Kavli IPMU 10th anniversary symposium
Kashiwa, Oct. 16, 2017

Atmospheric Neutrino Experiments

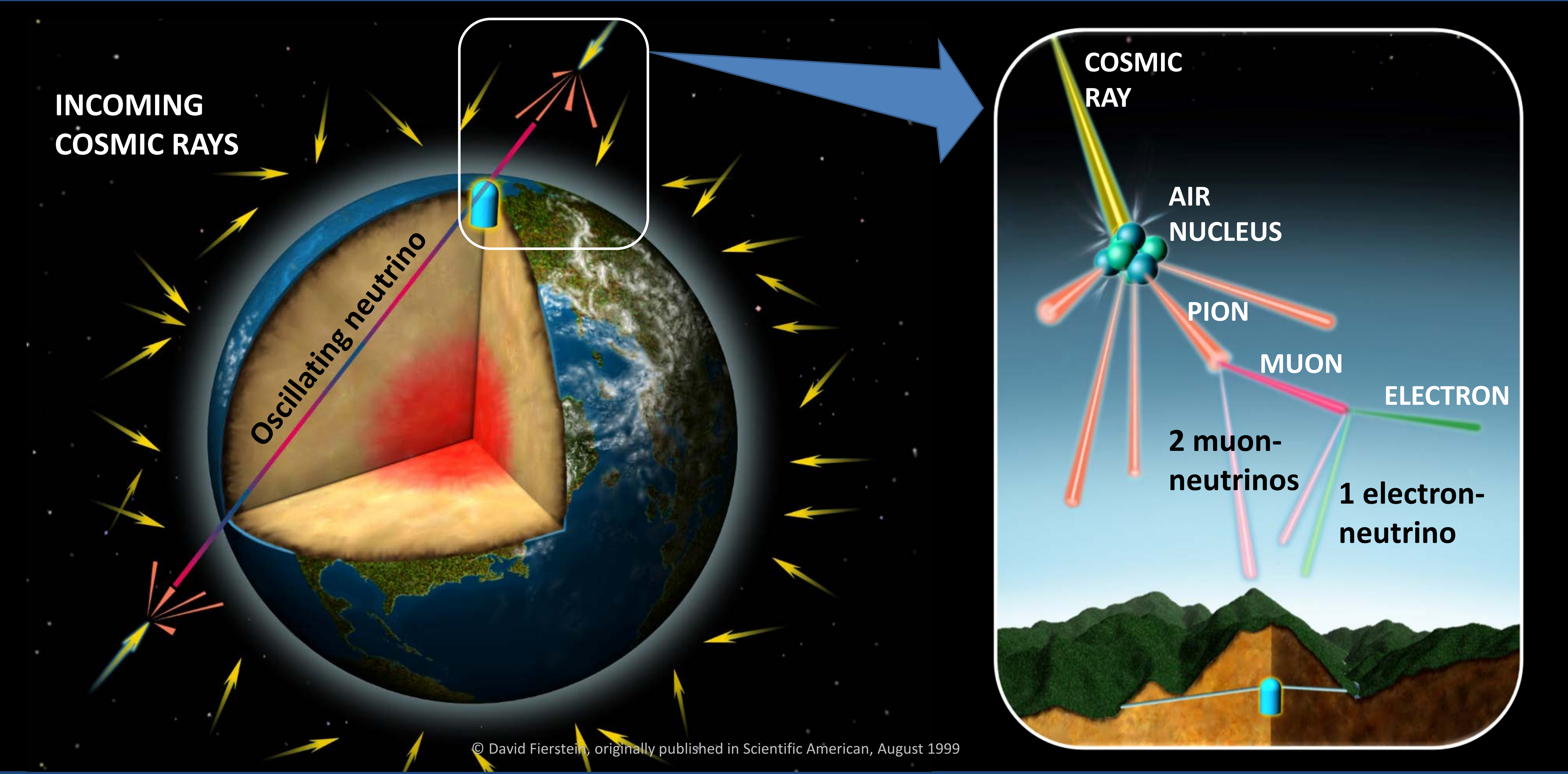
Takaaki Kajita
ICRR and Kavli IPMU, Univ. of Tokyo

outline

- Introduction & Before Oct. 2007
- The last 10 years
- Future prospect
- Summary

Introduction & Before Oct. 2007

Atmospheric neutrinos



Discovery of atmospheric neutrinos (1965)


Photo by H.Sbel

In 1965, atmospheric neutrinos were observed for the first time by detectors located very deep underground.

← In South Africa
F. Reines et al., PRL 15, 429 (1965)

→ In India
C.V. Achar et al., PL 18, 196 (1965)

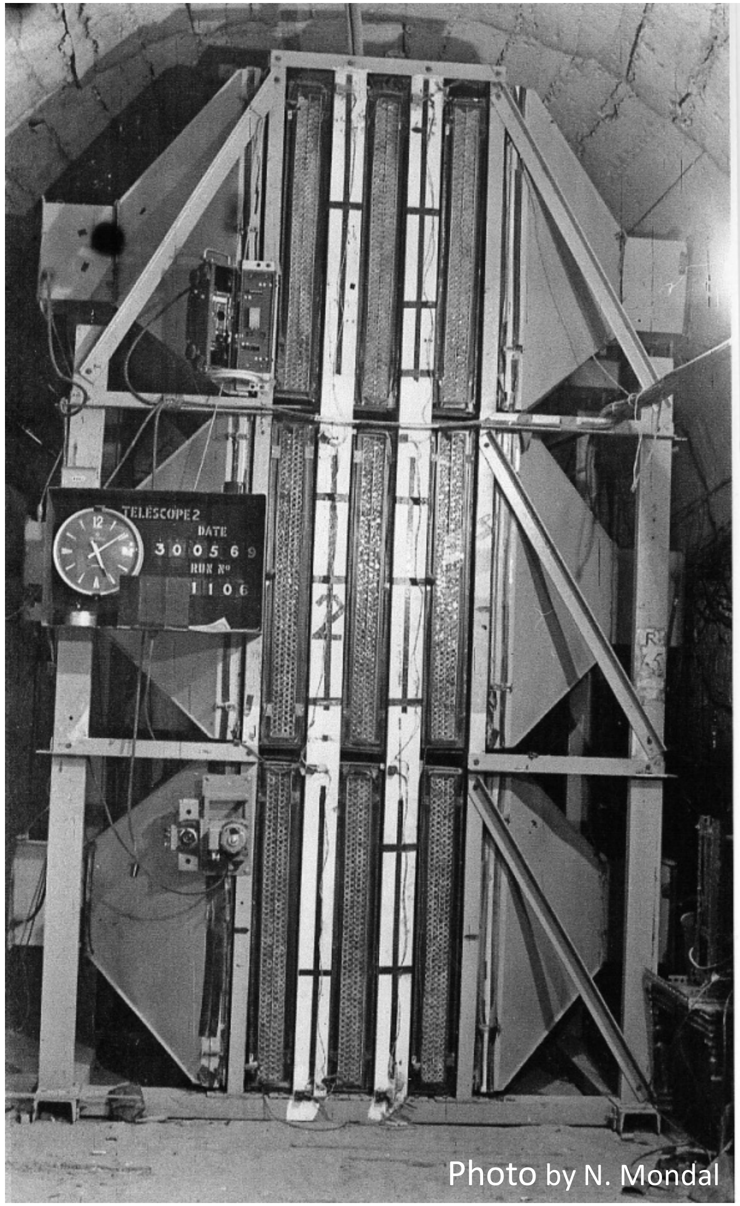
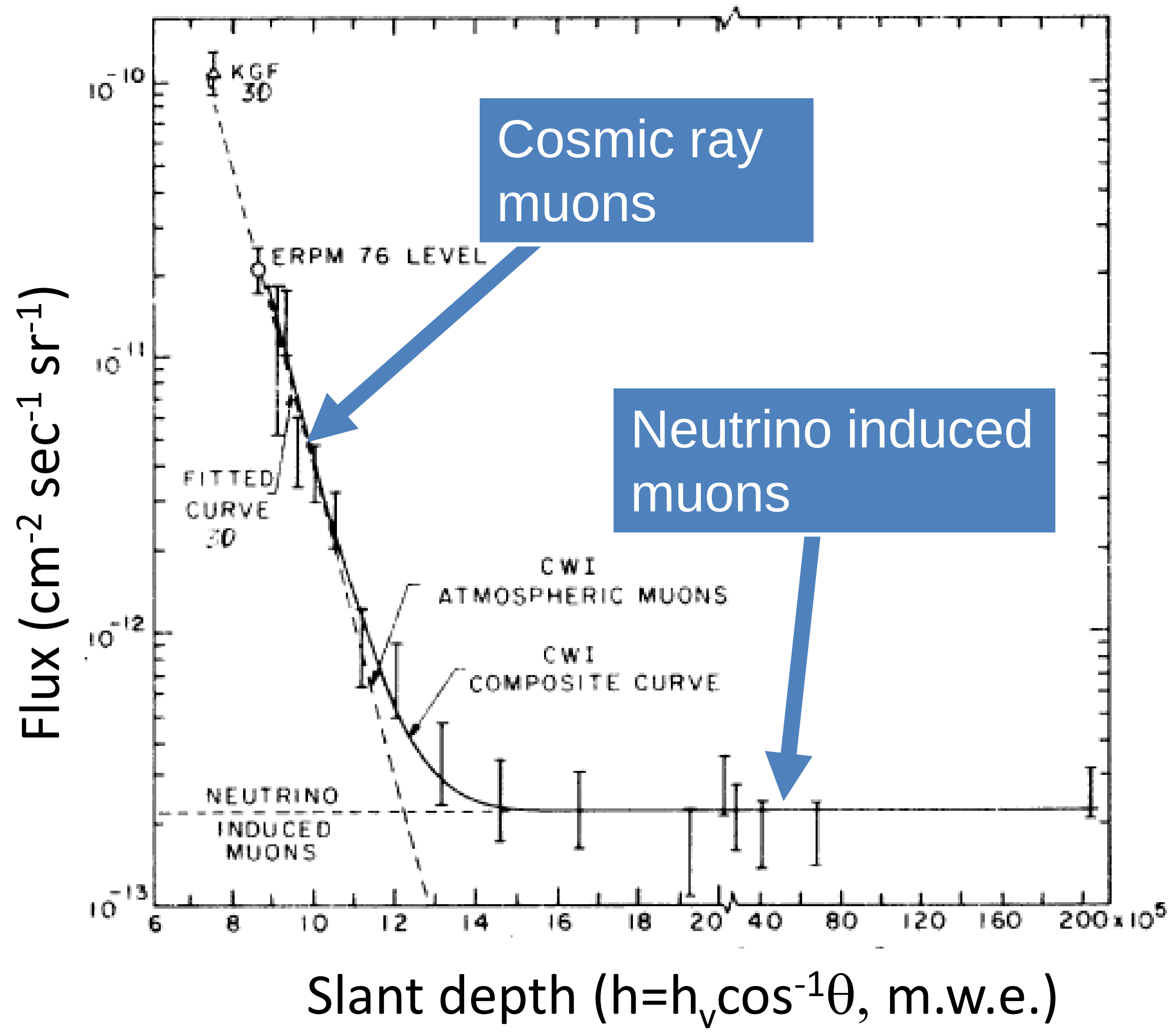


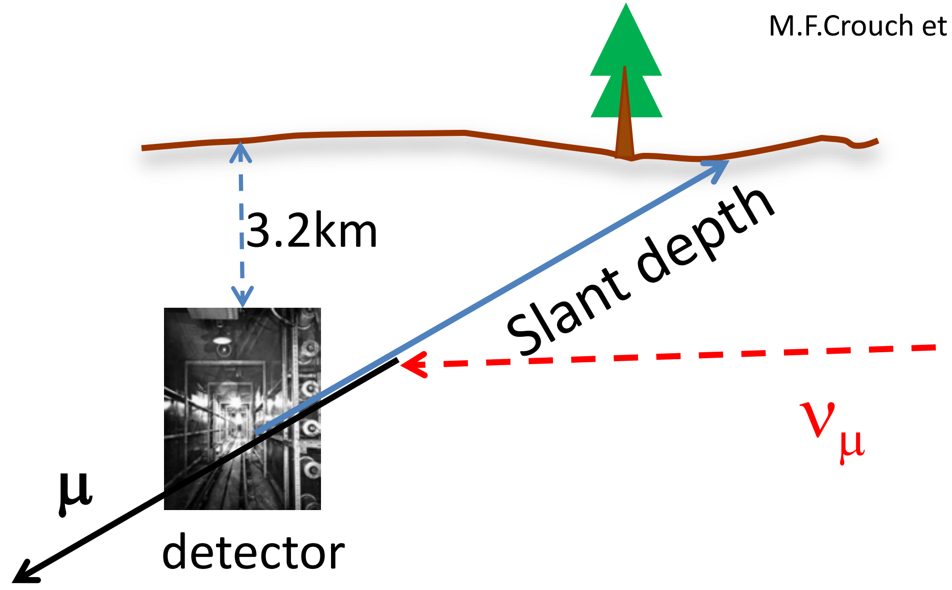
Photo by N. Mondal

Slant depth distribution

(from the South Africa experiment 1978)

M.F.Crouch et al., PRD 18 (1978) 2239

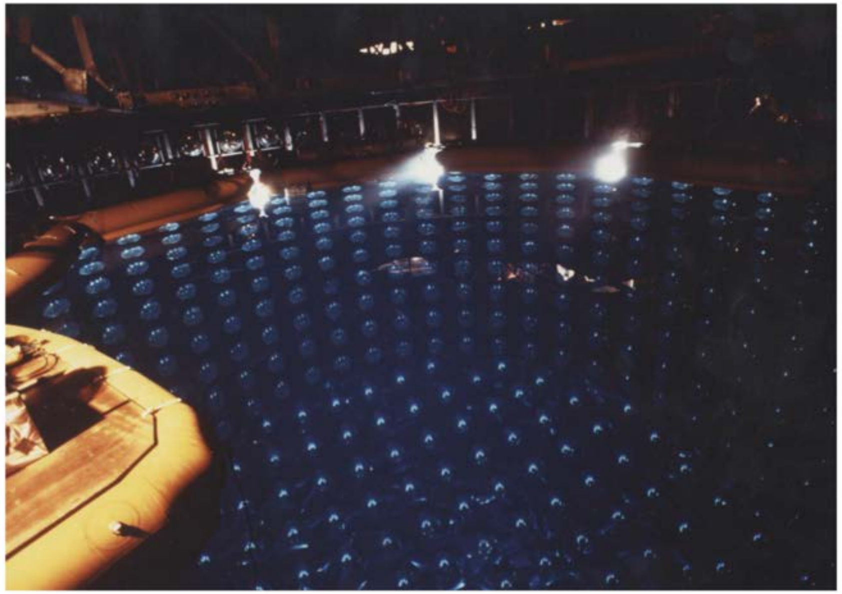




<u>Paper conclusion:</u>

We conclude that there is fair agreement between the total observed and expected neutrino induced muon flux, i.e., Flux (predicted)/ Flux (observed) =1.6+/-0.4. The uncertainty arises from the neutrino fluxes (+/-30% ….)

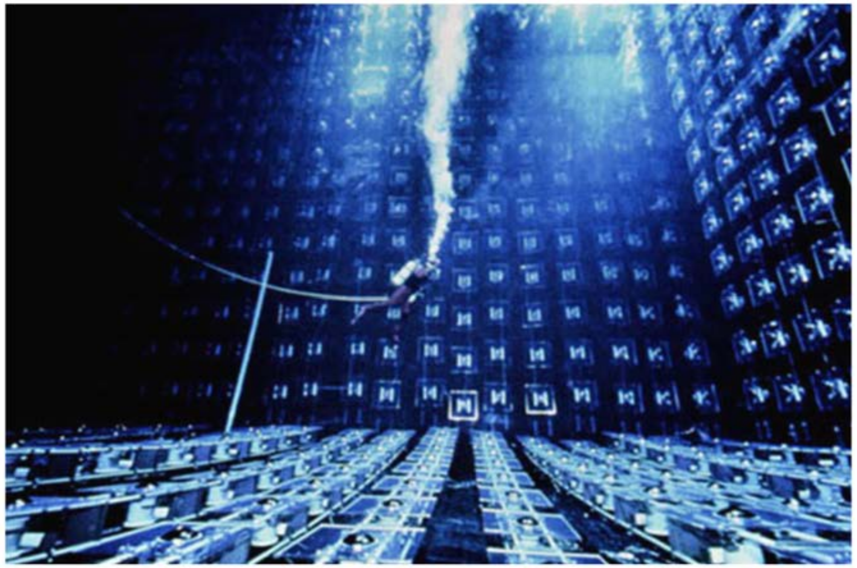
Proton decay experiments (1980's)



Grand Unified Theories
(in the 1970's)
➔ $\tau_p = 10^{30\pm2}$ years

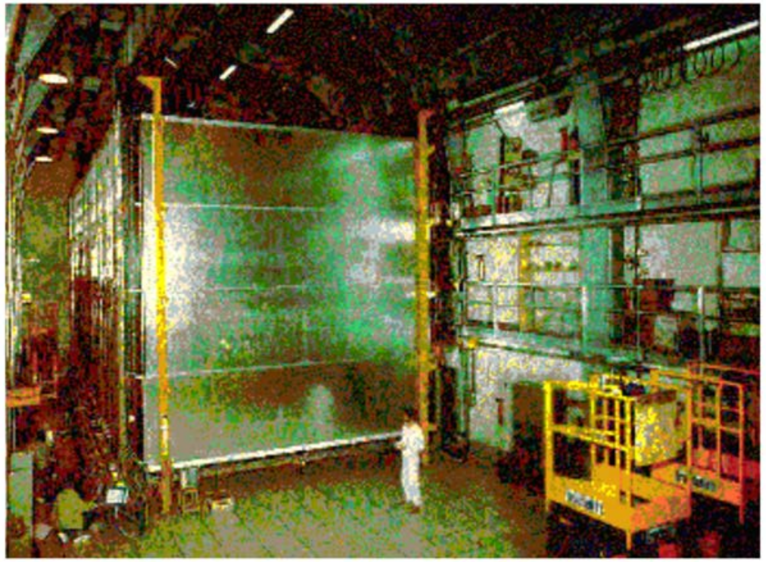
Kamiokande
(1000ton)

IMB
(3300ton)



NUSEX
(130ton)

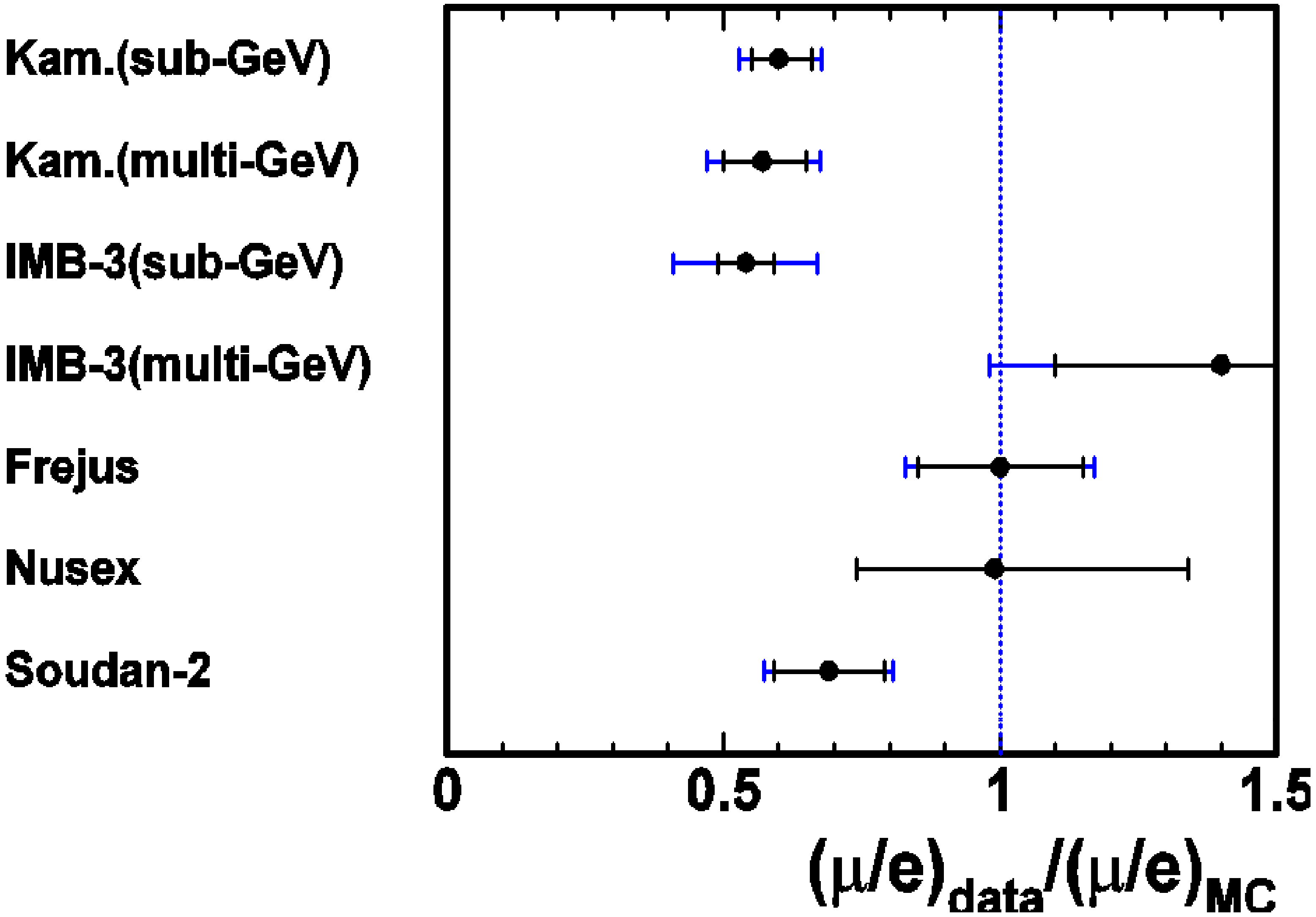
Frejus
(700ton)



These experiments had to study atmospheric neutrinos as the most serious background for the proton decay searches.

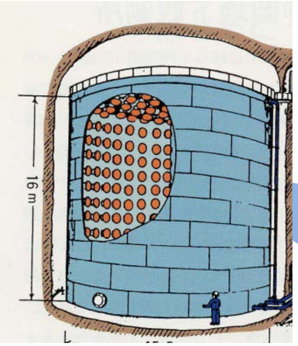
Fewer muon neutrinos than expected

Some of the large underground detectors observed the deficit of atmospheric muon-neutrinos.
However, the detectors in the 1980's and early 90's did not have powerful enough to find the reason for the deficit….

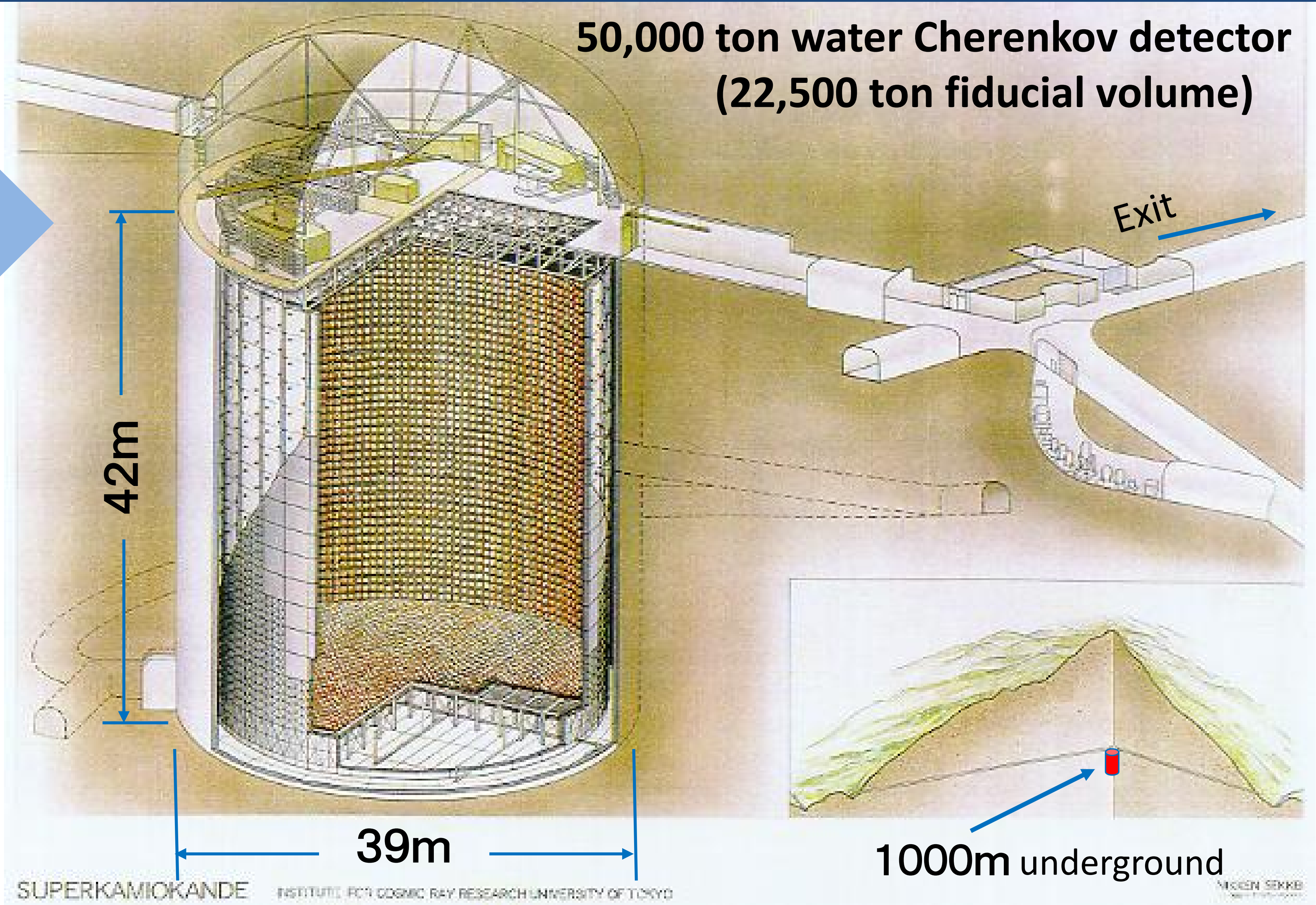


K. Hirata et al, Phys.Lett.B 205 (1988) 416.
M. Aglietta, et al., 1989, Europhys. Lett. 8, 611
Ch. Berger et al., Phys. Lett. B 227 (1989) 489.
Ch. Berger et al., Phys. Lett. B 245 (1990) 305.
D. Casper et al., PRL **66** (1991) 2561.
K.S. Hirata, et al., Phys. Lett. B 280 (192) 146.
R. Becker-Szendy, PRD **46** (1992) 3720.
Kamiokande Phys. Lett. B 335, 237 (1994)
WWM. Allison et al., Phys. Lett. B 391 (1997) 491.
R. Clark, et al., Phys. Rev. Lett. 79, (1997) 345.
And more...

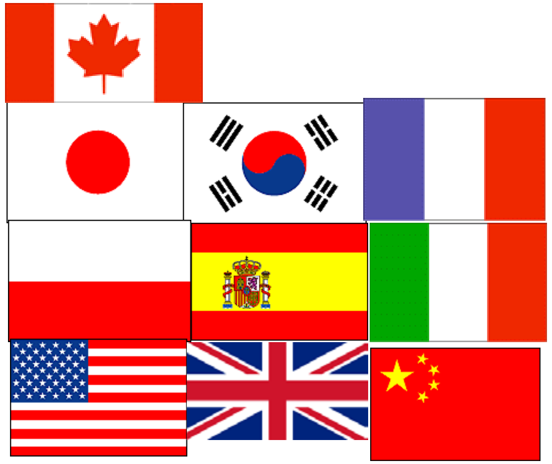
Super-Kamiokande detector



About 20 times
larger mass

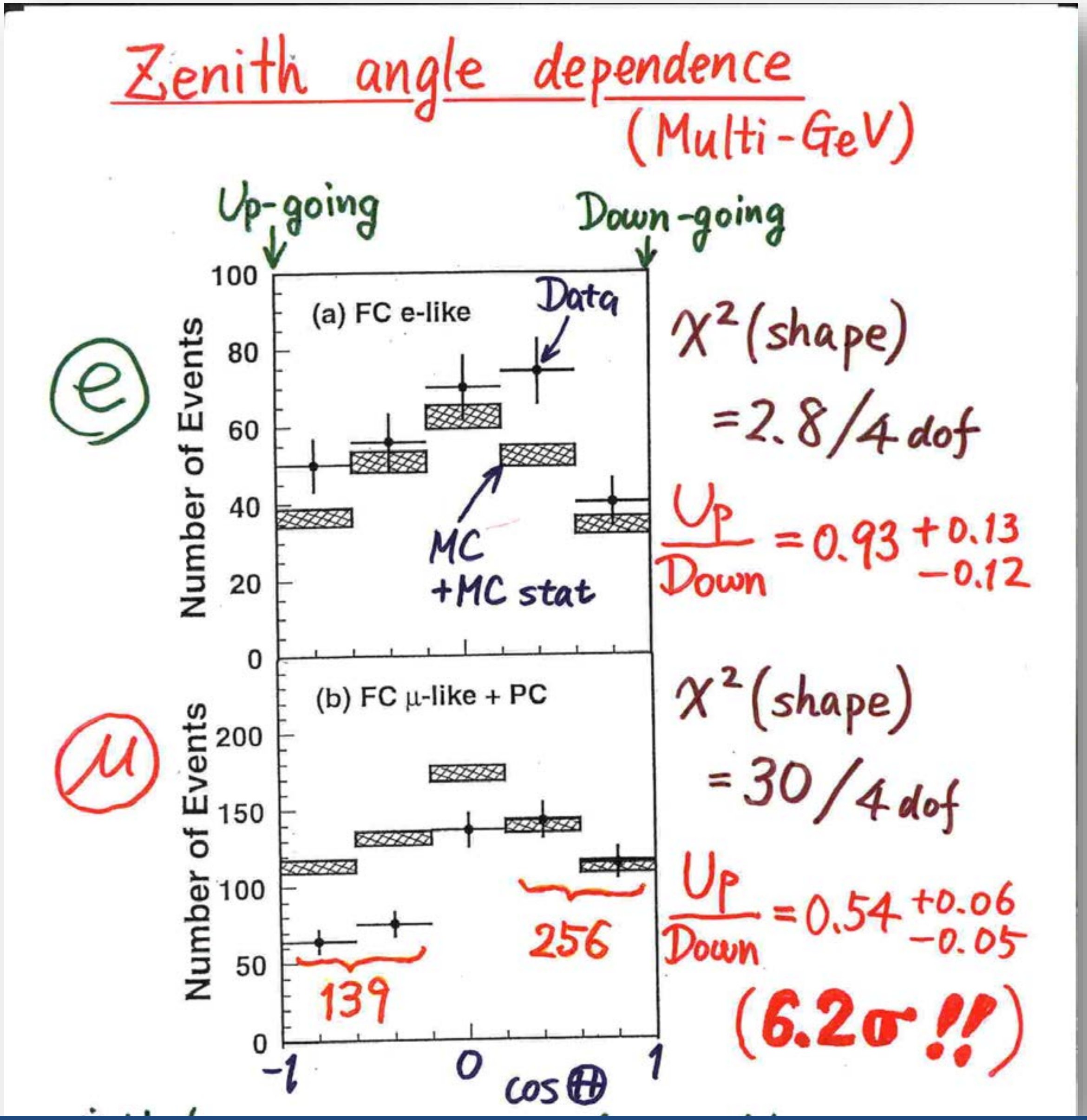


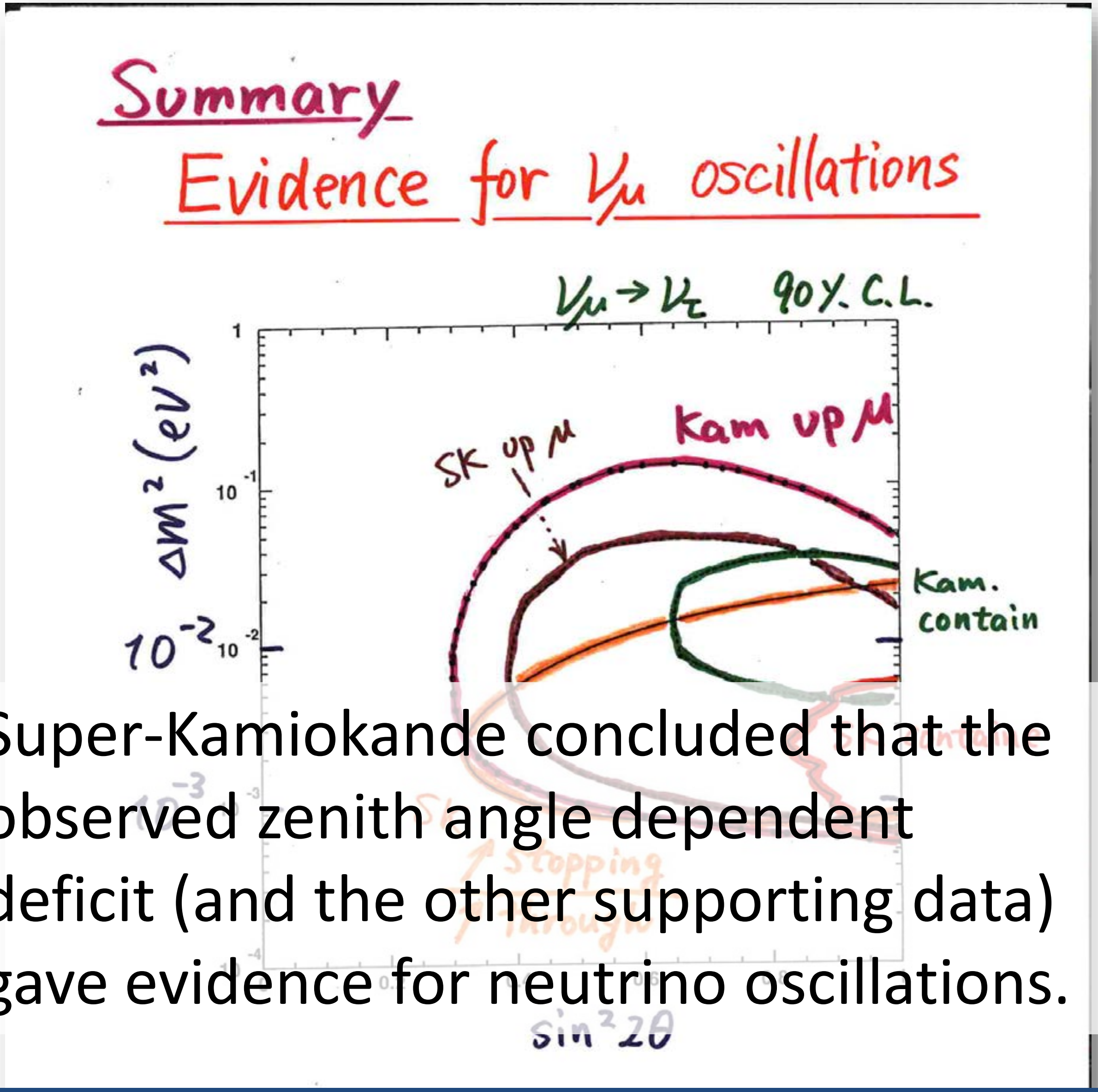
~160 collaborators



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

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





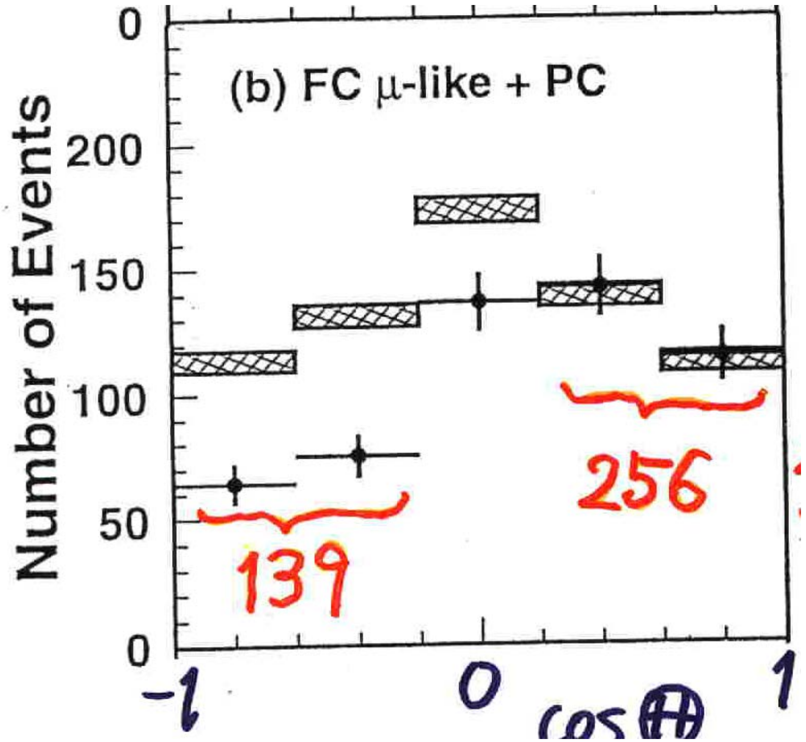
Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

The last 10 years

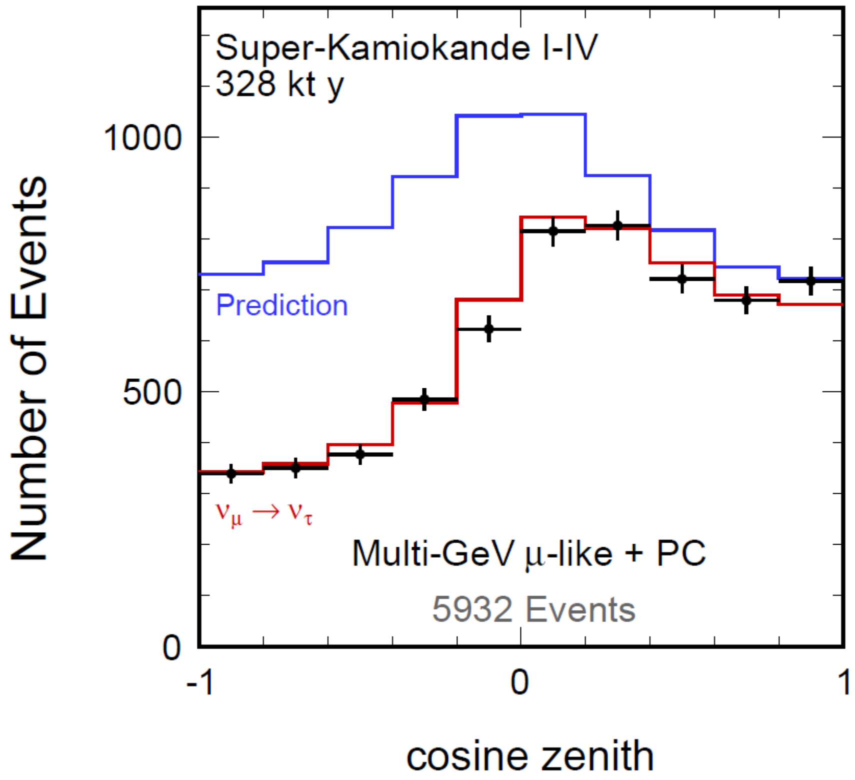
Kavli-IPMU has been playing an important role in the studies of atmospheric neutrinos.

Data updates

Super-K @Neutrino98 → Super-K (2016)



Super-K @Neutrino 2016



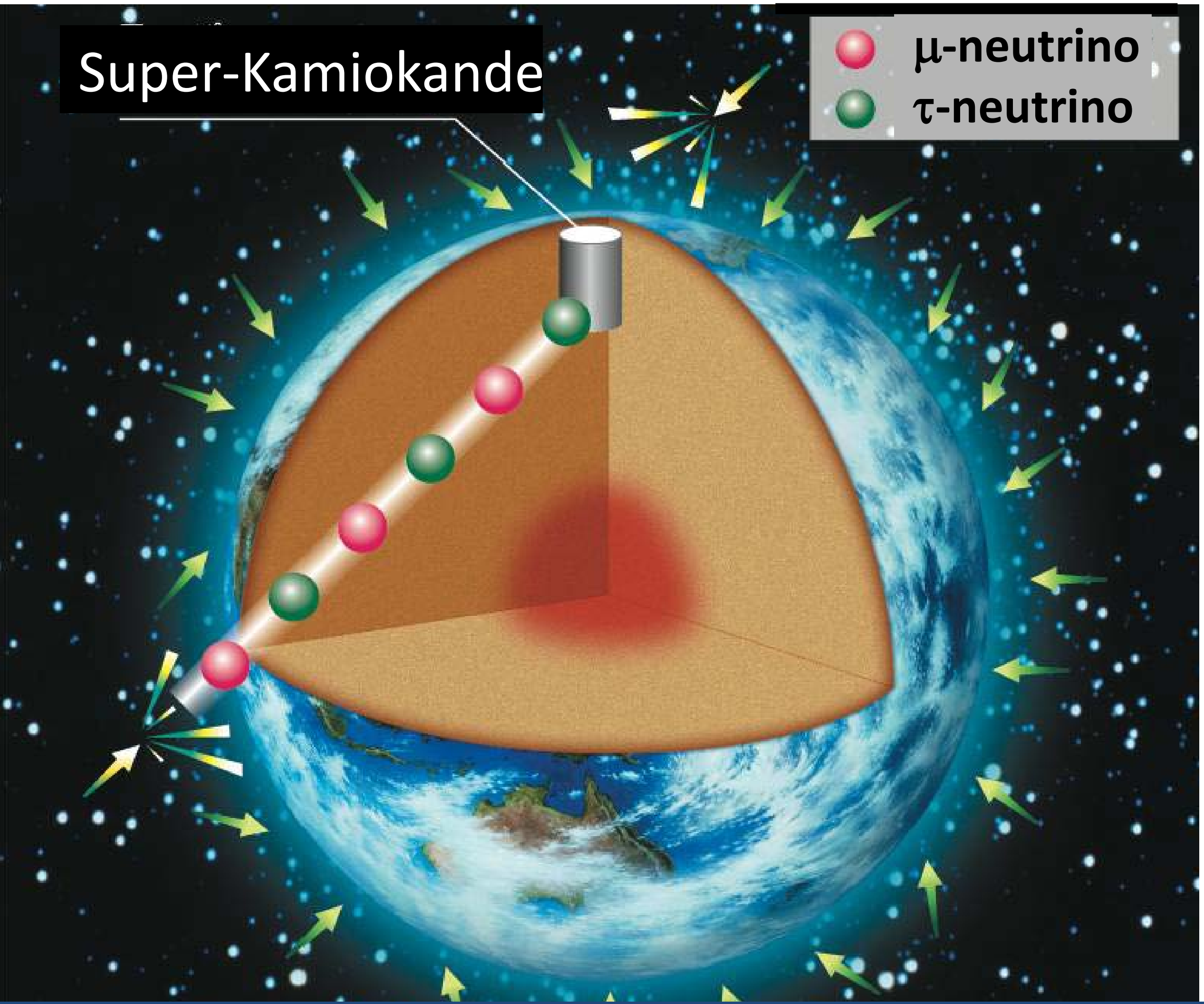
Number of events plotted:

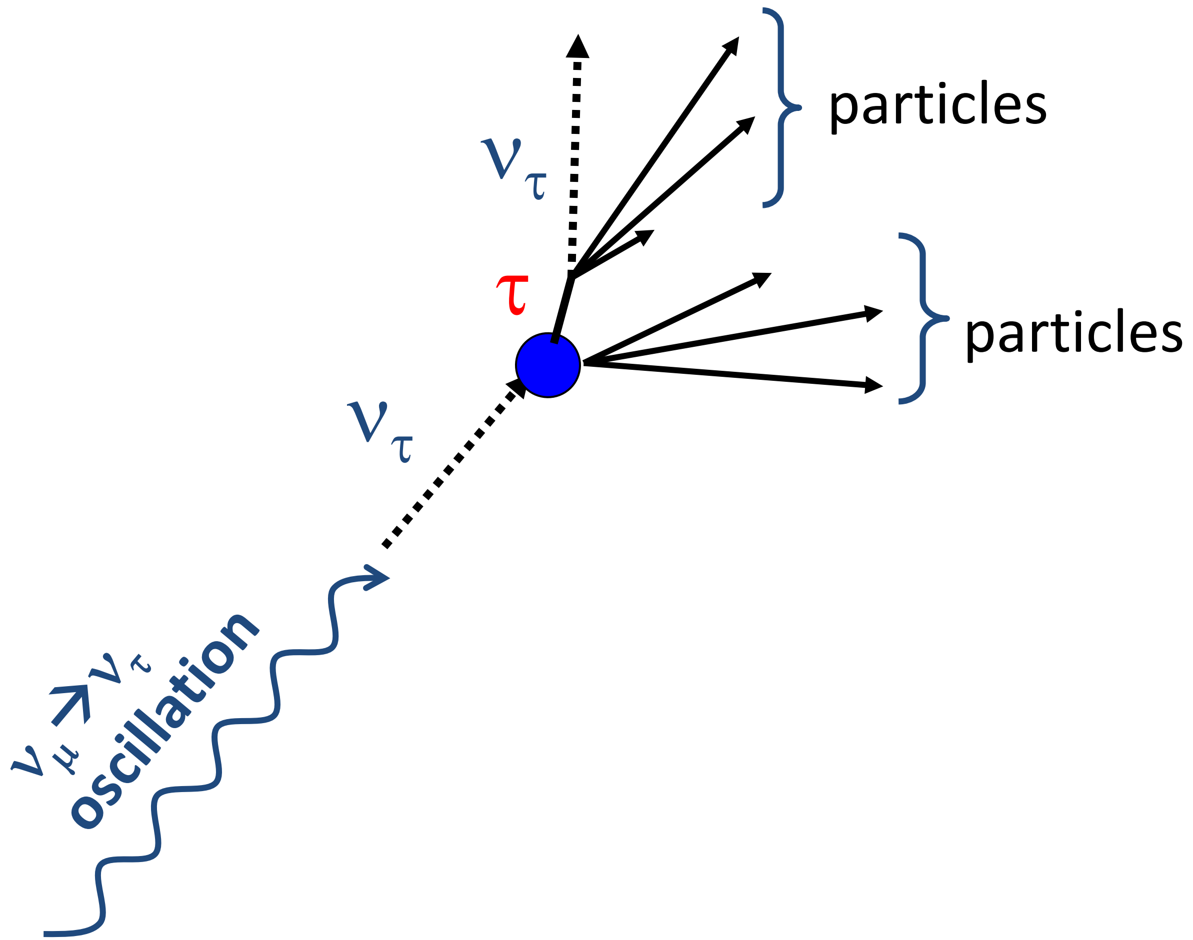
531 events → 5932 events

Detailed studies of oscillations!

tau neutrino appearance?

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

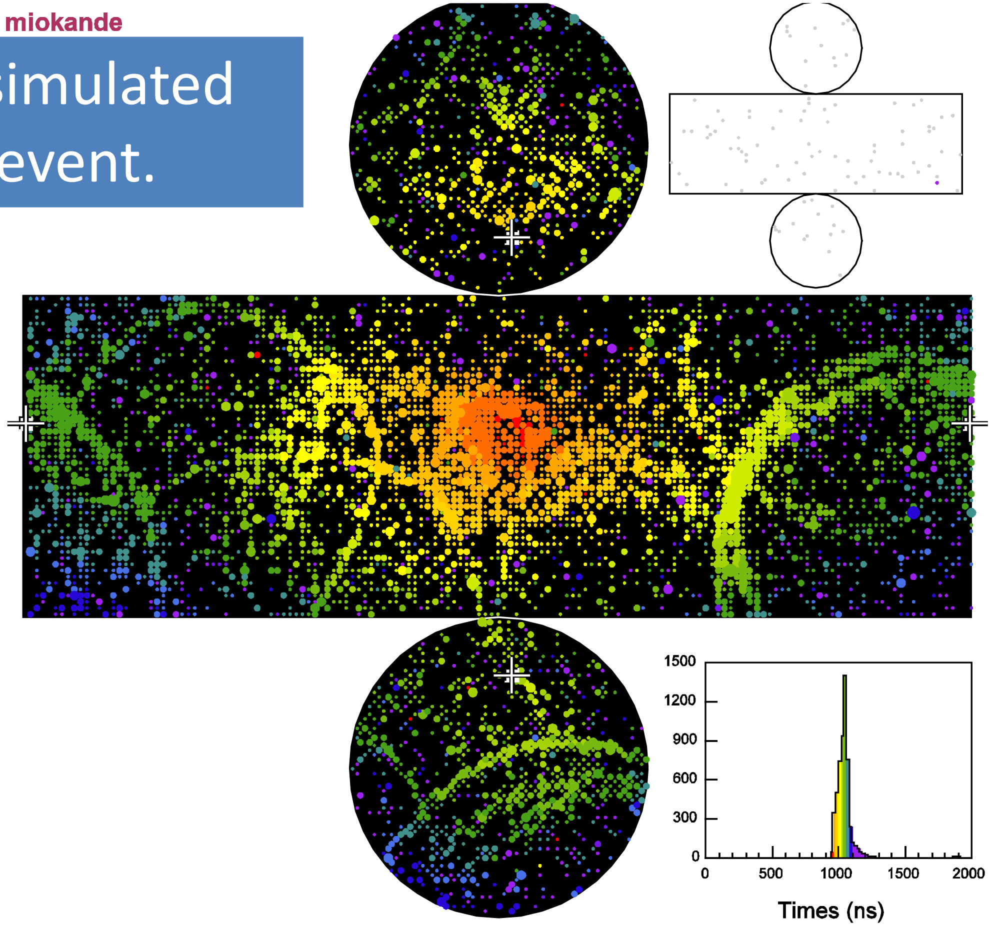


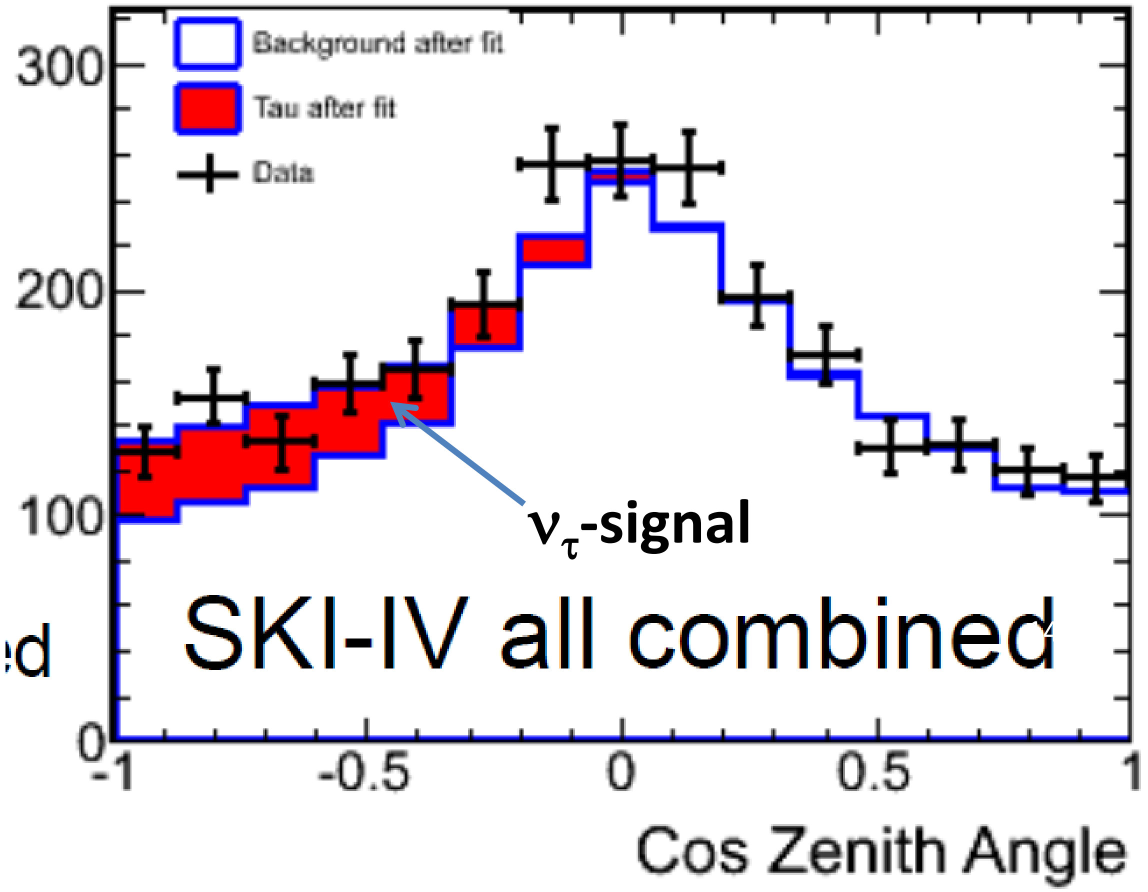


Detecting tau neutrinos

SK@Neutrino 2016,
See also, SK PRL 110(, 181802 (2013), SK PRL 97, 171801 (2006)

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)

Status of neutrino oscillation studies

<u>$\nu_\mu \rightarrow \nu_\tau$ oscillations (Δm_{23}, θ_{23})</u>

Atmospheric: Super-K, Soudan-2, MACRO IceCube/Deepcore, …

LBL: K2K, MINOS, OPERA, T2K, NOvA, …

<u>$\nu_e \rightarrow (\nu_\mu + \nu_\tau)$ oscillations (Δm_{12}, θ_{12})</u>

Solar: SNO, Super-K, Borexino, …

Reactor: KamLAND

<u>θ_{13} experiments</u>

LBL: MINOS, T2K, NOvA, …

Reactor: Daya Bay, Reno, Double Chooz

Status (before Neutrino 2016)

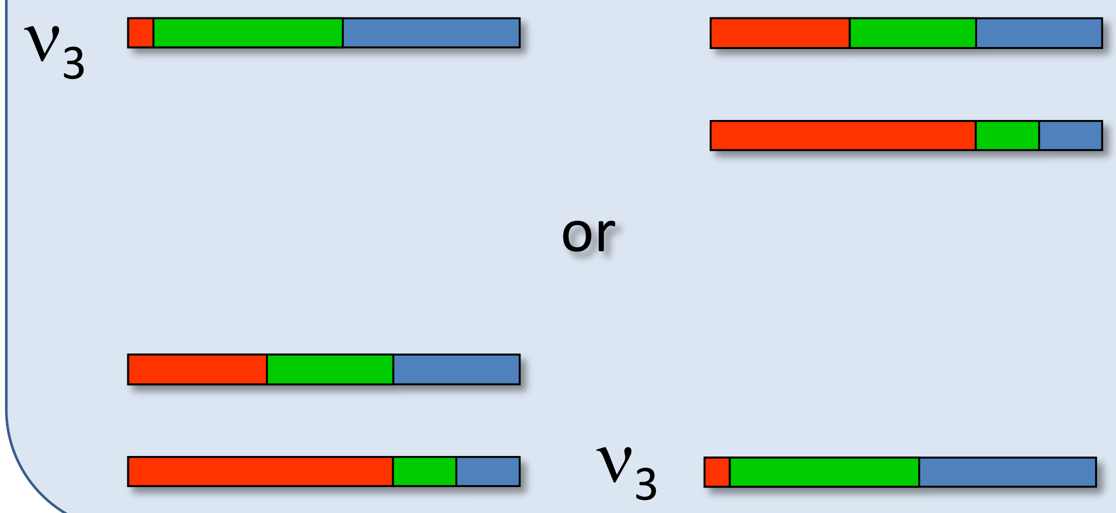
Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,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

K. Nakamura and S.T. Petcov, "14. Neutrino mass, mixing and oscillations"

Basic structure for 3 flavor oscillations has been understood!

What are the next?

Mass hierarchy ?



Is the mass pattern of neutrinos similar to those of quarks and charged leptons?

CP violation ?

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

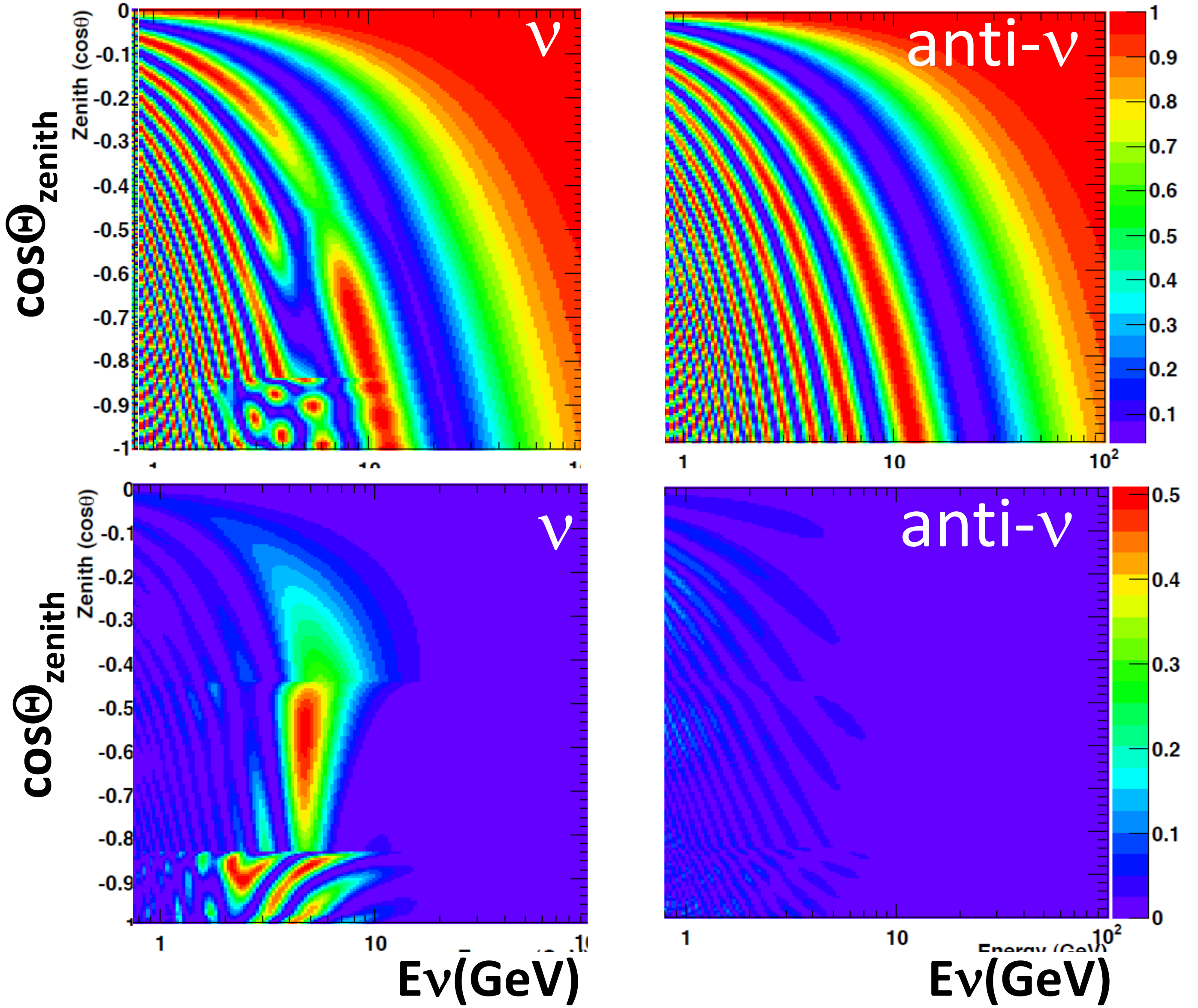
Baryon asymmetry of the Universe?

Oscillation probabilities

<u>Osci. Probabilities for Normal Hierarchy</u>

$P(\nu_\mu \rightarrow \nu_\mu)$

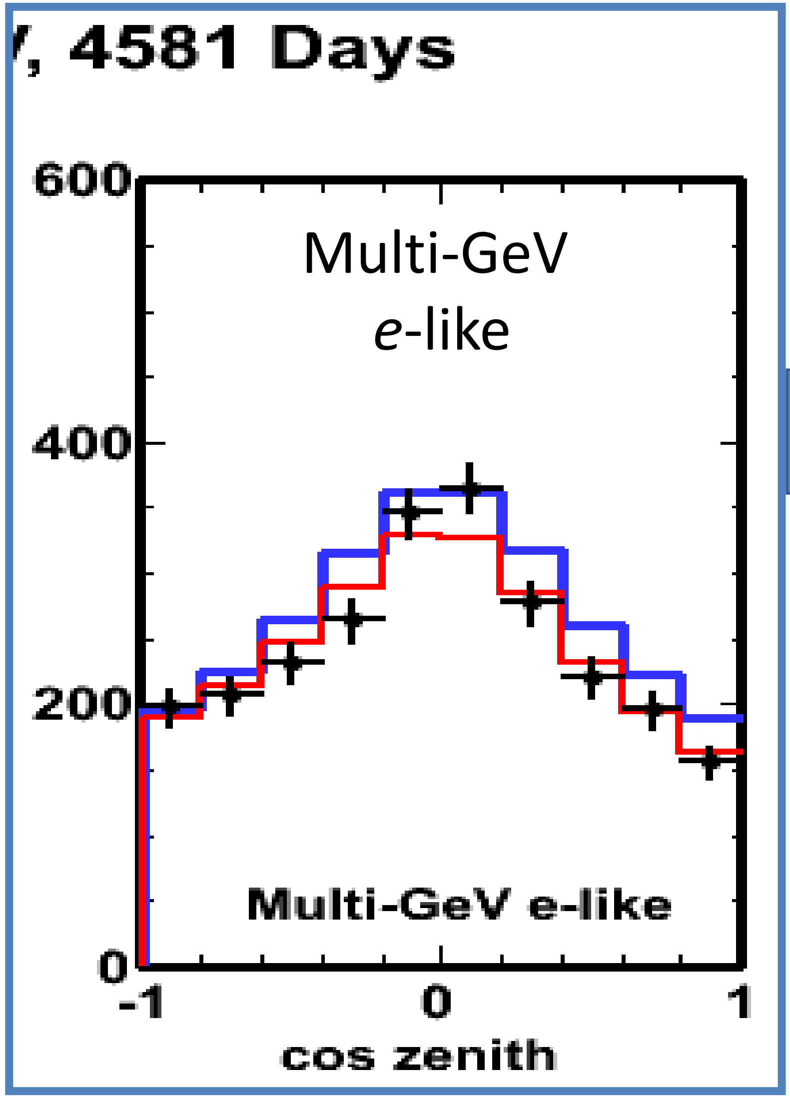
$P(\nu_\mu \rightarrow \nu_e)$



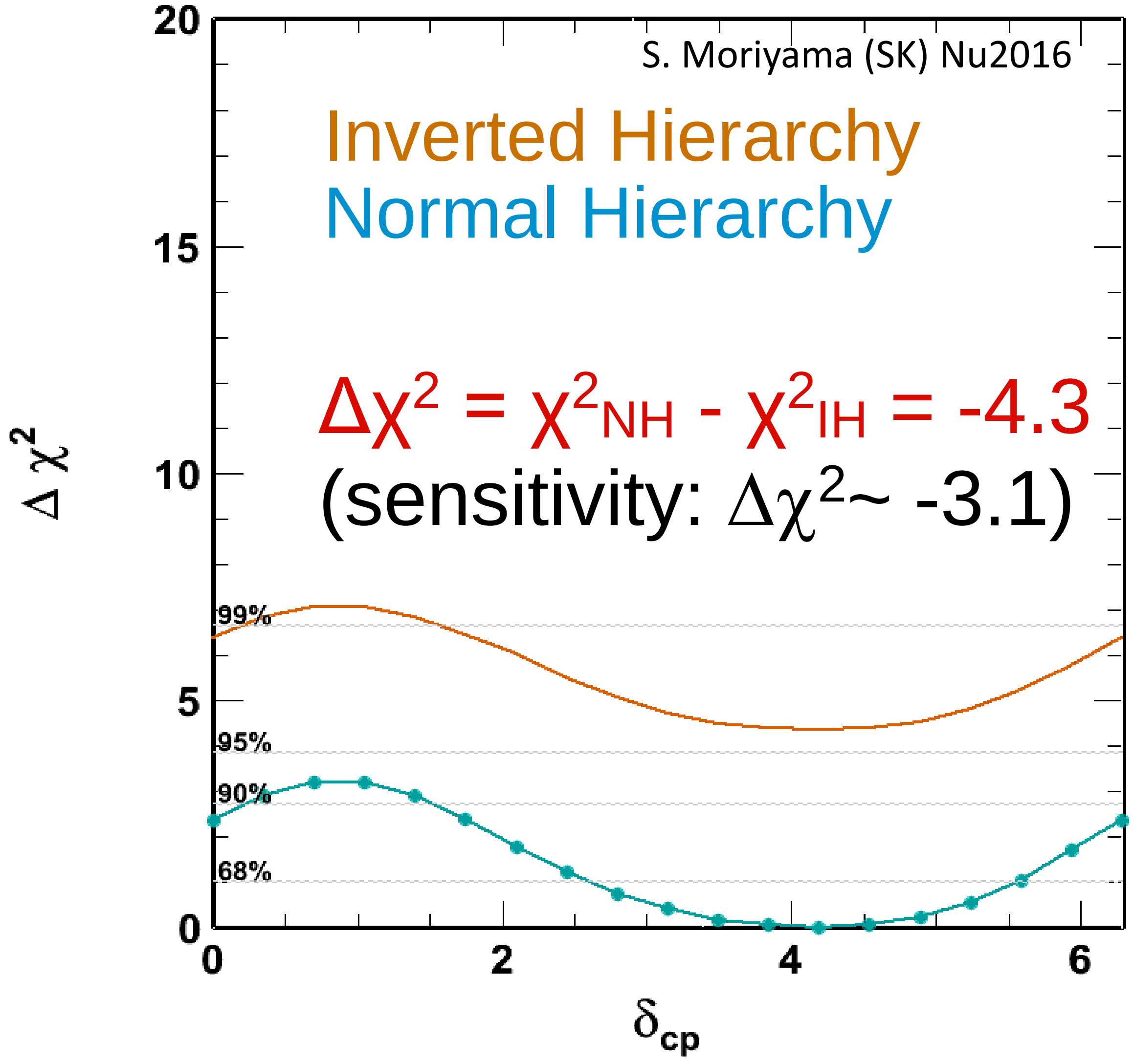
Inverted hierarchy:

$\nu \leftarrow\rightarrow$ anti-ν

Mass hierarchy study with atmospheric neutrinos



(together with the other plots….)

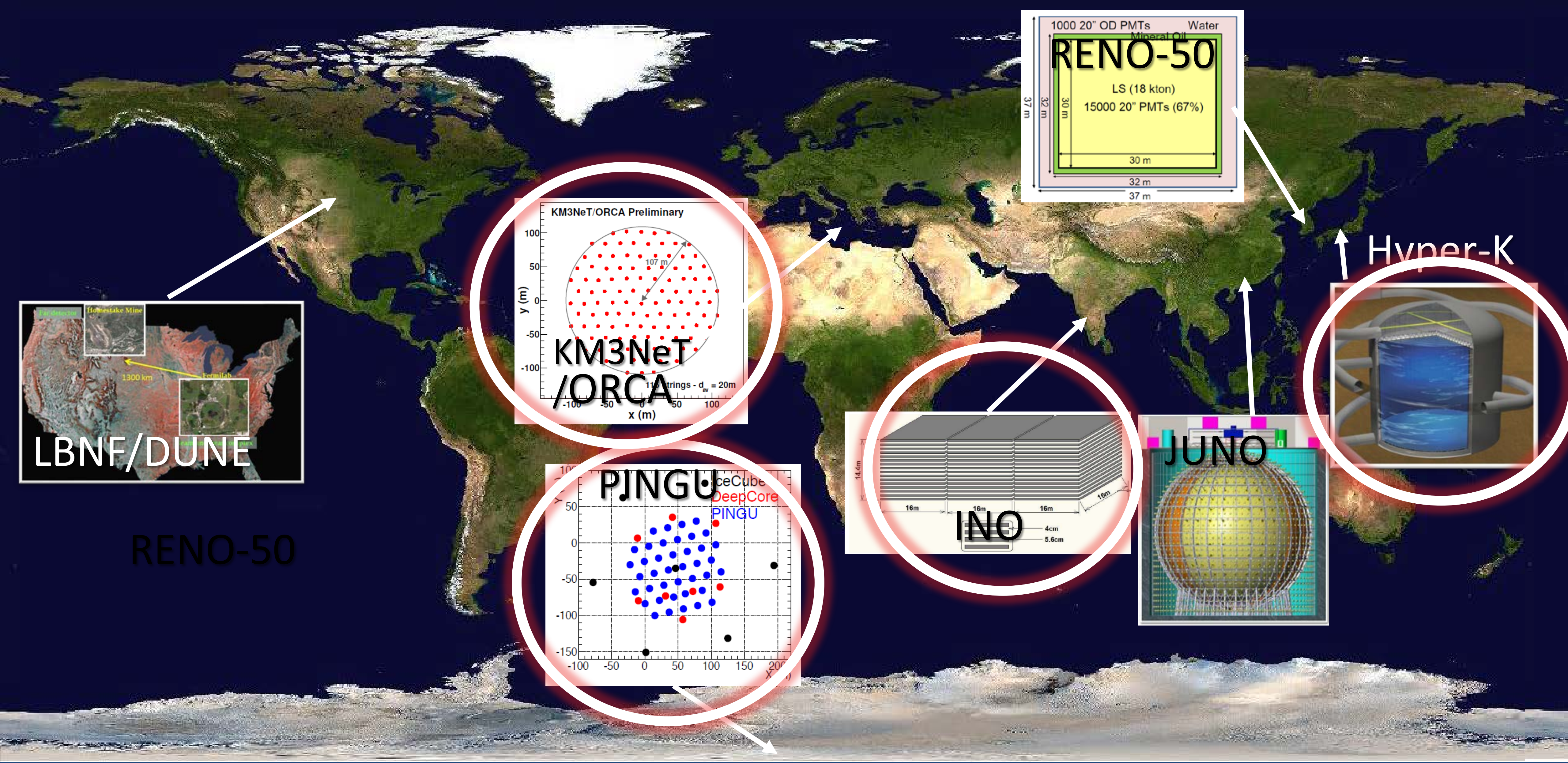


Interesting! But, we need more data.

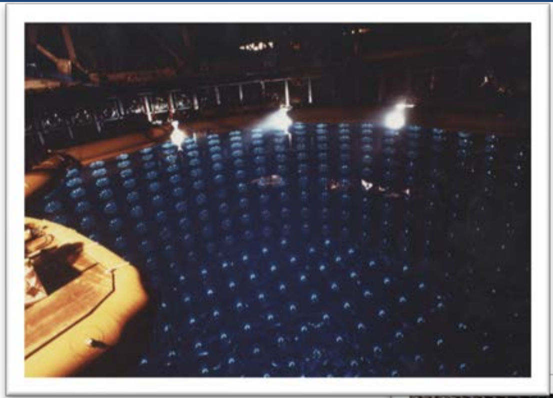
Future prospect

Kavli-IPMU will continue to play an important role in the studies of atmospheric neutrinos.

Future experiments that will tell us the neutrino masses hierarchy



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

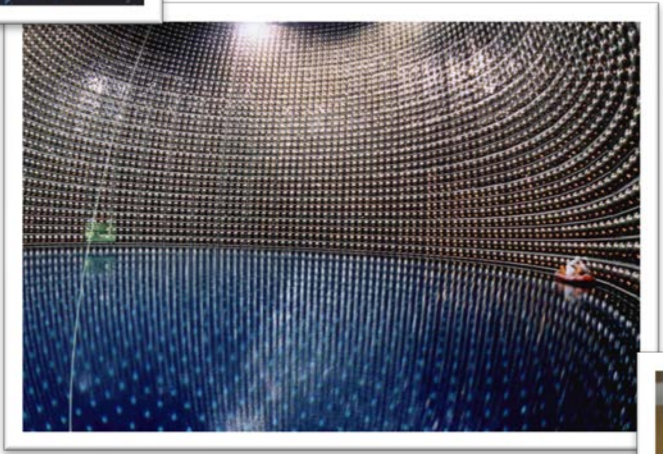


Kamiokande

Neutrinos from SN1987A

Atmospheric neutrino deficit

Solar neutrino

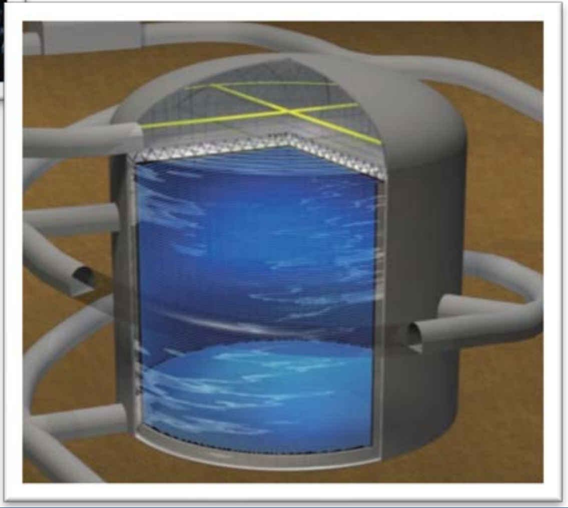


Super-K

Atmospheric neutrino oscillation

Solar neutrino oscillation with SNO

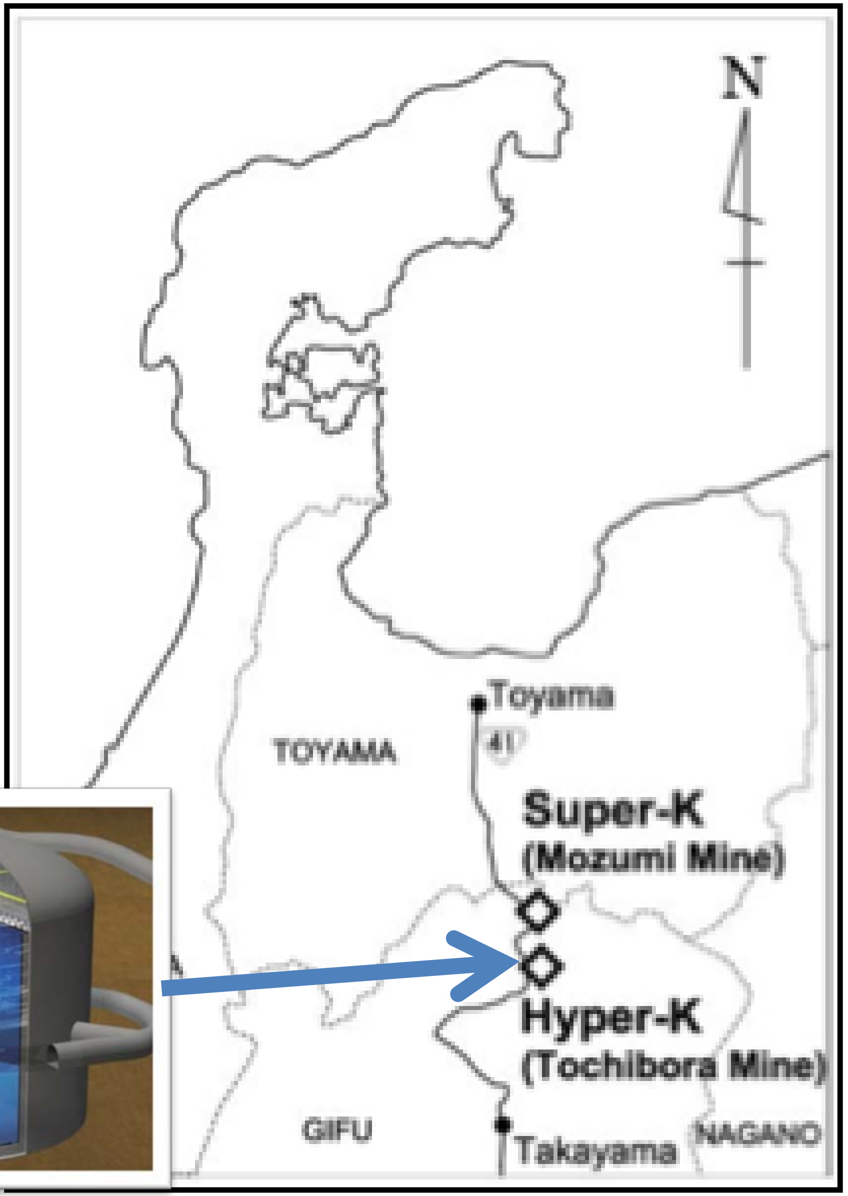
Far detector for K2K and T2K

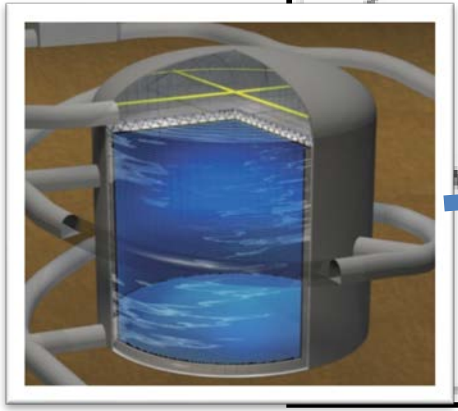


Hyper-K

The Hyper-K detector

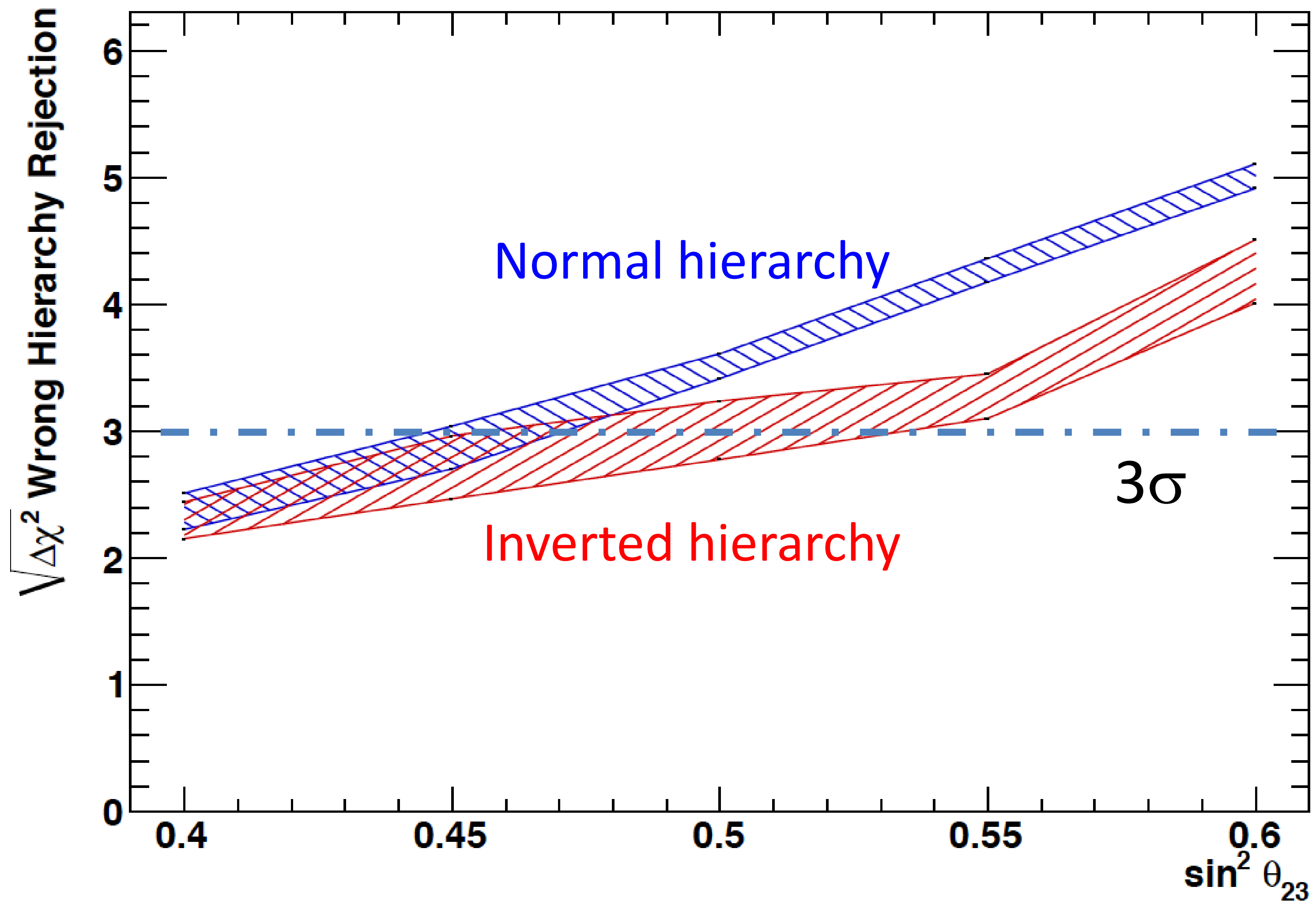
- The candidate site:
  - ~8km south from Super-K, 295km from J-PARC, 2.5° off-axis (same off-axis angle as Super-K)
  - Overburden ~650m (~1755 m.w.e.)
- Cylindrical tank with Φ 74 meters and H 60 meters.
- The total and fiducial volumes (for one tank) are 0.26 and 0.19 Mtons, respectively.
- Photo-cathode coverage is 40%. 40,000 ID PMTs and 6700 OD PMTs per tank.
- (The possible second tank should be located in Korea.)





Sensitivity to mass hierarchy

Atmospheric neutrinos only (10 years)

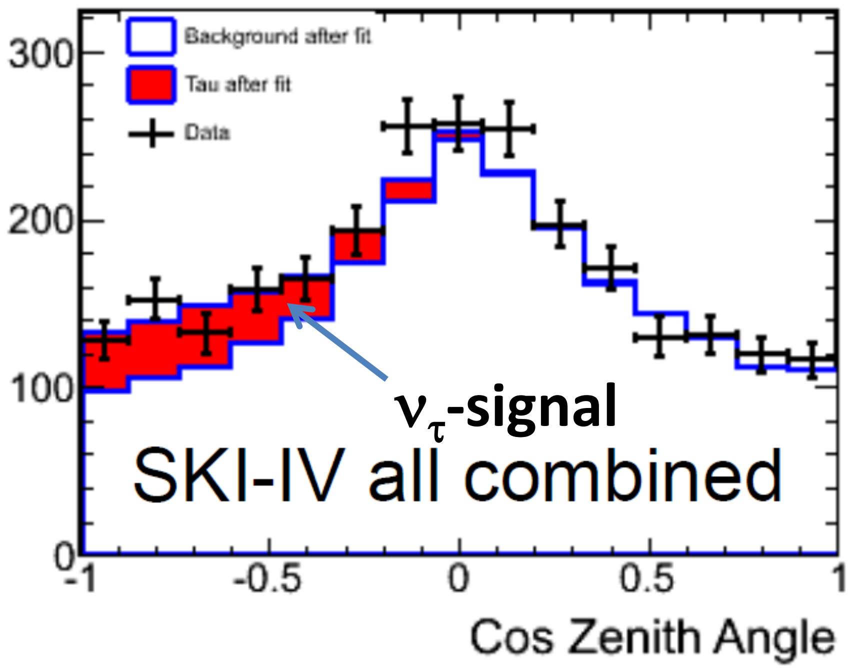


(Of course, if the data from accelerator beam are combined, the constraint to the mass hierarchy should be must stronger.)

Tau neutrino appearance

Super-Kamiokande

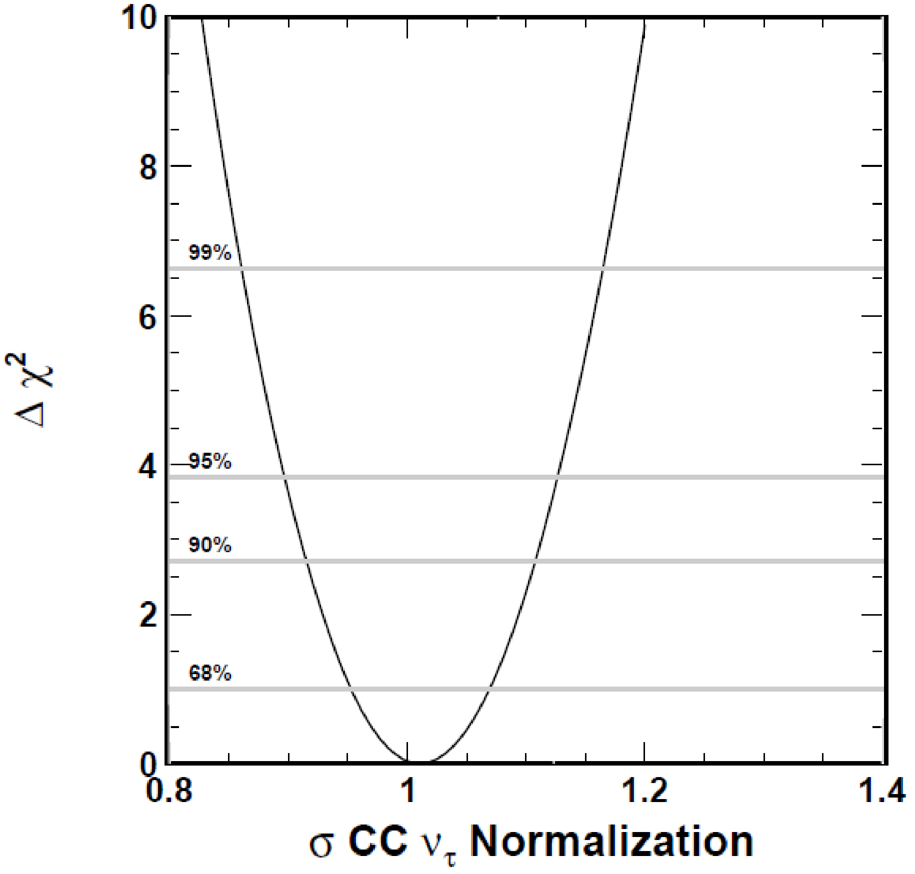
Super-K (S.Moriyama) @nu2016
See also, SK PRL 110(2013)181802



➔ τ-appearance signal at 4.6σ

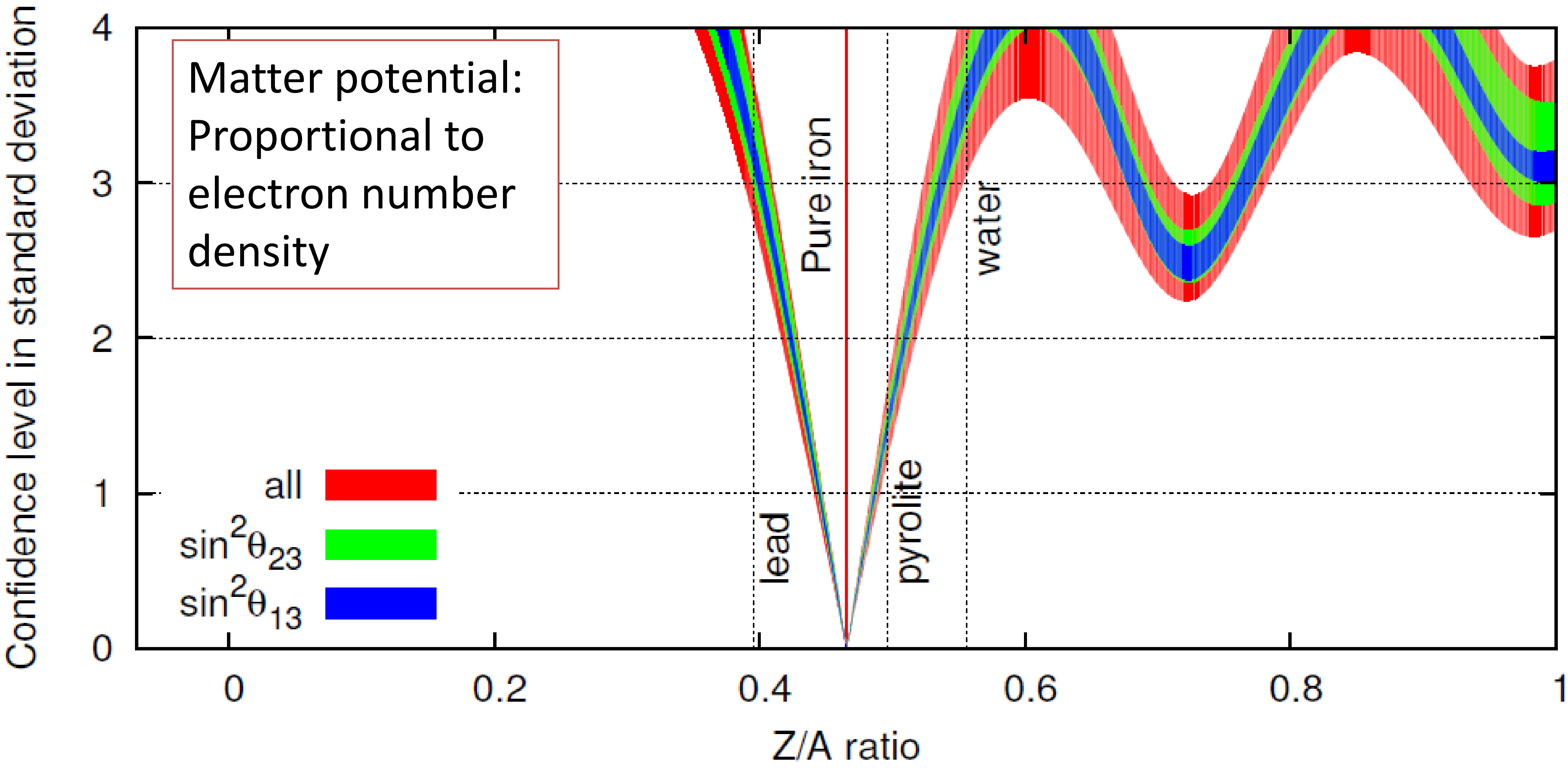
- In Hyper-K, the statistical significance is no more an issue.
- the normalization of the CC ν_τ cross section (relative to CC ν_μ cross section) can be constrained to ~7% with a 5.6 Mton year exposure of Hyper-K.
- This measurement will help understand the CC ν_τ cross section near the threshold, which is known rather poorly.

Hyper-K, 5.6 Mton-yrs
(Hyper-K 30 years)



Chemical composition of Earth's Outer Core

Sensitivity to Outer Core Chemical Composition, 10 Mton-yr (Hyper-K ~50 years)



- With 10 Mton-yr exposure, some extreme cases (water or lead core) are excluded at 3 σ level.

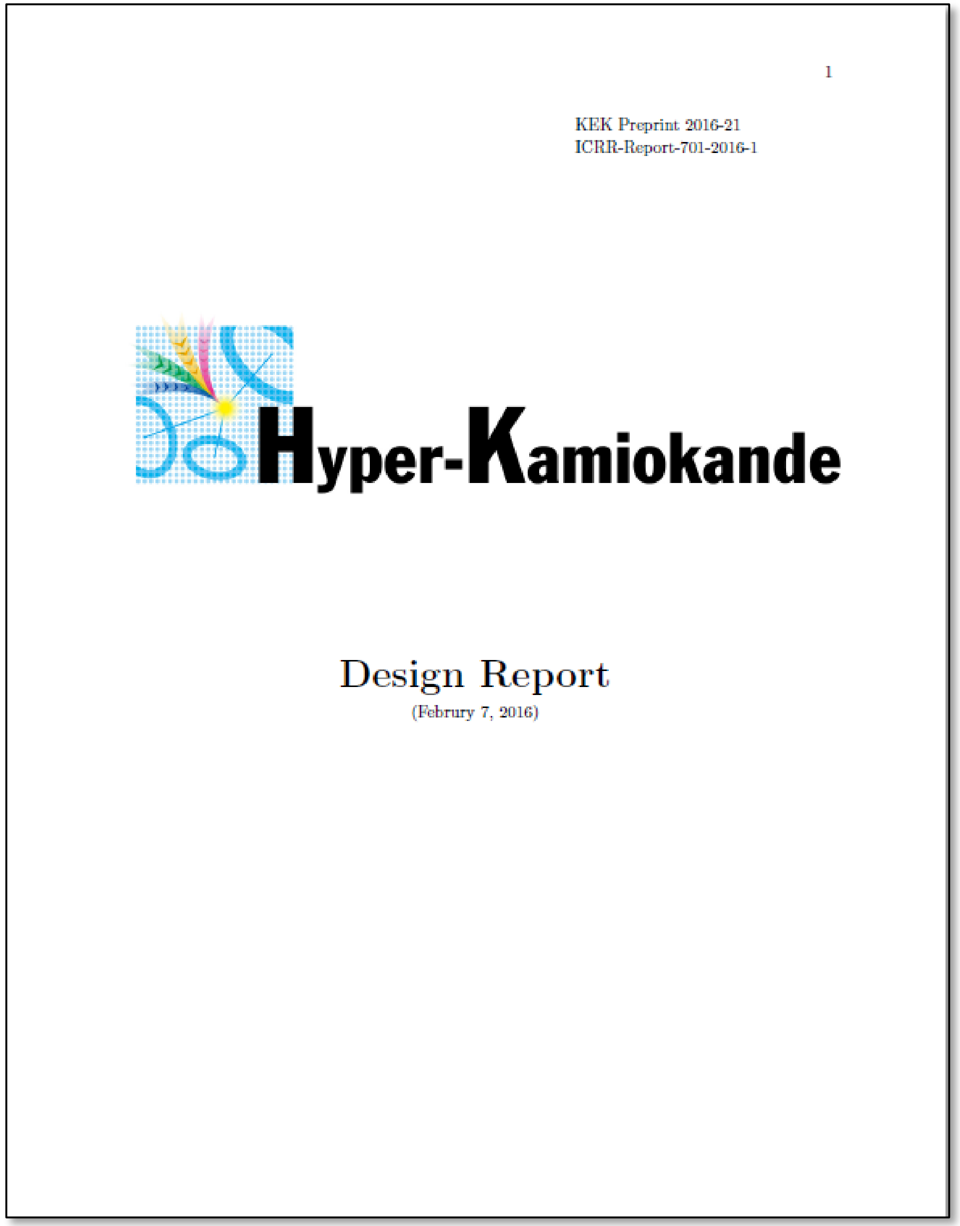
Appendix

Other physics with future atmospheric neutrino detectors (Hyper-K)

- Long baseline neutrino oscillation experiment (CP violation and others)
- Proton decays ($e\pi^0$, νK^+)
- Solar neutrinos (day-night effect, spectrum up-turn)
- Supernova neutrino burst
- Past supernova neutrinos
- Neutrinos from WIMPs annihilations
- ….

Status of Hyper-K

- ✓ The design report has been written (Feb. 2016).
- ✓ Science Council of Japan (SCJ) evaluated Hyper-K as one of the high priority projects in the "Master Plan 2017".
- ✓ Ministry of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) evaluated high priority projects listed in Mater Plan in the summer 2017. Hyper-K was listed as one of 7 projects in the MEXT "Roadmap".
- ✓ Hyper-K must be a serious candidate for the next generation large science projects by MEXT.
- ✓ On Oct. 1, 2017, a new organization was formed based on members from ICRR, Kavli-IPMU and School of Science in the Univ. of Tokyo to promote the Hyper-K project.


1

KEK Preprint 2016-21
ICRR-Report-701-2016-1

Hyper-Kamiokande

Design Report
(Februry 7, 2016)

Summary

- Atmospheric neutrino experiments have been playing a very important role in the neutrino oscillation studies.
- Atmospheric neutrino experiments are likely to contribute more to neutrino oscillation physics.
- Future atmospheric neutrino experiments can also contribute to the other physics such as long baseline neutrino oscillation, proton decays, solar neutrinos, supernova neutrinos….
- Hyper-K is proposed as the next generation neutrino experiment.