NCTS 20th Anniversary Symposium,
Aug. 3, 2017

Status and Prospect of Neutrino Oscillation Experiments

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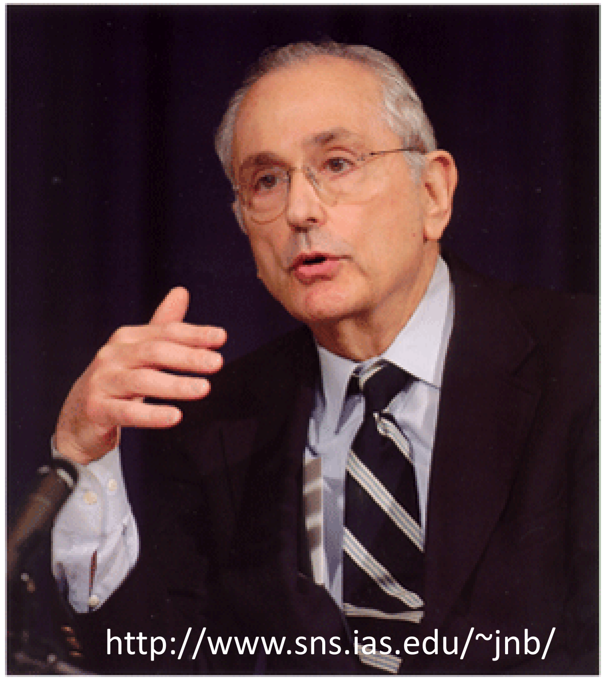
Outline

- Introduction
- Present status of neutrino oscillations
- Future oscillation studies
- Summary

Introduction

Solar neutrino problem



J. N. Bahcall

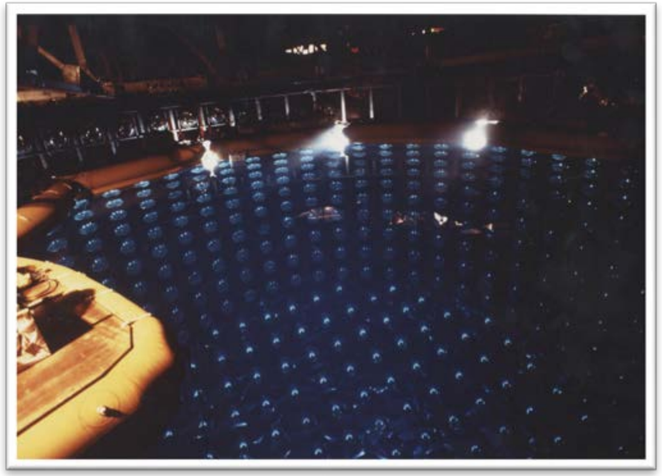
600ton C_2Cl_4

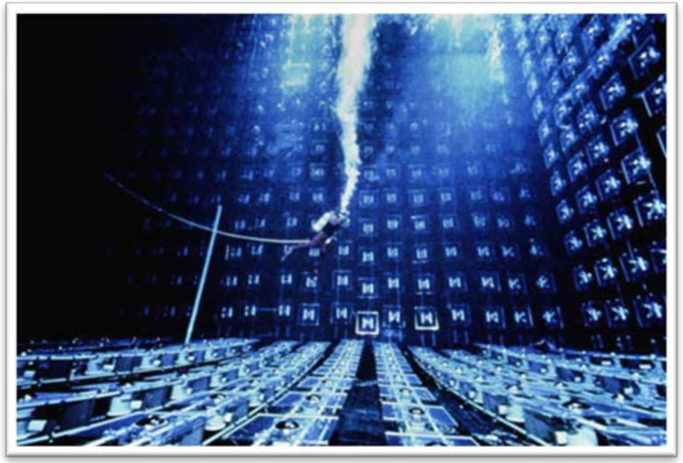
The pioneering Homestake solar neutrino experiment observed only about 1/3 of the predicted solar neutrinos (1960's).

Subsequent experiments in the 80's and 90's confirmed the solar neutrino deficit.

Atmospheric ν_μ deficit

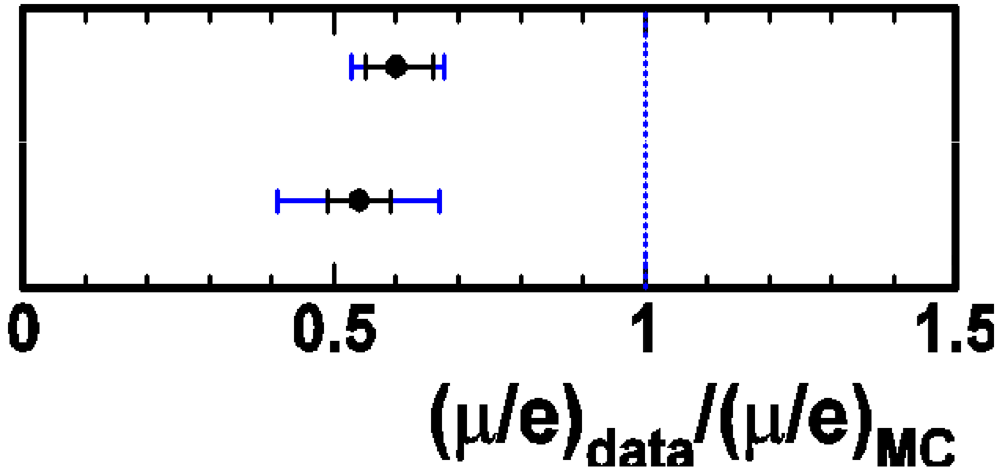
- ✓ It was necessary for “proton decay experiments” to understand atmospheric neutrino interactions as they were the most serious backgtound.
- ✓ During these studies, a significant deficit of atmospheric ν_μ events was observed.





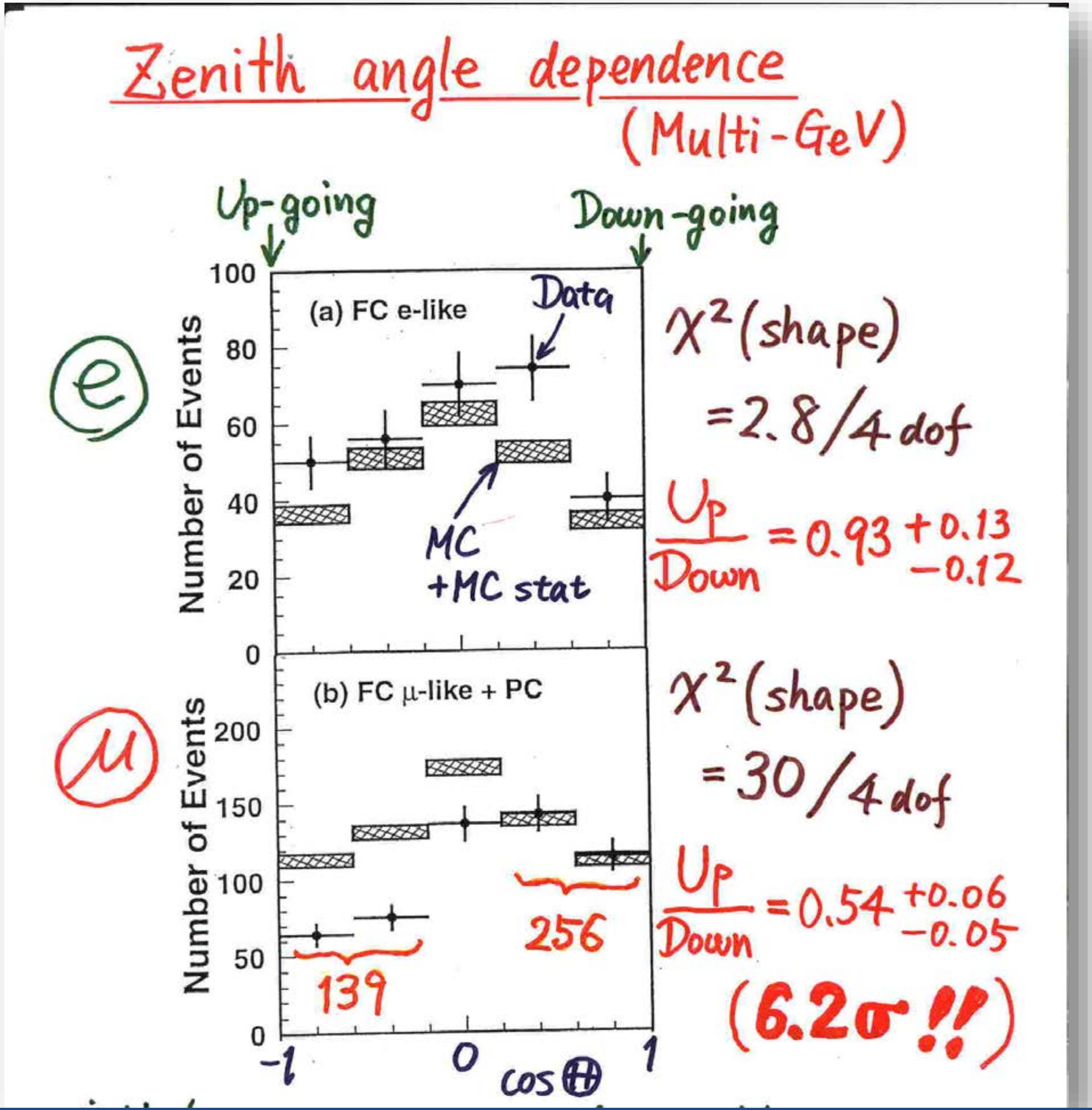
Kamiokande (1988, 92, 94)

IMB (1991, 92)

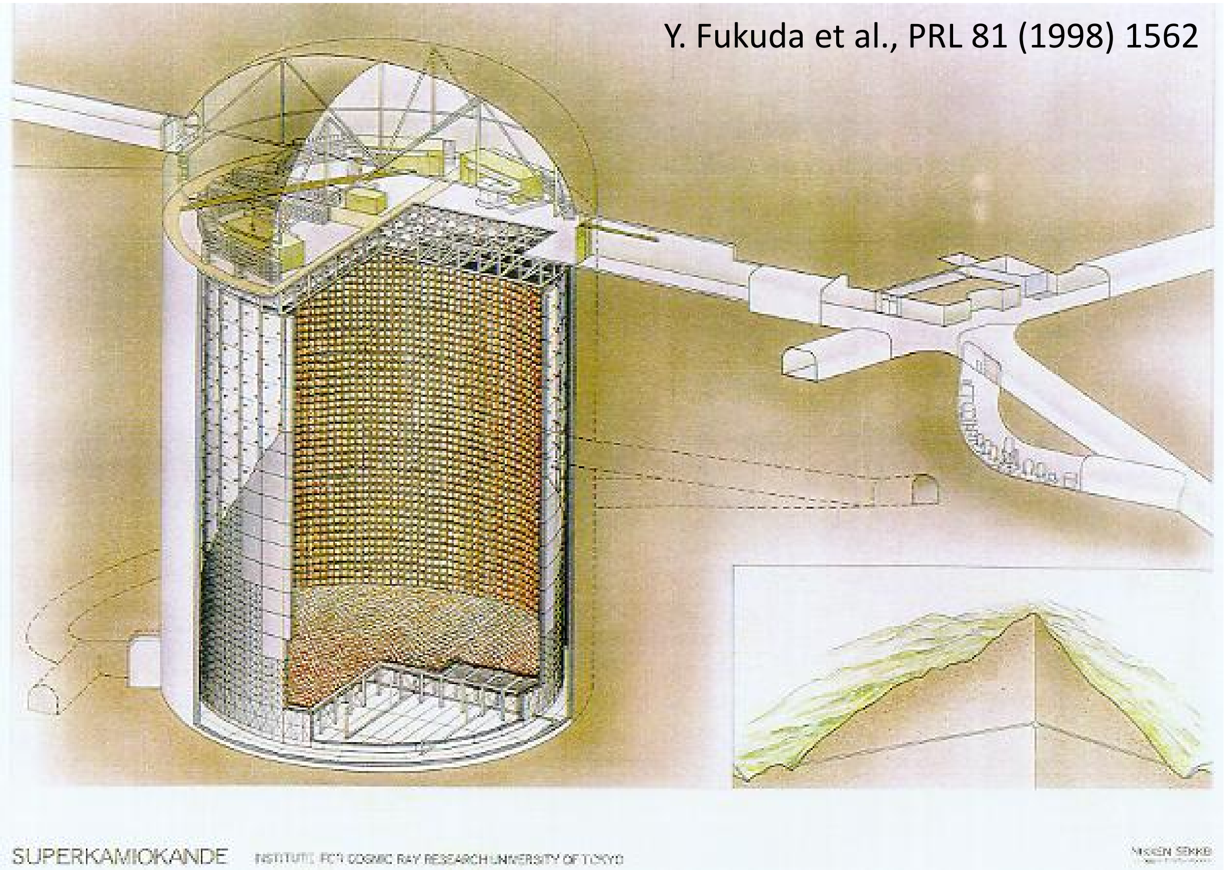


(In the 1990’s, Soudan-2 also observed the ν_μ deficit.)

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



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

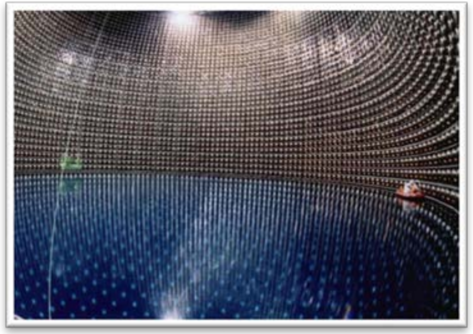


Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

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

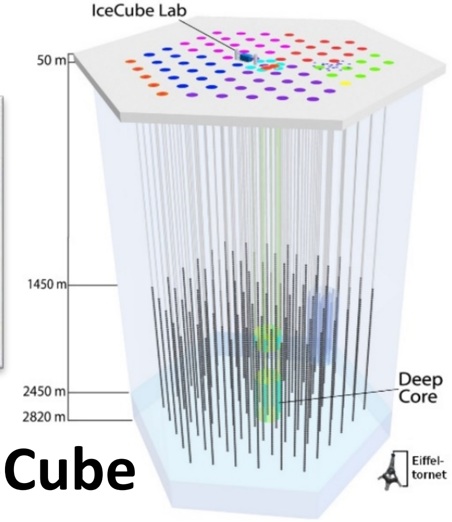
Atmospheric neutrinos

Super-K



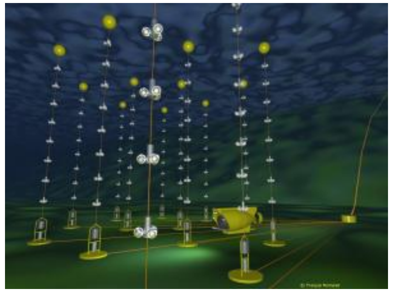
MACRO

Soudan-2



IceCube

ANTARES

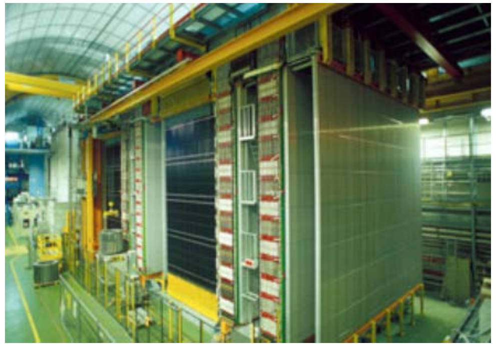


Accelerator based long baseline experiments

K2K

T2K

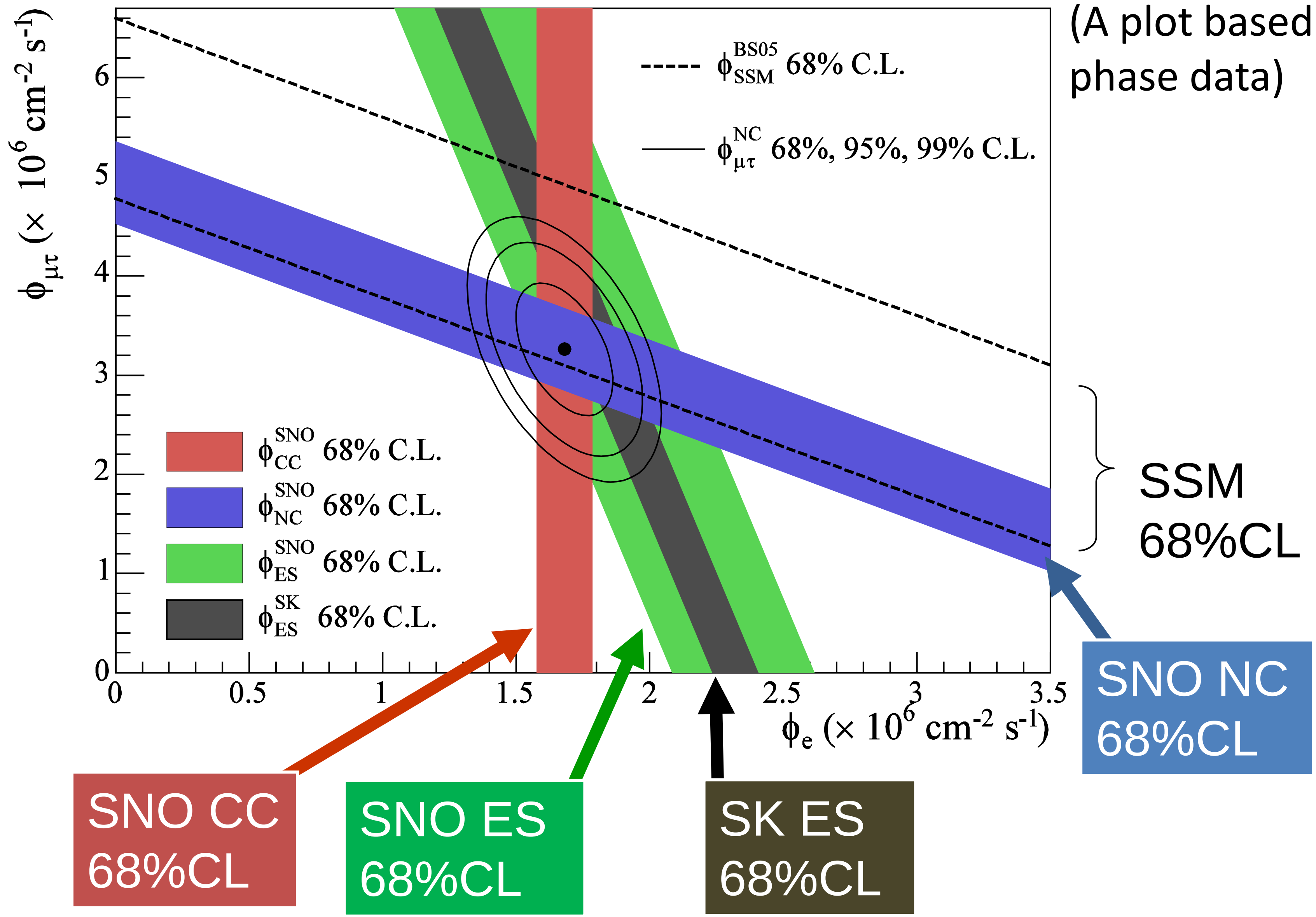
OPERA



MINOS

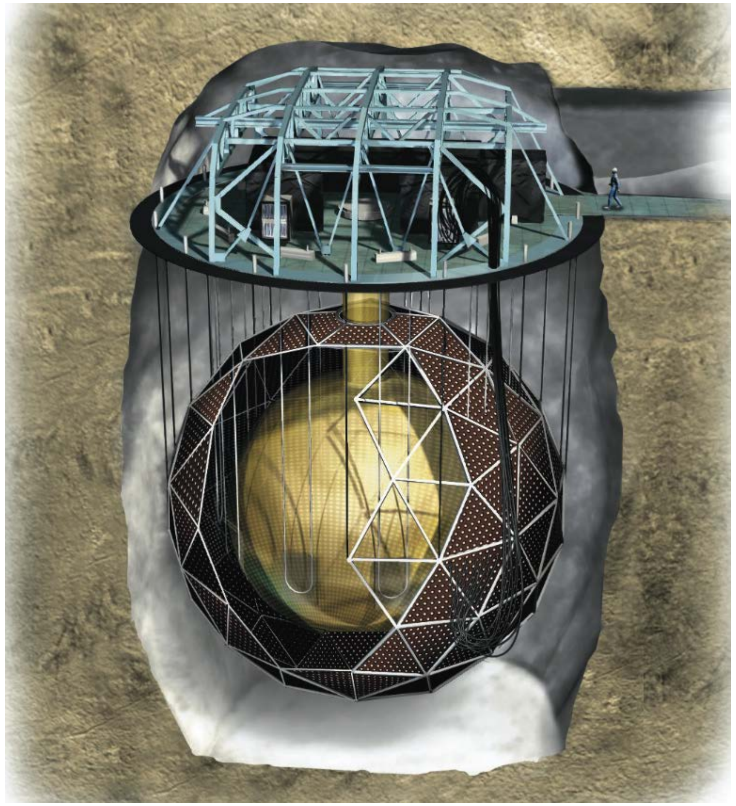
NOvA

Evidence for solar neutrino oscillations



(A plot based on the salt-phase data)

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

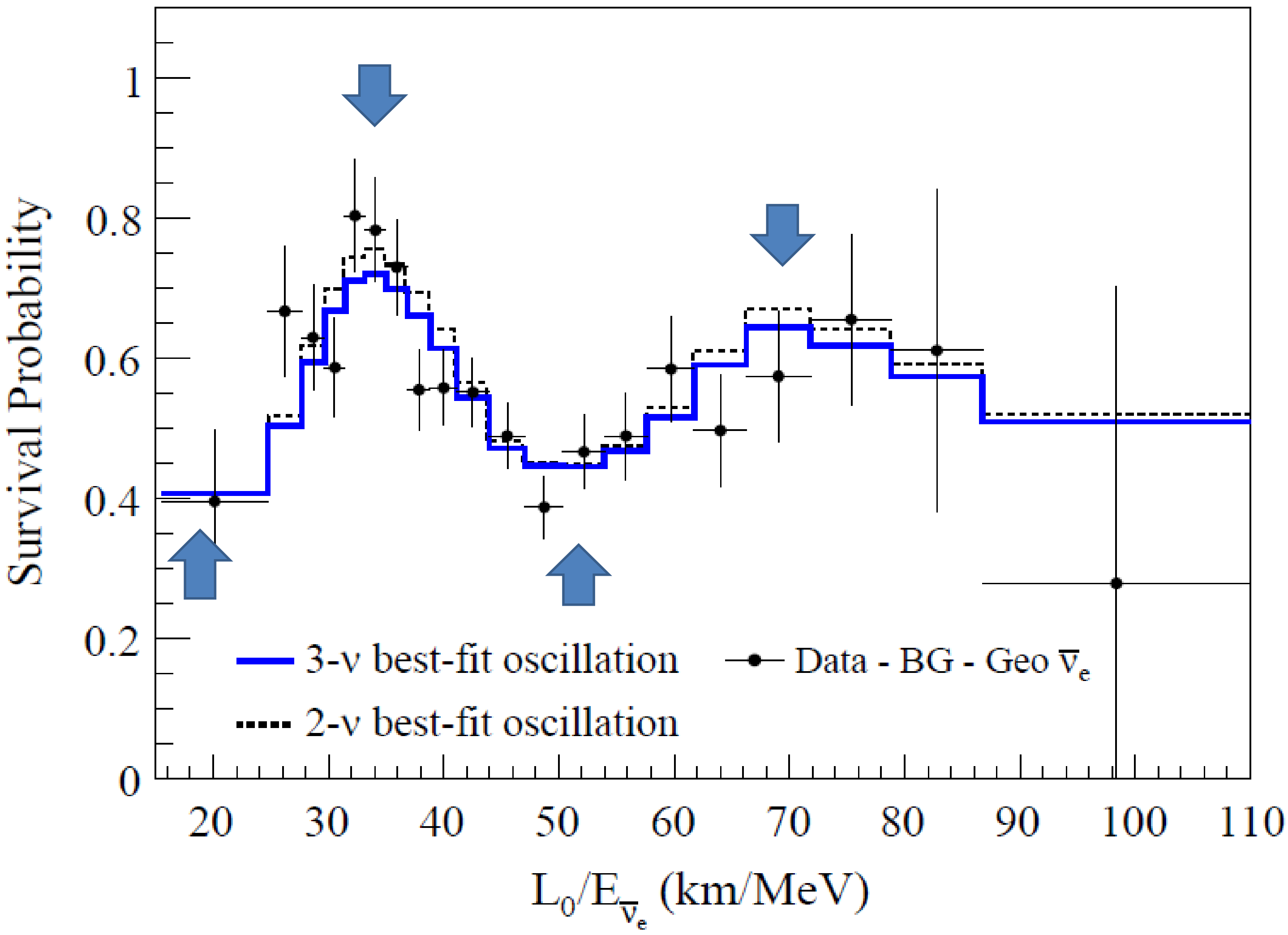


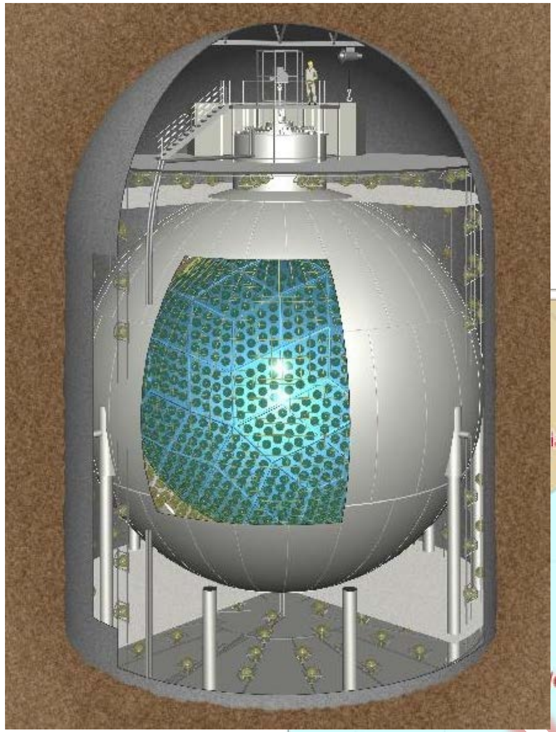
Three (or four) different measurements ➔ ***<u>evidence for (ν_μ+ν_τ) flux</u>***

Really neutrino oscillations !

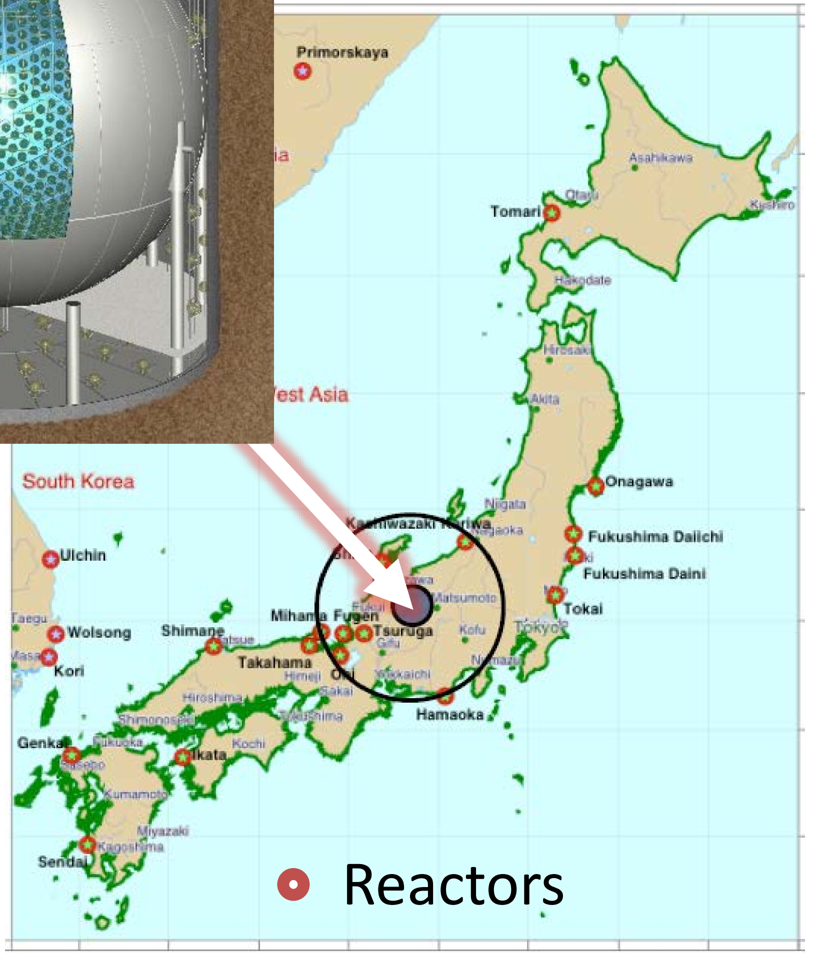
KamLAND observed neutrinos from nuclear power stations.

KamLAND, PRD 83, 052002 (2011)





KamLAND



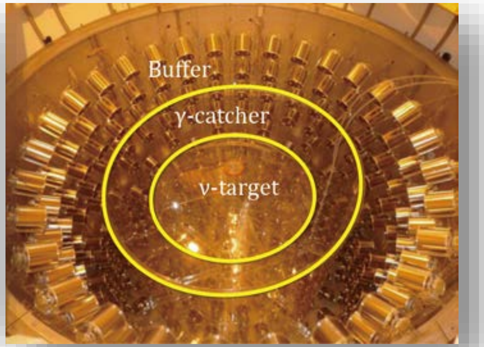
Discovery of the third neutrino oscillations (2011-2012~)

Reactor based (short baseline) neutrino oscillation exps

Daya Bay

RENO

Double CHOOZ



Accelerator based long baseline neutrino oscillation exps

MINOS

T2K

NOνA

Status (before Neutrino 2016)

Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ ($1.31^{+0.29}_{-0.33}$)

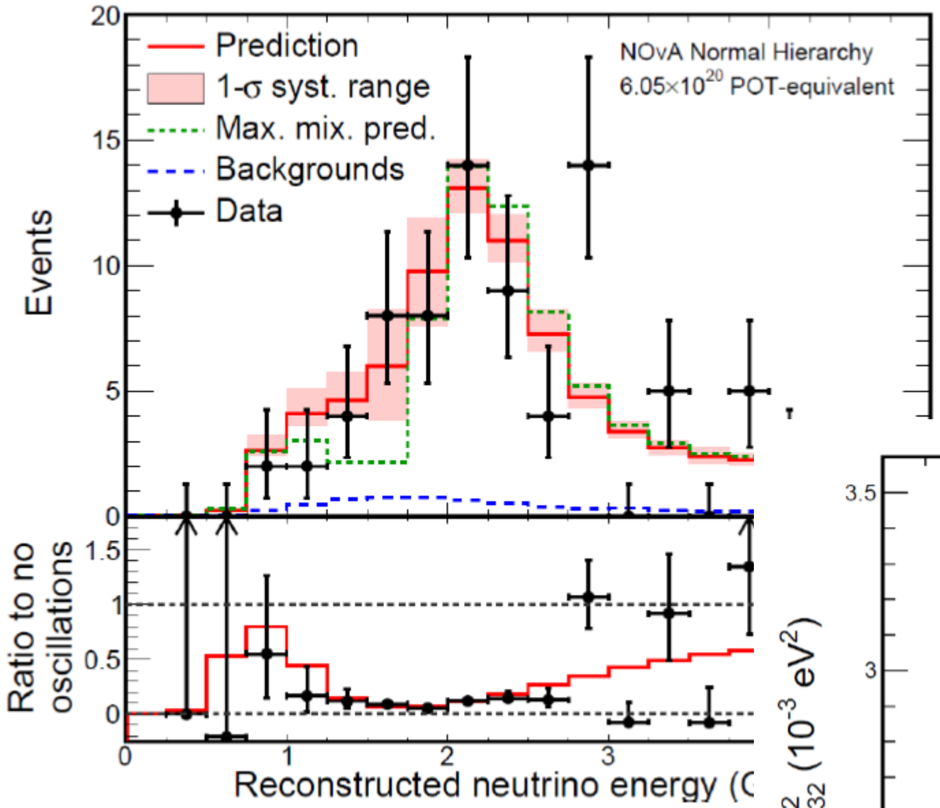
Review of Particle Physics (2015)
K. Nakamura and S.T. Petcov, "14. Neutrino mass, mixing and oscillations"

Basic structure for 3 flavor oscillations has been understood!

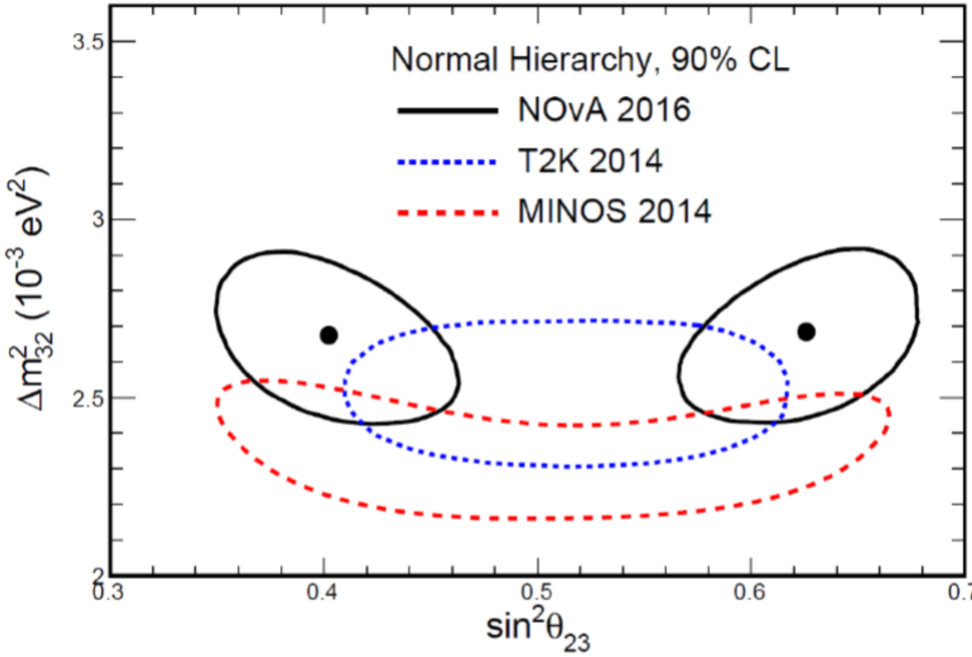
Present status of neutrino oscillations

Some highlights (ν_μ disappearance)

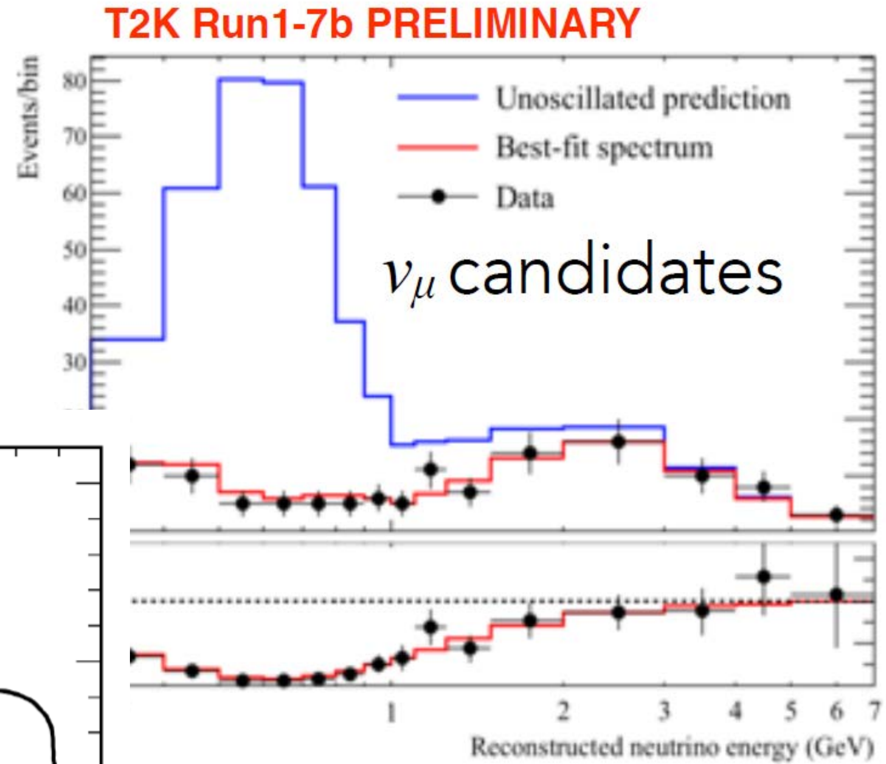
NOvA K. Bays, TAUP2017



Maximal mixing disfavored at 2.6 σ.



T2K T2K, PRL 112 (2014) 181801
T2K@neutrino 2016



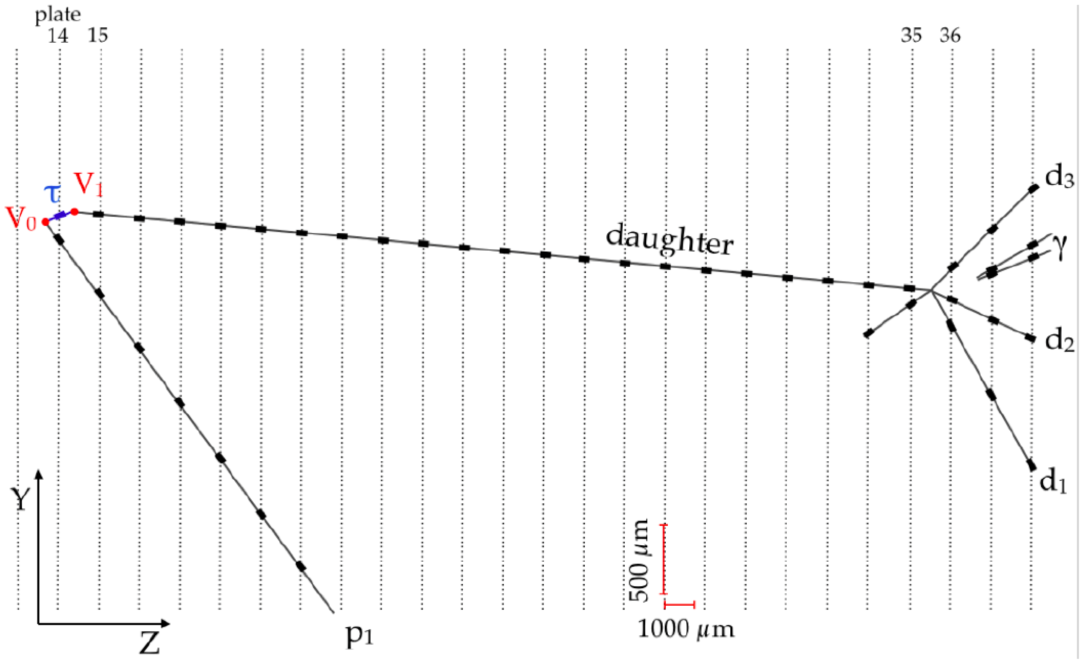
Consistent with maximal mixing…

Some highlights (ν_τ appearance)

OPERA

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

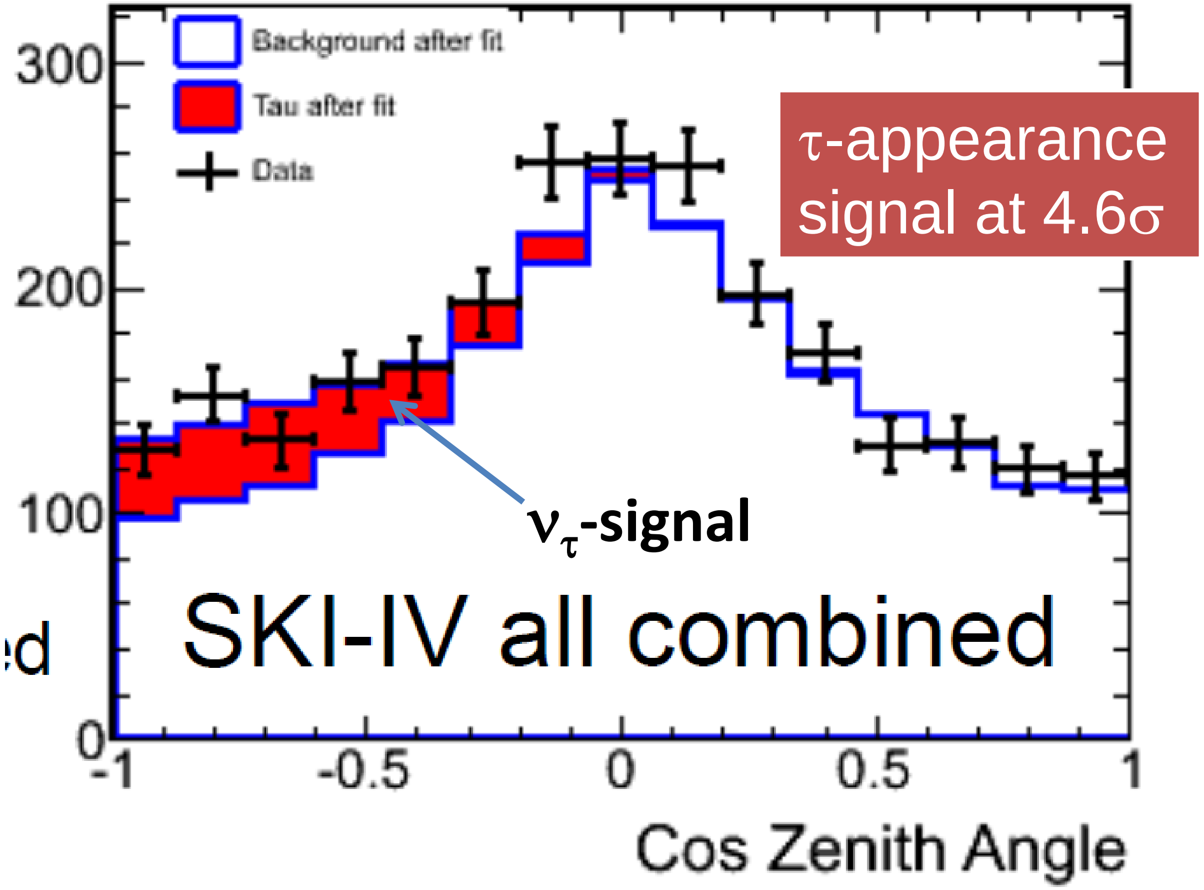
OPERA PRL 115 (2015) 121602



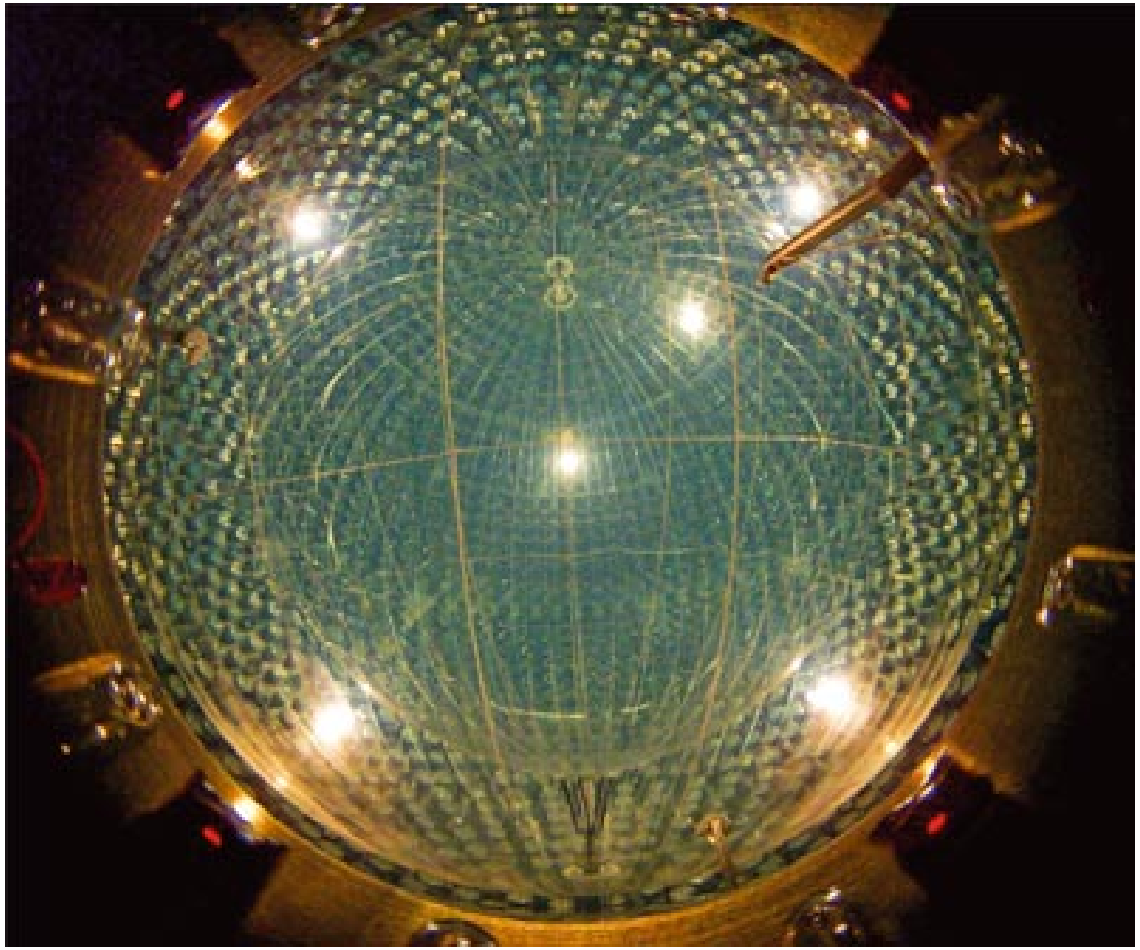
The fifth candidate event

Super-Kamiokande

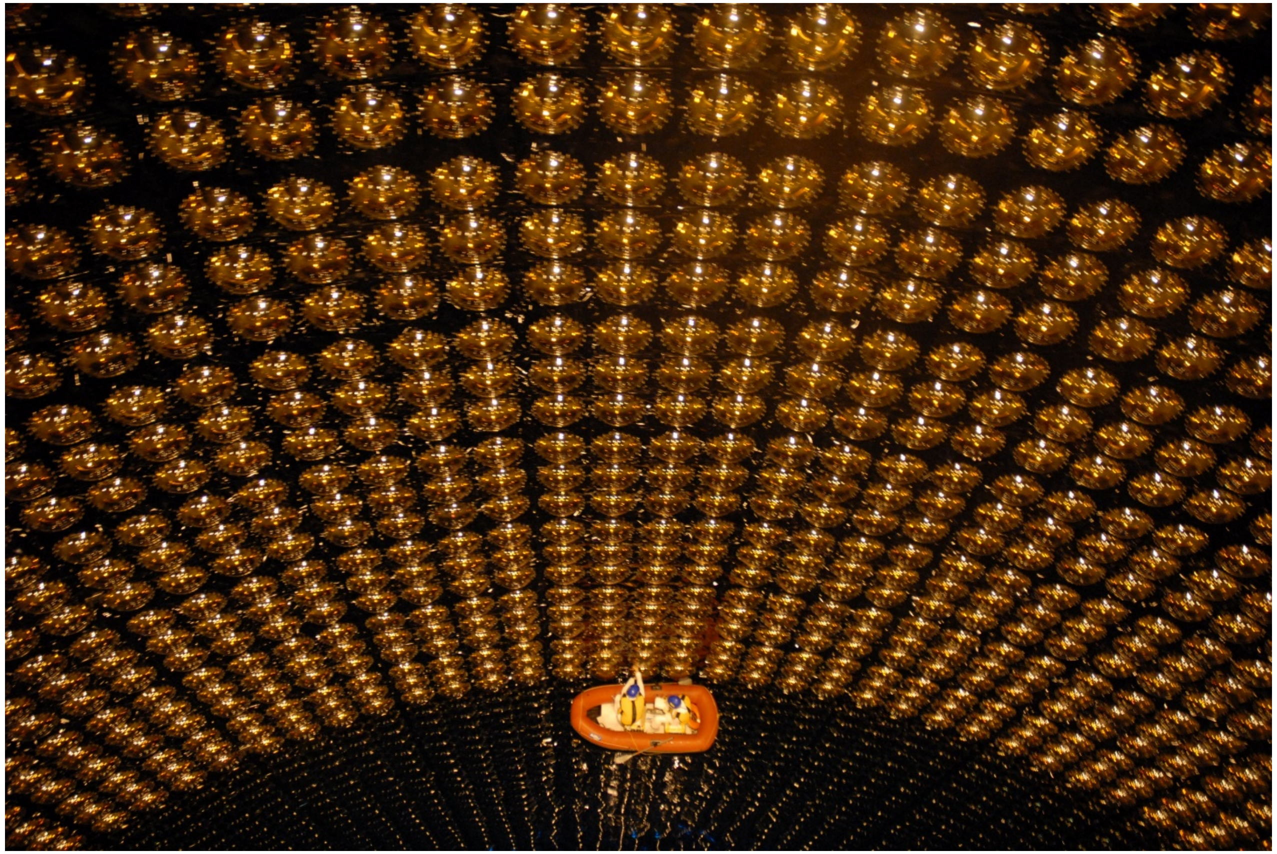
Super-K (S.Moriyama) @nu2016
See also, SK PRL 110(2013)181802



Present solar neutrino experiments



Borexino
(300 ton liq. Sci. detector)

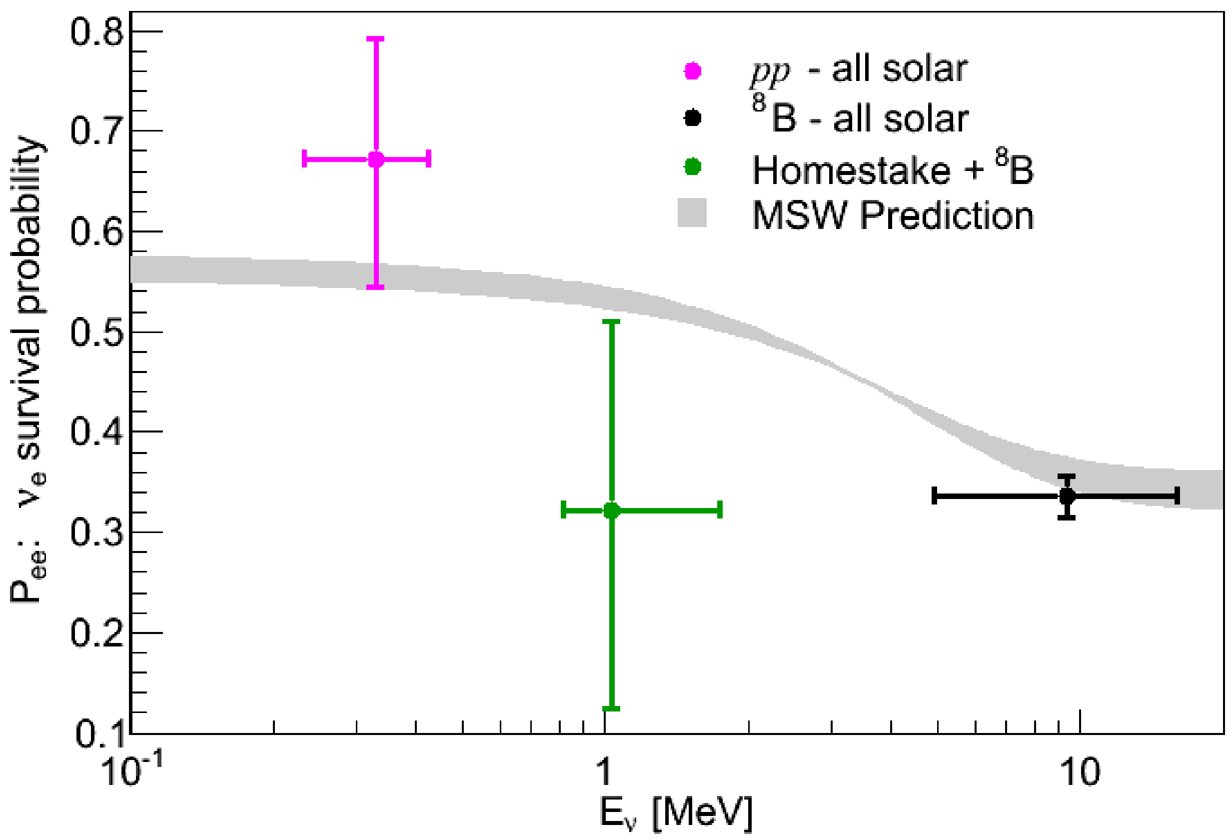


Super-Kamiokande
(22500 ton water detector)

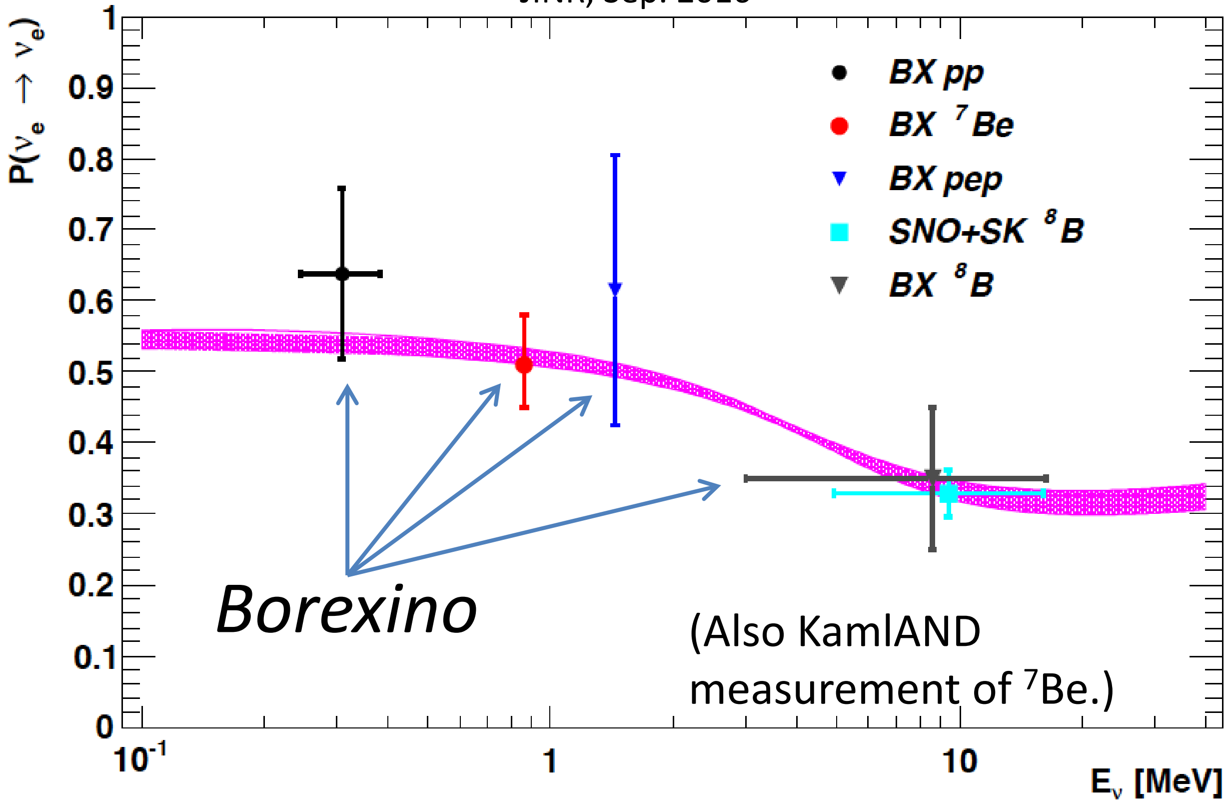
To what extent do we understand solar neutrino osci. (1)

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

Before Borexino



After Borexino

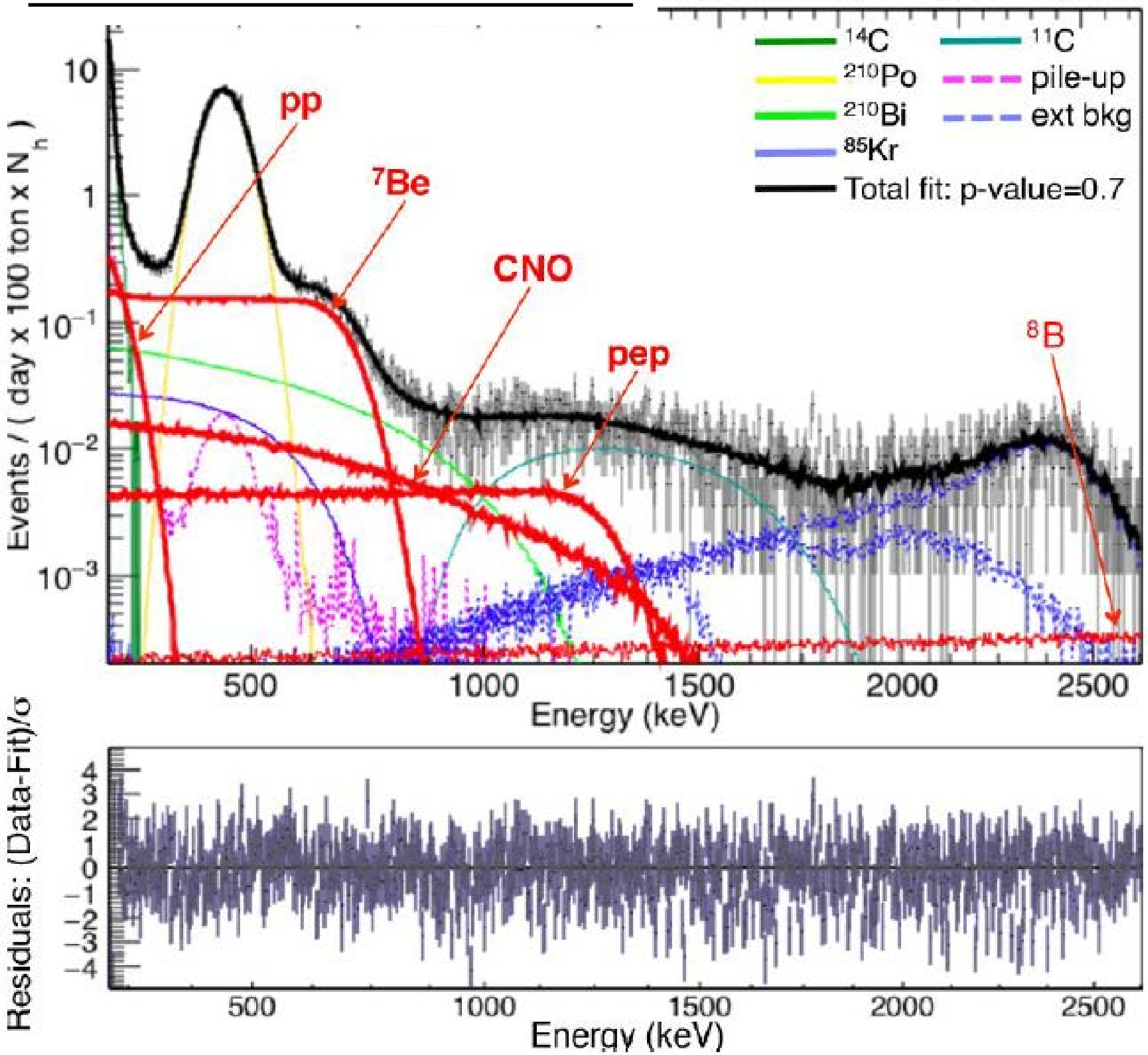


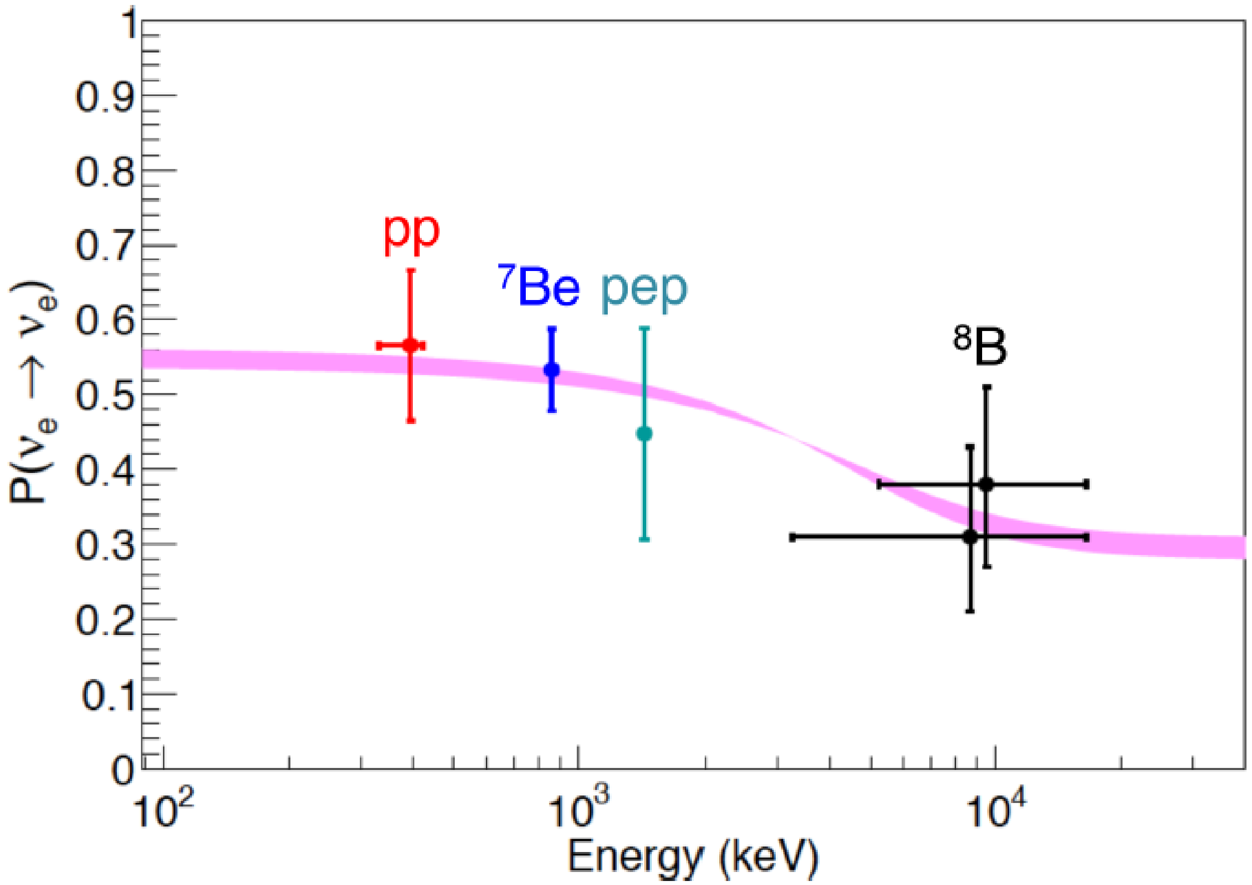
The data are consistent with the MSW prediction!

To what extent do we understand solar neutrino osci. (1)

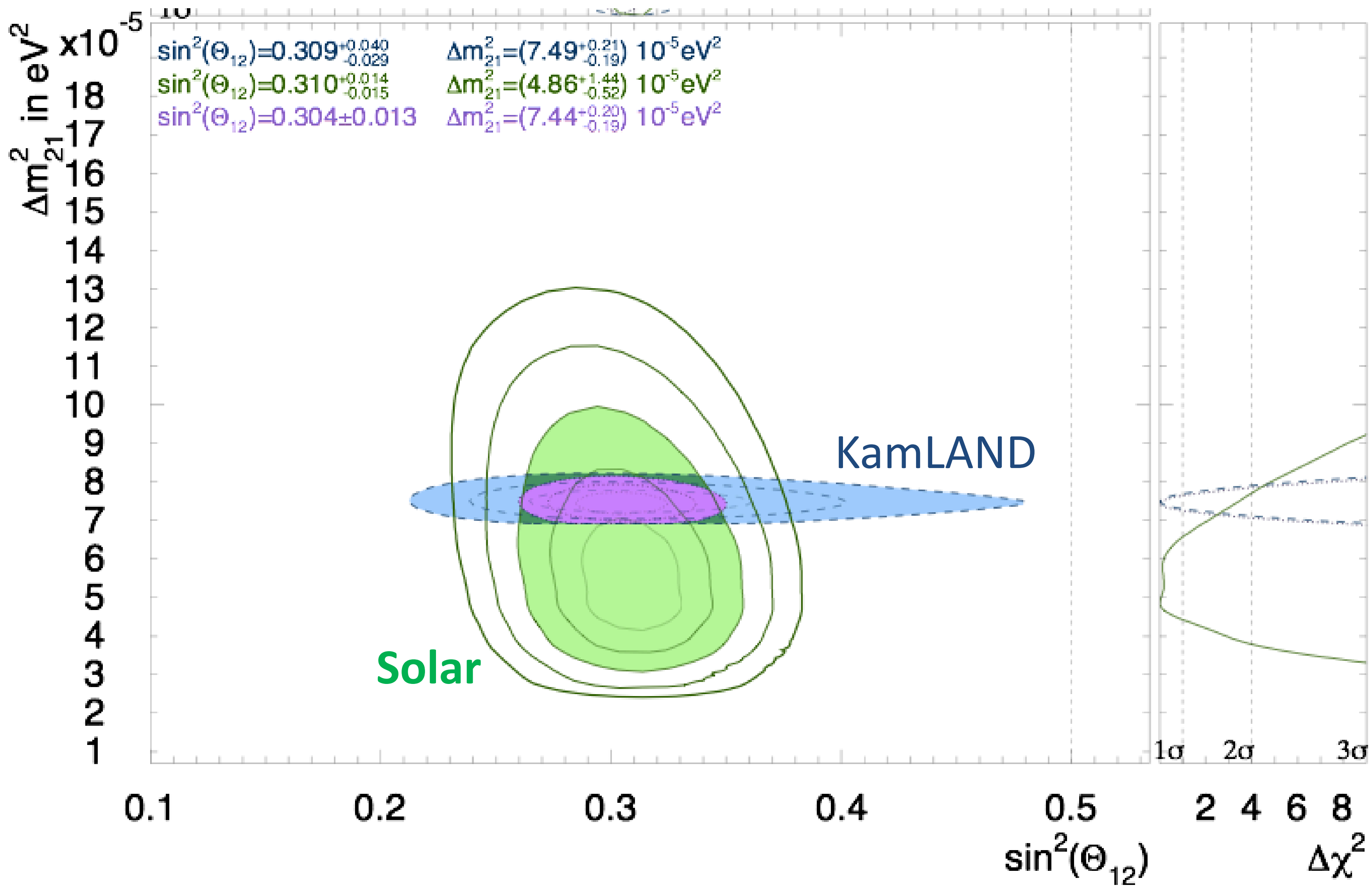
Borexino, TAUP2017

Borexino new results





To what extent do we understand solar neutrino osci. (2)

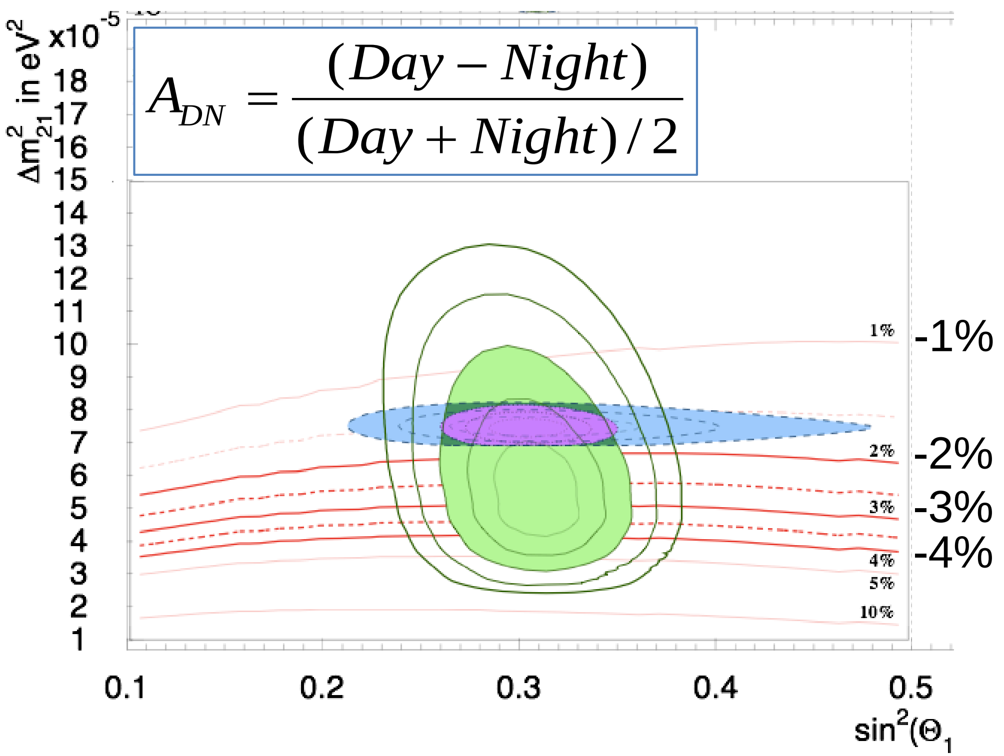


There is $\Delta\chi^2$ ~(<) 4 tension in Δm_{12}^2 (solar neutrinos vs. KamLAND).

To what extent do we understand solar neutrino osci. (2)

Day-Night effect

Super-K, PRD94, 052010 (2016)



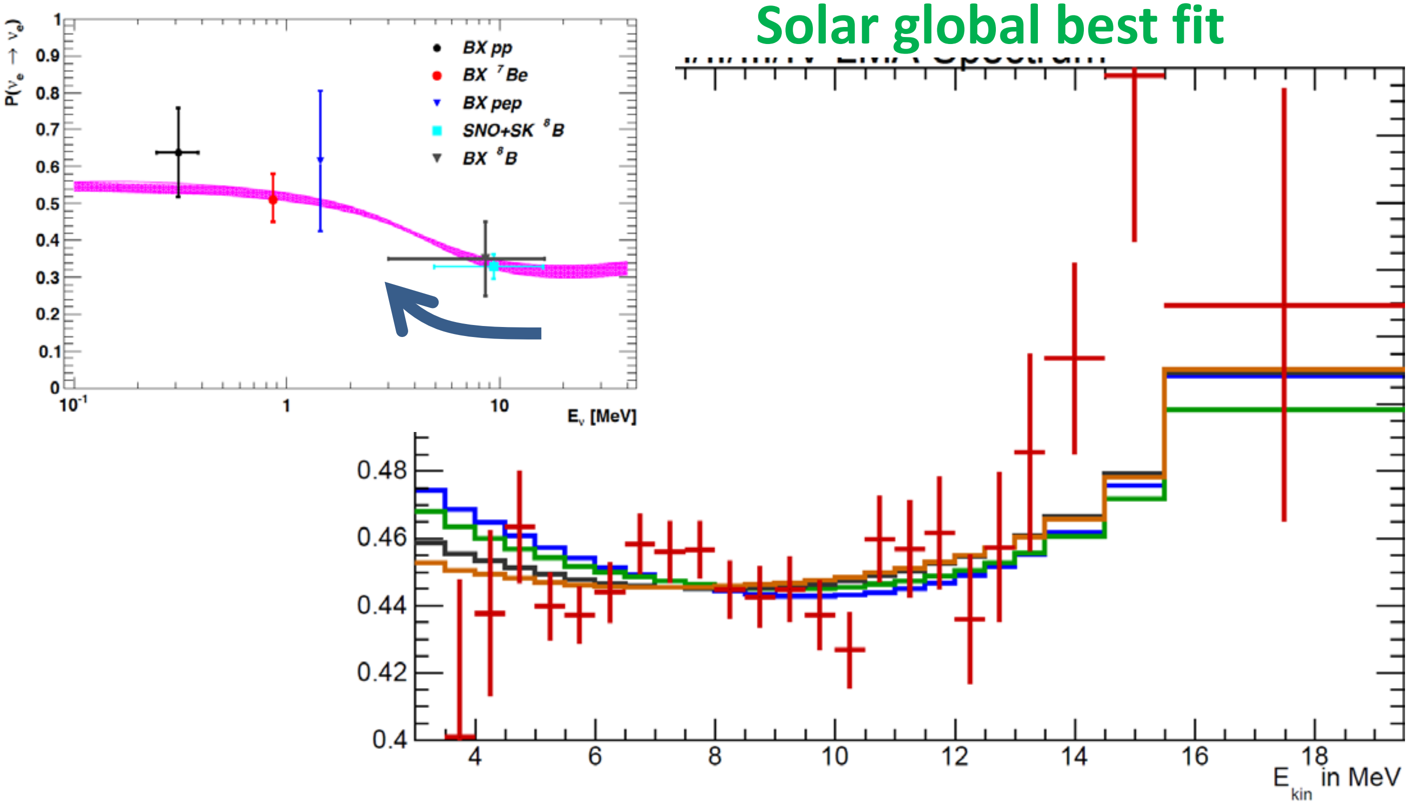
	A_{DN}^{fit} (%)
SK-I~IV, 4499 days	**-3.3+/-1.0+/-0.5**
Non-zero significance	**2.9 σ**

Spectrum upturn

(Super-K, June 2017)

Solar+KamLAND best fit

Solar global best fit



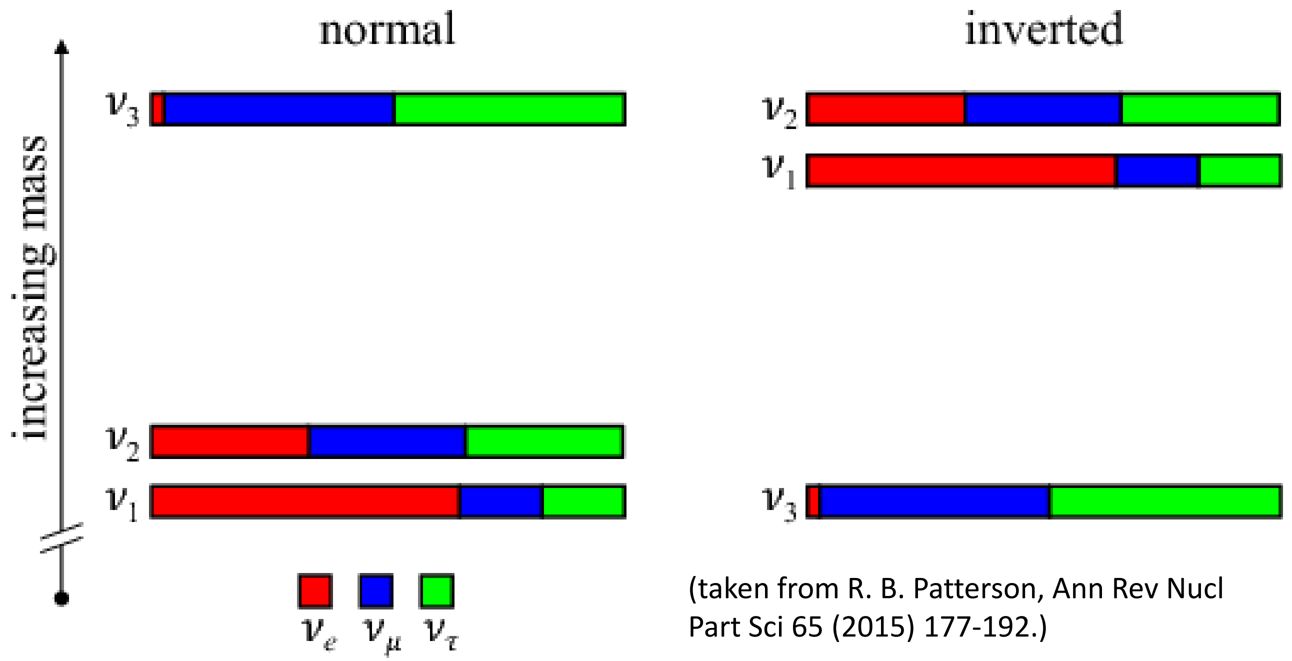
Solar best fit	**Consistent within ~1σ**
Solar+KamLAND best fit	Marginally within ~2σ

Interesting. But we need more data.

Future oscillation studies

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?)

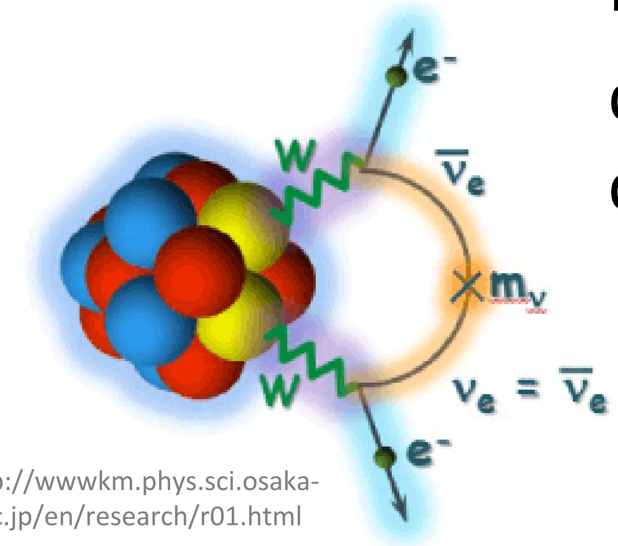
CP violation?

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

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?

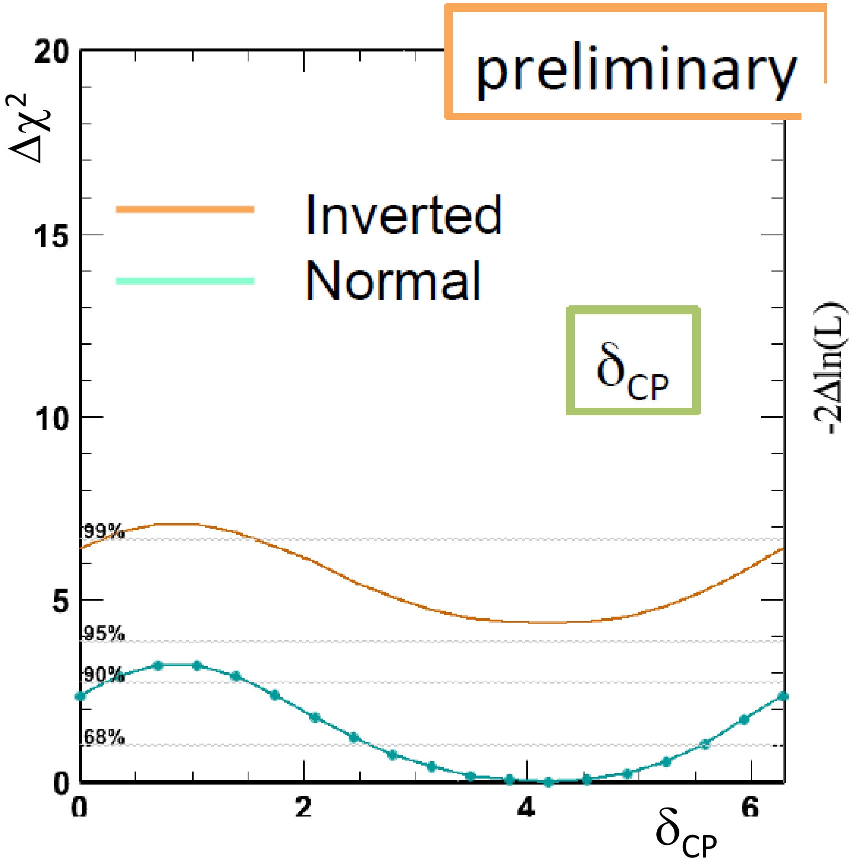
➔ Neutrinoless double beta decay



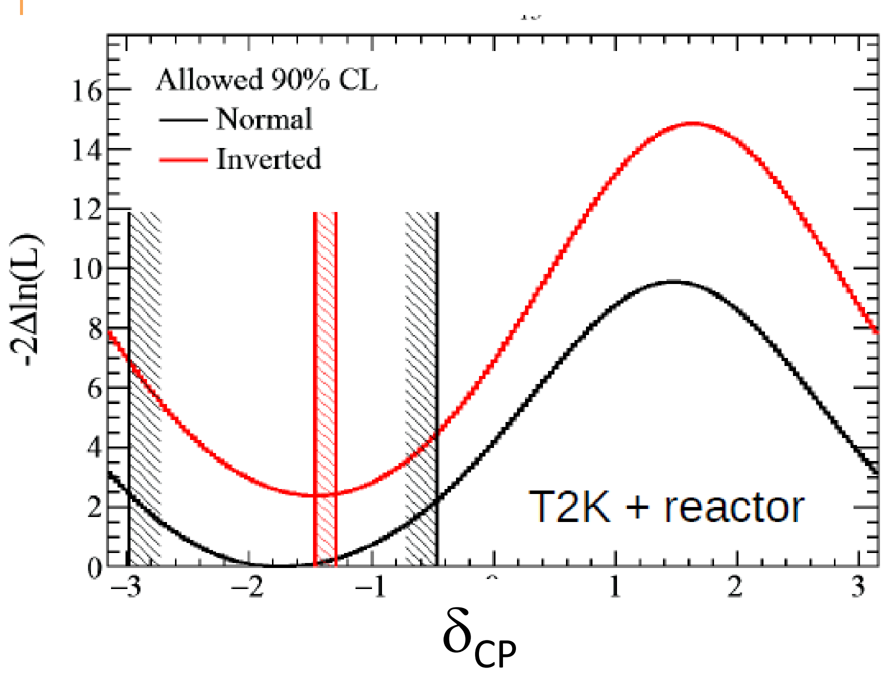
http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

Mass hierarchy and CP violation measurements

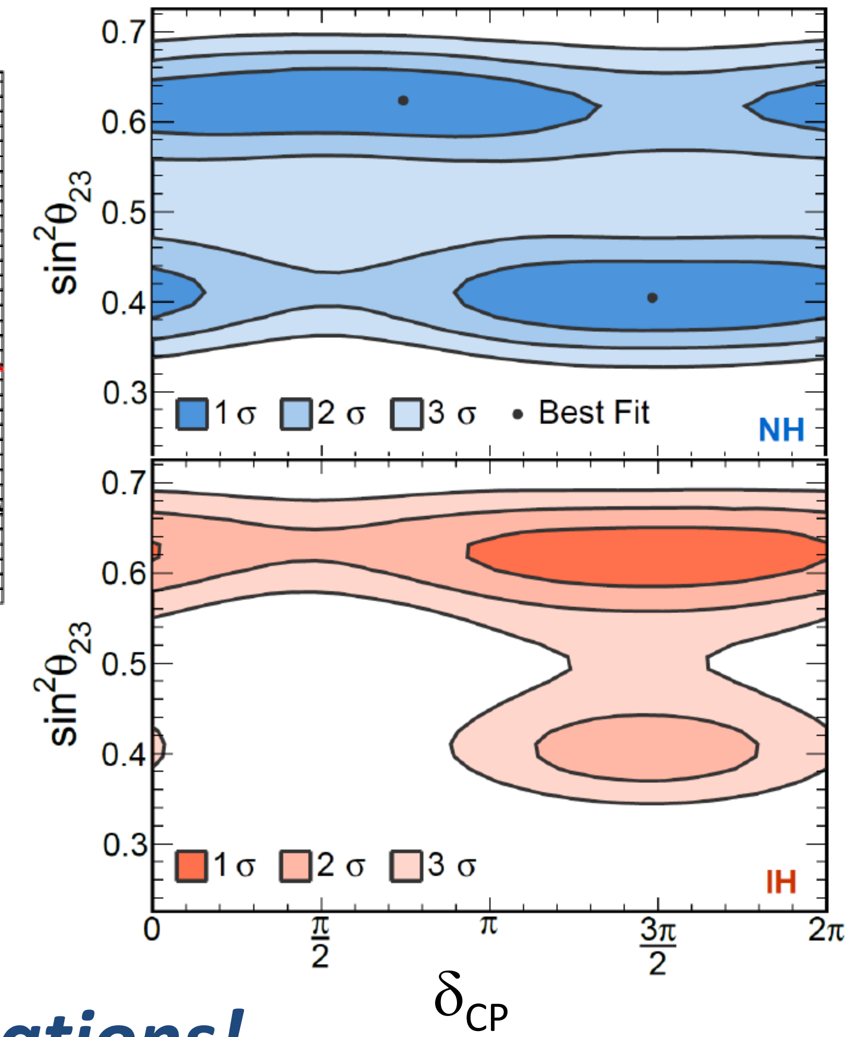
Super-K atmospheric (Neutirno2016)



T2K (TAUP2017)

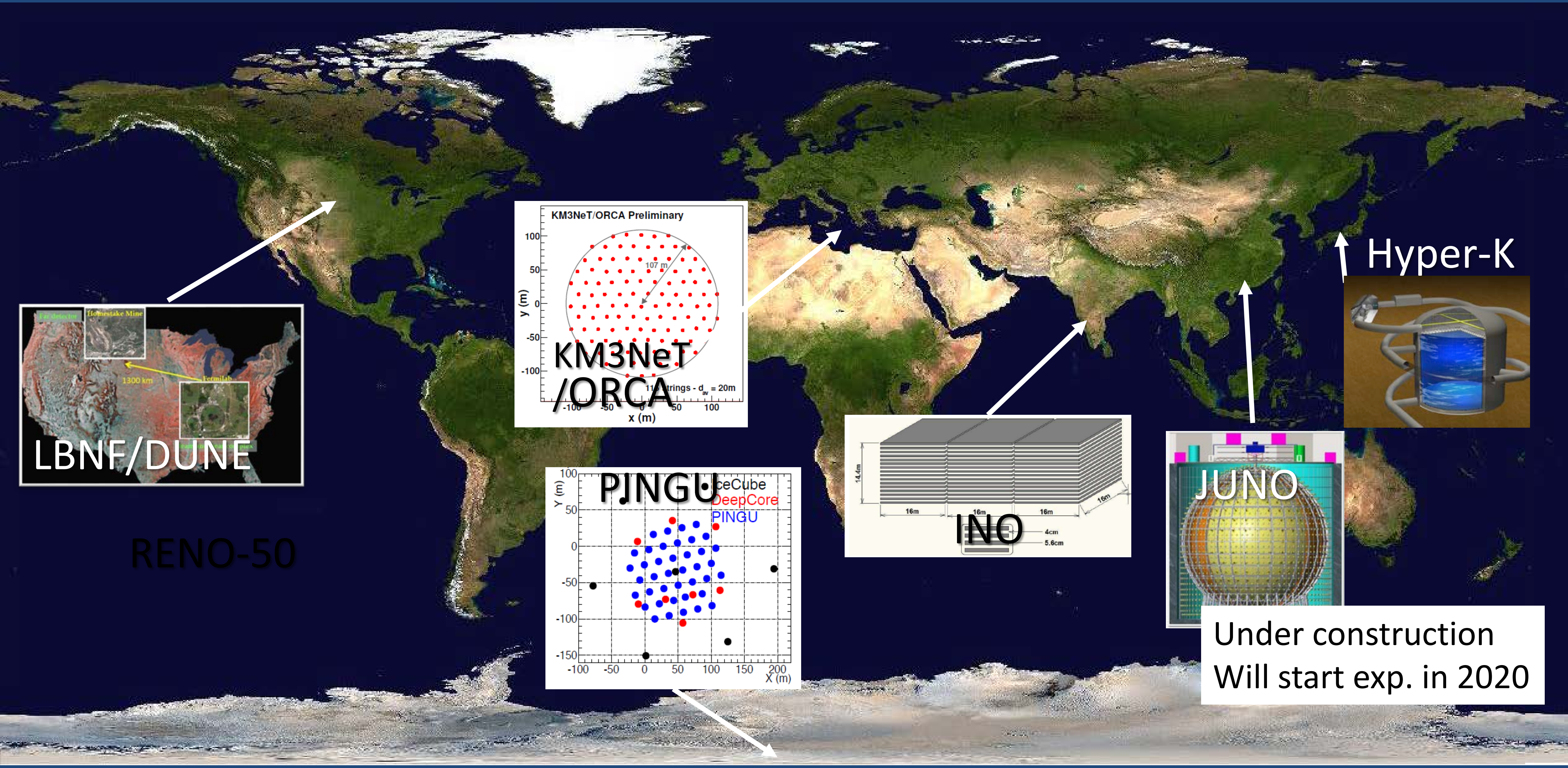


NOvA (TAUP2017)



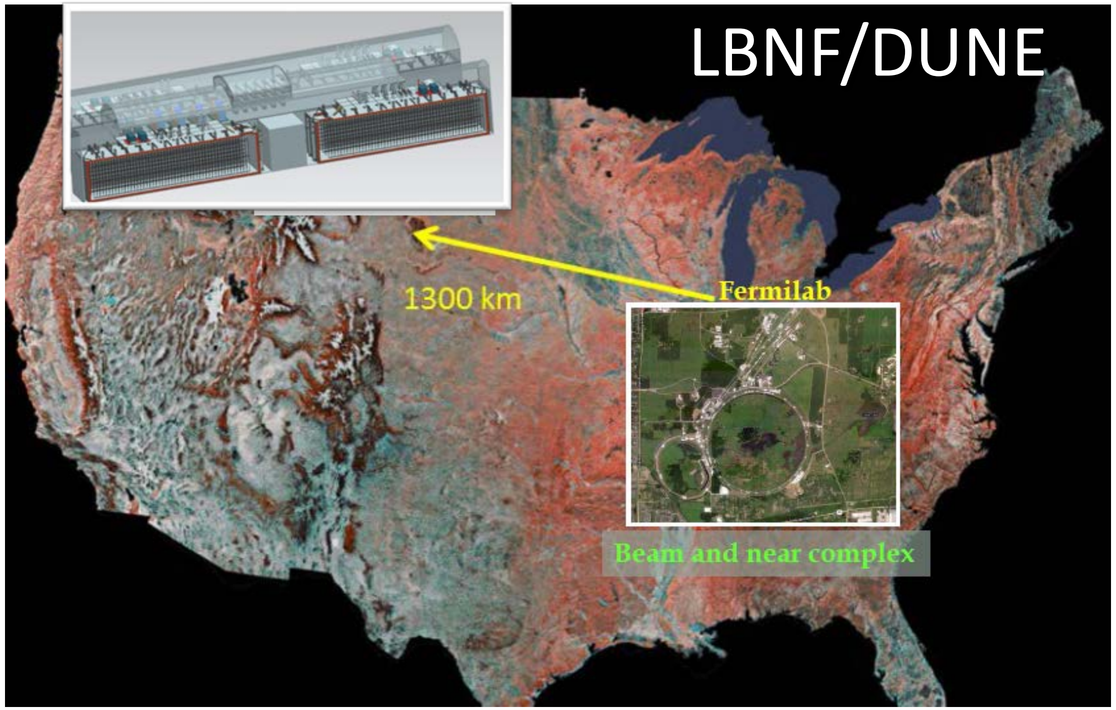
Already some interesting indications!

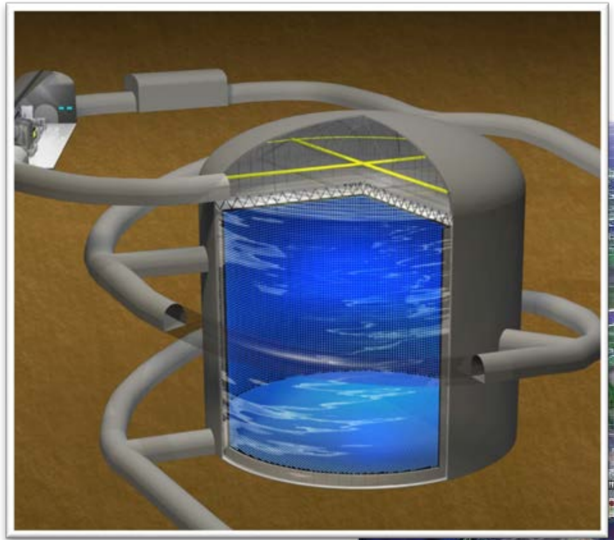
Future experiments that will tell us the neutrino masses hierarchy



CP violation measurements

- ✓ We would like to observe if CP is violated in neutrino sector.
- ✓ These are difficult experiments. We need the next generation long base line experiments with much higher performance neutrino detectors.





Hyper-Kamiokande

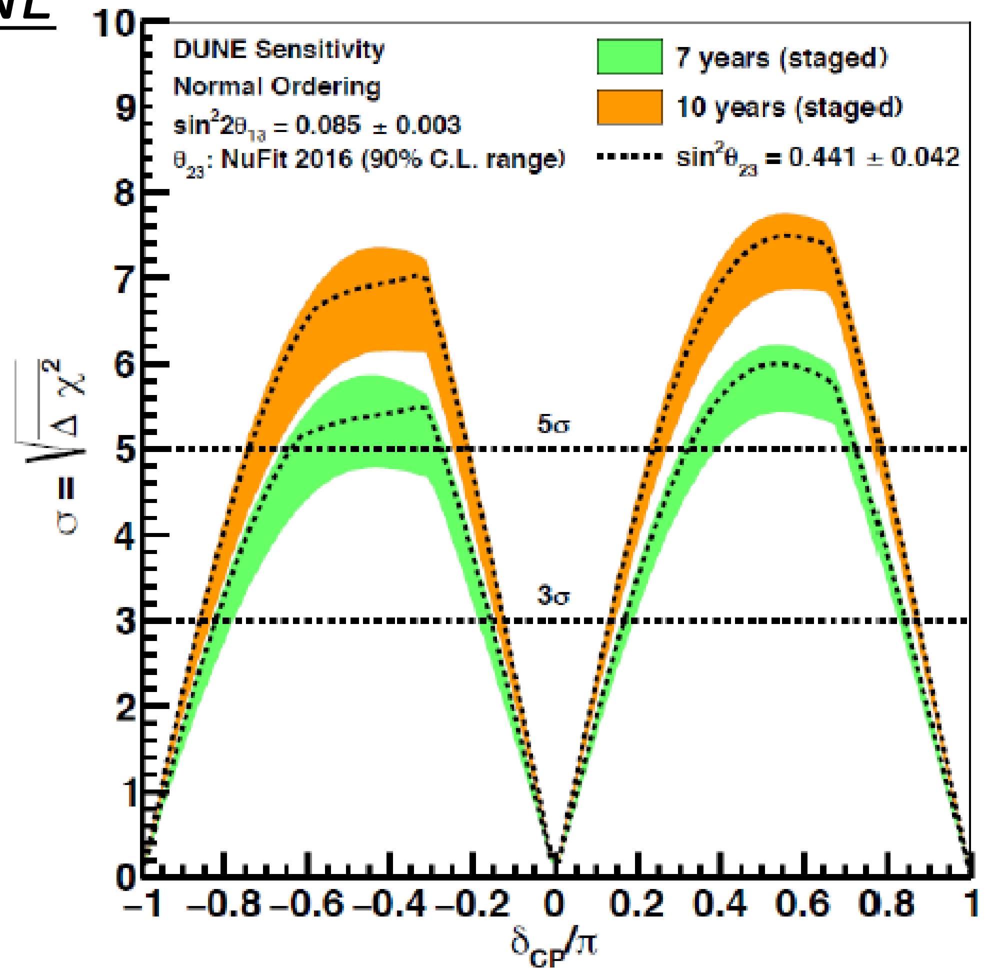
J-PARC

Beam power	**1.2MW (upgradable to 2.4MW)**	**1.3MW**
Baseline length	**1300 km**	**295 km**
detector	**40,000 ton (fid. Vol.) Liq. Ar**	**190,000 ton (fid. Vol.) water Ch.**

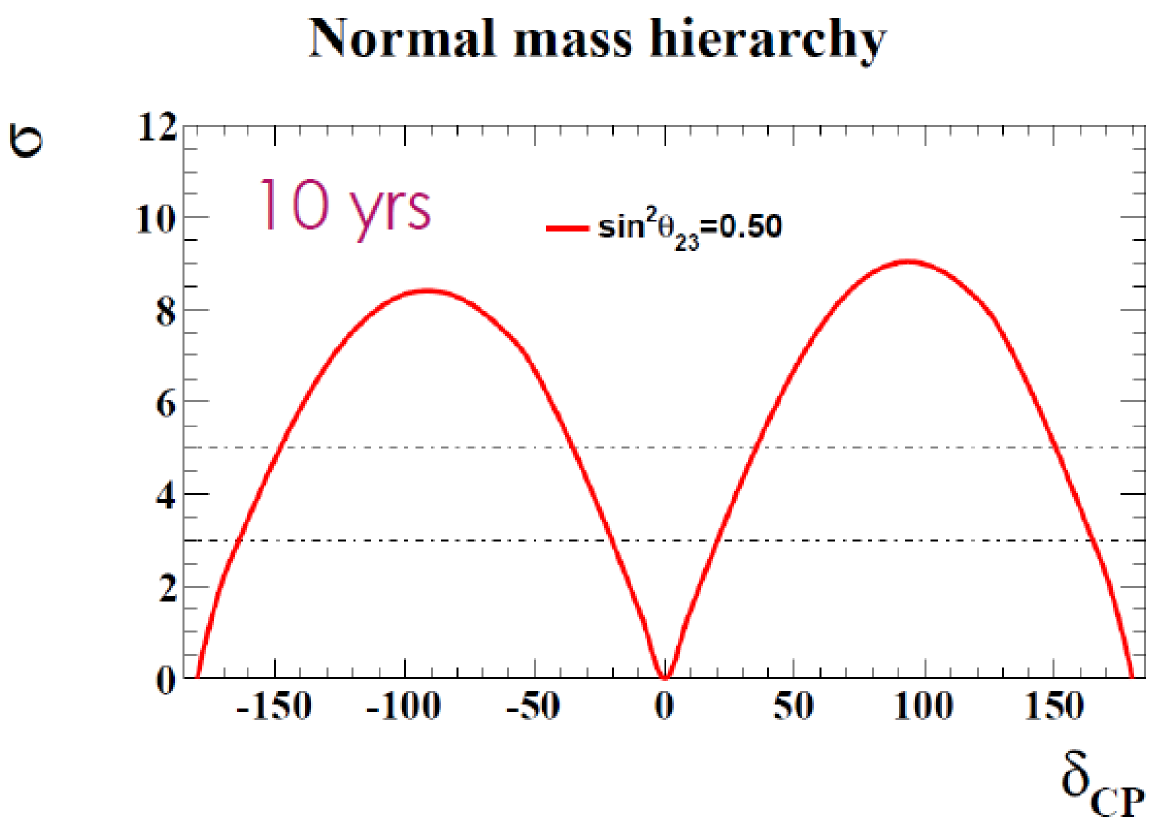
CP violation measurements: sensitivity

L. W. Koerner, TAUP 2017

DUNE



Hyper-K



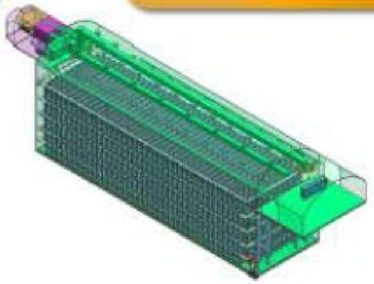
Both experiments have similar, good sensitivity for CP violation!

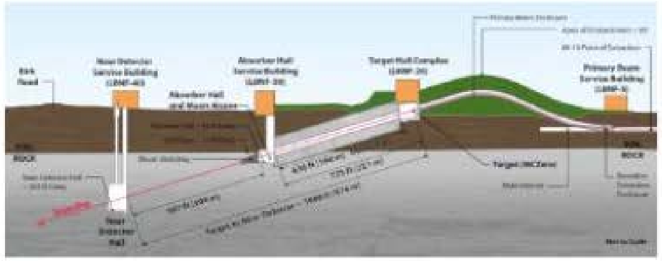
CP violation measurements: timeline

DUNE/LBNF

L. W. Koerner, TAUP 2017

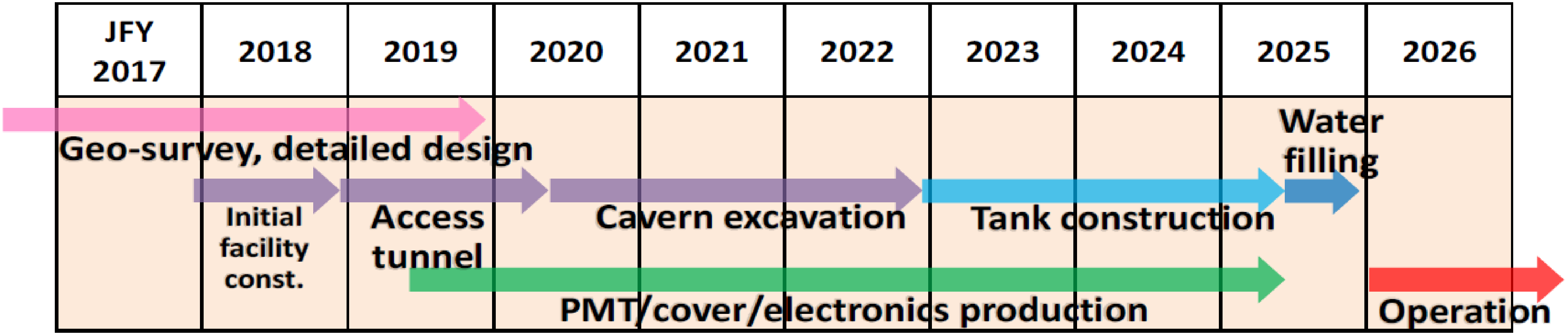
2017: Far Site Construction Begins → 2018: protoDUNEs at CERN → 2021: Far Detector Installation Begins → 2024: Physics Data (20 kt) → 2026: Neutrino Beam Available





J-PARC/Hyper-K

H. Tanaka, TAUP 2017

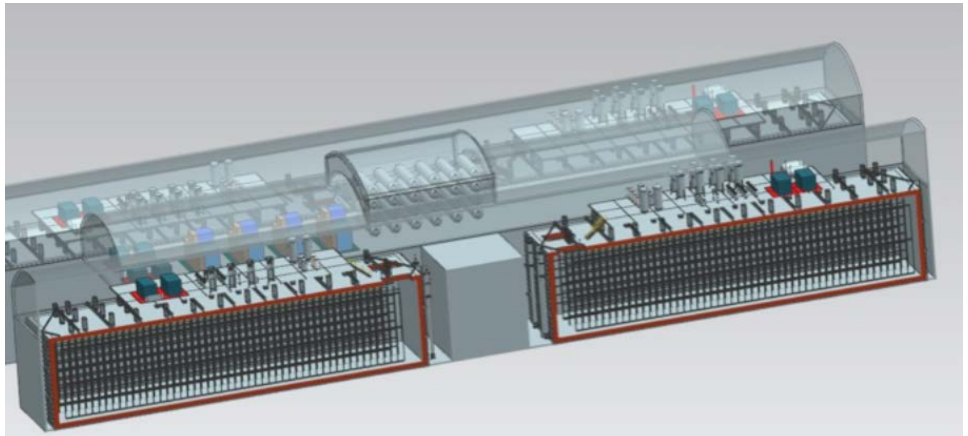


(Start of the project assumed in 2018)

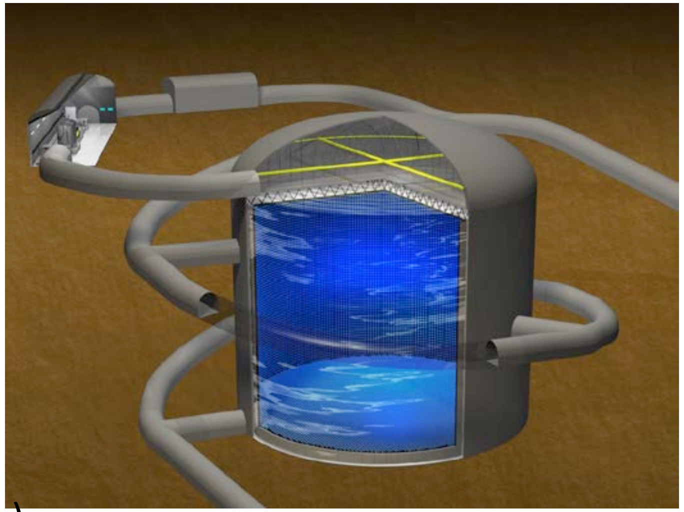
Appendix: proton decay

W.Wang, S. Parakash PoS (ICHEP2016) 968

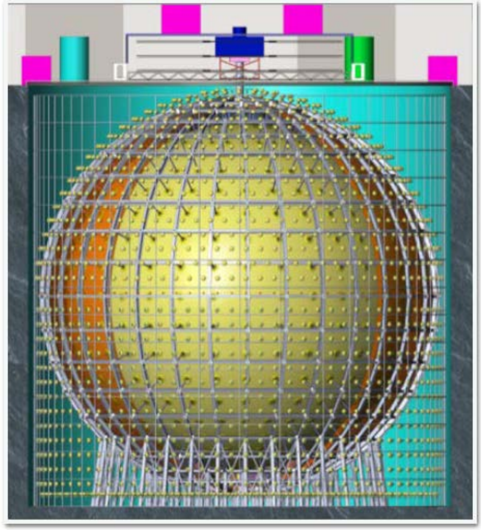
Liq. Ar (DUNE)



Water Ch. (Hyper-K)



Liq. Sci (JUNO)



Numbers for DUNE has been generated based on numbers in the literature (efficiency: 45/97%, bkg: 1/<1 event/Mton year).

	DUNE (90%CL)	Hyper-K (90%CL)	JUNO (90%CL)
P → e π^0 (after 10 years)	~ 2.2 X 10^{34}	~ 7 X 10^{34}	
(after 20 years)	~ 4 X 10^{34}	~ 1.3 X 10^{35}	
P → ν K^+ (after 10 years)	~ 3.5 X 10^{34}	~ 3 X 10^{34}	~ 1.9 X 10^{34}
(after 20 years)	~ 7 X 10^{34}	~ 5 X 10^{34}	

Summary

- There were "problems" in the neutrino data in the 1970's and 1980's. These problems were found to be due to neutrino oscillations by the Super-Kamiokande and SNO experiments.
- Since then, various experiments have studied neutrino oscillations. We understand the basic structure of neutrino masses and mixings.
- The small neutrino masses are a window to study physics beyond the Standard Model of particle physics. Neutrinos might also be the key to understand the baryon asymmetry of the Universe.

We should learn more from neutrinos!