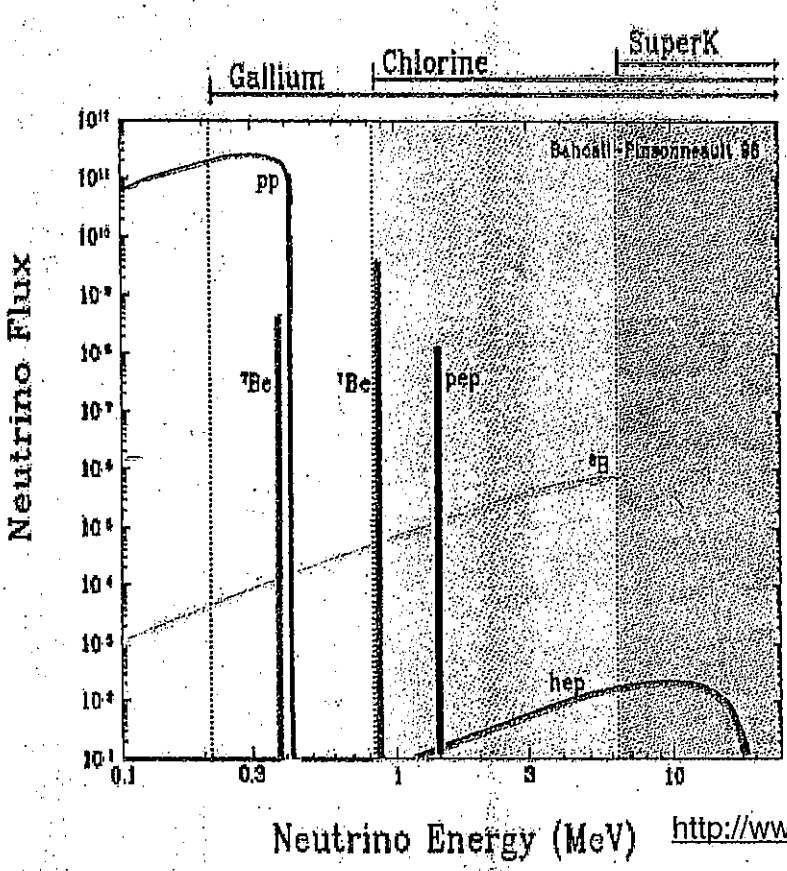
Recent results of solar neutrinos at Super-Kamiokande

July 5th, 2000

Y.Fukuda
for SuperKamiokande collaboration
I.C.R.R. Univ. of Tokyo

- Introduction
- Solar neutrino observation
- What's new
- Results and implications
- Summary

Solar neutrinos



http://www.sns.ias.edu/~jnb/

pp-chain

$$P + P \rightarrow {}^2H + e^+ + \nu_e \qquad P + e^- + P \rightarrow {}^2H + \nu_e$$

99.75% 0.25%

$${}^2H + p \rightarrow {}^3He + \gamma$$

86% 14%

$${}^3He + {}^3He \rightarrow \alpha + 2p \qquad {}^3He + \alpha \rightarrow {}^7Be + \gamma \qquad {}^3He + p \rightarrow {}^4He + e^+ + \nu_e$$

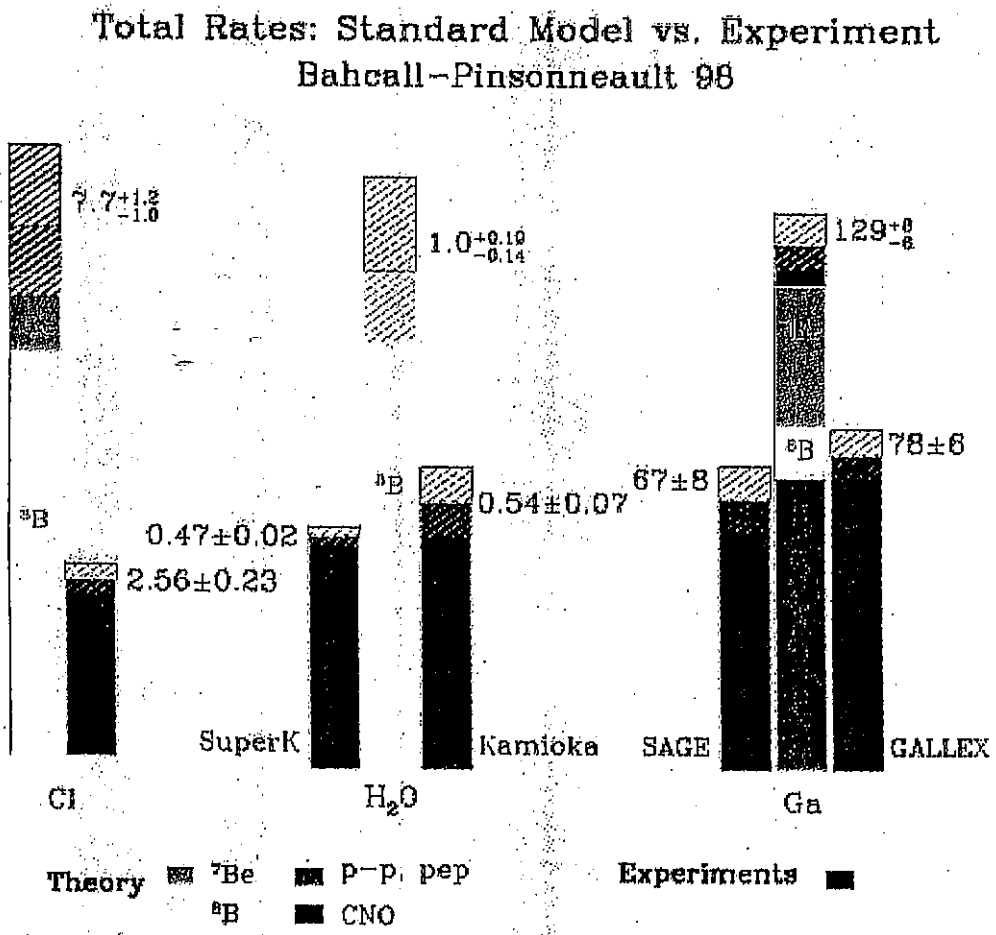
99.85% 0.15%

$${}^7Be + e^- \rightarrow {}^7Li + \nu_e \qquad {}^7Be + p \rightarrow {}^8B + \gamma$$

$${}^7Li + p \rightarrow 2\alpha \qquad {}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$$

$${}^8Be^* \rightarrow 2\alpha$$

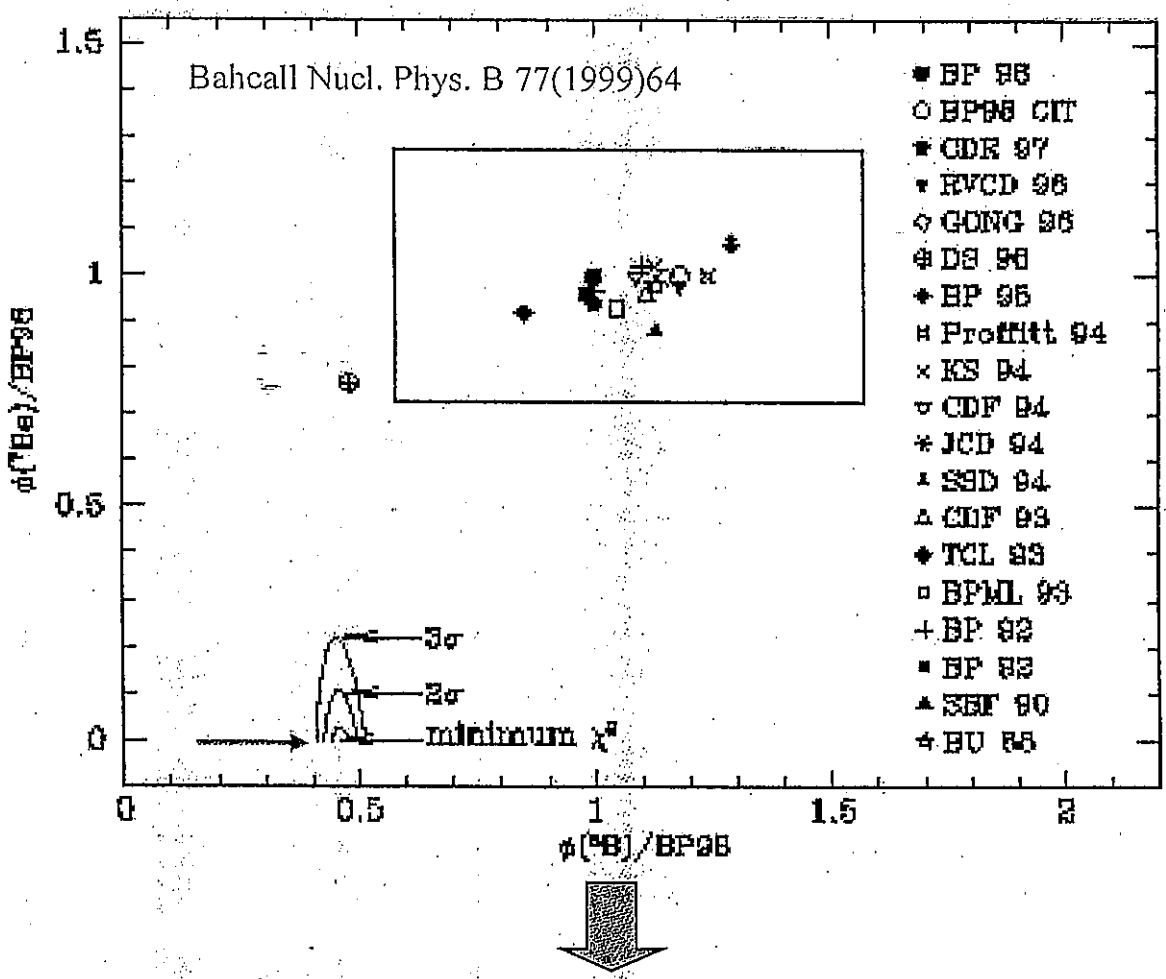
Solar neutrino problem



http://www.sns.ias.edu/~jnb

- Strong deficit of ^{7}Be neutrinos
- Is there any solution including non-standard solar model ?

Explanation by Solar models



- No models to explain the observational results
- There must be another solution likeneutrino oscillation ??
- $\nu e \rightarrow \nu x$ oscillation is expected in the range of $\Delta m^2 = 10^{-12} \sim 10^{-3} eV^2$ with solar neutrinos

Neutrino oscillation

Neutrino oscillation in matter(MSW effect)

$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\zeta - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\zeta = -\sqrt{2}\, G_F n_e E_\nu / \Delta m^2$$

$\zeta = \cos 2\theta$ (Resonance condition)

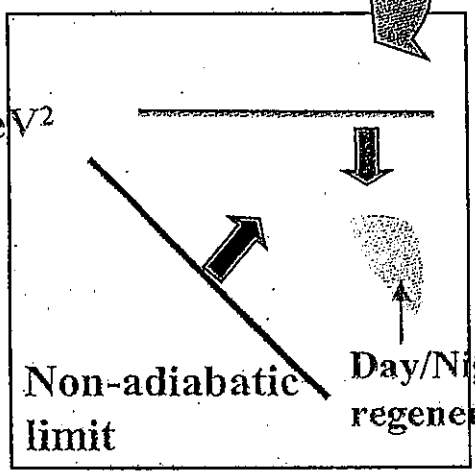
$\cos\theta \times \Delta m^2 = 1.5 \times 10^{-4}$ @ 10MeV

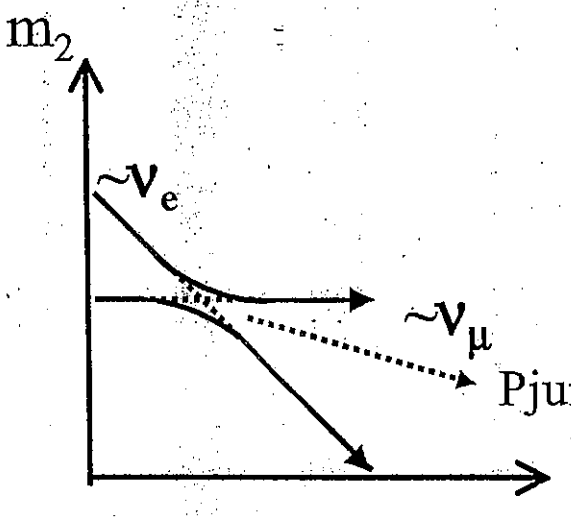
$$\frac{\Delta}{2E_\nu} \frac{\sin^2 2\theta}{\cos 2\theta} \gg \left| \frac{1}{n_e} \frac{dn_e}{dr} \right|$$

Adiabatic condition

Δm^2

$\sim 10^{-4}$eV^2

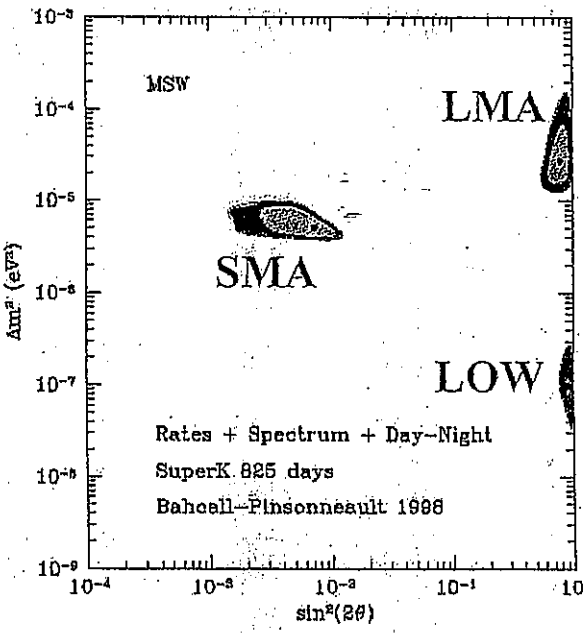




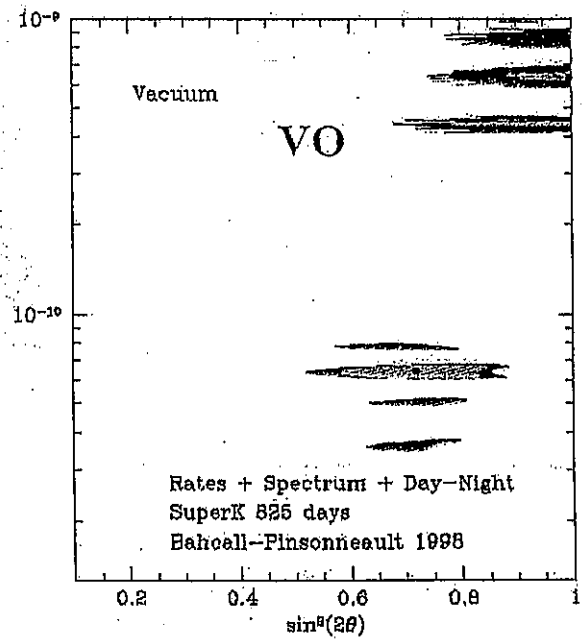
$$P_{jump} = \exp\left(-\underbrace{\frac{\pi}{4}\frac{\Delta}{E_\nu}\frac{\sin^2 2\theta}{\cos 2\theta}\left(\left|\frac{N_e}{dn_e/dr}\right|\right)}_{\sim 0}\right)$$

Allowed region by all experiment

MSW oscillation



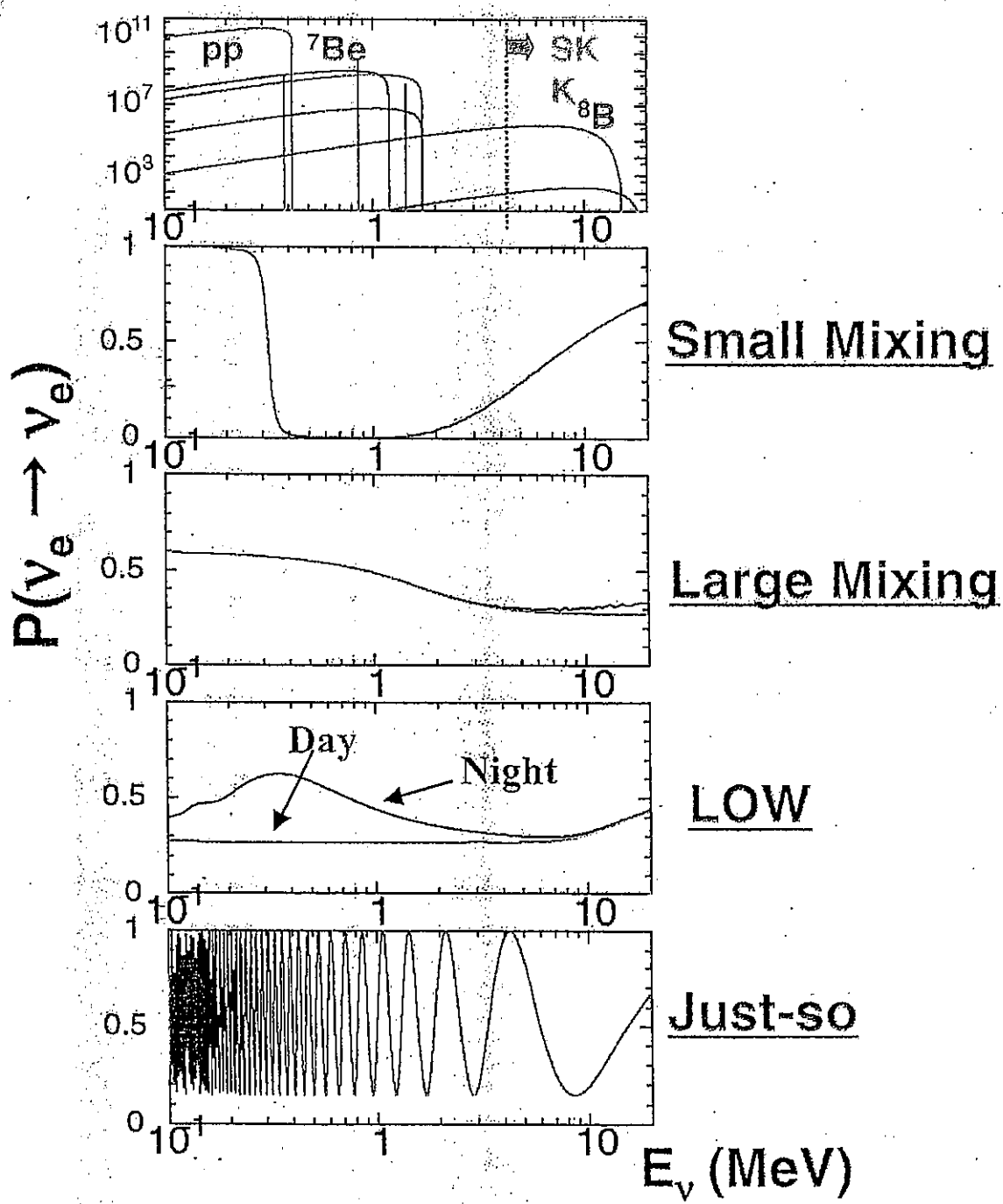
Just so oscillation



http://www.sns.ias.edu/~jnb

There are four regions to explain the results from all solar neutrino experiments

Neutrino survival probability



Probability have a strong dependence of oscillation parameters → energy spectrum can be distorted

How to confirm neutrino oscillation in solar neutrinos

- Measure energy spectrum of ^{8}B neutrinos

  ⇓

  Spectral distortions in the ^{8}B flux (SMA,VO)
- Measure Day-Night flux variations

  ⇓

  flux regeneration in the Earth(LOW,LMA)
- Measure seasonal variation of ^{8}B flux

  ⇓

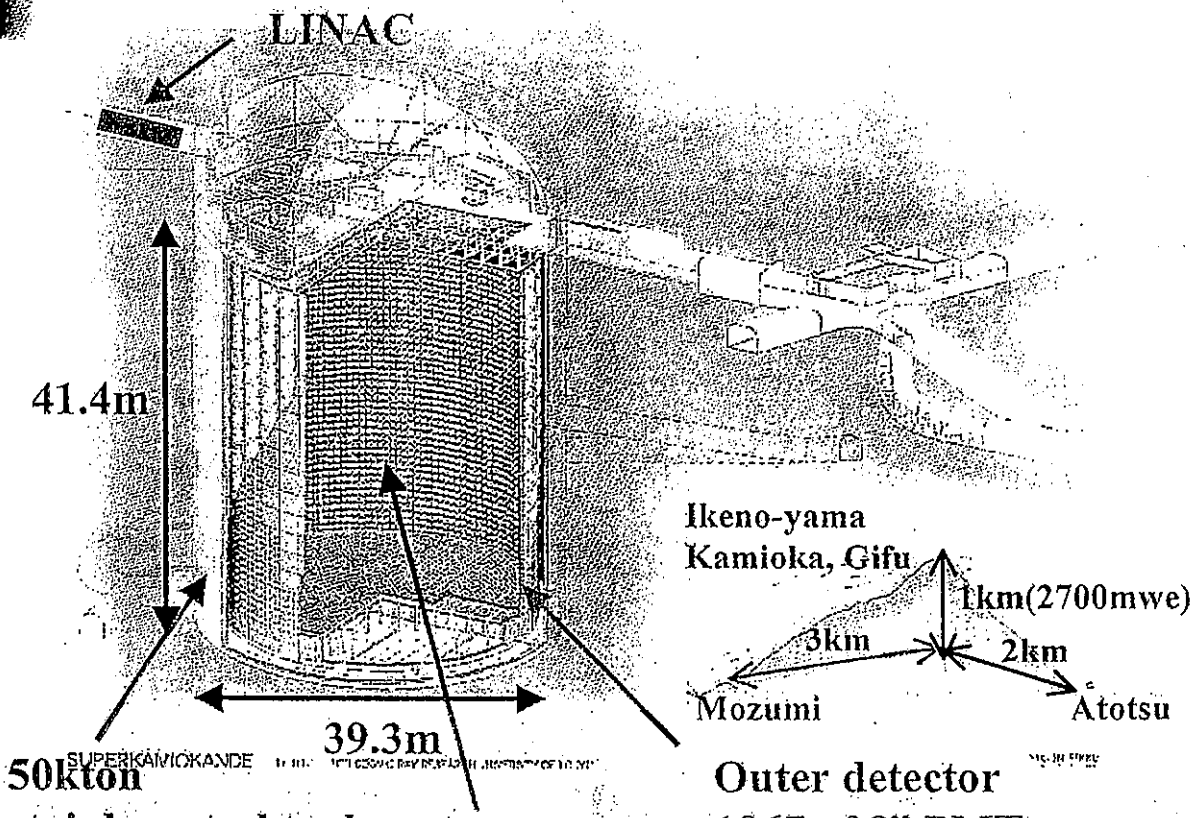
  sensitive vacuum oscillation (VO)
- Measure neutral current interaction

  ⇓

  new information to oscillation

	Spectrum	Day/Night	Seasonal	Neutral Current
^{37}Cl	×	×	○	×
^{71}Ga	×	×	○	×
SK	○	○	○	×
SNO	○	○	○	○
Scinti	○	○	○	×

Solar neutrino observation at SuperKamiokande



50kton stainless steel tank

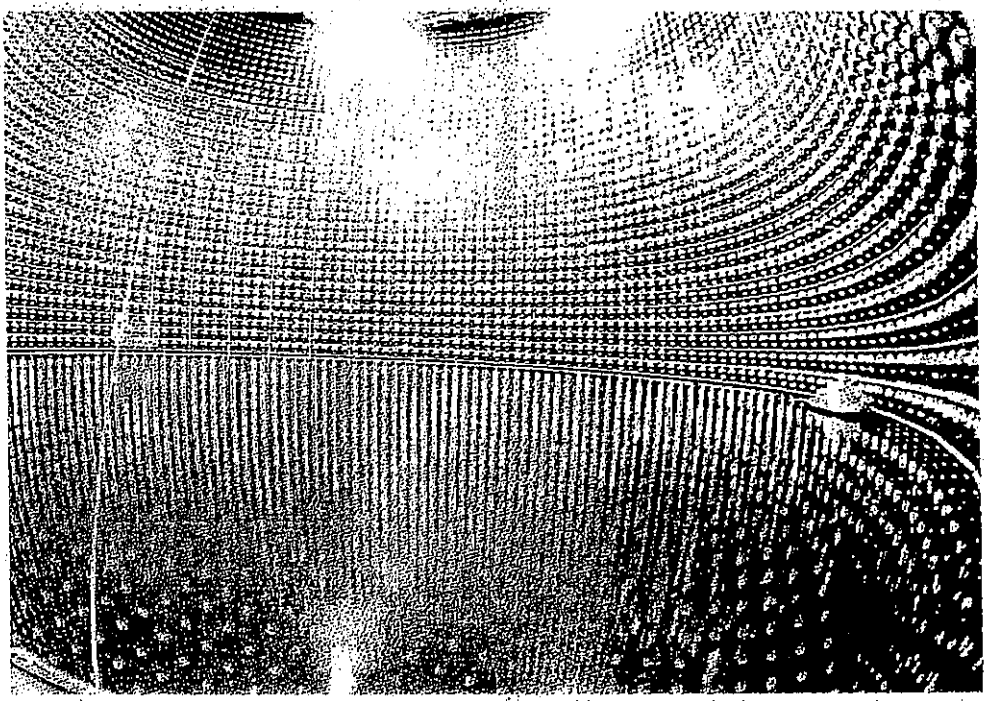
Inner detector 11146 of 20" PMT

Outer detector 1867 of 8" PMT

- Photo coverage 40%
- Outer detector 2.5m for all surface
- Fid. Vol. for solar ν 22.5kton
- Resolution (10MeV e^-)
  - Vertex 87cm
  - Energy 14%
  - Direction 26 degree

Solar neutrino experiments

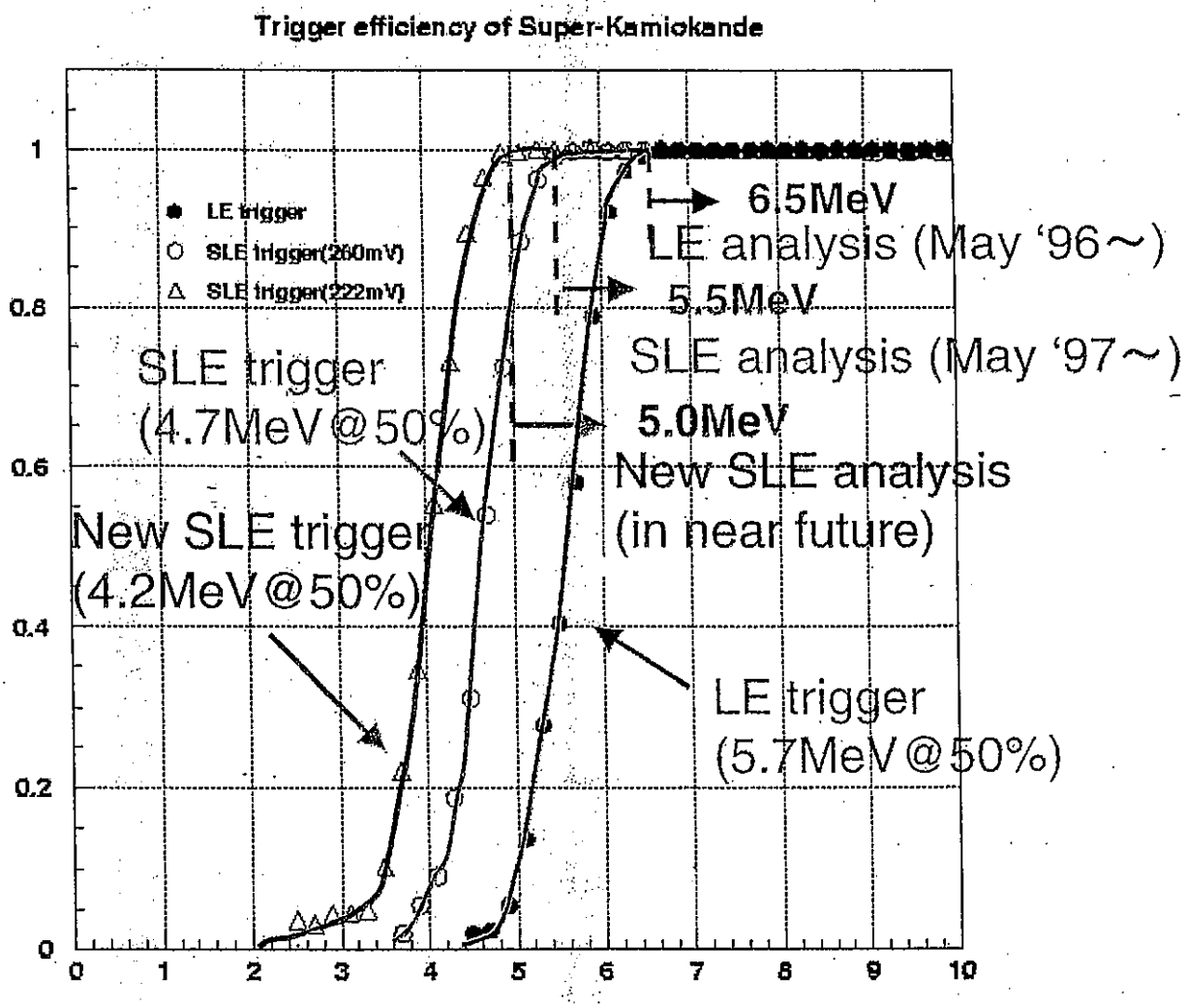
- $\nu e + e^- \rightarrow \nu e + e^-$
- Energy threshold : 5.0 MeV
- Target : light water 50,000ton
- Fiducial volume 22,500ton
- SSM prediction : 47events/day (E>5.0MeV)
- Data/SSM $=0.465 \pm 0.005\ ^{+0.015}_{-0.013}$



http://www-sk.icrr.u-tokyo.ac.jp/doc/sk

Energy threshold

- Low energy (LE) trigger
  ≧29 PMT hits / 200nsec (10Hz)
- Super-Low energy (SLE) trigger
  ≧24 PMT hits / 200nsec (120Hz)
- New Super-Low energy trigger (since Sep '99)
  ≧20 PMT hits / 200nsec (550Hz)



12

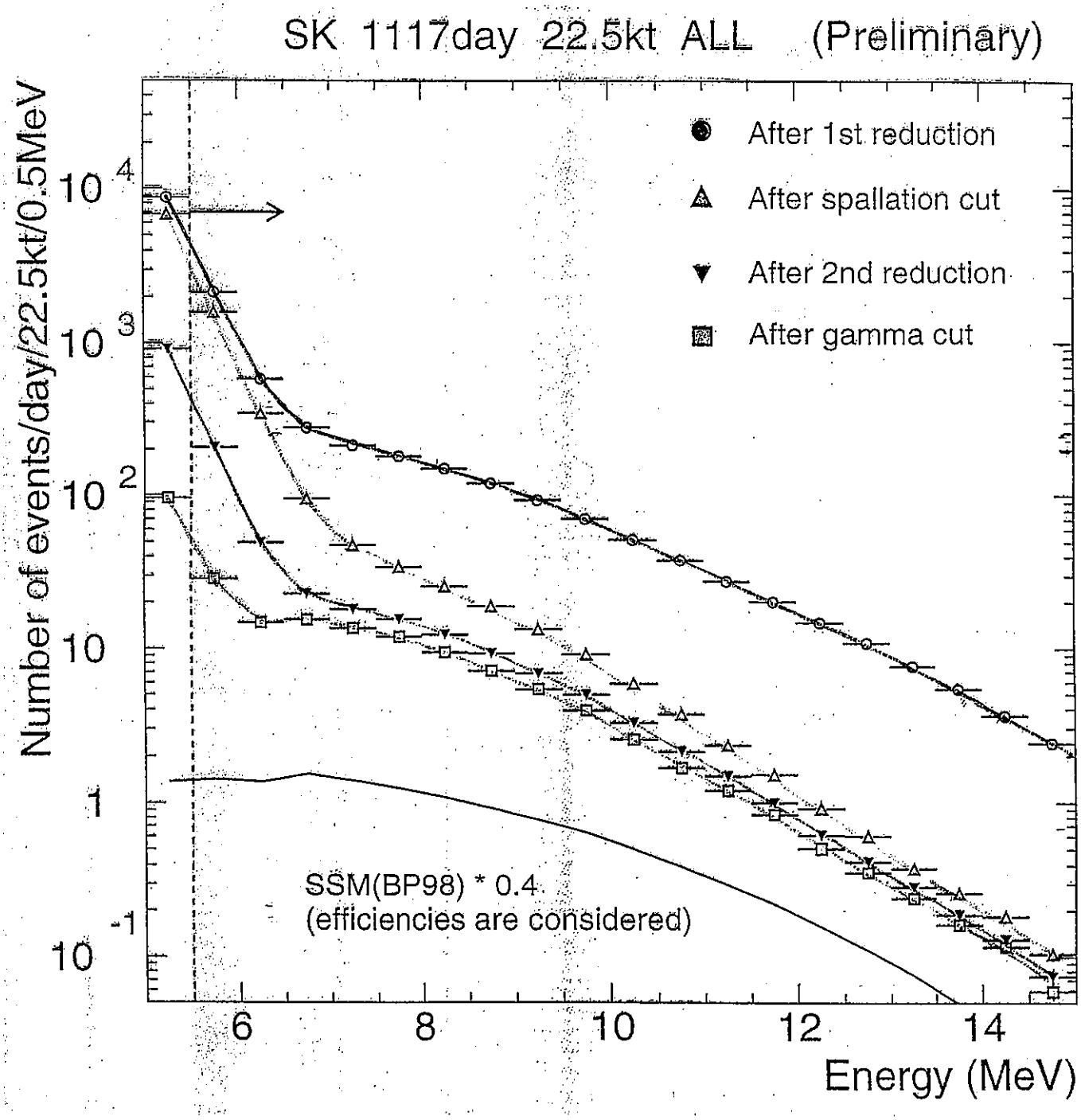
Low Energy Data reduction

May 31st.1996 - Apr 24th, 2000

Live-time 1117 days

	5.0 - 20.0 MeV number of events
RAW DATA	
total charge < 1000 p.e.	1.4×10^8
VERTEX RECONSTRUCTION	
FIRST REDUCTION	
Fiducial Volume cut (22.5kton)	2.4×10^7
ΔT to previous event < 50 μ sec	1.9×10^7
Electrical noise cut	1.8×10^7
Goodness of fitting cut	1.7×10^7
flasher cut	1.2×10^7
SPALLATION EVENT CUT	
	8.7×10^6
SECOND REDUCTION	
GRINGO cut	2.1×10^6
Cluster fitting cut	1.5×10^6
Ring Pattern cut	1.1×10^6
GAMMA CUT	
	2.0×10^5
EYE SCAN	
FINAL DATA SAMPLE	2.0×10^5

(3


SK 1117day 22.5kt ALL (Preliminary)
Number of events/day/22.5kt/0.5MeV
After 1st reduction
After spallation cut
After 2nd reduction
After gamma cut
SSM(BP98) * 0.4
(efficiencies are considered)
Energy (MeV)

14

What's new ?

Analysis method was unified

- Previous method :
  tight cut applied for E<6.5 MeV and *usual cut* applied for E>6.5 MeV
- New method :
  tight cut * applied for entire energy region (unified analysis) ⇒ 60% BG rejection!

*cut criteria was improved

MC was re-tuned :

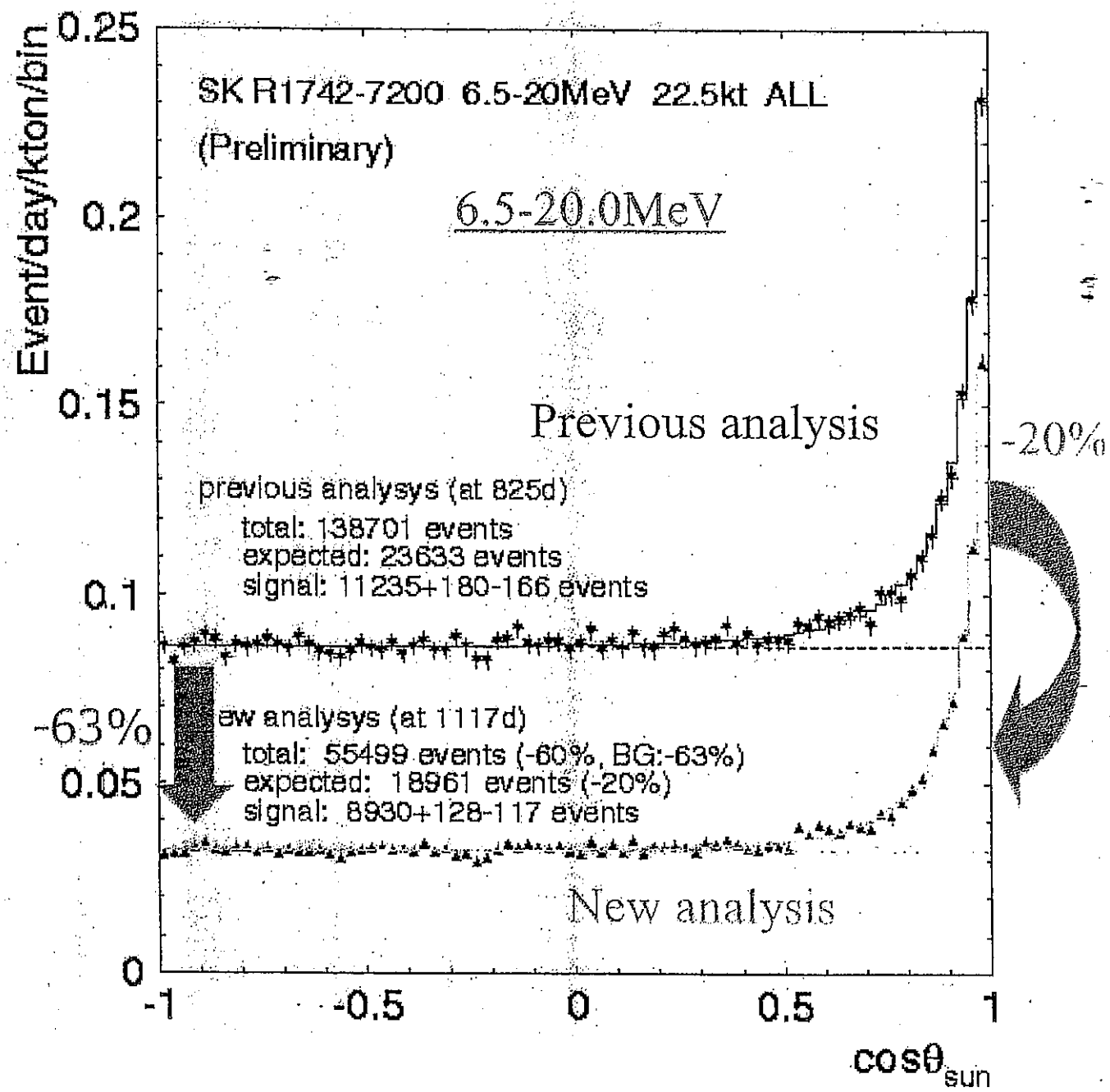
0.27% energy scale shift (within systematic error!

Down Energy threshold to 5MeV

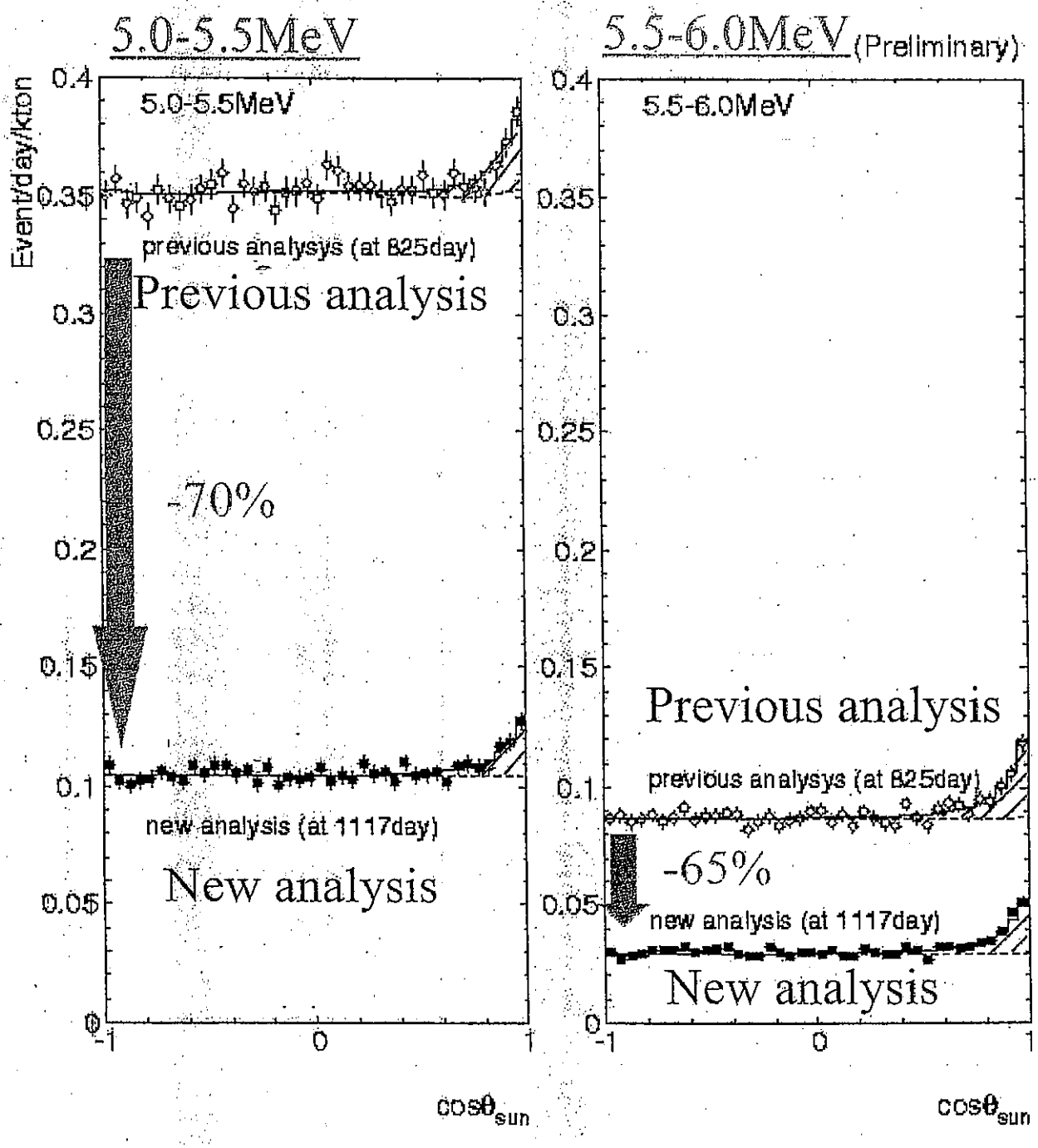
Systematic error re-evaluated

⇒ Analysis is very robust !!

Previous & new analysis

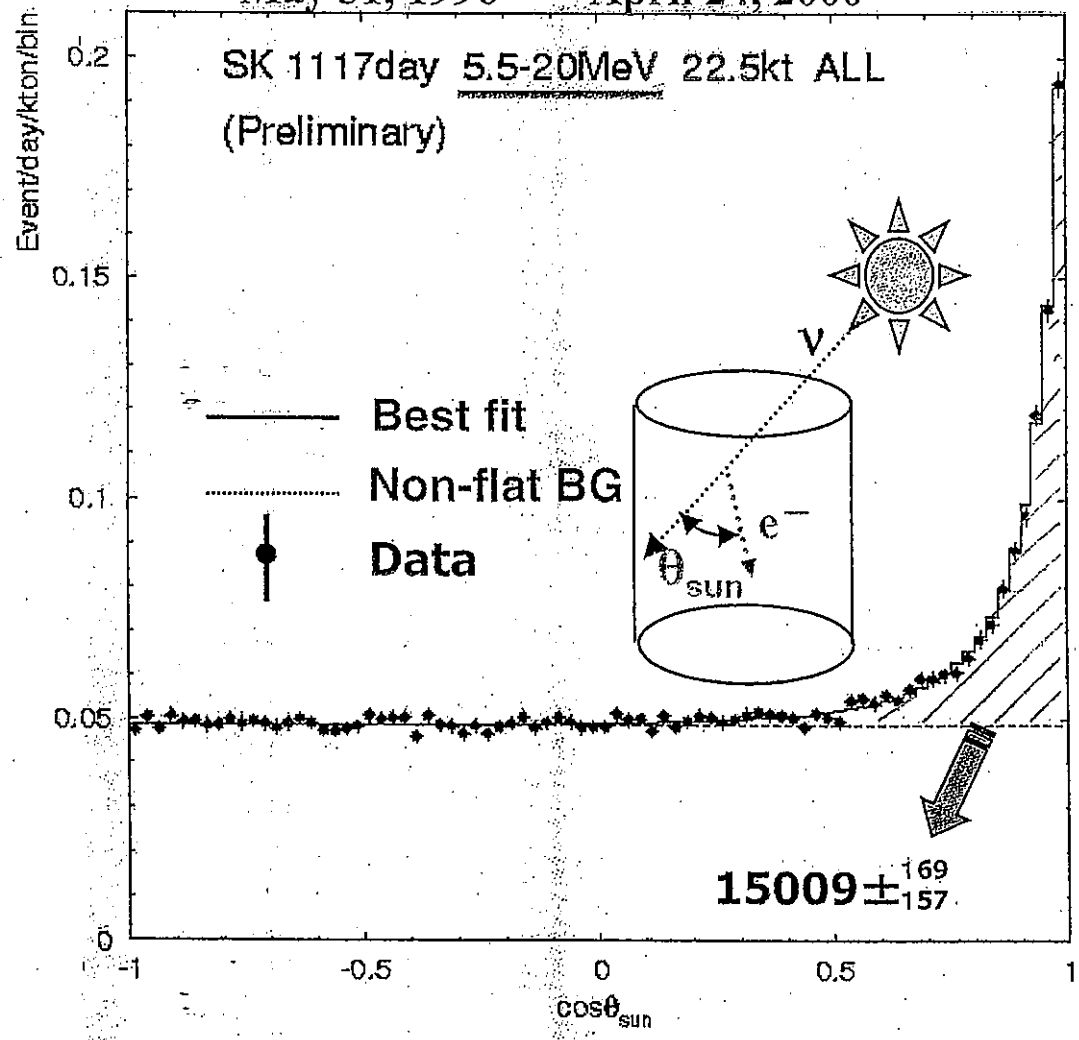


Previous & new analysis



Angular distribution with respect to the solar direction

May 31, 1996 ~ April 24, 2000

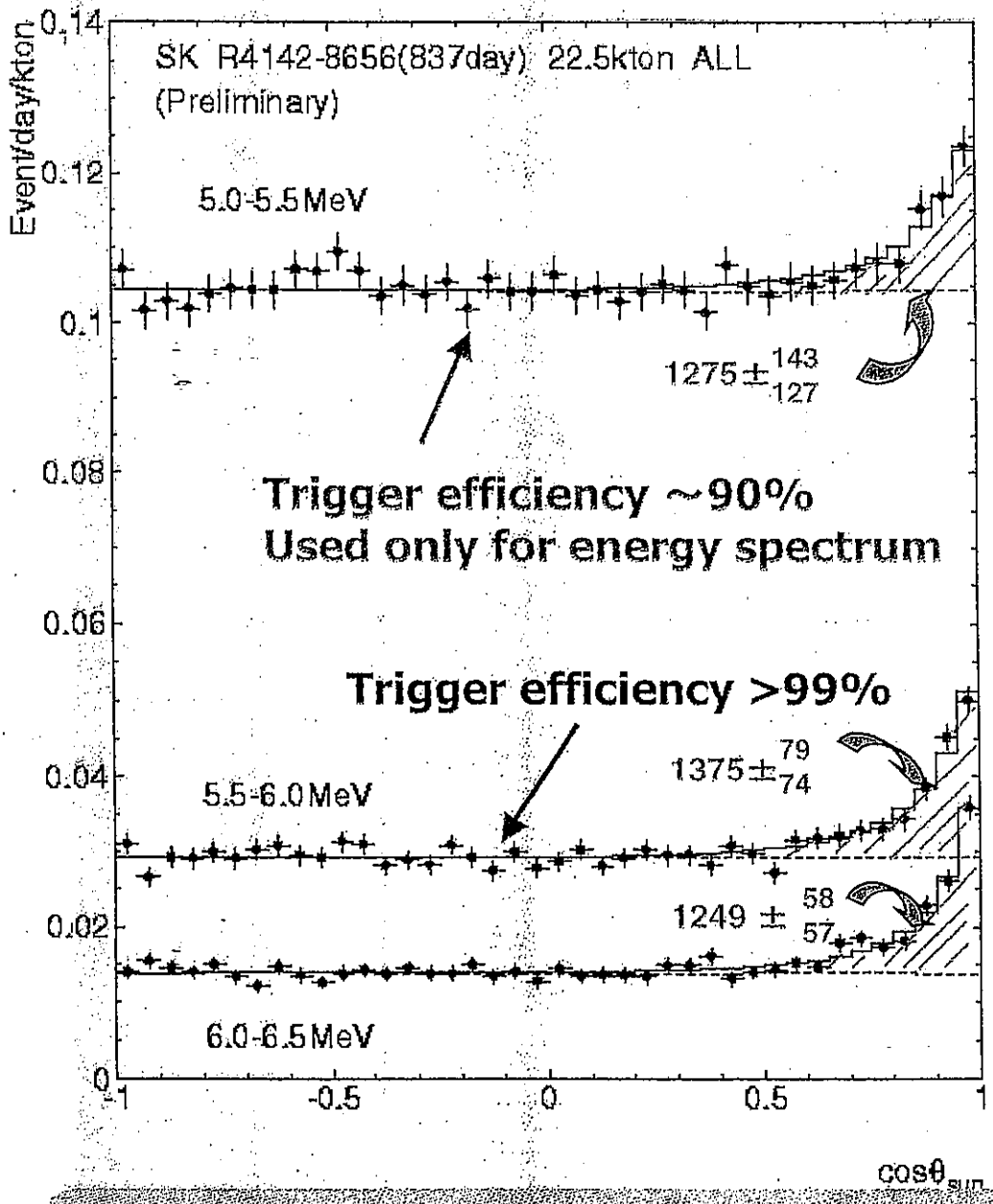


$\cos\theta_{sun}$

^{8}B flux : $2.40 \pm 0.03\ ^{+0.08}_{-0.07}$ [x 10^{6}/cm^{2}/sec]

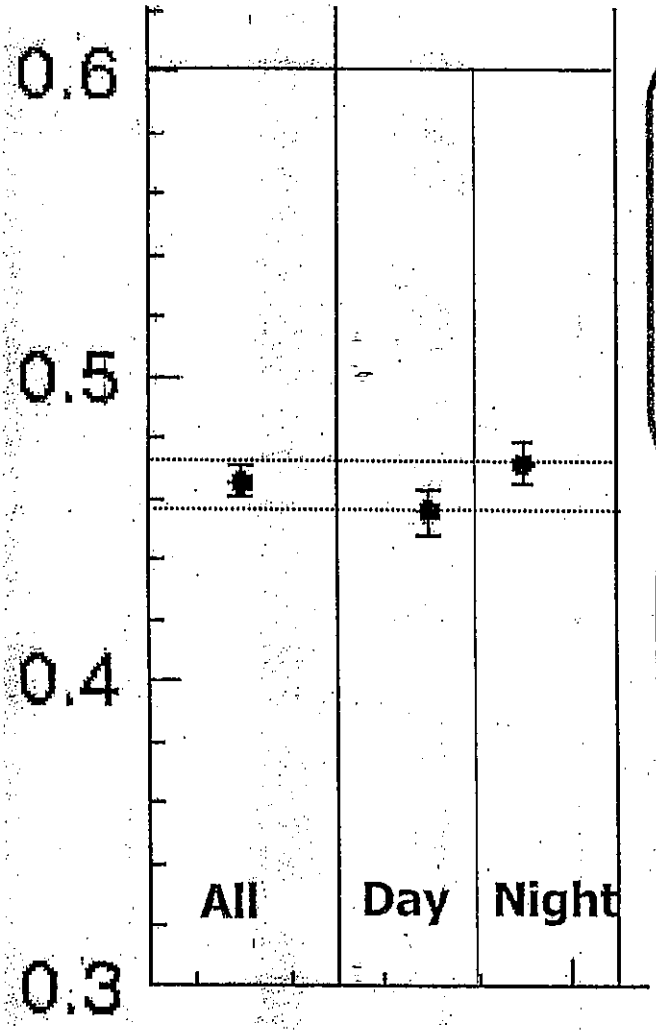
$\frac{\text{Data}}{\text{SSM(BP98)}} = 0.46 \pm 0.005(\text{stat.})\ ^{+0.015}_{-0.013}$ (syst.)

Angular distribution of SLE triggered



^{8}B energy spectrum with 5.0 - 6.5 MeV are now ready

Results and implication



Day 544.6days

$2.35 \pm 0.04(\text{stat.}) \pm {}^{0.08}_{0.07}$ (syst.) [$\times 10^6\ \text{cm}^{-2}\text{s}^{-1}$]

$\frac{\text{Data}}{\text{SSM}} = 0.456 \pm {}^{0.007}_{0.007}$ (stat.) $\pm {}^{0.015}_{0.013}$ (syst.)

Night 572.1days

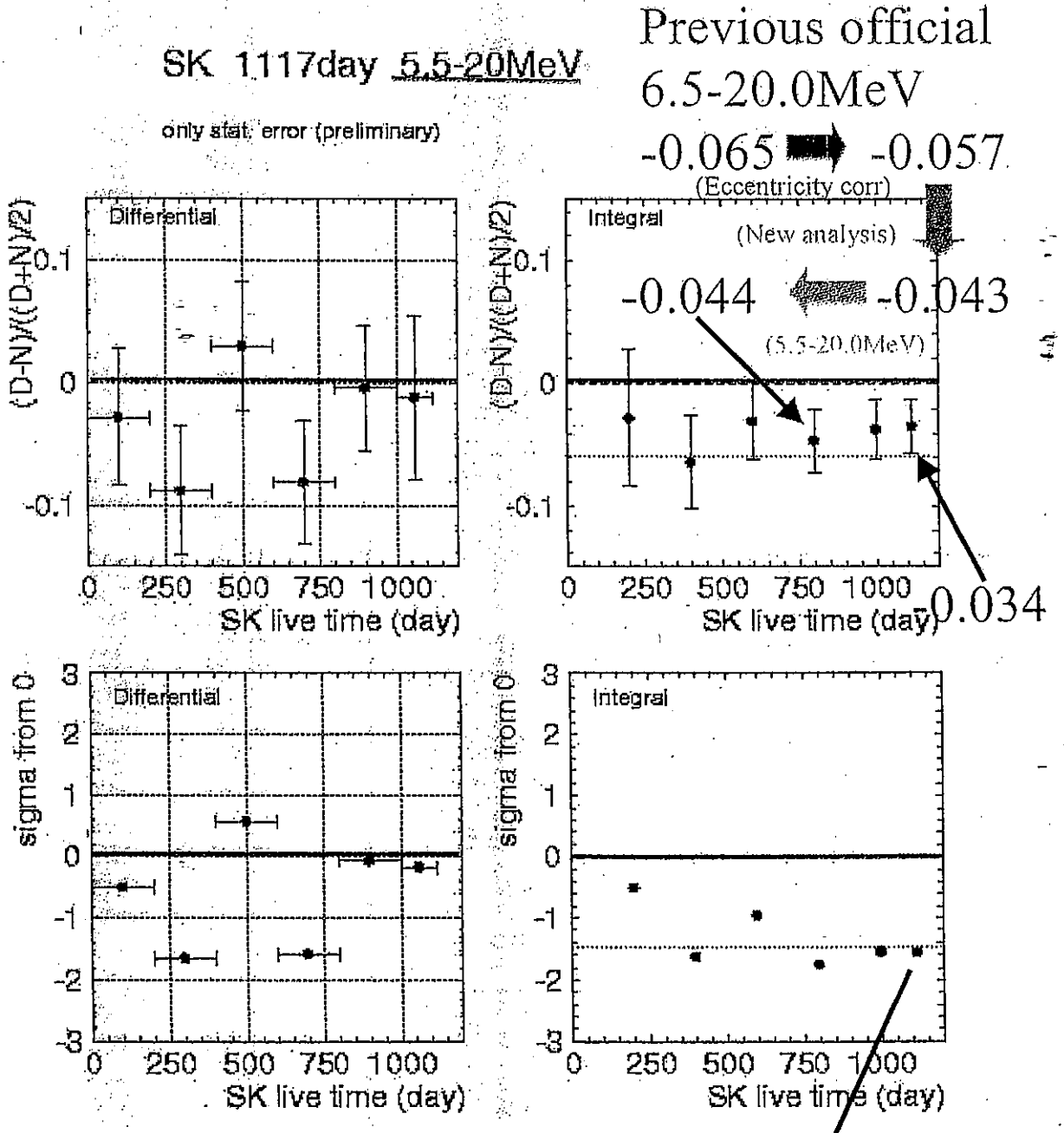
$2.43 \pm 0.04(\text{stat.}) \pm {}^{0.08}_{0.07}$ (syst.) [$\times 10^6\ \text{cm}^{-2}\text{s}^{-1}$]

$\frac{\text{Data}}{\text{SSM}} = 0.472 \pm {}^{0.007}_{0.007}$ (stat.) $\pm {}^{0.016}_{0.014}$ (syst.)

$$\frac{N-D}{(N+D)/2} = 0.034 \pm 0.022(\text{stat.}) \pm 0.013(\text{syst.})$$

(1.33 σ difference)

Profile of D/N significance



Previous official
6.5-20.0MeV
-0.065 ➡ -0.057
(Eccentricity corr)

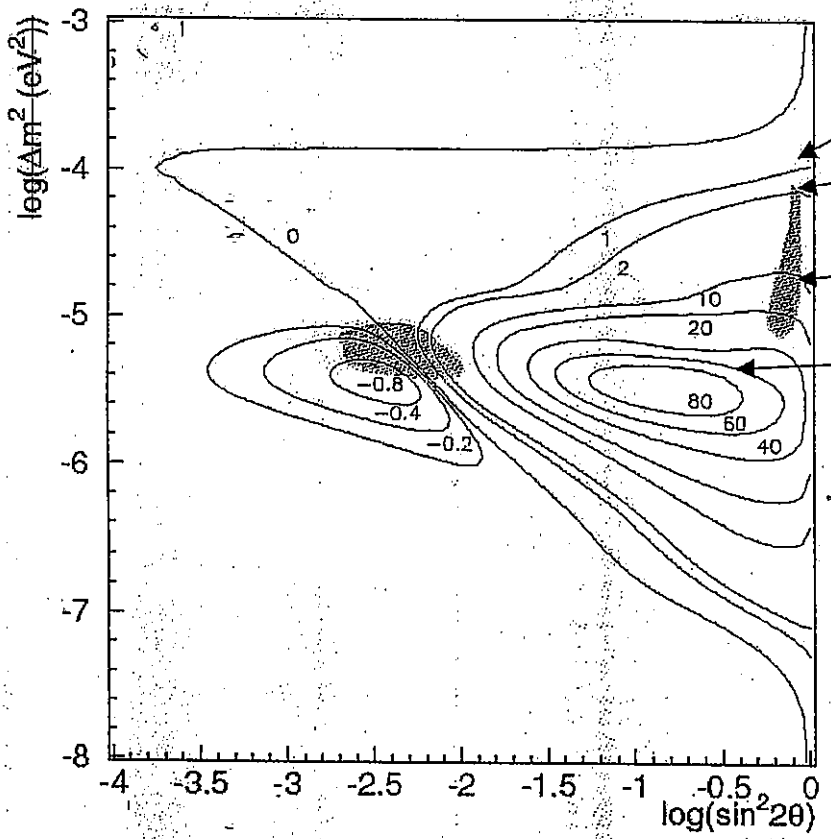
(New analysis)
-0.044 ⬅ -0.043
(5.5-20.0MeV)

-0.034

Including systematic error 1.33σ

D/N significance on oscillation parameters

$\Delta m^2 = a\ few \times 10^{-6} eV^2$



1%

2%

10%

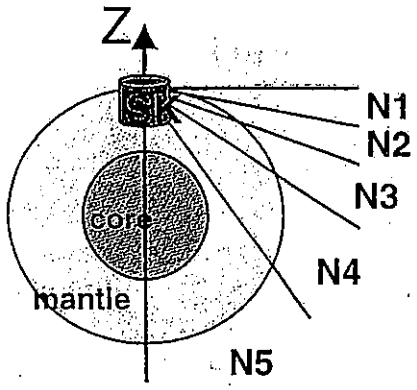
80%

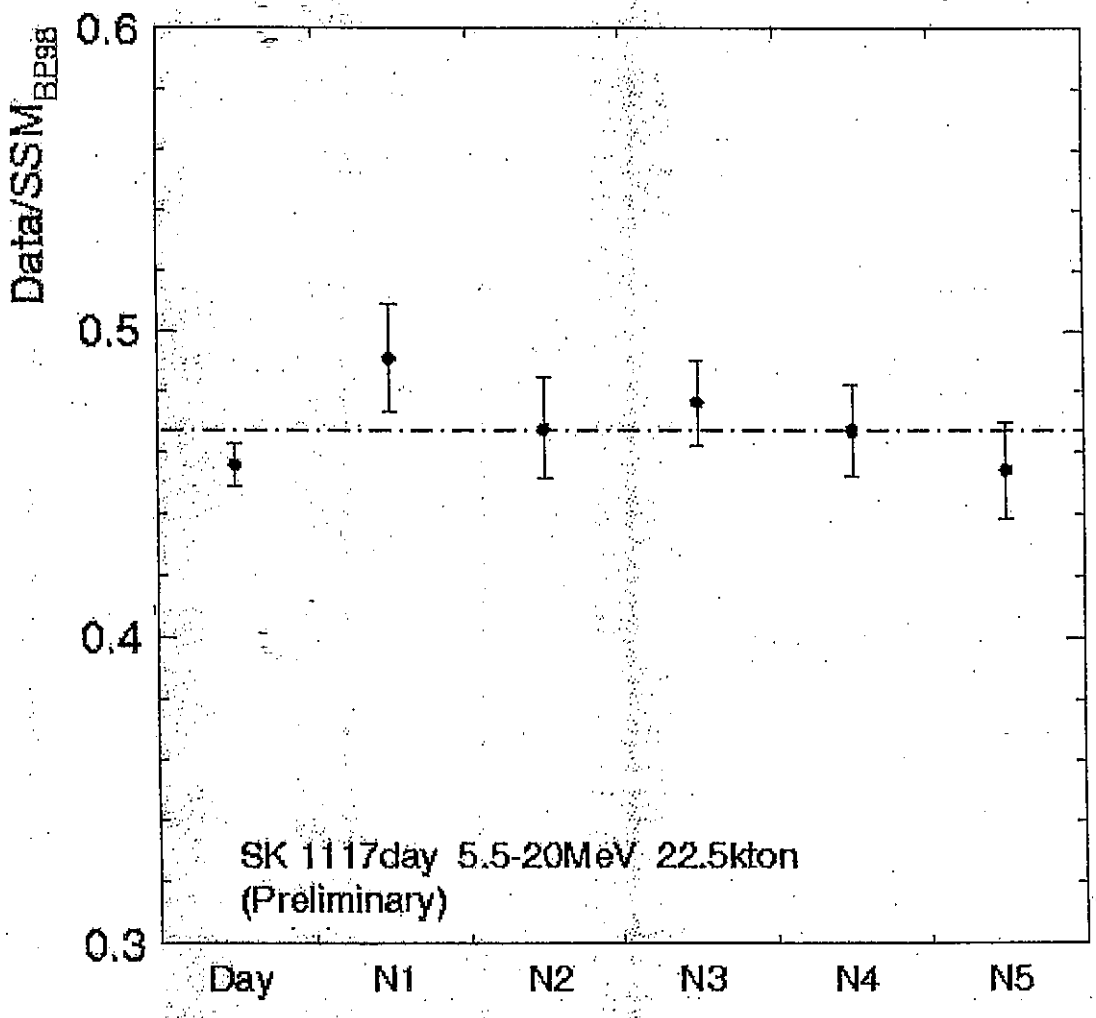
$$\frac{\text{(Night-Day)}}{\text{2(Night+Day)}}$$

Small but positive D/N difference maybe constraint on global fit allowed region

Day/Night fluxes variation

Regeneration effect depends on the trajectories inside of the Earth

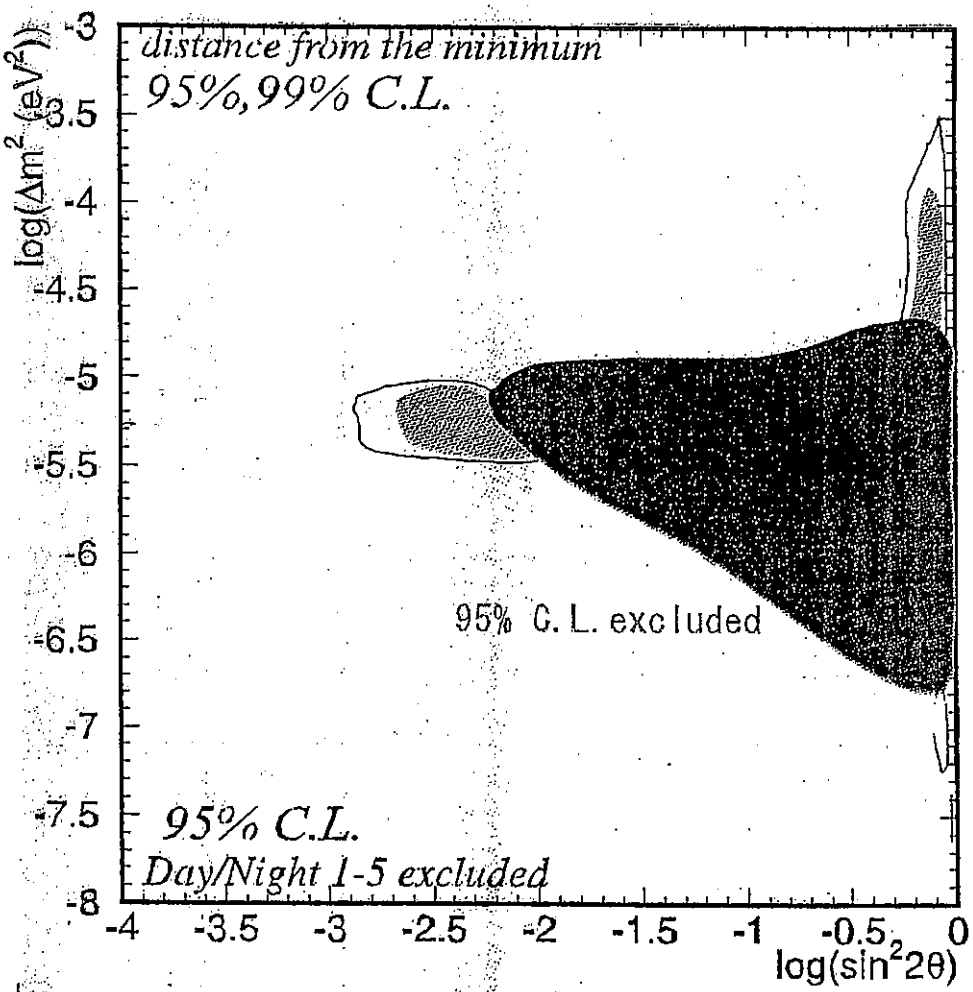




Independent analysis of SSM flux prediction

23

D/N spectrum excluded region on oscillation parameters



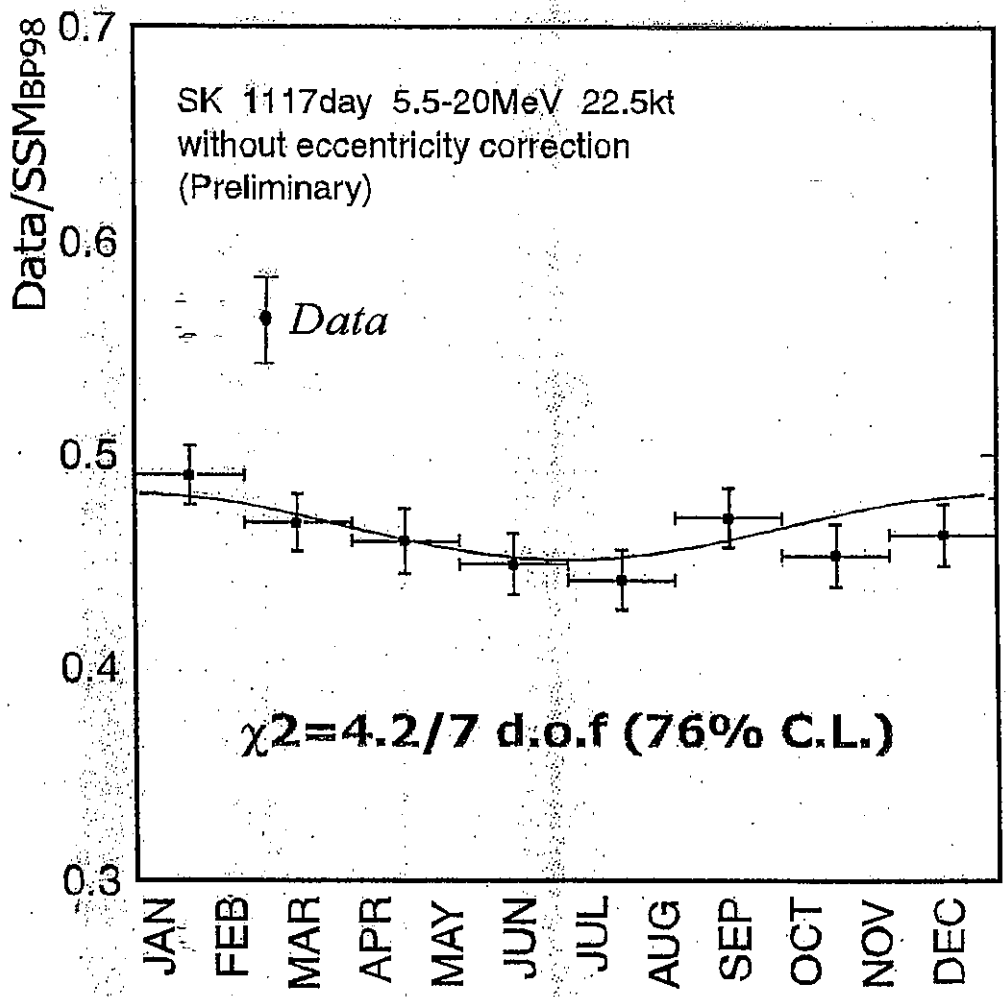
$$\chi^2 = \sum_{i=D,N1-N5} \left\{ \frac{\left[\frac{\text{Data}}{\text{SSM}}\right]_i - \left[\frac{\text{w/ oscil.}}{\text{w/o oscil.}}\right] \times \alpha}{\sigma_i} \right\}^2$$

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

D/N spectrum exclude part of global region

24

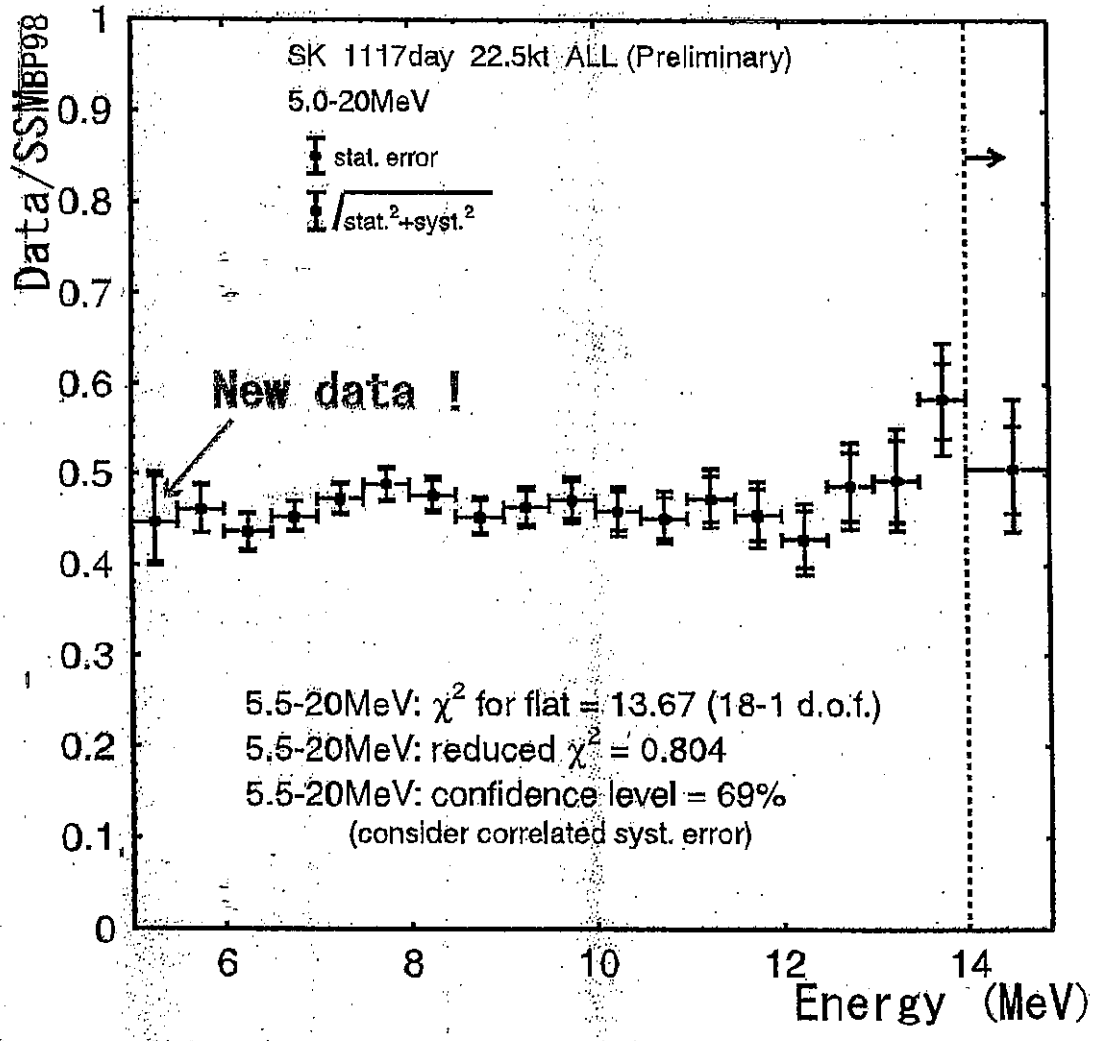
Seasonal variation



Agree with data and expectation from Eccentricity variation

25

Energy spectrum



It looks very flat !!!

First moment of energy spectrum analysis

$$\text{First moment : } \langle T \rangle = \frac{\sum \langle T \rangle_i \, N_i}{\sum N_i}$$

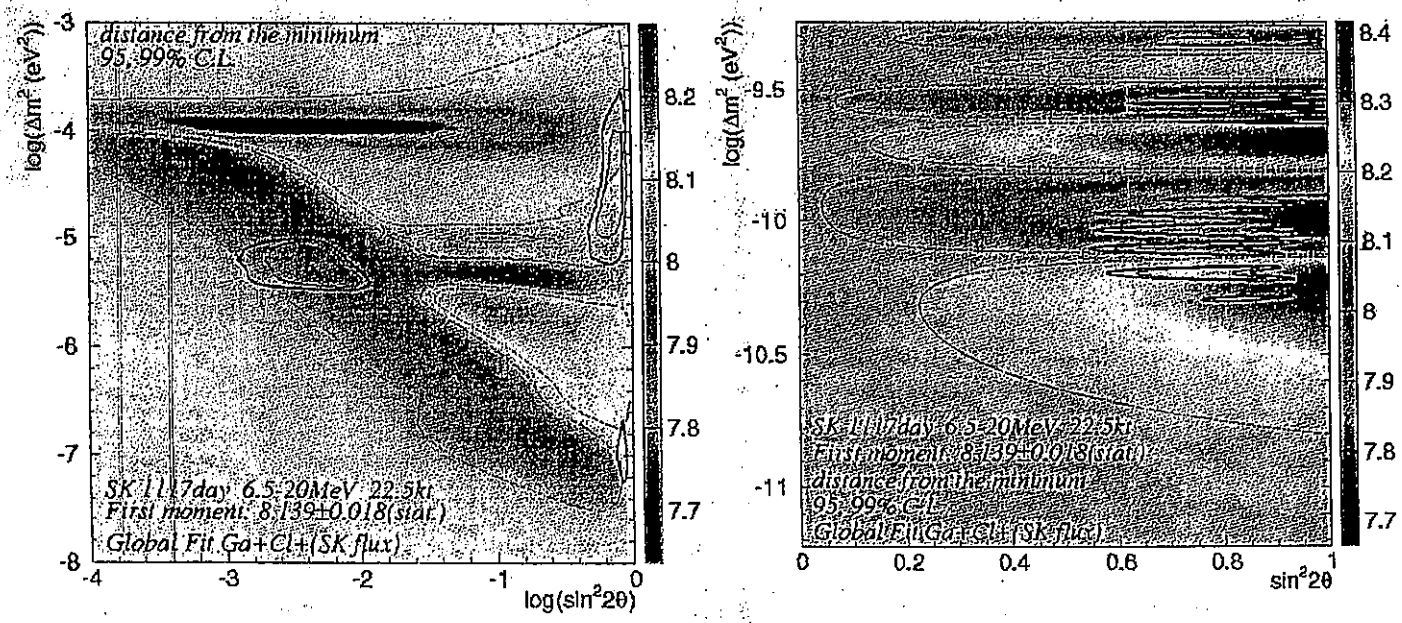
$\langle T \rangle$: average kinetic energy of electrons

σ : dispersion in the kinetic energy

i : energy bin

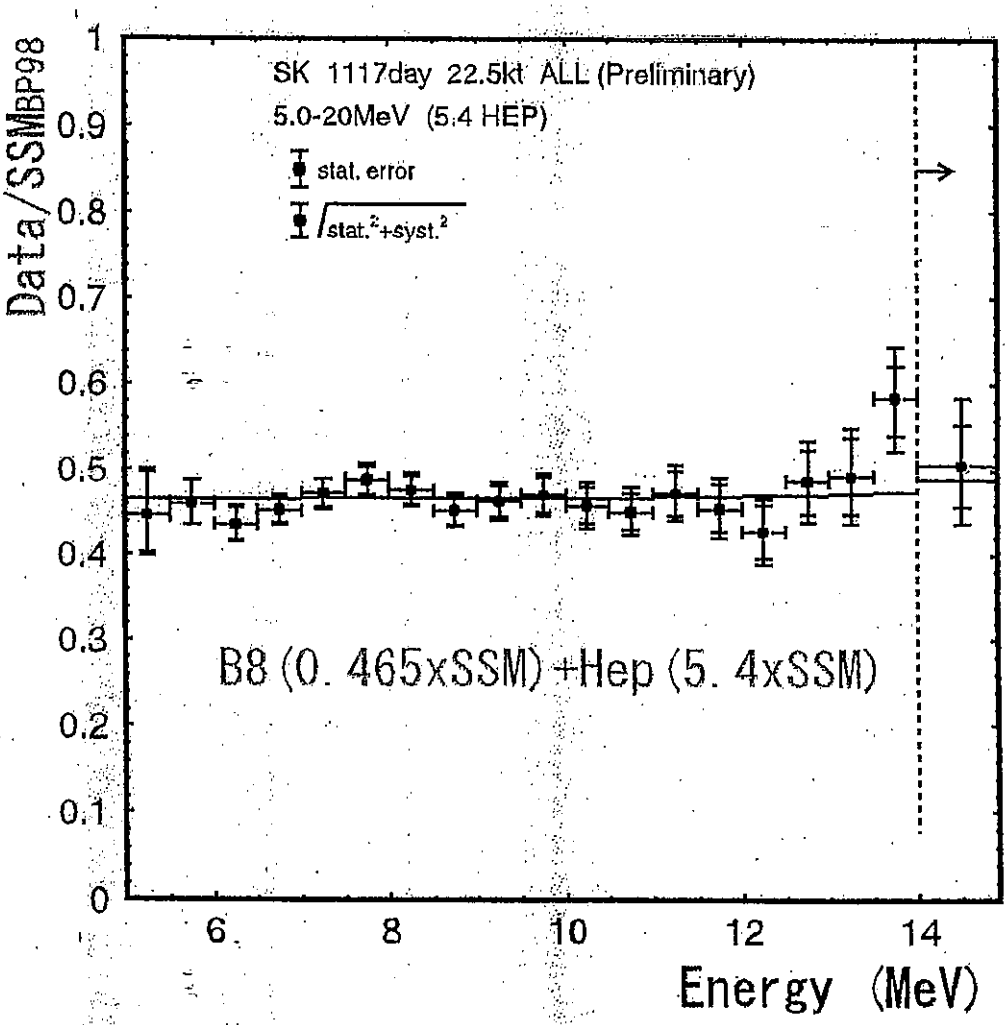
$\langle T \rangle_i$: average kinetic energy in i-th bin

N_i : number of events in i-th bin



First moment : 8.14 ± 0.02 MeV

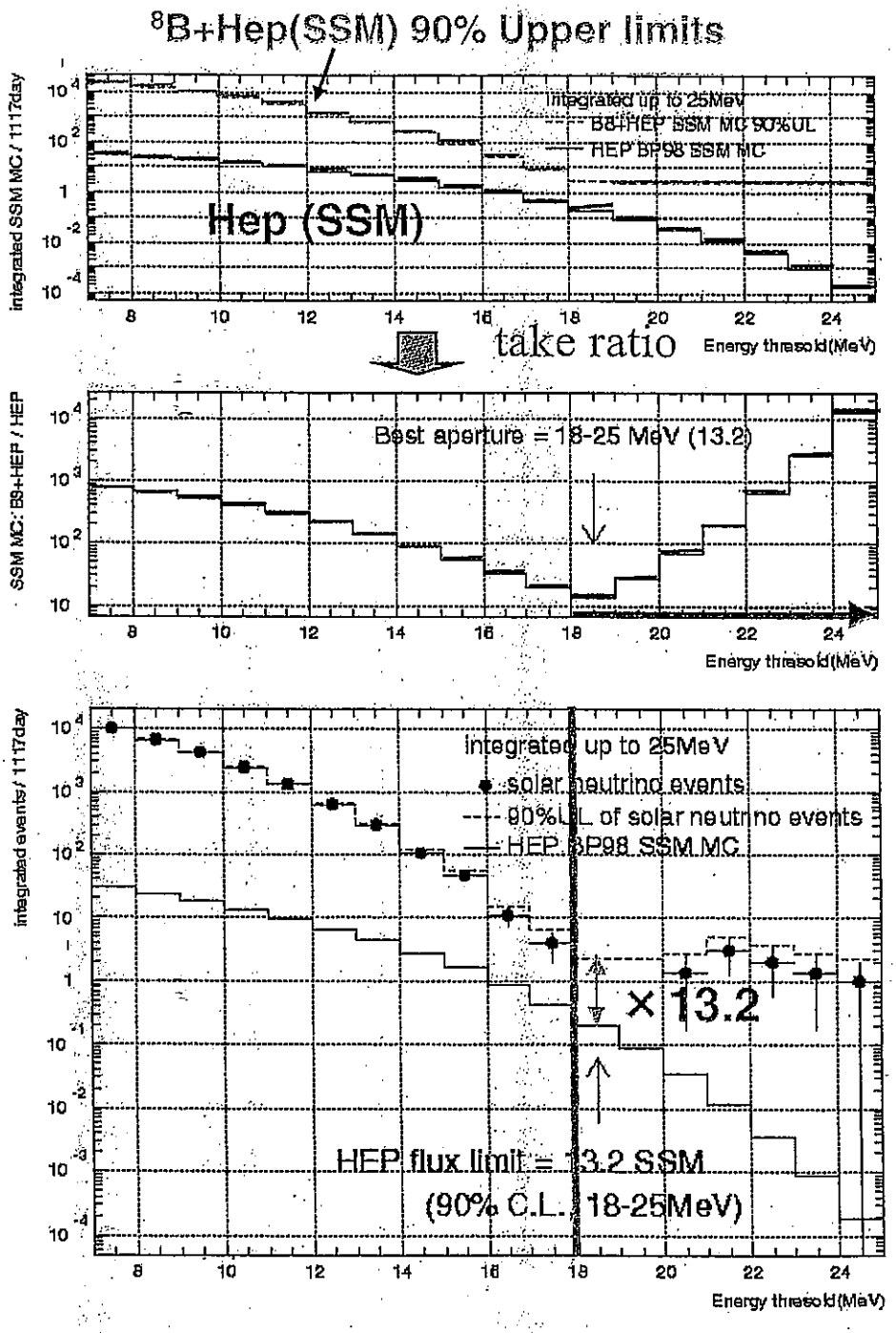
Hep free spectrum



Hep flux ($S(0)_{hep}$=2.3×10^{-20}kevb) might have large uncertainty

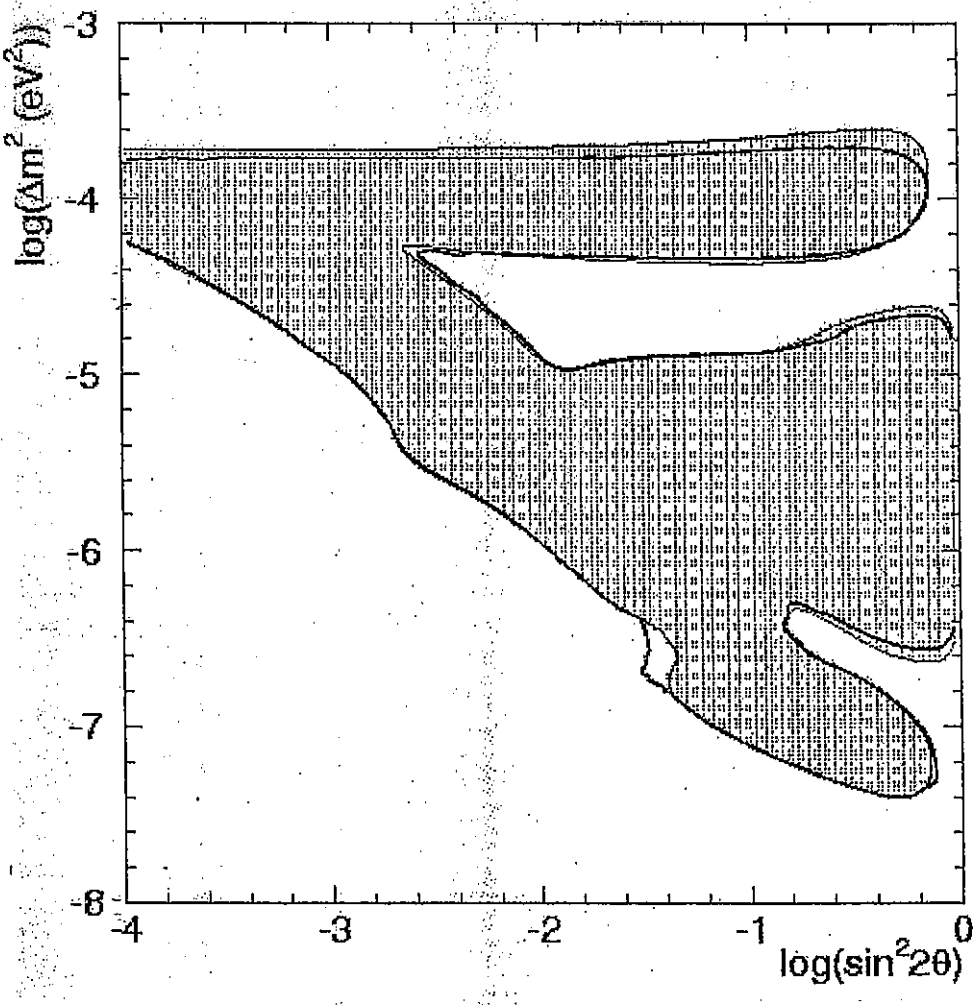
Recent calculation 10.1×10^{-20}kevb (nucl-th/0003065)

Upper limit of Hep ν flux



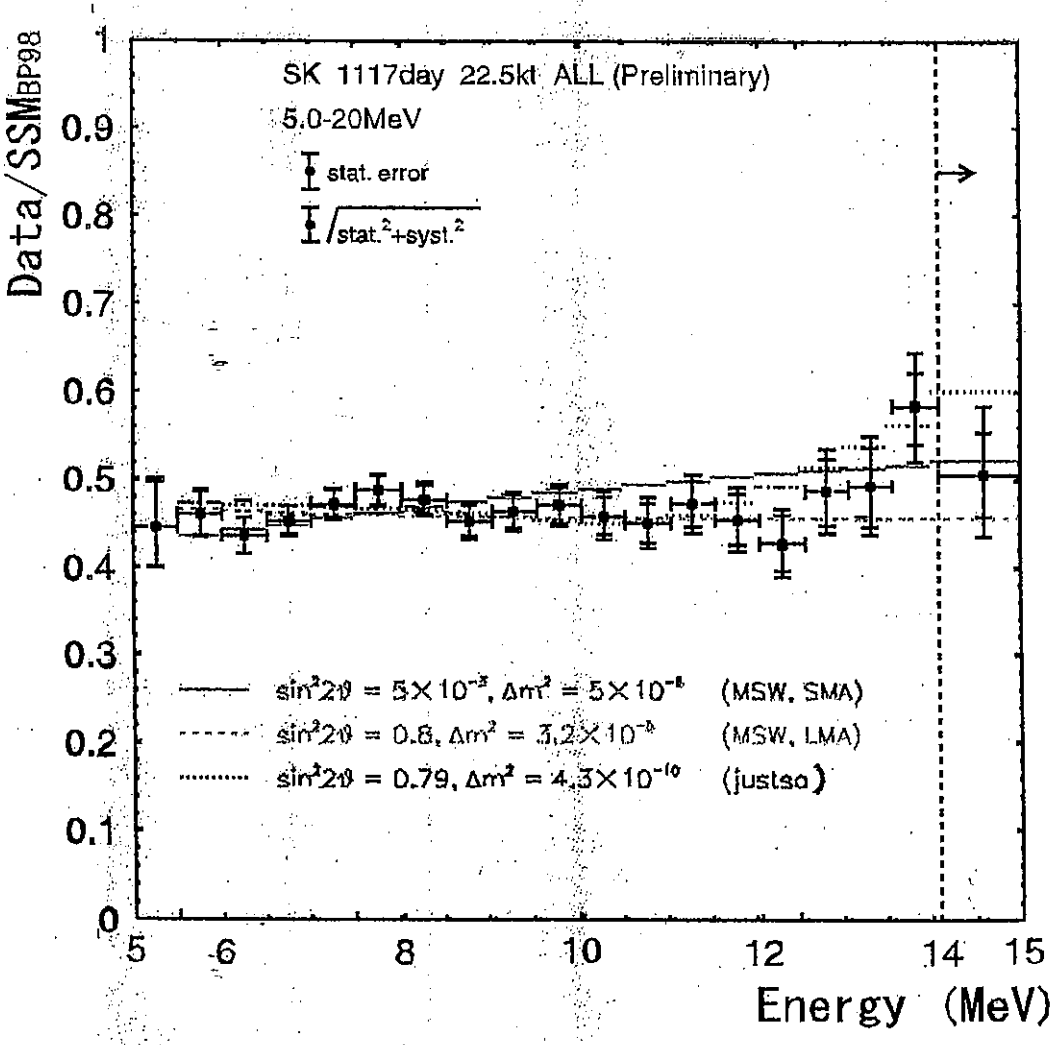
Hep flux limit = 13.2 SSM (90%C.L.)

Hep contribution on oscillation parameters



No effective difference seen on the excluded region

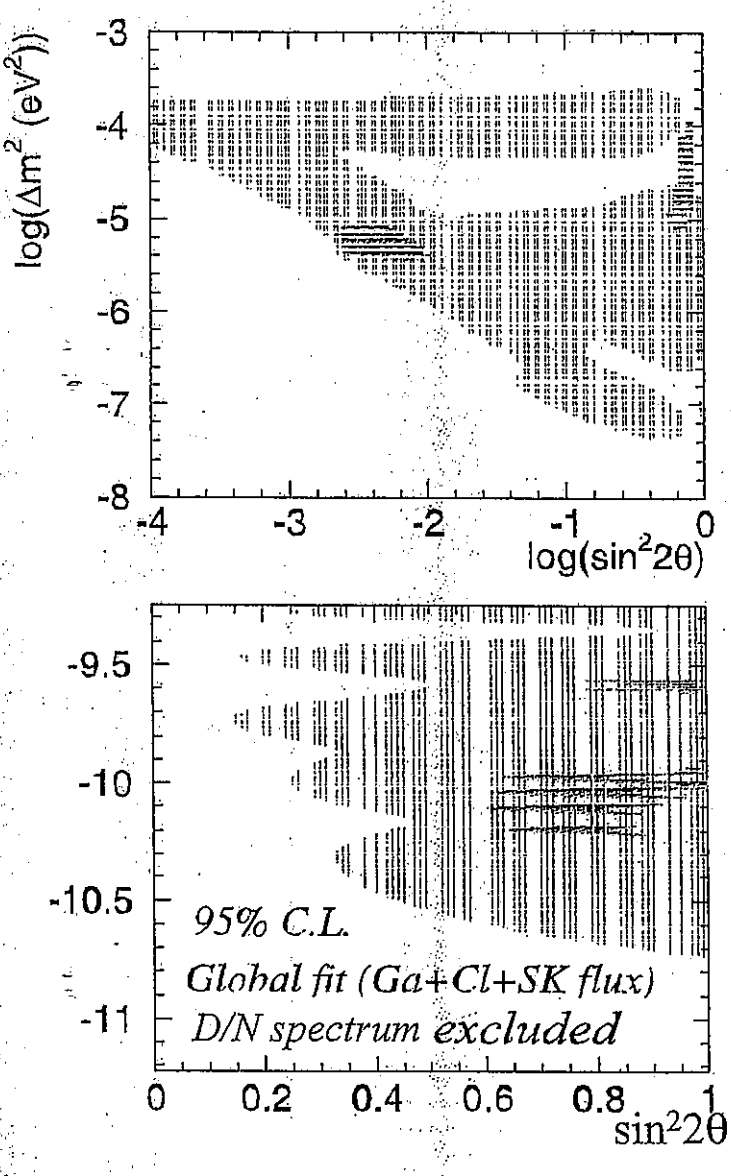
Expected energy spectrum



- Spectral shape is now flatter
- Looks no consistent with SMA and JustSo solution

31

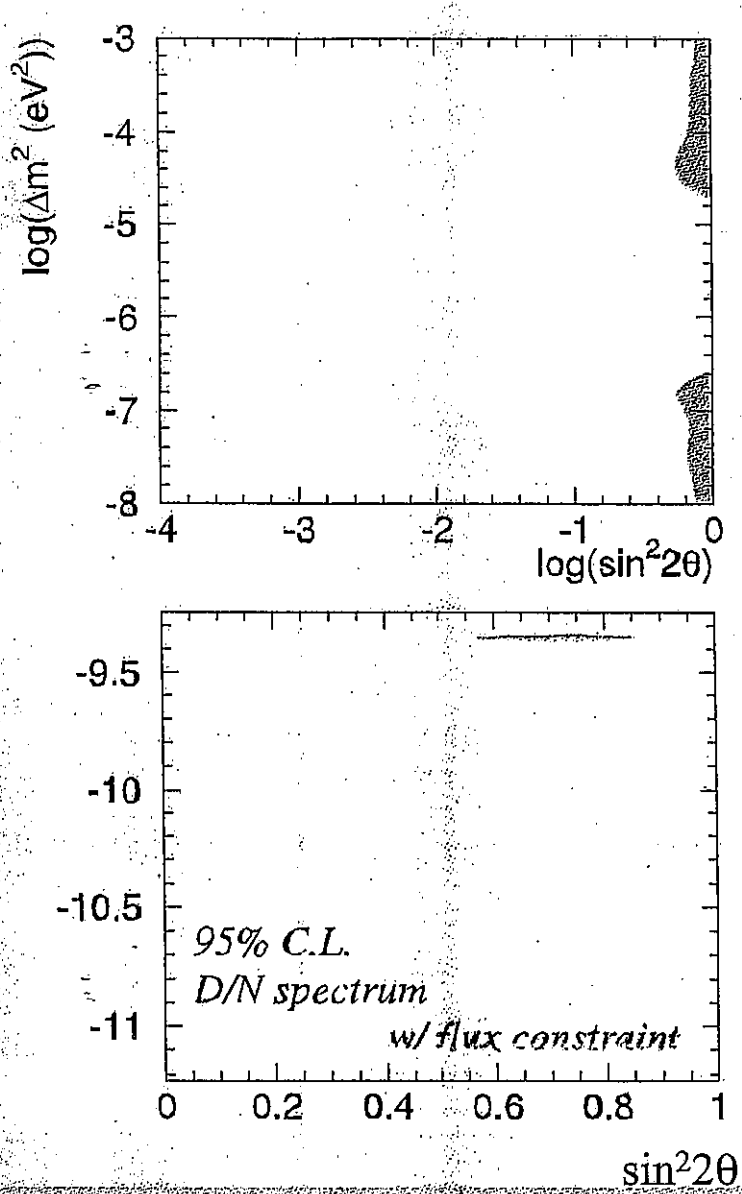
Flux independent ν oscillation analysis with day/night spectrum (active case)



SMA and Justso regions are disfavored by 95% C.L. D/N spectrum analysis

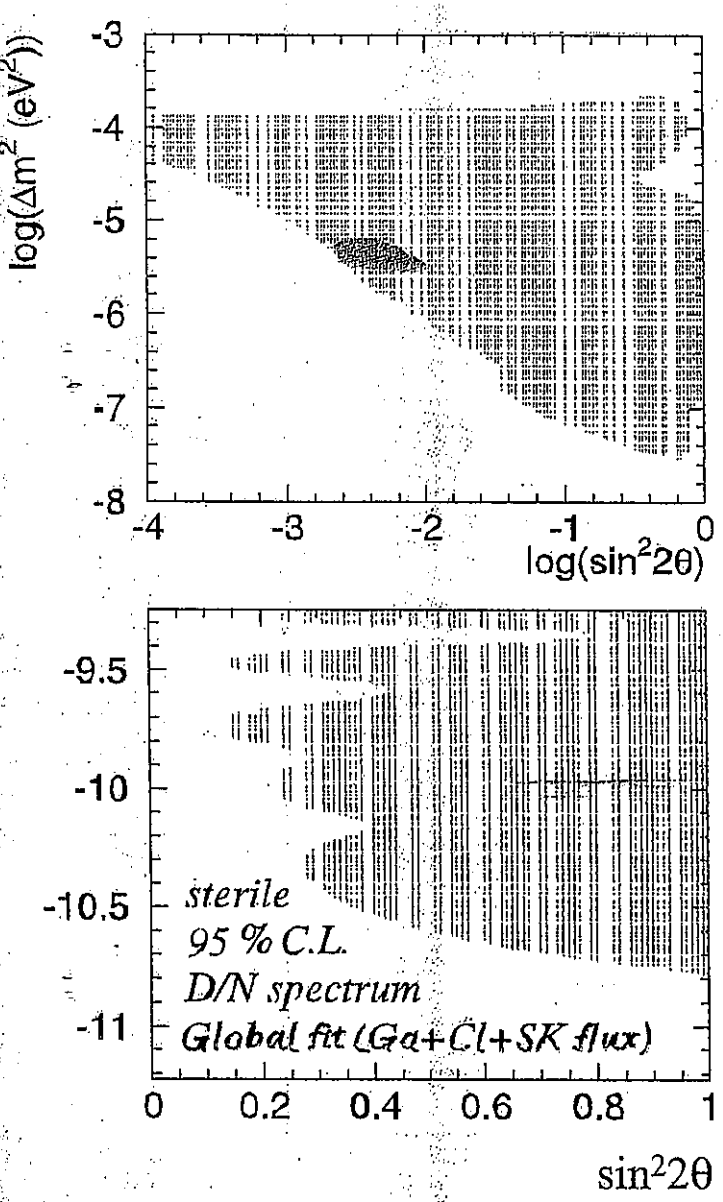
32

Flux constraint ν oscillation analysis with day/night spectrum (active case)



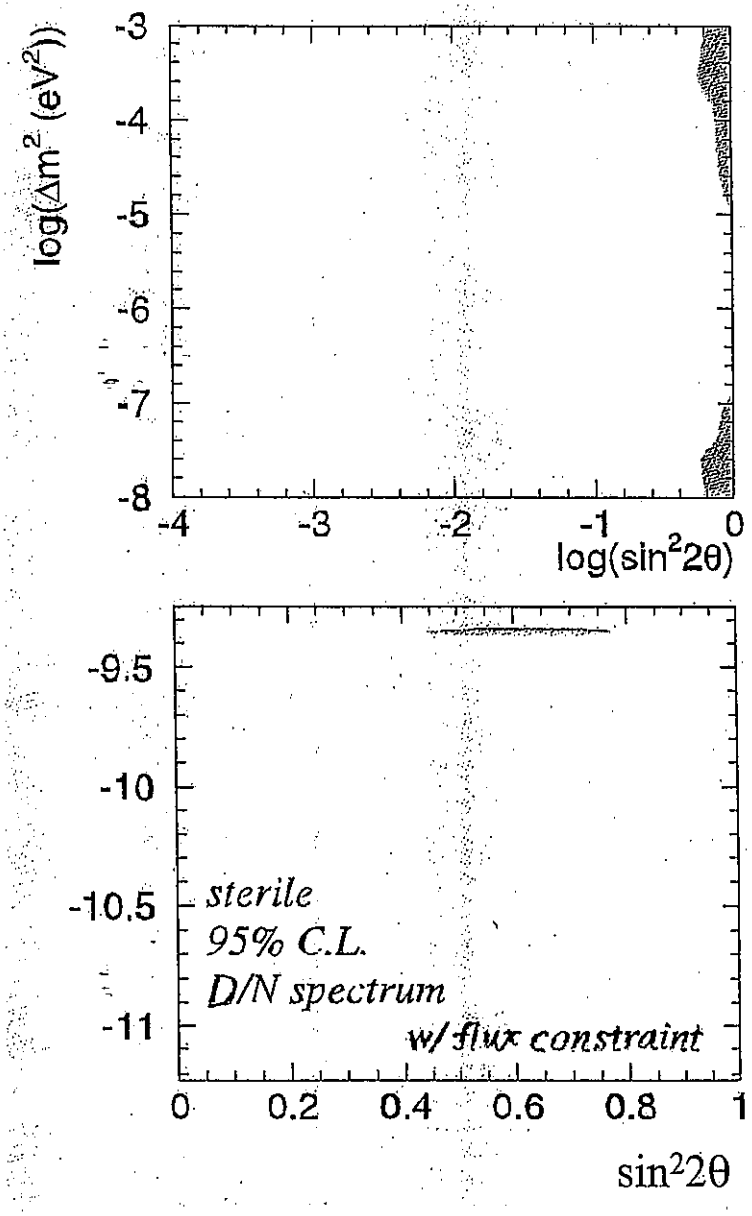
SK D/N spectrum with flux constraint favors LMA and LOW solution and small Justso region

Flux independent ν oscillation analysis with day/night spectrum (sterile case)

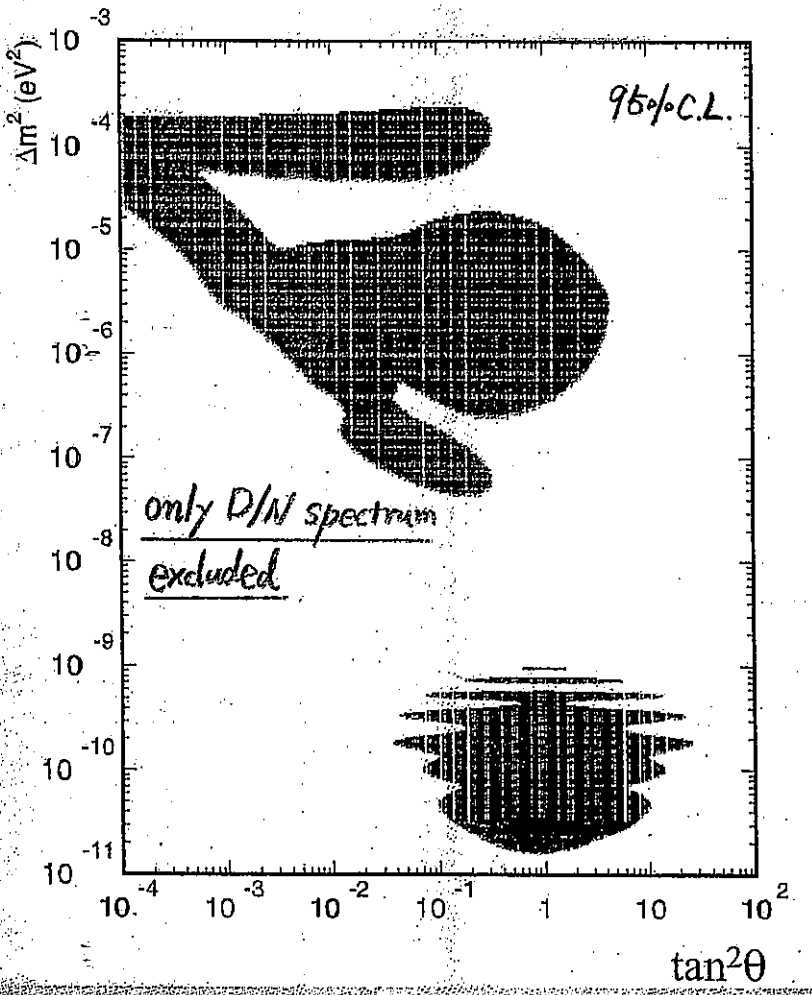


Sterile oscillation is likely disfavored @ 95%C.L.

Flux constraint ν oscillation analysis with day/night spectrum (sterile case)

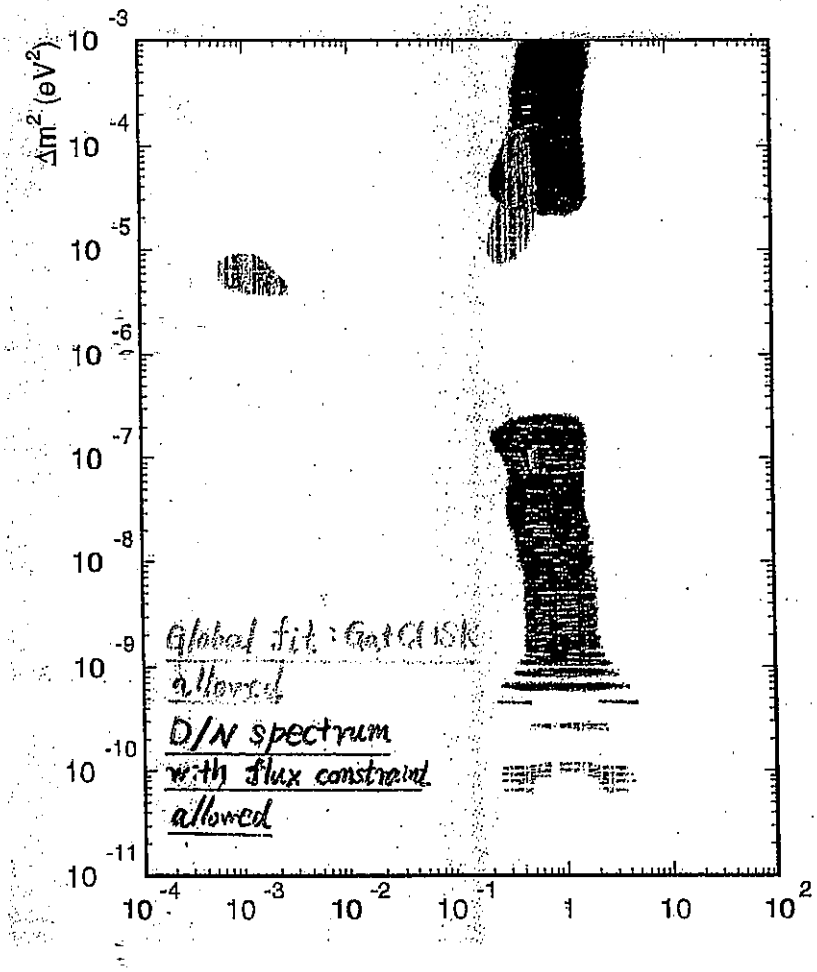


$\nu_e \rightarrow \nu_\mu$ oscillation 95% C.L.



D/N spectrum with flux constraint favors the LMA solution

$\nu_e \rightarrow \nu_\mu$ oscillation 95% C.L.



37

Future plans

- **Is small Day/Night difference really significant (1.3 σ) ?**

⇩

Need more statistics

- **Is the energy spectrum really flat ?**

⇩

more lower energy data may give us strong statement

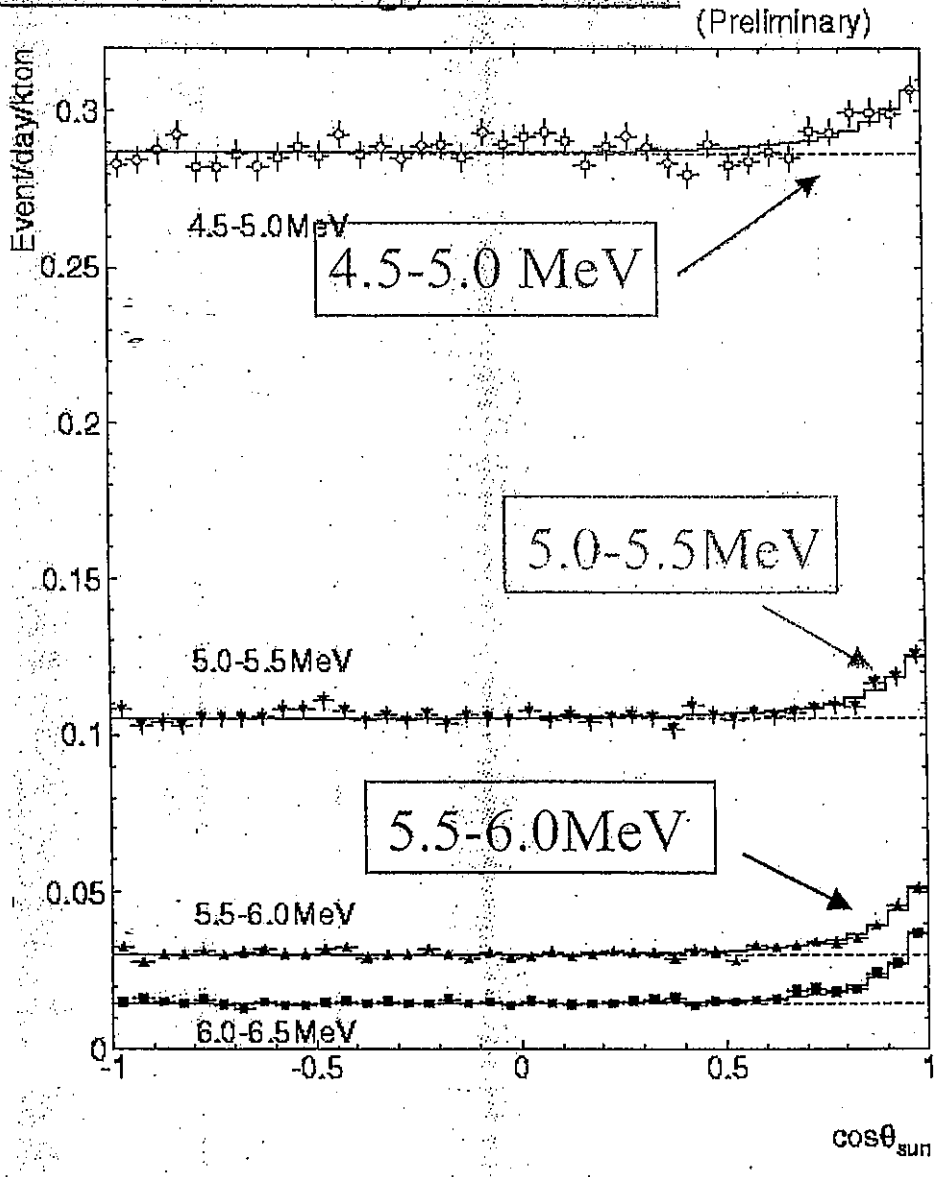
- **What is smoking gun ?**

⇩

- CC and NC from SNO
- Energy spectrum from pp, ^{7}Be neutrinos

Future plan (lower energy threshold)

plan 2 : lower energy threshold



We will start 4.5 MeV ν @ 100% efficiency in very near future!

Summary

- Observed ^{8}B flux :

$$\frac{\text{Data}}{\text{SSM(BP98)}} = 0.465 \pm 0.005\ ^{+0.015}_{-0.013}$$

- Day/Night flux variance :

$$\frac{\text{N-D}}{\text{(N+D)/2}} = 0.034 \pm 0.022\ ^{+0.013}_{-0.012}$$

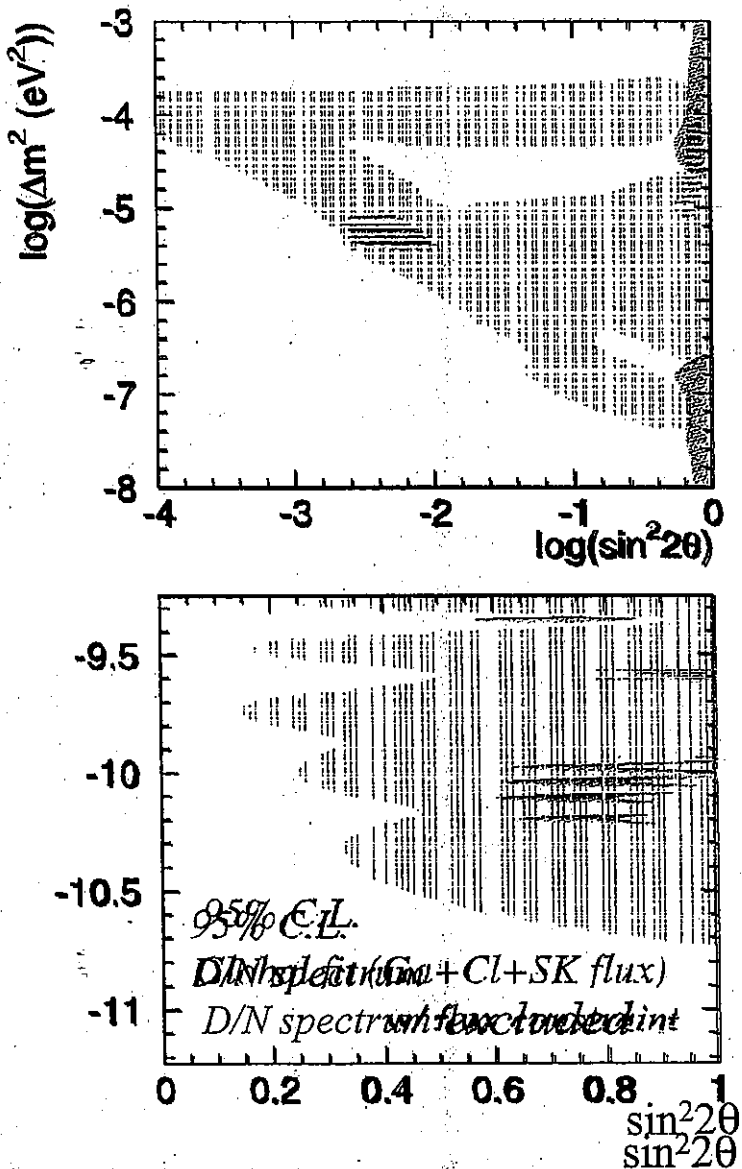
- Hep flux upper limits < 13.2 SSM
- Energy spectrum :

  χ^2 for flat 13.7/17d.o.f. (69%C.L.)
- For active neutrinos

  SMA and JustSo are disfavored @ 95% C.L.by D/N spectrum without flux constraint
- For sterile neutrinos

  $\nu e \rightarrow \nu s$ is disfavored @ 95% C.L. by D/N spectrum without flux constraint
- D/N spectrum with flux constraint favors LMA (and small LOW) @ 95% C.L.

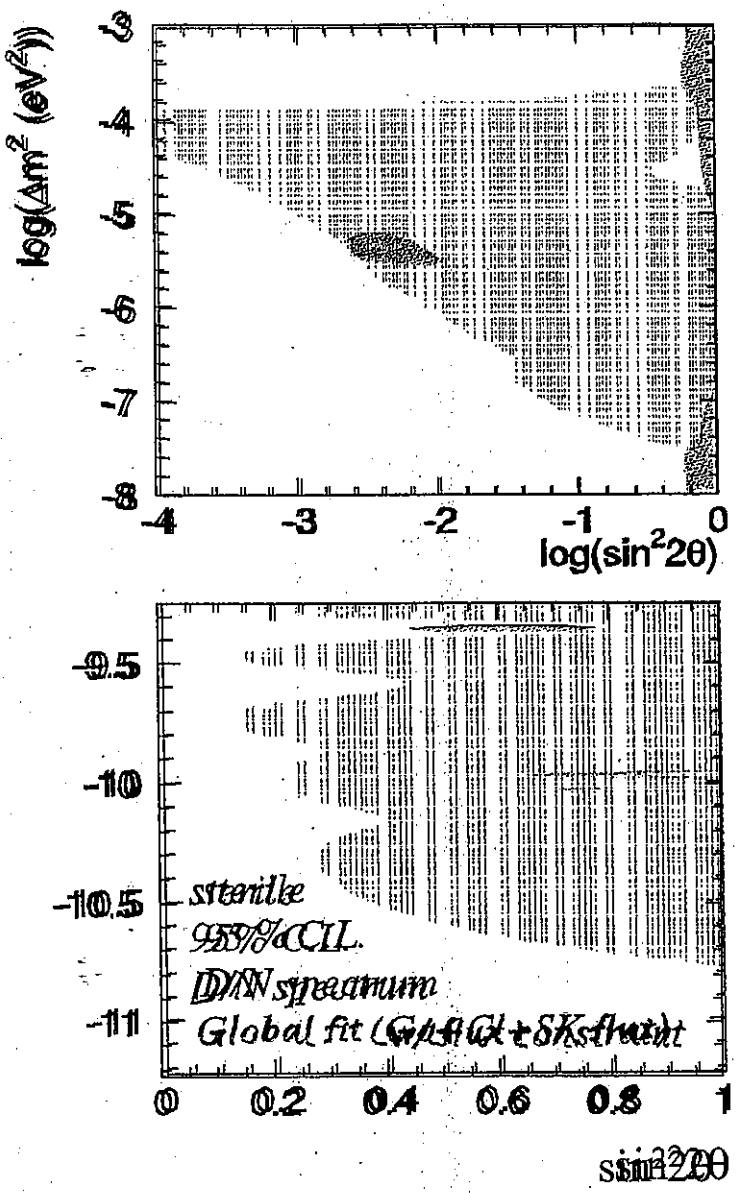
Flux independent oscillation analysis with day/night spectra (active case)



SK D/N spectrum with flux constraint favors LMA and LOW solution and small Just so region

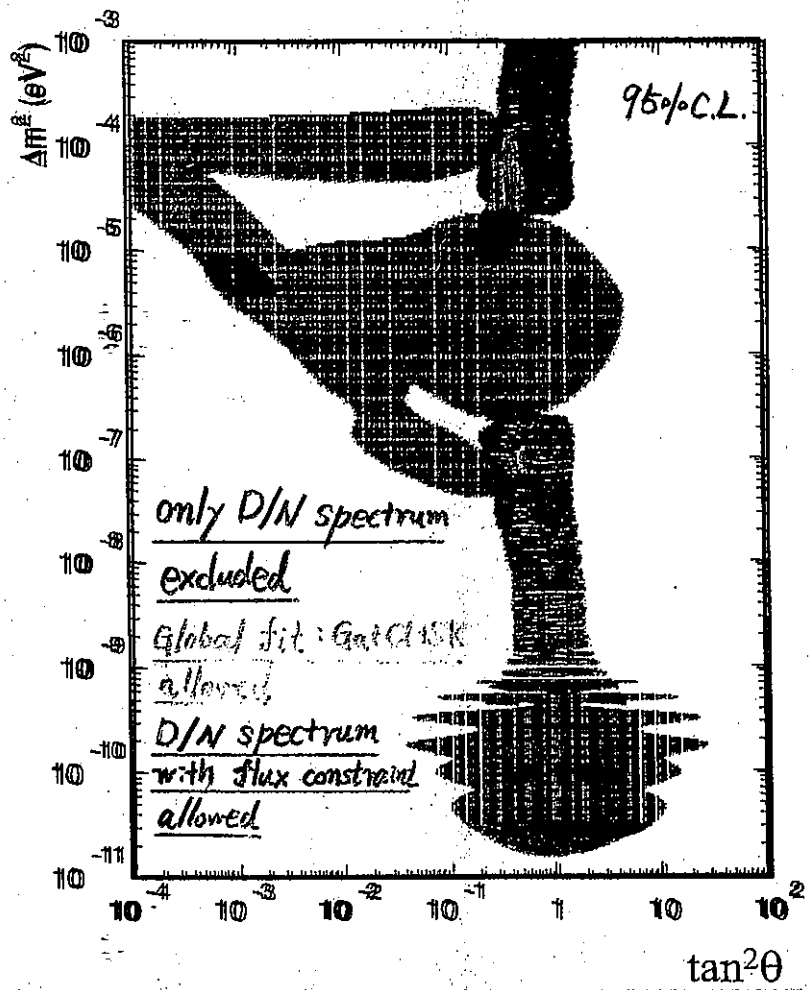
SMA and Just so regions are disfavored by 95% C.L. D/N spectrum analysis

Flux constraint to oscillation analysis with data/right shape spectrum (sterile case)



Sterile oscillation is likely disfavored @ 95%C.L.

$\nu_e \rightarrow \nu_\mu$ oscillation 95% C.L.



D/N spectrum with flux constraint favors the LMA solution