An Overview of Solar Neutrinos

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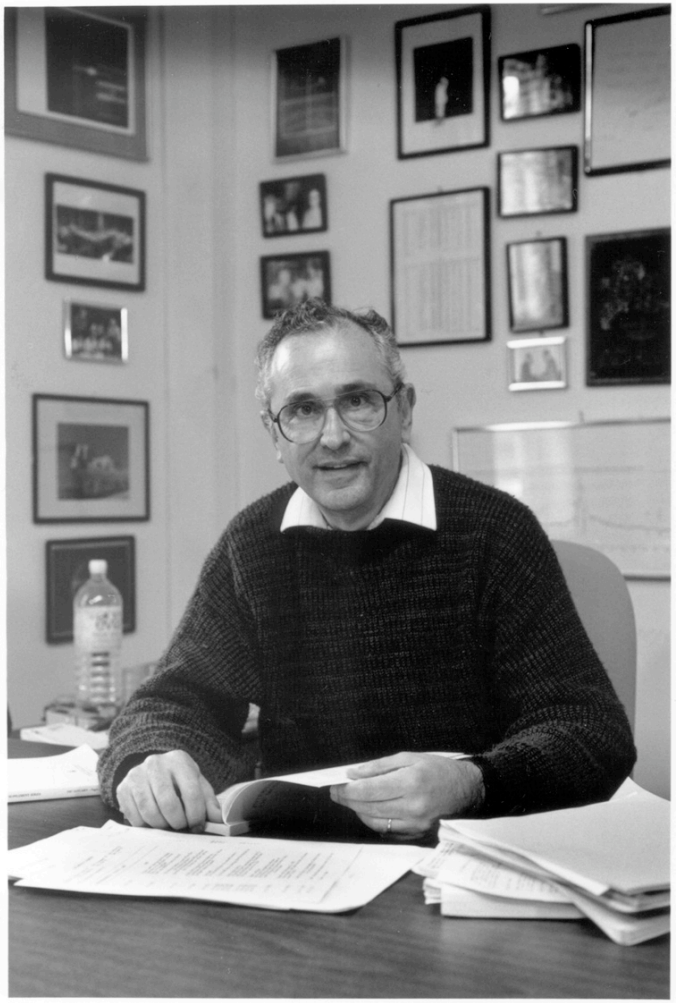
University of Wisconsin

PANIC05 Satellite Meeting
Future of Neutrino Physics
October 29, 2005; Santa Fe



John Bahcall

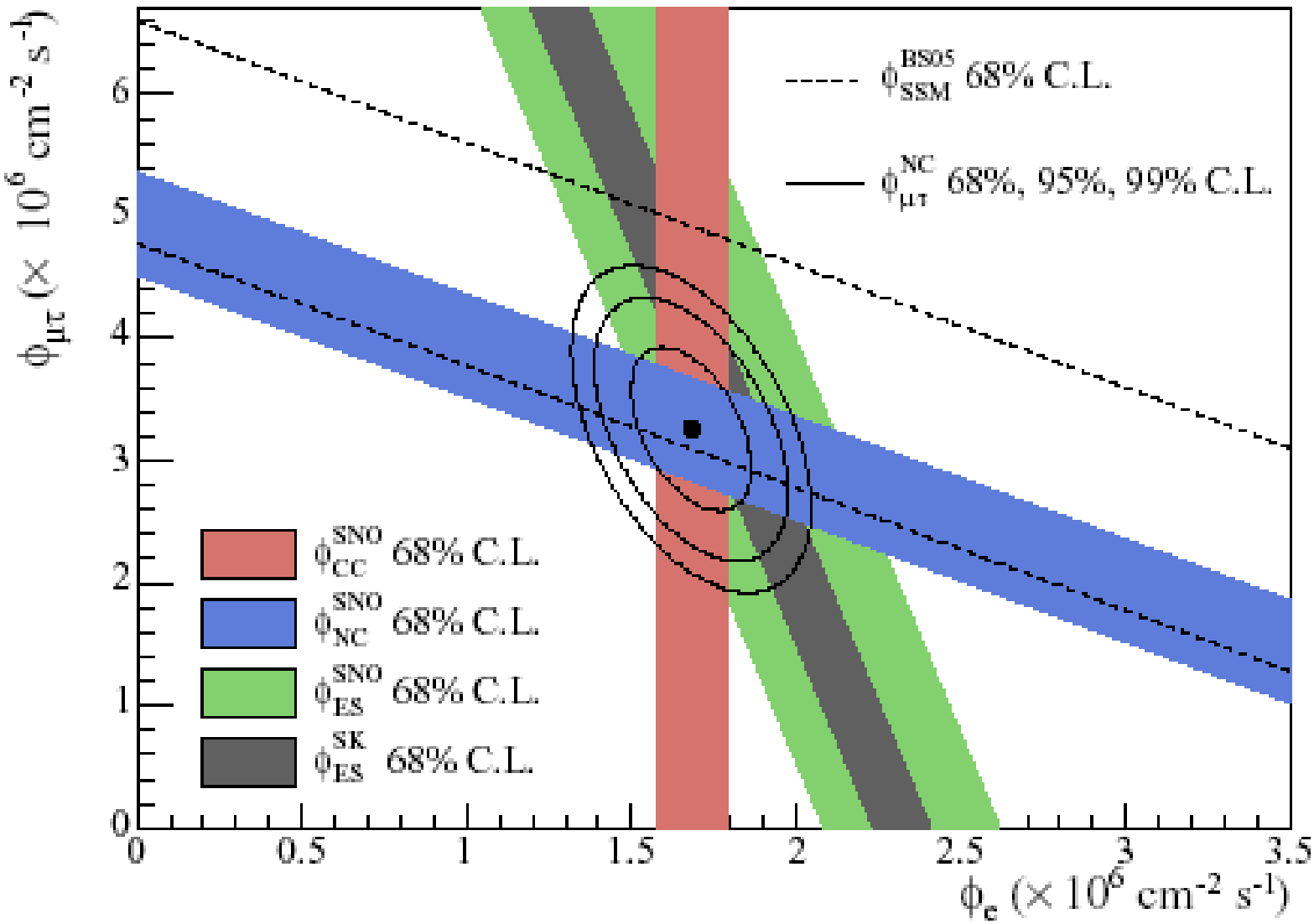
1934-2005

The legacy:

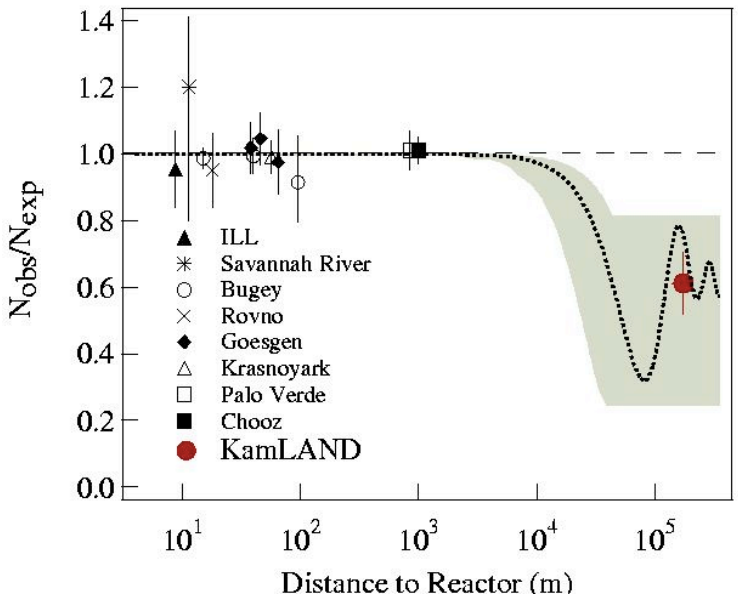
"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."

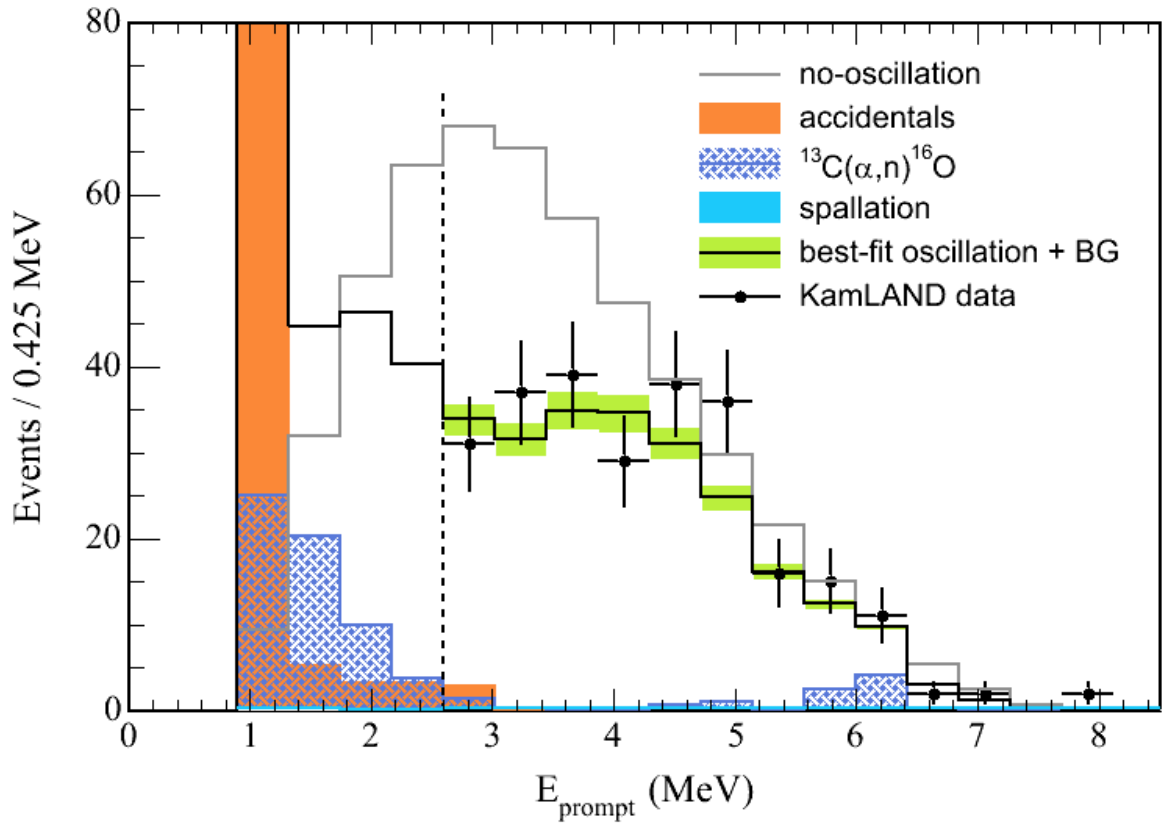
Bahcall and Davis, 1964

Results from SNO



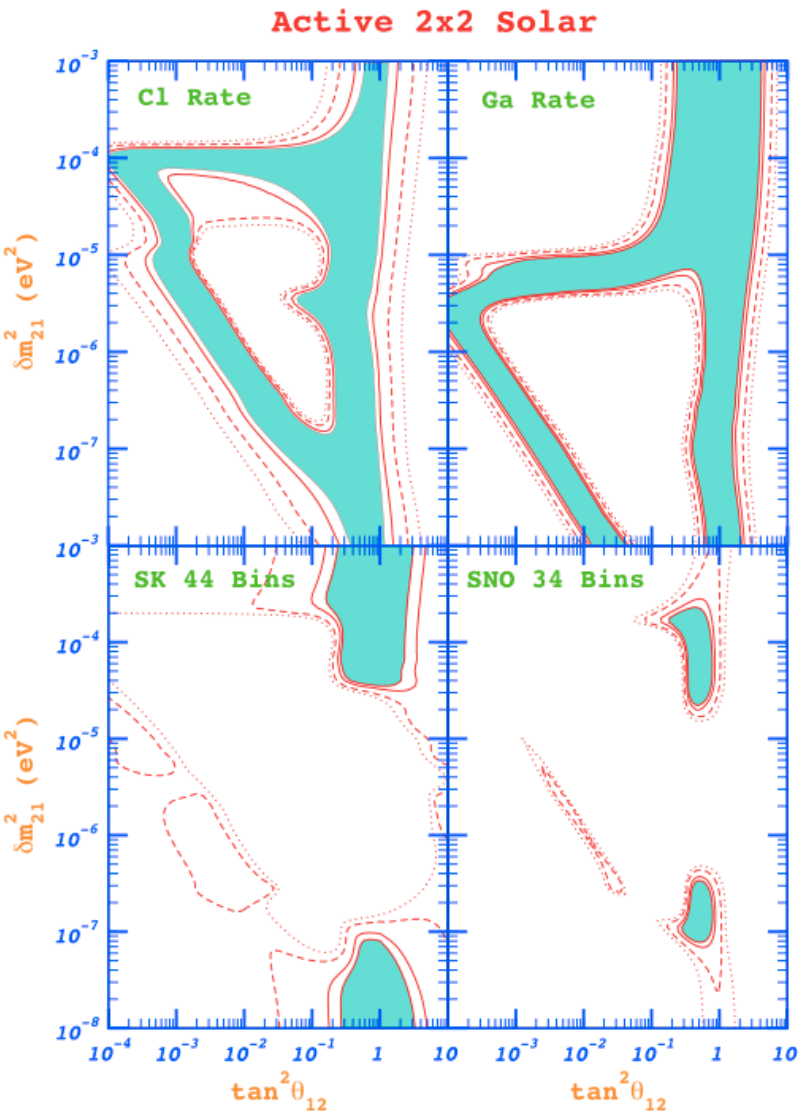
KamLAND

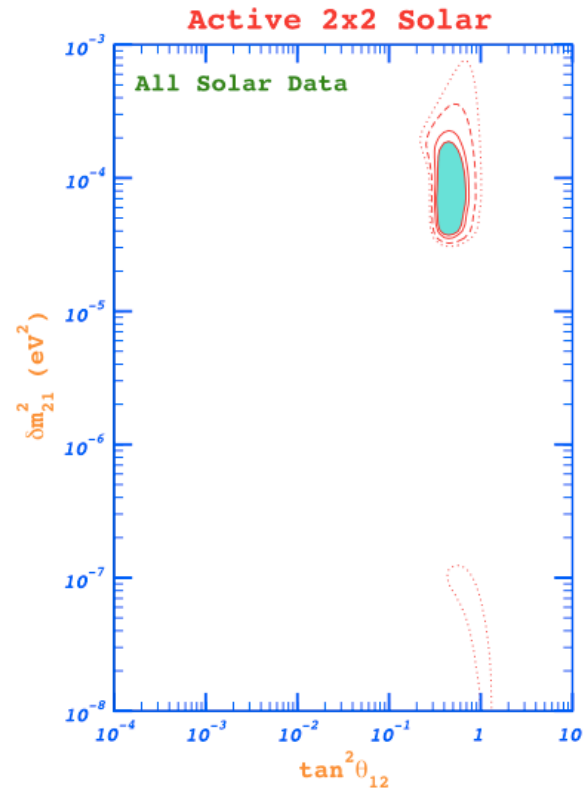




$\bar{\nu}_e + p \rightarrow n + e^+$

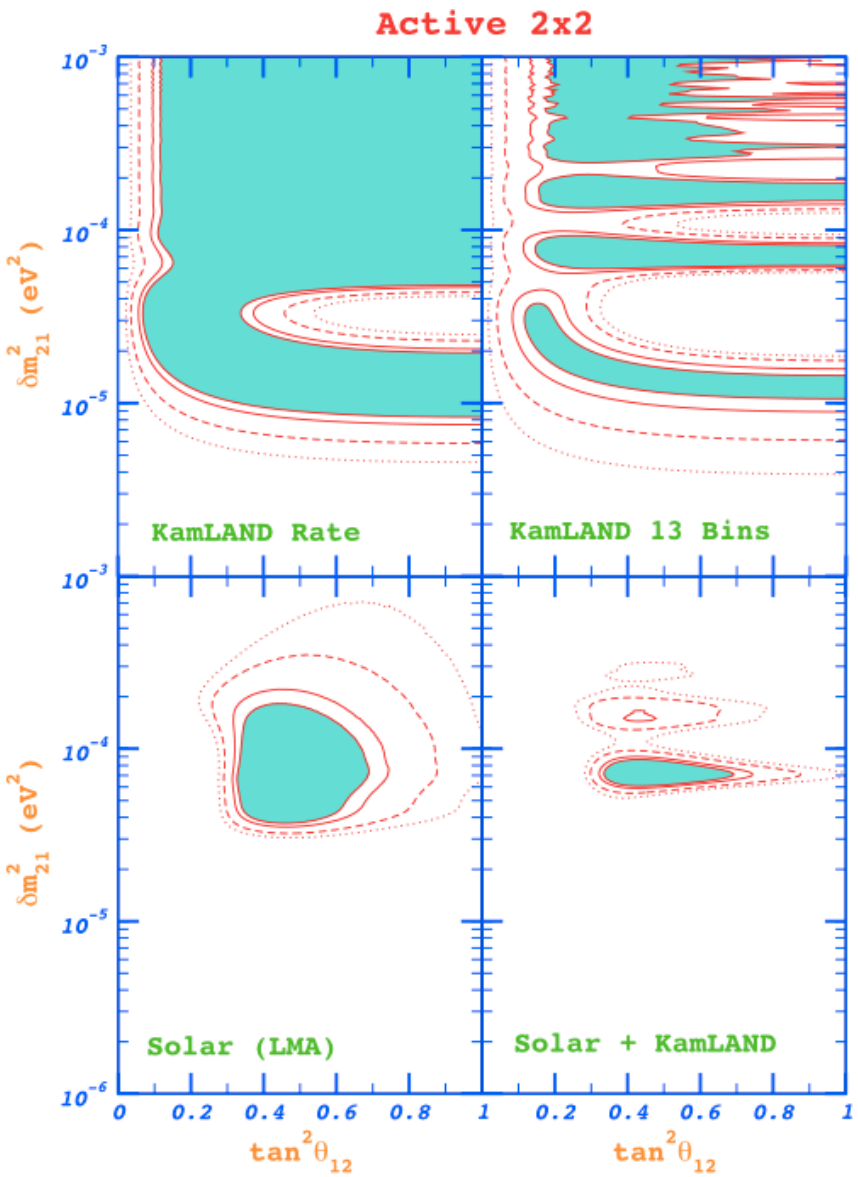
A global analysis of the solar neutrino data

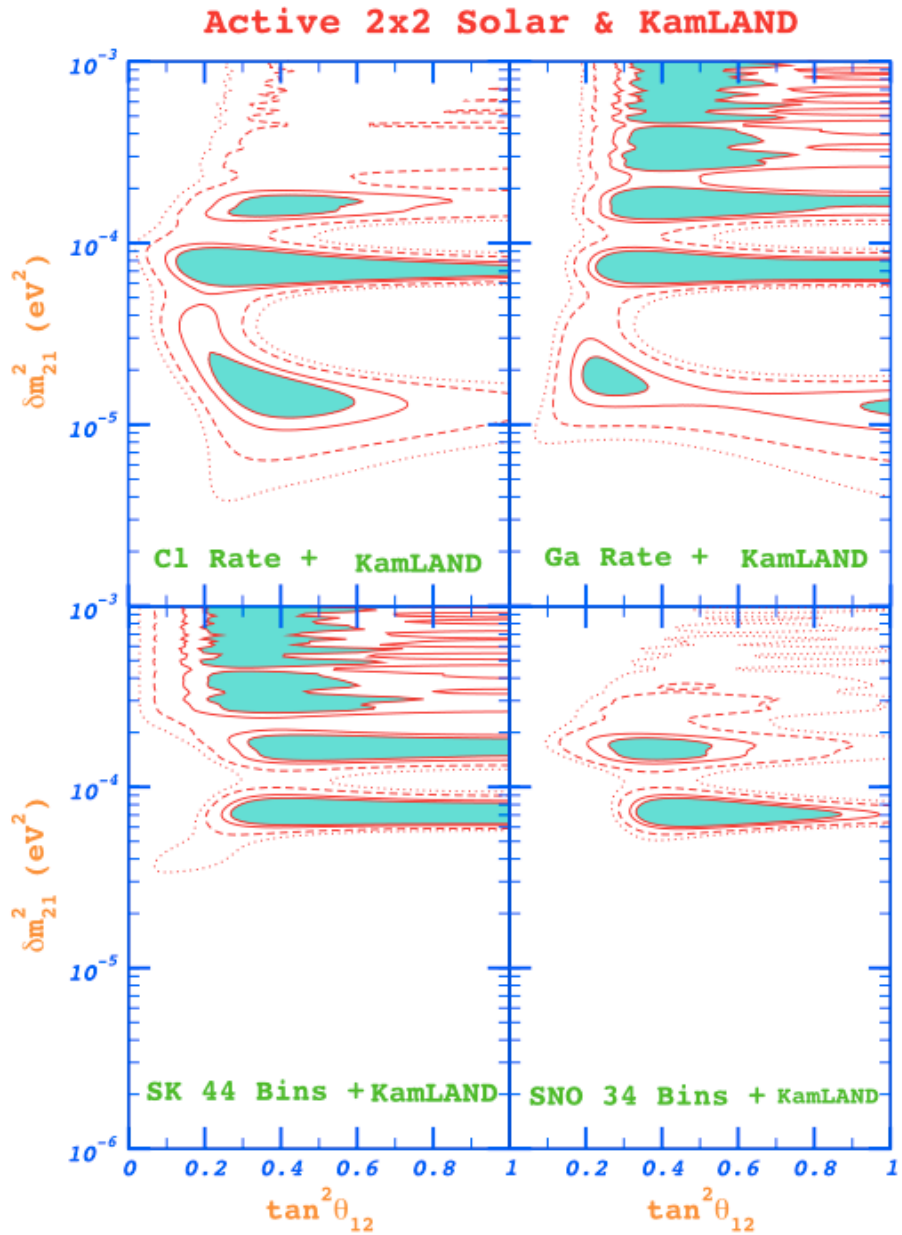




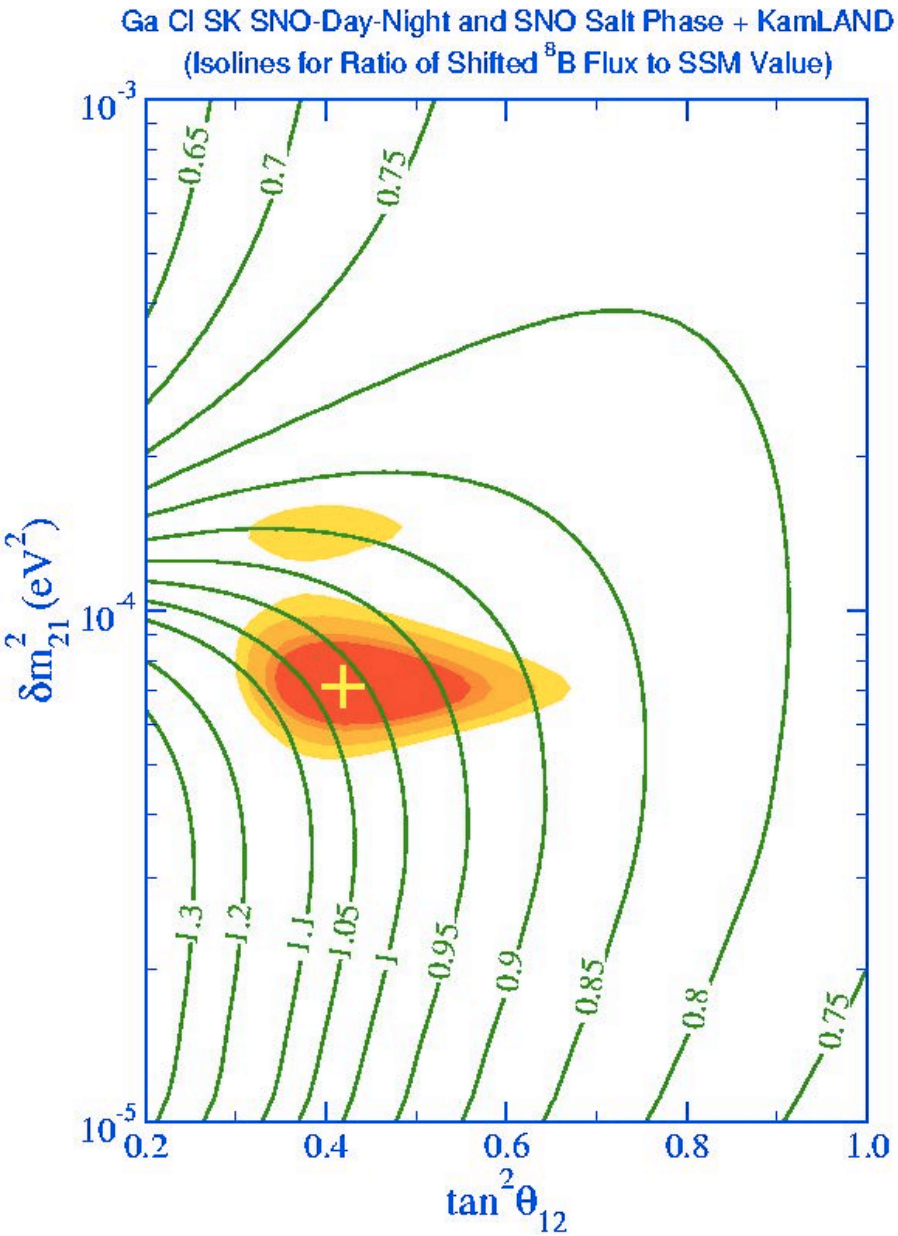
Balantekin & Yuksel, J. Phys. G 29, 665 (2003).

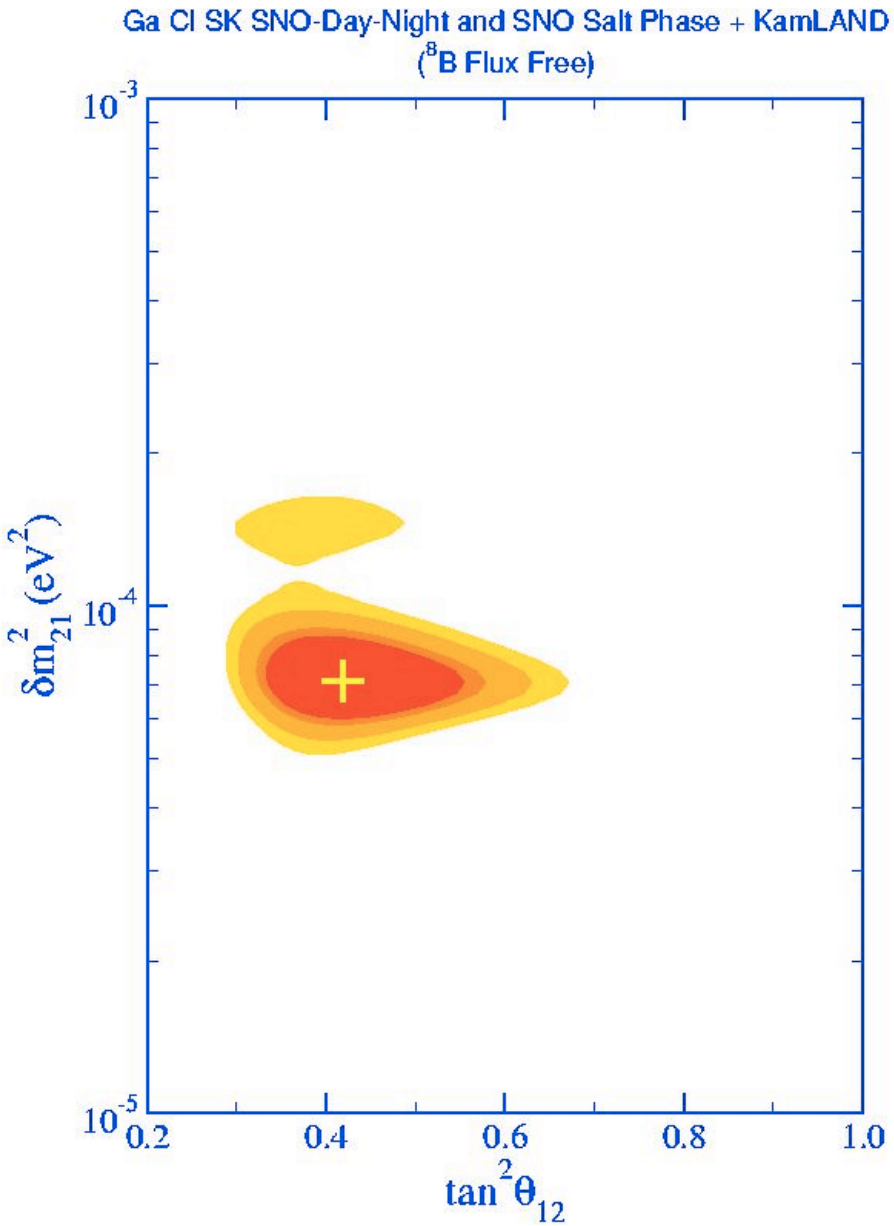
Solar + KamLAND Global Analysis





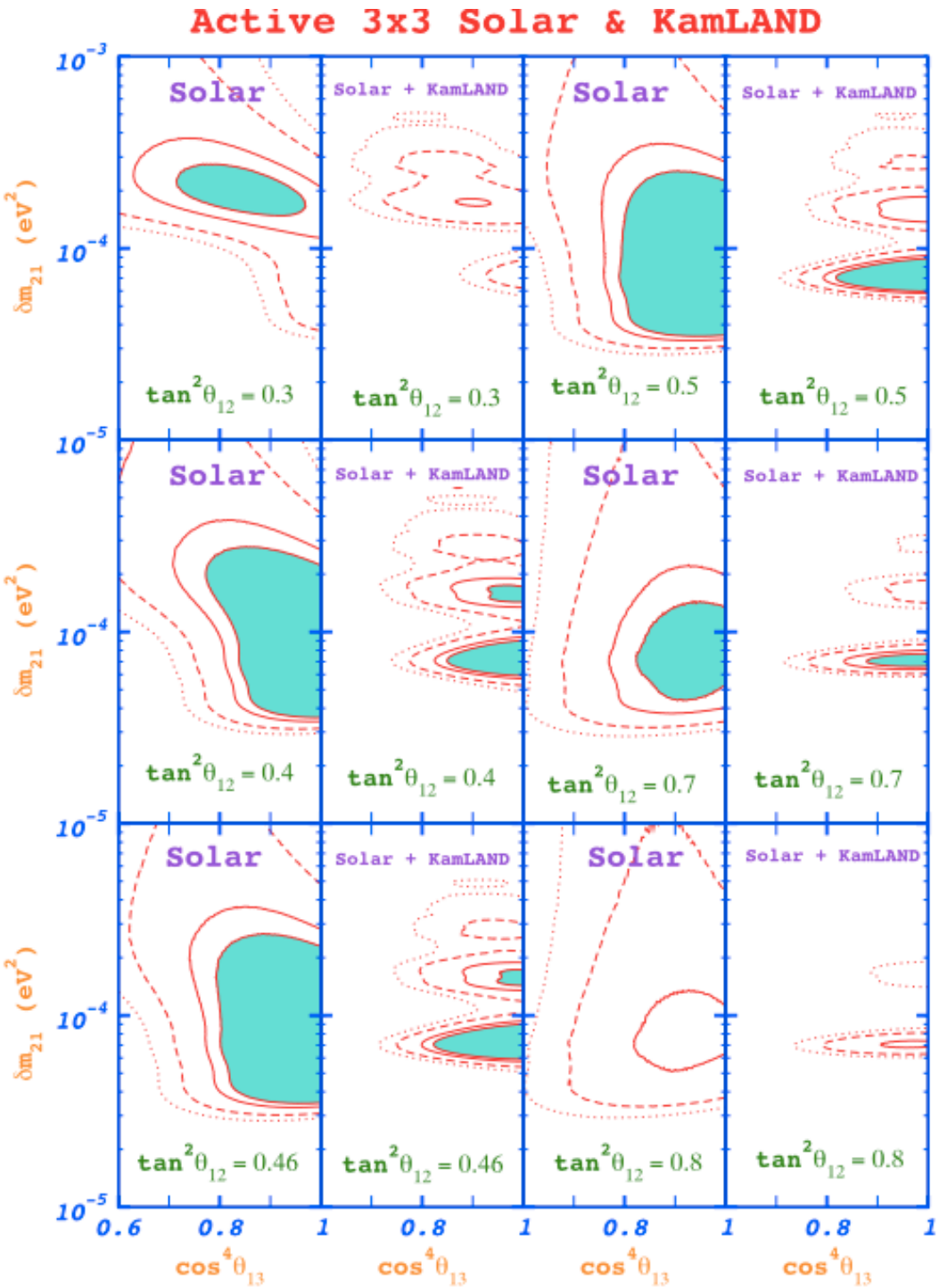
SNO first Salt Results , Balantekin and Yuksel, PRD 68, 113002 (2003)





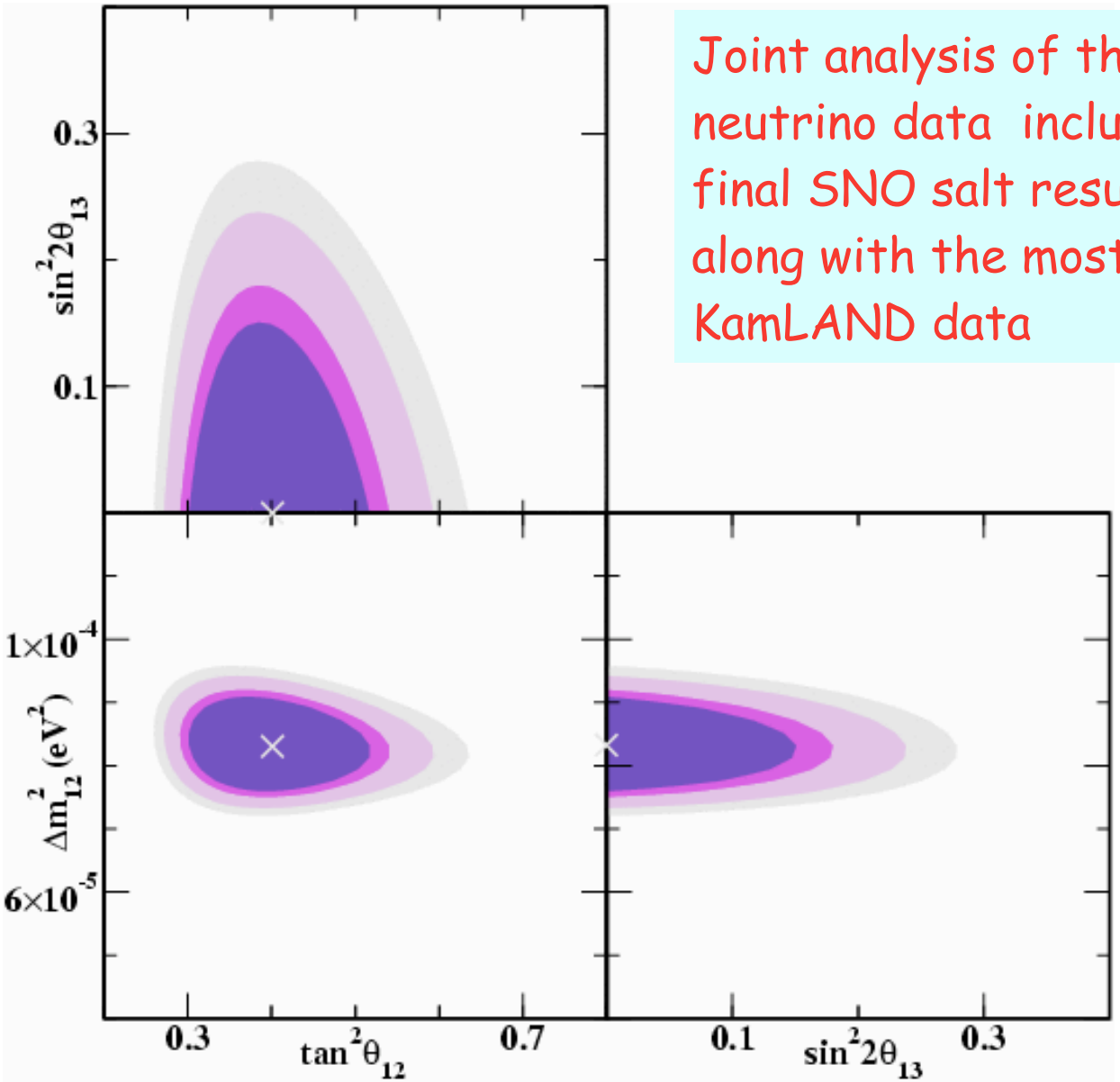
Can we probe θ_{13} in solar neutrino experiments?

Not easily!



3 parameter Global Fits to Solar Neutrino Experiments And KamLAND for different values of θ_{13}

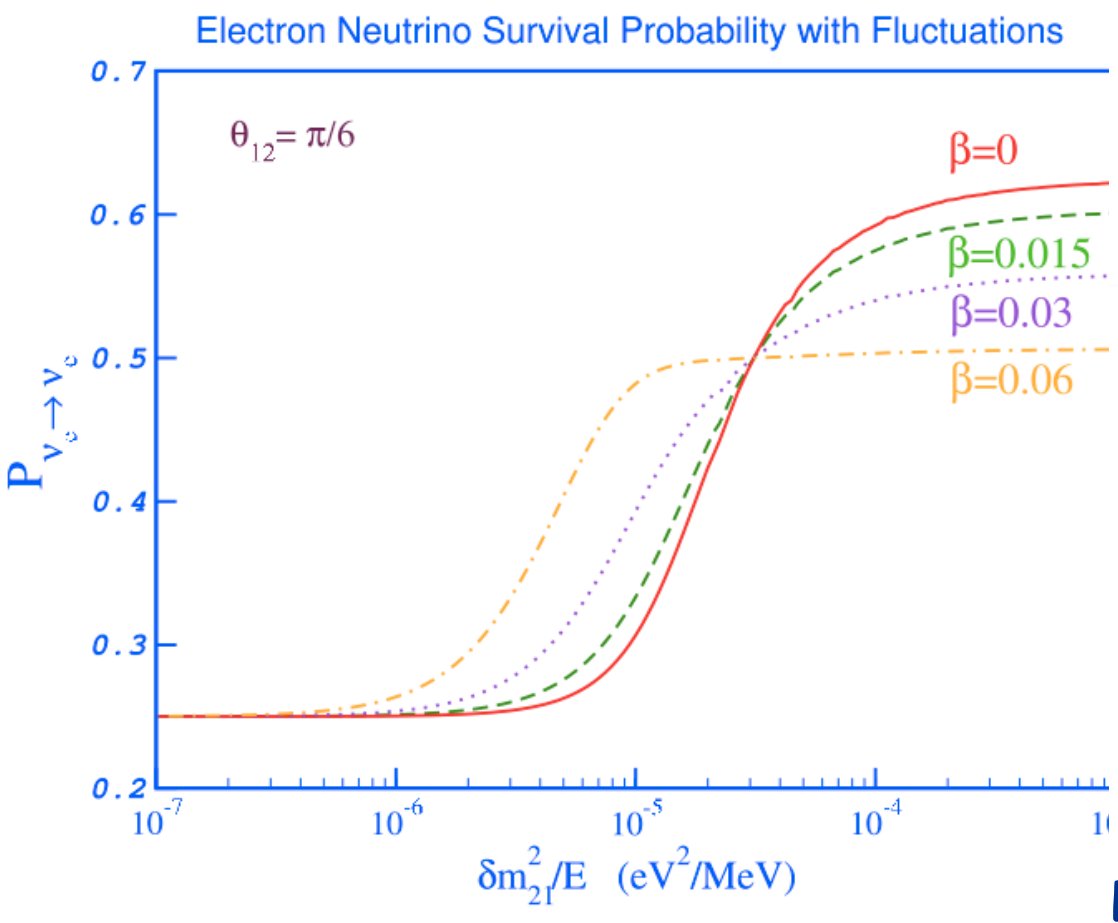
Balantekin & Yuksel, J. Phys. G 29, 665 (2003).

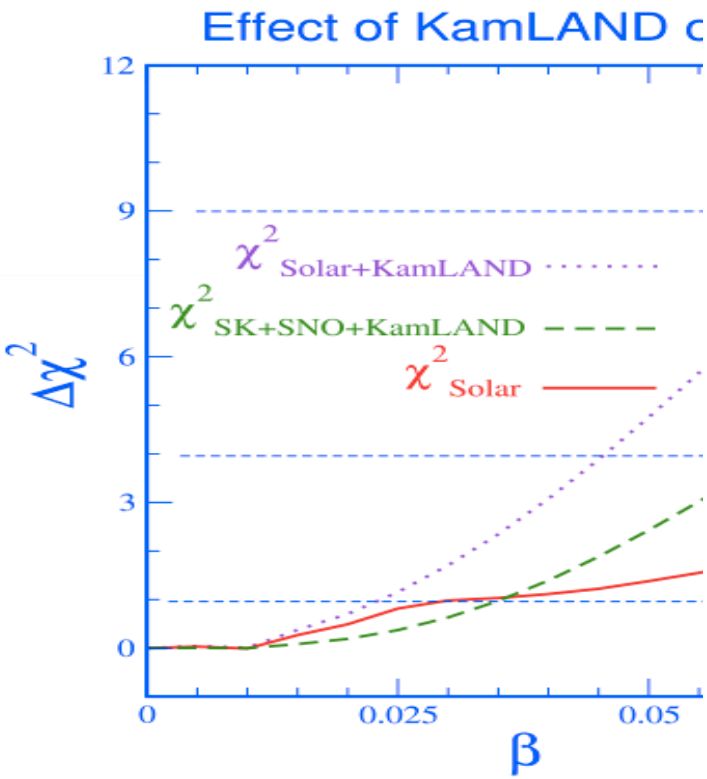


Joint analysis of the solar neutrino data including final SNO salt results along with the most recent KamLAND data

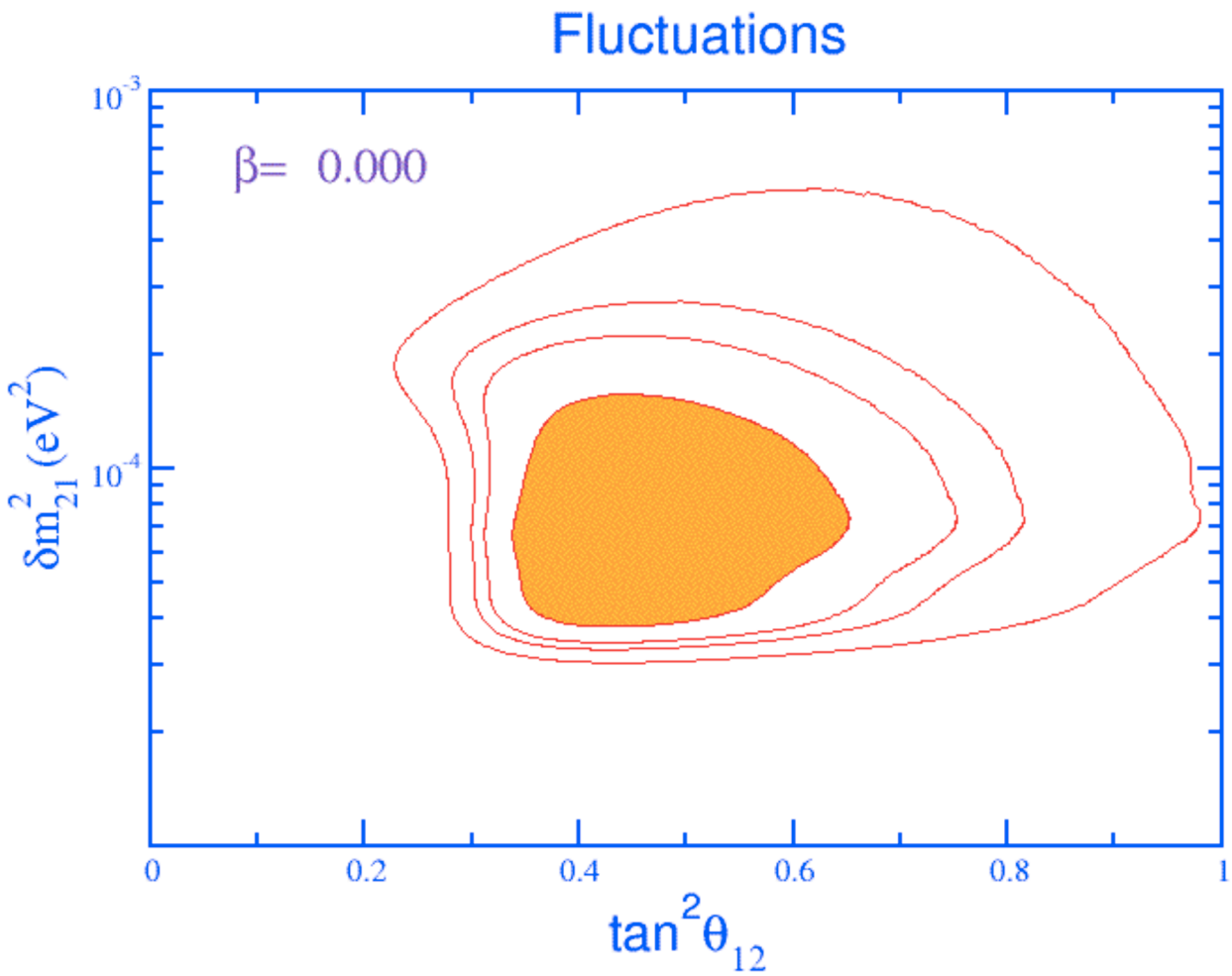
Balantekin, et al., PLB 613, 61 (2005)

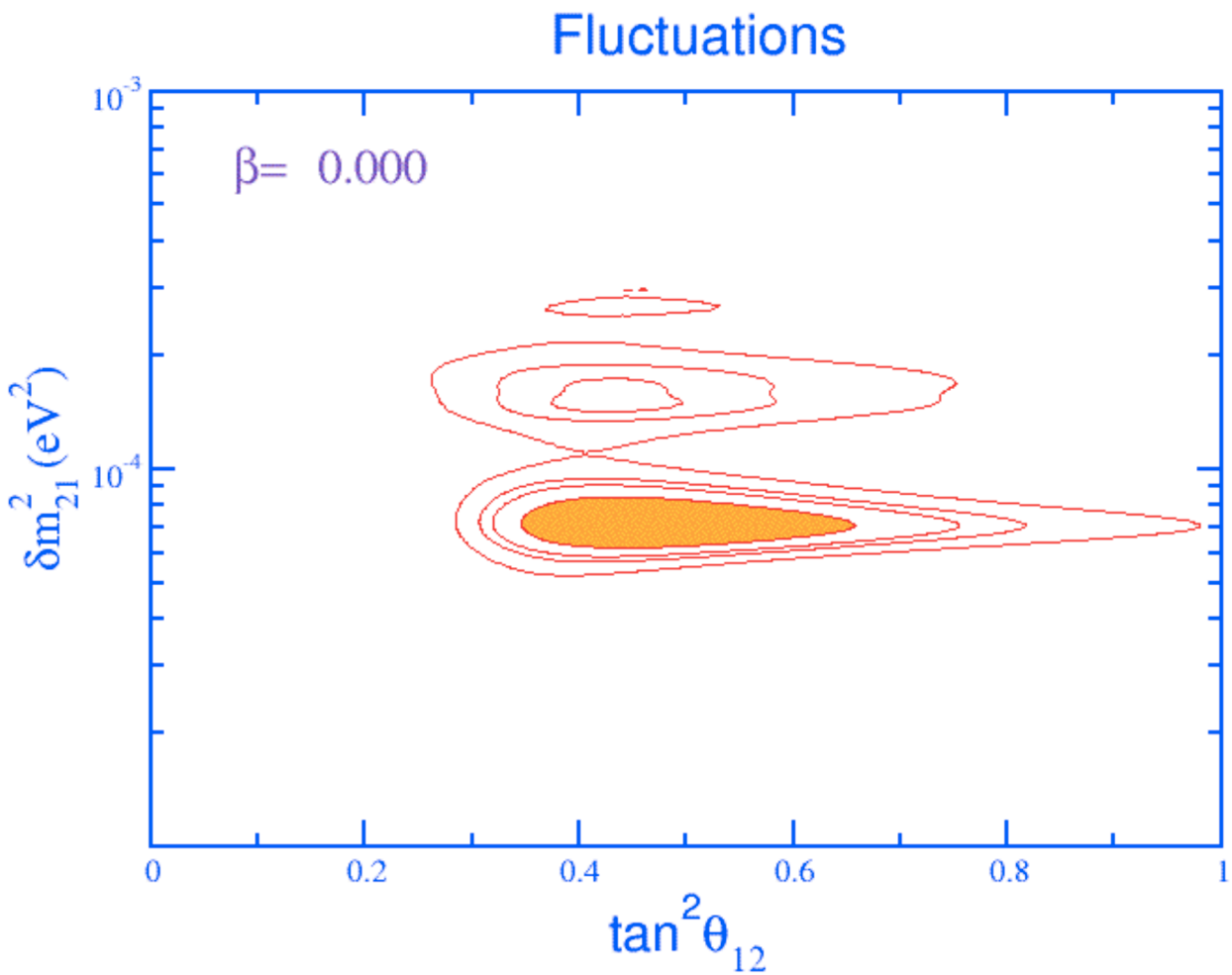
Can we rule out solar density fluctuations?

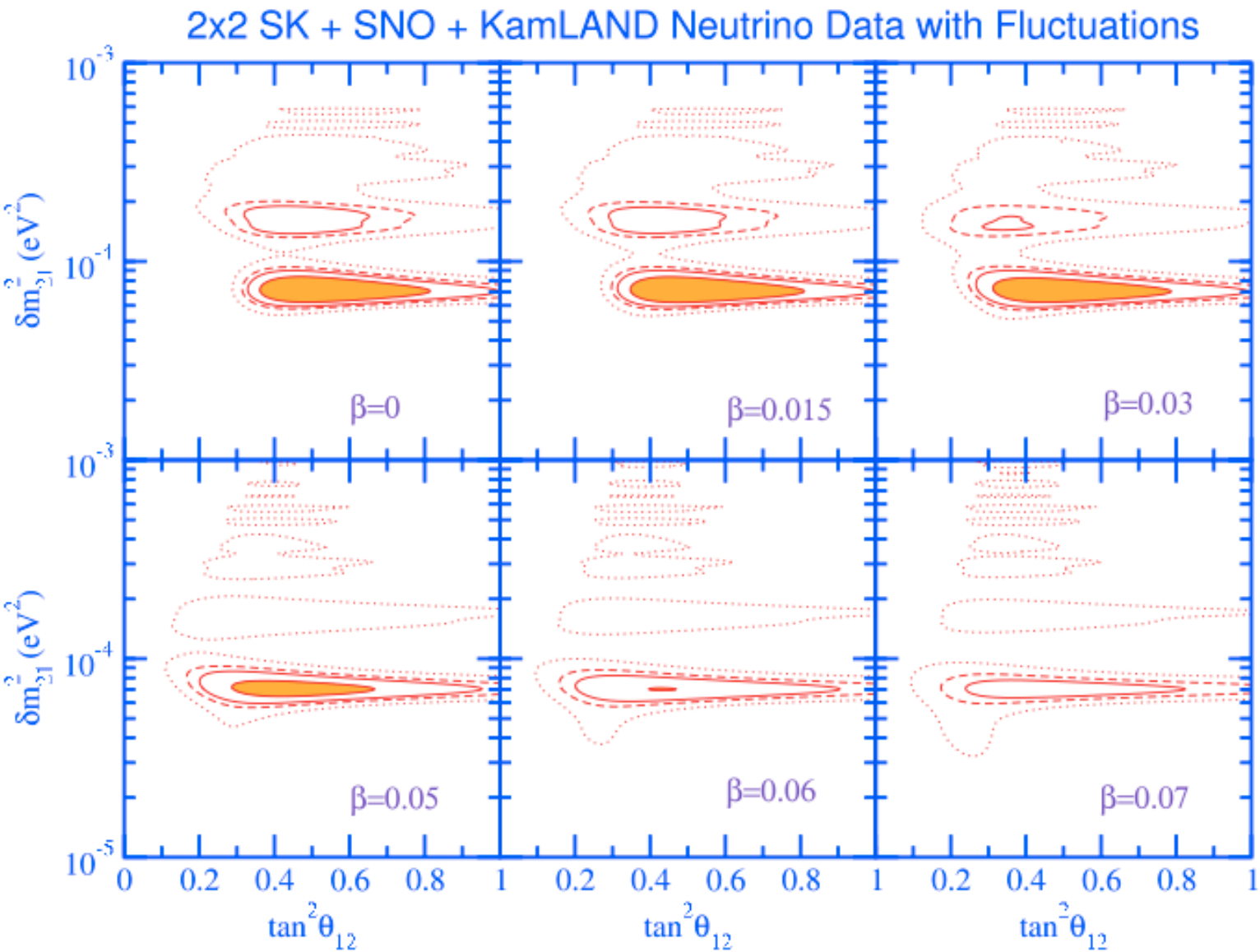




Balantekin and Yuksel, PRD 68, 013006 (2003)

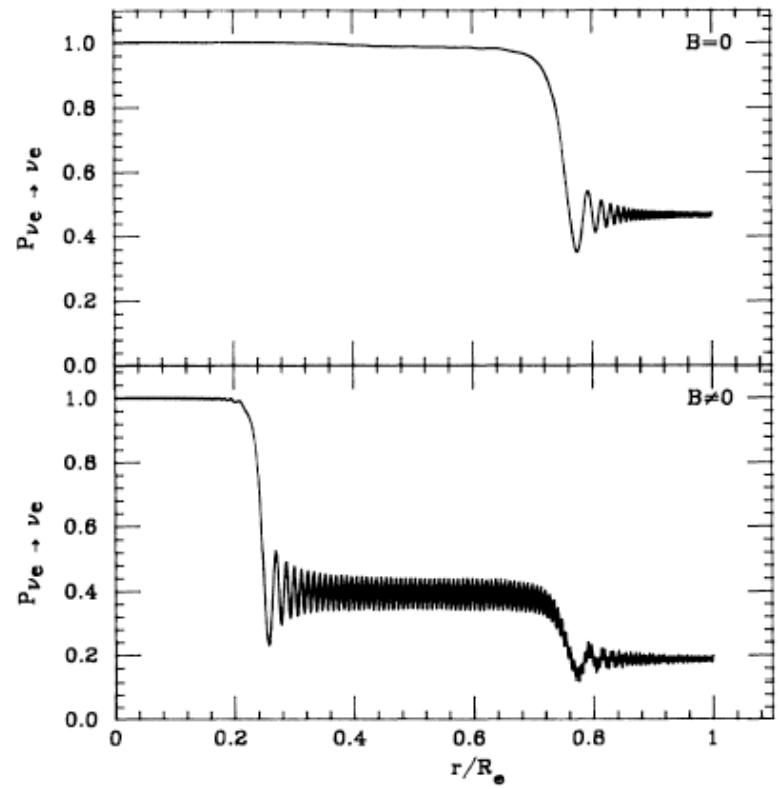

Fluctuations
β= 0.000
10^{-3}
10^{-4}
δm^2_{21} (eV^2)
0
0.2
0.4
0.6
0.8
1
$\tan^2\theta_{12}$


Fluctuations
β= 0.000
10^{-3}
10^{-4}
δm^2_{21} (eV^2)
0
0.2
0.4
0.6
0.8
1
$\tan^2\theta_{12}$


2x2 SK + SNO + KamLAND Neutrino Data with Fluctuations
δm^2_{21} (eV^2)
10^{-3}
10^{-4}
10^{-5}
β=0
β=0.015
β=0.03
β=0.05
β=0.06
β=0.07
0
0.2
0.4
0.6
0.8
1
$\tan^2\theta_{12}$

Spin-flavor precession in the Sun

$$i\frac{d}{dt}\begin{bmatrix}\nu_{e_L}\\ \nu_{\mu_L}\\ \nu_{e_R}\\ \nu_{\mu_R}\end{bmatrix}=\begin{bmatrix}H_L & BM^\dagger\\ BM & H_R\end{bmatrix}\begin{bmatrix}\nu_{e_L}\\ \nu_{\mu_L}\\ \nu_{e_R}\\ \nu_{\mu_R}\end{bmatrix}$$



$$H_L=\begin{bmatrix}\frac{\Delta m^2}{2E}\sin^2\theta+a_e & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{2E}\cos^2\theta+a_\mu\end{bmatrix}$$

$$H_R=H_L(a_e=0=a_\mu)$$

$$M=\begin{bmatrix}\mu_{ee} & \mu_{e\mu}\\ \mu_{\mu e} & \mu_{\mu\mu}\end{bmatrix}$$

$$a_e=\frac{G_F}{\sqrt{2}}(2N_e-N_n),\quad a_\mu=-\frac{G_F}{\sqrt{2}}N_n$$

Dirac neutrinos

Marciano, Lim and Akhmedov

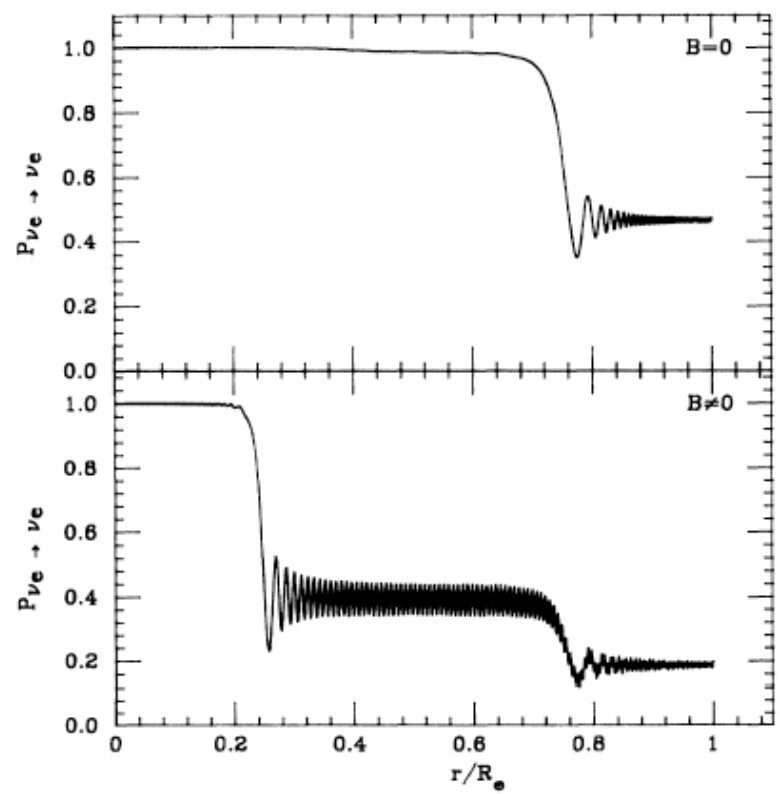
$$H_{\mathrm{Maj}} = \begin{pmatrix} a_e & \frac{\Delta m^2}{4E}\sin 2\theta & 0 & \mu^* B \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{2E}\cos 2\theta + a_\mu & -\mu^* B & 0 \\ 0 & -\mu B & -a_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \mu B & 0 & \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{2E}\cos 2\theta - a_\mu \end{pmatrix}$$

Majorana neutrinos

E_ν	SFP	MSW
2.50	0	0.07
3.35	0.05	0.10
5.00	0.10	0.13
8.00	0.15	0.18
13.00	0.20	0.22

Locations of the SFP and MSW resonances in the sun

For the solar neutrinos these resonances essentially overlap (Friedland)

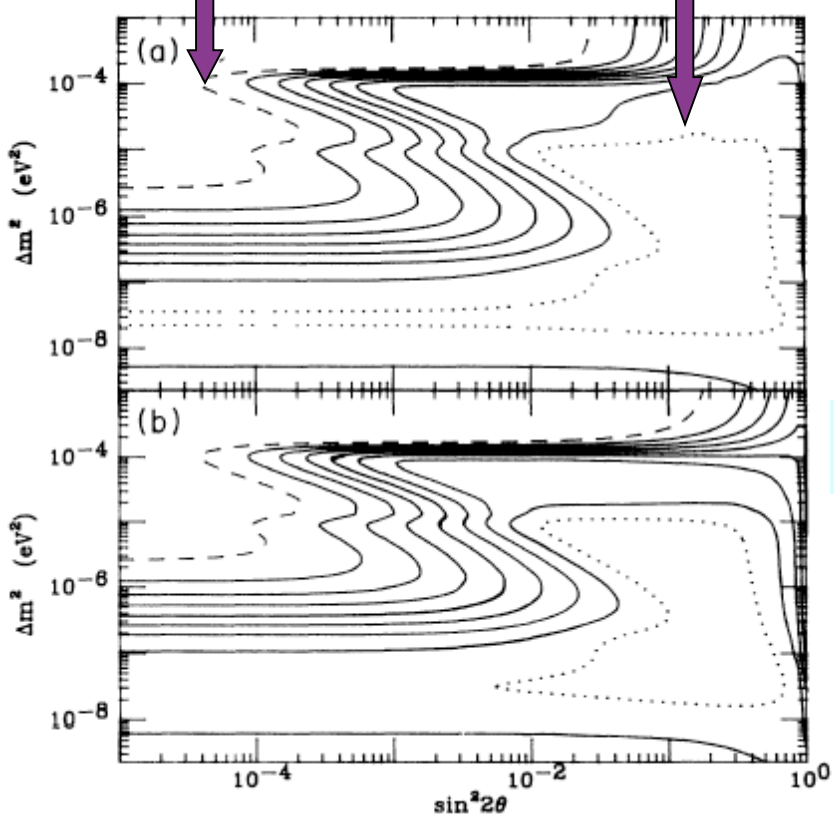


Solar magnetic fields

- Standard Solar Model requires $B < 10^8$ G.
- Helioseismology: If $B > 10^7$ G, sound speed profile would deviate from the observed values Turck-Chieze.
- Solar neutrino flux variations with heliographic latitude may imply magnetic fields Caldwell.

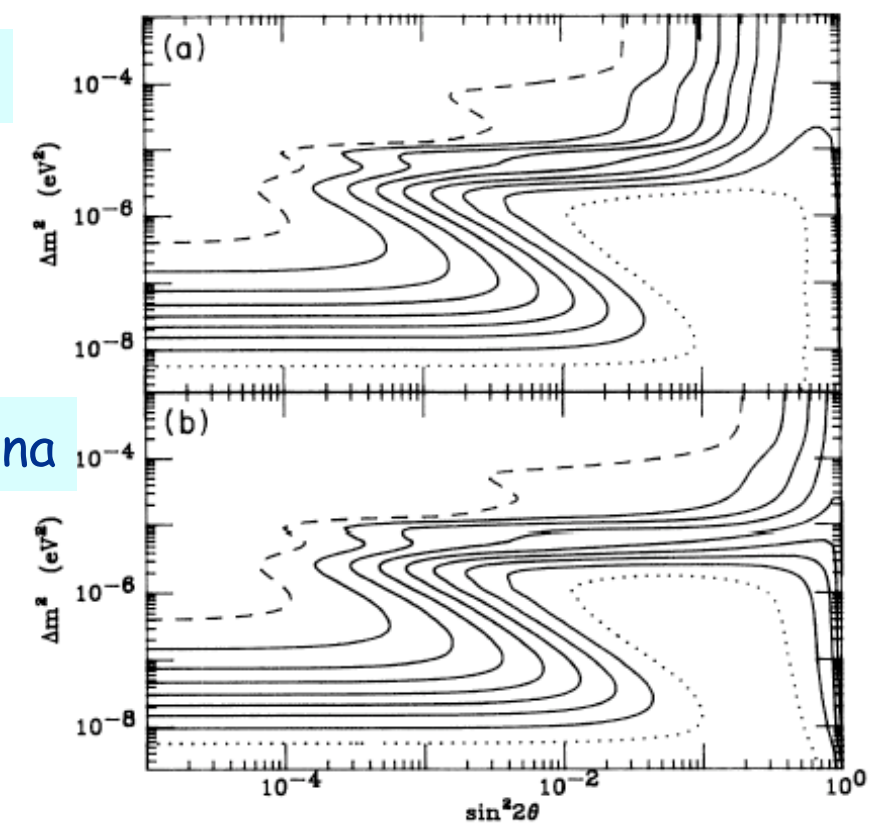
P=0.9

P=0.1



Dirac

Majorana



Cl-detector

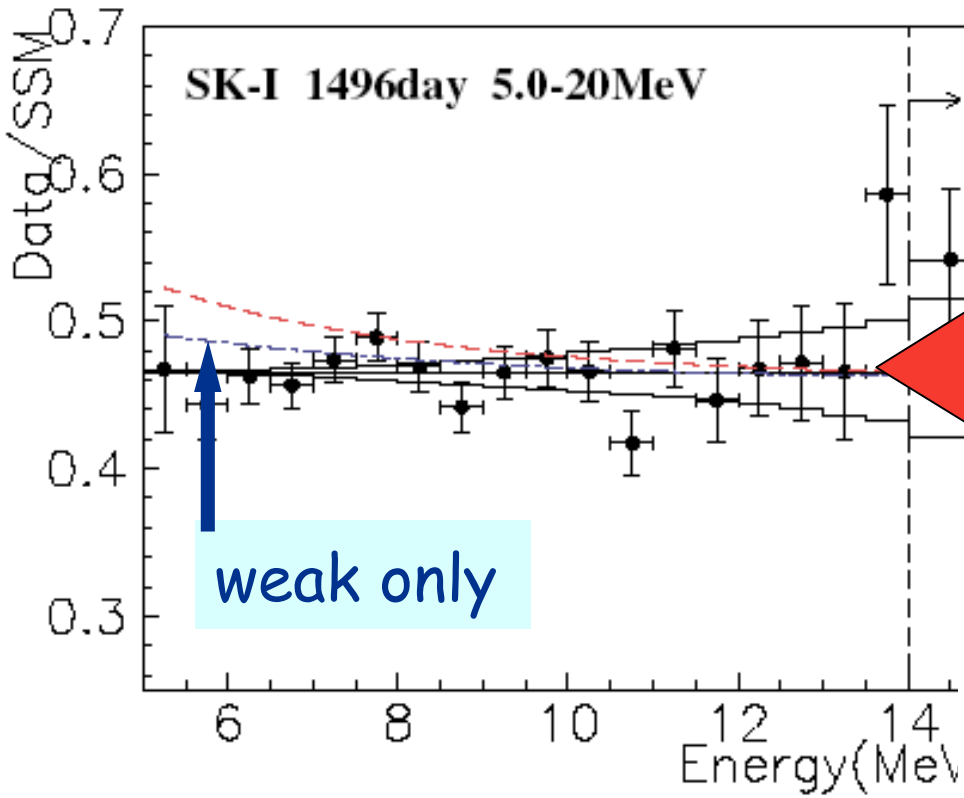
Ga-detector

A.B. Balantekin, P. Hatchell, F. Loreti, Phys. Rev. D41, 3583 (1990)

Balantekin, Loreti, Pakvasa, Raghavan. Spin-flavor precession changes neutrino helicity. If the neutrinos are of Majorana type this yields a solar antineutrino flux.

Kamland and SNO bounds on solar antineutrino flux:

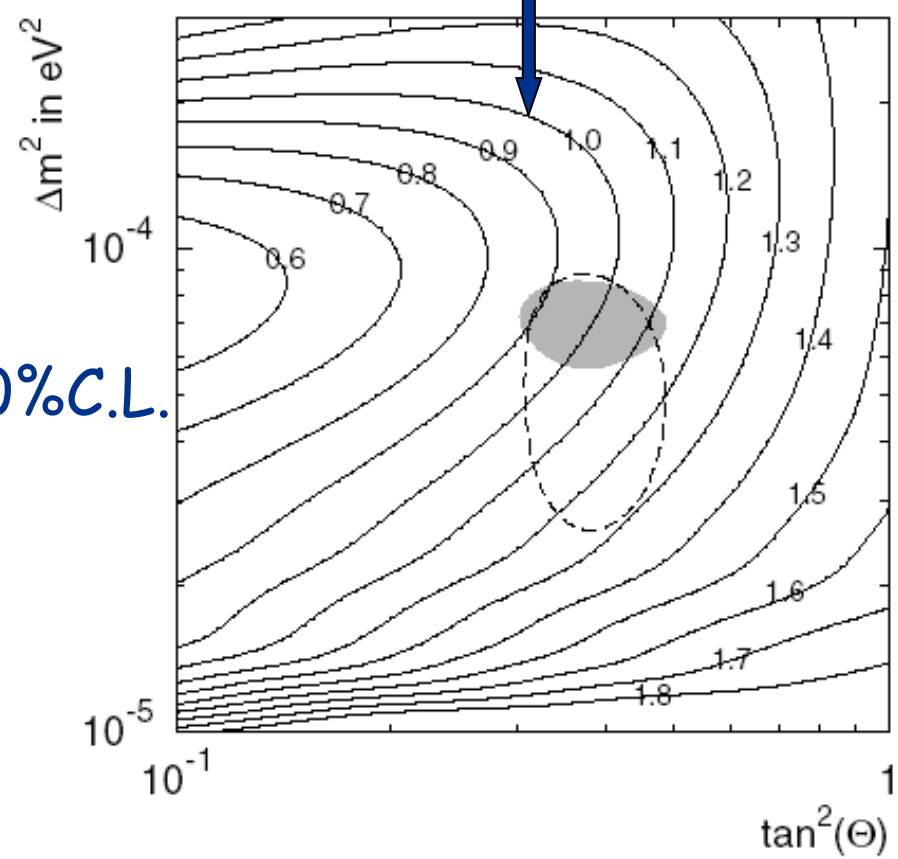
$$\Phi_{antineutrino} \leq 3 \times 10^{-4}\, \Phi_{B8\text{-}neutrino}$$



weak only

additional $\square_{\square}<10^{-10}\square_B$

$\square_{\square}=10^{-10}\square_B$



SuperK: $\square_{\square} \leq (3.6 \times 10^{-10})\square_B$ at 90%C.L.

SuperK + KamLAND:

$\square_{\square} \leq (1.1 \times 10^{-10})\square_B$ at 90%C.L.

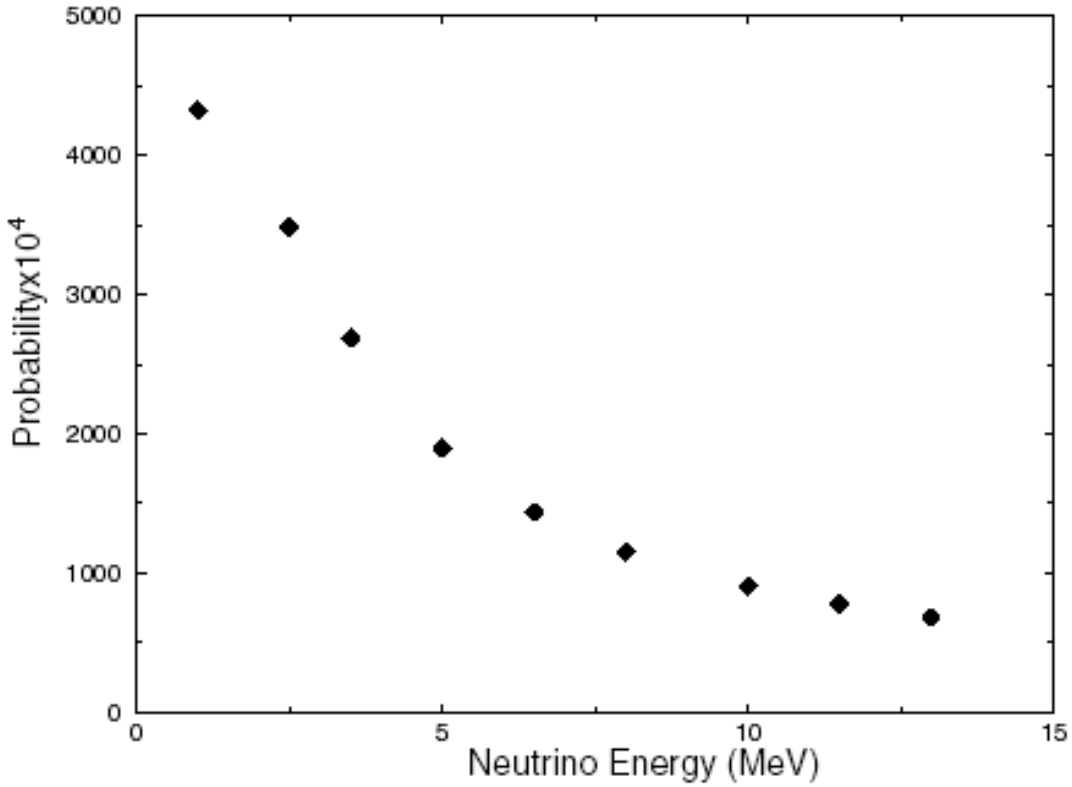
$$\frac{d^2}{dt^2}\nu_e^{(L)} + \left(\phi^2 + i\frac{d\phi}{dt} + \Delta^2 + (\mu B)^2\right)\nu_e^{(L)} + \mu B\sqrt{2}G_F N_n \nu_\mu^{(R)} = 0.$$

$$P(\nu_e \to \nu_e) = \frac{1}{2} - \frac{1}{2}\cos 2\theta_v (1 - 2P_{\rm hop}),$$

for the limiting case of $N_n = 0$, one gets

$$P_{\rm hop}(\mu B \neq 0) = P_{\rm hop}(\mu B = 0)\exp\left\{\frac{i}{\pi}\int_{r_0}^{r_0^*} dr \frac{\delta m^2}{2E}\left[\frac{(\mu B)^2}{\sqrt{\zeta^2(r) - 2\zeta(r)\cos 2\theta_v + 1}}\right]\right\}.$$

A.B. Balantekin and C. Volpe, Phys. Rev. D72, 033008 (2005)



- $\mu = 10^{-11}\ \mu_B$
- $B = 10^5\ G$
- $\Delta m^2 = 8 \times 10^{-5}\ eV^2$
- $\tan^2\theta = 0.4$

For these parameters the difference between MSW only and SFP+MSW is less than 10^{-5}.

A.B. Balantekin and C. Volpe, Phys. Rev. D72, 033008 (2005)

Probing non-standard neutrino interactions

Friedland, Lunardini, Pena-Gray, hep-ph/0402266;

Miranda, Tortola, Valle, hep-ph/0406280

$$L^{\mathrm{NSI}} = -2\sqrt{2}\, G_F (\bar{\nu}_\alpha \gamma_\rho \nu_\beta) \times \left(\epsilon_{\alpha\beta}^{f\tilde{f}L} \bar{f}_L \gamma^\rho \tilde{f}_L + \epsilon_{\alpha\beta}^{f\tilde{f}R} \bar{f}_R \gamma^\rho \tilde{f}_R\right) + \mathrm{h.c.}$$

$$\epsilon_{\alpha\beta} \equiv \sum_{f=u,d,e} \epsilon_{\alpha\beta}^{f} n_f / n_e$$

$$\epsilon_{11} = \epsilon_{ee} - \epsilon_{\tau\tau} \sin^2\theta_{23},$$
$$\epsilon_{12} = -2\epsilon_{e\tau} \sin\theta_{23}.$$

$$i\hbar \frac{\partial}{\partial x} \begin{bmatrix} \Psi_e(x) \\ \Psi_x(x) \end{bmatrix} = \begin{bmatrix} \varphi(x) & \sqrt{\Lambda} \\ \sqrt{\Lambda} & -\varphi(x) \end{bmatrix} \begin{bmatrix} \Psi_e(x) \\ \Psi_x(x) \end{bmatrix}$$

$$\varphi(x) = \frac{1}{\sqrt{2}} G_F N_e(x)[1+\epsilon_{11}(x)] - \frac{\delta m^2}{4E} \cos 2\theta_v$$

$$\sqrt{\Lambda} = \frac{\delta m^2}{4E} \sin 2\theta_v + \frac{1}{\sqrt{2}} G_F N_e(x) \epsilon_{12}(x)$$

$$i\hbar\frac{\partial}{\partial x}\begin{bmatrix}\Psi_e(x)\\ \Psi_x(x)\end{bmatrix}=\begin{bmatrix}\varphi(x) & \sqrt{\Lambda}\\ \sqrt{\Lambda} & -\varphi(x)\end{bmatrix}\begin{bmatrix}\Psi_e(x)\\ \Psi_x(x)\end{bmatrix}$$

$$\varphi(x)=\frac{1}{\sqrt{2}}G_F N_e(x)[1+\epsilon_{11}(x)]-\frac{\delta m^2}{4E}\cos 2\theta_v$$

$$\sqrt{\Lambda}=\frac{\delta m^2}{4E}\sin 2\theta_v+\frac{1}{\sqrt{2}}G_F N_e(x)\epsilon_{12}(x)$$

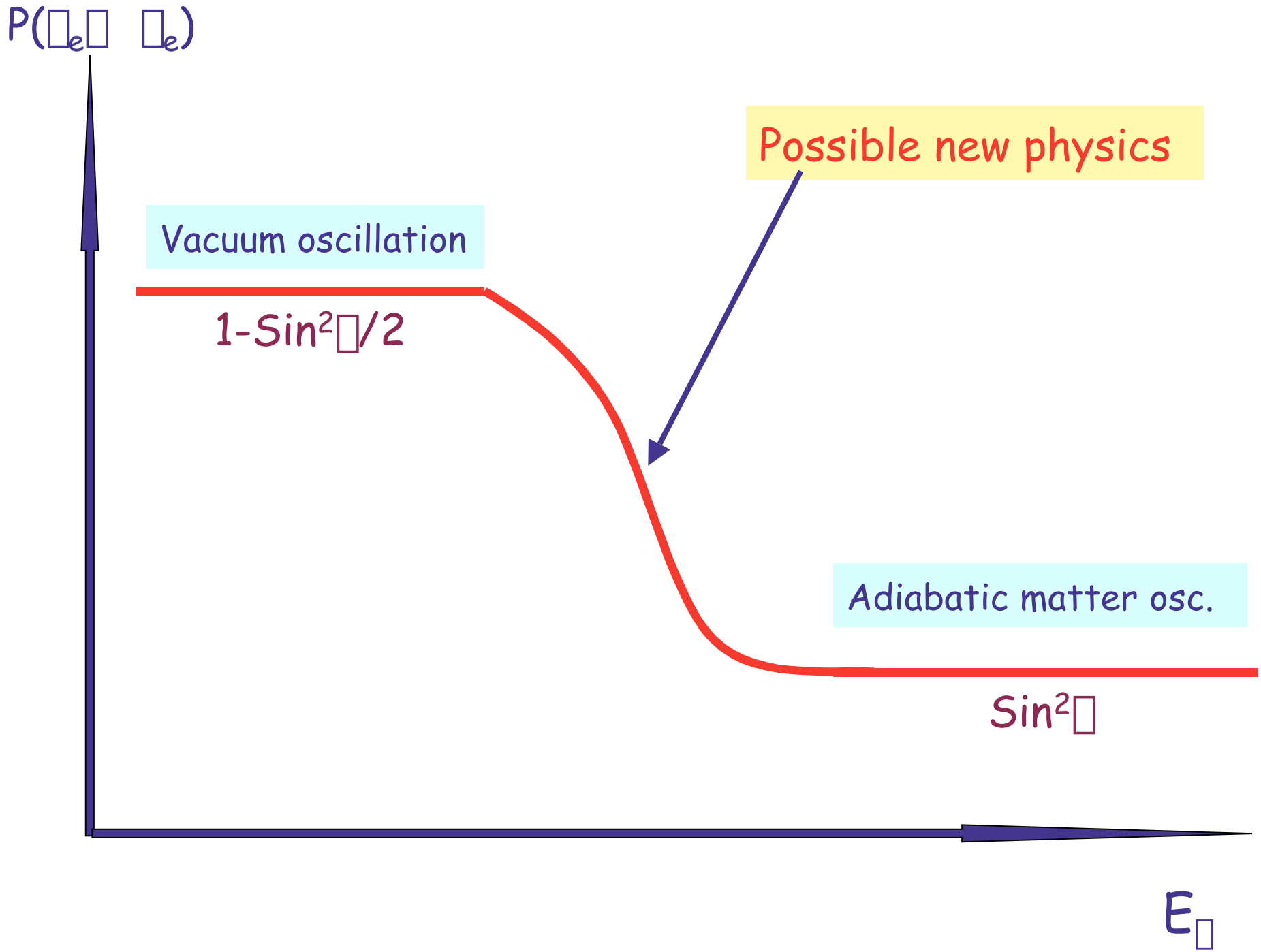
Adiabatic solution

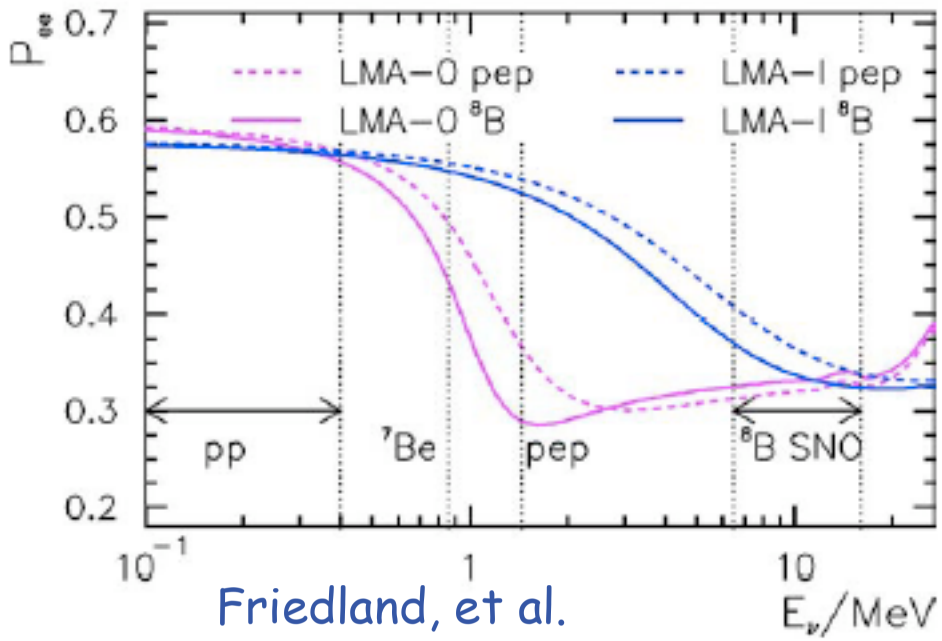
$$P(\nu_e\to\nu_e)=\frac{1}{2}+\frac{1}{2}\cos 2\theta_v\left[\frac{-\varphi(x)}{\sqrt{\Lambda+\varphi^2(x)}}\right]_{\text{source}}$$

$$\frac{1}{\sqrt{2}}G_F N_e(x)=\frac{\delta m^2}{4E}\cos 2\theta_v$$

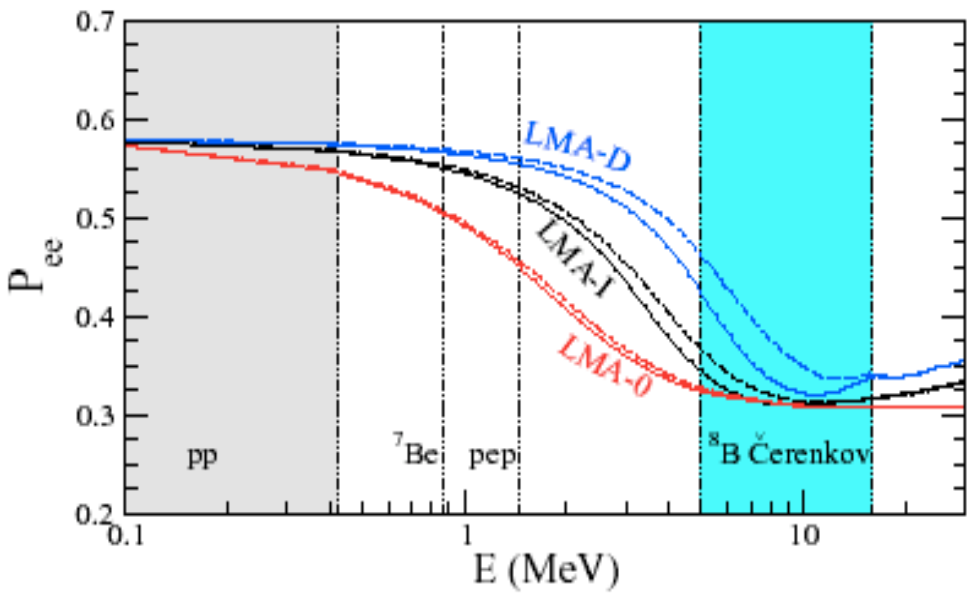
→ Most-pronounced contribution of non-standard interactions

For $\delta m^2 = 8 \times 10^{-5}$ eV^2, $\sin^2\theta_v = 0.3$, assuming an exponential density profile for the Sun, for neutrinos produced at the center of the Sun this gives $E_\square \approx 1.8$ MeV !

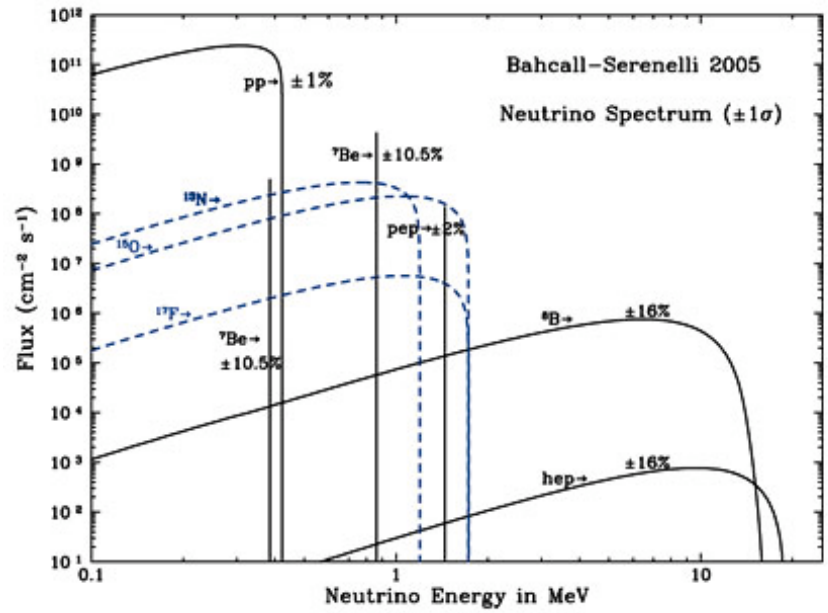

P(νe νe)
Possible new physics
Vacuum oscillation
1-Sin²θ/2
Adiabatic matter osc.
Sin²θ
Eν



Friedland, et al.



Miranda, et al.

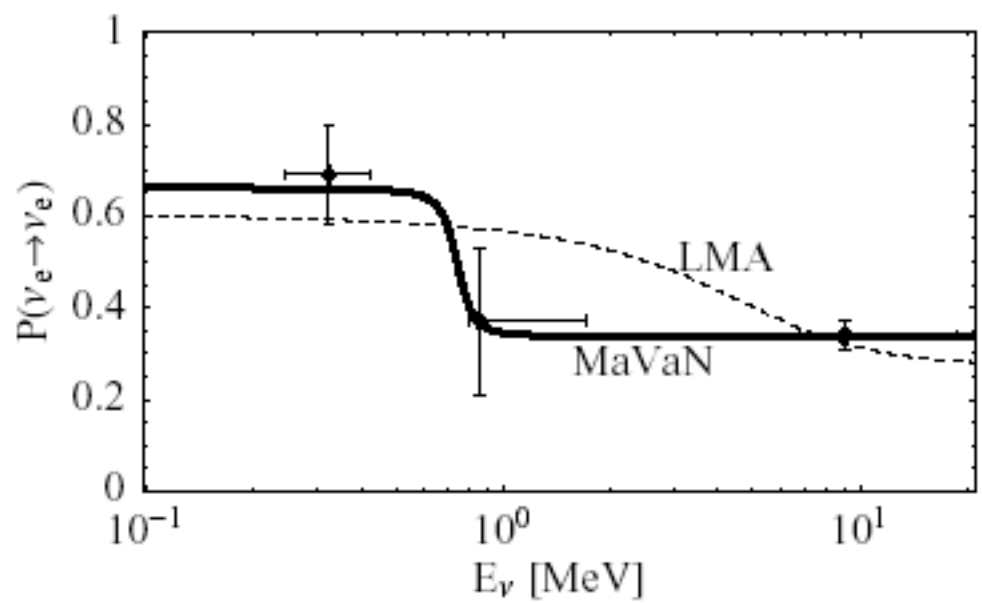


Mass-varying neutrinos, Fardon, et al., astro-ph/0309800

Scale of dark energy is similar to that of neutrino mass, $(2\times10^{-3}\ \mathrm{eV})^4$. Assume that they are related and dark energy and neutrino densities remain invariant under variations of neutrino mass. Introduce Yukawa coupling between a light sterile neutrino and a light scalar field

$$i\frac{d}{dr}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{2E_\nu}\left[U\begin{pmatrix}(m_1-M_1(r))^2 & M_3(r)^2\\ M_3(r)^2 & (m_2-M_2(r))^2\end{pmatrix}U^\dagger + \begin{pmatrix}A(r) & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}.$$

$$A(r) = 2\sqrt{2}\,G_F n_e(r) E_\nu$$



Barger, et al., hep-ph/0502196

Conclusions

- Solar neutrinos alone will not pinpoint θ_{13}, but they will help.

- A lot of new physics may show up at the solar neutrino spectrum near E_{ν} around 1 or 2 MeV.

- Currently we can rule out solar density fluctuations of 6 to 7%. In a fitting tribute to John Bahcall this represents a proof of principle that we can do *solar* physics with solar neutrinos.

- Solar neutrinos are unlikely to provide further new information about neutrino magnetic moment.