AEPSHEP 2016
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Super-Kamiokande

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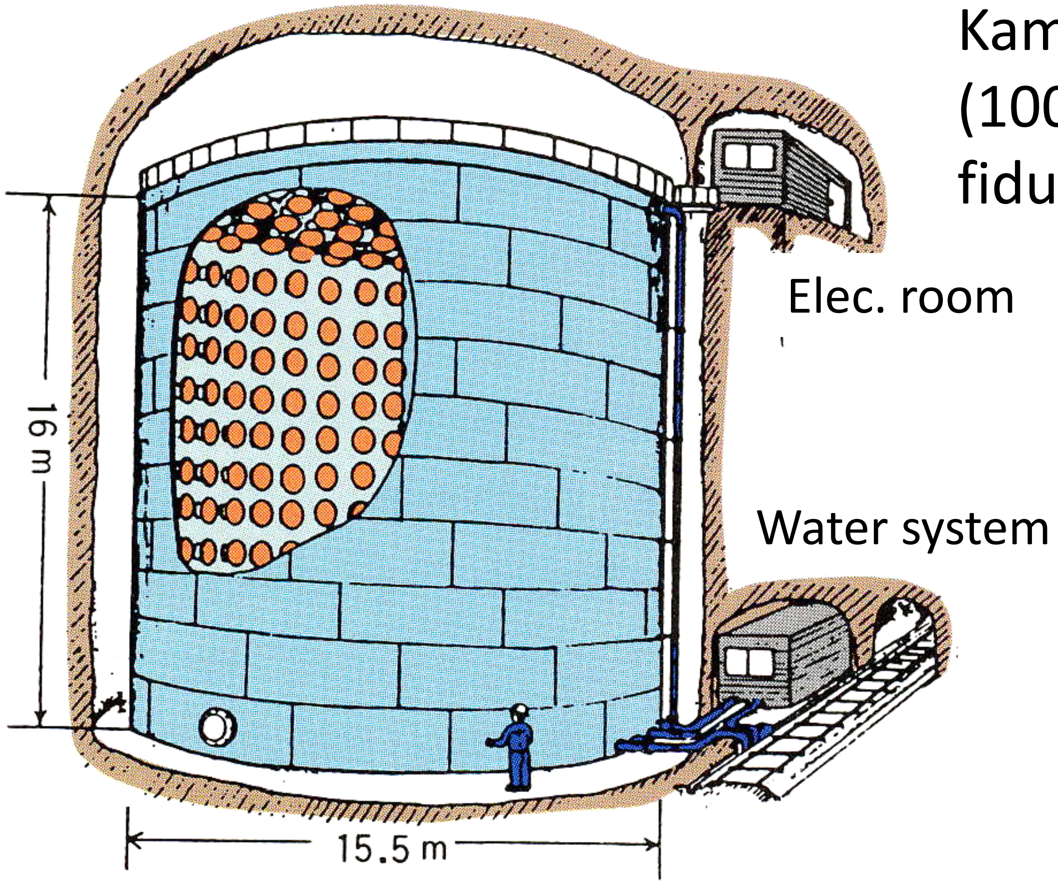
Outline

- *Introduction: Kamiokande*
- *Super-Kamiokande*
- *Discovery of atmospheric neutrino oscillations*
- *Contribution to the discovery of solar neutrino oscillations*
- *Some resent results from Super-Kamiokande (non-accelerator results)*
- *Future*
- *Summary*

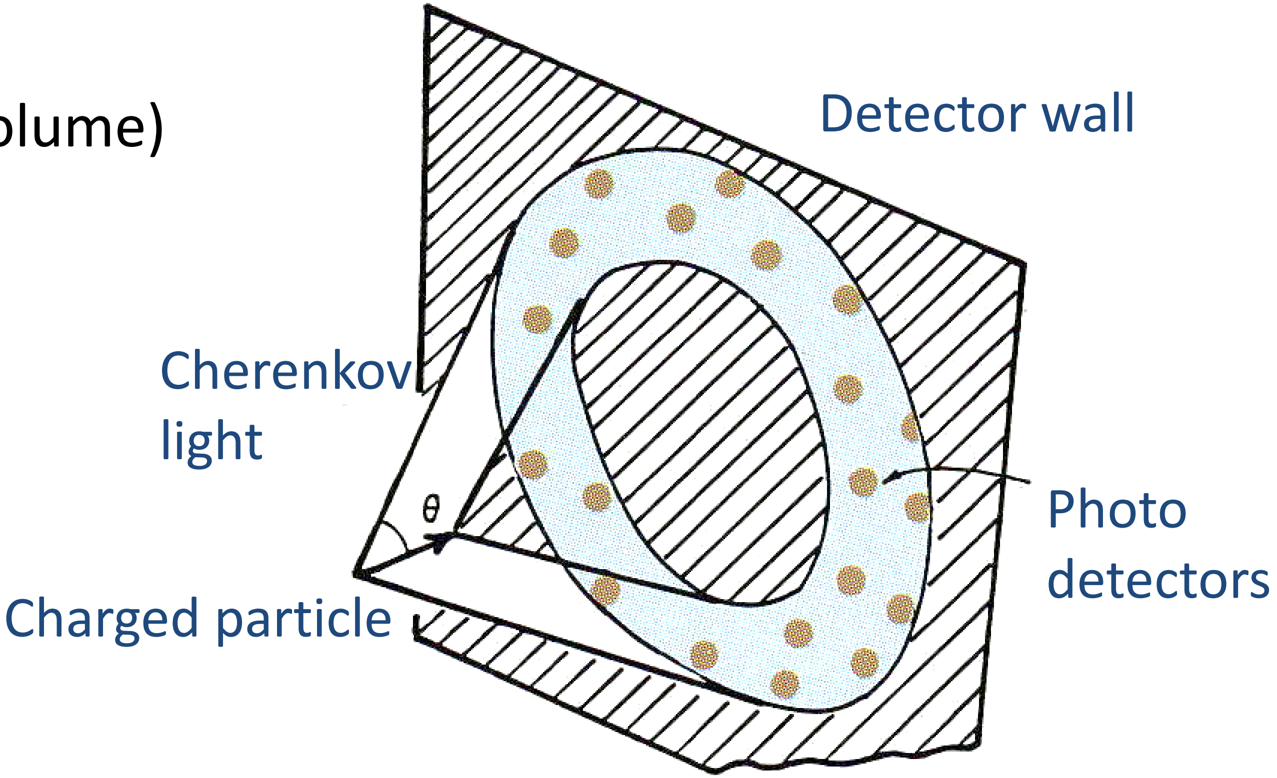
Introduction: Kamiokande

Kamioka Nucleon Decay Experiment (Kamiokande)

- ✓ In the late 1970’s, Grand Unified Theories were proposed.
- ✓ They predicted that protons and neutrons should decay with the lifetime of 10^{28} to 10^{32} years.
- ✓ Several proton decay experiments began in the early 1980’s. One of them was the Kamiokande experiment.



Kamiokande
(1000 ton
fiducial volume)

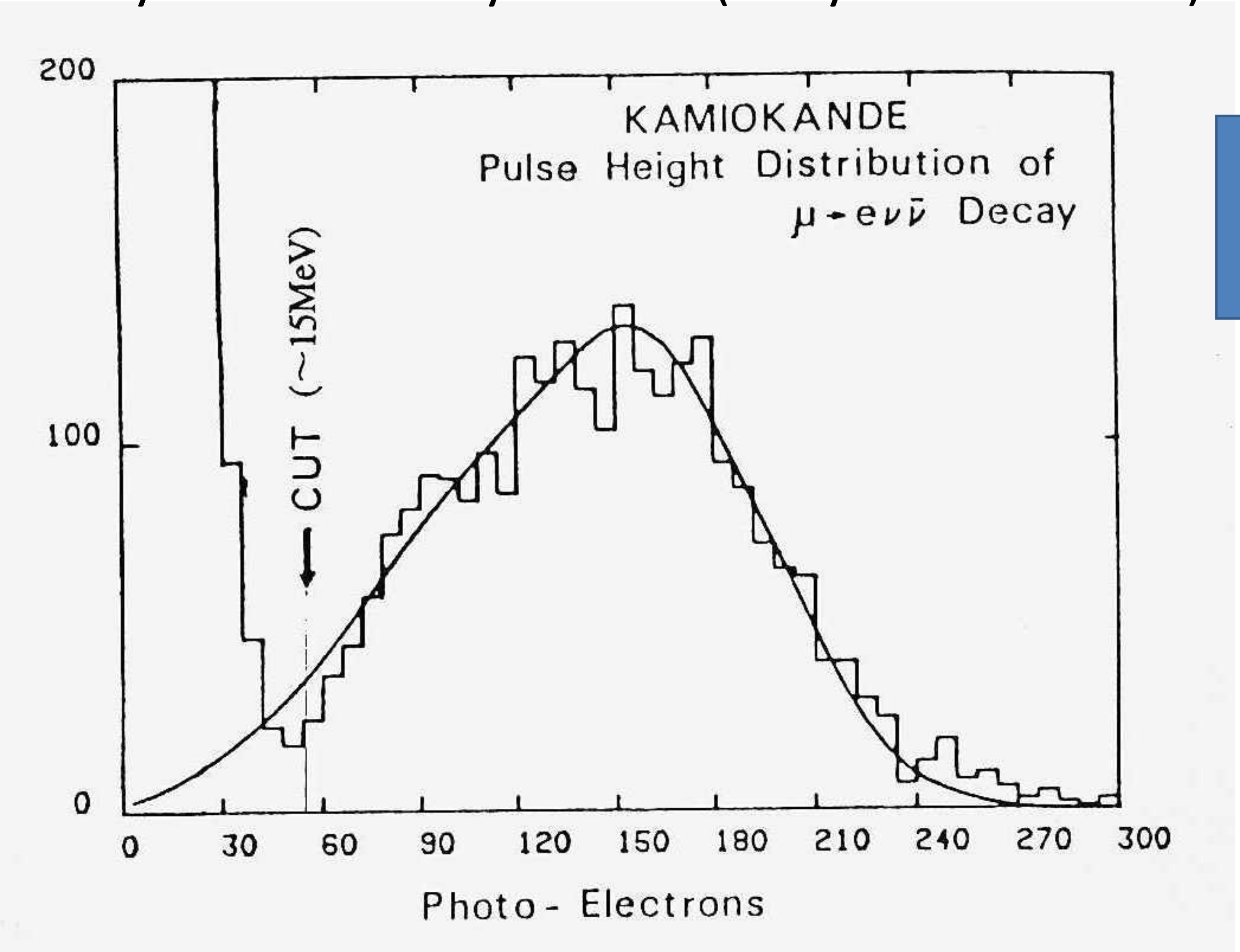


Construction of the Kamiokande detector (spring 1983)

The Kamiokande experiment started in July 1983.

Didn't observe proton decays, but…

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

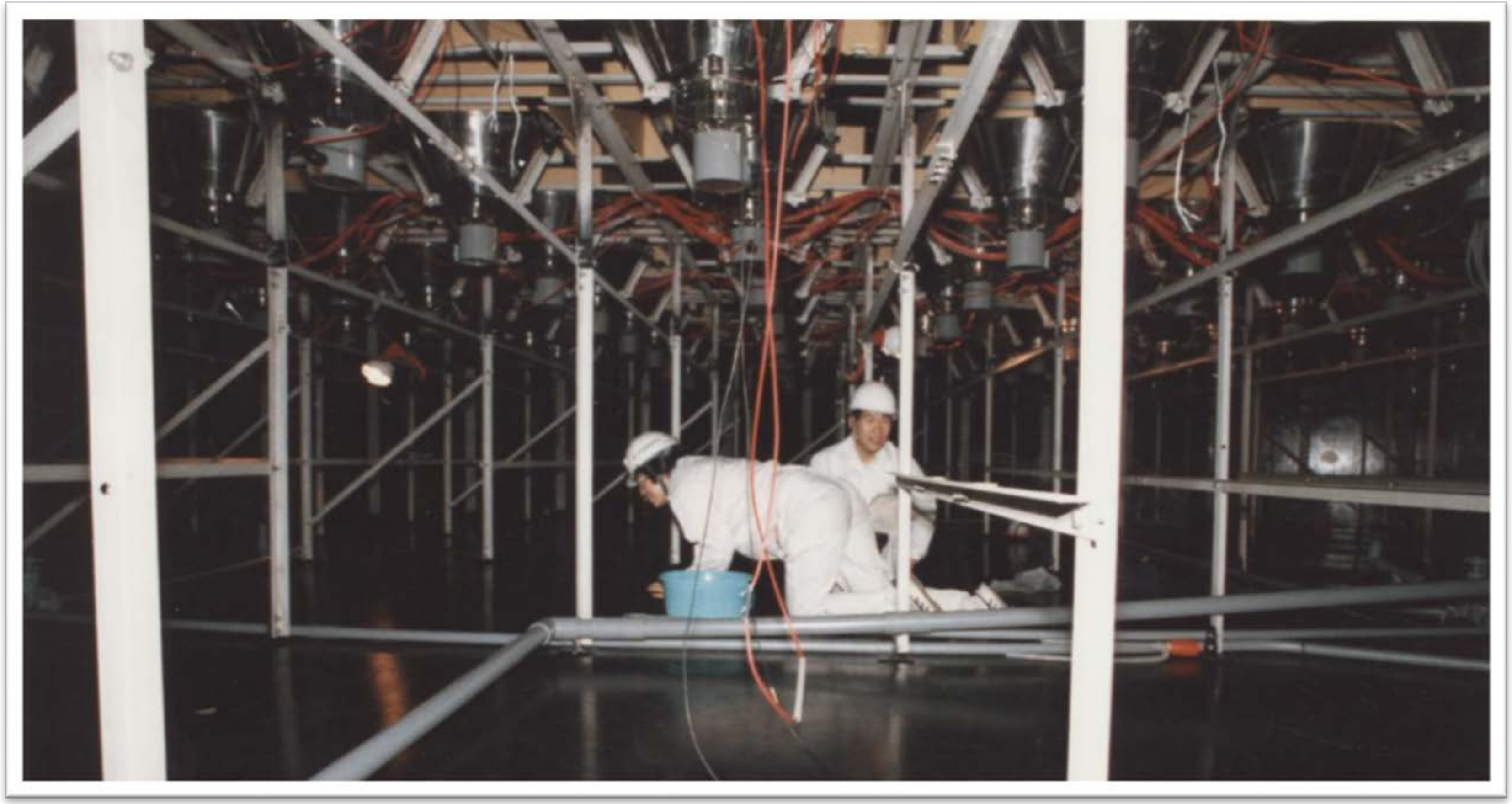


Neutrinos with the energies of about 10 MeV could be observed.

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

(both by M. Koshiba)

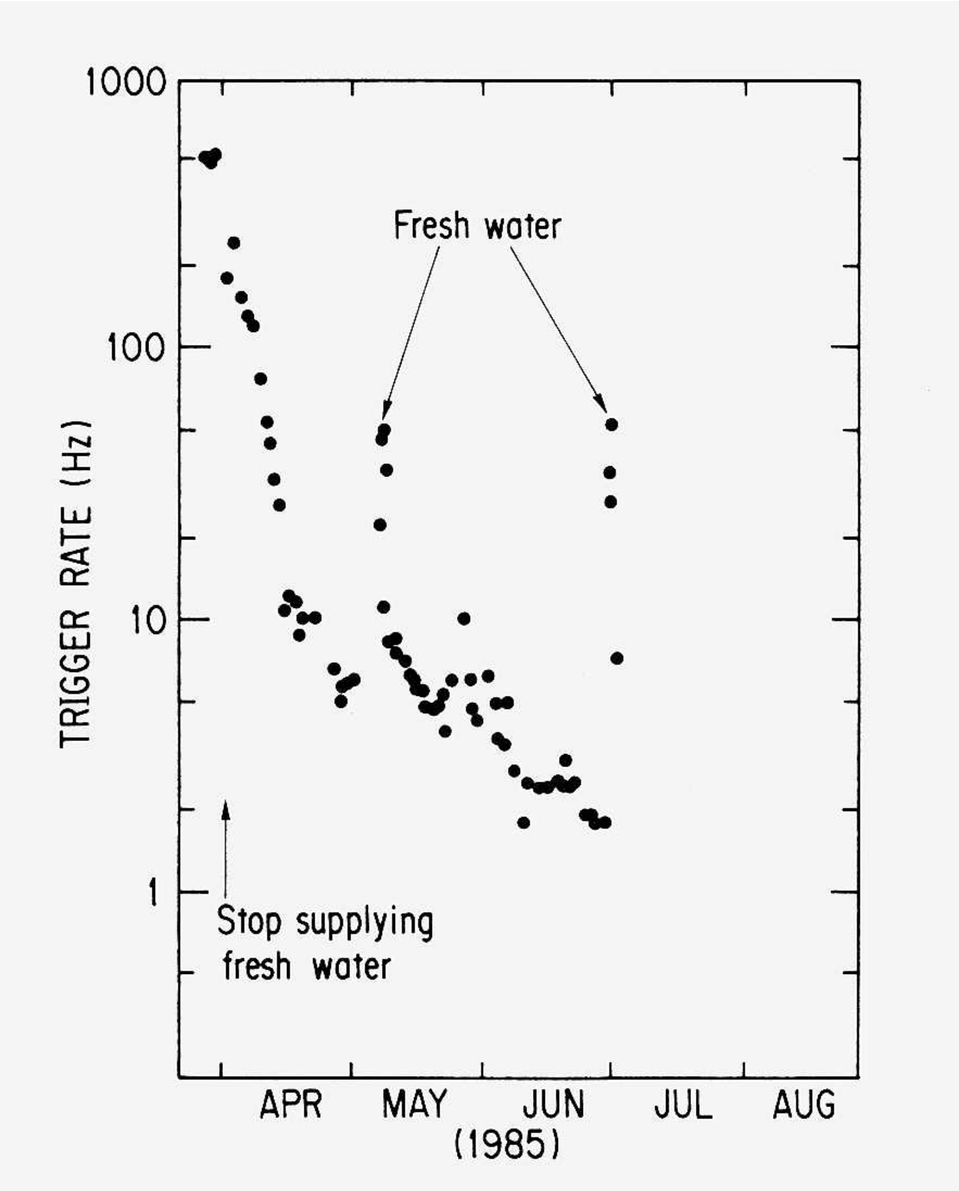
Toward Kamiokande-II (1984-5)

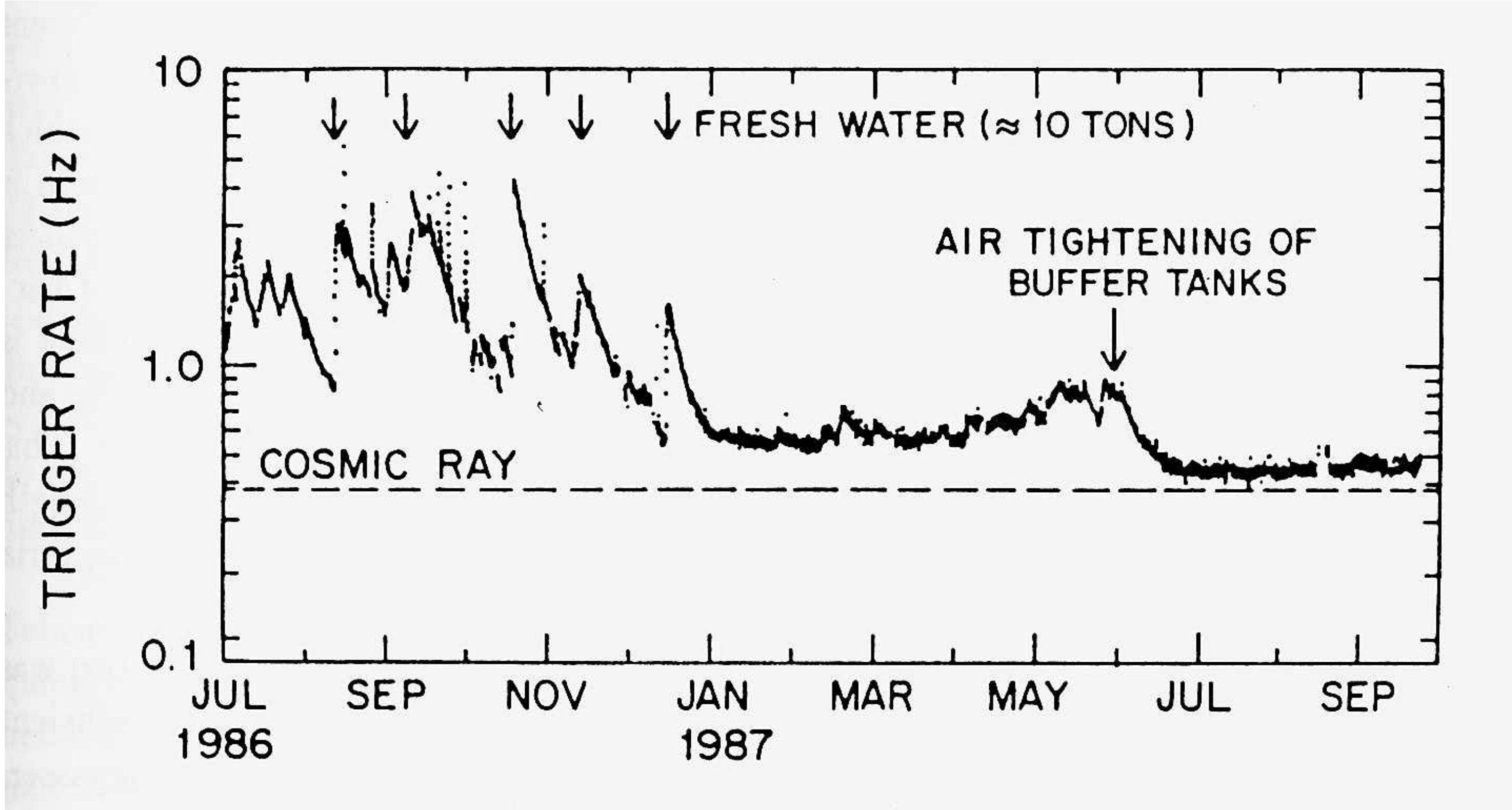


Construction of the bottom outer detector

Construction of the side outer detector
(between the steel tank and the rock)

Water and the trigger rate





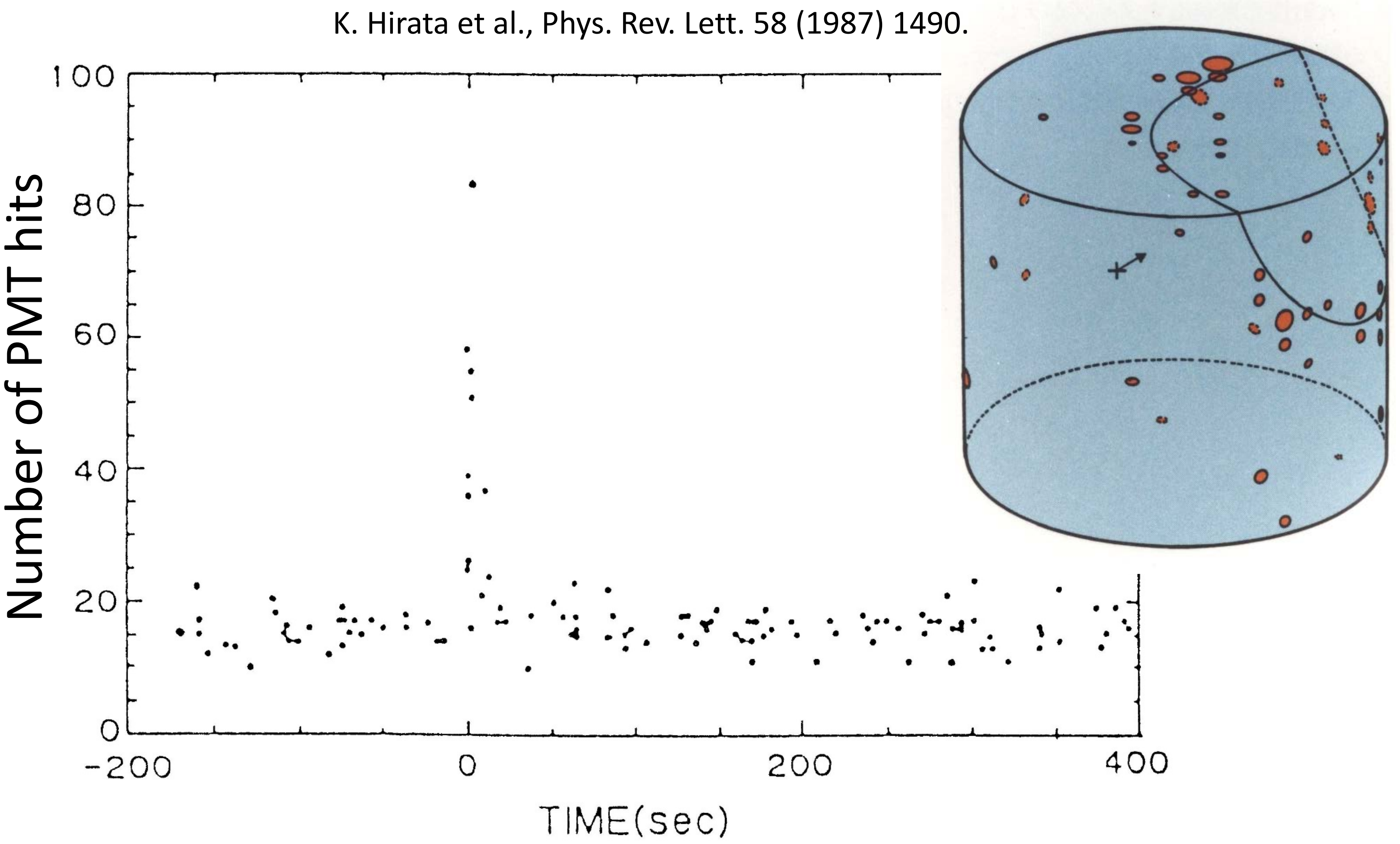
Radioactivities (mostly Rn at that stage) was the most serious issue.

Stable trigger rate after Jan. 1987.

SN1987A (Feb. 23, 1987)

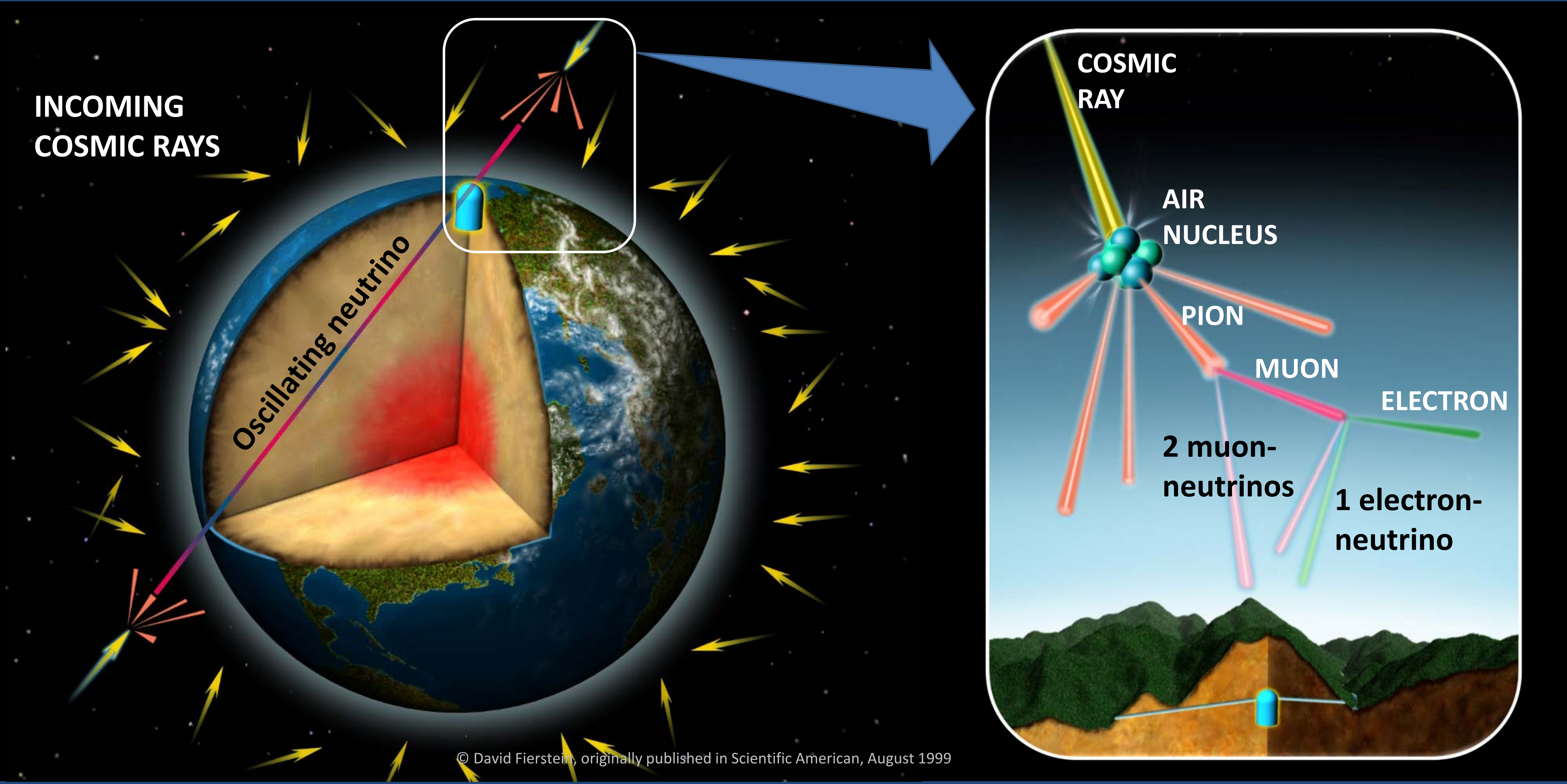
SN1987A (at LMC)

K. Hirata et al., Phys. Rev. Lett. 58 (1987) 1490.



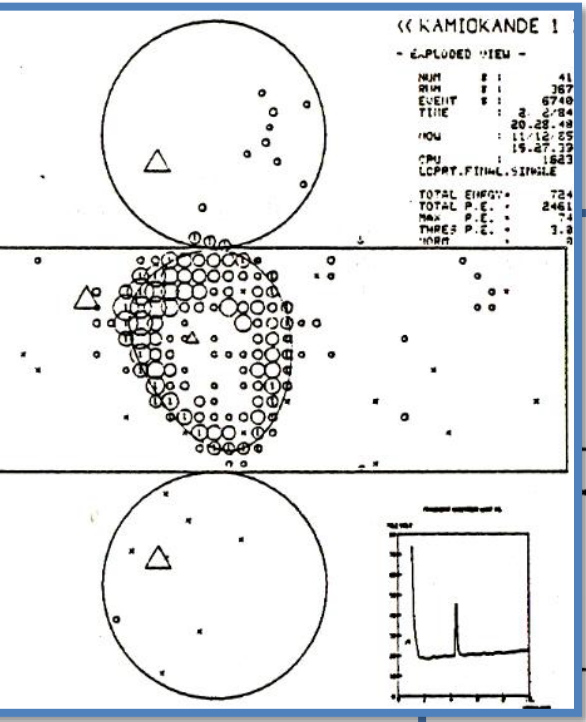
(The IMB experiment also observed the neutrino signal.)

Atmospheric neutrinos

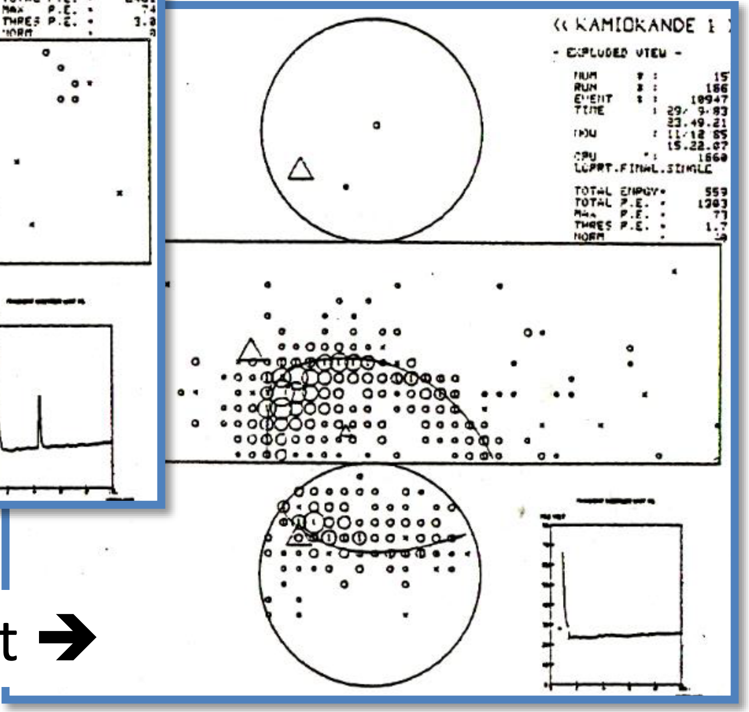


Atmospheric ν_μ deficit (1988)

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.



← Typical ν_μ event In Kamiokande



Typical ν_e event →

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

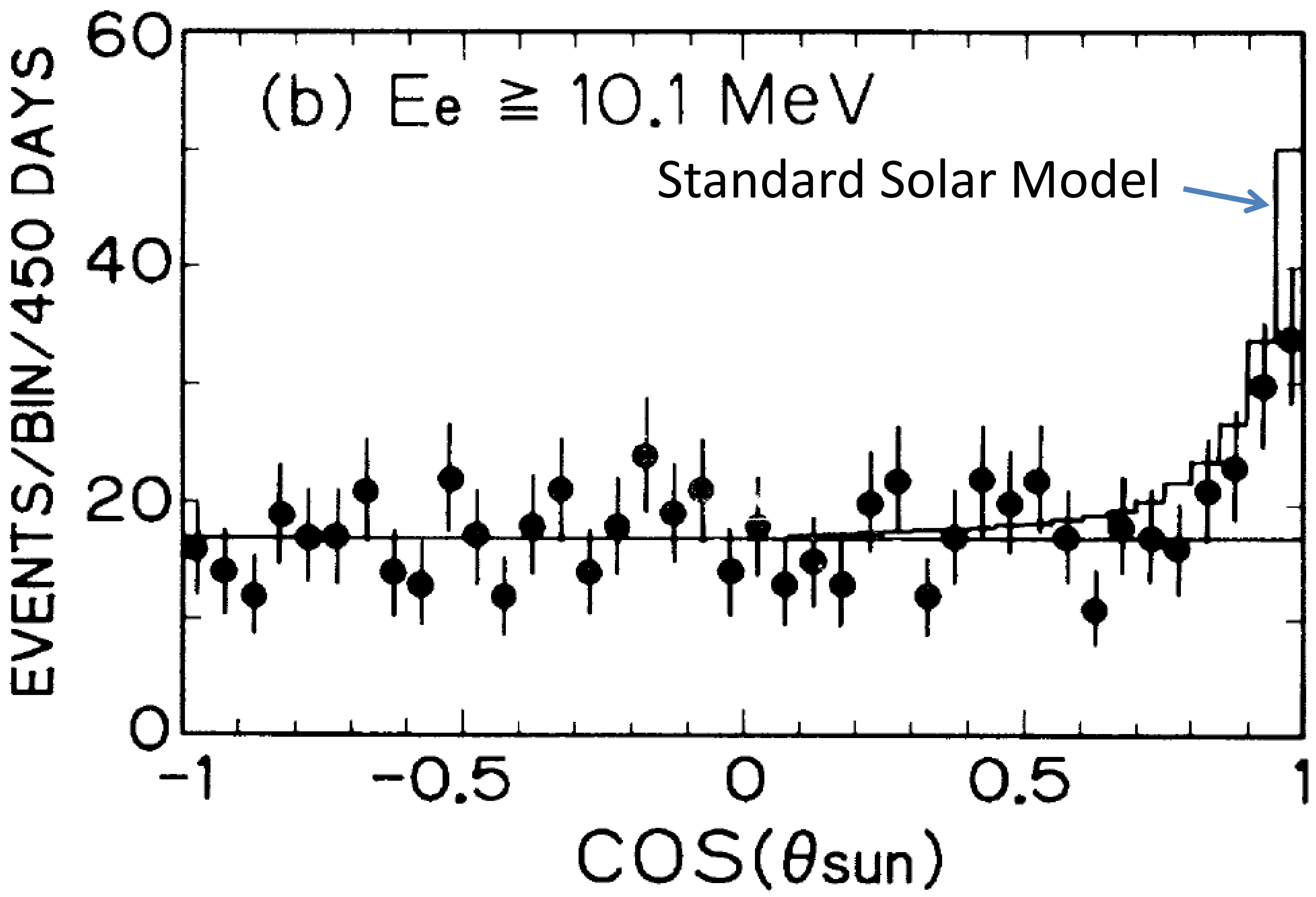
	Data	MC prediction
e-like (∼CC ν_e)	93	88.5
μ-like (∼CC ν_μ)	85	144.0

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 the similar results.)

Confirmation of solar ν_e deficit (1989)

Solar neutrino data between Jan. 1987 and May 1988:



K. S. Hirata et al., Phys. Rev. Lett. 63 (1989) 16.

The Kamiokande results on;

- Supernova neutrinos (1987)
- Atmospheric neutrino deficit (1988)
- Solar neutrino deficit (1989)

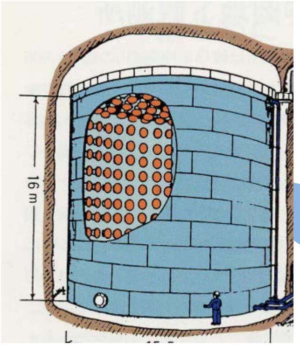
were evaluated to be very important.

⇩

The construction of the Super-Kamiokande experiment was approved in 1991 by the Japanese government.

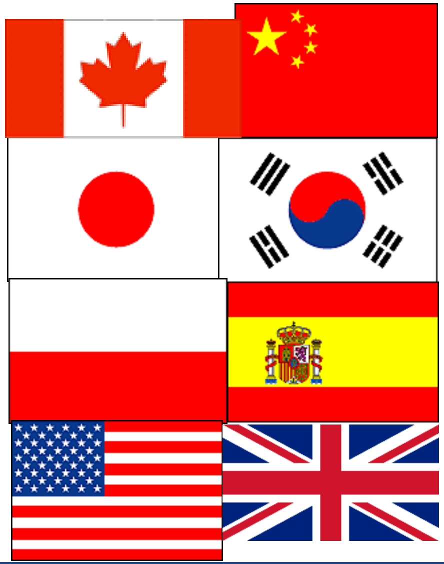
Super-Kamiokande

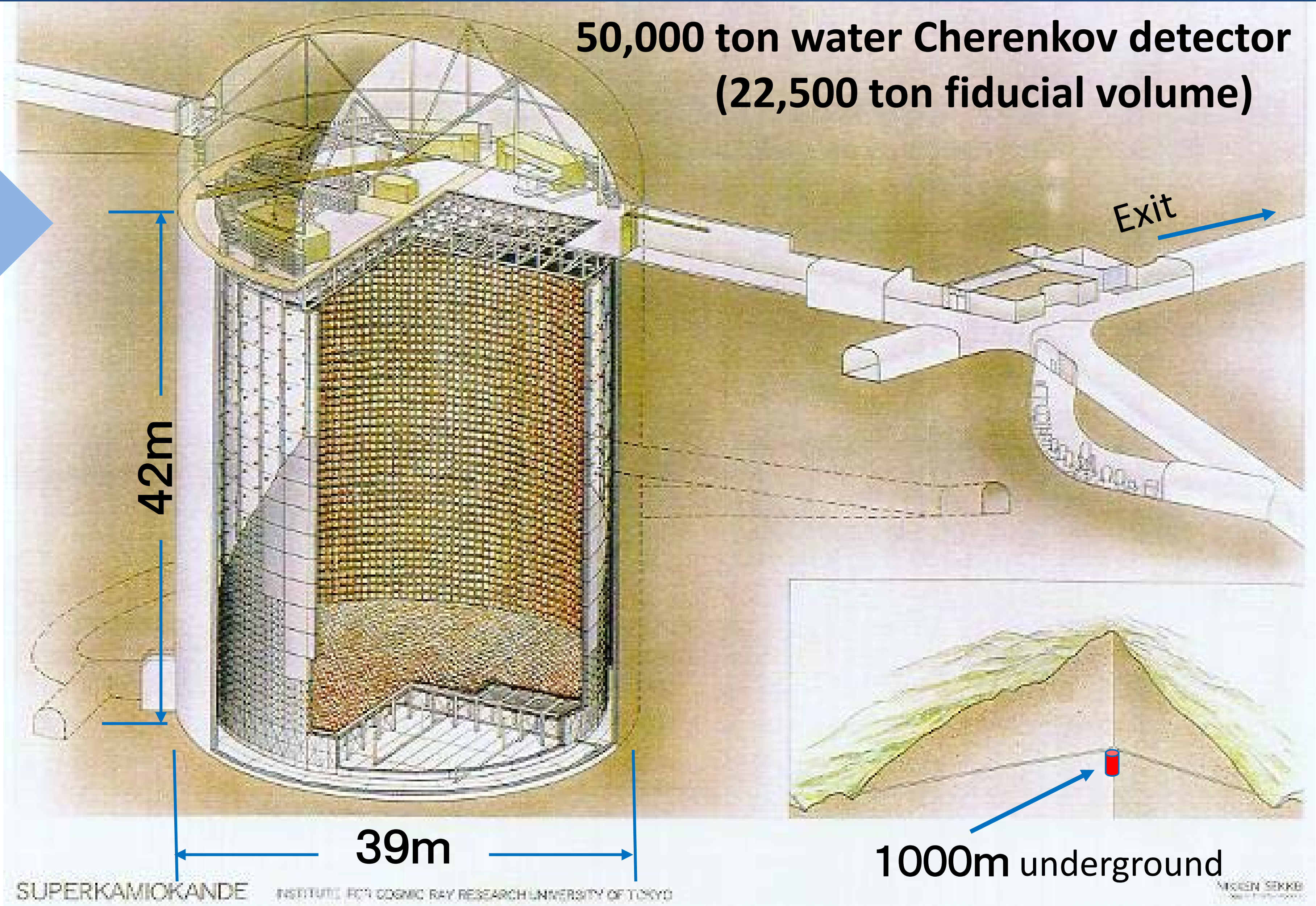
Super-Kamiokande detector



More than 20 times larger mass

~140 collaborators





Initial idea of Super-Kamiokande

KEK Report 84-12
September 1984
H

PROCEEDINGS OF

WORKSHOP ON GRAND UNIFIED THEORIES

AND COSMOLOGY

KEK, Tsukuba, Japan
December, 7-10, 1983

Edited by

K. ODAKA and A. SUGAMOTO

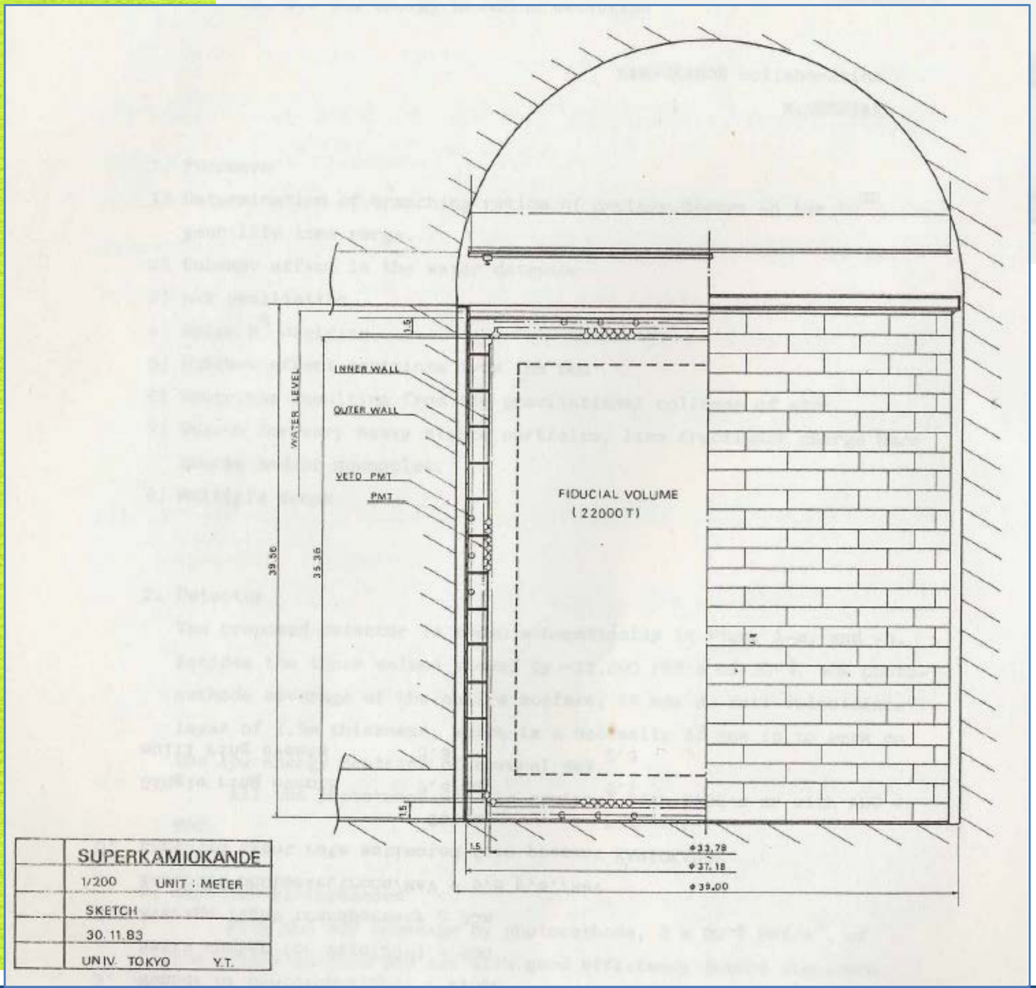
32 Kton Water Cerenkov Detector(JACK)

A proposal for detailed studies of nucleon decays

and for low energy neutrino detection

KAMIOKANDE collaboration

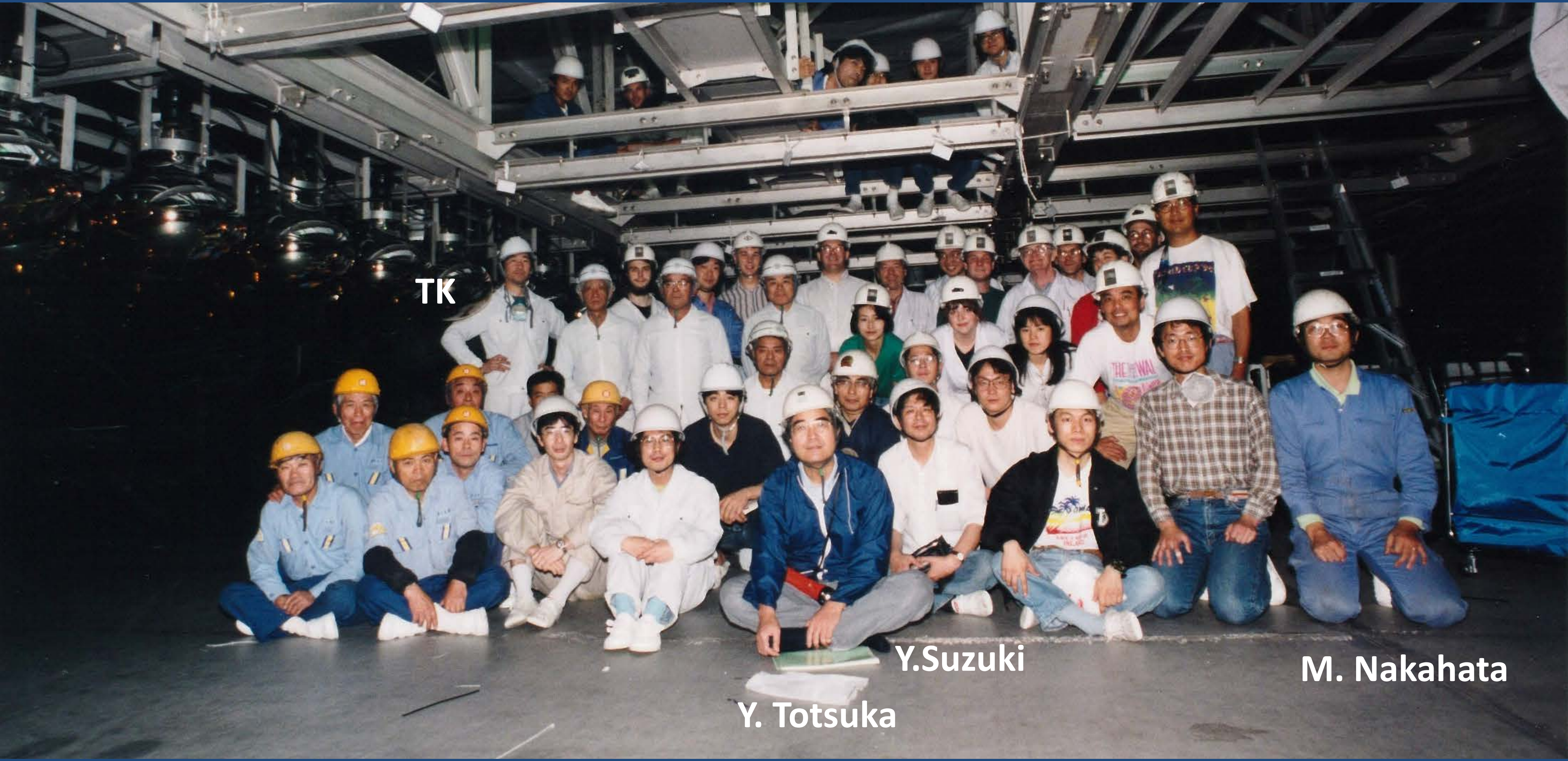
M.KOSHIBA



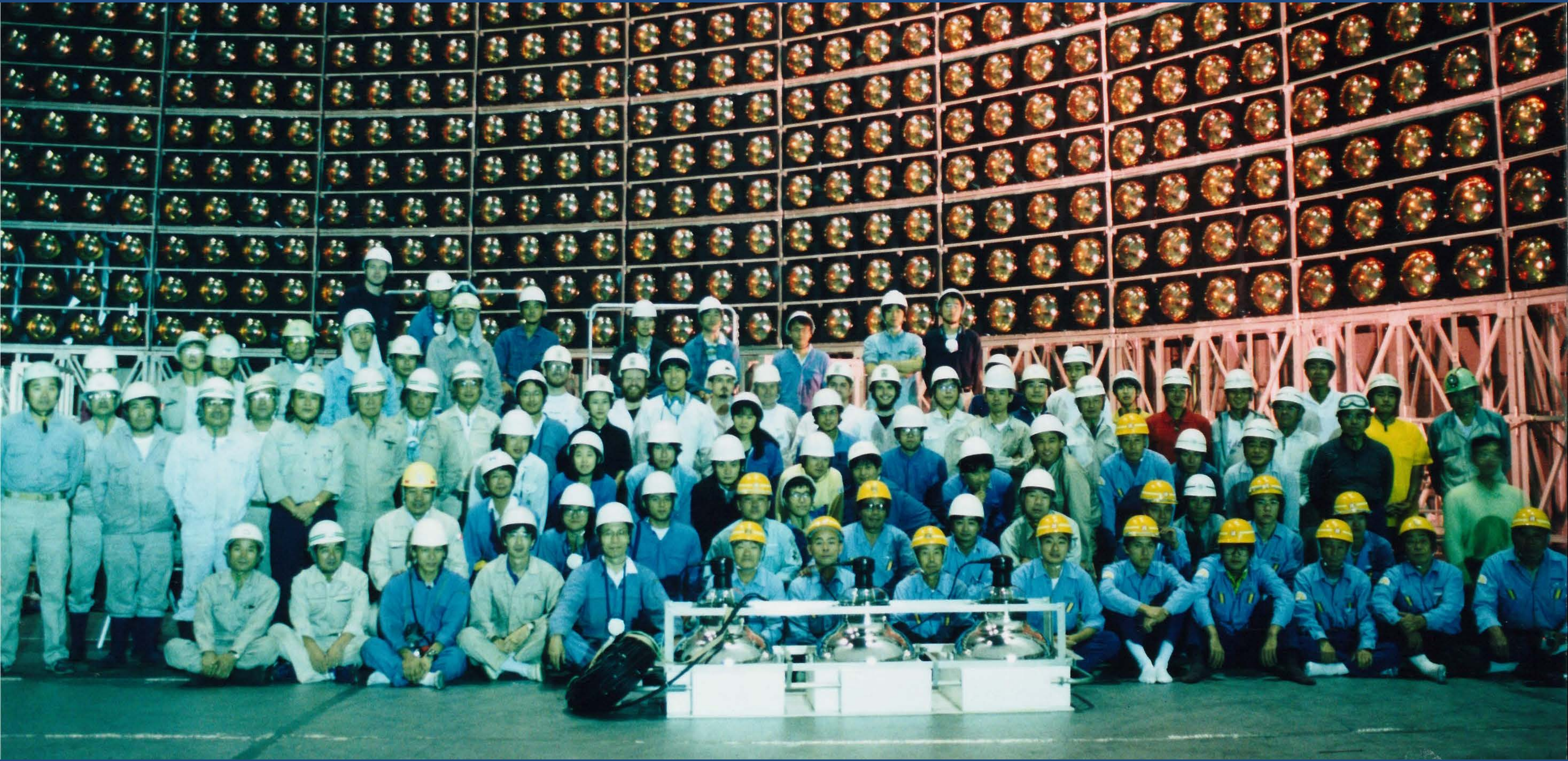
Beginning of the Super-Kamiokande collaboration between Japan and USA

@ Institute for Cosmic Ray Research, 1992

Constructing the Super-Kamiokande detector (spring 1995)



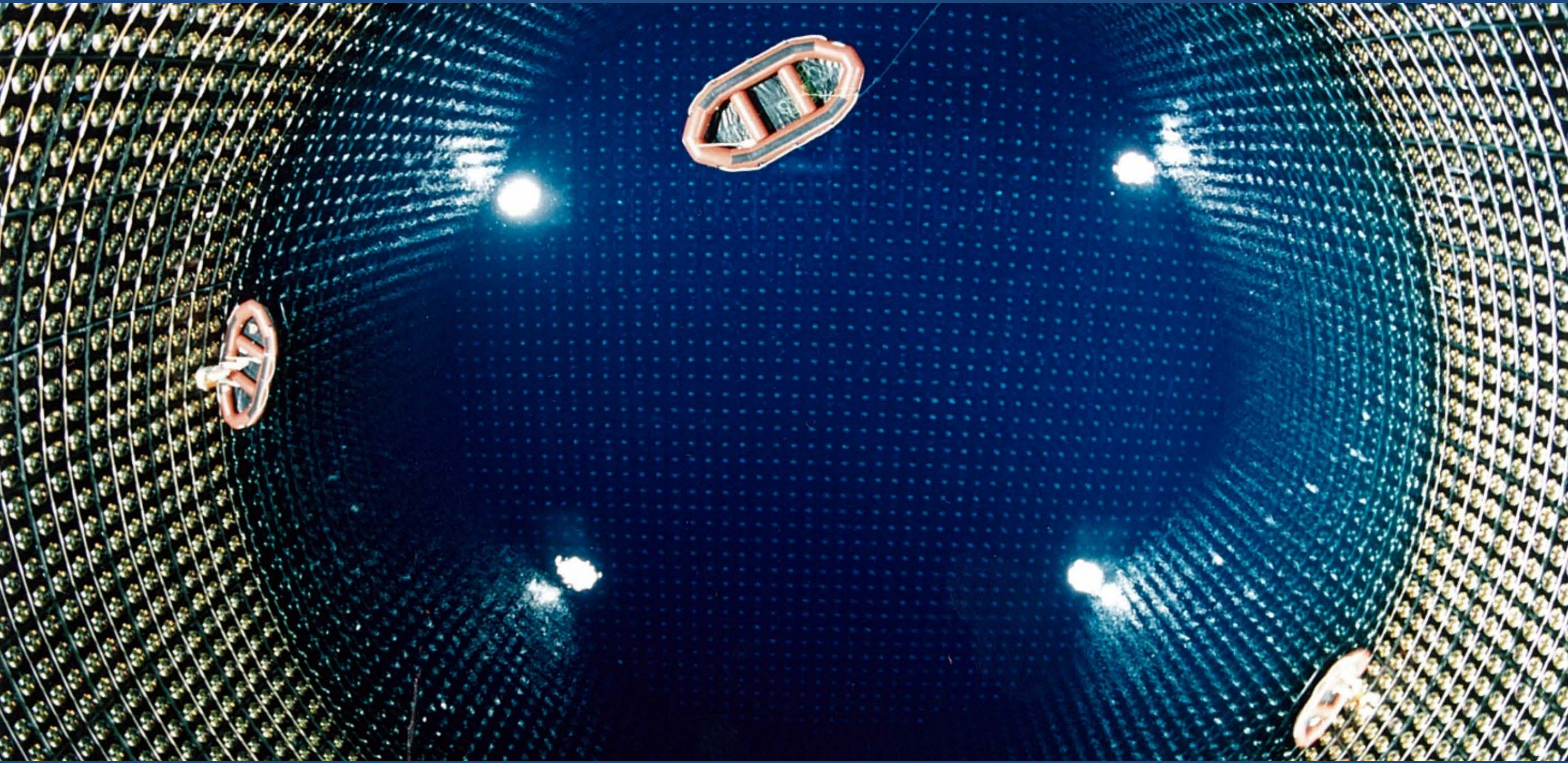
Constructing the Super-Kamiokande detector (Aug. 1995)



Constructing the Super-Kamiokande detector (Aug. 1995)

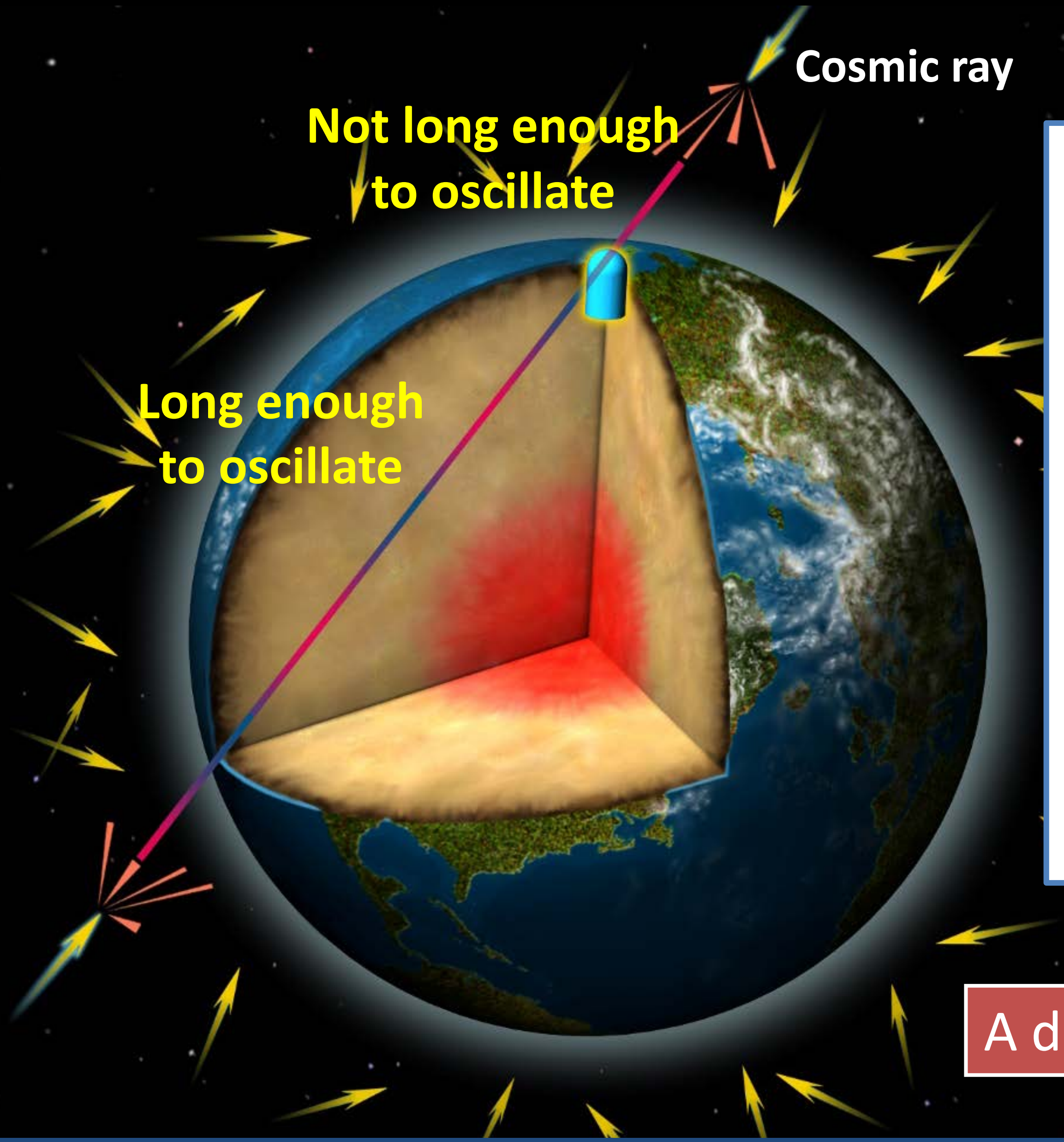
Filling water in Super-Kamiokande

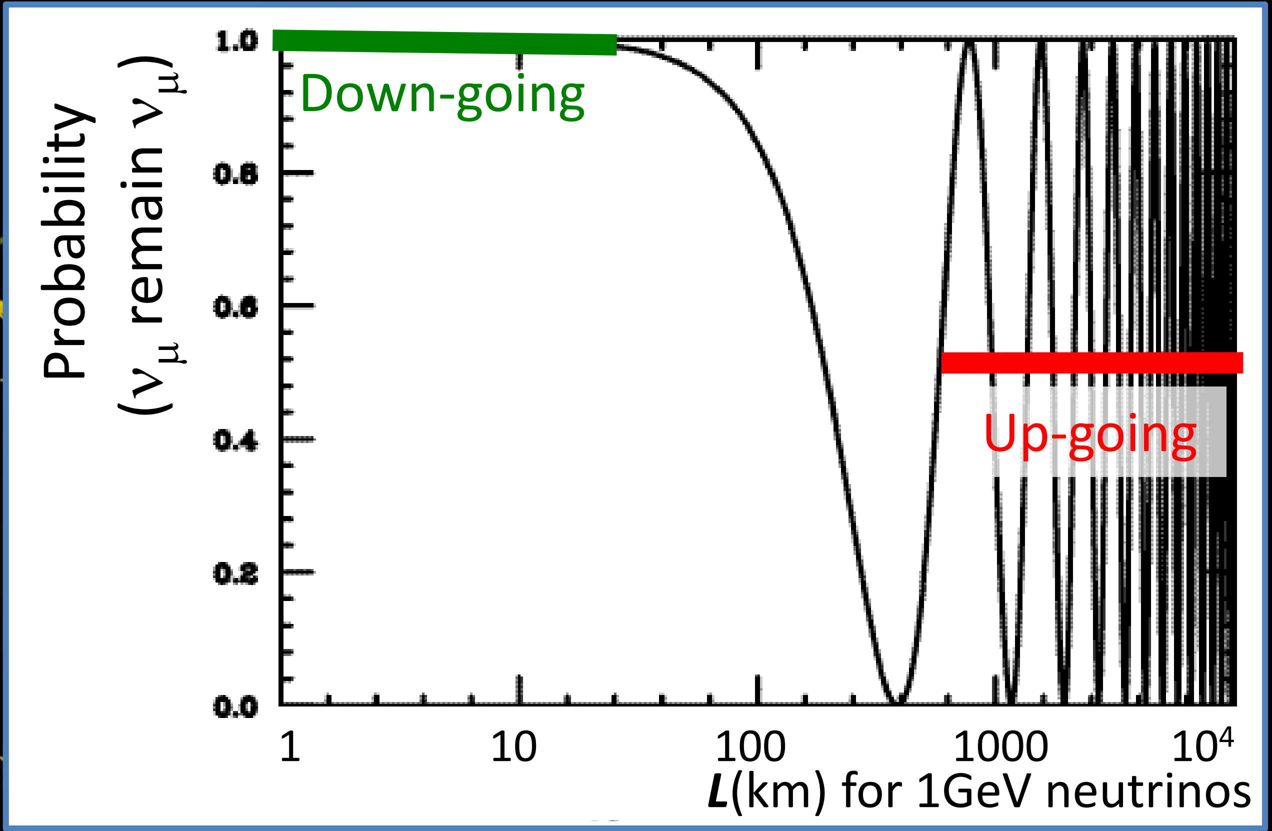
Jan. 1996



Discovery of atmospheric neutrino oscillations

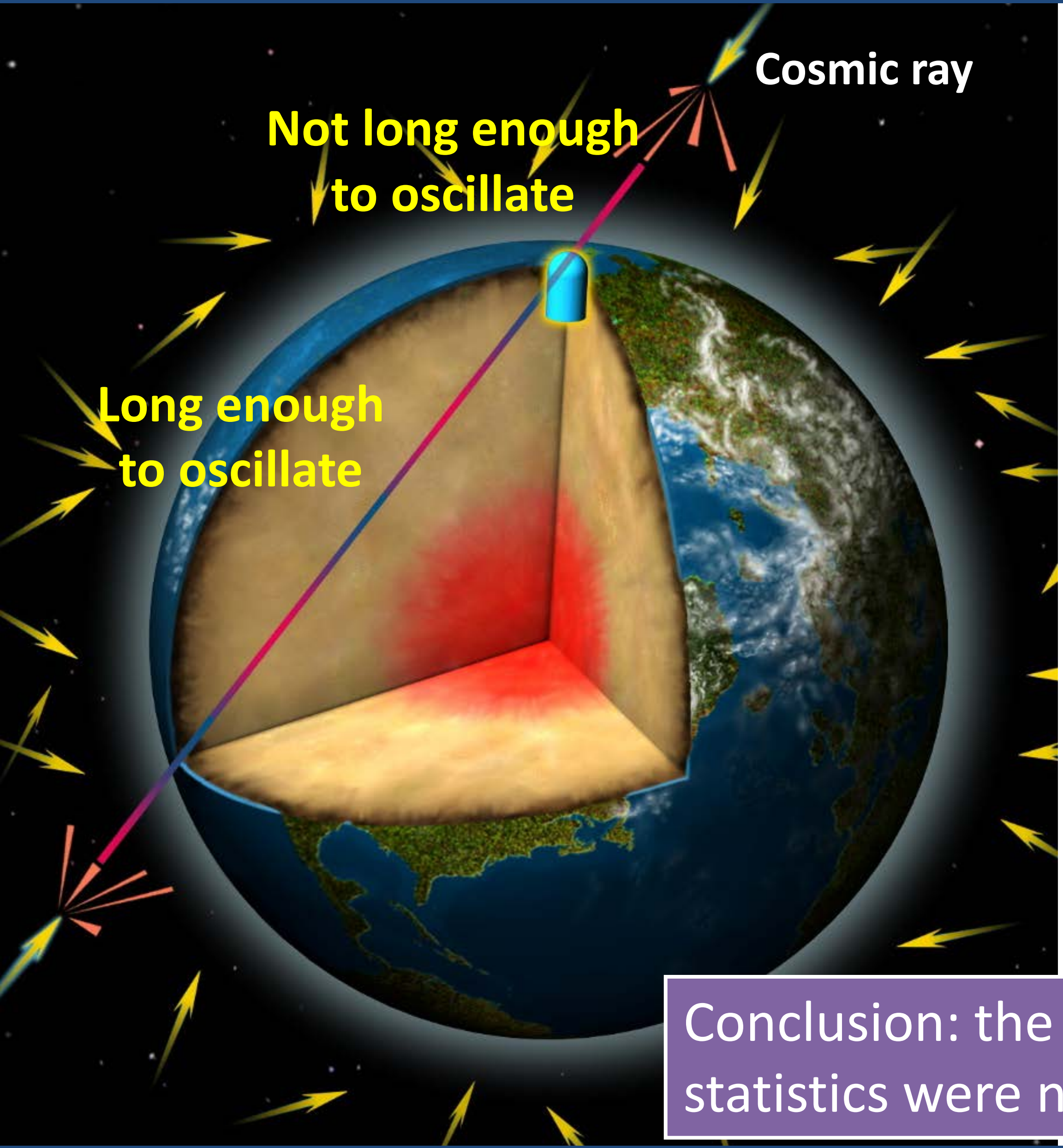
What will happen if the ν_μ deficit is due to neutrino oscillations



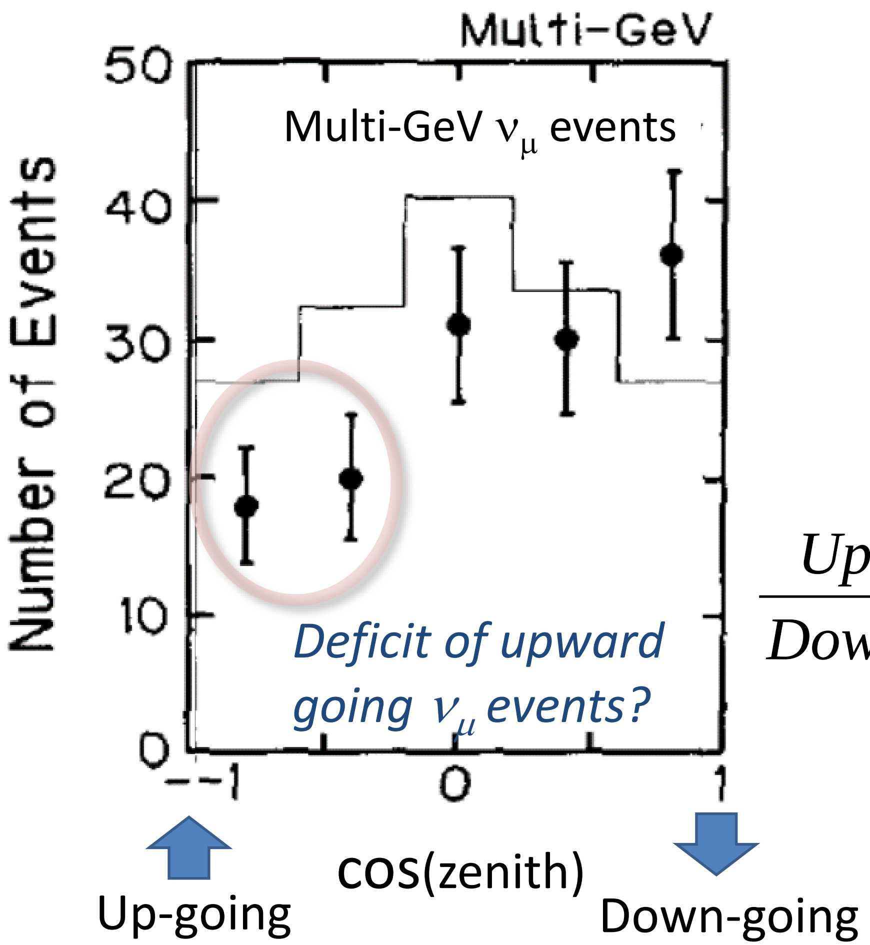


A deficit of upward going ν_μ's should be observed!

Appendix: Zenith angle distribution from Kamiokande (1994)



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



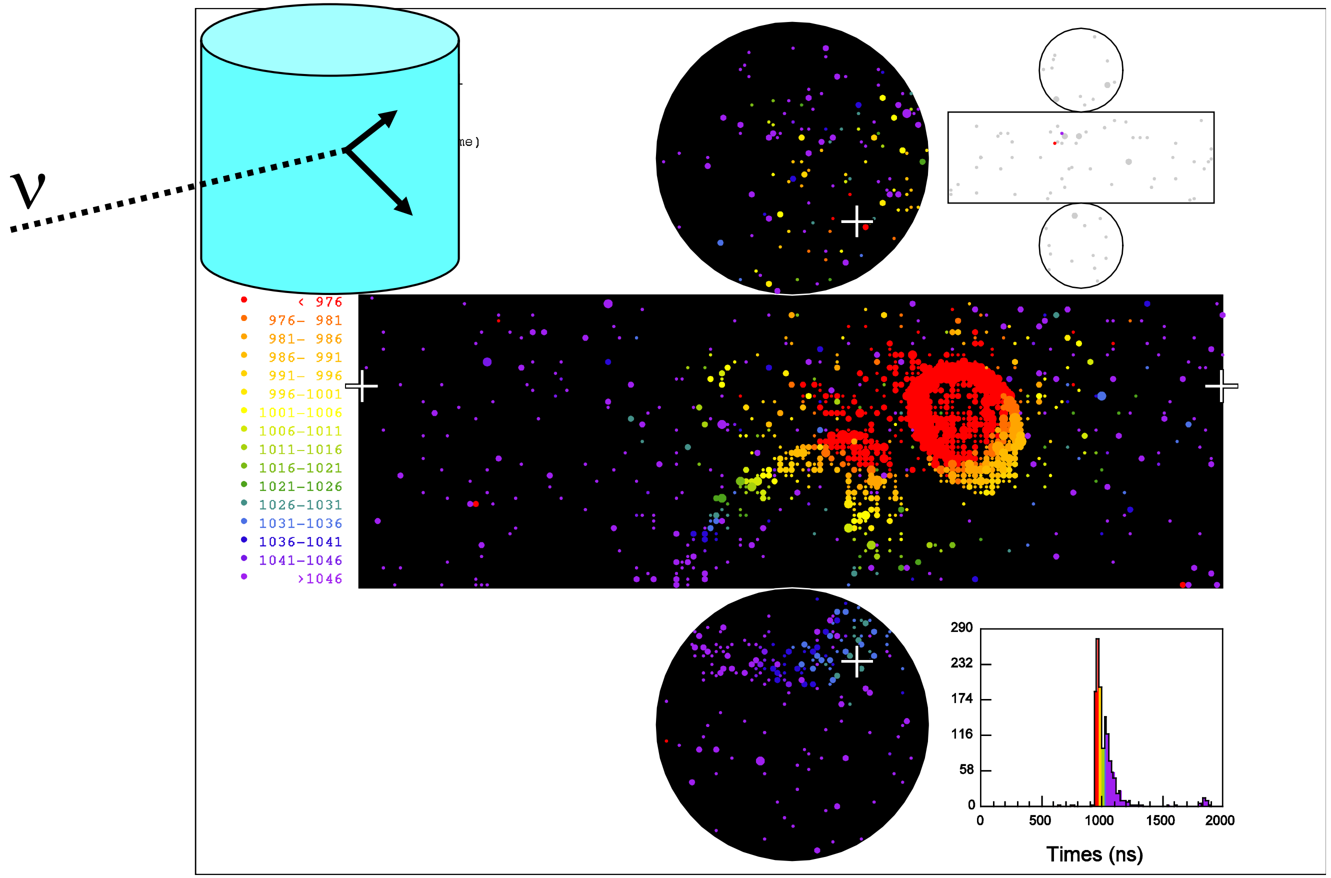
$$\frac{Up}{Down} = 0.58^{+0.13}_{-0.11} \; (2.9\sigma)$$

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

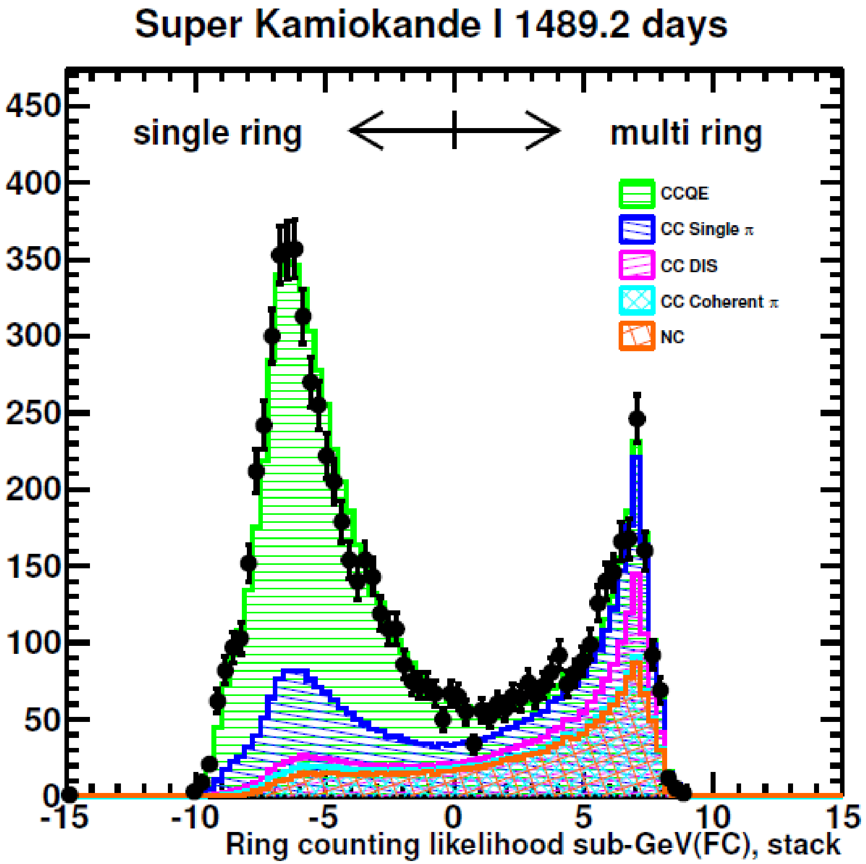
Fully automated analysis

▪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.

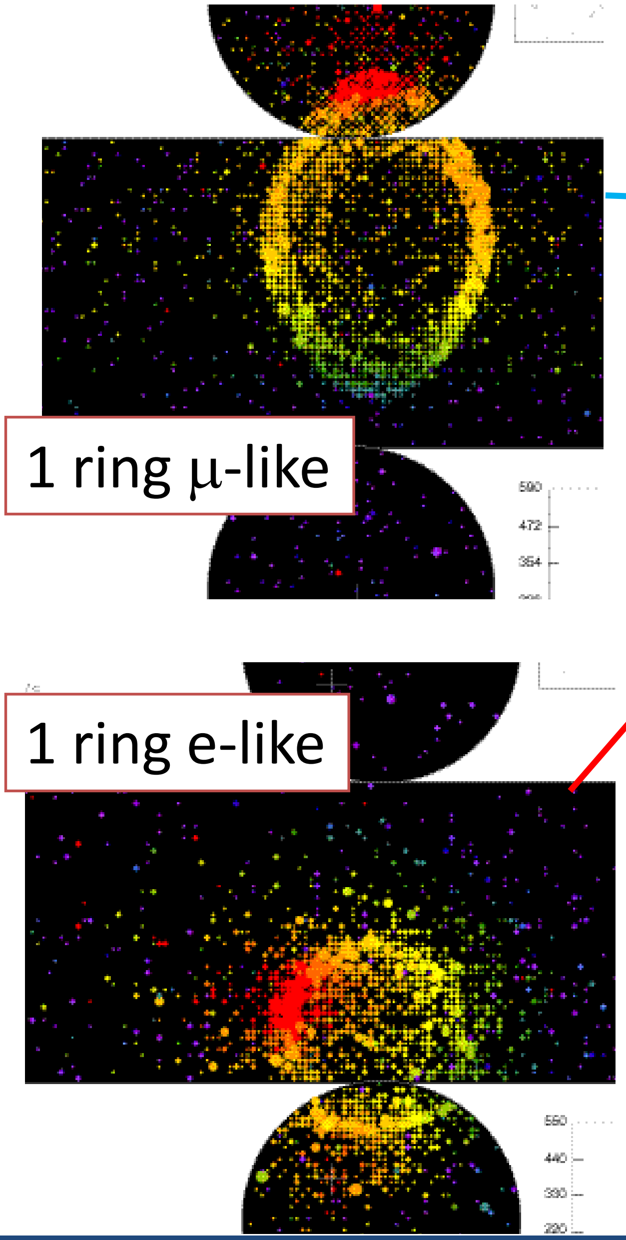
Multi Cherenkov ring event

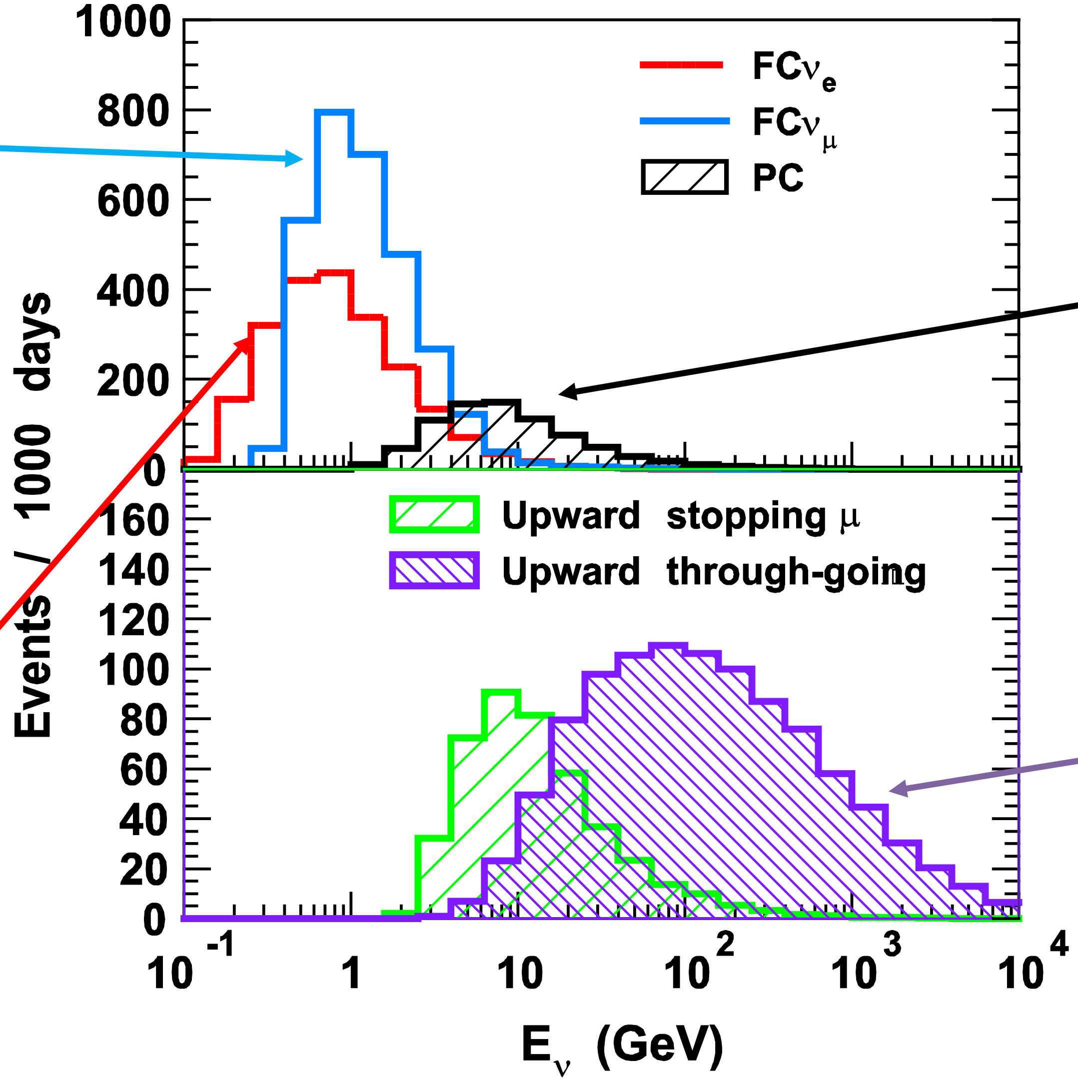


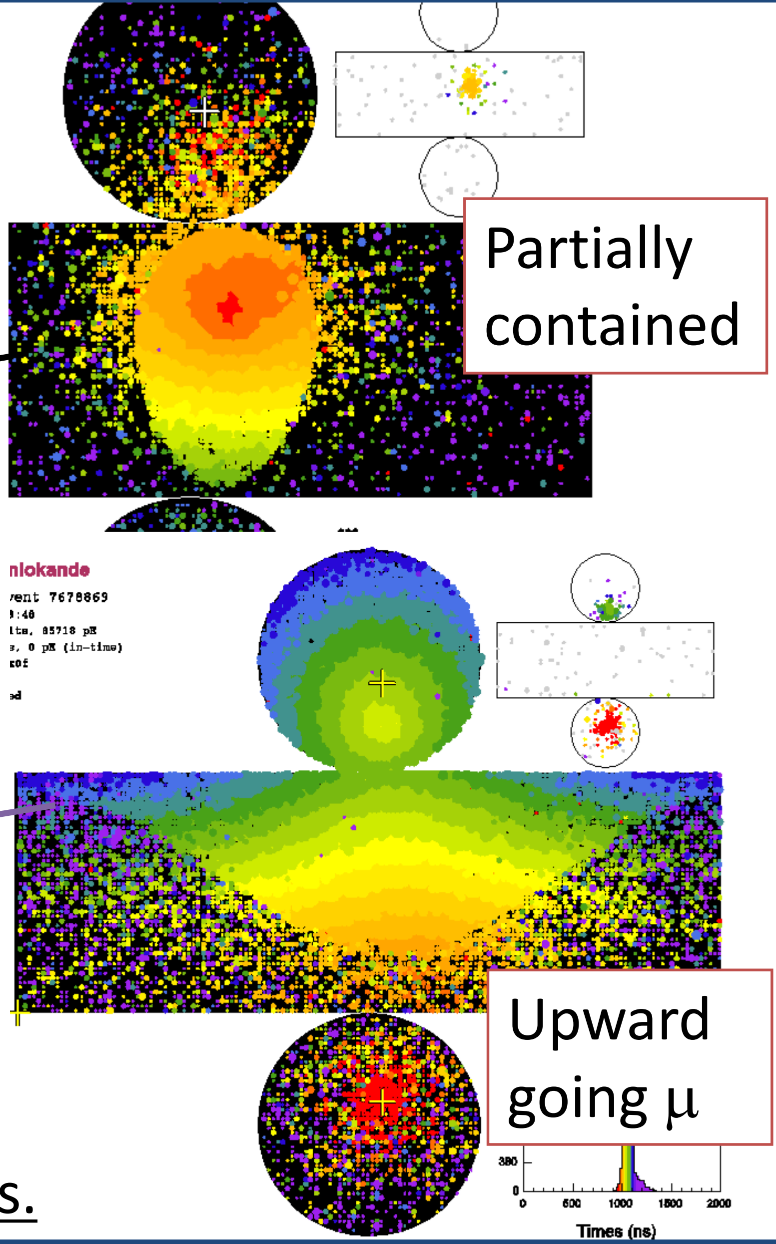
Hough transformation
+ maximum likelihood



Event type and neutrino energy



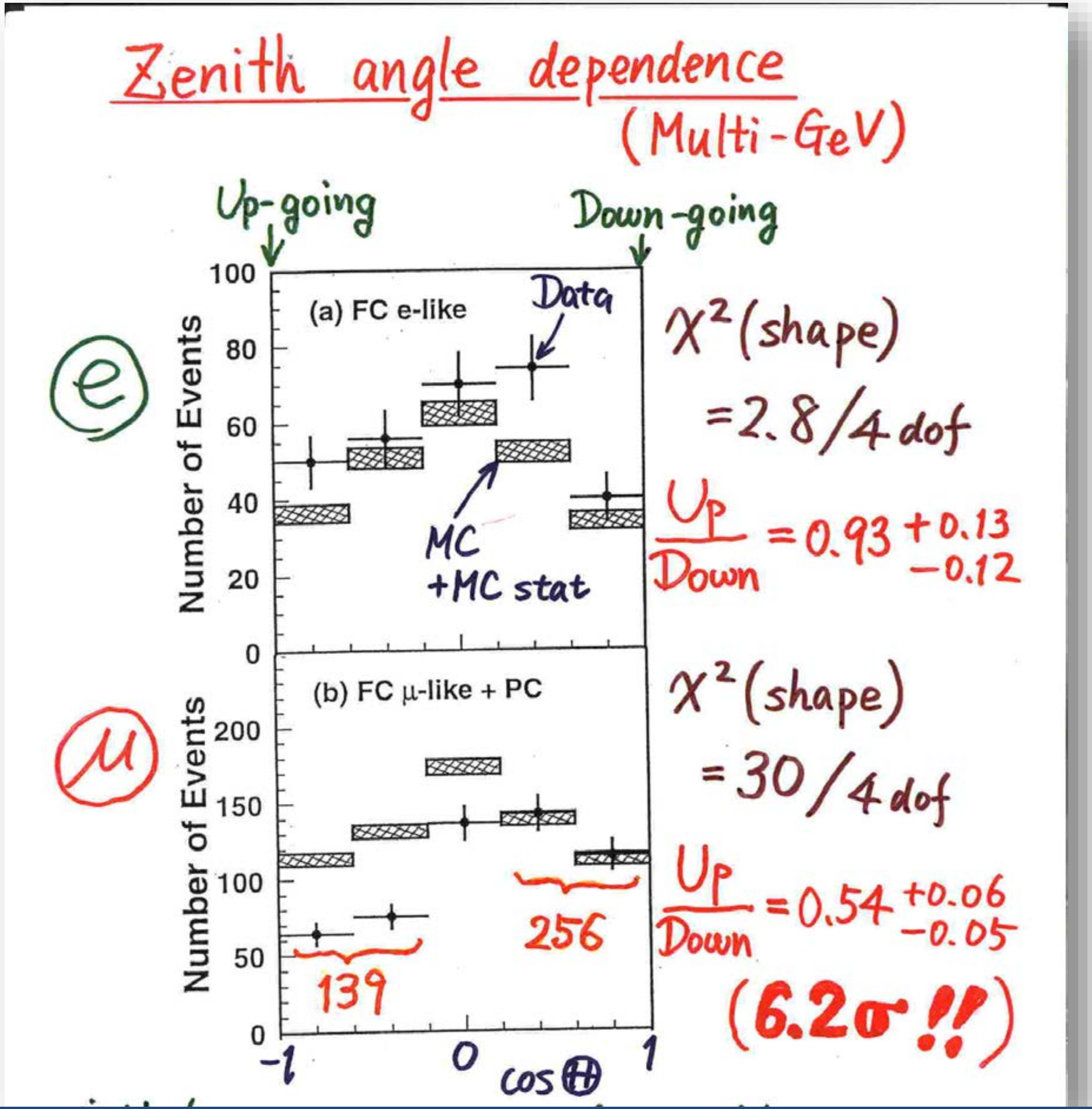


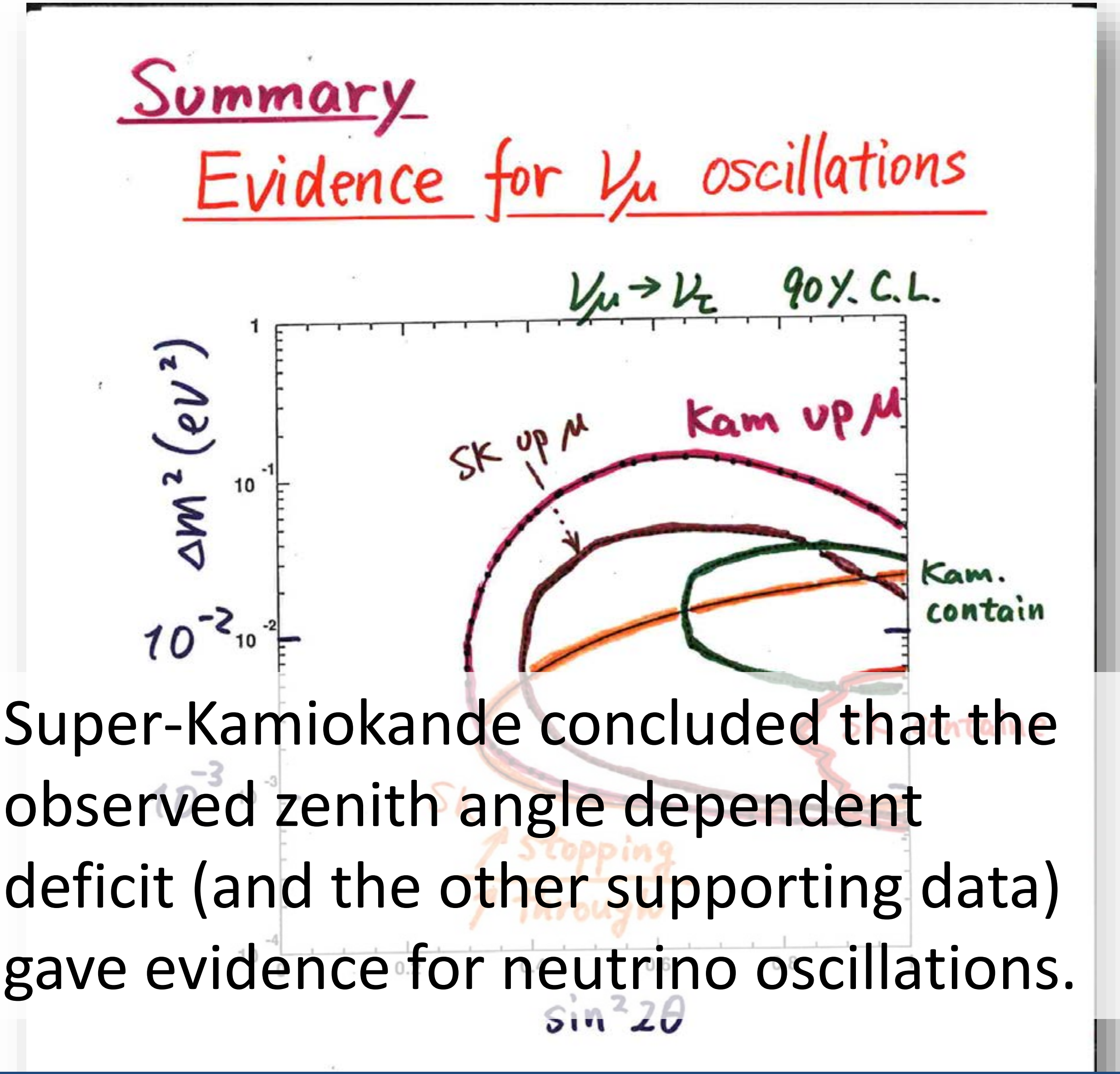


<u>All these events are used in the analysis.</u>

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

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

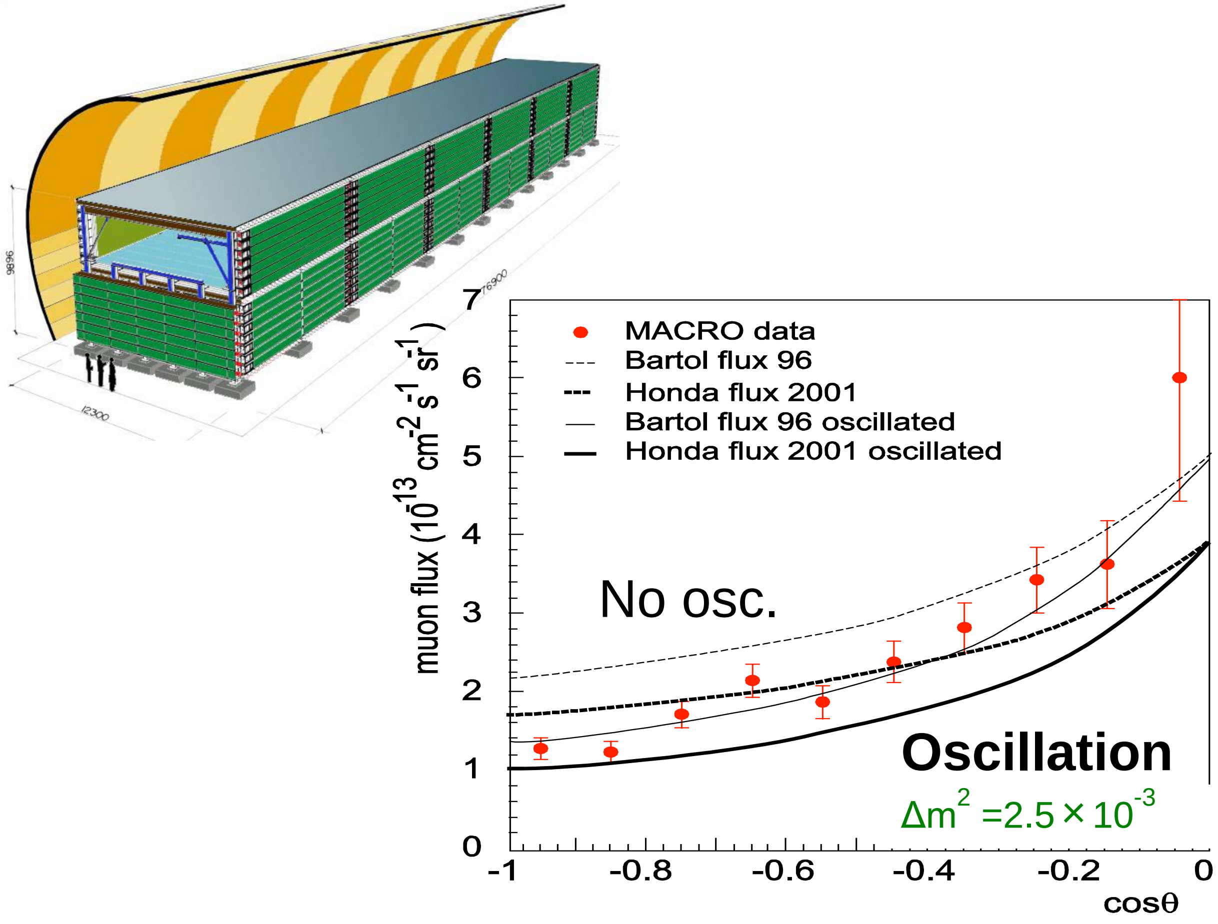




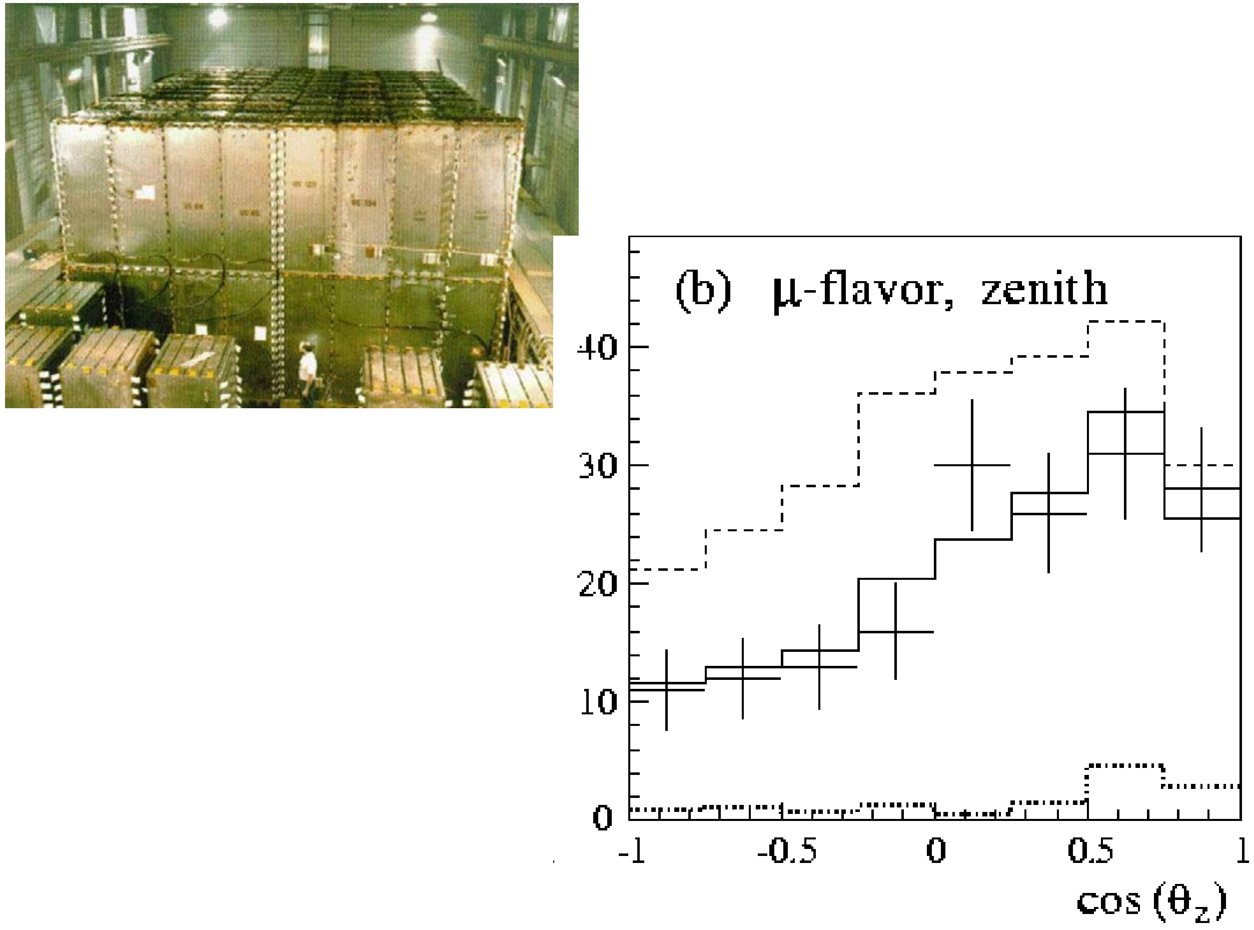
Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Results from the other atmospheric neutrino experiments

MACRO



Soudan-2

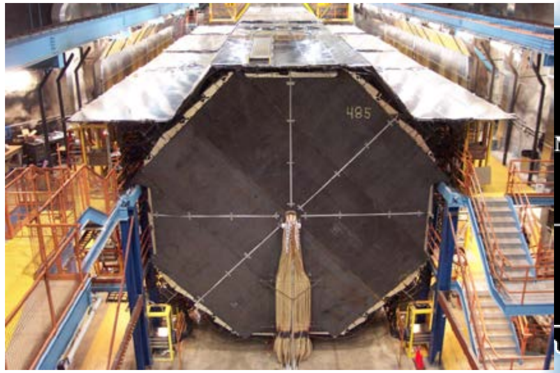


These experiments observed atmospheric neutrinos and confirmed neutrino oscillations.

Neutrino oscillation studies

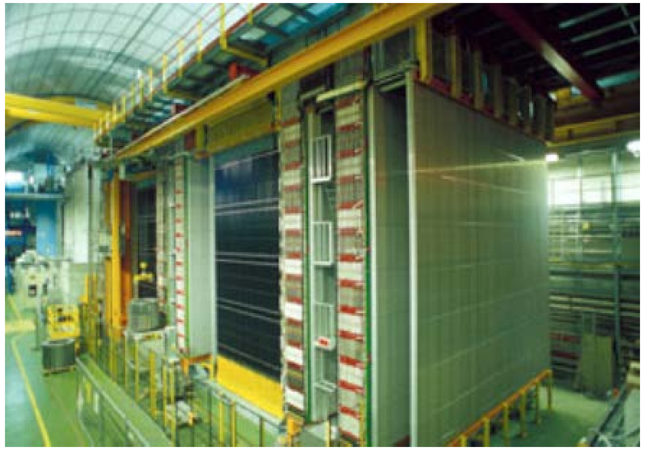
In addition to atmospheric neutrino experiments, various accelerator based long baseline neutrino oscillation have been studying neutrino oscillations in detail.

K2K



MINOS (USA)

OPERA



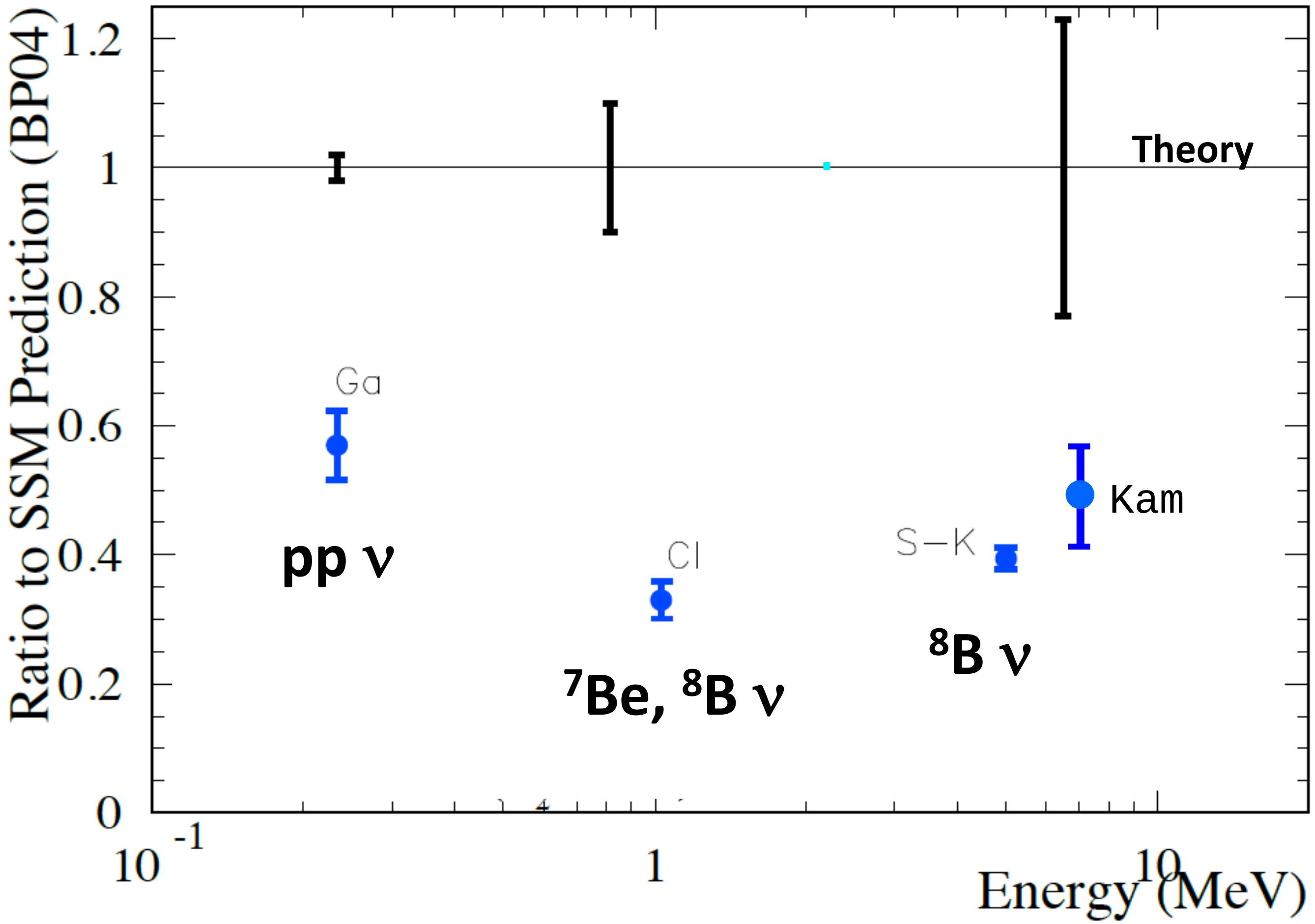
T2K

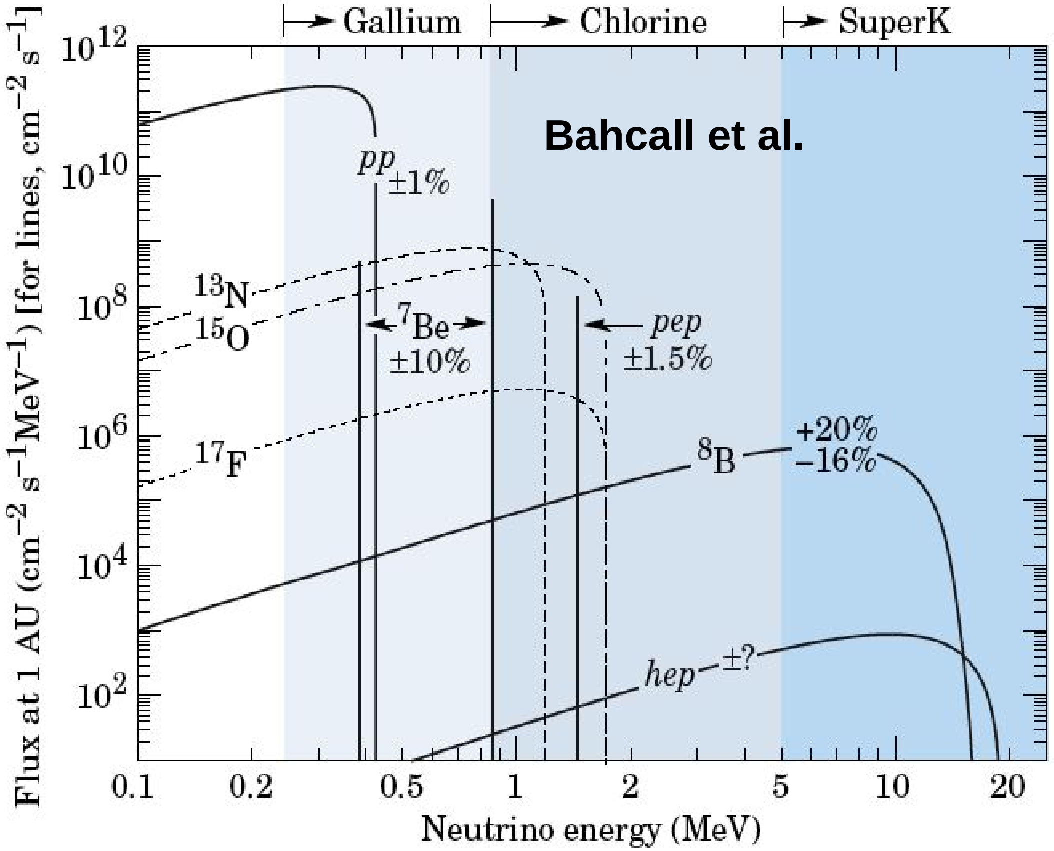
NOvA

(will be discussed by Nakaya-san)

Contribution to the discovery of solar neutrino oscillations

Results from solar neutrino experiments (before ~2000)

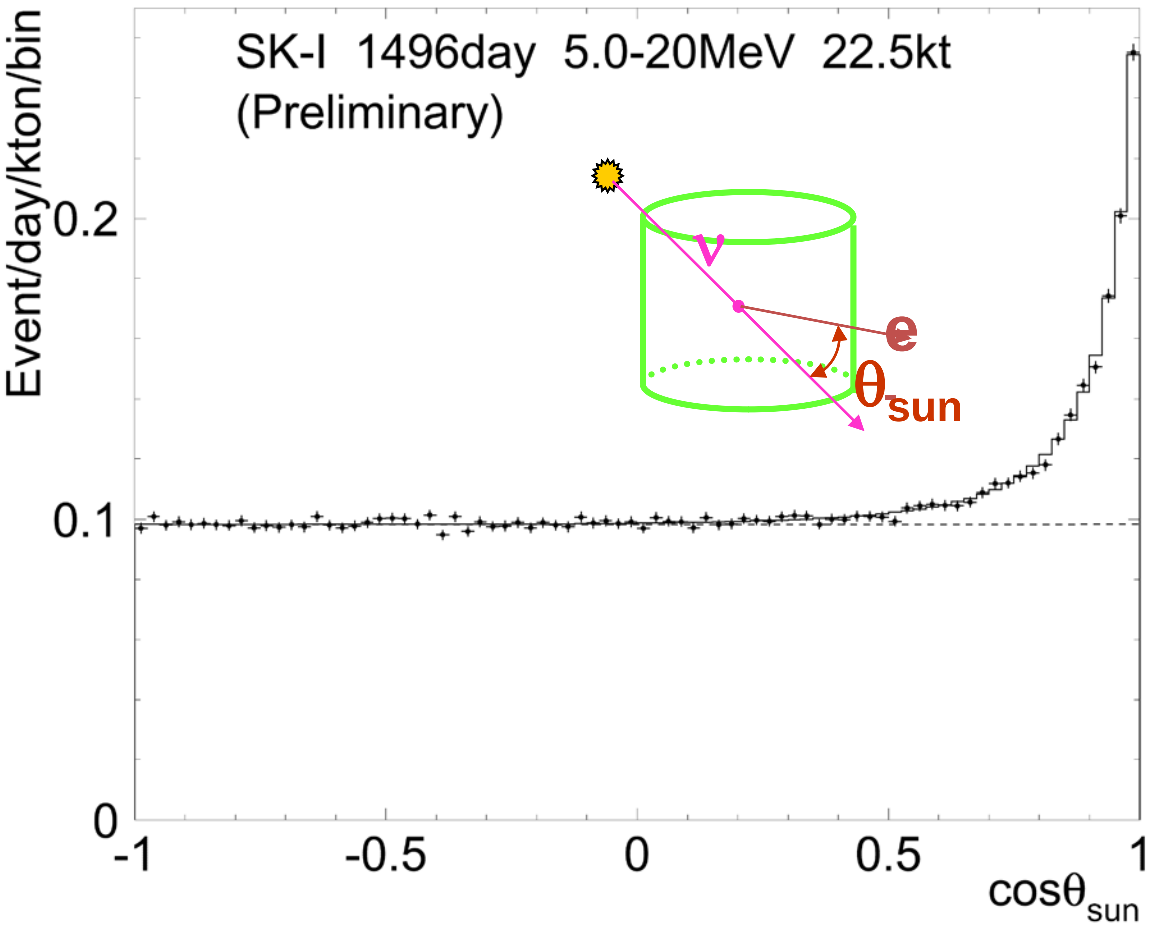


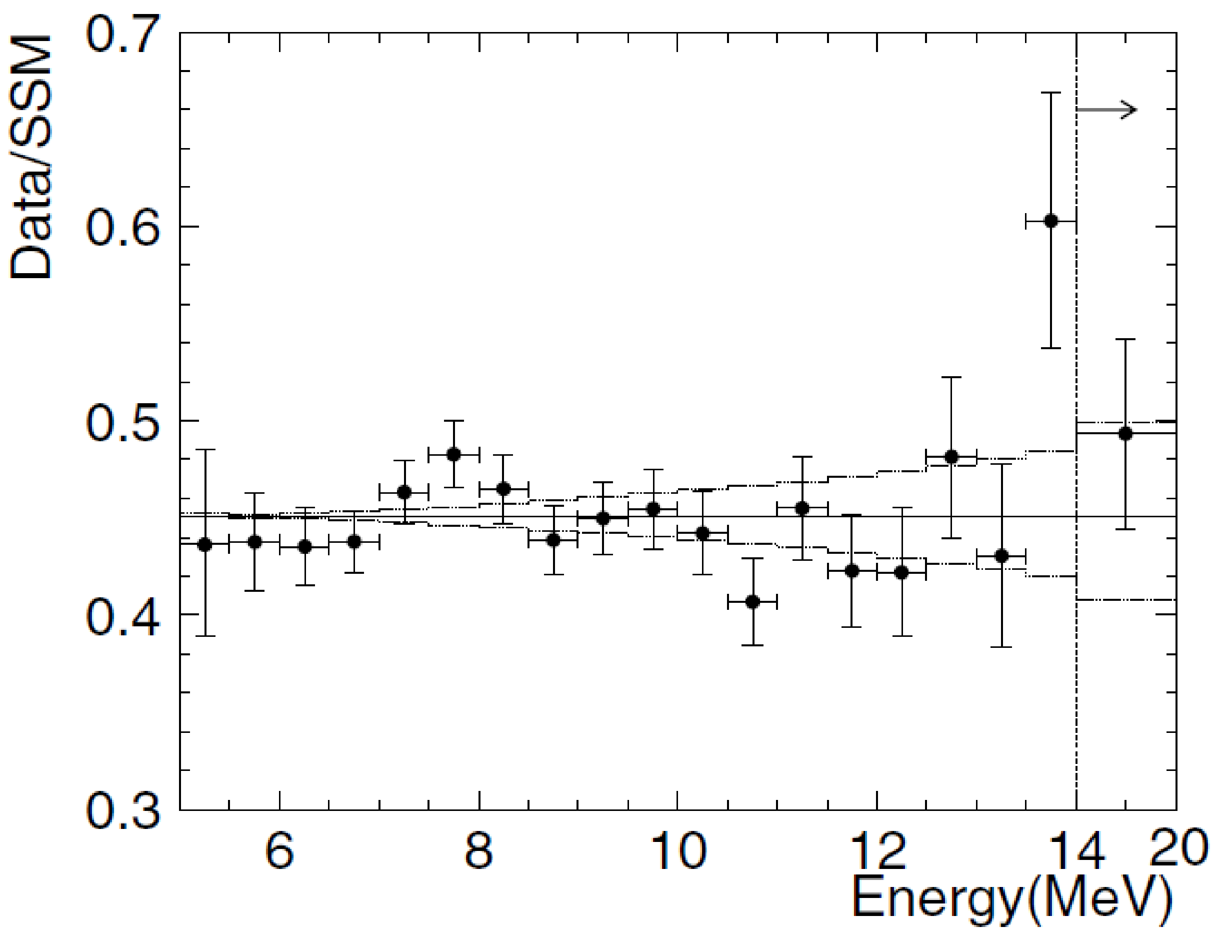


Subsequent solar neutrino experiments in the 80’s and 90’s confirmed the deficit of solar neutrinos.

Early solar neutrino data from Super-Kamiokande (2001)

SK collab. Phys. Rev. Lett. 86 (201) 5651.
SK collab. PLB 539 (2002) 179.



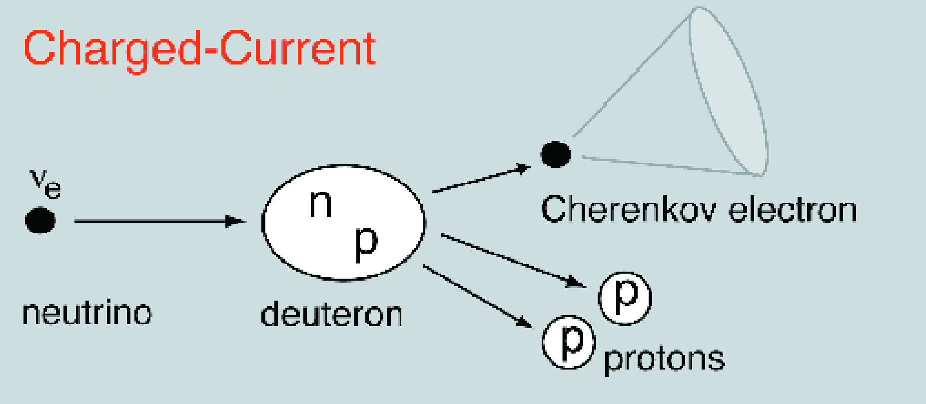


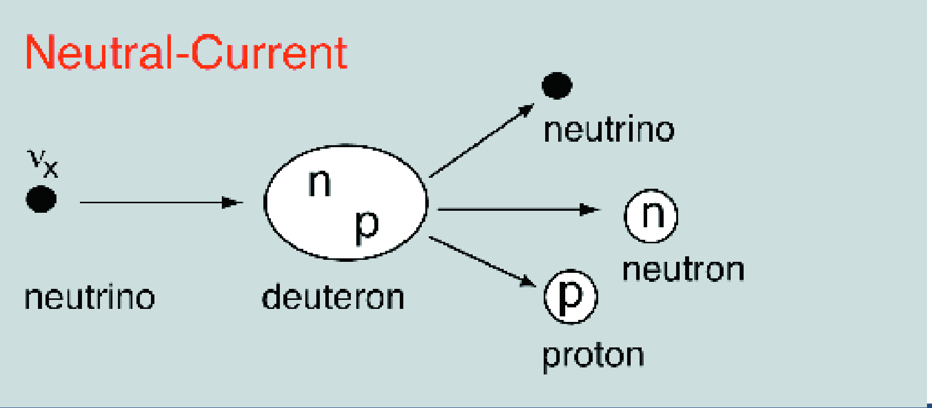
In spite of these precise measurements, the solar neutrino problem was unsolved by SK alone.

Unique signatures of heavy water (D_2O) experiments

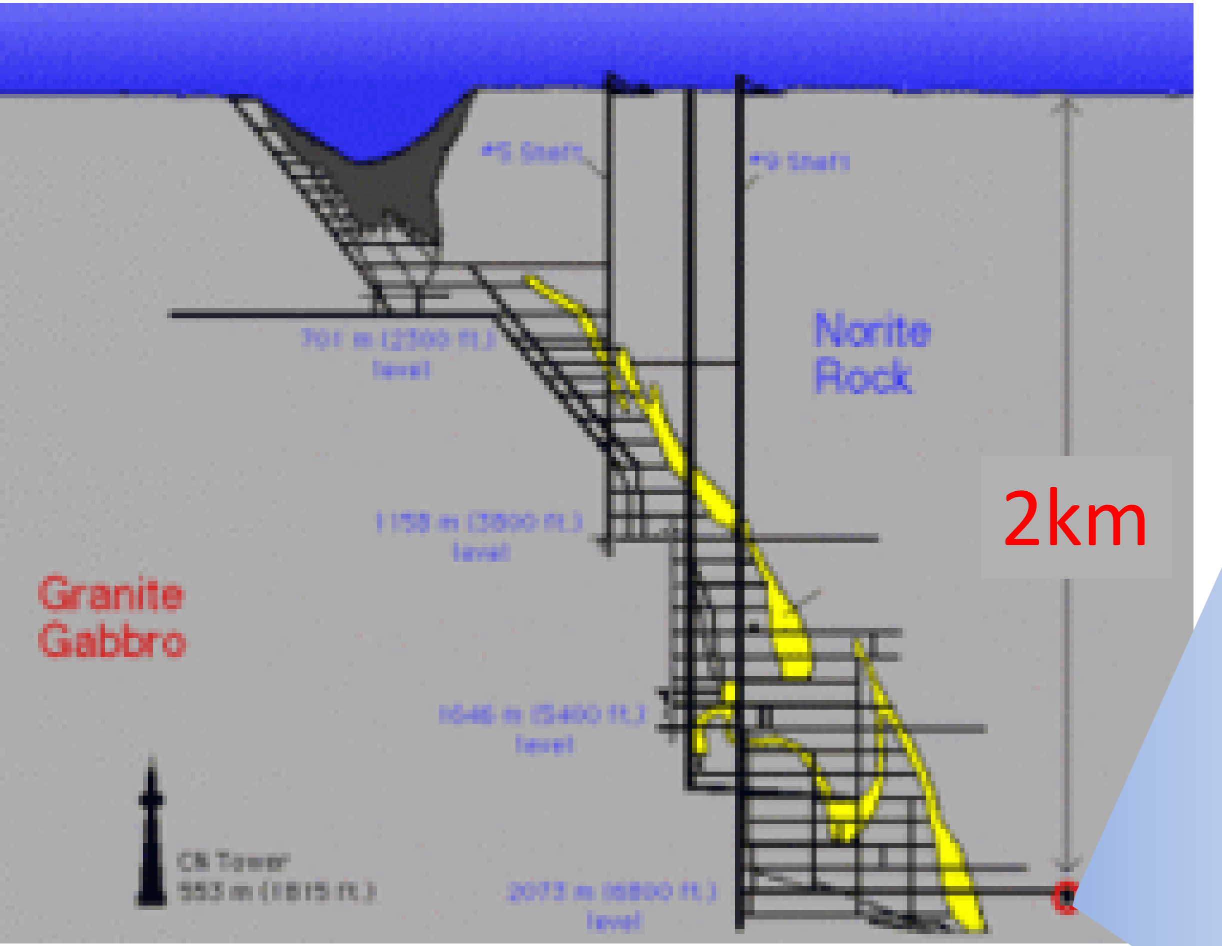
Herbert Chen, PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

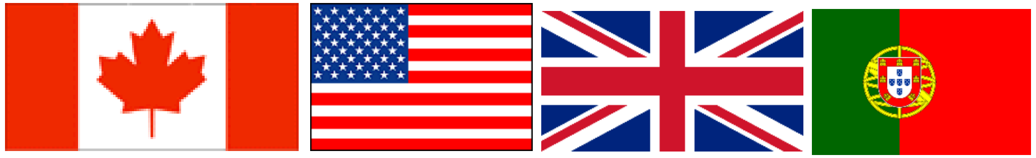
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu+d\rightarrow\nu+p+n$ and the charged-current reaction $\nu_e+d\rightarrow e^- +p+p$, is suggested for this purpose.

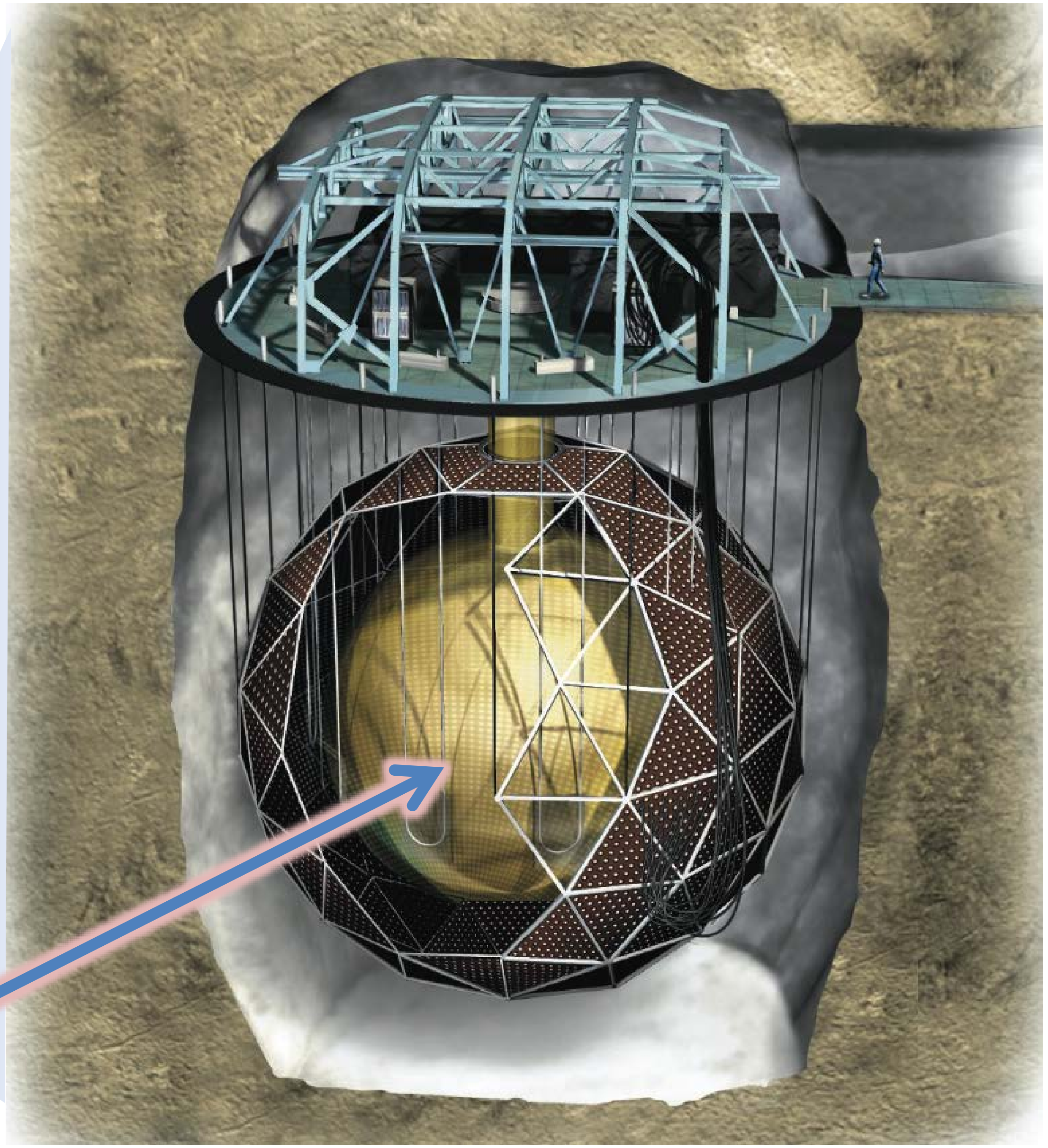




SNO detector







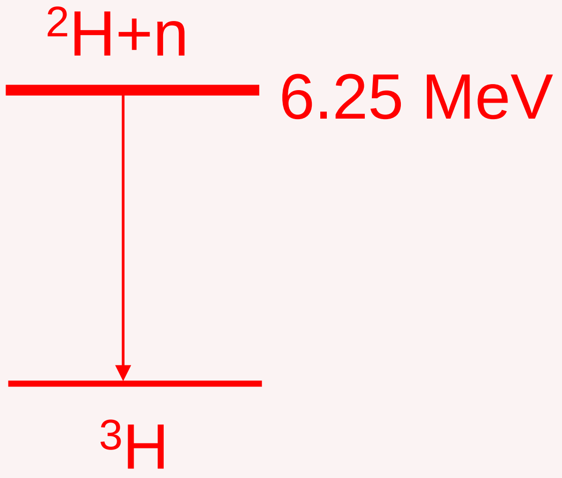
1000 ton of heavy water

3 neutron detection methods (for νd → νpn measurement)

Phase I (D_2O)

Nov. 99 - May 01

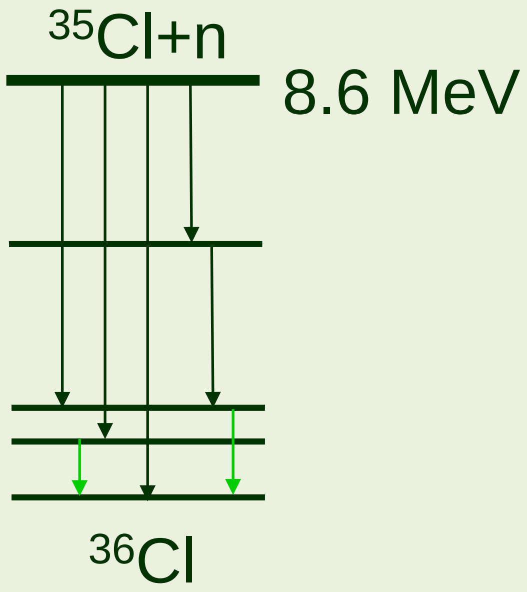
n captures on
$^{2}H(n, \gamma)^{3}H$
Eff. ~14.4%



Phase II (salt)

July 01 - Sep. 03

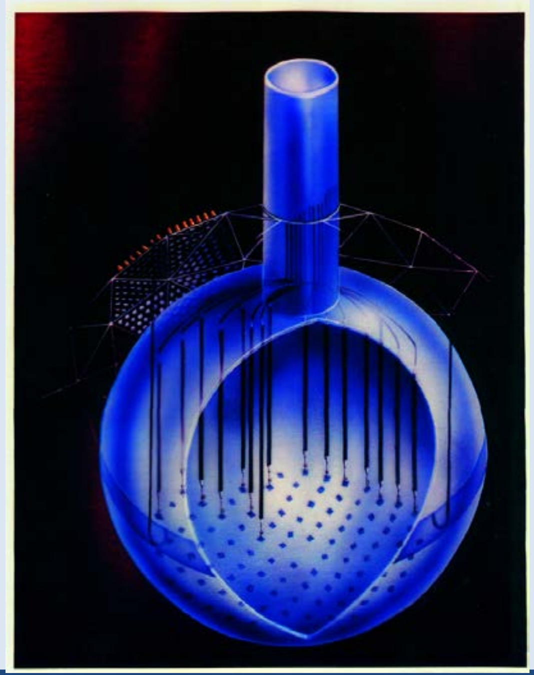
2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Eff. ~40%



Phase III (^{3}He)

Nov. 04-Dec. 06

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

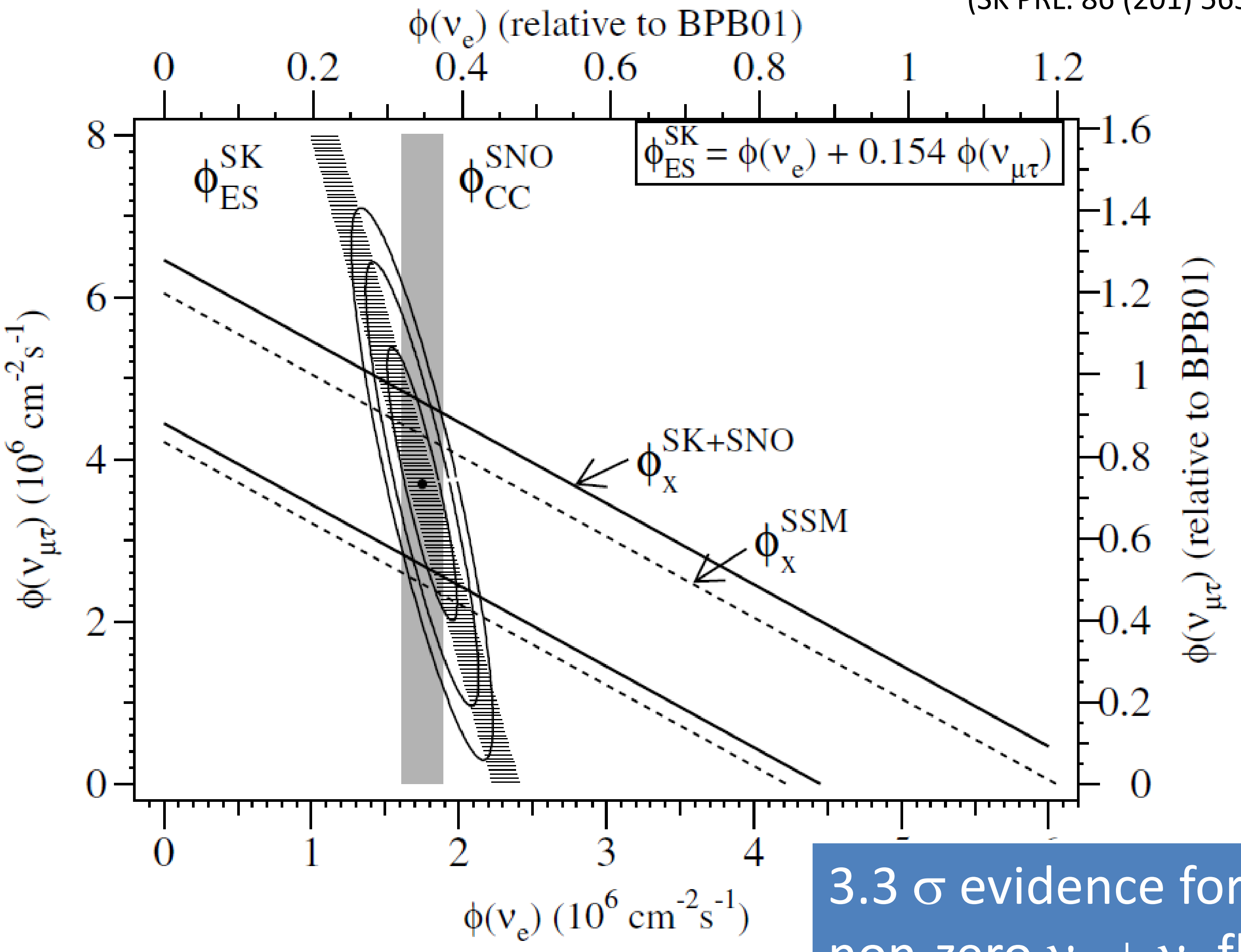


Initial evidence for solar neutrino oscillations

SNO PRL 87 (2001) 071301
(SK PRL. 86 (201) 5651.)

- SNO: $\nu_e + d \rightarrow p + p + e^-$
  (only sensitive to ν_e)
  ➔ 1.75+/- 0.07 +0.12/-0.11
  $*10^6$ /cm²/sec

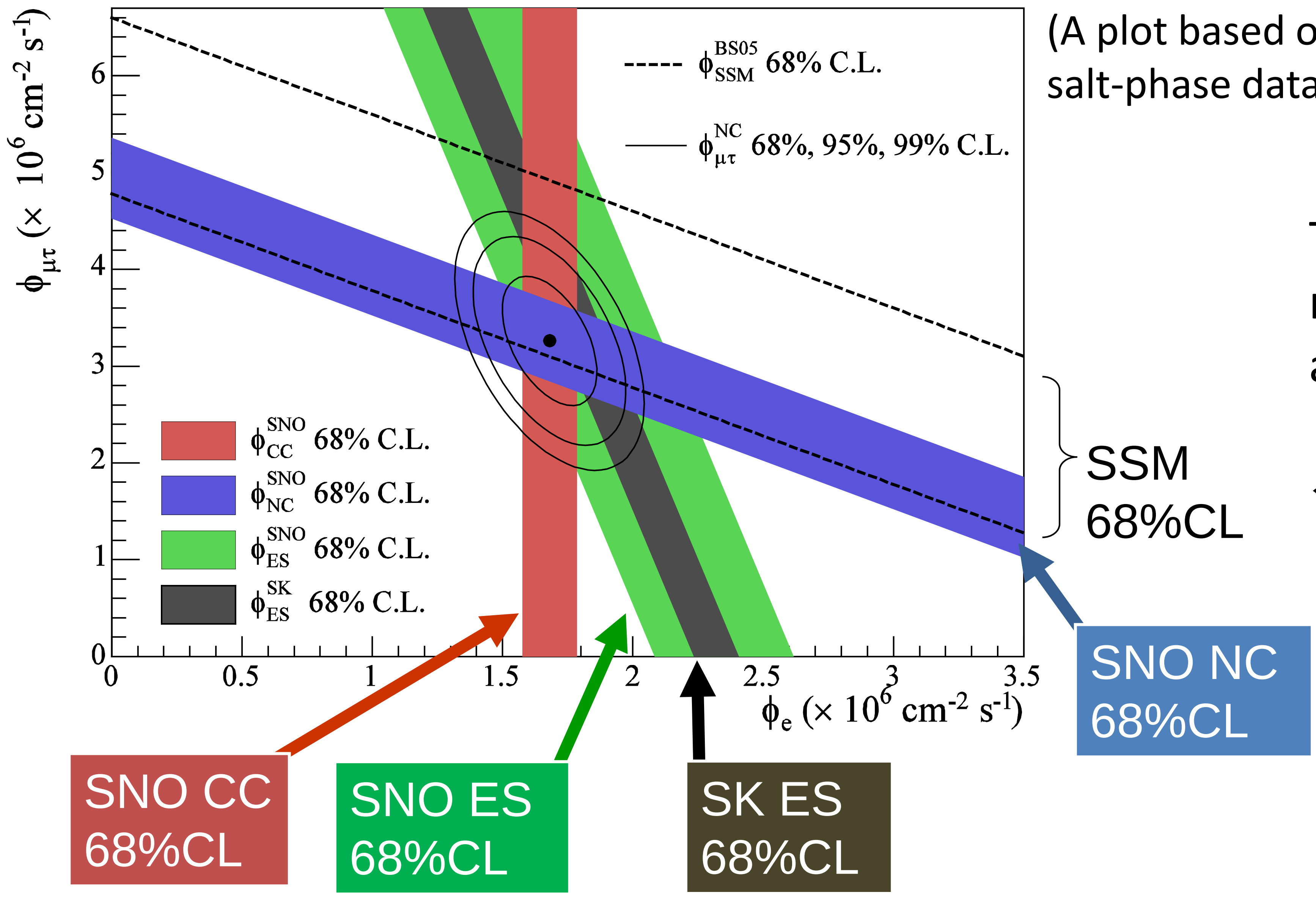
- SK: $\nu + e^- \rightarrow \nu + e^-$ (mostly sensitive to ν_e. but has ~1/7 sensitivity to ν_μ and ν_τ)
  ➔ 2.32 +/- 0.03 +0.08/-0.07
  $*10^6$ /cm²/sec
  (assuming ν_e only)



3.3 σ evidence for non-zero $\nu_\mu + \nu_\tau$ flux

Evidence for solar neutrino oscillations

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



(A plot based on the salt-phase data)

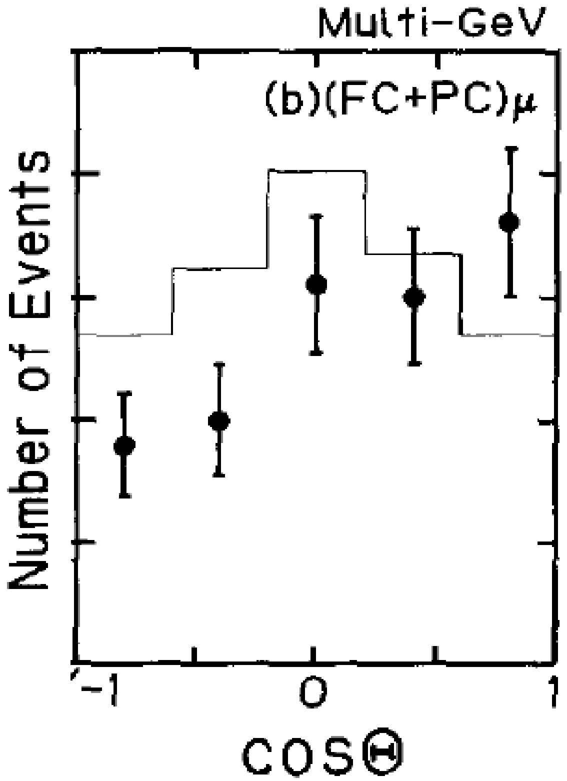
Three (or four) different measurements intersect at a point.

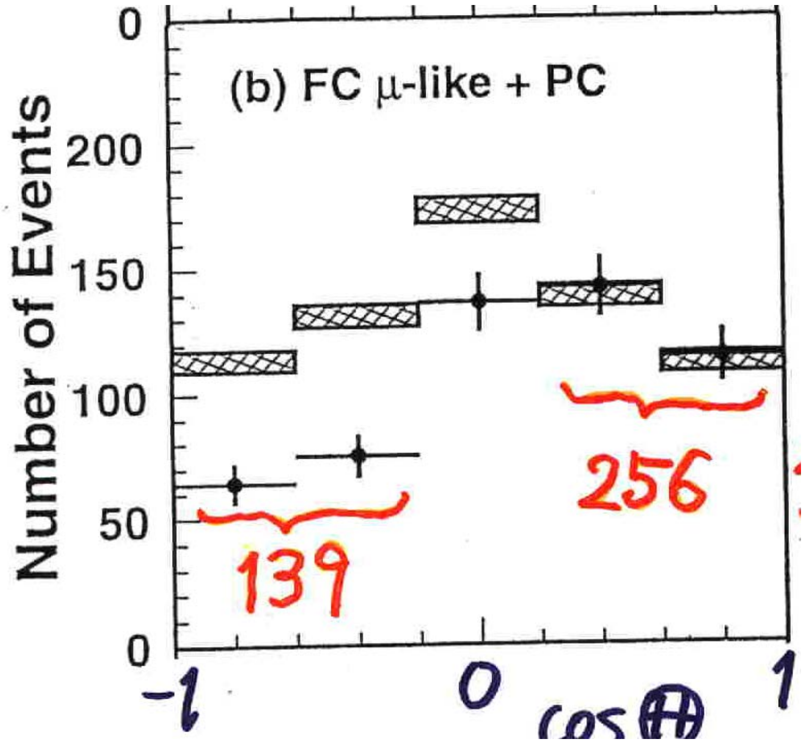
✓ *Evidence for ($\nu_\mu + \nu_\tau$) flux* ($> 5\sigma$)

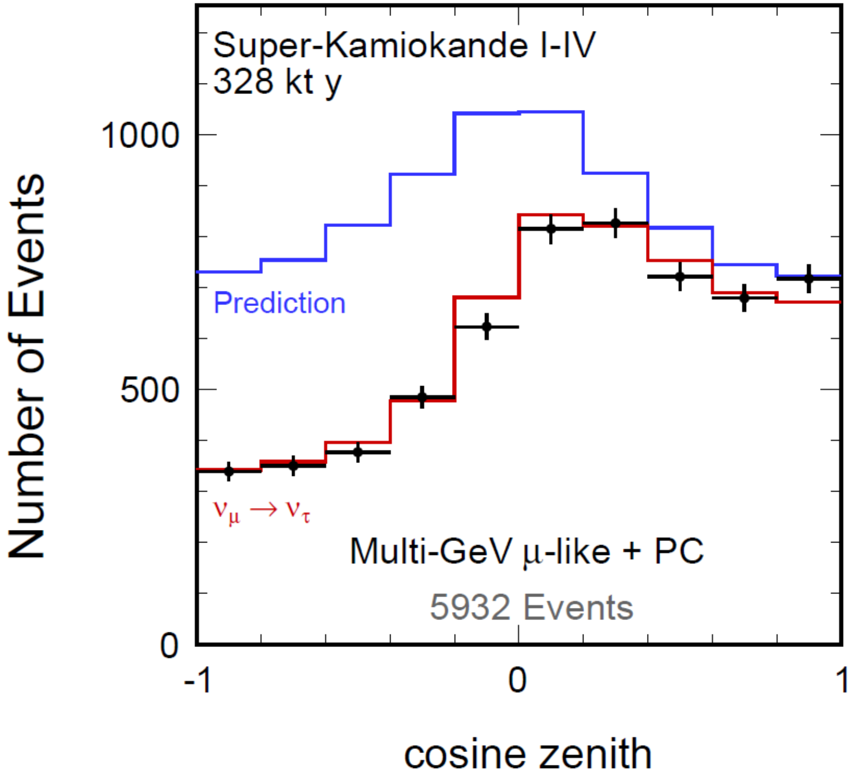
Some recent results from Super-kamiokande (non-accelerator results)

Atmospheric neutrinos: Data updates

Kamiokande (1994) → Super-K @Neutrino98 → Super-K (2016)







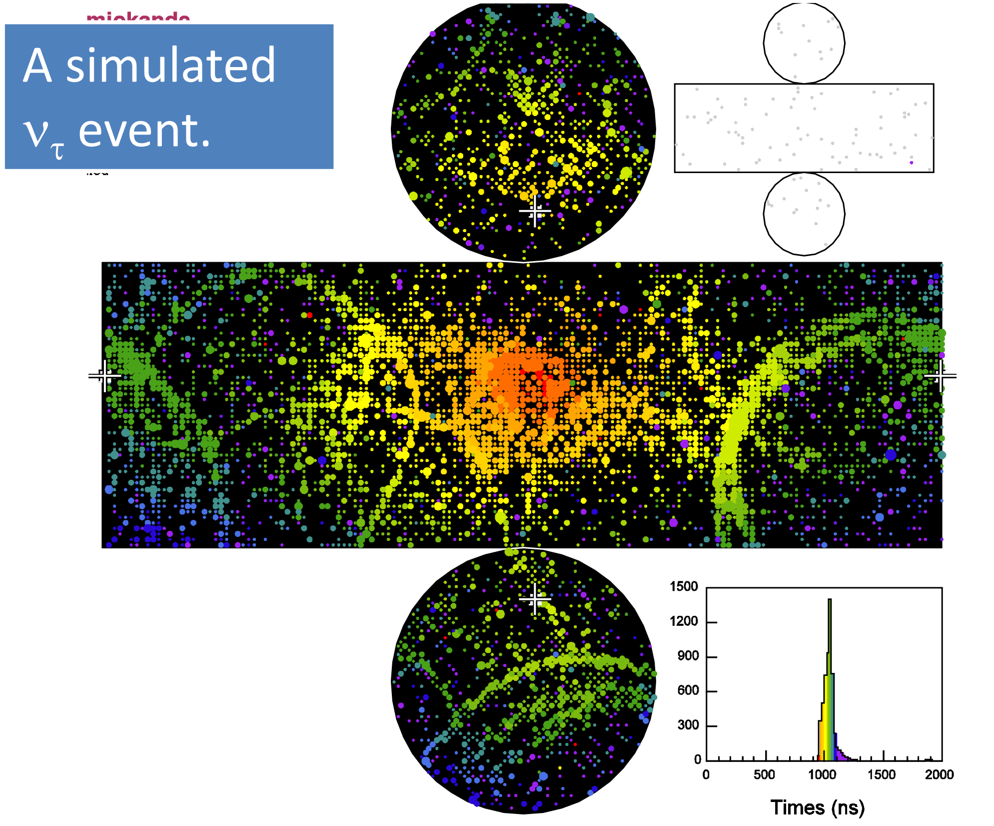
Number of events plotted:

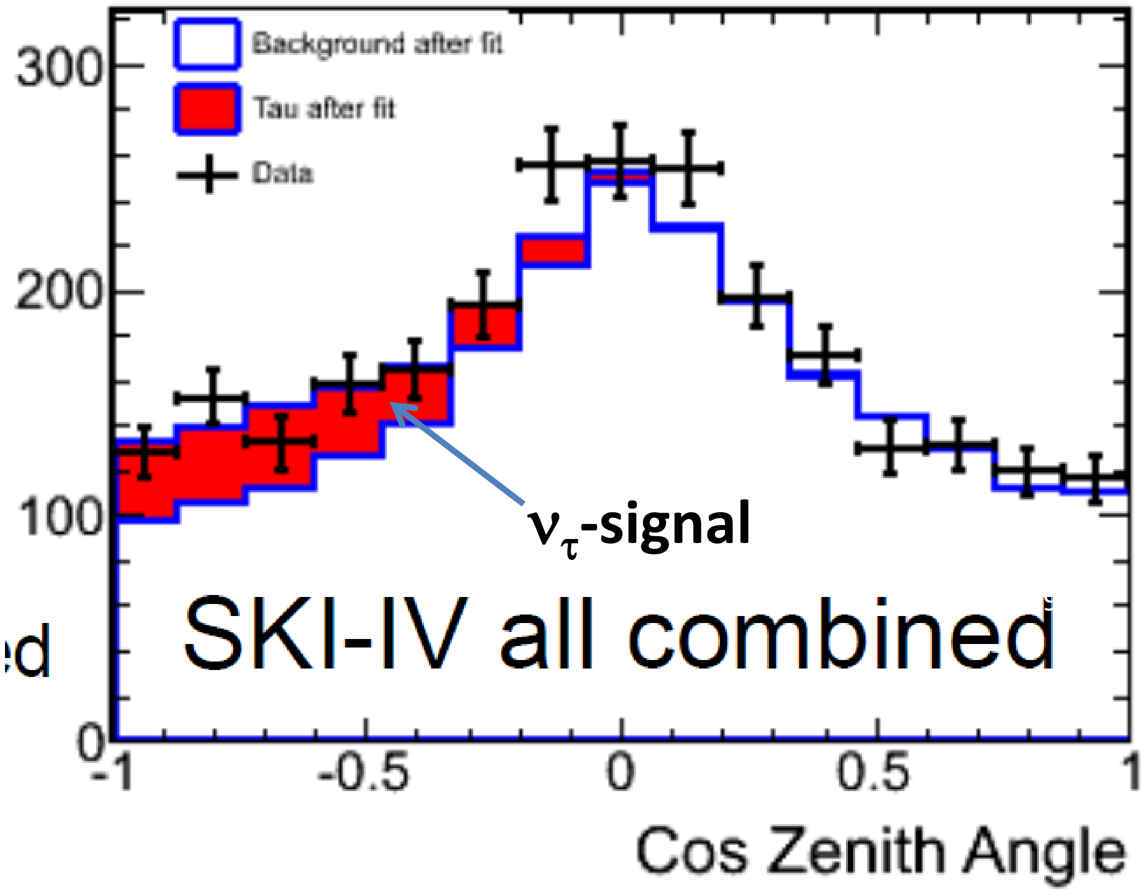
135 events → 531 events → 5932 events

Detecting tau neutrinos

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

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



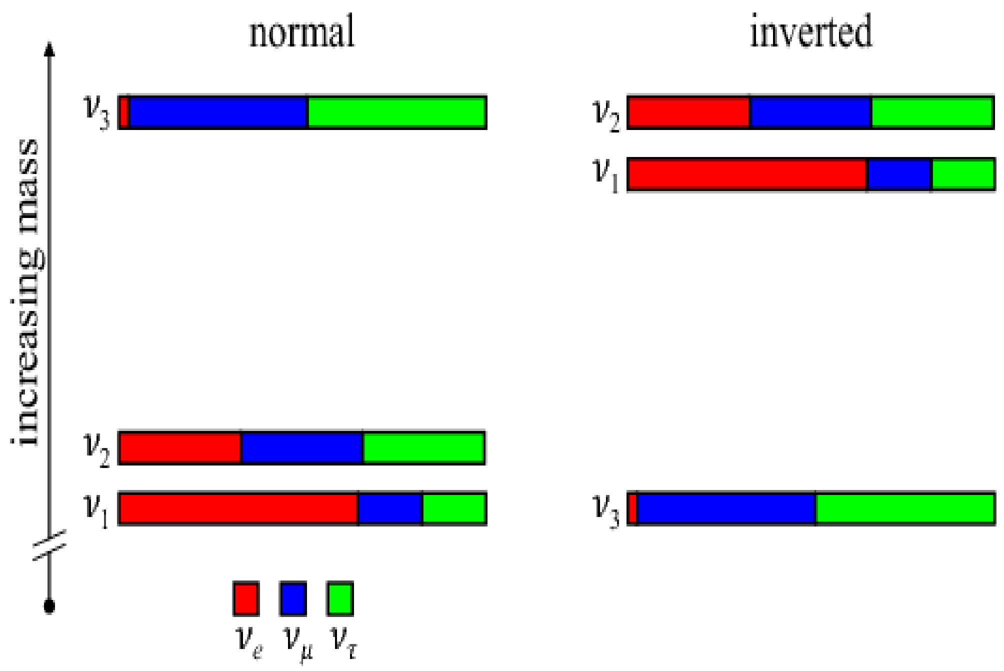


It is not possible for Super-K to identify ν_τ events by an event by event bases. ➔ Statistical analysis knowing that ν_τ's are upward-going only.

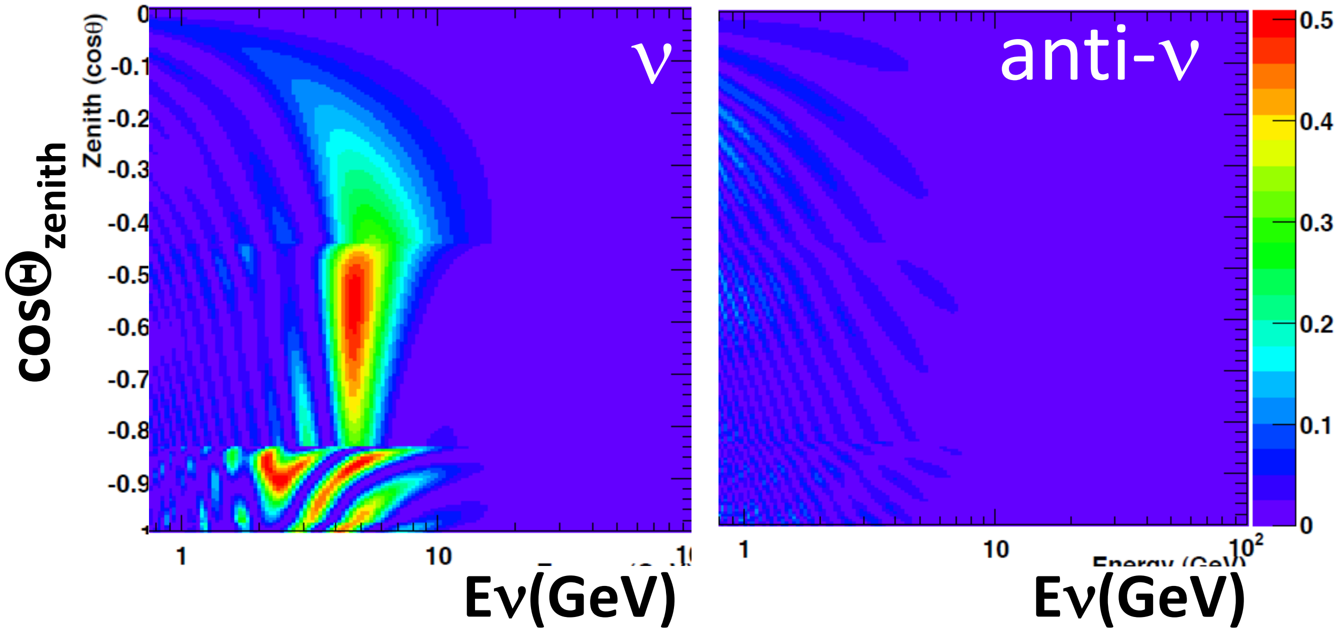
τ-appearance at 4.6σ (consistent with OPERA)

Studying neutrino mass hierarchy

Neutrino mass hierarchy?



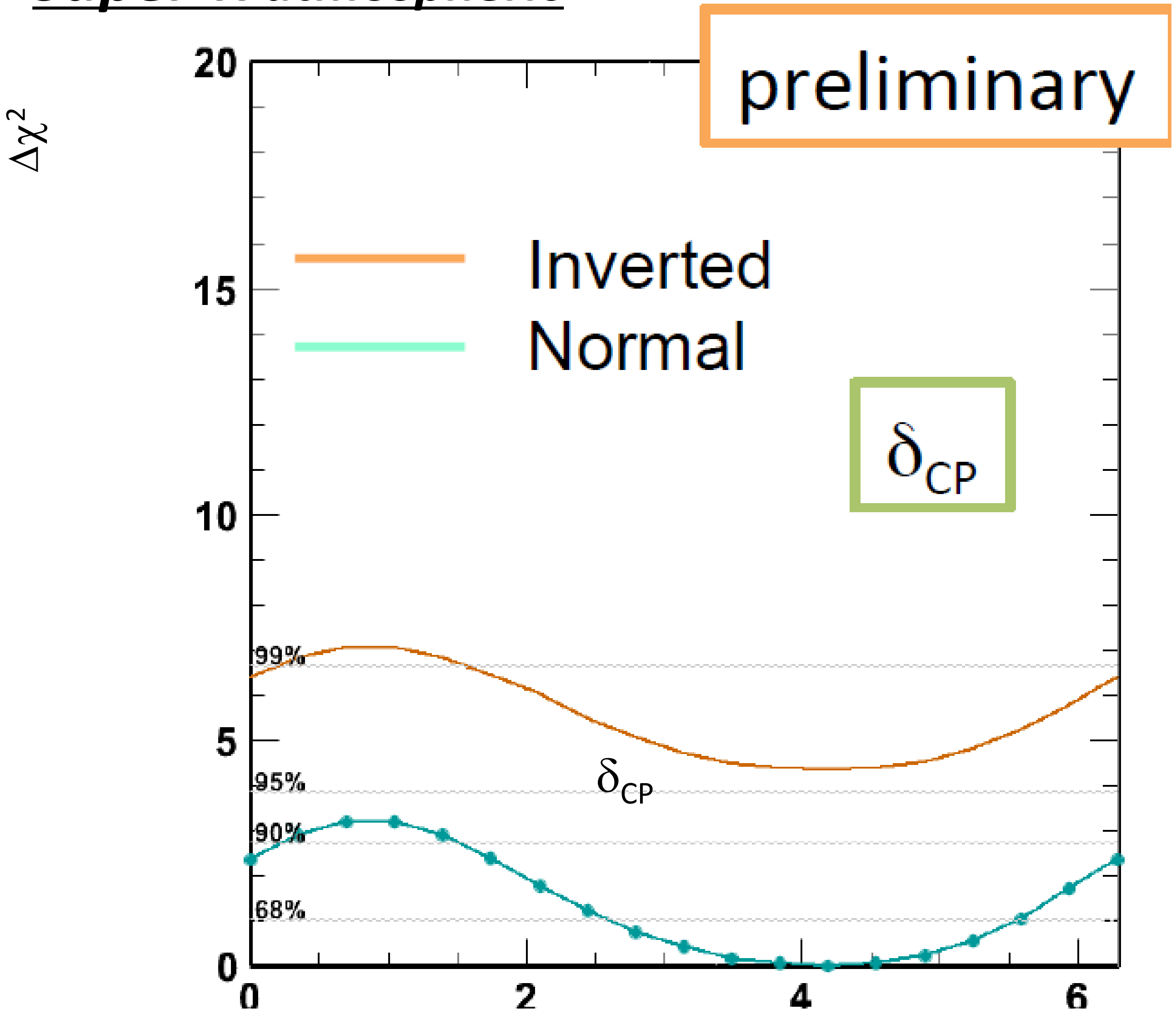
P($\nu_\mu \rightarrow \nu_e$*)* and *P(anti-*$\nu_\mu \rightarrow$*anti-*$\nu_e$*)*
for normal hierarchy



Inv. hierarchy: ν ←→ anti-ν

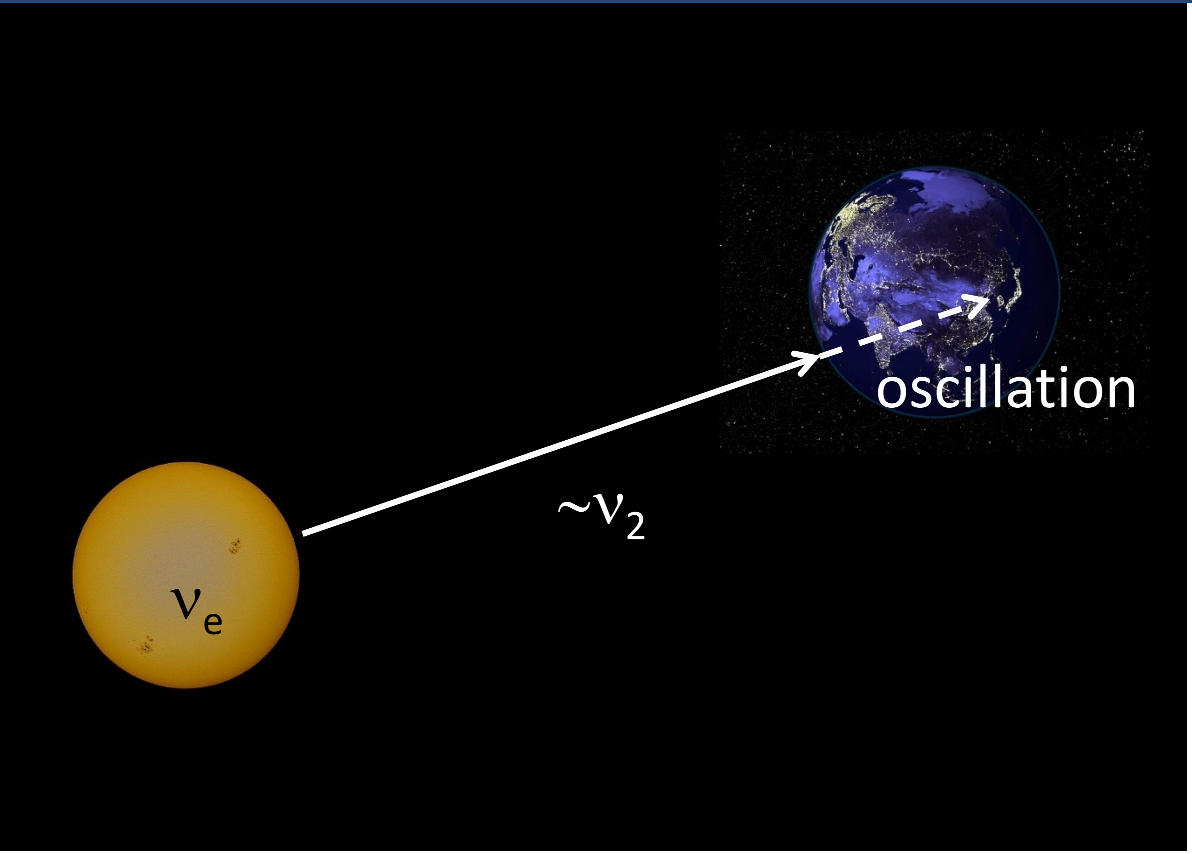
Mass hierarchy and CP violation measurements @Neutrino 2016

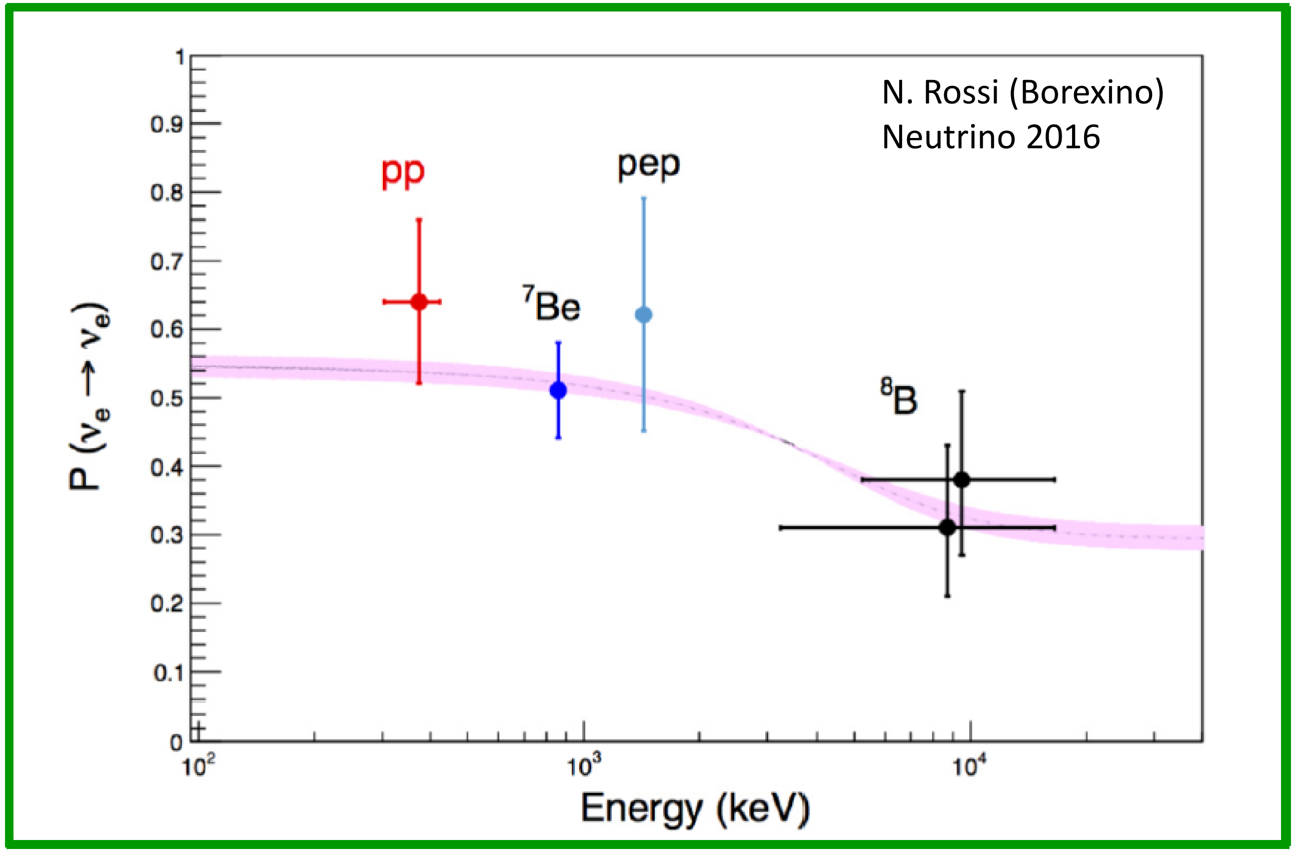
Super-K atmospheric



$\Delta\chi^2$ (IH-NH) = 4.3 (expt'd = 3.1)
and
Some preferred δ_{CP} range…

Solar neutrino oscillations: further confirmation of the MSW effect



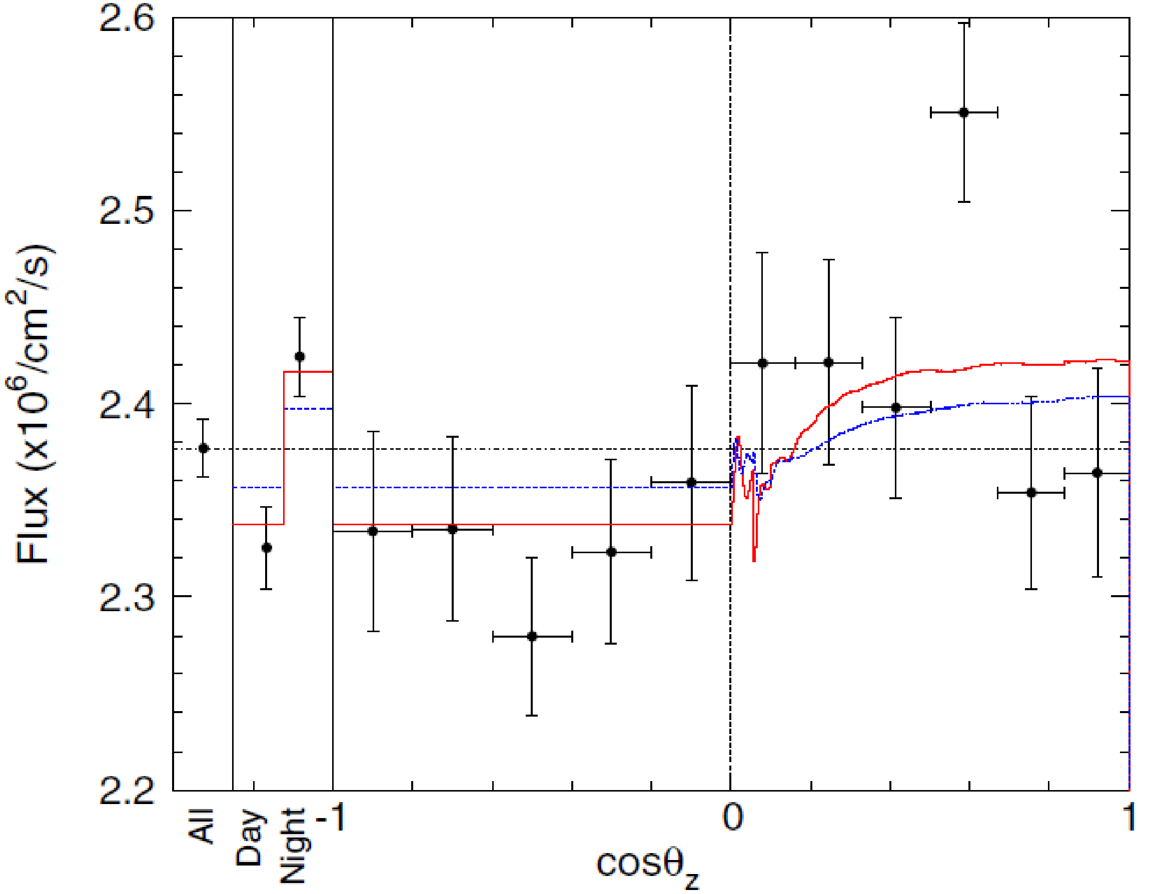


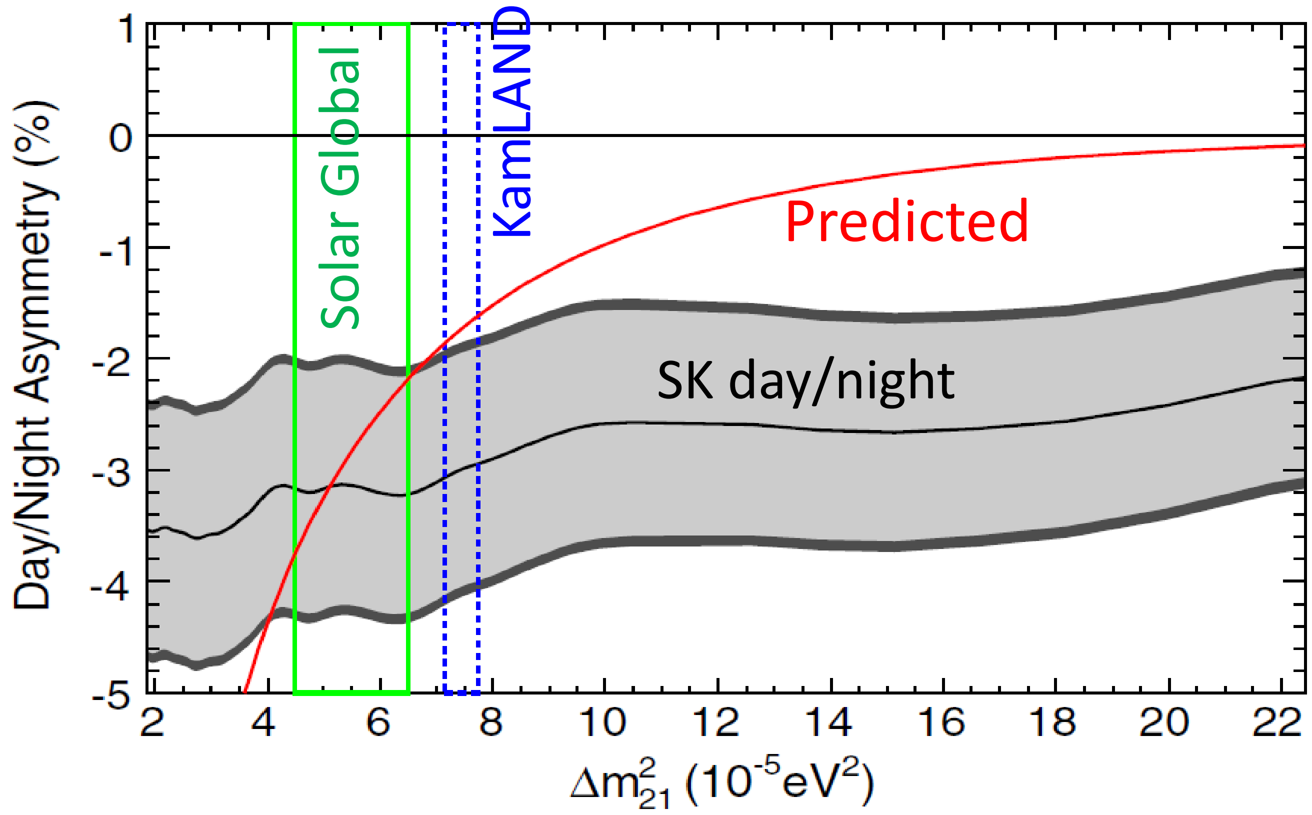
Oscillations (in matter) occur in the Earth ➔ day-night flux difference (night flux higher) ➔ Day-night effect should be observed.)

In the standard MSW scenario, the oscillation probability depends on the neutrino energy. ➔ Flux upturn should be observed for low-energy part of the ^{8}B solar neutrinos.

Precise solar neutrino measurements: Day-night effect

Super-K, PRL 112, 091805 (2014)



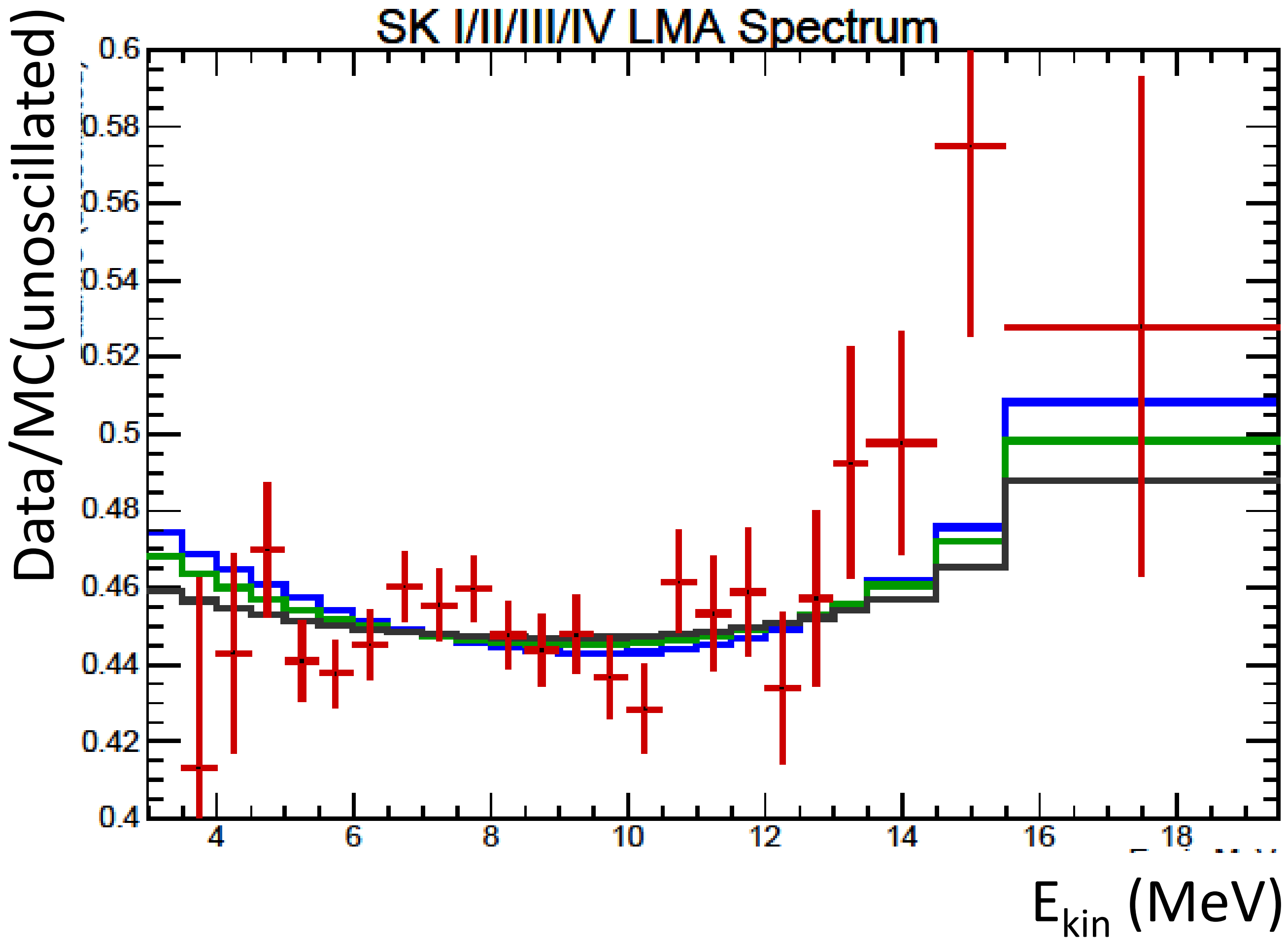


Day-night asymmetry: [-3.2 +/- 1.1 +/- 0.5] % (2.7σ effect!)

The observed day-night asymmetry is slightly larger than the expected value for the KamLAND Δm_{12}^2.

Precise solar neutrino measurements: spectrum

S. Moriyama, Neutrino 2016



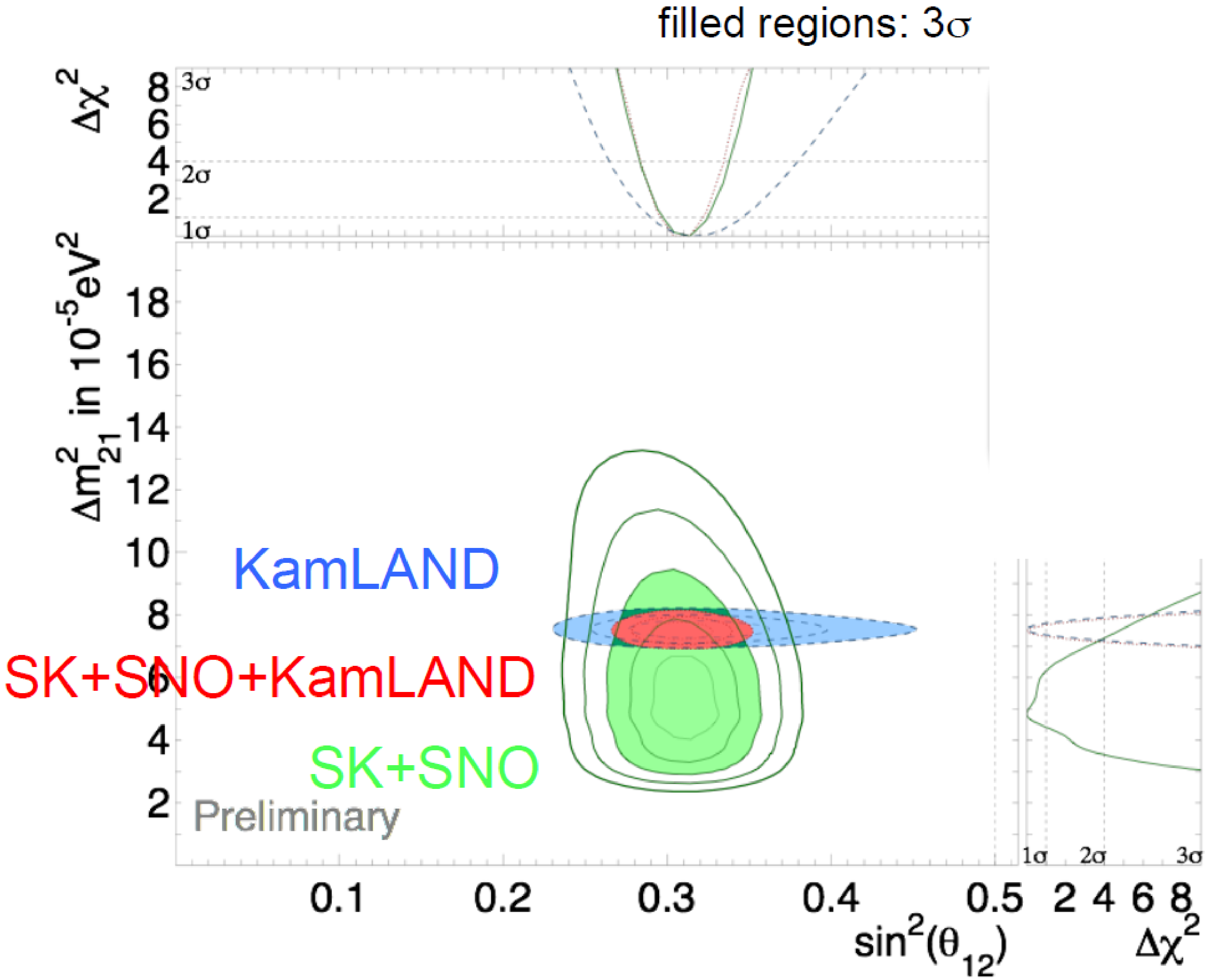
Assumptions	χ^2
Solar + KamLAND best fit	76.60
Solar best fit	73.86
Energy independent P_{ee}	72.72

"Solar + KamLAND" has slightly larger χ^2 than "Solar". ($\Delta\chi^2$=2.74). …

Data are more consistent with energy independent oscillations. (➔ No evidence for up-turn yet.)

$\Delta m_{12}{}^2$ tension ?

S. Moriyama (Super-K), Neutrino 2016

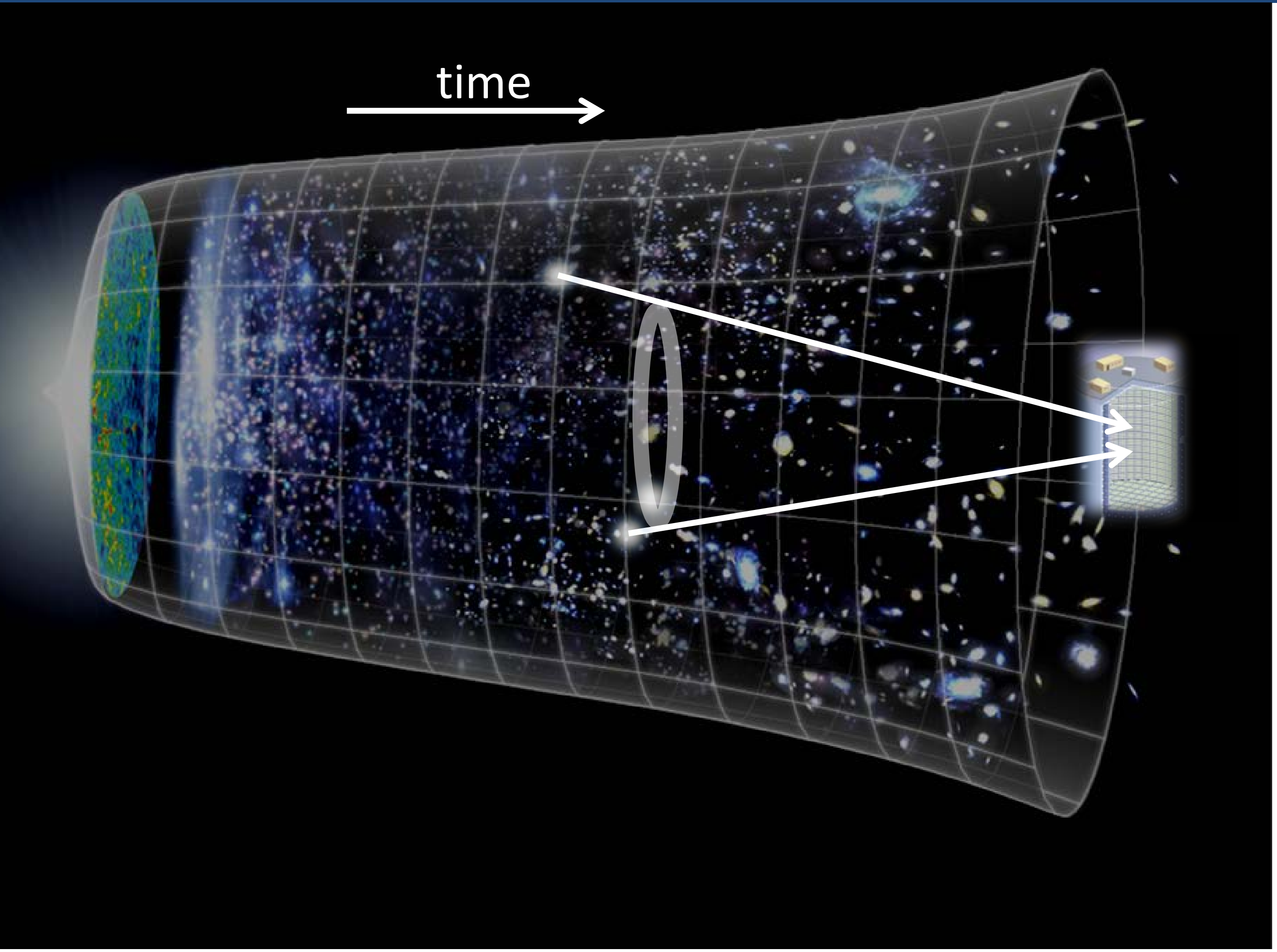


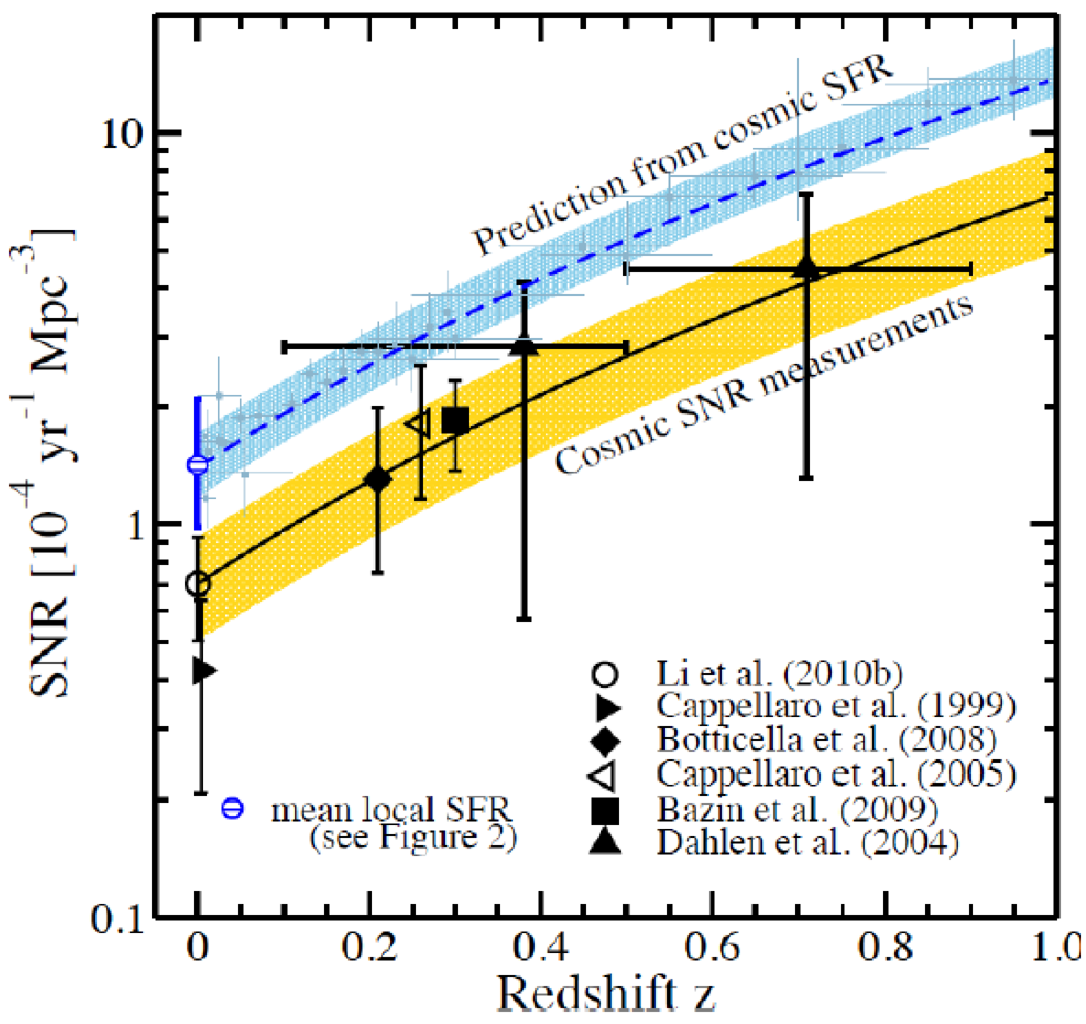
There is about 2σ tension between "solar" and "solar+KamLAND" best fit $\Delta m_{12}{}^2$'s.

Just a statistical fluctuation or …?

Future

Future of Super-Kamiokande (non-accelerator)

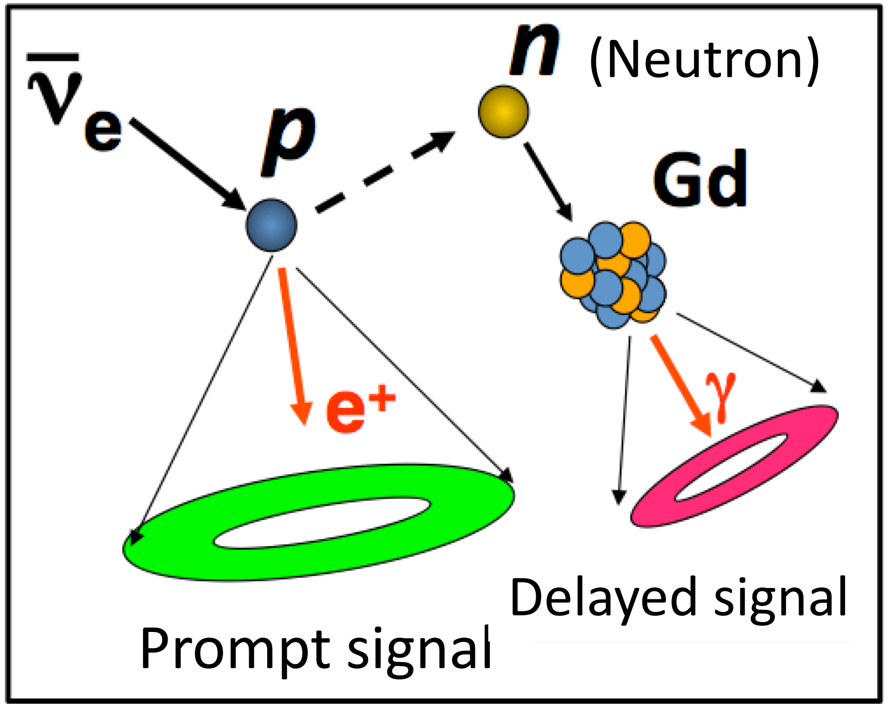


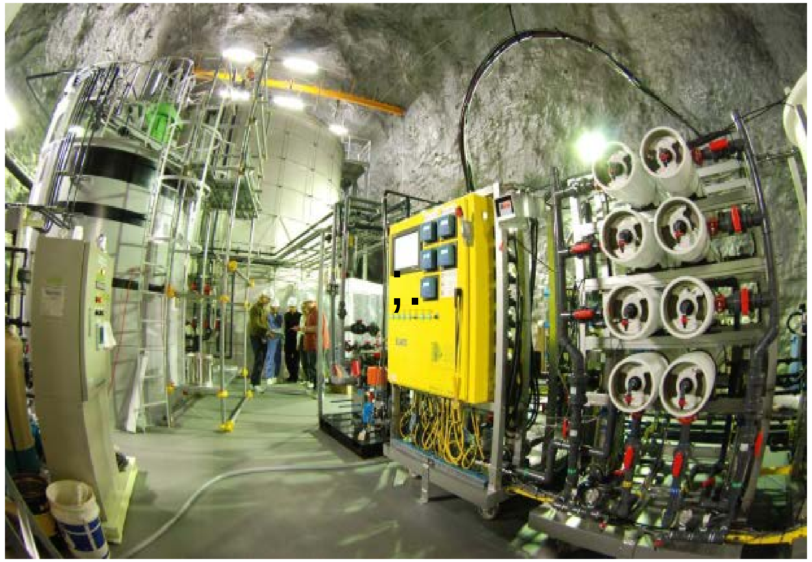


Horiuchi et al., Ap.J., 738(2011)154.

Toward the measurement of the past Supernova neutrinos

Idea: coincidence of prompt (e^+) and delayed (n) signals to reduce the non-anti-ν_e events.



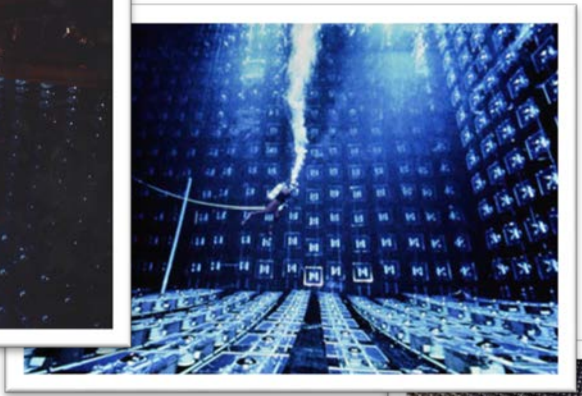


Water system R&D to clean the Gd loaded water without removing Gd. This R&D project has been successful.

A new cavern to install new water system.

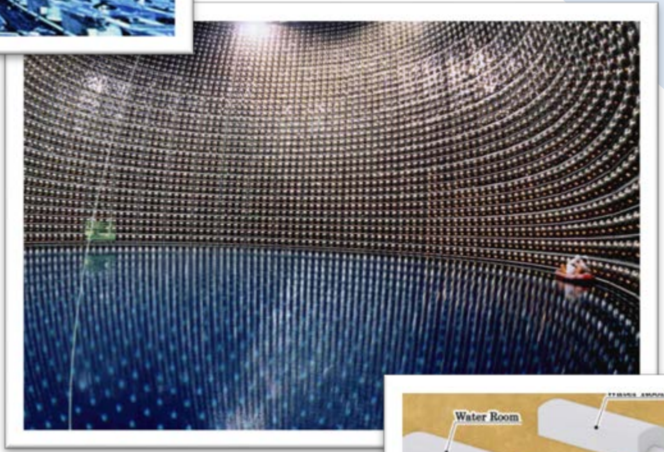
(The SK tank will de opened in 2018 for the SK-Gd phase.)

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



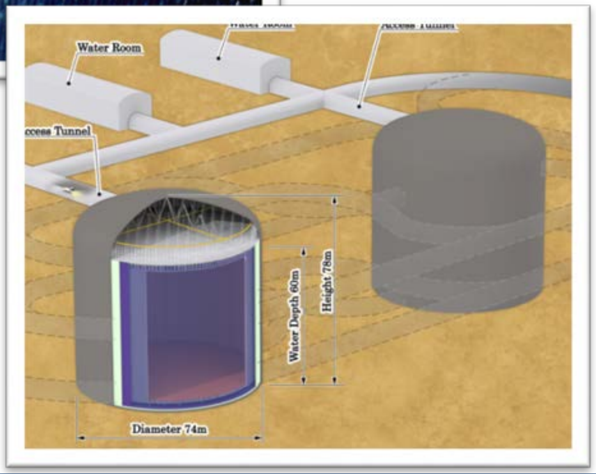
Kamiokande & IMB

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

Design of Hyper-K

✓Super-K-like structure

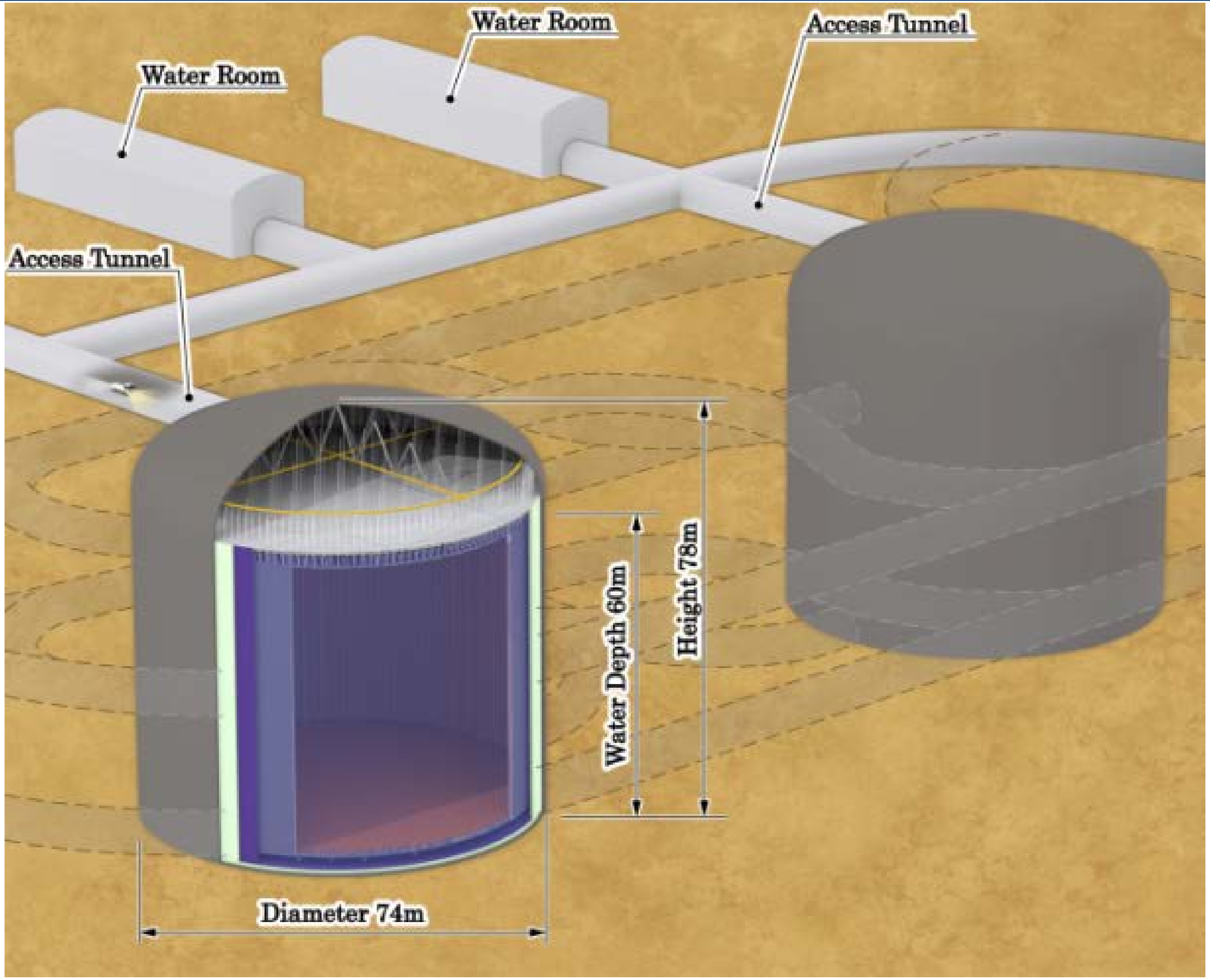
✓2 tanks with staging

(2nd tank assumed to be ready 6 years later)

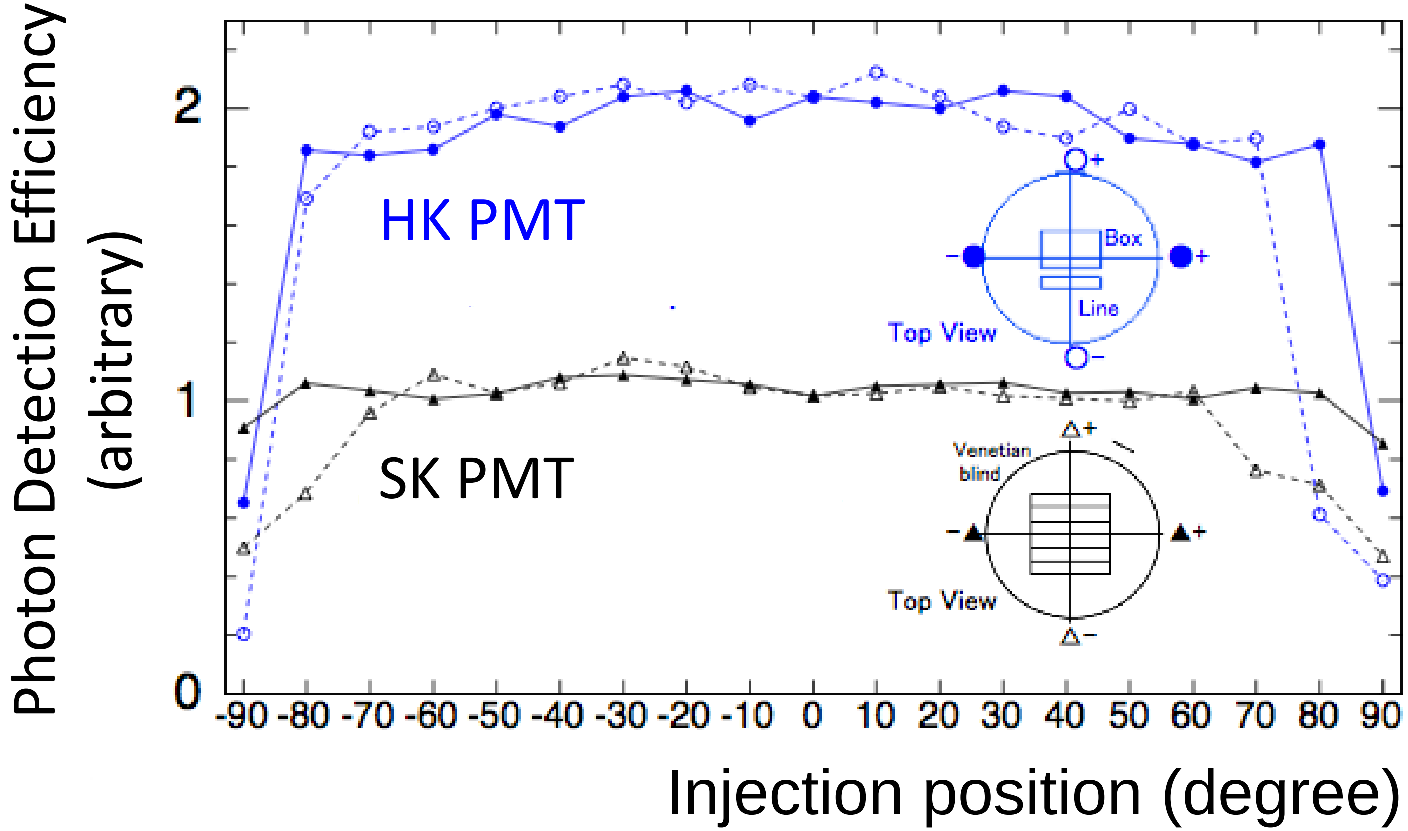
✓1 tank will be;

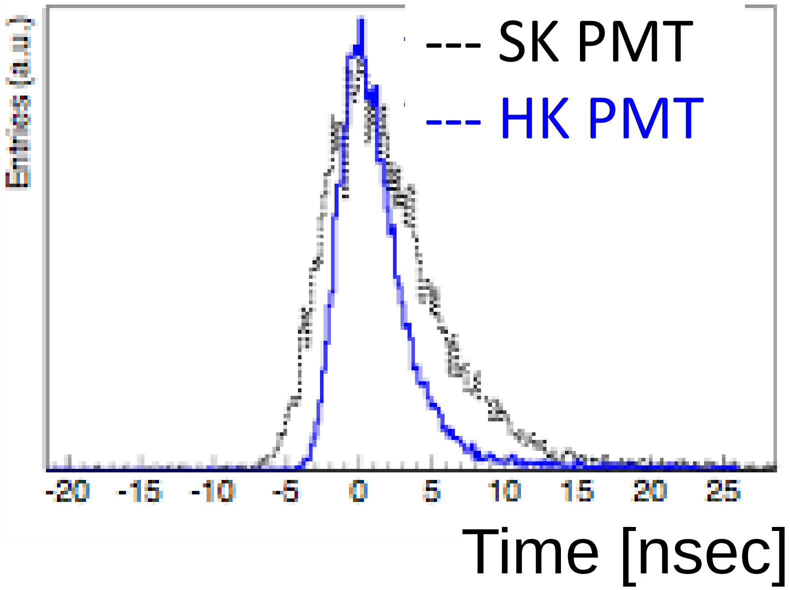
- 60m(H) ×74m(D)
- Total volume: 260 kton
- Fiducial volume(FV): 190 kton ~10 x Super-K FV
- PMT coverage 40%, 40,000 ID-PMT, 6,700 OD-PMT
- Newly developed PMTs

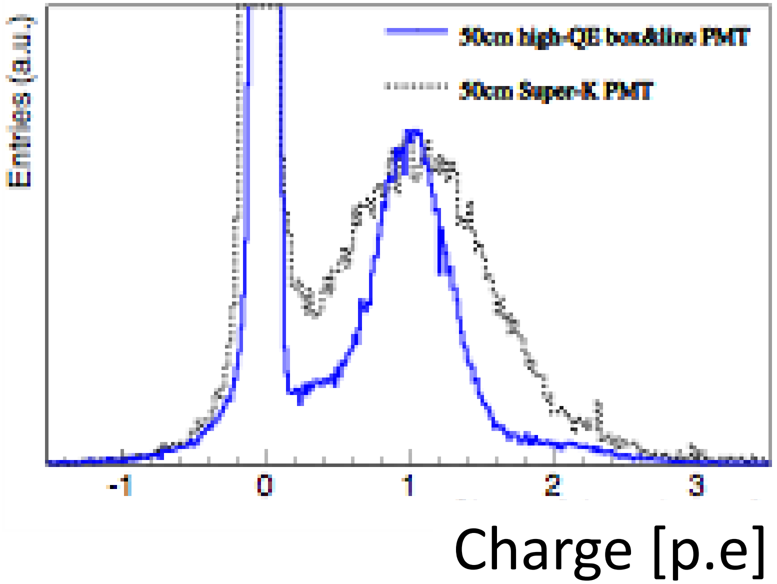
✓ The candidate site is ~8km south of SK (2.5 degree off axis beam, L=295km) ← CPV measurement.



A highlight of the Hyper-K R&D: New 50cmϕ PMT





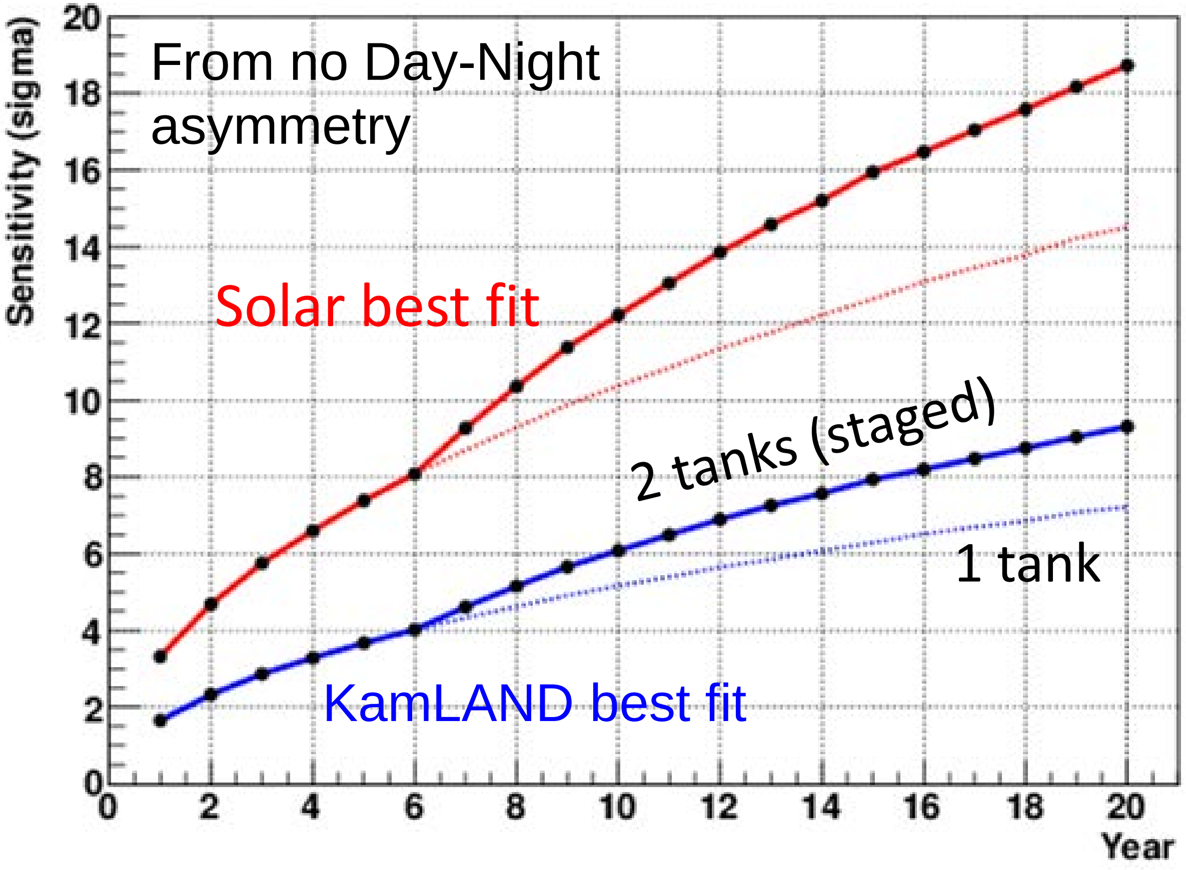


- ✓ Photon detection efficiency x 2,
- ✓ Timing & charge (@1 p.e.) resolution x 1/2
- ✓ (Pressure tolerance x 2 (>100m))

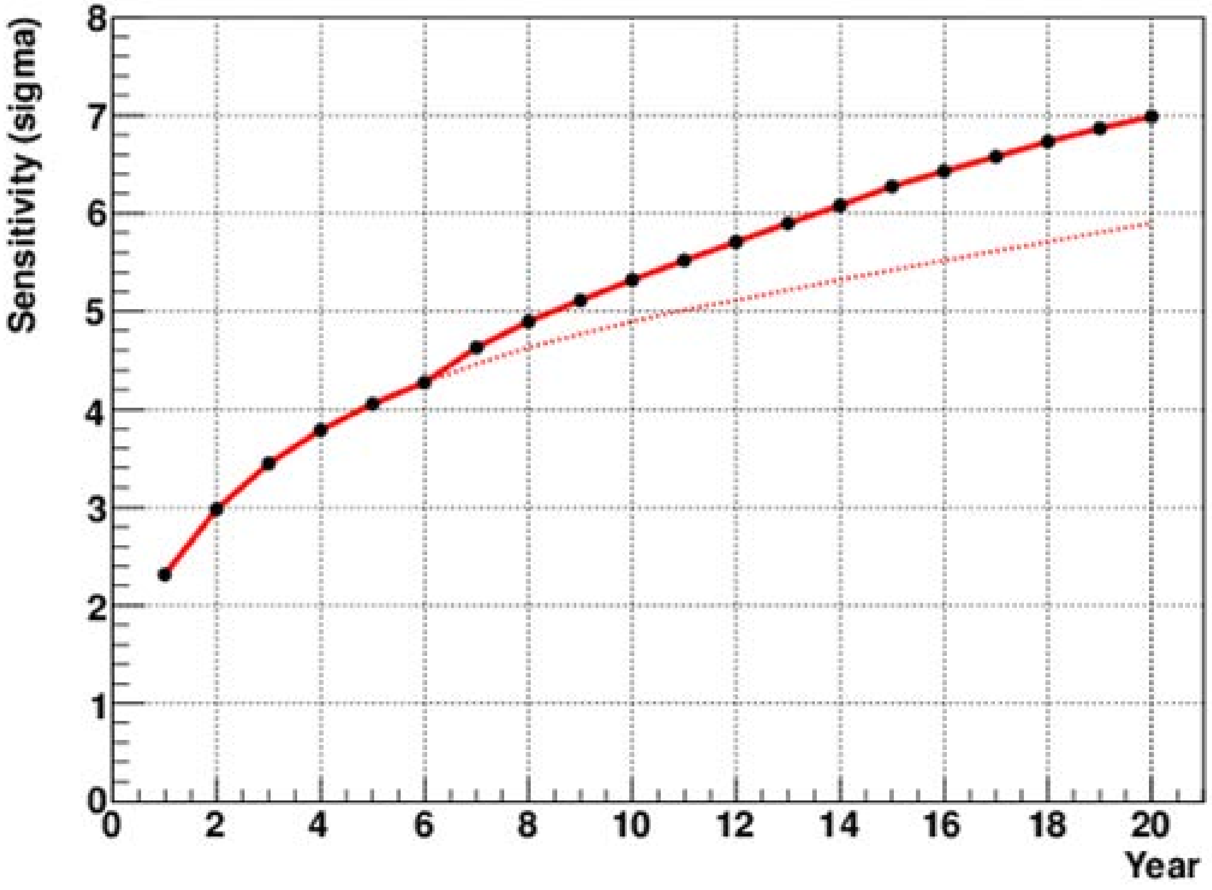
➔ Large impacts to physics

Hyper-K solar neutrino measurements

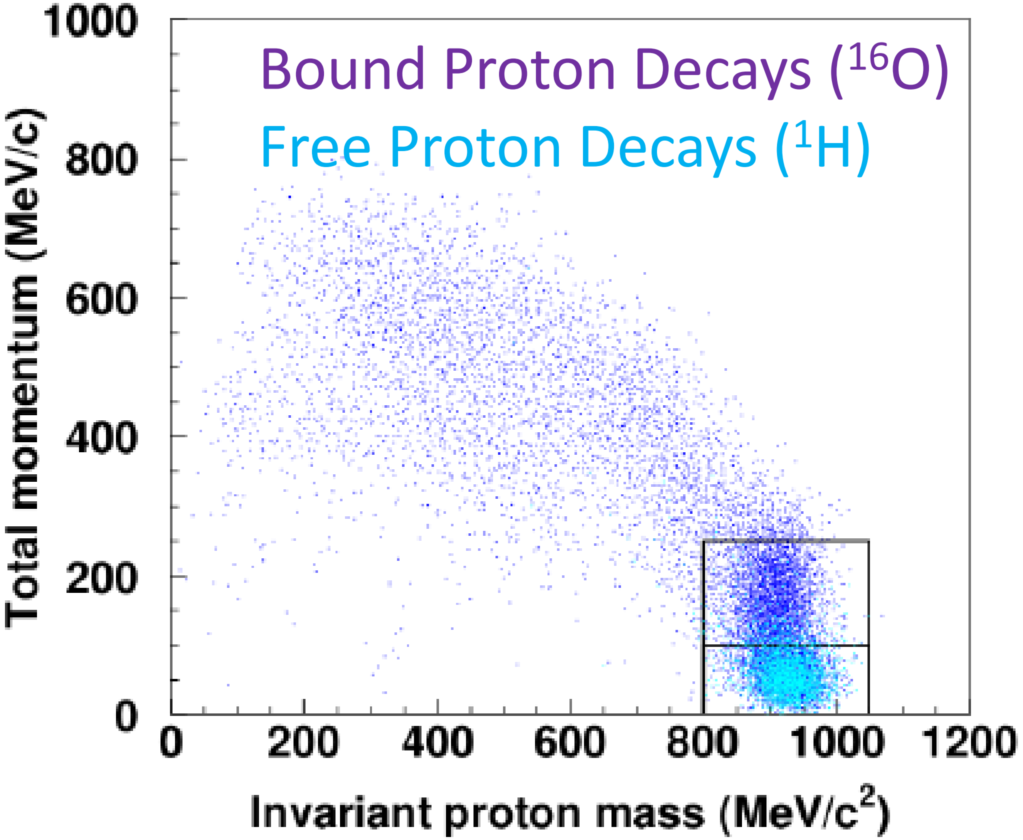
Day-night asymmetry sensitivity

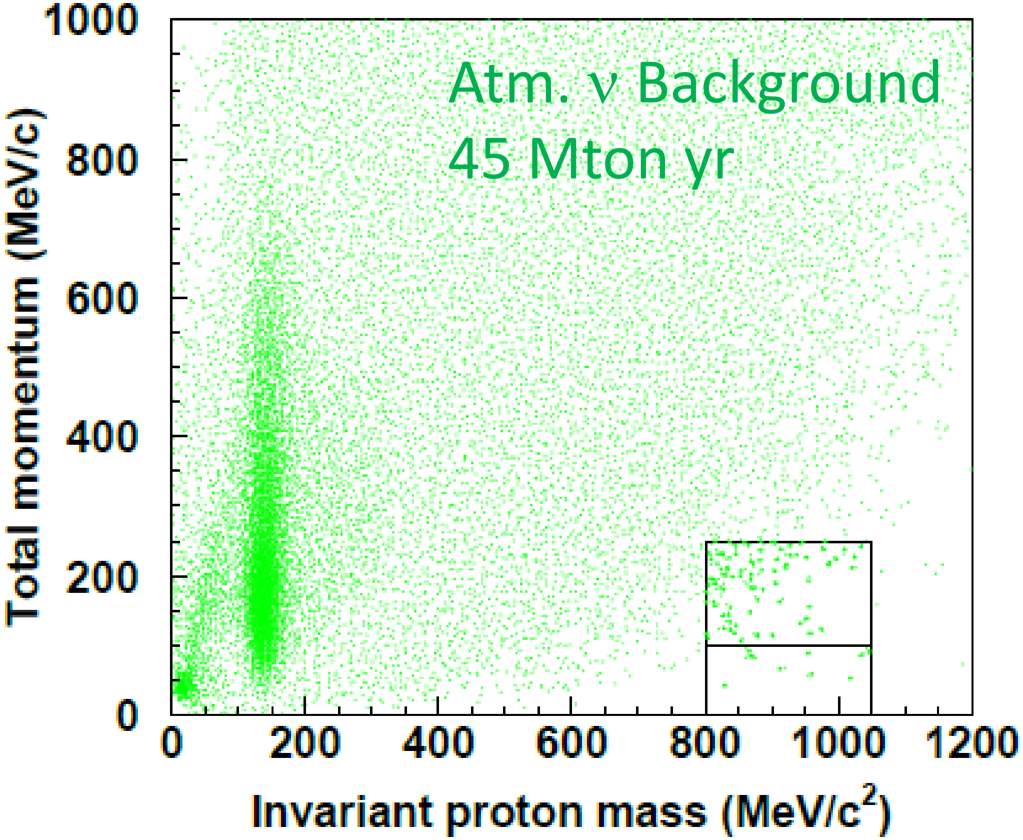


Spectrum upturn discovery sensitivity



Proton decay ($p \rightarrow e^+ \pi^0$)

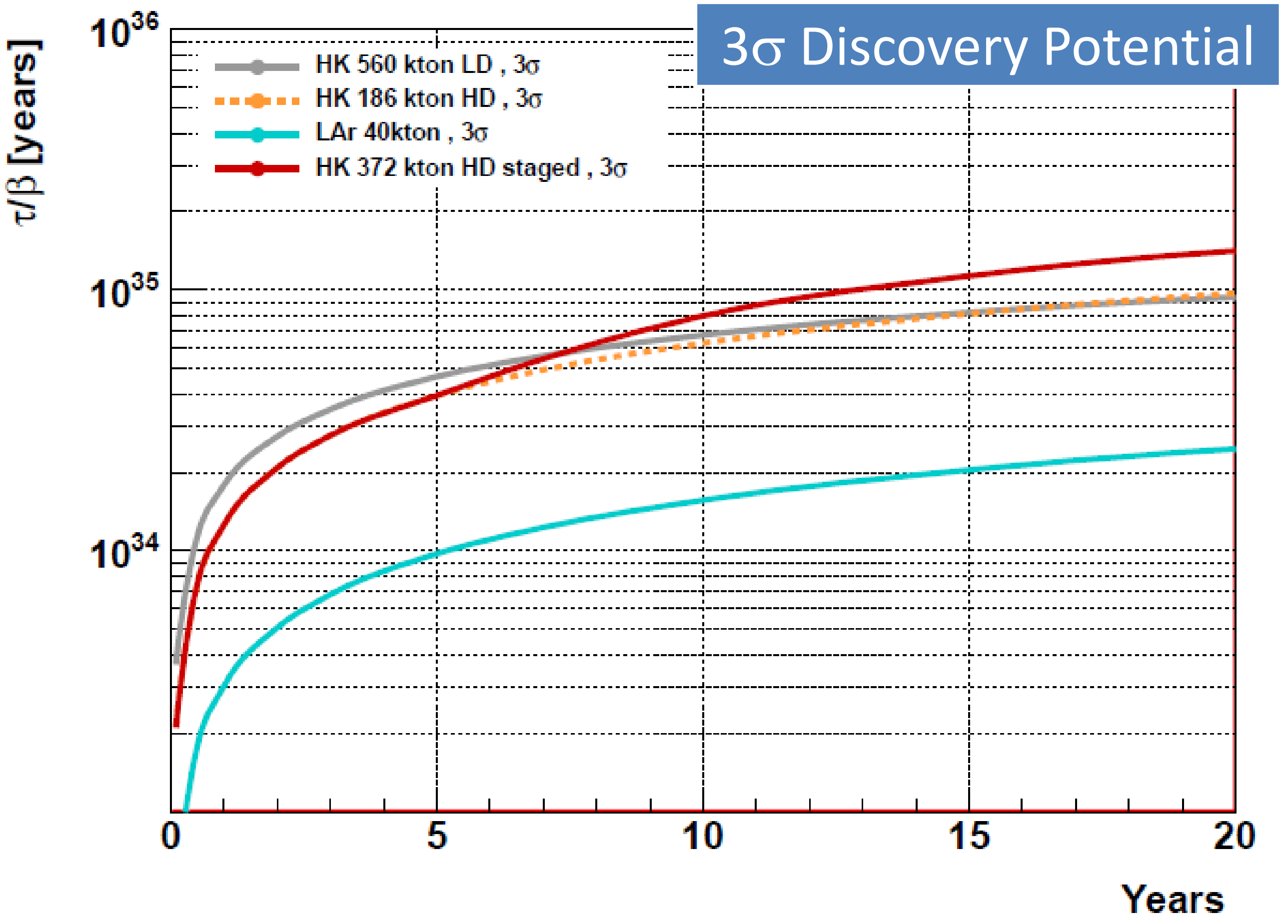


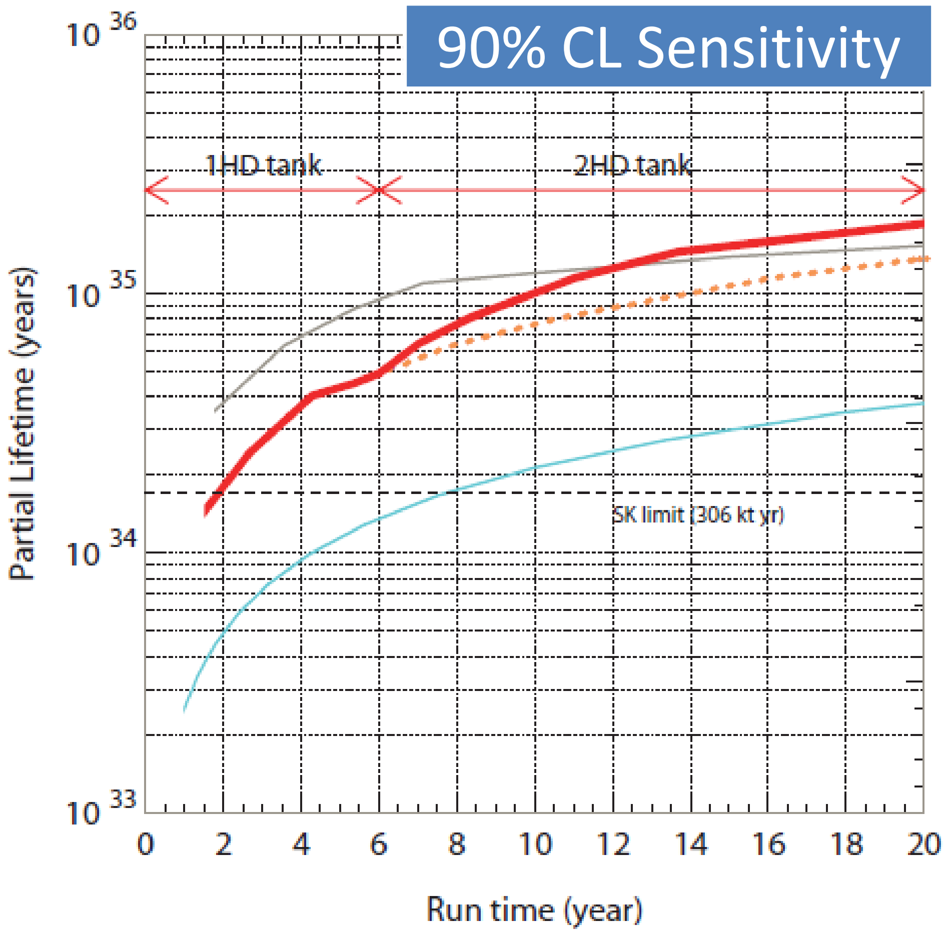


	P_{total} < 100 MeV/c		P_{total} < 250 MeV/c	
	efficiency	Background (/Mtonyr)(*)	Efficiency	Background (/Mtonyr)(*)
Hyper-K	18.7%	0.06	38.1%	0.68

(*) Neutron tagging included to reduce the background

$P \rightarrow e^{+} \pi^{0}$: sensitivity



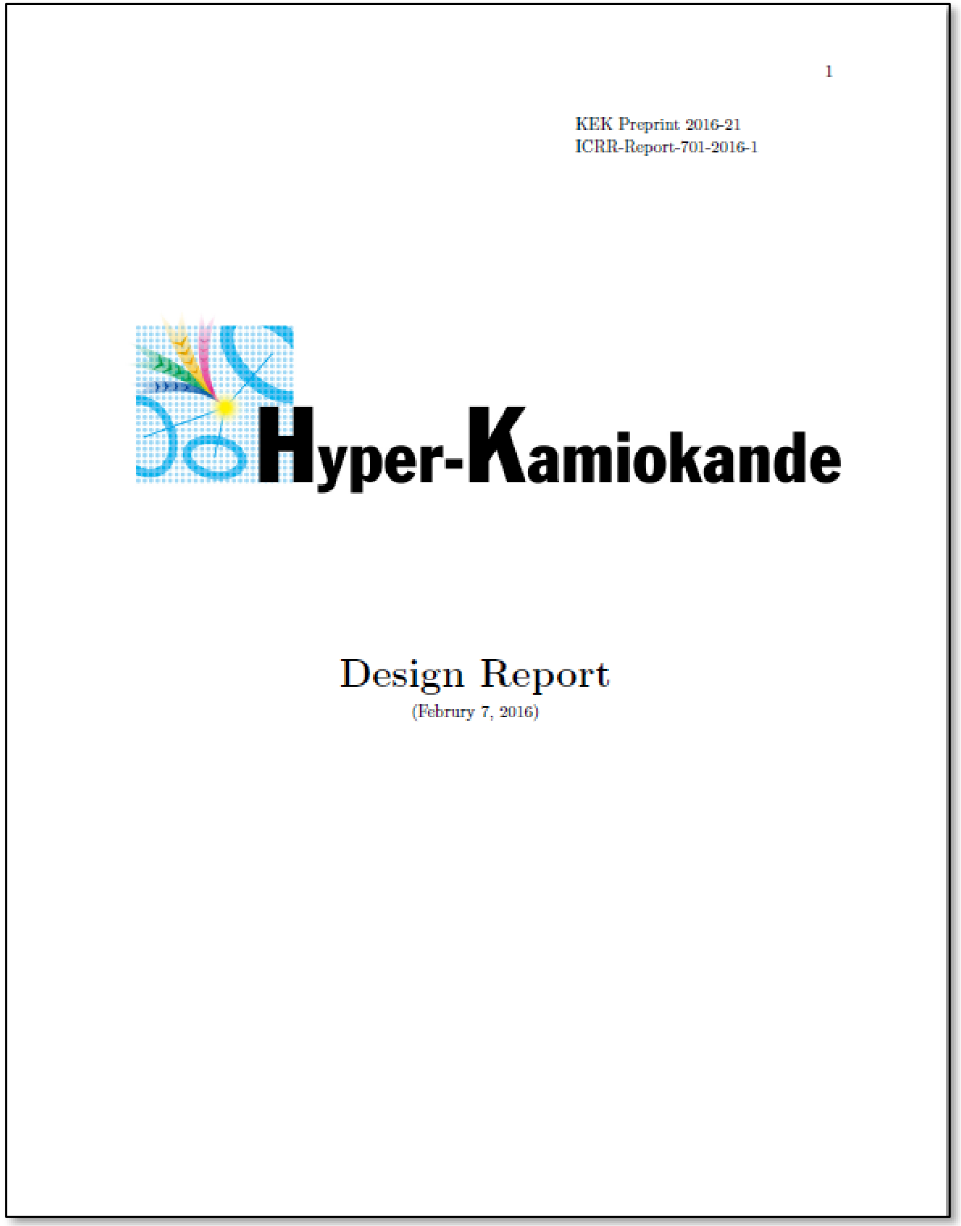


- ✓ > 1x10^{35} years after 2.7 Mton yr (90%CL). Or 3σ evidence for 1x10^{35} years with 4.0 Mtonyr.
- ✓ If proton lifetime is near the current Super-K limit (1.7x10^{34} years), Hyper-K will observe a positive signal at 8.9σ in 2.7 Mtonyr exposure.

(Lines for the liquid argon experiment have been generated based on numbers in the literature (efficiency: 45% bkg: 1 event/Mtonyr).)

Status of Hyper-K

- ✓ The design report has been written and reviewed by the Hyper-K Advisory Committee.
- ✓ The plan of Hyper-K was submitted to the Science Council of Japan (SCJ). If things goes well, Hyper-K will be listed as one of the "Master Plan Projects" of SCJ.
- ✓ Then, Hyper-K will be reviewed by the Ministry of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2017. If it is evaluated highly, it will be listed in the MEXT "Roadmap".
- ✓ Then, …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KEK Preprint 2016-21
ICRR-Report-701-2016-1

Hyper-Kamiokande

Design Report
(Februry 7, 2016)

Summary

- Kamiokade observed Supernova neutrinos, atmospheric ν_μ deficit and confirmed solar ν_e deficit. These results gave strong motivation for the construction of Super-Kamiokande.
- In 1998, Super-Kamiokande discovered atmospheric neutrino oscillations.
- Precise solar neutrino studies in Super-K contributed to the discovery of solar ν_e oscillations.
- Since then, Super-Kamiokande has been contributing to the studies of neutrino oscillations.
- It is already 20 years since the beginning of the Super-Kamiokande experiment. Super-K is still going to improve the detector to observe anti-ν_e's from the past Supernovae.
- Now, Hyper-K is proposed as the successor of Super-Kamiokande.