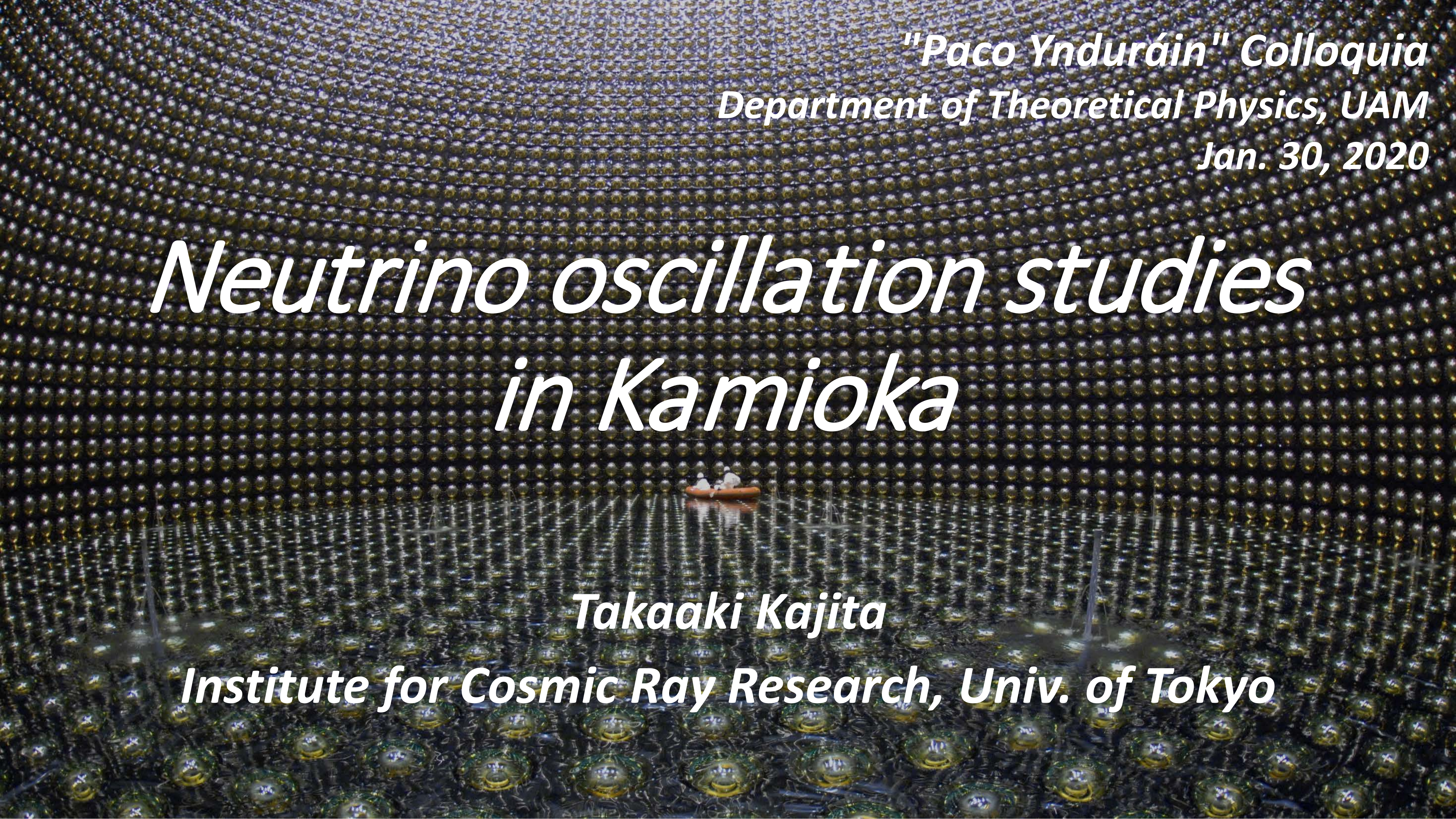


"Paco Ynduráin" Colloquia

Department of Theoretical Physics, UAM

Jan. 30, 2020

Neutrino oscillation studies in Kamioka

Takaaki Kajita

Institute for Cosmic Ray Research, Univ. of Tokyo

Outline

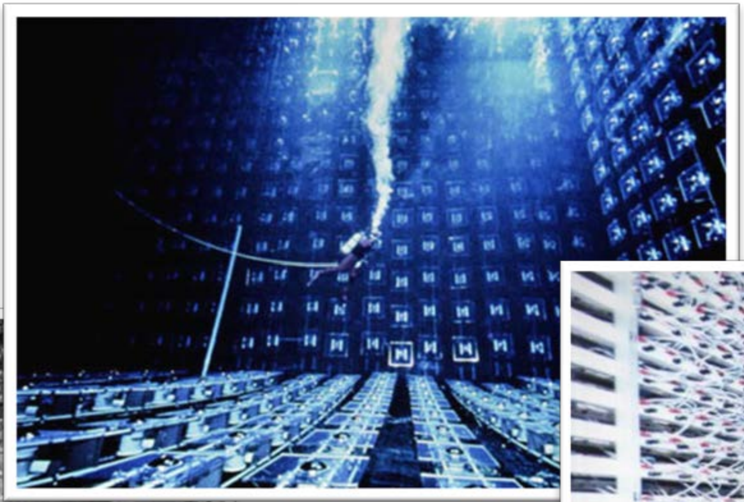
- *Kamiokande*
- *Super-Kamiokande*
- *Atmospheric neutrino oscillations*
- *Various oscillation studies*
- *Solar neutrino oscillations*
- *Future neutrino experiments in Kamioka*
  - *Appendix: Proton decay*
- *Summary*

Kamiokande

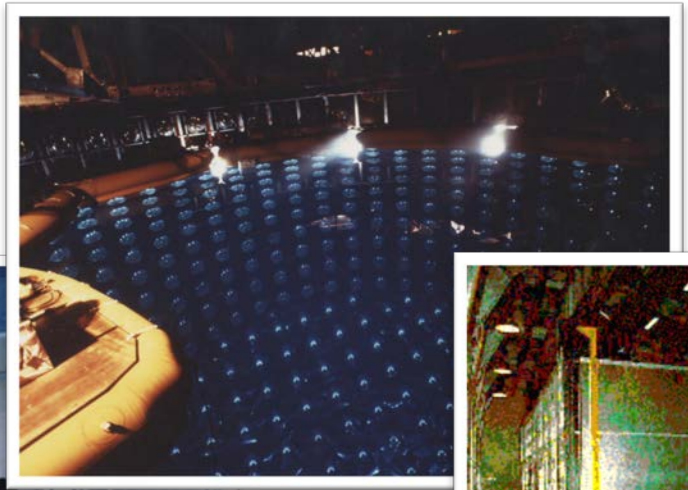
Proton decay experiments (1980's)

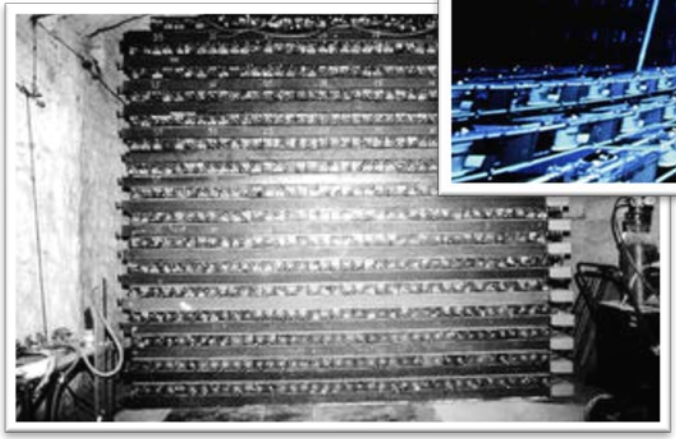
- ✓ In the 1970's, Grand Unified Theories, predicted that protons should decay with the lifetime of about 10^{30} years.
- ✓ Several proton decay experiments began in the early 1980's.
- ✓ One of then was the Kamioaknde experiment.

IMB (3300ton)

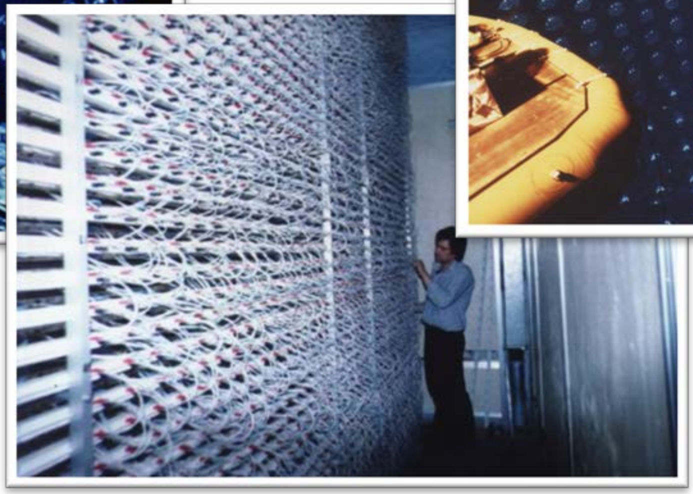


Kamiokande (1000ton)

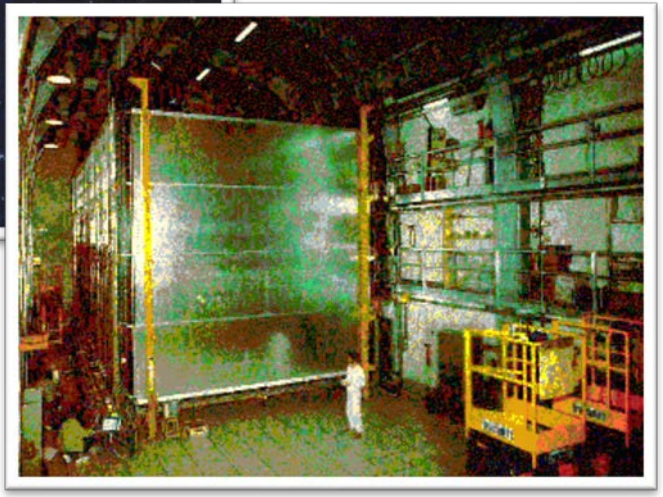




KGF (100ton)

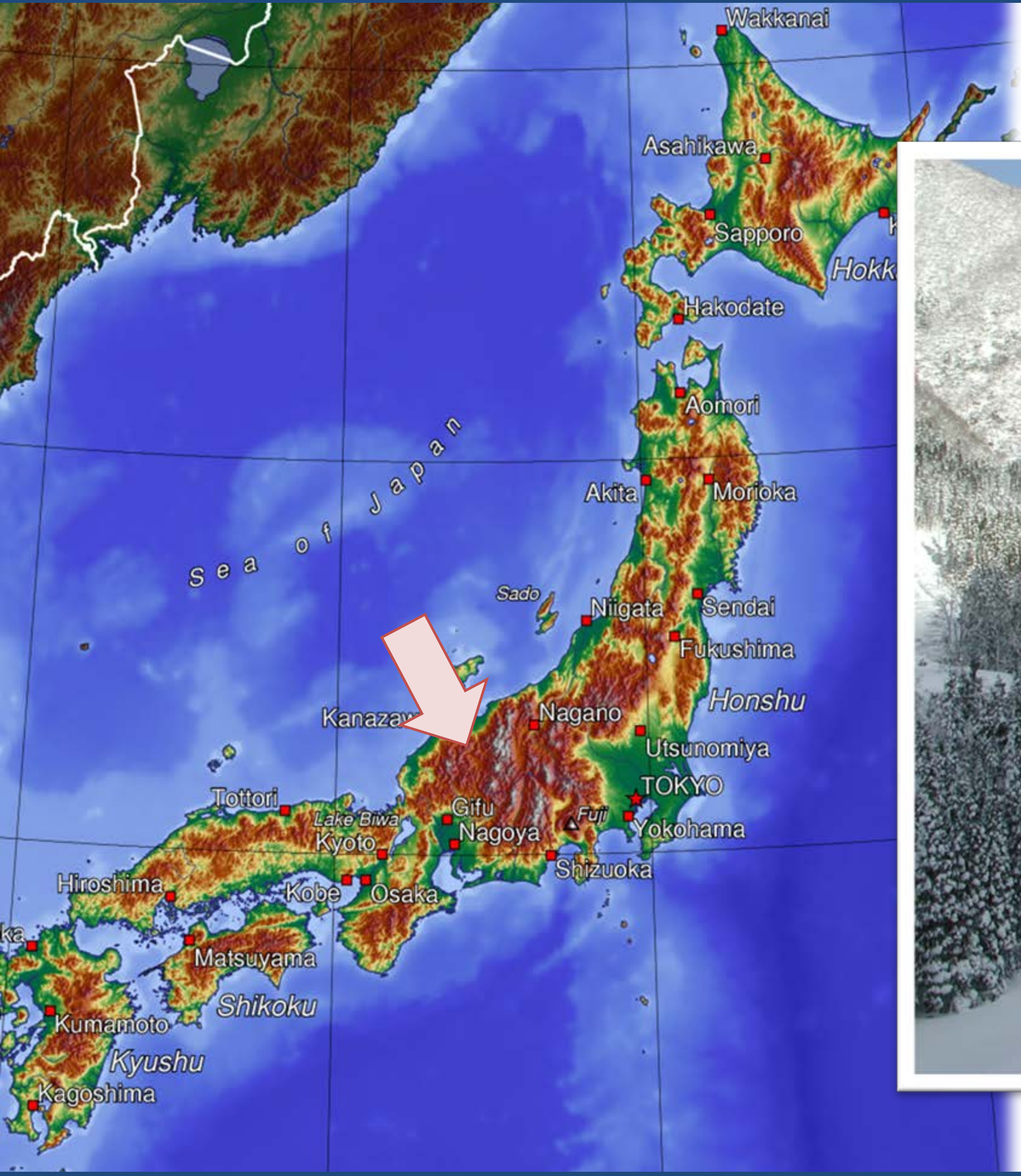


NUSEX (130ton)



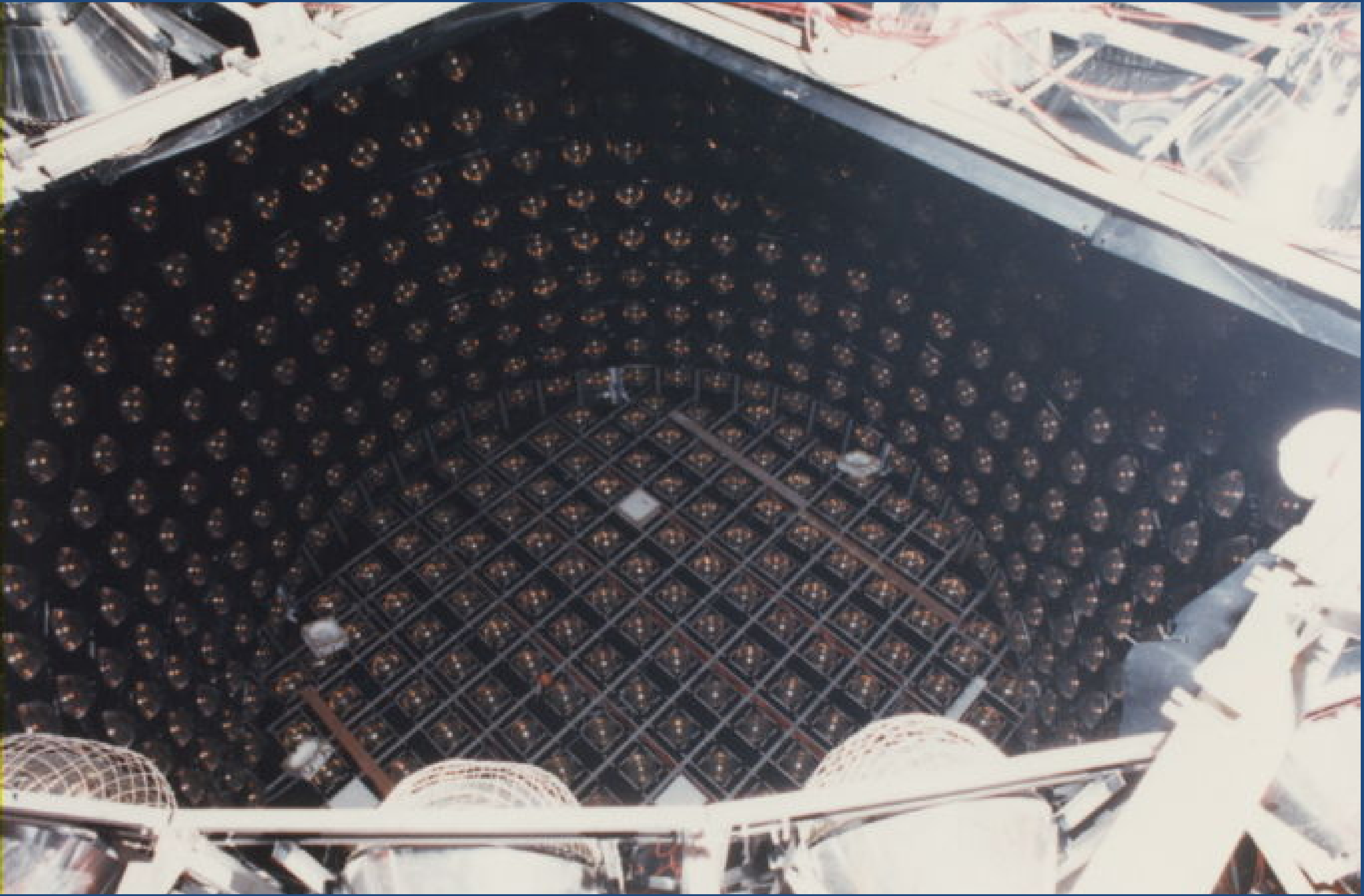
Frejus (700ton)

Where is Kamioka?



(A photo taken some years ago. This year almost no snow.)

The Kamiokande experiment (1983 – 1996)

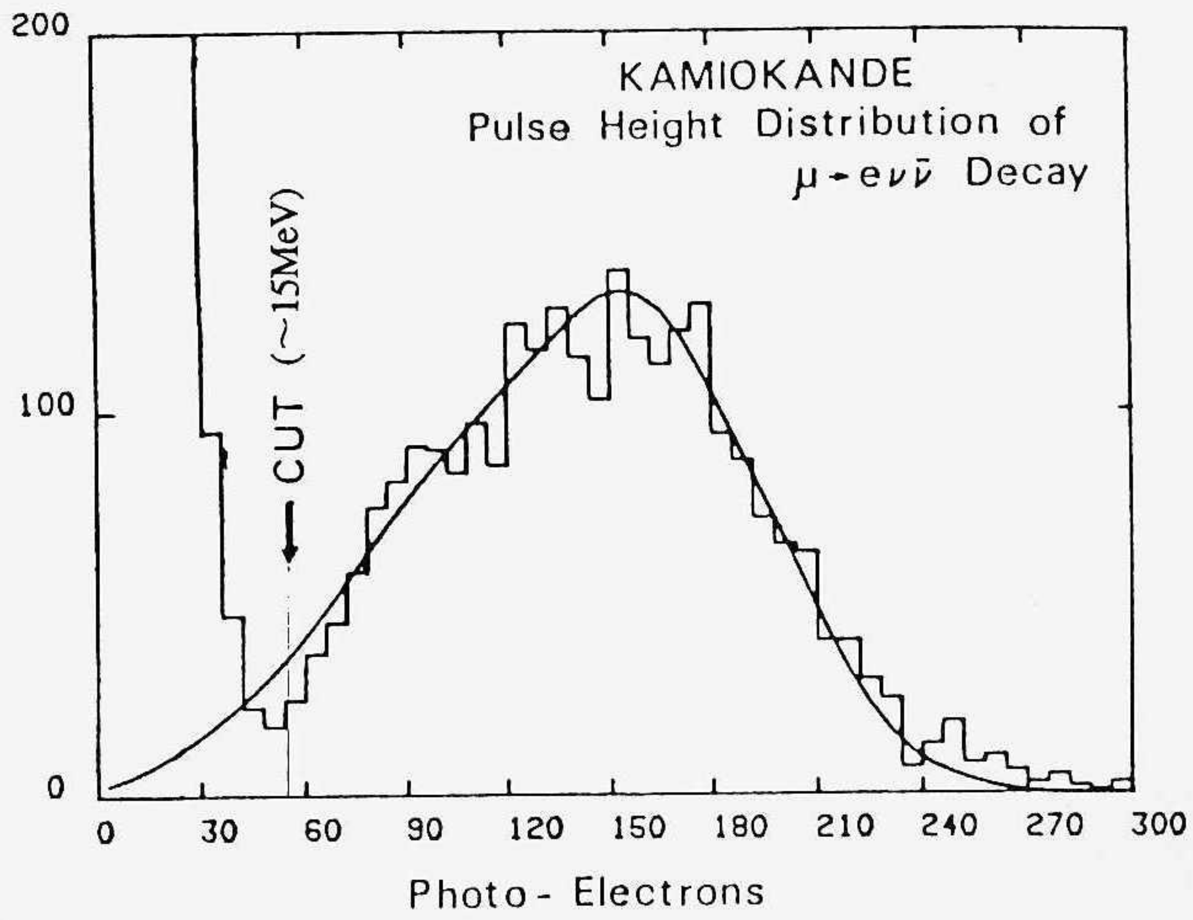


The original motivation was the search for proton decays.

Didn’t observe proton decays, but…

No proton decay signal….

Pulse height distribution for electrons from the decays of cosmic ray muons (early autumn 1983)



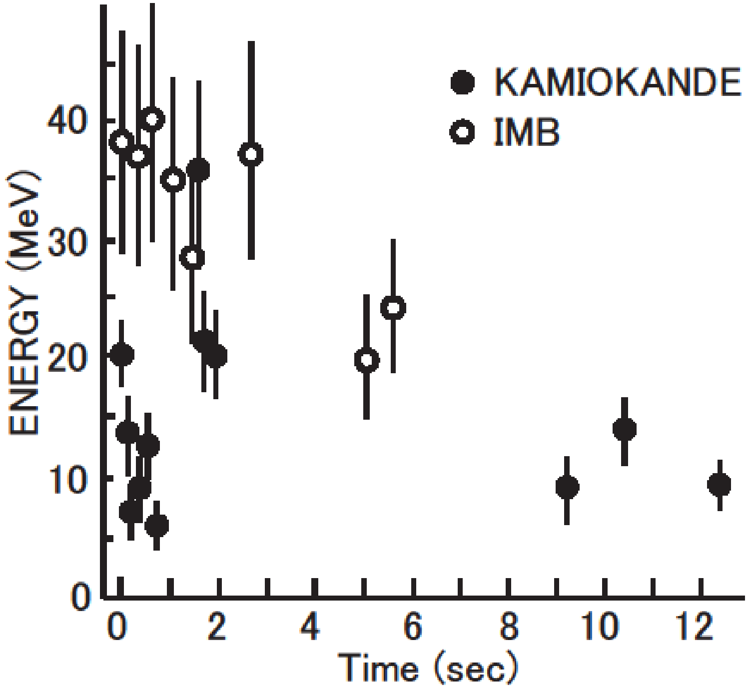
Neutrinos with the energies of about 10 MeV could be observed.

- ✓ Improvement of the Kamiokande detector to observe solar neutrinos.

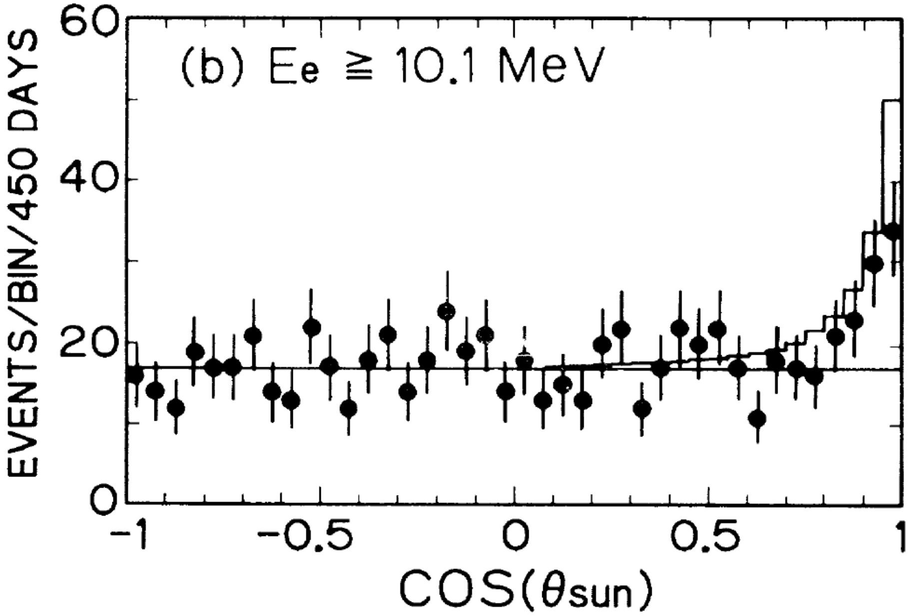
(by M. Koshiba)

Results from Kamiokande

Detection of Supernova neutrinos (1987)

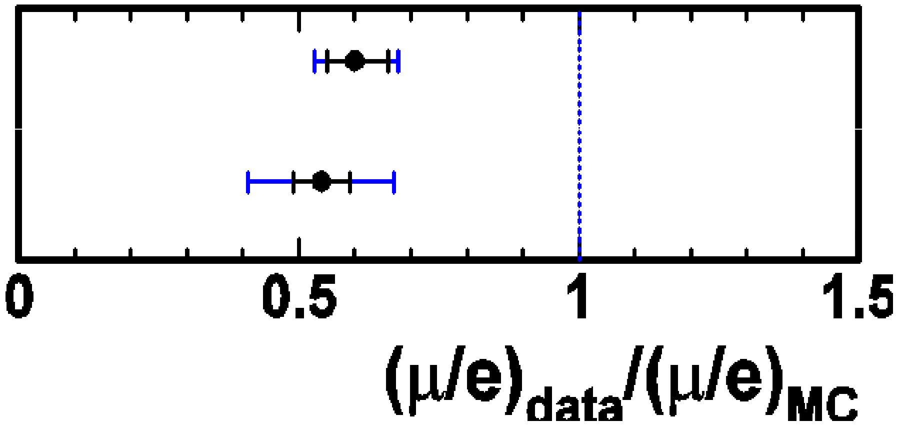


Observation of solar neutrinos (1989)



Kamiokande (1988, 92, 94)

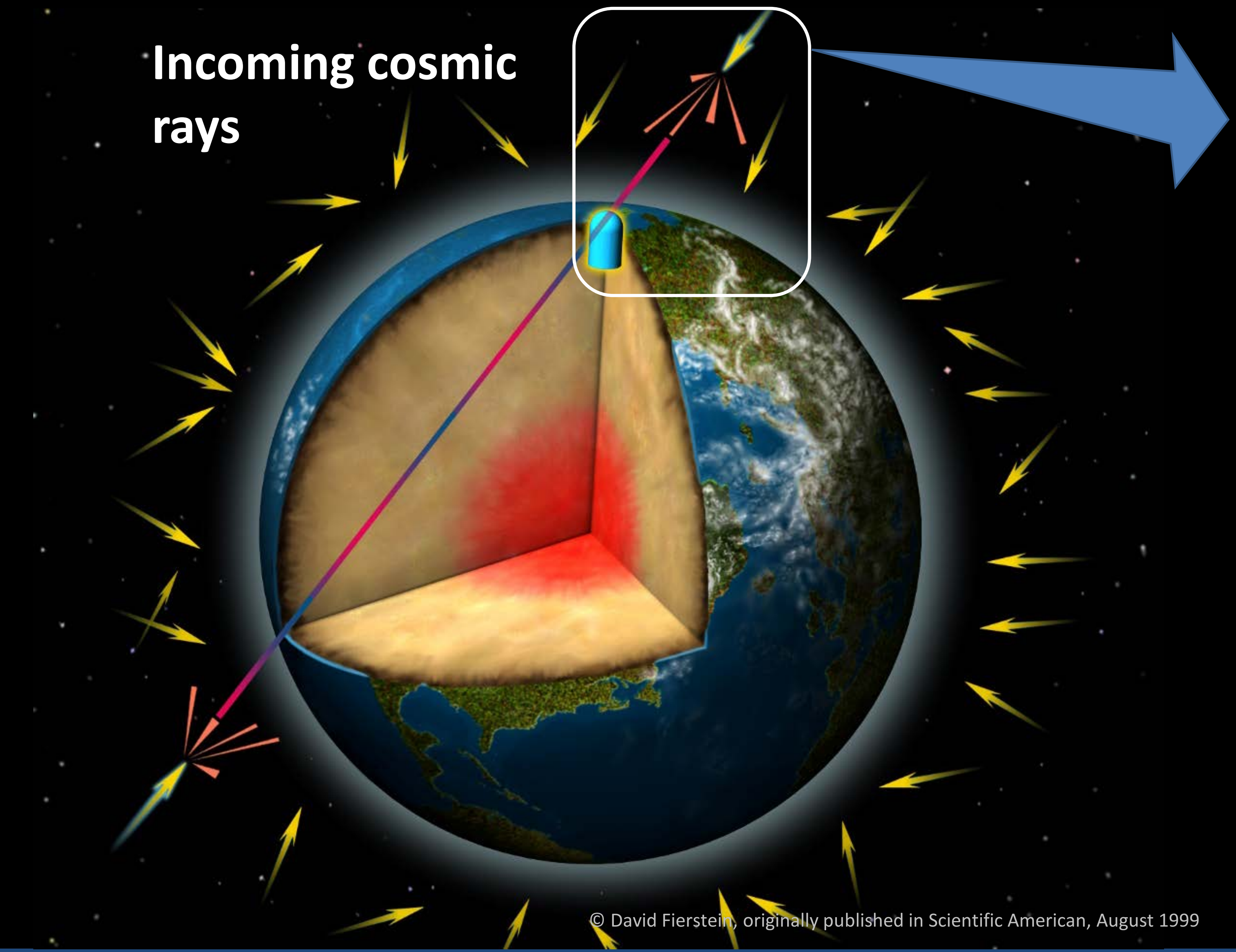
IMB (1991, 92)

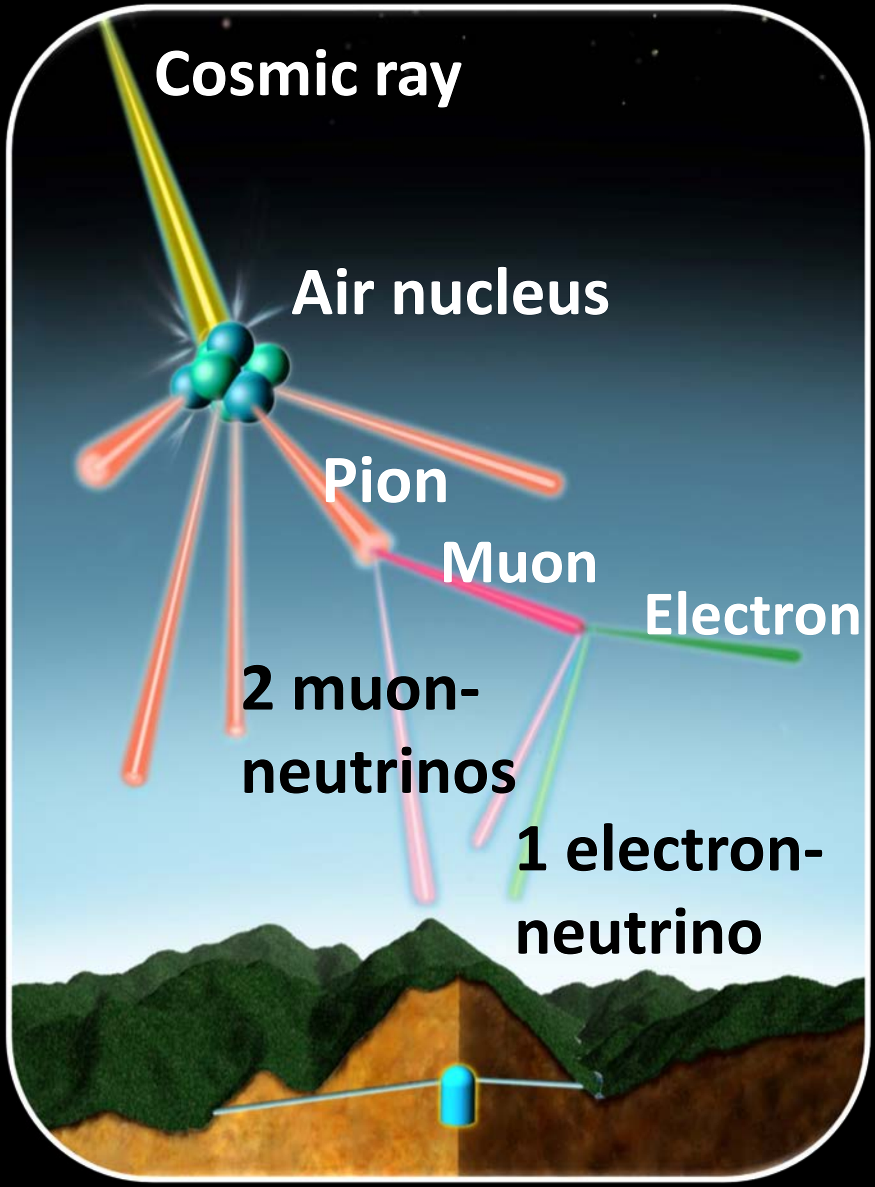


Observation of atmospheric neutrino deficit (1988)

Water Ch. is very important for neutrino phys. and astrophys.

Atmospheric neutrinos

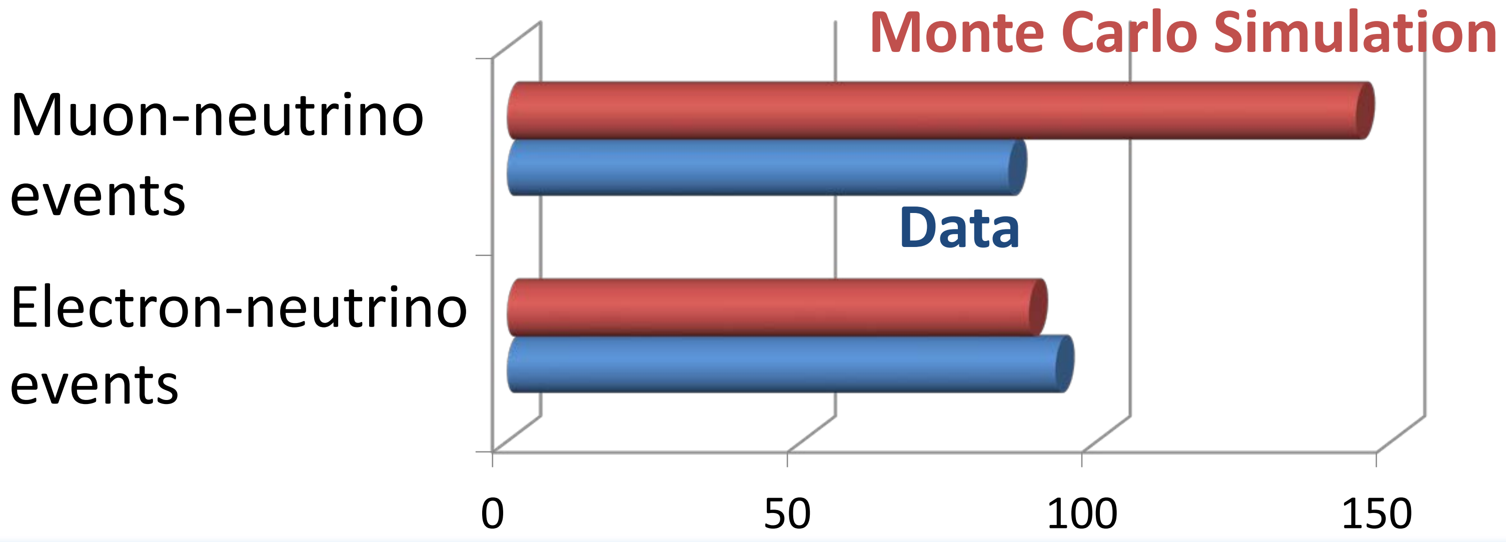




Atmospheric ν_μ deficit (1988)

- ✓ 1986, we wanted to improve the proton decay analysis. Therefore, several new software were developed. One of which was the particle identification (PID).
- ✓ As a test of new PID, the particle type for 1-ring atmospheric neutrino events was studied and realized the deficit of muon-neutrinos.

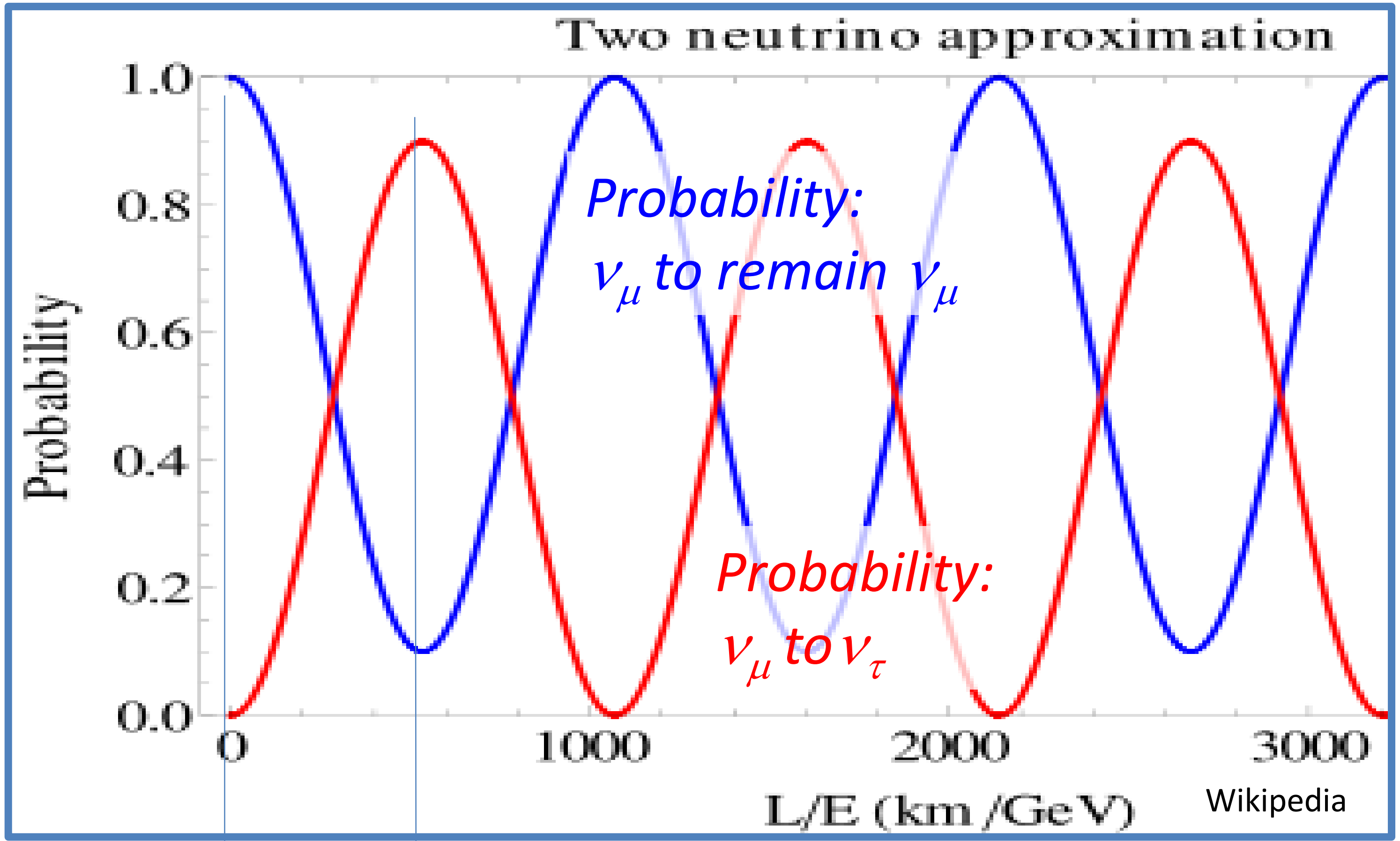
K. Hirata et al, Phys.Lett.B 205 (1988) 416.



Many people (both experimentalists and theorists) thought that there must be something wrong in the analysis... (Mixing angle cannot be large.)

Neutrino oscillations (in the vacuum)

If neutrinos have masses, neutrinos change their type (flavor) from one type (flavor) to the other. For example, a muon-neutrino may oscillate to a tau-neutrino.



Theoretically predicted by;

S. Sakata, Z. Maki, M. Nakagawa

arXiv:0910.1657

B. Pontecorvo

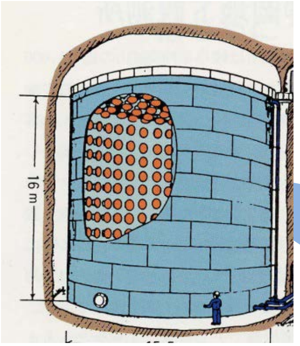
L is the neutrino flight length (km),

E is the neutrino energy (GeV).

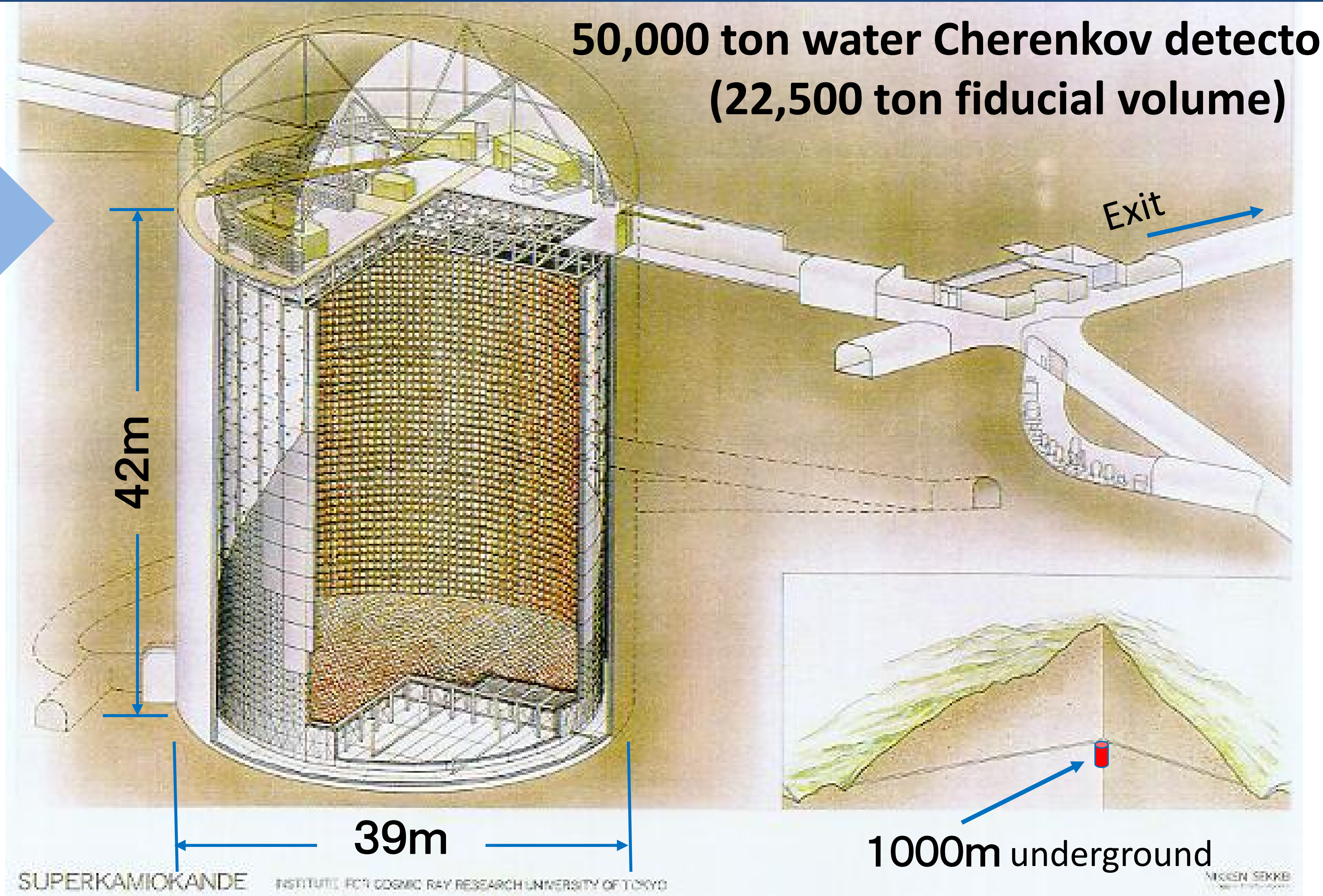
If neutrino mass is smaller, the oscillation length (L/E) gets longer.

Super-Kamiokande

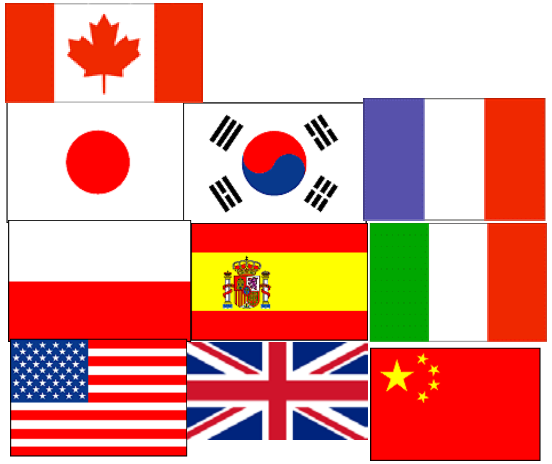
Super-Kamiokande detector



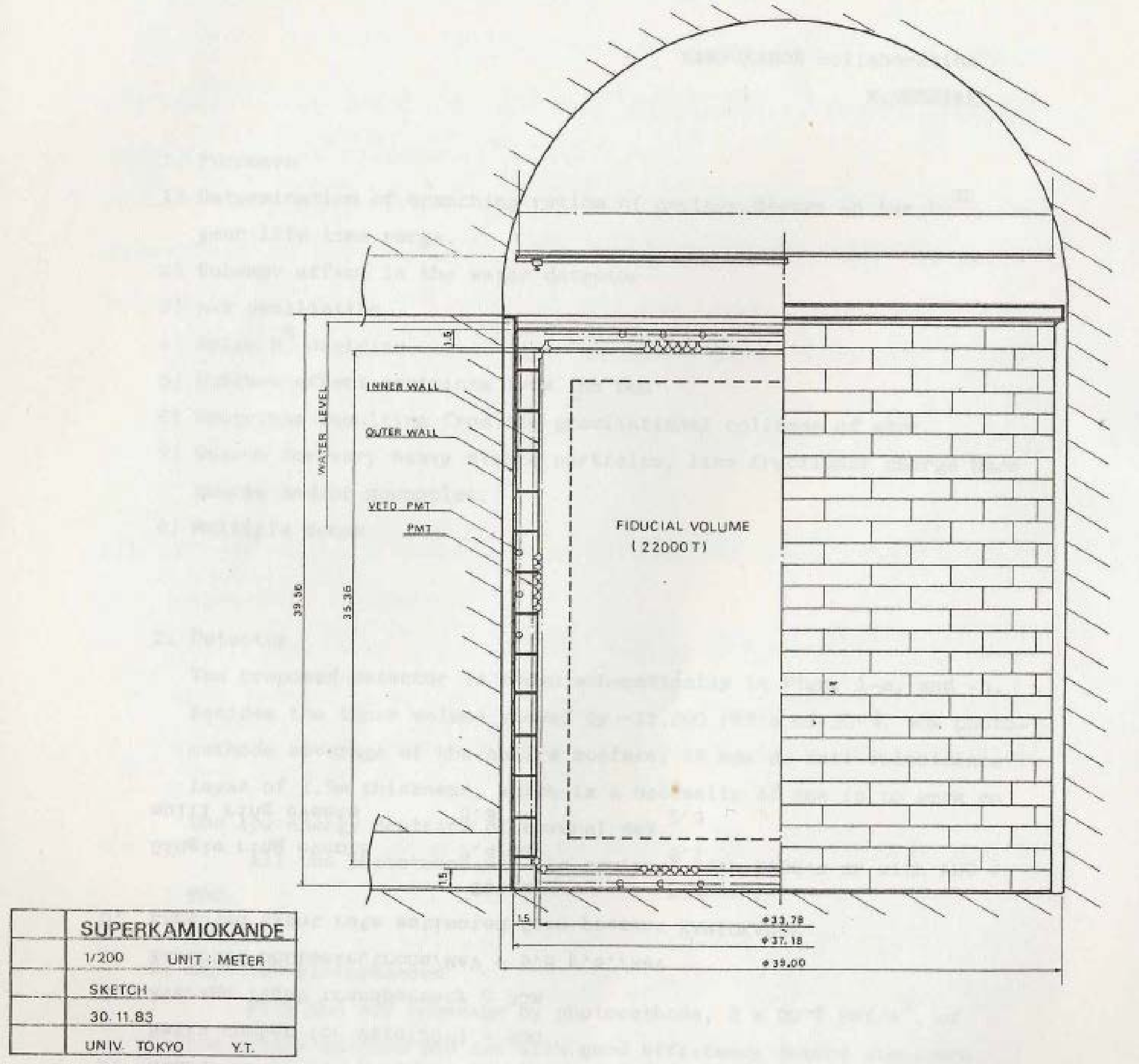
~20 times
larger mass



~180 collaborators



Initial idea of Super-Kamiokande (1983)



In the fall of 1983, Prof. Koshiba recognized that solar neutrinos can be detected in Kamiokande. At the same time, he proposed Super-Kamiokande to study solar neutrinos in detail (and to search for proton decays).

Initial drawing of the Super-Kamiokande detector

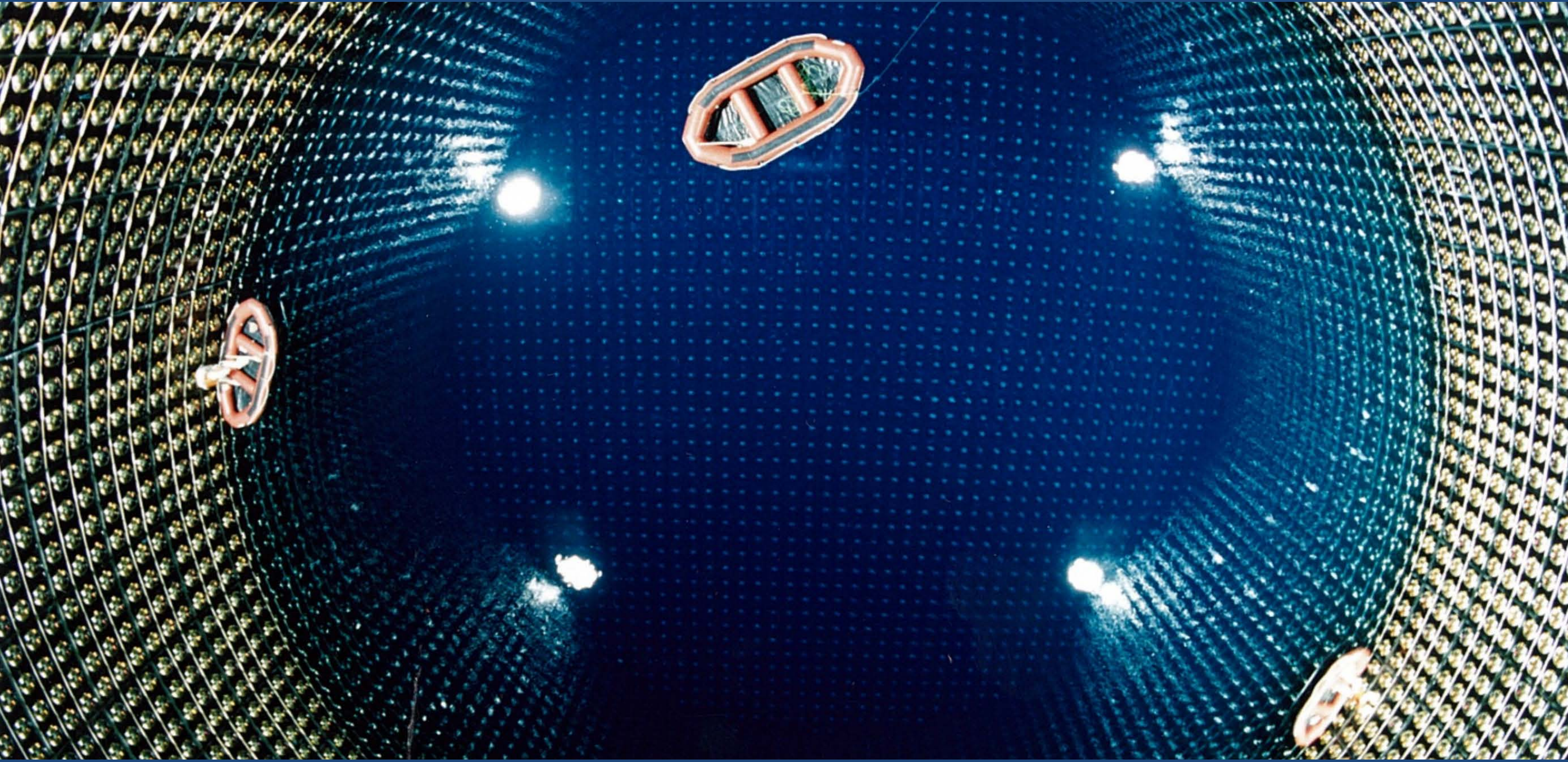
(In “32 kton Water Cherenkov Detector (JACK) A proposal for detailed studies of nucleon decays and for low energy neutrino detection” by M. Koshiba, in Proceedings of workshop on Grand Unified Theories and Cosmology (Dec. 7-10, 1983, KEK, Tsukuba, Japan)

Super-Kamiokande construction (Summer 1995)

Kamiokande

Filling water in Super-Kamiokande

Jan. 1996

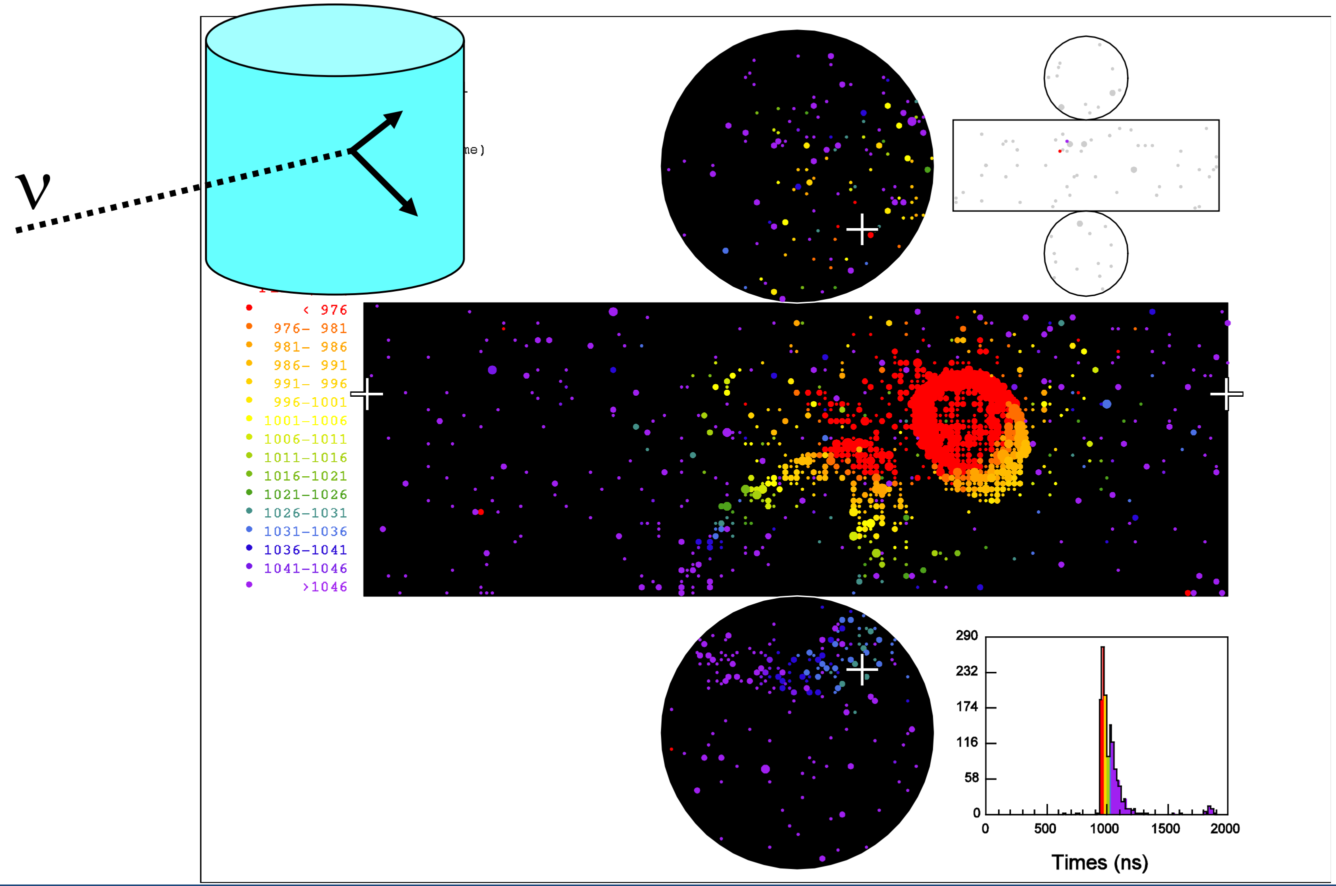


Atmospheric neutrino oscillations

Fully automated analysis

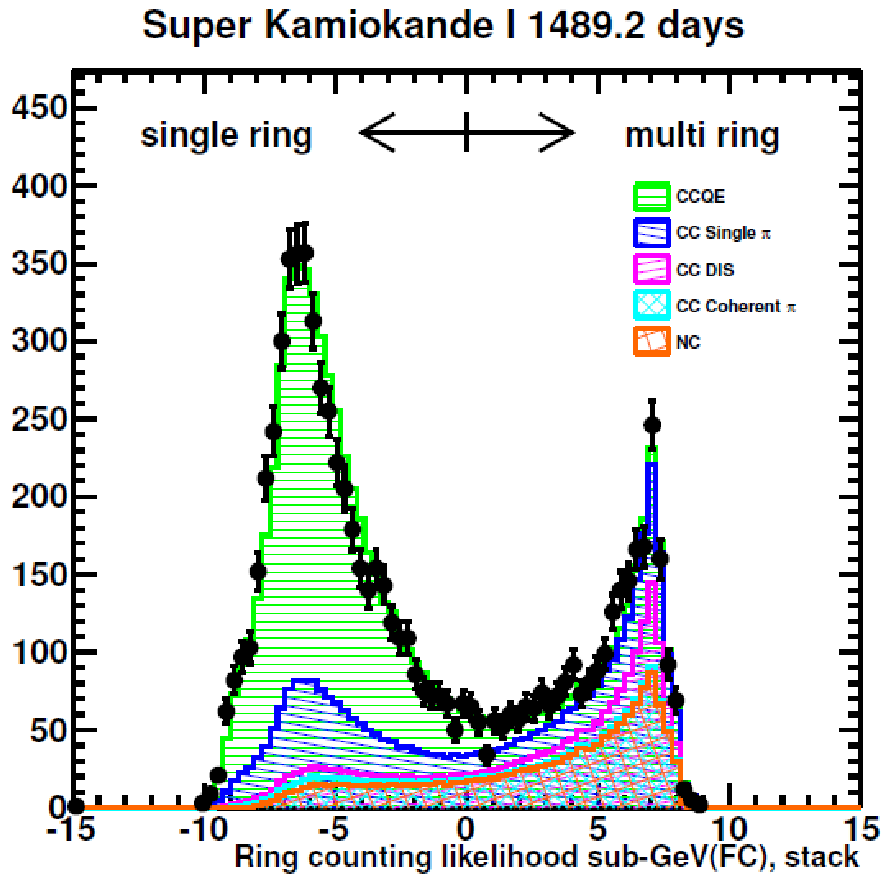
✓ One of the limitation of the Kamiokande's atmospheric neutrino analysis was the necessity of the event scanning for all data and Monte Carlo events, due to no satisfactory ring identification software.

Multi Cherenkov ring event

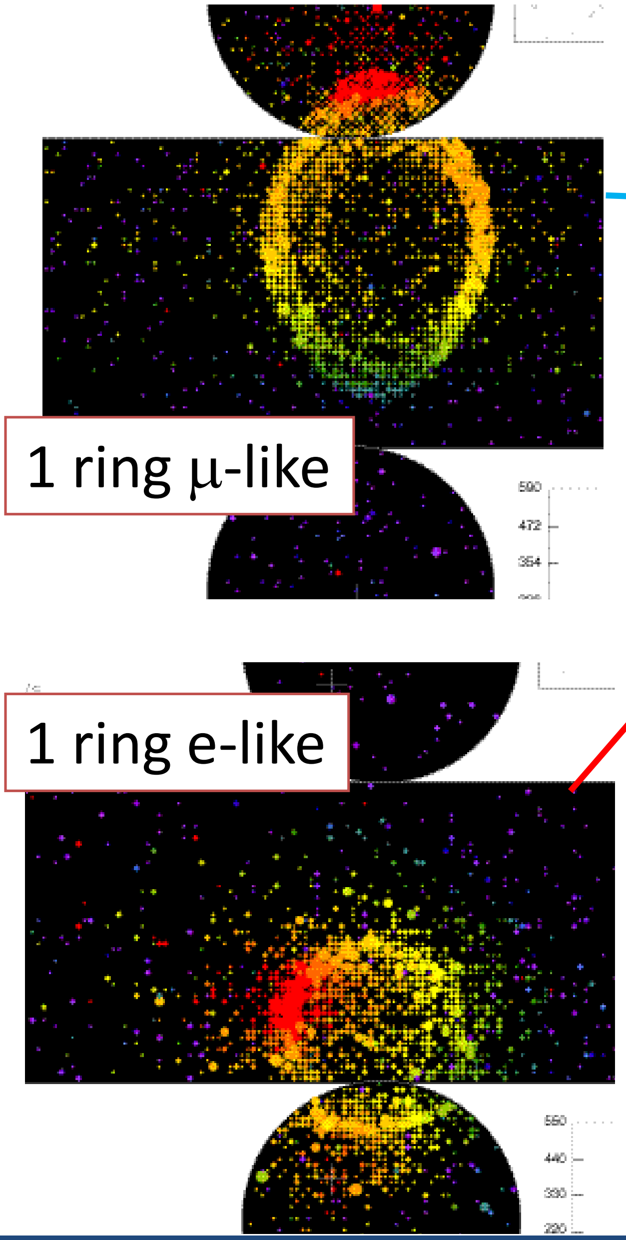


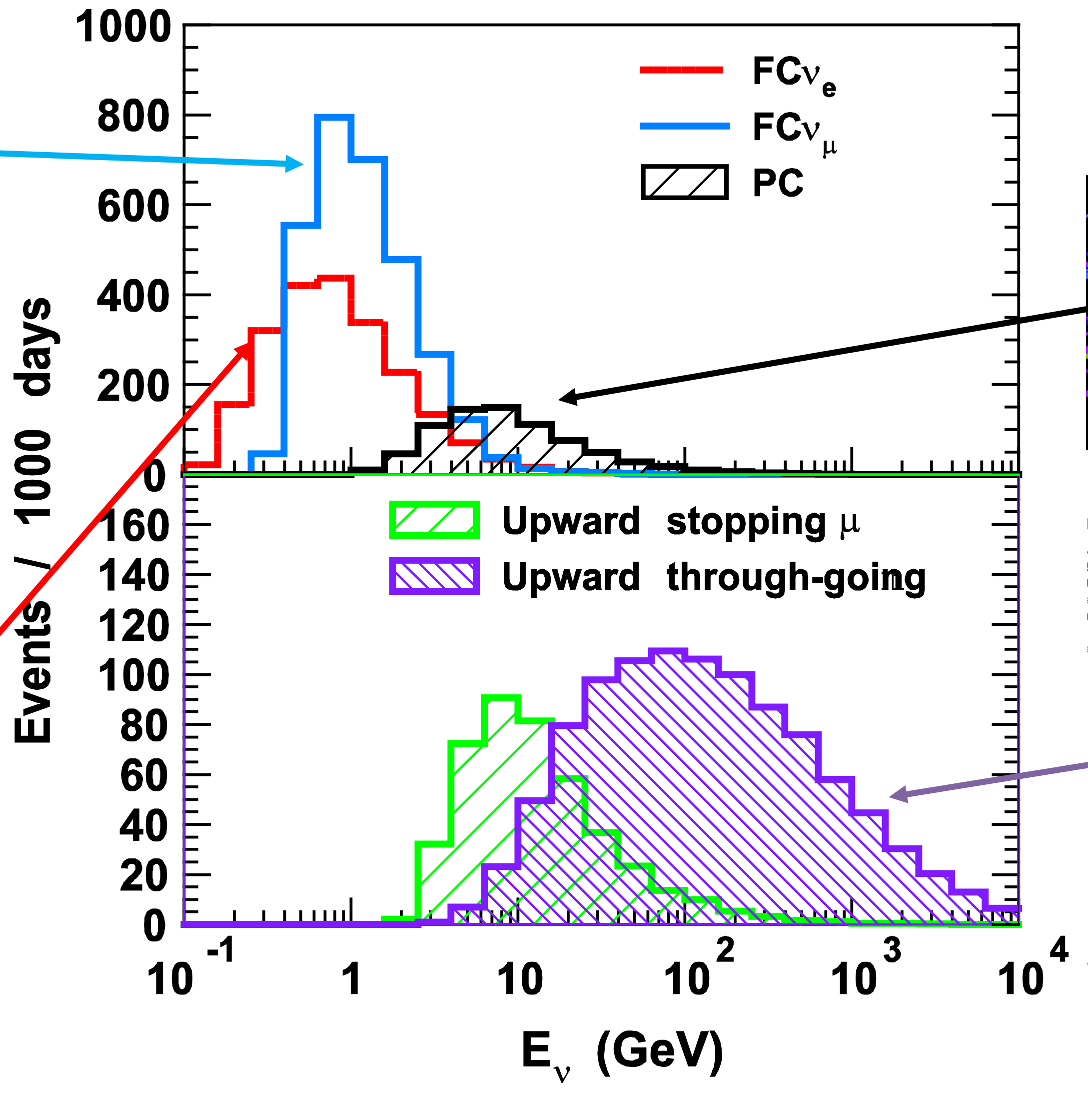
Hough transformation

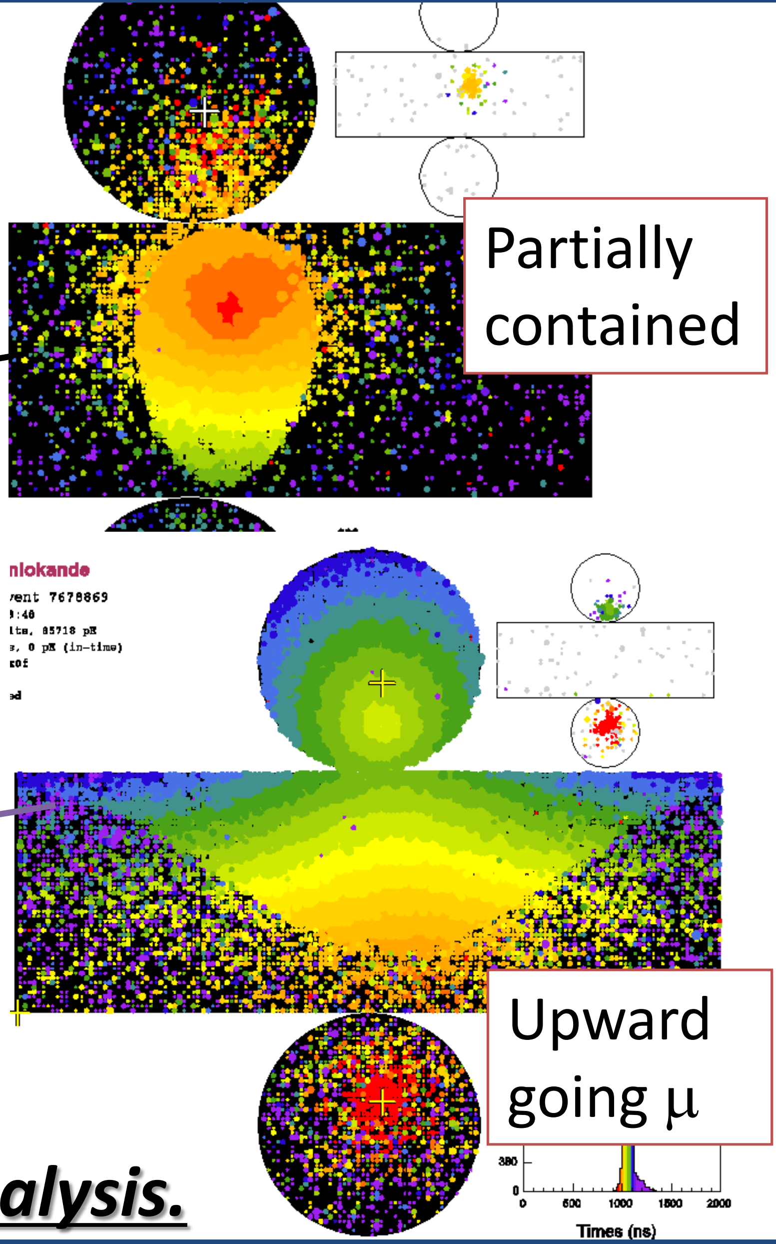
+ maximum likelihood



Event type and neutrino energy

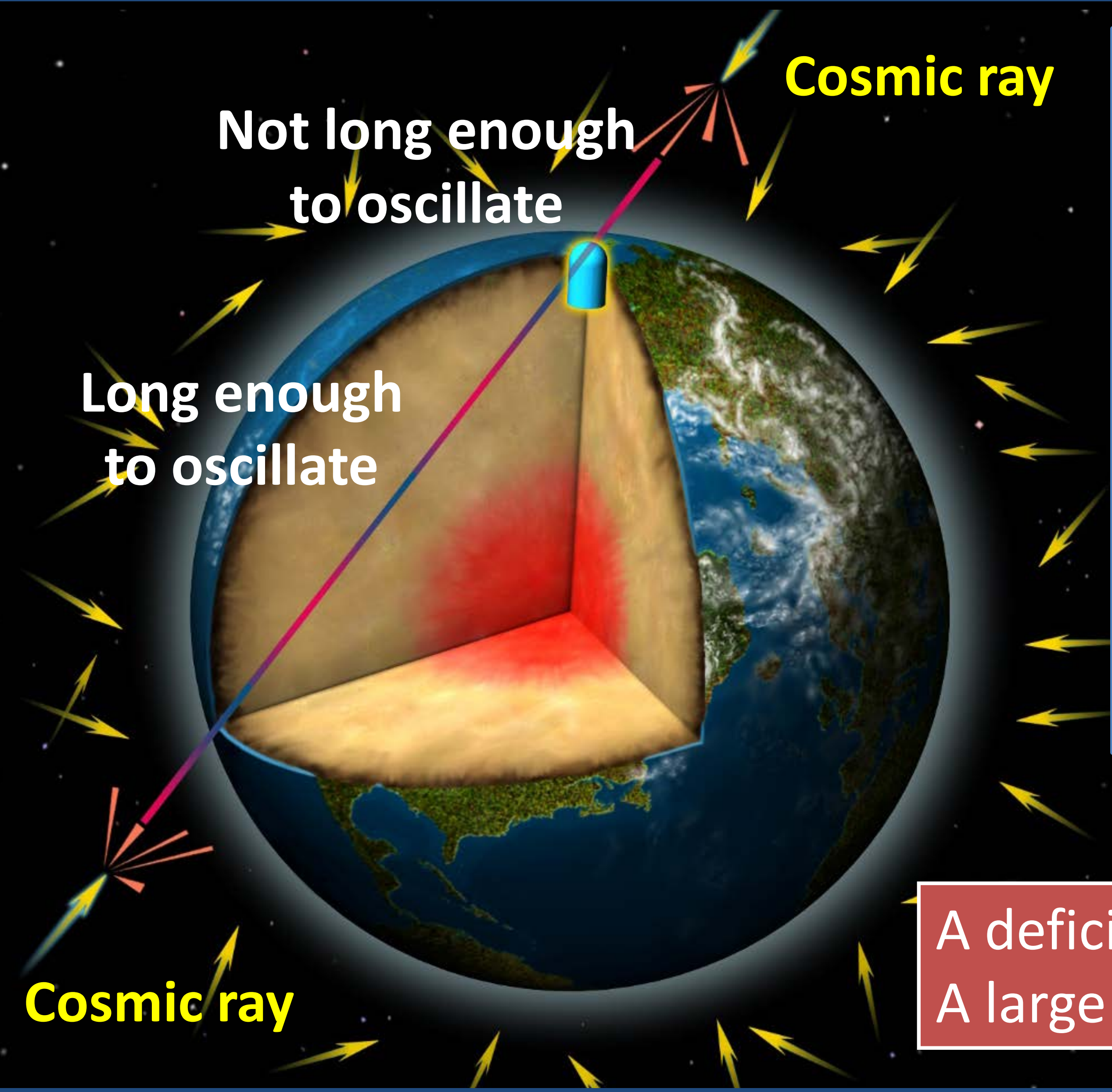


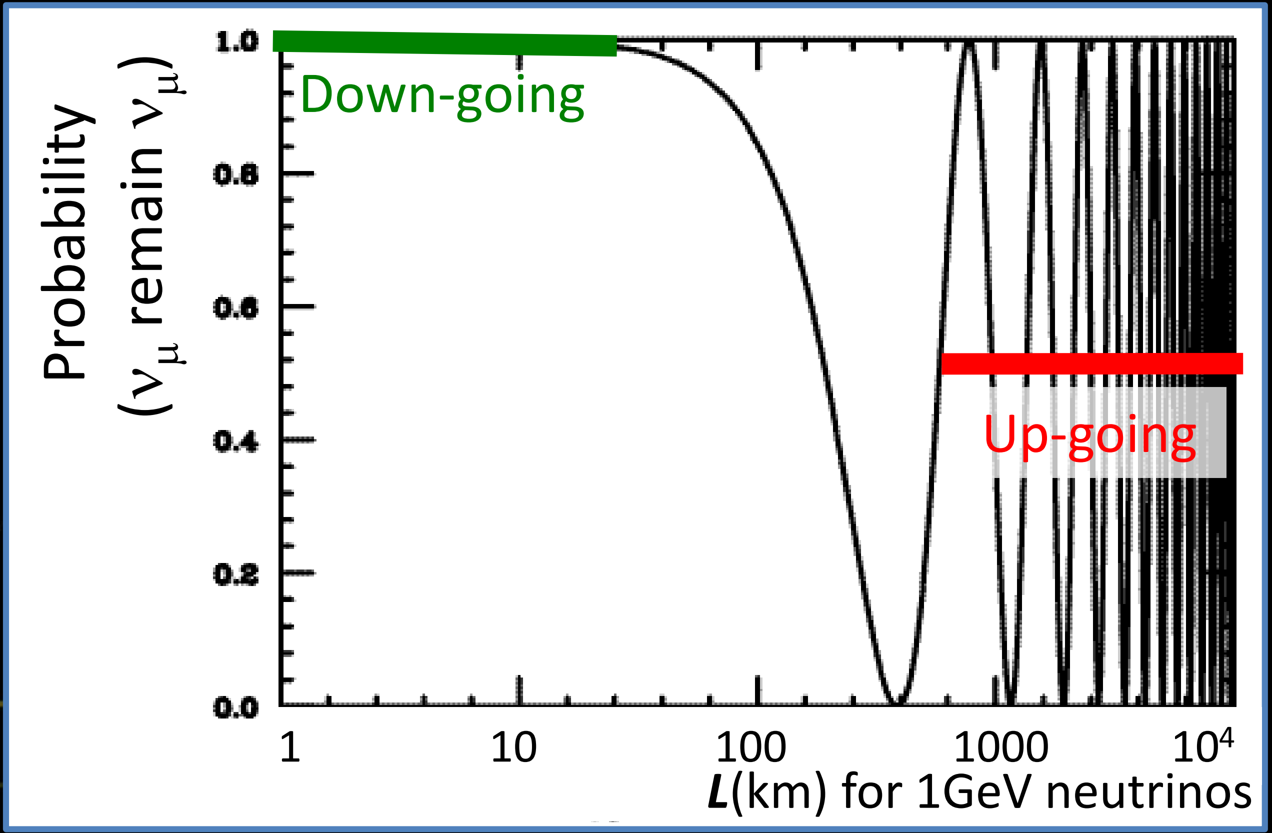




<u>All these events are used in the analysis.</u>

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

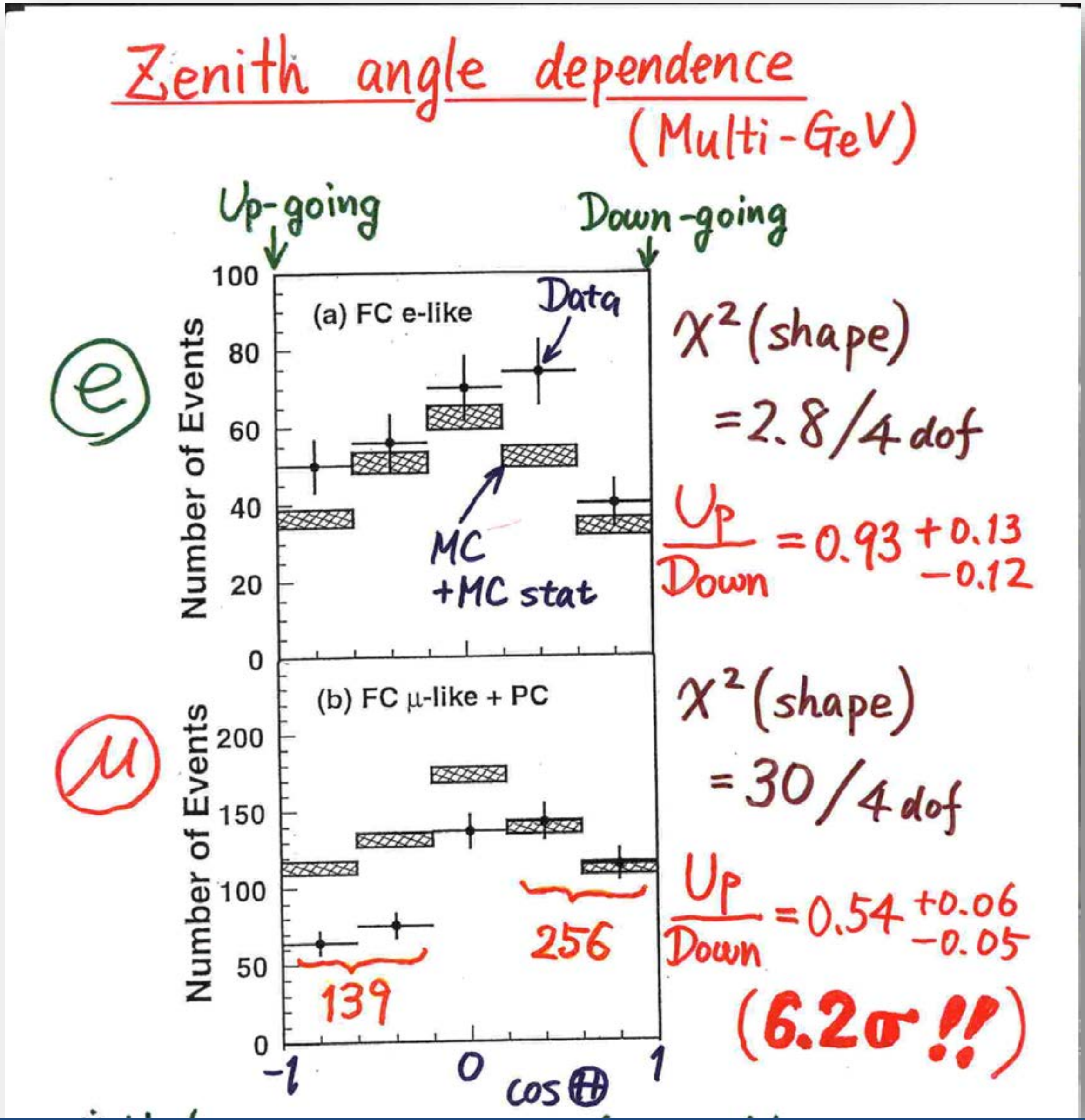


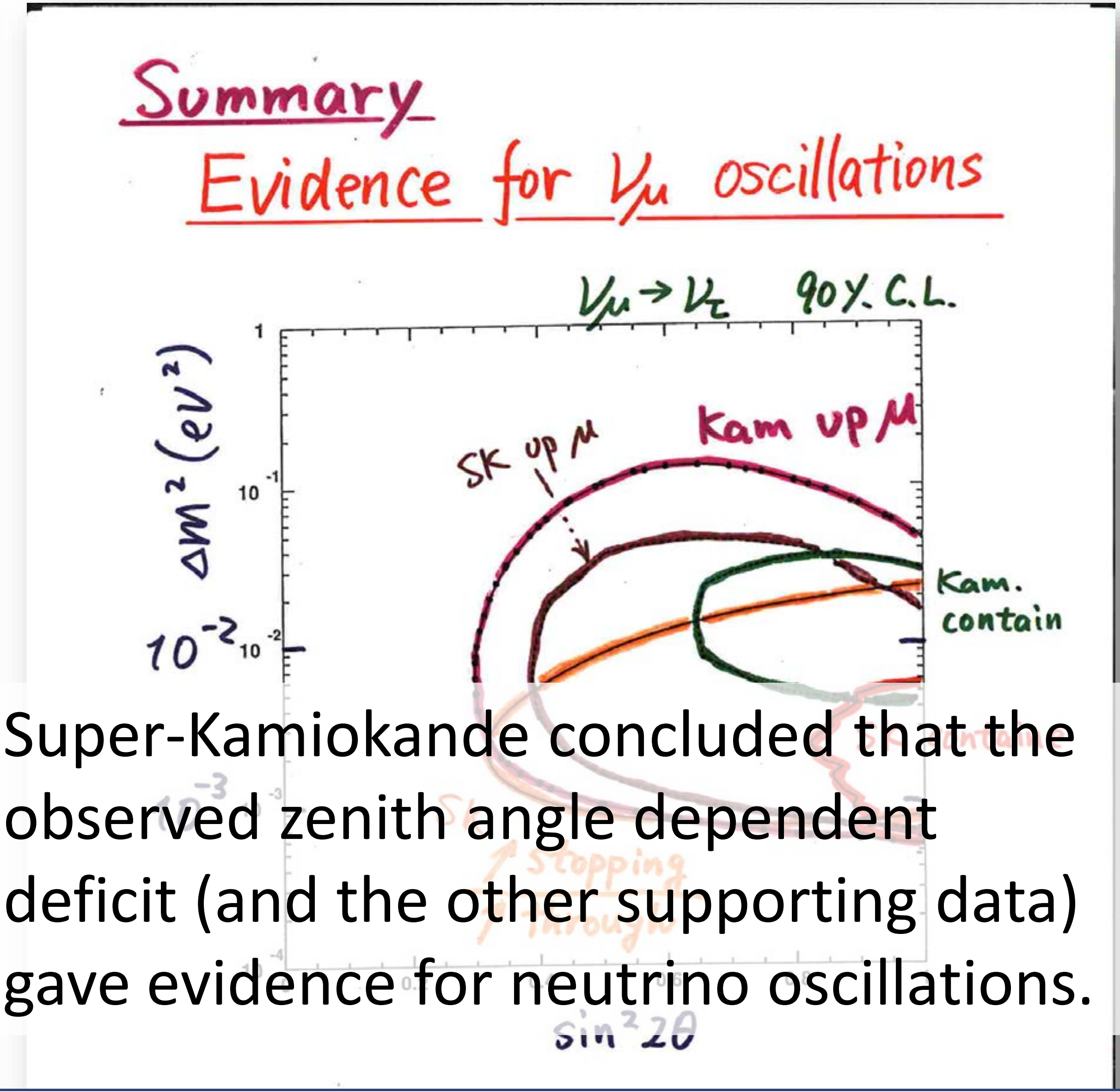


A deficit of upward going ν_μ's should be observed!
A large detector needed. ➔ Super-Kamiokande

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

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



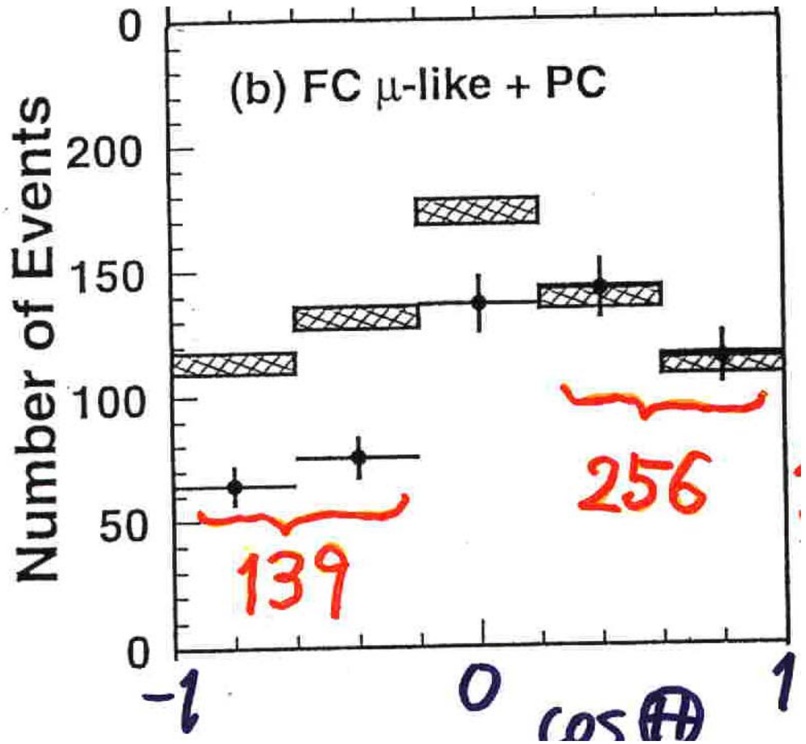


Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

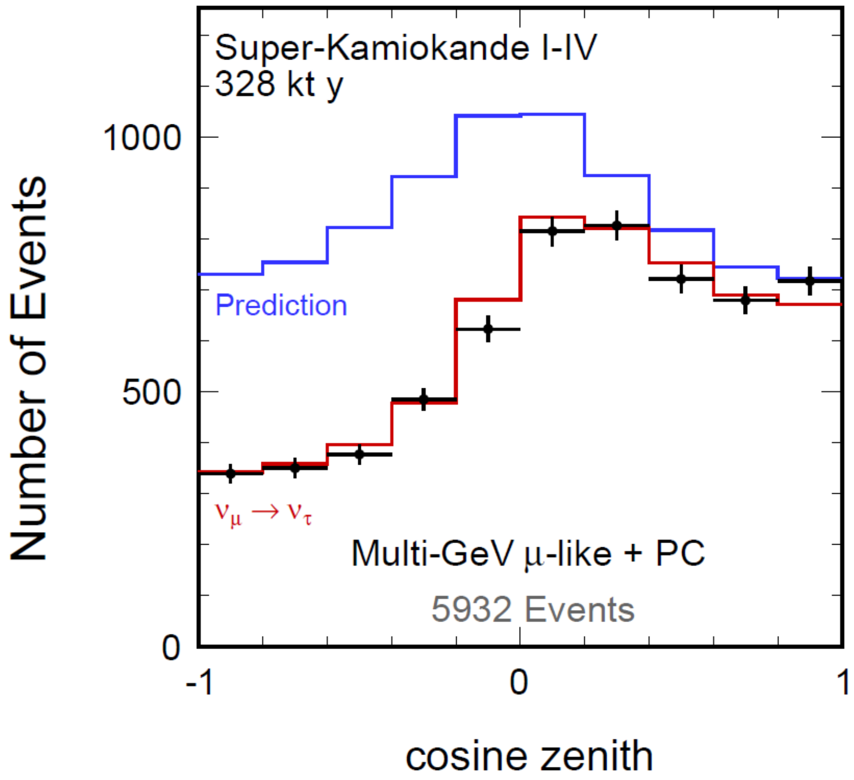
Various oscillation studies

Updating atmospheric neutrino data

Super-K @Neutrino98 → Super-K (2016)



Super-K @Neutrino 2016



Number of events plotted:

531 events → 5932 events

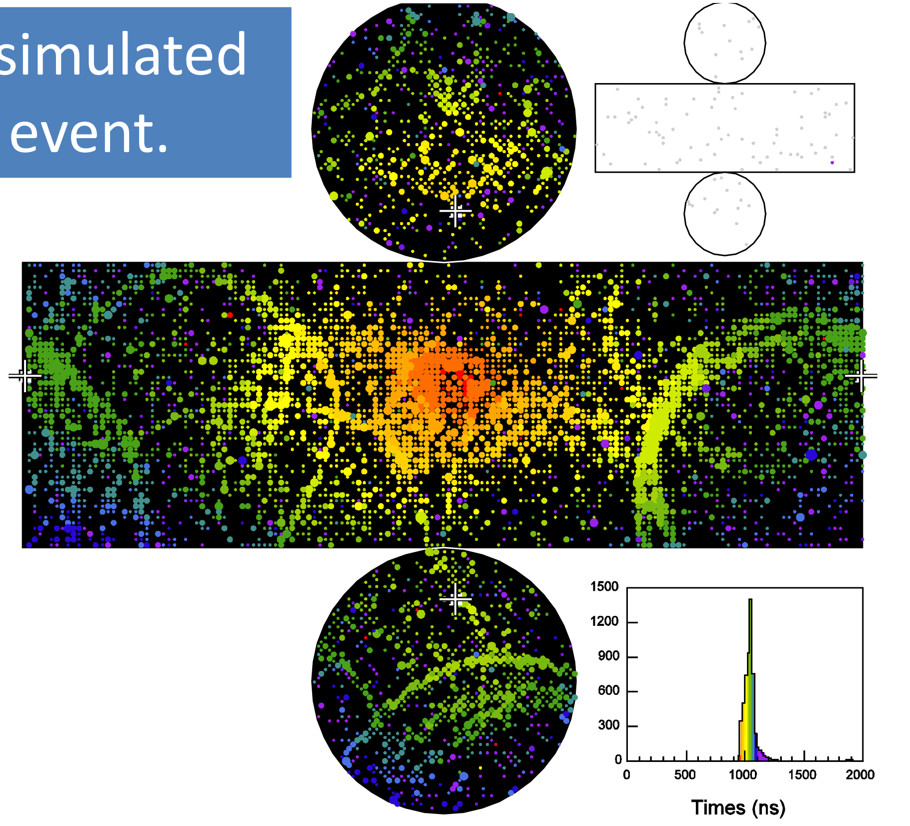
Detailed studies of oscillations!

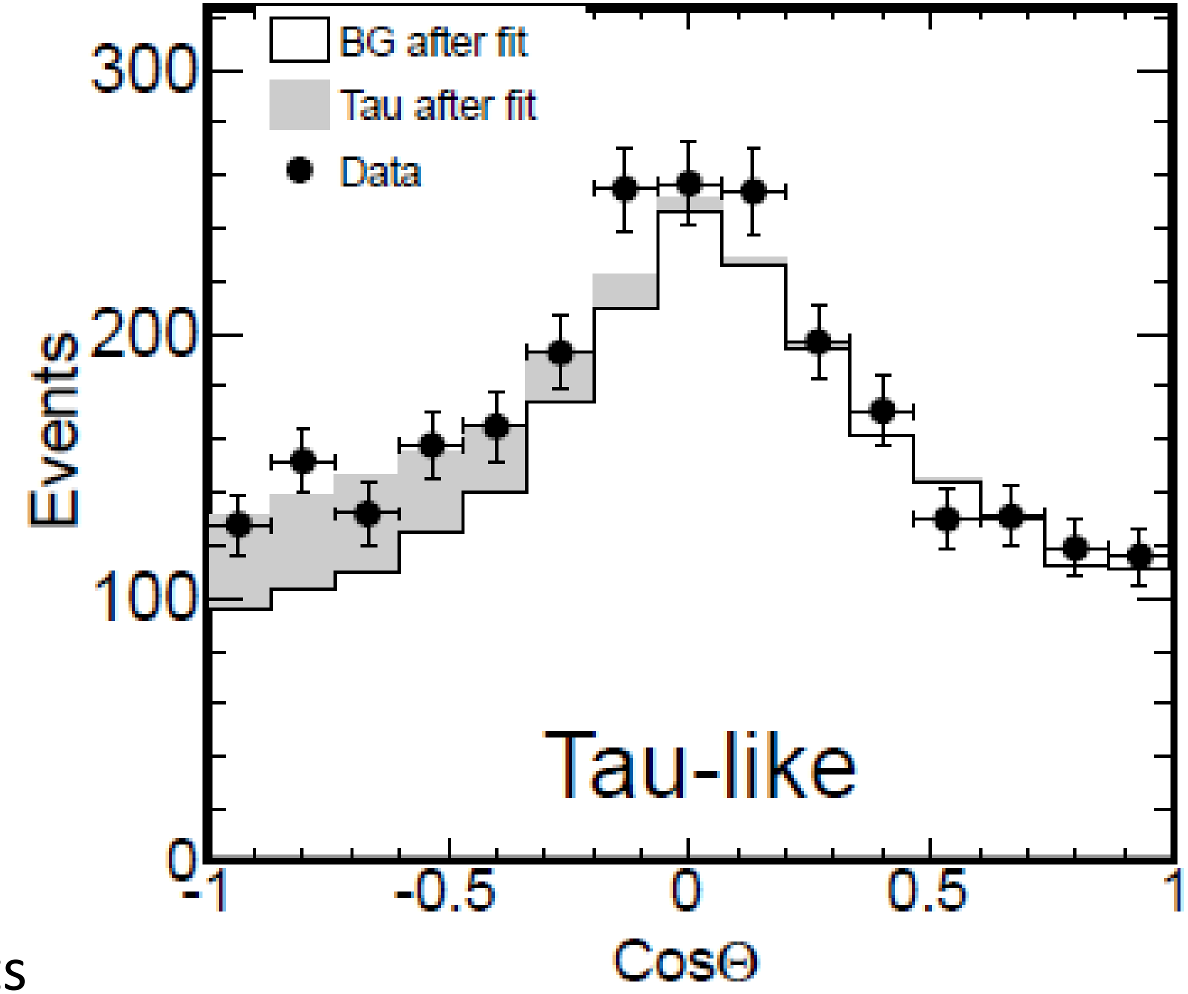
Detecting tau neutrinos

If the oscillations are between ν_μ and ν_τ, one should be able to observe ν_τ's.

Super-K, PRD 98 (2018) 052006

A simulated ν_τ event.





It is not possible for Super-K to identify ν_τ events by an event by event bases. ➔ Statistical analysis knowing that ν_τ's are upward-going only.

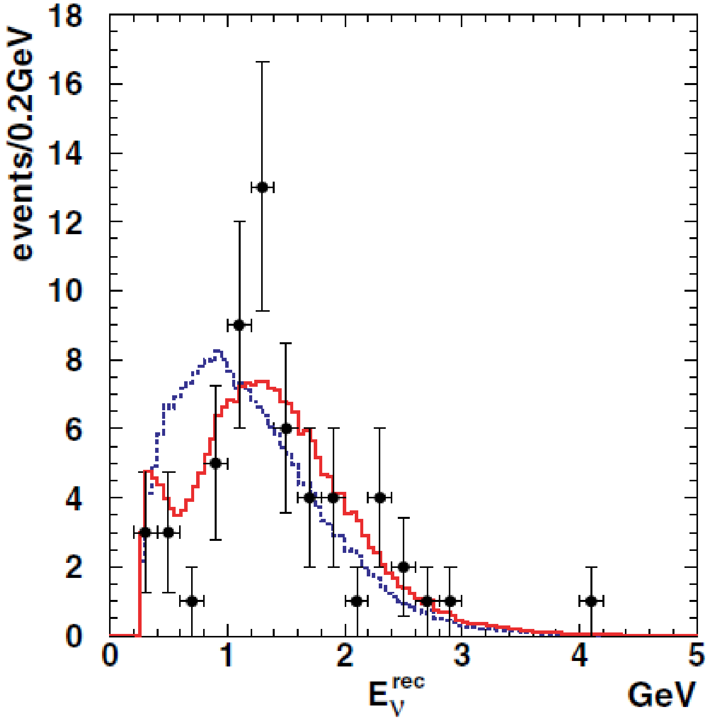
τ-appearance at 4.6σ

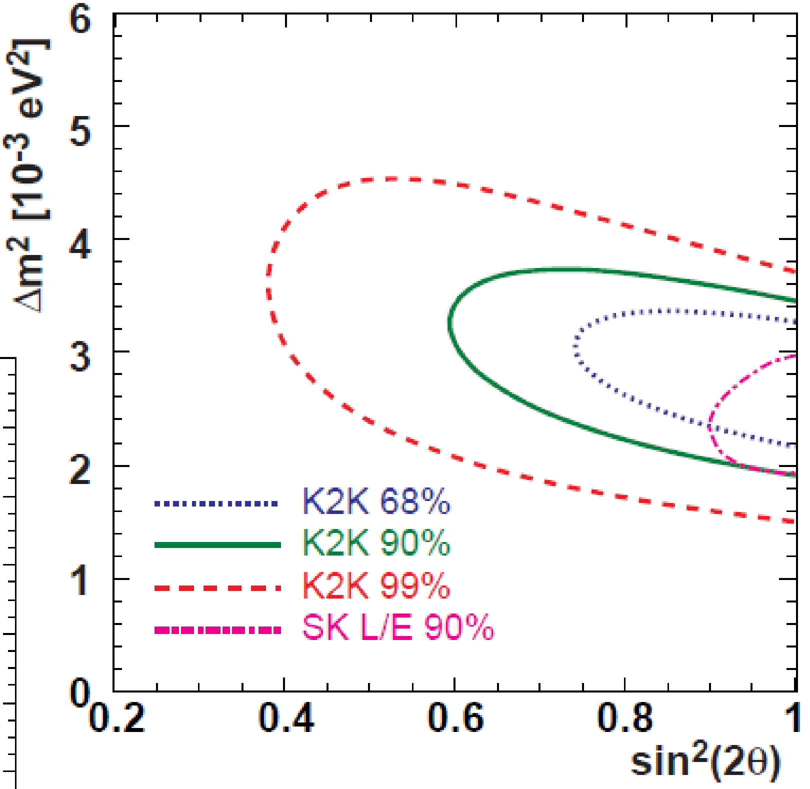
(consistent with OPERA)

Accelerator based long baseline neutrino oscillation experiments using Super-Kamiokande

K2K experiment (1999 – 2004)

K2K, PRD 74, 072003 (2006)





Confirmation of neutrino oscillation (ν_μ disappearance) with accelerator beam.

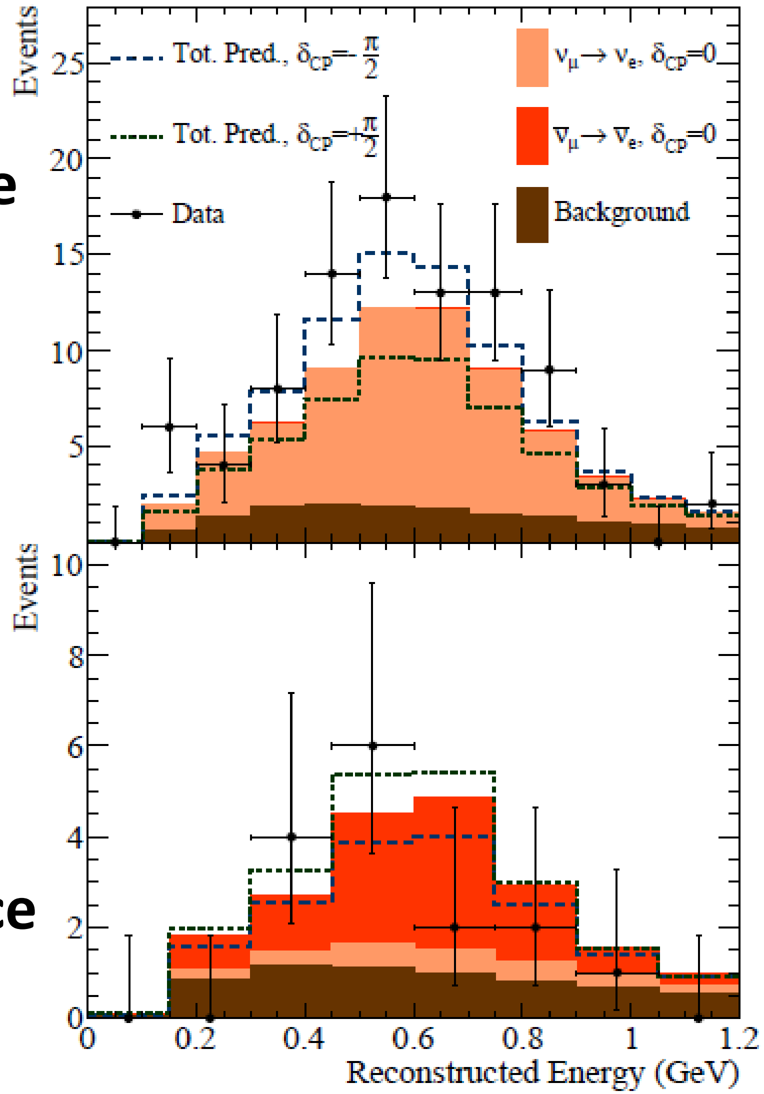
Accelerator based long baseline neutrino oscillation experiments using Super-Kamiokande (2)

T2K arXiv:1910.03887

T2K experiment (2010 -)

ν_e appearance

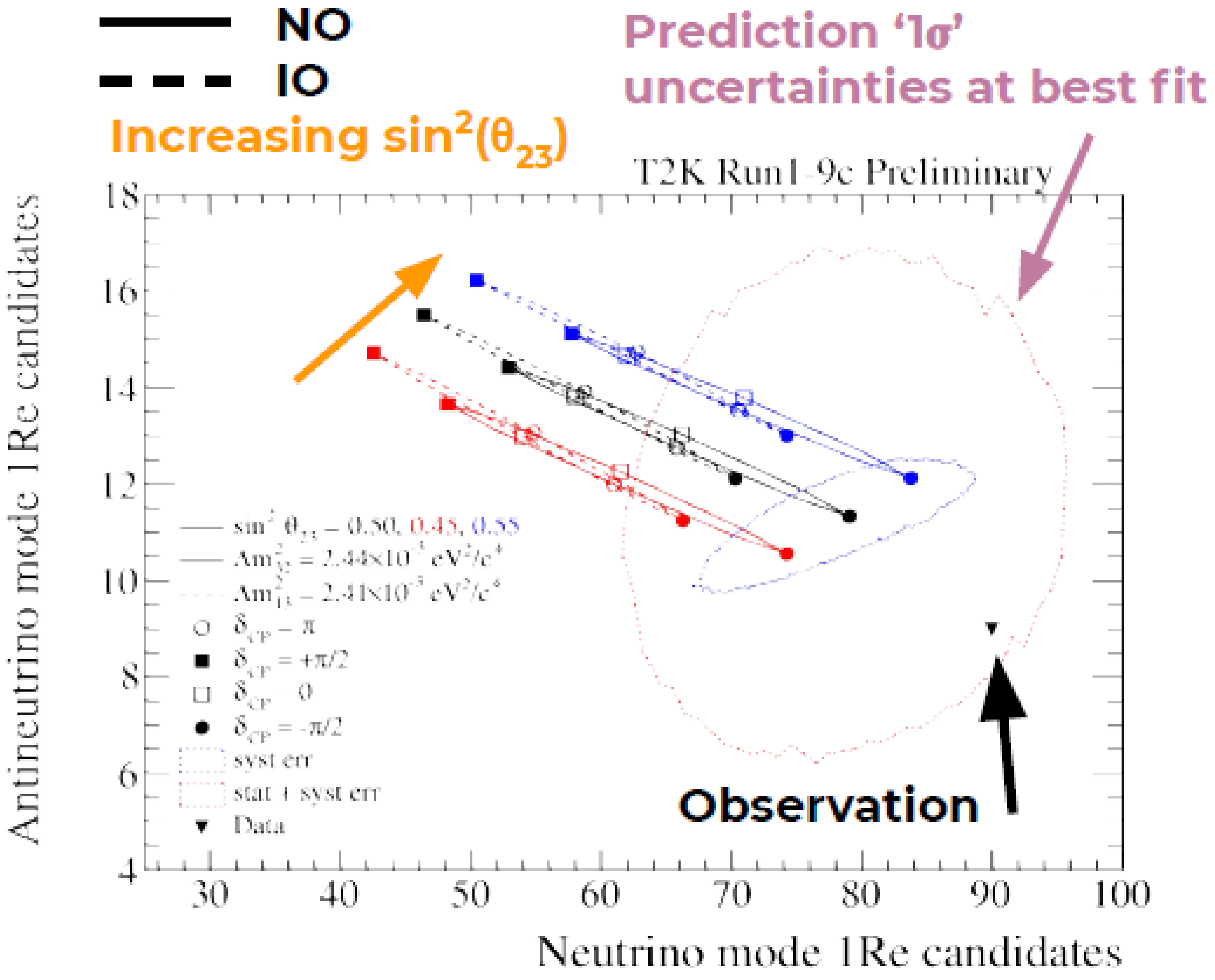
anti-ν_e appearance



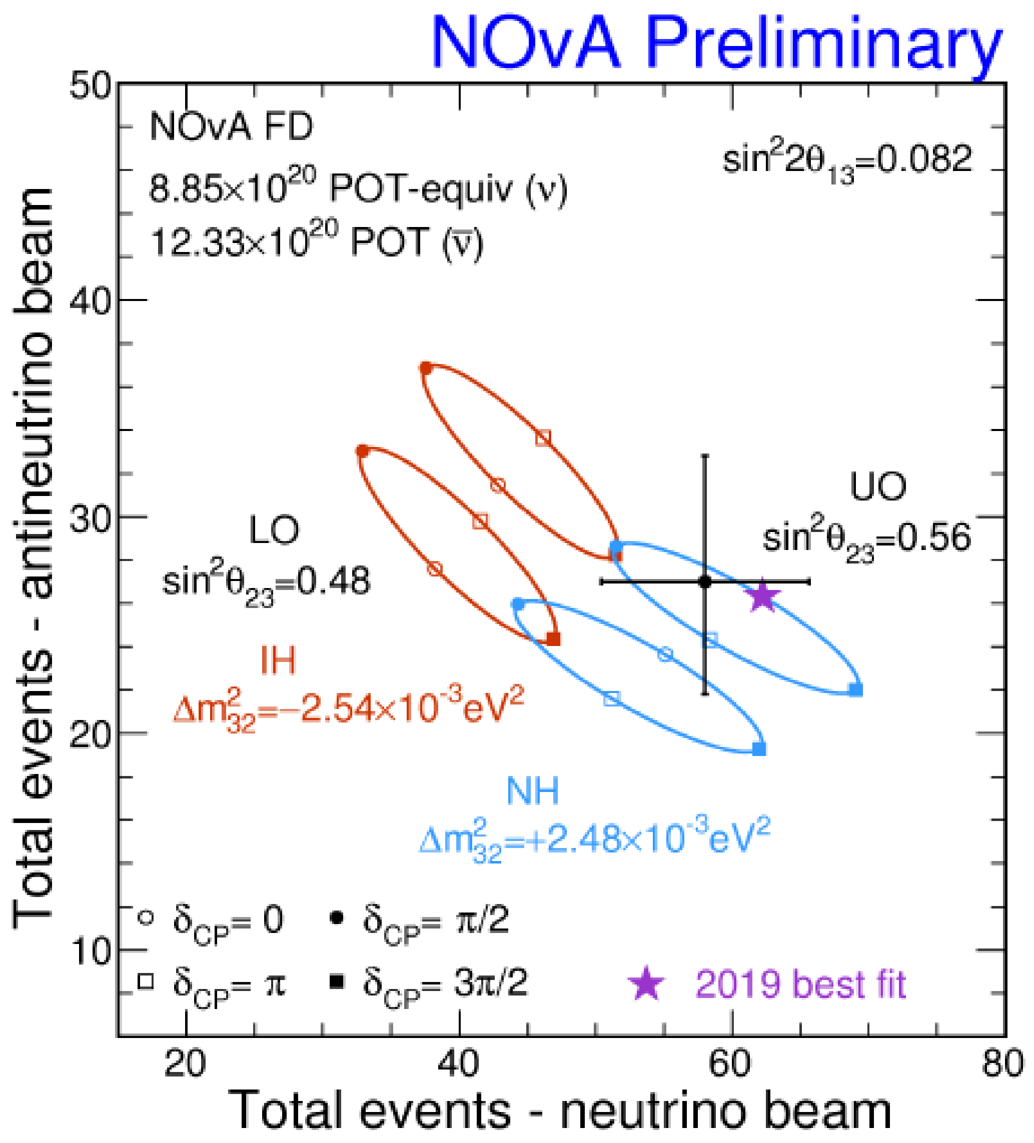
Electron neutrino appearance (evidence for 3 flavor oscillation effect).

T2K and NOvA ν_e and $\bar{\nu}_e$ appearance

T2K (L. Pickering, NNN2019)

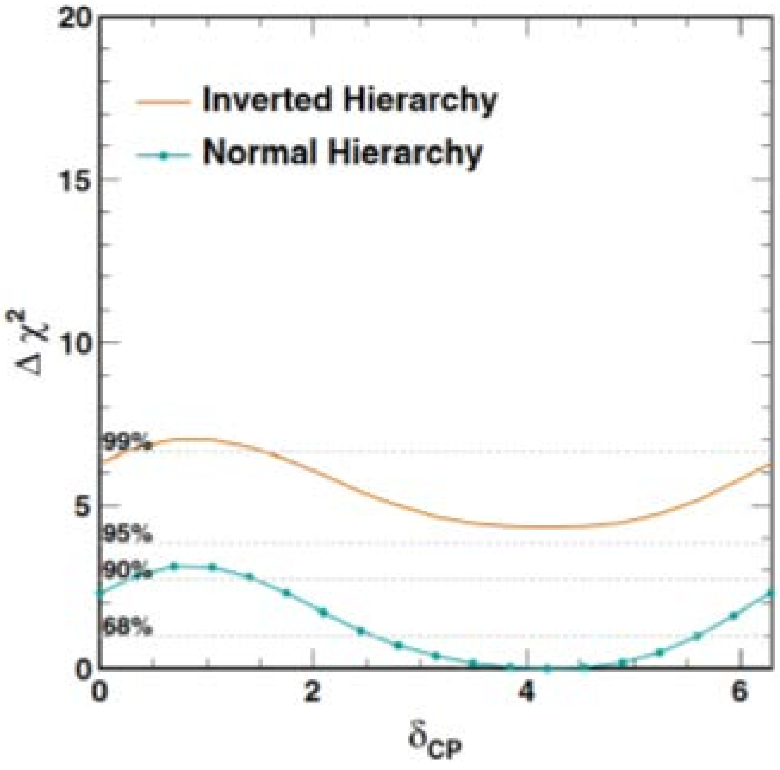


NOvA (E. C. Mur, NNN2019)



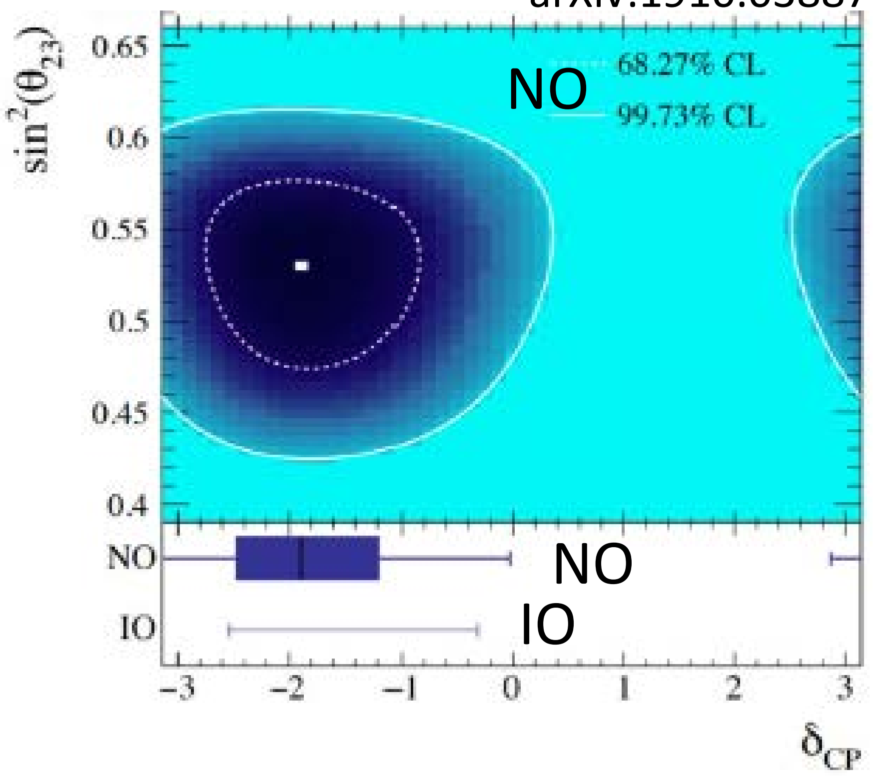
Constraints on the CP phase (based on NNN 2019, Nov. 2019)

Super-K atmospheric (L. Wan)

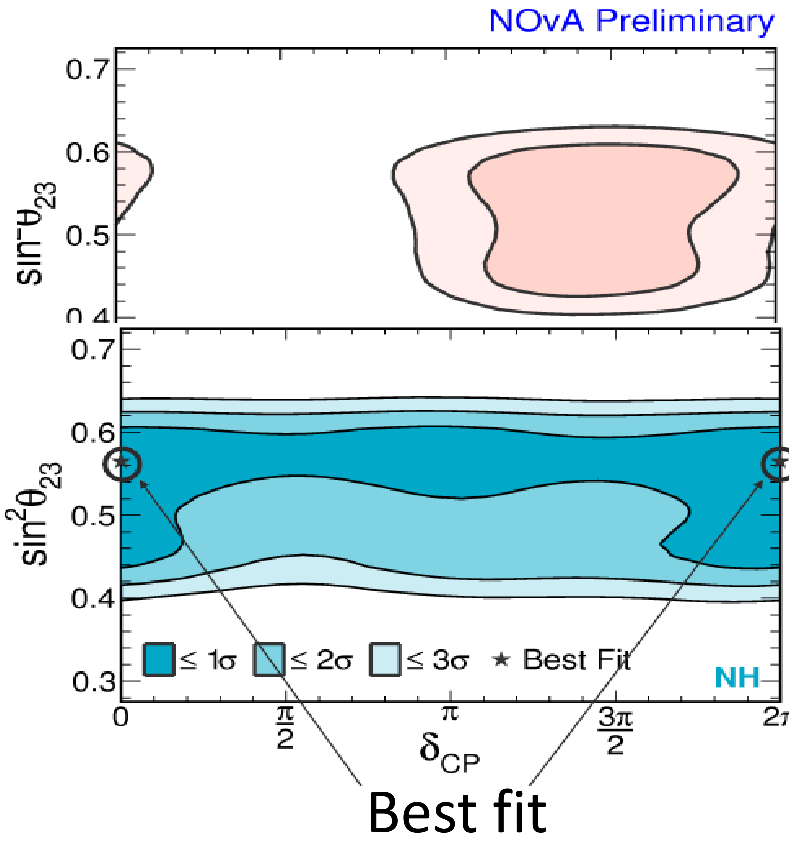


T2K (L. Pickering)

arXiv:1910.03887



NOvA (E. C. Mur)



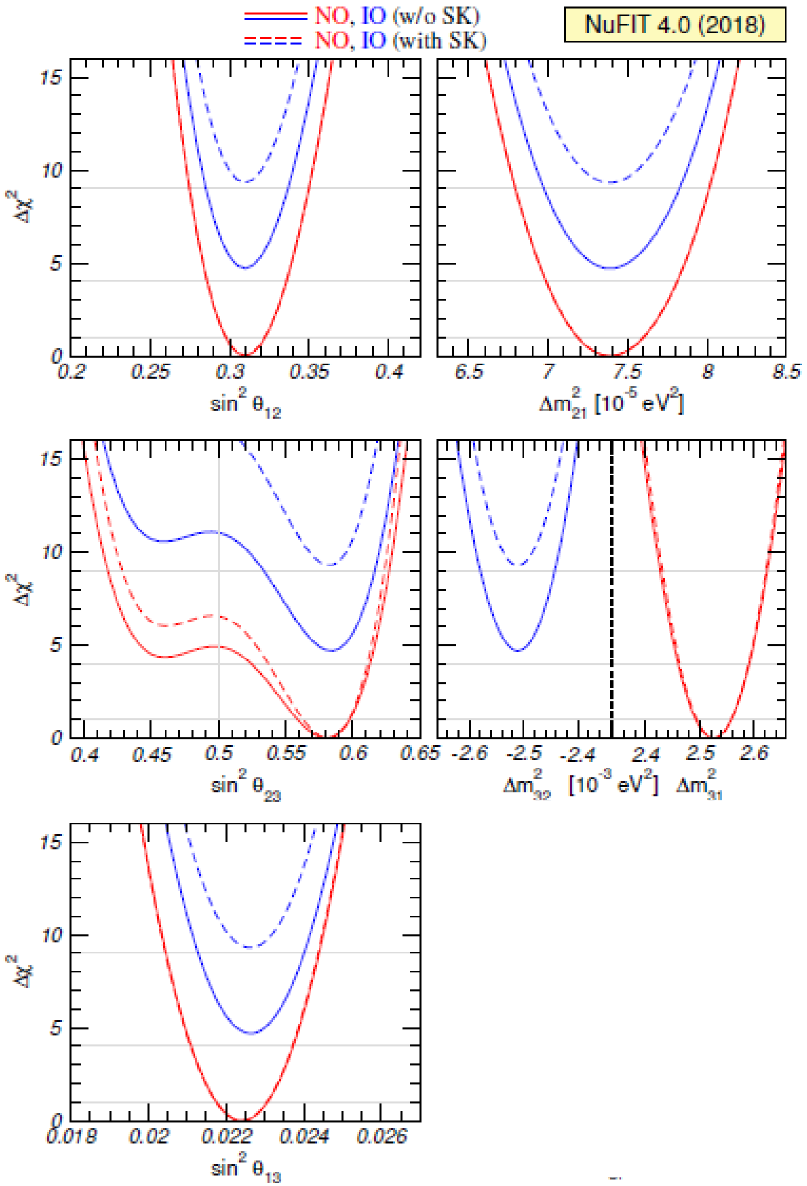
Already some interesting indications:

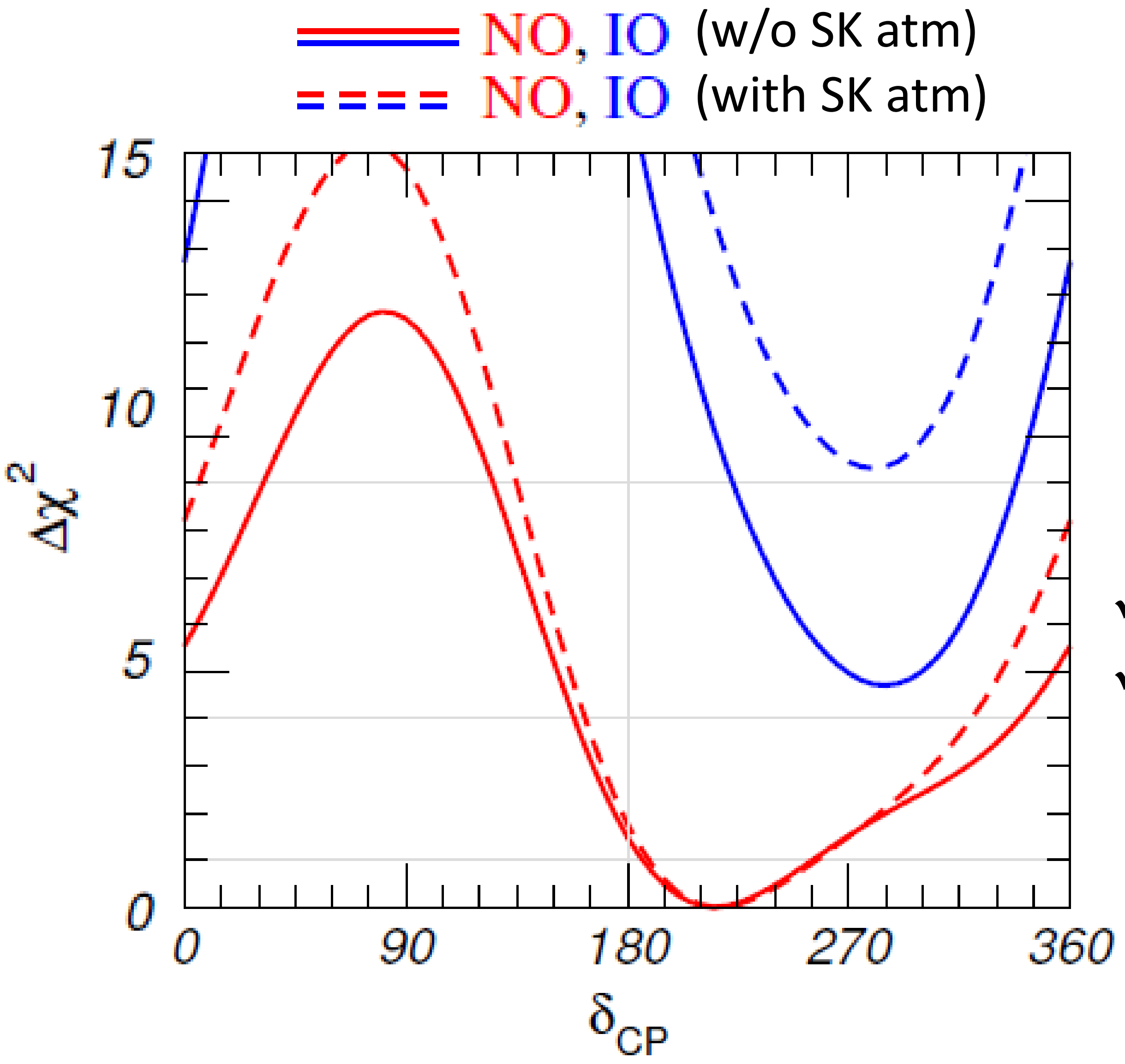
➔ NO favored by these 3 experiments at ~(1 ~ 2) sigma level each.

➔ These experiments give some favored δ_{CP} region(s).

Global fit (example)

I. Esteban et al., JHEP 1901 (2019) 106



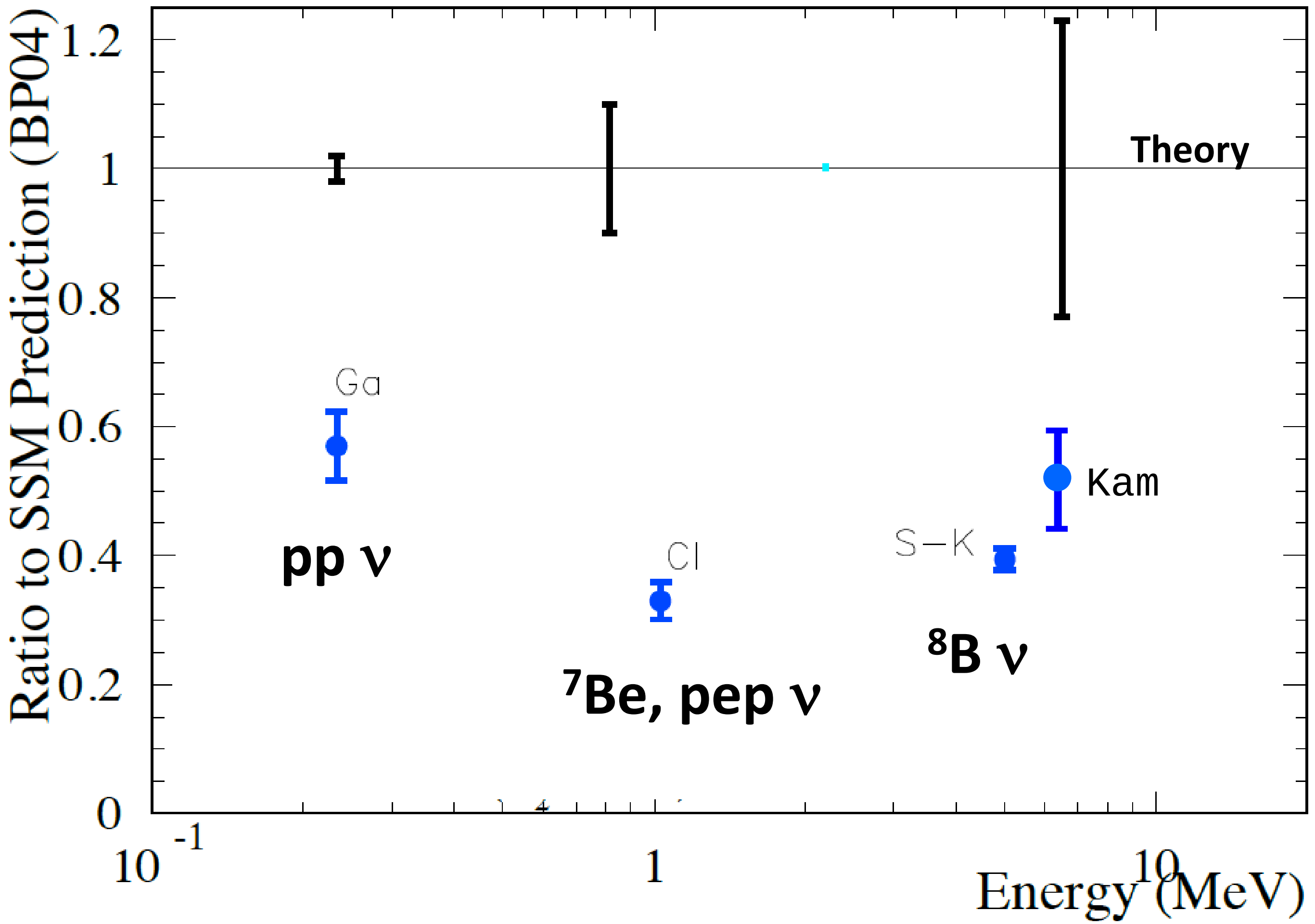


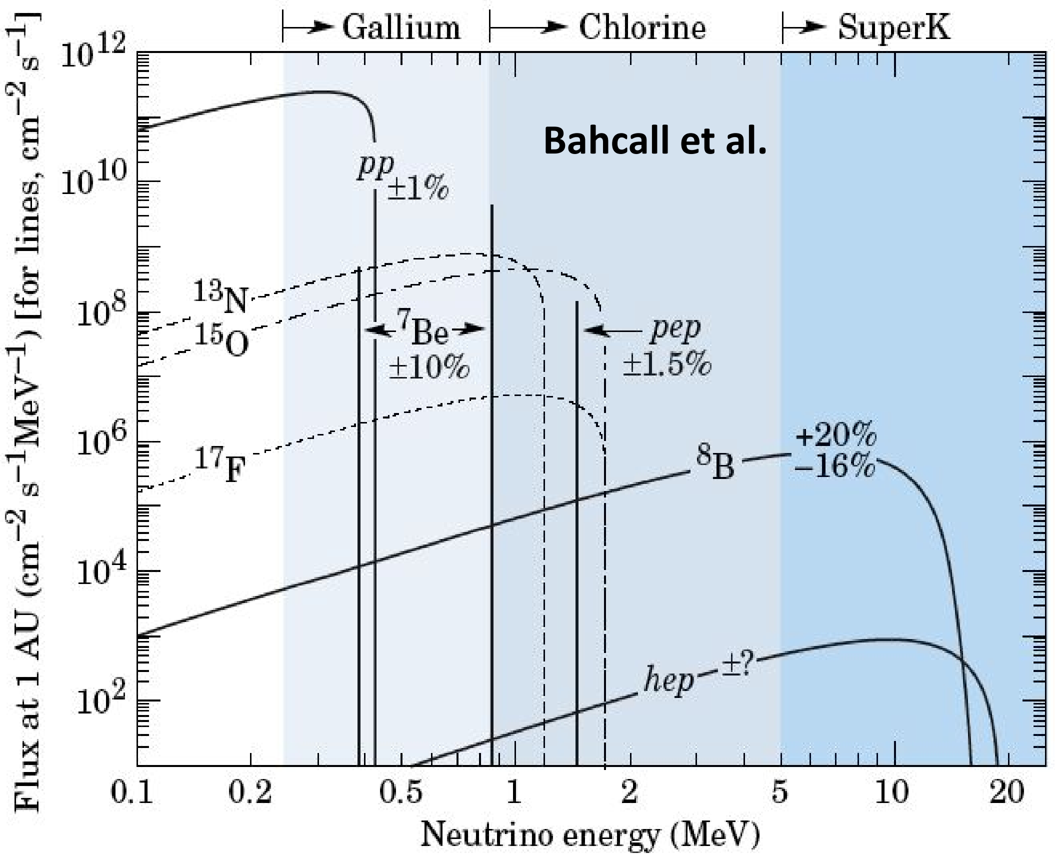
- ✓ NO favored.
- ✓ Suggested δ_{CP} range(s)

Solar neutrino oscillations

Results from solar neutrino experiments (before ~2000)

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

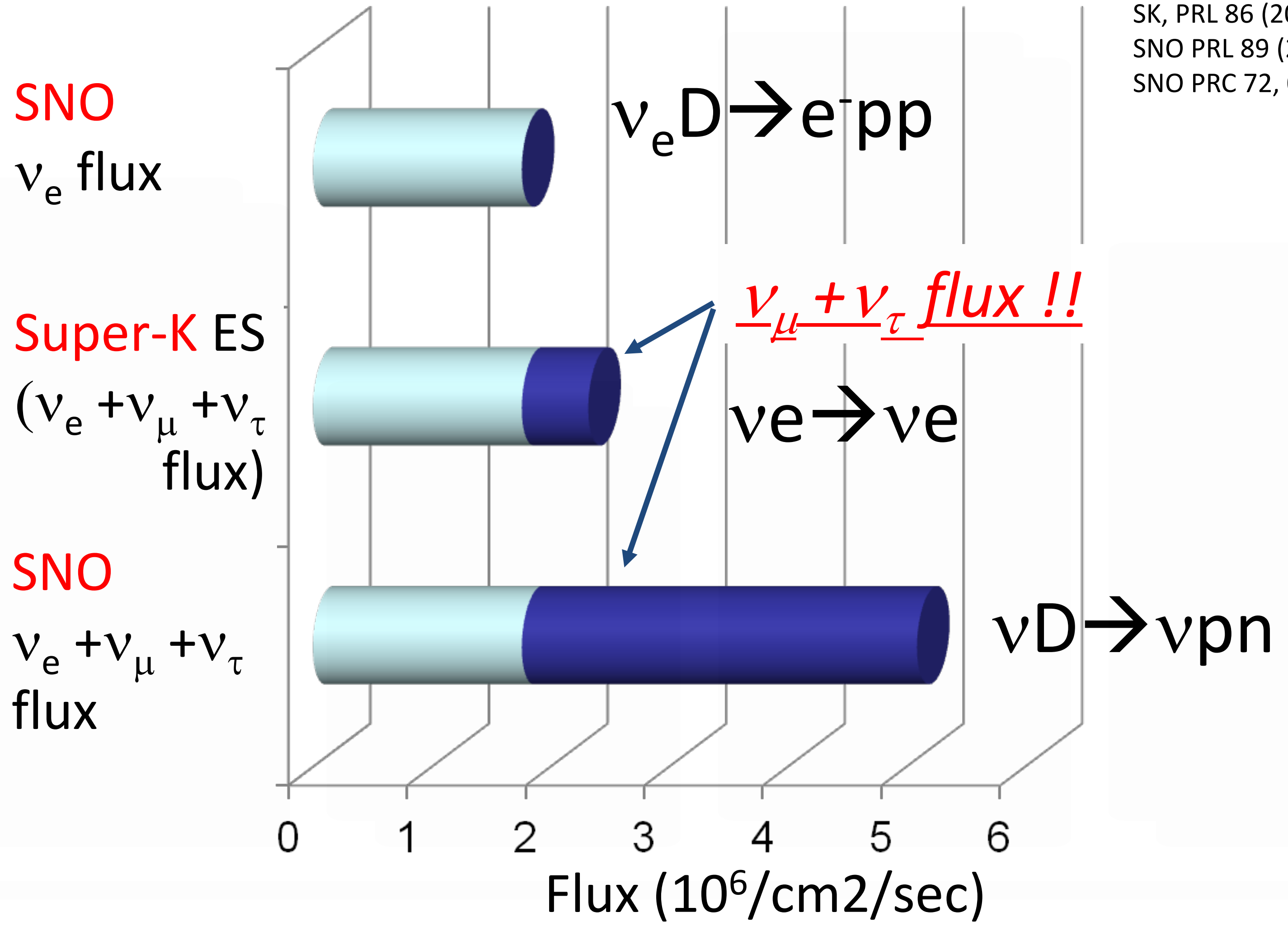


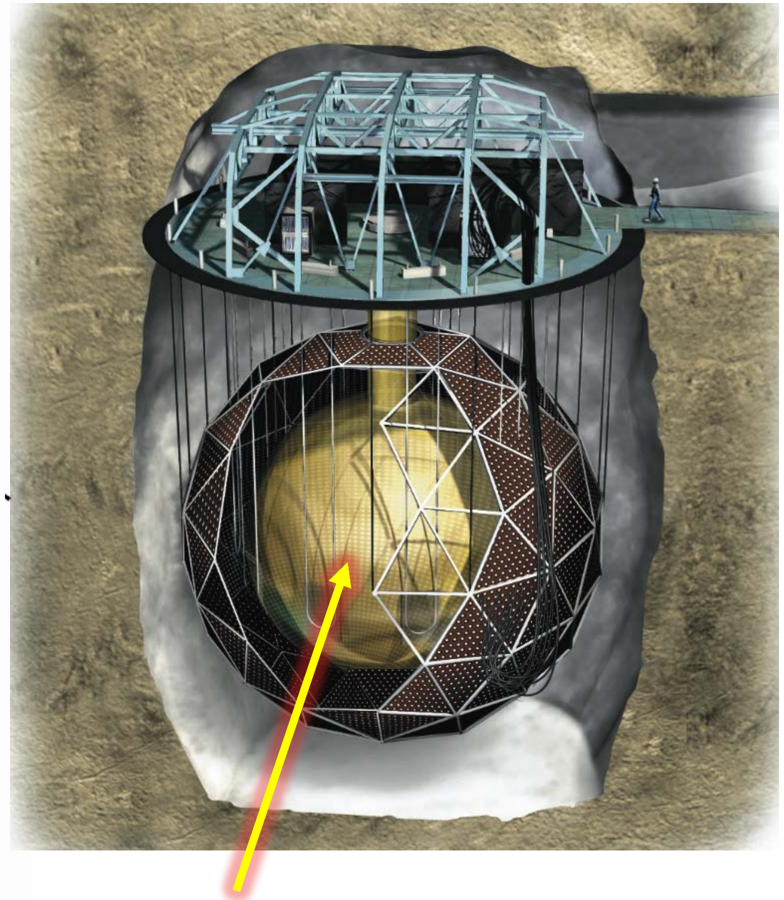


These solar neutrino experiments observed the deficit of solar neutrinos.

Solar neutrino oscillation (2001-2002)

SK, PRL 86 (2001) 5651
SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)



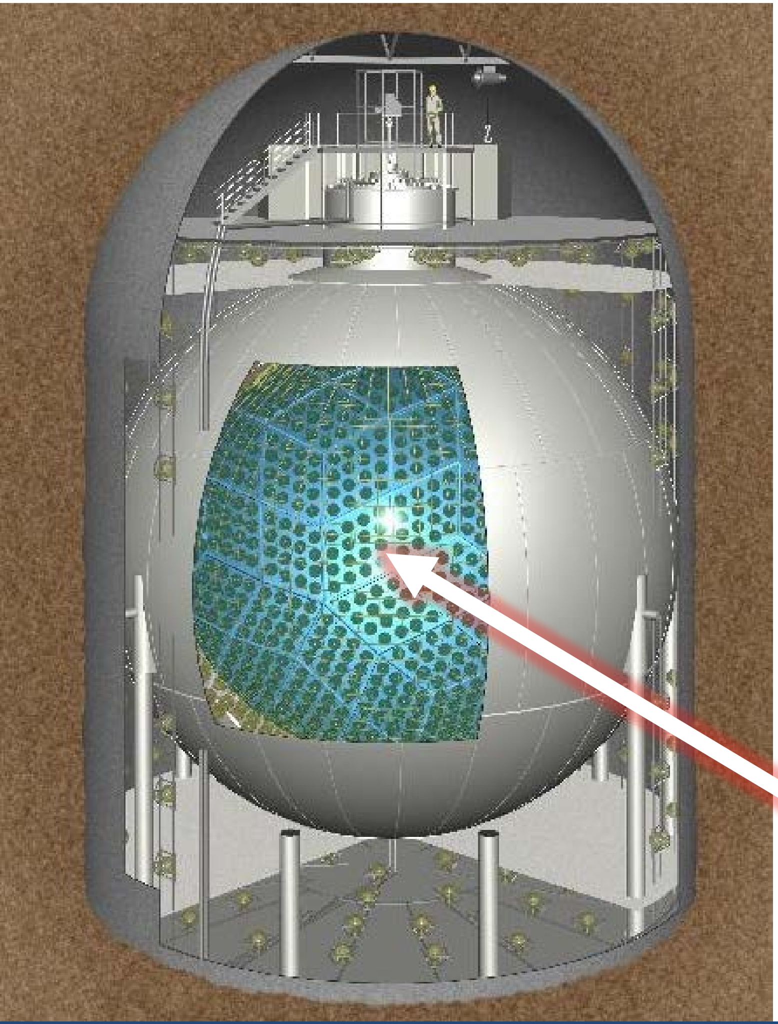


1000 ton of heavy water (D_2O)

Neutrino oscillation: electron neutrinos to the other neutrinos.

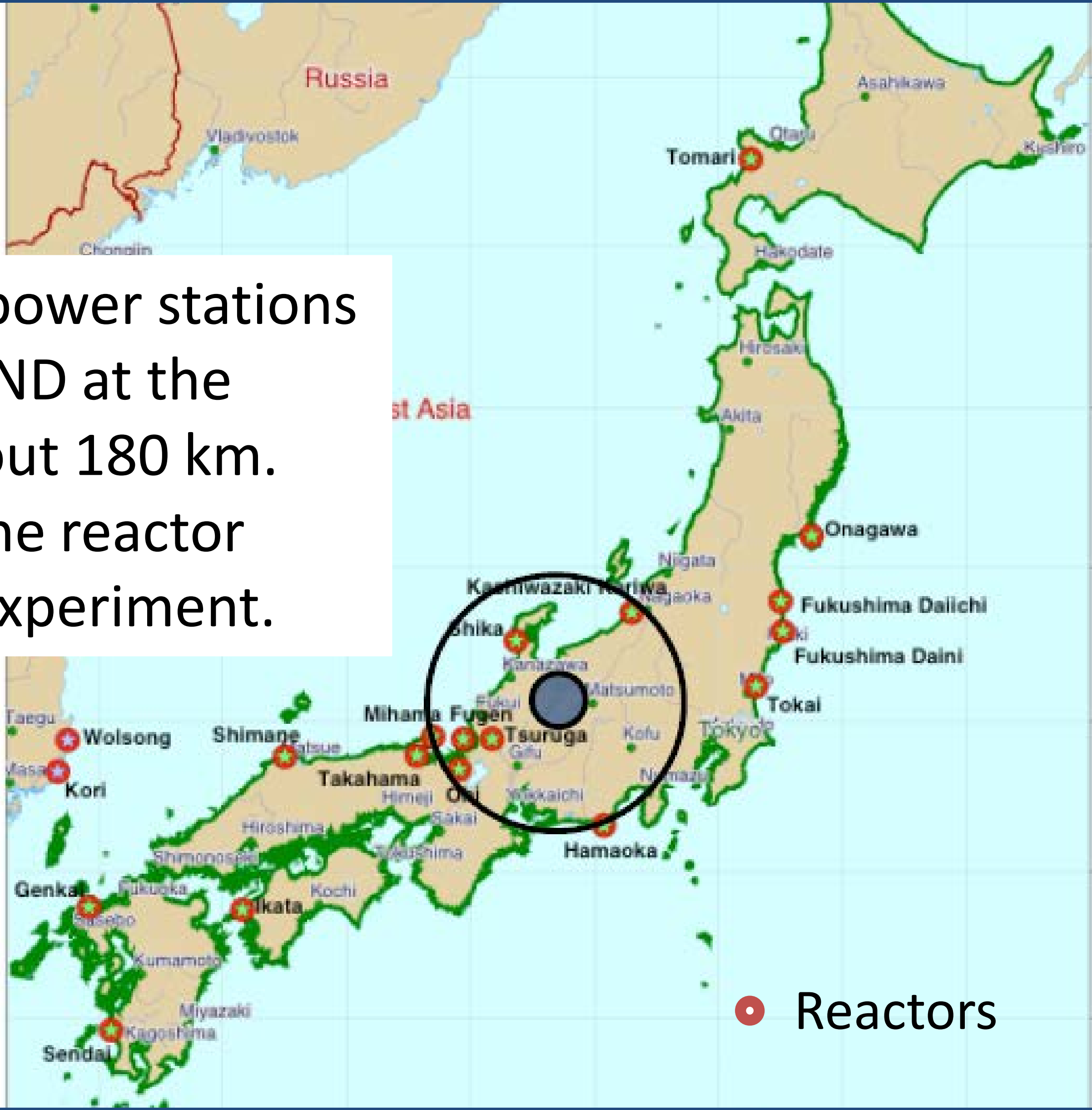
KamLAND (another experiment in Kamioka)

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

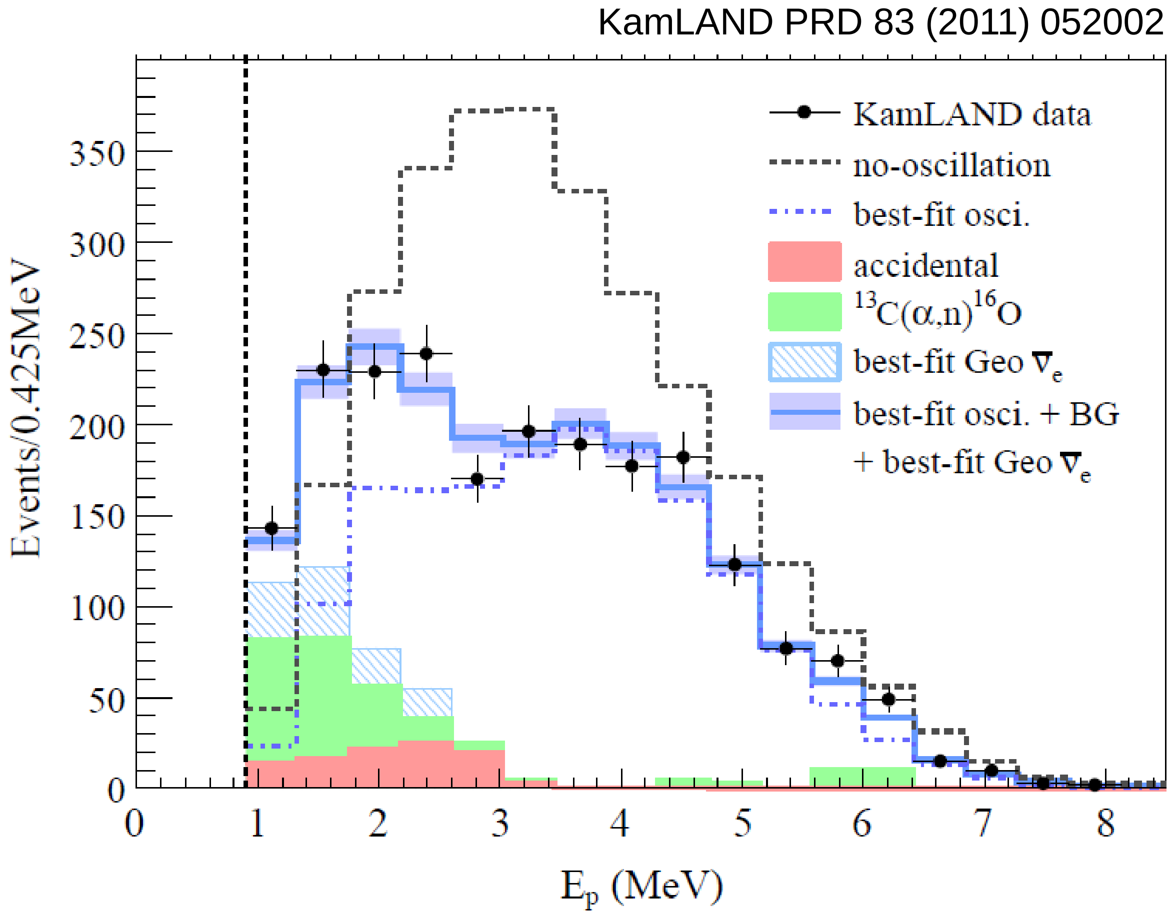


1kton liq. scintillator

Many nuclear power stations around KamLAND at the distance of about 180 km.
➔ Long baseline reactor neutrino osc. experiment.

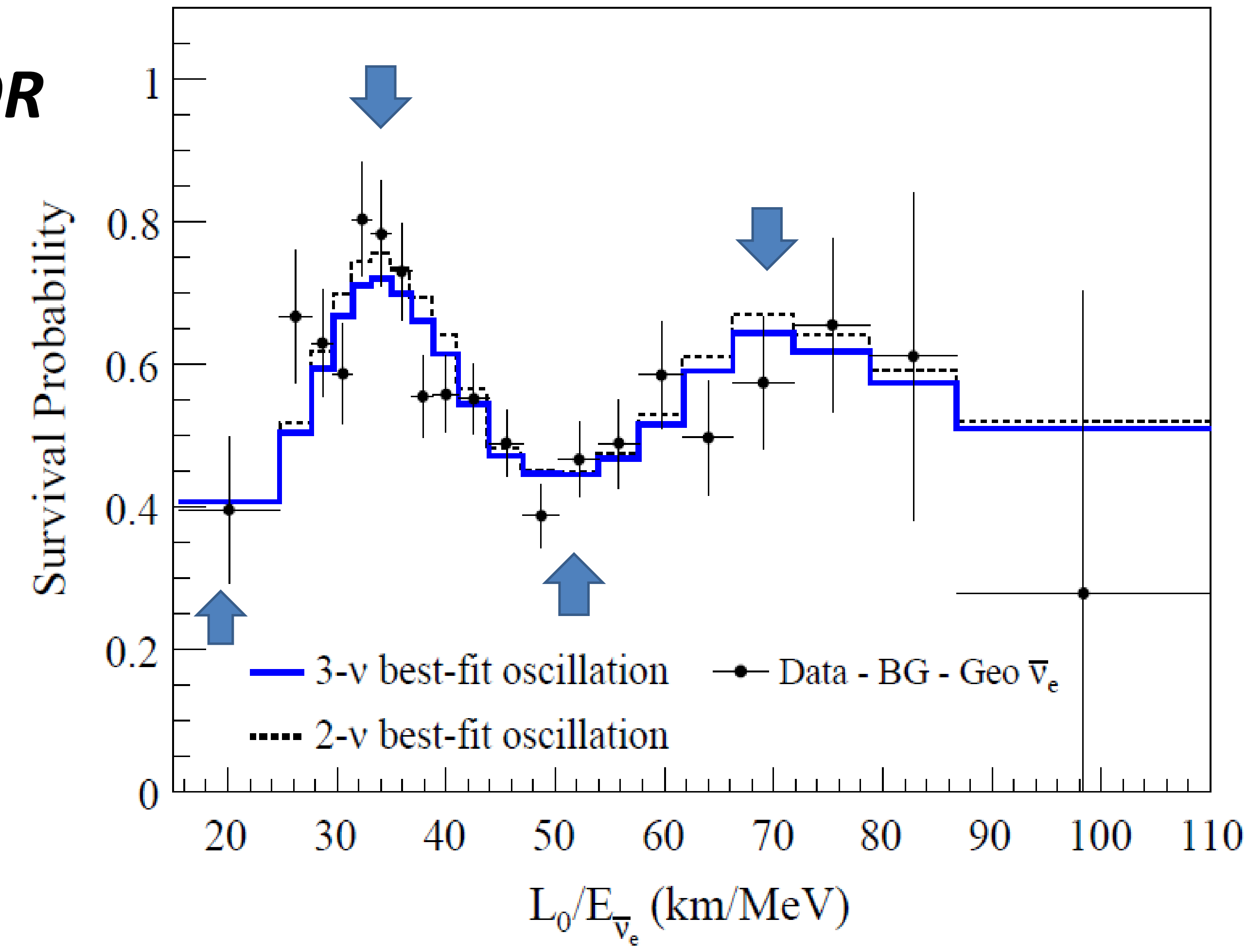


Really neutrino oscillations !



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

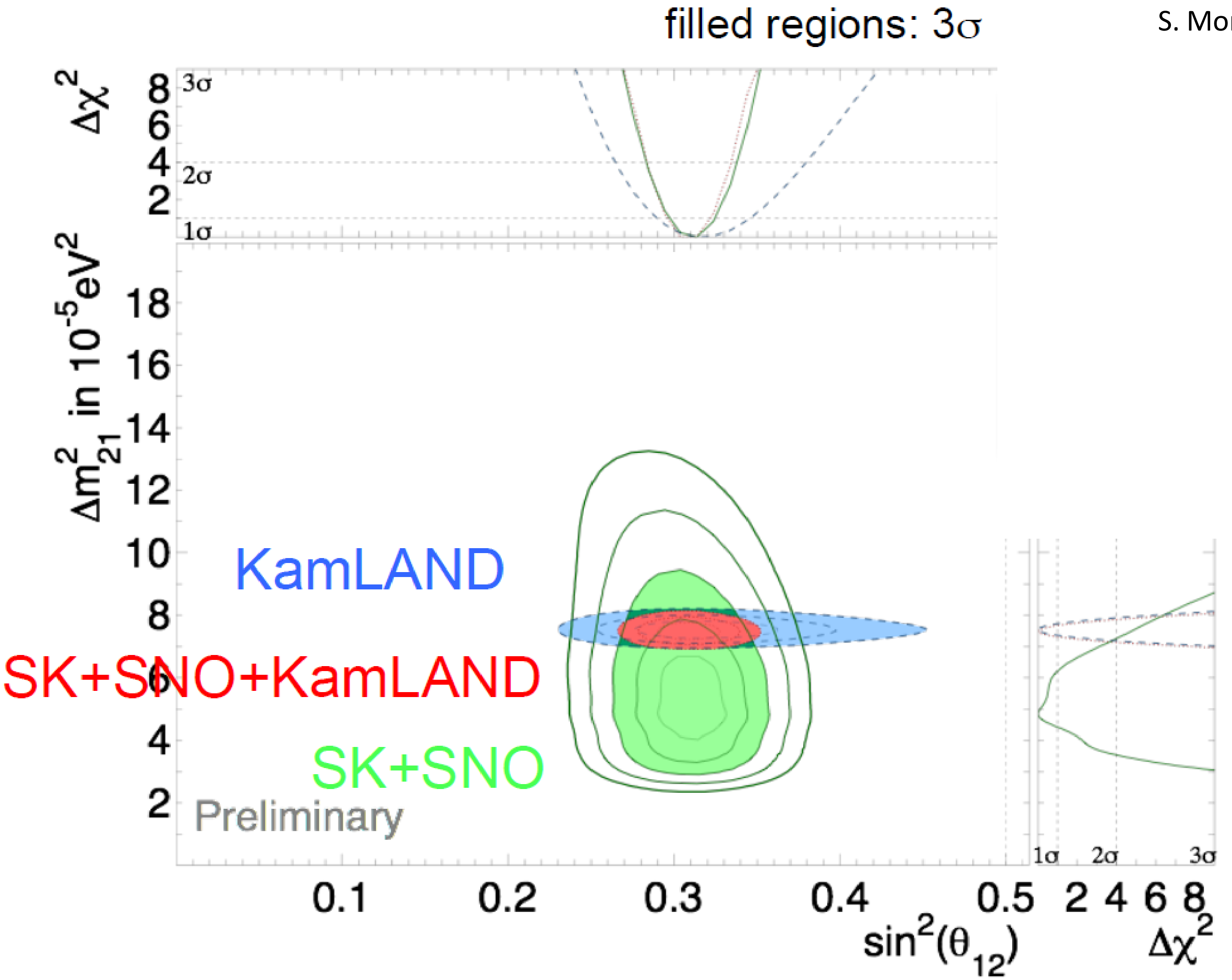
OR



Really neutrino oscillations!

Status of the 12-parameter measurements

S. Moriyama (Super-K), Neutrino 2016



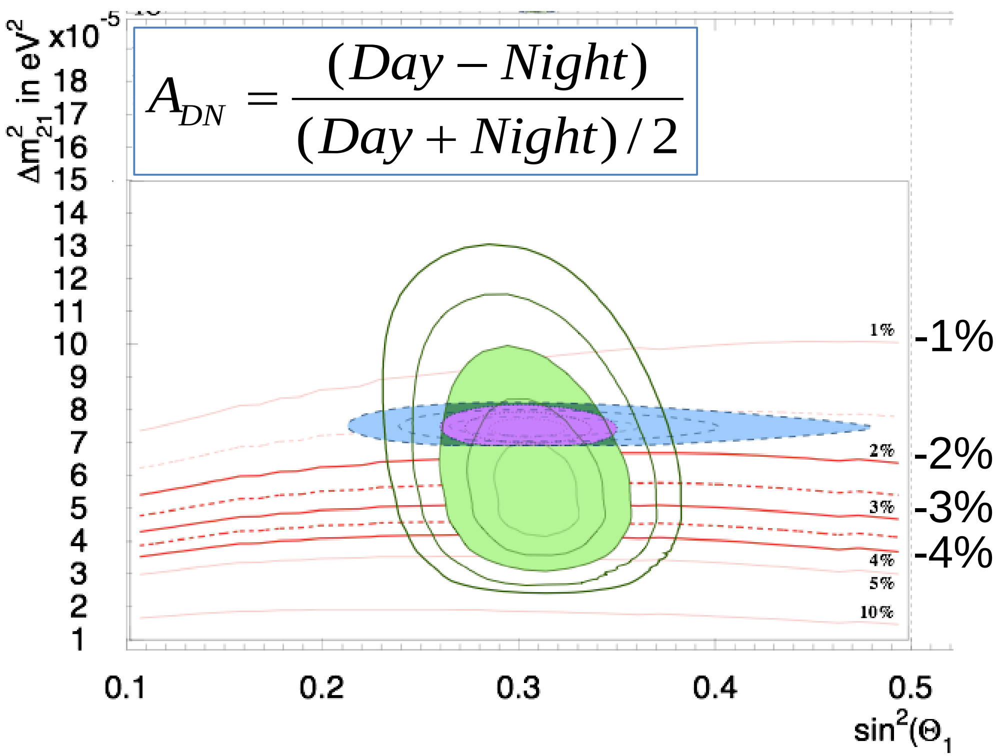
~2σ tension

Further studies of solar neutrino osci. with Super-K

Day-Night effect

Super-K, PRD94, 052010 (2016)

$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$



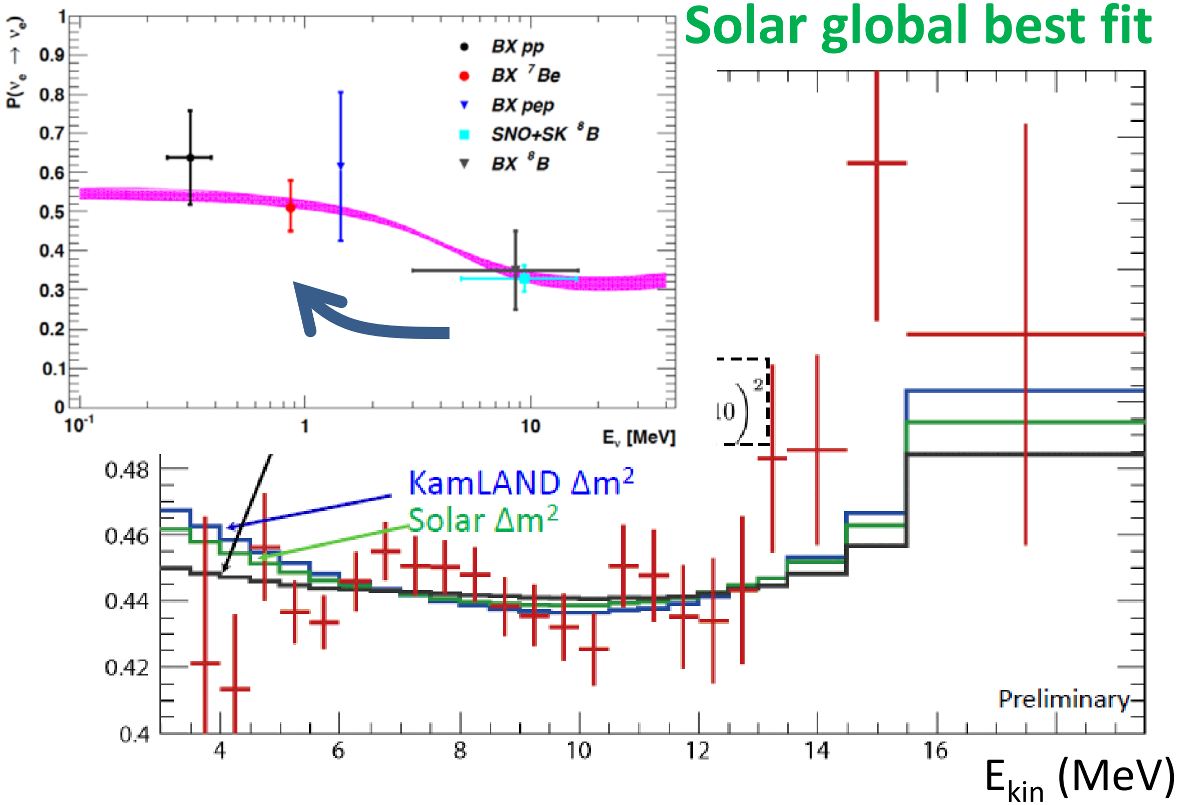
	A_{DN}^{fit} (%)
SK-I~IV, 4499 days	-3.3+/-1.0+/-0.5
Non-zero significance	2.9 σ

Spectrum upturn

(Super-K, Neutrino 2018)

Solar+KamLAND best fit

Solar global best fit



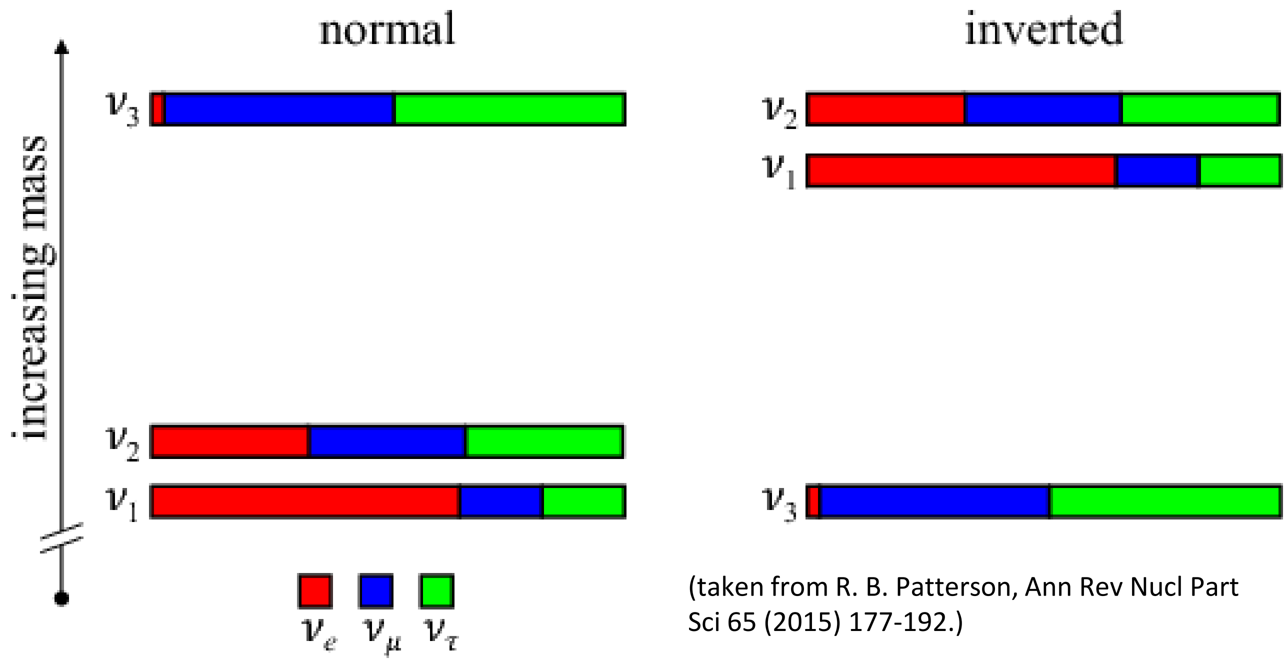
Solar best fit	Consistent within 1.5σ
Solar+KamLAND best fit	Marginally within ~2σ

Interesting. But we need more data.

Future neutrino experiments in Kamioka

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?

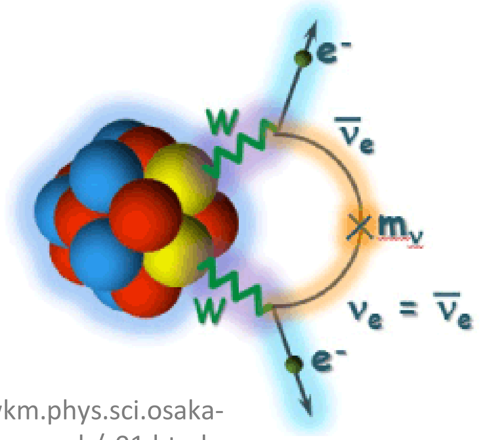
Beyond the 3 flavor framework? (Sterile neutrinos?)

CP violation?

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

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

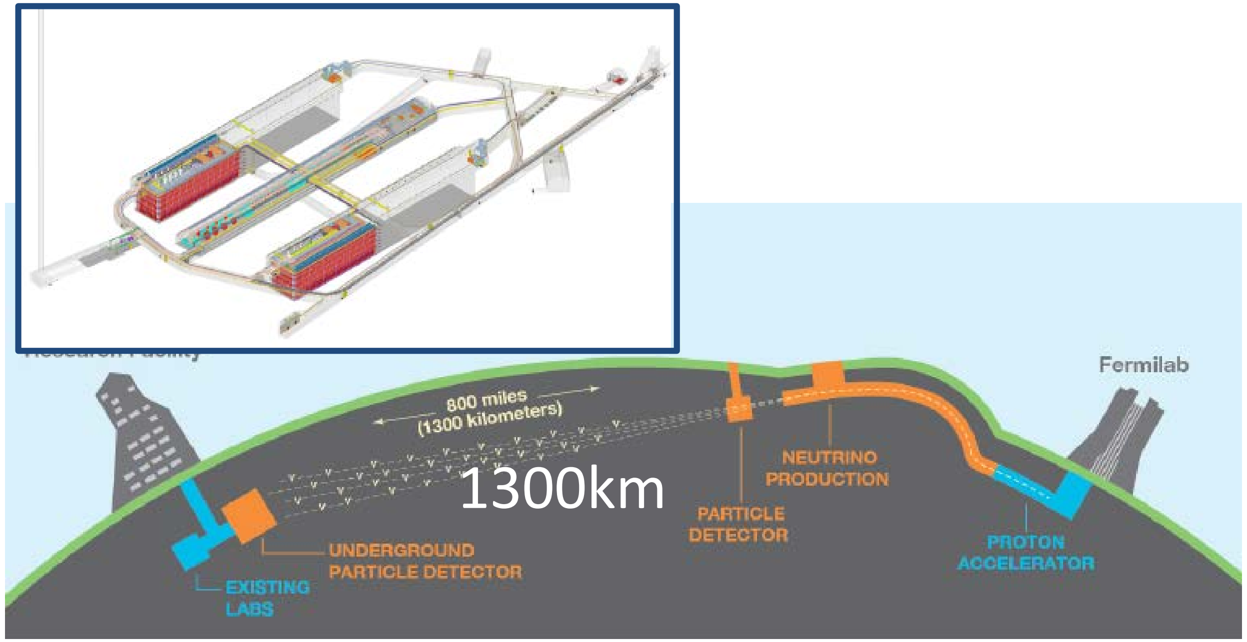
Motivation

- ✓ 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).
- ✓ …

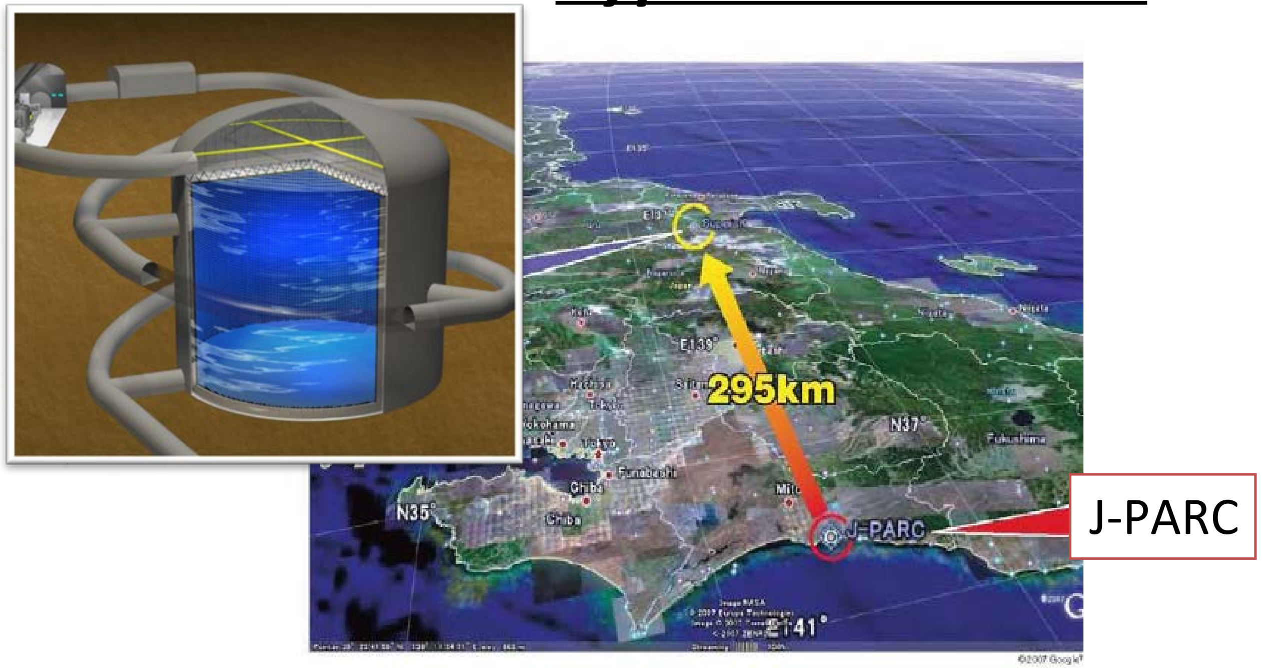
Next generation neutrino CPV experiments

- ✓Present experiments give some interesting hints…
- ✓We need the next generation experiments to clearly observe the CP violation in the neutrino sector.

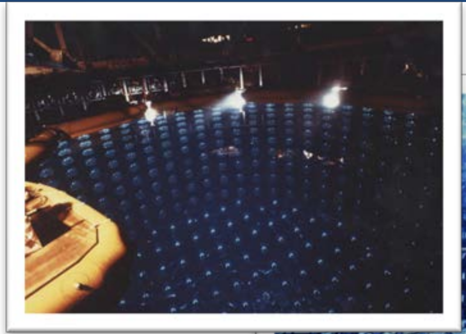
DUNE

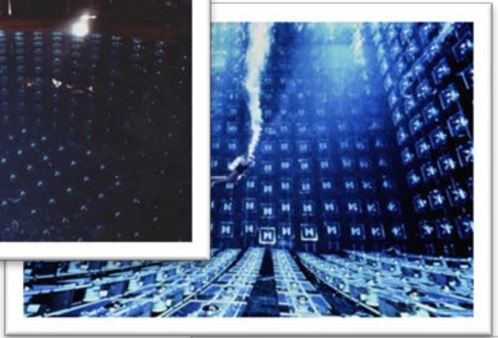


Hyper-Kamiokande



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



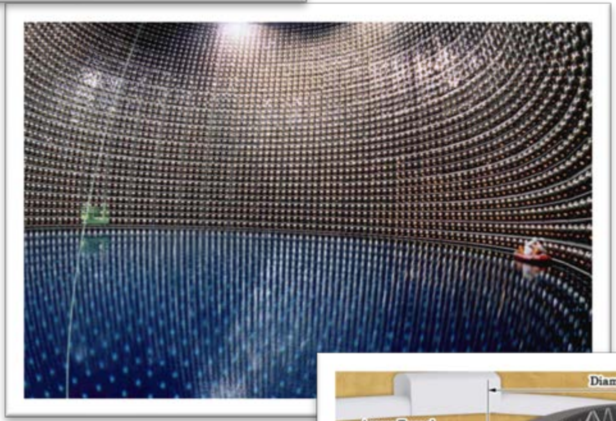


Kamiokande & IMB

Neutrinos from SN1987A

Atmospheric neutrino deficit

Solar neutrino (Kam)

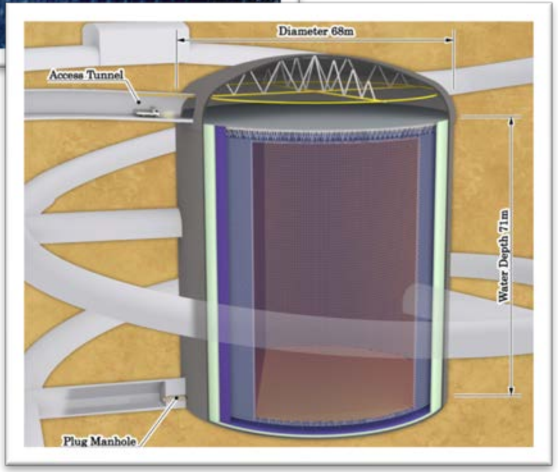


Super-K

Atmospheric neutrino oscillation

Solar neutrino oscillation with SNO

Far detector for K2K and T2K



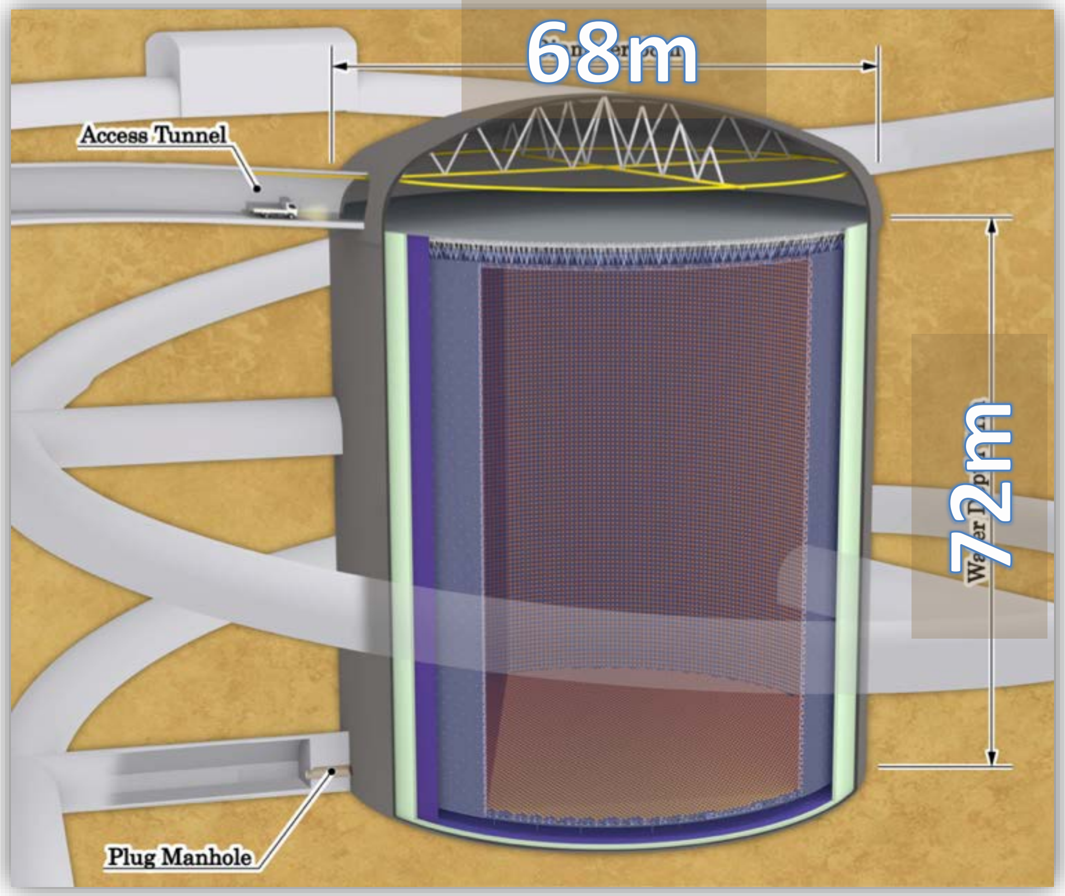
Hyper-K

KEK-PS

J-PARC

25 collaborators
from Russia in T2K

Hyper-K



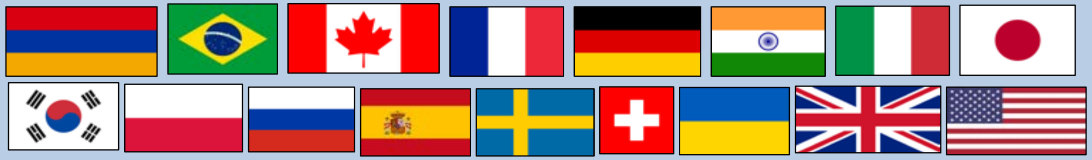
◆Φ 68 meters and H 72 meters.

◆The total and fiducial volumes are 0.26 and 0.19 M tons, respectively.

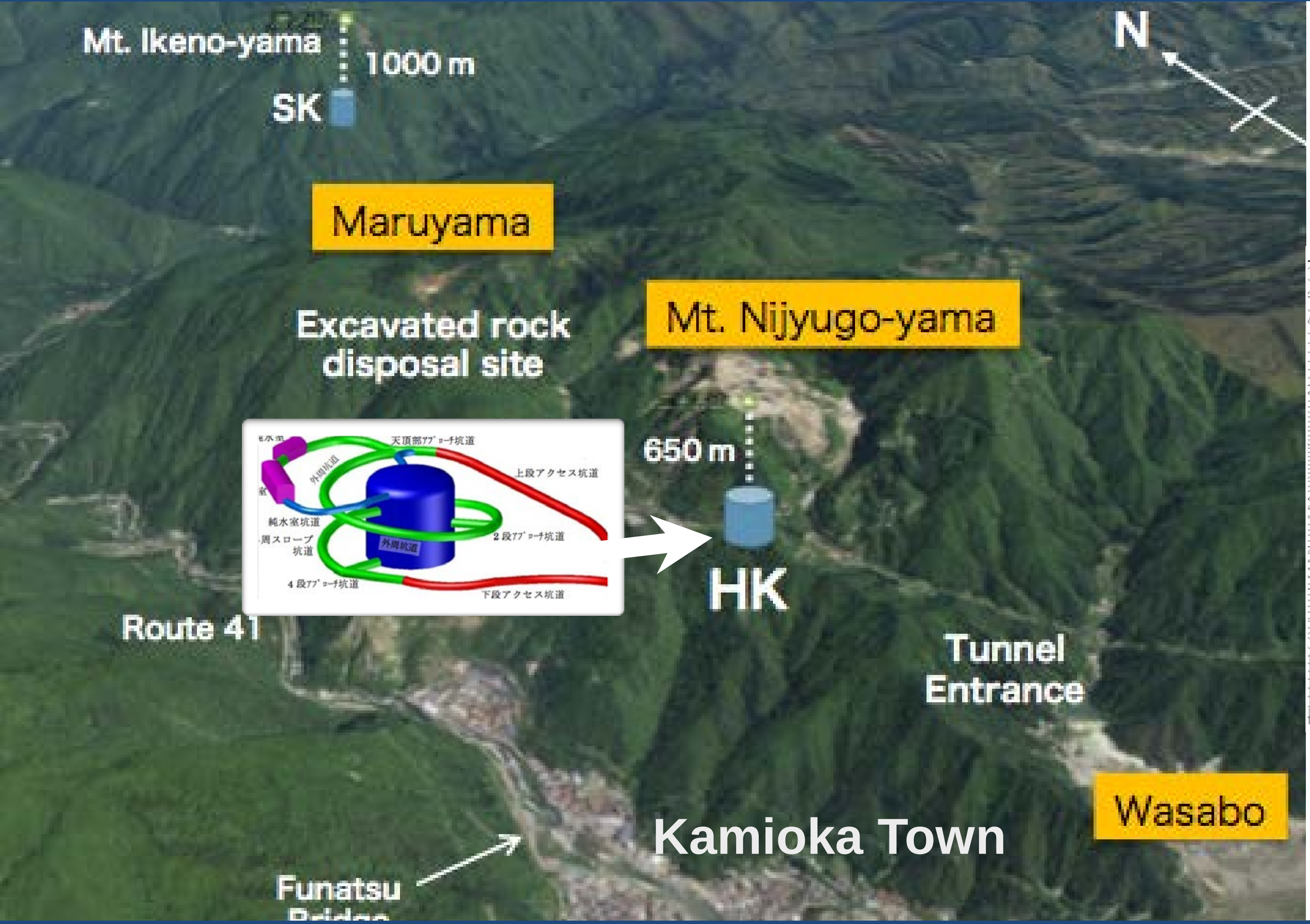
Hyper-K detector will be used to study:

- ✓ Neutrino oscillations with J-PARC neutrino beam(1.3MW beam),
- ✓ atmospheric neutrino oscillations,
- ✓ solar neutrino oscillations
- ✓ Proton decays
- ✓ Supernova neutrino burst
- ✓ Past supernova neutrinos
- ✓ ….

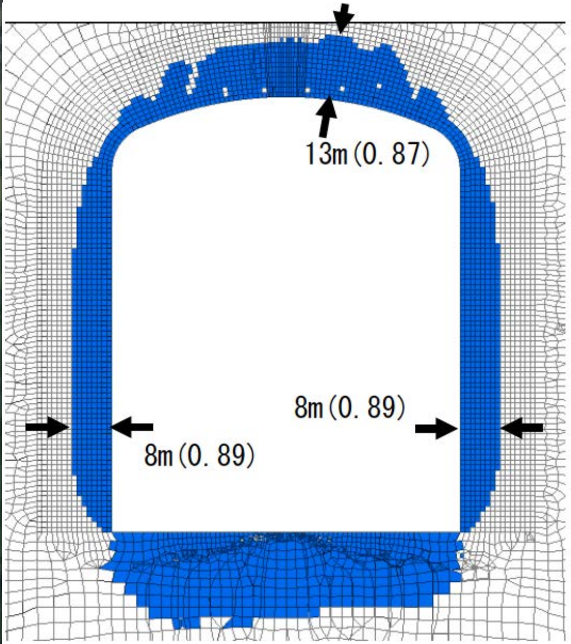
Hyper-Kamiokande proto-collaboration,
~340 members from 17 countries.
New members are most welcome!



Hyper-K location

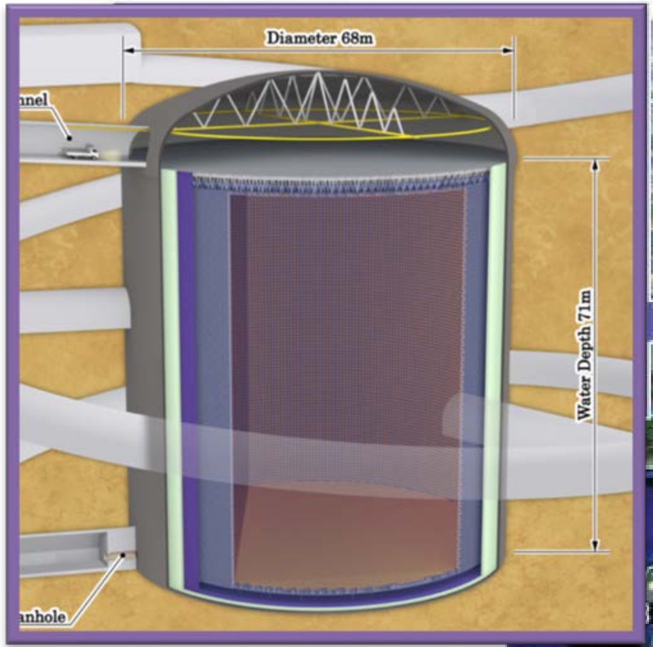


- ✓ ~8km south of Super-K.
- ✓ 295km from J-PARC and 2.5 deg. Off axis beam
- ✓ 650 m rock overburden



A result from a finite element analysis on cavity stability.
➔ OK with support structure.

Hyper-K with J-PARC neutrino beam



Hyper-K

J-PARC

22.5 kton (Super-K) to
19 Mton (Hyper-K)
= x 8.4

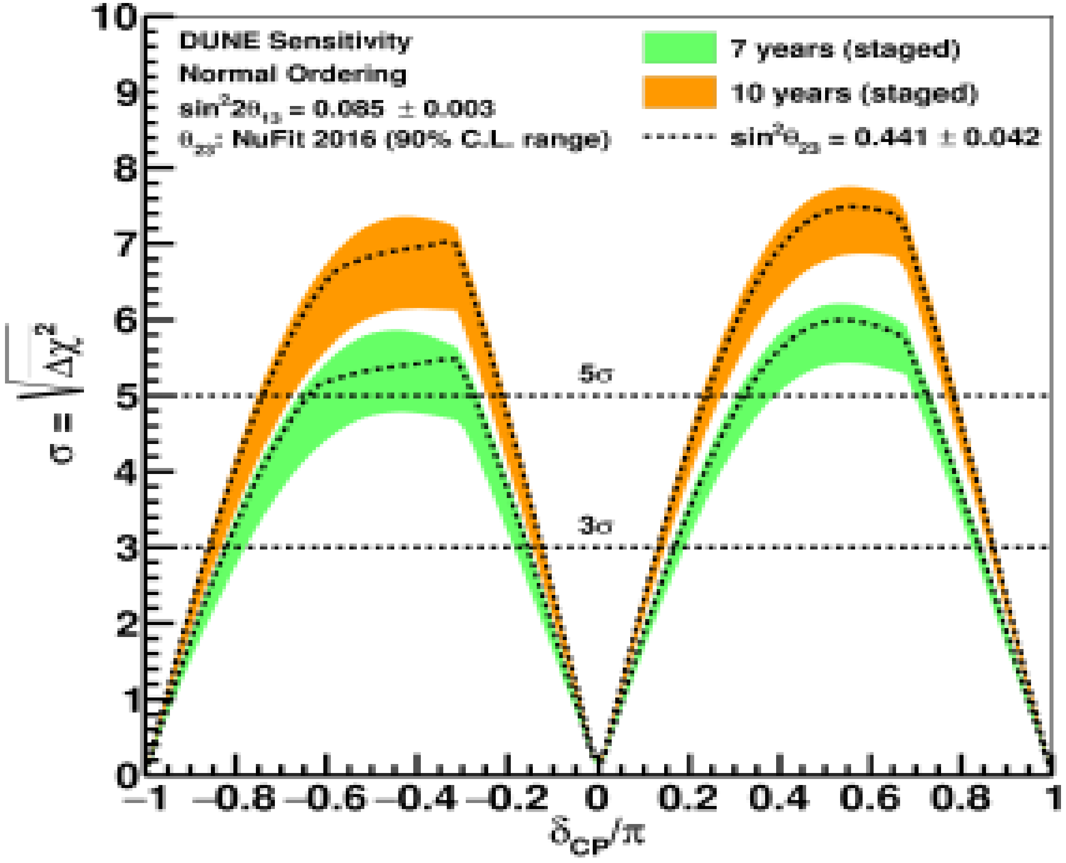
500 kW beam in 2019 to
1.3 MW beam in ~2028
= x 2.6

x ~22 higher neutrino event rate than T2K

Sensitivities

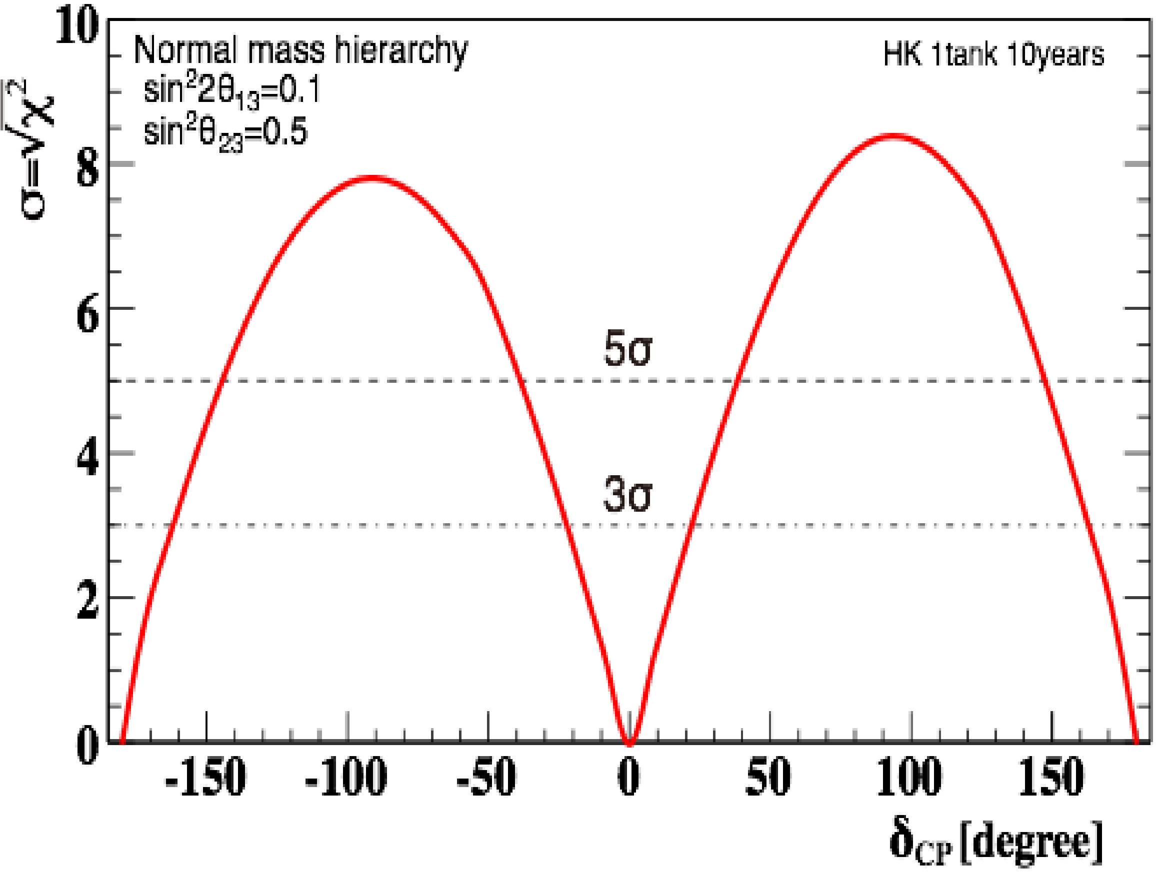
DUNE

(E. Worcester, nu2018)



Hyper-K

(M. Shiozawa, nu2018)



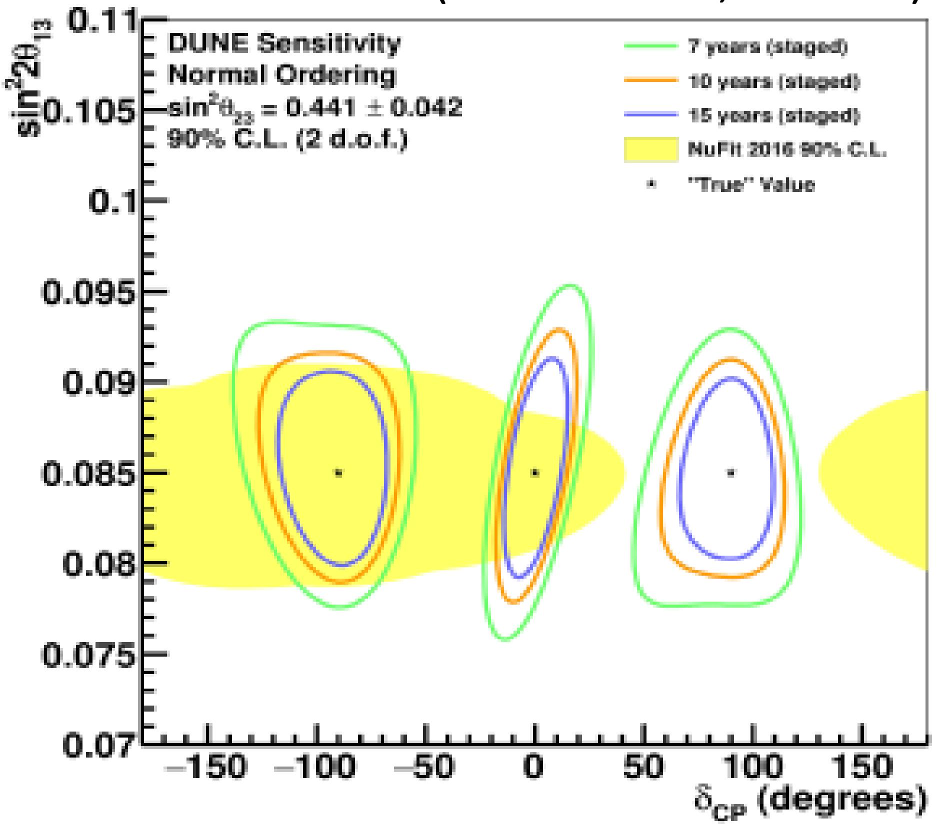
Complementarity

	DUNE	Hyper-K
Baseline	1300km ➔ Large matter effect (Good for Mass Ordering determination)	295km ➔ Small matter effect (Smaller effect of matter density uncertainty in δ_{CP})
Beam energy	~ Multi-GeV	~ Sub-GeV
Detector technology	Liq. Ar TPC	Water Cherenkov

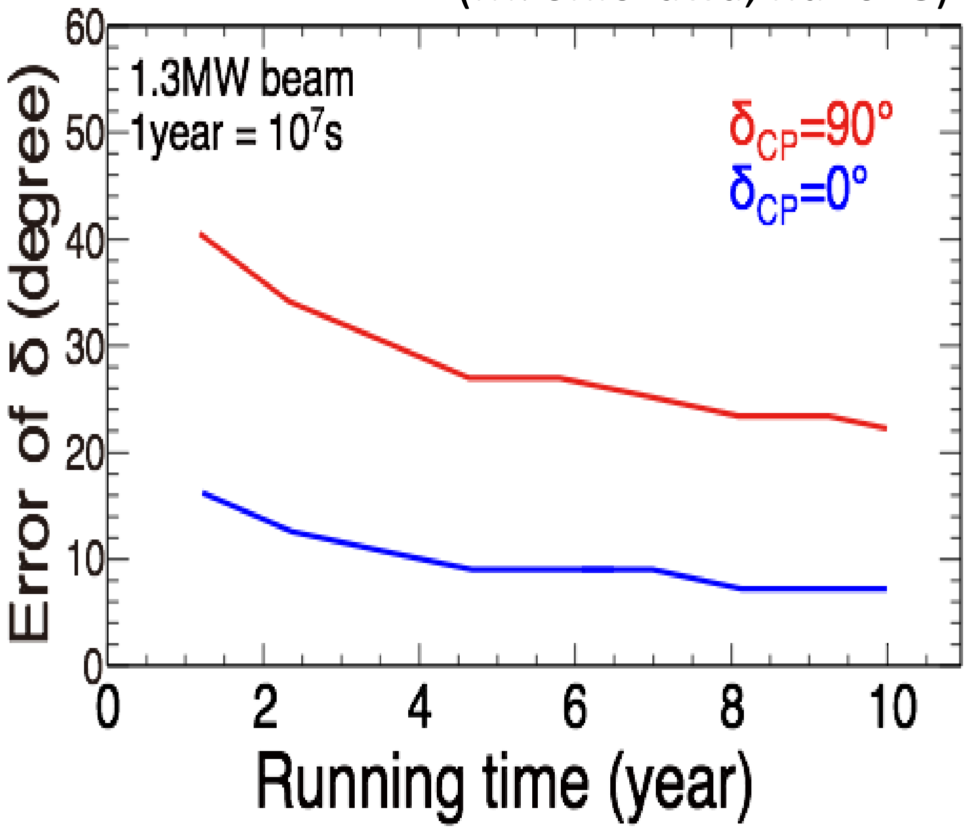
- ✓ ***We would like to be convinced the CP violation by the consistent results from these 2 experiments with very different systematics.***
- ✓ ***We hope that these 2 experiments will carry out the measurements in a similar timeline.***

After the initial CP results…

DUNE (E. Worcester, nu2018)



Hyper-K (M. Shiozawa, nu2018)



If the suggested CP phase by T2K and Super-K (around $3/2\pi$ or $-\pi/2$) is close to the real value, the determination of the CP phase angle will be rather poor.

➔ Should we better measure the phase angle? We would like to get inputs from theorists.

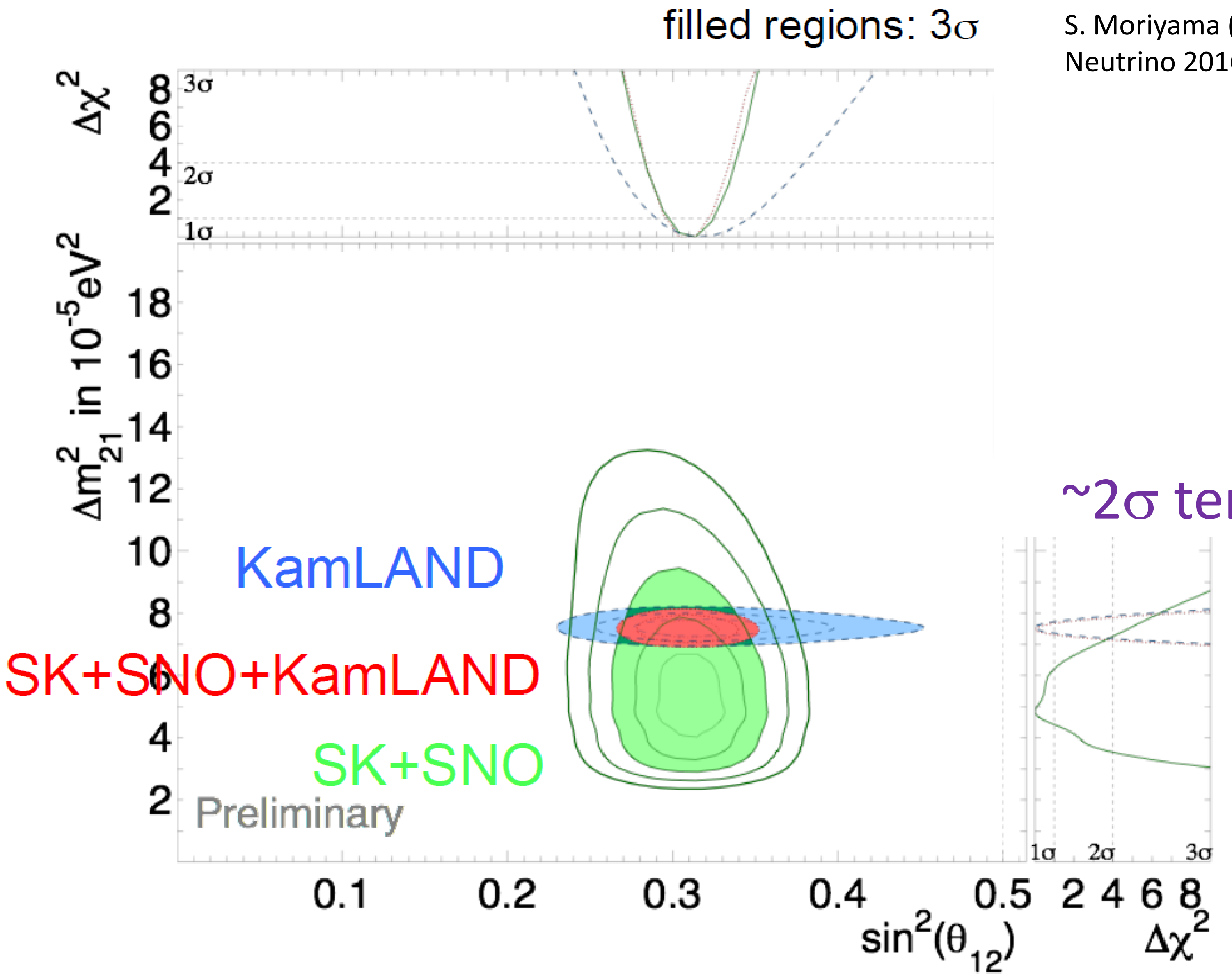
Other oscillation studies

Solar neutrino oscillations

Status of the 12-parameter measurements

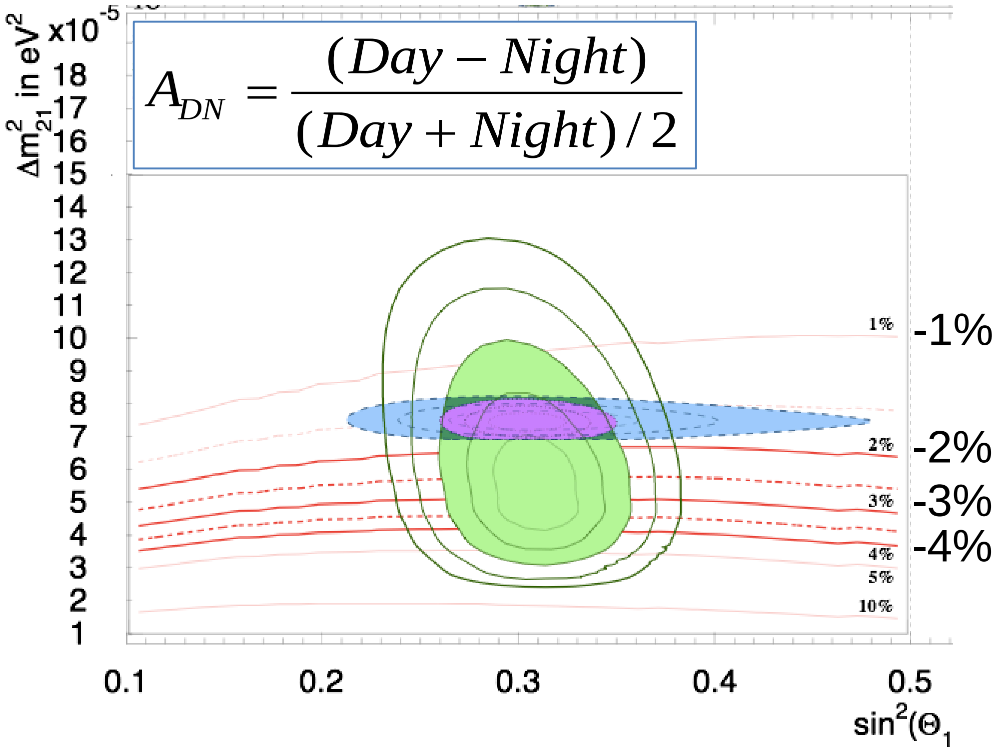
S. Moriyama (Super-K), Neutrino 2016

~2σ tension



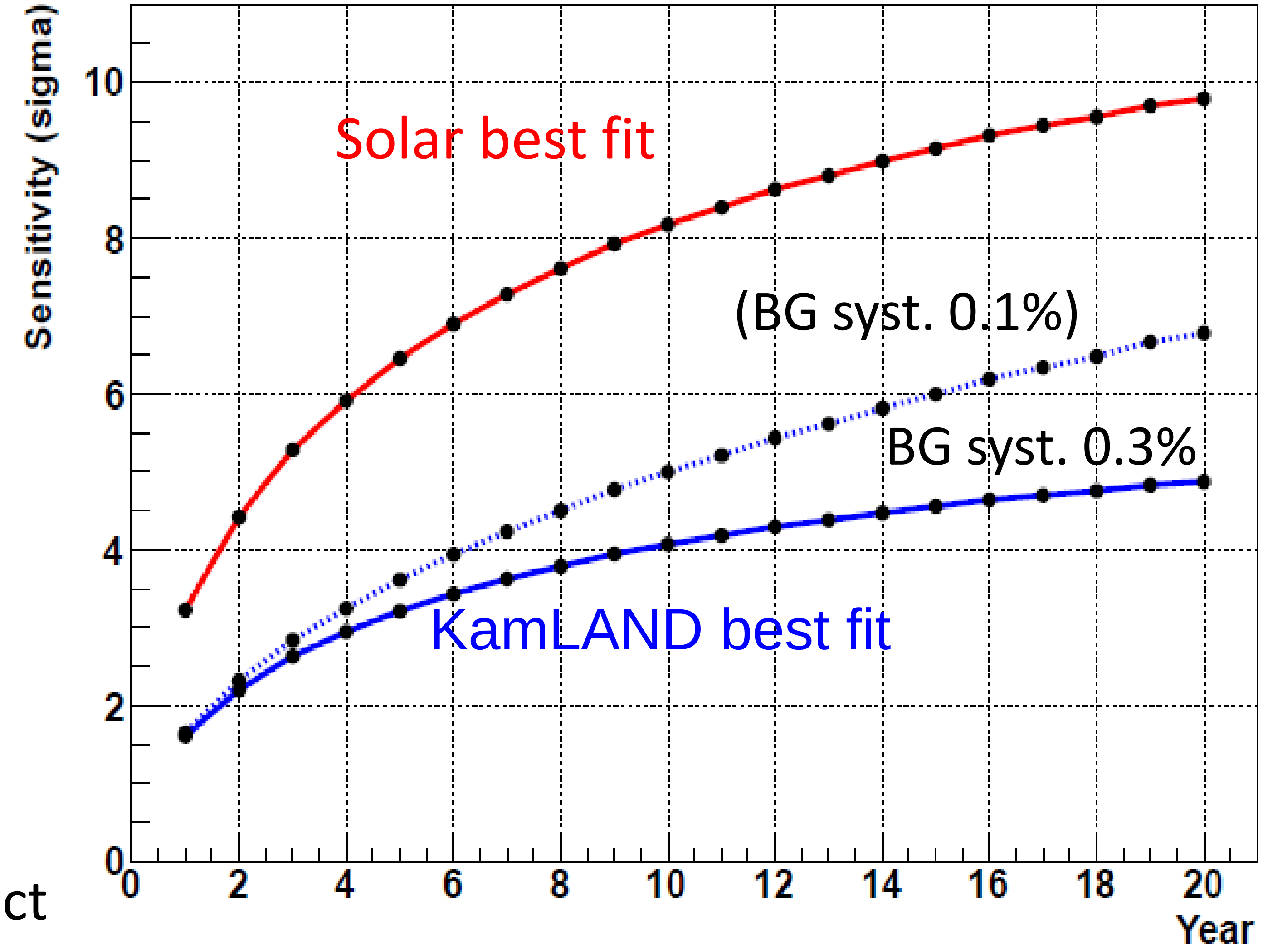
Day-night effect: Hyper-K

Day-Night effect and Δm_{12}^2



Day-night asymmetry sensitivity

(From no Day-Night asymmetry)



- ✓ Day-night effect is one of the keys;
  - to understand Δm_{12}^2
  - to confirm the standard matter effect

Appendix: Proton decay

Motivation

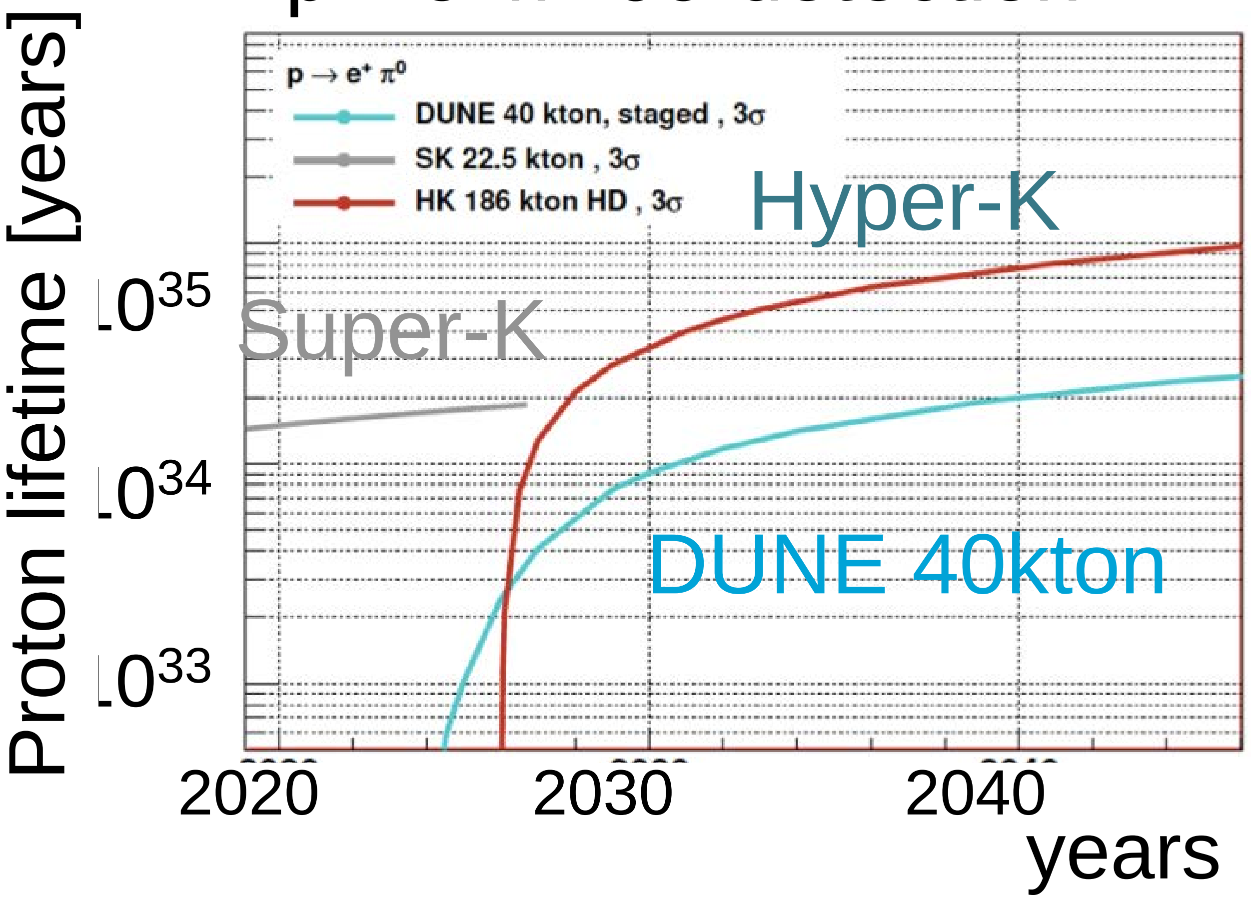
- ✓ It is clear that proton decay is very important for understanding of physics at the very high energy scale (GUTs).
- ✓ Neutrino masses/mixings and proton decays might be related to the physics at very high energy scale.

- ✓ We are in an extremely interesting era. New large neutrino detectors (JUNO, DUNE and Hyper-K) will begin the operation in the near future. These detectors are also very good proton decay detectors.
- ✓ Therefore, we should not forget the proton decay searches with the next generation “neutrino oscillation experiments”.

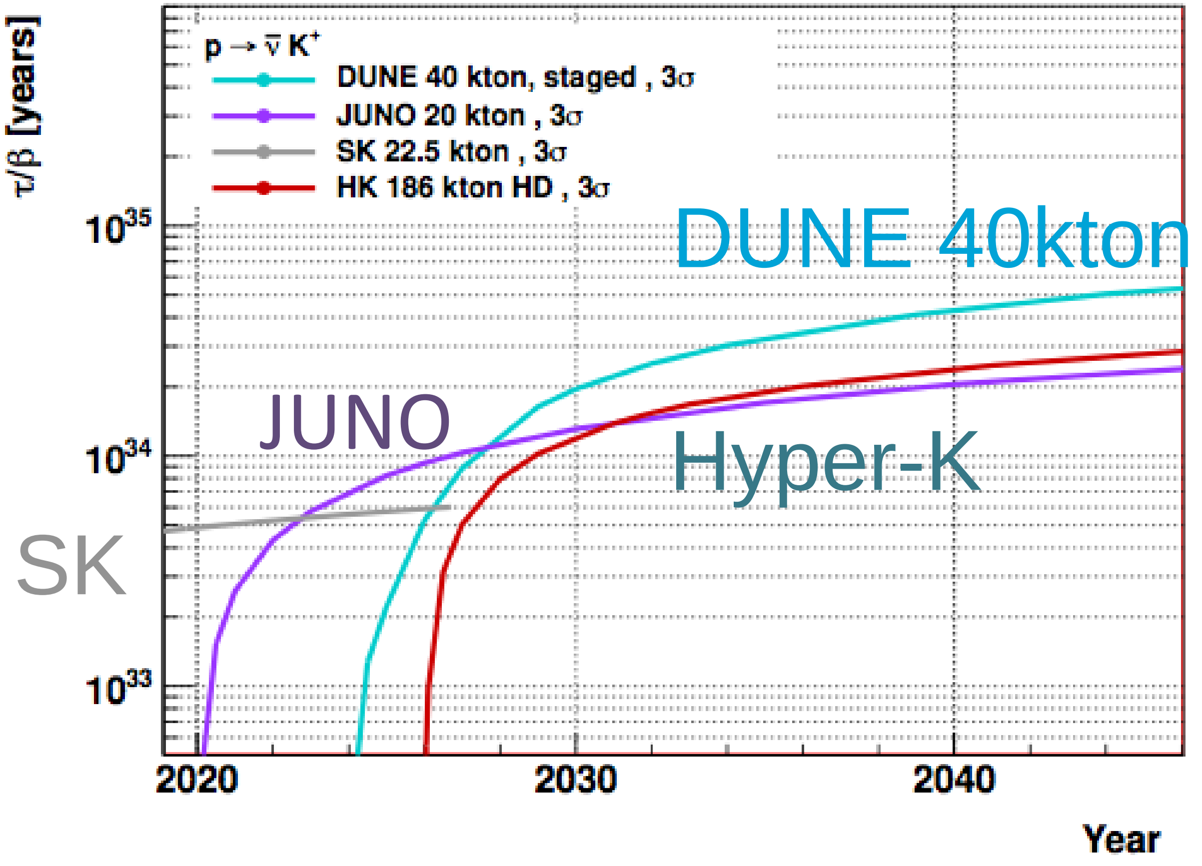
Proton decay sensitivities

DUNE arXiv:1601.05471
HK (M. Shiozawa)
JUNO arXiv:1507.05613

$p \rightarrow e^+\pi^0$ 3σ detection



$p \rightarrow \nu K^+$ 3σ detection

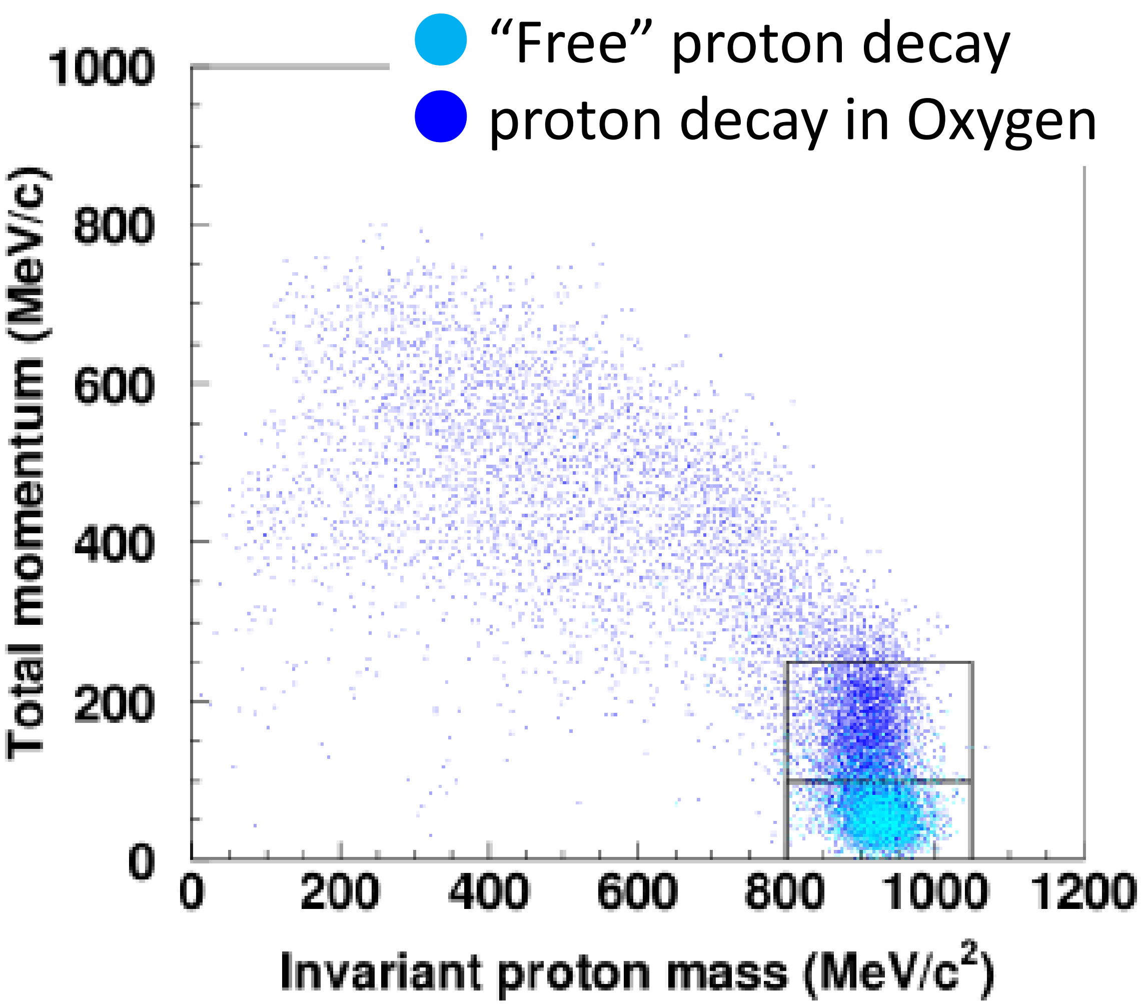


Hyper-K 3σ detection potential (20 years):
$\tau_p < 10^{35}$ years ($e\pi^0$) or $< 3\times10^{34}$ years (νk^+)

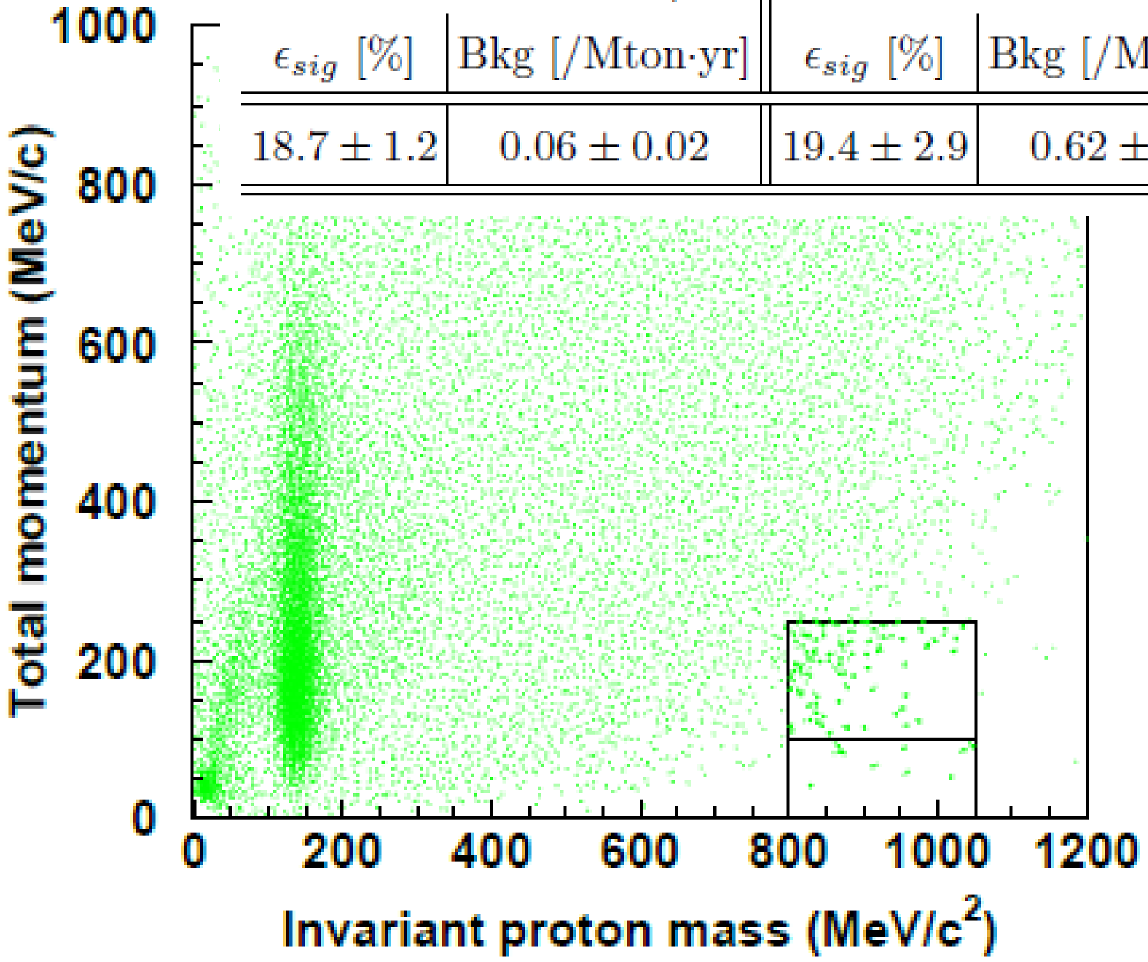
(Lines for DUNE and JUNO experiment have been generated based on numbers in the literature.)

Key plots for confirming $p \rightarrow e\,\pi^0$

(Hyper-K, arXiv:1805.04163v1)



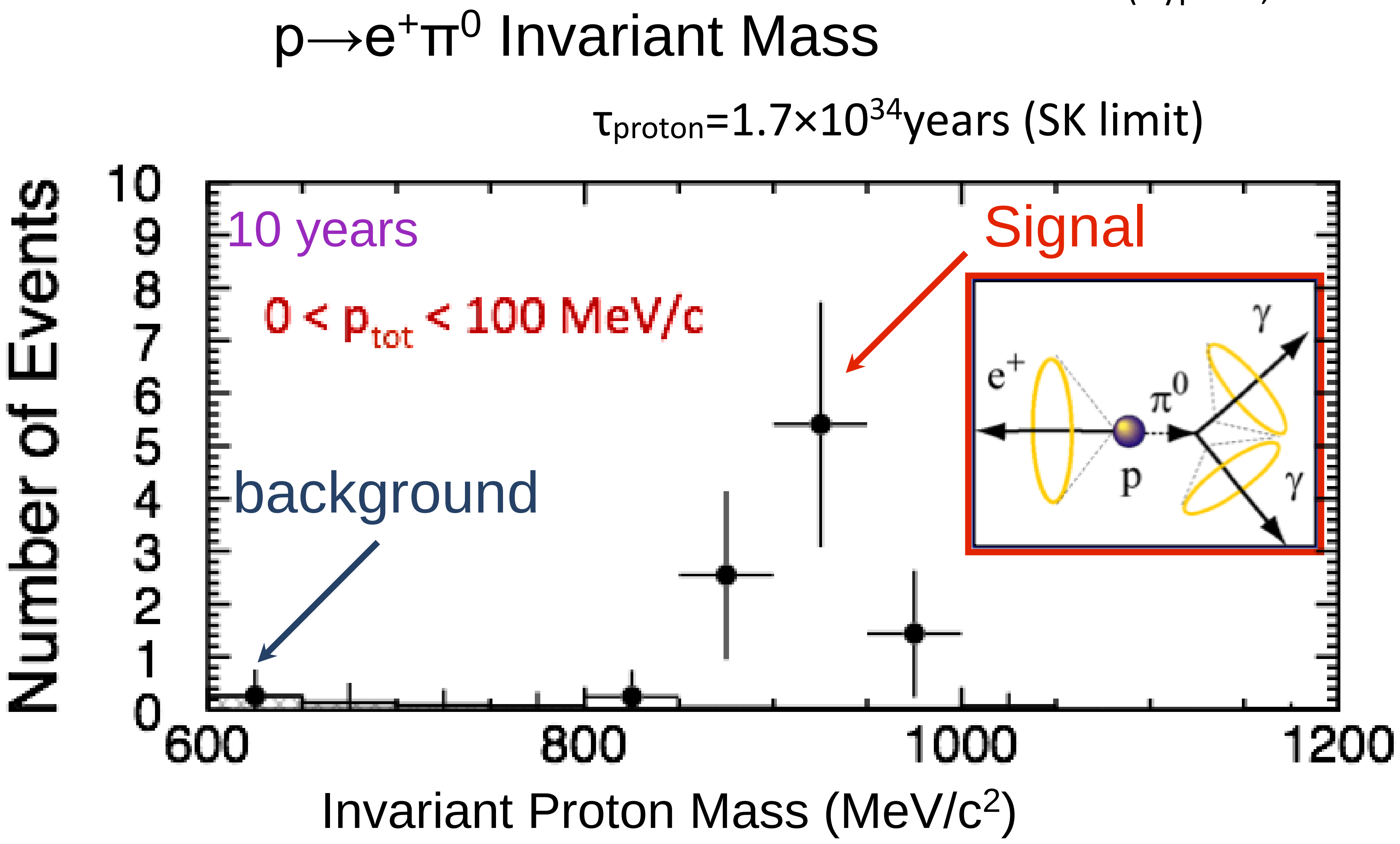
$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20



In order to reach 10^{35} years, "free" proton decay (from Hydrogen) is very important!

Key plots for confirming $p \rightarrow e\,\pi^0$

(Hyper-K, arXiv:1805.04163v1)



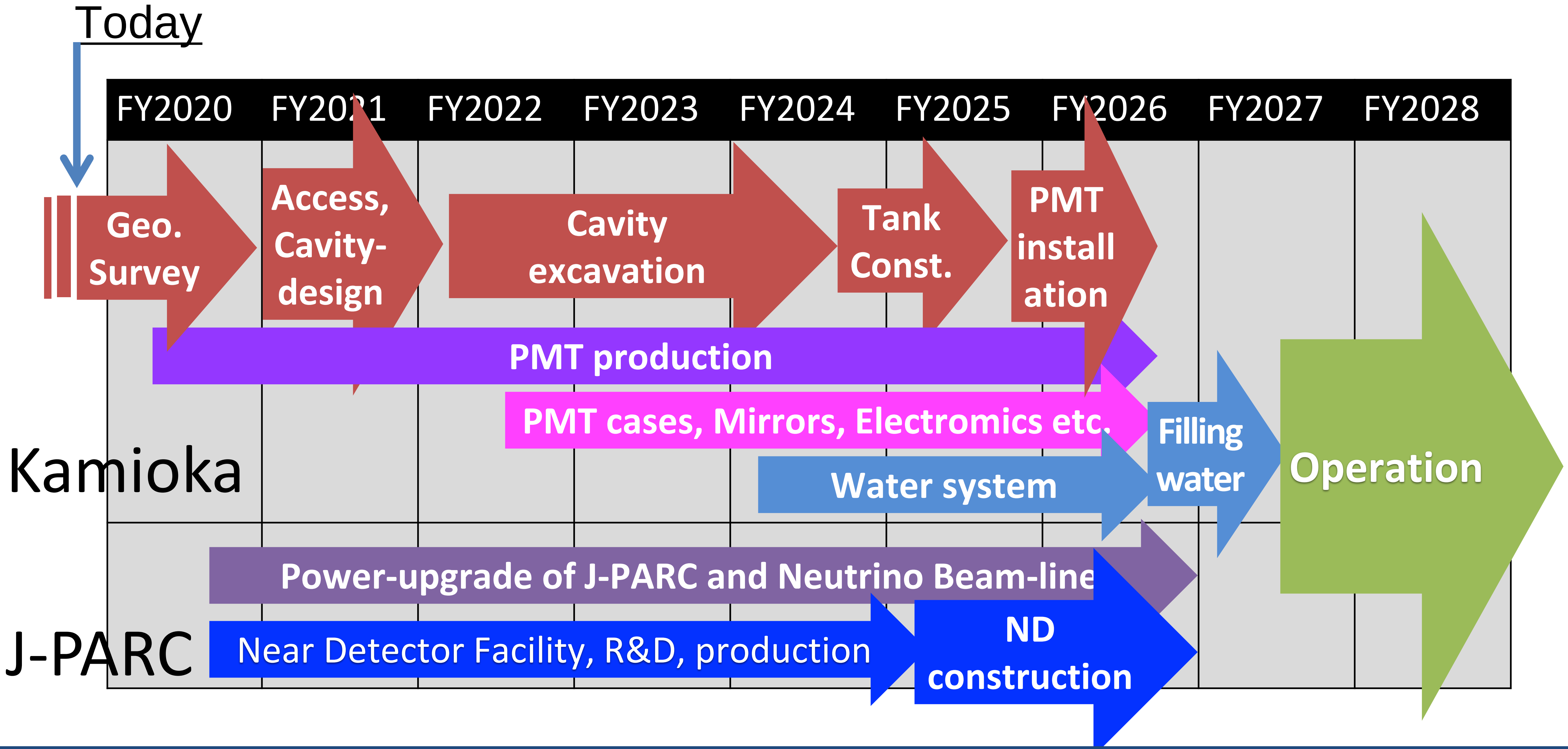
Status of Hyper-K

- ✓ In 2017, Hyper-K was selected as one of the 7 large scientific projects in the Roadmap of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT).
- ✓ In Japanese FY 2019, Hyper-K received the “seed funding” to prepare for the construction.
- ✓ On Dec. 13, 2019, the Japanese Cabinet has proposed the supplementary budget for FY2019. It includes the budget for the construction of Hyper-K.
- ✓ On Dec. 20, 2019, the Japanese Cabinet has proposed the regular budget for JFY 2020. It also includes the budget for the construction of Hyper-K.
- ✓ On January 30, 2020 (TODAY), the supplementary budget for JFY 2019 was approved by the Japanese Diet!

Hyper-K construction starts NOW!

You are most welcome to work together in Hyper-K!

Timeline


Today
FY2020
FY2021
FY2022
FY2023
FY2024
FY2025
FY2026
FY2027
FY2028
Geo. Survey
Access, Cavity-design
Cavity excavation
Tank Const.
PMT install ation
PMT production
PMT cases, Mirrors, Electromics etc.
Water system
Filling water
Operation
Kamioka
Power-upgrade of J-PARC and Neutrino Beam-line
Near Detector Facility, R&D, production
ND construction
J-PARC

Summary

- Experiments in Kamioka have been contributing to neutrino physics:
  - Kamiokande observed supernova neutrinos and the atmospheric neutrino deficit, and confirmed the solar neutrino deficit.
  - Super-Kamiokande discovered neutrino oscillations, and contributed to the solar neutrino oscillation and to the LBL neutrino oscillation experiments.
  - KamLAND observed reactor neutrino oscillations and geo-neutrinos.
- We would like to continue contributing to neutrino physics with the next generation experiment, Hyper-K.
- The Hyper-K project is approved. The experiment will start in ~2027!

We would like to work together with the Spanish and International colleagues in the Hyper-K project.