# Status and Future of Neutrino Physics

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Fermilab

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— APS $\nu$ Study —

# The Questions:

| | Theorists' Poll |
|---|---|
| • # of Light Neutrinos: | Three |
| • Majorana v Dirac: | Majorana |
| • Masses: | Seesaw |
| • Mixings: | ??? |
| • Exotics: | ~~None~~ |

No Consensus

# The Questions:

- # of Light Neutrinos: 3 active + ? steriles
- Majorana v Dirac: $\nu = \bar{\nu}$, 2 v 4 states per $\nu$, L viol.
- Masses: degenerate, normal/inverted, $M_{lite}$
- Mixings: $\theta_{13}$, $\theta_{23} \stackrel{?}{=} \frac{\pi}{4}$, U real v complex, CP viol., Leptogenesis
- Exotics: Non-Osc.,CPT-V, decays, $\mu$-mom etc

# Neutrino Mixing Matrix:

Like the Quark Sector:
The Neutrino Mass Eigenstates, $|\nu_i\rangle$, are a Mixture of Flavor States, $|\nu_\alpha\rangle$:
$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle$. (using $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$)

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

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$

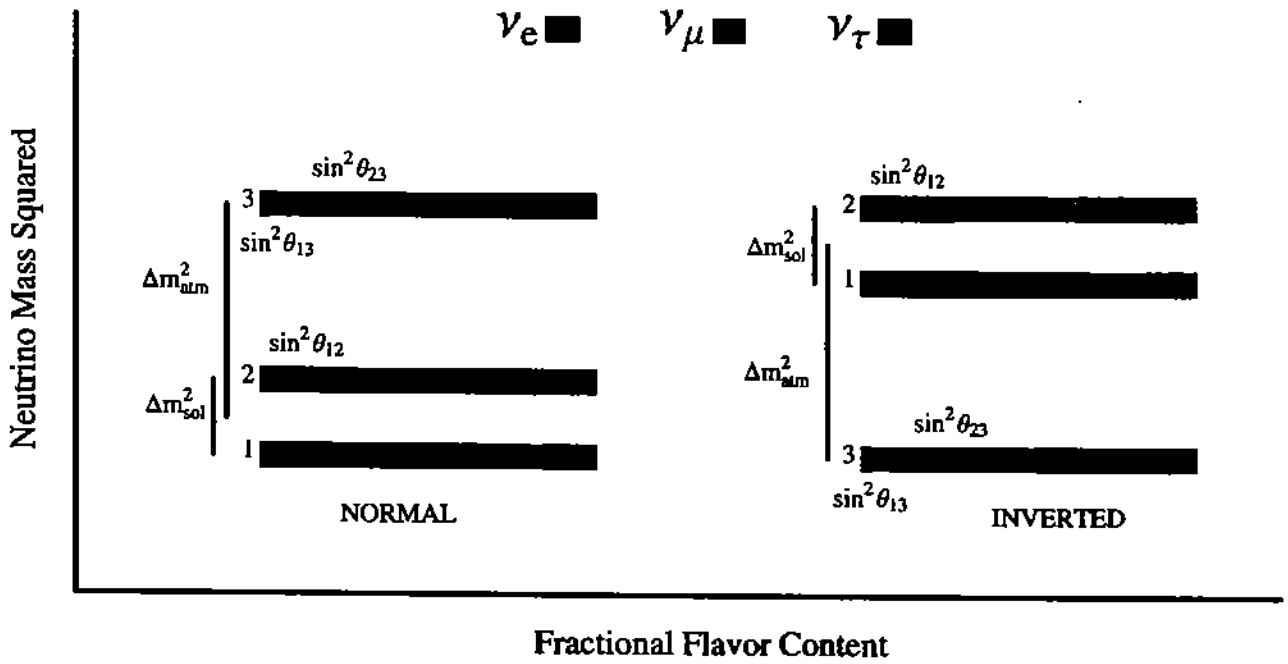
$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

If Majorana

$$U \to U \begin{pmatrix} 1 & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}$$

Phases $\alpha_2$, $\alpha_3$ are unobservable in oscillation phenomena, $(U_{\alpha i}U^*_{\beta i})$.
Important in neutrinoless double beta decay.

– sans LSND




Atmos. $\left[\begin{array}{l} |\delta m^2_{atm}| \approx 2 \times 10^{-3}\,eV^2 \\ \sin^2\theta_{23} \approx 0.5 \end{array}\right.$

Solar: $\left[\begin{array}{l} \delta m^2_{sol} \approx +7 \times 10^{-5}\,eV^2 \\ \sin^2\theta_{12} \approx 0.3 \end{array}\right.$

Chooz (SK) $\sin^2\theta_{13} < 0.03$ $\Big\}$ dependent on $|\delta m^2_{atm}|$

$0 \leq \delta < 2\pi$

# # of Light Neutrinos

Diamond in the rough ???

<u>LSND</u>: $\mu \to e\, \nu_\mu\, \nu_e$

$\bar{\nu}_\mu \to \bar{\nu}_e$ at 0.3% level

with $\Delta m^2 \sim 1\,eV^2$

$\sin^2 2\theta \sim 10^{-2 \pm 0.5}$

muon decay

DAR

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} = 0.264 \pm 0.067 \pm 0.045\%$$

$$\left( P_{\nu_\mu \to \nu_e} = 0.10 \pm 0.16 \pm 0.04\% \right)$$

DIF

More light neutrinos

OR.

violate CPT

( $\nu$ spectrum $\neq \bar{\nu}$ spectrum )

# Addressing Steriles.

- solar + atmos. $\nu$ exp.
- dissappearance exp.
- BBN # lite $\nu$'s = 3 ← Beacom
  (active + sterile)

- Short Baseline $\nu_\mu \to \nu_e$ exp.
  ( MiniBooNE )

# Are there any light sterile neutrinos?

$\delta M^2_{atm}$ scale:

SK { matter effects in atmospheric $\nu$'s
$< 20\%$ $\nu_s$

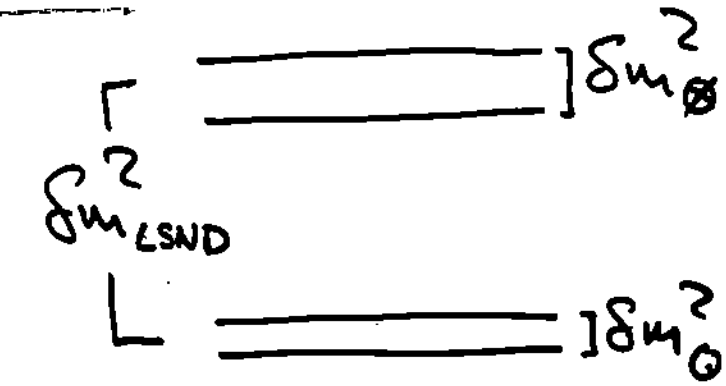
MINOS (NC/CC ratio)

$\delta M^2_{solar}$ scale:

SNO $< 50\%$ $\nu_s$

- comes from theoretical uncertainty in $^8B$ flux
- D/N asymmetry may improve this

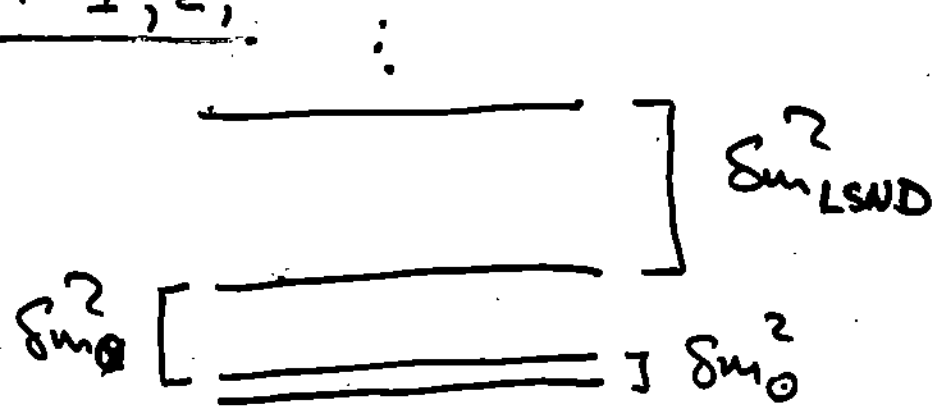
## 2 + 2




1 $\nu_s$ in solar + atmospheric ~ marginal

Weiler et al

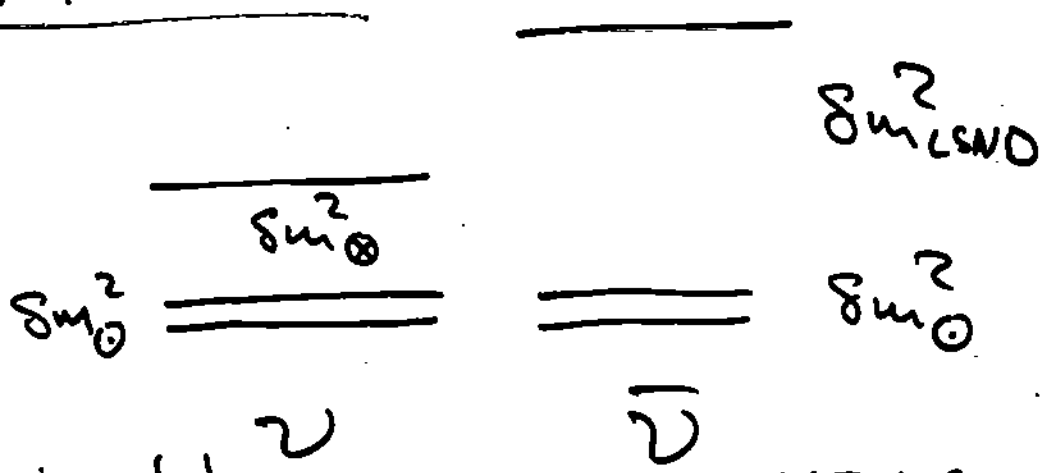
## 3 + 1, 2, ....




Constrainted by $\nu_\mu$, $\nu_e$ dissappearance

3+2 Sorel etc

## CPT Violation




Barenboim et al

MINOS atmospheric $\nu$ / $\bar{\nu}$

# mini-BOONE: $\pi \to \mu \nu_\mu$

Suppose mini-BOONE sees a convincing signal, consistent with LSND.

How many $\Delta m^2$ involved?

What are their mixings, $\sin^2 2\theta_{eff}$?

Do we need a NEAR Detector (FINeSE)

or a FAR Detector (BOONE)

or BOTH ???

What about CP violation?

$\nu_\mu \to \nu_e$ v. $\bar{\nu}_\mu \to \bar{\nu}_e$

How is $\nu_\tau$ involved?

Can [redacted] U.S.A. response in a timely fashion? [redacted] CERN Japan

## ◆ Number of light Neutrinos

If mini BOONE confirms LSND

then ~~[illegible]~~ U.S.A. must exploit this opportunity in a timely fashion:

- new detector(s)
- sufficient P.O.T.
- ~~maybe even~~ new $\nu$ beamlines

$\delta m^2$'s , $\sin^2 2\theta_{eff}$'s

also

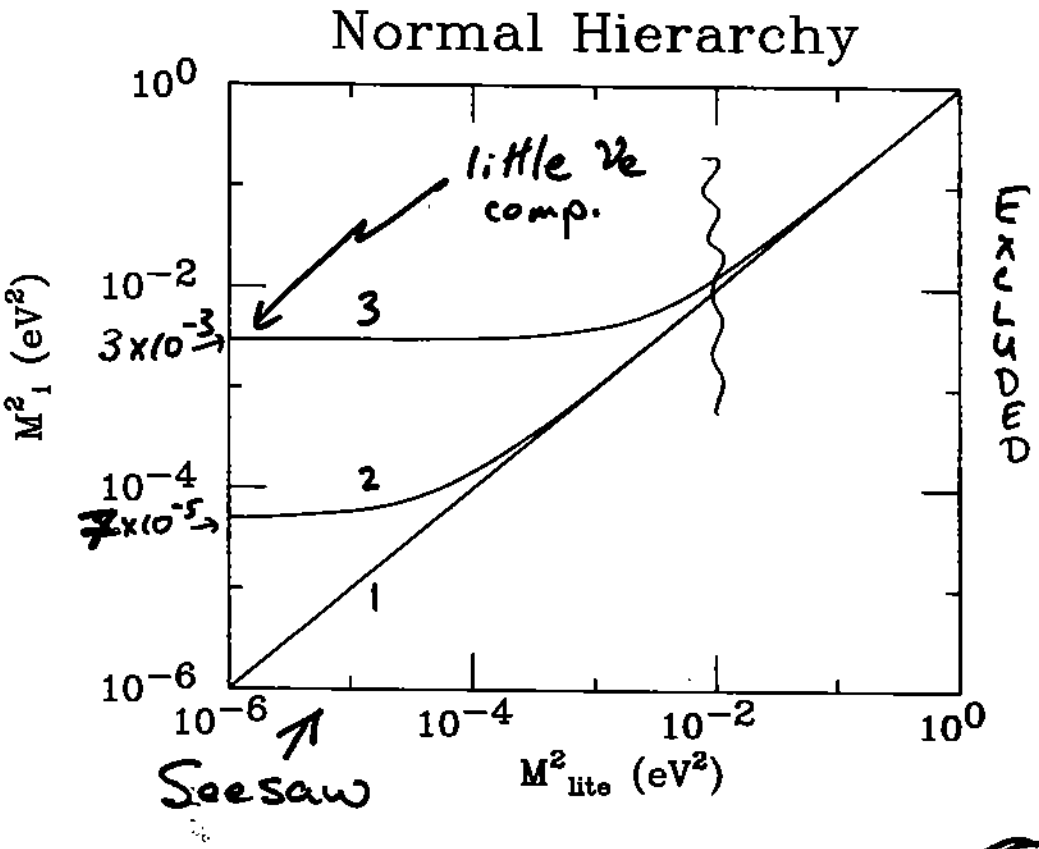
CP violation and role of $\nu_\tau$

# Masses

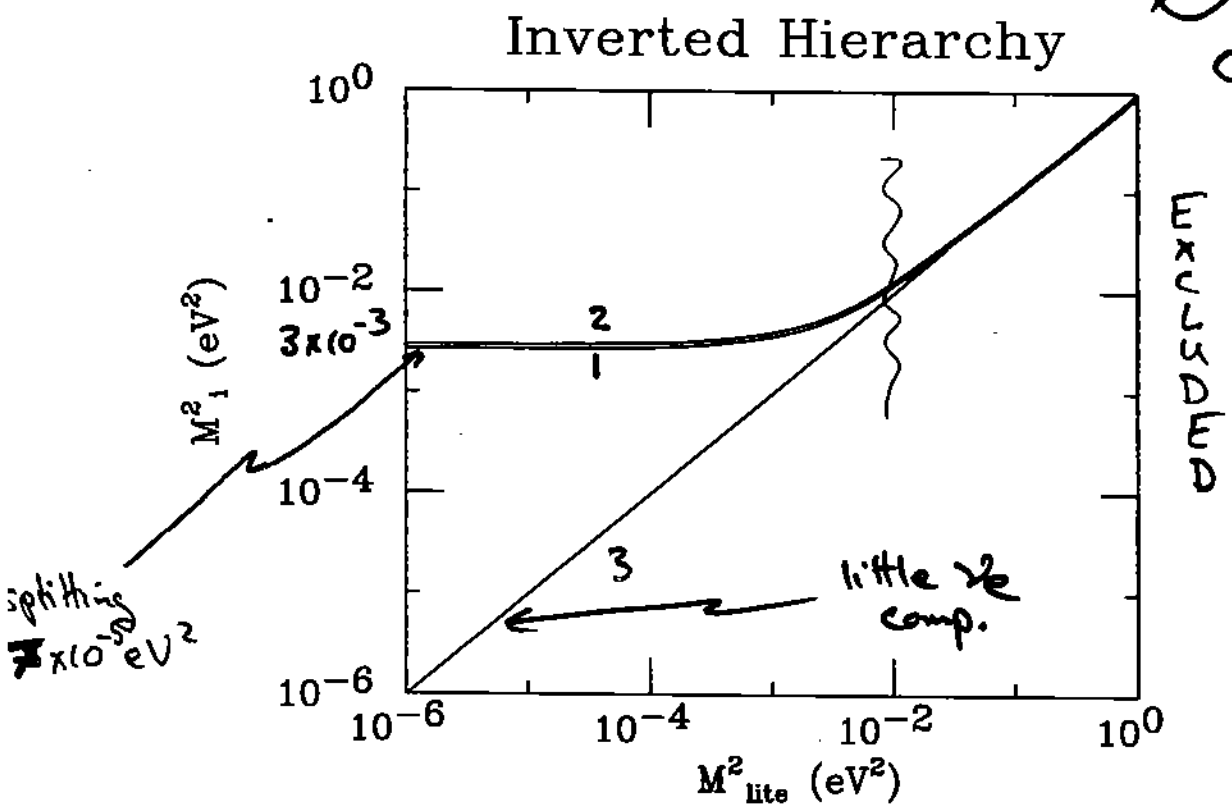
# &

# Majorana v Dirac

# MASS SPECTRUM: $n = 3$




tritium
$\beta\beta$ decay
cosmology




Beacom + Bell

# Absolute Mass Scale:

- Tritium Beta decay:

$$\langle m_e^2 \rangle = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$

KATRIN will probe down to

$$m_e \sim 0.3\,eV$$

– degenerate case –

- Large Scale Structure / Cosmology

Wmap etal $\sim 1eV = \sum m_\nu$

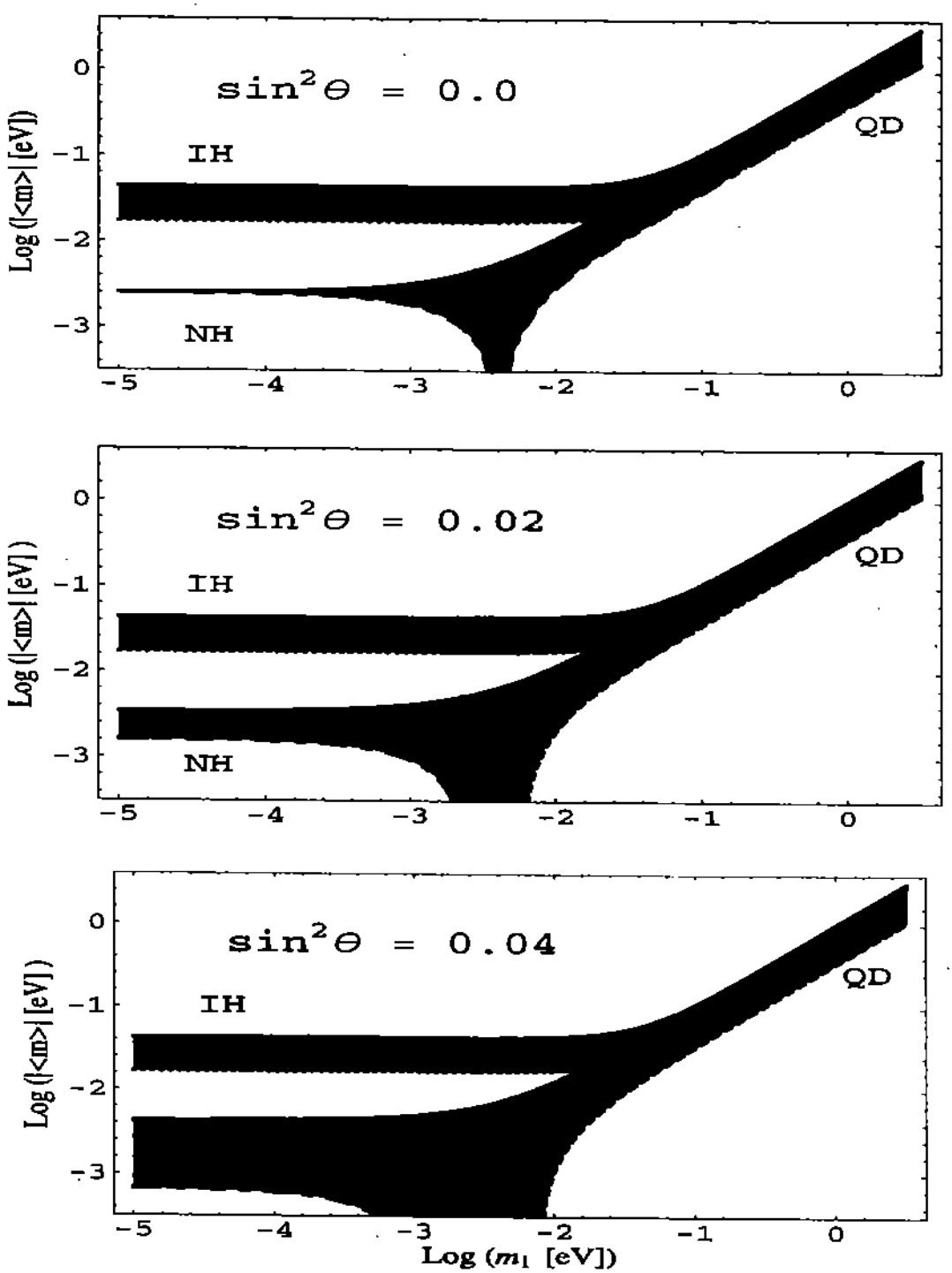
- $\nu$ $\beta\beta$ decay

$$\langle m_{\beta\beta} \rangle = |U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3|$$

but Majorana phases are important.

since $\sin^2\theta_{12} < \frac{1}{2}$ $\langle m_{\beta\beta} \rangle$ non-zero for inverted hierarchy:

S. Pascoli and S. T. Petcov, arXiv:hep-ph/0310003.



# Majorana $\nu$ Dirac

- Is Lepton # Violated ?

$$N \rightarrow N' + 2e$$

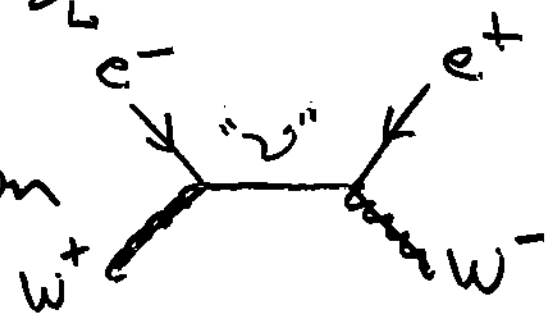
– Vogel + Elliot

- $\nu = \bar{\nu}$ ?

Majorana $\nu_L$ and $\bar{\nu}_R$ 2 states

Dirac $\begin{cases} \nu_L \text{ and } \bar{\nu}_R \\ \nu_R \text{ and } \bar{\nu}_L \end{cases}$ 4 states

- $\left(\frac{m_\nu}{E_\nu}\right)^2$ suppression




- $\nu\,\beta\beta$ decay ⟸ many proposed exp.

- cosmic background $\nu_s'$ $E_\nu \approx m_\nu$

— far future —

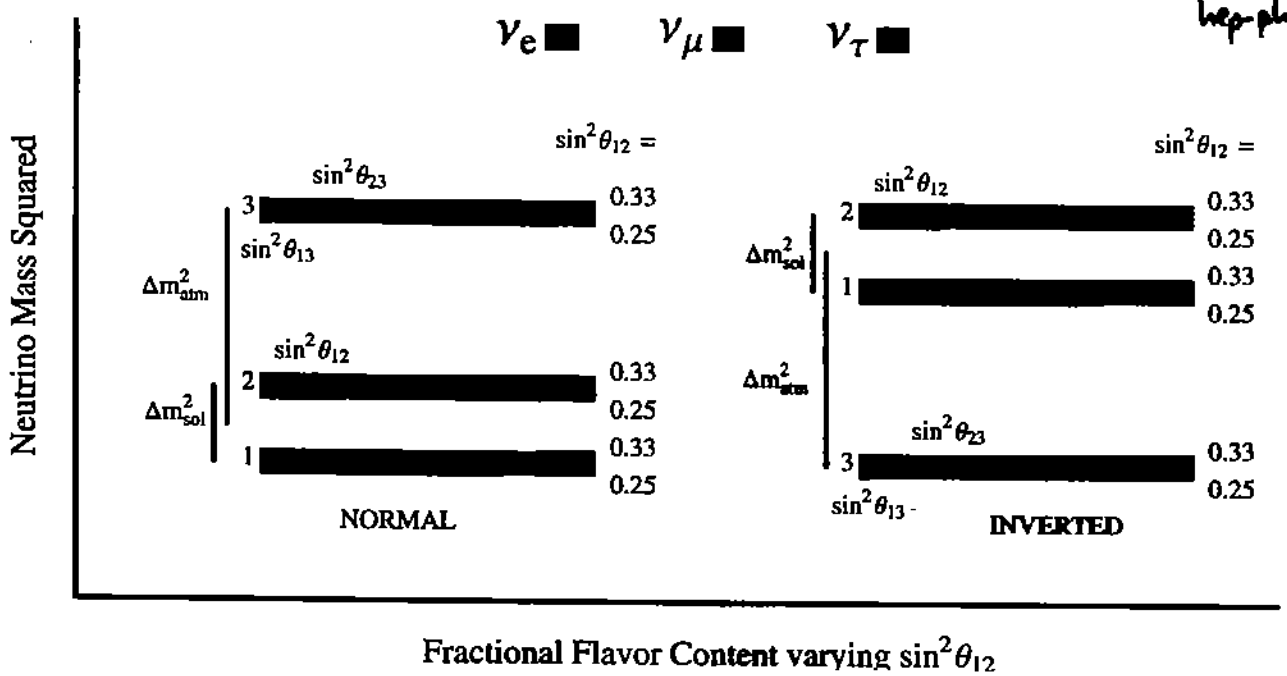
# Masses

# $\propto$

# Mixings

# Solar / Kam LAND: (12) - Sector:
(SNO, SK, Ga, Cl)

Olga Mena + SP
hep-ph/0312113




SNO

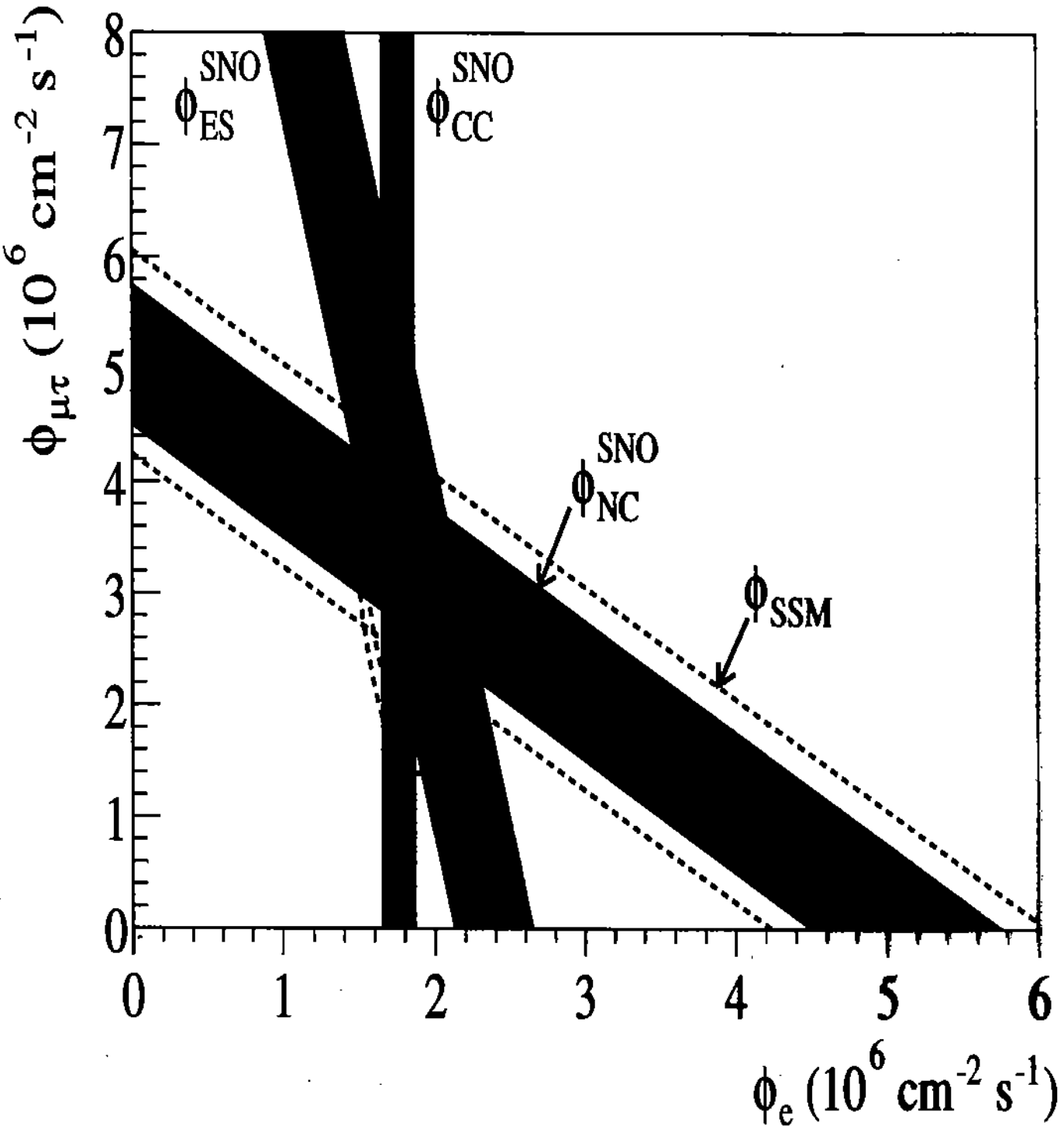
$$6.6\times10^{-5}\,eV^2 < \delta m^2_{21} < 8.7\times10^{-5}\,eV^2$$

$$0.25 < \sin^2\theta_{12} < 0.33$$

$\sin^2\theta_{12} < 0.5$ at $> 5\sigma$

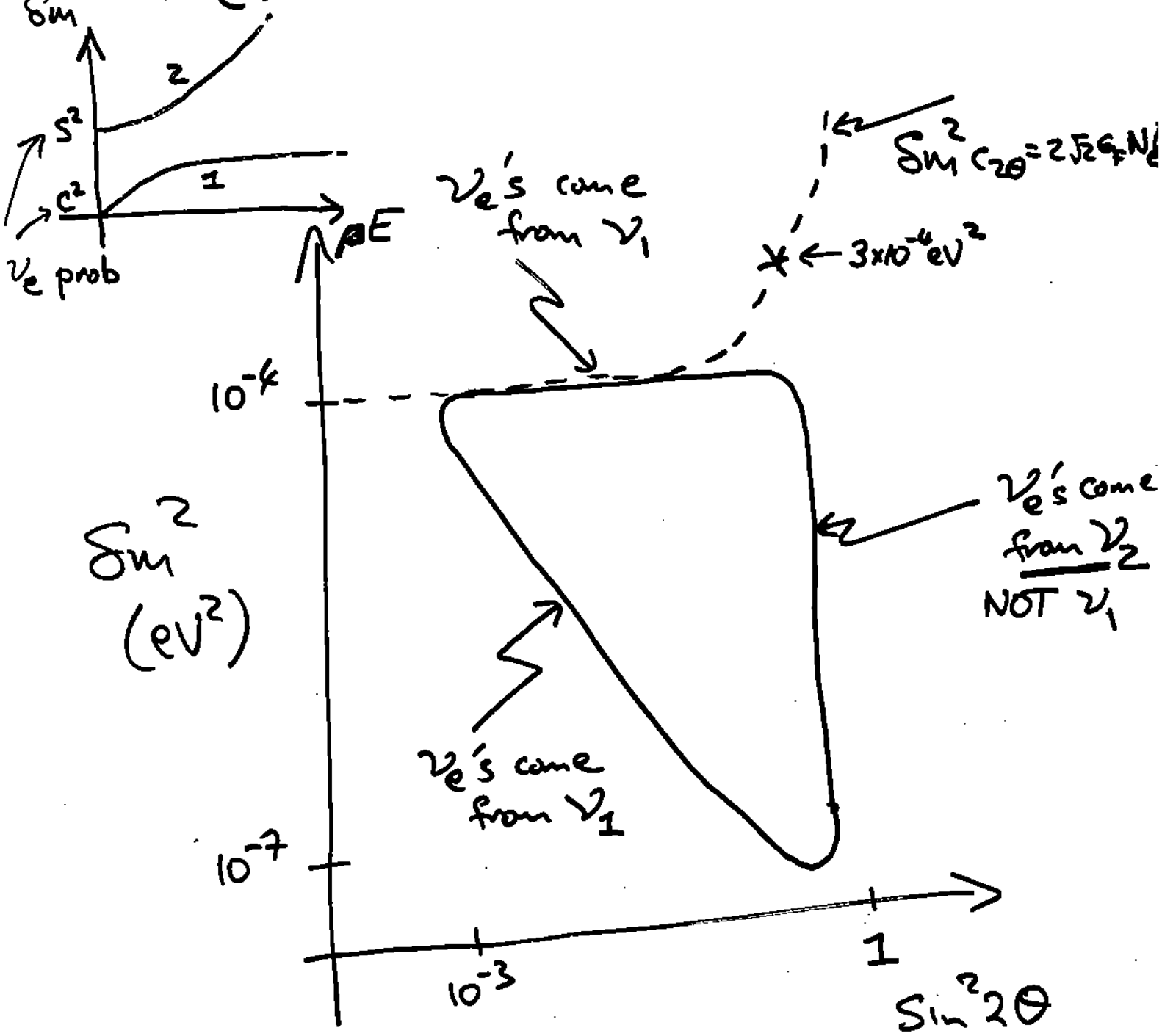
sign of $\delta m^2_{21}$ is <u>positive</u>

# — SNO —




works because
Spectral distortion
is small — (SK)

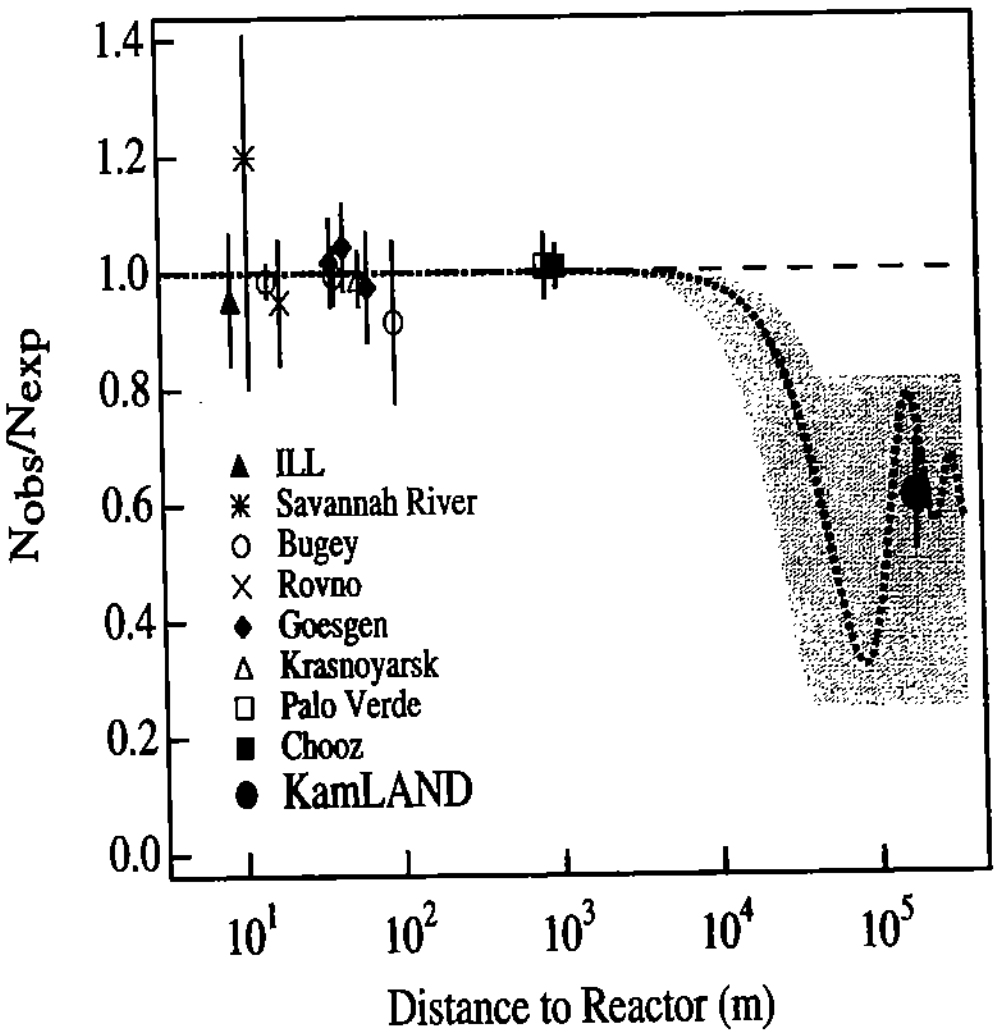
# $\langle P_{\nu_e} \rangle = 0.3$ for $^8B$ Neutrinos




$$\langle P_{\nu_e} \rangle = \frac{1}{2} + \left(\frac{1}{2} - P_{jump}\right) \cos 2\theta_{VAC} \cos 2\theta_{MATT}$$

SP PRL 57, 1275 (86)

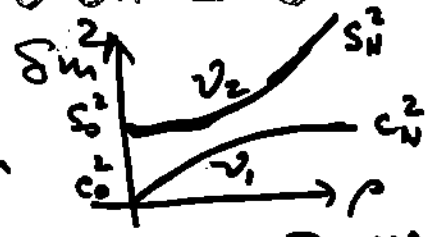
K. Eguchi *et al.* [KamLAND Collaboration],
Phys. Rev. Lett. 90 (2003) 021802
[arXiv:hep-ex/0212021].



# ELECTRON NEUTRINO SURVIVAL

$$P^{^8B}_{SNO} = 0.306 \pm 0.026 \pm 0.024$$ ← solar $\nu_e$

$$P^{Reac}_{Kam} = 0.611 \pm 0.085 \pm 0.041$$ ← Reactor $\bar{\nu}_e$




## Solar: Matter

$$\langle P^{^8B}_{\nu_e \to \nu_e} \rangle = \sin^2\theta_{12}^{VAC} \underbrace{\sin^2\theta_{12}^{MAT}}_{\approx 1} + \cos^2\theta_{12}^{VAC} \underbrace{\cos^2\theta_{12}^{MAT}}_{\simeq 0}$$

$$\simeq \sin^2\theta_{12}^{VAC} = 0.3$$

$\theta_{12}^{MAT} = \frac{\pi}{2}$ ?

## Reactor: VACUUM

$$\langle P^{Reac}_{\bar{\nu}_e \to \bar{\nu}_e} \rangle \simeq \sin^4\theta_{12}^{VAC} + \cos^4\theta_{12}^{VAC}$$

same as $\to 1 - \frac{1}{2}\sin^2 2\theta_{12}^{VAC}$

$$= 0.3^2 + 0.7^2$$

$$= 0.58$$

KAMLAND = 0.61 ✓

Energy Average?

# Future: (12) sector

- precision measurements: $\begin{cases} \delta m^2_{21} \\ \sin^2\theta_{12} \end{cases}$
  (LBL need $\delta m^2_{12} \sin 2\theta_{12}$)

- D/N asymmetries: CC and NC

- Spectral Distortion:

- $^7$Be and pp solar $\nu$'s

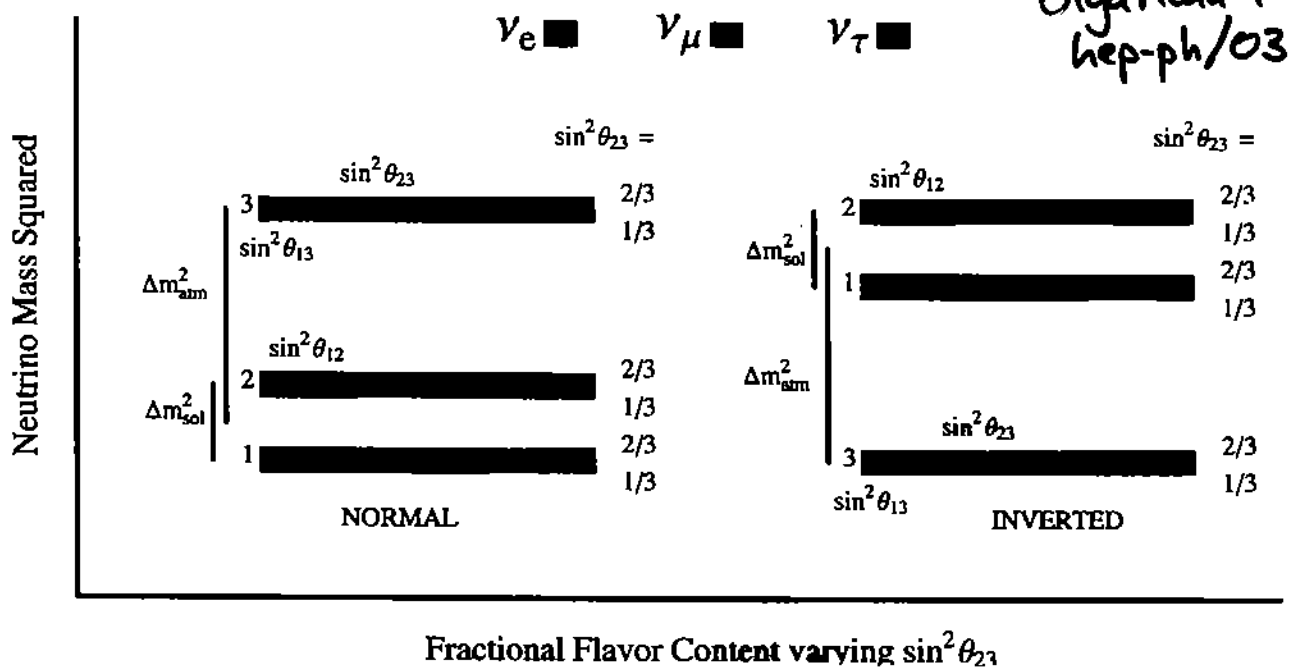
- Subleading effects: $\theta_{13}$

- $\nu_{sterile}$ component independent of Solar models.

- Inconsistencies and Surprises:

# 23 Sector: Atmospheric / K2K ...

Olga Mena + SP
hep-ph/0312131




$$1.3\times10^{-3}\,eV^2 < |\delta m^2_{32}| < 3.0\times10^{-3}\,eV^2$$

$$0.35 < \sin^2\theta_{23} < 0.65$$

$$\delta m^2_{atm} \simeq c_{12}^2\,\delta m^2_{32} + s_{12}^2\,\delta m^2_{31}$$

$\nu_\mu$ dissappearance $= \delta m^2_{32}\left(1 + s_{12}^2\,\frac{\delta m^2_{21}}{\delta m^2_{32}}\right)$

1% effect

Desperately Needing $\delta m^2$ !

$|\delta m^2_{32}|$

- improve marginally with more K2K running
- MINOS 10% measurement
- LBL exp – down to uncertainty $\sim 1 \times 10^{-4}\,eV^2$ (5%)

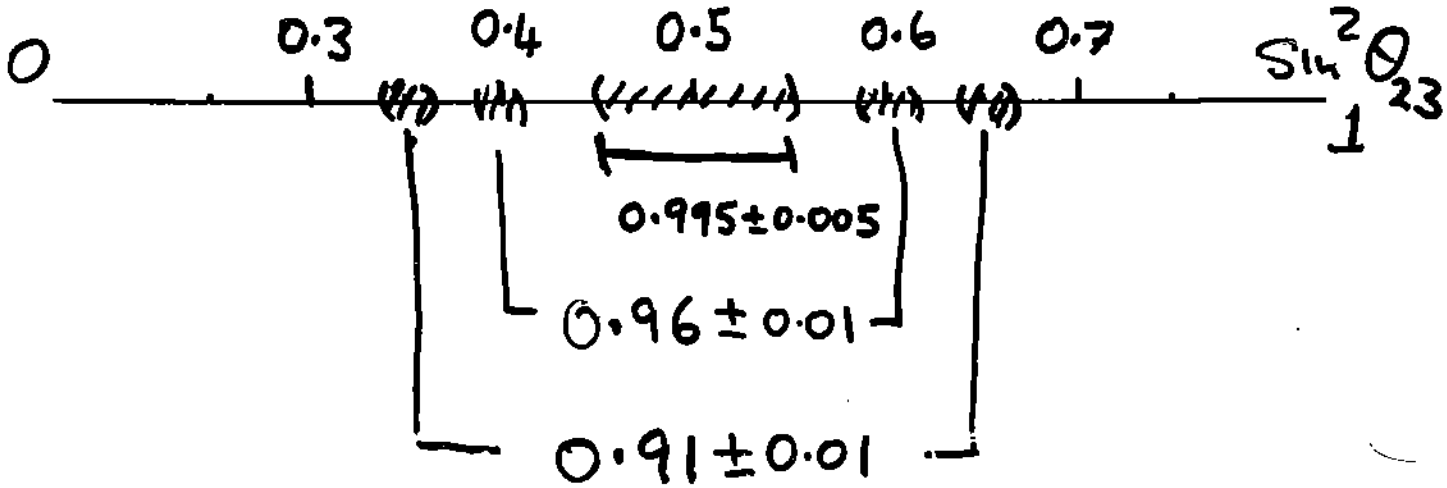
$$\underline{\sin^2 2\theta_{23} > 0.91}$$

$$0.35 < \sin^2\theta_{23} < 0.65$$

$\theta_{23} = \pi/4$ $\mu$-$\tau$ symmetry point

LBLs [ J Parc + NuMI-Off-Axis : $\sin^2 2\theta_{23}$ to 1%
Brookhaven

$$\sin^2\theta_{23} = (1 \pm \epsilon)/2$$



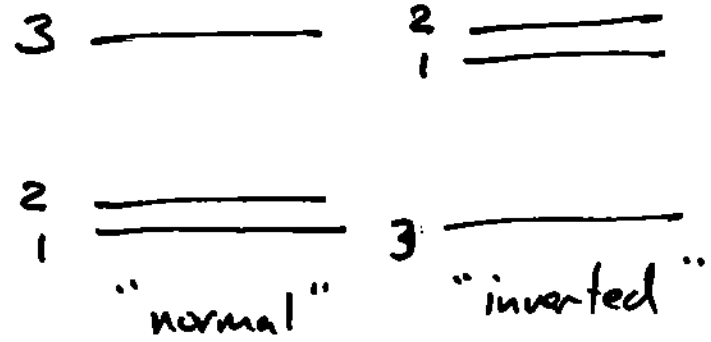

$$\sin^2 2\theta_{23} = 1 - \epsilon^2$$

$\nu_\mu \to \nu_\mu$ poor way to measure $\sin^2\theta_{23}$ near $\pi/4$

A Reactor measurement of $\theta_{13}$ can help!

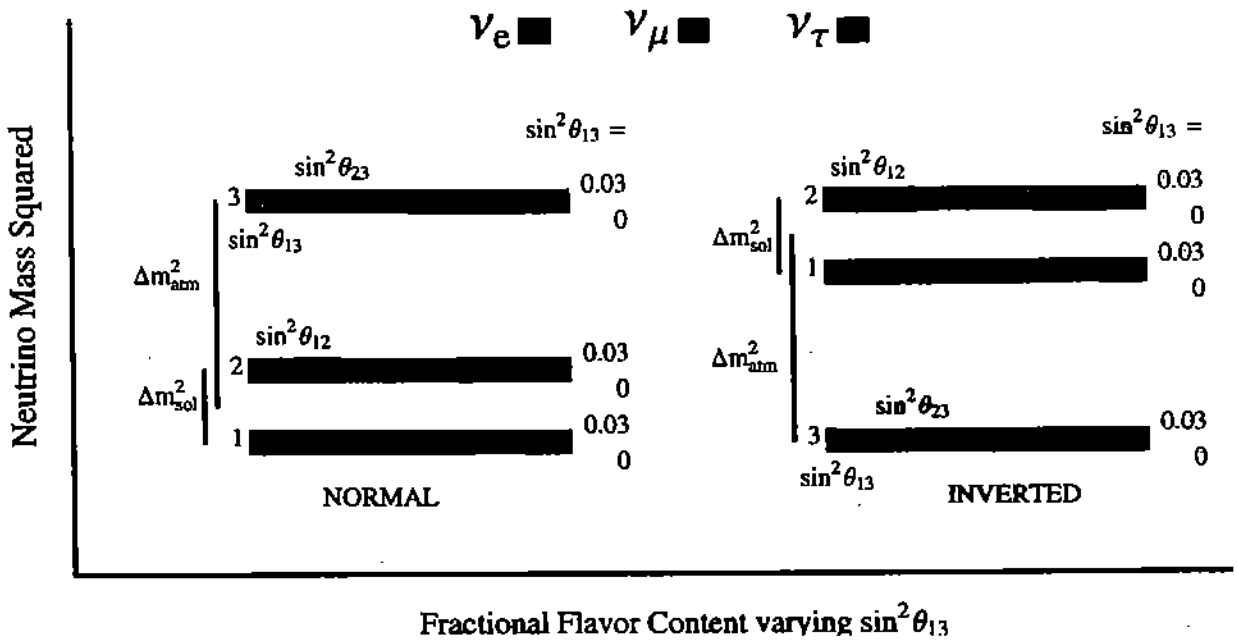
magnitude and sign of breaking:

# Sign $\delta m^2_{32}$




- $\cancel{\nu}$ $\beta\beta$ decay with $m_{\beta\beta} \sim 10\,\mathrm{meV}$
- Supernova ?
- Cosmology 1 v 2 $\nu$ at 50 meV
- Reactors:
  interference of solar + atmospheric
  at intermediate distances:
  20-30 km (Shape!)
- Matter Effects in LBL:

# 13 - Sector:

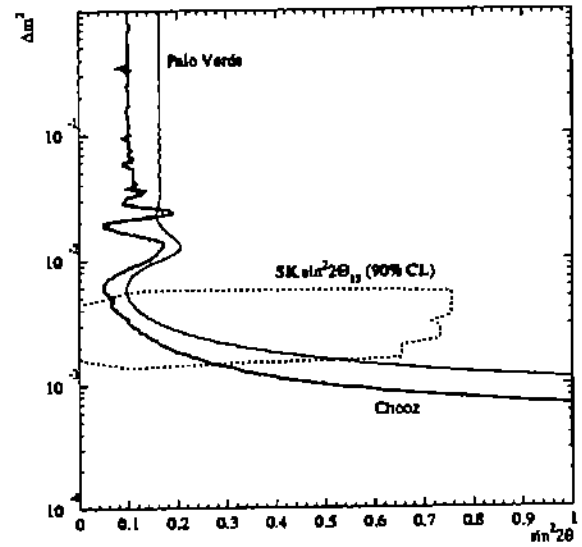



$$\sin^2\theta_{13} < 3\text{-}4 \times 10^{-2}$$

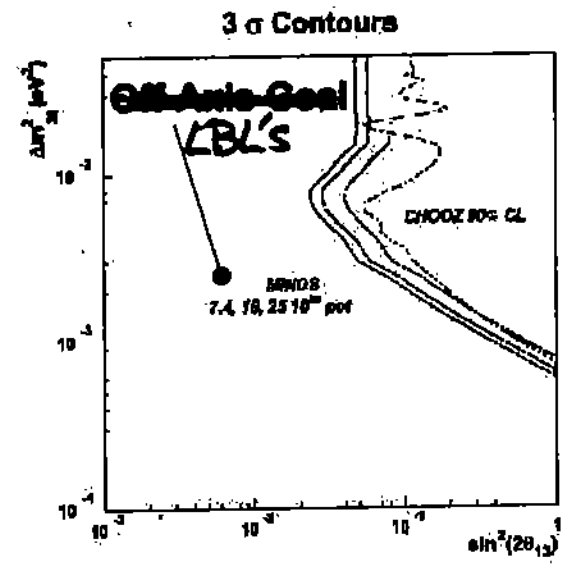
depends on $\sin^2_{atm}$

# Limits on $\theta_{13}$

Chooz and SuperKamiokande:
Chooz was a $\bar{\nu}_e$ **dissappearance** experiment using Reactors.
Energies few MeV.
K2K.




MINOS:
Has some sensitivity to $\nu_e$ above backgrounds.
Primary goal is to measure $|\delta m^2_{32}|$ to 10% — VERY IMPORTANT.



# Getting at $\theta_{13}$

- subleading effects in Solar:
- Atmospheric esp. near $\cos\theta_{zenith} \approx -1$
- Supernova ?
- Reactors
- Long Baseline Accelerator Exp.

## Reactors + Accelerators:

$$\underline{\sin^2\theta_{13} \quad (\ll 1)}$$

Reactors: $P_{e\to e} = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31}$
$+$ tiny terms.

LBL: $P_{\mu\to e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{31}$
no matter $+$ not so tiny terms.

SuperLBL: $P_{\mu\to e} = \sin^2\theta_{23} \sin^2 2\theta_{13}$
$\times \left(\frac{\Delta_{31}}{\Delta_{31} \mp aL}\right)^2 \sin^2(\Delta_{31} \mp aL)$
incl. matter $+$ not so tiny terms.

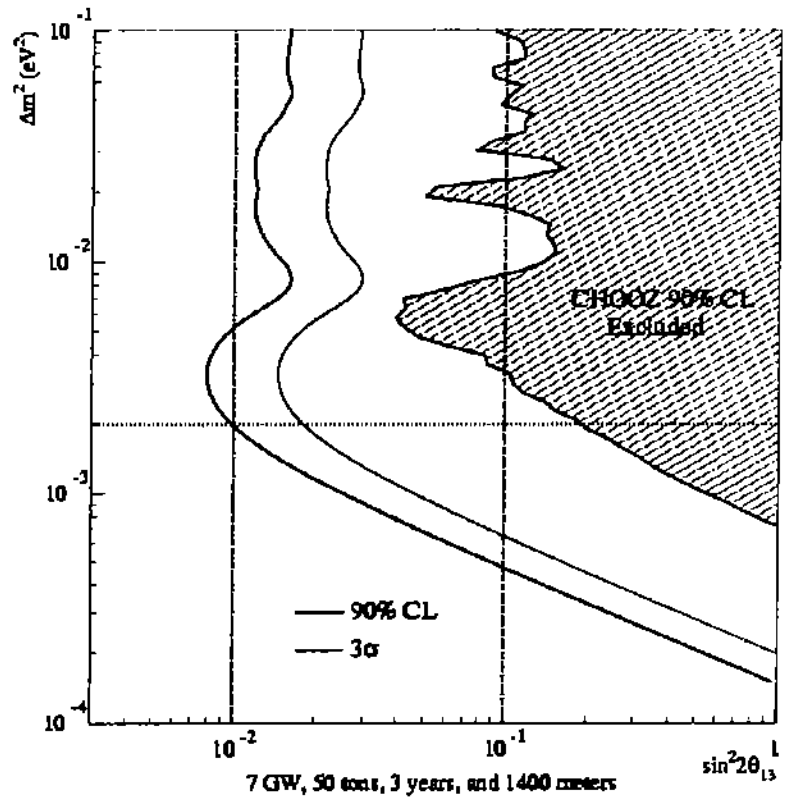
where $\Delta_{31} = \delta m^2_{31} L/4E = 1.27\ \delta m^2_{31} L/E$

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

# New Reactor Experiments:

"Super-Chooz:"
interest in Japan, Europe, Russia and USA (CA & IL).

Figure from J. Link, Columbia U.
Using two detectors with the far detector being able to be moved to along side the near detector for relative calibration.




Systematics Limited experiment.

Clean measurement of $\sin^2 2\theta_{13}$ down to ~0.01.

Could be a "quick" and "cheap" experiment, but ...

## $\theta_{13}$ using $\nu_\mu \to \nu_e$ (or $\nu_e \to \nu_\mu$ $\nu$-factory)

$$P^{VAC}_{\mu\to e} \approx \Big| \underbrace{2 s_{23} s_{13} c_{13} \sin\Delta_{31}}_{\text{Atm. Amp}} e^{-i(\Delta_{32}\pm\delta)} + \underbrace{2 c_{23} c_{13} s_{12} c_{12} \sin\Delta_{21}}_{\text{Solar Amp.}} \Big|^2$$

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

Leading term $= \underline{\sin^2\theta_{23}} \sin^2 2\theta_{13} \sin^2\Delta_{31}$

Sensitive to $\sin\theta_{13}$, $\sin\theta_{23}$

Peaks at $\Delta_{31} = \pi/2, \frac{3\pi}{2} \cdots (2n+1)\pi/2$

Interference term $= 8 J_r \sin\Delta_{21} \sin\Delta_{31} \cos(\Delta_{32}\pm\delta)$

$J_r = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2$

Sensitive to $\sin\delta$ and $\cos\delta$

$$\cos(\Delta_{32}\pm\delta) = \cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta$$

at above peaks

$$\sin\Delta_{21} \approx \frac{\delta m^2_{21}}{\delta m^2_{31}} \Delta_{31} = (2n+1)\frac{\delta m^2_{21}}{\delta m^2_{31}} \pi/2$$

GROWS LINEARLY with peaks.

# 3 flavor – $\nu_\mu \to \nu_e$

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

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. $U^*_{\mu 2} U_{e2} \approx c_{23} c_{13} s_{12} c_{12} + \mathcal{O}(s_{13})$:

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

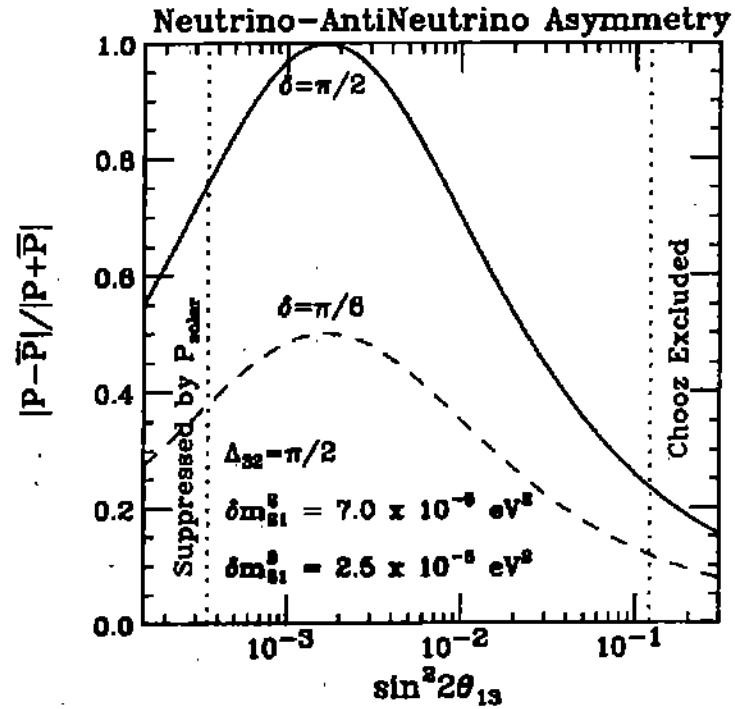
Interference term different for $\nu$ and $\bar{\nu}$: CP violation !!!

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

At the first atmospheric oscillation maximum, $\Delta_{32} = \frac{\pi}{2}$, the Neutrino-AntiNeutrino Asymmetry is maximum when

$$|a^{atm}| = |a^{sol}|$$

$$\sin^2 2\theta_{13} \approx \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}}\left[\frac{\pi}{2}\,\frac{\delta m^2_{21}}{\delta m^2_{31}}\right]^2$$




$\frac{3\pi}{2}$ second peak

$10^{-2}$ $10^{-1}$

At the second oscillation maximum, $\Delta_{32} = \frac{3\pi}{2}$, the peak in the Asymmetry occurs when $\sin^2 2\theta_{13}$ is 9 times larger.

## Matter Effects:

Sensitive to sign $\delta m^2_{31}$

$$\sin \Delta_{31} \rightarrow \frac{\Delta_{31}}{\Delta_{31} \mp aL} \sin(\Delta_{31} \mp aL)$$

$$\sin \Delta_{21} \rightarrow \frac{\Delta_{21}}{\Delta_{21} \mp aL} \sin(\Delta_{21} \mp aL) \approx \Delta_{21}$$

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

Important when

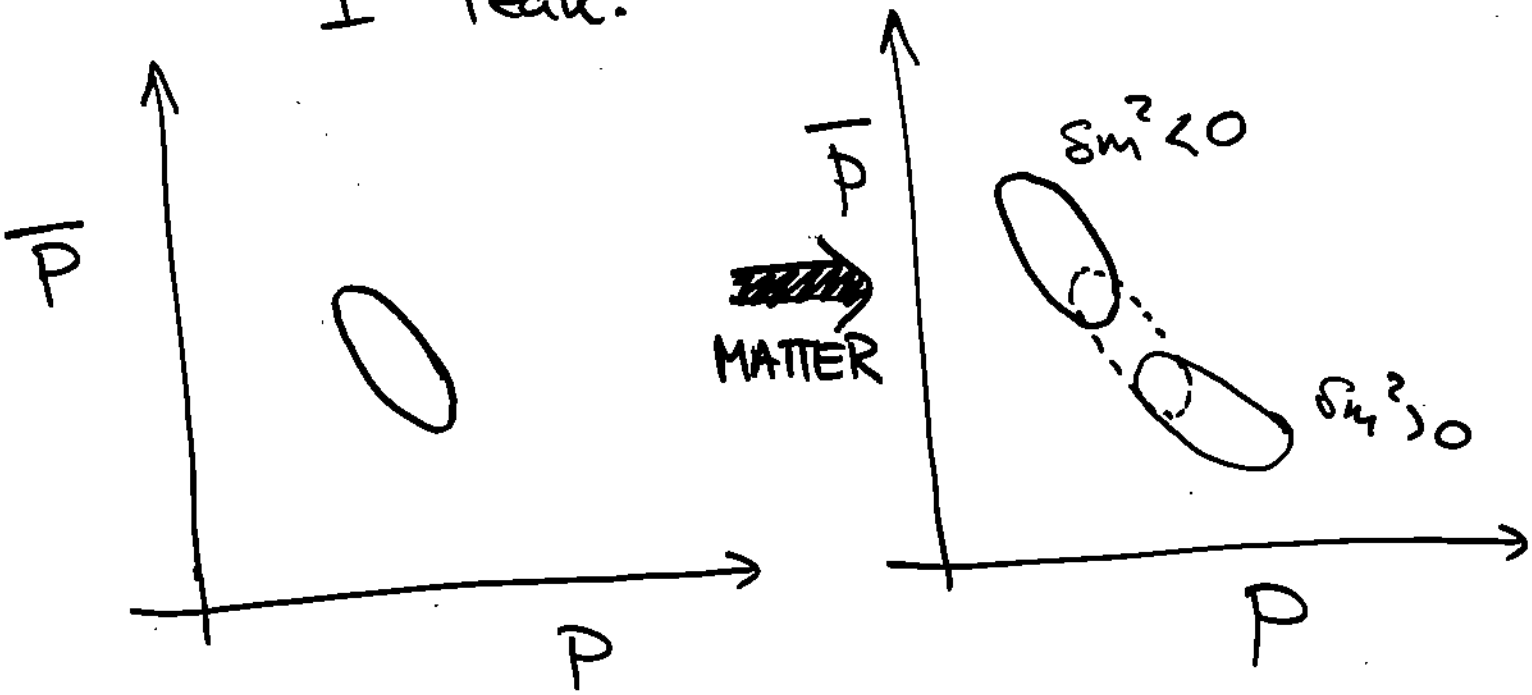
$$\sin(\Delta_{31} \mp aL) \neq \Delta_{31} \mp aL$$

At $\Delta_{31} = \pi/2, 3\pi/2, \ldots$

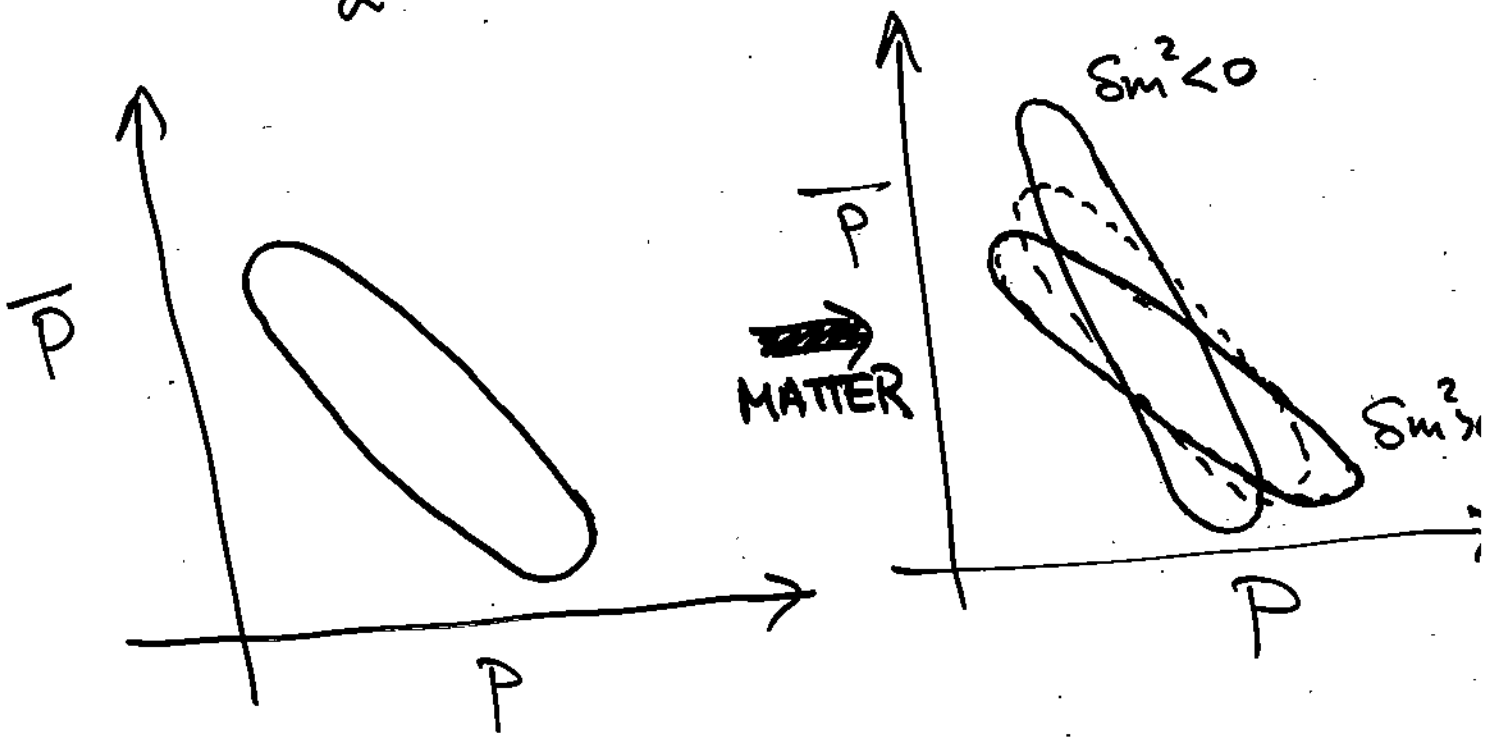
$$\frac{\Delta_{31}}{\Delta_{31} \mp aL} \sin(\Delta_{31} \mp aL) \approx 1 \pm \frac{aL}{\Delta_{31}} + \mathcal{O}(aL)^2$$

For a given $L$ matter effects are smaller (linearly) with successive peaks.

1st Peak:




2nd Peak:



If $\theta_{13}$ is very small such that

$$|a_{\mu\to e}^{atm}| < |a_{\mu\to e}^{solar}|$$

then amplifying

$a_{\mu\to e}^{atm}$ by Matter Effects

is very important for $\left\{ \begin{array}{l} \theta_{13} + \\ \text{CP violation:} \end{array} \right.$

— $\nu$ factory —

# Leptonic CP and T Violation in Oscillations

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

CP Violation in Neutrino Oscillations is related to Leptogenesis and hence Baryogenesis.

# CP Violation and Leptogenesis

- For most Neutrino Mass Models there is a relationship between the Dirac CP phase $\delta$ and Majorana CP phases $\alpha_2$, $\alpha_3$.
- At a minimum they are all zero or all non-zero.
- $\alpha_2$, $\alpha_3$ are responsible for Leptogenesis in the early universe by allowing for different decay rates of Neutral Heavy Leptons:

$$N \to l^+\phi^- \text{ and } N \to l^-\phi^+$$

- $B = \frac{1}{2}(B-L) + \frac{1}{2}(B+L)$, however $(B+L)$ violated.
- Hence the Dirac CP violating phase, $\delta$, is a handle on Leptogenesis and hence Baryogenesis.

Fukugita and Yanagida, Phys. Lett. B174, 45 (1986)
Frampton, Glashow and Yanagida – hep-ph/0208157
Endoh, Kaneko, Kang, Morozumi – hep-ph/0209098

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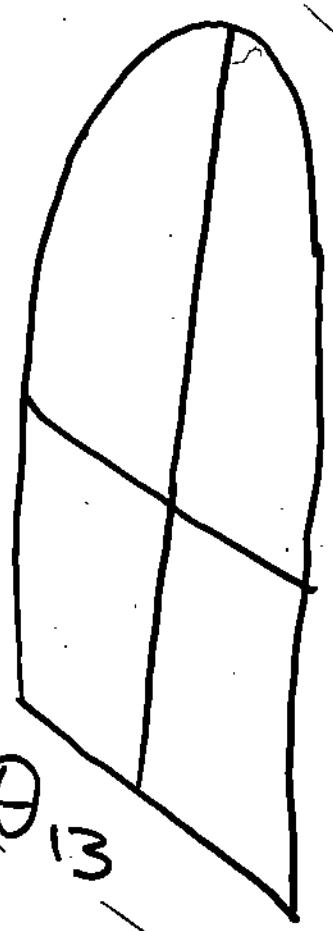
- CP Violation in $\nu$-Sector (Leptogenesis)
- Sign $\delta m^2_{atm}$ $\left\{ \begin{array}{c} \text{normal!} \\ \vee \\ \text{inverted} \end{array} \right.$
- $\theta_{23} \not\leftrightarrow \pi/2 - \theta_{23}$



$\theta_{13}$

Window

of Opportunity

# Summary:

The important questions are:

- # of light Neutrinos
- Absolute Mass — Majorana v. Dirac
- Mixings & $\delta m^2$'s

esp. $\theta_{13}$ ---- $\left\{ \begin{array}{l} \text{sign } \delta m^2_{atm} \\ \theta_{23} \leftrightarrow \pi/2 - \theta_{23} \\ \delta_{CP} \end{array} \right.$

BUT We need to plan for

Mass

Surprises & Models