Solar neutrino results from Super-Kamiokande

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(for the Super-Kamiokande Collaboration)

1. Introduction
2. What's new
3. Results
4. Oscillation analysis
   - Active
   - Sterile
5. Conclusions

Introduction

Reactions:

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

Sensitive to both CC and NC interactions

Directionality, spectrum and real time

Purpose:

Precise flux measurement

Spectrum

→ SMA

→ Just-So

Time variations

Day/Night → LMA

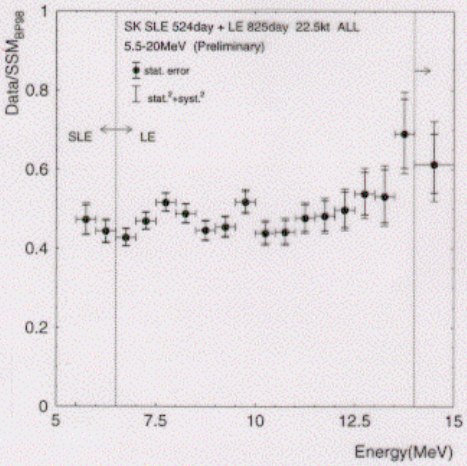
seasonal → Just-So

annual → mag. moment

High statistics:

Last Summer (825days)

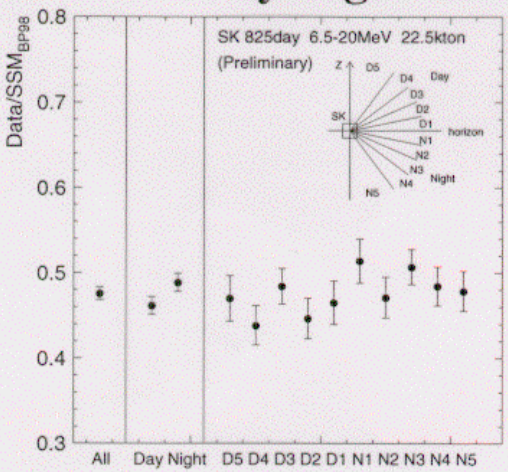
Spectrum ratio



Slight increase towards the end of the spectrum?

→ **oscillation effect?**
→ **Hep neutrino contribution?**

Day/Night flux



Day/Night flux difference? (1.8 σ)

→ **LMA/LOW?**

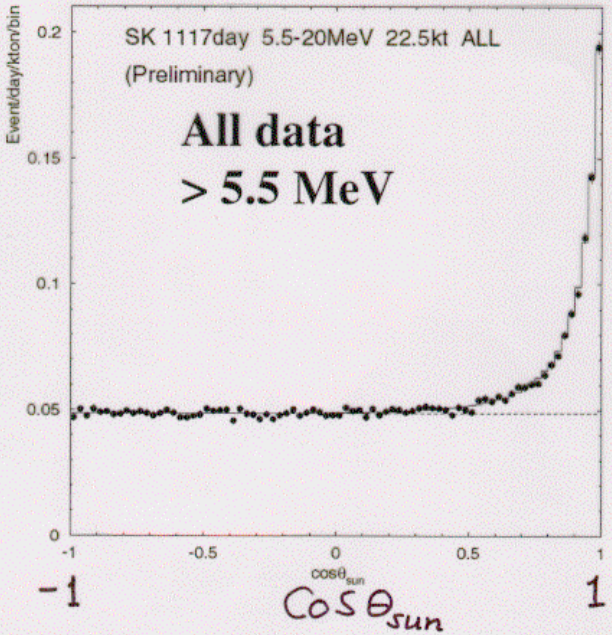
What's New

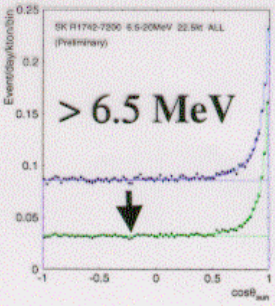
1) 824 days → 1117 day
   35% data increase
2) Unified analysis for the entire energy range and the improvement of the analysis
   → more BG rejection
   ~60% reduction above 6.5 MeV
   → reprocessed all the data
3) MC re-tuned (mostly water parameters: scattering, absorption,.....)
   →0.27% energy scale shift
   (within the estimated sys. error of 0.64%)
4) Threshold down to 5 MeV
   → more power for the energy spectrum in future (not used for oscillation analysis)
5) Re-evaluation of the systematic errors

Analysis is very robust!!

Details → to be published

Flux Measurement (1117 days)





5.5 MeV – 20 MeV (1117days)
(>6.5 MeV for first 361days)

Number of solar netrinos:

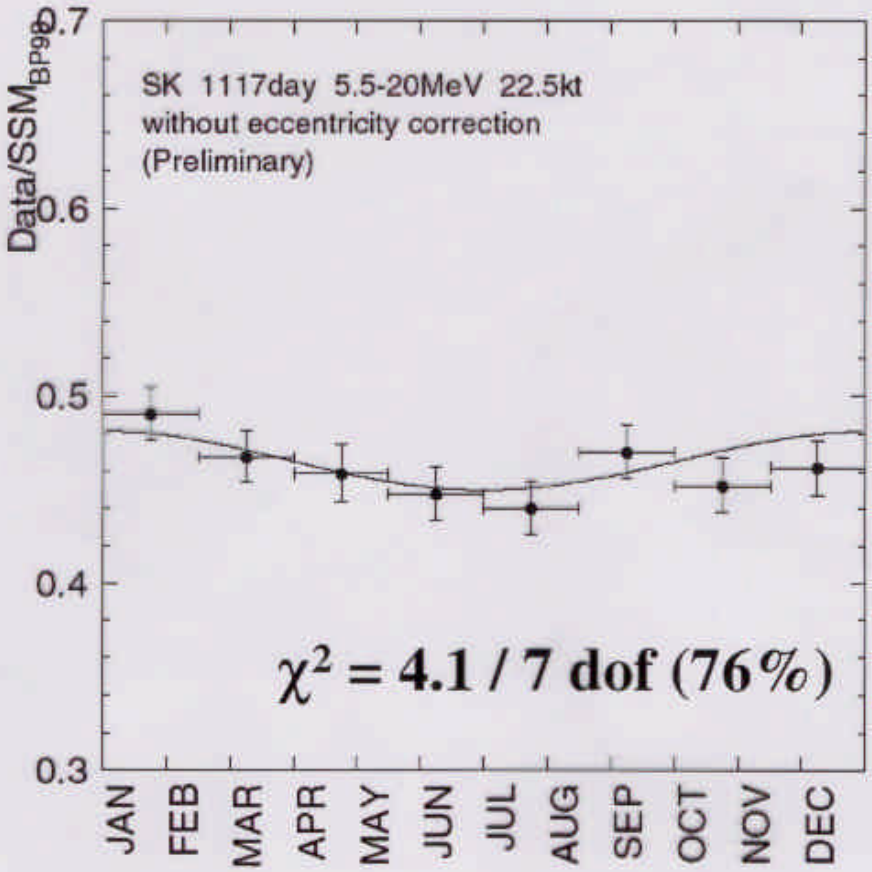
$$15009 \pm^{169}_{157}\,(\text{stat.}) \pm^{495}_{435}\ \text{events}$$

(13 events/day)

$$\text{flux} = 2.40 \pm 0.03(\text{stat.}) \pm^{0.08}_{0.07}(\text{syst.})\ \text{x}10^6/\text{cm}^2/\text{s}$$

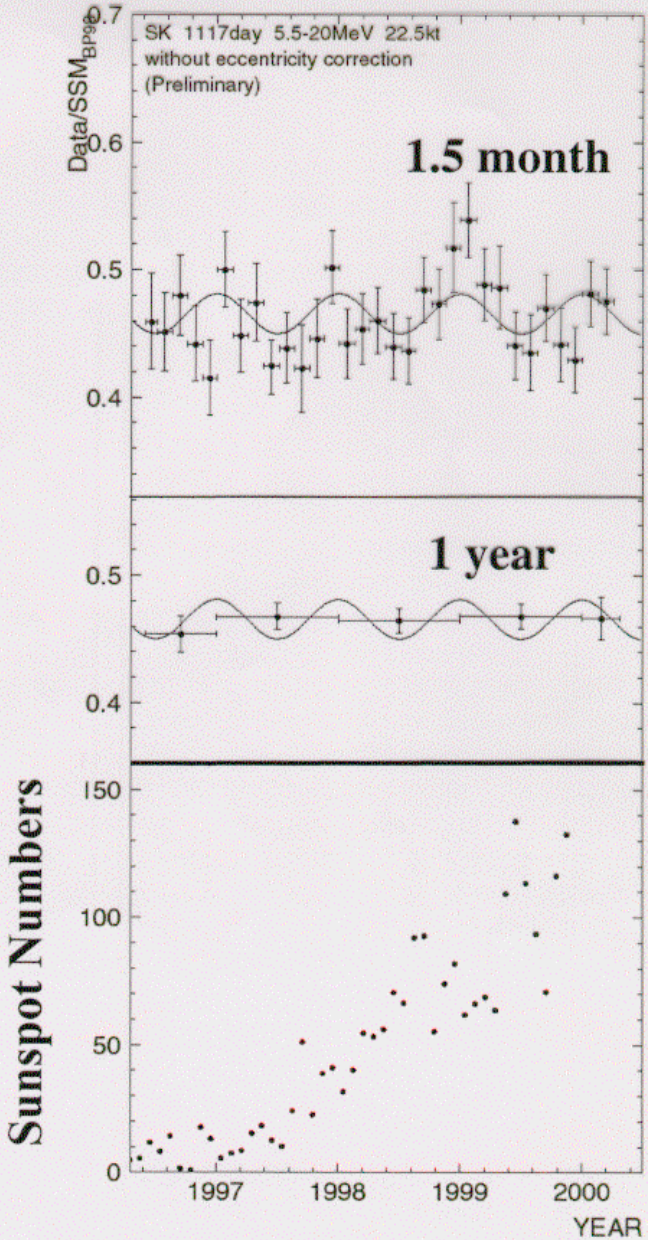
$$\frac{\text{Data}}{\text{SSM}_{\text{BP98}}} = 0.465 \pm 0.005\ (\text{stat.})\ ^{+0.015}_{-0.013}\ (\text{syst.})$$

Seasonal flux



Very good agreement with the expected seasonal variation due to the earth's eccentricity

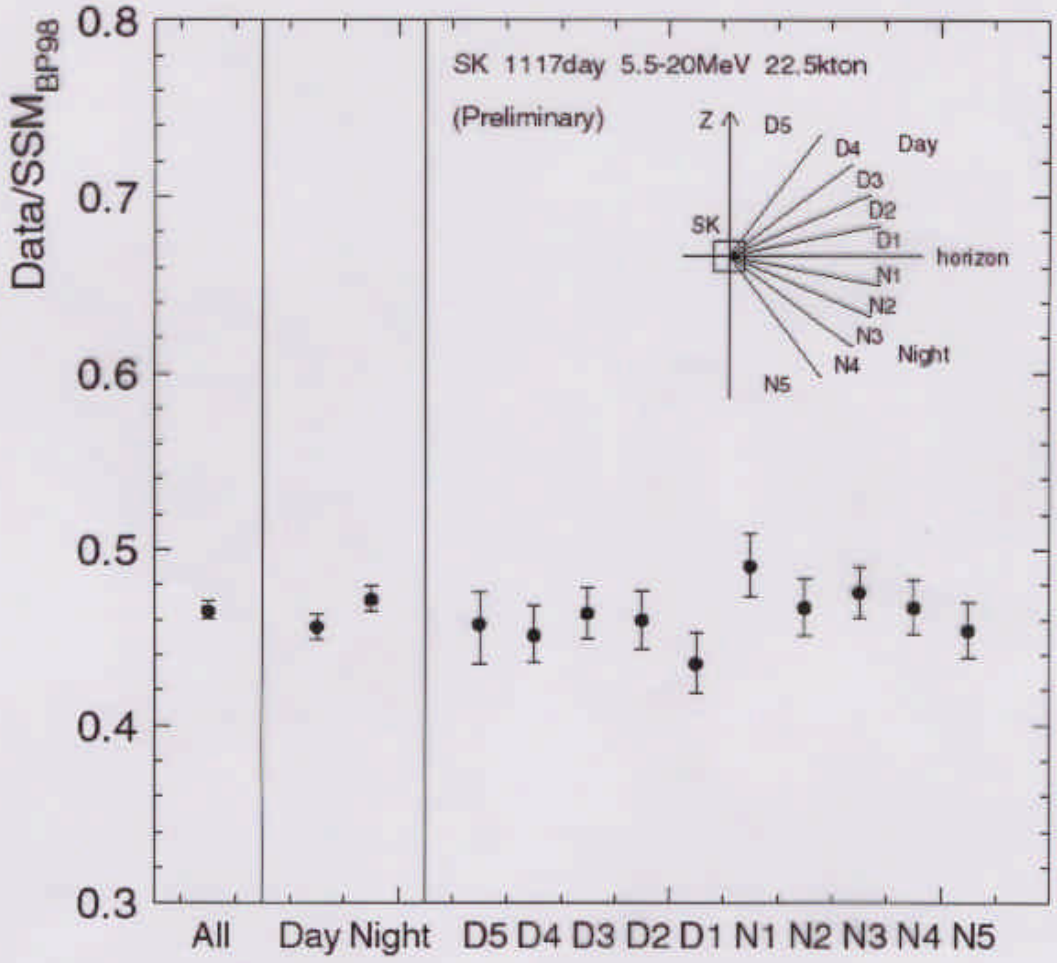
Long term



No long term variations.

No correlation with the variation of the SSN.

Day/Night Flux difference



$$\text{Day} = 2.35 \pm 0.04(\text{stat.}) \pm^{0.08}_{0.07}(\text{syst.})\ \text{x}10^6/\text{cm}^2/\text{s}$$

$$\text{Night} = 2.43 \pm 0.04(\text{stat.}) \pm^{0.08}_{0.07}(\text{syst.})\ \text{x}10^6/\text{cm}^2/\text{s}$$

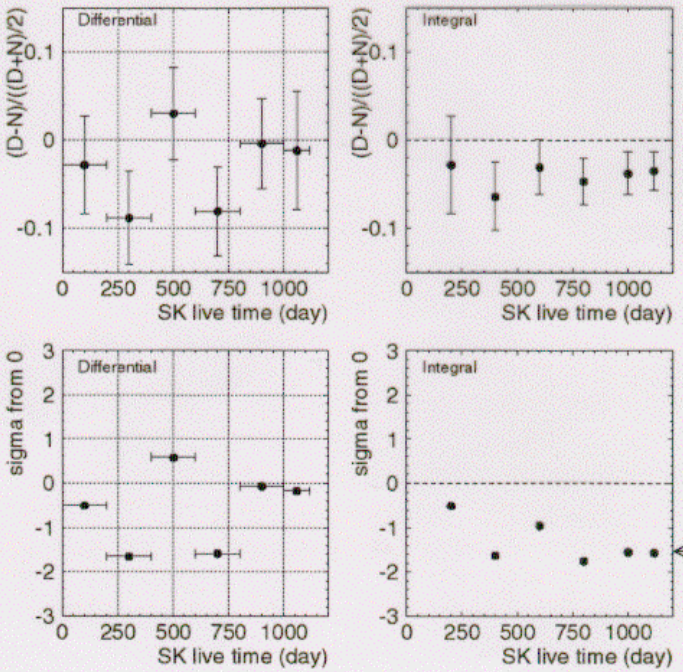
$$\frac{\text{D-N}}{\text{(D+N)/2}} = -0.034 \pm 0.022(\text{stat.})^{+0.013}_{-0.012}\ (\text{syst.})$$

1.3 σ level → not strong yet

Significance (Day/night)

$$\frac{(D-N)}{(D+N)/2}$$

σ



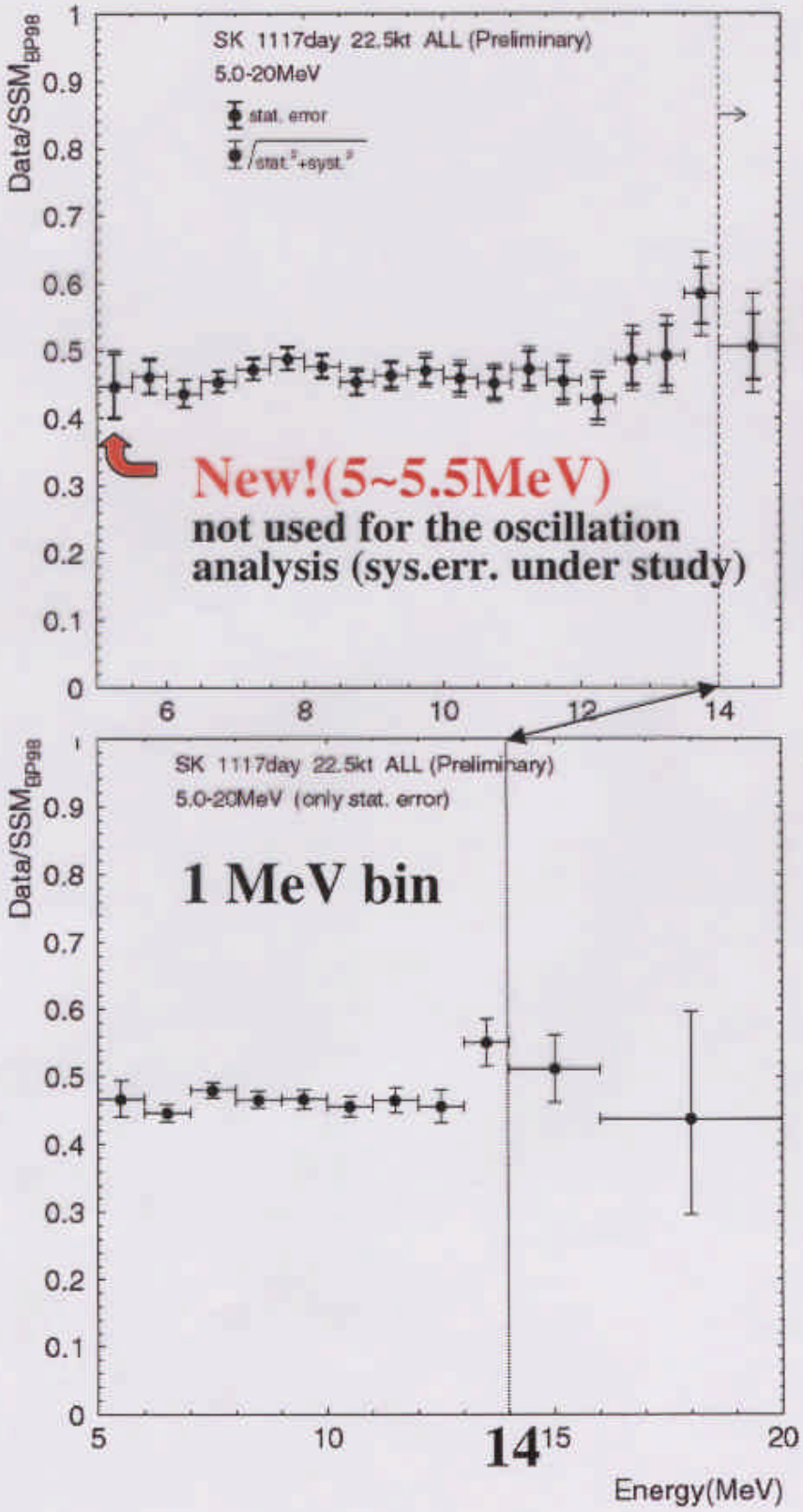
1.6σ

Errors: only statistical

1.3σ inc. sys. err.

may be following sqrt(t)

Spectrum Ratio to the SSM prediction



χ^2 for flat :
13.7 / 17dof
(69% C.L.)
incl. sys. err.

Consistent to be flat.

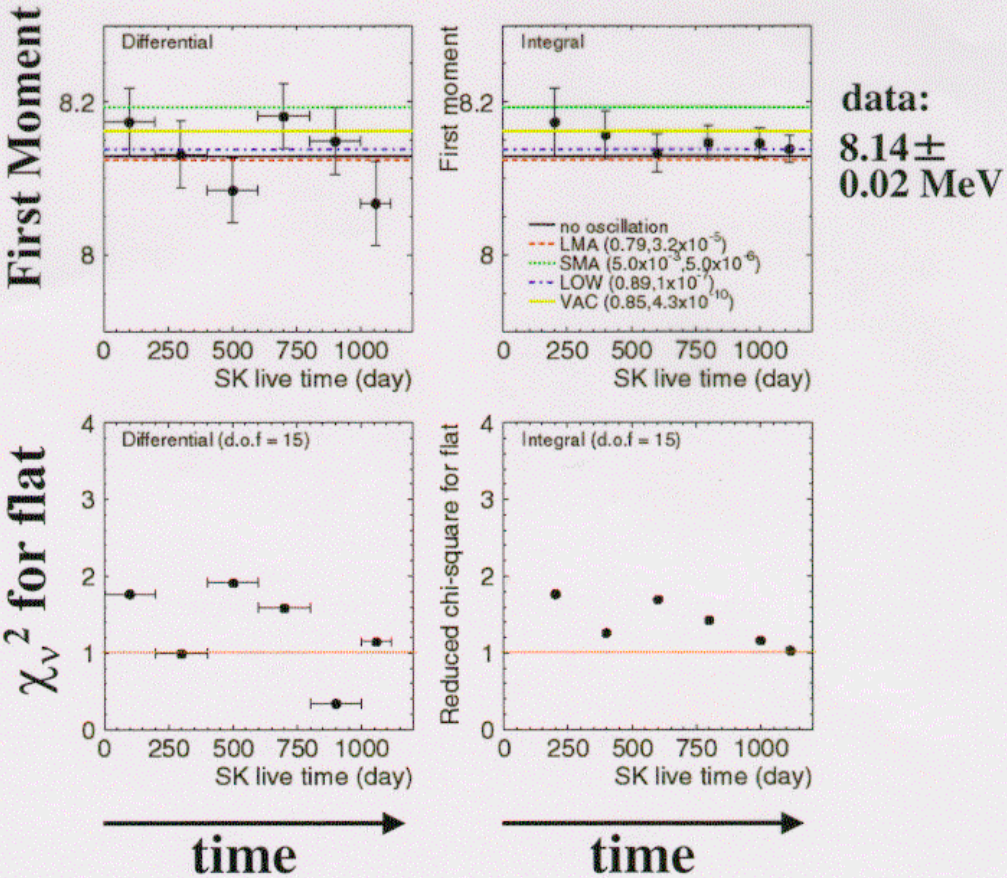
Significance (Spectrum)

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

cf. J.N.Bahcall and P.I.Krastev, PRC 56(1997)p2839

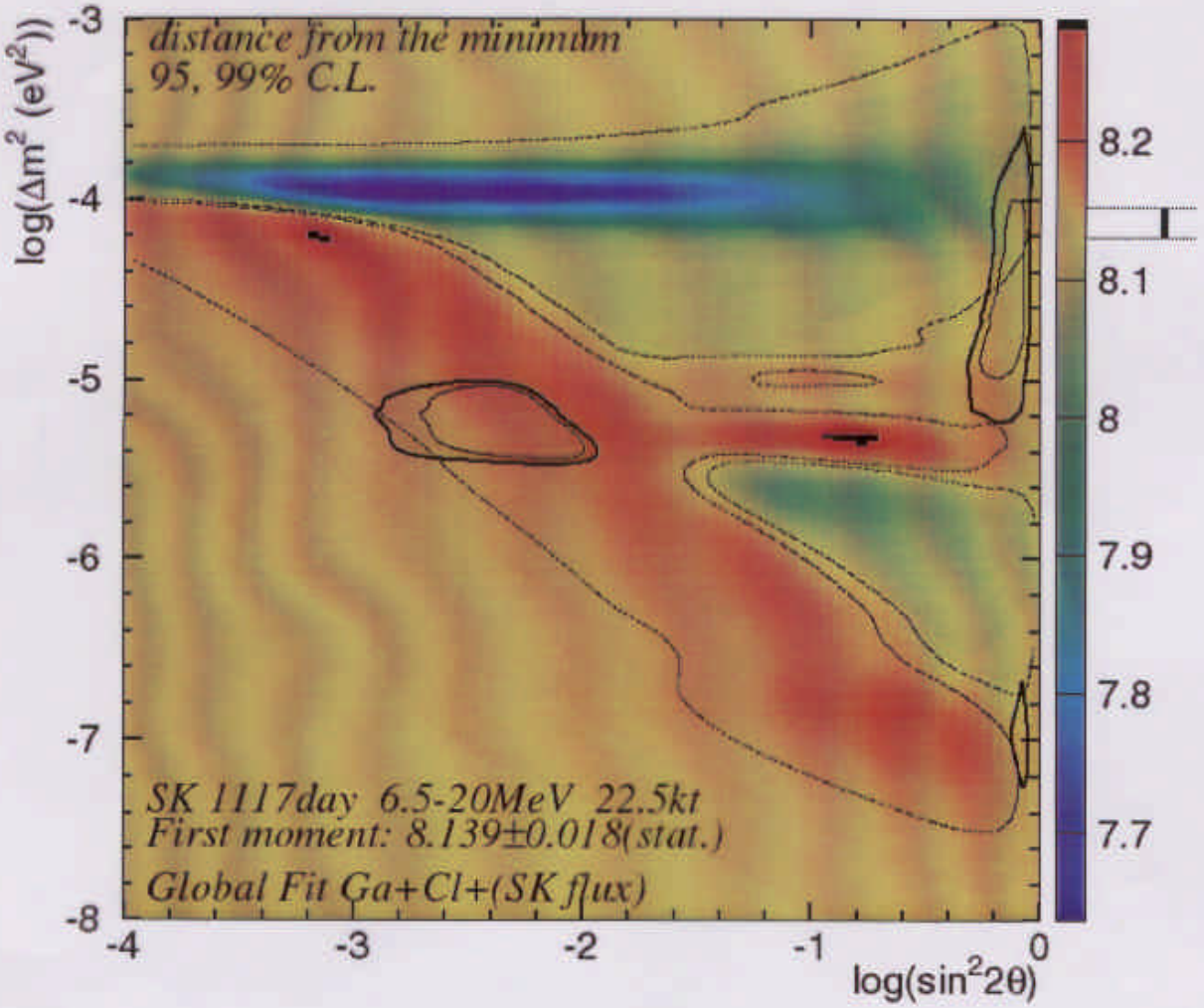
> 6.5 MeV data (stat. error only)

Differential **Integral**



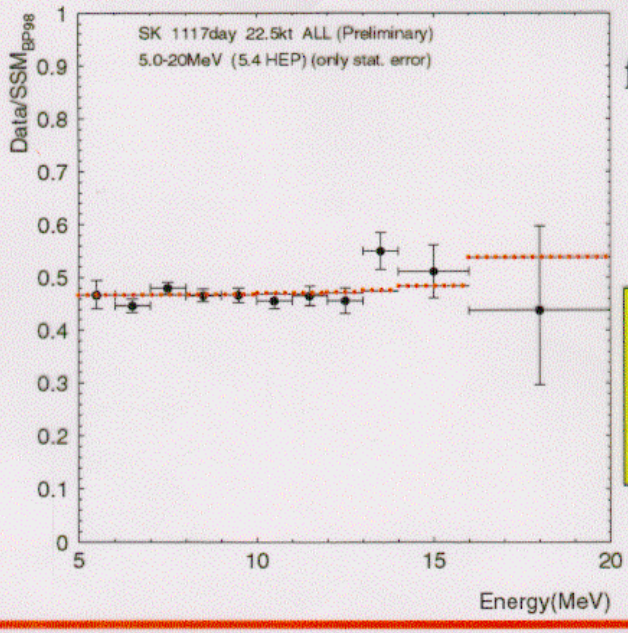
First moment

(Guide line of the sensitivity of spectrum distortion)



First moment ±1σ (stat.)

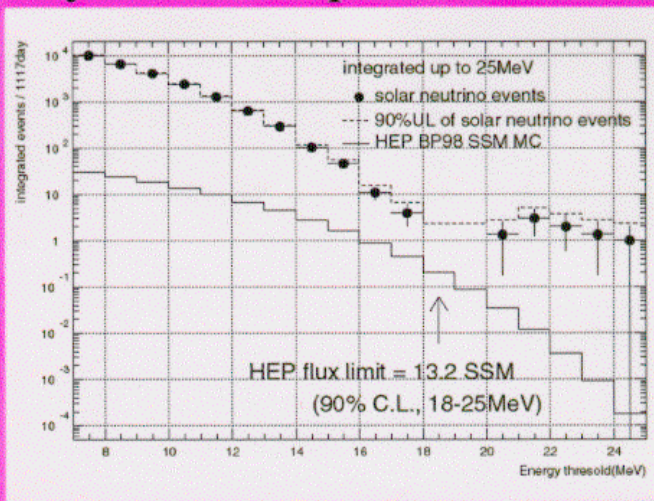
Hep flux



fit: ^{8}B and Hep flux simultaneously

Hep = 5.4±4.5 x SSM Hep

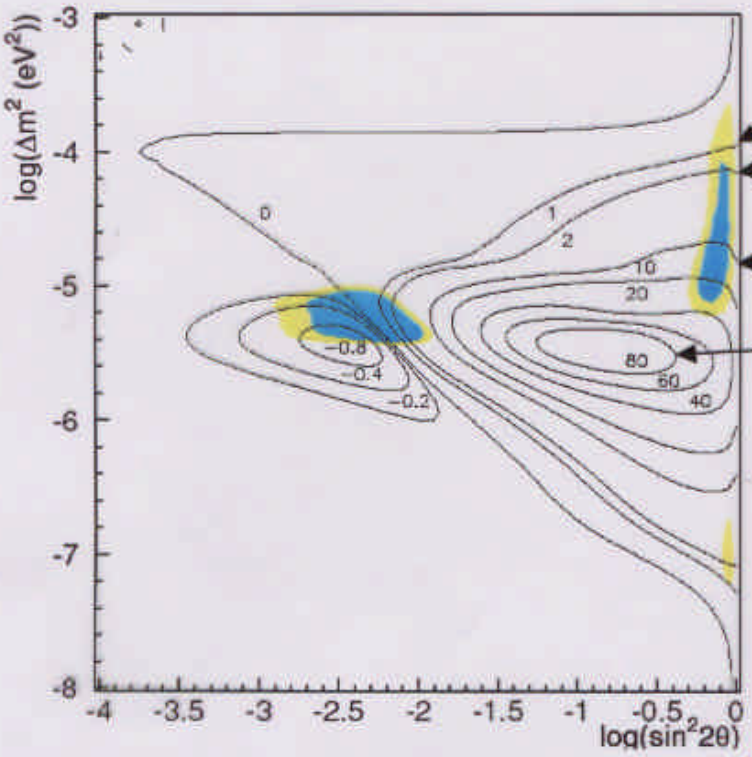
Flux beyond ^{8}B end point (>18MeV)



Hep < 13.2 x SSM Hep (quote this number)

Note: effect on the spectrum is very small now

Expected



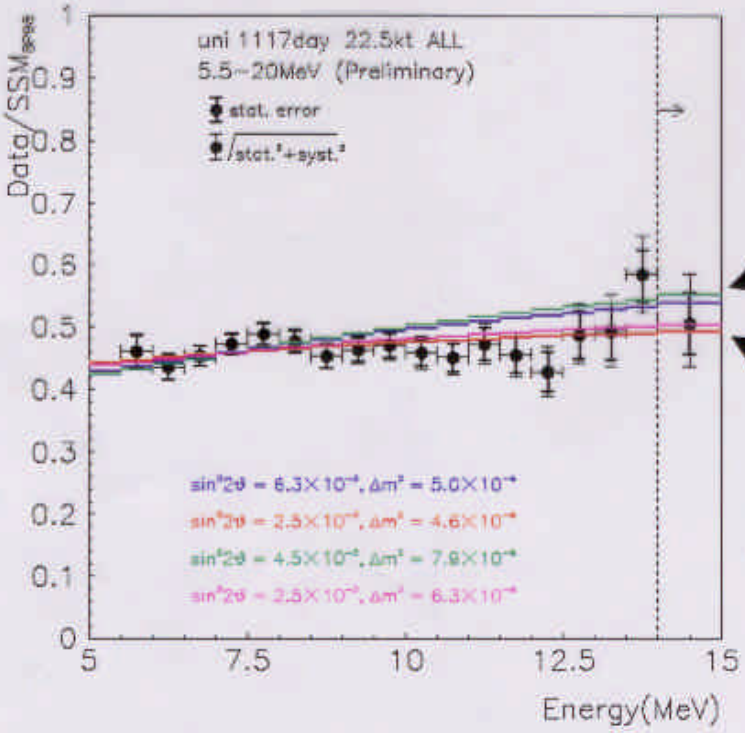
1%

2%

10%

80%

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



$\sin^2 2\theta = (4.5\text{-}6.3)\times10^{-3}$

$\sin^2 2\theta = 2.5\times10^{-3}$

χ^2

$$\chi^2 = \sum_{i=1}^{36} \left(\frac{R_i \times \alpha \times f_i(\varepsilon) - R_i^{exp}}{\sigma_i} \right)^2 + \left(\frac{\varepsilon}{\sigma_{cor}} \right)^2$$

$$\chi^2 = \sum_{i=1}^{36} \left\{ \left(\frac{R_i \times \alpha \times f_i(\varepsilon) - R_i^{exp}}{\sigma_i} \right)^2 + \left(\frac{1-\alpha}{\sigma_{flux}} \right)^2 \right\} + \left(\frac{\varepsilon}{\sigma_{cor}} \right)^2$$

R_i : expected rate of each bin assuming oscillation

R_i^{exp} : rate of each bin observed in SK

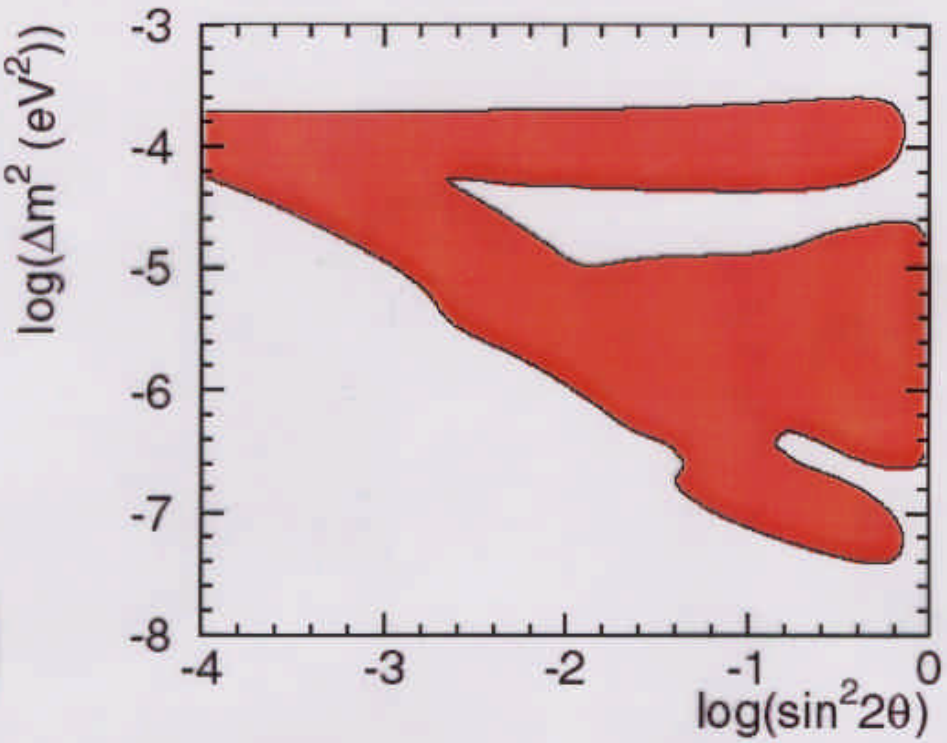
$\sigma_i^2 = \sigma_i^2(\text{stat}) + \sigma_i^2(\text{uncorrelated})$

α : flux normalization factor (free)

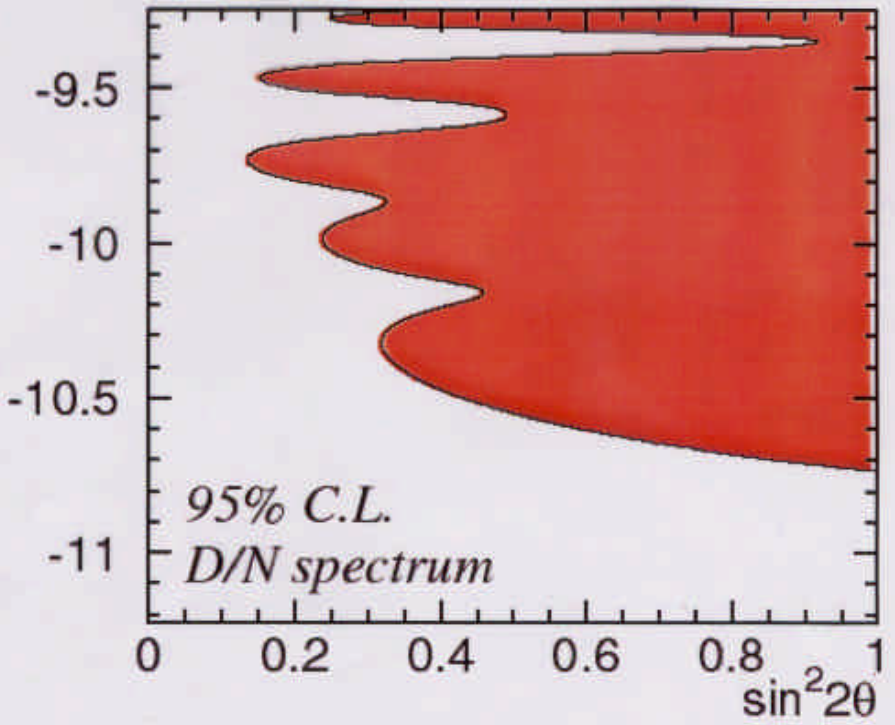
ε : shift factor of the correlated error

$f_i(\varepsilon)$: response function

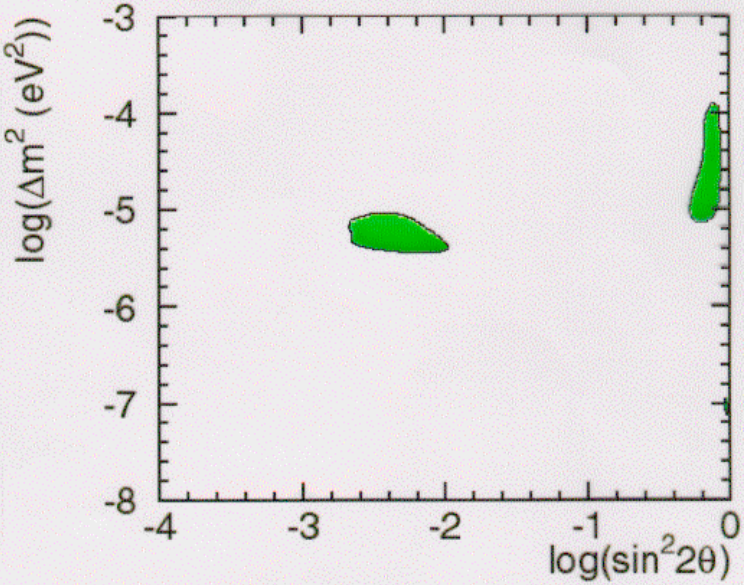
Super-Kamiokande
Day/Night+ Spectrum (Active neutrinos)



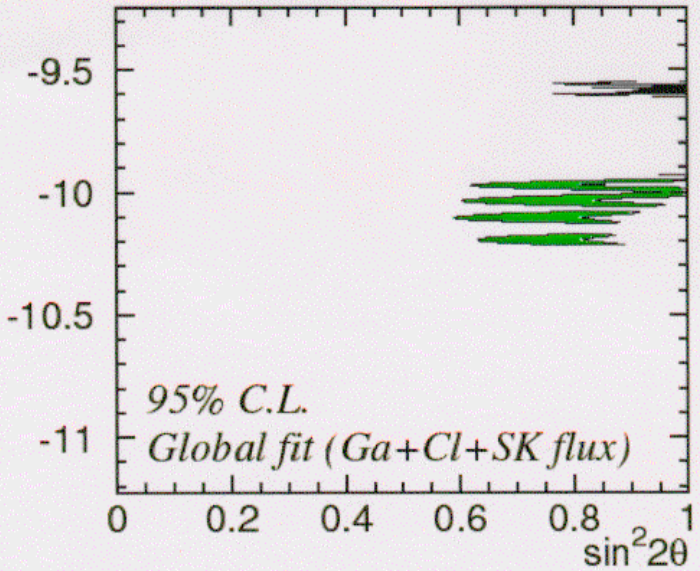
Excluded @95% CL



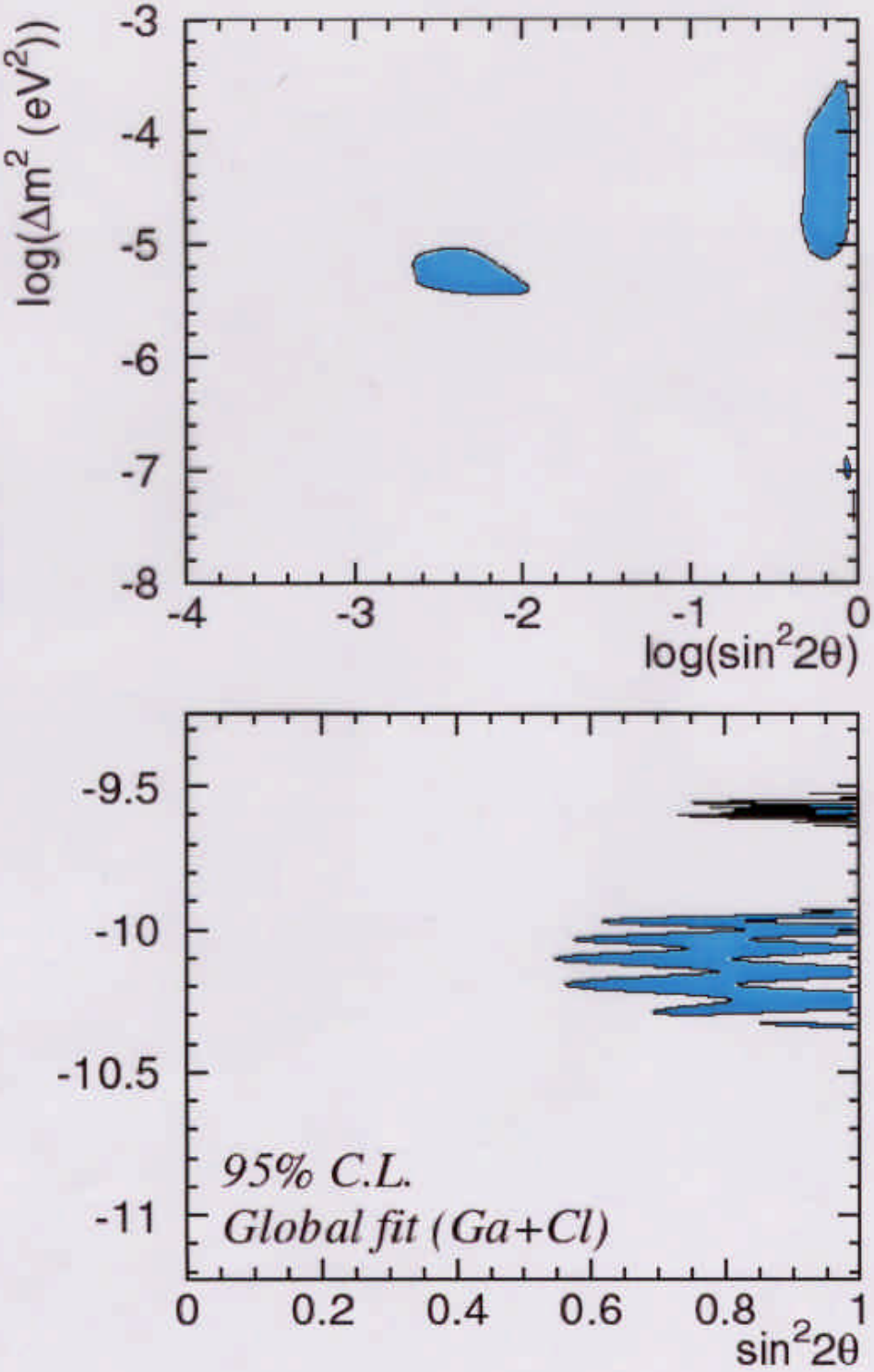
Flux-global (Cl+Ga+SKflux)



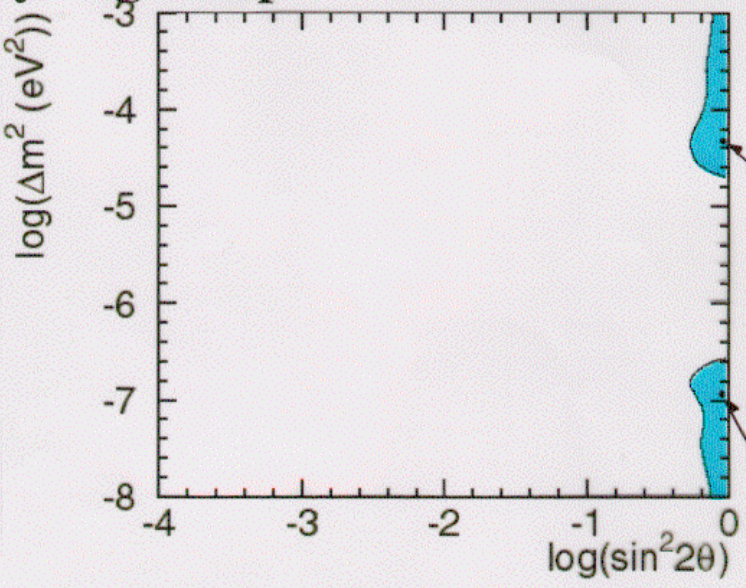
Allowed @95%CL



flux global (Ga+Cl)



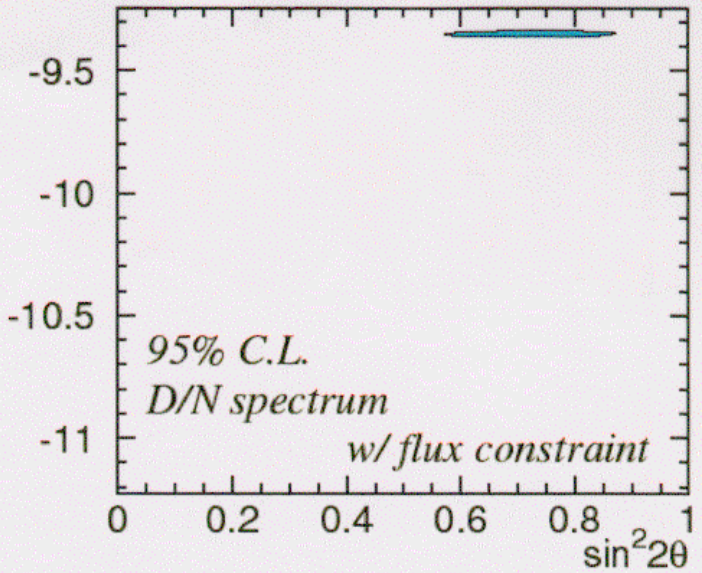
Super-Kamiokande
Day/Night+Spectrum+flux constraint



$\chi^2 = 31.6/34$ (58.6 %)

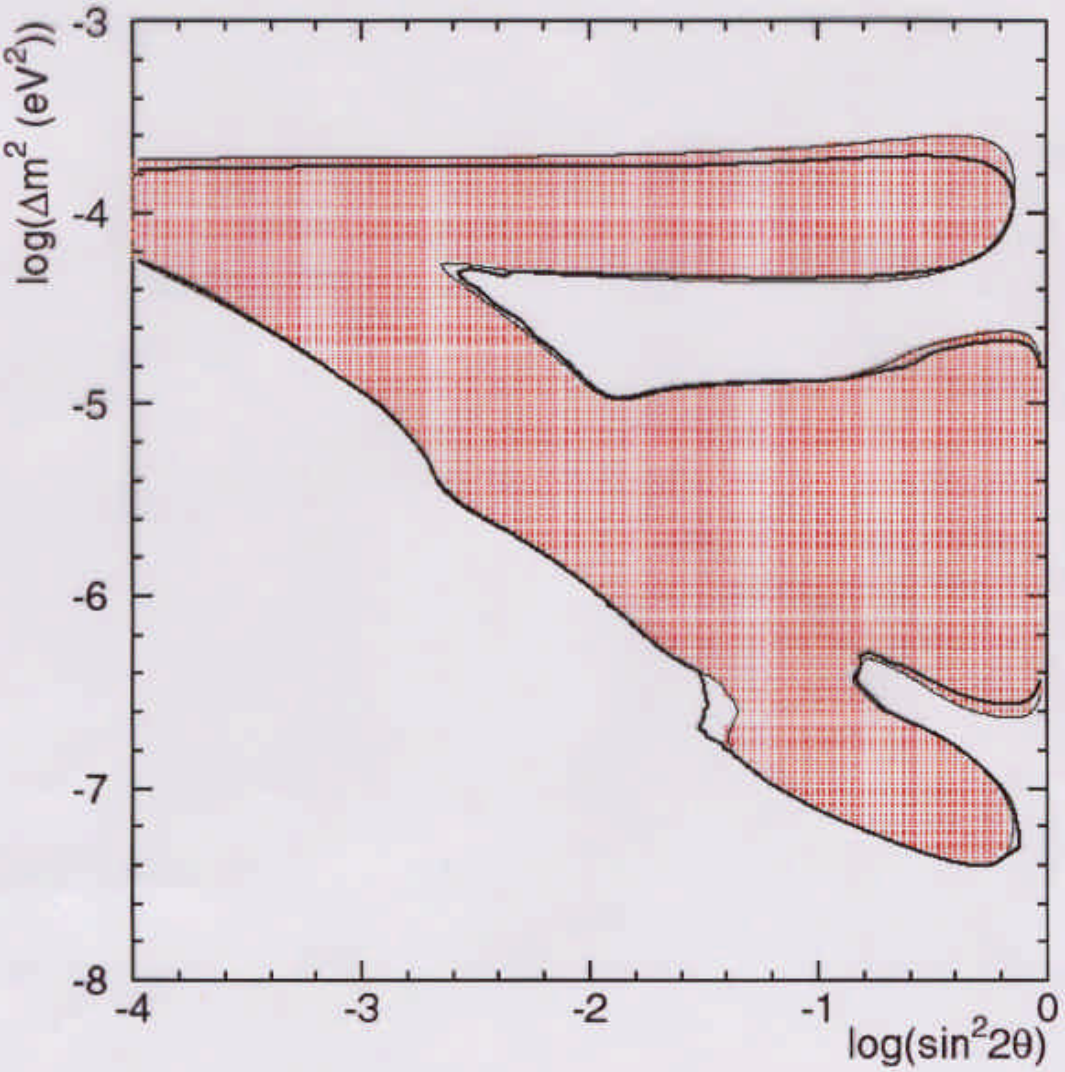
Allowed @95%CL

$\chi^2_{min} = 31.5/34$ (59.3 % C.L.)



Comments on Hep

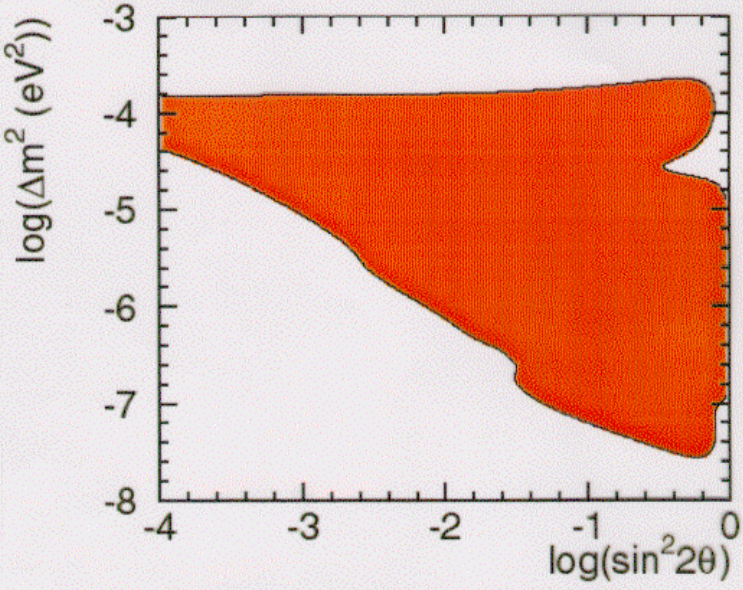
No significant effect on the oscillation analysis



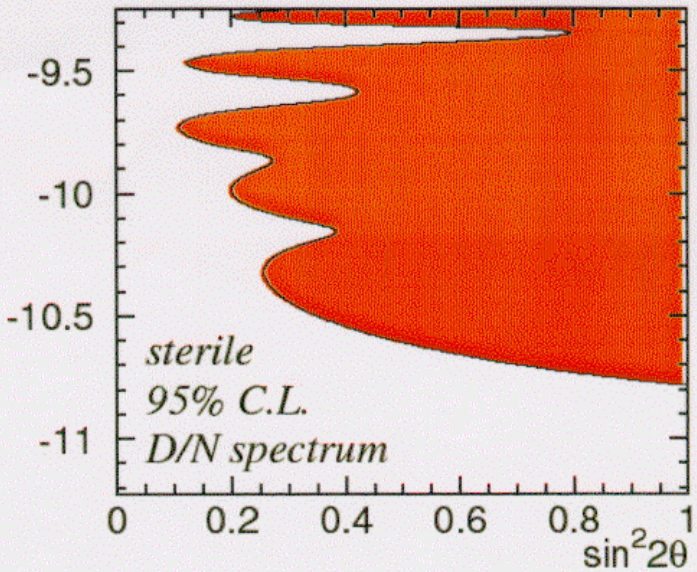
Hep-free

SSM-Hep

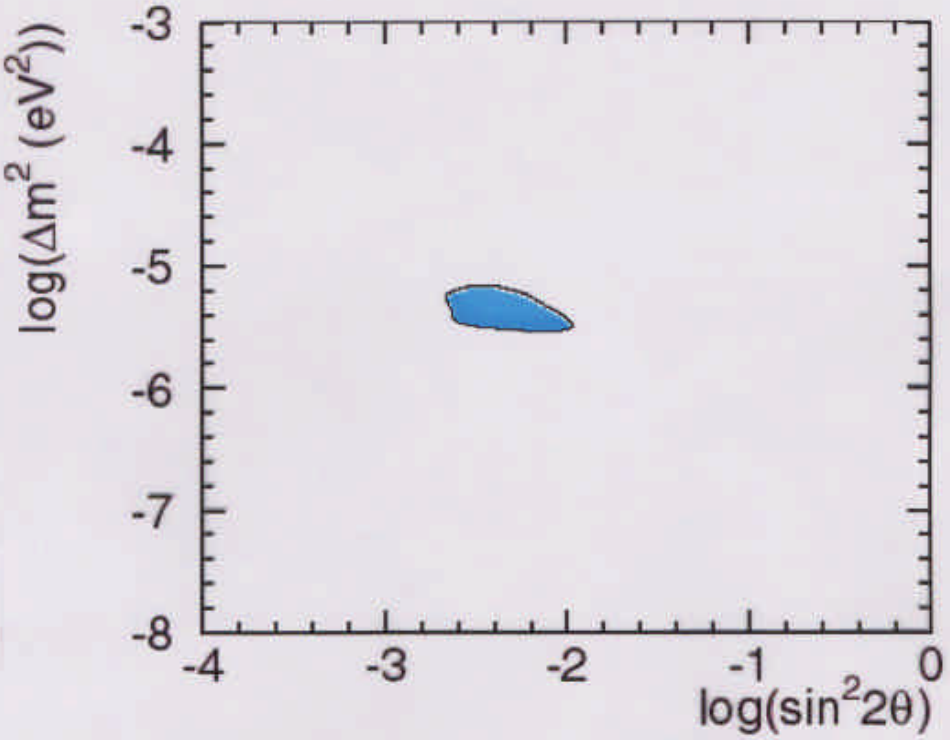
Super-Kamiokande
Day/Night Spectrum (Sterile)



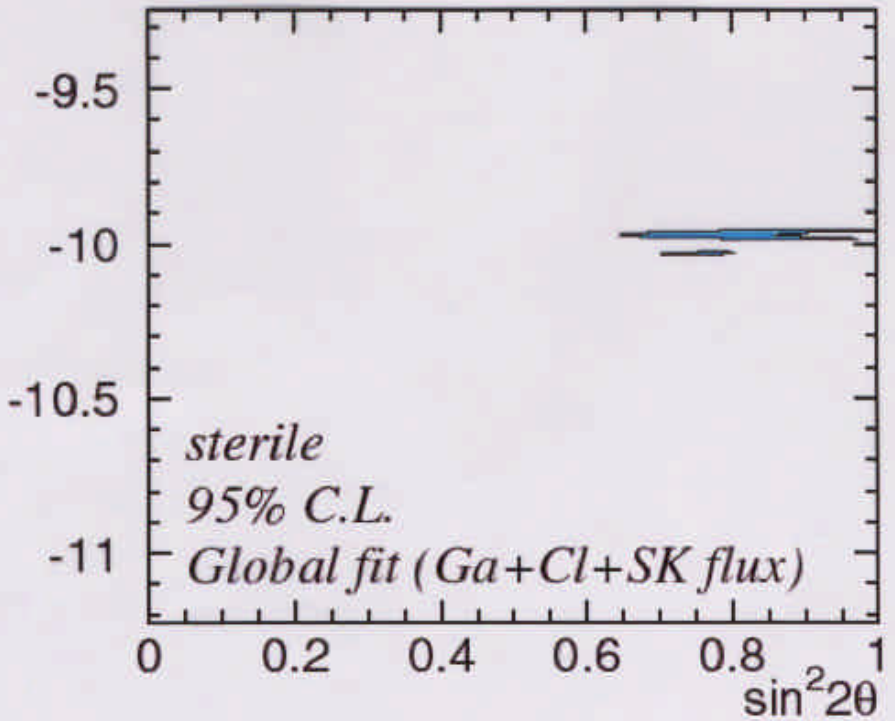
Excluded
@95% CL



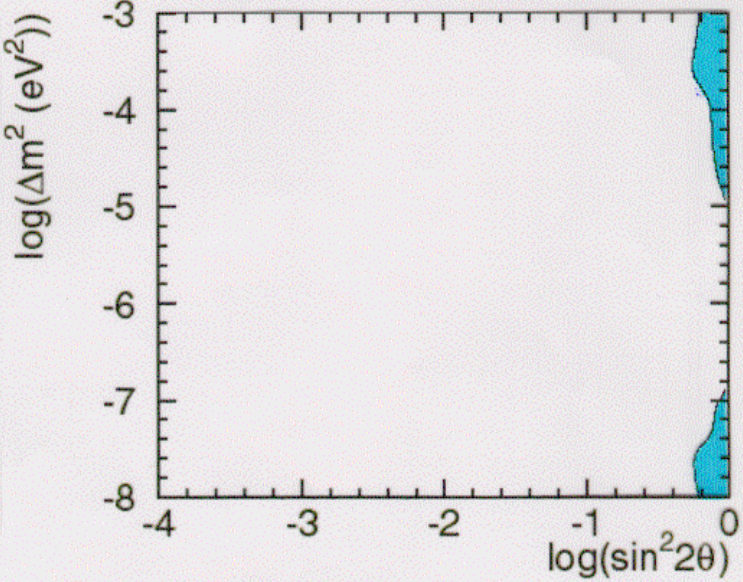
Flux-global (Cl+Ga+SKflux) (Sterile)



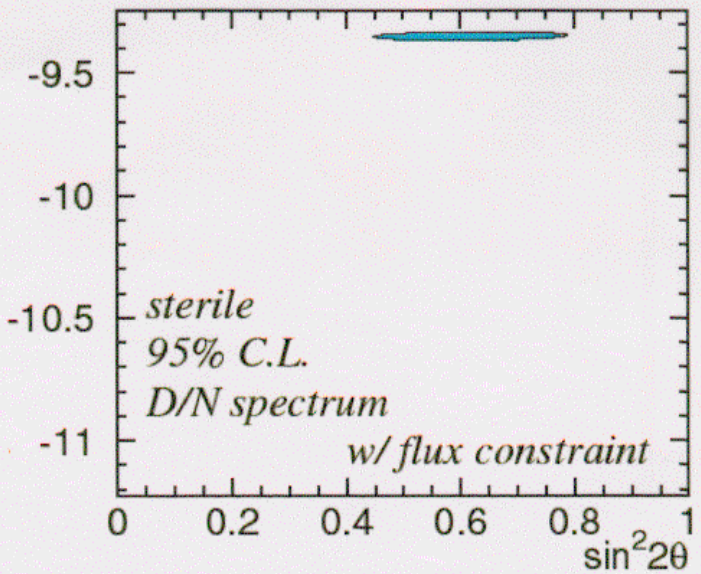
Allowed
@95%CL



Super-Kamiokande
Day/Night Spectrum+flux constraint (Sterile)

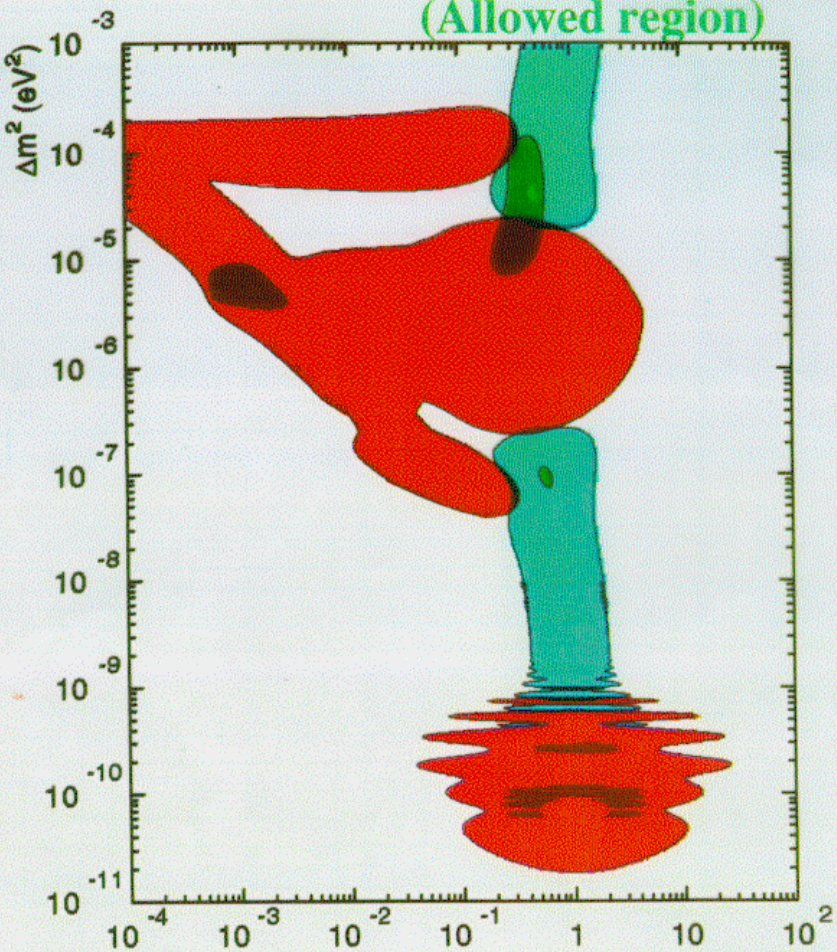


Allowed @95%CL



$\nu_e \longrightarrow \nu_\mu$ oscillation (95% C.L.)

Super-Kamiokande only
Day/Night Spectrum +flux
(Allowed region)



Flux global fit:
Ga+Cl+SKflux
(Allowed region)

Super-Kamiokande only
Day/Night Spectrum
(flux independent)
(Excluded region)

Summary and Conclusions

1) From the 1117 days of data (May-31-96 to April-24-00):

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

Day/Night effect:

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

Spectrum:

χ^2 for flat = 13.7 / 17dof (69% C.L.)

Hep flux: < 13.2 x SSM Hep

(best fit: 5.4±4.6 SSM Hep)

2) For active neutrinos:
SMA and Just-So solutions are disfavored at 95% C.L. by comparing the SK D/N spectrum (flux independent data) and the results of flux global analysis.

3) Sterile neutrinos are disfavored at 95% C.L. by comparing the SK D/N spectrum (flux independent data) and the results of flux global analysis.

4) SK D/N spectrum with a constrained by flux (SK-data only) favors large mixing and disfavors small mixing at 95% C.L.

Comments on the results

1) Why SMA and Just-So are disfavored:

- flat E-distribution
- small D/N effect

  (especially on SMA w/smaller mixing)

2) Smaller D/N:

- difficult to distinguish LMA and LOW
- takes long time to obtain positive evidence
- important task for future

3) low energy part of the spectrum plays a crucial role

→ down to 4.5 MeV (4.0 MeV)

4) pp/^{7}Be may see large D/N for the case of LOW

5) Neutral current measurements are important