

New Physics Beyond the Standard Models with Solar Neutrinos

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June 2007

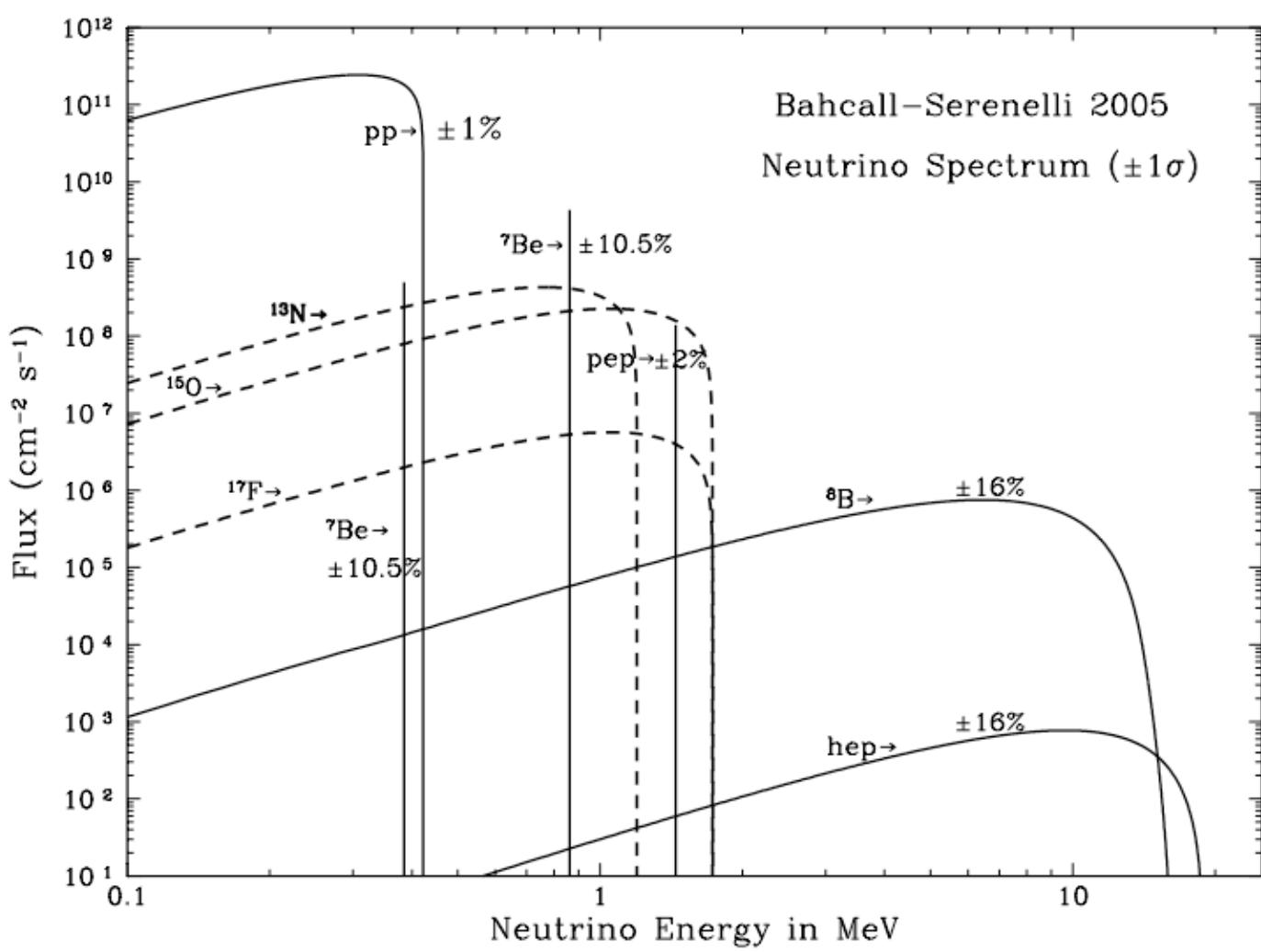
Trento, Italy

ECT*

Outline

- Standard Solar Neutrino Model
- Standard MSW
- Where Can We See New Physics?
- New Models
- Conclusions

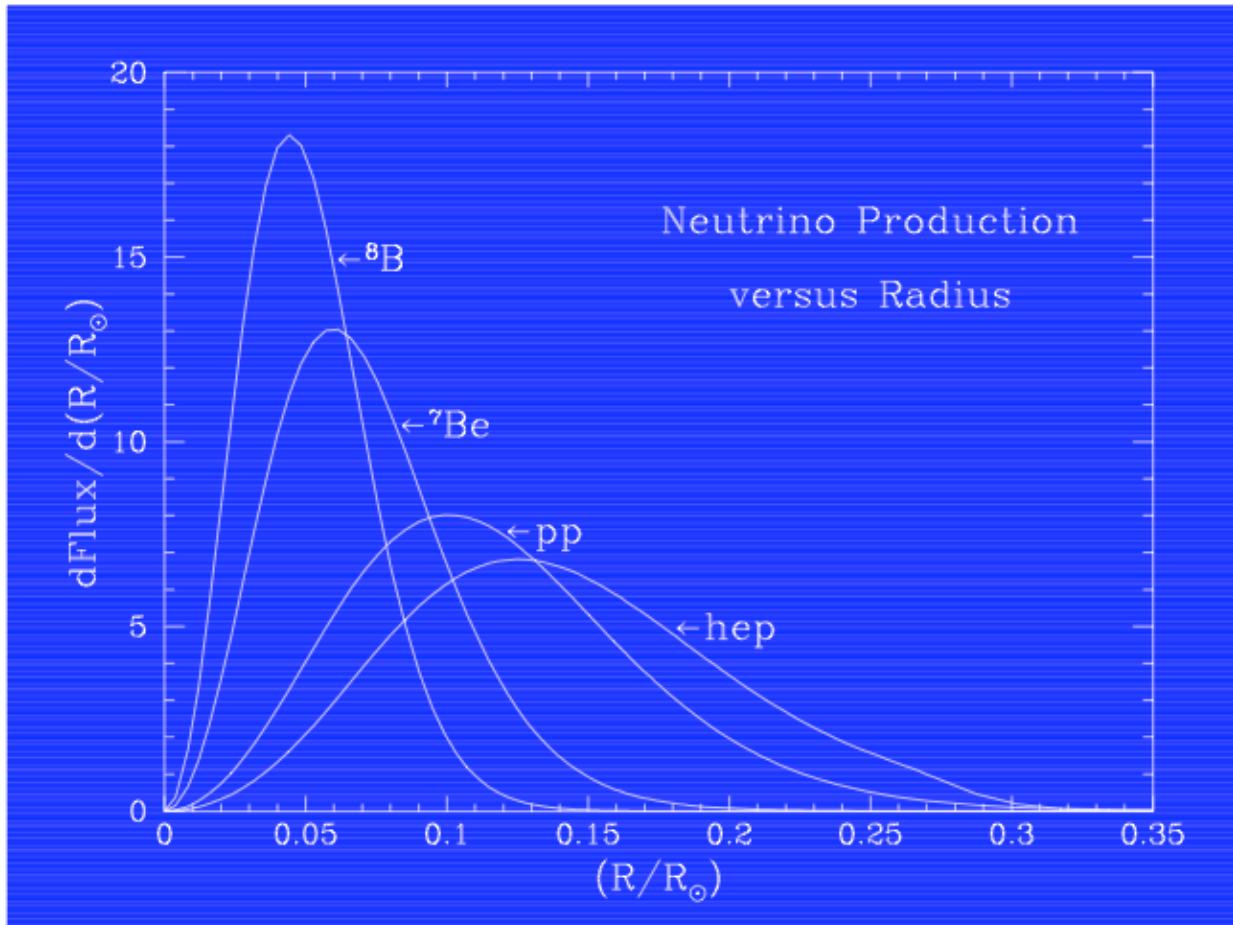
Solar Neutrino Spectrum



Bahcall, Serenelli, ApJ, 621, L85 (2005)

Radial Distribution

Figure 6.1 in *Neutrino Astrophysics*,
J.N. Bahcall



Electron Density

$$245N_A e^{-10.54t/R_{sun}} / \text{cm}^3$$

Standard MSW

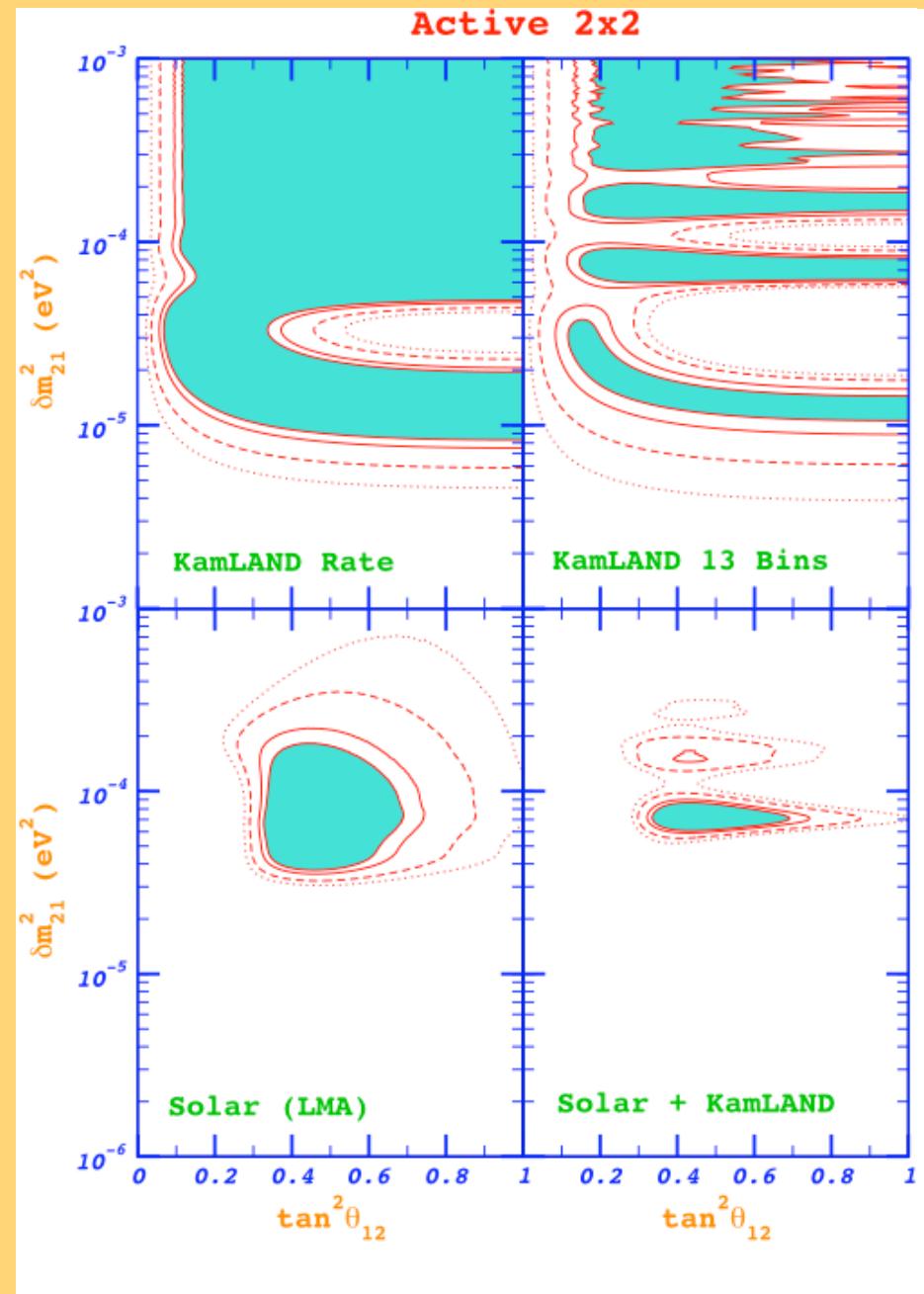
$$i \frac{\partial}{\partial t} \begin{pmatrix} \psi_e \\ \psi_x \end{pmatrix} = \begin{pmatrix} \varphi(t) & \sqrt{\Lambda} \\ \sqrt{\Lambda} & -\varphi(t) \end{pmatrix} \begin{pmatrix} \psi_e \\ \psi_x \end{pmatrix}$$

$$\varphi(t) = \frac{1}{\sqrt{2}} G_F N_e(t) - \frac{\delta m^2}{4E} \cos(2\theta_\nu)$$

$$\sqrt{\Lambda} = \frac{\delta m^2}{4E} \sin(2\theta_\nu)$$

Solar + KamLAND Global Analysis

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



What I Used

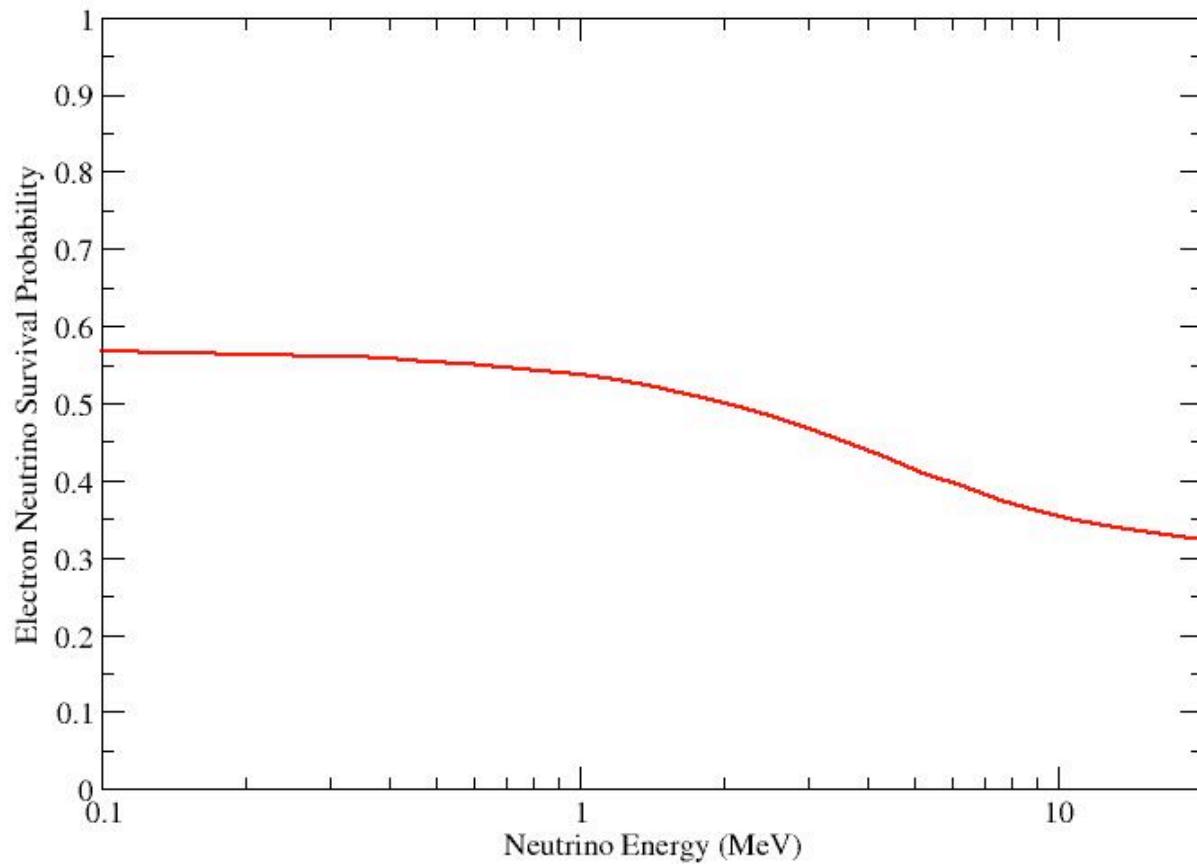
$$\delta m^2 = 8.0 \times 10^{-5} eV^2$$

$$\sin^2(2\theta_\nu) = 0.86$$

W.M. Yao et al. (Particle Data Group), J. Phys. G 33, 1
(2006) (URL:<http://pdg.lbl.gov>)

Electron Neutrino Survival Probability

Standard MSW Effect



Where Can We See New Physics?

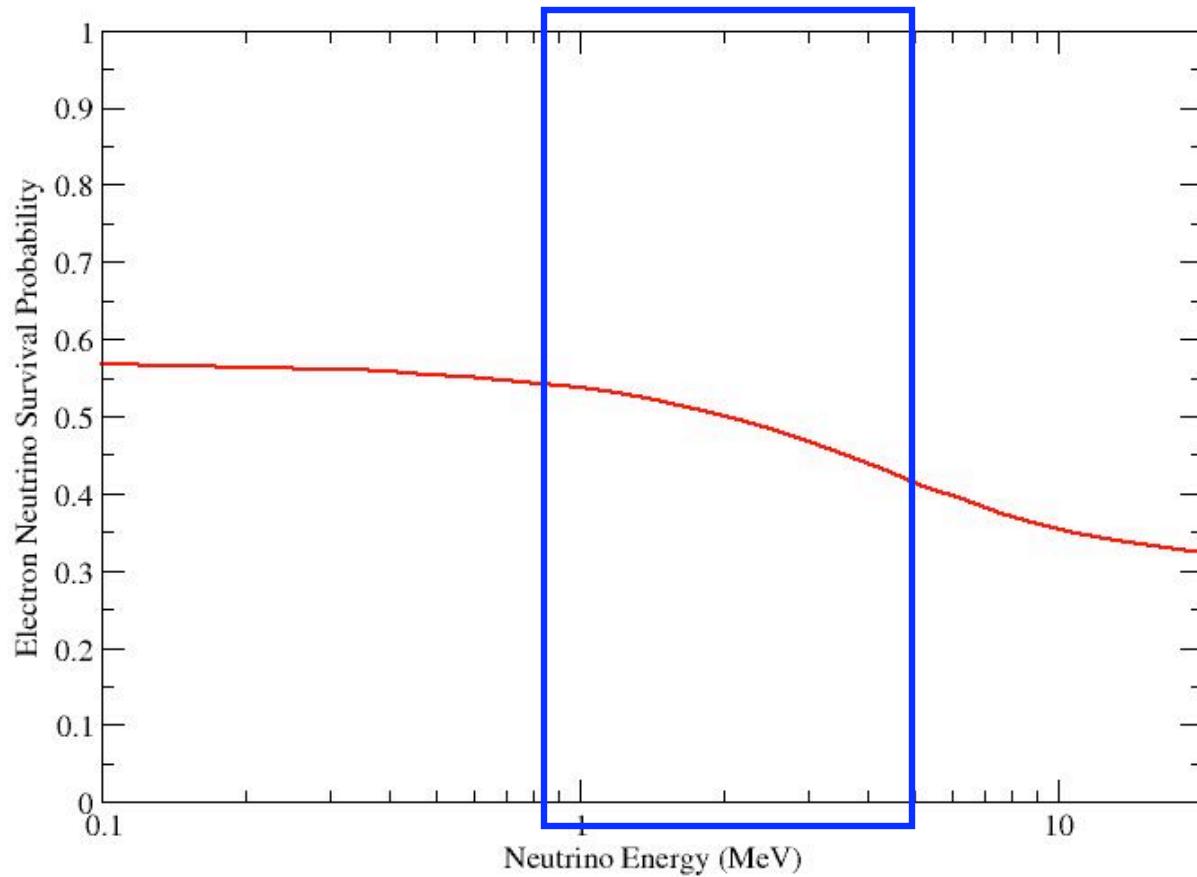
- Adiabatic Solution

$$\begin{aligned} P(\nu_e \rightarrow \nu_e) &= \frac{1}{2} + \frac{1}{2} \cos(2\theta_\nu) \langle \cos(2\theta_i) \rangle_{source} \\ &= \frac{1}{2} + \frac{1}{2} \cos(2\theta_\nu) \left\langle \frac{-\varphi(t)}{\sqrt{\Lambda + \varphi^2(t)}} \right\rangle_{source} \end{aligned}$$

- Resonance

$$\begin{aligned} \varphi(t) \Big|_{resonance} &= \frac{1}{\sqrt{2}} G_F N_e(t) - \frac{\delta m^2}{4E} \cos(2\theta_\nu) = 0 \\ \varphi'(t) \Big|_{resonance} &= \varphi(t) \Big|_{resonance} + \delta\varphi \\ &= \frac{1}{\sqrt{2}} G_F N_e(t) - \frac{\delta m^2}{4E} \cos(2\theta_\nu) + \delta\varphi = \delta\varphi \end{aligned}$$

Right Here!



Introduction to New Models

- New Interactions
- Mass-Varying Neutrinos
- Long Range Leptonic Forces
 - Scalar
 - Vector
 - Tensor
- Solar Density Fluctuations

New Interactions

$$L^{NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha \gamma_\rho \nu_\beta)(\varepsilon_{\alpha\beta}^{f\bar{f}L}\bar{f}_L \gamma^\rho \tilde{f}_L + \varepsilon_{\alpha\beta}^{f\bar{f}RE}\bar{f}_R \gamma^\rho \tilde{f}_R) + h.c.$$

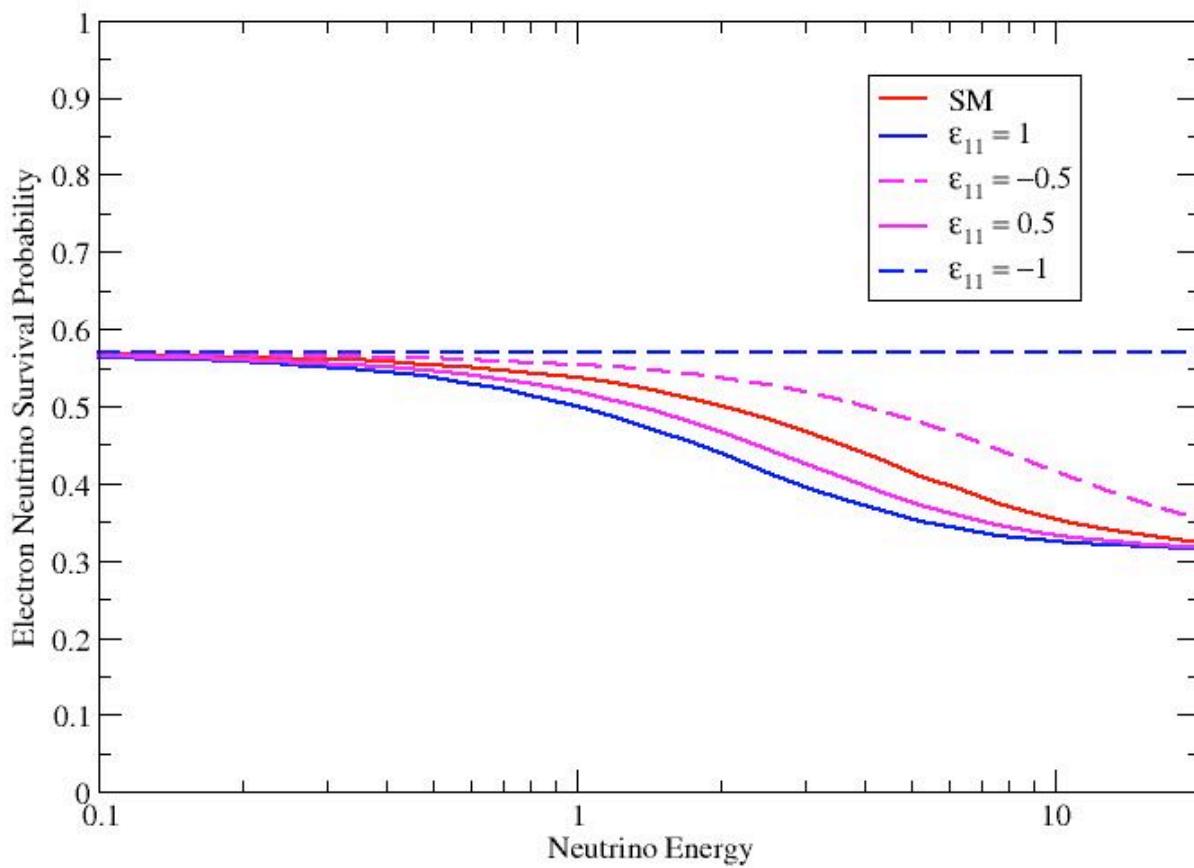
$$\varphi(t) = \frac{1}{\sqrt{2}}G_F N_e(t)[1 + \varepsilon_{11}] - \frac{\delta m^2}{4E} \cos(2\theta_\nu)$$

$$\sqrt{\Lambda} = \frac{\delta m^2}{4E} \sin(2\theta_\nu) + \frac{1}{\sqrt{2}}G_F N_e(t)\varepsilon_{12}$$

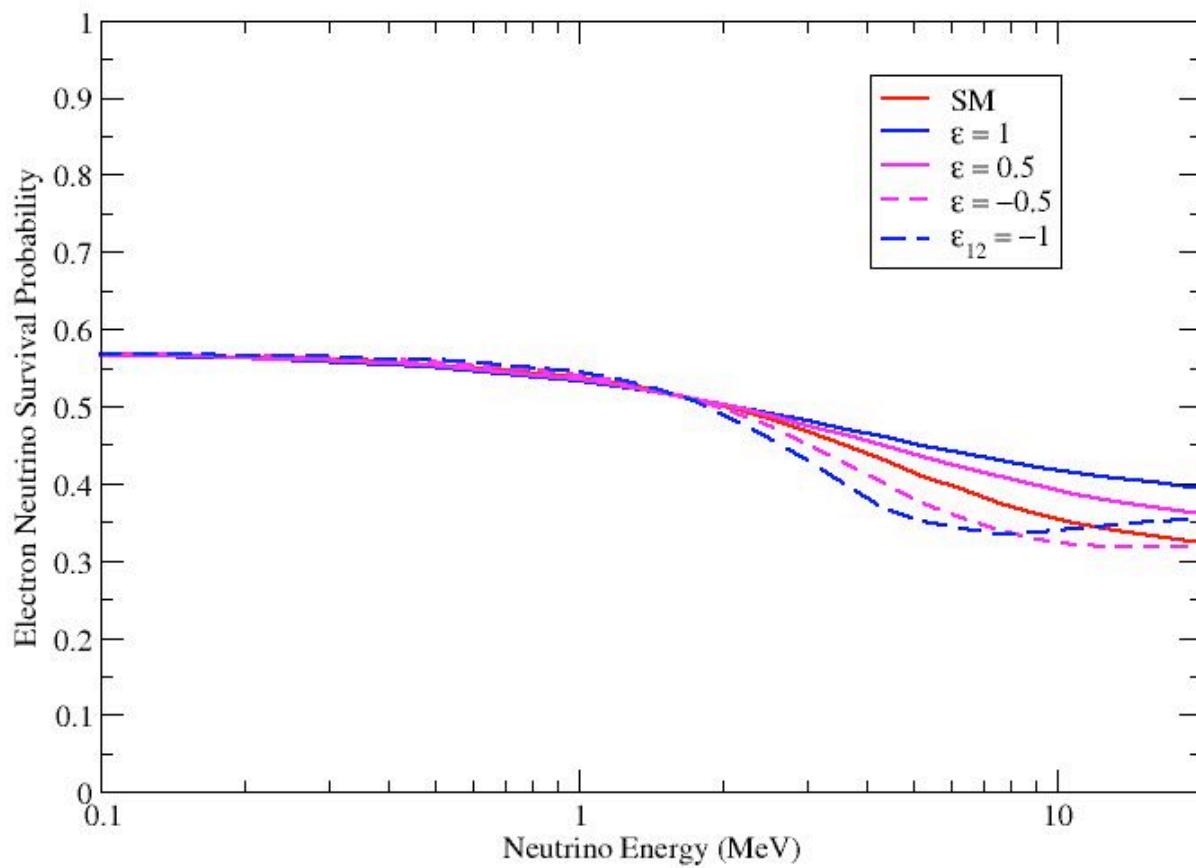
$$\varepsilon_{ij} = \varepsilon_{ij}^u \frac{N_u}{N_e} + \varepsilon_{ij}^d \frac{N_d}{N_e}$$

A. Friedland, C. Lundardini and
C. Pena-Garay, Phys. Lett. B
594, 347 (2004)

Modify Phi



Modify Lambda



Mass-Varying Neutrinos

Cosmic Coincidence Problem:

$$\rho_{CDM} \sim \rho_\Lambda$$

Use another “coincidence” to help:

$$\rho_\nu \sim \rho_\Lambda$$

Neutrinos couple to dark energy with scalar field, acceleron.

R. Fardon, A.E. Nelson and N. Weiner, JCAP **0410** 005 (2004)
[arXiv:astro-ph/0309800]

Mass-Varying Neutrinos

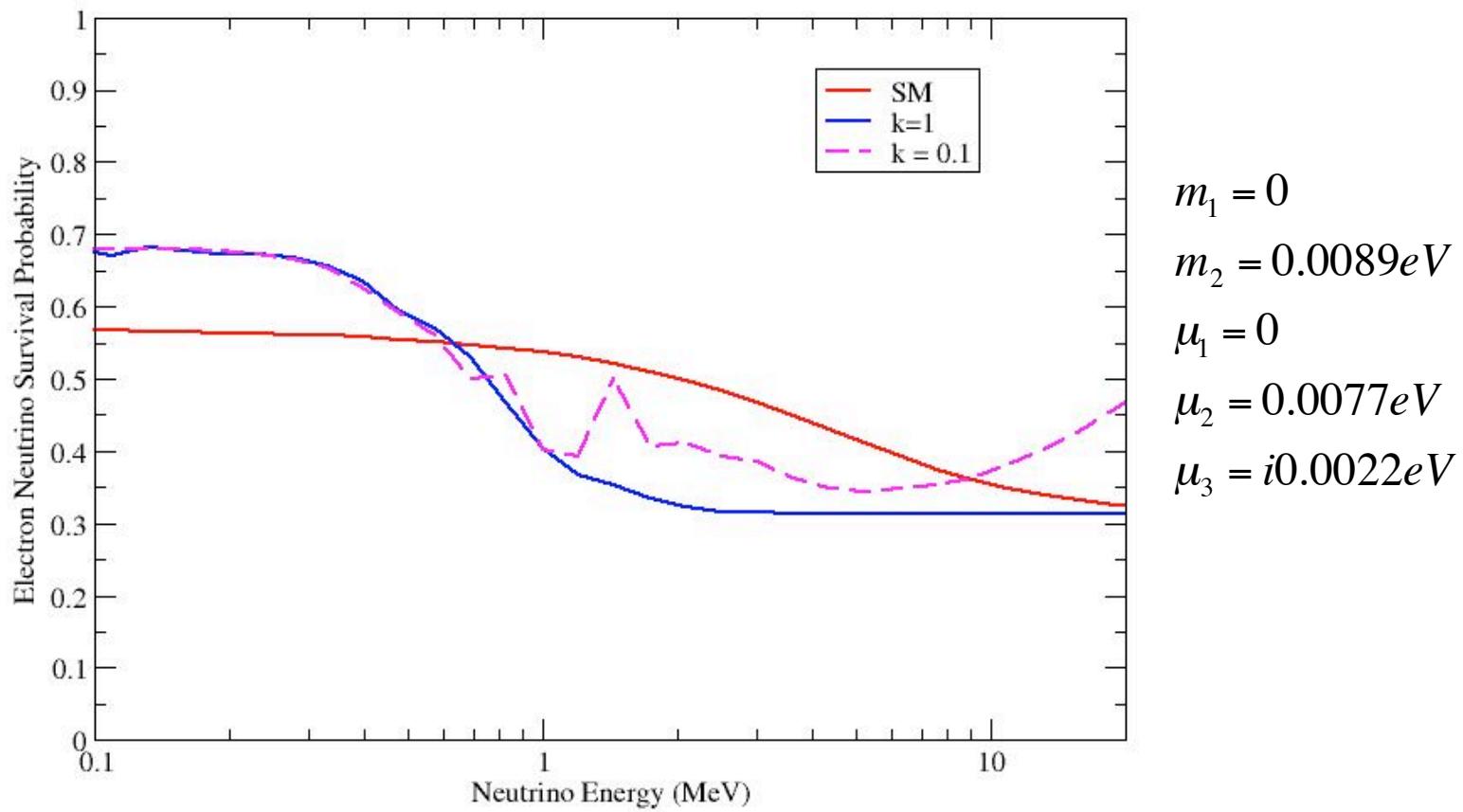
$$i \frac{\partial}{\partial t} \begin{pmatrix} \psi_e \\ \psi_x \end{pmatrix} = \frac{1}{2E} \left[U \begin{pmatrix} (m_1 - M_1(t))^2 & M_3(t)^2 \\ M_3(t)^2 & (m_2 - M_2(t))^2 \end{pmatrix} U^\dagger + \begin{pmatrix} 2\sqrt{2}G_F N_e(t)E & 0 \\ 0 & 0 \end{pmatrix} \right] \begin{pmatrix} \psi_e \\ \psi_x \end{pmatrix}$$

$$M_i(t) = \mu_i \left(\frac{N_e(t)}{N_e(t_0)} \right)^k$$

$$\varphi(t) = \frac{1}{\sqrt{2}} G_F N_e(t) - (m_2 - M_2(t))^2 \frac{\cos(2\theta_\nu)}{2E} + 2M_3(t)^2 \frac{\sin(2\theta_\nu)}{2E}$$
$$\sqrt{\Lambda} = 2M_3(t)^2 \cos(2\theta_\nu) - \frac{(m_2 - M_2(t))^2}{4E} \sin(2\theta_\nu)$$

V. Barger, P. Huber, D. Marfatia, Phys. Rev. Lett. **95** 211802 (2005)

Electron Neutrino Survival Probability



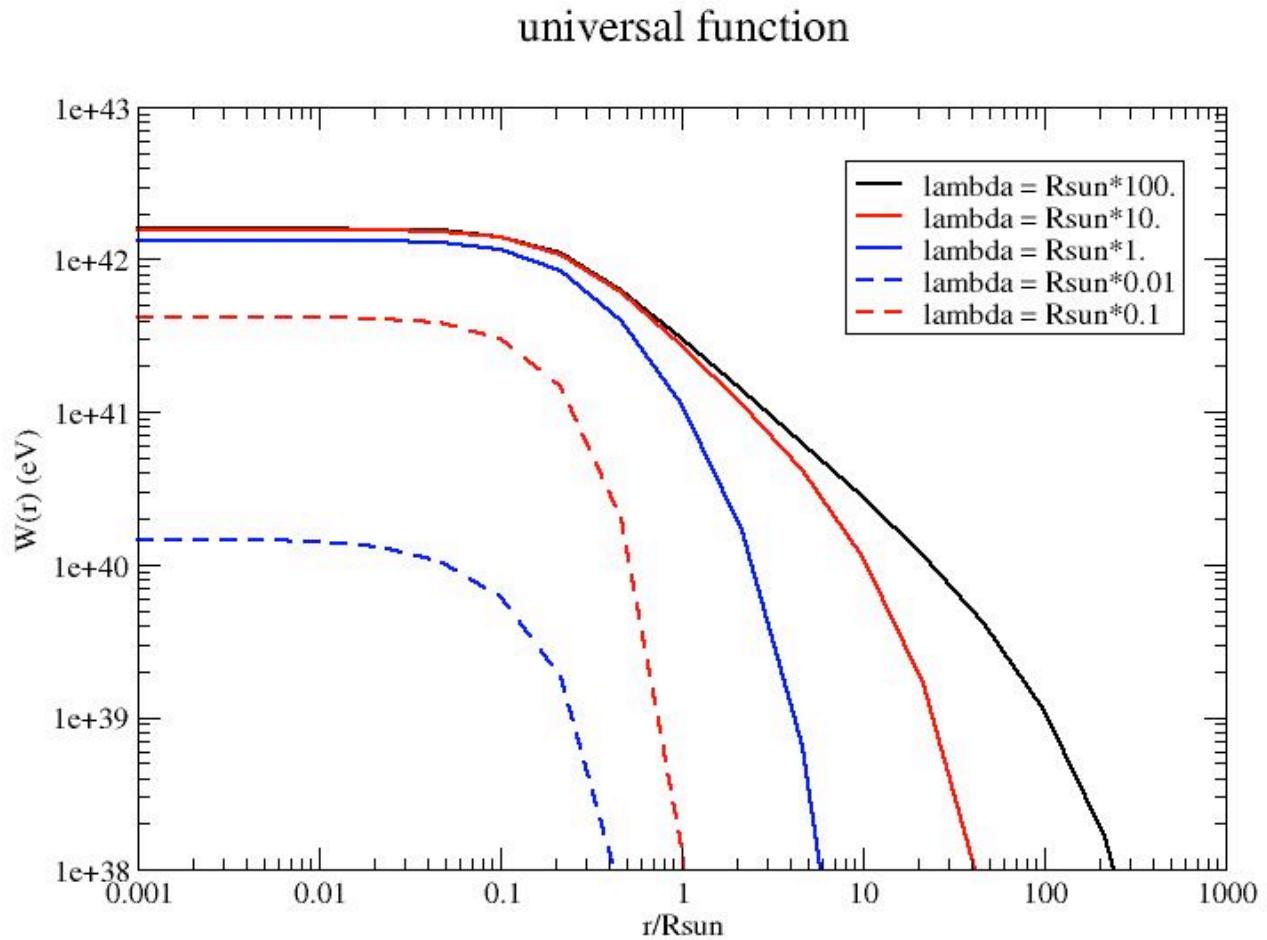
Long Range Leptonic Forces

Forces Couple to Lepton Number
Universal Function

$$W(t) = \int_0^{R_{\text{sun}}} N_e(\rho) \frac{e^{-|\rho-t|/\lambda}}{|\rho - t|} d^3\rho$$

M.C. Gonzales-Garcia, P.C. deHolanda, E. Masso and R.
Zukanovich Funchal, arXiv:hep-ph/0609094

Long Range Leptonic Forces



Scalar

$$\varphi(t) = \sqrt{2}G_F N_e(t)$$

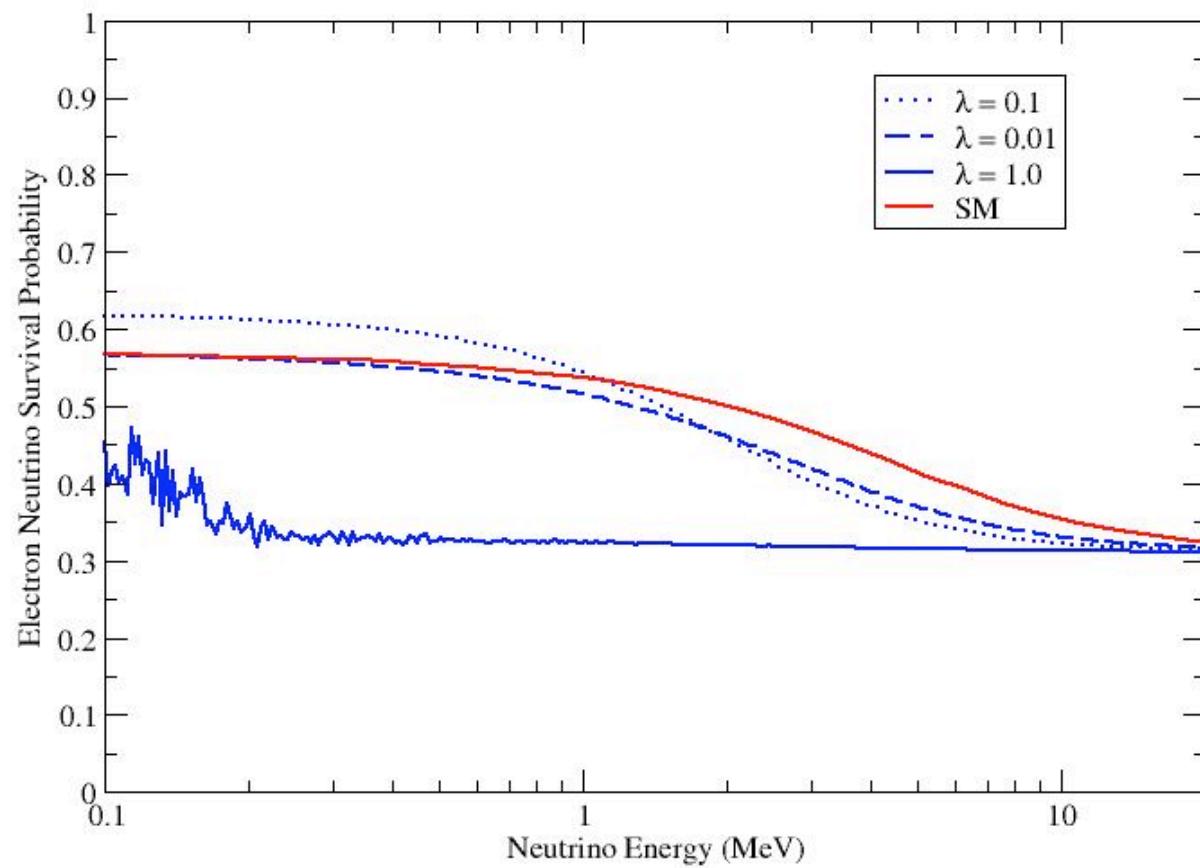
$$+ \frac{1}{2E} \left[m_1^2 \left(\cos^2 \theta_v - \frac{1}{2} \right) + m_2^2 \left(\sin^2 \theta_v - \frac{1}{2} \right) - m_1 k_s W(t) \cos^2 \theta_v - m_2 k_s W(t) \sin^2 \theta_v + \frac{k_s^2 W^2}{2} \right]$$

$$\sqrt{\Lambda} = \frac{1}{2E} [(m_2 - m_1)(m_2 + m_1 - k_s W(t)) \cos \theta_v \sin \theta_v]$$

$$m_1 = 0$$

$$k_s(e) = \frac{g_0^2}{4\pi} = 10^{-44}$$

Electron Neutrino Survival Probability



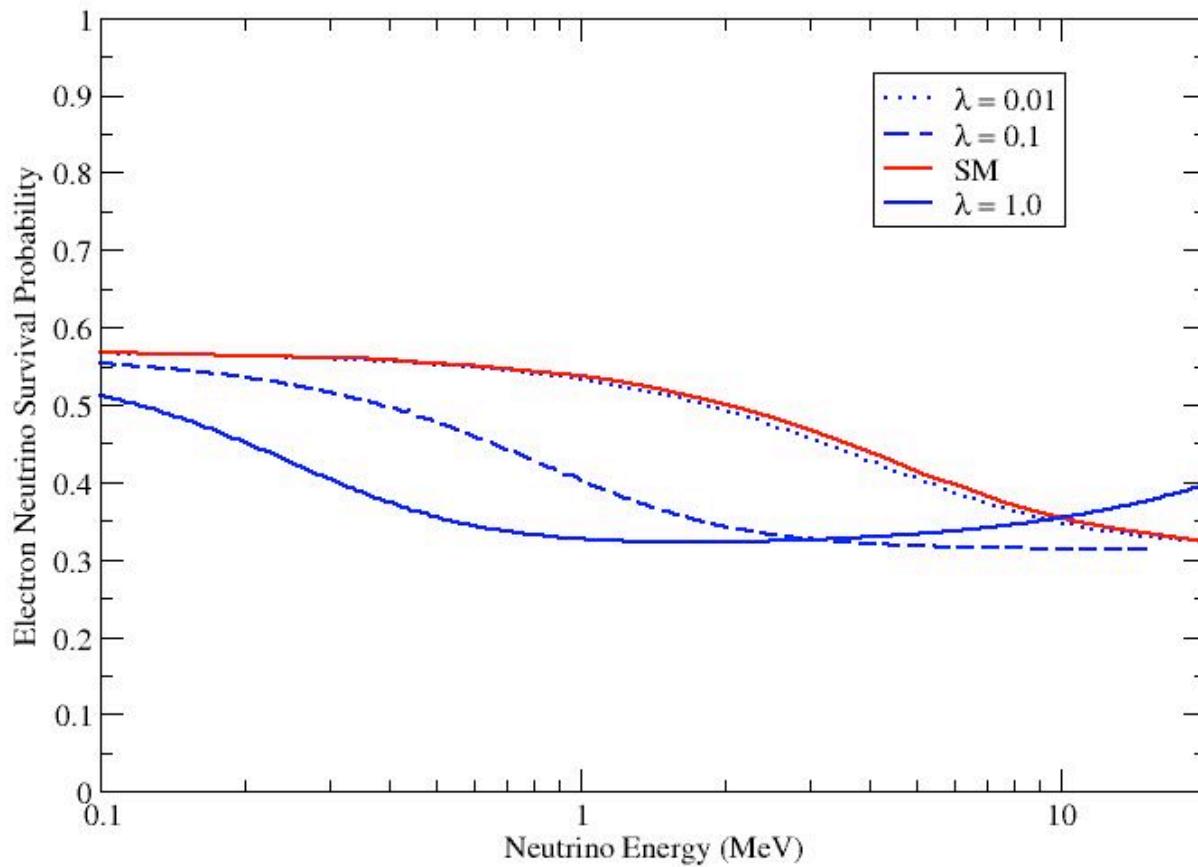
Vector

$$\varphi(t) = \frac{1}{\sqrt{2}} G_F N_e(t) - \frac{\delta m^2}{4E} \cos(2\theta_\nu) + k_\nu W(t)$$

$$\sqrt{\Lambda} = \frac{\delta m^2}{4E} \sin(2\theta_\nu)$$

$$k_V(e) = \frac{g_1^2}{4\pi} = 10^{-52}$$

Electron Neutrino Survival Probability



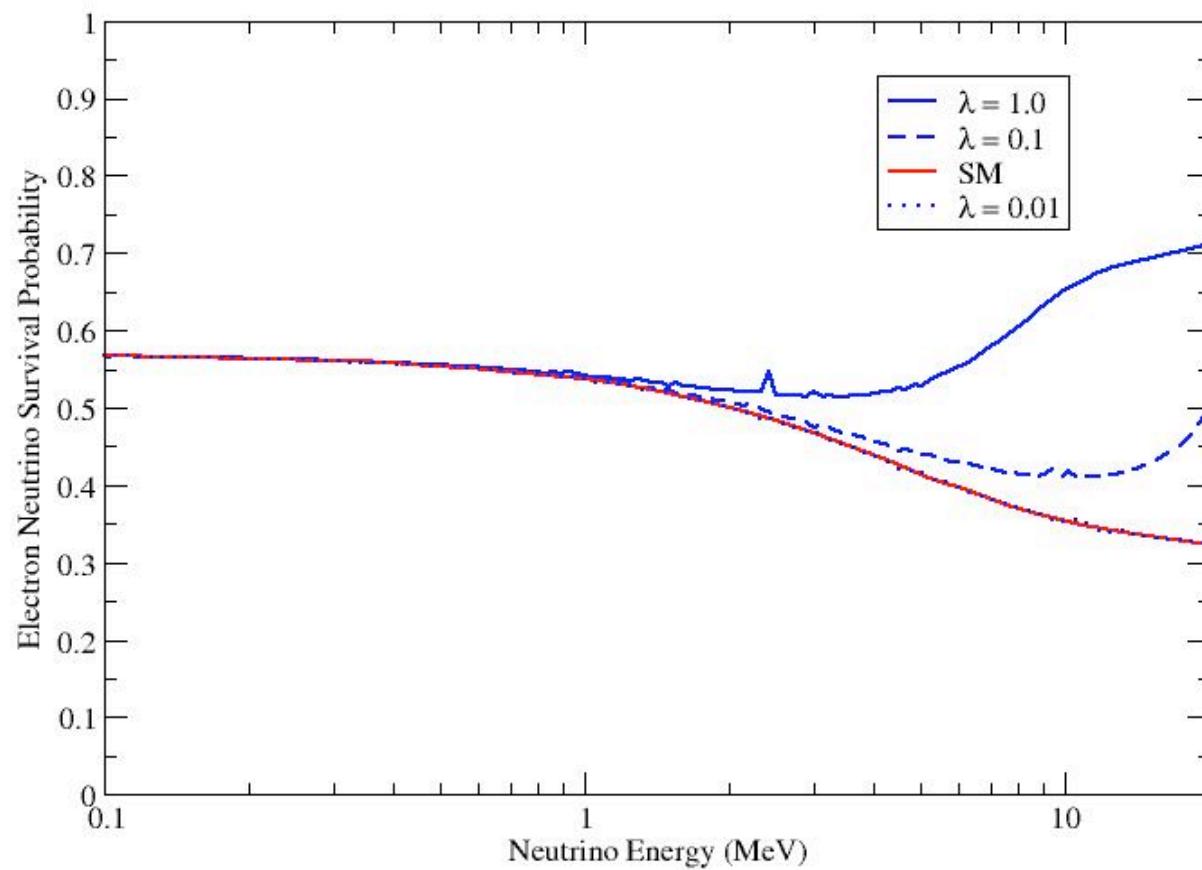
Tensor

$$\varphi(t) = \frac{1}{\sqrt{2}} G_F N_e(t) - \frac{\delta m^2}{4E} \cos(2\theta_\nu) - E_\nu k_T(e) W(t)$$

$$\sqrt{\Lambda} = \frac{\delta m^2}{4E} \sin(2\theta_\nu)$$

$$k_T(e) = m_e \frac{g_2^2}{4\pi} = 10^{-60} eV^{-1}$$

Electron Neutrino Survival Probability



Solar Density Fluctuations

$$\varphi(t) = \frac{1}{\sqrt{2}} G_F N_e(t) - \frac{\delta m^2}{4E} \cos(2\theta_\nu) + \frac{G_F}{\sqrt{2}} \beta \langle N_e(t) \rangle F_f(t)$$
$$\sqrt{\Lambda} = \frac{\delta m^2}{4E} \sin(2\theta_\nu)$$

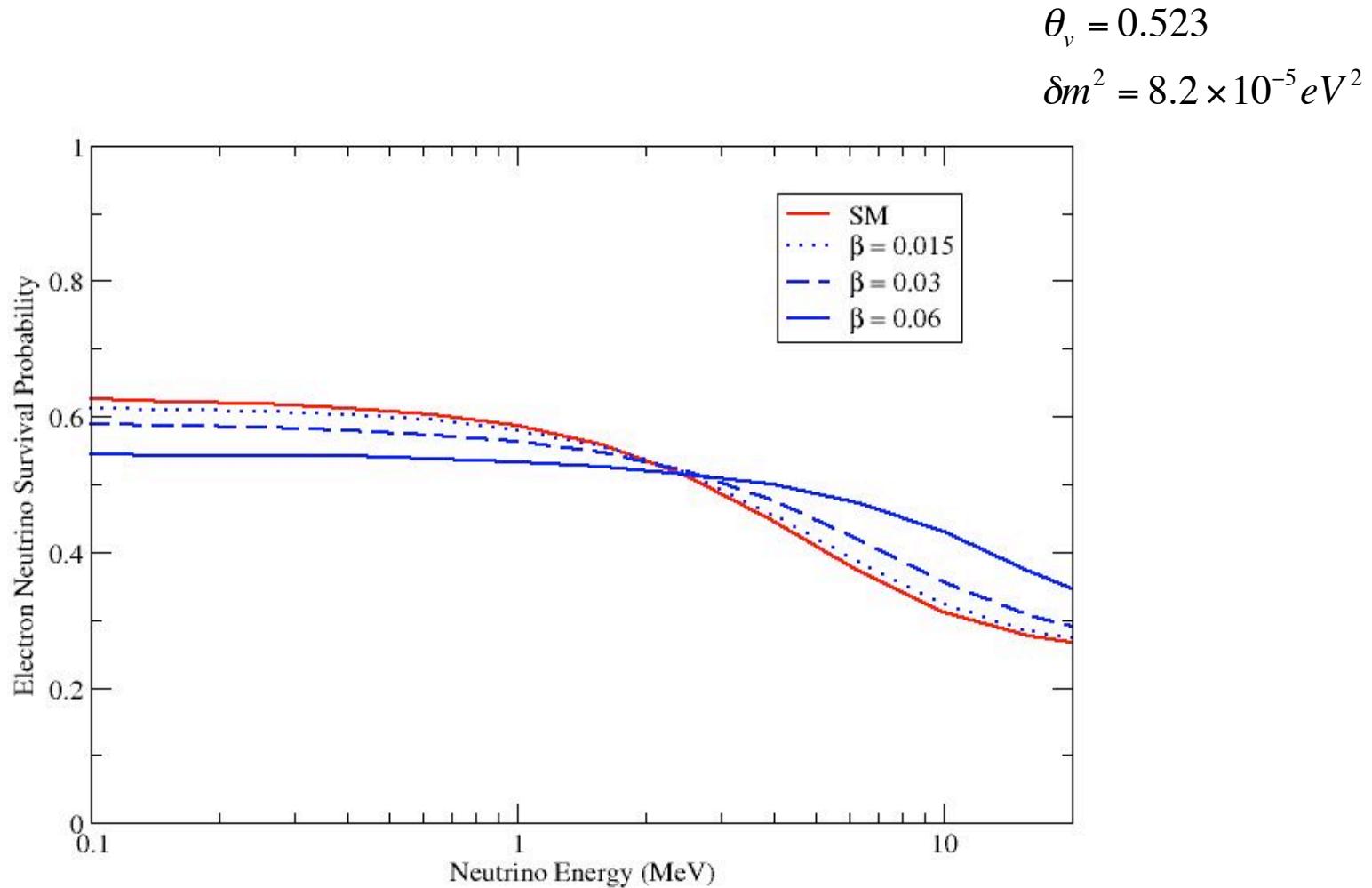
$$\langle F_f(t) \rangle = 0$$

$$\langle F_f(t) F_f(t') \rangle = 2\tau \delta(t - t')$$

F.N. Loret and A.B. Balantekin,
Phys. Rev. D **50** 4762 (1994)
[arXiv:nucl-th/9406003];

A.B. Balantekin and H. Yuksel,
Phys. Rev. D. **68**, 013006 (2003)
[arXiv:hep-ph/0303169

Electron Neutrino Survival Probability



Summary

- Many new models contain similar formulation:

$$\varphi'(t) = \varphi(t) + \delta\varphi$$

- This is visible at ~ 1 MeV, independent of model

How Can We Detect This?

SNO +

References

1. Bahcall, Serenelli, ApJ, **621**, L85 (2005)
2. Figure 6.1 in *Neutrino Astrophysics*, J.N. Bahcall
3. Solar+KamLAND parameter space
4. SNO Salt + KamLAND
5. PDG(2007)
6. A. Friedland, C. Lundardini and C. Pena-Garay, Phys. Lett. B **594**, 347 (2004)
7. V. Barger, P. Huber, D. Marfatia, Phys. Rev. Lett. **95** 211802 (2005); R. Fardon, A.E. Nelson and N. Weiner, JCAP **0410** 005 (2004) [arXiv:astro-ph/0309800]
8. M.C. Gonzales-Garcia, P.C. deHolanda, E. Masso and R. Zukanovich Funchal, arXiv:hep-ph/0609094
9. F.N. Loreti and A.B. Balantekin, Phys. Rev. D **50** 4762 (1994) [arXiv:nucl-th/9406003]; A.B. Balantekin and H. Yuksel, Phys. Rev. D. **68**, 013006 (2003) [arXiv:hep-ph/0303169]

Dickens

It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to heaven, we were all going direct the other way - in short, the period was so far like the present period, that some of its noisiest authorities insisted on its being received, for good or for evil, in the superlative degree of comparison only.

Grueling Detail-Solving Evolution

- For all hermitian matrices, we can diagonalize, using either the adiabatic approximation or numerically

$$\psi(t + \Delta t) = U e^{-i\Delta t D} U^\dagger \psi(t)$$

- Otherwise, we must solve completely numerically

$$D_{\text{adiabatic}} = \begin{pmatrix} -\sqrt{\varphi^2 + \Lambda} & 0 \\ 0 & \sqrt{\varphi^2 + \Lambda} \end{pmatrix}$$

$$D = U H U^\dagger$$

$$U = \begin{pmatrix} \cos \theta_m & -\sin \theta_m \\ \sin \theta_m & \cos \theta_m \end{pmatrix}$$

$$\cos(2\theta_m) \equiv \frac{-\varphi}{\sqrt{\varphi^2 + \Lambda}}$$

$$\sin(2\theta_m) \equiv \frac{\sqrt{\Lambda}}{\sqrt{\varphi^2 + \Lambda}}$$

Survival Far From Origin

- Average over behavior at large t

$$\psi(t_0) = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$
$$\langle \psi(t_0, E) \rangle_{2R_{\text{sun}}}$$

Grueling Detail-Hermite Weights

- Approximate radial distributions as gaussian distributions, with σ_j, r_j
- Each process, j , is produced on a different distribution.

$$\overline{\langle \psi(E) \rangle}_j = \frac{\sum_i W_i \left\langle \psi \left(t_j + \frac{x_i}{\sigma_j} R_{sun}, E \right) \right\rangle}{\sum_i W_i}$$

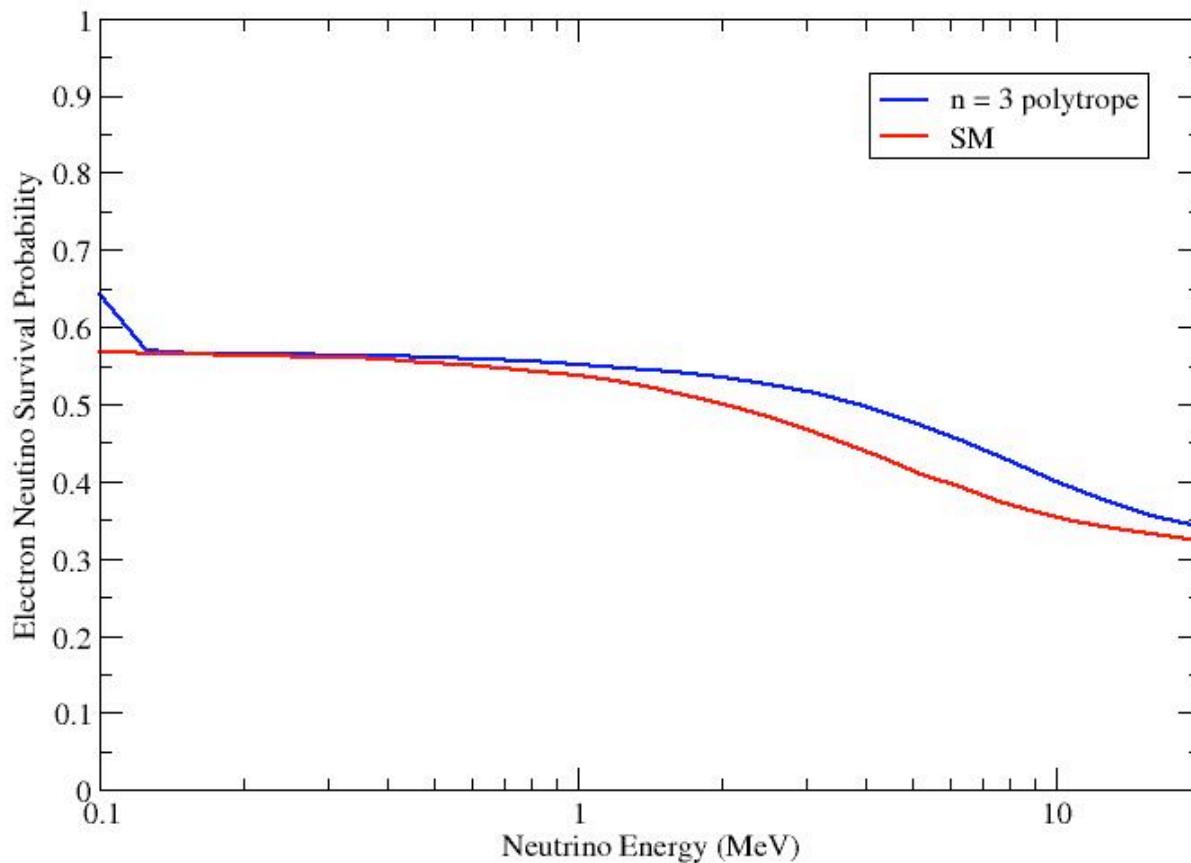
Grueling Detail-Weighting by Flux

- For each process, j , the flux of neutrinos varies by energy

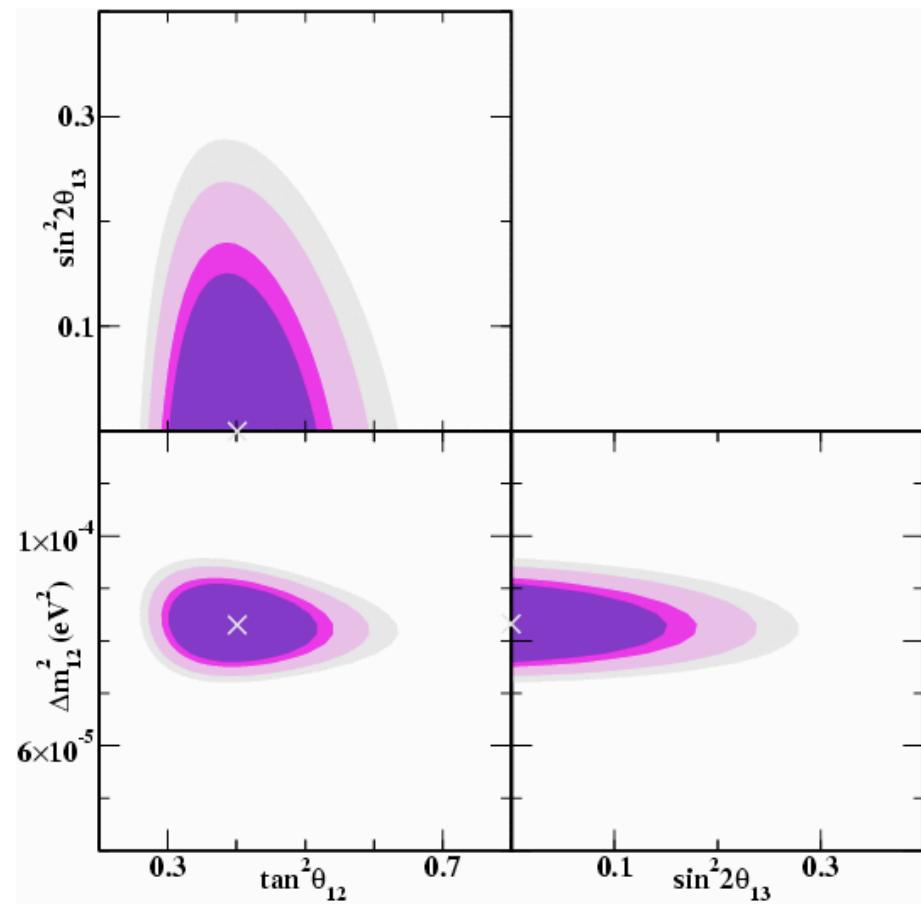
$$\overline{\langle \psi(E) \rangle}_{total} = \frac{\sum_{j=Be,B,pp} \overline{\langle \psi(E) \rangle}_j \Phi_j}{\sum_{j=Be,B,pp} \Phi_j}$$

Toys-Polytropic Sun

$$P(t) = K\rho^{1+1/n}(t)$$

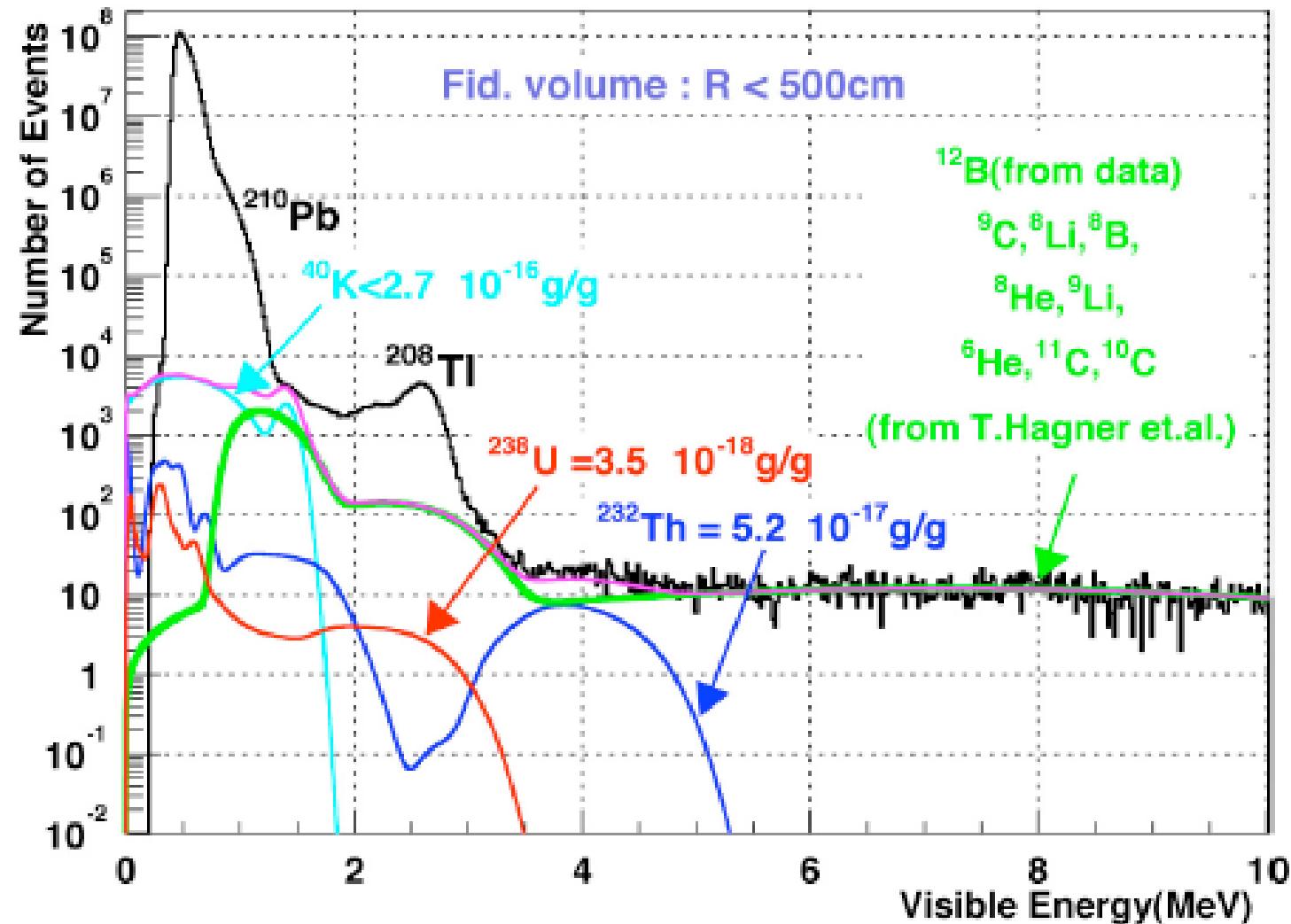


SNO Salt and KamLAND [4]



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

How Can We Detect This?



Solar Density Fluctuations

$$\frac{\partial}{\partial t} \begin{pmatrix} z \\ y \\ x \end{pmatrix} = -2 \begin{pmatrix} 0 & 0 & \varphi \\ 0 & k & -\sqrt{\Lambda} \\ -\varphi & \sqrt{\Lambda} & k \end{pmatrix} \begin{pmatrix} z \\ y \\ x \end{pmatrix}$$

$$z = 2\langle \nu_e * \bar{\nu}_e \rangle - 1$$

$$y = 2\text{Im}\langle \nu_\mu * \bar{\nu}_e \rangle$$

$$x = 2\text{Re}\langle \nu_\mu * \bar{\nu}_e \rangle$$

$$k = G_F^2 \langle N_e(t) \rangle^2 \beta^2 \tau$$

β is the percent fluctuation