Neutrino Physics: Lecture 8

Solar neutrino problem: the solution

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Outline

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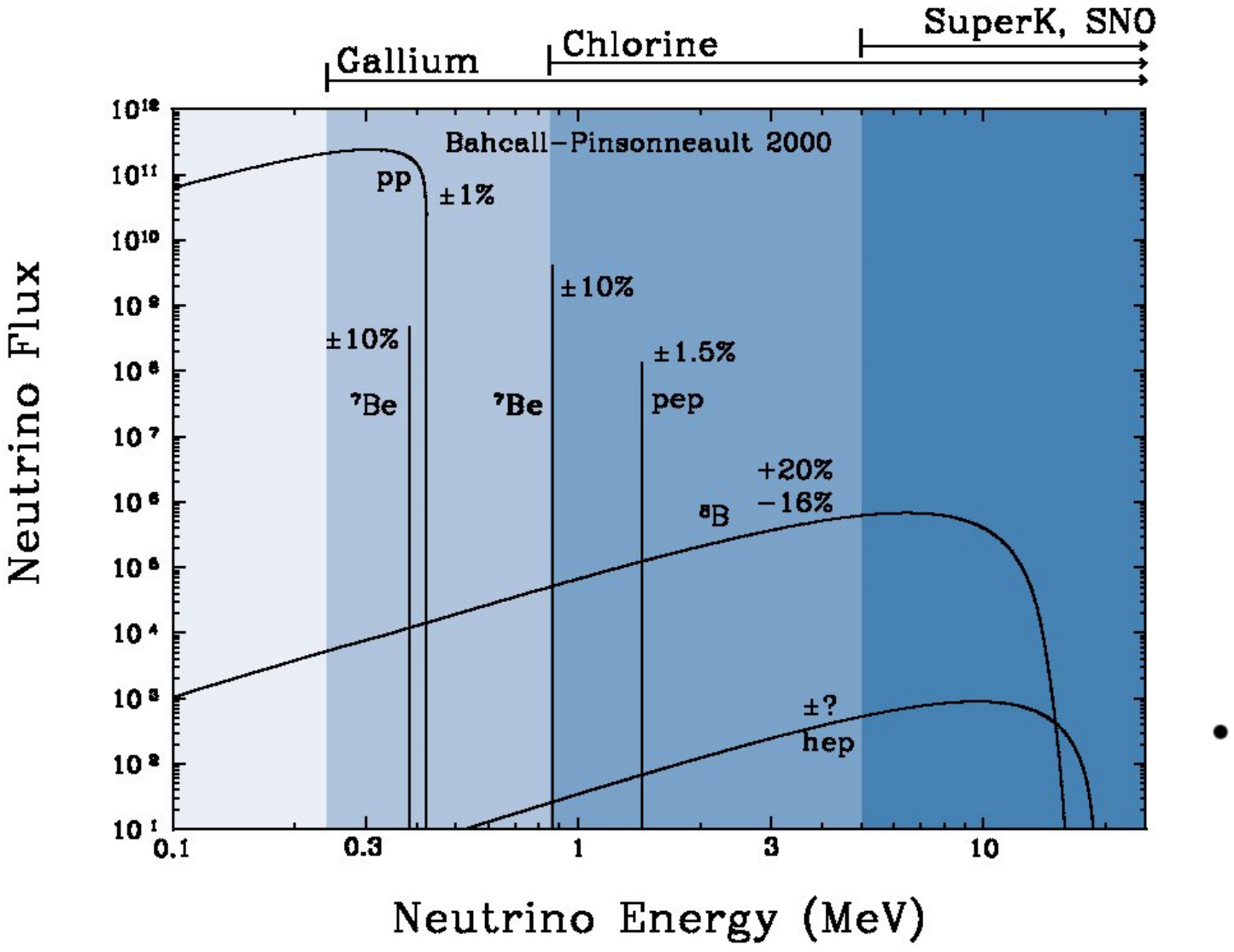
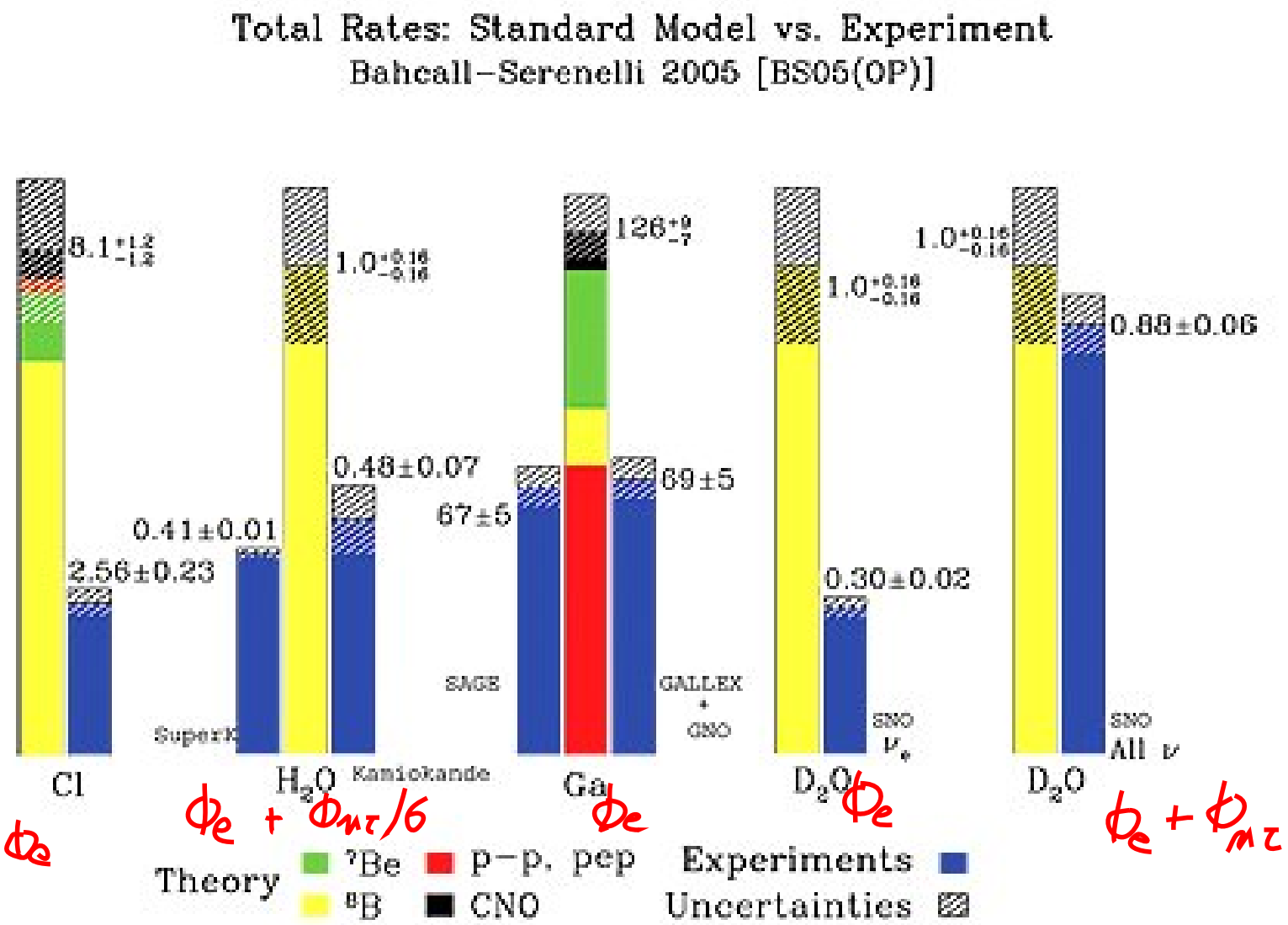
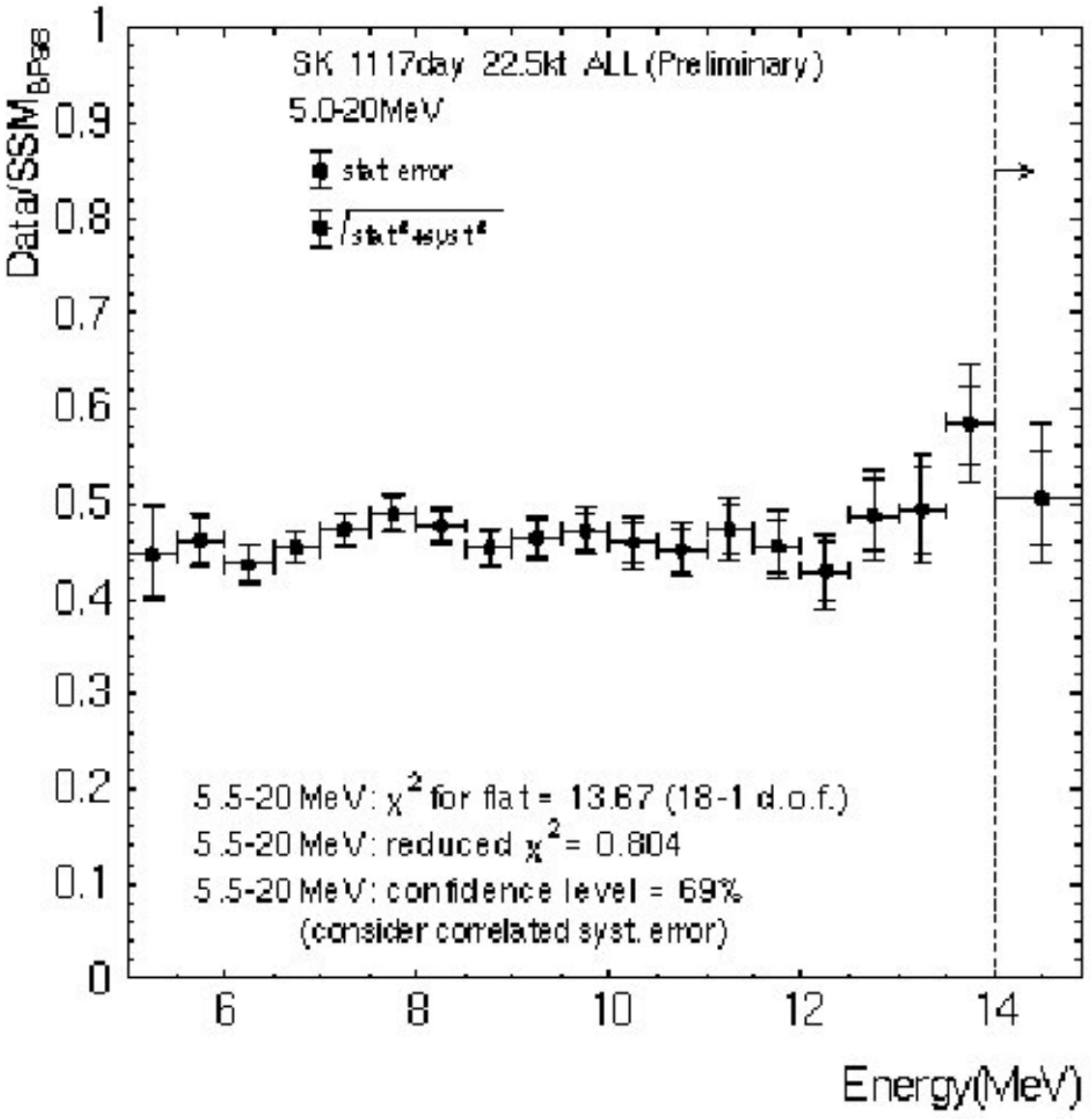
The solar neutrino spectra



Results from different experiments

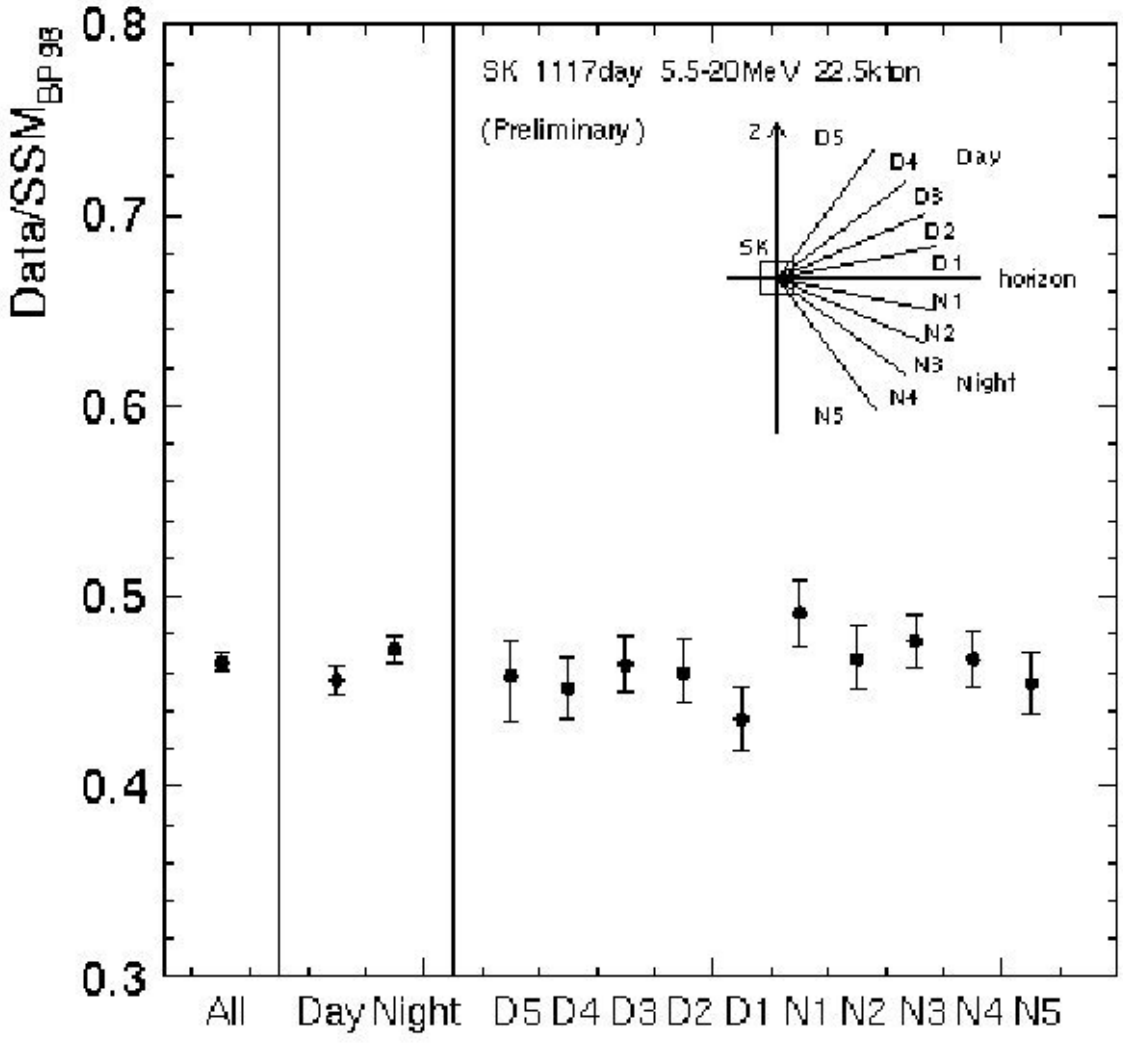


Energy spectrum at Super-Kamiokande



$$\phi_e + \frac{\phi_{\mu\tau}}{6}$$

Day-night asymmetry at Super-Kamiokande



Survival probability with matter effects

Survival probability:

$$\begin{aligned} P_{ee} &= P_f \cos^2\theta + (1-P_f)\sin^2\theta \\ &\quad +2\sqrt{P_f(1-P_f)}\cos\theta\sin\theta\cos\left(\chi_1 - \chi_2 + \int 2\Delta_m dt\right) \end{aligned}$$

$$\begin{aligned} P_f &\approx \exp\left(-\frac{\pi\gamma_{res}}{2}\right) \quad (\gamma_{res} \gg 1) \\ &\approx \cos^2\theta \quad (\gamma_{res} \ll 1) \end{aligned}$$

$$\gamma_{res} = \frac{\Delta m^2}{2E}\frac{\sin^2 2\theta}{\cos 2\theta}\left|\frac{1}{V_C}\frac{dV_C}{dx}\right|^{-1}_{res}$$

Parameters: $\Delta m^2, \theta$ (Given $V_C(x)$)

Day-night asymmetry

Day-night asymmetry

$$A_{DN} = P_f(P_{1e} - \cos^2\theta) + (1 - P_f)(P_{2e} - \sin^2\theta)$$

In general, nonzero day-night asymmetry !

Possible vanishing of day-night asymmetry

When $\theta_m - \theta \approx 0$:

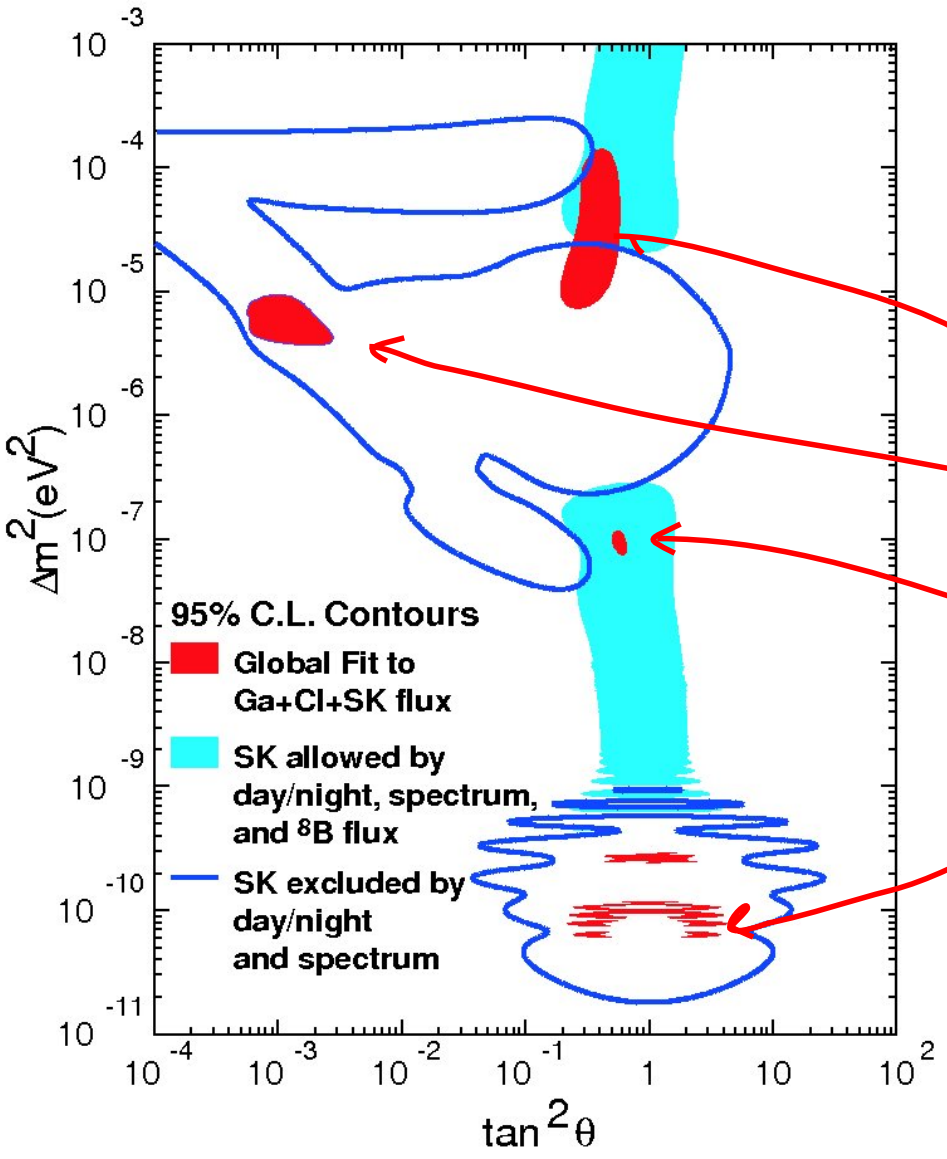
$$P_{1e} \approx \cos^2\theta\,, \quad P_{2e} \approx \sin^2\theta$$

Happens when $\theta \approx 45^\circ$ (rule of thumb)

$P_f(P_{1e} + \cos^2\theta) + (1 - P_f)(P_{2e} + \sin^2\theta)$

Outline

Four qualitatively different solutions



- LMA
- SMA
- LOW
- VAC

2001

The vacuum solution (VAC)

Characteristics

- $\Delta m^2 \ll 10^{-9}\ \text{eV}^2$, $\theta \approx 45°$
- Resonance in outer parts of the Sun, $\Delta \cos 2\theta \simeq \frac{V_e}{2}$
  $\gamma \ll 1, \quad P_f \approx \cos^2\theta$
- Survival probability
  $P_{ee} \approx \cos^4\theta + \sin^4\theta + 2\sin^2\theta\cos^2\theta\cos\left(\chi_1 - \chi_2 + \int 2\Delta dt\right)$
- Almost like “no matter effects”
- $\int 2\Delta dt \sim 10 \Rightarrow$ no decoherence if Δ measured to 1%

Predictions

- Reduced flux
- Seasonal variation
- Energy dependence of P_{ee}

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The vacuum solution (VAC)

$L_{\text{Earth Sun}} \sim 10^{11}$ m

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Small Mixing Angle MSW solution (SMA MSW)

Characteristics

- $\Delta m^2 \ll 10^{-6} - 10^{-5}$ eV^2, $\theta \sim 0.01°$
- Resonance in the core of the Sun,
  $\gamma \sim 1, \quad P_f(E) \approx 0.2 - 0.8$
- $\int 2\Delta_m dt \gg 10^5 \Rightarrow$
  Decoherence even when $\Delta E/E \approx 1\%$
- Survival probability
  $P_{ee} \approx P_f(E)\cos^2\theta + (1 - P_f(E))\sin^2\theta$

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- Substantial Day - night asymmetry ✗
- Energy dependence of P_{ee} ✗

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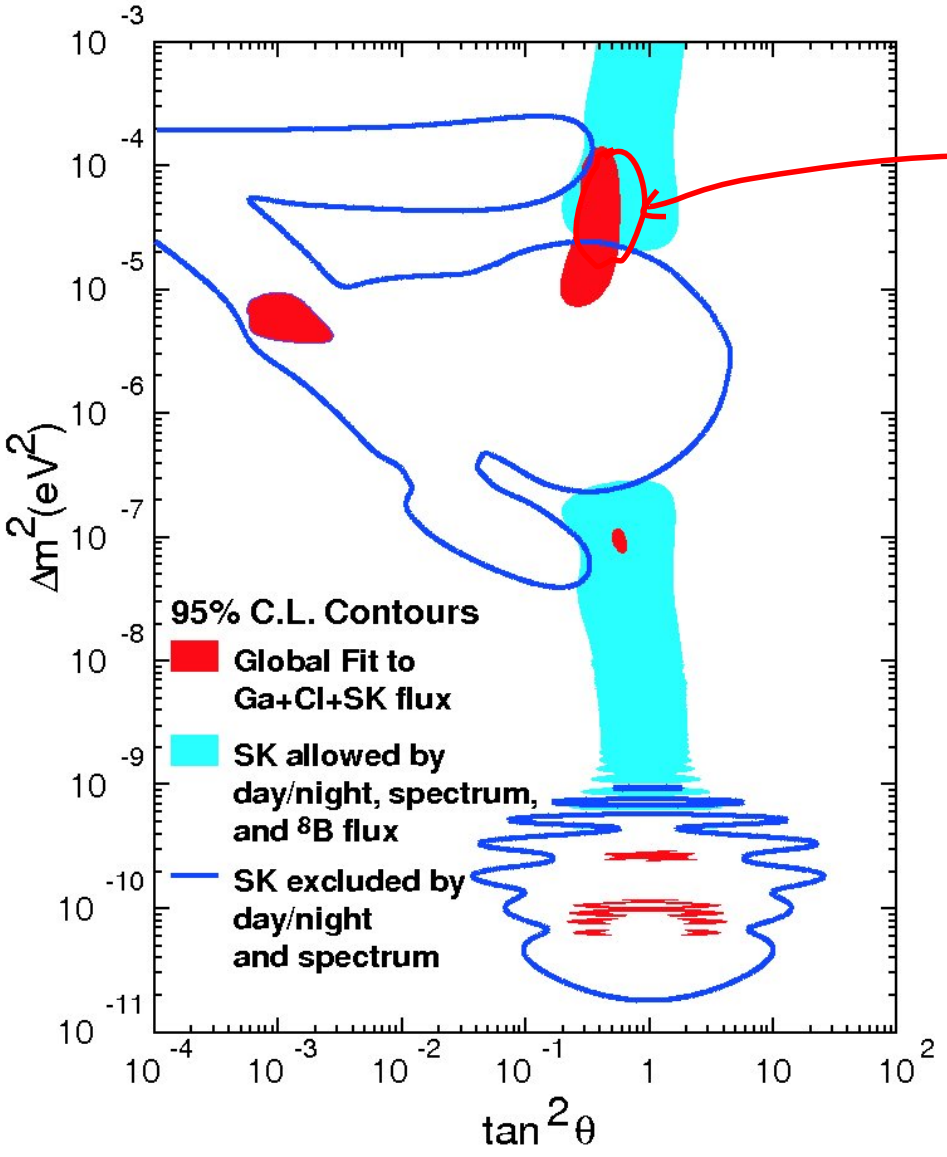
Outline

Zooming on to LMA solution



The solution

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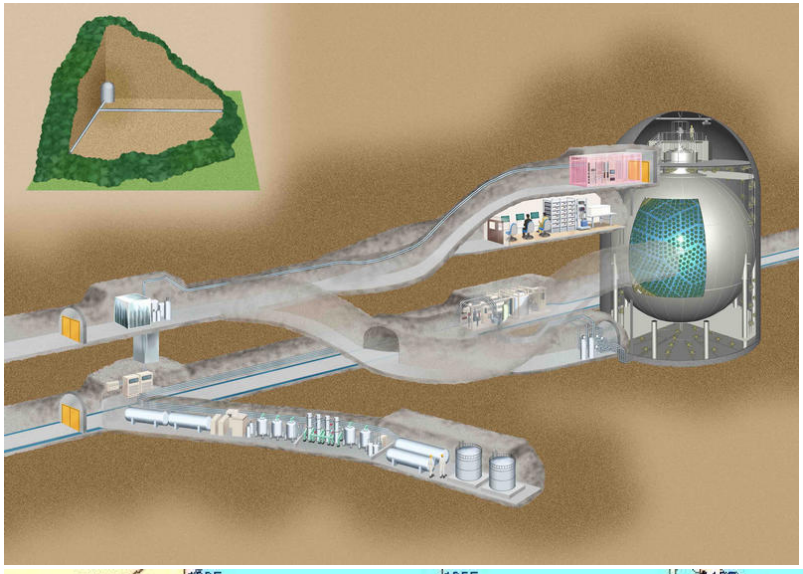
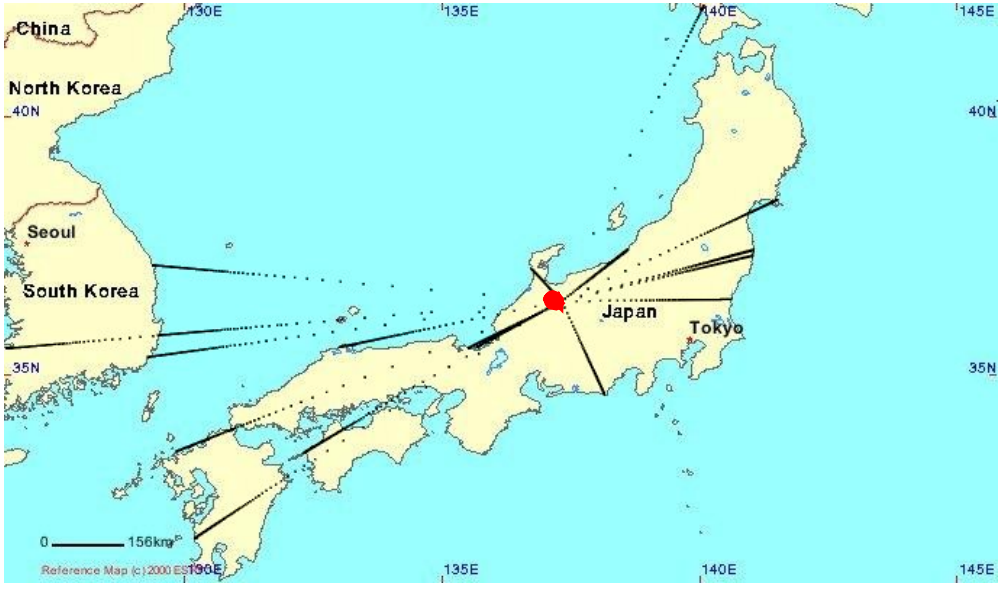
Reactor $\bar{\nu}_e$ from KamLAND



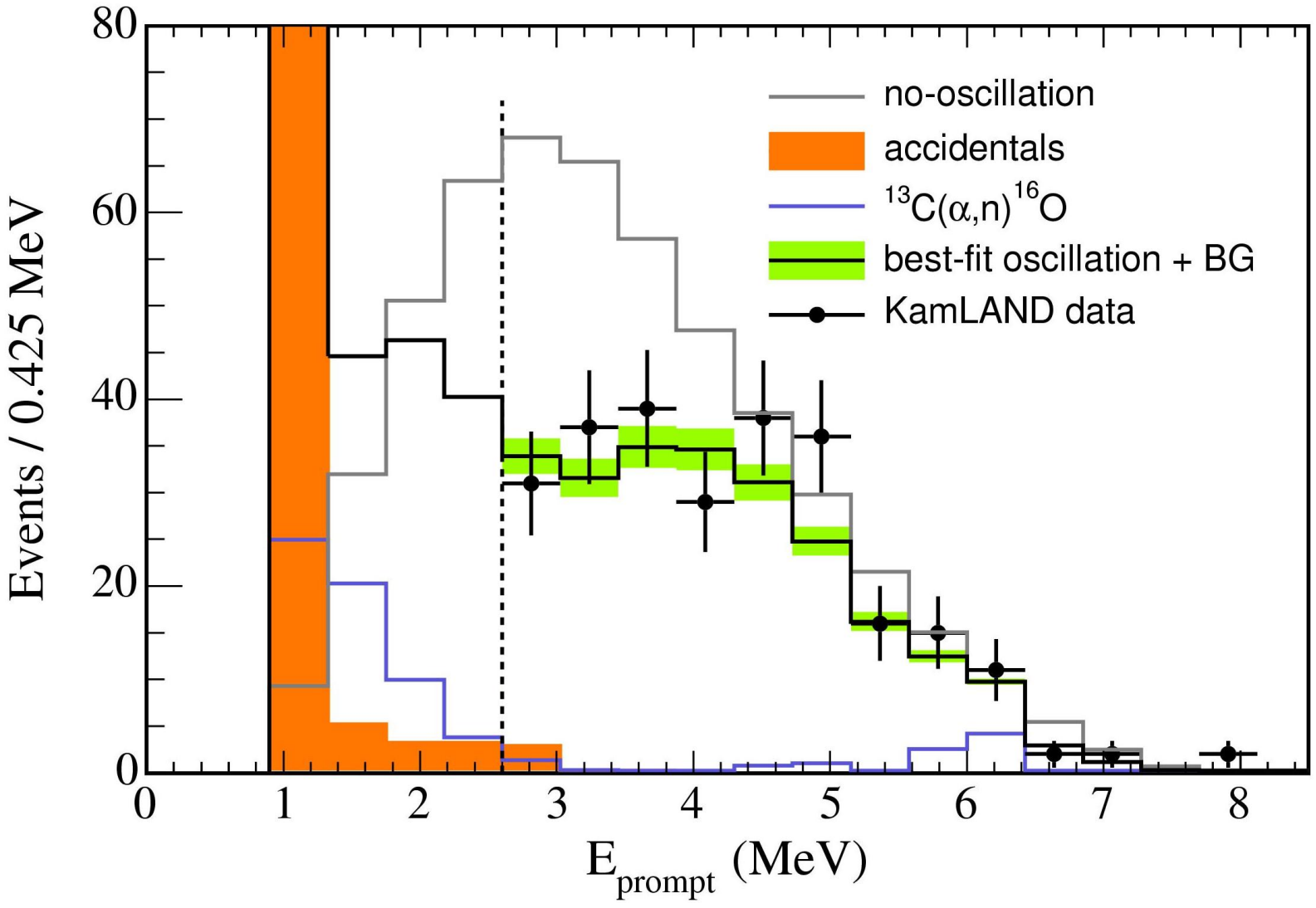


$$\sum_i P_{ee}(i)\,\phi_{\bar{\nu}_e}(i)$$

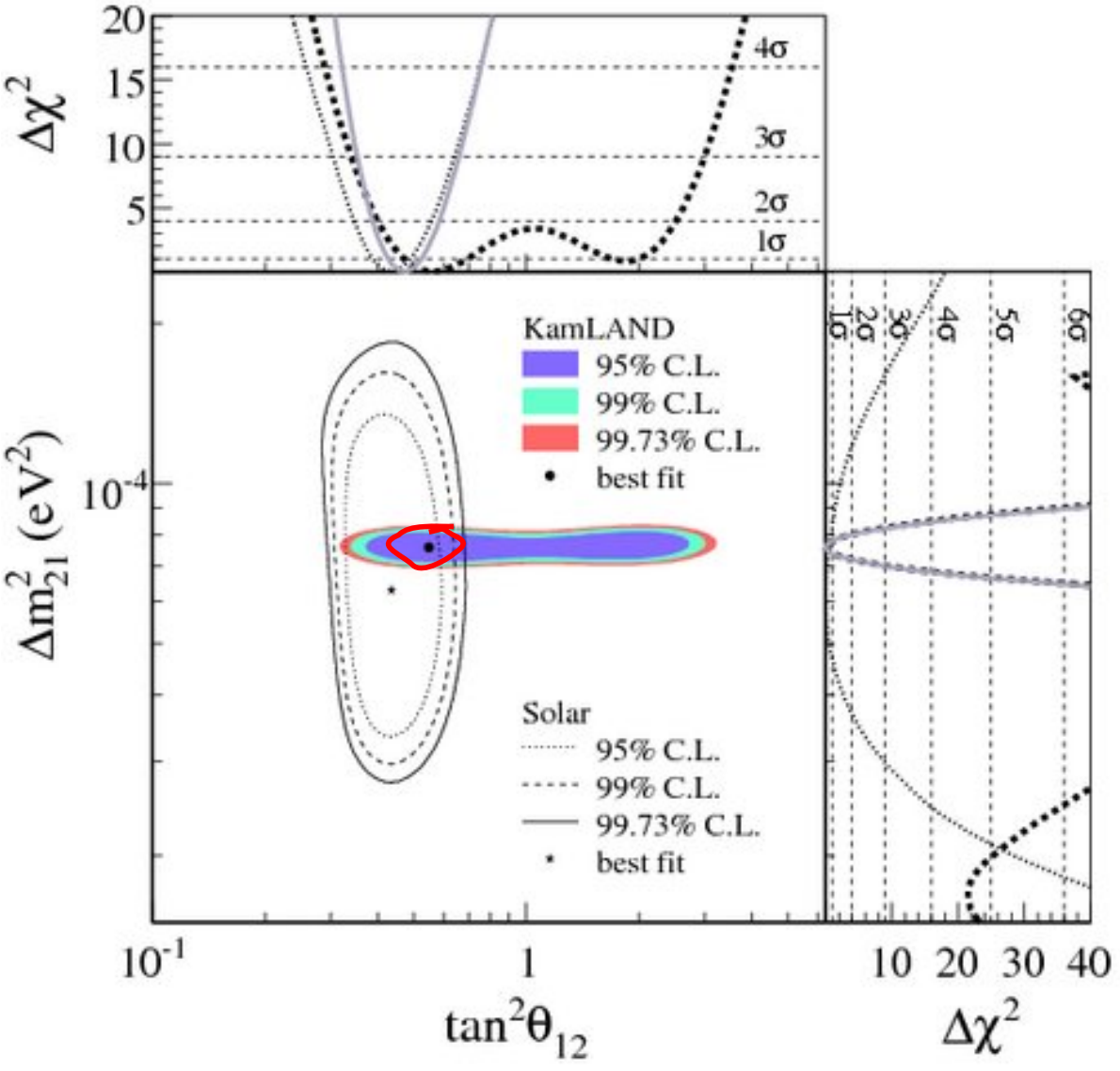
$$\downarrow$$

$$\Delta m^2, \theta, L_i$$

$\bar{\nu}_e$ spectrum at KamLAND



Net fit for solar neutrino parameter space



Features of solar neutrino solution

- LMA MSW solution:
  $\Delta m^2_\odot \approx (7.05 - 8.35) \times 10^{-5}\ \text{eV}^2$
  $\sin^2\theta_\odot \approx 0.25 - 0.37$

- Almost adiabatic propagation:
  $P_{ee} \approx \sin^2\theta$

- No energy dependence, no day-night asymmetry

Explaining features of experiments