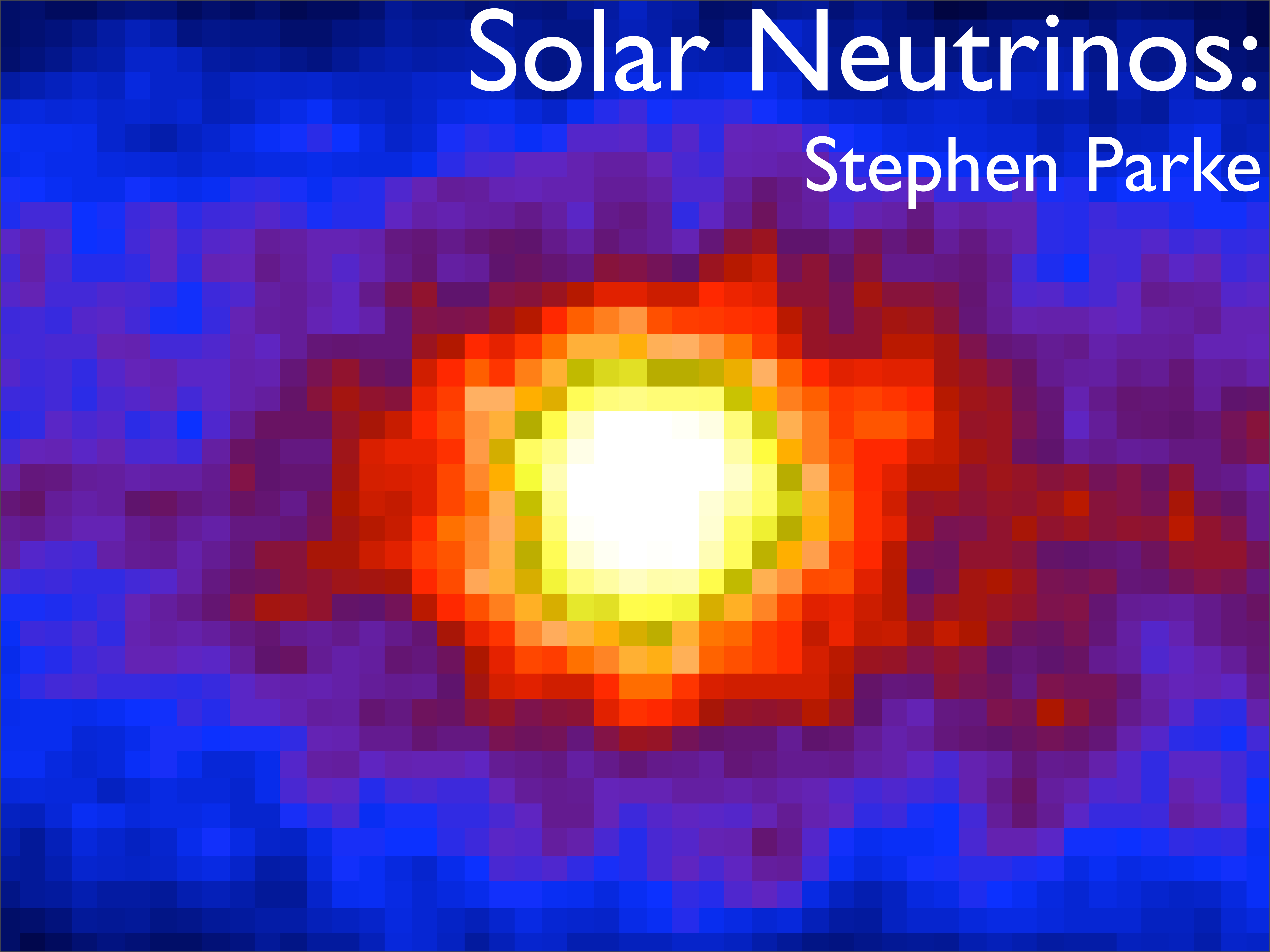
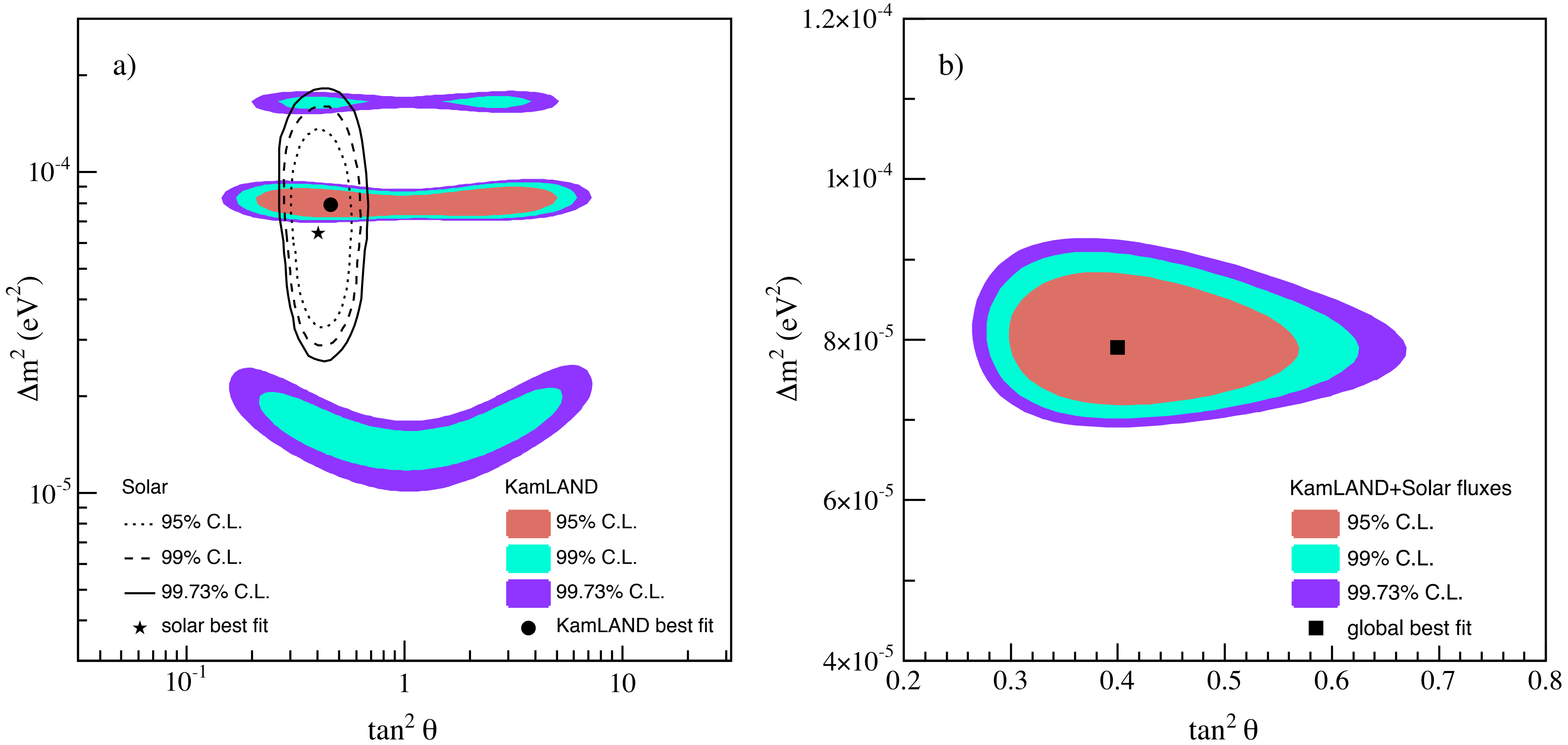
Solar Neutrinos:

Stephen Parke



2006



KamLAND Only

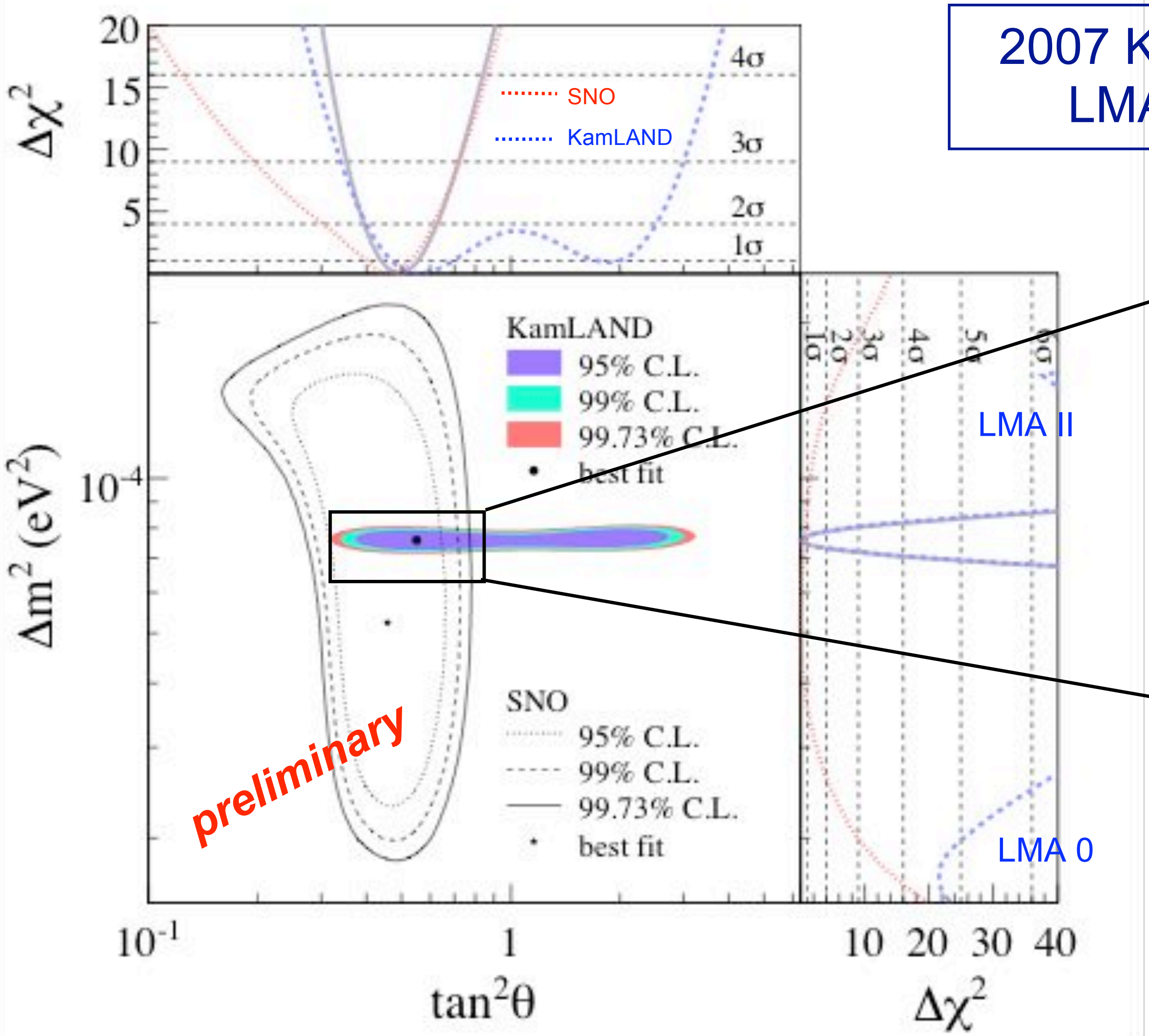
Solar + KamLAND

$$\delta m^2_\odot = 8.0^{+0.4}_{-0.3} \times 10^{-5}\mathrm{eV}^2,$$

$$\sin^2\theta_\odot = 0.310 \pm 0.026,$$

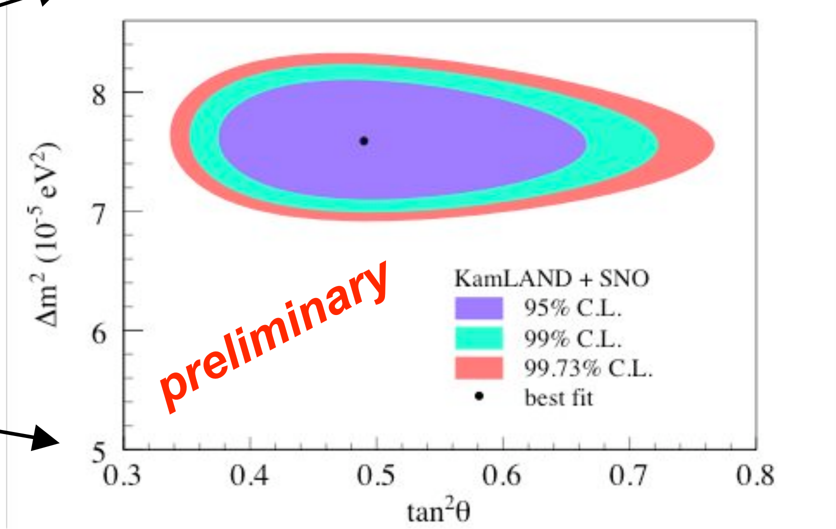
2007

Oscillation Parameter Space



2007 KamLAND result excludes LMA 0 and LMA II at > 4σ

Combined KamLAND + SNO



Combined Best-Fit Parameters:

$$\Delta m^2 = 7.59^{+0.21}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta = 0.49^{+0.07}_{-0.05}$$

SNO ref: Phys Rev C 72, 055502(2005)

$$\sin^2\theta_\odot = 0.33 \pm 0.03$$

Solar Engine:

$$4p + 2e^- \rightarrow {}^4 He + 2\nu_e + 26.7 MeV$$

$$E = mc^2$$

1 ν_e for every 13.4 MeV (=2.1 $\times 10^{-12}$ J)

$\mathcal{L}_\odot$ at earth's surface 0.13 watts/cm^2

$$\phi_\nu = \frac{0.13}{2.1 \times 10^{-12}} = 6 \times 10^{10}/cm^2/sec$$

This corresponds to an average of 2 ν's per cm^3
since they are going at speed c.

Solar Spectrum:

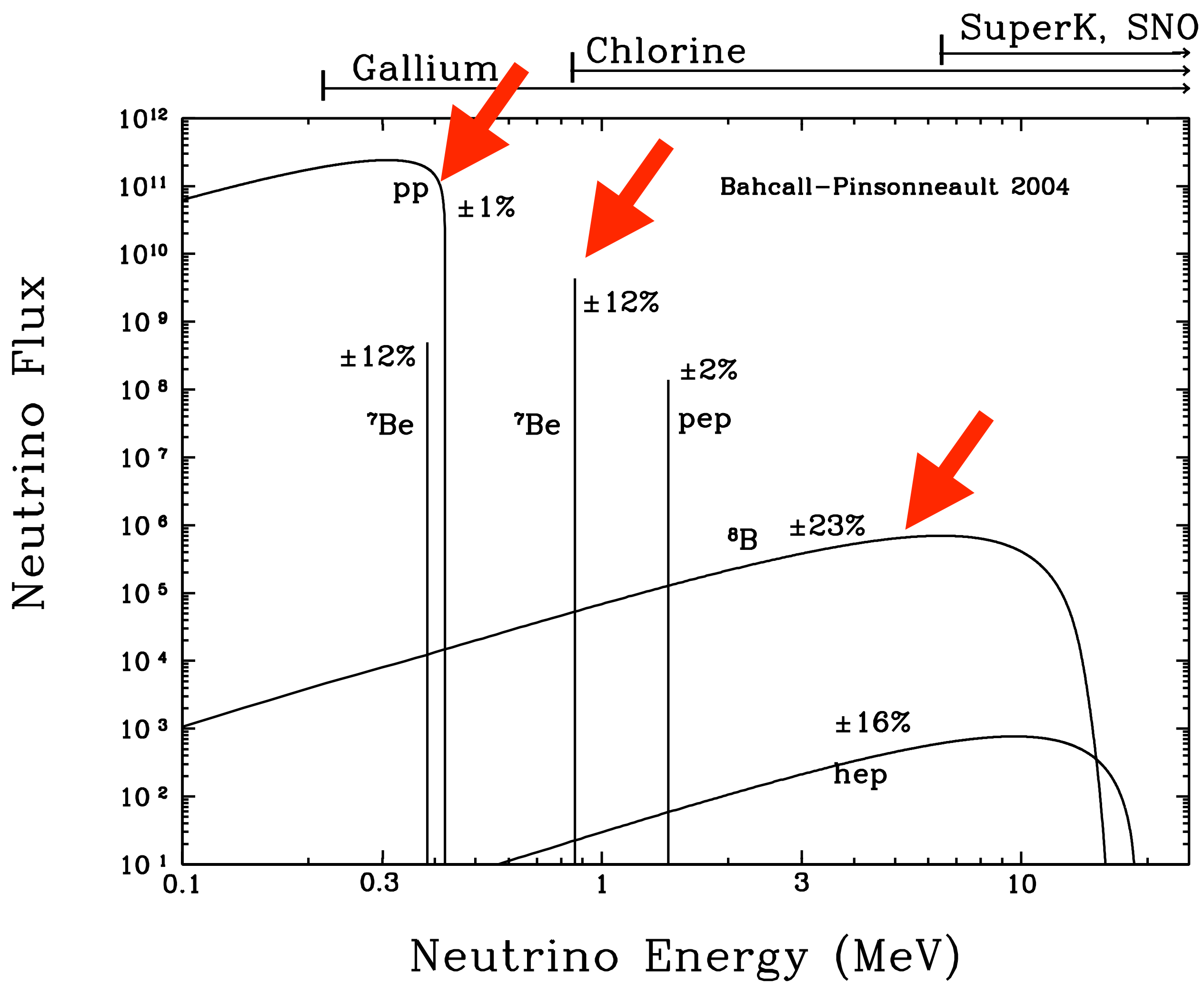


Figure 1. The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [22]. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2}\,s^{-1}\,MeV^{-1}$ at the Earth's surface. For line sources, the units are number of neutrinos $cm^{-2}\,s^{-1}$. Total theoretical uncertainties taken from column 2 of table 1 are shown for each source. To avoid complication in the figure, we have omitted the difficult-to-detect CNO neutrino fluxes (see table 1).

$$p + p \rightarrow^2 H + e^+ + \nu_e$$

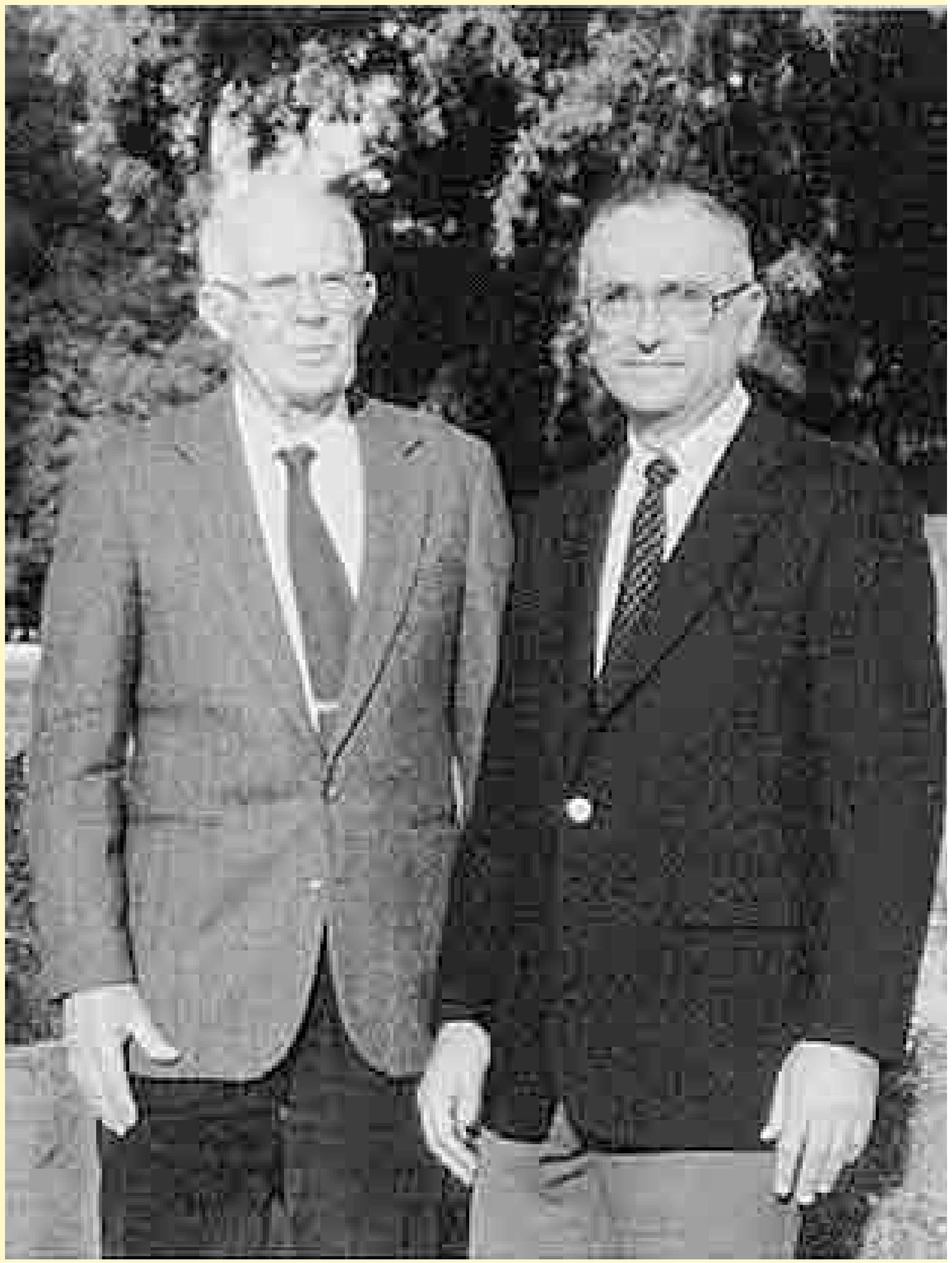
$$\phi_{pp} = 5.94(1 \pm 0.01) \times 10^{10} cm^{-2} sec^{-1}$$

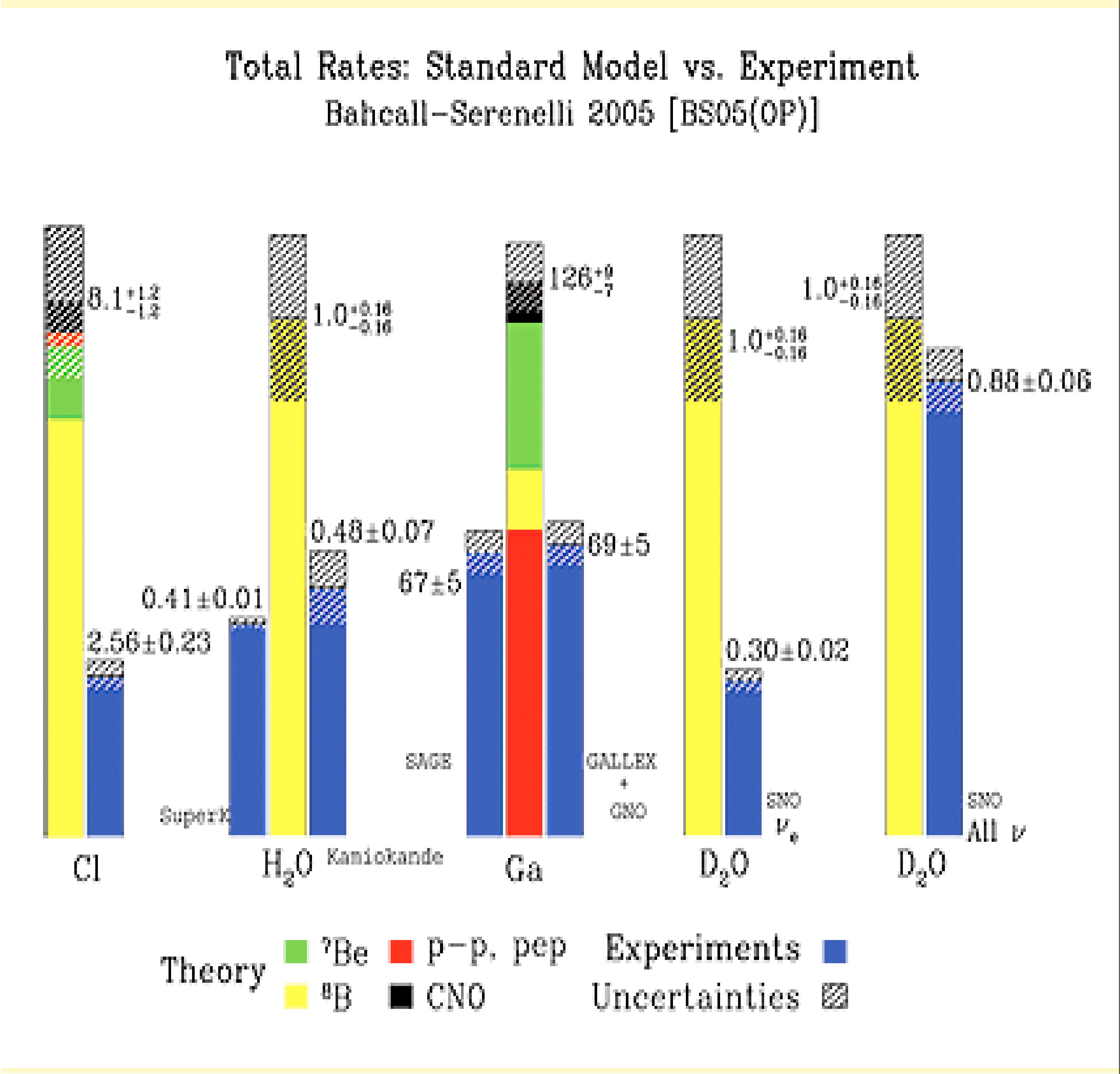
$$^7Be + e^- \rightarrow^7 Li + \nu_e$$

$$\phi_{^7Be} = 4.86(1 \pm 0.12) \times 10^{9} cm^{-2} sec^{-1}$$

$$^7Be + p \rightarrow^8 B \rightarrow^8 Be^* + e^- + \nu_e$$

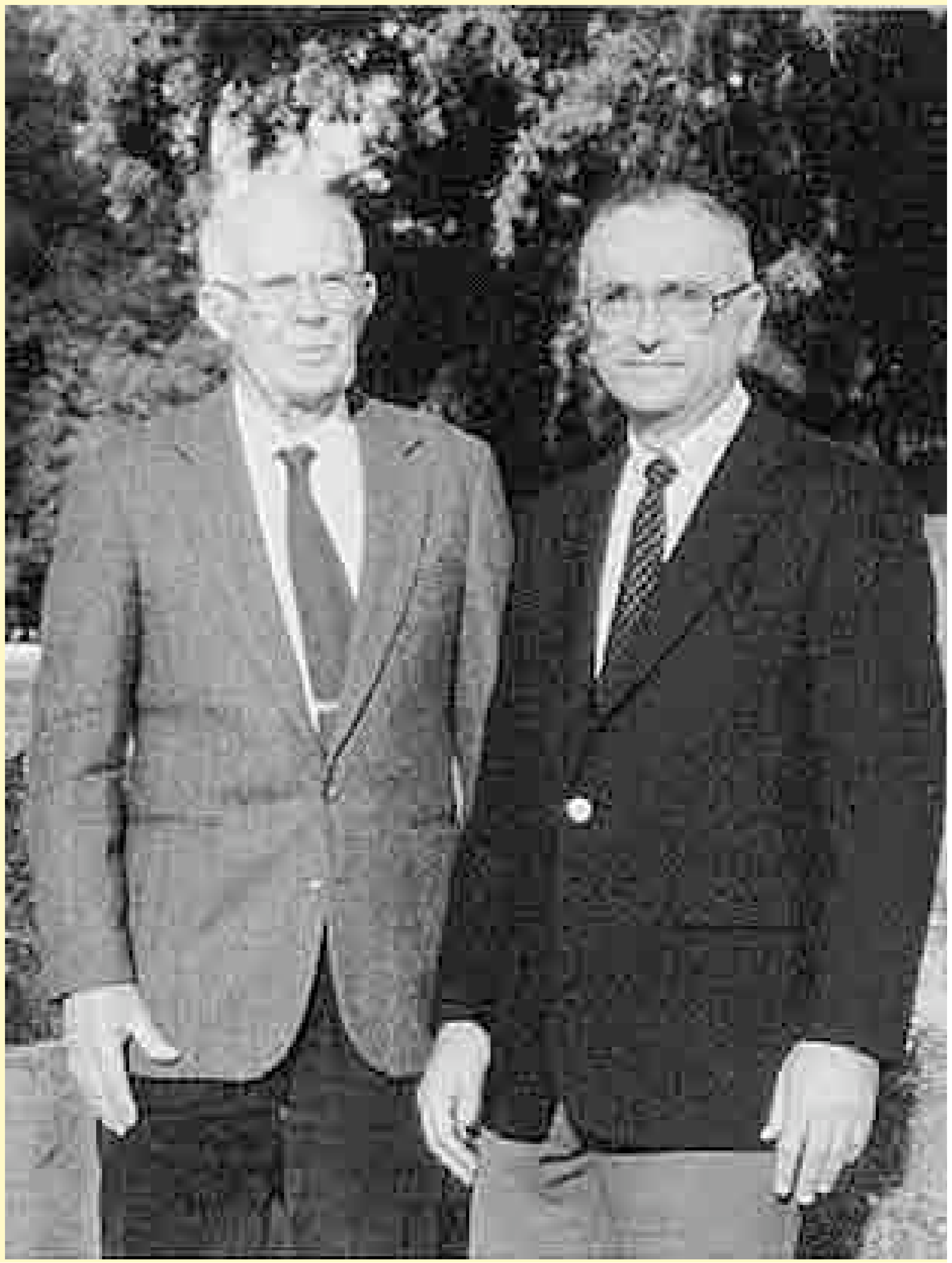
$$\phi_{^8B} = 5.82(1 \pm 0.23) \times 10^{6} cm^{-2} sec^{-1}$$



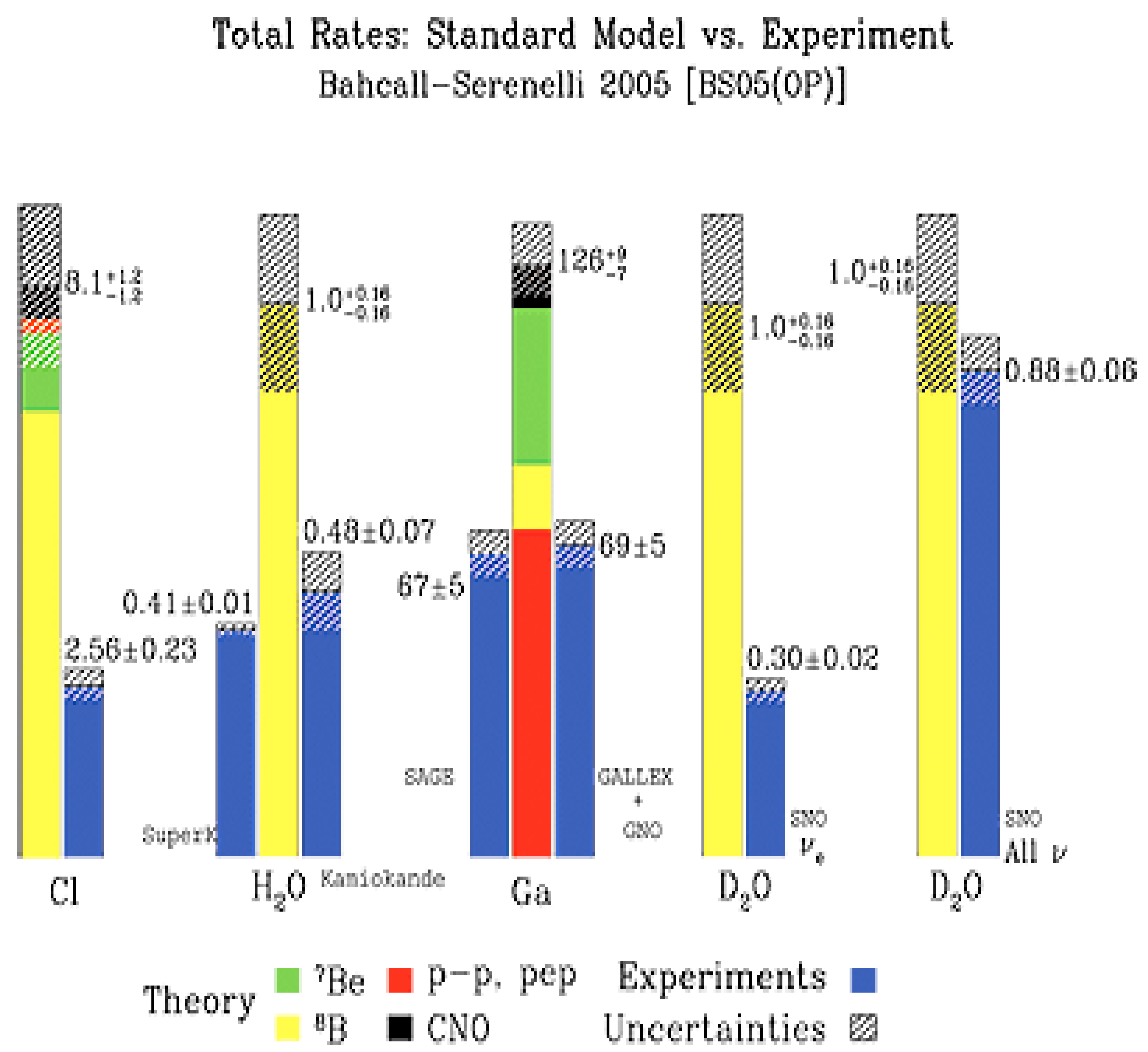


Ray Davis & John Bahcall

Theory v Exp.



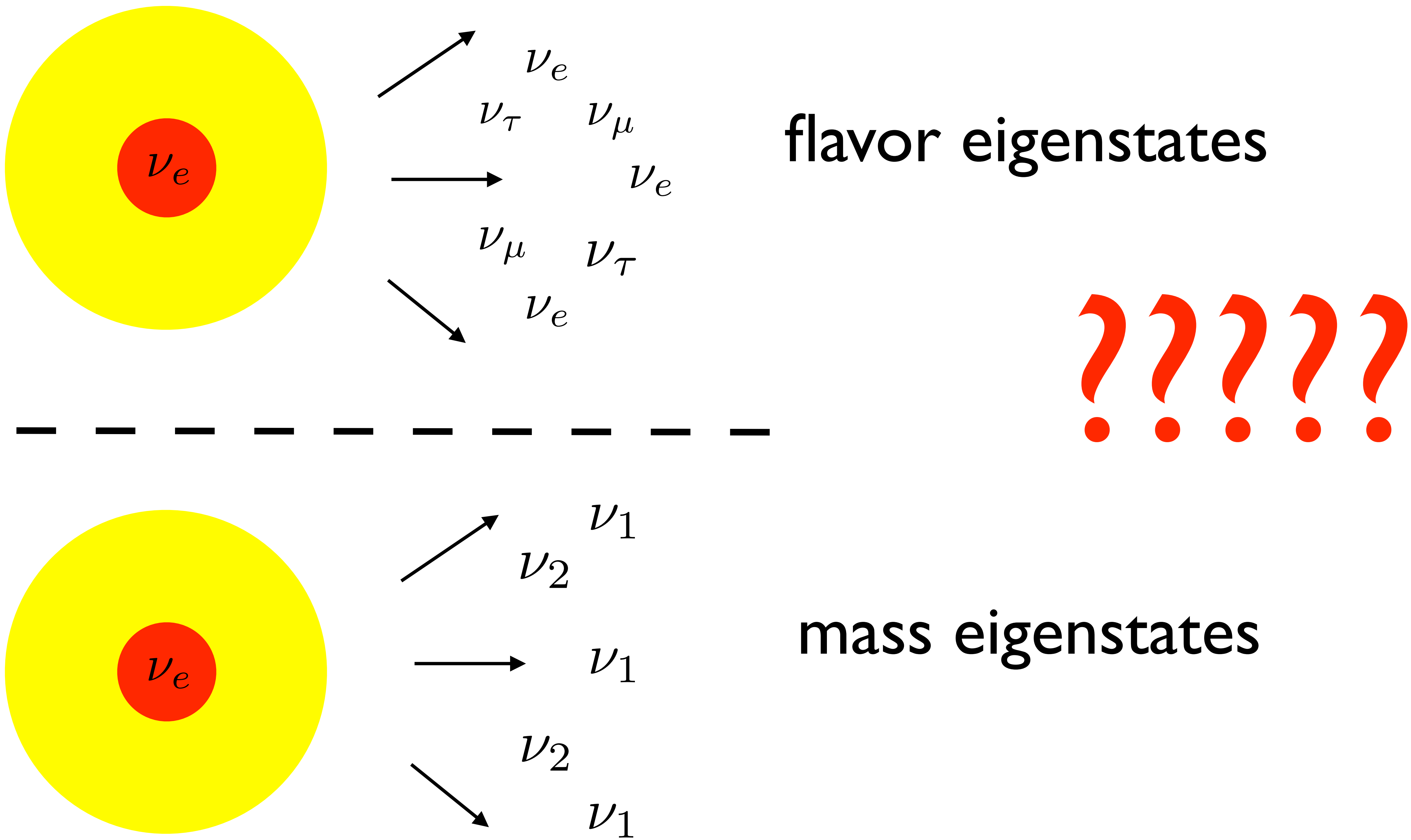
Ray Davis & John Bahcall



Theory v Exp.

Neutrino Flavor Transistions!!!

Identical Solar Twins:



Kinematical Phase:

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

$$\sin^2 \theta_{\odot} = 0.31$$

$$\Delta_{\odot} = \frac{\delta m_{\odot}^2 L}{4E} = 1.27 \quad \frac{8 \times 10^{-5}\ eV^2 \cdot 1.5 \times 10^{11}\ m}{0.1 - 10\ MeV}$$

$$\Delta_{\odot} \approx 10^{7 \pm 1}$$

Effectively Incoherent !!!

Vacuum ν_e Survival Probability:

$$\langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

where f_1 and f_2 are the fraction of ν_1 and ν_2 at production.

In vacuum $f_1 = \cos^2\theta_\odot$ and $f_2 = \sin^2\theta_\odot$.

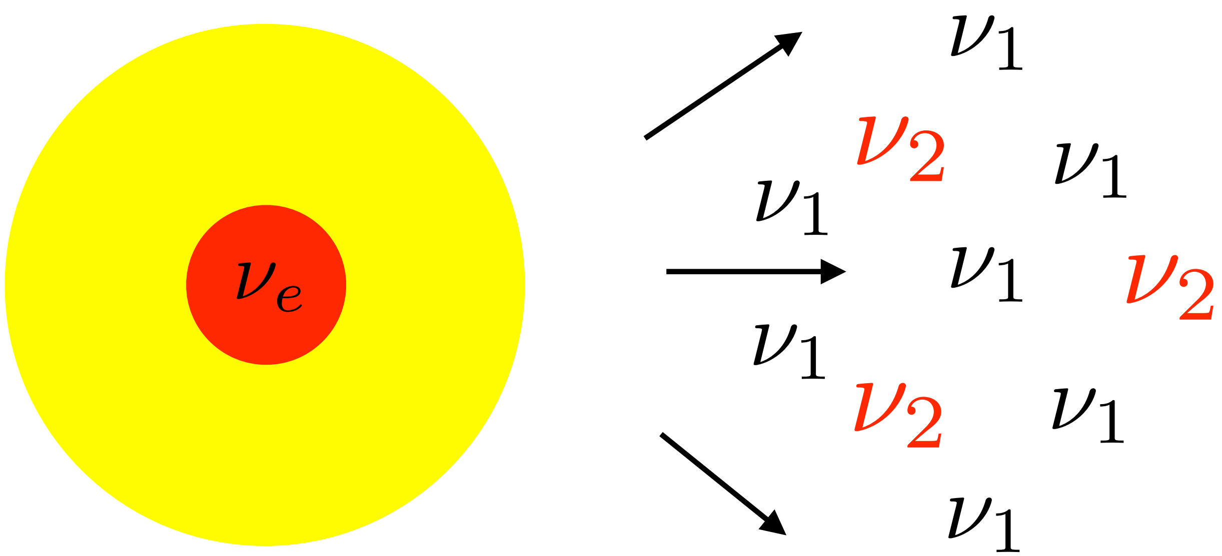
Note energy independence.

$$\langle P_{ee} \rangle = \cos^4\theta_\odot + \sin^4\theta_\odot = 1 - \frac{1}{2}\sin^2 2\theta_\odot$$

for pp and ^{7}Be this is approximately THE ANSWER.

$f_1 \sim 69\%$ and $f_2 \sim 31\%$ and $\langle P_{ee} \rangle \approx 0.6$

pp and ^{7}Be



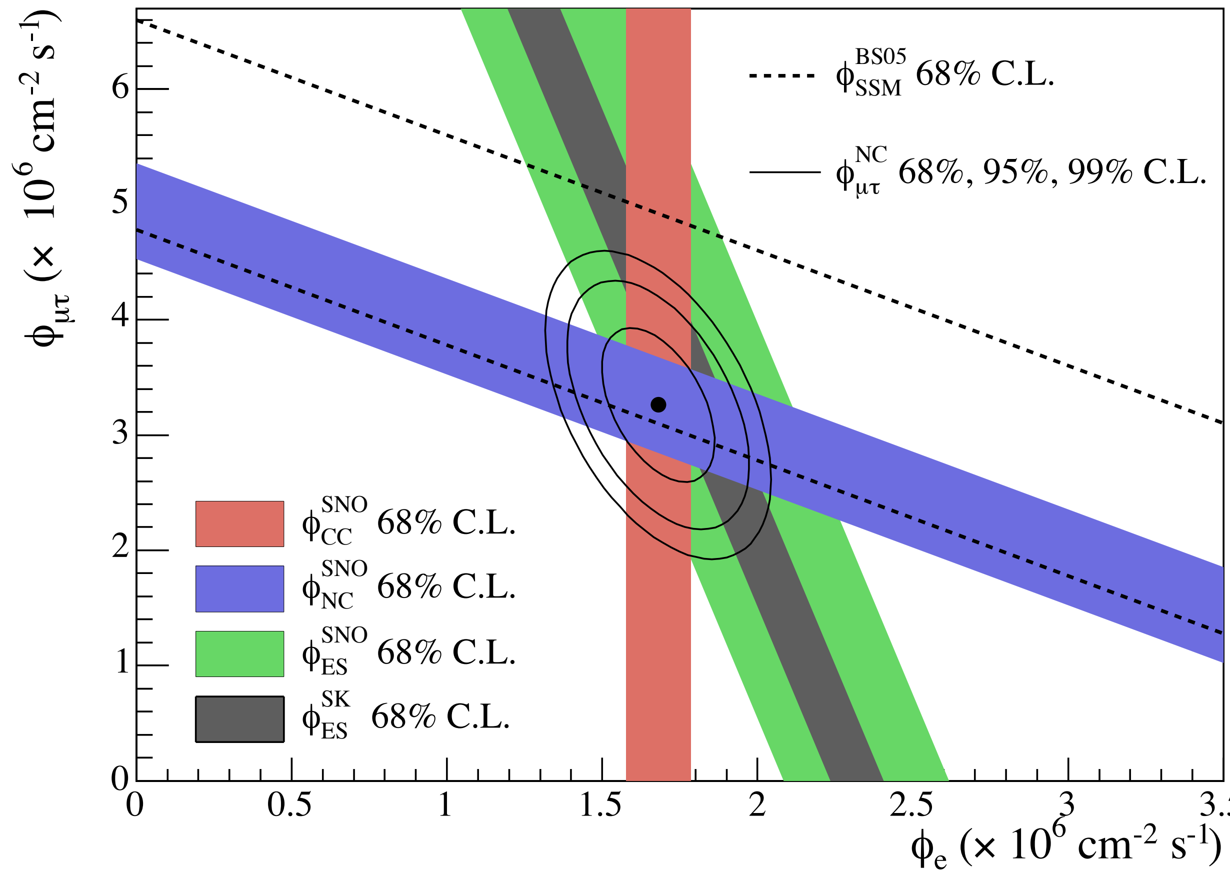
$f_1 \sim 69\%$

$f_2 \sim 31\%$

$$\langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot \approx 0.6$$

$f_3 = \sin^2\theta_{13} < 4\%$

What about ^8B ?



CC: $\nu_e + d \rightarrow e^- + p + p$

NC : $\nu_x + d \rightarrow \nu_x + p + n$

ES: $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$

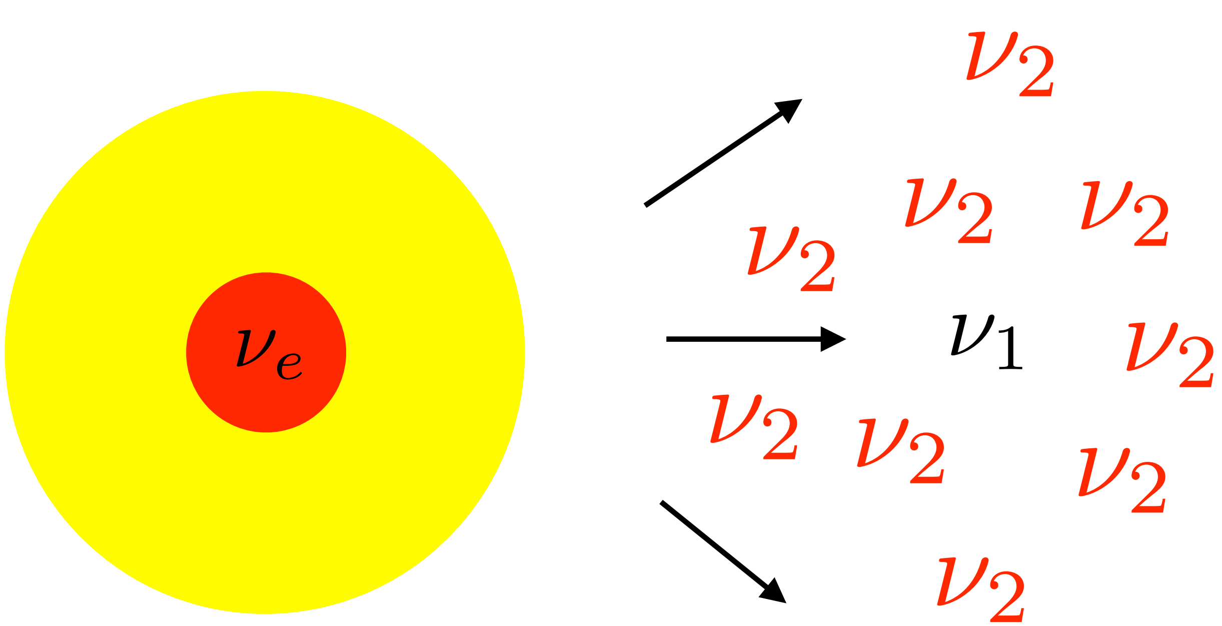
SNO's CC/NC

$$\frac{CC}{NC} = \langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

$$f_1 = \left(\frac{CC}{NC} - \sin^2\theta_\odot\right) / \cos 2\theta_\odot$$

$$= (0.35 - 0.31)/0.4 \approx 10 \ \pm\ ???\%$$

^{8}B



$$f_2 \sim 90\%$$

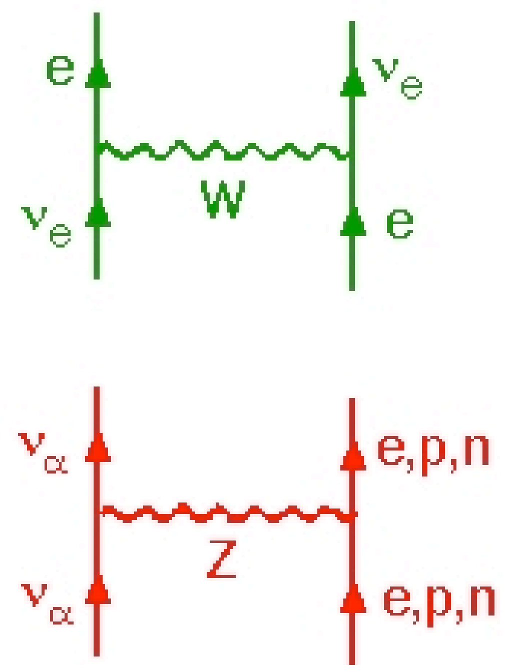
$$f_1 \sim 10\%$$

$$\langle P_{ee} \rangle = \sin^2\theta + f_1 \cos 2\theta_\odot \approx \sin^2\theta_\odot = 0.31$$

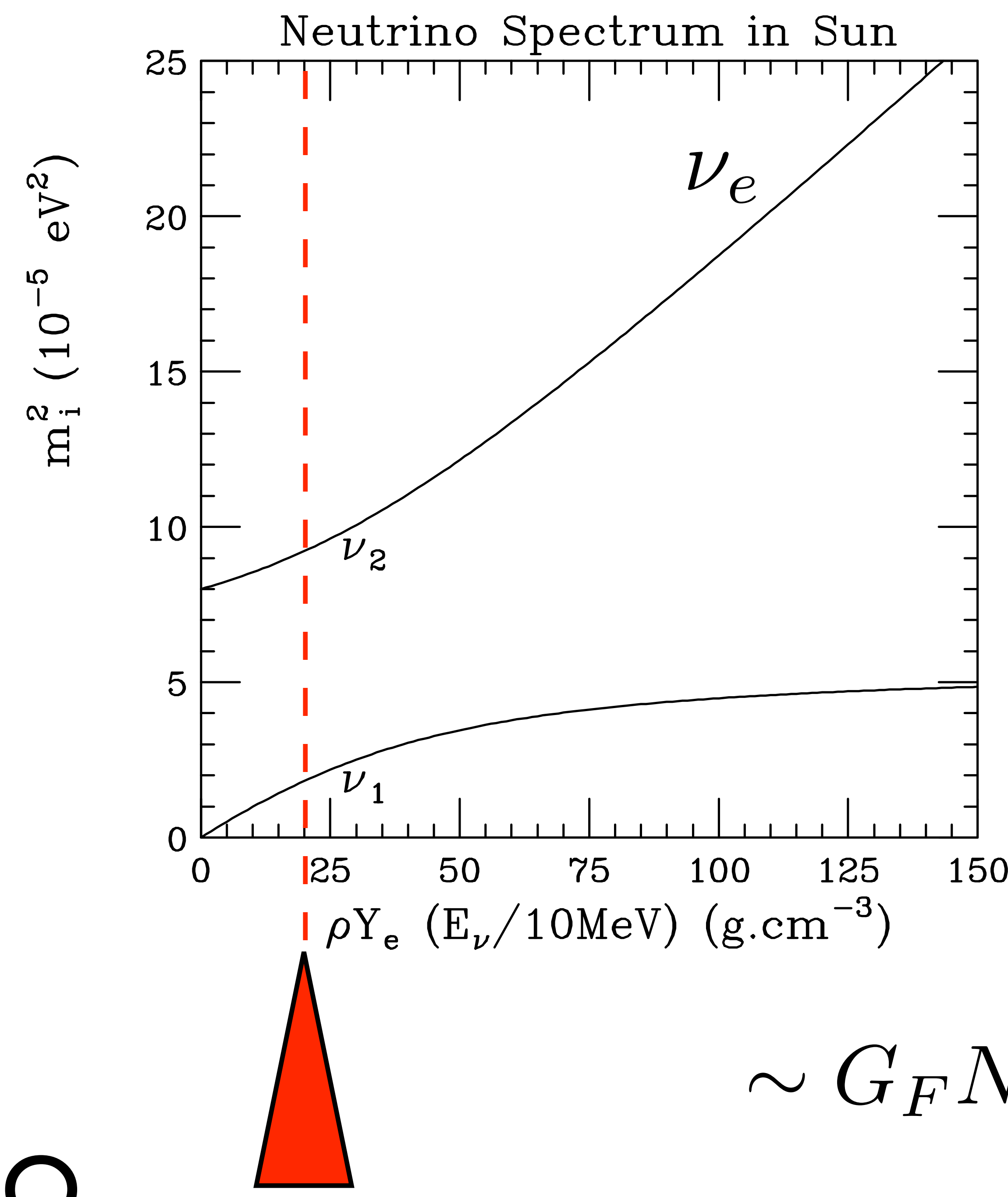
Wow!!! How did that happen???

energy dependence!!!

Coherent Forward Scattering:



Wolfenstein '78



$$\sim G_F N_e E_\nu$$

MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS

Mikheyev + Smirnov Resonance WIN '85

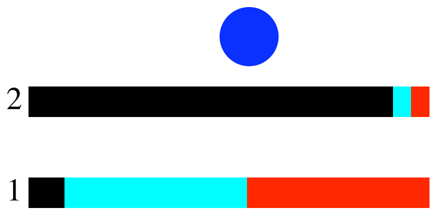
MSW

Life of a Boron-8 Solar Neutrino:

ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:

$\nu_e \approx \nu_2$
for ^{8}B



at birth

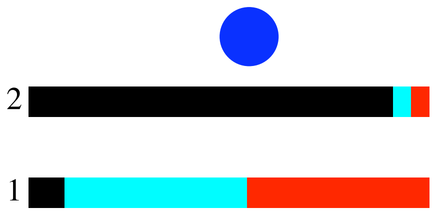
Solar Center

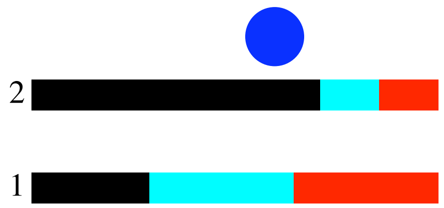
ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:

$\nu_e \approx \nu_2$
for ^{8}B

Once a ν_2 always a ν_2!





at birth

toddler

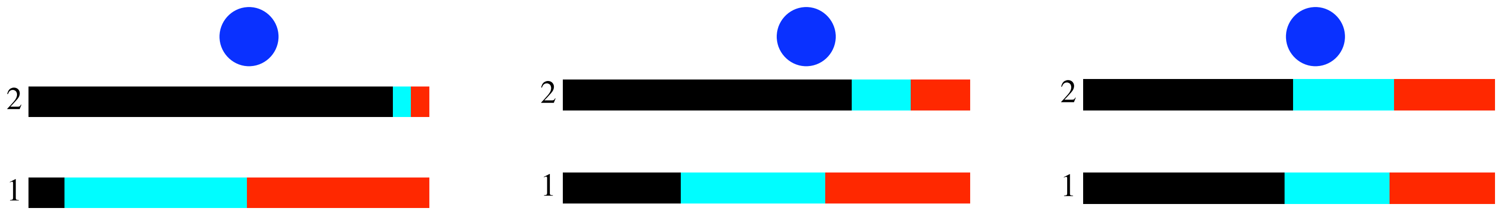
Solar Center

ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:

$\nu_e \approx \nu_2$
for ^{8}B

Once a ν_2 always a ν_2!



at birth

toddler

teenager

Solar Center

Exit Core

ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:

$\nu_e \approx \nu_2$
for ^{8}B

Once a ν_2 always a ν_2!

at birth

toddler

teenager

adult

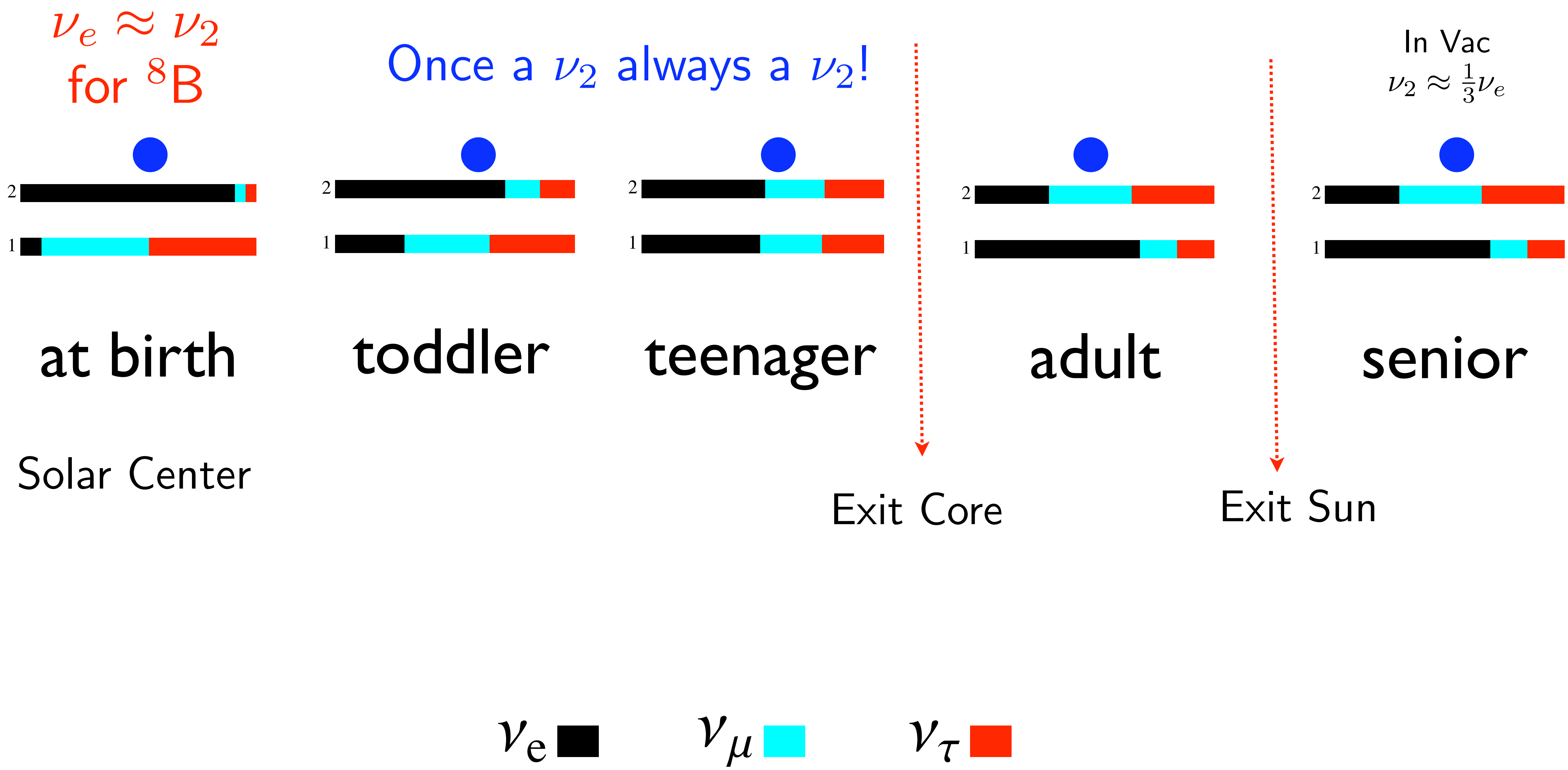
Solar Center

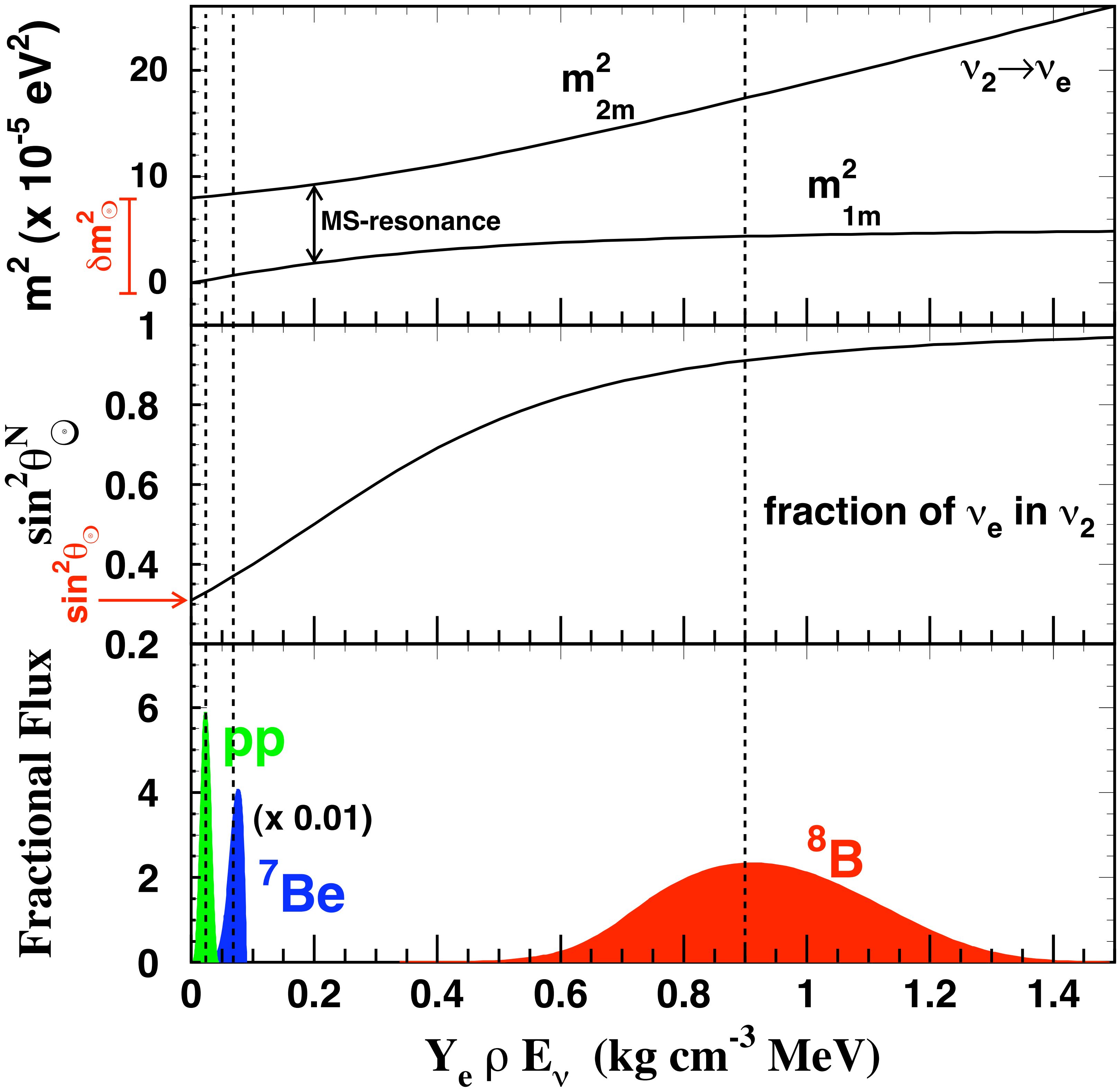
Exit Core

Exit Sun

ν_e ν_μ ν_τ

Life of a Boron-8 Solar Neutrino:





In Vacuum

$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5}\ eV^2$$
$$\sin^2\theta_\odot = 0.31 \pm 0.03$$

Whereas for ^{8}B at center of Sun

$$\delta m^2_N = 14 \times 10^{-5}\ eV^2$$
$$\sin^2\theta^N_\odot = 0.91$$

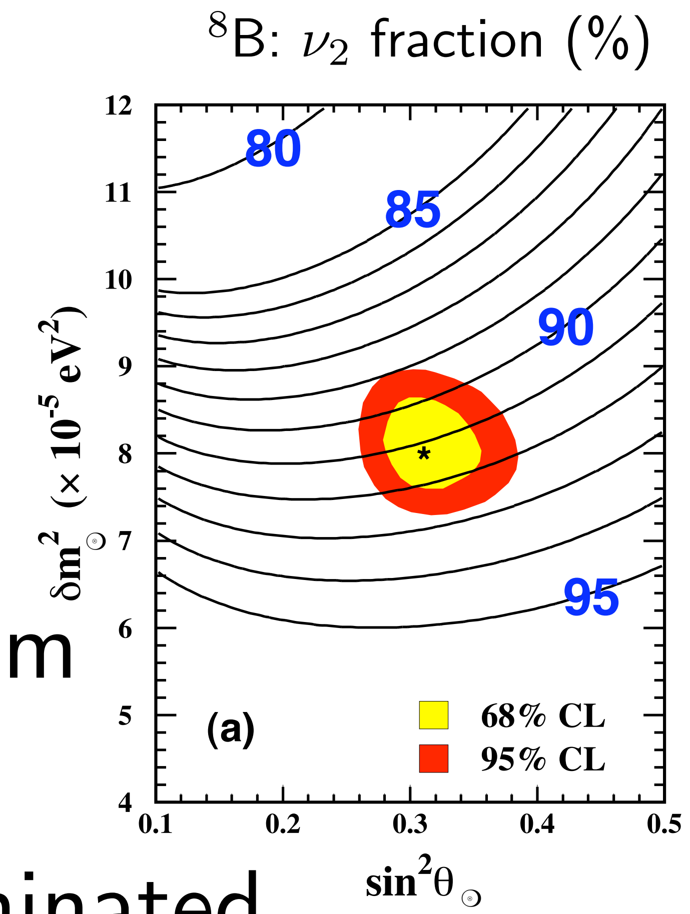
hep-ph/0601198

Mass Eigenstate Purity:

	$\langle f_1 \rangle$ (%)	$\langle f_2 \rangle$ (%)
vac	69 ± 3	31 ∓ 3
pp	67 ± 4	33 ∓ 4
^{7}Be	63 ± 4	37 ∓ 4
^{8}B	9 ∓ 2	91 ± 2

quasi-vacuum

matter dominated



$f_1 = \cos^2\theta_\odot^N$ and $f_2 = \sin^2\theta_\odot^N$

$\langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$

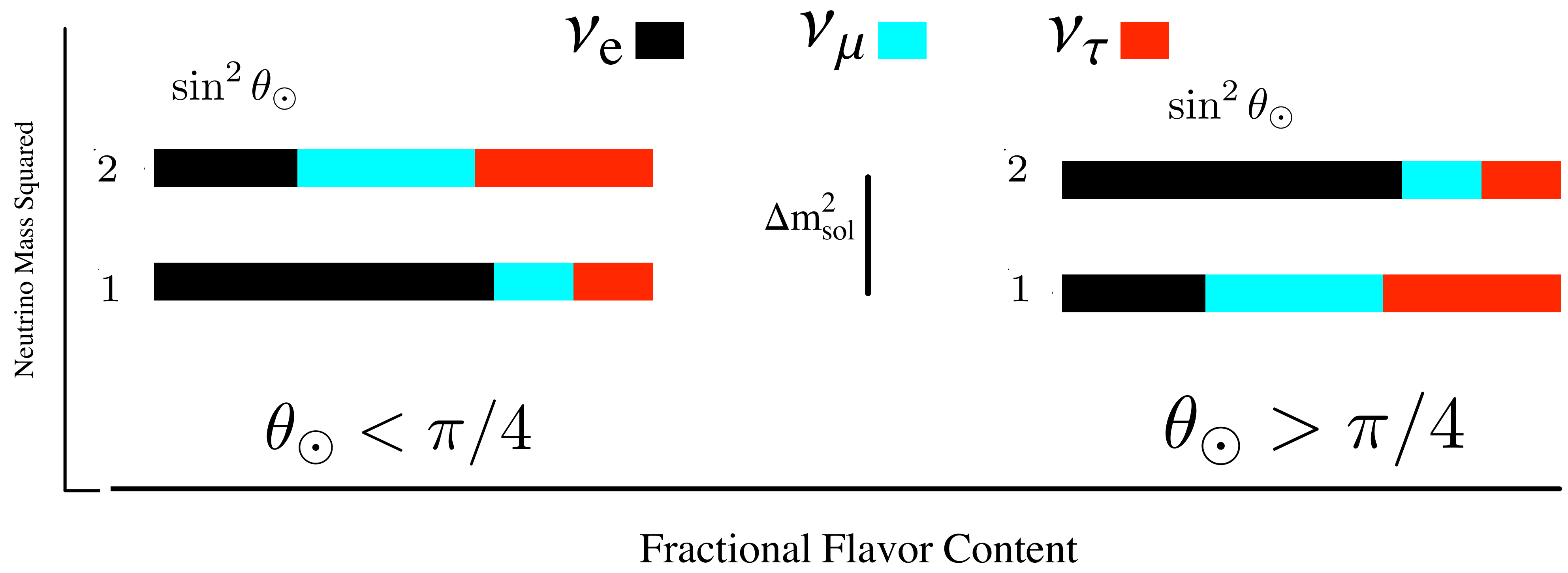
vac pp ^{7}Be ^{8}B

$N_e E_\nu$

$\langle P_{ee} \rangle = \cos^4\theta_\odot + \sin^4\theta_\odot$

$\Rightarrow \sin^2\theta_\odot$

Solar Pair Mass Hierarchy:



KamLAND doesn't care since $\sin^2 2\theta_\odot$ same for $\theta_\odot$ and $\frac{\pi}{2} - \theta_\odot$

but SNO does !!!

for neutrino in matter
$\theta_\odot^N > \theta_\odot$

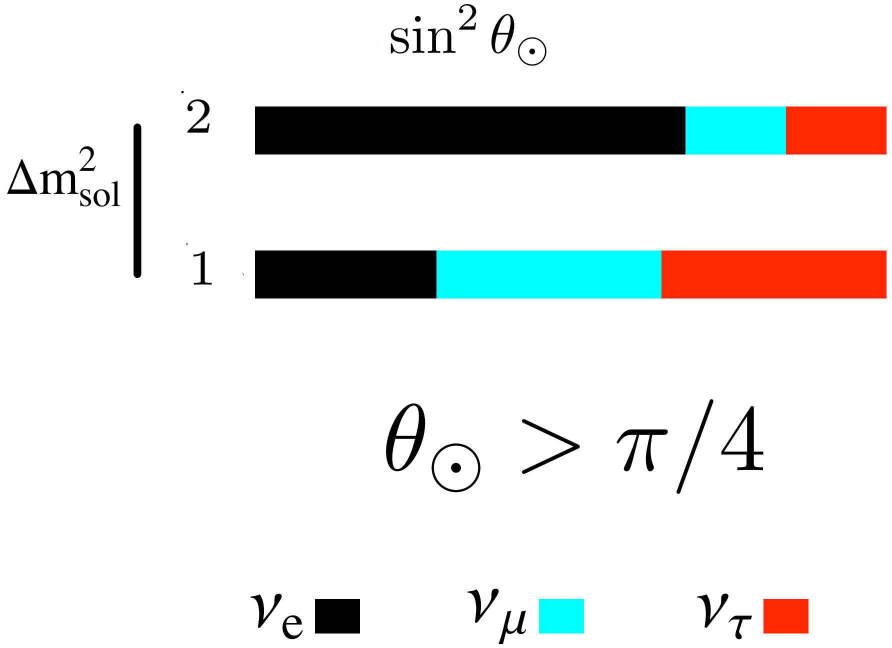
$$\langle P_{ee}\rangle = \cos^2\theta_\odot^N \cos^2\theta_\odot + \sin^2\theta_\odot^N \sin^2\theta_\odot = \frac{1}{2} + \frac{1}{2}\cos 2\theta_\odot^N \cos 2\theta_\odot$$

if $\theta_\odot < \pi/4$
$\langle P_{ee}\rangle \geq \sin^2\theta_\odot$

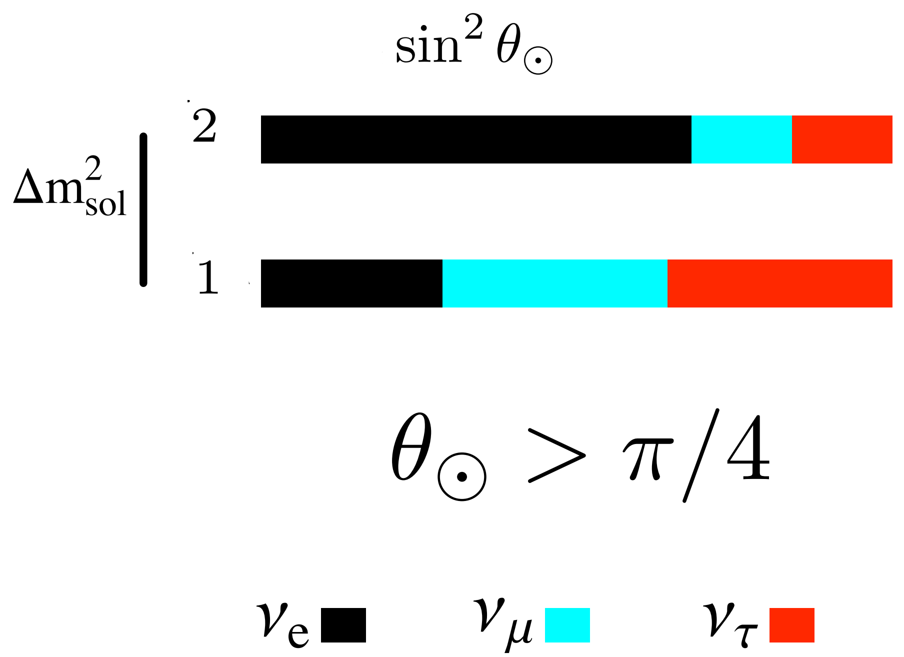
if $\theta_\odot > \pi/4$
$\langle P_{ee}\rangle \geq \frac{1}{2}(1 + \cos^2 2\theta_\odot) \geq \frac{1}{2}$

SNO: $\langle P_{ee}\rangle_{day} = 0.347 \pm 0.038$

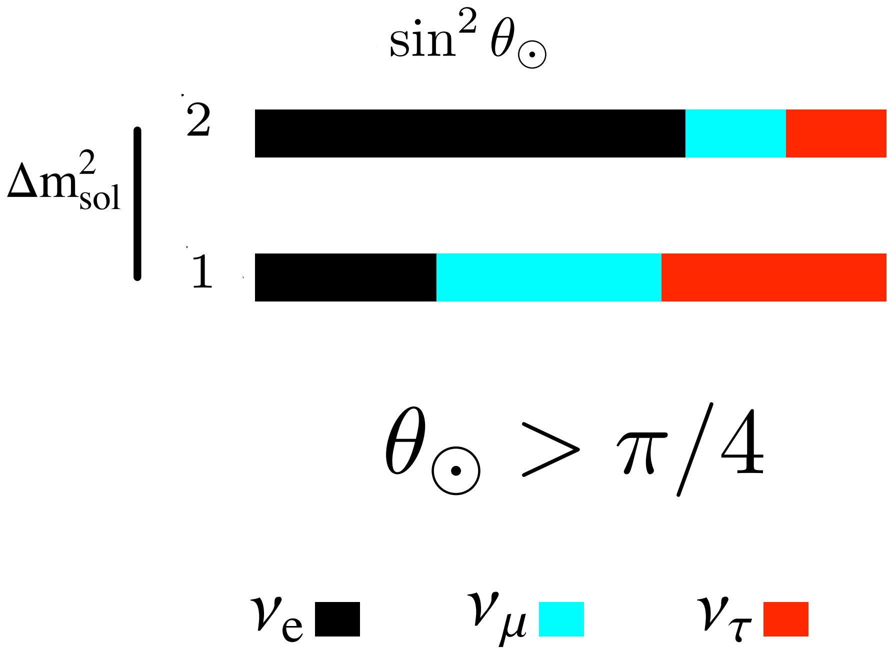
Solar Hierarchy Determined !!!



$\sin^2\theta_\odot$
2
Δm^2_{sol}
1
$\theta_\odot > \pi/4$
ν_e
ν_μ
ν_τ



Solar matter effects put more of the neutrino into ν_2.
This raises the survival probability above vacuum value since ν_2 has more ν_e.
But the minimum of P_{ee} in vacuum is $1/2$.



$$\theta_\odot > \pi/4$$

Solar matter effects put more of the neutrino into ν_2.
This raises the survival probability above vacuum value since ν_2 has more ν_e.
But the minimum of P_{ee} in vacuum is 1/2.

For this hierarchy $P_{ee}^{matter} \geq P_{ee}^{vac} \geq 1/2$

But $P_{ee}^{SNO} = 0.347 \pm 0.038 < 1/2$

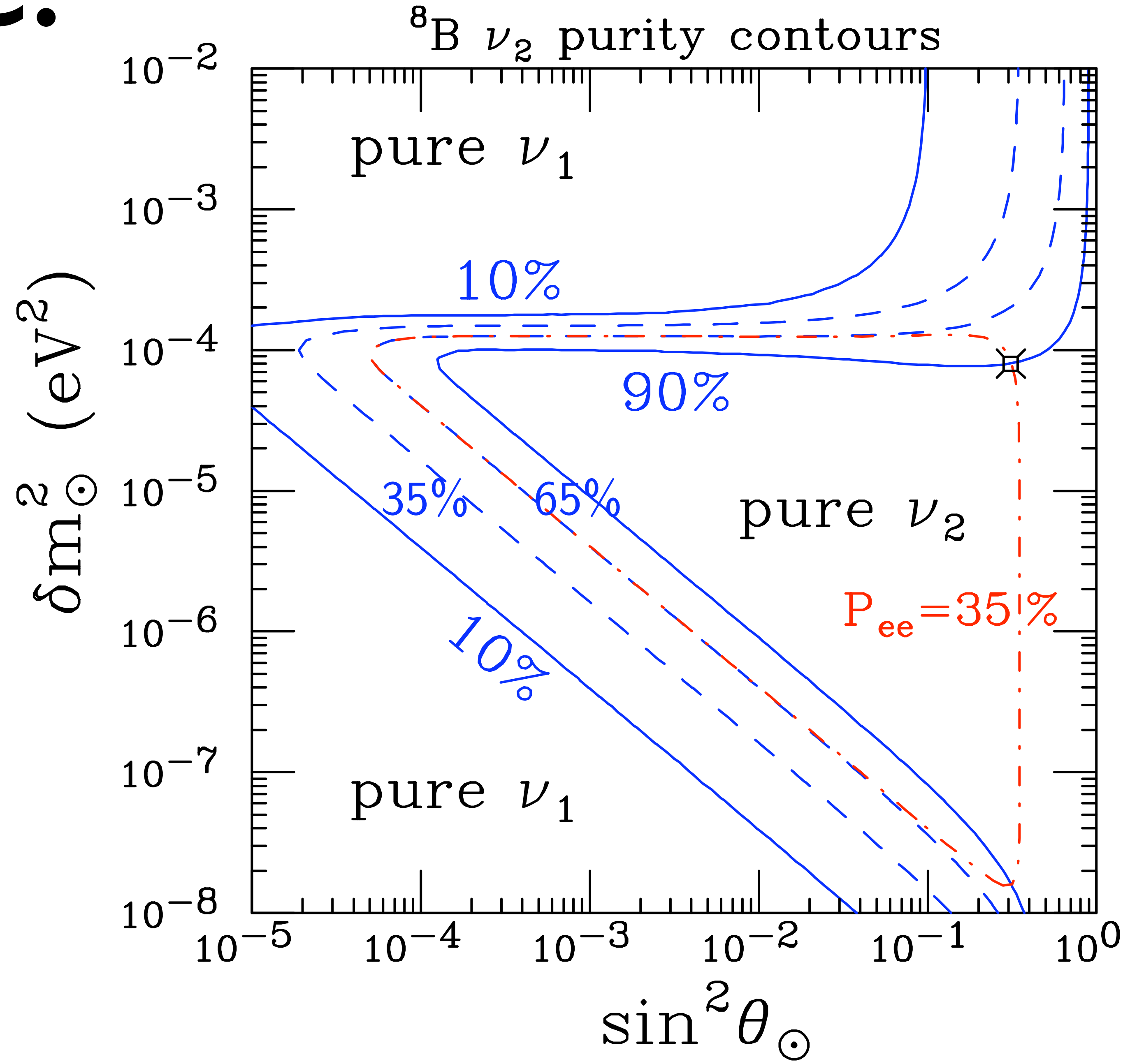
This solar hierarchy EXCLUDED !!!.

The Big Picture:

$$P_{ee} = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

$$f_1 = (1 - P_x)\cos^2\theta_\odot^N + P_x \sin^2\theta_\odot^N$$

$$f_2 = (1 - P_x)\sin^2\theta_\odot^N + P_x \cos^2\theta_\odot^N$$



P_x is the probability to jump from ν_2 to ν_1 (or ν_1 to ν_2) during MS-resonance crossing.

$$P_{ee} = \frac{1}{2} + \left(\frac{1}{2} - P_x\right)\cos 2\theta_\odot^N \cos 2\theta_\odot$$

Jump Probability:

$$P_x \approx \exp\left(-\pi \frac{Width\ of\ Resonance}{Oscillation\ Length}\right)$$

SP PRL, 57, 1275 and 2322 (1986)

Day/Night Asymmetry:

$\sin^2\theta_\odot \rightarrow \sin^2\theta_\oplus = \sin^2\theta_\odot + \frac{1}{2}\sin^2 2\theta_\odot \left(\frac{A_\oplus}{\delta m^2_\odot}\right)$ in the earth.

A=2(D-N)/(D+N) expected to be few %

SK:

$$A_{ES} = -1.8 \pm 1.6(\mathrm{stat})^{+1.3}_{-1.2}(\mathrm{syst})\%$$

Spectral Distortion:

A characteristic of matter effects is that the Fraction of ν_2 is energy dependent .

Smaller at smaller E.

Implies an increase in P_{ee} near threshold.

Maybe in SK with 4.5MeV threshold!!!

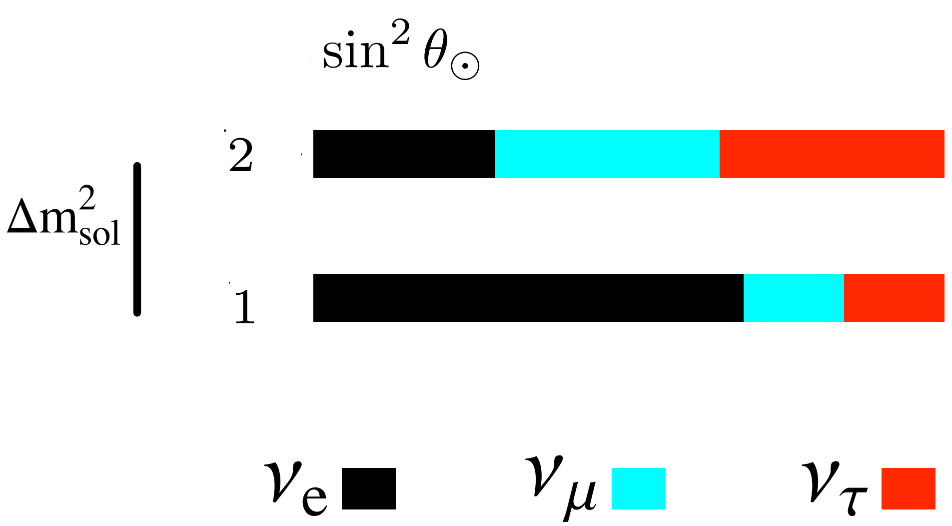
Summary:

The low energy pp and ^{7}Be Solar Neutrinos exit the sun as two thirds ν_1 and one third ν_2 due to (quasi-) vacuum oscillations.

$f_1 = 65 \pm 2\%,\ f_2 = 35 \mp 2\%$ with $P_{ee} \approx 0.56$

The high energy ^{8}B Solar Neutrinos exit the sun as "PURE" ν_2 mass eigenstates due to matter effects.

$f_2 = 91 \pm 2\%$ and $f_1 = 9 \mp 2\%$ with $P_{ee} \approx 0.35$.



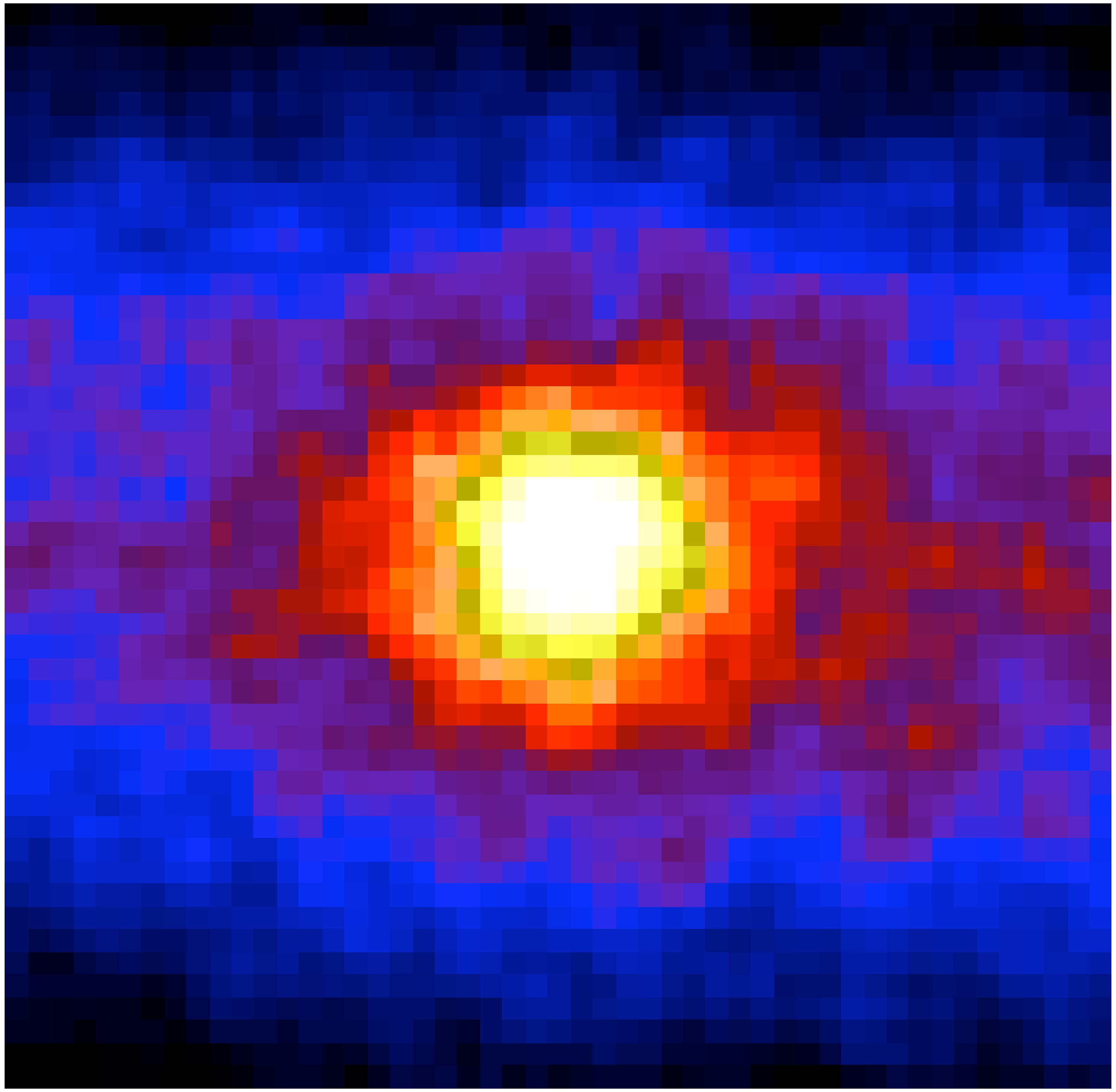
$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5} eV^2$$

$$\sin^2\theta_\odot = 0.310 \pm 0.026$$

at 68% CL

SNO, KamLAND, SK/K, GNO/Gallex, SAGE, Cl

SuperK

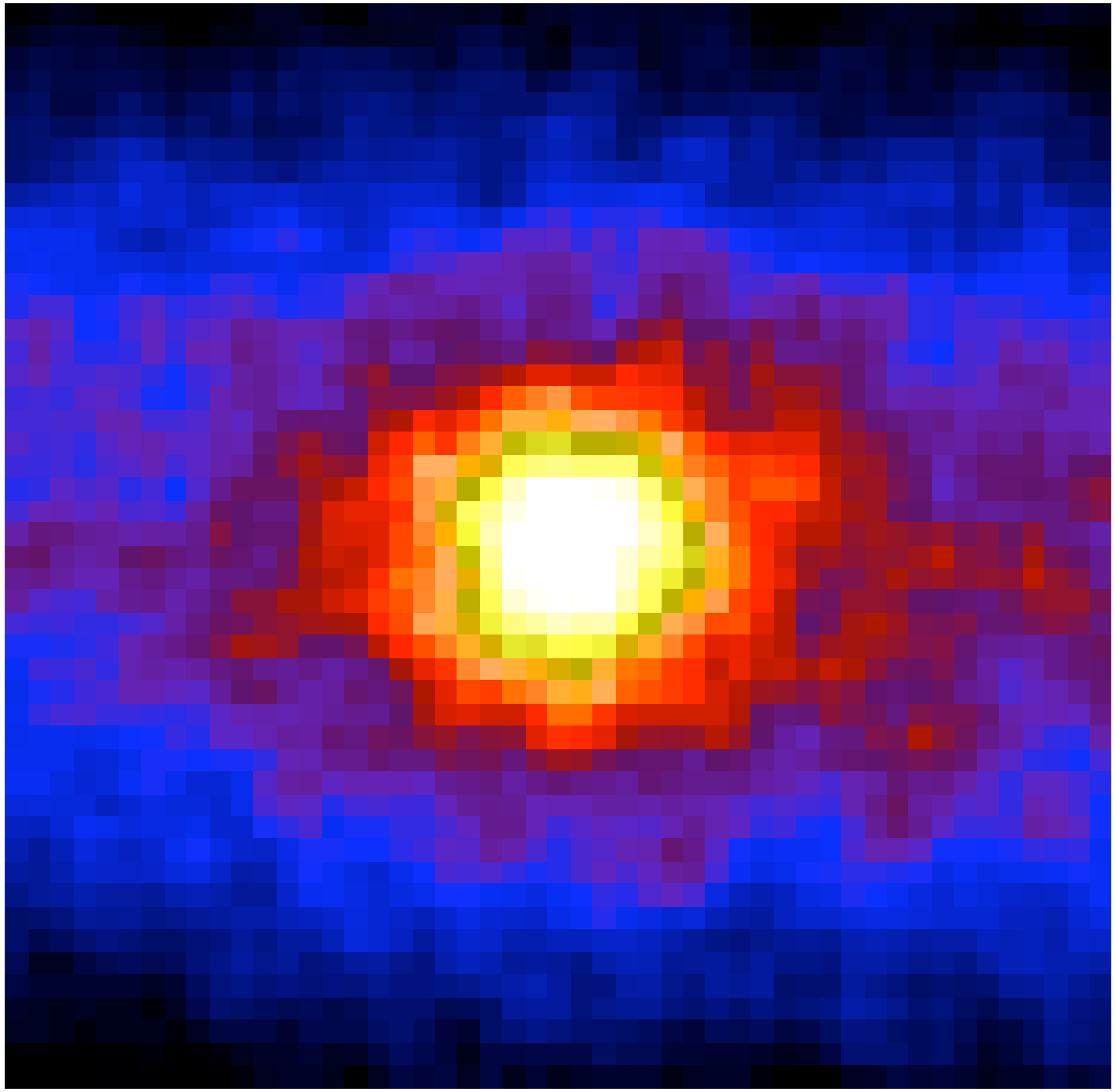


$$\nu_? + e \longrightarrow \nu + e$$

Which Neutrinos ?

SuperK

Flavor
Fraction
76% ν_e's



$$\nu_? + e \longrightarrow \nu + e$$

Which Neutrinos ?

SuperK

Flavor
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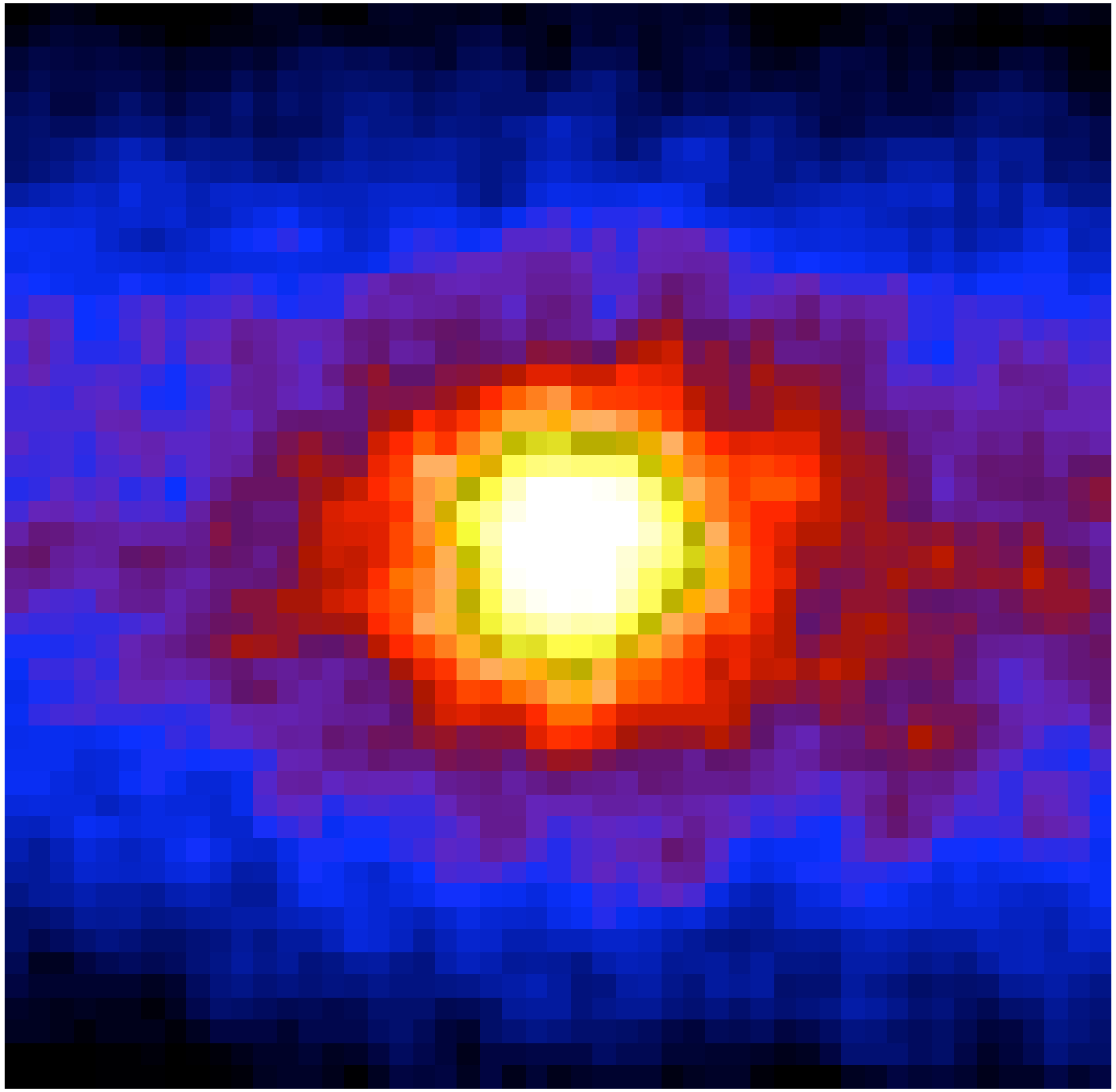

Mass E-state
Fraction
84% ν_2's

$$\nu_? + e \longrightarrow \nu + e$$

Which Neutrinos ?