30 min

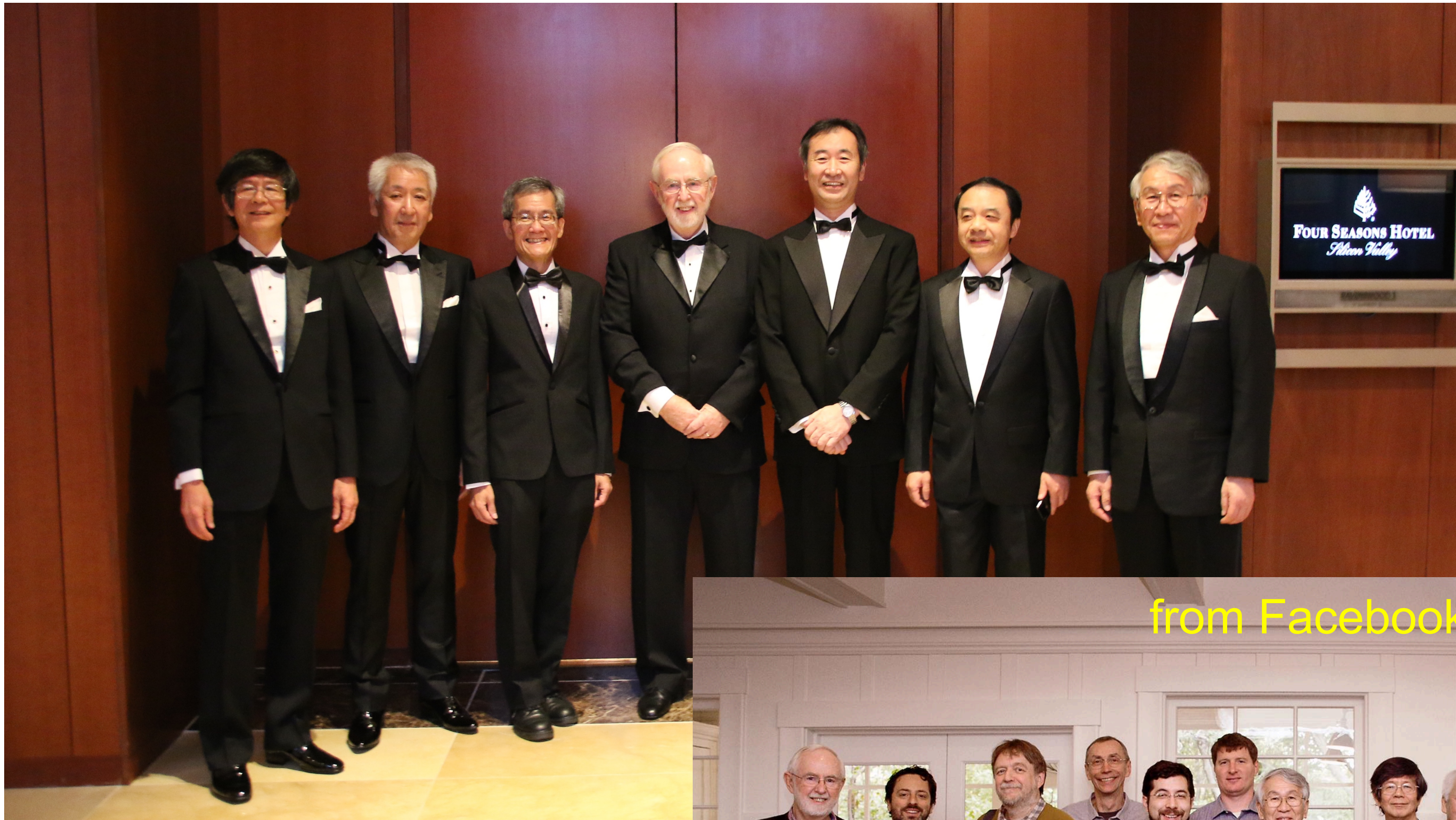
Super-Kamiokande

Y. Suzuki
Kavli Institute for the Physics and Mathematics of the Universe,
The University of Tokyo

2016 Breakthrough Prize

- More than **1300** Laureates,
  - including 7 leaders
    - **T. Kajita, Y. Suzuki, A. MacDonald, A. Suzuki, K. Nishikawa, Y. Wang, K.B. Luk**
  - from 5 experiments
    - **Super-K, SNO, KamLAND, K2K/T2K, Daya Bay**
  - 141 Laureates for Super-Kamiokande from '98 (atmospherics) and 2001 (Solar) papers
- Citation:

  For the fundamental discovery of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics.


Four Seasons Hotel
Silicon Valley

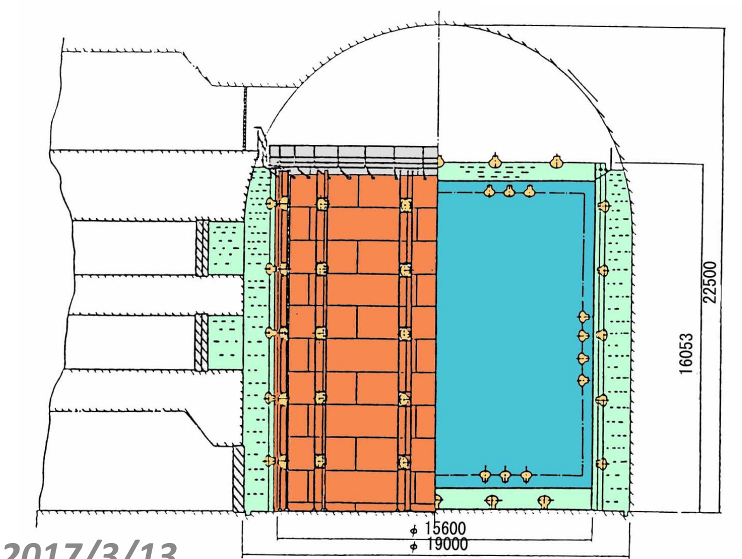

from Facebook of Mark Zuckerberg

Pre-history of Super-Kamiokande

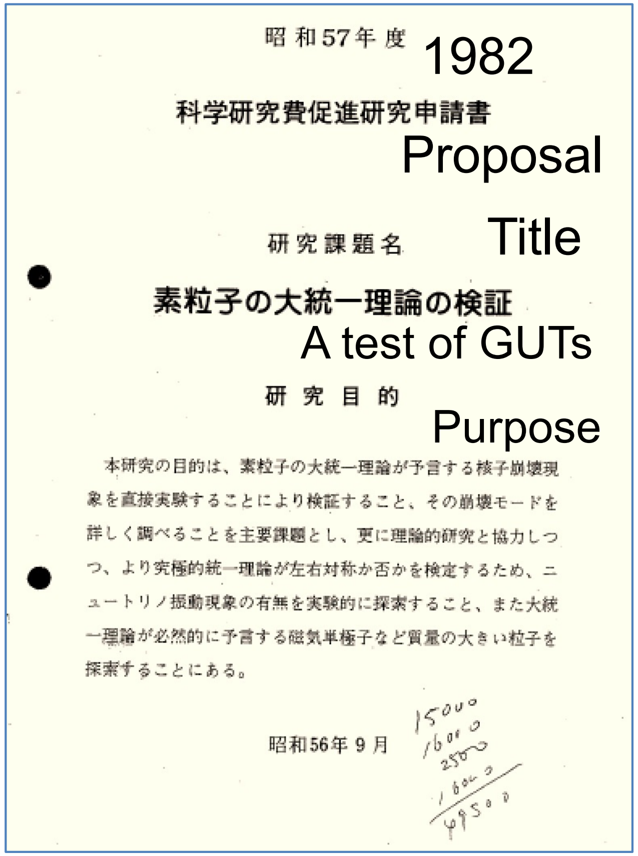
- Super-Kamiokande is a kind of continuation of the Kamiokande (KM) experiment
- **1974**, George and Glashow, SU(5) GUT
  - "It also predicts that the proton decays----but with an unknown and adjustable rate"
- Later papers: Proton decay → $10^{30+/-2}$ years
- Realized 1000 ton detector could reach $\sim 10^{32}$ years that motivated people to look for proton decay in a significant way.
- **1979**: Koshiba and his colleagues proposed 1000 tons water Cherenkov detector (KamiokaNDE)
  - KEK report 79-18

Kamiokande

- **1982**: KamiokaNDE funded [operation:1983-1996]
  - scientific objects in the proposal: proton decay, neutrino oscillation by atmospheric neutrinos, SN neutrino burst.
  - <u>Initially solar neutrino was not strongly mentioned</u>
    - Since they did not expect that the threshold would become low enough to observe solar neutrinos.



Total: 3000 tons
16m high, 15.6m diameter
Inner: 2140 tons
948 20-in PMTs
Fid. 680 tons for solar ν
Photo-coverage: 20%



昭和57年度 1982

科学研究費促進研究申請書 Proposal

研究課題名 Title

素粒子の大統一理論の検証 A test of GUTs

研究目的 Purpose

本研究の目的は、素粒子の大統一理論が予言する核子崩壊現象を直接実験することにより検証すること、その崩壊モードを詳しく調べることを主要課題とし、更に理論的研究と協力しつつ、より究極的統一理論が左右対称か否かを検定するため、ニュートリノ振動現象の有無を実験的に探索すること、また大統一理論が必然的に予言する磁気単極子など質量の大きい粒子を探索することにある。

昭和56年9月

Two Proposals in 1984

- 1983: KM started
  - Observed μ decay electrons down to 15 MeV
    - Realized lowering the threshold to 10 MeV
    - → solar neutrino measurements possible
- 1984: ICOBAN84 (Park City, Maryland): 2 talks

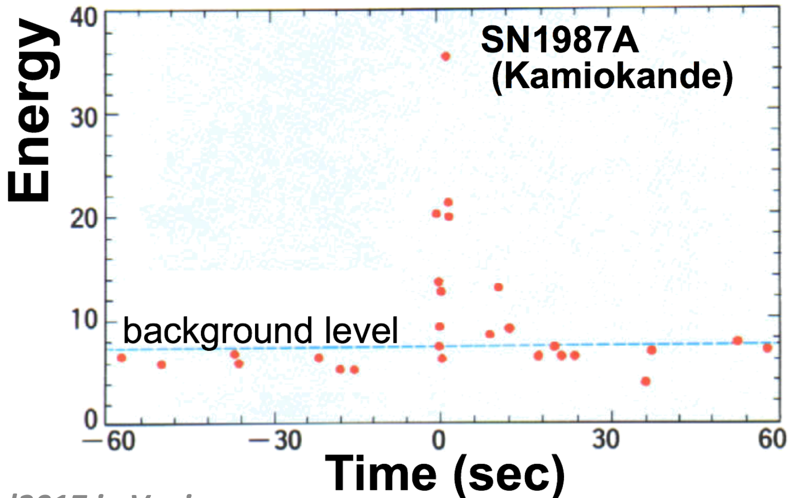
22. **22-kton Water Cherenkov Detector (jack)**
    Kamiokande Collaboration (M. Koshiba for the collaboration). 1985. 17 pp.
23. **Kamioka Nucleon Decay Experiment. (transparencies Only)**
    M. Koshiba (Tokyo U., ICRR & KEK, Tsukuba & Niigata U.) *et al.*. 1985.

  - **Latest results of KM → upgrade plan of KM to measure solar neutrinos (KM-II).**
  - **Proposal of 22.5 kton detector called JACK**
    (Japan America Collaboration at Kamioka)
    Later called Super-Kamiokande !!!

→ Asking new collaborators for both!

Kamiokande-II

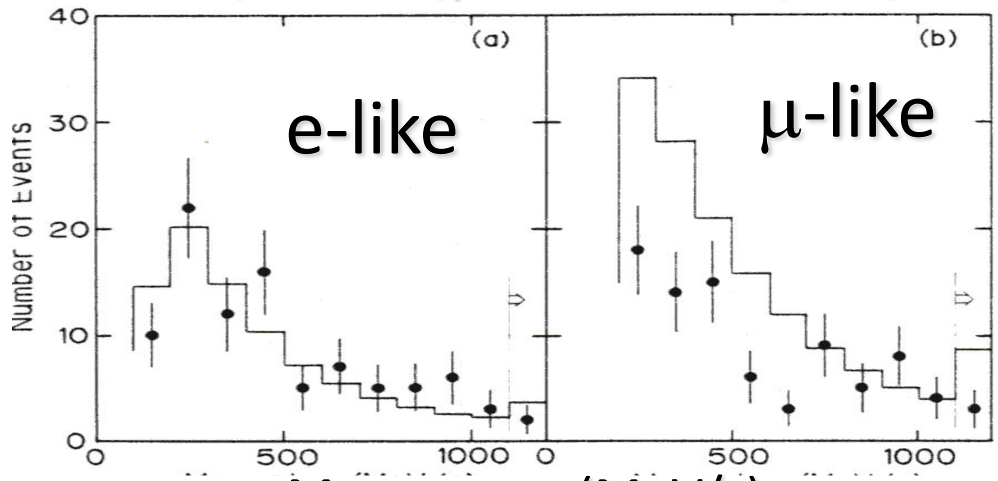
- For the upgrade of Kamiokande detector
  - Penn Group (Al Mann and his colleagues) joined KM w/timing electronics
  - KM-II formed
- 1987: KM-II started
- 1987: detection of SN1987A



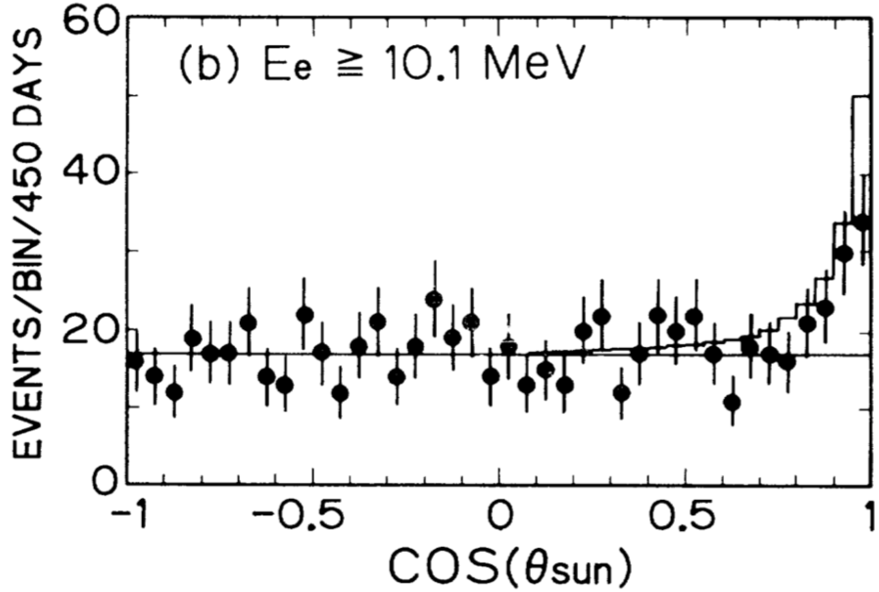
Two Early Hints from KM-II

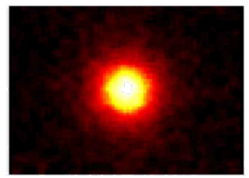
- **1988: atmospheric neutrino anomaly**
  - Kamiokande Observed fewer μ-like events in atmospheric ν interactions than expected
  - Phys. Lett. in 1988
- **1989: solar neutrino detection**
  - Confirmed the solar neutrino deficits of the Davis's experiment

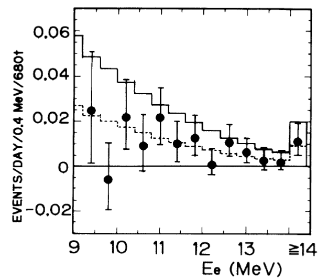
R= (Obs./MC)μ-like = 59$\pm$7% (stat.)



Momentum (MeV/c)



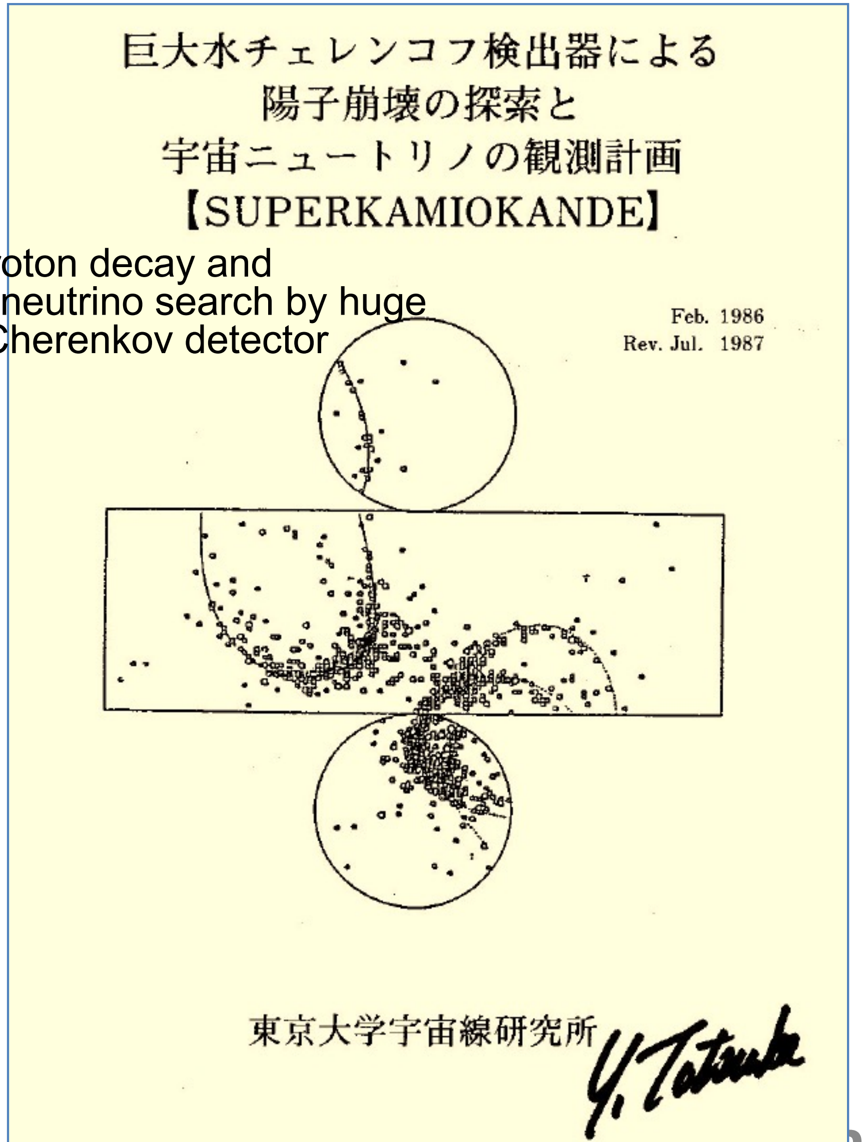




Towards Super-Kamiokande

- **1984 ICOBAN84 (JACK)**
  - No interest from abroad
- 1986 Proposal (rev in 1987 after the SN1987A)
  - Proton decay main
  - + astrophysics (due to 1987A)
  - Less emphasis on atm-ν (before anomaly)
- 1988, Yoji Totsuka moved to ICRR, and formed a core group to promote SK, with also a vital participation from KEK, and started to submit a budget request for Super-K, very seriously
- Remember
  - 1988: atmospheric ν anomaly,
  - 1989: confirmation of solar ν prob.
- **1991: Super-K was approved as a 5 year construction project**

$108M (for 1$=¥100)



Title: Proton decay and cosmic neutrino search by huge Water Cherenkov detector

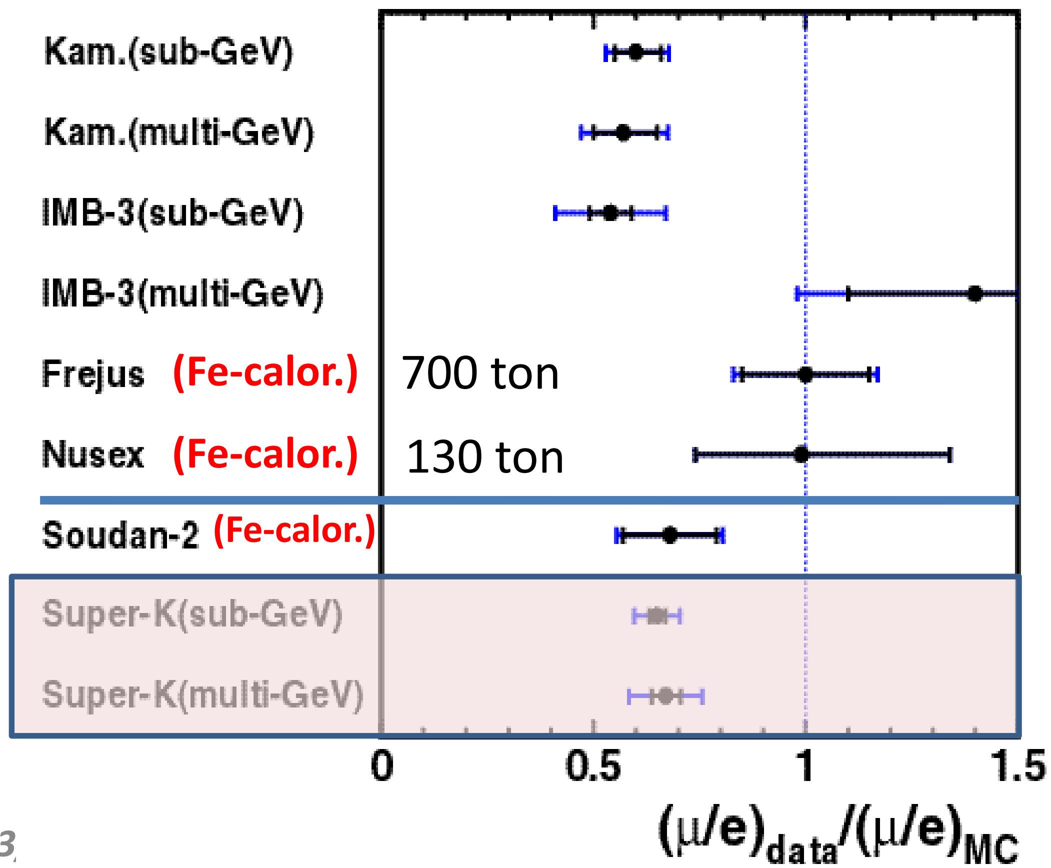
Progress of neutrino oscillation study during the SK construction period

- Situation of neutrino oscillation had drastically changed even during the Super-Kamiokande construction periods between 1991 and 1996

Confusions in atm ν in early 90's

- Other experiments: inconsistent with the KM result
  - IMB, Frejus, Nusex
    - But IMB confirmed 1992
  - Systematic bias (?) between Iron Calorimetry (no deficits) vs Water Ch.

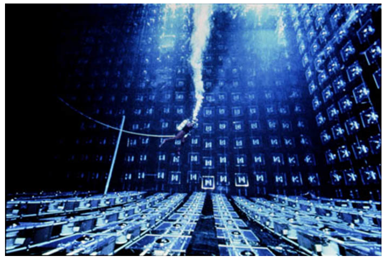
    → settled 1997 by Soudan-II

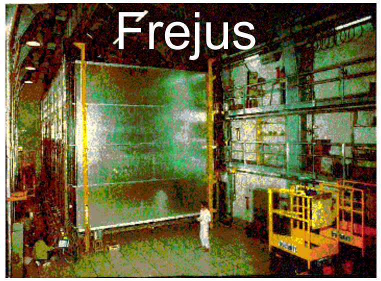


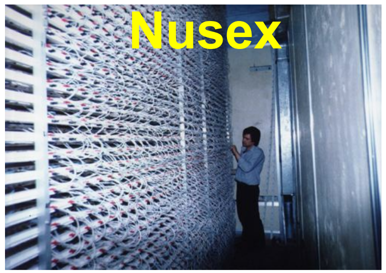
1988

1992

1997

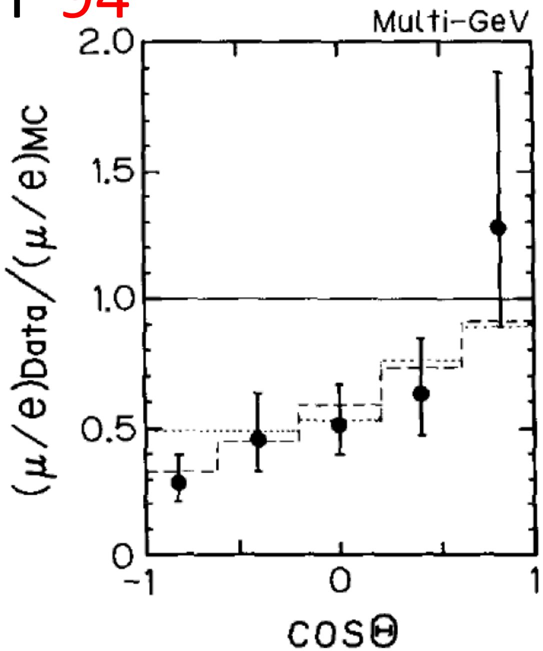






To establish the atm-ν oscillation

- In order to 'establish' the atmospheric neutrino anomaly as a neutrino oscillation, it is necessary to have an evidence which does not depend on the 'flux calculations'
- Indication was already seen in the zenith angle distribution by KM in '94



Kamiokande, PLB, 335 (94)237

------- $\nu_\mu \rightarrow \nu_e$ (1.0, 1.8 x 10^{-2} eV^2)

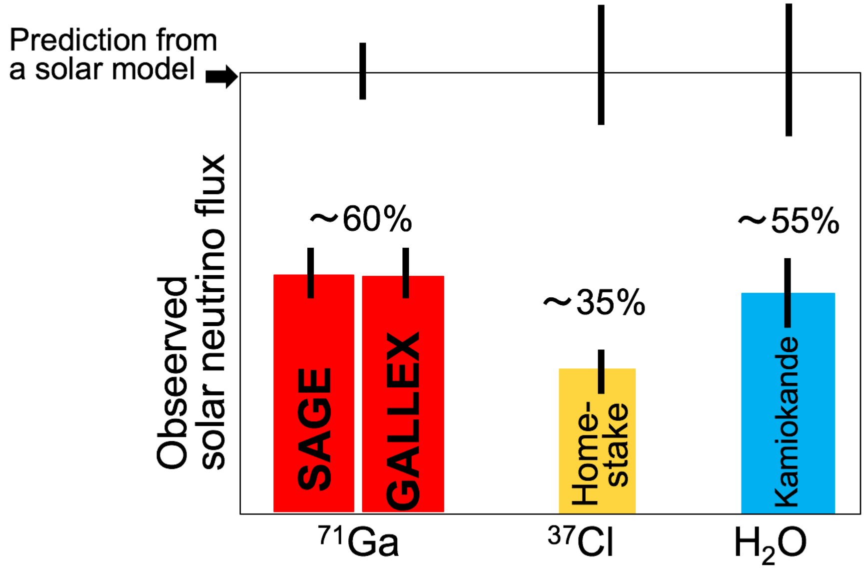
- - - - $\nu_\mu \rightarrow \nu_\tau$ (1.0, 1.6 x 10^{-2} eV^2)

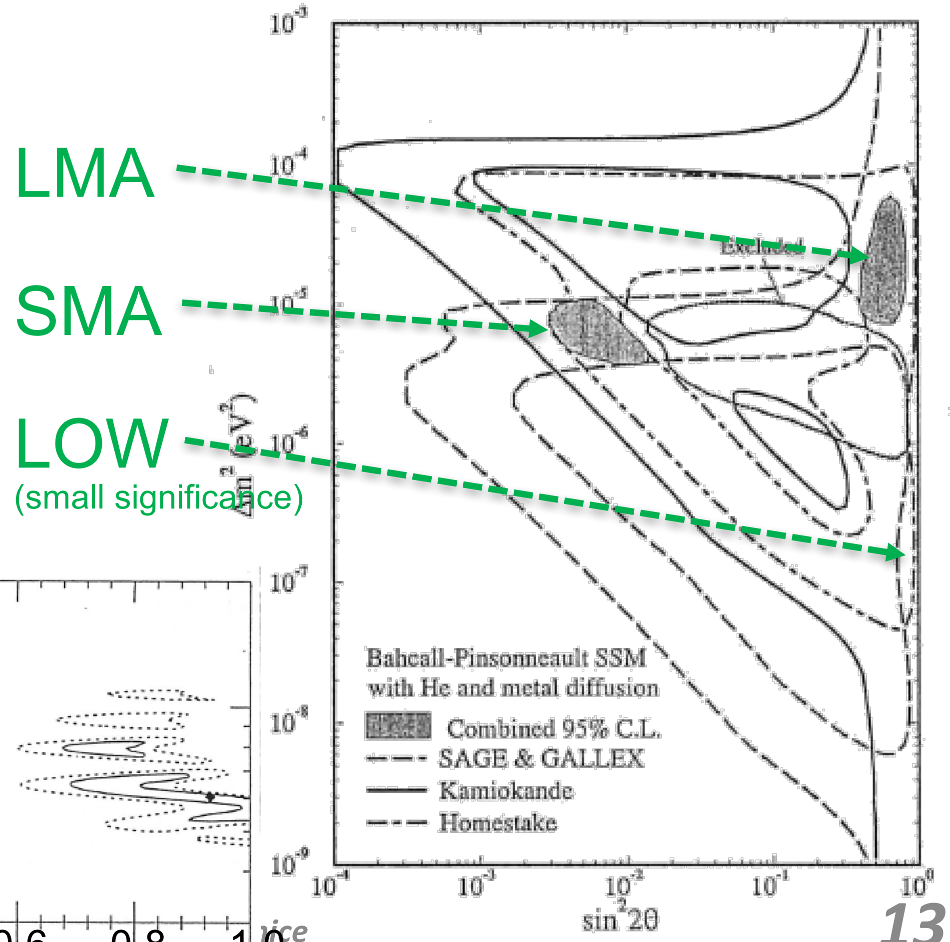
This was thought as a compelling evidence for the ν oscillation

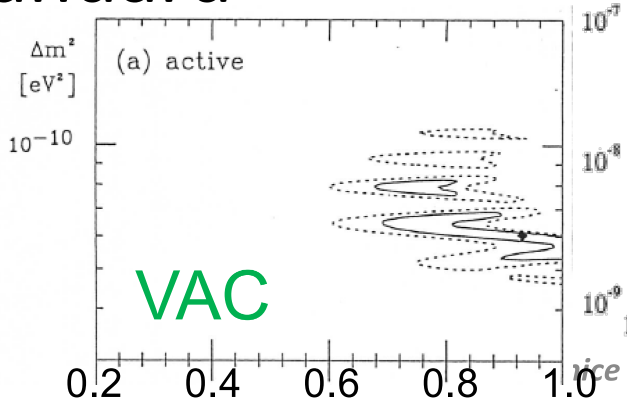
→ **Strategy of Super-K**

4 solar ν experiments and 4 solutions

- 4 experiments: Cl, KM and
  - Gallium experiments (SAGE and GALLEX) in early ‘90
  - All showed deficits of solar neutrinos
- 4 solutions by oscillation hypothesis (using a flux prediction from standard solar models)



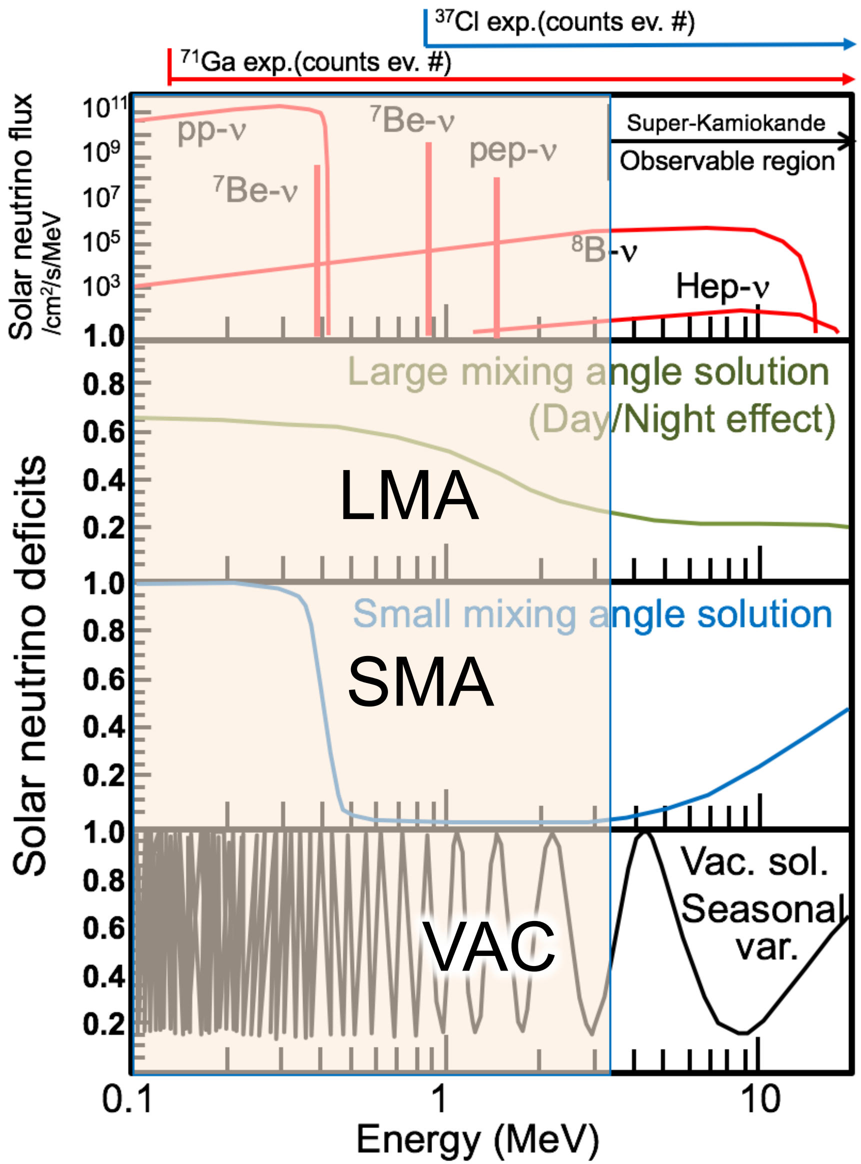




To resolve the solar neutrino problem

smoking gun evidence

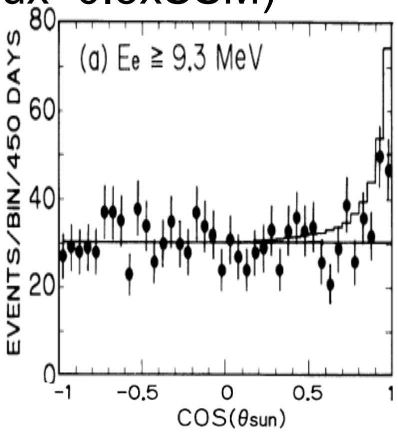
- 4 different solutions:
  - Different characteristics
  - Large Mixing Angle:
    - No energy distortion, day/night flux difference)
  - Small Mixing Angle:
    - Energy distortion
  - Vacuum:
    - Energy distortion, seasonal variation
- Strategy for SK solar ν ➔
- Super-K can measure the energy spectrum and time variation very precisely
  - Able to determine the solution
  - Flux independent & compelling evidence

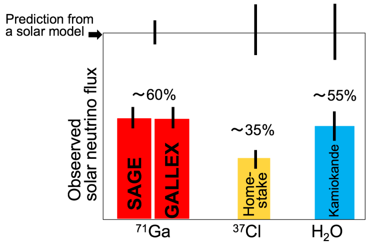


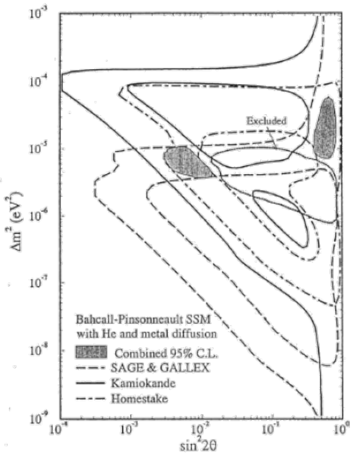
Summary of the scientific situation before Super-K

SN1987a

First solar ν observation (flux=0.5xSSM)

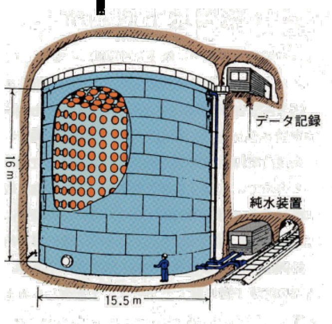




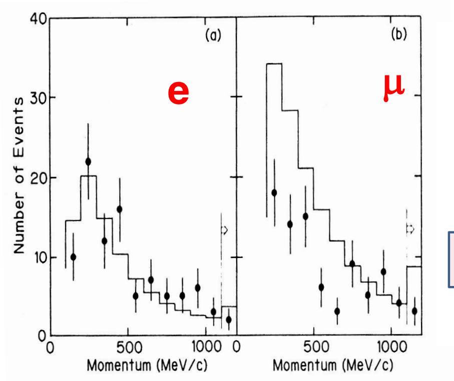


1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997

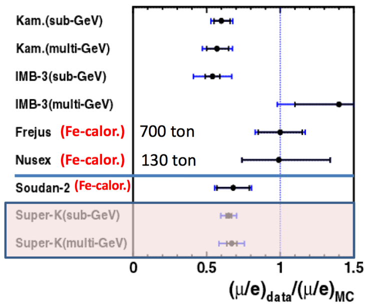
Construction

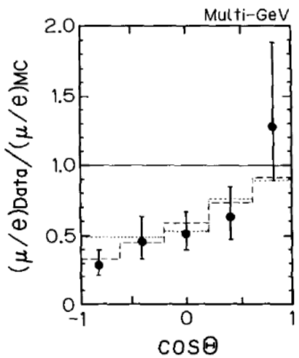


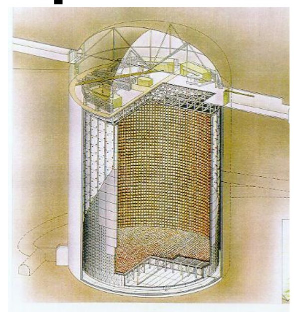
Kamiokande start



First atmospheric ν anomaly paper







Super-Kamiokande start

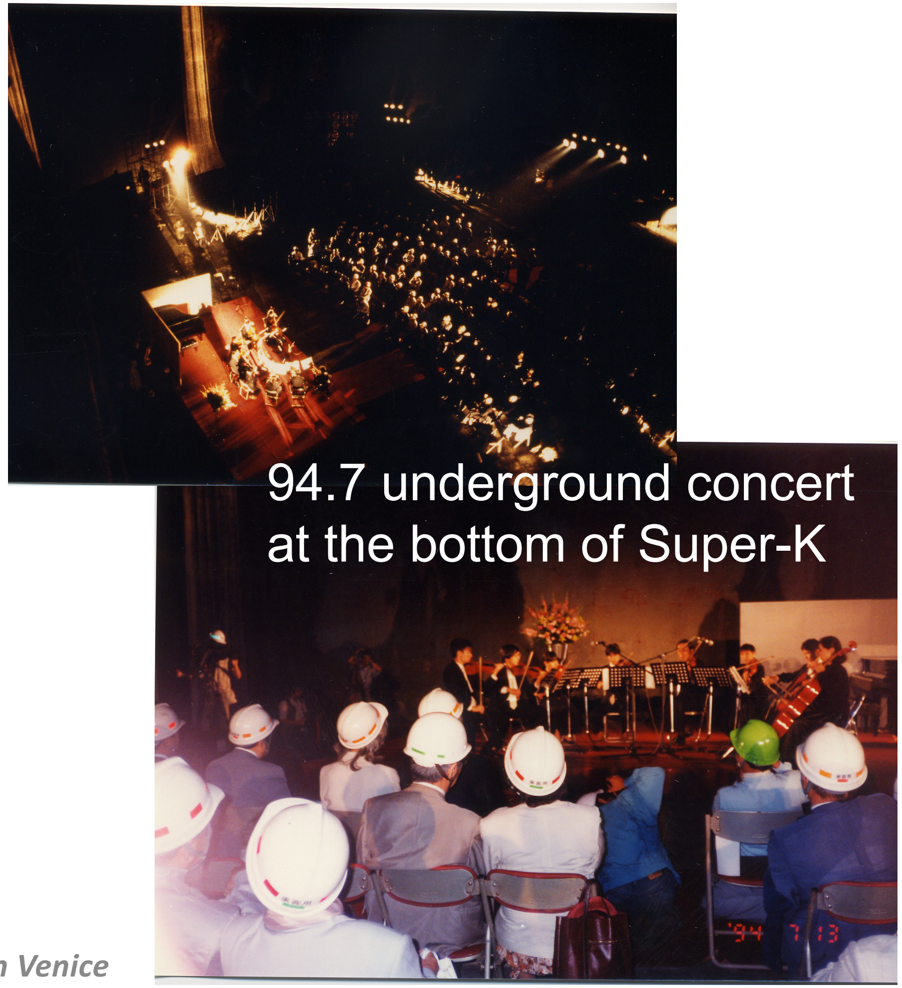
Construction of Super-Kamiokande

- SK construction budget was approved for JFY1991
- 1991. December: A ground breaking ceremony & party

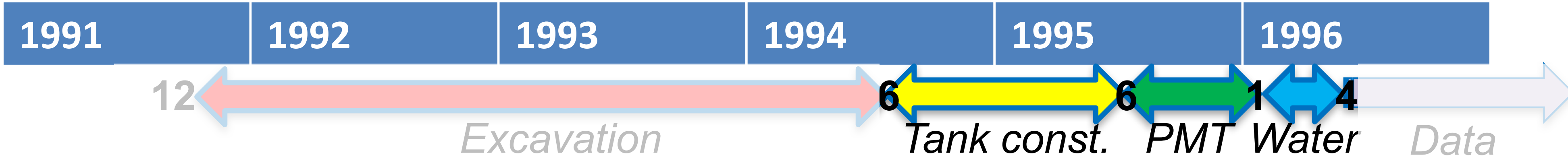
Construction of Super-Kamiokande

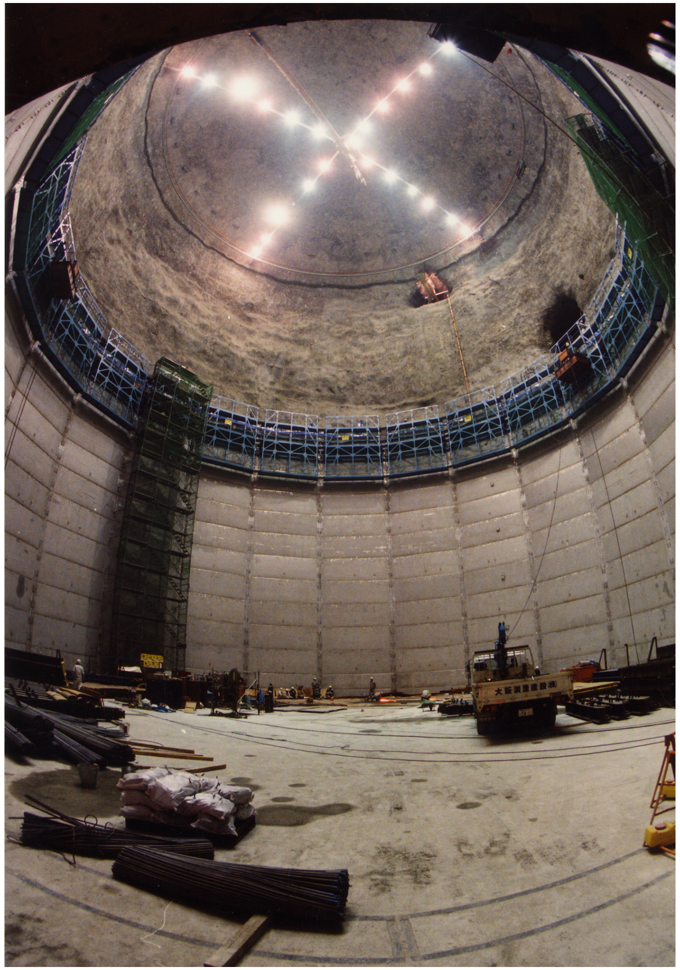
1991	1992	1993	1994	1995	1996

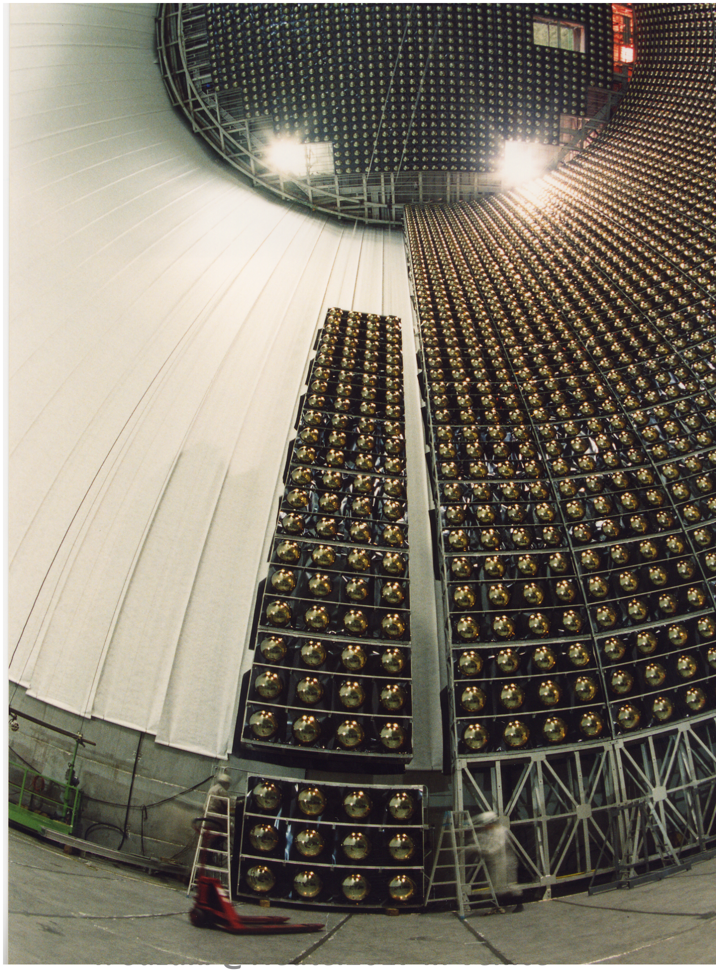
12 ← Excavation → 6 ← Tank const. → 6 ← PMT → 1 ← Water → 4 → Data

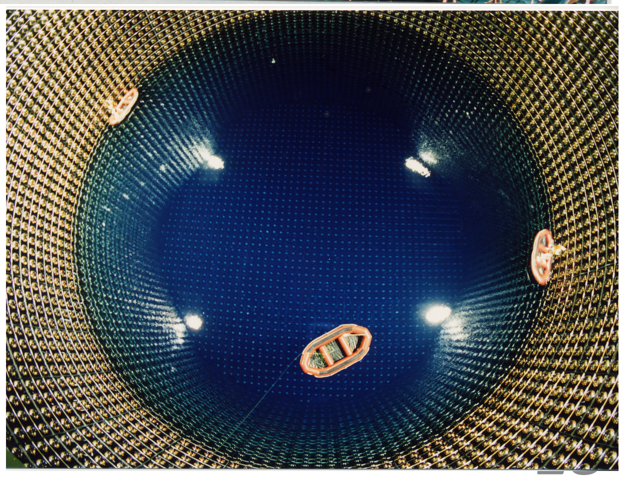


Construction of Super-Kamiokande

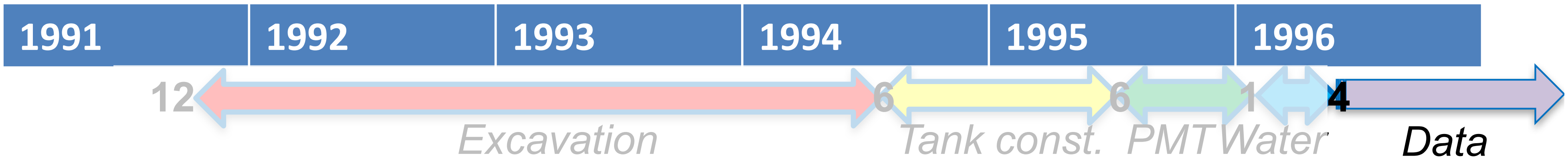






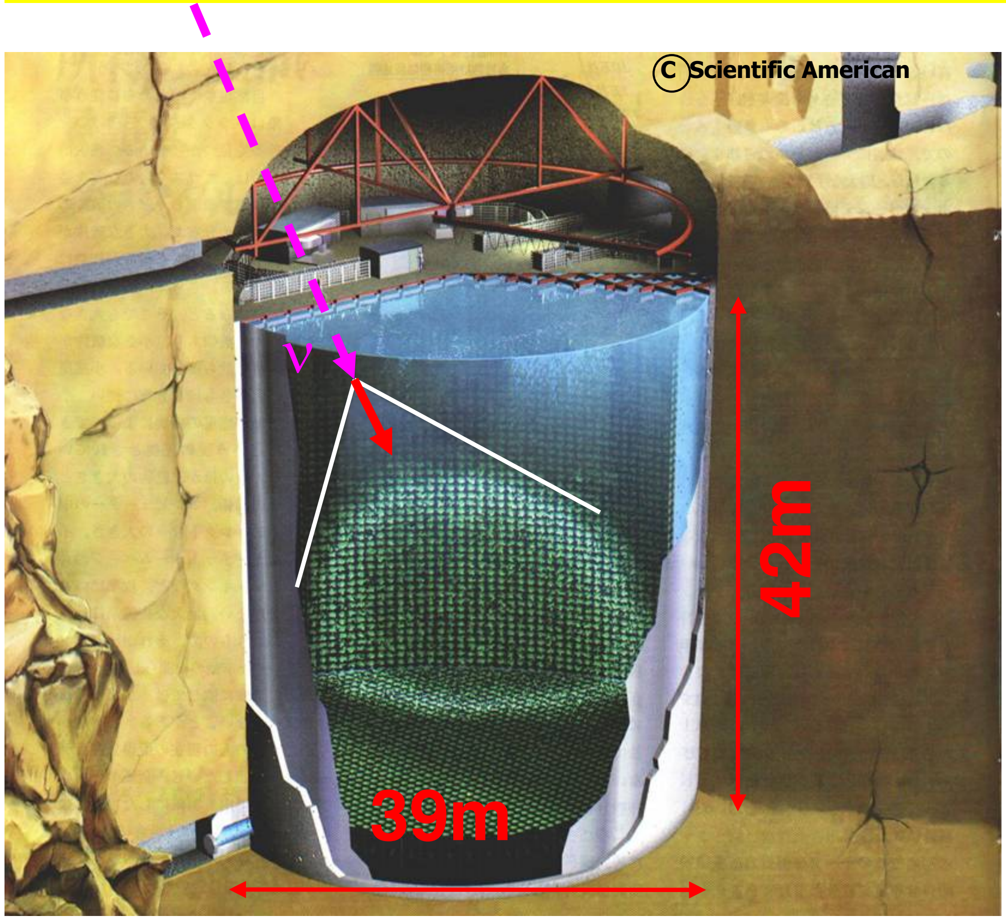


Start of the experiment



Super-Kamiokande started at 0:00, April-1st 1996

Super-Kamiokande (21 years old !)



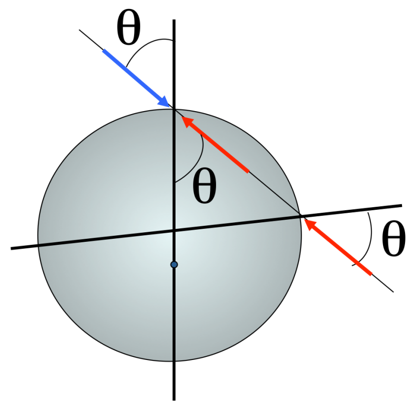
- 50,000 tons (22,500 ton fid.) Imaging Water Cherenkov Detector
- 1,000 m underground
- Inner-Detector (ID)
  - 11,146 50cm PMTs (40%)
- Outer-Detector (OD)
  - 1,885 20cm PMTs

- ~ 130 collaborators from 36 institutions (10 countries) as of 2017
  - ***Japan, US, Poland, Spain, China, Korea, Canada, UK, France, Italy***

Start of the International Collaboration with US in 1992

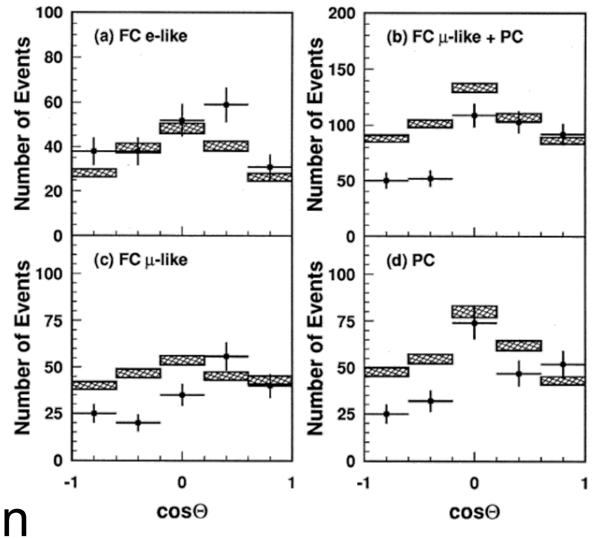
Atmospheric neutrinos in SK

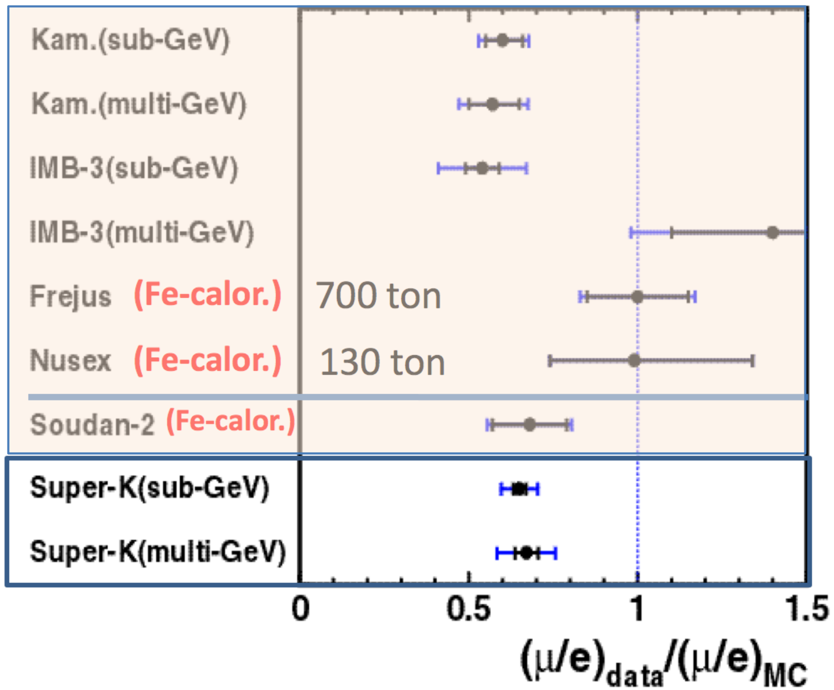
- SK: 22.5 kton ➔ very high statistics
  - ~8 atmospheric ν events /day :
    - Very quick to reach the conclusions
  - Key issue ➔ zenith angle distribution



[1st paper] Feb.-'98 (414days-25.5 ktyr)
"Measurement of a small atmospheric ν_e/ν_μ ratio"
(sub-GeV) R= 0.61±0.03±0.05

[2nd paper] May.-'98 (414days-25.5ktyr)
"Study of the atmospheric neutrino flux in the multi-GeV energy range"
(multi-GeV) [414days]
R= 0.66±0.06±0.08
and
Zenith angle distribution





From: totsuka@suketto.icrr.u-tokyo.ac.jp (Yoji Totsuka)
Date: April 25, 1998 at 2:53:15 AM EDT
To: kajita@suketto.icrr.u-tokyo.ac.jp, kearns@budoe.bu.edu, takita@oskjcc.hep.sci.osaka-u.ac.jp, shige@uhhepj.phys.hawaii.edu
Cc: sk_exe_com@suketto.icrr.u-tokyo.ac.jp
Subject: combined analysis

Hi,
Please make the following combined analyses and
present the results at the collaboration meeting

Data sets; sub-GeV atm-nu, multi-GeV atm-nu,
up-thru-mu, up-stop-m

Hypothesis; nu-mu <--> nu-tau oscillations
Parameters; delta m^2 and sin2(2theta)

Make a simultaneous fit to all the above data sets.

Obtain;
Validity of the hypothesis
Allowed region of the parameters

Overlay fitted curves of a typical set of parameters to all the
distributions (R(momentum, zenith), e(momentum, zenith),
mu(momentum, zenith), thrumu(zenith), stopmu(zenith)
stop/thru(zenith), east-west of atm-mu, etc

I want to know if we can announce that Super-K has discovered
the firm evidence for the non-zero delta m^2

Best regards,
Yoji

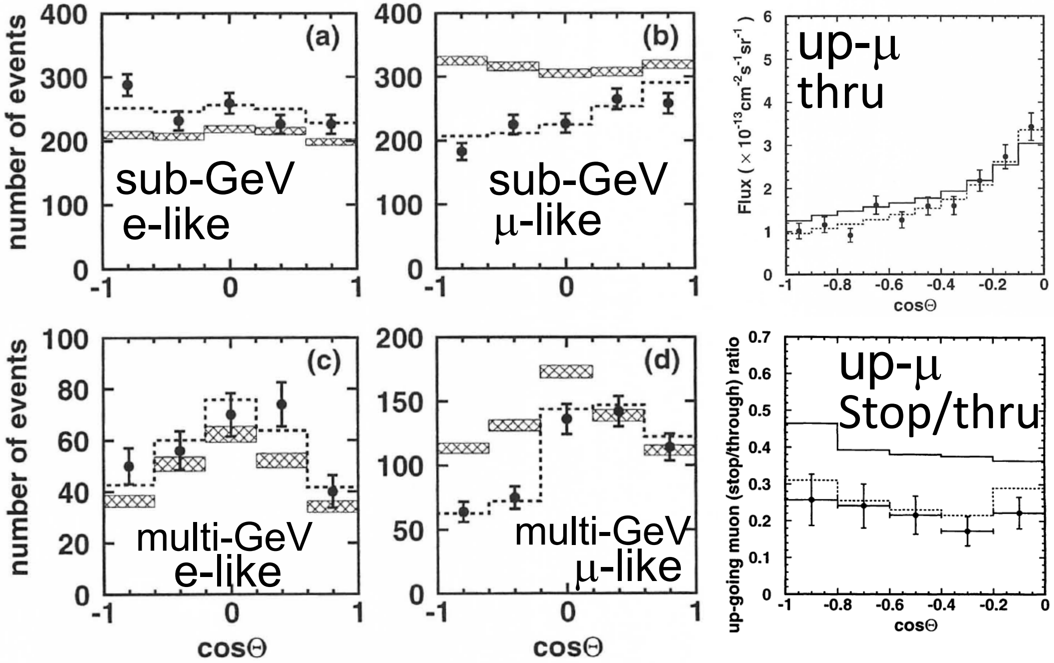
An email from spokesperson,
Yoji Totsuka,
to the four conveners of
the atmospheric neutrino
analysis

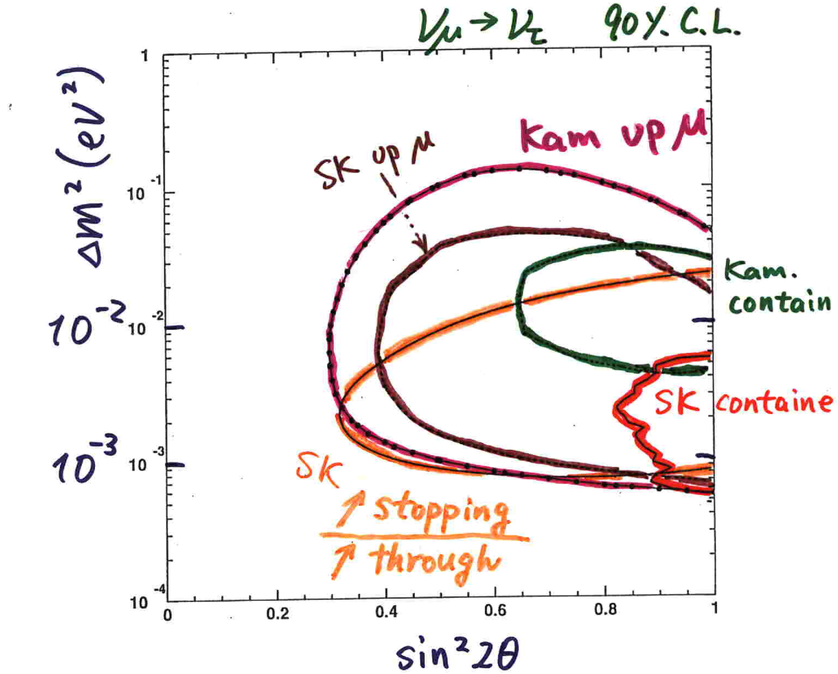
dated on 25th of April

~ 2 month before NEUTRINO ‘98
at Takayama, Japan

Evidence @NEUTRINO’98 (June-98)

- 33 ktyr (537days): with all the data samples





Beyond The Standard Model: This Time for Real

Frank Wilczek[a] *

[a]Institute for Advanced Study,
School of Natural Sciences, Olden Lane,
Princeton, New Jersey 08540

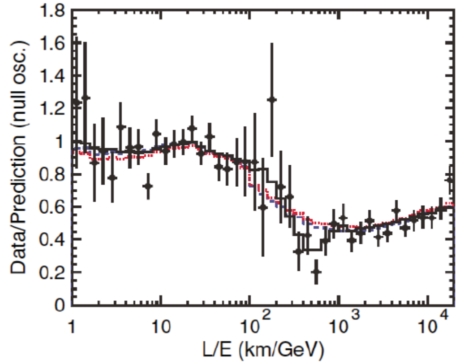
F. Wilczeck

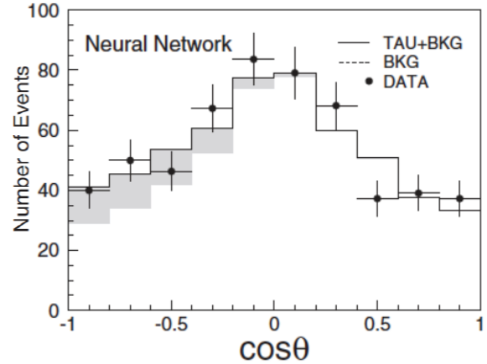
Summary Talk
@NEUTRINO’98

The value of the neutrino mass reported by the SuperK collaboration fits beautifully into the framework of gauge theory unification. Here I justify this claim, and review the other main reasons to believe in that framework. Supersymmetry and $SO(10)$ symmetry are important ingredients; nucleon instability is a dramatic consequence.

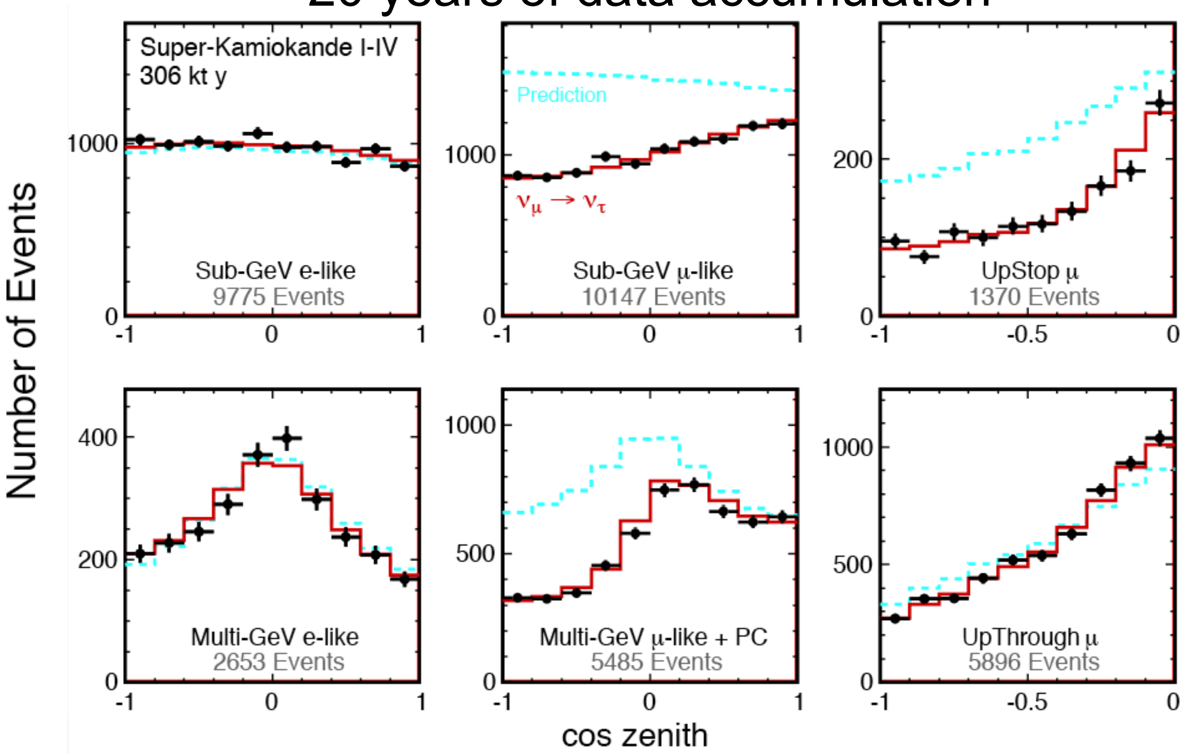
After the discovery

- 2004: Oscillatory behavior
- 2007: Tau appearance

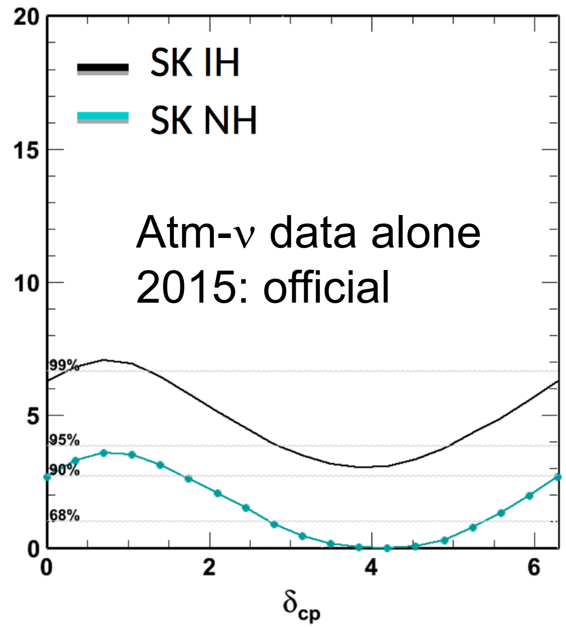




~ 20 years of data accumulation



- **Mass Hierarchy & δ_{CP}**



- ***Also used as a far detector of K2K/T2K***

Super-K Solar ν results
Two SK papers in PRL on 18th June 2001 issue (1258 days)

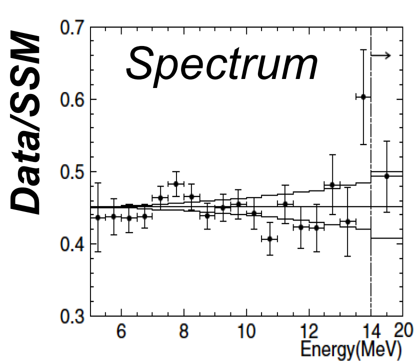
Paper 1: Flux measurement

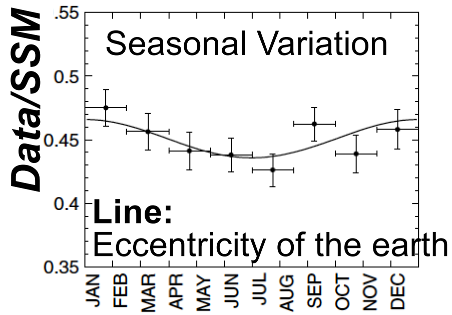
- Solar ^{8}B and hep Neutrino Measurements

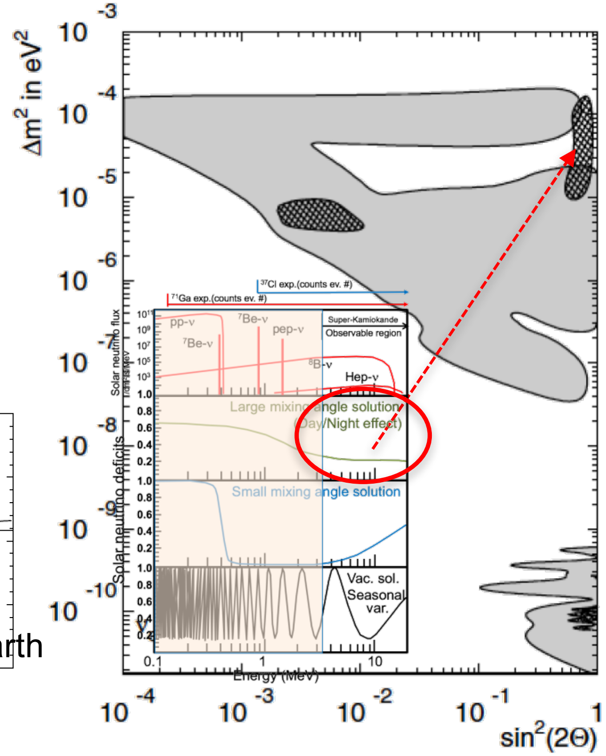
Paper 2: Oscillation analysis

- No strong spectrum distortion
  - excluded SMA and Vacuum
- No seasonal
  - exculuded Vacuum

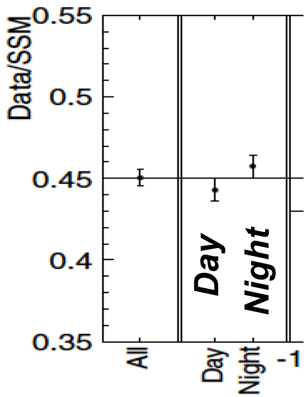
➔ LMA solution remained







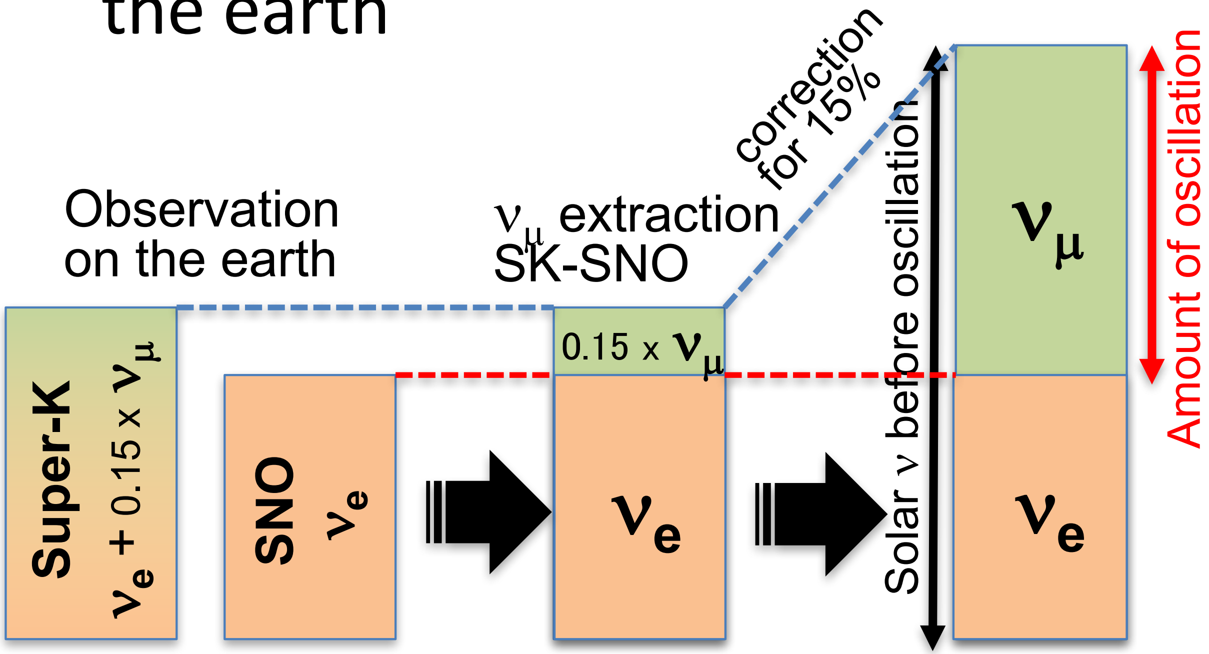
- However, the Day/Night effect, the smoking evidence for LMA, was less than 2 sigma, not sufficient to claim positive evidence
- A kind of strange situation !
- We, SK, found the solution, but needed another evidence which was independent from the flux calculation

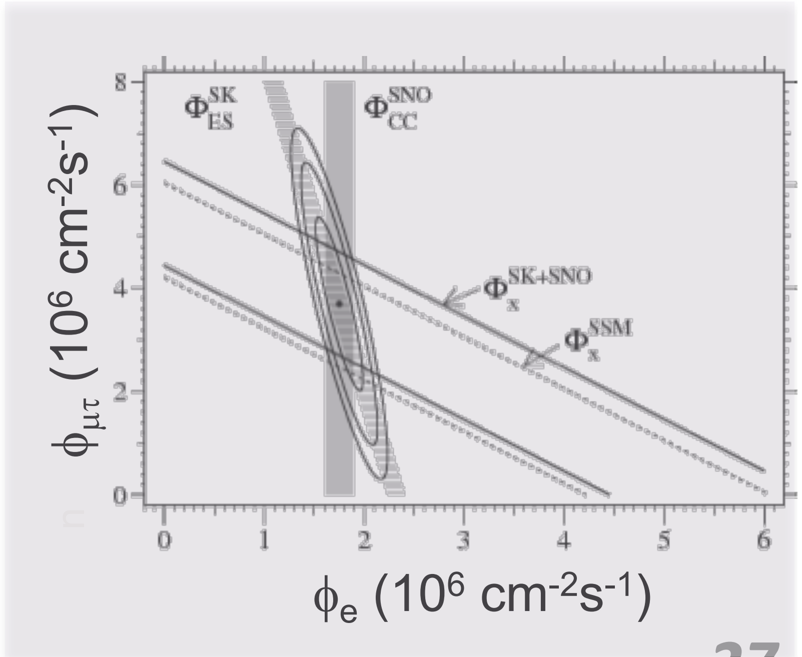


Evidence on 18th June, 2001

- **18-June-2001: SNO announced the discovery of Solar Neutrino Oscillation**
  using
  - **SNO: charged current $\rightarrow \nu_e$** 35%
  - **SK: Electron Scattering $\rightarrow \nu_e + 0.15(\nu_\mu + \nu_\tau)$** 46.5%
- Found there are non-electron neutrino components in the solar neutrinos measured on the earth

3.3σ



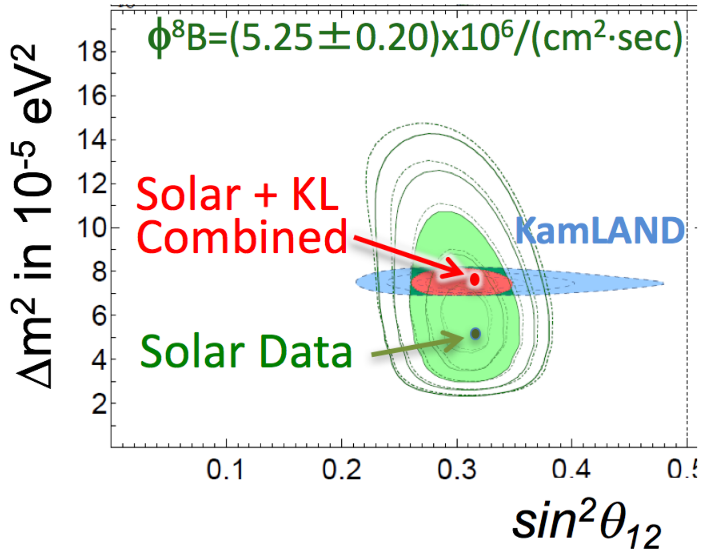


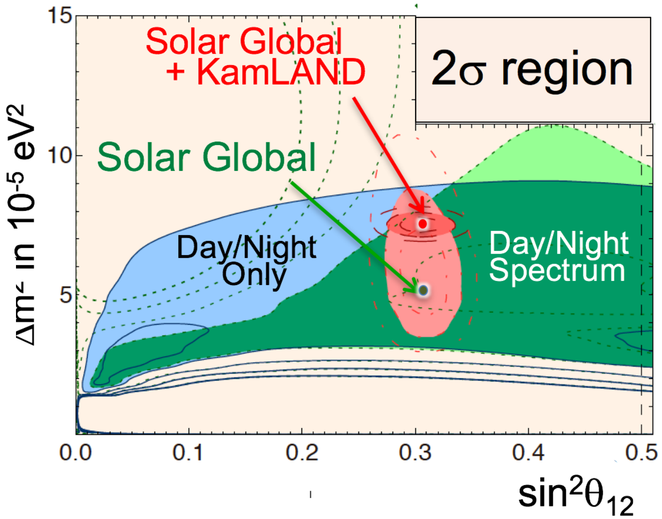
Discovery of the solar neutrino oscillation

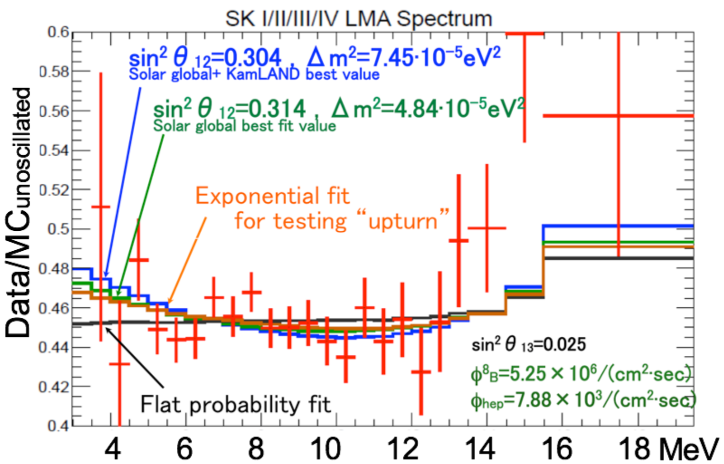
- The first evidence of the solar neutrino oscillation was obtained by comparing Super-K measurement (sensitive to ν_e + 15% of ν_μ) and SNO measurement (sensitive to ν_e) in 2001 showing the existence of non-electron neutrino components.
- Either of the results alone could not provide the evidence.
- Super-K results, no distortion, no seasonal, small day/night suggested the right oscillation parameters, the Large Mixing Angle solution.

SK Solar neutrino after the discovery

- Oscillation parameters (all solar ex's)
  - Precisely determined
  - Stress between KL and solar
- Observed day/night matter effect (2.6 σ)
  - Flux independent
  - LMA
  - Also stress between KL and solar
  - Need to increase statistics
- Upturn
  - Need to lower the energy threshold
  - Achieved 3.5 MeV (K.E.)





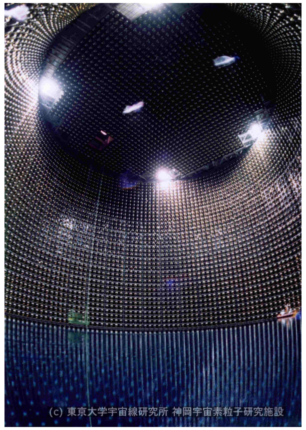
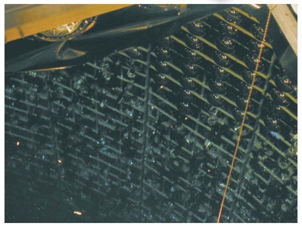
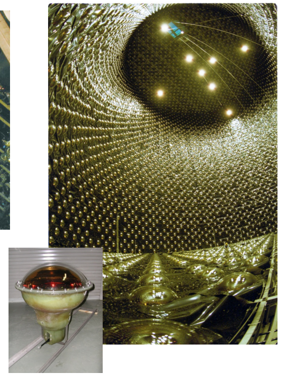
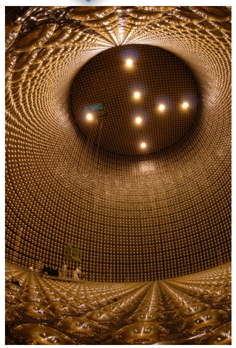


Summary of Ups and Downs of Super-K

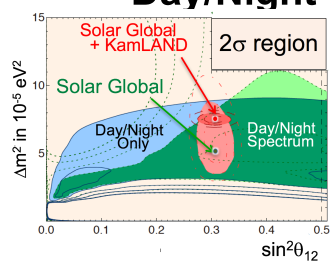
4			4		6 11	12			11	7		9									▼
96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17

SK-I | **Accident** | **SK-II** *~Half PMTs* | **Full restoration** | **SK-III** | **SK-IV**

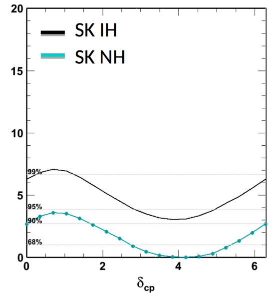
K2K | **K2K-II** | **T2K** | Earthquake Tsunami | **T2K**

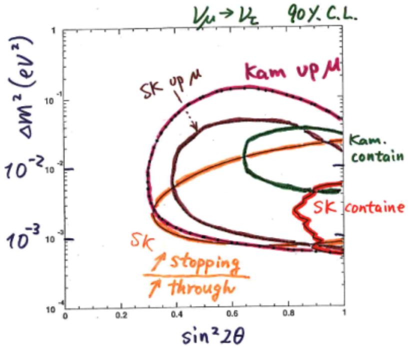
'14 Day/Night



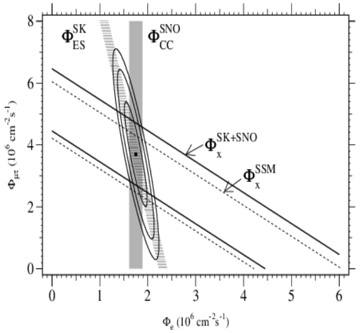
latest: Atm-ν CPV & MH



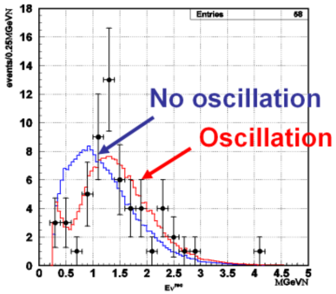
'98 Discovery of Atmospheric ν Oscillation



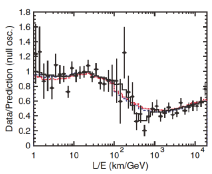
'01 Discovery of Solar ν Osc. SK vs SNO CC



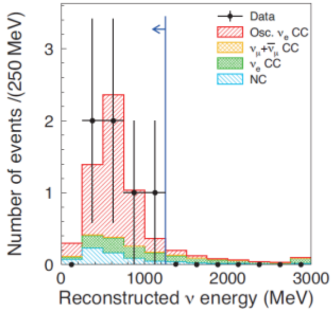
'04 as a far detector K2K confirmed atmospheric n osc.



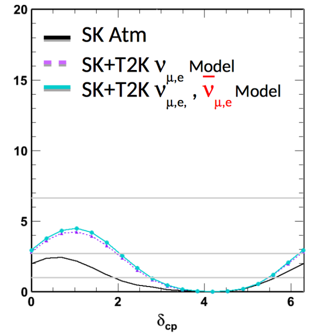
'04 Oscillatory behavior



'11 as a far detector T2K indicated finite θ_{13}



'15 as a far detector T2K indicated CPV & MH



Y. Suzuki @Neutel2017 in Venice

Future of Super-K

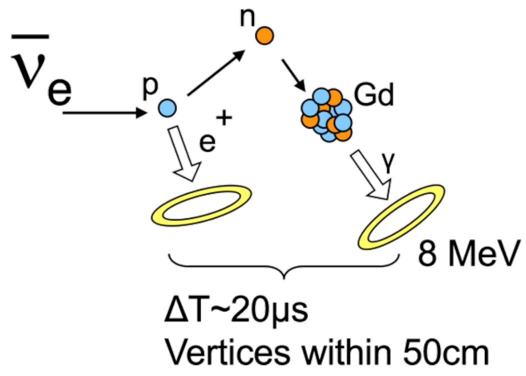
Immediate future of Super-K

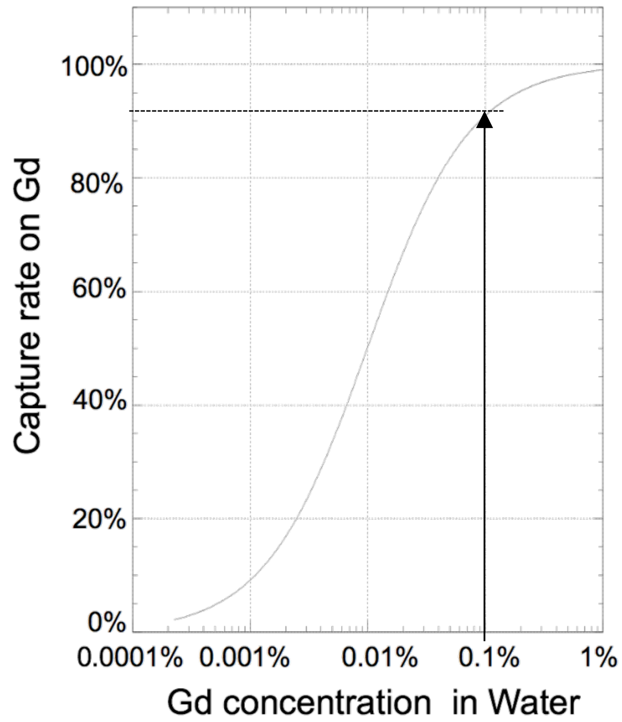
- SKGD [identify neutron]
  - dope 0.1% of Gd in the water
  - measure $\bar{\nu}_e$ interactions
  - aim to detect SN relic neutrinos
- Schedule
  - Stop water leak in the tank in 2018
  - Gd doping in a few years.

Remaining issues

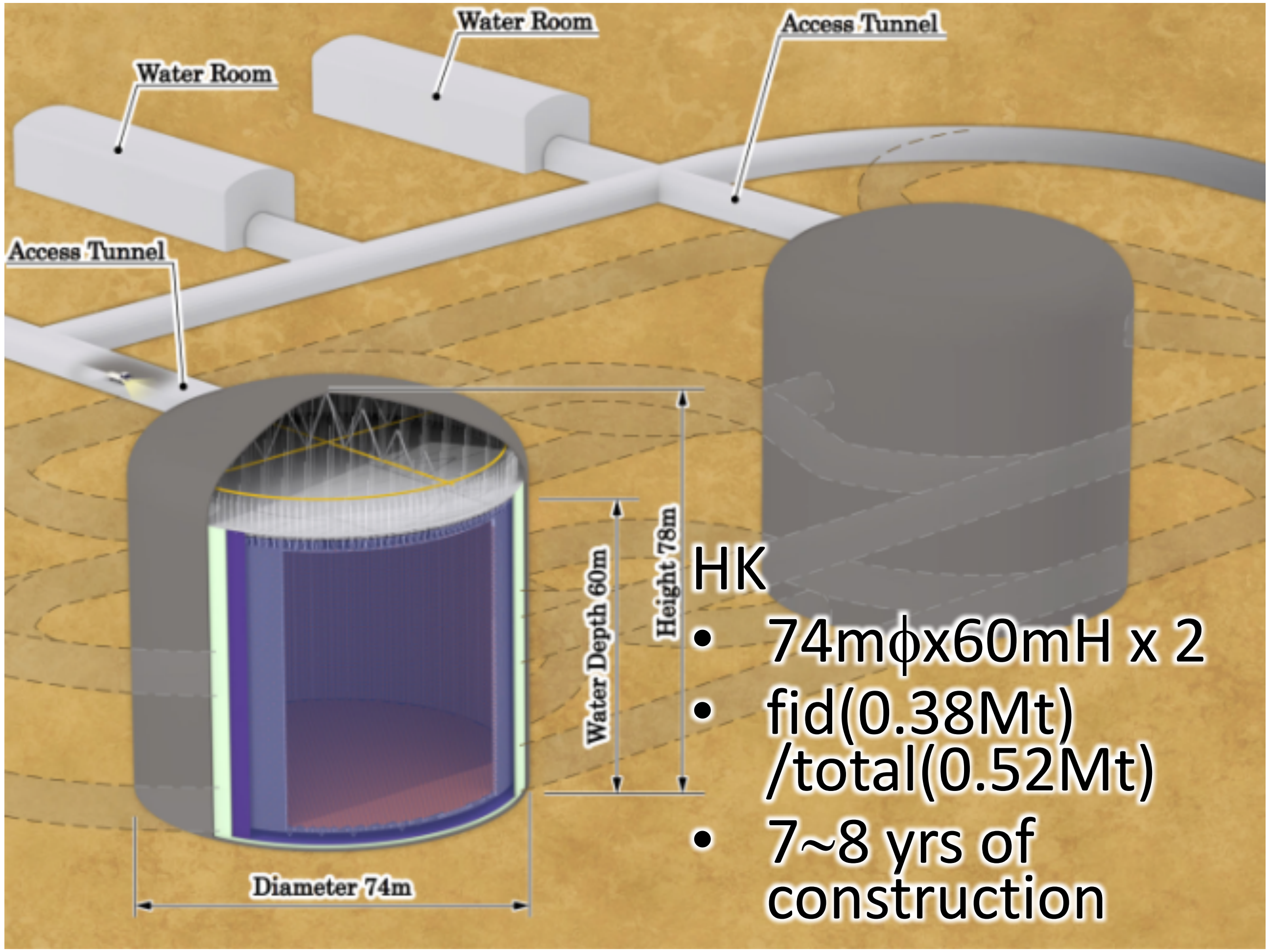
- CPV, MH
- Proton decay
- SN burst neutrinos
- Other surprise

→ May need Hyper-K



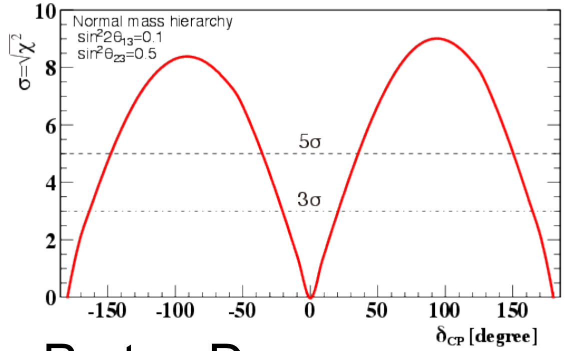


Hyper-Kamiokande

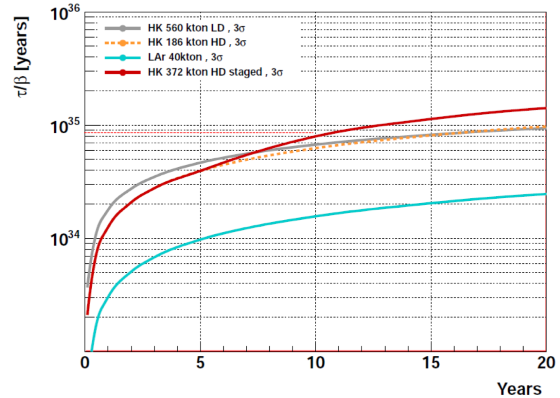


HK
- 74mφx60mH x 2
- fid(0.38Mt) /total(0.52Mt)
- 7~8 yrs of construction

- CPV, MH
  MH determination in 5 yrs
  sinδ_{CP}=0 exclusion



- Proton Decay
  10^{35}yrs in12yrs ($e^{+}\pi^{0}$)



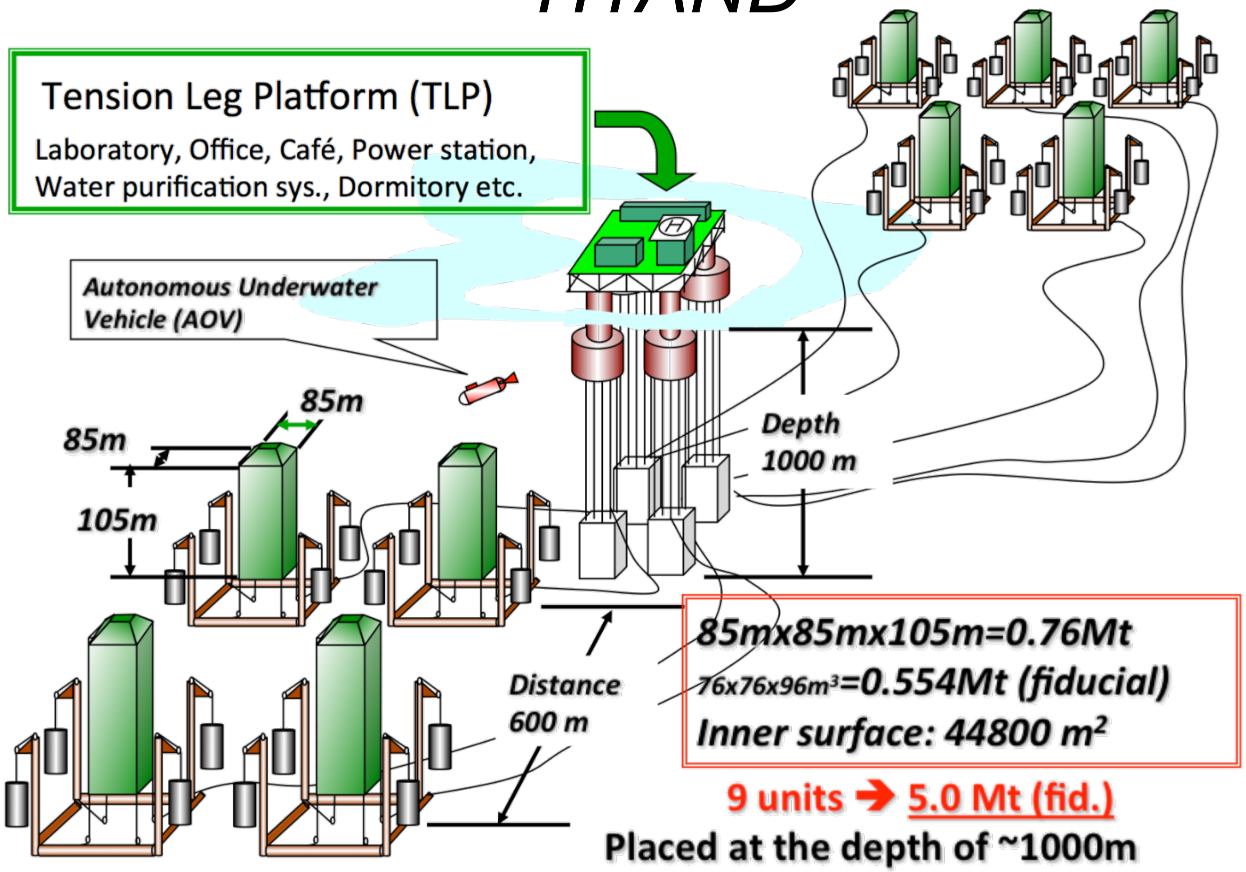
- SN neutrino bursts
  100k~150k events for SN at 10kpc
  sensitivity up to 1~2 Mpc

One more step: 10 Megaton

- TITAND-D
  - proton decay up to ~10^{36} years
  - SN burst every year

➔ SN Observatory

TITAND



Ref:1) Y. Suzuki, hep-ex/0110005 (in 2001)
2) Y. Suzuki, in Proc. of Neutrino Oscillation in Venice, Feb, 2006

Ring Imaging Water Cherenkov detectors

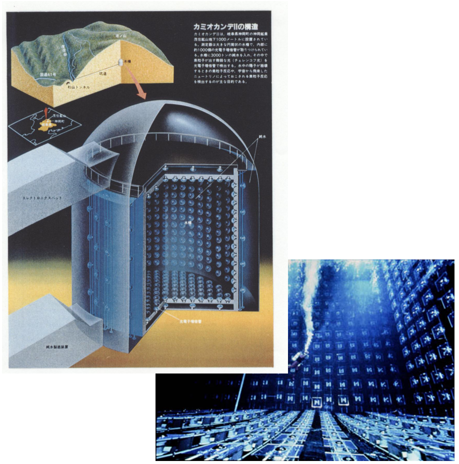
80’ s	90’ s	00’ s	10’ s	20’ s	30’ s	40’s

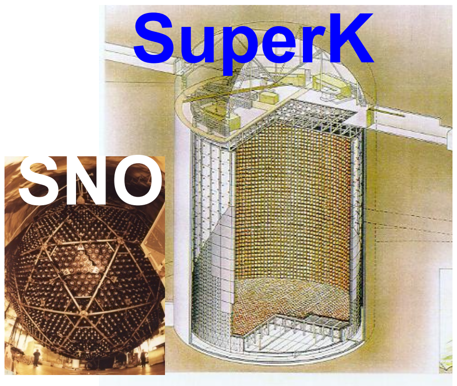
Kamiokande, IMB
(a few thousand tons)

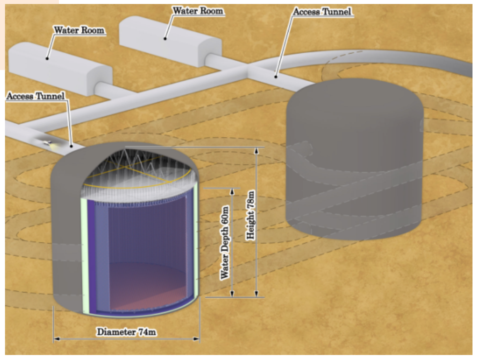
Super-Kamiokande
(50, 000 tons)
SNO (D_2O)
(1000 tons)

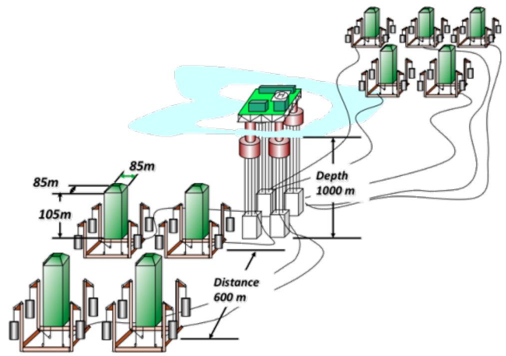
Hyper-Kamiokande
(~1Mton)

Multi-Megaton









Supernova-ν:
SN1987A
Solar ν problem
Atm ν anomaly

Atm ν oscillation
Solar ν oscillation
Supernova-ν ??

Mass hierarchy, CPV
Supernova Relic ν
Supernova ν
Proton decay
New physics ?

Summary

- Thanks for the recognition of the results from Super-K collaboration and we miss

  Y. Totsuka, K. Kaneyuki, D. Kielczewska,

  K. K. Young, W. Gajewski, M. Goldhaber,

  F. Reines