Neutrino physics (theory & phenomenology)

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ν_{II}

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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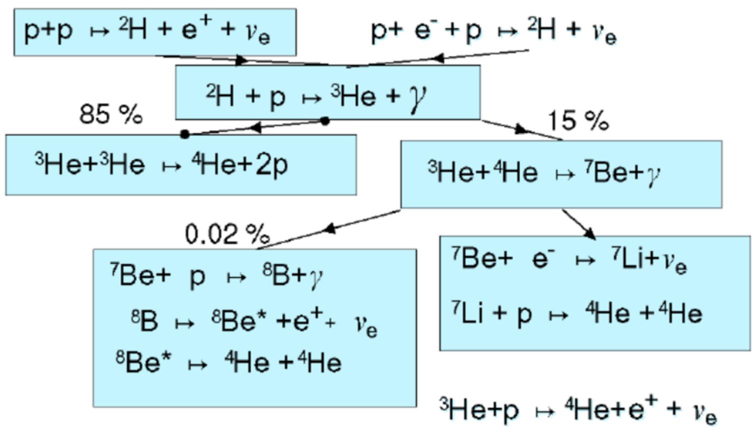


Solar Spectrum:

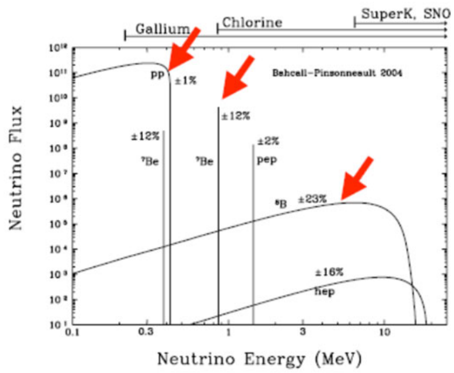


Figure 1. The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [22]. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2} s^{-1} MeV^{-1}$ at the Earth's surface. For line sources, the units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

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

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

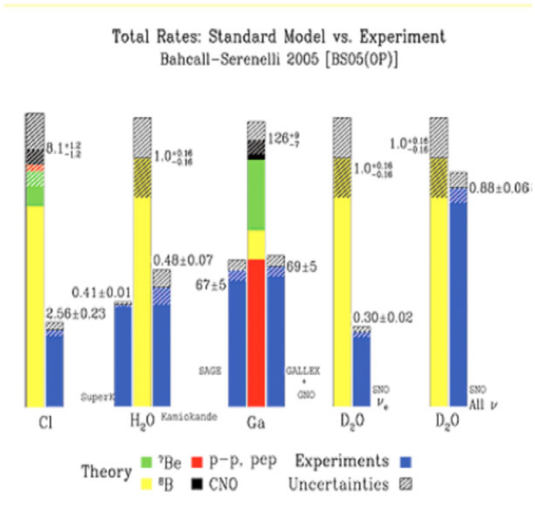
$${}^7Be + e^- \rightarrow {}^7Li + \nu_e$$

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

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

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

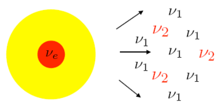
Ray Davis & John Bahcall



Theory v Exp.

Neutrino Flavor Transistions!!!

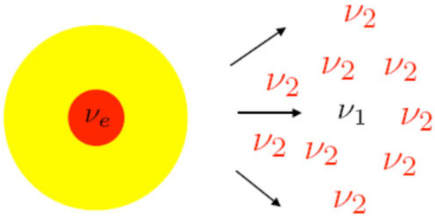
pp and ^{7}Be



$f_1 \sim 69\%$

$f_2 \sim 31\%$

^8B



$f_2 \sim 90\%$

$f_1 \sim 10\%$

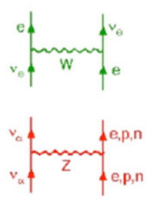
$$\langle P_{ee} \rangle = \sin^2\theta + f_1 \cos 2\theta_\odot \approx \sin^2\theta_\odot = 0.31$$

Wow!!! How did that happen???

energy dependence!!!

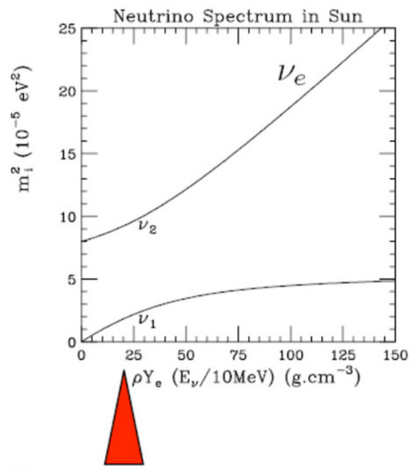
MSW

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

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

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

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

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

in the flavor basis

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

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

and therefore in flavor basis

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

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

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

Coherent Forward Scattering:

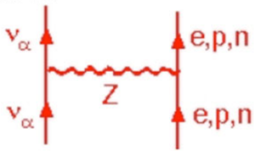
dimensions $[G_F N_e] = M^{-2}L^{-3} = M$

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

N_e is number density of electrons

+(-) for neutrinos (anti-neutrinos)

Wolfenstein '78



Same for all active flavors, therefore overall phases

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

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 $\theta_\odot^N$

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

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

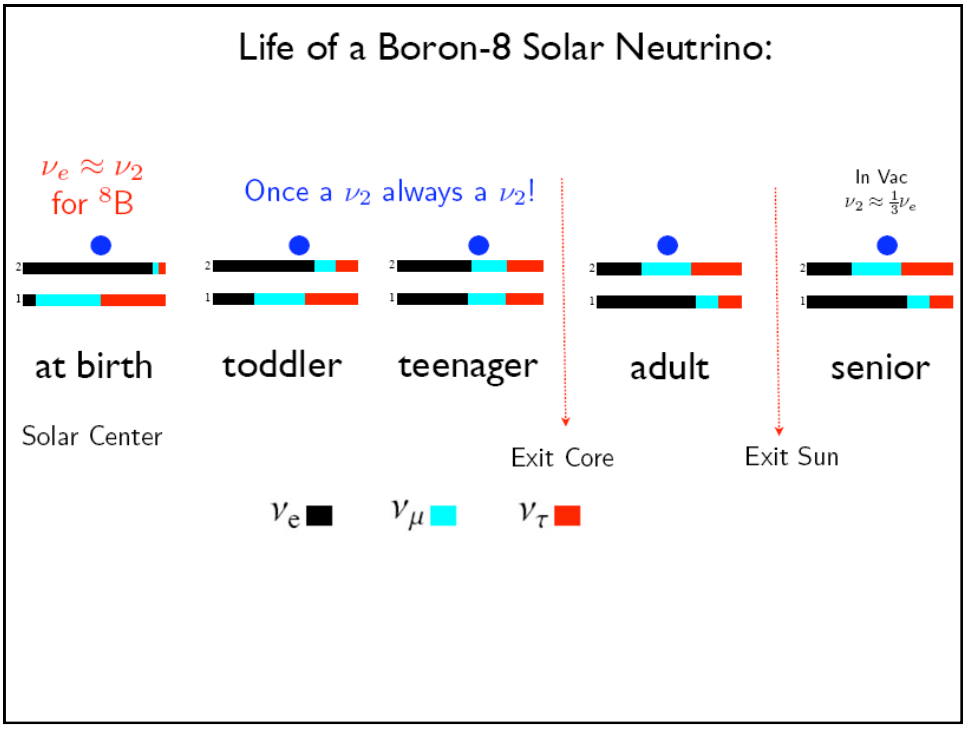
$$\delta m_N^2 = \delta m^2 \text{ and } \theta_\odot^N = \theta_\odot$$

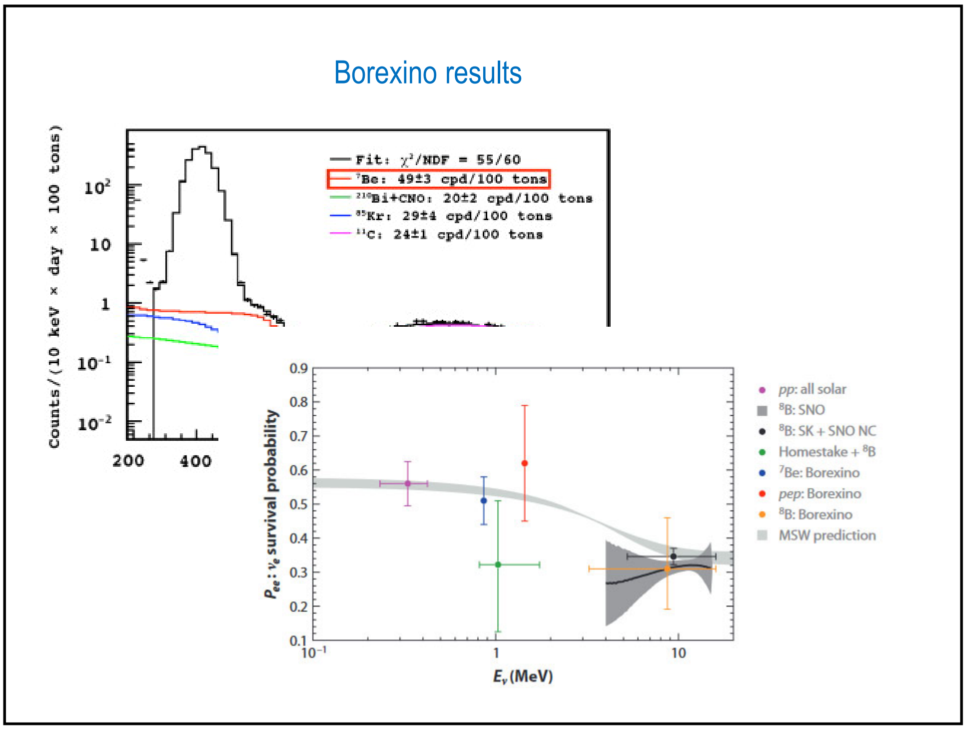
Resonance (Mikheyev + Smirnov '85): $2\sqrt{2} G_F N_e E_\nu = \delta m^2 \cos 2\theta_\odot$

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

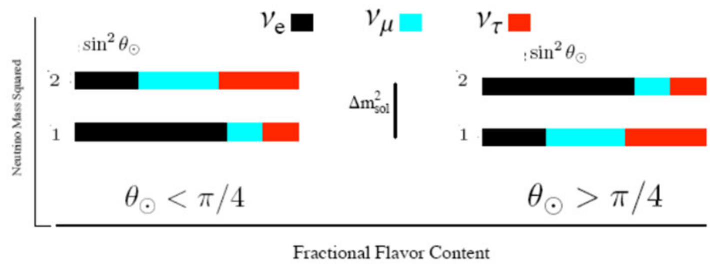
Matter Dominated: $2\sqrt{2} G_F N_e E_\nu \gg \delta m^2 \cos 2\theta_\odot$ — ^8B

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


Life of a Boron-8 Solar Neutrino:
$\nu_e \approx \nu_2$ 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


Borexino results
Counts / (10 keV × day × 100 tons)
Fit: χ^2/NDF = 55/60
^{7}Be: 49±3 cpd/100 tons
^{210}Bi+CNO: 20±2 cpd/100 tons
^{85}Kr: 29±4 cpd/100 tons
^{11}C: 24±1 cpd/100 tons
P_{ee}: ν_e survival probability
E_ν (MeV)
pp: all solar
^{8}B: SNO
^{8}B: SK + SNO NC
Homestake + ^{8}B
^{7}Be: Borexino
pep: Borexino
^{8}B: Borexino
MSW prediction

Solar Pair Mass Hierarchy:



Who cares ?
SNO does !!!

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

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

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 !!!

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 %

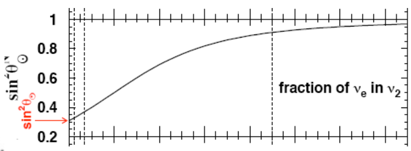
	Amplitude fit		separate D, N:
	Δm	Δm	(D-N)/((D+N)/2)
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
comb	-3.3±1.0±0.5%	-3.1±1.0±0.5%	-4.1±1.2±0.8%
non-zero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



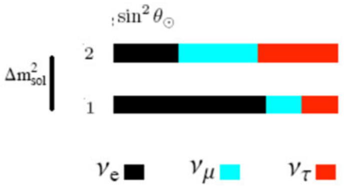
Summary:

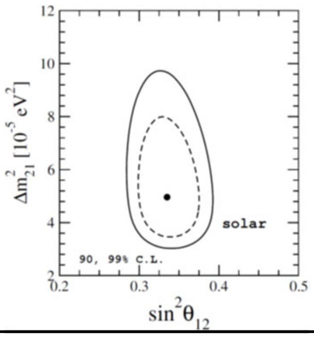
The low energy pp and ^{7}Be Solar Neutrinos exit the sun as two thirds ν_1 and one third ν_2 due to (quasi-) vacuum oscillations.

$f_1 = 65 \pm 2\%$, $f_2 = 35 \mp 2\%$ 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 $P_{ee} \approx 0.35$.





Testing solar neutrino oscillations with reactors

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

10^{-5} eV^2

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

10^5m = 100 km

1 MeV

Reactor Neutrinos

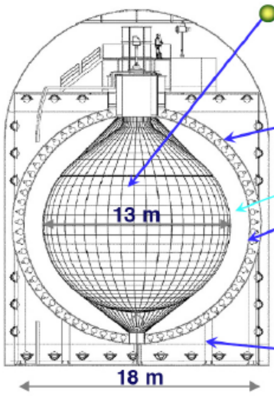
KamLAND Detector

- 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

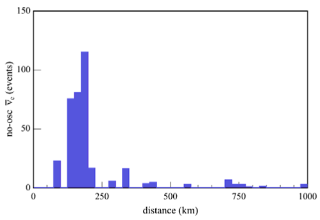
commissioned in February, 2003

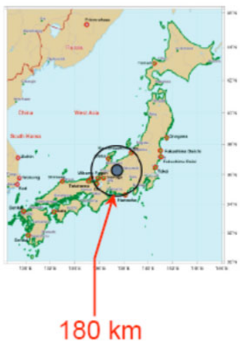
photocathode coverage : 22% → 34%
energy resolution at 1 MeV : 7.3% → 6.3%

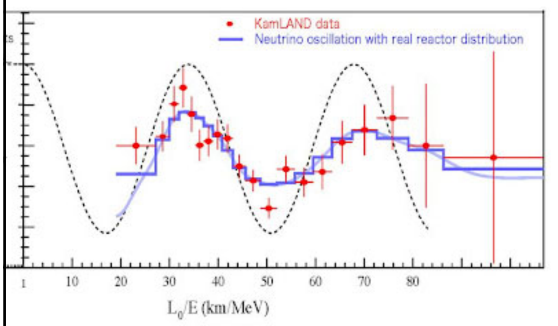
- water Cerenkov outer detector

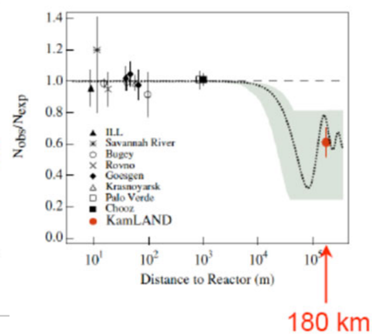


expected no-oscillation neutrino event rate at KamLAND









Summary:

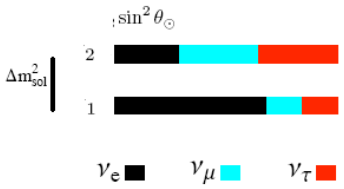
The low energy pp and ^{7}Be Solar Neutrinos exit the sun as two thirds ν_1 and one third ν_2 due to (quasi-) vacuum oscillations.

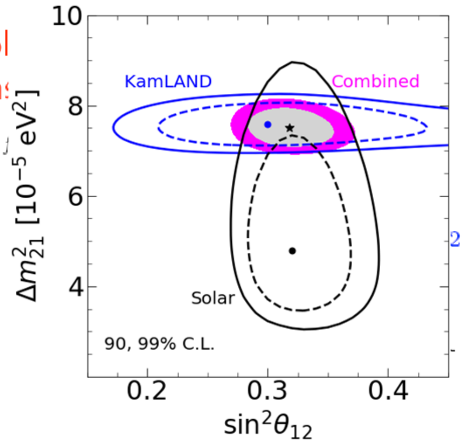
$f_1 = 65 \pm 2\%$, $f_2 = 35 \mp 2\%$ with $P_{ee} \approx 0.56$

The high energy ^{8}B Sol

"PURE" ν_2 mass eigen

$f_2 = 91 \pm 2\%$ and f

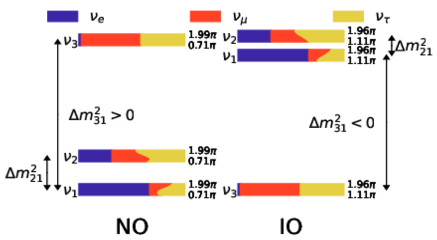




Three-neutrino oscillations

Neutrino mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



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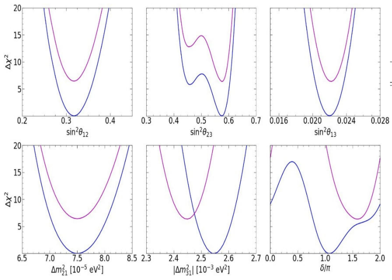


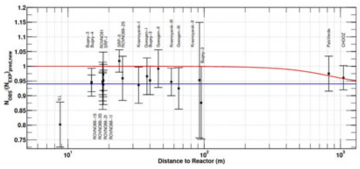
de Salas et al, JHEP 02 (2021) 071[arXiv:2006.11237]

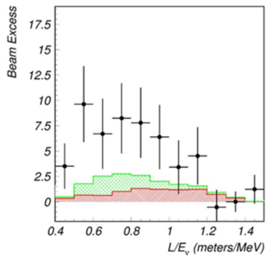
parameter	best fit ± 1σ	2σ range	3σ range	Relative 1σ uncertainty	
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14	2.7%	PRECISION
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63	1.1%	ORDERING?
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53		
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69	5.2%	PRECISION
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10	5.1%	OCTANT?
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08		
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405	3.0%	PRECISION
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424		
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99	20%	CPV?
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96	9.0%	

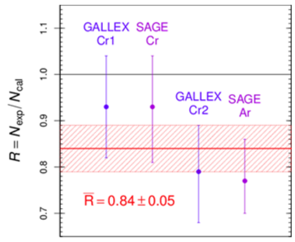
Parameter	Main contribution	Other contributions
θ_{12}	SOL	KamLAND
θ_{13}	REAC	ATM+LBL and SOL+KamLAND
θ_{23}	ATM+LBL	-
δ_{CP}	LBL	ATM
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
MO	LBL+REAC and ATM	-

SOL: Solar
ATM: Amtopsheric neutrinos
LBL: Long baseline accelerator experiments
REAC: Short-baseline reactor experiments

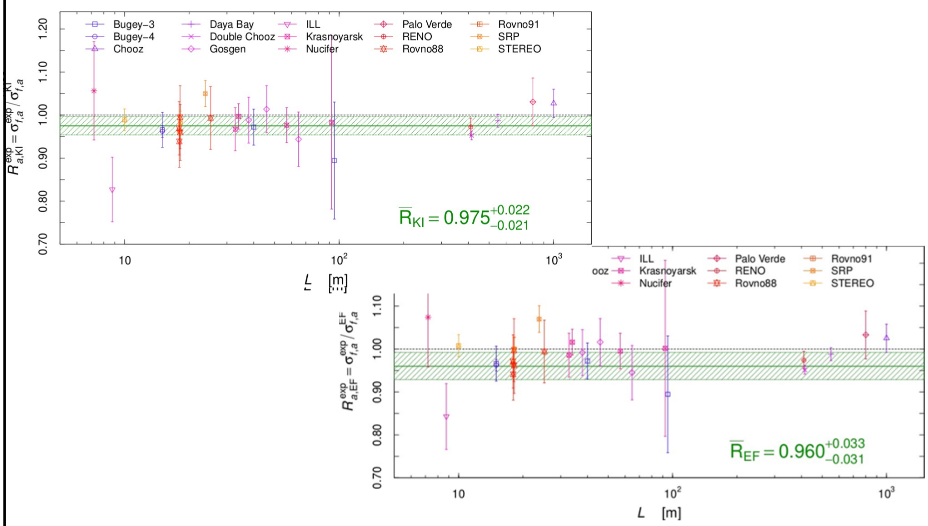
Anomalies







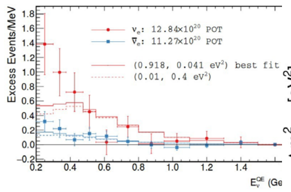
Need extra states !!!



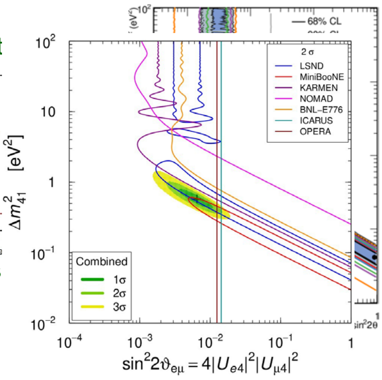
MiniBooNE

MiniBooNE was built to check the LSND results with a different baseline, but similar L/E

MiniBooNE has no near det



MiniBooNE sees an excess at ~5σ at low energies



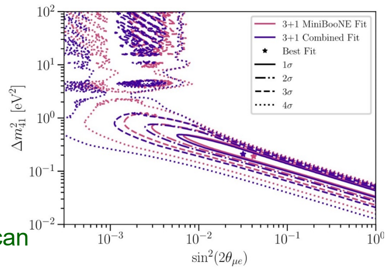
MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels

The collaboration did not perform an oscillation analysis

A combined analysis shows that MicroBooNE can not exclude the region of parameter space preferred by MiniBooNE



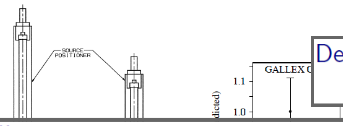
2201.01724

The Gallium Anomaly

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

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$



Deficit could be due to overestimate of $\sigma(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-)$

Bahcall: [Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

$$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46}\,\text{cm}^2 \left(1^{+0.036}_{-0.028}\right)_{1\sigma} \implies R_{\text{Ga}} = 0.86 \pm 0.05$$

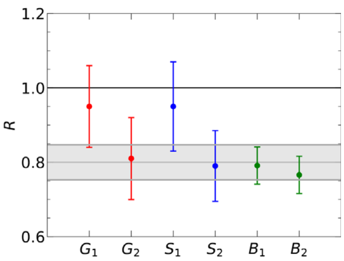
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

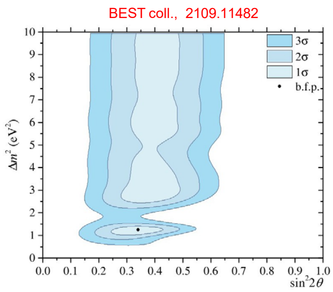
Haxton: [Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

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

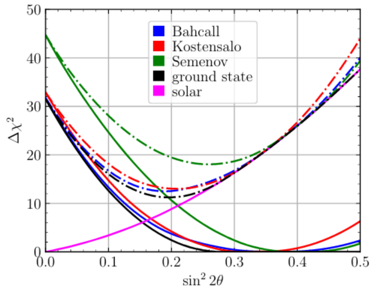
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]

The Gallium anomaly



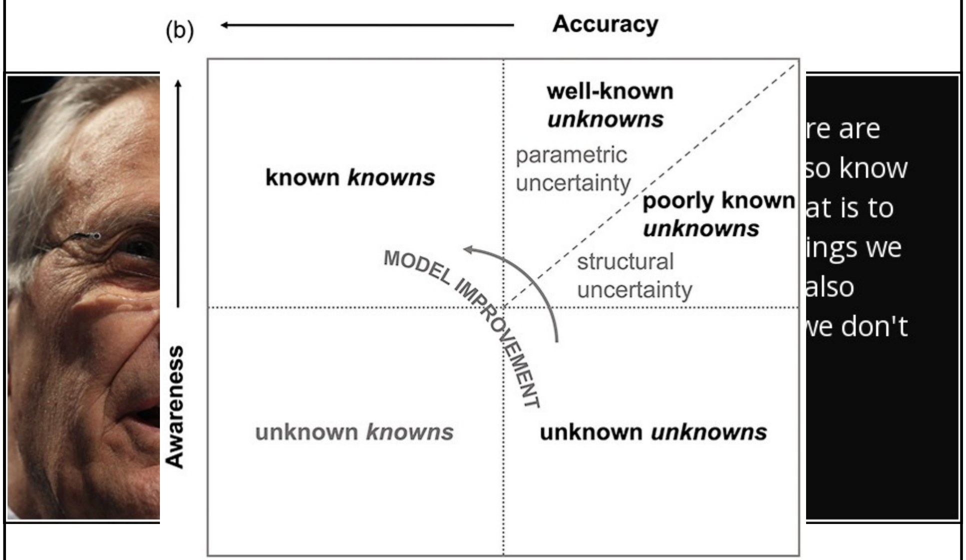


The Gallium anomaly is now at more than 5σ significance



Berryman et al, 2111.12530, JHEP 2022

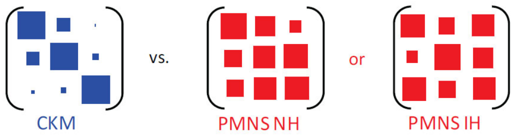
Can not be explained due to cross section mistakes



The Known Unknowns

★ **Next generation Long-Baseline experiments (such as DUNE) can address three of these questions:**

- **Are neutrinos Dirac or Majorana ?**
  - Is there a connection to the GUT scale?
- **Are there light sterile neutrino states ?** → Breaks 3-flavor paradigm
  - No clear theoretical guidance on mass scale, M, …
- **What is the neutrino mass hierarchy ?**
  - An important question in flavor physics, e.g. CKM vs. PNMS



- **Is CP violated in the leptonic sector ?**
  - Are νs key to understanding the matter-antimatter asymmetry?

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_{31}) by

•Passing neutrinos through matter (Earth)

•Beating the unknown sign(Δm^2_{31}) against the known sign[forward $\nu_e\, e \longrightarrow \nu_e\, e$ ampl]

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

The Known Unknowns

★ **Next generation Long-Baseline experiments (such as DUNE) can address three of these questions:**

- **Are neutrinos Dirac or Majorana ?**
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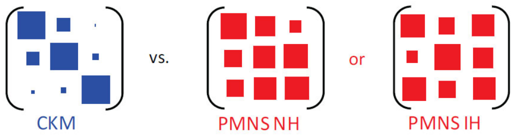


- **Is CP violated in the leptonic sector ?**
  - Are νs key to understanding the matter-antimatter asymmetry?

In principle, it is straightforward

★ CPV ⇨ different oscillation rates for νs and $\overline{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = 4 s_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \times \left[\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \times \sin\left(\frac{\Delta m_{23}^2 L}{4E}\right) \times \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\right]$$

vacuum osc.

★ Requires $\{\theta_{12}, \theta_{13}, \theta_{23}\} \neq \{0, \pi\}$

- now know that this is true, $\theta_{13} \approx 9^\circ$
- but, despite hints, don't yet know "much" about δ

★ So "just" measure $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$?

★ Not quite, there is a complication…

Neutrino Oscillations in Matter

★ Accounting for this potential term, gives a Hamiltonian that is not diagonal in the basis of the mass eigenstates

$$\mathcal{H}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = \begin{pmatrix}E_1 & 0 & 0\\0 & E_2 & 0\\0 & 0 & E_3\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} + V|\nu_e\rangle \leftarrow \text{ME}$$

★ Complicates the simple picture !!!!

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) =$$

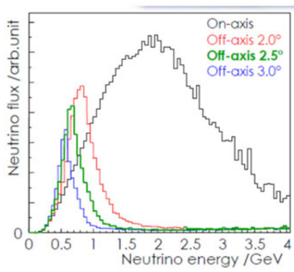
ME $$\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

ME $$-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

CPV $$-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta\; s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$

with $A = 2\sqrt{2}G_F n_e E = 7.6\times10^{-5}\mathrm{eV}^2\cdot\frac{\rho}{\mathrm{g\,cm^{-3}}}\cdot\frac{E}{\mathrm{GeV}}$

Experimental Strategy



EITHER:

★ Keep L small (~200 km): so that matter effe

- First oscillation maximum:

$$\frac{\Delta m^2_{31}L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\mathrm{GeV}$$

- Want high flux at oscillation maximum

⇨ **Off-axis beam:** narrow range of neutrino energies

OR:

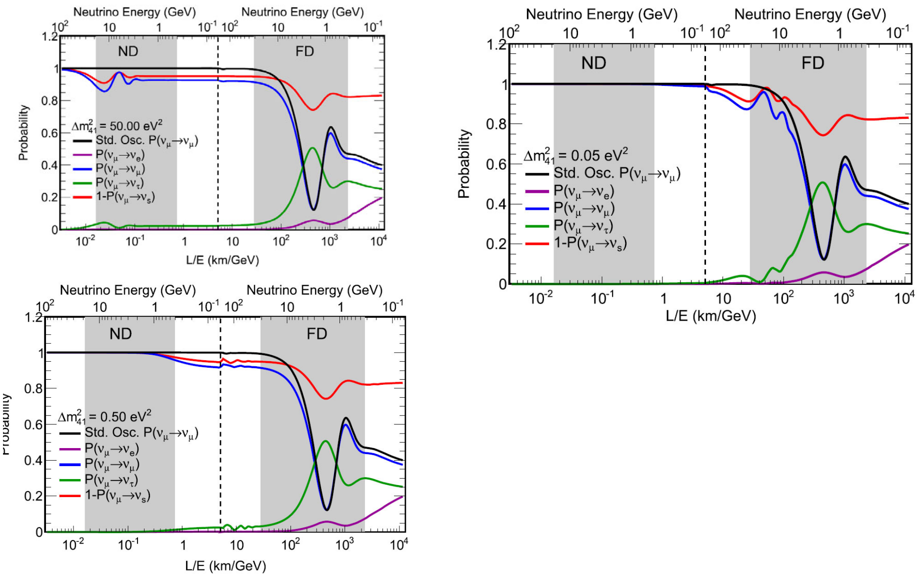
★ Make L large (>1000 km): measure the matter effects (i.e. MH)

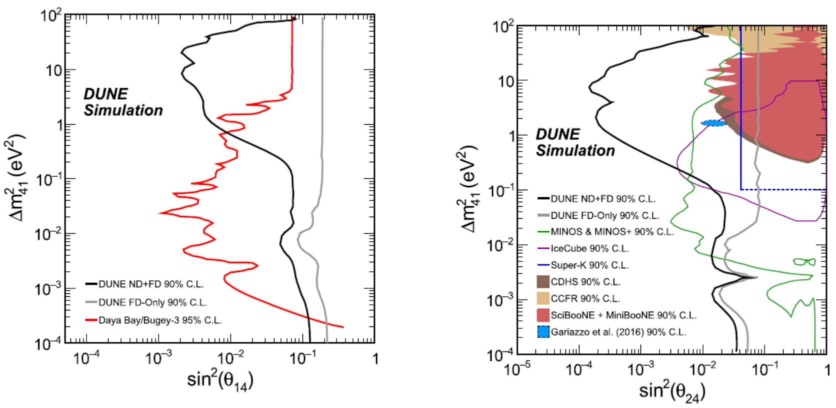
- First oscillation maximum:

$$\frac{\Delta m^2_{31}L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2\,\mathrm{GeV}$$

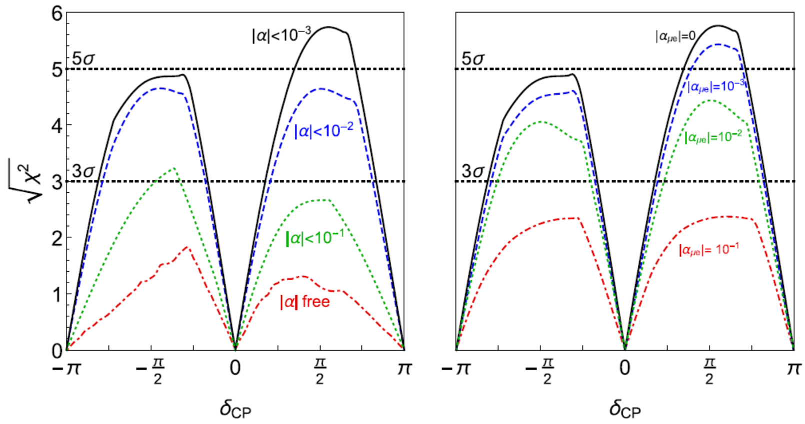
- **Unfold CPV from Matter Effects through E dependence**

⇨ **On-axis beam:** wide range of neutrino energies


Neutrino Energy (GeV)
ND
FD
Probability
Δm^2_{41} = 50.00 eV^2
Std. Osc. P($\nu_\mu \to \nu_\mu$)
P($\nu_\mu \to \nu_e$)
P($\nu_\mu \to \nu_\mu$)
P($\nu_\mu \to \nu_\tau$)
1-P($\nu_\mu \to \nu_s$)
L/E (km/GeV)
Δm^2_{41} = 0.05 eV^2
Δm^2_{41} = 0.50 eV^2


DUNE Simulation
Δm^2_{41} (eV^2)
$\sin^2(\theta_{14})$
DUNE ND+FD 90% C.L.
DUNE FD-Only 90% C.L.
Daya Bay/Bugey-3 95% C.L.
$\sin^2(\theta_{24})$
MINOS & MINOS+ 90% C.L.
IceCube 90% C.L.
Super-K 90% C.L.
CDHS 90% C.L.
CCFR 90% C.L.
SciBooNE + MiniBooNE 90% C.L.
Gariazzo et al. (2016) 90% C.L.

Non unitarity



Non standard neutrino interactions

They can be described by effective four-fermion operators of the form

$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f'\right)$$

normalizing the operator with the Fermi constant

$$\varepsilon_{\alpha\beta} = \frac{M_W^2}{M_{NSNI}^2}$$

NSNI can appear at every step. It is therefore necessary to break down the analysis in three stages

- the production process
- the time evolution
- the detection process

We are left "only" with neutral current NSNI

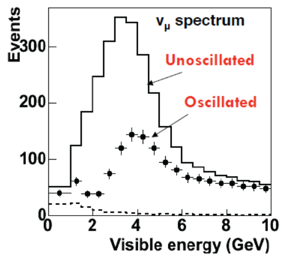
$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\overline{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$$

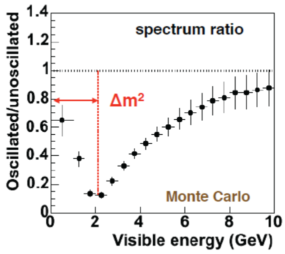
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\frac{1}{2E}\left[U\begin{pmatrix}0&0&0\\0&\Delta m_{21}^2&0\\0&0&\Delta m_{31}^2\end{pmatrix}U^\dagger+a\begin{pmatrix}1+\varepsilon_{ee}&\varepsilon_{e\mu}&\varepsilon_{e\tau}\\ \varepsilon_{e\mu}^*&\varepsilon_{\mu\mu}&\varepsilon_{\mu\tau}\\ \varepsilon_{e\tau}^*&\varepsilon_{\mu\tau}^*&\varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

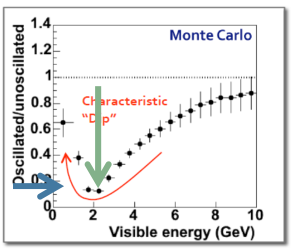
$$a\equiv 2\sqrt{2}G_F n_e E$$

$$H=\frac{1}{2E}\left[U\begin{pmatrix}0&\\&\Delta m_{32}^2\end{pmatrix}U^\dagger+a\begin{pmatrix}\epsilon_{\mu\mu}&\epsilon_{\mu\tau}\\ \epsilon_{\mu\tau}^*&\epsilon_{\tau\tau}\end{pmatrix}\right]$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$







$\varepsilon_{\mu\tau}$ changes the disspearence probability at large energies shifts the position of the minimum in energy

$$\Delta m^2$$

$\varepsilon_{\tau\tau}$ modifies the dissapearence probability near the first oscillation minimum, especially the depth of the minimum

$$sin^2(2\ \theta_{23})$$