The Neutrino Physics Summer School
Fermilab, July 2007

The Evidence for Flavor Change and Oscillations II

Takaaki Kajita (ICRR, U.of Tokyo)

Overall Outline

Lecture 1:

Discovery of atmospheric neutrino oscillations

Lecture 2:

Solving the Solar Neutrino Problem with Solar neutrino oscillations

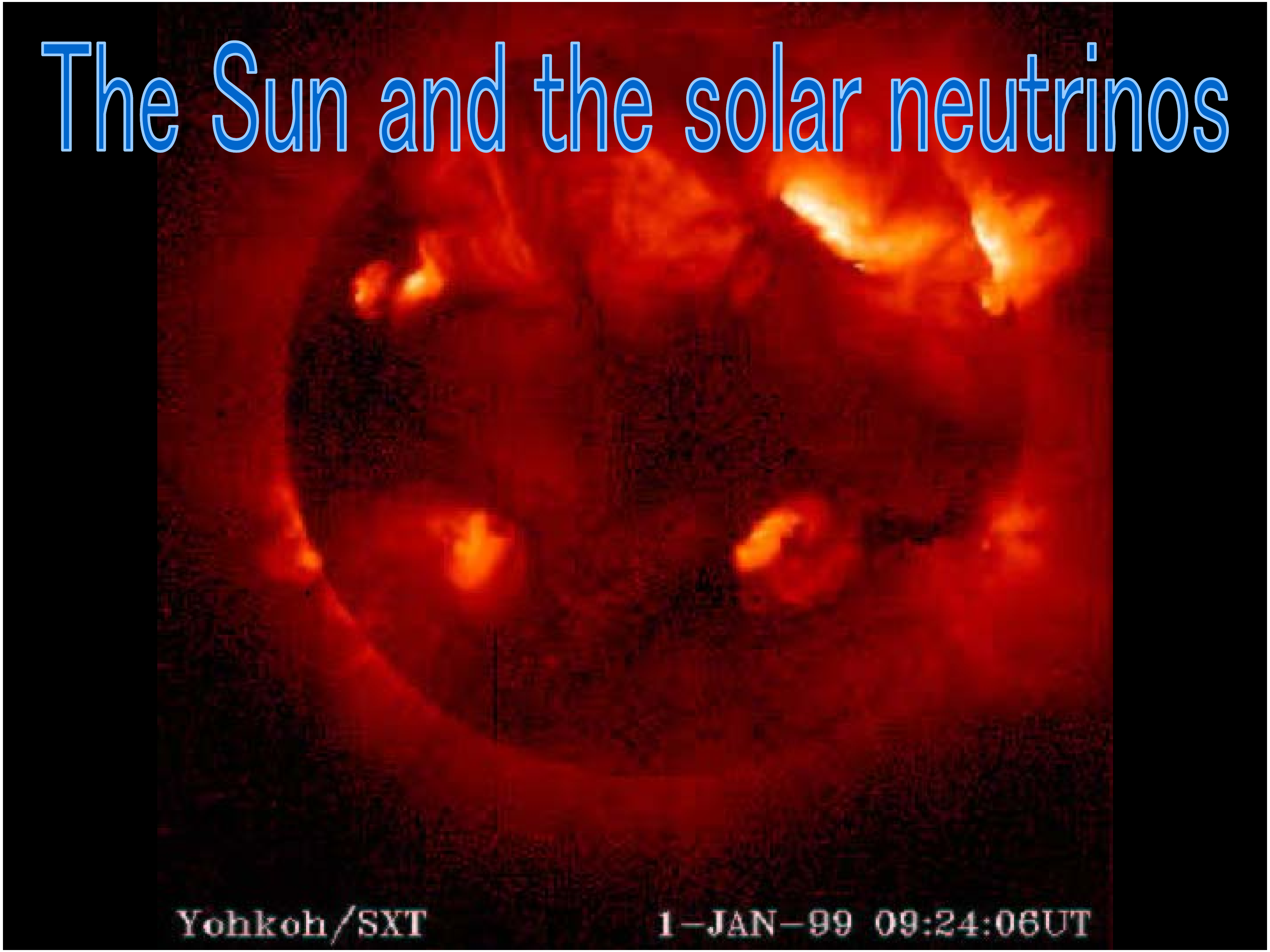
Lecture 3:

Studies of neutrino oscillations with accelerator and reactor neutrinos

Outline - Lecture 2 -

- The Sun and the solar neutrinos
- Some early history (solar neutrino problem)
- Solving solar neutrino problem with neutrino oscillations
- Summary of Lecture 2

The Sun and the solar neutrinos



How does the Sun shine?

Quick answer: nuclear fusion reactions

A Helium nucleus is produced by the fusion of 4 Hydrogen nuclei;

$$4p \rightarrow He + 2e^{+} + 2\nu_e$$

This reaction produces about 27 MeV energy.

Then, the total neutrino flux on the Earth is;

$$flux = \frac{1}{4\pi R^2} \times \frac{L_{sun}}{27MeV} \times 2\nu_e$$

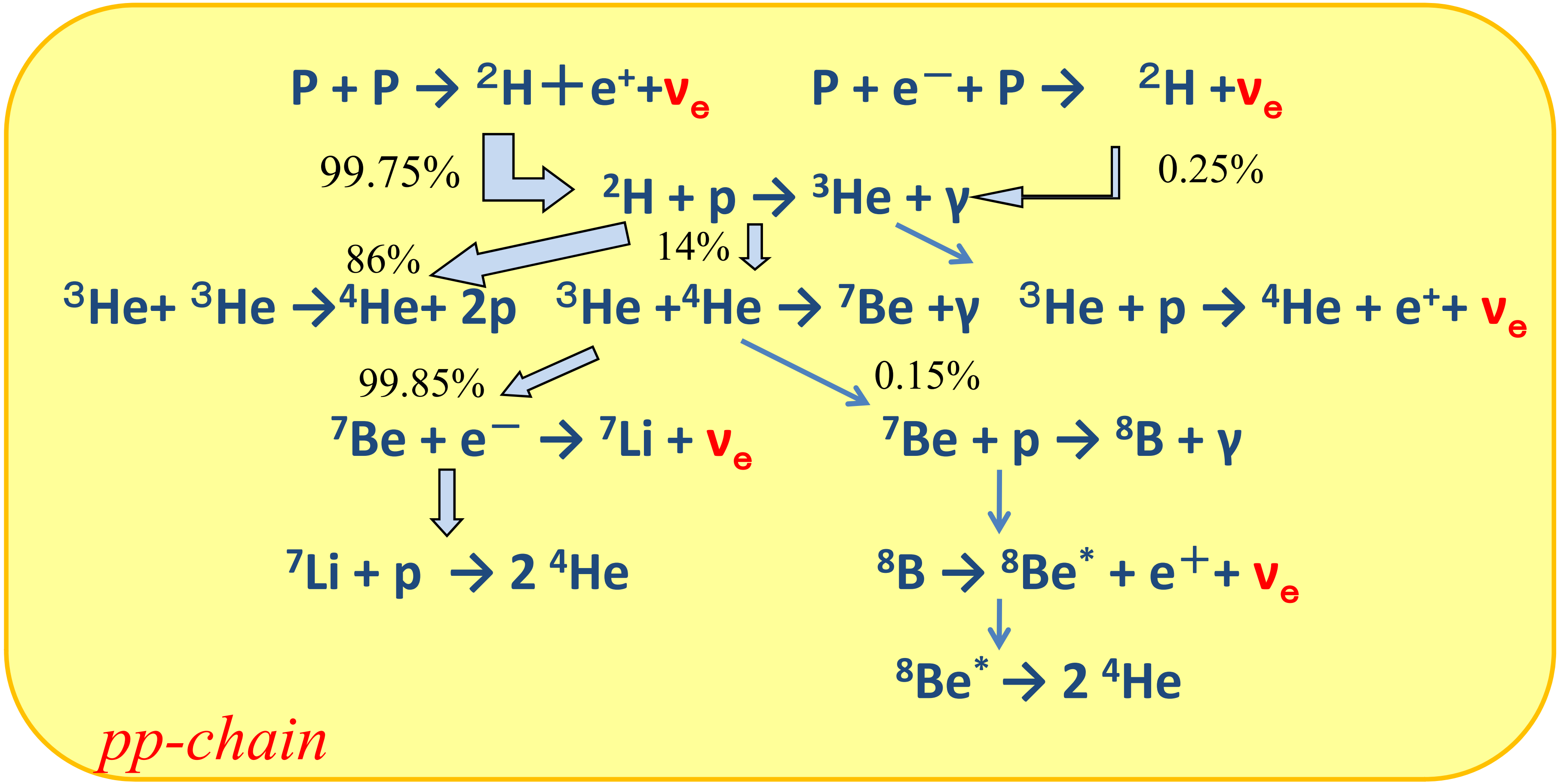
$$(L_{sun} = 3.86 \times 10^{33} erg/\sec)$$

$$= 6 \times 10^{10} \nu_e / cm^2 / \sec$$

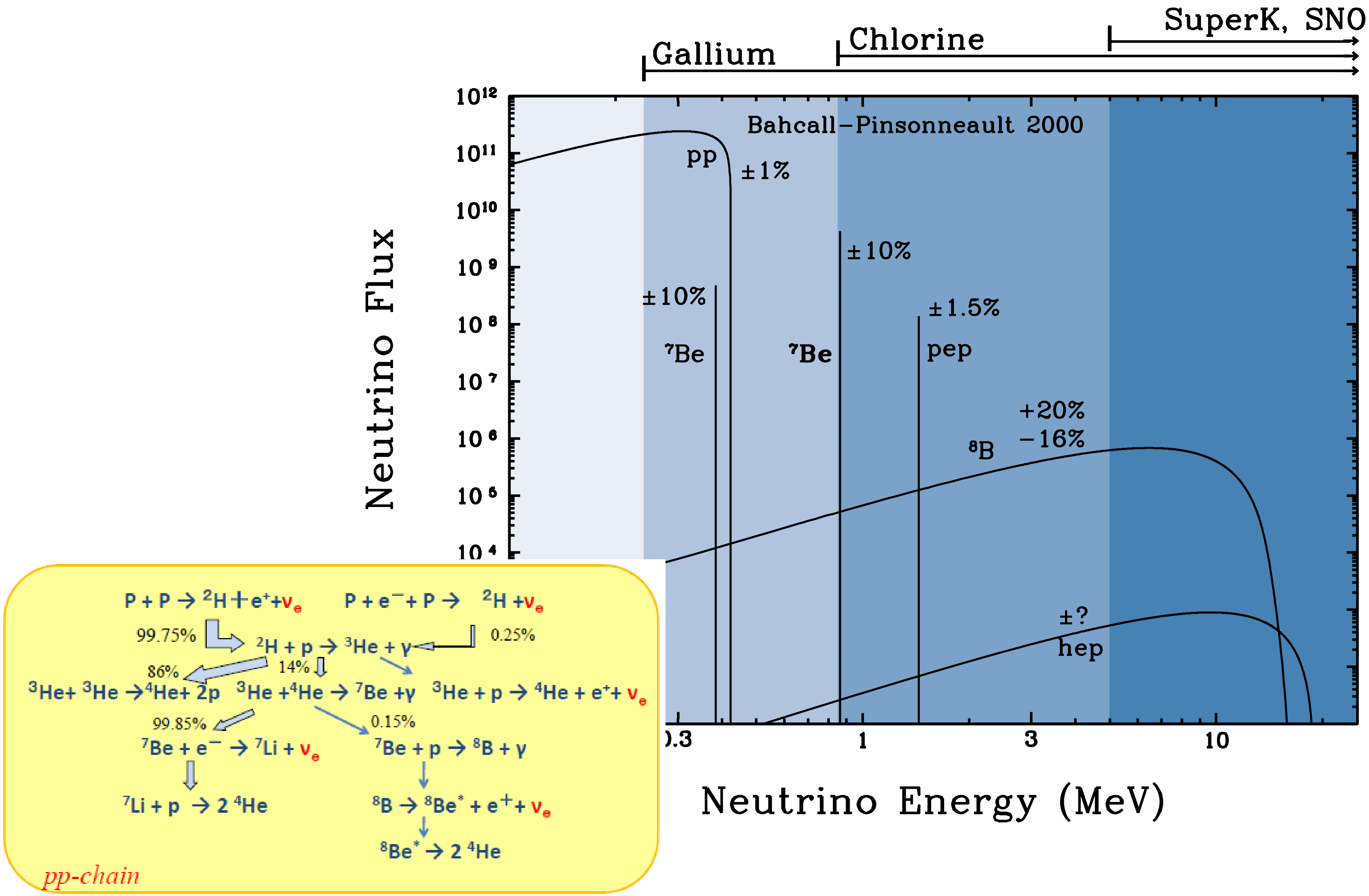
If one observe these neutrinos, it is a proof that the generation of the energy in the Sun is due to nuclear fusion.

How does the Sun shine (2) ?

However, in reality, 4 protons cannot make a fusion reaction at a time…

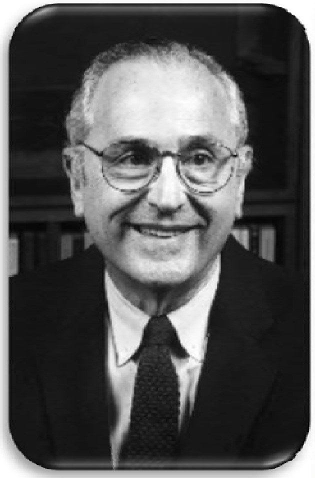


Solar neutrino spectrum

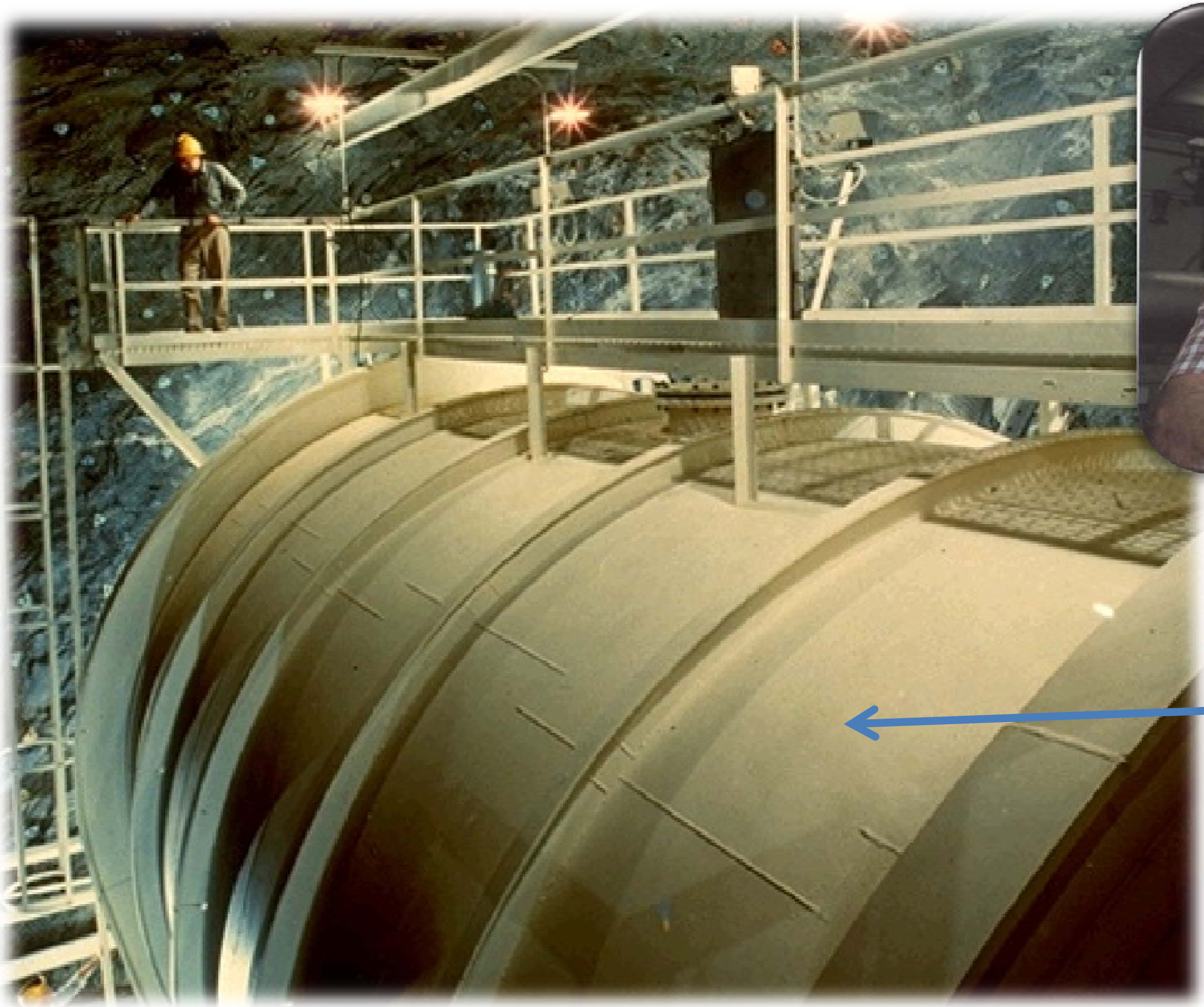


Detecting Solar Neutrinos

J.N. Bahcall “Solar neutrinos I: Theoretical” P.R.L. 12, 300 (1964)
R. Davis Jr. “Solar neutrinos II: Experimental”, P.R.L.12, 303 (1964)



J. N. Bahcall

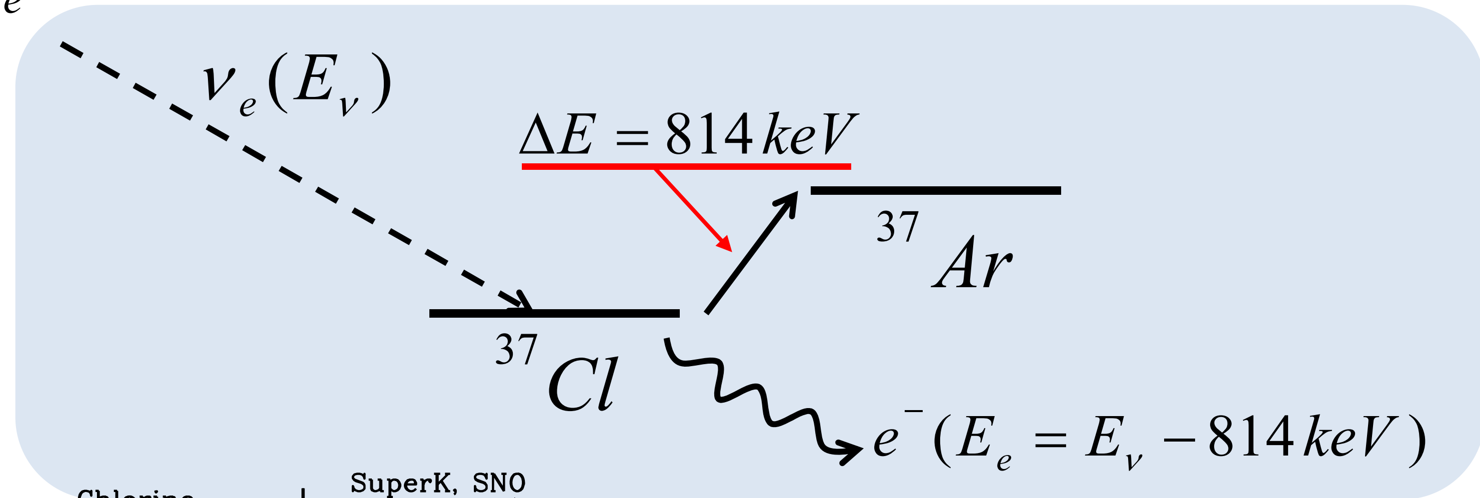


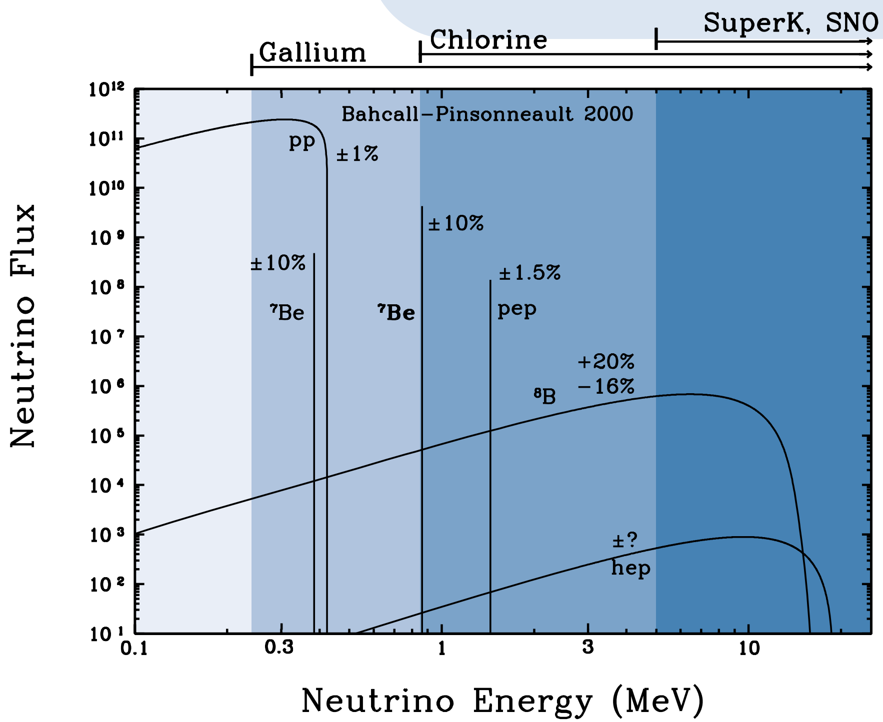
R. Davis Jr.

600ton
C_2Cl_4

Interaction of solar neutrinos with ^{37}Cl

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$ (Threshold = 814keV)





pp: 0

pep: 0.22

^{7}Be: 1.16

^{8}B: 6.32

Others: 0.41

Total: $8.1^{+1.4}_{-1.1}$ SNU (solar neutrino unit

= interactions/10^{36}target/sec)

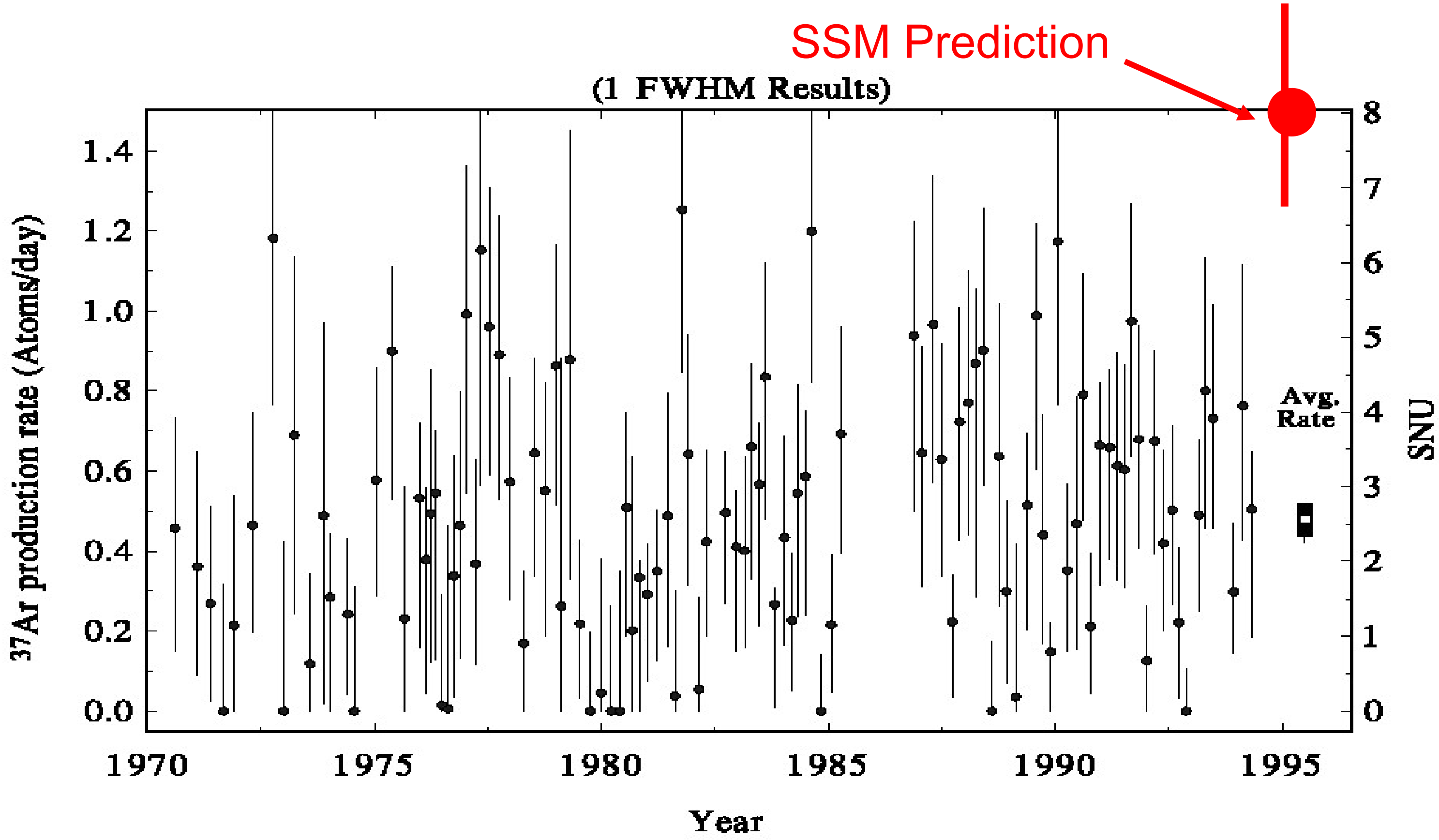
(These numbers are slightly old…)

Solar Neutrino Problem

Search for Neutrinos from the Sun

R. Davis Jr., D.S. Harmer, and K.C. Hoffman, PRL 20, 1205 (1968)

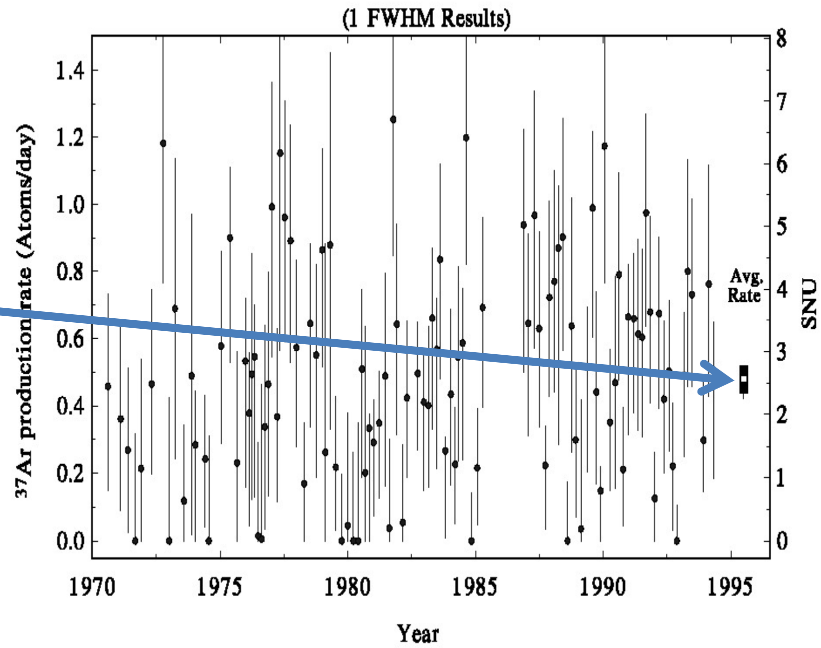
The Ar production rate by $\nu_e {}^{37}Cl \rightarrow e^- {}^{37}Ar$ was less than 3×10^{-36} sec^{-1} per ^{37}Cl atom, which was substantially smaller than the prediction by the Standard Solar Model.



Solar neutrino experiments are difficult

0.5 ^{37}Ar production per day

600ton C_2Cl_4

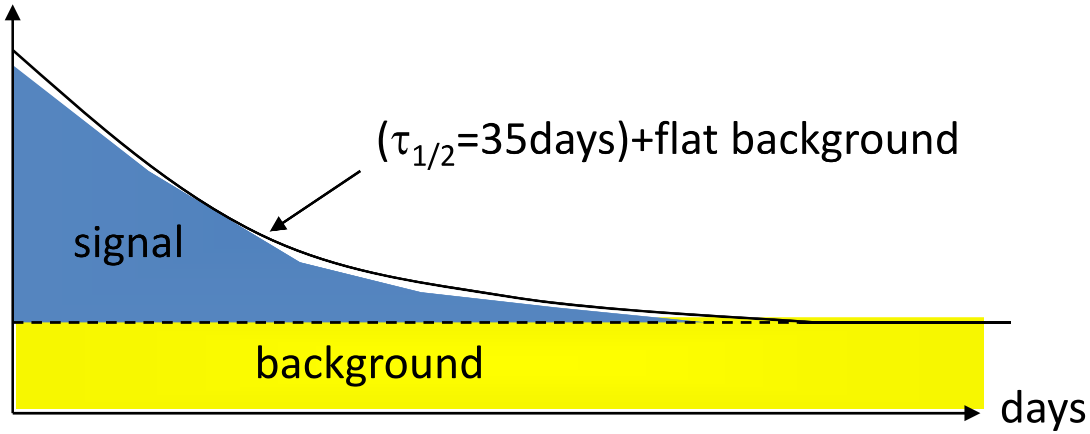


Extract ^{37}Ar from the 600ton tank.

Then,

$$^{37}Ar + e^- \rightarrow ^{37}Cl + \nu_e$$

Electrum capture
Detect 2.82keV Auger electrons

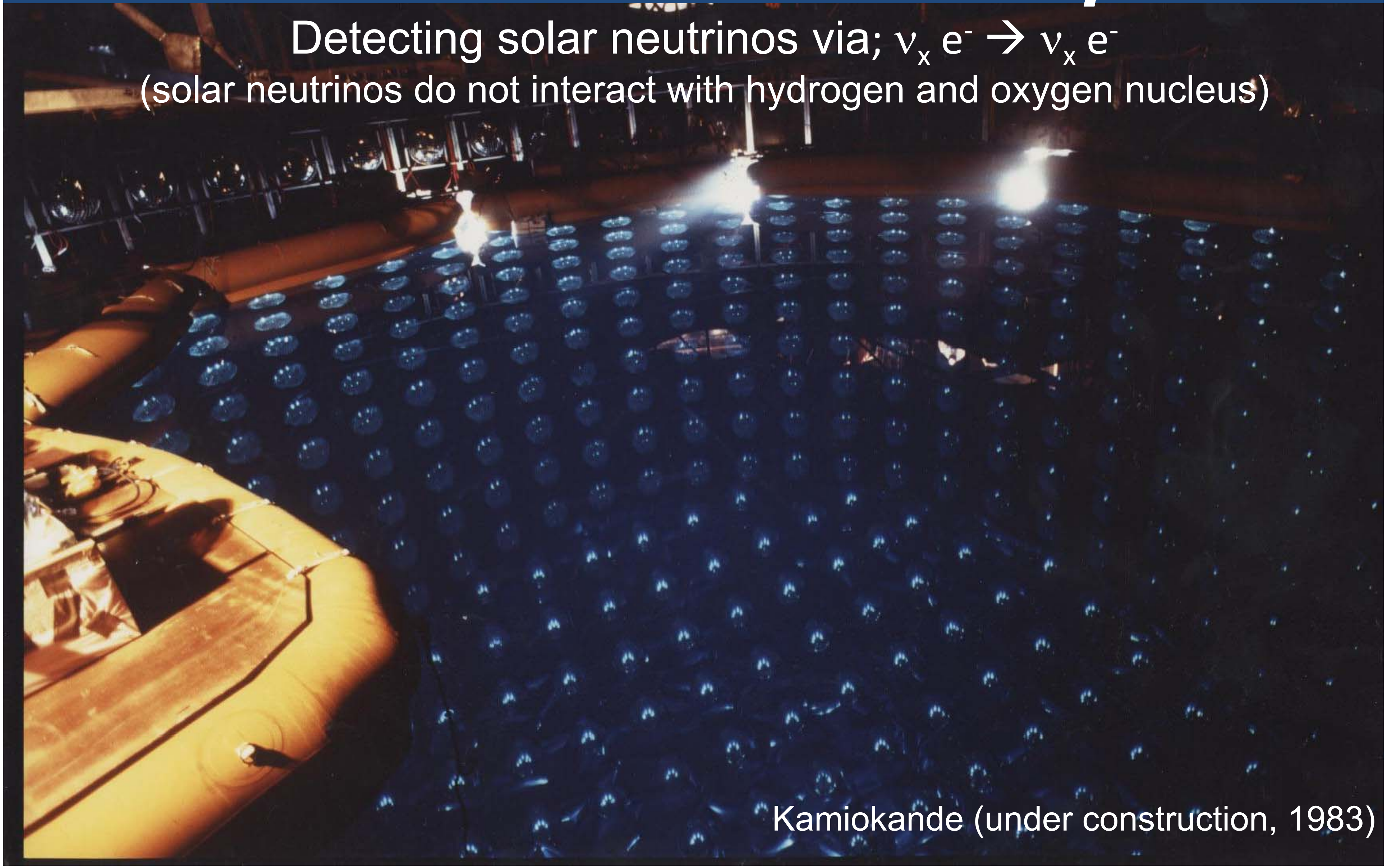


Possible solutions to the solar neutrino problem (before mid. 1980's)

- Experiment might be wrong…
- Theory (SSM) might be wrong….

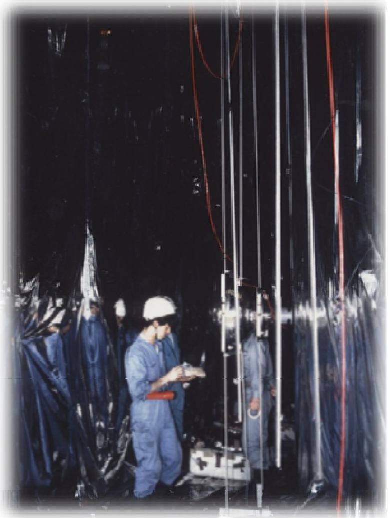
- Some new physics (but less serious ??) …
  - ➔ 3 flavor full mixing oscillation ?
  - ➔ 2 flavor "just-so" oscillation ?
  - ➔ …

Detecting solar neutrinos with the water Cherenkov technique



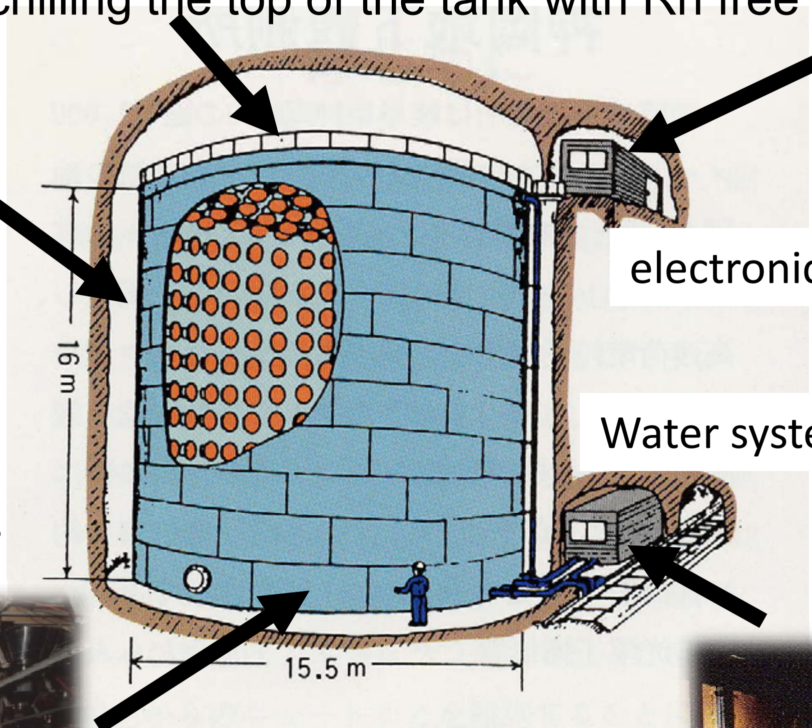
Toward the observation of solar neutrinos

(difficulty: Kamiokande was designed to detect 1GeV (not 10MeV) signal)



Installation of anti-counters

Schilling the top of the tank with Rn free air



electronics

Water system

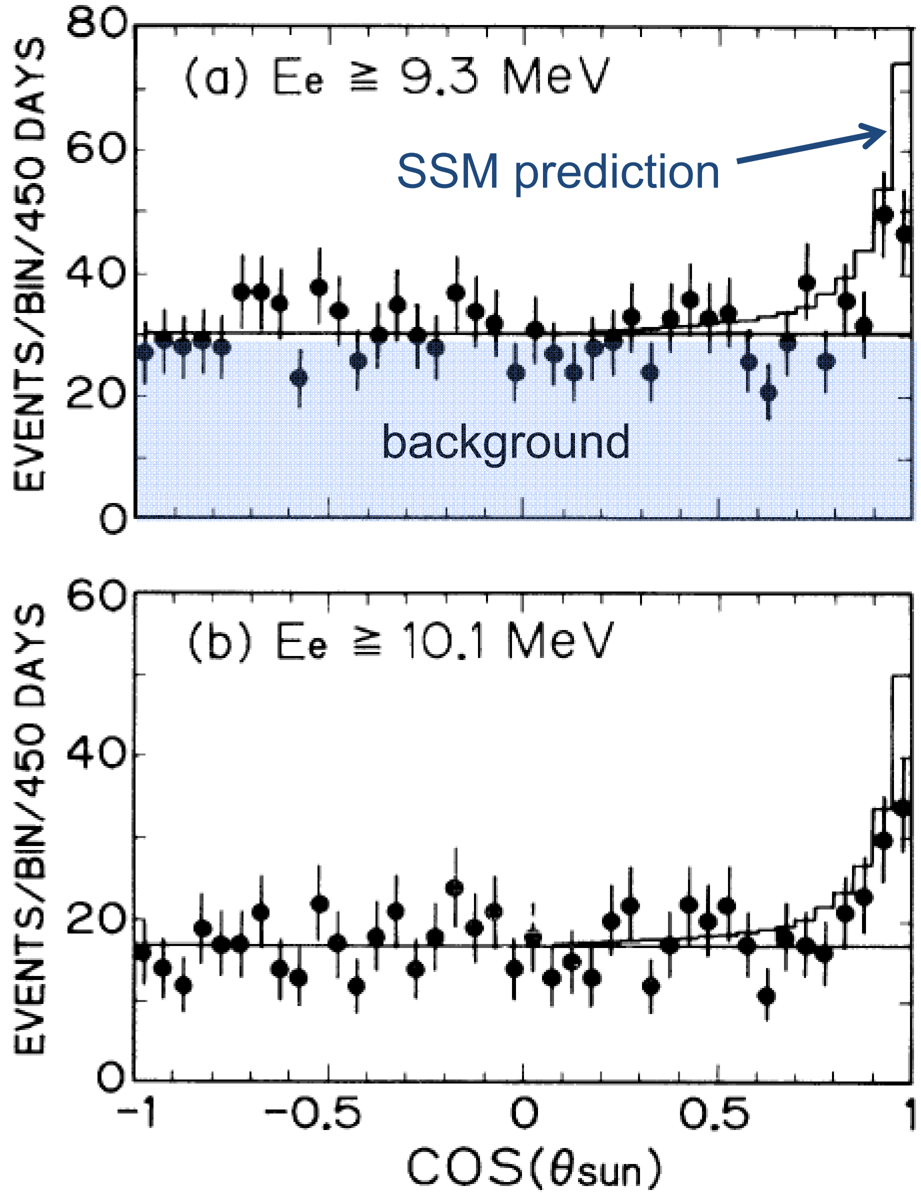
Electronics that measure multi-hit T and Q (U. of Penn)

Improving the water purification system

Solar neutrino detection in Kamiokande

Observed flux was;
0.46±0.13(stat)±0.08(syst)
of the SSM prediction.
PRL 63, 16 (1989)

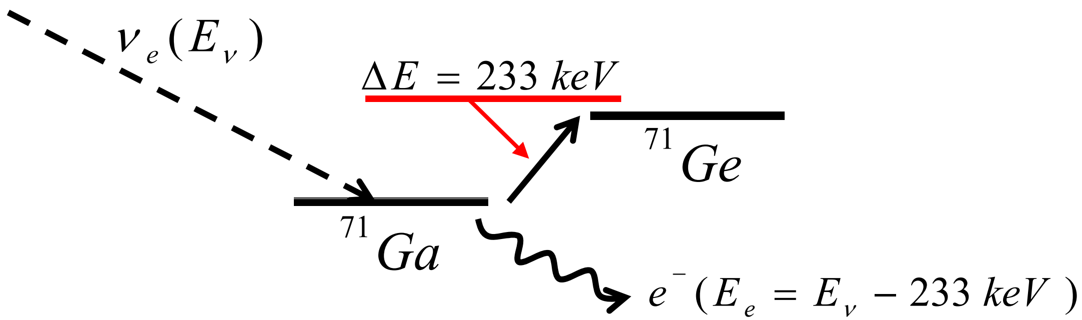
"Experiment wrong" solution ruled out.



Can we detect neutrinos whose flux is less dependent on SSM ?

Yes, one should observe *pp* neutrinos.
How? ➔ Ga experiments.

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge \quad \text{(threshold = 233 keV)}$$



pp: 69.9

pep: 2.9

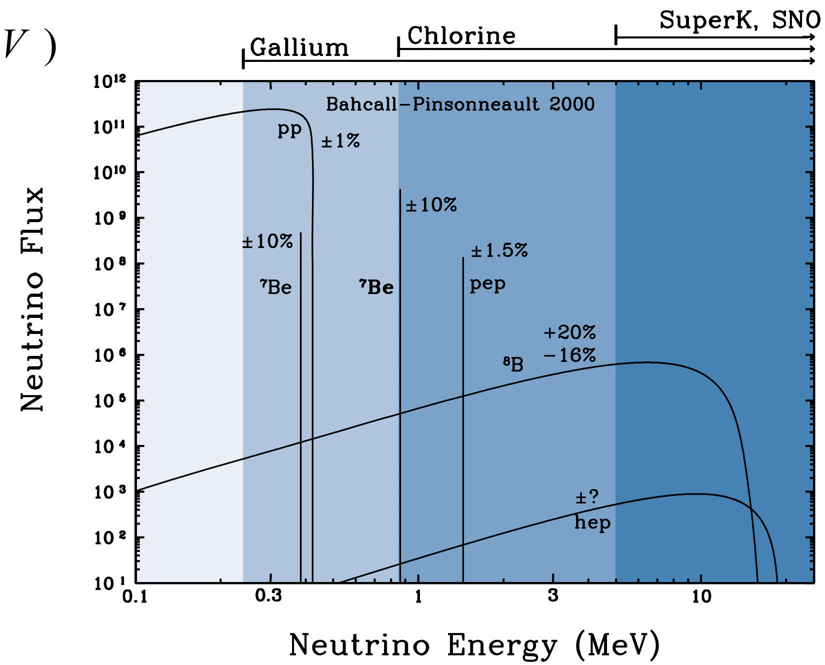
^{7}Be: 34.5

^{8}B: 12.3

others: 9.1

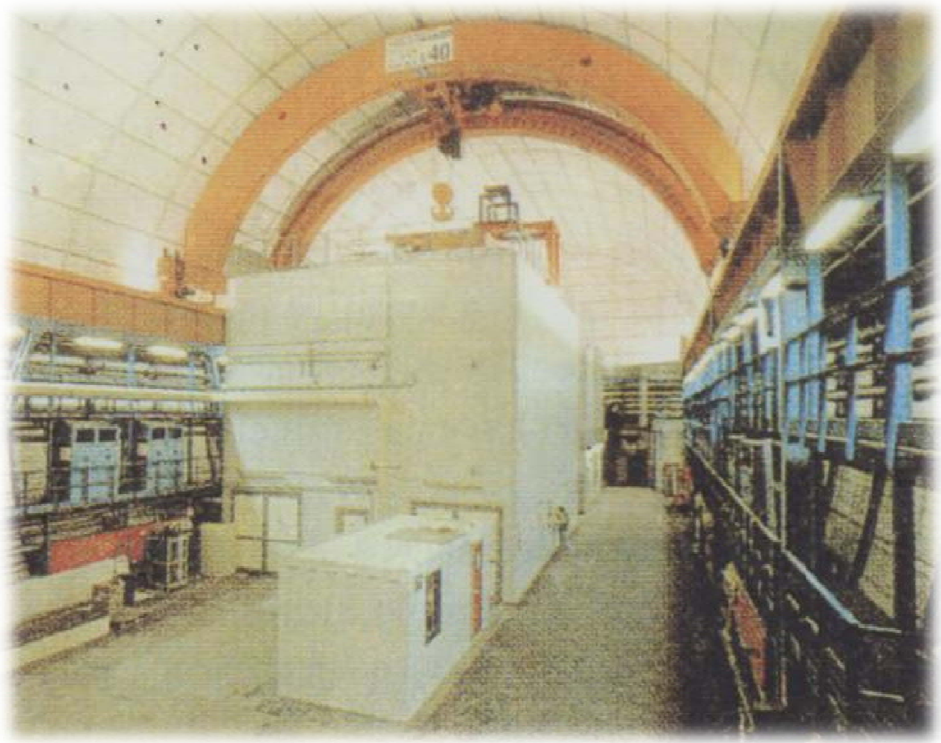
Total: 129^{+9}_{-7} SNU

(These numbers are slightly old...)



Ga experiments

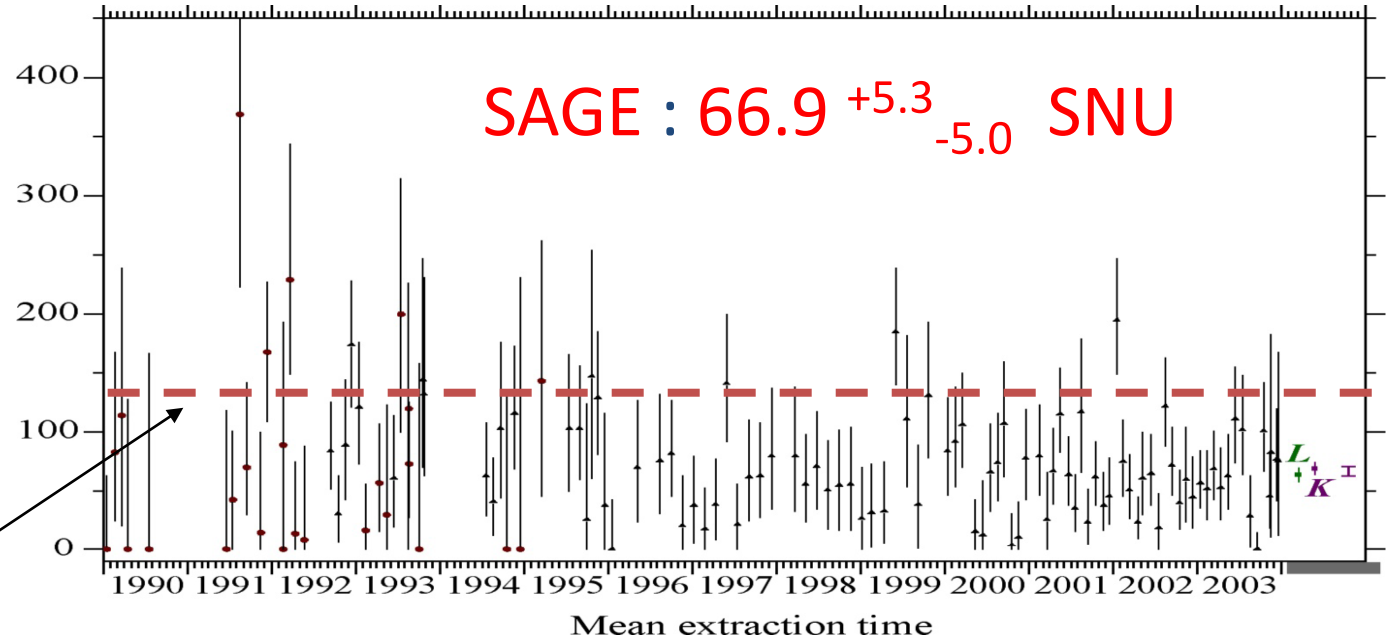
SAGE (Baksan, Russia)



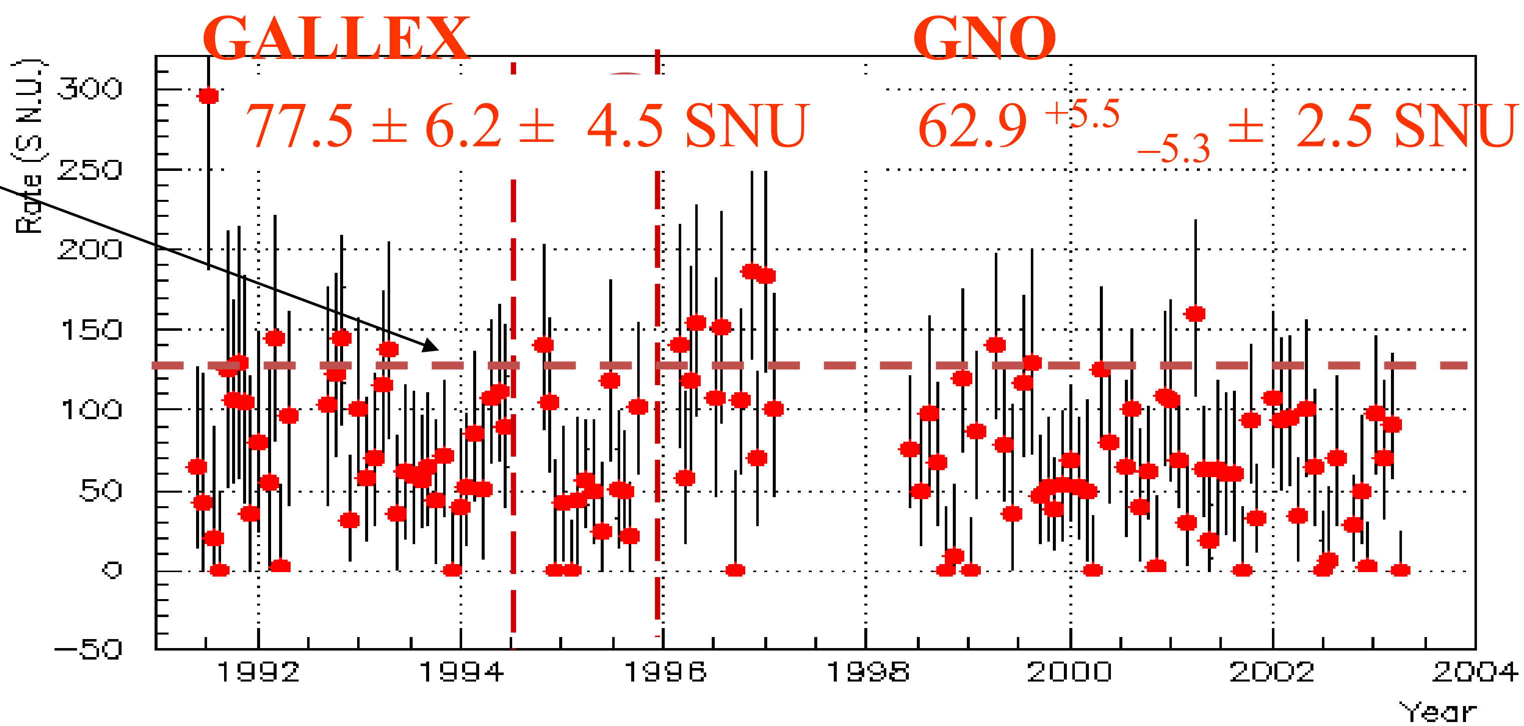
Gallex/GNO (Gran Sasso, Italy)

Experimental method: radiochemical technique (similar to the Cl experiment, but more complicated.)

Results from Ga experiments



SSM prediction



Conclusions from Ga experiments

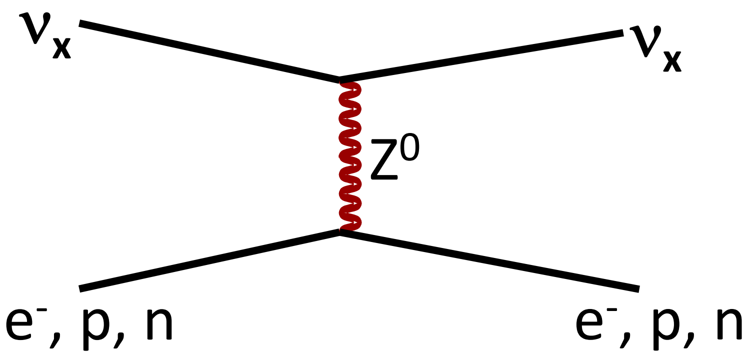
- Ga experiments also observed the solar neutrino deficit.
- The data might suggest neutrino oscillations.
- However, the data might be explained (within a few standard deviations) that the pp neutrinos are detected as expected, while the other neutrinos have much lower flux than calculated by the SSM.

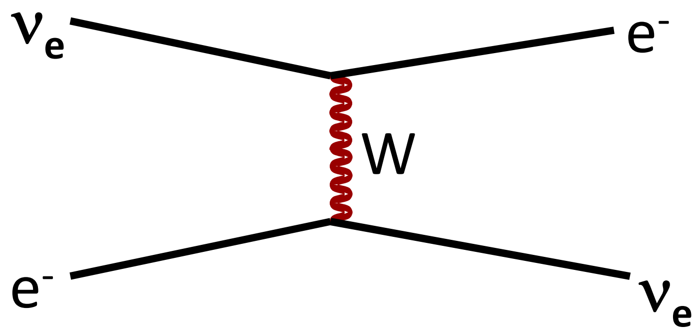
⇩

- Conclusion: It is difficult to conclude…

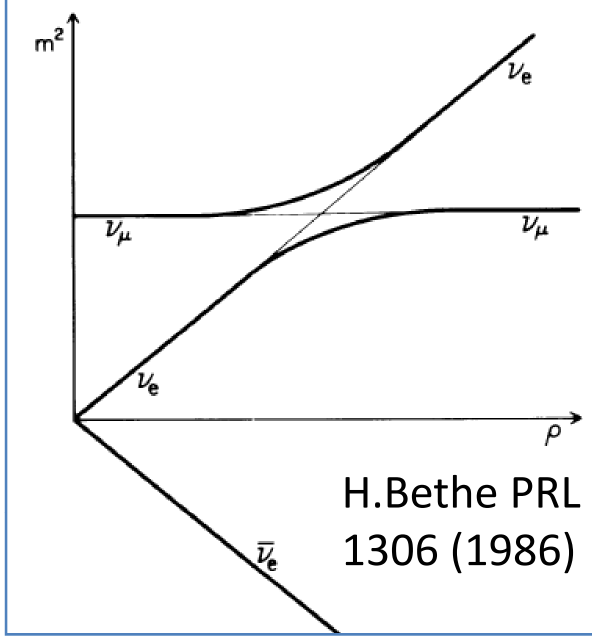
Breakthrough in neutrino oscillation theory: the MSW effect

Neutrino oscillation in matter is different from that in the vacuum due to;





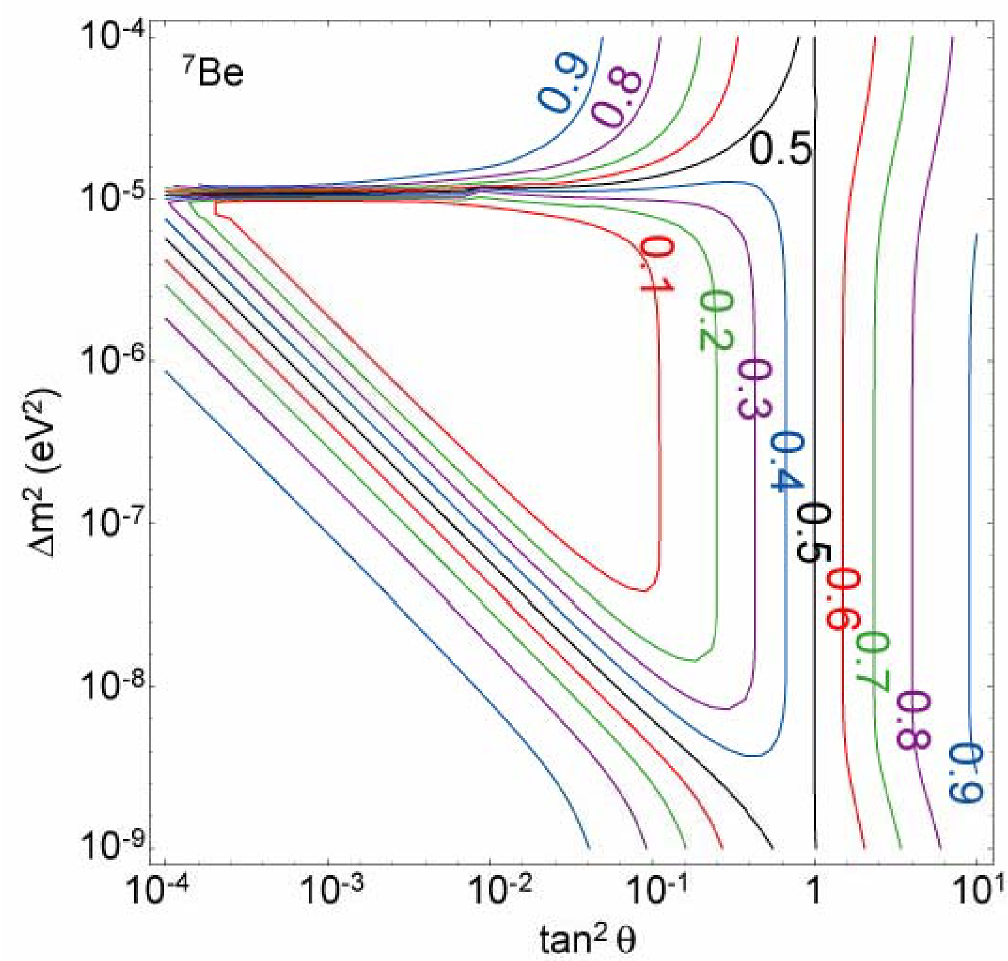
Wolfenstein pointed out the matter effect in neutrino oscillations (1978).
Mikheyev and Smirnov pointed out that the large flavor conversion can happen due to the matter effect (1985).



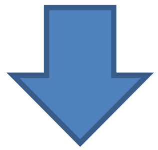
H.Bethe PRL 56, 1306 (1986)

MSW effect and solar neutrino oscillation probabilities

ν_e survival probability for ^7Be neutrinos

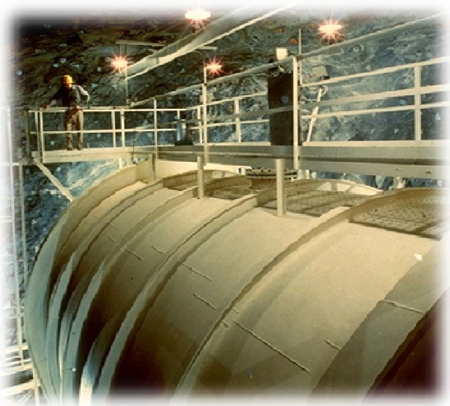


Small mixing angle (θ) (which was generally expected from the quark mixing angles) can generate large solar ν_e deficit !



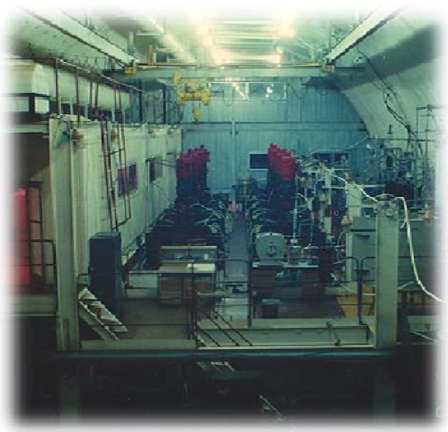
Neutrino oscillation
➔ A serious possibility !

Summary of solar neutrino experiments before the present generation exp's.



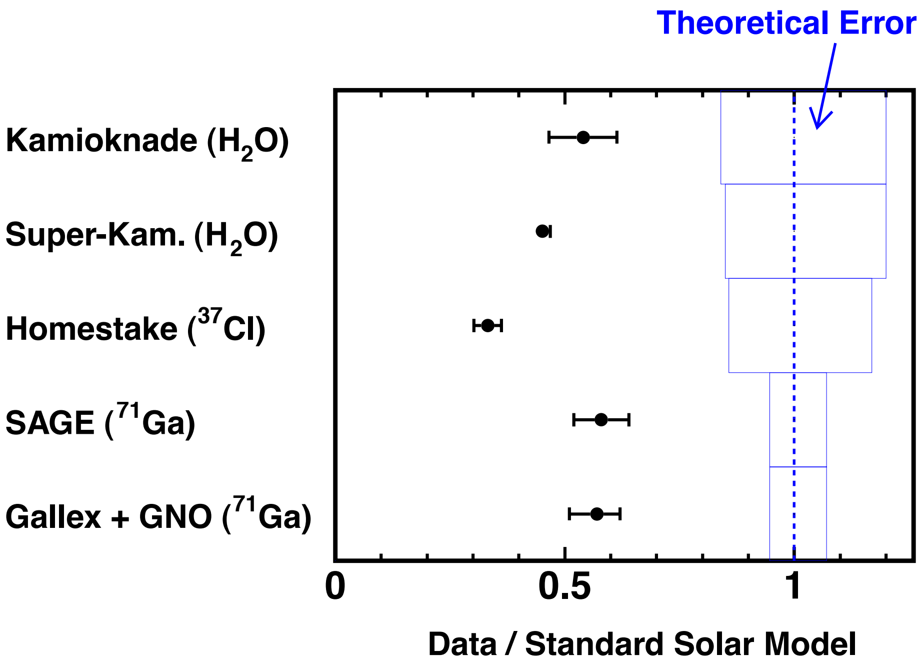
Homestake (Cl)

Kamiokande (H_2O)

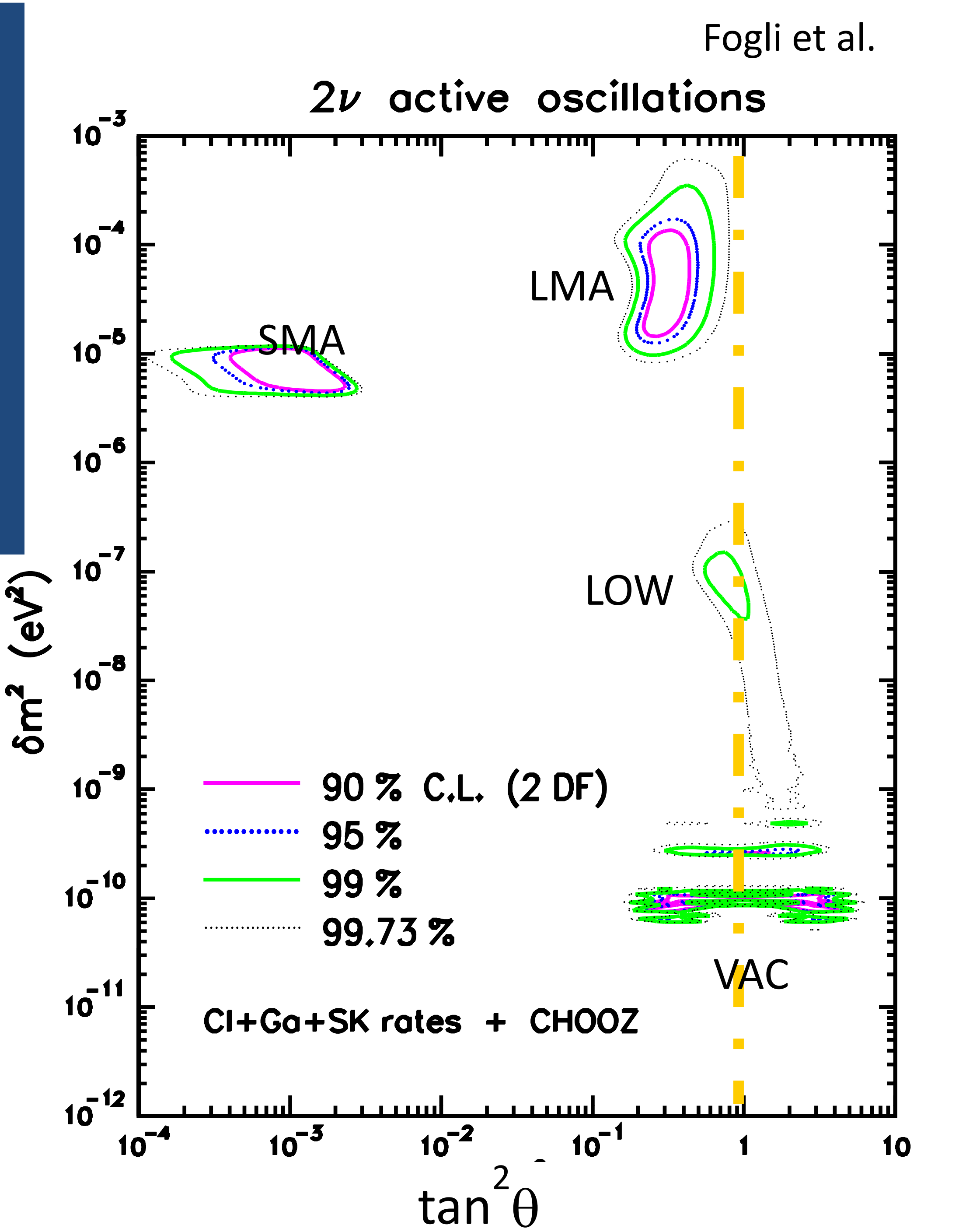


SAGE (Ga)

Gallex/GNO (Ga)

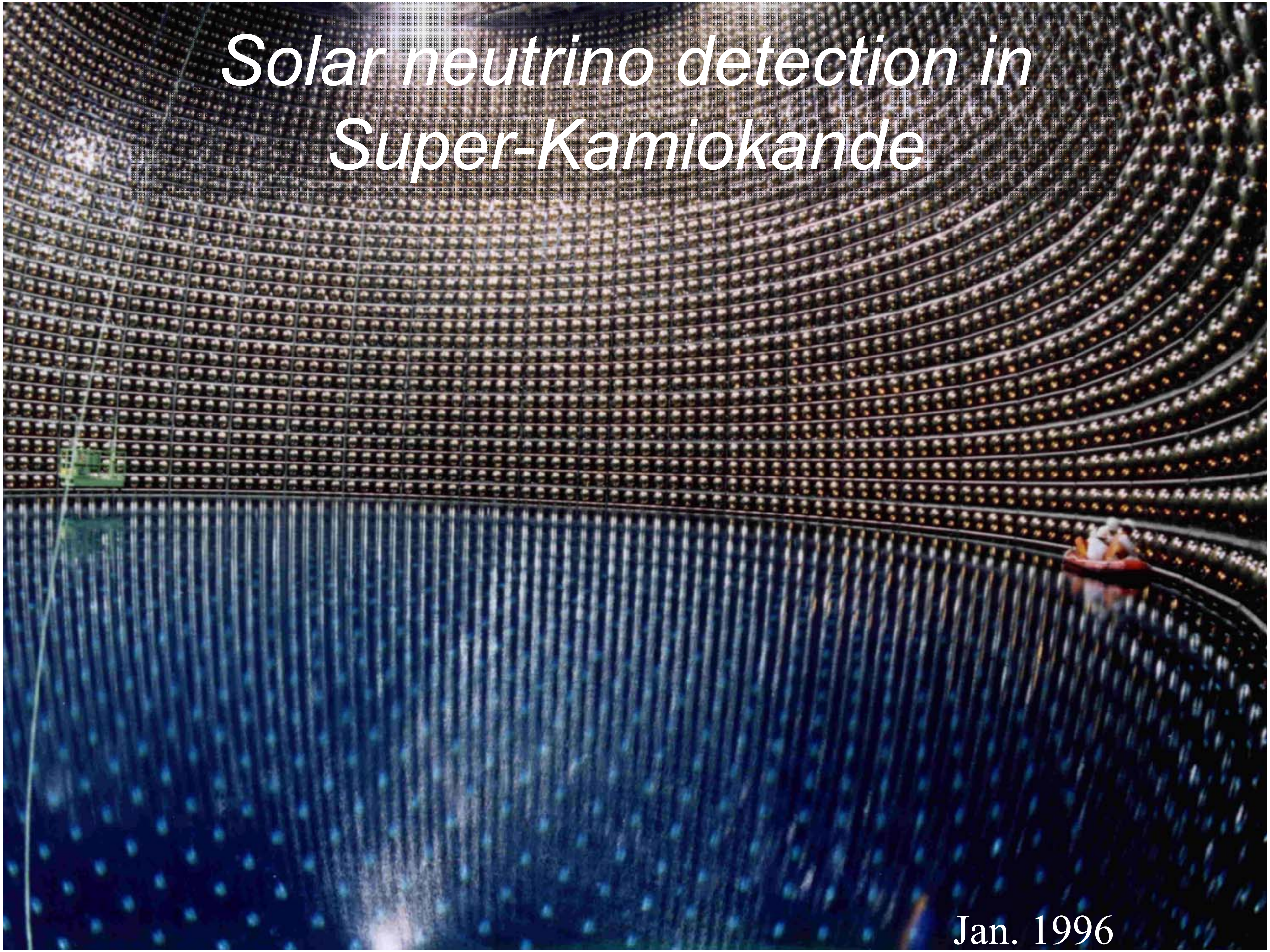


Neutrino oscillation parameters at the end of the last century….

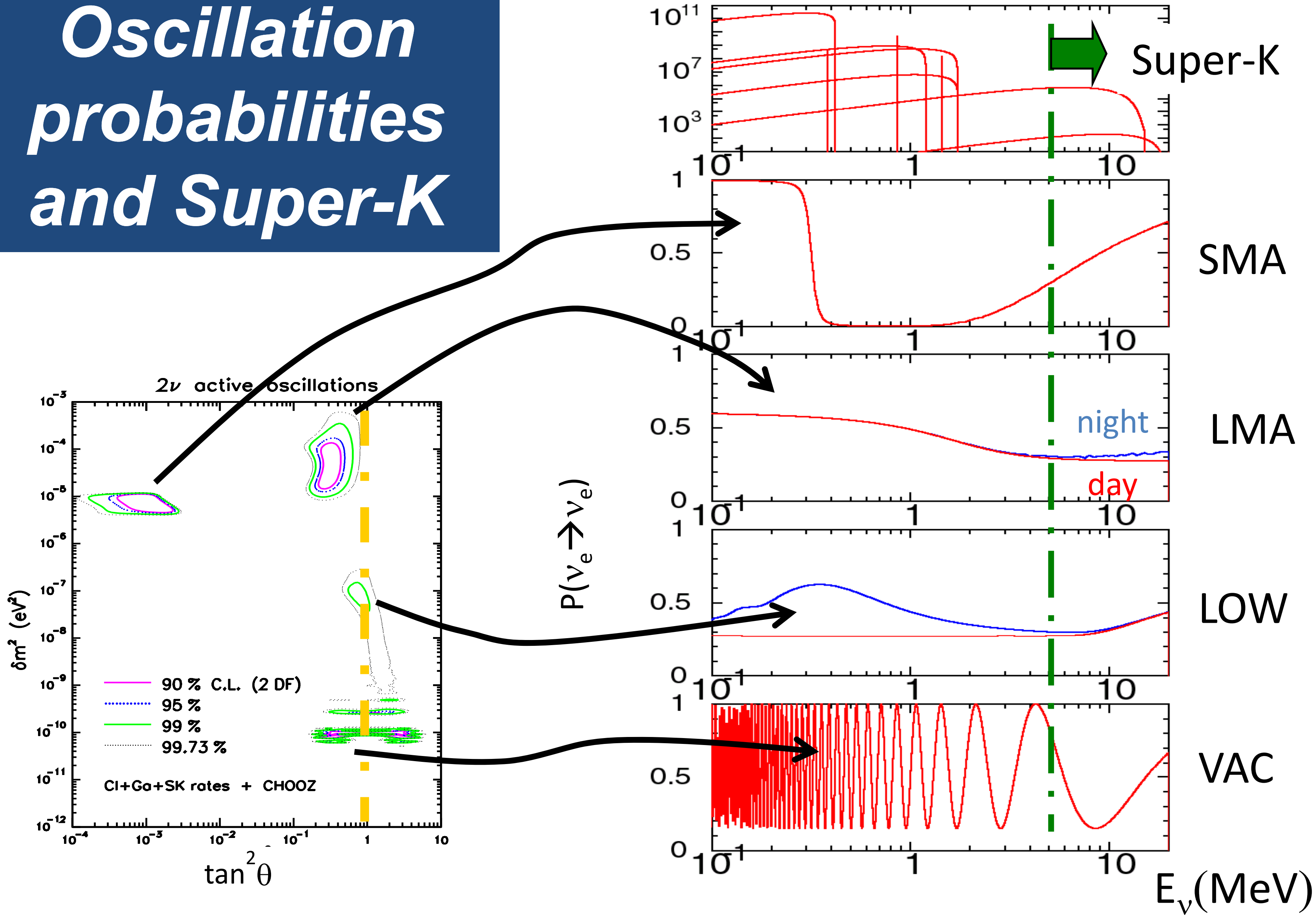


But no smoking gun evidence…

Solar neutrino detection in Super-Kamiokande



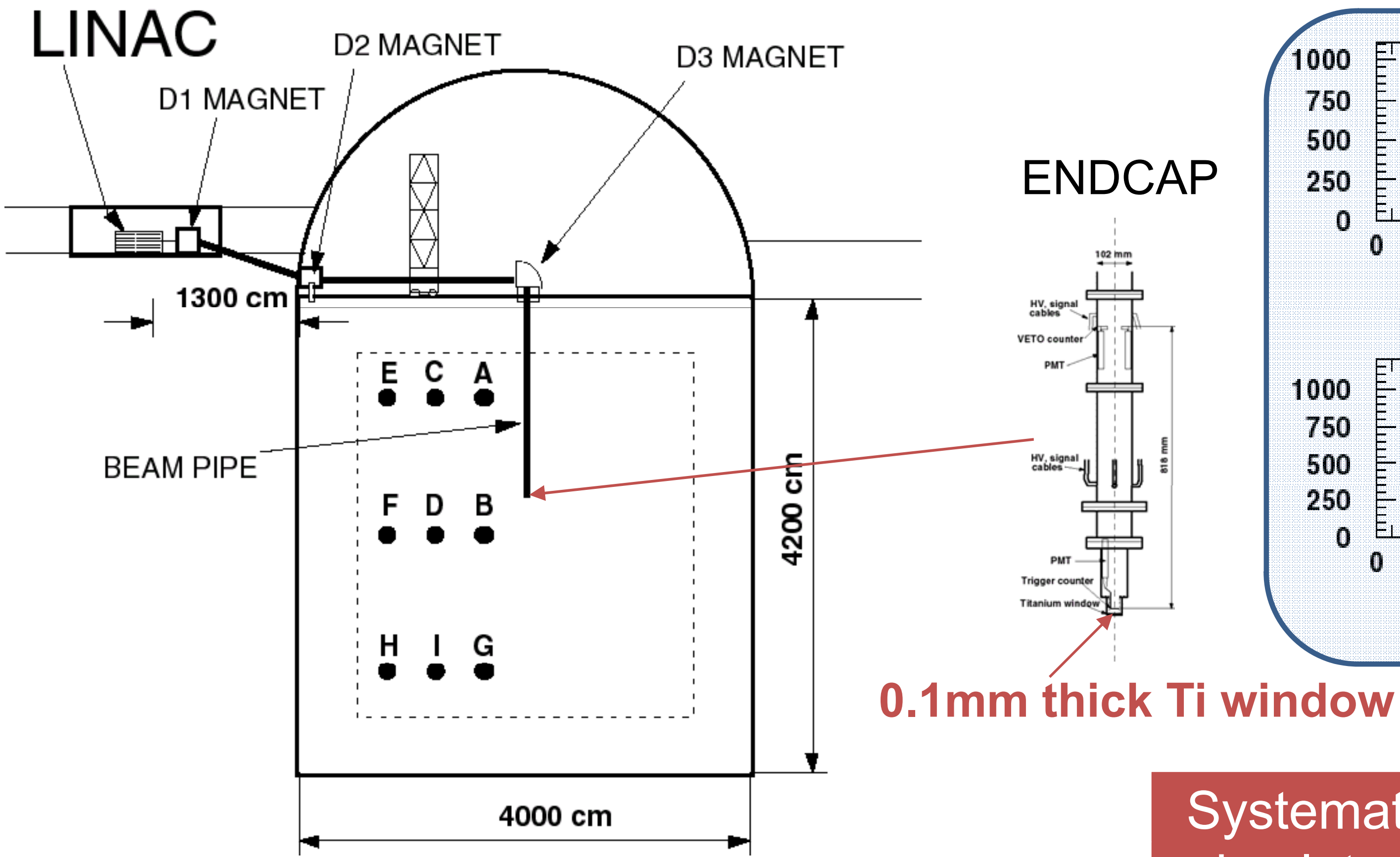
Oscillation probabilities and Super-K

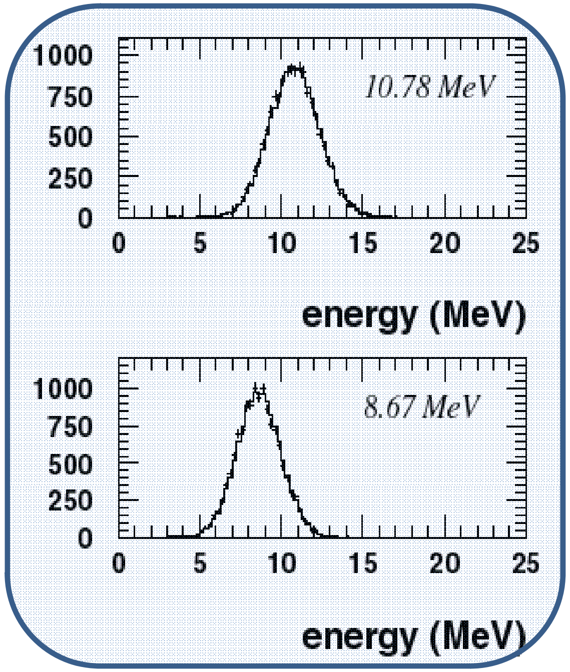


Day-night flux difference, spectrum distortion

Calibration of Super-K with an electron LINAC

Precise calibration of absolute energy scale, energy resolution, and angular resolution using electron LINAC.

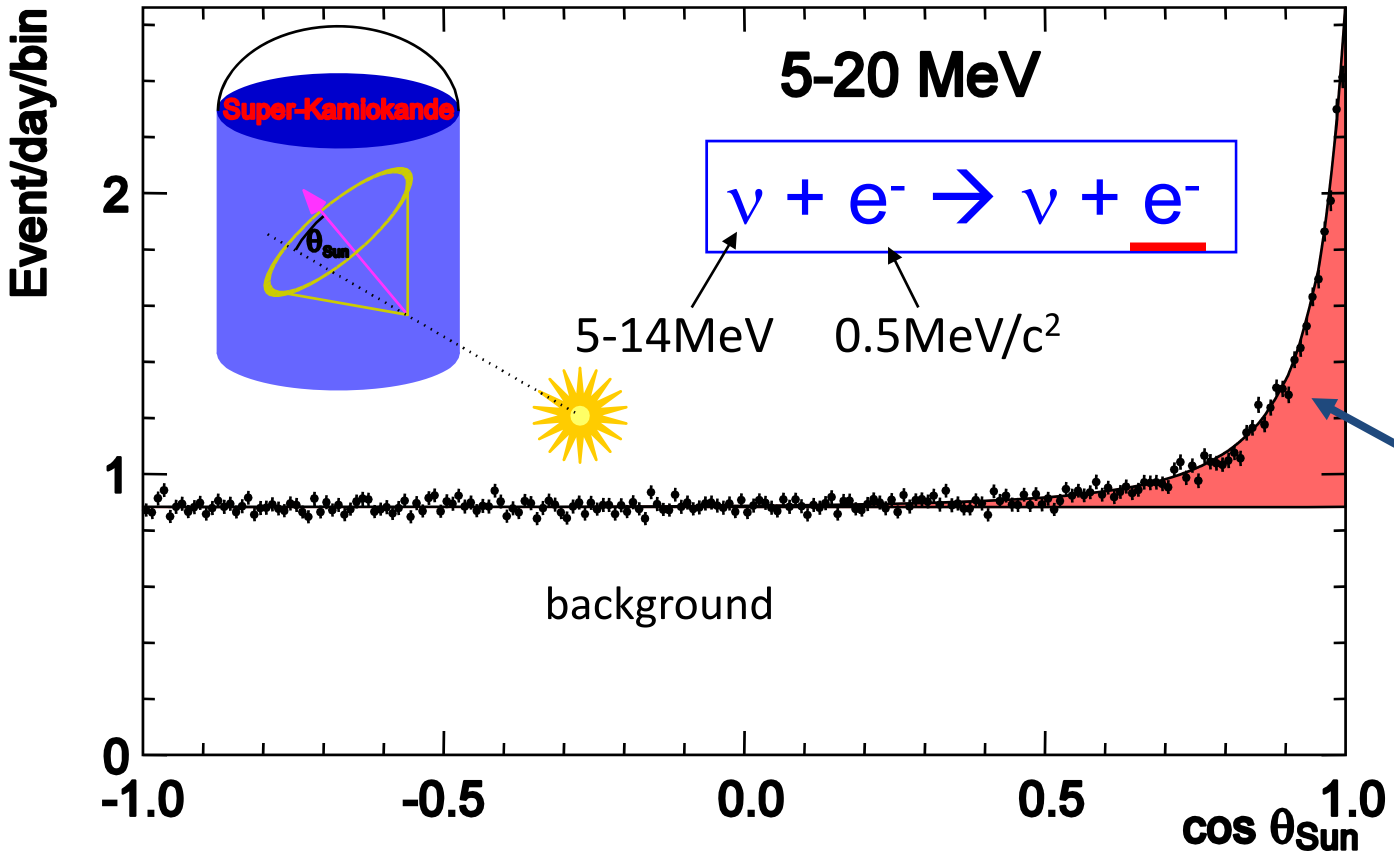




- Beam energy: 5 ~ 16 MeV/c

Systematic error in the absolute energy scale : 0.64 %.

Solar neutrino data from Super-K



May 31, 1996 –
July 13, 2001
(1496 days)

22400±230
solar ν events

(14.5 ev/day)

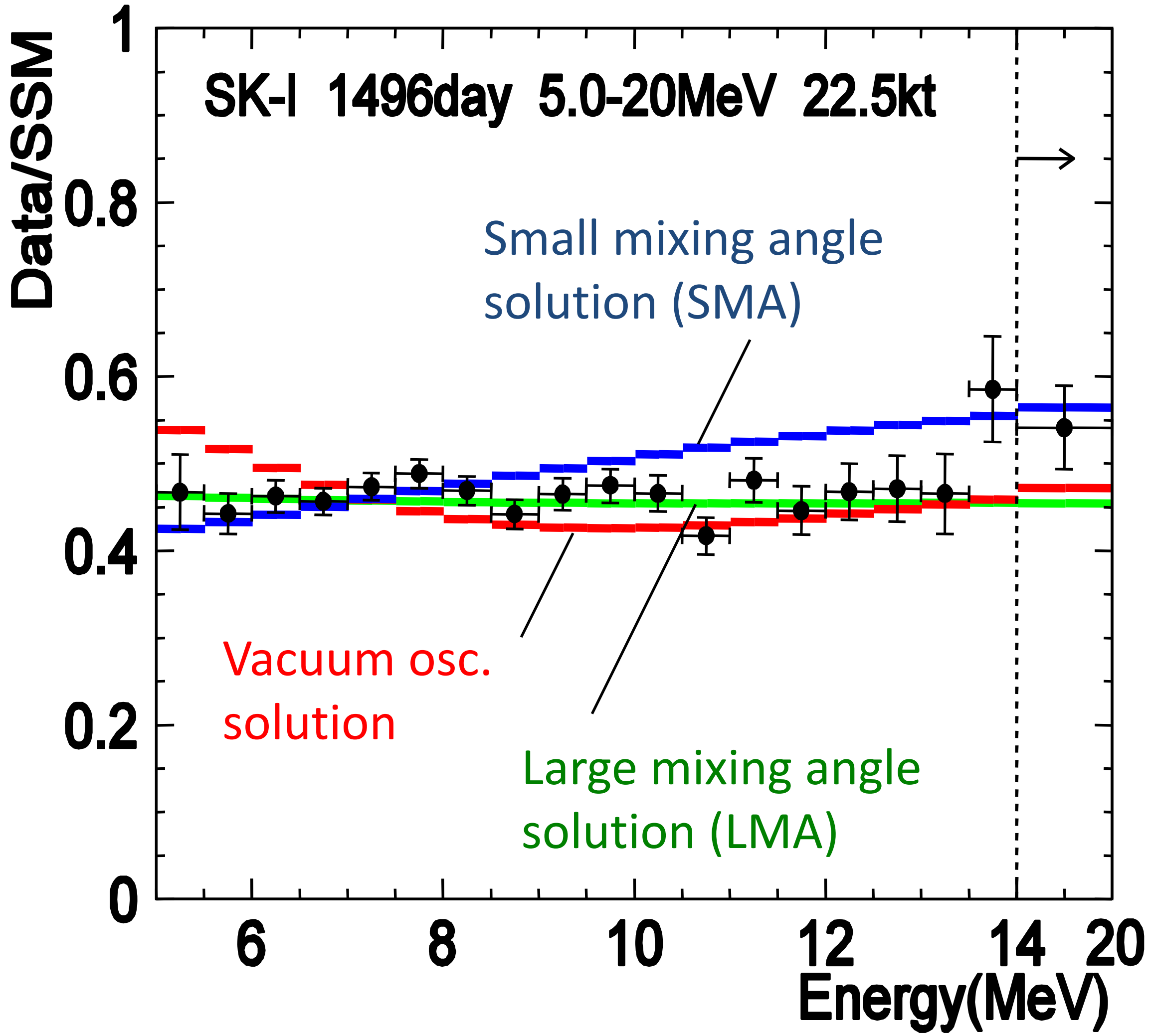
Assuming ν_e only:

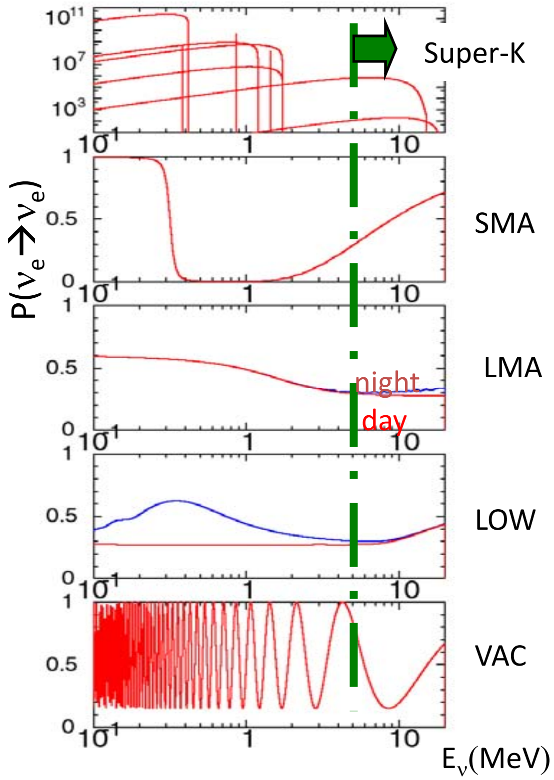
^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm²/sec]

$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.465 \pm 0.005 \begin{matrix} +0.016 \\ -0.015 \end{matrix}$$

Electron energy spectrum

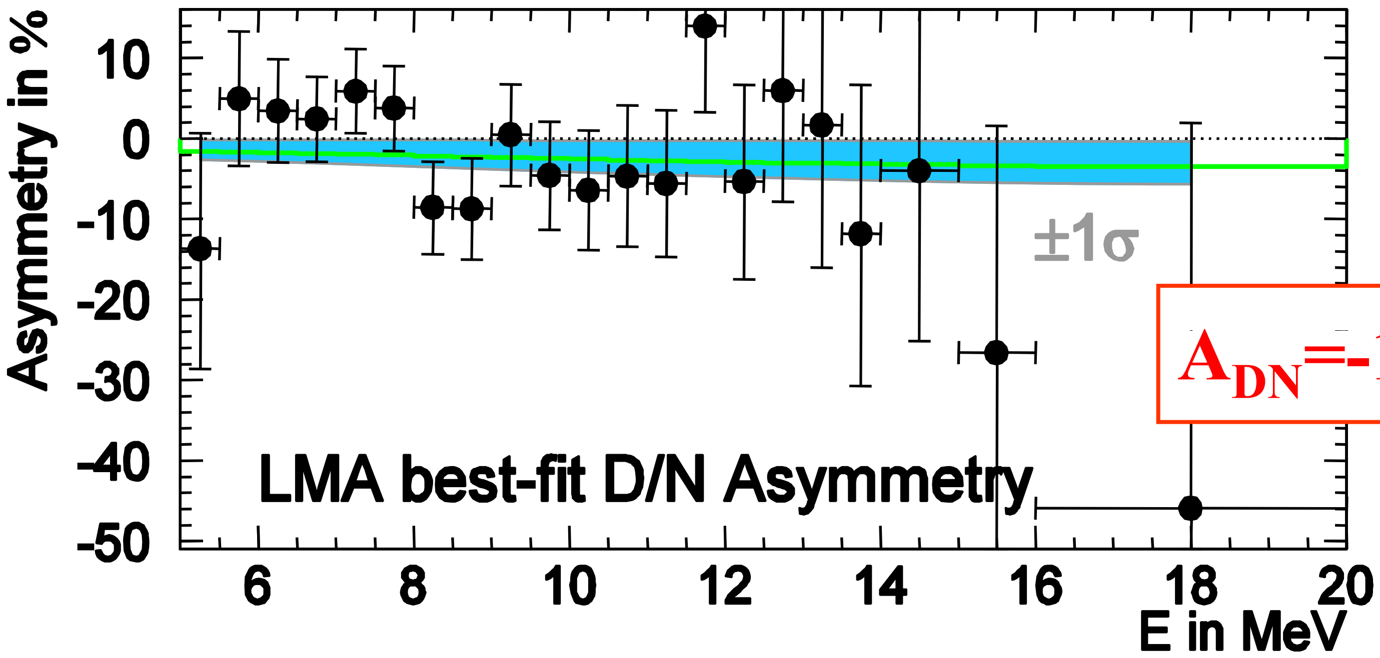
M.Smy, et al., Phys. Rev. D 69 (2004) 011104





No evidence for spectrum distortion,
→ inconsistent with SMA, VAC

Day-night flux asymmetry



$A_{DN} = -1.8 \pm 1.6^{+1.3}_{-1.2}\ \%$

$$A_{DN} = \frac{\phi_D - \phi_N}{(\phi_D + \phi_N)/2}$$

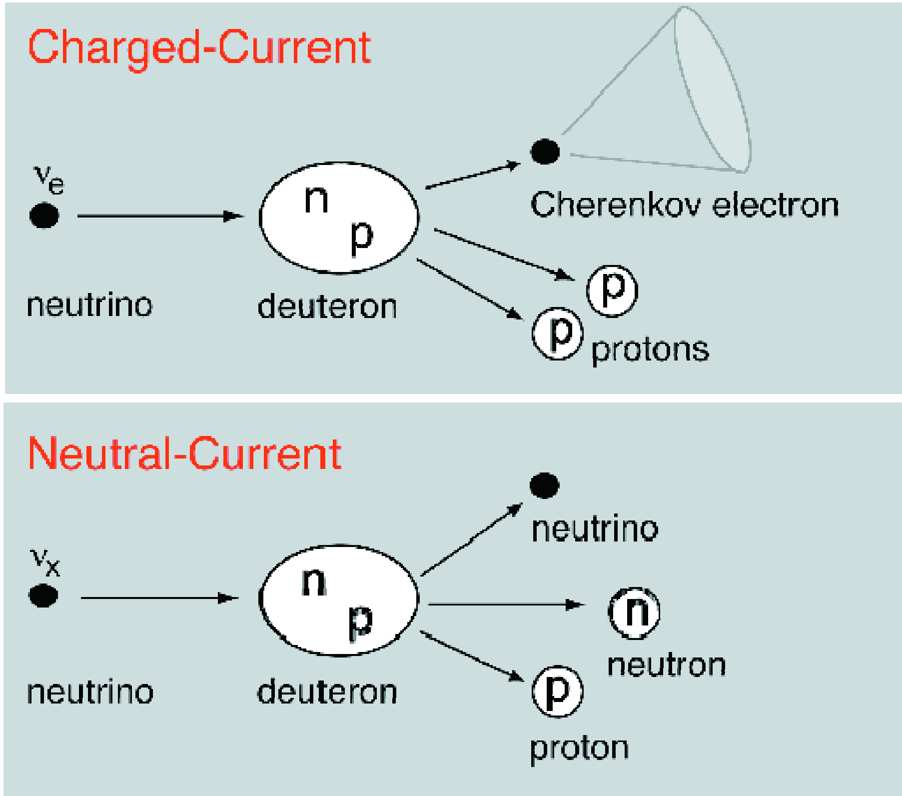
No evidence for day-night flux asymmetry
→ oscillation parameters are constrained

Summary of SK solar: A lot of precise measurements, stronger constraint on oscillation parameters. But no smoking gun evidence for oscillations. However, …

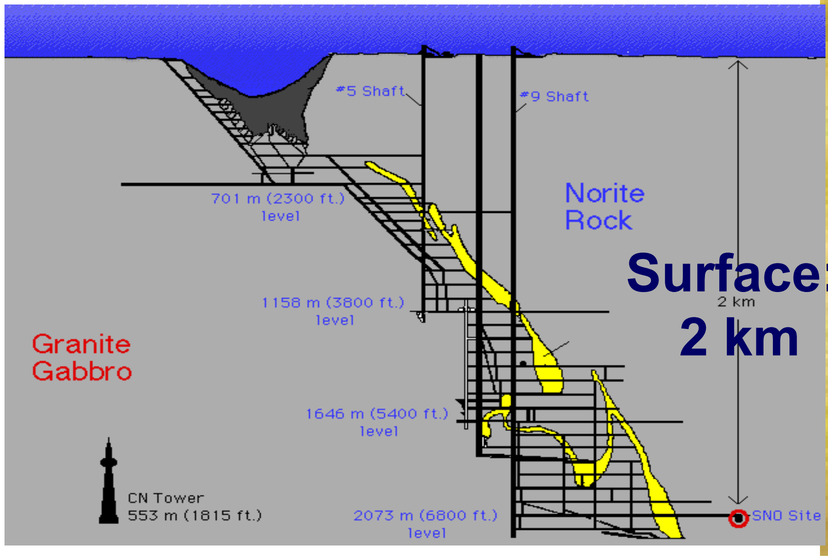
Heavy water experiment

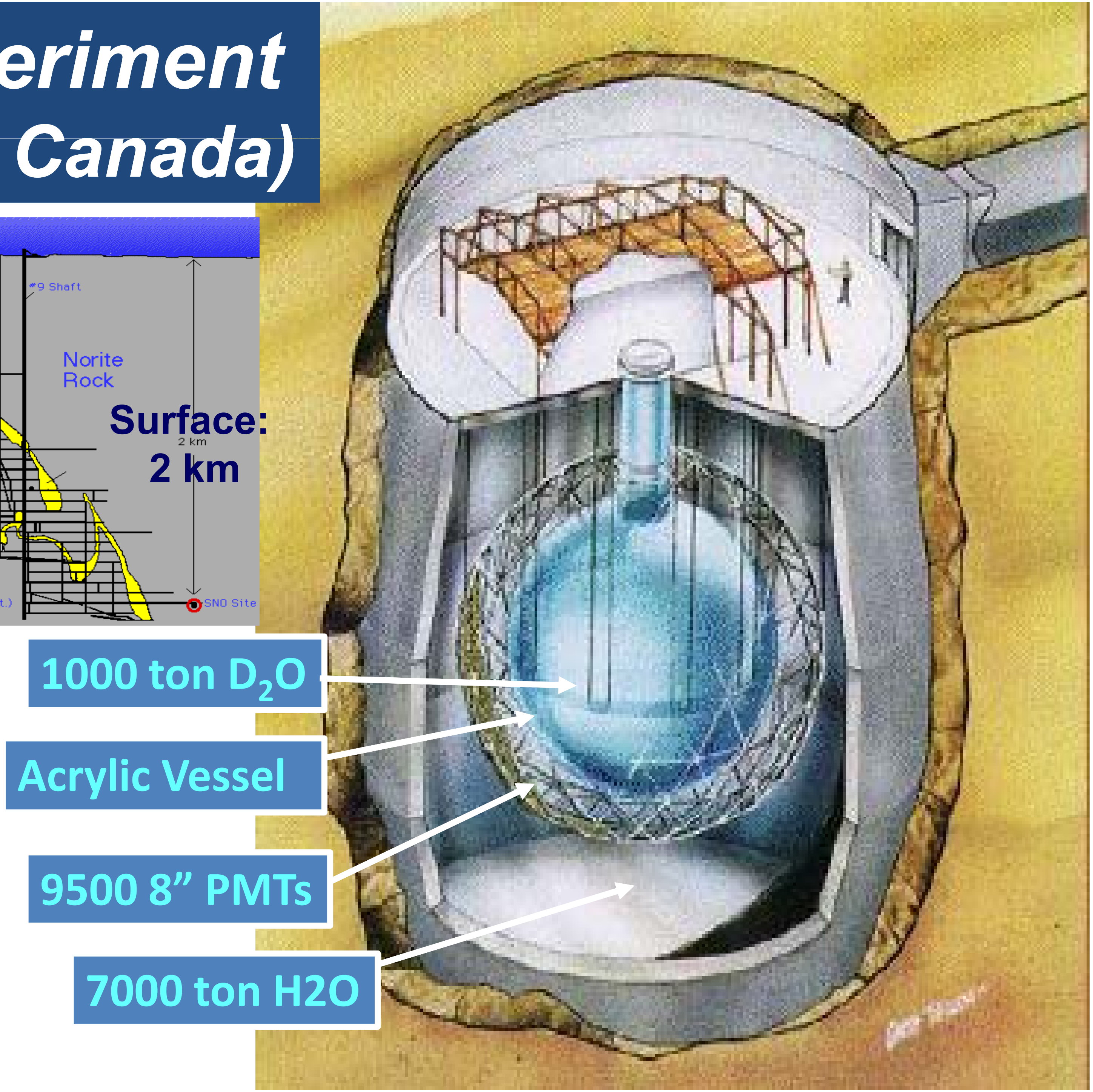
H.Chen PRL 55, 1534 (1985)
"Direct Approach to Resolve the Solar-neutrino Problem"

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 ^8B 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.



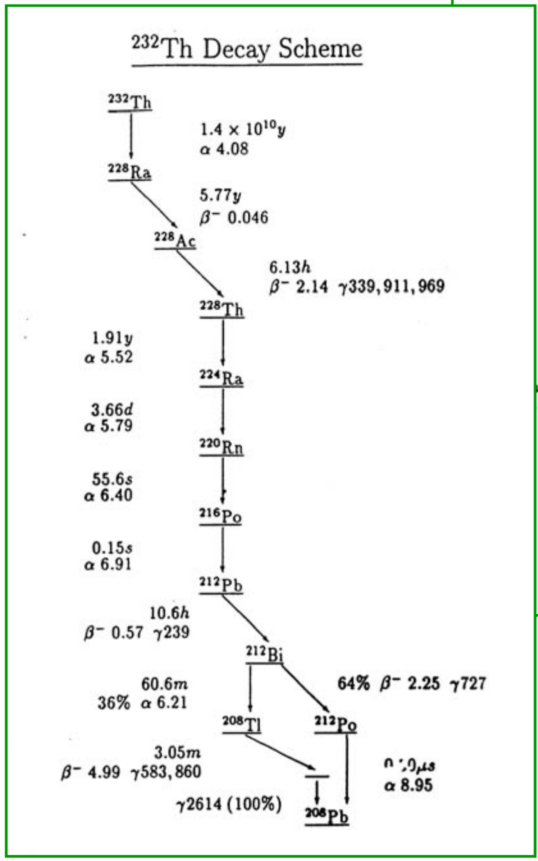
SNO experiment (Sudbury, Canada)

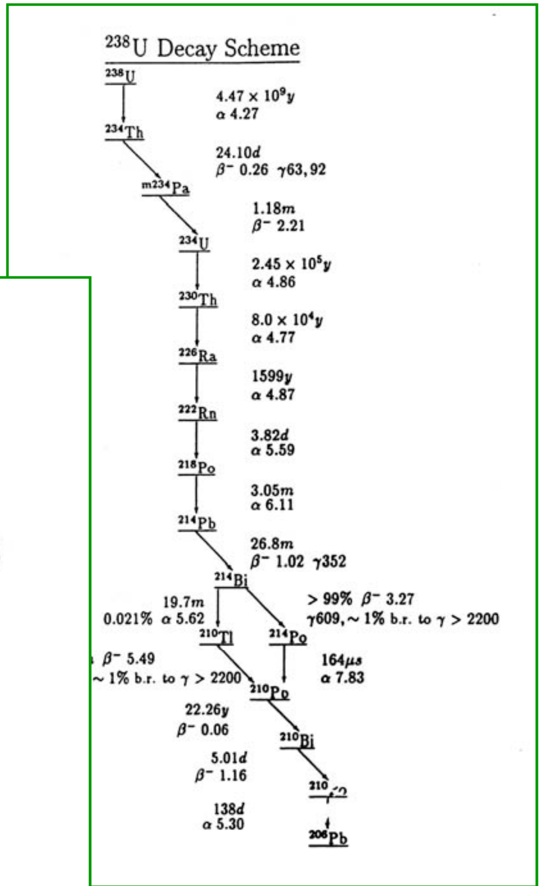




SNO detector (under construction)

The background: radioactivity





βs and γs from decays in U/Th chains interfere with the signals at low energies

Especially, γs over 2.2 MeV cause $d + \gamma \rightarrow n + p$
(Background for NC)

Requirements:

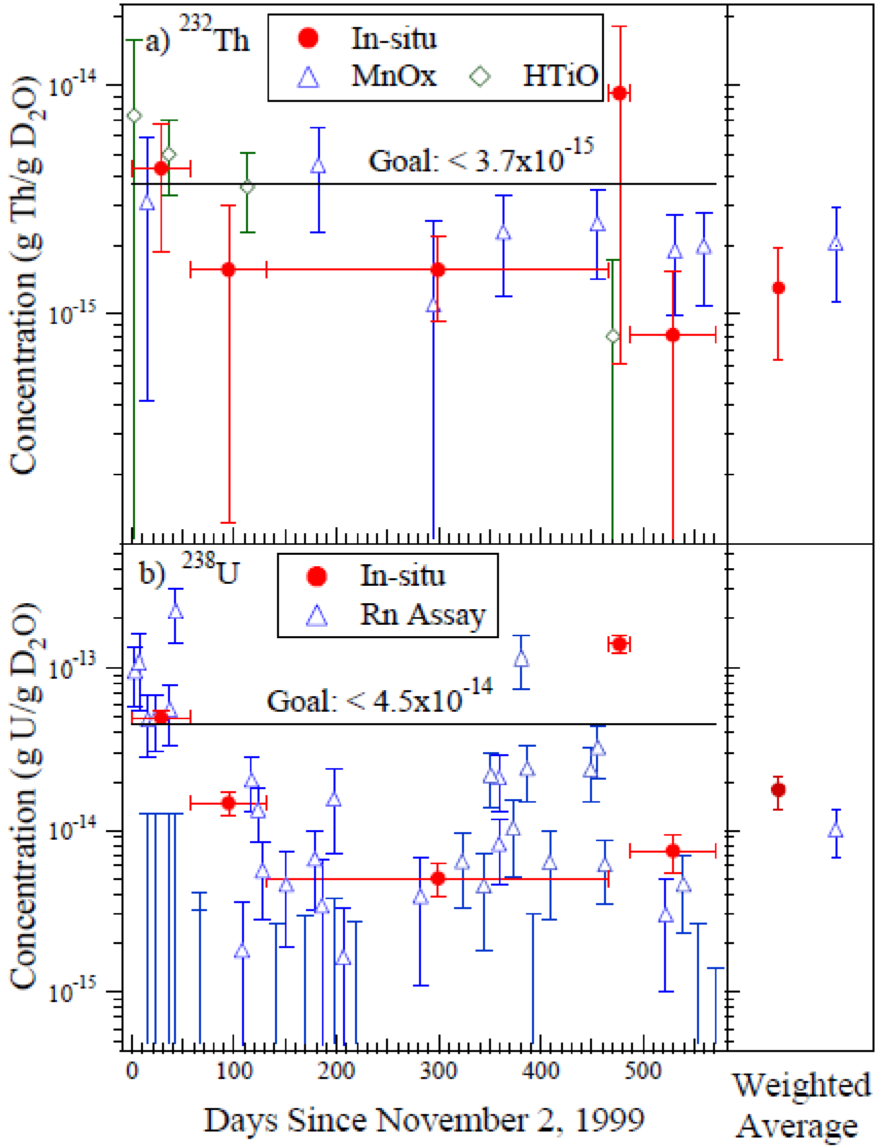
D_2O $< 10^{-15}$ gm/gm U/Th

H_2O $< 10^{-14}$ gm/gm U/Th

Acrylic $< 10^{-12}$ gm/gm U/Th

U/Th in D_2O

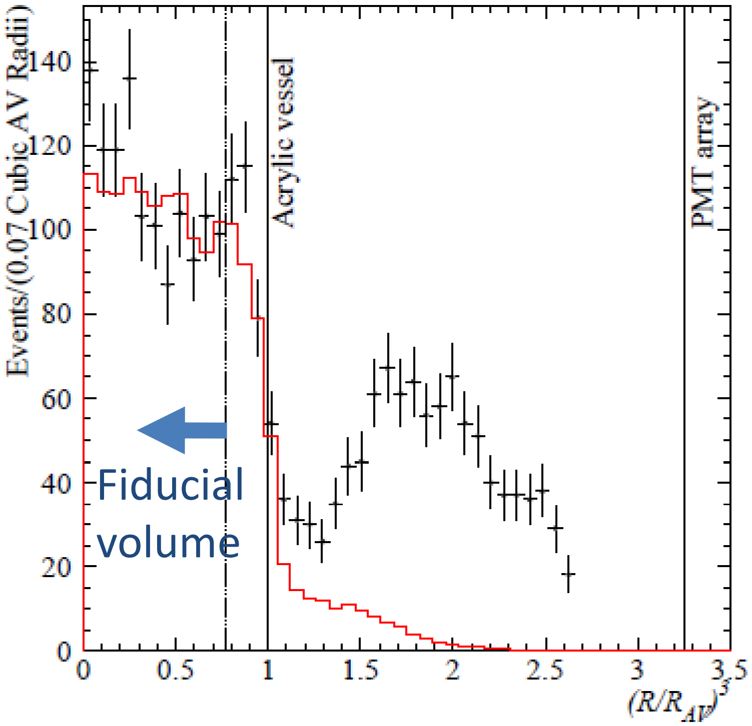
nucl-ex/0204008

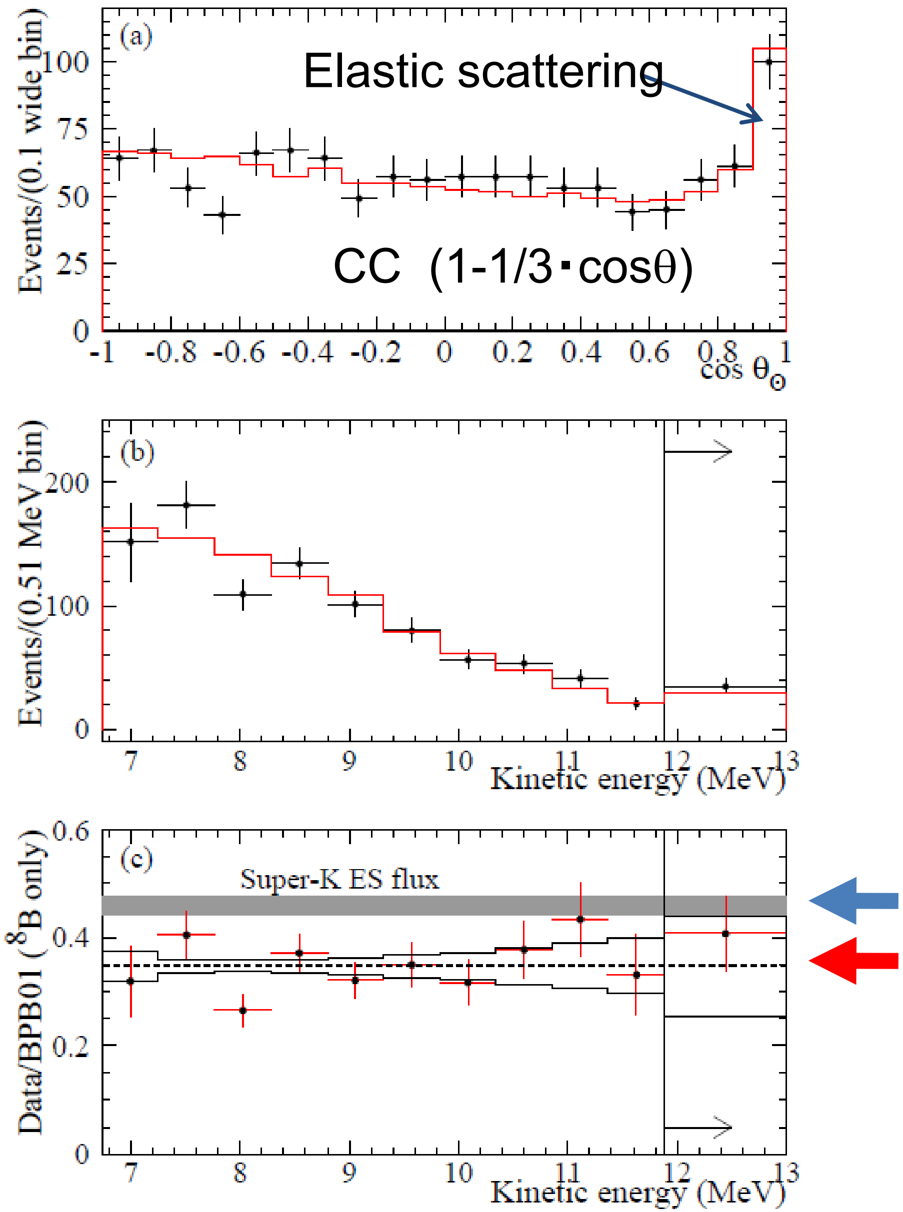


Both U and Th below the requirements

CC measurement

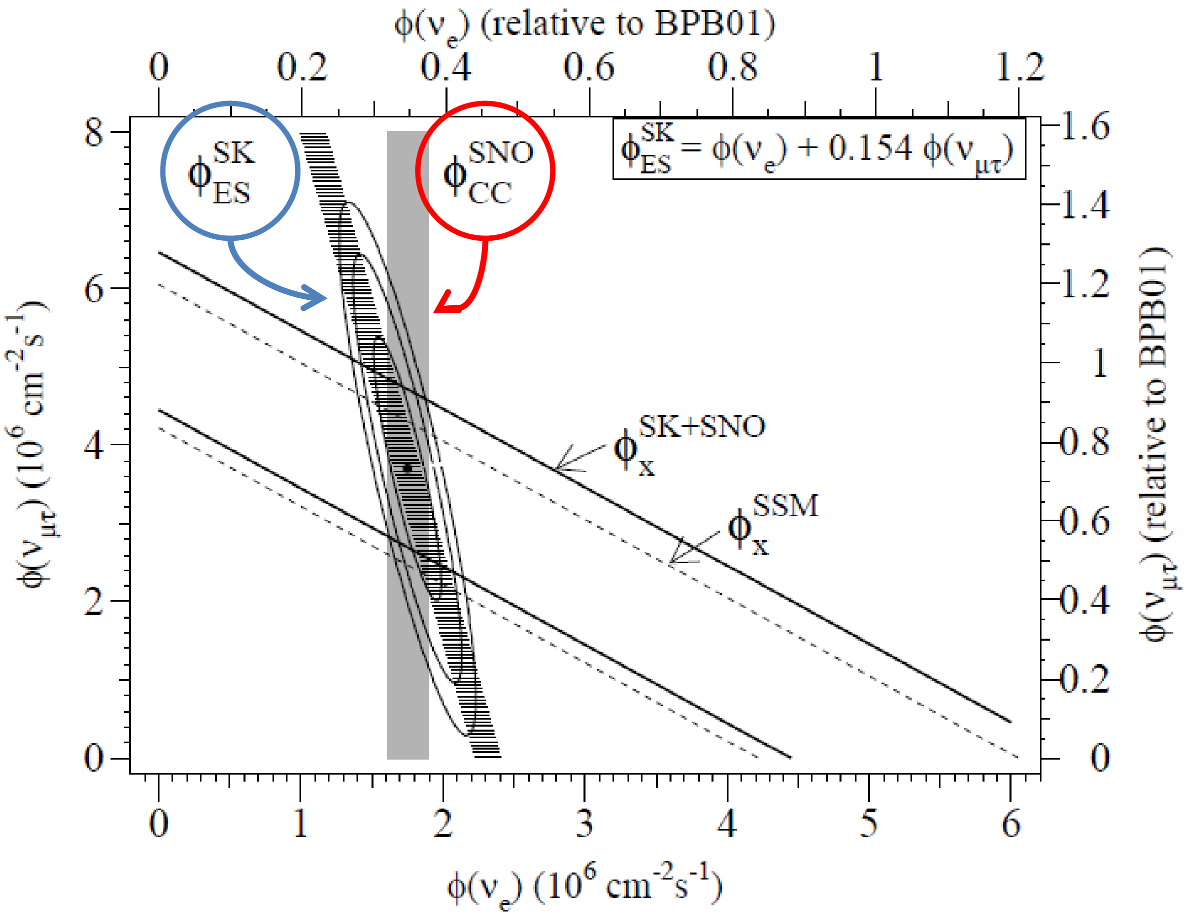
Radial distribution of events with >6.75 MeV





SNO CC vs. Super-K elastic scattering

Super-K elastic scattering (ES) flux is higher than the SNO CC flux.
ES is not only sensitive to the ν_e flux but also sensitive to the ν_μ and ν_τ fluxes with the reduced cross section (× (6-7) of that of ν_e+e→ν_e+e) !
The difference can be interpreted as evidence for "$\nu_\mu+\nu_\tau$ flux on the Eearth".



3.1 σ evidence for non-zero $\nu_\mu+\nu_\tau$ flux (or flavor change)

Three ways to measure the NC events

Neutron Detection Method

(1) Pure D_2O

$\nu + d \rightarrow \nu + p + n$

$n + d \rightarrow t + \gamma$ (E_γ = 6.3 MeV)

(γ produces e by Compton scattering)

(2) D_2O with salt

$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$'s ($\Sigma(E\gamma)$ = 8.6 MeV)

(Competing process: $n+d \rightarrow t+\gamma$)

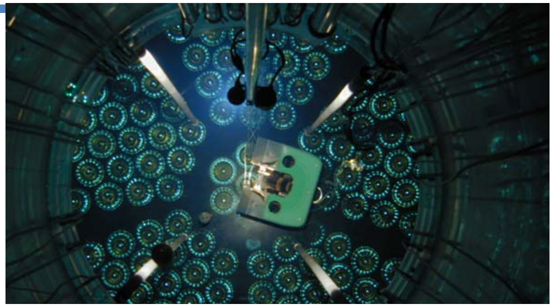
NaCl 2tons

Higher total energy
Higher capture efficiency
Different event pattern compared with the CC events

(3) ^3He counters in D_2O

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

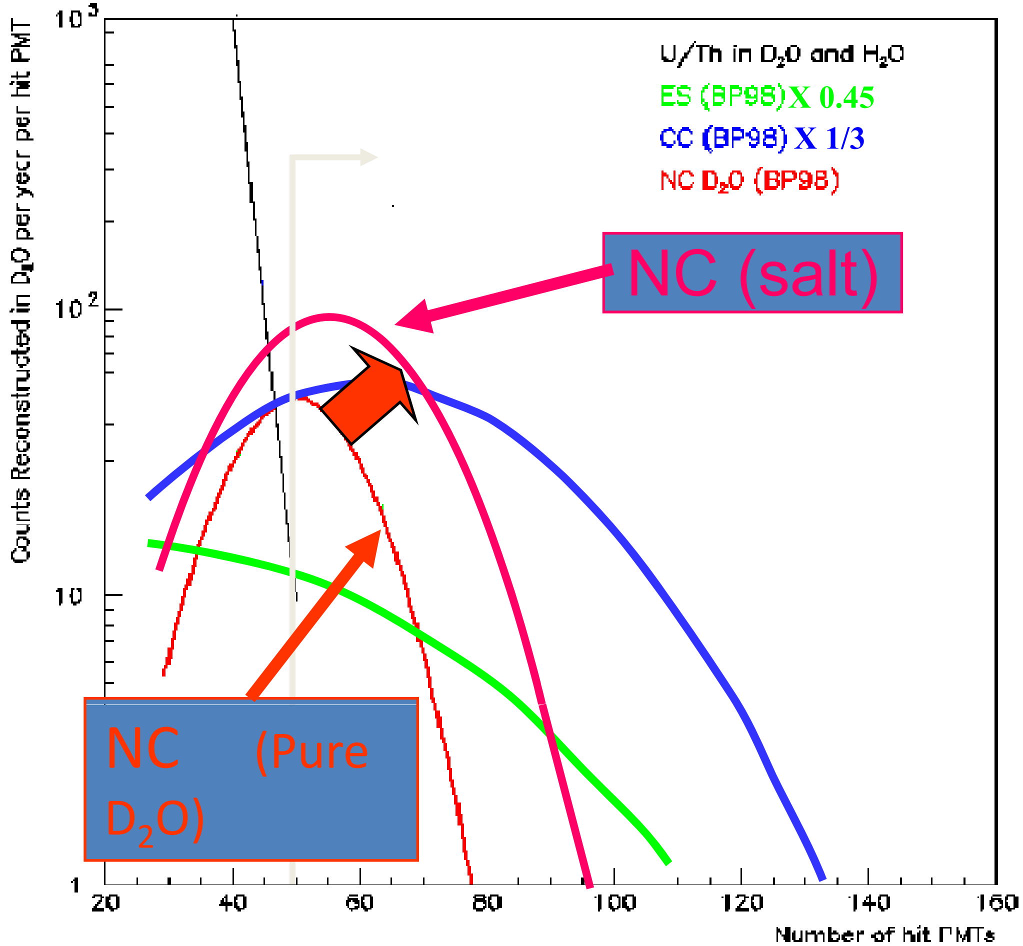
(This talk will not cover (3), since no results based on (3) have been published yet.)



SNO NC: Pure D_2O vs. Salt phase

2 tons of NaCl added into 1000 ton D_2O

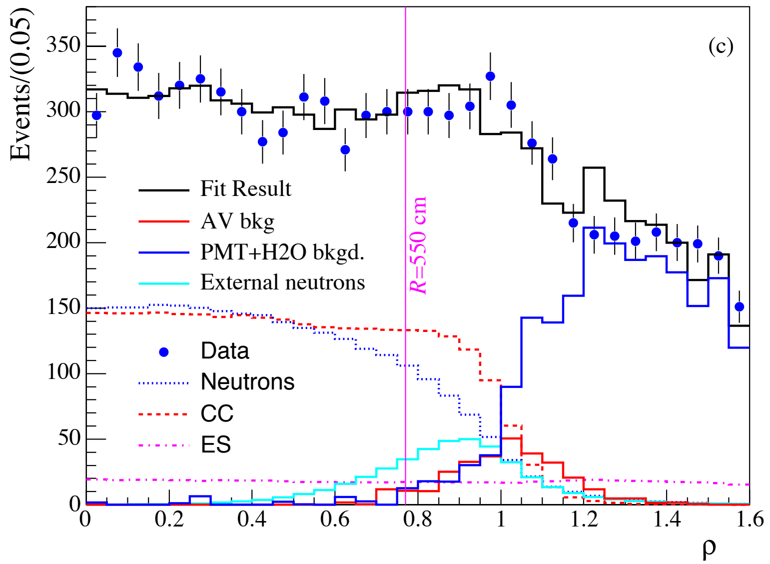
(Salt phase: 2001-2003)



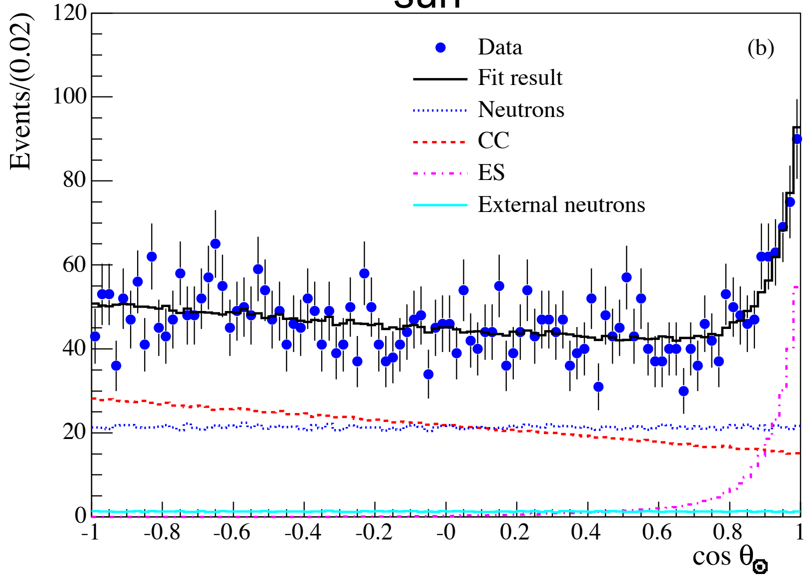
~ 9 NHIT/MEV

Salt phase flux measurement method

vertex

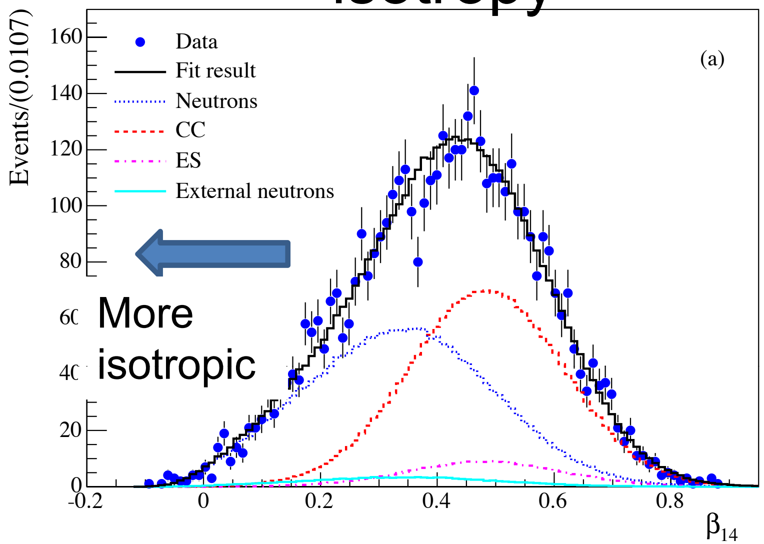


$\cos\theta_{sun}$

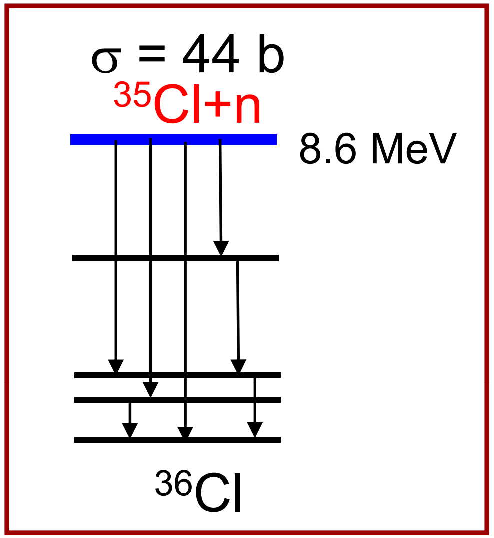


--- CC
--- NC
--- ES
--- BG

~ isotropy

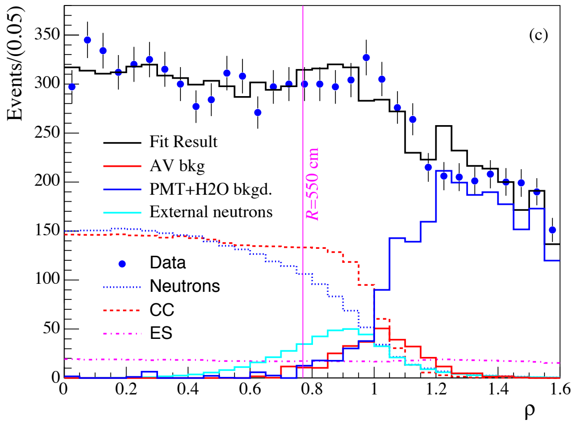


Several γ's
➔ Isotropic

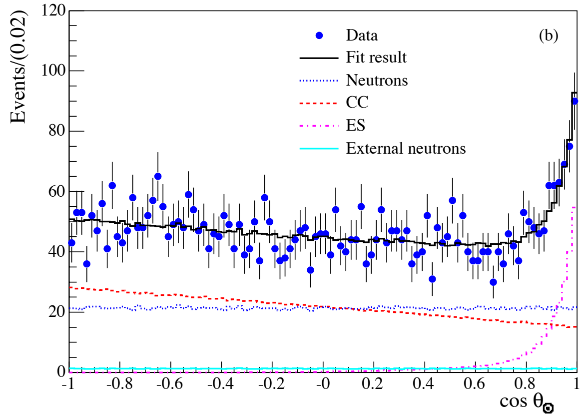


391-day salt phase flux measurements

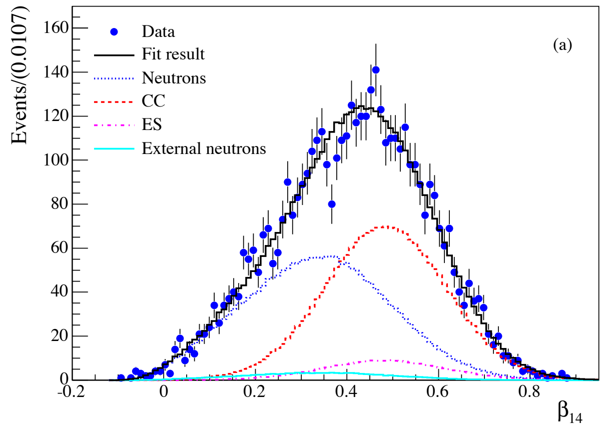
vertex



$\cos\theta_{sun}$



~ isotropy



w/o ^{8}B energy constraint

$$\phi_{CC}(\nu_e) = 1.68\,^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.08}_{-0.09}\,(\text{syst.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{ES}(\nu_x) = 2.35\,^{+0.22}_{-0.22}\,(\text{stat.})\,^{+0.15}_{-0.15}\,(\text{syst.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

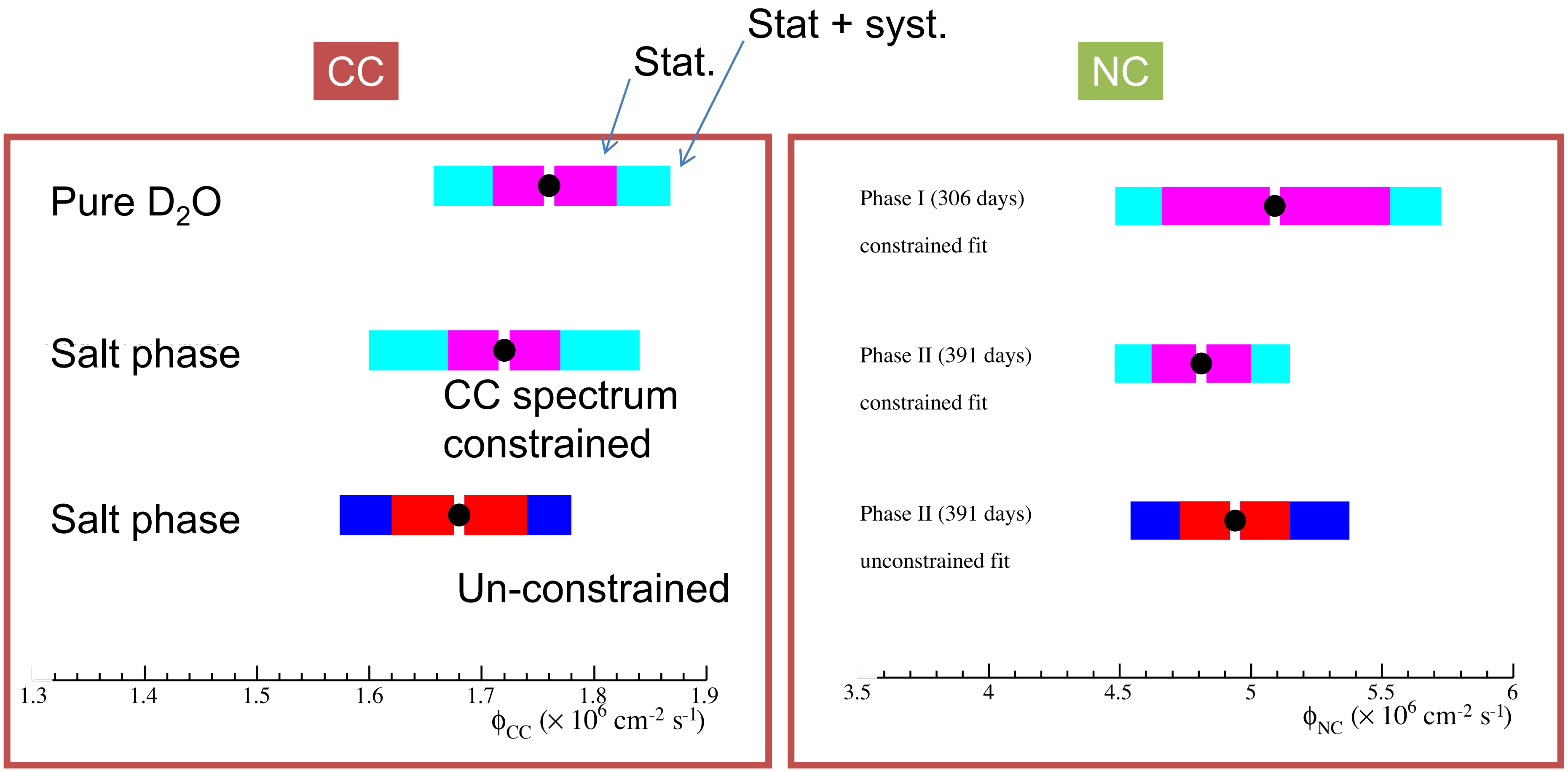
$$\phi_{NC}(\nu_x) = 4.94\,^{+0.21}_{-0.21}\,(\text{stat.})\,^{+0.38}_{-0.34}\,(\text{syst.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

SNO collab.
nucl-ex/
0502012

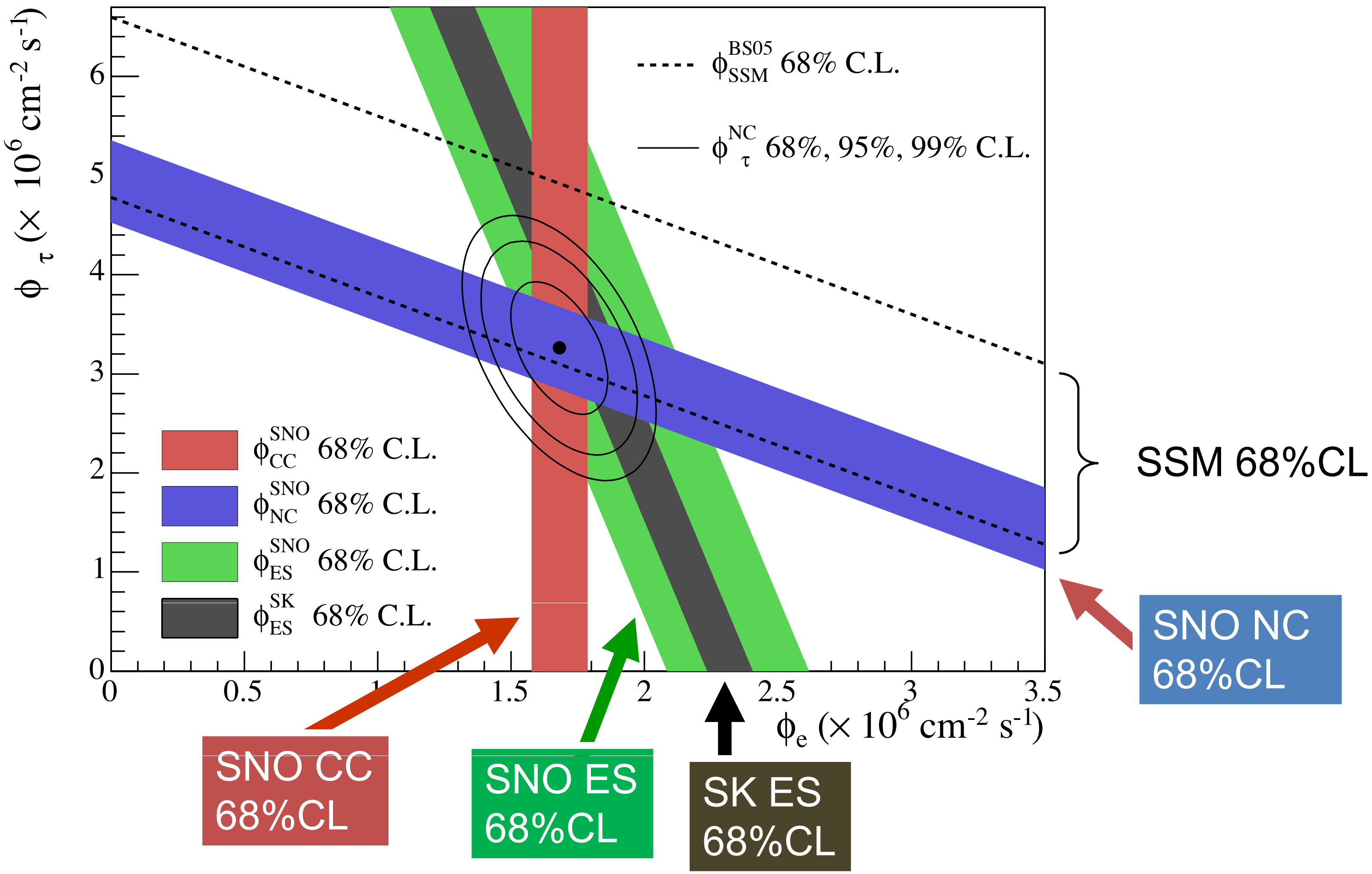
$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023\,^{+0.029}_{-0.031}$$

Very clear evidence for non-zero $\nu_\mu+\nu_\tau$ flux (flavor change)

Comparison of results from SNO-D_2O phase and SNO-salt phase



ν_e and $(\nu_\mu+\nu_\tau)$ fluxes

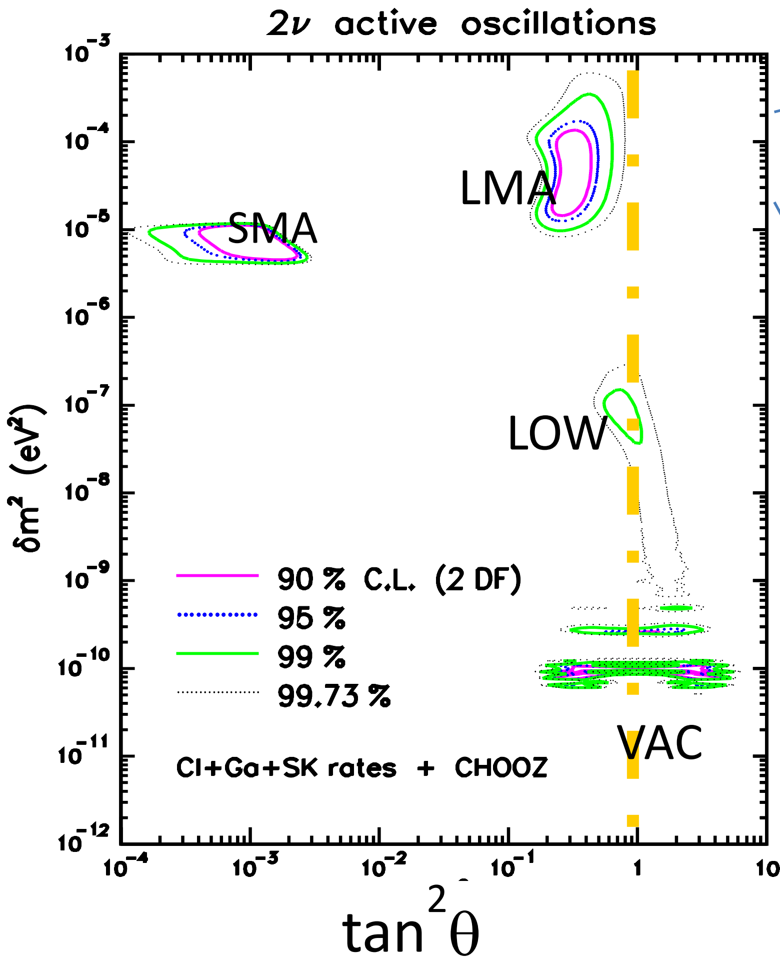


Three (or 4) different measurements intersect at a point (➔non trivial).
All the data are consistently explained within the standard oscillation

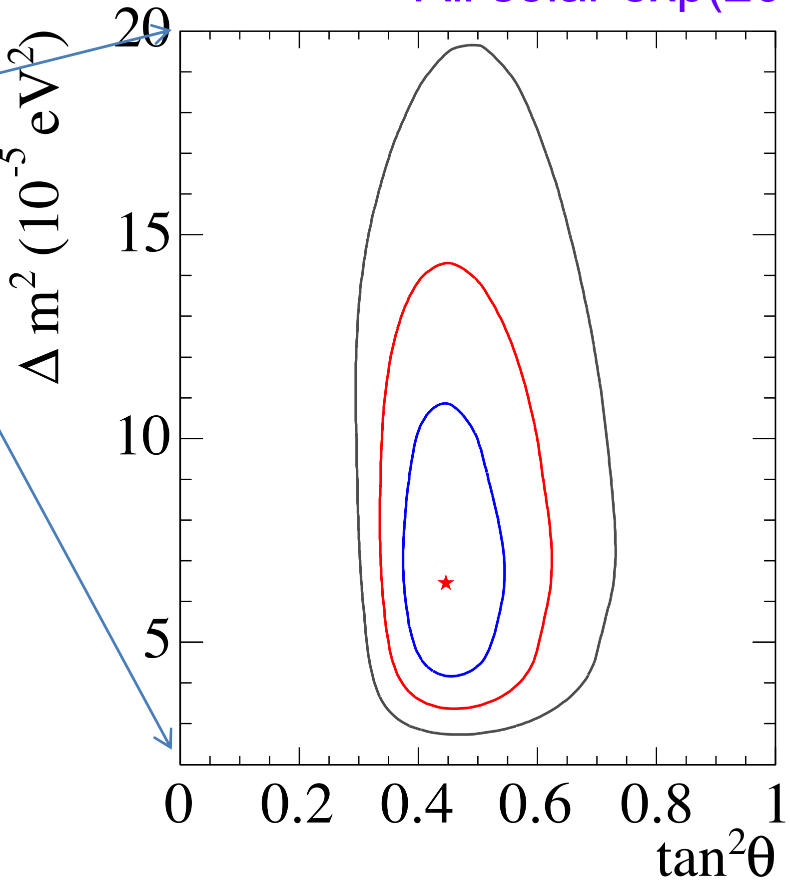
Oscillation Analysis with all solar neutrino data

SNO collab nucl-ex/0502021
Also many other analyses

Earlier in this talk….
(assuming oscillations)



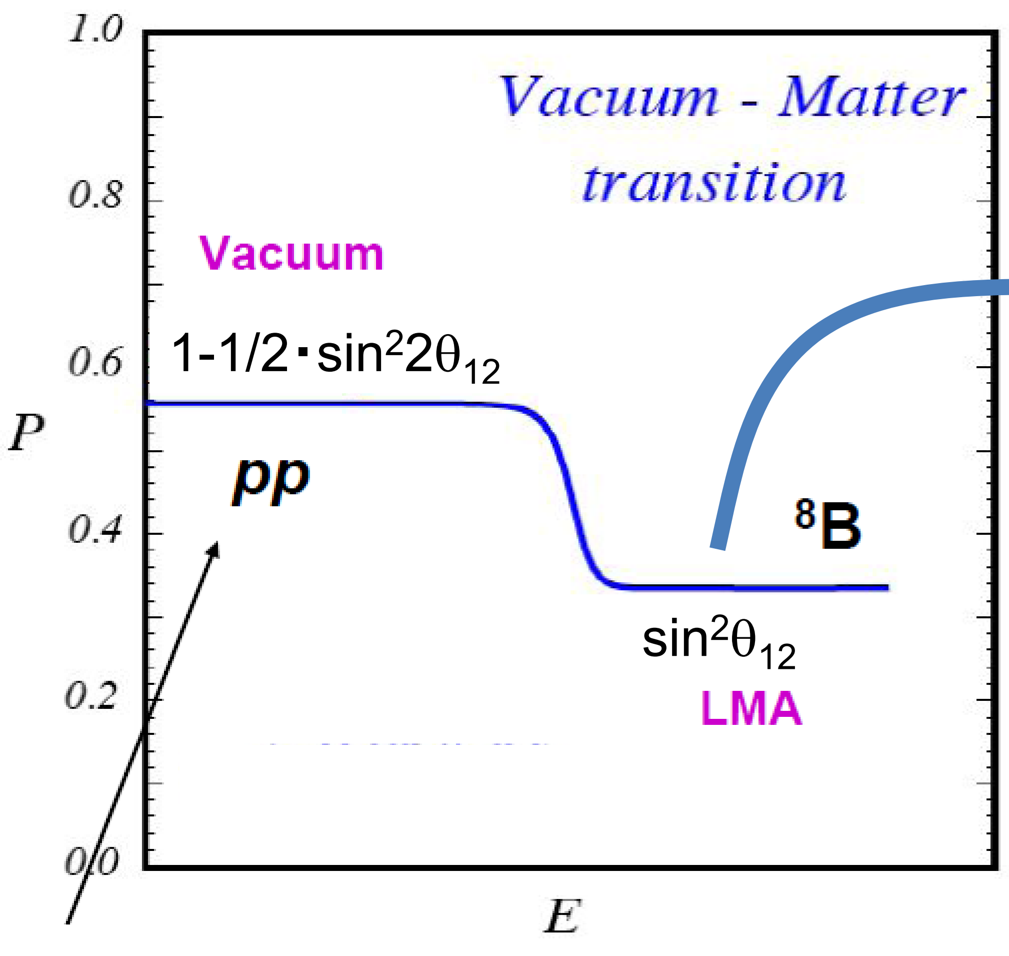
All solar exp(2005)



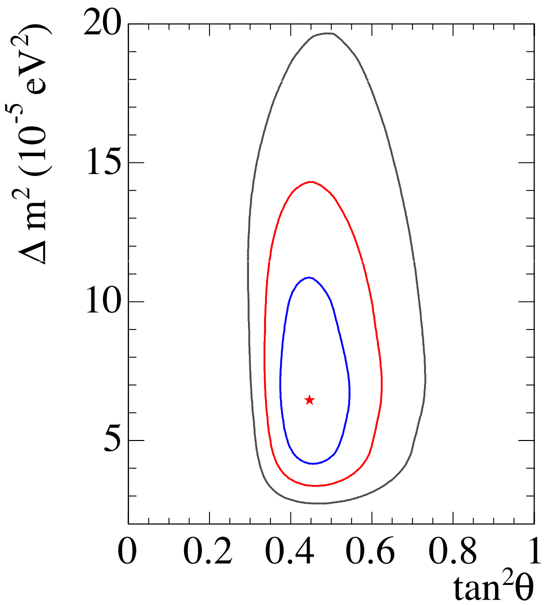
CC/NC and the measurement of θ_{12}

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \;{}^{+0.029}_{-0.031}$$

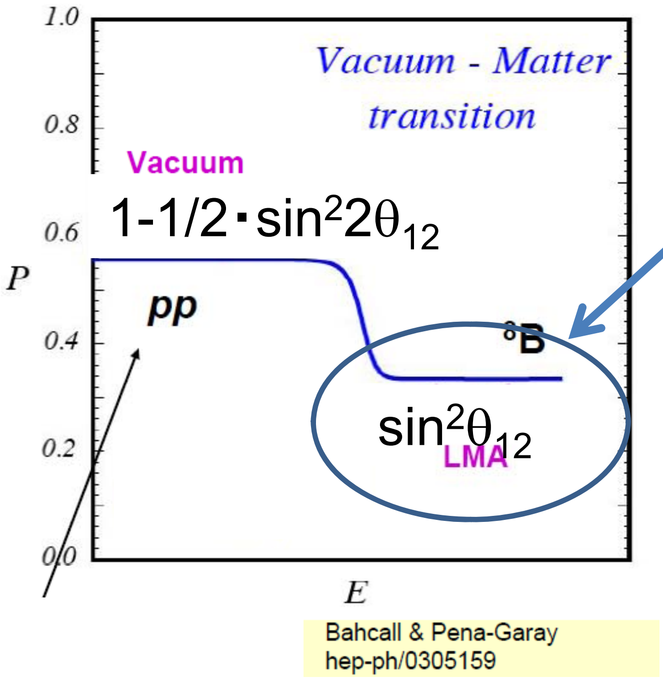
Accurate measurement of $\sin^2\theta_{12}$ is possible by the CC/NC ratio measurement.



Bahcall & Pena-Garay
hep-ph/0305159



CC/NC and the measurement of θ_{12}



This happens only if;

Furthermore,

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023 \ {}^{+0.029}_{-0.031}$$

Is less than 0.5.

➔ $\theta_{12} < 45$ degree. (about 34 deg.).

These conclusions were obtained based on the matter effect.

Summary of Lecture-2

- Nearly 40 years ago, the first solar neutrino experiment (Homestake ^{37}Cl experiment) observed solar neutrinos. But this experiment also found "The missing solar neutrino problem".
- The deficit was confirmed by many experiments, constraining possible solutions.
- The problem was clearly solved by the SNO D_2O experiment, with an important contribution from the Super-K data.