Past, Present, and Future of Solar Neutrino Physics

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SMU eBubble Workshop
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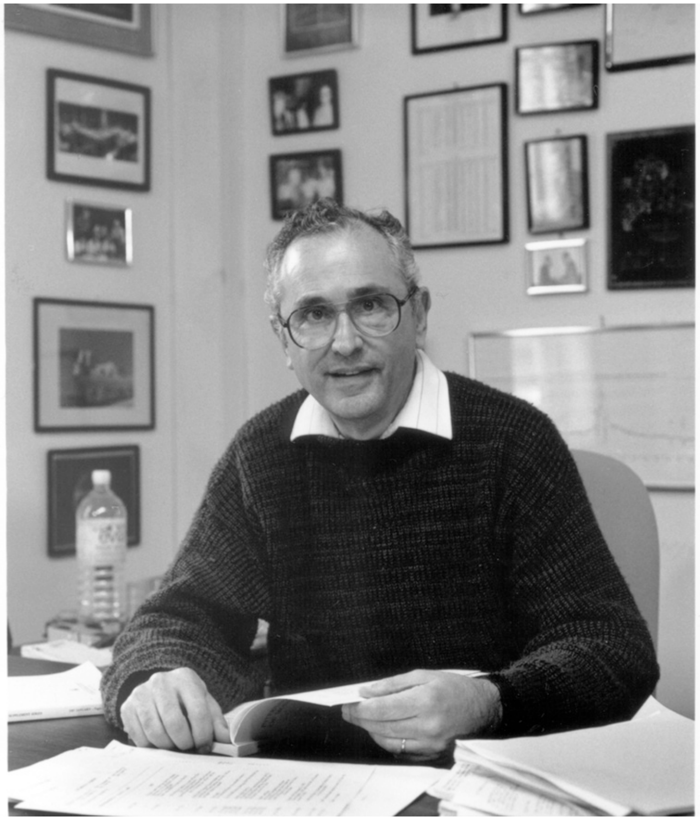
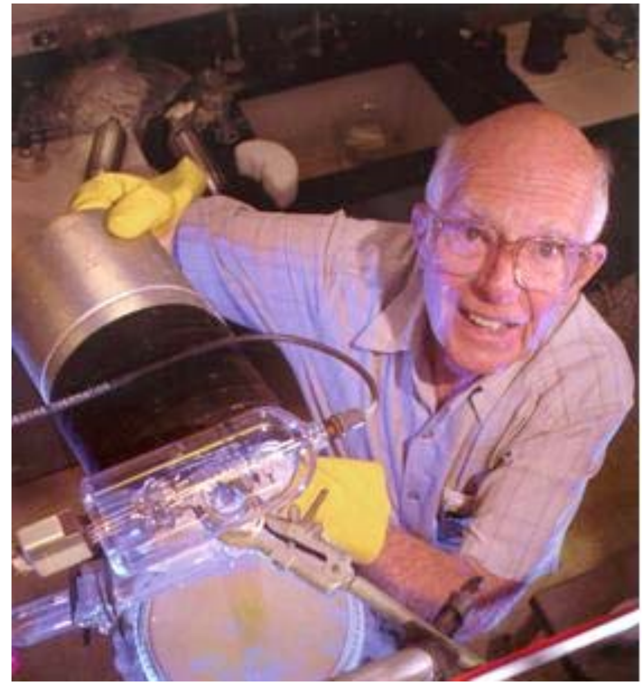
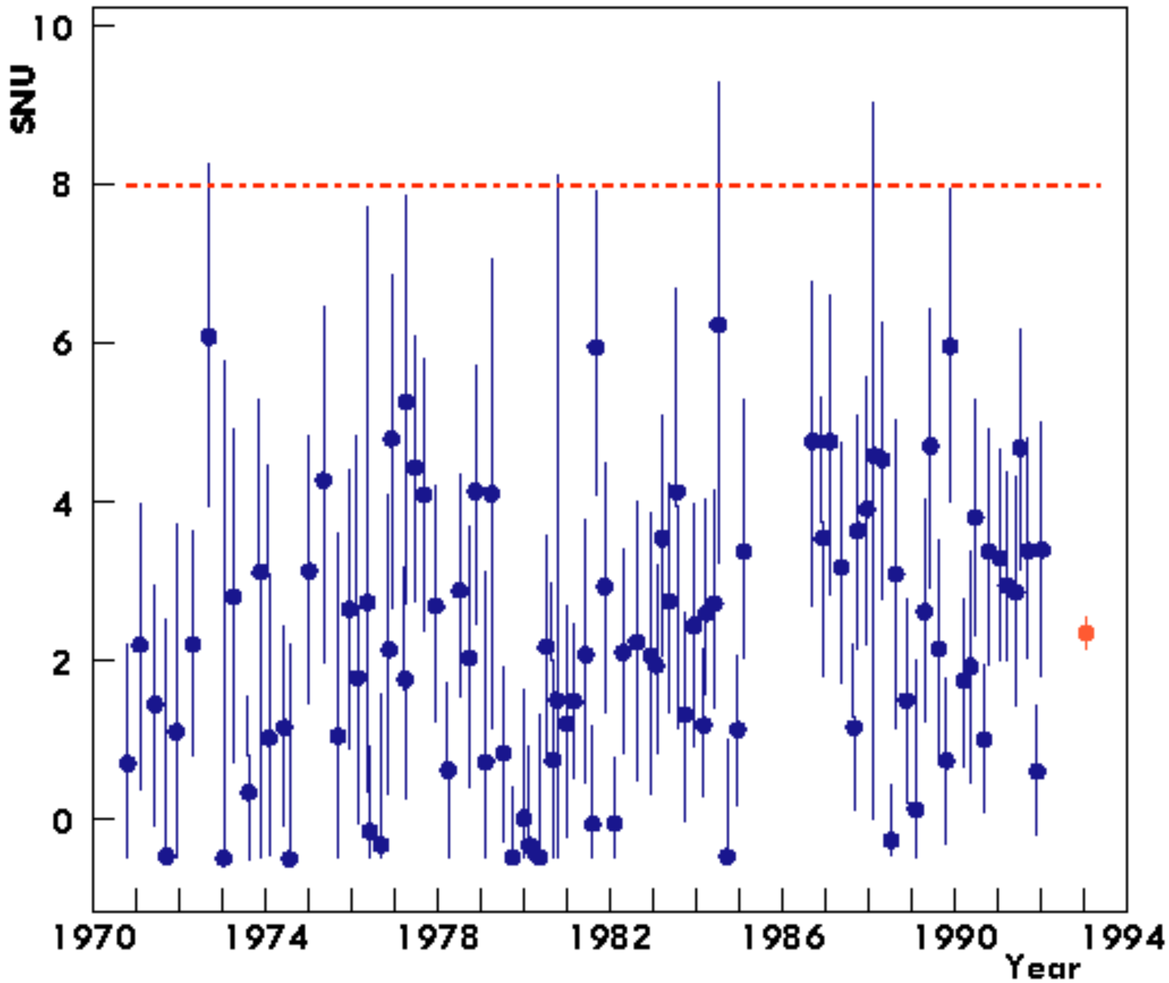




"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."

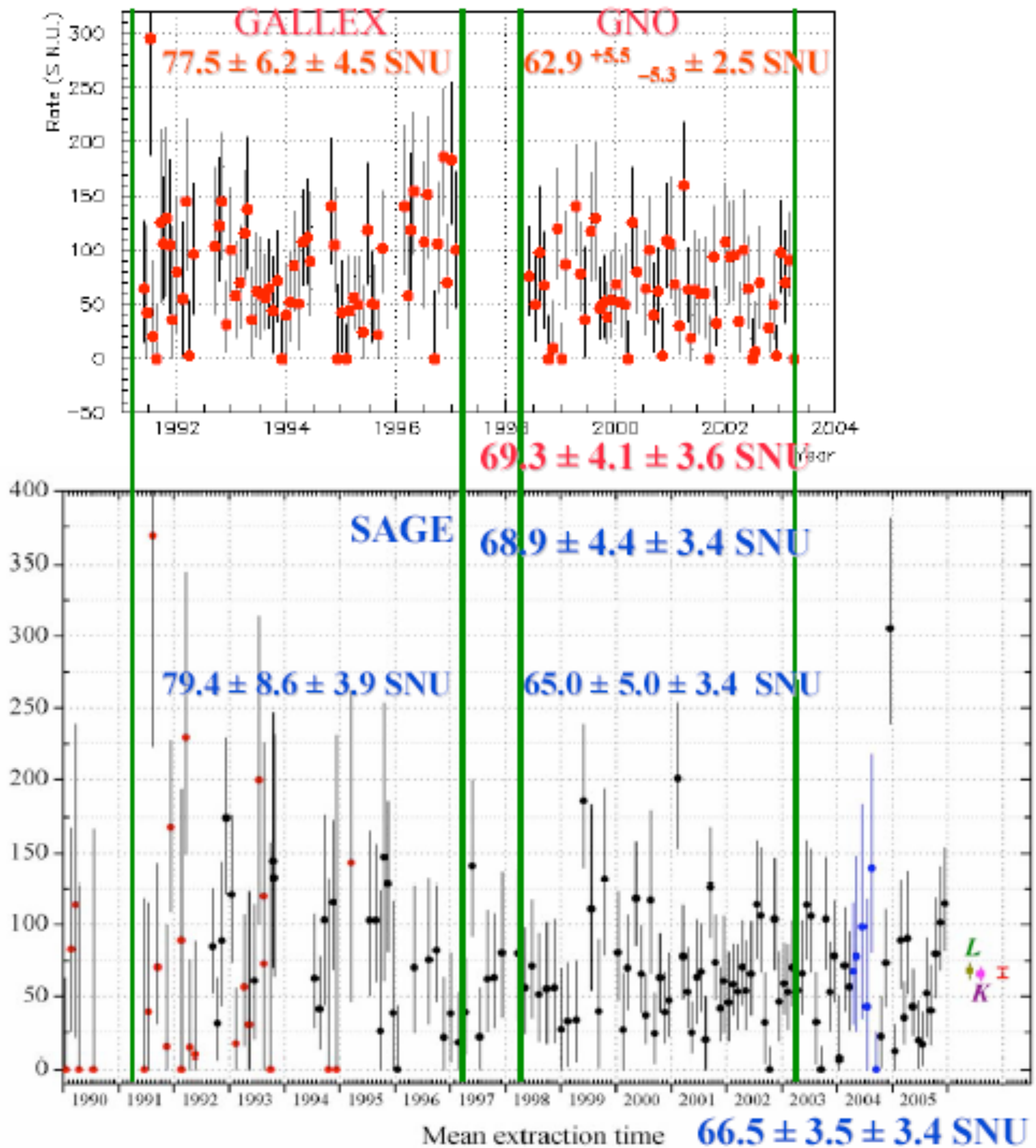
Bahcall and Davis, 1964

Then: Homestake Count Rate



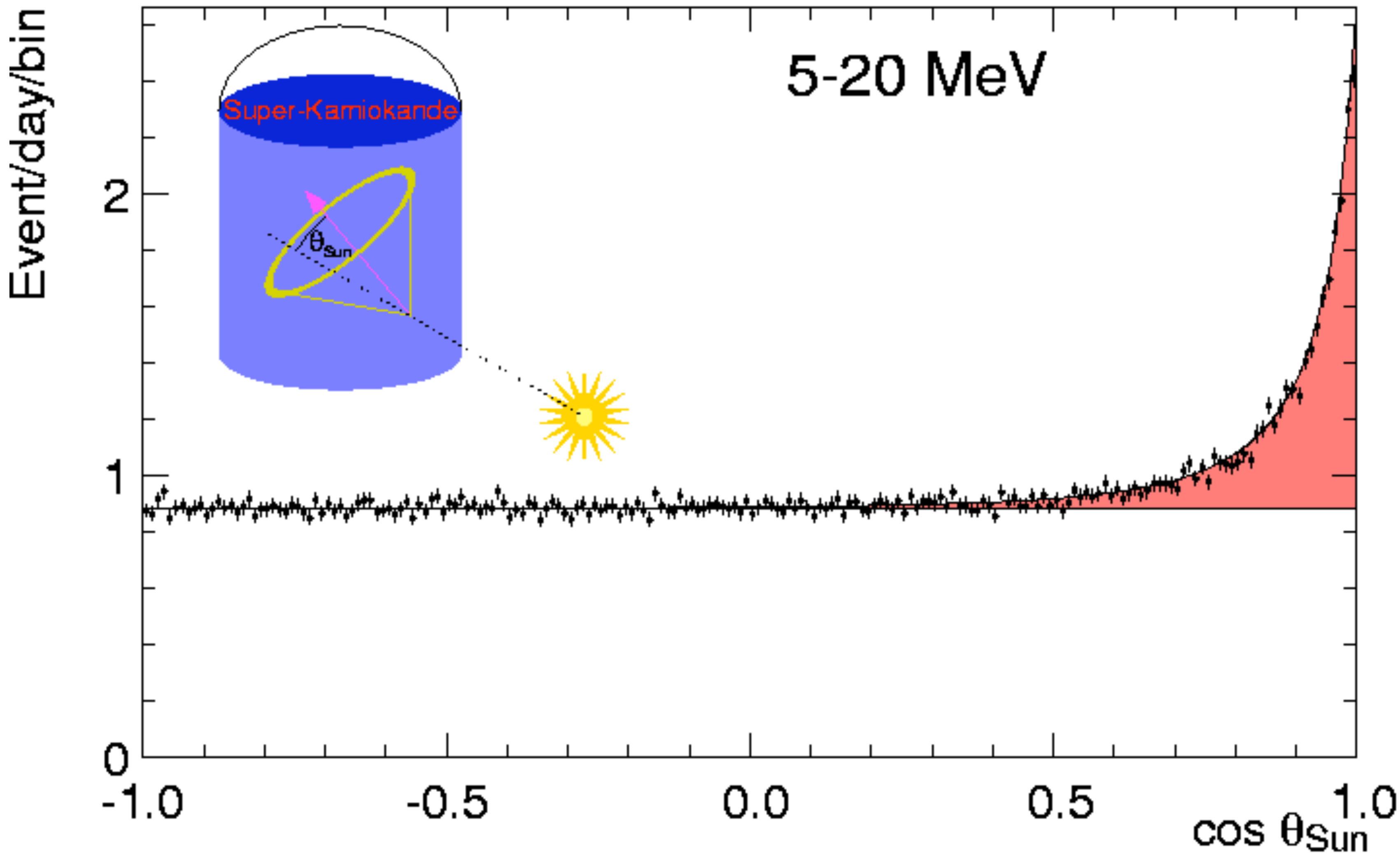
Those of us who believed the data thought that neutrino mixing angles are, like quark mixing angles, small for vacuum mixing, but, thanks to MSW, matter-enhanced oscillations do the reduction. Most people did not even believe the data.

Now:

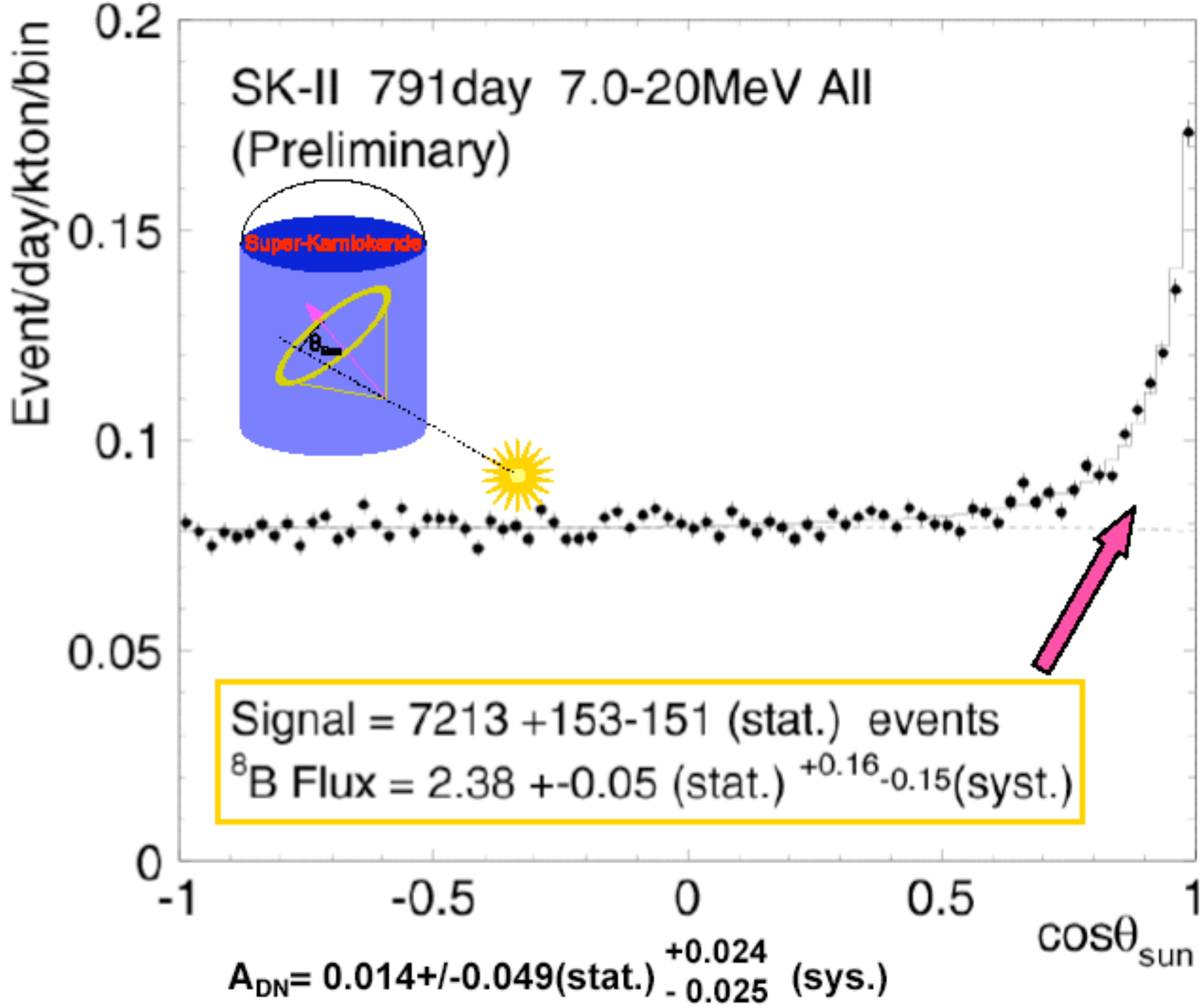


Adopted from Gavrin

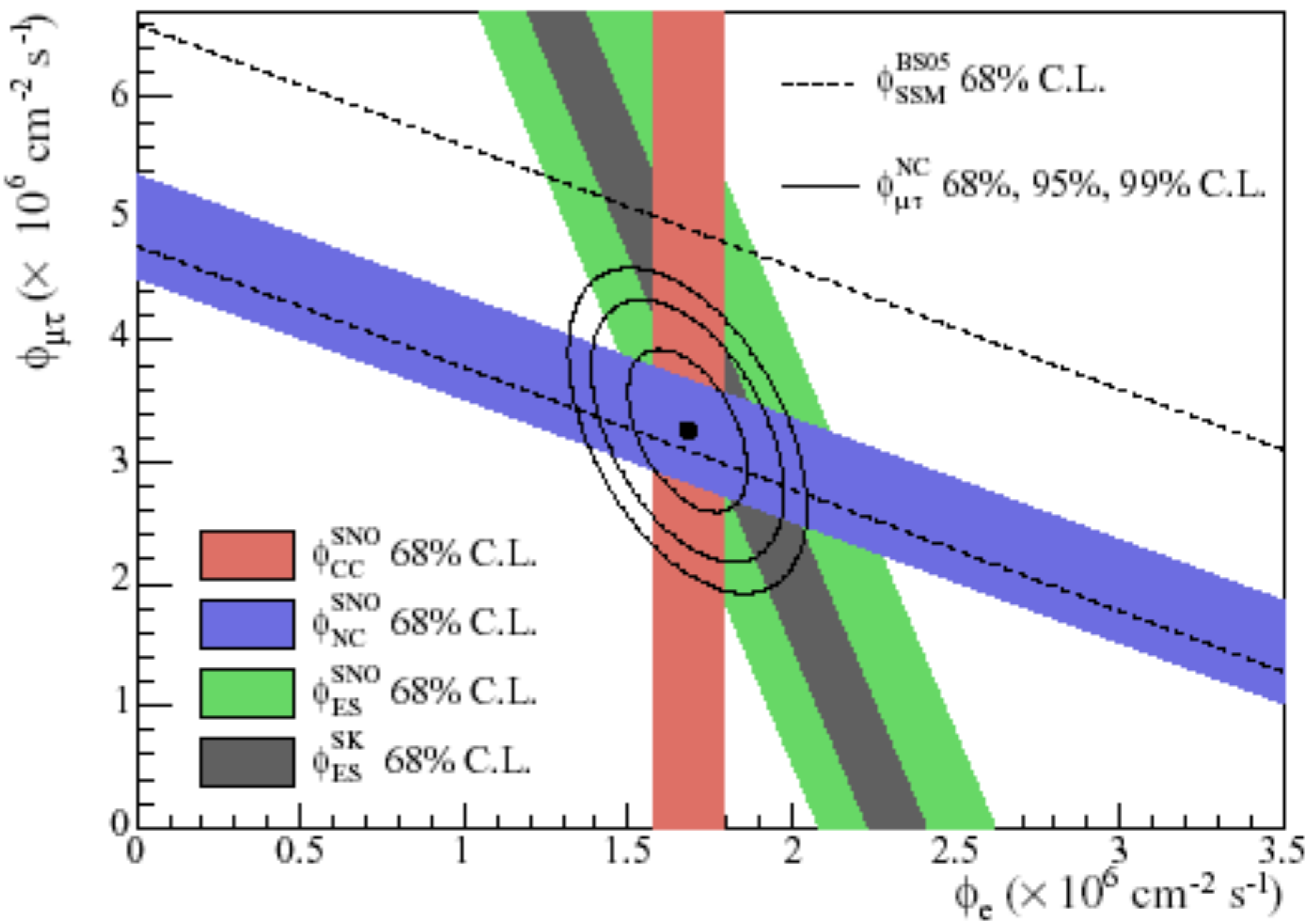
SuperKamiokande-I ^8B solar ν's



hep-ex/0508053

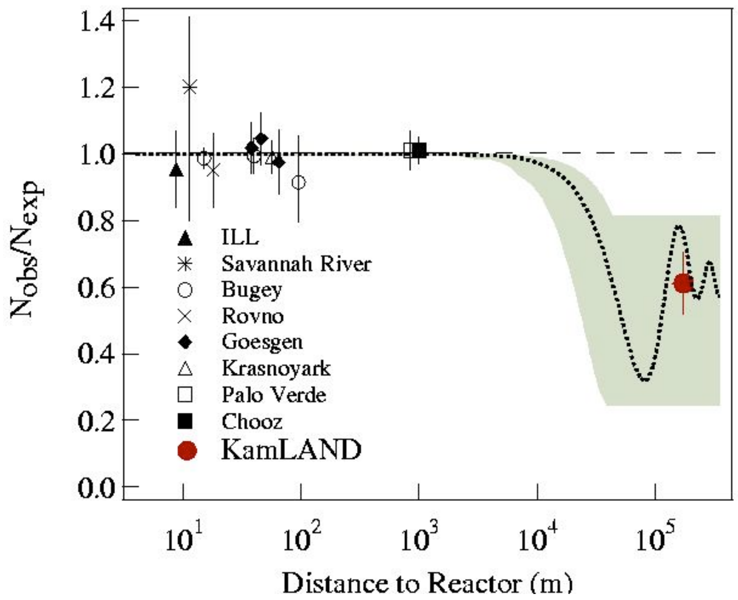

SK-II 791day 7.0-20MeV All
(Preliminary)
Super-Kamiokande
Event/day/kton/bin
0.2
0.15
0.1
0.05
0
-1
-0.5
0
0.5
1
cosθsun
Signal = 7213 +153-151 (stat.) events
8B Flux = 2.38 +-0.05 (stat.) +0.16-0.15(syst.)
ADN= 0.014+/-0.049(stat.) +0.024 - 0.025 (sys.)

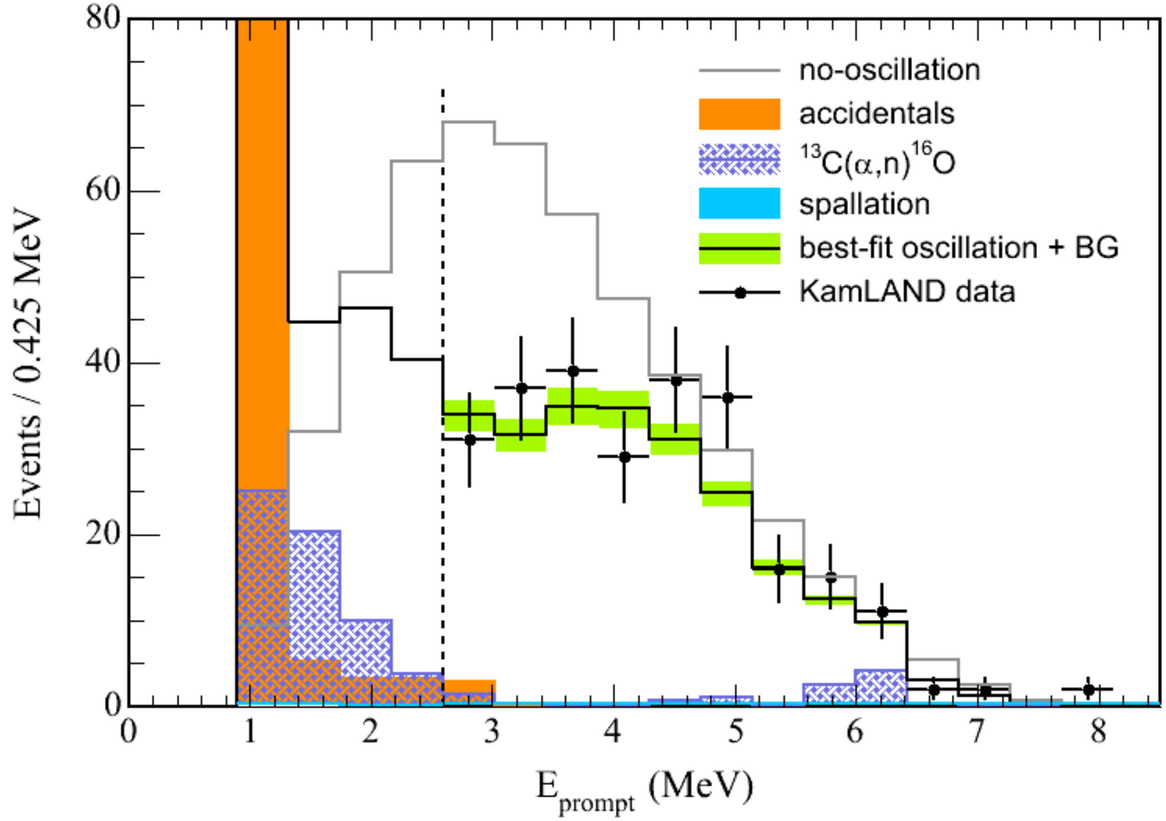
SNO



ϕ^{BS05}_{SSM} 68% C.L.
$\phi^{NC}_{\mu\tau}$ 68%, 95%, 99% C.L.
ϕ^{SNO}_{CC} 68% C.L.
ϕ^{SNO}_{NC} 68% C.L.
ϕ^{SNO}_{ES} 68% C.L.
ϕ^{SK}_{ES} 68% C.L.
$\phi_{\mu\tau}$ ($\times$ 10^6 cm^{-2} s^{-1})
ϕ_e ($\times$ 10^6 cm^{-2} s^{-1})
0
0.5
1
1.5
2
2.5
3
3.5
0
1
2
3
4
5
6

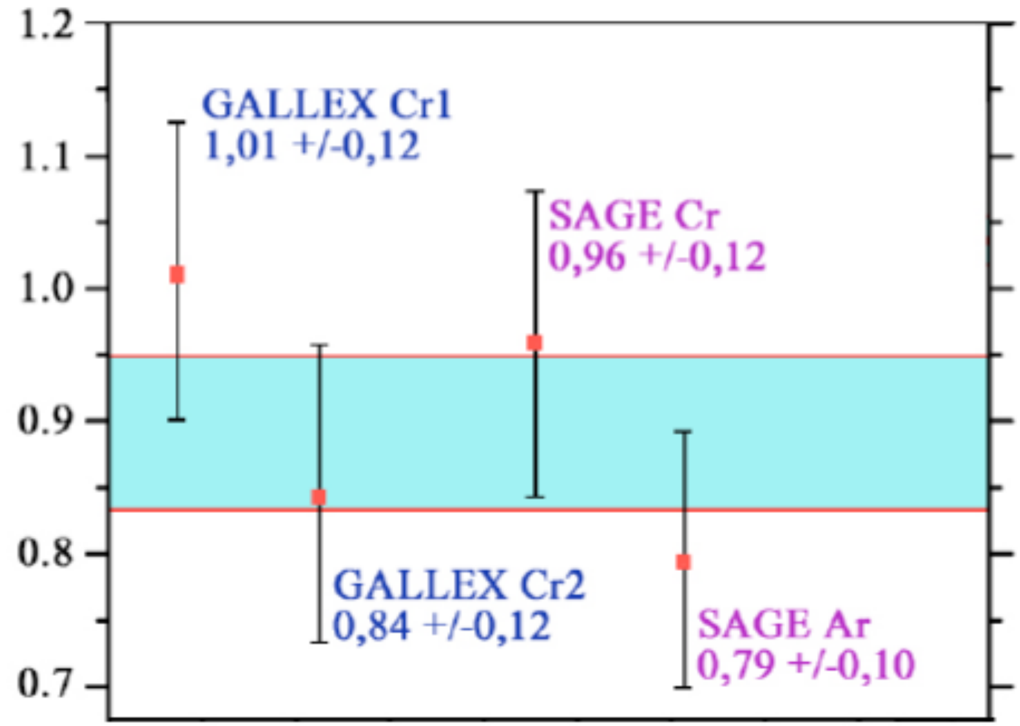
KamLAND

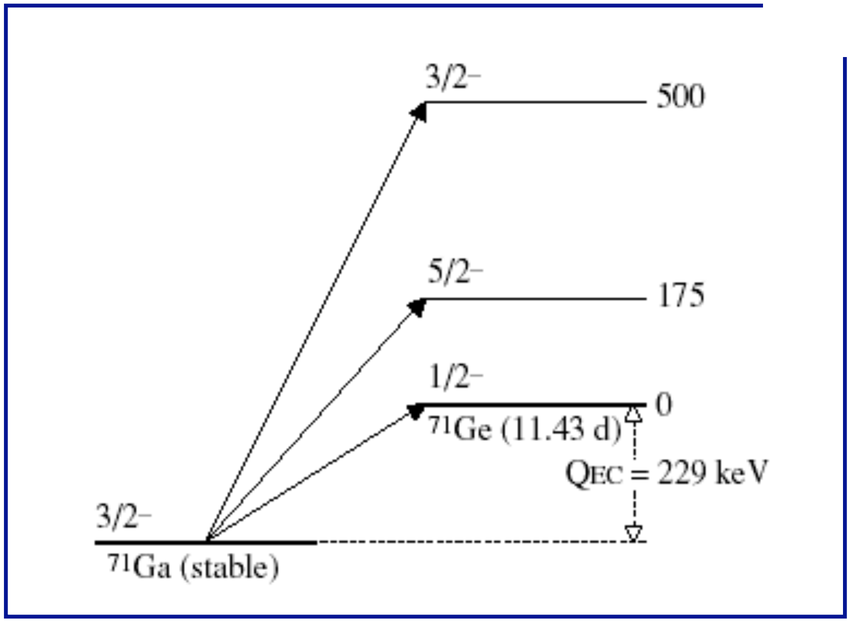




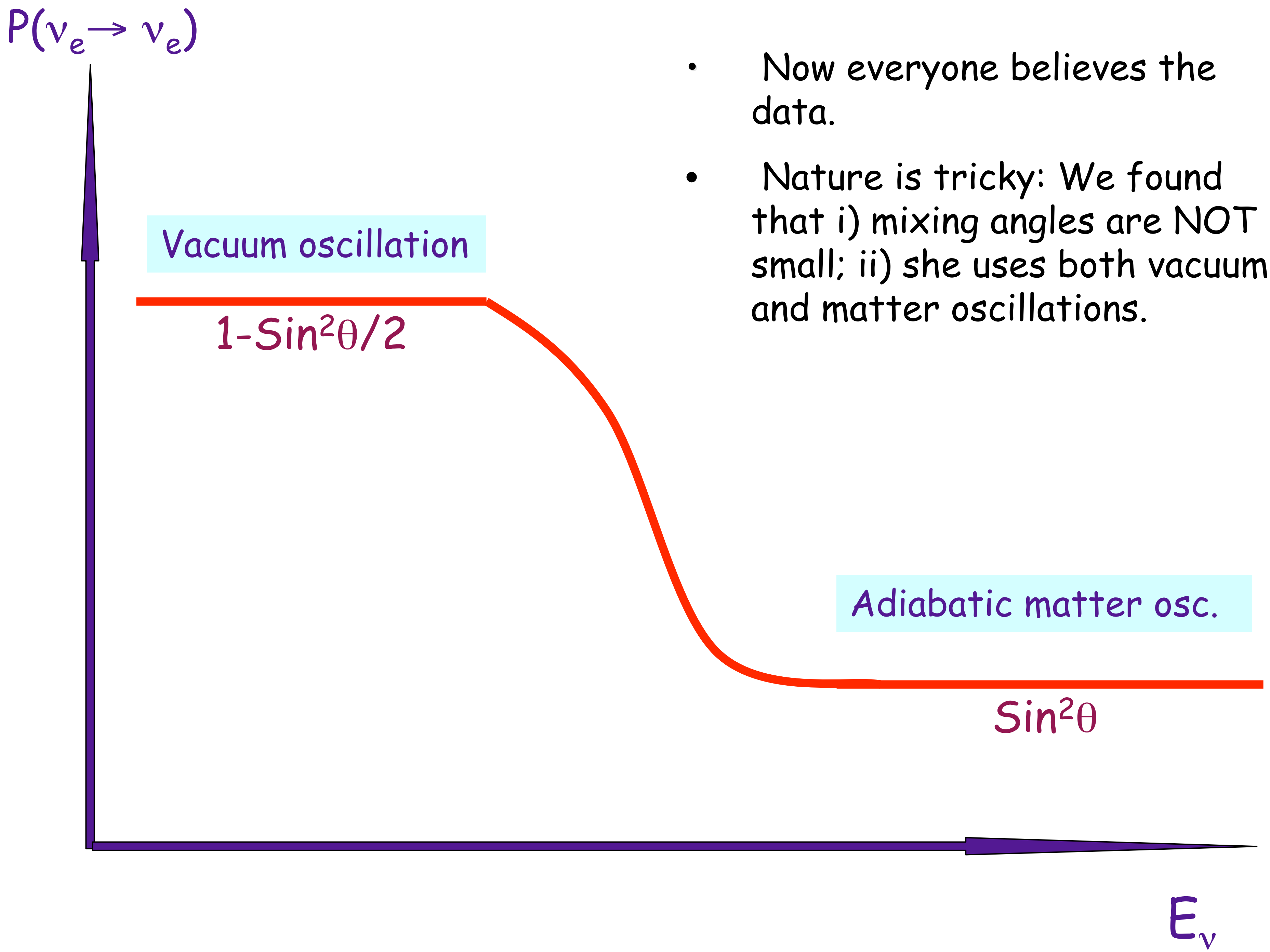
$\overline{\nu}_e + p \rightarrow n + e^+$

What are the Ga source experiments telling us?





Ground state cross-section is fixed from the beta-decay (via detailed balance). Correction is due to the excited states, which contribute little to the solar neutrino capture rate.



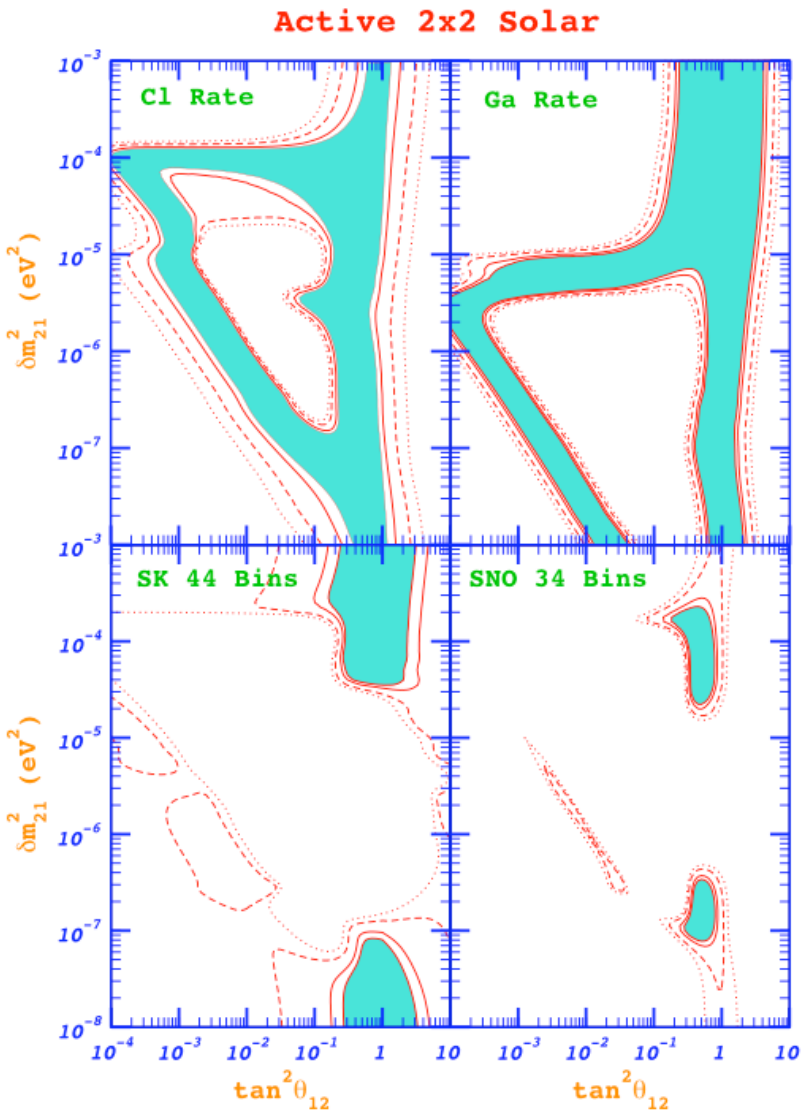
- Now everyone believes the data.
- Nature is tricky: We found that i) mixing angles are NOT small; ii) she uses both vacuum and matter oscillations.

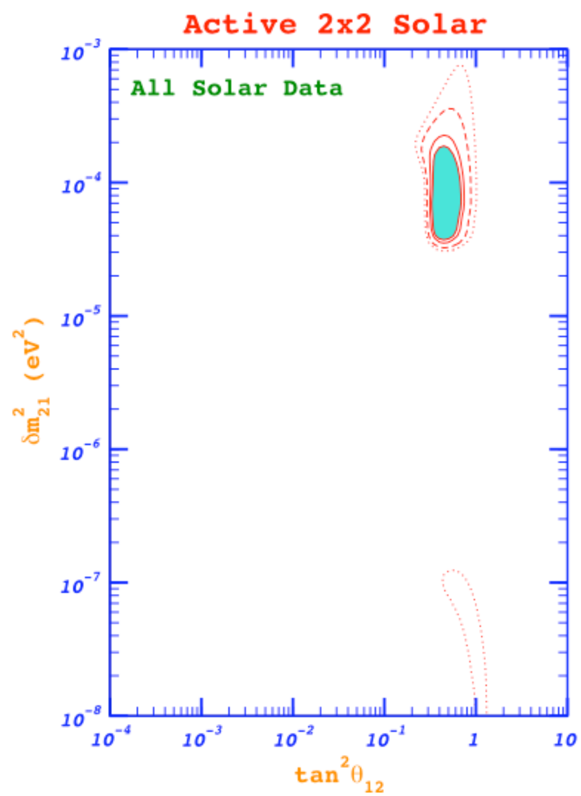
Typically solar neutrino analyses assume that ν_e mixes with a combination of ν_μ and ν_τ. This is exact only when θ_{13} is zero. When θ_{13} is non-zero, but small we can use

$$P_{3x3}(\nu_e \rightarrow \nu_e) = \mathrm{Cos}^4\theta_{13}\, P_{2X2}(\nu_e \rightarrow \nu_e \text{ calc. with } \mathrm{Cos}^2\theta_{13} N_e) + \mathrm{Sin}^4\theta_{13}$$

This works both for vacuum and matter oscillations…

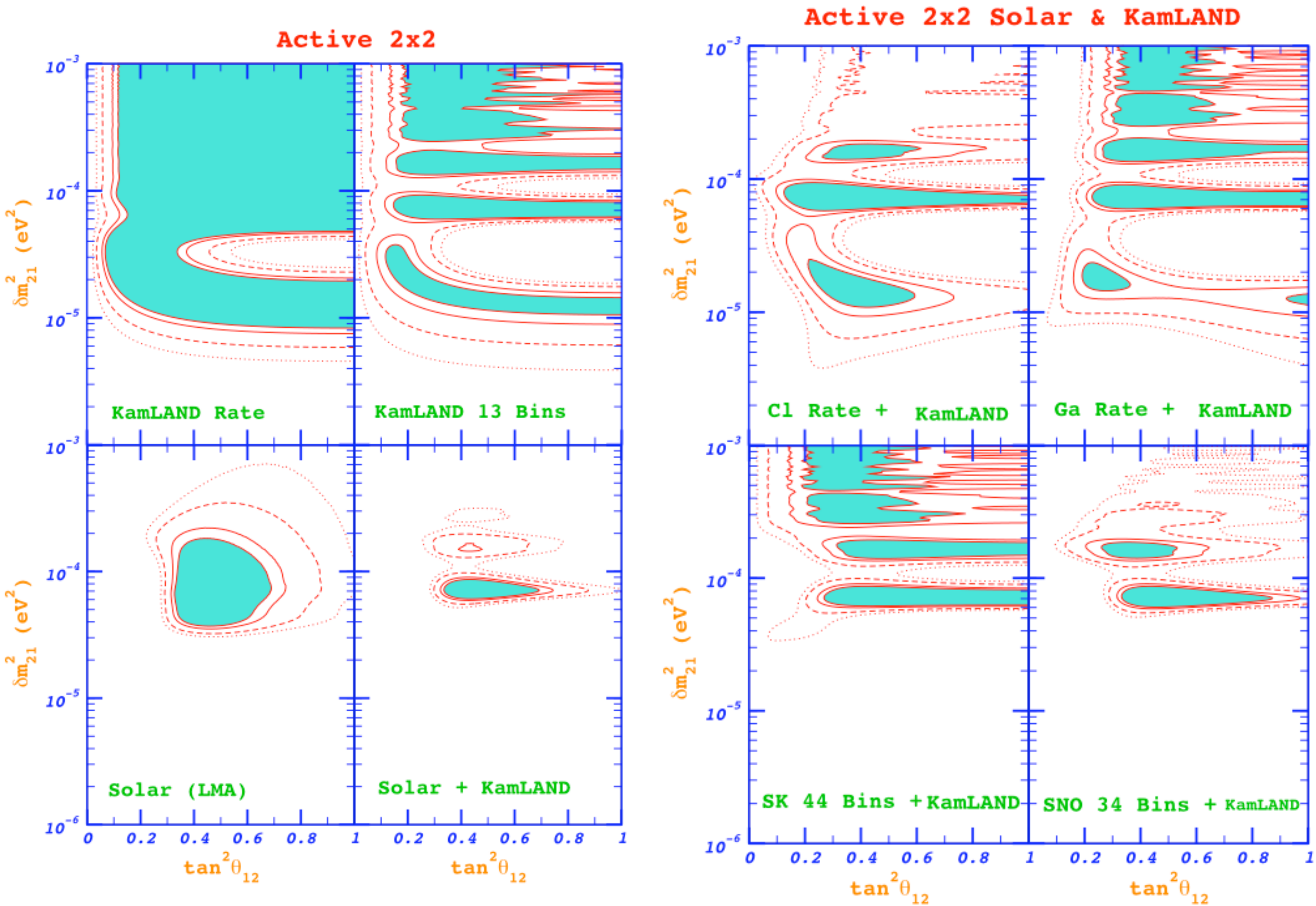
A global analysis of the solar neutrino data



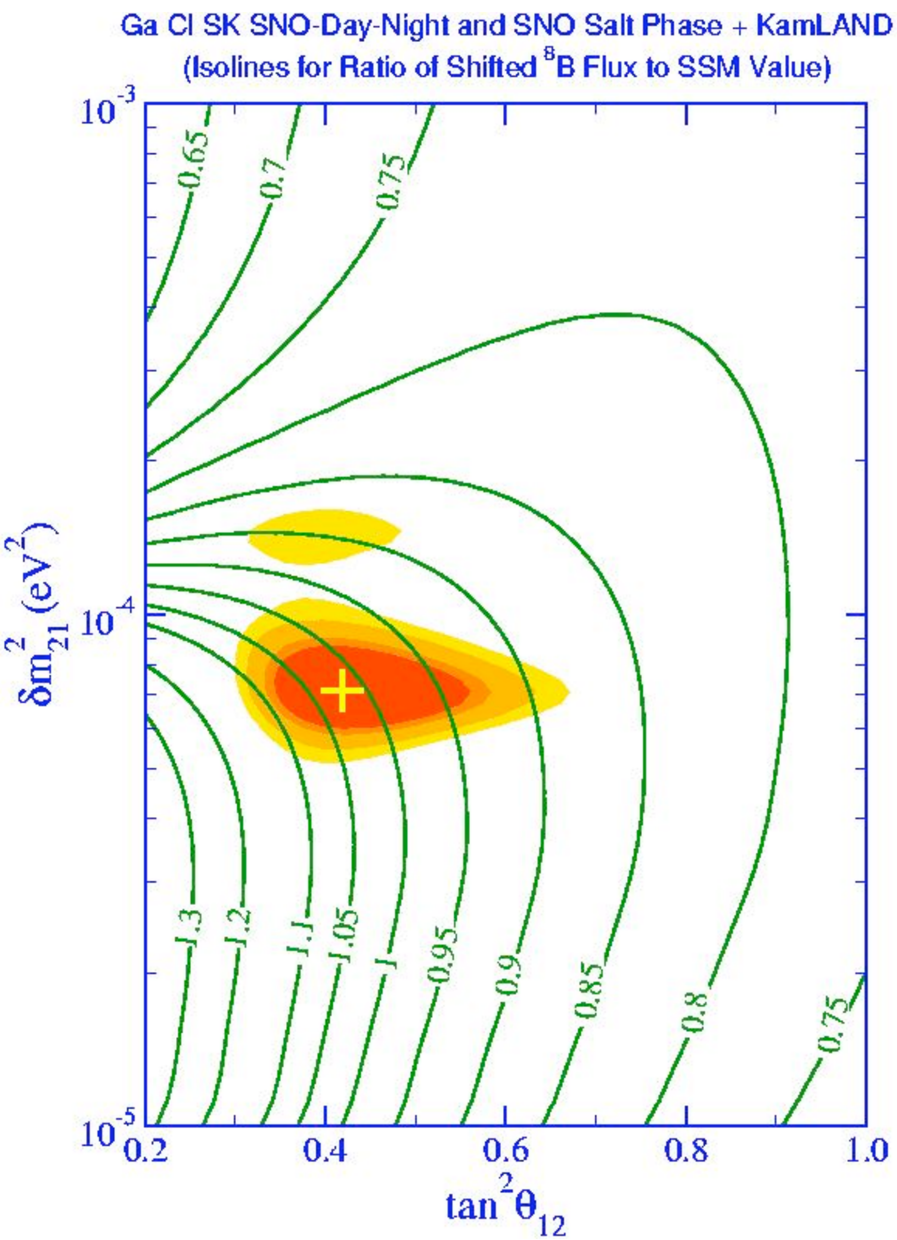


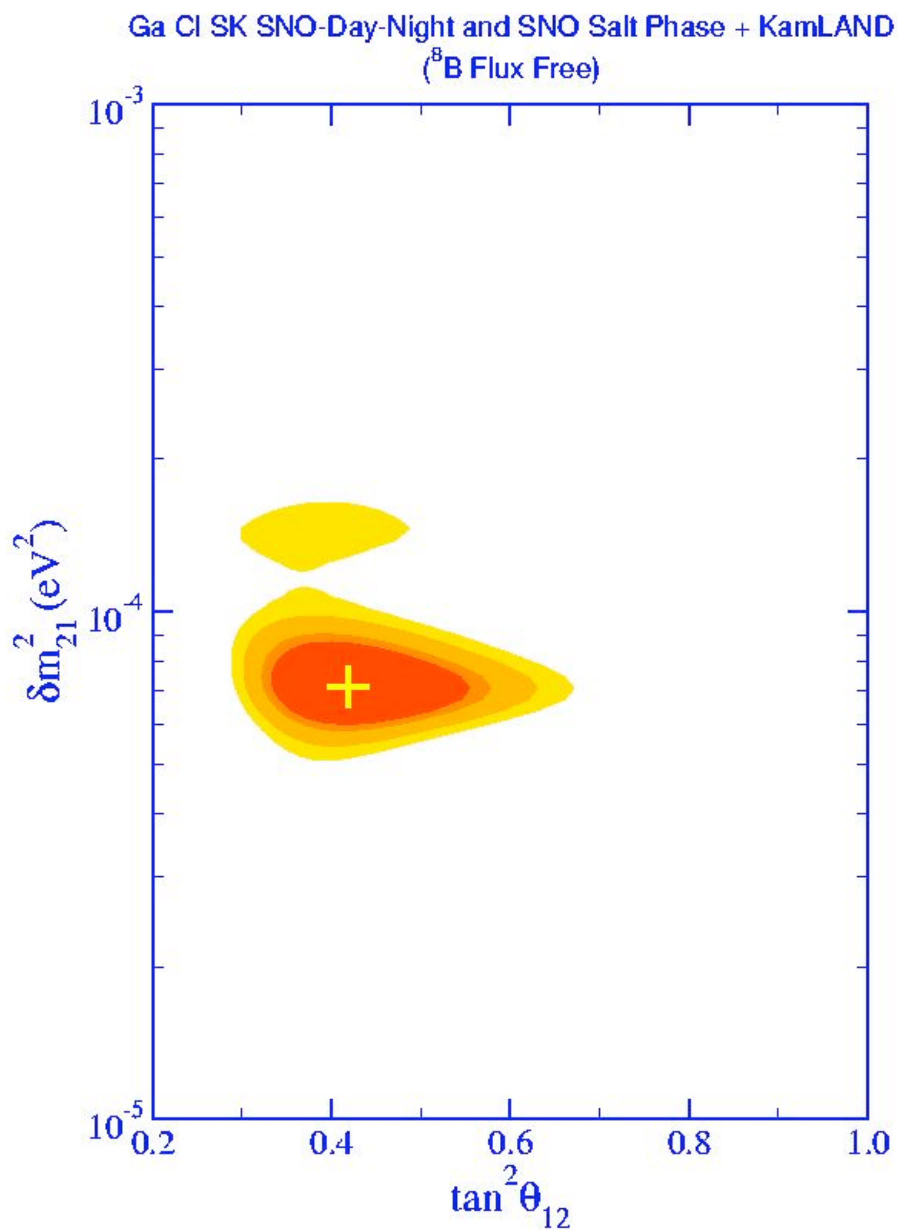
Balantekin & Yuksel, J. Phys. G 29, 665 (2003).

Solar + KamLAND Global Analysis



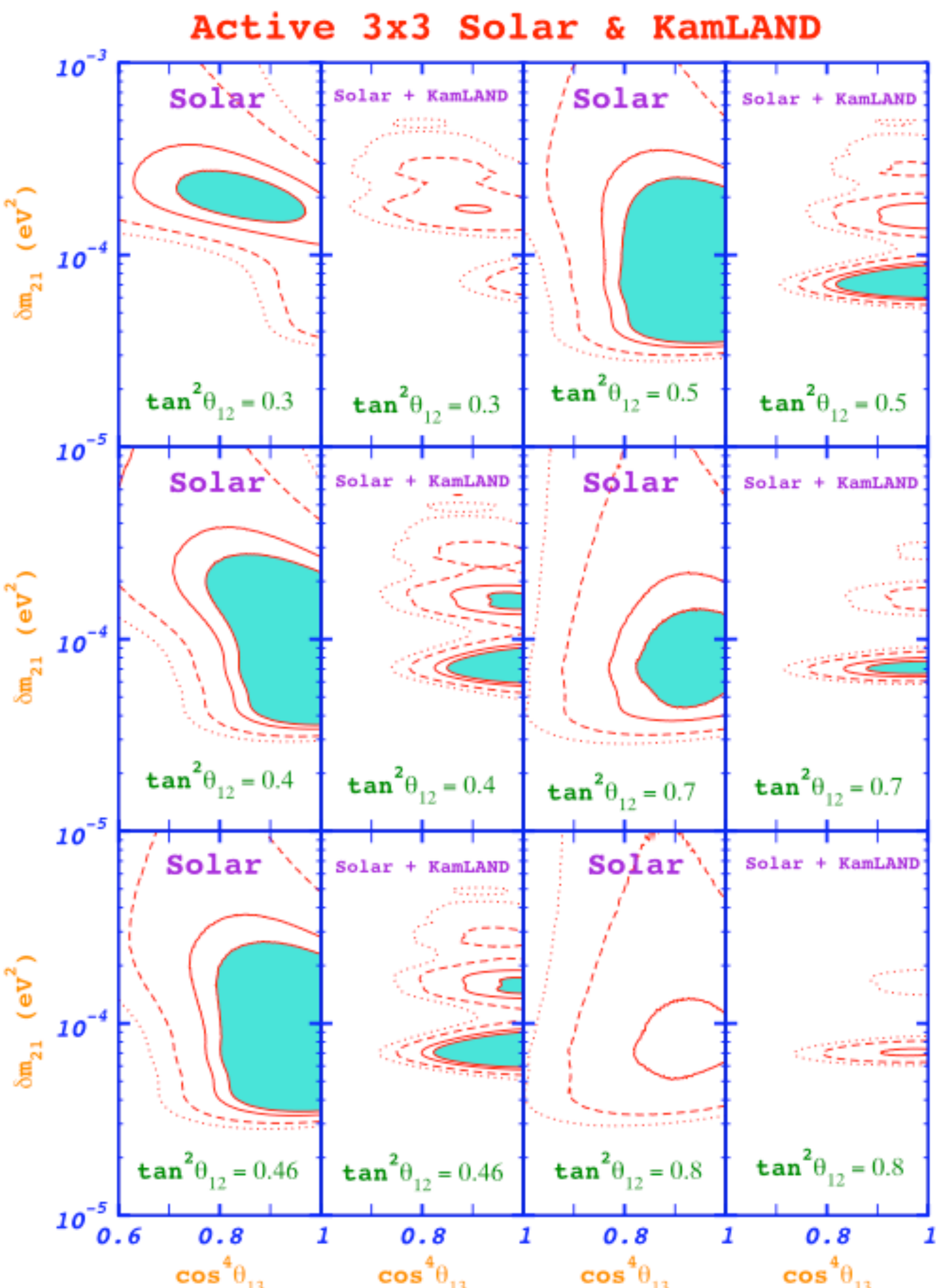
SNO first Salt Results , Balantekin and Yuksel, PRD 68, 113002 (2003)





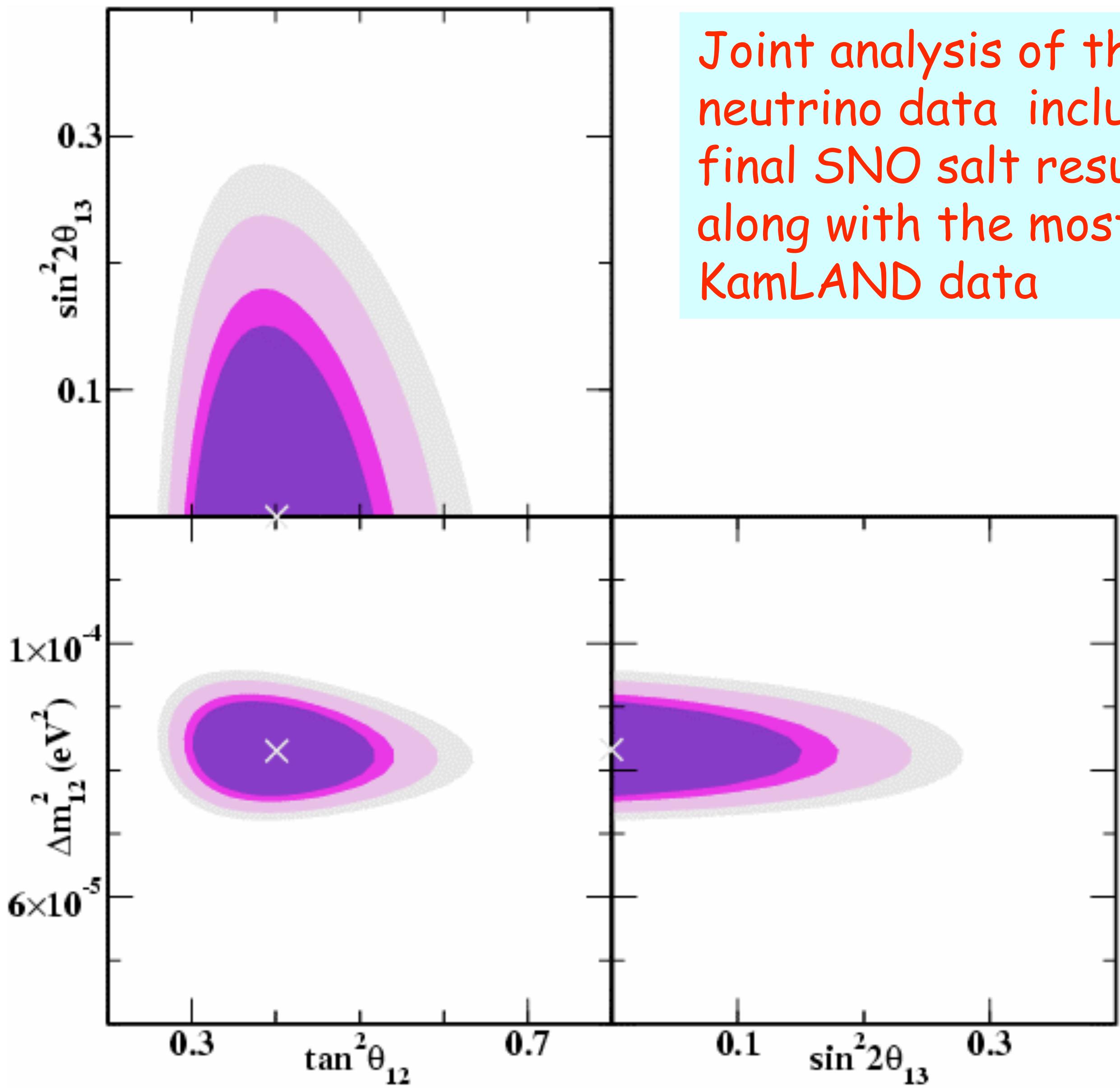
Can we probe θ_{13} in solar neutrino experiments?

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).



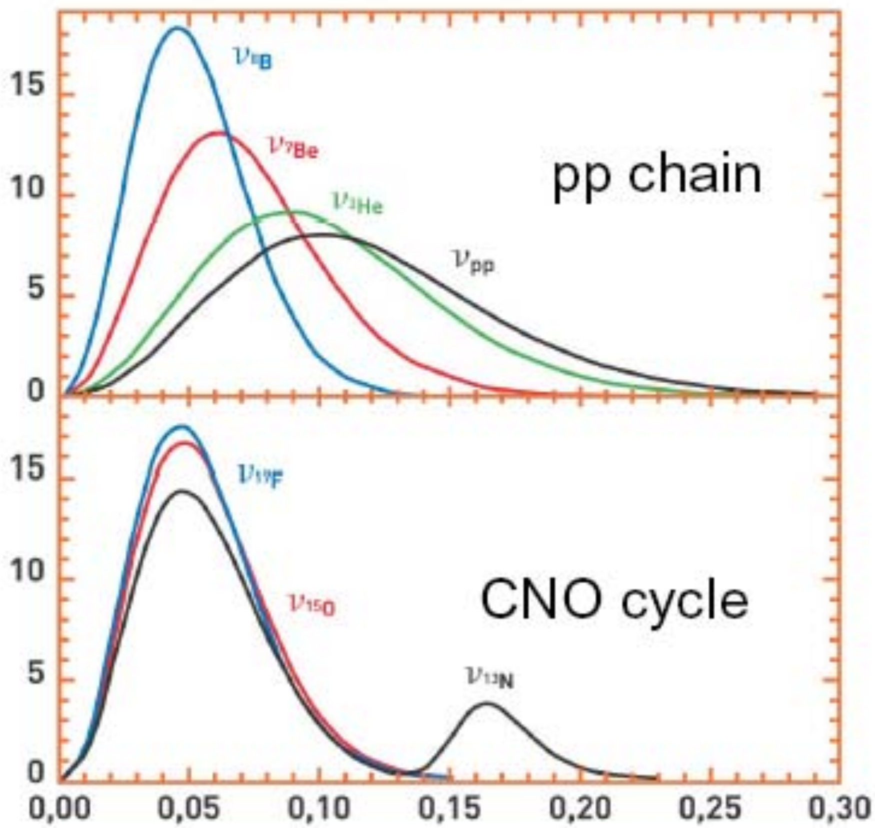
Joint analysis of the solar neutrino data including final SNO salt results along with the most recent KamLAND data

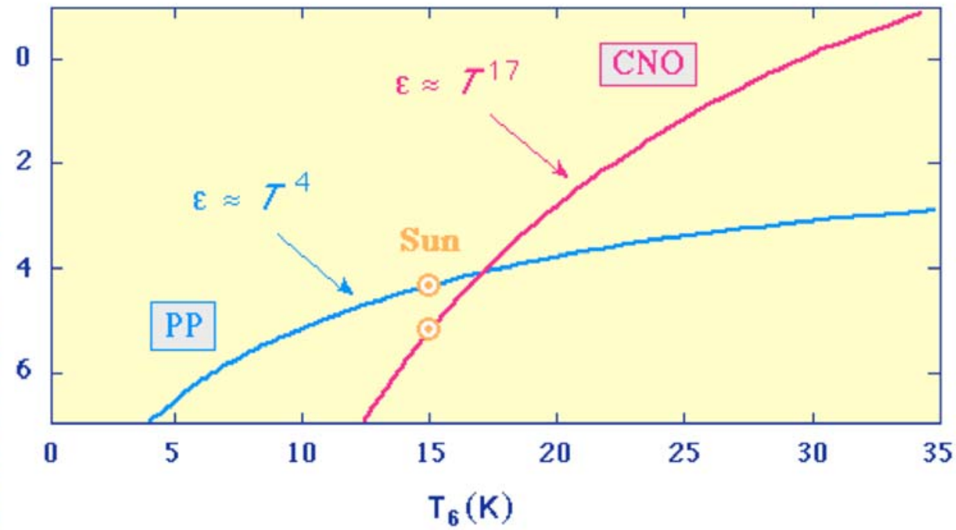
Balantekin, et al., PLB 613, 61 (2005)

Open Questions:

- Can we test the relation between solar photon and neutrino luminosities? Is there a subdominant neutrino source?
- Does the Sun really work via the pp-chain? What is the contribution form the CNO cycle?
- Does the neutrino have a magnetic moment? If so, does it effect solar neutrino flux? Are there solar antineutrinos?
- Can we use neutrinos to measure solar properties such as density scale height?
- Can we use solar neutrinos to do physics beyond both the Standard Model of the Sun and the Standard Model of particle physics? Are the signatures for such physics generic?
- Once we are done with the solar nuclear fusion neutrinos, can we ever detect solar plasma neutrinos?

How much does the CNO cycle contribute in the Sun?

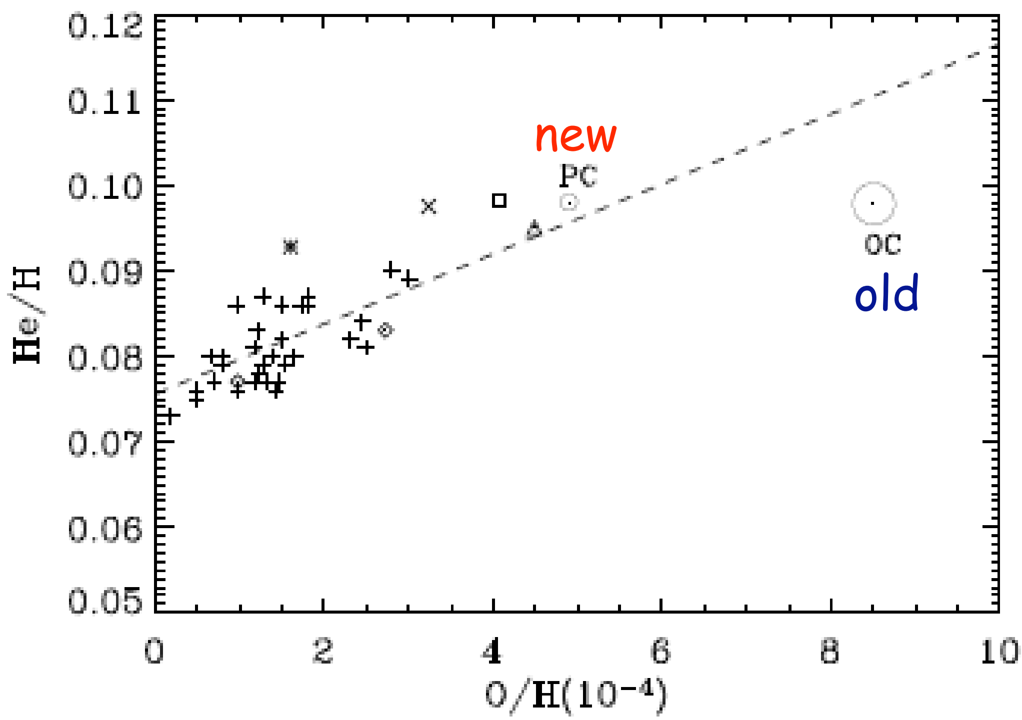




In SSM CNO cycle contribute about 0.8% of the neutrino flux. Data are consistent with this. A more precise measurement of the CNO contribution will provide a test of SSM.

Solar C, N, and O composition was recently reduced by 30%

Turck-Chieze, et al. Phys. Rev. Lett. **93**, 211102 (2004).



Old ^{8}B neutrino flux = 4×10^6 cm^{-2}s^{-1}

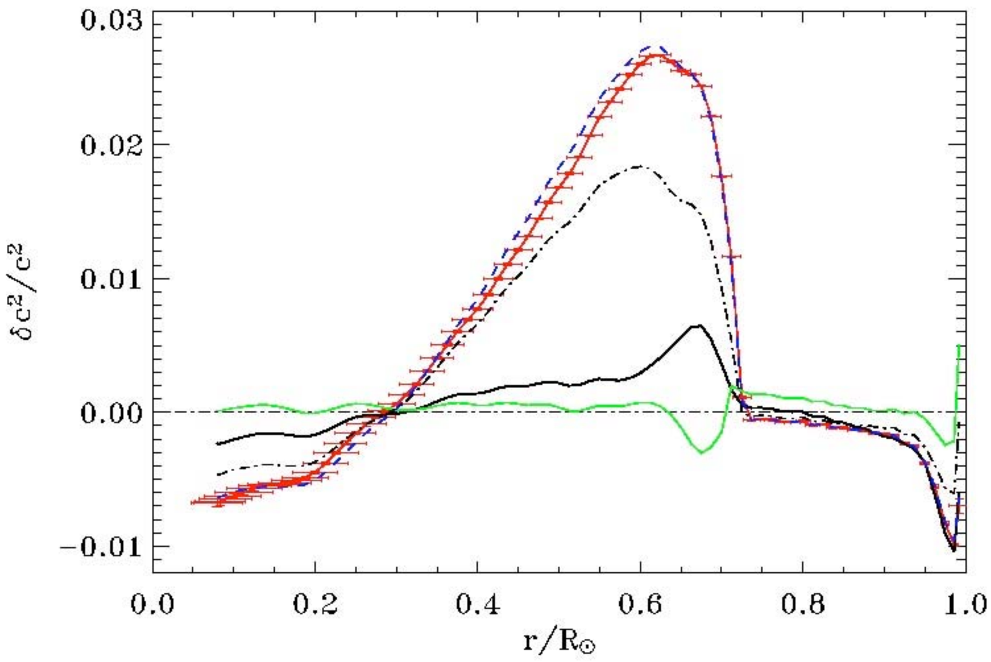
New ^{8}B neutrino flux = 5.31×10^6 cm^{-2}s^{-1}

Sun is no longer an "odd" star enriched in heavy elements!

Are nuclear fusion reactions the only source of solar energy? To answer this question we need to accurately measure solar neutrino luminosity!

- This is a crucial test of energy generation during the main stage of stellar evolution.
- It is a test independent of the detailed dynamics of the solar models.
- It requires pp, pep, ^{7}Be, and CNO neutrino fluxes.
- Present uncertainty is very big, but a few percent of accuracy is within reach.

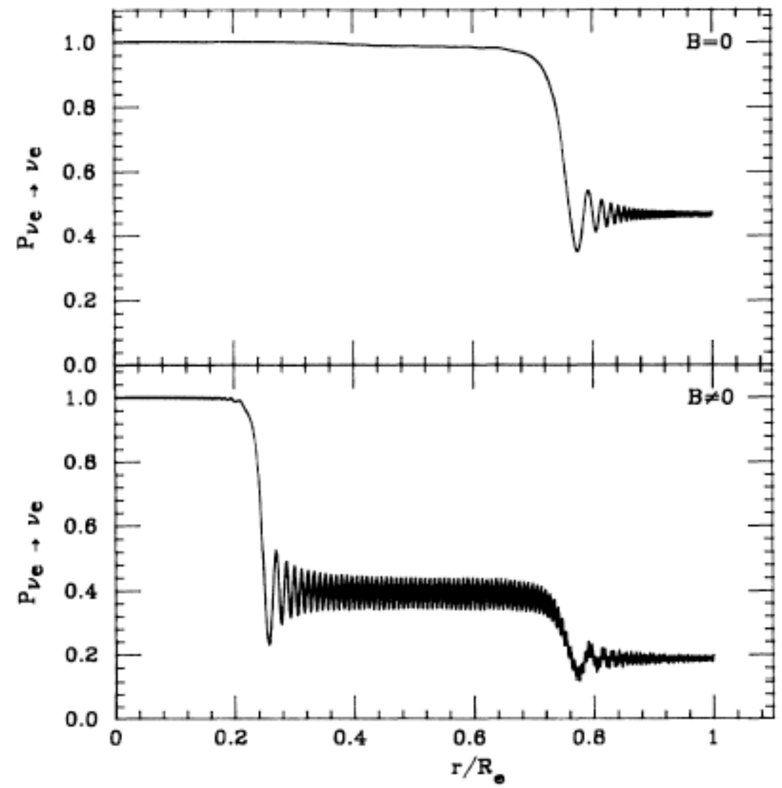
Deviations of the sound speed from the prediction of the Standard Solar Model:



Do we need new physics to understand the sound speed or is it an indication of an opacity problem?

Spin-flavor precession in the Sun

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



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

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

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

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

Dirac neutrinos

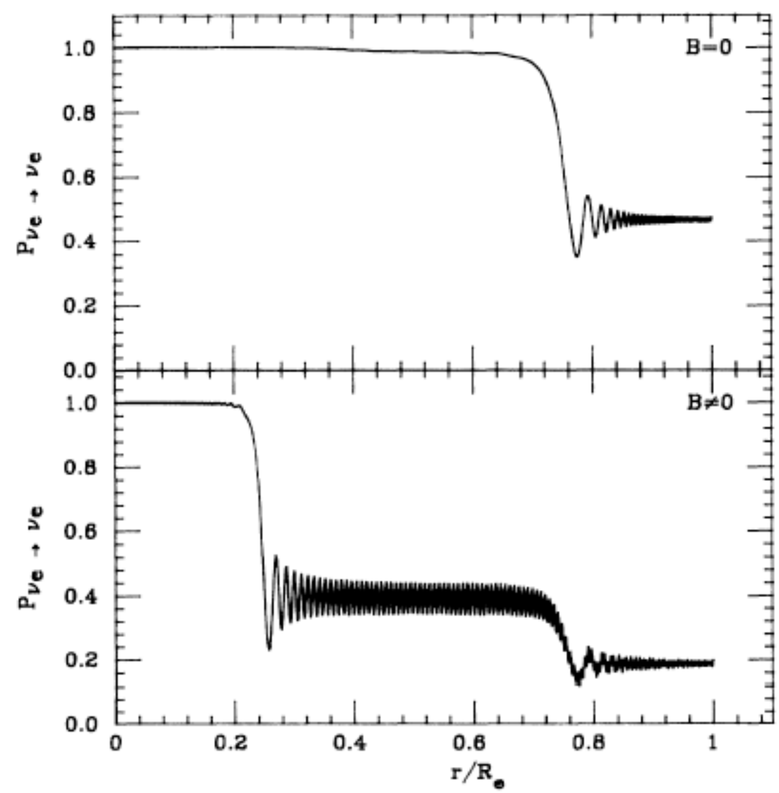
Marciano, Lim and Akhmedov

Solar magnetic fields

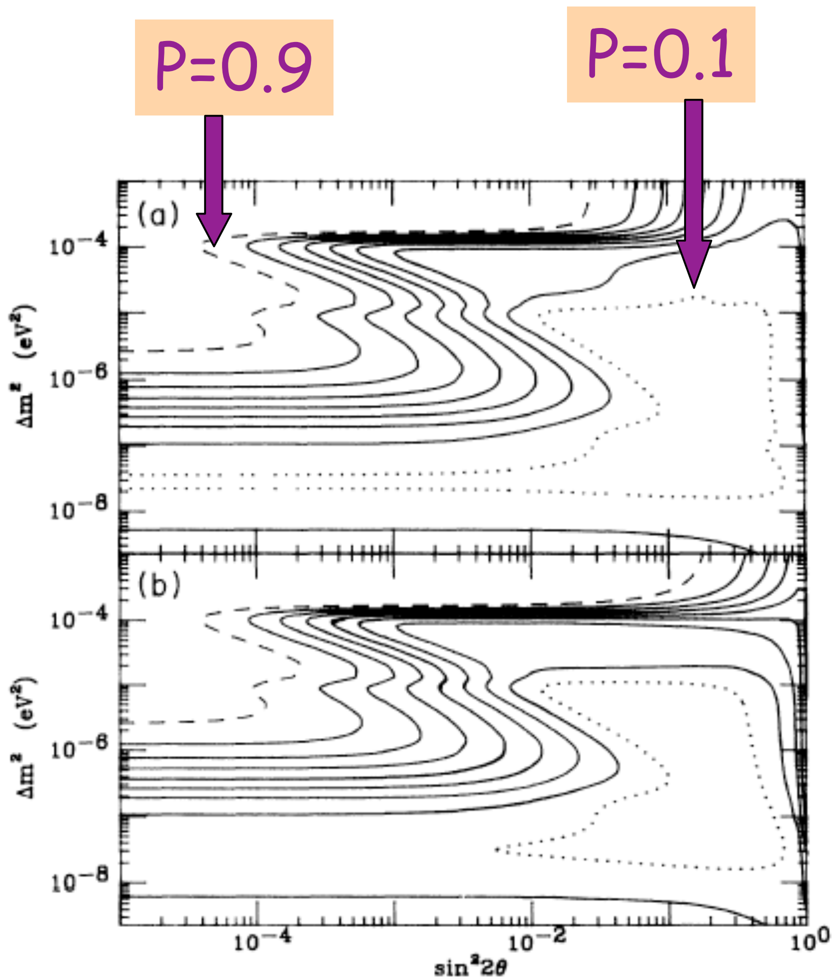
- Standard Solar Model requires $B < 10^8$ G (for magnetic pressure << matter pressure).
- Helioseismology: If $B > 10^7$ G, sound speed profile would deviate from the observed values Turck-Chieze.
- Solar neutrino flux variations with heliographic latitude may imply magnetic fields Caldwell.

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

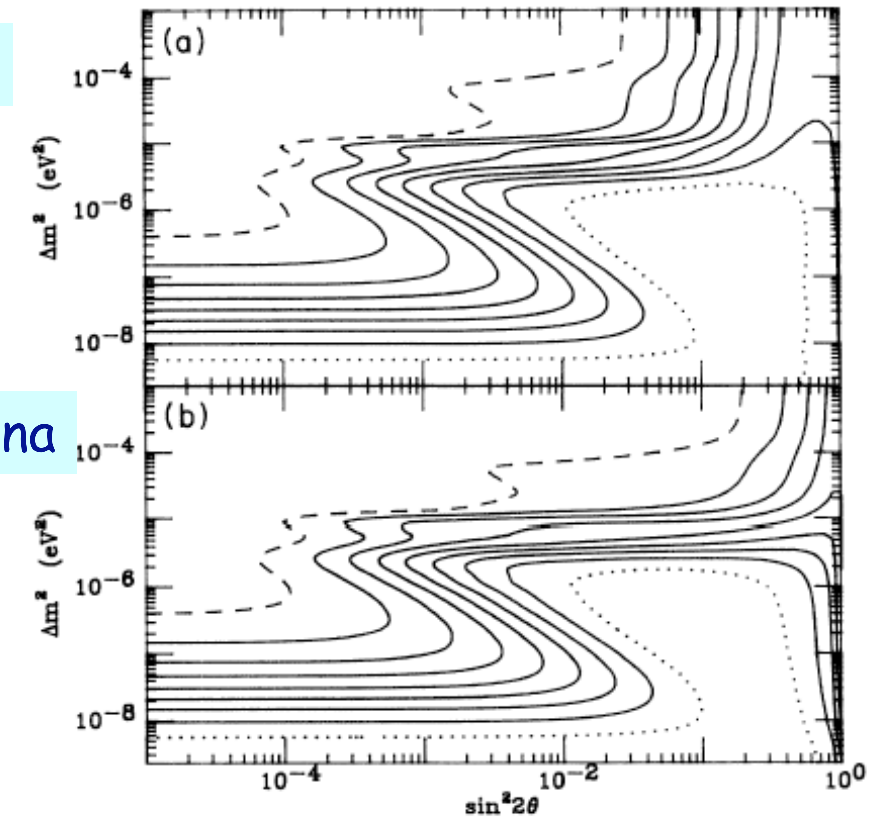


For the solar neutrinos, where $N_n \approx$ small, these resonances essentially overlap



Dirac

Majorana



Cl-detector

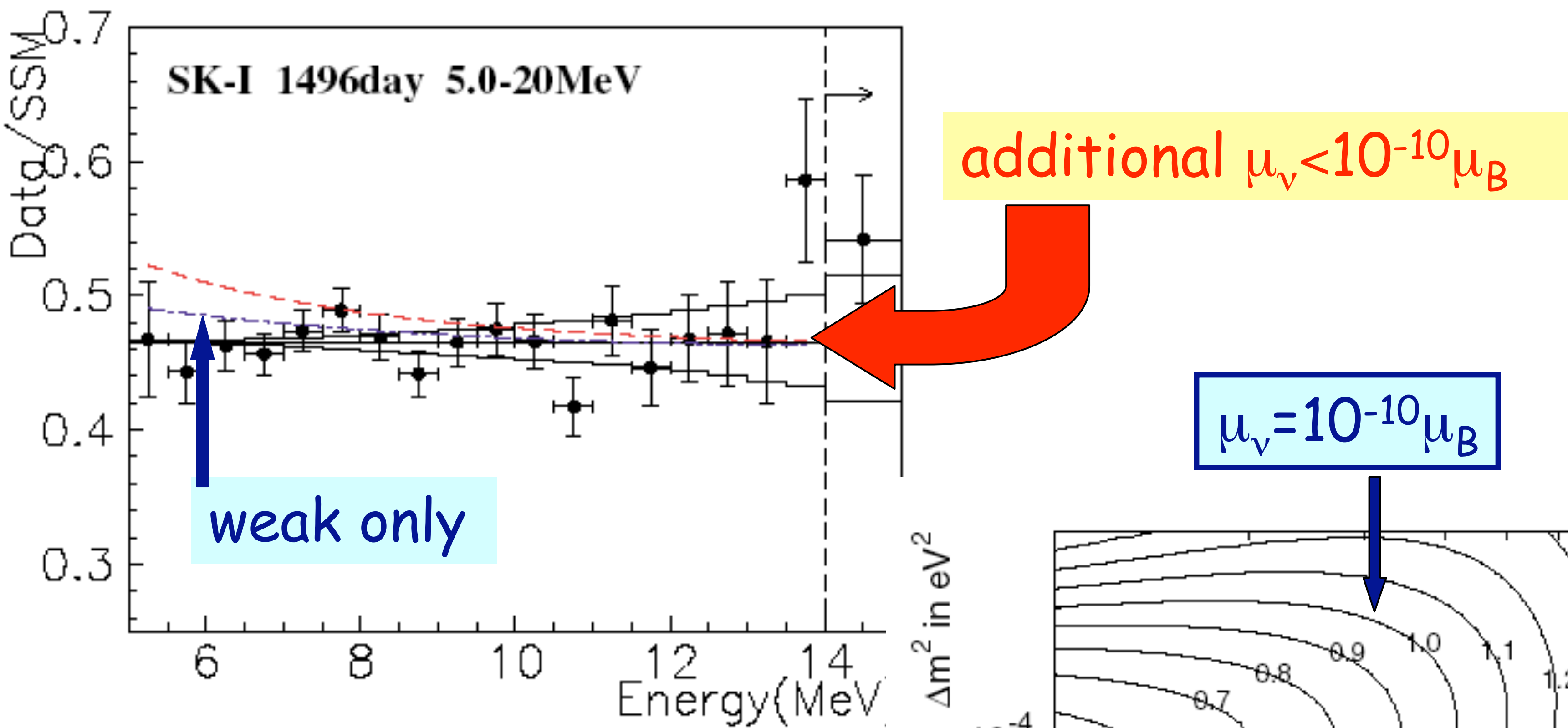
Ga-detector

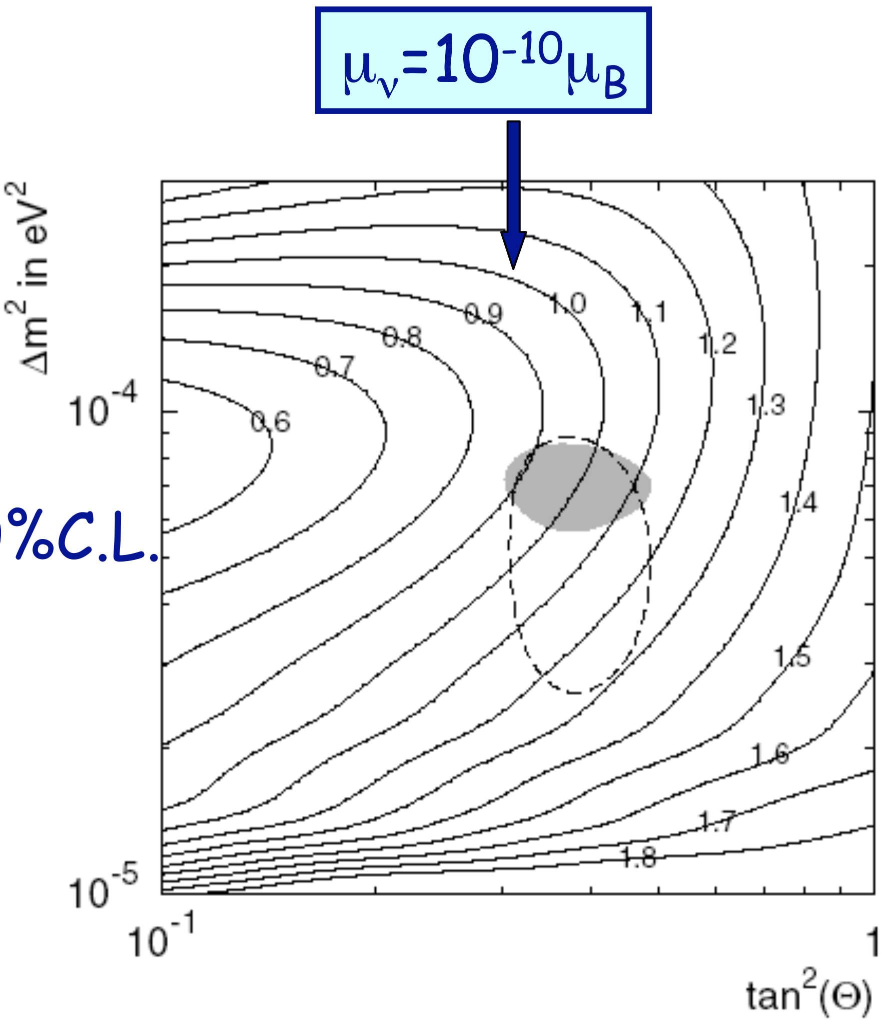
A.B. Balantekin, P. Hatchell, F. Loreti, Phys. Rev. D41, 3583 (1990)

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:

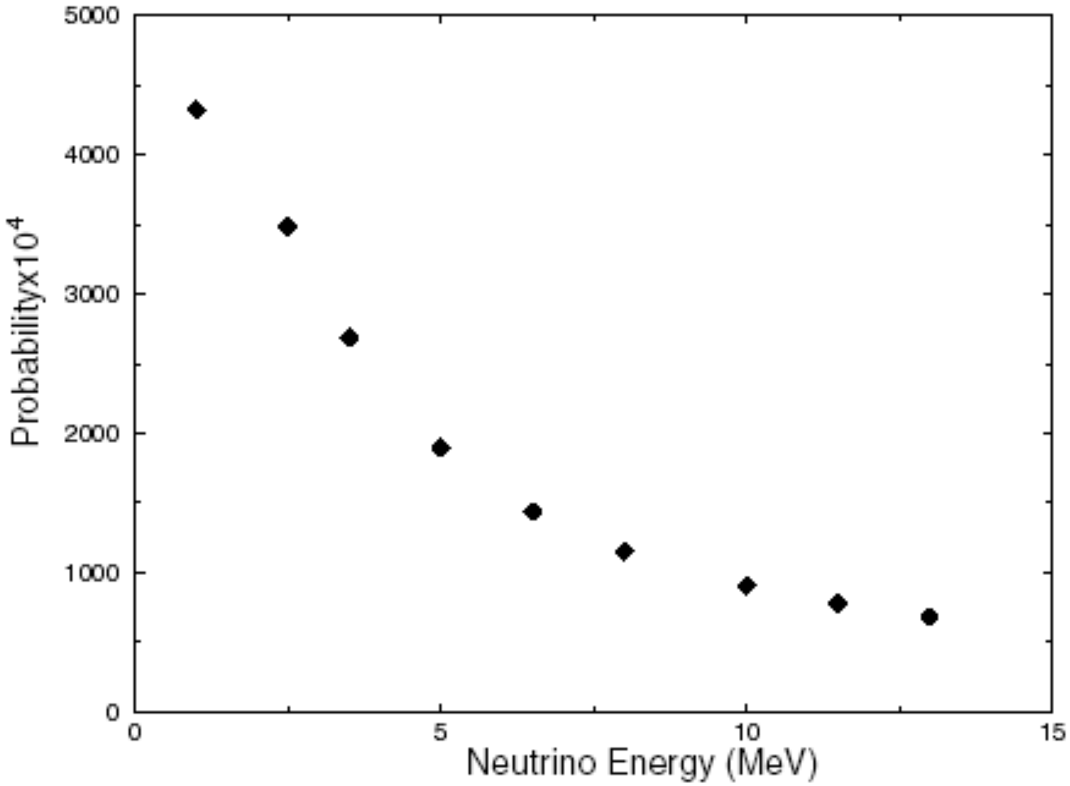
$$\varphi_{antineutrino} \leq 3 \times 10^{-4}\, \varphi_{B8\text{-}neutrino}$$





SuperK: $\mu_\nu \leq (3.6 \times 10^{-10})\mu_B$ at 90%C.L.

SuperK + KamLAND:
$\mu_\nu \leq (1.1 \times 10^{-10})\mu_B$ at 90%C.L.

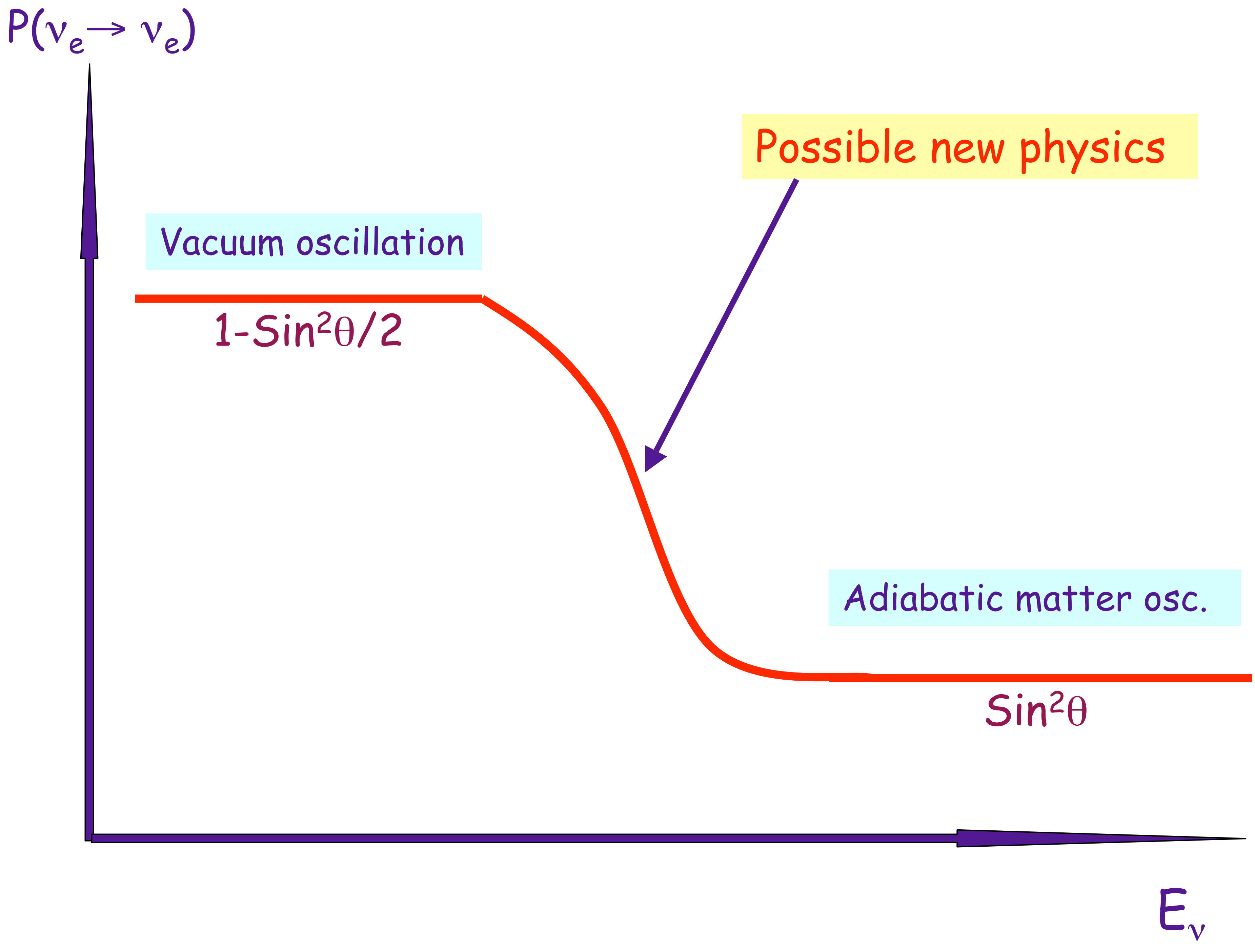


- $\mu = 10^{-11}\ \mu_B$
- $B = 10^5\ G$
- $\delta m^2 = 8 \times 10^{-5}\ eV^2$
- $\tan^2\theta = 0.4$

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)

Also: No experimental evidence for temporal variations of the solar neutrino flux (both SK and SNO)


$P(\nu_e \rightarrow \nu_e)$
Possible new physics
Vacuum oscillation
$1\text{-}Sin^2\theta/2$
Adiabatic matter osc.
$Sin^2\theta$
E_ν

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

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

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

Adiabatic solution

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

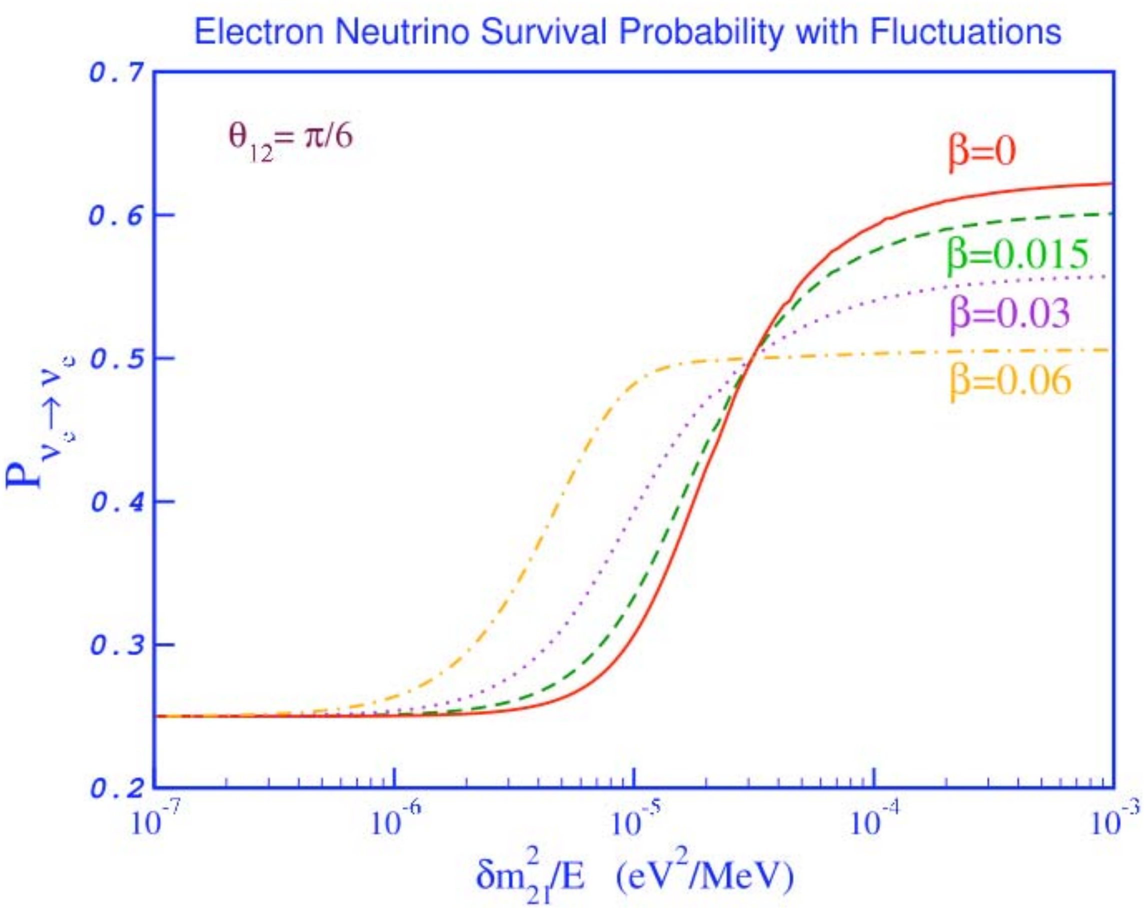
$$\frac{1}{\sqrt{2}} G_F N_e(x) = \frac{\delta m^2}{4E} \cos 2\theta_v$$

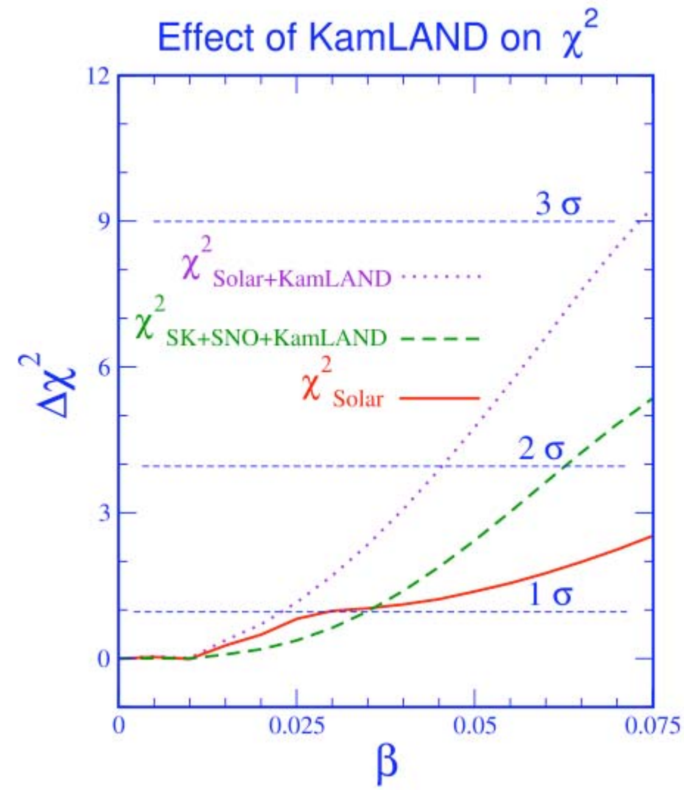
→ Most-pronounced contribution of non-standard interactions

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

This behavior is generic, A.B. Balantekin and A.Malkus

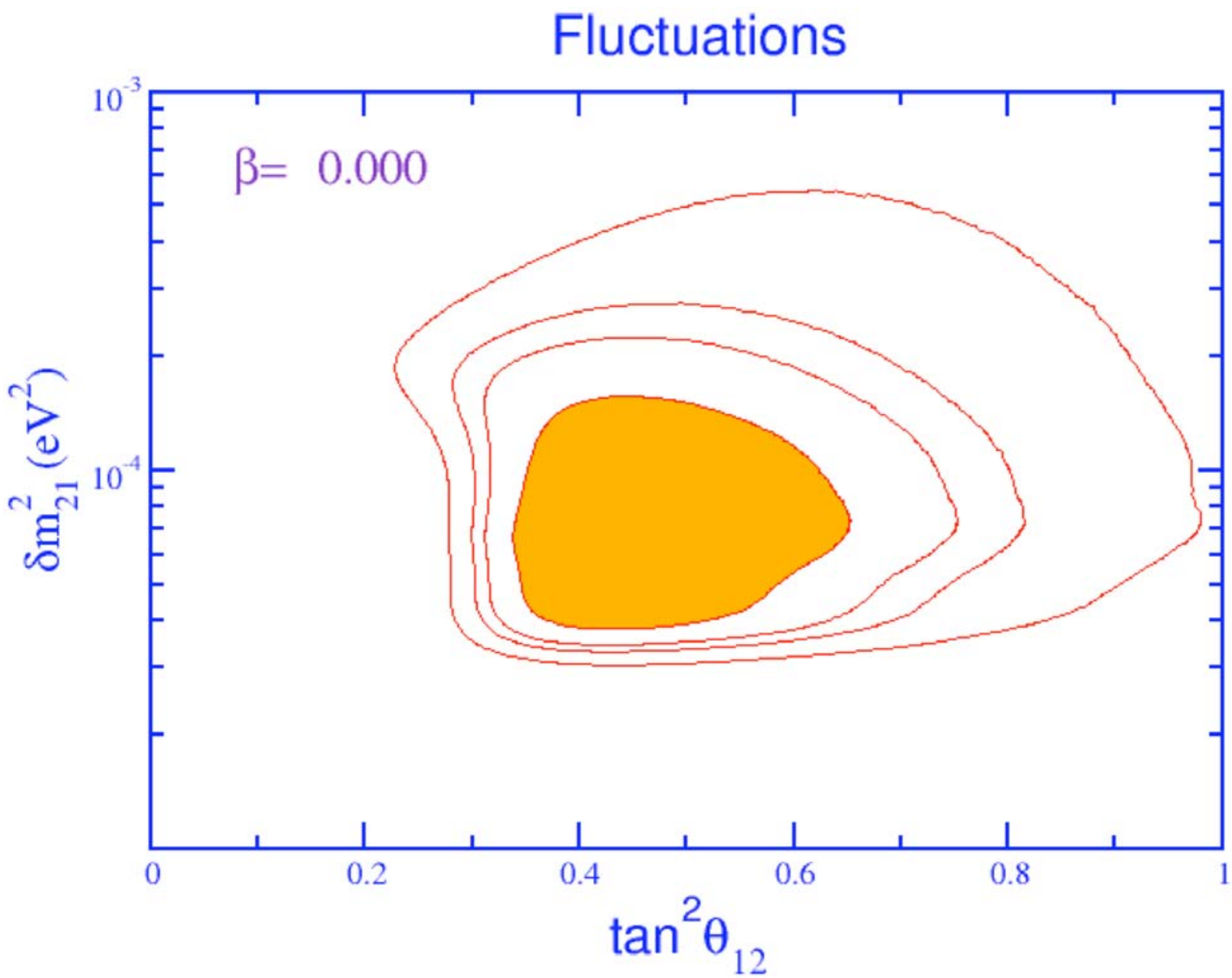
Does the solar density fluctuate?



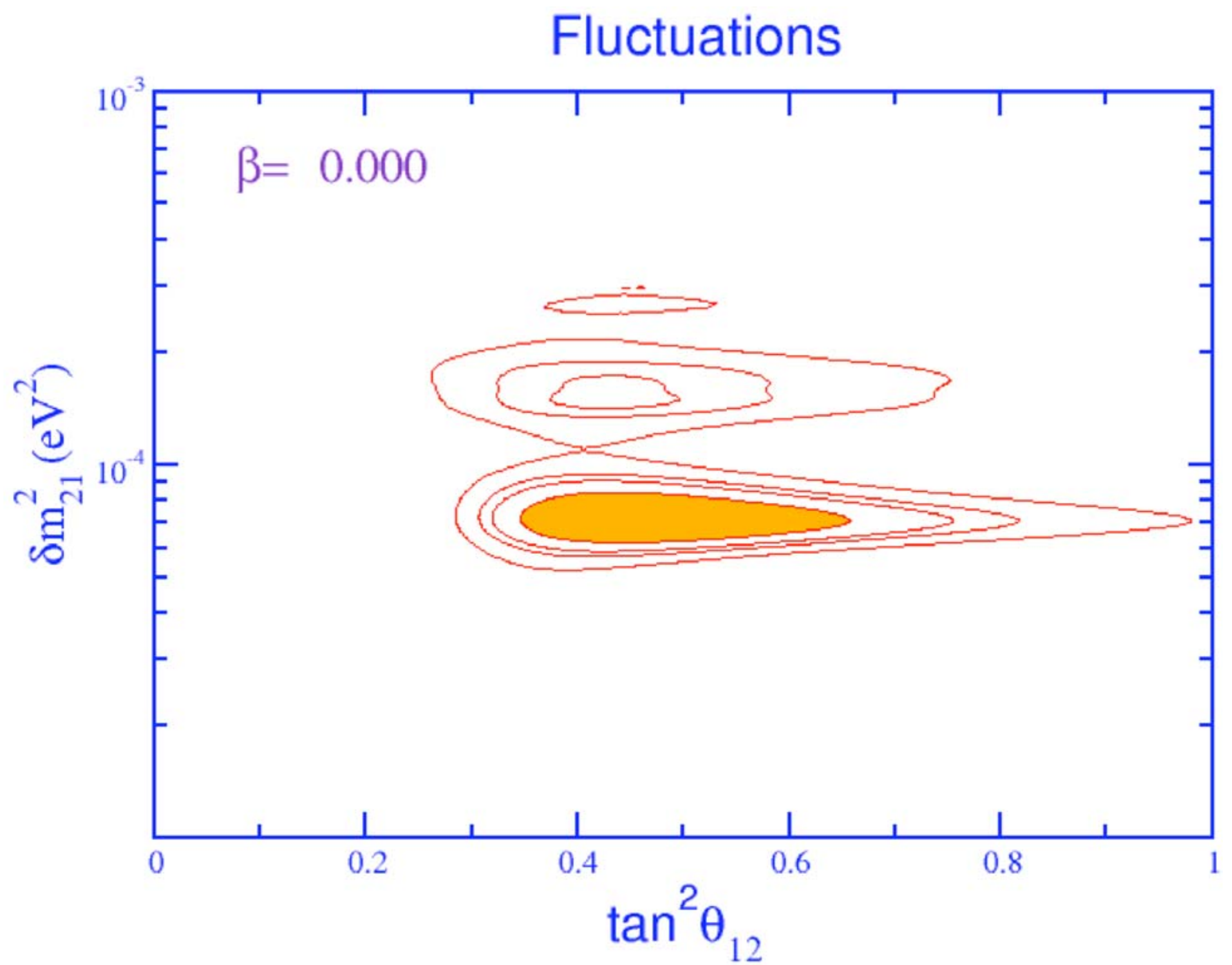


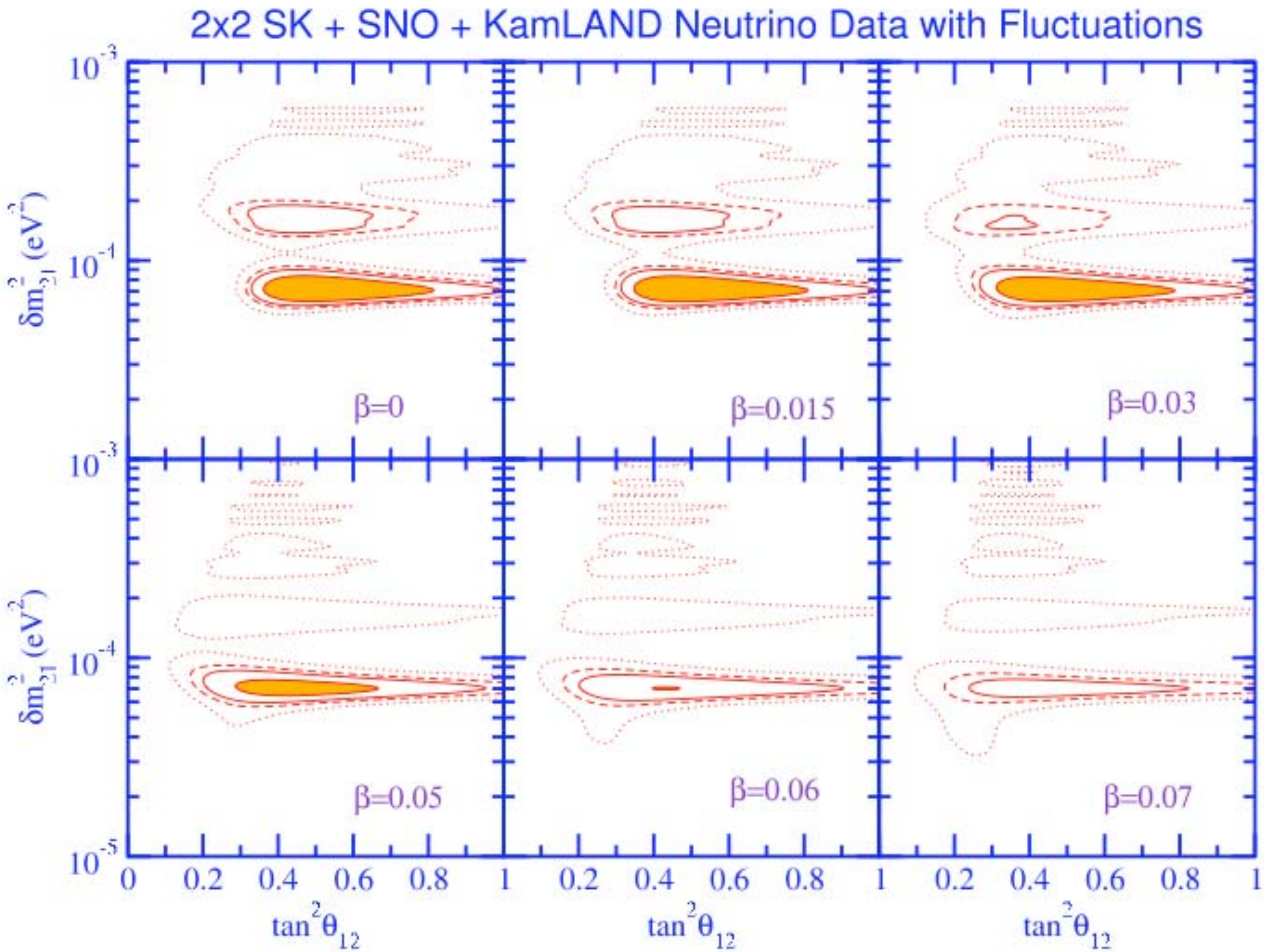
Balantekin and Yuksel,
PRD 68, 013006 (2003)

Solar data only



Solar + KamLAND




2x2 SK + SNO + KamLAND Neutrino Data with Fluctuations
β=0
β=0.015
β=0.03
β=0.05
β=0.06
β=0.07
δm²₂₁ (eV²)
tan²θ₁₂
0
0.2
0.4
0.6
0.8
1

Probing non-standard neutrino interactions

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

Miranda, Tortola, Valle, hep-ph/0406280

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

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

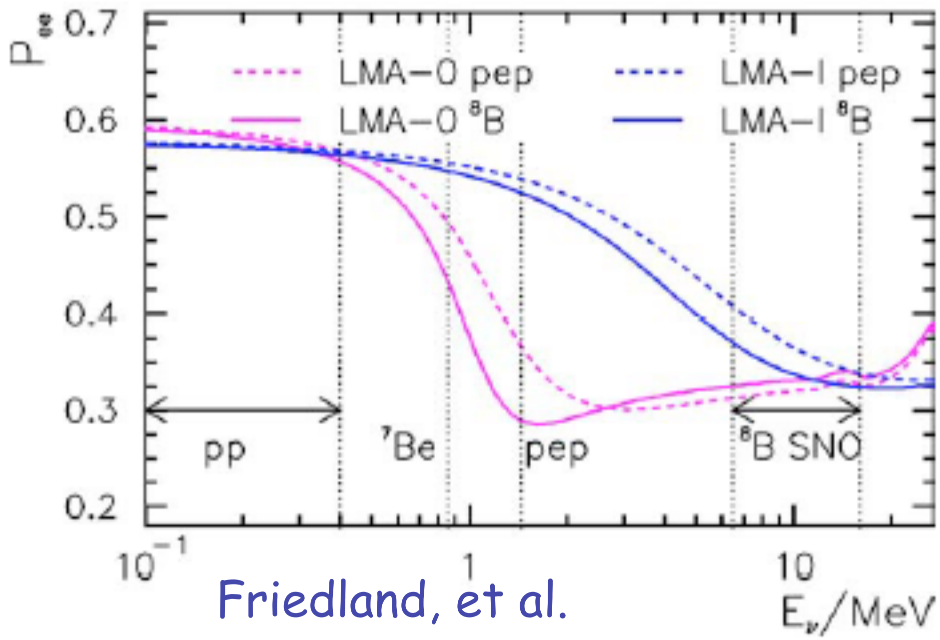
$$\epsilon_{11} = \epsilon_{ee} - \epsilon_{\tau\tau} \sin^2\theta_{23},$$

$$\epsilon_{12} = -2\epsilon_{e\tau} \sin\theta_{23}.$$

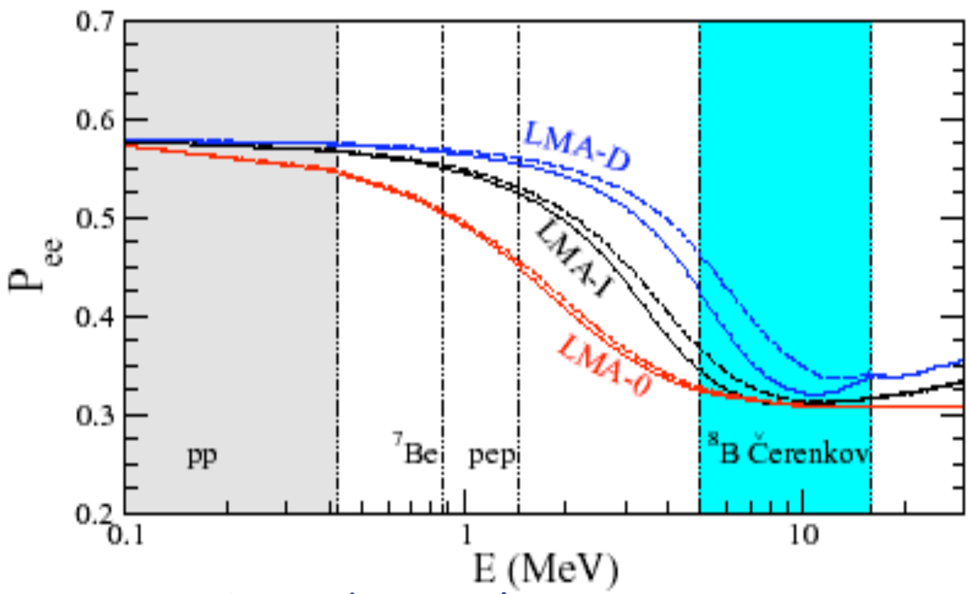
$$i\hbar \frac{\partial}{\partial x} \begin{bmatrix} \Psi_e(x) \\ \Psi_x(x) \end{bmatrix} = \begin{bmatrix} \varphi(x) & \sqrt{\Lambda} \\ \sqrt{\Lambda} & -\varphi(x) \end{bmatrix} \begin{bmatrix} \Psi_e(x) \\ \Psi_x(x) \end{bmatrix}$$

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

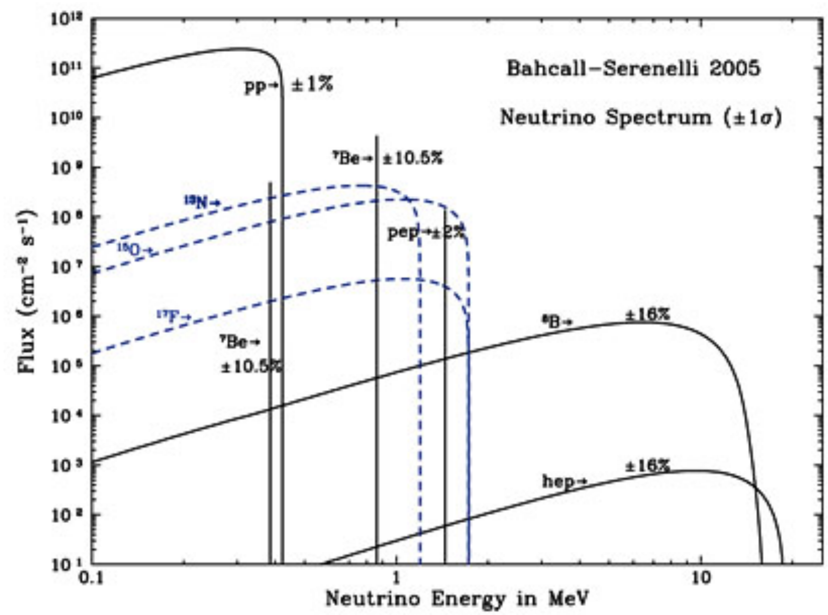
$$\sqrt{\Lambda} = \frac{\delta m^2}{4E} \sin 2\theta_v + \frac{1}{\sqrt{2}} G_F N_e(x) \epsilon_{12}(x)$$



Friedland, et al.



Miranda, et al.

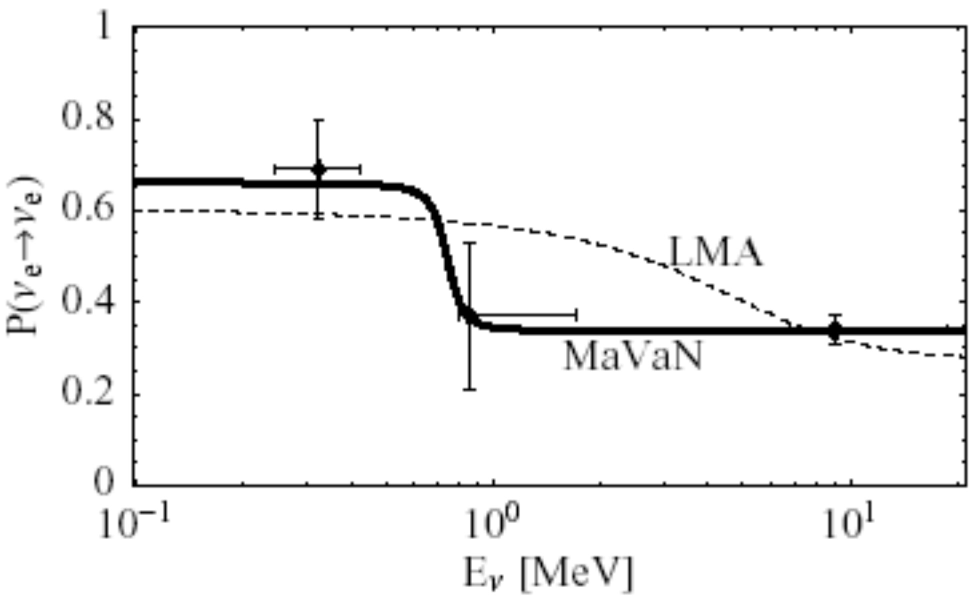


Mass-varying neutrinos, Fardon, et al., astro-ph/0309800

Scale of dark energy is similar to that of neutrino mass, $(2\times10^{-3}$ 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

Q: Does the classical solution of the coupled Einsteinian gravity - Majorana Fermion - Scalar field equations exist?

A: Yes! With $V_0 = \Lambda$

$$\frac{2}{\kappa}\frac{\ddot{R}}{R} + \frac{1}{\kappa}\left(\frac{\dot{R}}{R}\right)^2 + \frac{\dot{\phi}^2}{2} - V_0 = 0,$$

$$\frac{3}{\kappa}\left(\frac{\dot{R}}{R}\right)^2 - \frac{\dot{\phi}^2}{2} - V_0 - \frac{n}{R^3}M(\phi) = 0,$$

$$\ddot{\phi} + 3\frac{\dot{R}}{R}\dot{\phi} + \frac{n}{R^3}\frac{dM}{d\phi} = 0,$$

$$\phi(t) = \phi_0 + \frac{2\alpha}{\kappa + 6\alpha^2}\ln\left|\sinh^2\left(\sqrt{\frac{\kappa\Lambda}{8\alpha^2}(\kappa+6\alpha^2)}t\right)\right|, \quad H(t) = \sqrt{\frac{2\kappa\alpha^2\Lambda}{\kappa+6\alpha^2}}\coth\left(\sqrt{\frac{\kappa\Lambda}{8\alpha^2}(\kappa+6\alpha^2)}t\right).$$

Balantekin & Dereli, Phys. Rev. D 75, 024039 (2007)

A Few Final Remarks

- 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.