International Symposium on Neutrino Physics and Beyond (NPB 2024)
HKUST, Feb. 19-21, 2024

Neutrino Oscillation Experiments

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

Outline

- *Introduction: Neutrino problems*
- *Neutrino oscillations:*

  $\nu_\mu \rightarrow \nu_\tau$

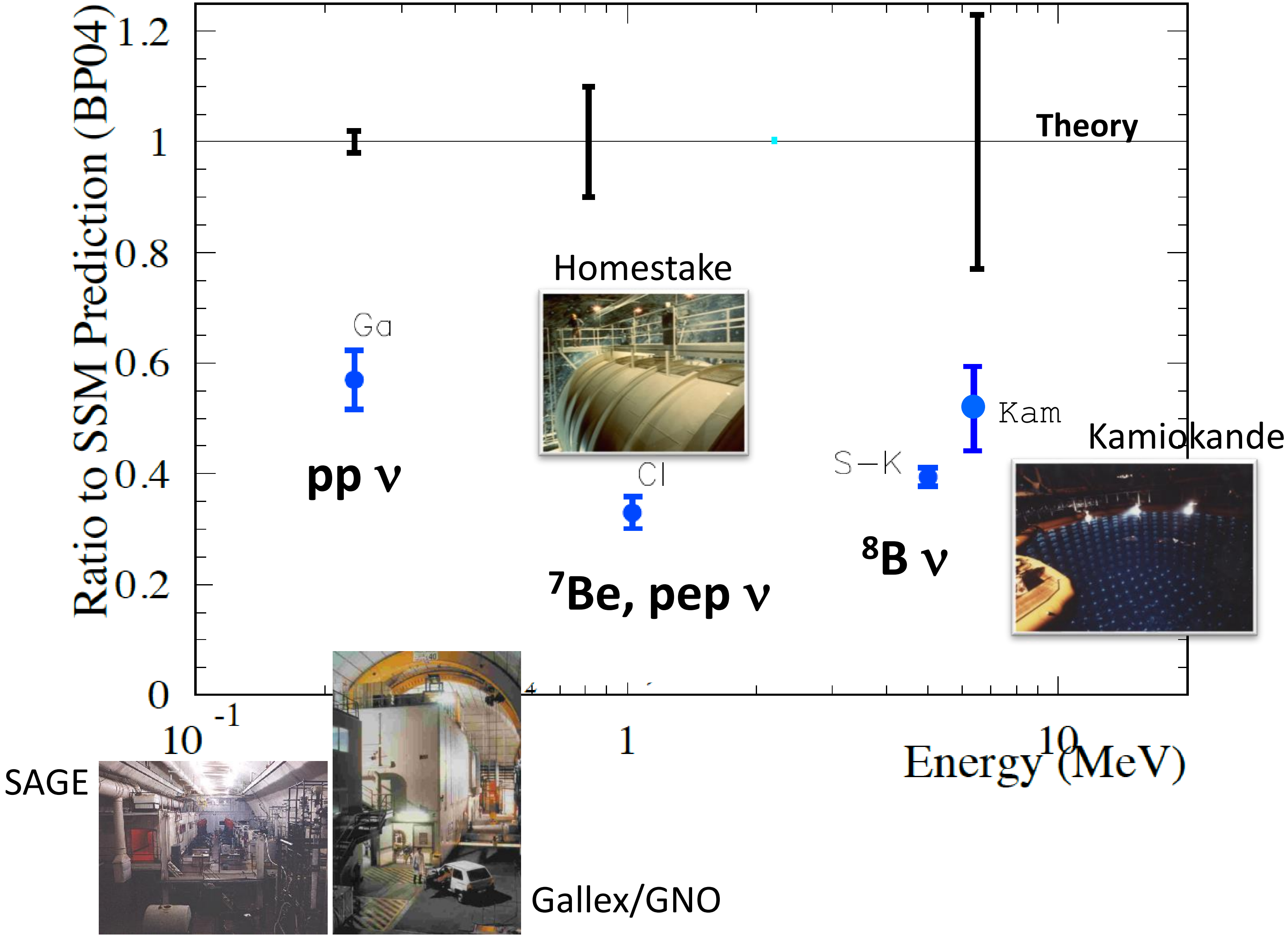
  $\nu_e \rightarrow \nu_\mu + \nu_\tau$

  the third oscillation channel
- *Agenda for future neutrino studies*
- *Summary*

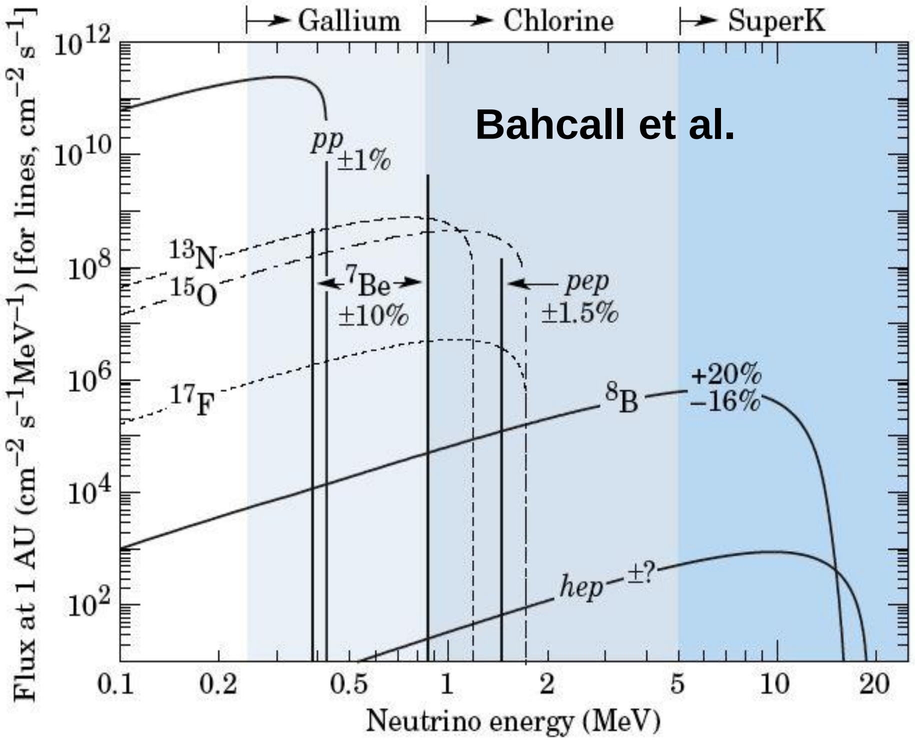
Introduction: Neutrino problems

Solar neutrino problem

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



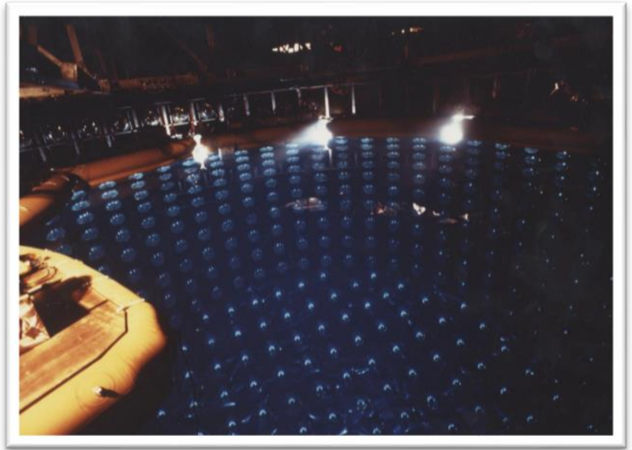
Energy spectrum: Solar neutrinos

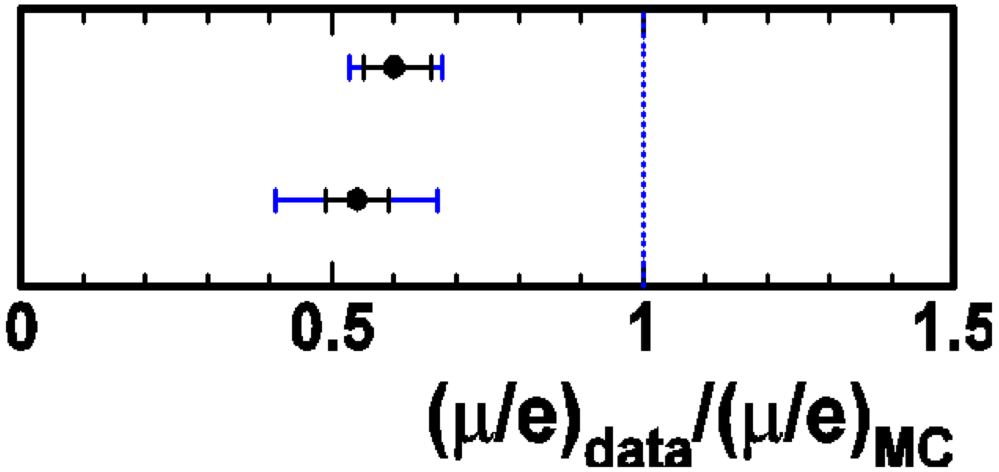


Solar neutrino experiments observed the deficit of solar neutrinos.

Atmospheric neutrino problem

- ✓ 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 the muon-neutrinos events was observed.





Neutrino oscillations: $\nu_\mu \rightarrow \nu_\tau$

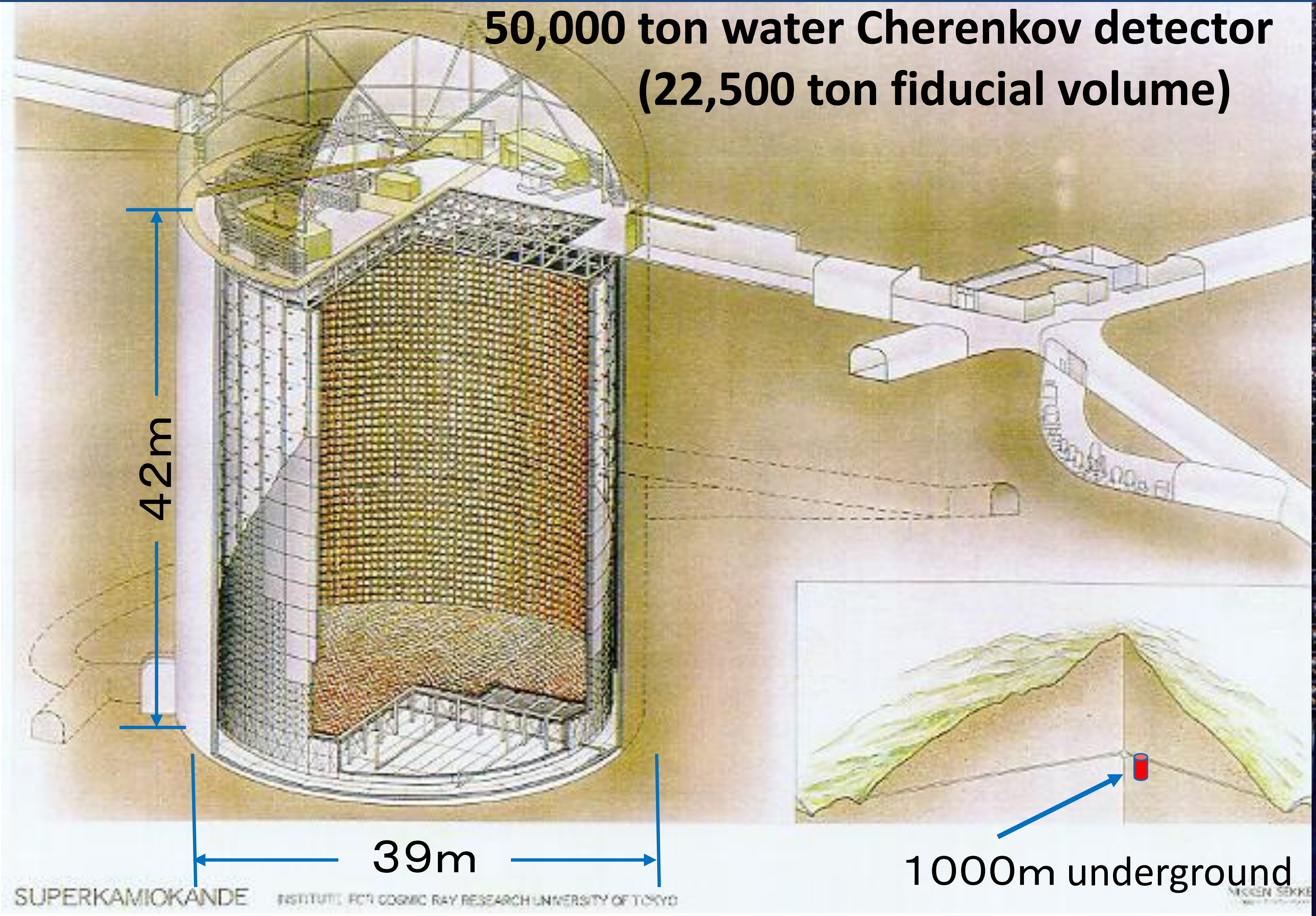
Neutrino oscillations

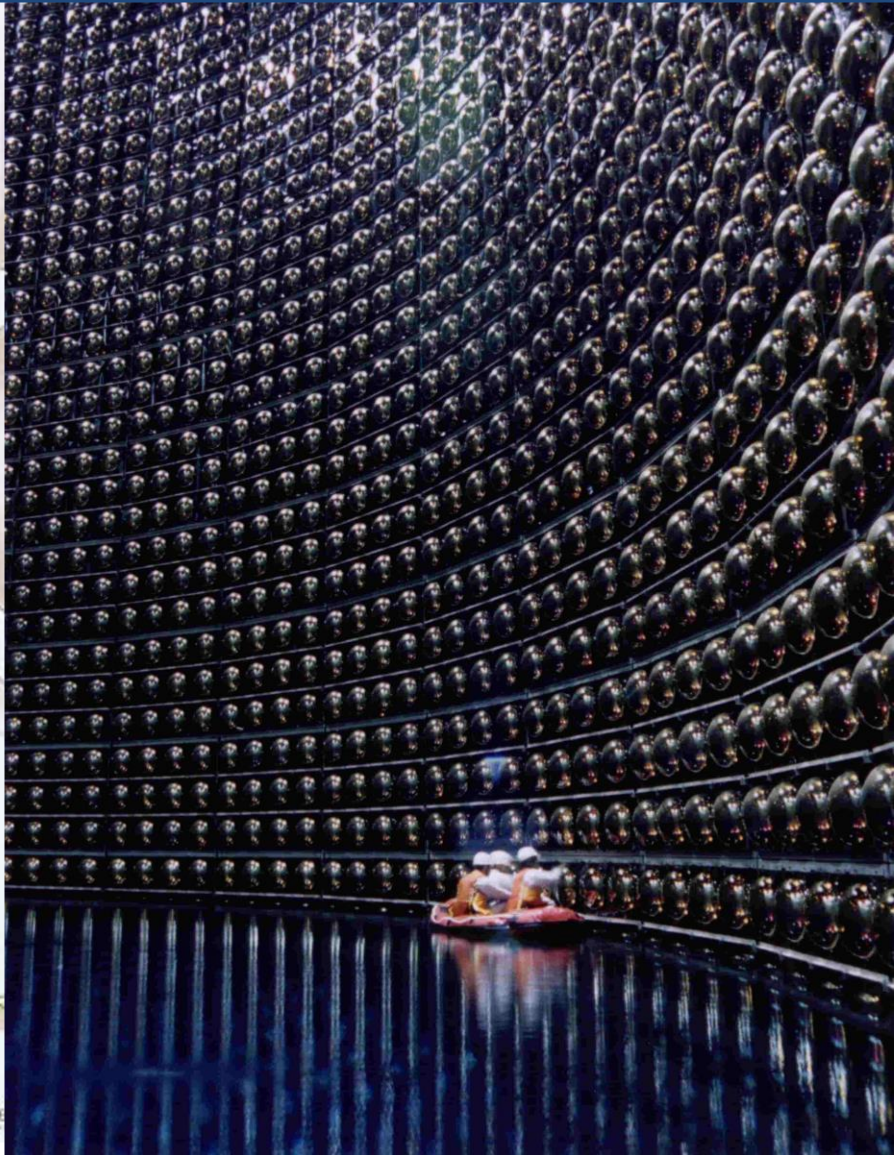
- ✓ In the Standard Model of particle physics, neutrinos are assumed to be massless.
- ✓ However, physicists have been asking neutrinos really have no mass.
- ✓ Also, it was generally believed that, if neutrinos have very small mass, the small neutrino mass may imply physics beyond the Standard Model (See-saw mechanism). (P. Minkowski, Phys. Lett. B67 (1977) 421, T. Yanagida, in Proc. Workshop on the Unified Theories and the Baryon Number in the Universe, KEK report 79-18, Feb. 1979, p.95, M. Gell-Mann, P. Ramond and R. Slansky, in Supergravity. Amsterdam, NL: North Holland, 1979, p. 315)
- ✓ If neutrinos have very small mass, they change their flavor while propagating in the vacuum (or in the matter), namely neutrino oscillations. (Z. Maki, M. Nakagawa, S. Sakata, Prof. theo. Phys. 28 (1962) 870, B. Pontecorvo, Soviet Physics JETP 26 (1968) 984)

$$P_{a\to b} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$ (2 flavor vacuum oscillation case)

➔ ***Neutrino oscillation experiments!***

Super-Kamiokande

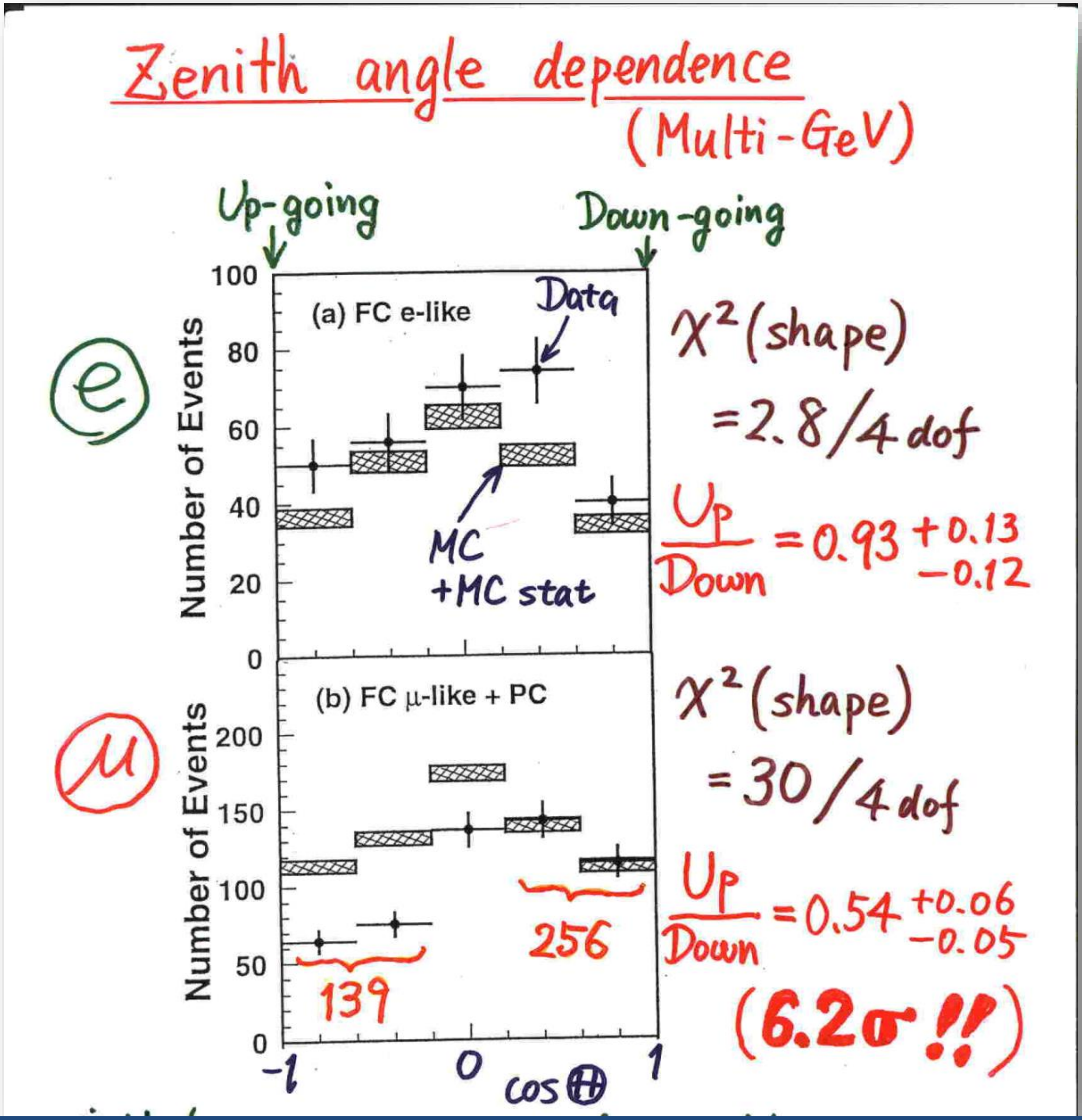


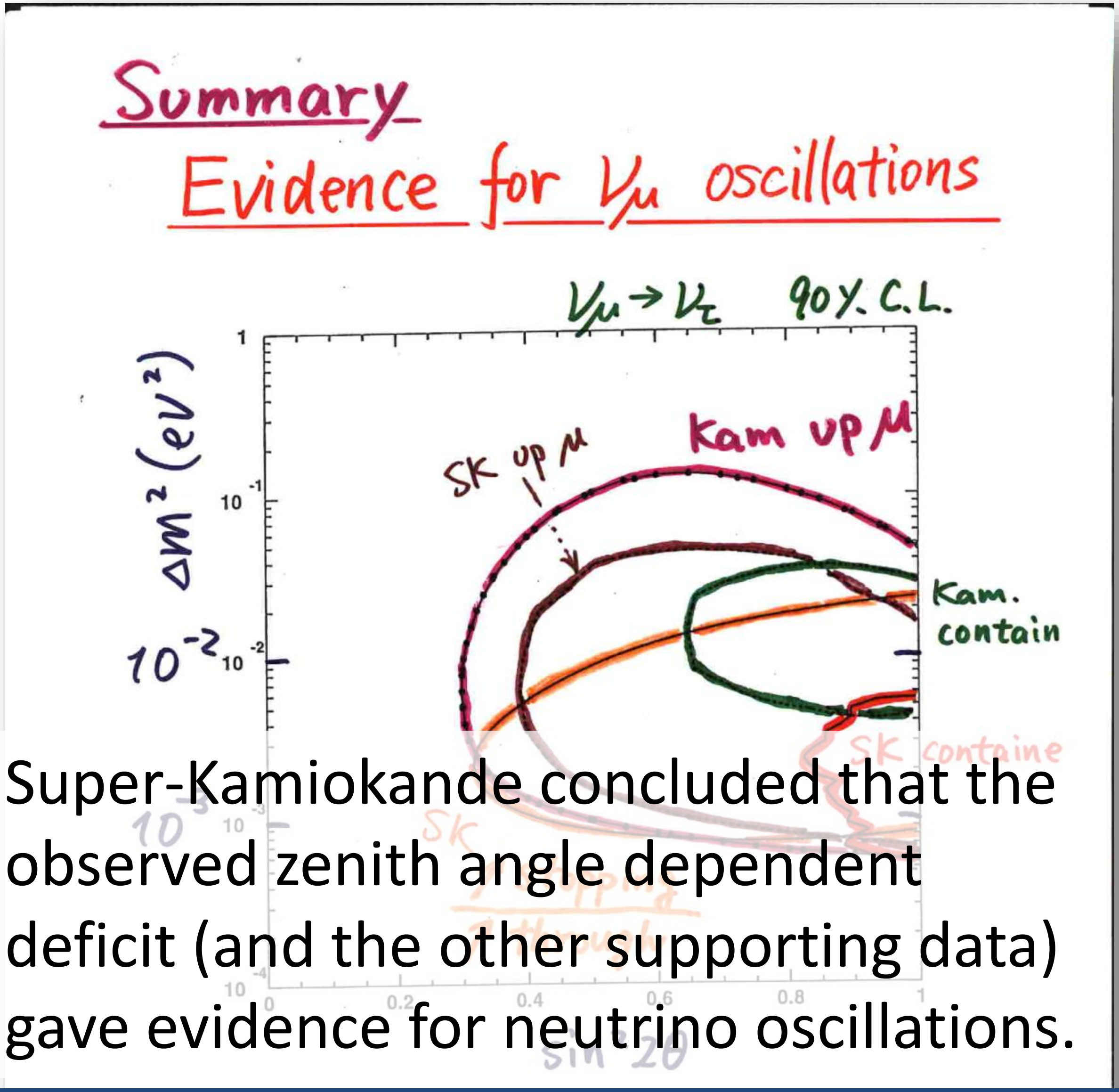


~230 collaborators

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

Super-K, Neutrino 98, Super-K., PRL 81 (1998) 1562

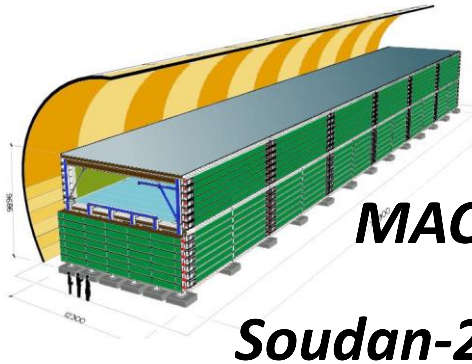




Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Neutrino oscillation studies

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

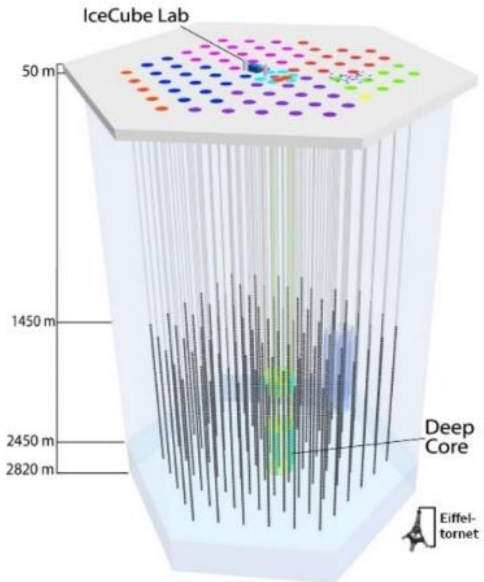


MACRO

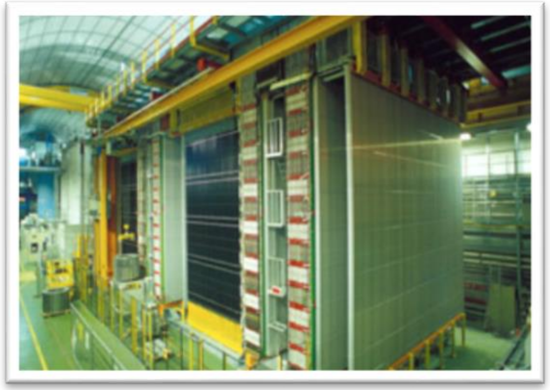
K2K

MINOS

Soudan-2

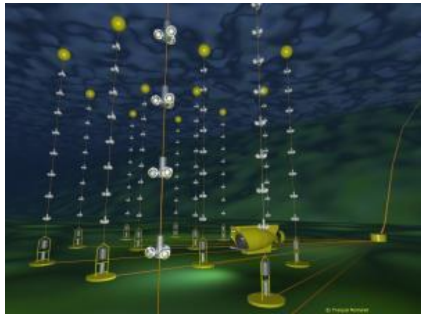


IceCube



OPERA

NOvA



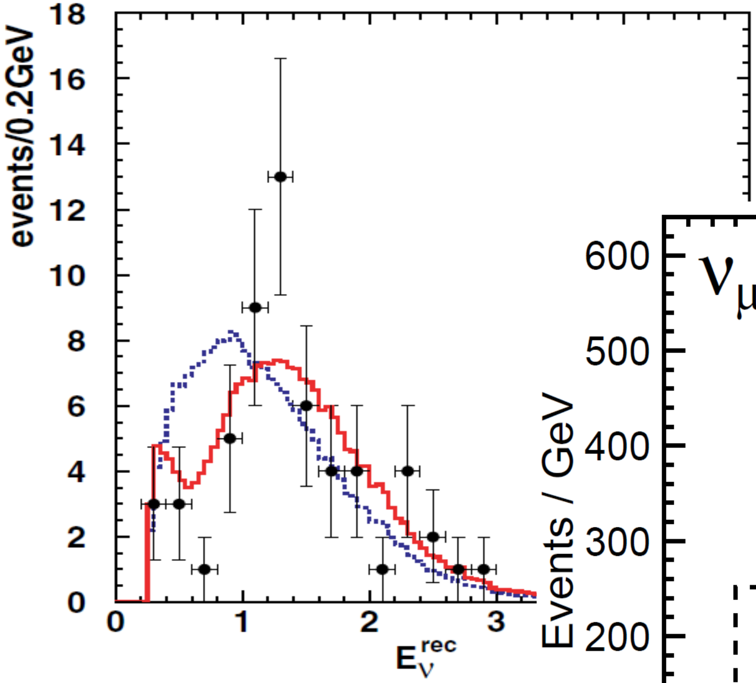
ANTARES

T2K

ν_μ disappearance studies (accelerator experiments)

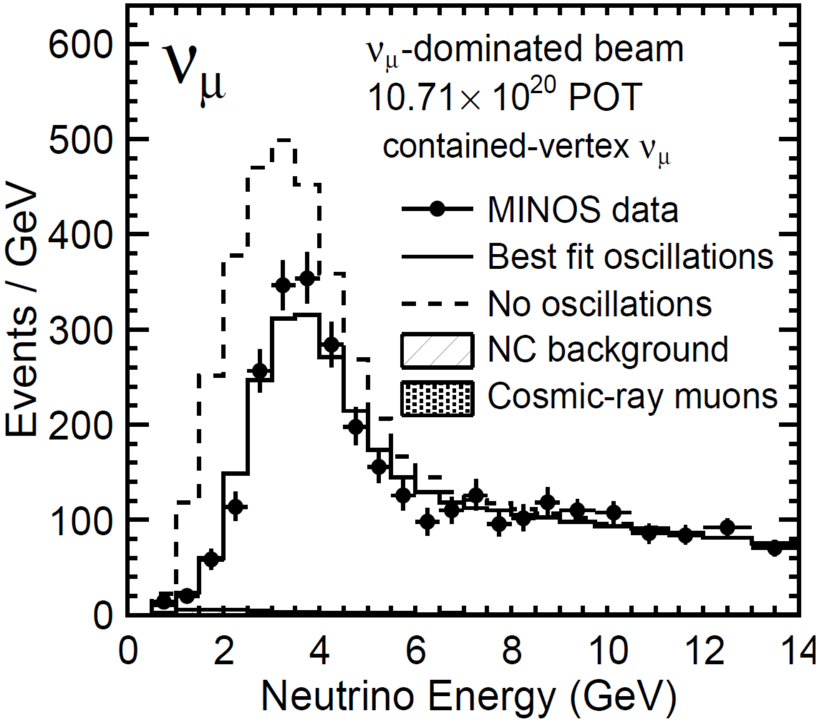
K2K

K2K, PRD 74 (2006) 072003



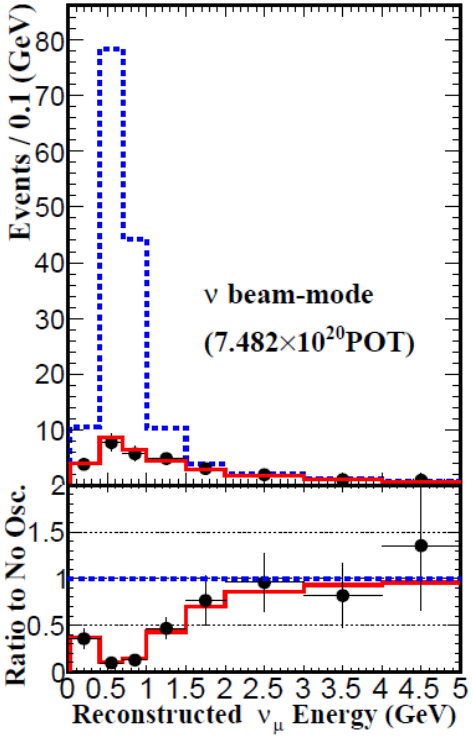
MINOS

MINOS PRL 110 (2013) 251801



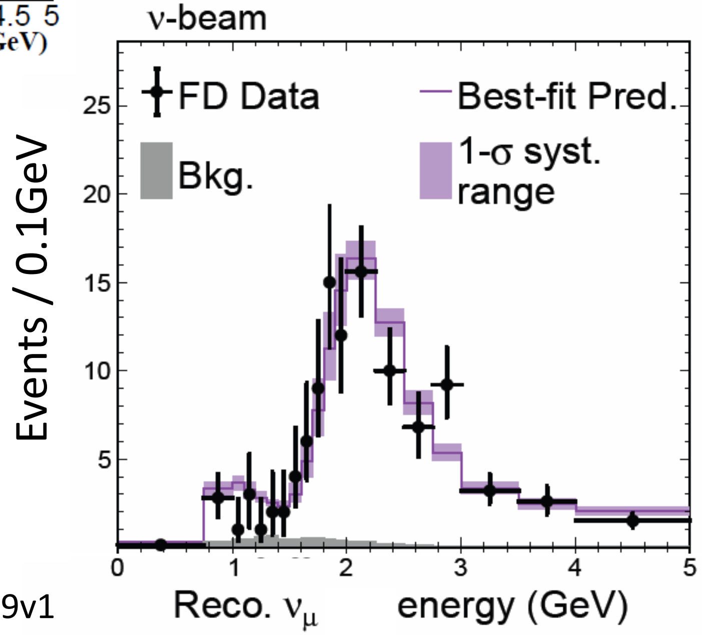
T2K

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



NOvA

NOvA, arXiv:2108.08219v1

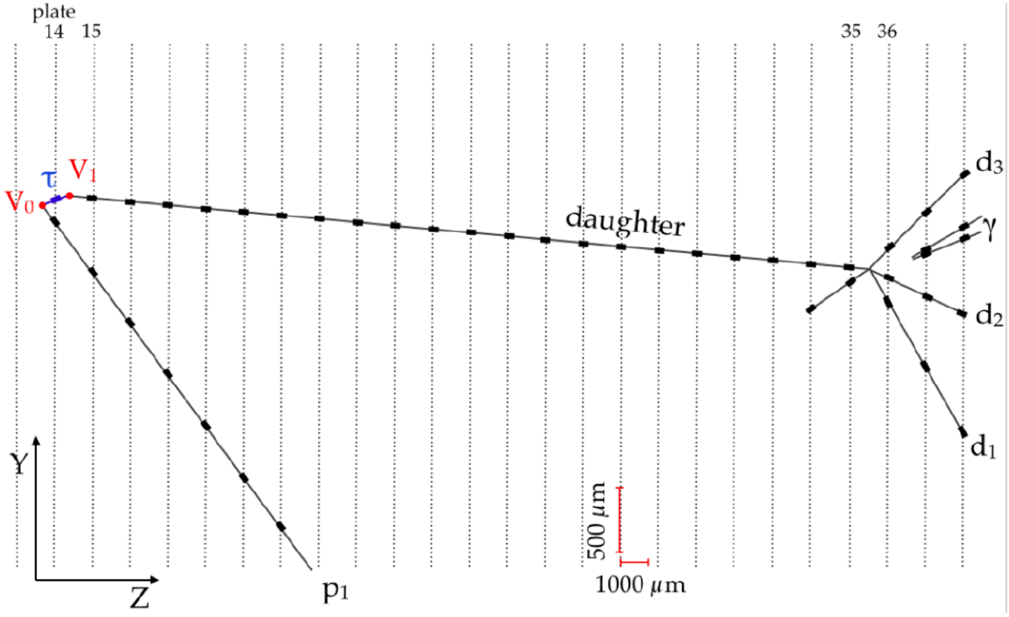


ν_τ appearance

OPERA

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

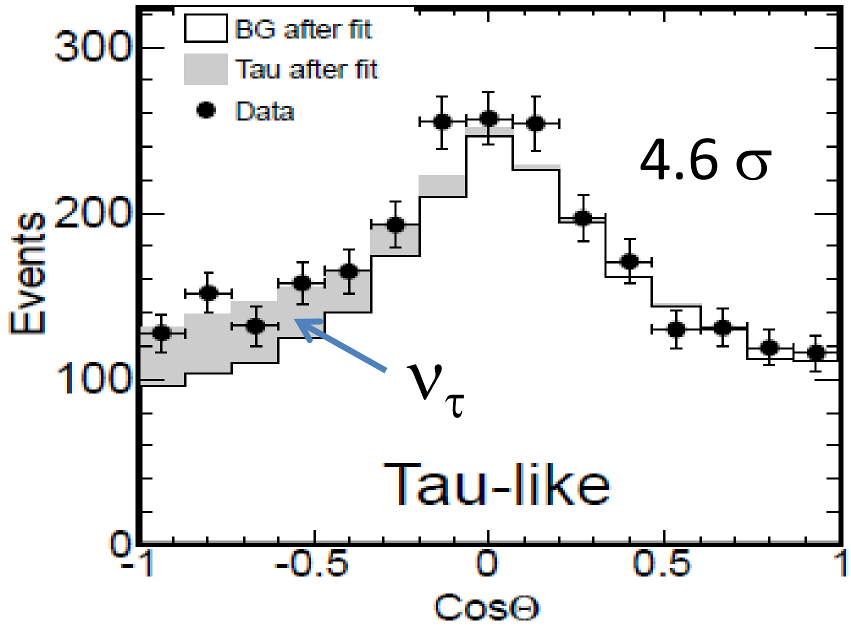
OPERA PRL 115 (2015) 121602



The fifth candidate event

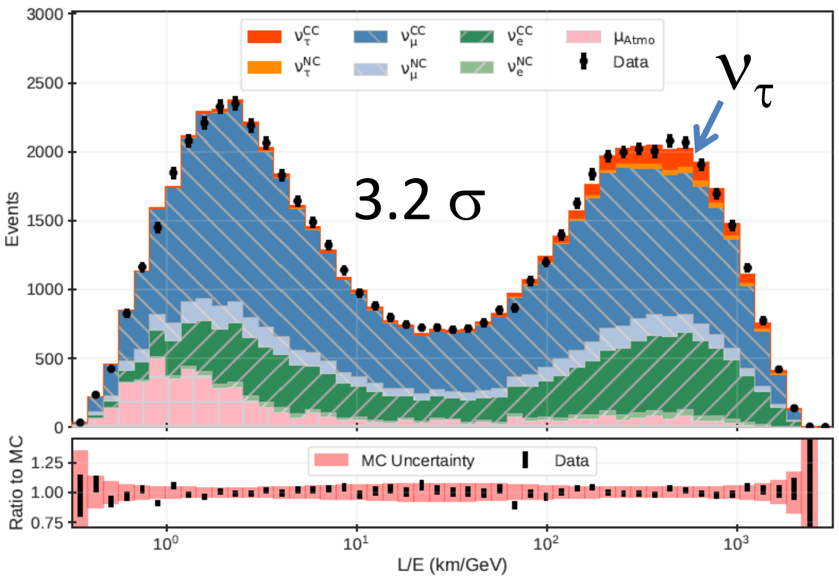
Super-Kamiokande

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



IceCube

IceCube,
PRD 99 (2019) 3, 032007

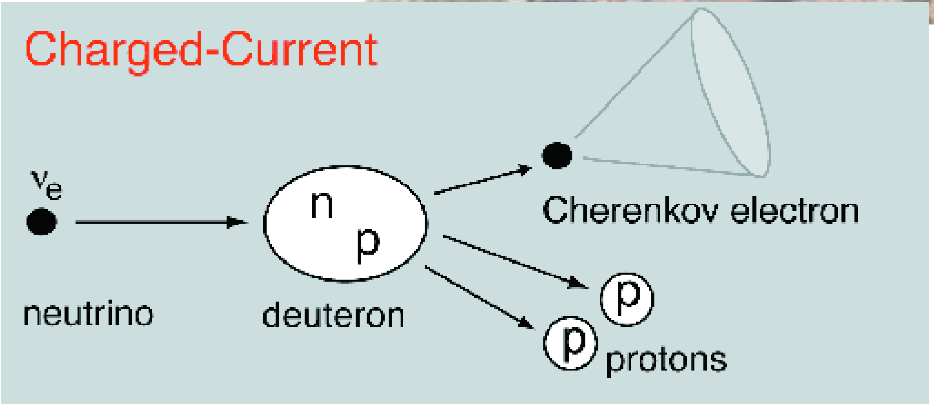


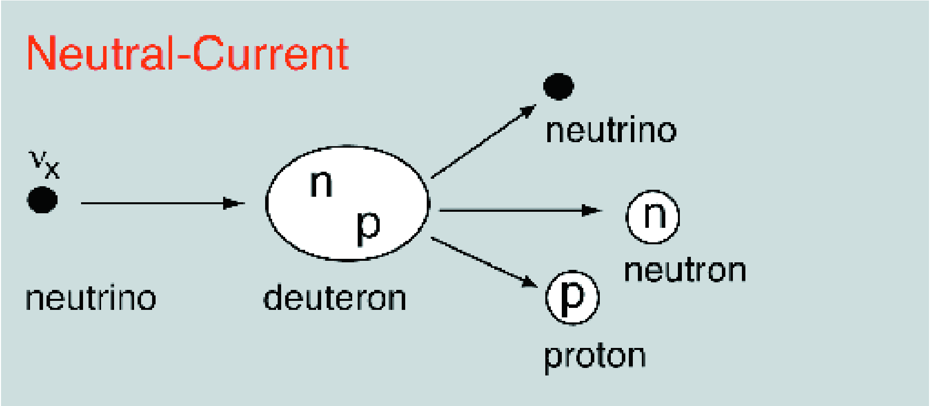
Neutrino oscillations: $\nu_e \rightarrow \nu_\mu + \nu_\tau$

Initial idea

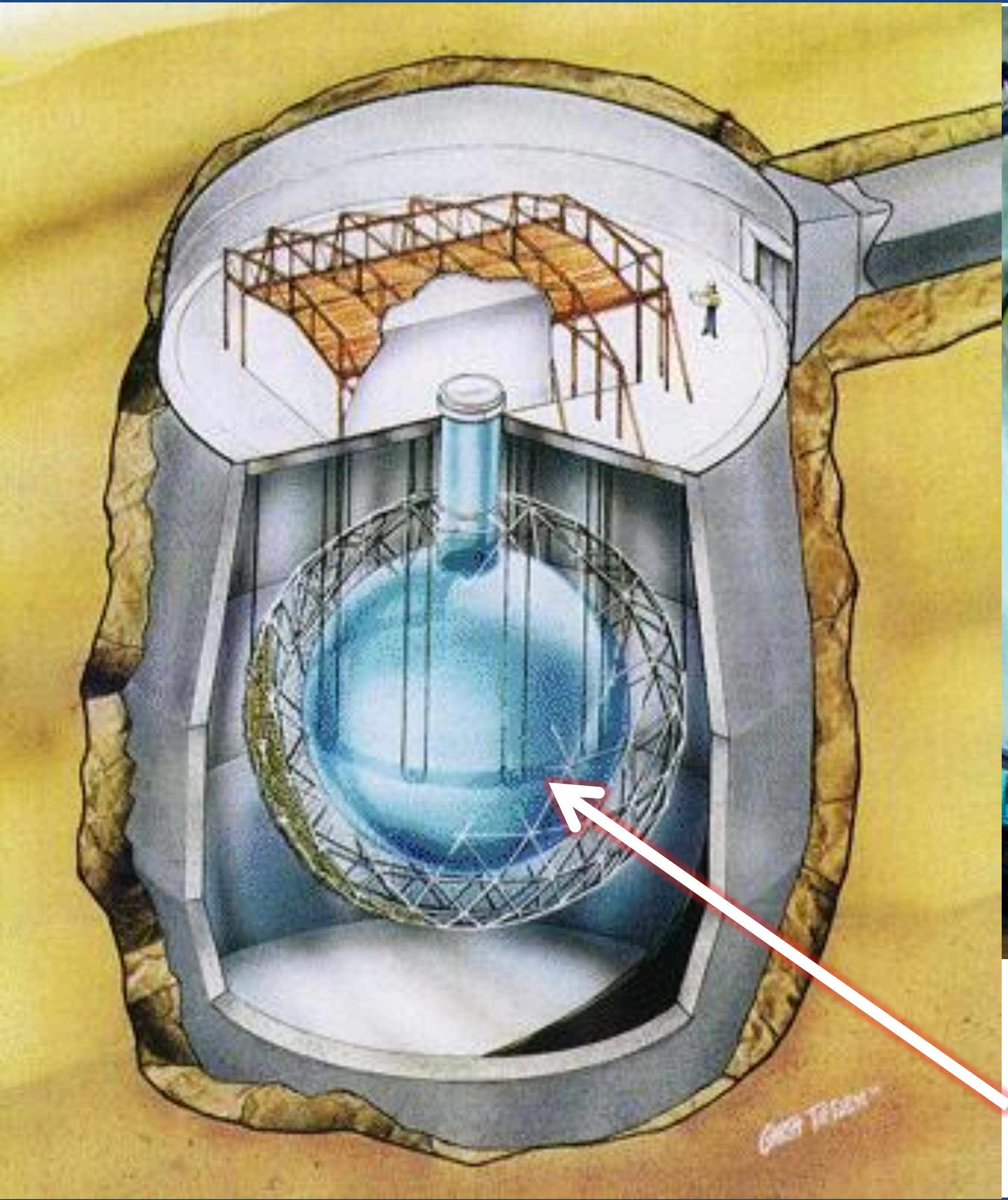
Herbert Chen, PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

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-current reaction $\nu+d \rightarrow \nu+p+n$ and the charged-current reaction $\nu_e+d \rightarrow e^-+p+p$, is suggested for this purpose.

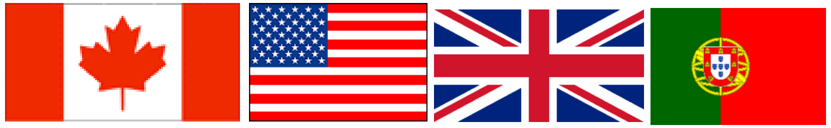




SNO detector



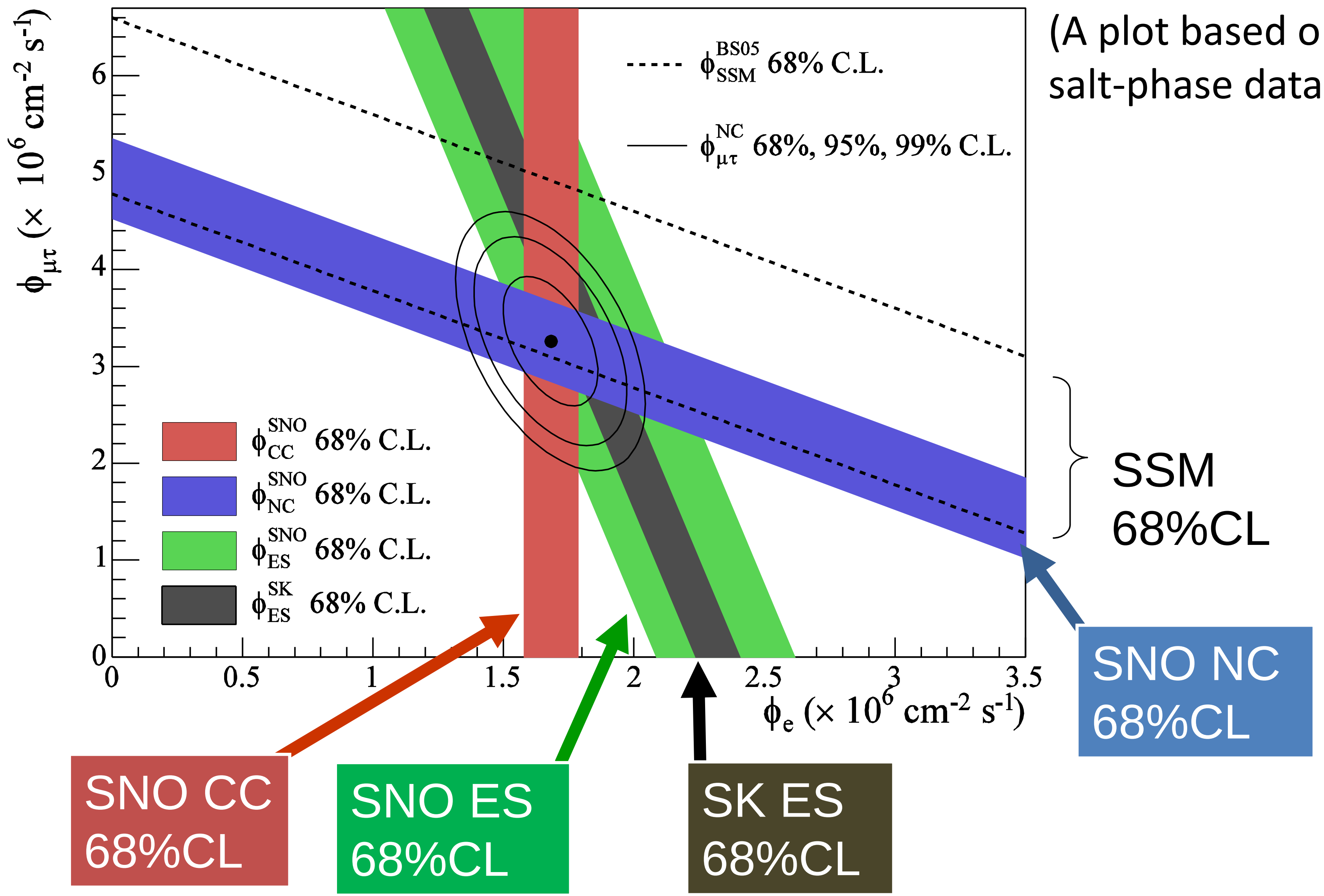
1000 ton of D_2O



Evidence for solar neutrino oscillations

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

(A plot based on the salt-phase data)



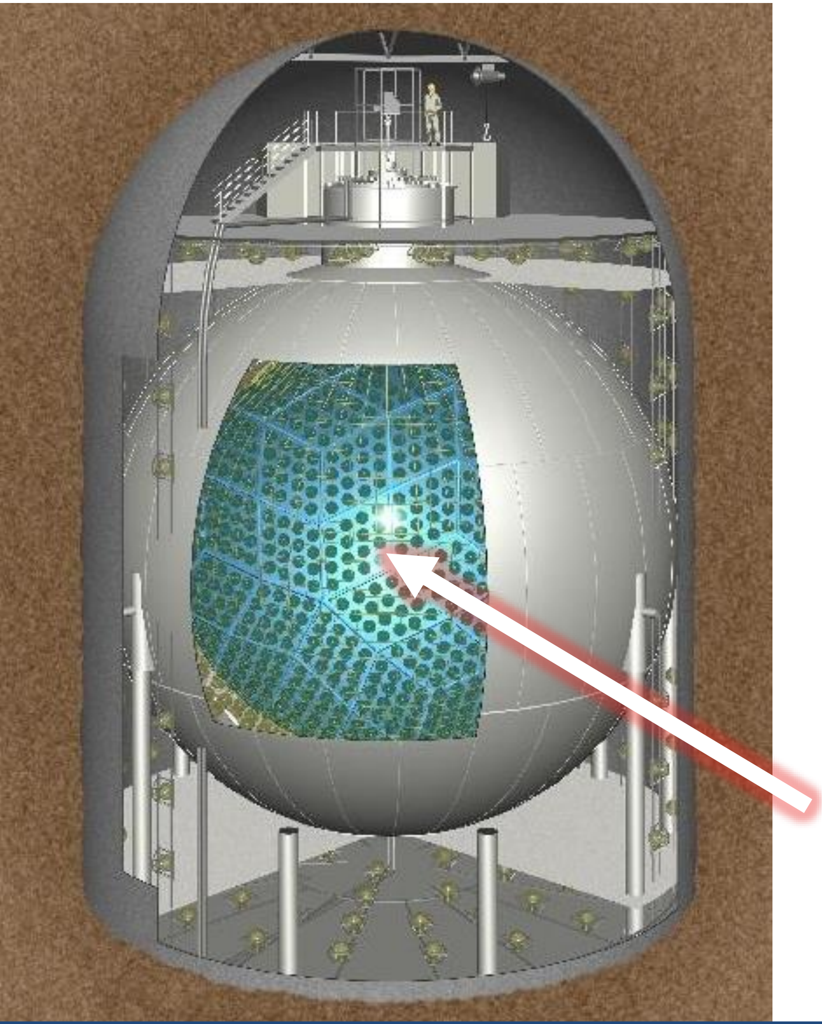
Three (or four) different measurements intersect at a point.

The intersect point clearly indicates non-zero $\nu_\mu + \nu_\tau$ flux.

$\rightarrow$ $\nu_e \rightarrow \nu_\mu + \nu_\tau$

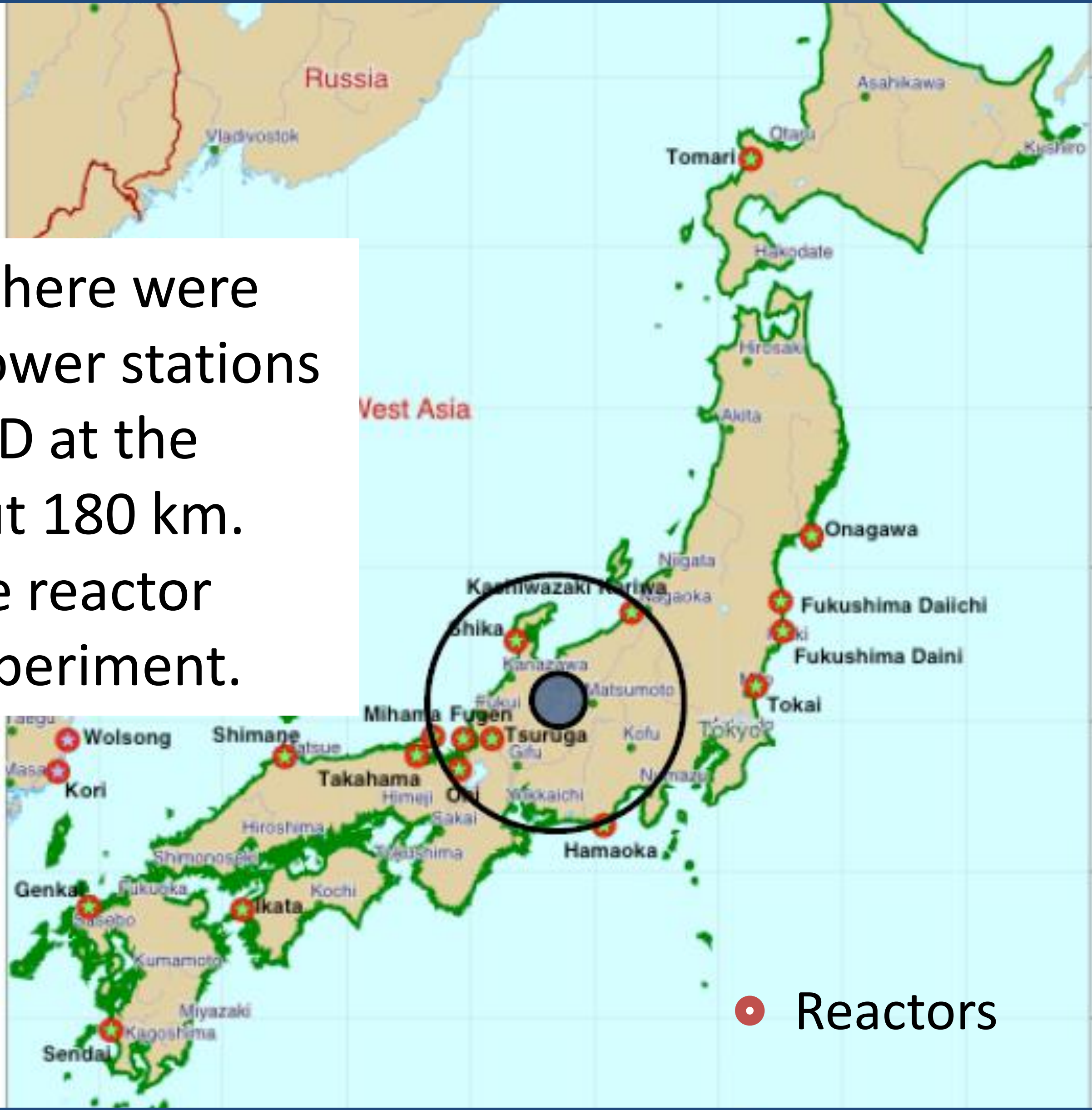
KamLAND (another experiment in Kamioka)

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



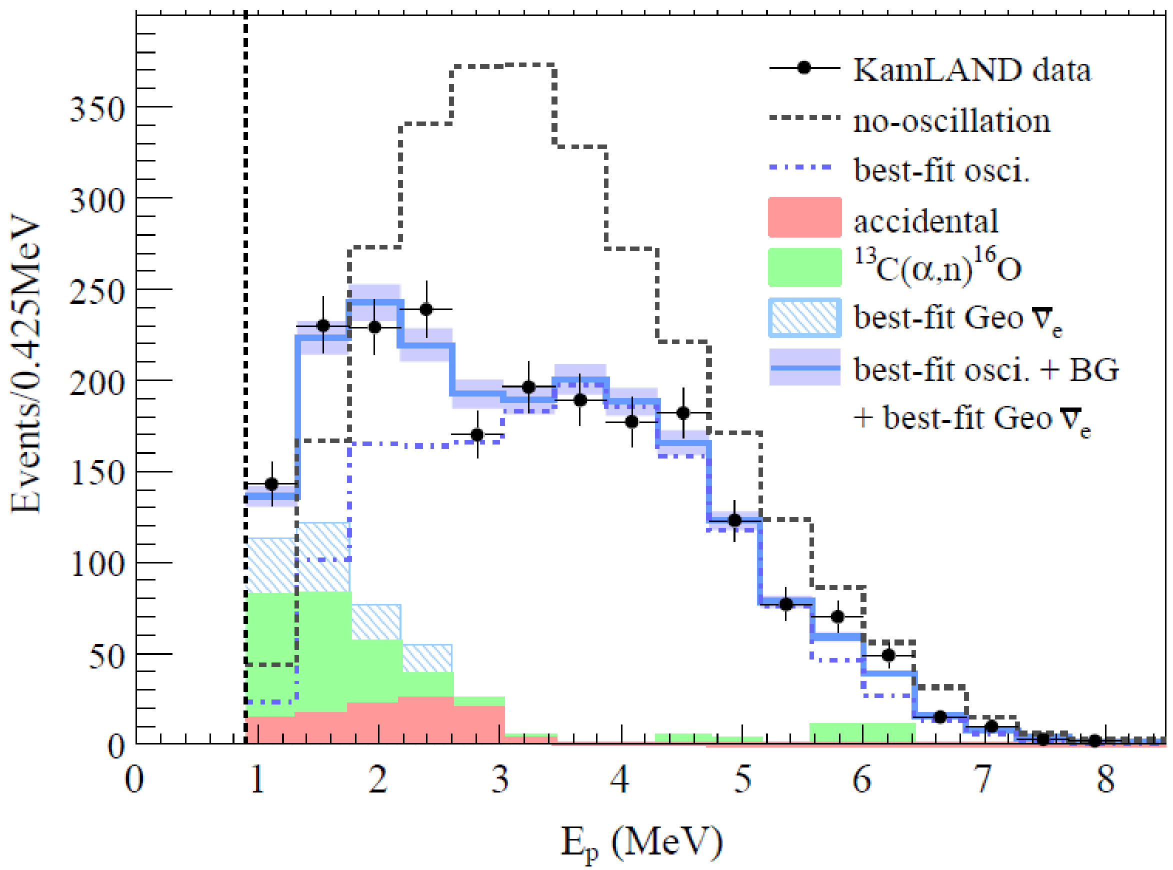
1kton liq. scintillator

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.



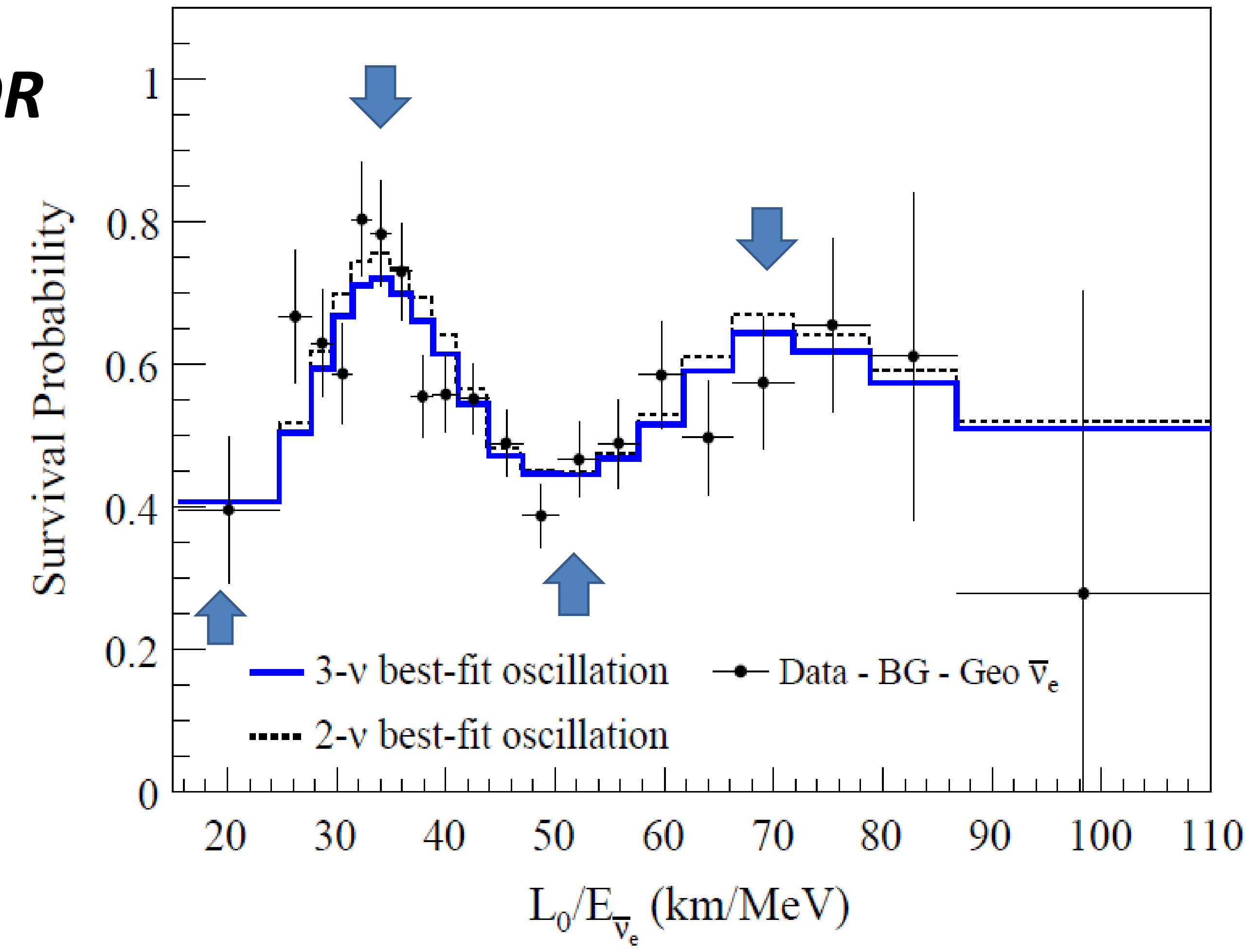
Really neutrino oscillations !

KamLAND PRD 83 (2011) 052002



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

OR



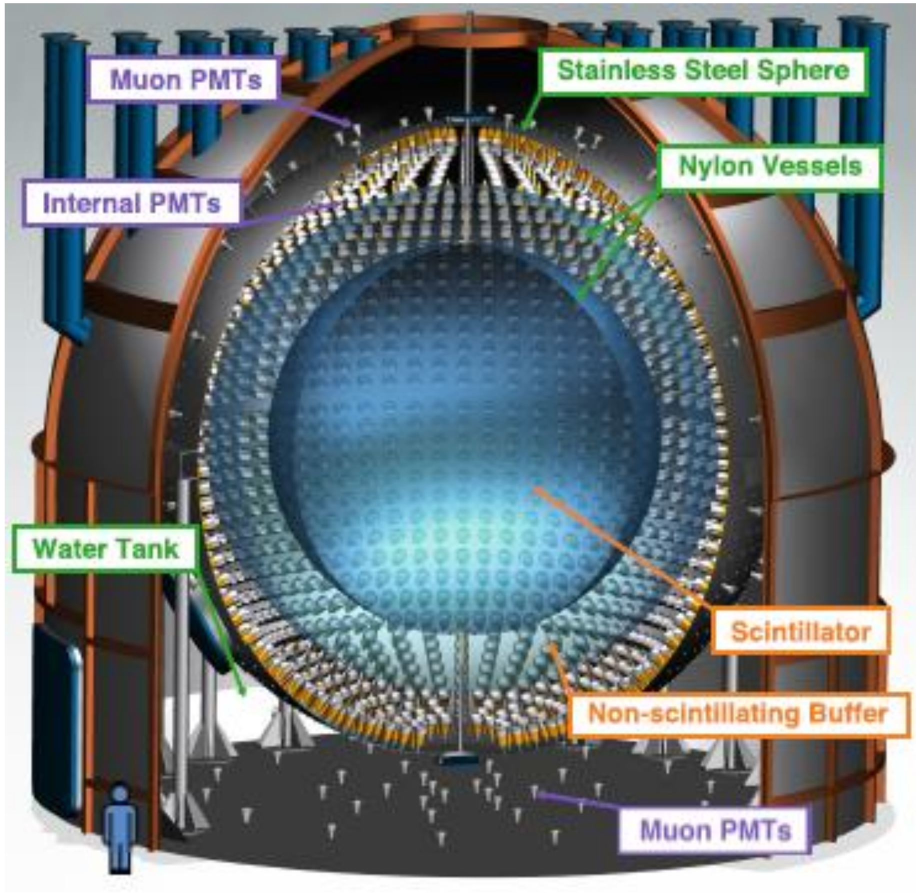
Really neutrino oscillations!

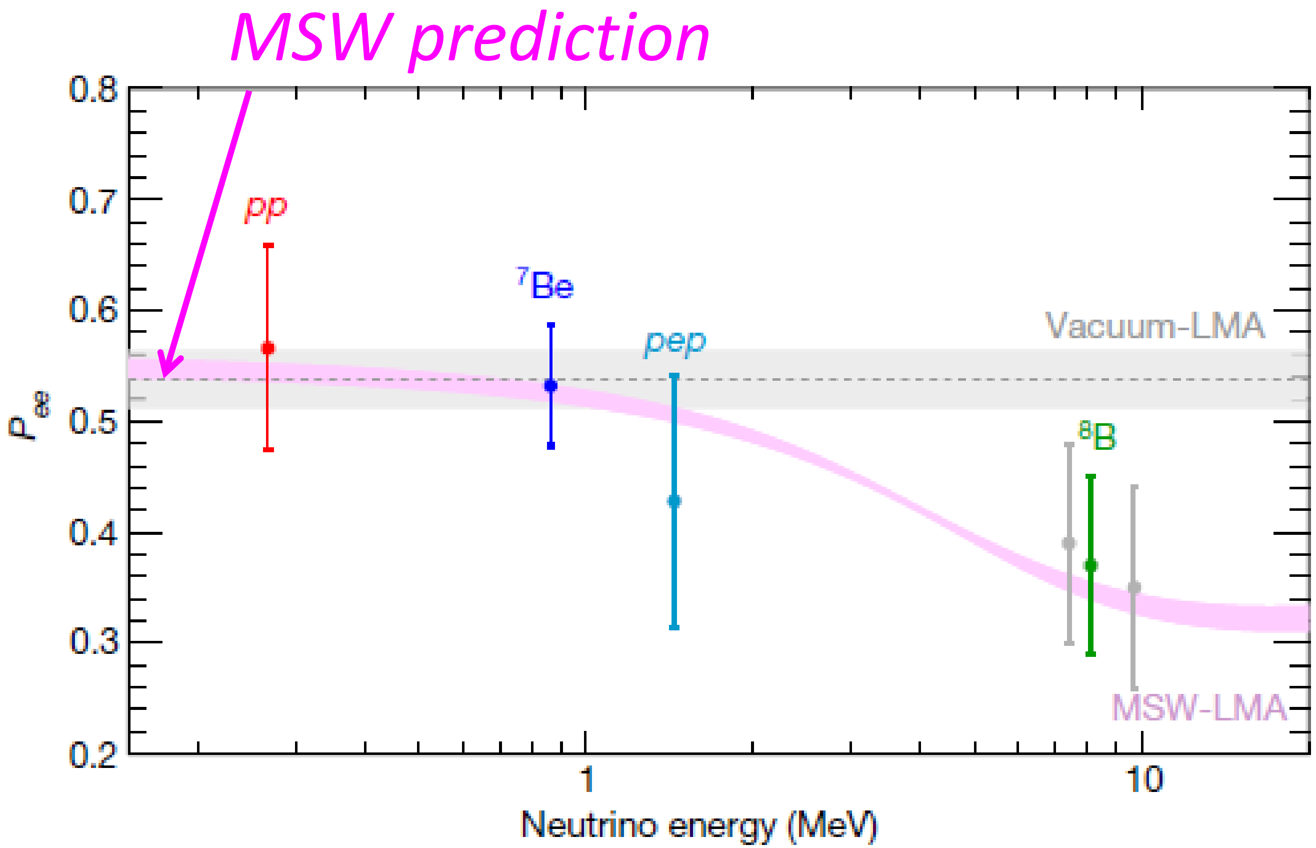
Consistent with MSW (neutrino oscillations in matter) !

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





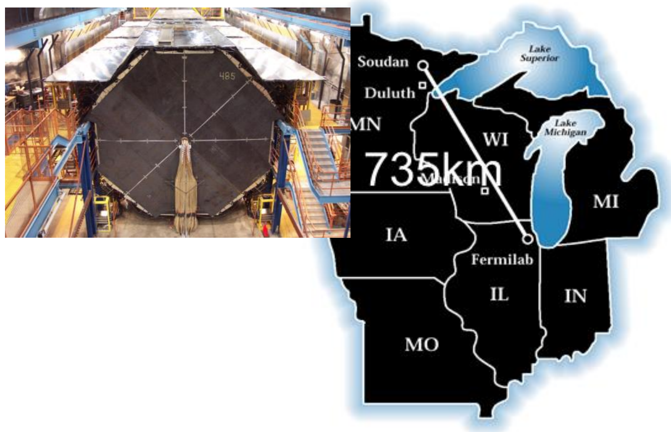
- ✓ *The data are consistent with the MSW prediction!*
- ✓ *Also, observation of CNO neutrinos (Nature 587 (2020) 577-582) !*

Neutrino oscillations: The third oscillation channel

Experiments for the third neutrino oscillations

Accelerator based long baseline neutrino oscillation experiments

MINOS

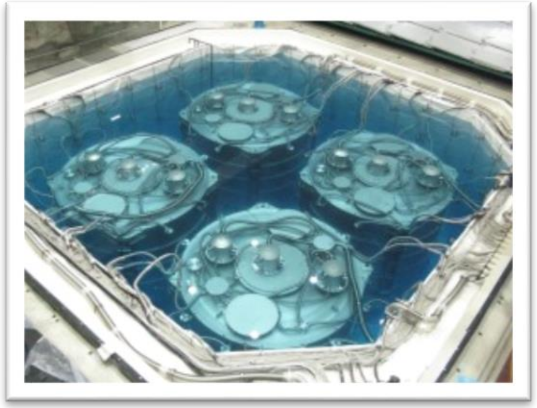


T2K

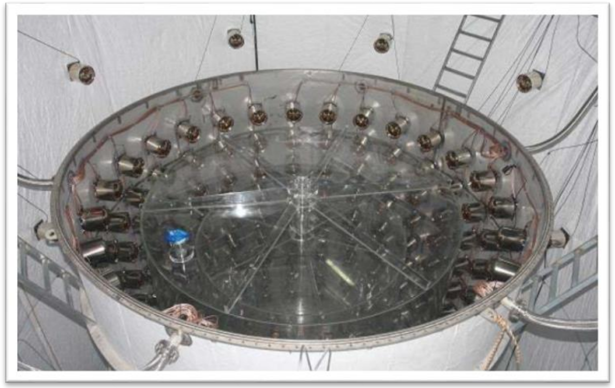
NOνA *(came slightly late)*

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

Daya Bay



RENO

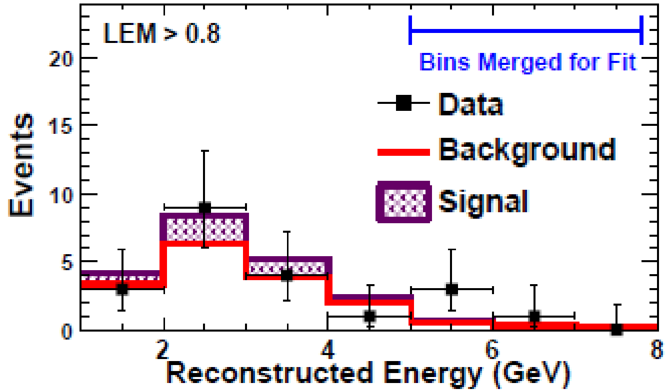


Double Chooz

Discovery of the third neutrino oscillations (2011-2012)

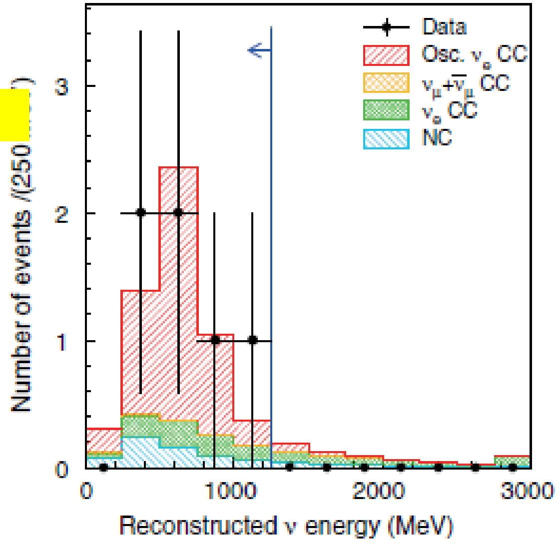
Accelerator based ν_e appearance experiments

MINOS PRL 107 (2011) 181802



T2K

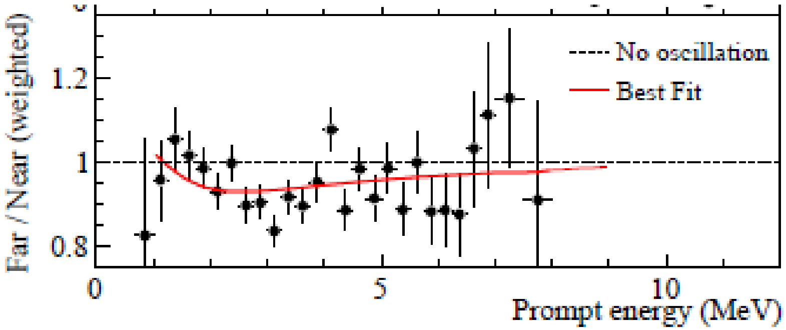
PRL 107 (2011) 041801



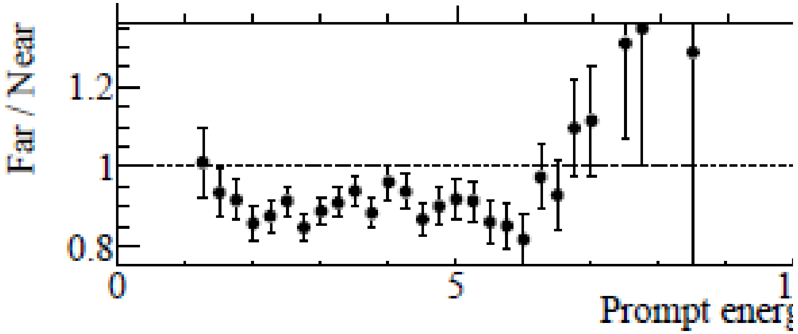
Note: these data are those in 2011-2012. The updated data are much better (including those from NOvA).

Reactor based anti-ν_e disappearance experiments

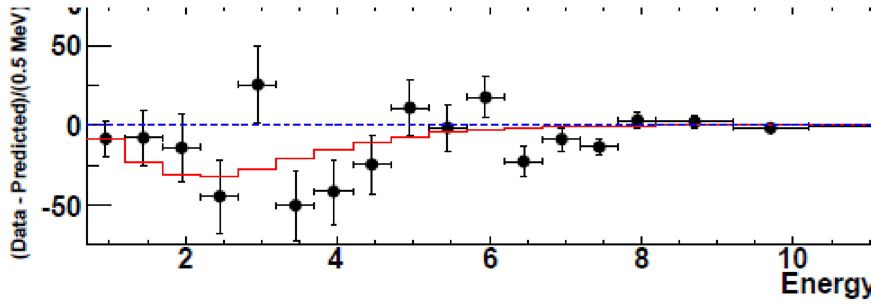
Daya Bay PRL 108 (2012) 171803



RENO PRL 108 (2012) 191802



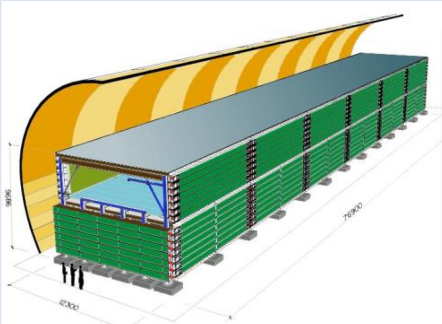
Double Chooz PRL 108 (2012) 131801

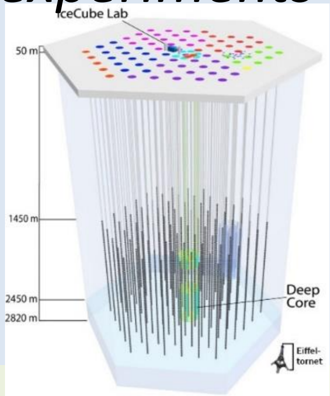


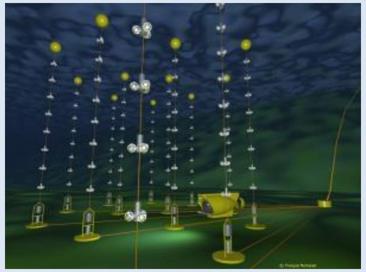
The basic structure for 3 flavor neutrino oscillations has been understood!

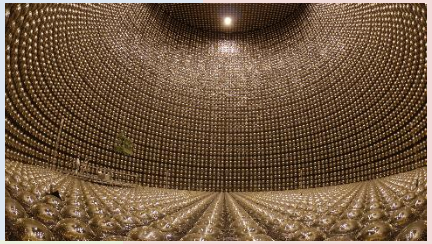
Many exciting results in neutrino oscillations (partial list)

Atmospheric neutrino oscillation experiments

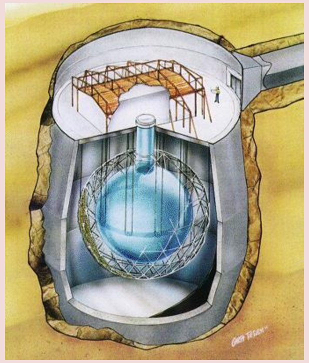


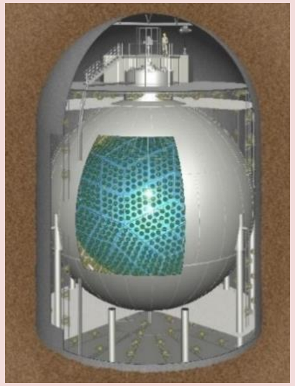


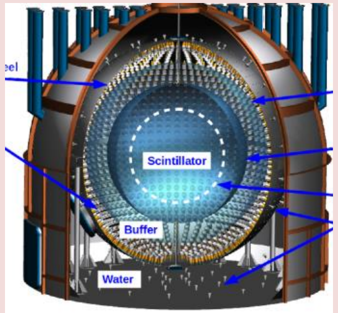




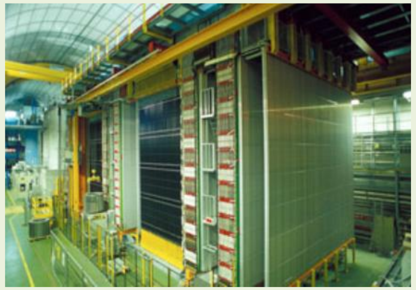
Solar neutrino oscillation experiments



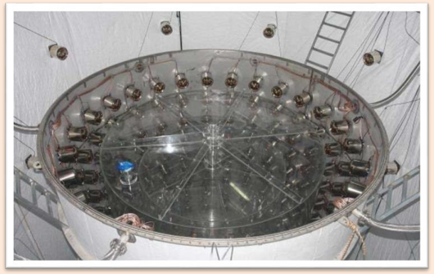


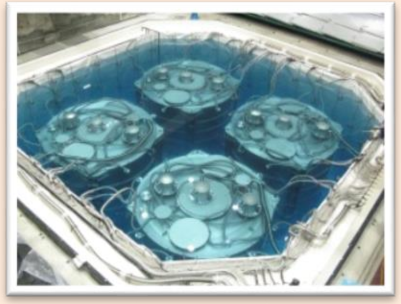


Accelerator based neutrino oscillation experiments



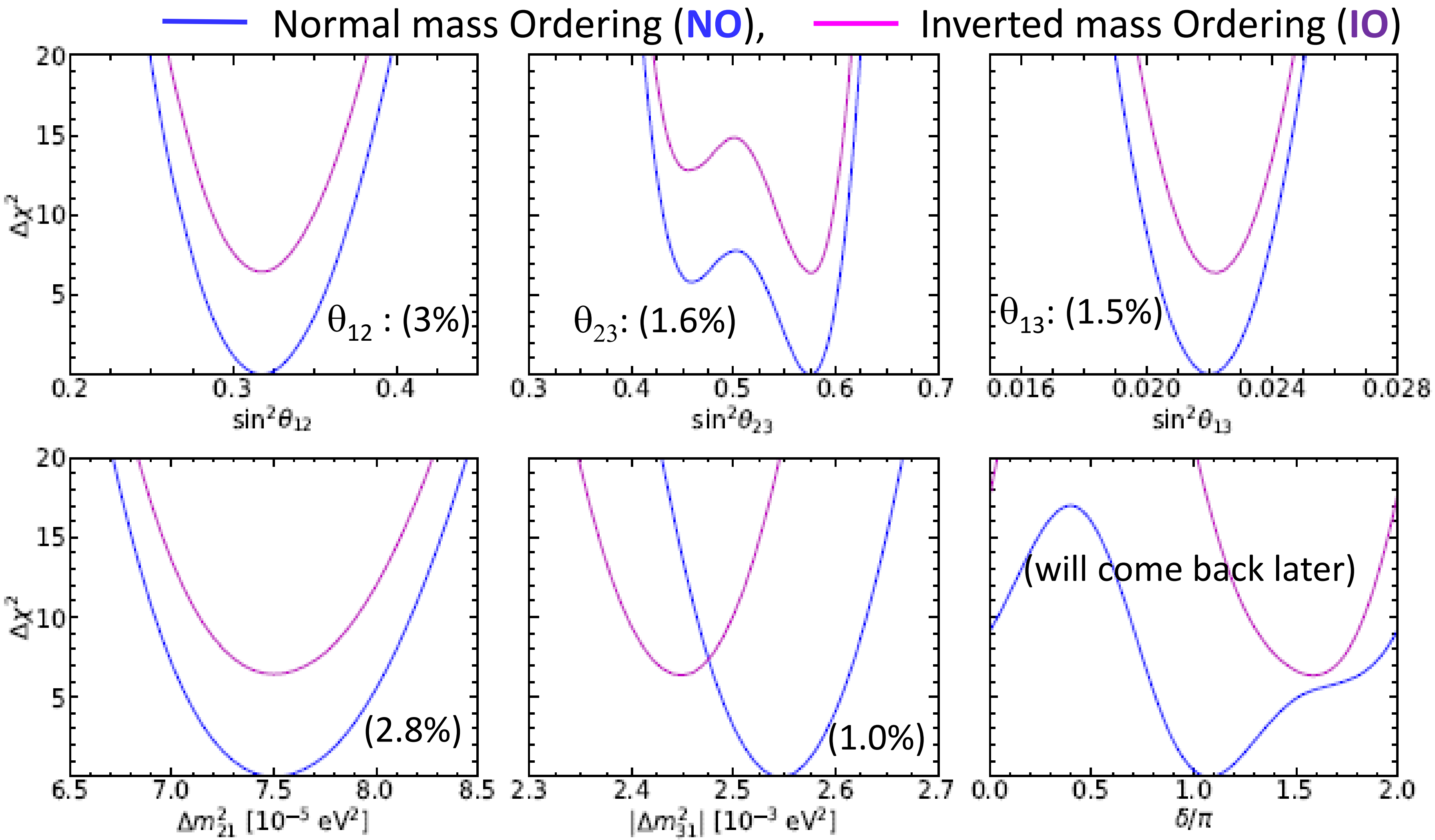
3 flavor(type) neutrino oscillation experiments

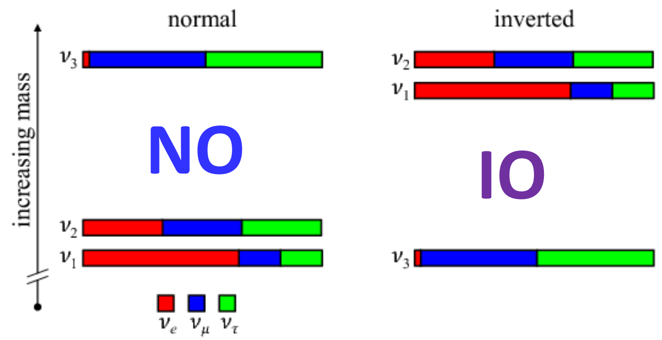




Oscillation parameters

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





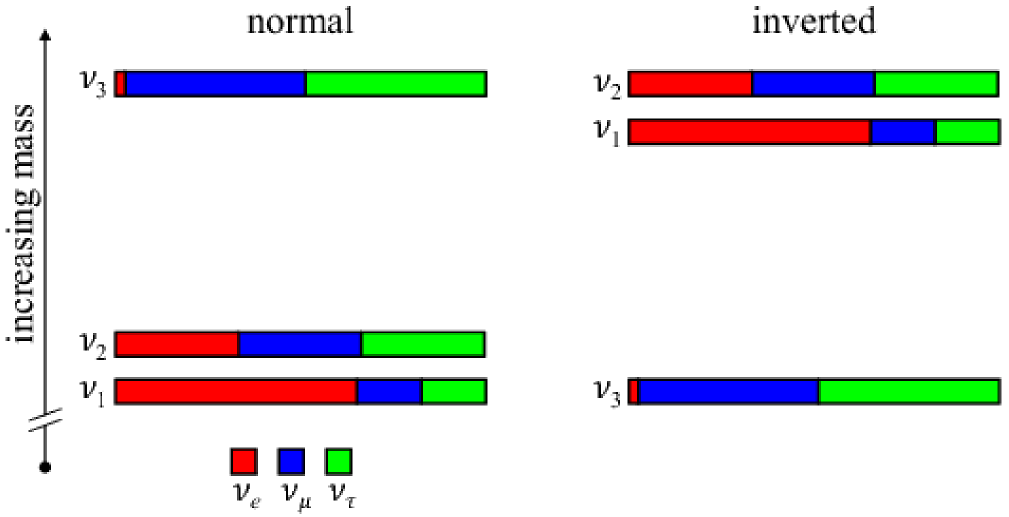
(numbers in parenesis are 1σ uncertainties assuming **NO**)

➔ 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

Agenda for future neutrino studies

Neutrino mass ordering?



Absolute neutrino mass?

Beyond the 3 flavor framework? (Sterile neutrinos?)

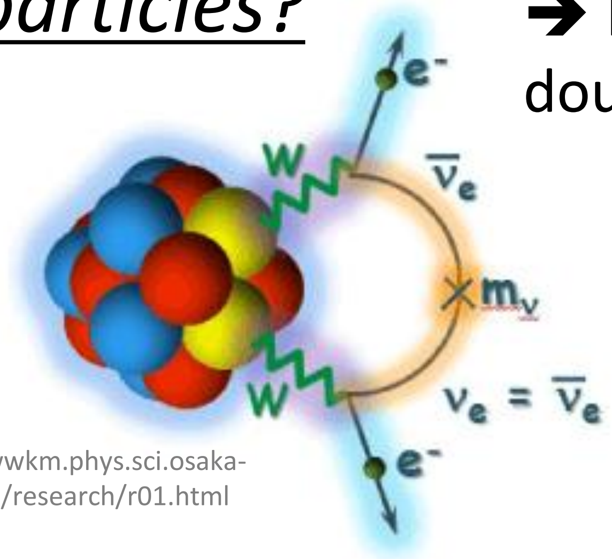
CP violation?

$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \ ?$$

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

- Neutrinos have been playing very important roles in understanding the laws of nature, in particular the laws at the smallest scales.
- Recent discovery and studies of neutrino oscillations and the small neutrino mass must be very important to understand the physics beyond the Standard Model of particle physics. Neutrinos with small mass might also be the key to understand the big question in the largest scale, namely the Universe; why only matter particles exist at the present Universe.
- Neutrinos are likely to continue playing very important roles in understanding the nature in the smallest and the largest scales.