Recent Solar ν Results from Super-Kamiokande

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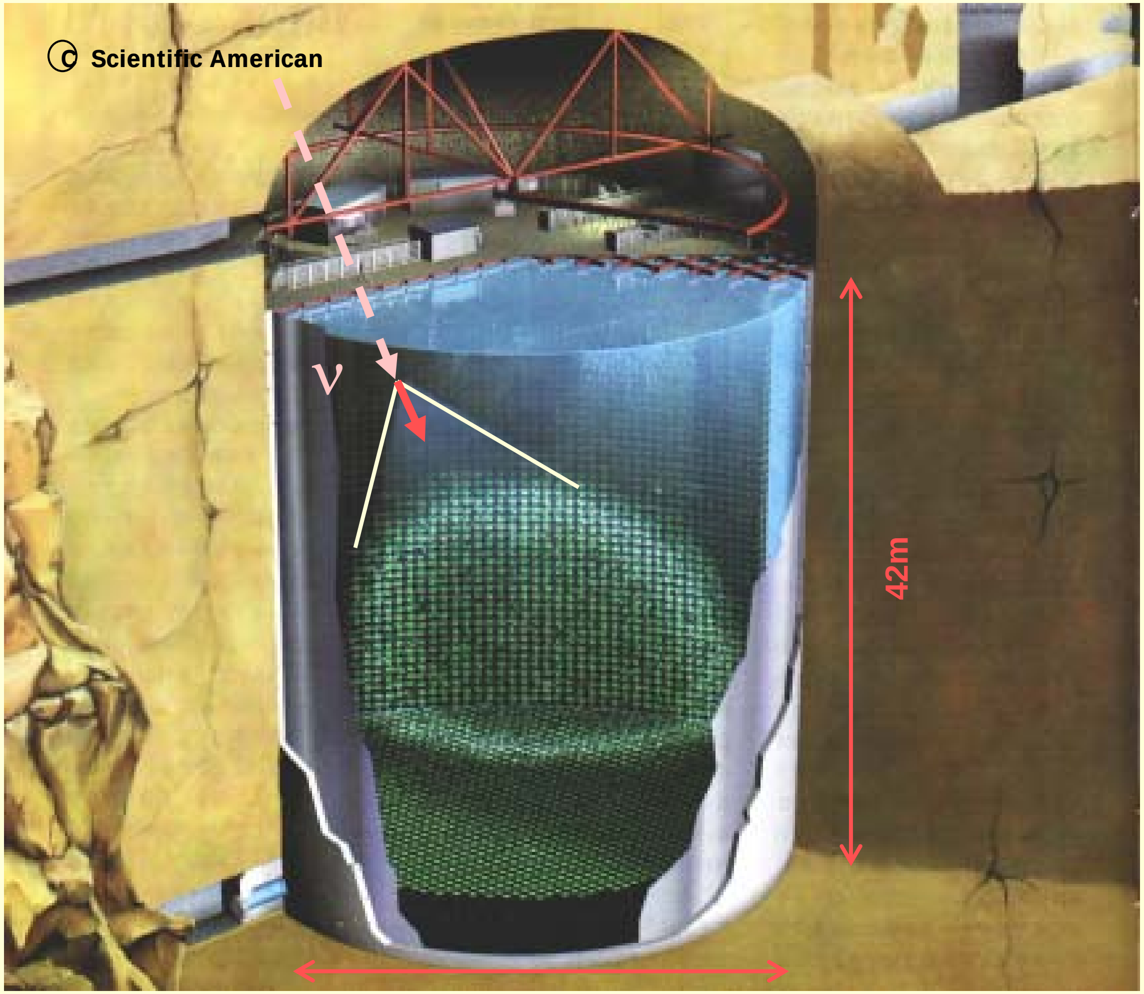
Super- Kamiokande



Water Cherenkov detector

- **1000 m underground**
- **50,000 ton (22,500 ton fid.)**
- **11,146 20 inch PMTs**
- **1,885 anti-counter PMTs**

Recovery work from Nov12-01 accident

PMT coverage
40%(SK-I)
20%(SK-II)

SK-I:Apr1996 – Jul2001

SK-II:Oct2002 –

Autumn, 2005~ full recovery work (back to 11,000 PMTs)

Neutrino oscillation

Two neutrino case

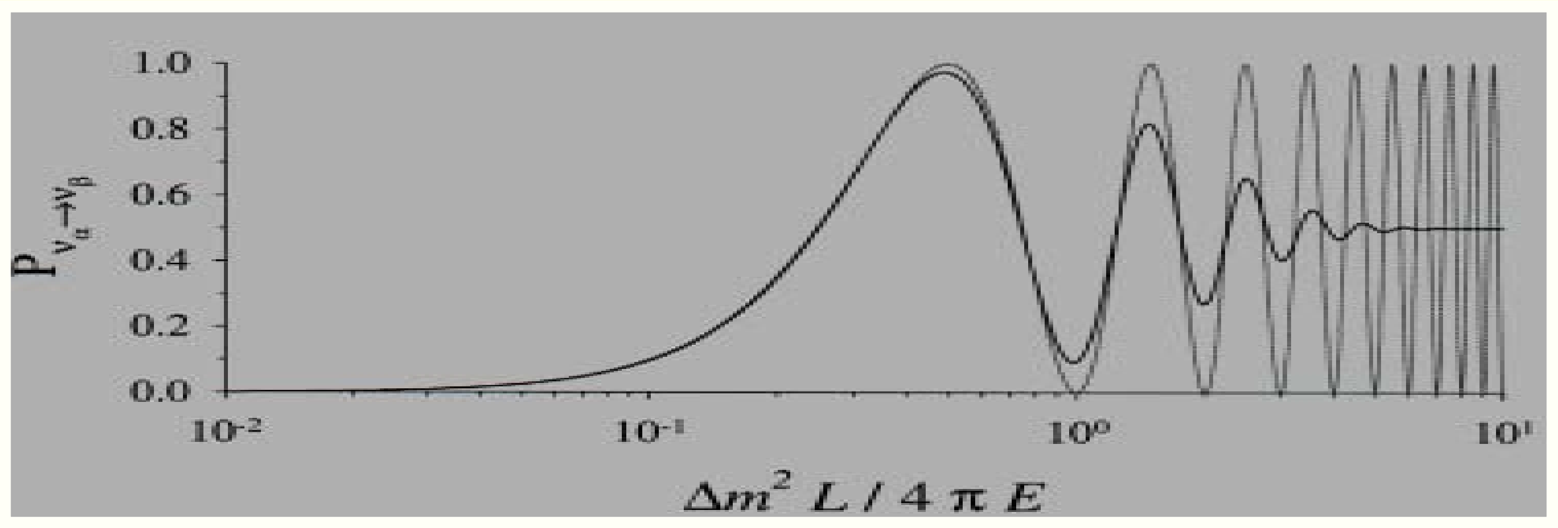
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$

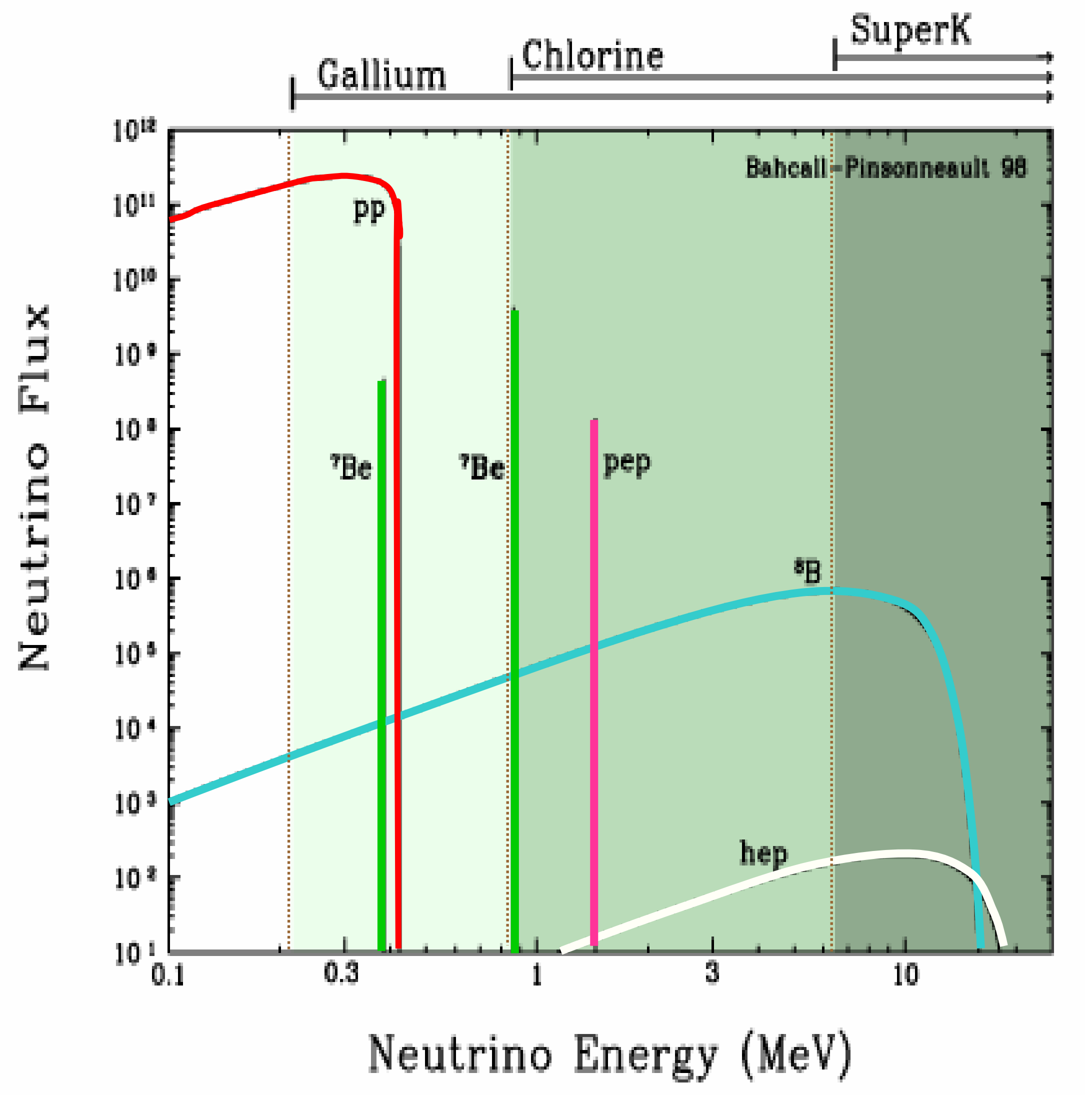
$\Delta m^2 = m_2^2 - m_1^2$ (eV^2)

L (km): Distance from source to detector

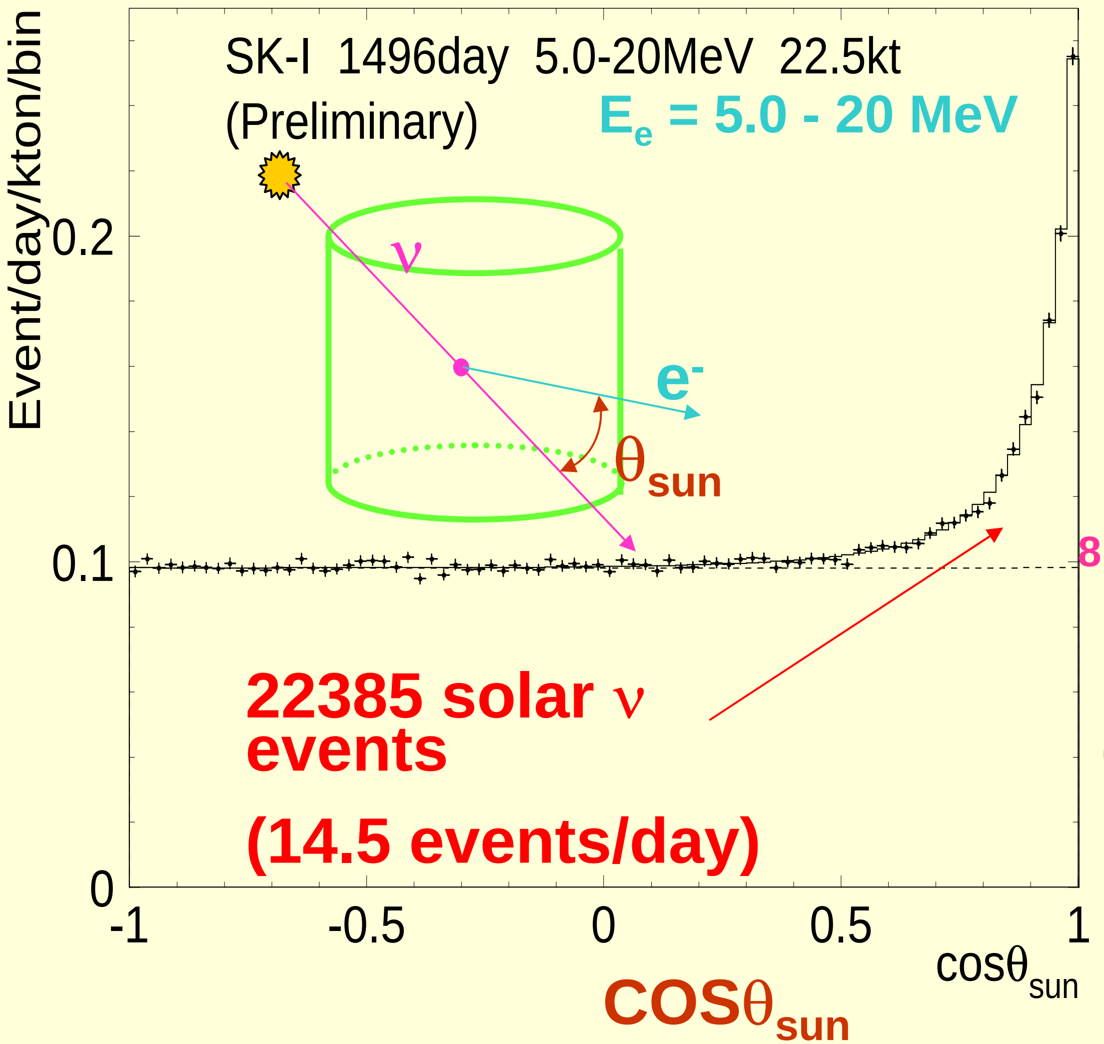
E (GeV): Neutrino energy



Solar Neutrinos



Solar ν measurement in SK-I

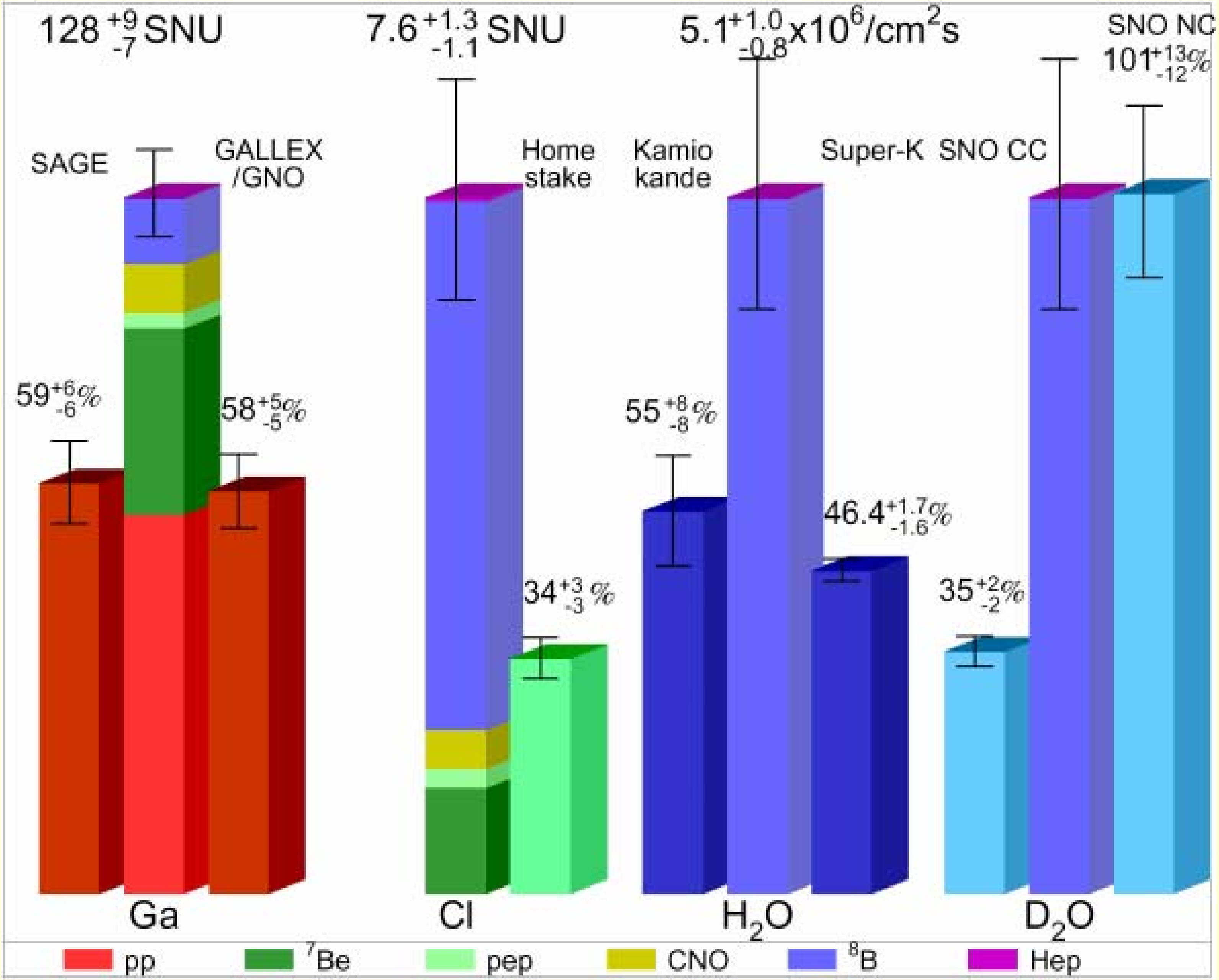


$\nu_e\, e \rightarrow \nu_e e$ scattering
(contains 15% of NC)

^{8}B flux : 2.35 ± 0.02 ± 0.08
[x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM}} = 0.465 \pm 0.005\ ^{-0.015}_{+0.016}$$

Solar ν Problem



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Solar ν oscillation is confirmed by Super-K and SNO

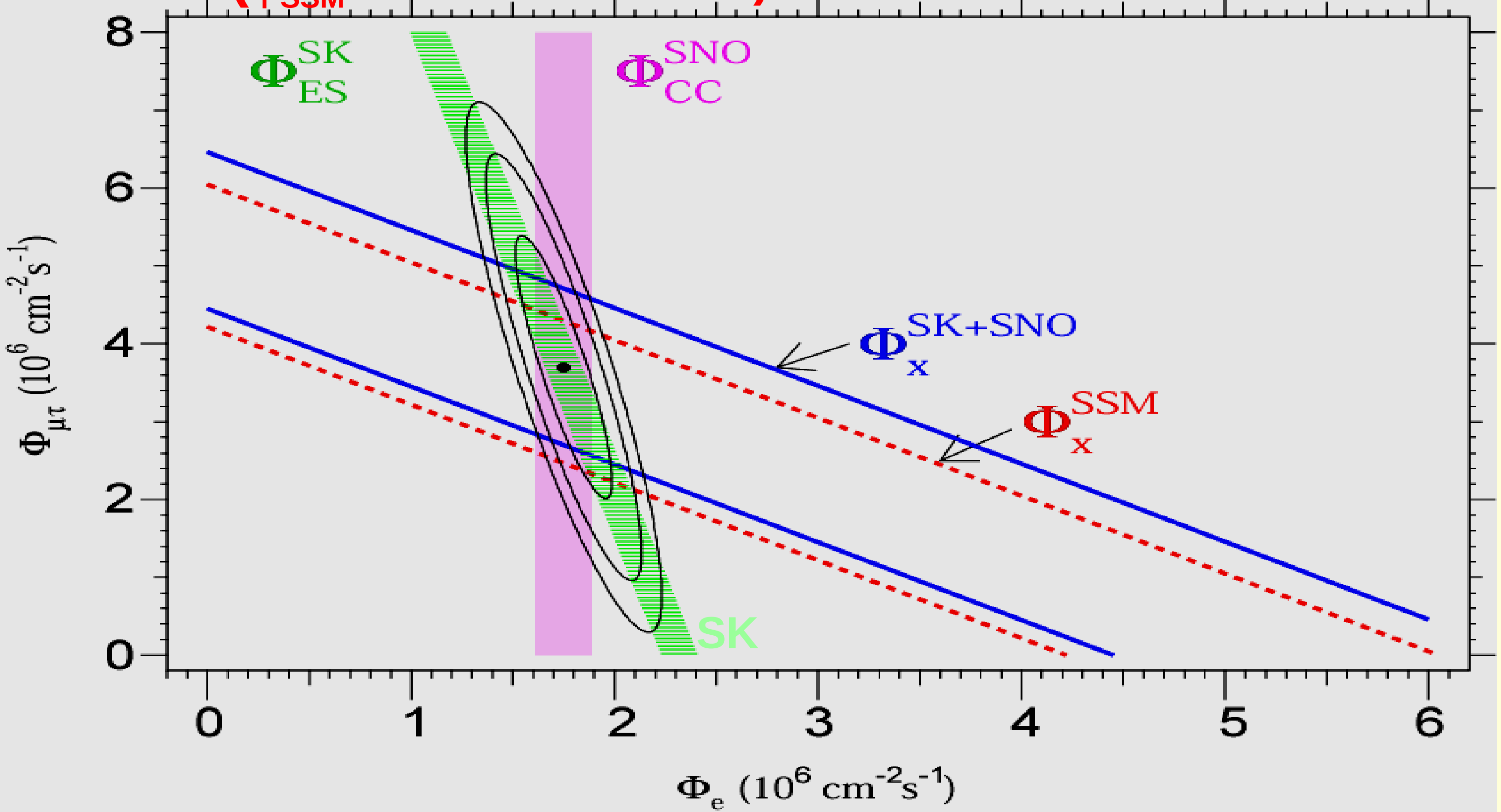
SNO ϕ_{CC} **= 1.75±0.15** [x10^6/cm^2/s] $\phi_{CC} = \phi_e$

SK ϕ_{ES} **= 2.32±0.09** $\phi_{ES} = \phi_e + 0.154\,\phi_{\mu,\tau}$

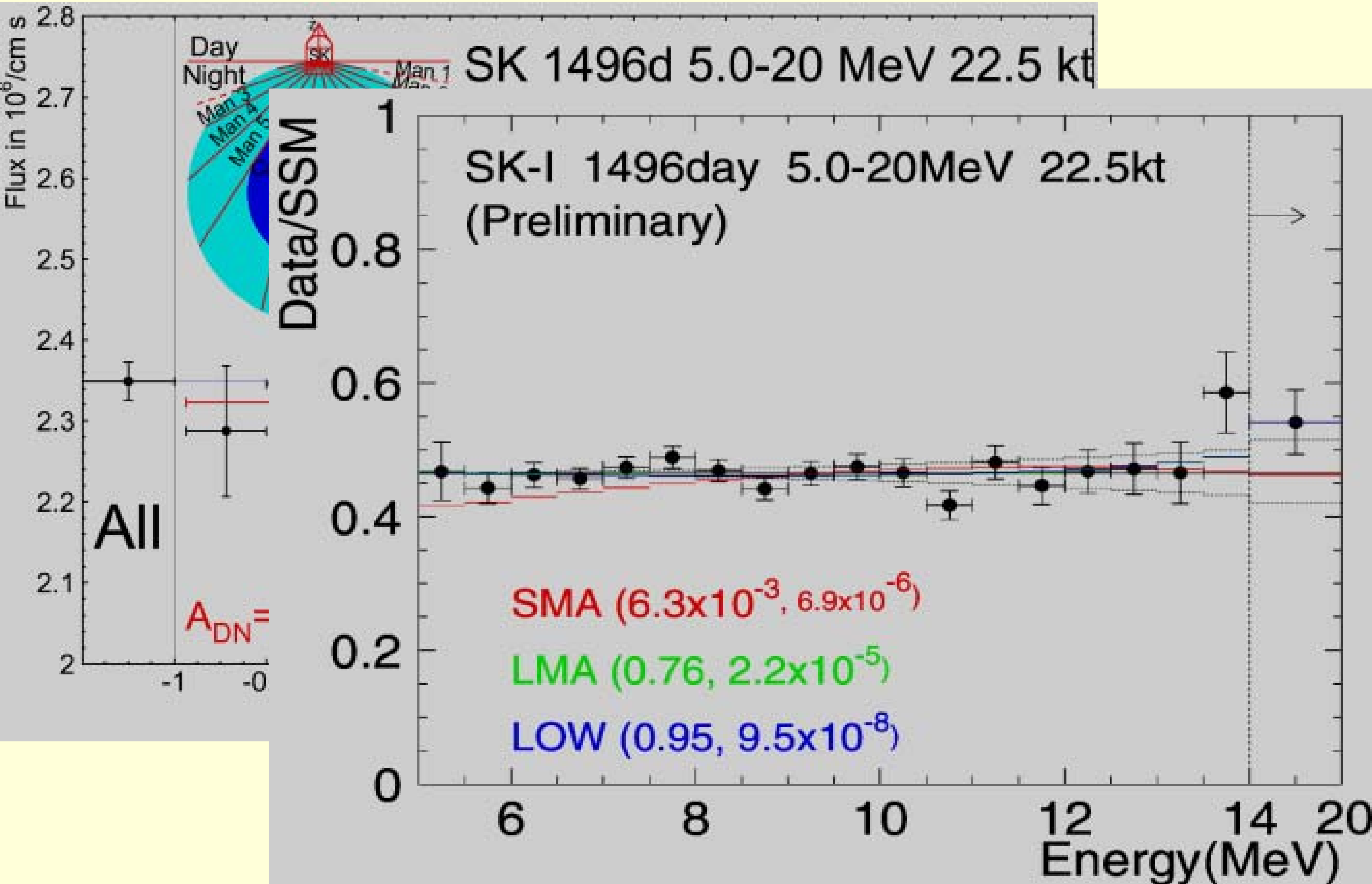
⇒ $\phi_{\mu,\tau}$ **= 3.69±1.13**

ϕ_x **= 5.44±0.99** **(total active ^{8}B neutrino flux)**

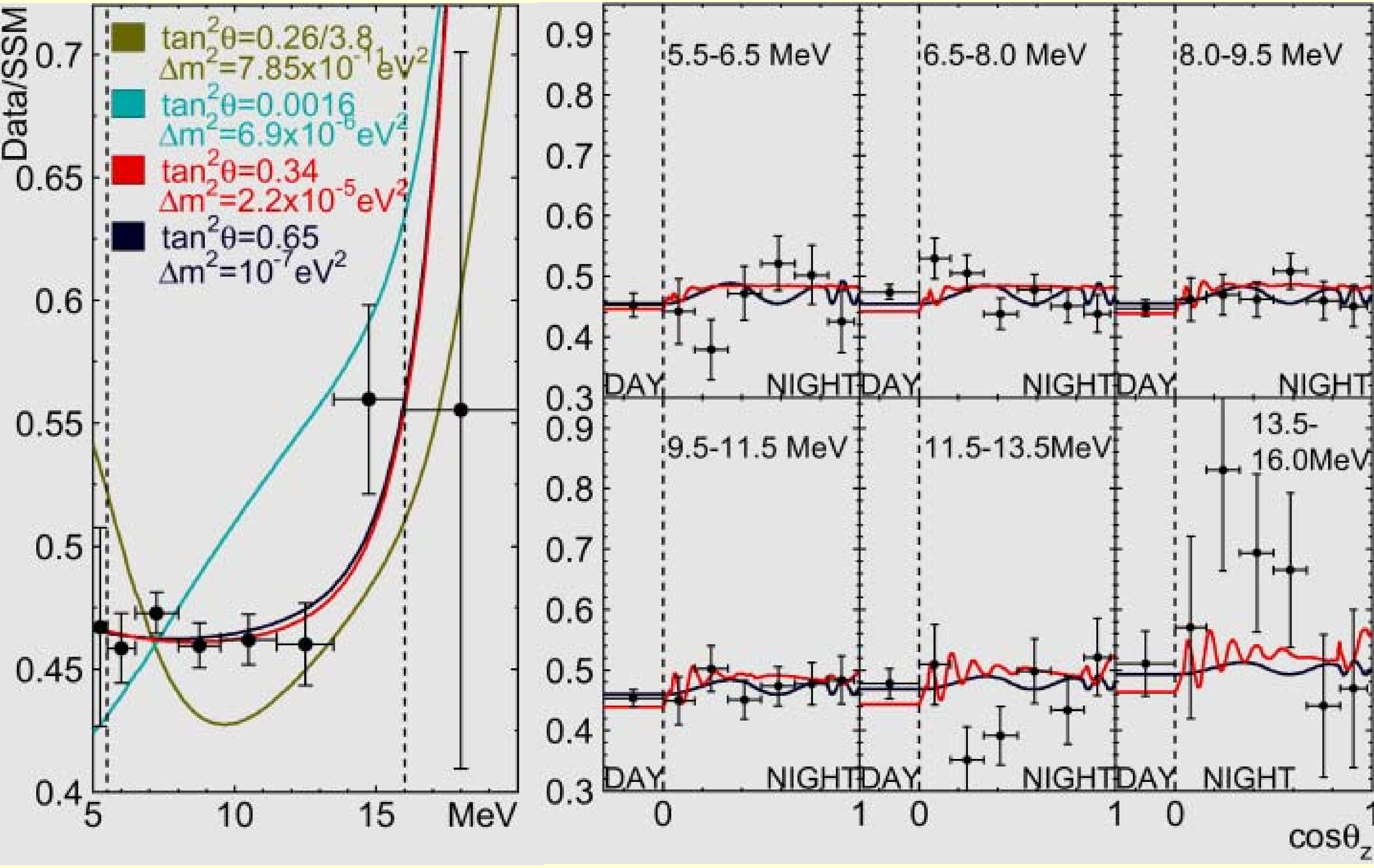
(ϕ_{SSM} = 5.05+1.01/-0.81)

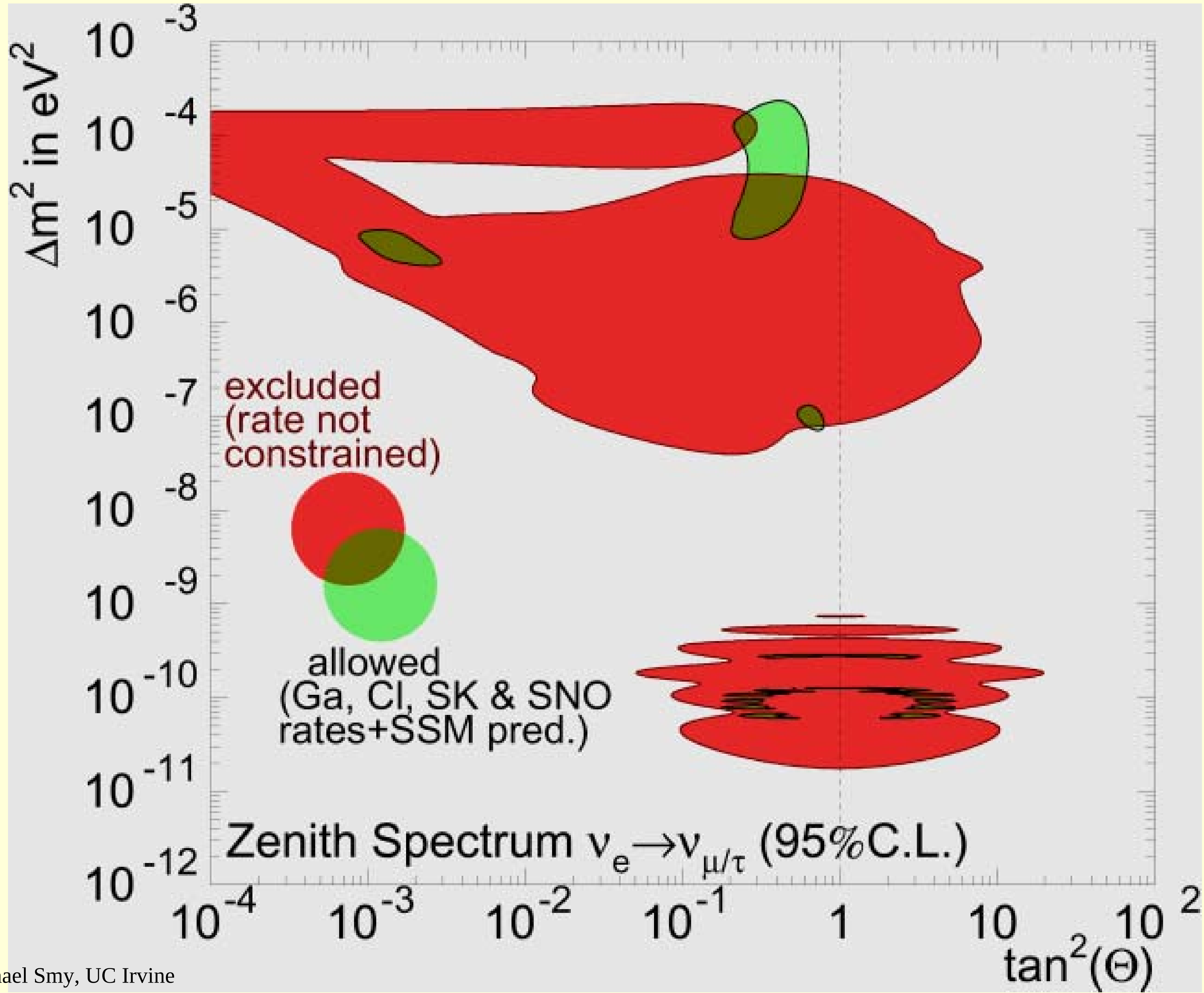


SK conventional Eν spectrum and Day/Night



Zenith Spectrum: Data & Solutions




Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
excluded
(rate not
constrained)
allowed
(Ga, Cl, SK & SNO
rates+SSM pred.)
Zenith Spectrum $\nu_e \rightarrow \nu_{\mu/\tau}$ (95%C.L.)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
$\tan^2(\Theta)$

Un-binned time variation method

Likelihood for solar neutrino extraction

Backgrounds in each energy bins

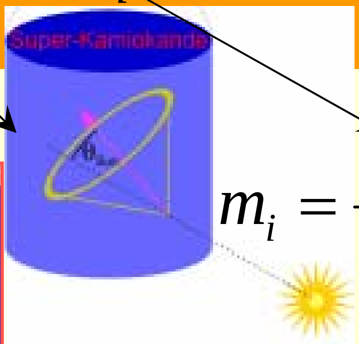
Signal Events

Event Energy

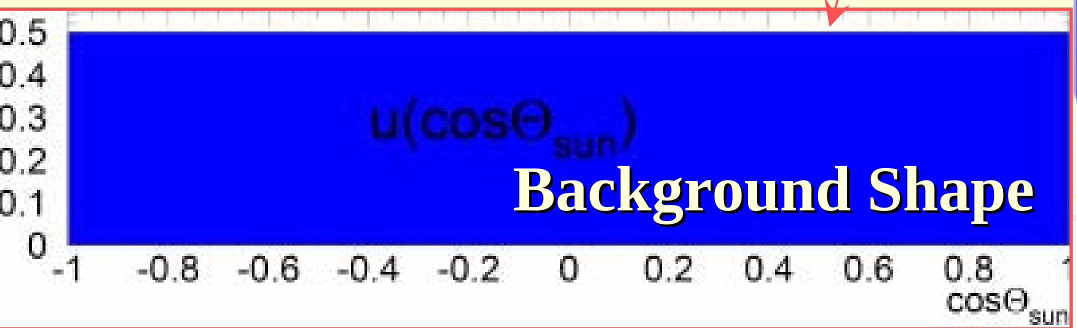
Event "Time"

$$\mathbf{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} \left(B_i \cdot u_i(c_\nu) + m_i S \cdot p(c_\nu, E_\nu) \quad \right)$$

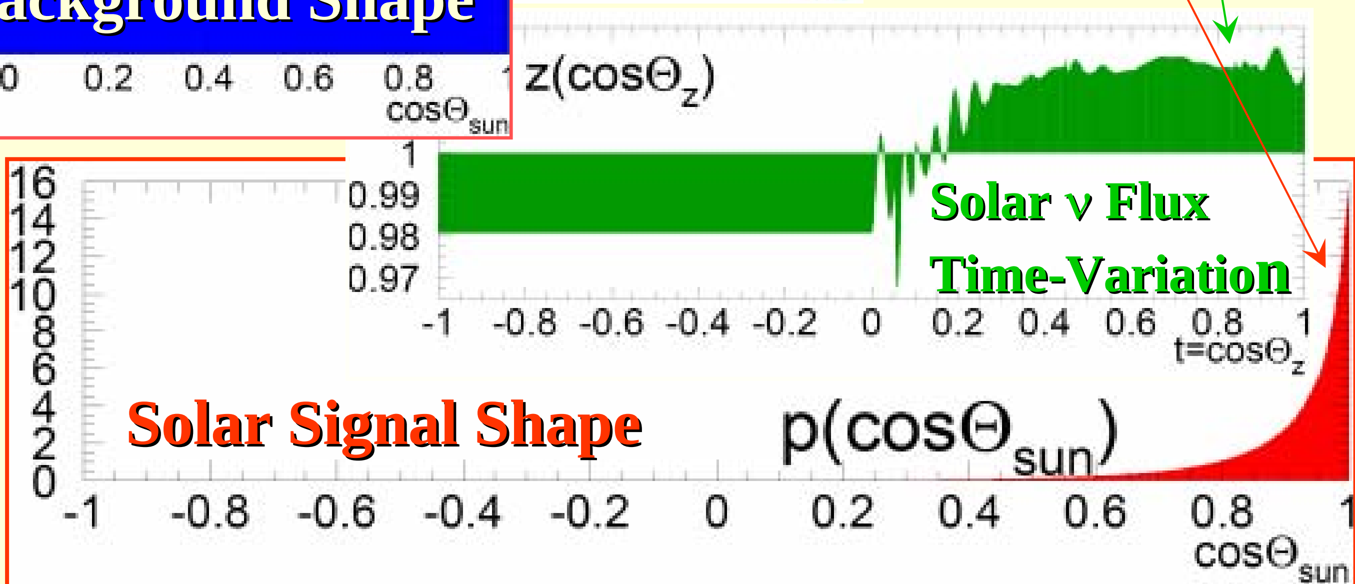
21 Energy bins



$$m_i = \frac{\mathrm{MC}_i}{\sum_j \mathrm{MC}_j}$$

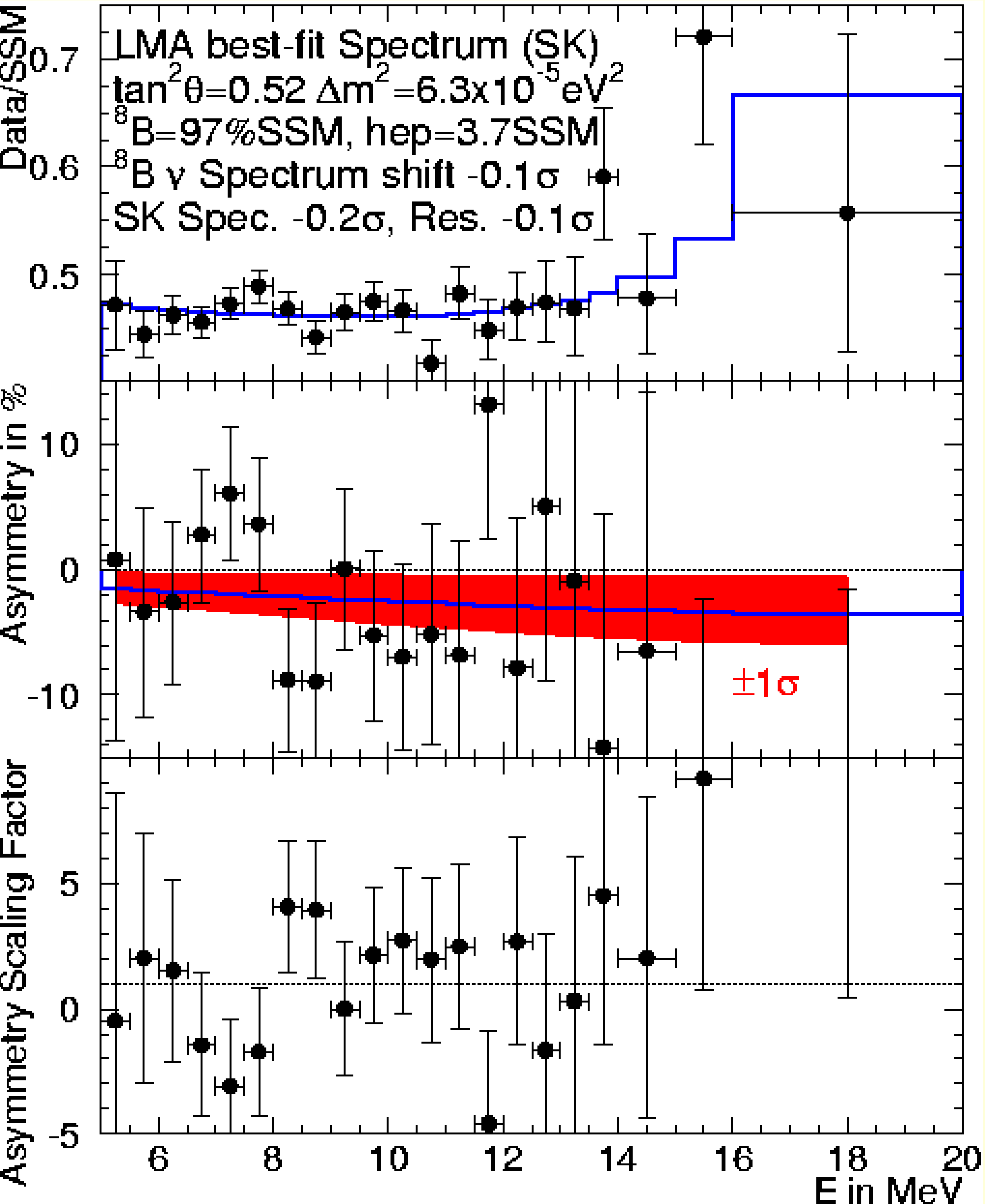


Background Shape



Solar ν Flux Time-Variation

Solar Signal Shape



$$\chi^2 = \sum_{i=1}^{N_{bin}} \frac{(d_i - \rho_i)^2}{\sigma_i^2} + \frac{\delta_B^2}{\sigma_B^2} + \frac{\delta_S^2}{\sigma_S^2} + \frac{\delta_R^2}{\sigma_R^2}$$

$$-2\Delta\log\mathrm{L}_{\mathrm{timevar}} + \frac{(\beta - 1)^2}{\sigma_B^2}$$

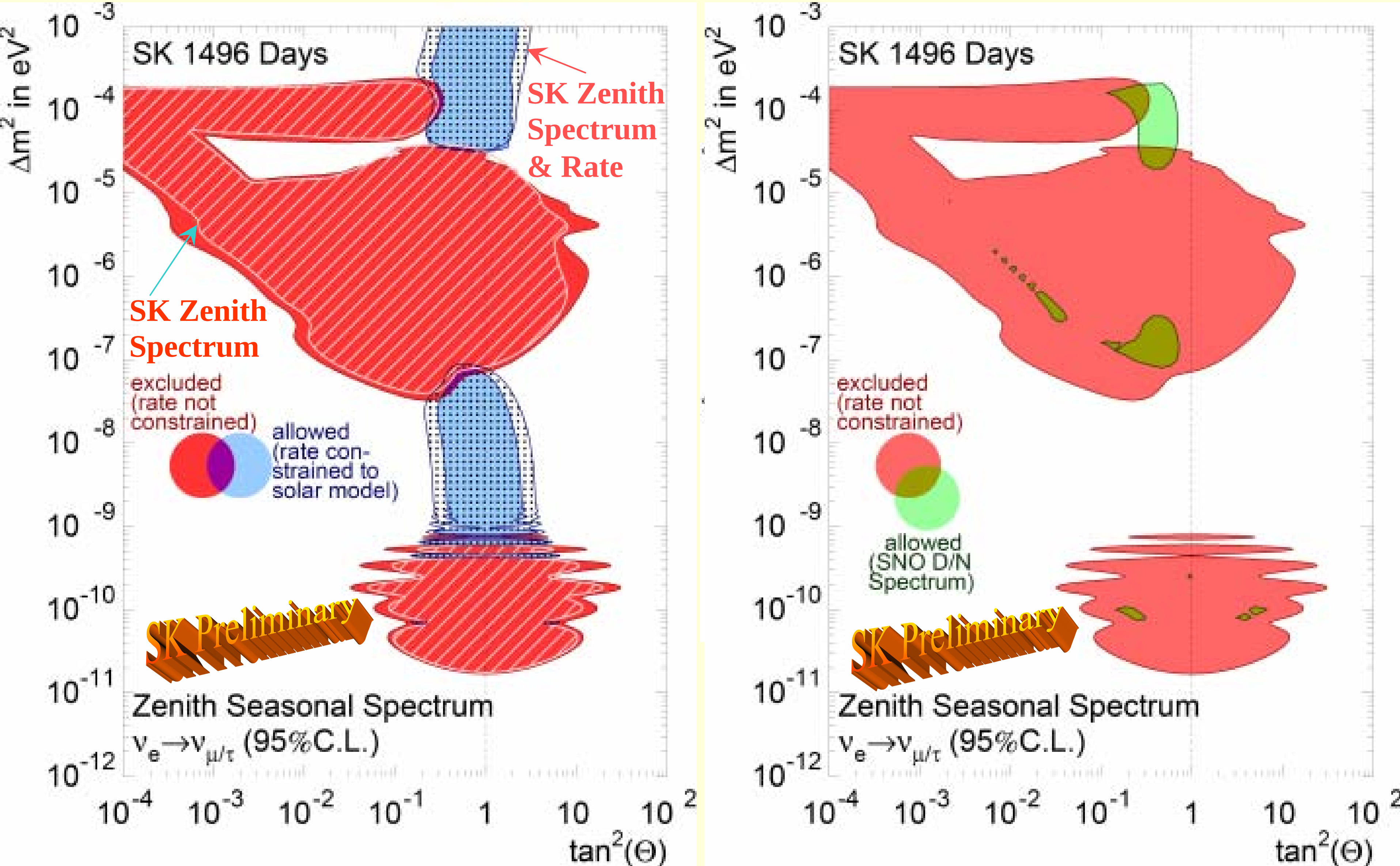
$$\mathrm{d_i} = \frac{\mathrm{Data}_i}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}$$

$$b_i = \frac{{}^8\mathrm{B}_i^{\mathrm{osc}}(\Delta m^2, \tan^2\theta)}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}, \quad h_i = \frac{hep_i^{\mathrm{osc}}(\Delta m^2, \tan^2\theta)}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}},$$

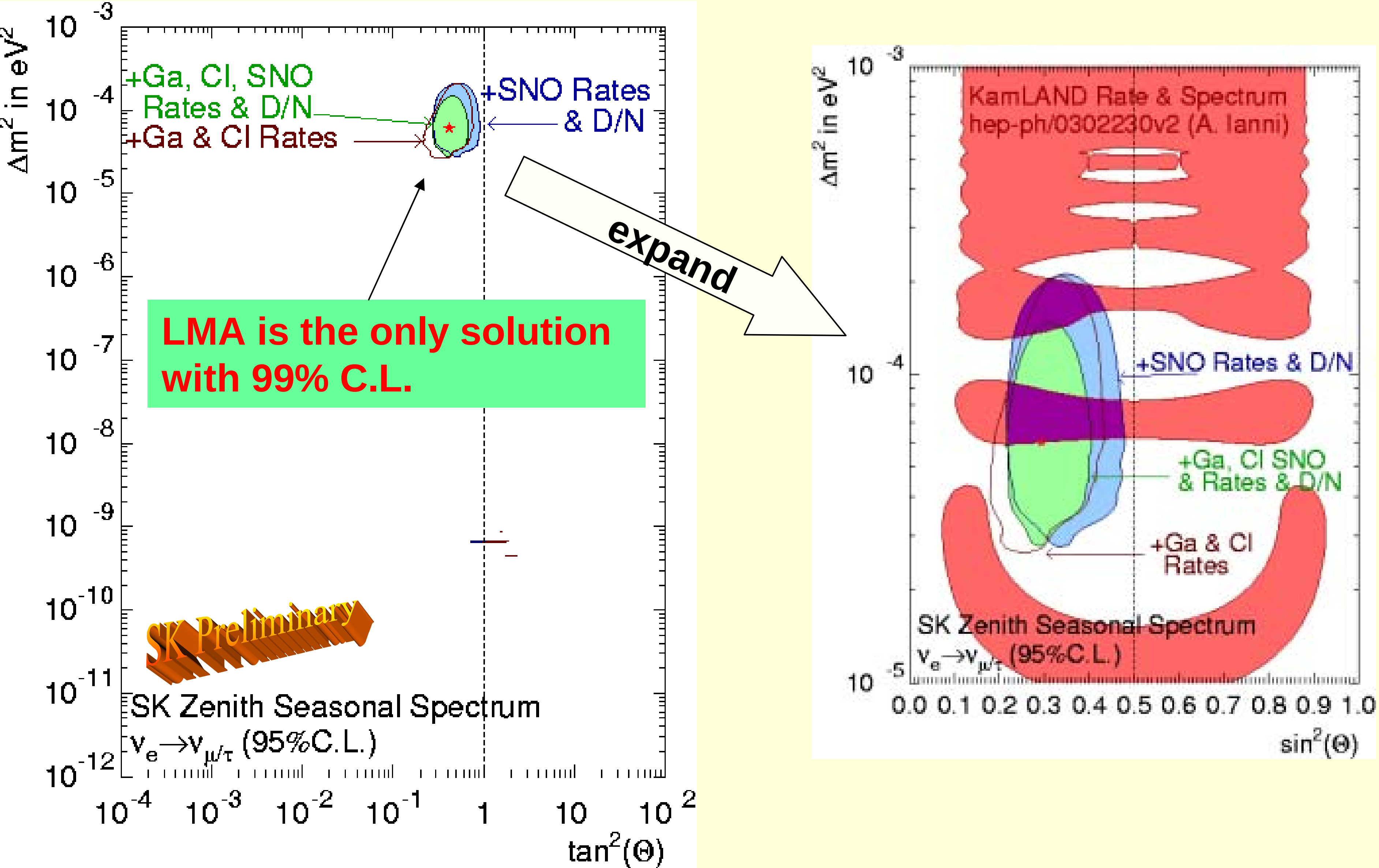
$$f_i(\delta_\mathrm{B}, \delta_S, \delta_R) = f_i^B(\delta_\mathrm{B}) \times f_i^S(\delta_S) \times f_i^R(\delta_R), \quad \rho_i = \frac{\beta b_i + \eta h_i}{f_i}$$

$$m_i = \frac{\rho_i}{\sum_j \rho_j}$$

SK excludes all small mixing angles, disfavor LOW/HLMA

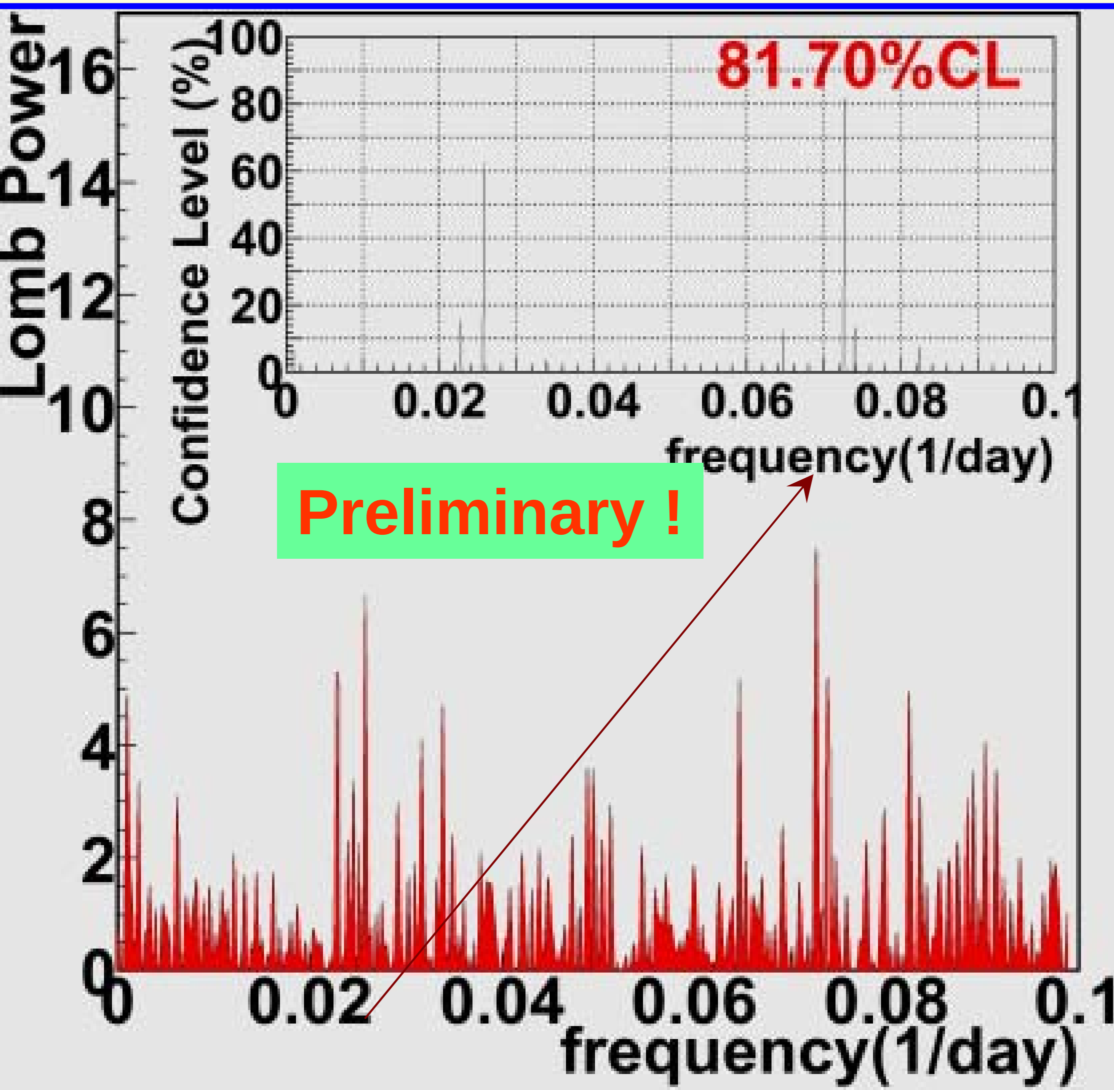


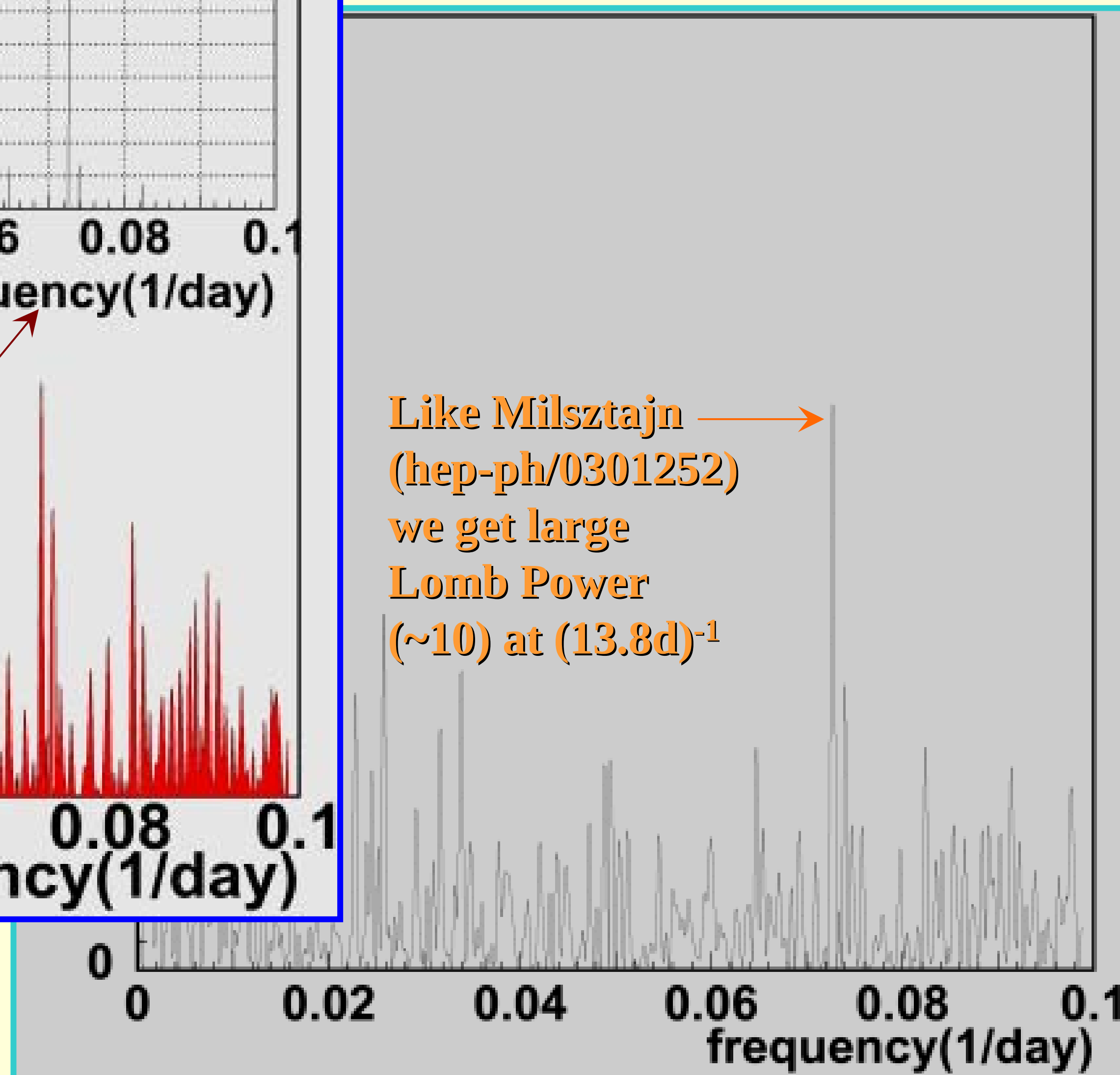
With all solar neutrino experiments



Other topics

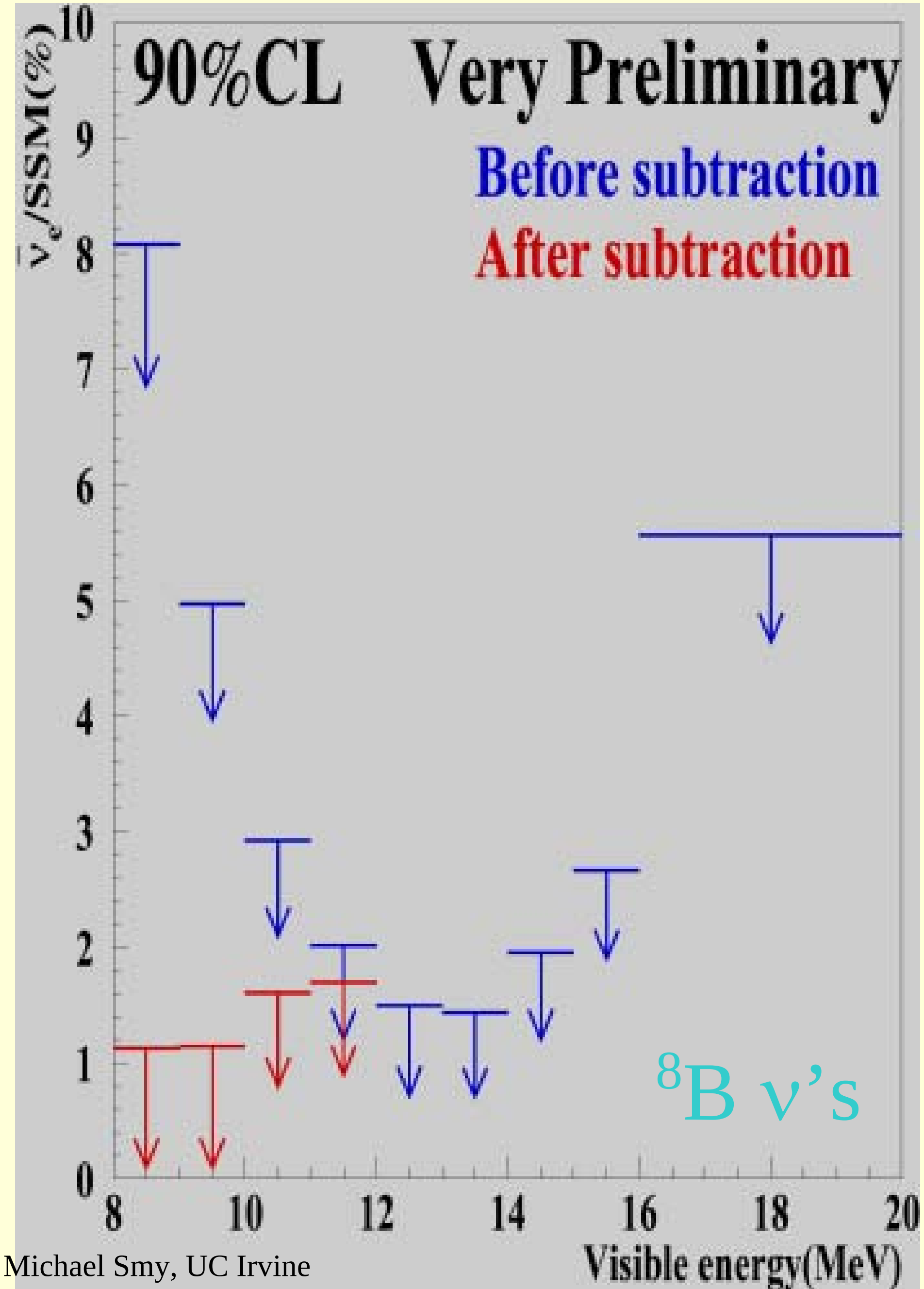
13.8 day modulation of solar neutrinos ??

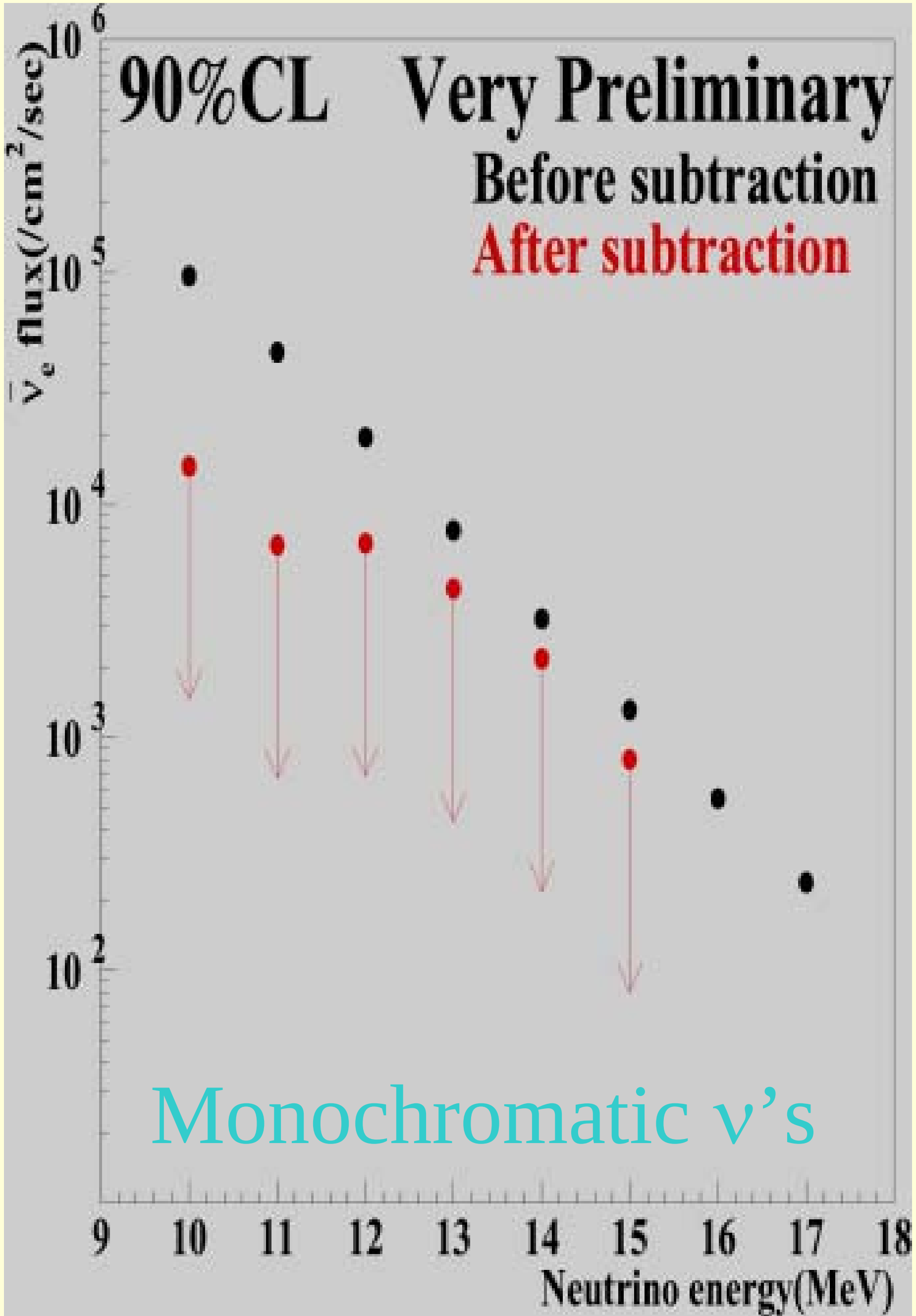




Lomb Power decreases, if Correct bin-time is used!!

Solar Antineutrino Limit





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New Development

Why Liquid Xenon?

General properties:

Large scintillation yield (~42000photons/MeV ~NaI(Tl))

Scintillation wavelength (175nm, direct read out by PMTs)

Higher operation temperature (~165K, LNe~27K, LHe~4K)

Compact (ρ=3.06g, 10t detector ~ 1.5m cubic)

Not so expensive

Well-known EW cross sections for neutrinos

External gamma ray background:

Self shielding (large Z=54)

Internal background:

Purification (distillation, etc) **ALWAYS possible**

No long-life radio isotopes

Isotope separation is relatively easy

No ^{14}C contamination (can measure low energy)

Development of
... ti purpose
Liquid ... illation detector

γ (U/Th/K/
Co/Cs/…)

μ

Self

No long

- **Low energy solar neutrino detection; pp and ^{7}Be**

Precise determination of osc. parameters by pp exp. + KamLAND

- **Dark Matter**

Large number of events are expected

(large volume, large atomic number, and low threshold).

- **Double beta decay**

0νββ (2νββ) decay of ^{136}Xe (natural abundance 8.87%) search

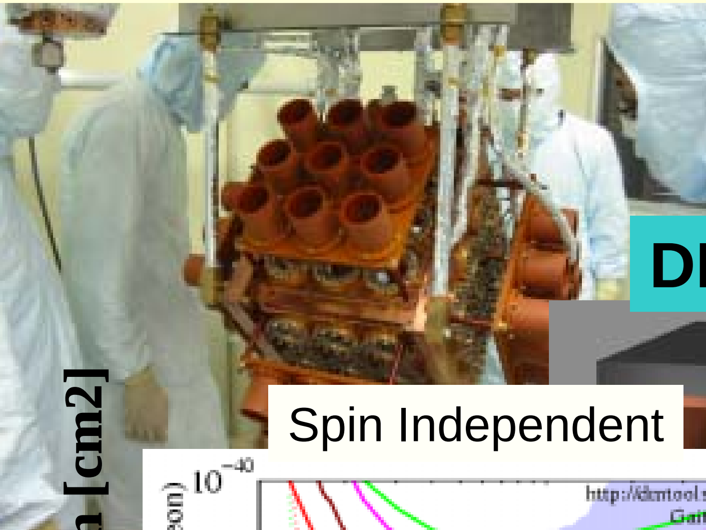
High purity/enriched xenon can be used.

neutron

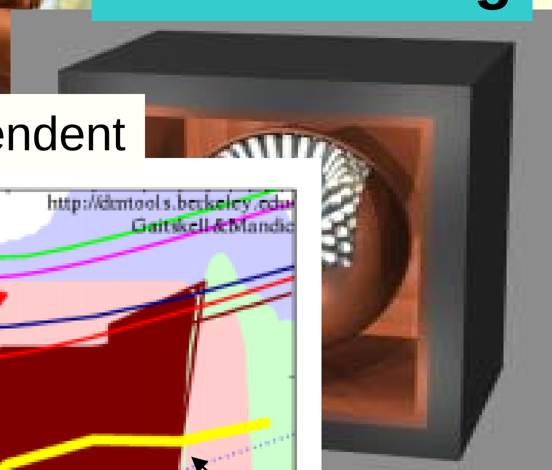
^{85}Kr, ^{42}Ar, U/Th

Staging of d

R&D with 100kg

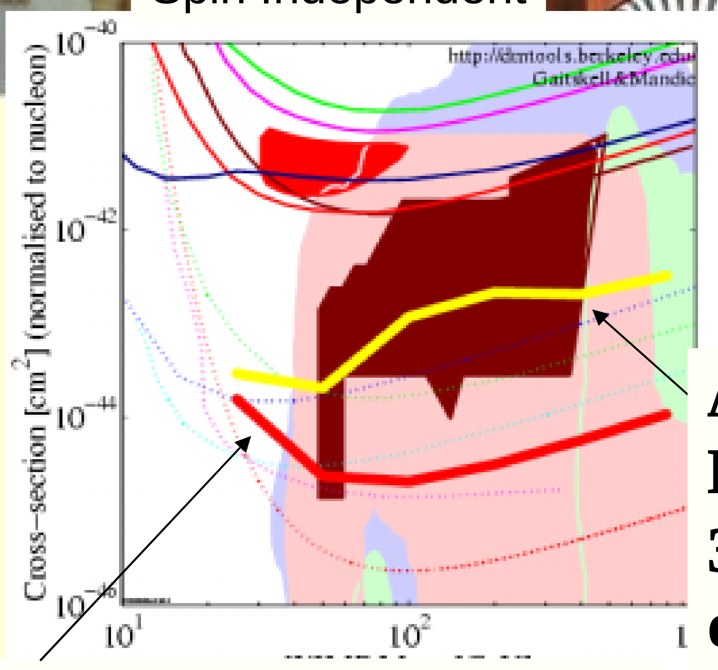


DM for 800kg



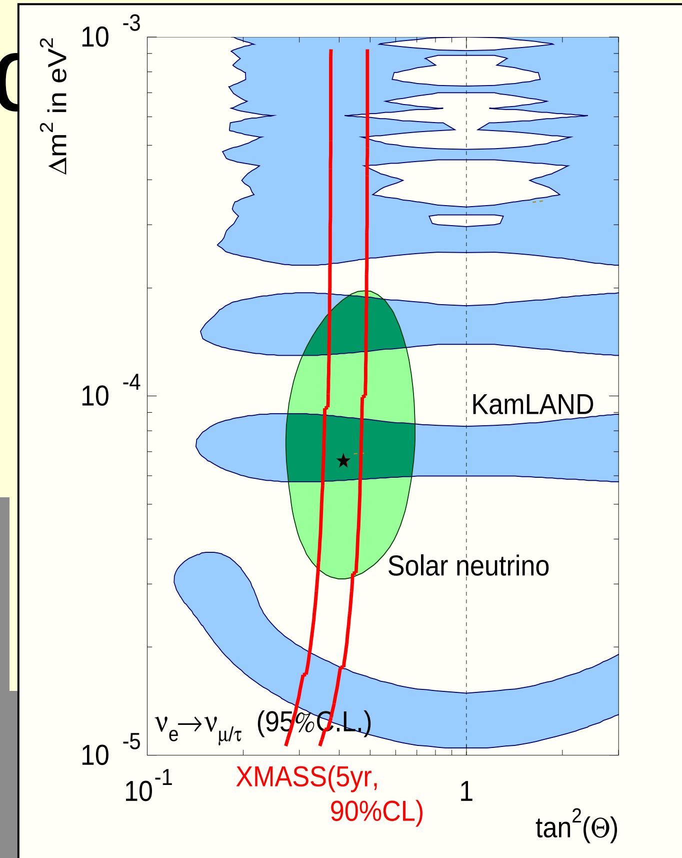
Spin Independent

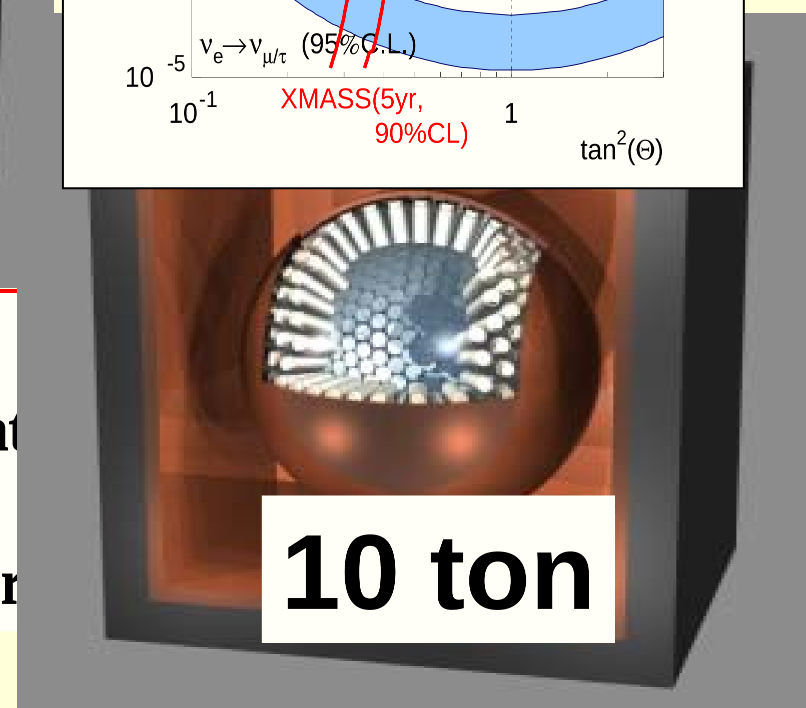
Cross section for nucleon [cm2]



Annual Modulat
3σ
discover

Raw spectrum, 3σ discovery





10 ton

Summary

- Super-Kamiokande has measured precisely solar neutrino flux, recoil electron spectrum and time variations of the flux.
- No significant time variation and energy distortion appear.
- Solar neutrino oscillation studies :
  - New analysis method **(un-binned time variation)** has been installed.
  - The results of Super-Kamiokande (flux, spectrum and day/night flux differences) favors Large neutrino mixing at 95%C.L.
  - **Only LMA solutions remain at 99.0%C.L. combined with all the solar neutrino data.**
- Various experiments will determine oscillation parameters precisely and check consistency in future.