INTERNATIONAL SCHOOL
DANIEL CHALONGE – HECTOR DE VEGA
(ONLINE)
Nov. 2, 2022

Neutrino Oscillations

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Outline

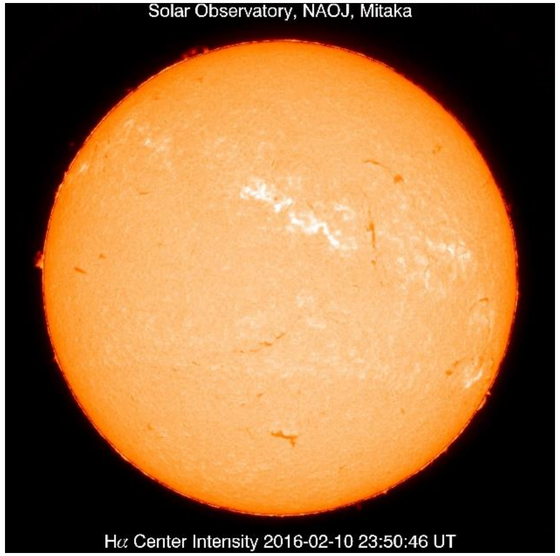
- *Introduction: Neutrino problems*
- *Neutrino oscillations:*

  $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\mu + \nu_\tau$, *the third oscillation channel*
- *Future prospect*

  CP violation
- *Summary*

Introduction: Neutrino problems

Solar neutrino problem



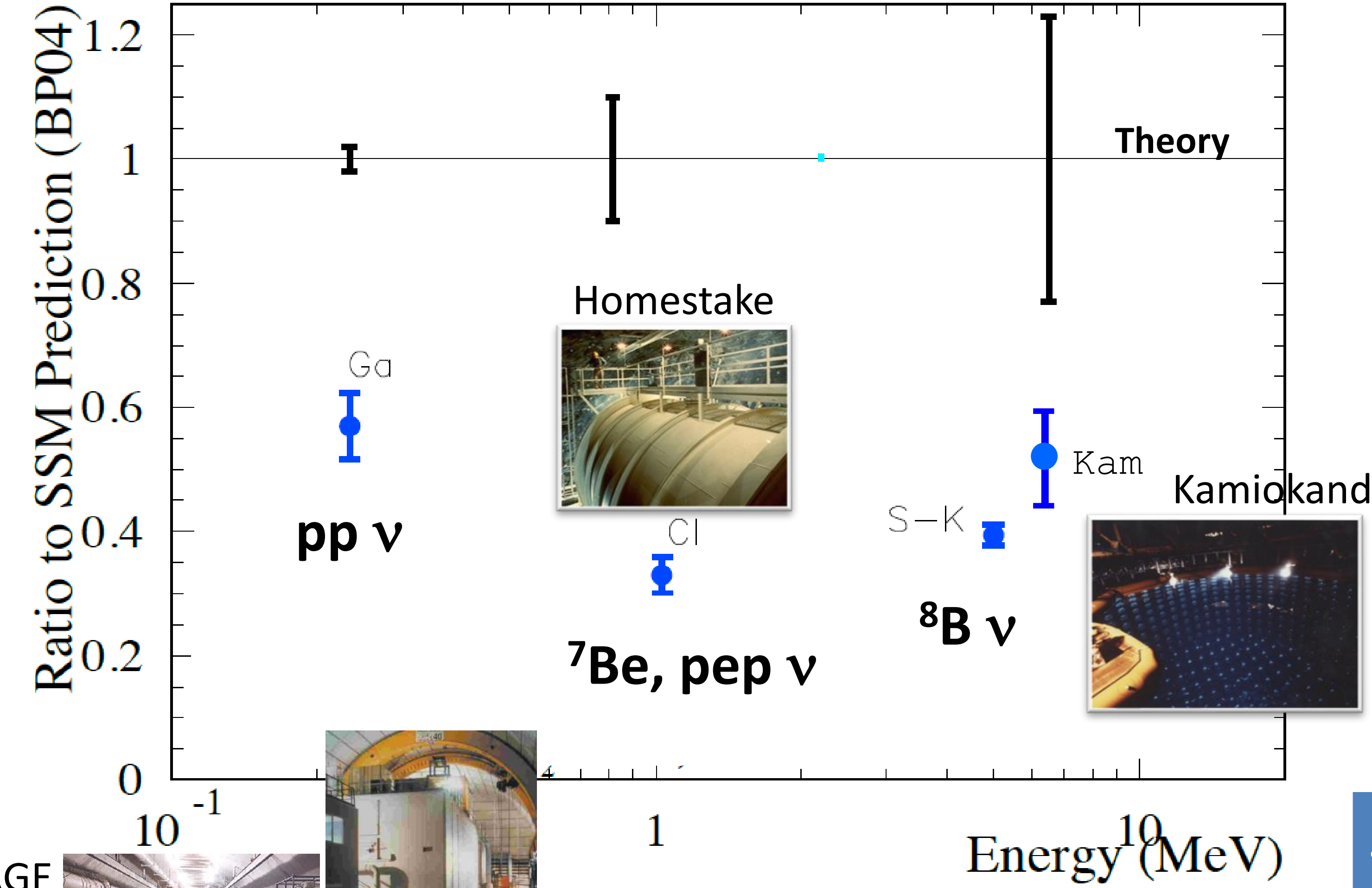
The Sun generates energy by nuclear fusion processes. Neutrinos are created by these processes. Therefore, the observation of solar neutrinos is very important to understand the energy generation mechanism in the Sun.

600ton C_2Cl_4

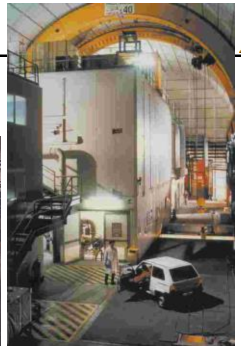
Pioneering Homestake experiment observed solar neutrinos for the first time (R. Davis Jr., D. S. Harmer and K. C. Hoffman PRL 20 (1968) 1205). However, the observed event rate was only about 1/3 of the prediction (since 1960's).

Results from solar neutrino experiments (before ~2000)

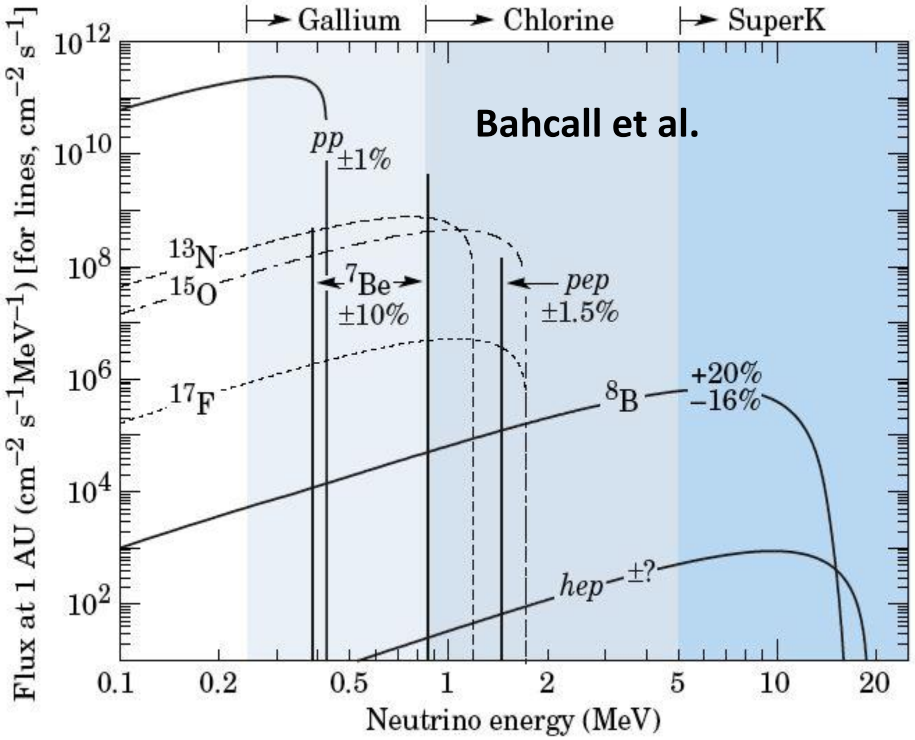
Following the initial observation, several experiments observed solar neutrinos.



SAGE

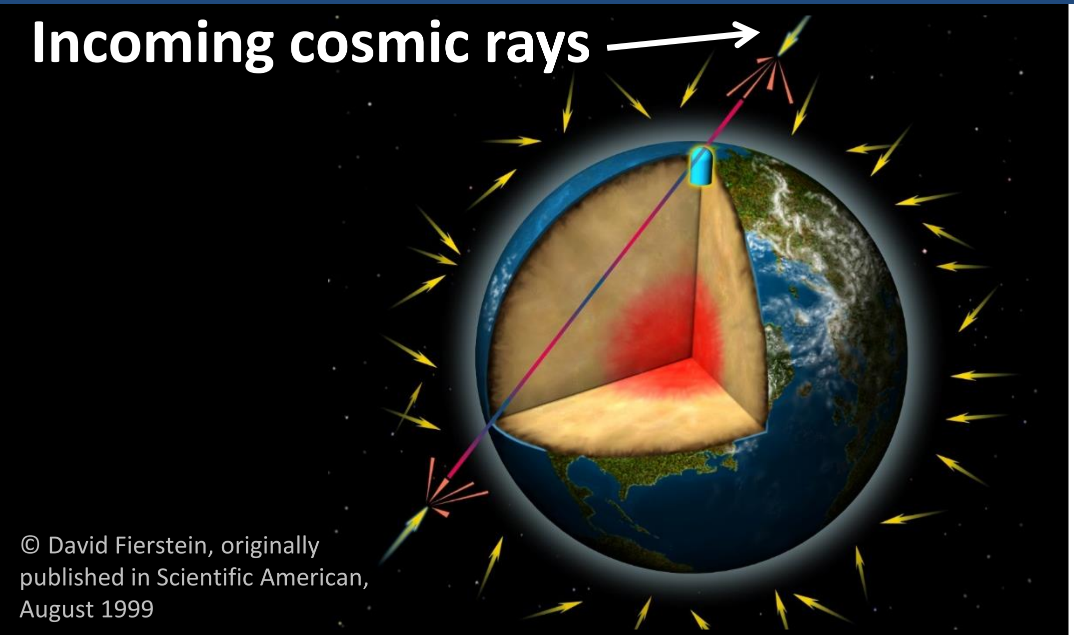


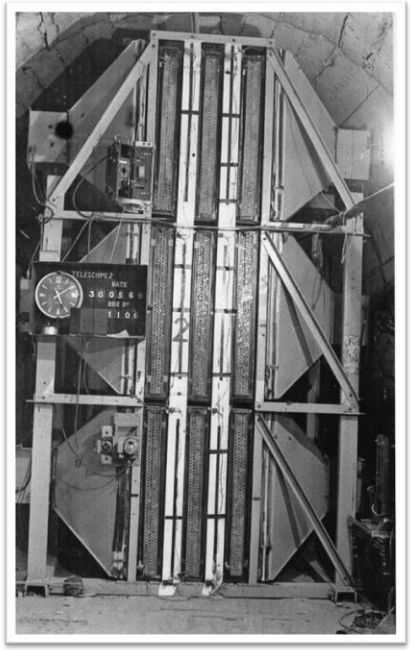
Gallex/GNO



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

Atmospheric neutrinos



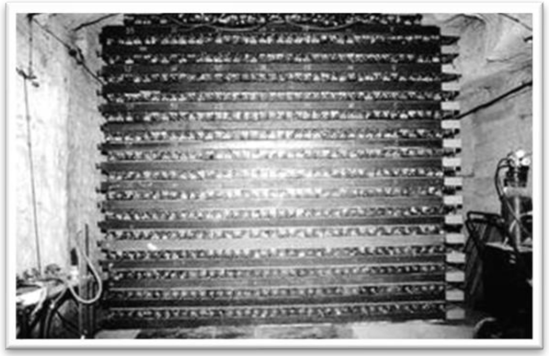


In 1965, atmospheric neutrinos were observed for the first time by detectors located extremely deep underground, one in India (left) and one in in South Africa (right).

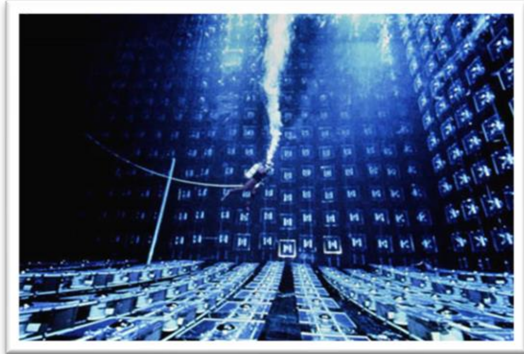
Photo by N. Mondal

Photo by H.Sobel

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



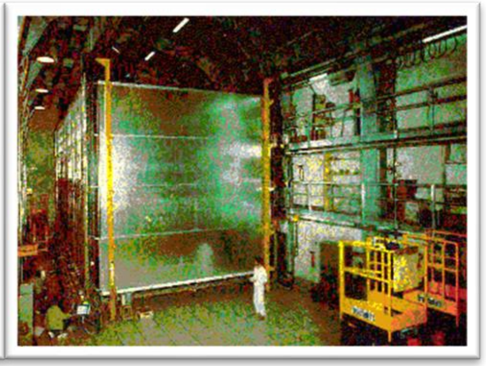
KGF



IMB

NUSEX

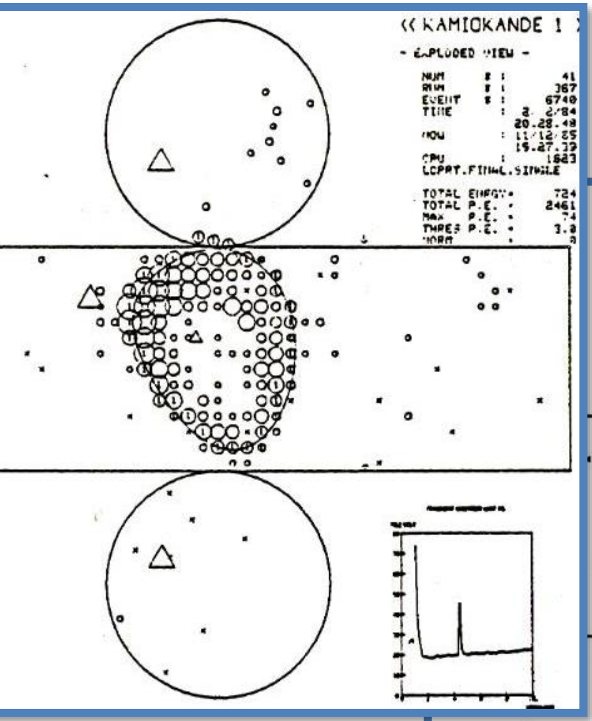
Kamiokande



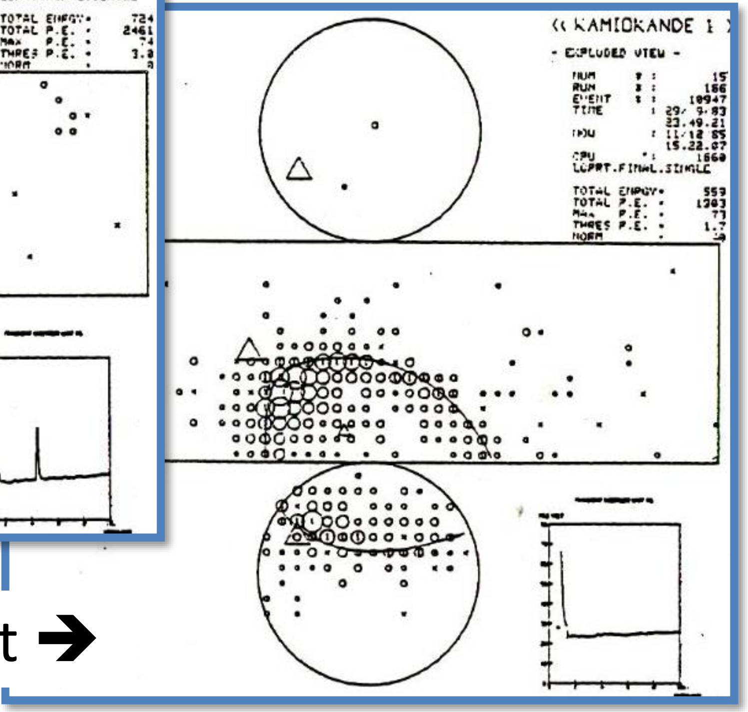
Frejus

Atmospheric ν_μ deficit (1988)

Atmospheric neutrinos have been the most serious background for the proton decay searches… Therefore, these background should be understood in order to find the proton decay signals. During these studies, a significant deficit of atmospheric nm events was observed.



← Typical ν_μ event in Kamiokande



Typical ν_e event →

K. Hirata et al, Phys.Lett.B 205 (1988) 416.

	Data	MC prediction
e-like (∼CC ν_e)	93	88.5
μ-like (∼CC ν_μ)	85	144.0

Paper conclusion: "We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data."

(The IMB experiment also observed similar results.)

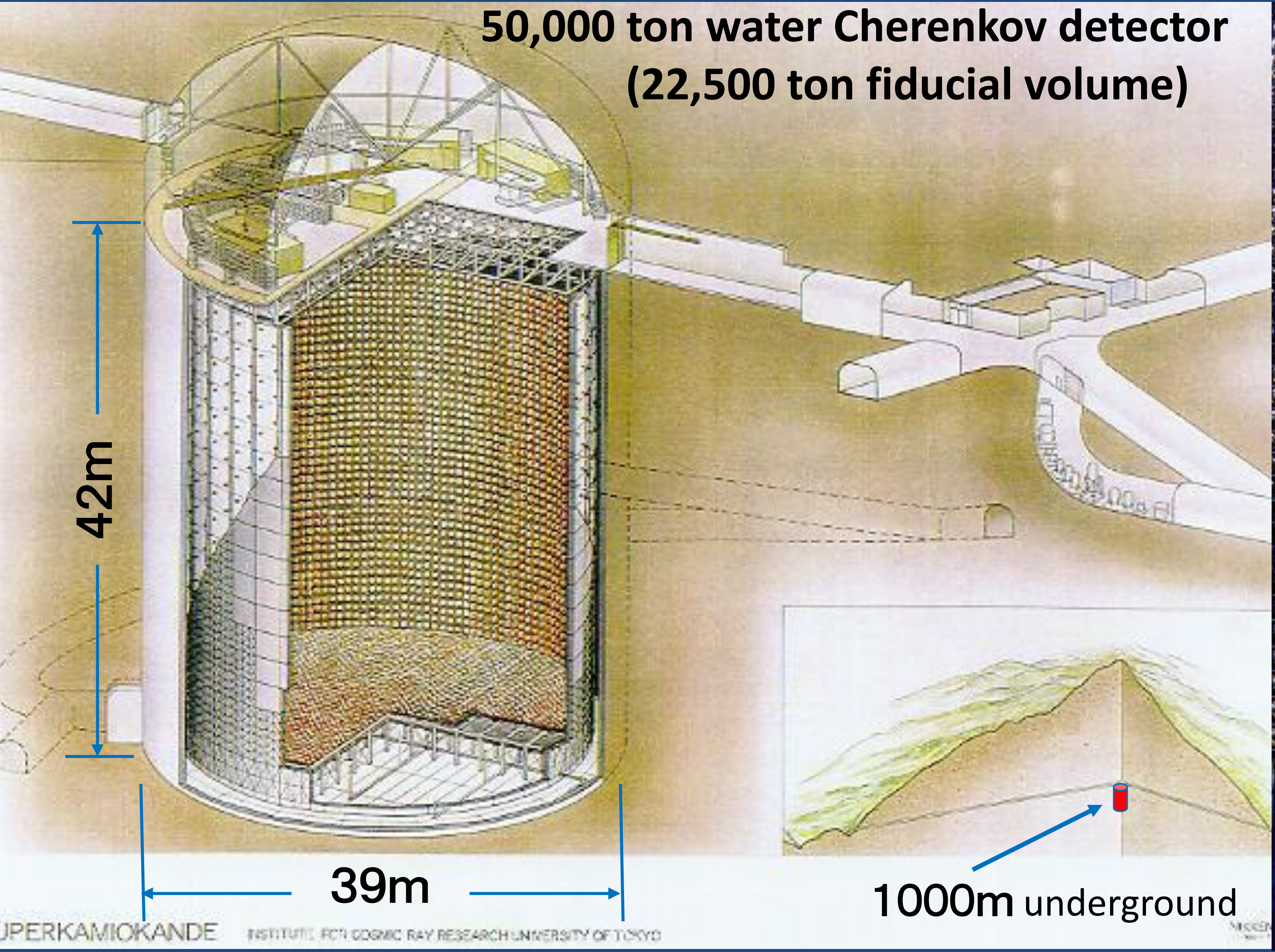
Neutrino oscillations: $\nu_\mu \rightarrow \nu_\tau$

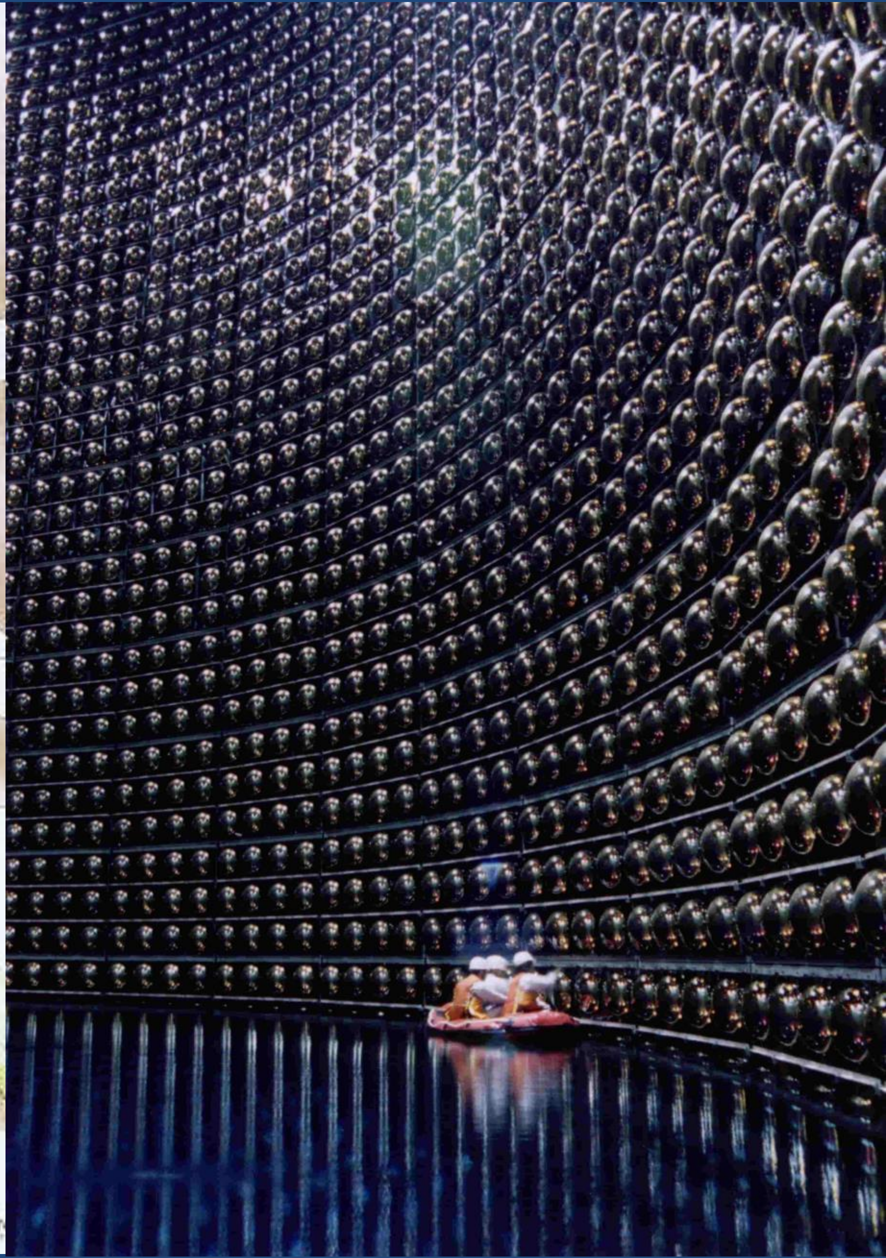
Neutrino oscillations

- ✓ 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)

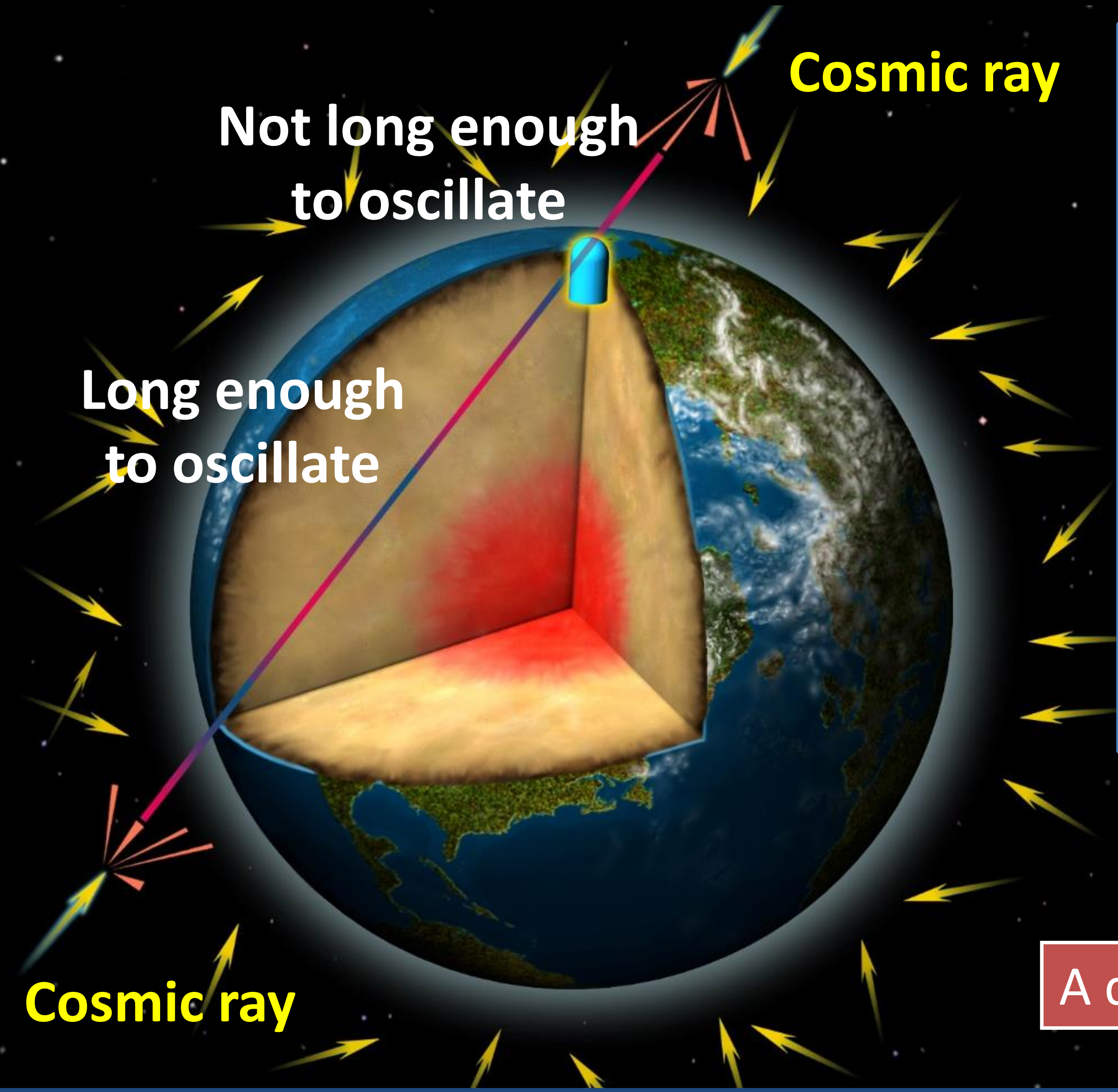
➔ Neutrino oscillation experiments!

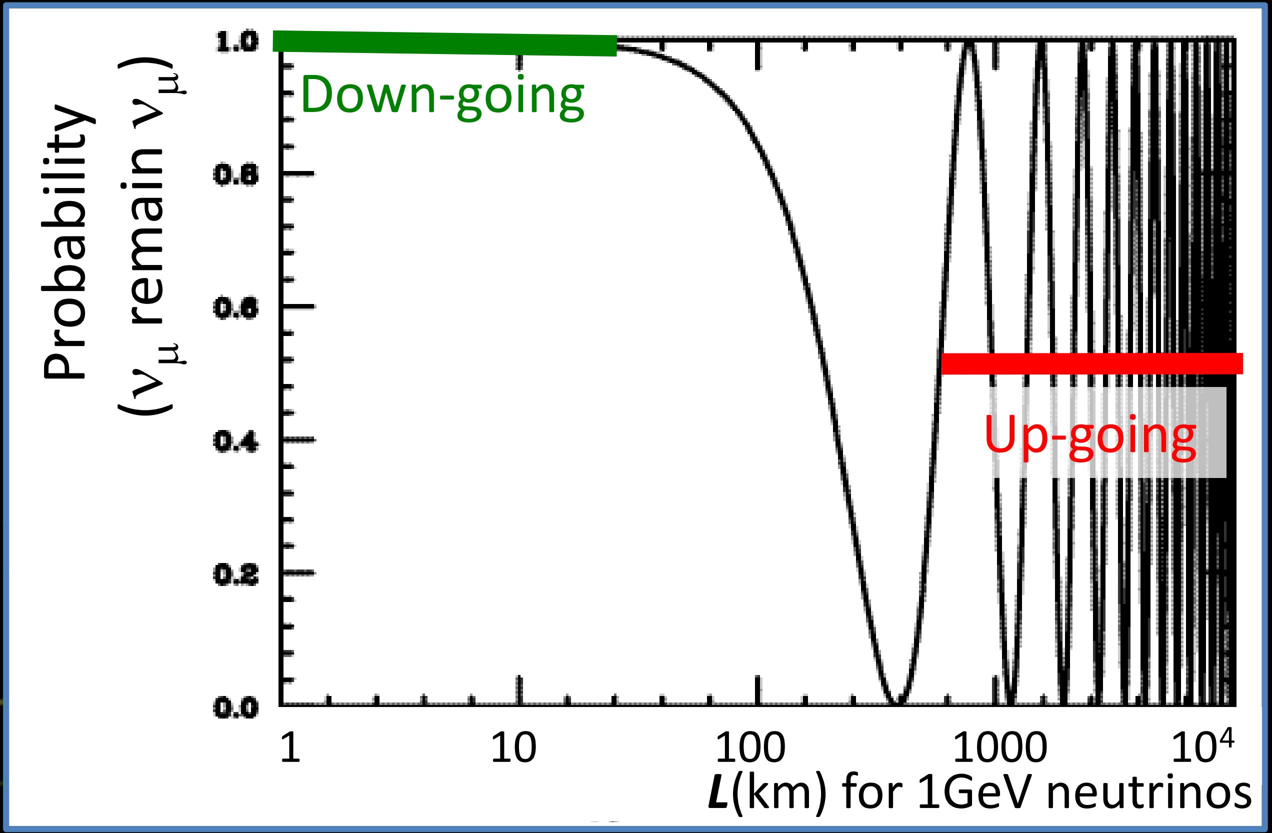
Super-Kamiokande detector





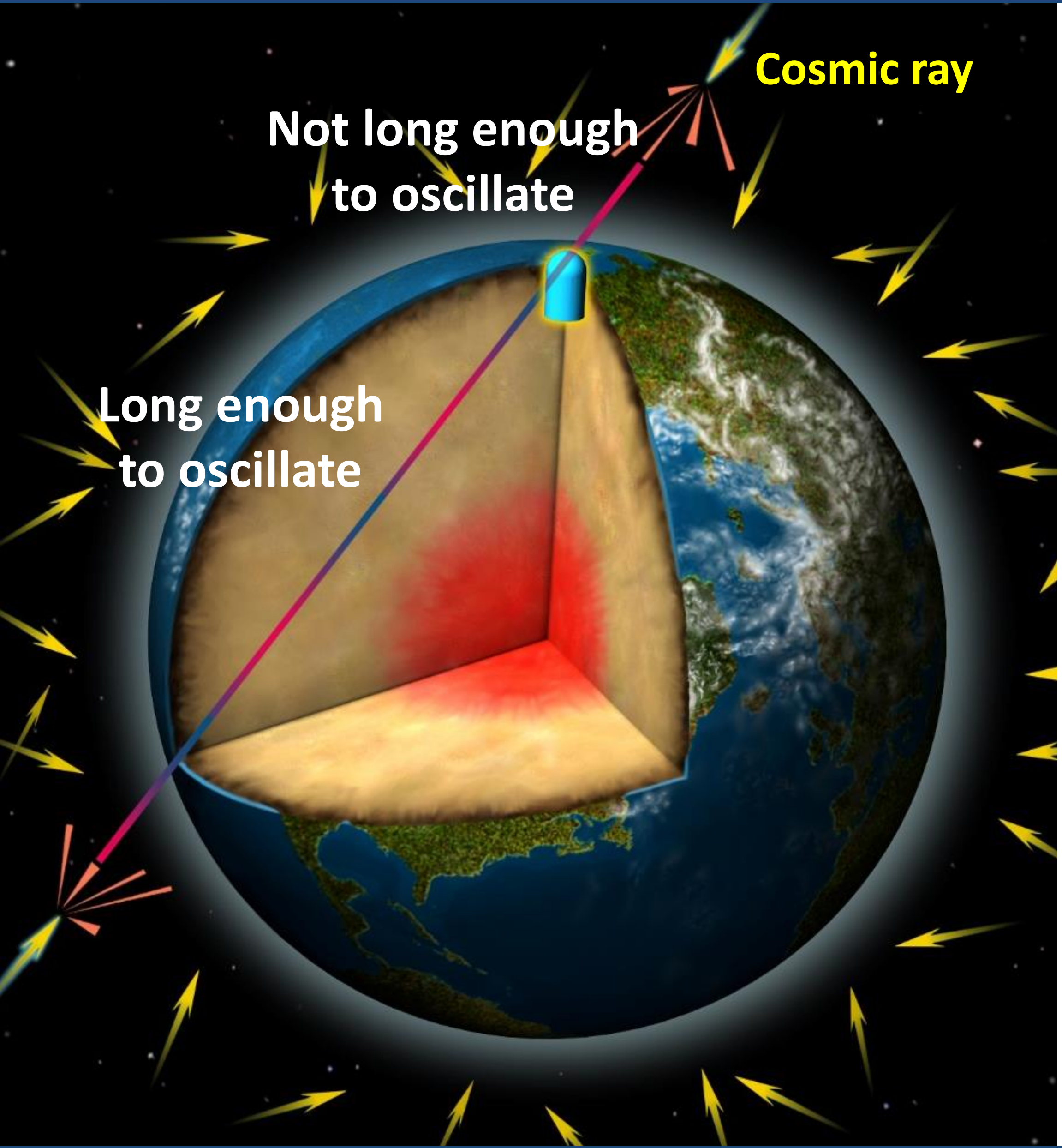
What will happen if the ν_μ deficit is due to neutrino oscillations



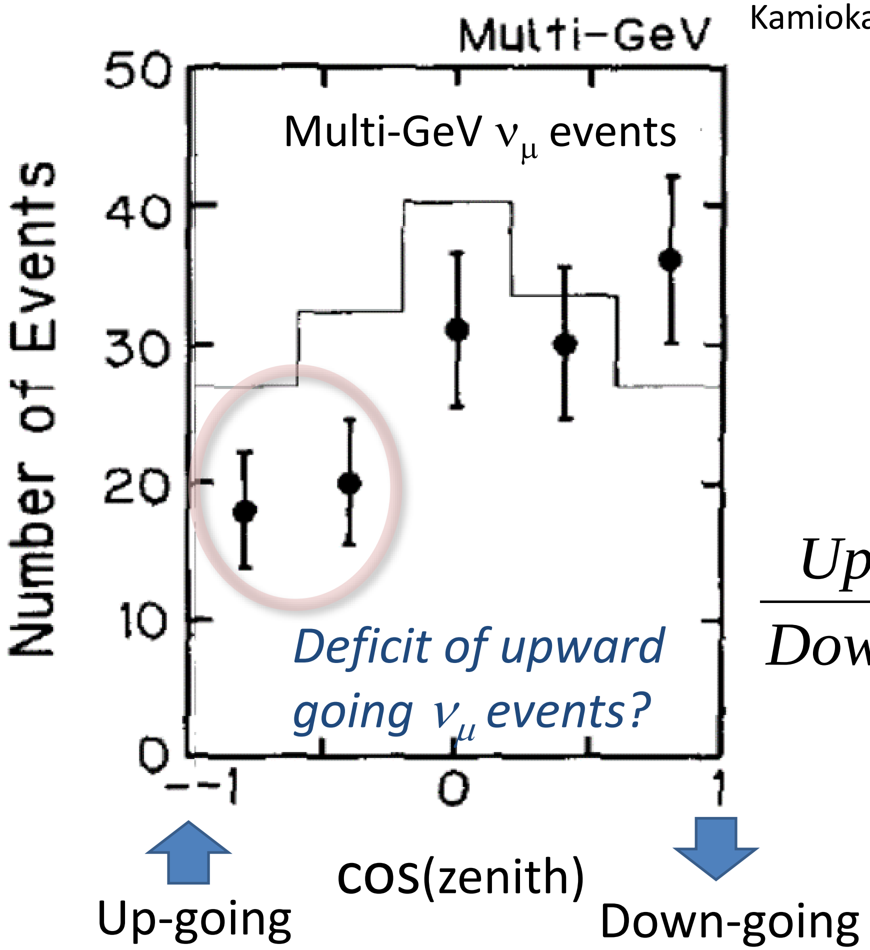


A deficit of upward going ν_μ's should be observed!

Appendix: Zenith angle distribution from Kamiokande (1994)



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



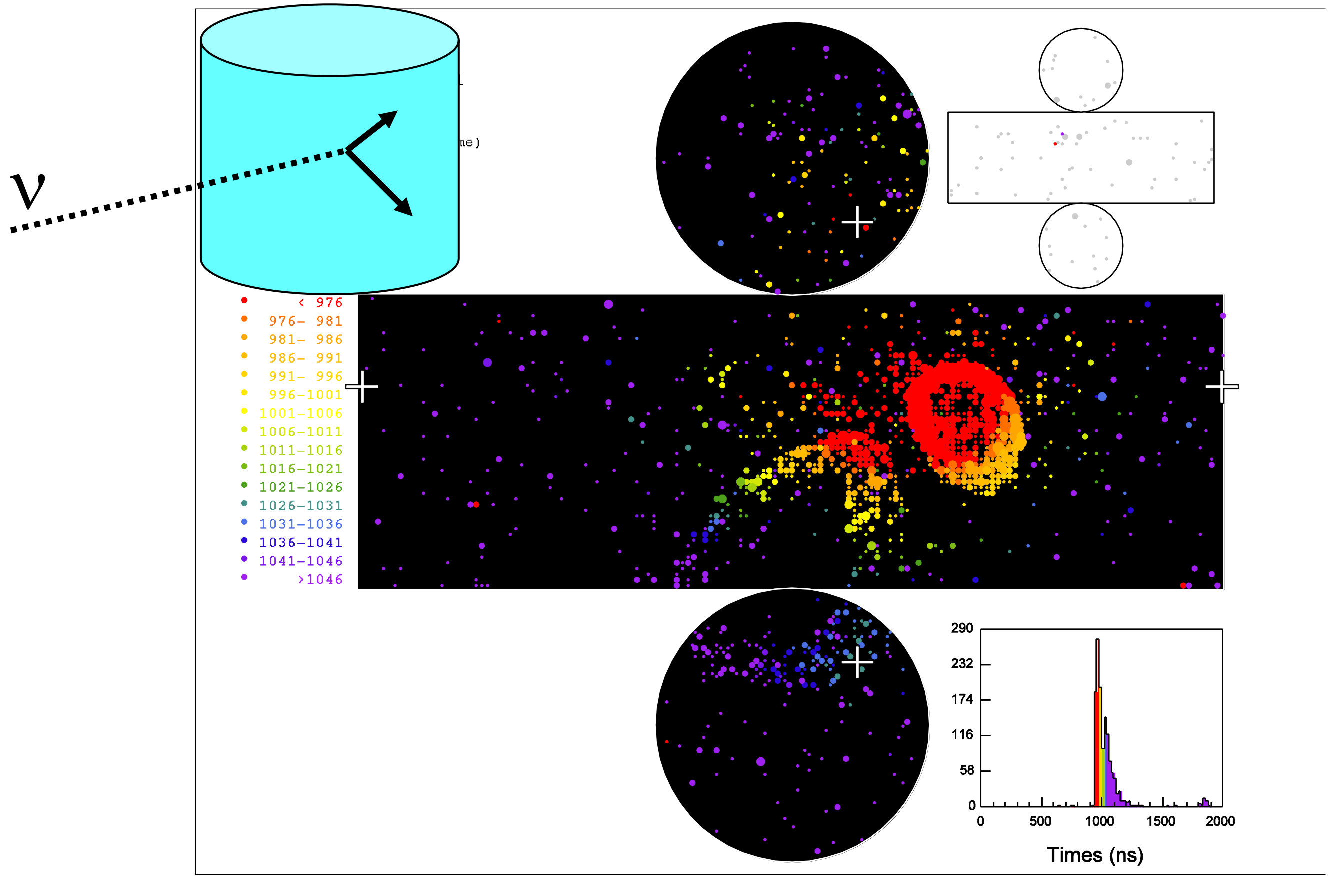
$$\frac{Up}{Down} = 0.58^{+0.13}_{-0.11} \ (2.9\sigma)$$

Conclusion: the data suggested something interesting. But the data statistics were not large enough. Much larger detector needed.

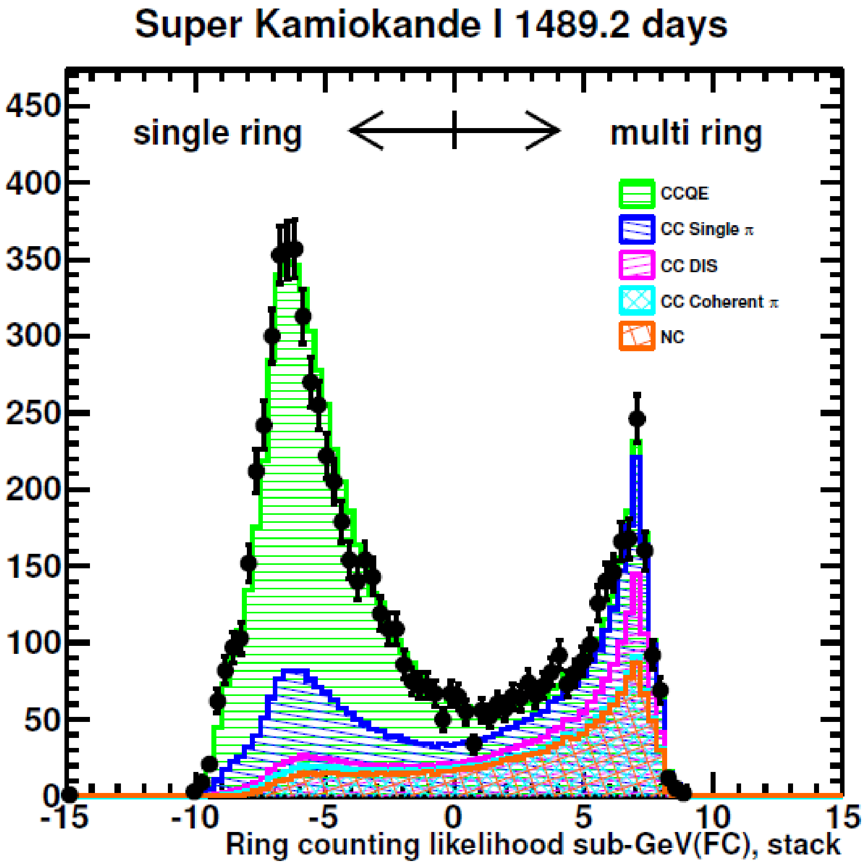
Fully automated analysis

- One of the limitation of the Kamiokande's analysis was the necessity of the event scanning for all data and Monte Carlo events, due to no satisfactory ring identification software.

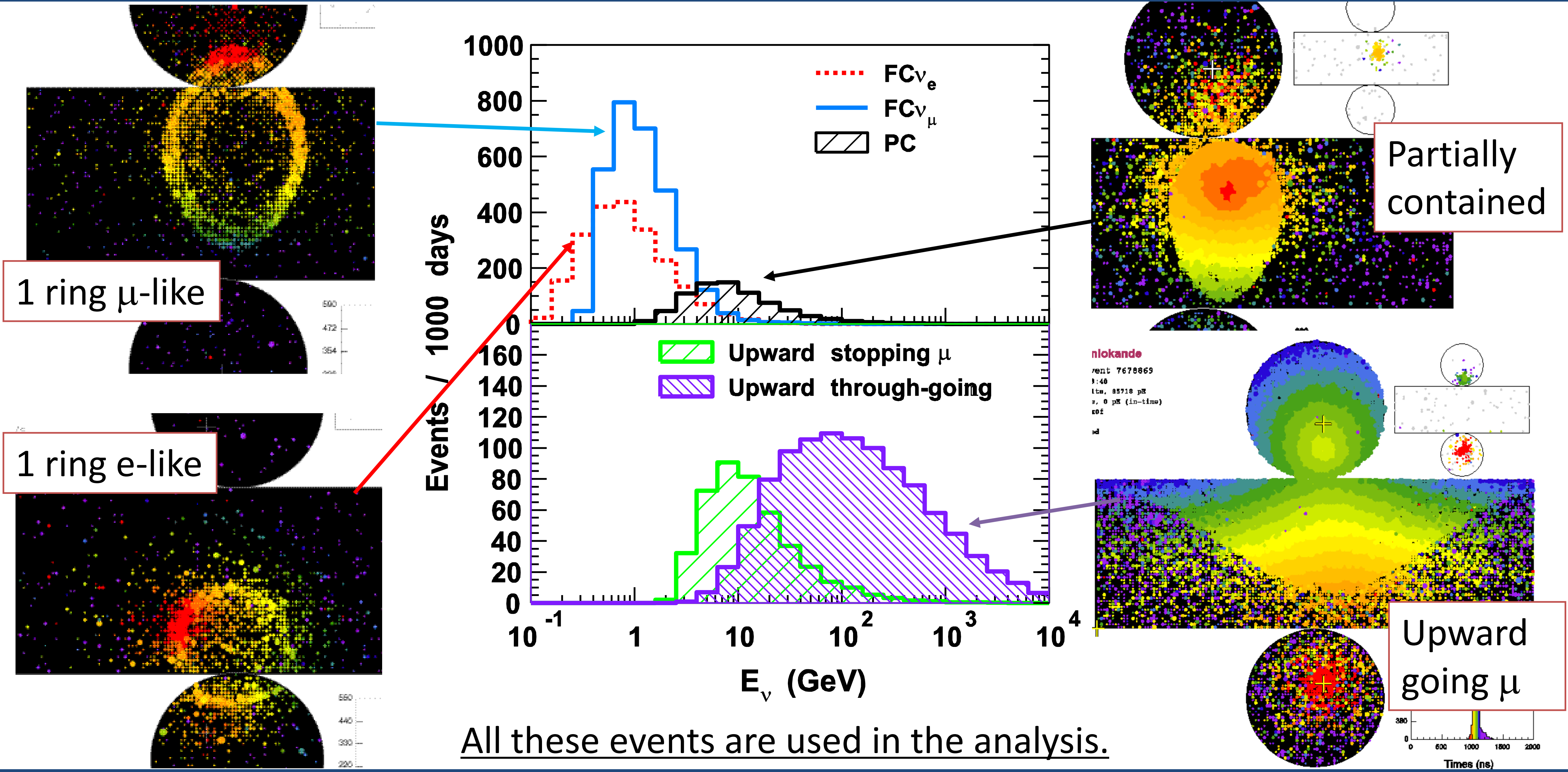
Multi Cherenkov ring event



Hough transformation
+ maximum likelihood



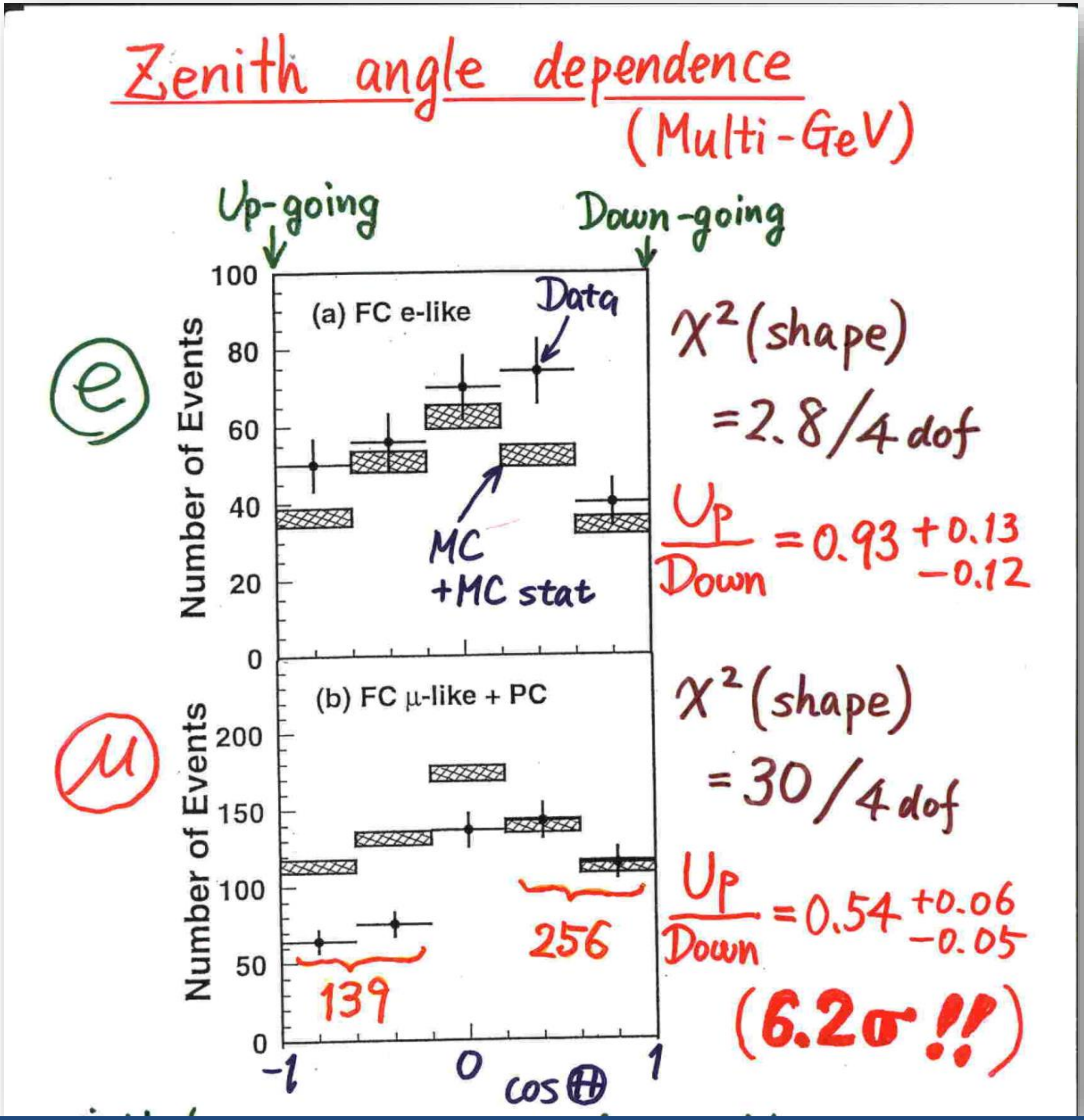
Event type and neutrino energy

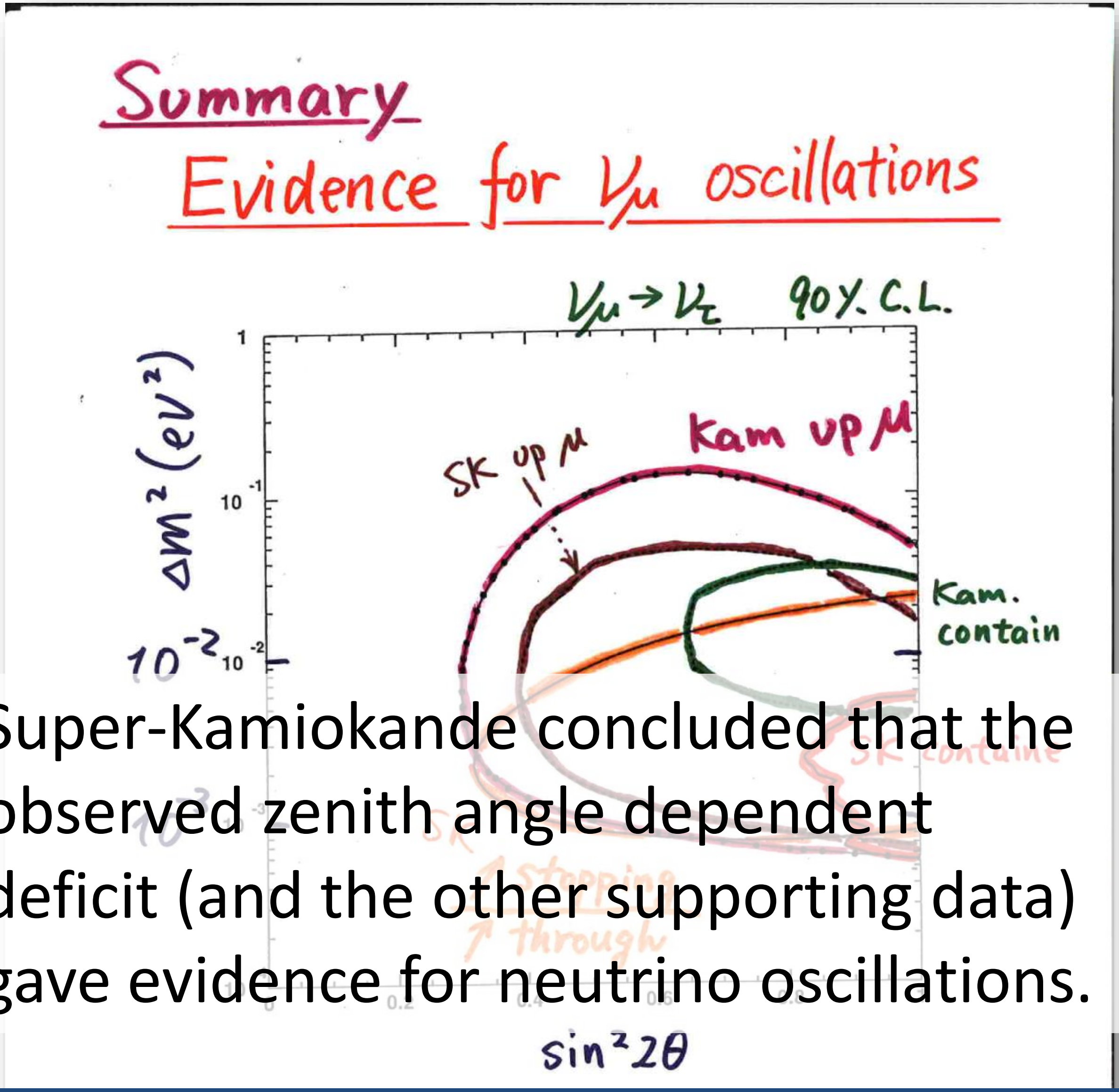


All these events are used in the analysis.

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

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

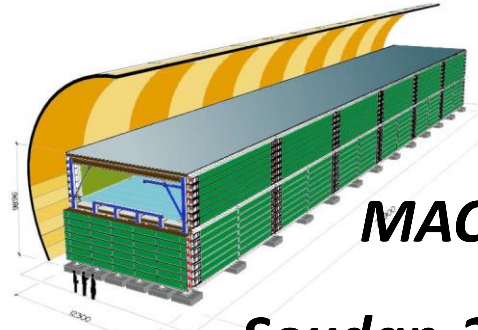




Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Neutrino oscillation studies

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

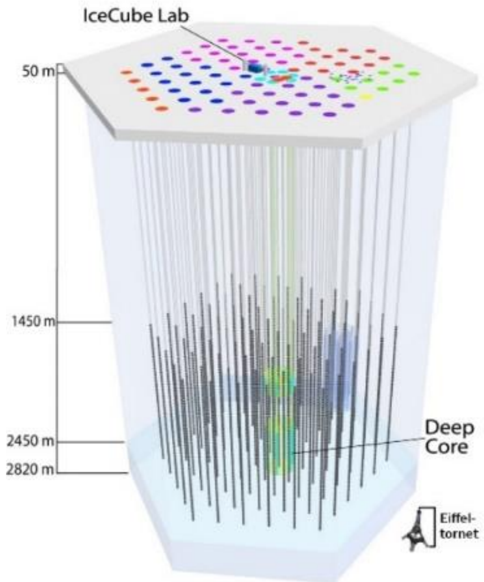


MACRO

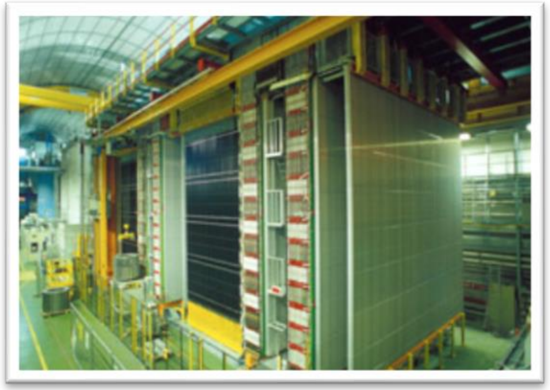
K2K

MINOS

Soudan-2

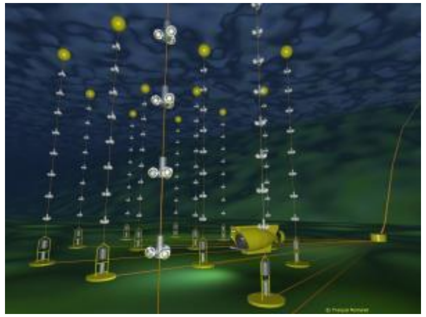


IceCube



OPERA

NOvA



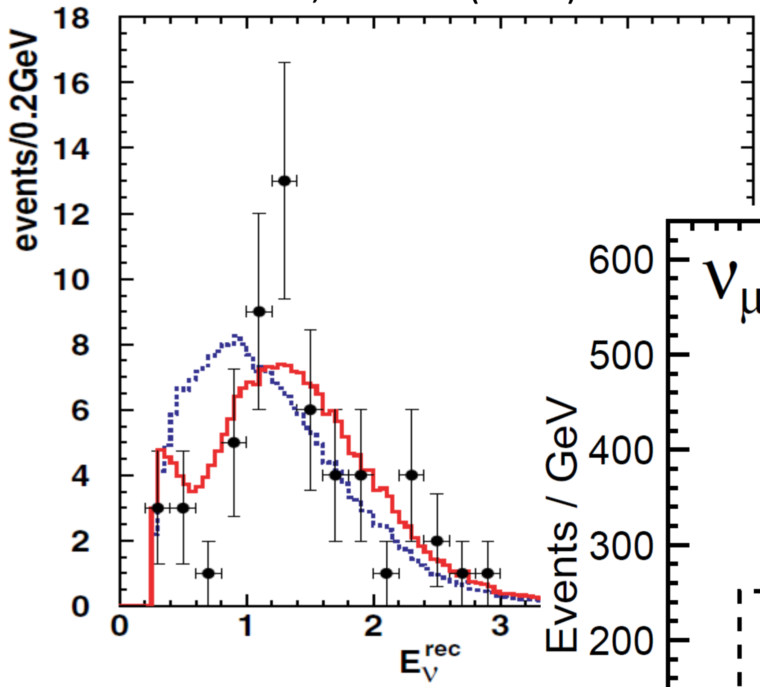
ANTARES

T2K

ν_μ disappearance studies (accelerator experiments)

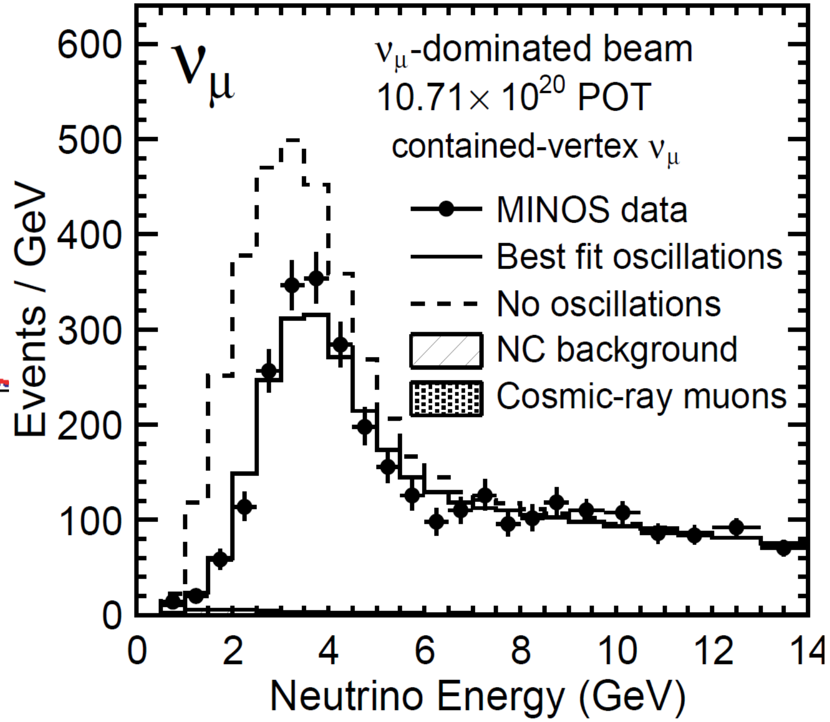
K2K

K2K, PRD 74 (2006) 072003



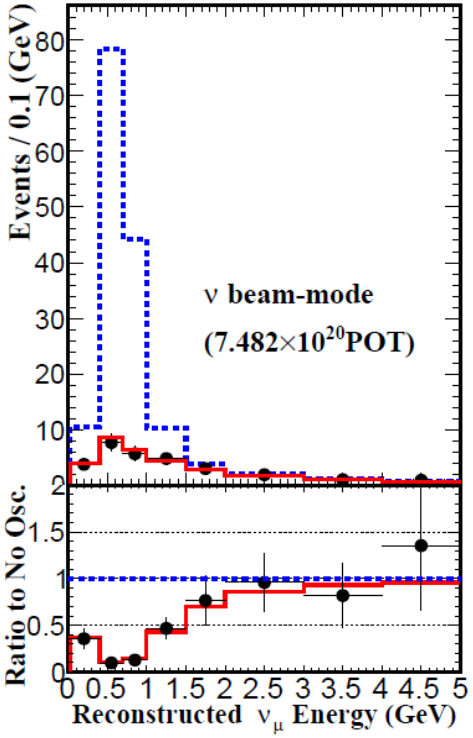
MINOS

MINOS PRL 110 (2013) 251801



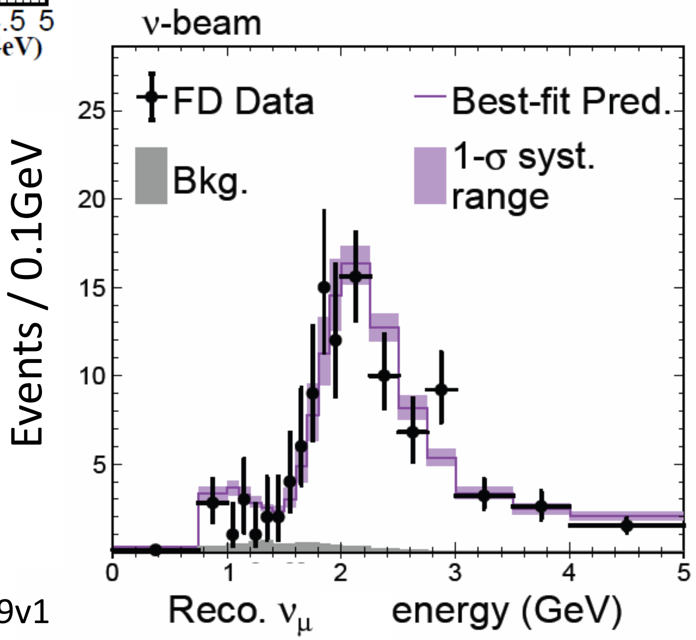
T2K

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



NOvA

NOvA, arXiv:2108.08219v1

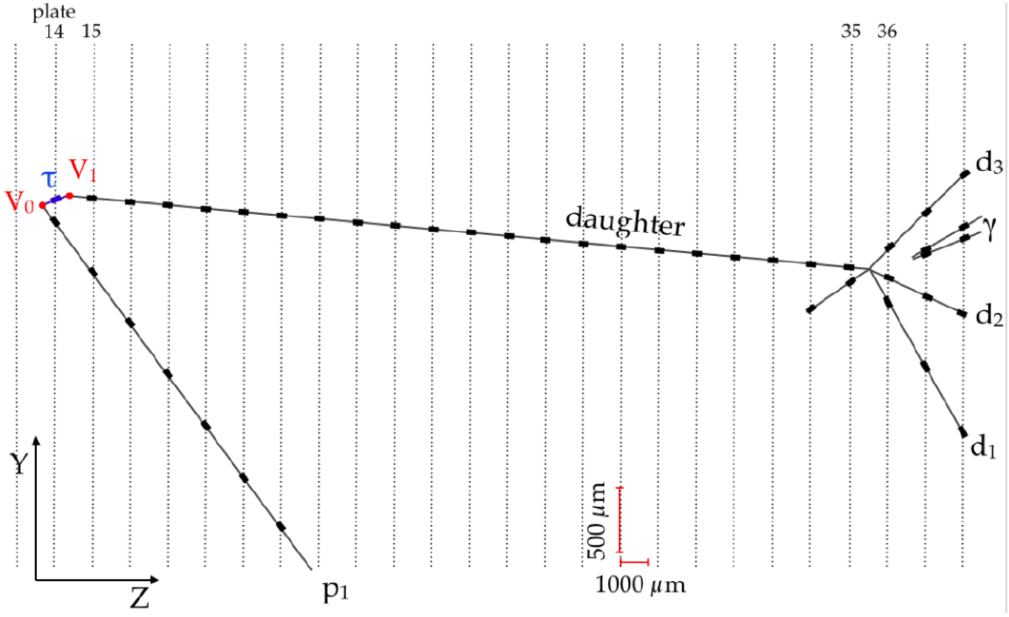


ν_τ appearance

OPERA

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

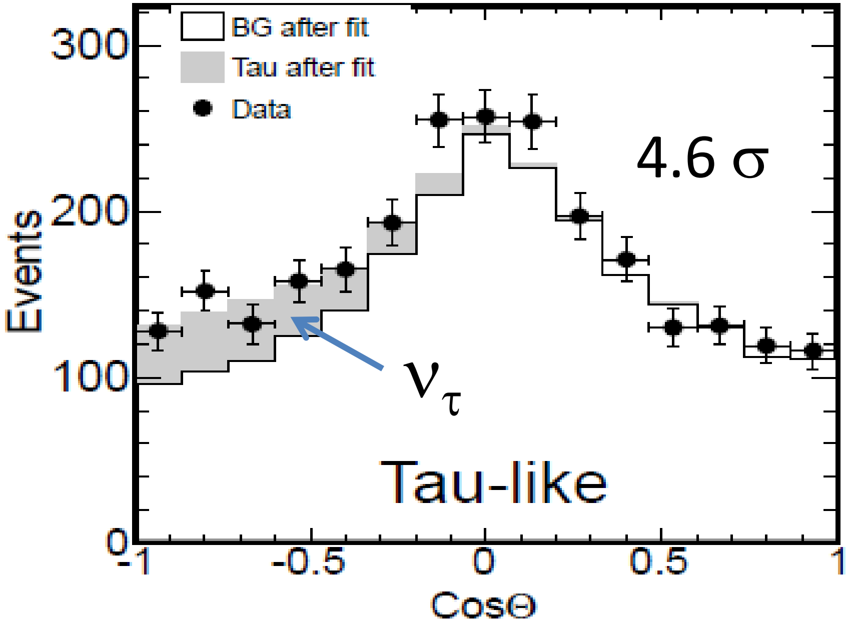
OPERA PRL 115 (2015) 121602



The fifth candidate event

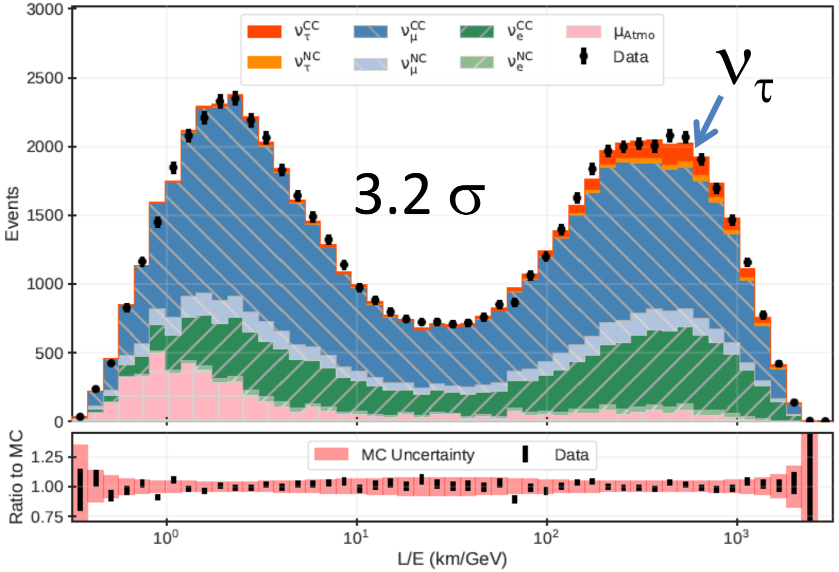
Super-Kamiokande

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



IceCube

IceCube,
PRD 99 (2019) 3, 032007

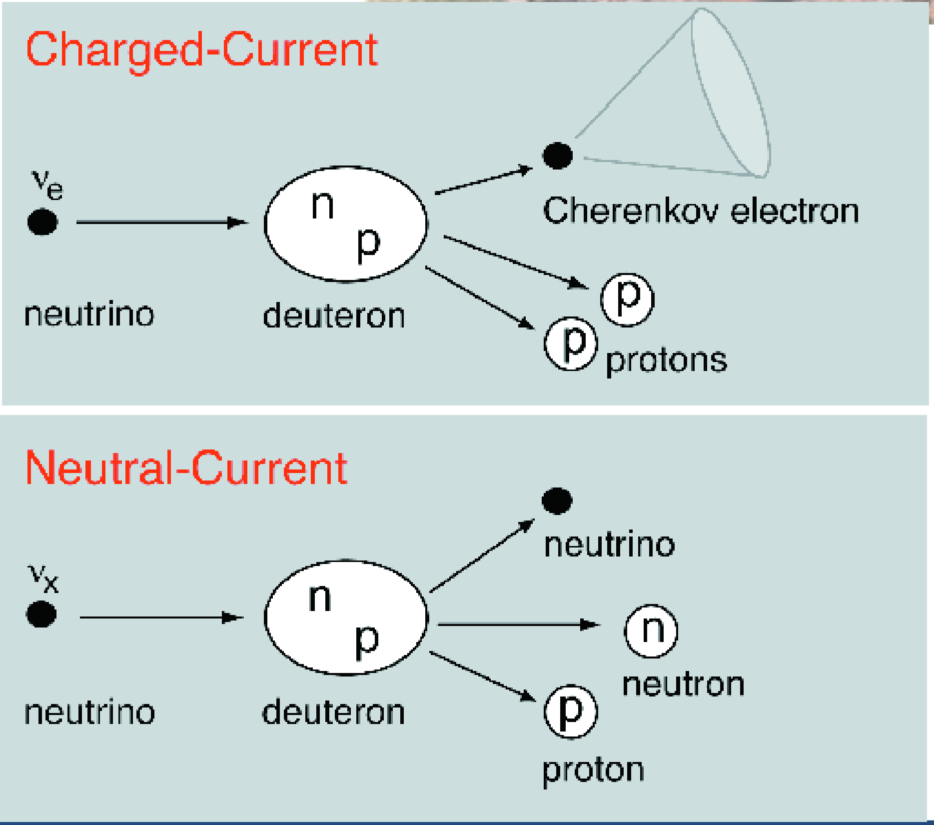


Neutrino oscillations: $\nu_e \rightarrow \nu_\mu + \nu_\tau$

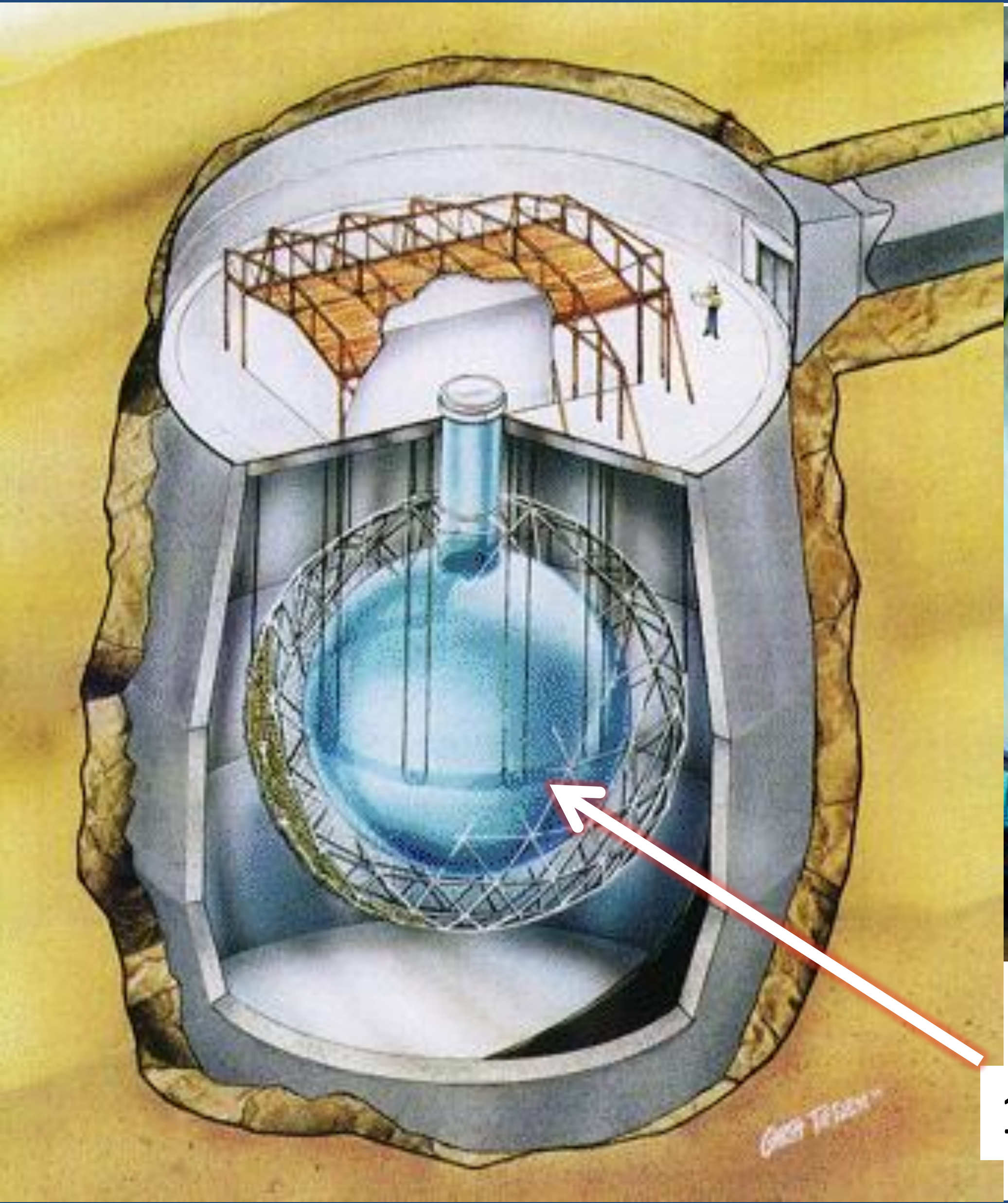
Initial idea

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

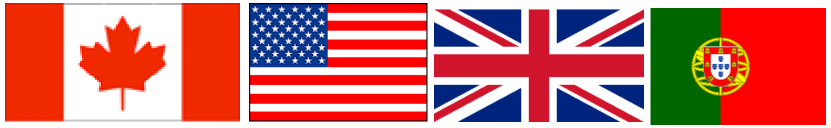
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis 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

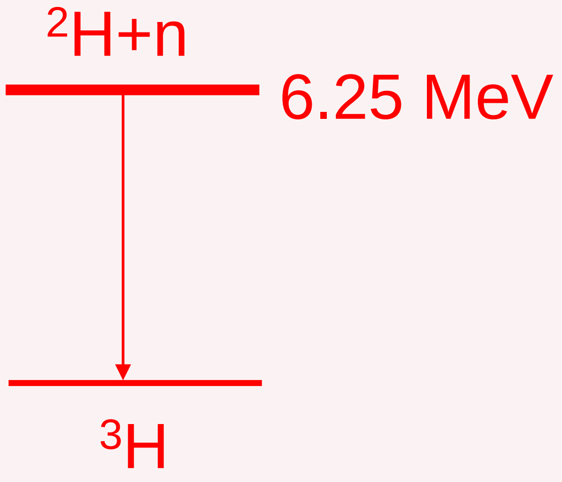


3 neutron detection methods (for νd → νpn measurement)

Phase I (D_2O)

Nov. 99 - May 01

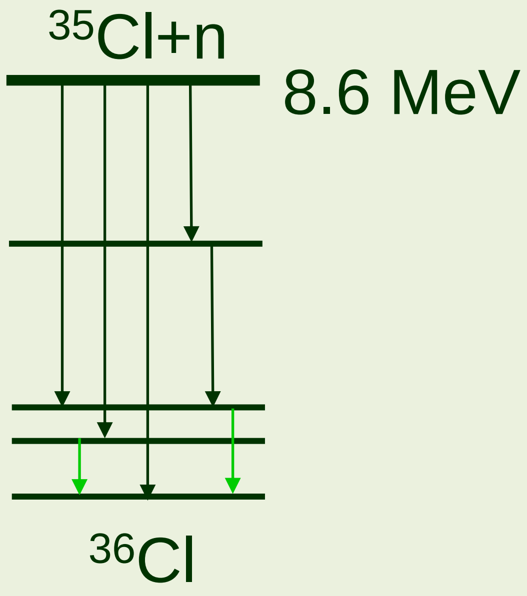
n captures on
$^{2}H(n, \gamma)^{3}H$
Eff. ~14.4%



Phase II (salt)

July 01 - Sep. 03

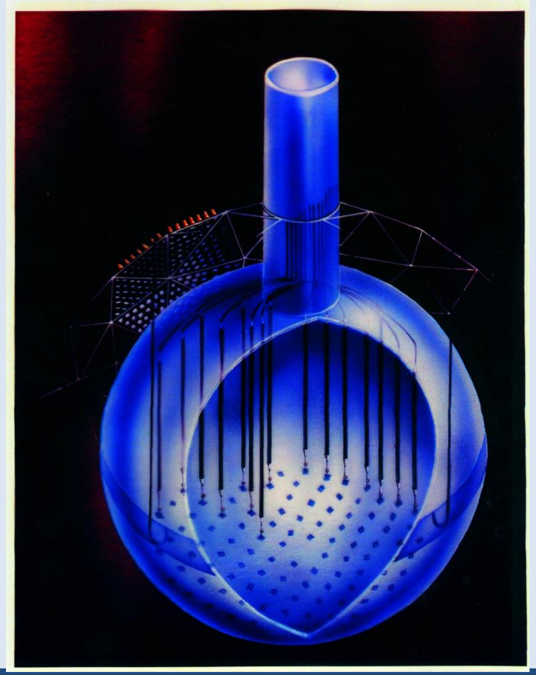
2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Eff. ~40%



Phase III (^{3}He)

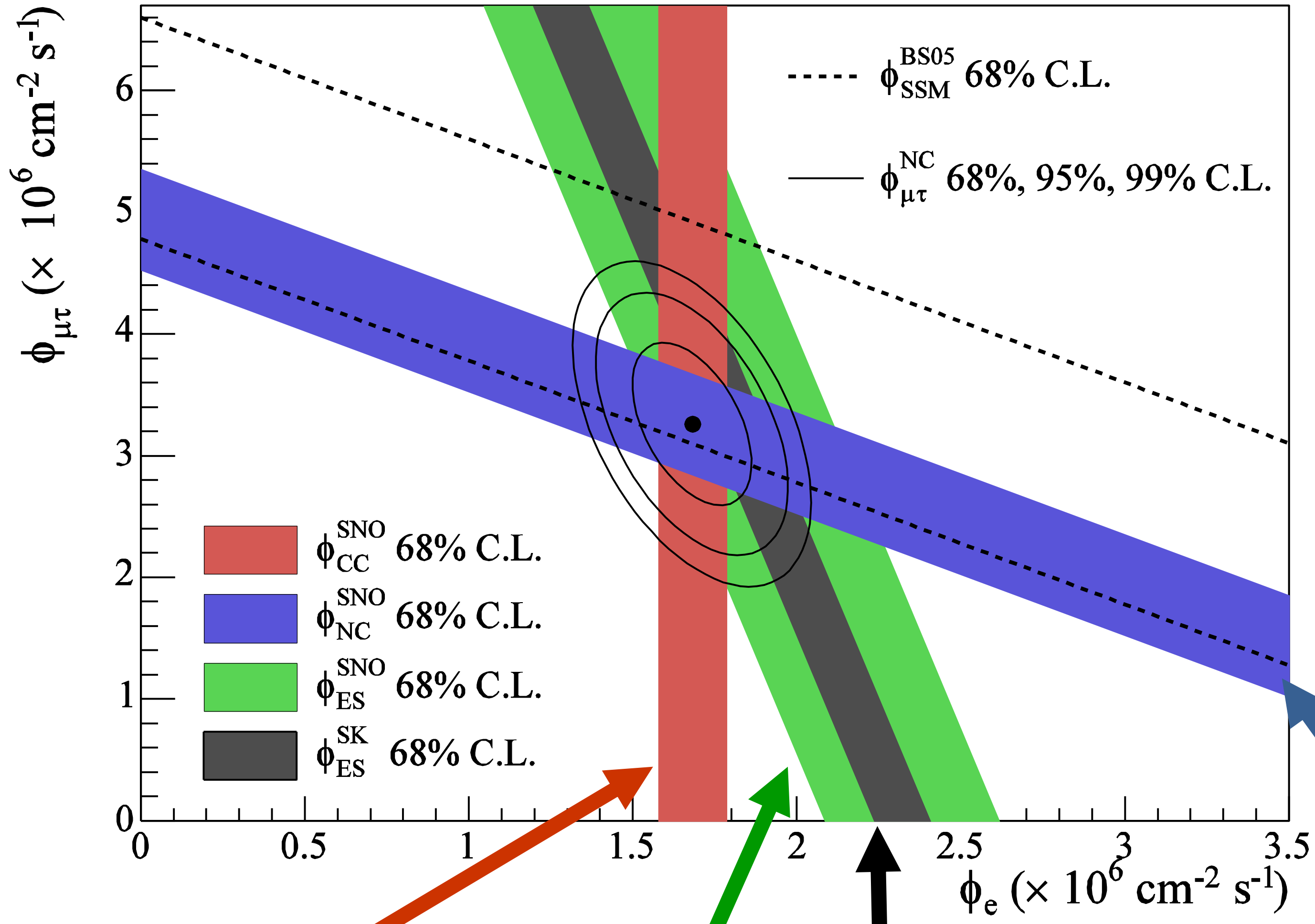
Nov. 04-Dec. 06

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



Evidence for solar neutrino oscillations

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



(A plot based on the salt-phase data)

SSM 68%CL

SNO NC 68%CL

SNO CC 68%CL

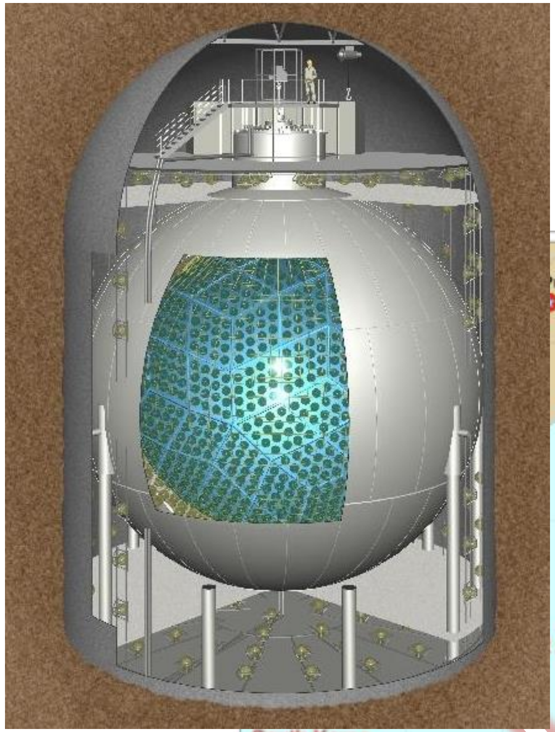
SNO ES 68%CL

SK ES 68%CL

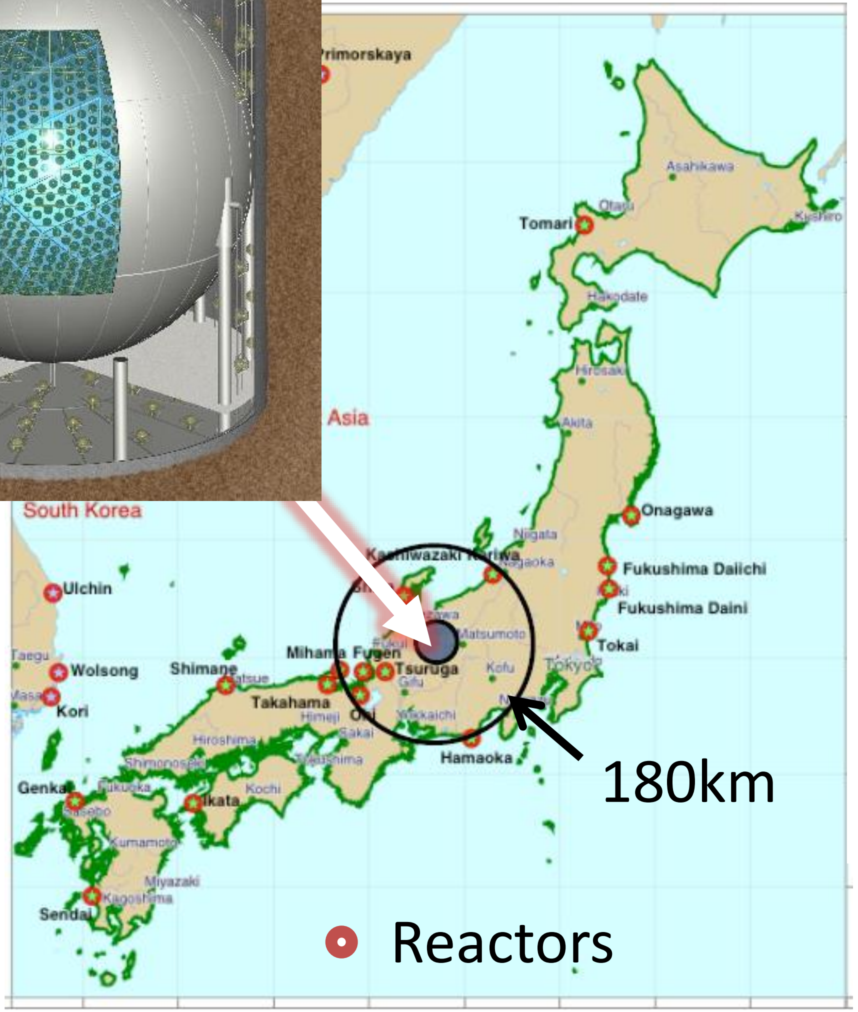
Three (or four) different measurements intersect at a point.
The intersect point clearly indicates non-zero $\nu_\mu + \nu_\tau$ flux.

➔ $\underline{\nu_e \rightarrow \nu_\mu + \nu_\tau}$

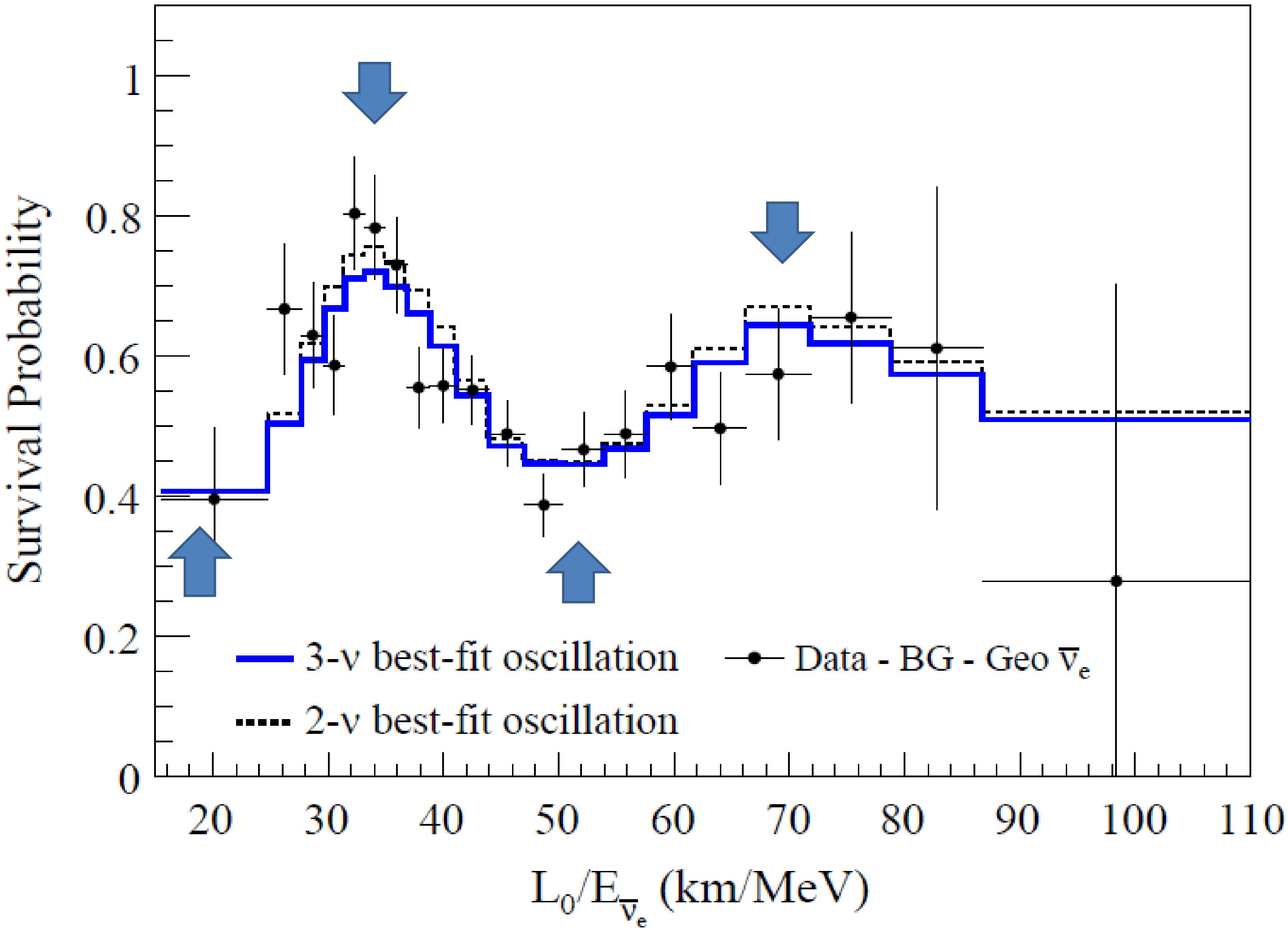
Really neutrino oscillations!



KamLAND



KamLAND, PRD 83, 052002 (2011)



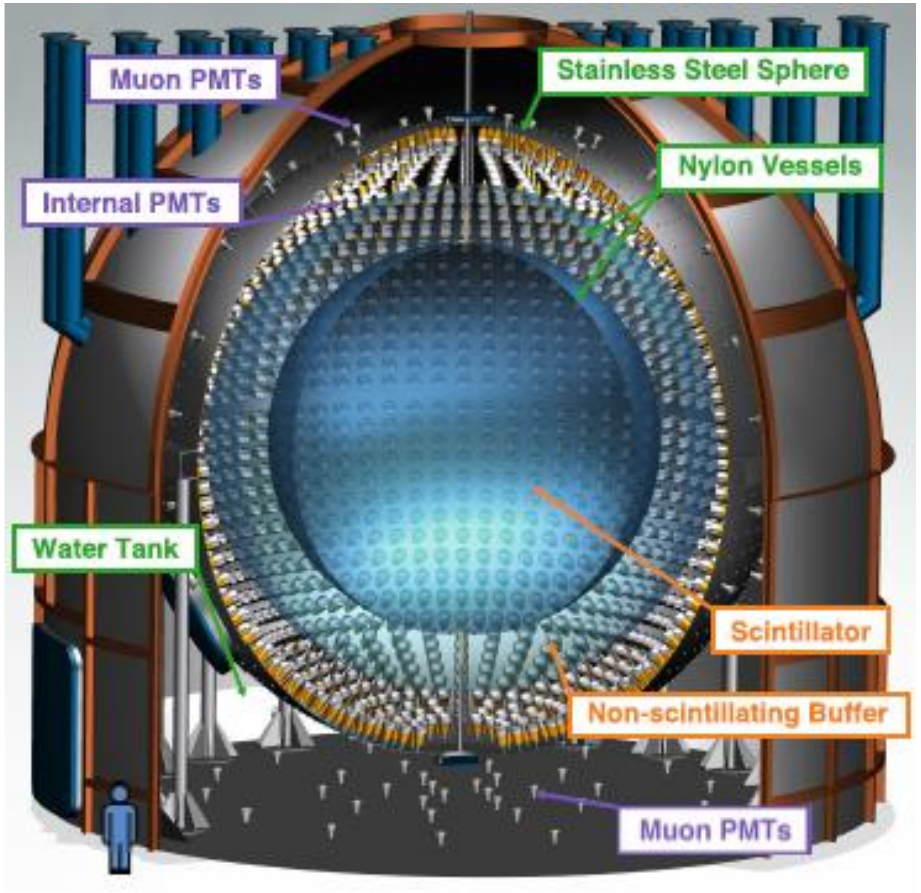
Really neutrino ***oscillations !***

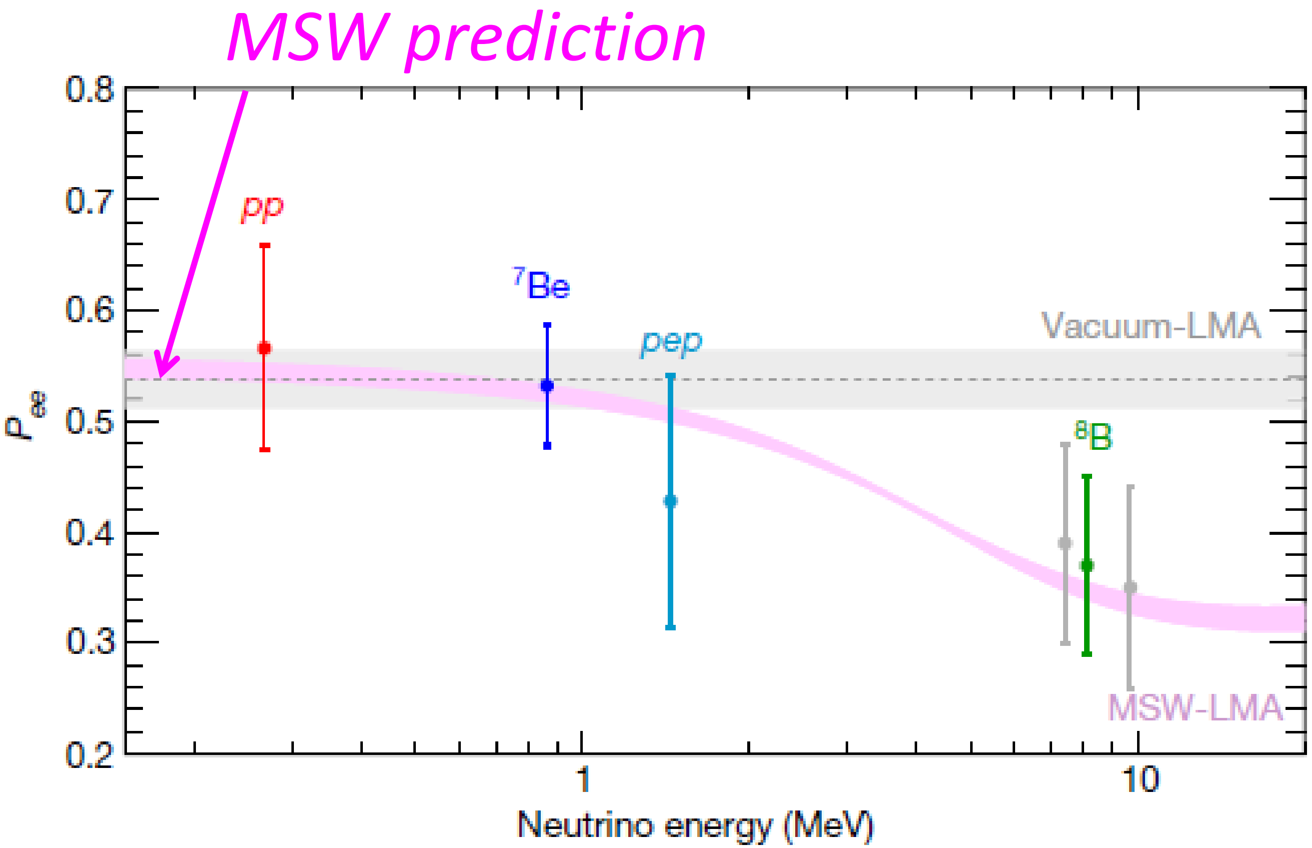
Consistent with MSW (neutrino oscillations in matter) !

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





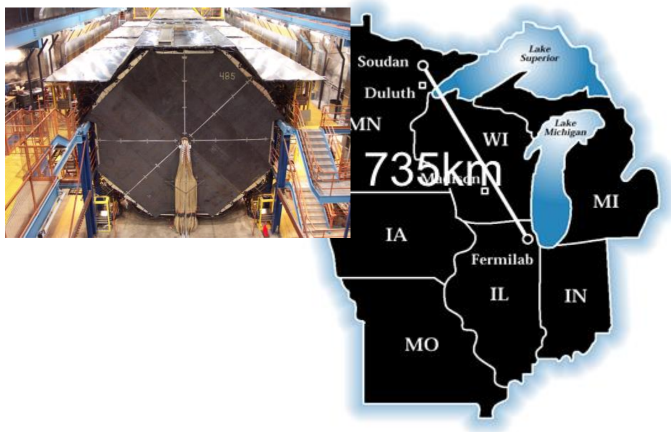
- ✓ *The data are consistent with the MSW prediction!*
- ✓ *Also, observation of CNO neutrinos (Nature 587 (2020) 577-582) !*

Neutrino oscillations: The third oscillation channel

Experiments for the third neutrino oscillations

Accelerator based long baseline neutrino oscillation experiments

MINOS

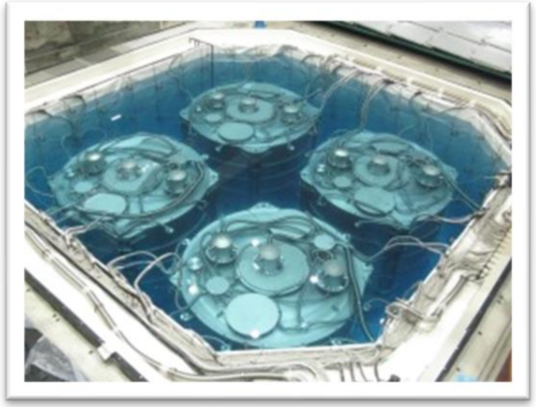


T2K

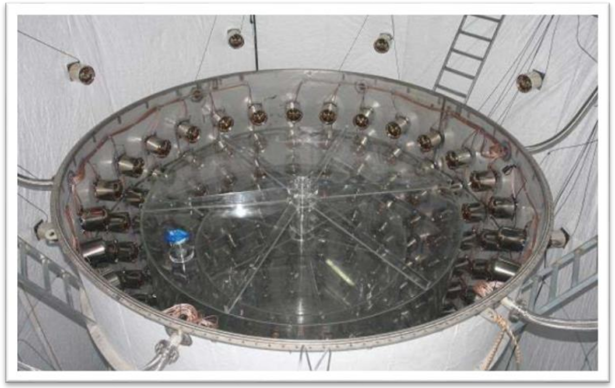
NOνA *(came slightly late)*

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

Daya Bay



RENO

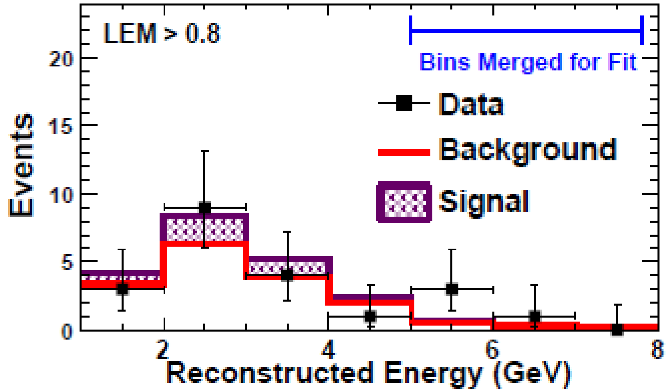


Double Chooz

Discovery of the third neutrino oscillations (2011-2012)

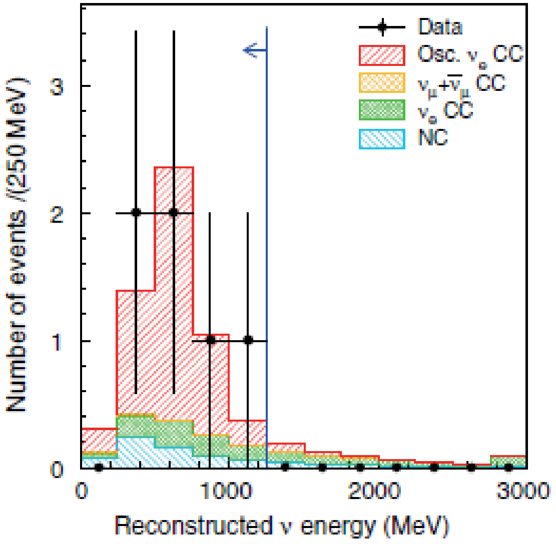
Accelerator based ν_e appearance experiments

MINOS PRL 107 (2011) 181802



T2K

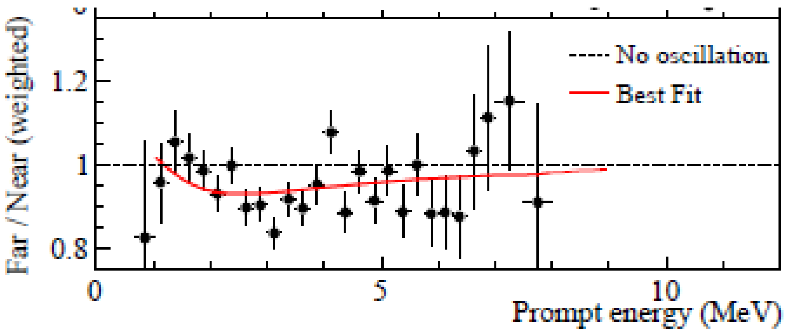
PRL 107 (2011) 041801



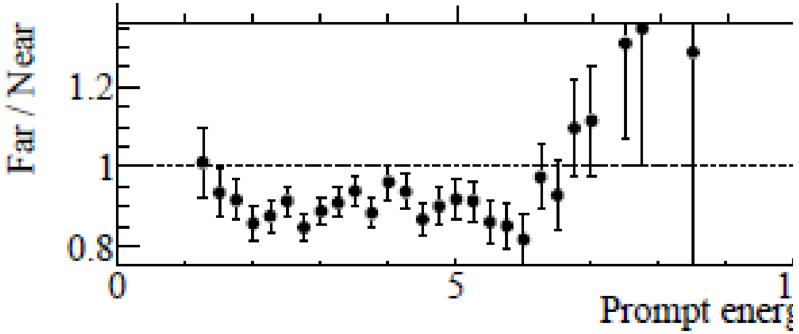
Note: these data are those in 2011-2012. The updated data are much better (including those from NOvA).

Reactor based anti-ν_e disappearance experiments

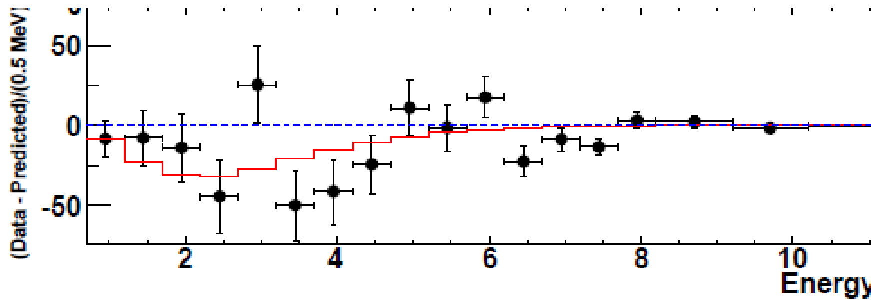
Daya Bay PRL 108 (2012) 171803



RENO PRL 108 (2012) 191802



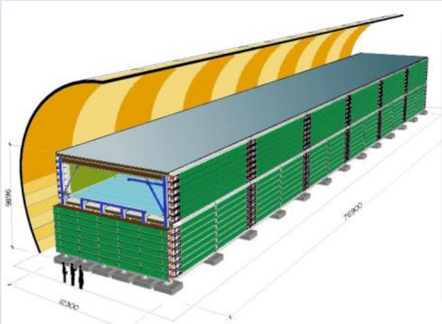
Double Chooz PRL 108 (2012) 131801

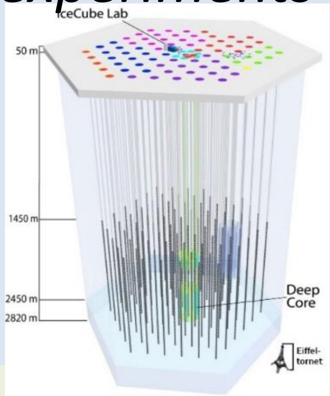


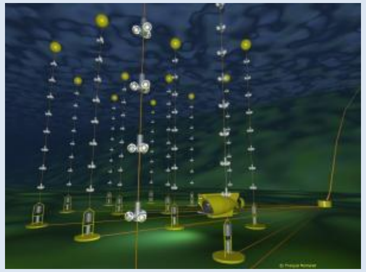
The basic structure for 3 flavor neutrino oscillations has been understood!

Many exciting results in neutrino oscillations (partial list)

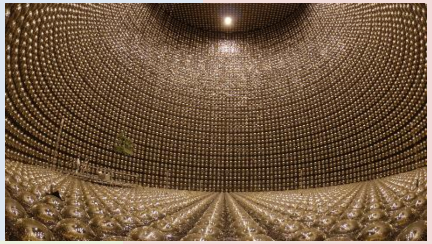
Atmospheric neutrino oscillation experiments

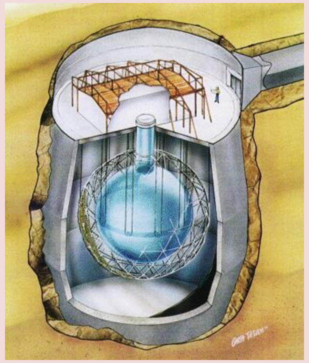




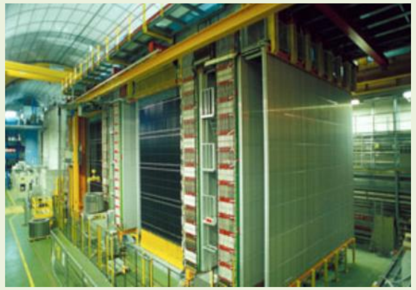


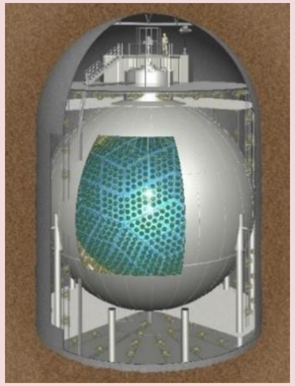
Solar neutrino oscillation experiments

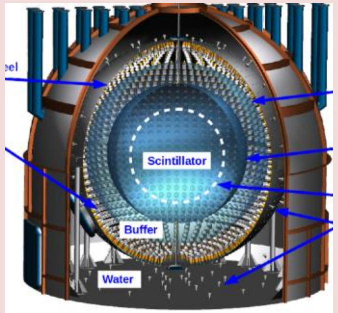




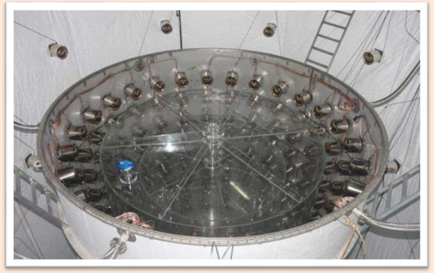
Accelerator based neutrino oscillation experiments

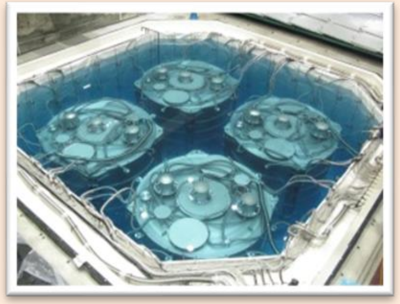






3 flavor(type) neutrino oscillation experiments

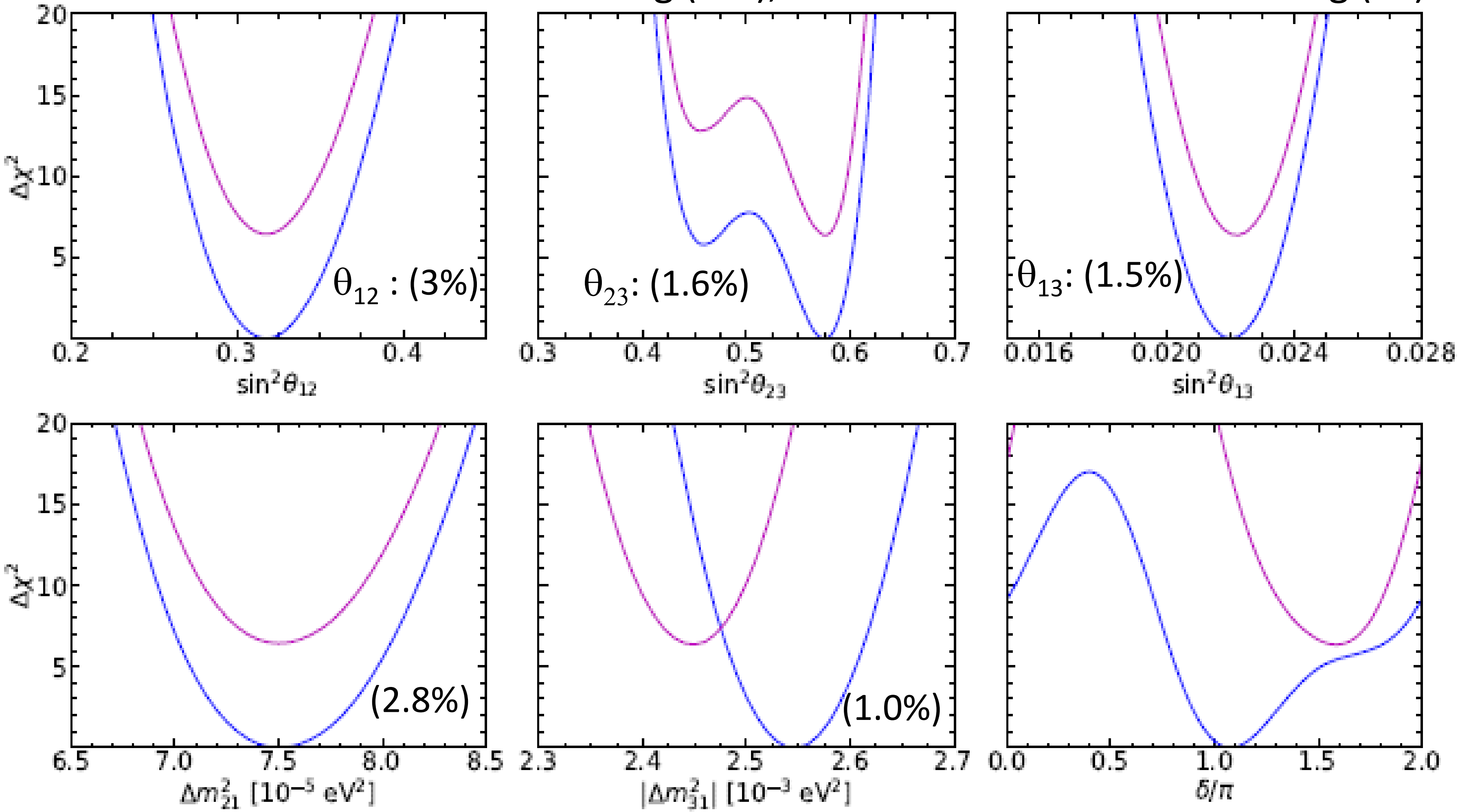


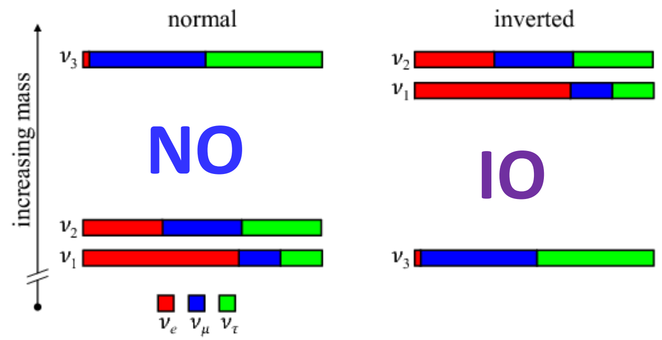


Oscillation parameters

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

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





➔ Neutrino mass is very small. Probably more than 10 orders of magnitude smaller than the corresponding mass of quarks and charged leptons.

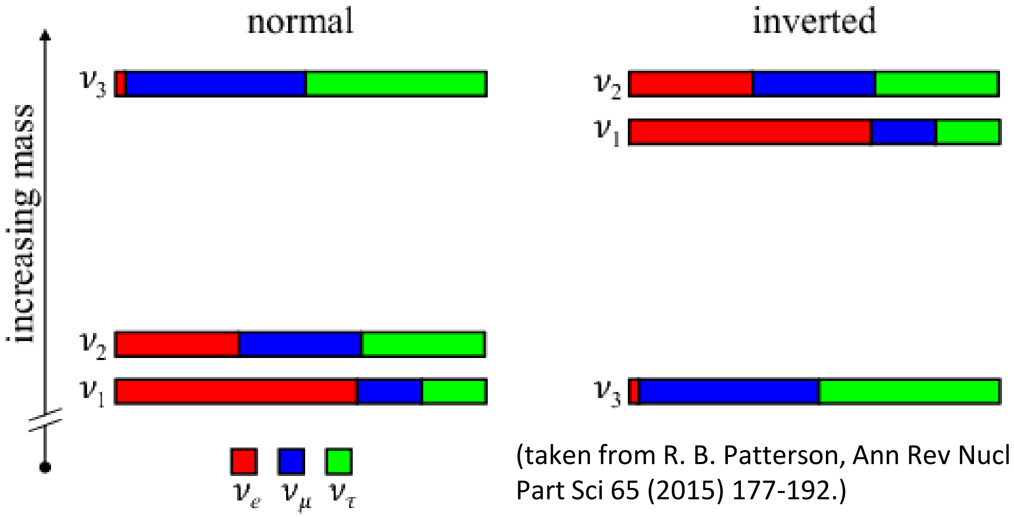
➔ Neutrino mixing angles are large compared with the corresponding quark mixing angles.

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

future prospect

Agenda for the future neutrino measurements

Neutrino mass ordering?



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

Absolute neutrino mass?

Beyond the 3 flavor framework? (Sterile neutrinos?)

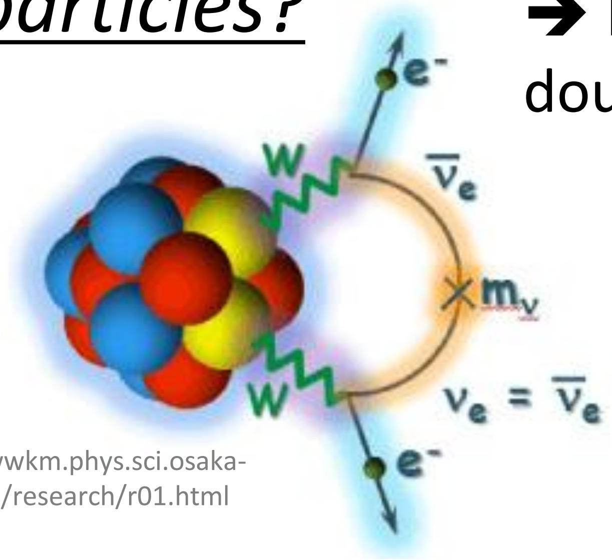
CP violation?

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

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

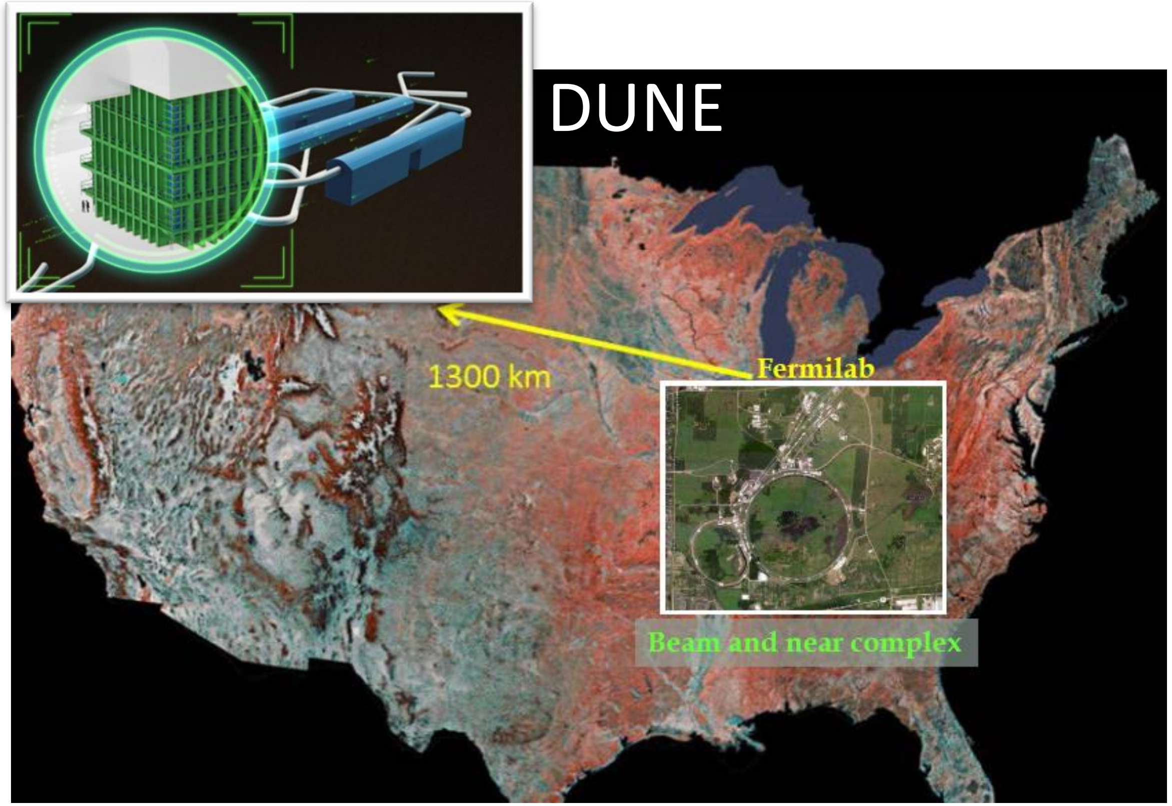
Future prospect: CP Violation

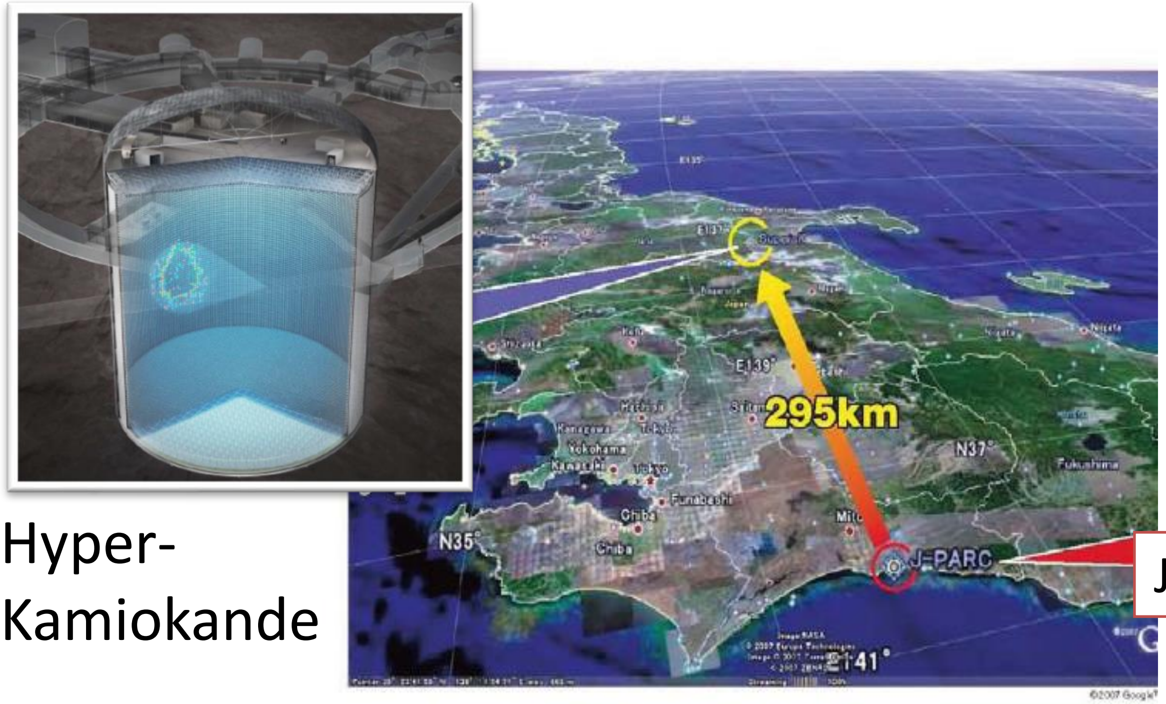
Motivation

- ✓We would like to confirm that CP is violated in the neutrino sector.
- ✓CP violation in the neutrino sector might be the key to understand the baryon asymmetry of the Universe (Leptogenesis, M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45-47).
- ✓…

Future

- ✓ We would like to know if neutrinos are related to the origin of the matter in the Universe.
- ✓ We would like to observe if neutrino oscillations of neutrinos and those of anti-neutrinos are different. ➔ We need the next generation long baseline experiments with much higher performance neutrino detectors.





Hyper-Kamiokande

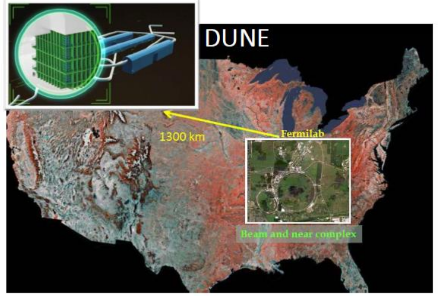
J-PARC

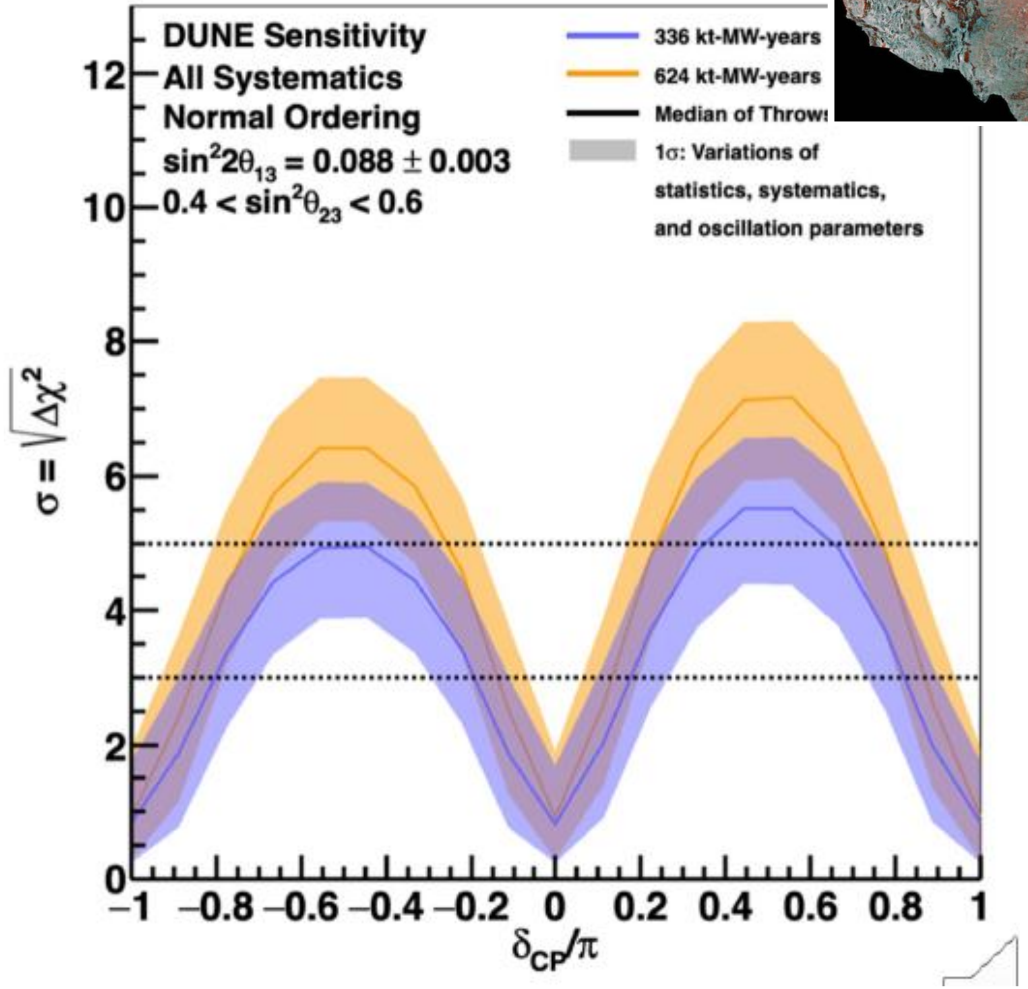
(Several other possibilities…)

Sensitivities

DUNE

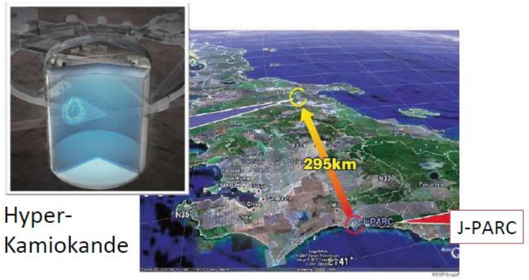
(Nu2022, M. Muether)

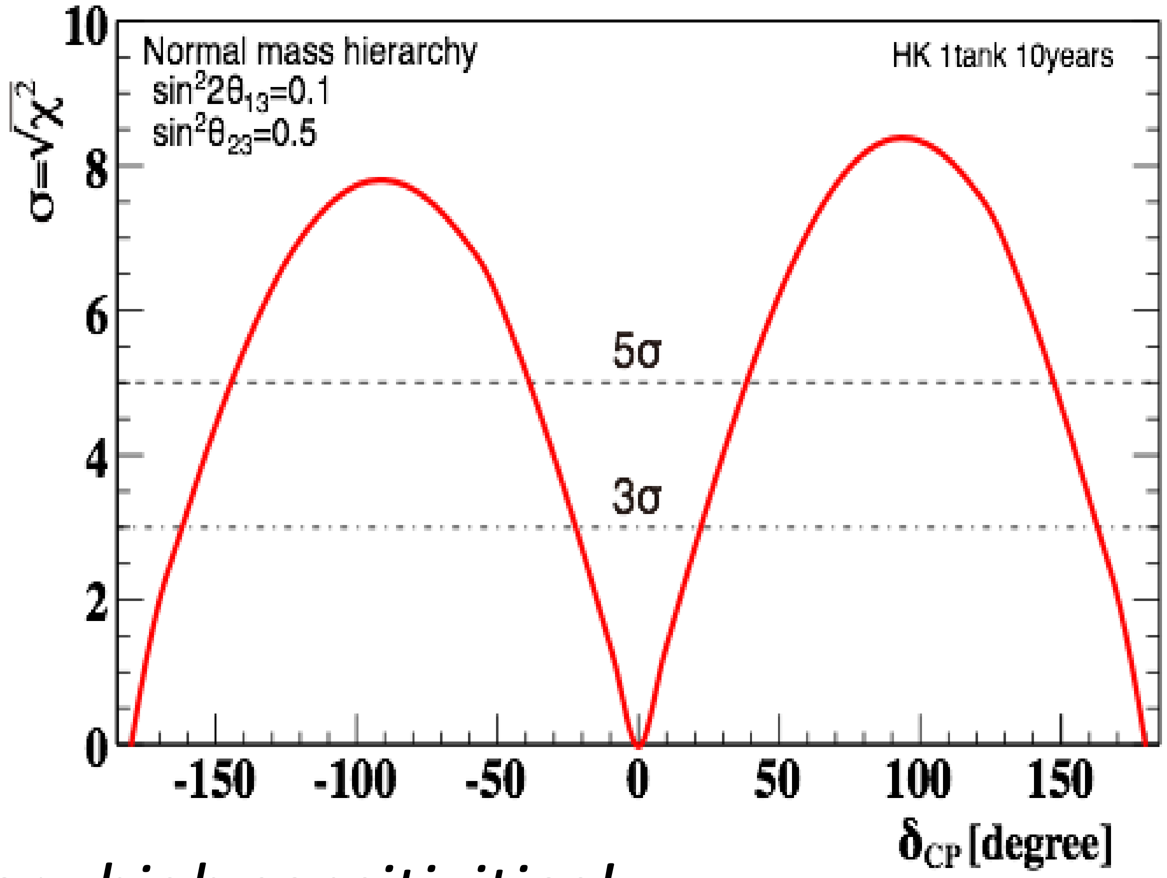




Hyper-K

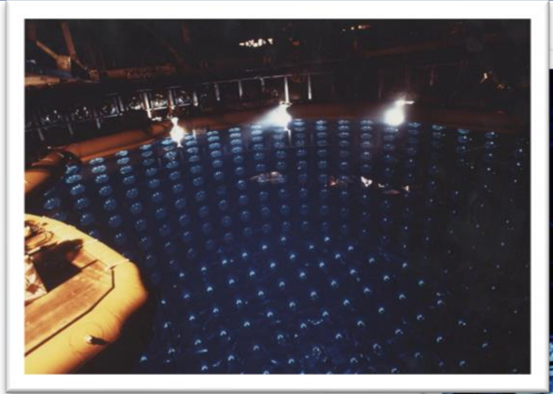
(Hyper-K design report arXiv: 1805.04163)

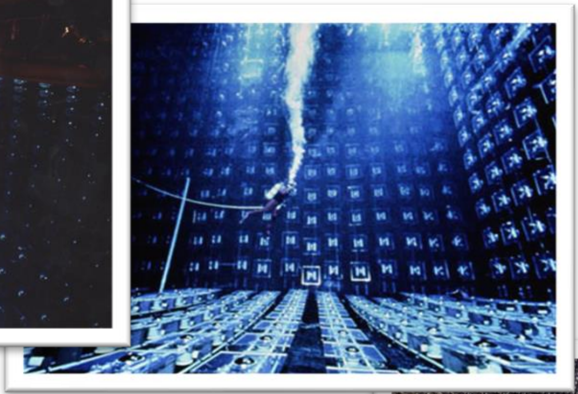




➔ *Both experiments have very high sensitivities!*

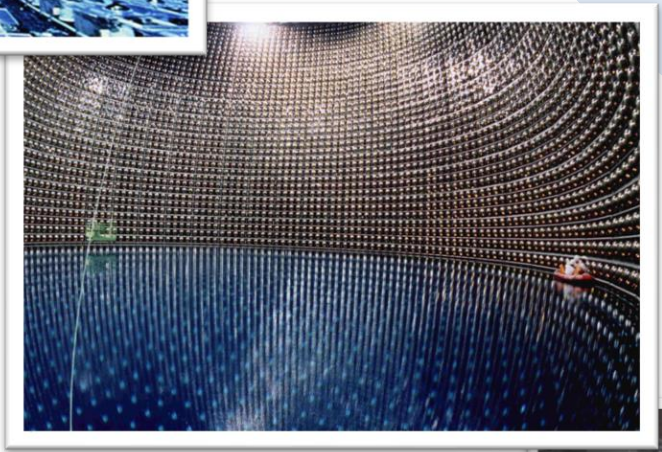
Hyper-K as a natural extension of water Ch. detectors





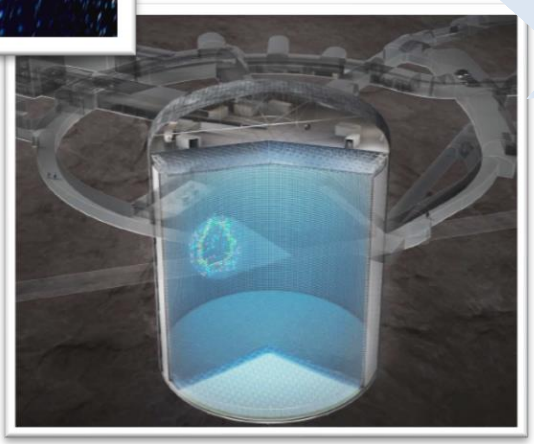
<u>Kamiokande & IMB</u>

Neutrinos from SN1987A
Atmospheric neutrino deficit
Solar neutrino (Kam)



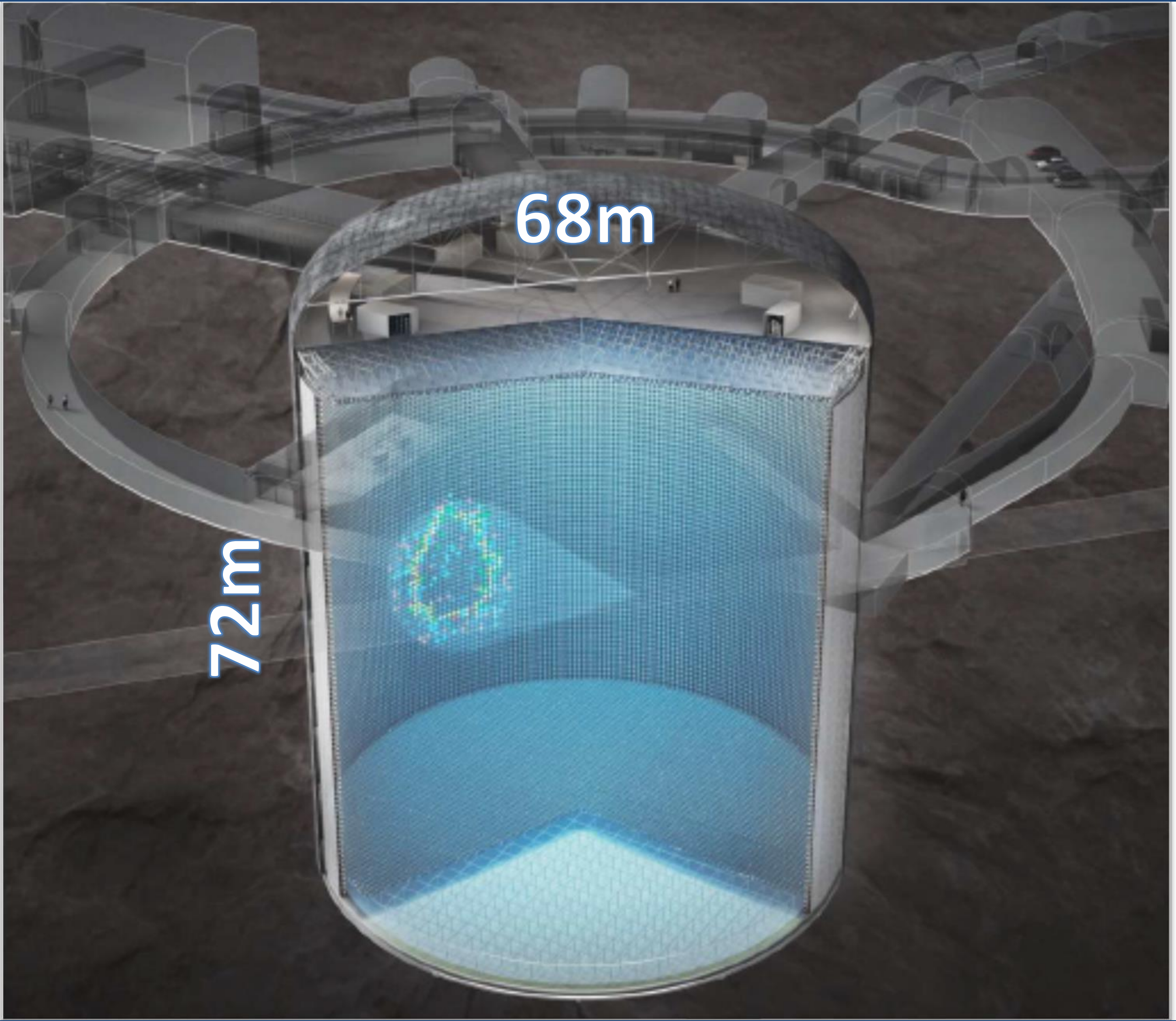
<u>Super-K</u>

Atmospheric neutrino oscillation
Solar neutrino oscillation with SNO
Far detector for K2K and T2K



<u>Hyper-K</u>

Hyper-Kamiokande



- About 8 times larger (in the fiducial mass) than Super-K.
- Many important research topics in neutrino physics and astrophysics.
- The construction started in 2020.
- The experiment will start in ~2027!

Hyper-Kamiokande collaboration:
~500 members from 20 countries.

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 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 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 smallest and the largest scales.