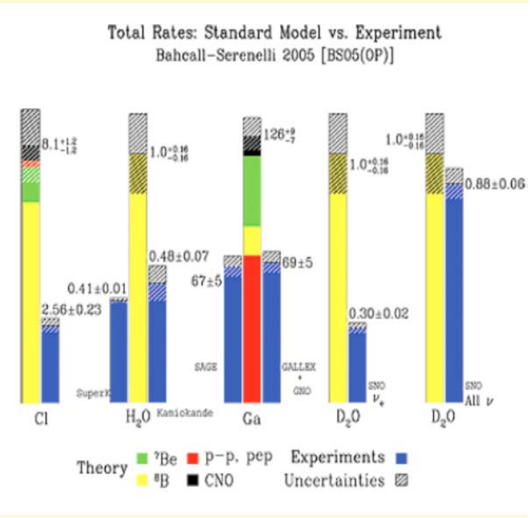
Fast & Curious 2

BSModel. Original Parts.

Gabriela Barenboim, TAE, September 15

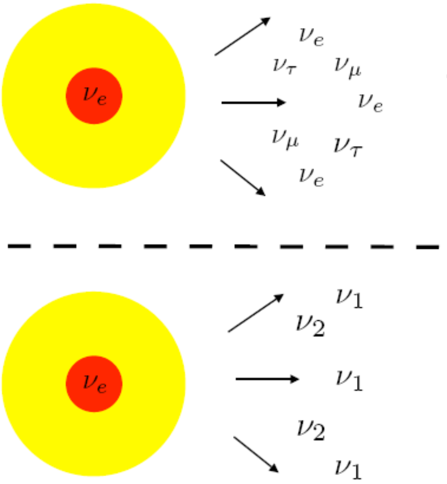
Ray Davis & John Bahcall



Theory v Exp.

Neutrino Flavor Transistions!!!

Identical Solar Twins:



flavor eigenstates

?????

mass eigenstates

Kinematical Phase:

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

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

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

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

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

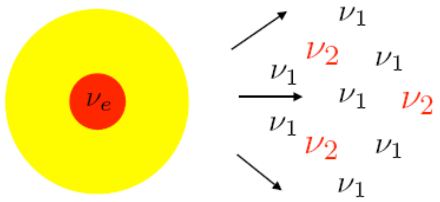
Note energy independence.

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

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

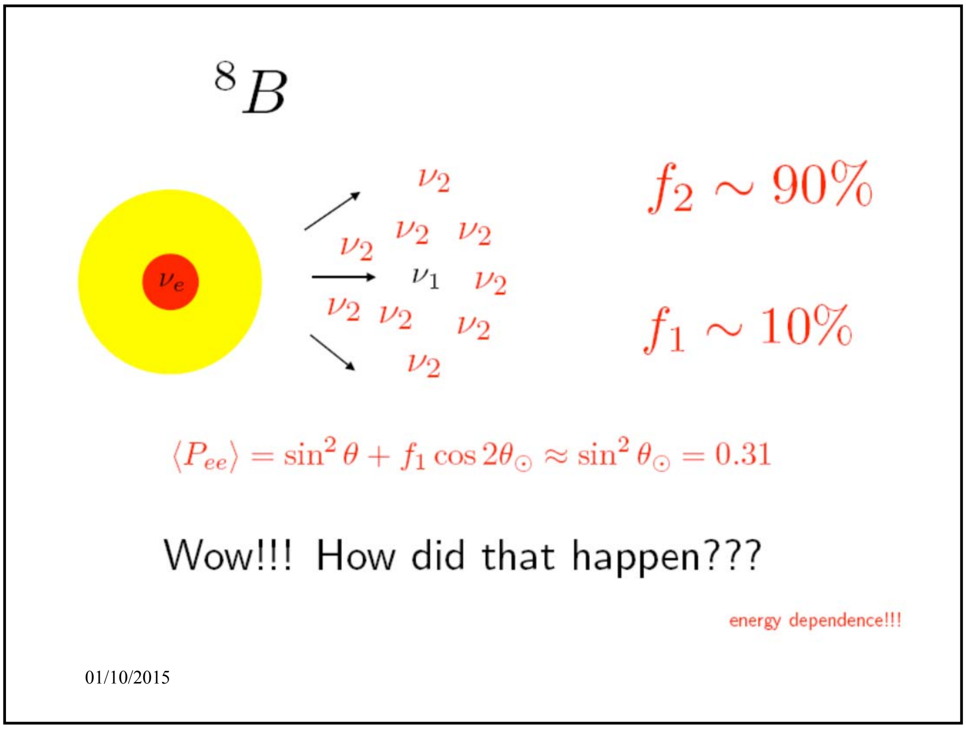


$f_1 \sim 69\%$

$f_2 \sim 31\%$

$$\langle P_{ee}\rangle \approx 0.6$$

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



^{8}B

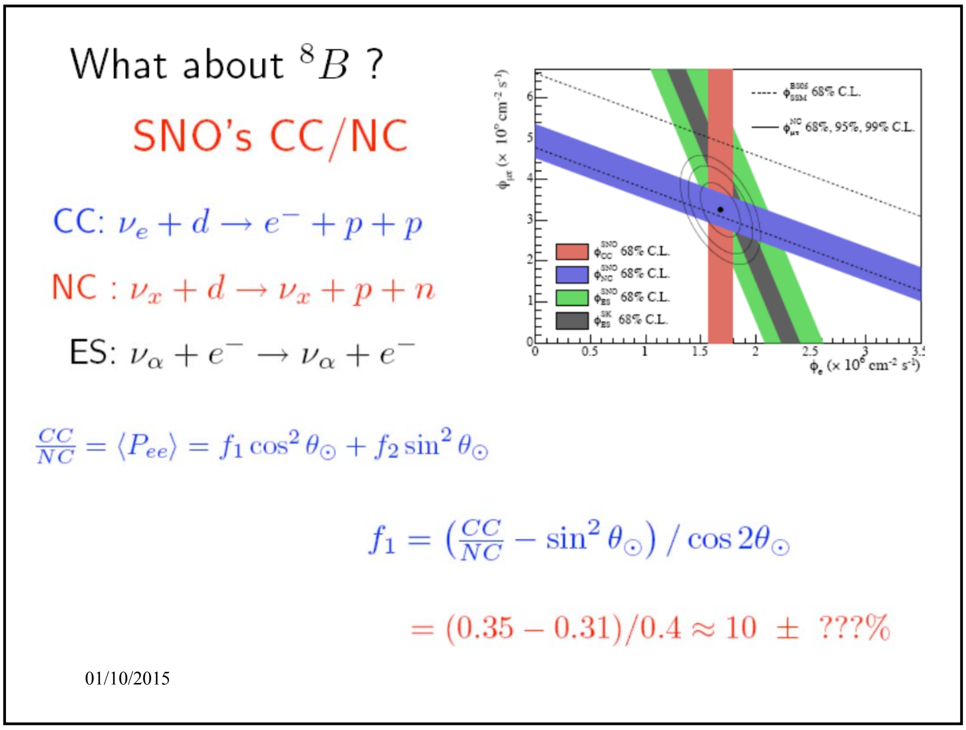
$f_2 \sim 90\%$

$f_1 \sim 10\%$

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

Wow!!! How did that happen???

energy dependence!!!



What about ^{8}B ?

SNO's CC/NC

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

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

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

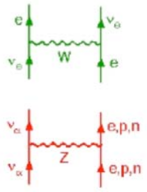
$$\frac{CC}{NC} = \langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

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

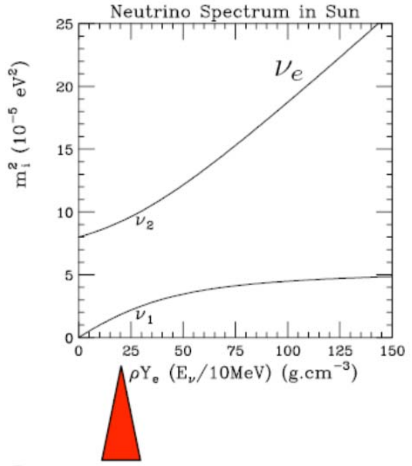
$$= (0.35 - 0.31)/0.4 \approx 10 \pm\ ???\%$$

MSW

Coherent Forward Scattering:



Wolfenstein '78



Mikheyev + Smirnov Resonance WIN '85

MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS

01/10/2015

Neutrino Evolution:

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

in the mass eigenstate basis

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

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

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

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

01/10/2015

in the flavor basis

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

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

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Coherent Forward Scattering:

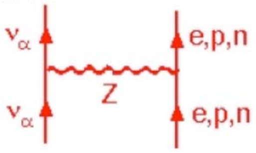
dimensions $[G_F N_e] = M^{-2}L^{-3} = M$

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

N_e is number density of electrons

+(-) for neutrinos (anti-neutrinos)

Wolfenstein '78



Same for all active flavors, therefore overall phases

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

01/10/2015

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:

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

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

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

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

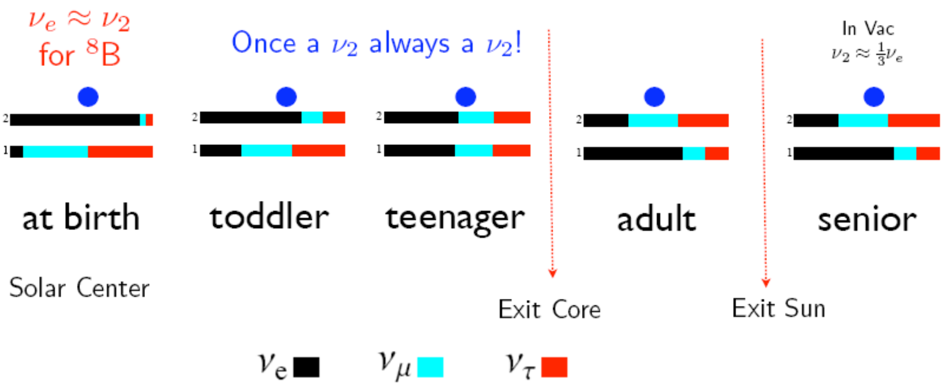
Resonance (Mikheyev + Smirnov '85): $2\sqrt{2} G_F N_e E_\nu = \delta m^2 \cos 2\theta_\odot$

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

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

$$\delta m_N^2 \to 2\sqrt{2} G_F N_e E_\nu \text{ and } \theta_\odot^N \to \pi/2 \qquad {}^8B$$

Life of a Boron-8 Solar Neutrino:



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

Once a ν_2 always a ν_2!

In Vac $\nu_2 \approx \frac{1}{3}\nu_e$

at birth

toddler

teenager

adult

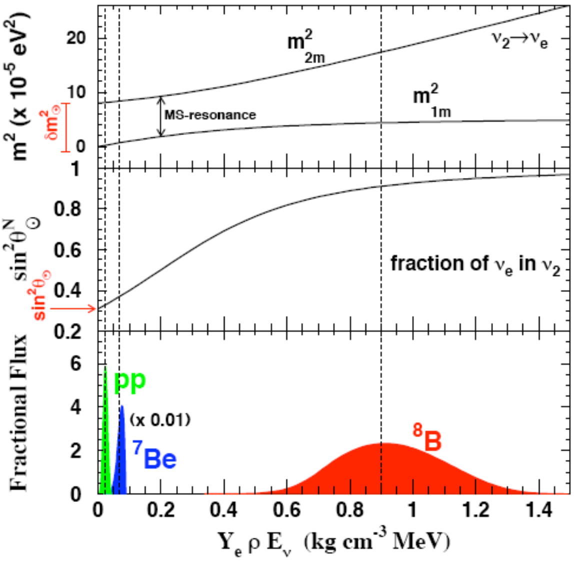
senior

Solar Center

Exit Core

Exit Sun

ν_e ■ ν_μ 🟦 ν_τ 🟥



In Vacuum

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

$$\sin^2\theta_\odot = 0.31 \pm 0.03$$

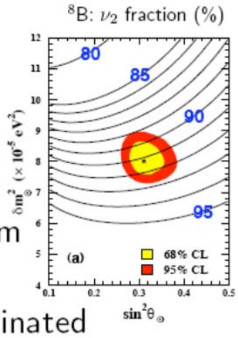
Whereas for ^{8}B at center of Sun

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

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

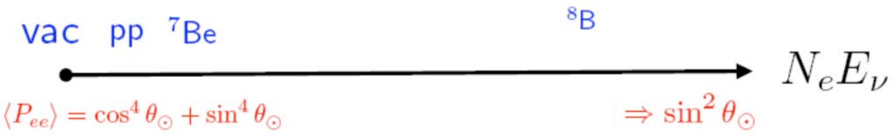
Mass Eigenstate Purity:

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



$f_1 = \cos^2\theta^N_\odot$ and $f_2 = \sin^2\theta^N_\odot$

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



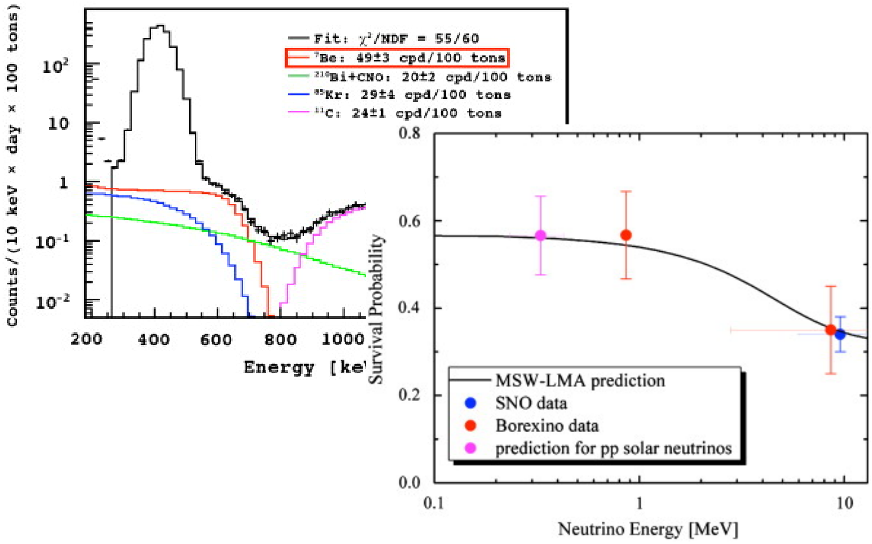
vac pp ^{7}Be ^{8}B

$N_e E_\nu$

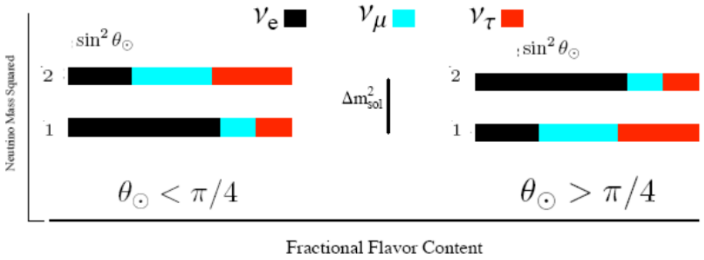
$\langle P_{ee} \rangle = \cos^4\theta_\odot + \sin^4\theta_\odot$

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

Borexino results (2012)



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 $\theta_\odot < \pi/4$

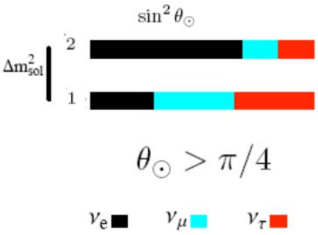
$\langle P_{ee}\rangle \geq \sin^2\theta_\odot$

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

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

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

Solar Hierarchy Determined !!!



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

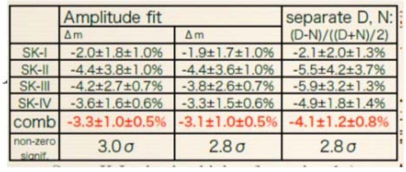
But $\boldsymbol{P_{ee}^{SNO} = 0.347 \pm 0.038 < 1/2}$

This solar hierarchy EXCLUDED !!!.

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 %



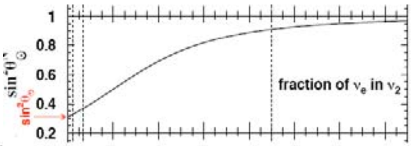
	Amplitude fit		separate D, N:
	Δm	Δm	(D-N)/((D+N)/2)
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
comb	-3.3±1.0±0.5%	-3.1±1.0±0.5%	-4.1±1.2±0.8%
non-zero signif.	3.0σ	2.8σ	2.8σ

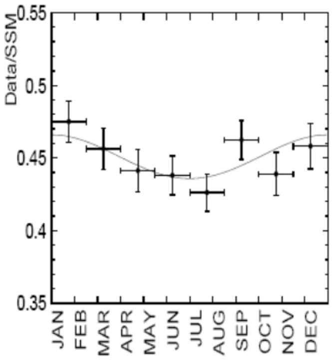
Spectral Distortion:

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

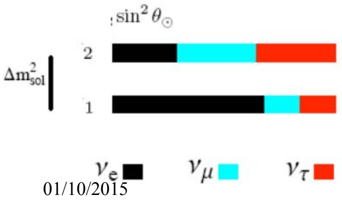
Summary:

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

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

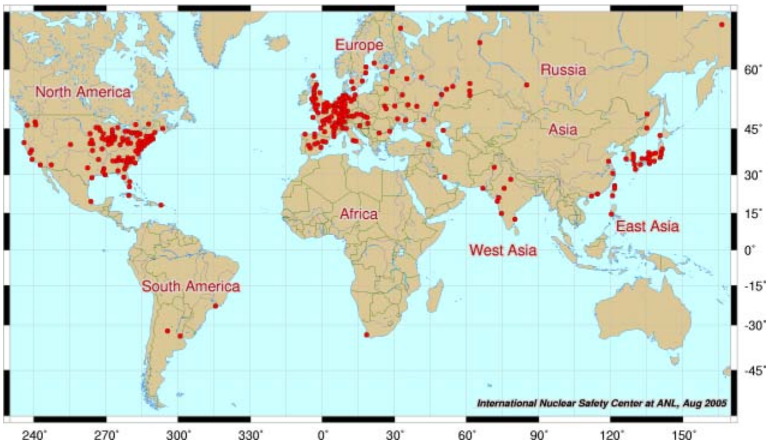
10^{-5} eV^2

10^5m = 100 km

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

1 MeV

Reactor Neutrinos



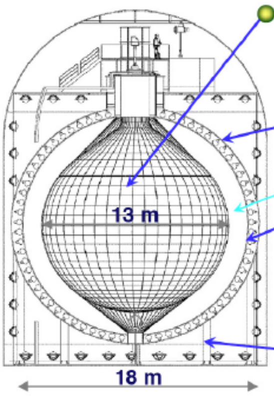
International Nuclear Safety Center at ANL, Aug 2005

Reactor Neutrinos

Reactor Neutrinos

KamLAND Detector

- detector location: old Kamiokande site
  : 2700 m.w.e.



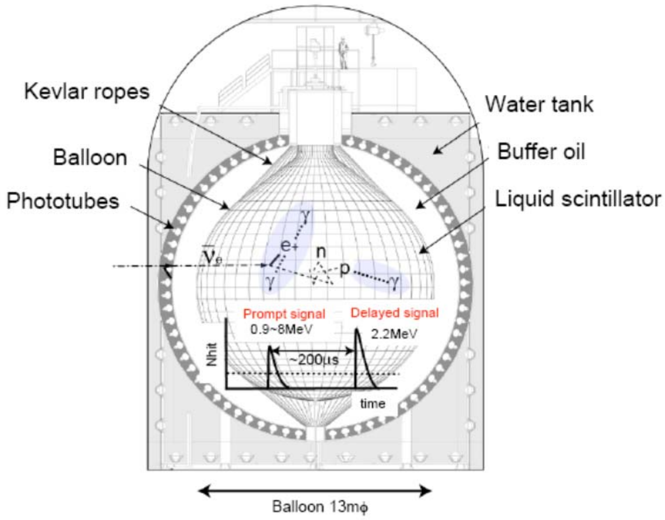
- 1000 ton liquid scintillator
  : 80% (dodecane) + 20% (pseudocumene) + 1.52 g/l PPO
  : housed in spherical plastic balloon
- 3000 m³ stainless steel vessel
  : filled with a mixture of paraffin oil and dodecane ($\Delta\rho = 0.04\%$)
- 1325 17-inch + 554 20-inch PMT's

commissioned in February, 2003

photocathode coverage : 22% → 34%
energy resolution at 1 MeV : 7.3% → 6.3%

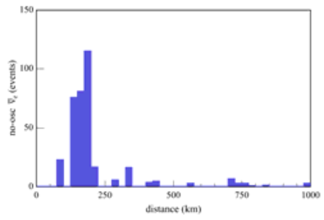
- water Cerenkov outer detector

Kamioka Liquid *Antineutrino* Detector

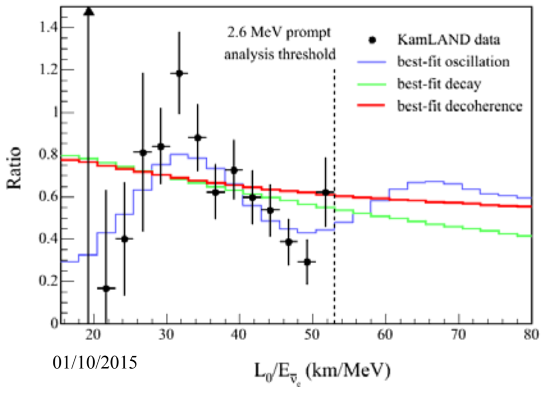


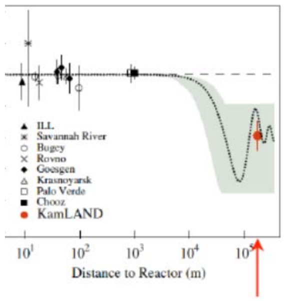
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

expected no-oscillation neutrino event rate at KamLAND



180 km





180 km

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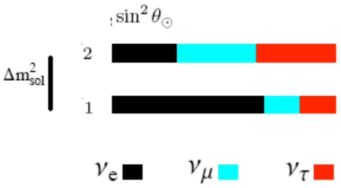


$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5} eV^2$$

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

at 68% CL

01/10/2015

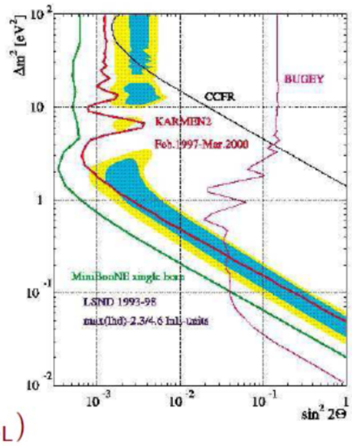
SNO, KamLAND, SK/K, GNO/Gallex, SAGE, Cl

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:

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

- 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.



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

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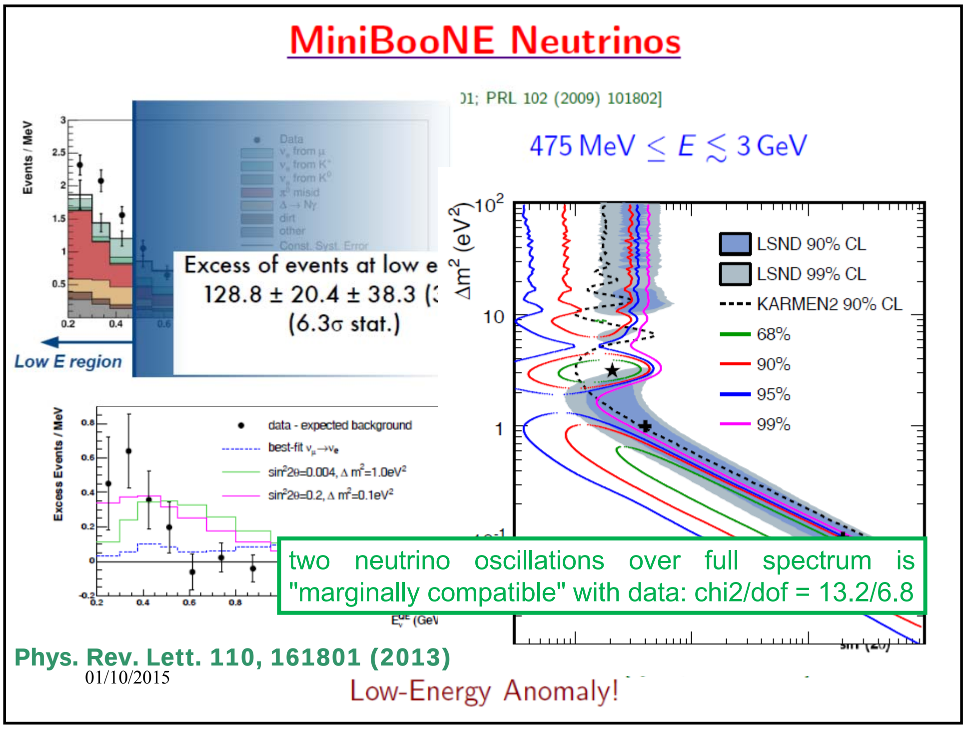


MiniBooNE Neutrinos

01; PRL 102 (2009) 101802]

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

Excess of events at low e
128.8 ± 20.4 ± 38.3 (
(6.3σ stat.)

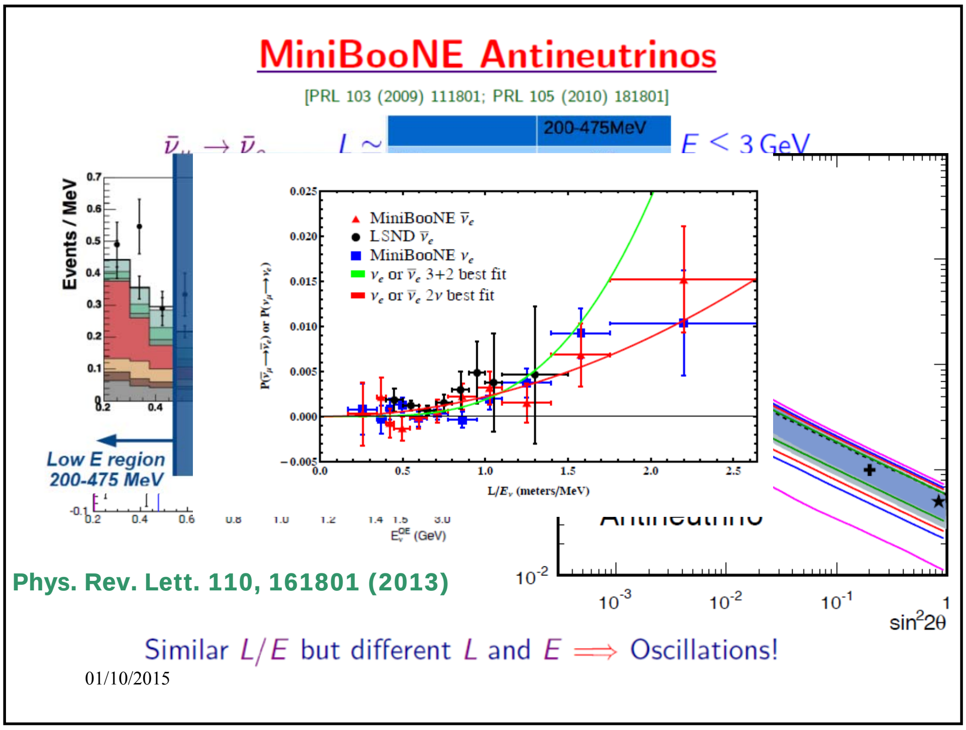
Low E region

two neutrino oscillations over full spectrum is "marginally compatible" with data: chi2/dof = 13.2/6.8

Phys. Rev. Lett. 110, 161801 (2013)

01/10/2015

Low-Energy Anomaly!



MiniBooNE Antineutrinos

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

200-475MeV

$E < 3\,\text{GeV}$

Low E region 200-475 MeV

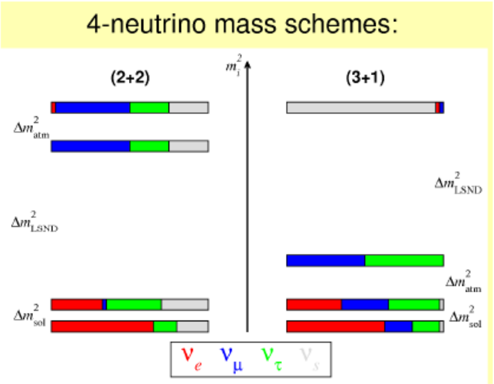
Phys. Rev. Lett. 110, 161801 (2013)

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

01/10/2015

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. But: 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:

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

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)

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

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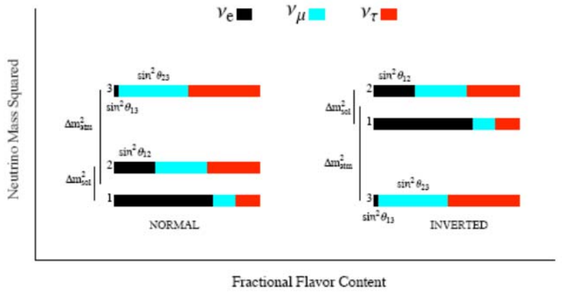
(12)-Sector:



(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.

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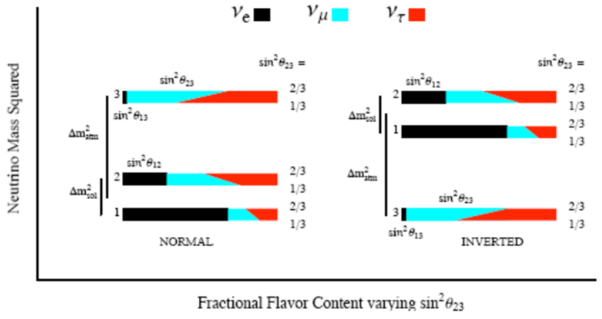
(23)-Sector:



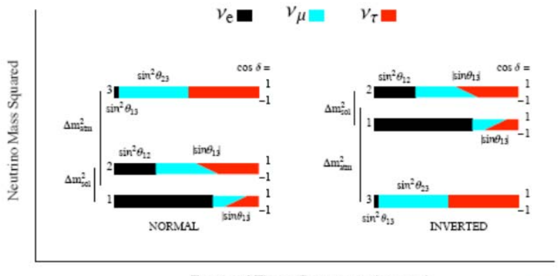
(23) Parameters: SK, K2K

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

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

(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

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

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

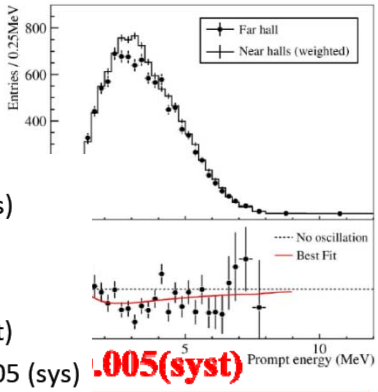
- **T2K: 2.5 σ over bkg**

0.03 < $sin^2(2\theta_{13}) = 0.140^{+0.038}_{-0.032}$ **for NH**
0.04 < **for IH**

- **Minos: 1.7 σ over bkg**

0 < $Sin^2 2\theta_{13}$ < 0.12 @ 90%C.L. NH
0 < $Sin^2 2\theta_{13}$ < 0.19 @ 90%C.L. IH

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



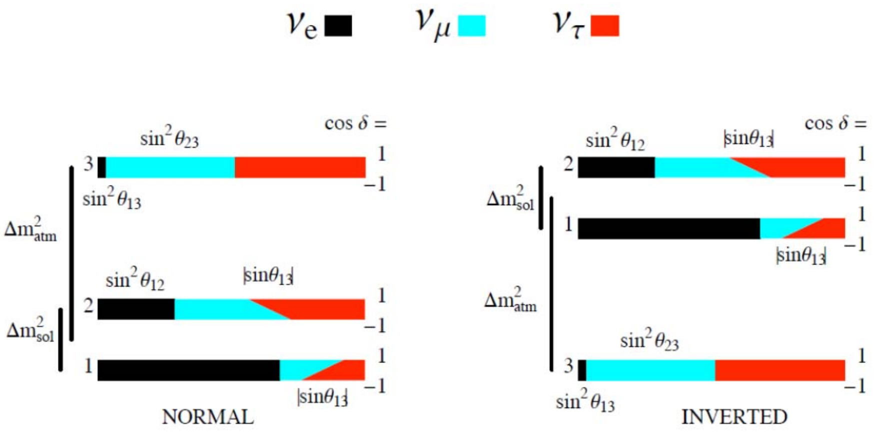
Observed: 9901 neutrinos at far site
Prediction: 10530 neutrinos if no os

- Double Chooz
  - $\sin^2 2\theta_{13}$=0.109±0.03(stat)±0.025(sys)
  - zero is excluded at 99.9% (3.1σ)
- Daya Bay
  - R = 0.944 ± 0.007 (stat) ± 0.003 (syst)
  - $\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (sys)
- RENO
  - R=0.920 ± 0.009(stat) ± 0.014(syst) (4.9σ)
  - $\sin^2 2\theta_{13}$= 0.113±0.013(stat)±0.019(sys)

.005(syst)

pectral distortion
onsistent with oscillation

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

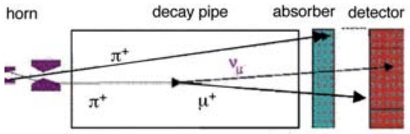
- Passing neutrinos through matter (Earth)
- Beating the unknown sign(Δm^2_{32}) against the known sign[forward $\nu_e\, e \rightarrow \nu_e\, e$ ampl]

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

$\cancel{CP}$: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

Remember what happens in the quark sector !!!

$$\begin{aligned}
P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} \quad &= \quad s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23} L}{2}\right) \quad \equiv P^{atmos} \\
&+ \quad c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) \quad \equiv P^{solar} \\
+\tilde{J} \quad & \cos\left(\pm\delta - \frac{\Delta_{23} L}{2}\right) \frac{\Delta_{12} L}{2} \sin\left(\frac{\Delta_{23} L}{2}\right) \quad \equiv P^{inter}
\end{aligned}$$

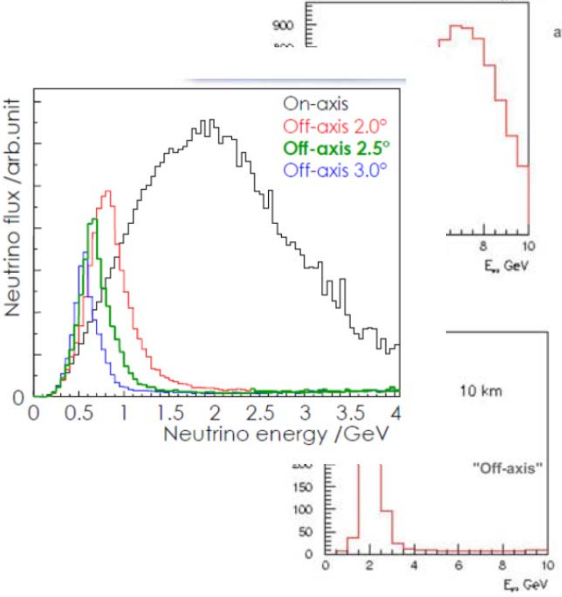
$$(\tilde{J} \equiv c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{12} \ \sin 2\theta_{23}, \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu} \ )$$

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

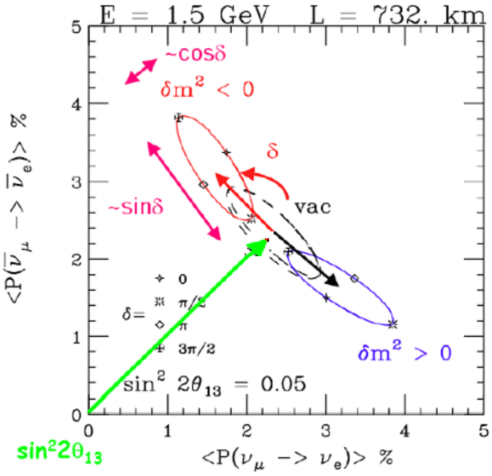
The off axis idea

By going o
energy is r
spectrun

Allows an
pick an e
maximum o



What will we get ?



Minakata and Nunokawa

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

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

$\updownarrow$

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

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

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

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

in vac $\sin\Delta_{31}$

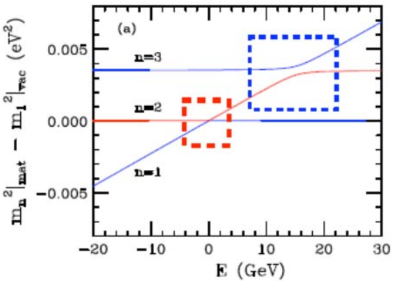
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\dfrac{\sin(aL)}{(aL)}\ \Delta_{21}$

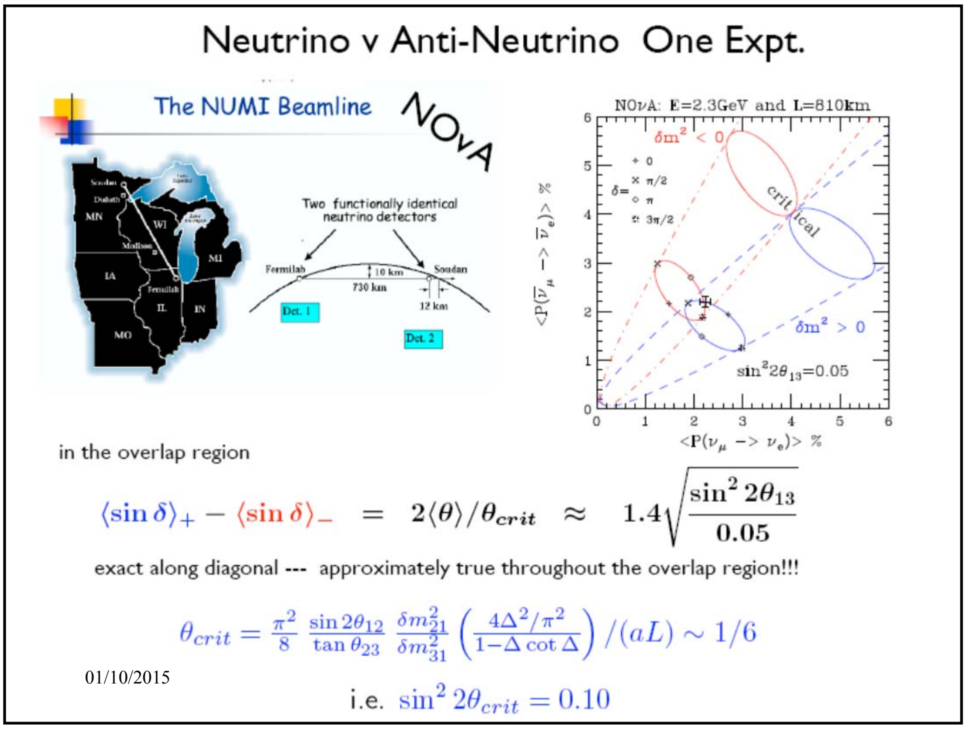
in vac $\sin\Delta_{21}$

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

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

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





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!!!

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

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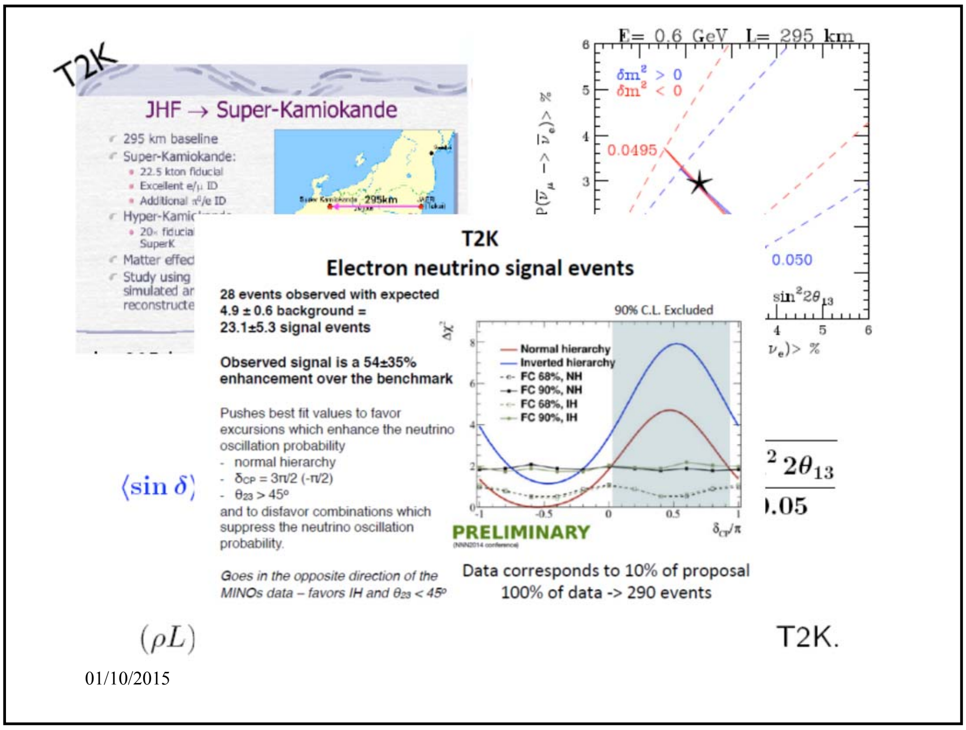
i.e. $\sin^2 2\theta_{crit} = 0.10$



JHF → Super-Kamiokande

- 295 km baseline
- Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent e/μ ID
  - Additional π⁰/e ID
- Hyper-Kamic
  - 20× fiducia SuperK
- Matter effec
- Study using simulated ar reconstructe

T2K

Electron neutrino signal events

28 events observed with expected 4.9 ± 0.6 background = 23.1±5.3 signal events

Observed signal is a 54±35% enhancement over the benchmark

Pushes best fit values to favor excursions which enhance the neutrino oscillation probability
- normal hierarchy
- $\delta_{CP} = 3\pi/2\ (-\pi/2)$
- $\theta_{23} > 45°$

and to disfavor combinations which suppress the neutrino oscillation probability.

Goes in the opposite direction of the MINOs data – favors IH and $\theta_{23} < 45°$

Data corresponds to 10% of proposal
100% of data -> 290 events

$\langle\sin\delta\rangle$ $^2 2\theta_{13}$ $.05$

(ρL) T2K.

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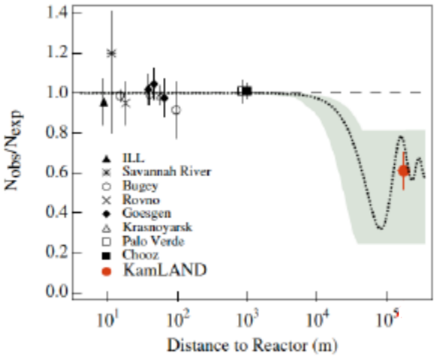
On March 2011 …. ArXiv 1101.2755

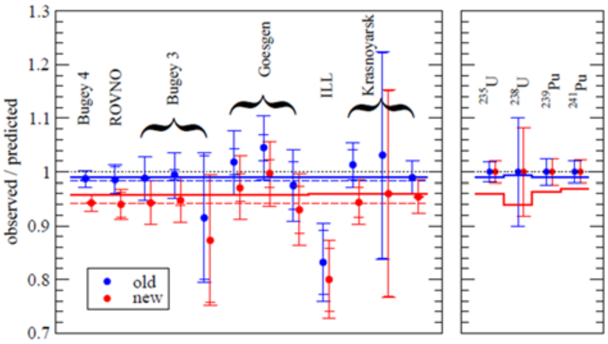


New reactor antineutrino spectra hav
and ^{238}U, increasing the mean flux b

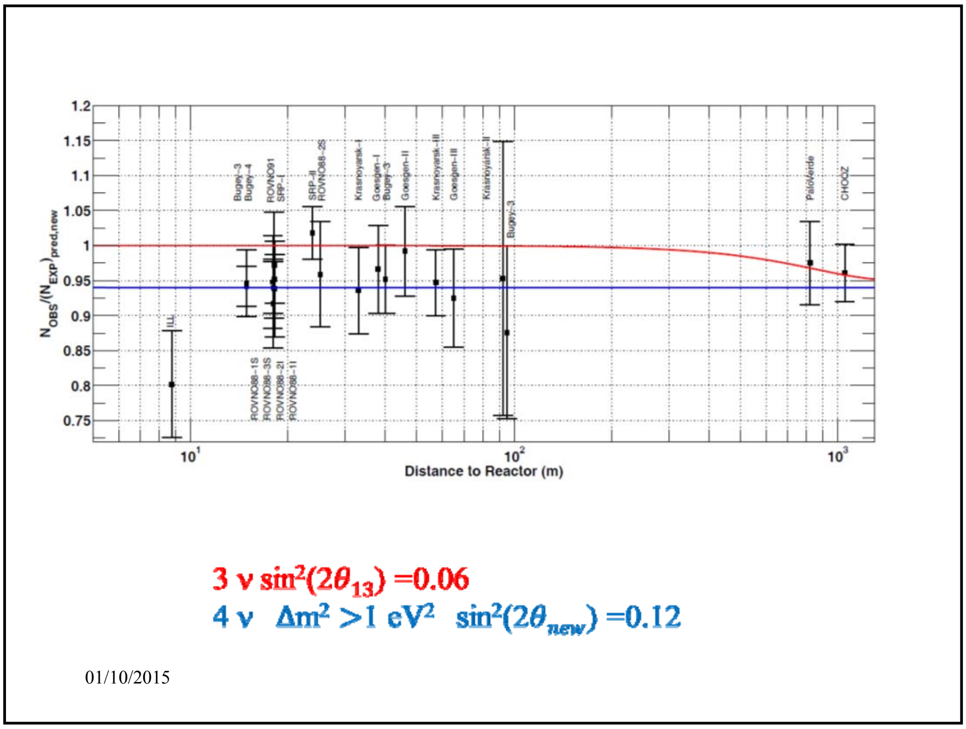
This reevaluation applies to all react

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

0.976 ± 0.024 → 0.943 ± 0.023



"The Reactor Antineutrino Anomaly," Phys. Rev. D 83: 073006, 2011



3 ν $\sin^2(2\theta_{13})$ =0.06

4 ν $\Delta m^2 > 1$ eV² $\sin^2(2\theta_{new})$ =0.12

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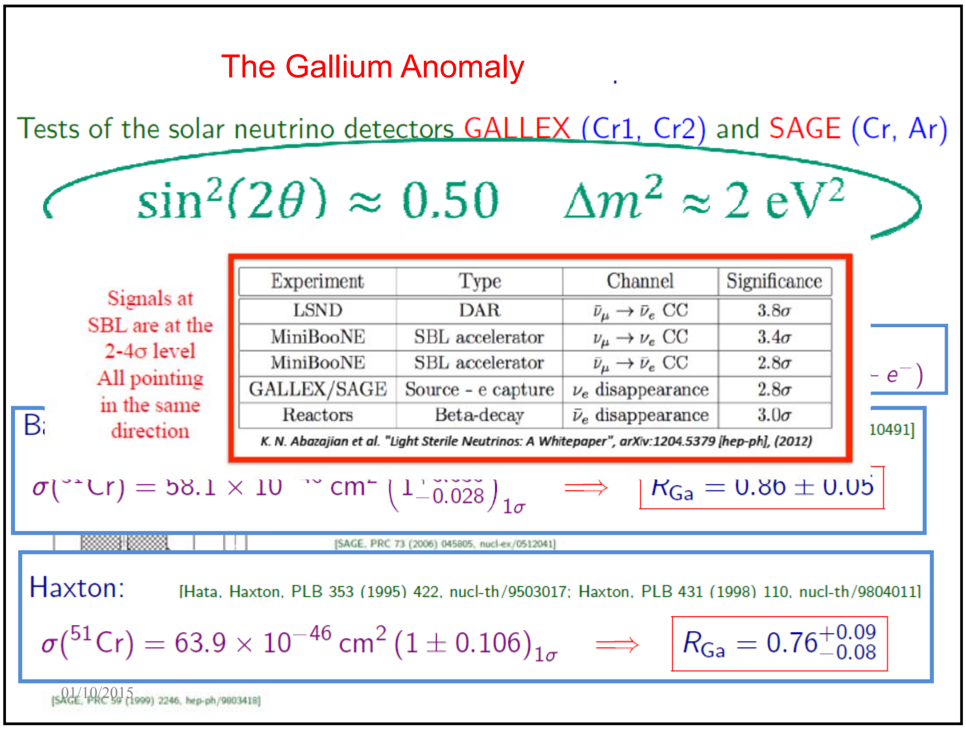

The Gallium Anomaly

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

$$\sin^2(2\theta) \approx 0.50 \quad \Delta m^2 \approx 2\ \mathrm{eV}^2$$

Signals at
SBL are at the
2-4σ level
All pointing
in the same
direction

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

$- e^-)$

B

10491]

$\sigma(\ \mathrm{Cr}) = 58.1 \times 10\ \ \mathrm{cm}\ (1_{-0.028})_{1\sigma} \implies R_{\mathrm{Ga}} = 0.86 \pm 0.05$

[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

Haxton: [Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

$$\sigma({}^{51}\mathrm{Cr}) = 63.9 \times 10^{-46}\ \mathrm{cm}^2\ (1 \pm 0.106)_{1\sigma} \implies R_{\mathrm{Ga}} = 0.76^{+0.09}_{-0.08}$$

01/10/2015

[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]