# Neutrino Phenomenology:

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Fermilab

WIN'05 Delphi

Nu Standard Model
Beyond Nu SM
Predictions/Models

# "The" $\nu$ Standard Model

- 3 light ($m_i$ <1 eV) Majorana Neutrinos: $\Rightarrow$ only 2 $\delta m^2$
- 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,

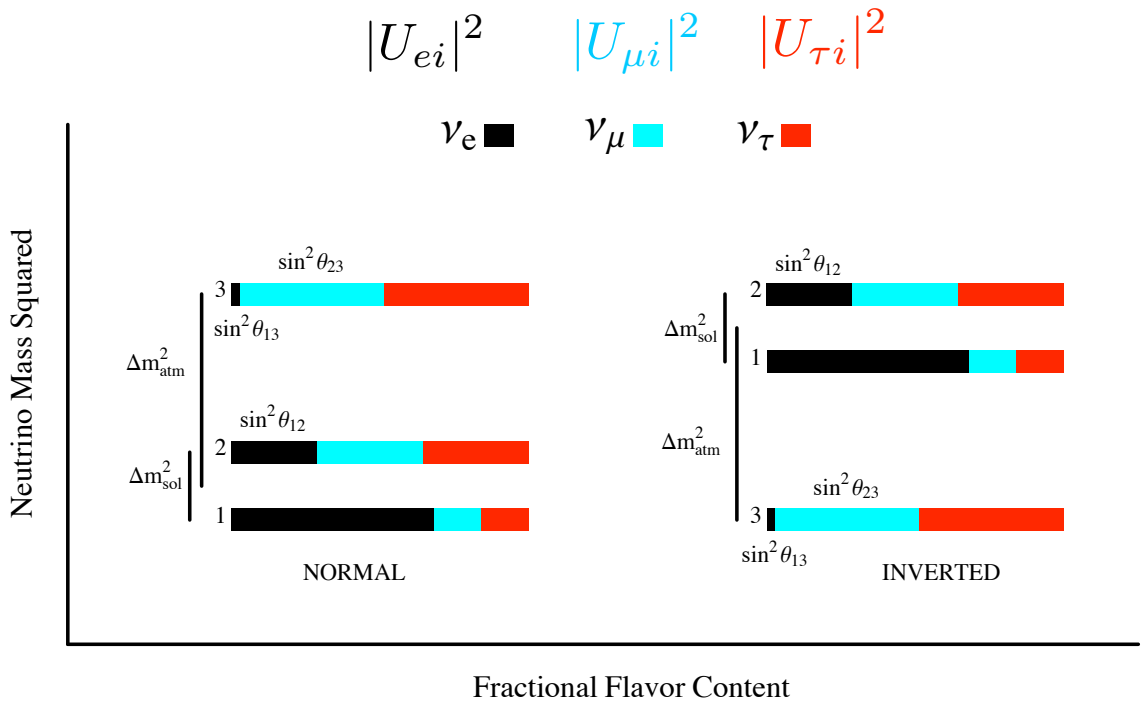
the phases $\alpha,\ \beta$ are unobservable ($U_{\alpha i}U^*_{\beta i}$)
as well as the value of $m_{lite}$ ($\delta m^2$).

In $0\nu\beta\beta$ decay

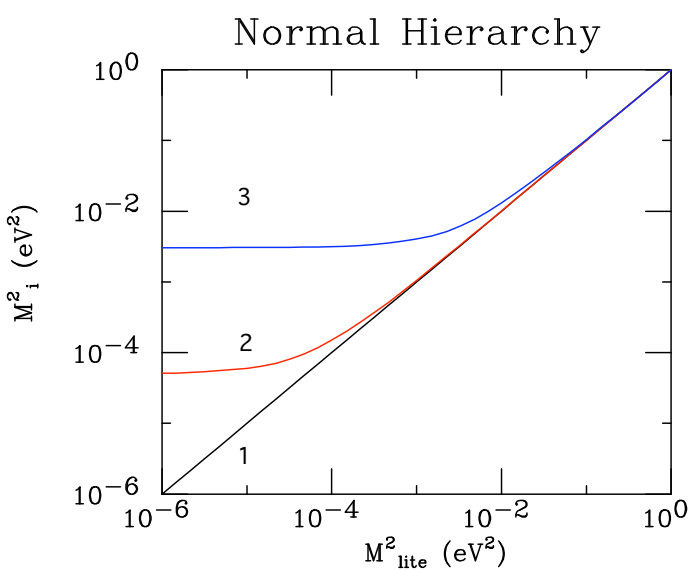
only a combination of the phases $\alpha,\ \beta$ observable
in this CP conserving phenomena.

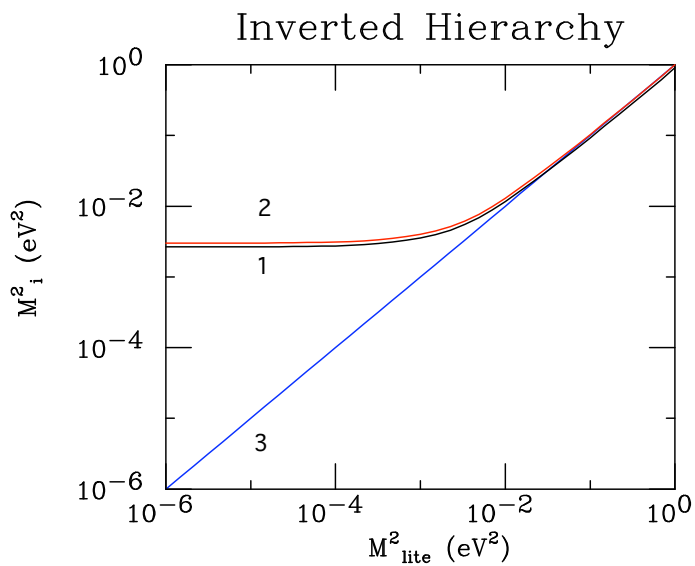
# Mixings:

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

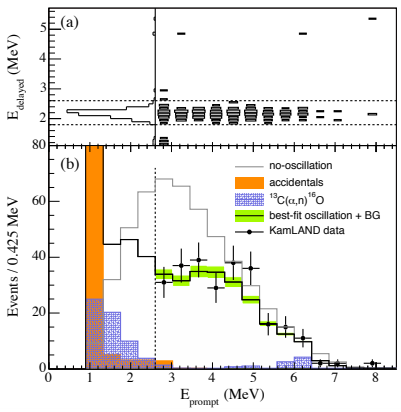



# Masses:



# 12- Sector (Solar)



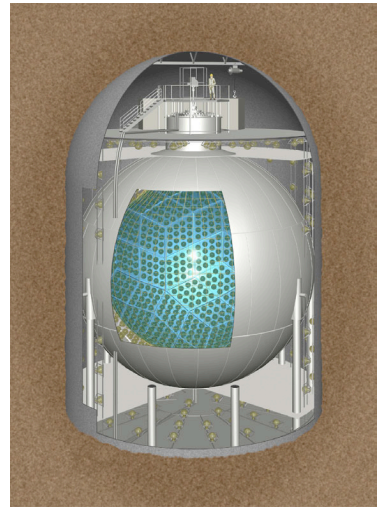
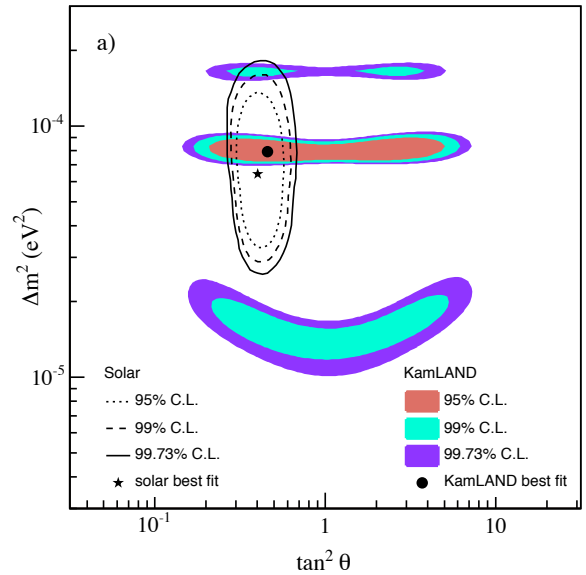
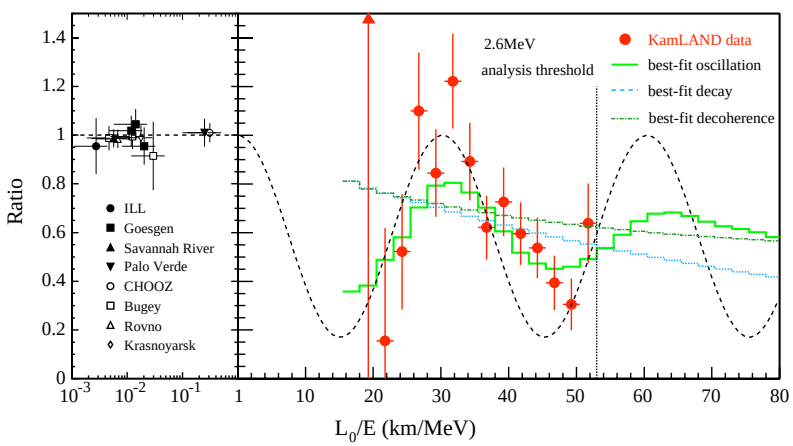



**Figure 3.** Schematic view of the KamLAND detector.

# KamLAND:



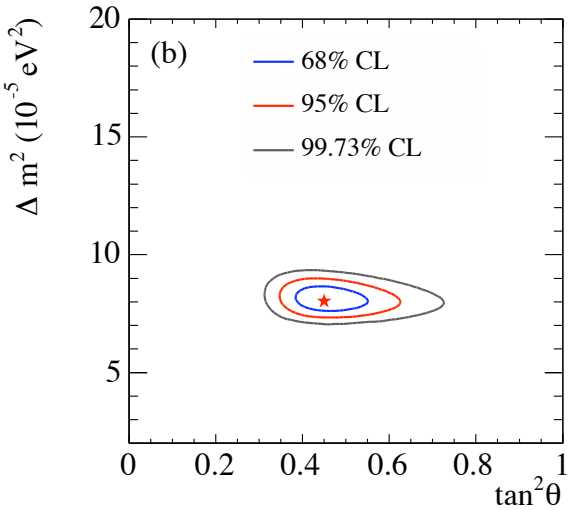

$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\mathrm{eV}^2$$

Pure Vac. Osc.

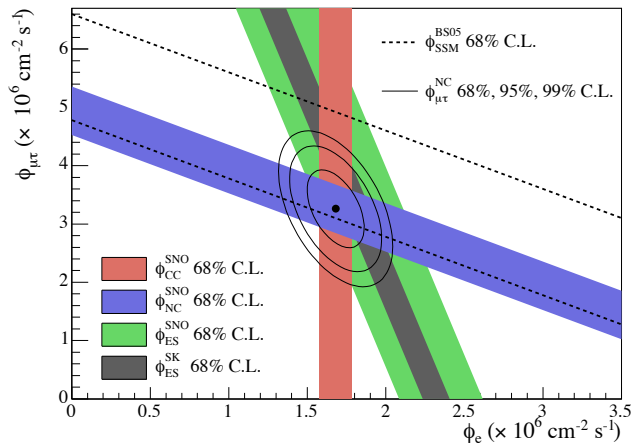
$$P = 1 - \sin^2 2\theta_\odot \sin^2 \frac{\delta m^2_\odot L}{4E}$$

# 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 | $\Delta m^2$ ($10^{-5}$ 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 | $8.0^{+0.6}_{-0.4}$ | $0.45^{+0.09}_{-0.07}$ |




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

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

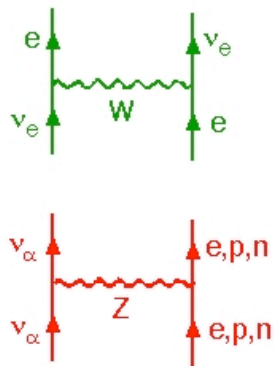
# SK: (ES)

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

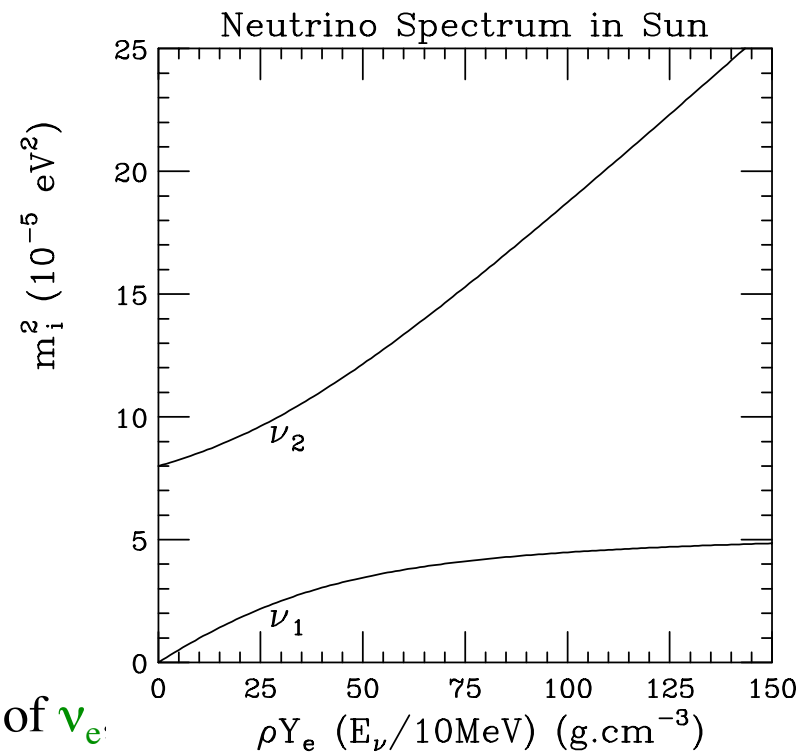
D/N asym -2 +/-1% Holanda+Smirnov
hep-ph/0212270

# Physics of LMA:

## Coherent Forward Scattering:



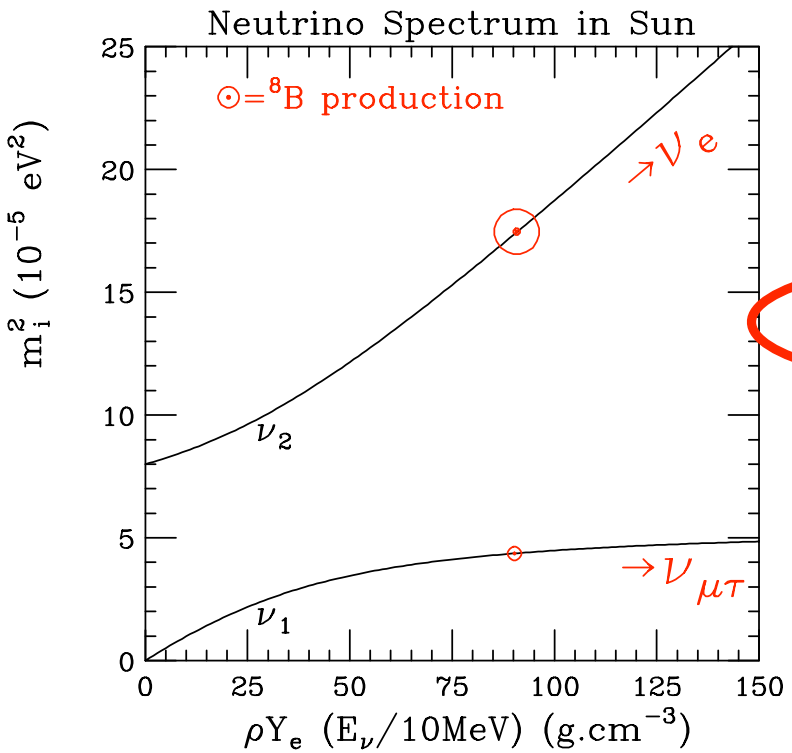

Wolfenstein '78




raises the effective mass of $\nu_e$

Mikheyev + Smirnov Resonance WIN '85

# $^8$Boron Neutrinos

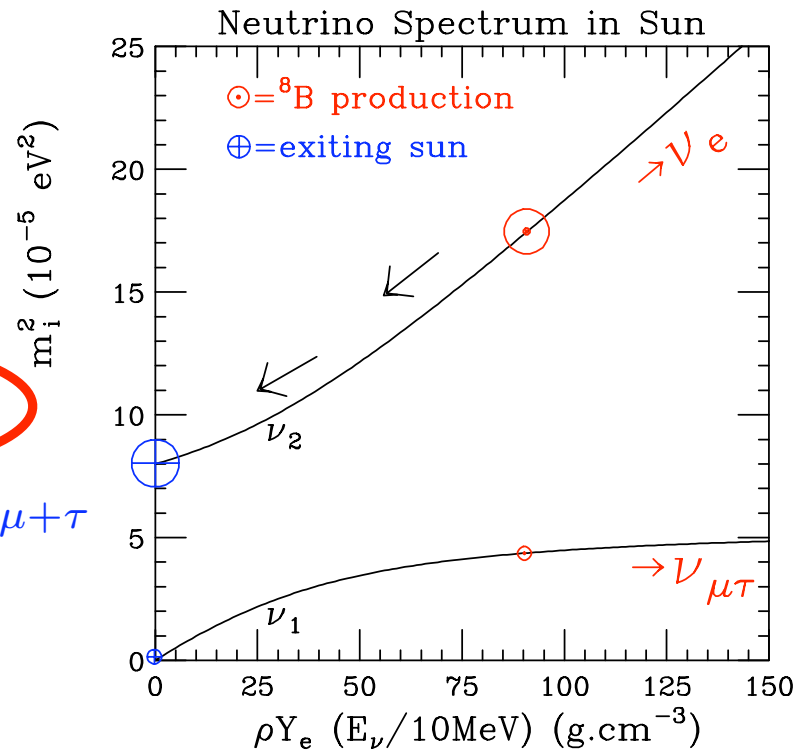



$$\nu_e = \sin\theta_N \, \nu_2 + \cos\theta_N \, \nu_1$$

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

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

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




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

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

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

where $f_1$ and $f_2 = 1 - f_1$ are the fractions of $\nu_1$ and $\nu_2$ 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
$f_2 = \langle \sin^2\theta_N \rangle \gg f_1 = \langle \cos^2\theta_N \rangle$

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

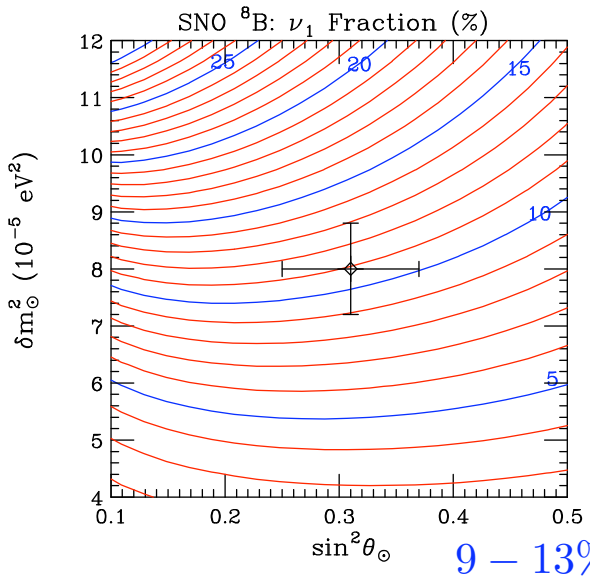
$$0.358 = 0.31 + f_1 \star 0.38$$

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

$^8B$ Neutrinos that SNO is sensitive to are about 90% $\nu_2$ !!!

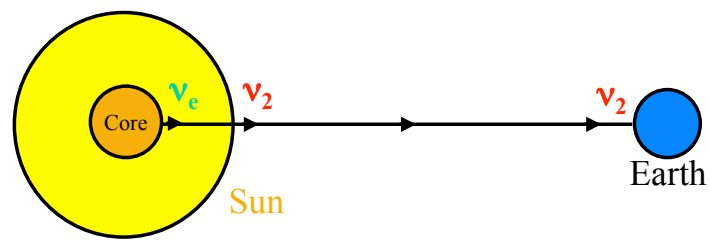
thus SNO is measuring the $\nu_e$ fraction of $\nu_2 \equiv \sin^2\theta_\odot$

(upto ~10% corrections)



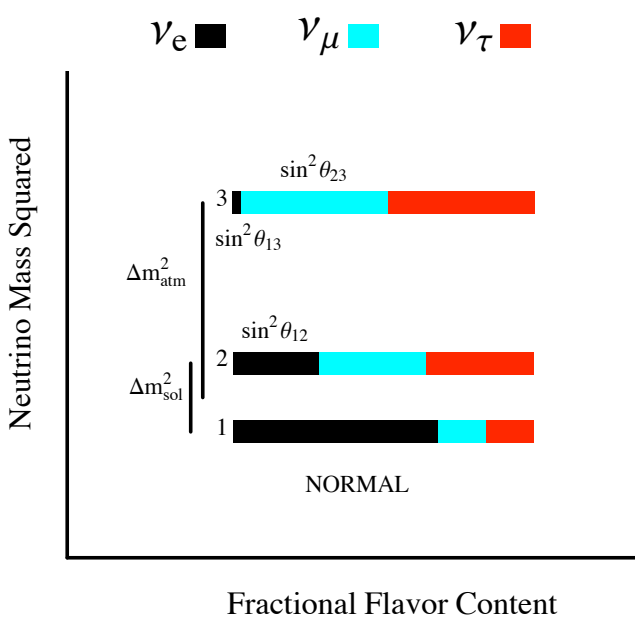

$9 - 13\%$ at $90\% C.L.$

# $^8$Boron Neutrinos




**Born as $\nu_e$ they exit the Sun and arrive at the earth as $\nu_2$ !!!**

$(\nu_1 \sim 10\%)$




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

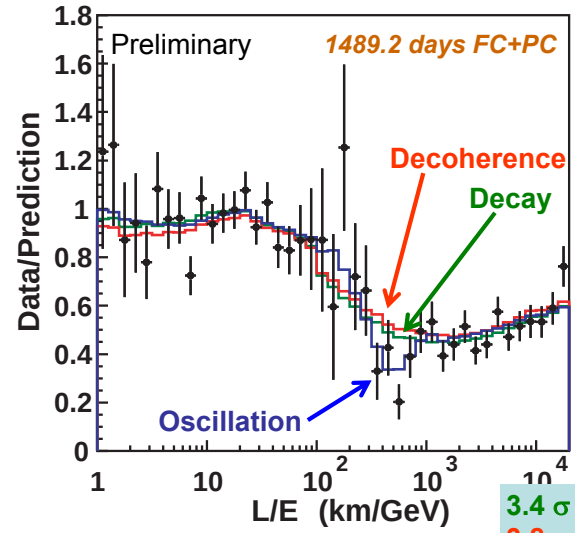
$$0.25 < \sin^2\theta_{12} < 0.37$$

at the 90 % confidence level.

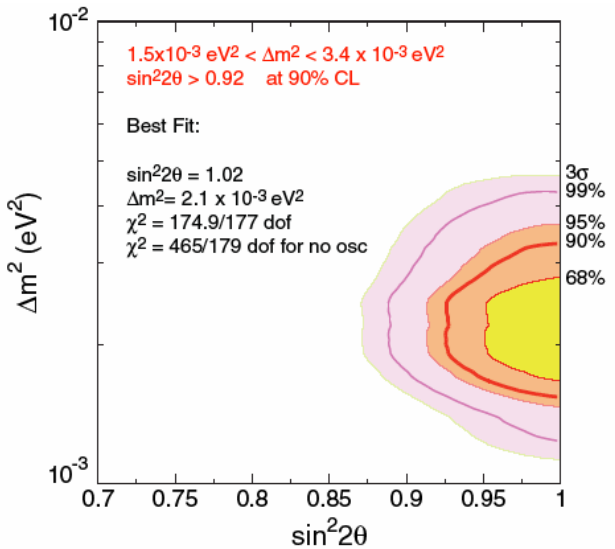
# 23- Sector (Atmospheric)

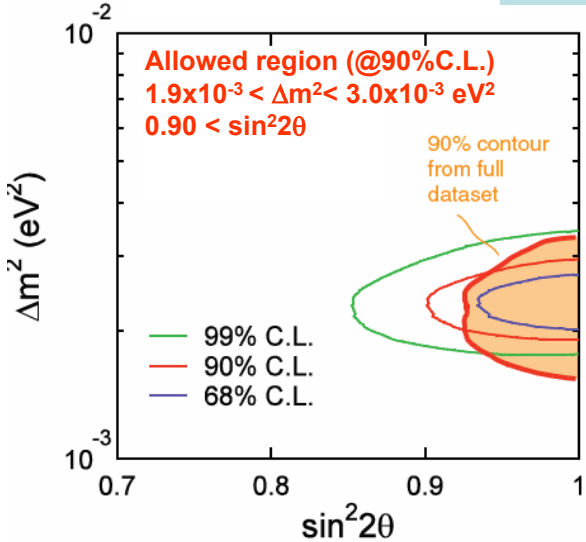
# SK:

## L/E analysis



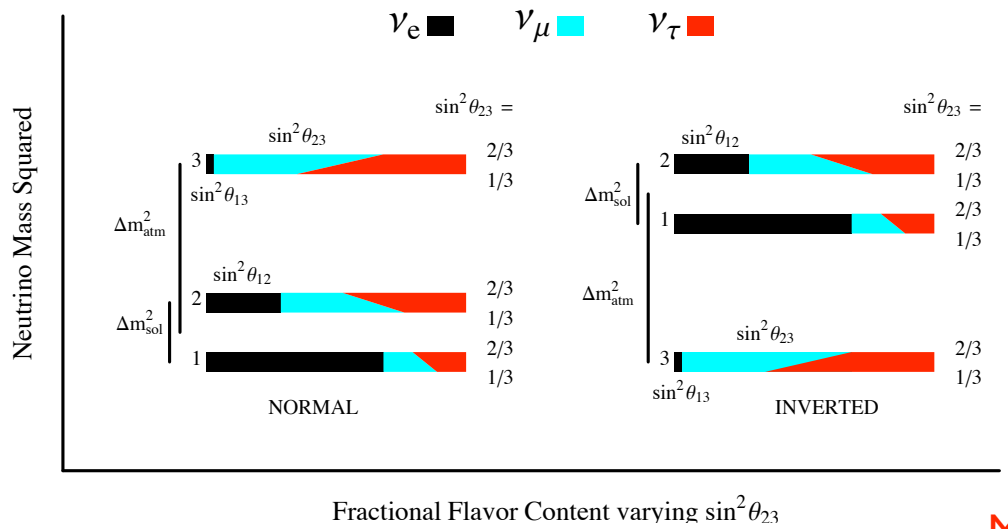

3.4 σ to decay
3.8 σ to decoherence




**Stronger constraint on $\Delta m^2$ even with fewer data sample**

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




Mena + SP hep-ph/0312131

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

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

at the 90 % confidence level.

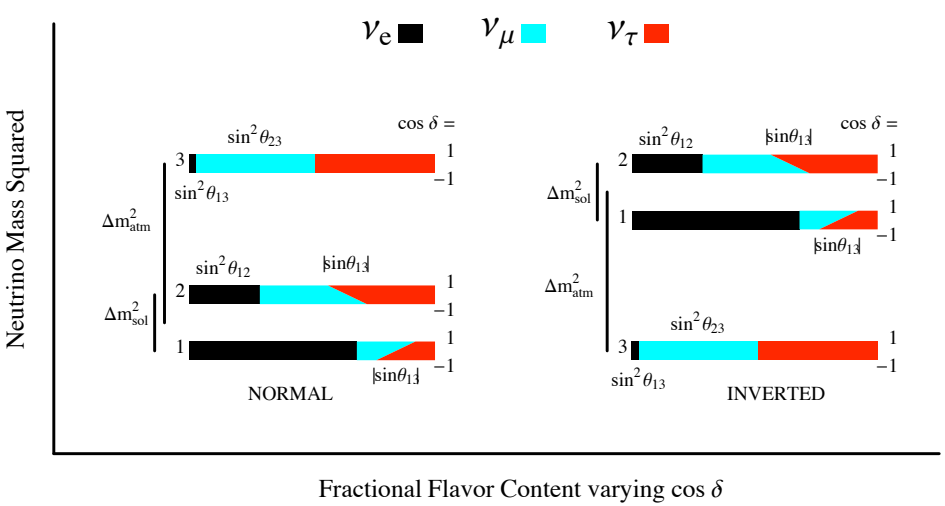
# 13- Sector (Reactor)

## Chooz bound

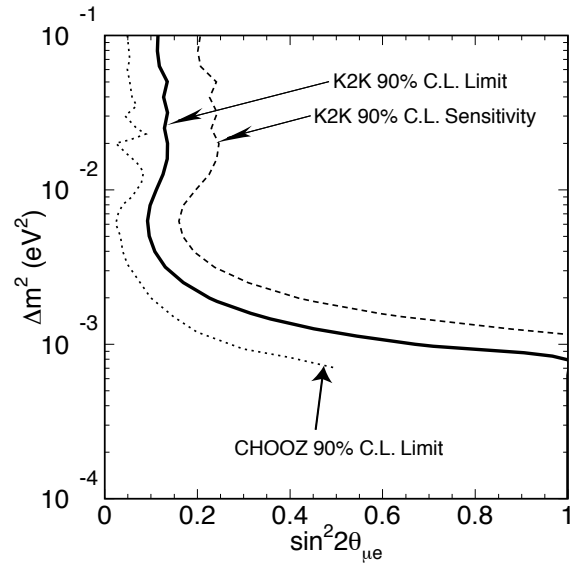
$$\sin^2\theta_{13} < \quad 0.04$$

limit $\delta m^2_{31}$ dependent.

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




# K2K:




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

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

# Mixing Summary:

(+ Unitarity)

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

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

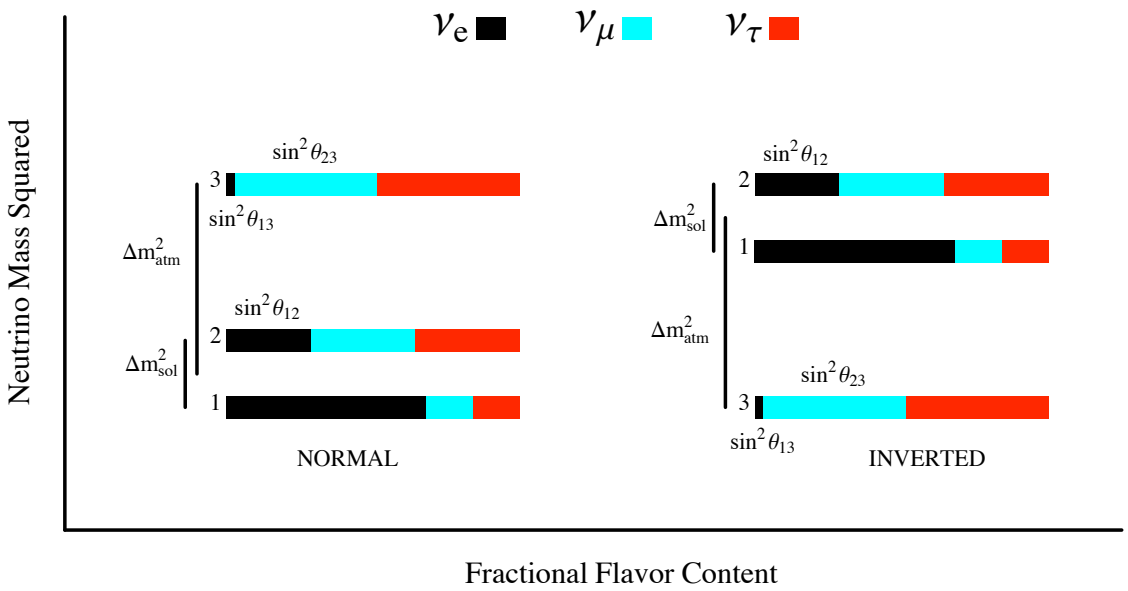
$$U_{\alpha i} = \begin{pmatrix} \sqrt{\tfrac{2}{3}}(1+\sigma) & \sqrt{\tfrac{1}{3}}(1-2\sigma) & \epsilon\, e^{-i\delta} \\ -\sqrt{\tfrac{1}{6}}(1-2\sigma+\lambda) - \sqrt{\tfrac{1}{3}}\,\epsilon\, e^{i\delta} & \sqrt{\tfrac{1}{3}}(1+\sigma+\lambda) - \sqrt{\tfrac{1}{6}}\,\epsilon\, e^{i\delta} & \sqrt{\tfrac{1}{2}}(1-\lambda)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

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 $\nu$ Standard Model

The Big Questions to be Addressed are

- $\nu_e$ fraction of $\nu_3$: – $\sin^2\theta_{13}$
- mass hierarchy: – sign of $\delta m^2_{31}$
- 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 $\nu_e$ fraction in $\nu_3$: $\sin^2\theta_{13}$

- 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 $\delta m^2_{31}$

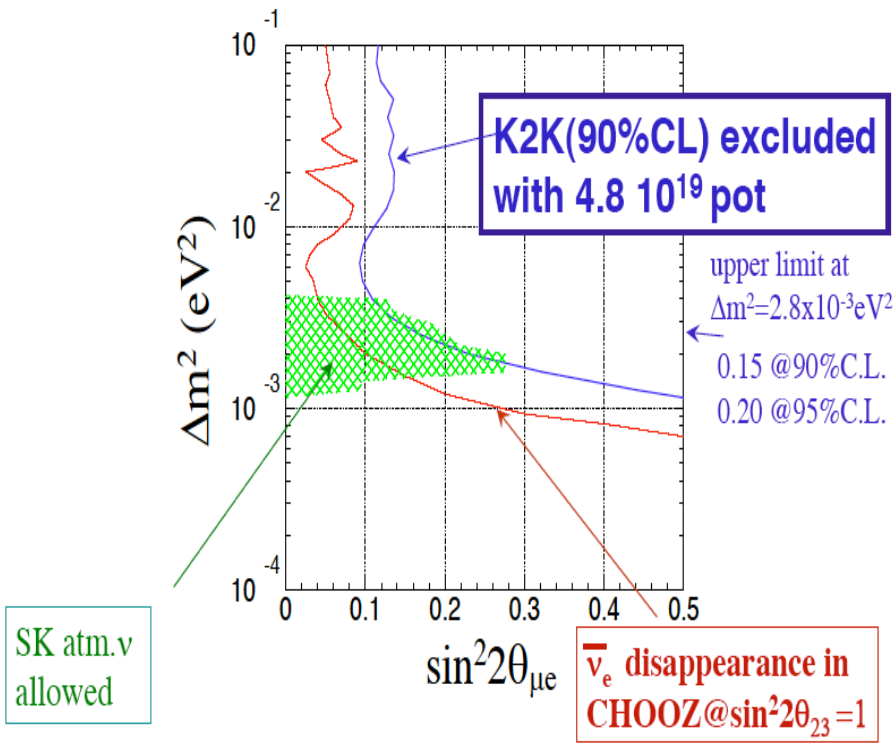
- $0\nu\beta\beta$ decay
- Atmospheric Neutrinos
- Supernova Neutrinos
- Future Long Baseline (NuMI, NuMI+T2K, BNL2? ...)
- Neutrino Factories (hi-$\gamma$ Beta Beams)

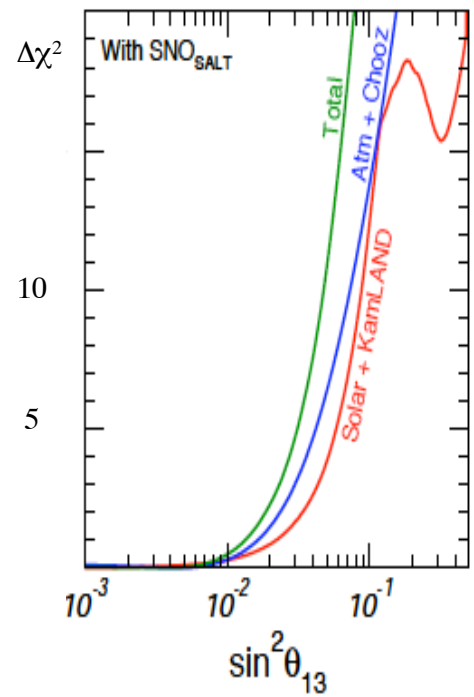
## Quest for CP Violation: $\sin\delta$

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

# Quest for $\nu_e$ fraction in $\nu_3$: $\sin^2\theta_{13}$

# No indication yet of nonzero $\theta_{13}$ 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, ...)

$\nu_e$ Survival Probability is

where $\Delta$ 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 $\delta m^2_{eff}$ is the effective atmospheric $\delta m^2$ for $\nu_e$ disappearance:

Nunokawa, Zukanovich +SP
hep-ph/0503282

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

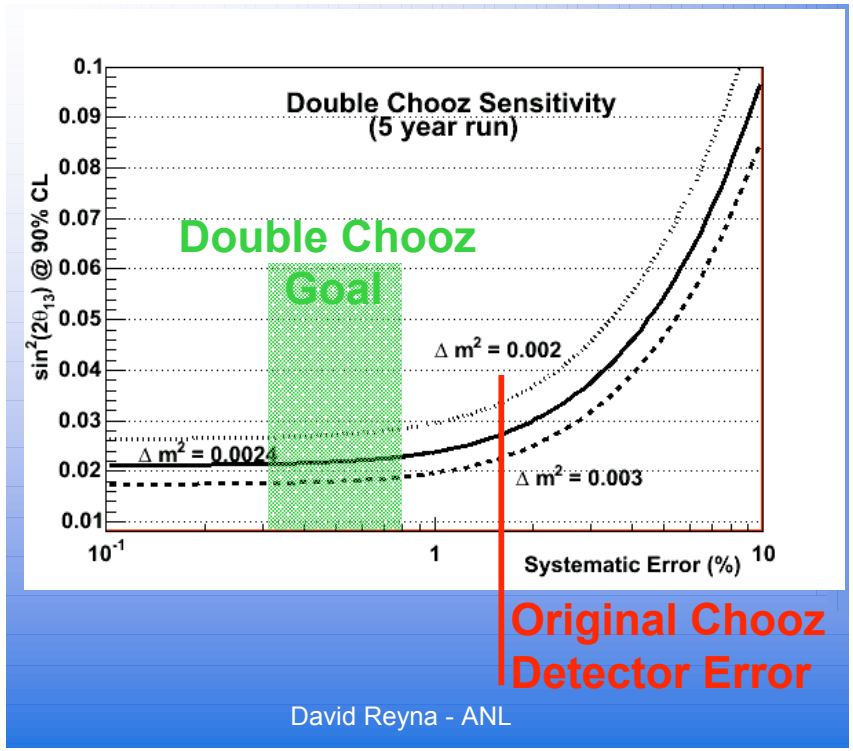
Direct measurement of $\nu_e$ fraction of $\nu_3$:

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

(independent of $sign\ \delta m^2_{31}$, $\delta$ 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 $\delta m^2_{eff}$ ???



- Low and High Energy Solar Neutrinos

Goswami + Smirnov
hep-ph/0411359

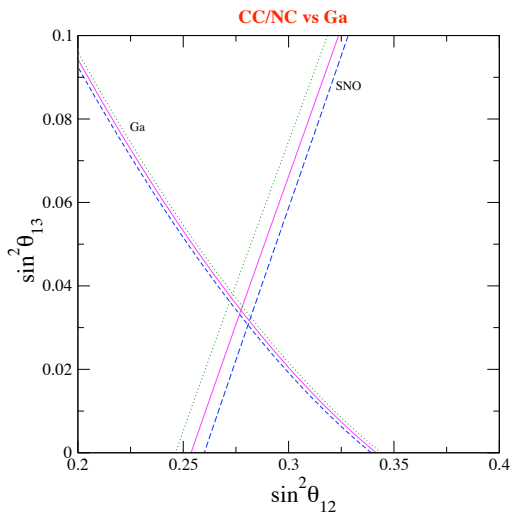



Figure 6: The iso-contours of CC/NC = 0.31 at SNO and $Q_{Ge} = 68.1$ SNU in Ga experiments in the $\sin^2\theta_{12} - \sin^2\theta_{13}$ plane for different values of $\Delta m^2_{21}$ : $\Delta m^2_{21} = 9 \cdot 10^{-5}$ eV$^2$ - the dotted lines; $\Delta m^2_{21} = 8 \cdot 10^{-5}$ eV$^2$ - the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

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

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

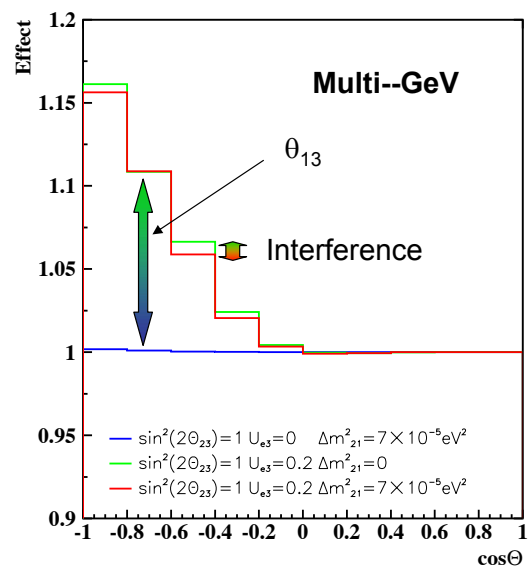
$$Ga \sim \cos^4\theta_{13}\cos^4\theta_{12} + \cdots$$

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

- Atmospheric Neutrinos

SK - Suzuki

— $|U_{e3}|=0.2$
— $\Delta m_{12}^2=7\times10^{-5}\text{eV}^2$
— Interference



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

$$P_{\mu\to e} = \left| \sum_{j=1}^{3} U^*_{\mu j}\, U_{ej} e^{-i m_j^2 L/2E} \right|^2$$

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

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

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

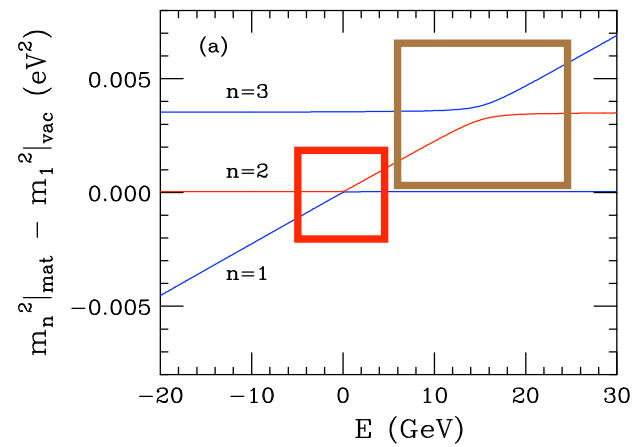
$$P_{\mu\to e} \approx \left| 2 s_{23} s_{13} c_{13} \sin\Delta_{31} e^{-i(\Delta_{32} \pm \delta)} + 2 c_{23} s_{12} c_{12} \sin\Delta_{21} \right|^2$$

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

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

# 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: $\nu_\mu \to \nu_e$

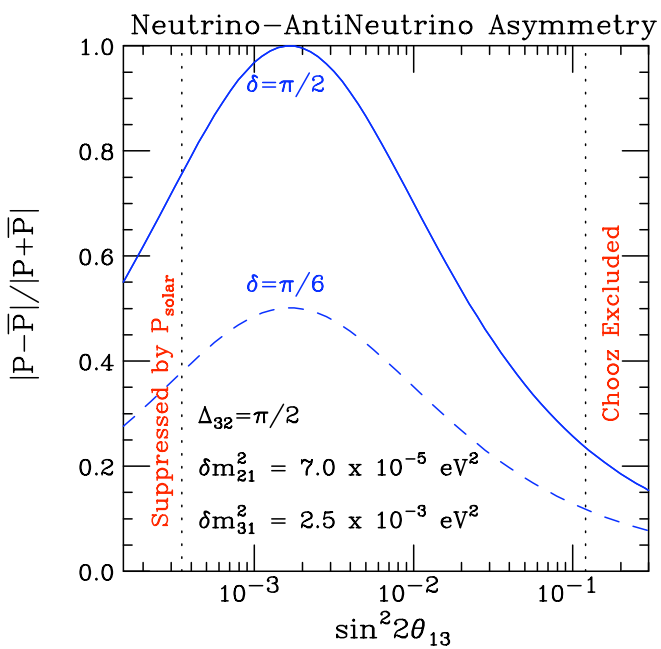
CP violation !!!

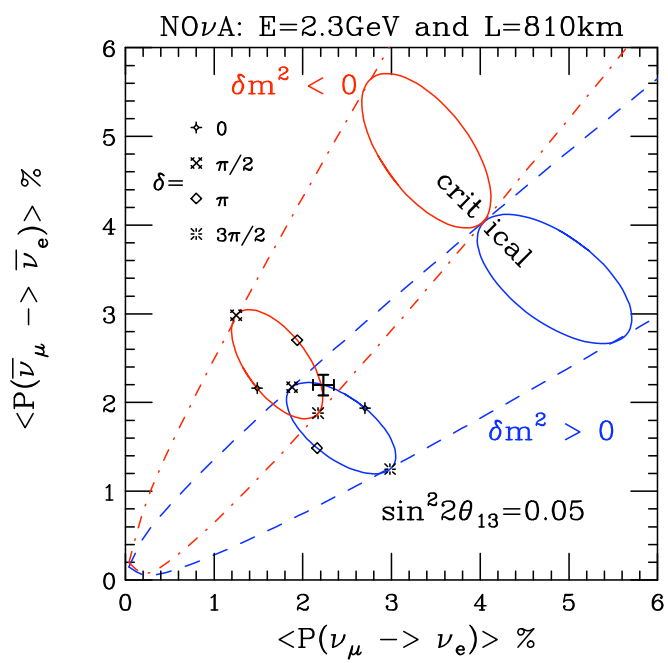
$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{31}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

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

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

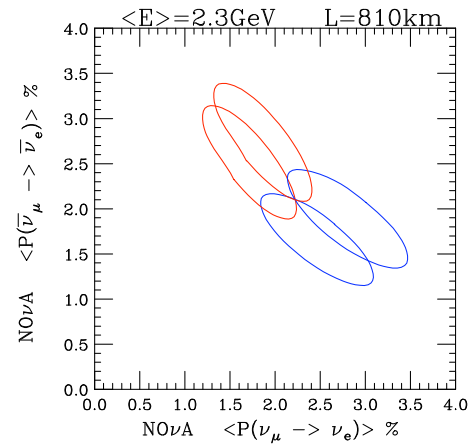
and $\sqrt{P_{sol}} = \cos\theta_{13} \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

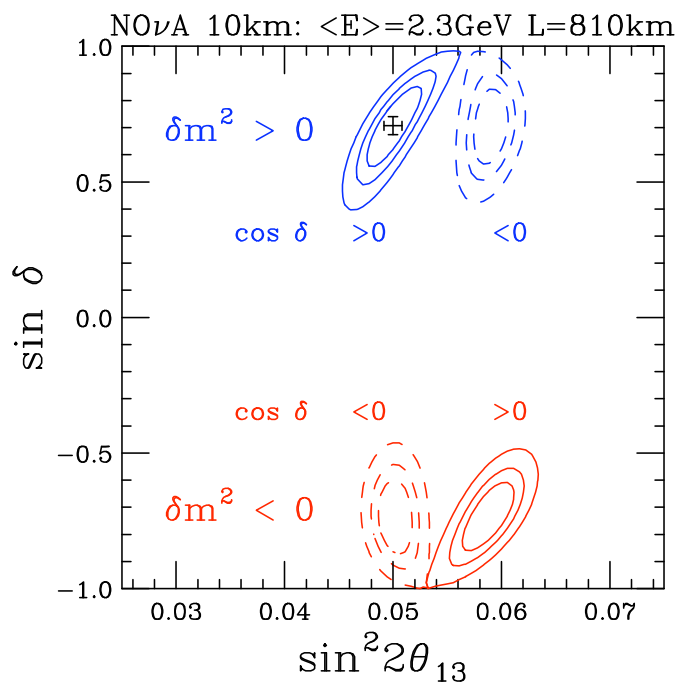


# Parameter Degeneracies:

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

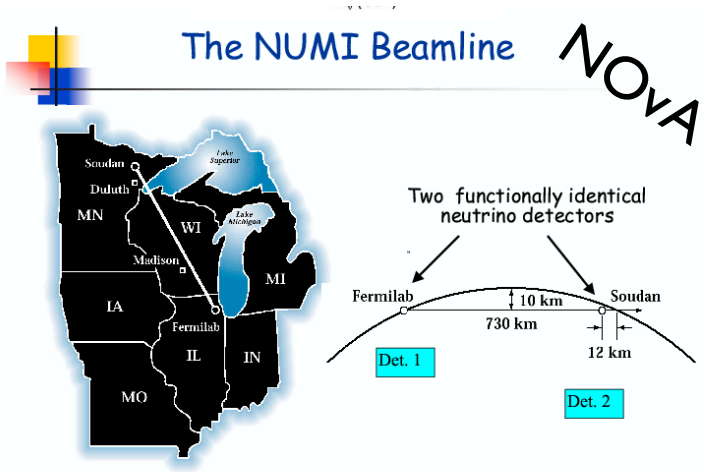
Burget-Castell etal
hep-ph/0103258

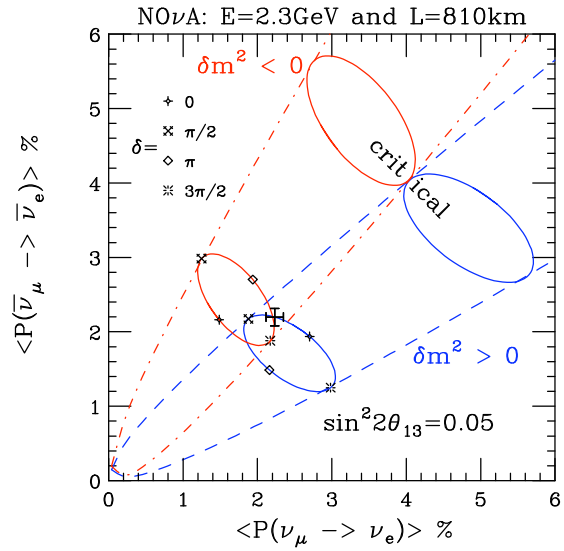
$$\Leftrightarrow$$

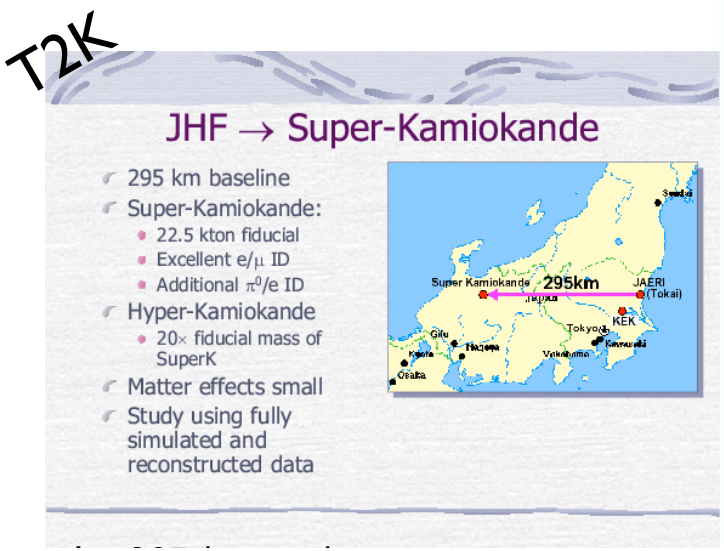
$$\sim \Delta_{31}\cot\Delta_{31}$$

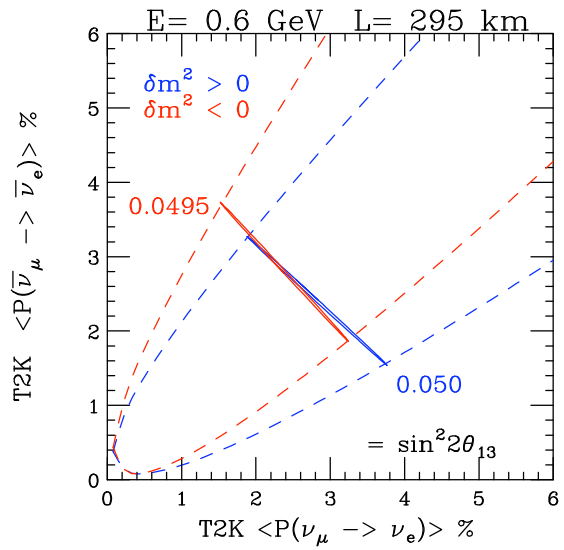
0 when $\boldsymbol{\Delta_{31} = \pi/2}$

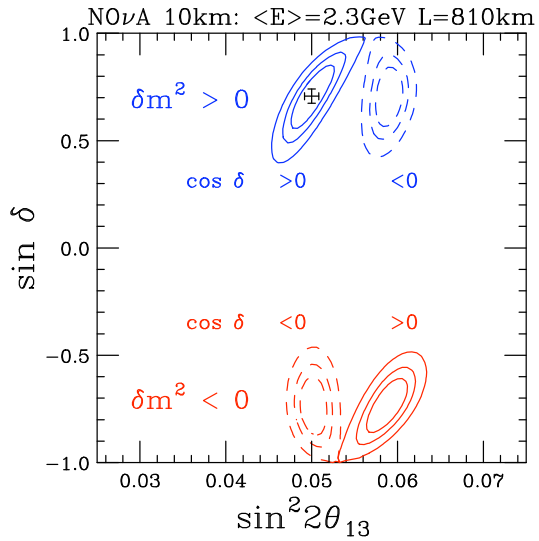
Mena + SP
hep-ph/0408070


The NUMI Beamline
NOvA
Soudan
Duluth
MN
WI
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
δm² < 0
δm² > 0
δ= 0
π/2
π
3π/2
critical
sin²2θ13=0.05
<P(ν̄μ -> ν̄e)> %
<P(νμ -> νe)> %


T2K
JHF → Super-Kamiokande
295 km baseline
Super-Kamiokande:
22.5 kton fiducial
Excellent e/μ ID
Additional π⁰/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


E= 0.6 GeV L= 295 km
δm² > 0
δm² < 0
0.0495
0.050
= sin²2θ13
T2K <P(ν̄μ -> ν̄e)> %
T2K <P(νμ -> νe)> %

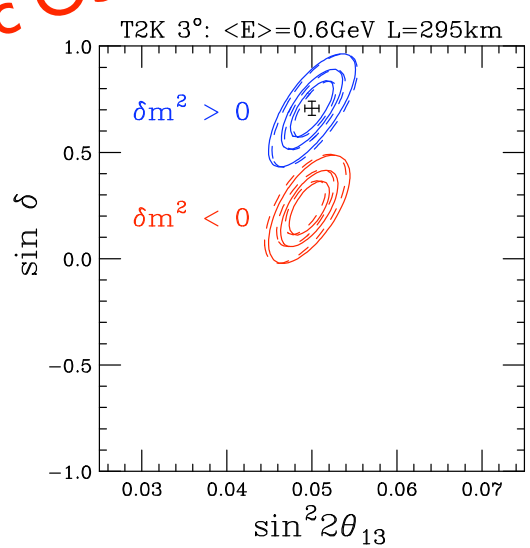



$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- = 1.41\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

factor of 3 !!!

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

Vac Osc Max




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

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

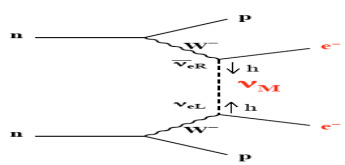
BNL2HSK 1 per E bin

# 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 $\theta_{23}$ and $\theta_{13}$ |
| sign($\Delta m^2_{32}$) | 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 |

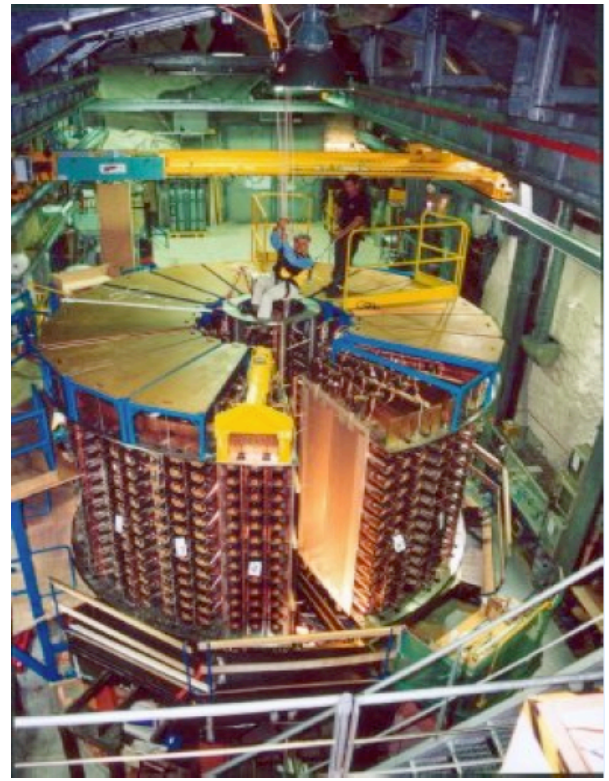
# Neutrinoless double beta decay

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



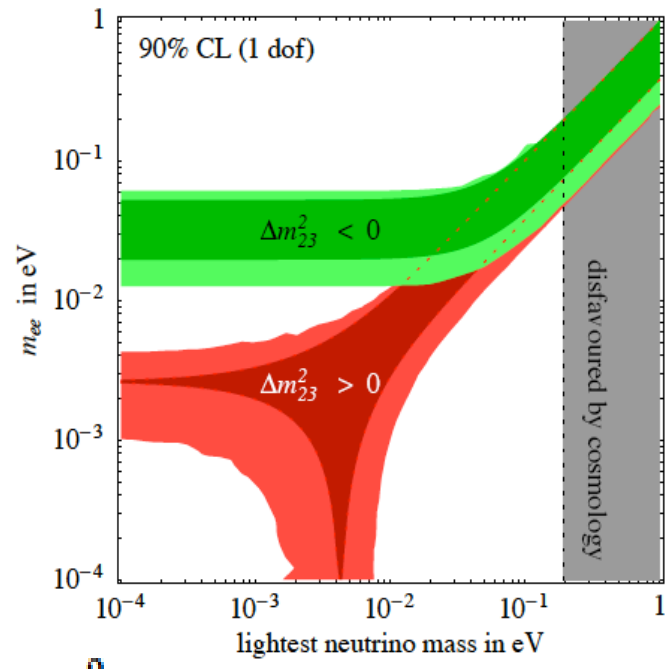

$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

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



• 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 $\nu$ 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:

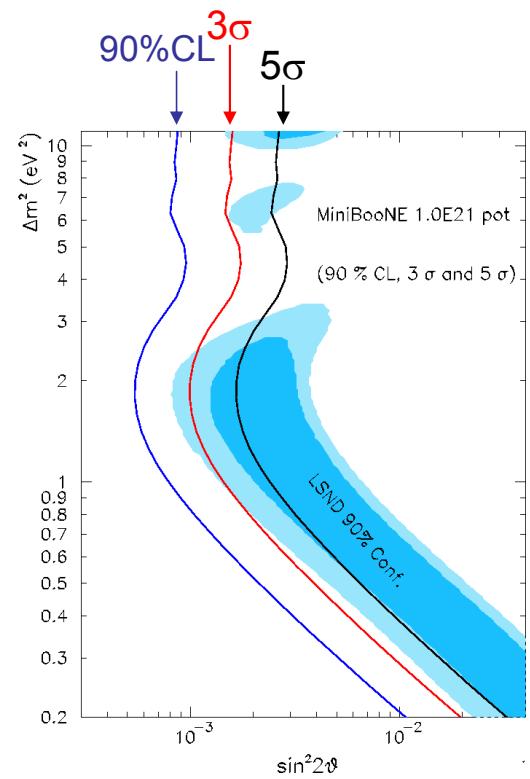
## LSND/miniBOONE

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

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

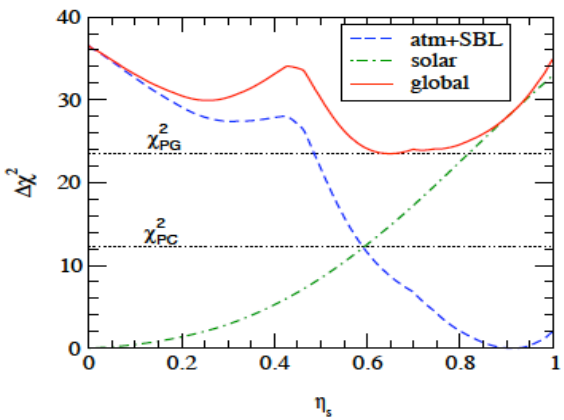
Various schemes are proposed motivated by the LSND data, which include:

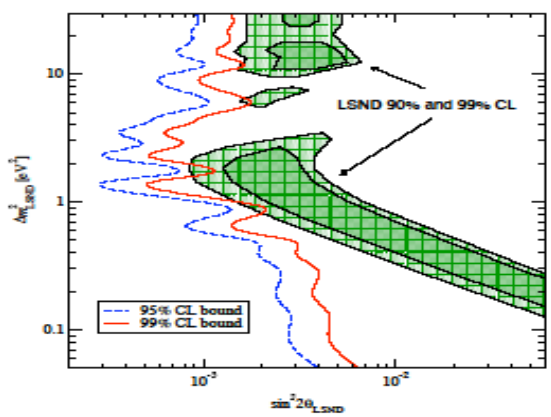
- 2+2 sterile-active scheme
- 3+1
- 3+2
- CPT violation
- Sterile + CPT violation
- …..




to definitively exclude LSND in the event that MiniBooNE does not see a signal, we need $1 \times 10^{21}$ POT

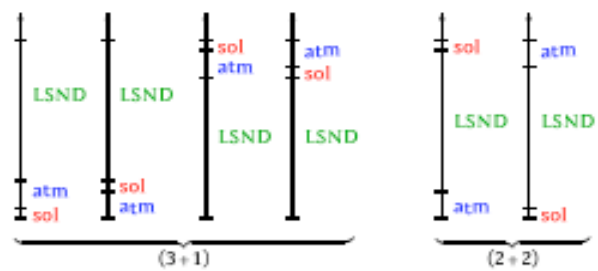
# Four Neutrino Scenarios




- 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

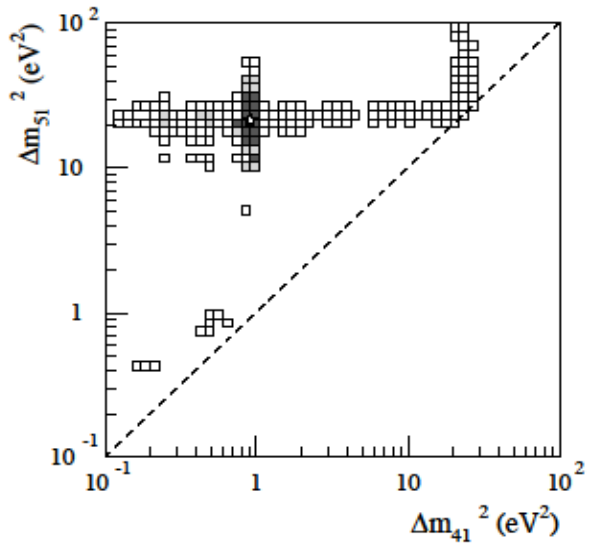
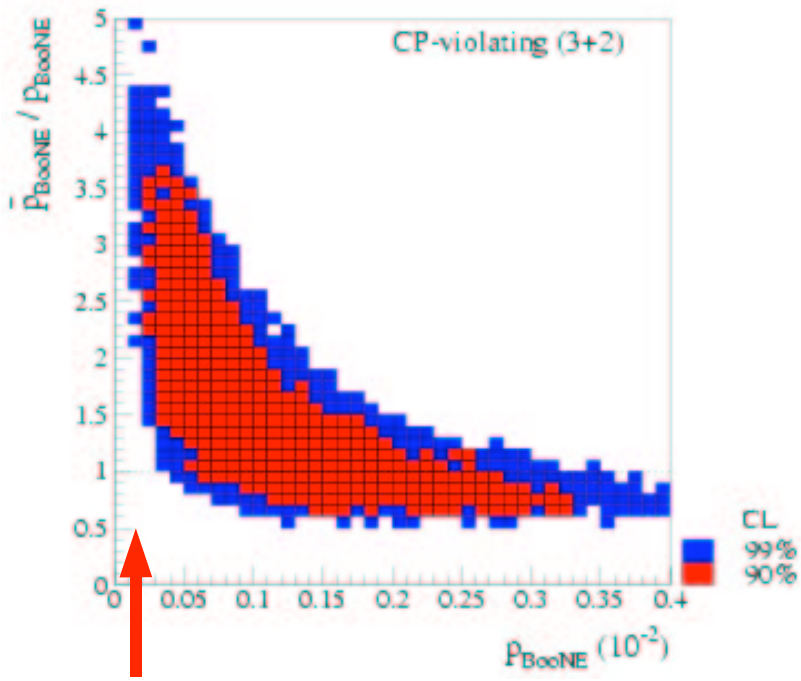



FIG. 6: Allowed ranges in $(\Delta m^2_{41}, \Delta m^2_{51})$ space for (3+2) models, for the combined NSBL+LSND analysis, assuming statistical compatibility between the NSBL and LSND data sets. The star indicates the best-fit point, the grey-shaded regions indicate the 90, 95, 99% CL allowed regions.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

- 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?)

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

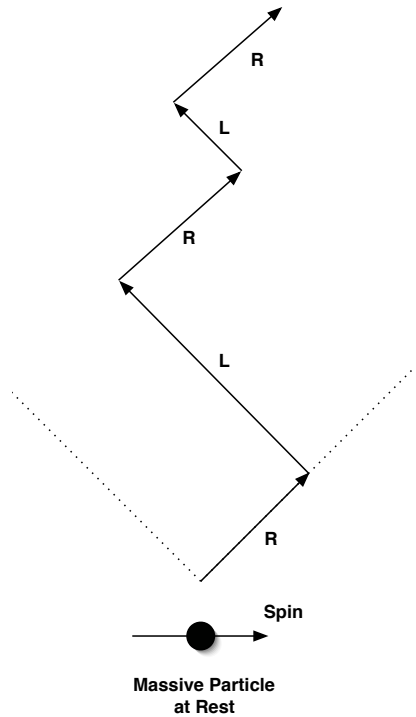



MiniBooNE can have
a small signal in neutrino-mode
(which could easily fluctuate to a null signal!)
**&** a ×**3 larger signal in antinneutrino mode**

# 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:

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

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

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

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 | | |

(notation!!!)

Coupling of

- $\nu_L$ to $\nu_R$ AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- $\nu_L$ to $\bar{\nu}_R$ forbidden by weak isospin.
- $\nu_R$ 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 $M$

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

Also applies to sterile neutrinos.

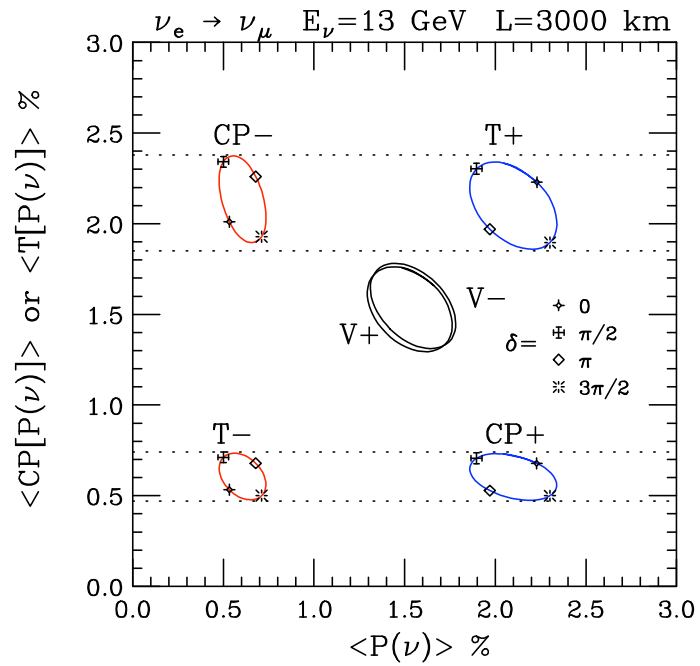
Light Sterile Neutrinos and/or Dirac Neutrinos Unexpected!!!

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

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

$\nu_\mu \leftrightarrow \nu_e$

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




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

Minakata, Nunokawa + SP
hep-ph/0204171

$\nu_e \leftrightarrow \nu_\mu$

# Predictions from Models:

## Selected $SO(10)$ Models and $\theta_{13}$ 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 | $\sim 0.19$ |
| KRV-S | (4) $SU(\ ) \times Z_2 \times U(1)_A$ | Sym/Asym | ? | 0.02 |
| M | (2) $U(1)_A \times Z_2$ | Lopsided | | $\sim 0.19$ |

| | | |
|---|---|---|
| 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 | $\sin 2\beta = 0.74$, $\delta_{CKM} \sim \quad ^\circ$ |
| 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? |

# 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 | $0.10 \pm 0.032$ | 0.025 | $1.5 \times 10^{-3}$ |
| lepton bi-maximal | $-6 \times 10^{-4}$ | $2 \times 10^{-3}$ | $0.035^*$ | $5 \times 10^{-3}$ |
| hybrid bi-maximal | $1.4 \times 10^{-4}$ | $3.3 \times 10^{-4}$ | $0.04^*$ | $2.1 \times 10^{-3}$ |
| neutrino max+large | $0.057 \pm 0.023$ | $0.10 \pm 0.032$ | SK bound | $\leq 6.8 \times 10^{-3}$ |
| lepton max+large | $-6 \times 10^{-4}$ | $2 \times 10^{-3}$ | SK bound | $\leq 5 \times 10^{-3}$ |
| hybrid max+large | $1.4 \times 10^{-4}$ | $3.3 \times 10^{-4}$ | SK bound | $\leq 2.1 \times 10^{-3}$ |
| single maximal | 0.015 | 0.034 | $0.06 - 0.16$ | $9.1 \times 10^{-3}$ |

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 $\theta_{23}$. Whenever there exist uncertainty due to the CP violating phase $\delta$ 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 $\nu_e$ 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