θ_{13} & Beyond
Nu Worlds

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Fermilab
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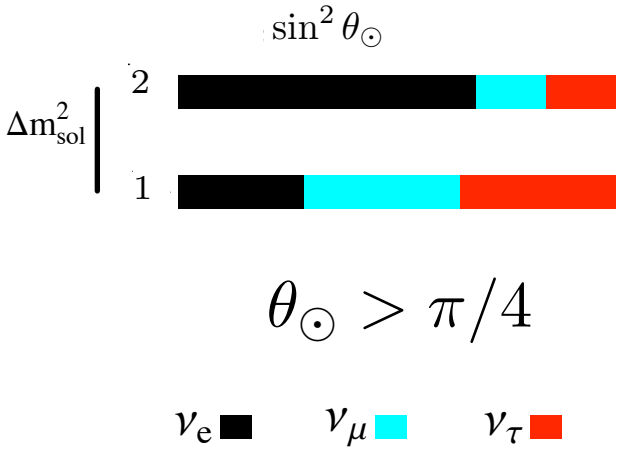
Solar Summary:

- ^{8}Boron: born where $\nu_e = \nu_2$ remain ν_2's forever (no oscillations)
- pp and ^{7}Be: full averaged vacuum oscillations $\Rightarrow$ 2/3 ν_1 and 1/3 ν_2
- Solar hierarchy determined by matter effect.
  ($P_{ee} < 1/2$ impossible for one hierarchy)



Solar matter effects put more of the neutrino into ν_2.
This raises the survival probability above vacuum value since ν_2 has more ν_e.
But the minimum of P_{ee} in vacuum is 1/2.

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

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

This solar hierarchy EXCLUDED !!!.

http://theory.fnal.gov/people/parke/TALKS/2006

What happens to the neutrino oscillation length in the semi-classical limit, $\hbar \to 0$?

- $L_{osc} \to \infty$
- $L_{osc} \to 0$
- Other

$$\boldsymbol{\Delta = \frac{\delta m^2 L}{4\,\hbar c\; E} \quad \Rightarrow \quad L_{osc} = 4\pi\hbar c E/\delta m^2}$$

So in the limit $\hbar \to 0$ then $L_{osc} \to 0$
same as $\delta m^2 \to large$!!!

and
$W^+ \to e^+\nu_1$ with probability $\cos^2\theta_\odot$
$W^+ \to e^+\nu_2$ with probability $\sin^2\theta_\odot$

compare quark sector !

The ν Standard Model

- 3 light (m_i <1 eV) Majorana Neutrinos:

  $\Rightarrow$ only 2 δm^2

  $|\delta m^2_{atm}| \sim 2.5 \times 10^{-3}$ eV^2 and $\delta m^2_{solar} \sim +8.0 \times 10^{-5}$ eV^2

- Only Active flavors (no steriles):
  $e,\ \mu,\ \tau$

- Unitary Mixing Matrix:

  3 angles ($\theta_{12},\ \theta_{23},\ \theta_{13}$), 1 Dirac phase ($\delta$),

  2 Majorana phases (α_2, α_3)

$$|\nu_\alpha\rangle_{flavor} = U_{\alpha i}|\nu_i\rangle_{mass}.$$

Atmos. L/E $\mu \to \tau$ (500km/GeV) Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ (15km/MeV) $\beta\beta0\nu$ decay

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

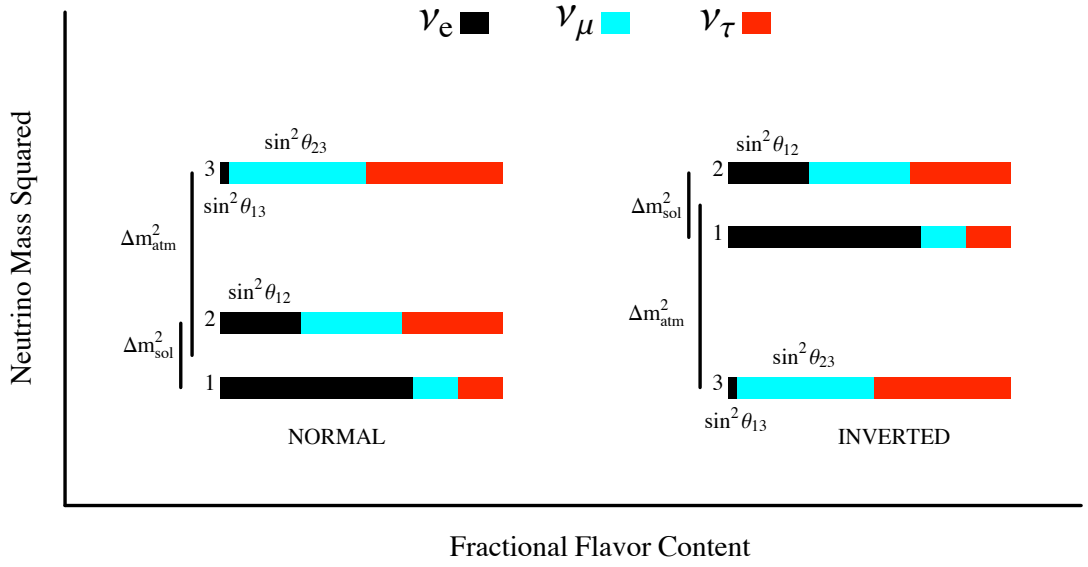
In oscillation phenomena,

the phases $\alpha_2,\ \alpha_3$ are unobservable $(U_{\alpha i}U^*_{\beta i})$

and also the value of m_{lite} is irrelevant (δm^2)

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

(12)-Sector:



(12) Parameters: SNO, KamLAND, SK

$$\delta m^2_{21} = +8.0 \pm 0.8 \times 10^{-5}\ eV^2$$

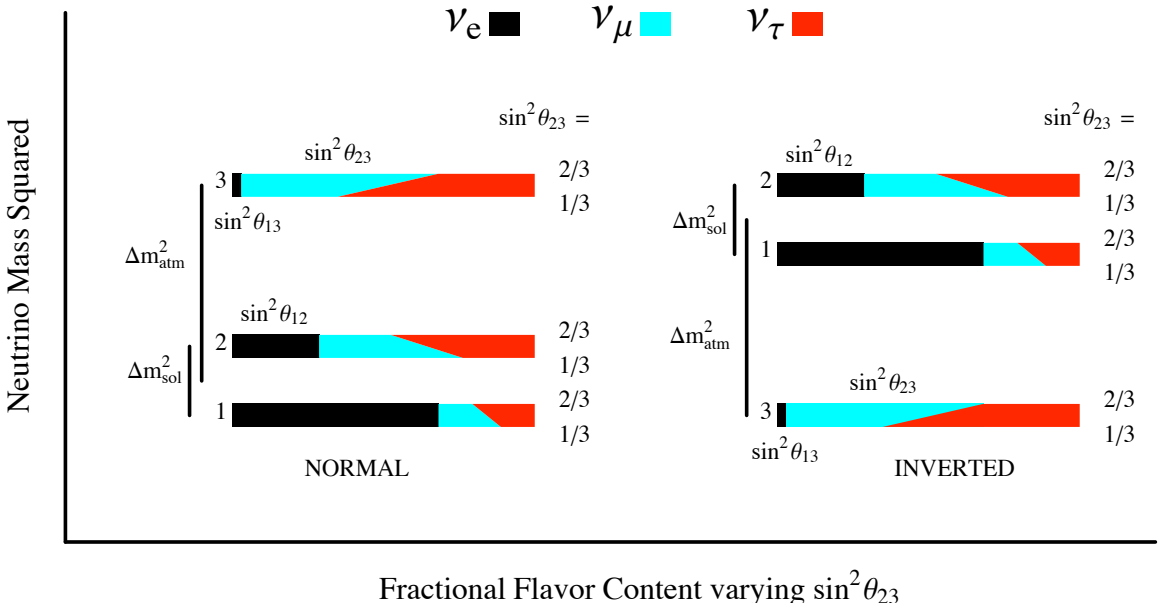
$$0.25 < \sin^2\theta_{12} < 0.37$$

$\sin^2\theta_{12} \geq \frac{1}{2}$ excluded at $> 5\ \sigma$!

sign of δm^2_{21} determined at this C.L.

(23)-Sector:

Mena + SP hep-ph/0312131



(23) Parameters: SK, K2K

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

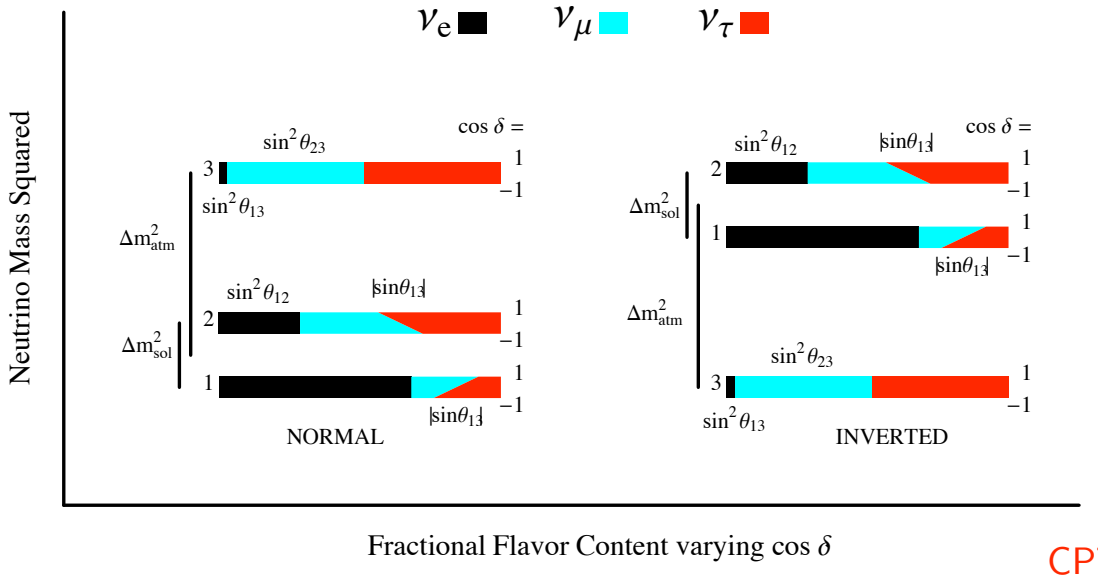
$$0.36 < \sin^2\theta_{23} < 0.64$$

(obtained from $\sin^2 2\theta_{23} > 0.91$)

Magnitude of δm^2_{32} and $\sin^2\theta_{23}$ not as well known!

Sign of δm^2_{32} Unknown !!!

(13)-Sector:



Less than
4% ν_e
in the 3 state!

CPT: $\delta \Leftrightarrow -\delta$ Invariant!

(13) Parameters: Chooz, SK, K2K

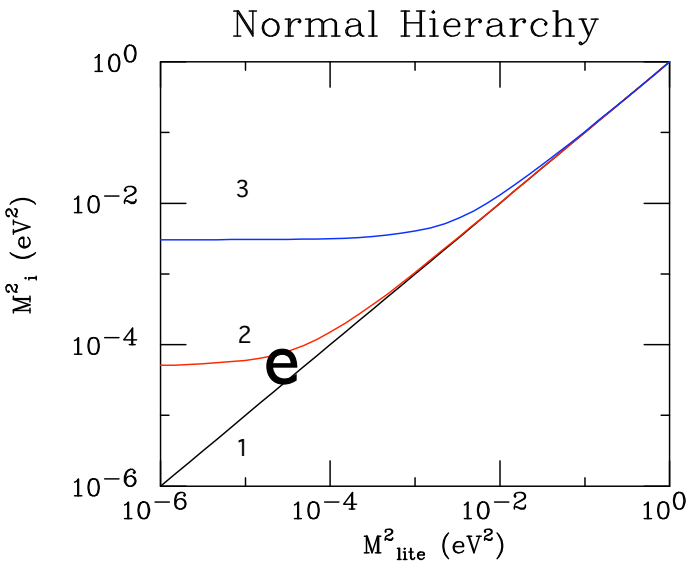
$$\sin^2\theta_{13} < 0.03 - 0.05$$

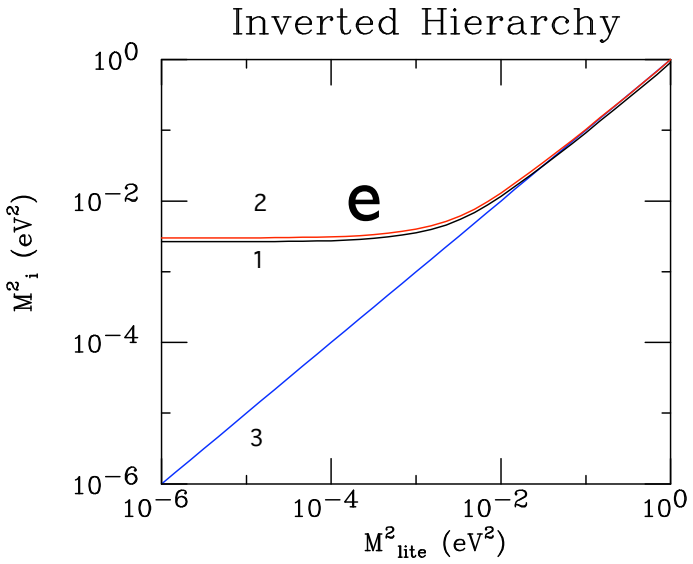
limit $|\delta m^2_{32}|$ dependent

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

Unknown!

Masses:



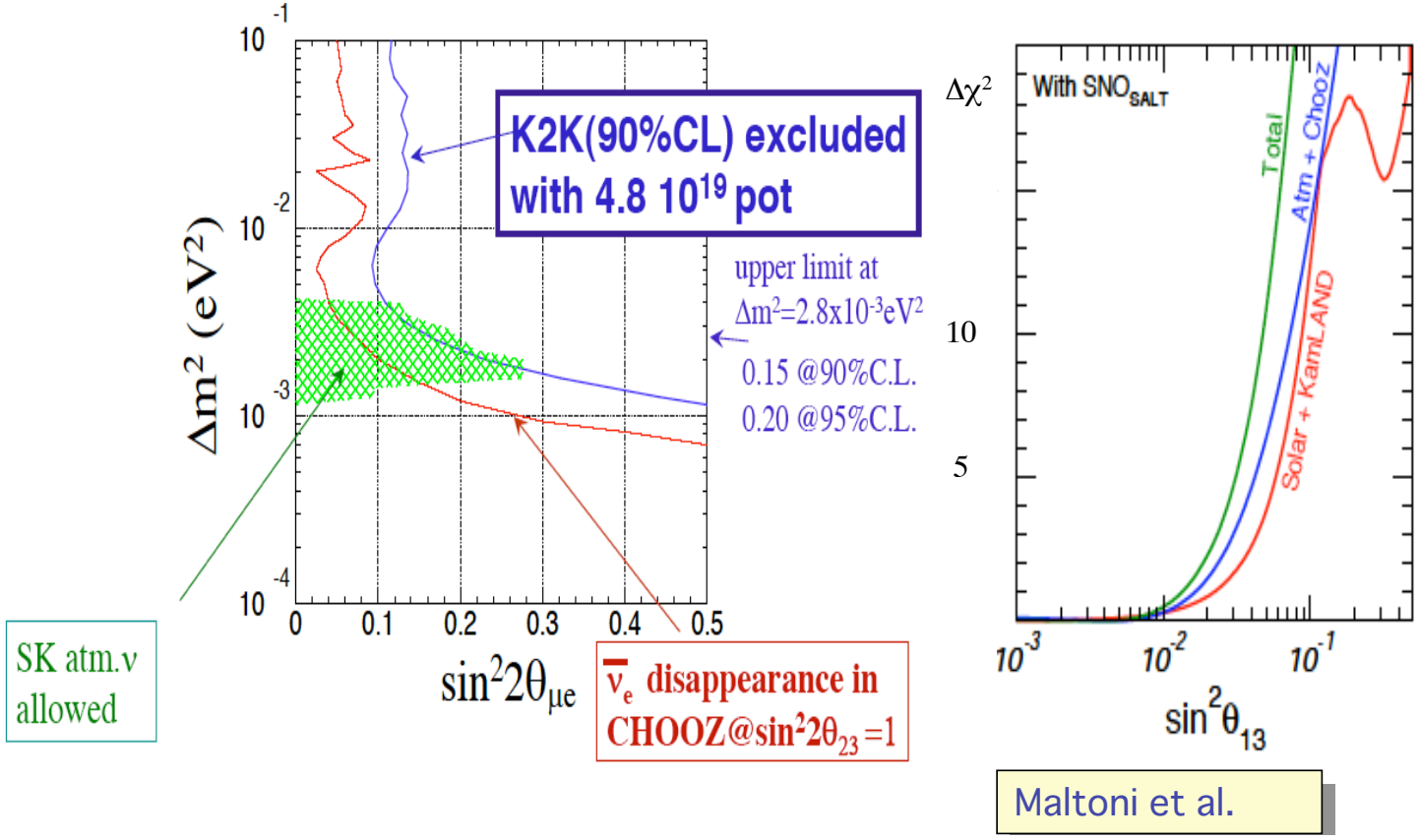


States 1 and 2 are ν_e rich.

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

^
observable

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

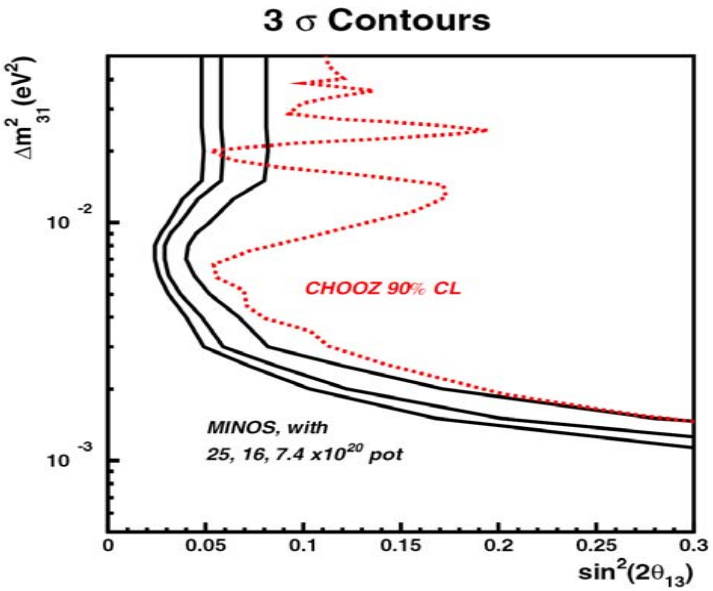


Chooz bound $\sin^2\theta_{13} < 0.04$

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

MINOS:



ν_e appearance =>non-zero θ_{13}

Can improve CHOOZ limit by ~2 with adequate protons

Has some sensitivity to ν_e above backgrounds.

Primary goal is to measure $|\delta m^2_{32}|$ to 10%

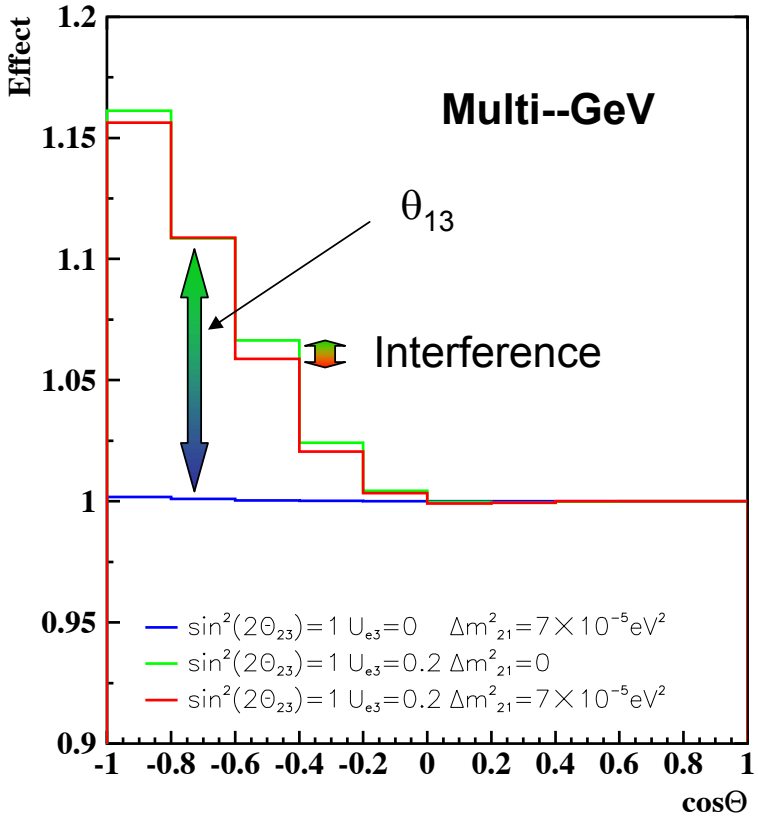
- Atmospheric Neutrinos

SK - Suzuki

— $|U_{e3}|=0.2$

— $\Delta m_{12}^2=7\times10^{-5}eV^2$

— Interference



• Low and High Energy Solar Neutrinos

Goswami + Smirnov
hep-ph/0411359

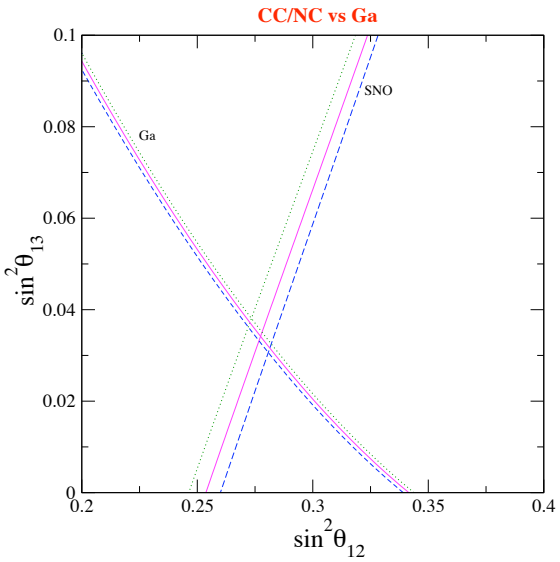


Figure 6: The iso-contours of CC/NC = 0.31 at SNO and $Q_{Ge} = 68.1$ SNU in Ga experiments in the $\sin^2\theta_{12} - \sin^2\theta_{13}$ plane for different values of Δm^2_{21} : $\Delta m^2_{21} = 9 \cdot 10^{-5}$ eV^2 - the dotted lines; $\Delta m^2_{21} = 8 \cdot 10^{-5}$ eV^2 - the solid lines;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

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

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

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

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

$$\sin^2\theta_\odot^{^8B} \approx \sin^2\theta_{12} - 0.9\sin^2\theta_{13}$$

$$\sin^2\theta_\odot^{^8pp} \approx \sin^2\theta_{12} + 1.5\sin^2\theta_{13}$$

$$\sin^2\theta_\odot^{^8pp} - \sin^2\theta_\odot^{^8B} \approx 2.4\sin^2\theta_{13}$$

$$\sin^2\theta_\odot^{^8pep} \approx \sin^2\theta_{12} + (0.5???)\sin^2\theta_{13}$$

Nunokawa, Zukanovich + SP
hep-ph/0601198

$\bar{\nu}_e$ (reactor) Disappearance: $e^{-iE_it} \Rightarrow e^{-im_i^2L/2E}$

$$\begin{aligned} P_{ee} = & \quad | \; U_{e1}^* e^{-im_1^2 L/2E} U_{e1} + U_{e2}^* e^{-im_2^2 L/2E} U_{e2} + U_{e3}^* e^{-im_3^2 L/2E} U_{e3} \; |^2 \\ = & \quad |U_{e1}|^4 + \cdots \\ & + \; 2|U_{e1}|^2 |U_{e2}|^2 \cos 2\Delta_{21} + \cdots \end{aligned}$$

$$\cos 2\Delta_{ji} = 1 - 2\sin^2 \Delta_{ji}$$

$$\begin{aligned} P_{ee} = & \quad 1 - 4|U_{e3}|^2 |U_{e1}|^2 \sin^2 \Delta_{31} - \quad 4|U_{e3}|^2 |U_{e2}|^2 \sin^2 \Delta_{32} \\ & - \quad 4|U_{e2}|^2 |U_{e2}|^2 \sin^2 \Delta_{21} \end{aligned}$$

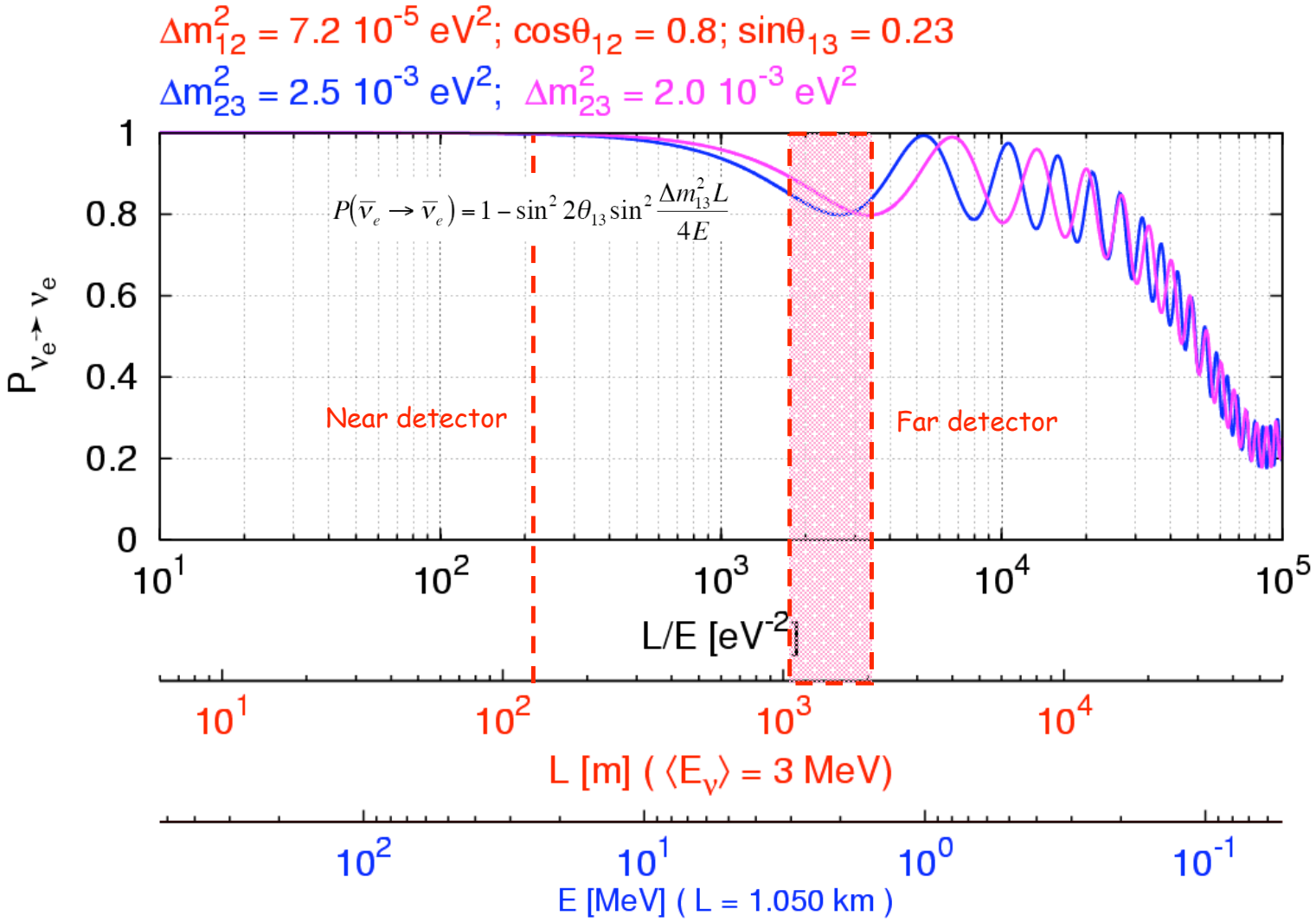
$$\Delta_{31} \approx \Delta_{atm} \approx \Delta_{32}$$

$$P_{ee} = \quad 1 - 4|U_{e3}|^2 (1 - |U_{e3}|^2) \sin^2 \Delta_{atm} - 4|U_{e2}|^2 |U_{e1}|^2 \sin^2 \Delta_{\odot}$$

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

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{atm} - \cos^4 \theta_{13} \sin^2 2\theta_{\odot} \sin^2 \Delta_{\odot}$$

$$\delta m^2_{atm} \approx \cos^2 \theta_{\odot} \delta m^2_{31} + \sin^2 \theta_{\odot} \delta m^2_{32}$$

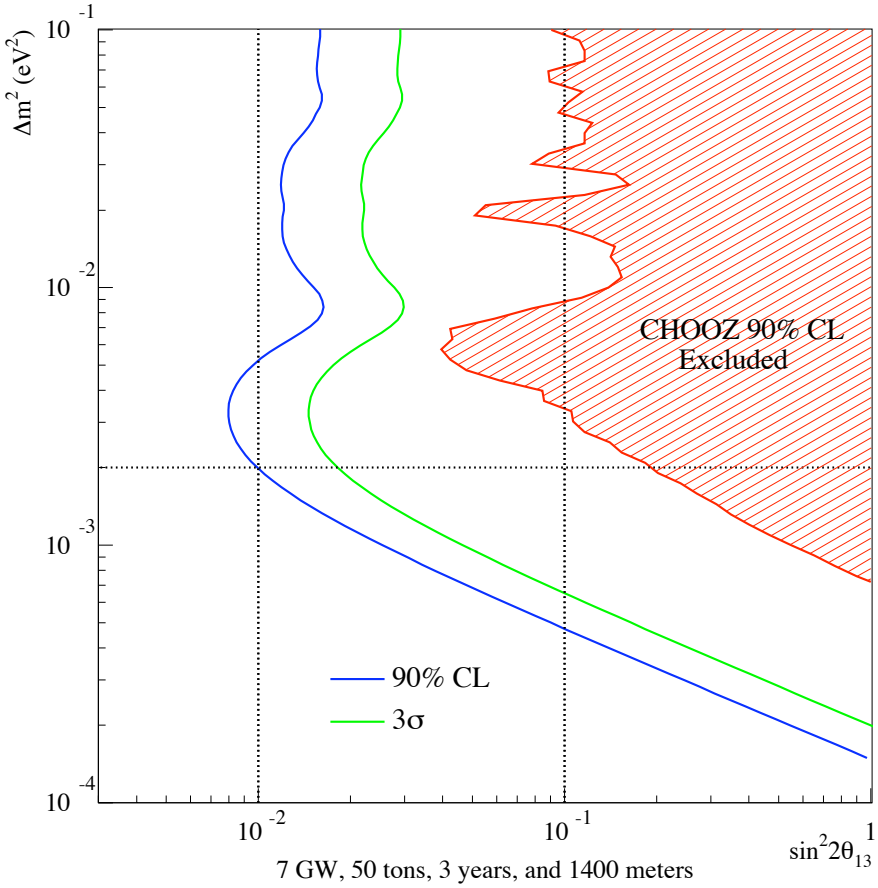


$$P_{ee} \;=\; 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{atm} - \cos^4 \theta_{13} \sin^2 2\theta_{\odot} \sin^2 \Delta_{\odot}$$

Clean measurement of

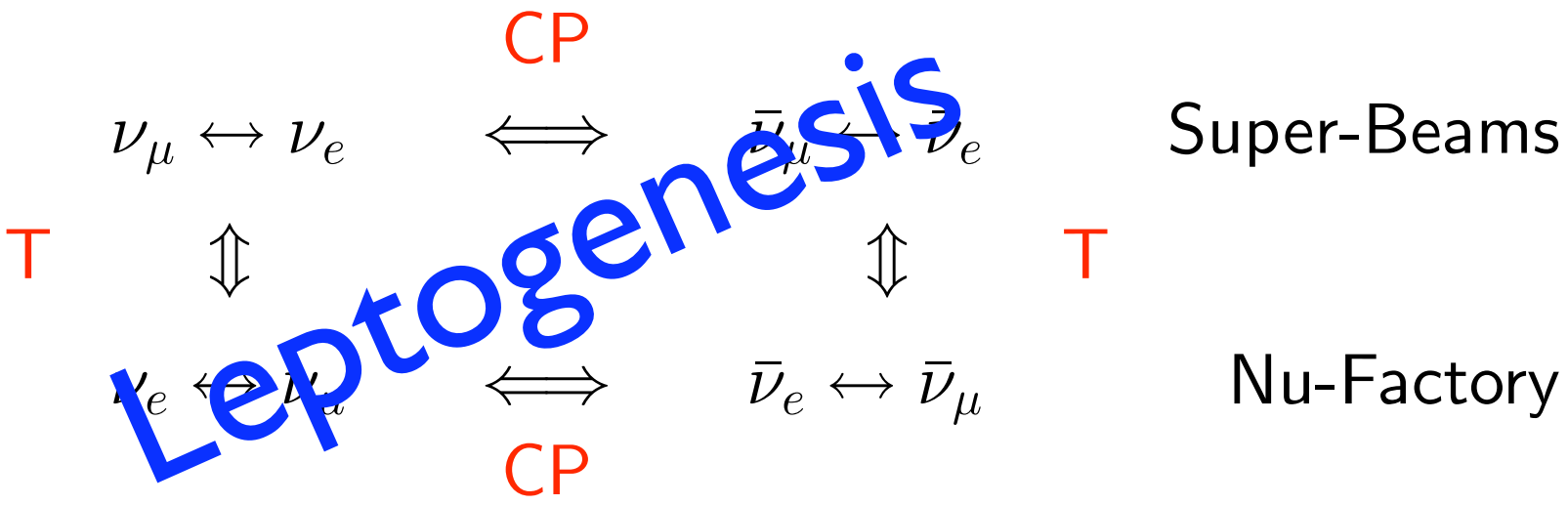
$\sin^2 2\theta_{13}$ down to 0.01

Systematics limit experiment:
Could be "quick" and "cheap" but ...



J. Link, Columbia

Leptonic CP and T Violation in Neutrino Oscillations



Vacuum: $\nu_\mu \longrightarrow \nu_e$

$$P(\nu_\mu \to \nu_e) = | U^*_{\mu 1} e^{-im_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-im_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-im_3^2 L/2E} U_{e3} |^2$$

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

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

$e^{-iE_i t} \Rightarrow e^{-im_i^2 L/2E}$

CP violation !!! $\delta \to -\delta$ for $\bar{\nu}$

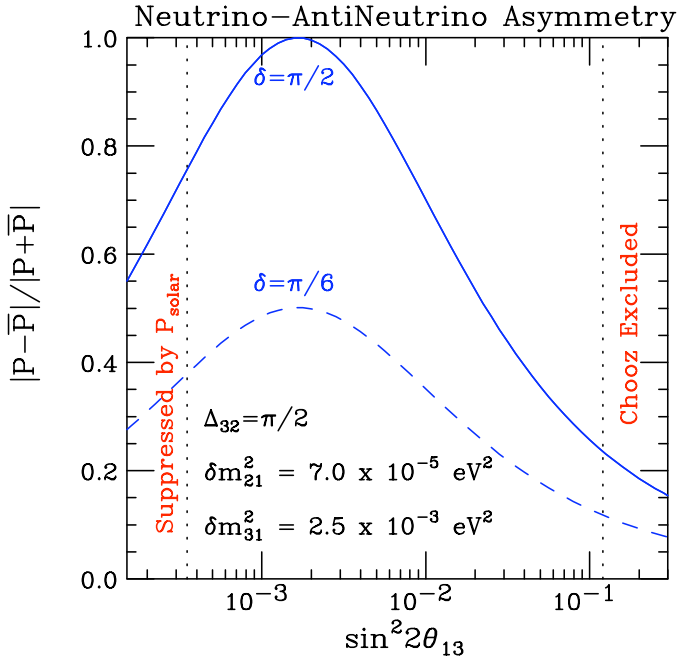
where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \sin \Delta_{31}$ and $\sqrt{P_{sol}} \approx \cos\theta_{23} \sin 2\theta_{12} \sin \Delta_{21}$

$$P(\nu_\mu \to \nu_e) = P_{atm} + 2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} + \delta) + P_{sol}$$

CP violation !!!
$\delta \to -\delta$ for $\bar{\nu}$

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

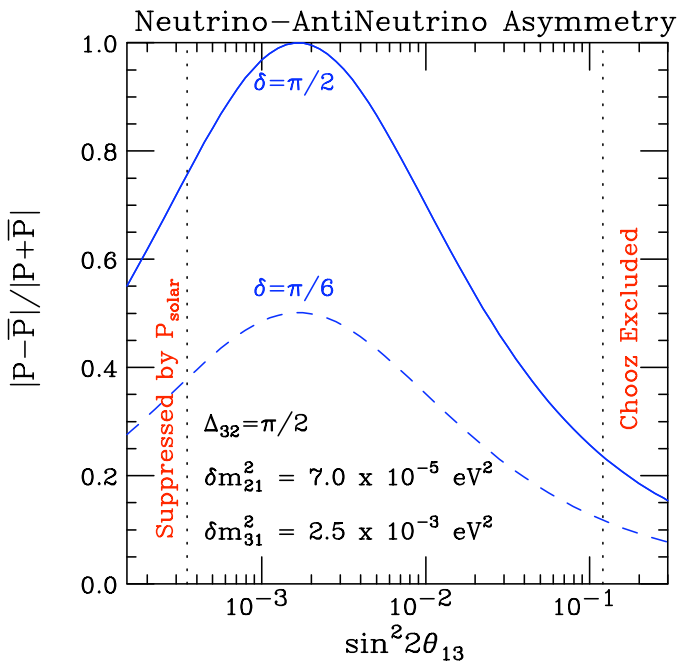
Asymmetry Peaks:



$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

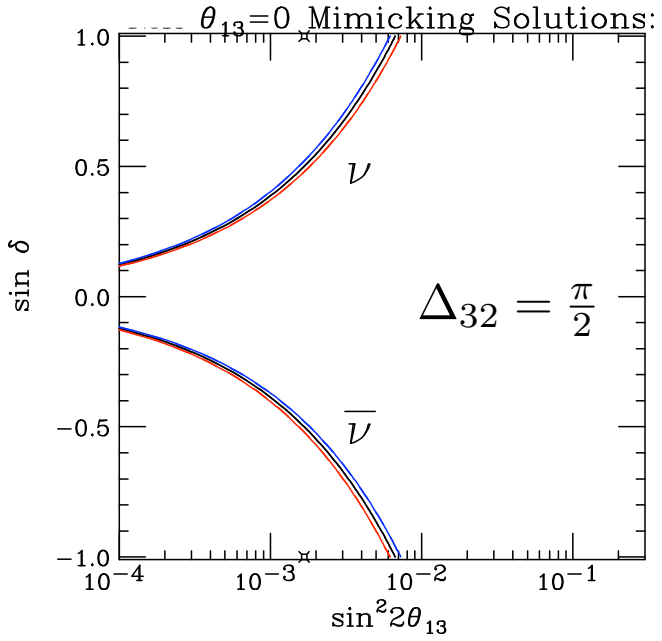
$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}} \right|^2$$

Asymmetry Peaks:



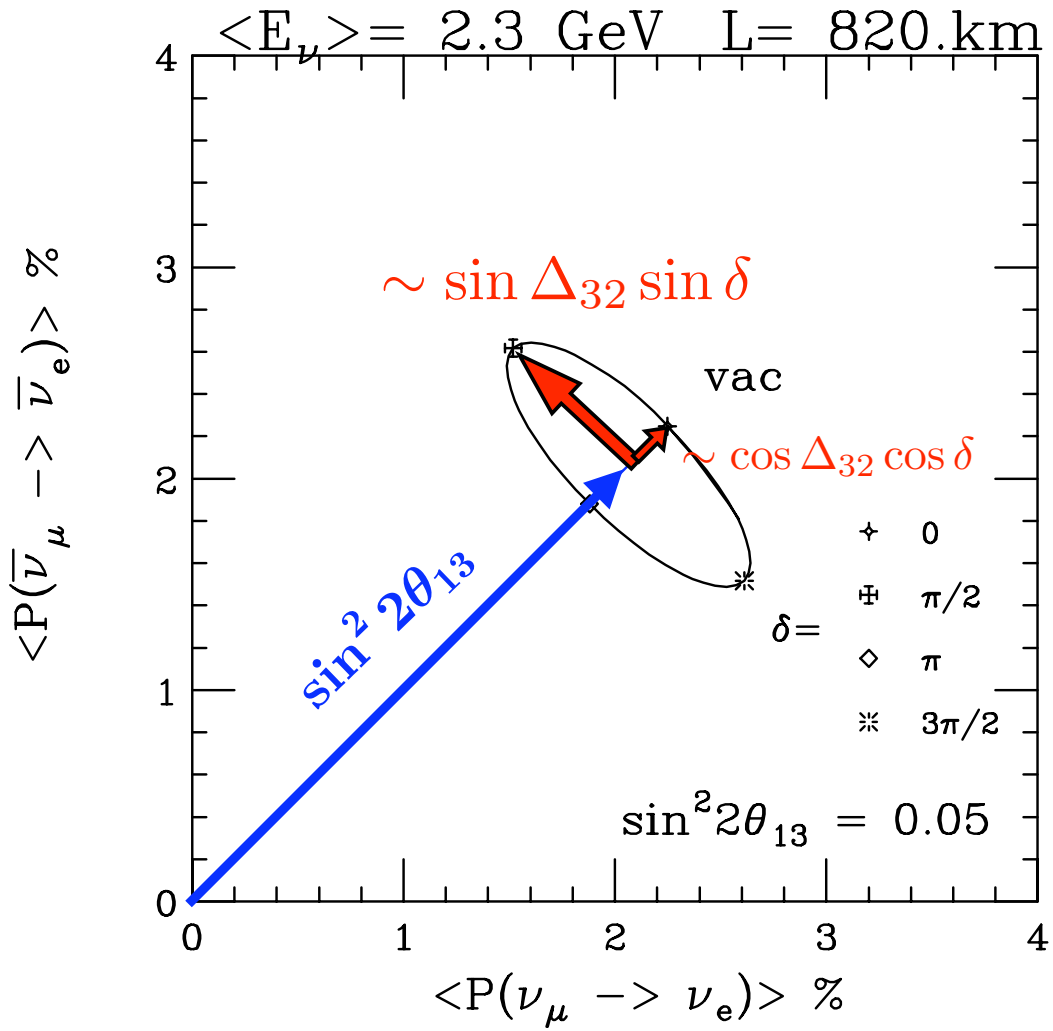
$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

Zero Mimicking Solutions:



$$\sqrt{P_{atm}} = -2\sqrt{P_{sol}}\cos(\Delta_{32} \pm \delta)$$

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



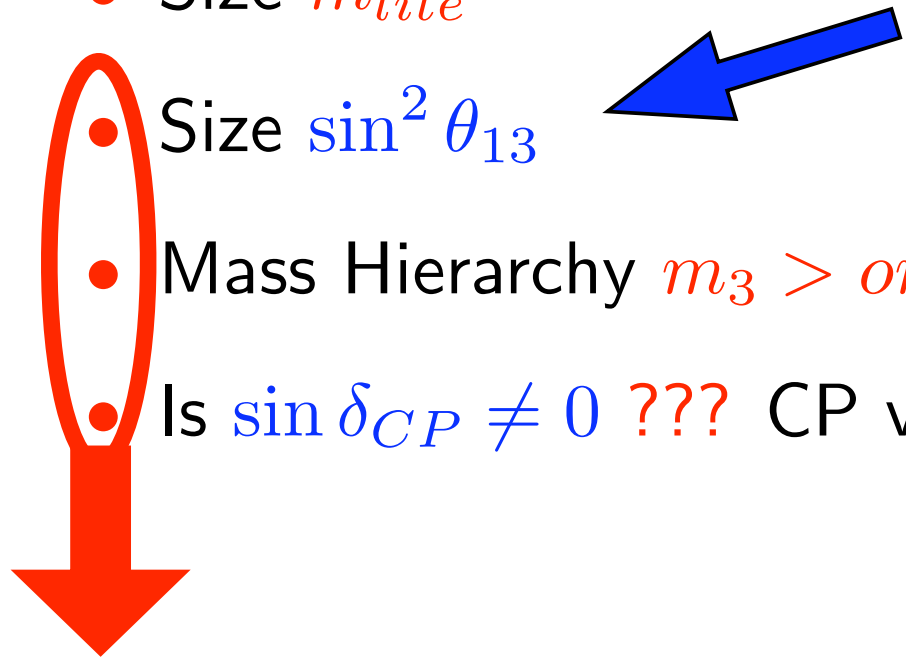
Next Time:

In Matter:

Masses and Mixings in MATTER: δm^2_N and θ^N

SUMMARY:

- Majorana or Dirac
- Size m_{lite}
- Size $\sin^2\theta_{13}$
- Mass Hierarchy $m_3 > or < m_1, m_2$
- Is $\sin\delta_{CP} \neq 0$??? CP violation !!!



Reactor $(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

Long Baseline $(\nu_\mu \rightarrow \nu_e)$