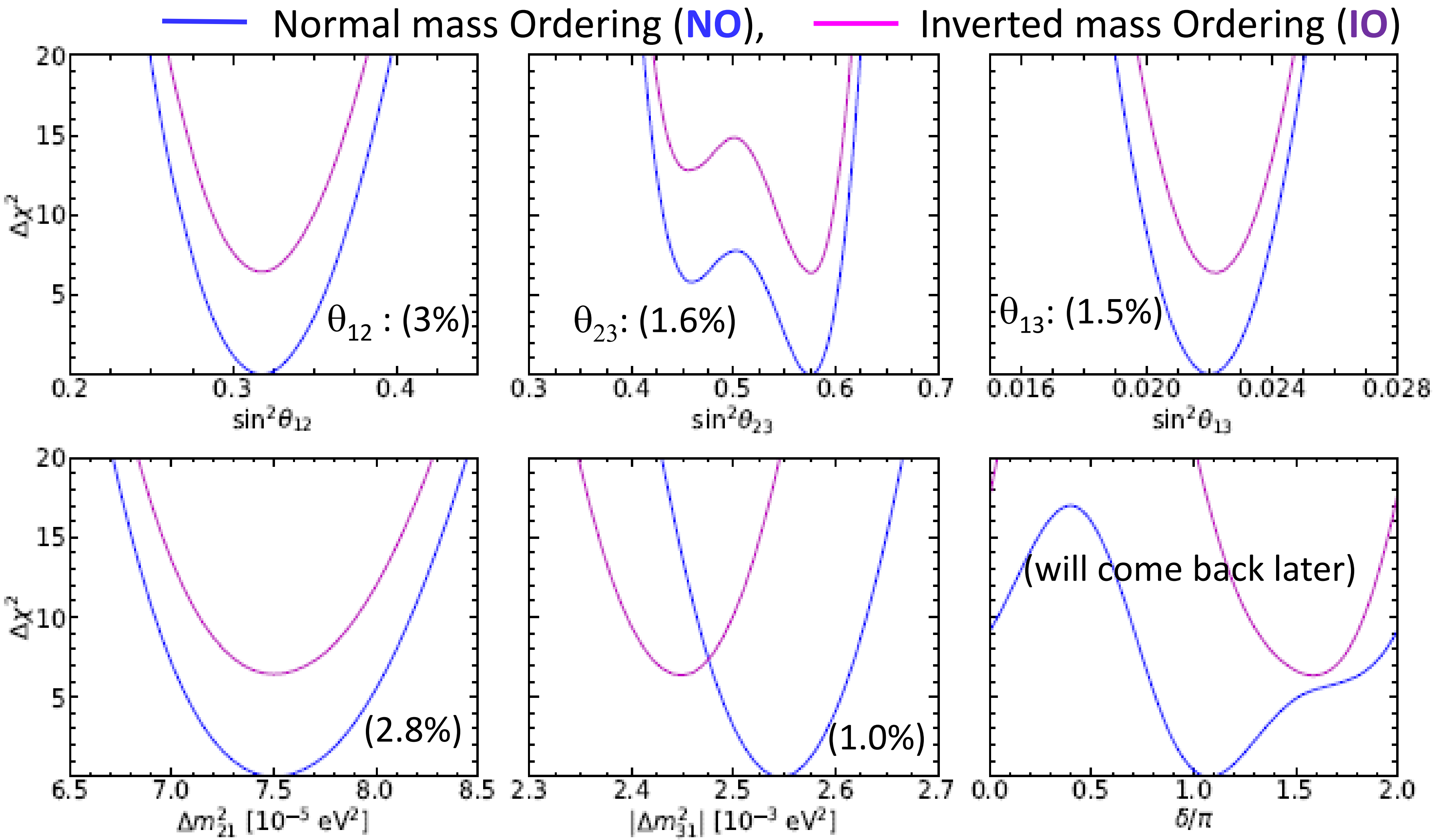
3 flavor(type) neutrino oscillation experiments

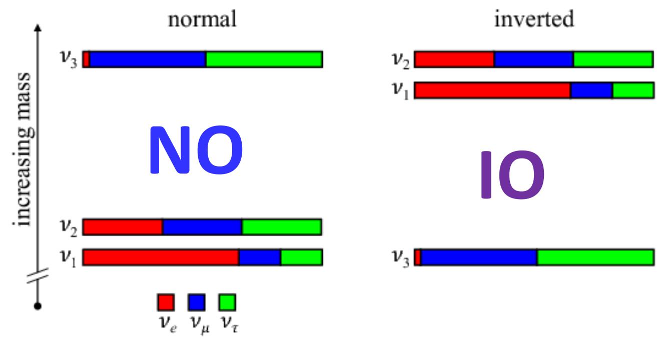


Oscillation parameters

P.F.de Salas et al., JHEP 02 (2021) 071 • e-Print: 2006.11237 [hep-ph]
See also many other references



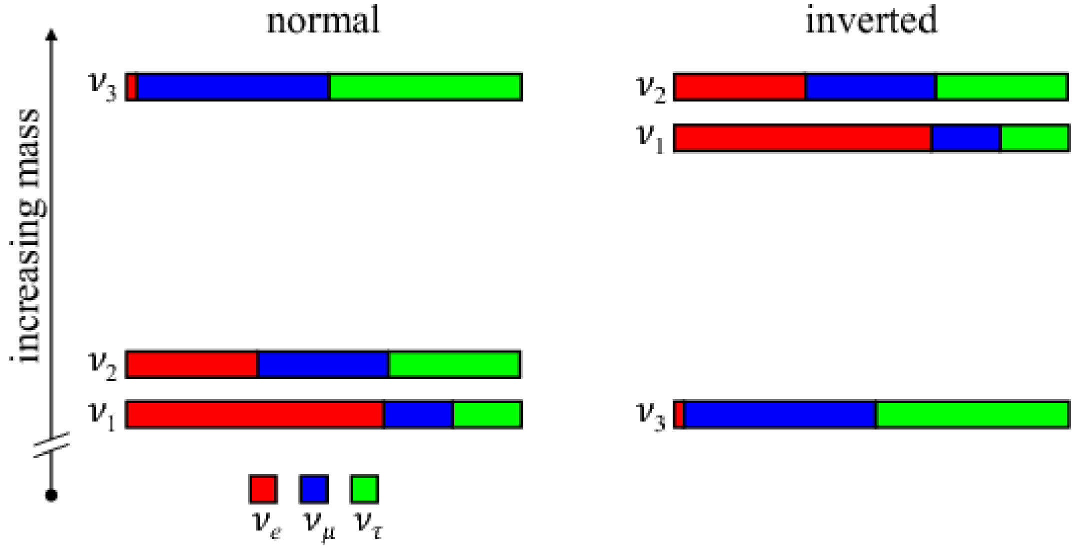
(numbers in parenesis are 1σ uncertainties assuming **NO**)



➔ Neutrino mass is very small. Probably more than 10 orders of magnitude smaller than the corresponding mass of quarks and charged leptons.
➔ Neutrino mixing angles are large compared with the corresponding quark mixing angles.

Agenda for future neutrino studies

Neutrino mass ordering?



Absolute neutrino mass?

Beyond the 3 flavor framework? (Sterile neutrinos?)

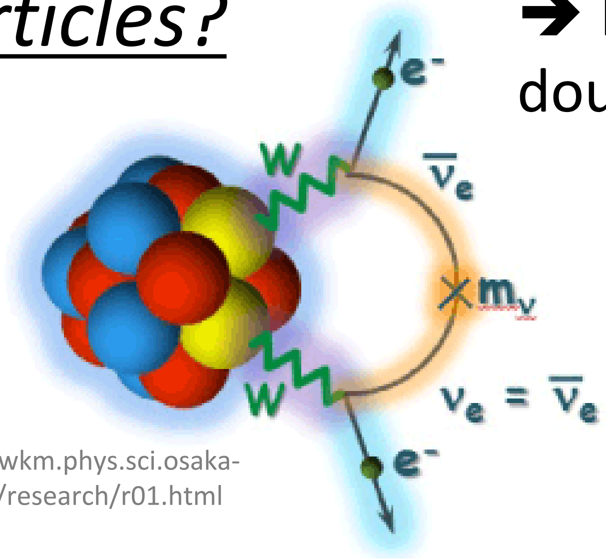
CP violation?

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)\ ?$$

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?

➔ Neutrinoless double beta decay



http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

Summary

- "Proton decay experiments" in the 1980's observed many contained atmospheric neutrino events, and discovered the atmospheric ν_μ deficit. Subsequently, in 1998, Super-Kamiokande discovered neutrino oscillations.
- Solar neutrino experiments began in the 1960's. Various solar neutrino experiments before 2000 observed the deficit of solar neutrinos. Then the SNO experiment discovered solar neutrino oscillations by the measurements of CC and NC reactions of solar neutrinos.
- Since then, various 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. Neutrinos might also be the key to understand the baryon asymmetry of the Universe.

It is very important to learn the most from neutrinos!

backups