Solar Neutrinos

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1. Introduction
    - Solar ν experiments
    - Solar ν problem
2. Flux measurements and oscillation solutions
3. 'Smoking Guns'
    - Day/Night, Spectrum, Seasonal
    - Flux independent oscillation analysis
4. Global oscillation analysis
5. Future

Atmospheric ν

Discovery of the neutrino oscillation and the finite neutrino mass

$\nu_\mu \rightarrow \nu_x$ **($\Delta\chi^2$=122) Most likely x = τ (~2σ level)**

⇒ See the latest results from SuperK

Next important issue is the Solar Neutrino Problem:

$\nu_e \rightarrow \nu_x$ **(Most likely x = μ)**

More or less de-coupled from atmospheric ν oscillation

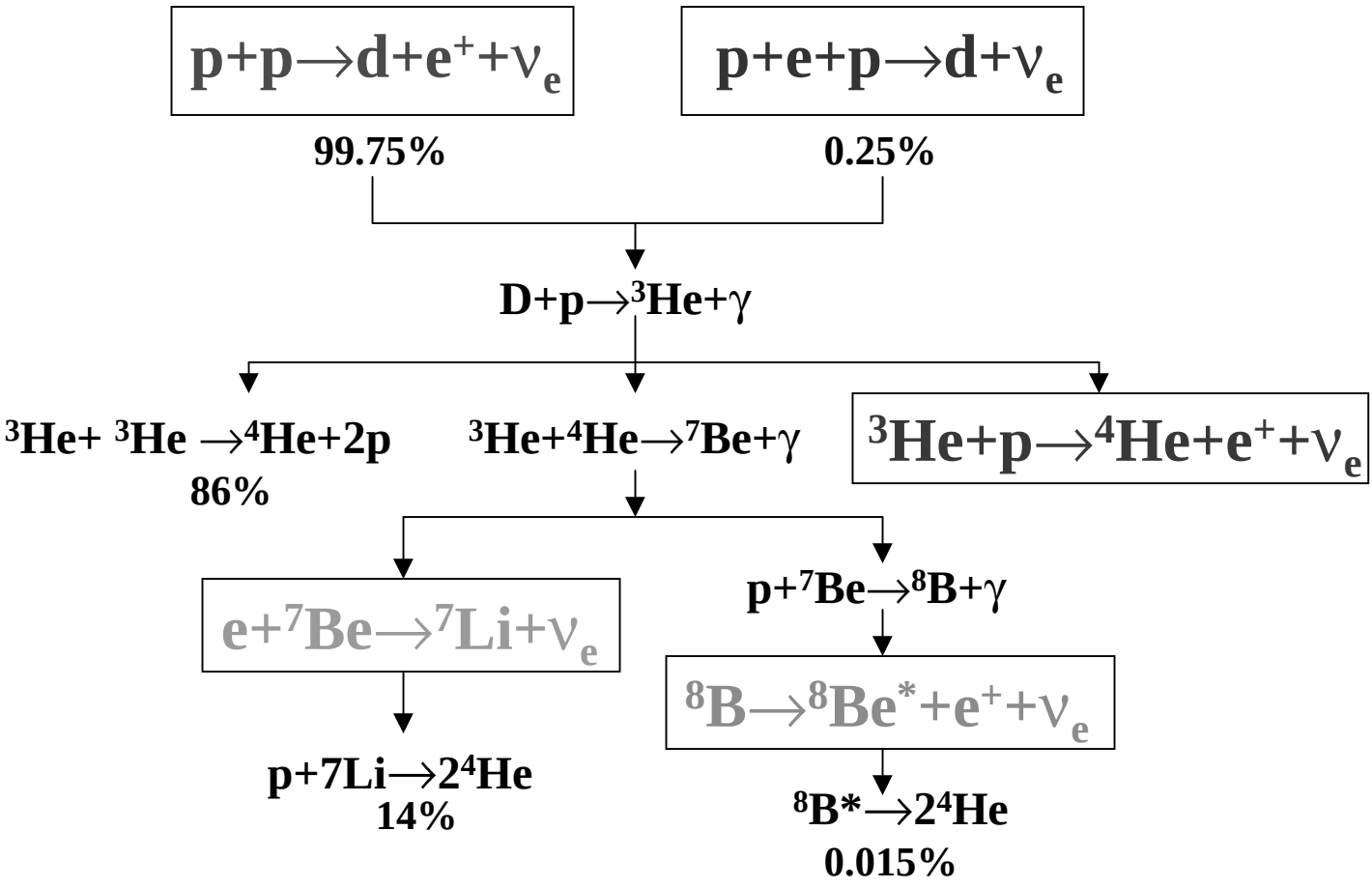
Solar neutrino problem has been there since early 1970, well before the 1st indication of the atmospheric ν anomaly (e/μ) by Kamiokande in 1987.

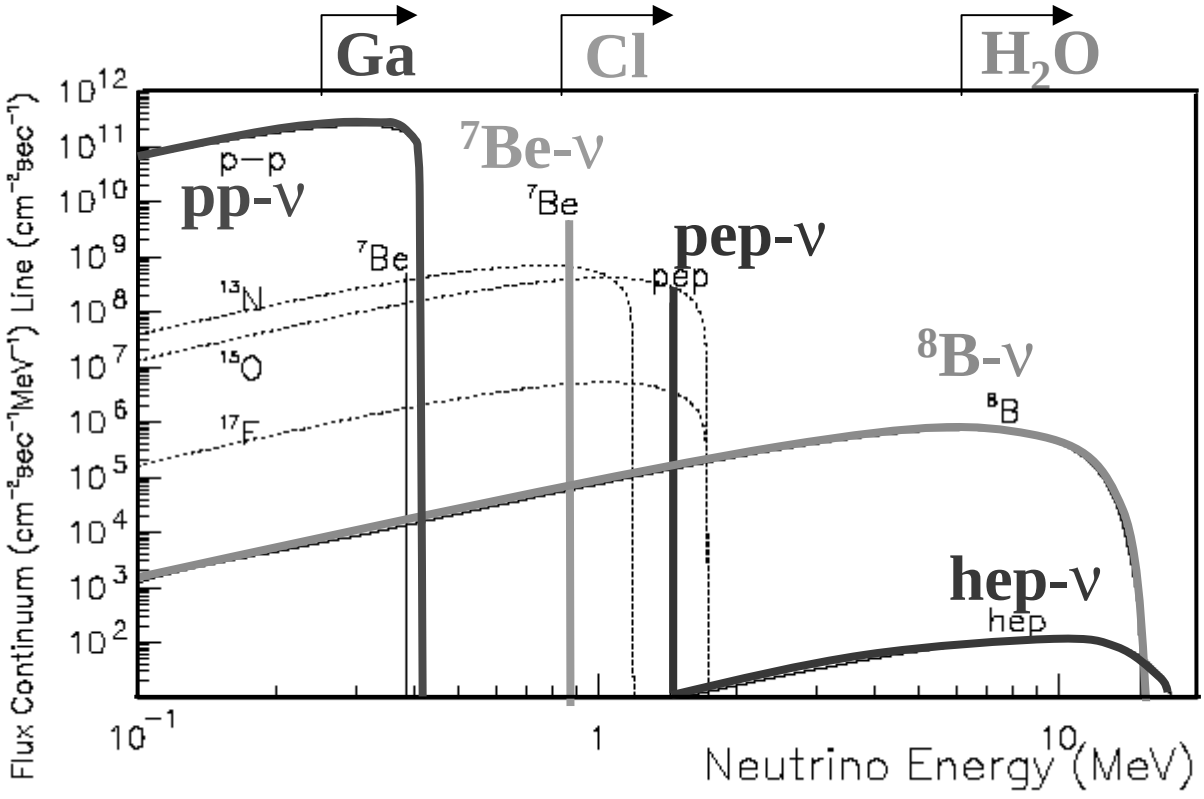
$\tau_{\text{solar } \nu \text{ prob}} > 30$ **years**

$(\tau_{\text{atm } \nu \text{ prob}} \sim 10$ **years)**

Solar neutrinos

The pp-chain





Solar neutrino experiments

Homestake : $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ E_{th}= 817keV

615tons

R=0.33±0.028

SAGE (GALLEX) GNO $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ E_{th}= 235keV

30□60 tons

R=0.52±0.07 (SAGE)
R=0.59±0.06 (Gallex)

(Kamiokande) : $\nu_e + e^- \rightarrow \nu_e + e^-$ (H_2O)
SuperKamiokande : E_{th}= 5.5MeV-7MeV

4,500 tons
50,000 tons

R=0.54±0.07 (Kam)
R=0.475±0.015 (SK)

SNO (D_2O) **Just turned on, to be explained later**

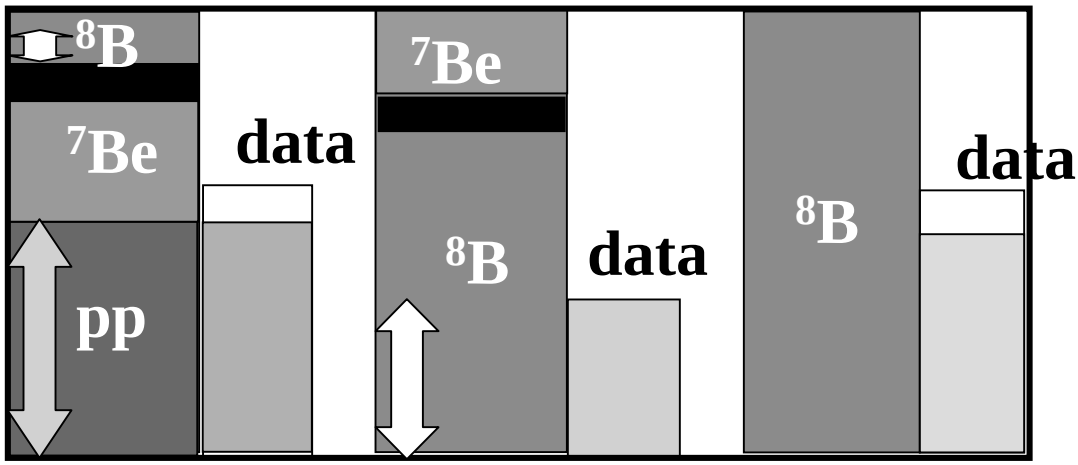
Radio chemical experiments: Cl, Ga

- Homestake, SAGE, GALLEX
- Integrated flux above a threshold
- CC

Water Cherenkov :

- Kamiokande, SuperK, SNO
- Directionality (ν□e→ν□e case)
- Energy
- Event time measurement
- CC+NC (SK)
- CC/NC (SNO)

Solar Neutrino Problem



$m_\nu = 0$

$m_\nu \neq 0$

Neutrino Oscillation

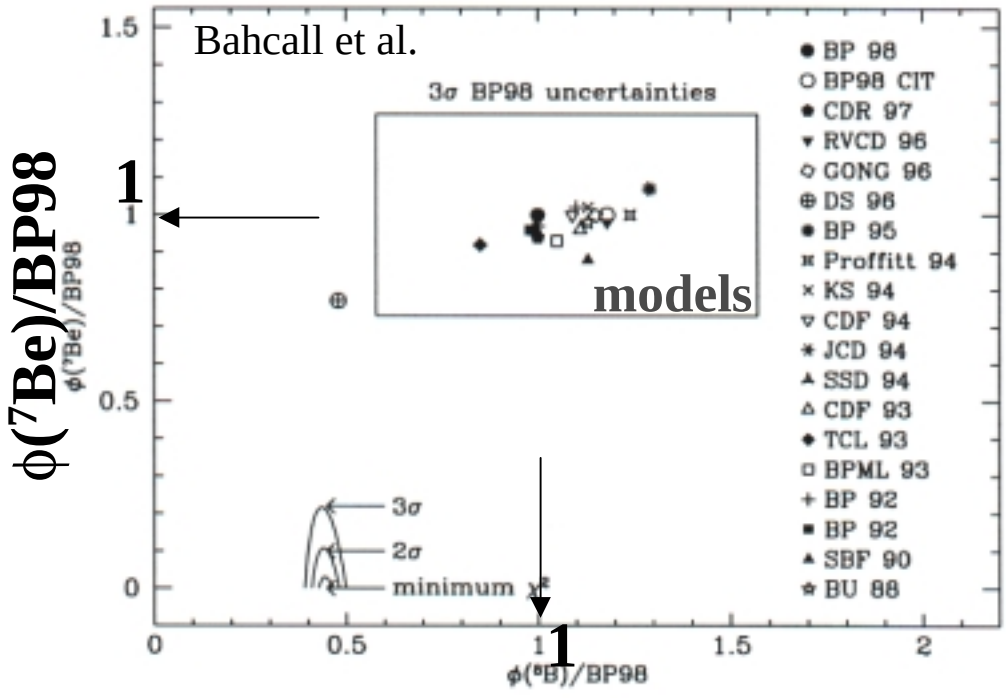
Astrophysical solutions?

★ **Kam(SK) ↔ Cl**

★ **Ga** [**Luminosity constraint** / **Ga vs Kam**]

$\phi_{7Be} = 0$

Hard to explain by modification of the solar models



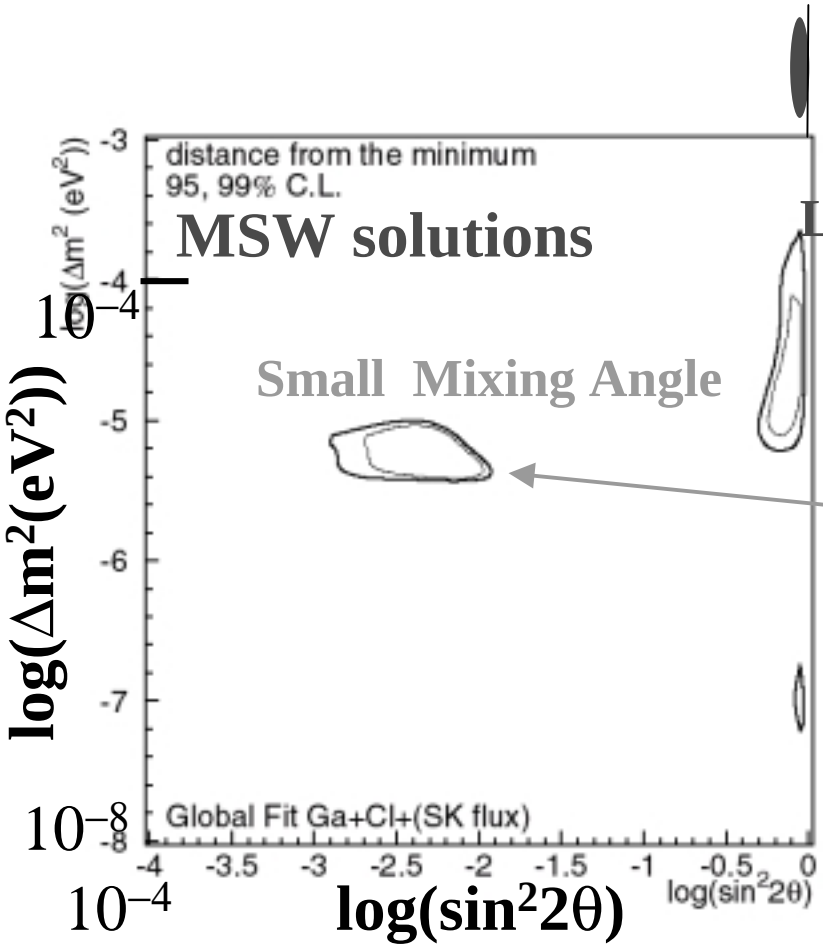
Fluxes as free parameters

Excluded by 99% C.L.

$\phi(^8B)/BP98$

Oscillation analysis by the flux measurements

(Homestake, SAGE, GALLEX, Super-Kamiokande)



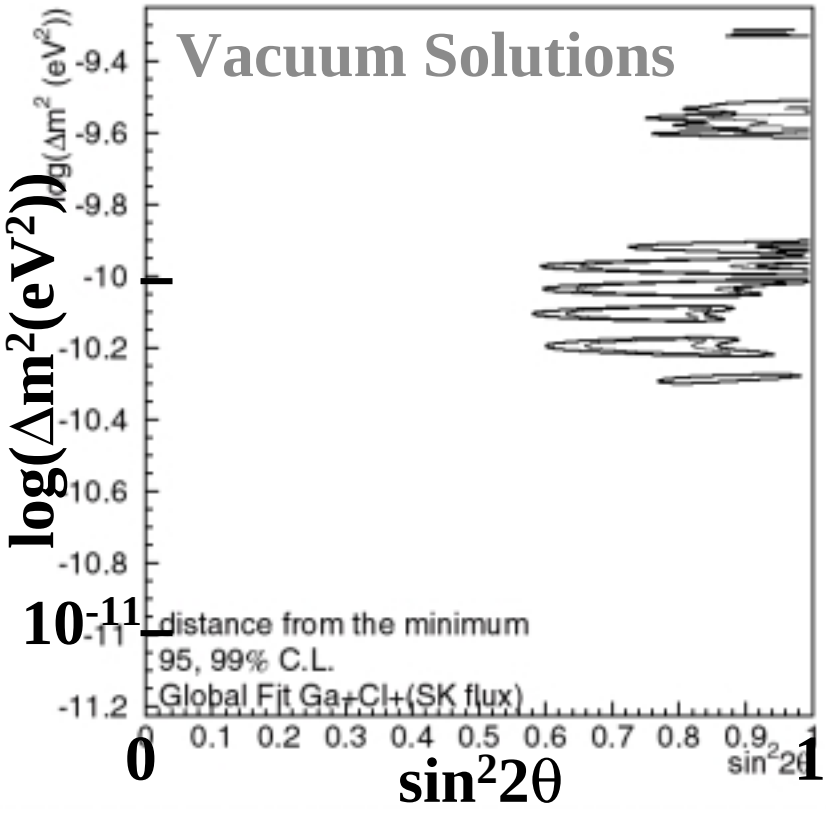
Atm-ν
($\nu_\mu \rightarrow \nu_\tau$)

Large Mixing Angle
$10^{-5}<\Delta m^2<10^{-4}eV^2$

Small Mixing Angle

Δm^2~ a few$\times 10^{-5}eV^2$
$10^{-3}<\sin^2 2\theta<10^{-2}$

LOW
$\Delta m^2 \sim 10^{-7}eV^2$



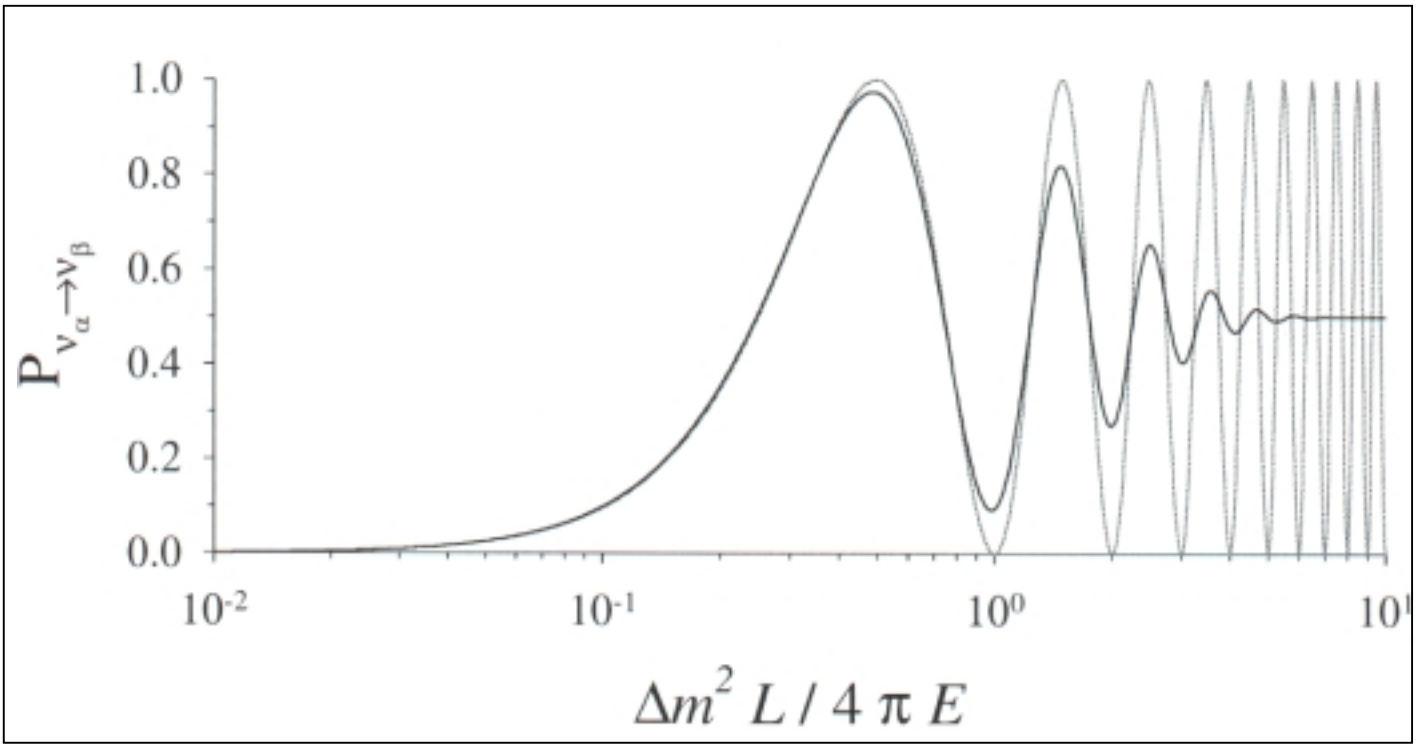
a few$\times 10^{-11}<\Delta m^2$
$<$ a few$\times 10^{-10}eV^2$

10^{-4}
10^{-8}
10^{-4}
$\log(\Delta m^2(eV^2))$
$\log(\sin^2 2\theta)$

10^{-11}
0
$\sin^2 2\theta$
1

Vacuum Oscillations

$$P(\nu_e\text{-}\nu_x) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$



$\Delta m^2 \approx E/L$

Just -so

solar neutrino case

$\Delta m^2 \sim 10^{-11} \sim 10^{-10}$ eV^2

$\Delta m^2 > E/L$

$P(\nu_e\text{-}\nu_x) = 1/2 * \sin^2 2\theta$

uniform suppression

not for solar ν

pp-ν : ~50% suppression

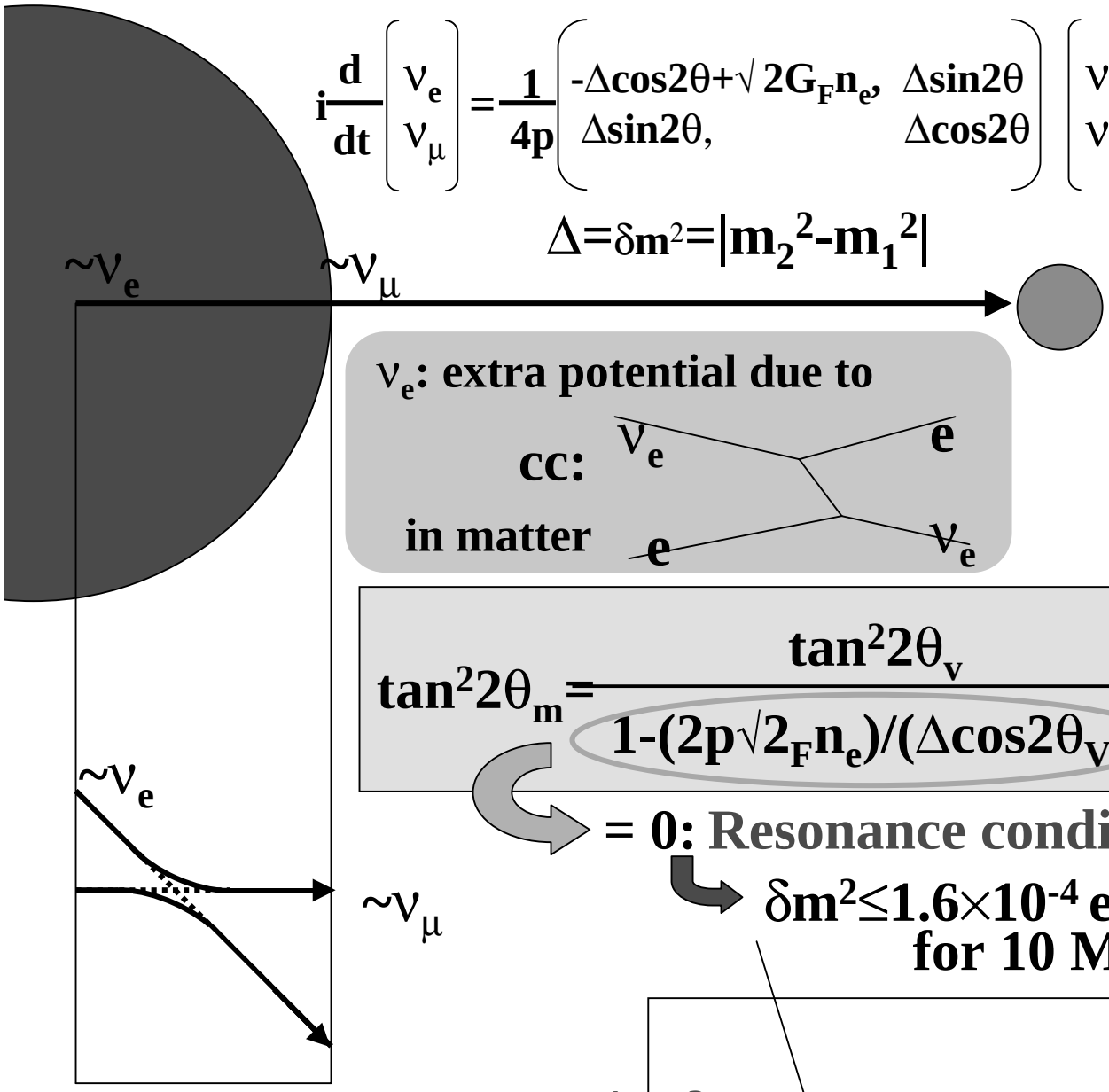
^{7}Be : 0 ~ full suppression

^{8}B : ~ 50% suppression

MSW effect

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4p}\begin{pmatrix}-\Delta\cos2\theta+\sqrt{2}G_F n_e, & \Delta\sin2\theta\\ \Delta\sin2\theta, & \Delta\cos2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

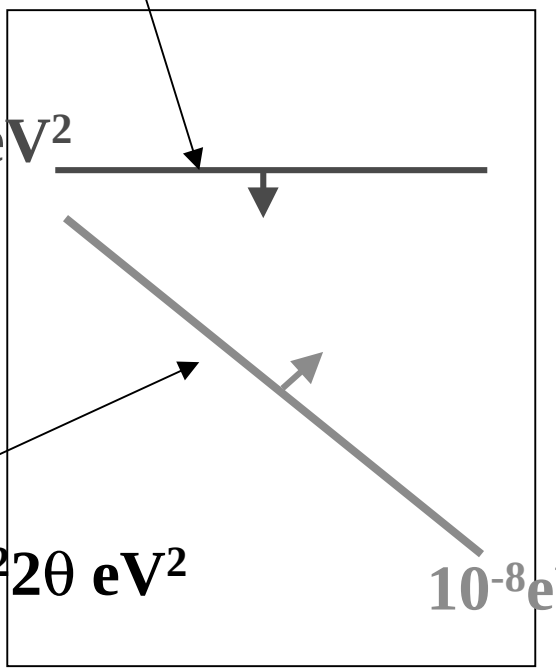
$$\Delta=\delta m^2=|m_2^2-m_1^2|$$



$$\tan^2 2\theta_m=\frac{\tan^2 2\theta_v}{1-(2p\sqrt{2}_F n_e)/(\Delta\cos2\theta_V)}$$

= 0: Resonance condition

$\delta m^2 \le 1.6\times10^{-4}\ eV^2$ for 10 MeV



$$\frac{\Delta}{2E_\nu}\frac{\sin^2 2\theta}{\cos^2 2\theta}\ge\left|\frac{1}{n_e}\frac{dn_e}{dr}\right|$$

Adiabatic condition

$\delta m^2 \ge 6.3\times10^{-8}\cos^2 2\theta/\sin^2 2\theta\ eV^2$ for 10 MeV

All the results have very strong deficits and the oscillation interpretation works very well over other explanations.

Why do people have not convinced that the solar neutrinos are oscillating?

Why solar neutrinos could not get a credit for the discovery of neutrino oscillations.

Atm–ν has won!!

Reason1. People working on solar ν is too shy to claim that.

Reason2. Doubt on the flux

No body has looked inside of the sun

Although

the astrophysical solution is not favored, and
the recent development of the Helioseismology
have proved that the SSM is correct.

Reason3. Possible solutions are not unique.
At least four solutions.

Need ⇓

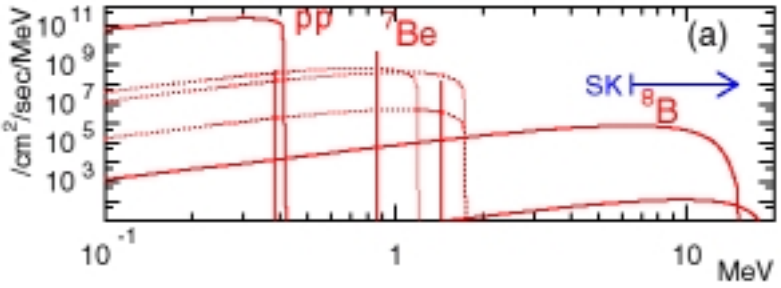
Flux independent evidence
Like atm-ν zenith angle distribution
Obtain unique solution

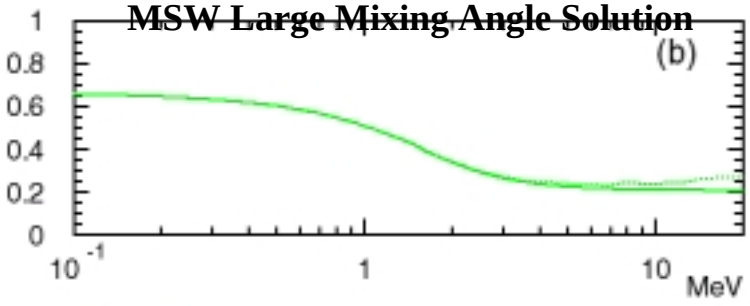
By ⇑

Somking Guns

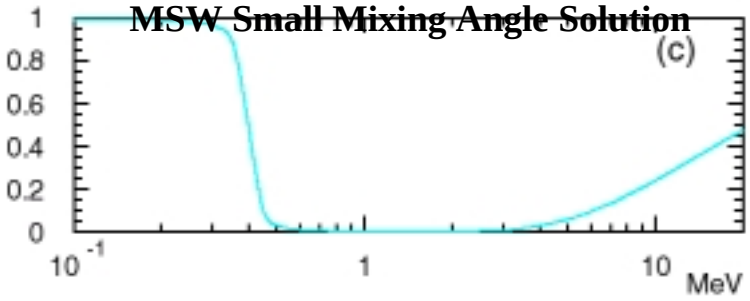
energy spectrum distortion
day/night flux difference
seasonal variations

Smoking Guns (Flux independent analysis)

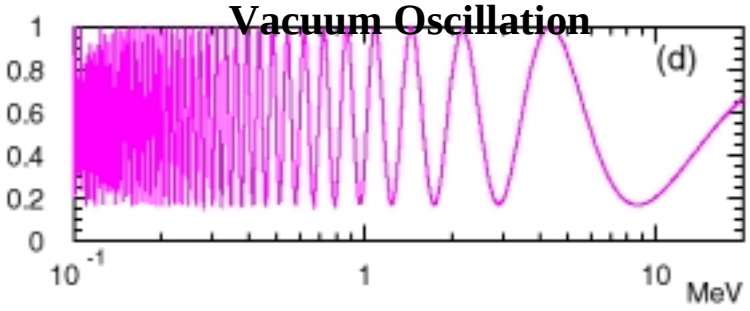




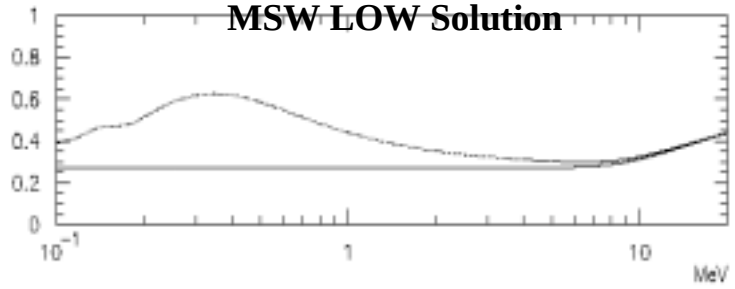
Day/night
flux difference



Spectrum Distortion



Spectrum Distortion
Seasonal Variation

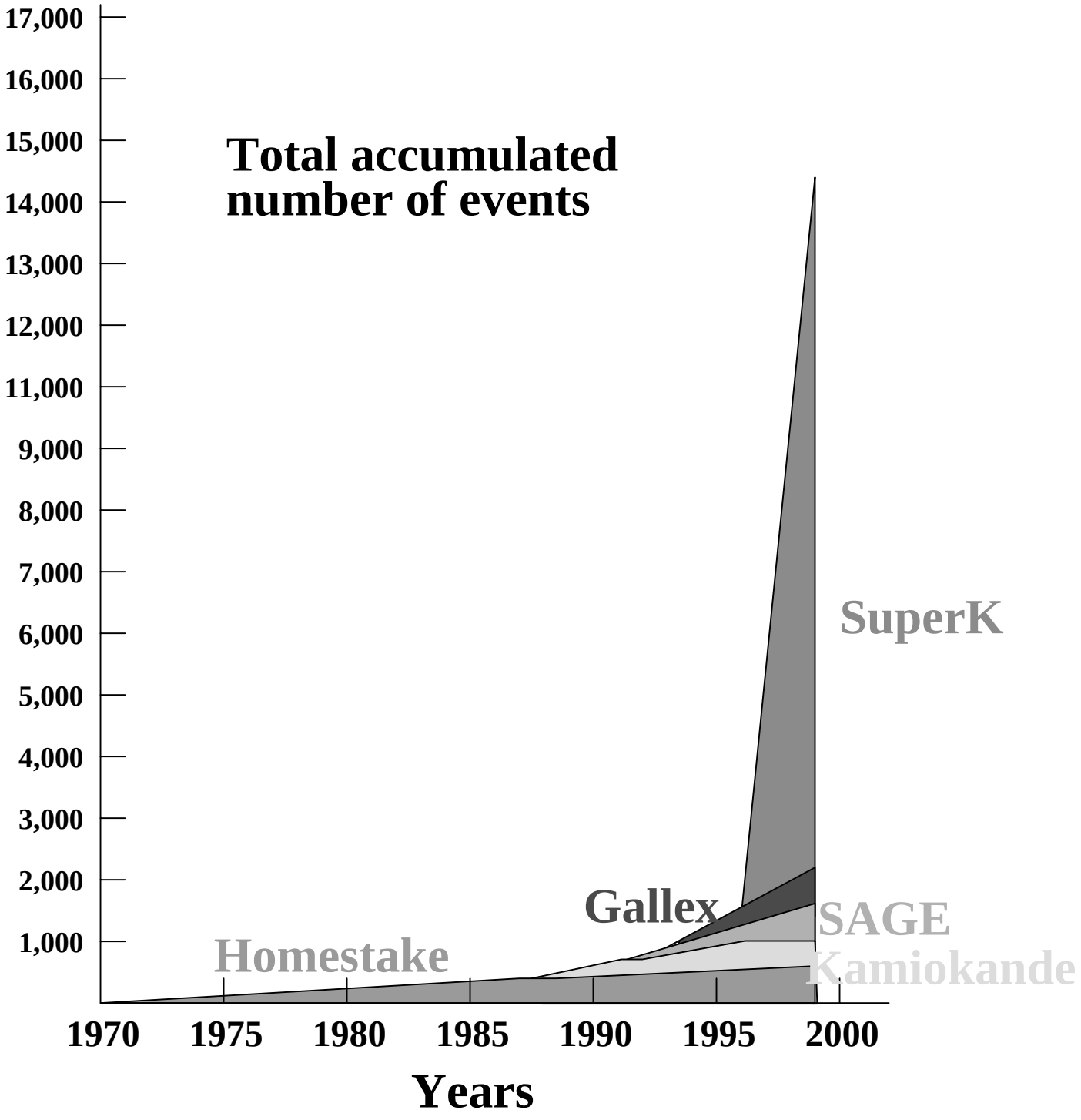


Spectrum Distortion
Day/night
flux difference

Neutral Current: unique for SNO

Flux independent evidence for neutrino oscillation
Can not determine the oscillation parameter

New era ---- high statistic experiments

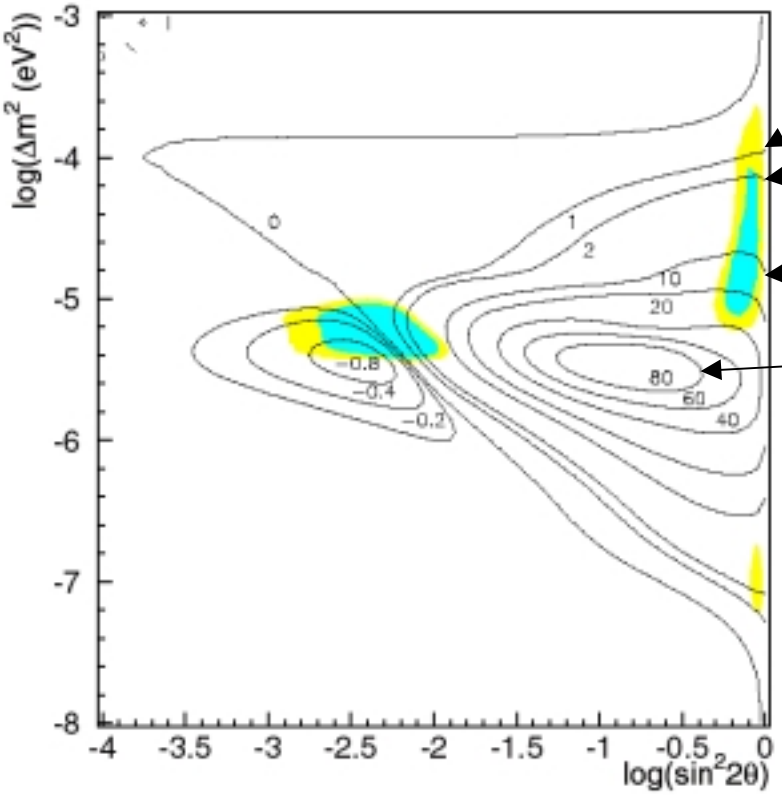


1) Day/Night Effect SuperK

regeneration through the earth

ρ=5 (the earth) $\leftrightarrow$ ρ=0~100 (the sun)

Δm^2 = a few$\times 10^{-6} eV^2$



1%

2%

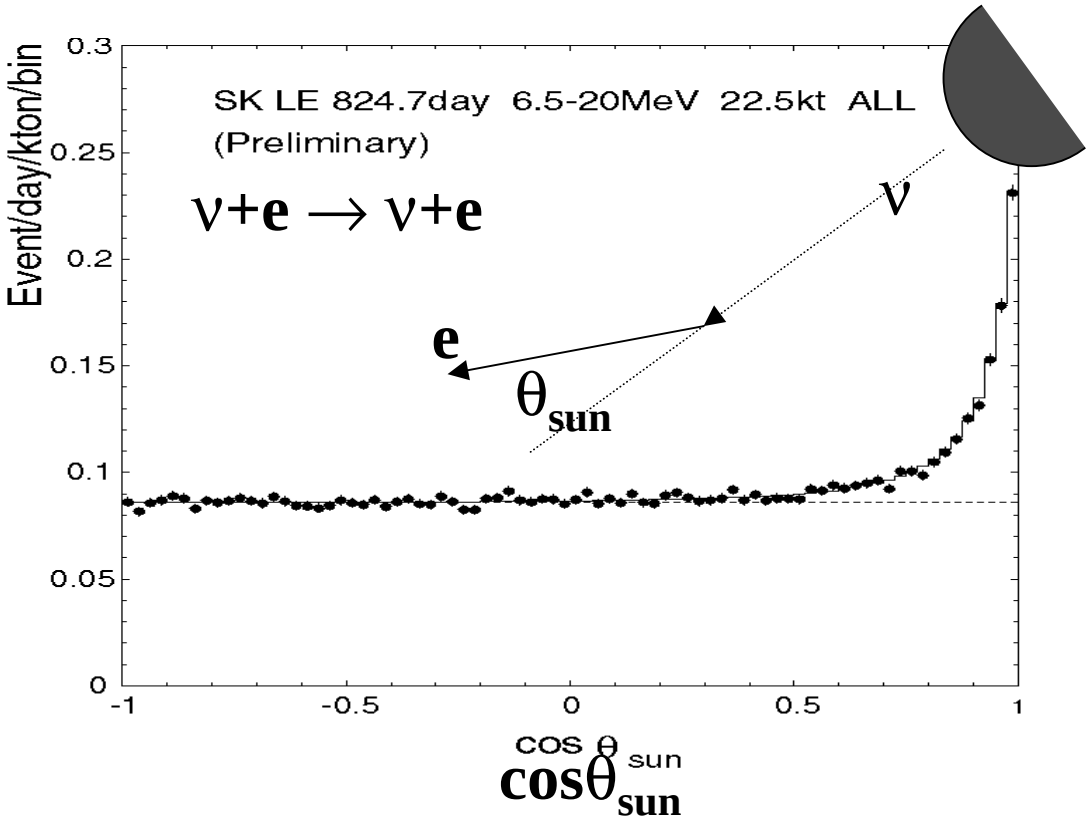
10%

80%

$$\frac{\text{(Night-Day)}}{\text{2(Night+Day)}}$$

real data from SK

Status of Super-Kamiokande (50 ktons WaterC)



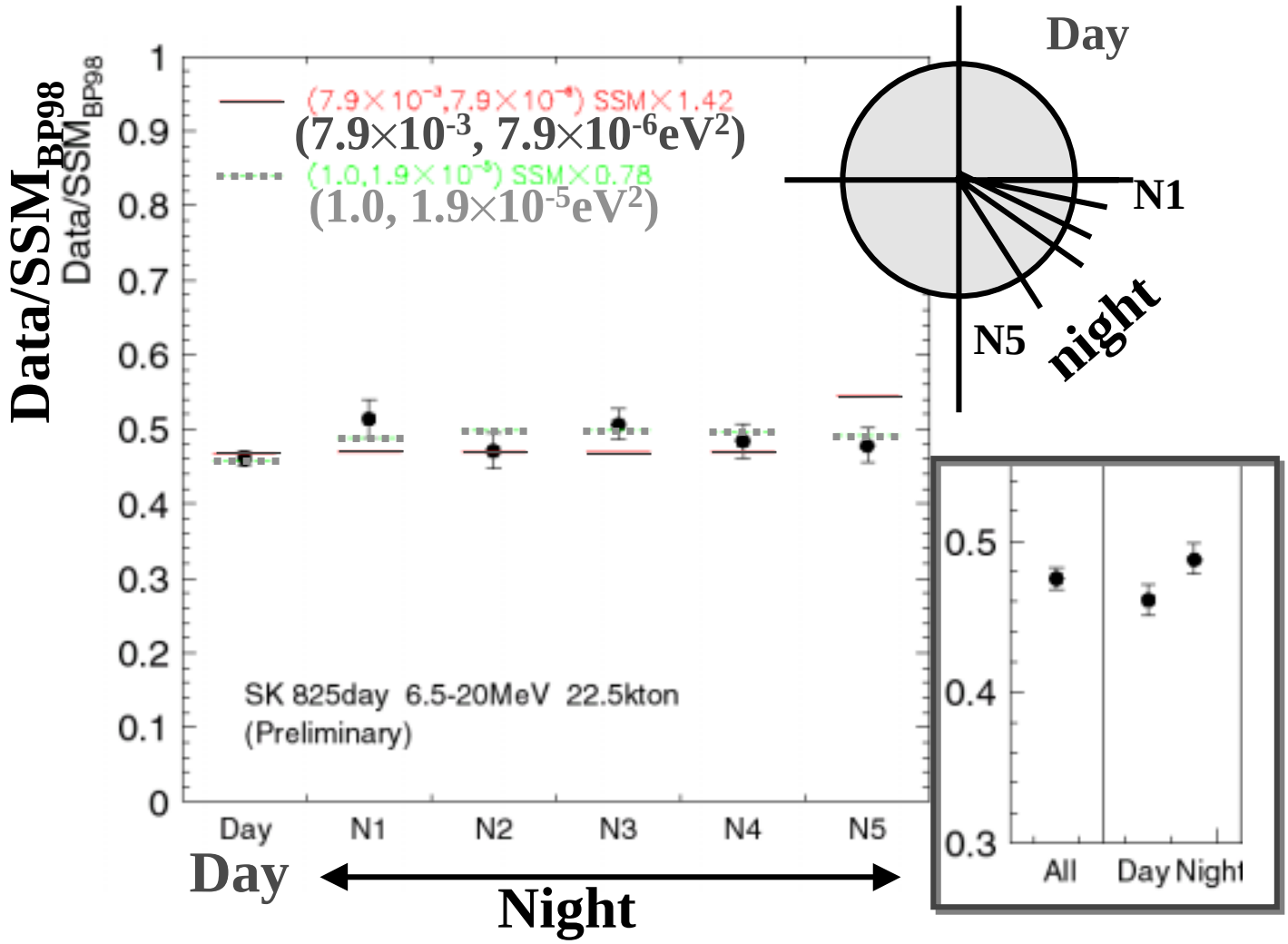
data : May 31, 1996 ⟶ April 3, 1999
825 effective days

first 301 days : with 6.5 MeV threshold
last 524 days : with 5.5 MeV threshold

number of events : > 6.5 MeV
$$11{,}235 \pm {}^{180}_{166}(\text{stat.}) \pm {}^{315}_{303}(\text{syst.})$$

$$\phi(^8\text{B}) = 2.45 \pm 0.04 \pm 0.07\ [\times 10^6/\text{cm}^2/\text{s}]$$

$$\frac{\text{Data}}{\text{SSM}_{\text{BP98}}} = 0.475 \pm {}^{0.008}_{0.007} \pm 0.013$$



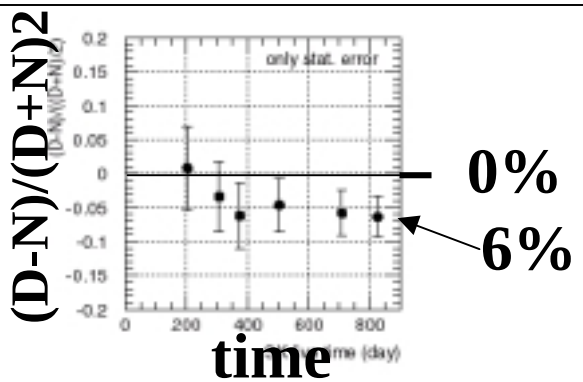
Day 403.2 effective days: $5317 \pm {}^{123}_{116}$ ev.

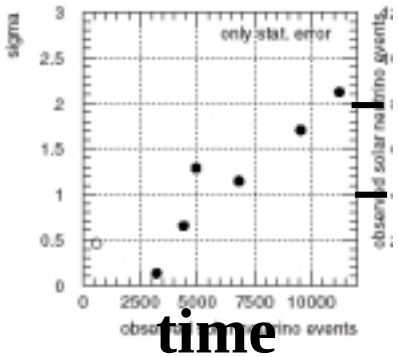
$\phi(^8B) = 2.37 \pm 0.05 \pm {}^{0.07}_{0.06}$ [$\times 10^6/cm^2/s$]

Night 421.5 effective days: $5905 \pm {}^{131}_{120}$ ev.

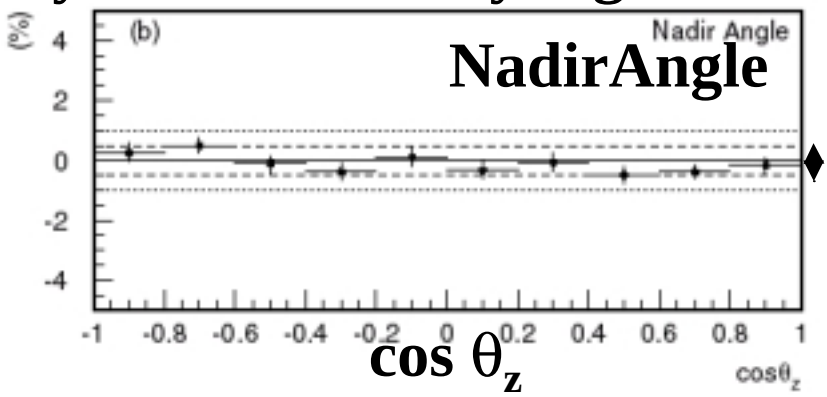
$\phi(^8B) = 2.51 \pm {}^{0.06}_{0.05} \pm 0.07$ [$\times 10^6/cm^2/s$]

$$\left(\frac{N-D}{N+D}\right) = 0.065 \pm 0.031(stat.) \pm 0.013(syst.)$$

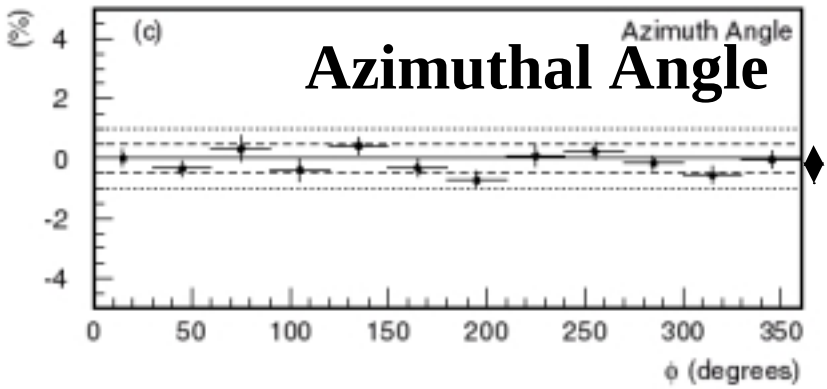




Systematics of day/night effect ⟸ Energy scale



Spallation events



Systematic errors (D/N ~ Up/Down)

Energy scale	$^{+1.2}_{-1.1}$ %
Reduction	±0.1%
non-flat BG	±0.4%
spallation	
dead time	±0.1%
live time	±0.1%
Total syst. errors for (N/D)	$^{+1.3}_{-1.2}$ %

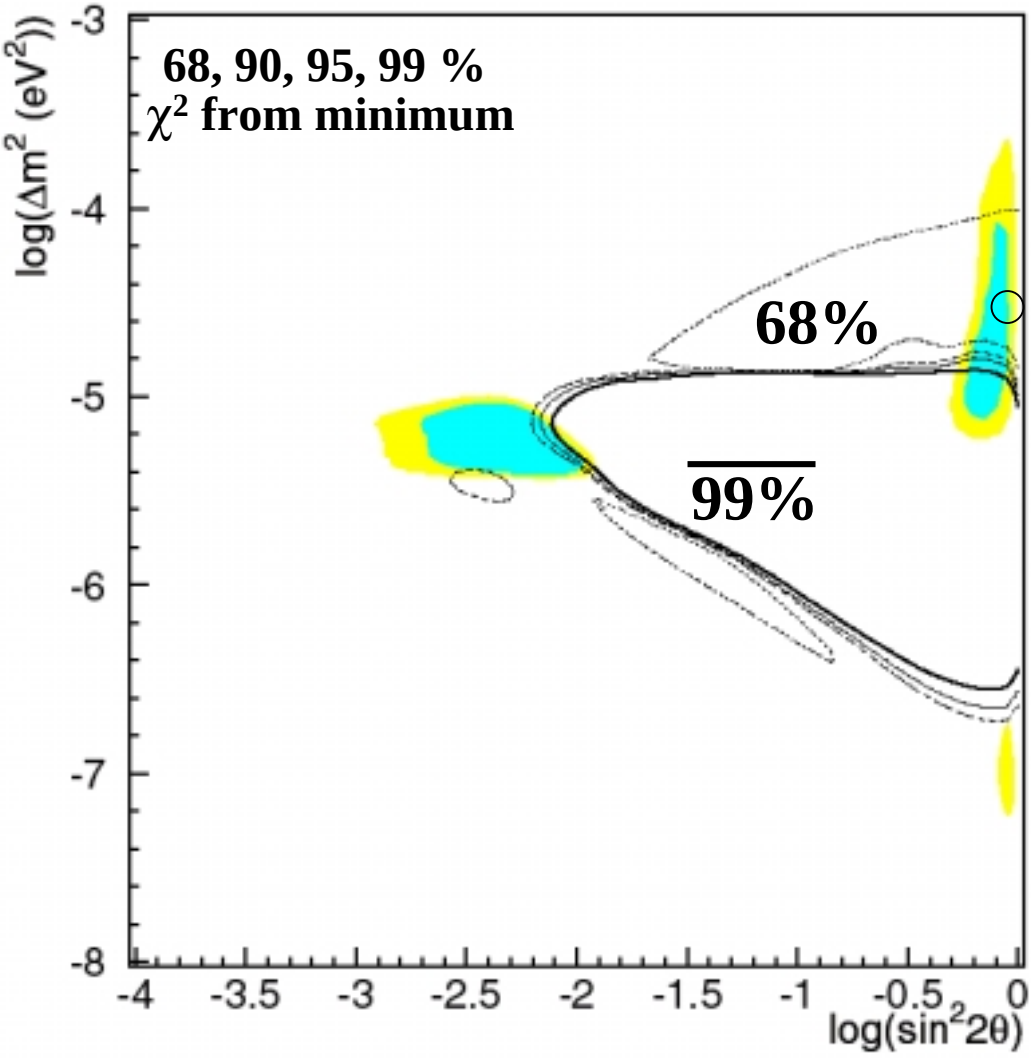
Significant? Too early to say anything definite. Should keep watching

Definition of χ^2

$$\chi^2 = \sum_{i=D,N1-N5} \left\{ \frac{\left[\frac{\text{Data}}{\text{SSM}}\right]_i - \left[\frac{\text{w/ oscil.}}{\text{w/o oscil.}}\right] \times \alpha}{\sigma_i} \right\}^2$$

$$\sigma_i = (\sigma_{st,i}^2 + \sigma_{sys,i}^2)^{1/2}, \qquad \alpha : \text{free}$$

D/N Contour



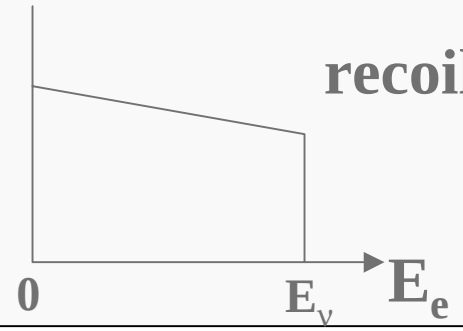
$\chi^2_{min} = 2.7/5$
(75% C.L.)

Energy Spectrum SuperK; SNO

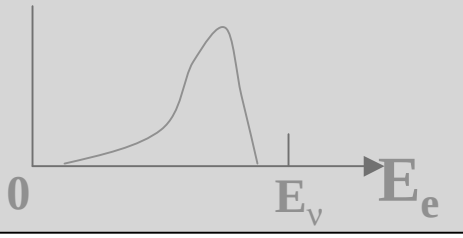
Super-Kamiokande: $\nu_e + e^- \rightarrow \nu_e + e^-$

recoil electron energy

$E^{th}_e = 5.5MeV$ (total energy)

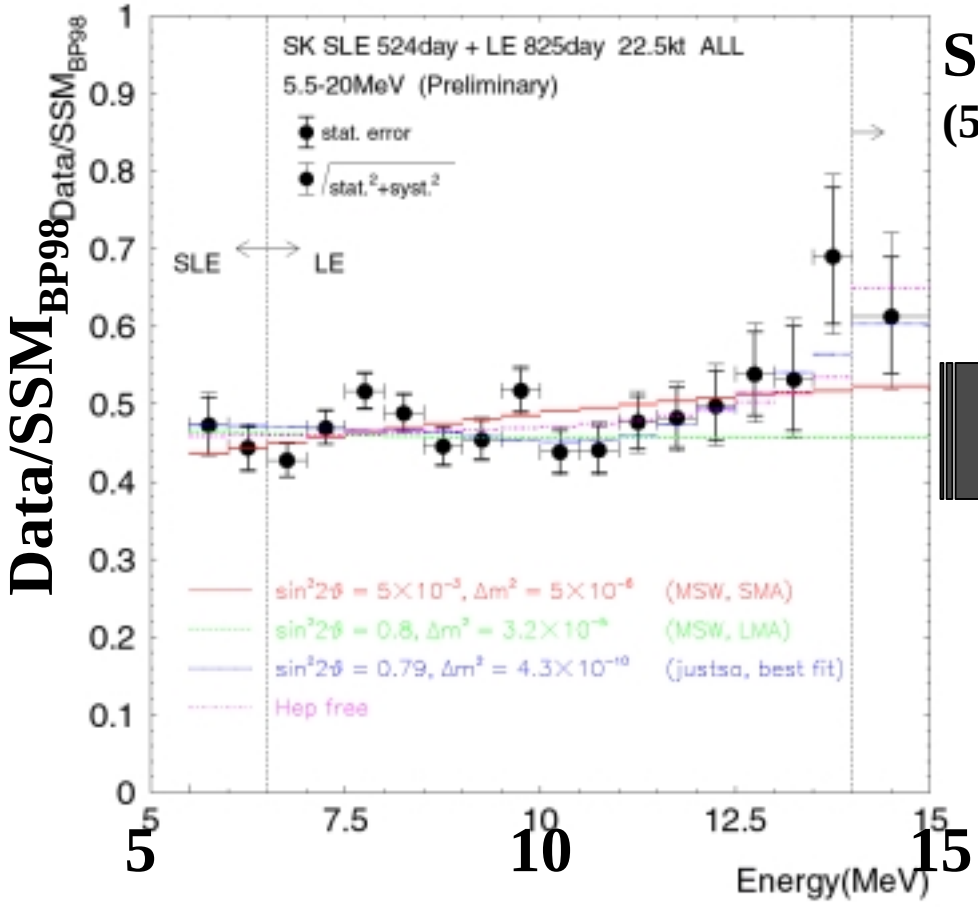


SNO: $\nu_e + d \rightarrow p + p + e^-$



$E^{th}_e = ?$

Near future!



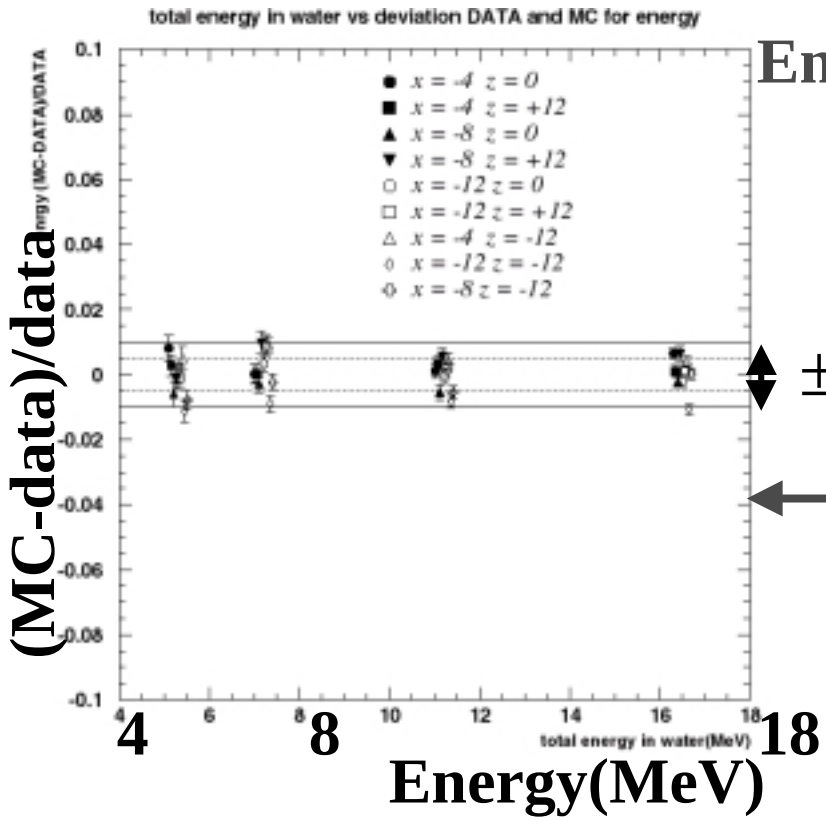
Super-K 825days
(5.5-6.5 MeV:524days)

Spectrum distortion??

1) wrong in a systematic error estimate?

⟹ **Not likely**

Energy Calibration by electron LINAC



Energy Scale

± 1%

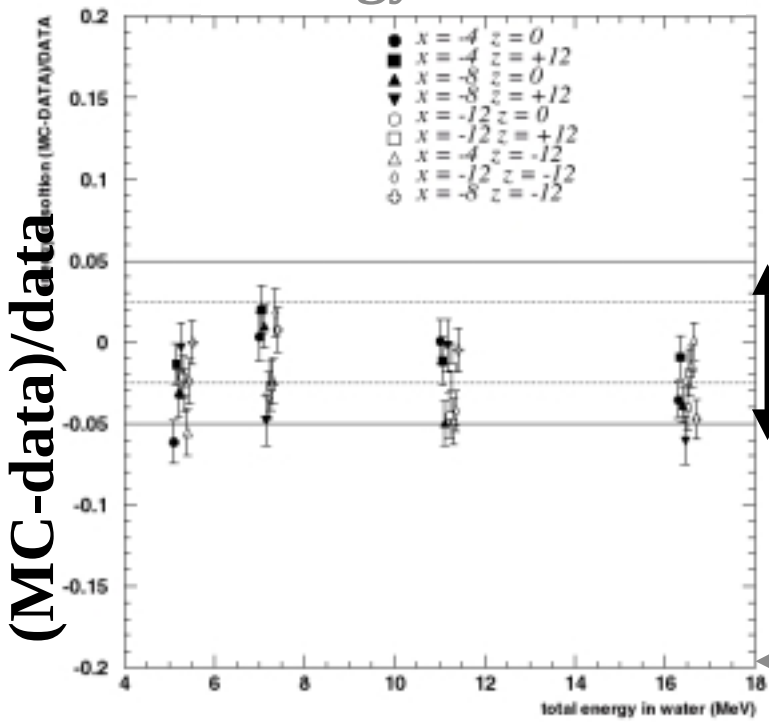
3.6%

4 8 18

Energy(MeV)

shift need to explain the rise at high energy

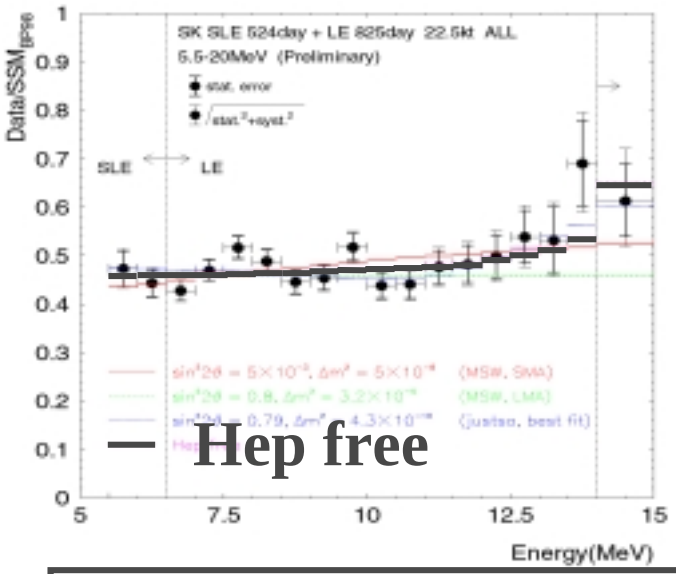
Energy Resolution



± 5%

20%

2) statistical fluctuation? and/or large Hep ν



χ^2 for flat

χ^2= 24.3/17 (11%CL)
for spectrum

χ^2= 19.5/16 (24.4%CL)
for spectrum w/ Hep free
(w/ 16.7× standard Hep)

^{8}B-neutrino E_ν < 15 MeV	$5.15\times10^6(1.00 \pm {}^{0.19}_{0.14})$ /cm^2/s
Hep-neutrino E_ν < 18.8 MeV	2.10×10^3(no estimate) /cm^2/s

$S(0)_{hep}$=2.3x10^{-20}keV b

uncertain

S_0(hep) (10^{-20} kev b)	Physics	Year
630	single particle	1952
3.7	forbidden; $M_\beta \propto M_\gamma$	1967
8.1	better wave function	1973
4-25	D-states + meson exchange	1983
15.3 ± 4.7	measured $^3He(n,\gamma)^4He$	1989
57	measured $^3He(n,\gamma)^4He$ shell model	1991
1.3	destructive interference, detailed wavefunctions	1991
1.4-3.1	Δ-isobar current	1992

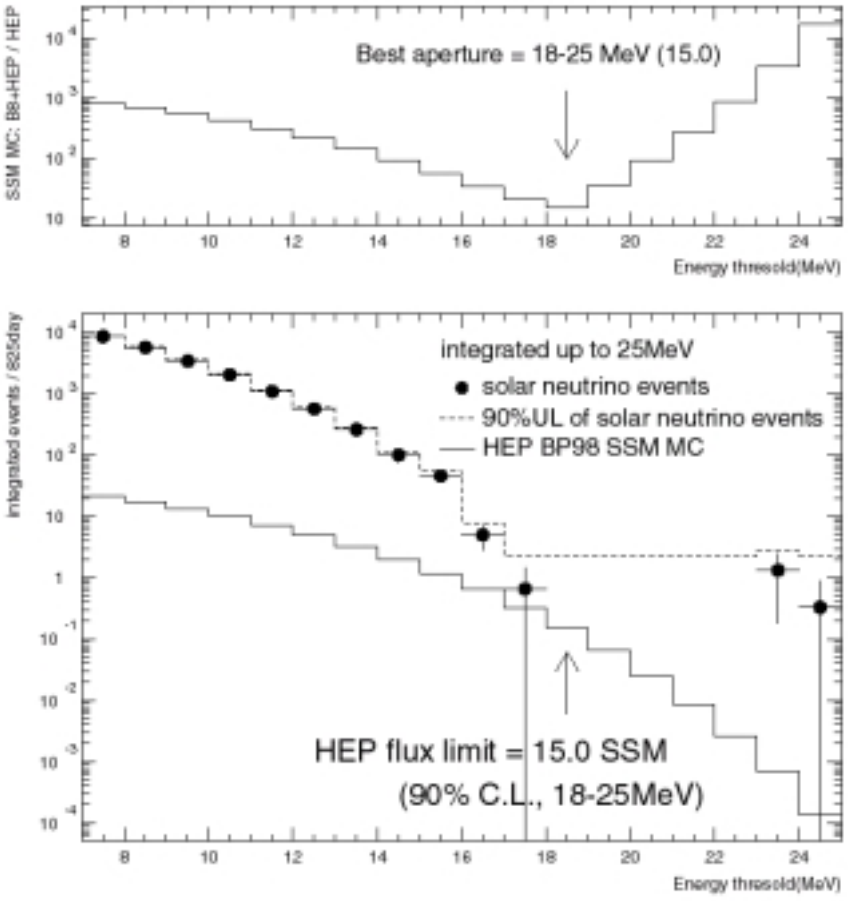
BP98 hep

ref)

for example
PLB, 436, 243 (98)
and refs therein

Direct hep measurement by SuperK

Measure hep beyond the ^{8}B end point (must consider the resolution tail)



use the data between 18 and 25MeV

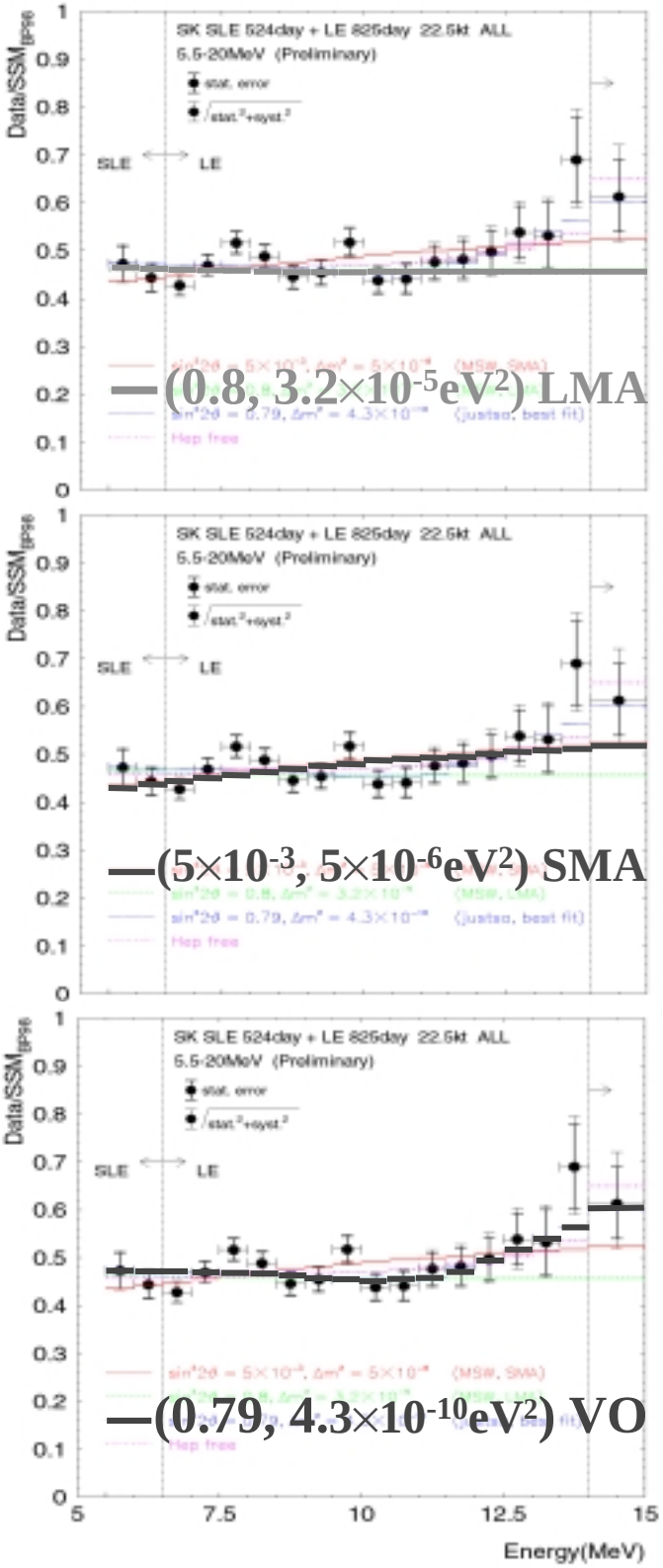
Upper limit is

$< 15.0 \times$ Hep(BP98)

If you consider an oscillation effect of ~ 50%, then the upper limit means

~30 $\times$ Hep(BP98)

3) Oscillation? (Day/Night+Spectrum)



SSM hep

Effect of free hep

χ^2=47.3/35 ($\Delta\chi^2$=3.2)
χ^2=47.5 ($\Delta\chi^2$=3.4)
LOW

hep free → **χ^2=42.2/34 ($\Delta\chi^2$=0.2)**
χ^2=42.0/34 (min)
LOW

—(0.8, 3.2×10^{-5}eV^2) LMA

χ^2=53.3/35 ($\Delta\chi^2$=9.2)

hep free → **χ^2=51.2/34 ($\Delta\chi^2$=9.2)**

—(5×10^{-3}, 5×10^{-6}eV^2) SMA

χ^2=44.1/35 (min)

hep free → **χ^2=44.2/34 ($\Delta\chi^2$=2.2)**

—(0.79, 4.3×10^{-10}eV^2) VO

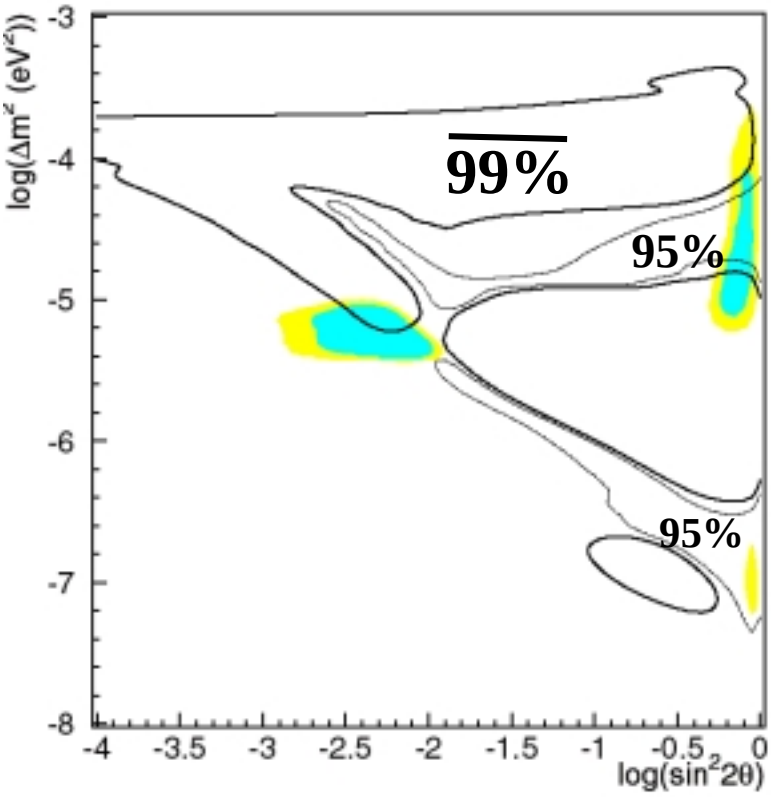
No Oscillation

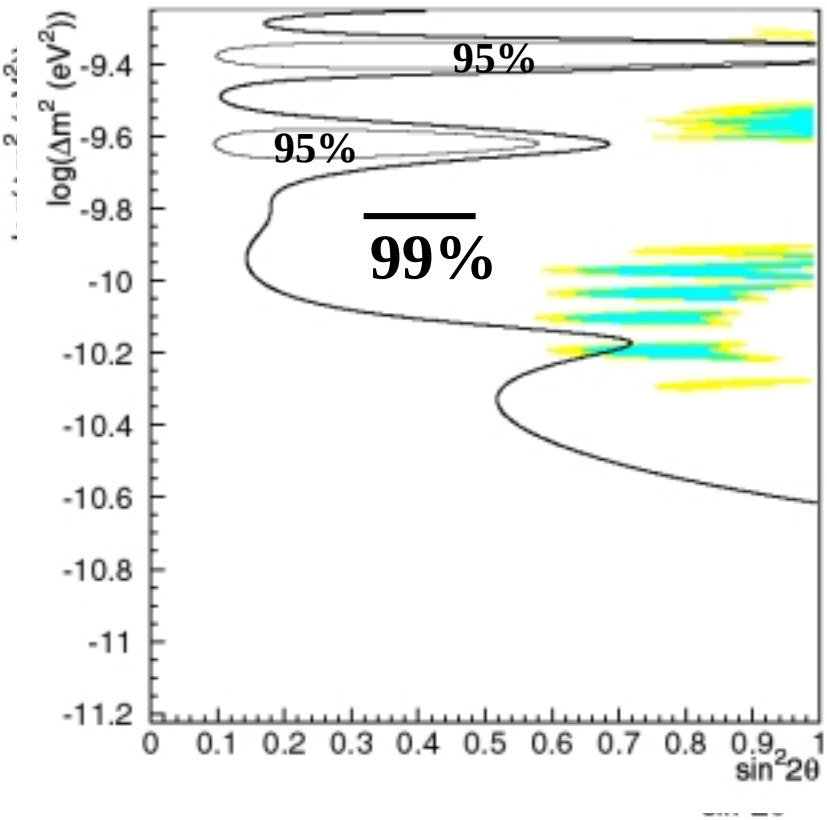
χ^2=51.4/35 ($\Delta\chi^2$=7.3)

hep free → **χ^2=46.2/34 ($\Delta\chi^2$=4.2)**

Flux independent analysis (Spectrum+day/night)

(w/ SSM Hep) Super-K

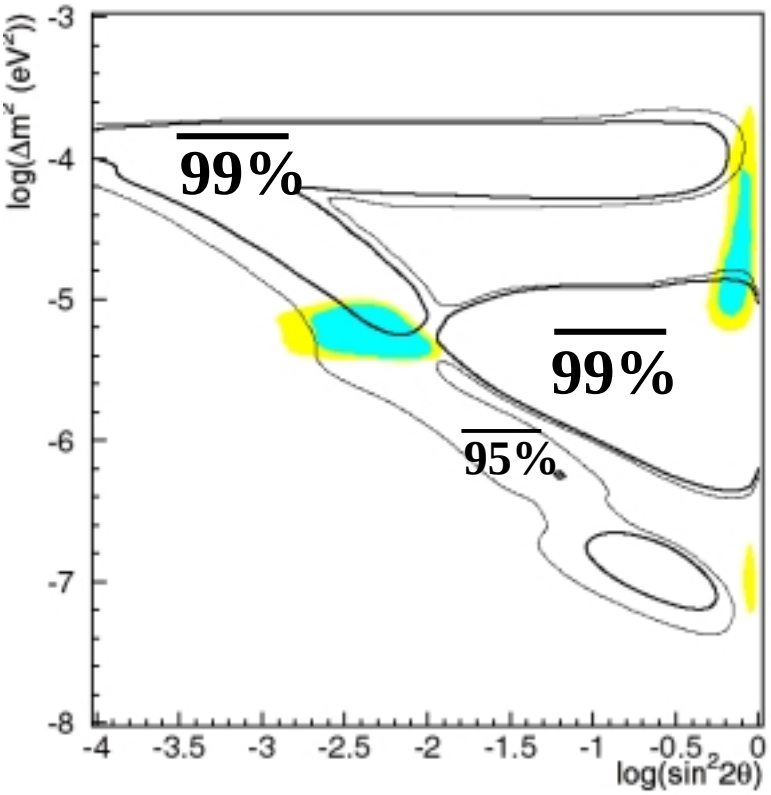




No oscillation:
~ 1~ 5% C. L.

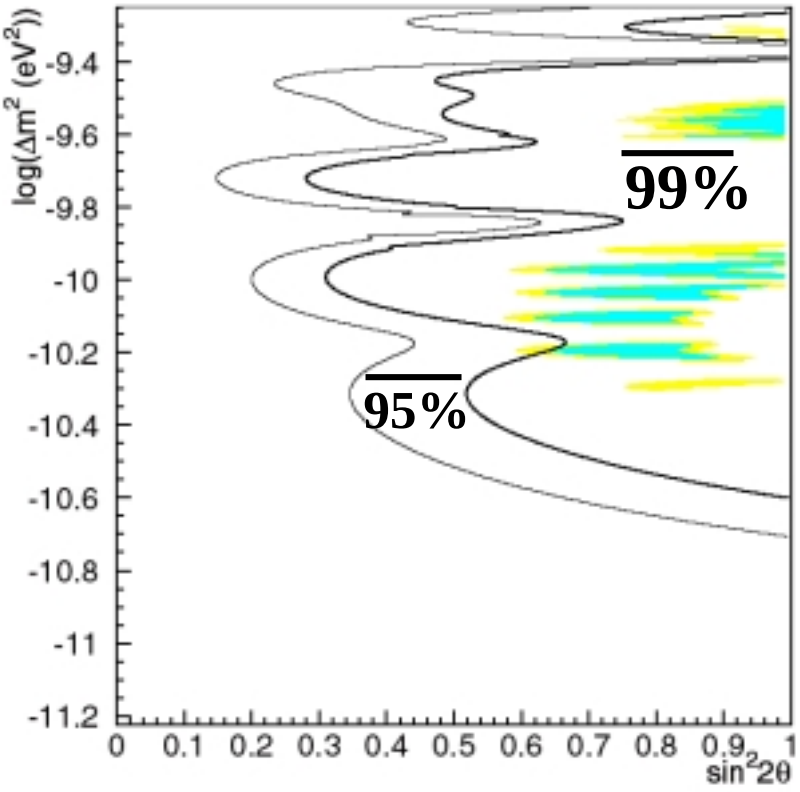
Flux independent analysis (Spectrum+day/night)
(Hep flux as a free parameter)

SuperK



free Hep helps MSW solutions

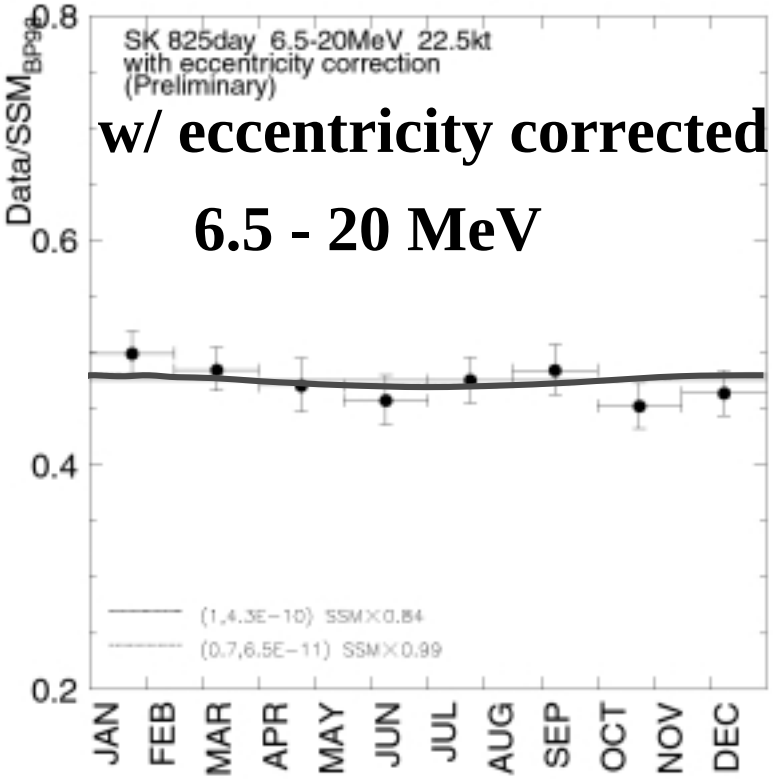
χ^2_{min} moved to MSW region

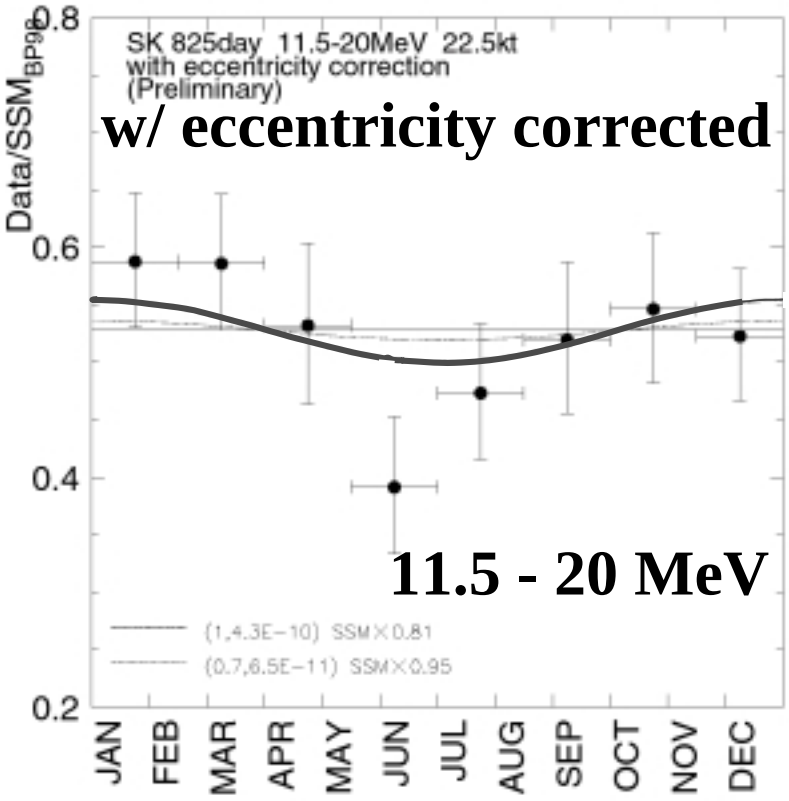


No oscillation: ~ 5~10% level

If vacuum,

seasonal variation may be seen

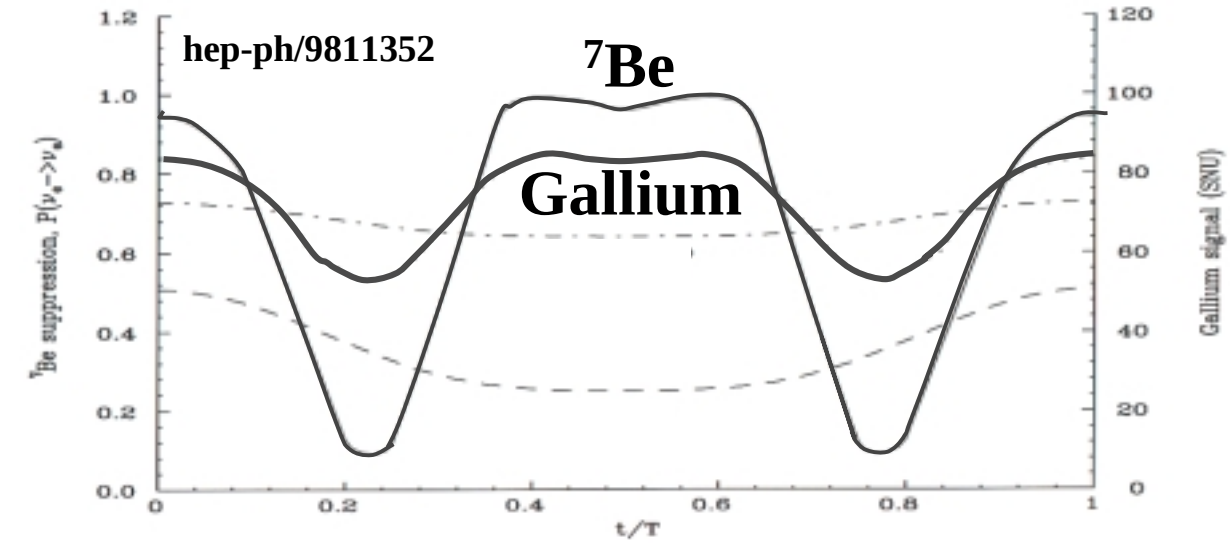


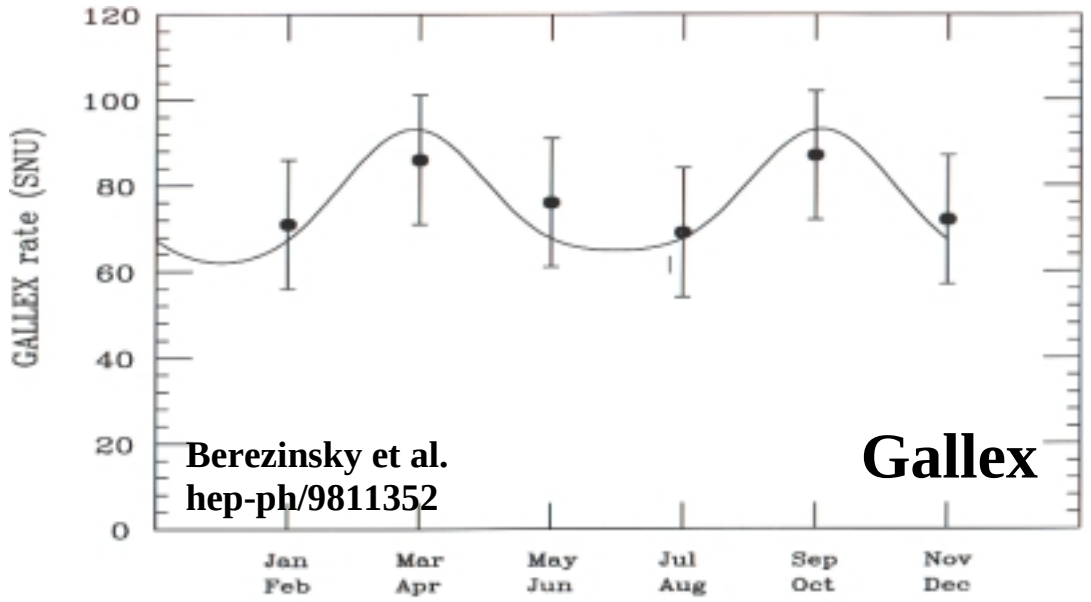


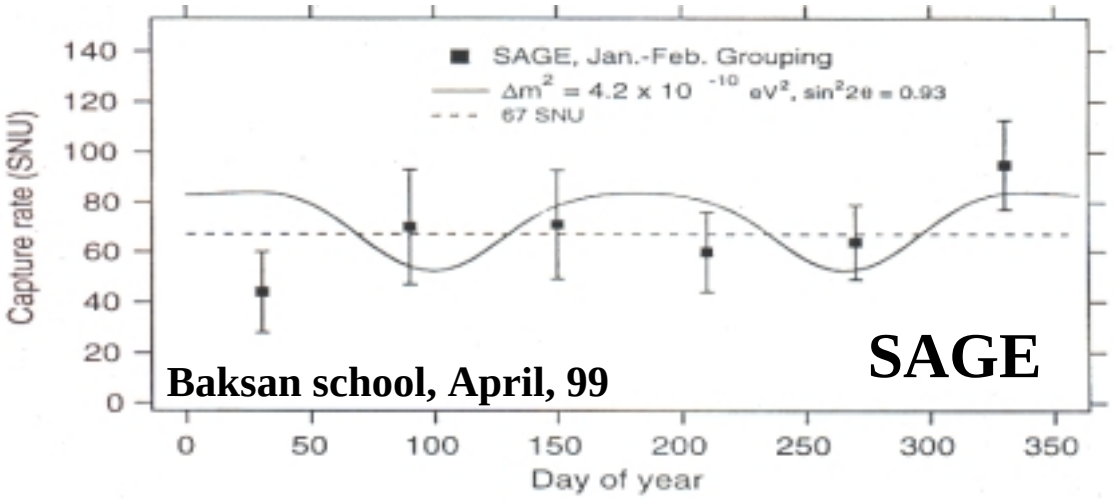
χ^2=7.9 for no oscill.
(34.1% C.L.)

χ^2=4.92 for V.O.
(SK min)
(67.0% C.L.)

Both OK!







We should ignore seasonal for time being until we get reasonable statistics.

We cannot say anything significant.

Comments on V.O. (SK minimum)
(consistency check with flux measurement)

V.O.	**Flux**	↓	**20% (1σ)**
	Cl	↑	**30% (3.5σ)**

⇒

weakened when combined with the flux measurements in the fitting for the parameter search.

Global Analysis

data set

flux
Homestake, SAGE, Gallex, Kamiokande, SuperK
day/night, spectrum from SK

including systematic errors of SSM

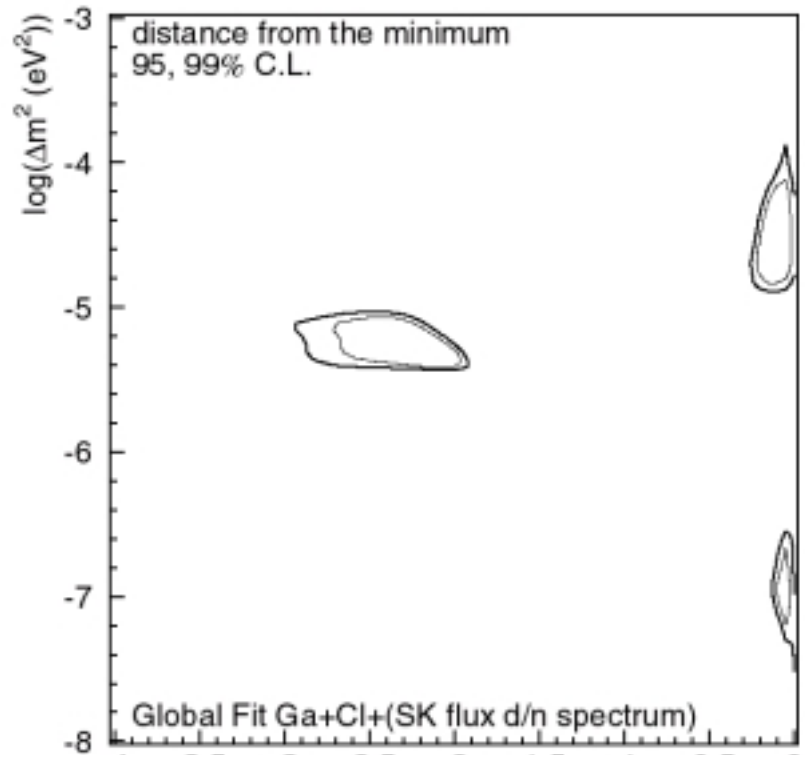
flux correlation

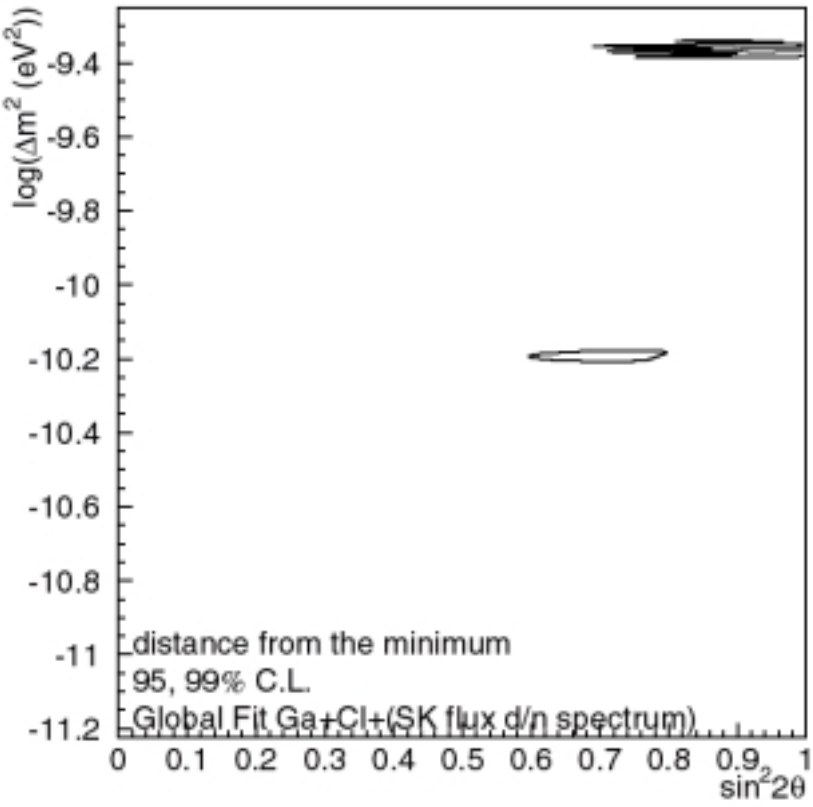
1) SSM Hep
2) Hep as a free parameter

Prescription similar to

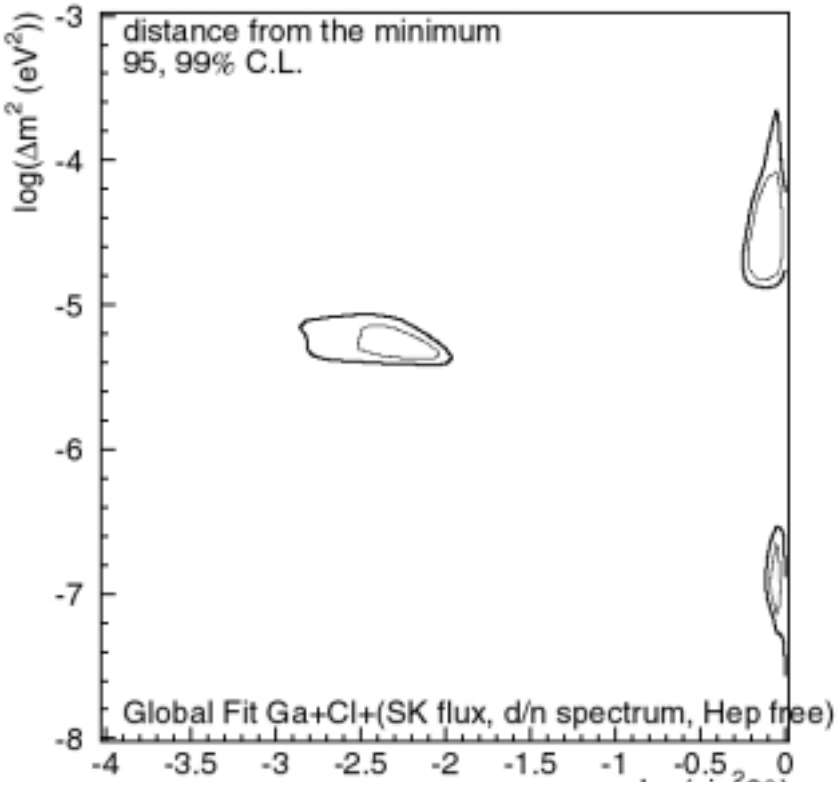
J.N.Bacall, P.I.Krastev and A.Yu.Smirnov
Phys. ReV. D58,096016(1998)
and references therein

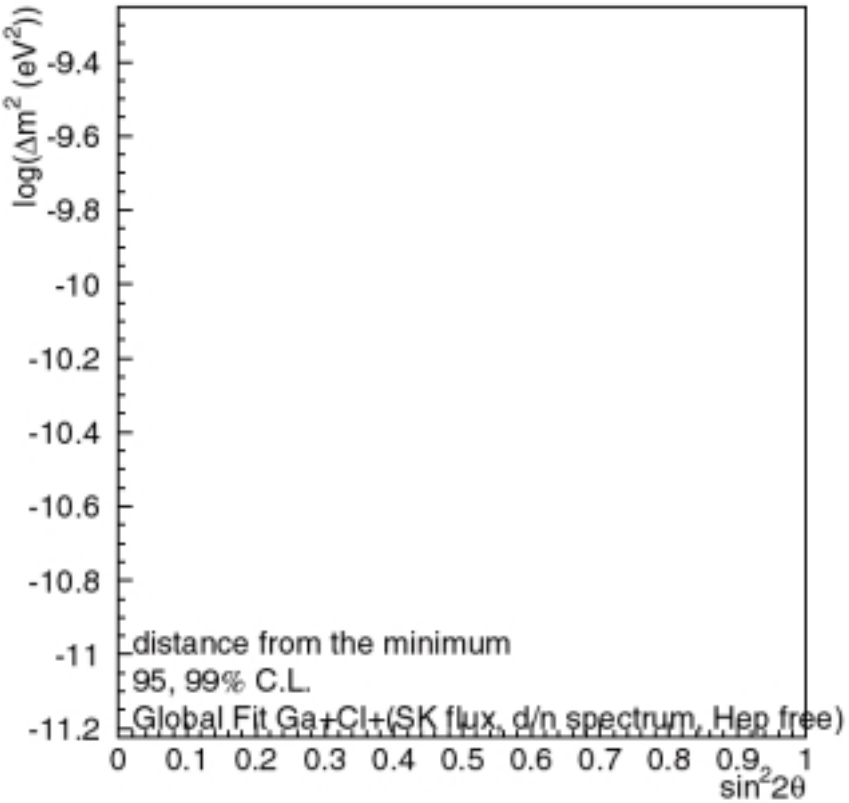
Global (with SSM hep)





Global (hep as a free parameter)



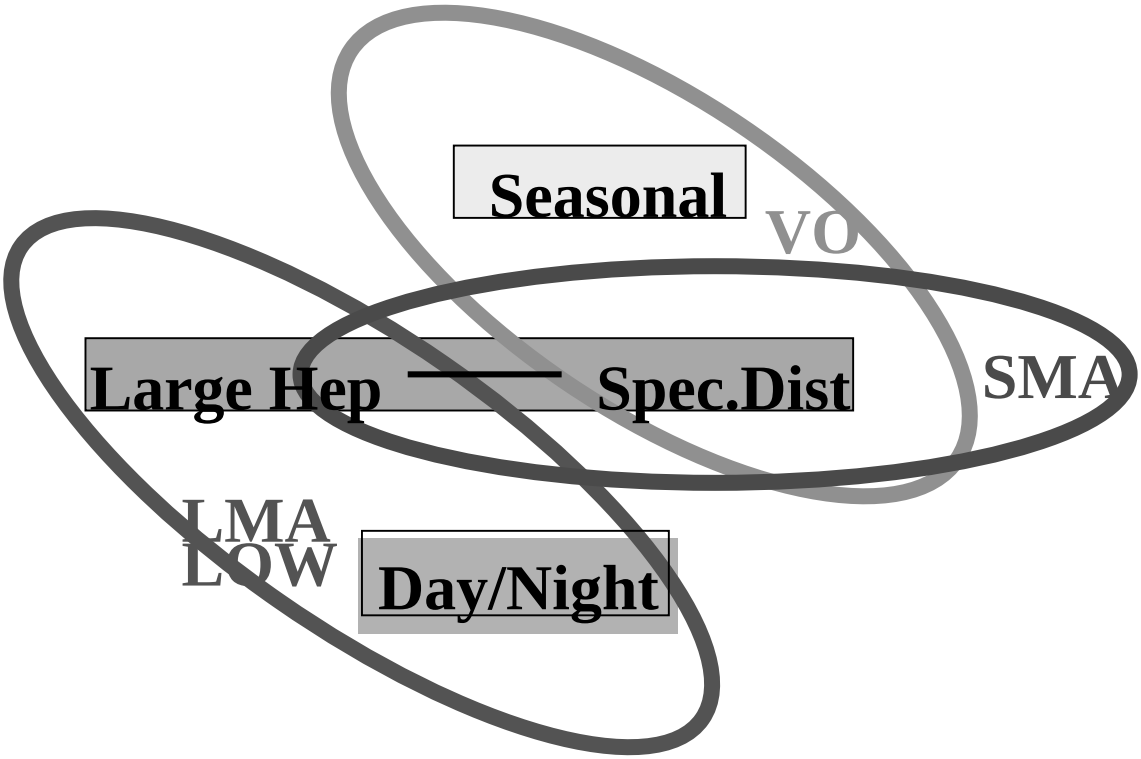


Flux independent analysis has started to give us useful information.

Hint: Super-Kamiokande Day/Night
Spectrum distortion

It does not strengthen the effect if combined.

	Day/Night	Sp. distortion
LMA (LOW)	○	△ Hep-ν
SMA	**disappear**	○
VO	**disappear**	○



Unfortunately the current statistics is not enough.

Near future:

Super-Kamiokande

SNO

Borexino

KAMLAND
(not a solar neutrino experiment)

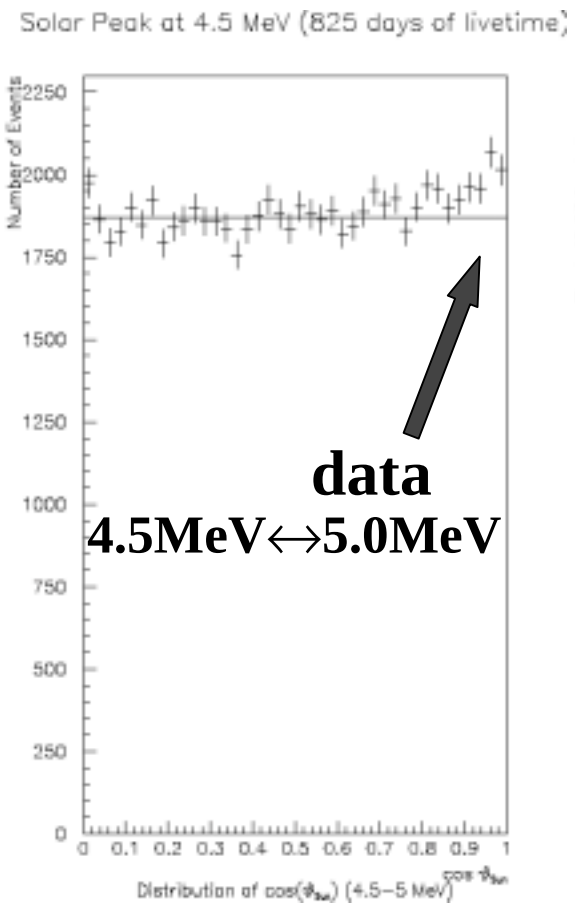
Homestake
GNO - Gallex
SAGE

HELLAZ (contribution paper)
LENS
….
….

Super-Kamiokande

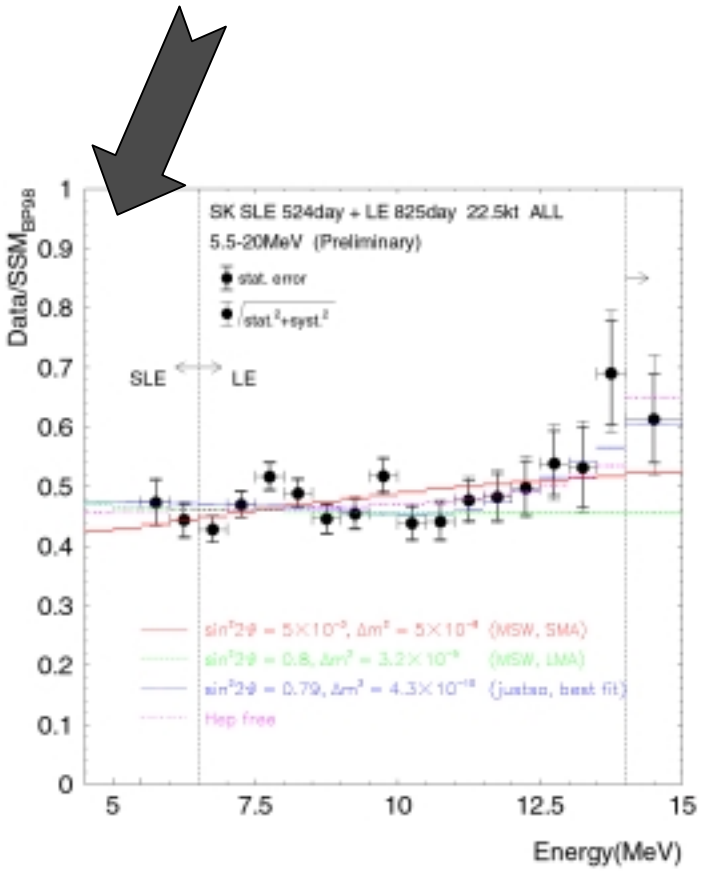
1) increase statistics

2) lower threshold down to 4.5 MeV

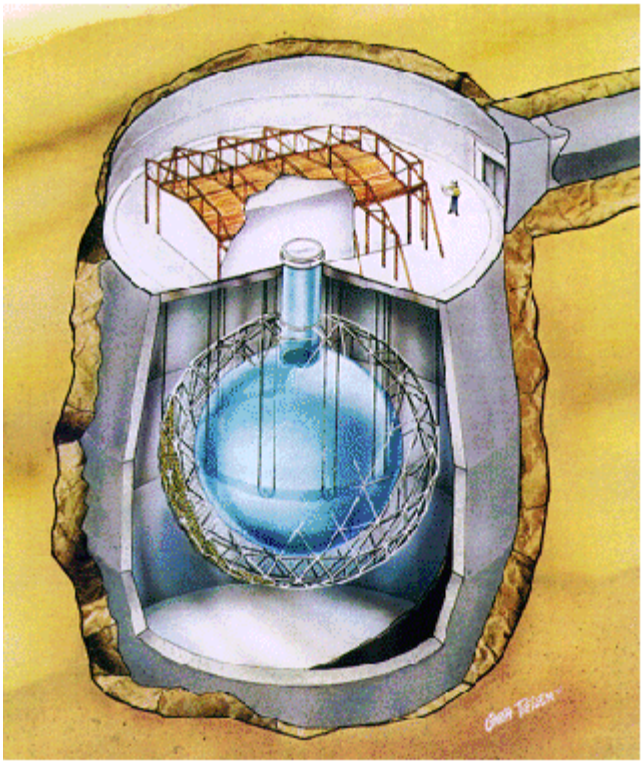


data

4.5MeV↔5.0MeV



3) reduce background in the low energy region and also even in the high energy region



SNO

1000 tons of D_2O

2,000 m underground

~9,500 8“ PMTs

CC: $\nu_e + d \rightarrow p + p + e^-$ **(Q=-1.44MeV) ~9ev/day**

$\hookrightarrow 1-(1/3)\cos\theta$

NC: $\nu_x + d \rightarrow p + n + \nu_x$ **(Q=-2.2MeV) ~3ev/day**

$\hookrightarrow {}^3$He-counter

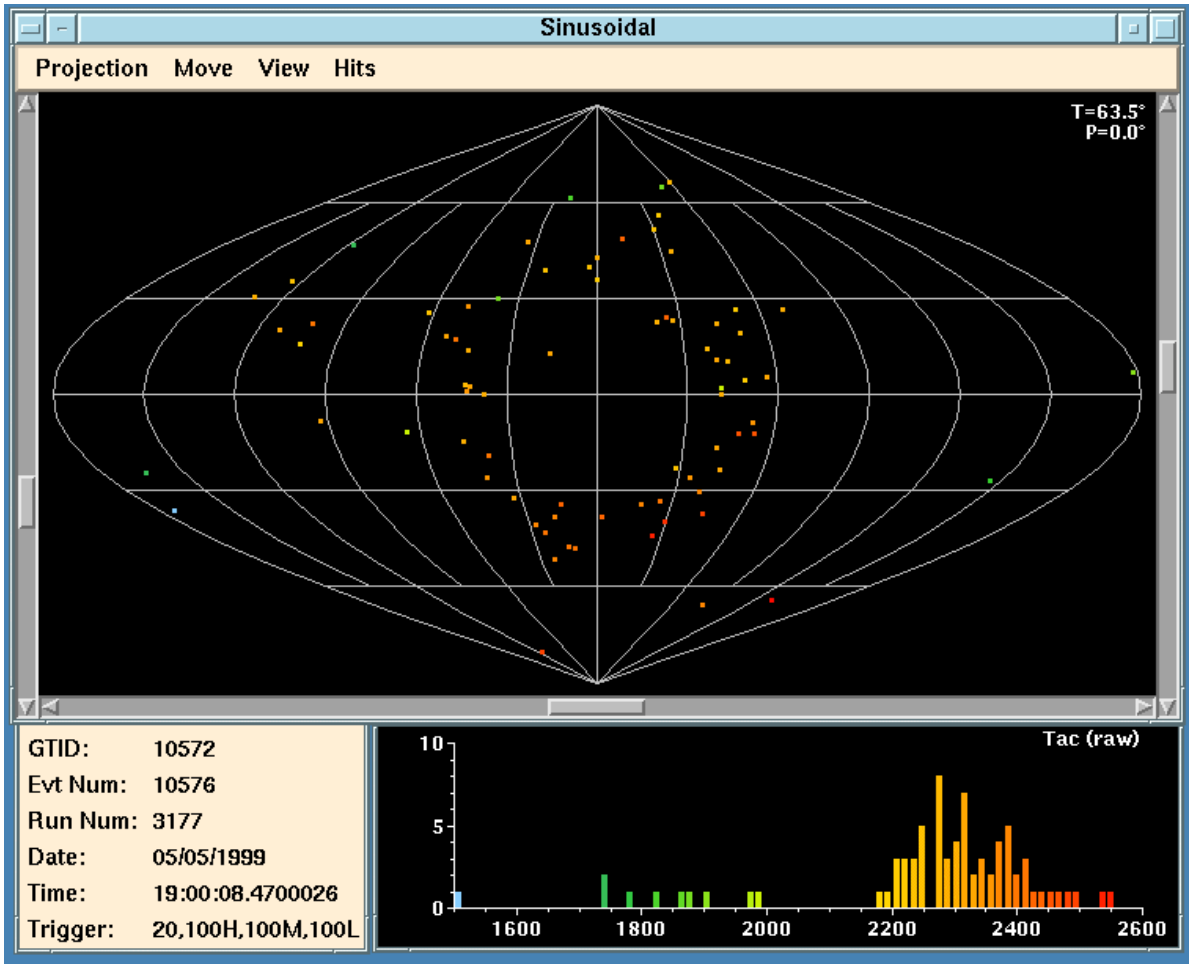
$\hookrightarrow {}^{35}Cl(n, \gamma)^{36}Cl$

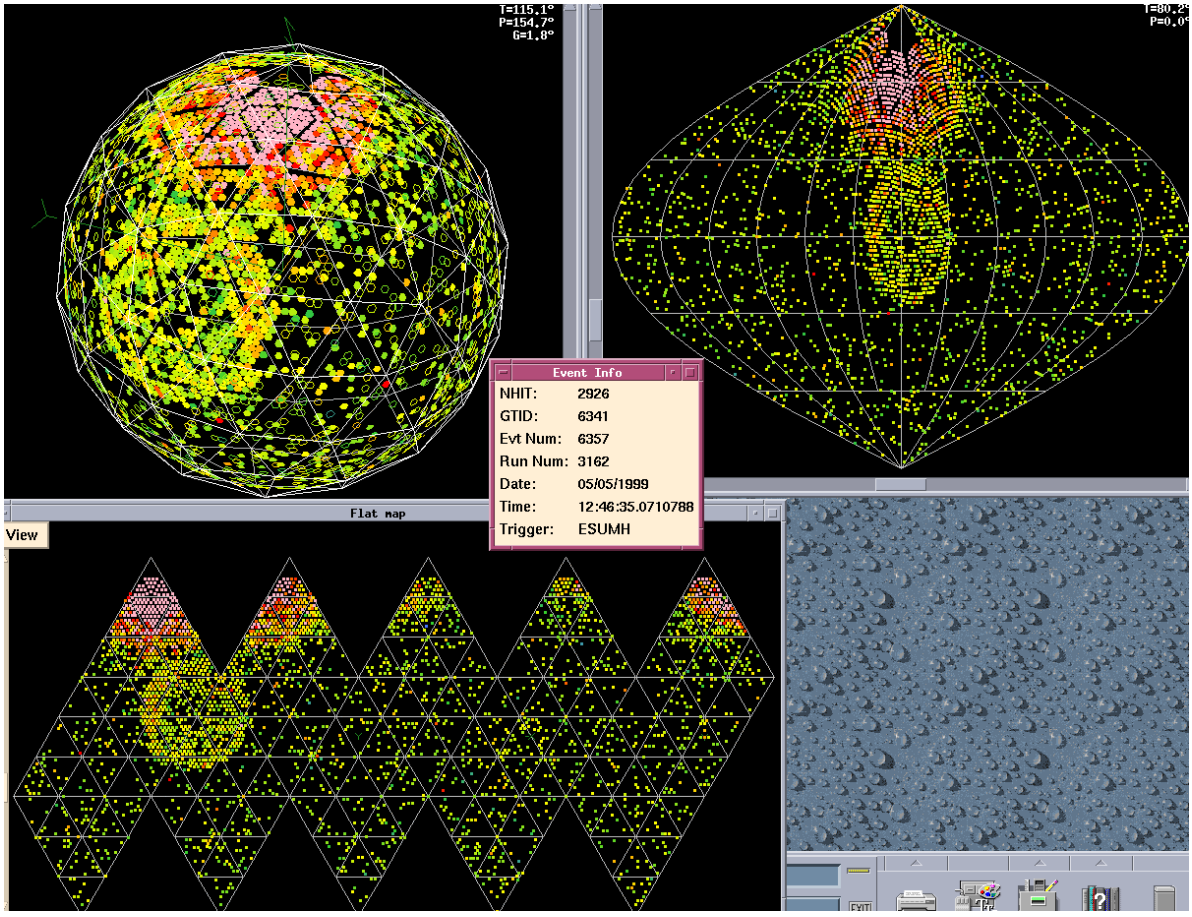
ES: $\nu_x + e \rightarrow \nu_x + e$ **~1ev/day**

CC/NC :	**fraction of solar ν^e’s oscillation evidence but cannot determine the parameters**
CC:	**energy spectrum, D/N**
ES:	**consistency check**

SNO has started on 1st of May 1999.

Calibration → Data taking


Sinusoidal
Projection
Move
View
Hits
T=63.5°
P=0.0°
GTID: 10572
Evt Num: 10576
Run Num: 3177
Date: 05/05/1999
Time: 19:00:08.4700026
Trigger: 20,100H,100M,100L
Tac (raw)
10
5
0
1600
1800
2000
2200
2400
2600


Event Info
NHIT: 2926
GTID: 6341
Evt Num: 6357
Run Num: 3162
Date: 05/05/1999
Time: 12:46:35.0710788
Trigger: ESUMH
Flat map
View

Borexino

300 tons liquid scintillator (100 fid. tons)

$\nu + e \rightarrow \nu + e$

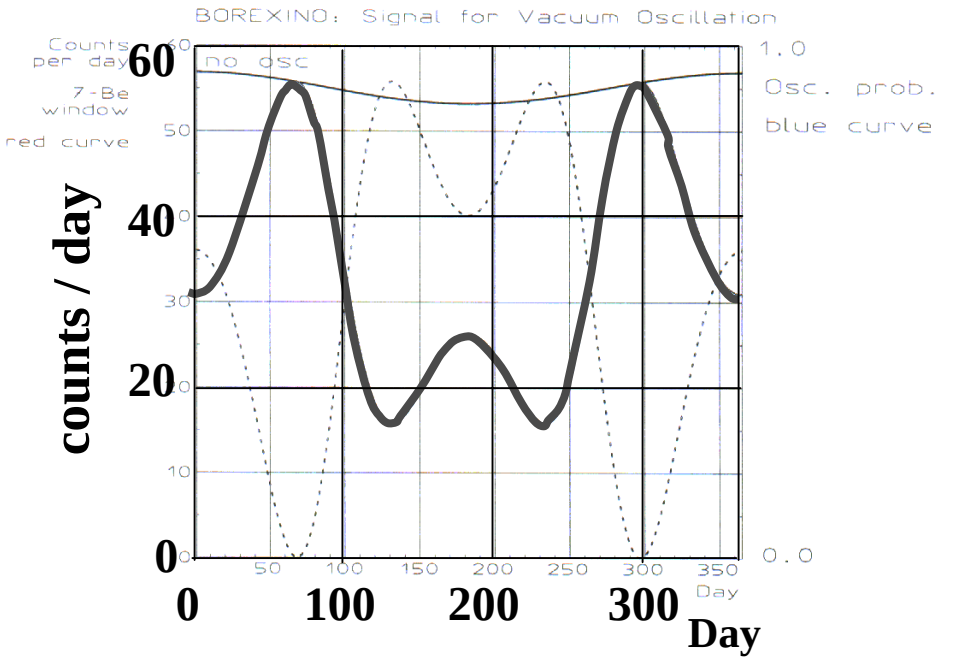
$E_\nu^{thre} \sim 250keV$ 55ev/day for SSM

detection of ^7Be neutrinos
(edge 660 keV)

SMA ⇨ ~ full suppression

LMA ⇨ ~ half suppression

V.O. ⇨ seaonal variation

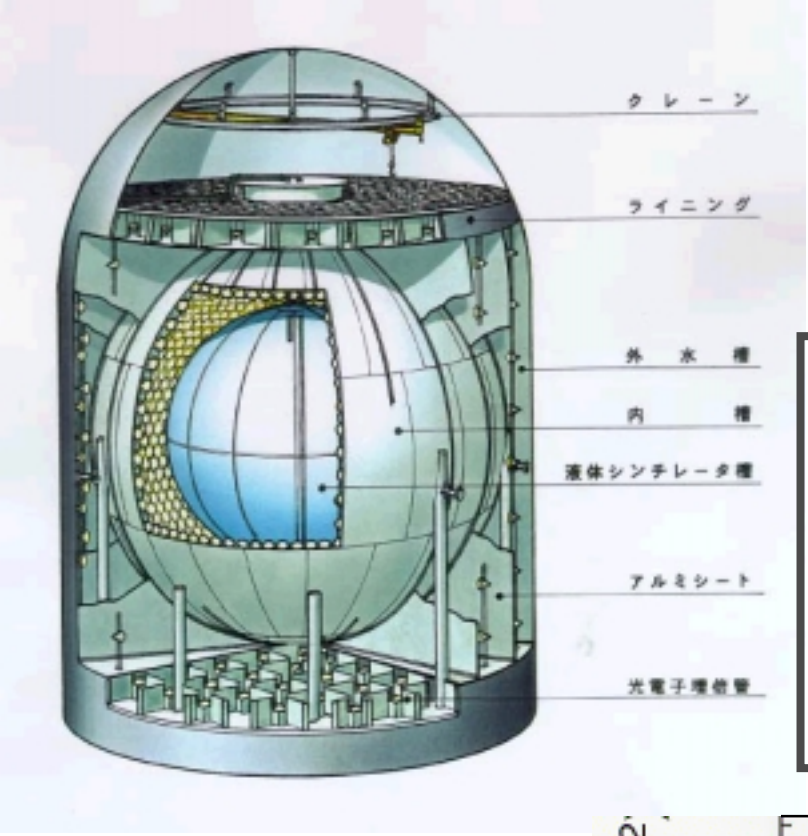


Expected operation in 2001

KAMLAND

Long baseline Reactor experiment converted from KAMIOKANDE

hosted by Tohoku University



1,200 m^3 liq. scint.

1,280 17“ PMTs

20% coverage

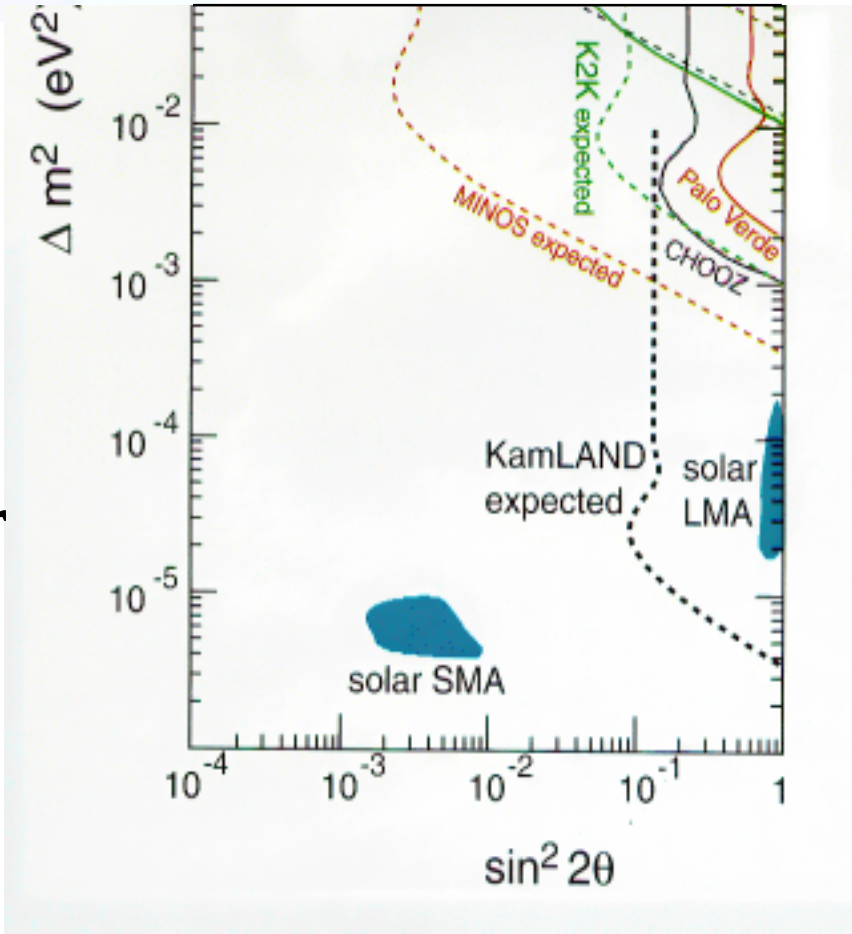
anti: 3,000m^3 water

Ee > 1.8 MeV

reactor L~150km

700 events/kt/year

April 2001~

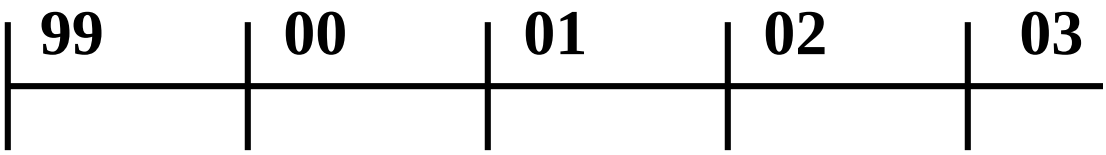


Conclusion
the throes of creation

Who will win the race!? Let's BET!

right solution

Guestimate (do not take too seriously)



LMA

SK 2σ----------->3σ

SNO 0----------->2σ

Kamland 0-------->3σ

Borexino 0-------->2σ

SMA

SK –1σ----------->1σ

SNO 0------>1σ-------->2σ

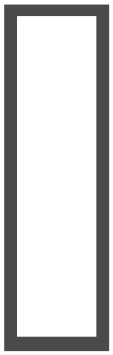
Borexino 0-------->2σ

V.O.

SK 1σ----------->2σ

SNO 0------>1σ-------->2σ

Borexino 0------->3σ



Helioseismology

thousands of solar frequencies (p-mode)

$\Delta\nu/\nu \approx 10^{-4}$ → **Sound velocity: $\Delta u/u = \pm 0.4\%$**

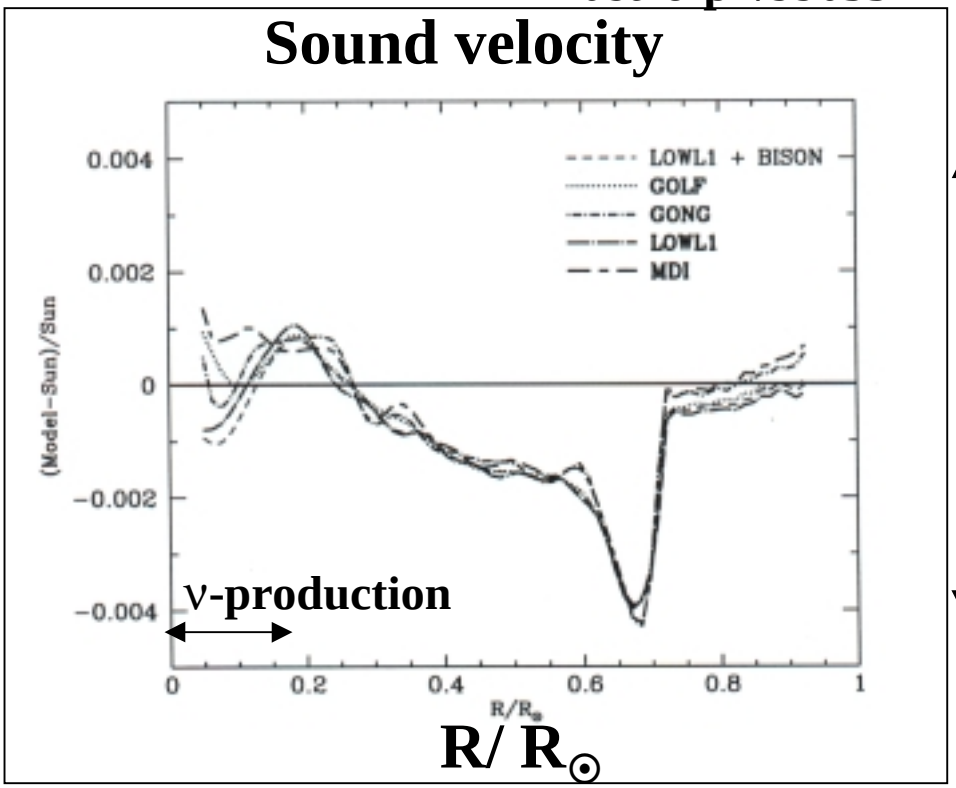
→ **$R_b = 0.711(1 \pm 0.4\%) R_\odot$**
$\rho_b = 0.192(1 \pm 0.4\%)$ g/cm^3

±1% at the center

E.O.S & μ → (ref.) → **Temperature at the center**

astro-ph/9905341

Sound velocity



± 0.4%

R/ $R_\odot$

Standard Solar Models are OK

Flux uncertainty ⇐ **Nuclear physics uncertainty**

^{8}B ⇐ **$S_{17}(0)$**

Hep ν flux

Experimental ability

	Neutral Current	Day/Night (LMA)	Spectrum (SMA,VO)	Seasonal (VO)
Cl				
Ga				
H_2O				
D_2O				
Scintillator			**^7Be**