Neutrino Physics

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Outline

- *About 100 years ago*
- *Discovery of neutrinos*
- *Neutrino problems*
- *Neutrino oscillations*
- *Neutrinos as messengers of the Universe*
- *Summary*

This is an experimental talk (no theory, I apologize).
Also some important topics may not be mentioned.

About 100 years ago

β decays

- In 1899, Ernest Rutherford showed that two types of radiation exist, which he called alpha and beta.
- In 1902, Walter Kaufmann showed that beta radiation was nothing more than electrons.

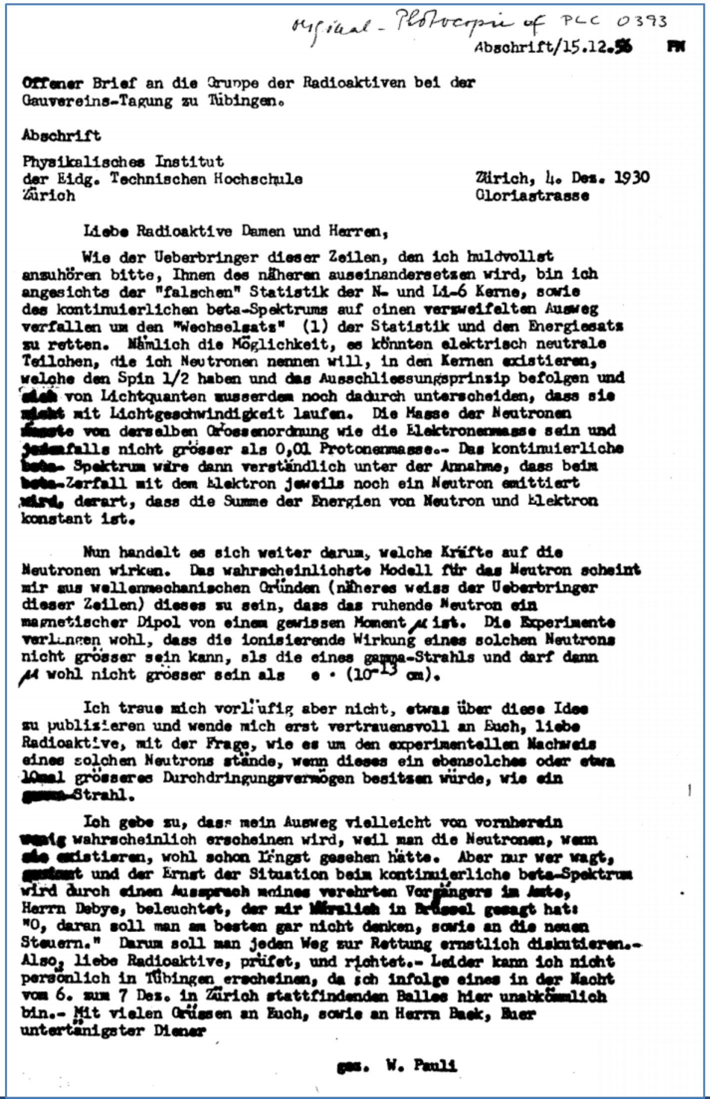
$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^{-} \qquad \text{(}e^{-}\text{ should have a fixed energy.)}$$

- The Kaufmann's experiments also showed that beta rays have wide range of velocities. A similar result was also found by Becquerel.
- (During the first decade of the 20th century, the physics community did not accept that the energy spectrum of electrons emitted in beta decays was continuous.)
- ….
- In 1927, Charles D. Ellis and William A. Wooster made a decisive experiment on radium E (bismuth-210), using a calorimetric technique giving a direct proof that the electron spectrum was continuous. The average heating energy was 344 +/- 40 keV, in good agreement with the average energy of the ionization measurement, which was 390 +/- 60 keV, and in marked disagreement with the value of more than 1MeV expected for the monoenergetic hypothesis.

Allan Franklin, in "History of the Neutrino 1930-2018", Ed. M.Cribier, J.Dumarchez, D.Vignaud, pp 9 – 30.
https://neutrino-history.in2p3.fr/prehistory-and-birth-of-the-neutrino/

Birth of neutrino

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



Original - Photocopie of PLC 0393
Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

W. E. Pauli (Wikipedia)

The continuous beta spectrum would then become understandable by the assumption that in beta decay a "neutron" is emitted in addition to the electron such that the sum of the energies of the "neutron" and the electron is constant...

(http://www.pp.rhul.ac.uk/~ptd/TEACHING/PH2510/pauli-letter.html)

At the end of 1933, incorporating the Pauli's neutrino hypothesis, Enrico Fermi built the theory of beta decay, which describes the decay of a neutron into a proton, emitting an electron and a "neutrino".

Enrico Fermi (Wikipedia)

ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL' ECONOMIA NAZIONALE

Tentativo di una teoria dell' emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

In 1934, Hans Bethe and Rudolf Peierls showed that the cross section between a neutrino and a proton should be extremely small. ➔weak interaction

https://neutrino-history.in2p3.fr/prehistory-and-birth-of-the-neutrino/

Discovery of neutrinos

Discovery of (anti-electron) neutrino

- In the 1934 paper, Bethe and Peierls wrote "There is no practical way of observing the neutrino".
- In 1946, Bruno Pontecorvo proposed to use the inverse beta-process to detect the neutrinos.
- In 1956, Frederick Reines and Clyde Cowan observed interactions of (anti-electron) neutrinos that were generated by nuclear plant of Savannah River.

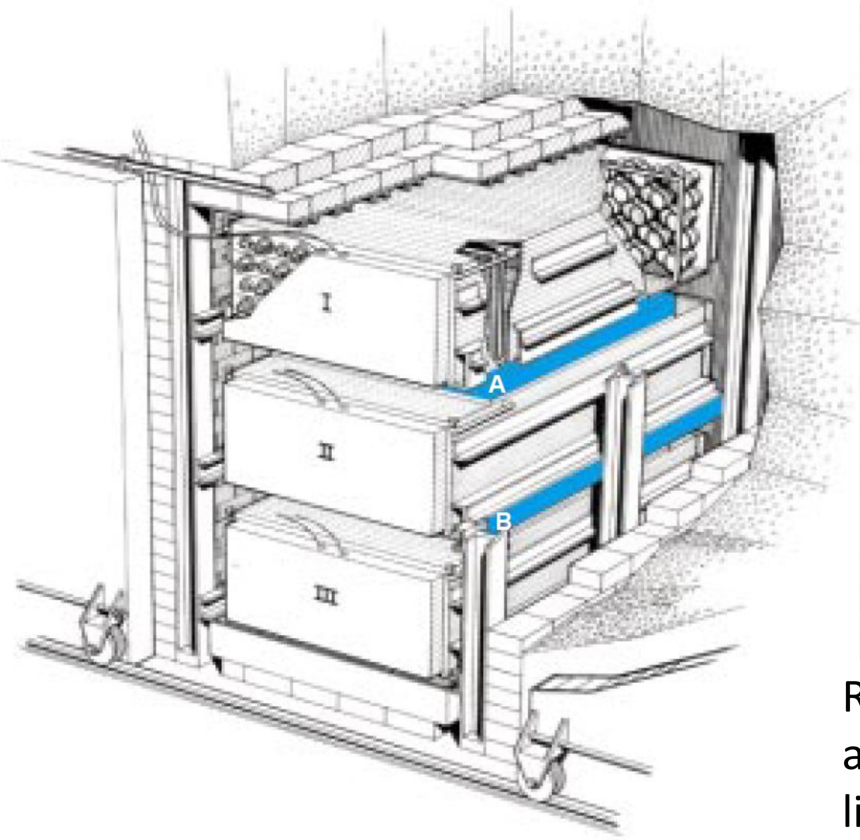
20 July 1956, Volume 124, Number 3212 SCIENCE

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were used to analyze and record the operation

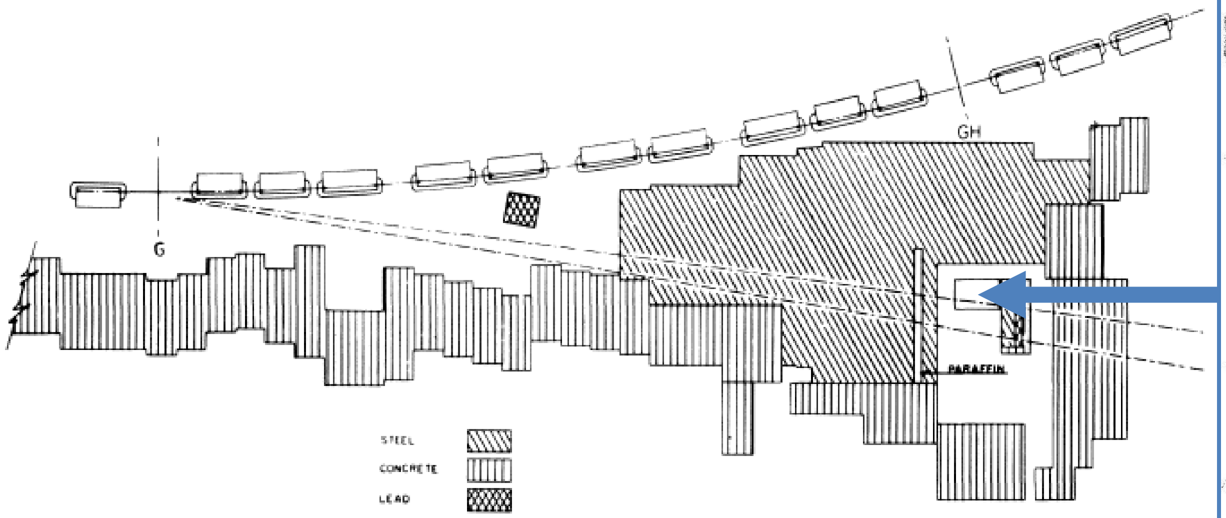


Reines & Cowan experiment in 1956. A and B show the plastic tanks with 200 liters of water each. (Photo by H. Sobel)

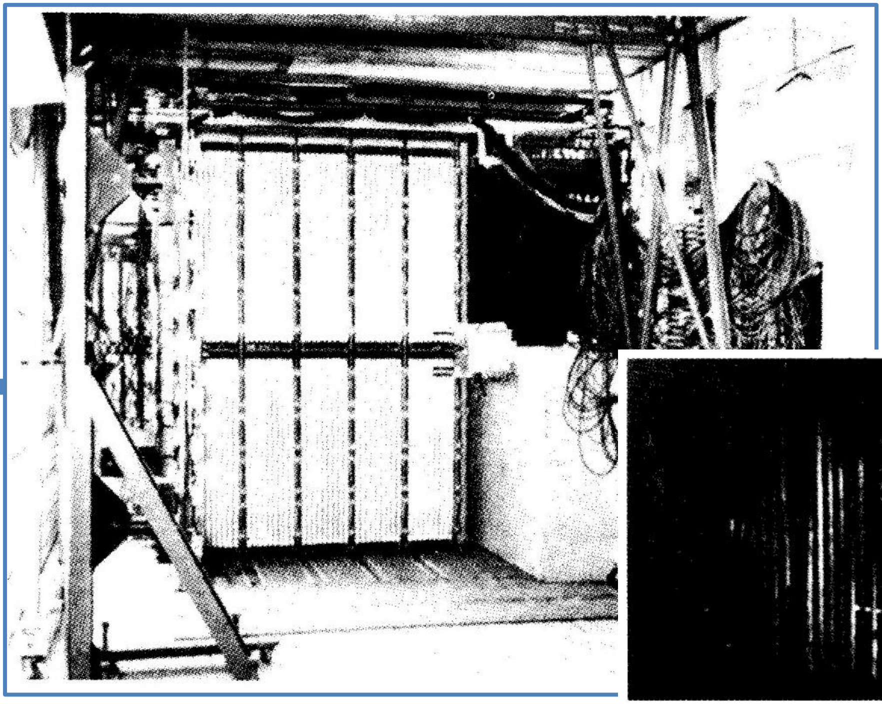
https://library.lanl.gov/cgi-bin/getfile?00326606.pdf

Discovery of muon neutrino (second type of neutrino)

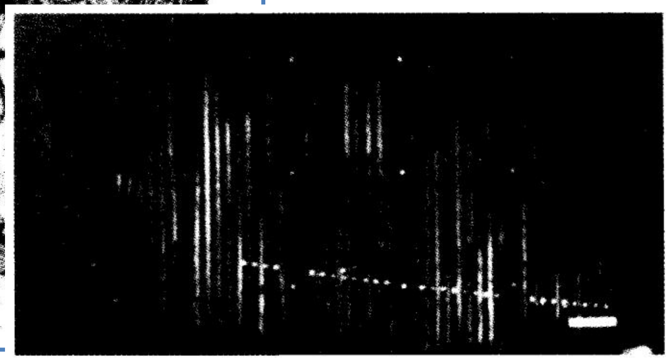
- In late 1959, Melvin Schwartz attended a coffee-hour discussion led by T.D. Lee about investigations of weak interactions at high energy. In that evening, Schwartz had an idea to make a neutrino beam in order to directly make these investigations (M. Schwartz, Phys. Rev. Lett. 4 (1960) 306).
- Pontecorvo had published an earlier paper with similar ideas for creating neutrino beams (Soviet Physics JETP 10 (1960) 1236 ; J. Exp. Theoret. Phys. 37 (1959) 1751).
- The first experiment was carried out at BNL. In 1962, the results demonstrated 2 types of neutrinos: 34 single muon events were detected from 3.48 x 10^{16} circulating protons. No certified electrons were observed.



Plan view of the AGS neutrino experiment



A single muon event

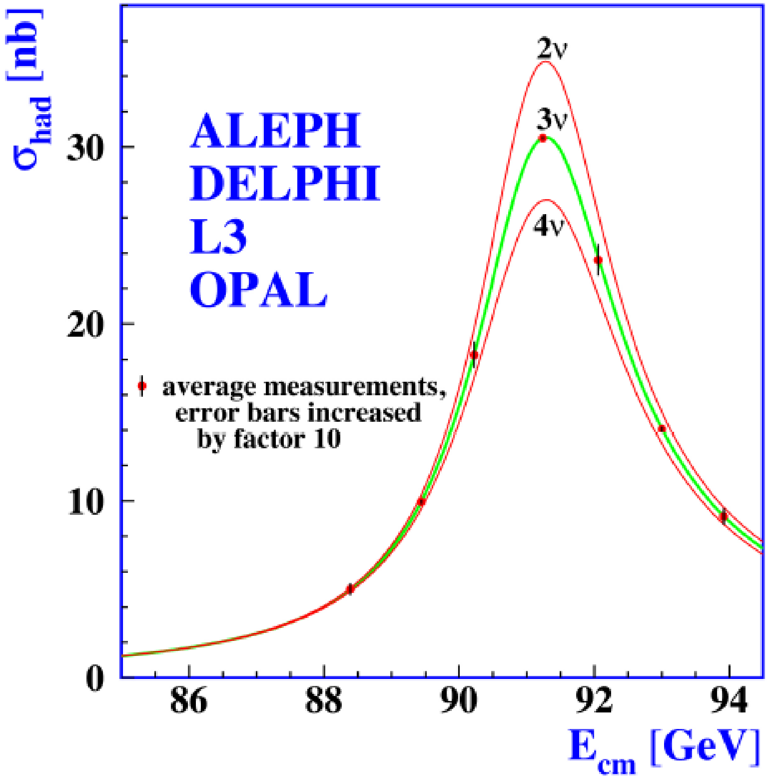


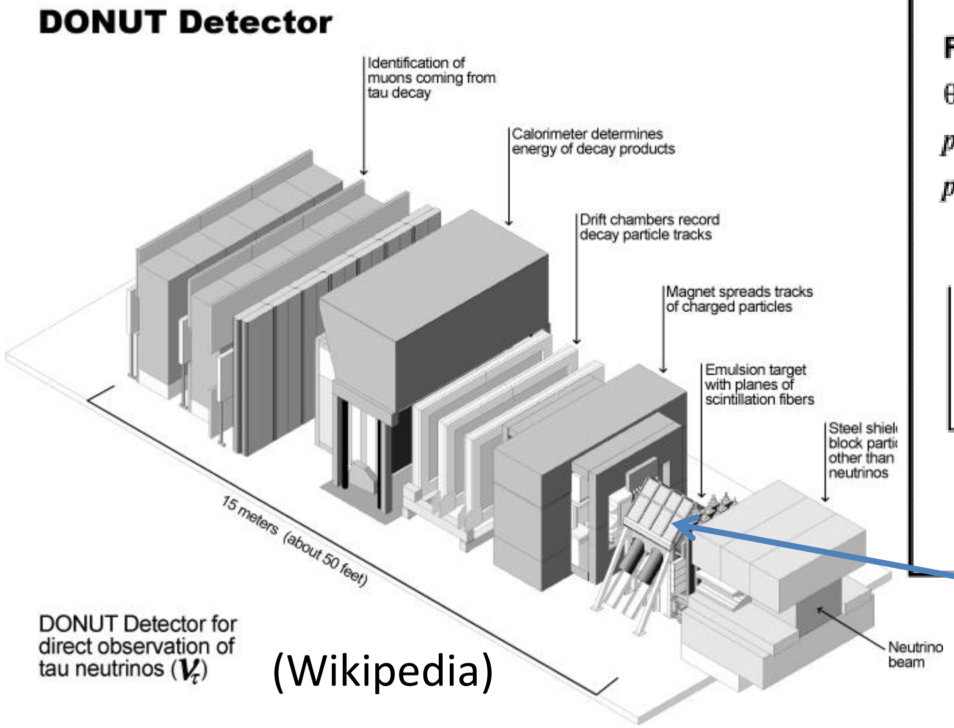
A

Lee Grodzins, Discoveries from 1955 to 1962, in History of the Neutrino (in https://neutrino-history.in2p3.fr/new-families-of-neutrino/)

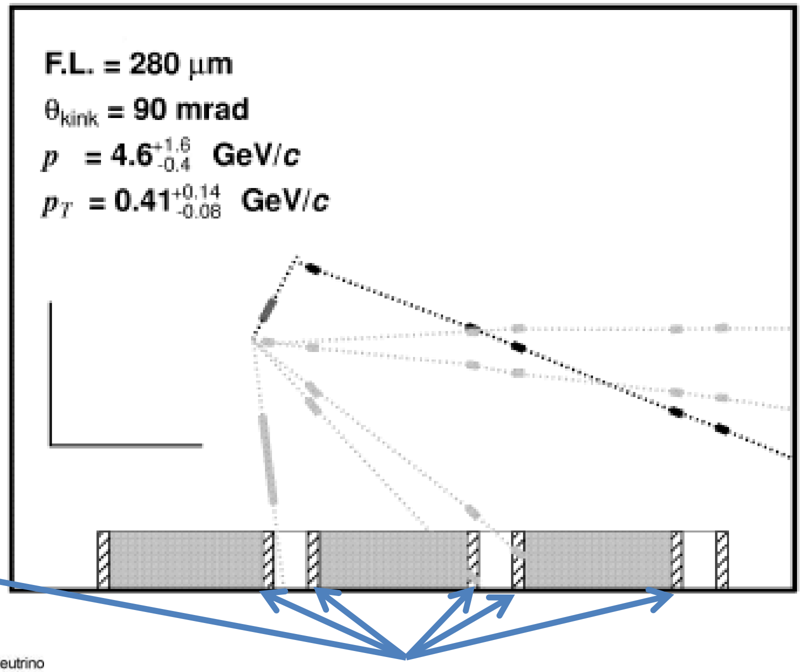
The number of neutrinos and the discovery of tau-neutrinos

- An important question was the number of neutrino flavors.
- The experiments at LEP precisely measured the number of light, active neutrino flavors to be 2.9840 +/- 0.0082 (S. Schael et al., Phys. Rep. 427 (2006) 257-454).
- $N_\nu = 3$ ➔ we should observe tau-neutrinos. ➔ In 2000, DONUT experiment reported the observation of the charged current ν_τ interactions (K. Kodama et al., Phys. Lett. B504, 218–224 (2001) .





(Wikipedia)



Emulsion

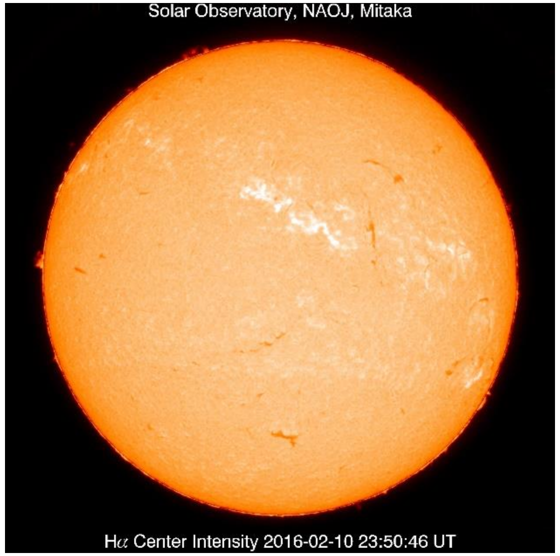
Alain Blondel, The third family of neutrinos, in History of the Neutrino (in https://neutrino-history.in2p3.fr/new-families-of-neutrino/)

Apology

There are various very important contributions of neutrinos to the establishment of the Standard Model of particle physics, such as the Parity violation, neutrino helicity, and the discovery of neutral current interactions. But let me move on to the other neutrino topics.

Neutrino problems

Solar neutrino problem



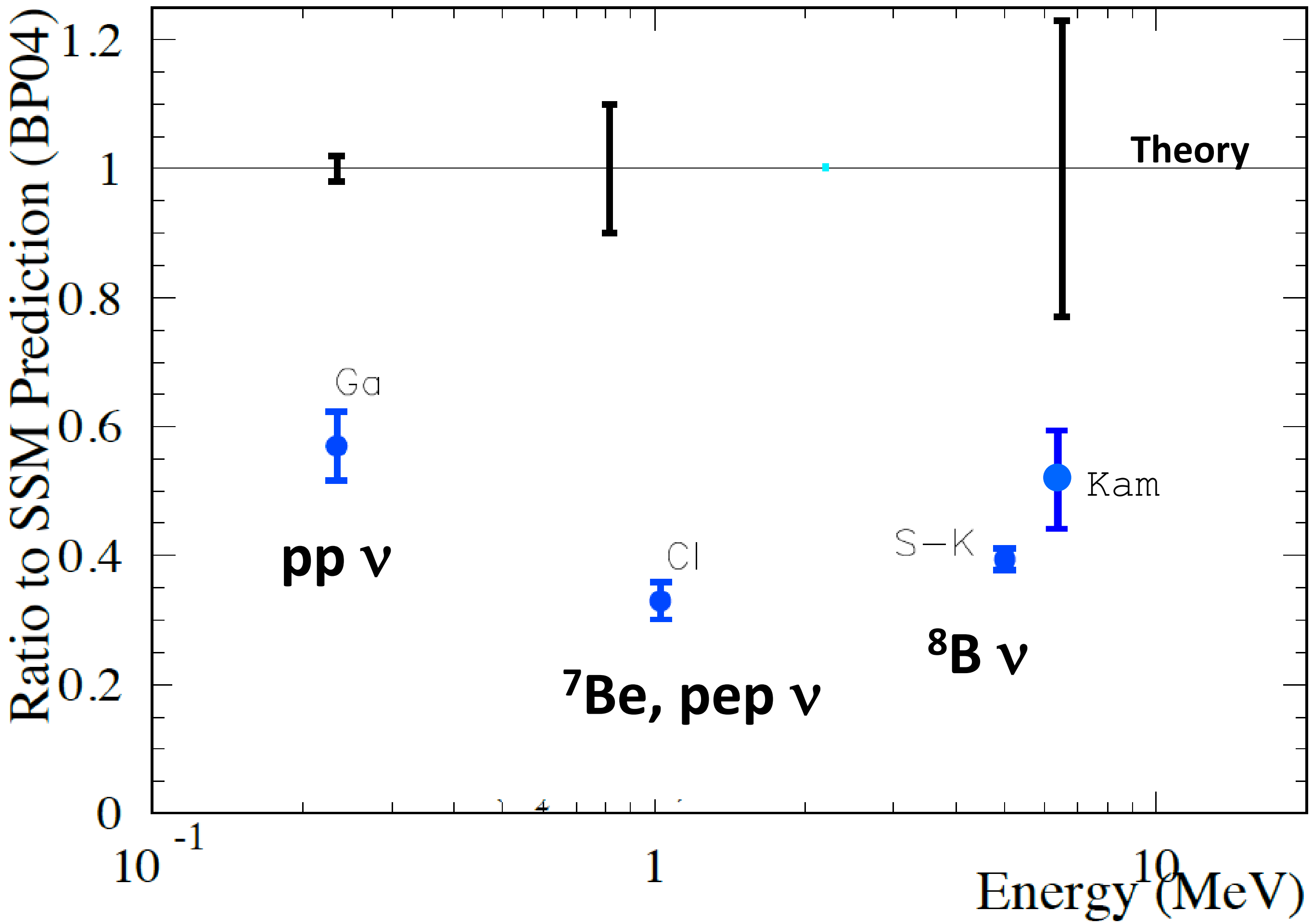
The Sun generates energy by nuclear fusion processes. Neutrinos are created by these processes. Therefore, the observation of solar neutrinos is very important to understand the energy generation mechanism in the Sun.

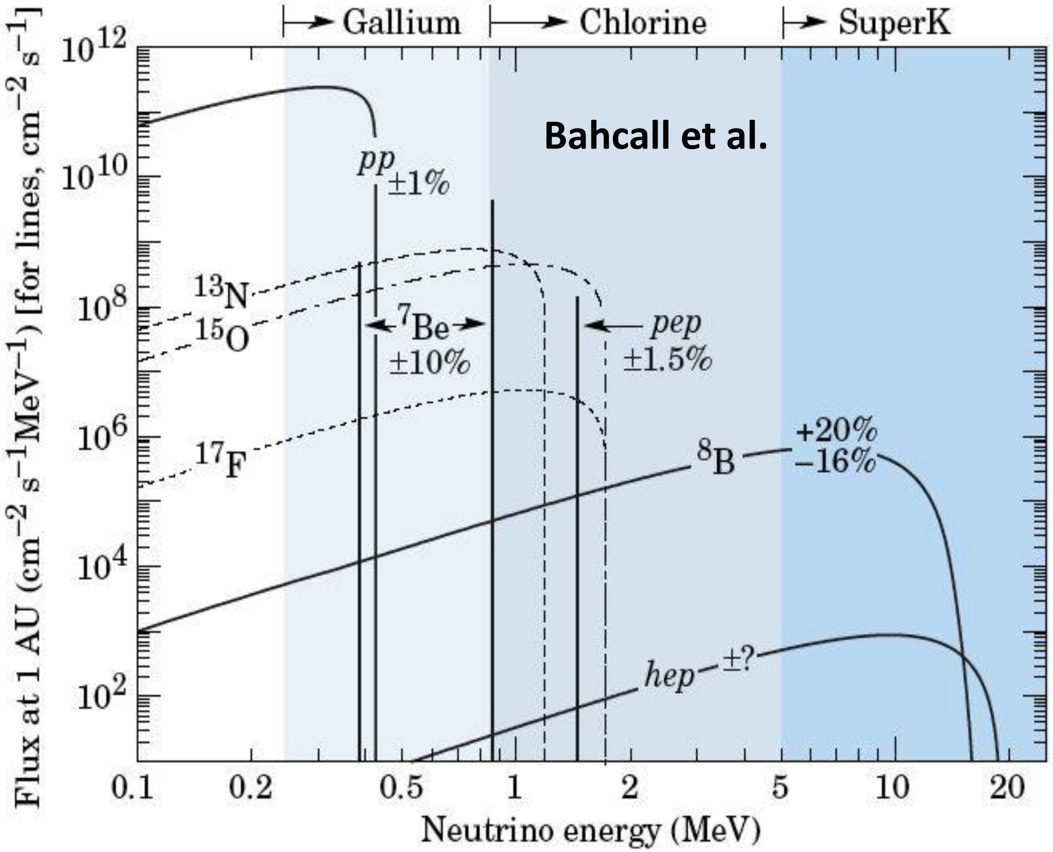
600ton C_2Cl_4

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 1960's).

Results from solar neutrino experiments (before ~2000)

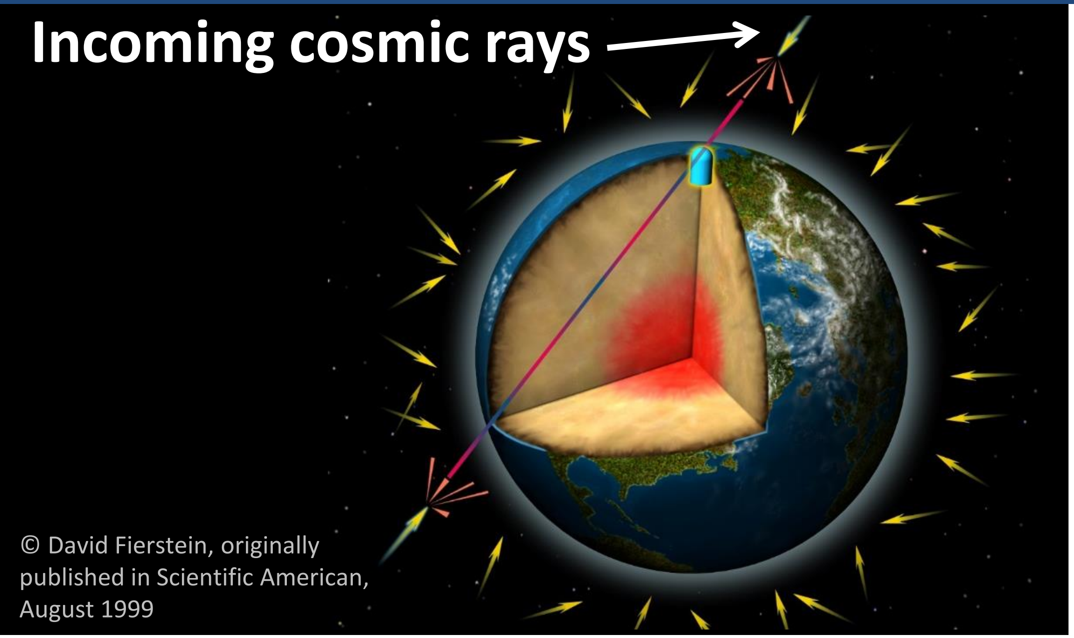
Following the initial observation, several experiments observed solar neutrinos.





Solar neutrino experiments in the 80's and 90's confirmed the deficit of solar neutrinos.

Atmospheric neutrinos



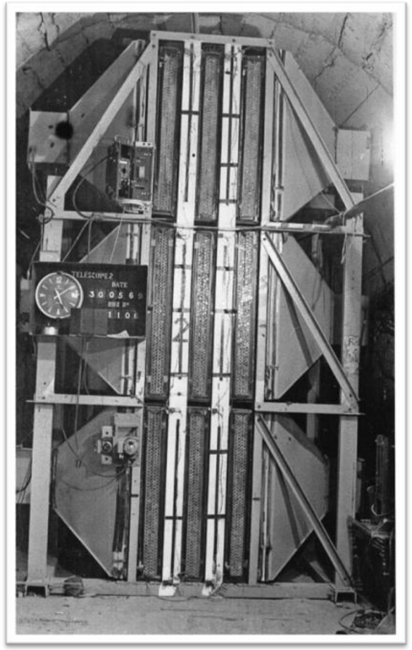
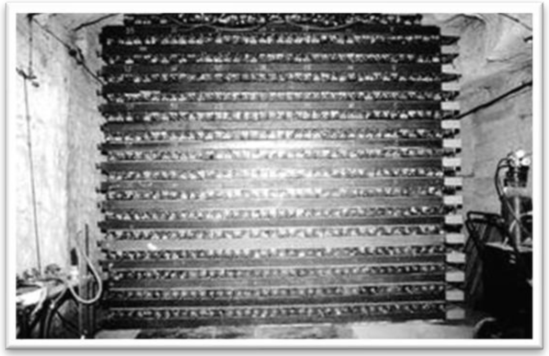


Photo by N. Mondal

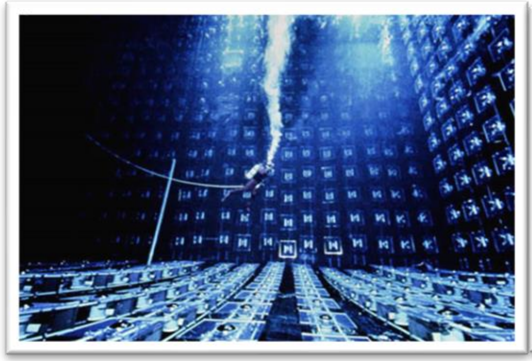
In 1965, atmospheric neutrinos were observed for the first time by detectors located extremely deep underground, one in India (left) and one in in South Africa (right).

Photo by 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.

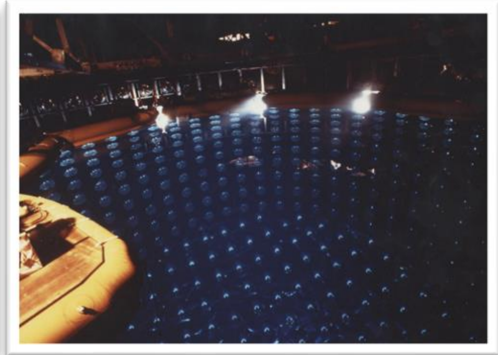


KGF

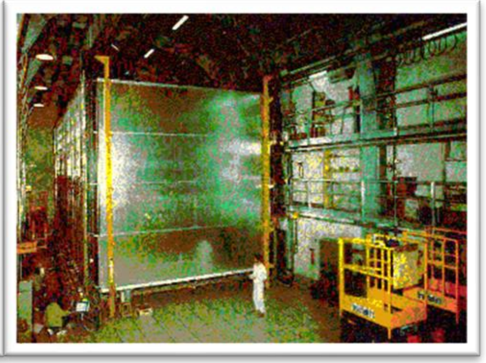


IMB

NUSEX



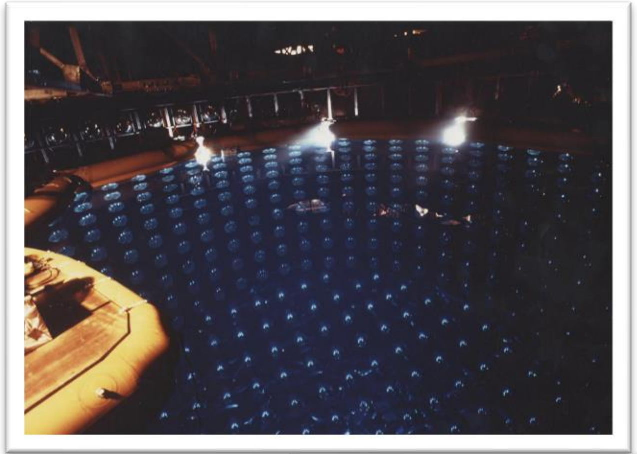
Kamiokande

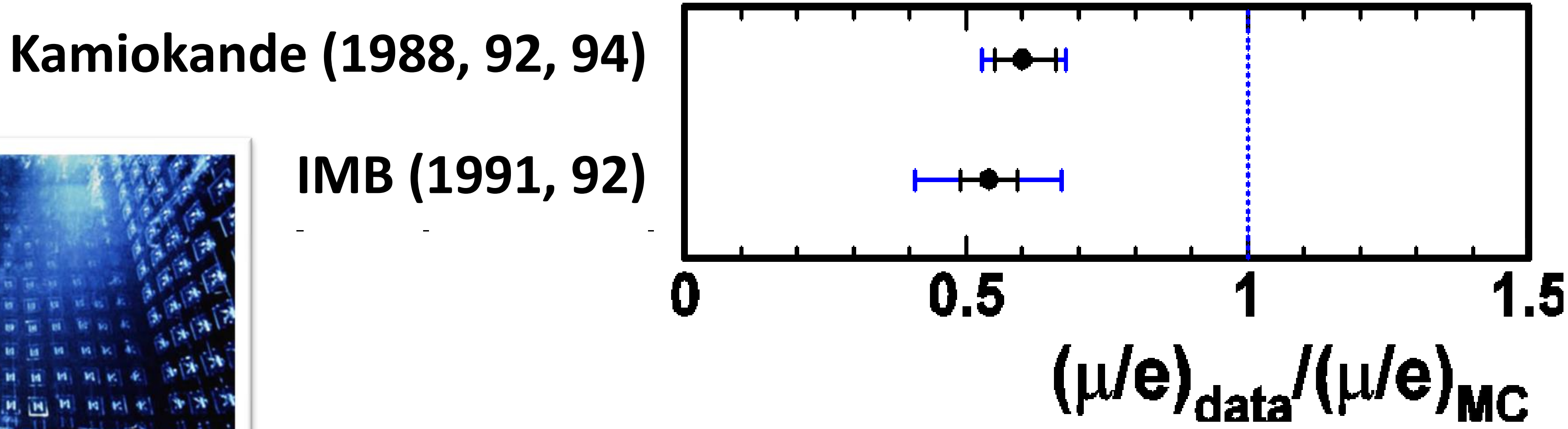


Frejus

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.





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

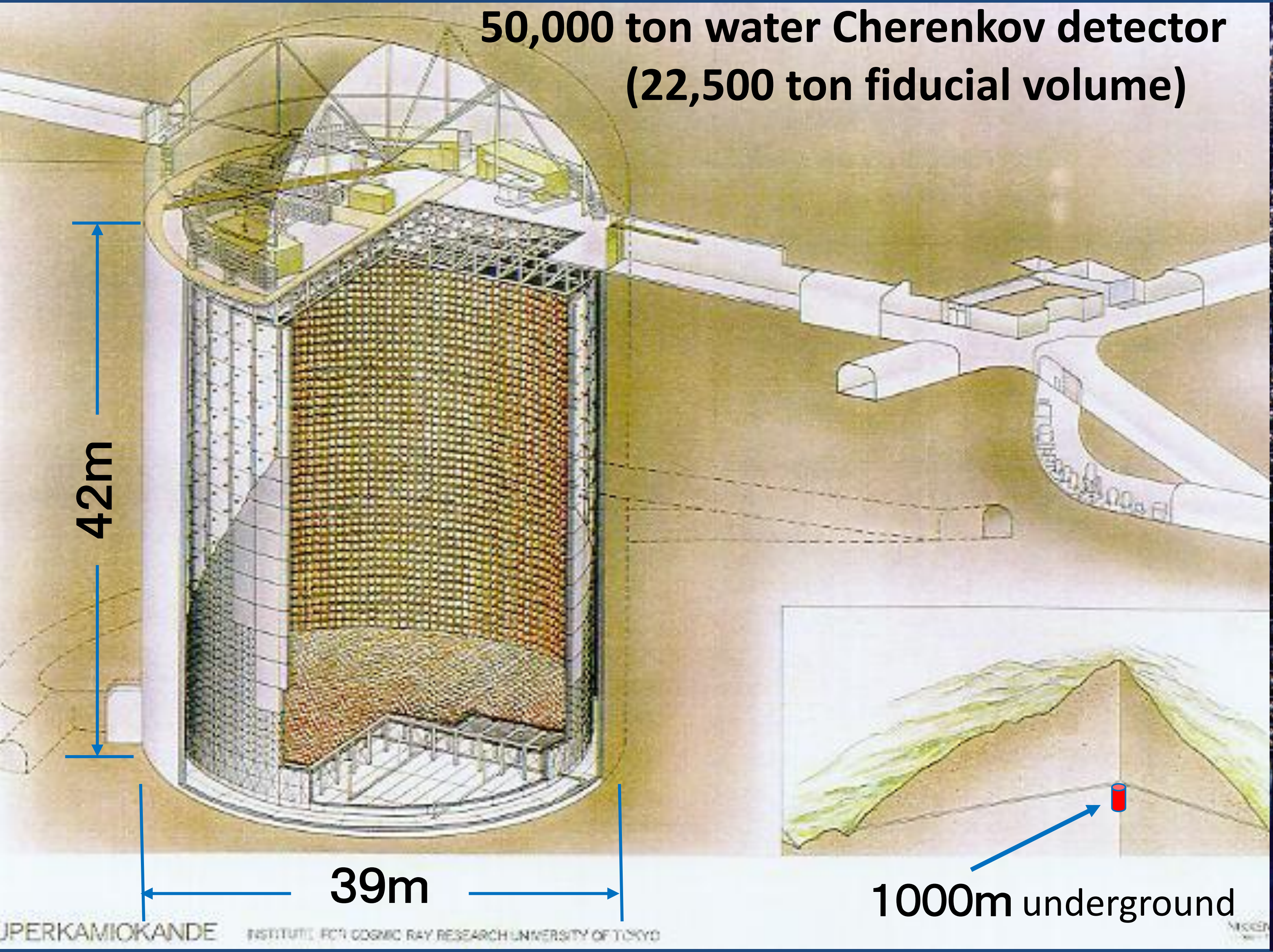
Neutrino oscillations

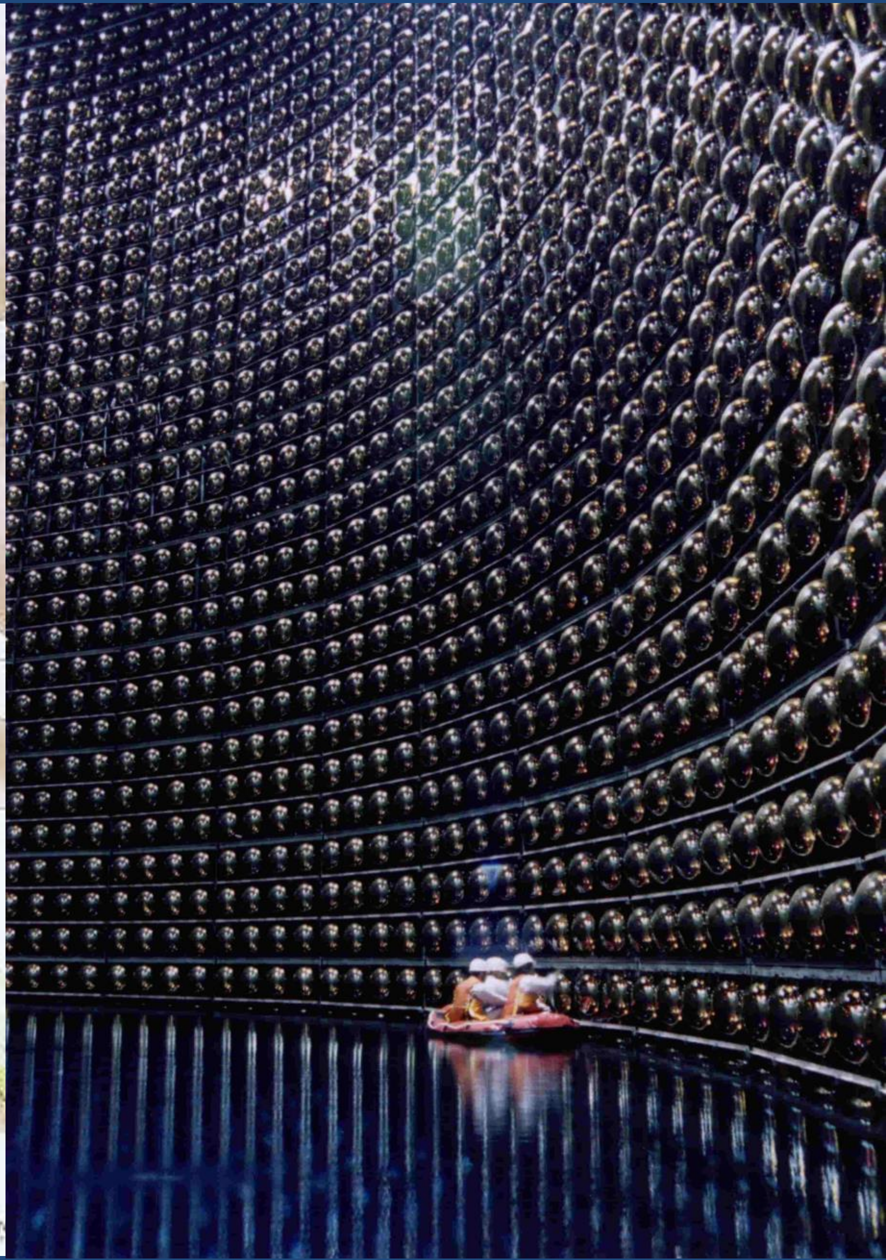
- ✓ In the Standard Model, neutrinos are assumed to be massless.
- ✓ However, physicists have been asking neutrinos really have no mass.
- ✓ Also, it was generally believed that, if neutrinos have very small mass, the small neutrino mass may imply physics beyond the Standard Model (See-saw mechanism). (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)

➔ Neutrino oscillation experiments!

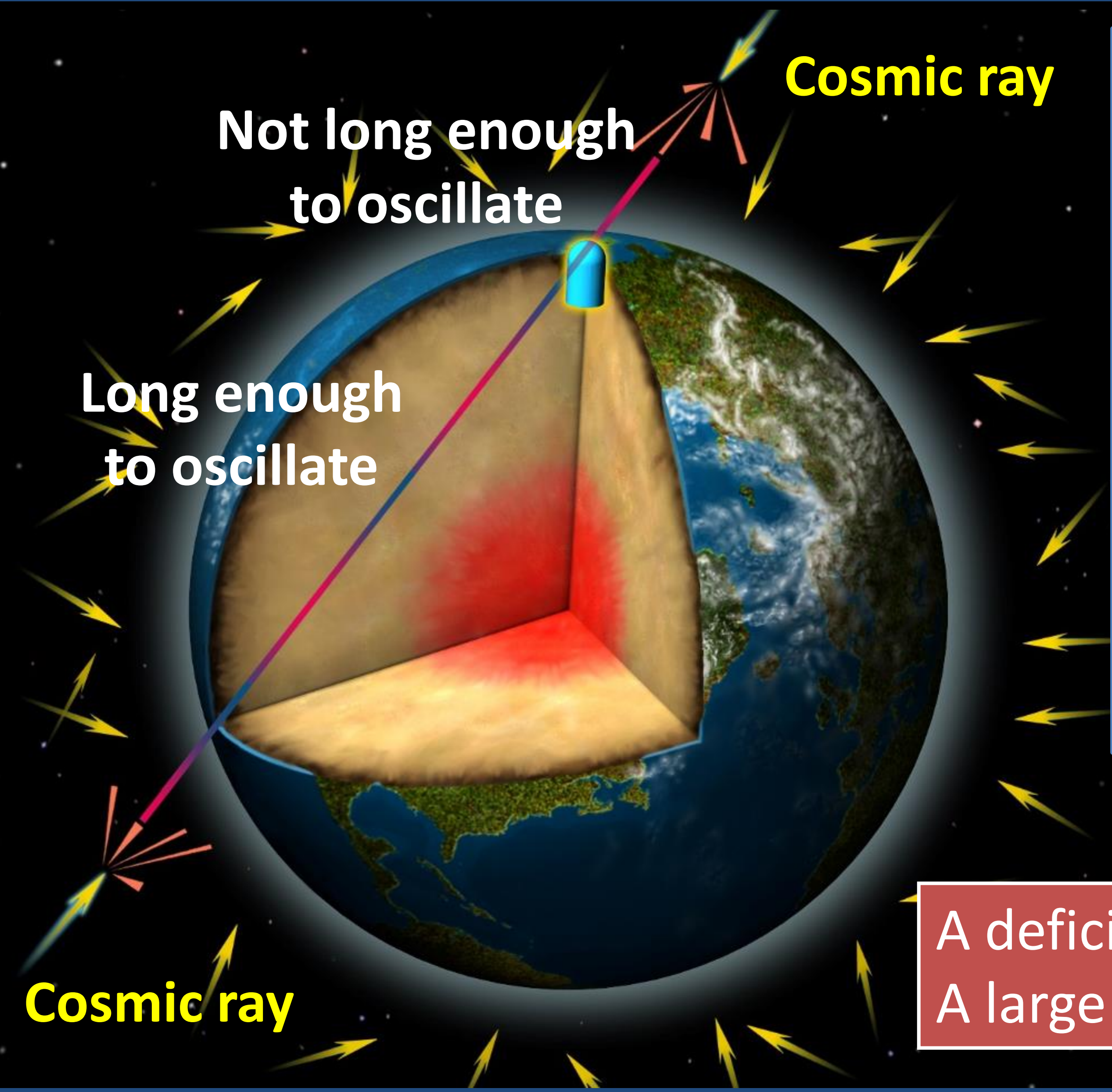
Super-Kamiokande detector

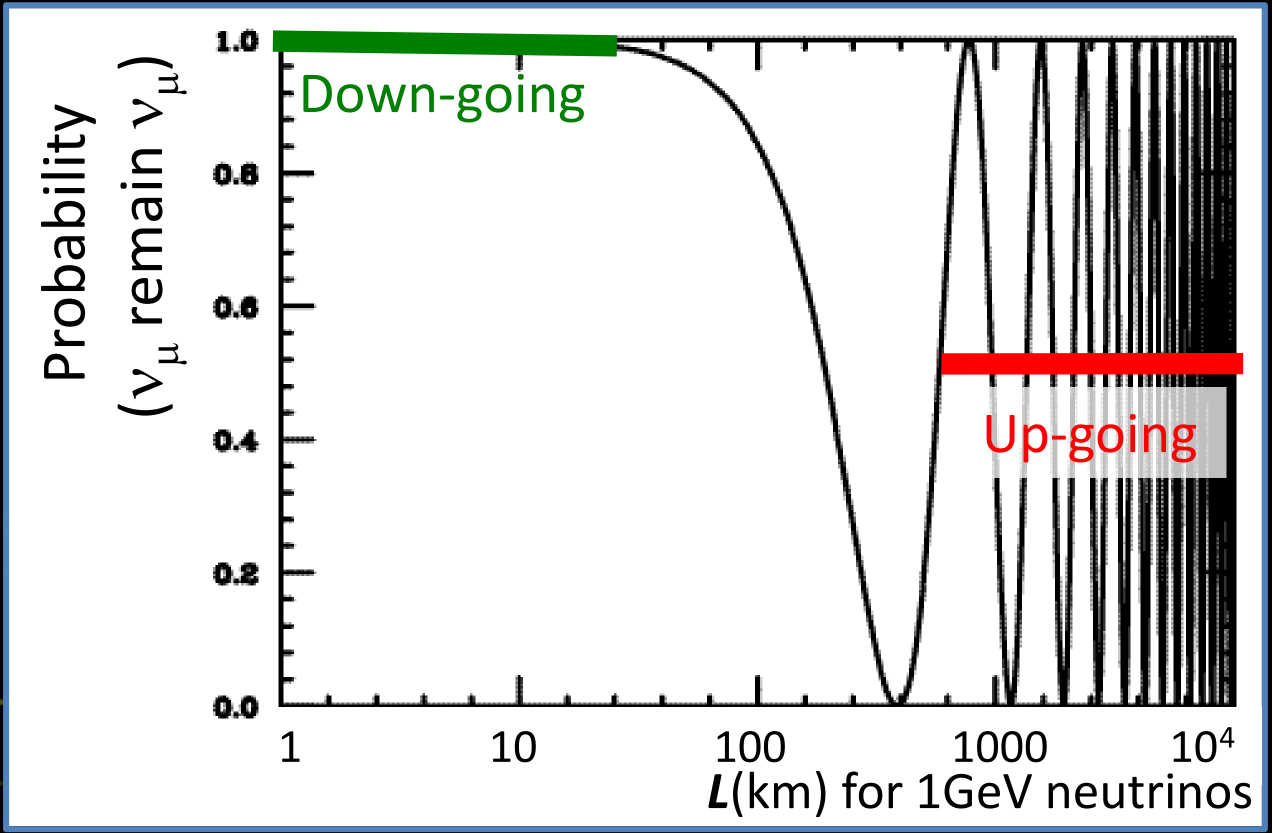
50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)





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

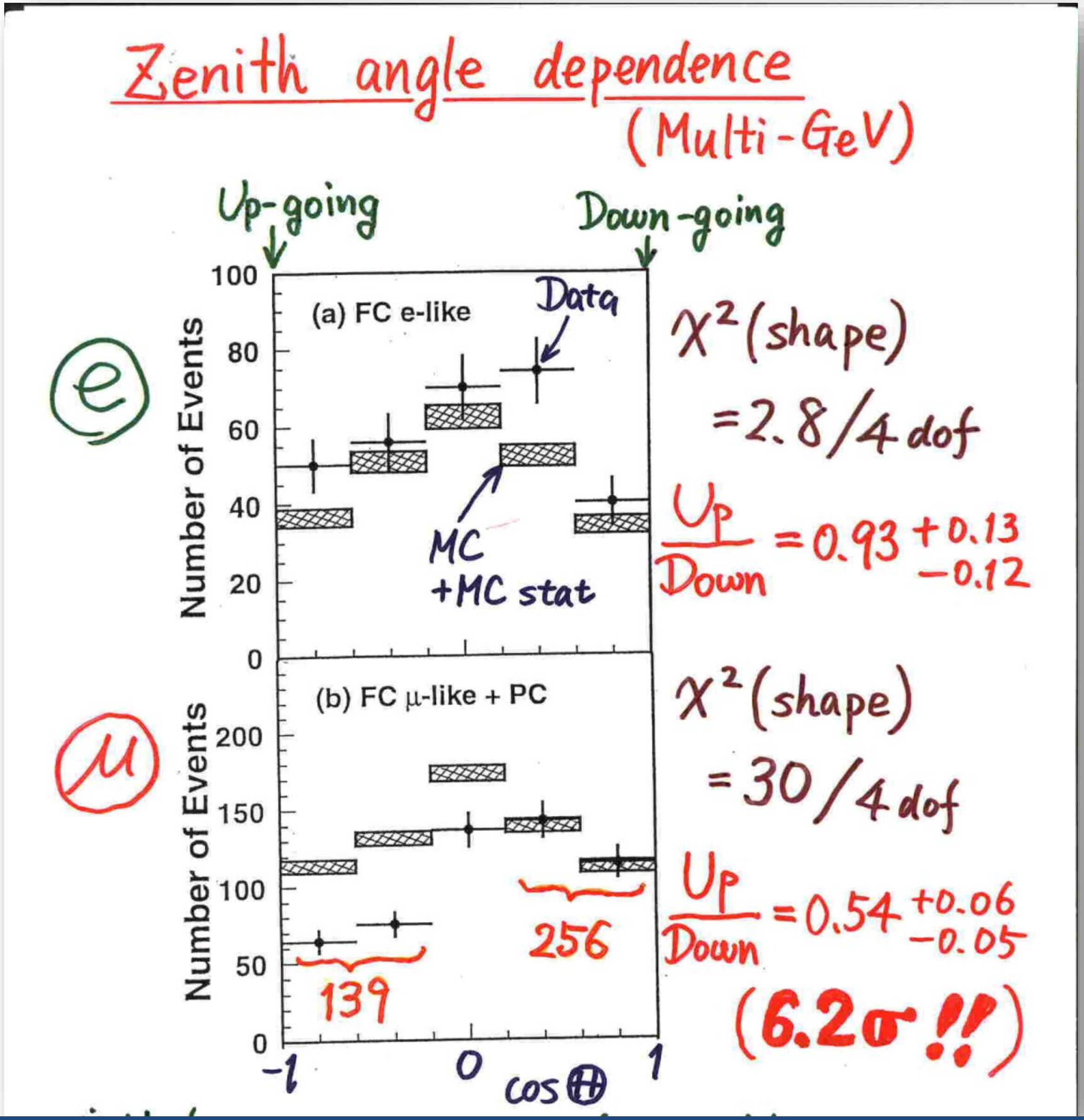


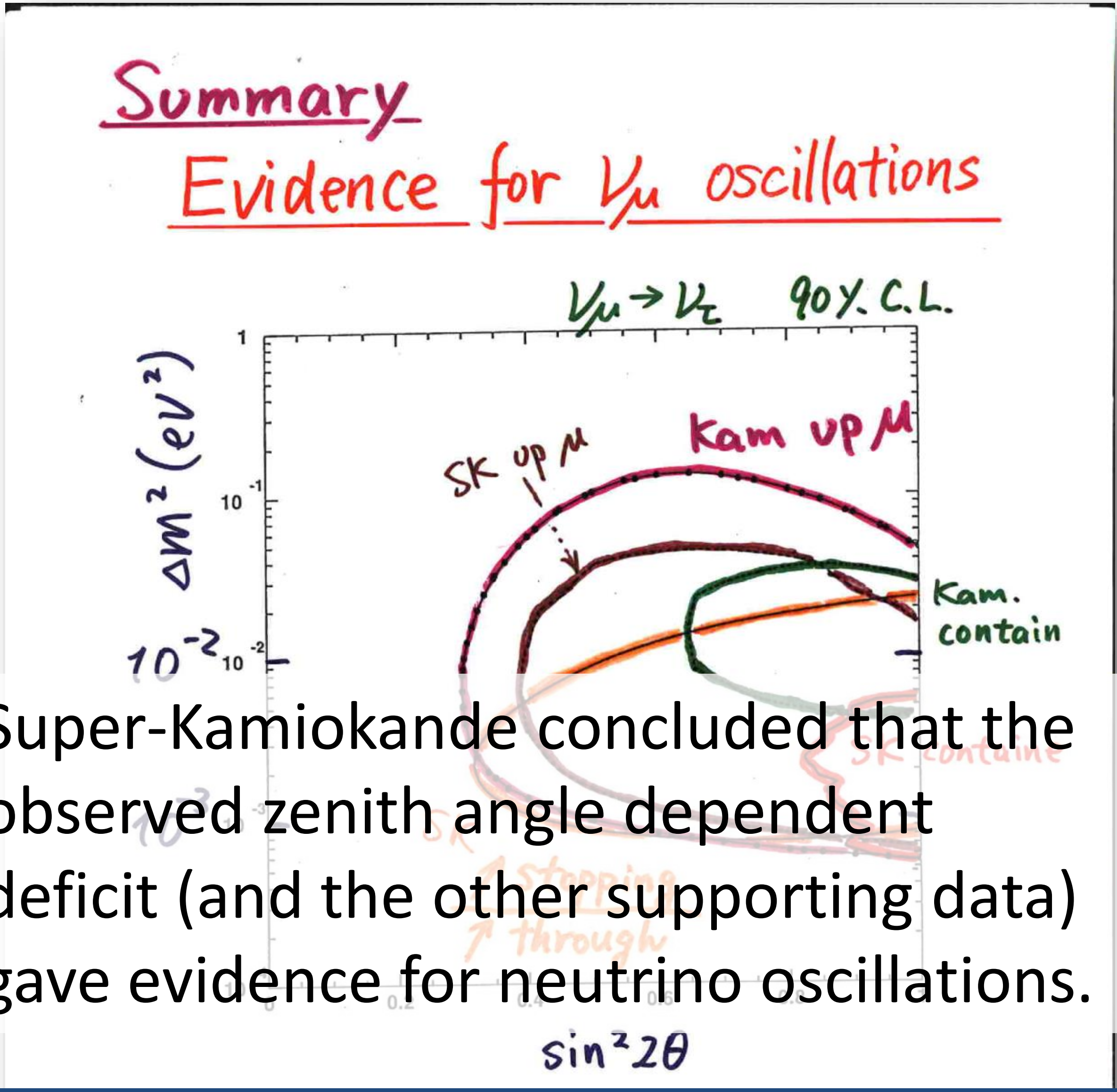


A deficit of upward going ν_μ's should be observed!
A large detector needed. → Super-Kamiokande

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

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



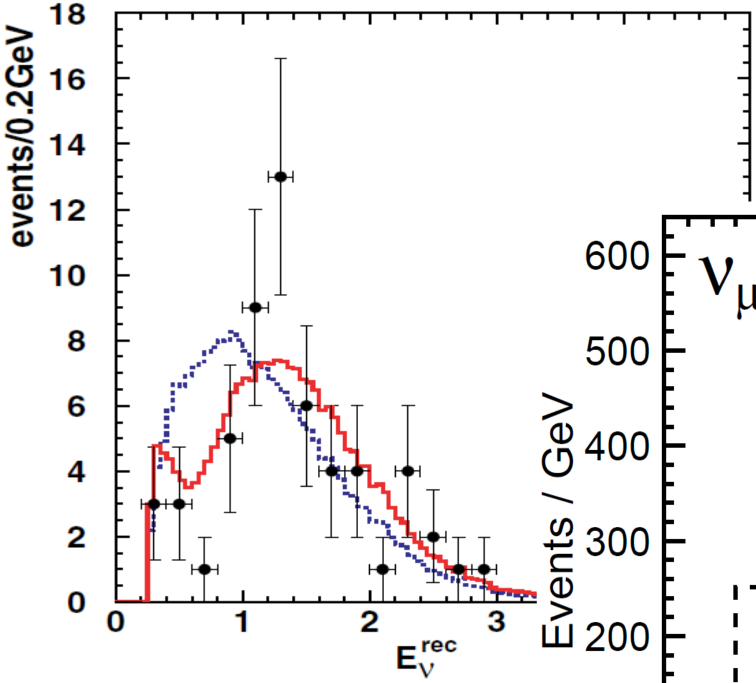


Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

ν_μ disappearance studies (accelerator experiments)

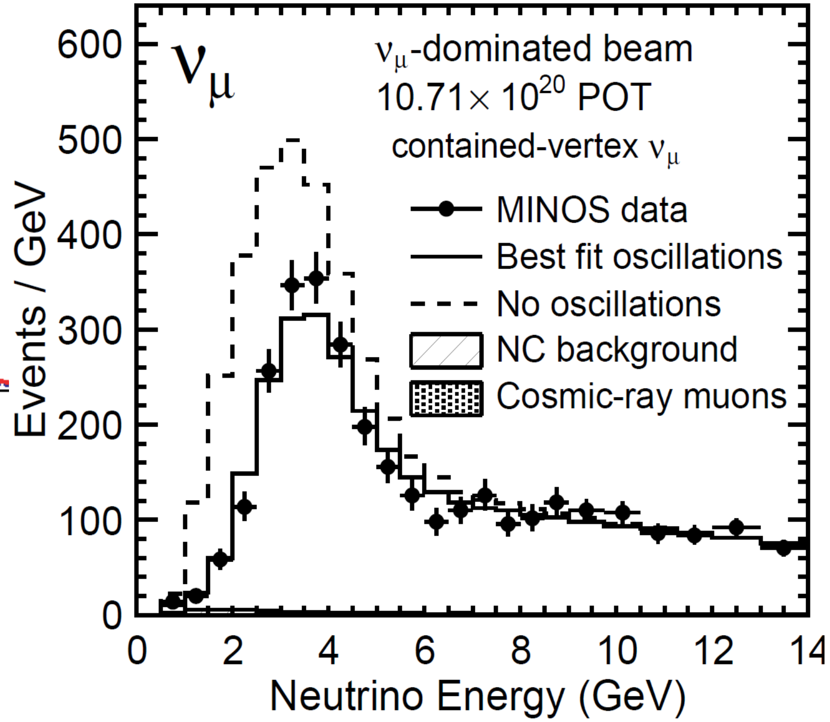
K2K

K2K, PRD 74 (2006) 072003



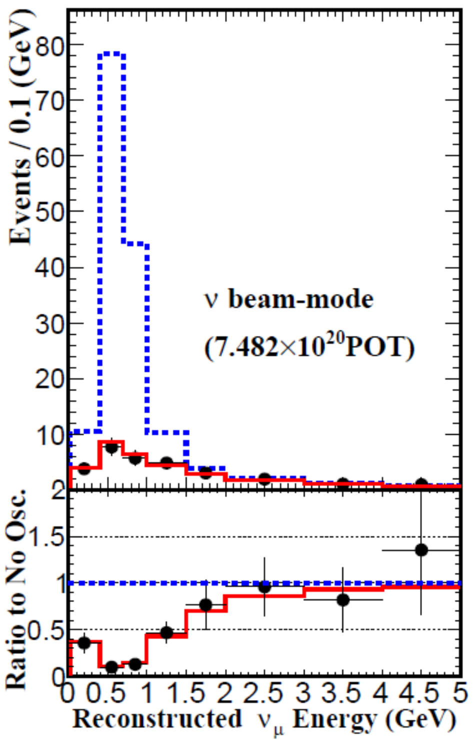
MINOS

MINOS PRL 110 (2013) 251801



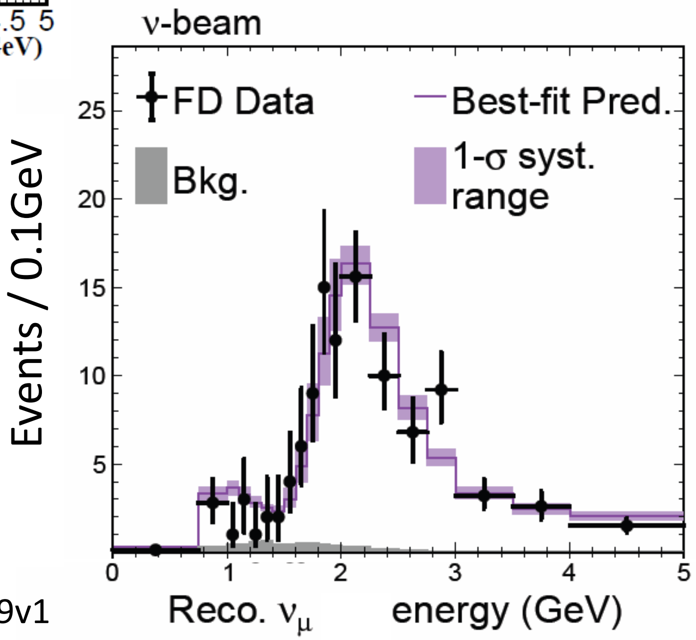
T2K

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



NOvA

NOvA, arXiv:2108.08219v1



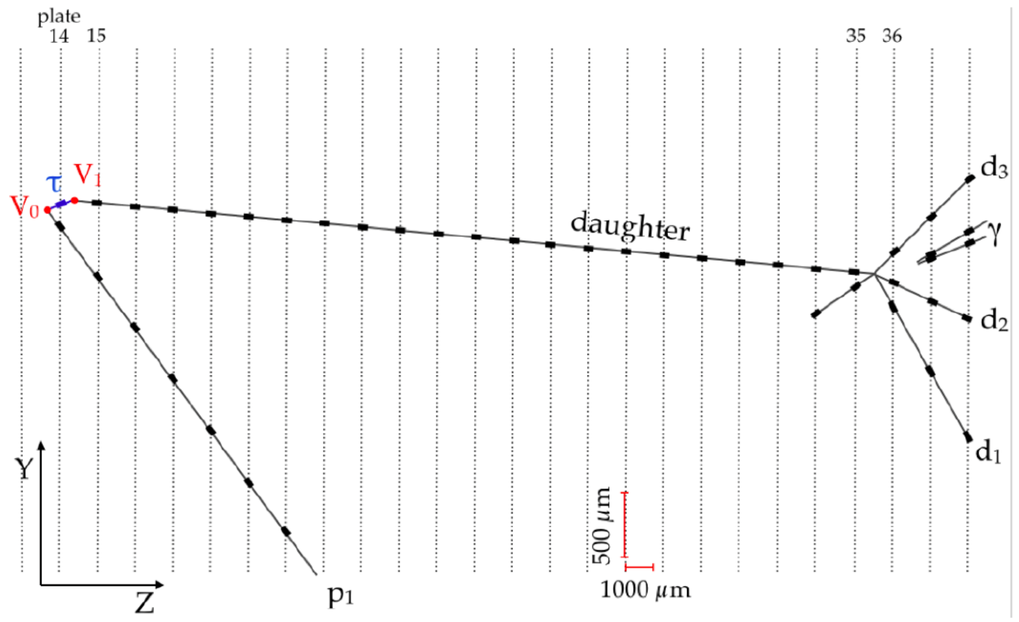
ν_τ appearance

OPERA

5 tau-neutrino candidates observed.

Expected BG = 0.25 evens. **(5.1σ)**

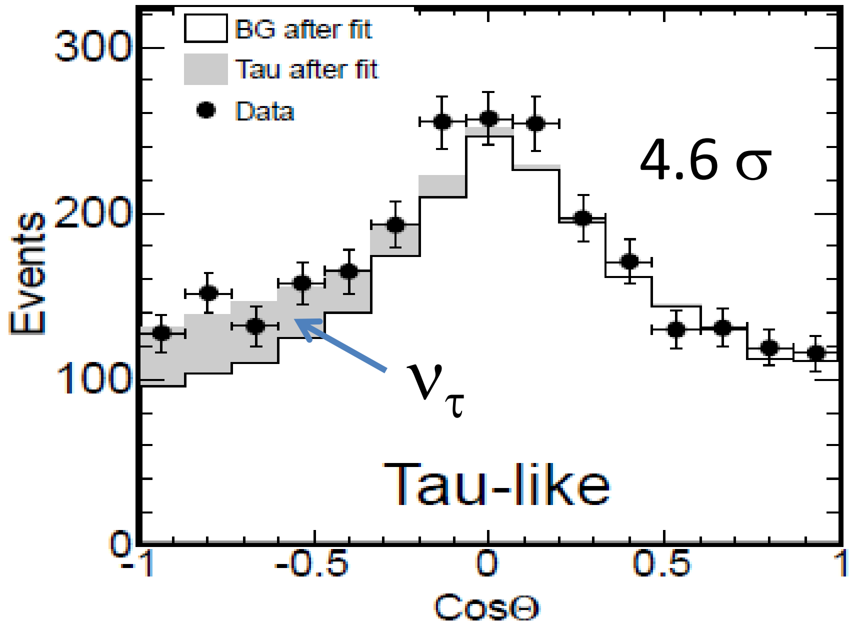
OPERA PRL 115 (2015) 121602



The fifth candidate event

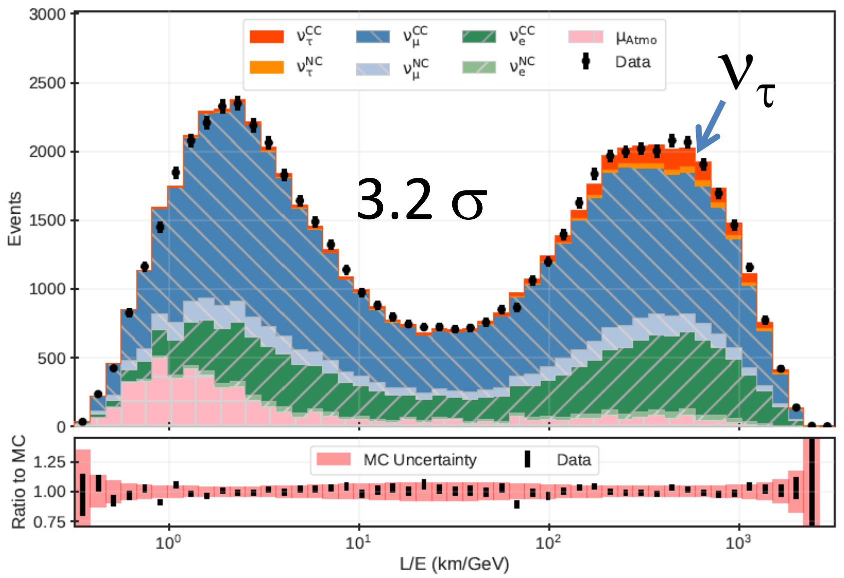
Super-Kamiokande

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



IceCube

IceCube,
PRD 99 (2019) 3, 032007

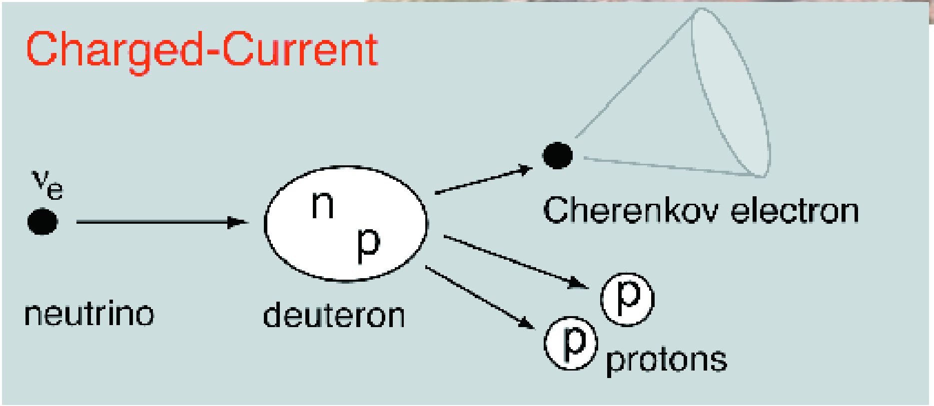


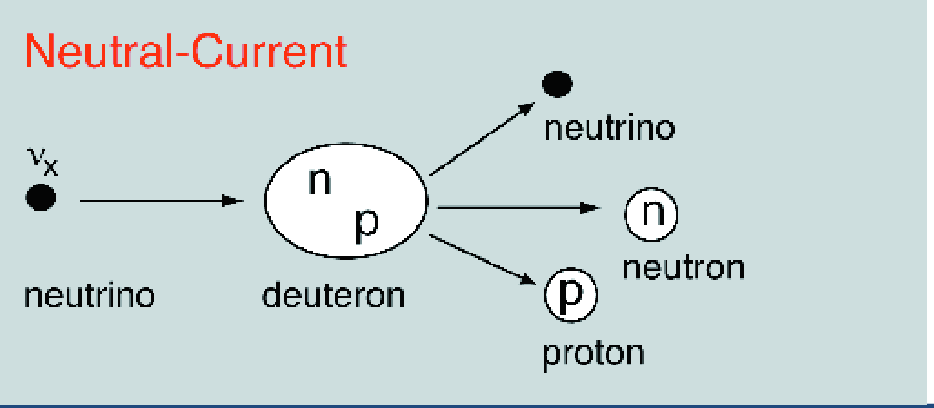
Neutrino oscillations: $\nu_e \rightarrow \nu_\mu + \nu_\tau$

Initial idea

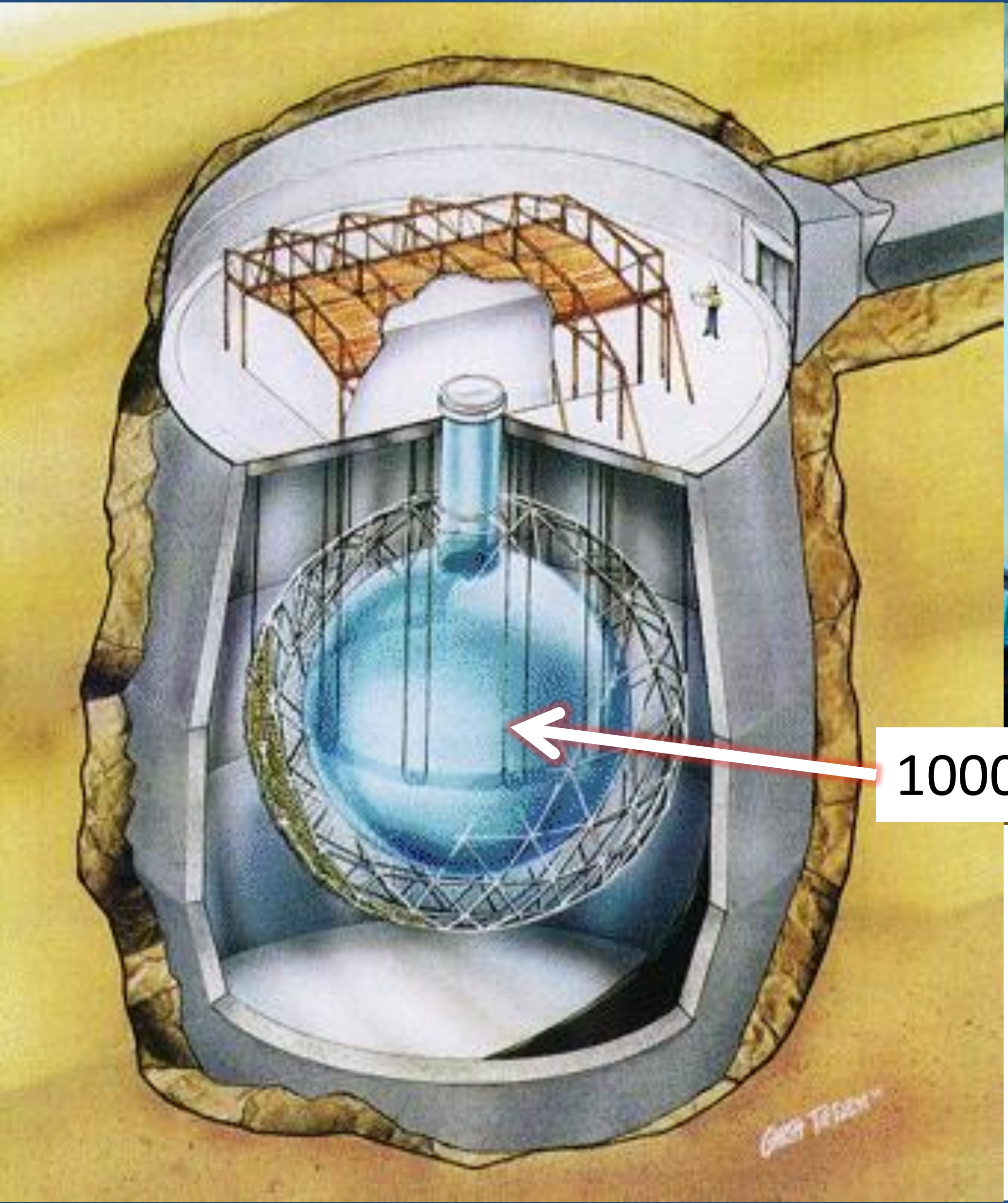
Herbert Chen, PRL 55, 1534 (1985)
“Direct Approach to Resolve the Solar-neutrino Problem”

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

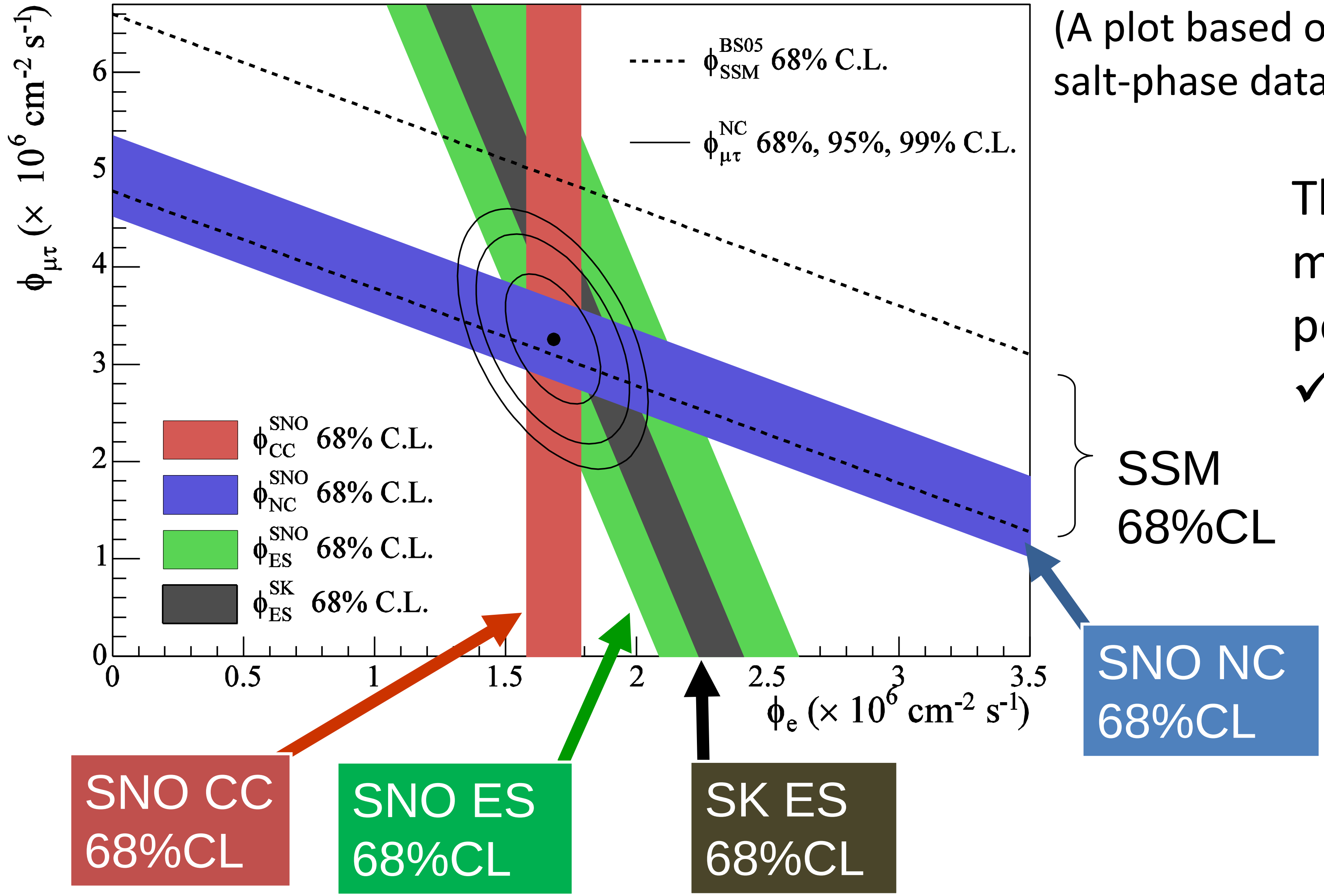


1000 ton of D_2O

<u>Neutral Current events (ν_x + D → ν_x + p + n) (or produced neutrinos in NC reactions) were observed by 3 methods independently:</u>

1) Pure D_2O (n is absorbed by D, then 6.25 MeV γ ray emitted)
2) 2 tons of salt (NaCl) in D^2O → $^{35}Cl(n, \gamma)^{36}Cl$ ($\Sigma(E\gamma)$=8.6MeV)
3) ^3He counters in D_2O → $^3He(n, p)^3H$

Evidence for solar neutrino oscillations



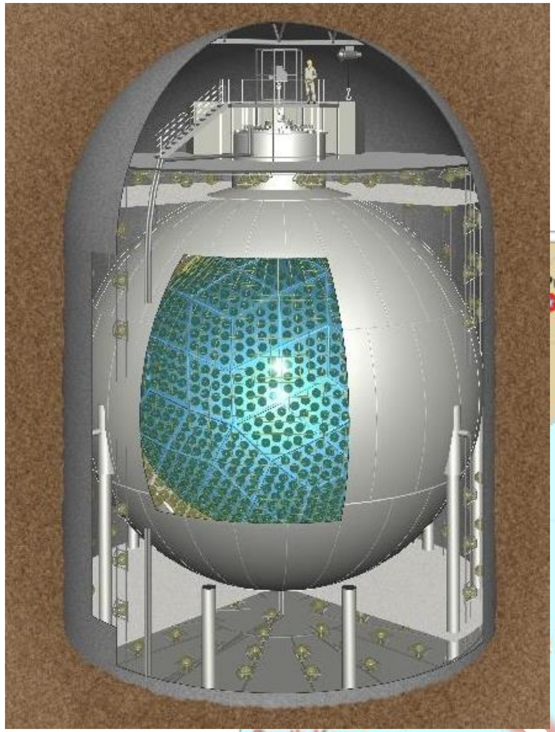
(A plot based on the salt-phase data)

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

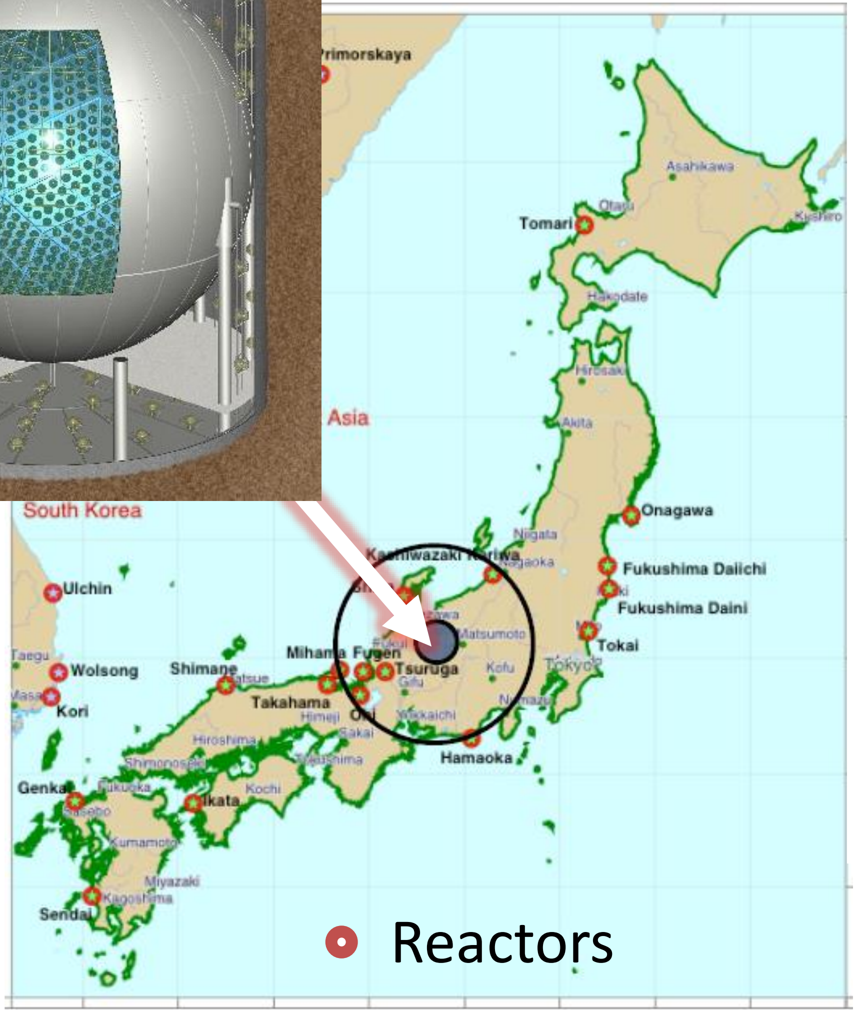
Three (or four) different measurements intersect at a point.

✓ *Evidence for (ν_μ+ν_τ) flux*

Really neutrino oscillations!

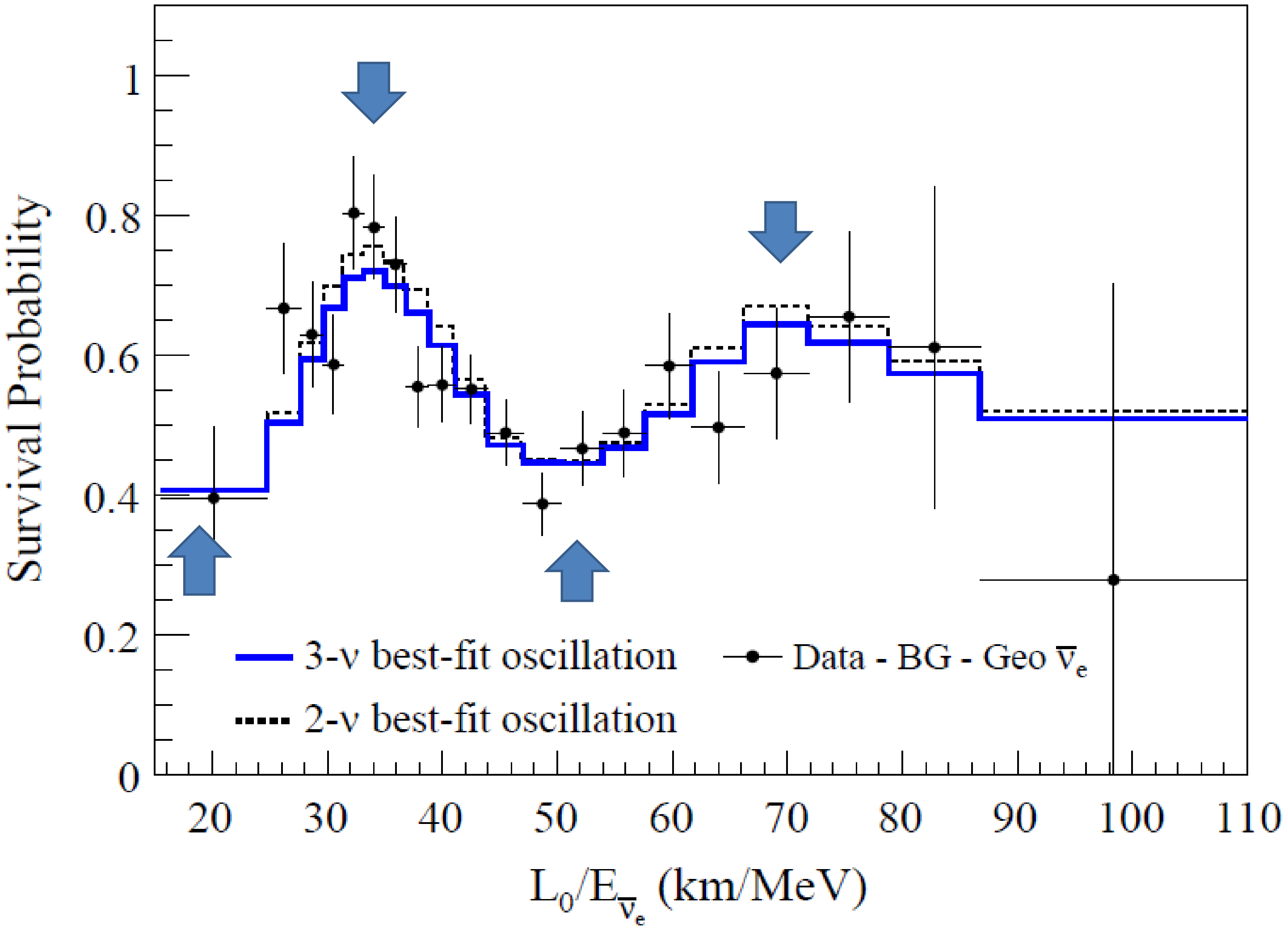


KamLAND



Reactors

KamLAND, PRD 83, 052002 (2011)



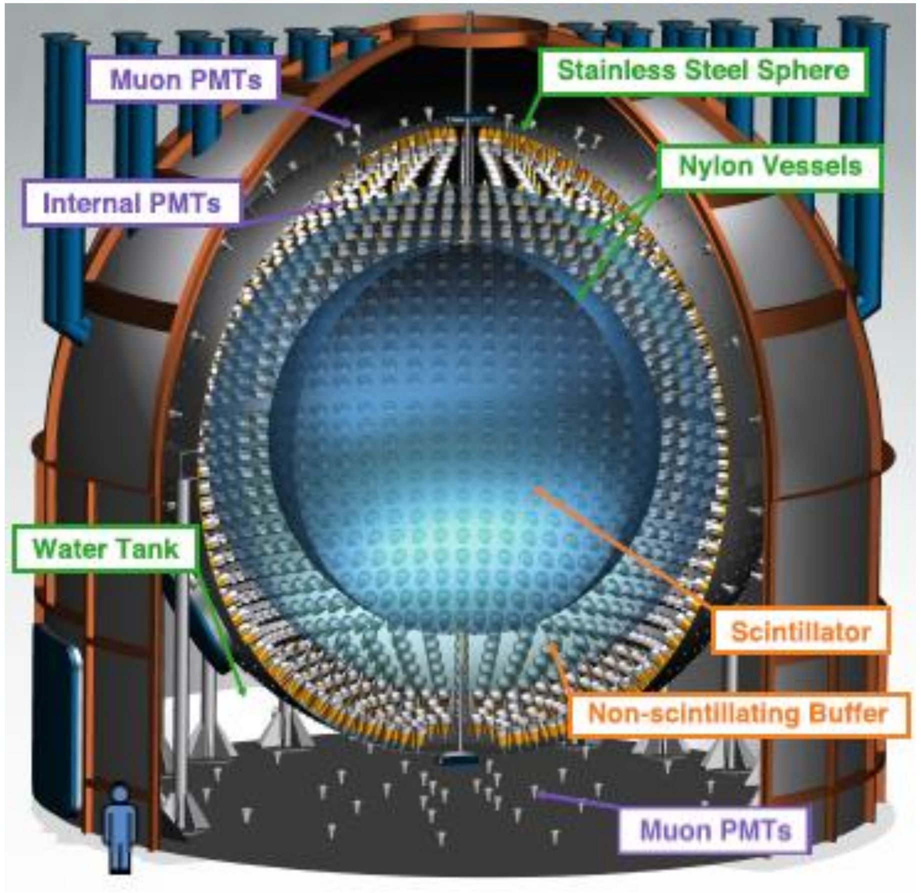
Really neutrino ***oscillations !***

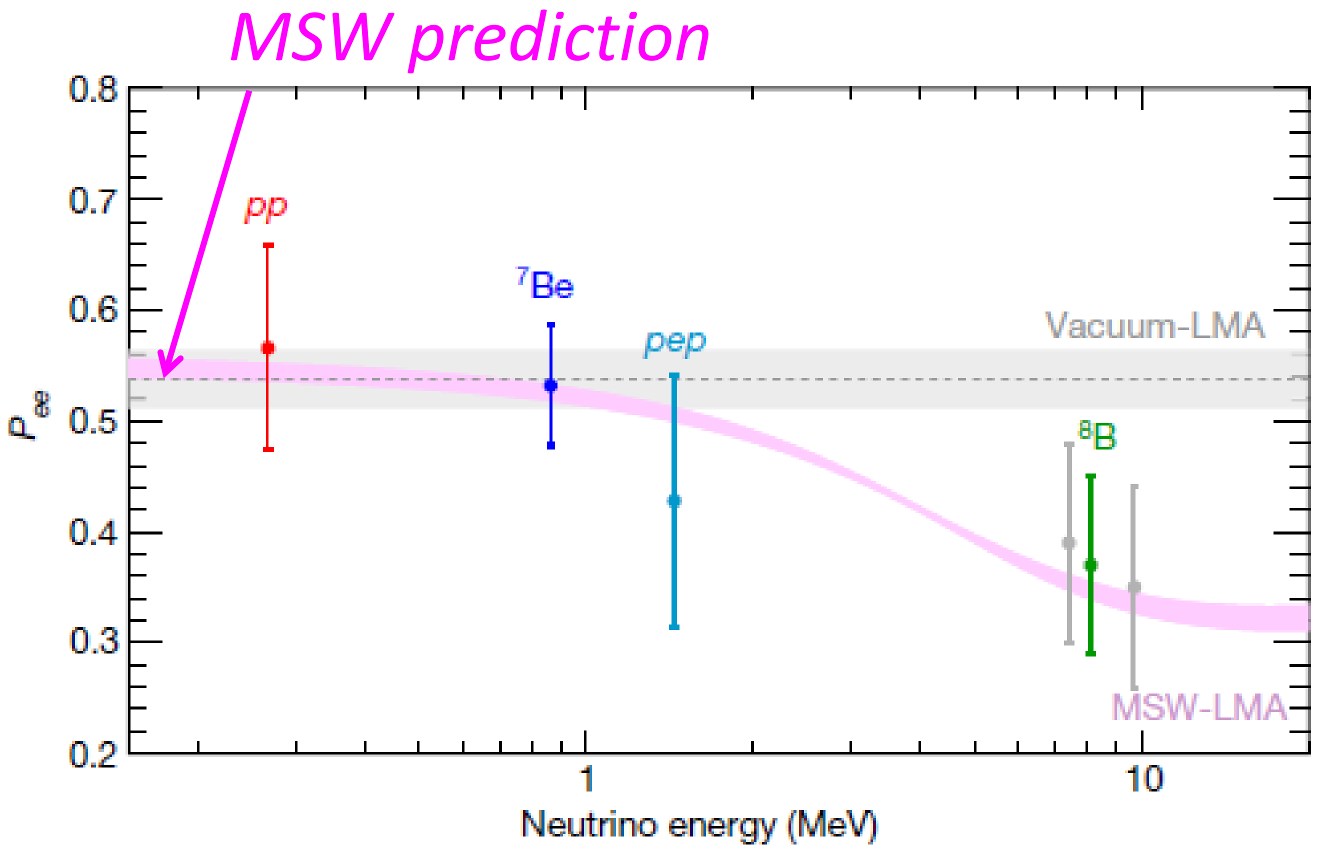
Consistent with MSW (neutrino oscillations in matter) !

Borexino

Measurement of 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





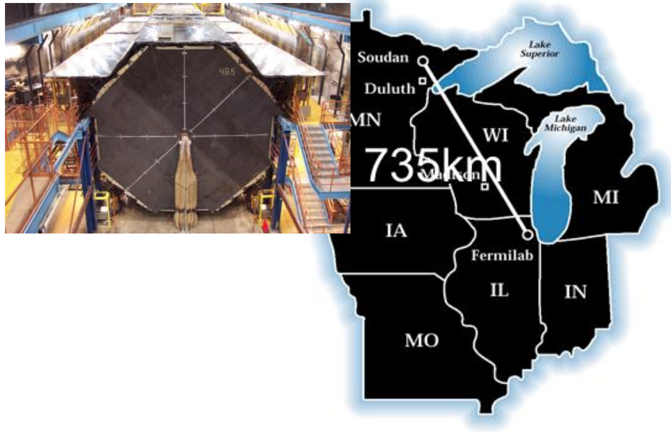
- ✓ *The data are consistent with the MSW prediction!*
- ✓ *Also, observation of CNO neutrinos (Nature 587 (2020) 577-582) !*

Neutrino oscillations: The third oscillation channel and beyond

Experiments for the third neutrino oscillations

Accelerator based long baseline neutrino oscillation experiments

MINOS

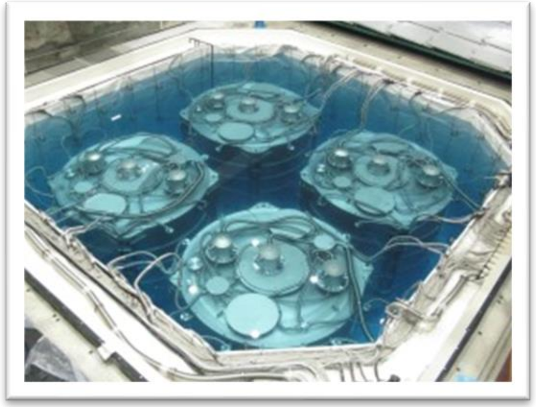


T2K

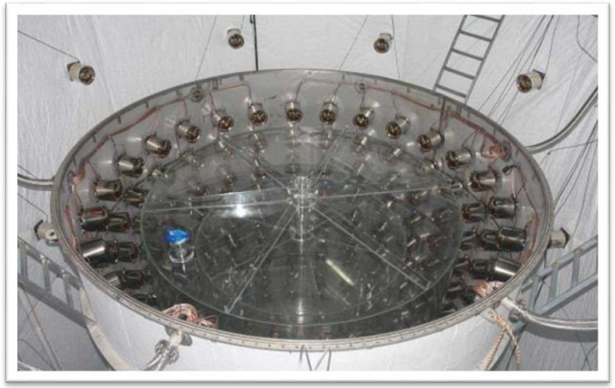
NOνA

Reactor based (short baseline) neutrino oscillation experiments

Daya Bay



RENO

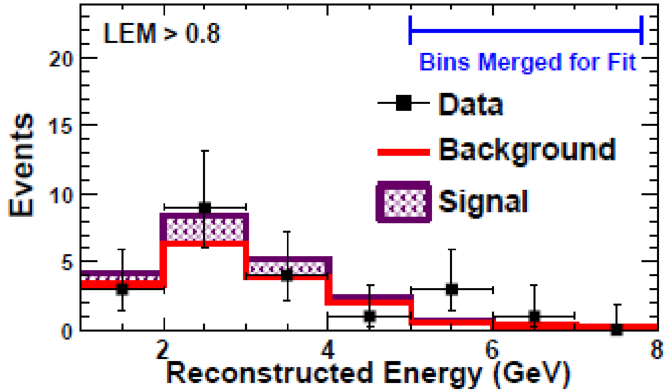


Double Chooz

Discovery of the third neutrino oscillations (2011-2012)

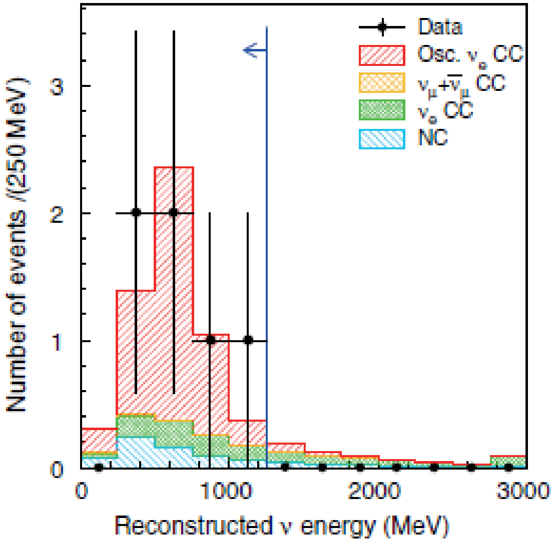
Accelerator based ν_e appearance experiments

MINOS PRL 107 (2011) 181802



T2K

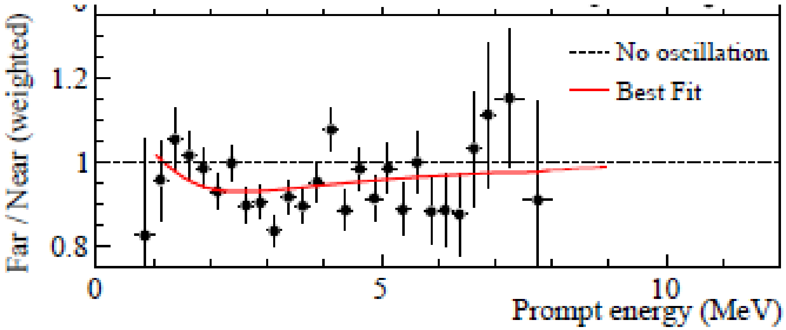
PRL 107 (2011) 041801



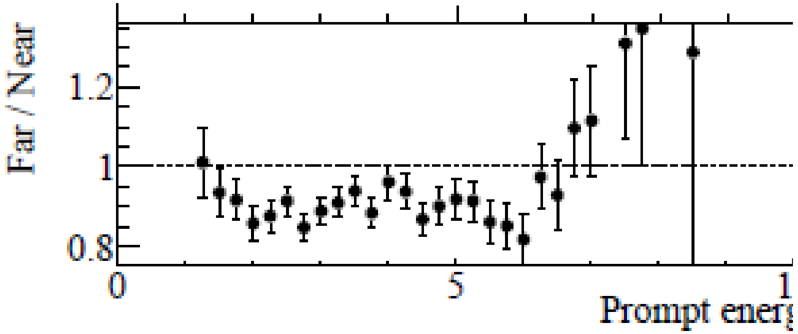
Note: these data are those in 2011-2012. The updated data are much better (including those from NOvA).

Reactor based anti-ν_e disappearance experiments

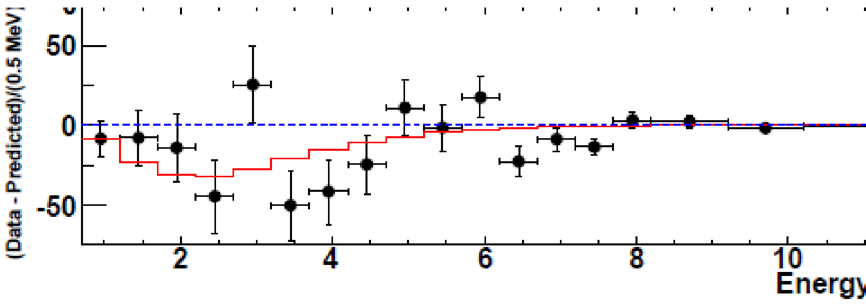
Daya Bay PRL 108 (2012) 171803



RENO PRL 108 (2012) 191802



Double Chooz PRL 108 (2012) 131801

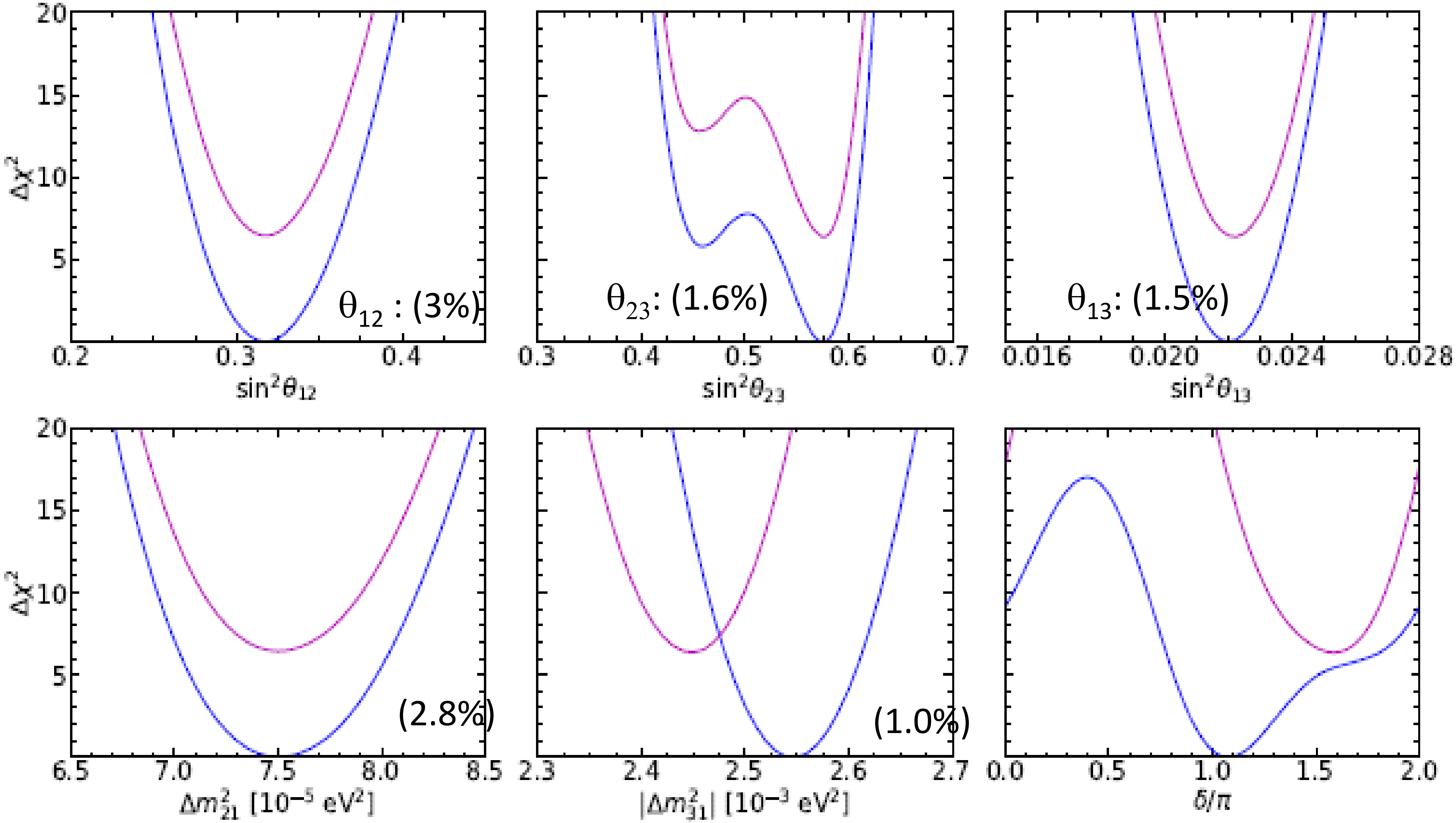


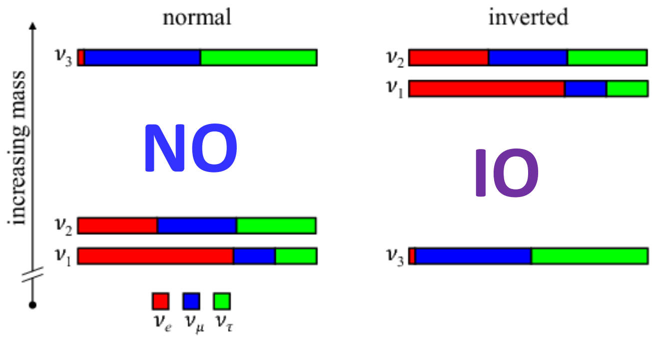
Tthe basic structure for 3 flavor neutrino oscillations has been understood!

Oscillation parameters

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

Normal mass Ordering (**NO**), Inverted mass Ordering (**IO**)



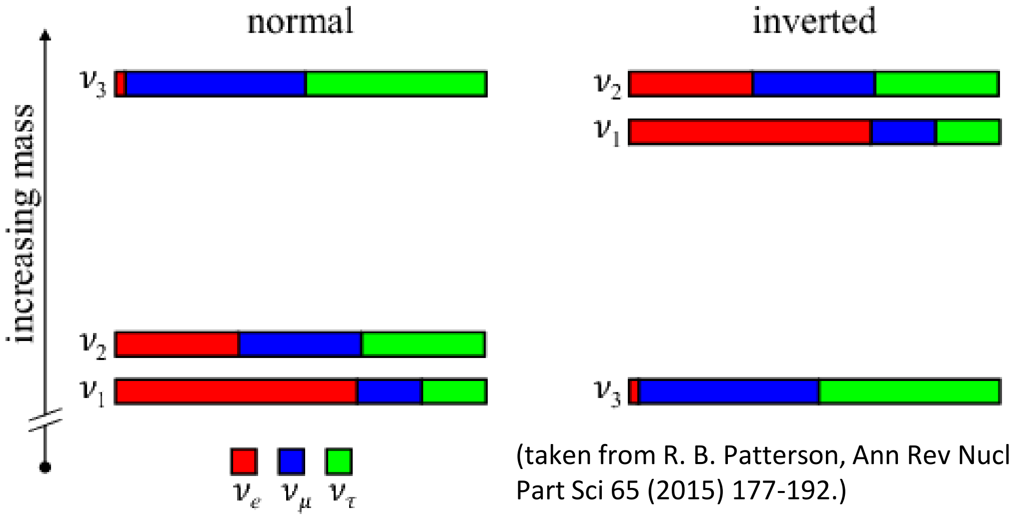


parameter	best fit $\pm$ 1σ
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16
$\theta_{12}/^\circ$	34.3 ± 1.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$
δ/π (NO)	$1.08^{+0.13}_{-0.12}$
$\delta/^\circ$ (NO)	194^{+24}_{-22}
δ/π (IO)	$1.58^{+0.15}_{-0.16}$
$\delta/^\circ$ (IO)	284^{+26}_{-28}

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

Agenda for the future neutrino measurements

Neutrino mass hierarchy?



(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

Absolute neutrino mass?

Beyond the 3 flavor framework? (Sterile neutrinos?)

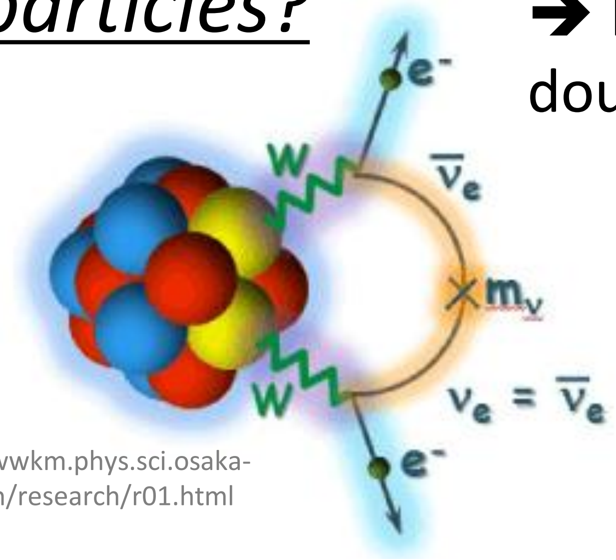
CP violation?

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

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?

➔ Neutrinoless double beta decay

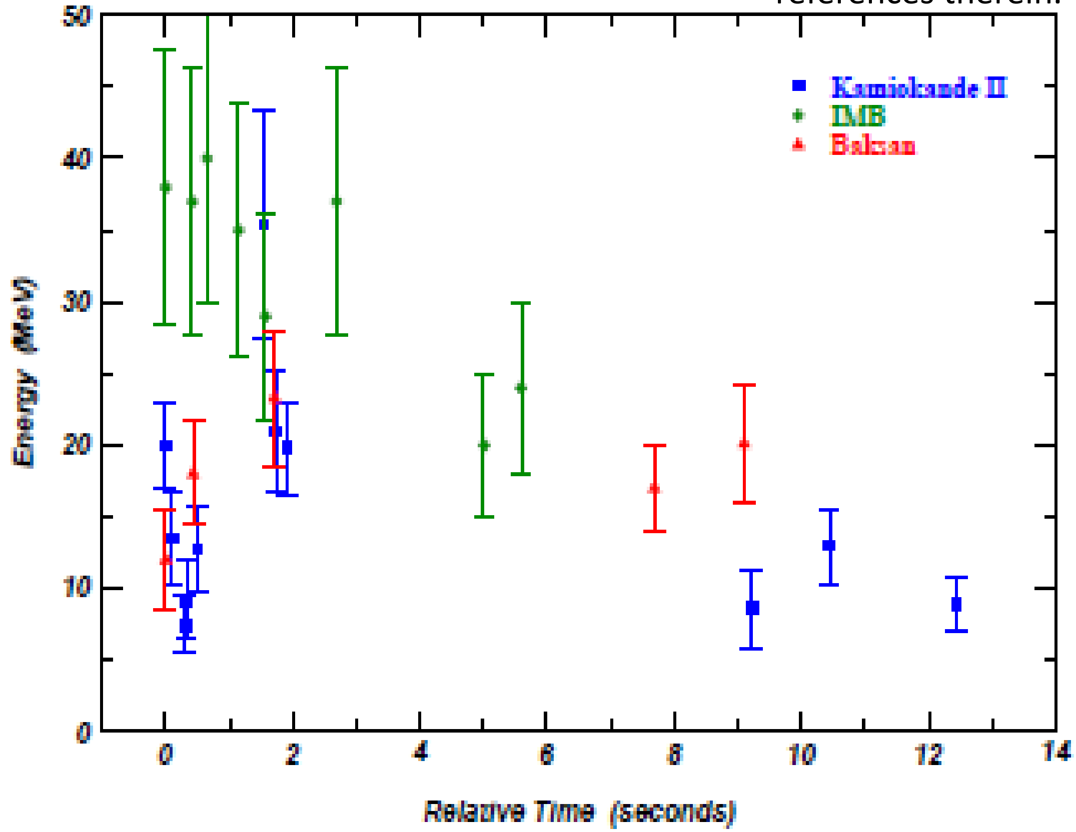


http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

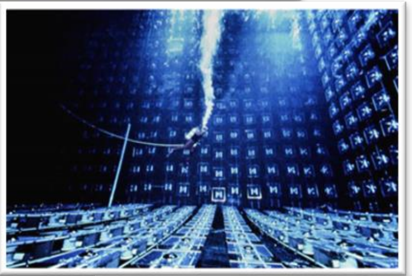
Neutrinos as messengers of the Universe

Birth of Neutrino Astronomy: SN1987A

A. McDonald et al., Rev.Sci.Instrum. 75 (2004) 293-316, and references therein.



Kam-II



IMB

Baksan

- ✓ A total of ~24 neutrino events by these 3 detectors.
- ✓ Understood the basin mechanism of the supernova explosion. (Approximately, 99% of the total energy of the supernova explosion is carried away by neutrinos.)

High Energy Neutrino Astronomy

- ✓ We would like to know where and how the cosmic ray particles (hadrons) are accelerated.
- ✓ We would like to understand the high-energy phenomena in the Universe.

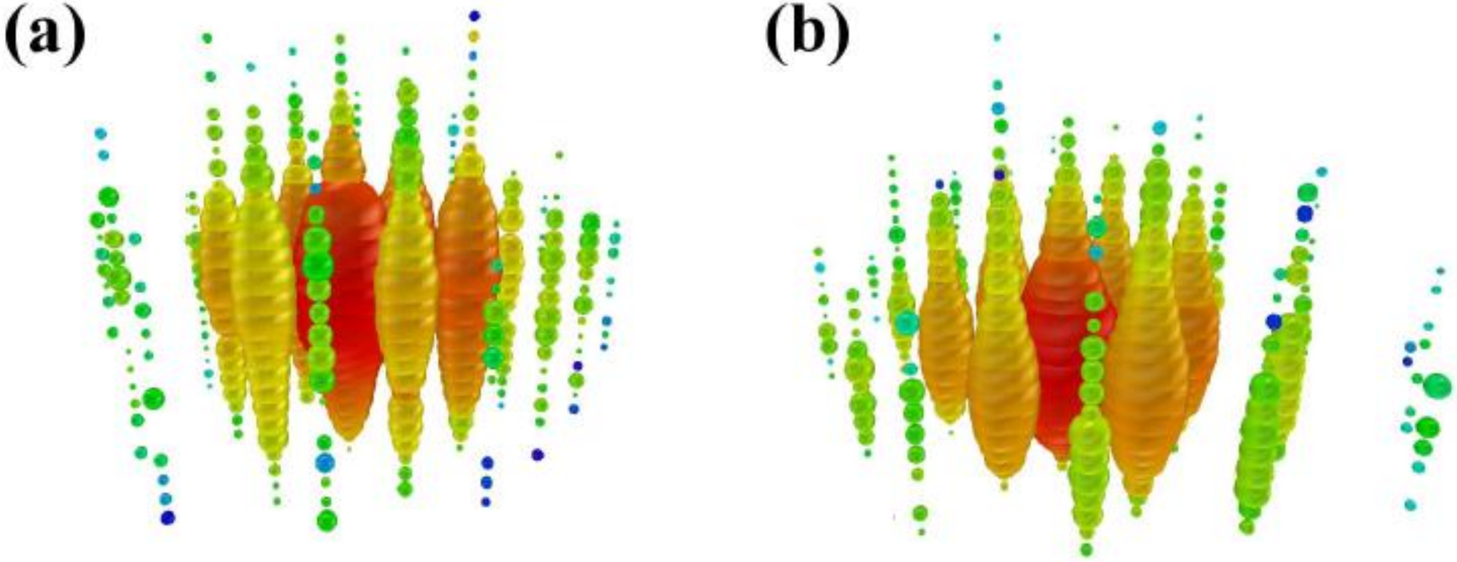
- ✓ Unfortunately, measurements of cosmic ray particles does not tell us the location of the cosmic ray accelerators.
- ✓ Measurements of gamma rays give useful information for high-energy Universe. However, gamma rays can be produced by electrons (as well as by hadrons).

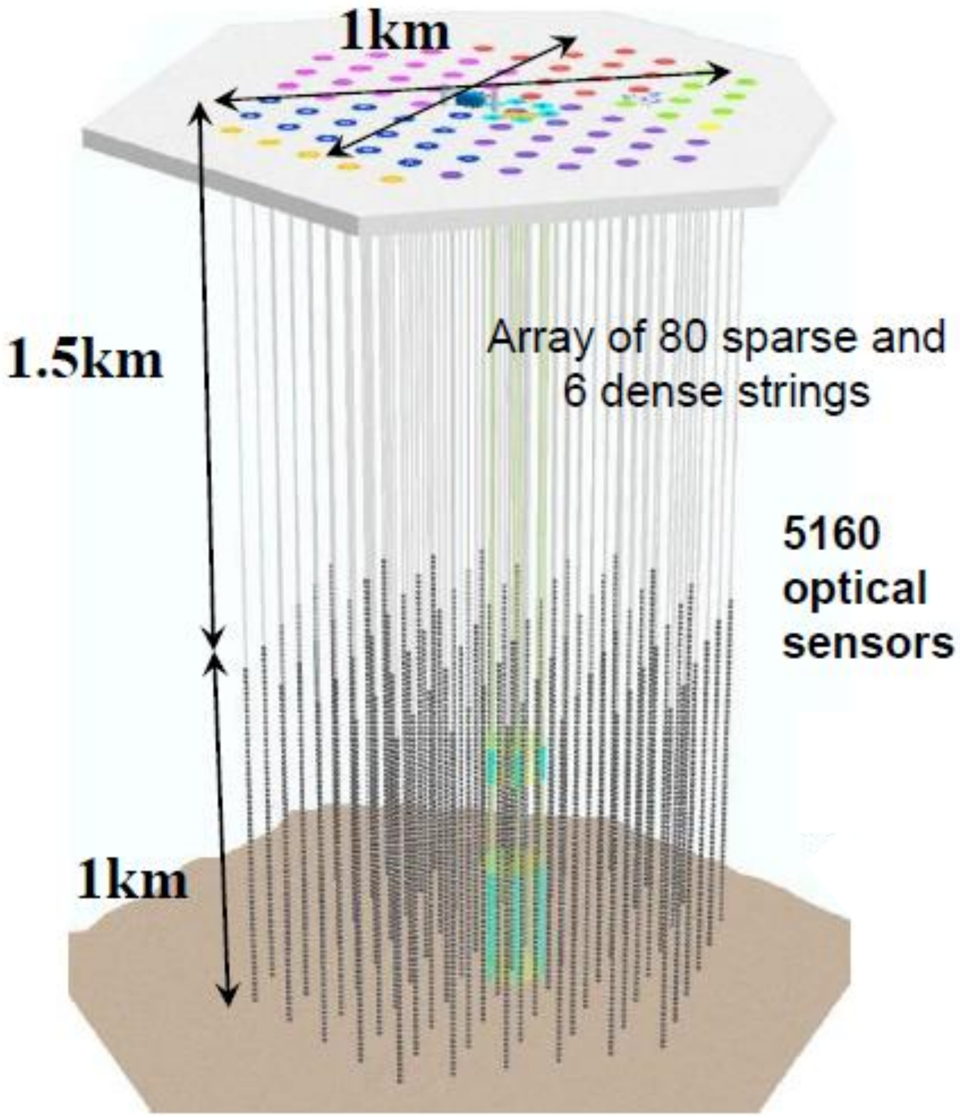
➔ Neutrinos

First observation of PeV neutrinos in IceCube

IceCube collab., Phys.Rev.Lett. 111 (2013) 021103

- ✓ Using the data between 2010 and 2012, IceCube observed two neutrino events which have an estimated deposited energy of 1.04 ± 0.16 and 1.14 ± 0.17 PeV, respectively. The expected number of atmospheric background was 0.082 ± 0.004(stat) +0.041/−0.057(syst). (2.8σ observation).
- ✓ First observation of high-energy astrophysical neutrinos!

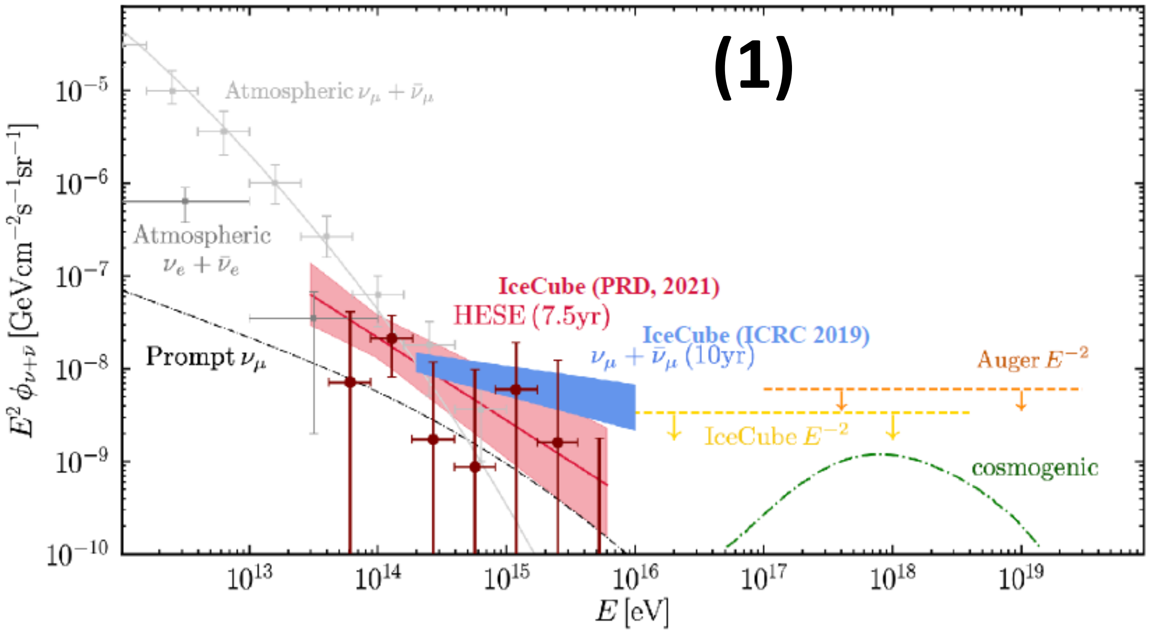




Highlights of the IceCube results

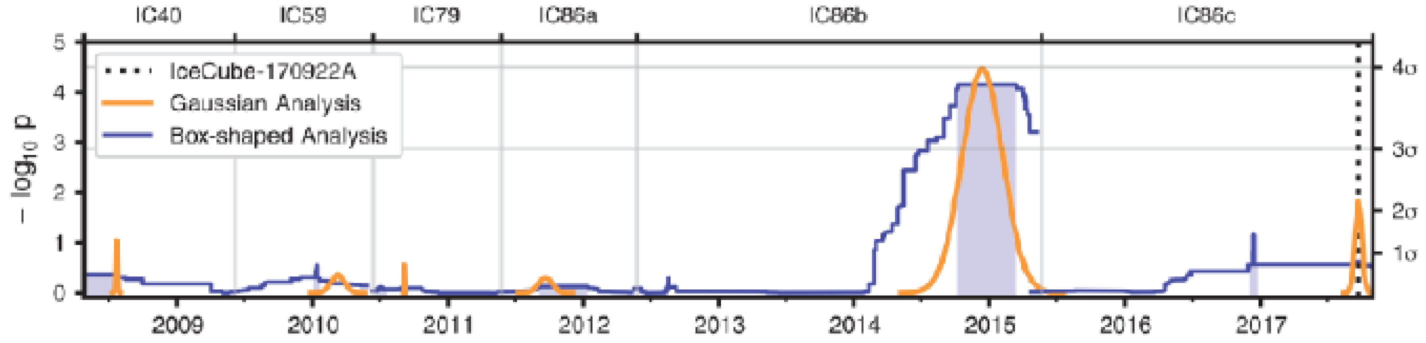
1. Measurements of astrophysical neutrino flux with multiple analyses. (Consistent result from Bikal-GVD @Neutrino 2022)
2. A cascade event with an estimated energy of 6.05 +/- 0.72 PeV, consistent with the resonant formation of a W-boson predicted by Glashow.
3. Extreme high energy neutrino alert from IceCube followed by detection of very high energy gamma rays from a flaring blazar TXS 0506+056.
4. Archival neutrino search found neutrino excess around 2014 around TXS 0506+056.
5. ….

N. Park, for the IceCube collab., talk at Neutrino 2022. and references therein.



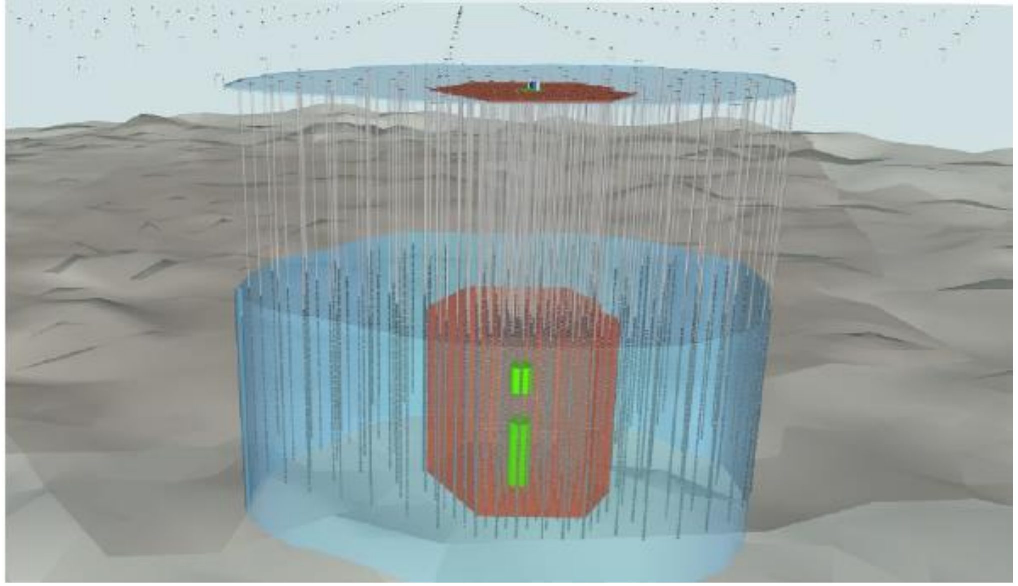
(4)

◉ 13 ± 5 events above the background over 100 days: significance of 3.5σ

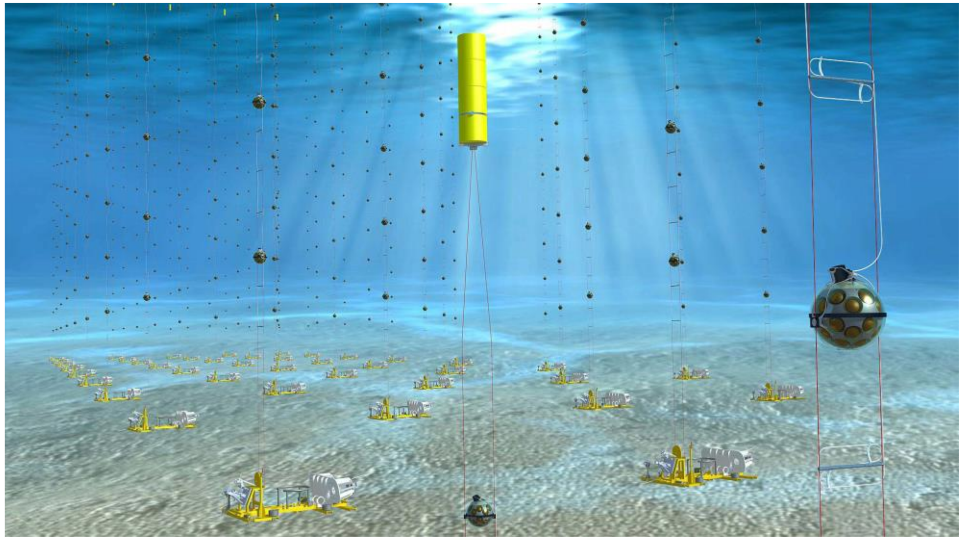


High Energy Neutrino Astronomy: near future

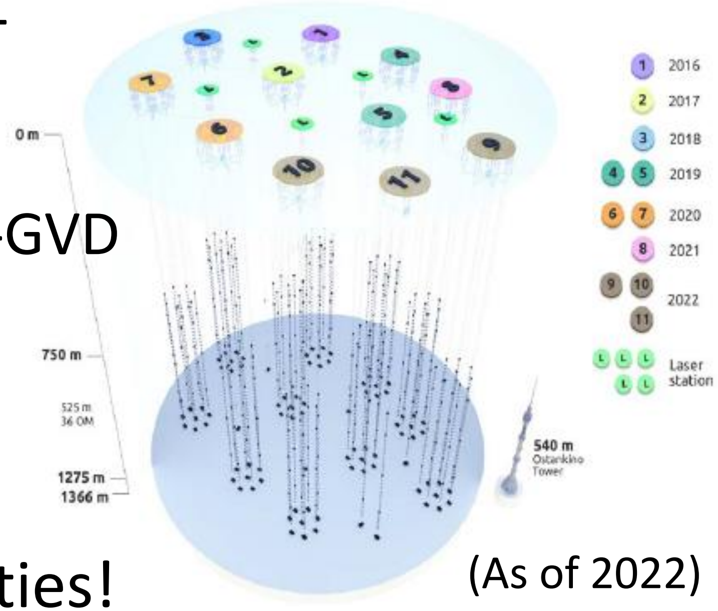
- ✓ In the last 10 years, there have been exciting results in high energy neutrino astronomy. They have suggested that the future observations of high energy astrophysical neutrinos are very important for our understanding of the high-energy phenomena in the Universe!



Icecube-Gen2



KM3NeT



Baikal-GVD

(As of 2022)

And many more possibilities!

N. Park (IceCube), A. Heijboer (KM3Net), and Zh. -A. Dzhilkibaev (Bikal-GVD), talks at Neutrino 2022.

Summary

- During the last 100 years, 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 will 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 Universe; why only matter particles exist at the present Universe.
- Neutrinos are unique messengers of the Universe. Recently, neutrino telescopes have begun to observe very high energy neutrinos coming from (somewhere in) the Universe.
- Neutrinos are likely to continue playing very important roles in understanding the smallest and the largest scales.