Perspectives on Solar Neutrinos and Astronuclear Physics

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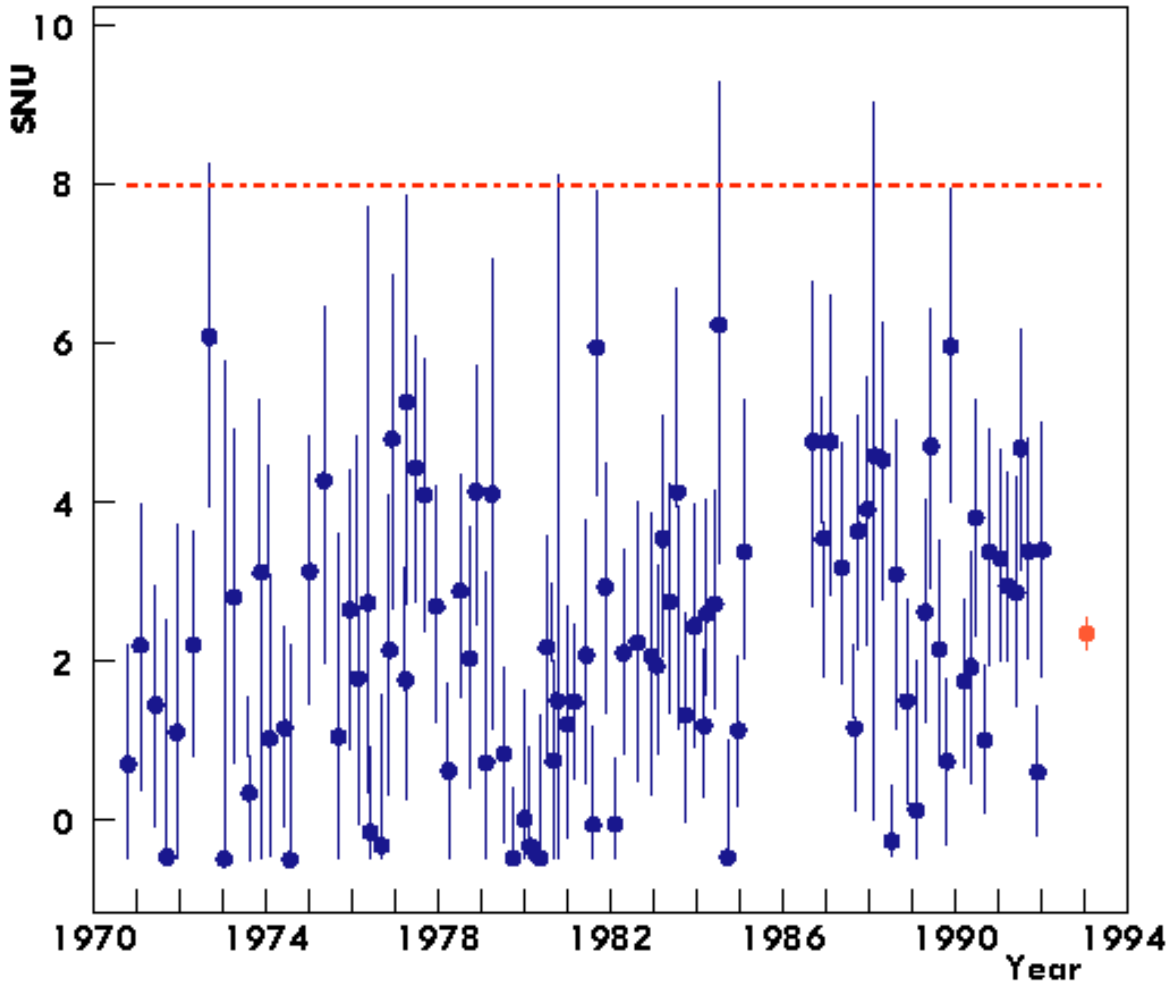
NDM06 Symposium
Neutrinos, Dark Matter, and Dark Energy
September 2006; Paris

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

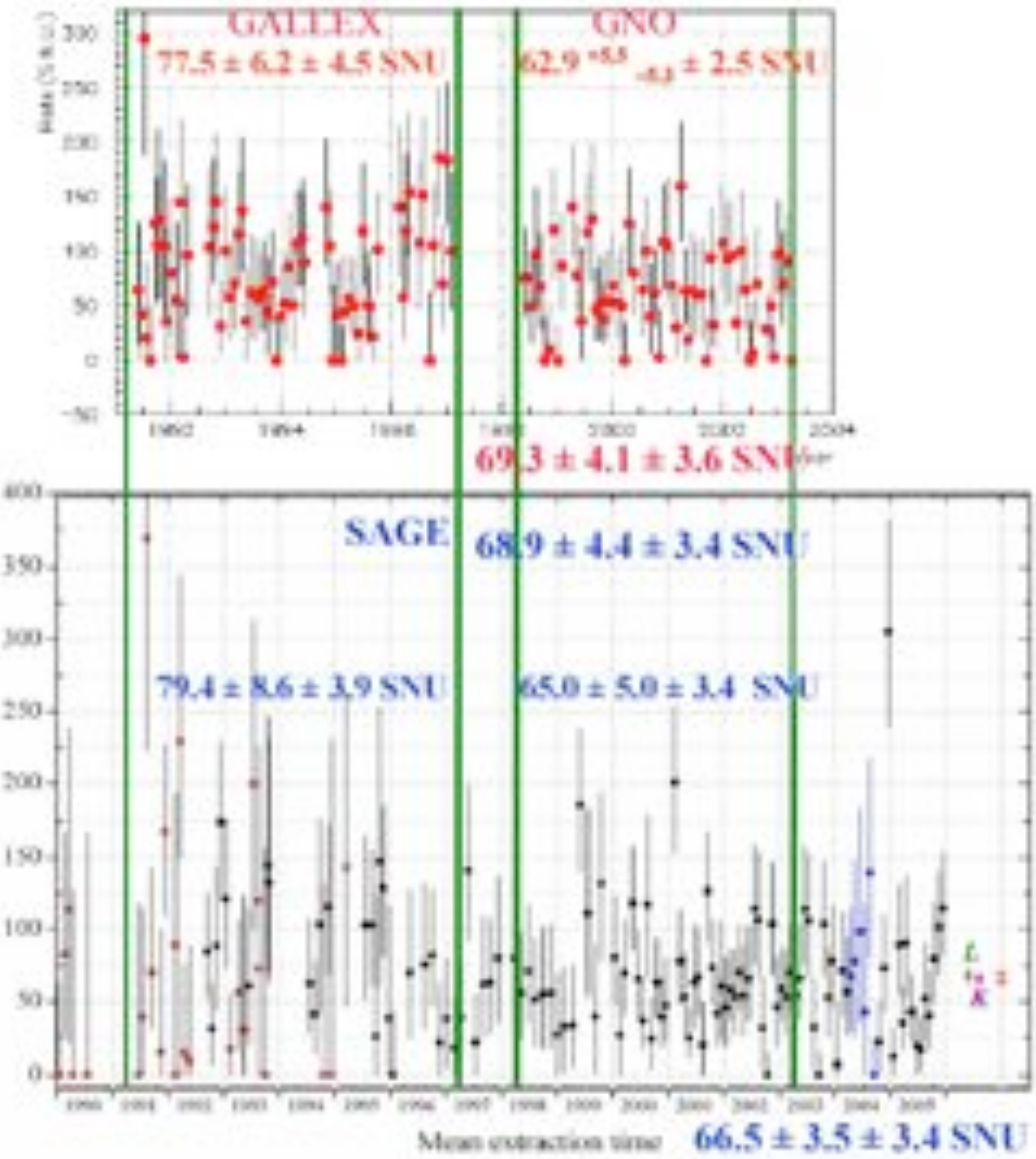
Bahcall and Davis, 1964

Then: Homestake Count Rate



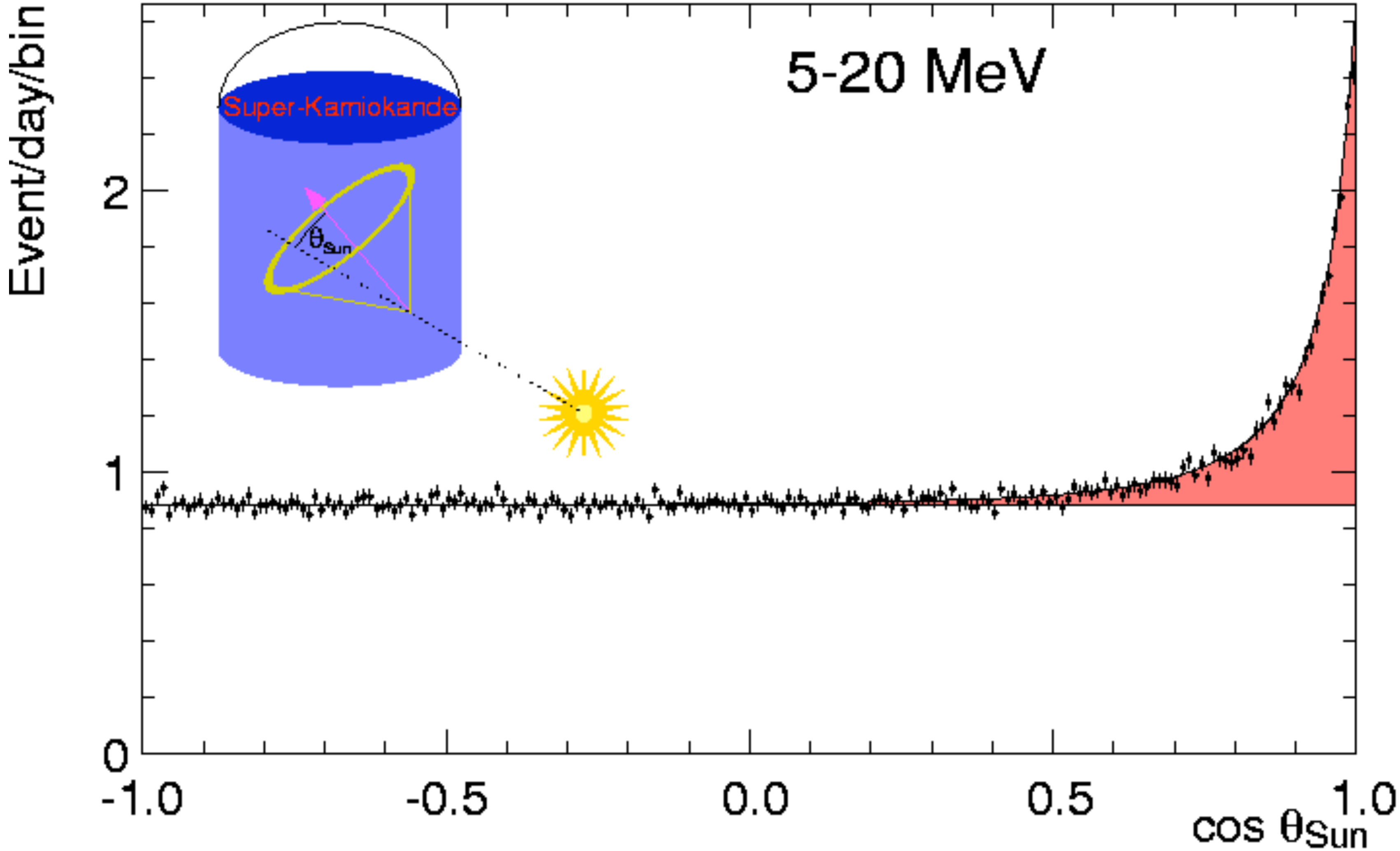
Those of us who believed the data thought that neutrino mixing angles are, like quark mixing angles, small for vacuum mixing, but, thanks to MSW, matter-enhanced oscillations do the reduction. Most people did not even believe the data.

Now:

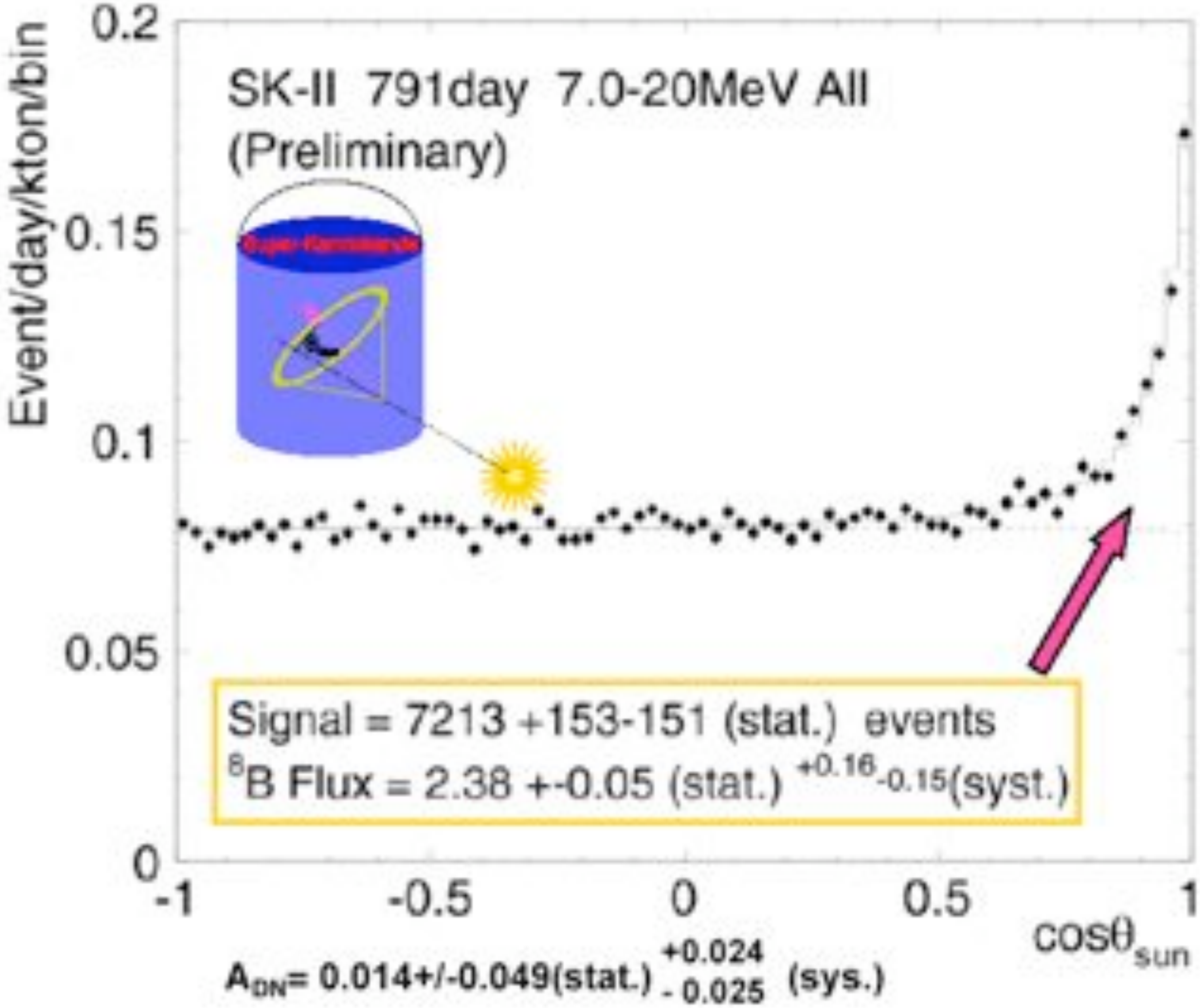


Adopted from Gavrin

SuperKamiokande-I ^{8}B solar ν's

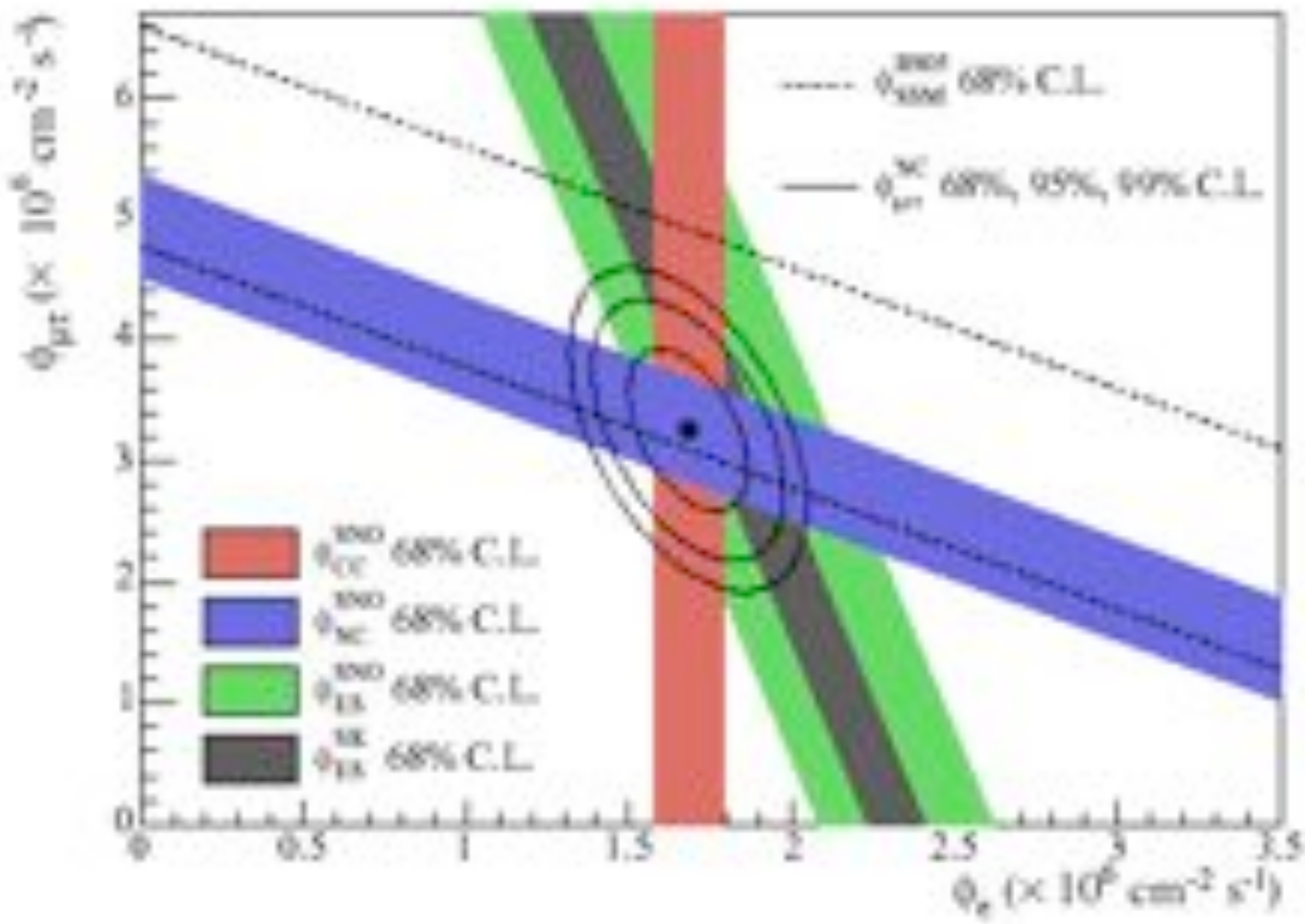


hep-ex/0508053



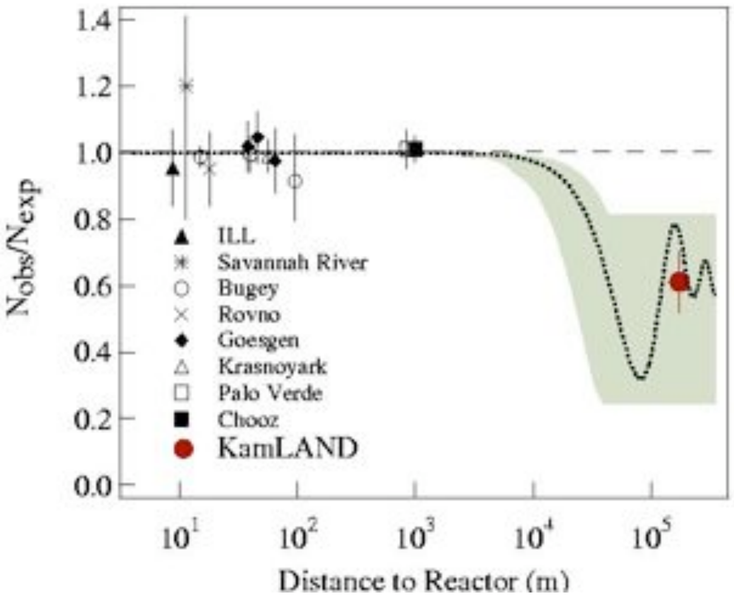
0.2
0.15
0.1
0.05
0
Event/day/kton/bin
SK-II 791day 7.0-20MeV All
(Preliminary)
Signal = 7213 +153-151 (stat.) events
^{8}B Flux = 2.38 +-0.05 (stat.) $^{+0.16}_{-0.15}$(syst.)
-1
-0.5
0
0.5
1
$\cos\theta_{sun}$
A_{DN}= 0.014+/-0.049(stat.) $^{+0.024}_{-0.025}$ (sys.)

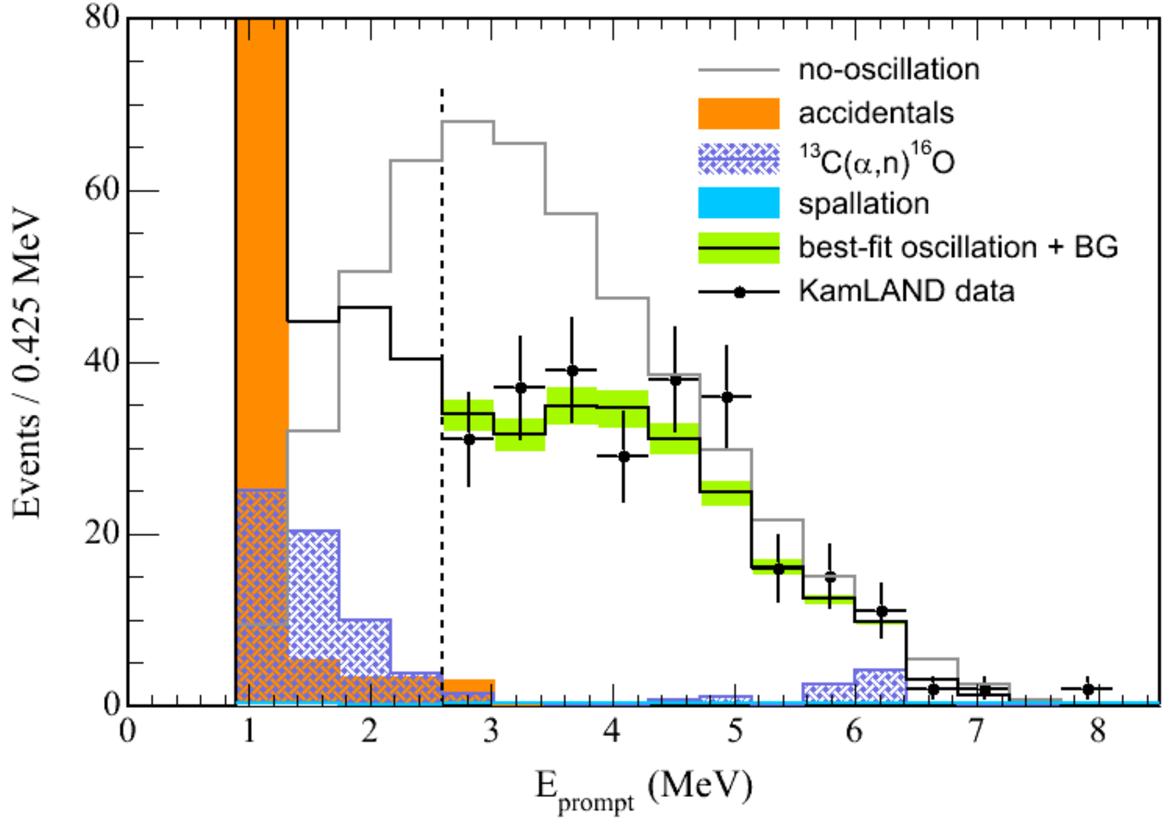
SNO



ϕ^{SSM}_{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})

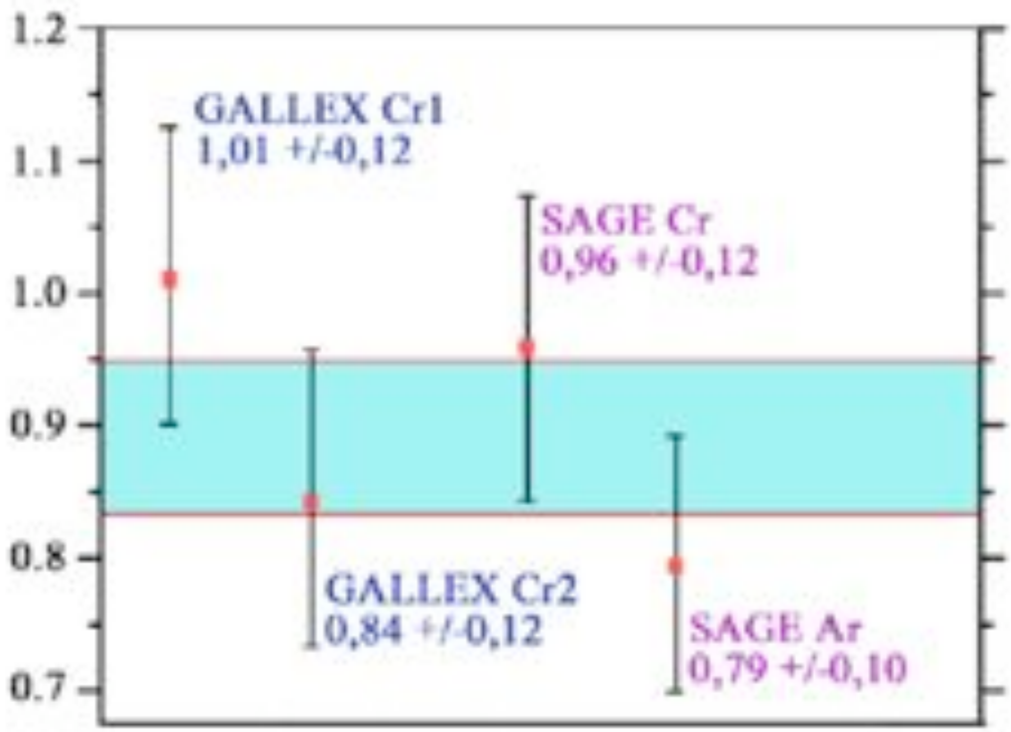
KamLAND

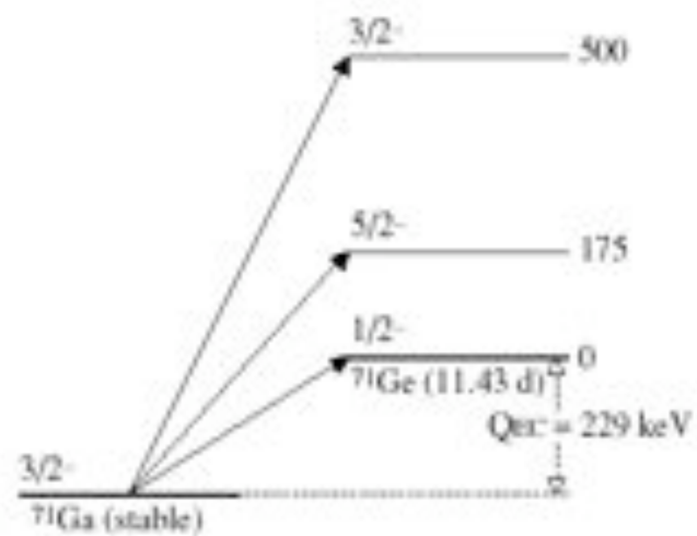




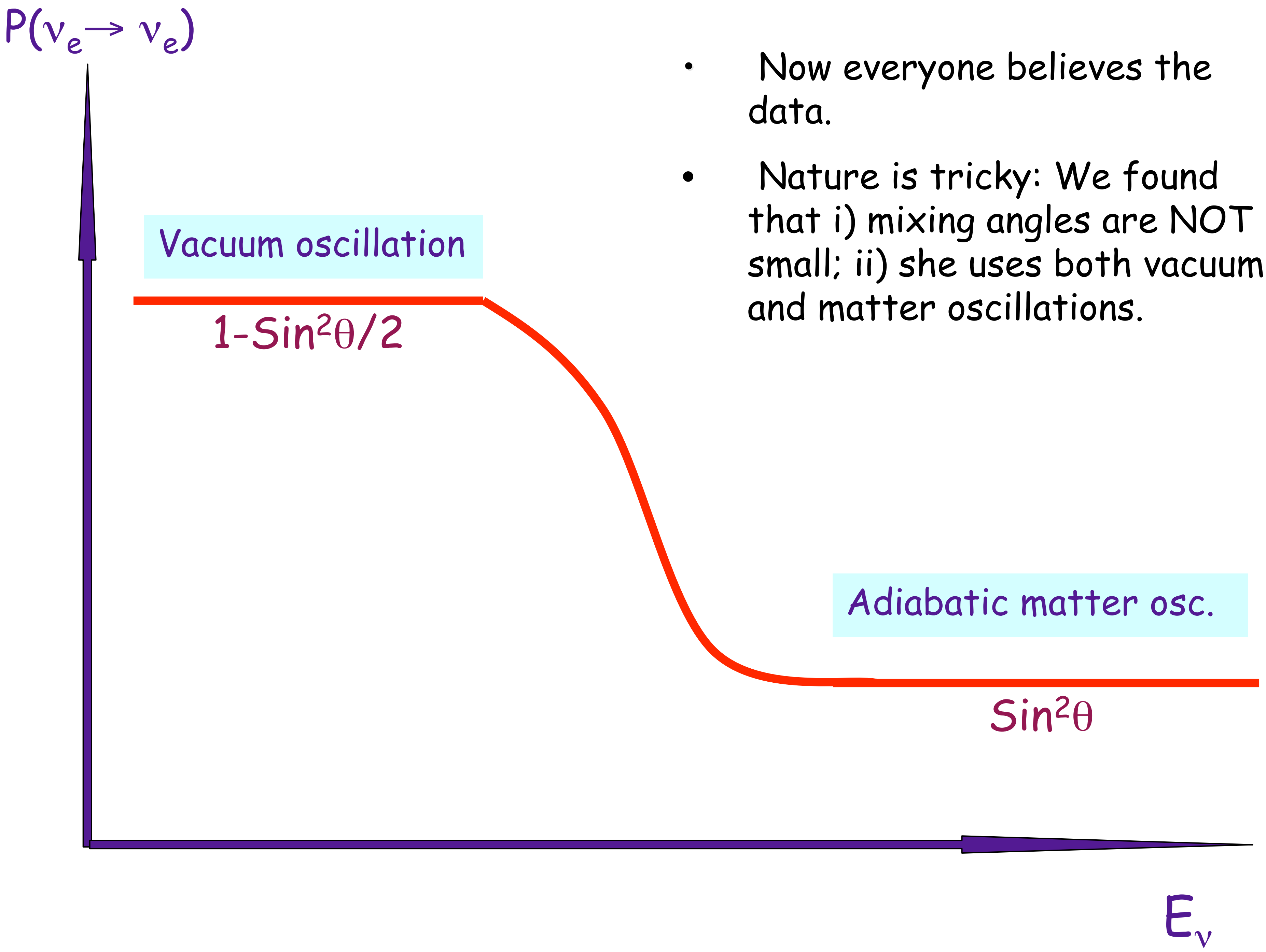
$$\overline{\nu}_e + p \rightarrow n + e^+$$

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.



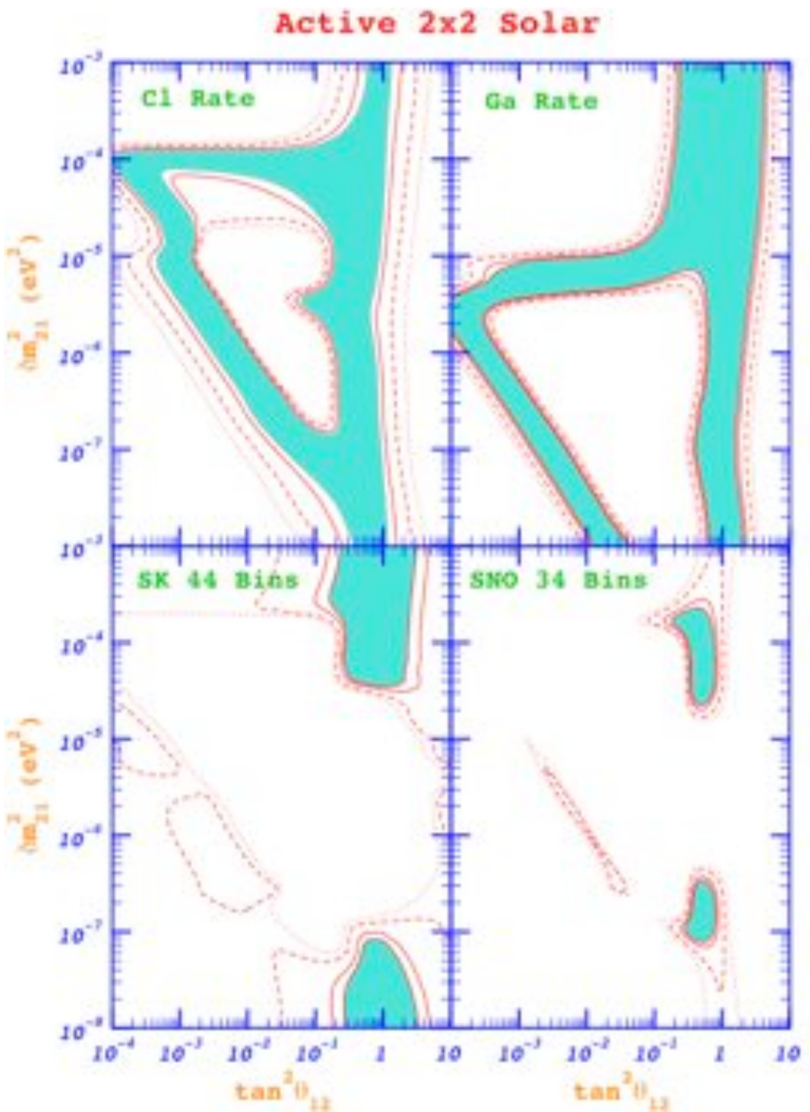
- Now everyone believes the data.
- Nature is tricky: We found that i) mixing angles are NOT small; ii) she uses both vacuum and matter oscillations.

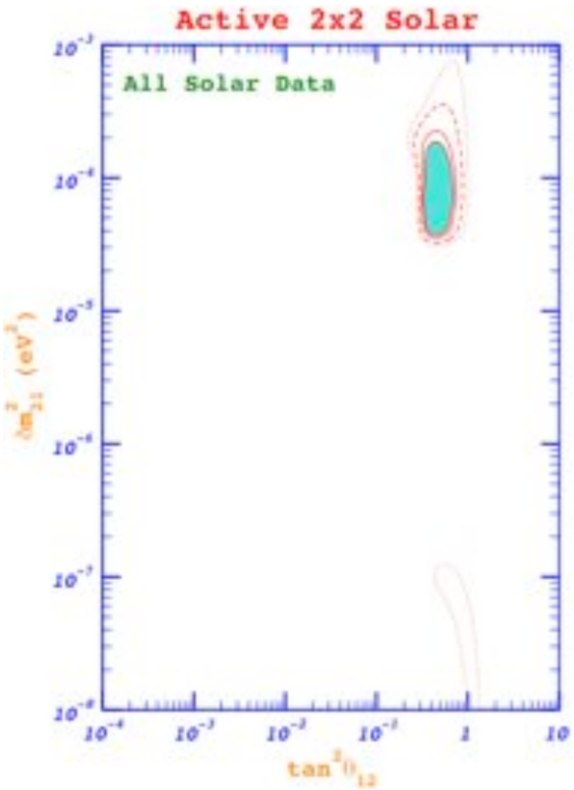
Typically solar neutrino analyses assume that ν_e mixes with a combination of ν_μ and ν_τ. This is exact only when θ_{13} is zero. When θ_{13} is non-zero, but small we can use

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

This works both for vacuum and matter oscillations…

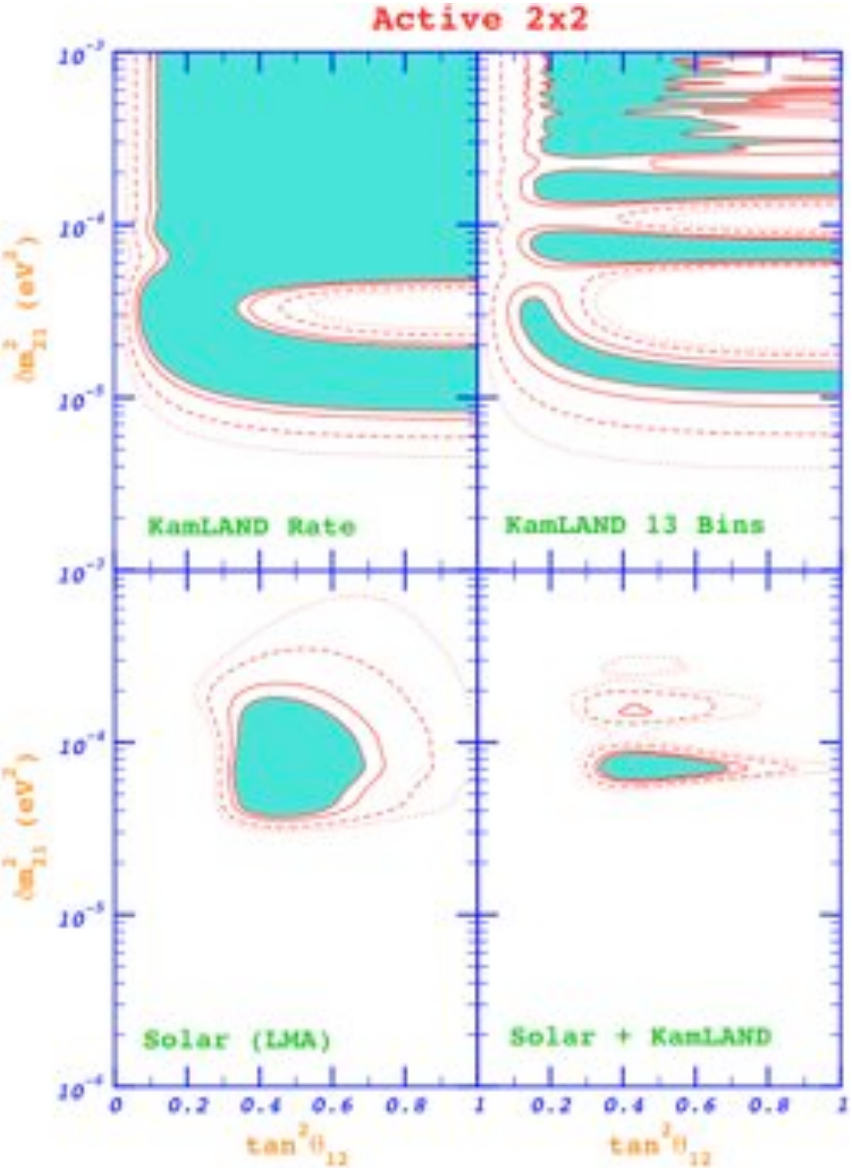
A global analysis of the solar neutrino data

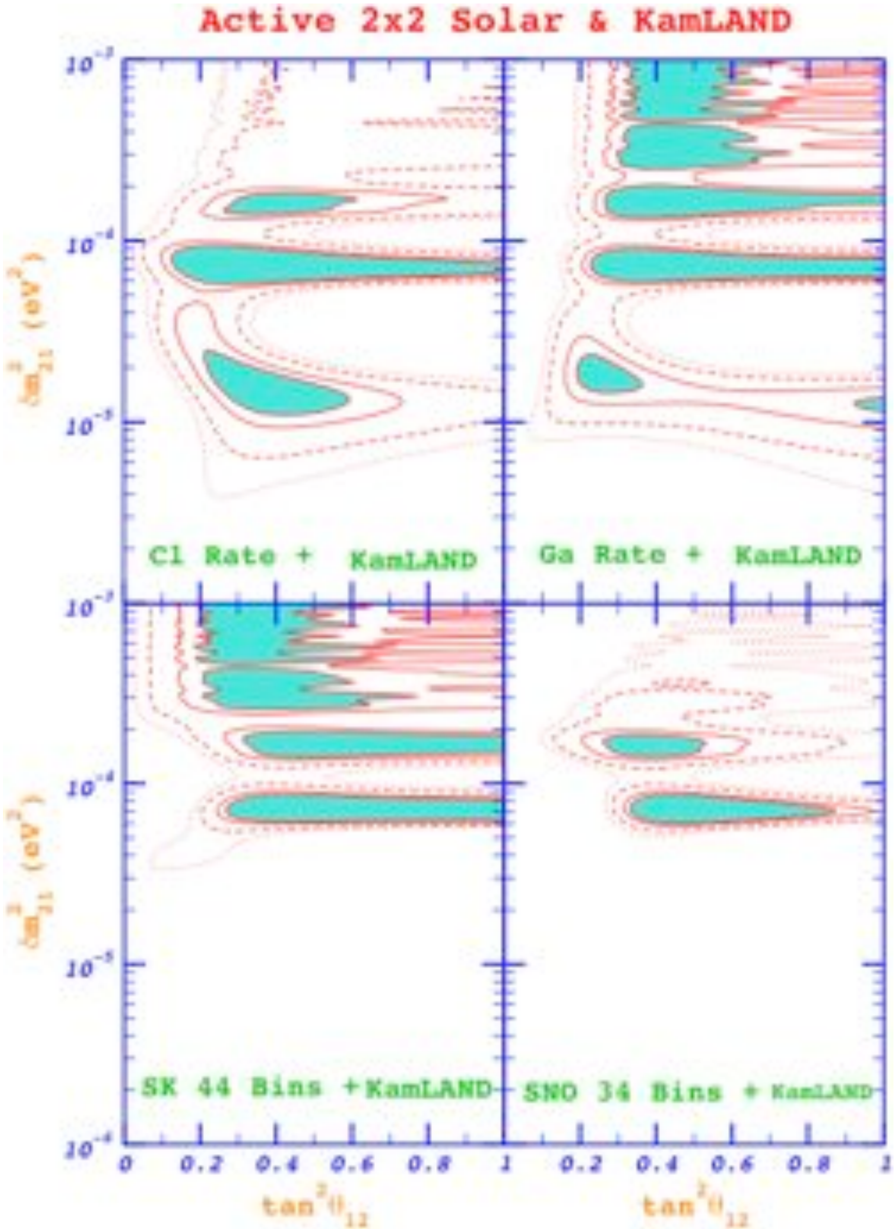




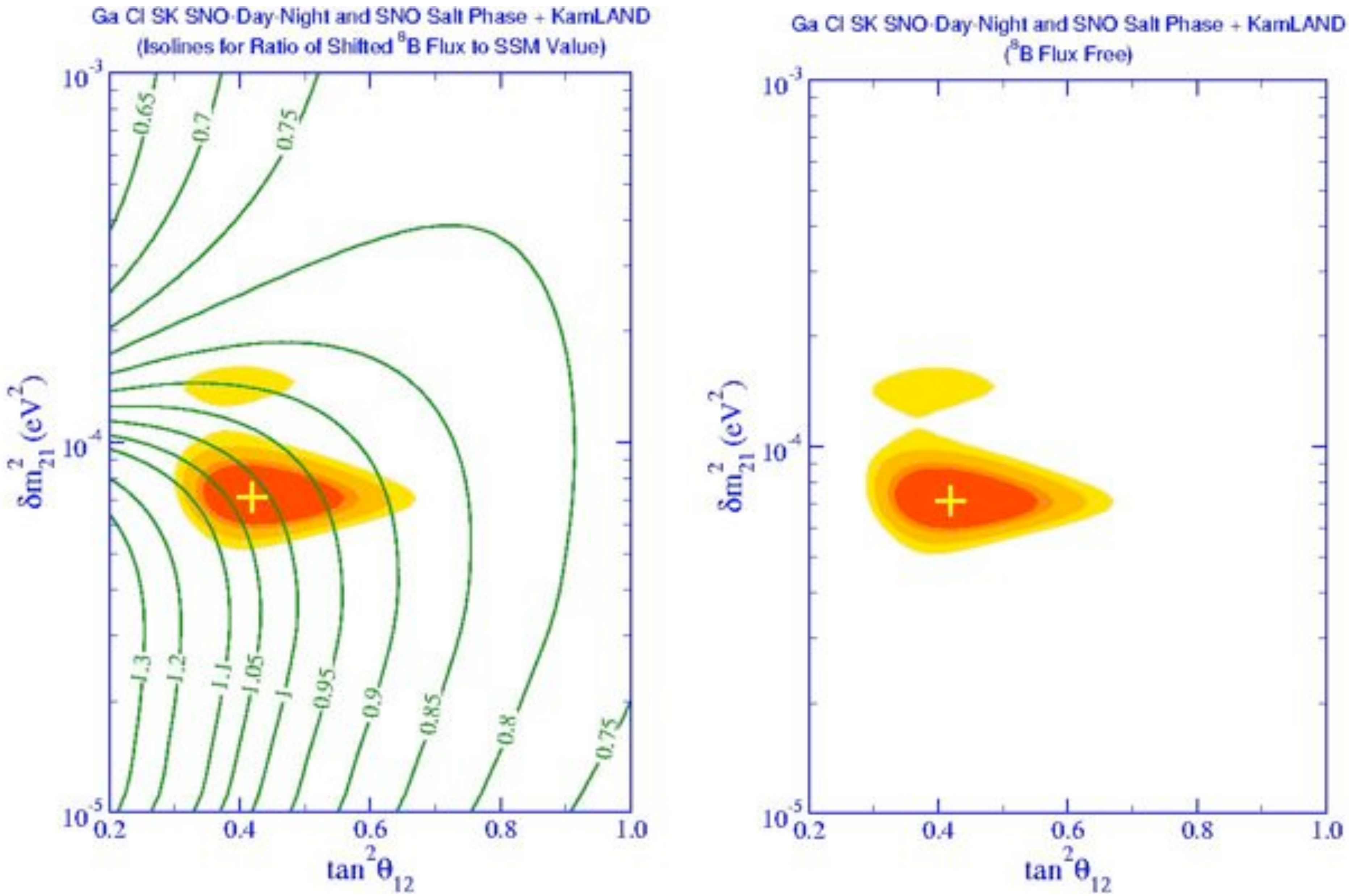
Balantekin & Yuksel, J. Phys. G 29, 665 (2003).

Solar + KamLAND Global Analysis



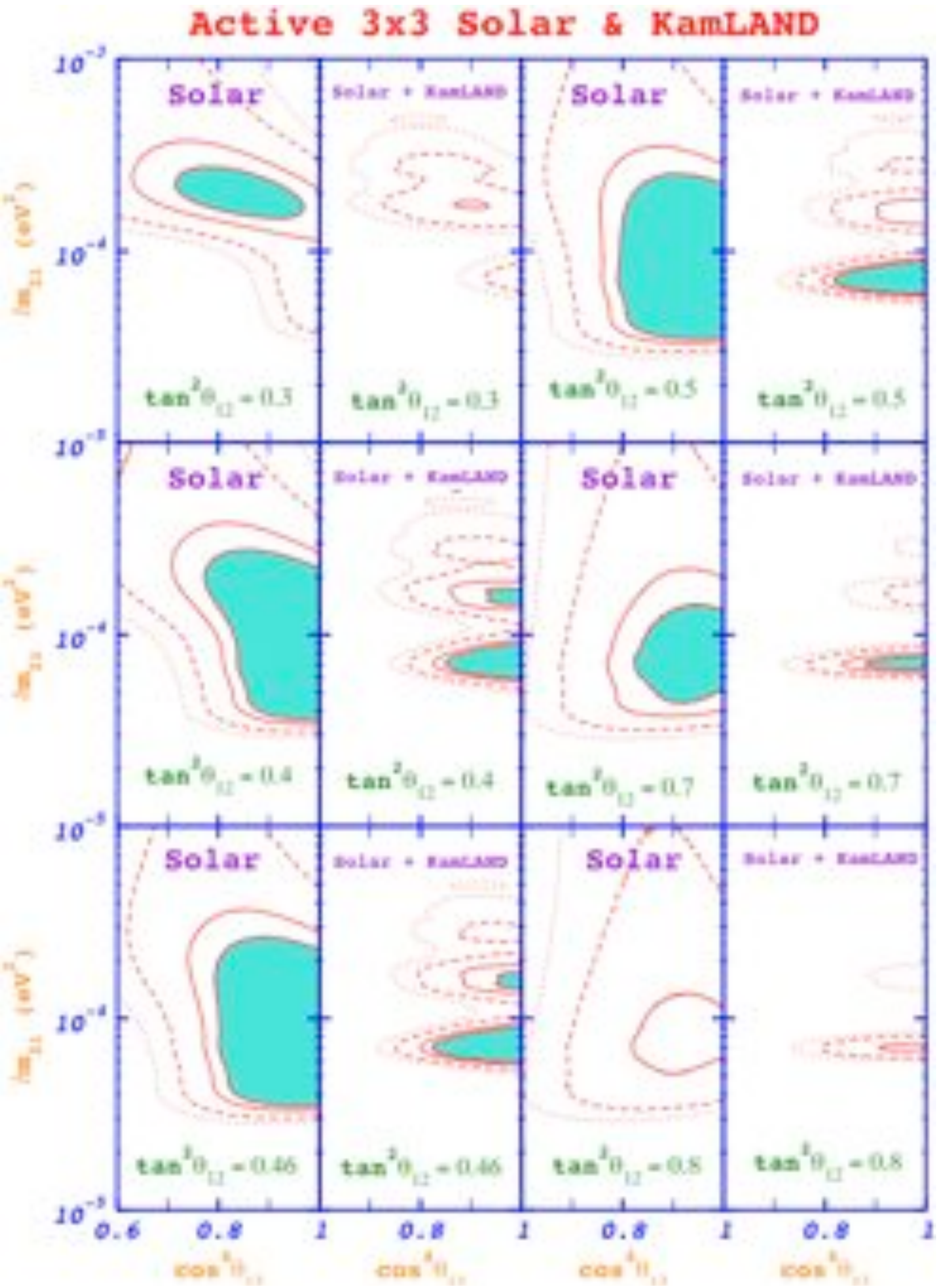


SNO first Salt Results , Balantekin and Yuksel, PRD 68, 113002 (2003)



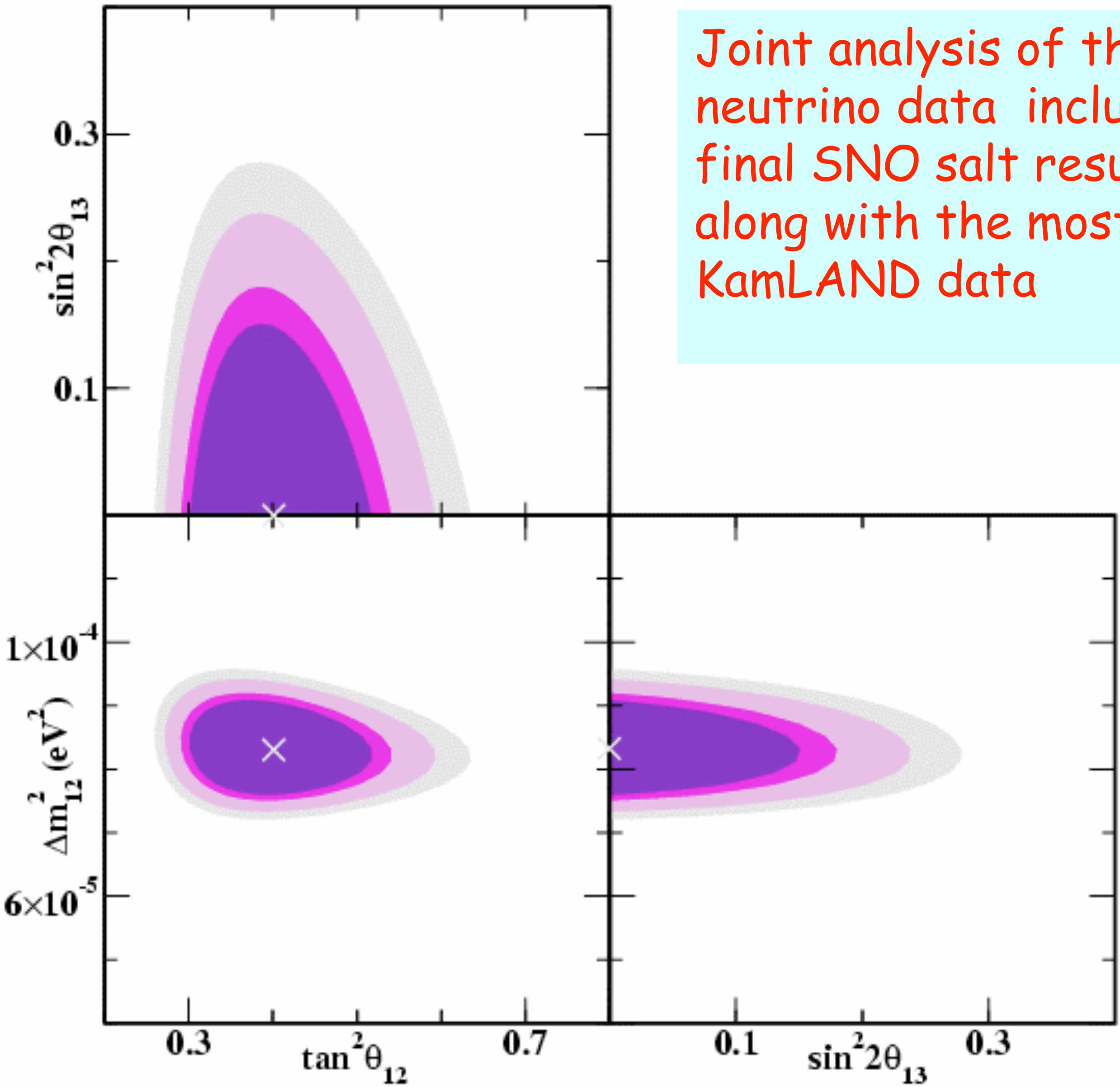
Can we probe θ_{13} in solar neutrino experiments?

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).



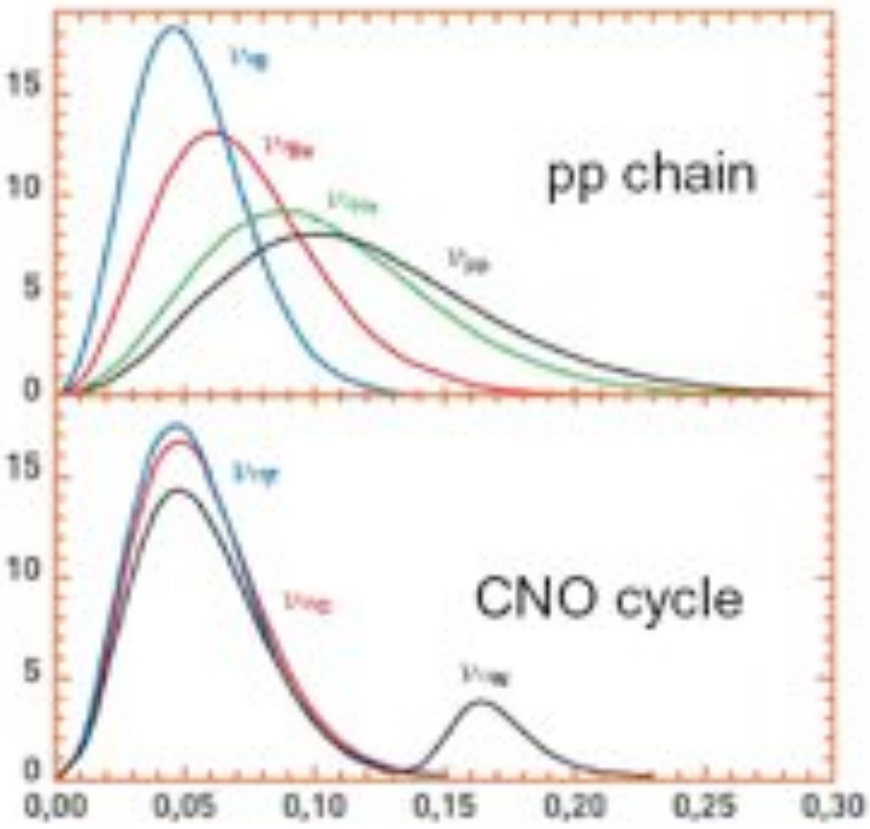
Joint analysis of the solar neutrino data including final SNO salt results along with the most recent KamLAND data

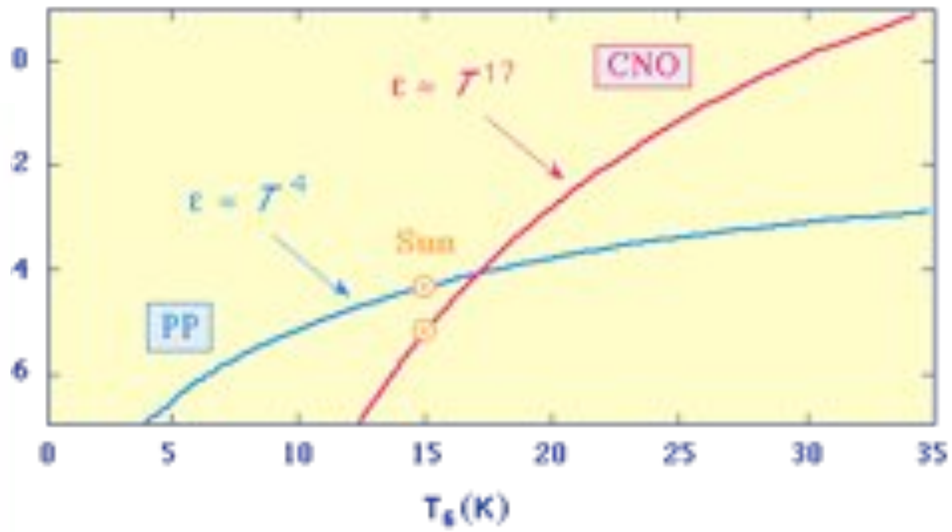
Balantekin, et al., PLB 613, 61 (2005)

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?

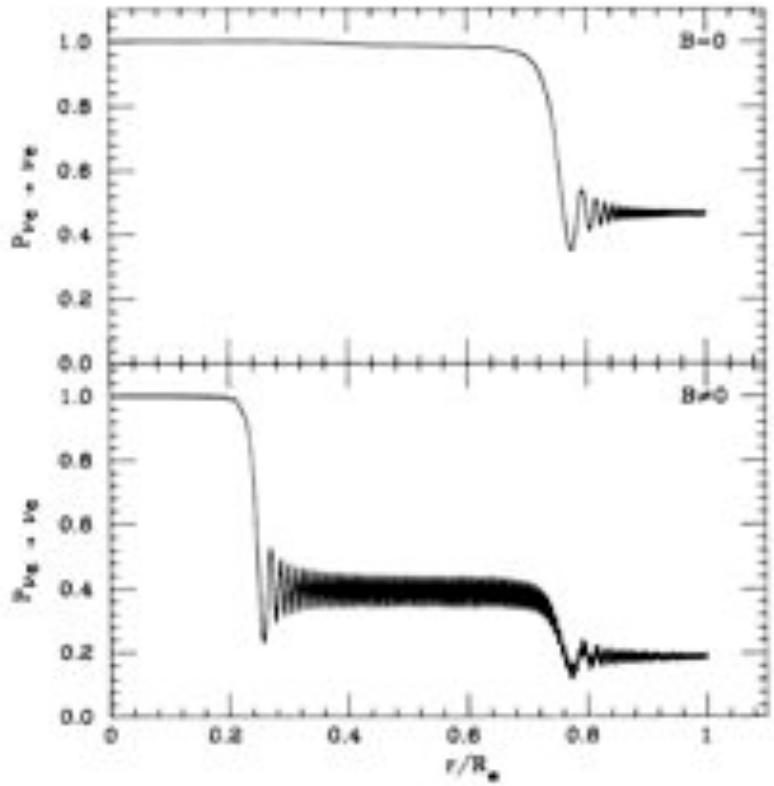




In SSM CNO cycle contribute about 0.8% of the neutrino flux. Data are consistent with this. A more precise measurement of the CNO contribution will provide a test of SSM.

Spin-flavor precession in the Sun

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



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

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

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

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

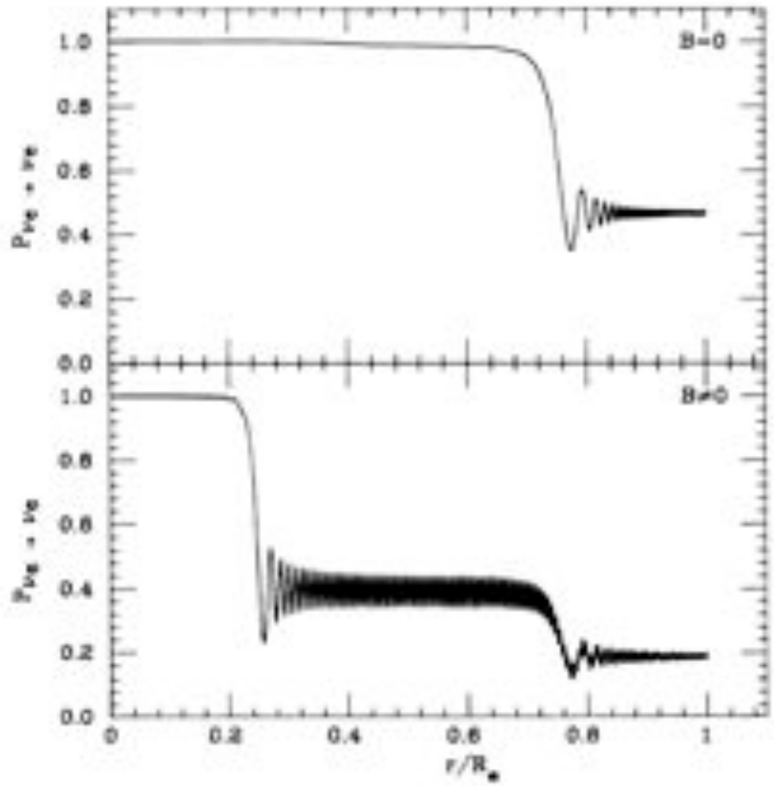
Dirac neutrinos

Marciano, Lim and Akhmedov

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

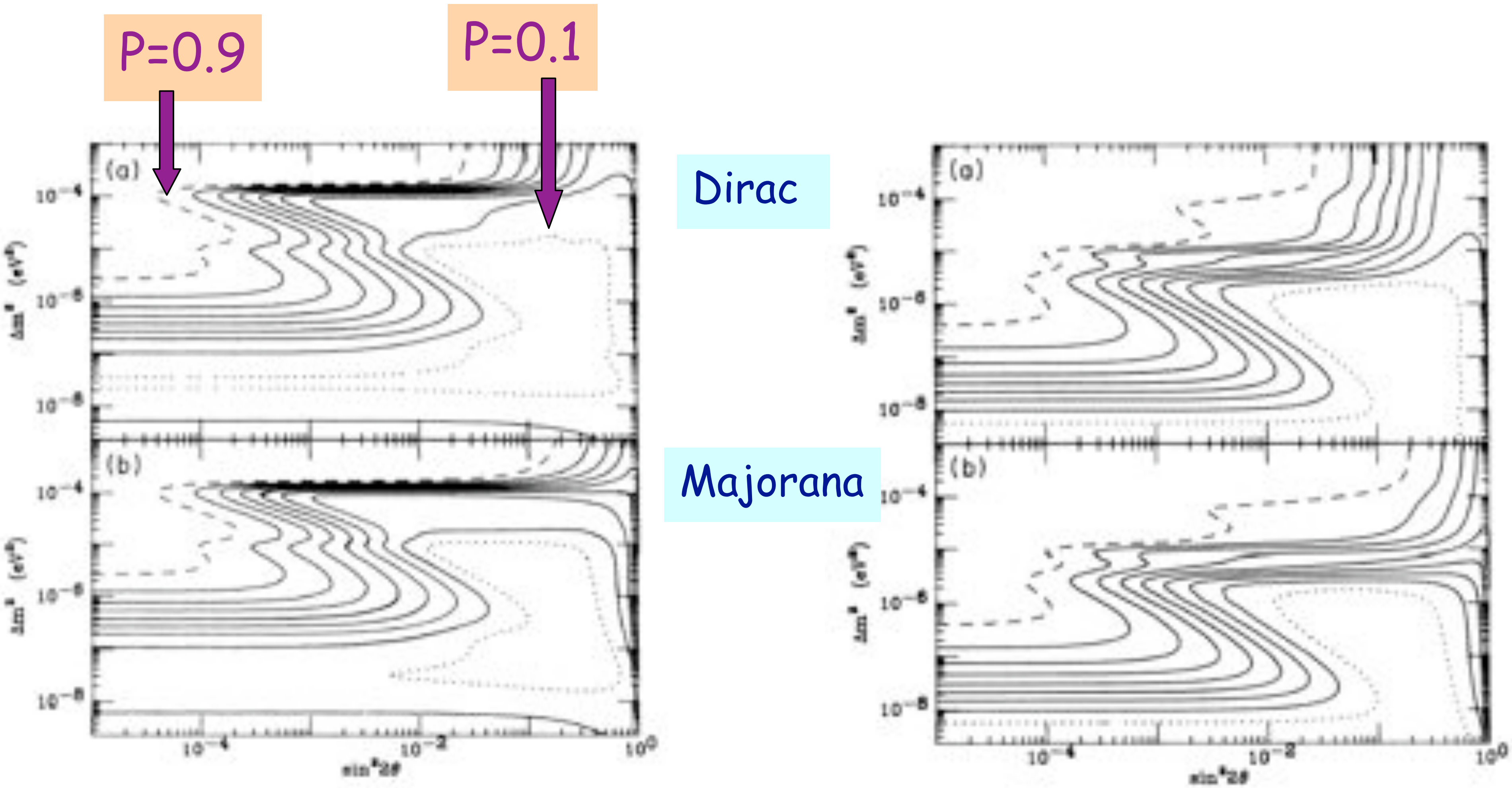


Solar magnetic fields

• 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.



Cl-detector

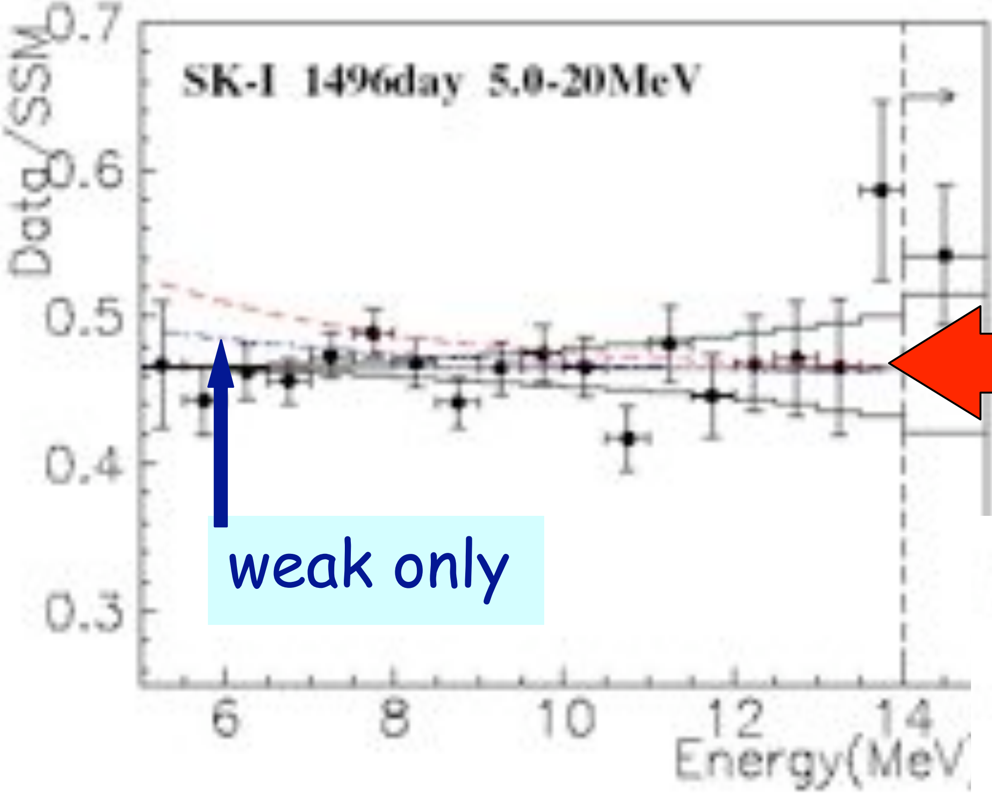
Ga-detector

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:

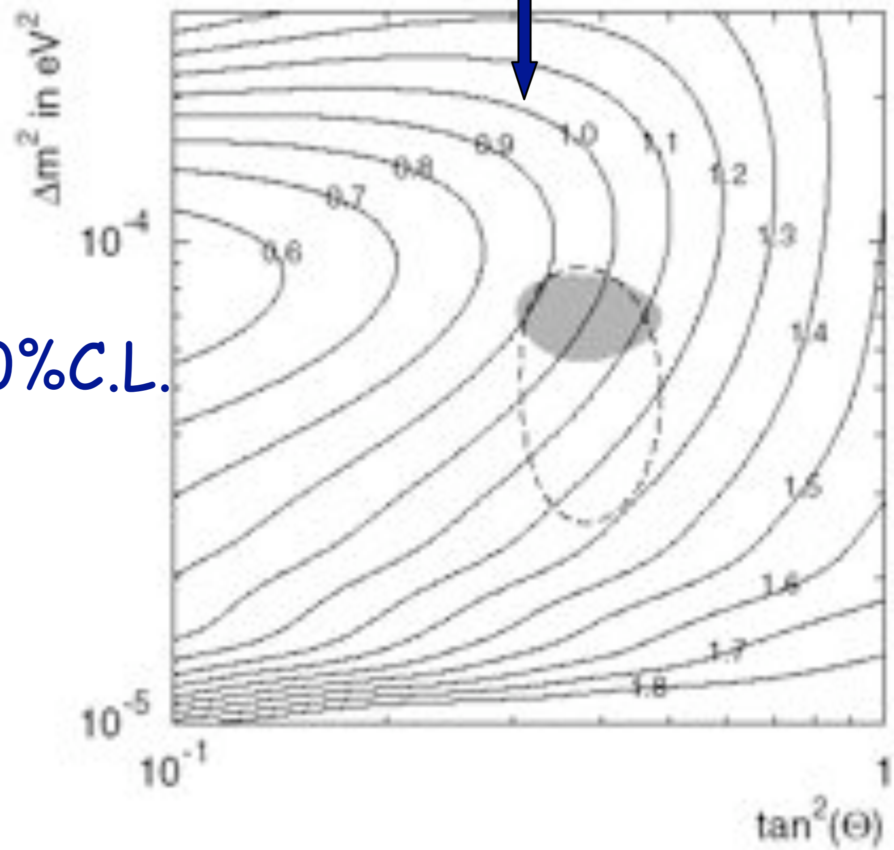
$$\varphi_{\text{antineutrino}} \leq 3 \times 10^{-4}\, \varphi_{\text{B8-neutrino}}$$



additional $\mu_\nu < 10^{-10}\mu_B$

weak only

$\mu_\nu = 10^{-10}\mu_B$



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.

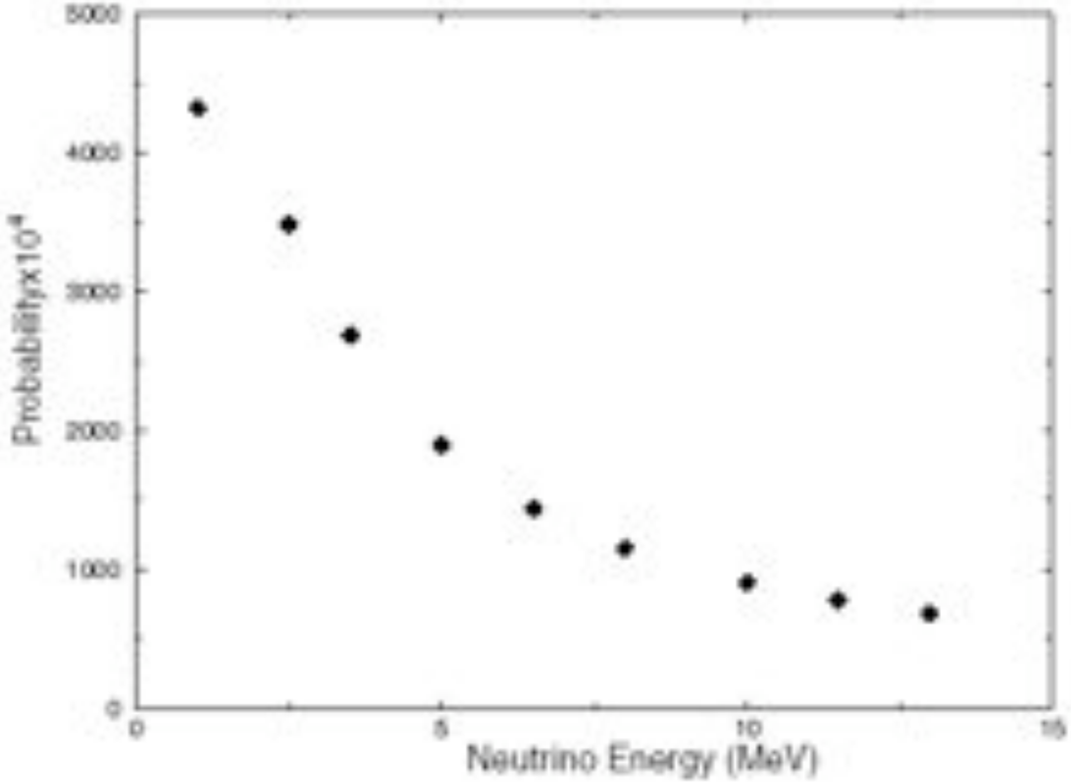
$$\frac{d^2}{dt^2}\nu_e^{(L)} + \left(\phi^2 + i\frac{d\phi}{dt} + \Delta^2 + (\mu B)^2\right)\nu_e^{(L)} + \mu B\sqrt{2}G_F N_n \nu_\mu^{(R)} = 0.$$

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

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

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

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

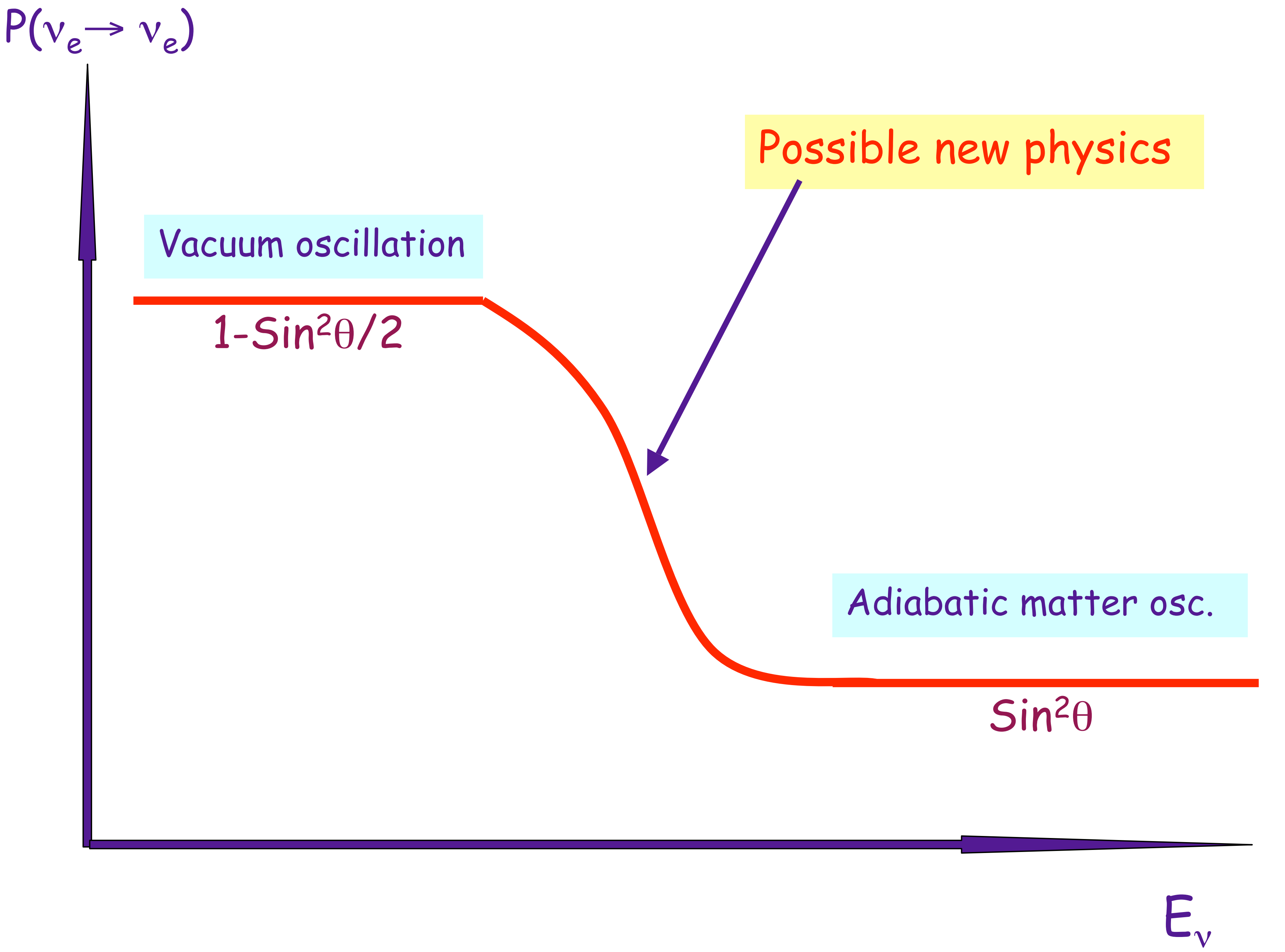


- $\mu = 10^{-11}\ \mu_B$
- $B = 10^5$ G
- $\delta m^2 = 8 \times 10^{-5}\ eV^2$
- $\tan^2\theta = 0.4$

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)

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



$P(\nu_e \to \nu_e)$
Possible new physics
Vacuum oscillation
$1-\sin^2\theta/2$
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

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

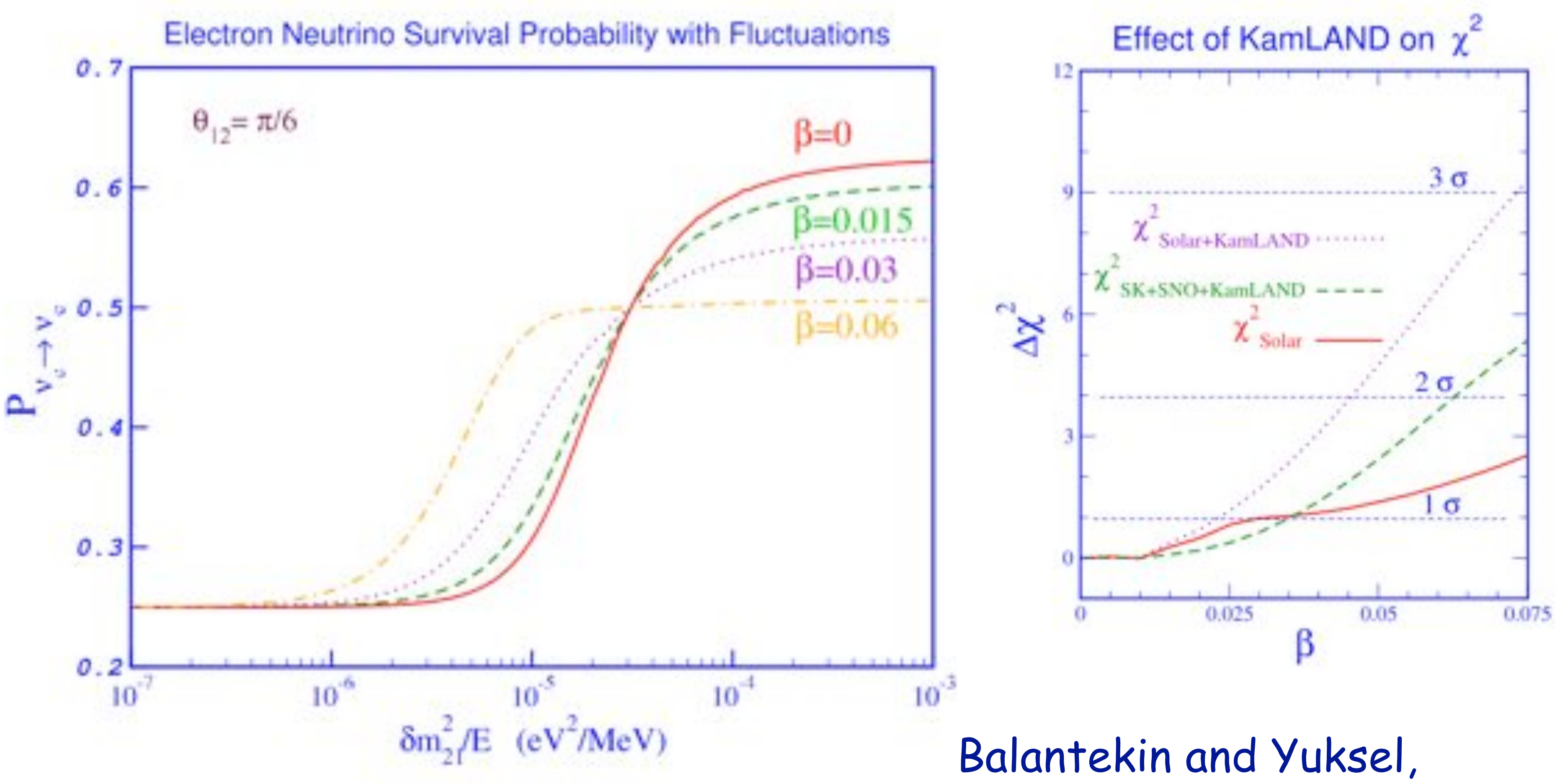
$$\frac{1}{\sqrt{2}}G_F N_e(x)=\frac{\delta m^2}{4E}\cos 2\theta_v$$

Most-pronounced contribution of non-standard interactions

For δm^2 = 8 x 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 $E_\nu \approx 1.8$ MeV !

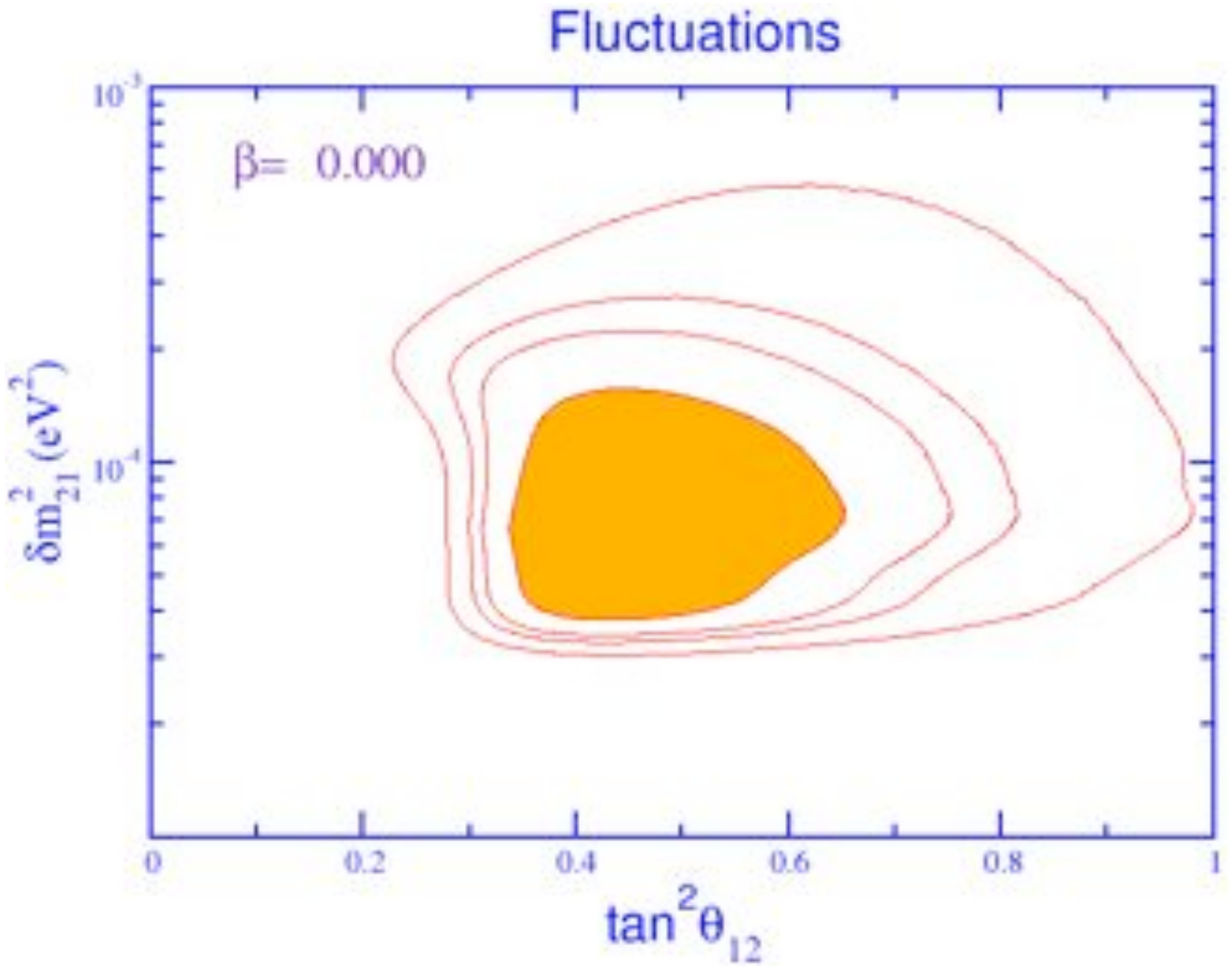
This behavior is generic, A.B. Balantekin and A.Malkus

Does the solar density fluctuate?

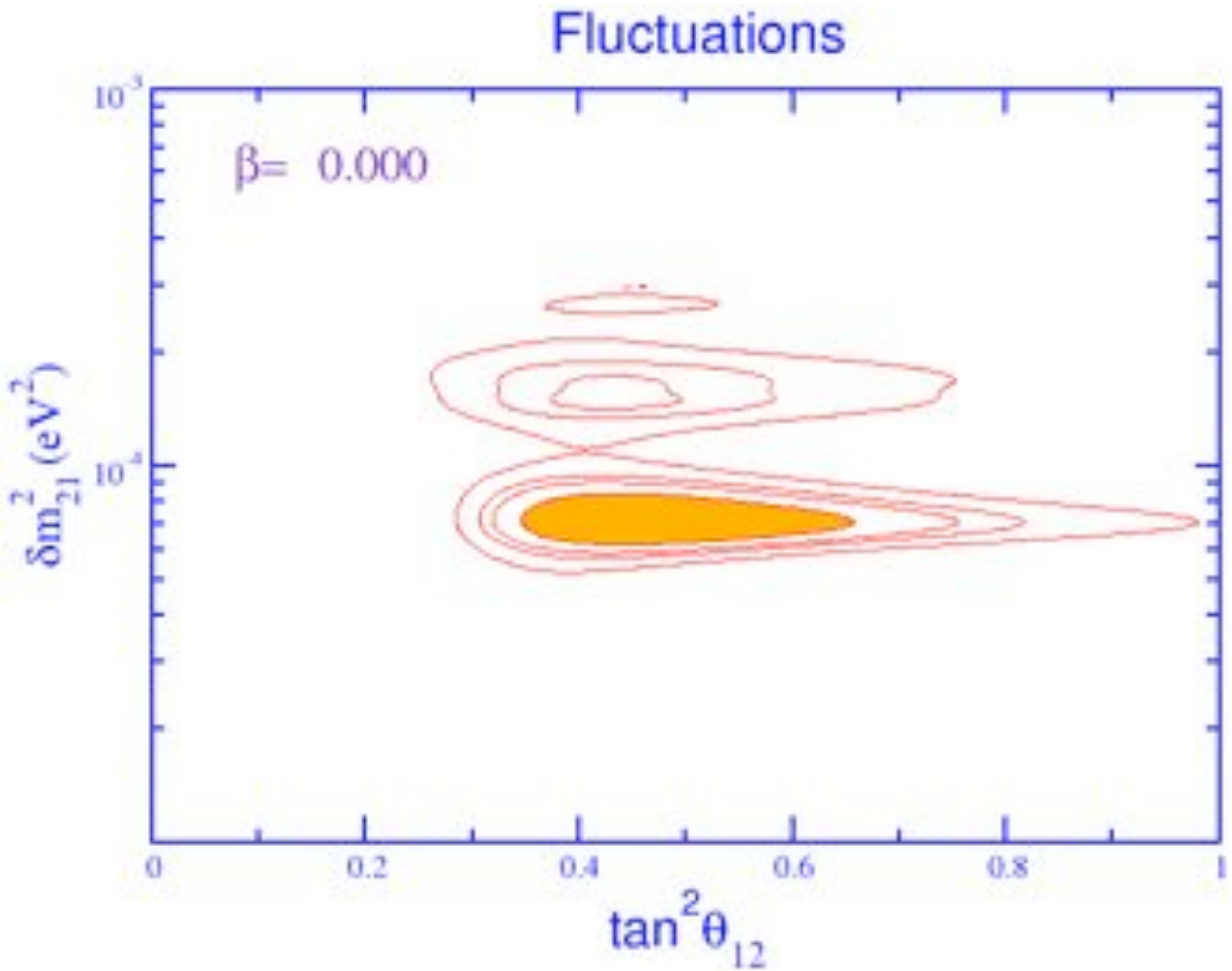


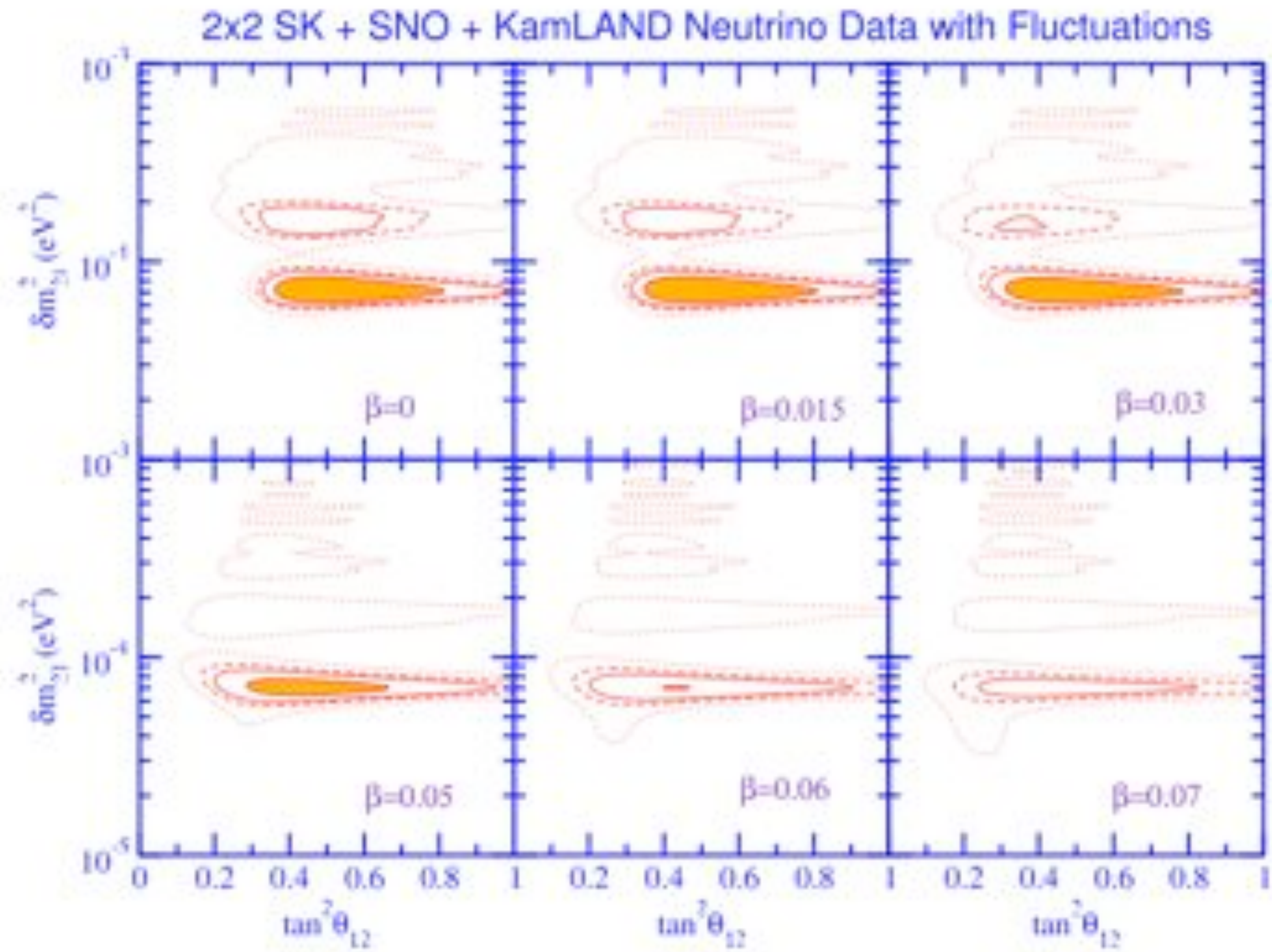
Balantekin and Yuksel,
PRD 68, 013006 (2003)

Solar data only



Solar + KamLAND





2x2 SK + SNO + KamLAND Neutrino Data with Fluctuations
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
$\tan^2\theta_{12}$

Probing non-standard neutrino interactions

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

Miranda, Tortola, Valle, hep-ph/0406280

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

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

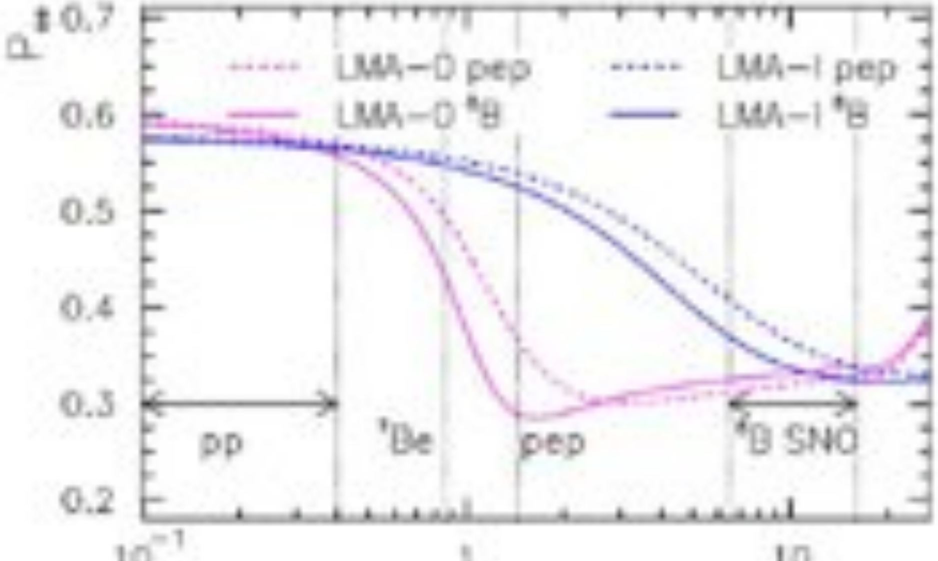
$$\epsilon_{11} = \epsilon_{ee} - \epsilon_{\tau\tau} \sin^2\theta_{23},$$

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

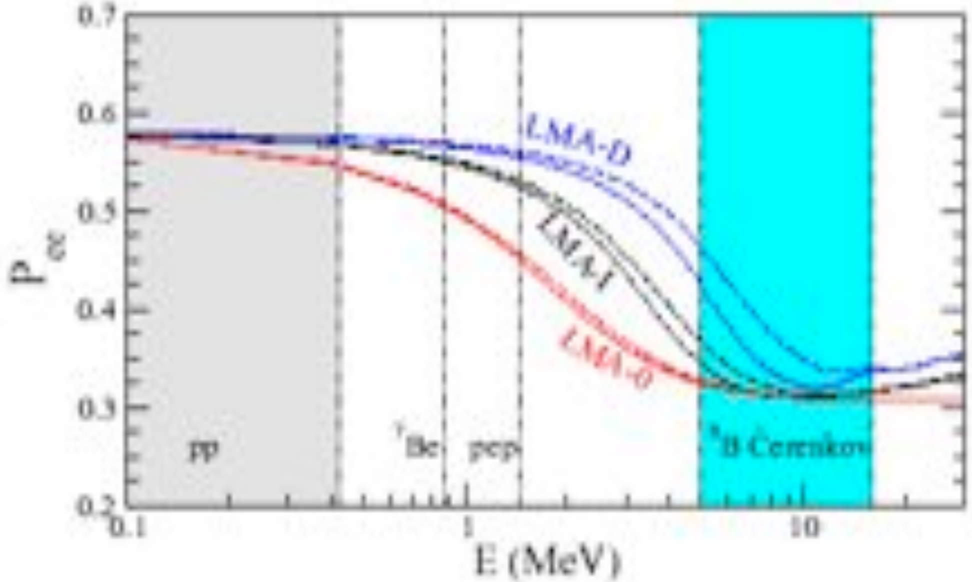
$$i\hbar \frac{\partial}{\partial x} \begin{bmatrix} \Psi_e(x) \\ \Psi_x(x) \end{bmatrix} = \begin{bmatrix} \varphi(x) & \sqrt{\Lambda} \\ \sqrt{\Lambda} & -\varphi(x) \end{bmatrix} \begin{bmatrix} \Psi_e(x) \\ \Psi_x(x) \end{bmatrix}$$

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

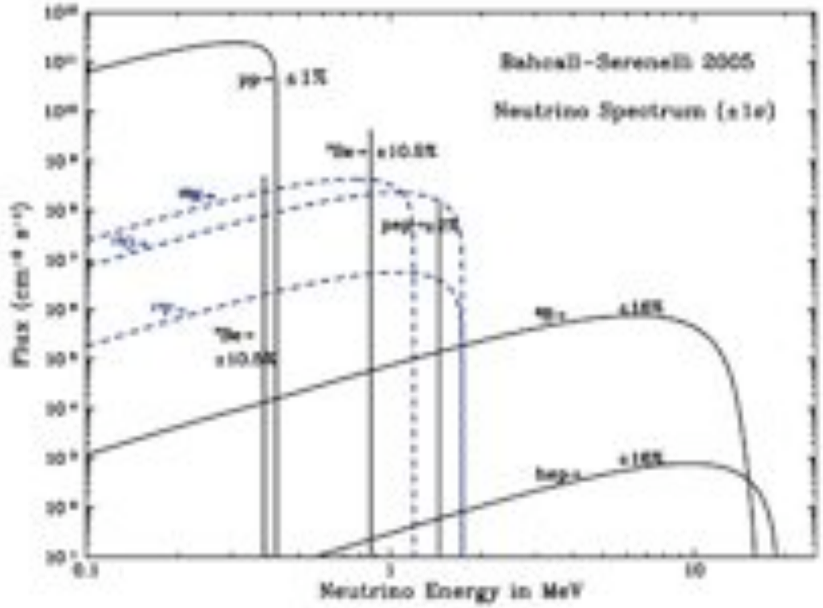
$$\sqrt{\Lambda} = \frac{\delta m^2}{4E} \sin 2\theta_v + \frac{1}{\sqrt{2}} G_F N_e(x) \epsilon_{12}(x)$$



Friedland, et al.



Miranda, et al.

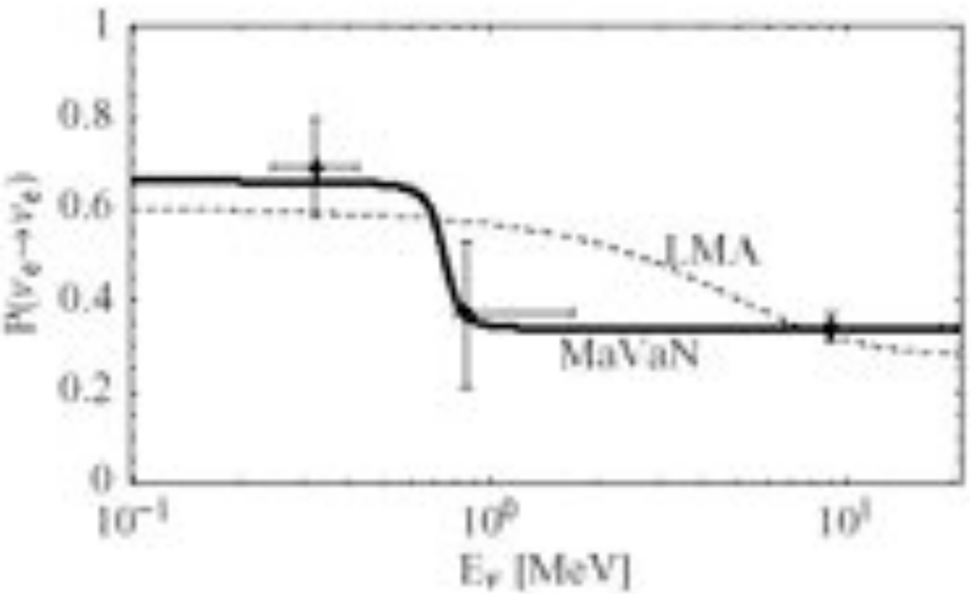


Mass-varying neutrinos, Fardon, et al., astro-ph/0309800

Scale of dark energy is similar to that of neutrino mass, $(2\times10^{-3}\ \mathrm{eV})^4$. 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

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

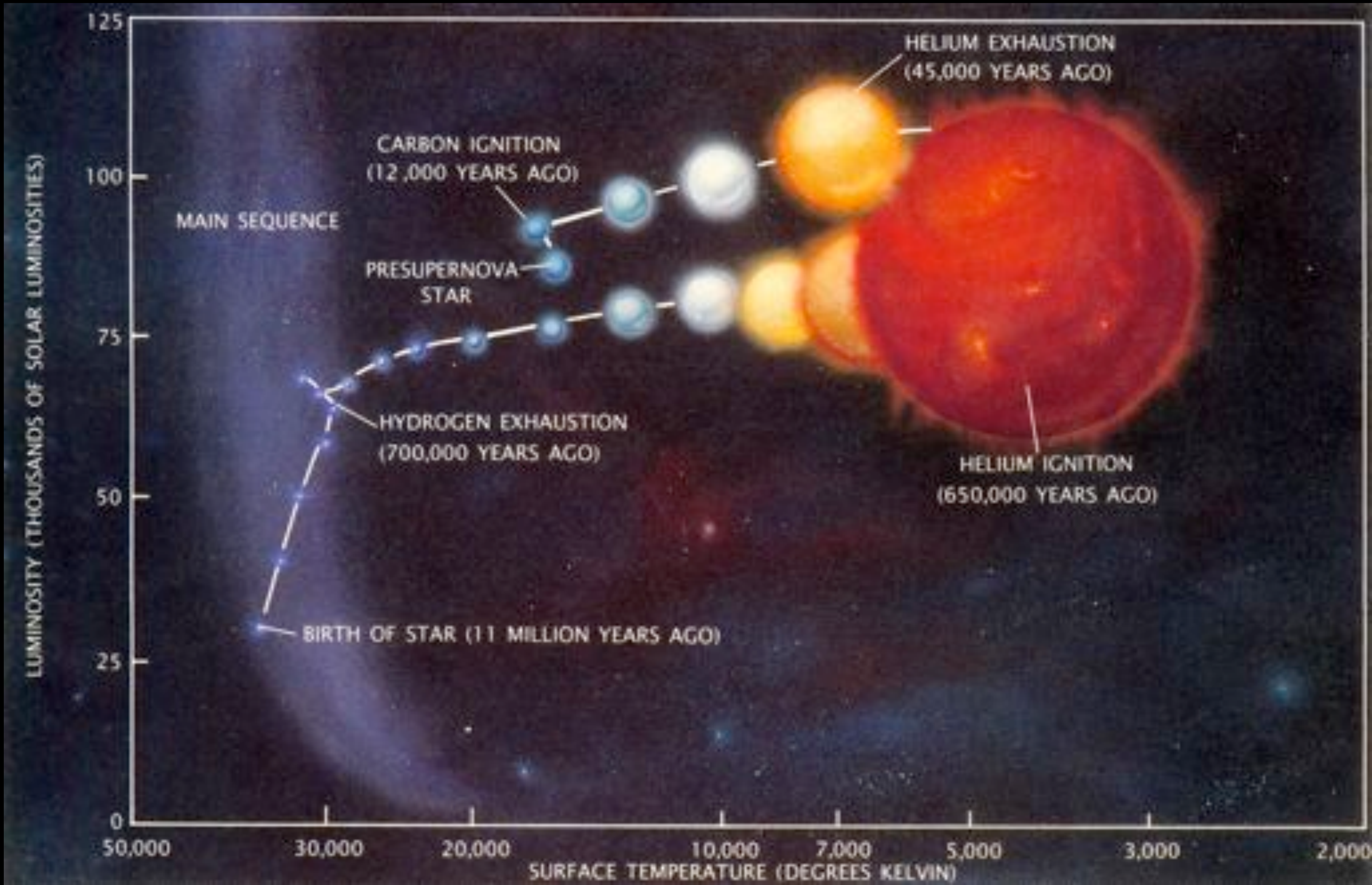
$$A(r) = 2\sqrt{2}\,G_F n_e(r) E_\nu$$



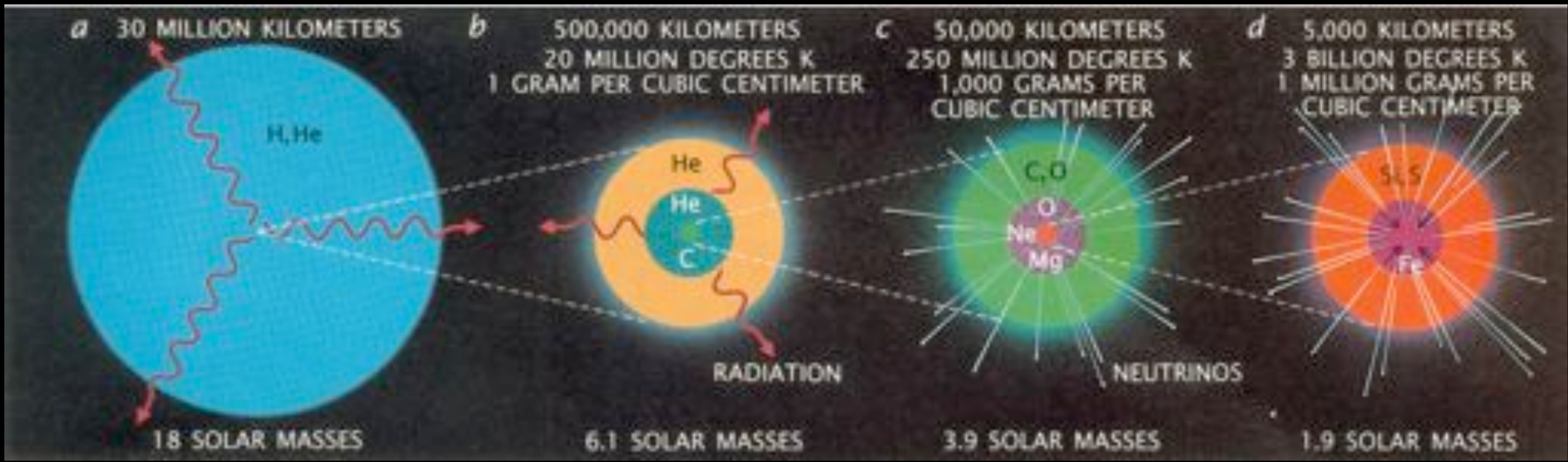
Barger, et al., hep-ph/0502196

Solar Neutrino 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.

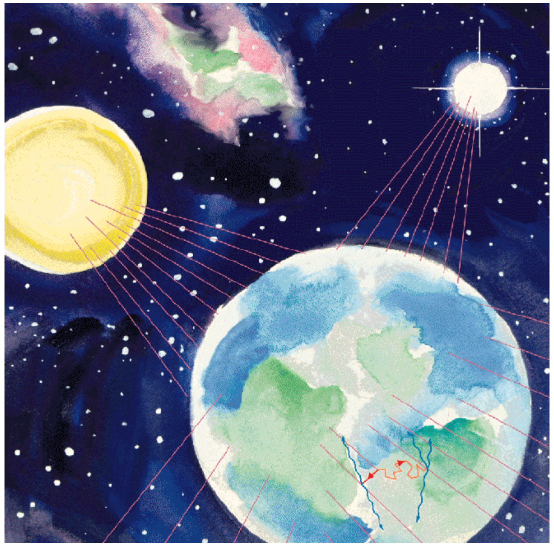


Weaver & Woosley, *Sci Am*, 1987

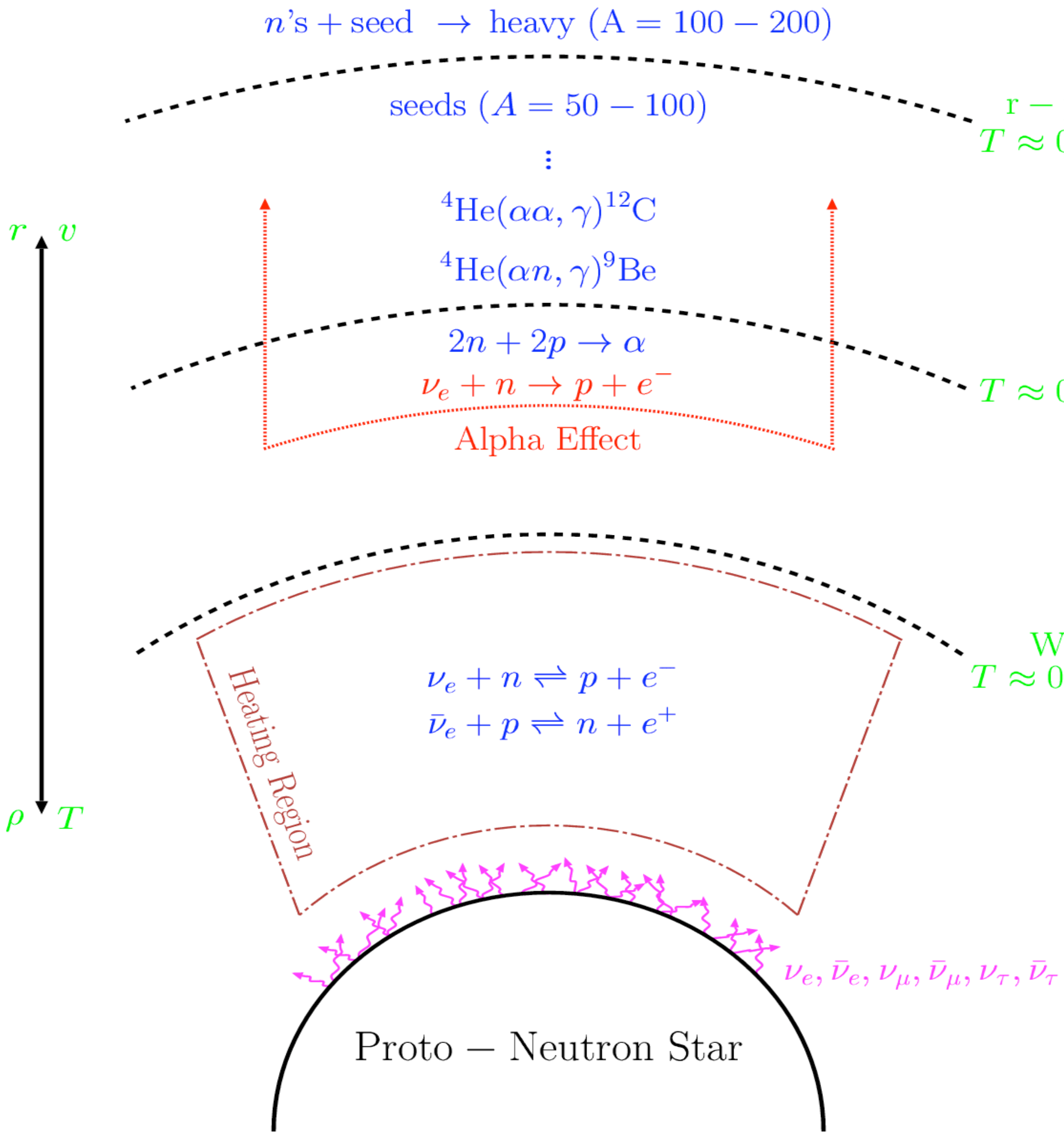


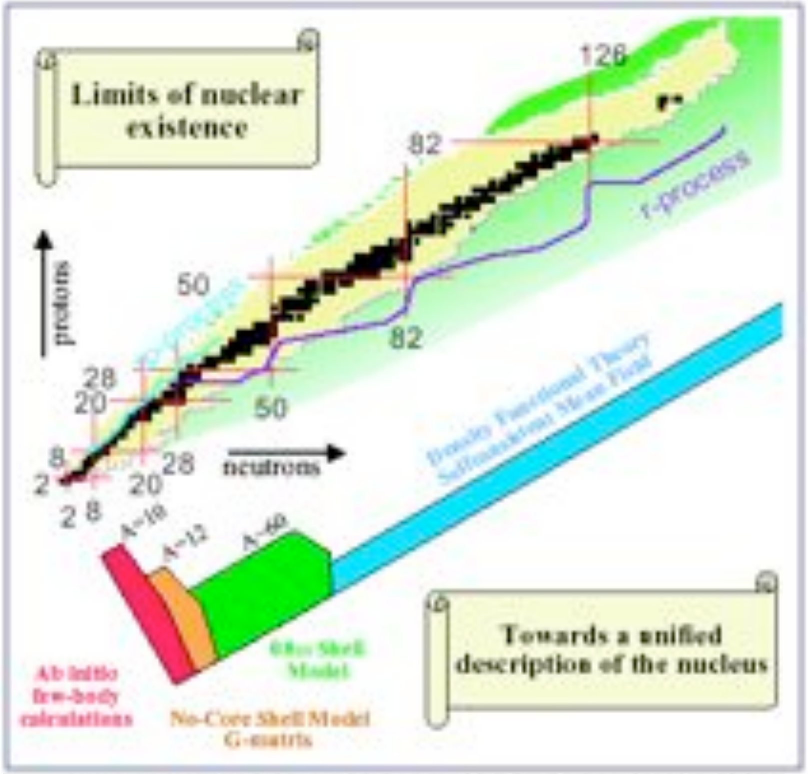
Weaver & Woosley, *Sci Am*, 1987

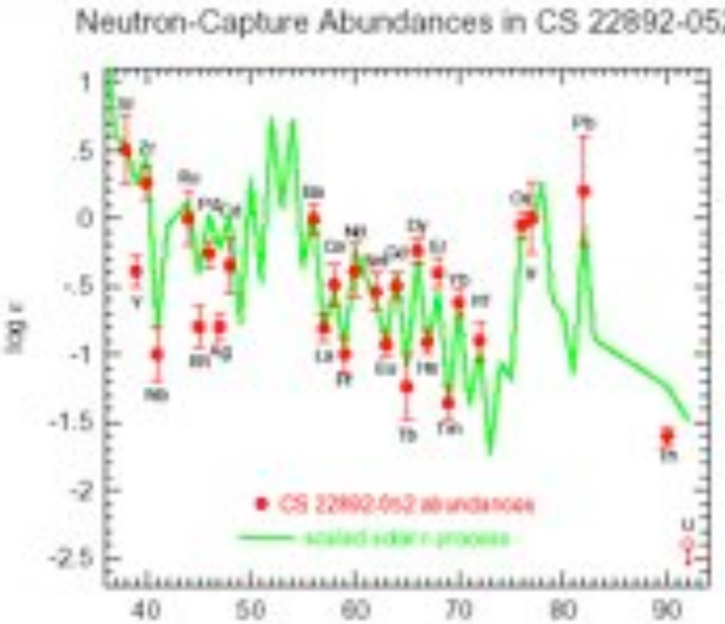
Neutrinos from core-collapse supernovae



- $M_{prog} \geq 8\ M_{Sun}$
- $\Delta E \approx 10^{53}$ ergs $\approx 10^{59}$ MeV
- 99% of the energy is carried away by neutrinos and antineutrinos with $10 \leq E_\nu \leq 30$ MeV
- 10^{59} Neutrinos!


n's + seed $\rightarrow$ heavy (A = 100 − 200)
seeds ($A = 50 - 100$)
⋮
^{4}He$(\alpha\alpha,\gamma)^{12}$C
^{4}He$(\alpha n,\gamma)^{9}$Be
$2n + 2p \rightarrow \alpha$
$\nu_e + n \rightarrow p + e^-$
Alpha Effect
r − process
$T \approx 0.25$ MeV
$T \approx 0.75$ MeV
WFO
$T \approx 0.9$ MeV
r v
ρ T
$\nu_e + n \rightleftharpoons p + e^-$
$\bar{\nu}_e + p \rightleftharpoons n + e^+$
Heating Region
$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$
Proto − Neutron Star



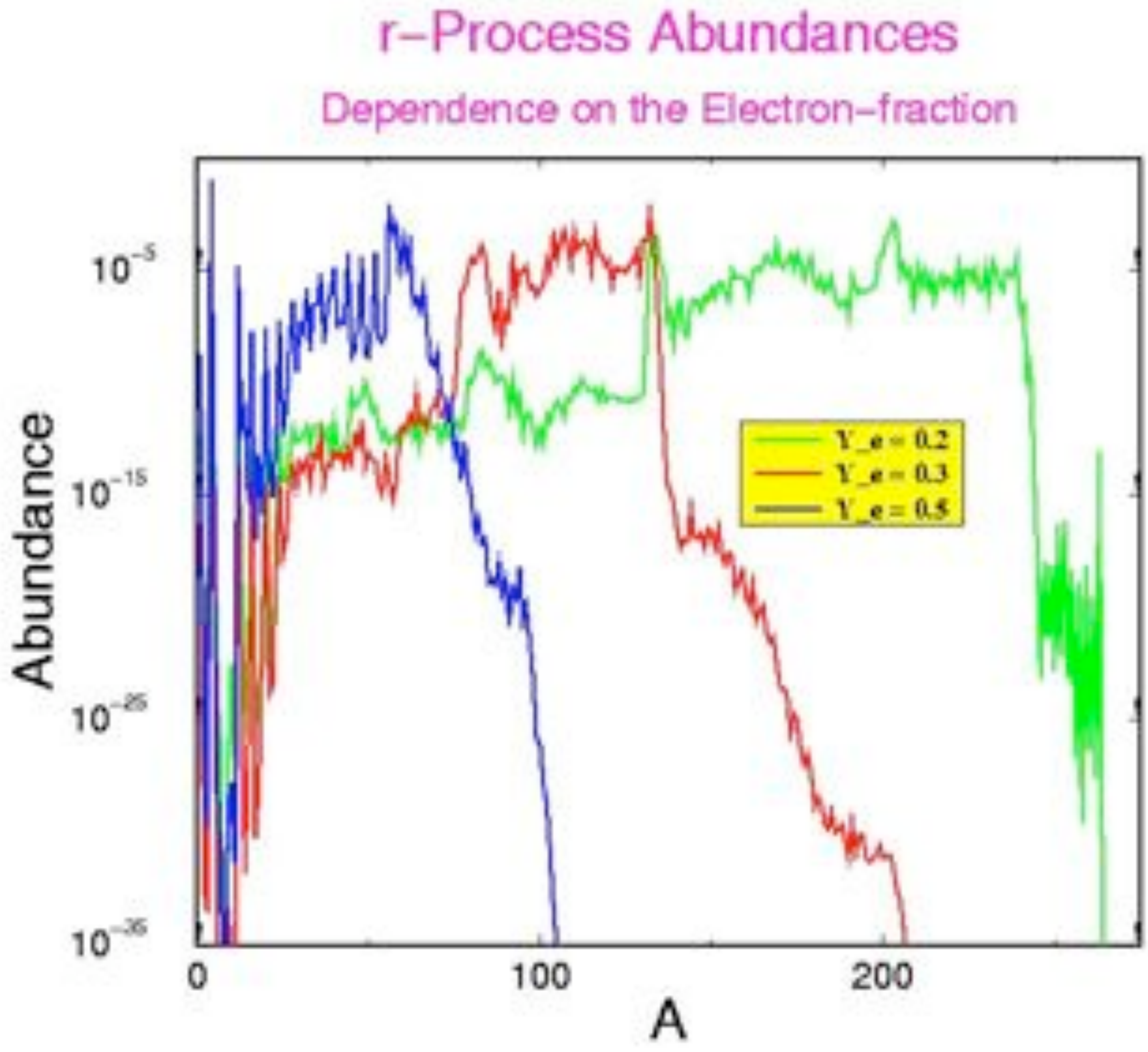


To understand the r-process one needs to first understand beta-decays of nuclei both at and far-from stability:

• Half-lifes at the r-process ladders (N=50, 82, 126) where abundances peak.

• One needs accurate values of the energies of initial and final states.

• Matrix elements of the Gamow-Teller operator $\sigma.\tau$ (even the forbidden operators $r\sigma.\tau$) between the initial and final states.


r–Process Abundances
Dependence on the Electron–fraction
Abundance
10^{-5}
10^{-15}
10^{-25}
10^{-35}
0
100
200
A
Y_e = 0.2
Y_e = 0.3
Y_e = 0.5

Meyer

$$H_\nu + H_{\nu\nu} = \int dp \left(\frac{\delta m^2}{2p} \cos 2\theta - \sqrt{2} G_F N_e \right) J_0(p)$$
$$+ \frac{1}{2} \int dp \frac{\delta m^2}{2p} \sin 2\theta \left(J_+(p) + J_-(p)\right)$$
$$+ \sqrt{2} G_F \int dp\, dq\, (1 - \cos \vartheta_{pq})\, \vec{J}(p) \cdot \vec{J}(q)$$

Smirnov, Fuller and Qian, Pantaleone, McKellar, Raffelt, Balantekin, Yuksel, Pehlivan…

Neutrino gas with one and two-body interactions: a many-body problem that needs to be solved to understand r-process nucleosynthesis in SN.

$$J_+(p) = a_x^\dagger(p) a_e(p), \quad J_-(p) = a_e^\dagger(p) a_x(p),$$
$$J_0(p) = \frac{1}{2}\left(a_x^\dagger(p) a_x(p) - a_e^\dagger(p) a_e(p) \right)$$

$$[J_+(p), J_-(q)] = 2\delta^3(p-q) J_0(p), \quad [J_0(p), J_\pm(p)] = \pm\delta^3(p-q) J_\pm(p)$$

N : Allowed values of neutrino momenta N
distinct commuting SU(2) algebras

Recall that nucleosynthesis in core-collapse supernovae occurs in conditions which are the isospin-mirror of the conditions for Big-bang nucleosynthesis!

Big-Bang: $n/p \ll 1$

Core-collapse SN: $n/p \gg 1$

In both cases species decouple when the expansion rate exceeds their interaction rate

Two possible hierarchies of neutrino energies:

- a) A pronounced hierarchy: $E(\nu_x) > E(\bar{\nu}_e) > E(\nu_e)$
- b) A less-pronounced hierarchy: $E(\nu_x) \sim E(\bar{\nu}_e) \sim E(\nu_e)$

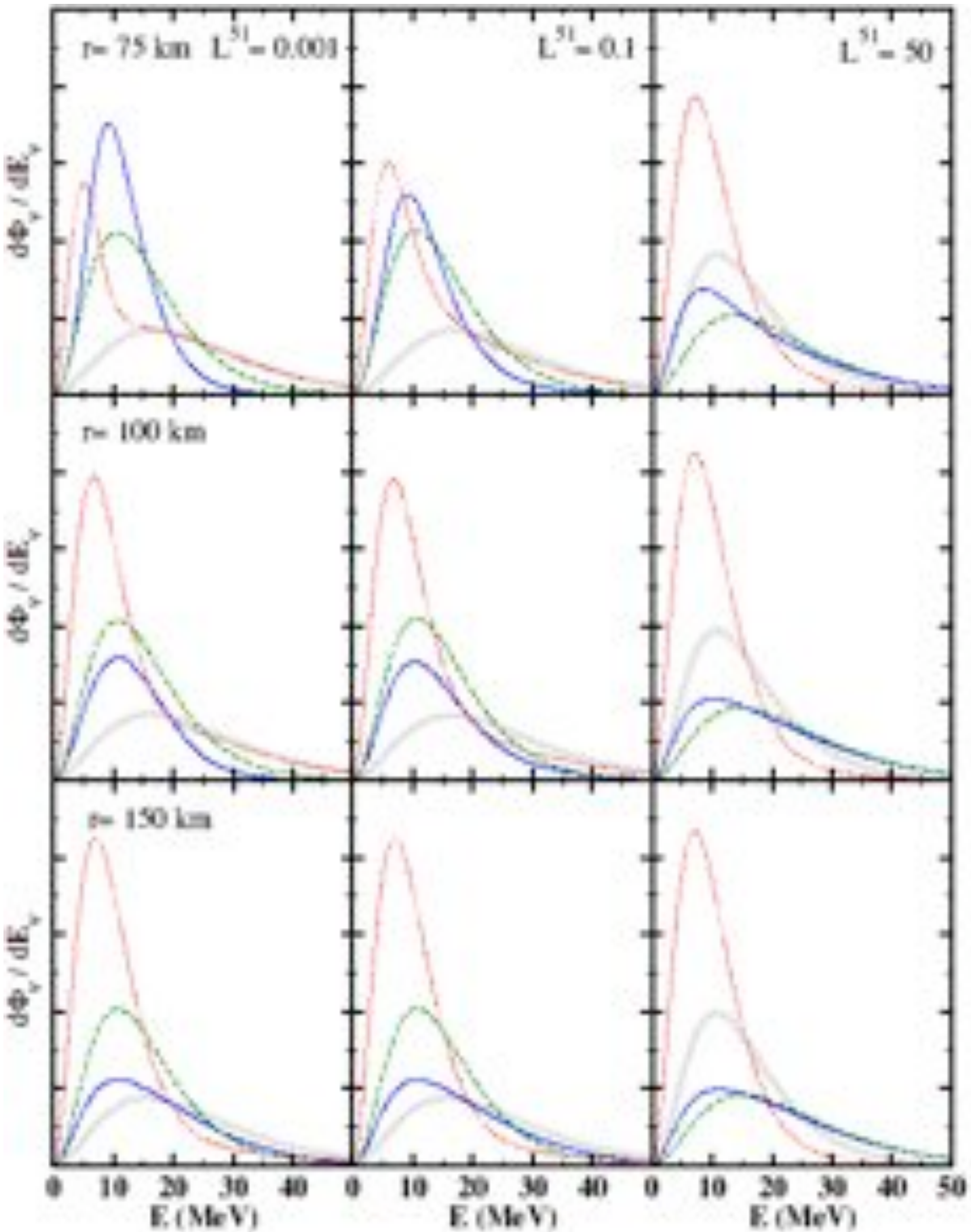
Evolution of neutrino fluxes ($1/r^2$ -dependence removed)

ν_e

$\bar{\nu}_e$

ν_x

$\bar{\nu}_x$



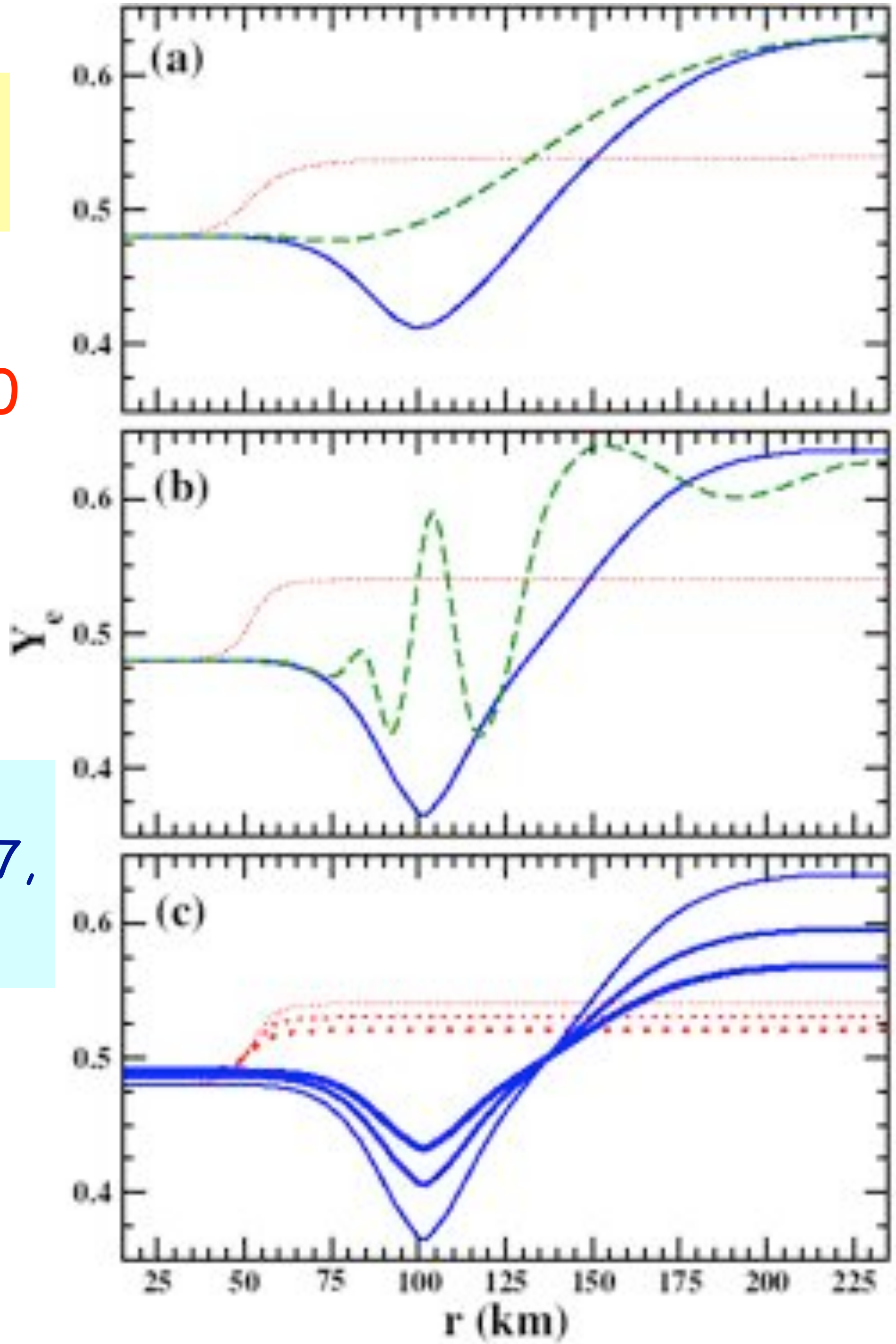
L^{51}: luminosity in units of 10^{51} ergs s^{-1}

Equilibrium electron fraction

L^{51} = 0.001, 0.1, 50

From Balantekin and Yuksel, New J. Phys. 7, 51 (2005).

X_{α}= 0, 0.3, 0.5 (thin, medium, thick lines)



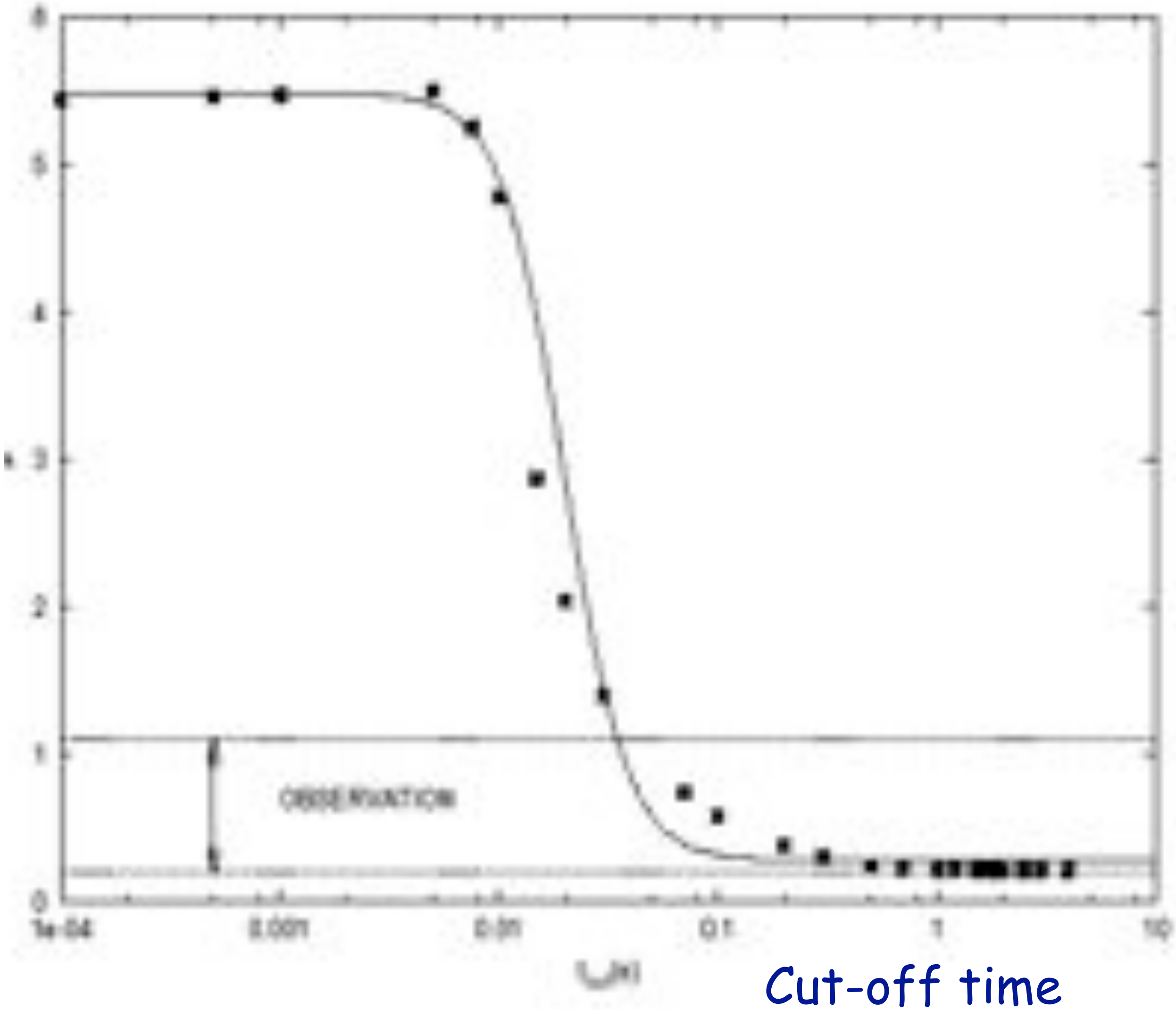
θ_{13}~ π/10

θ_{13}~ π/20

θ_{13} ~ π/20 with α effect

Black hole or neutron star?

$$\frac{^{232}\mathrm{Th}}{^{151}\mathrm{Eu} + ^{153}\mathrm{Eu}}$$



Cut-off time

Sasaqui, Kajino, Balantekin, Ap. J 634, 534 (2005)

SN Conclusions

- The study of exotic nuclei play a very important role in nuclear astrophysics, in areas ranging from the origin to elements (i.e. nucleosynthesis in a variety of environments) to the structure of neutron stars and the evolution of the Early Universe.

- Neutrinos dominate a good fraction of the physics in a core-collapse supernova. Neutrinos set the value of the neutron-to-proton ratio. Hence matter-enhanced neutrino flavor transformation can impact the physics of the explosion and the r-process nucleosynthesis.

- Neutrino-neutrino interactions could be the crucial component. At the moment calculation of the neutrino propagation by taking the ν-ν interactions into account is an open, unsolved, problem.