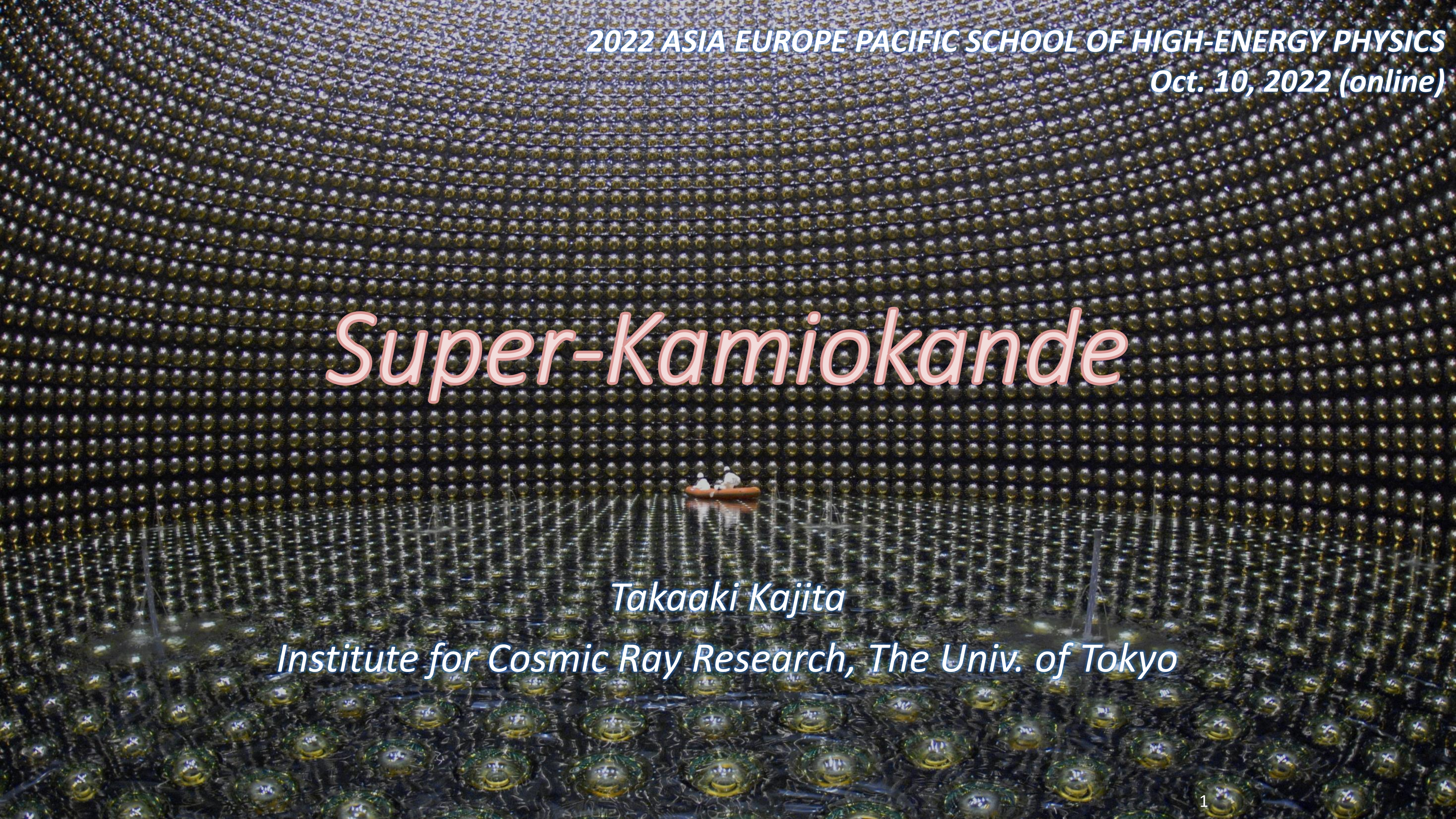
2022 ASIA EUROPE PACIFIC SCHOOL OF HIGH-ENERGY PHYSICS
Oct. 10, 2022 (online)



Super-Kamiokande

Takaaki Kajita

Institute for Cosmic Ray Research, The Univ. of Tokyo

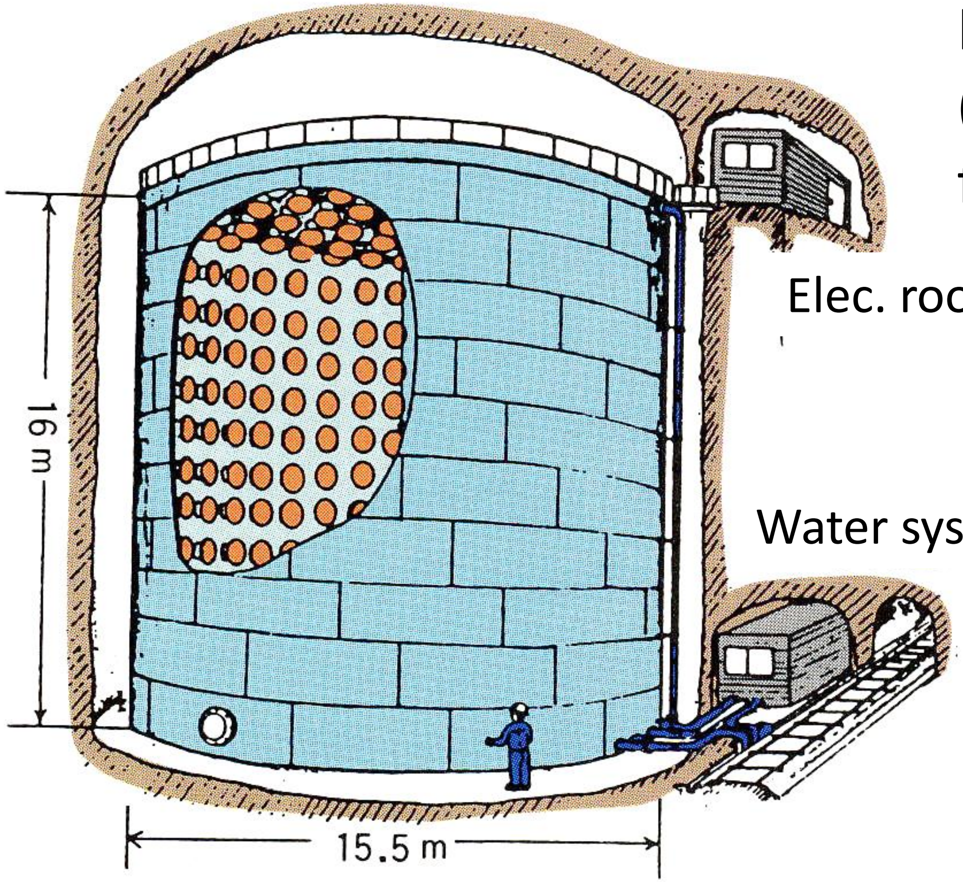
Outline

- *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)

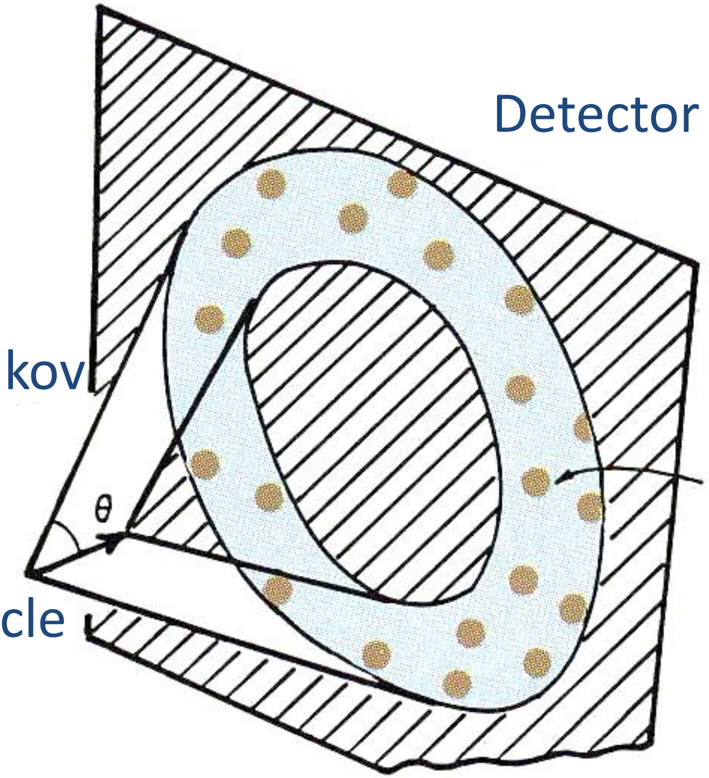
- ✓ In the late 1970's, Grand Unified Theories were proposed.
- ✓ They predicted that protons and neutrons should decay with the lifetime of 10^{28} to 10^{32} years.
- ✓ Several proton decay experiments began in the early 1980's. One of them was the Kamiokande experiment.



Kamiokande
(1000 ton
fiducial volume)

Elec. room

Water system



Detector wall

Cherenkov
light

Photo
detectors

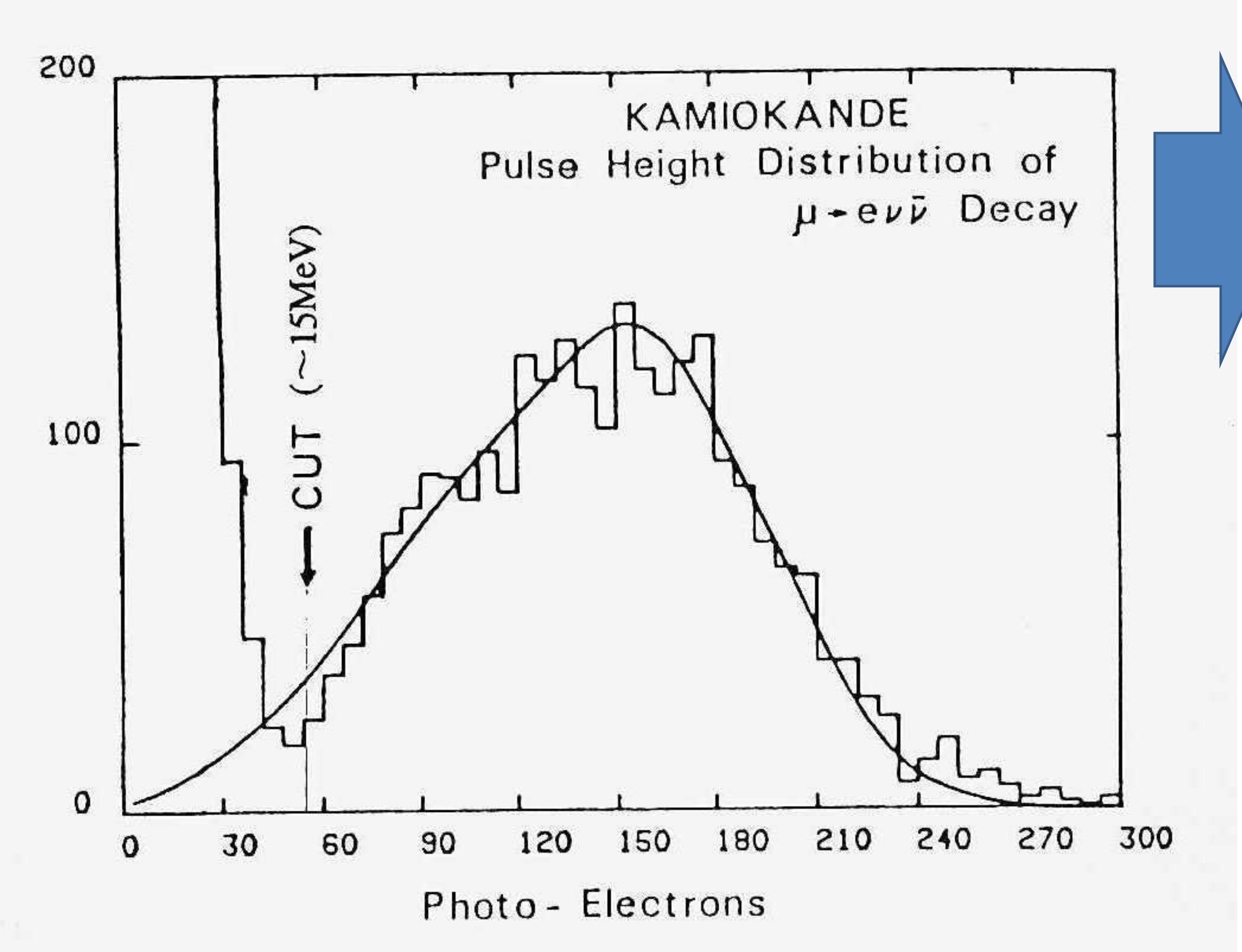
Charged particle

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 stopping cosmic ray muons (early autumn 1983)

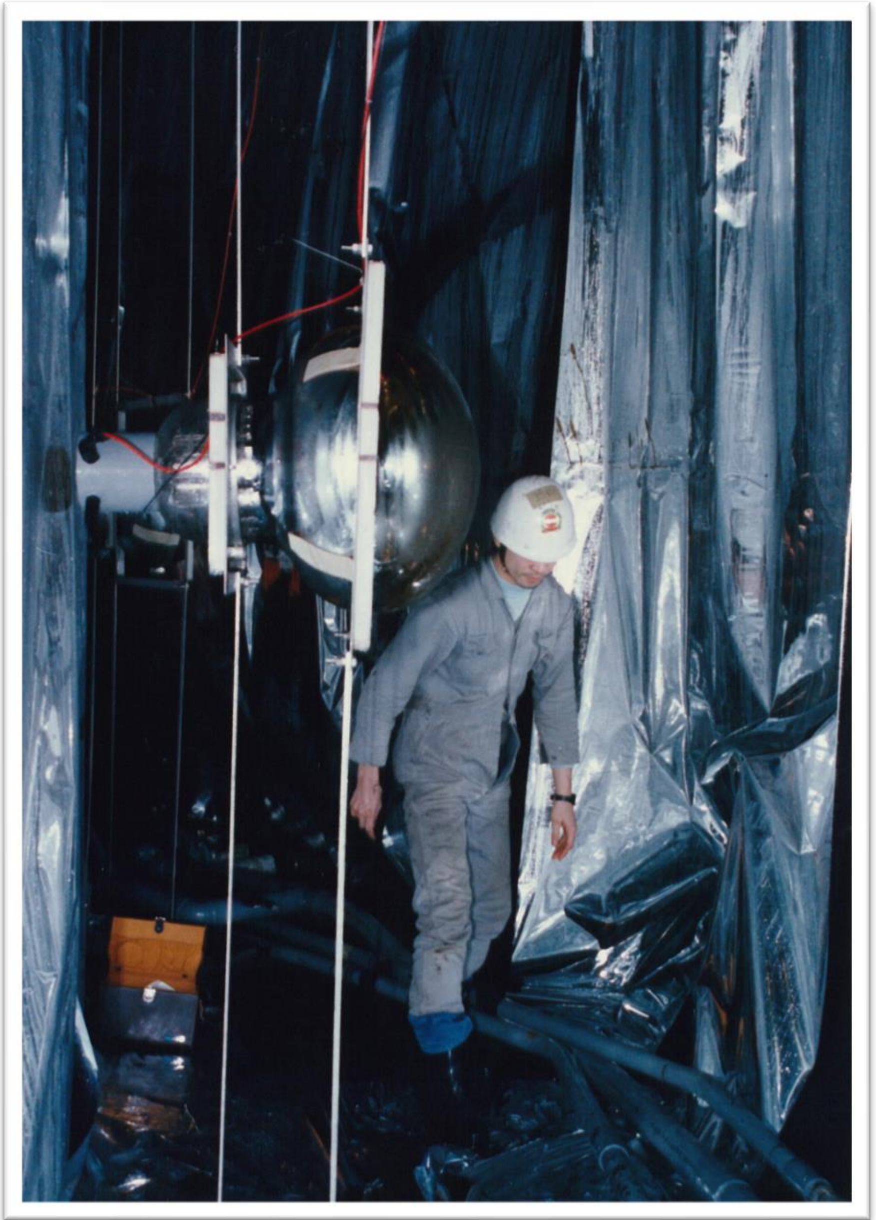


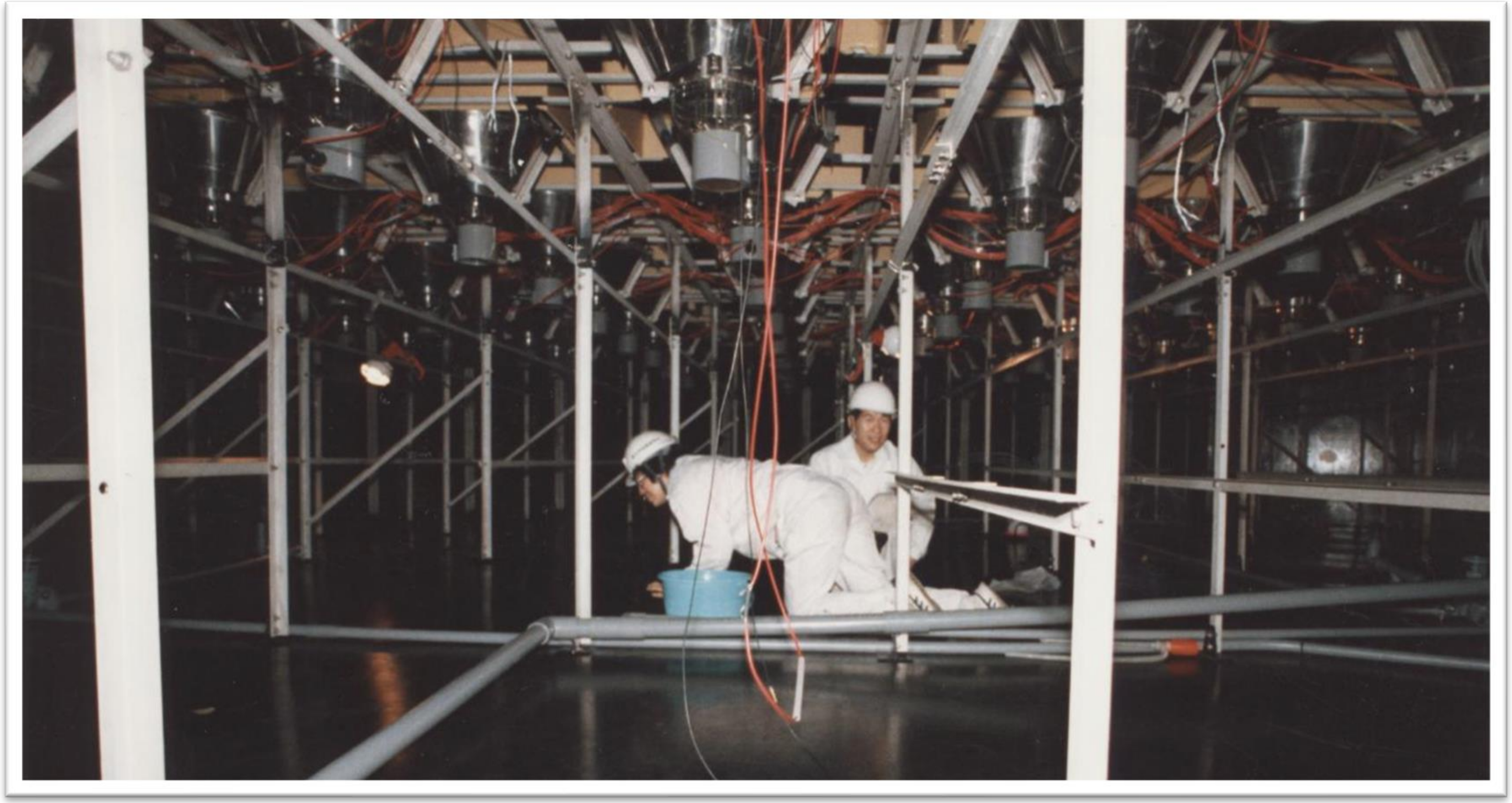
Neutrinos with the energies of about 10 MeV could be observed.

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

(both by M. Koshiba)

Toward Kamiokande-II (1984-5)

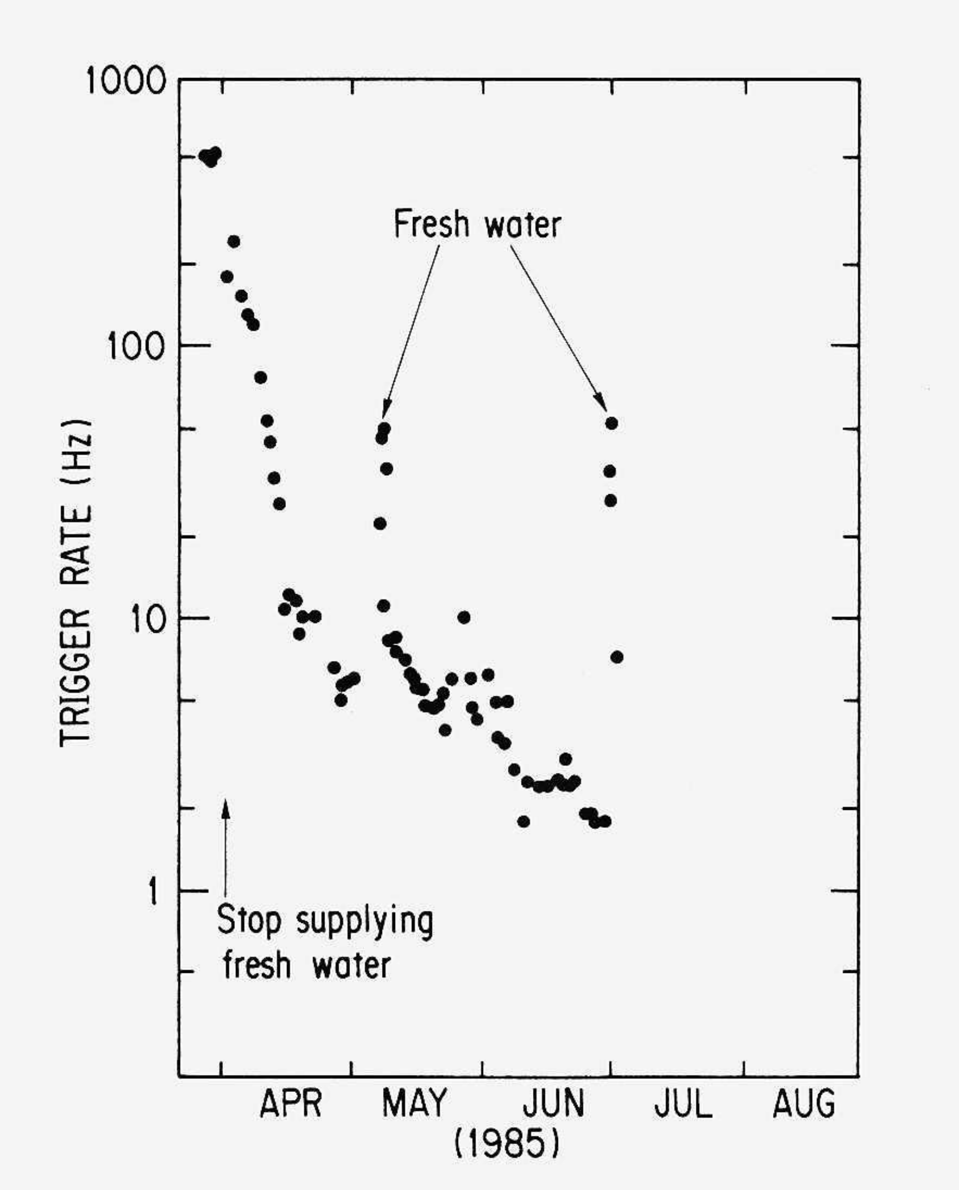


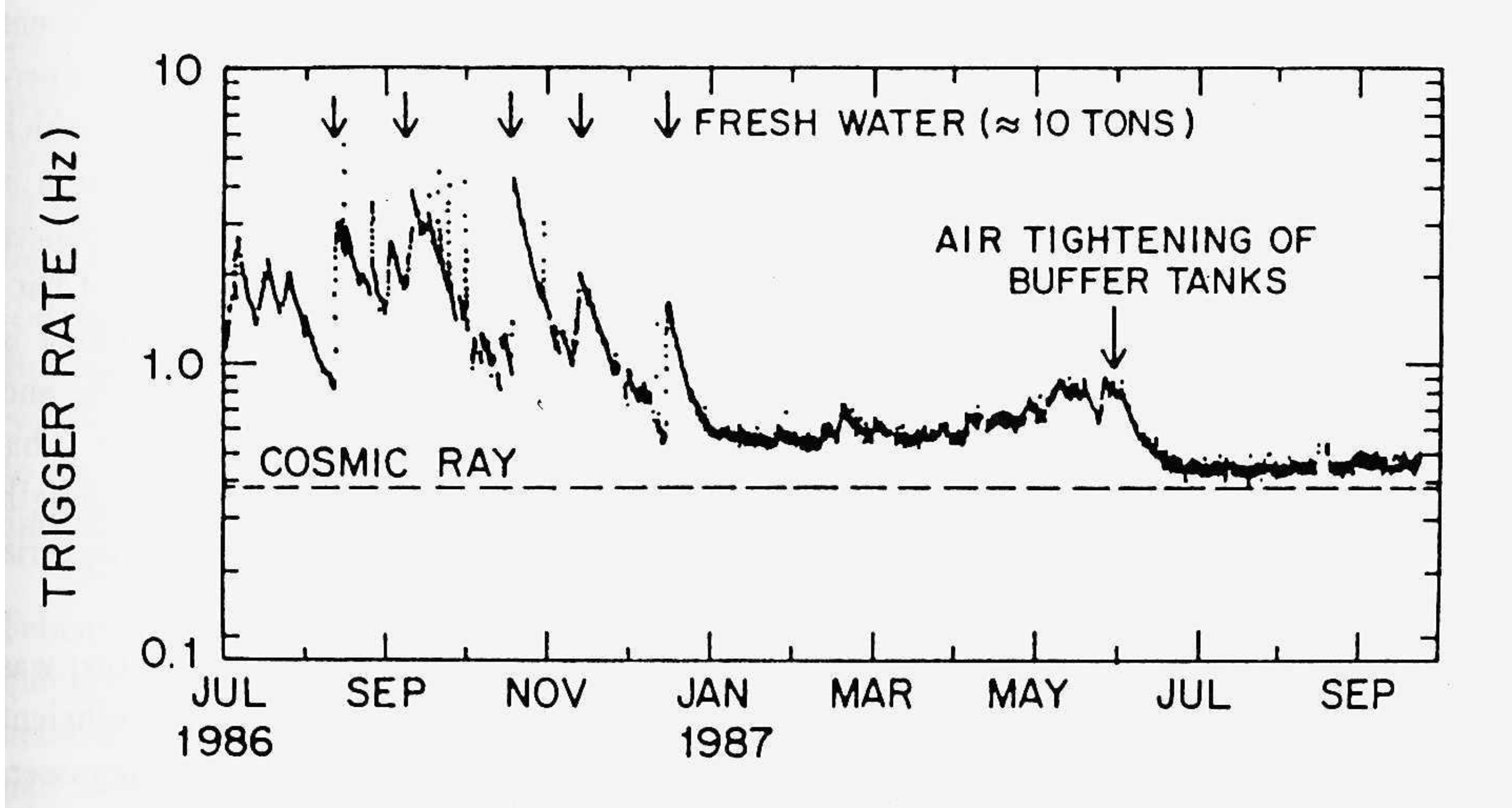


Construction of the bottom outer detector

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

Water and the trigger rate



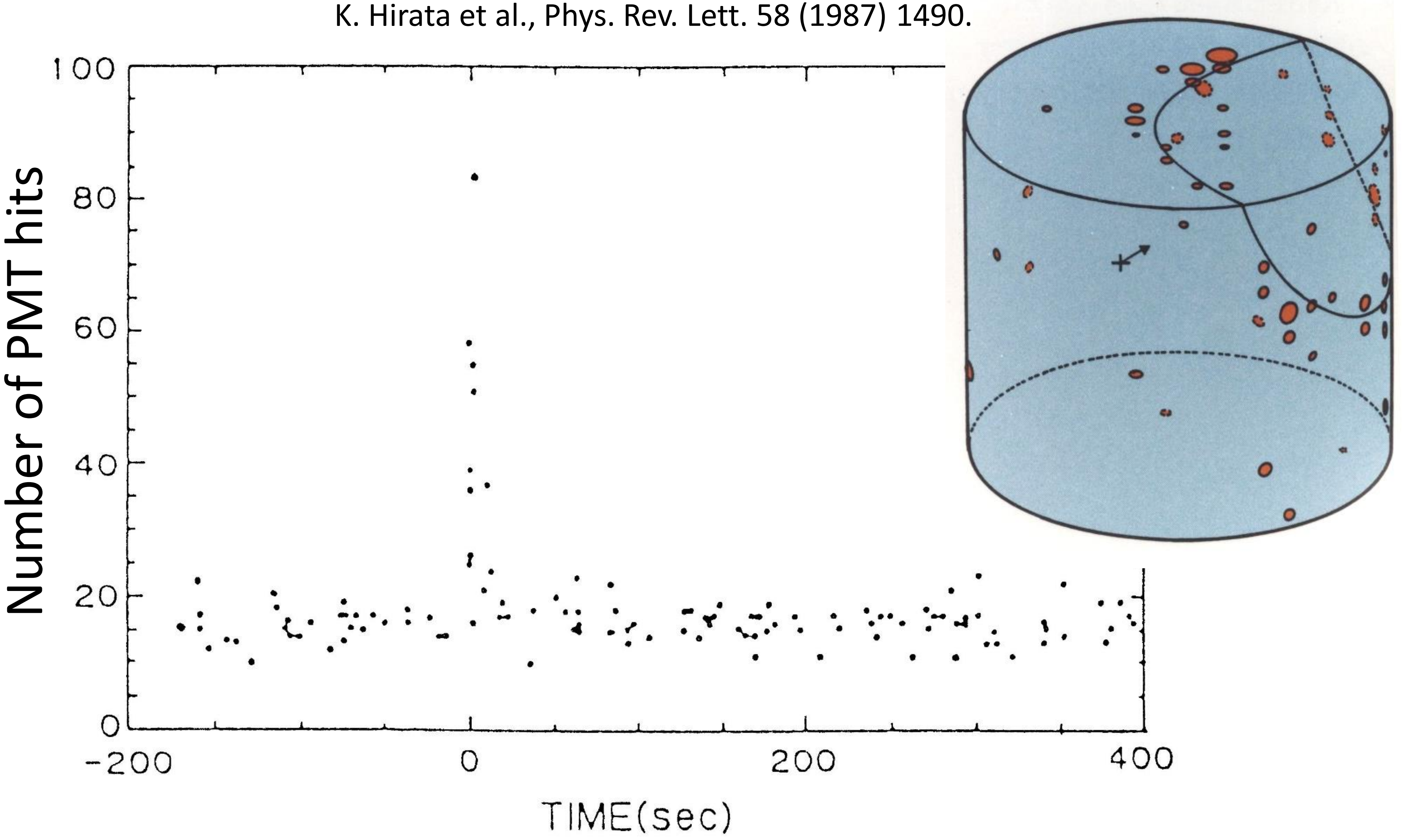


Radioactivities (mostly Rn at that stage) was the most serious issue.
Stable trigger rate after Jan. 1987.

SN1987A (Feb. 23, 1987)

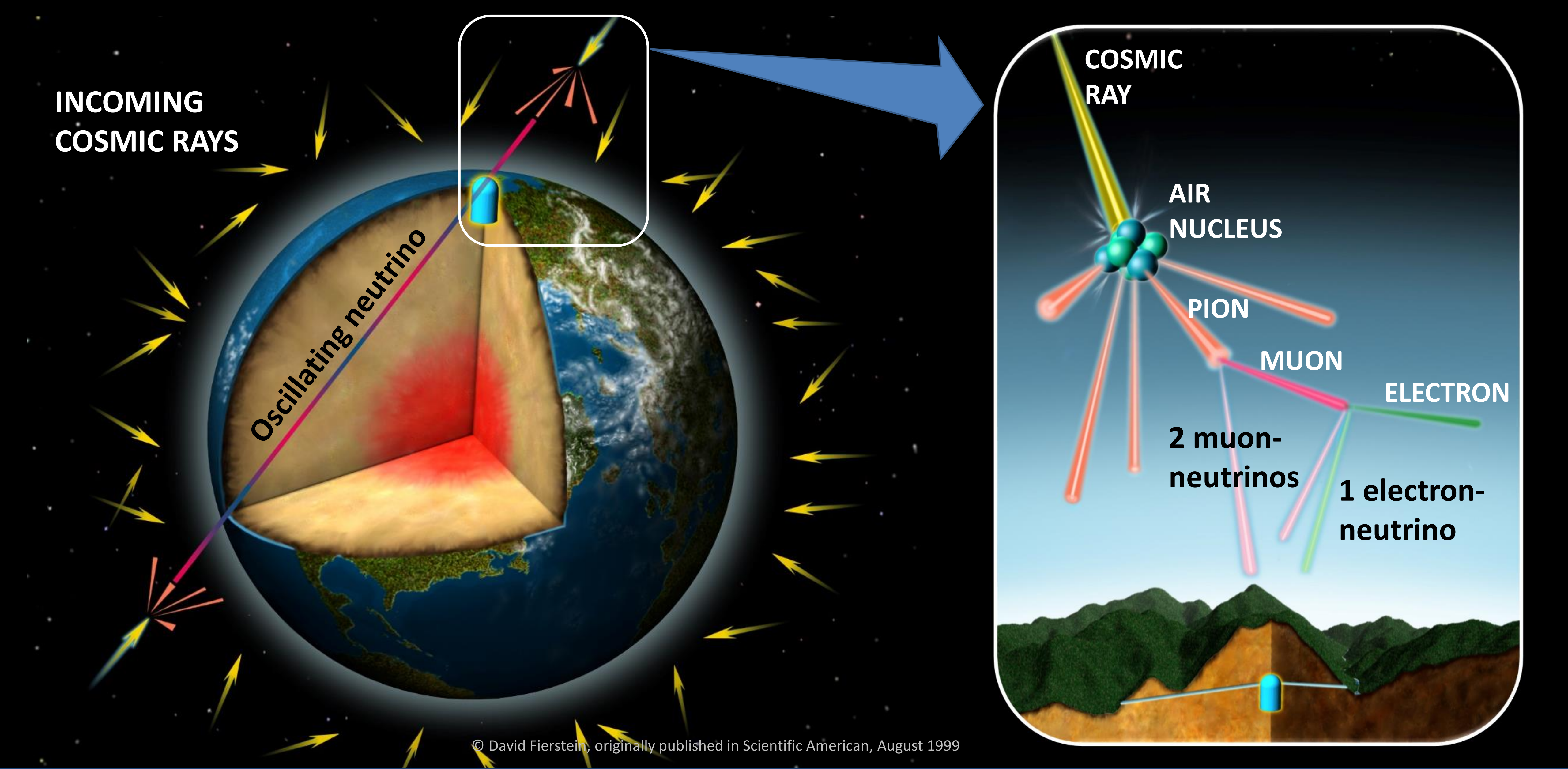
SN1987A (at LMC)

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



(The IMB experiment also observed the neutrino signal.)

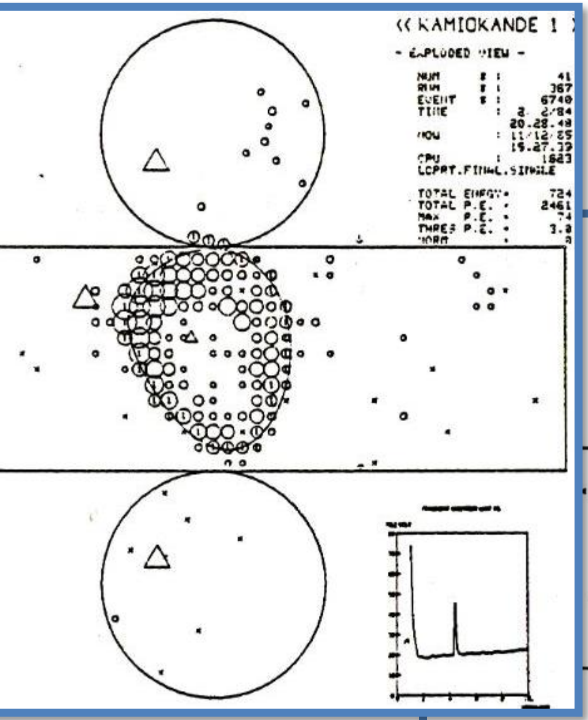
Atmospheric neutrinos



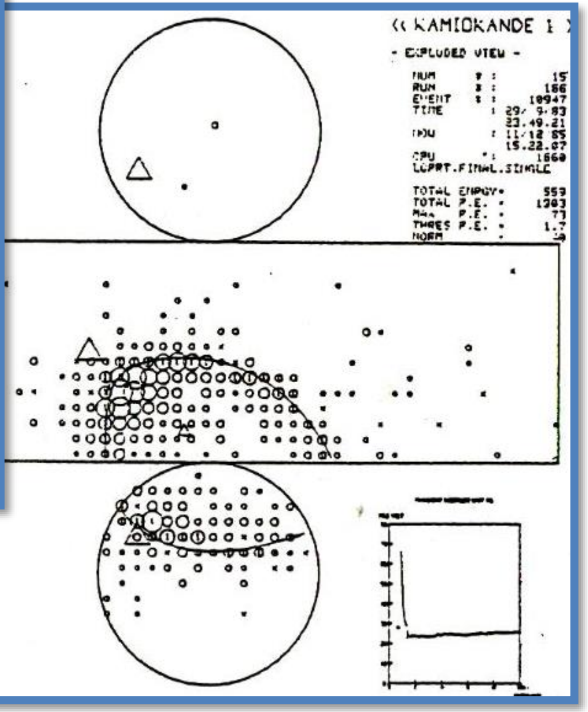
© David Fierstein, originally published in Scientific American, August 1999

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.

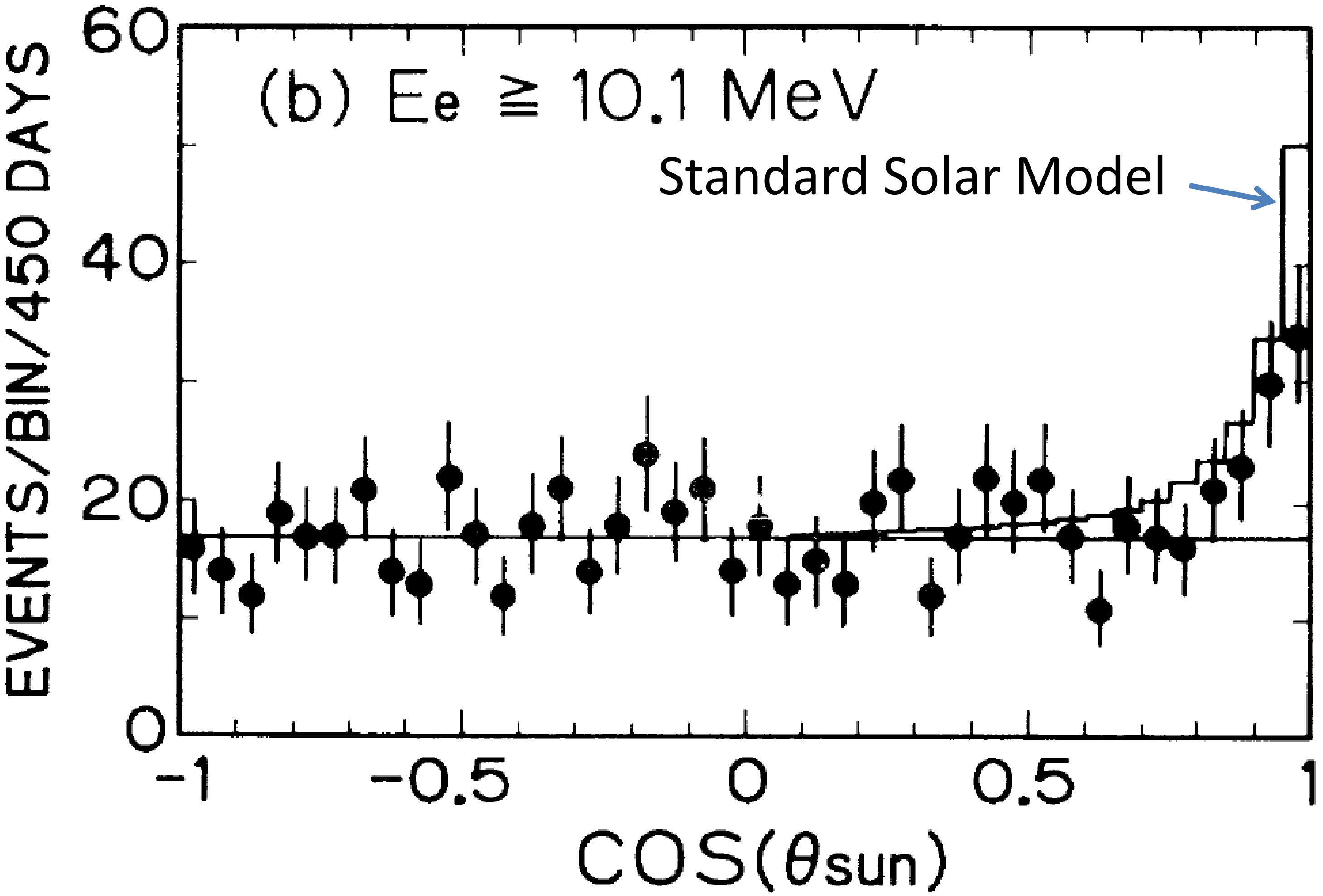
	Data	MC prediction
e-like (∼CC ν_e)	93	88.5
μ-like (∼CC ν_μ)	85	144.0

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)

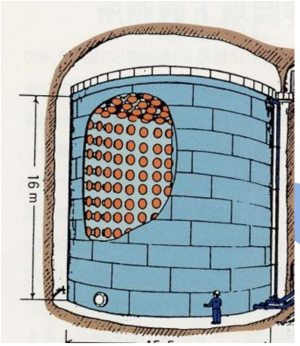
were evaluated to be very important.

↓

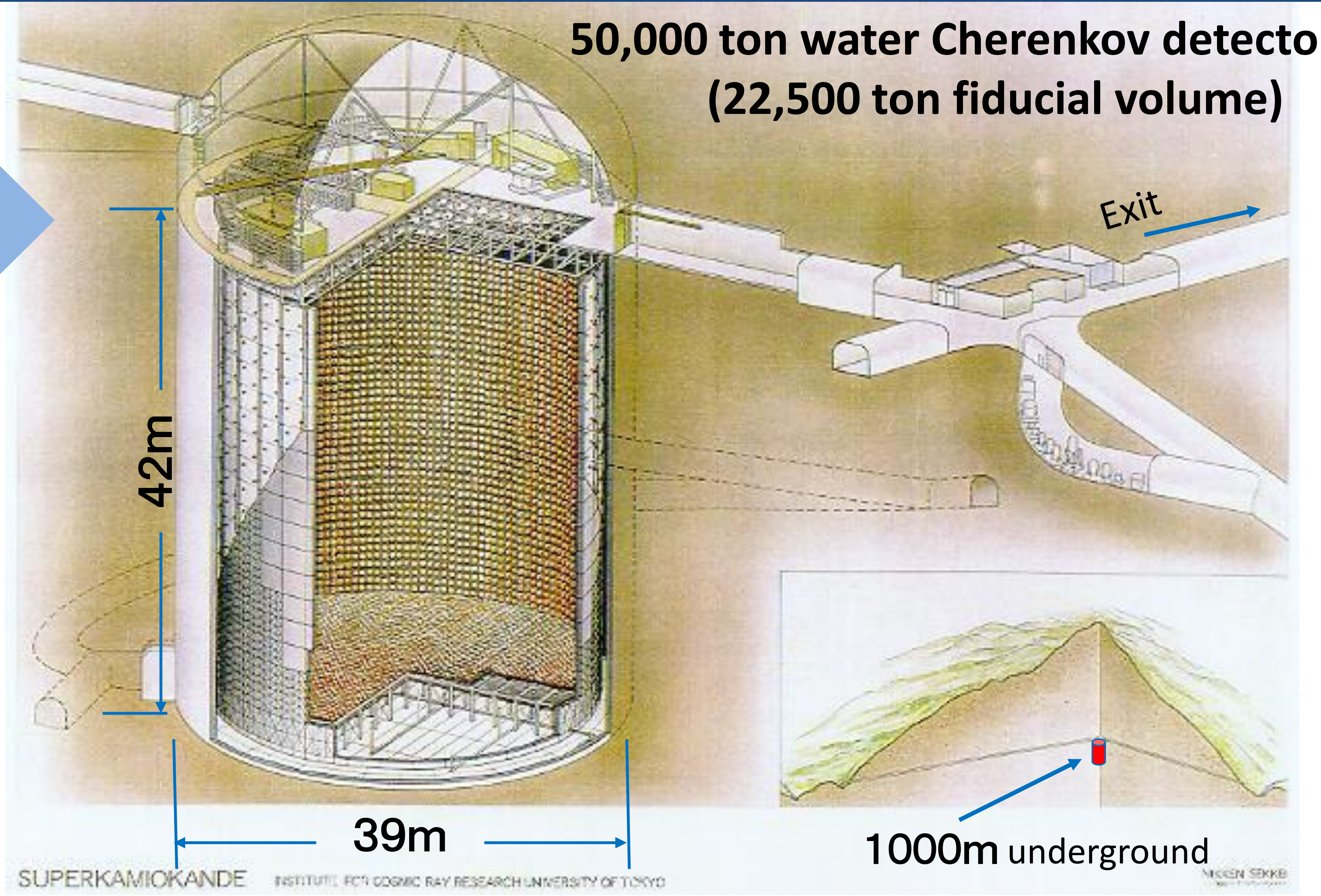
The construction of the Super-Kamiokande experiment was approved in 1991 by the Japanese government.

Super-Kamiokande

Super-Kamiokande detector

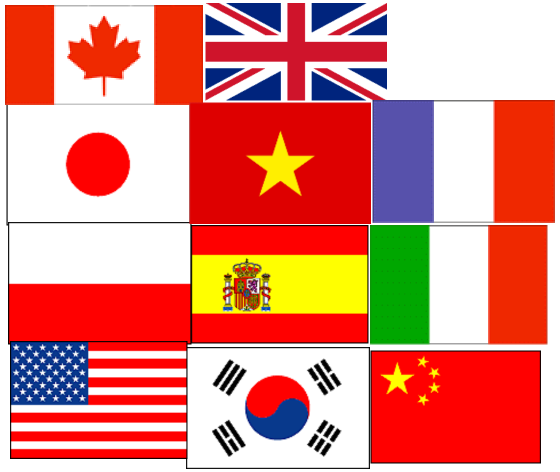


~20 times
larger mass

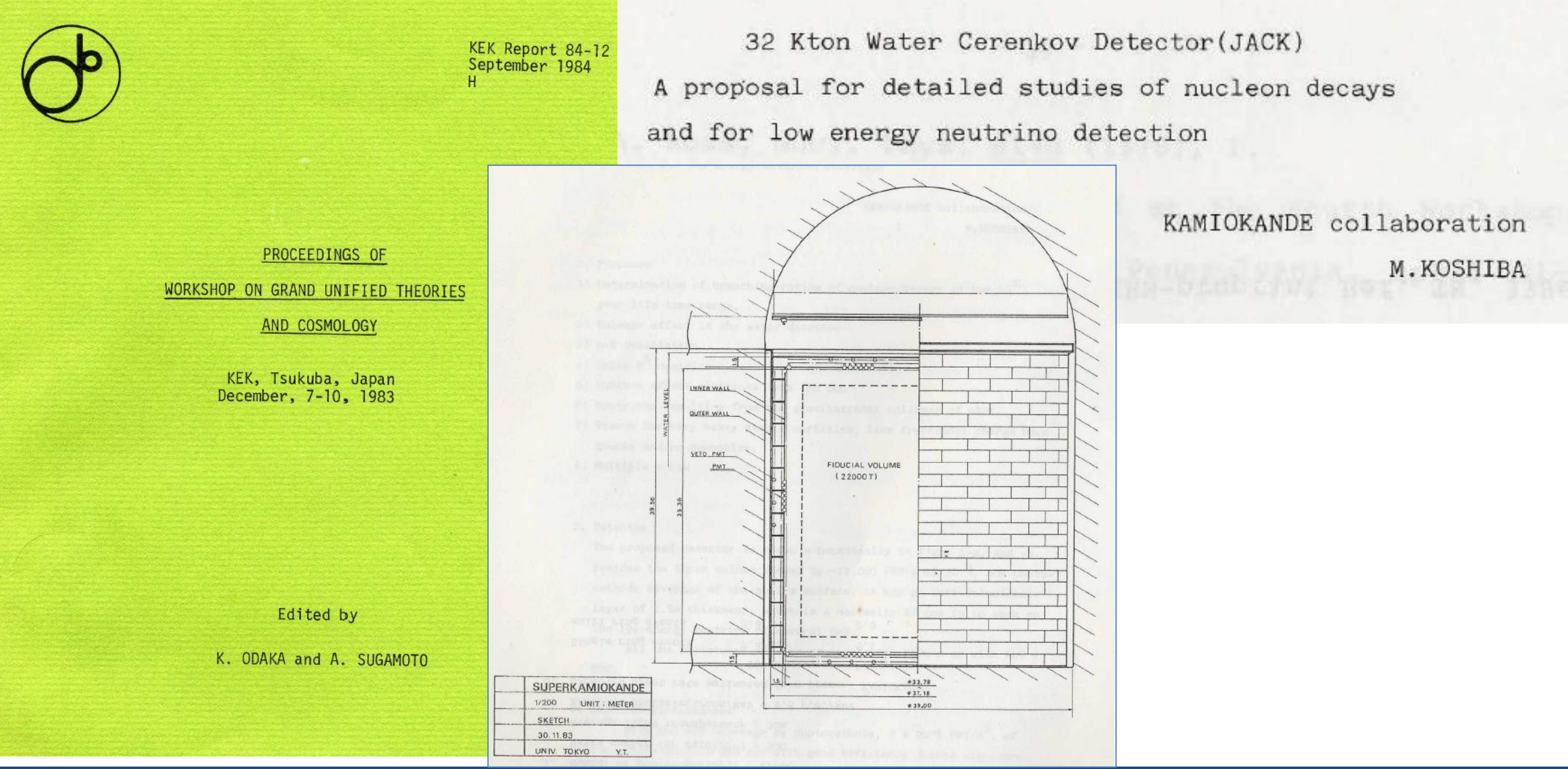


50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)

~230 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

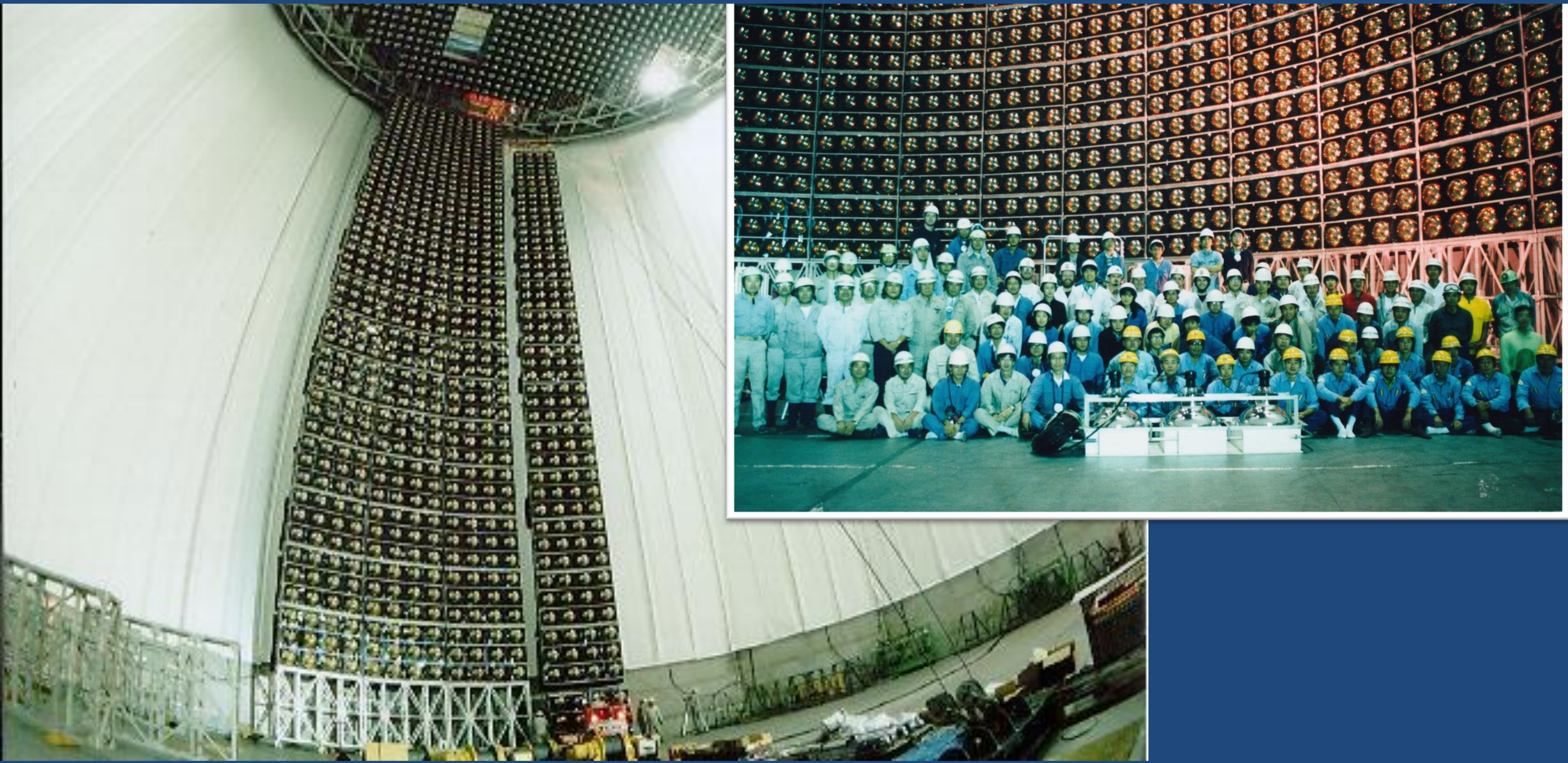
M.KOSHIBA

Beginning of the Super-Kamiokande collaboration between Japan and USA

@ Institute for Cosmic Ray Research, 1992

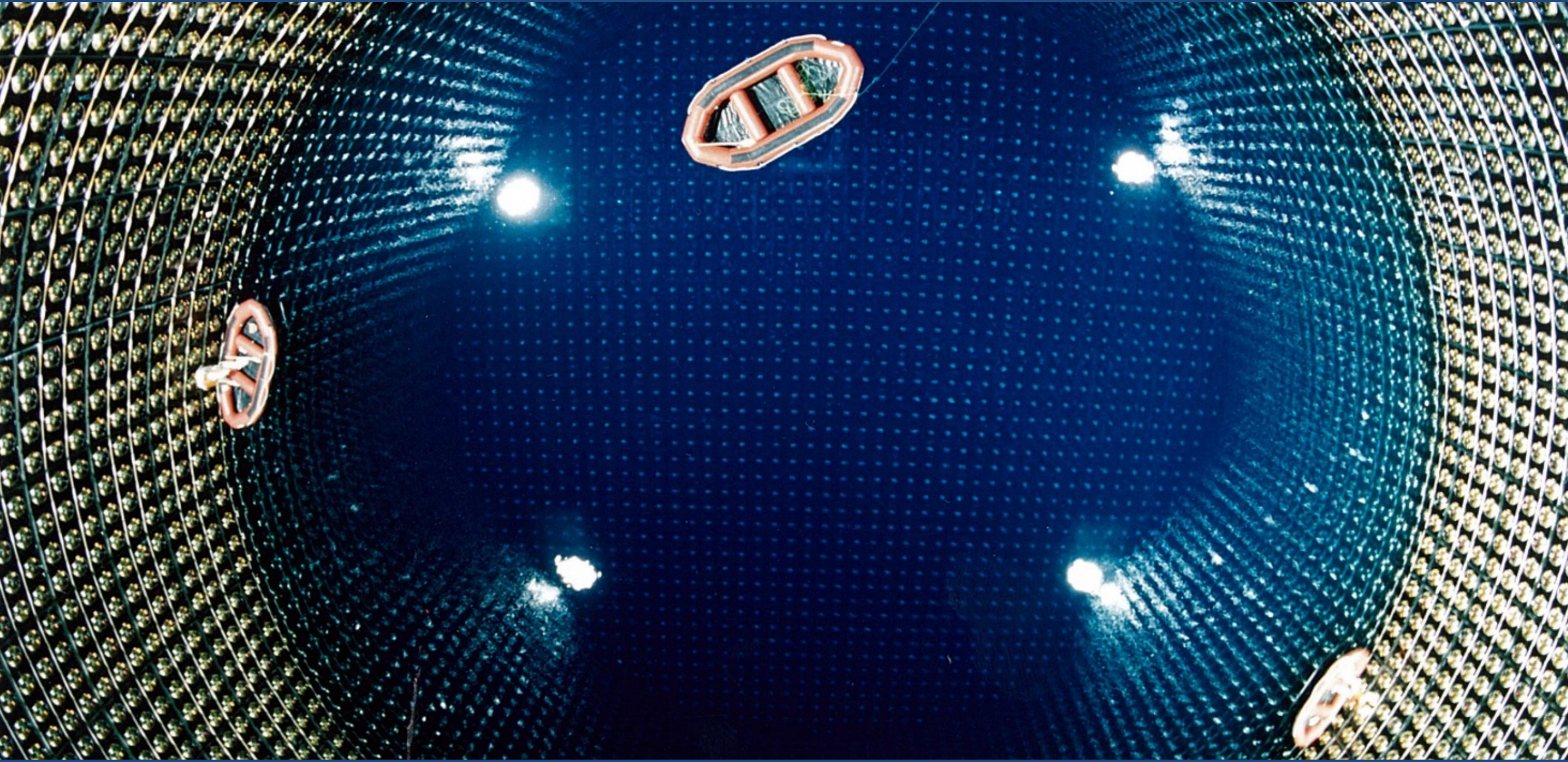
Constructing the Super-Kamiokande detector (spring 1995)

Constructing the Super-Kamiokande detector (Aug. 1995)



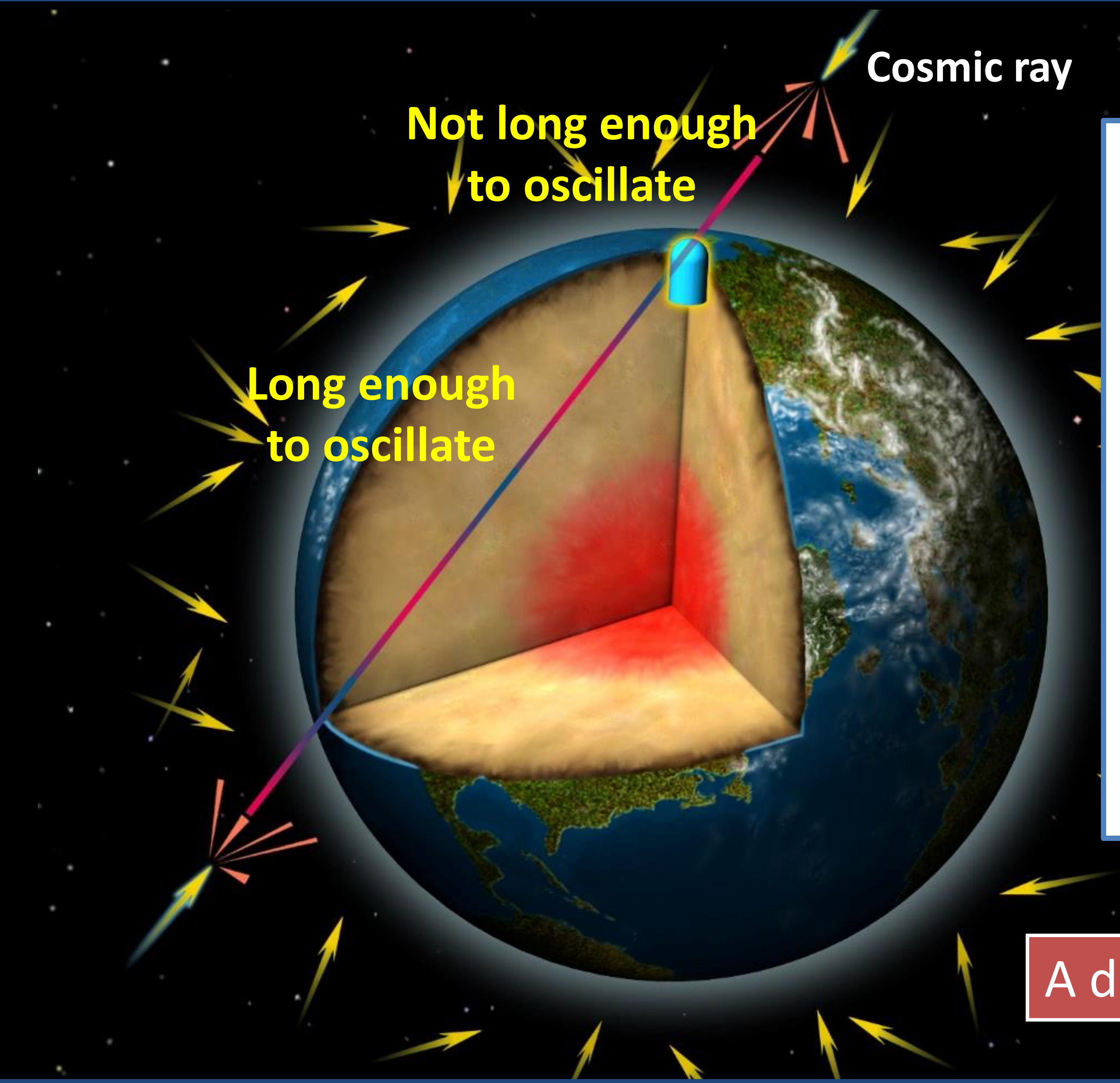
Filling water in Super-Kamiokande

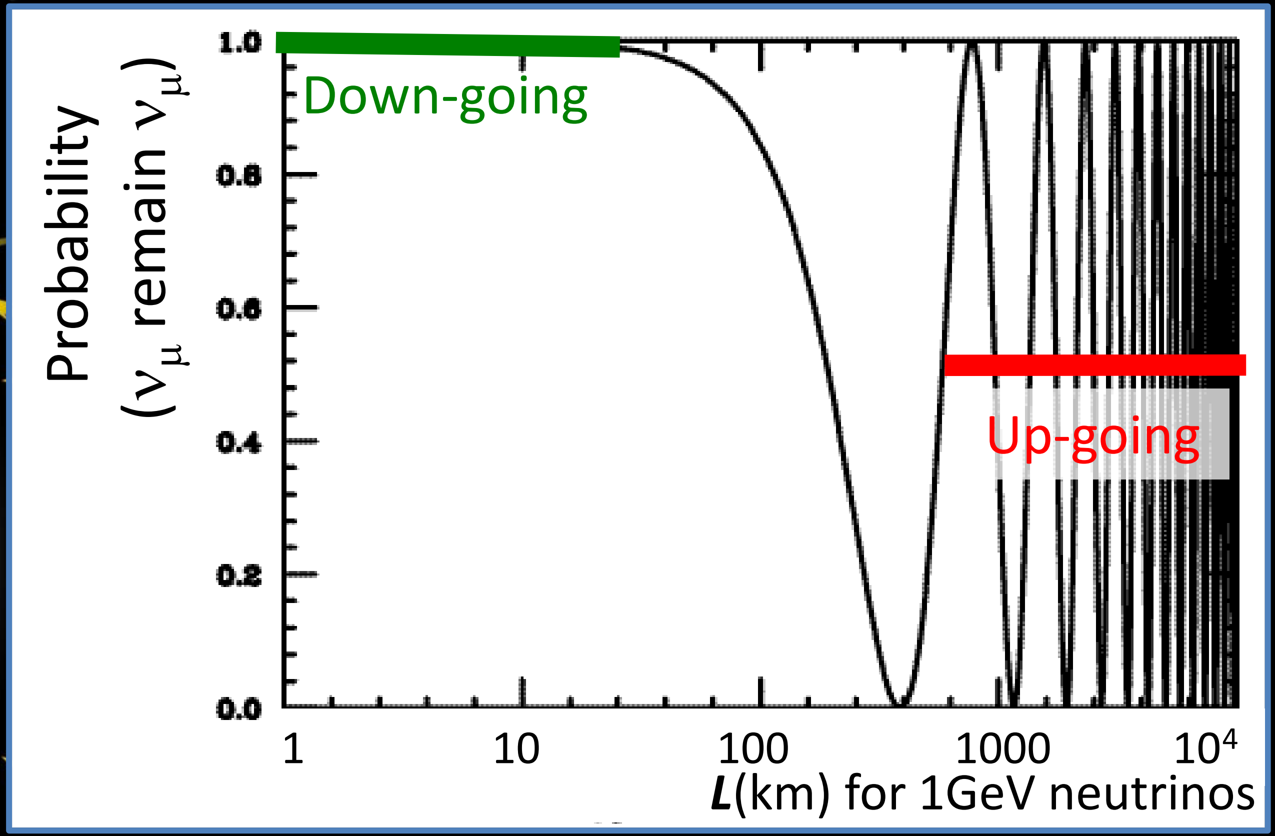
Jan. 1996



Discovery of atmospheric neutrino oscillations

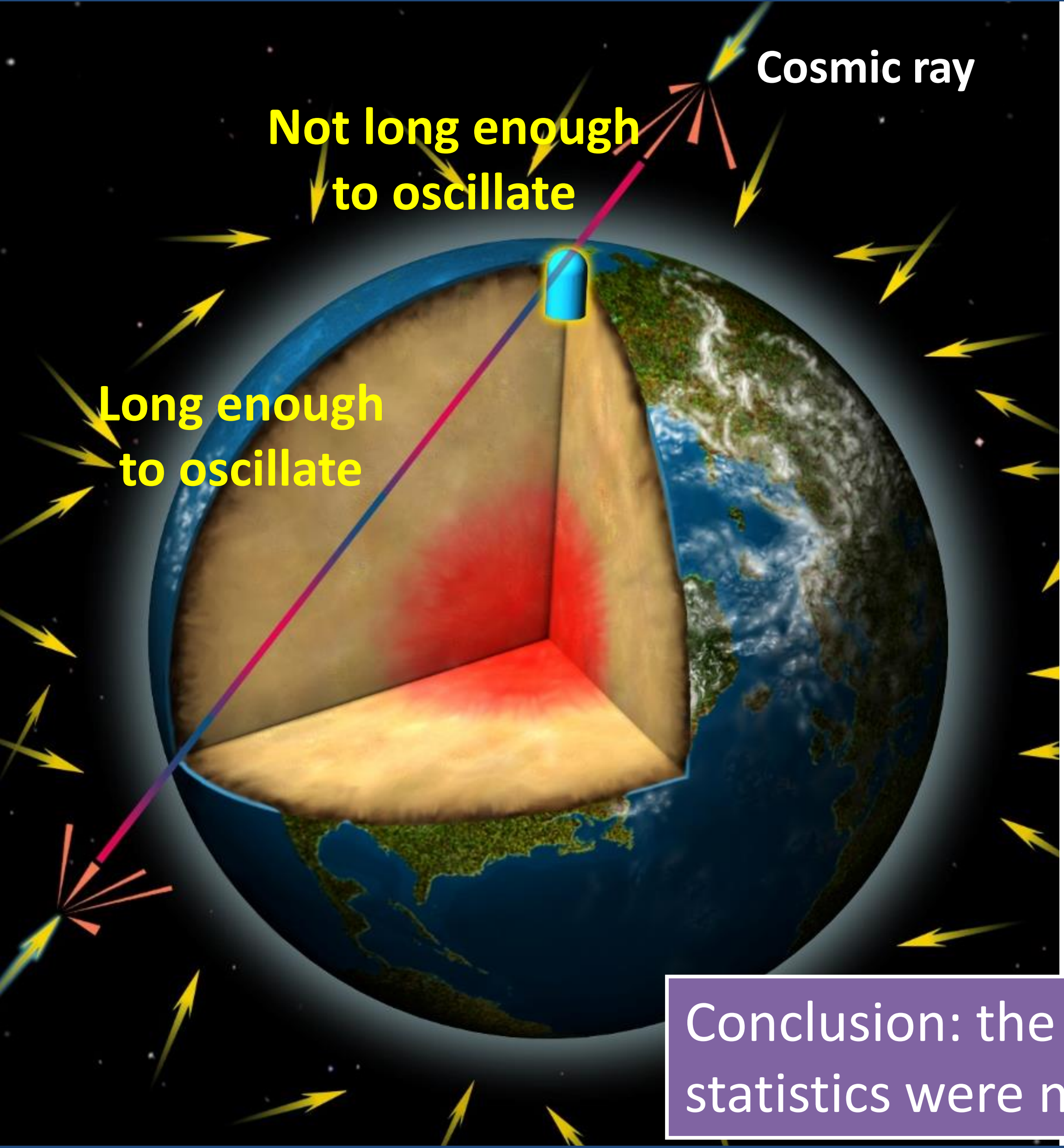
What will happen if the ν_μ deficit is due to neutrino oscillations



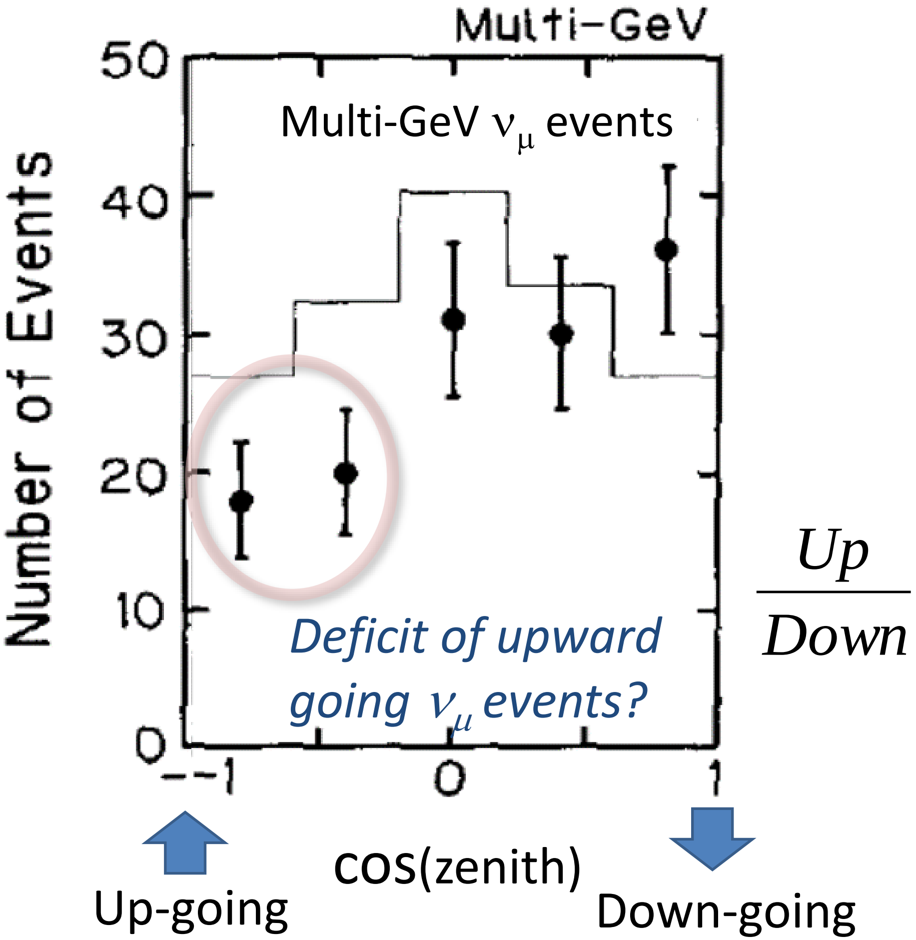


A deficit of upward going ν_μ's should be observed!

Appendix: Zenith angle distribution from Kamiokande (1994)



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



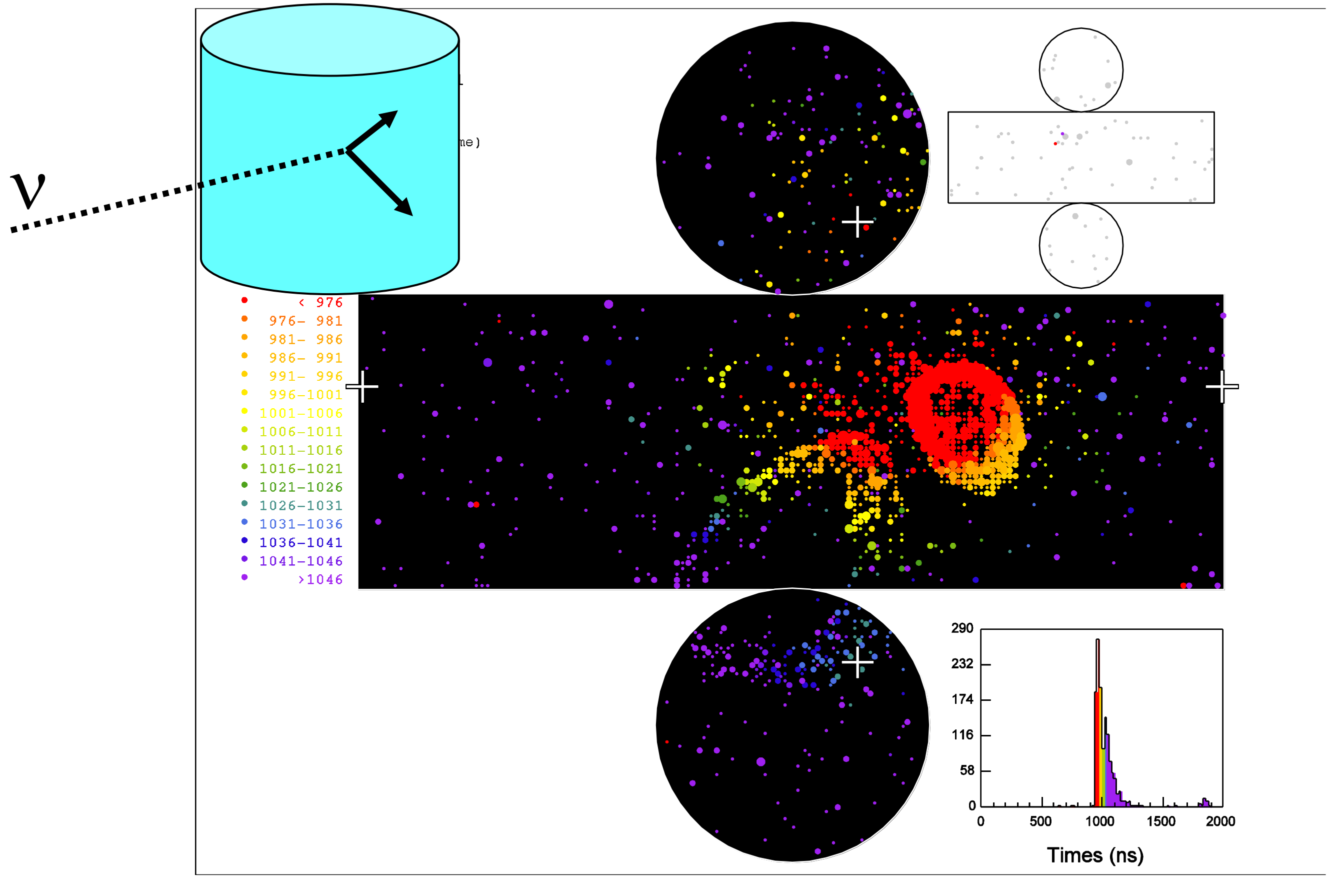
$$\frac{Up}{Down} = 0.58^{+0.13}_{-0.11}\ (2.9\sigma)$$

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

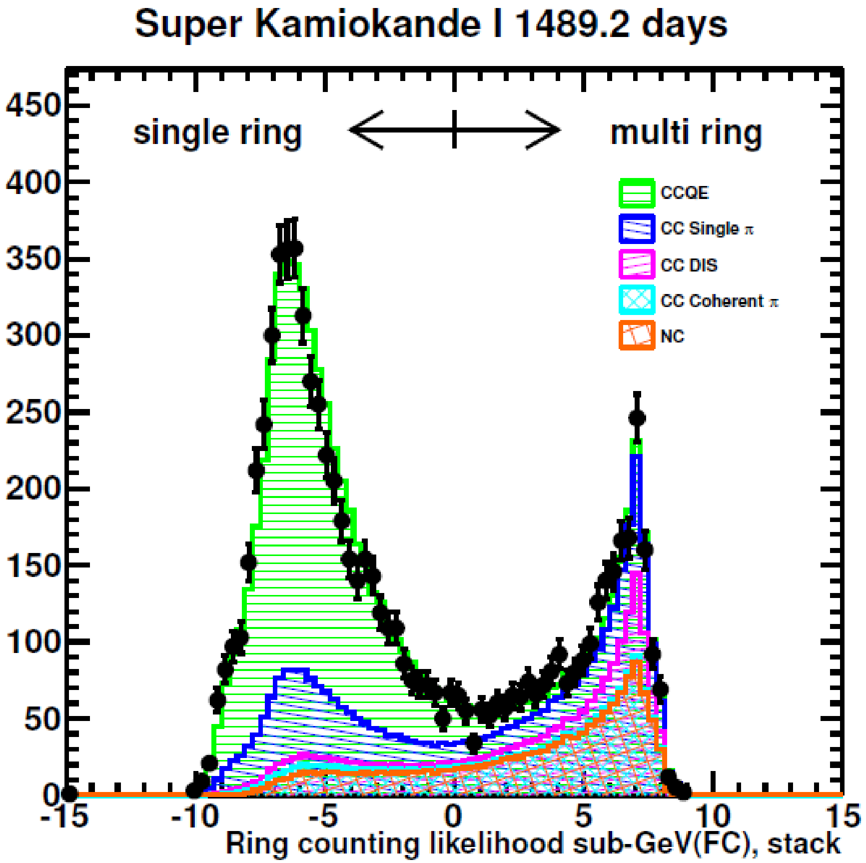
Fully automated analysis

- 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.

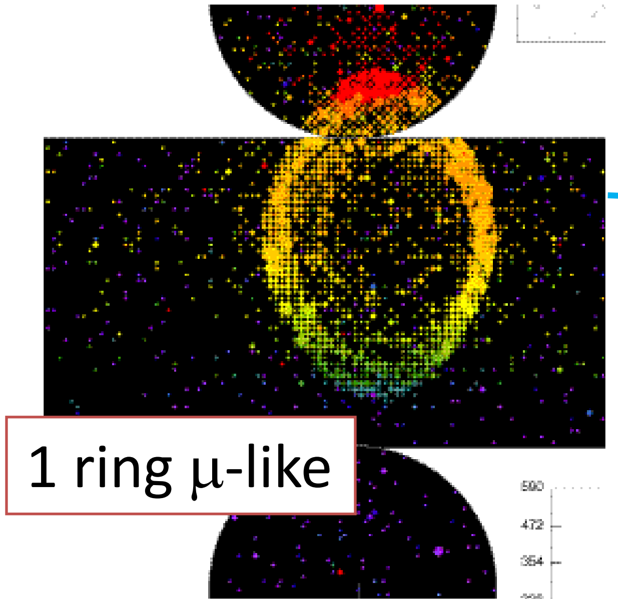
Multi Cherenkov ring event

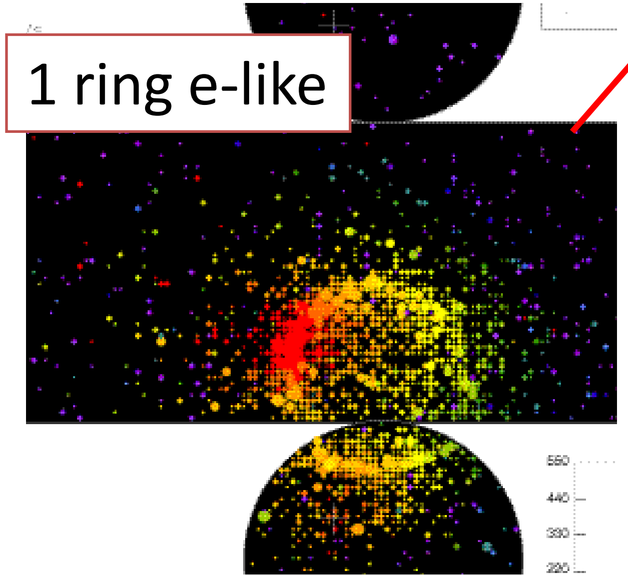


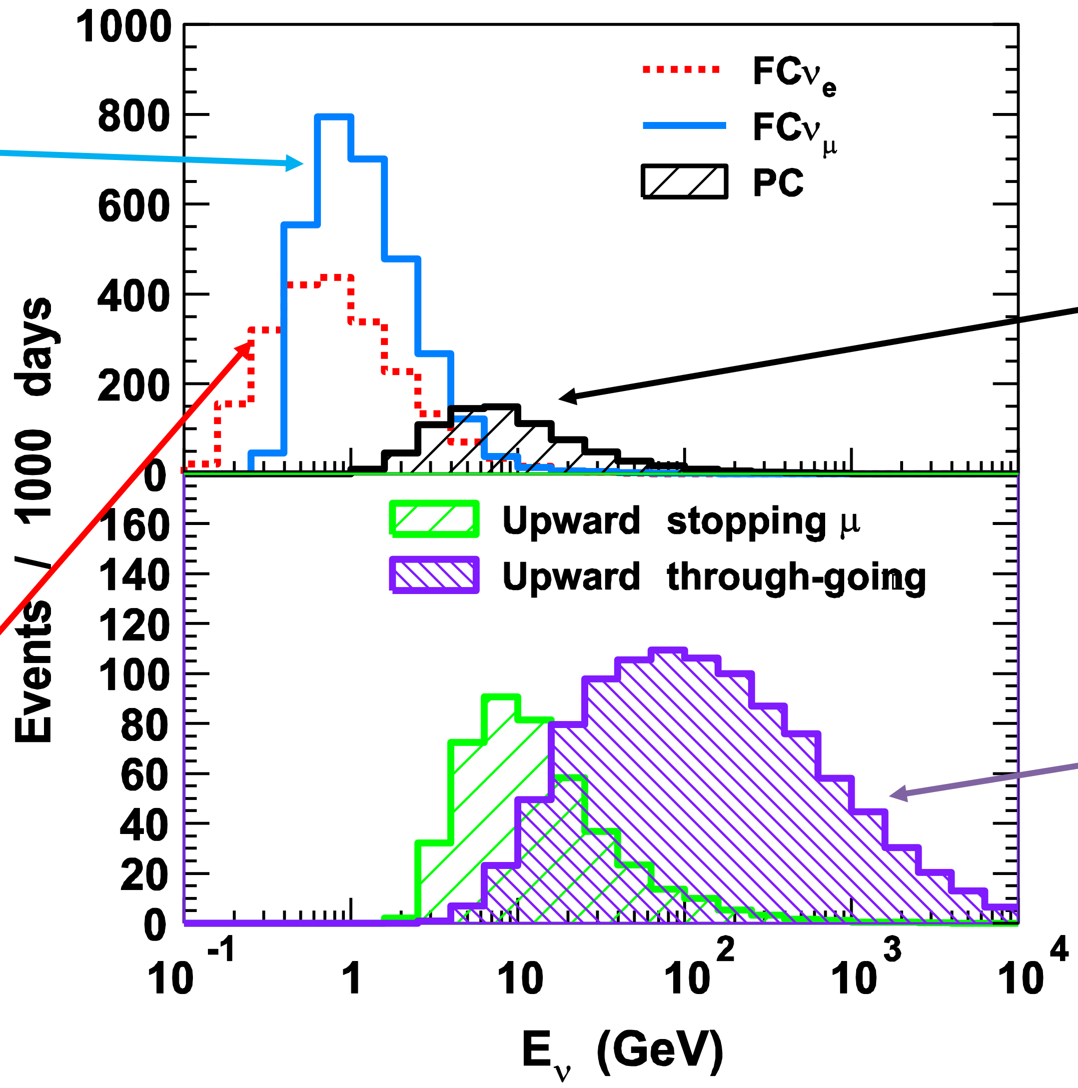
Hough transformation
+ maximum likelihood

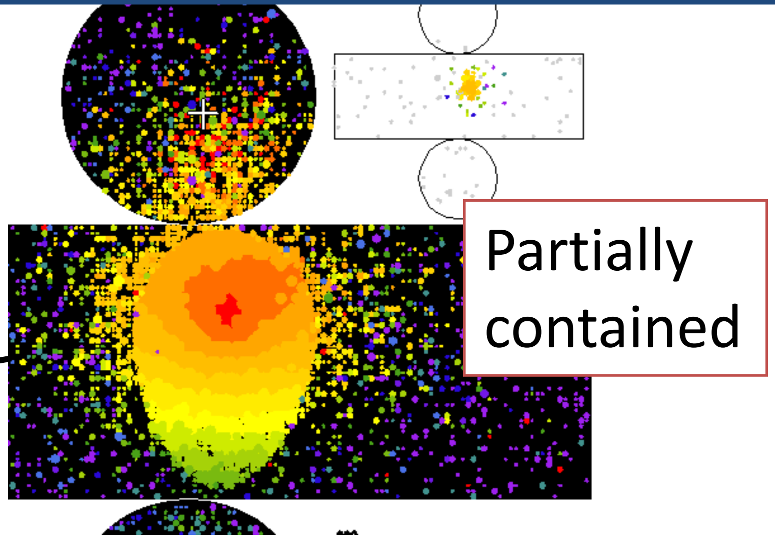


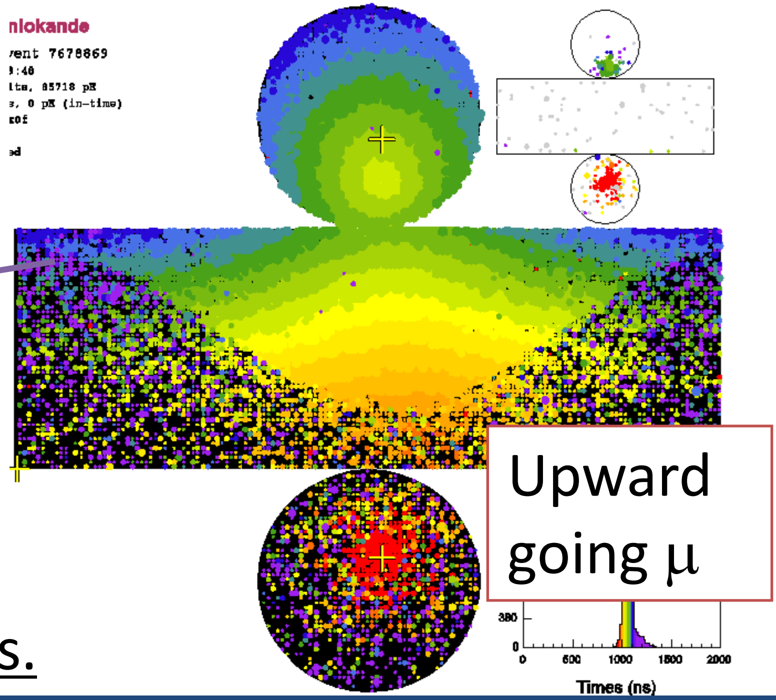
Event type and neutrino energy


1 ring μ-like


1 ring e-like



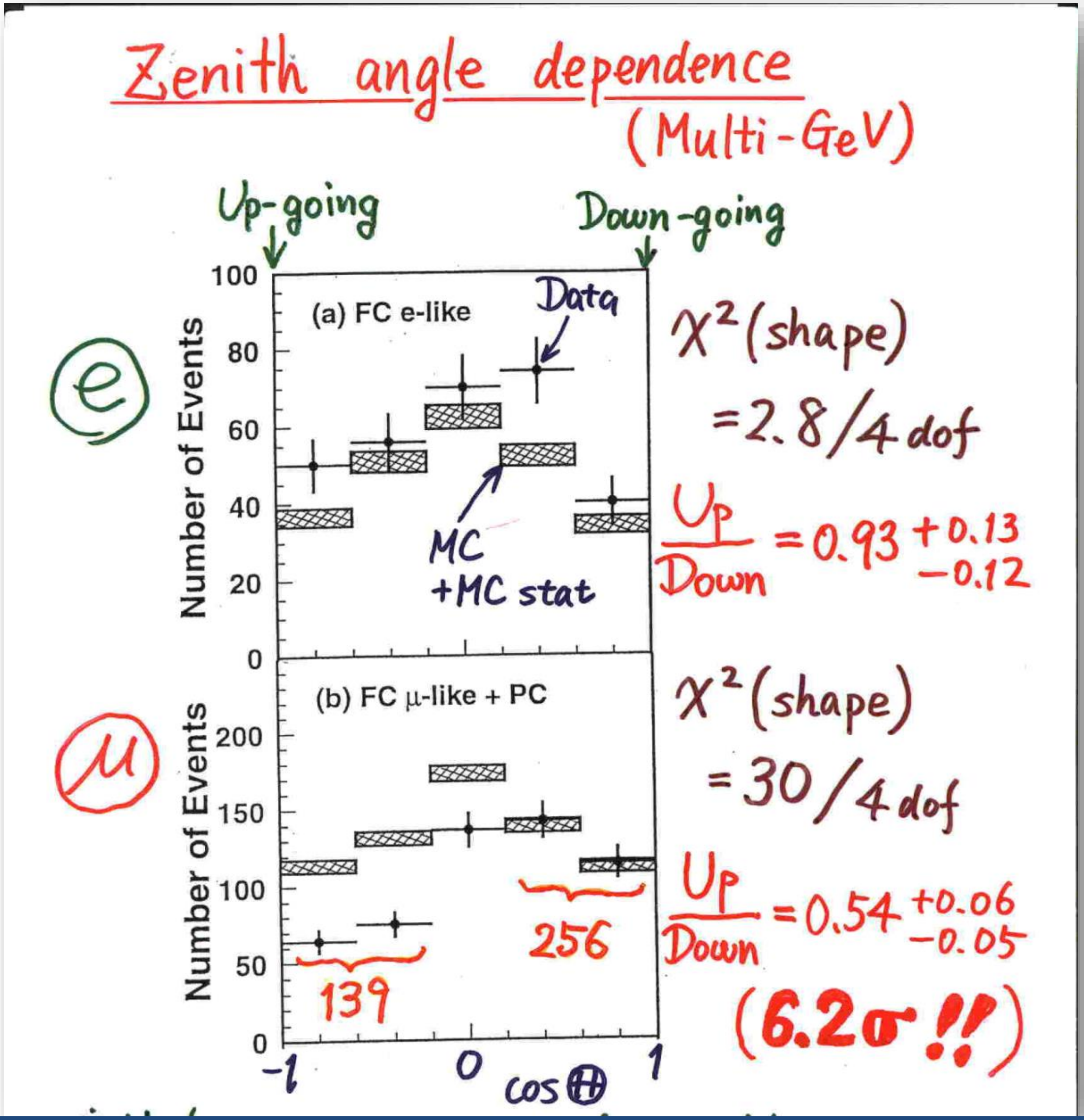

Partially contained

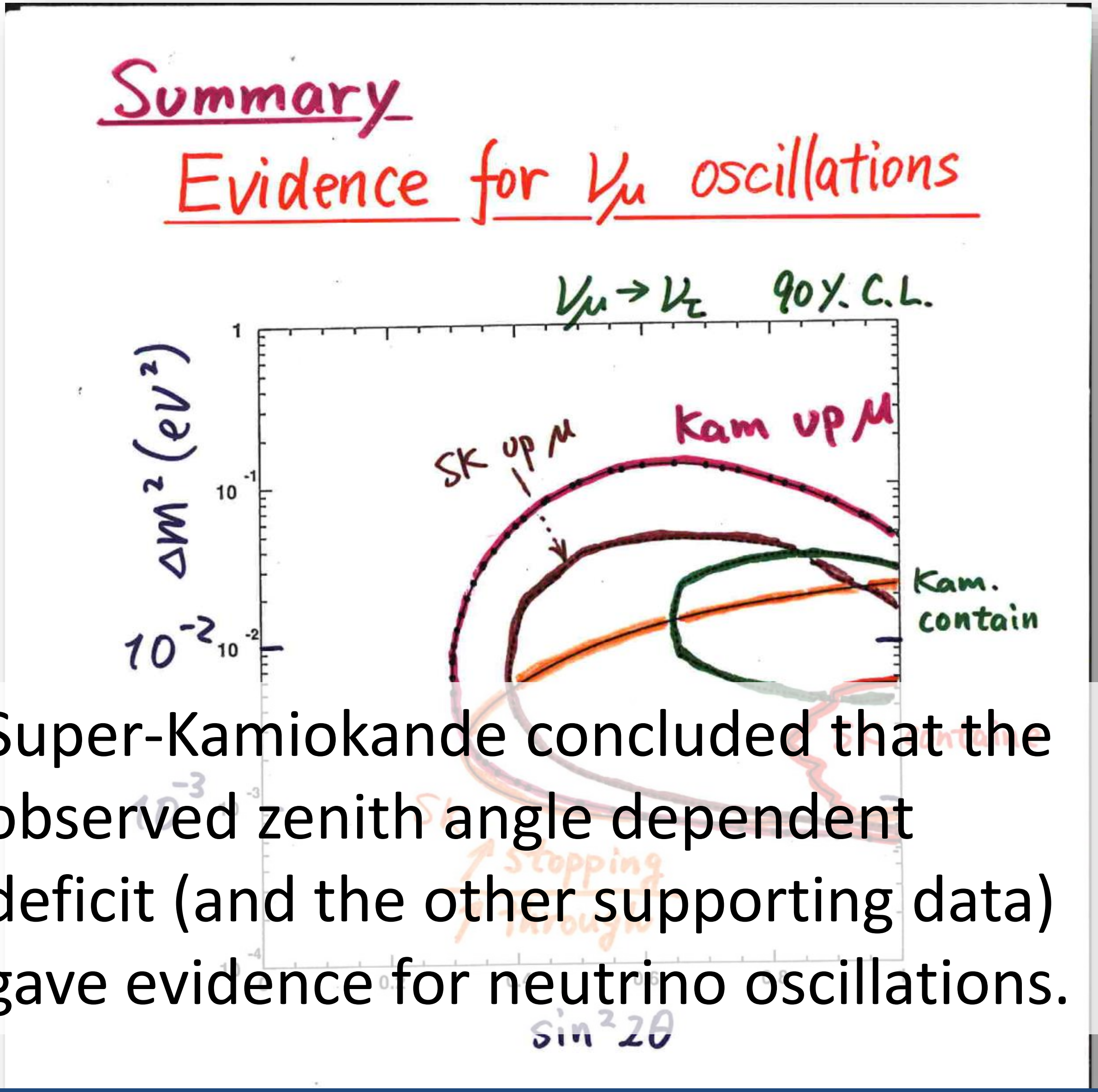

Upward going μ

All these events are used in the analysis.

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

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

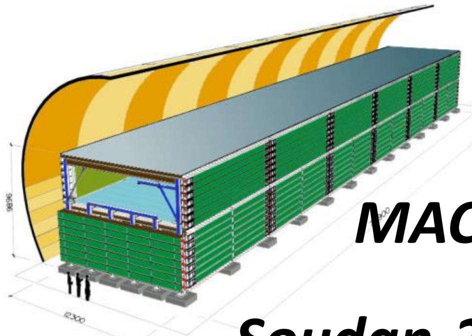




Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Neutrino oscillation studies

Various atmospheric neutrino and accelerator based long baseline neutrino oscillation experiment have been studying neutrino oscillations in detail.

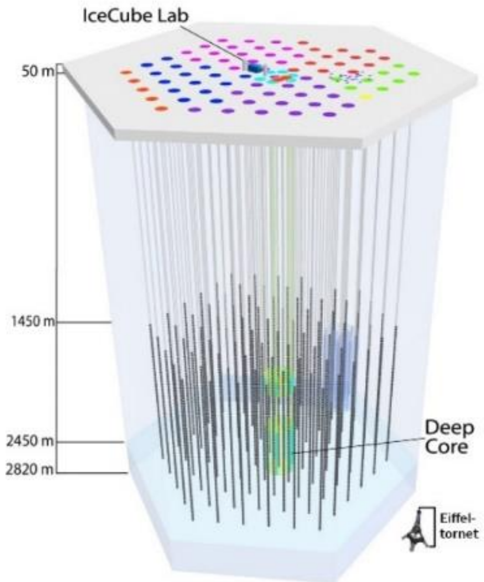


MACRO

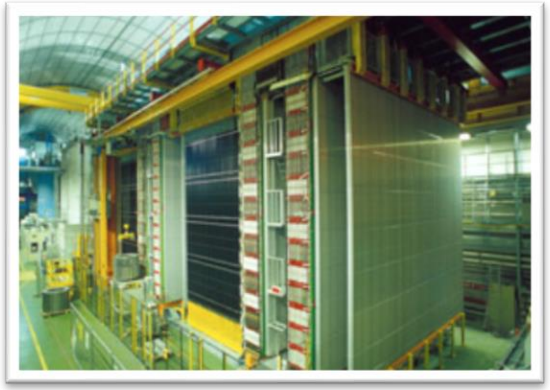
K2K

MINOS

Soudan-2

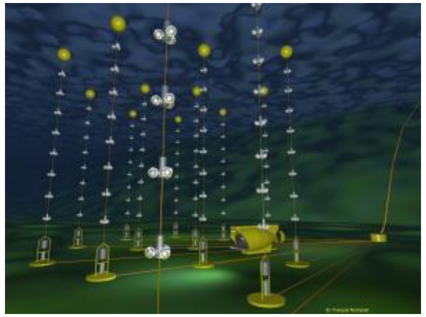


IceCube



OPERA

NOvA

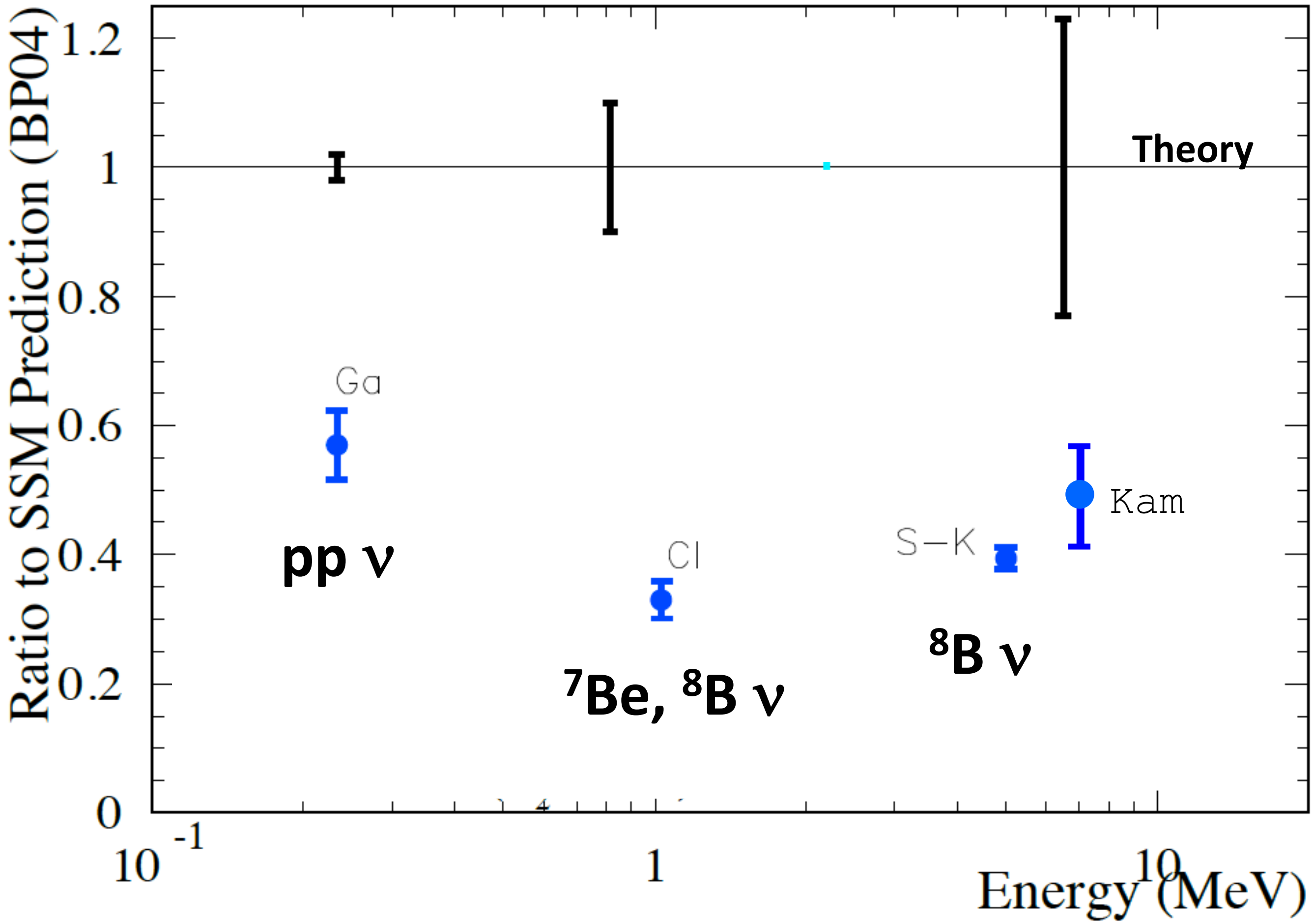


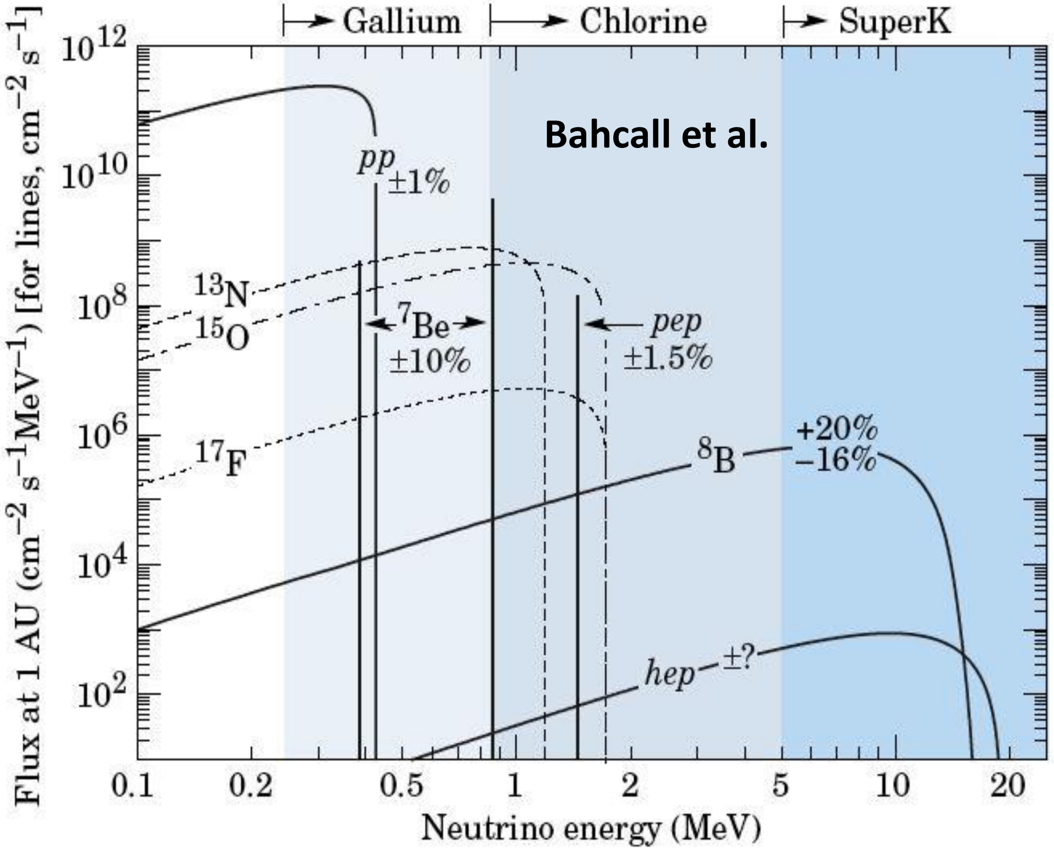
ANTARES

T2K

Contribution to the discovery of solar neutrino oscillations

Results from solar neutrino experiments (before ~2000)



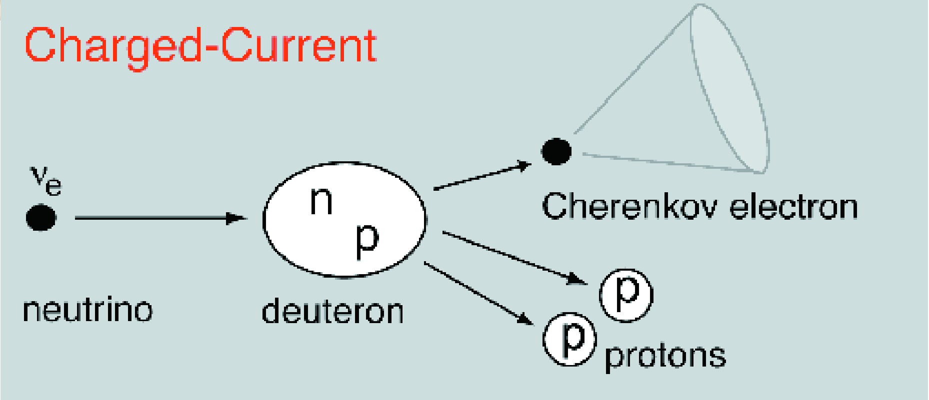


Solar neutrino experiments in the 80’s and 90’s confirmed the deficit of solar neutrinos.

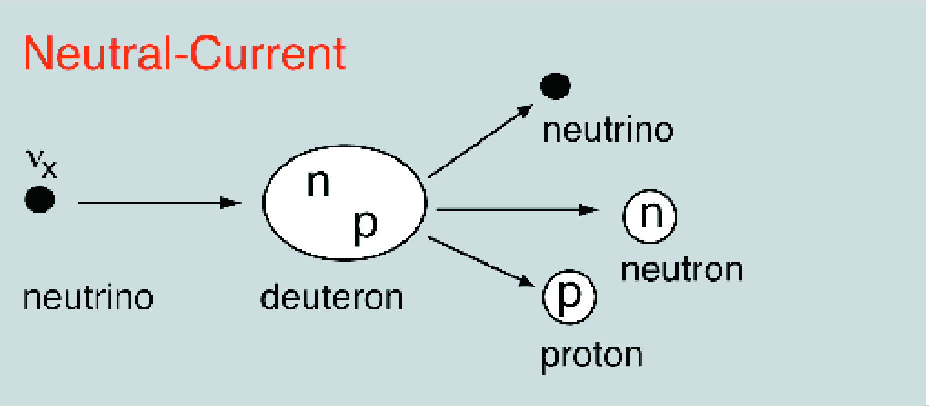
Unique signatures of heavy water (D_2O) experiments

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.

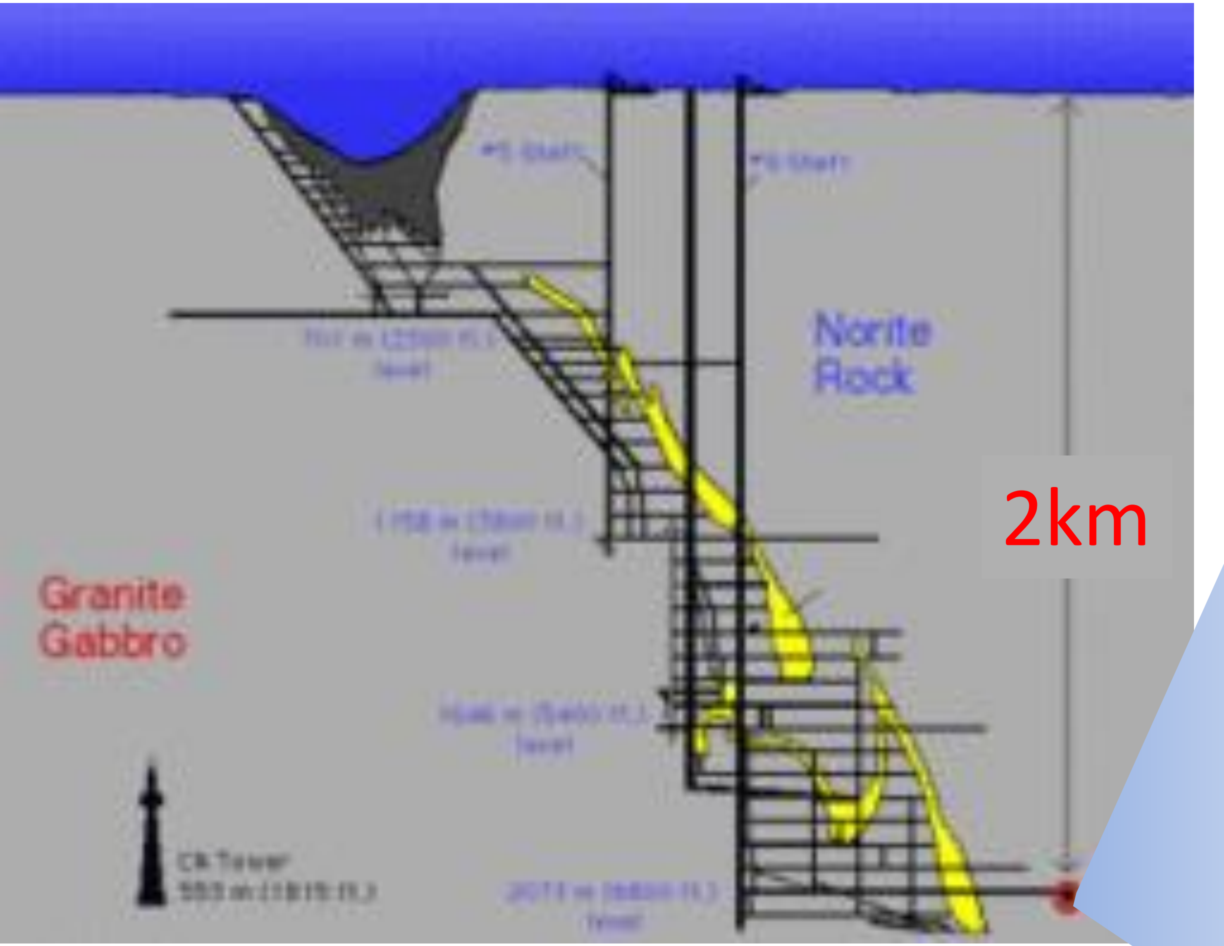


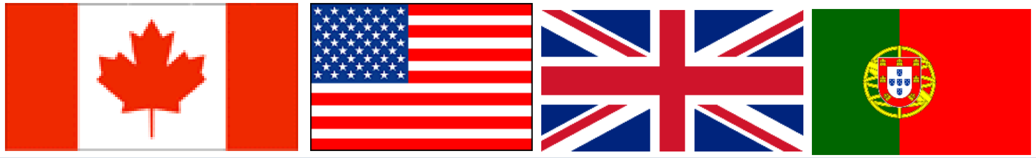
Charged-Current

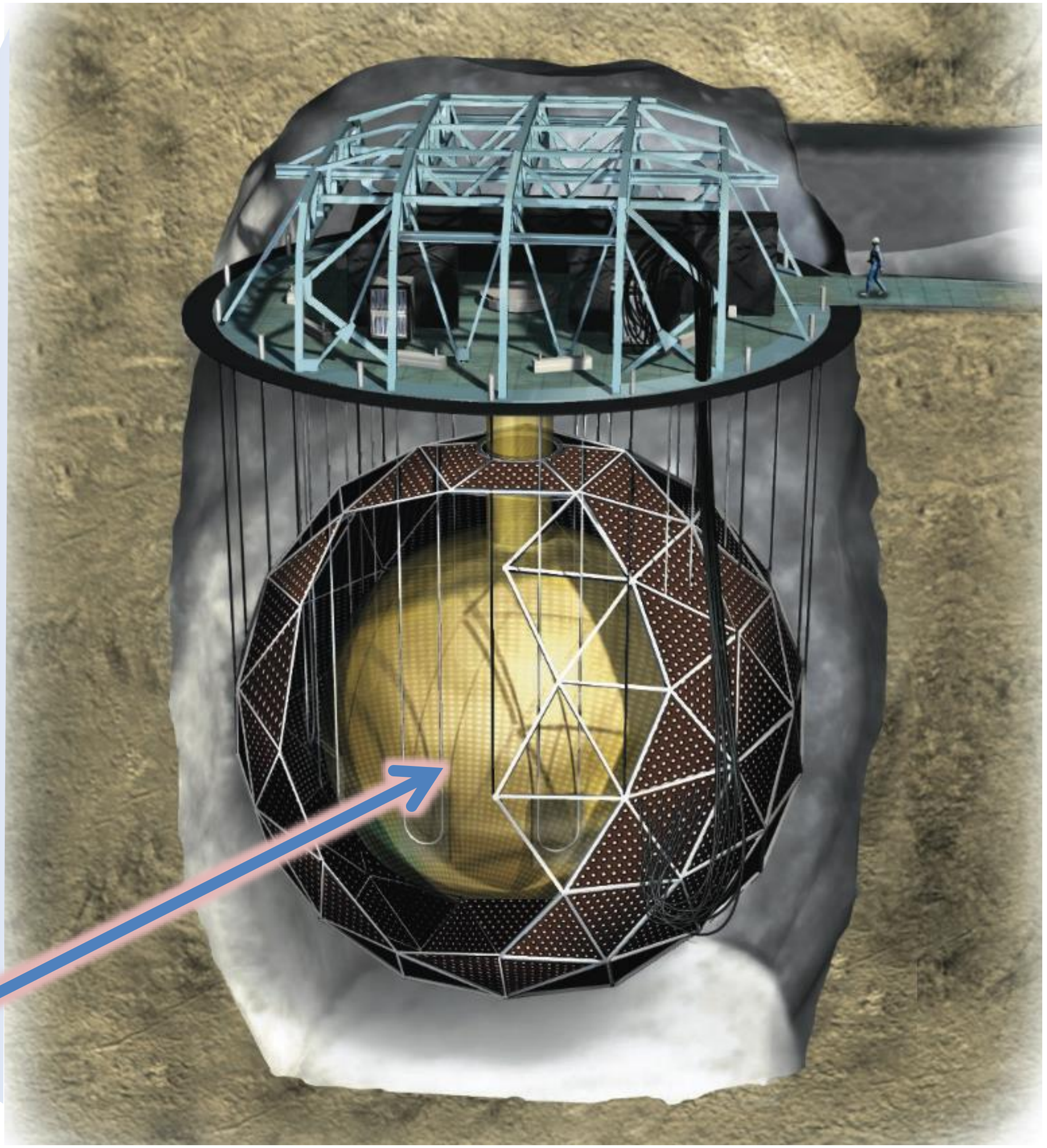


Neutral-Current

SNO detector







1000 ton of heavy water

3 neutron detection methods (for νd → νpn measurement)

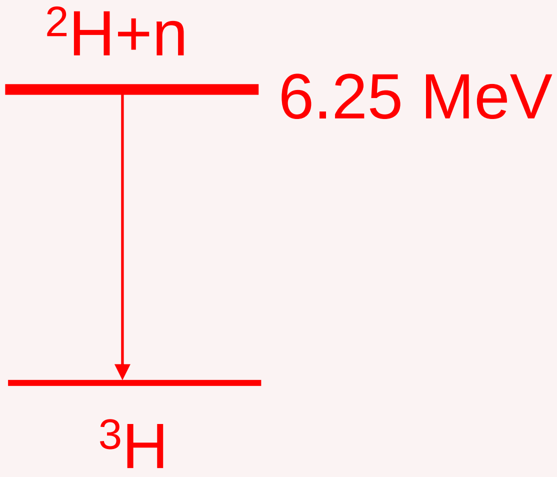
Phase I (D_2O)

Nov. 99 - May 01

n captures on

$^2H(n, \gamma)^3H$

Eff. ~14.4%



^2H+n

6.25 MeV

^3H

Phase II (salt)

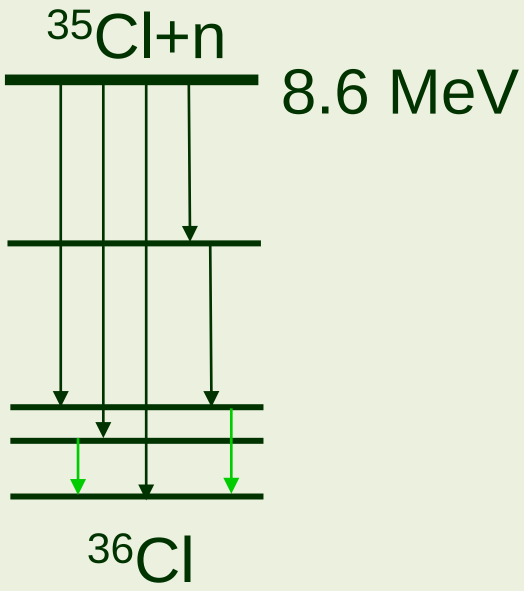
July 01 - Sep. 03

2 tonnes of NaCl

n captures on

$^{35}Cl(n, \gamma)^{36}Cl$

Eff. ~40%



$^{35}Cl+n$

8.6 MeV

^{36}Cl

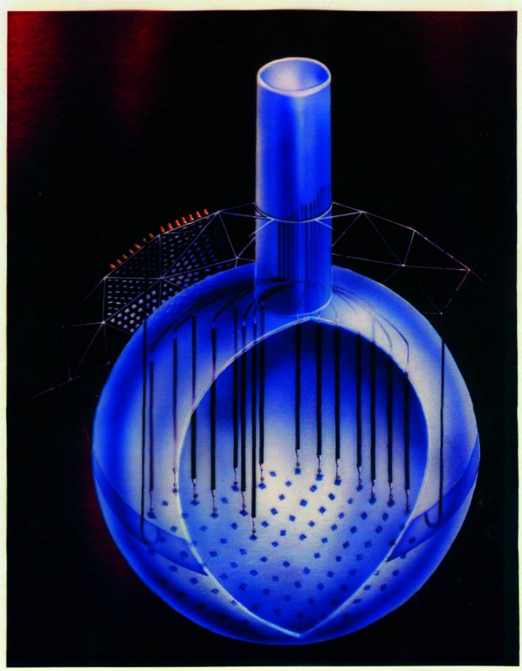
Phase III (^3He)

Nov. 04-Dec. 06

400 m of proportional counters

$^3He(n, p)^3H$

Effc. ~ 30% capture

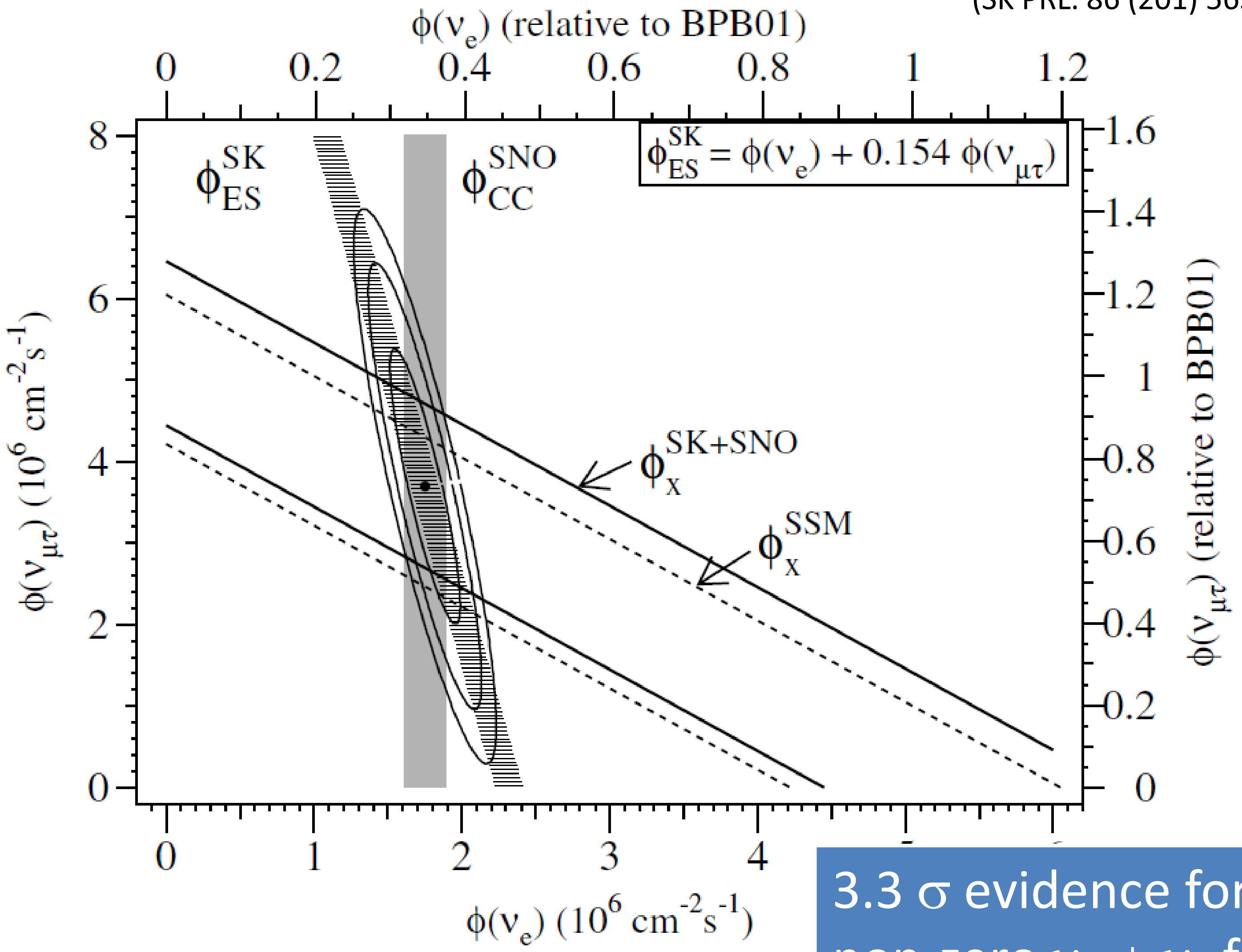


Initial evidence for solar neutrino oscillations

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 /cm^2/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 /cm^2/sec
(assuming ν_e only)

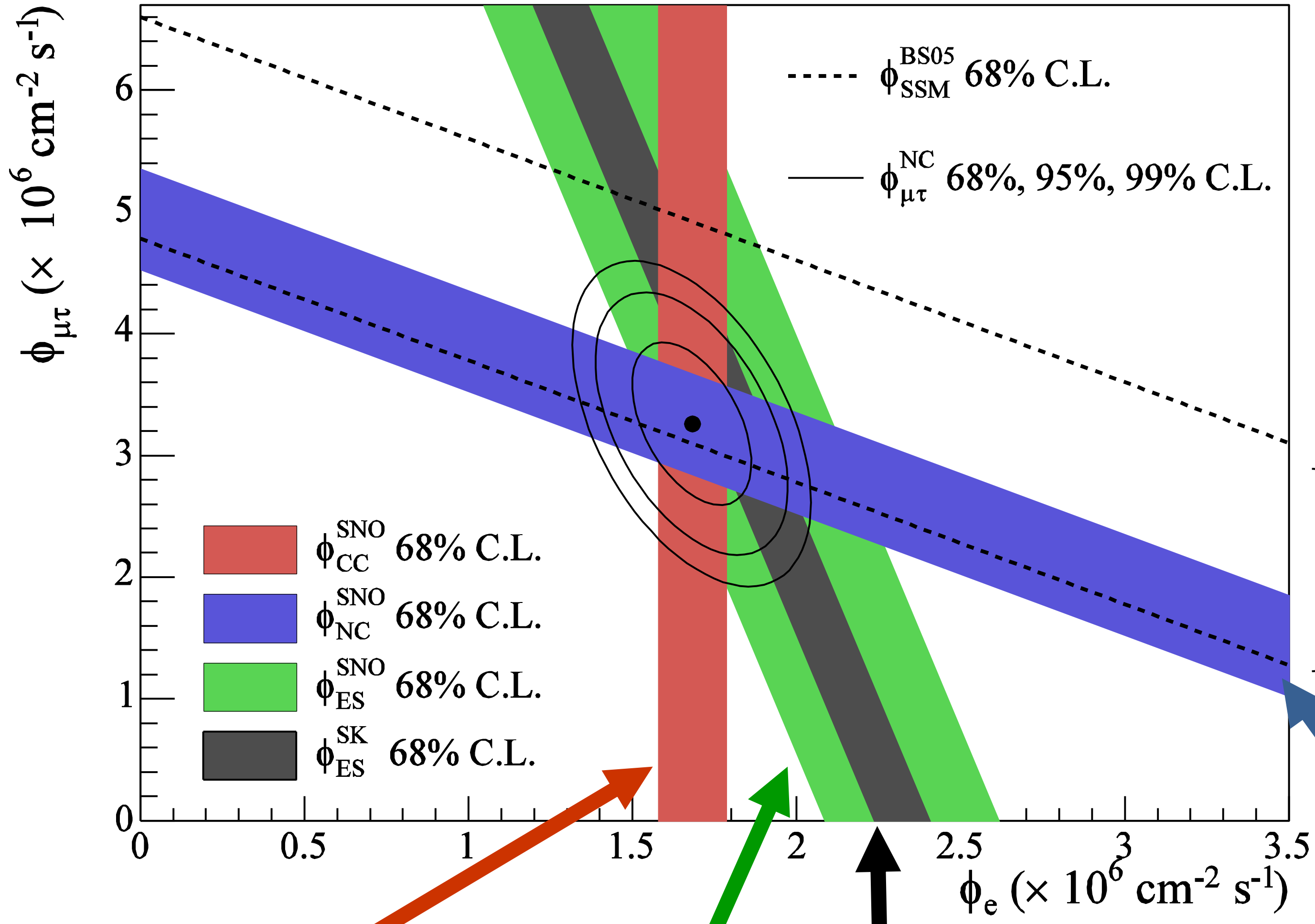


3.3 σ evidence for non-zero $\nu_\mu + \nu_\tau$ flux

Evidence for solar neutrino oscillations

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

(A plot based on the salt-phase data)



SSM
68%CL

SNO NC
68%CL

SNO CC
68%CL

SNO ES
68%CL

SK ES
68%CL

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

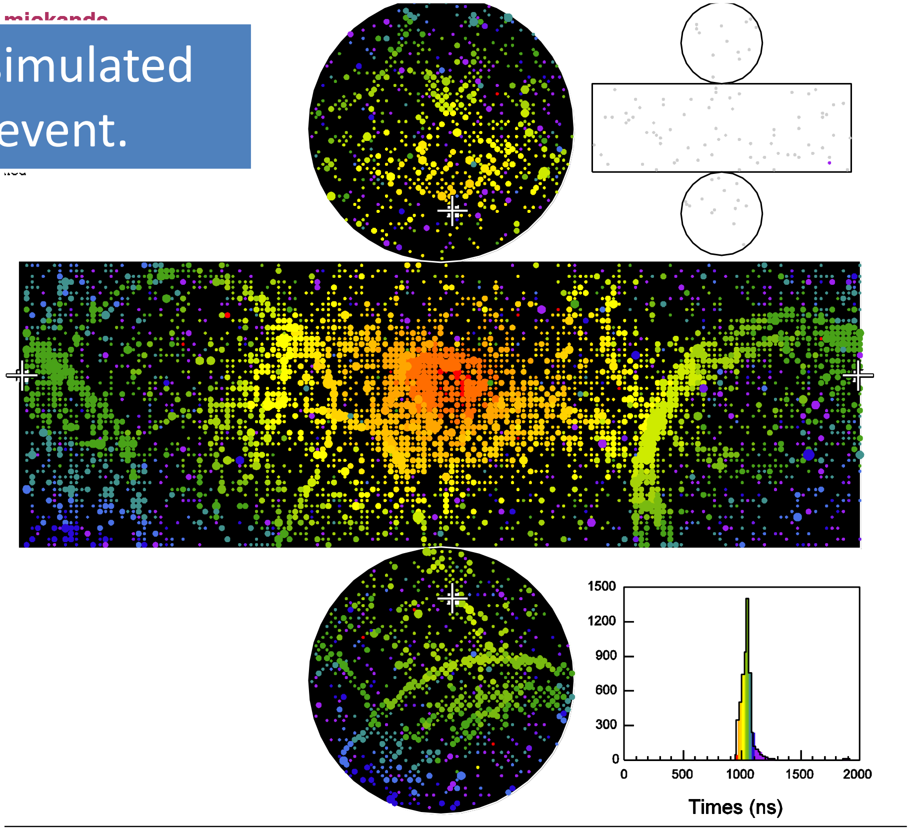
✓ *Evidence for ($\nu_\mu+\nu_\tau$) flux* *($> 5\sigma$)*

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

Detecting tau neutrinos

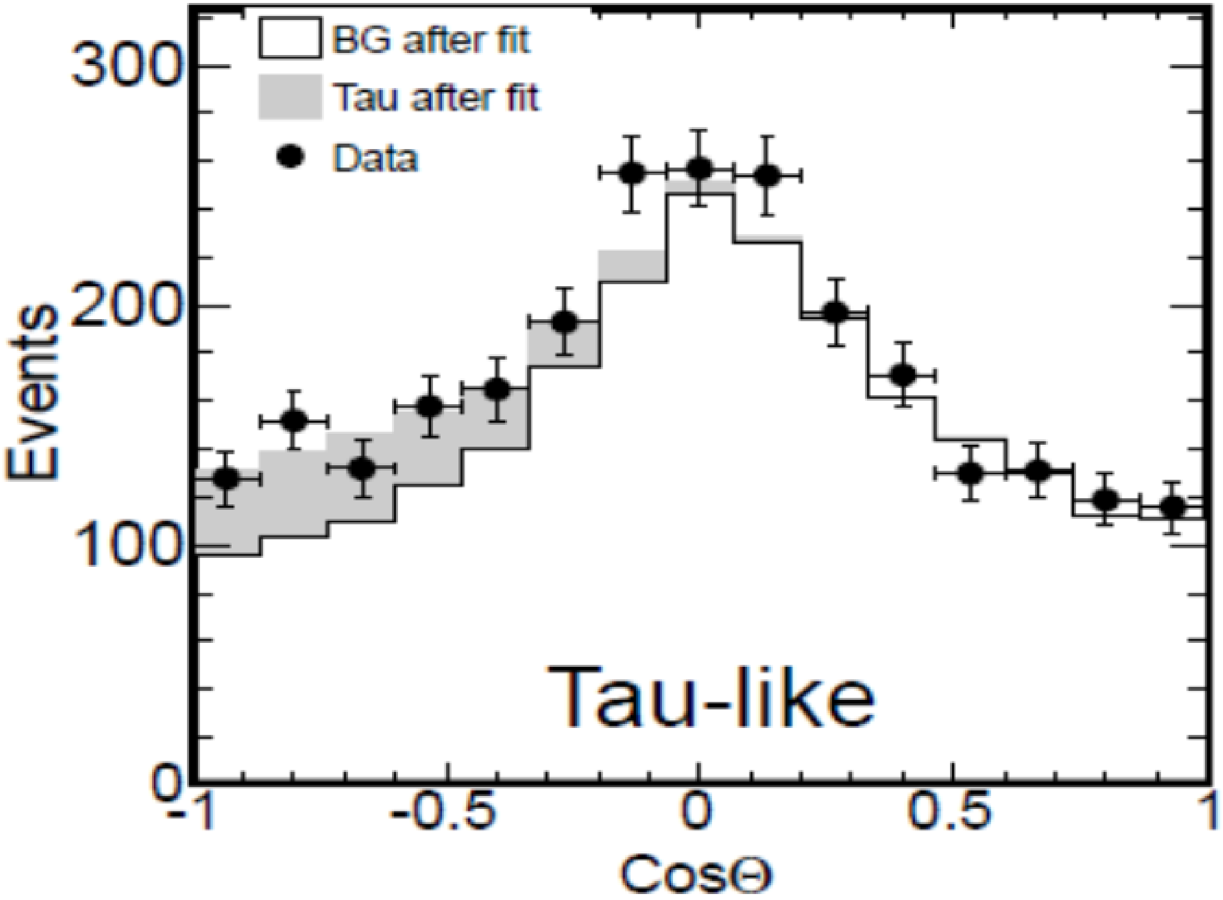
If the oscillations are between ν_μ and ν_τ, one should be able to observe ν_τ's.

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.

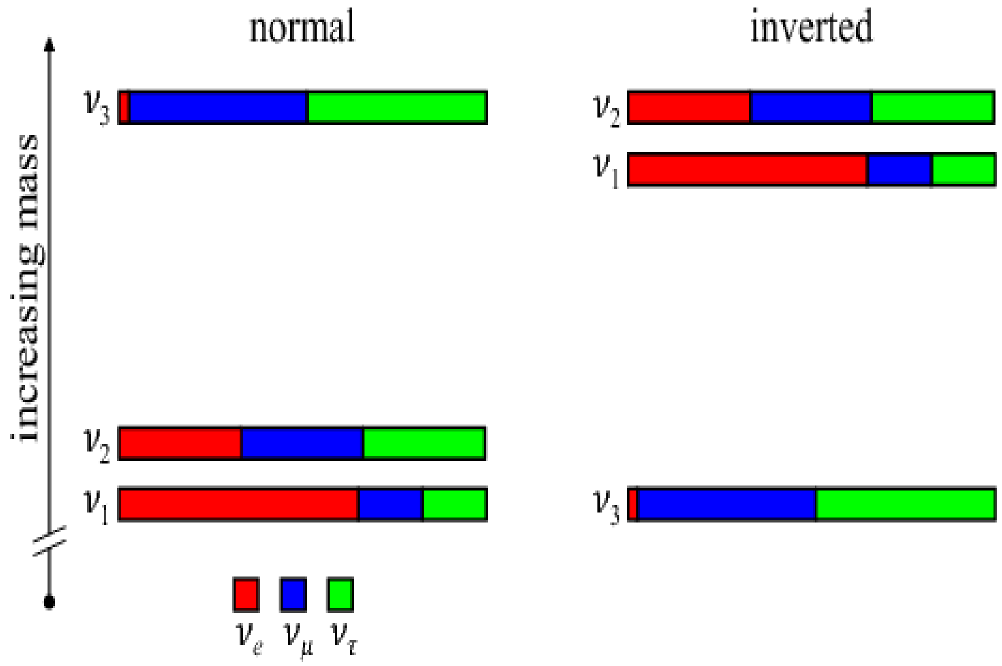
Super-K, PRD 98 (2018) 5, 052006



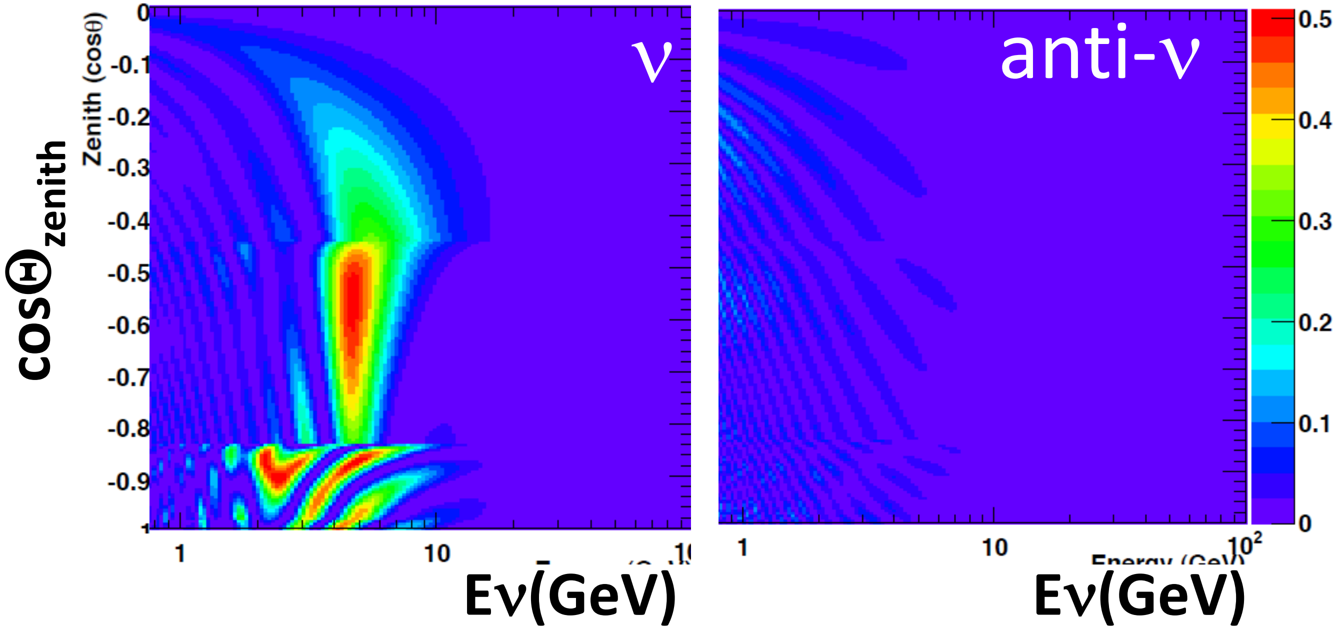
τ-appearance at 4.6σ (consistent with OPERA)

Studying neutrino mass ordering

Neutrino mass hierarchy?



P(ν_μ→ν_e) and *P(anti-ν_μ→anti-ν_e)* for normal hierarchy

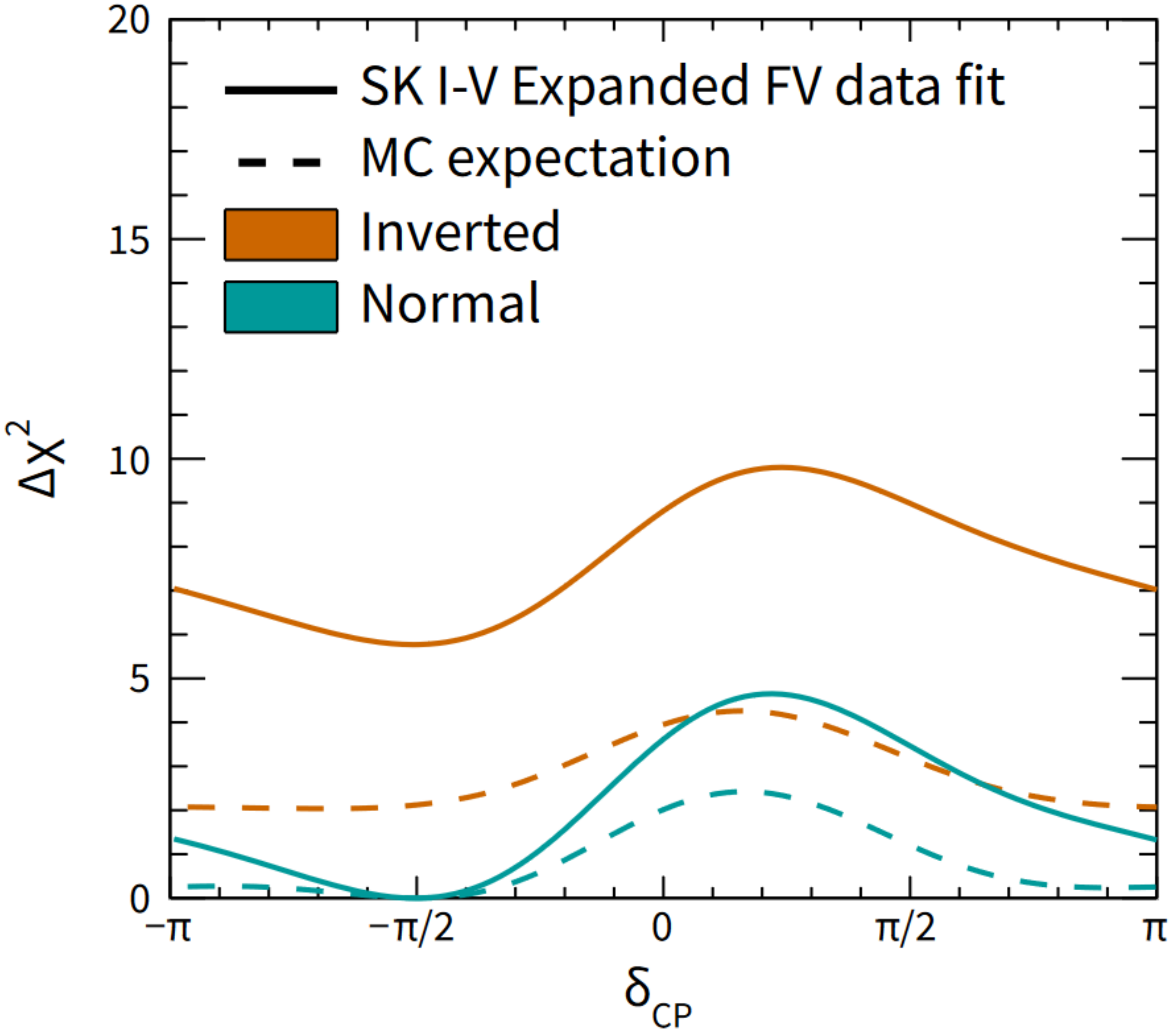


Inv. hierarchy: ν ←→ anti-ν

Mass ordering and CP violation measurements @Neutrino 2022

Super-K atmospheric

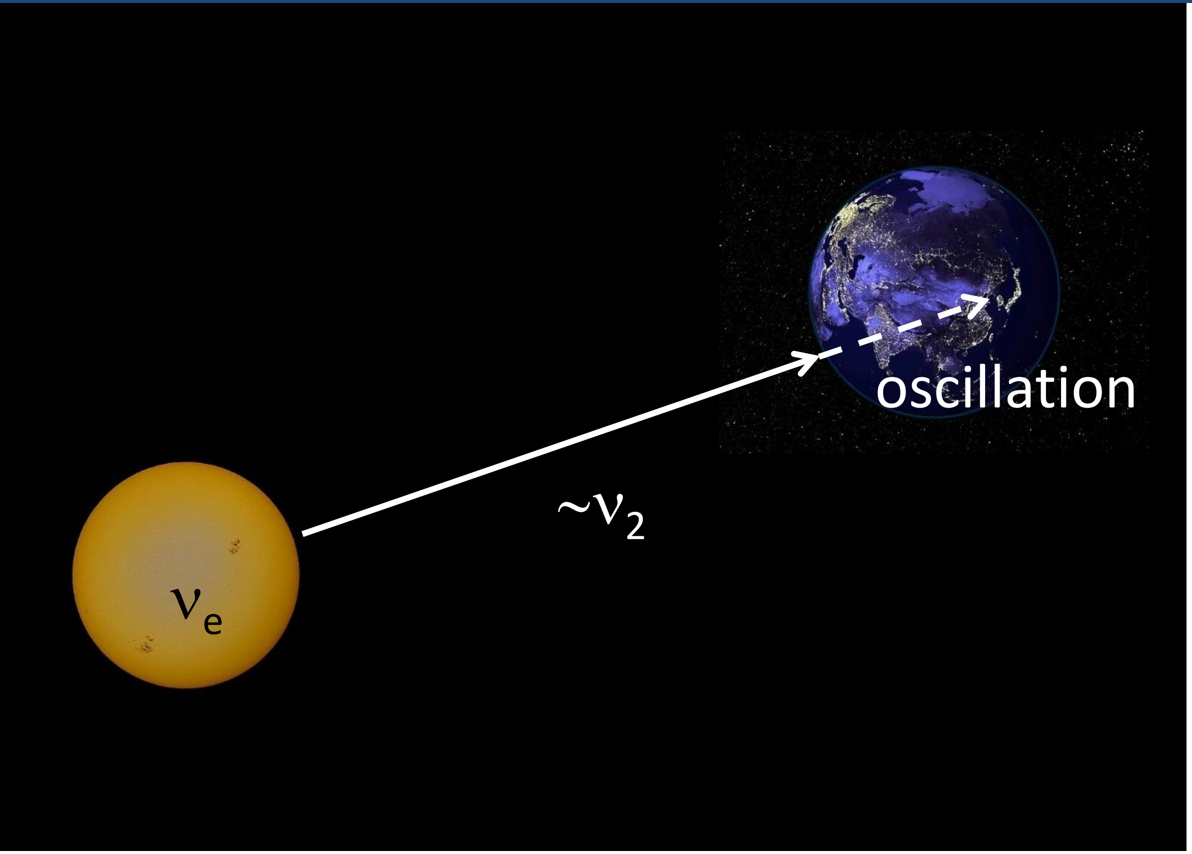
Linyan Wan (Super-K collab) neutrino 2022



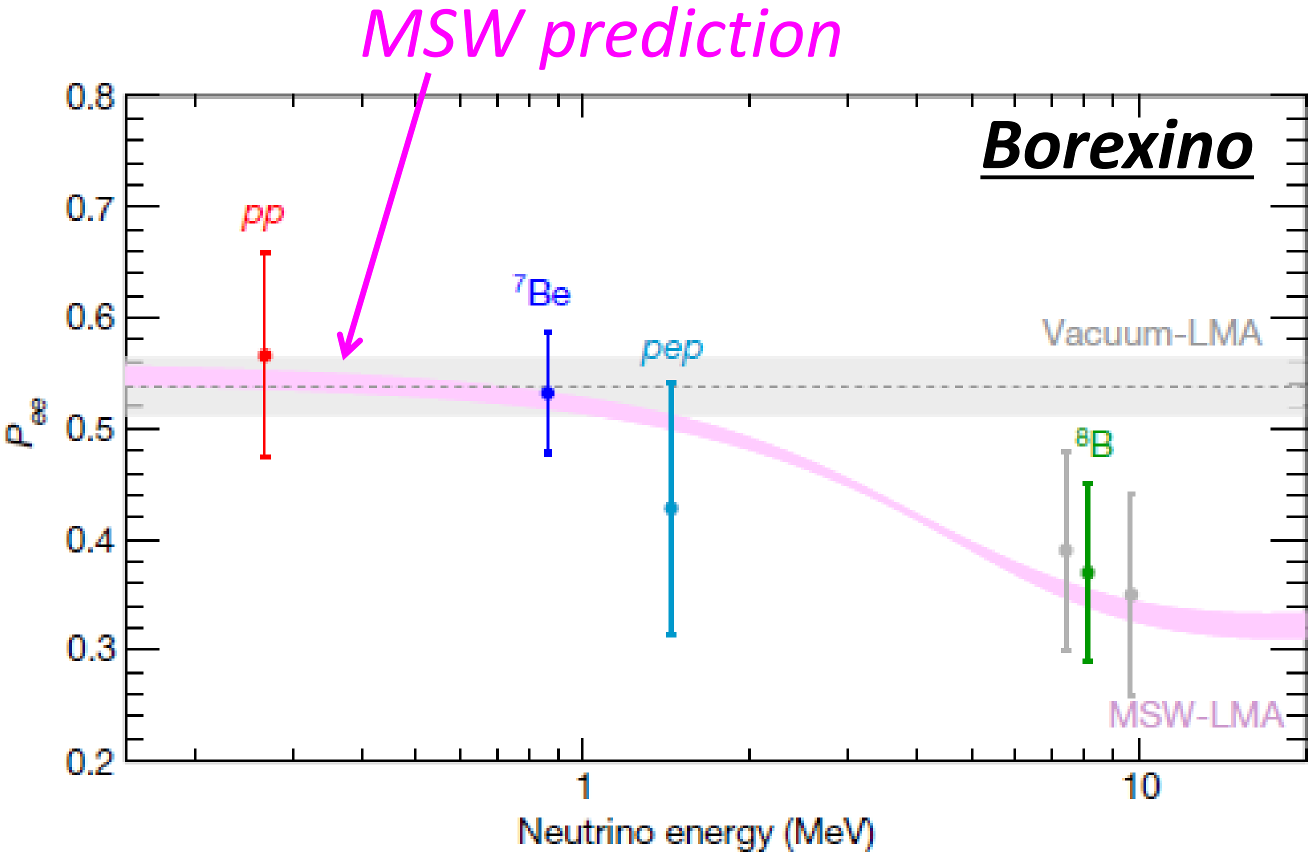
$\Delta\chi^2$ (Inverted-Normal) = 5.8
(larger than expected…)
and
Some preferred δ_{CP} range
(around $\delta_{CP} = -\pi/2$)

(By combining with T2K the result is more impressive.)

Solar neutrino oscillations: further confirmation of the MSW effect



Borexino, PRL 101, 091302 (2008), PRD 82 (2010) 033006, PRL 108, 051302 (2012), Nature 512, 383 (2014), PRD 89, 112007 (2014), Nature 562 (2018) 7728, 505-510

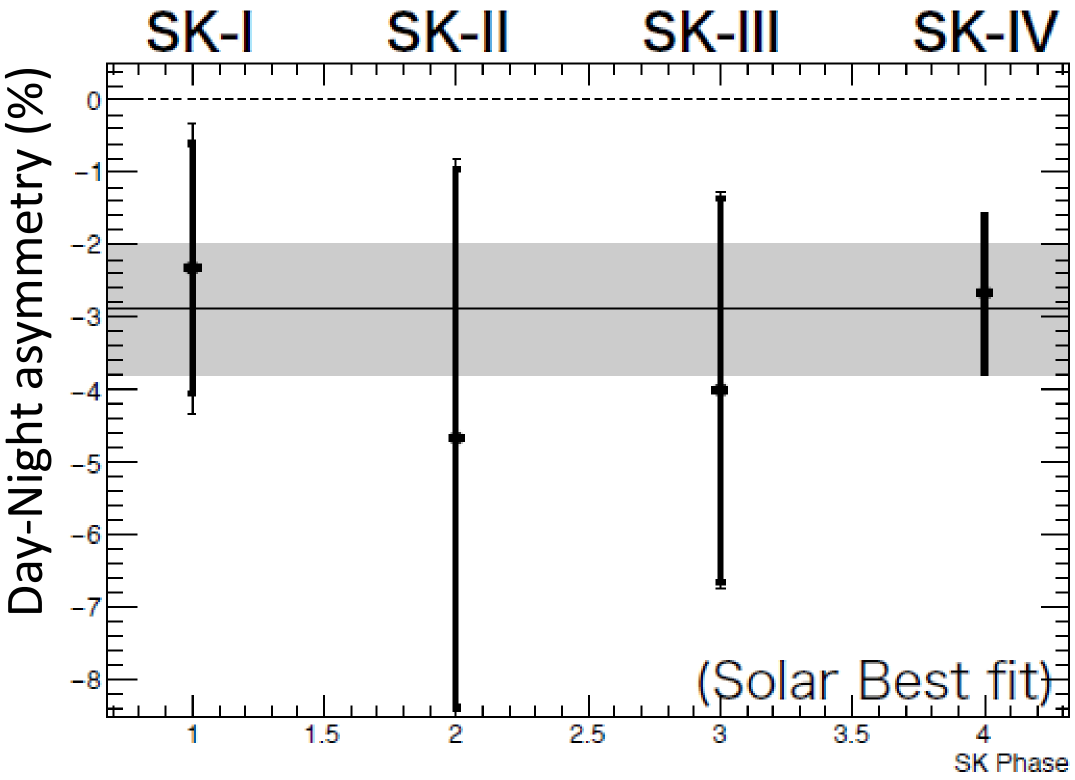


Oscillations (in matter) occur in the Earth ➔ day-night flux difference (night flux higher) ➔ Day-night effect should be observed.)

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

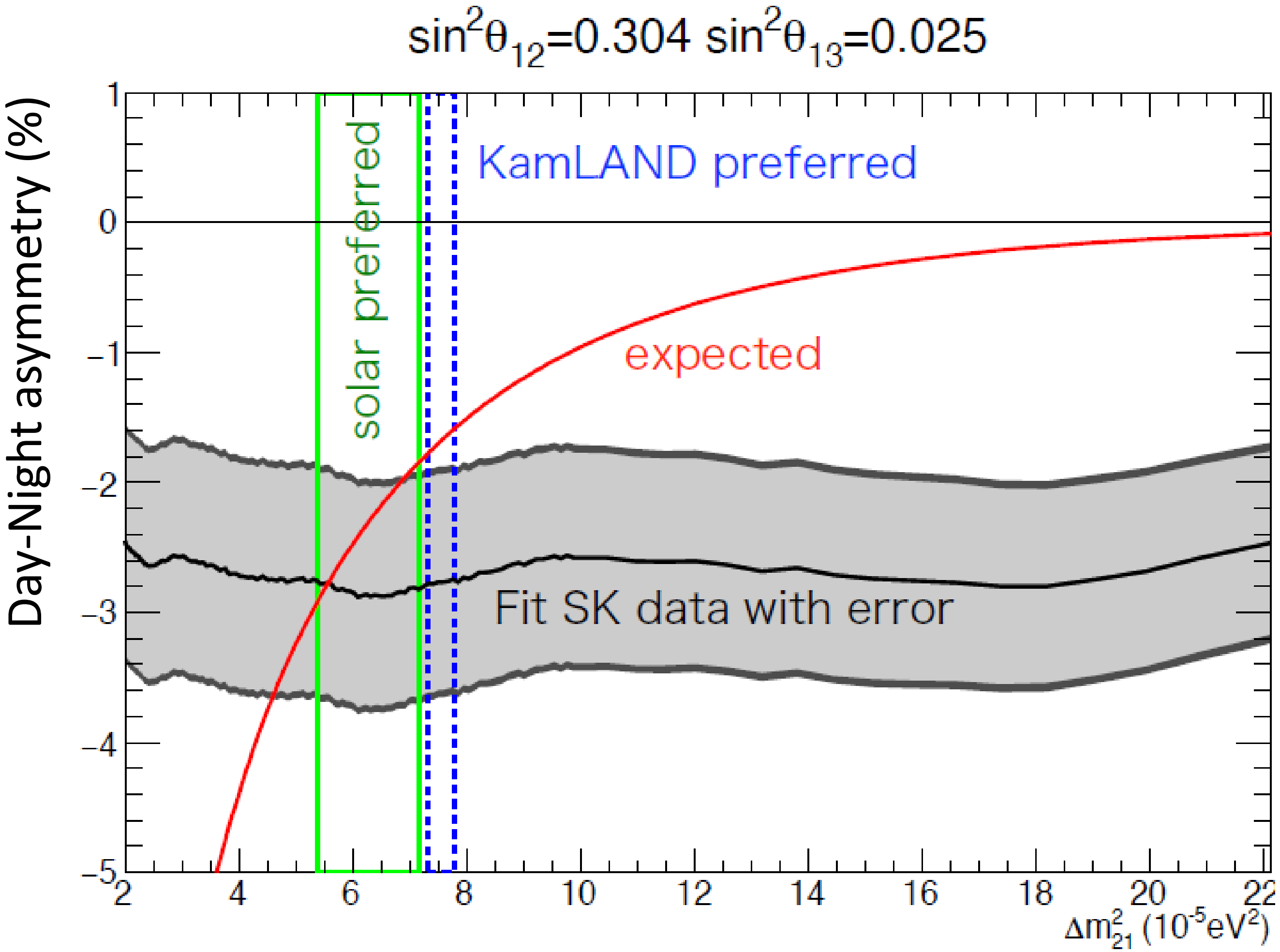
Y. Koshio, talk at Neutrino 2022



Significance of D/N asymmetry:

3.2σ for Solar Best fit

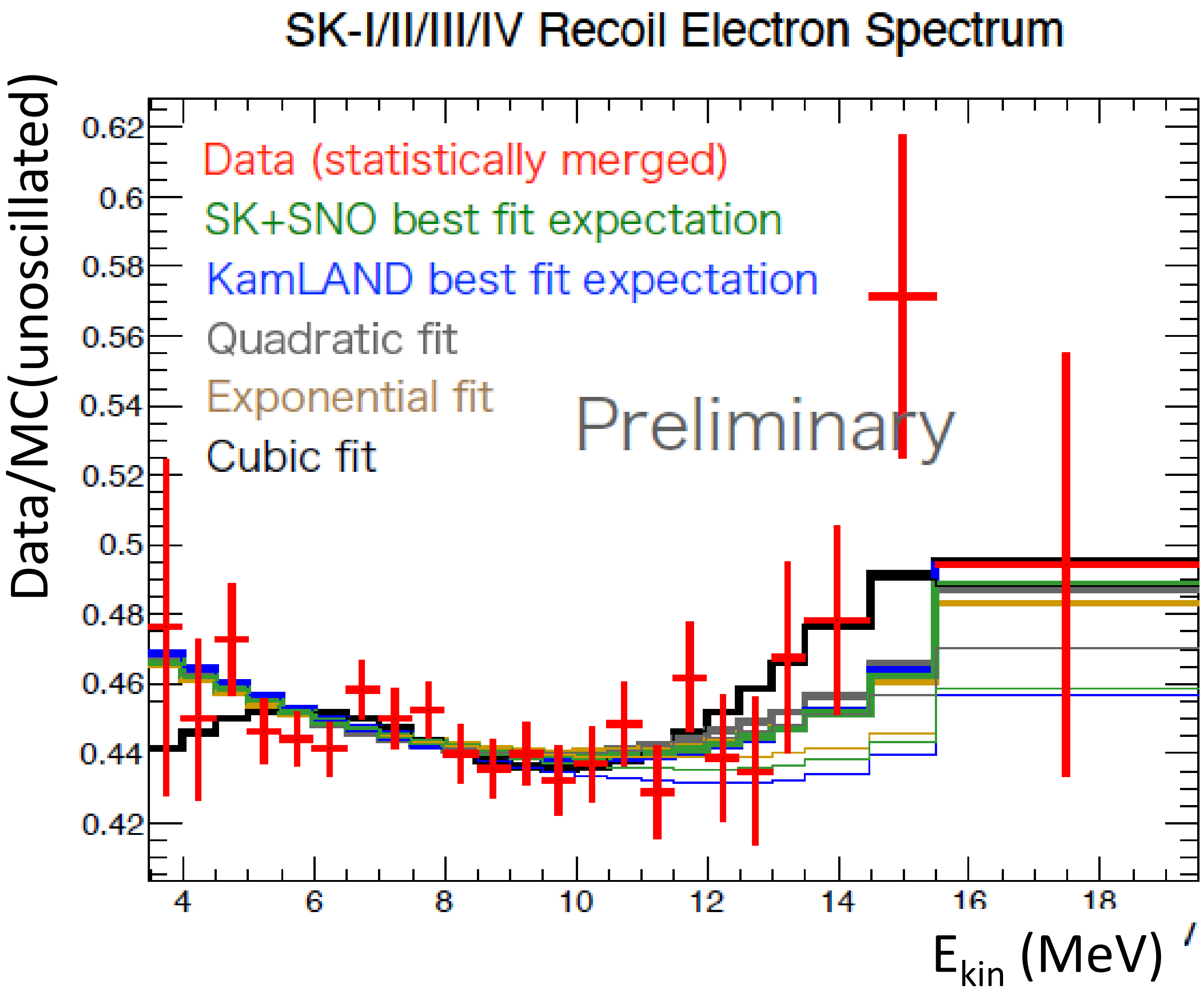
3.1σ for Global Best fit



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

Precise solar neutrino measurements: spectrum

Y. Koshio, talk at Neutrino 2022

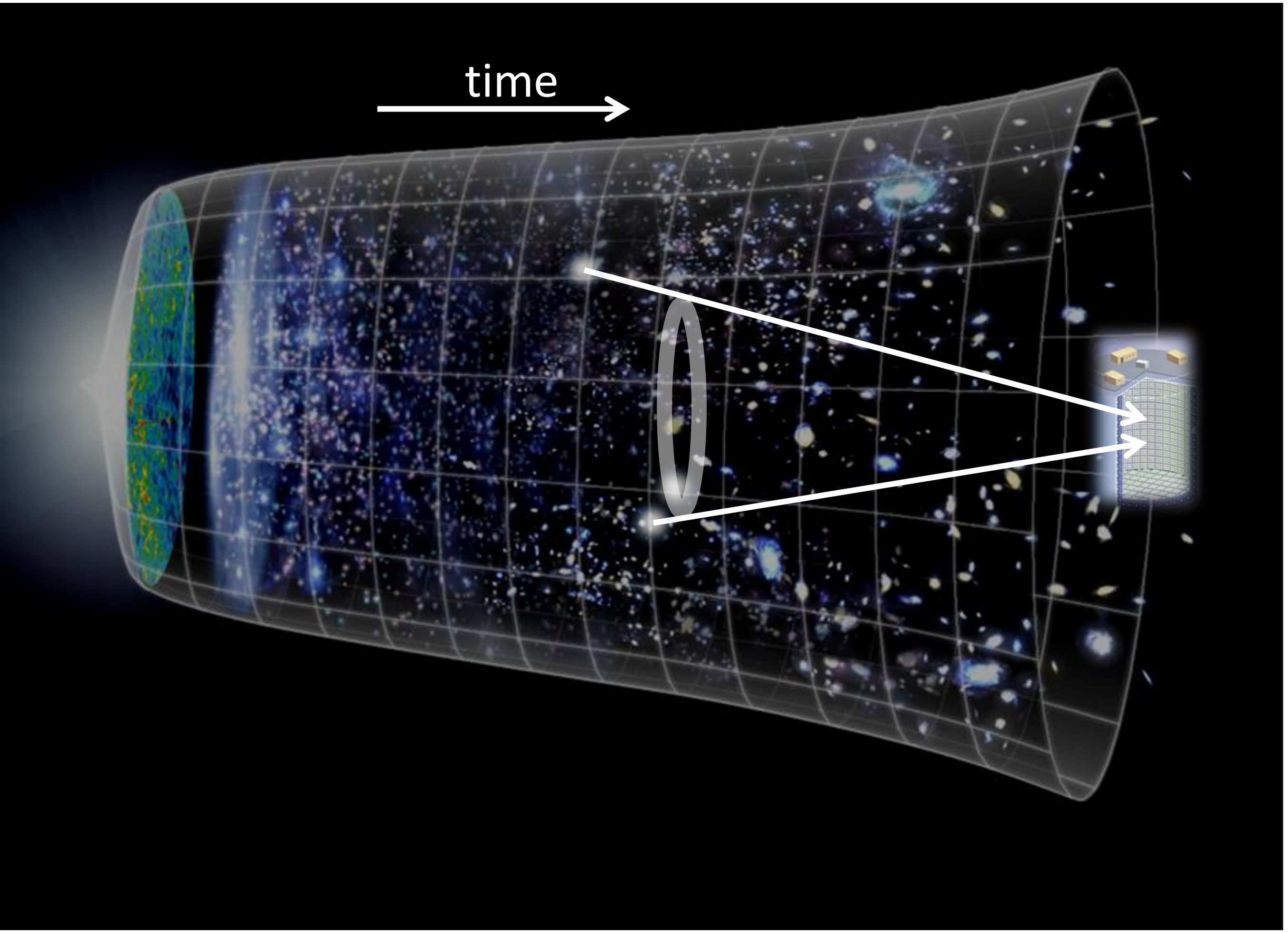


The data (finally) slightly
favor the up-turn!
(More data needed.)

Future

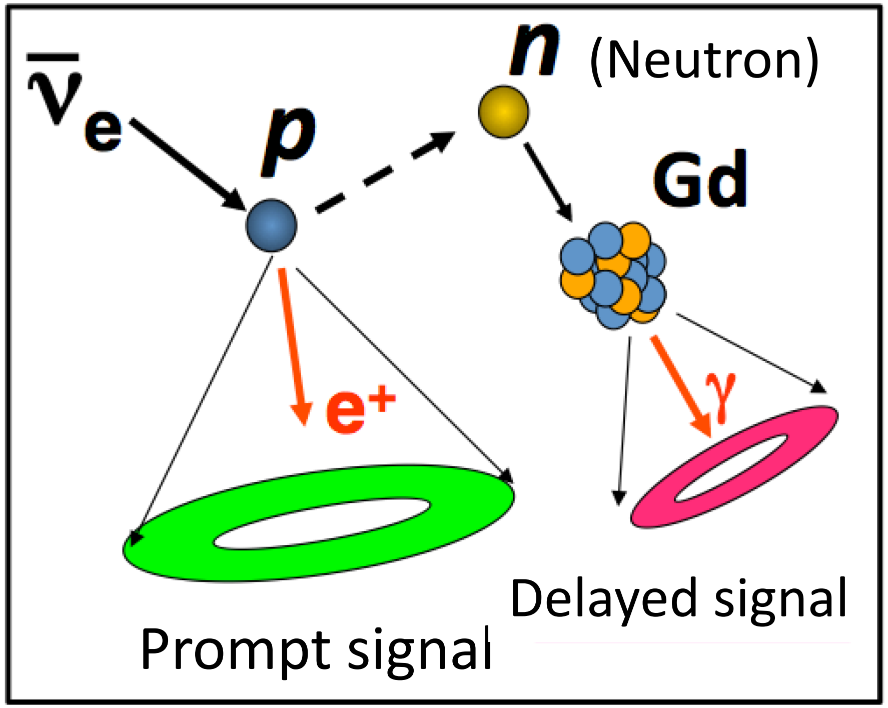
Super-Kamiokande upgrade (SK-Gd)

Diffuse Supernova Neutrino Background (DSNB)



Signal: anti-ν_e + $p \rightarrow e^+ + n$

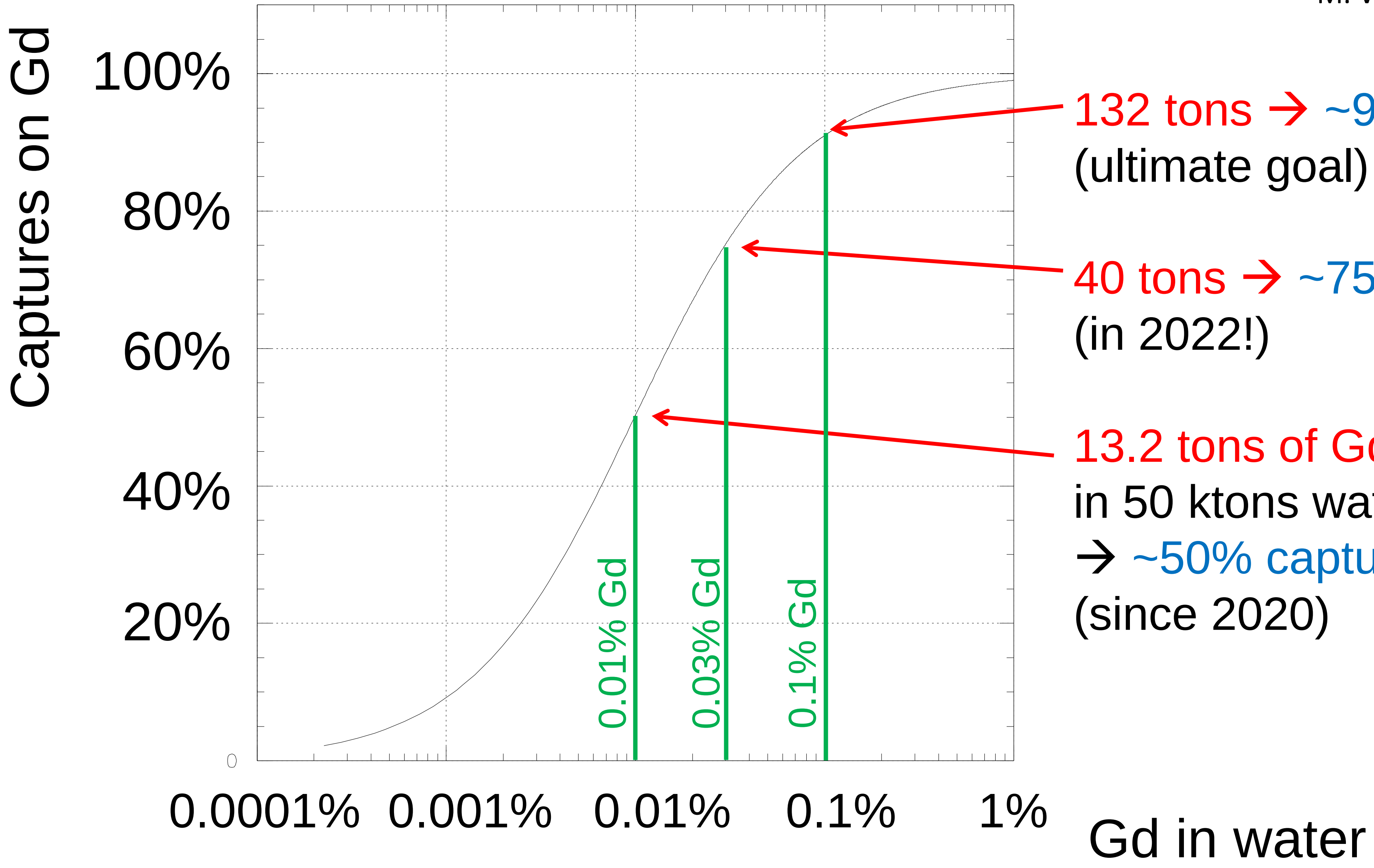
Idea: coincidence of prompt (e^+) and delayed (n) signals to reduce the non-anti-ν_e events.



J. Beacom and M. Vagins, PRL 93 (2004) 171101

Neutron capture efficiency

M. Vagins, talk at Neutrino 2022



132 tons → ~90%
(ultimate goal)

40 tons → ~75%
(in 2022!)

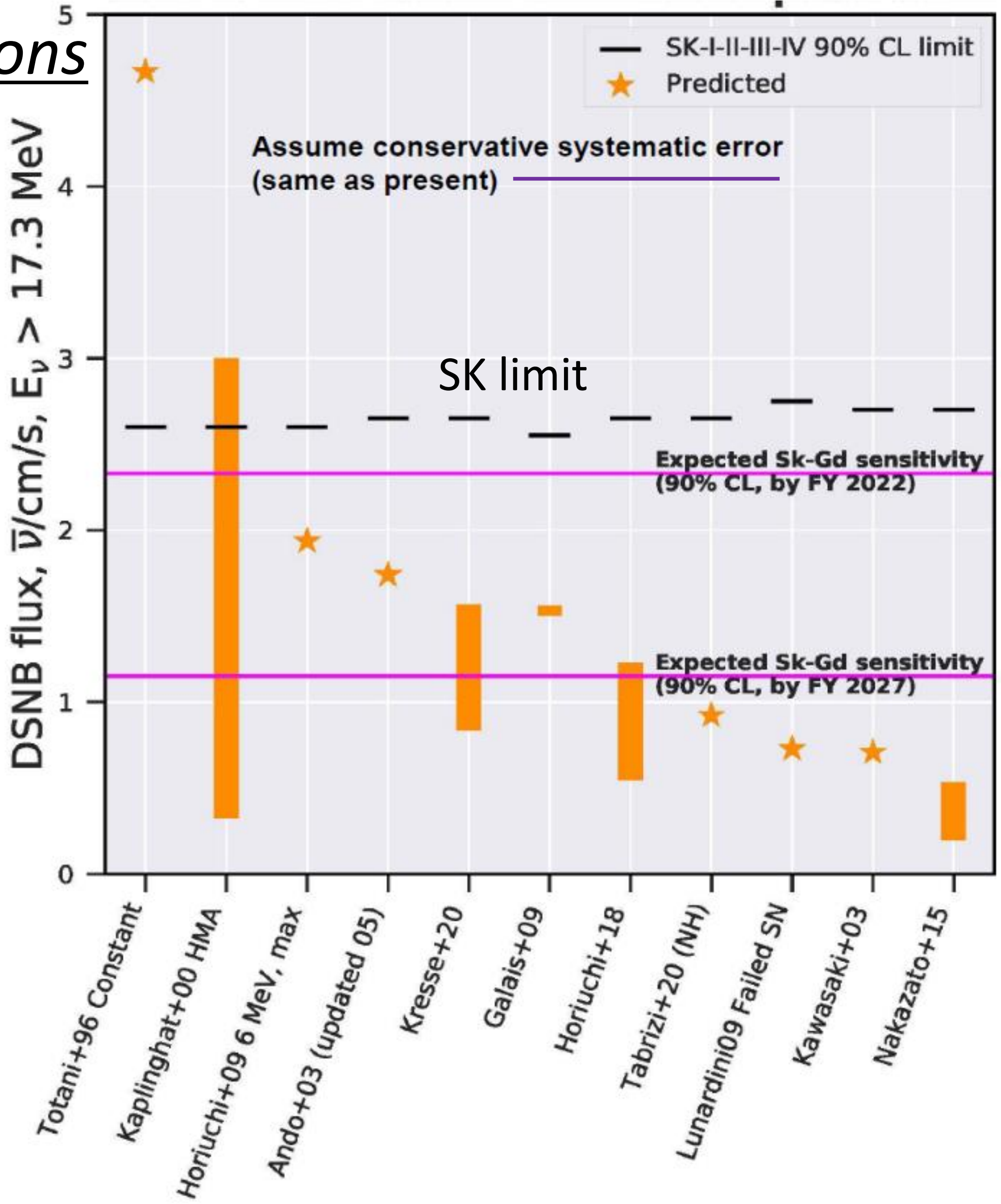
13.2 tons of $Gd_2(SO_4)_3 {}^* 8H_2O$
in 50 ktons water
→ ~50% capture on gadolinium
(since 2020)

DSNB: Predictions and SK-Gd sensitivity

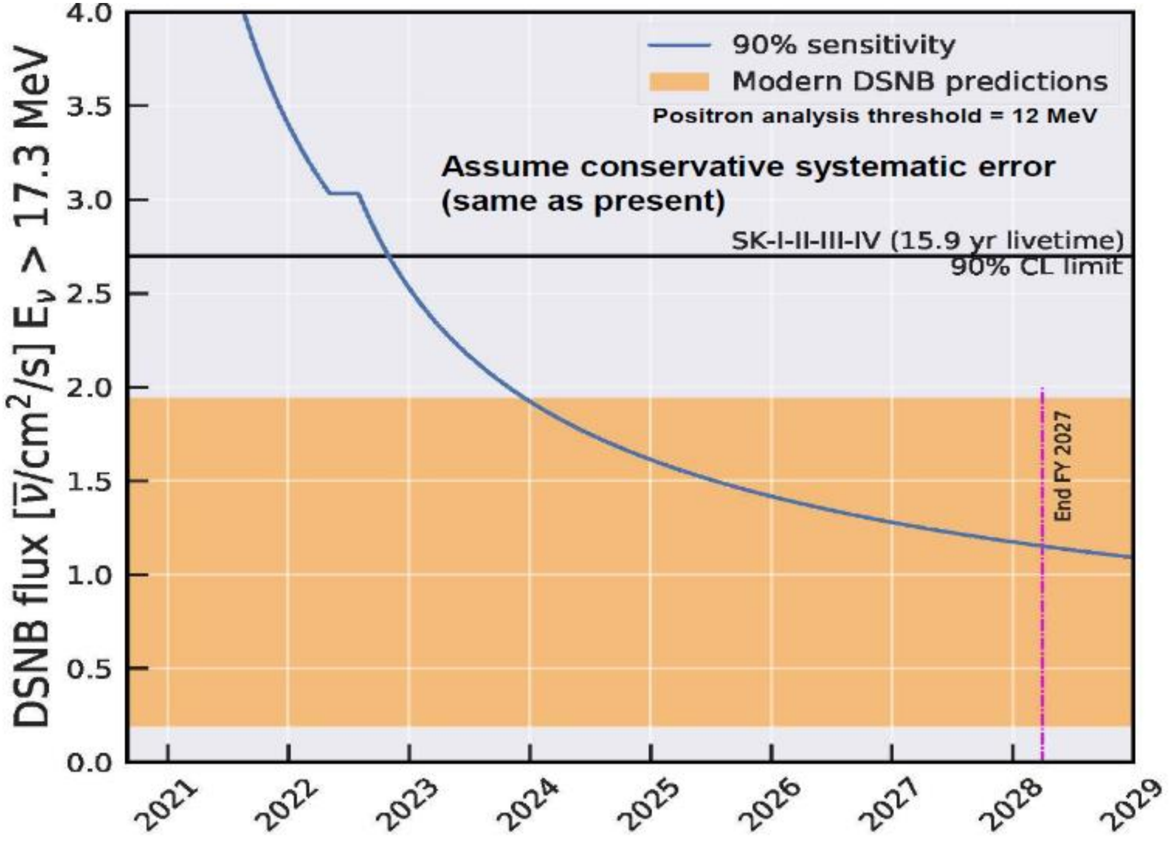
SK, PRD 104, 122002 (2021)

Y. Takeuchi, talk at NOW2022

Predictions

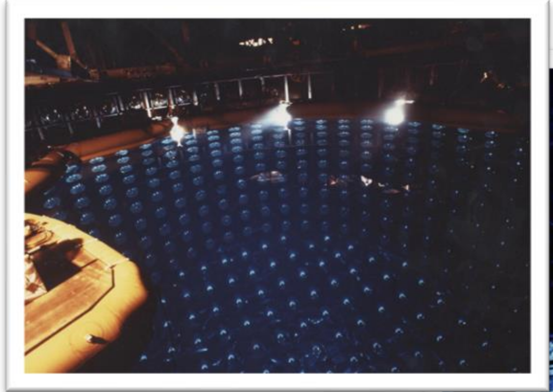


Expected SK-Gd sensitivity on DSNB



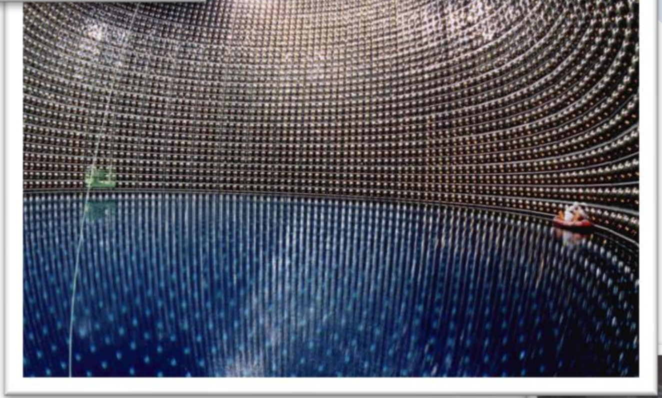
SK-Gd will test several predictions by the end of JFY 2027.

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



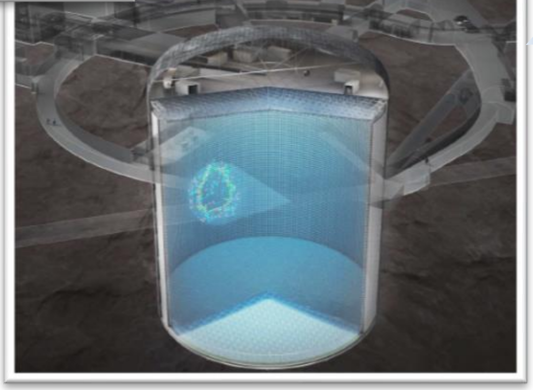
Kamiokande & IMB

- *Neutrinos from SN1987A*
- *Atmospheric neutrino deficit*
- *Solar neutrino (Kam)*



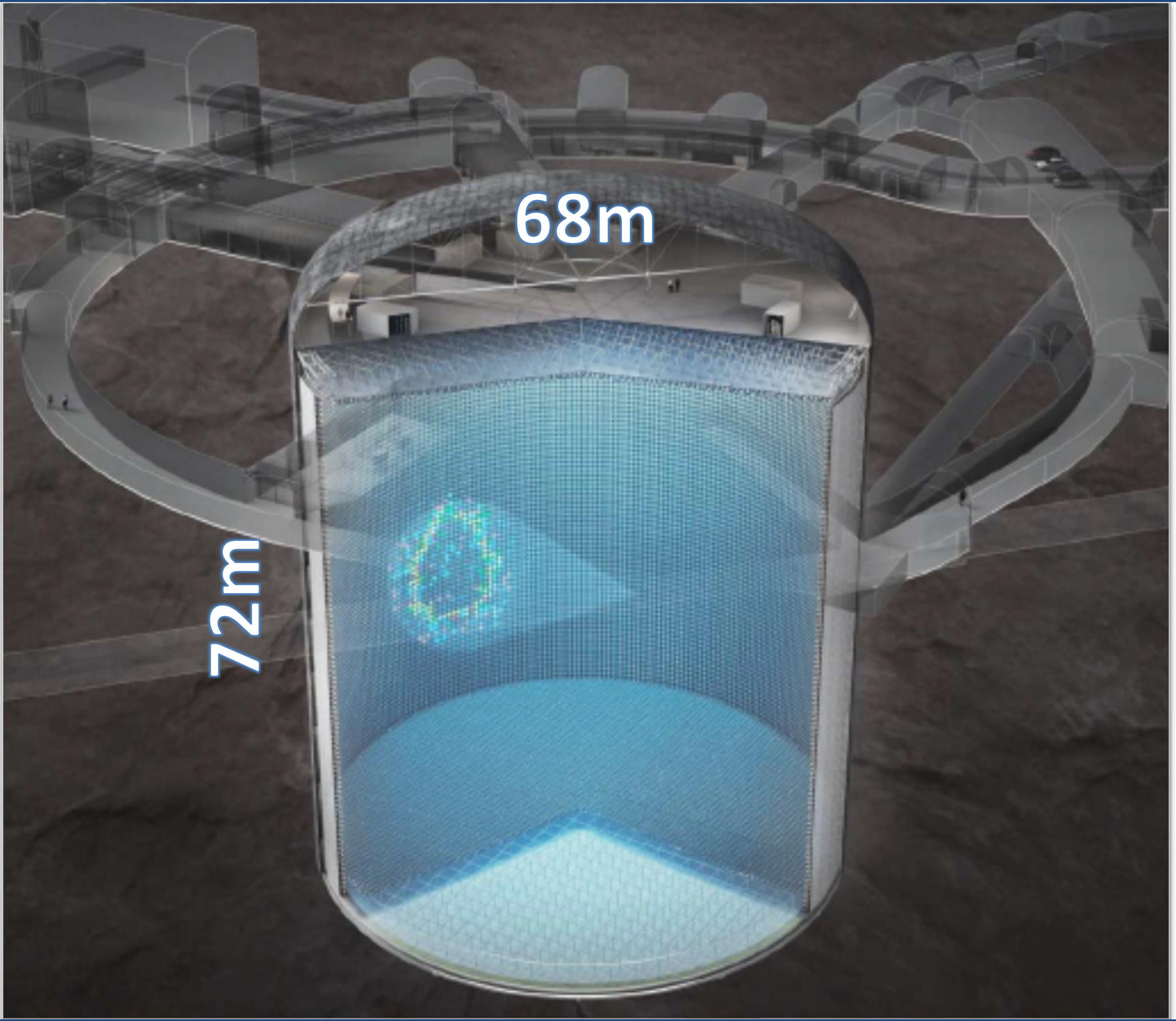
Super-K

- *Atmospheric neutrino oscillation*
- *Solar neutrino oscillation with SNO*
- *Far detector for K2K and T2K*



Hyper-K

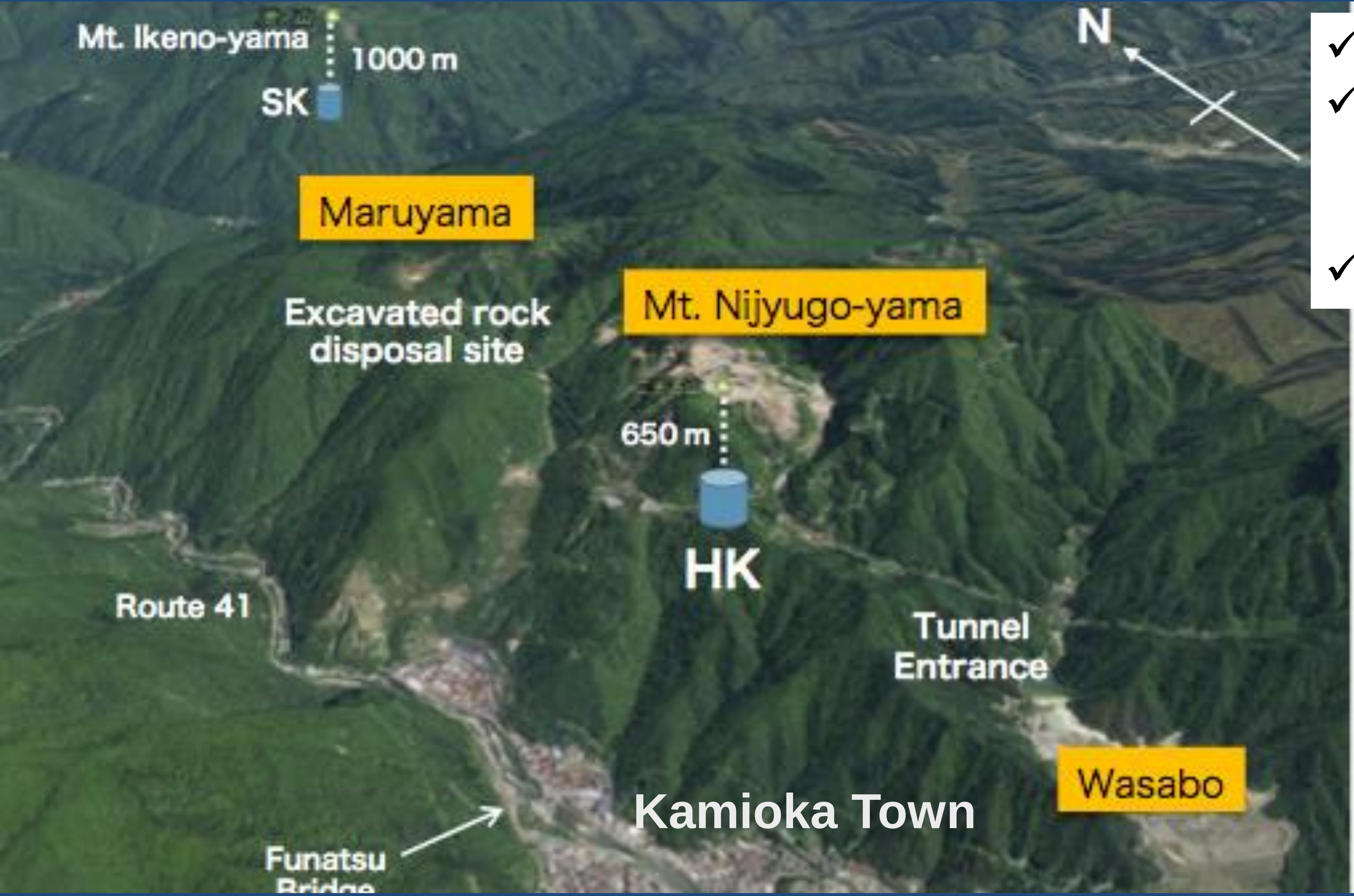
Hyper-K



- About 8 times larger (in the fiducial mass) than Super-K.
- Many important research topics in neutrino physics and astrophysics.
- The construction started in 2020.
- The experiment will start in ~2027!

Hyper-Kamiokande collaboration:
~500 members from 20 countries.

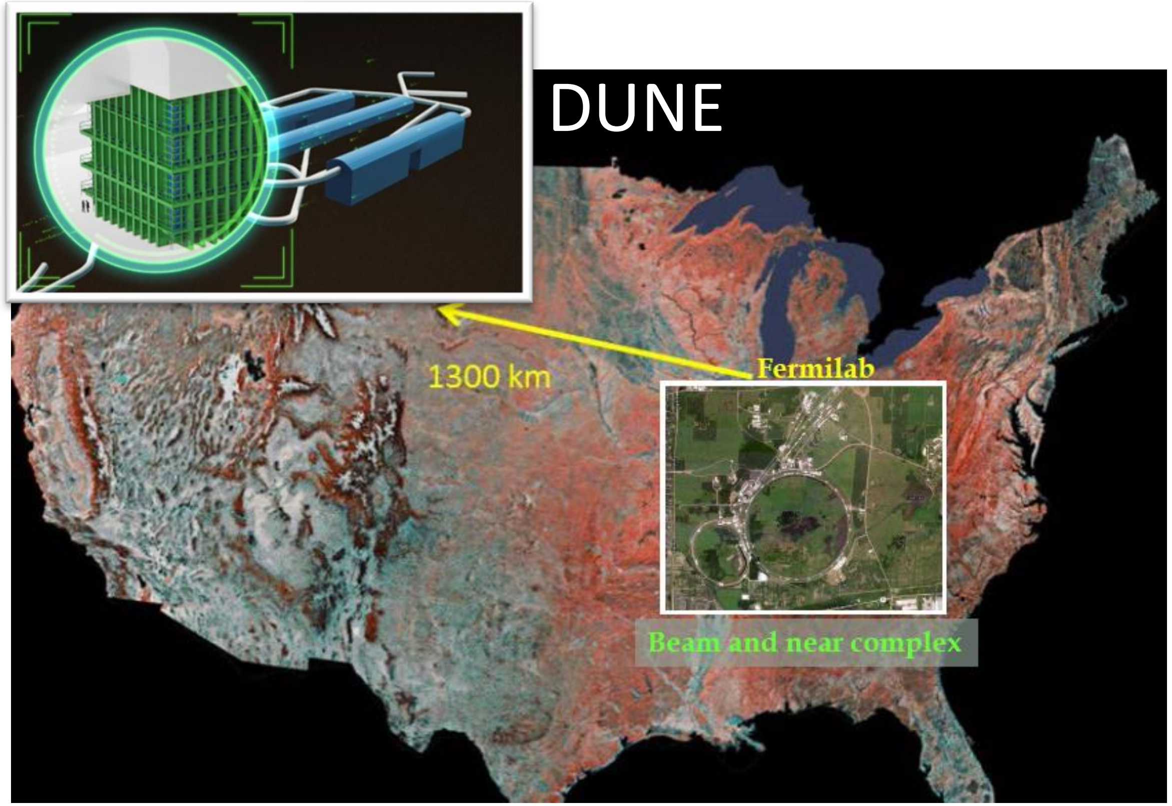
Hyper-K location

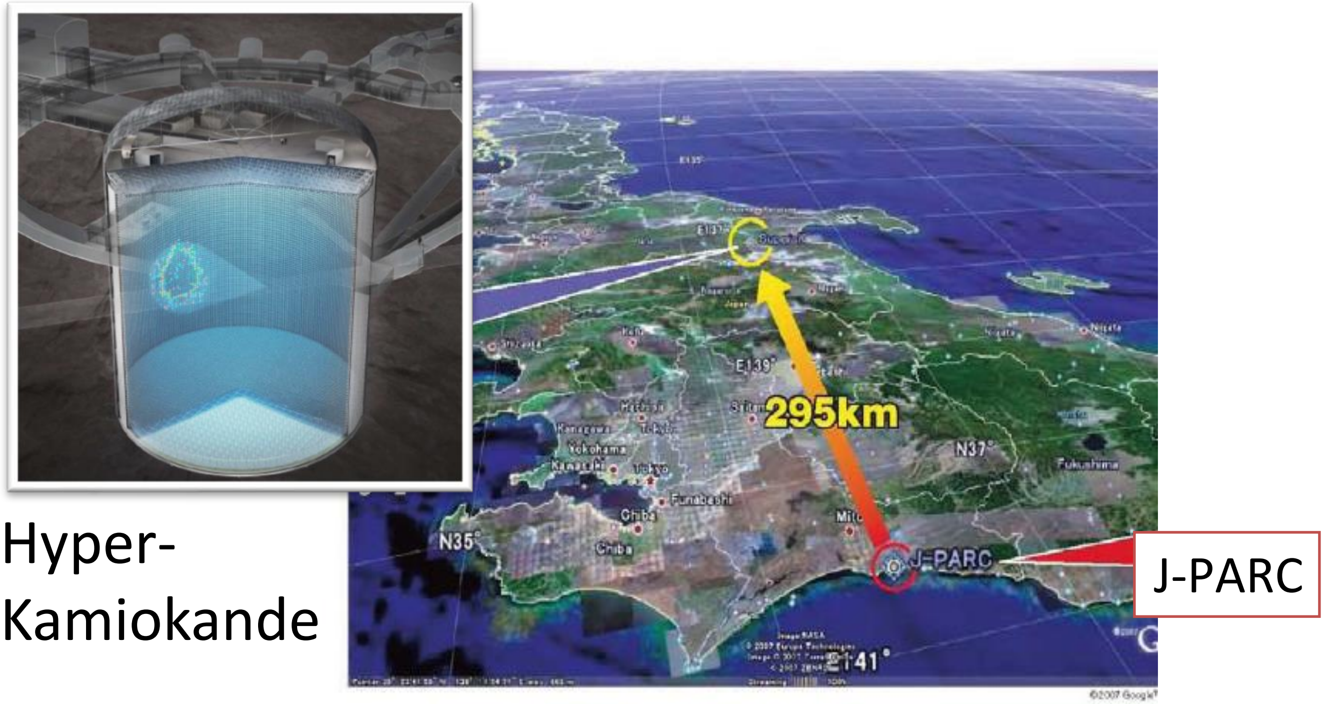


- ✓ ~8km south of Super-K.
- ✓ 295km from J-PARC and 2.5 deg. Off axis beam (same as Super-K)
- ✓ 650 m rock overburden

CP violation

- ✓ We would like to know if neutrinos are related to the origin of the matter in the Universe.
- ✓ We would like to observe if neutrino oscillations of neutrinos and those of anti-neutrinos are different. ➔ We need the next generation long baseline experiments with much higher performance neutrino detectors.





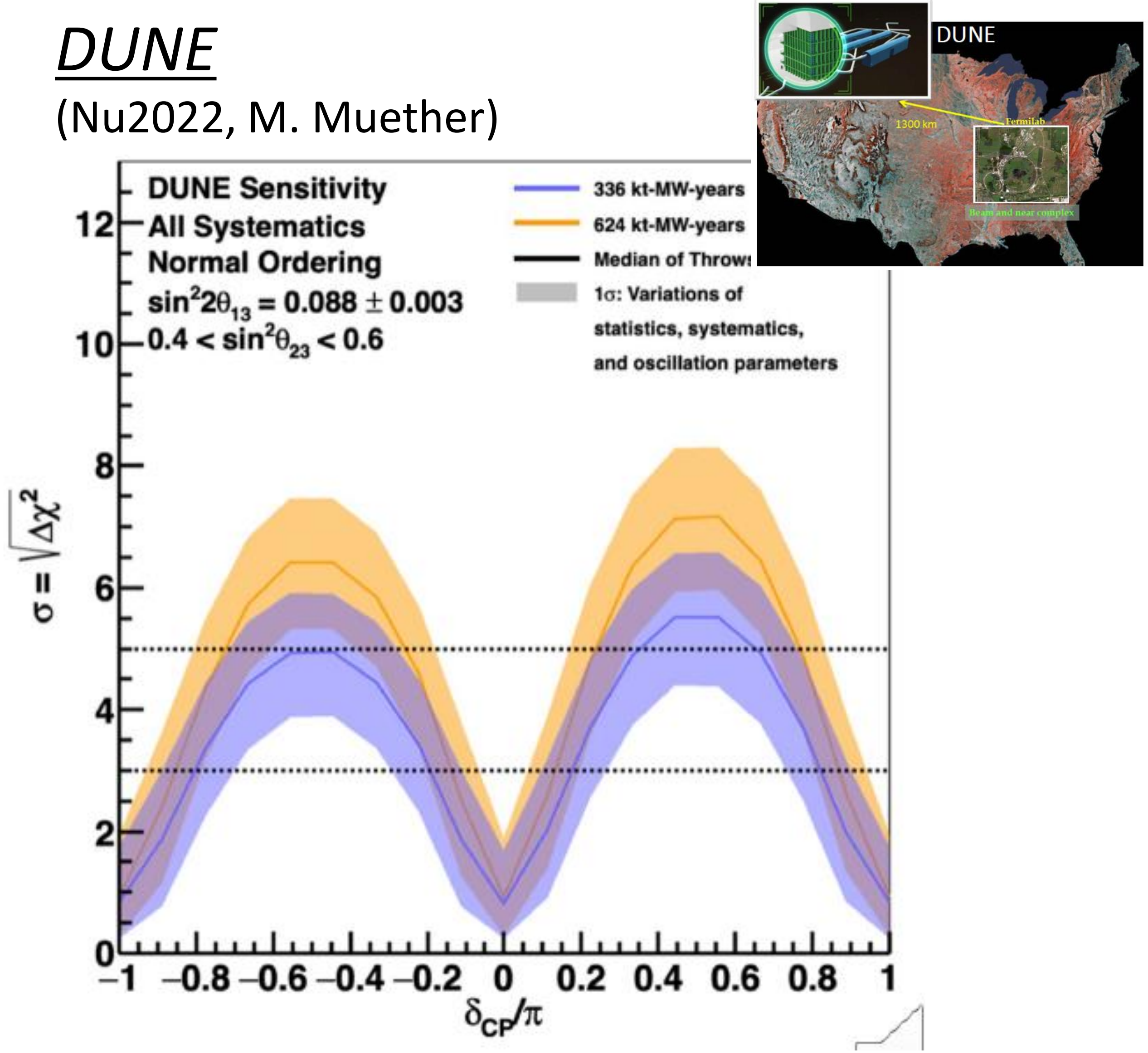
Hyper-Kamiokande

(Several other possibilities…)

CP violation sensitivity

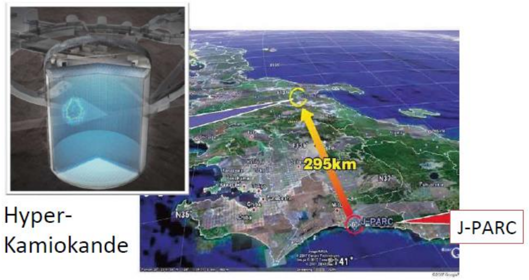
DUNE

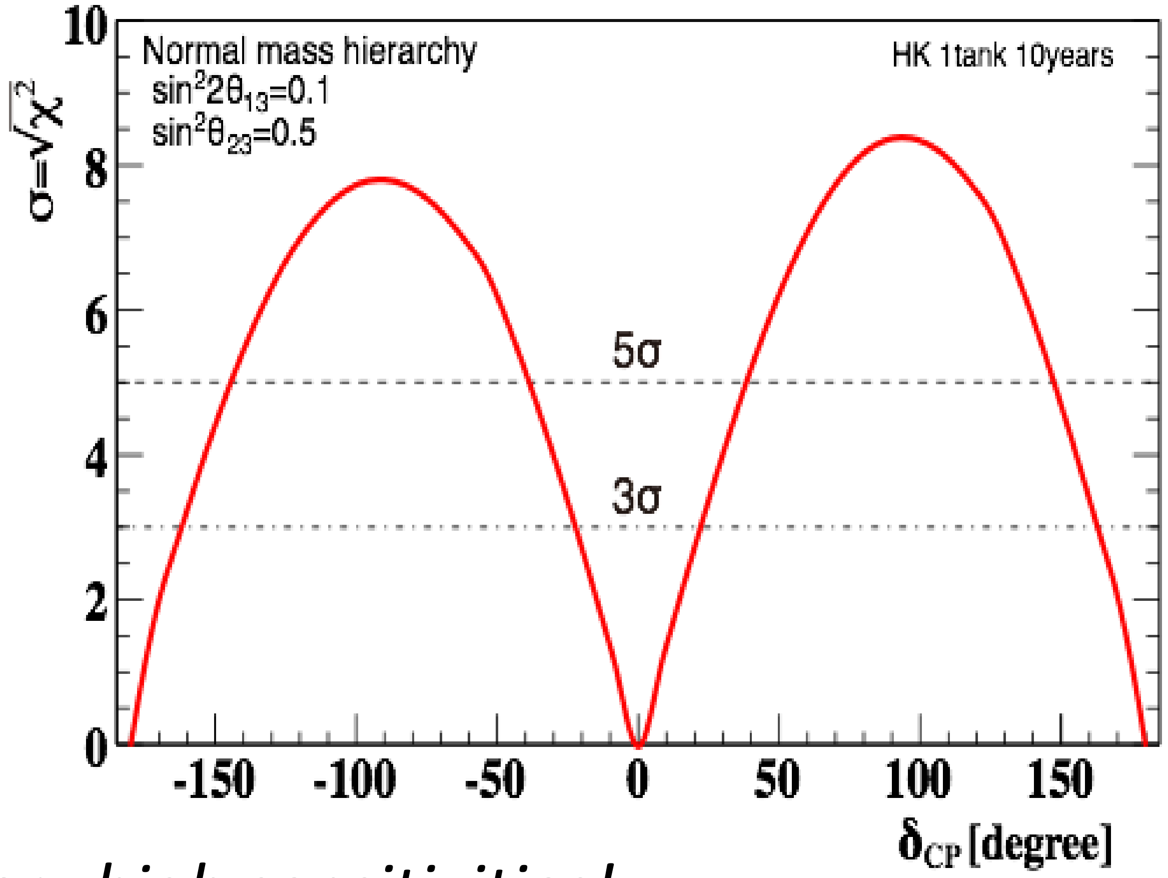
(Nu2022, M. Muether)



Hyper-K

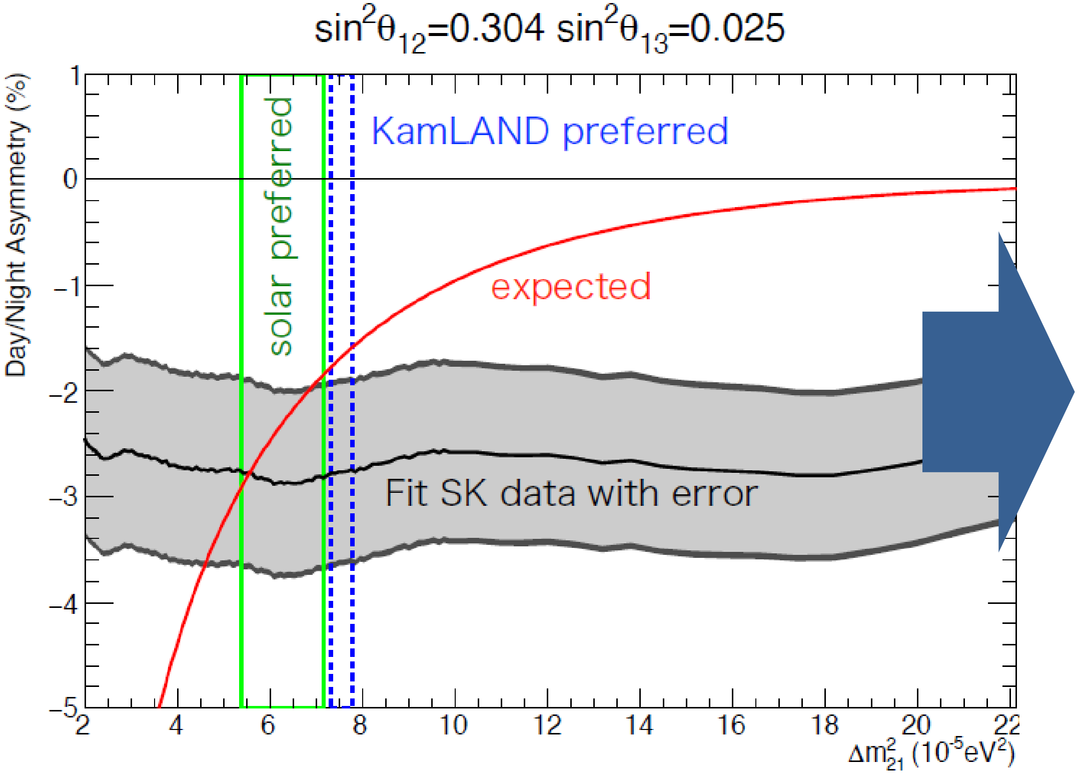
(Hyper-K design report arXiv: 1805.04163)





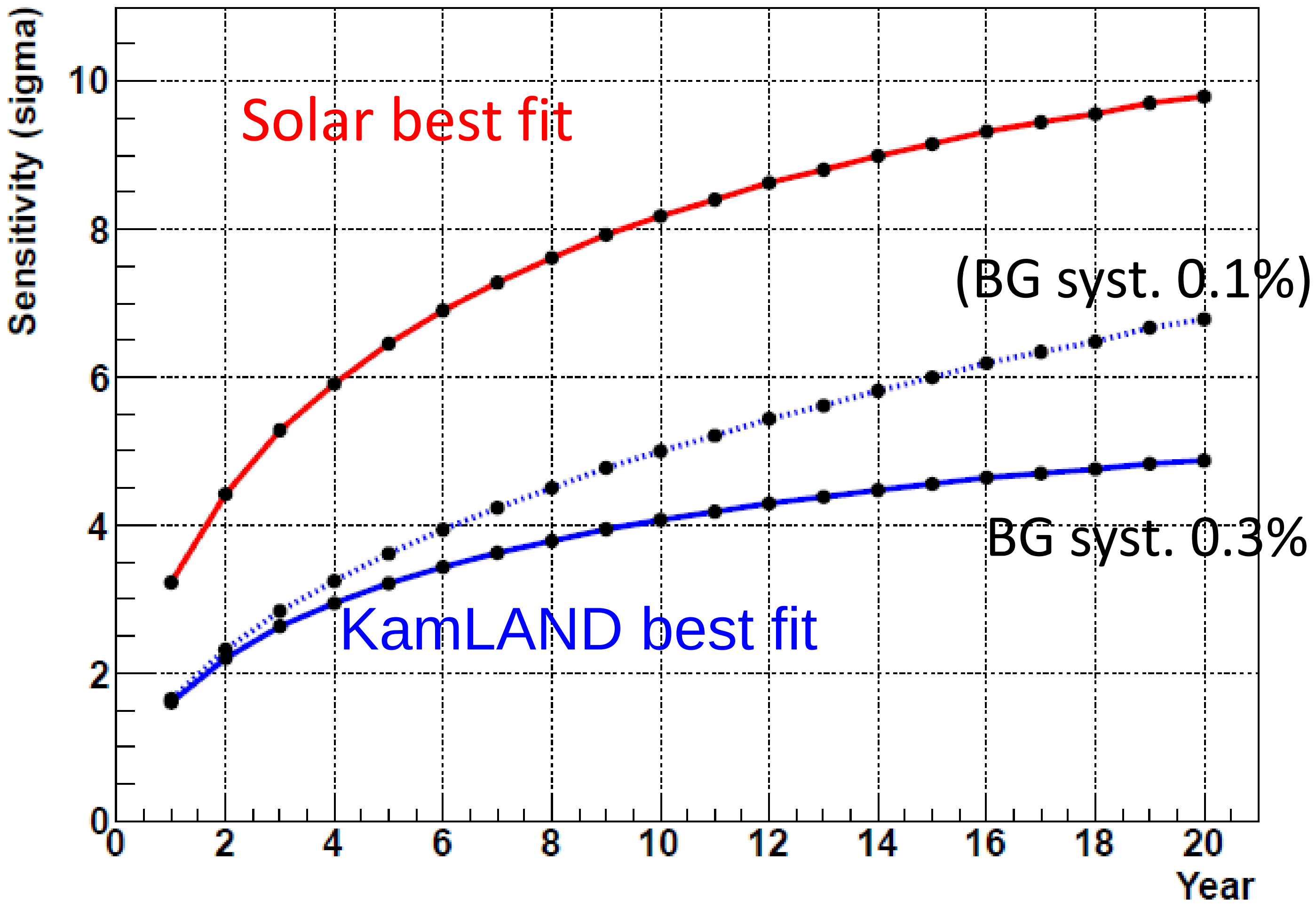
➔ *Both experiments have very high sensitivities!*

Hyper-K solar neutrino measurements



Day-night asymmetry sensitivity

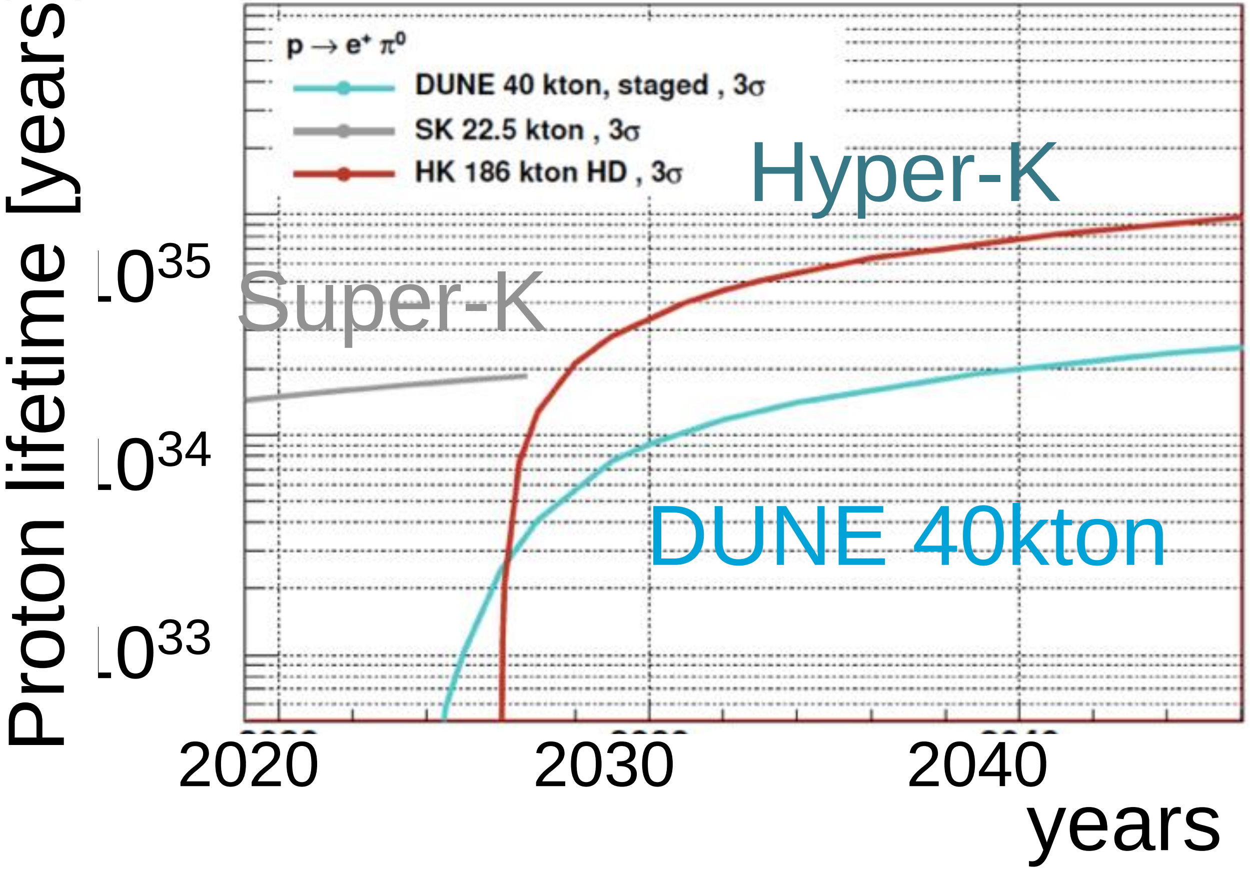
(From no Day-Night asymmetry)



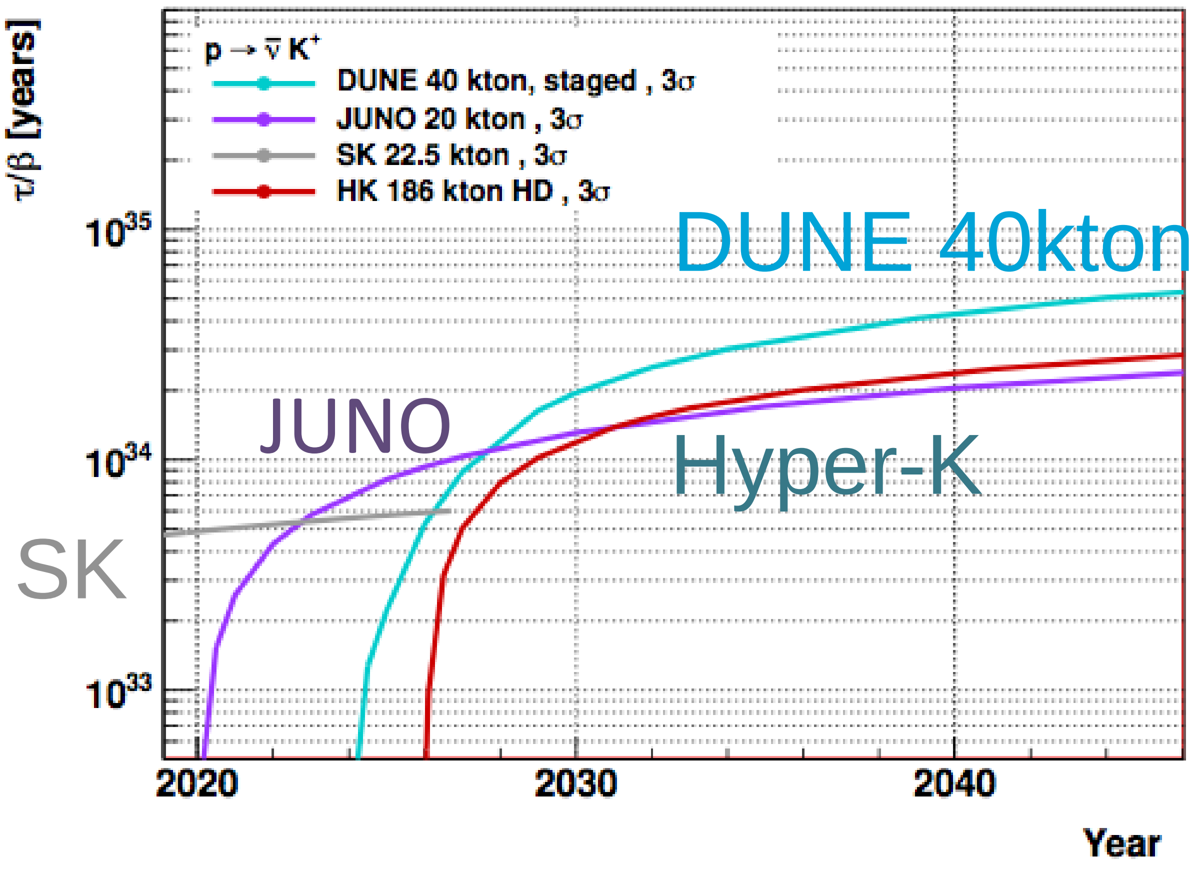
Proton decay sensitivities

DUNE arXiv:1601.05471
HK arXiv:1805.04163v1
JUNO arXiv:1507.05613

$p \to e^+\pi^0$ 3σ discovery



$p \to \nu K^+$ 3σ discovery

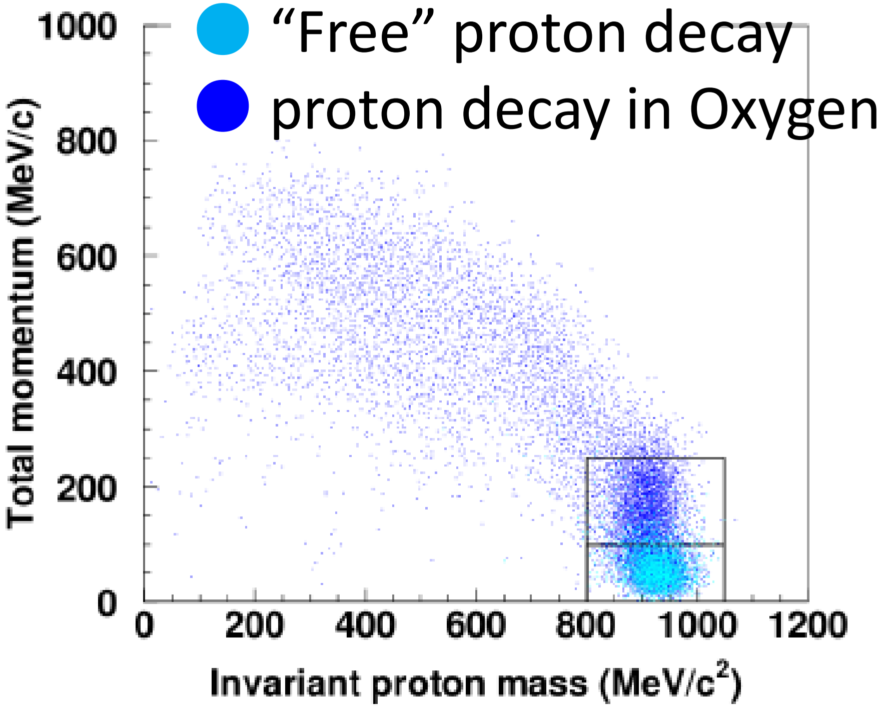


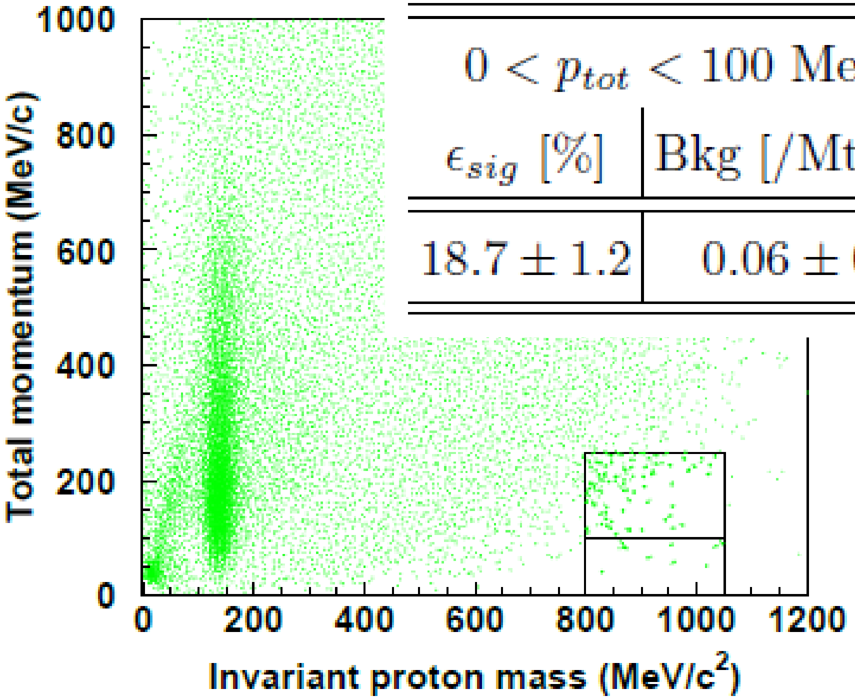
3σ discovery potential, if $\tau_p < 10^{35}$ years ($e\pi^0$) or $< 5*10^{34}$ years (νk^+)

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

Key plots for confirming p → e π^0

(Hyper-K, arXiv:1805.04163v1)

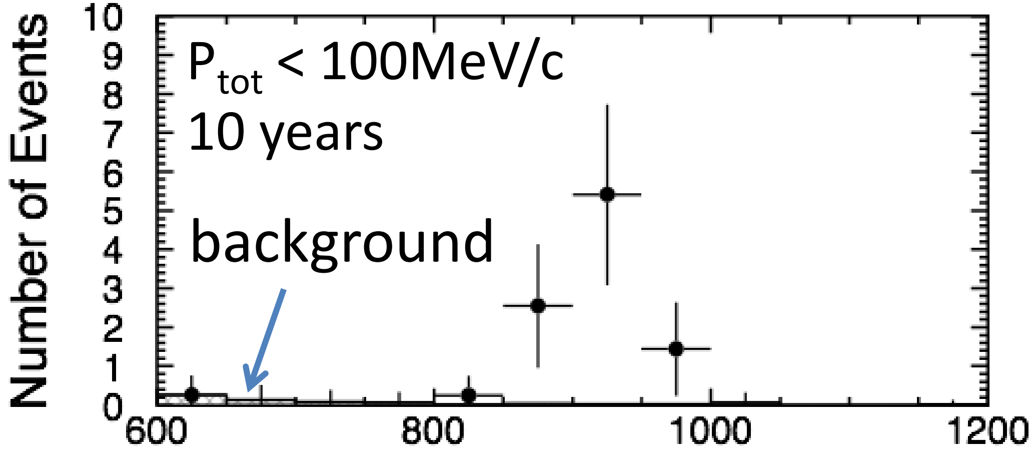




$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

$p \to e^+\pi^0$ Invariant Mass

$\tau_{proton} = 1.7 \times 10^{34}$ years



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

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 more than 25 years since the beginning of the Super-Kamiokande experiment. Super-K is still improving the detector to observe anti-ν_e's from the Diffuse Supernova Neutrino Background.
- Now, Hyper-K is under construction as the successor of Super-Kamiokande.