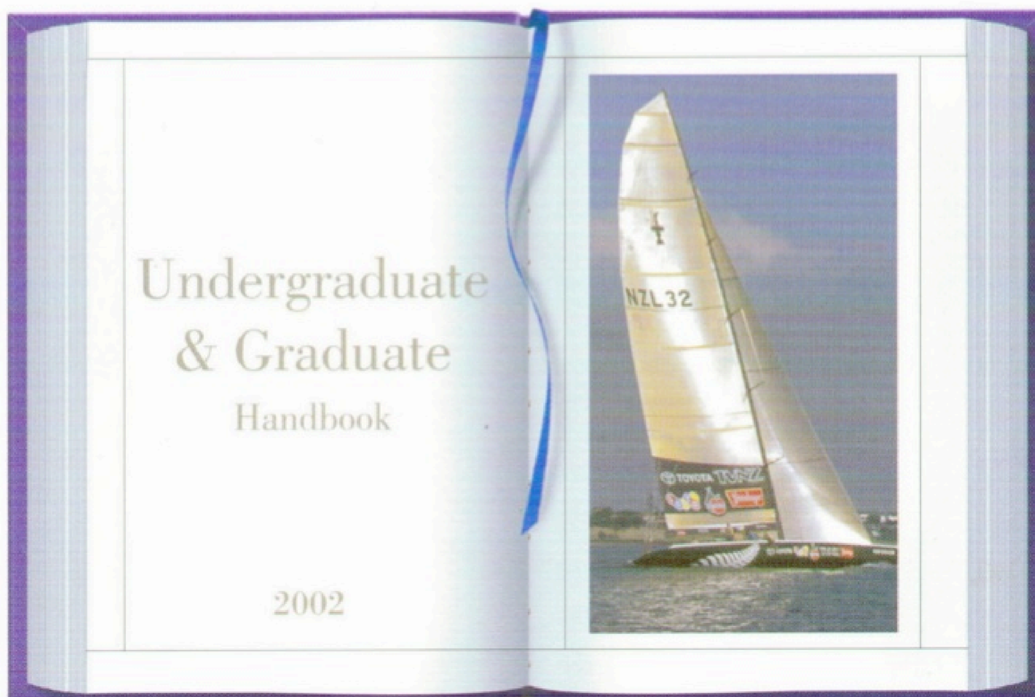
Physics



Handbook

YEAR 2002

SCIENCE

The University of Auckland | New Zealand

The Neutrino Oscillation Landscape

Stephen Parke, Fermilab

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

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

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

500km/GeV

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

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

15km/MeV

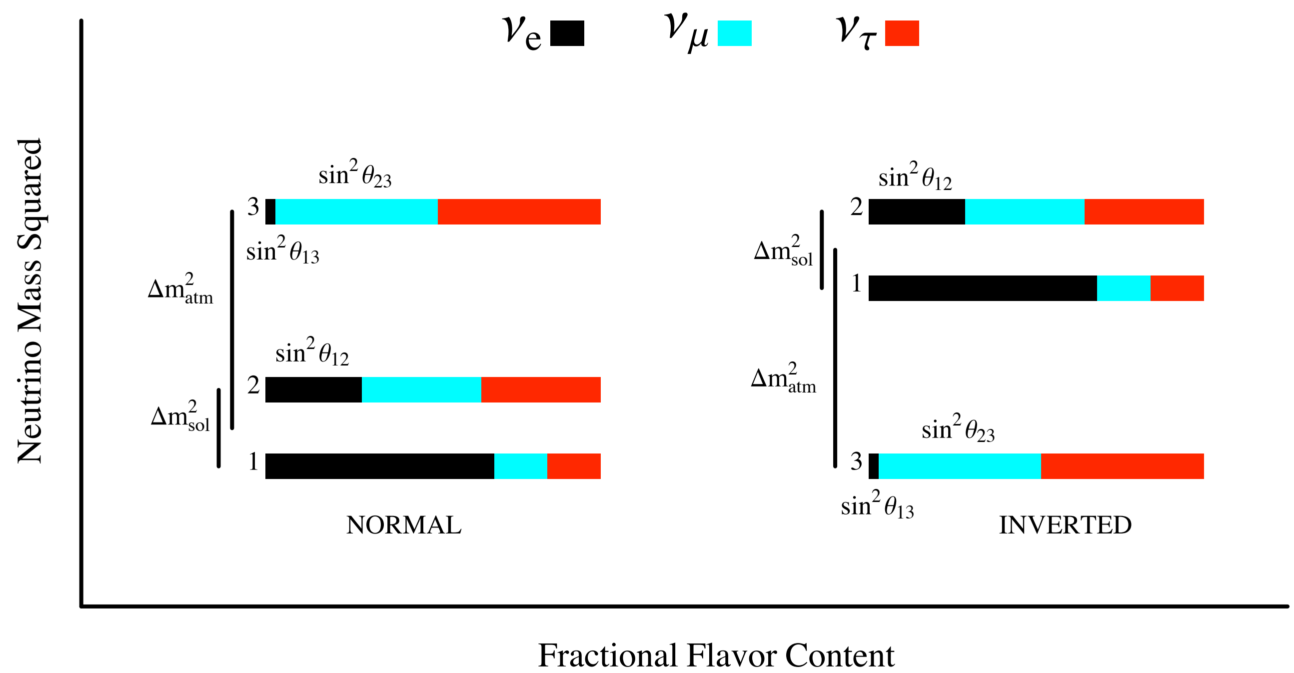
In oscillation phenomena:

the phases α, β are unobservable, $U^*_{\sigma,k} U_{\rho,k}$

and also the value of m_{lite} is irrelevant, δm^2.

Solar Sector: {12}

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



$\delta m^2_{21} = 8.0 \pm 0.4 \times 10^{-5}\ eV^2$ KamLAND + SNO, SK, Ga, Cl

$\sin^2\theta_{12} = 0.31 \pm 0.03$ SNO + SK, Ga, Cl, KamLAND

SNO's $\frac{CC}{NC} \approx \sin^2\theta_{12}$

(0.35)

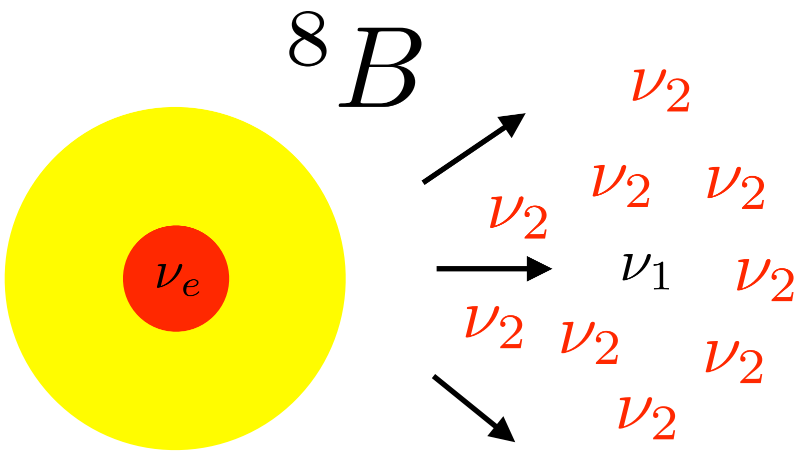
Kinematic phase: $\Delta \equiv \frac{\delta m_\odot^2 L}{4E} = 10^{7\pm1}$ for ^{8}B to pp

mass eigenstates are "Effectively Incoherent"

SNO's

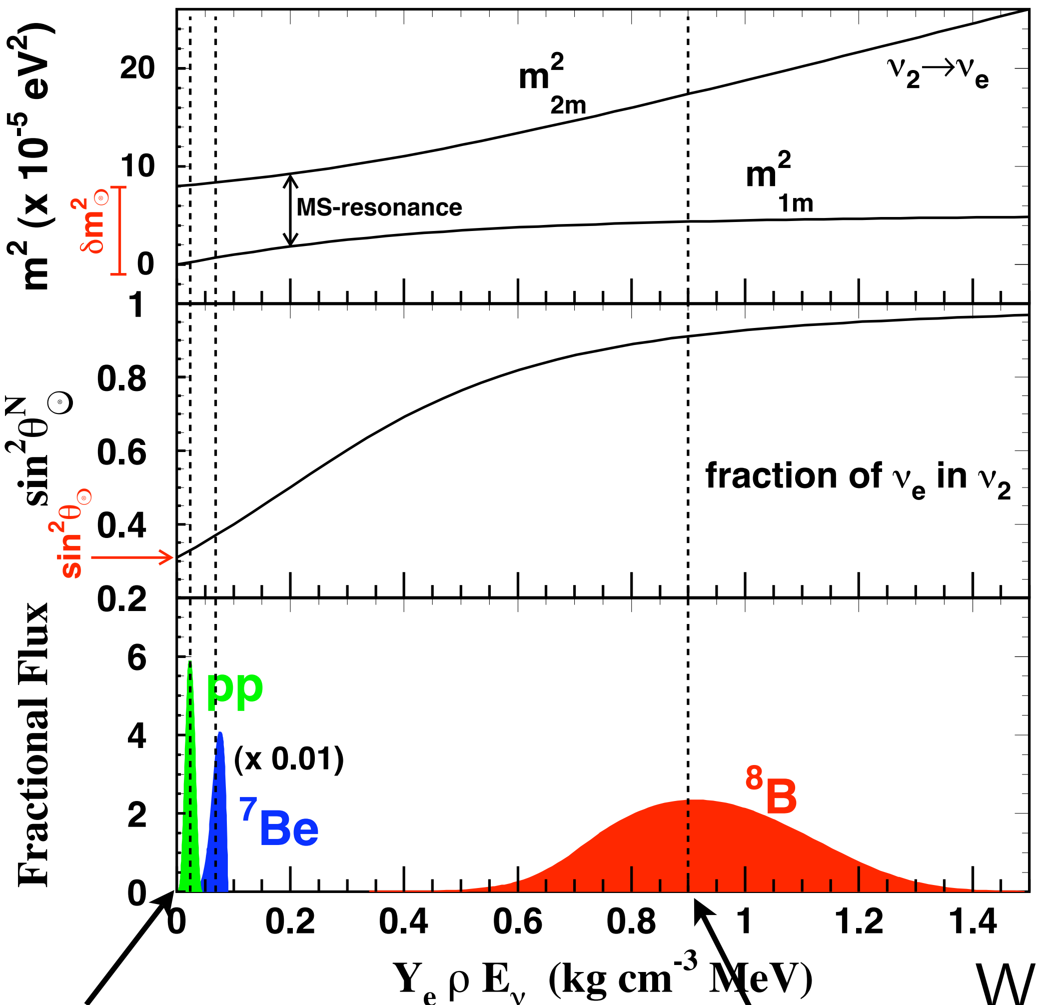
$$\frac{CC}{NC} = \langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$
$$= \sin^2\theta_\odot + f_1 \cos^2 2\theta_\odot$$

$$f_1 = \frac{\frac{CC}{NC} - \sin^2\theta_\odot}{\cos 2\theta_\odot}$$
$$= \frac{0.35 - 0.31}{0.4} \approx 10\%$$



^8B fraction of ν_2's is 90 % !!!

hep-ph/0601198



Weighted by detector sensitivity (x-section + threshold)

In Vacuum

Whereas for ^{8}B at center of Sun

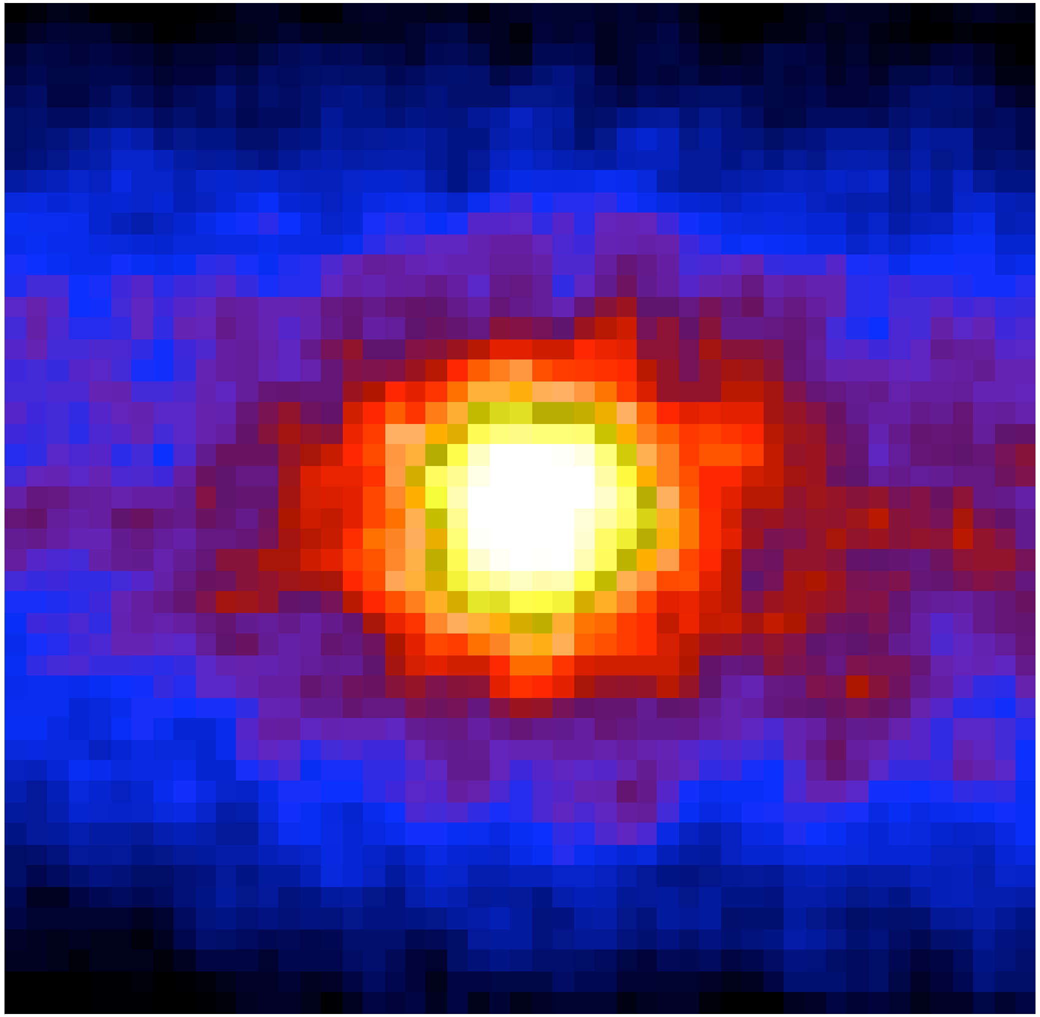
$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5}\ eV^2$$
$$\sin^2\theta_\odot = 0.31 \pm 0.03$$

$$\delta m^2_N = 14 \times 10^{-5}\ eV^2$$
$$\sin^2\theta^N_\odot = 0.91$$

{3-flavors: $f_3 = \sin^2\theta_{13}$: $f_2 = 0.91 \pm 0.02 - \sin^2\theta_{13}$: $f_1 = 0.09 \mp 0.02$ }

SuperK

Flavor Fraction 76% ν_e's



Mass E-state Fraction 84% ν_2's

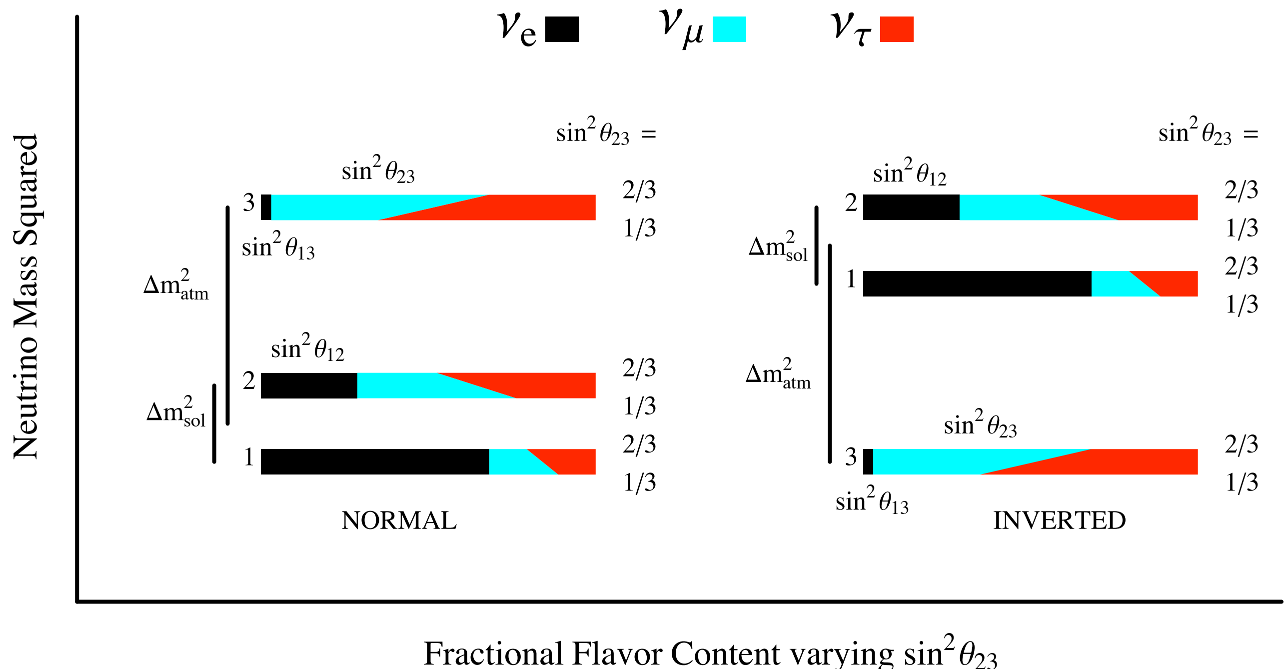
$$\nu_? + e \longrightarrow \nu + e$$

Which Neutrinos ?

Atmospheric Sector: $\{23\}$

O. Mena + SP
hep-ph/0312131

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



$\sin^2\theta_{23} = 0.50 \pm 0.14$ SuperK

$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2$ MINOS + SK, K2K

Hierarchy?

Which δm^2_{atm} ?

kinematic phase: $\Delta_{ij} \equiv \frac{\delta m_{ij}^2 L}{4E}$

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 2}|^2|U_{\mu 1}|^2 \sin^2 \Delta_{21} - 4|U_{\mu 3}|^2|U_{\mu 1}|^2 \sin^2 \Delta_{31} - 4|U_{\mu 3}|^2|U_{\mu 2}|^2 \sin^2 \Delta_{32}$$

Which δm_{atm}^2 ?

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \sin^2 \left(\frac{\delta m_{\mu\mu}^2 L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

No term linear in Δ_{21}

$$\delta m_{\mu\mu}^2 = \frac{|U_{\mu 1}|^2|\delta m_{31}^2| + |U_{\mu 2}|^2|\delta m_{32}^2|}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2}$$

$$\approx \sin^2 \theta_{12}|\delta m_{31}^2| + \cos^2 \theta_{12}|\delta m_{32}^2|$$

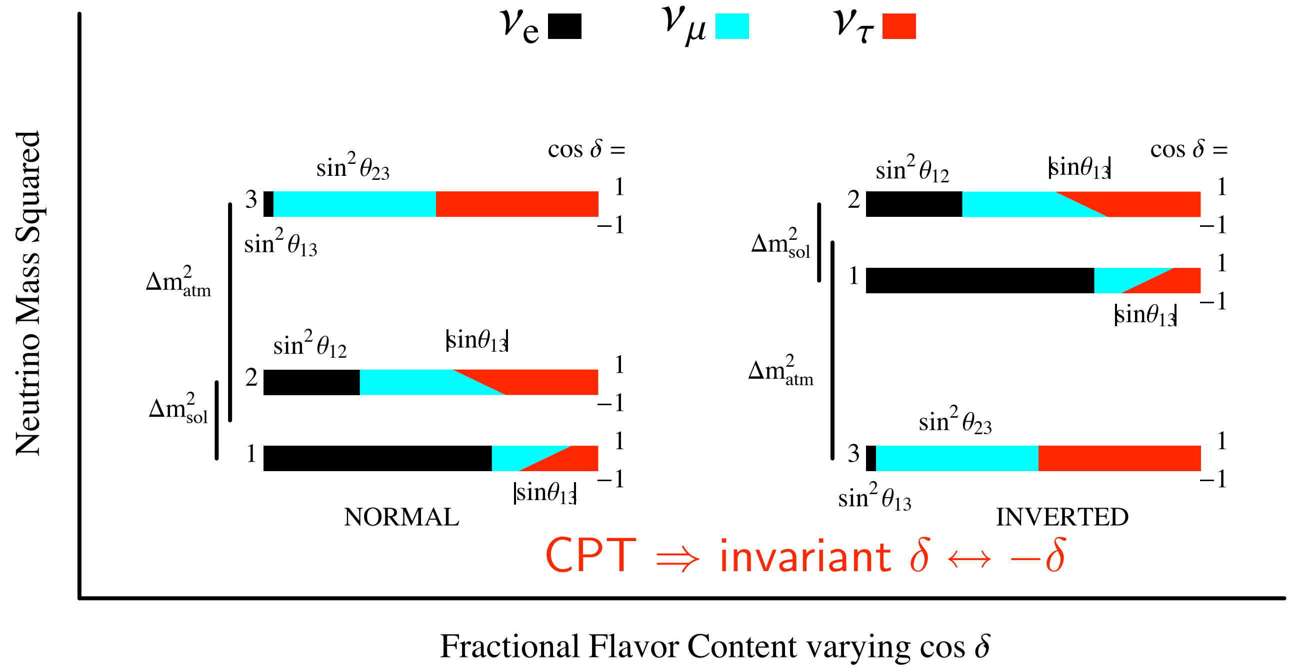
Physically

$$\delta m_{\mu\mu}^2 = \left| m_3^2 - \frac{|U_{\mu 1}|^2 m_1^2 + |U_{\mu 2}|^2 m_2^2}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2} \right|$$

ν_μ weighted average of m_1^2 and m_2^2

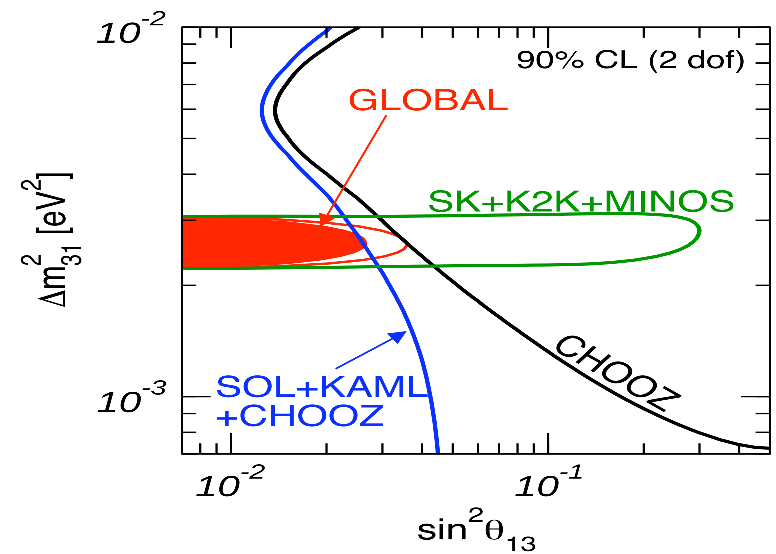
Reactor/Accelerator Sector: {13}

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



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

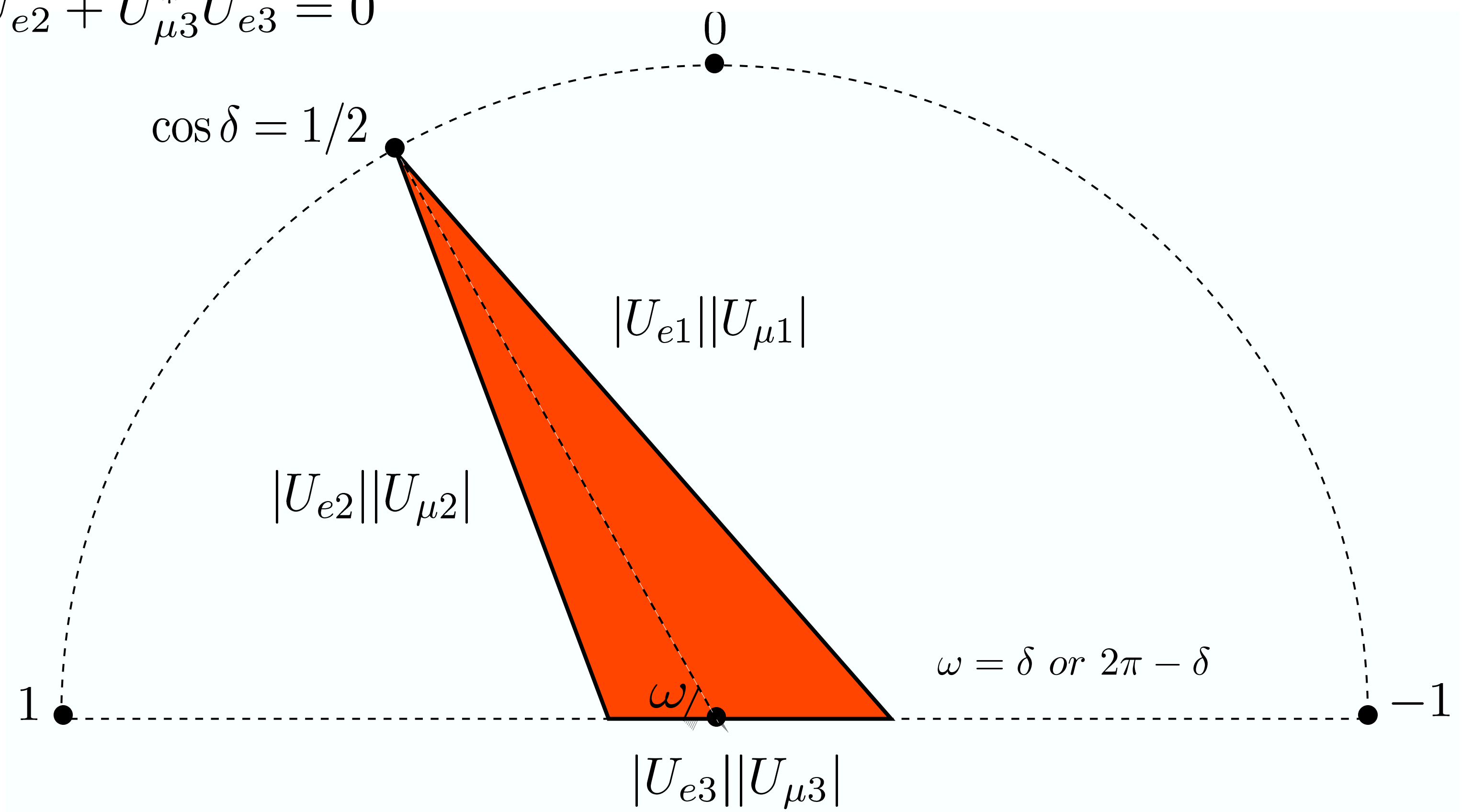
$$0 \le \delta < 2\pi$$



Maltoni etal
hep-ph/0405172v5

Unitarity Triangle:

$U_{\mu 1}^* U_{e1} + U_{\mu 2}^* U_{e2} + U_{\mu 3}^* U_{e3} = 0$



$$|J| = 2 \times Area$$

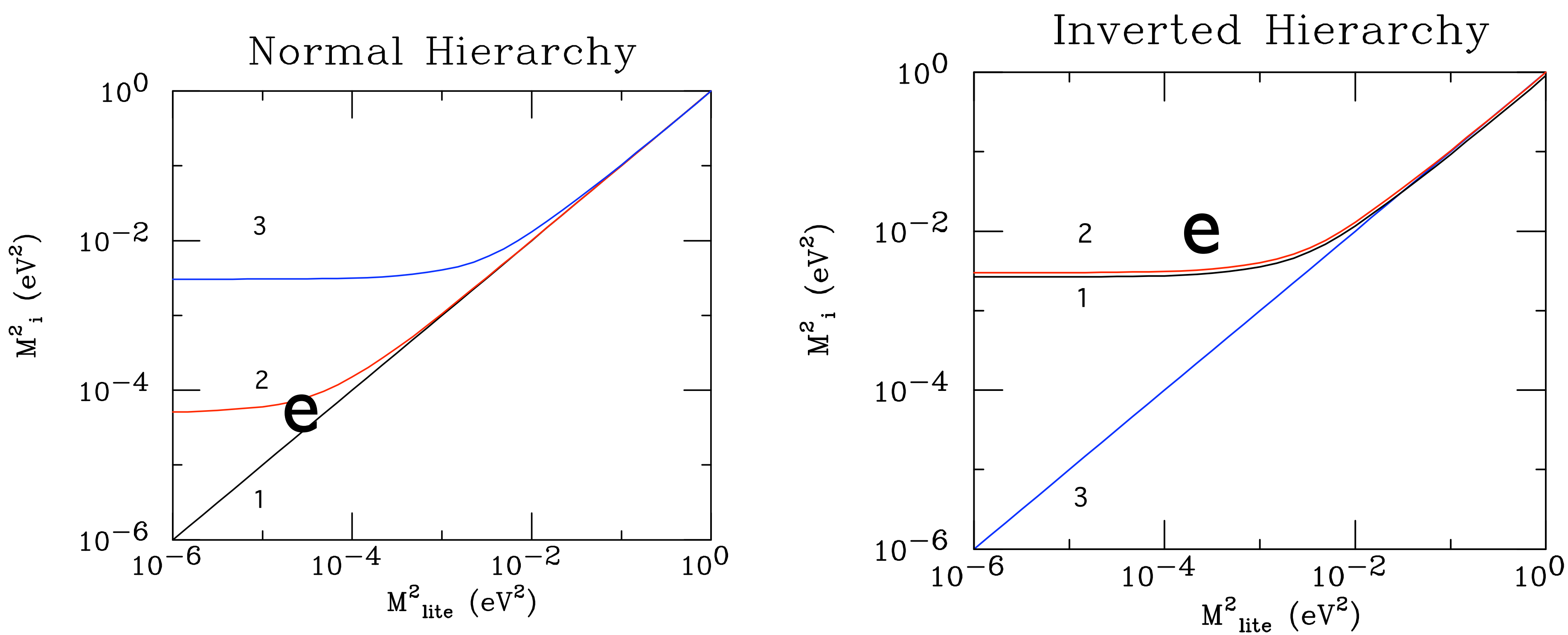
$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin\delta$$

Sine/Signs

- $|U_{e3}|^2$: $\sin^2\theta_{13}$
- Hierarchy: $sign(\delta m^2_{31}\ or\ \delta m^2_{32})$
- CPV: $\sin\delta$
- Maximal Mixing: $\sin^2\theta_{23} = \frac{1}{2}$
- Quadrant of δ: $\cos\delta = \pm\sqrt{1-\sin^2\delta}$
- Unitarity: lite sterile ν's
- New Interactions and Surprises

- Majorana v Dirac
- Absolute mass scale: m$_{Heavy}$ and m$_{Lite}$
- New Interactions and Surprises

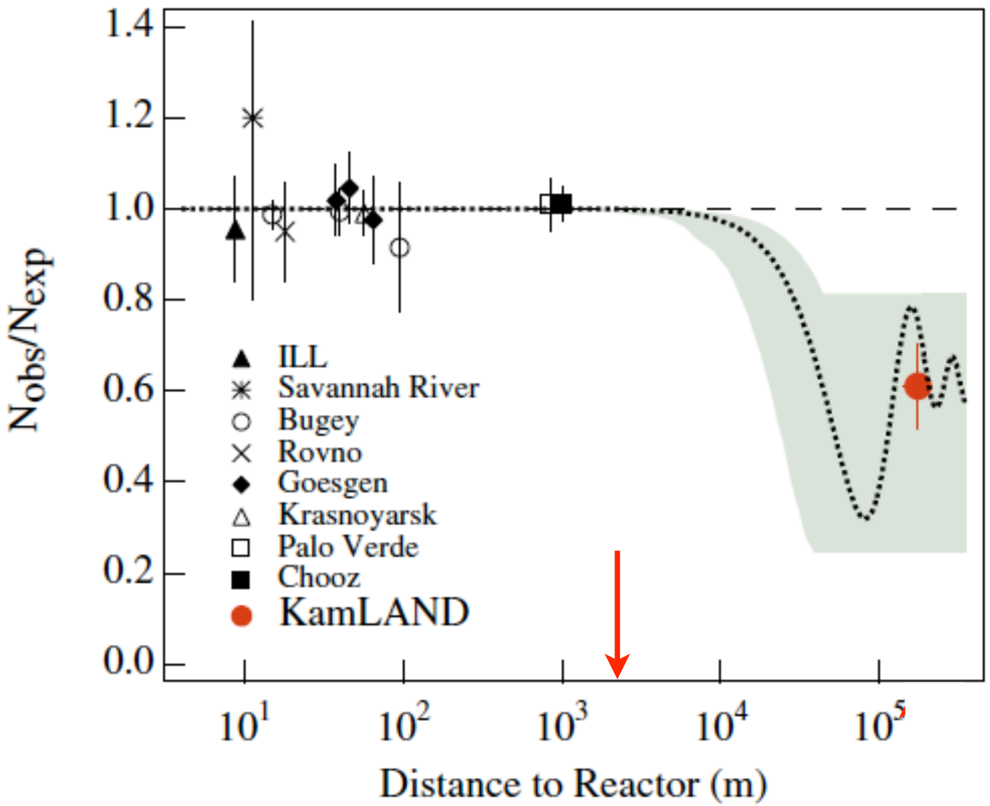
Masses:



States 1 and 2 are ν_e rich.

θ_{13} from Reactor Disappearance

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$



kinematic phase:

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

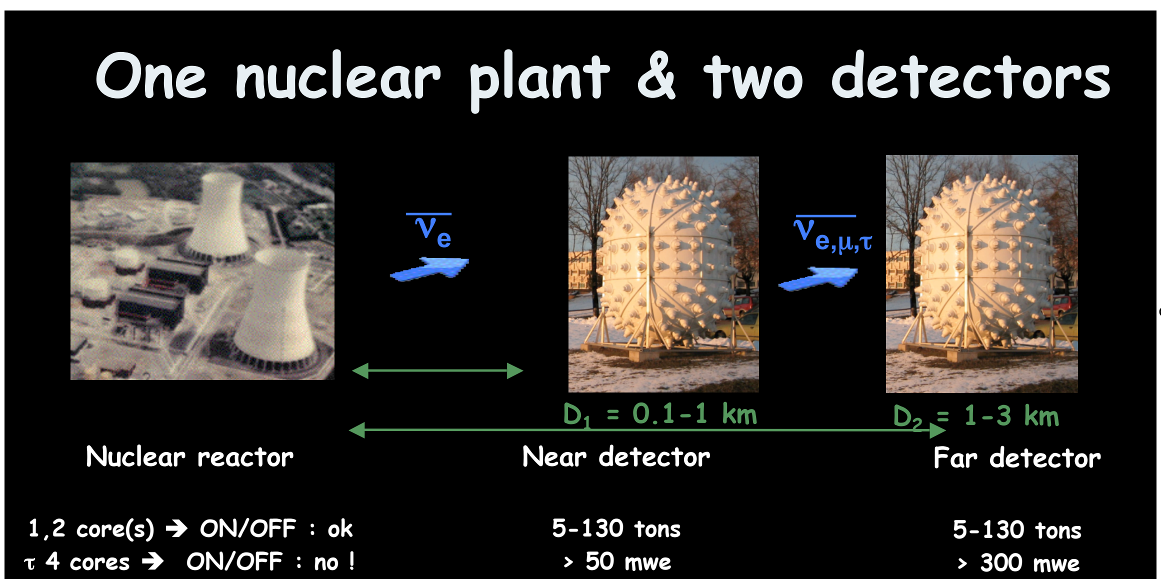
< 0.002

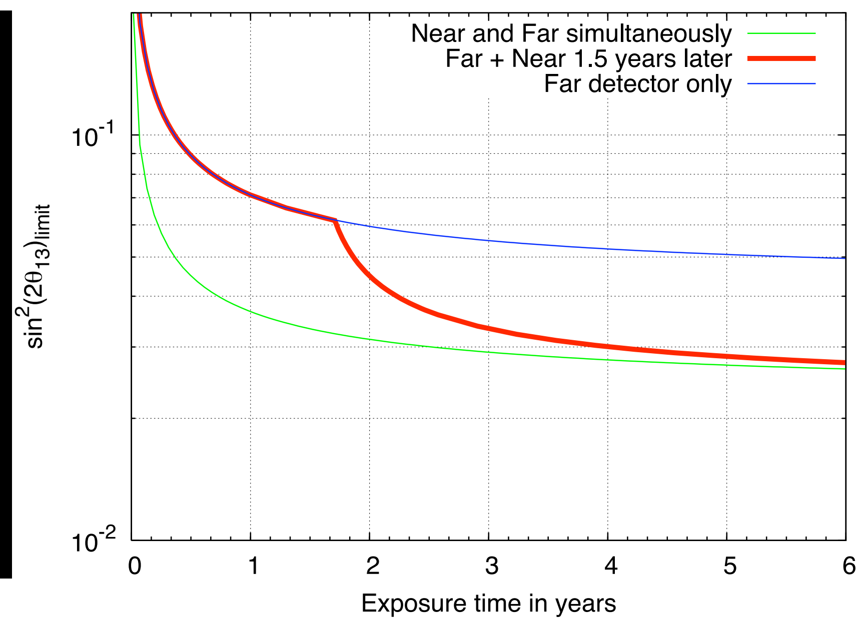
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

> 0.01

$$\delta m^2_{ee} = \cos^2\theta_{12}|\delta m^2_{31}| + \sin^2\theta_{12}|\delta m^2_{32}|$$

Double Chooz:





.03

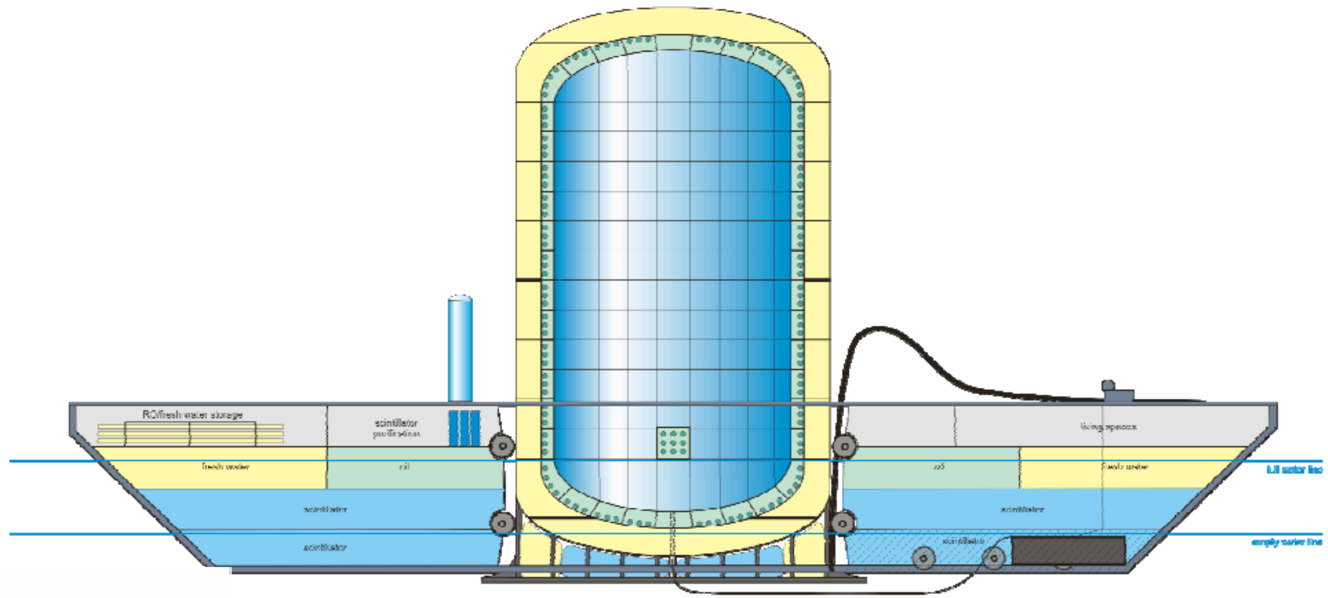
Figure 18: $\sin^2(2\theta_{13})$ sensitivity limit for the detectors installation scheduled scenario

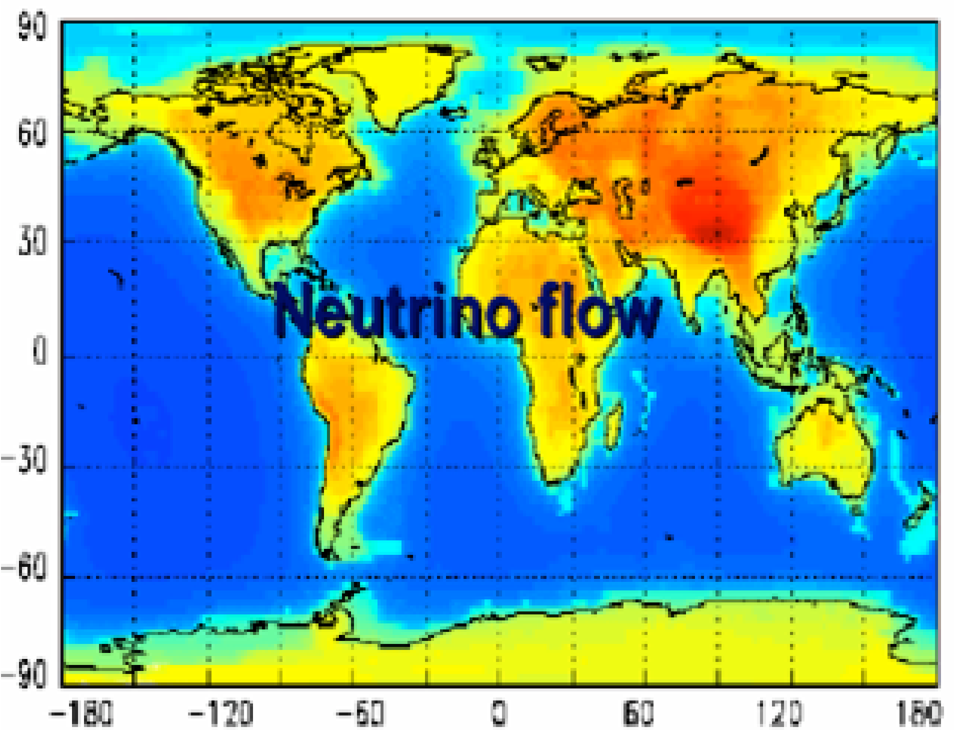
Daya Bay

push the limit on

$$\sin^2 2\theta_{13} < 0.01$$

HanoHano Hierarchy:





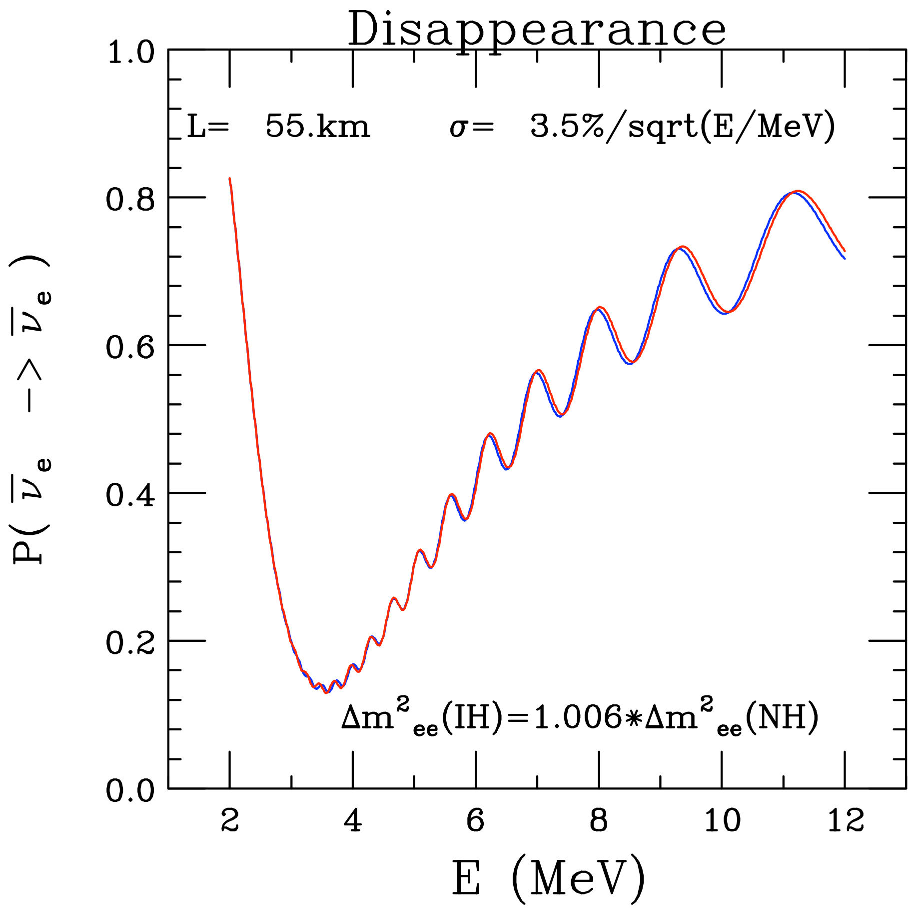
Fourier Analysis:
4 freq.

NH: $|\Delta m^2_{31}| > |\Delta m^2_{32}|$

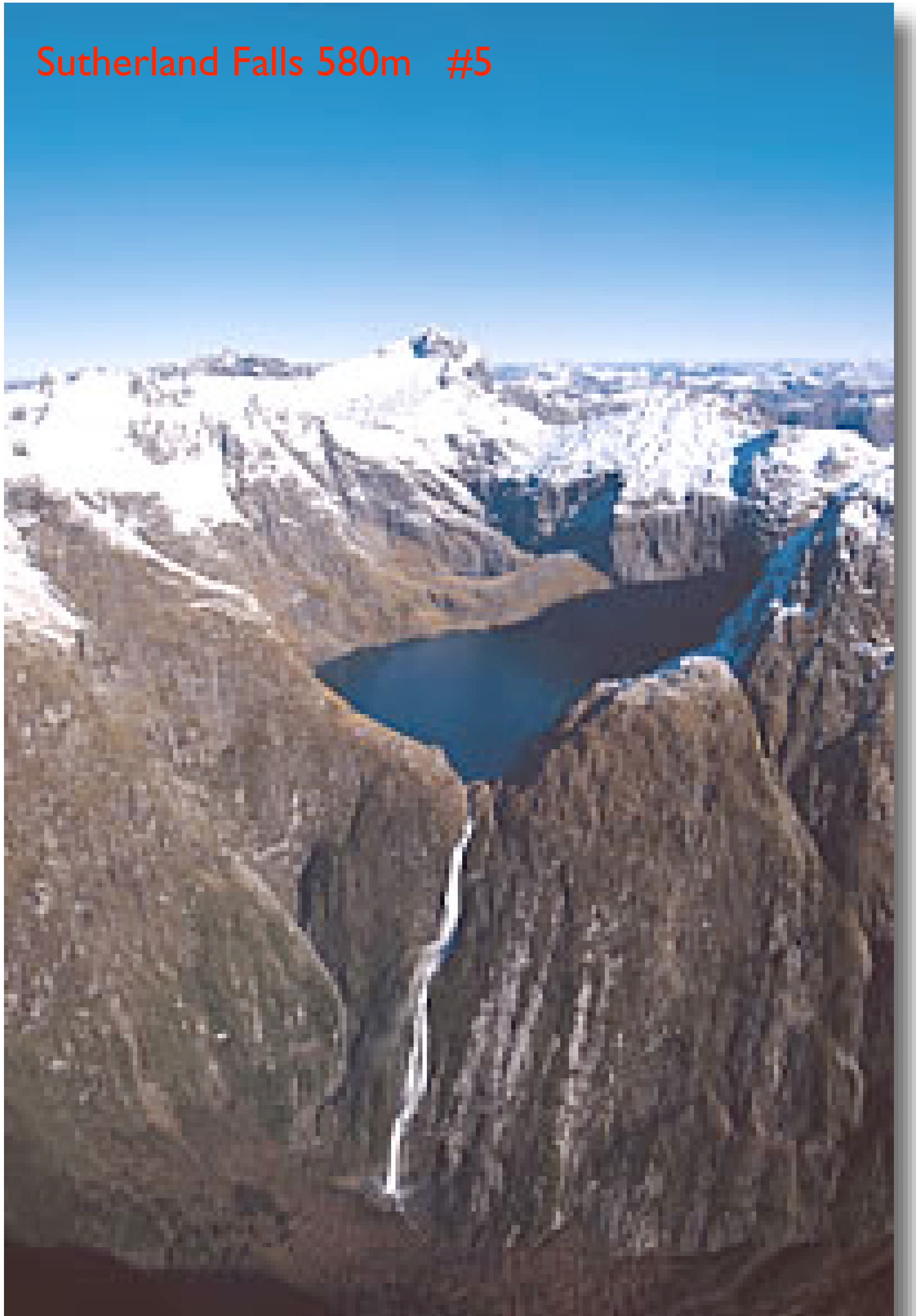
IH: $|\Delta m^2_{31}| < |\Delta m^2_{32}|$

Power: $\cos^4\theta_{12} \; : \; \sin^4\theta_{12}$

Neutrinos from 2-8 MeV:



% diff < 2% !!!



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

and related processes:

CP

$$\nu_\mu \longrightarrow \nu_e \qquad \Longleftrightarrow \qquad \bar{\nu}_\mu \longrightarrow \bar{\nu}_e$$

T $\Updownarrow$ CPT across diagonals $\Updownarrow$ T

$$\nu_e \longrightarrow \nu_\mu \qquad \Longleftrightarrow \qquad \bar{\nu}_e \longrightarrow \bar{\nu}_\mu$$

CP

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

Even in matter, a vestige of CPT exists:
Instead of switch matter to anti-matter, switch neutrino hierarchy !!!

$\nu_\mu \longrightarrow \nu_e$

$$| \; U^*_{\mu 3} e^{-im_3^2 L/2E} U_{e3} + U^*_{\mu 2} e^{-im_2^2 L/2E} U_{e2} + U^*_{\mu 1} e^{-im_1^2 L/2E} U_{e1} \; |^2$$

use unitarity to eliminate $U^*_{\mu 1} U_{e1}$ term:

$$P(\nu_\mu \rightarrow \nu_e) \;\; = \;\; |2U^*_{\mu 3} U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin \Delta_{21}|^2$$

Atmospheric δm^2 Solar δm^2

$$2U^*_{\mu 3} U_{e3} = \sin \theta_{23} \sin 2\theta_{13} e^{-i\delta}$$

$$2U^*_{\mu 2} U_{e2} \approx \cos \theta_{23} \sin 2\theta_{12}$$

Vacuum LBL:

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

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

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

CP violation !!!

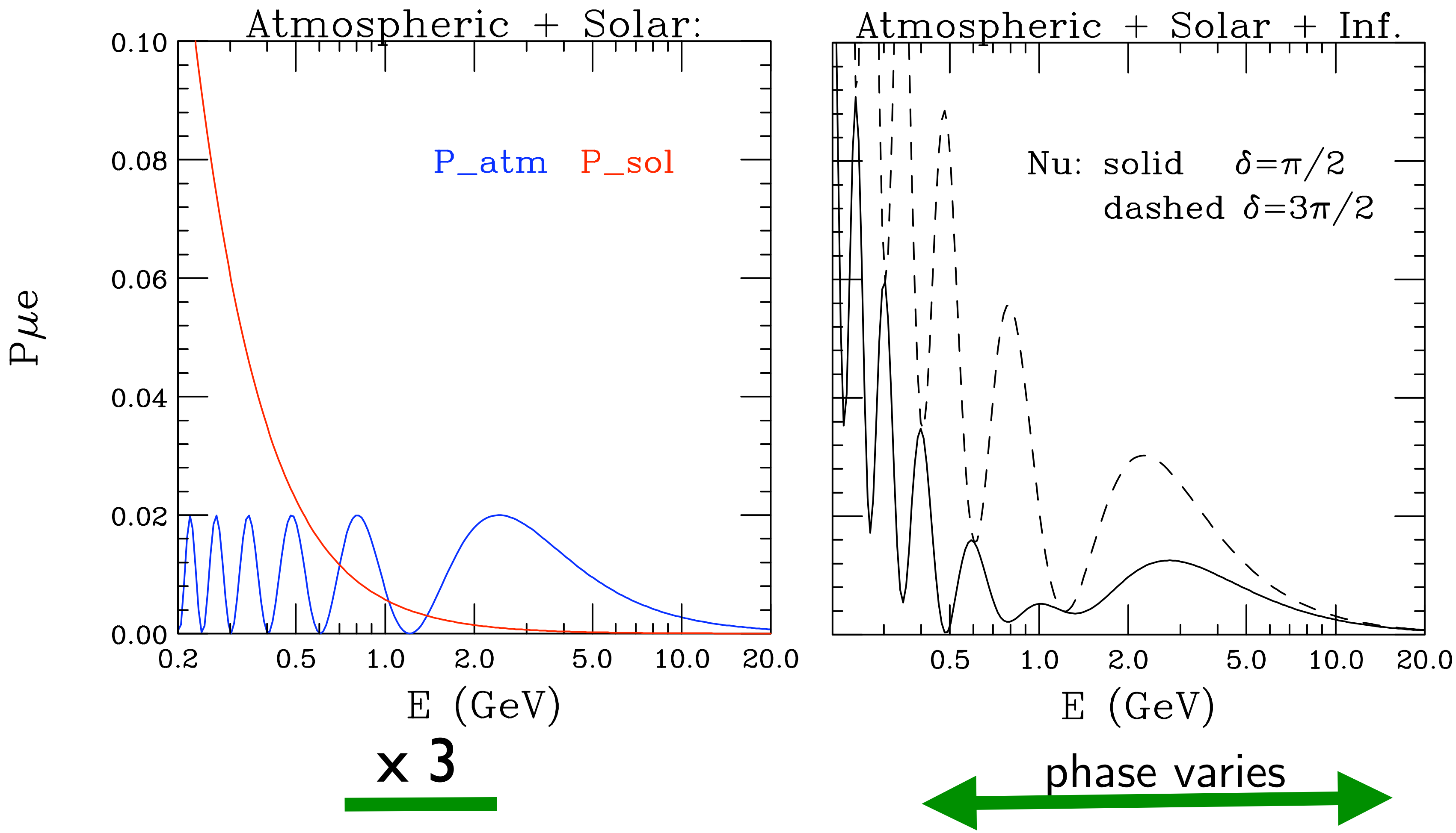
where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \sin\Delta_{31}$

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

$$P \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32}\pm\delta) + P_{sol}$$

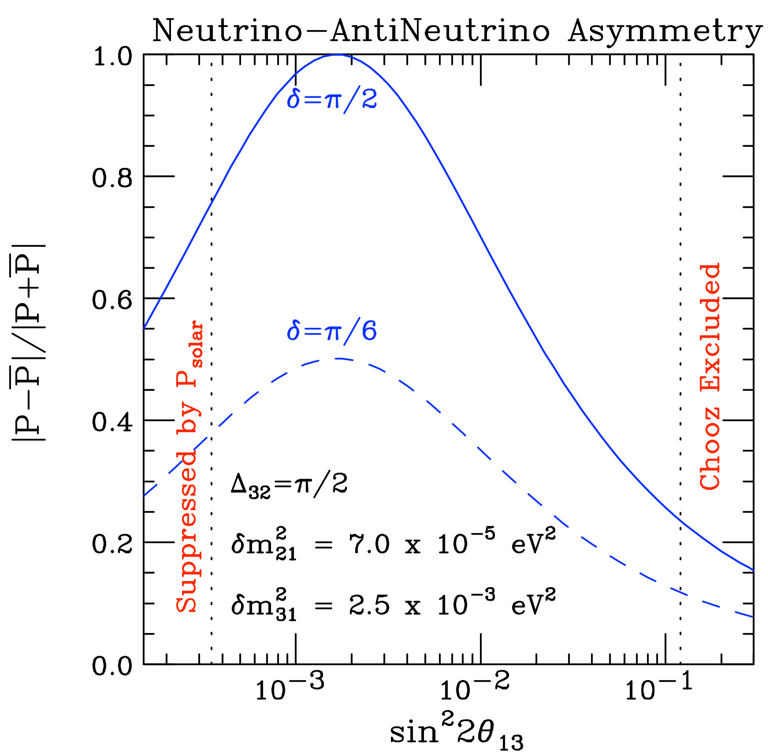
$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}|^2$$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$



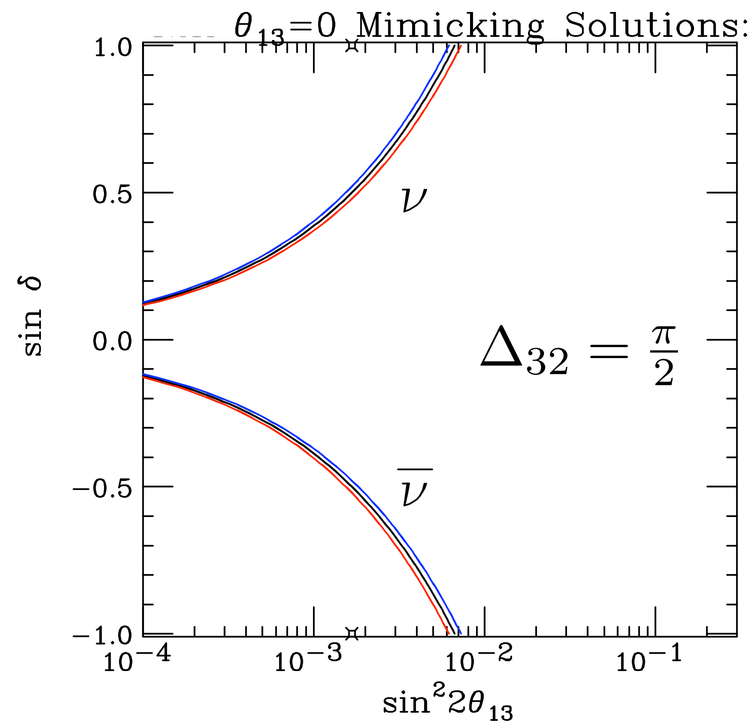
$$P_{\mu\to e} \approx |\ \sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

Asymmetry Peaks:



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

Zero Mimicking Solutions:



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

$$P = P_{sol}$$

Two Flavors: Vacuum and Uniform Matter

Vacuum: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta_0 \sin^2 \Delta_0$

Matter: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta_N \sin^2 \Delta_N$

BUT $\delta m_0^2 \sin 2\theta_0 = \delta m_N^2 \sin 2\theta_N \quad \Rightarrow \quad \sin^2 2\theta_N = \left(\frac{\delta m_0^2}{\delta m_N^2}\right)^2 \sin^2 2\theta_0$

Therefore: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta_0 \left(\frac{\sin^2 \Delta_N}{\Delta_N^2}\right) \Delta_0^2$

$$\begin{aligned}\delta m_N^2 &= \sqrt{(\delta m_0^2 \cos 2\theta_0 - 2\sqrt{2} G_F N_e E)^2 + (\delta m_0^2 \sin 2\theta_0)^2} \\ &\approx \delta m_0^2 - 2\sqrt{2} G_F N_e E \qquad \text{for small } \theta_0.\end{aligned}$$

$\Delta_N = \Delta - aL$ where $a = G_F N_e/\sqrt{2}$

Therefore in Matter: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta_0 \left(\frac{\sin \Delta_0 \mp aL}{\Delta_0 \mp aL}\right)^2 \Delta_0^2$

$\nu_\mu \to \nu_e$ with MATTER

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

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

in vac $\sin\Delta_{31}$

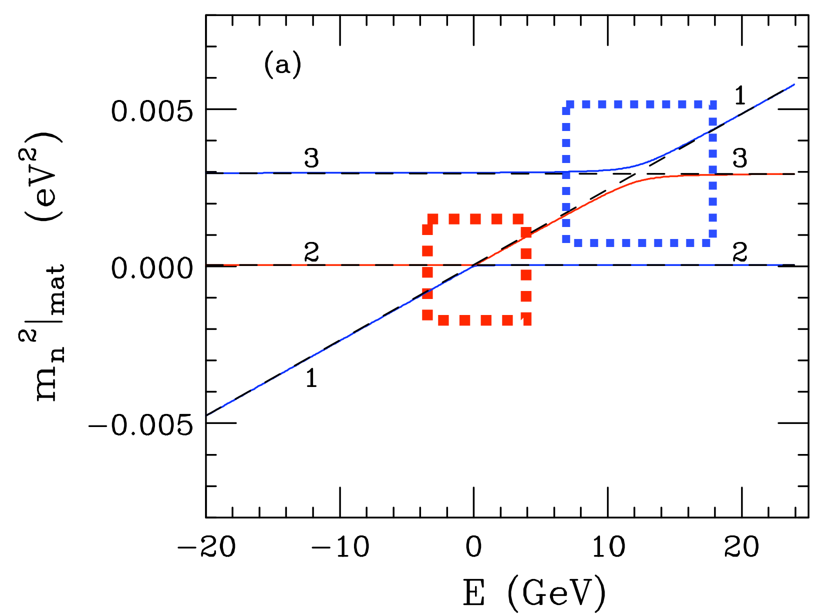
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\, \frac{\sin(aL)}{(aL)}\, \Delta_{21}$

in vac $\sin\Delta_{21}$

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

$$\pm = sign(\delta m^2_{31}) \qquad \Delta_{ij} = |\delta m^2_{ij}| L/4E$$

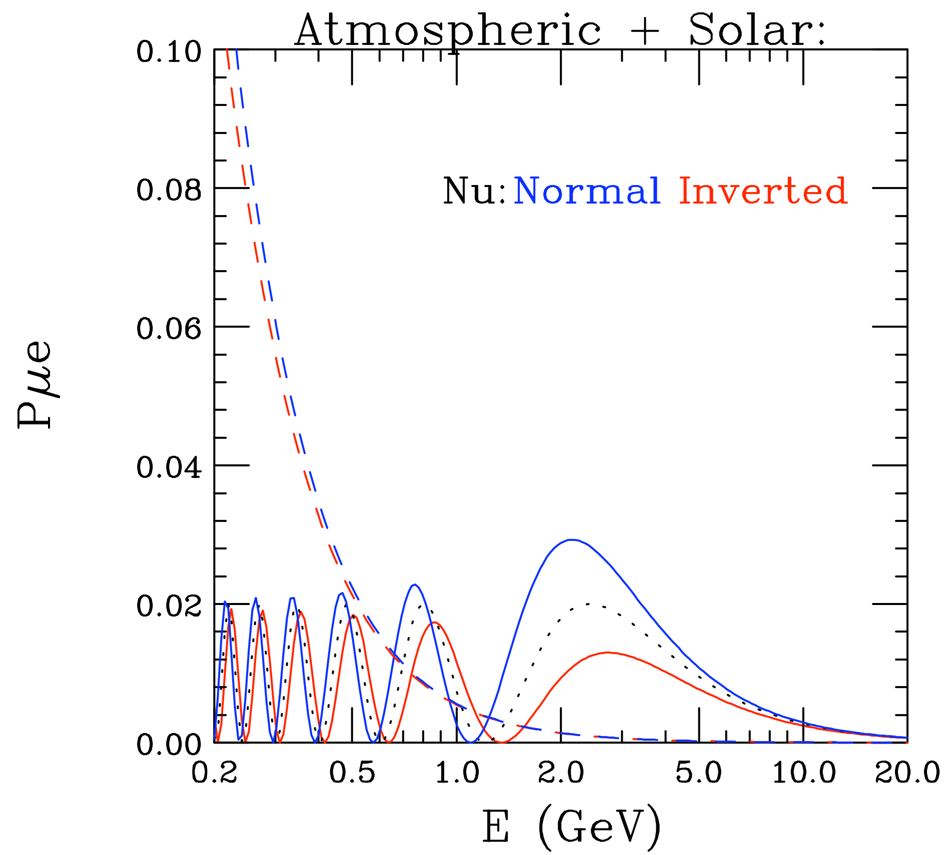
$\{\delta m^2 \sin 2\theta\}$ is invariant

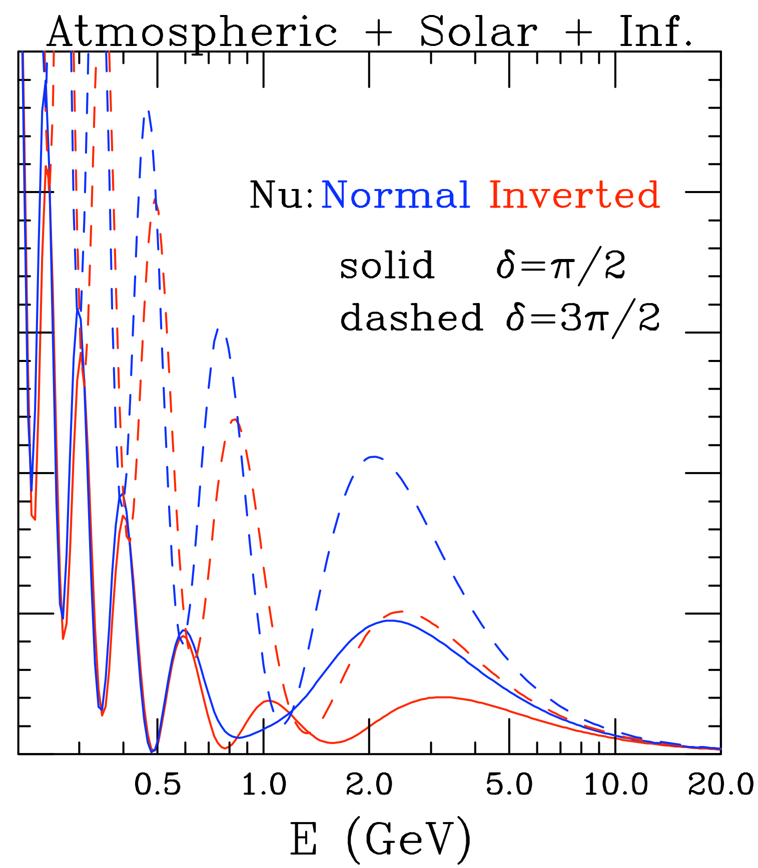


In Matter:

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

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

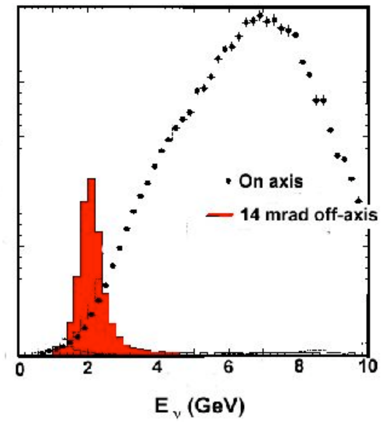




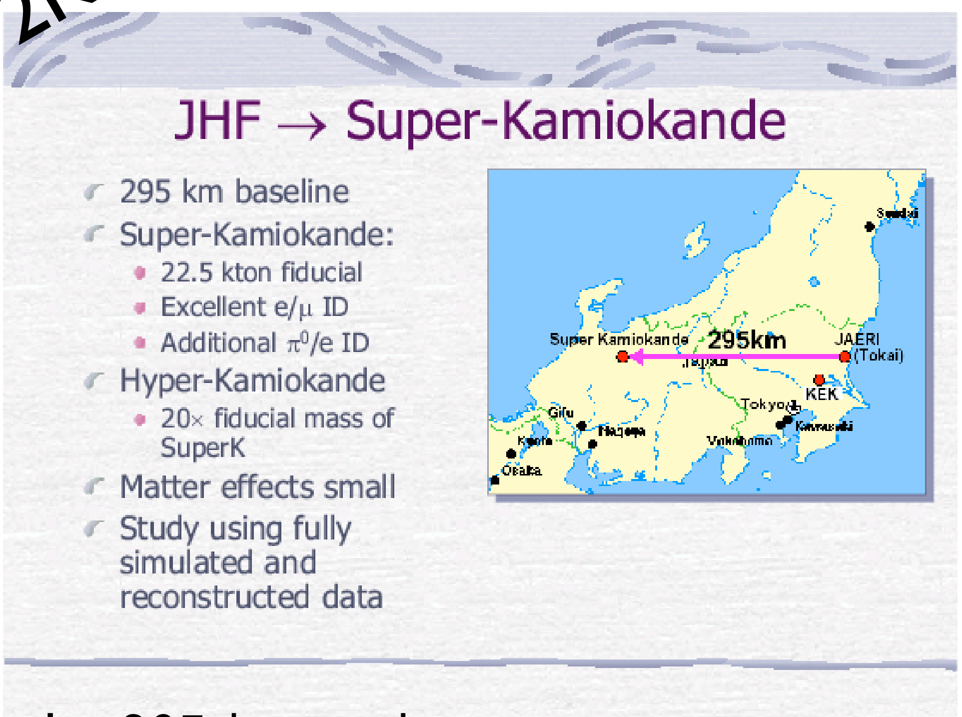
Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$

Off-Axis Beams

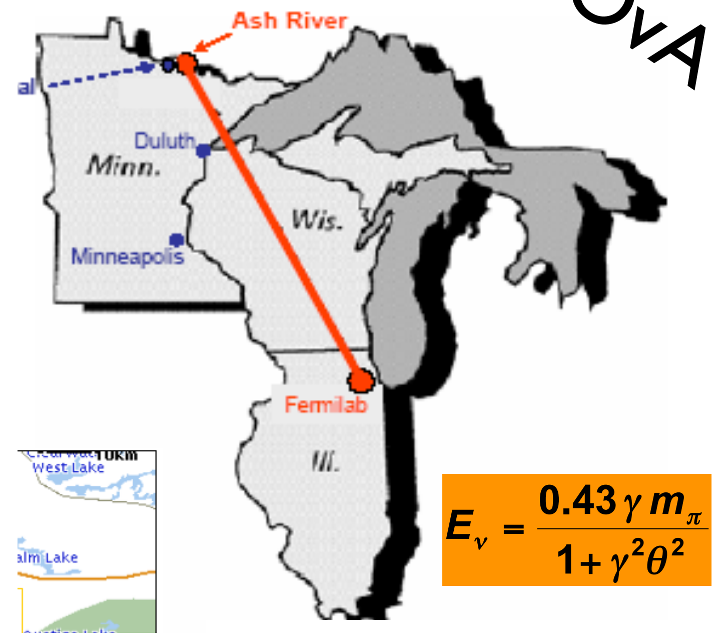
BNL 1994



T2K



NOvA



L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{\frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2}\right\}$$

0.75 upgrade to 4 MW

L=700 - 1000 km and

Energy near 2 GeV

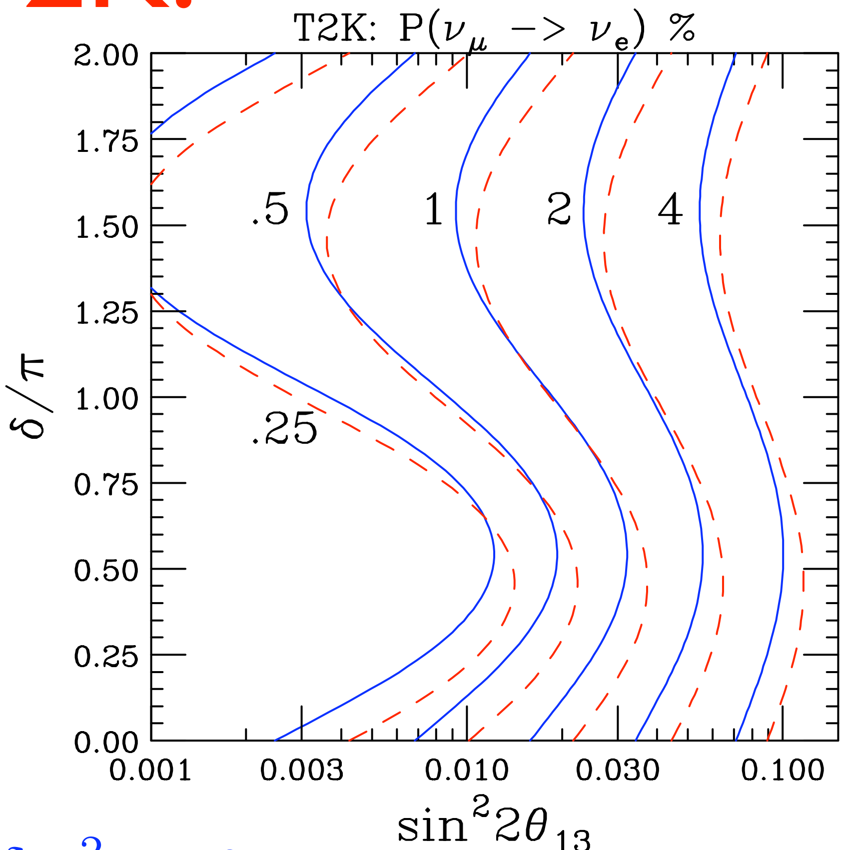
$$E_{vom} = 1.8\ GeV \left\{\frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2}\right\} \times \left\{\frac{L}{820\ km}\right\}$$

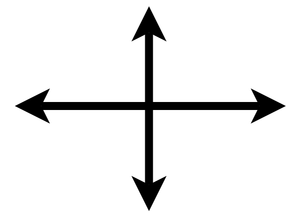
0.4 upgrade to 2 MW

Sensitivity to $\sin^2 2\theta_{13}$

T2K:

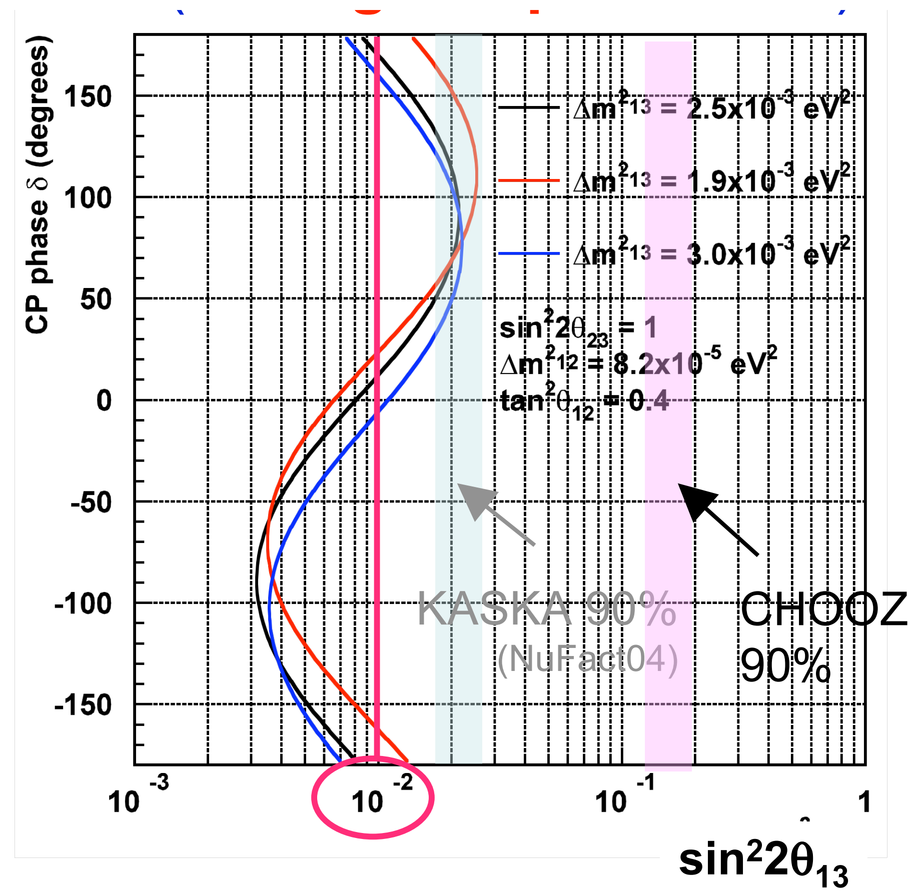
VOM: $\Delta_{31} \neq \pi/2$





Matter Effect:

Aihara for T2K, P5 talk



$\delta m^2_{31} > 0$

$\delta m^2_{31} < 0$

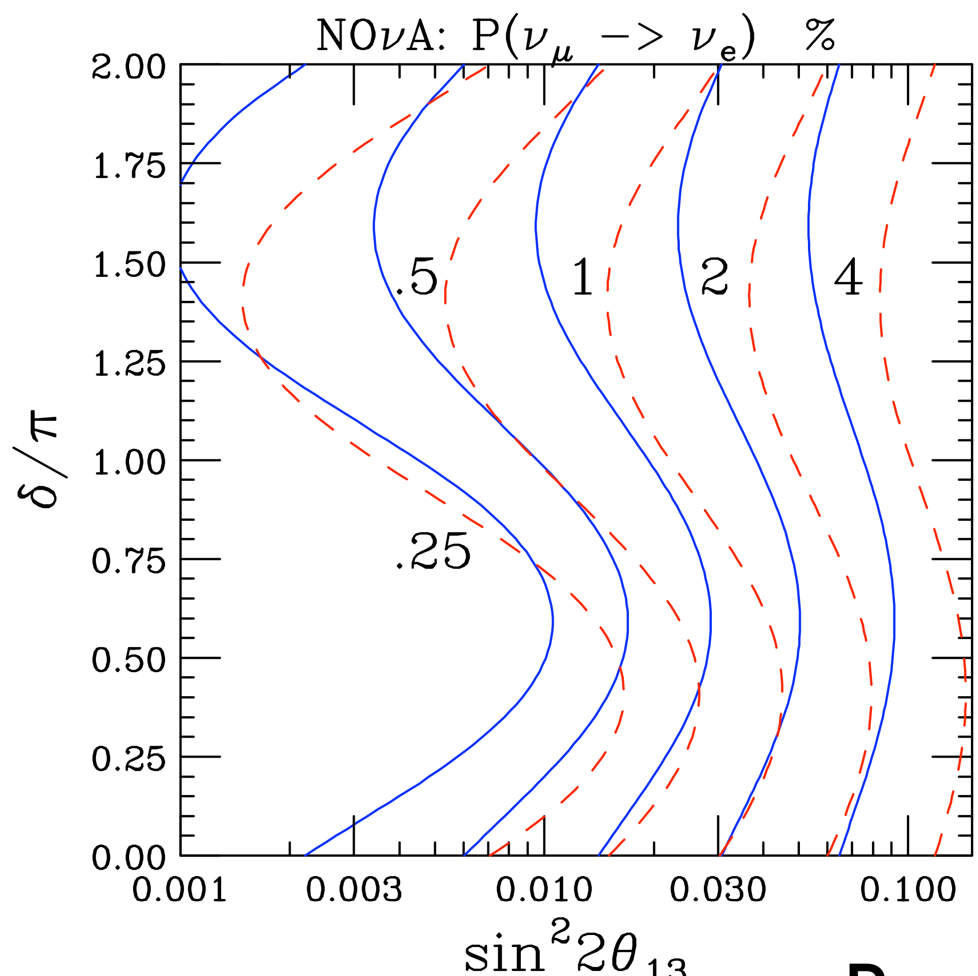
Beam 1%

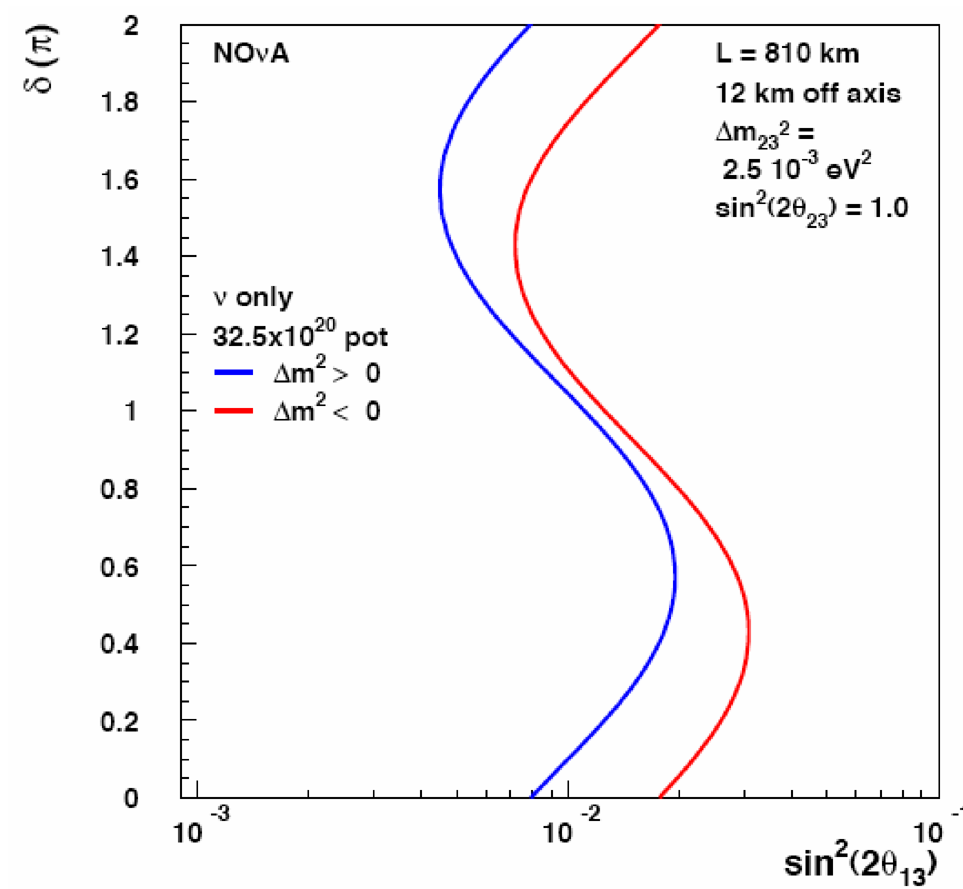
Phase I

Sensitivity approx 0.5%

NOvA:

NOvA @ NO-VE 2007





Beam 1%

$\delta m^2_{31} > 0$

$\delta m^2_{31} < 0$

Phase I

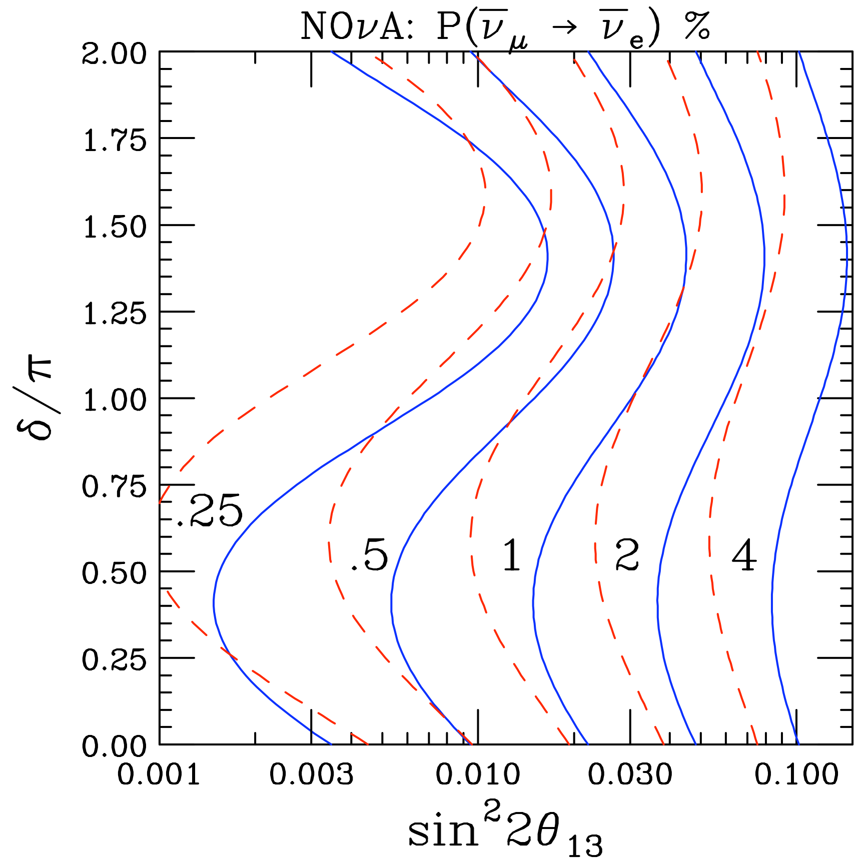
Sensitivity approx 0.5%

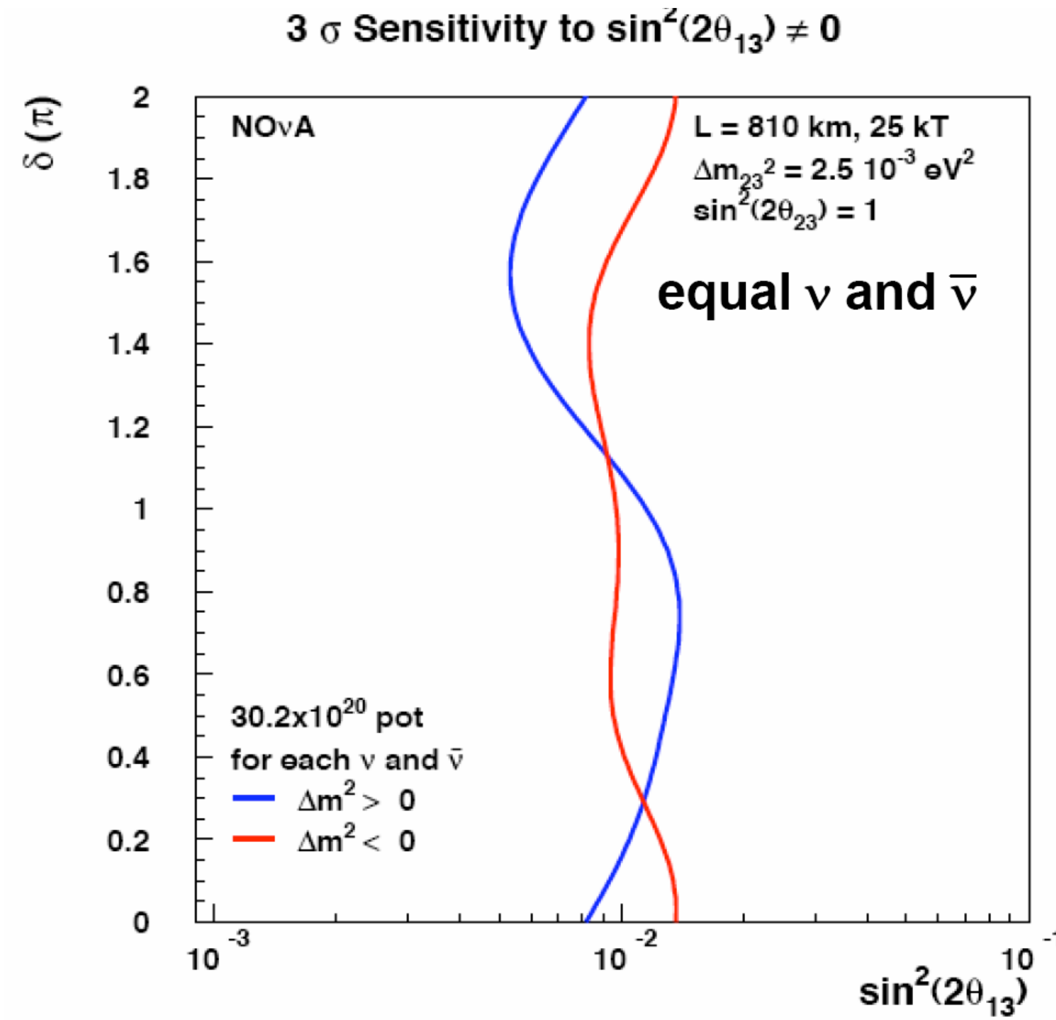
5 years with ν only run

NOvA:

$\delta m^2_{31} > 0$

$\delta m^2_{31} < 0$

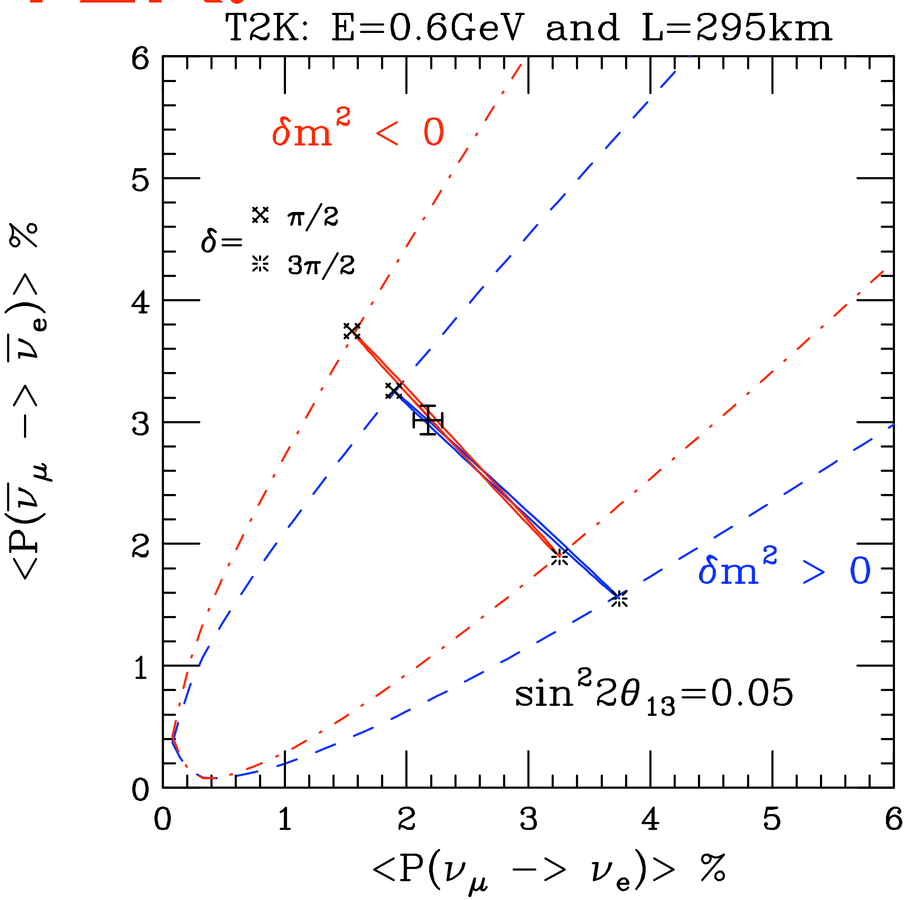




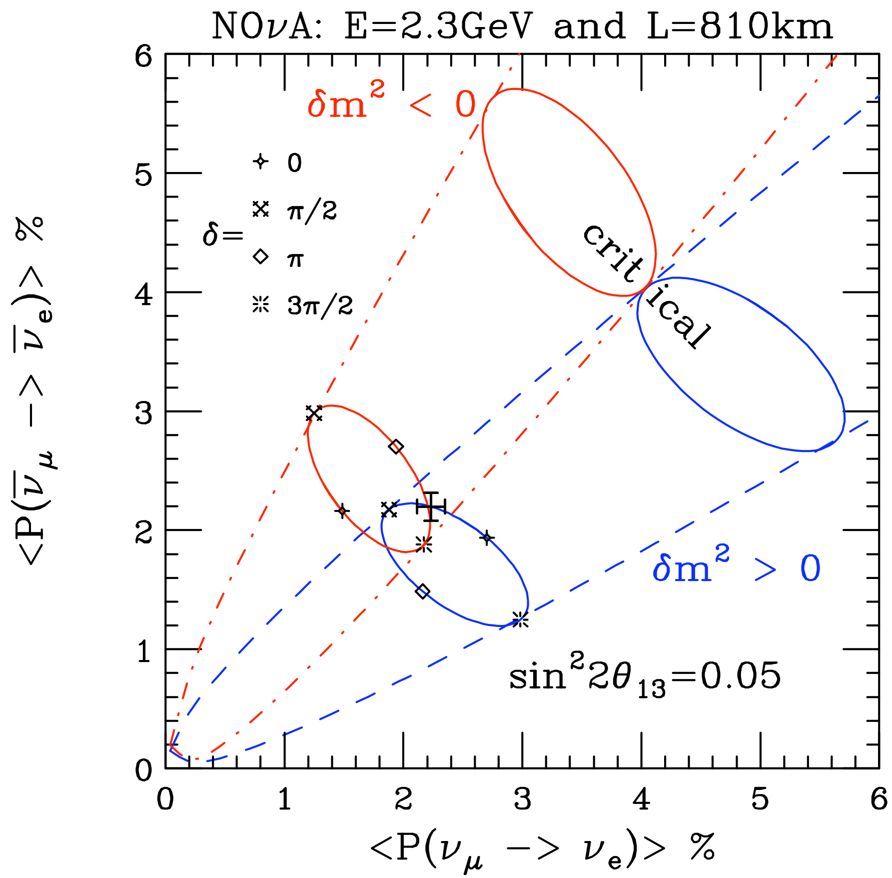
Beam >1%

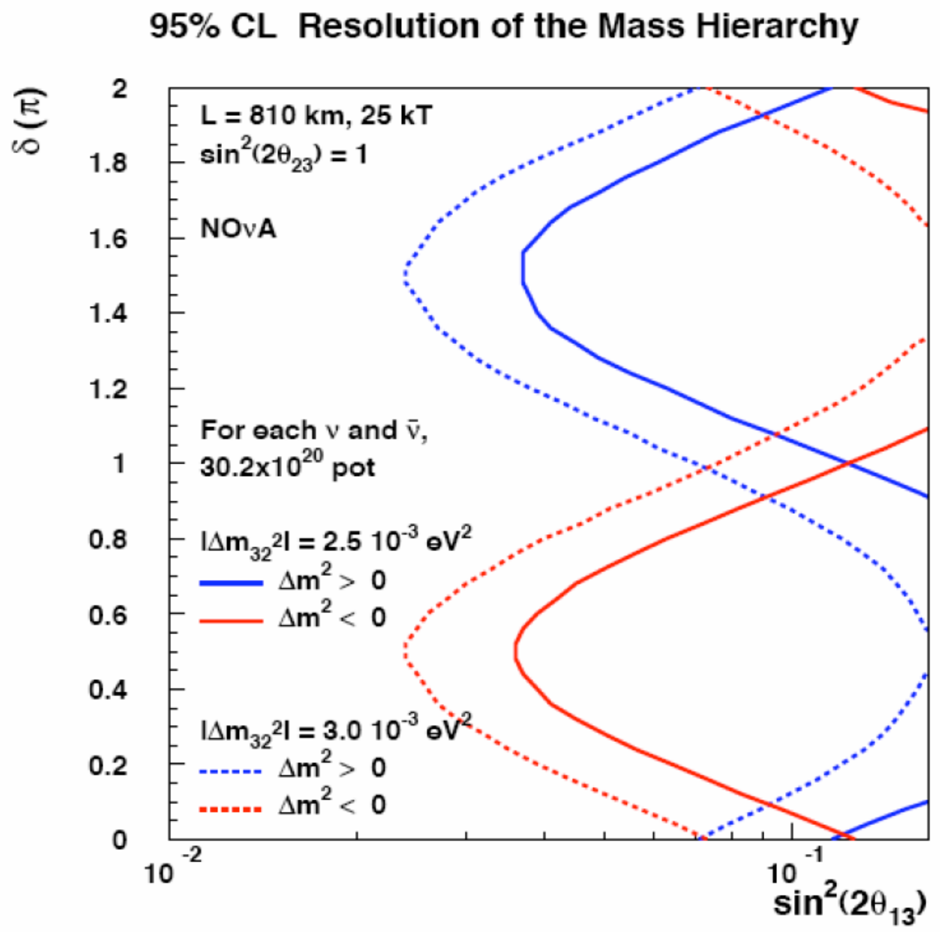
Sensitivity to Hierarchy: $sign\ \delta m^2_{31}$

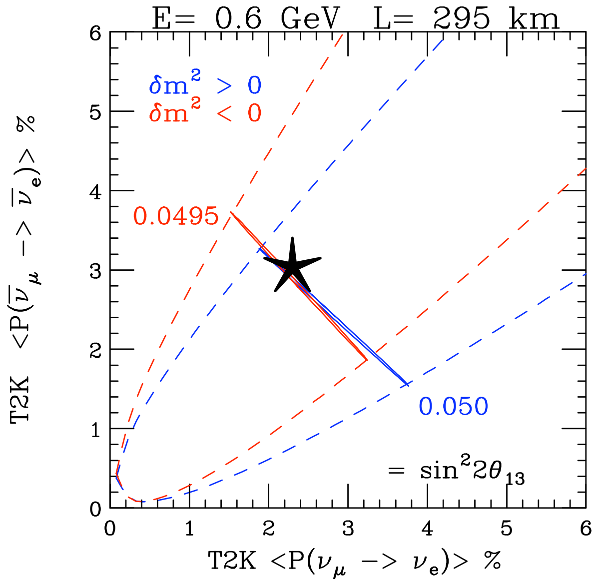
T2K:

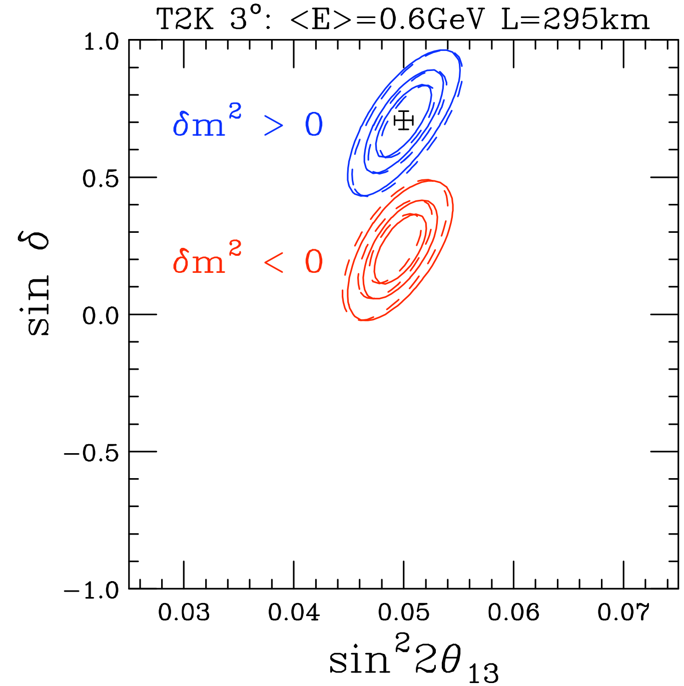

T2K: E=0.6GeV and L=295km
$\delta m^2 < 0$
$\delta m^2 > 0$
$\delta=$ $\pi/2$ $3\pi/2$
$\sin^2 2\theta_{13}=0.05$
$<P(\nu_\mu \to \nu_e)>$ %
$<P(\bar\nu_\mu \to \bar\nu_e)>$ %

NOvA:

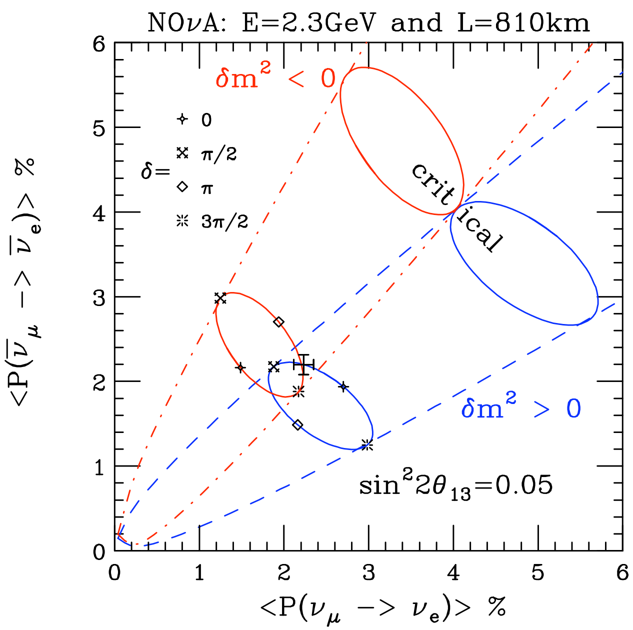

NOνA: E=2.3GeV and L=810km
$\delta m^2 < 0$
$\delta m^2 > 0$
$\delta=$ 0 $\pi/2$ π $3\pi/2$
critical
$\sin^2 2\theta_{13}=0.05$
$<P(\nu_\mu \to \nu_e)>$ %
$<P(\bar\nu_\mu \to \bar\nu_e)>$ %

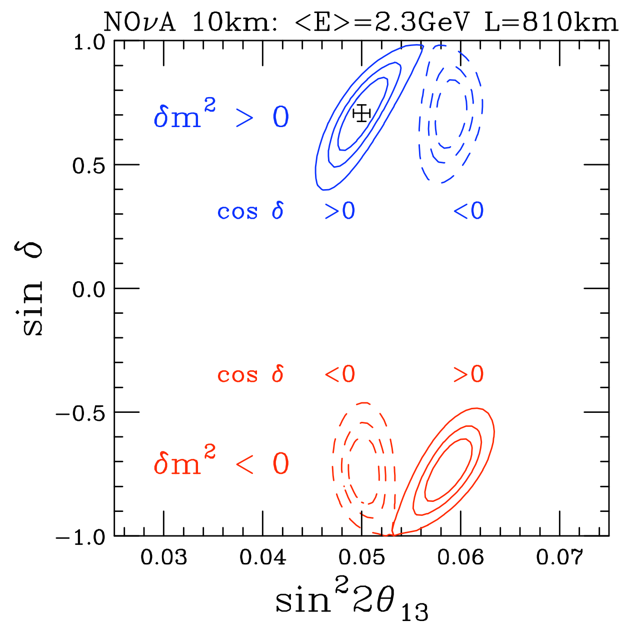

95% CL Resolution of the Mass Hierarchy
δ (π)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
L = 810 km, 25 kT
sin²(2θ₂₃) = 1
NOνA
For each ν and ν̄,
30.2x10²⁰ pot
|Δm₃₂²| = 2.5 10⁻³ eV²
Δm² > 0
Δm² < 0
|Δm₃₂²| = 3.0 10⁻³ eV²
Δm² > 0
Δm² < 0
10⁻²
10⁻¹
sin²(2θ₁₃)



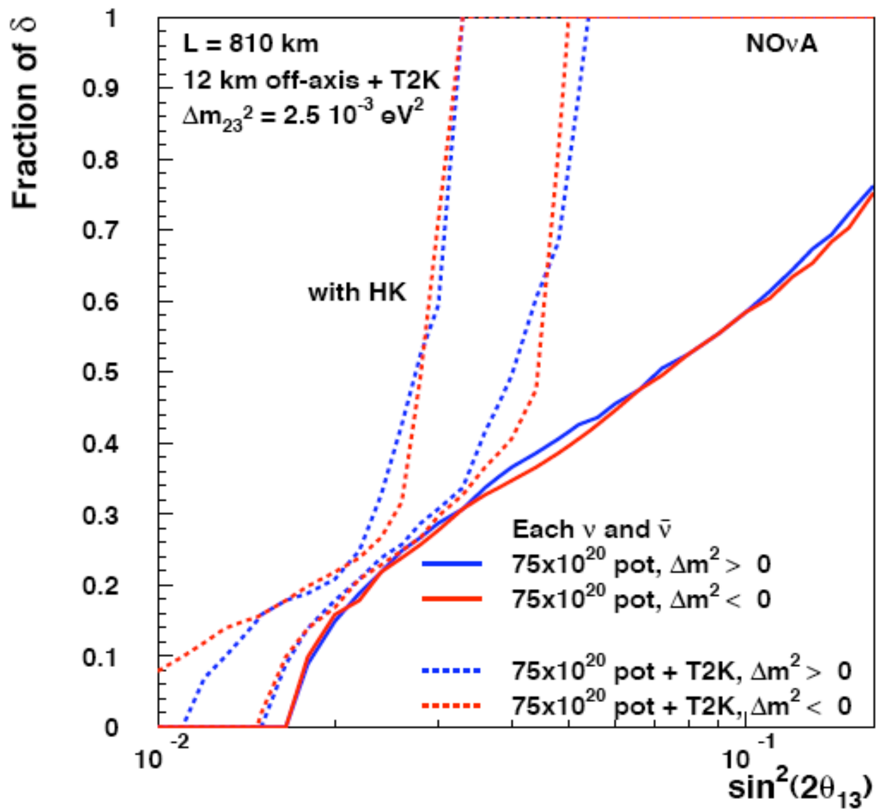


$$\langle \sin\delta \rangle_+ \;-\; \langle \sin\delta \rangle_- \approx 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$





$$\langle \sin\delta \rangle_+ \;-\; \langle \sin\delta \rangle_- \approx 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

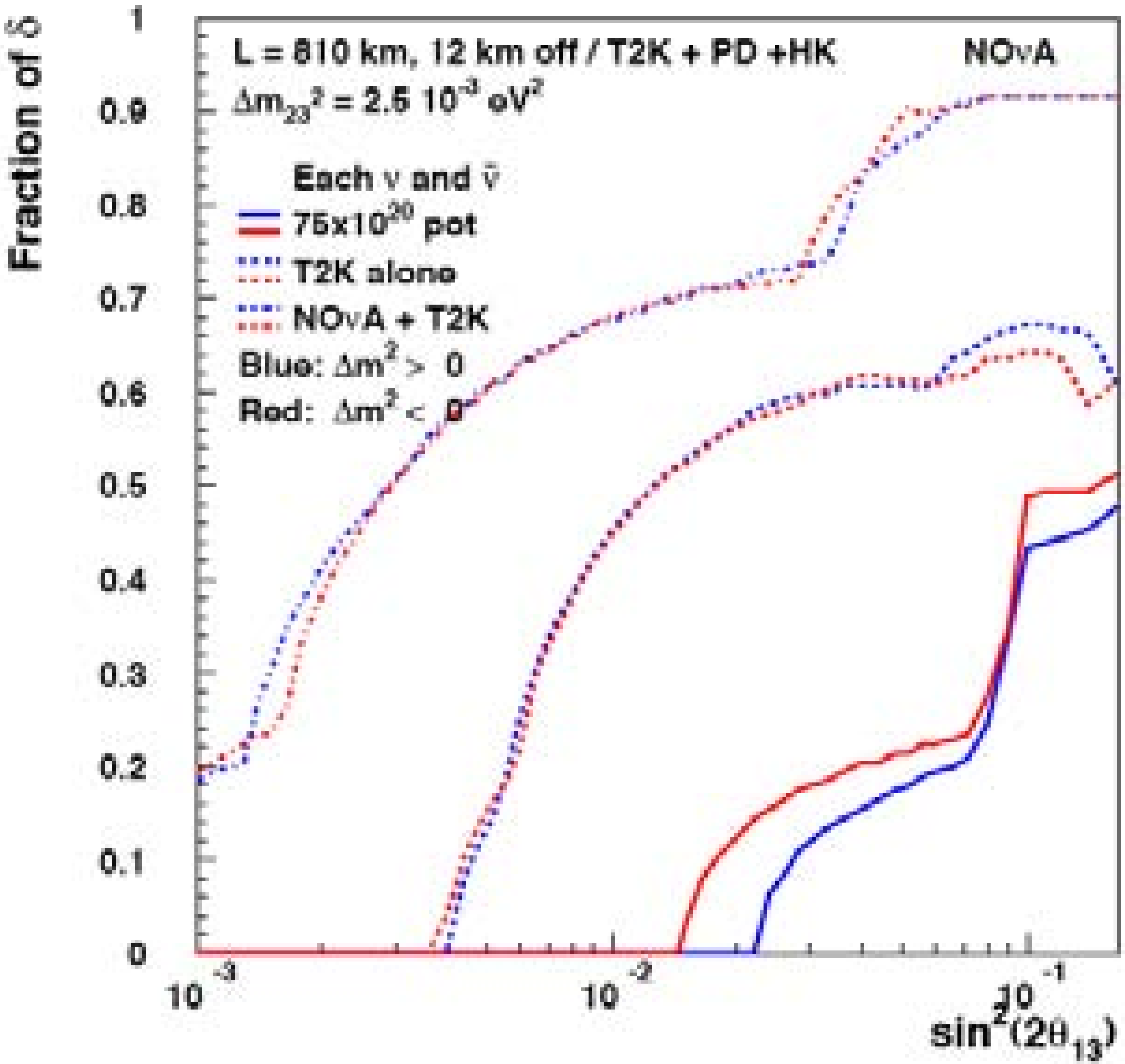


NOνA/PD with T2K Phase 2

95% CL Resolution of the Mass Ordering

Sensitivity to CP violation: $\sin\delta$

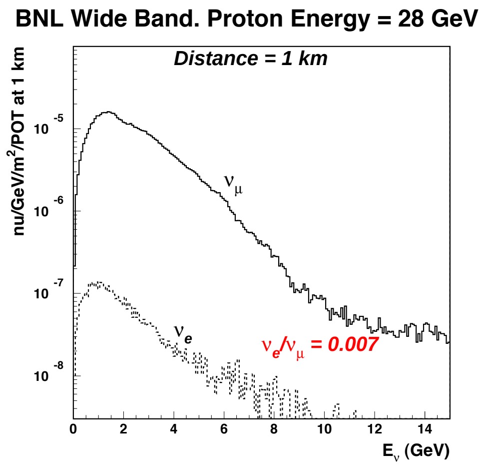
3 σ Determination of CP Violation



Beyond the First Oscillation Maximum:

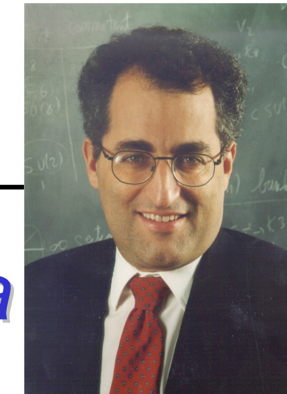
On Axis Beams:

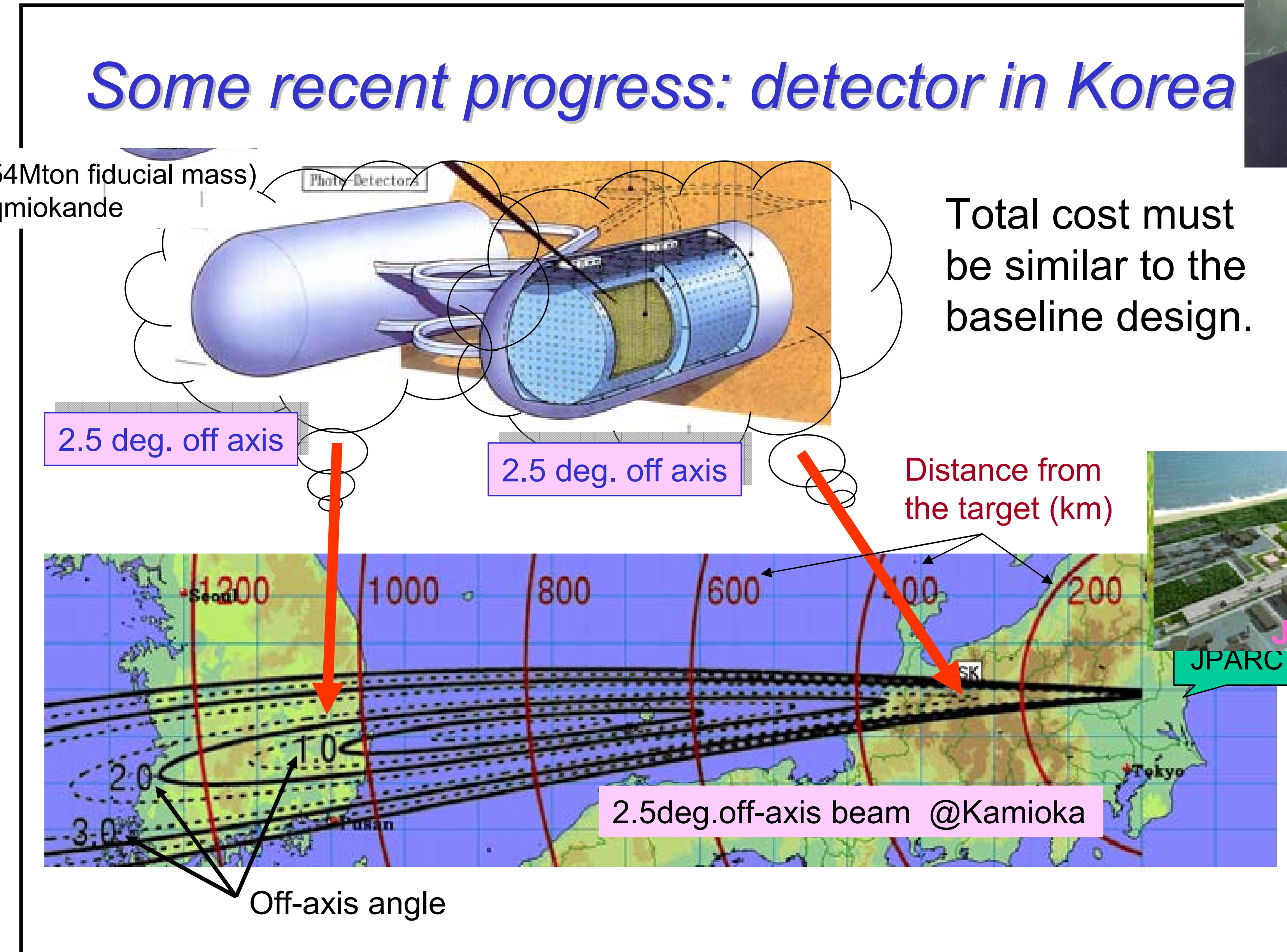
- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector.
- baseline > 2500 km. WIPP, Henderson, Homestake



Brookhaven Proposal

Off Axis:





see Kajita talk:

Broadband Beam: Same L, Lower E Fermilab to DUSEL

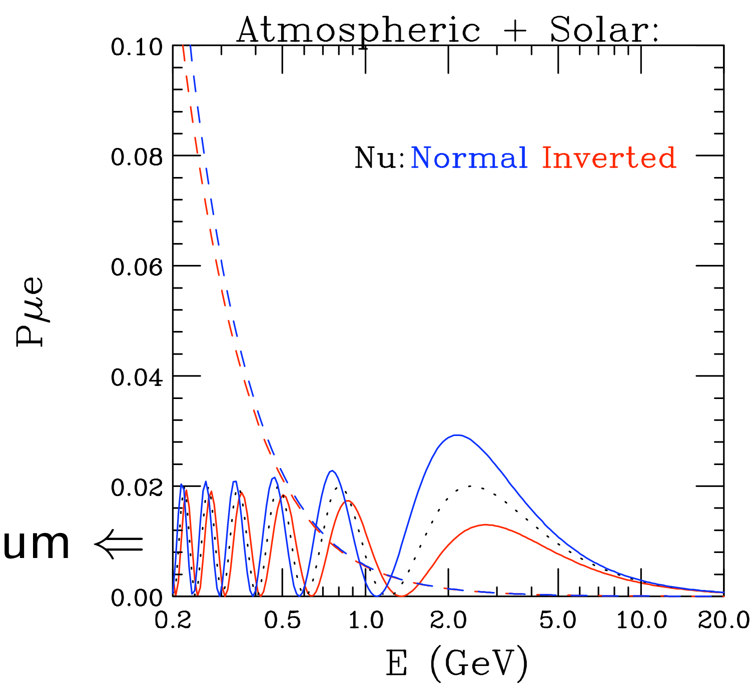
Narrow Band Beam: Same E, Longer L T2KK

In VACUUM the SAME but NOT in MATTER

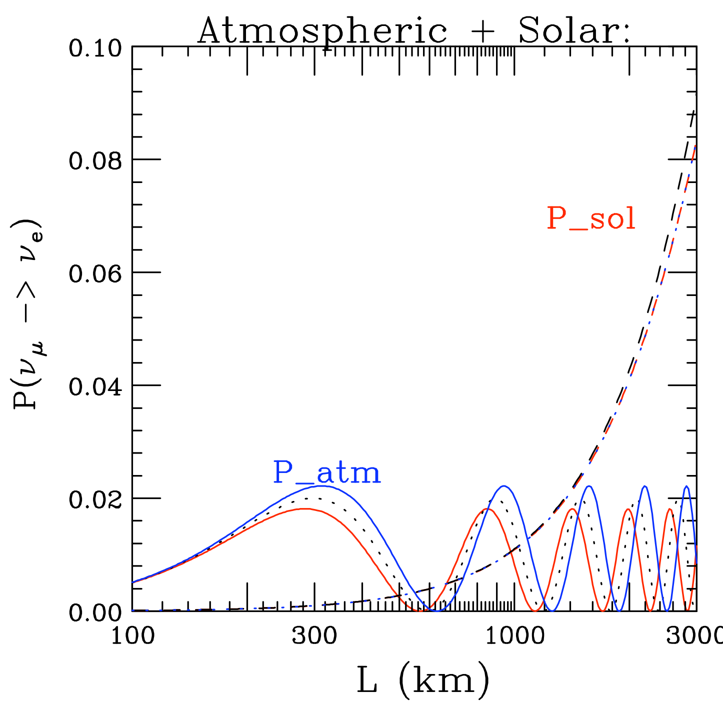
$$\sin^2 2\theta_{13} = 0.04$$

L=1200km

vacuum ⇐



E=0.6 GeV



⇐ same height

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

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

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

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

depends on θ_{13}
amplification or suppression
by matter (E)

Suppression $\geq$ Enhancement

independent of θ_{13}
$\approx$ independent of
matter effect

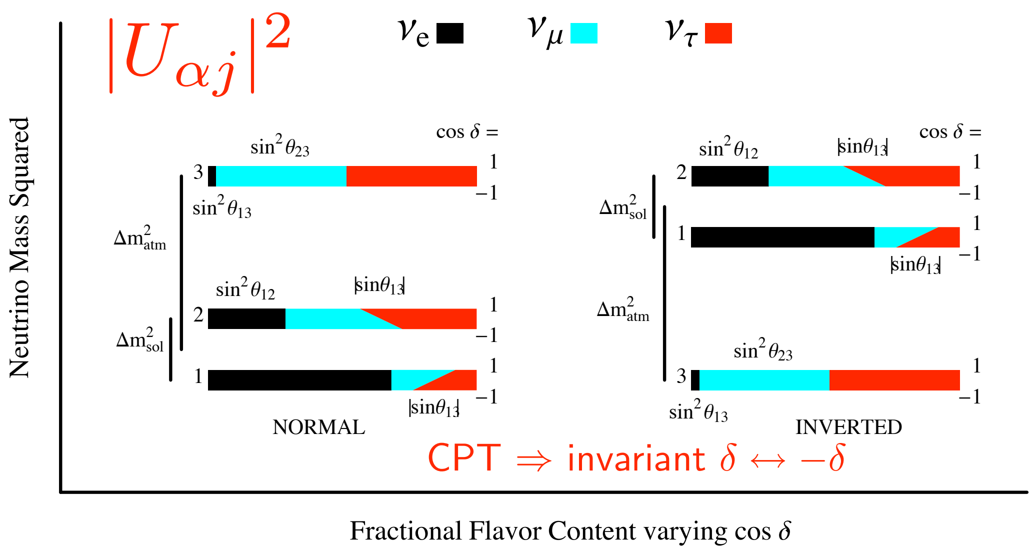
L/E $\geq$ significant fraction of 500 km/GeV

Event rate: $E(E/L)^2$

Summary:

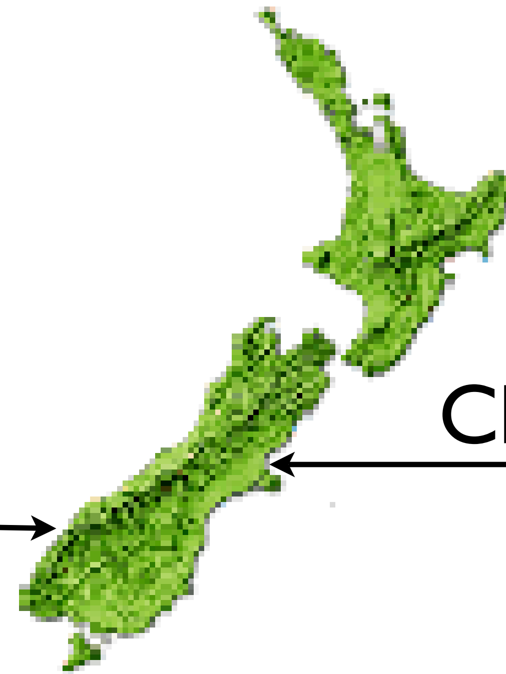
$$\begin{array}{ccccc} & & \text{CP} & & \\ & \nu_\mu \to \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \to \bar{\nu}_e & \\ \text{T} & \Updownarrow & \text{CPT across diagonals} & \Updownarrow & \text{T} \\ & \nu_e \to \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \to \bar{\nu}_\mu & \\ & & \text{CP} & & \end{array}$$

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination



- Size of $|U_{e3}|^2$
- Hierarchy ?
- CPV ?
- Maximal {23} Mixing ?
- .....
- New Interactions and Surprises !!!

Neutrino 2008
May 26-31



Christchurch
NZ

www.neutrino2008.co.nz

CP

$\nu_\mu \longrightarrow \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

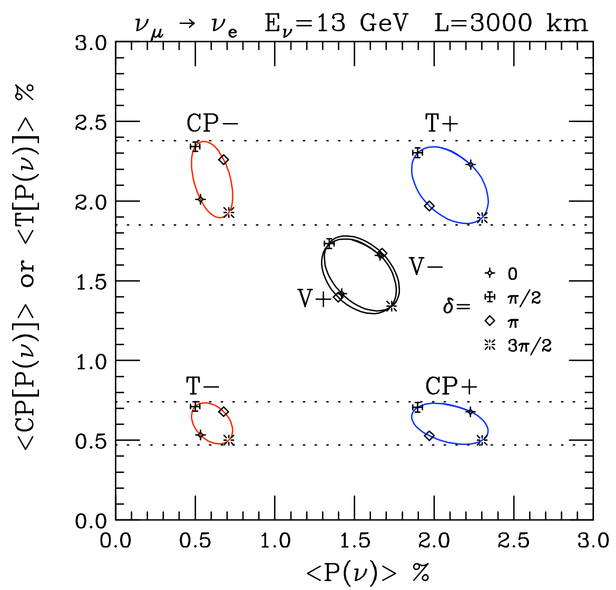
T $\Updownarrow$ CPT across diagonals $\Updownarrow$ T

$\nu_e \longrightarrow \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \longrightarrow \bar{\nu}_\mu$

CP

$\nu_e \longrightarrow \nu_\mu$

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



$\nu_\mu \longrightarrow \nu_e$

Suppression $\geq$ Enhancement

$$P(\nu_e \rightarrow \nu_\mu, matter)$$

$$= P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e, anti-matter)$$

$$\Downarrow$$

$$P(\nu_e \rightarrow \nu_\mu, \delta m^2_{31}, \delta)$$

$$\approx P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e, -\delta m^2_{31}, \pi - \delta)$$