
GABRIELA BARENBOIM PRESENTS
THE IνCREDIBLES
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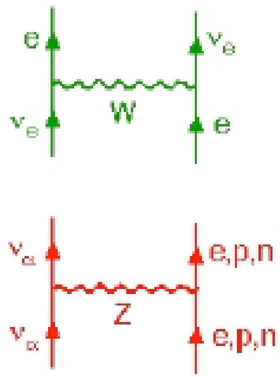
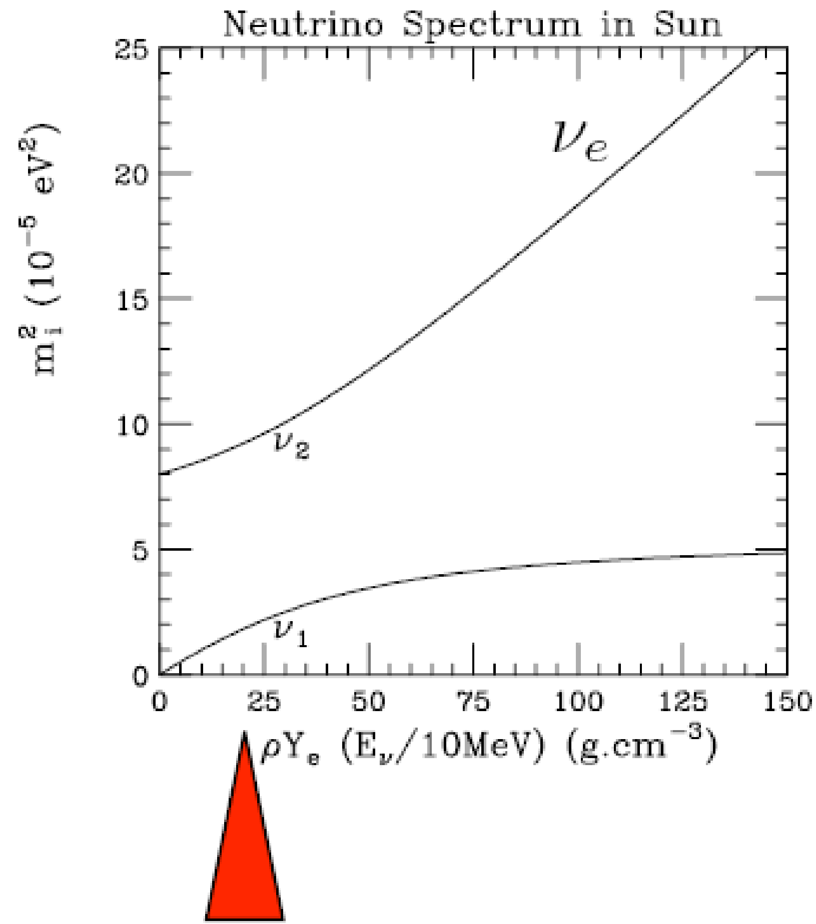
MSW

Coherent Forward Scattering:



Wolfenstein '78

MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS



Mikheyev + Smirnov Resonance WIN '85

Neutrino Evolution:

$$-i\frac{\partial}{\partial t}\nu = H\nu$$

in the mass eigenstate basis

$$\nu = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \text{ and } H = \begin{pmatrix} \sqrt{p^2+m_1^2} & 0 \\ 0 & \sqrt{p^2+m_2^2} \end{pmatrix}$$

$$E = \sqrt{p^2+m^2}$$

$$H = (p + \tfrac{m_1^2+m_2^2}{4p})I + \tfrac{1}{4E}\begin{pmatrix} -\delta m^2 & 0 \\ 0 & \delta m^2 \end{pmatrix}$$

$$\delta m^2 = m_2^2 - m_1^2 > 0$$

in the flavor basis

$$\nu \to U\nu \text{ and } H \to UHU^\dagger$$

where $\nu = \begin{pmatrix} \nu_e \\ \nu_\sigma \end{pmatrix}$ and $U = \begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot \\ -\sin\theta_\odot & \cos\theta_\odot \end{pmatrix}$

$0 < \theta_\odot < \frac{\pi}{2}$

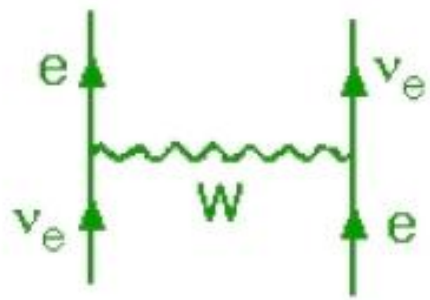
and therefore in flavor basis

$$H = \frac{\delta m^2}{4E} \begin{pmatrix} -\cos 2\theta_\odot & \sin 2\theta_\odot \\ \sin 2\theta_\odot & \cos 2\theta_\odot \end{pmatrix}$$

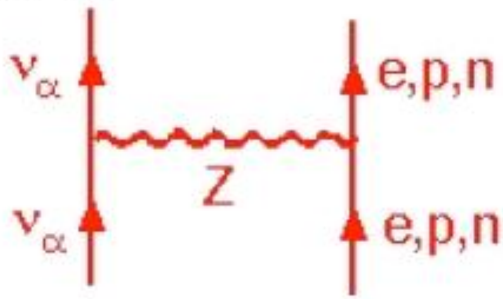
i.e. $\begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}_{mass} \Rightarrow \frac{\delta m^2}{4E} \begin{pmatrix} -\cos 2\theta_\odot & \sin 2\theta_\odot \\ \sin 2\theta_\odot & \cos 2\theta_\odot \end{pmatrix}_{flavor}$

Coherent Forward Scattering:

dimensions $[G_F N_e] = M^{-2} L^{-3} = M$



Wolfenstein '78



$$\pm\sqrt{2} G_F N_e \, \delta_{ee}$$

N_e is number density of electrons

+(-) for neutrinos (anti-neutrinos)

Same for all active flavors, therefore overall phases

$$\begin{pmatrix} +\sqrt{2} G_F N_e & 0 \\ 0 & 0 \end{pmatrix} \to \cancel{\frac{G_F N_e}{\sqrt{2}} I_2} + \frac{1}{2} \begin{pmatrix} +\sqrt{2} G_F N_e & 0 \\ 0 & -\sqrt{2} G_F N_e \end{pmatrix}$$

Including Matter Effects in the Flavor Basis:

$$H_{flavor} = \frac{1}{4E_\nu}\begin{pmatrix} -\delta m^2 \cos 2\theta_\odot + 2\sqrt{2}G_F N_e E_\nu & \delta m^2 \sin 2\theta_\odot \\ \delta m^2 \sin 2\theta_\odot & \delta m^2 \cos 2\theta_\odot - 2\sqrt{2}G_F N_e E_\nu \end{pmatrix}$$

Diagonalize by identifying with

$$H_{flavor} = \frac{1}{4E_\nu}\begin{pmatrix} -\delta m_N^2 \cos 2\theta_\odot^N & \delta m_N^2 \sin 2\theta_\odot^N \\ \delta m_N^2 \sin 2\theta_\odot^N & \delta m_N^2 \cos 2\theta_\odot^N \end{pmatrix}$$

Masses and Mixings in MATTER: δm_N^2 and $\theta_\odot^N$

$$\boxed{\begin{aligned} \delta m_N^2 \cos 2\theta_\odot^N &= \delta m^2 \cos 2\theta_\odot - 2\sqrt{2}G_F N_e E_\nu \\ \delta m_N^2 \sin 2\theta_\odot^N &= \delta m^2 \sin 2\theta_\odot \end{aligned}}$$

Notice:

(1) Possible zero when $\delta m^2 \cos 2\theta_\odot = 2\sqrt{2}G_F N_e E_\nu$

(2) the invariance of the product $\delta m^2 \sin 2\theta_\odot$

ν_e disappearance in Loooong Block of Lead:

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

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

same form as vacuum

The Solution:

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

$$\sin^2 \theta_\odot^N = \frac{1}{2}\left(1 - \frac{(\delta m^2 \cos 2\theta_\odot - 2\sqrt{2} G_F N_e E_\nu)}{\delta m_N^2}\right) \qquad \theta_\odot^N > \theta_\odot$$

Quasi-Vacuum: $2\sqrt{2} G_F N_e E_\nu \ll \delta m^2 \cos 2\theta_\odot$ pp and ^{7}Be

$$\delta m_N^2 = \delta m^2 \text{ and } \theta_\odot^N = \theta_\odot$$

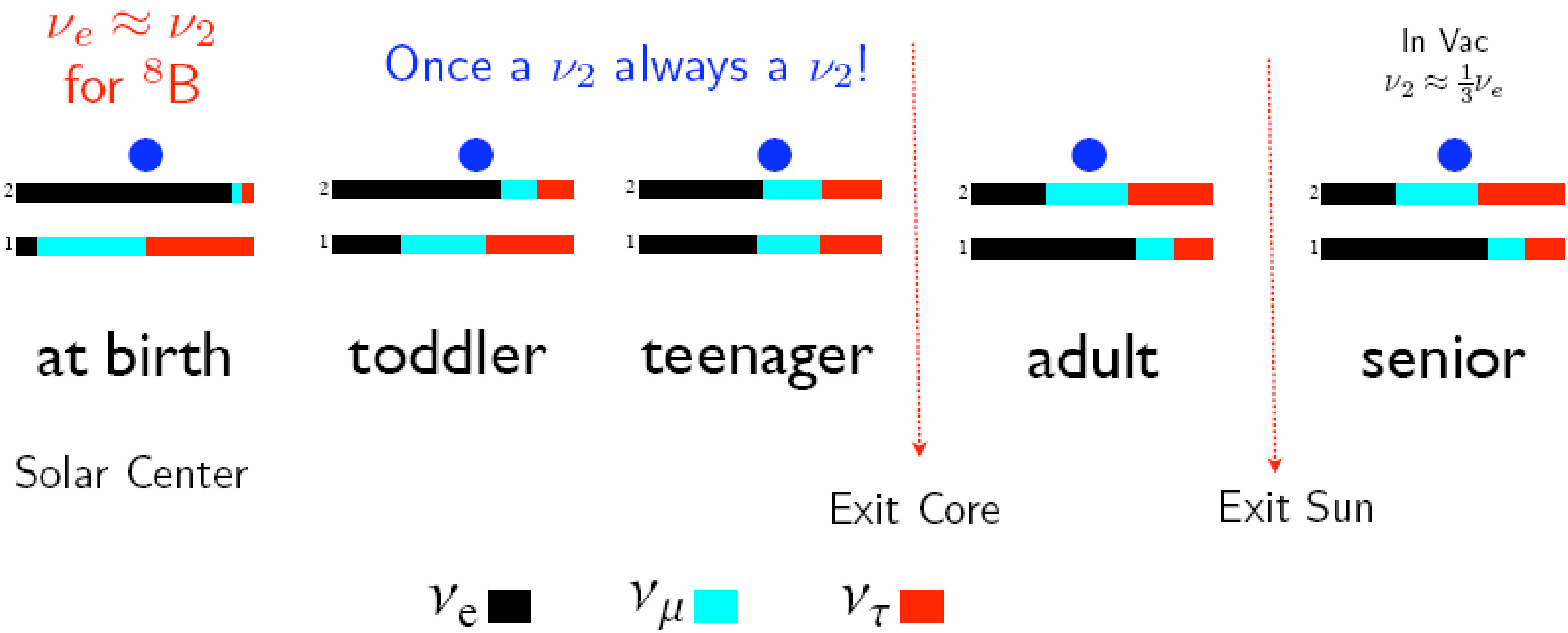
Resonance (Mikheyev + Smirnov '85): $2\sqrt{2} G_F N_e E_\nu = \delta m^2 \cos 2\theta_\odot$

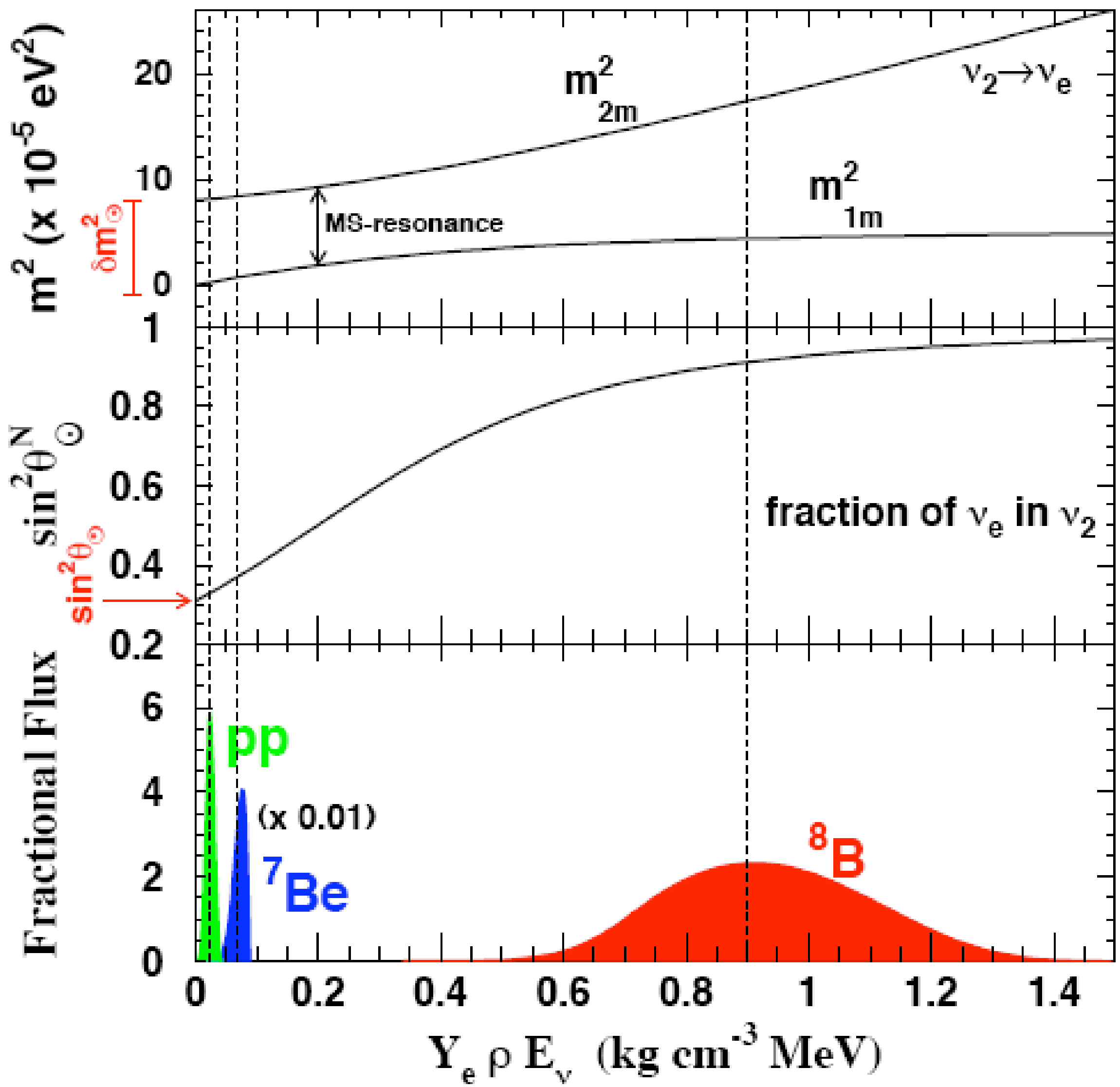
$$\delta m_N^2 = \delta m^2 \sin 2\theta_\odot \text{ and } \theta_\odot^N = \pi/4$$

Matter Dominated: $2\sqrt{2} G_F N_e E_\nu \gg \delta m^2 \cos 2\theta_\odot$ ^8B

$$\delta m_N^2 \to 2\sqrt{2} G_F N_e E_\nu \text{ and } \theta_\odot^N \to \pi/2$$

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

$$\delta m^2_N = 14 \times 10^{-5}\ eV^2$$

$$\sin^2\theta^N_\odot = 0.91$$

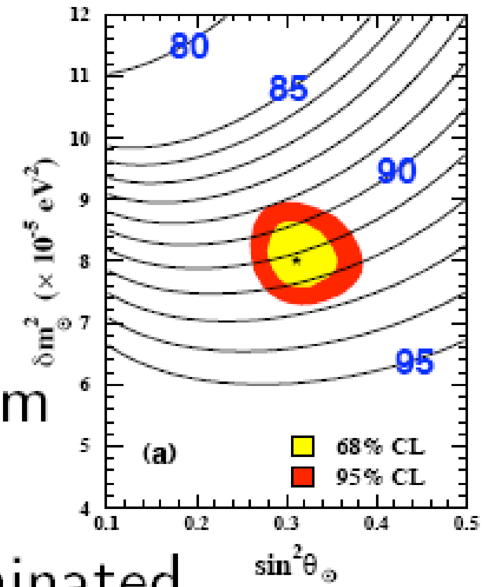
Mass Eigenstate Purity:

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



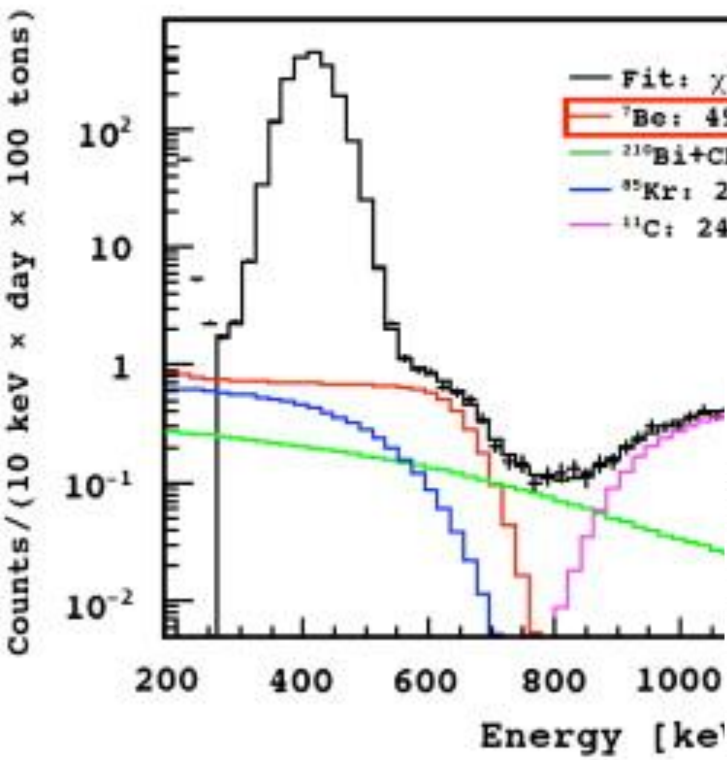
$f_1 = \cos^2\theta^N_\odot$ and $f_2 = \sin^2\theta^N_\odot$ $\qquad \langle P_{ee}\rangle = f_1\cos^2\theta_\odot + f_2\sin^2\theta_\odot$

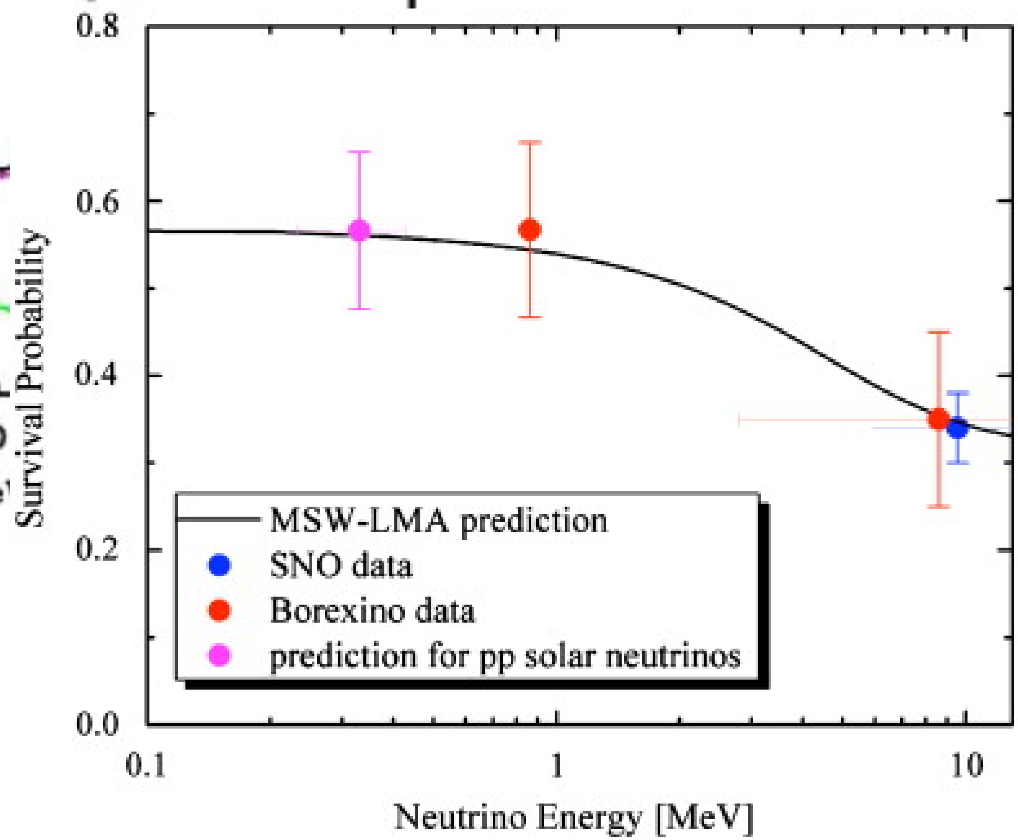
vac pp ^{7}Be ^{8}B

$N_e E_\nu$

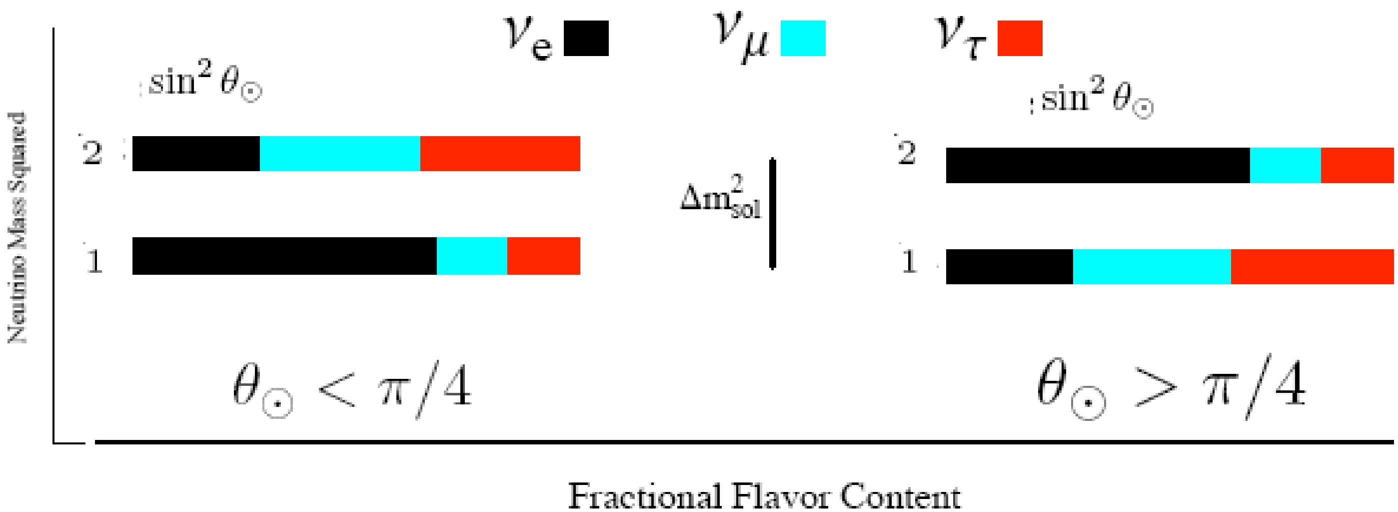
$\langle P_{ee}\rangle = \cos^4\theta_\odot + \sin^4\theta_\odot$ $\qquad \Rightarrow \sin^2\theta_\odot$

Borexino results (2011)





Solar Pair Mass Hierarchy:



Who cares ?

SNO does !!!

for neutrino in matter

$\theta_\odot^N > \theta_\odot$

$$\langle P_{ee}\rangle = \cos^2\theta_\odot^N \cos^2\theta_\odot + \sin^2\theta_\odot^N \sin^2\theta_\odot = \tfrac{1}{2} + \tfrac{1}{2}\cos 2\theta_\odot^N \cos 2\theta_\odot \quad \sqrt{2}G_F N_e E_\nu)$$

if $\theta_\odot < \pi/4$

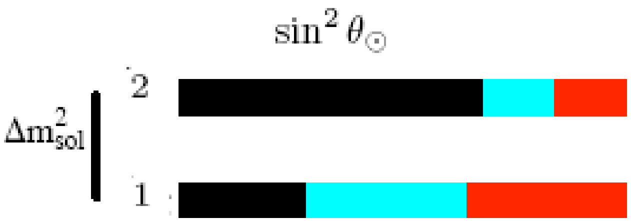
$$\langle P_{ee}\rangle \geq \sin^2\theta_\odot$$

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

$$\langle P_{ee}\rangle \geq \tfrac{1}{2}(1+\cos^2 2\theta_\odot) \geq \tfrac{1}{2}$$

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

Solar Hierarchy Determined !!!



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

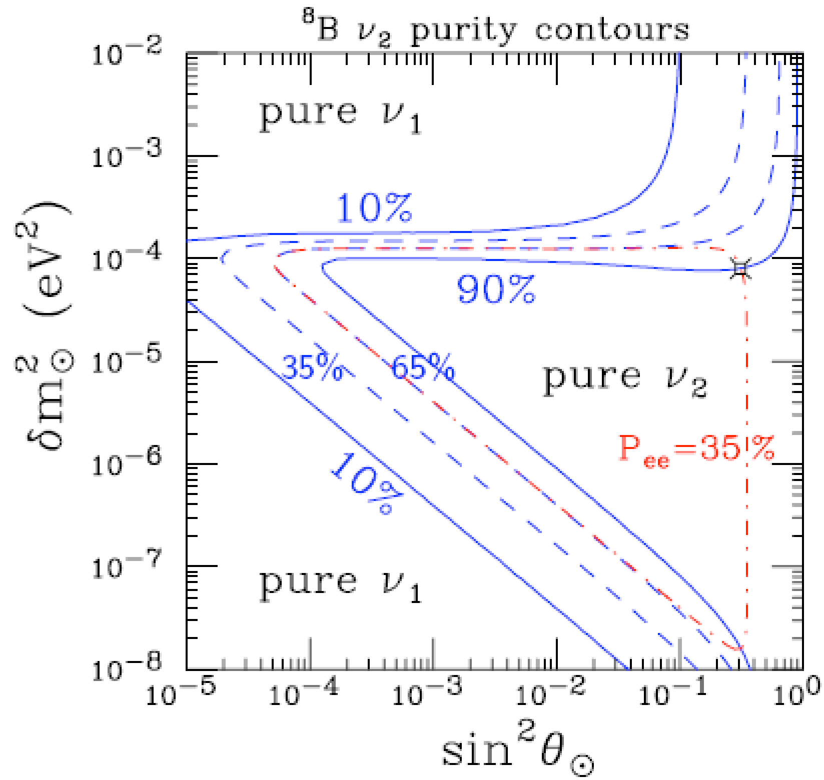
Solar matter effects put more of the neutrino into ν_2.
This raises the survival probability above vacuum value since ν_2 has more ν_e.
But the minimum of P_{ee} in vacuum is 1/2.

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:

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

Day/Night Asymmetry:

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

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

SK:

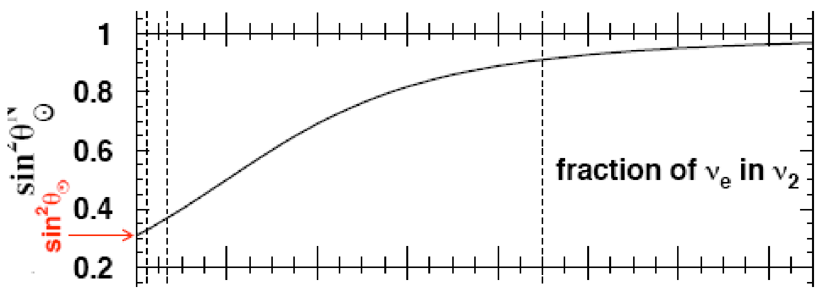
$$A_{ES} = -1.8 \pm 1.6(\mathrm{stat})^{+1.3}_{-1.2}(\mathrm{syst})\%$$

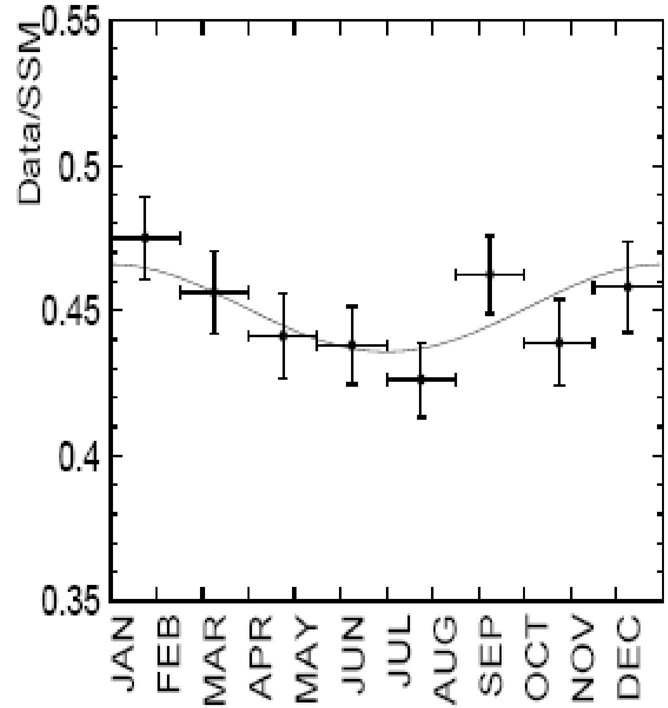
Spectral Distortion:

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.





The neutrinos definitely come from the Sun, expected seasonal variation, no spectral distorsion and no significant day-night asymmetry

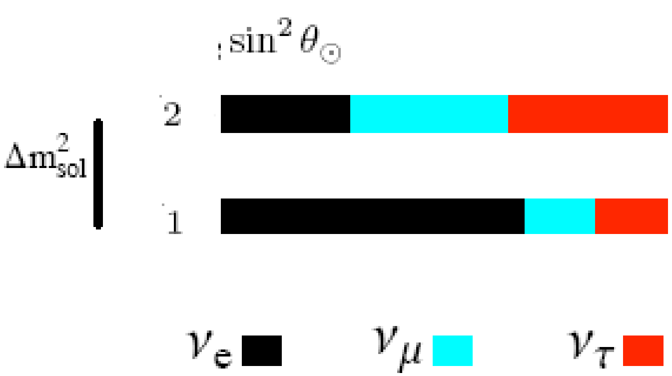
Summary:

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

Testing solar neutrino oscillations with reactors

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

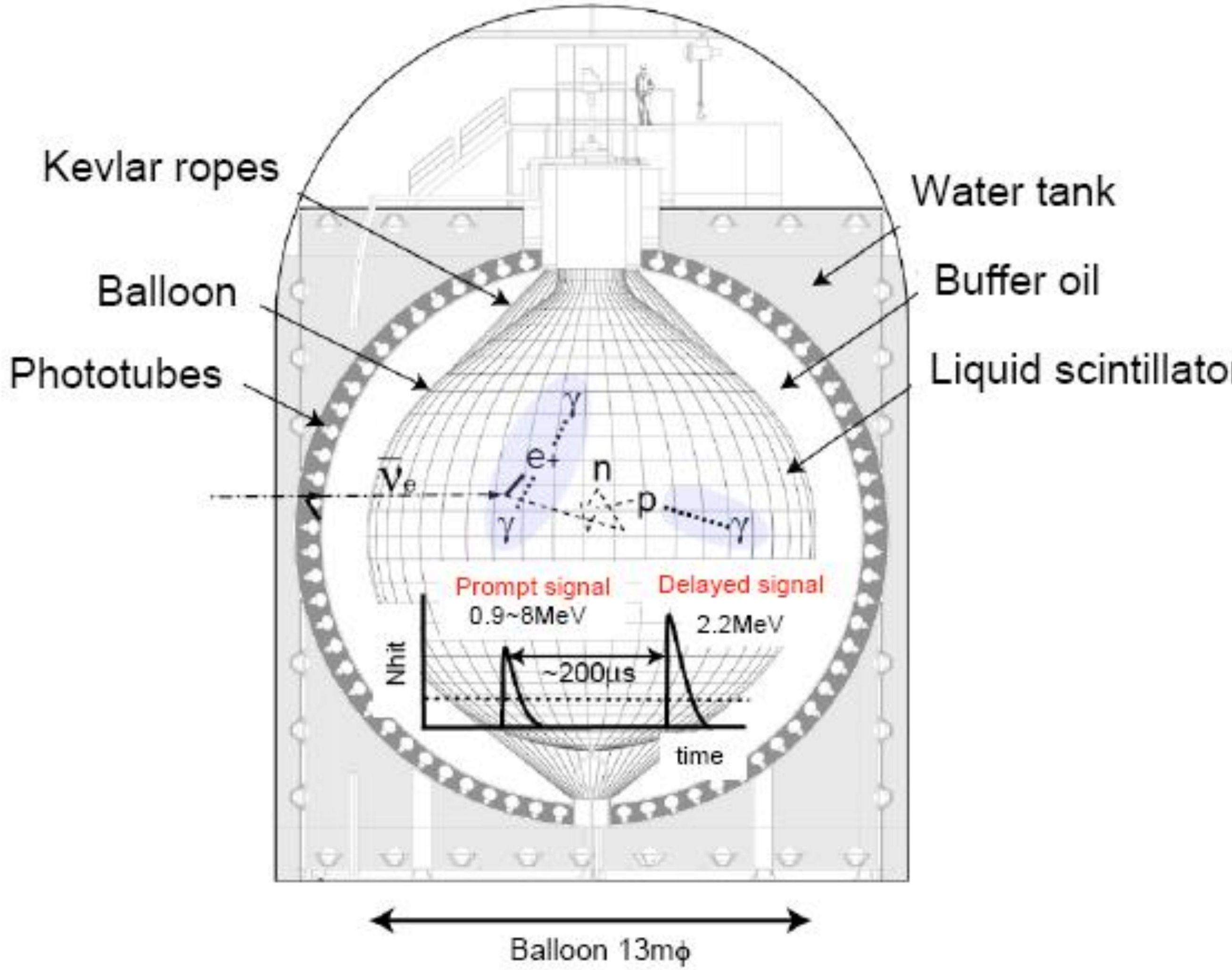
$10^{-5}\ \mathrm{eV}^2$

$10^5\mathrm{m} = 100\ \mathrm{km}$

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

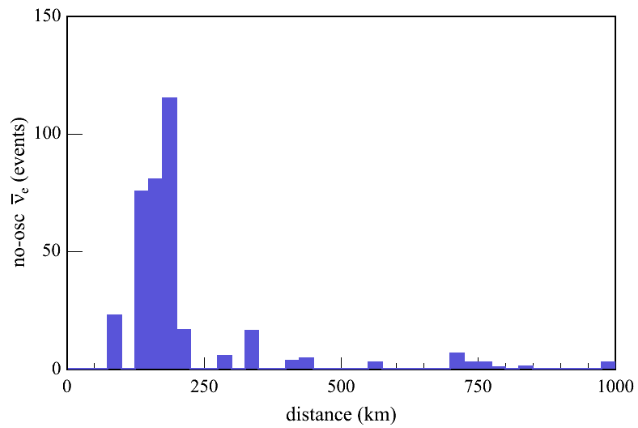
1 MeV

Kamioka Liquid *Antineutrino* Detector

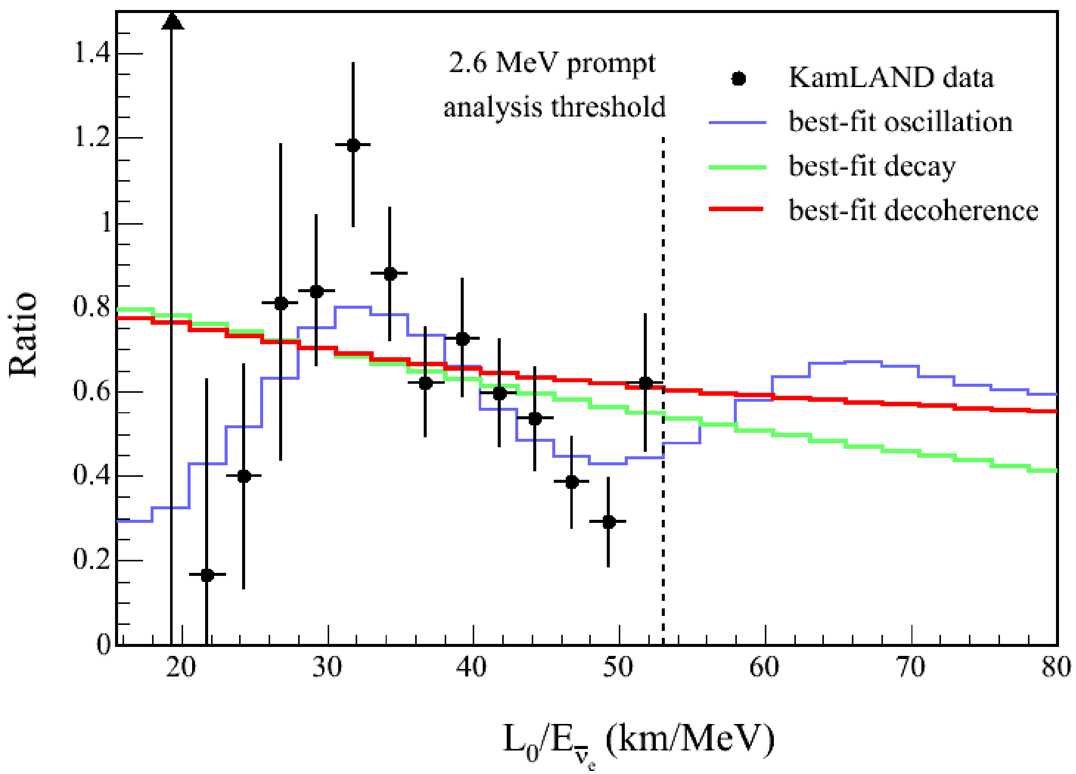


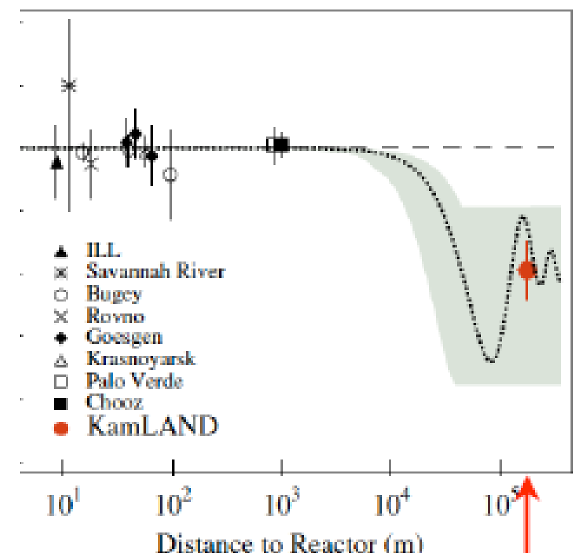
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

expected no-oscillation neutrino event rate at KamLAND



180 km





180 km

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.

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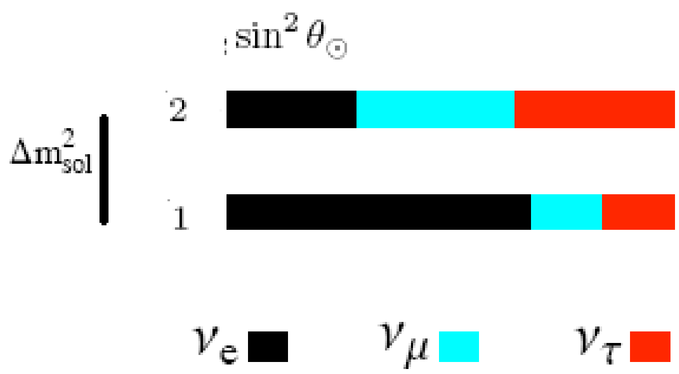

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$$\sin^2\theta_\odot = 0.310 \pm 0.026$$

at 68% CL

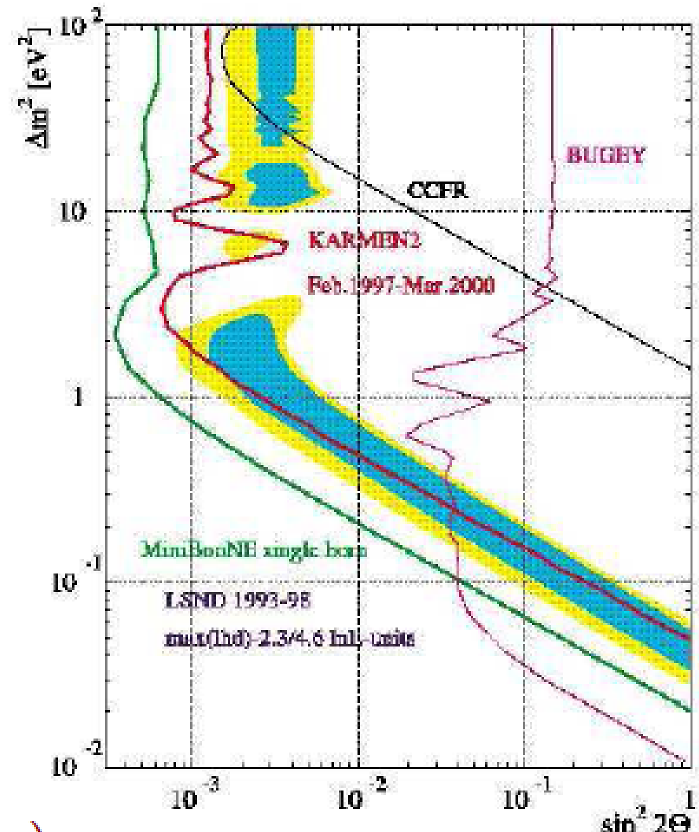
SNO, KamLAND, SK/K, GNO/Gallex, SAGE, Cl

The LSND experiment

- The only short distance signal for oscillation: $L = 30$ m with $\langle E_\nu \rangle \sim 30$ MeV;

- Used the proton beam of Los Alamos. Same production chain as in ATM:

$$\boxed{1} \quad p + \text{target} \to \pi^+ + X,$$
$$\boxed{2} \quad \pi^+ \to \mu^+ + \nu_\mu,$$
$$\boxed{3} \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu;$$



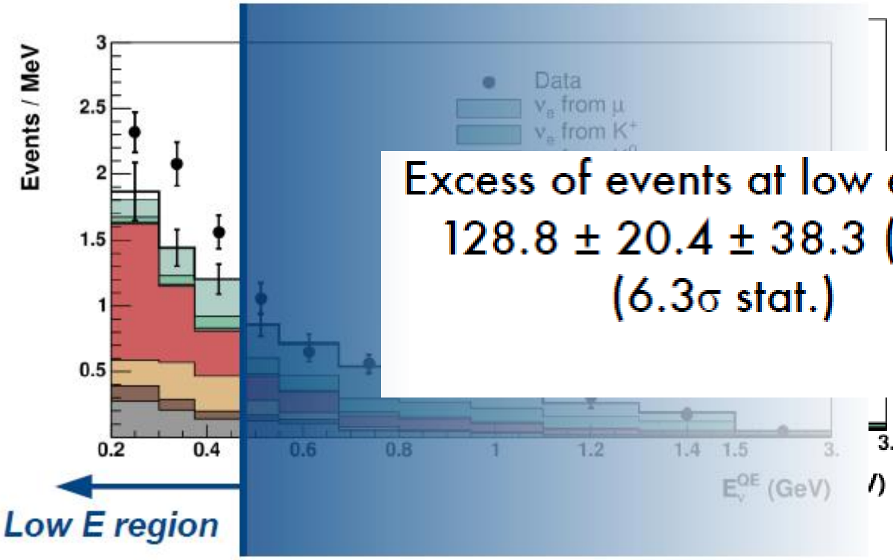
- observed $\bar{\nu}_\mu \to \bar{\nu}_e$ with probability $\langle P_{e\mu} \rangle = (0.26 \pm 0.07 \pm 0.05)\%$

- Karmen which searched for the same signal and did not observe oscillations.

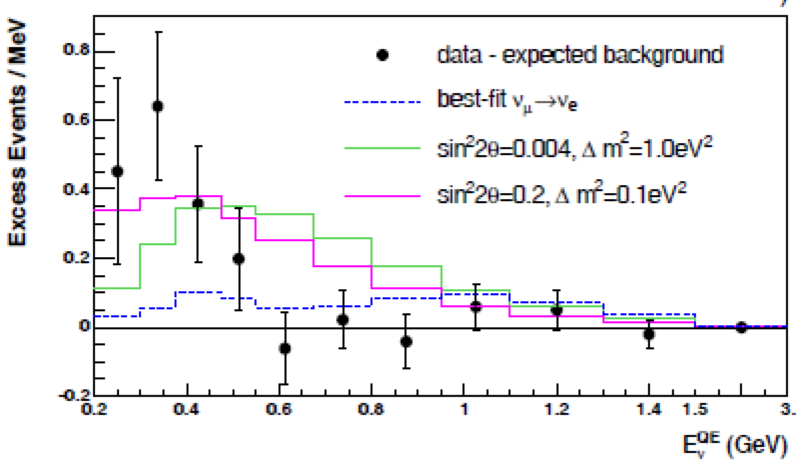
$$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}})$$

MiniBooNE Neutrinos

01; PRL 102 (2009) 101802]

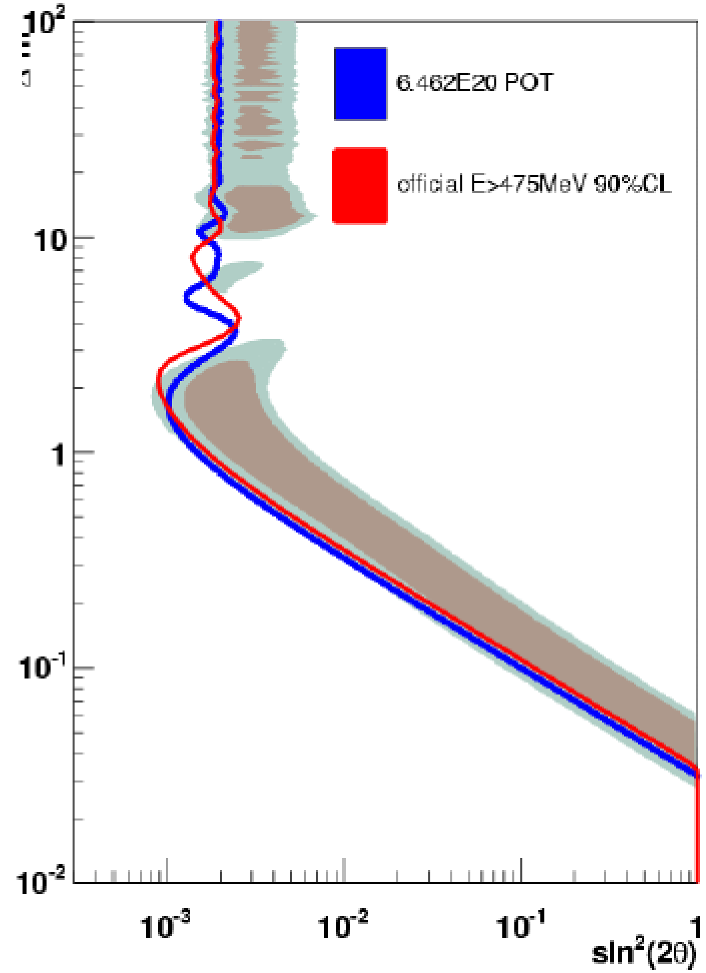


Excess of events at low energy:
128.8 ± 20.4 ± 38.3 (3.0σ)
(6.3σ stat.)



[MiniBooNE, PRL 102 (2009) 101802, arXiv:0812.2243]

$475 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$



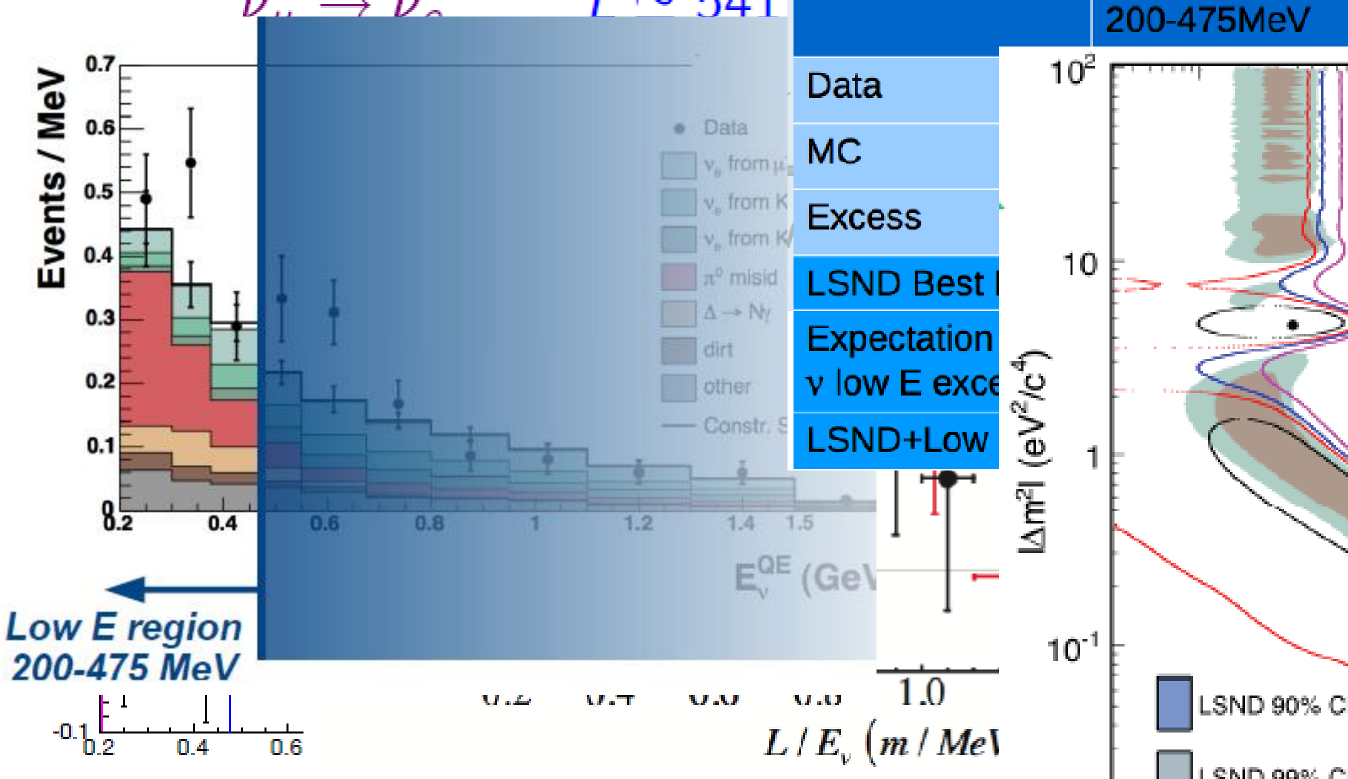
[Djurcic, arXiv:0901.1648]

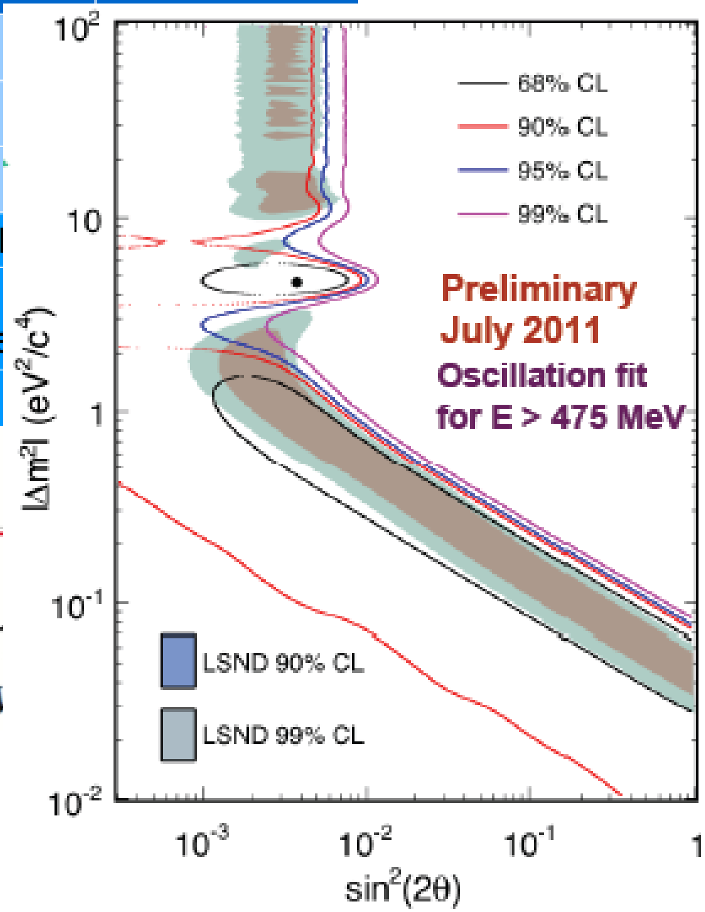
Low-Energy Anomaly!

MiniBooNE Antineutrinos

[PRL 103 (2009) 111801; PRL 105 (2010) 181801]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \sim 541$ m $\quad 475$ MeV $\lesssim E \lesssim 3$ GeV



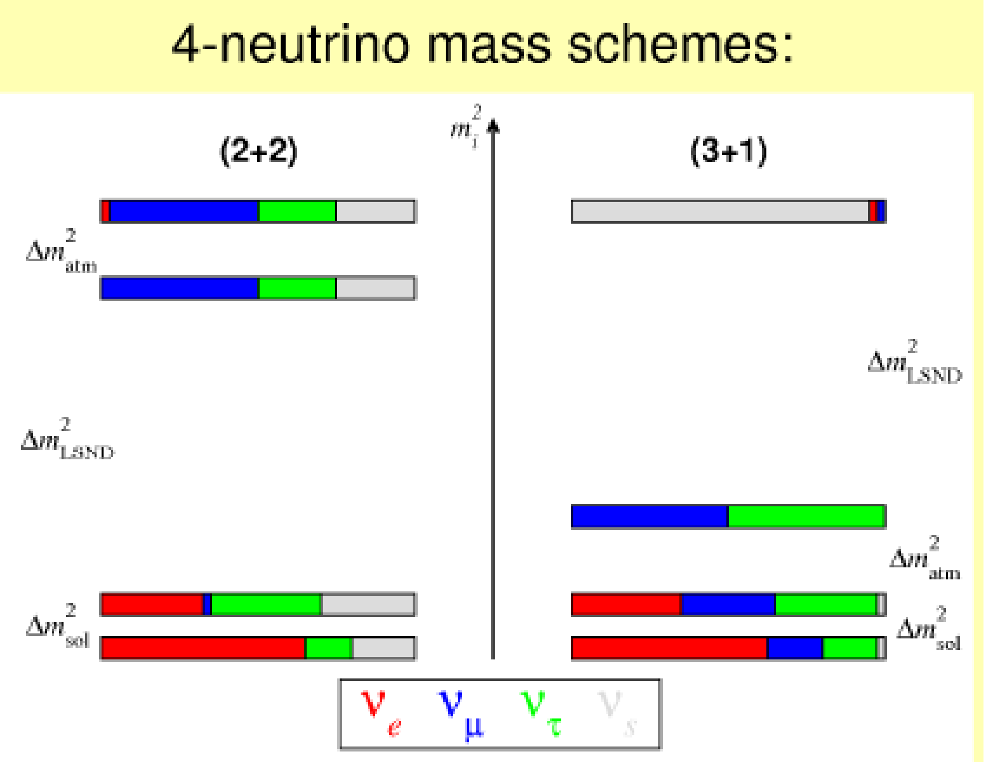


With new data the significance went down

Similar L/E but different L and E $\Longrightarrow$ Oscillations!

With 3 different Δm^2 4 light neutrinos needed!

4th ν: cannot be active – must be sterile. Mixing matrix: 6 θ_{ij}, 3 Dirac-type $\not{C}\not{P}$ phases. <u>But:</u> simplifications occur – only two possible type of schemes: 2+2 and 3+1



Nu Standard Model:

The ν Standard Model

- 3 light (m_i <1 eV) Majorana Neutrinos:

  $\Rightarrow$ only 2 δm^2

  $|\delta m^2_{atm}| \sim 2.5 \times 10^{-3}$ eV^2 and $\delta m^2_{solar} \sim +8.0 \times 10^{-5}$ eV^2

- Only Active flavors (no steriles):
  $e,\ \mu,\ \tau$

- Unitary Mixing Matrix:

  3 angles ($\theta_{12},\ \theta_{23},\ \theta_{13}$), 1 Dirac phase ($\delta$),

  2 Majorana phases (α_2, α_3)

$(n \times n)$ unitary mixing matrix $\tilde{U}$ $\Rightarrow$ n^2 real parameters:

$$\frac{n(n-1)}{2} \quad \text{mixing angles}, \qquad \frac{n(n+1)}{2} \quad \text{phases}$$

In Dirac ν case: $n+(n-1)=2n-1$ phases unphysical – can be absorbed into redefinition of charged lepton and neutrino fields. Number of physical phases:

$$\frac{n(n+1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$$

In Majorana case – only n phases can be absorbed (redefinition of ν fields not possible) $\Rightarrow$ In addition to Dirac-type phases there are $(n-1)$ physical Majorana-type phases.

$$|\nu_\alpha\rangle_{flavor} = U_{\alpha i}|\nu_i\rangle_{mass}.$$

Atmos. L/E $\mu \to \tau$ | Atmos. L/E $\mu \leftrightarrow e$ | Solar L/E $e \to \mu, \tau$ | $\beta\beta 0\nu$ decay

500km/GeV | 15km/MeV

$$\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}\begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

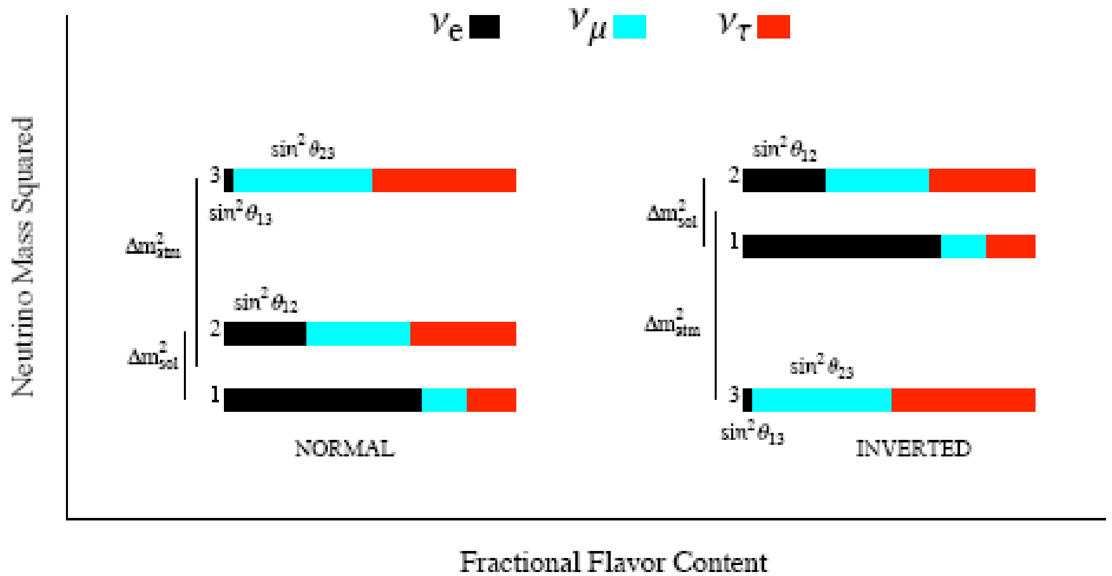
In oscillation phenomena,

the phases $\alpha_2,\ \alpha_3$ are unobservable $(U_{\alpha i}U^*_{\beta i})$

and also the value of m_{lite} is irrelevant (δm^2)

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

(12)-Sector:



(12) Parameters: SNO, KamLAND, SK

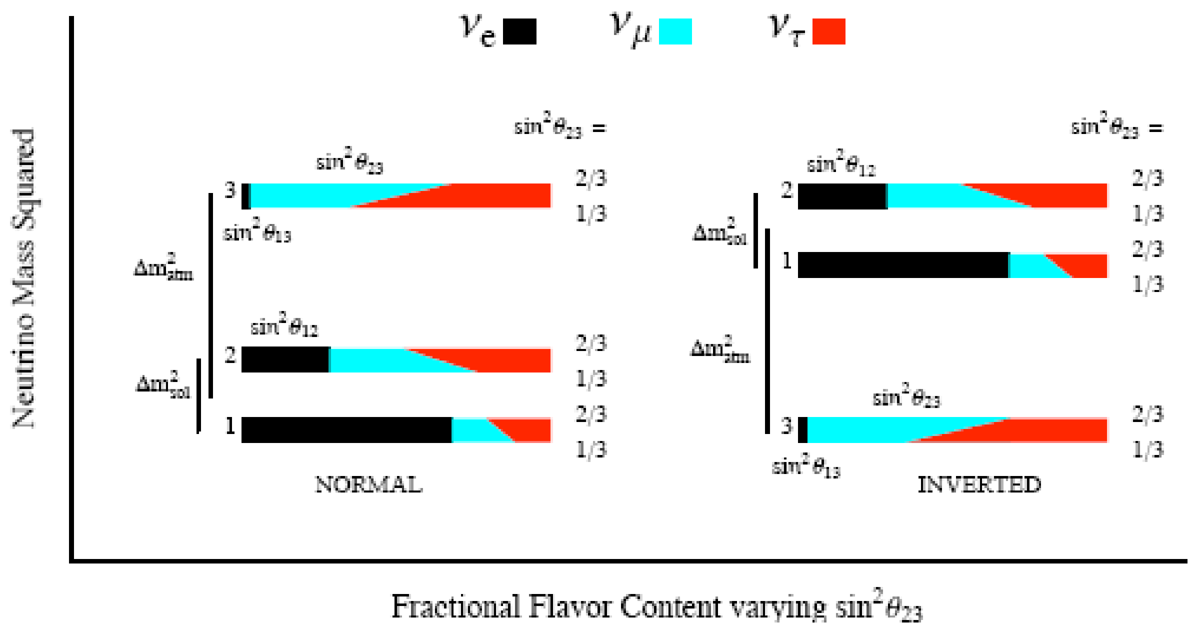
$$\delta m^2_{21} = +8.0 \pm 0.8 \times 10^{-5}\ eV^2$$

$$0.25 < \sin^2\theta_{12} < 0.37$$

$\sin^2\theta_{12} \geq \frac{1}{2}$ excluded at $> 5\ \sigma$!

sign of δm^2_{21} determined at this C.L.

(23)-Sector:



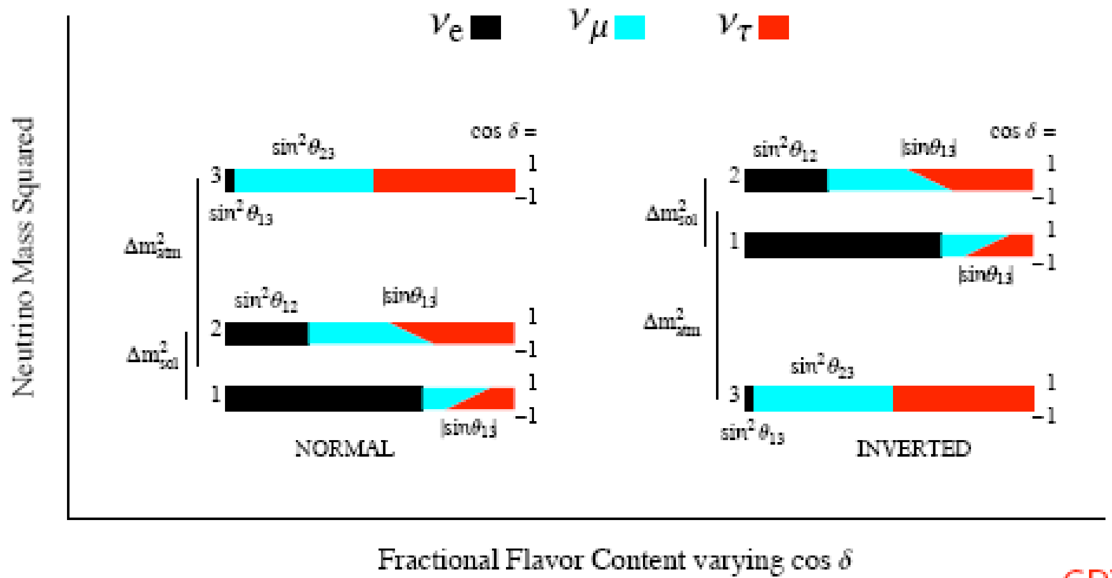
(23) Parameters: SK, K2K

$$|\delta m^2_{32}| = 1.5 - 3.4 \times 10^{-3}\ eV^2$$

$$0.36 < \sin^2\theta_{23} < 0.64$$

(obtained from $\sin^2 2\theta_{23} > 0.91$)

(13)-Sector:



CPT: $\delta \Leftrightarrow -\delta$ Invariant!

$$\boxed{P(\nu_e \to \nu_e) = 1 - 4|U_{e1}|^2|U_{e2}|^2 \sin^2\Delta_{21} - 4|U_{e1}|^2|U_{e3}|^2 \sin^2\Delta_{31} - 4|U_{e2}|^2|U_{e3}|^2 \sin^2\Delta_{32}}$$

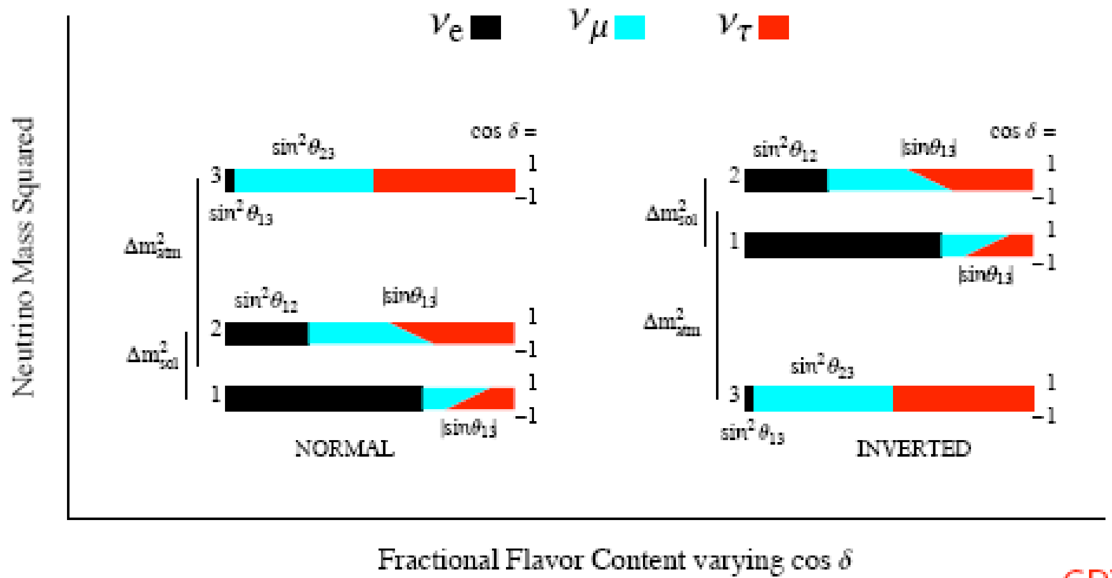
$$m_3^2 - m_1^2 = (m_3^2 - m_2^2) + (m_2^2 - m_1^2)$$

$L_{32} \sim 0.8$ km

$$P(\nu_e \to \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

$L_{21} \sim 30$ km

(13)-Sector:

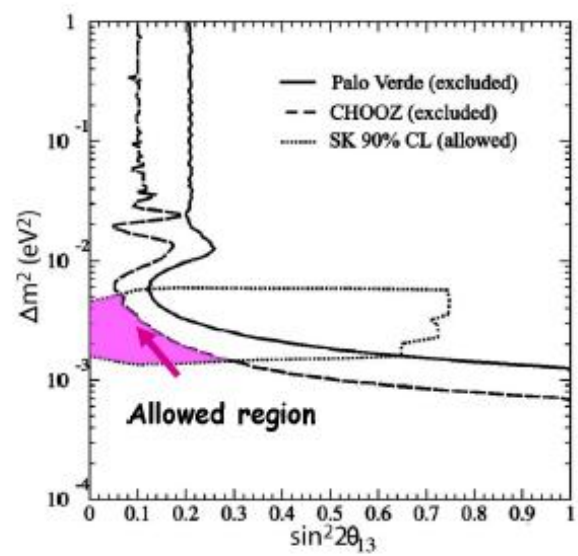


Less than
4% ν_e
in the 3 state!

CPT: $\delta \Leftrightarrow -\delta$ Invariant!

- **Palo Verde & Chooz: no signal**

$\text{Sin}^2 2\theta_{13} < 0.12$ @ 90%C.L. if $\Delta M^2_{23} = 0.0024\ \text{eV}^2$



- **Double Chooz: 1.7 σ**

$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{sys})$

$$\boxed{P(\nu_e \rightarrow \nu_\mu) \approx -4U_{e1}U_{\mu 1}U_{e2}U_{\mu 2}\sin^2\Delta_{21} + 4U_{e3}^2U_{\mu 3}^2\sin^2\Delta_{32}}$$

$$\boxed{\approx \sin^2(2\theta_{13})\ \sin^2(2\theta_{23})\ \sin^2(\Delta_{32})}$$

- **T2K: 2.5 σ over bkg**

$$\boxed{\begin{array}{l} 0.03 < \sin^2 2\theta_{13} < 0.28 \text{ @ 90\%C.L. for NH} \\ 0.04 < \sin^2 2\theta_{13} < 0.34 \text{ @ 90\%C.L. for IH} \end{array}}$$

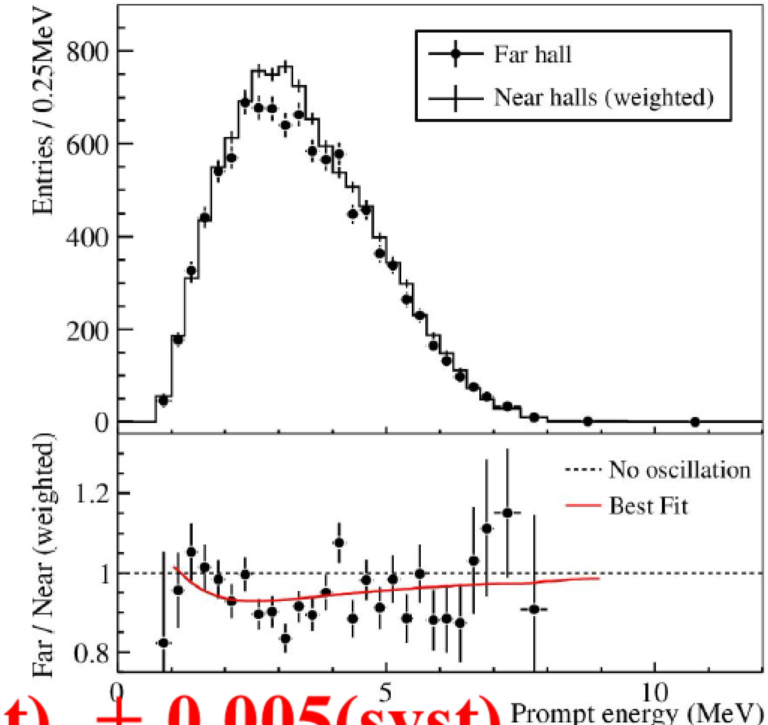
- **Minos: 1.7 σ over bkg**

$$\boxed{\begin{array}{l} 0 < \sin^2 2\theta_{13} < 0.12 \text{ @ 90\%C.L. NH} \\ 0 < \sin^2 2\theta_{13} < 0.19 \text{ @ 90\%C.L. IH} \end{array}}$$

March 8, 2012, Daya Bay (electron antineutrino disaprearance)

Observed: 9901 neutrinos at far site
Prediction: 10530 neutrinos if no os

R = 0.940 ±0.011 (stat) ±0.00

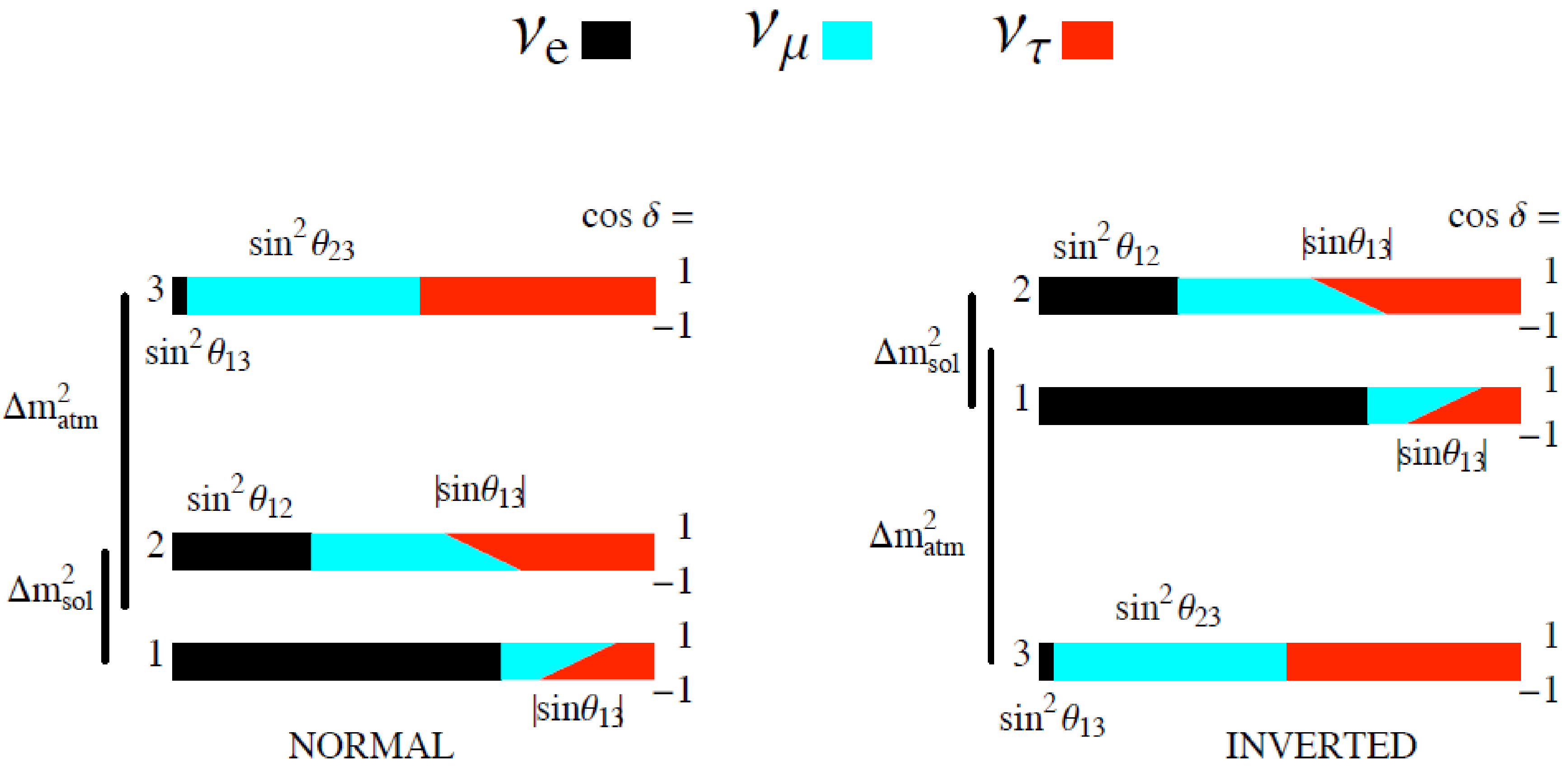


$\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

Spectral distortion
Consistent with oscillation

5.2 σ for nonzero θ_{13}

What's to be done …



We determined that $m(K_L) > m(K_S)$ by

- Passing kaons through matter (regenerator)
- Beating the unknown sign$[m(K_L) - m(K_S)]$ against the known sign[reg. ampl.]

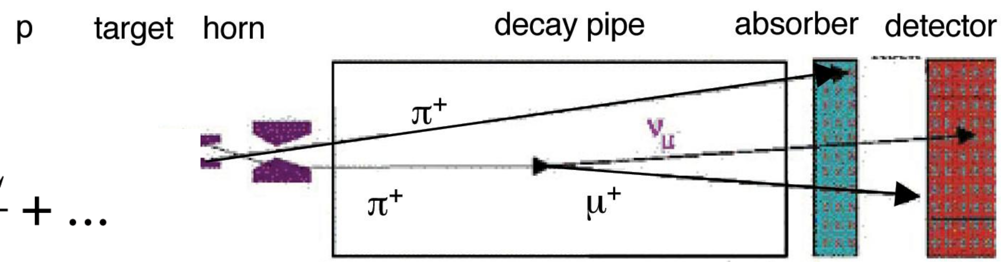
We will determine the sign(Δm^2_{32}) by

- Passing neutrinos through matter (Earth)
- Beating the unknown sign(Δm^2_{32}) against the known sign[forward $\nu_e e \rightarrow \nu_e e$ ampl]

$$\mathrm{L} \approx \frac{2\pi}{G_F n_e} \approx 1.16\ 10^4\ \mathrm{km} \left(\frac{1.69\ 10^{24}\ cm^3}{n_e}\right)$$

~~CP~~ :How we are going to do it ?

Accelerator experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \ldots$$

- Appearance experiment $\nu_\mu \rightarrow \nu_e$
- Measurement of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ yields δ

<u>Remember what happens in the quark sector !!!</u>

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} \quad = \quad s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}L}{2}\right) \qquad \equiv P^{atmos}$$

$$+ \quad c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}L}{2}\right) \qquad \equiv P^{solar}$$

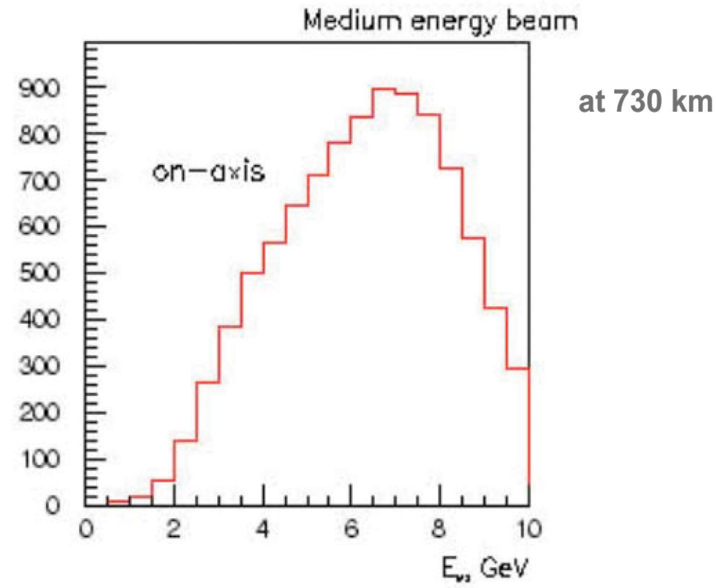
$$+\tilde{J} \quad \cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right) \frac{\Delta_{12}L}{2} \sin\left(\frac{\Delta_{23}L}{2}\right) \qquad \equiv P^{inter}$$

$$(\tilde{J} \equiv c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{12} \ \sin 2\theta_{23}, \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu} \ )$$

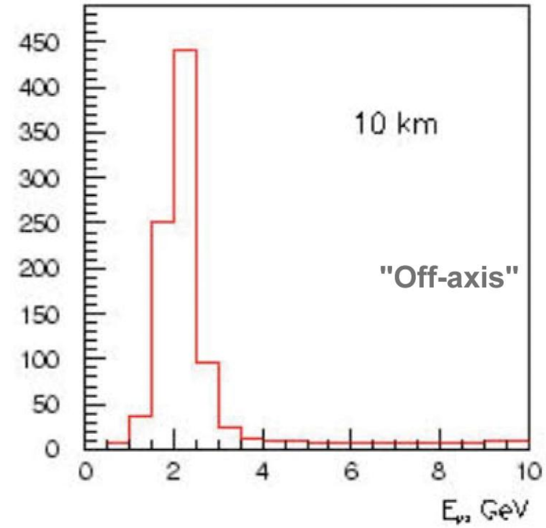
$$P\left(\overline{\nu}_\mu \to \overline{\nu}_e\right) - P\left(\nu_\mu \to \nu_e\right) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$
$$\times \sin\left(\Delta m^2 31 \frac{L}{4E}\right)\sin\left(\Delta m^2 32 \frac{L}{4E}\right)\sin\left(\Delta m^2 21 \frac{L}{4E}\right)$$

The off axis idea

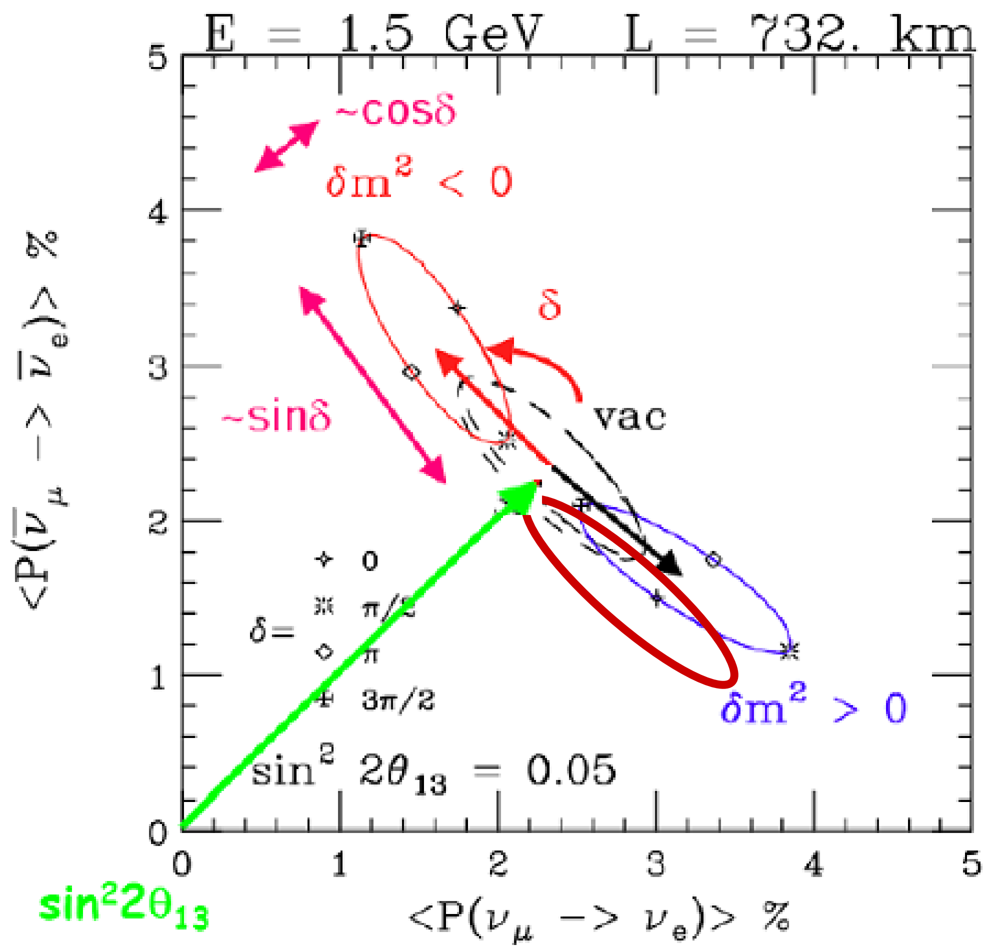
By going off axis, the beam energy is reduced and the spectrum becomes very sharp.



Allows an experiments to pick an energy for the maximum oscillation length.



What will we get ?



Minakata and Nunokawa

Vacuum LBL:

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

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

$$\Delta_{ij} = |\delta m^2_{ij}| L/4E$$

CP violation !!!

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

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

$\nu_\mu \rightarrow \nu_e$ with MATTER

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

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 $\sin \Delta_{31}$

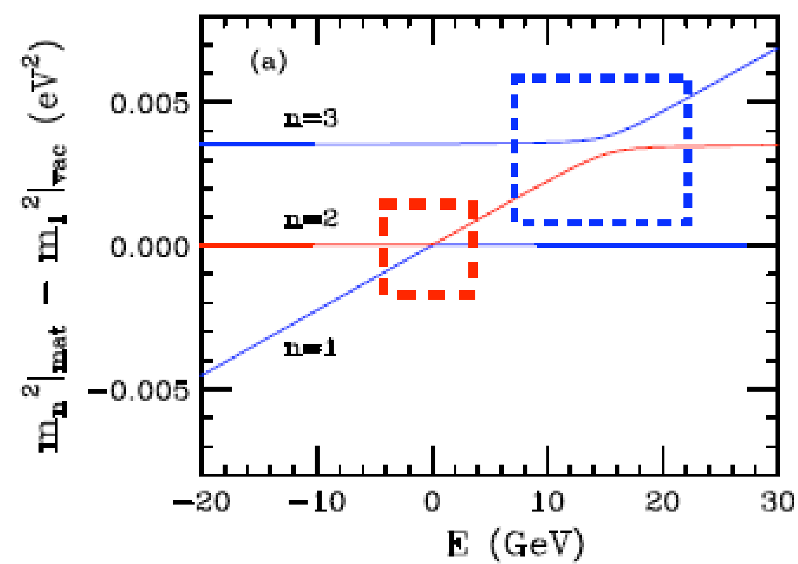
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

in vac $\sin \Delta_{21}$

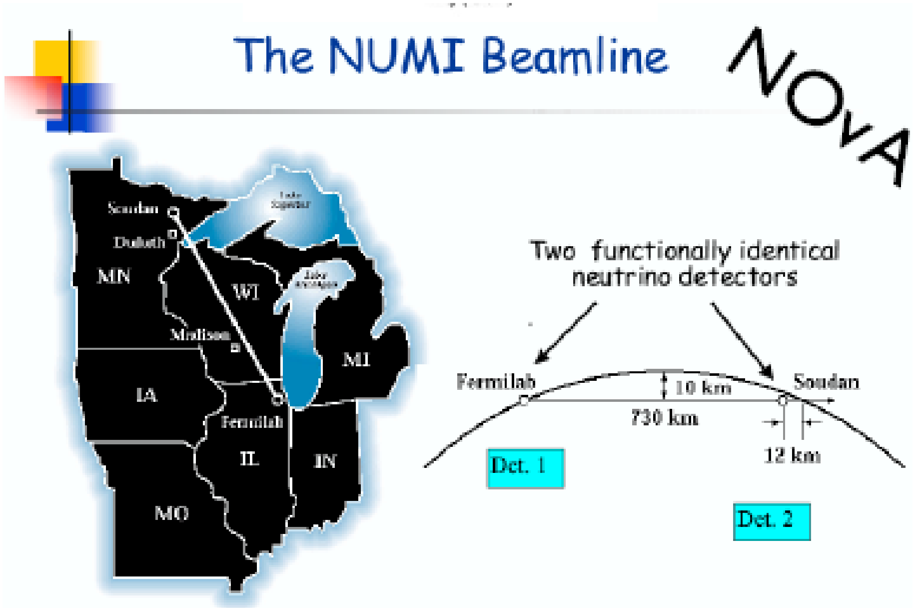
$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

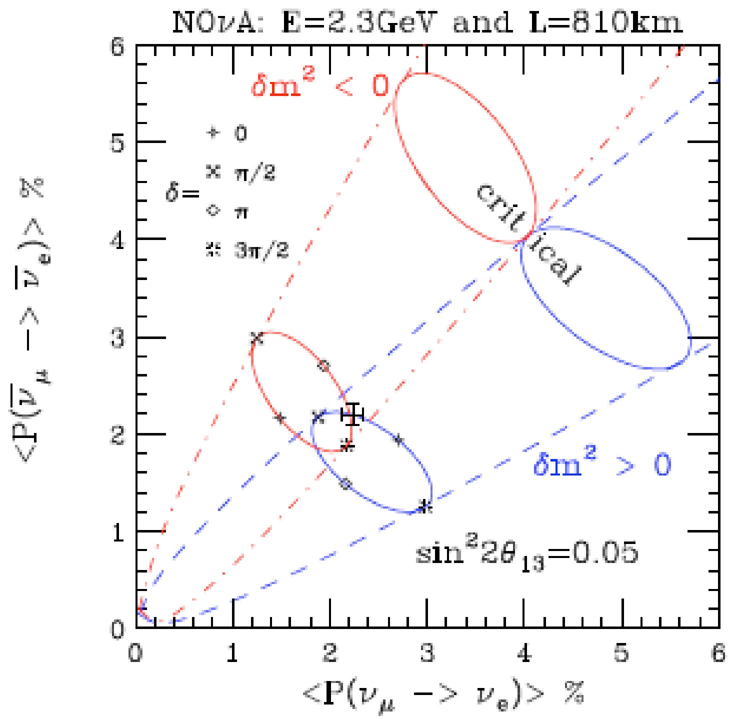
$$\pm = sign(\delta m^2_{31}) \quad \Delta_{ij} = |\delta m^2_{ij}| L/4E$$

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



Neutrino v Anti-Neutrino One Expt.





in the overlap region

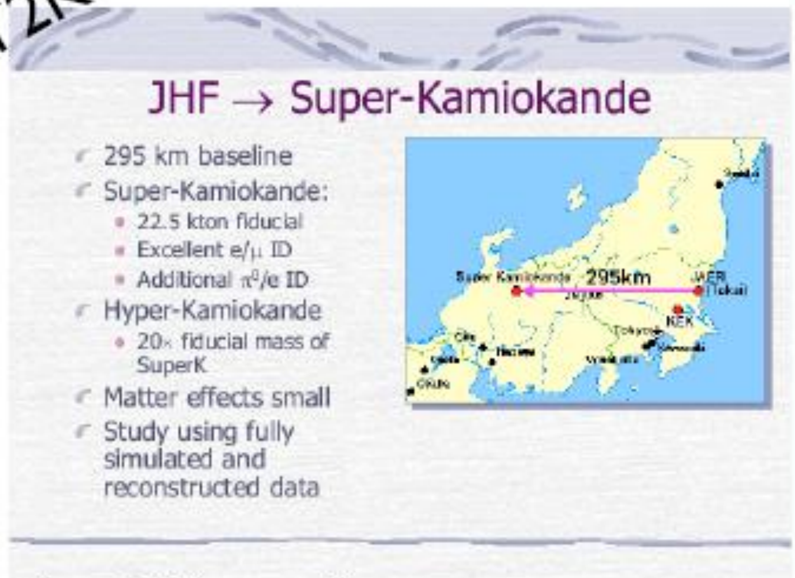
$$\langle \sin\delta\rangle_+ - \langle \sin\delta\rangle_- \;=\; 2\langle\theta\rangle/\theta_{crit} \;\approx\; 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

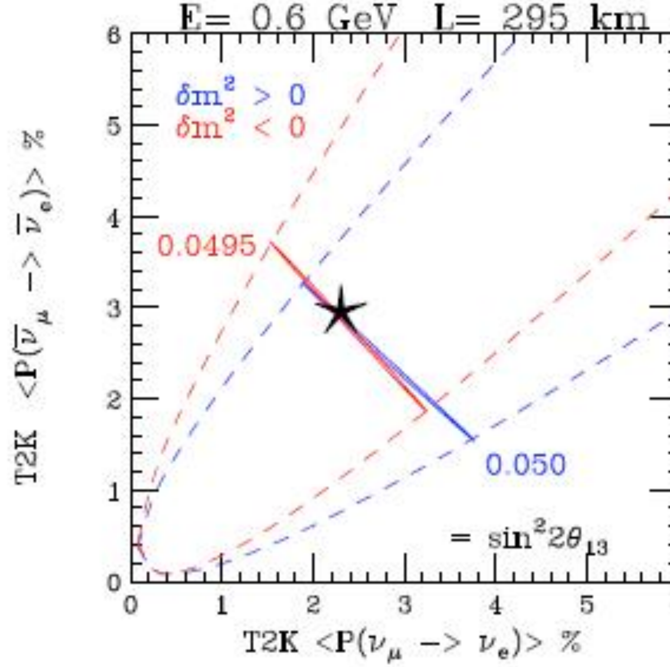
exact along diagonal --- approximately true throughout the overlap region!!!

$$\theta_{crit} = \frac{\pi^2}{8}\,\frac{\sin 2\theta_{12}}{\tan\theta_{23}}\,\frac{\delta m^2_{21}}{\delta m^2_{31}}\left(\frac{4\Delta^2/\pi^2}{1-\Delta\cot\Delta}\right)/(aL) \sim 1/6$$

i.e. $\sin^2 2\theta_{crit} = 0.10$

T2K





$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- \;=\; 2\langle\theta\rangle/\theta_{crit} \;\approx\; 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

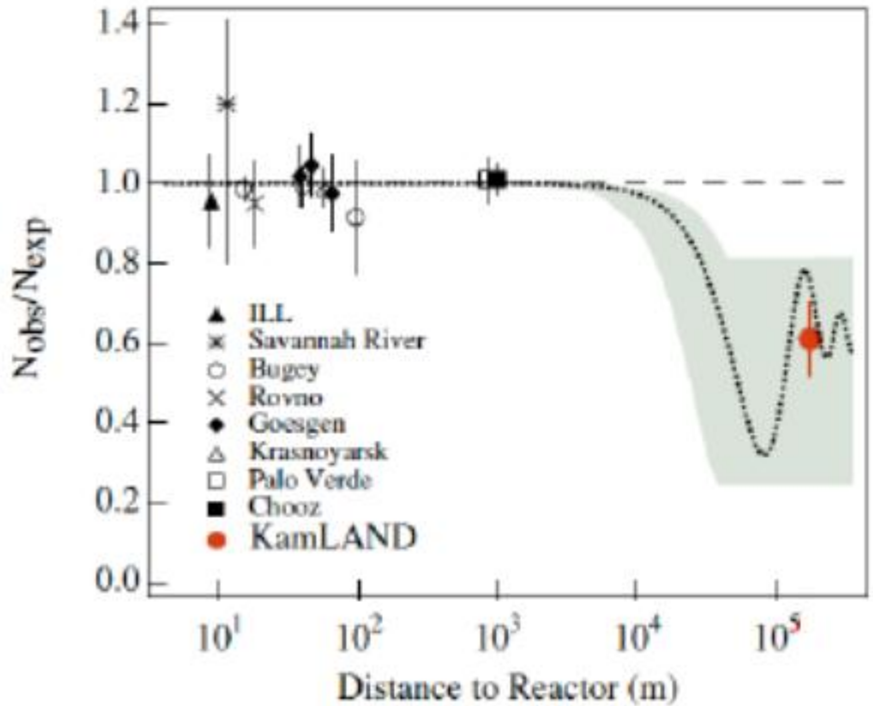
(ρL) for NOvA <u>three</u> times larger than (ρL) than T2K.

- ν_e fraction of ν_3: $-\ \sin^2\theta_{13}$
- mass hierarchy: $-$ sign of δm^2_{31}
- observable CP violation: $-\ \sin\delta \neq 0$

On March 2011 …. ArXiv 1101.2755

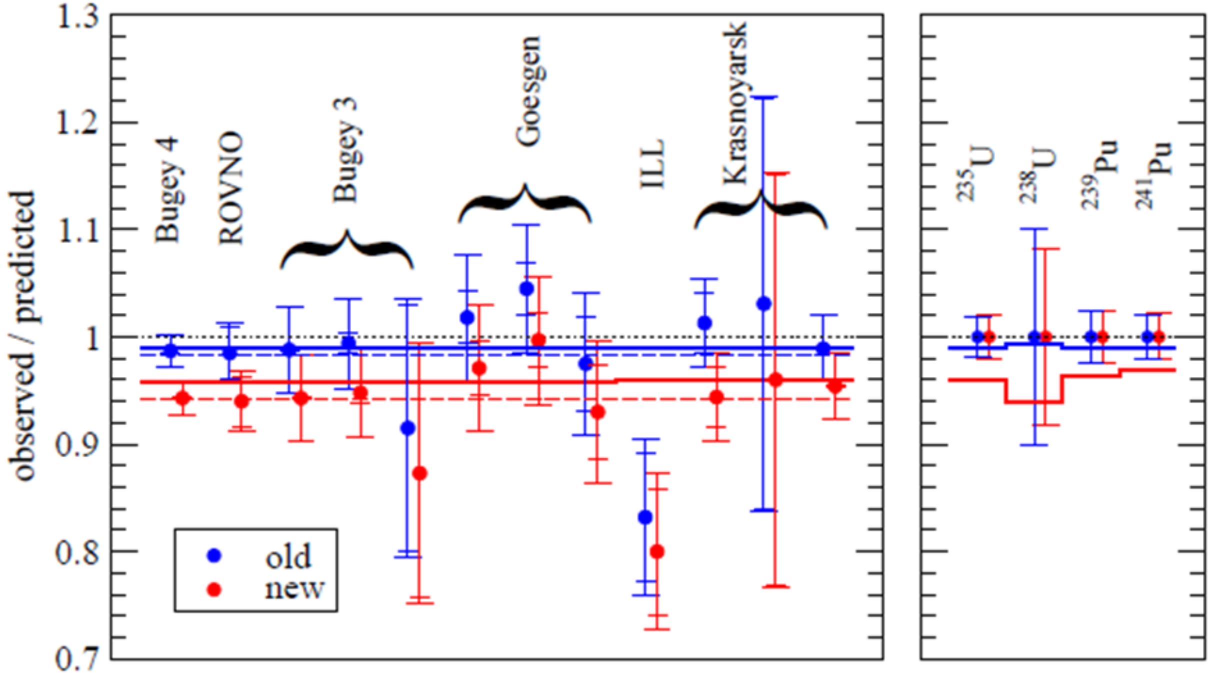
New reactor antineutrino spectra hav
and ^{238}U, increasing the mean flux b

This reevaluation applies to all react

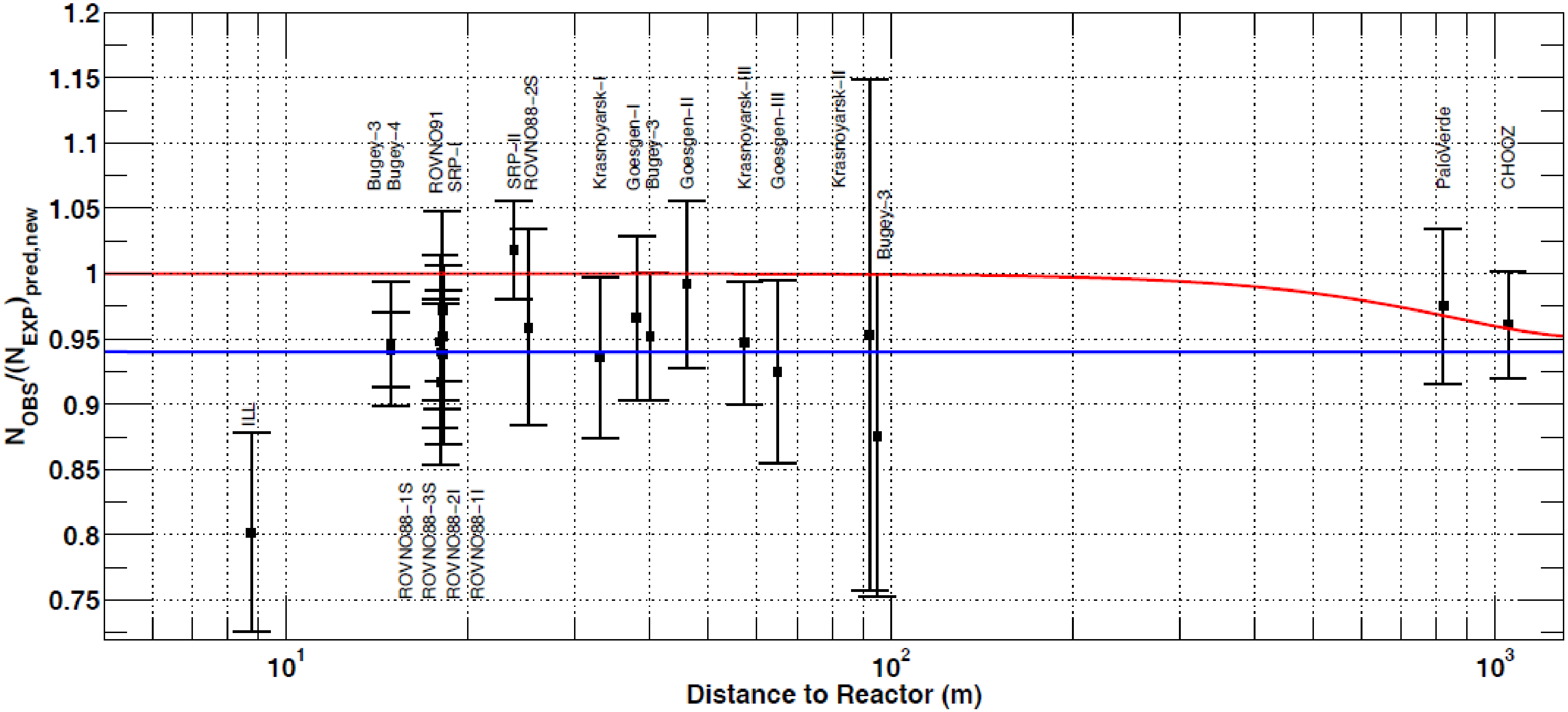


It means that for experiments at reactor-detector distances < 100 m the ratio of observed event rate to predicted rate shifts

$$0.976 \pm 0.024 \rightarrow 0.943 \pm 0.023$$



"The Reactor Antineutrino Anomaly," Phys. Rev. D 83: 073006, 2011 (ArXiv preprint, 14 Jan. 2011)



$3\ \nu\ \sin^2(2\theta_{13}) = 0.06$

$4\ \nu\quad \Delta m^2 > 1\ \mathrm{eV}^2\quad \sin^2(2\theta_{new}) = 0.12$