Neutrino Phenomenology:

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WIN'05 Delphi

Nu Standard Model
Beyond Nu SM
Predictions/Models

"The" ν Standard Model

- 3 light (m_i <1 eV) Majorana Neutrinos: $\Rightarrow$ only 2 δm^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 ($\alpha_2, \alpha_3$)

  Low Energy CP violation

  $$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

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

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

500km/GeV   15km/MeV

In oscillation phenomena,

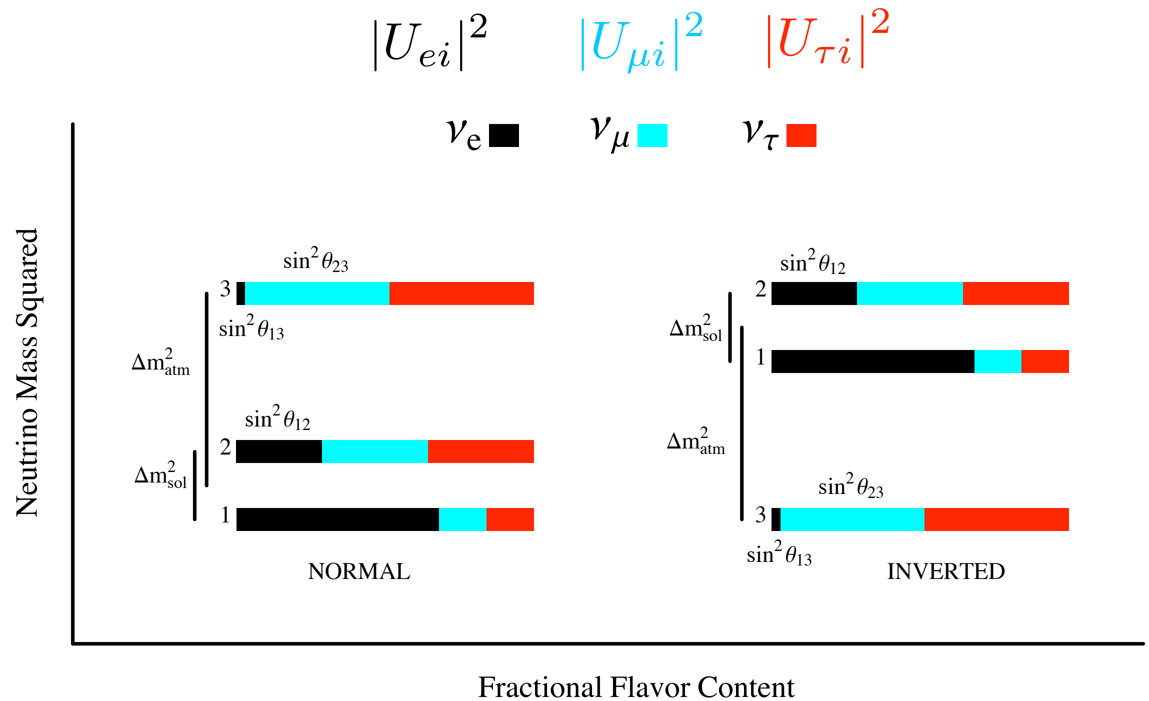
the phases $\alpha,\ \beta$ are unobservable ($U_{\alpha i} U^*_{\beta i}$)
as well as the value of m_{lite} (δm^2).

In $0\nu\beta\beta$ decay

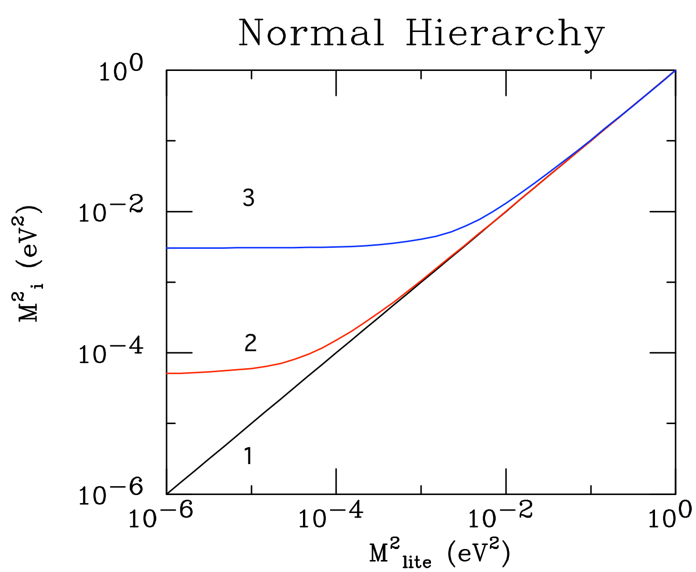
only a combination of the phases $\alpha,\ \beta$ observable
in this CP conserving phenomena.

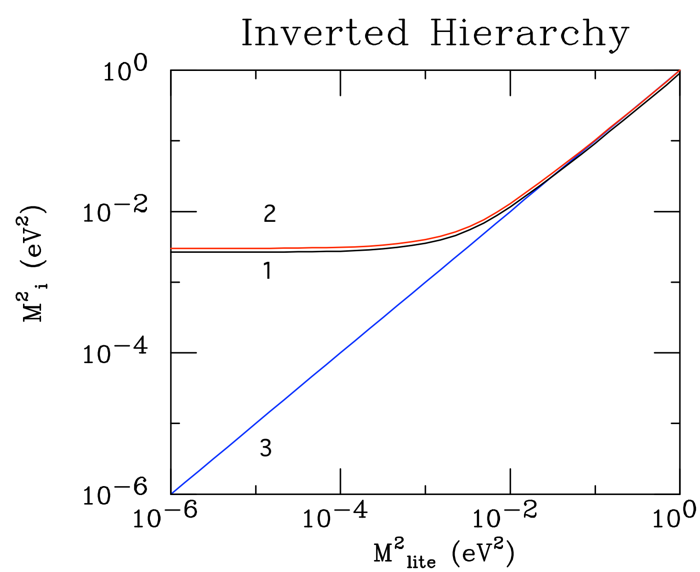
Mixings:

$$|U_{\alpha i}|^2$$



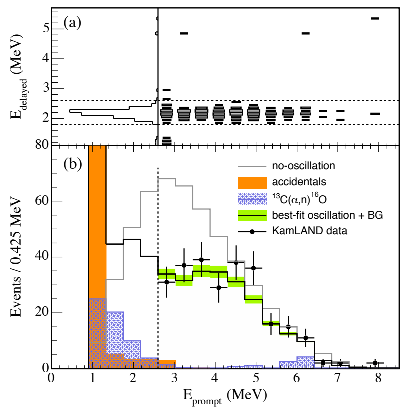
Masses:





12- Sector (Solar)

KamLAND:



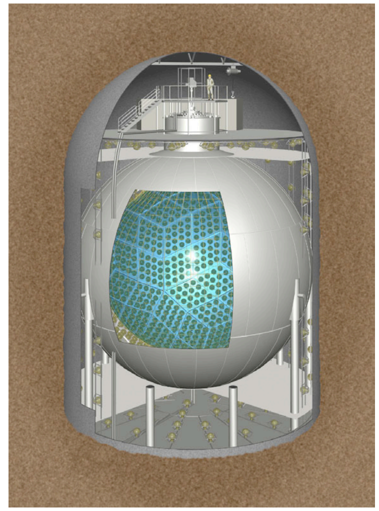
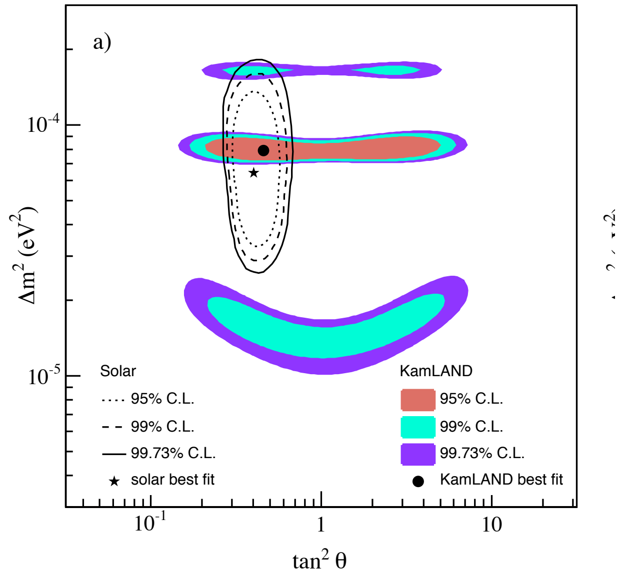
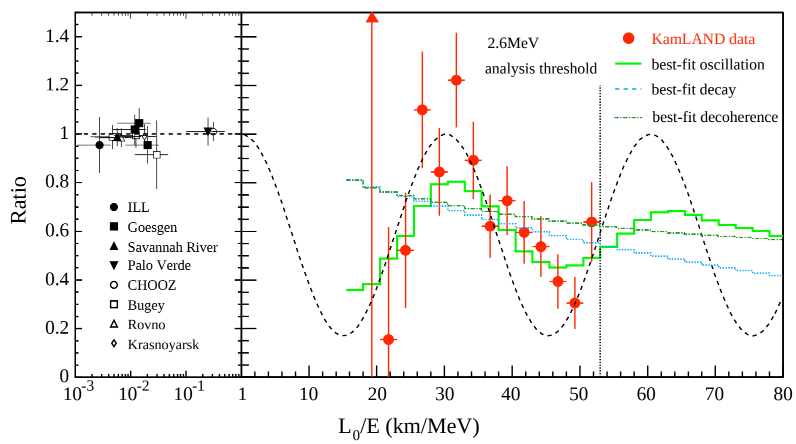


Figure 3. Schematic view of the KamLAND detector.





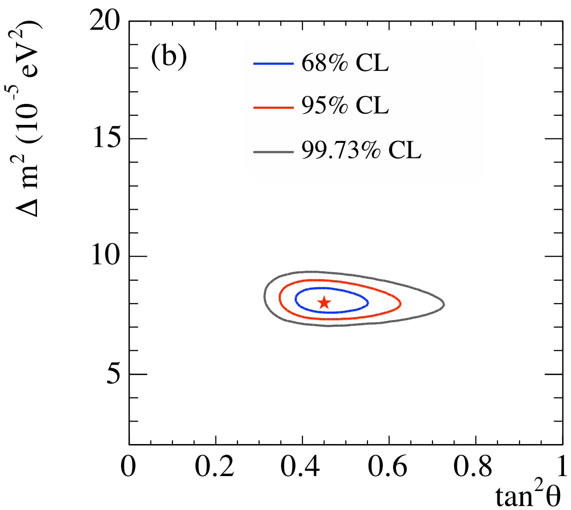
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\, \mathrm{eV}^2$$

Pure Vac. Osc.

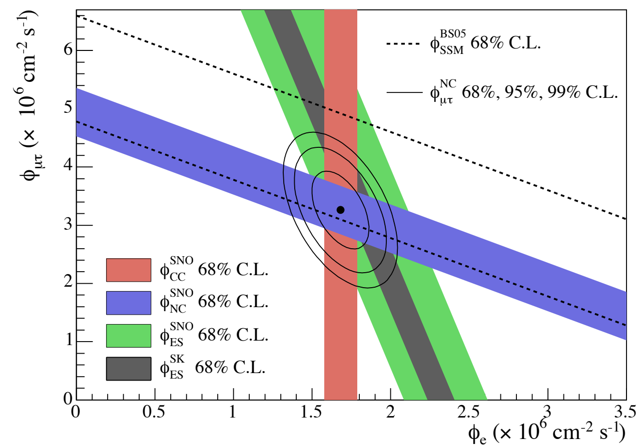
$$P = 1 - \sin^2 2\theta_\odot \sin^2 \frac{\delta m^2_\odot L}{4E}$$

SNO:

$$\frac{CC}{NC} = \frac{\phi_{\rm CC}^{\rm con}}{\phi_{\rm NC}^{\rm con}} = 0.358 \pm 0.021\ (\text{stat})\ ^{+0.028}_{-0.029}\ (\text{syst})$$



Oscillation analysis	$\Delta m^2\ (10^{-5}\ \text{eV}^2)$	$\tan^2\theta$
SNO-only	$5.0^{+6.2}_{-1.8}$	$0.45^{+0.11}_{-0.10}$
Global solar	$6.5^{+4.4}_{-2.3}$	$0.45^{+0.09}_{-0.08}$
Solar plus KamLAND	$8.0^{+0.6}_{-0.4}$	$0.45^{+0.09}_{-0.07}$



$A_{\rm NC} \equiv 0. \qquad A_{ES} \approx 0.7 A_{CC}$

$$\begin{aligned} A_{\rm CC} &= -0.015 \pm 0.058 \pm 0.027 \\ A_{\rm ES} &= 0.070 \pm 0.197 \pm 0.054. \end{aligned}$$

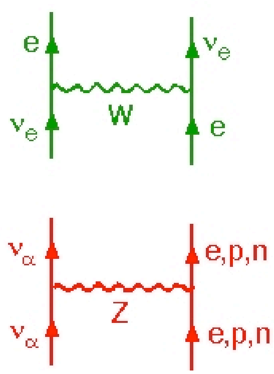
SK: (ES)

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

D/N asym -2 +/-1% Holanda+Smirnov
hep-ph/0212270

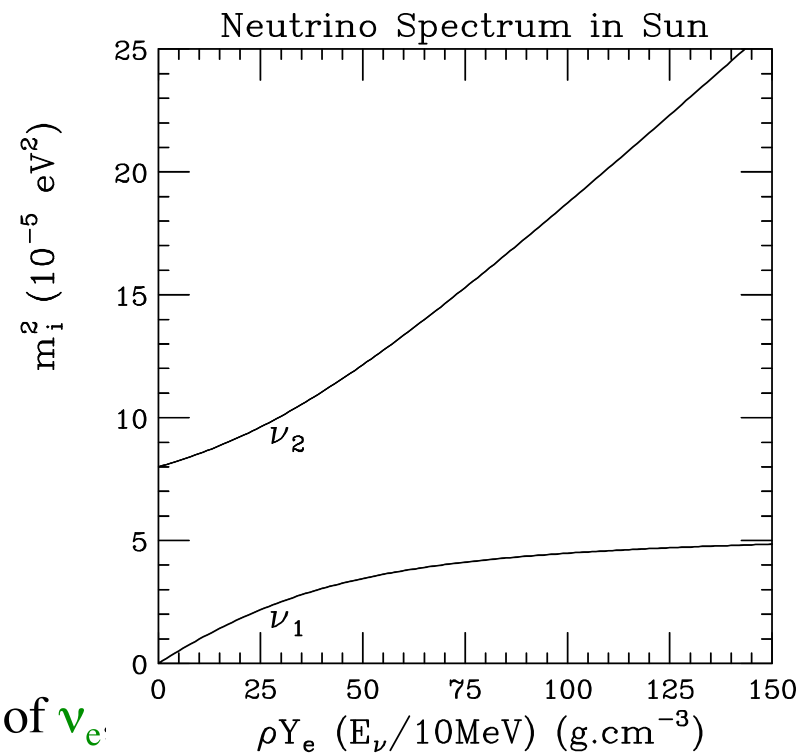
Physics of LMA:

Coherent Forward Scattering:



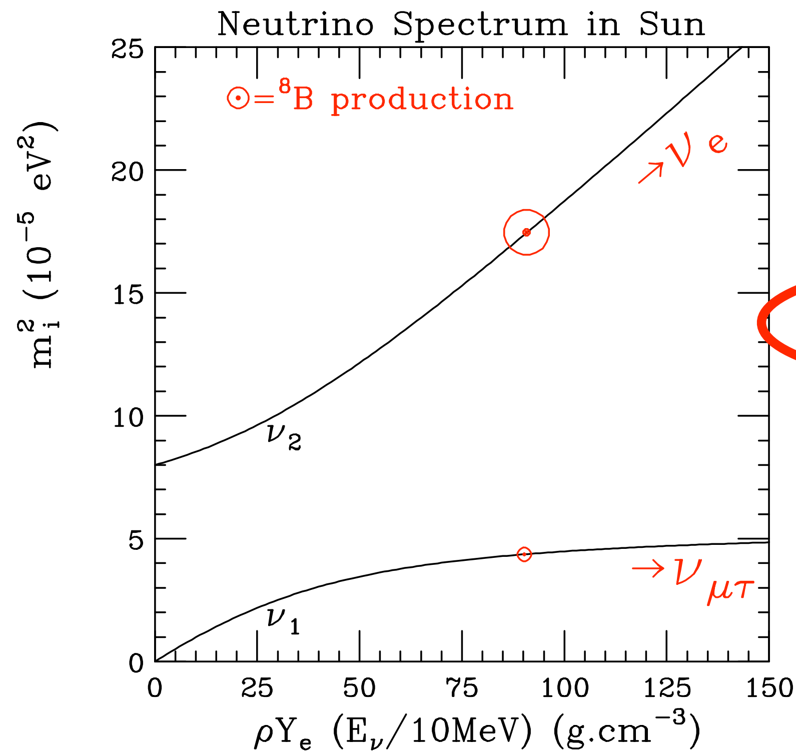
Wolfenstein '78

raises the effective mass of ν_e



Mikheyev + Smirnov Resonance WIN '85

^{8}Boron Neutrinos

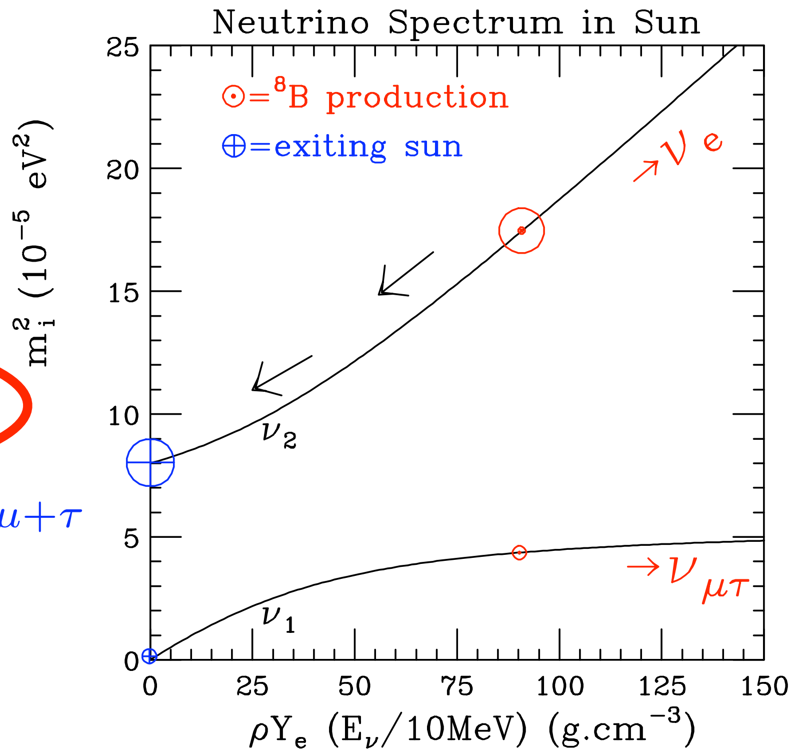


$\theta_N = \theta_0$ $\quad \pi/4 \quad \rightarrow \pi/2$

$$\boxed{\nu_e = \sin\theta_N \ \nu_2}$$
$$+ \cos\theta_N \ \nu_1$$

$$\nu_2 = \sin\theta_0\ \nu_e + \cos\theta_0\ \nu_{\mu+\tau}$$

$$\nu_1 = \cos\theta_0\ \nu_e - \sin\theta_0\ \nu_{\mu+\tau}$$



$\theta_N = \theta_0 \qquad \pi/4 \qquad \to \pi/2$

$$\nu_e = \sin\theta_N\ \nu_2 + \cos\theta_N\ \nu_1$$

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

where f_1 and $f_2 = 1 - f_1$ are the fractions of ν_1 and ν_2 of the ^8B neutrinos arriving at the earth, weighted by the energy response of the SNO detector.

(Daytime CC/NC)

(two flavor analysis)

In MSW-LMA region
$f_2 = \langle \sin^2\theta_N \rangle \gg f_1 = \langle \cos^2\theta_N \rangle$

$$\begin{aligned} \frac{CC}{NC} &= \sin^2\theta_\odot + f_1 \cos 2\theta_\odot \\ 0.358 &= 0.31 + f_1 \star 0.38 \end{aligned}$$

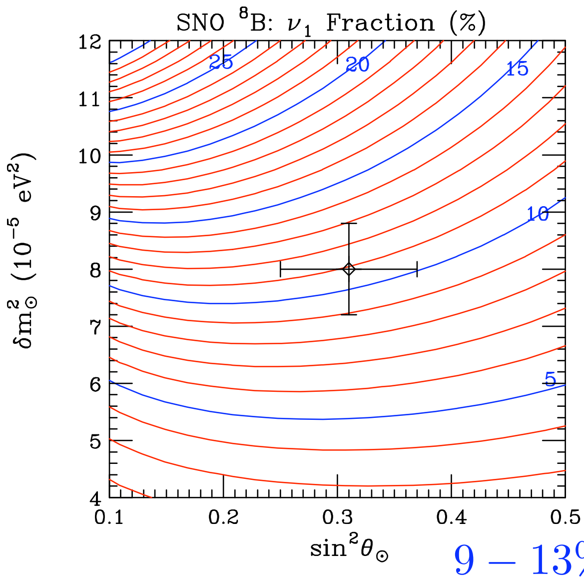
$$\Rightarrow f_1 \approx 10\%$$

^8B Neutrinos that SNO is sensitive to are about 90% ν_2 !!!

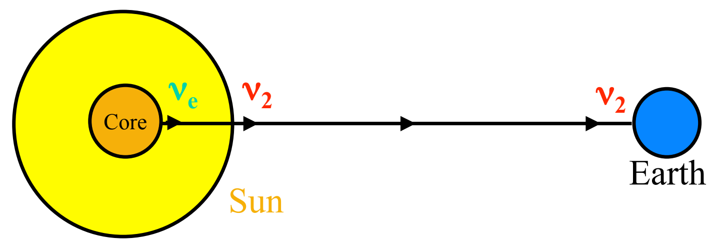
thus SNO is measuring the ν_e fraction of $\nu_2 \equiv \sin^2\theta_\odot$

(upto $\sim$10% corrections)

SNO's ^{8}Boron Neutrinos

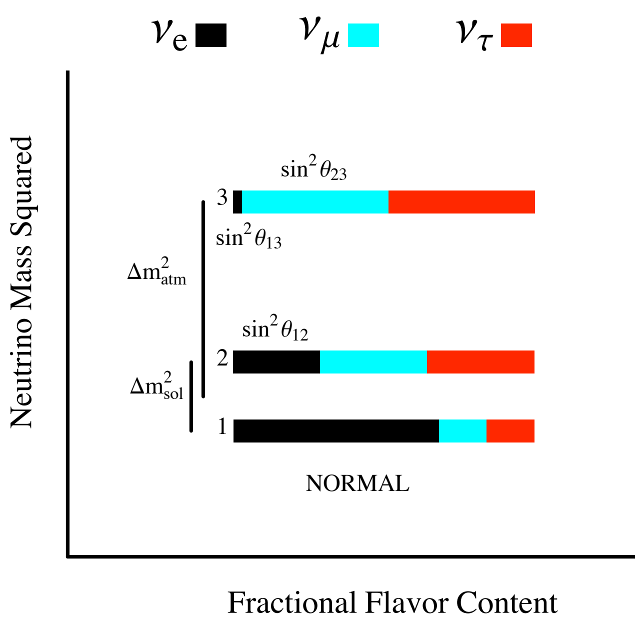


$9 - 13\%$ at $90\% C.L.$



Born as ν_e they exit the Sun and arrive at the earth as ν_2 !!!

$(\nu_1 \ \sim 10\%)$



$$+7.3 \times 10^{-5} eV^2 < \quad \delta m^2_{21} \quad < +9.0 \times 10^{-5} eV^2$$

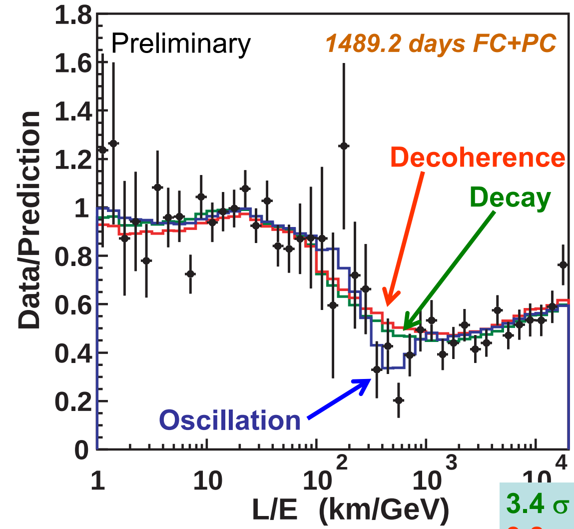
$$0.25 < \quad \sin^2\theta_{12} \quad < 0.37$$

at the 90 % confidence level.

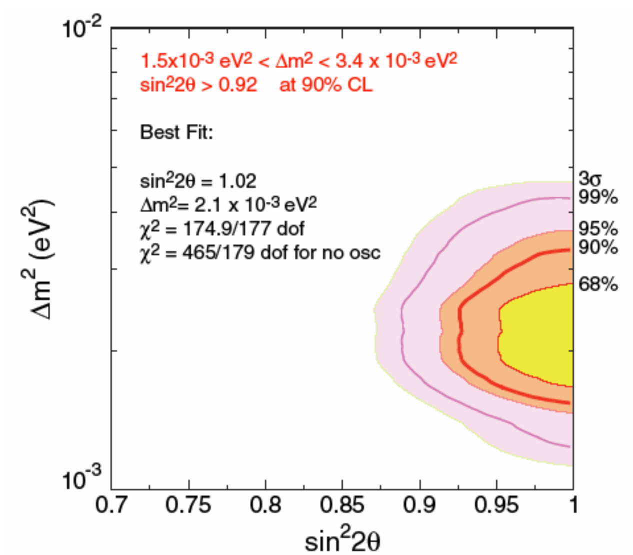
23- Sector (Atmospheric)

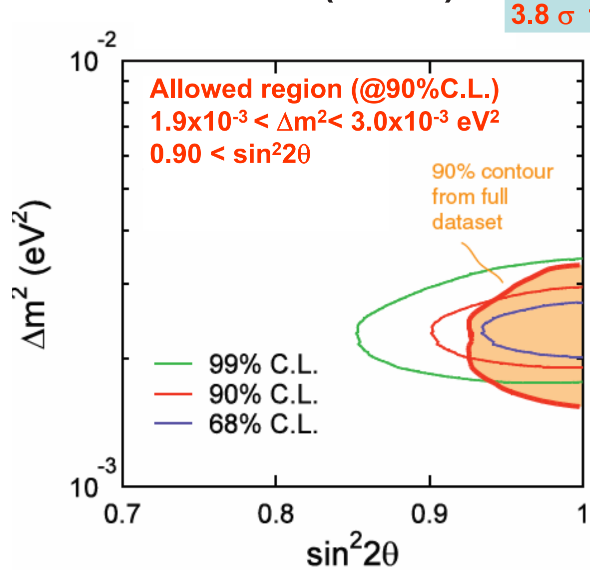
SK:

L/E analysis



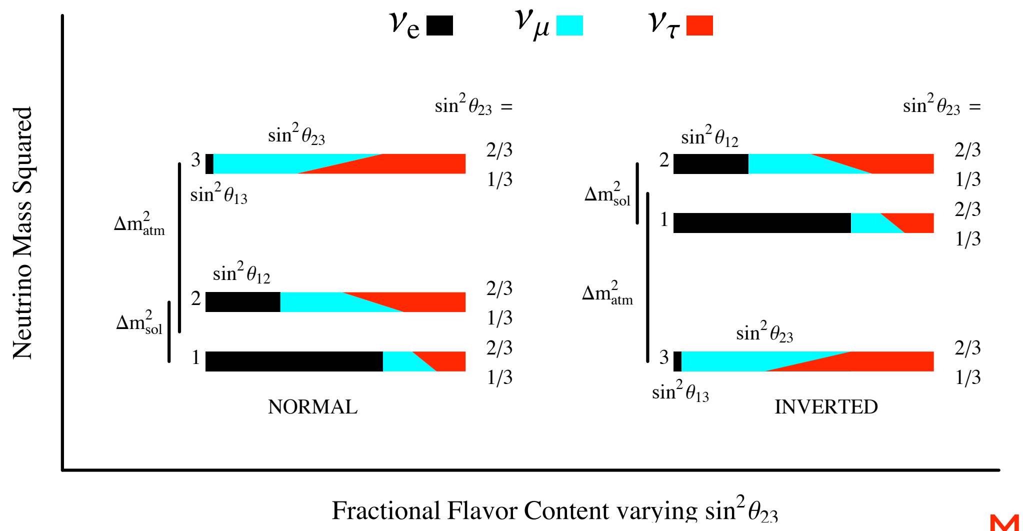
3.4 σ to decay
3.8 σ to decoherence





*K2K has confirmed neutrino oscillations at **3.9σ***

Stronger constraint on Δm^2 even with fewer data sample



Mena + SP hep-ph/0312131

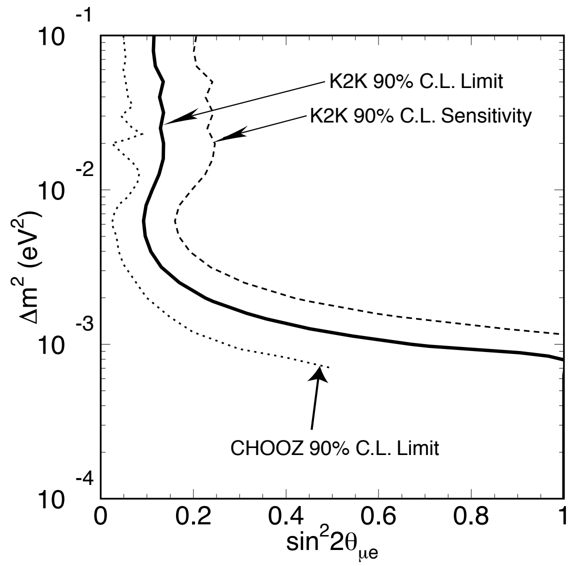
$$1.9 \times 10^{-3} eV^2 < \quad |\delta m^2_{32}| \quad < 3.0 \times 10^{-3} eV^2$$

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

at the 90 % confidence level.

13- Sector (Reactor)

K2K:



$$\sin^2 2\theta_{\mu e} = \frac{1}{2}\sin^2 2\theta_{13}.$$

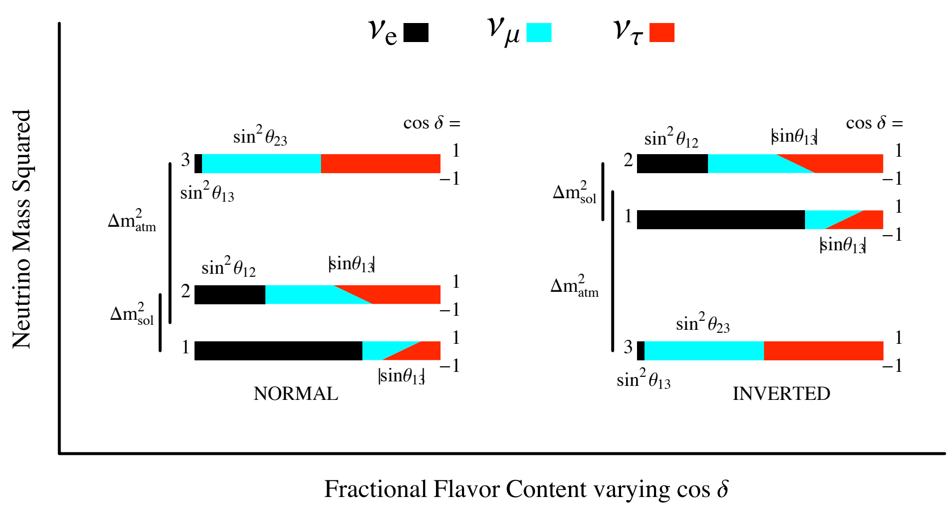
Chooz bound

$$\sin^2\theta_{13} < \quad 0.04$$

limit δm^2_{31} dependent.

$$0 < \delta_{CP} < \quad 2\pi$$

independent of $sign(\sin\delta_{CP})$



Mixing Summary:
(+ Unitarity)

$$\sin^2\theta_{12} = \tfrac{1}{3}(1-4\sigma) \quad , \quad \sin^2\theta_{23} = \tfrac{1}{2}(1-\lambda) \quad and \quad \sin^2\theta_{13} = \epsilon^2$$

$$-0.24 < 4\sigma < 0.12 \quad , \quad -0.28 < \lambda < 0.28 \quad and \quad 0 < \epsilon < 0.2$$

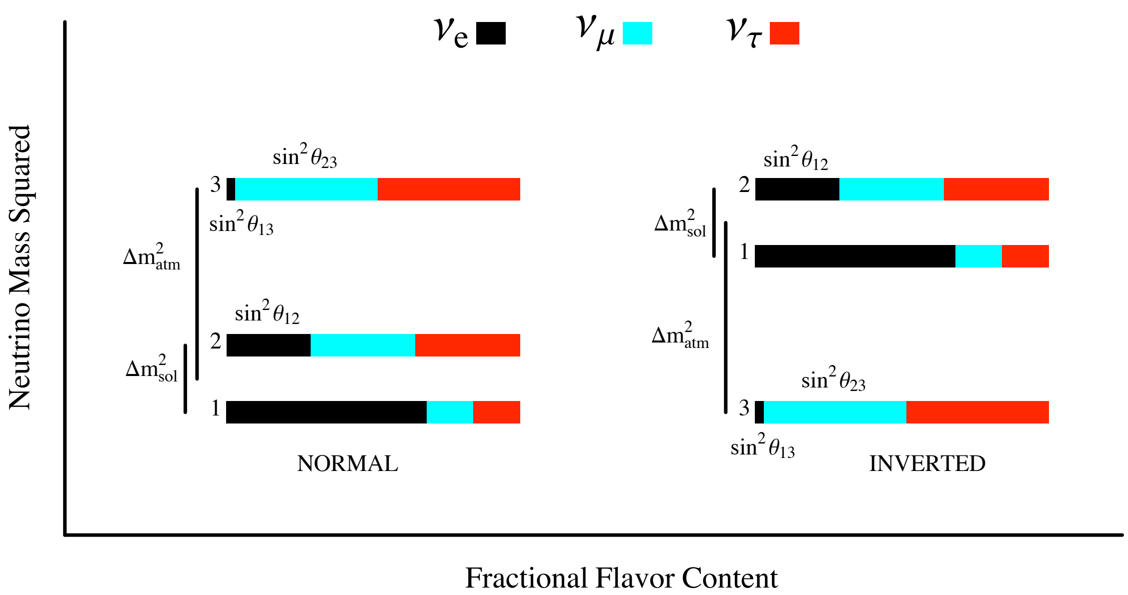
$$U_{\alpha i} = \begin{pmatrix} \sqrt{\tfrac{2}{3}}(1+\sigma) & \sqrt{\tfrac{1}{3}}(1-2\sigma) & \epsilon\ e^{-i\delta} \\ -\sqrt{\tfrac{1}{6}}(1-2\sigma+\lambda) - \sqrt{\tfrac{1}{3}}\ \epsilon\ e^{i\delta} & \sqrt{\tfrac{1}{3}}(1+\sigma+\lambda) - \sqrt{\tfrac{1}{6}}\ \epsilon\ e^{i\delta} & \sqrt{\tfrac{1}{2}}(1-\lambda) \\ \sqrt{\tfrac{1}{6}}(1-2\sigma-\lambda) - \sqrt{\tfrac{1}{3}}\ \epsilon\ e^{i\delta} & -\sqrt{\tfrac{1}{3}}(1+\sigma-\lambda) - \sqrt{\tfrac{1}{6}}\ \epsilon\ e^{i\delta} & \sqrt{\tfrac{1}{2}}(1+\lambda) \end{pmatrix}$$

at $\sigma = \lambda = 0$

$$|U_{\alpha i}|^2 \approx \begin{pmatrix} \frac{2}{3} & \frac{1}{3} & \epsilon^2 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{pmatrix} + \frac{\sqrt{2}}{3}\epsilon\cos\delta \begin{pmatrix} & & \\ 1 & -1 & \\ -1 & 1 & \end{pmatrix}$$

$$+7.3 \times 10^{-5} eV^2 < \delta m^2_{21} < +9.0 \times 10^{-5} eV^2$$

$$1.9 \times 10^{-3} eV^2 < |\delta m^2_{32}| < 3.0 \times 10^{-3} eV^2$$



$\sin^2\theta_{13} = 0.04$
at Chooz bound
and maximal CP violation,
$|\sin\delta| = 1$

two small quantities $\sin^2\theta_{13} < 0.04$ and $\frac{\delta m^2_{21}}{\delta m^2_{32}} \approx 0.03$

Within ν Standard Model

The Big Questions to be Addressed are

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

Other Questions

- $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$
- sign of $\cos\delta = \pm\sqrt{1-\sin^2\delta}$

Quest for ν_e fraction in ν_3: $\sin^2\theta_{13}$

- Current LBL (MINOS)
- Atmospheric Neutrinos
- Low and High Energy Solar Neutrinos
- Supernova Neutrinos
- Short Baseline Reactor (Double Chooz, ...)
- Future Long Baseline (T2K, NuMI, BNL2?, ...)
- Neutrino Factories
- Beta Beams

Hierarchy Quest: sign of δm^2_{31}

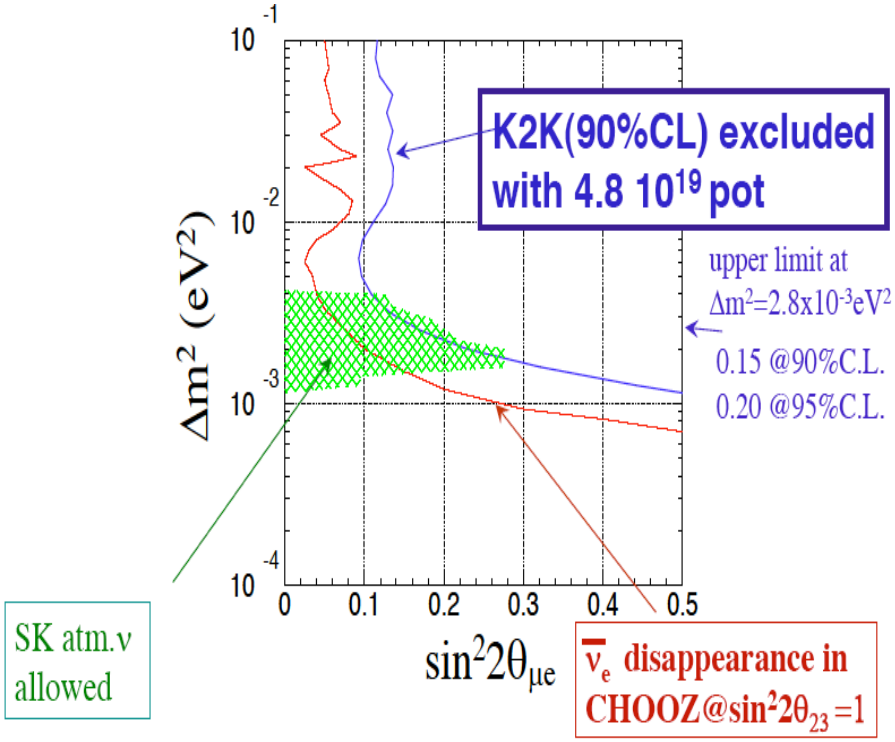
- $0\nu\beta\beta$ decay
- Atmospheric Neutrinos
- Supernova Neutrinos
- Future Long Baseline (NuMI, NuMI+T2K, BNL2? ...)
- Neutrino Factories (hi-γ Beta Beams)

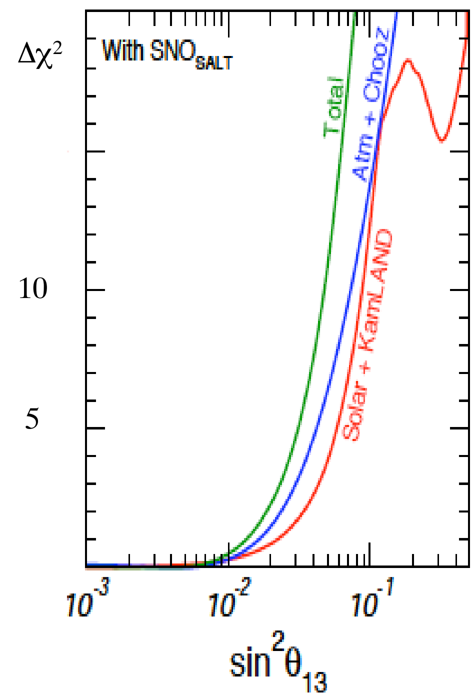
Quest for CP Violation: $\sin\delta$

- Future Long Baseline with Superbeams (T2HK, NuMI, BNL2? ...)
- Neutrino Factories
- Beta Beams

Quest for ν_e fraction in ν_3: $\sin^2\theta_{13}$

No indication yet of nonzero θ_{13} from atmospheric, solar and terrestrial ν





Maltoni et al.

$$\sin^2 2\theta_{\mu e} \equiv \sin^2 \theta_{23} \sin^2 2\theta_{13}$$

Short Baseline Reactor (Double Chooz, ...)

ν_e Survival Probability is

where Δ is the kinematical phase $\Delta_{ij} = \delta m^2_{ij} L/4E$

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = 4|U_{e3}|^2(1 - |U_{e3}|^2)\sin^2\Delta_{eff} + \mathcal{O}(\Delta^2_{21})$$

and δm^2_{eff} is the effective atmospheric δm^2 for ν_e disappearance:

Nunokawa, Zukanovich +SP
hep-ph/0503282

$$\delta m^2_{eff} = \cos^2\theta_{12}\ \delta m^2_{31} + \sin^2\theta_{12}\ \delta m^2_{32} = m^2_3 - (\cos^2\theta_{12}\ m^2_1 + \sin^2\theta_{12}\ m^2_2)$$

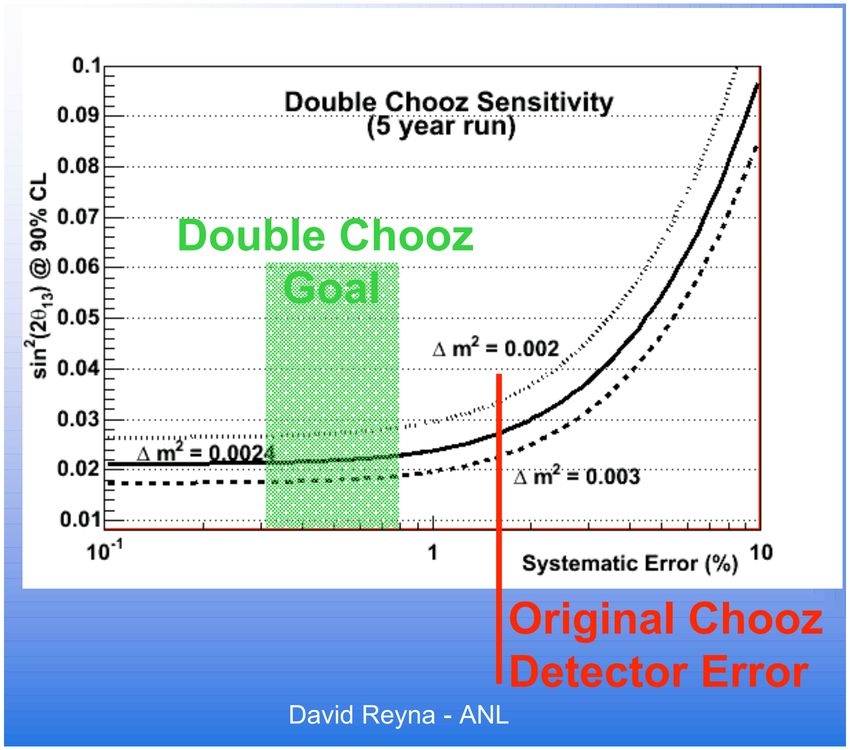
Direct measurement of ν_e fraction of ν_3:

$|U_{e3}|^2 = \sin^2\theta_{13} > 0.006$ (ultimately to 0.002)

(independent of $sign\ \delta m^2_{31}$, δ etc)

LBLs measure $\sin^2\theta_{23}\sin^2\theta_{13}$
remember $\theta_{23} \leftrightarrow \pi/2 - \theta_{23}$ degeneracy!!!

How well can you measure δm^2_{eff} ???



- Low and High Energy Solar Neutrinos

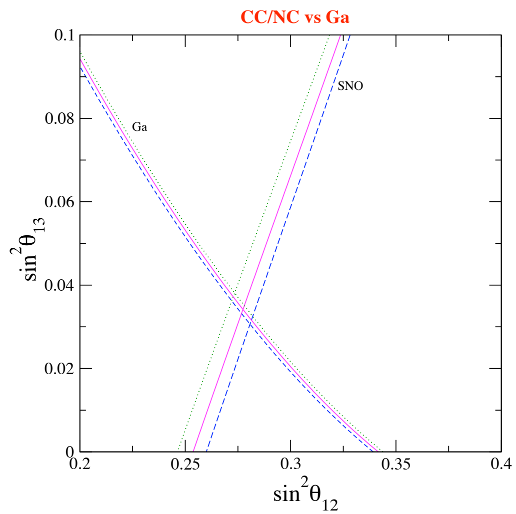


Figure 6: The iso-contours of CC/NC = 0.31 at SNO and Q_{Ge} = 68.1 SNU in Ga experiments in the $\sin^2\theta_{12} - \sin^2\theta_{13}$ plane for different values of Δm^2_{21} : $\Delta m^2_{21} = 9 \cdot 10^{-5}$ eV^2 - the dotted lines; $\Delta m^2_{21} = 8 \cdot 10^{-5}$ eV^2 - the solid lines; $\Delta m^2_{21} = 7 \cdot 10^{-5}$ eV^2 - the dashed lines.

$$\frac{CC}{NC} \sim \cos^2\theta_{13}\sin^2\theta_{12} + \cdots$$

$$\sin^2\theta_{13} \uparrow \quad \Rightarrow \quad \sin^2\theta_{12} \uparrow$$

$$Ga \sim \cos^4\theta_{13}\cos^4\theta_{12} + \cdots$$

$$\sin^2\theta_{13} \uparrow \quad \Rightarrow \quad \sin^2\theta_{12} \downarrow$$

Goswami + Smirnov
hep-ph/0411359

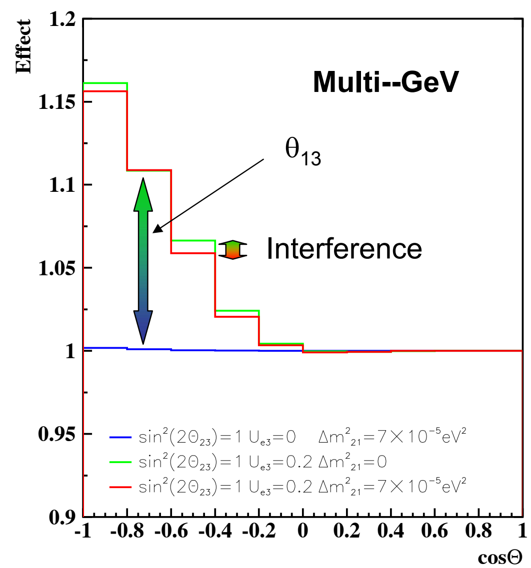
- Atmospheric Neutrinos

SK - Suzuki

— $|U_{e3}|=0.2$

— $\Delta m_{12}^2=7\text{x}10^{-5}\text{eV}^2$

— Interference



$\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} = \Big| \; \sum_{j=1}^{3} U^*_{\mu j} \; U_{ej} e^{-im_j^2 L/2E} \; \Big|^2$$

Elimate $U^*_{\mu 1} U_{e1}$
using unitarity of U.
Use $\Delta_{ij} = \delta m^2_{ij} L/4E = 1.27 \delta m^2_{ij} L/E$

$$P_{\mu\to e} = \Big| \; 2U^*_{\mu 3} U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin\Delta_{21} \; \Big|^2$$

Square of Atmospheric+Solar amplitude:
$U^*_{\mu 3} U_{e3} = s_{23} s_{13} c_{13} e^{\mp i\delta}$ for ν and $\bar{\nu}$:
Approx. $U^*_{\mu 2} U_{e2} \approx c_{23} s_{12} c_{12} + \mathcal{O}(s_{13})$:

$$P_{\mu\to e} \approx \Big| \; 2 s_{23} s_{13} c_{13} \sin\Delta_{31} e^{-i(\Delta_{32}\pm\delta)} + 2 c_{23} s_{12} c_{12} \sin\Delta_{21} \; \Big|^2$$

Interference term different for ν and $\bar{\nu}$:

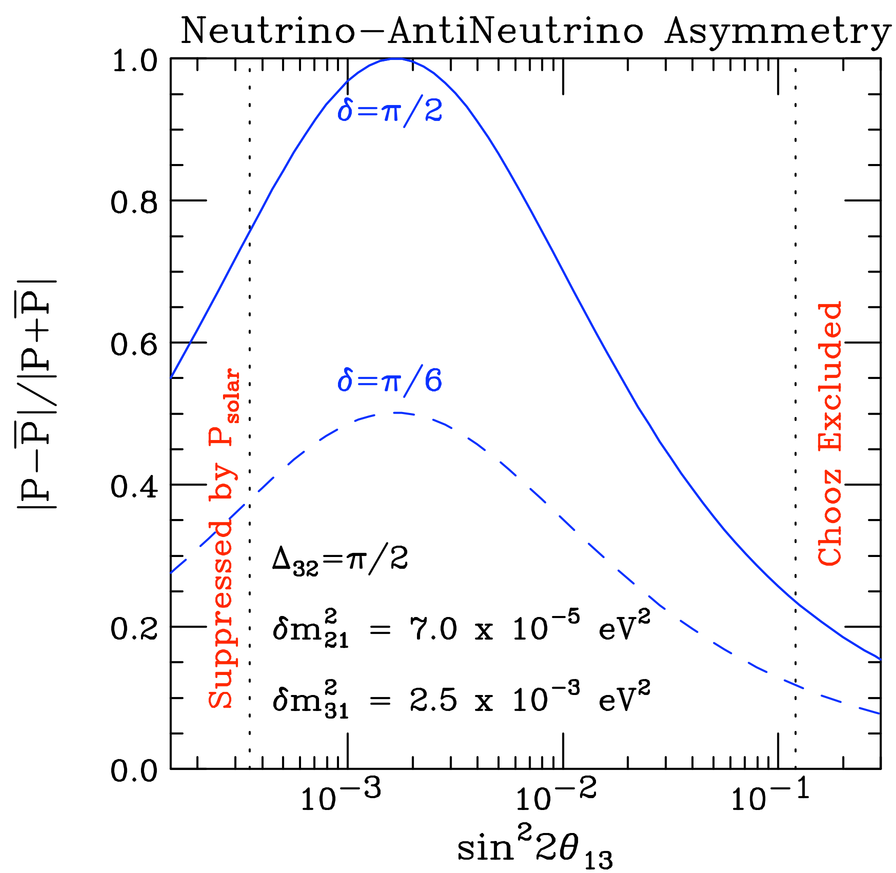
CP violation !!! provided $\Delta_{32} \neq 0$

VAC LBL: $\nu_\mu \to \nu_e$

CP violation !!!

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

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\;\sin\Delta_{31}$ and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\;\sin\Delta_{21}$



$\nu_\mu \longrightarrow \nu_e$ with MATTER

CP violation !!!

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

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

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

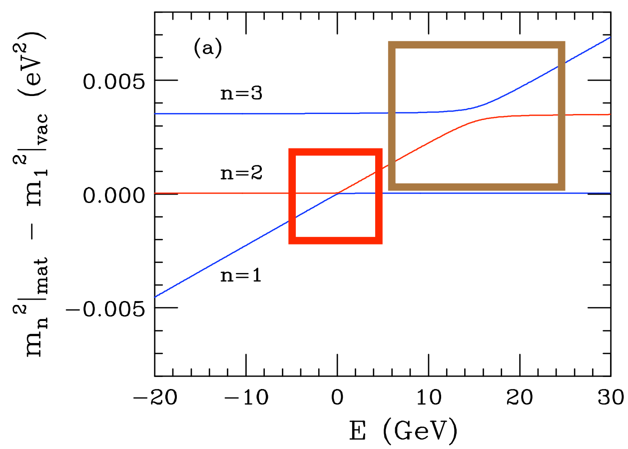
$$a\ =\ G_F N_e/\sqrt{2}\ =\ (4000\ \ km)^{-1},$$
$$\pm = sign(\delta m^2_{31})$$
$$\Delta_{ij}\ =\ |\delta m^2_{ij}|L/4E$$

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

$$\sin\Delta_{31} \Rightarrow \left(\frac{\Delta_{31}}{\Delta_{31}\mp aL}\right)\sin(\Delta_{31}\mp aL)$$

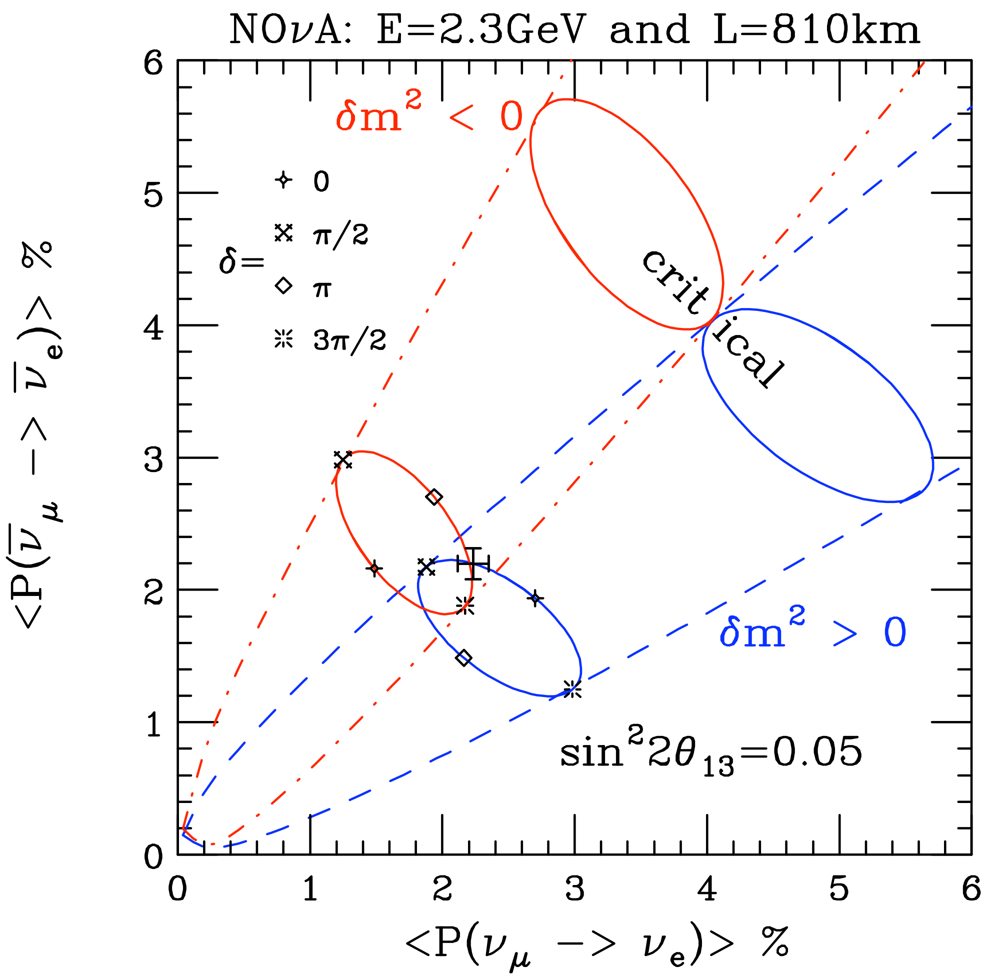
$$\sin\Delta_{21} \Rightarrow \left(\frac{\Delta_{21}}{\Delta_{21}\mp aL}\right)\sin(\Delta_{21}\mp aL)$$

$$\sin\Delta_{32} \Rightarrow \sin\Delta_{32}$$



Matter effects are IMPORTANT when $\sin(\Delta\mp aL) \neq (\Delta\mp aL)$.

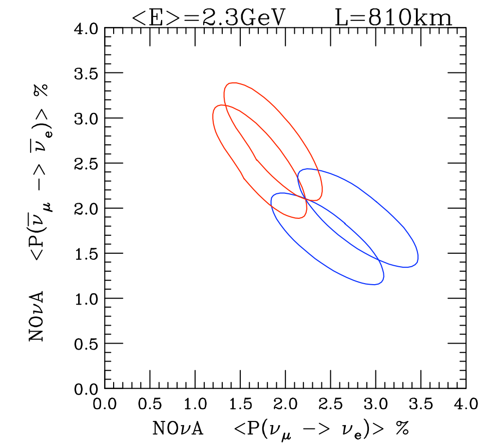
Bi-Probability Diagram:

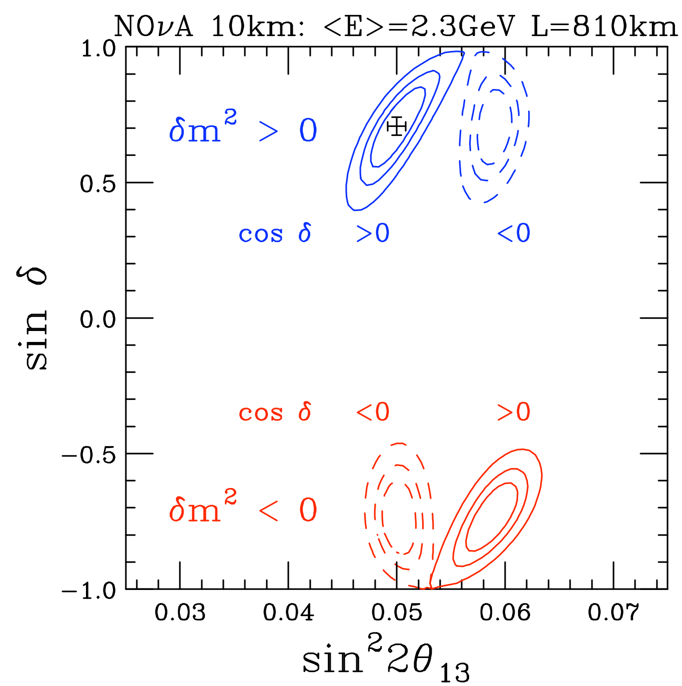


Minakata+Nunokawa
hep-ph/0108085

Parameter Degeneracies:

4 ellipses:





$$\Uparrow$$

$$\frac{2\theta_{13}}{\theta_{crit}} \sim (aL)\theta_{13}$$

$$\Downarrow$$ 0 in vacuum

$$\theta_{crit} = \frac{\cot\theta_{23}\sin 2\theta_{12}\Delta_{21} \;\; \mathcal{S}(aL) \;\; \mathcal{S}(\Delta_{31})}{\{\mathcal{S}(\Delta_{31}-aL)-\mathcal{S}(\Delta_{31}+aL)\}}$$

where $\mathcal{S}(\Delta) \equiv \frac{\sin\Delta}{\Delta}$

Burget-Castell etal
hep-ph/0103258

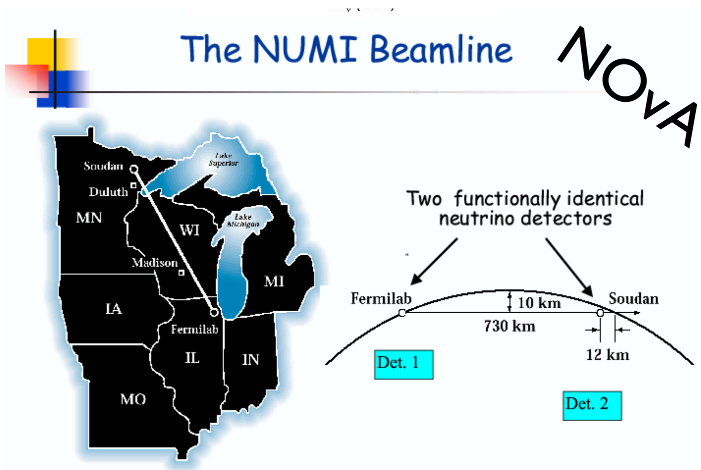
$$\Leftrightarrow$$

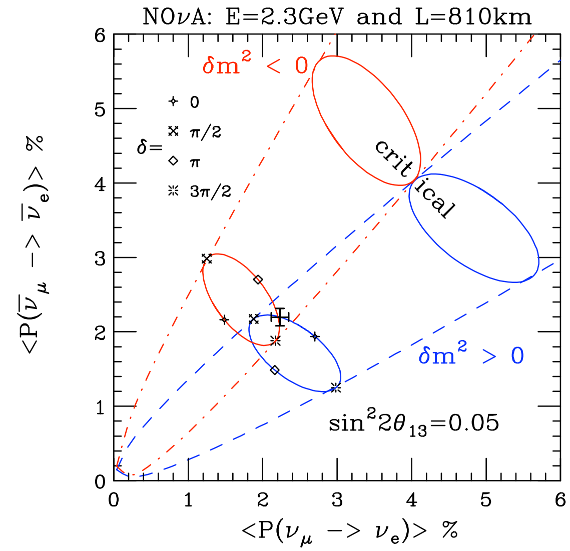
$$\sim \Delta_{31}\cot\Delta_{31}$$

0 when $\boldsymbol{\Delta_{31} = \pi/2}$

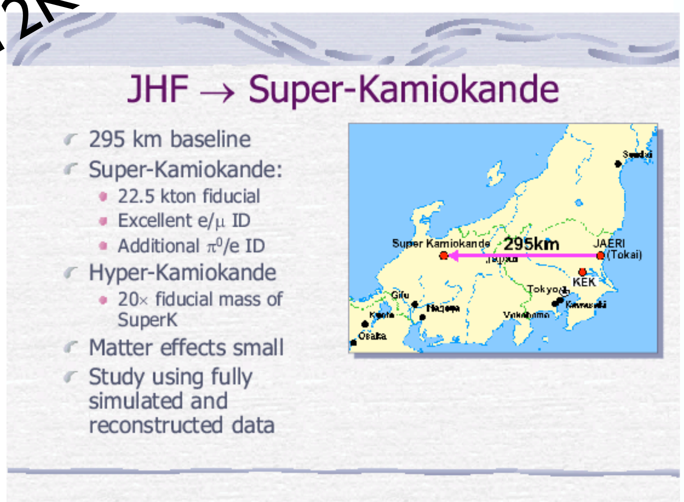
Mena + SP
hep-ph/0408070

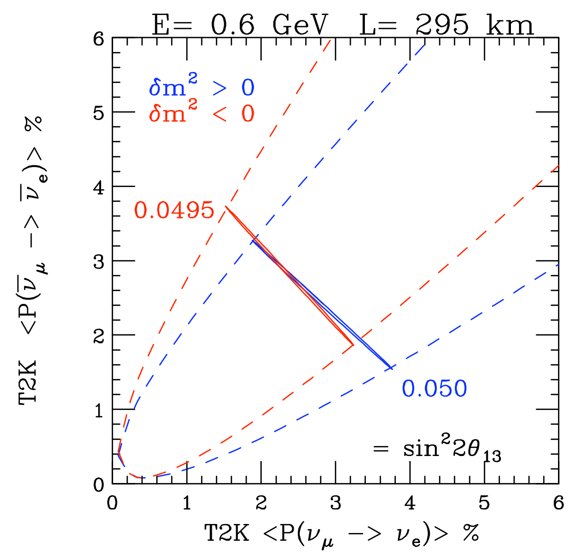
NOvA

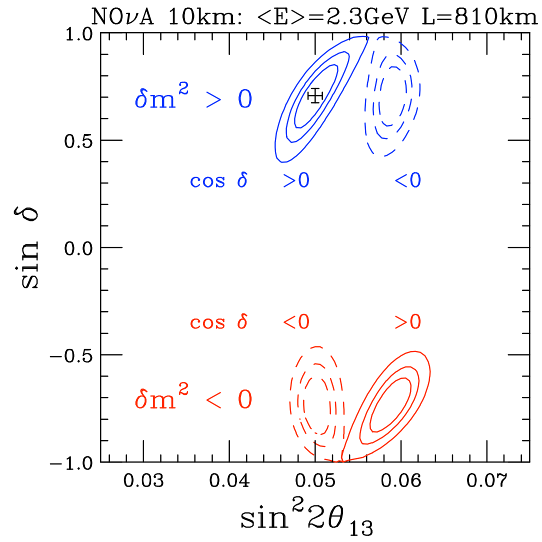

The NUMI Beamline
Soudan
Duluth
Lake Superior
MN
WI
Lake Michigan
Madison
MI
IA
Fermilab
IL
IN
MO
Two functionally identical neutrino detectors
Fermilab
Soudan
10 km
730 km
12 km
Det. 1
Det. 2


NOνA: E=2.3GeV and L=810km
$\delta m^2 < 0$
$\delta=$
0
$\pi/2$
π
$3\pi/2$
critical
$\delta m^2 > 0$
$\sin^2 2\theta_{13}=0.05$
$<P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)>$ %
$<P(\nu_\mu \rightarrow \nu_e)>$ %

T2K


JHF → Super-Kamiokande
295 km baseline
Super-Kamiokande:
22.5 kton fiducial
Excellent e/μ ID
Additional π^0/e ID
Hyper-Kamiokande
20× fiducial mass of SuperK
Matter effects small
Study using fully simulated and reconstructed data
Super Kamiokande
295km
JAERI (Tokai)
KEK
Tokyo
Sendai
Gifu
Nagoya
Kyoto
Osaka
Yokohama
Kawasaki


E= 0.6 GeV L= 295 km
$\delta m^2 > 0$
$\delta m^2 < 0$
0.0495
0.050
$= \sin^2 2\theta_{13}$
T2K $<P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)>$ %
T2K $<P(\nu_\mu \rightarrow \nu_e)>$ %

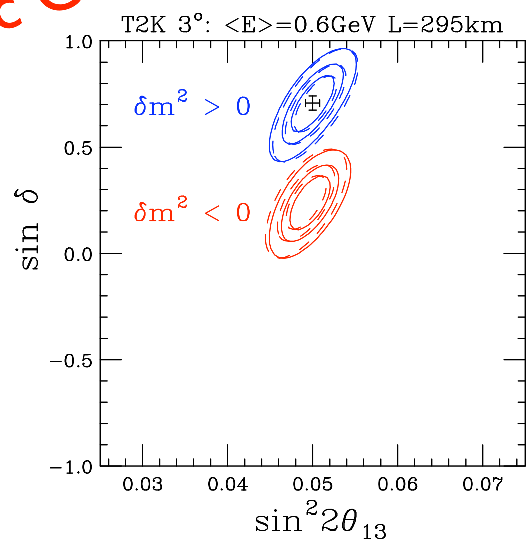


$$\langle \sin\delta\rangle_{+} - \langle \sin\delta\rangle_{-} = 1.41\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

factor of 3 !!!

$$|\ \langle \sin\delta\rangle^{T2K}_{true} - \langle \sin\delta\rangle^{NO\nu A}_{true}\ | \approx 0.$$

Vac Osc Max



$$|\ \langle \sin\delta\rangle^{T2K}_{fake} - \langle \sin\delta\rangle^{NO\nu A}_{fake}\ | = 0.94\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}.$$

$$\langle \sin\delta\rangle_{+} - \langle \sin\delta\rangle_{-} = 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

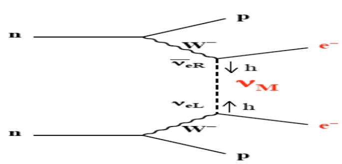
BNL2HSK 1 per E bin

Solving Degeneracies:

Variable Measured	LBL $\nu_\mu \to \nu_\mu$	LBL $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	Reactor $\bar{\nu}_e \to \bar{\nu}_e$	Comments
$\lvert\Delta m^2_{32}\rvert$	Y	n	n	magnitude but not sign
$\sin^2 2\theta_{23}$	Y	n	n	$\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ ambiguous
$\sin^2 \theta_{13}$	n	n	Y	direct measurement
$\sin^2 \theta_{23} \sin^2 \theta_{13}$	n	Y	n	combination of θ_{23} and θ_{13}
sign(Δm^2_{32})	n	Y	n	via matter effects
$\cos\theta_{23} \sin\delta_{CP}$	n	Y	n	CP violation
$\cos\theta_{23} \cos\delta_{CP}$	n	?	n	extremely difficult

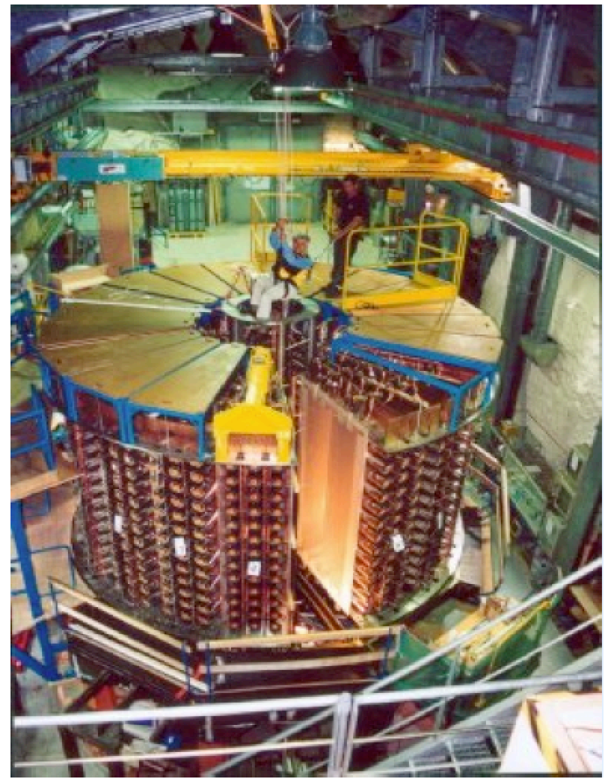
Neutrinoless double beta decay

- Most sensitive (terrestrial) probe of the absolute neutrino mass
- Unique way of proving Majorana nature of ν
- If Majorana ν is the only mechanism, ===>



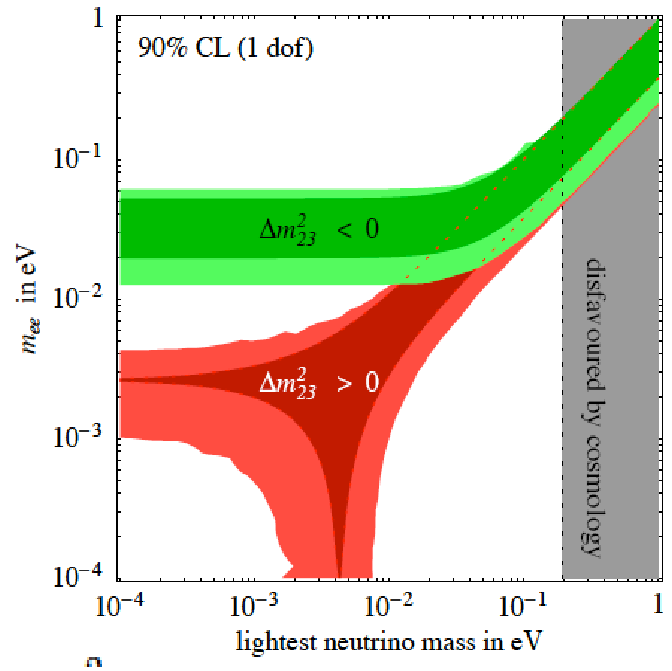
$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$



• If Inverted hierarchy and Majorana then a signal above 10 meV.

dividing point $m_{\beta\beta} \approx 10\ meV$ $\Longrightarrow$



• If Inverted hierarchy and no signal above 10 meV then Dirac !!!

Petcov // talk

Beyond the ν Standard Model

- Sterile Neutrinos, (LSND/miniBOONE) e.g. 3+n models
- Dirac Neutrinos
- CP and/or T violation requiring more than one phase
- CPT violation
- Exotic interactions:
  magnetic moments, addition matter interactions, . . .
- . . .

unexpected

Light Sterile Neutrinos:

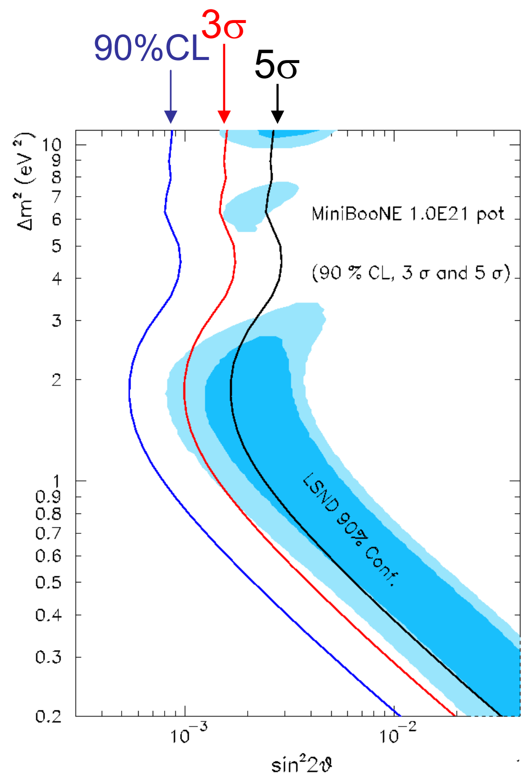
LSND/miniBOONE

LSND: $\bar{\nu}_\mu \to \bar{\nu}_e$ from μ^- decay.

miniBOONE: $\nu_\mu \to \nu_e$ from π^+ decay.

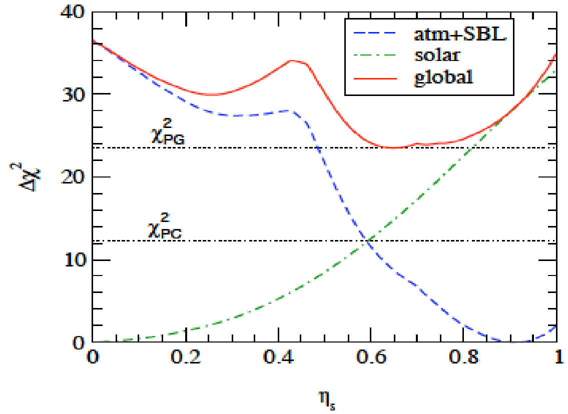
Various schemes are proposed motivated by the LSND data, which include:

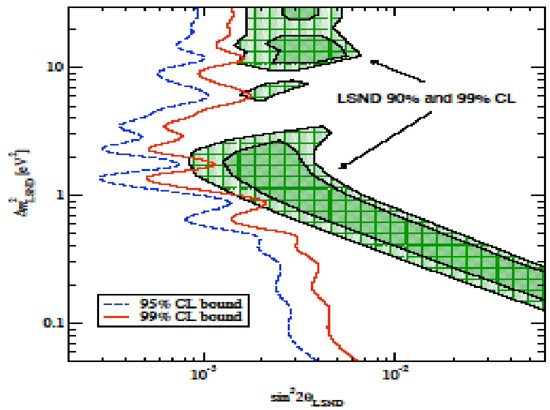
- 2+2 sterile-active scheme
- 3+1
- 3+2
- CPT violation
- Sterile + CPT violation
- …..



to definitively exclude LSND in the event that MiniBooNE does not see a signal, we need 1x10²¹ POT

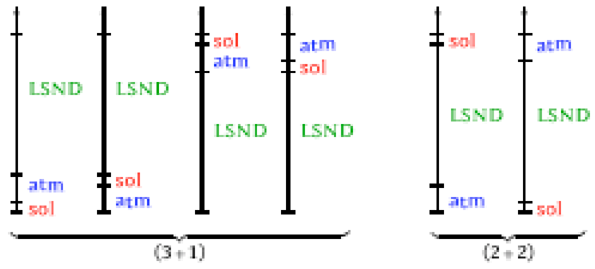
Four Neutrino Scenarios





- 2+2 scheme: strongly disfavored by atmospheric and solar data (99.95% CL)
- 3+1 scheme: constrained by SBL experiments, allowed only marginally

(Maltoni, Schwetz Tortola, Valle
hep-ph/0209368)



3+2 Active-Sterile Scenario

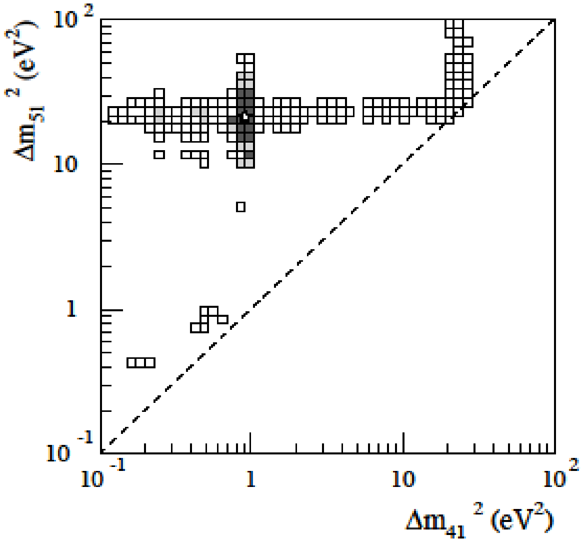
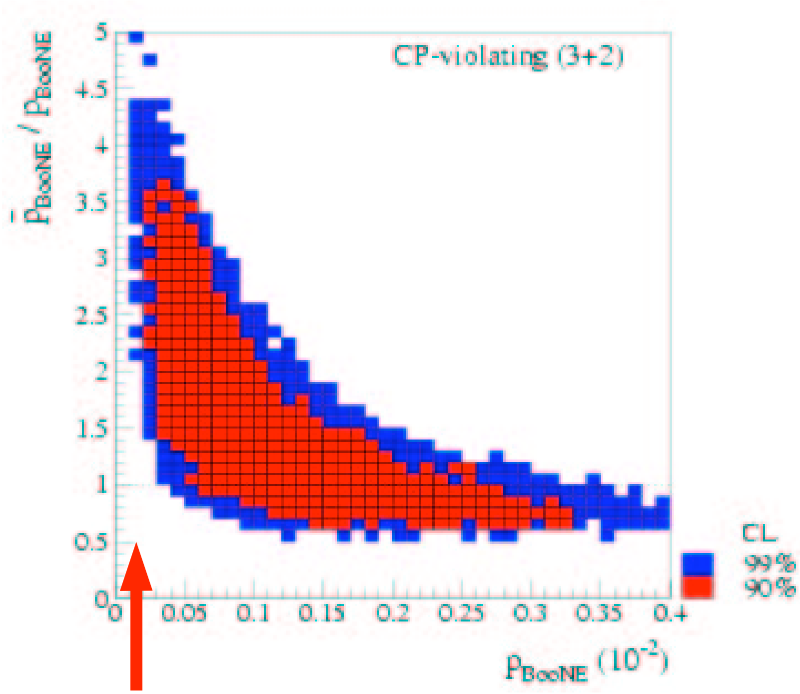


FIG. 6: Allowed ranges in $(\Delta m^2_{41}, \Delta m^2_{51})$ space for (3+2) models, for the combined NSBL+LSND analysis, assuming statistical compatibility between the NSBL and LSND data sets. The star indicates the best-fit point, the grey-shaded regions indicate the 90, 95, 99% CL allowed regions. Only the $\Delta m^2_{51} > \Delta m^2_{41}$ region is shown; the complementary region $\Delta m^2_{41} > \Delta m^2_{51}$ can be obtained by interchanging Δm^2_{41} with Δm^2_{51}.

- Best-fit point utilizes a "dip" in sensitivity of SBL experiments (Sorel-Conrad-Shaevitz, hep-ph/0305255)
- Constrained by disappearance measurement in the Mini-BOONE (When?)

$$\mathbf{P_{osc}(\nu_\alpha \to \nu_\beta) \neq P_{osc}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}$$

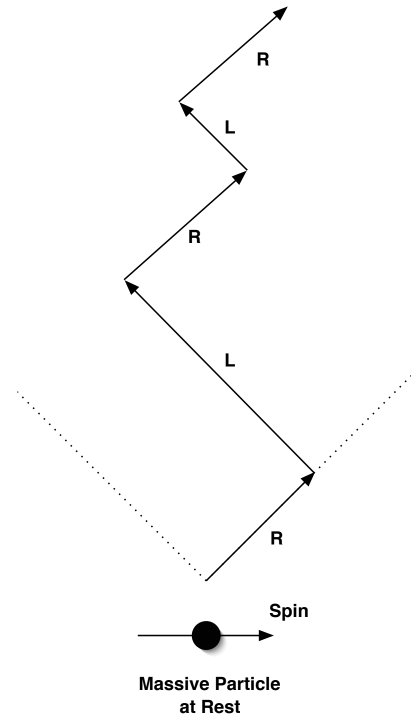


MiniBooNE can have
a small signal in neutrino-mode
(which could easily fluctuate to a null signal!)
& a **×3 larger signal in antinneutrino mode**

Fermion Masses:

massless

	electron	positron	
Left Chiral	e_L	$\bar{e}_R$	SU(2)×U(1)
Right Chiral	e_R	$\bar{e}_L$	U(1)



CPT: $e_L \leftrightarrow \bar{e}_R$ and $e_R \leftrightarrow \bar{e}_L$

Mass couples L to R:

$$P^2 = M^2, \quad P \cdot S = 0 \quad and \quad S^2 = -1$$

e_L to e_R AND also $\bar{e}_R$ to $\bar{e}_L$ Dirac Mass terms.

$$u(P,S) = \frac{(1+\gamma_5)}{2} u(\frac{P+MS}{2}) + e^{i\phi} \frac{(1-\gamma_5)}{2} u(\frac{P-MS}{2})$$

right massless   left massless

A coupling of
e_L to $\bar{e}_R$ OR e_R to $\bar{e}_L$ would be (Majorana) mass term
but this violates conservation of electric charge!

Seesaw / Dirac Neutrinos / Light Sterile Neutrinos

	Nu		Anti-Nu	
Left Chiral	$\boldsymbol{\nu_L}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_R}$	
	$\Updownarrow$		$\Updownarrow$	Dirac Masses
Right Chiral	$\boldsymbol{\nu_R}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_L}$	
		Majorana Masses		

Coupling of

- ν_L to ν_R AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- ν_L to $\bar{\nu}_R$ forbidden by weak isospin.
- ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$$

Two Majorana neutrinos with masses m_D^2/M and M

Seesaw: Yanagida, Gell-man-Ramond-Slansky

- Coupling of ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

Also applies to sterile neutrinos.

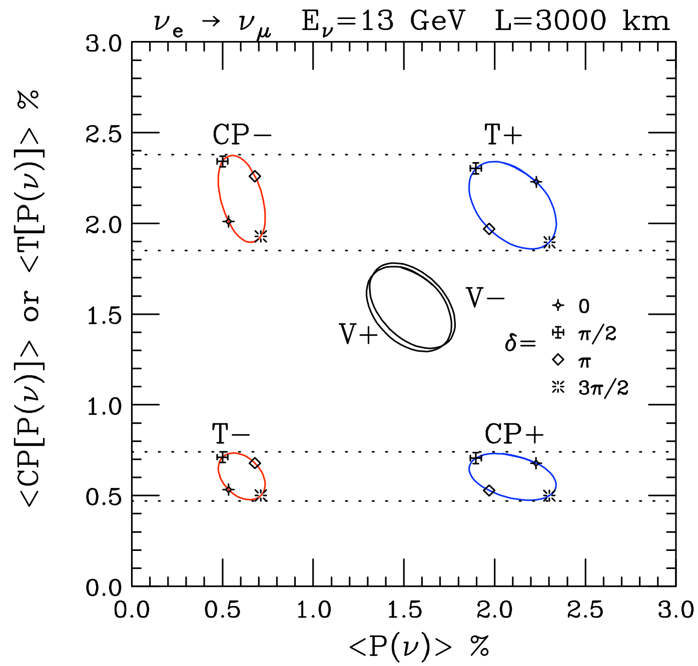
Light Sterile Neutrinos and/or Dirac Neutrinos Unexpected!!!

- CP and/or T violation requiring more than one phase

$$
\begin{array}{cccccc}
 & & \text{CP} & & & \\
 & \nu_\mu \leftrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e & & \text{Super-Beams} \\
\text{T} & \Updownarrow & & \Updownarrow & \text{T} & \\
 & \nu_e \leftrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu & & \text{Nu-Factory} \\
 & & \text{CP} & & &
\end{array}
$$

$\nu_\mu \leftrightarrow \nu_e$

$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$



$\nu_e \leftrightarrow \nu_\mu$

$$P_{mat}(\nu_e \rightarrow \nu_\mu, \delta m^2_{31}, \delta m^2_{21}, \delta)$$
$$\approx P_{mat}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e, -\delta m^2_{31}, \delta m^2_{21}, \pi - \delta)$$

Minakata, Nunokawa + SP
hep-ph/0204171

Predictions from Models:

Selected $SO(10)$ Models and θ_{13} Predictions

Model	(Level) Flavor Sym.	Texture	$\tan\beta$	$\sin^2 2\theta_{13}$
AB	(4) $U(1) \times Z_2 \times Z_2$	Lopsided	$\sim$	0.0008-0.00
ABMSV	(1) Min. eff. ops.	Sym (II)	?	0.10
BO	(1) Min. eff. ops.	Sym	?	0.004-0.008
BKOT	(1) Min. eff. ops.	Sym	?	0.0004-0.01
BPW	( ) $U(1)$ eff. ops.	Sym (II)	low	?
CM	(4) $U(2) \times (Z_2)^3$	Sym	10	0.09
FKO	(1) Min. eff. ops.	Sym	4	0.1
GMN	(1) Min. eff. ops.	Sym(II)	10	0.10
KM	(2) $SU(\ ) \times U(1)$	Lopsided	small	~ 0.19
KRV-S	(4) $SU(\ ) \times Z_2 \times U(1)_A$	Sym/Asym	?	0.02
M	(2) $U(1)_A \times Z_2$	Lopsided		~ 0.19

AB	Albright, Barr	$\sin^2 2\theta_{atm} \simeq 0.99$
ABMSV	Aulakh, Bajc, Melfo, Senjanovic, Vissani	not spelled out
BO	Bando, Obara	
BKOT	Bando, Kaneko, Obaro, Tanimoto	
BPW	Babu, Pati, Wilczek	
CM	Chen, Mahanthappa	$\sin 2\beta = 0.74$, $\delta_{CKM} \sim\ ^\circ$
FKO	Fukuyama, Kikuchi, Okada	$\Delta m^2_{sol}/\Delta m^2_{atm} = 0.188$
GMN	Goh, Mohapatra, Ng	$\sin^2 2\theta_{atm} \leq 0.92$, $\sin^2 2\theta_{12} \geq 0.9$
KM	Kitano, Mimura	satisfies LMA mixing?
KRV-S	King, Ross, Velasco-Sevilla	
M	Maekawa	satisfies LMA mixing?

Albright'04

QUARK-LEPTON COMPLEMENTARITY; A REVIEW

Scenarios	$\Delta \sin^2 \theta_{12}$	$\sin^2 2\theta_{13}$	$D_{23} \equiv \frac{1}{2} - s_{23}^2$	$J_{lep}/\sin\delta$
neutrino bi-maximal	0.051	0.10 ± 0.032	0.025	1.5×10^{-3}
lepton bi-maximal	-6×10^{-4}	2×10^{-3}	0.035^*	5×10^{-3}
hybrid bi-maximal	1.4×10^{-4}	3.3×10^{-4}	0.04^*	2.1×10^{-3}
neutrino max+large	0.057 ± 0.023	0.10 ± 0.032	SK bound	$\leq 6.8 \times 10^{-3}$
lepton max+large	-6×10^{-4}	2×10^{-3}	SK bound	$\leq 5 \times 10^{-3}$
hybrid max+large	1.4×10^{-4}	3.3×10^{-4}	SK bound	$\leq 2.1 \times 10^{-3}$
single maximal	0.015	0.034	$0.06 - 0.16$	9.1×10^{-3}

Table 1: Predictions to the deviation from the QLC relation $\Delta \sin^2 \theta_{12}$, $\sin^2 2\theta_{13}$, the deviation parameter from the maximal 2-3 mixing D_{23}, and the leptonic Jarlskog factor J_{lep} for different scenarios. The uncertainties indicated with $\pm$ come from the experimental uncertainty of the atmospheric mixing angle θ_{23}. Whenever there exist uncertainty due to the CP violating phase δ we assume that $\cos\delta = 0$ to obtain an "average value". For the quantities which vanish at $\cos\delta = 0$ (indicated by *) the numbers are calculated by assuming $\cos\delta = 1$ "SK bound" implies the whole region allowed by the Super-Kamiokande: $|D_{23}| \leq 0.16$. The numbers for the last row (single-maximal case) are computed with the assumed values of $\theta_{23}^l = \theta_C$ and $\theta_{23}^\nu = 27°$.

Minakata hep-ph/0505262

Summary + Conclusions

Tremendous progress has been made in the last 10 years,
Many hard questions left (the low olives have been picked):

- # of light sterile neutrinos
- Majorana v Dirac
- absolute mass, m_{lite}
- fraction ν_e in m_3
- mass hierarchy
- CP violation
- mass and mixing models

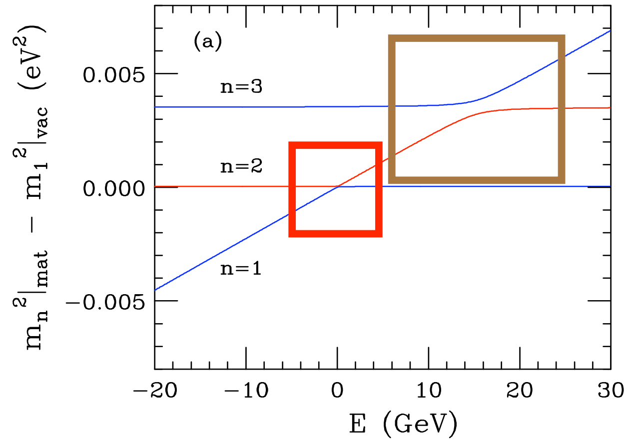
BUT watch out for SURPRISES, THE UNEXPECTED...

Summary + Conclusions (conti)

- miniBOONE confirms LSND osc.
- inverted hierarchy
- Dirac neutrinos
- degenerate masses
- new neutrino interactions
- STHNTO

Matter Effects:

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



$$\sin\Delta_{31} \Rightarrow \left(\frac{\Delta_{31}}{\Delta_{31} \mp aL}\right) \sin(\Delta_{31} \mp aL)$$

$$\sin\Delta_{21} \Rightarrow \left(\frac{\Delta_{21}}{\Delta_{21} \mp aL}\right) \sin(\Delta_{21} \mp aL)$$

$$\sin\Delta_{32} \Rightarrow \sin\Delta_{32}$$

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

Matter effects are IMPORTANT when $\sin(\Delta \mp aL) \neq (\Delta \mp aL)$.

LBL: $\nu_\mu \to \nu_e$

CP violation !!!

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

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

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

and $\sqrt{P_{sol}} = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}\,\frac{\sin(aL)}{(aL)}\,\Delta_{21}$

$$\pm = sign(\delta m^2_{31})$$

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