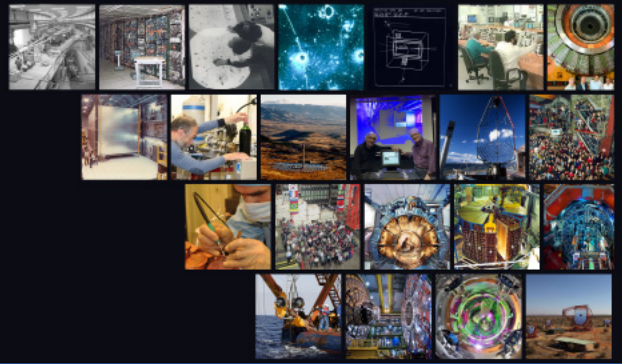
INTERNATIONAL SYMPOSIUM

FROM PARTICLES TO THE UNIVERSE



International Symposium "From Particles to the Universe",
Paris (+ online), Dec. 10, 2021

Neutrino Physics and Astrophysics

Takaaki Kajita

Institute for Cosmic Ray Research, The Univ. of Tokyo

Outline

If we discuss the neutrino physics in the last 50 years, one of the main topics is neutrino oscillations. Therefore, today, I will mostly discuss experimental neutrino physics related to neutrino oscillations.

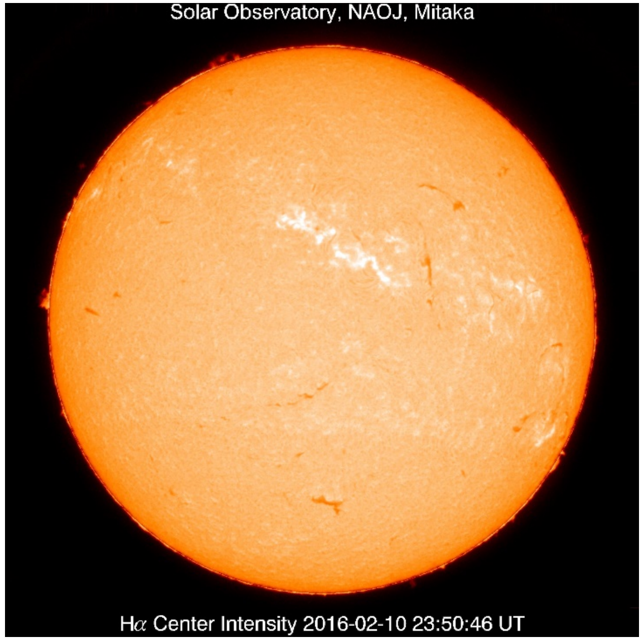
- *Solar neutrinos*
- *Atmospheric neutrinos and Long-baseline neutrino oscillation experiments*
- *The third oscillation channel*
- *Agenda for the future neutrino measurements*
- *Summary*

In this talk, I use this flag to show the IN2P3's contribution to neutrino physics.

Many thanks to Marco Zito and Michel Gonin.

Solar neutrinos

Solar neutrino problem



The Sun generate energy by nuclear fusion processes. During these processes, many neutrinos are generated.

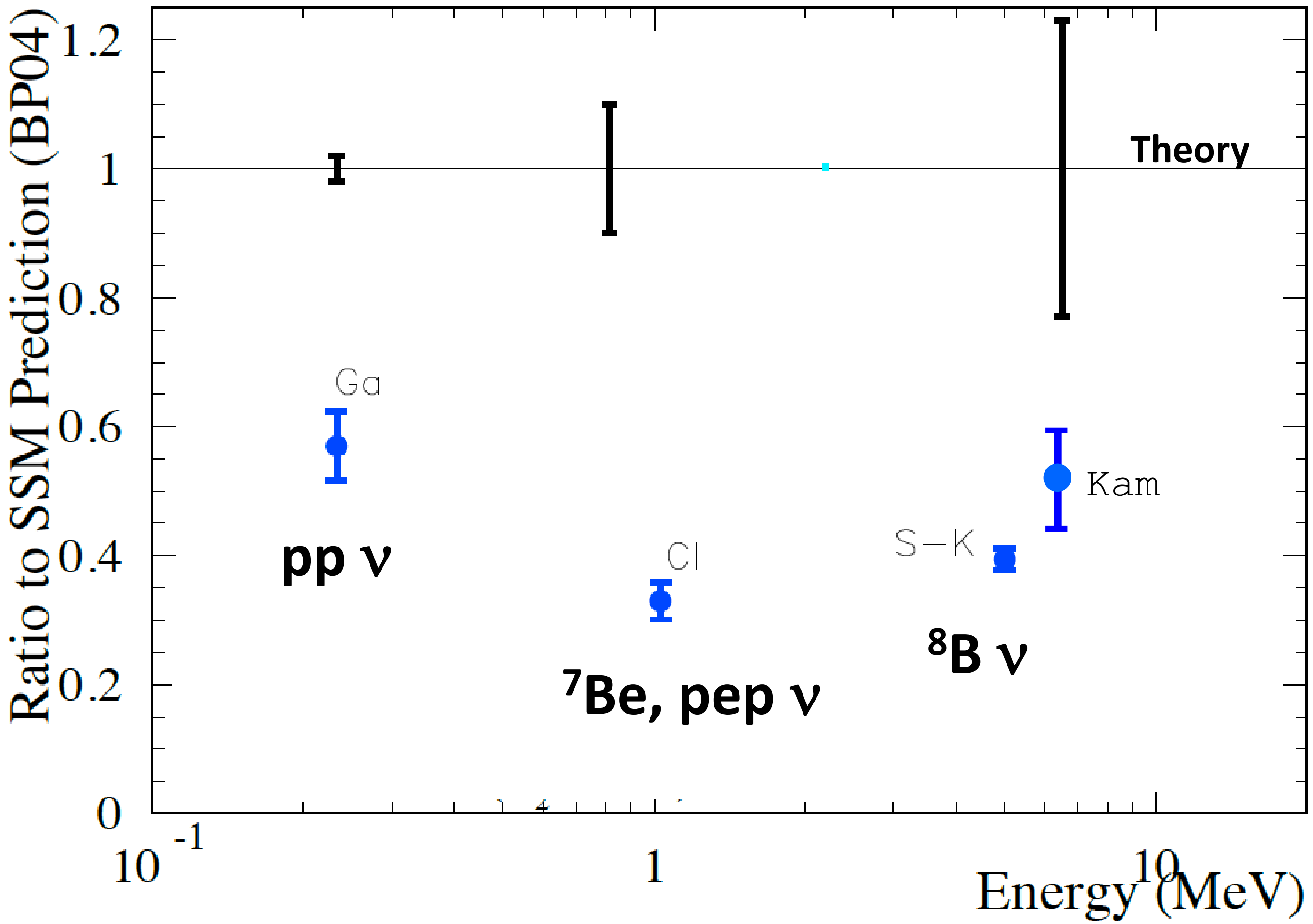
600ton C_2Cl_4

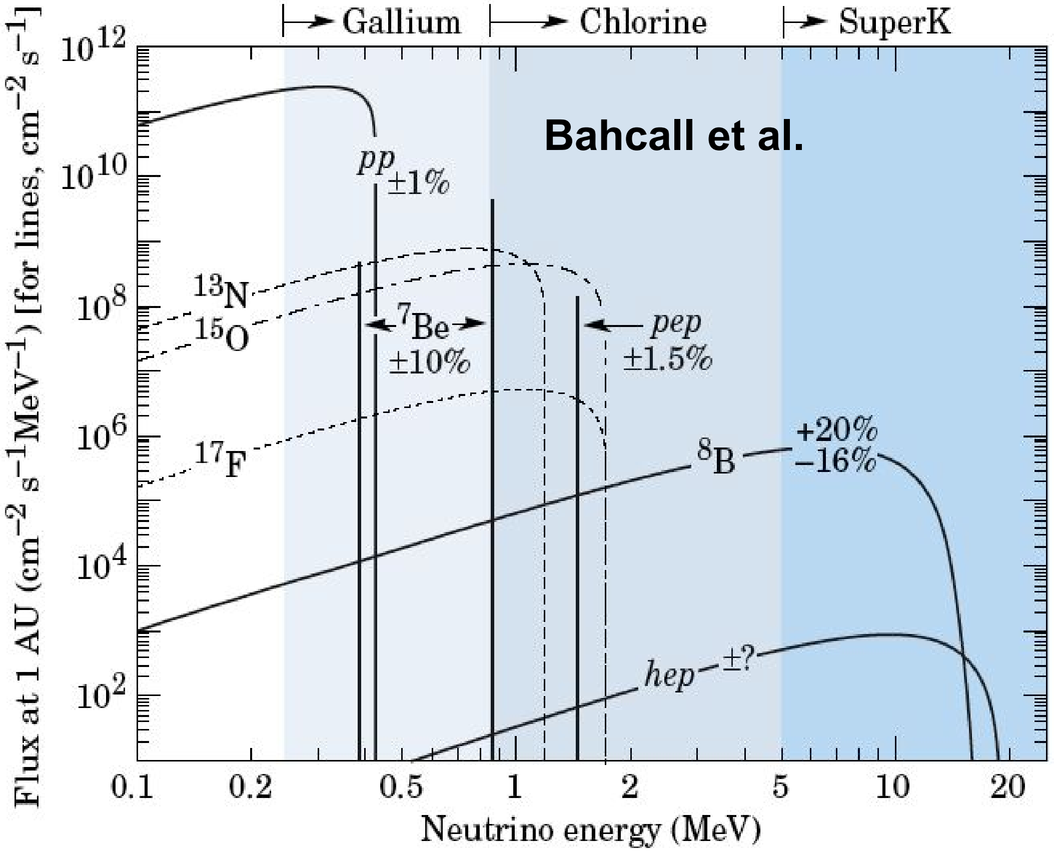
R. Davis Jr.

About 50 years ago, the pioneering Homestake experiment observed solar neutrinos for the first time. However, the observed event rate was only about 1/3 of the prediction.

Results from solar neutrino experiments (before ~2000)

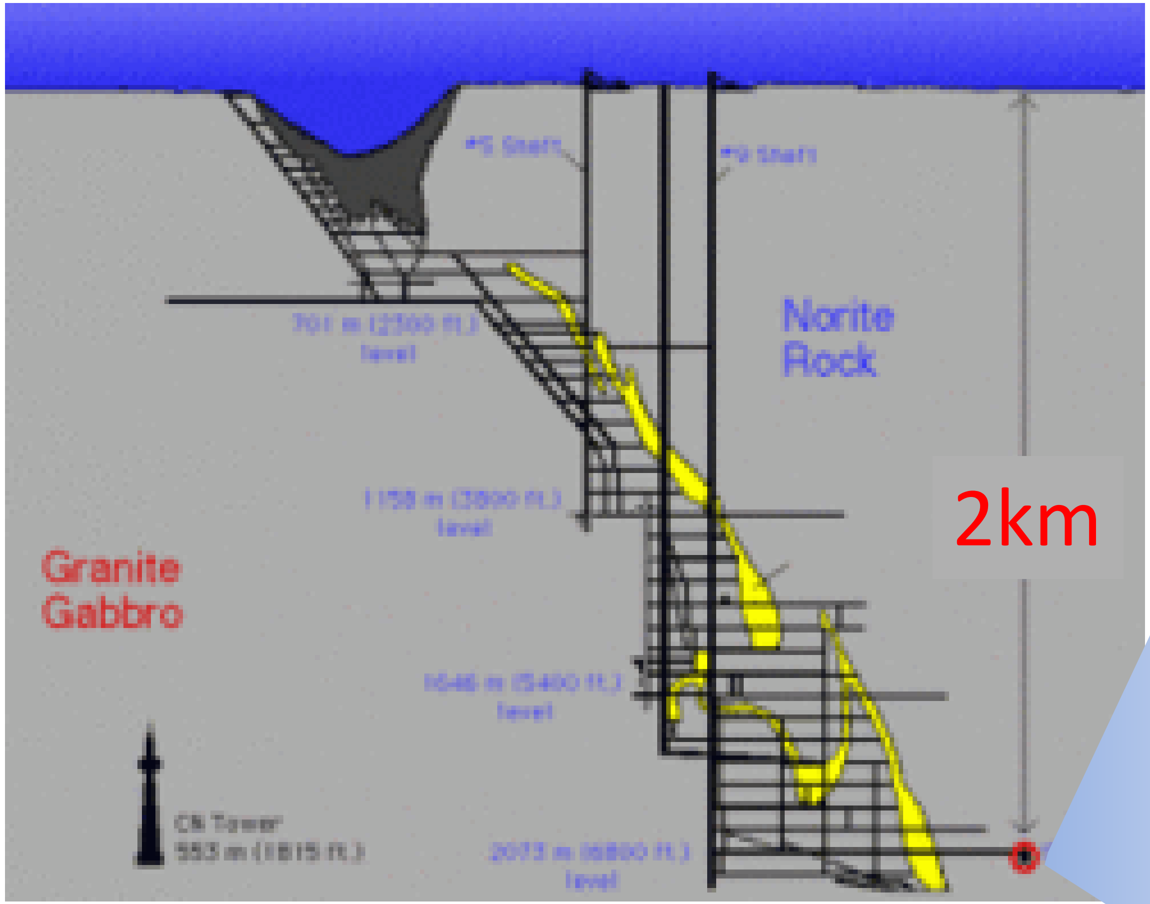
Following the initial observation, several experiments observed solar neutrinos.

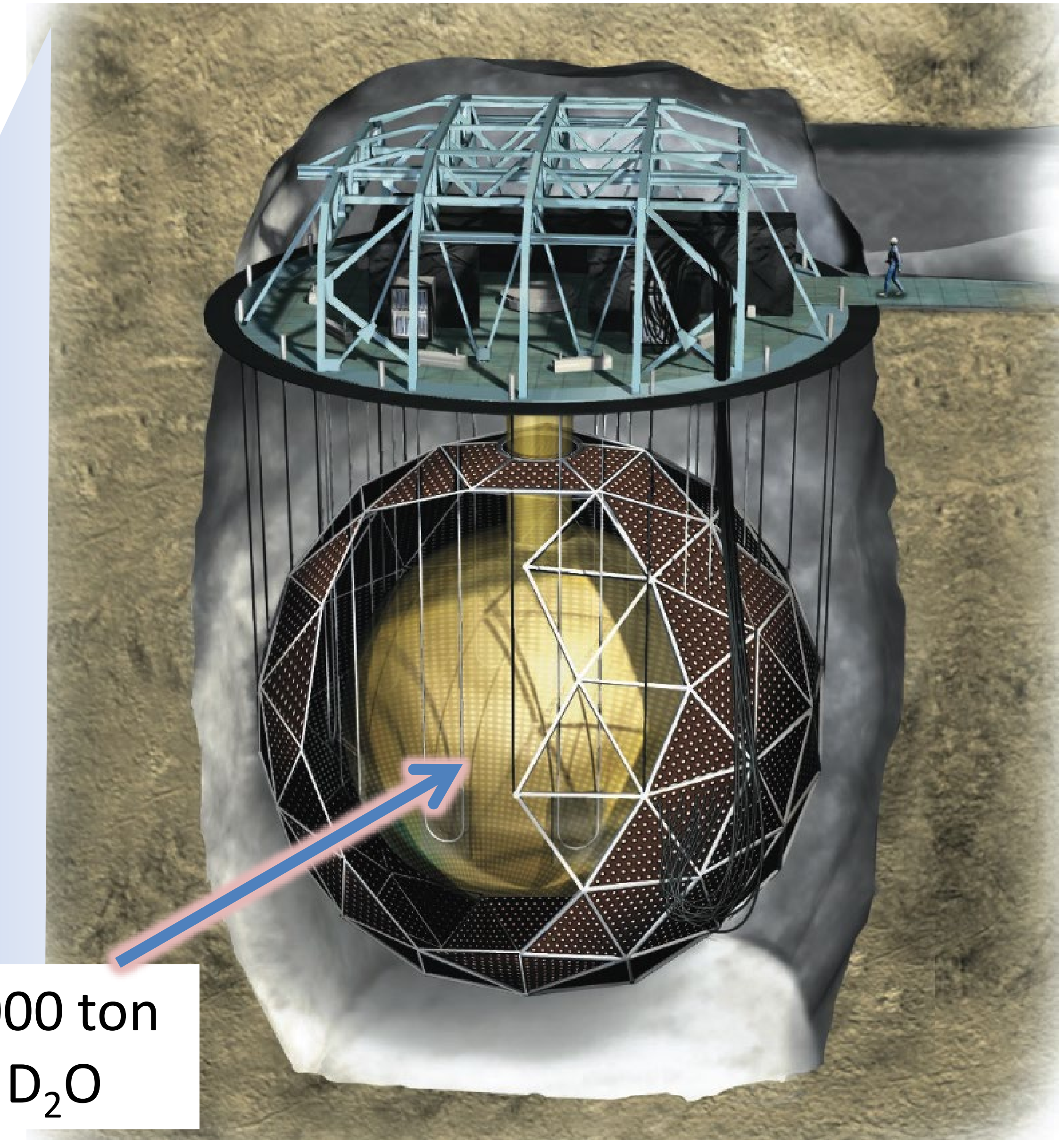




Solar neutrino experiments in the 80's and 90's confirmed the deficit of solar neutrinos.

SNO detector





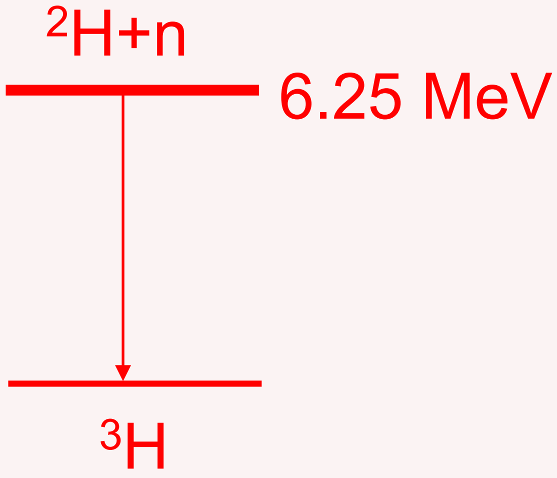
SNO was able to observe the ν_e flux by CC interactions ($\nu_e + D \rightarrow e + p + p$) and the total flux by NC interactions ($\nu_x + D \rightarrow \nu_x + p + n$).

3 neutron detection methods (for $\nu\ d \rightarrow \nu\ pn$ measurement)

Phase I (D_2O)

Nov. 99 - May 01

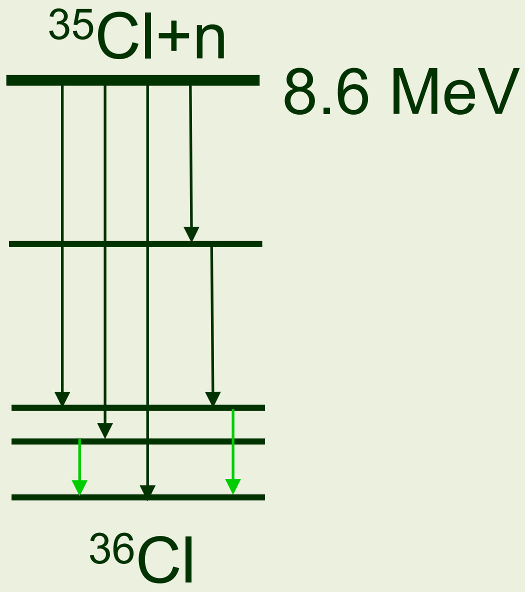
n captures on
$^{2}H(n, \gamma)^{3}H$
Eff. ~14.4%



Phase II (salt)

July 01 - Sep. 03

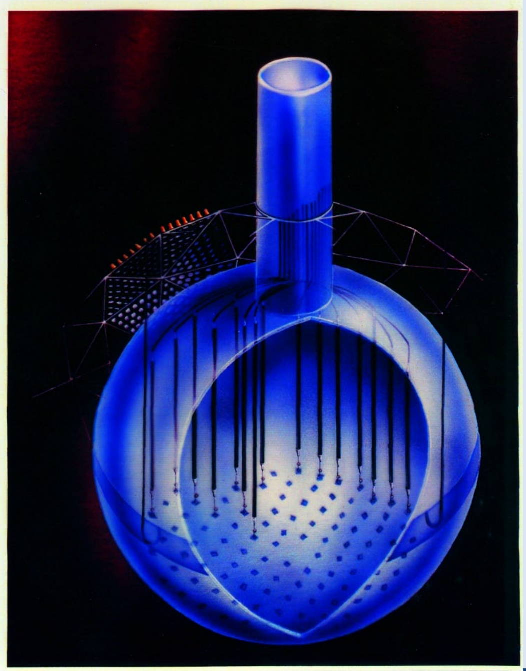
2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Eff. ~40%



Phase III (^{3}He)

Nov. 04-Dec. 06

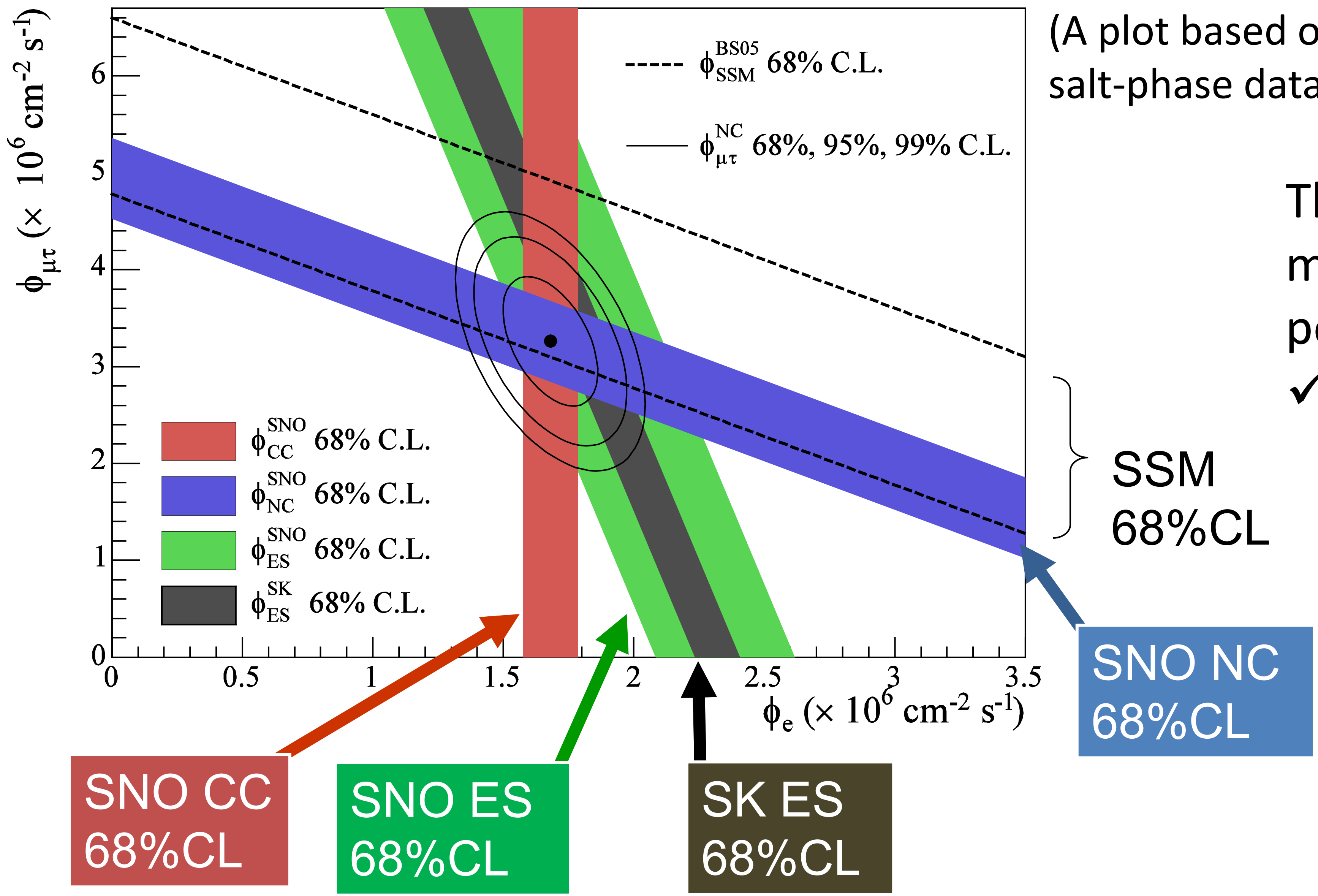
400 m of proportional counters
$^{3}He(n, p)^{3}H$
Effc. ~ 30% capture



Evidence for solar neutrino oscillations

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

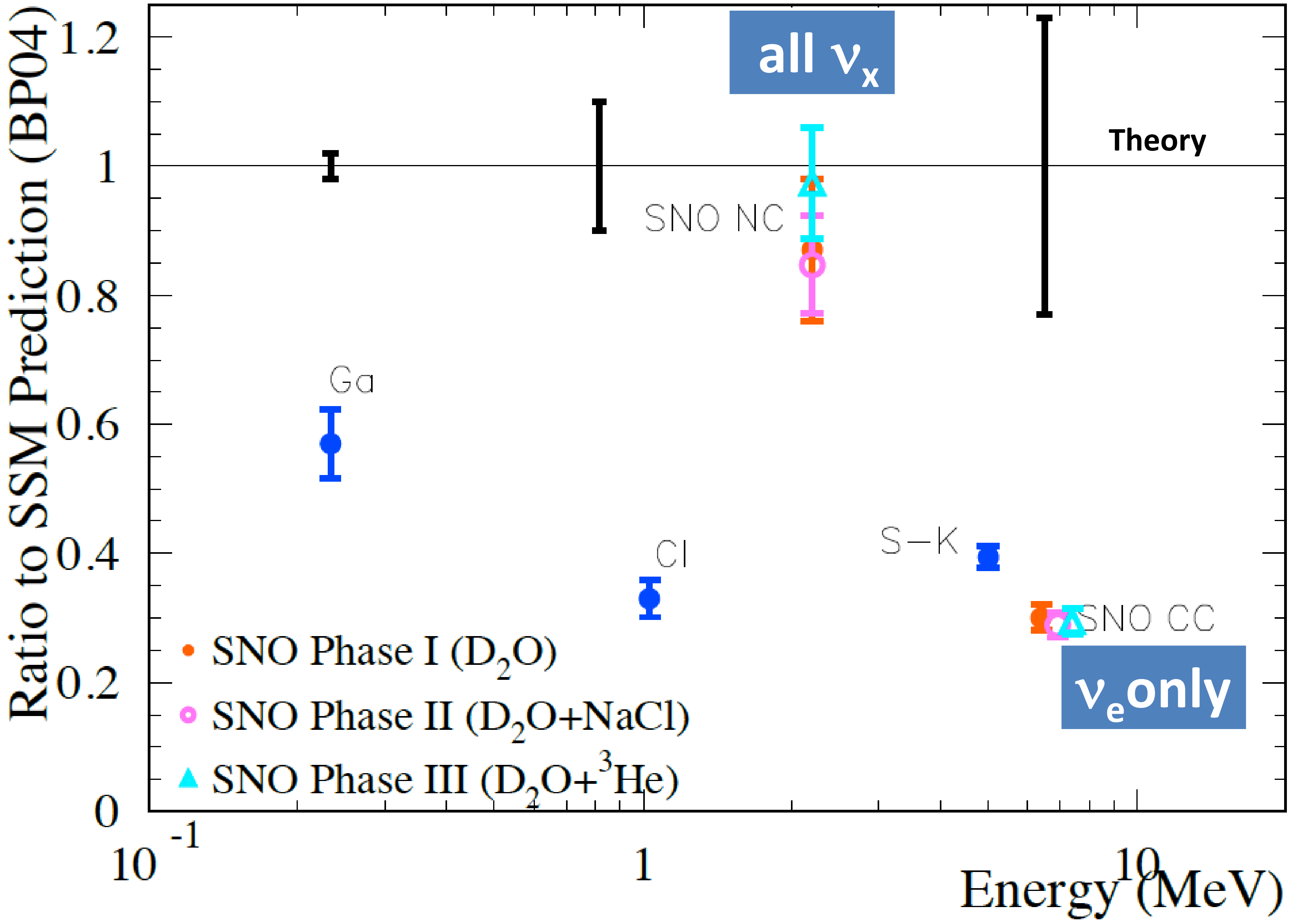
(A plot based on the salt-phase data)



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

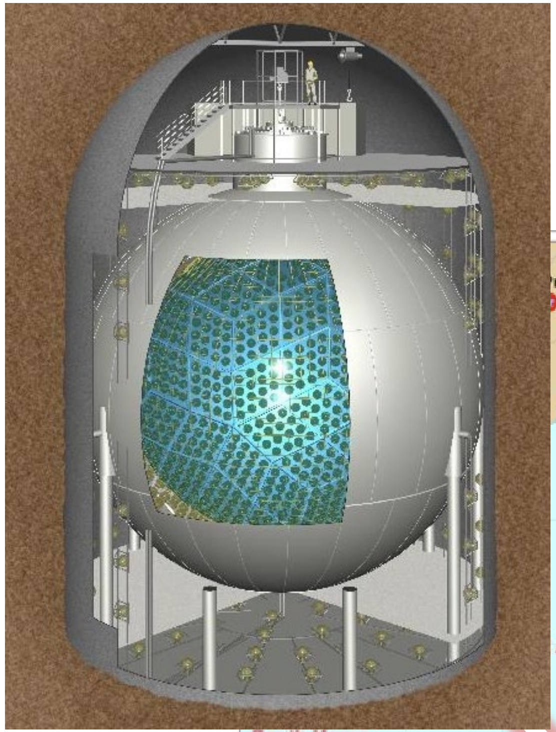
✓ *Evidence for* $(\nu_\mu + \nu_\tau)$ *flux*

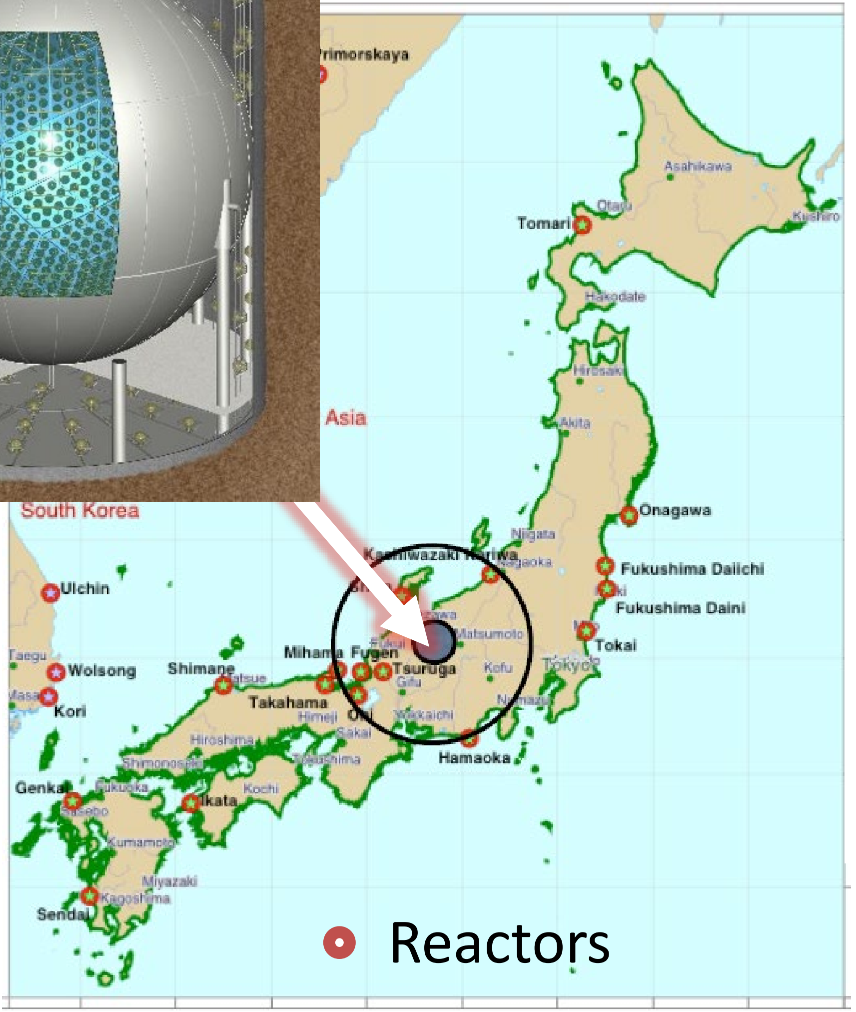
SNO results from 3 phases



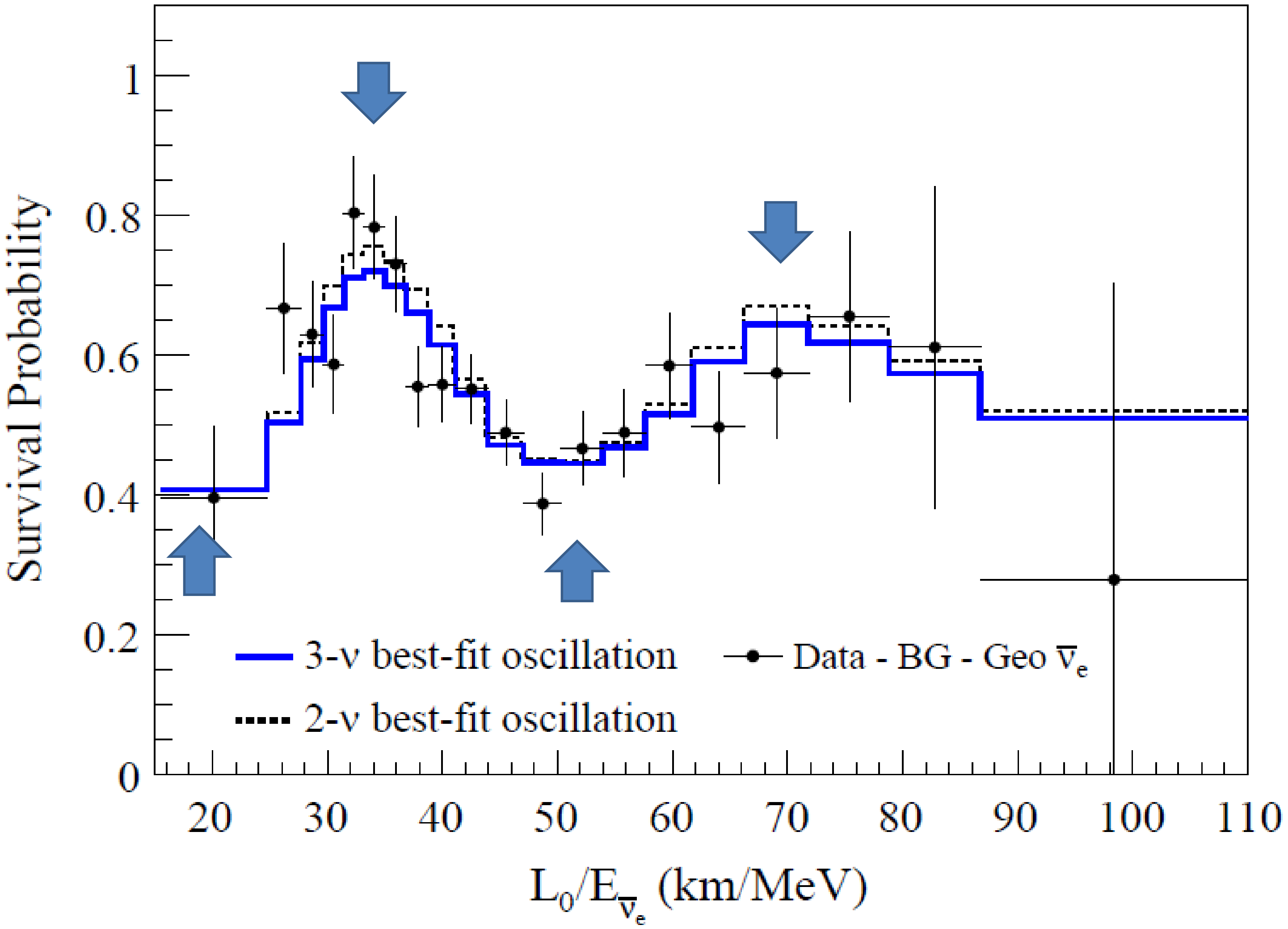
Really neutrino oscillations!

KamLAND





KamLAND, PRD 83, 052002 (2011)

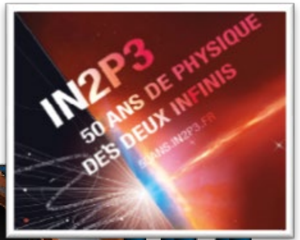


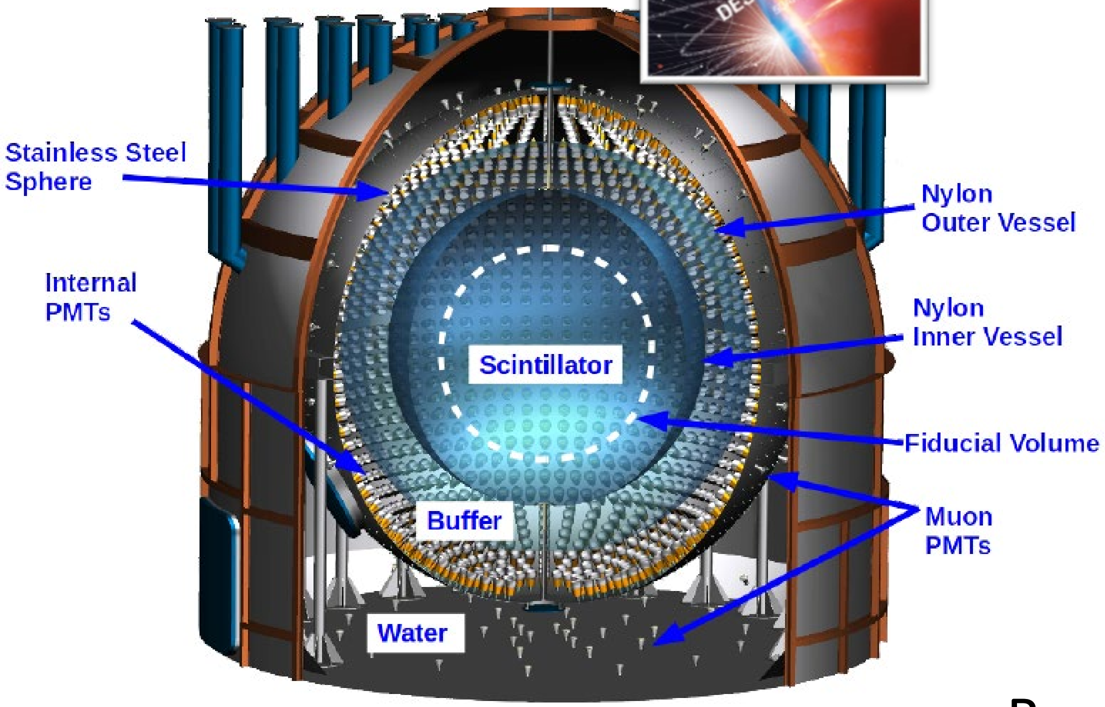
Really neutrino ***oscillations !***

Consistent with MSW !

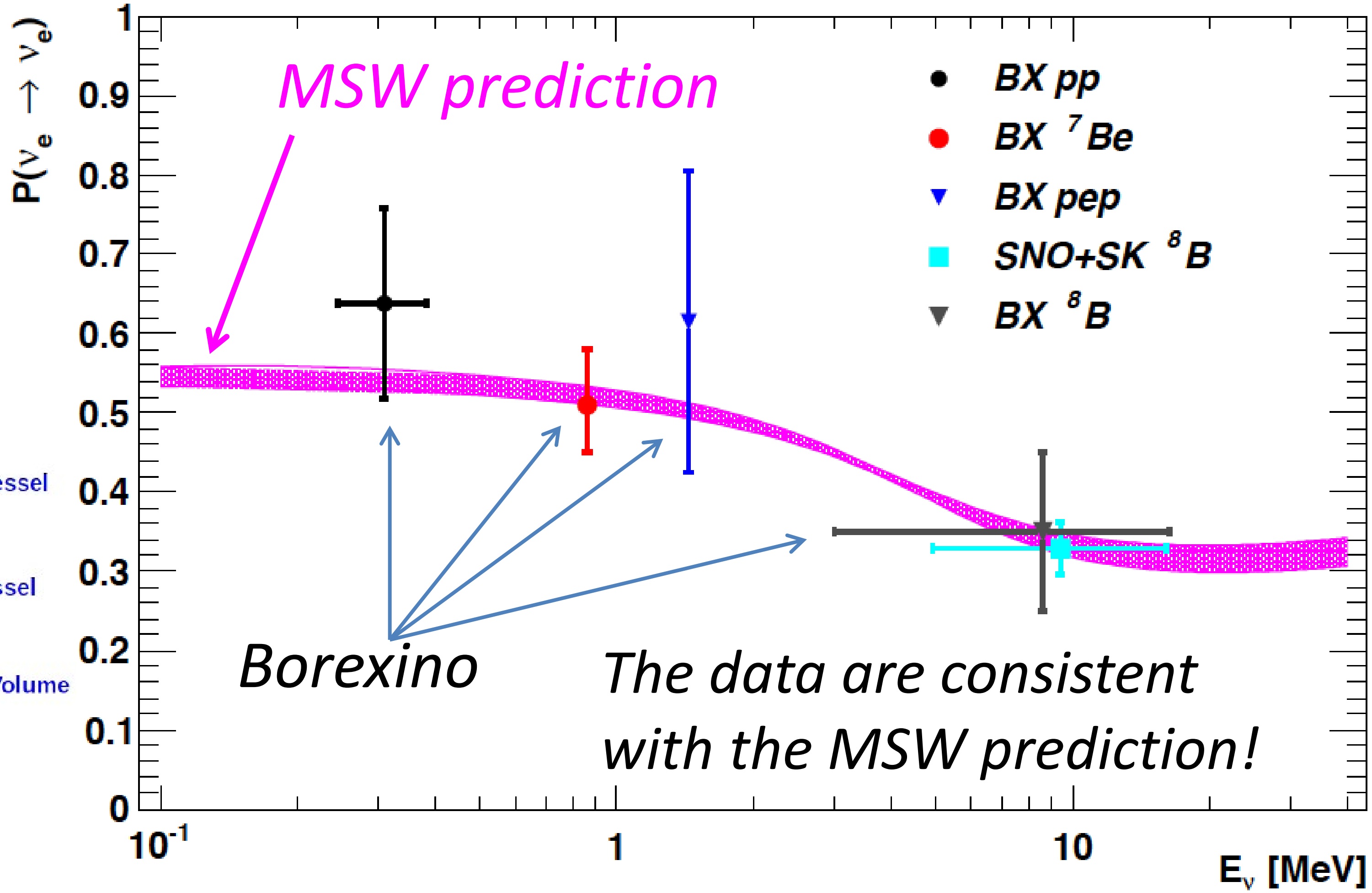
Borexino

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), G. Bellini, JINR, Sep. 2016

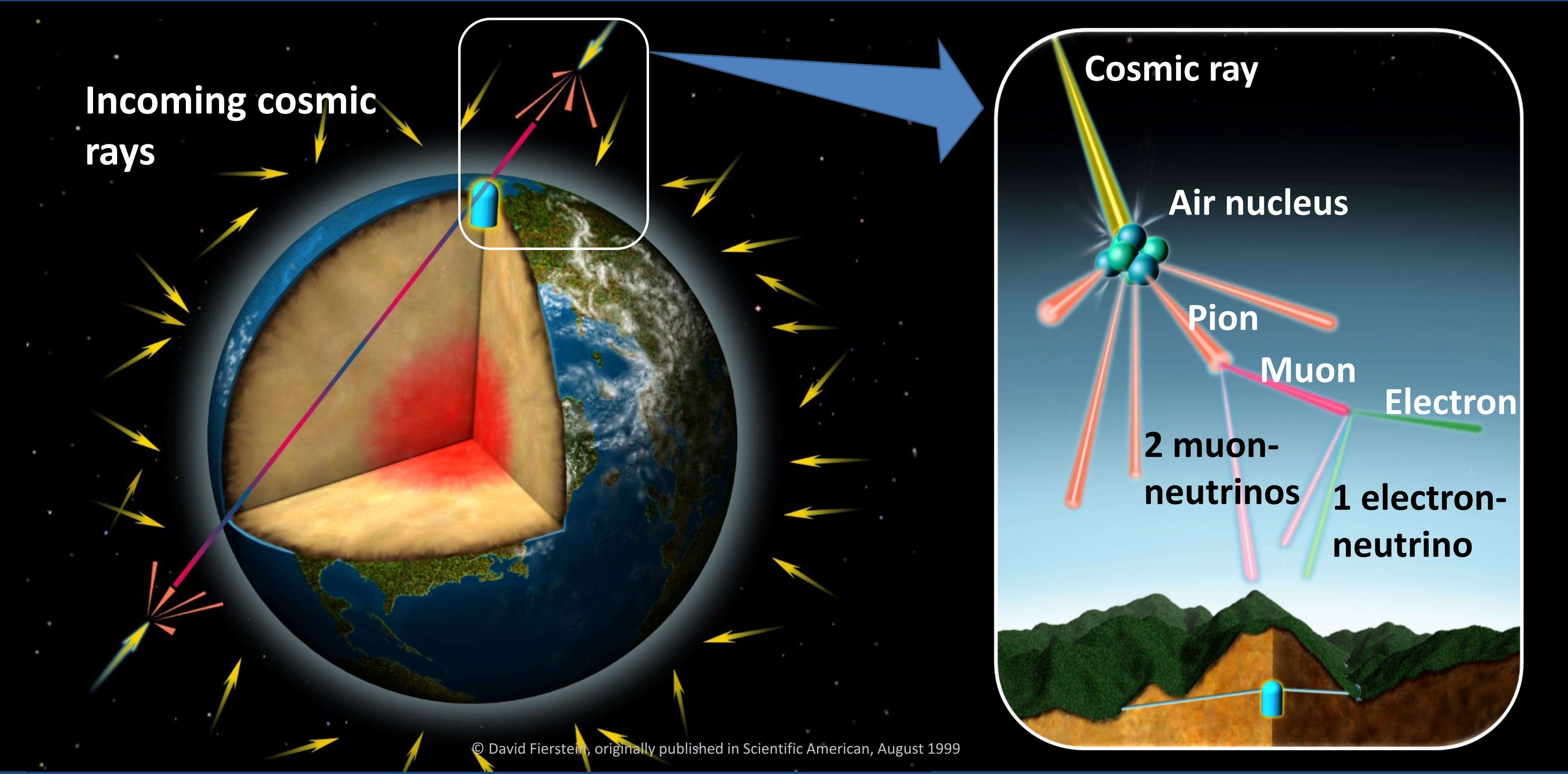


Borexino reported the detection of CNO neutrinos as well!

Borexono, Nature 587 (2020) 577-582.

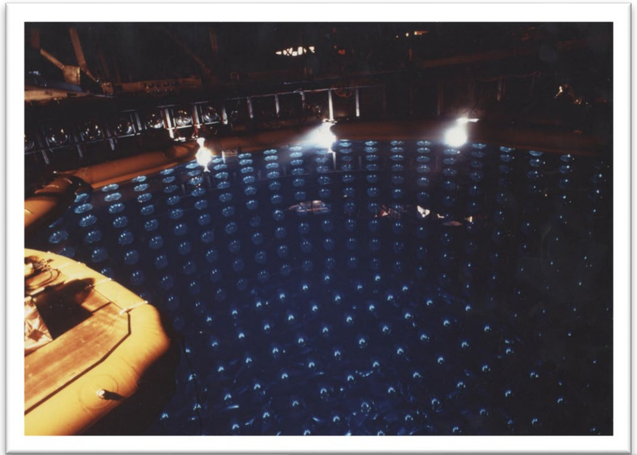
Atmospheric neutrinos and long-baseline neutrino oscillation experiments

Atmospheric neutrinos



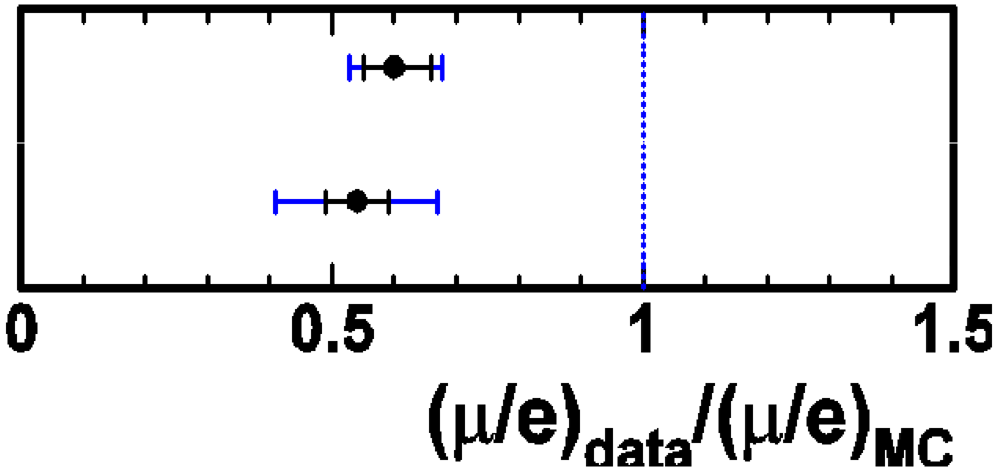
Atmospheric ν_μ deficit (1980's to 90's)

- ✓ 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, they had to understand atmospheric neutrino interactions.
- ✓ During these studies, a significant deficit of atmospheric ν_μ events was observed.

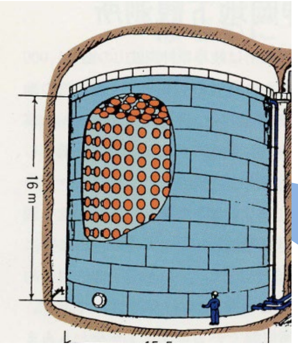


Kamiokande (1988, 92, 94)

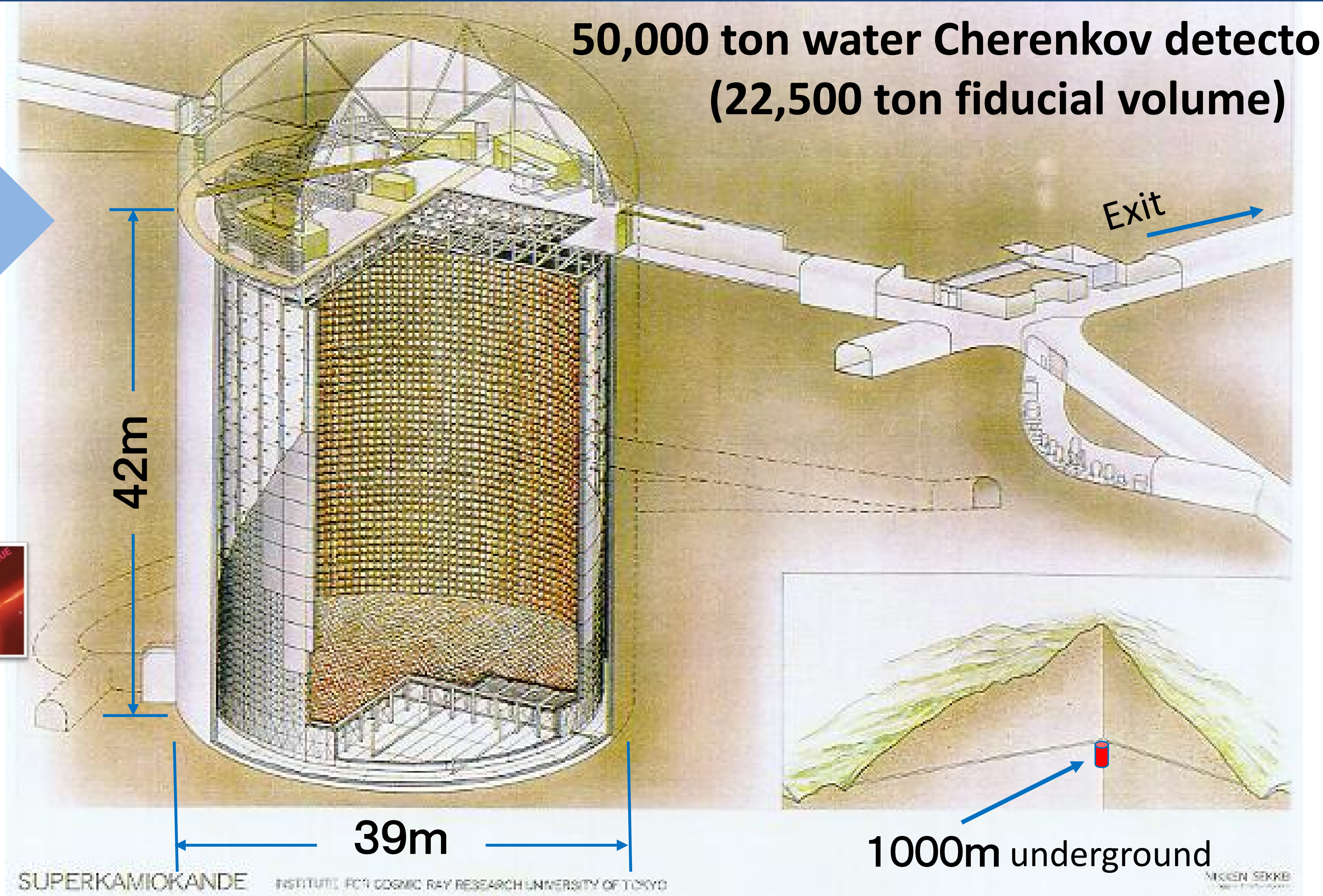
IMB (1991, 92)



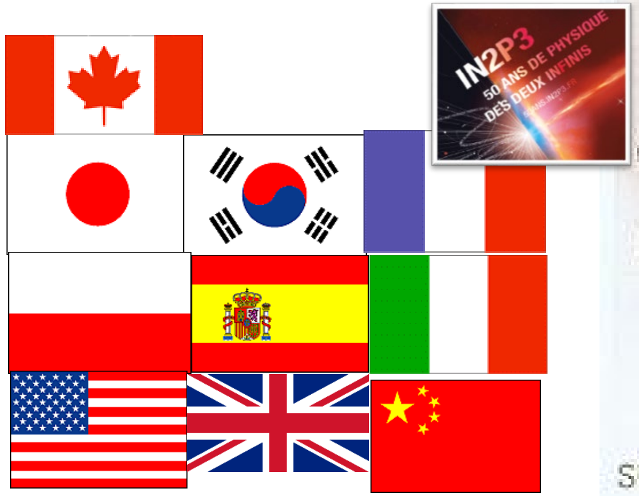
Super-Kamiokande detector



~20 times
larger mass

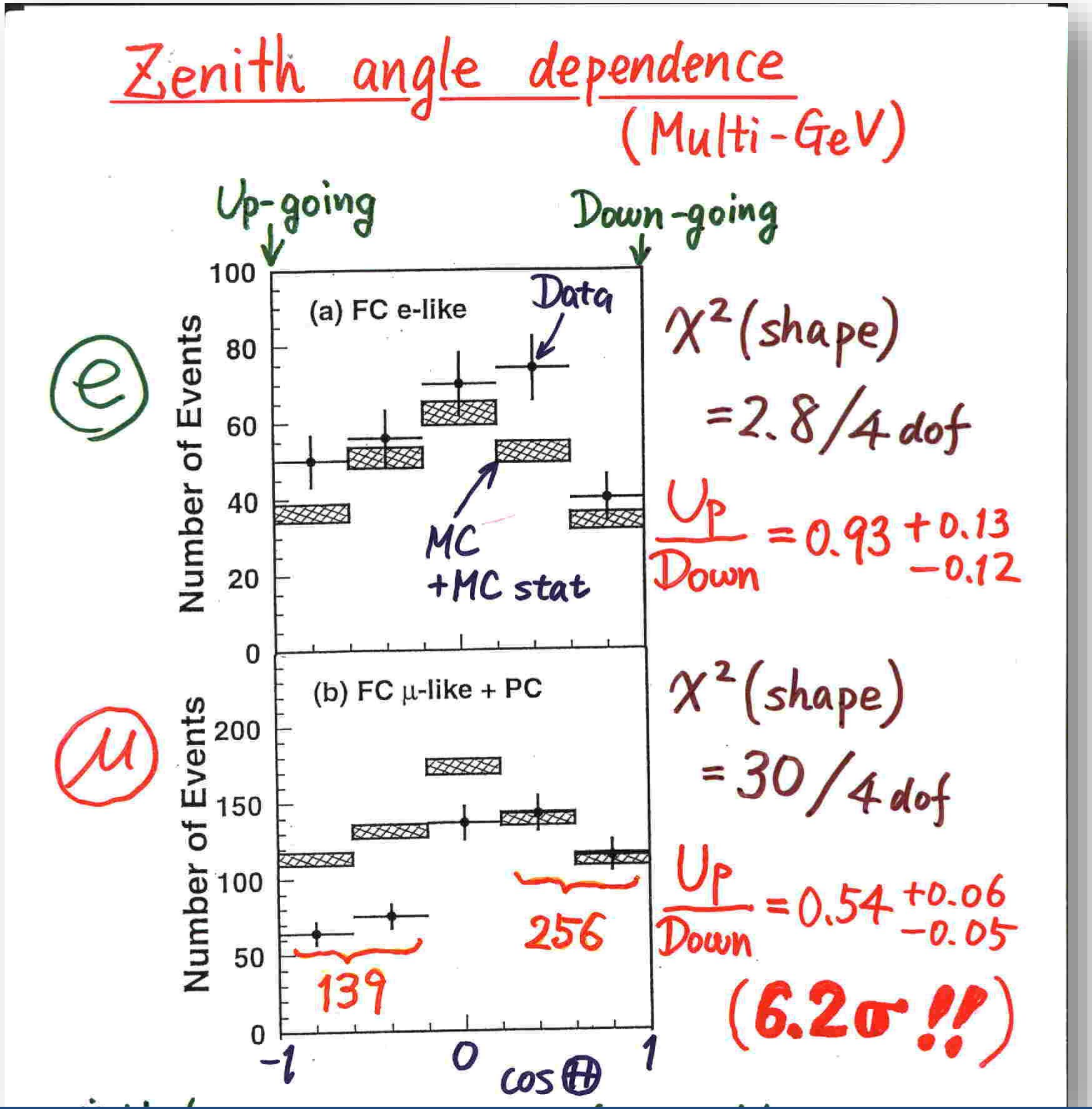


~200 collaborators



Evidence for neutrino oscillations (Super-Kamiokande, 1998)

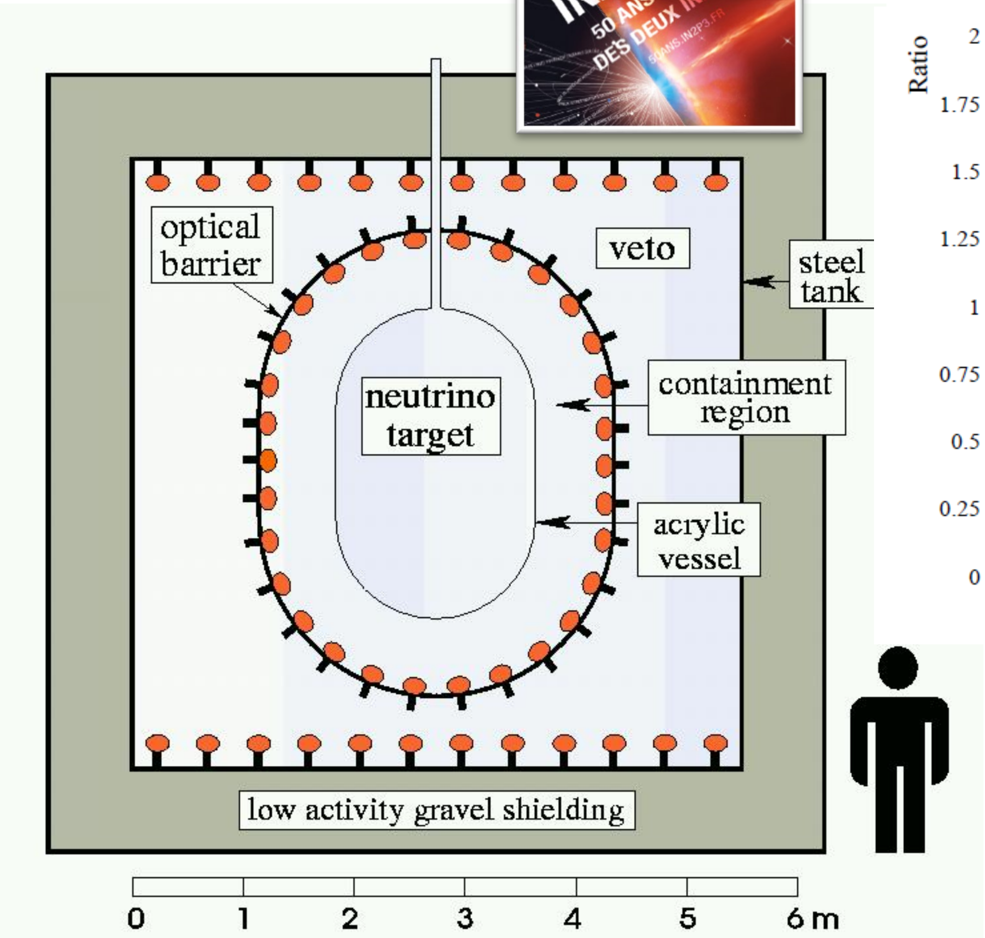
Super-K, Neutrino 98, Super-K., PRL 81 (1998) 1562

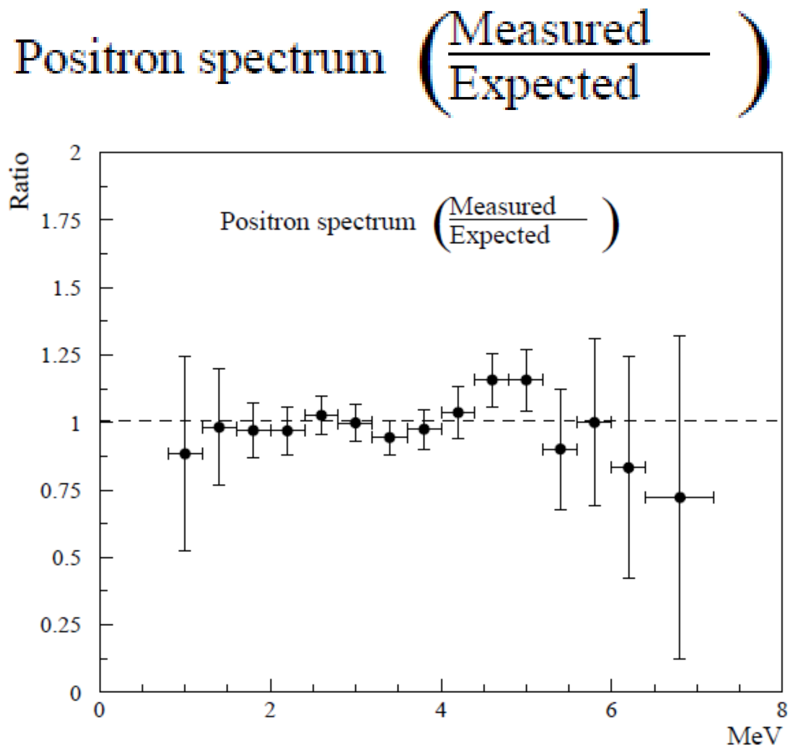


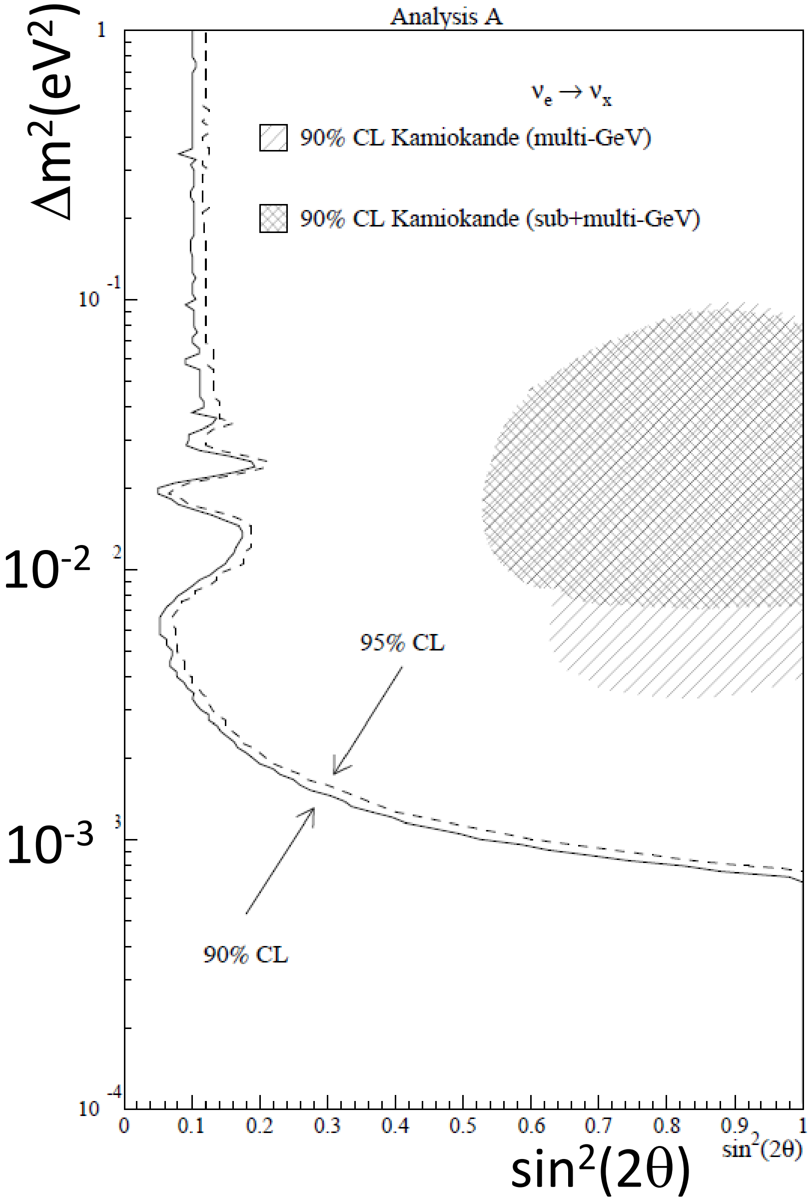
Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

CHOOZ: $\nu_\mu \rightarrow \nu_\tau$?

CHOOZ, PLB 466 (1999) 415-430





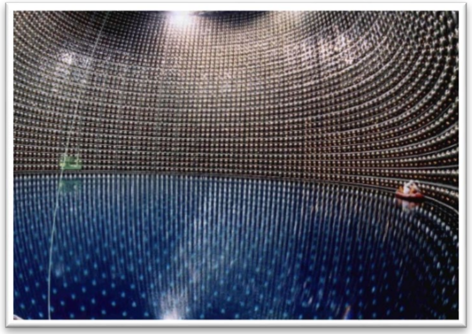


Based on the CHOOZ result, people generally thought that the atmospheric oscillation should be ν_μ to ν_τ.

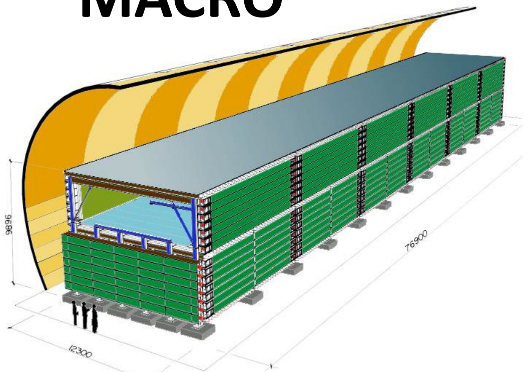
Studies of $\nu_\mu \rightarrow \nu_\tau$ oscillations

Atmospheric neutrinos

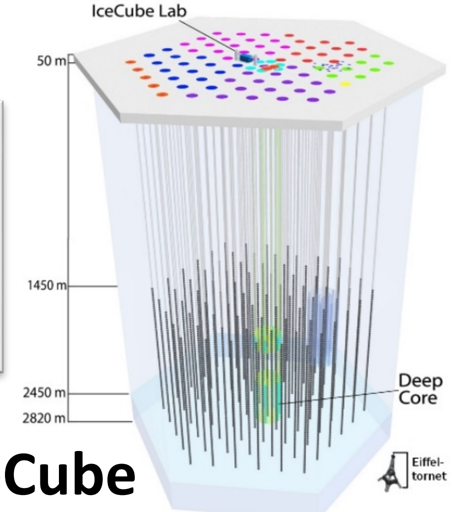
Super-K



MACRO

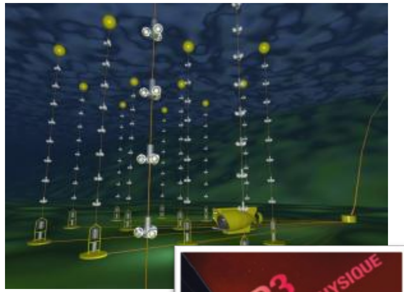


Soudan-2



IceCube

ANTARES

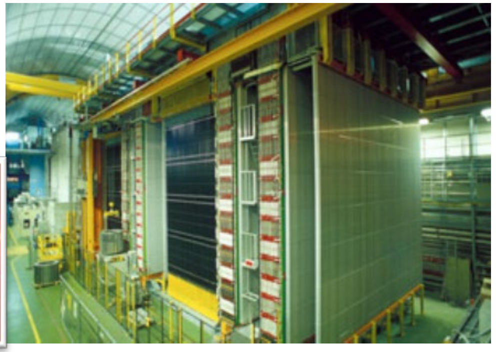


Accelerator based long baseline experiments

K2K

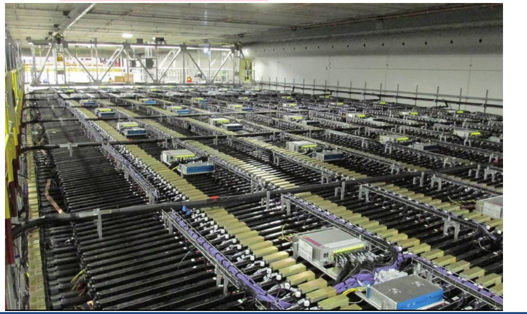
T2K

OPERA



MINOS

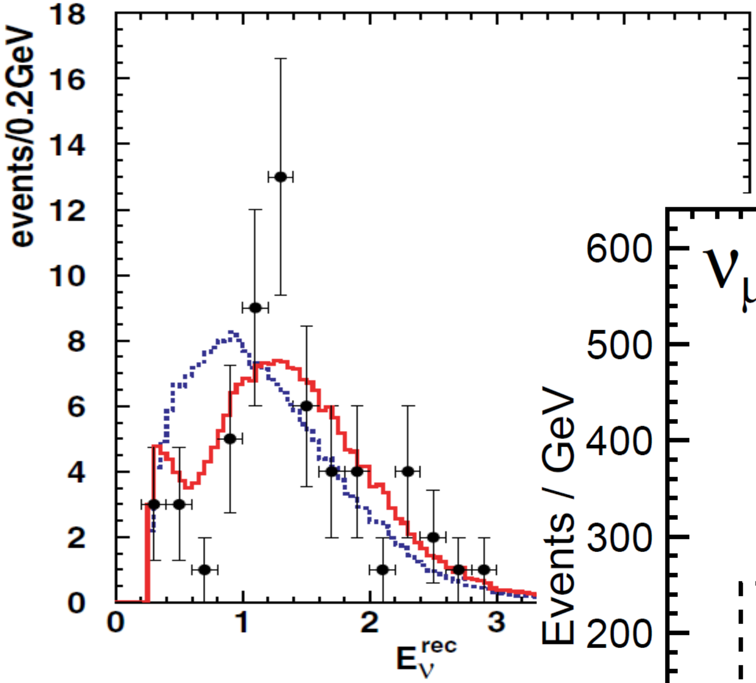
NOvA



ν_μ disappearance studies (accelerator experiments)

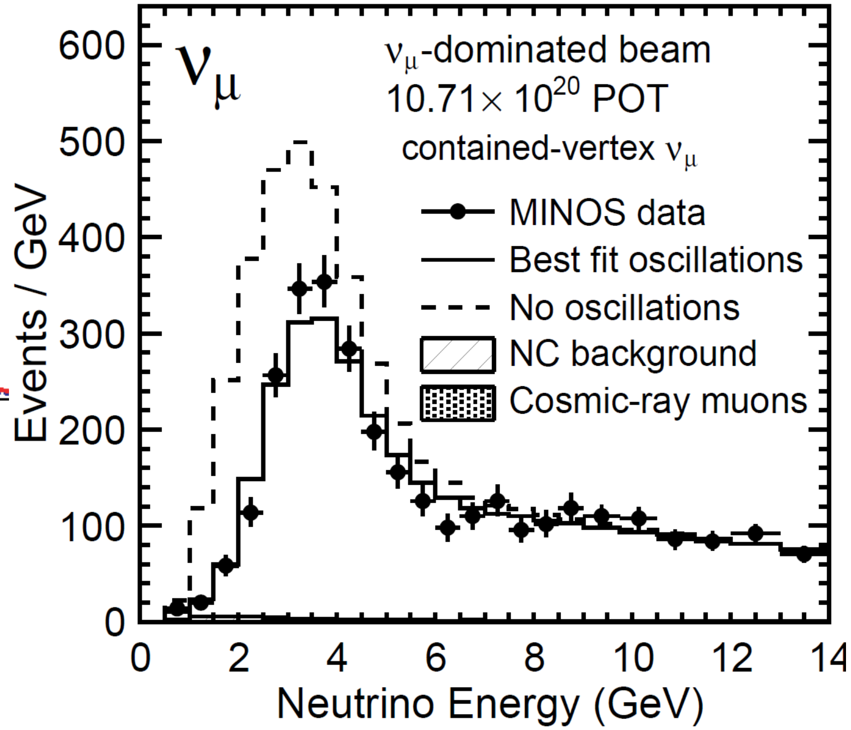
K2K

K2K, PRD 74 (2006) 072003



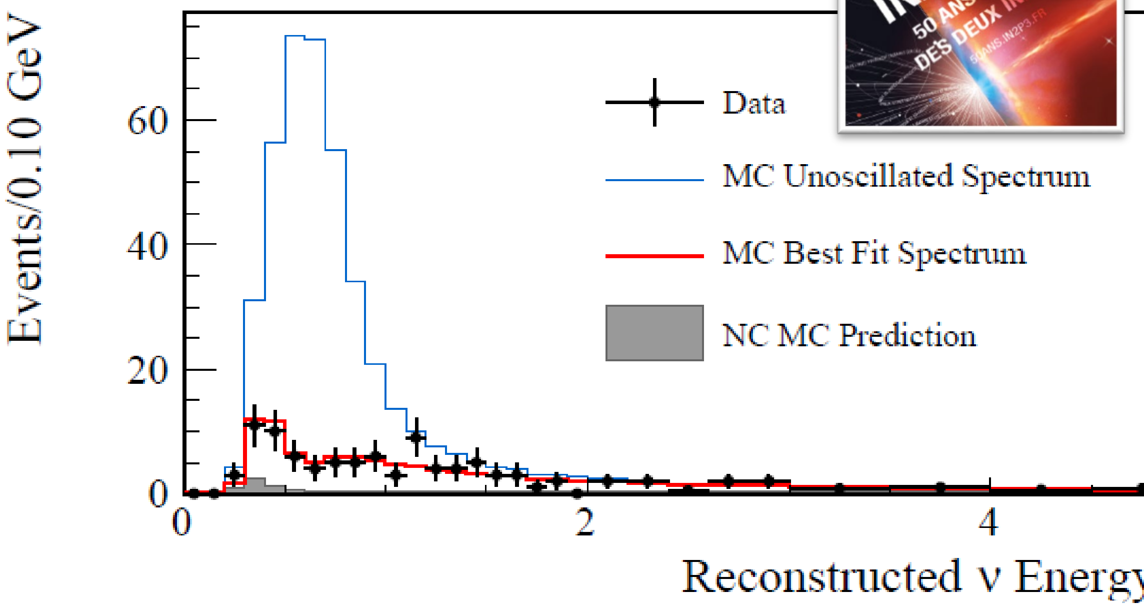
MINOS

MINOS PRL 110 (2013) 251801



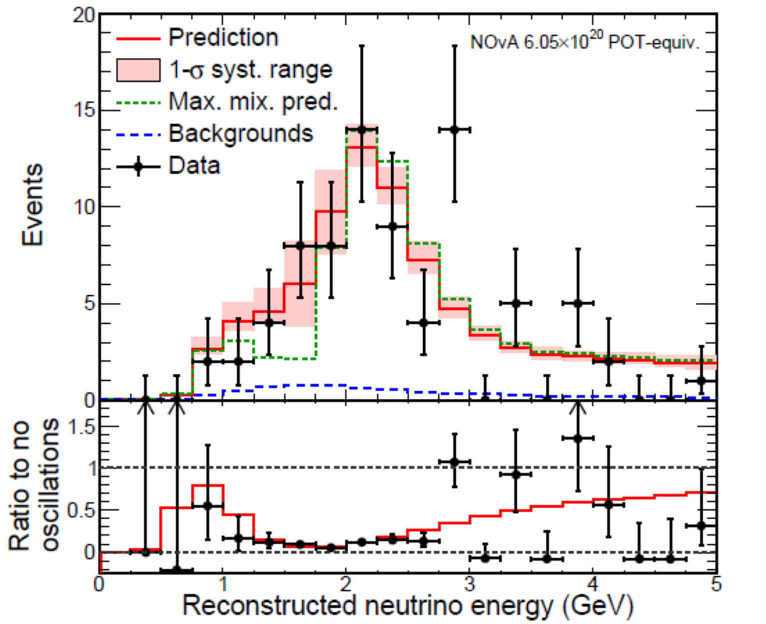
T2K

T2K, PRD 91 (2015) 072010



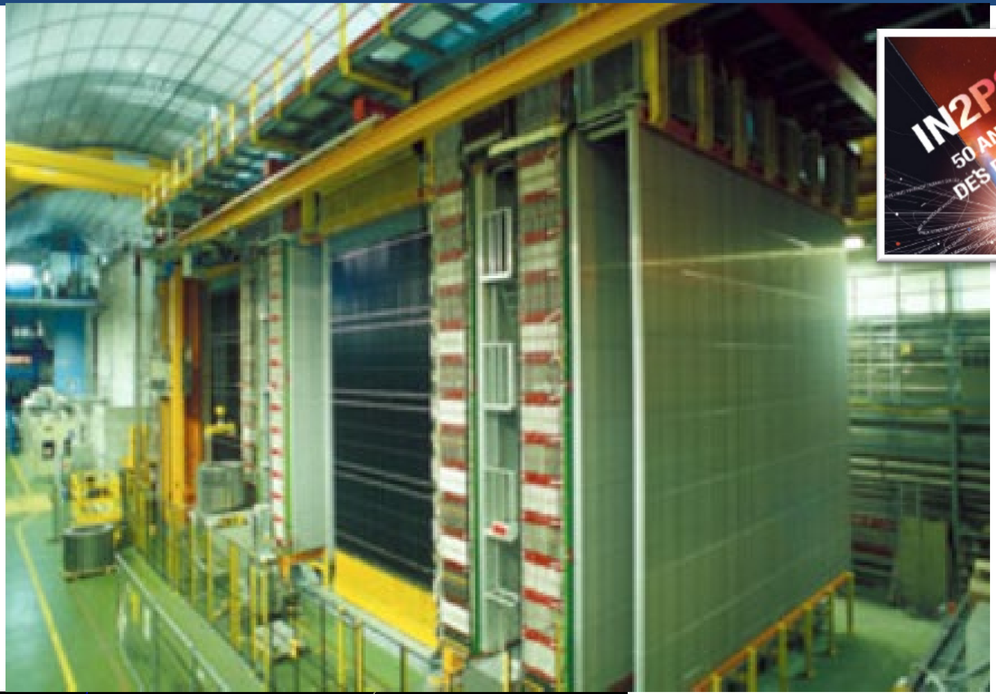
NOvA

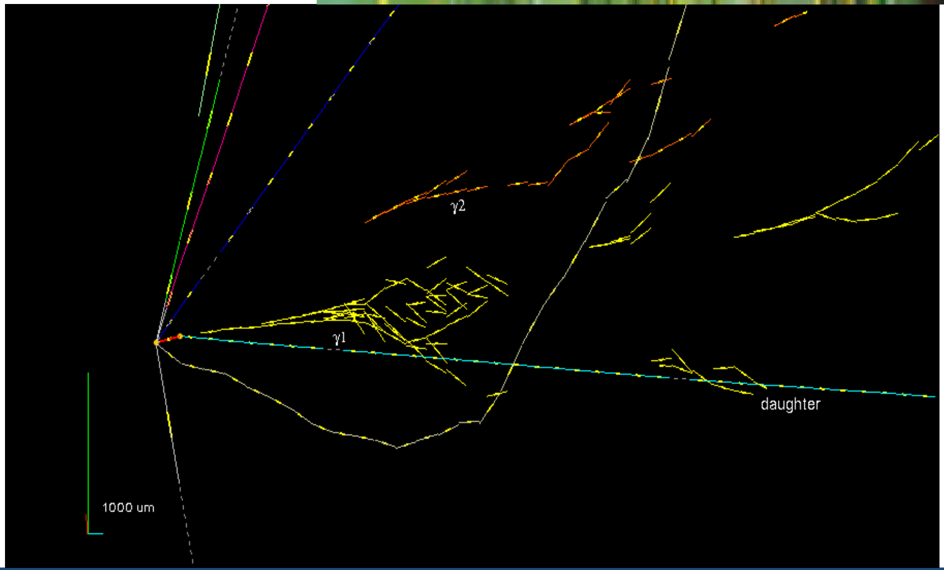
NOvA, PRL 118 (2017) 151802



ν_τ appearance

OPERA





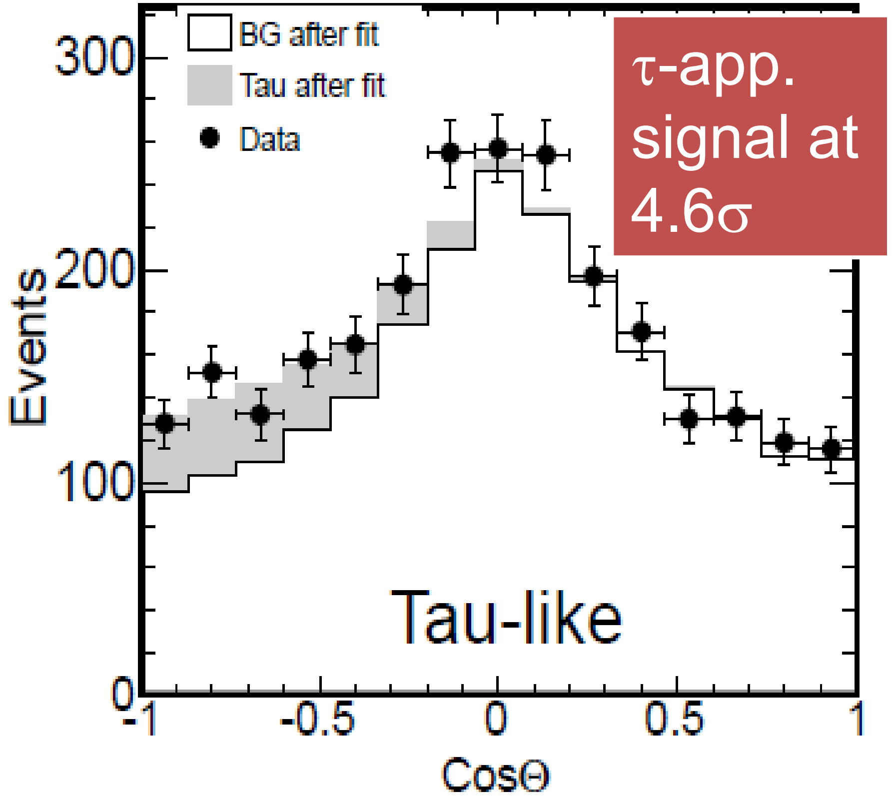
The first candidate event

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

OPERA PRL 115 (2015) 121602

Super-Kamiokande

Super-K, PRD 98 (2018) 052006



τ-app. signal at 4.6σ

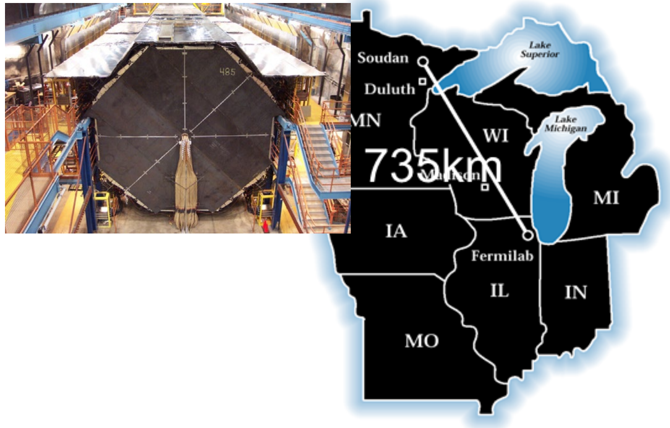
IceCube DeepCore also observed the ν_τ appearance.
PRD 99 (2019) 032007

The third oscillation channel

Experiments for the third neutrino oscillations

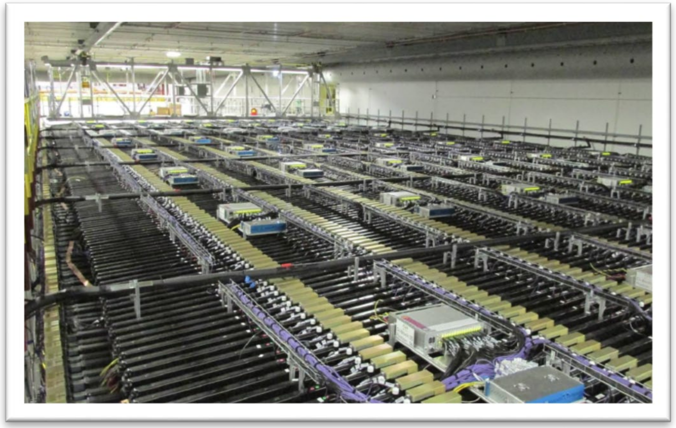
Accelerator based long baseline neutrino oscillation experiments

MINOS



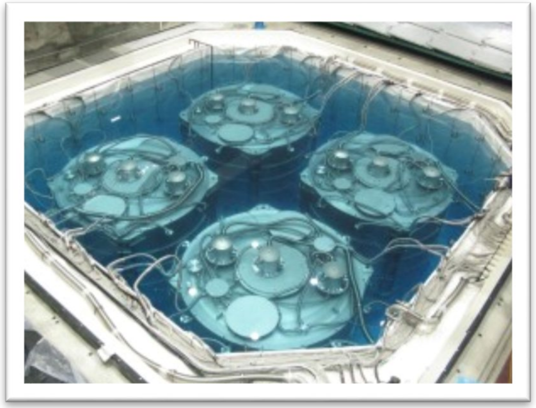
T2K

NOνA



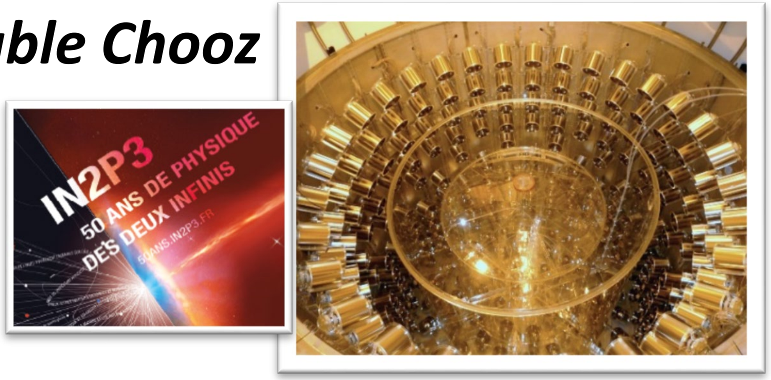
Reactor based (short baseline) neutrino oscillation experiments

Daya Bay



RENO

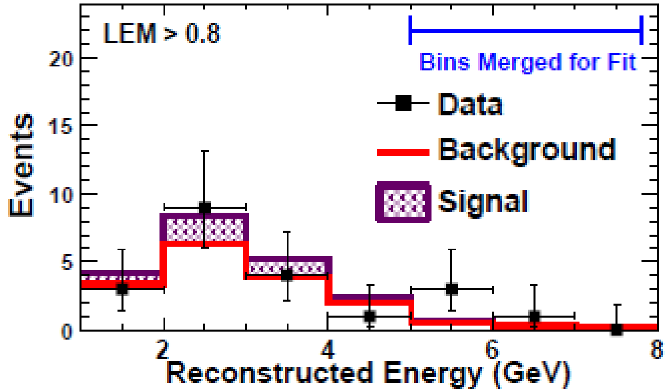
Double Chooz



Discovery of the third neutrino oscillations (2011-2012)

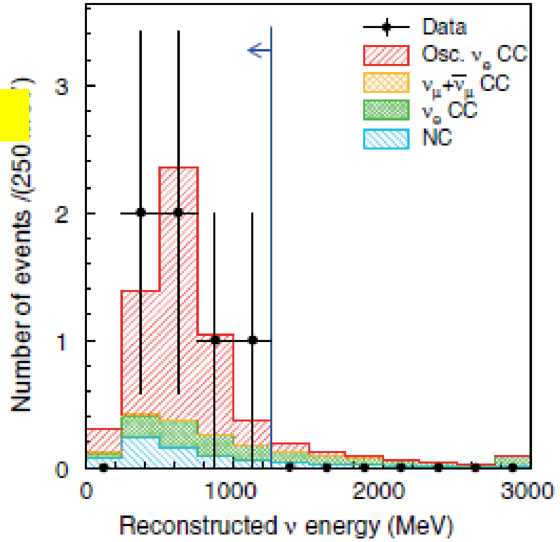
Accelerator based ν_e appearance experiments

MINOS PRL 107 (2011) 181802



T2K

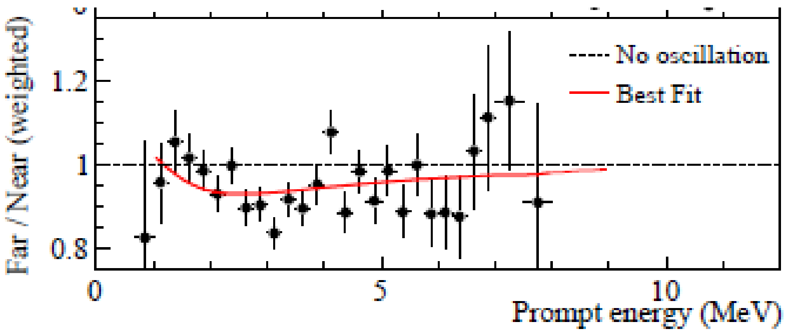
PRL 107 (2011) 041801



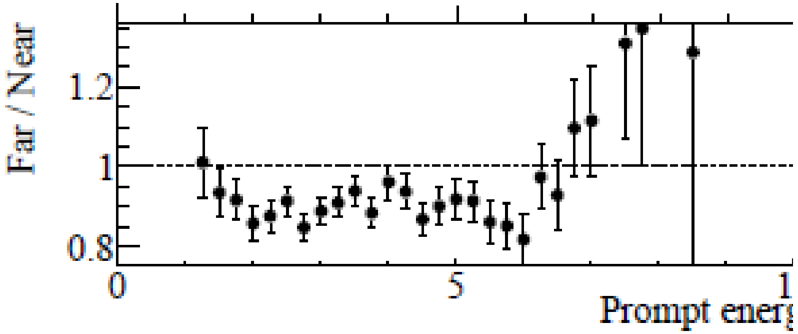
Note: these data are those in 2011-2012. The updated data are much better (including those from NOvA).

Reactor based anti-ν_e disappearance experiments

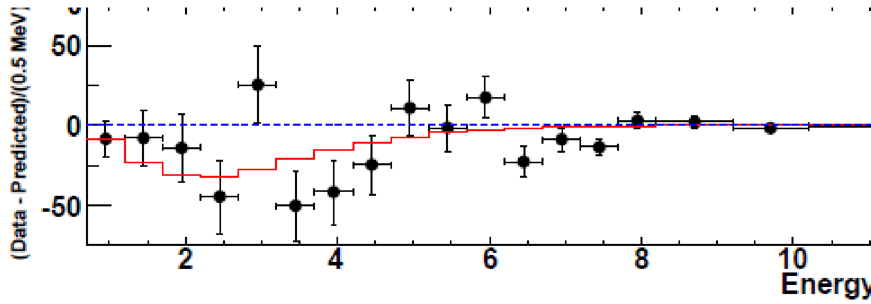
Daya Bay PRL 108 (2012) 171803



RENO PRL 108 (2012) 191802



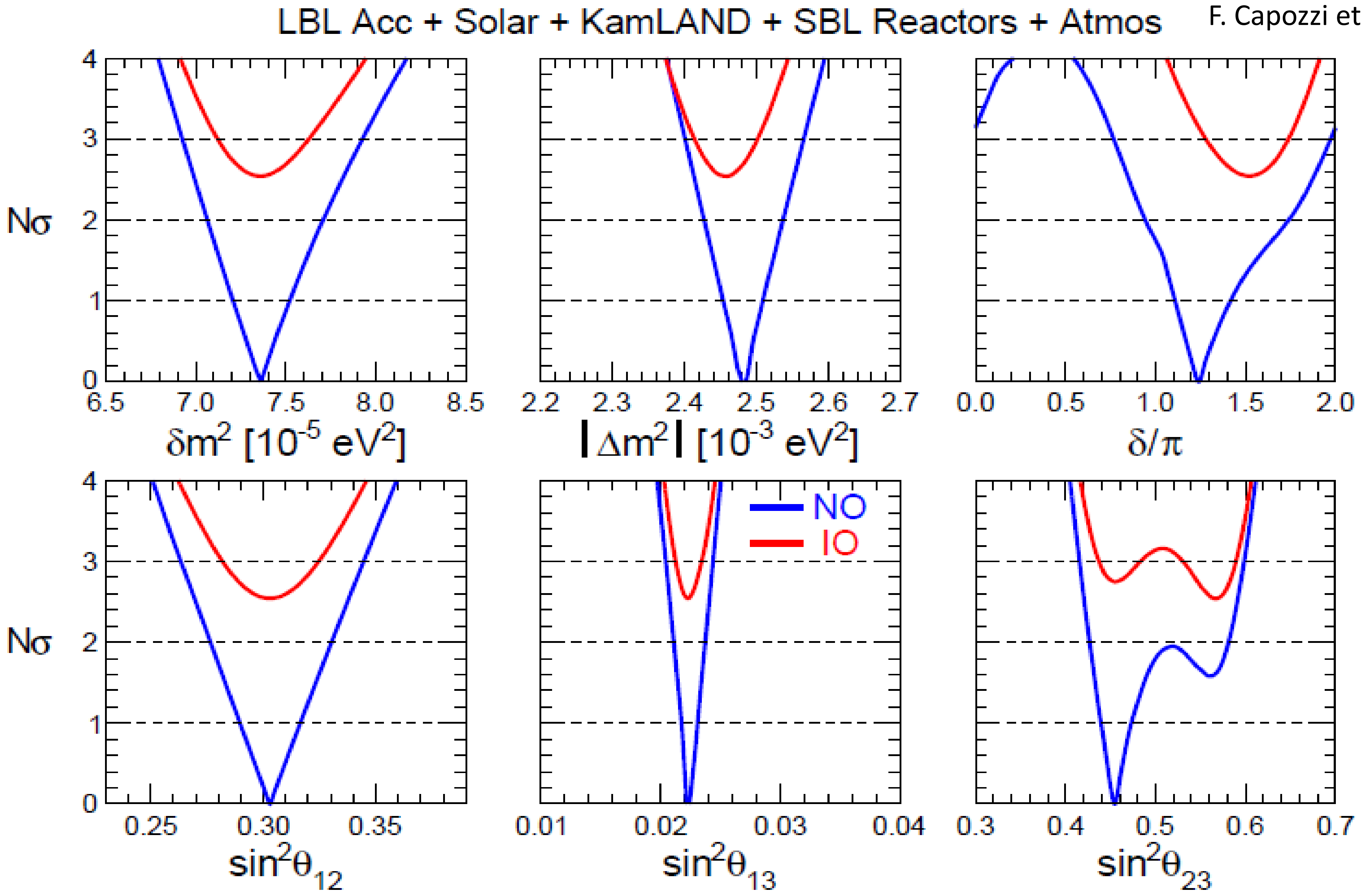
Double Chooz PRL 108 (2012) 131801



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

Oscillation parameters

F. Capozzi et al.,arXiv:2107.00532v2 (Sep 2021)

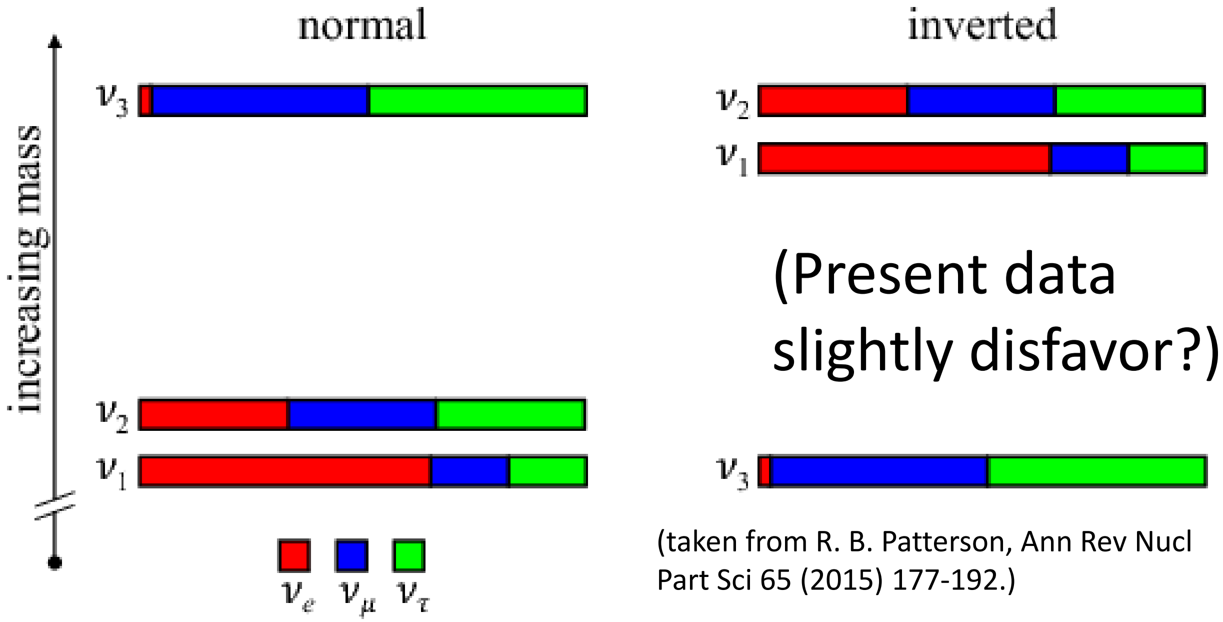


See also, P.F.de Salas et al.,arXiv:2006.11237v2 (Jan 2021) and many other references

Agenda for the future neutrino measurements

Agenda for the future neutrino measurements

Neutrino mass hierarchy?



(Present data slightly disfavor?)

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

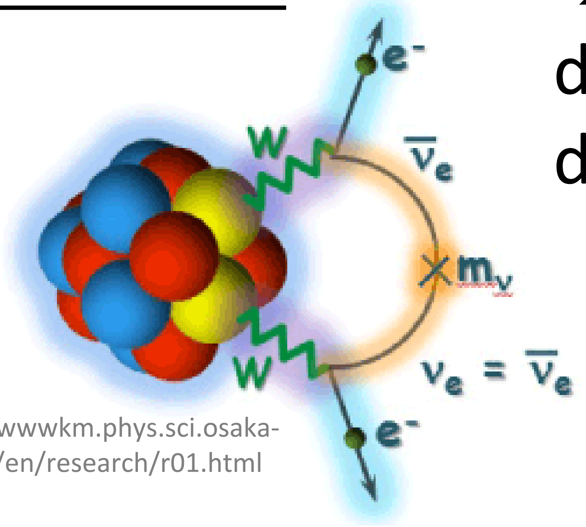
CP violation?

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

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

Absolute neutrino mass?

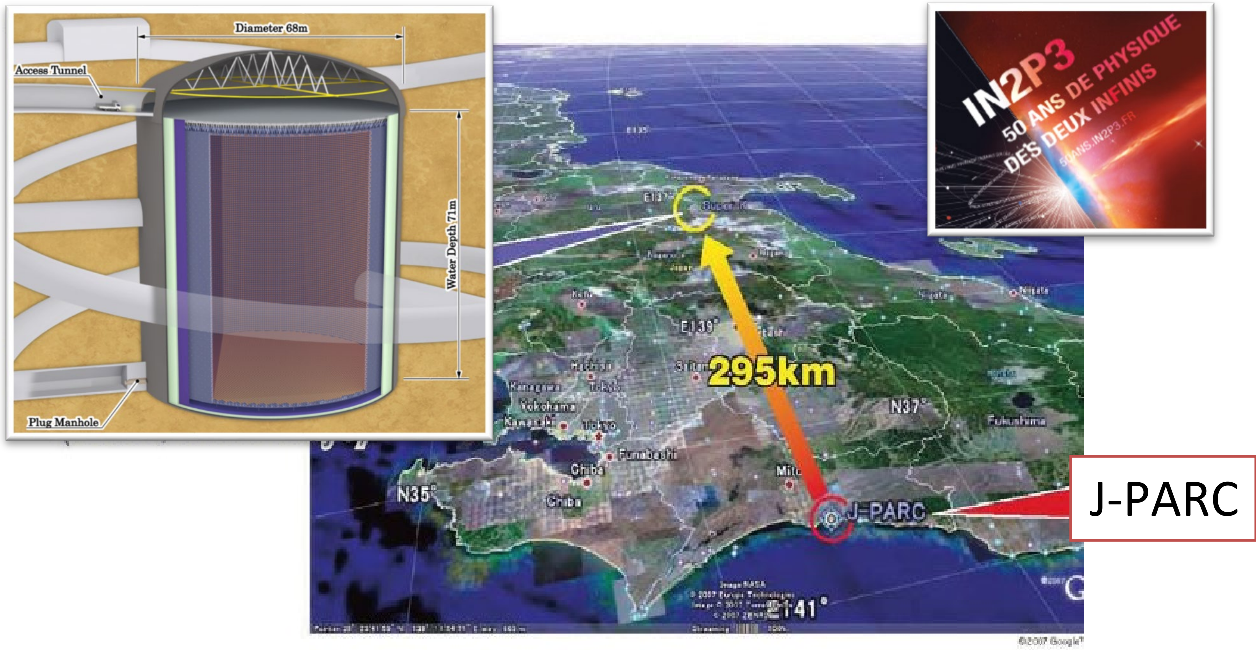
Beyond the 3 flavor framework? (Sterile neutrinos?)

Next generation neutrino oscillation experiments

✓ We would like to observe if oscillation of neutrinos and those of anti-neutrinos are different. If observed, it will the first step to understand the origin of the matter in the Universe.

DUNE

Hyper-Kamiokande (Hyper-K)

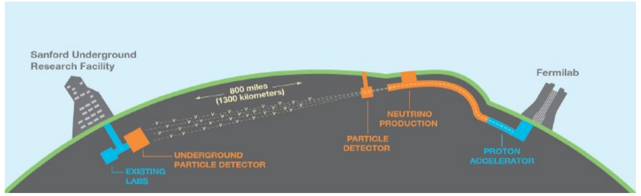


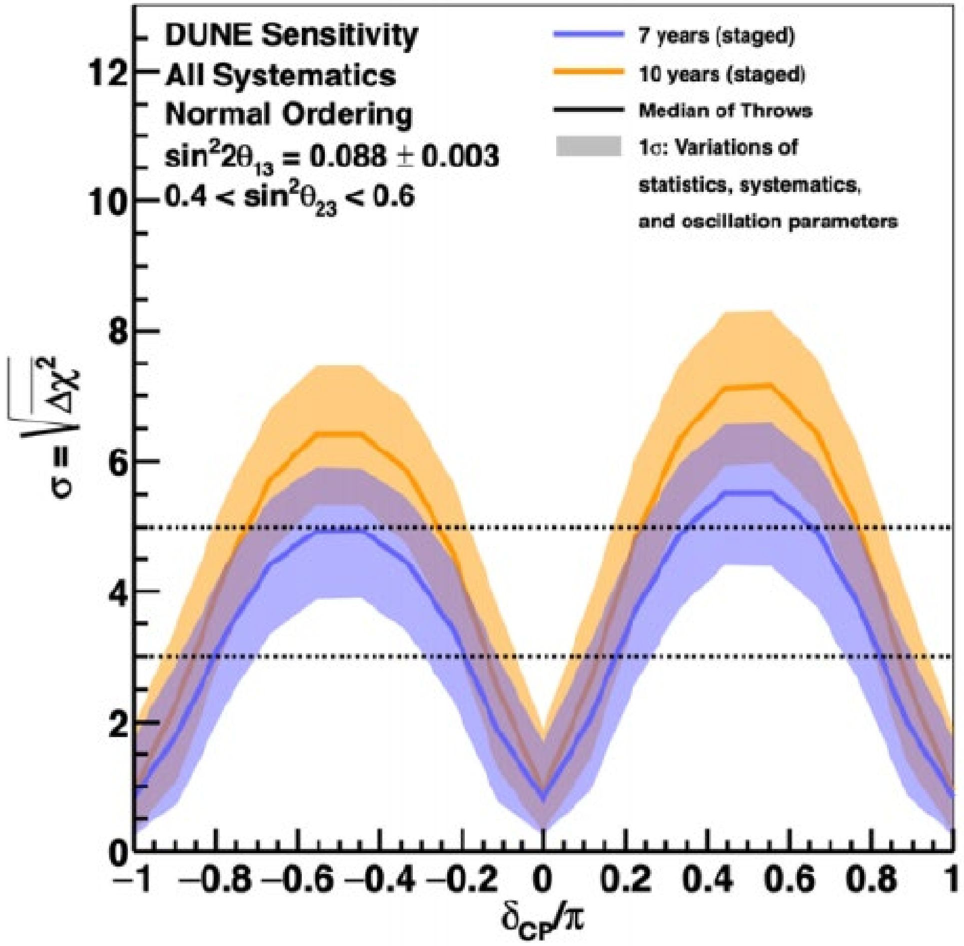
DUNE (located in USA) and Hyper-Kamiokande (located in Japan) have similar sensitivities, although the experimental details are largely different. We would like to see the consistent results from these 2 complementary experiments!

sensitivities

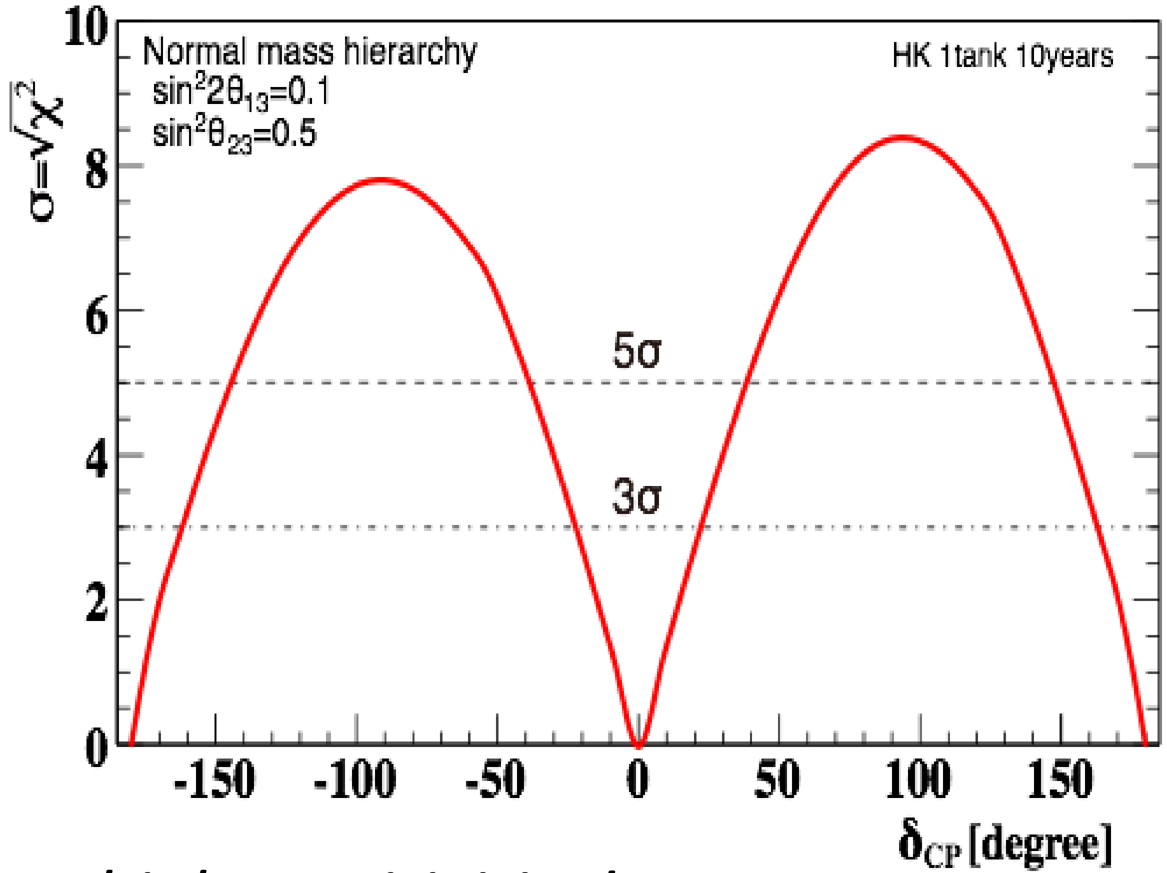
DUNE

(Neutrino Telescope 2021, Georgia Karagiorgi)





Hyper-K



➔ *Both experiments have very high sensitivities!*

ILANCE

International
Laboratory for
Astrophysics,
Neutrino and
Cosmology
Experiments

https://ilance.cnrs.fr/

ILANCE was created on April 1, 2021. The founding Institutions are CNRS and the Univ. of Tokyo. ILANCE's office is located at the Kashiwa campus of the Univ. of Tokyo. The teams of IN2P3/CNRS and the University of Tokyo have been actively involved together in research projects in neutrino physics, cosmology, astrophysics, high energy astrophysics and particle physics. In particular, ILANCE will be a key laboratory for the collaboration between France and Japan in the T2K and Hyper-Kamikande experiments.

Summary

- During the last 50 years, we discovered that neutrinos have small mass (and large mixings).
- IN2P3 has been playing very important roles in neutrino physics and astrophysics.
- We expect that IN2P3 will continue to play major roles in neutrino physics and astrophysics.
- Let us keep working together and enjoy neutrino physics and astrophysics!

Congratulations for IN2P3 50 years!