From the Solar Neutrino Problem to the Oscillation Discovery and beyond

Y. Suzuki
Kamioka Satellite, Kavli Institute for the Physics and Mathematics of the Universe (IPMU), the University of Tokyo

Prolog

- Historical overview of the discovery of the neutrino oscillatons (solar and atmospheric)
- from 1968 (Davis' first paper)

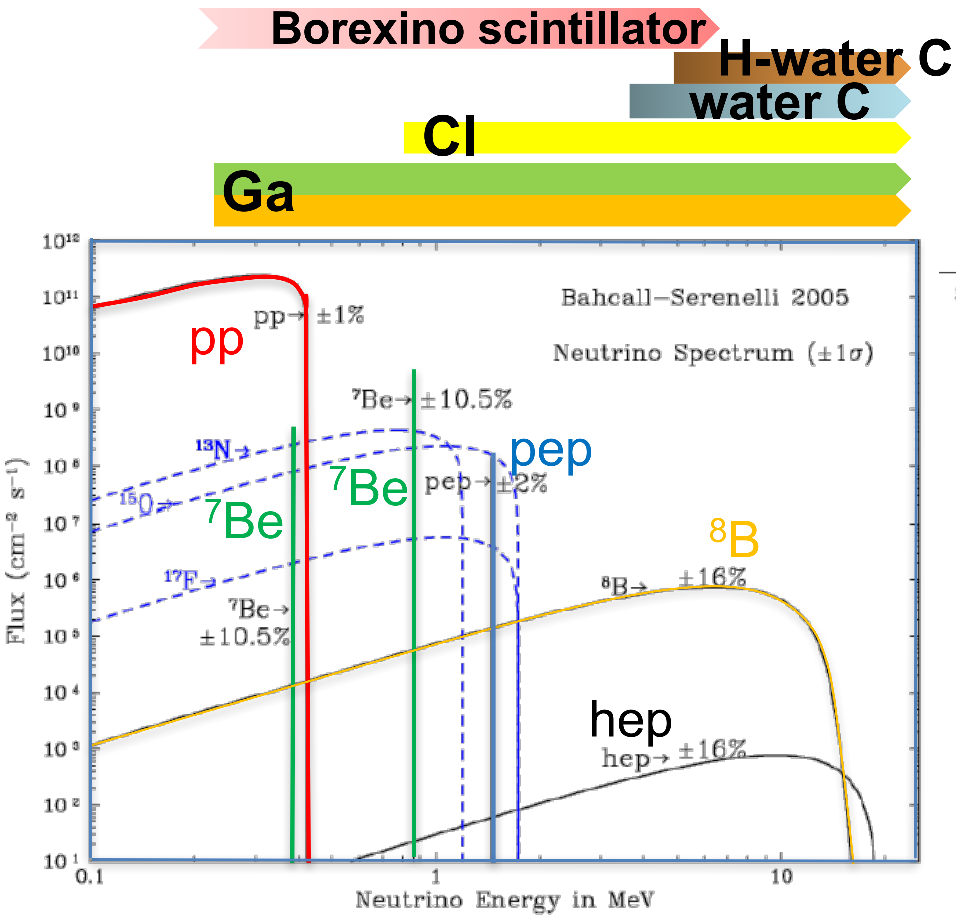
  2018 : ~ 50 year anniversary of the solar neutrino (oscillation) experiments
- 1969: I have entered the undergraduate school....

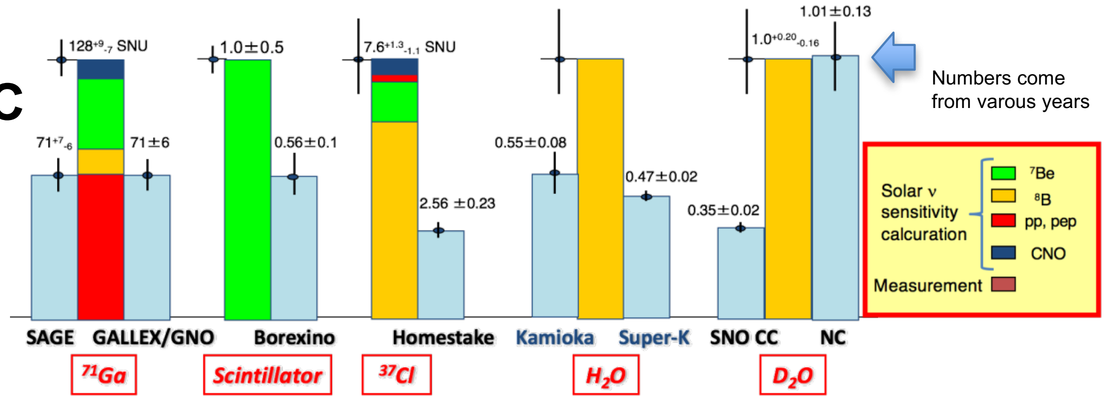
Neurino-heliograph
by Super-Kamioande
exposure ~2,000 days

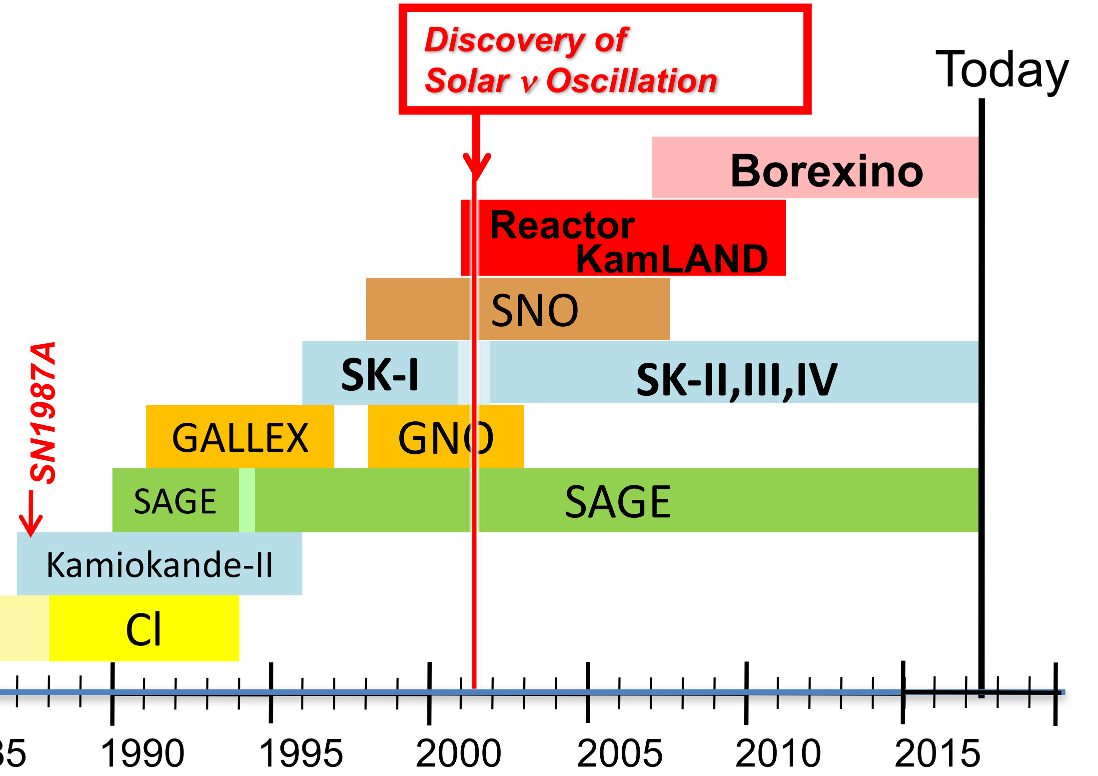
This is my personal view [may be a Super-K point of view], but, I will try my best not to create a fake news.

Solar neutrinos

Major players of the Solar Neutrino Experiments for the last 50 years

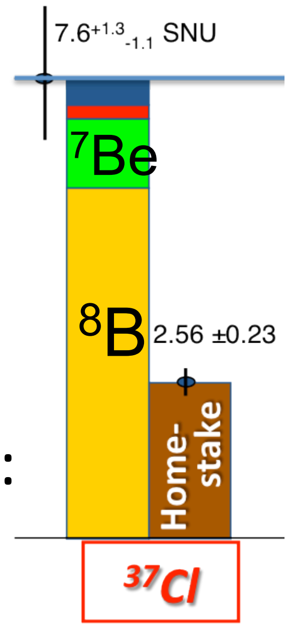


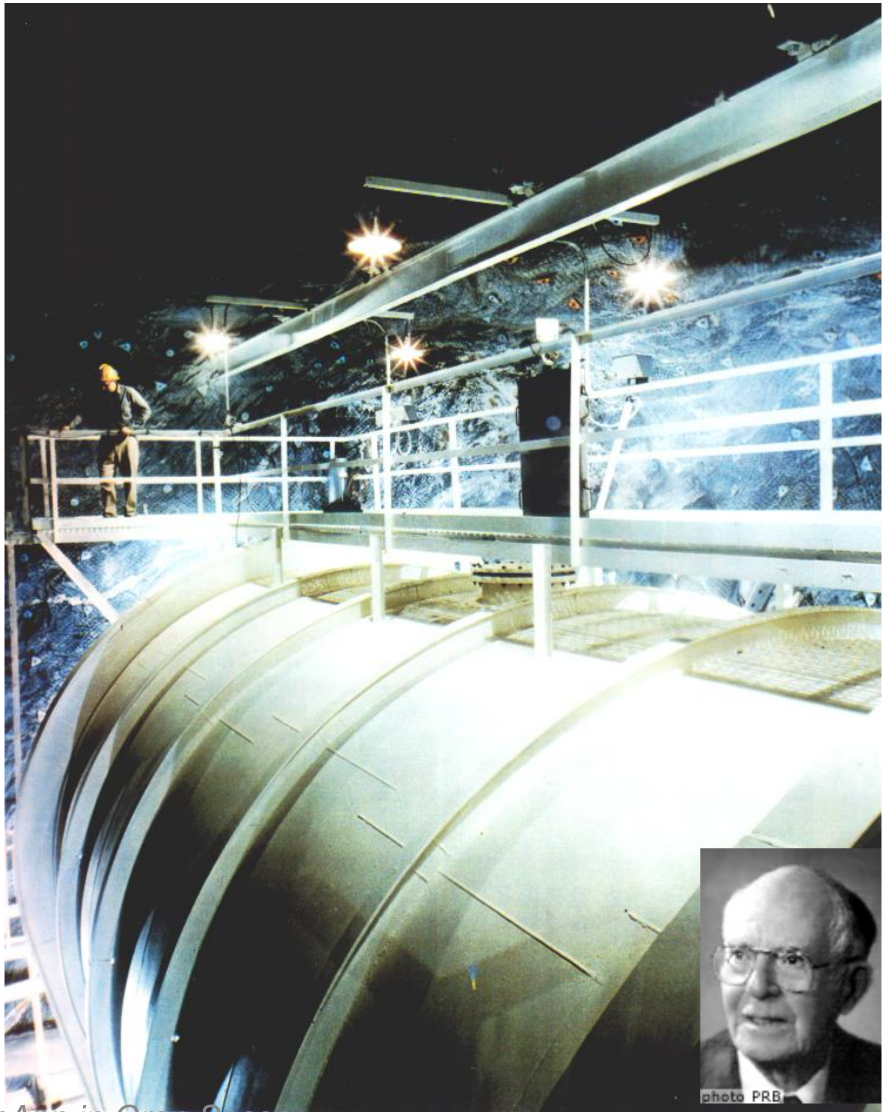




Towards the solar ν measurements

- 1946: B. Pontecorvo
- 1949: L. W. Alvarez
  - Idea to detect neutrinos through the process:
    $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
    (E_{th} > 817 keV)
- **1964: R. Davis**
  - proposed the Cl experiment at Homestake Mine, South Dakota in US
  - using ~600 tons of tetrachloroethylene: C_2Cl_4





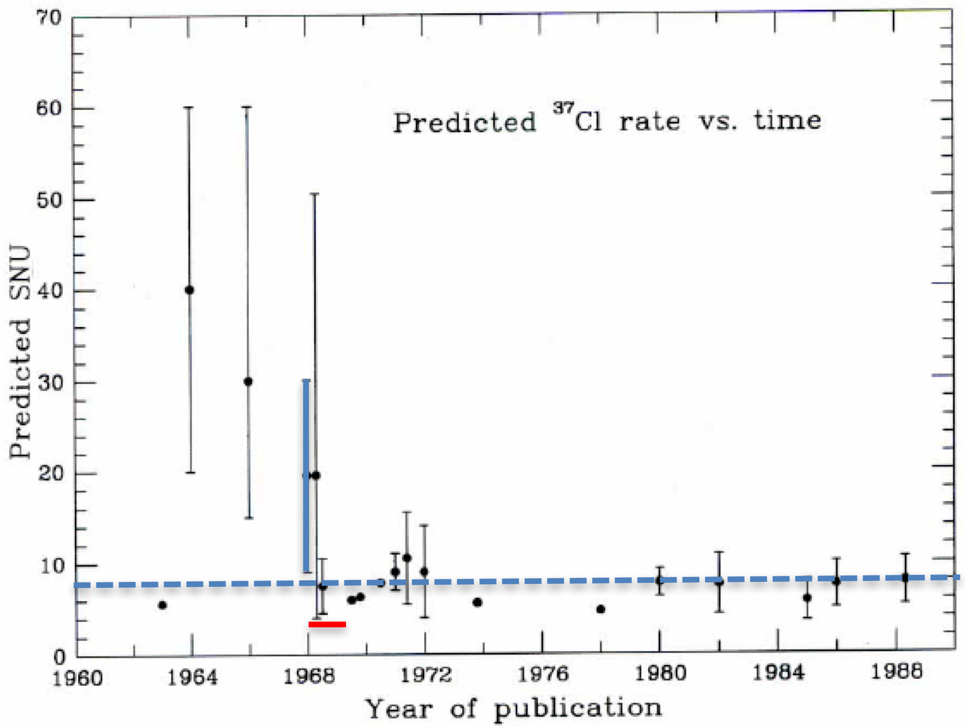
First result

VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)

A search was made for solar neutrinos with a detector based upon the reaction $Cl^{37}(\nu, e^-)Ar^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was 3×10^{-36} sec^{-1} per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than 2×10^6 cm^{-2} sec^{-1} at the earth, and that less than 9% of the sun's energy is produced by the



First results (1968) : upper bounds

- Rate < 3 x 10^{-36} sec^{-1} per ^{37}Cl atom

  < 3 SNU [Solar Neutrino Unit]

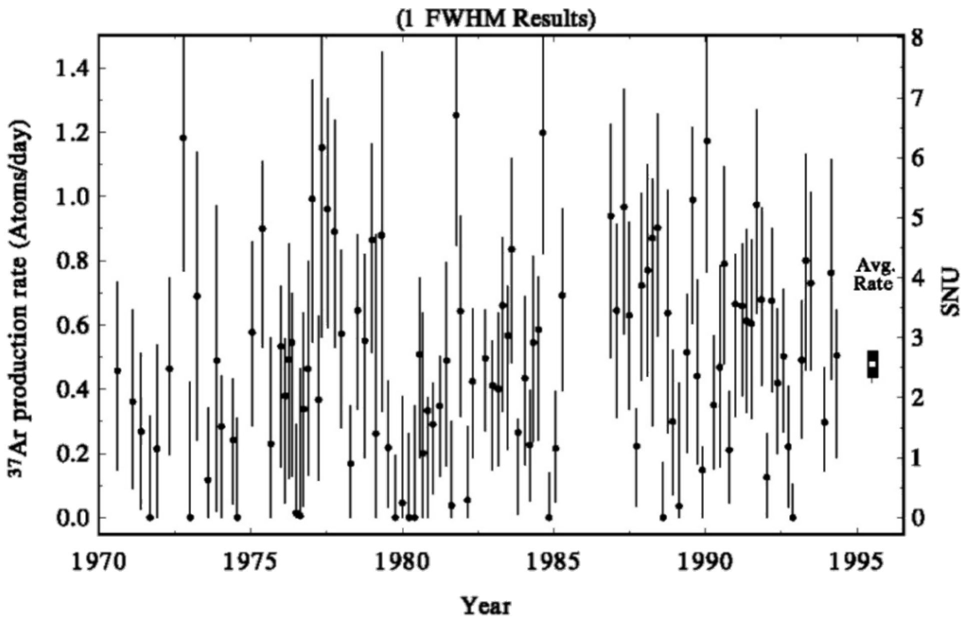
  (1 capture /sec /10^{36} atoms)

- Upper limit on ^{8}B < $2x10^6$ $cm^{-2}sec^{-1}$

Prediction: ~ 8 SNU

Solar neutrino problem
Homestake Cl experiment

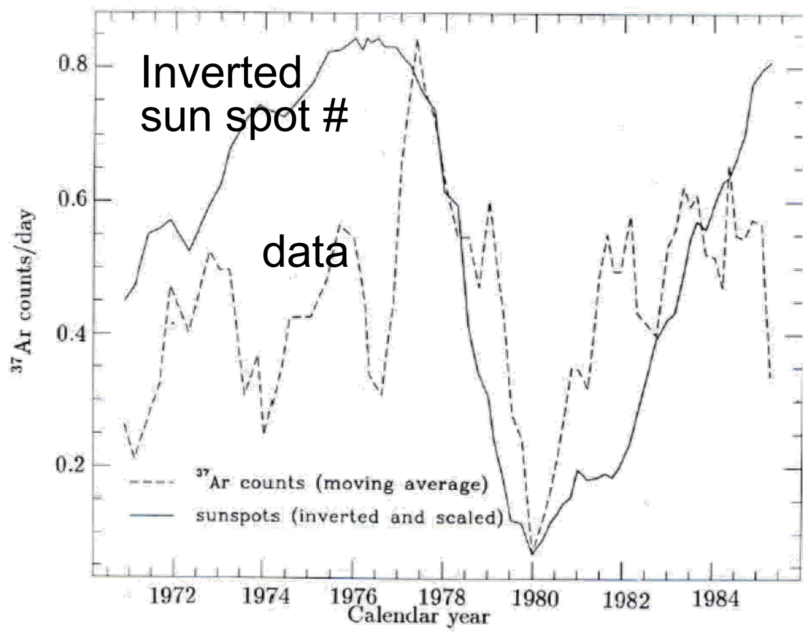
- **Result (1/3 of predicted) are persistent for about a quarter of century.**
  - Average(1970~1994)
    - $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU
  - Ratio(data/SSM) = 0.33 ± 0.3
- **Solar Neutrino Problem was recognized in early '70**



Questions:

- **Validity of the flux calculation**
  - Mostly ^{8}B (~76%) and ^{7}Be (~15%) neutrinos
  - ^{8}B: ~$1/10^4$ of the total solar neutrino flux
- **Radiochemical expeirment:**
  - unfamiliar to physicists
  - extract a few atoms from ~600 tons of material
- **Confusing 11 year modulation**

  → not confirmed later
- **not consistent with a simple 2ν vaccum oscillation**



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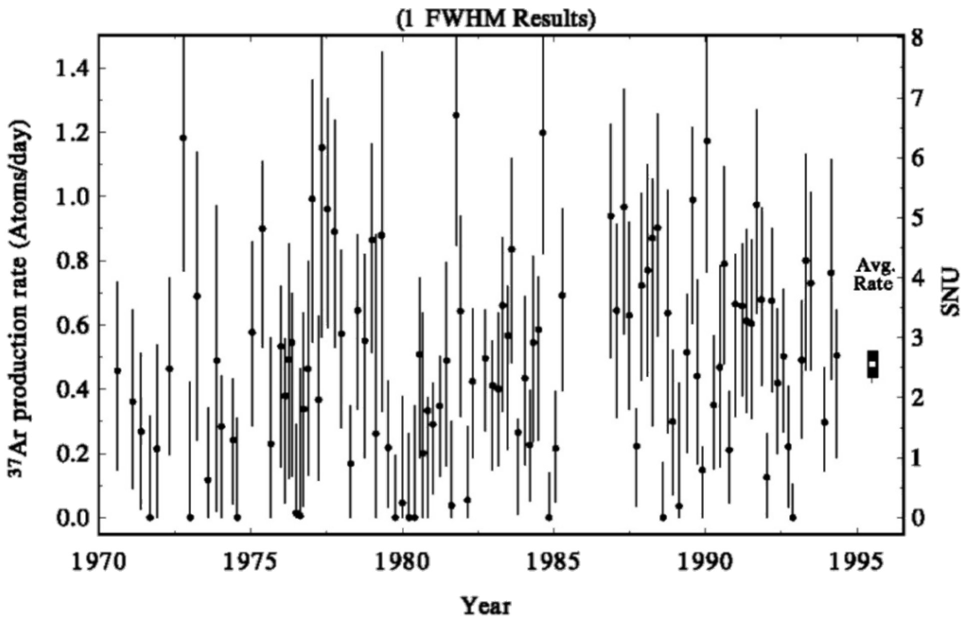

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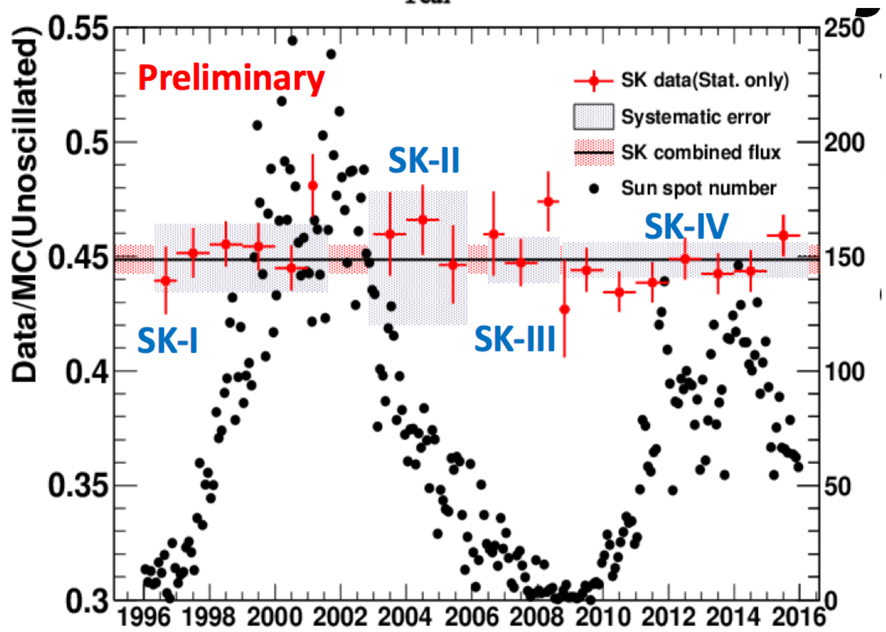
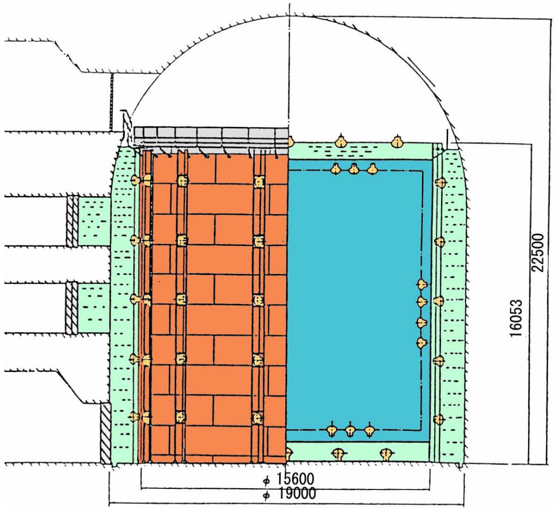


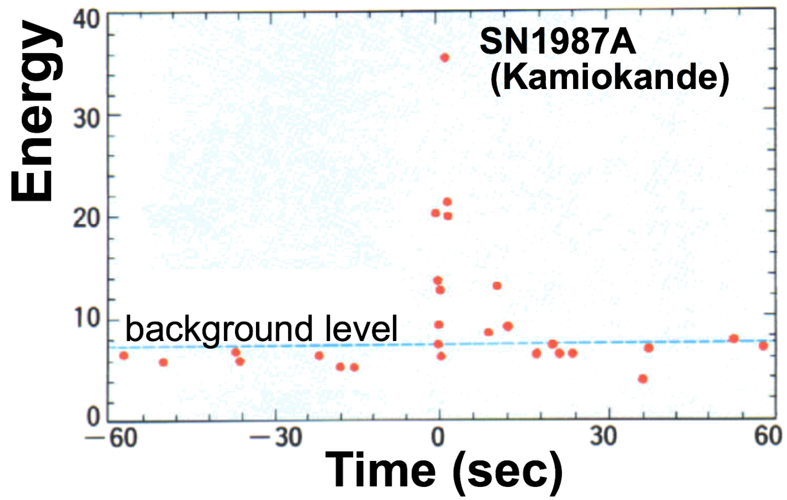
- **not consistent with a simple 2ν vaccum oscillation**

Kamiokande-II
2nd Solar neutrino experiment

- **1982: KamiokaNDE funded [operation:1983-1996]**
  - Scientific objects: proton decay, neutrino oscillation by atmospheric neutrinos, SN neutrino burst;
  - Initially solar neutrino was not strongly mentioned
  - Observation of $\mu \rightarrow e\nu\nu$ decay, realized that they were able to measure solar neutrinos by reducing the background (mostly Rn) and lowering the threshold……
- **Upgrade of the Kamiokande detector**
  - Set up anti-counter; Introducing timing electronics
  - Many efforts to reduce Rn: threshold → (9 MeV ~ 7.5 MeV)
- **1987: KM-II started, and 2 months later, observed ν burst from SN1987A**



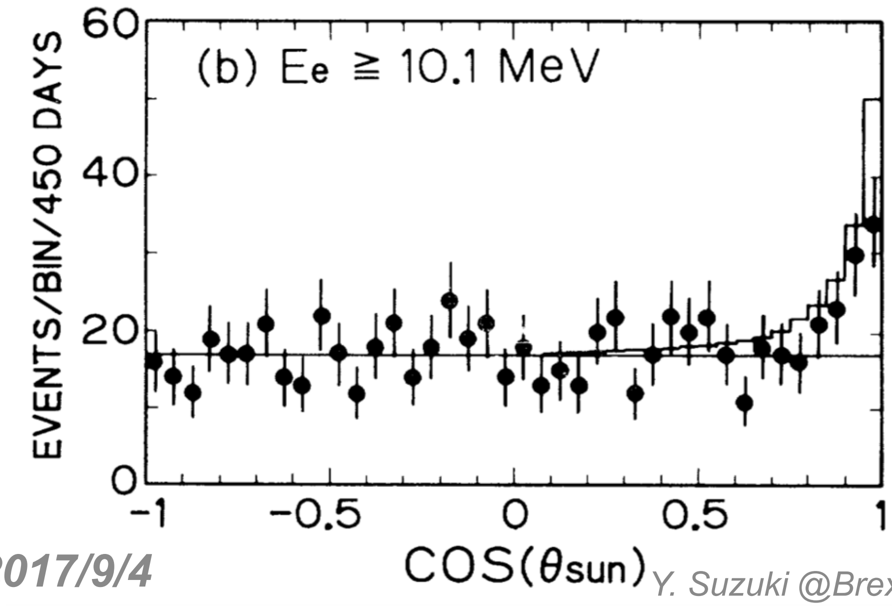
Total: 3000 tons
16 m in hight,
15.6m in diameter
Inner: 2140 tons
948 20-in PMTs
Fid. 680 tons for solar ν
Photo-coverage: 20%

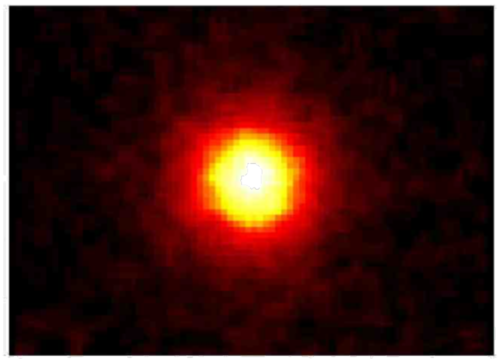


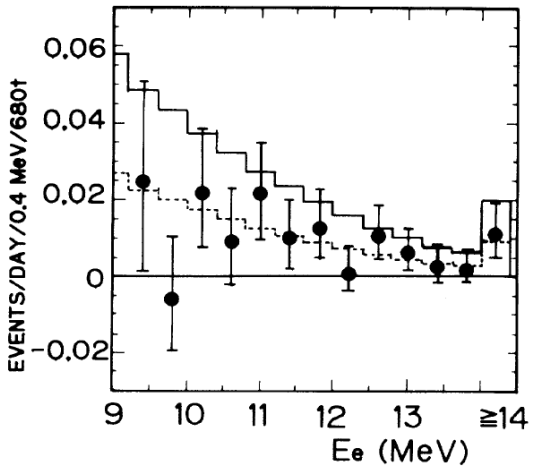
Kamiokande-II results

Homestake Cl experiment was the only solar ν experiment for ~20 years untill KM-II data was shown in 1989……

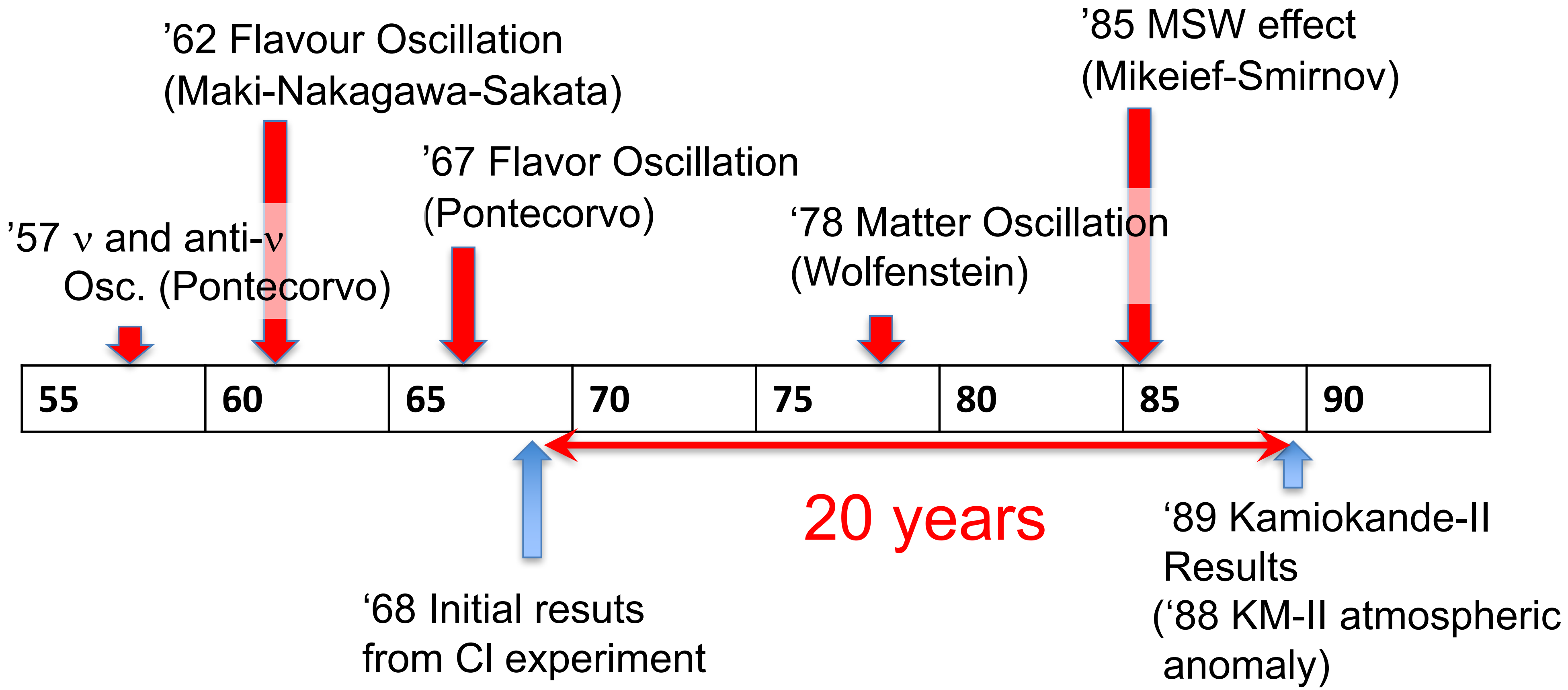
- **Kamiokande-II detects solar neutrinos through**
  - $\nu_e + e^- \rightarrow \nu_e + e^-$ (H_2O): CC + NC
  - $\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-$ (H_2O): NC $\quad \sigma(\nu_{\mu,\tau}e^-)/\sigma(\nu_e e^-) = \sim 0.15$
- **<u>1989 Result: confirmed the solar neutrino problem</u>**
  - **R(data/SSM)= 0.46±0.13(stat)±0.08(syst)**
  - **Homestake + KM-II → Stronger indication of the solar ν deficits**
- KM-II: measures Direction, Time, and Energy Spectrum







Development of the theoretical framework



3rd generation:

1974: tau
1977: bottom quark
1983: discovery of W/Z
1995: top quark
2000: tau neutrino

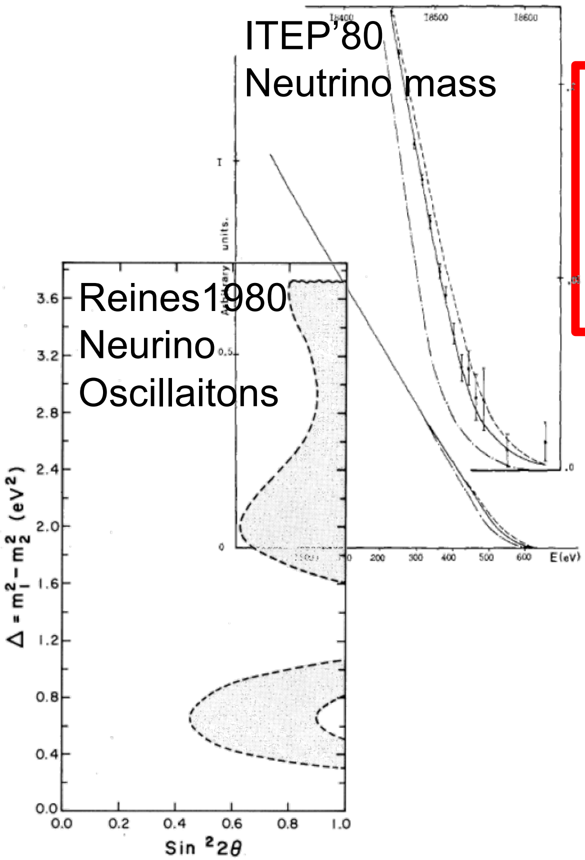
But ‘80s are not quiet time
“many discoveries”: 1st fever of ν mass and oscillation

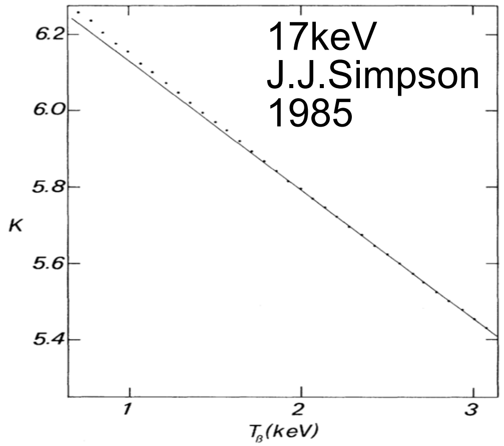
55	60	65	70	75	80	85	90

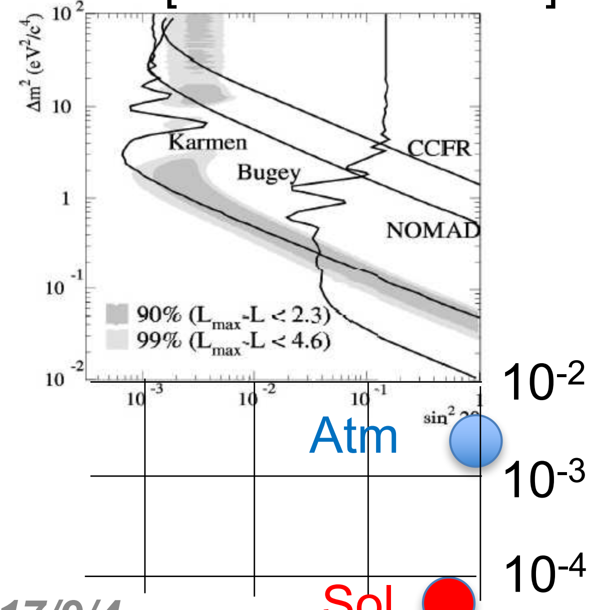
‘68 Initial results from Cl experiment

‘89 Kamiokande-II solar results
‘88 KM-II atmospheric anomaly

- **WRONG results**
  ➔ stimulate to create many new ν oscillation experiments
- especially reactor and accelerator neutrino oscillation experiments.
- >2 orders smaller to reach the true solution. [~1km ➔ ~100km]







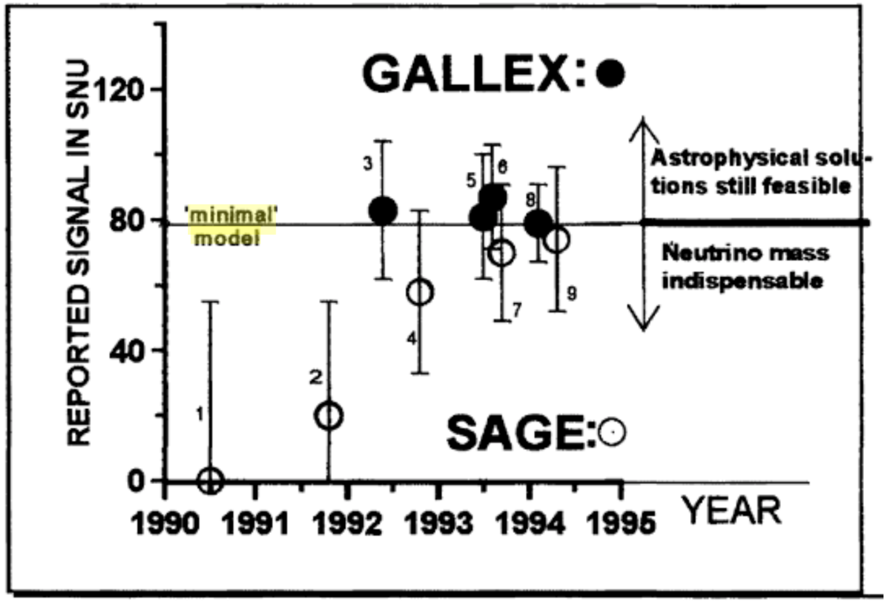
Experiments showing evidence for a heavy neutrino with a mass of 17 keV launched the new particle on an erratic eight-year career, during which it raised questions about the Standard Model of particle physics and about cosmological theories, stimulated many theoretical papers and pushed experimental techniques to their limit. Its demise provides grounds for faith in the efficacy of the scientific method. (D. Morrison, in Nature)

Early '90s
Gallium experiments

- In 1966 (Idea)
  V.A. Kuzmin and G.T. Zatsepin
  $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$
  $E_{th} > 230keV$
- Attempt to measure pp-ν

- **SAGE in Baksan**
  - (1989 ~ still running)
  - Metallic Ga
- **GALLEX/GNO in GranSasso**
  - (1991~2004)
  - $GaCl_3$

GALLEX-Neutrino94

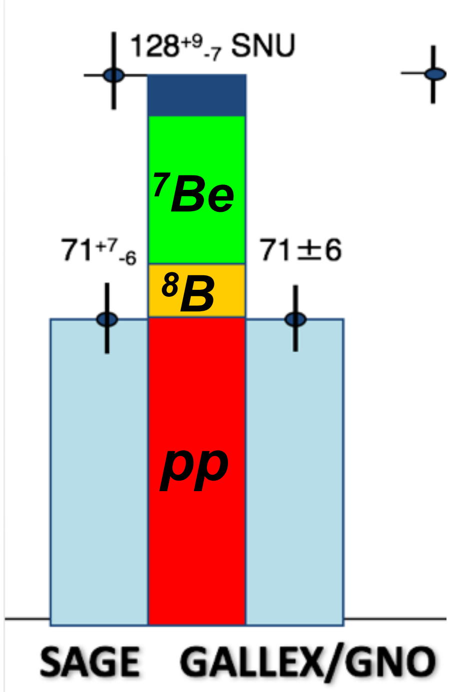


Gallium experiments pp-neutrinos

SAGE: 65.4+3.1/-3.0(stat)+2.6/-2.8(syst) SNU
(data: December 89 ~ December-07) → continuing

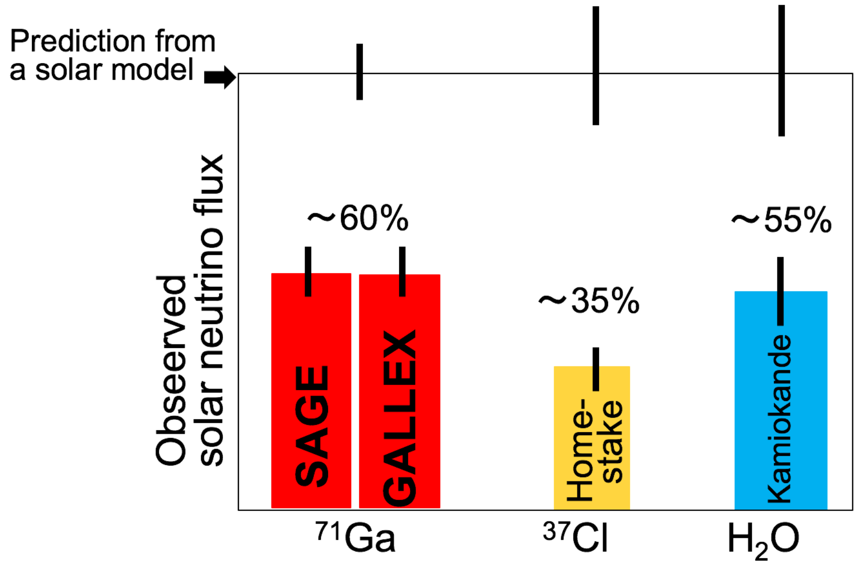
GALLEX/GNO 69.3+/-4.1(stat)+/-3.6(syst) SNU
(data: May 91 ~ April 03)

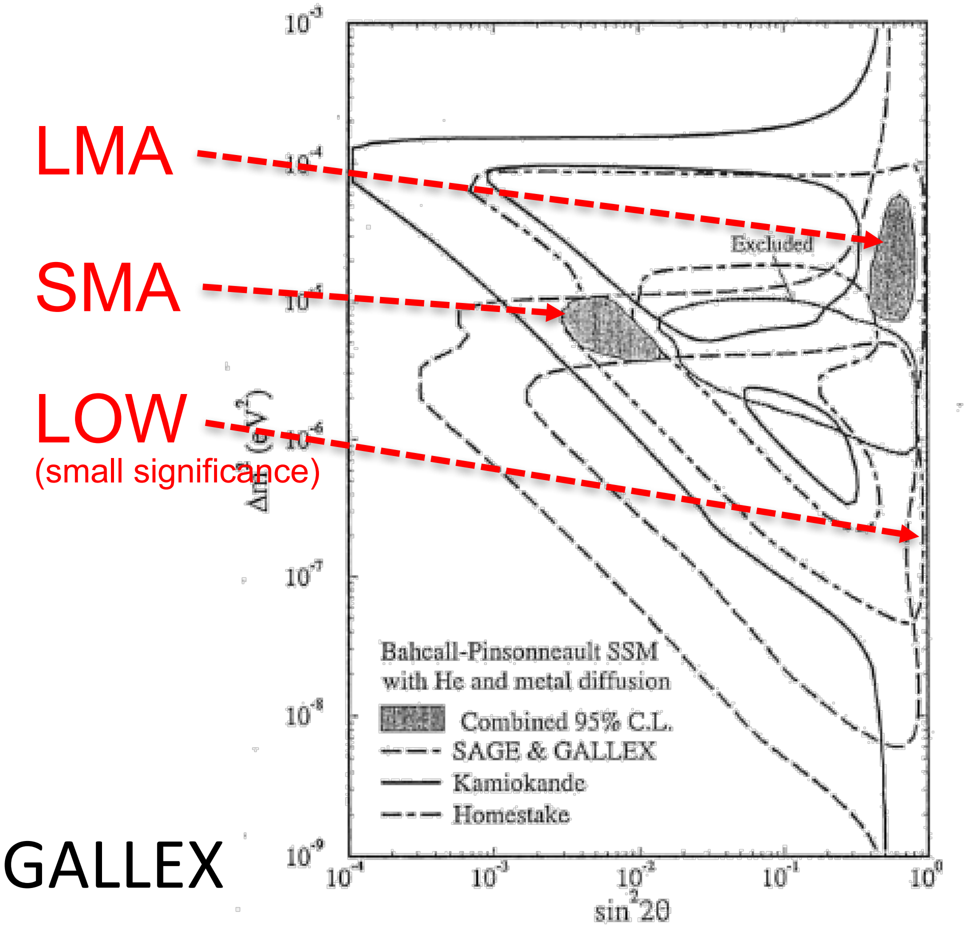
Ratio to SSM: 0.51(SAGE); 0.54 (GALLEX/GNO)



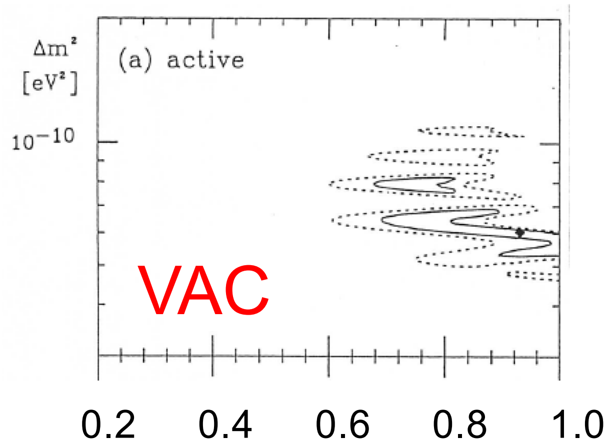
- Observed deficit of neutrinos
  - Ga: pp-ν + ^{7}Be + ^{8}B + CNO + pep
    (Homestake & KM ~ ^{8}B neutrinos)
- Solar luminosity constraint on pp-ν
  ➔ thought to be a big constraint
  - but could not provide a definitive conclution
- ...minimal model......Astrophysics STILL possible

4 solar ν experiments give 4 solutions





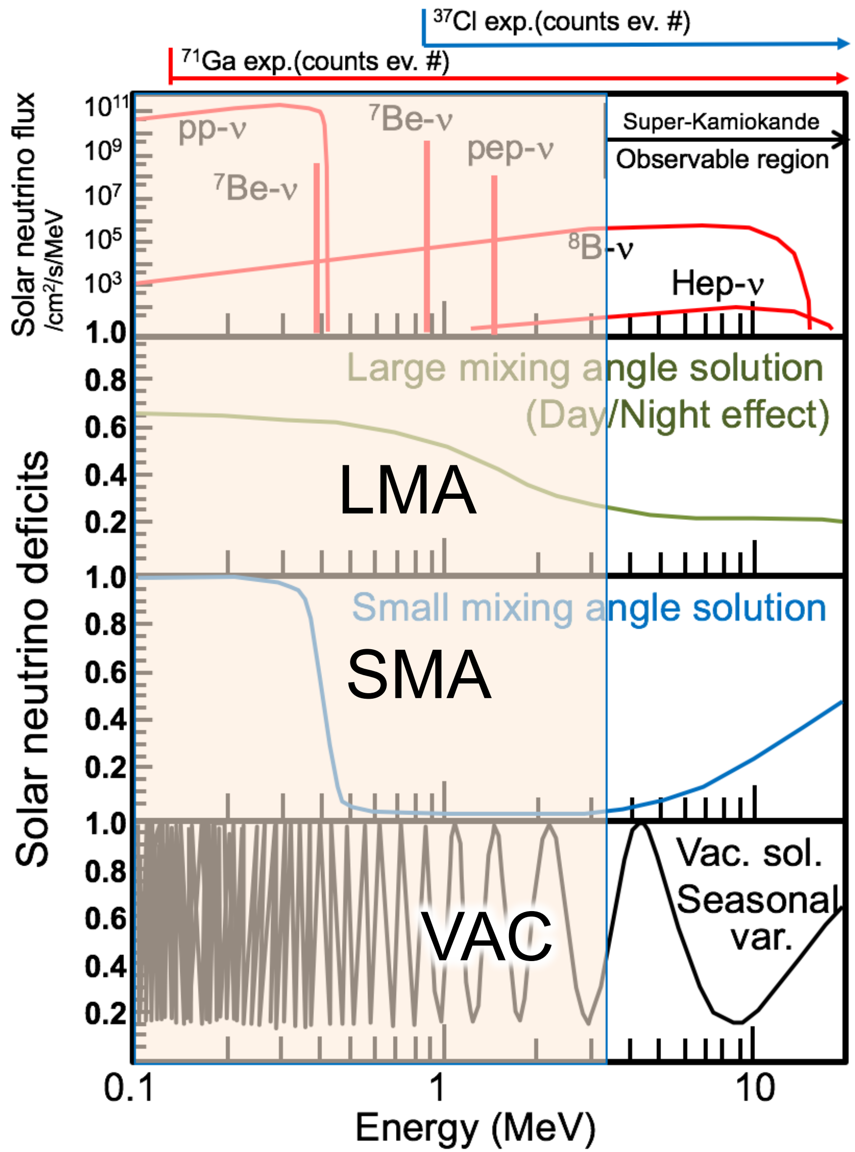
- 4 experiments: Cl, KM, SAGE, GALLEX
  - ➔ showed deficits of solar neutrinos
- Let's use the neutrino flux expected from a standard solar model
  - ➔ 4 allowed parameter (Δm^2, $\sin^2 2\theta$) regions by the oscillation hypothesis



To resolve the solar neutrino problem
smoking gun evidence

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

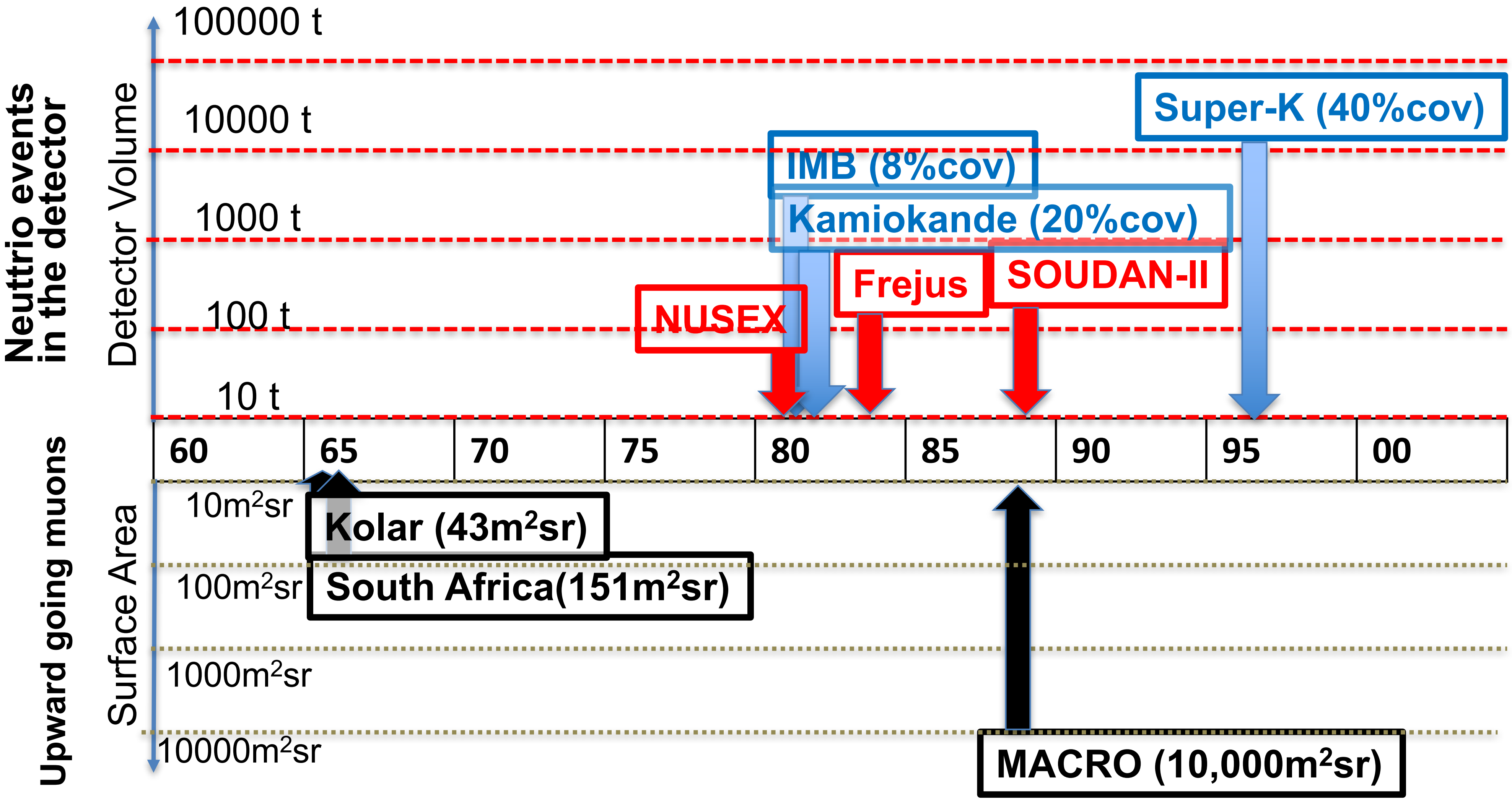
➔ Strategy for SK solar ν



Will be back to
the solar neutrino later

Atmospheric Neutrinos

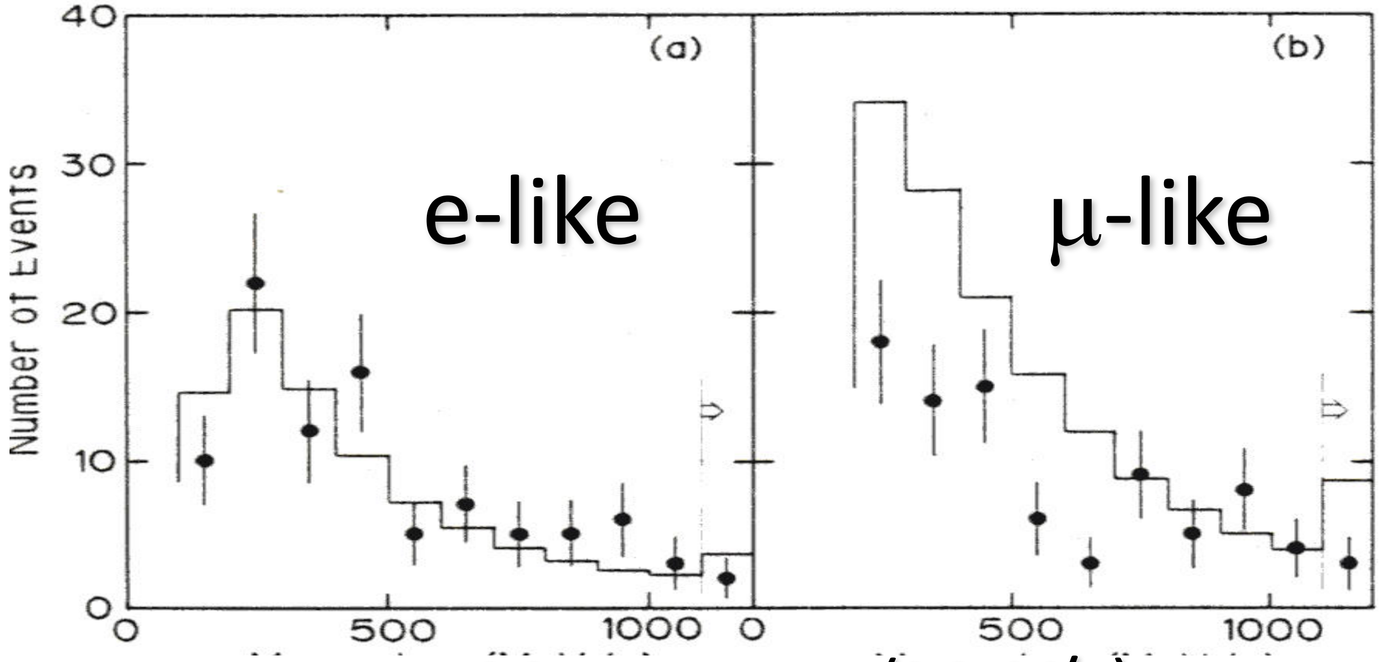
Major players of the atmosphric neutrinos



Early Hints from Kamiokande-II

- **1988: atmospheric neutrino anomaly**
  - Kamiokande Observed fewer μ-like events in atmospheric ν interactions than expected

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



Atmospheric Neutrino Anomaly

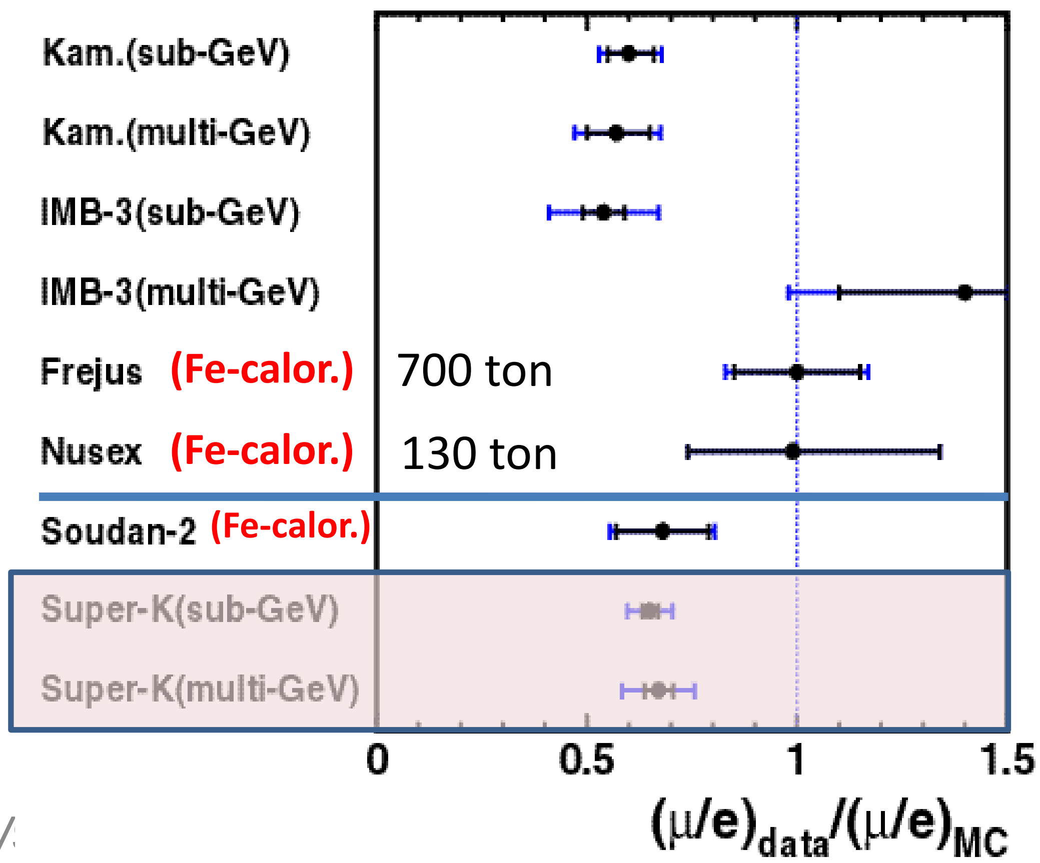
- Why this observation was not widely accepted as a neutrino oscillation?
- Probably the reasons were the followings
  1. Statistic was small
  2. Results strongly depend upon the atmospheric neutrino flux calculations
  3. There were large uncertainties in the flux calculations
     - Primary cosmic ray flux, primary interactions, secondary particles productions, decays, earth's magnetic fields, modulations, parameters for atmosphere,………

Atmospheric Neutrino Anomaly

4. Another important issue was that theorists did not believe ‘large mixing’. This was the prejudice that mixing must be small like quark mixing.
5. In late 80’s, neutrinos were one of the candidates of dark matter particles and the mass needed was $\sim$ O(1 eV) which contradicted with the indication from atmospheric neutrinos unless strong degeneracy was assumed
6. The earth size is just so to observe atmospheric neutrino oscillation which people thought ‘fine tuning’.

Confusions in atm ν in early 90’s

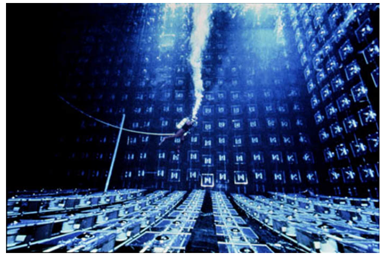
- Other experiments: inconsistent with the KM result
  - IMB, Frejus, Nusex ➔ But IMB confirmed 1992
  - Systematic bias (?) between Iron Calorimetry (no deficits) vs Water Ch. ➔ settled 1997 by Soudan-II

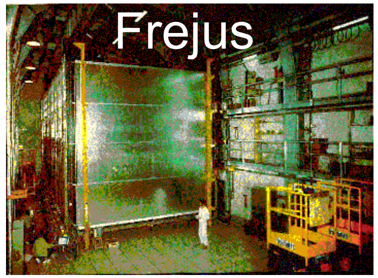


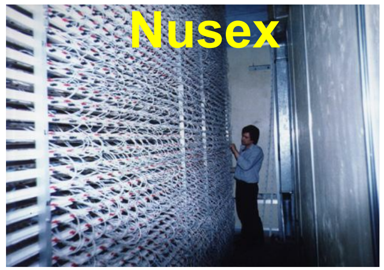
1988

1992

1997

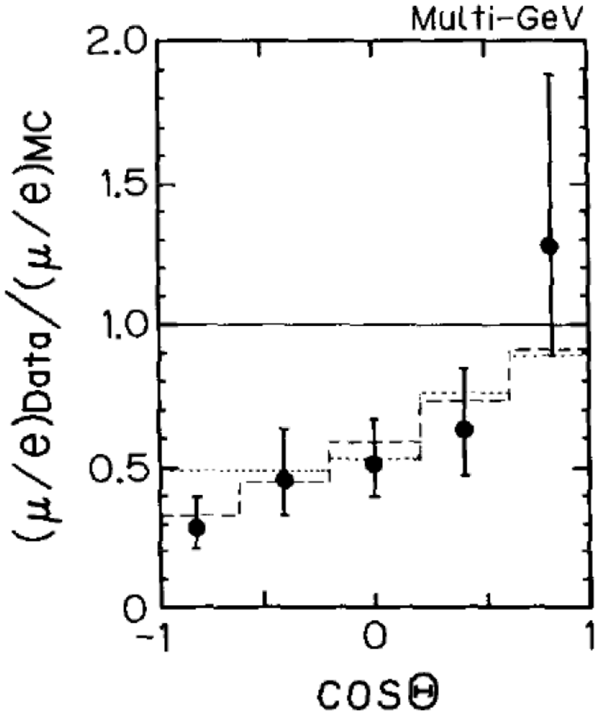






To establish the atm-ν oscillation

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



Kamiokande, PLB, 335 (94)237

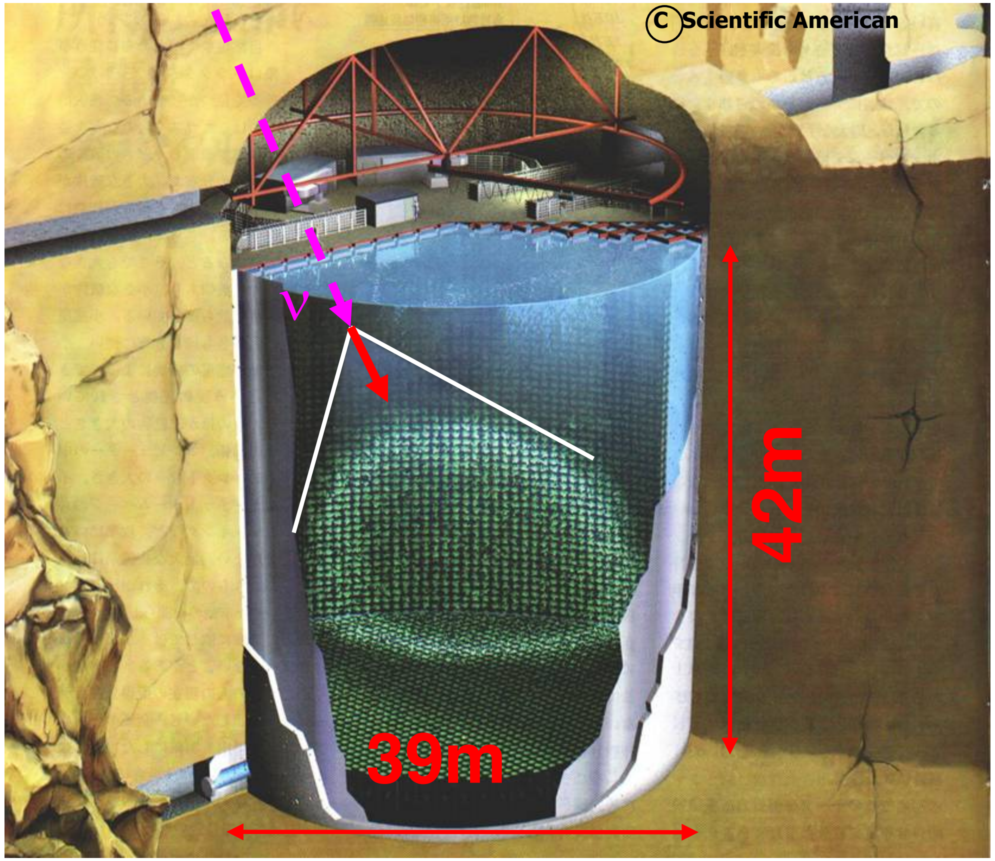
---------- $\nu_\mu \rightarrow \nu_e$ (1.0, 1.8 x 10^{-2} eV^2)

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

This was thought as a compelling evidence for the ν oscillation

→ **Strategy of Super-K**

Super-Kamiokande (21 years old !)

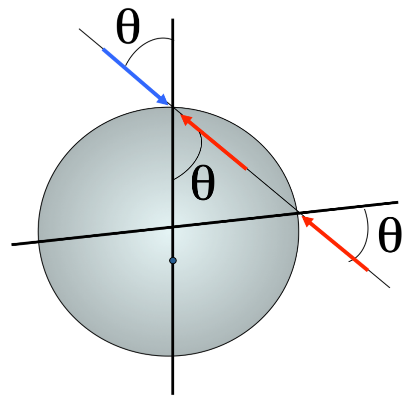


- 50,000 tons (22,500 ton fid.) Imaging Water Cherenkov Detector
- 1,000 m underground
- Inner-Detector (ID)
  - 11,146 50cm PMTs (40%)
- Outer-Detector (OD)
  - 1,885 20cm PMTs

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

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)

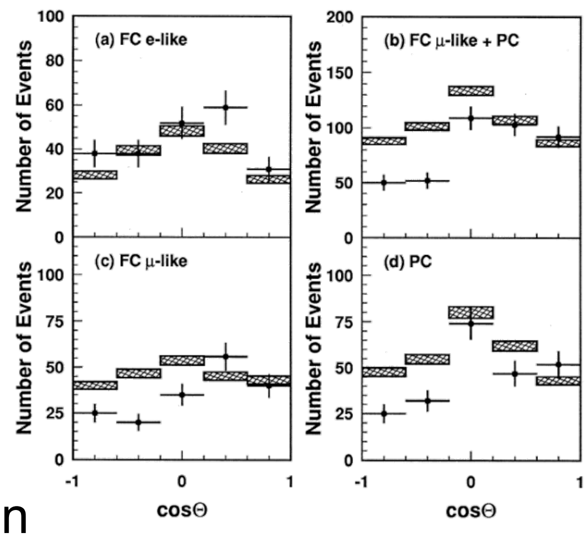
"Study of the atmospheric neutrino flux in the multi-GeV energy range"

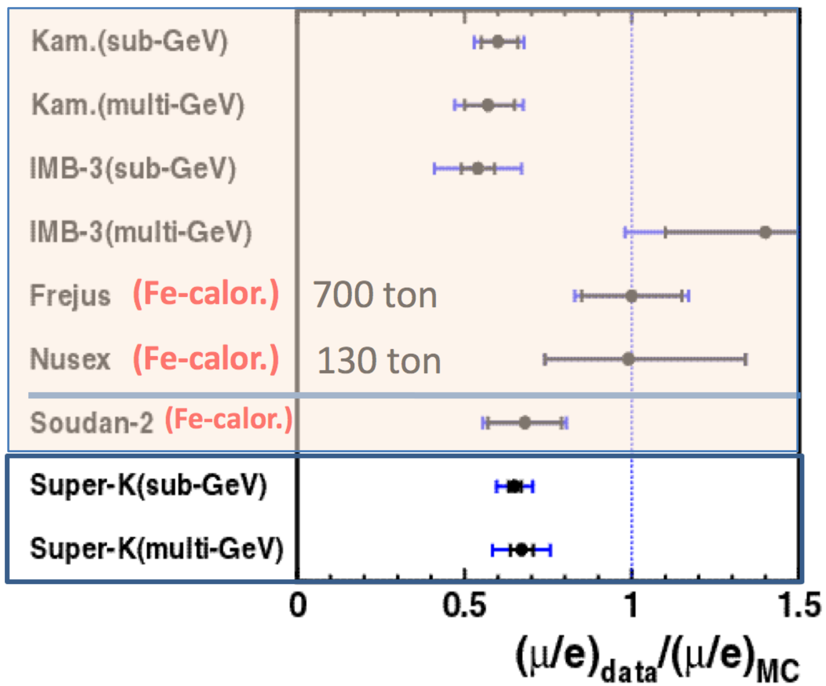
(multi-GeV) [414days]

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

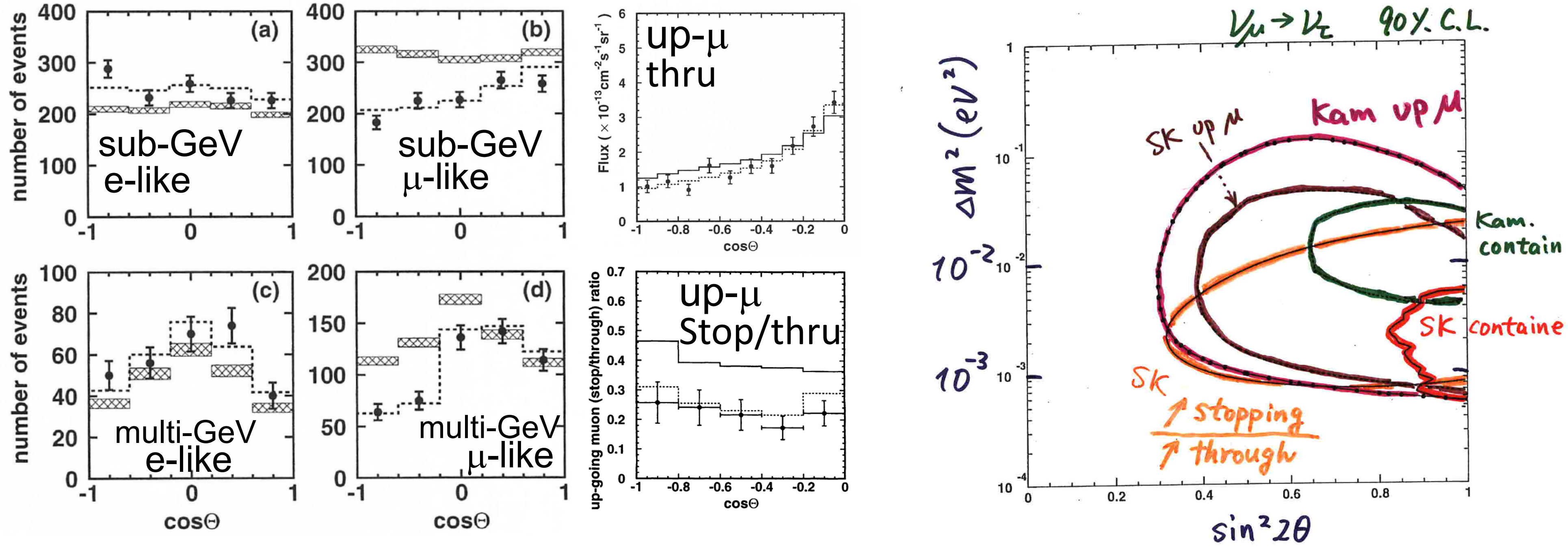
An email from spokesperson, Yoji Totsuka, to the four conveners of the atmospheric neutrino analysis

dated on 25th of April, 1998

~ 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] *

F. Wilczeck

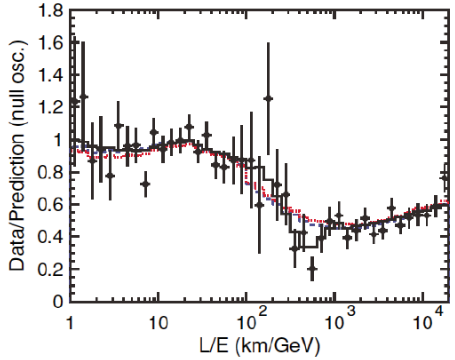
[a]Institute for Advanced Study,
School of Natural Sciences, Olden Lane,
Princeton, New Jersey 08540

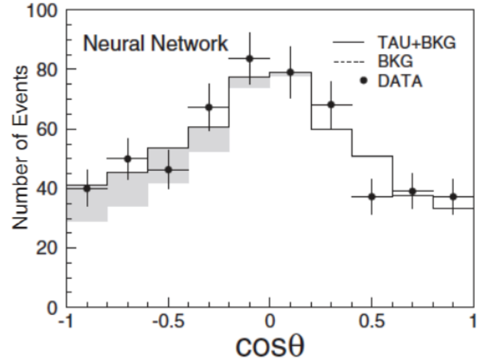
Summary Talk
@NEUTRINO'98

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.

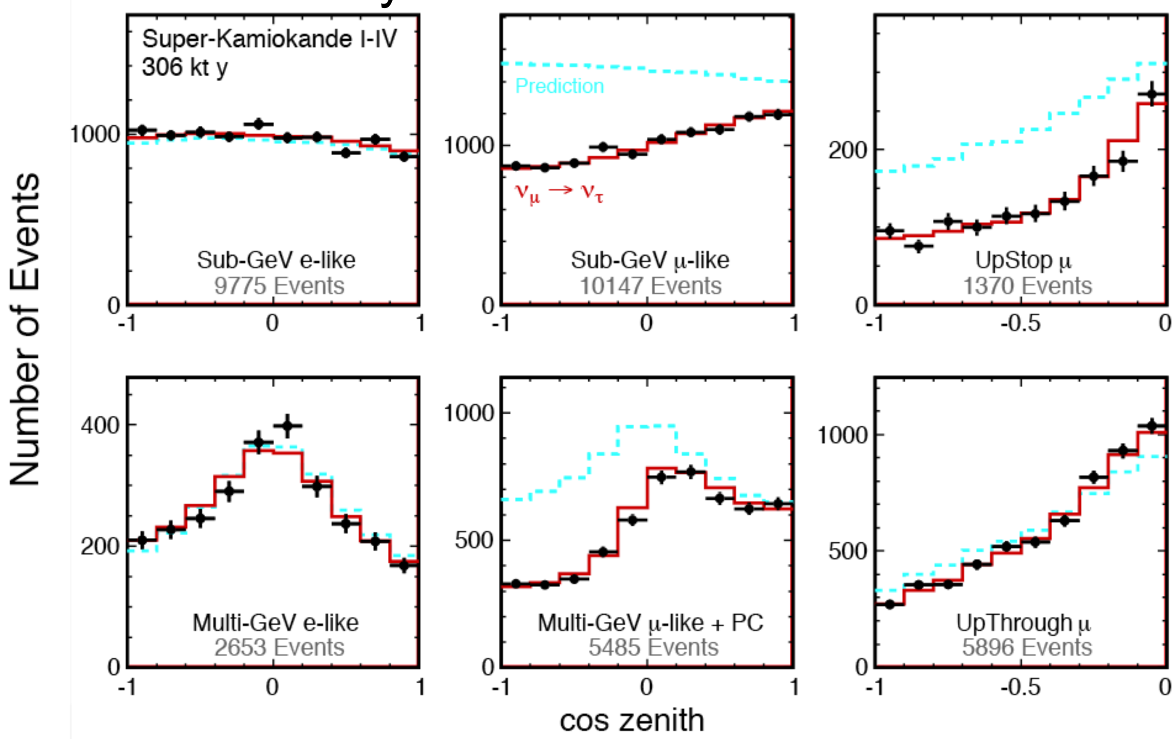
After the discovery

- 2004: Oscillatory behavior
- 2007: Tau appearance

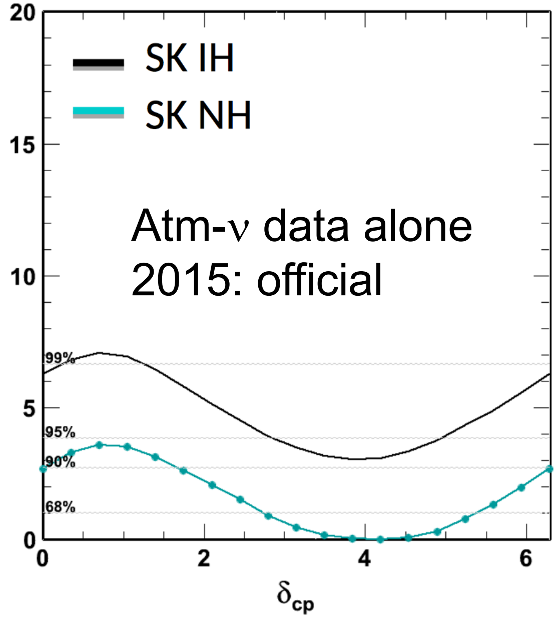




~ 20 years of data accumulation



- **Mass Hierarchy & δ_{CP}**



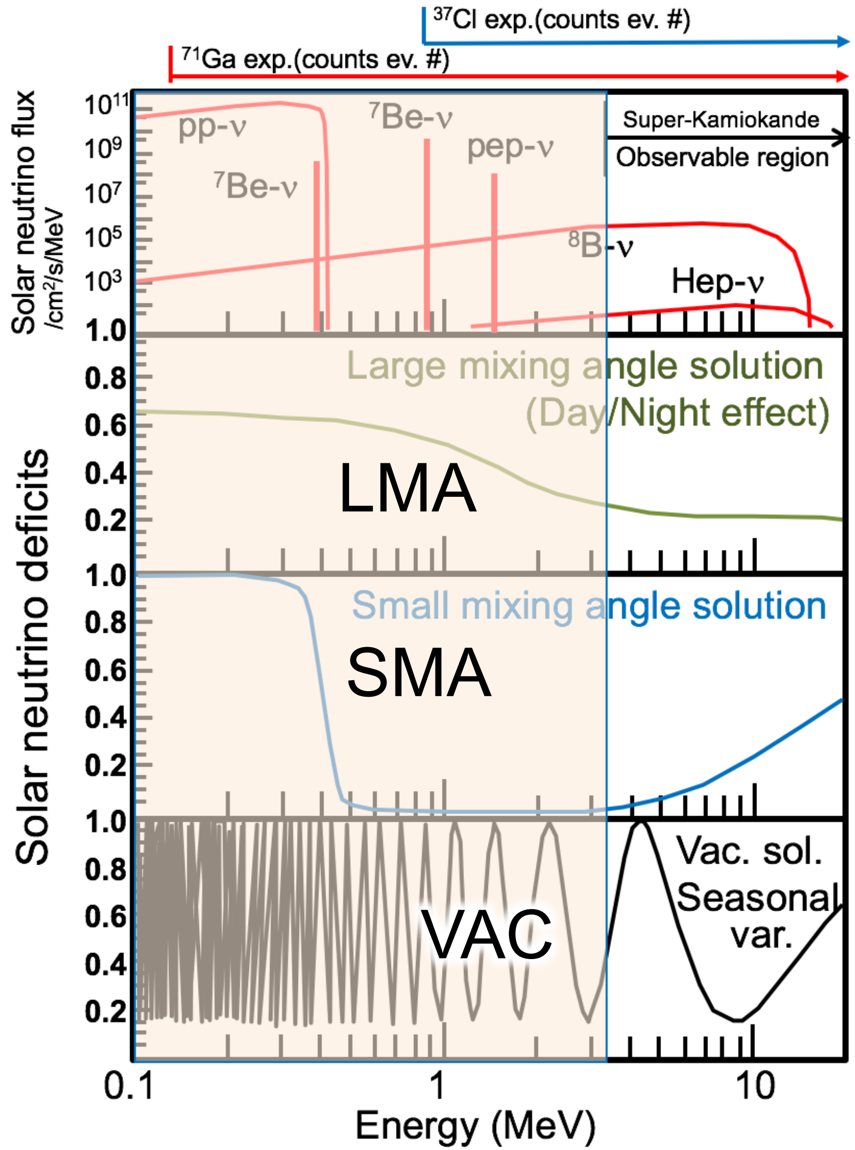
- ***<u>long-baseline oscillation experiments, K2K/T2K, Minos and so on later have provided significant results on θ_{23}, θ_{13}, MH and δ_{CP} as well as atm-ν</u>***

Back to Solar Neutrino Oscillations

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
- Flux independent & compelling evidence fpr the oscillations
- Able to determine the solution
  - Super-K can measure the energy spectrum and time variation very precisely



➔ Strategy for SK solar ν

Super-K Solar ν results

Two SK papers in PRL on 18th June 2001 issue (1258 days)

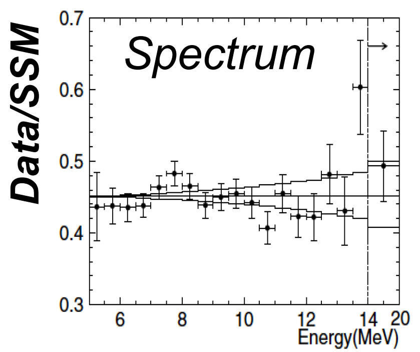
Paper 1: Flux measurement

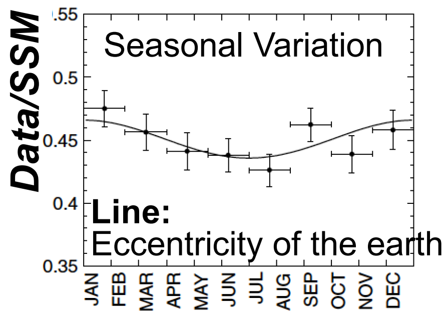
- Solar ^{8}B and hep Neutrino Measurements

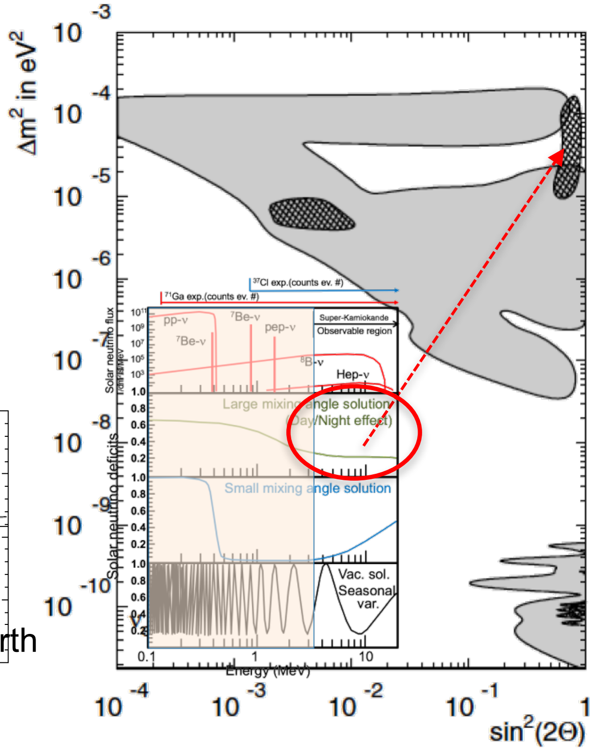
Paper 2: Oscillation analysis

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

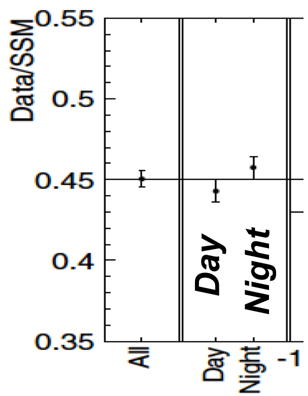
➔ LMA solution remained





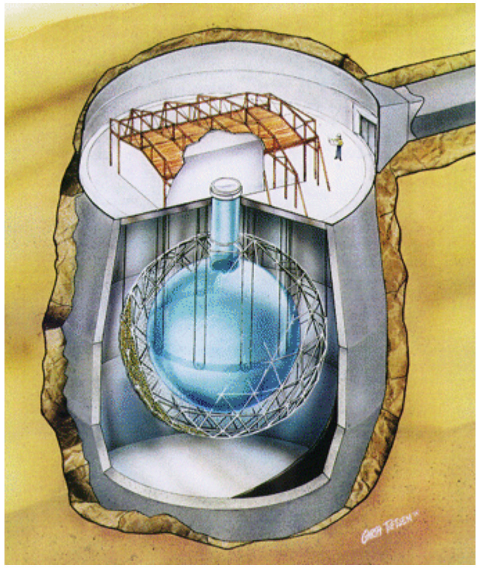


- <u>However, the Day/Night effect, the smoking evidence for LMA, was less than 2 sigma, not sufficient to claim positive evidence</u>
- A kind of strange situation !
- We, SK, found the solution, but needed “another” evidence which was independent from the flux calculation



SNO

- 1000 tons D_2O
  - 12m Diameter Acrylic Vssel
- 1700 tons H_2O Inner Shield
- 9500 PMTs, 60% coverage
- Outer Shield H_2O
  - 5300 tons



Charged Current (CC)

$\nu_e + d \rightarrow p + p + e^-$

sensitive only to ν_e

Electron scattering (ES)

$\nu + e^- \rightarrow \nu + e^-$

ν_e and (ν_μ, ν_τ)x~0.15

Neutral current interaction (NC)

$\nu_x + d \rightarrow \nu_x + p + n$

1) $n + d \rightarrow t + 6.25$ MeV γ

2) $n + {}^{35}Cl \rightarrow {}^{36}Cl + 8.6$ MeV $\sum\gamma$

3) $n + {}^{3}He \rightarrow p + t + 0.76$ MeV

sensitive to all neutrinos

Evidence from SNO+SK on 18th June, 2001

- **18-June-2001: SNO announced the discovery of Solar Neutrino Oscillation**

  using
  - **SNO: charged current →ν_e** 35%
  - **SK: Electron Scattering →ν_e+0.15(ν_μ+ν_τ)** 46.5%
- Found there are non-electron neutrino components in the solar neutrinos measured on the earth

3.3σ

Phys. Rev. Lett. 87, 071301, SNO Collaboration

(Received 18 June 2001; published 25 July 2001)

Solar neutrinos from ^{8}B decay have been detected at the Sudbury Neutrino Observatory via the charged current (CC) reaction on deuterium and the elastic scattering (ES) of electrons. The flux of ν_e's is measured by the CC reaction rate to be $\phi^{CC}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{syst}) \pm 0.05(\text{theor}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$. Comparison of $\phi^{CC}(\nu_e)$ to the Super-Kamiokande Collaboration's precision value of the flux inferred from the ES reaction yields a 3.3σ difference, assuming the systematic uncertainties are normally distributed, providing evidence of an active non-ν_e component in the solar flux. The total flux of active ^{8}B neutrinos is determined to be $5.44 \pm 0.99 \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$.

Evidence from SNO+SK on 18th June, 2001

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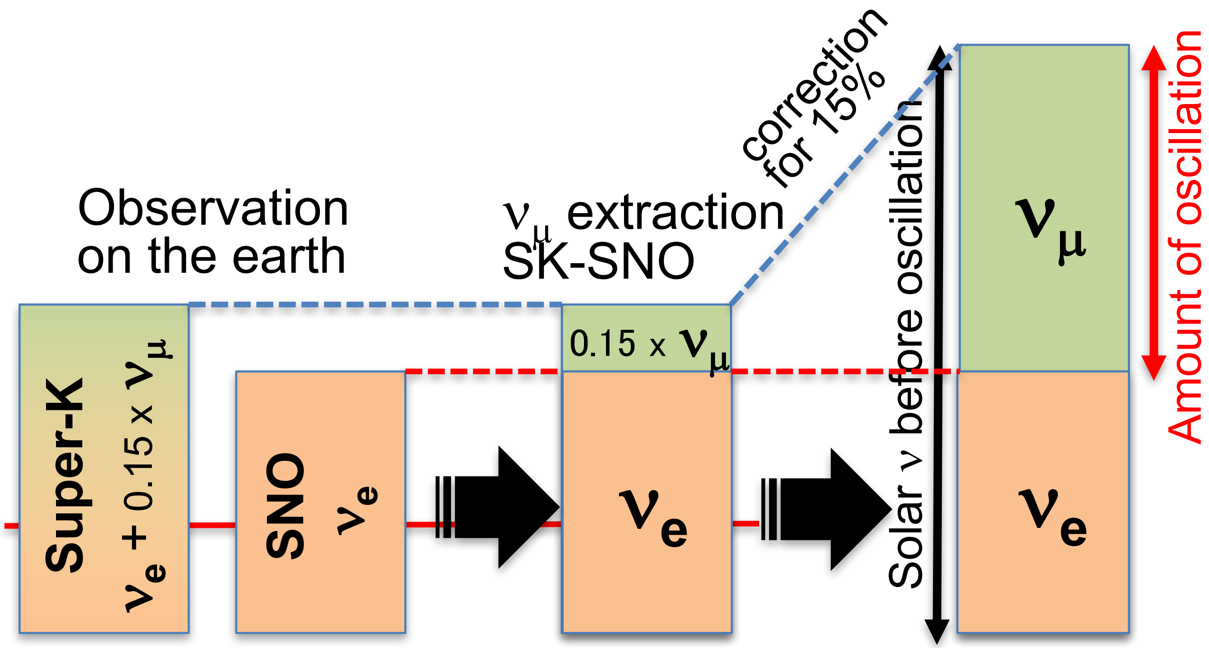
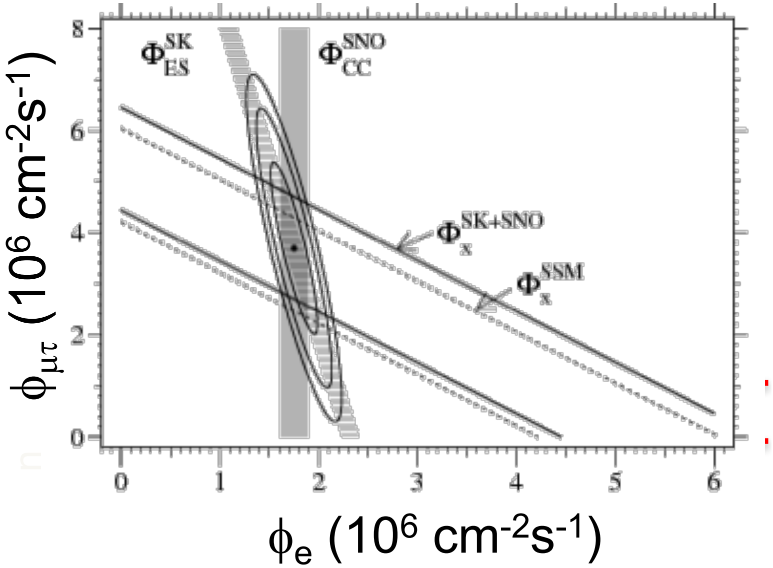
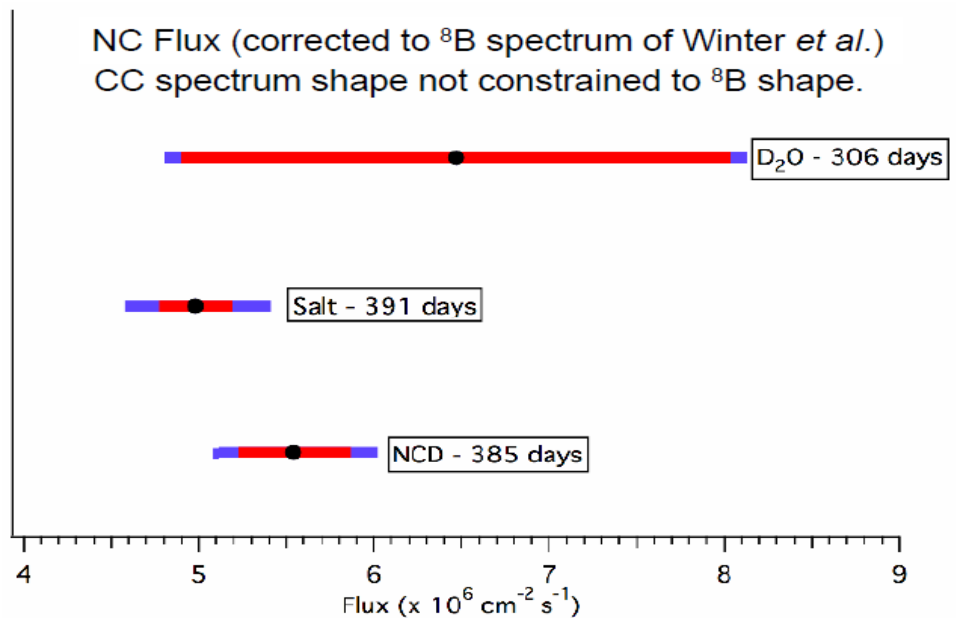
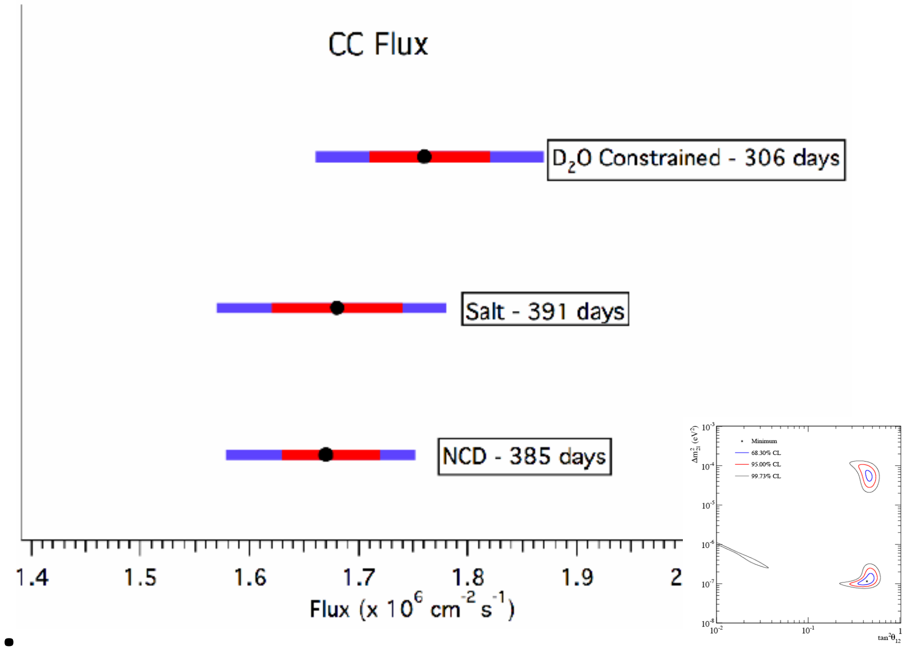


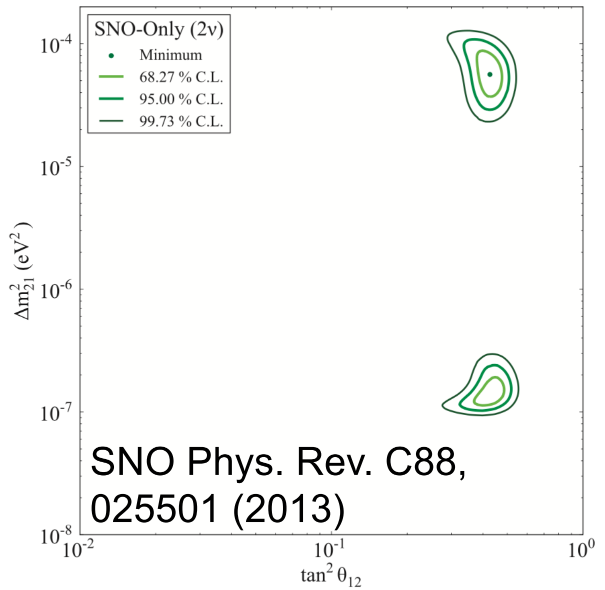


2002~ SNO Neutral Current

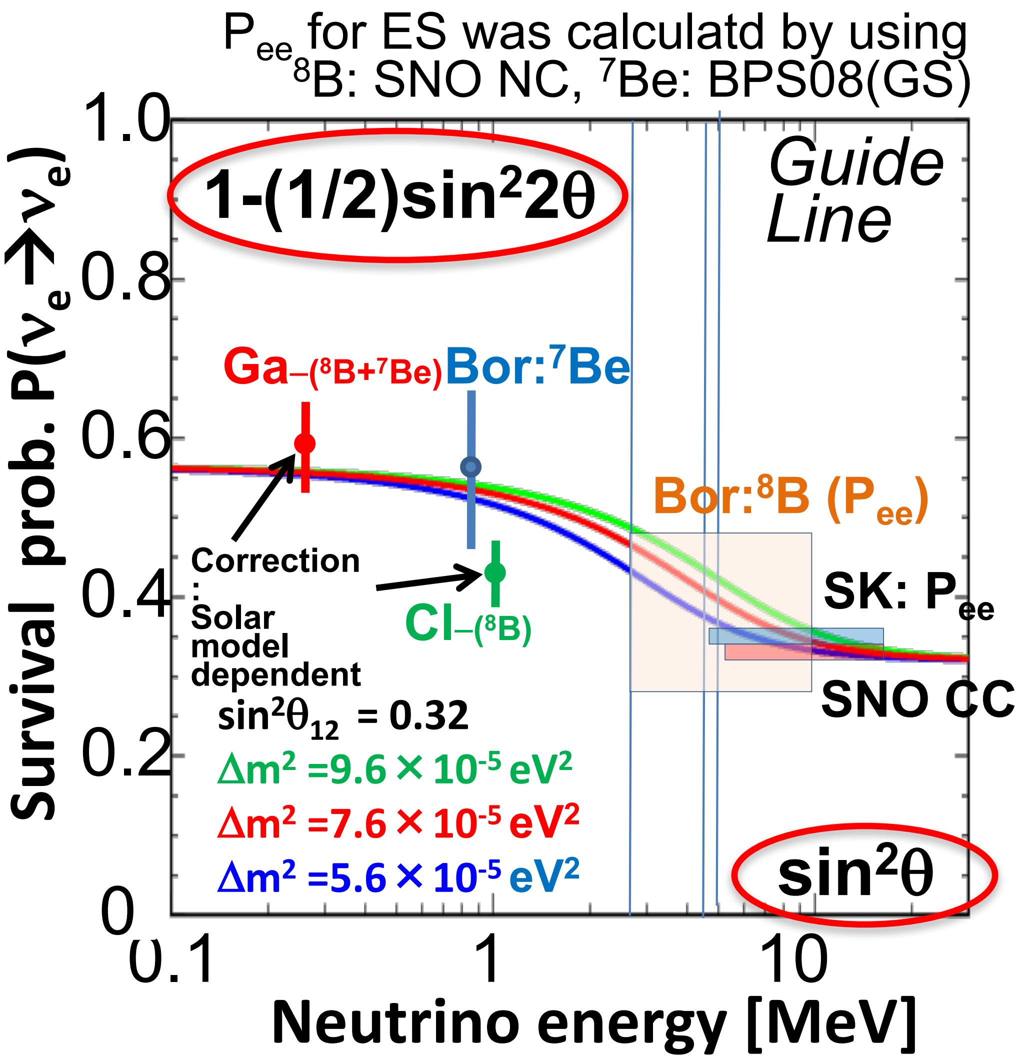




- **SNO firmly established the solar neutrino oscillation by itself.**
- SNO data itself cannot point the large mixing angle solution.
- We need to combine the results from <u>all the solar neutrino experiments</u> to obtaine the LMA
- **In this sense the observation of day/night effect (direct evidence for LMA) is still very important.**



Large Mixing Angle (LMA) Solution



- **Vacuum in low energy:**
  - $P_{ee}=1-(1/2)\sin^2 2\theta$
- **Matter in high energy (>5 MeV):**
  - $P_{ee}=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$

    ➔ $P_{ee}=\sin^2\theta$ ($\theta_m \to \pi/2$)

$$\tan^2 2\theta_m = \frac{\tan^2 2\theta_v}{1-(2p\sqrt{2}G_F n_e)/(\Delta m^2\cos 2\theta_v)}$$

= 0 **Resonance condition**

- **Δm^2 region 10^{-5} to 10^{-4} eV^2**

  $\Delta m^2 < 1.6\times10^{-4}$ eV^2 **Eν >10MeV ➔ resonance**

  $\Delta m^2 < 0.8\times10^{-4}$ eV^2 **Eν > 5MeV ➔ resonance**

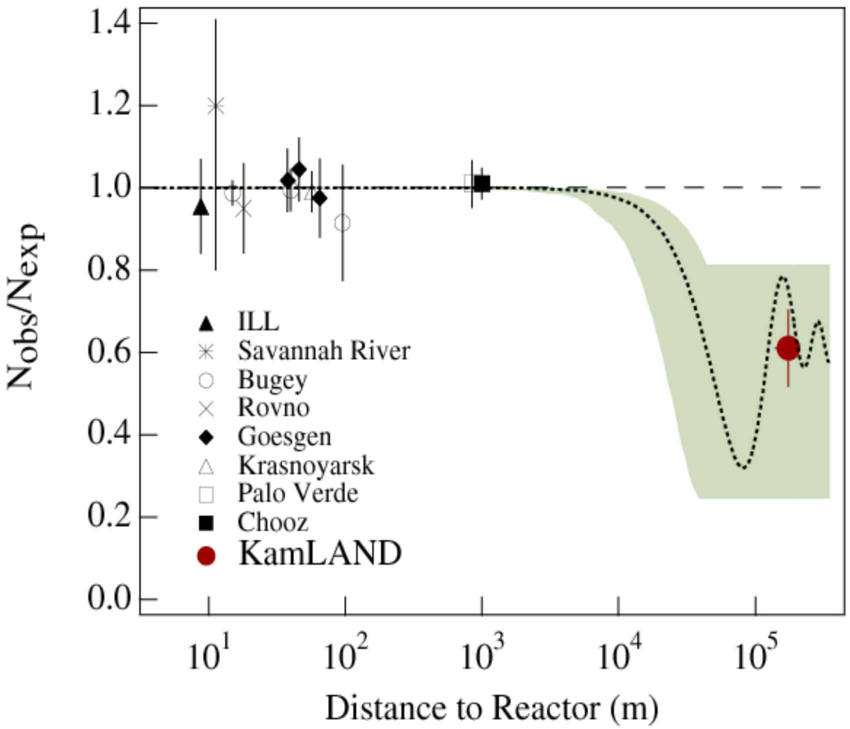
  $\Delta m^2 > 1.6\times10^{-5}$ eV^2 **Eν < 1 MeV ➔ no res.**

- **Transition Vac ➔ Matter: 1~a few MeV**

  ➔ sensitivity on Δm^2 from the exp's

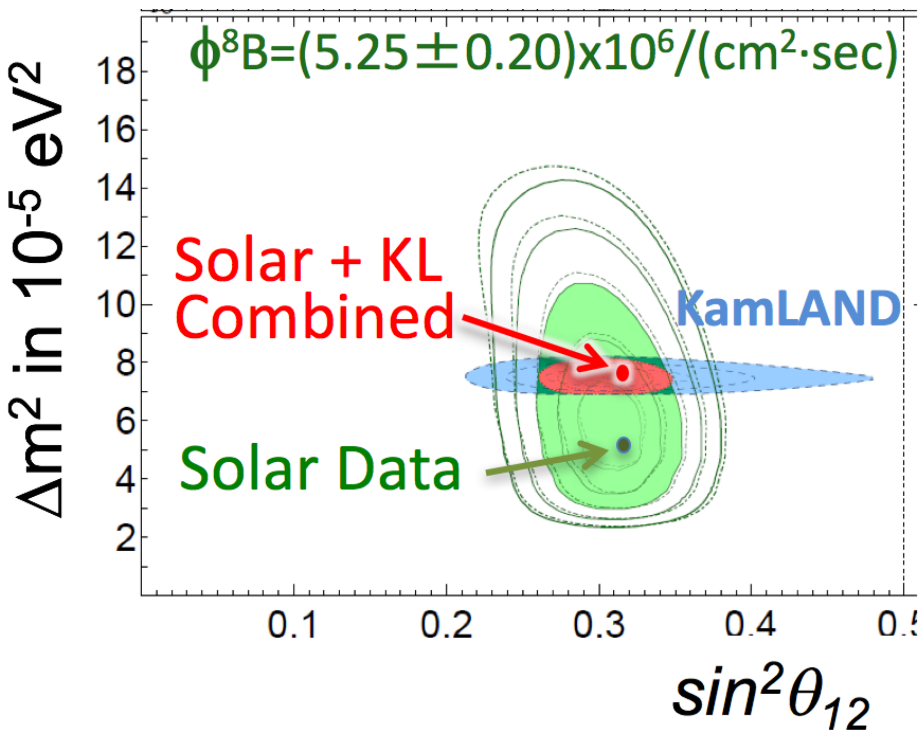
  ➔ good place to look for exotics

2004 KamLAND vs Solar



- KamLAND (Reactor): Known distance and known energy E
  → precise determination of Δm^2~E/L
  Just a right distance
  (1st or 2nd oscillation phase)

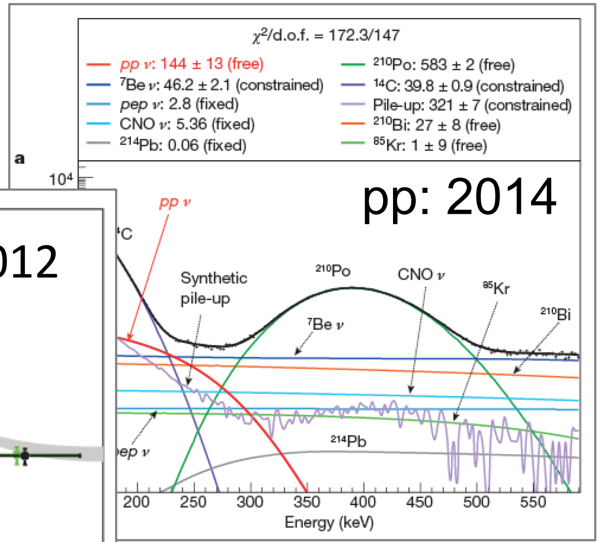
- Solar (LMA) → mixing angle determination

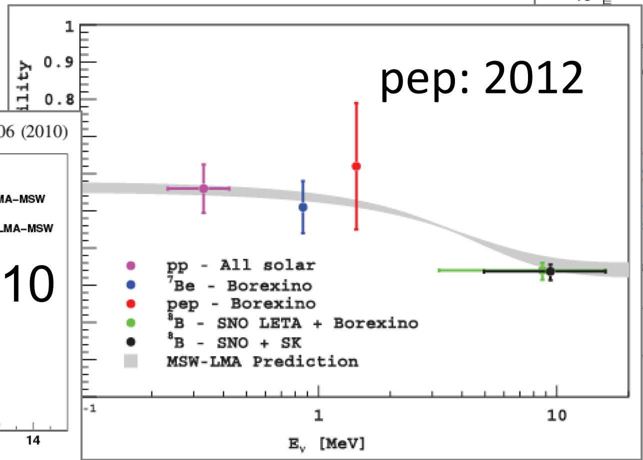


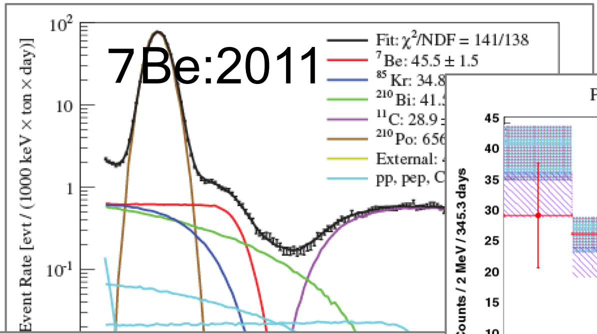
- First data in 2004: 141.1 days
- Observe: 54 events (expects 86±5.6 events)
- Ratio = 0.661±0.085±0.041

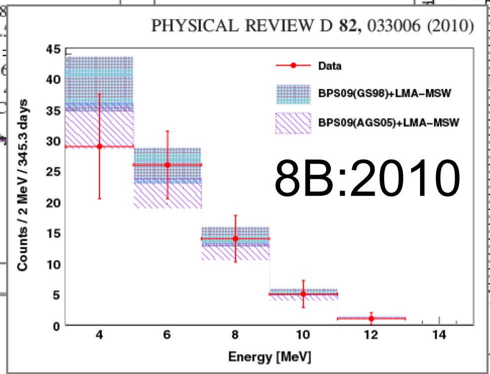
Solar neutrinos after the discovery

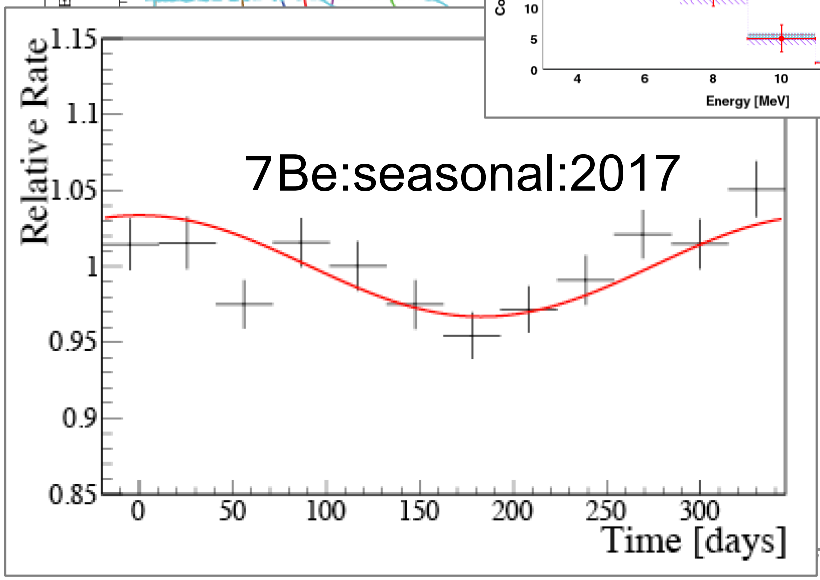
- ***Borexino:*** making many important new measurements of low energy solar neutrinos
  - – ^{7}Be, ^{8}B, pep, pp,,,,testing solar models
  - ➔ will be discussed more in the later section











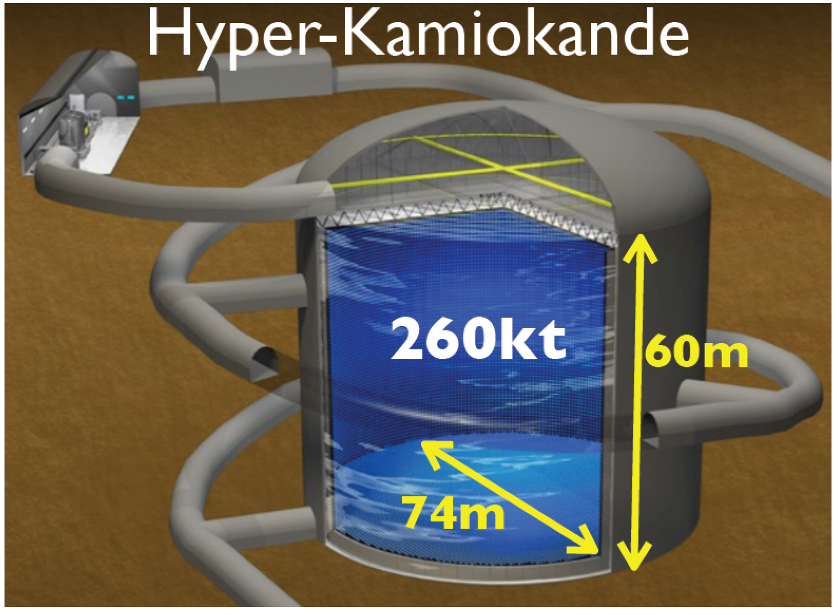
SAGE, SK are still running

- SAGE: precise measurement; sterile neutrinos,,,,
- SK: observed D/N effect with 2.6σ. Need more significance [Stress between solar solutions and KamLAND]; Upturn ? → need statistics and lower threshold

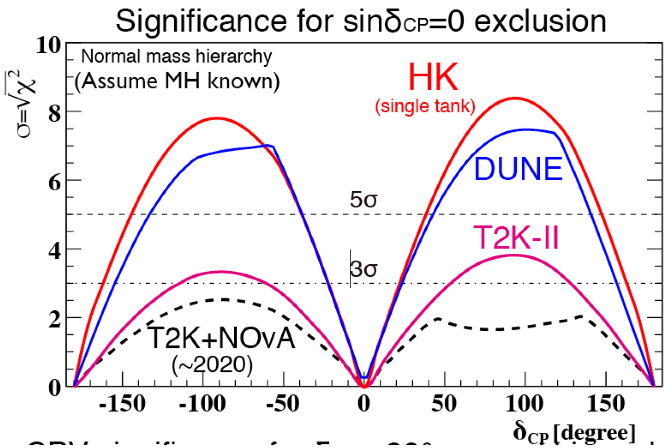
→ HK

Hyper-Kamiokande

now on the ROADMAP2017 of Japanese funding agency



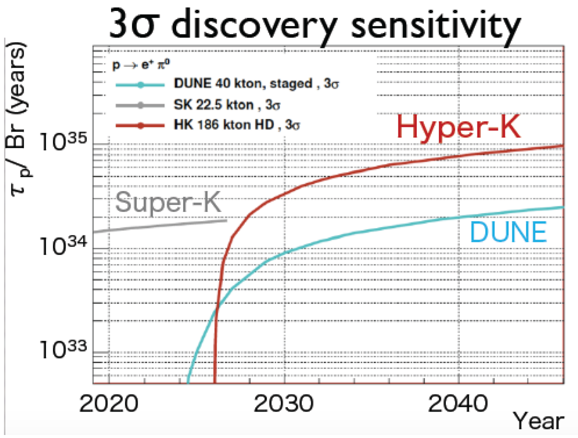
- 7-8 years of construction
- Possible 2nd detector in Korea
- 40K of 50cm PMT
  - PMT: 2 times higher sensitivity than SK



with beam data

CPV: ~8σ
if $\delta_{CP}=\pm 90^o$

MH: determination in 5 yrs



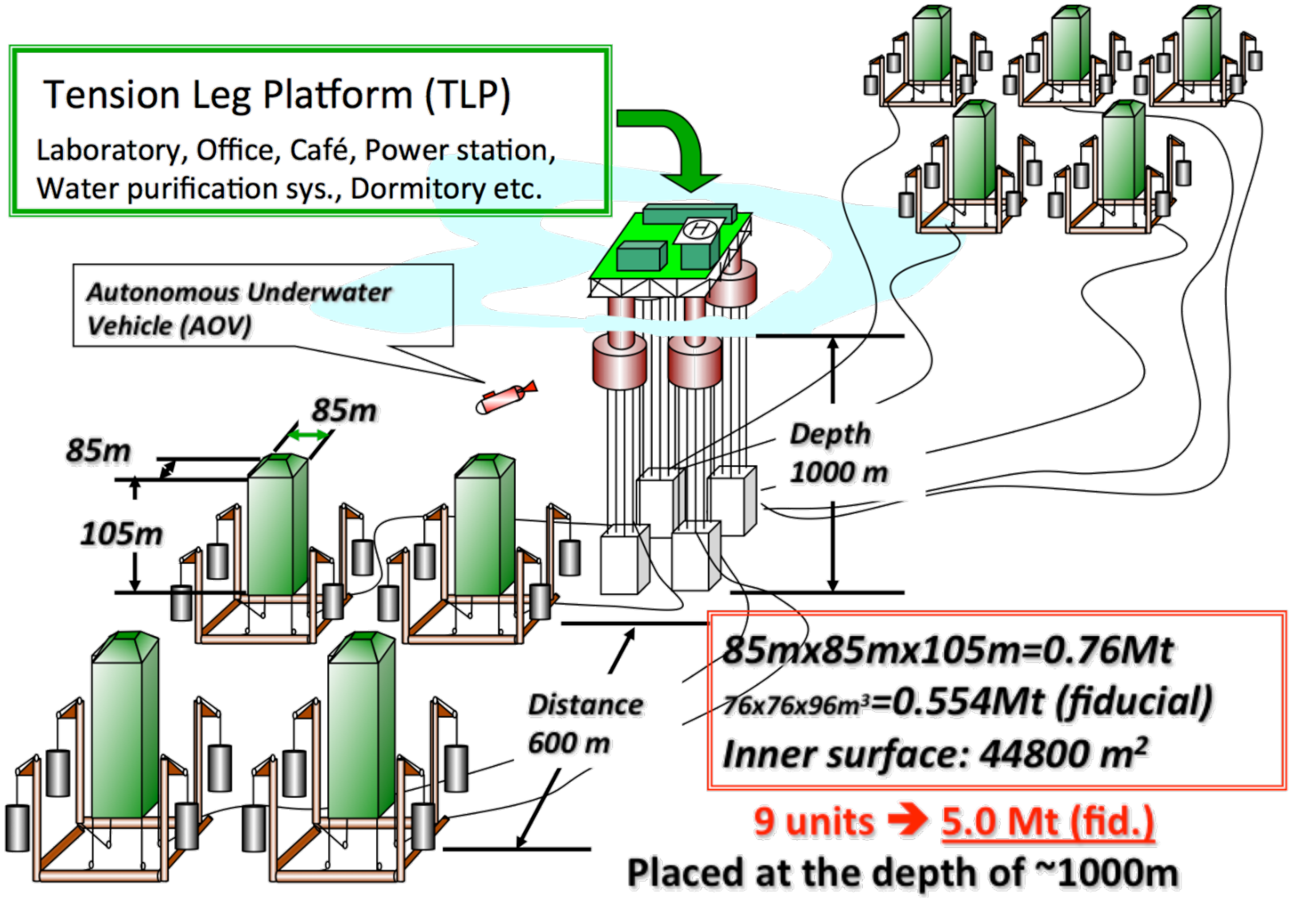
Proton Decay
$(e^+\pi^0)$
10^{35}yrs in12yrs

- SN neutrino bursts
  100k~150k events for SN at 10kpc
  sensitivity up to 1~2 Mpc
- **Solar neutrinos: 70 events/day**

One more step: 10 Megaton
My dream in future !

TITAND ***(under sea)***

- **proton decay up to ~10^{36} years**
- **SN burst every year**
  →SN Observatory
- Atmospheric ν
- Long baseline ν

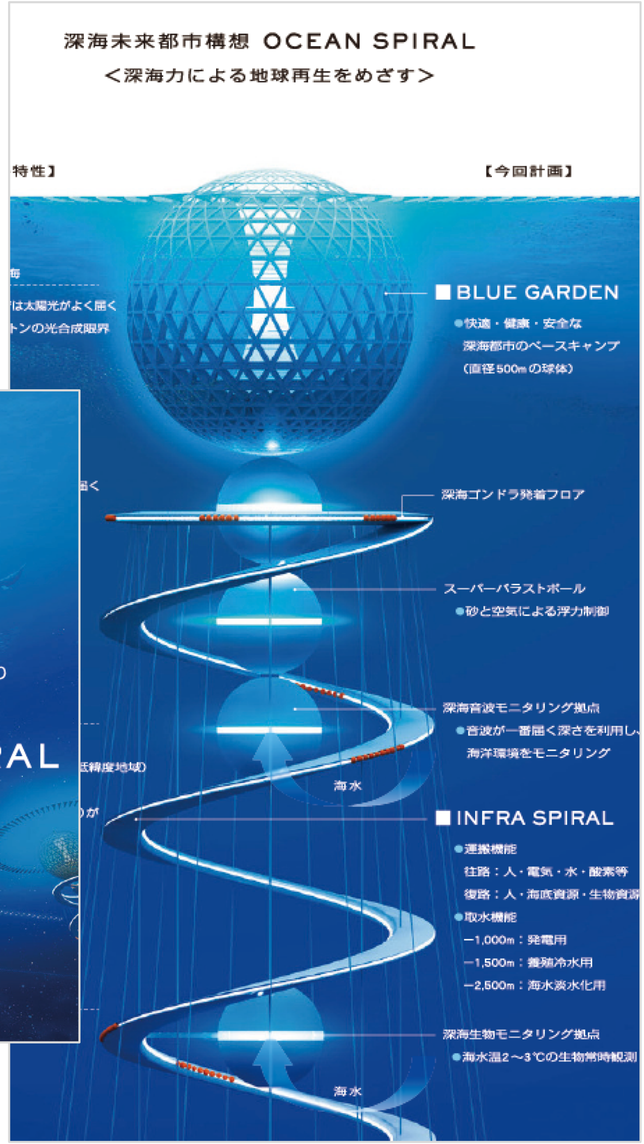


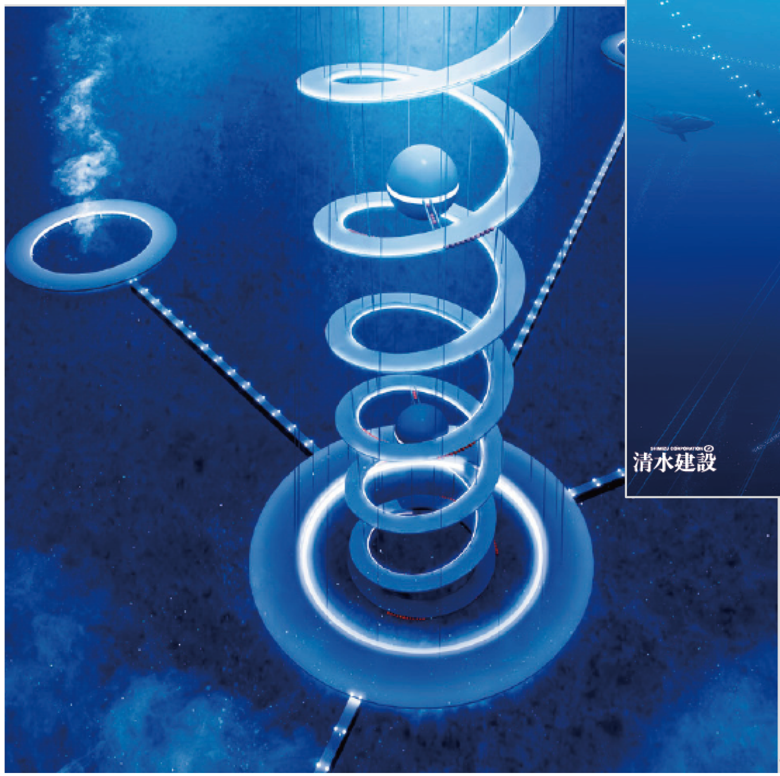
- **sol ν: difficult**

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

Ocean Spirals

Deep Ocean project
http://www.shimz.co.jp/theme/dream/oceanspiral.html



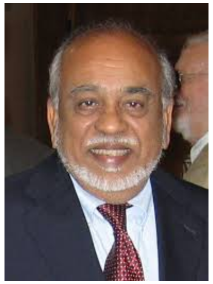


Under water lab.
@2000 m depth

Epilog

- Solar ν oscillation: Hint in 1968, solved in 2001. Took 33 years
- Atm ν oscillation: Hint in 1988, solved in 1998. Took 10 years.
- These results are the consequence of the efforts of many experiments and many people, and
- many theoretical works on the oscillation related phenomena, the atmospheric ν flux calculations, the solar models.
- We should not forget those strong leaders
  - We miss Y. Totsuka, H Chen, J. Bahcall, R. Rahgavan,,,,,,,,,



- I am happy to have been with a saga of the discovery of neutrino oscillatons
- Hope there will be fruitefull and exciting new results from neutrino experiments in future.