"All the News
That's Fit to Print"

The New York

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Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the

Detecting Neutrinos

Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

. . . and collide with other particles . . .

. . . producing a cone-shaped flash of light.

The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on

OKLAHOMA BLAST BRINGS LIFE TERM FOR TERRY NICHOLS

'ENEMY OF CONSTITUTION'

Judge Denounces Conspiracy and Hears From the Victims of a Terrifying Ordeal

By JO THOMAS

DENVER, June 4 — Calling him "an enemy of the Constitution," a Federal judge today sentenced Terry L. Nichols to life in prison without the possibility of parole for conspiring to bomb the Oklahoma City Federal Building, the deadliest terrorist attack ever on American soil.

In passing sentence after hearing from survivors of the blast and relatives of some of the 168 people who died in it, the judge, Richard P. Matsch of Federal District Court, said, "This was not a murder case."

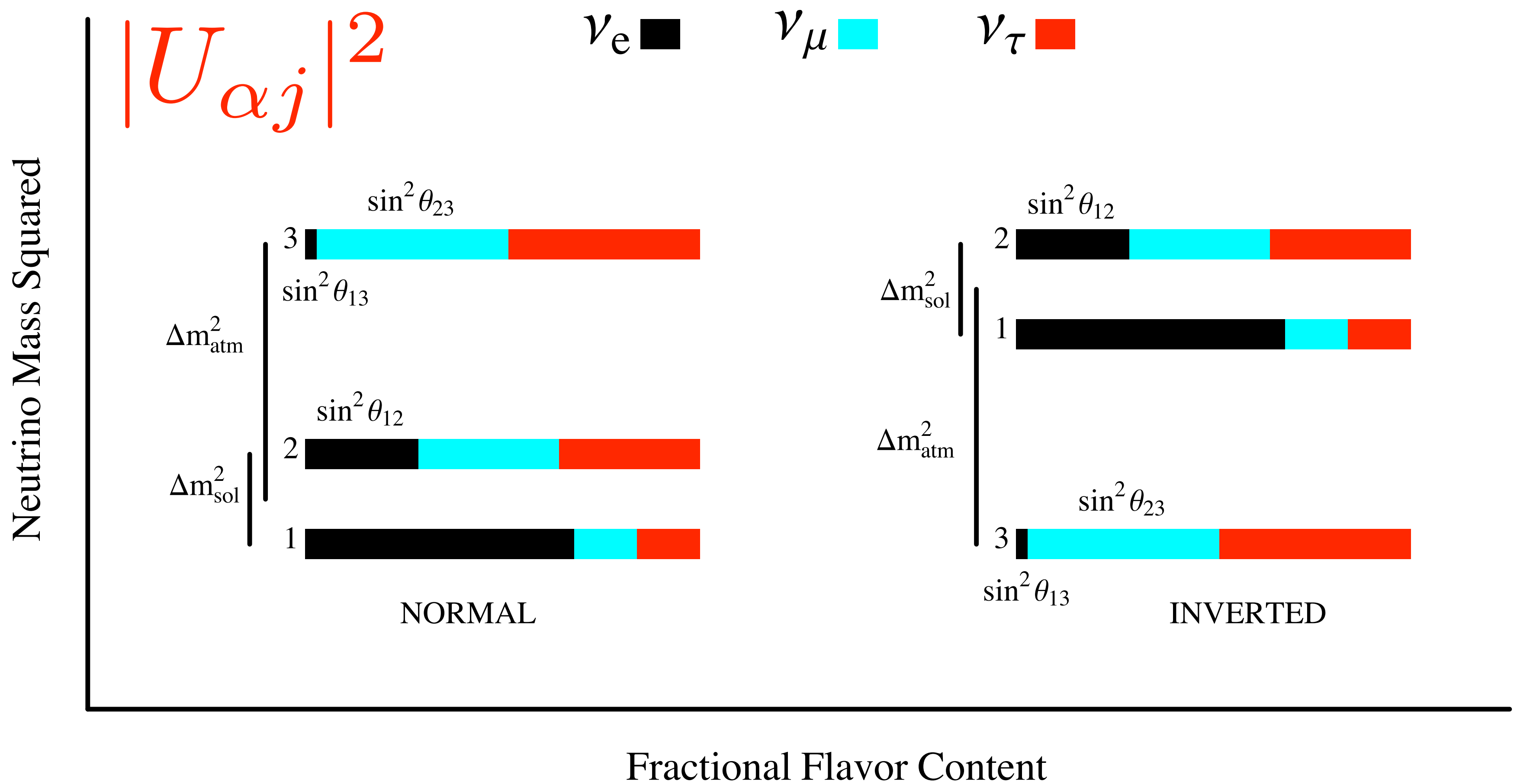
He added: "It is a crime and the victims have spoken eloquently here. But it is not a crime as to them so much as it is a crime against the Constitution of the United States. That's the victim."

Last December, Mr. Nichols was convicted of conspiring with Timothy

Bajram Curri, in nc
Yugoslavia in three

Mixing Parameters I

Stephen Parke, Fermilab
Fermilab Nu Summer School 2009



$$\sin^2\theta_{12} \sim 1/3 \qquad \delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2 \quad \text{(15 km/MeV)}$$

$$\sin^2\theta_{23} \sim 1/2 \qquad |\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2 \quad \text{(500 km/GeV)}$$

$$\sin^2\theta_{13} < 3\% \qquad |\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

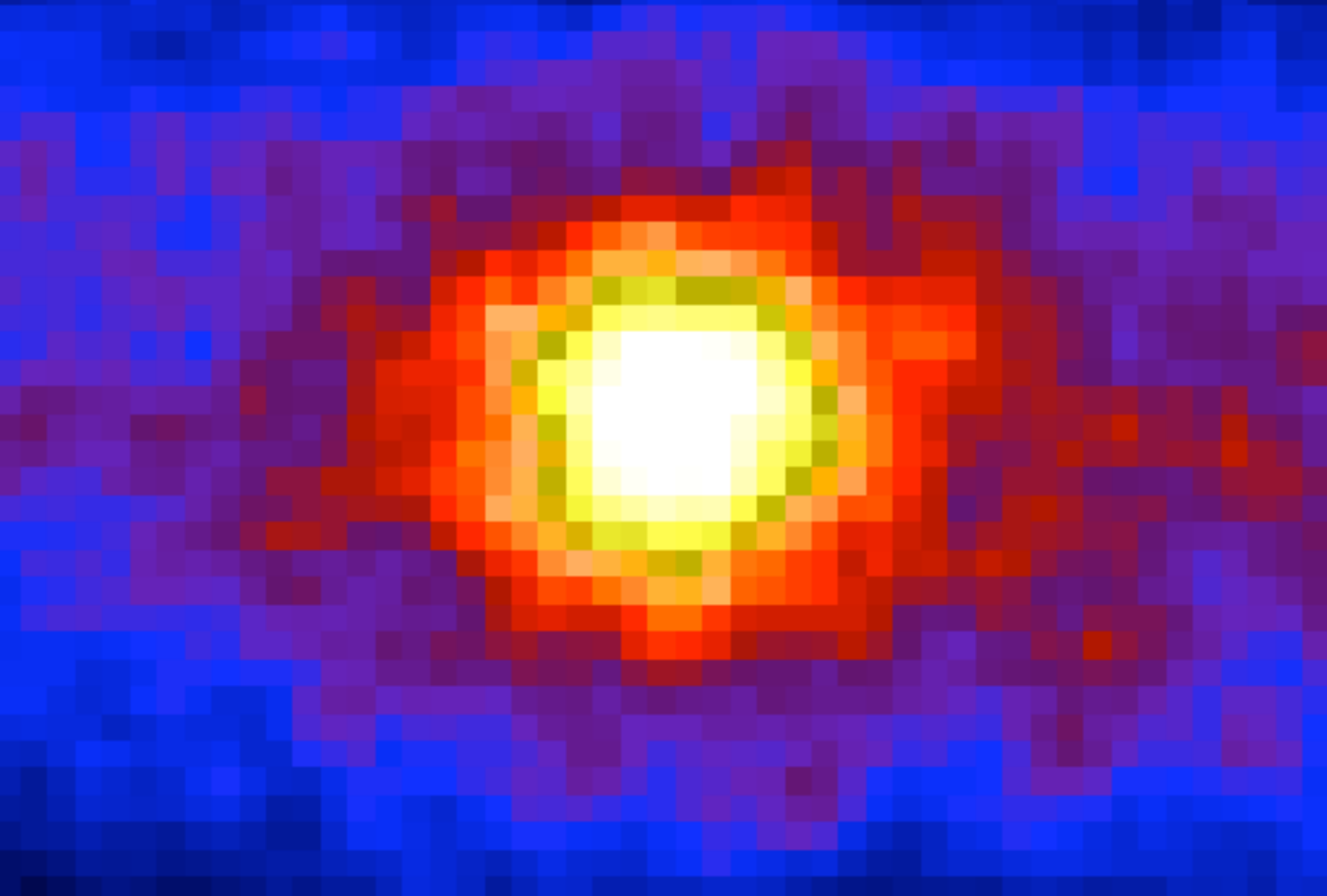
One Global Fit:

Dominated by

parameter	best fit	2σ	3σ	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34	KamLAND
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75	MINOS
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37	SNO
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67	SuperK
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056	Chooz

arXiv:0808.2016

Solar Neutrinos:



Solar Engine:

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

$$E = mc^2$$

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:

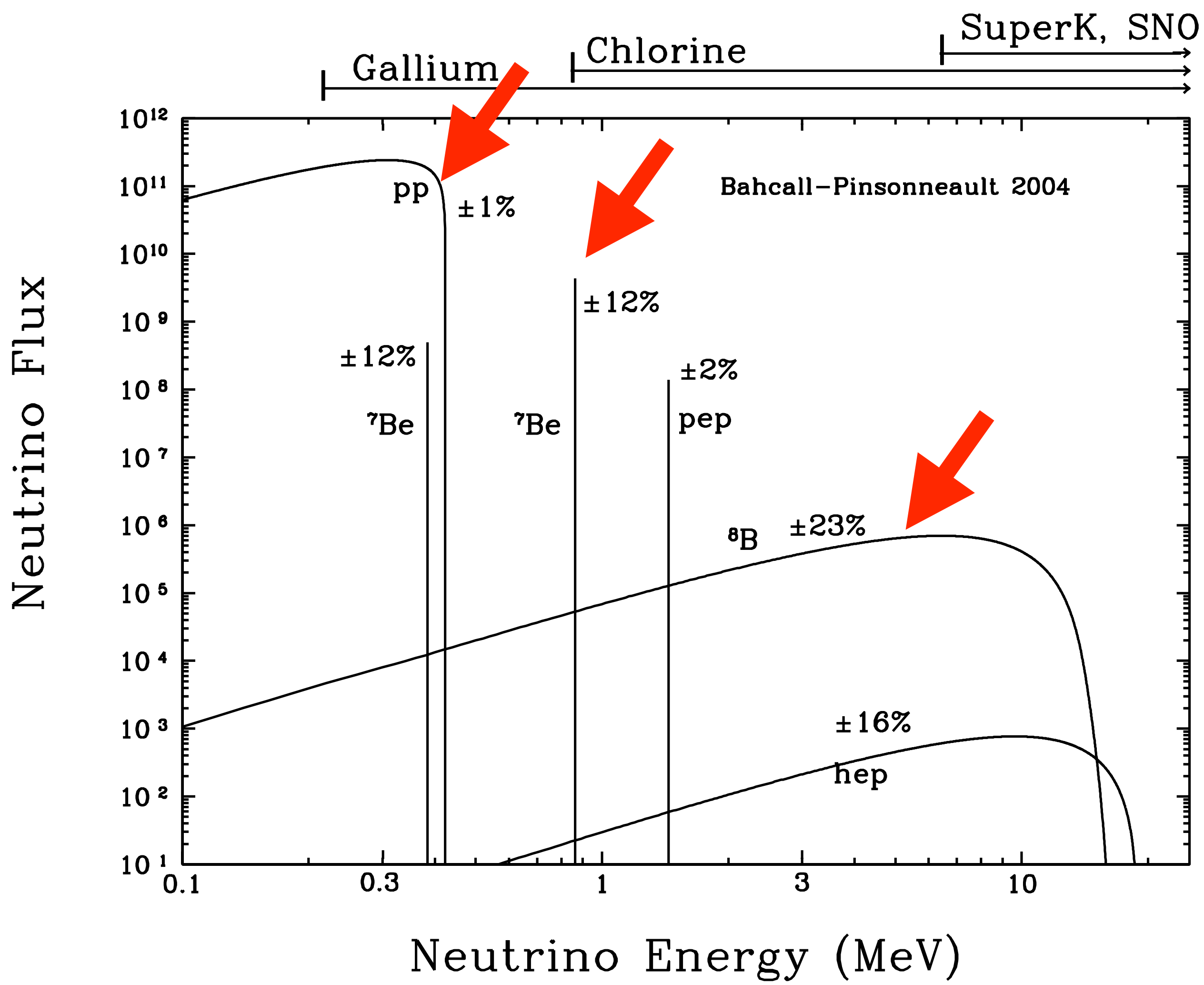


Figure 1. The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [22]. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2}\,s^{-1}\,MeV^{-1}$ at the Earth's surface. For line sources, the 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).

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

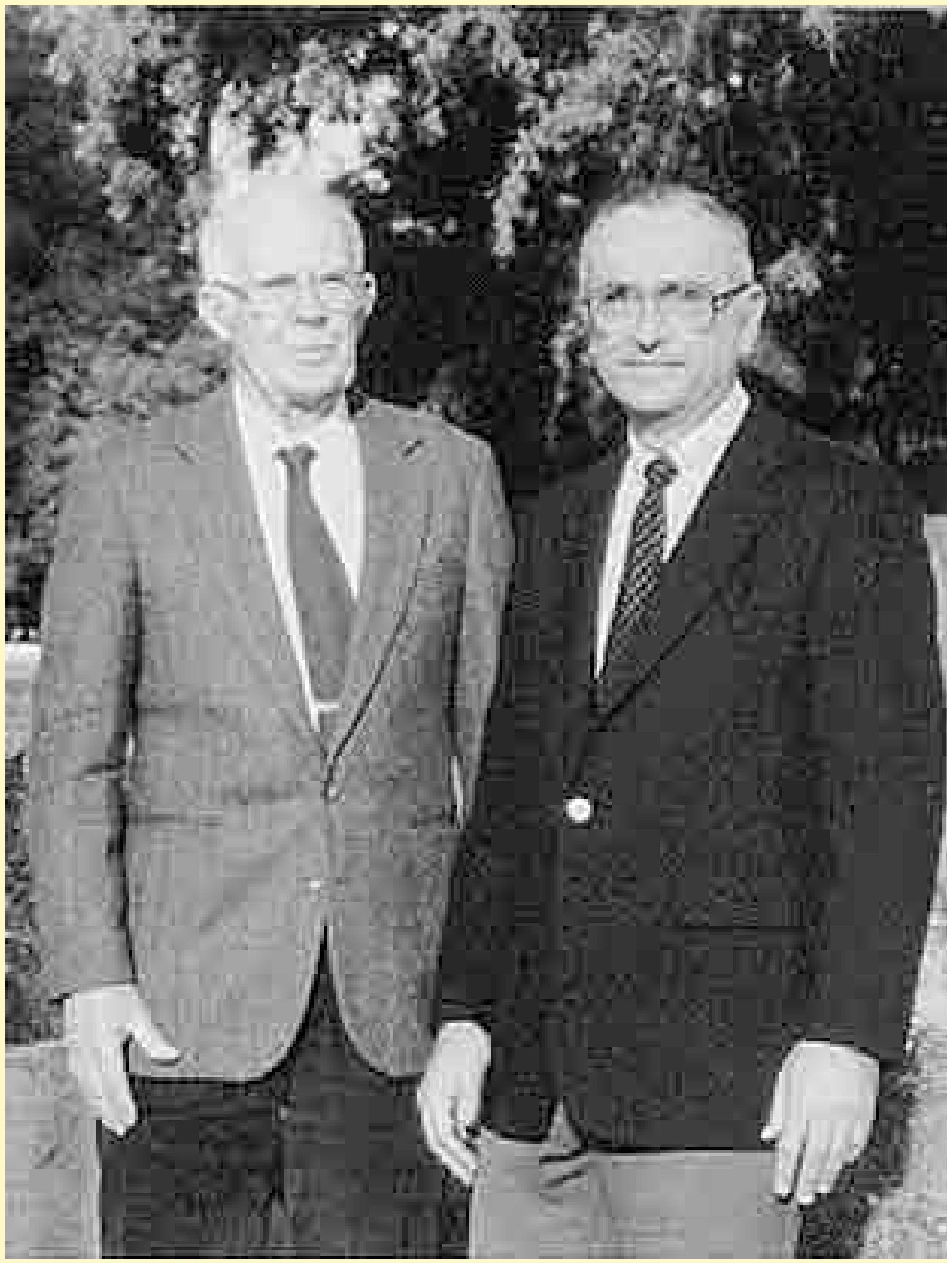
$$\phi_{pp} = 5.94(1 \pm 0.01) \times 10^{10} cm^{-2} sec^{-1}$$

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

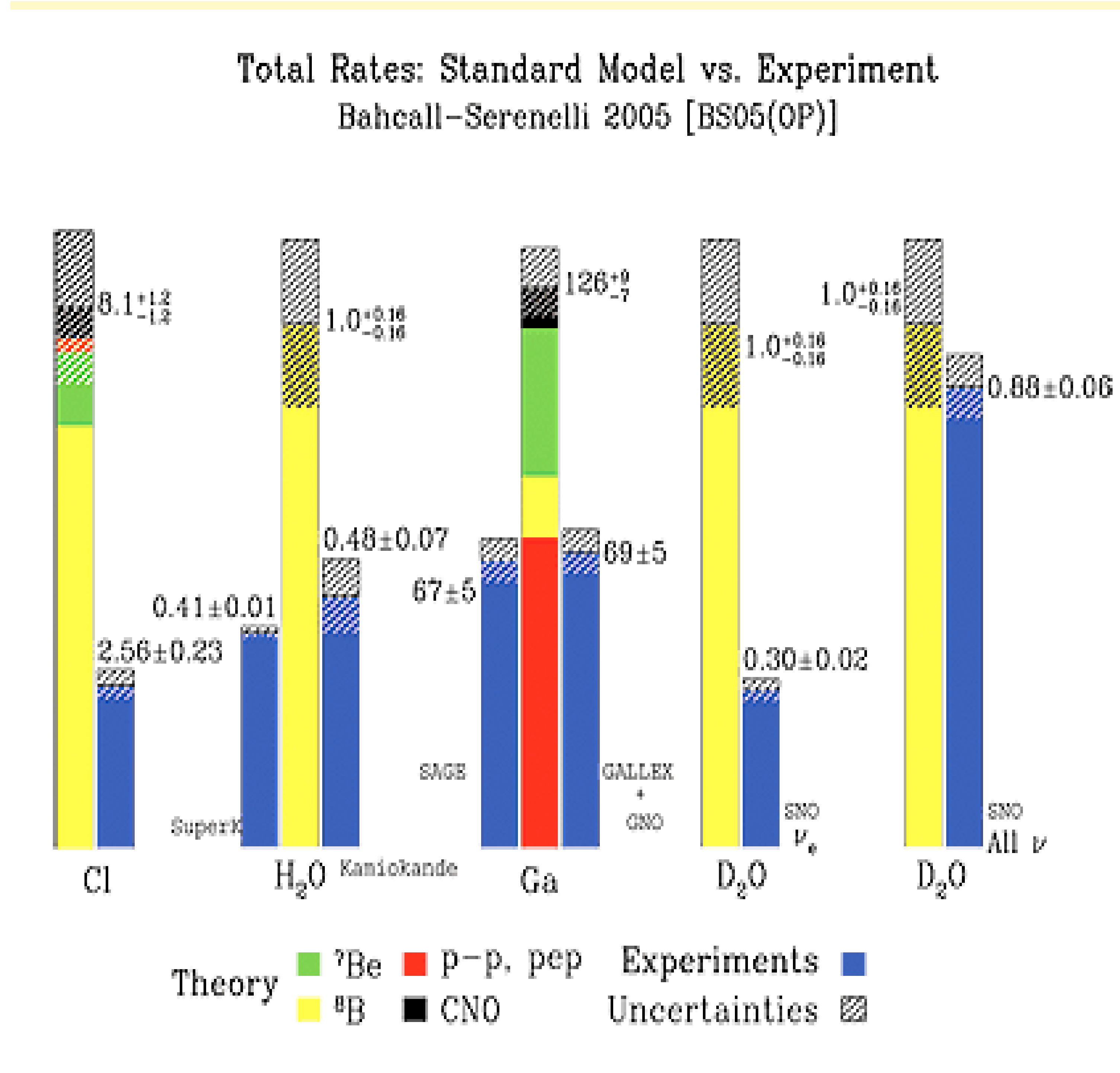
$$\phi_{^7Be} = 4.86(1 \pm 0.12) \times 10^{9} cm^{-2} sec^{-1}$$

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

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



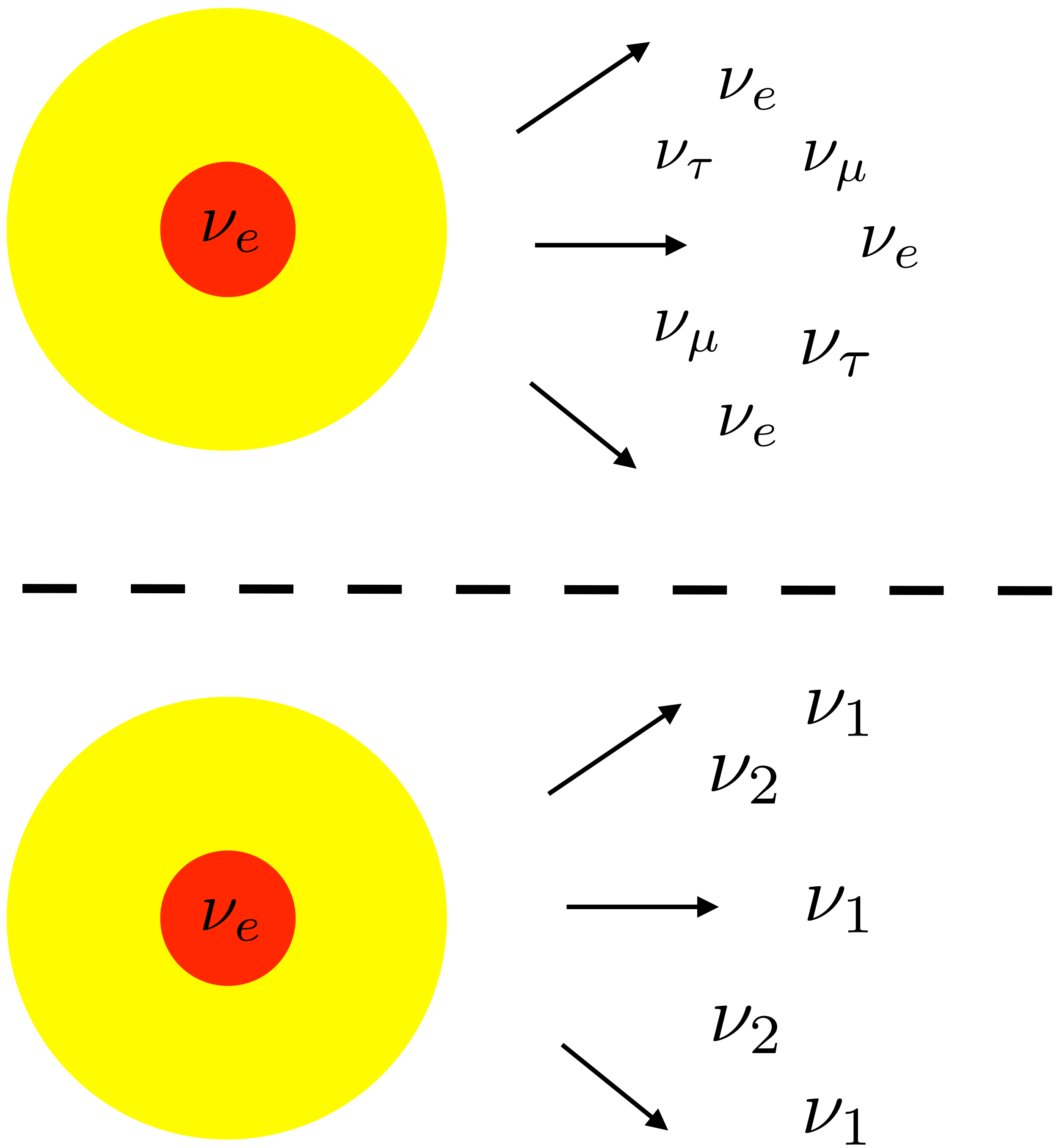
Ray Davis & John Bahcall



Theory v Exp.

Neutrino Flavor Transistions!!!

Identical Solar Twins:



flavor eigenstates

?????

mass eigenstates

Kinematical Phase:

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

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

$$\Delta_\odot = \frac{\delta m^2_\odot L}{4E} = 1.27 \quad \frac{8\times10^{-5}\ eV^2 \cdot 1.5\times10^{11}\ m}{0.1-10\ MeV}$$

$$\Delta_\odot \approx 10^{7\pm1}$$

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 $f_2 = \sin^2\theta_\odot$.

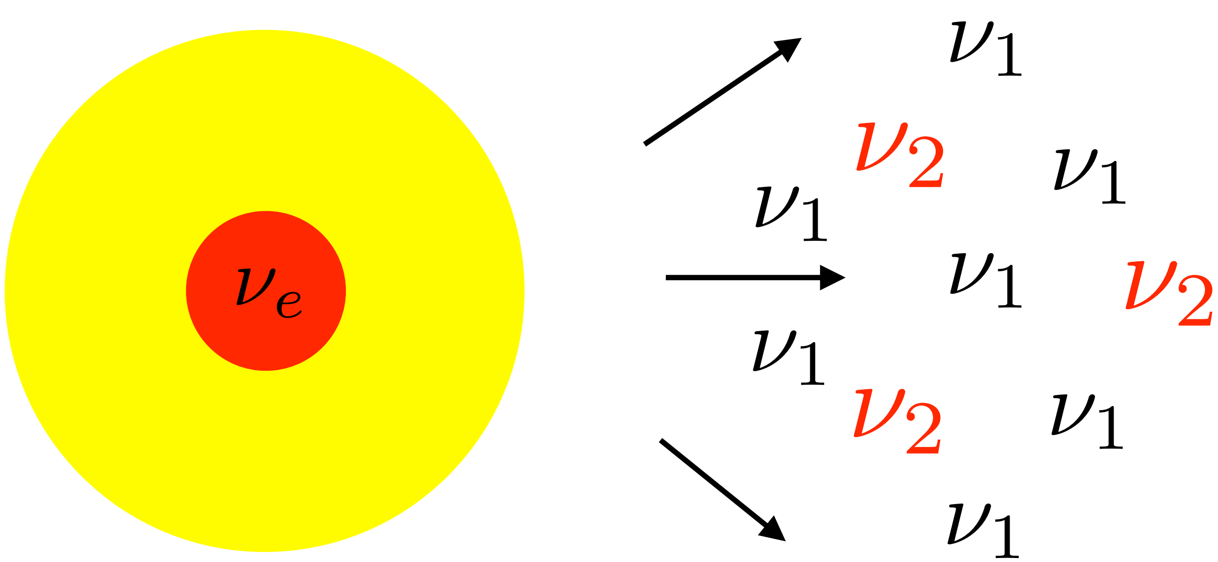
Note energy independence.

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

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



$f_1 \sim 69\%$

$f_2 \sim 31\%$

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

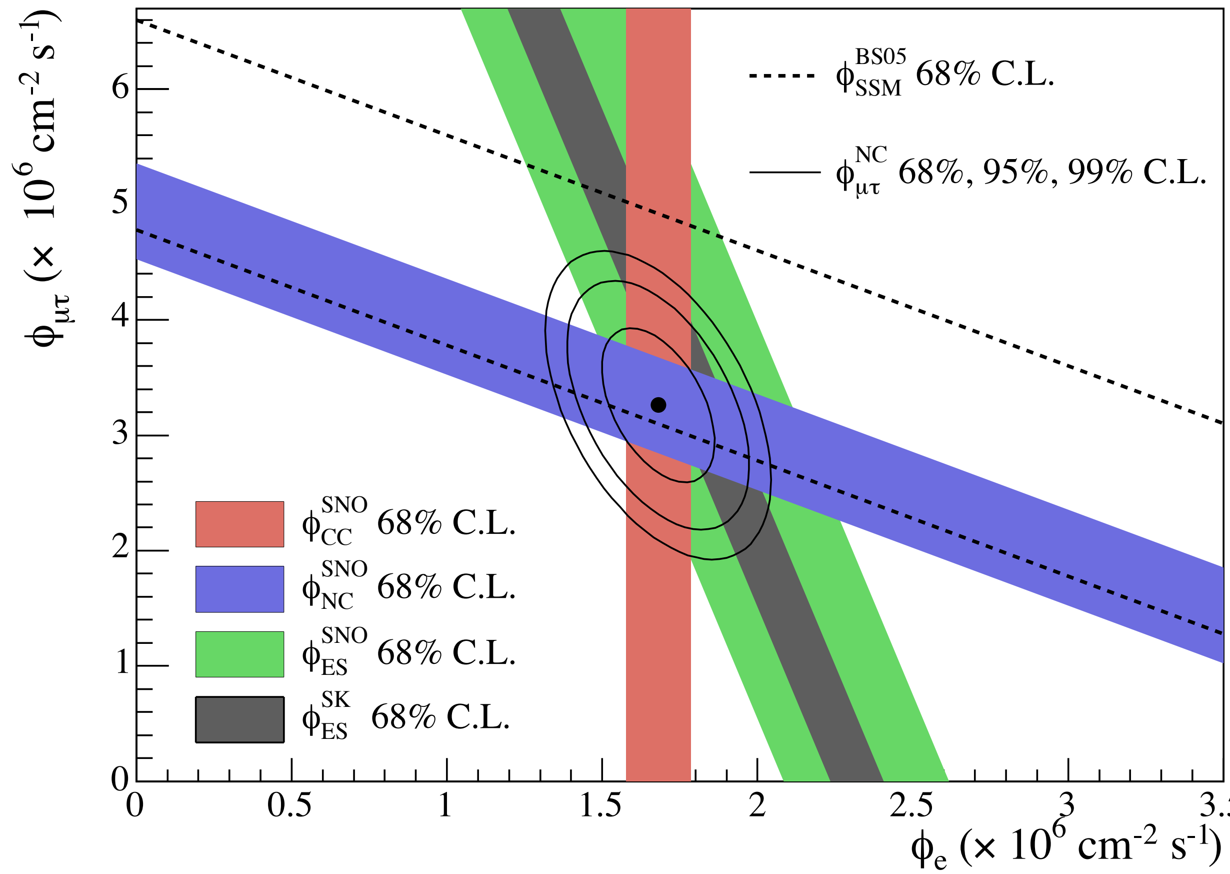
$f_3 = \sin^2\theta_{13} < 4\%$

What about ^{8}B ?

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

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

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



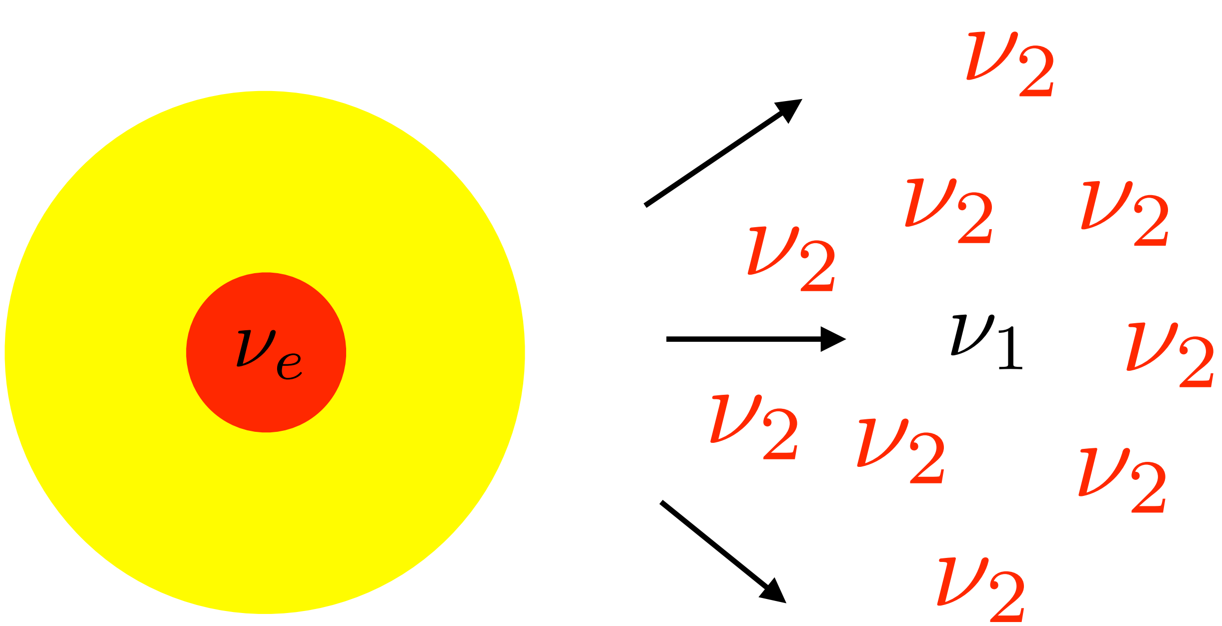
SNO's CC/NC

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

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

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

^{8}B



$$f_2 \sim 90\%$$

$$f_1 \sim 10\%$$

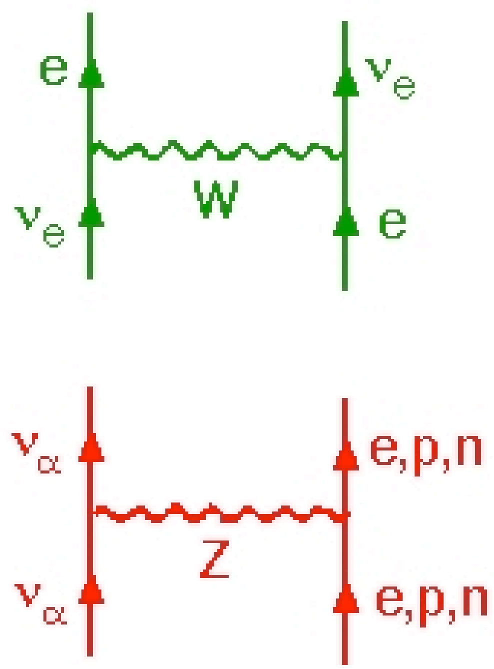
$$\langle P_{ee} \rangle = \sin^2\theta + f_1 \cos 2\theta_\odot \approx \sin^2\theta_\odot = 0.31$$

Wow!!! How did that happen???

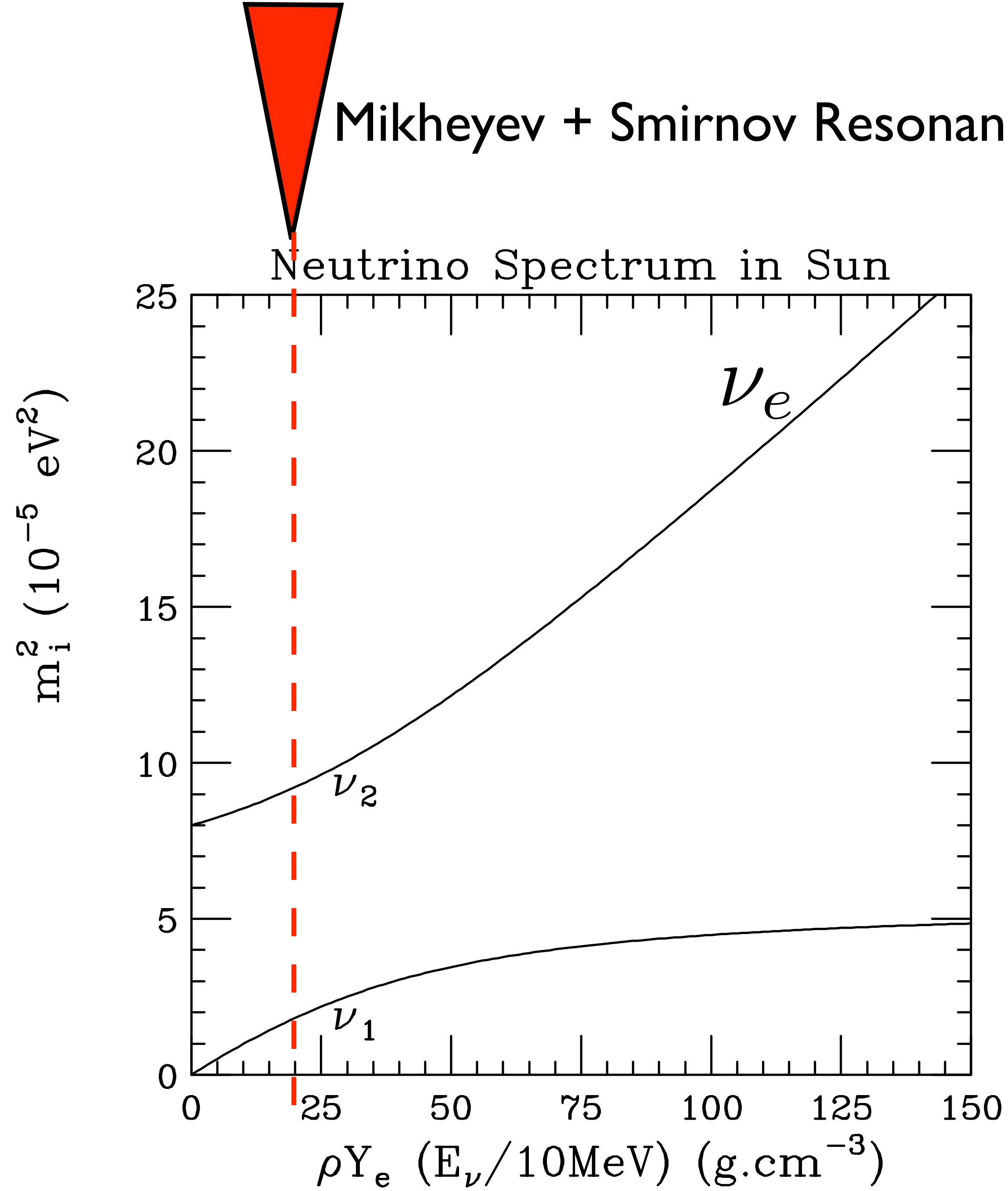
energy dependence!!!

Mikheyev + Smirnov Resonance WIN '85

Coherent Forward Scattering:



Wolfenstein '78



MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS

$$\sim G_F N_e E_\nu$$

MSW

From Frameworks III

$$H_M = \frac{\Delta m^2}{4E} \begin{bmatrix} -(\cos 2\theta - x) & \sin 2\theta \\ \sin 2\theta & \cos 2\theta - x \end{bmatrix}$$

with $\quad x \equiv \dfrac{V_W/2}{\Delta m^2/4E} = \dfrac{2\sqrt{2} G_F N_e E}{\Delta m^2} \quad .$

$$H_M = \frac{\Delta m_M^2}{4E} \begin{bmatrix} -\cos 2\theta_M & \sin 2\theta_M \\ \sin 2\theta_M & \cos 2\theta_M \end{bmatrix}$$

If we define —

$$\Delta m_M^2 \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

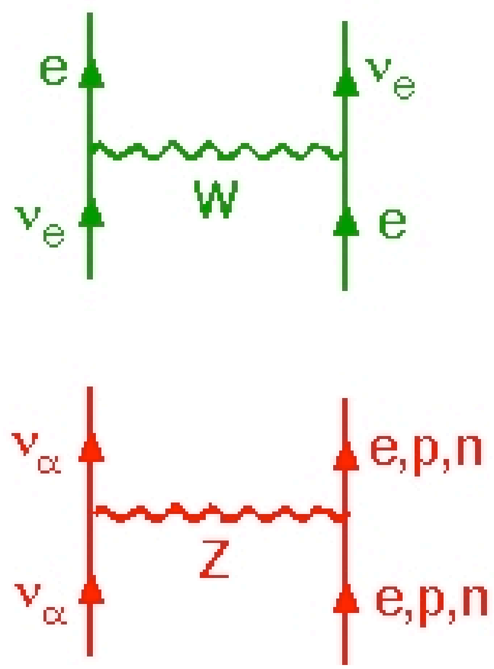
and

$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \quad ,$$

then

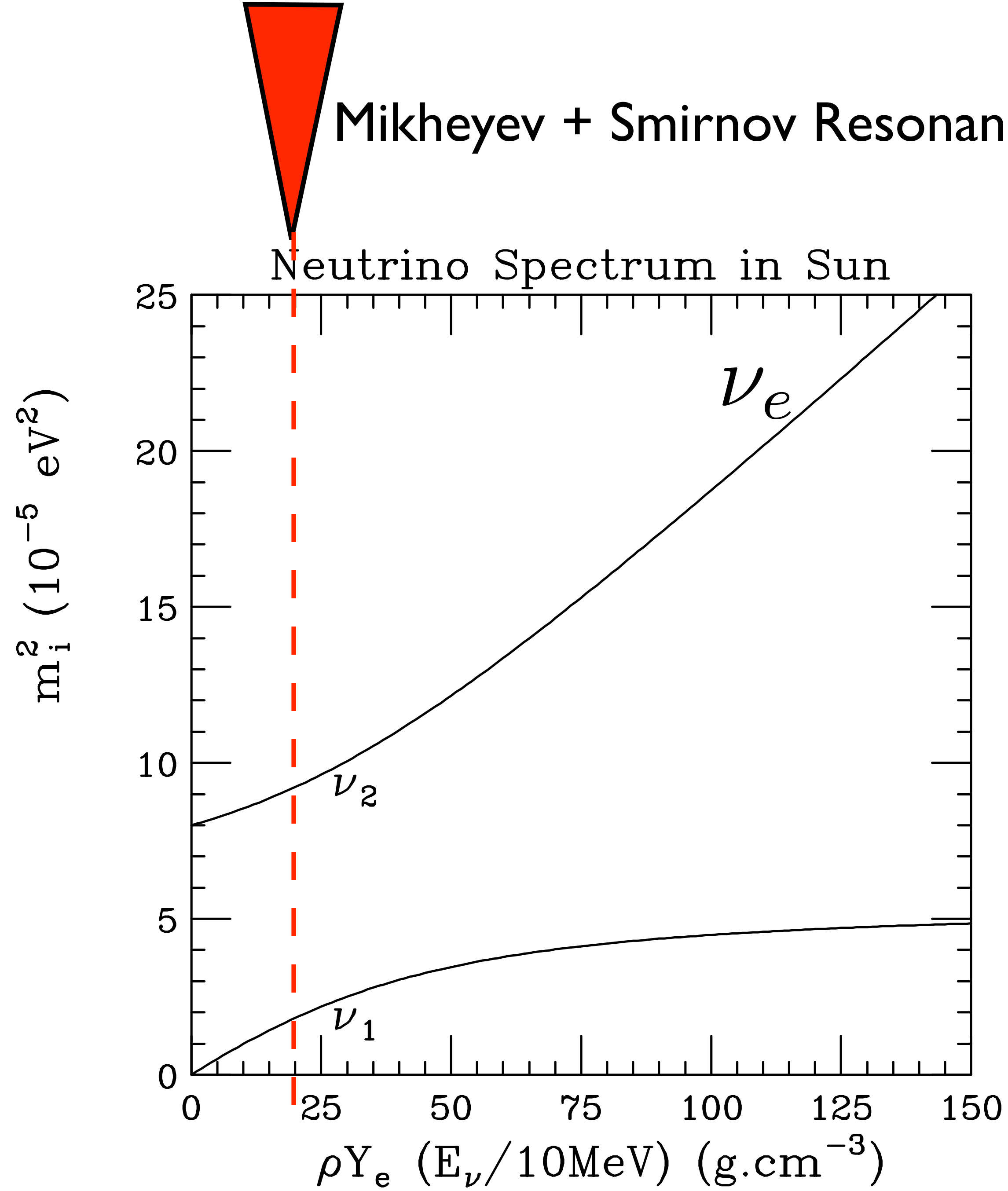
$\{\delta m^2 \sin 2\theta\}$ is invariant

Coherent Forward Scattering:



Wolfenstein '78

Mikheyev + Smirnov Resonance WIN '85

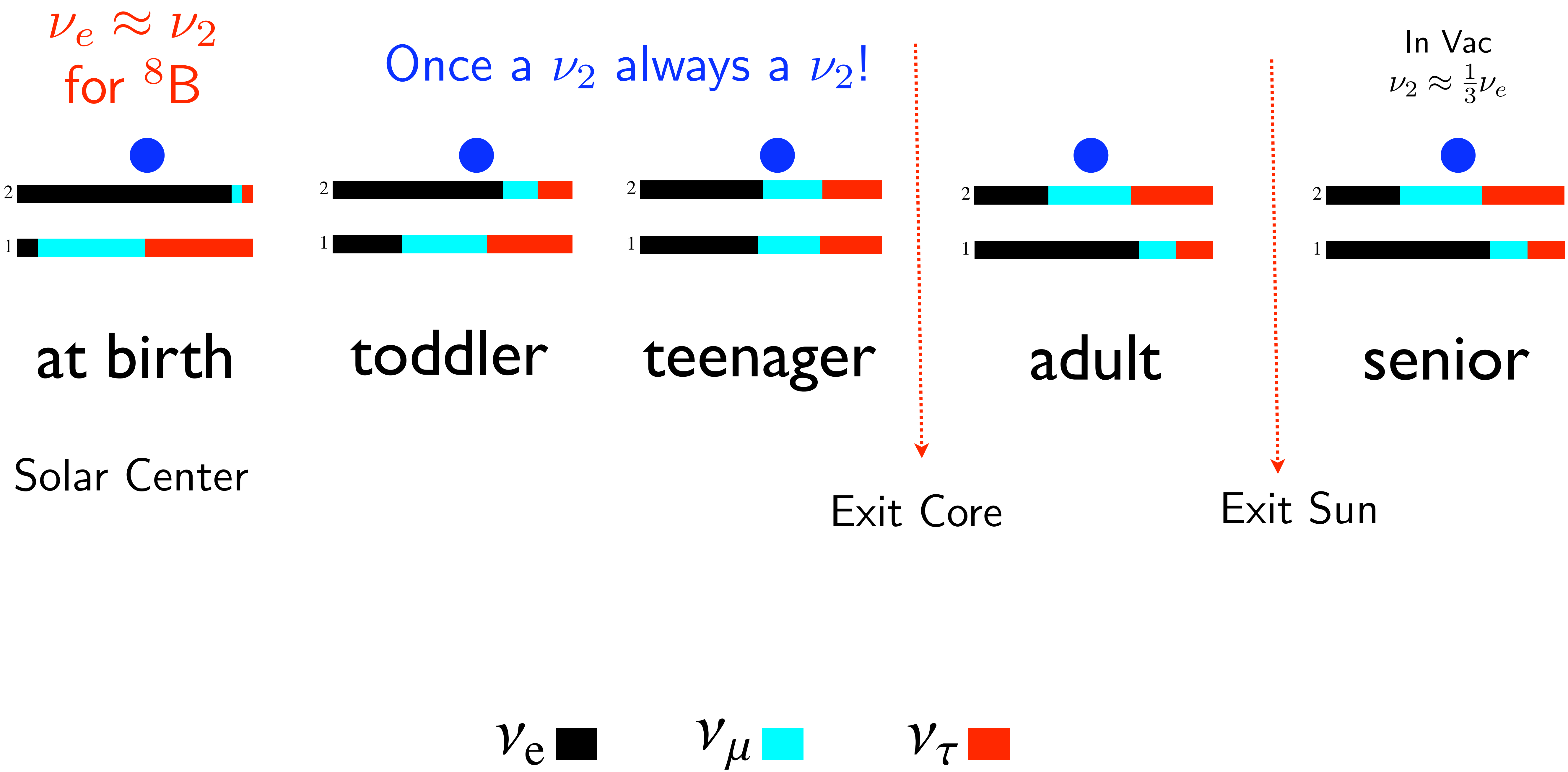


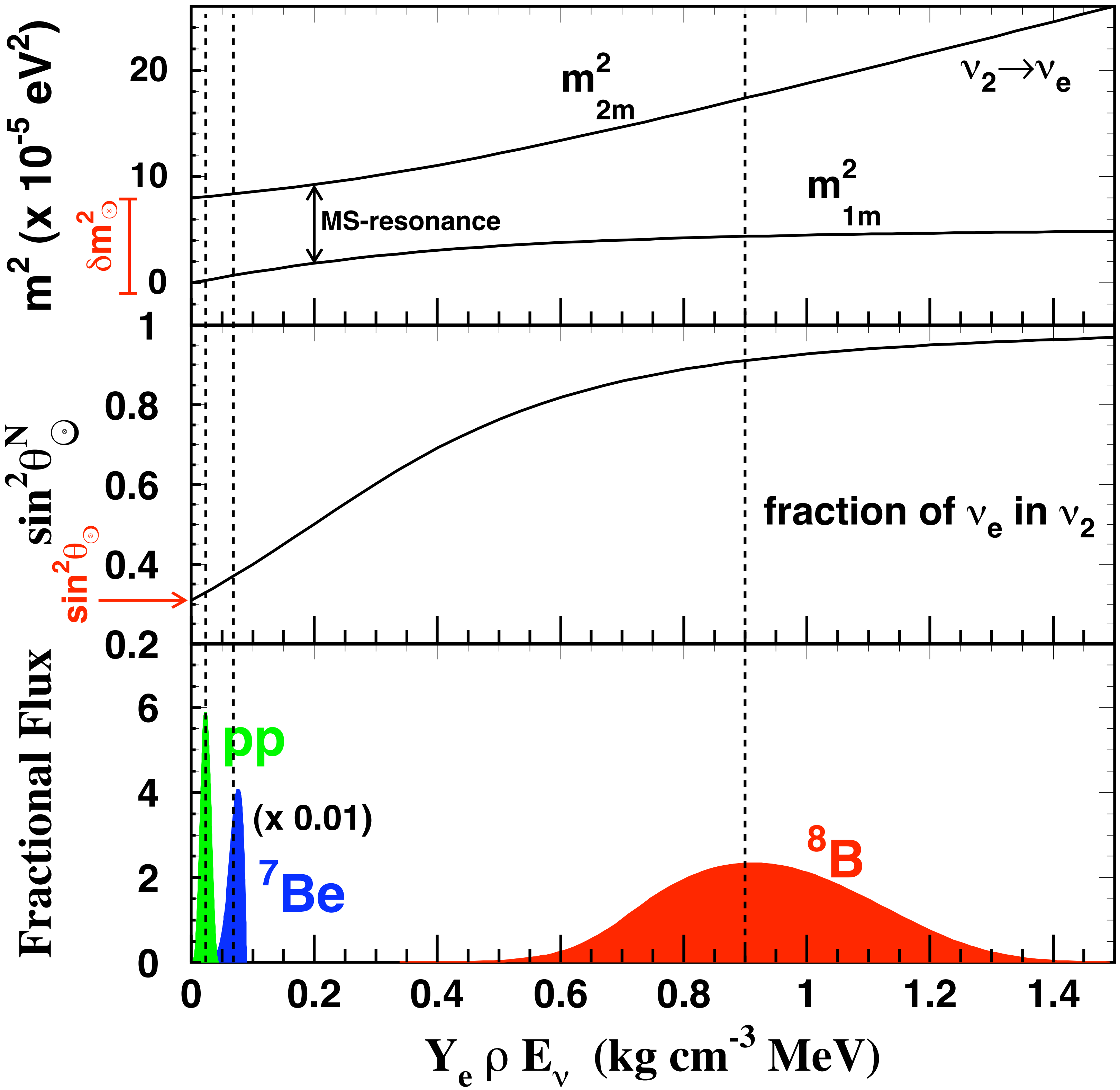
$$\sim G_F N_e E_\nu$$

MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS

MSW

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

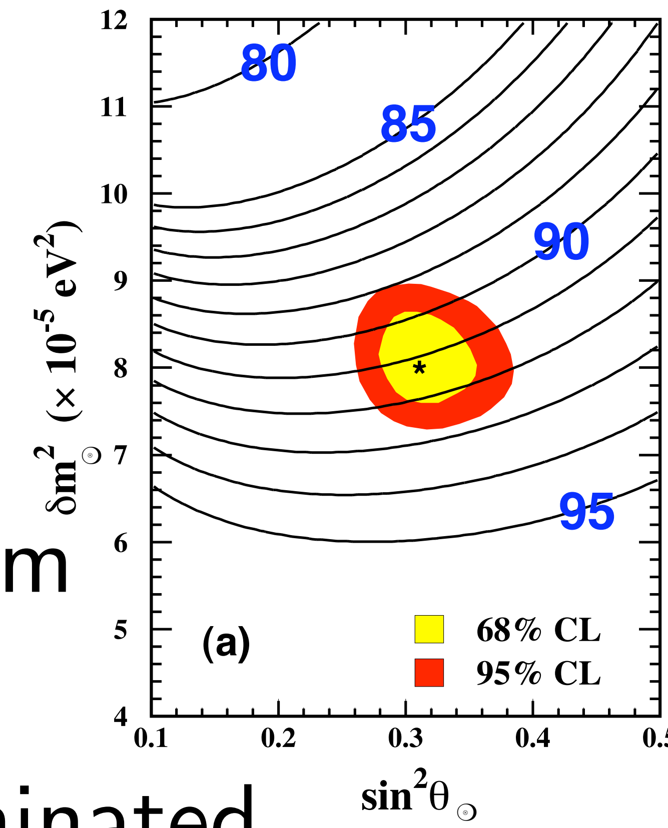
Mass Eigenstate Purity:

	$\langle f_1 \rangle$ (%)	$\langle f_2 \rangle$ (%)
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

^{8}B: ν_2 fraction (%)



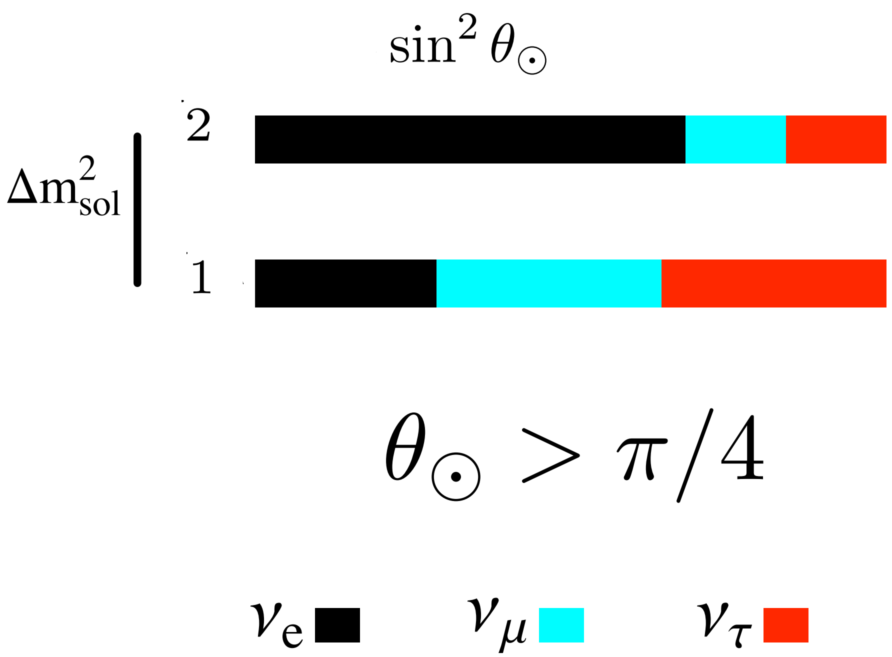
$f_1 = \cos^2\theta_\odot^N$ and $f_2 = \sin^2\theta_\odot^N$

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

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 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 $\boldsymbol{P_{ee}^{matter} \geq P_{ee}^{vac} \geq 1/2}$

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

This solar hierarchy EXCLUDED !!!.

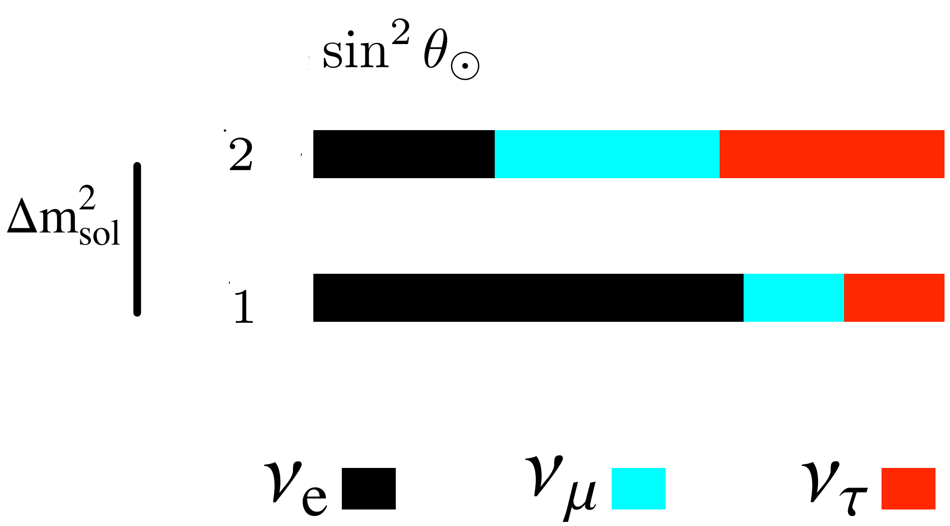
Summary:

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 $P_{ee} \approx 0.35$.



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

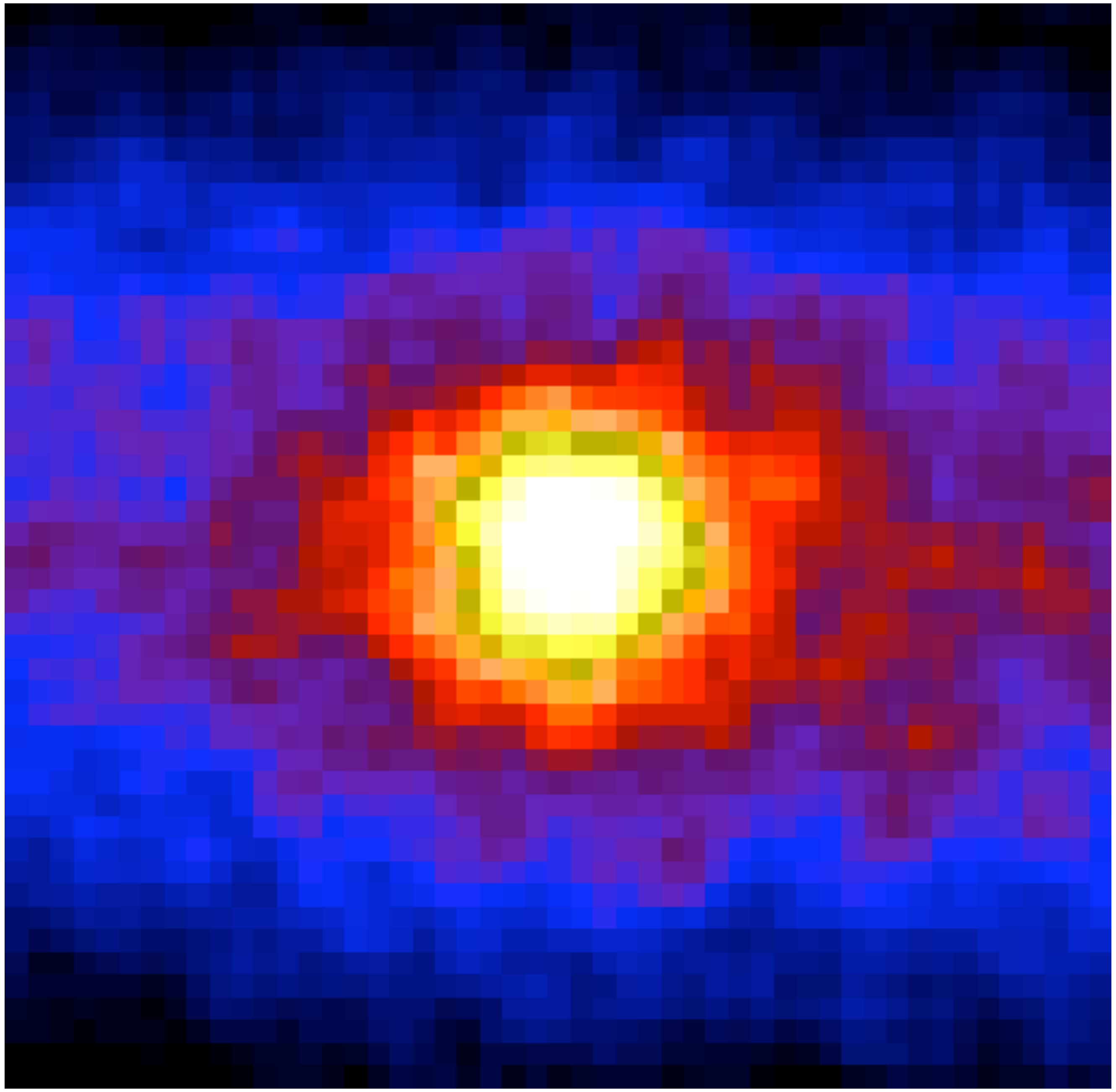
$$\sin^2\theta_\odot = 0.310 \pm 0.026$$

at 68% CL

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

SuperK

Flavor Fraction 76% ν_e's

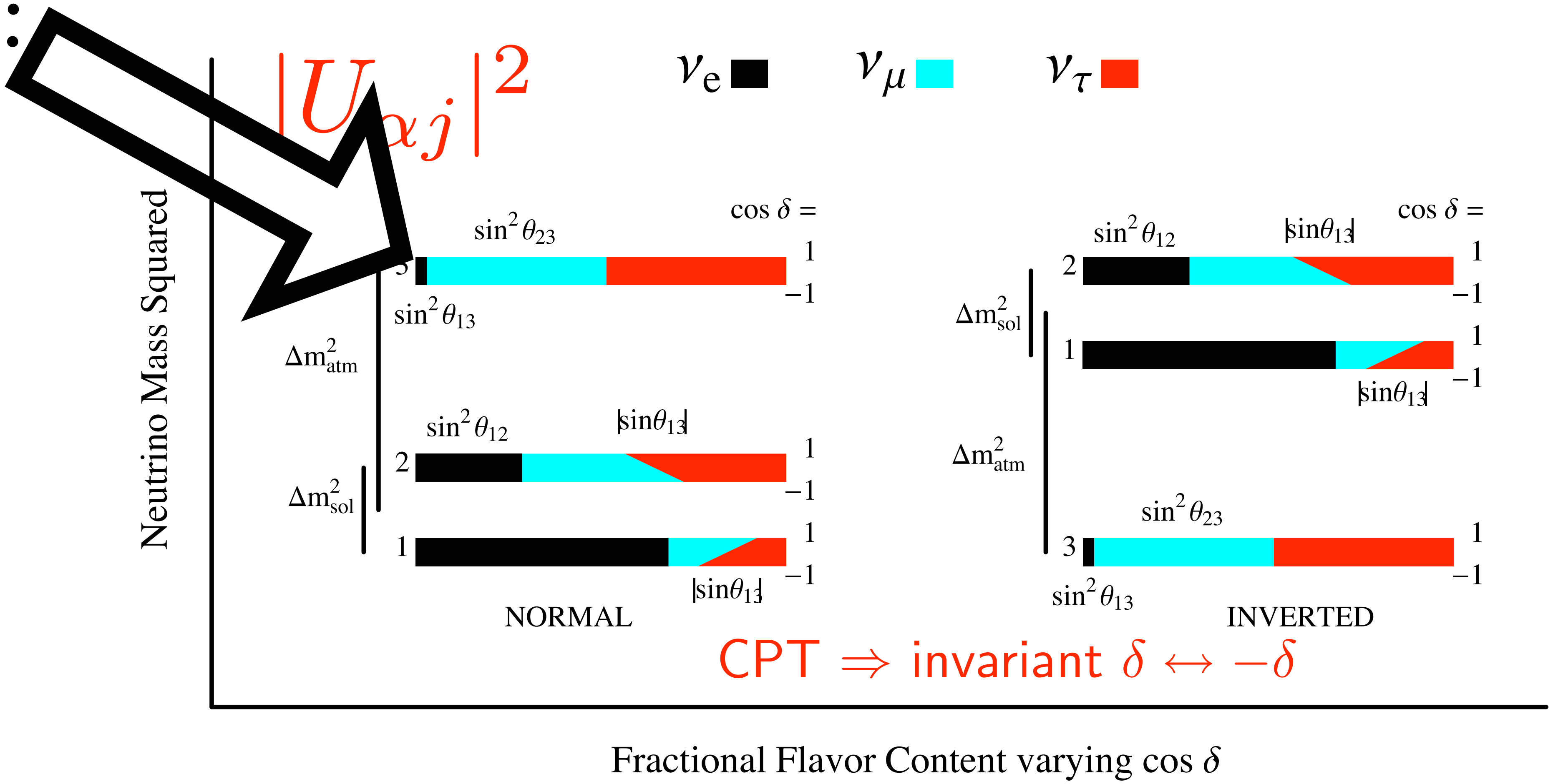


Mass E-state Fraction 84% ν_2's

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

Which Neutrinos ?

KEY:



$$\sin^2\theta_{12} \sim 1/3$$

$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$\sin^2\theta_{23} \sim 1/2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$\sin^2\theta_{13} < 3\%$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

$$0 \leq \delta < 2\pi$$

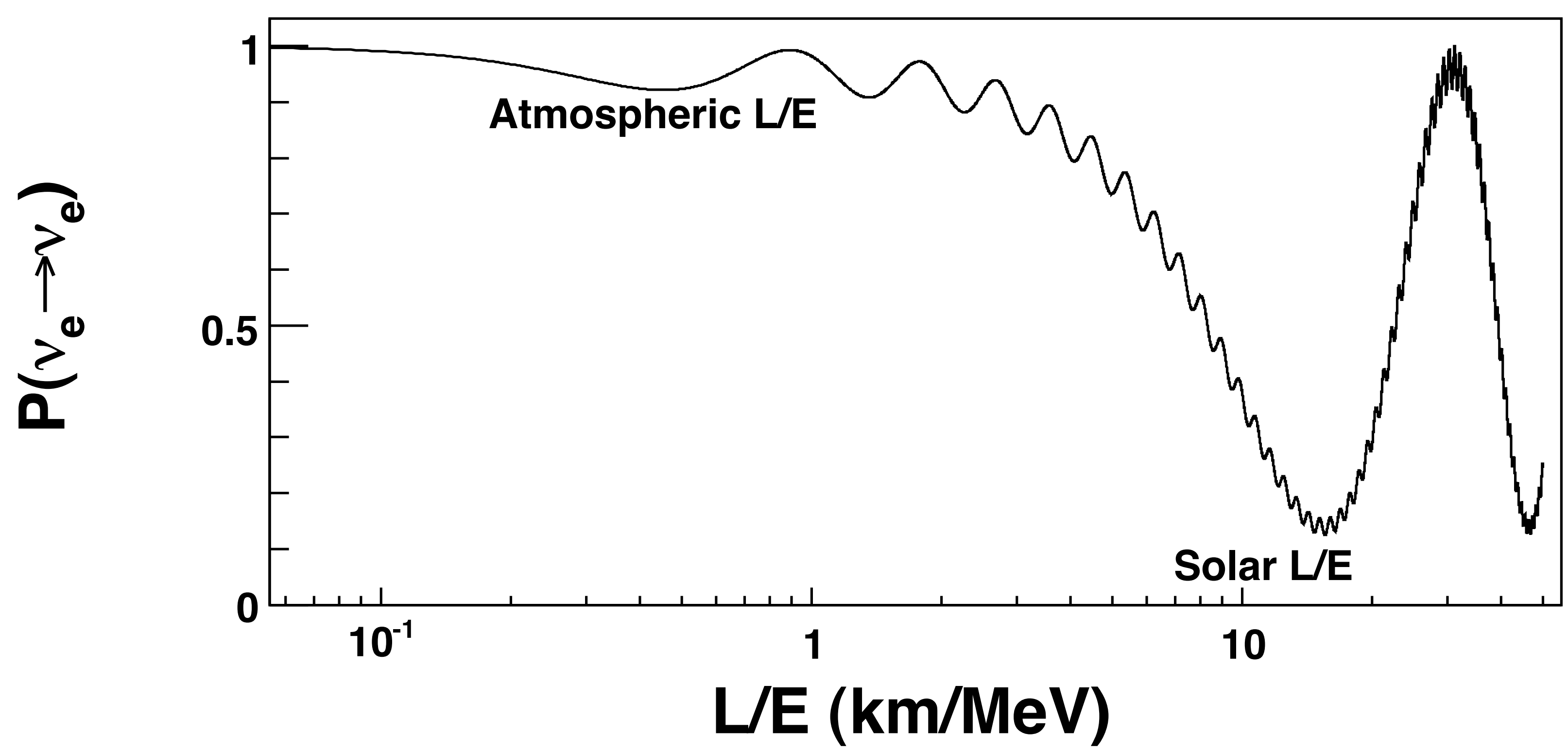
- Size of $|U_{e3}|^2$
- Hierarchy ?
- CPV ?
- Maximal $\{23\}$ Mixing ?
- .....
- New Interactions and Surprises !!!

θ_{13} from Reactor Disappearance

kinematic phase:

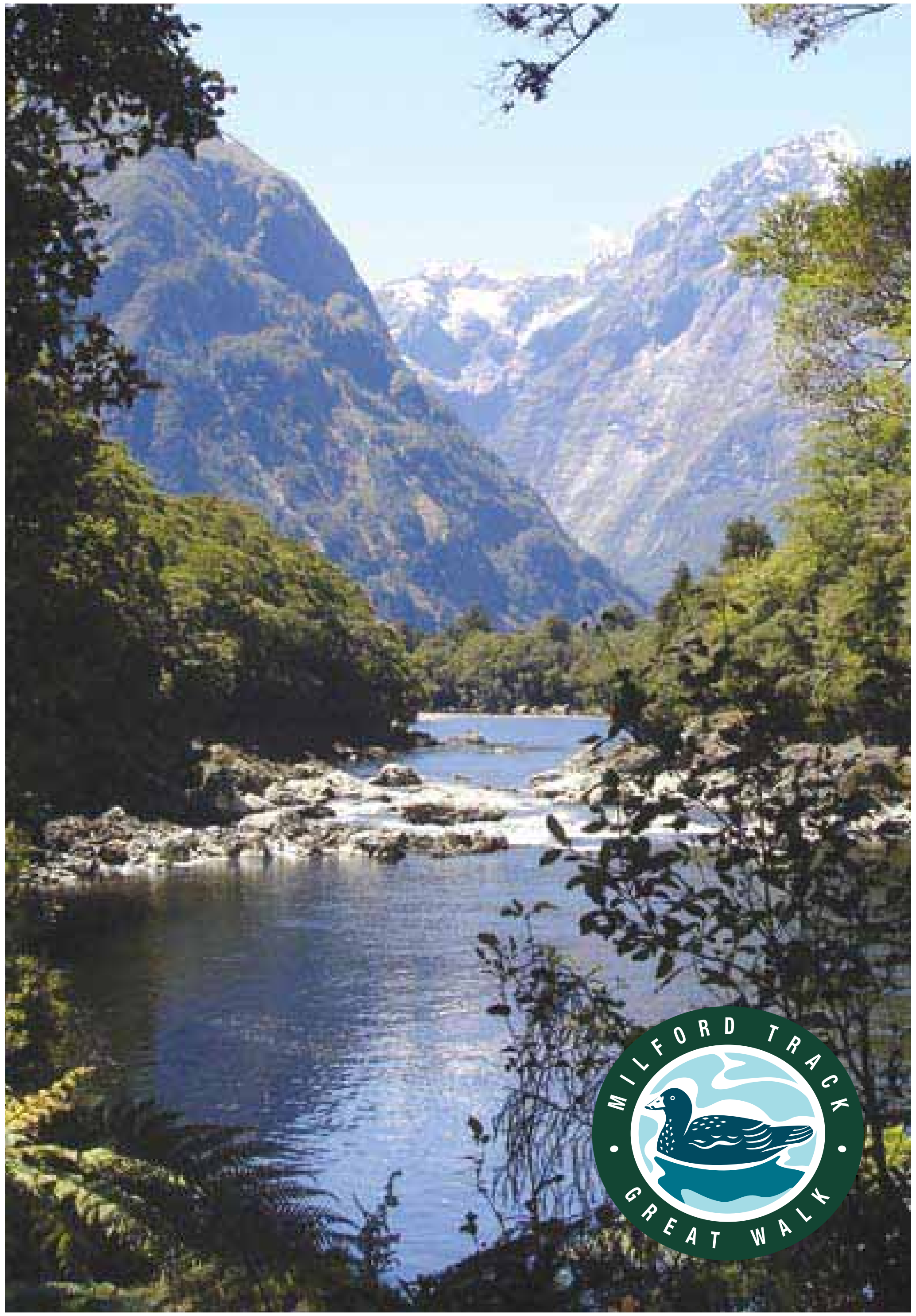
$$\Delta_{ij} \equiv \frac{\delta m_{ij}^2 L}{4E}$$

$$\begin{aligned} P(\bar{\nu}_e \to \bar{\nu}_e) &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\quad - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \end{aligned}$$



$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m_{ee}^2 L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

$$\delta m_{ee}^2 = \cos^2\theta_{12}|\delta m_{31}^2| + \sin^2\theta_{12}|\delta m_{32}^2|$$



Department of Conservation
Te Papa Atawhai

$\sin^2\theta_{13}$ from LBL:

$$\nu_\mu \longrightarrow \nu_e$$

and related processes:

$$\begin{array}{ccccc} & & \text{CP} & & \\ & \nu_\mu \longrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \longrightarrow \bar{\nu}_e & \\ \text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\ & \nu_e \longrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \longrightarrow \bar{\nu}_\mu & \\ & & \text{CP} & & \end{array}$$

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

$$\nu_\mu \to \nu_e$$

$$| \; U_{\mu 3}^* e^{-im_3^2 L/2E} U_{e3} + U_{\mu 2}^* e^{-im_2^2 L/2E} U_{e2} + U_{\mu 1}^* e^{-im_1^2 L/2E} U_{e1} \; |^2$$

use unitarity to eliminate $U_{\mu 1}^* U_{e1}$ term:

$$P(\nu_\mu \to \nu_e) \quad = \quad |2U_{\mu 3}^* U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U_{\mu 2}^* U_{e2} \sin \Delta_{21}|^2$$

Atmospheric δm^2

Solar δm^2

$\sqrt{P_{atm}}$

$\sqrt{P_{sol}}$

Vacuum LBL: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}|^2$$

$\Delta_{ij} = \delta m_{ij}^2 L/4E$

CP violation !!!

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \sin\Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \sin\Delta_{21}$

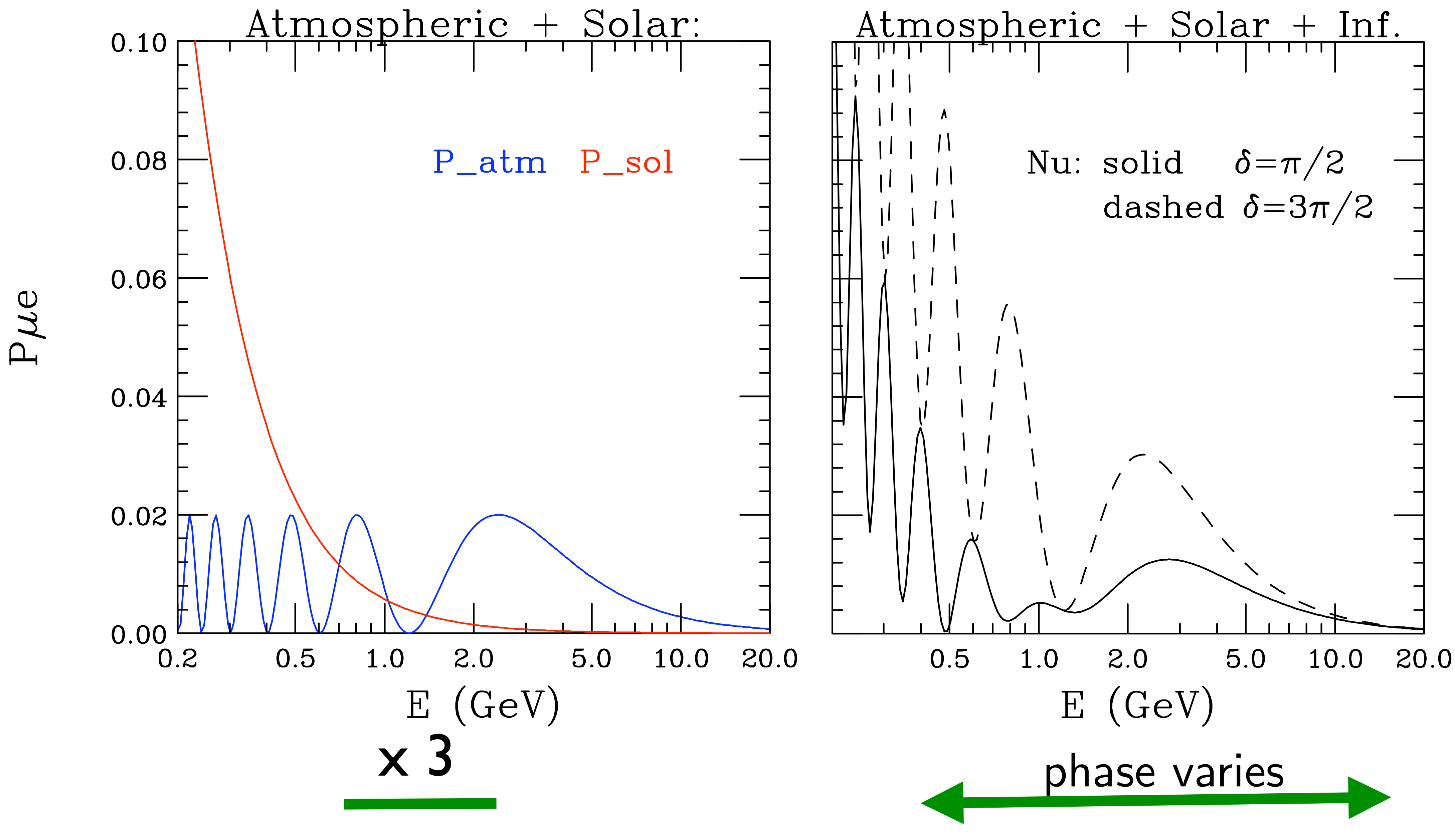
$$\boxed{P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32}\pm\delta) + P_{sol}}$$

only CPV

$$\cos(\Delta_{32}\pm\delta) = \cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta$$

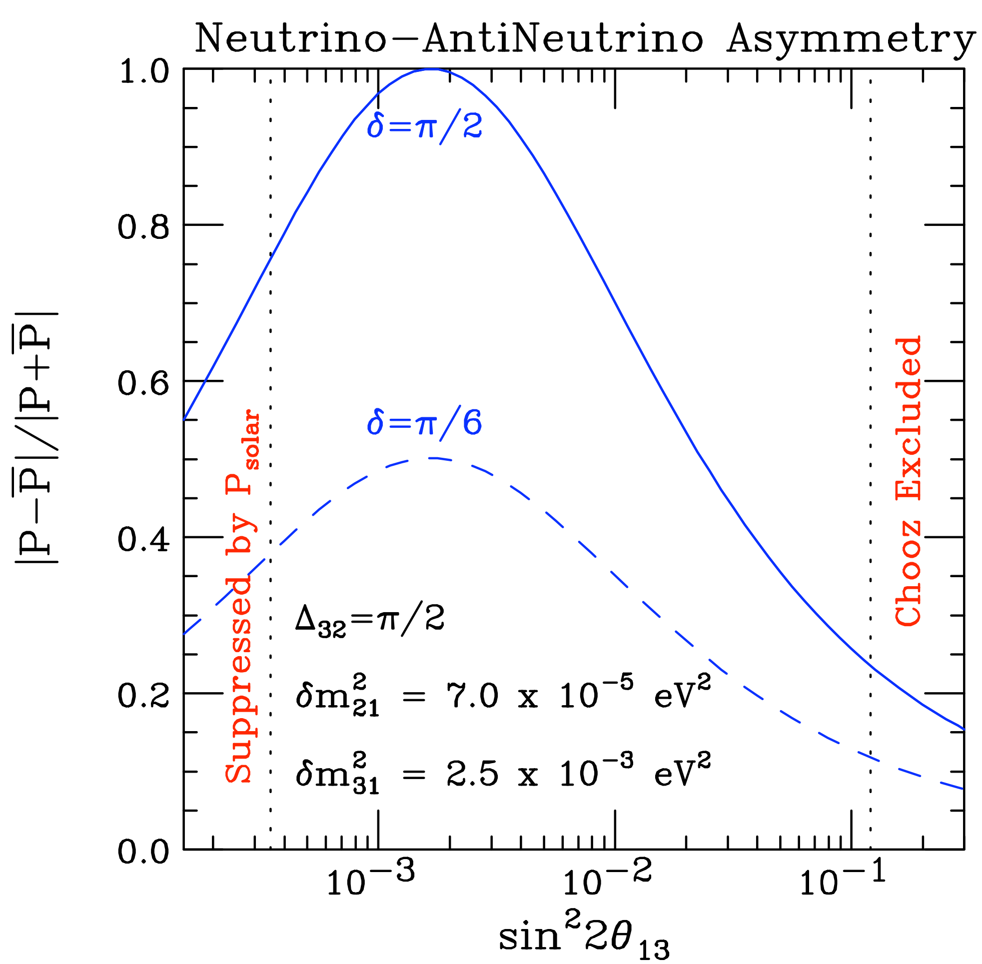
$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$



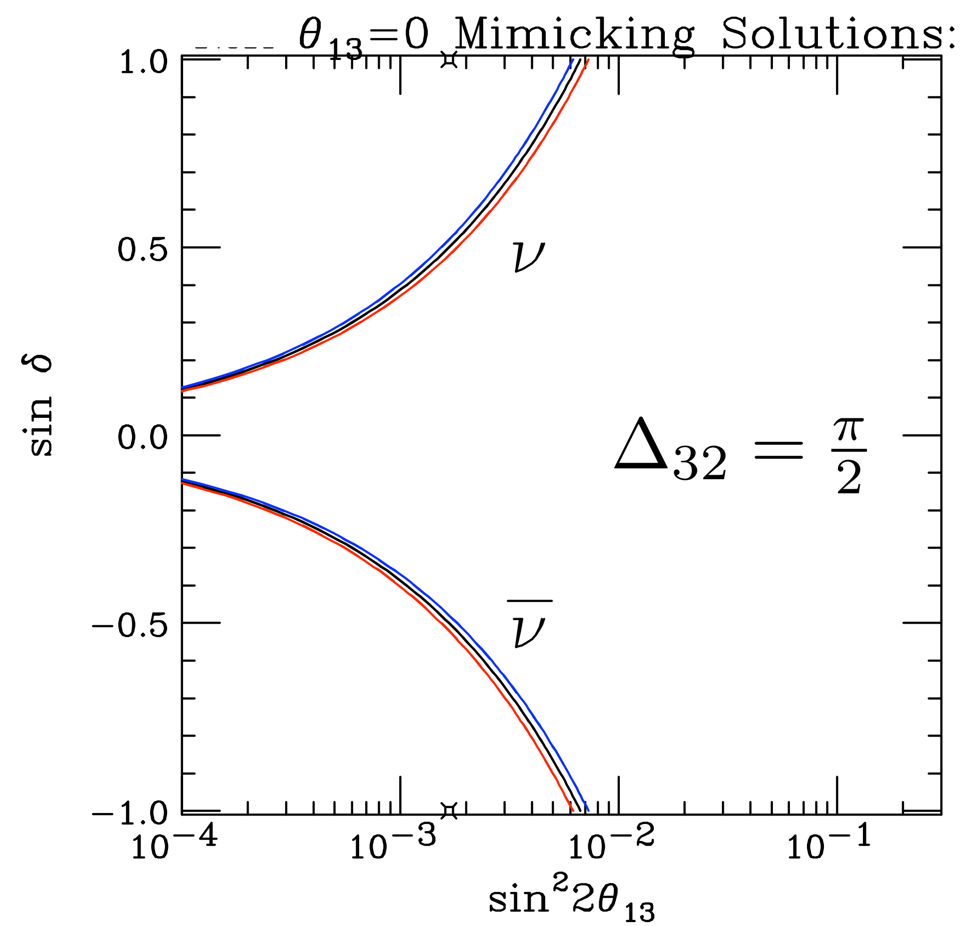
$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

Asymmetry Peaks:



$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

Zero Mimicking Solutions:



$$\sqrt{P_{atm}} = -2\sqrt{P_{sol}}\cos(\Delta_{32}\pm\delta)$$

$P_{atm} \leq P_{sol}$ when $\sin^2 2\theta_{13} \leq \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}}\left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \approx 0.001$

2 Flavor in Matter:

ν_e disappearance in Loooong Block of Lead:

$\Delta_N = \frac{\delta m_N^2 L}{4E}$

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta^N \sin^2 \Delta_N$$

same form as vacuum

BUT from $\delta m^2 \sin 2\theta$ invarance $\sin^2 2\theta^N = \left(\frac{\delta m^2}{\delta m_N^2}\right)^2 \sin^2 2\theta$

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta \left(\frac{\delta m^2}{\delta m_N^2}\right)^2 \sin^2 \Delta_N = \sin^2 2\theta \ \left(\frac{\sin^2 \Delta_N}{\Delta_N^2}\right) \ \Delta^2$$

$\Delta = \frac{\delta m^2 L}{4E}$

enhancement or suppression depending on

$$\frac{\sin^2 \Delta_N}{\Delta_N^2} \quad \lessgtr \quad \frac{\sin^2 \Delta}{\Delta^2}$$

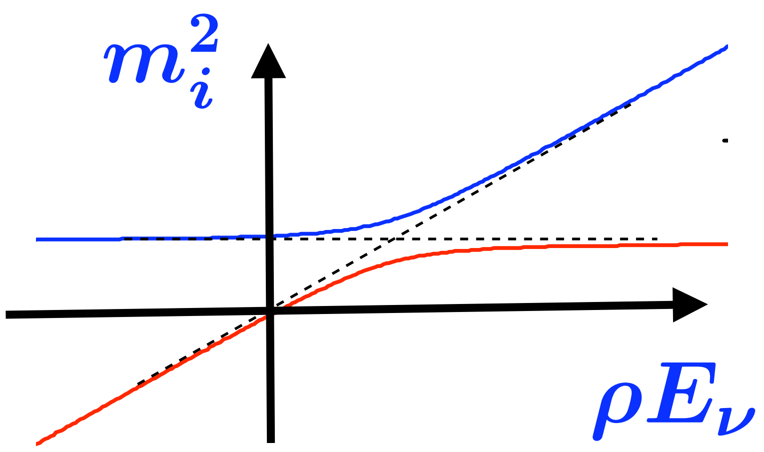
for small L this reduces to

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta \ \Delta^2$$

same as vacuum small L.

$$\delta m_N^2 = \sqrt{(\delta m^2 \cos 2\theta - 2\sqrt{2} G_F N_e E_\nu)^2 + (\delta m^2 \sin 2\theta)^2}$$

$$\approx |\delta m^2 - 2\sqrt{2} G_F N_e E_\nu|$$



except near resonance:

$$\delta m^2 \cos 2\theta = 2\sqrt{2} G_F N_e E_\nu$$

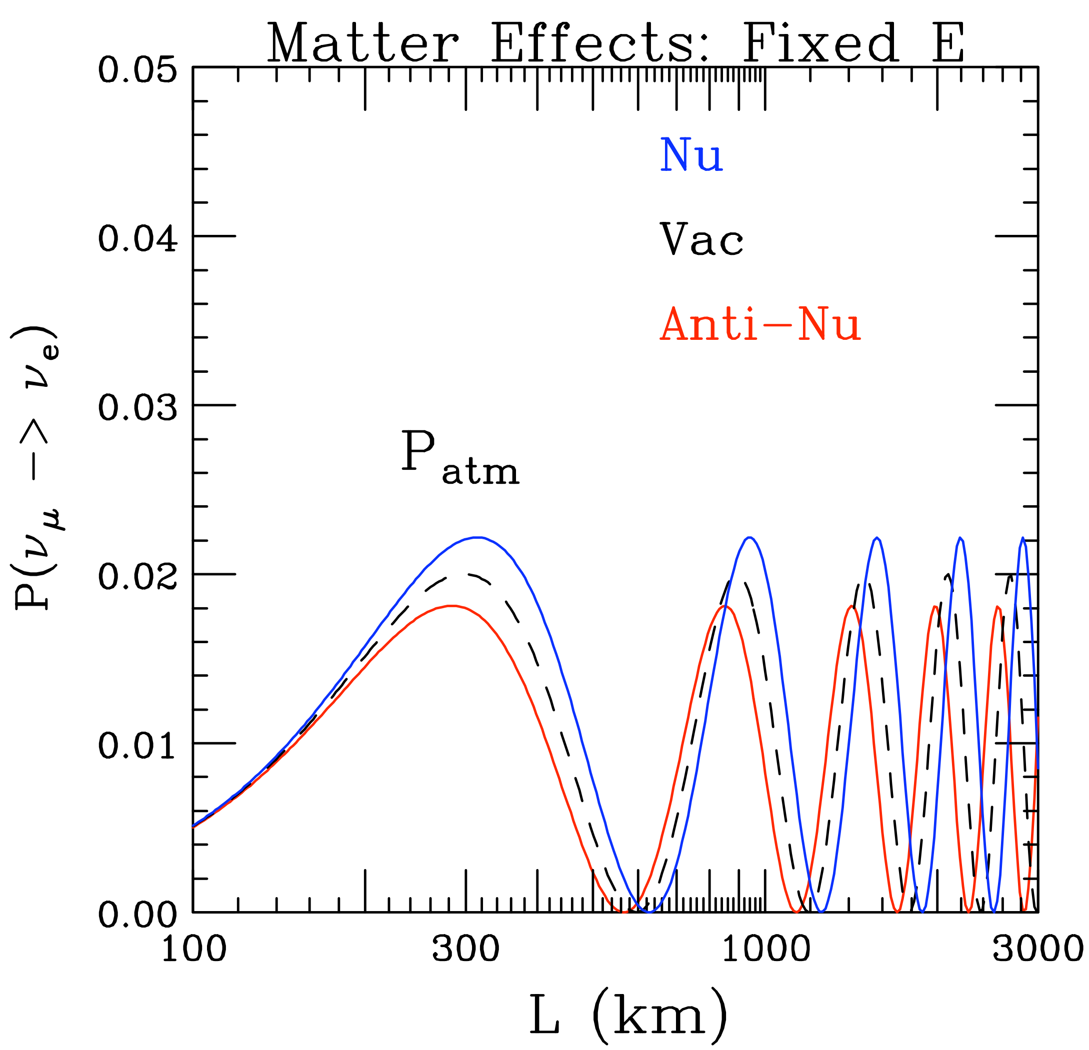
$\Delta_N \approx |\Delta - aL|$ where $a = G_F N_e/\sqrt{2} \approx (4000km)^{-1} \left(\frac{\rho}{3\ g.cm^{-3}}\right)$

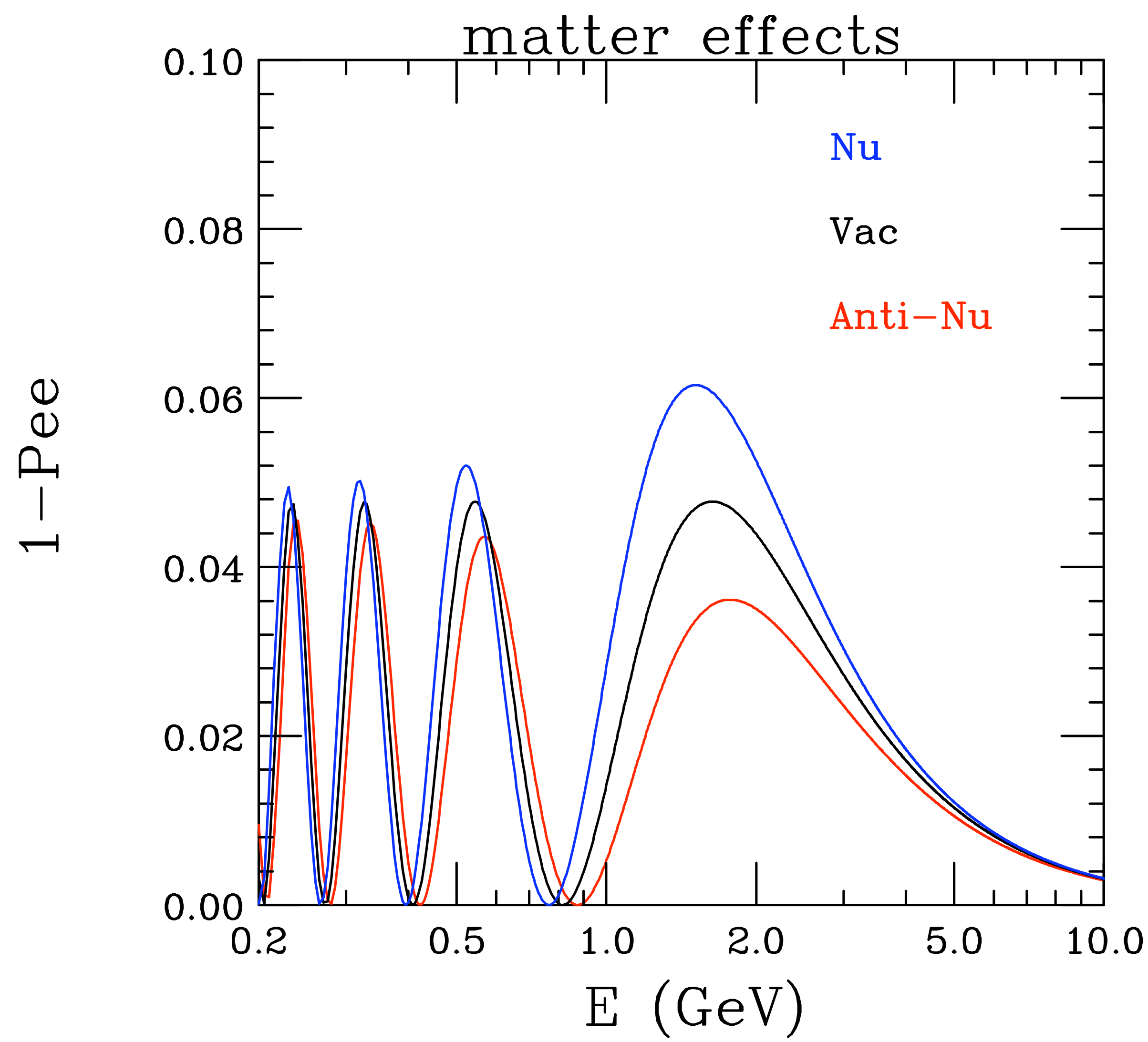
$a \to -a$ for anti-neutrinos:

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta \, \frac{\sin^2(\Delta - aL)}{(\Delta - aL)^2} \, \Delta^2$$

2 Flavors:

$$1 - P(\nu_e \rightarrow \nu_e) = \sin^2 2\theta \; \frac{\sin^2(\Delta - aL)}{(\Delta - aL)^2} \; \Delta^2$$





$$E = 0.6 \; GeV$$

$$L = 810 \; km$$

$$\rho = 2.5 \; g.cm^{-3}$$

$\nu_\mu \to \nu_e$ with MATTER

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13} \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)} \Delta_{31}$

in vac $\sin\Delta_{31}$

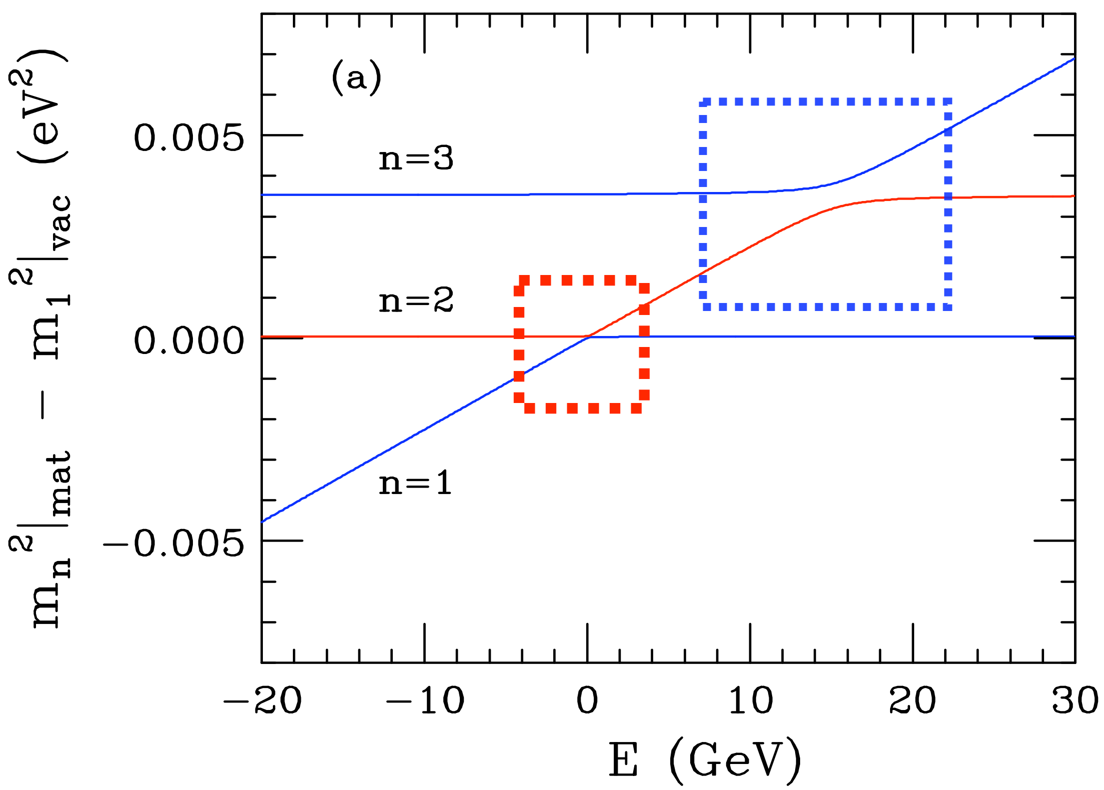
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

$\Delta_{21} << (aL)$ in vac $\sin\Delta_{21}$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

$$\pm = sign(\delta m^2_{31}) \quad \Delta_{ij} = |\delta m^2_{ij}|L/4E$$

$\{\delta m^2 \sin 2\theta\}$ is invariant



Full Probability:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+2\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}$$

$$*\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}$$

$$*(\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta)$$

CPV

CPC

$$+\cos^4\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$(\Delta_{31}-aL) = \Delta_{31}\left(1-\frac{aL}{\Delta_{31}}\right) = \Delta_{31}\left(1-\frac{2\sqrt{2}G_F N_e E}{\delta m_{31}^2}\right)$$

$$\Delta_{32}\approx\Delta_{31}$$

$$J = \sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}\sin\delta$$

In Matter:

$$P_{\mu\to e} \approx |\ \sqrt{P_{atm}}\, e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

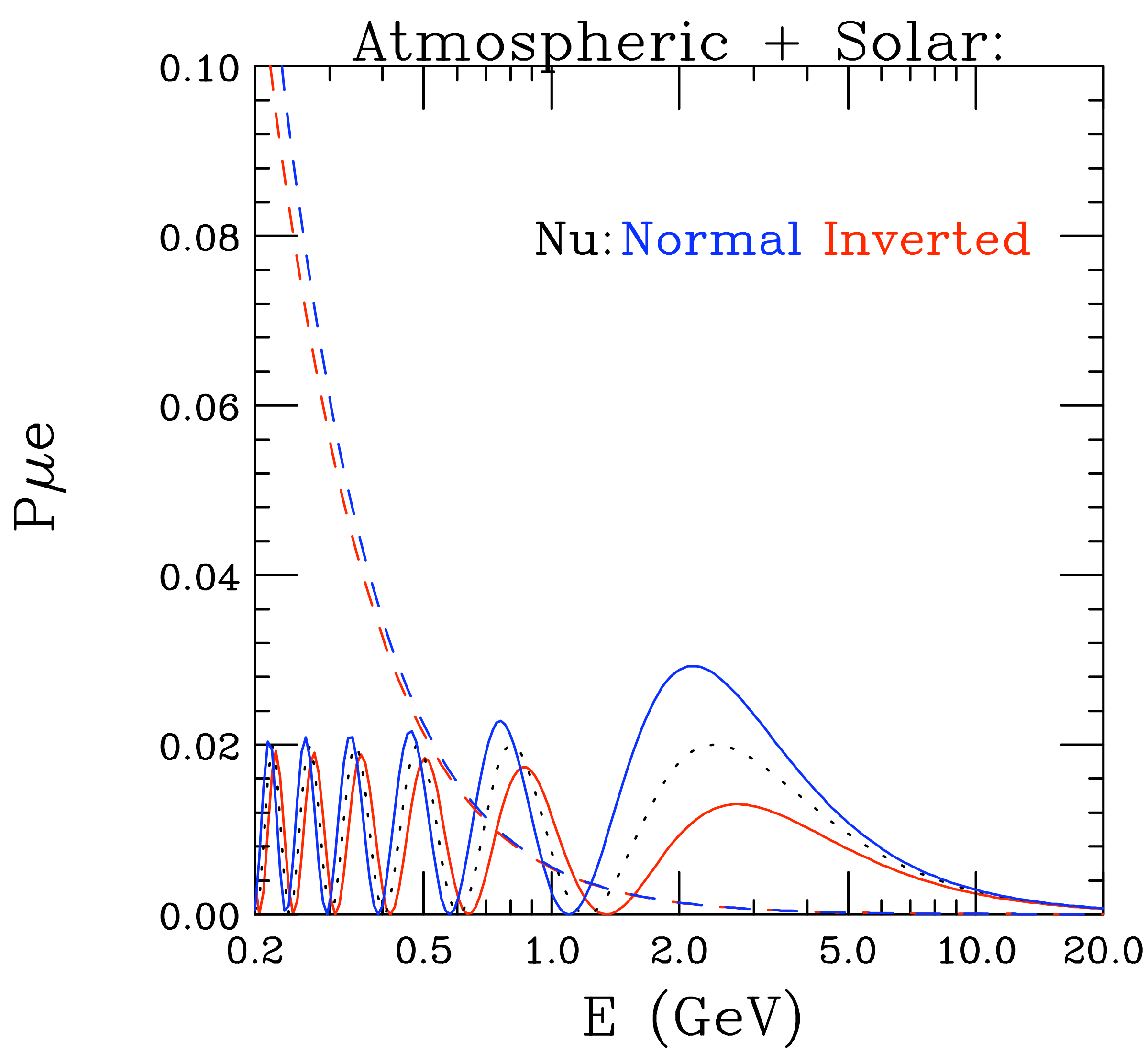
where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\ \Delta_{31}$

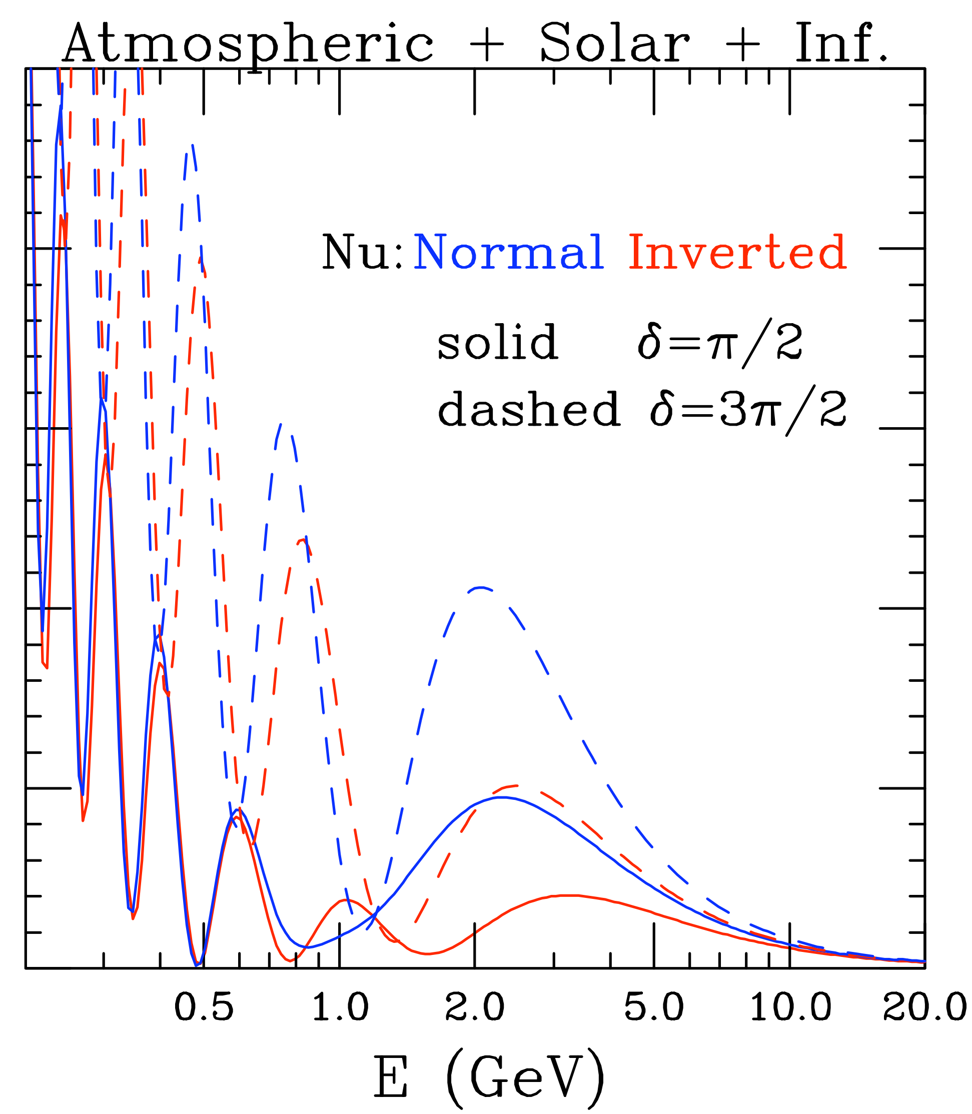
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

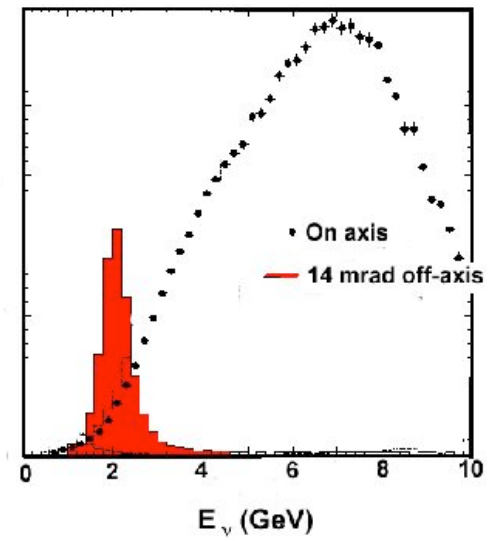
Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





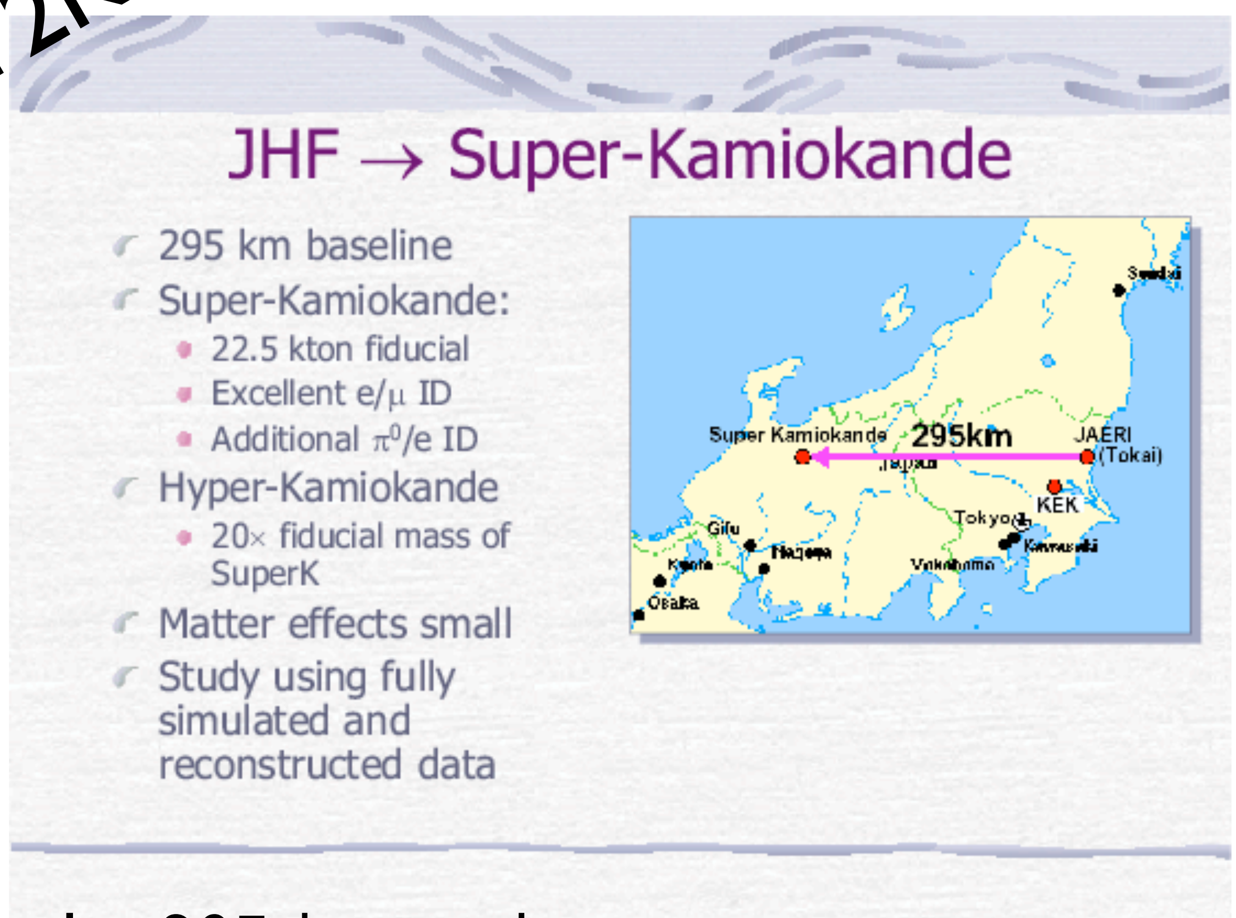
Off-Axis Beams

BNL 1994

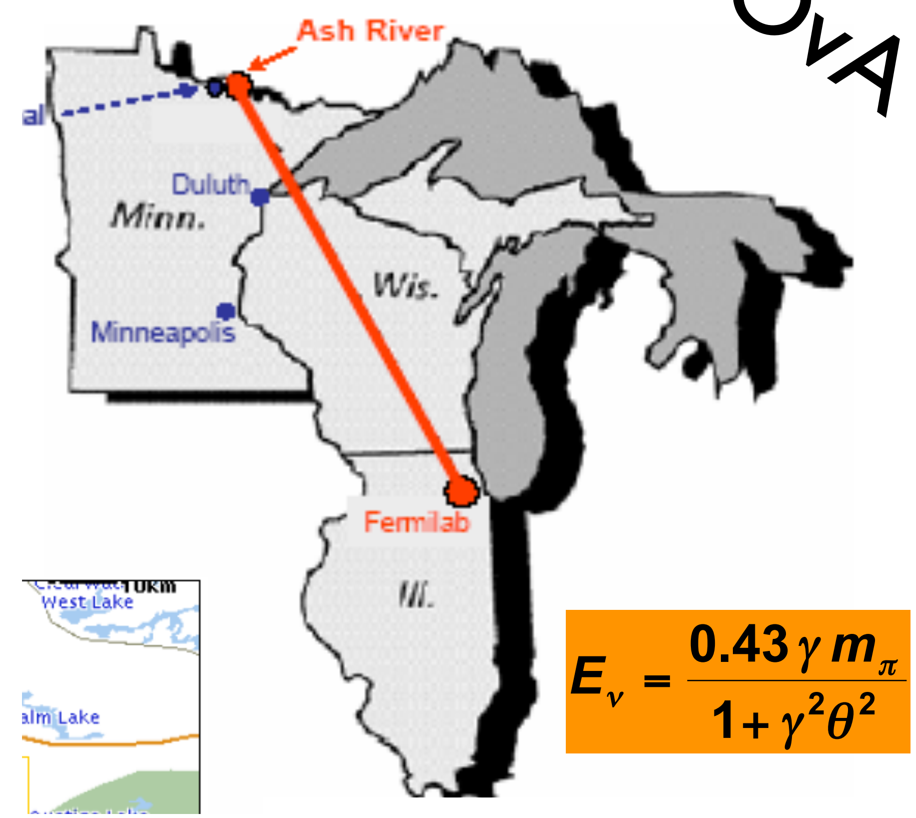


π^0 suppression

T2K



NOvA



L=295 km and
Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\}$$

0.75 upgrade to 4 MW

L=700 - 1000 km and
Energy near 2 GeV

$$E_{vom} = 1.8\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\} \times \left\{ \frac{L}{820\ km} \right\}$$

0.4 upgrade to 2 MW

- Size of $|U_{e3}|^2$
- Hierarchy ?
- CPV ?
- Maximal $\{23\}$ Mixing ?
- .....
- New Interactions and Surprises !!!

What happens to the neutrino oscillation length in the semi-classical limit, $\hbar \to 0$?

- $L_{osc} \to \infty$
- $L_{osc} \to 0$
- Other