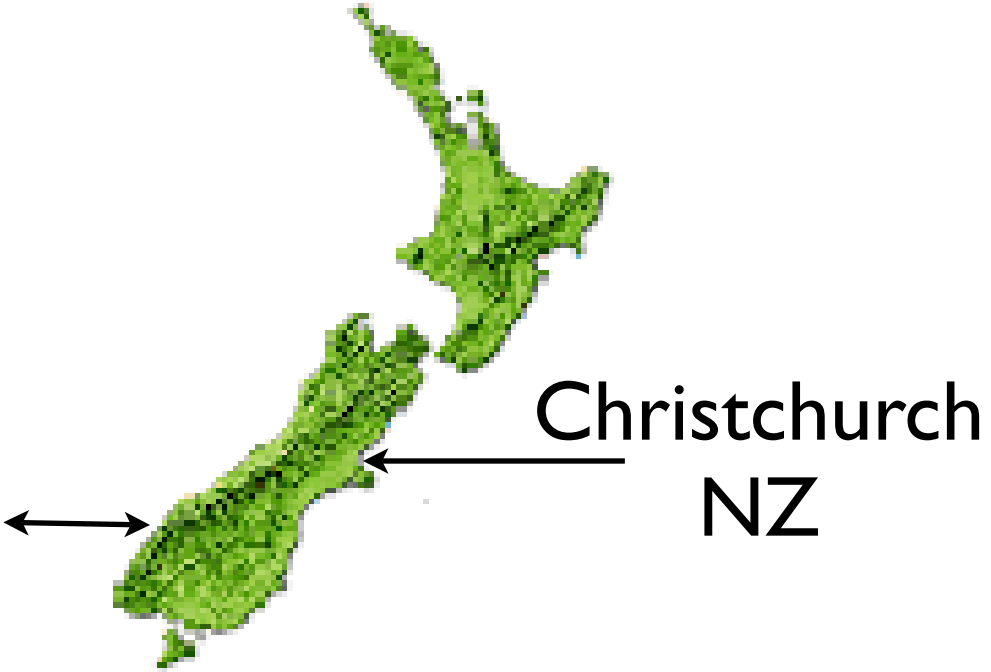
Neutrino 2008
May 25-31



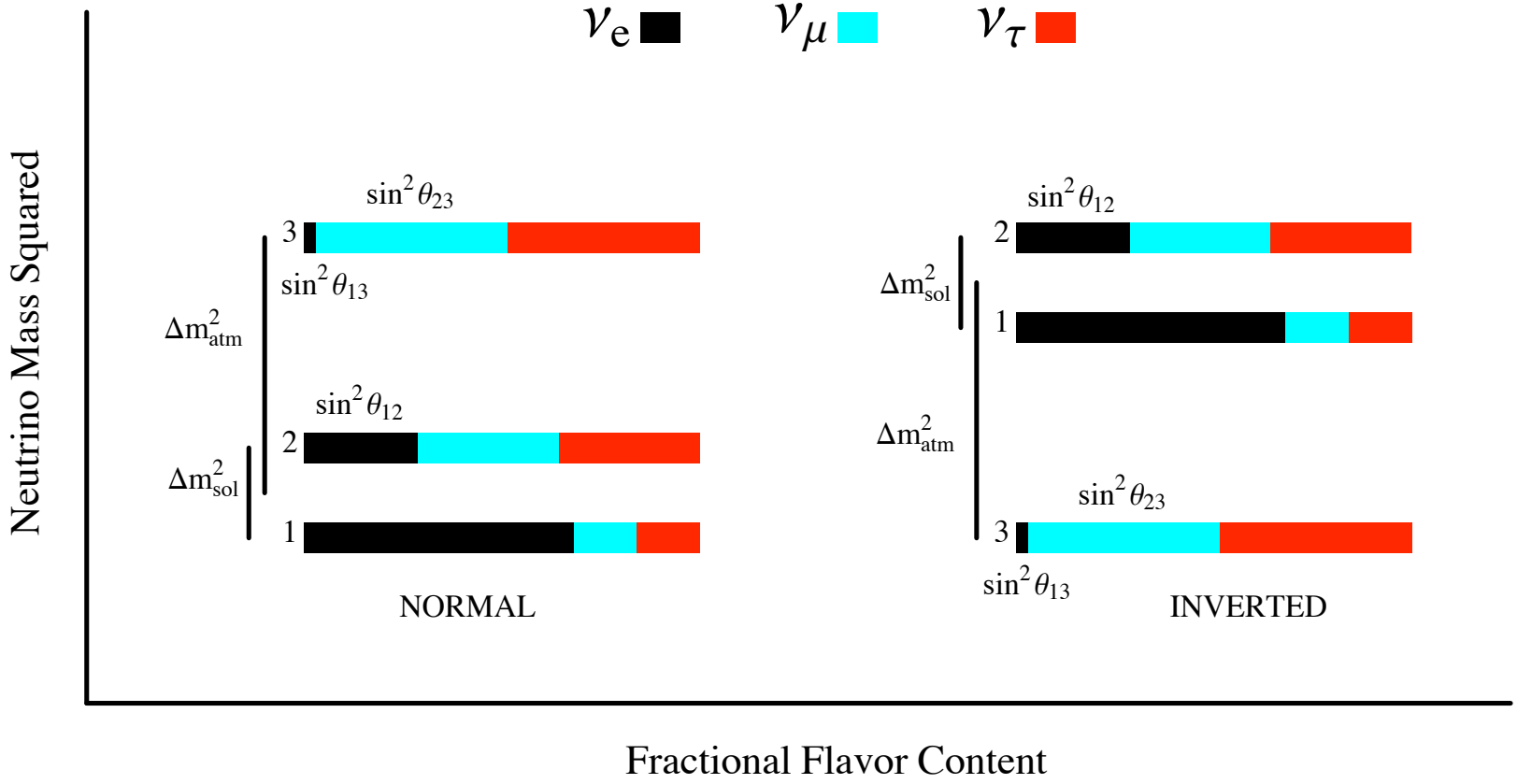
www.neutrino2008.co.nz

Fun with Neutrinos

Stephen Parke
Fermilab

- Current Status
- Future Experiments - especially LBL

Overview:



$$\delta m^2_{atm} = 2.4 \times 10^{-3}\ eV^2$$

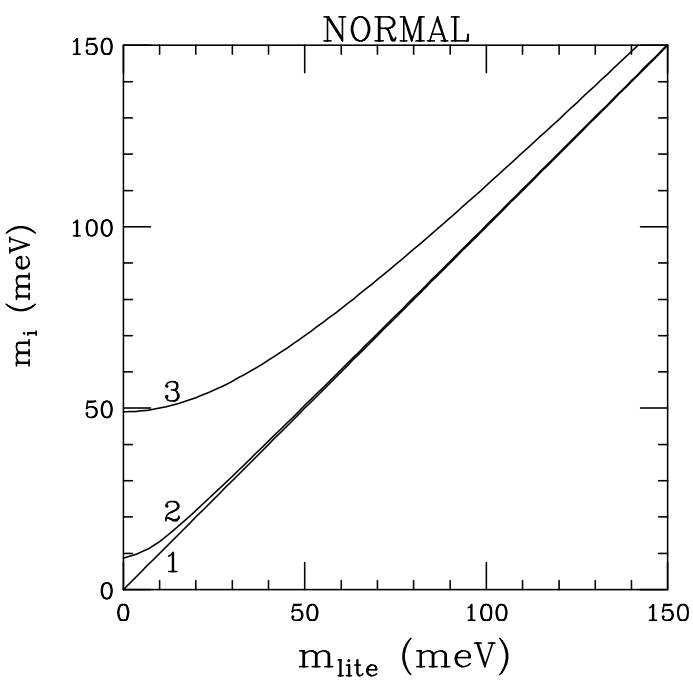
$$\delta m^2_{sol} = 7.6 \times 10^{-5}\ eV^2$$

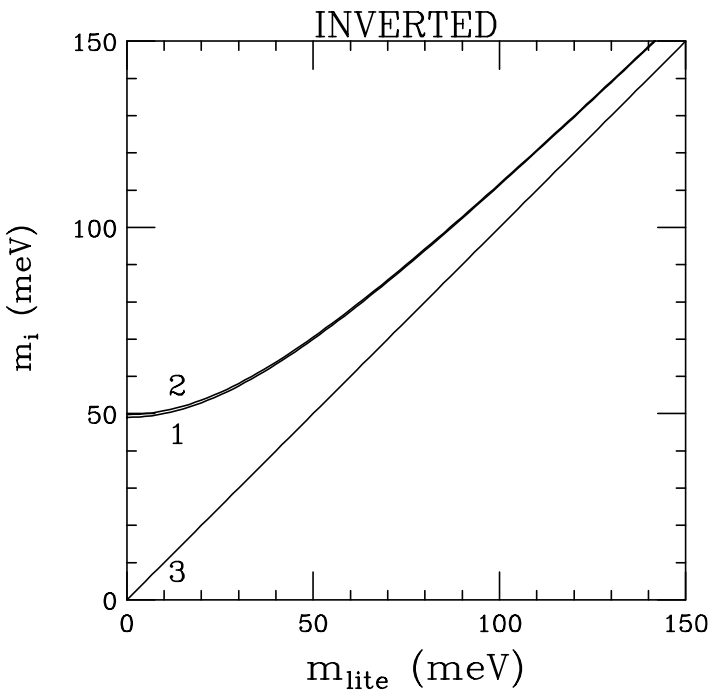
$$\delta m^2_{atm} \approx 30 * \delta m^2_{sol}$$

$$\left.\begin{array}{l} \sin^2\theta_{23} \sim 1/2 \\ \sin^2\theta_{12} \sim 1/3 \\ \sin^2\theta_{13} < 3\% \end{array}\right\}$$

Absolute Mass Scale:

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$





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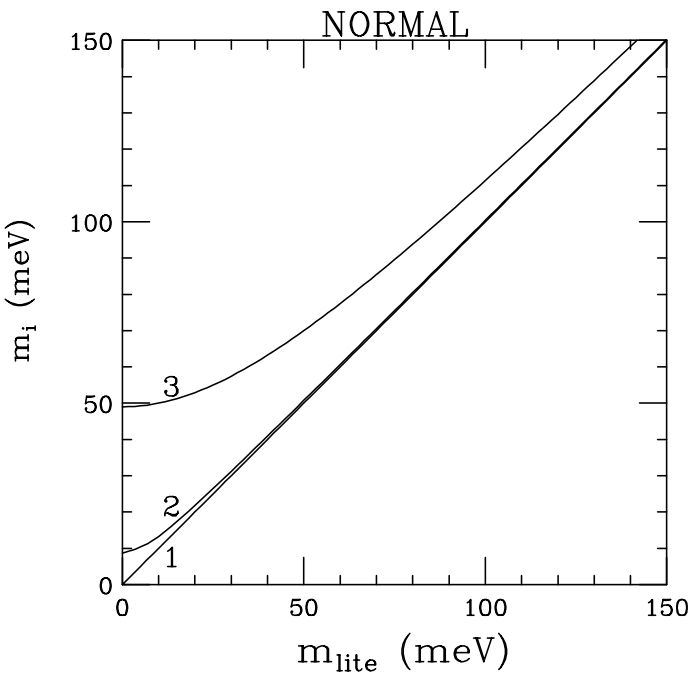
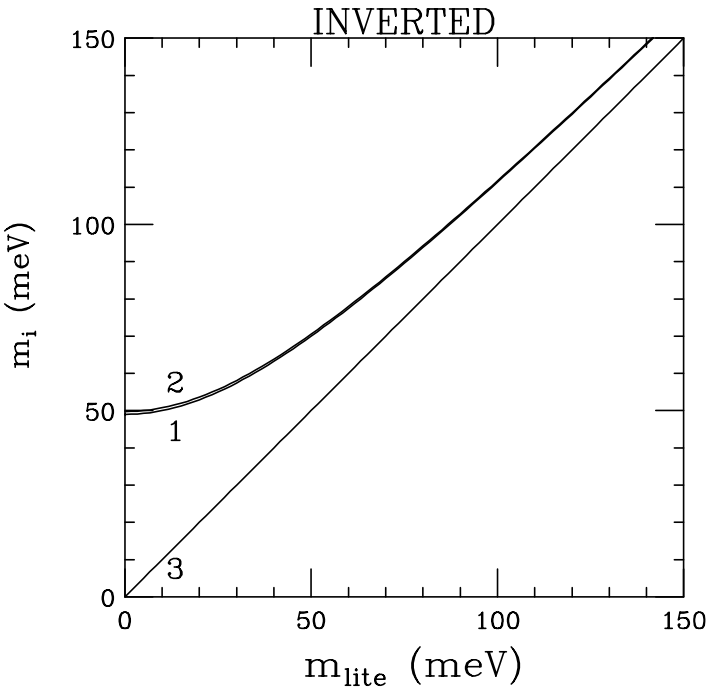
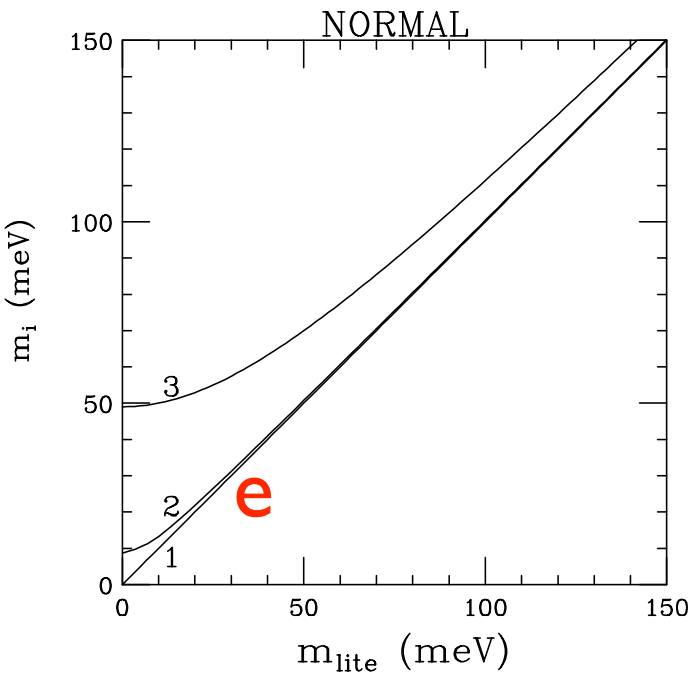


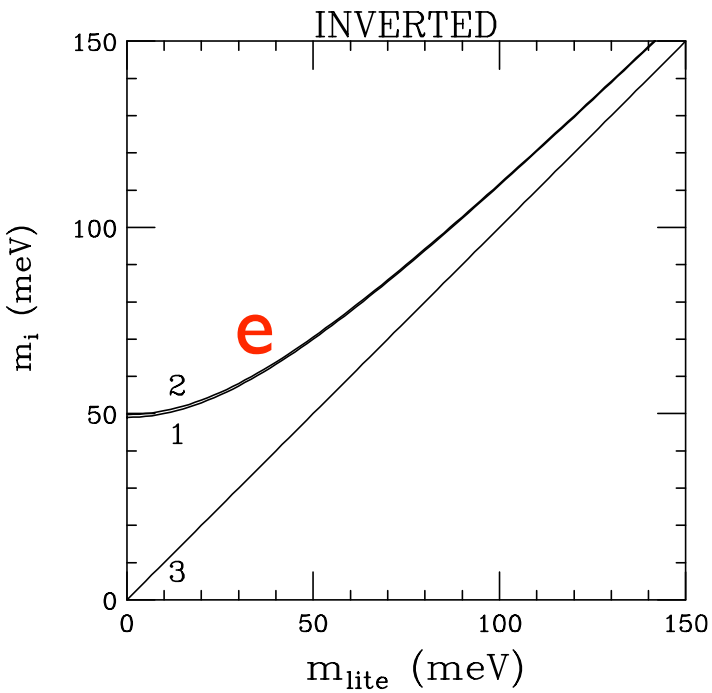


$\sum m_{\nu_i} =$ 60 450 100 450 meV

Absolute Mass Scale:

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$





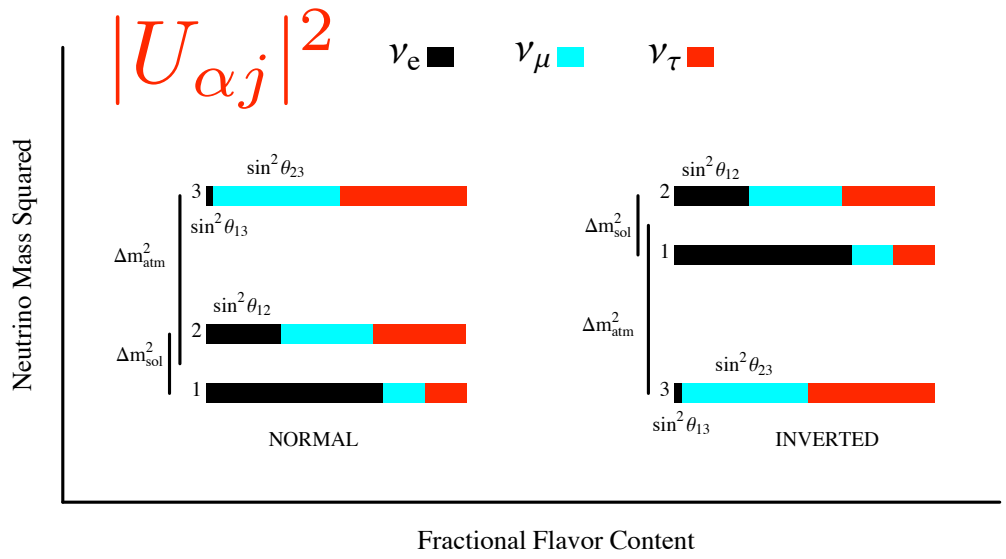
$\sum m_{\nu_i} =$ 60 450 100 450 meV

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

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

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

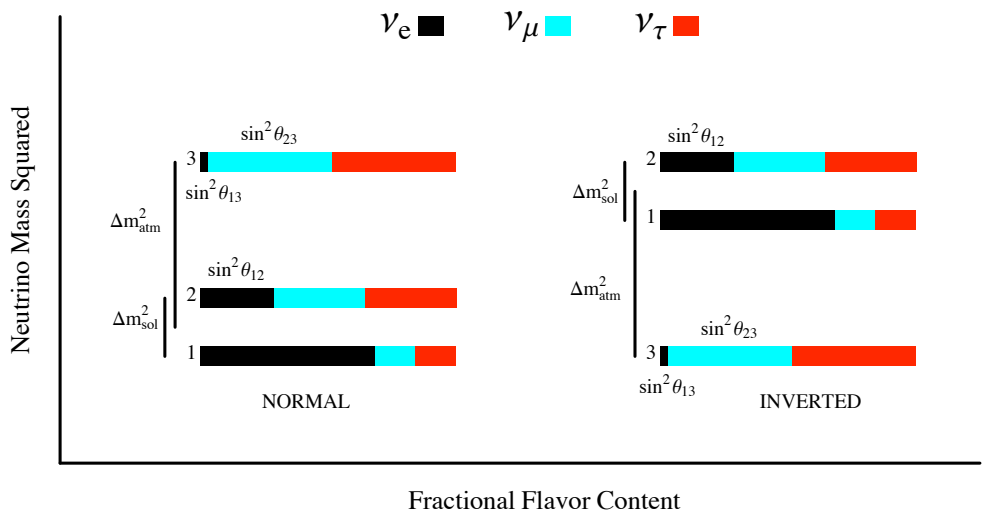


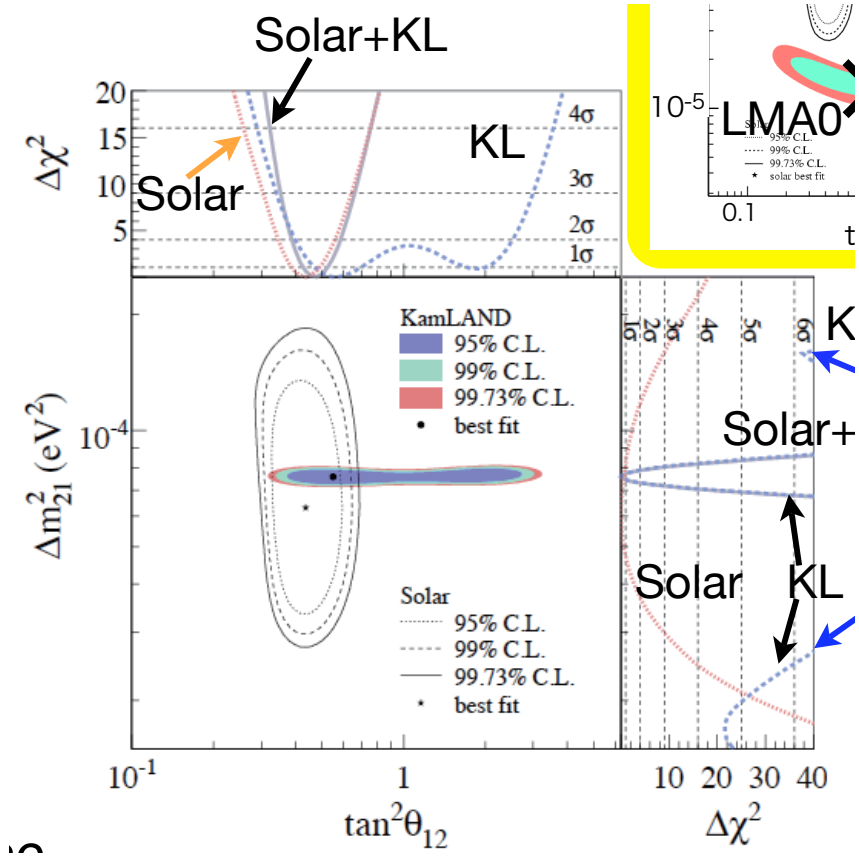
In oscillation phenomena:

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

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

Solar Sector: {12}



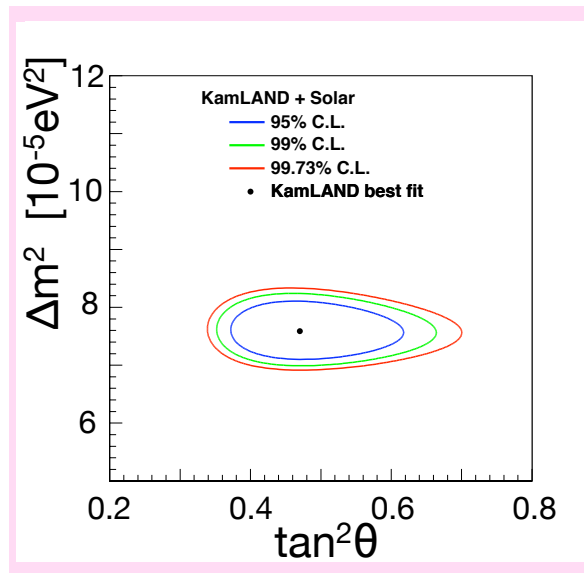


$$\delta m^2_{21} = 7.59 \pm 0.21 \times 10^{-5}\ eV^2$$

KamLAND + SNO, SK, Ga, Cl

$$\sin^2\theta_{12} = 0.32 \pm 0.02$$

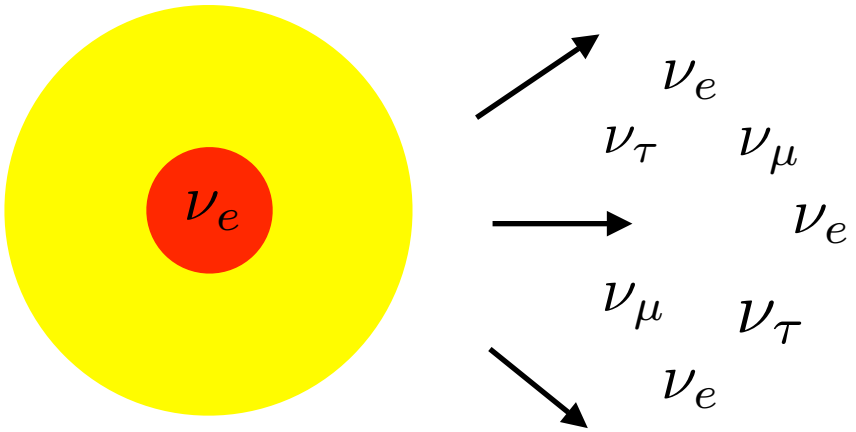
SNO + SK, Ga, Cl, KamLAND



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

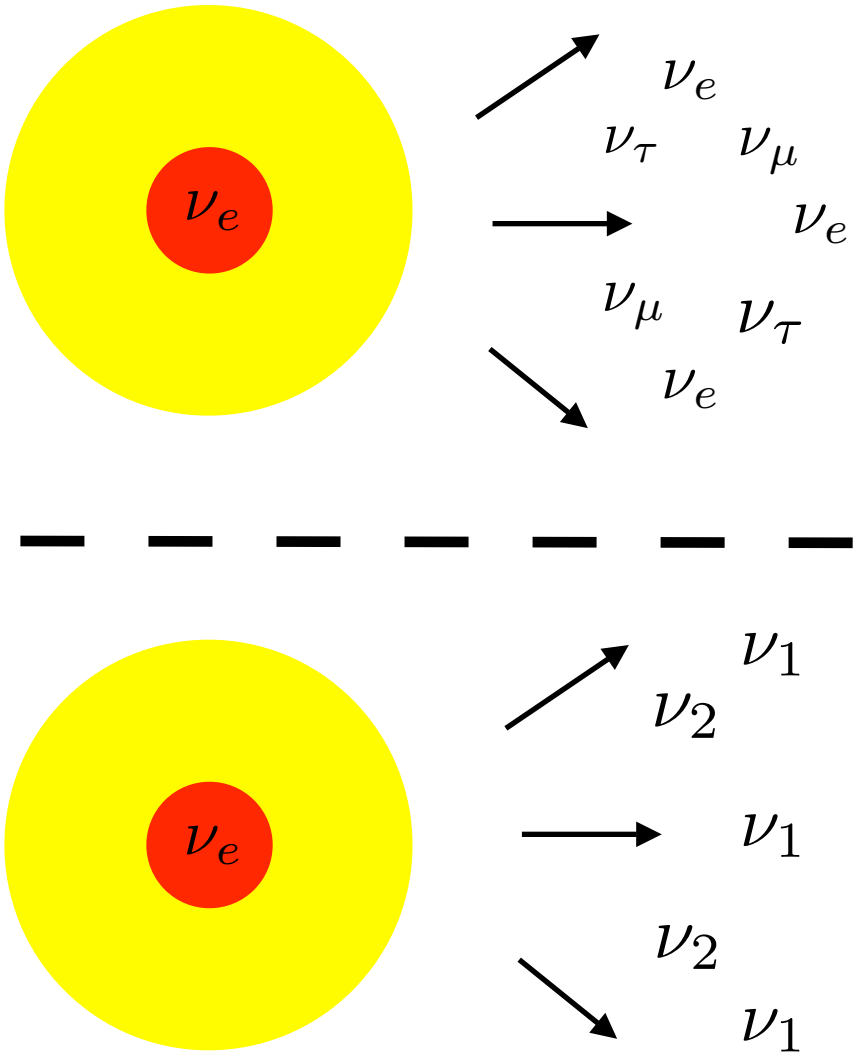
(0.35) (0.31)

Identical Solar Twins:



flavor eigenstates

Identical Solar Twins:



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

mass eigenstates are "Effectively Incoherent"

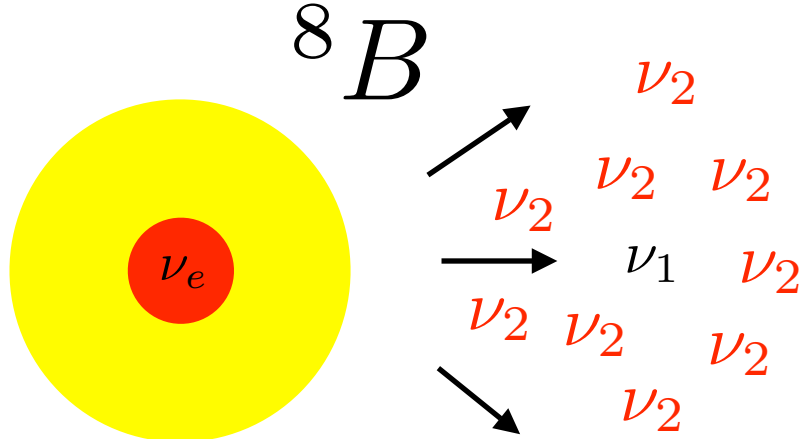
SNO's

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

$$= \sin^2\theta_\odot + f_1 \cos^2 2\theta_\odot$$

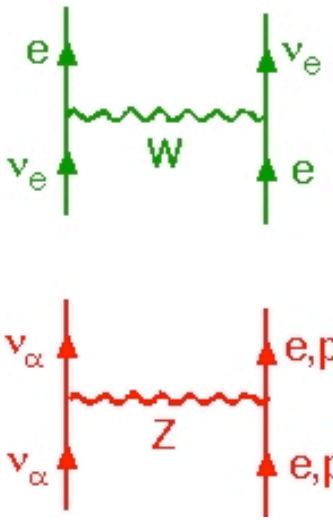
$$f_1 = \frac{\frac{CC}{NC} - \sin^2\theta_\odot}{\cos 2\theta_\odot}$$

$$= \frac{0.35 - 0.31}{0.4} \approx 10\%$$



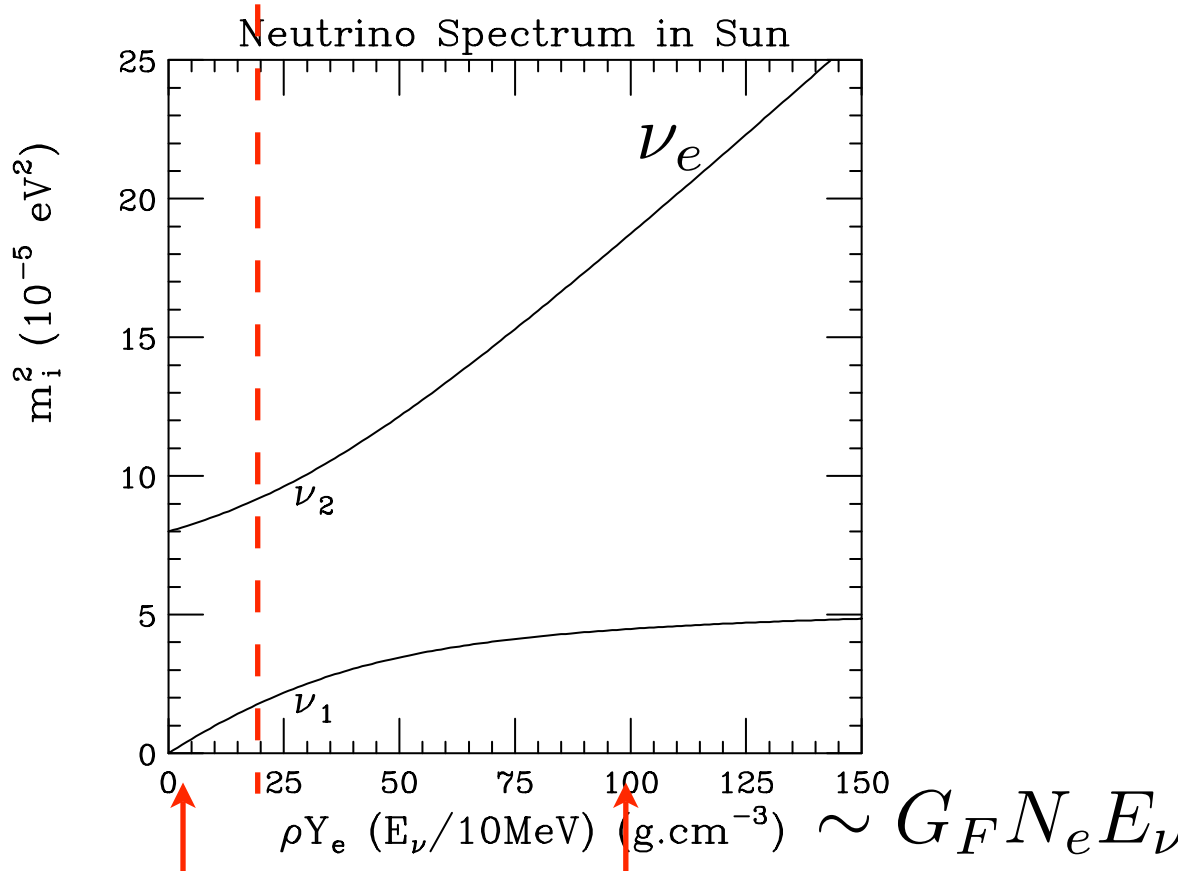
^8B fraction of ν_2's is 90 % !!!

Coherent Forward Scattering:



Wolfenstein '78

Mikheyev + Smirnov Resonance WIN '85



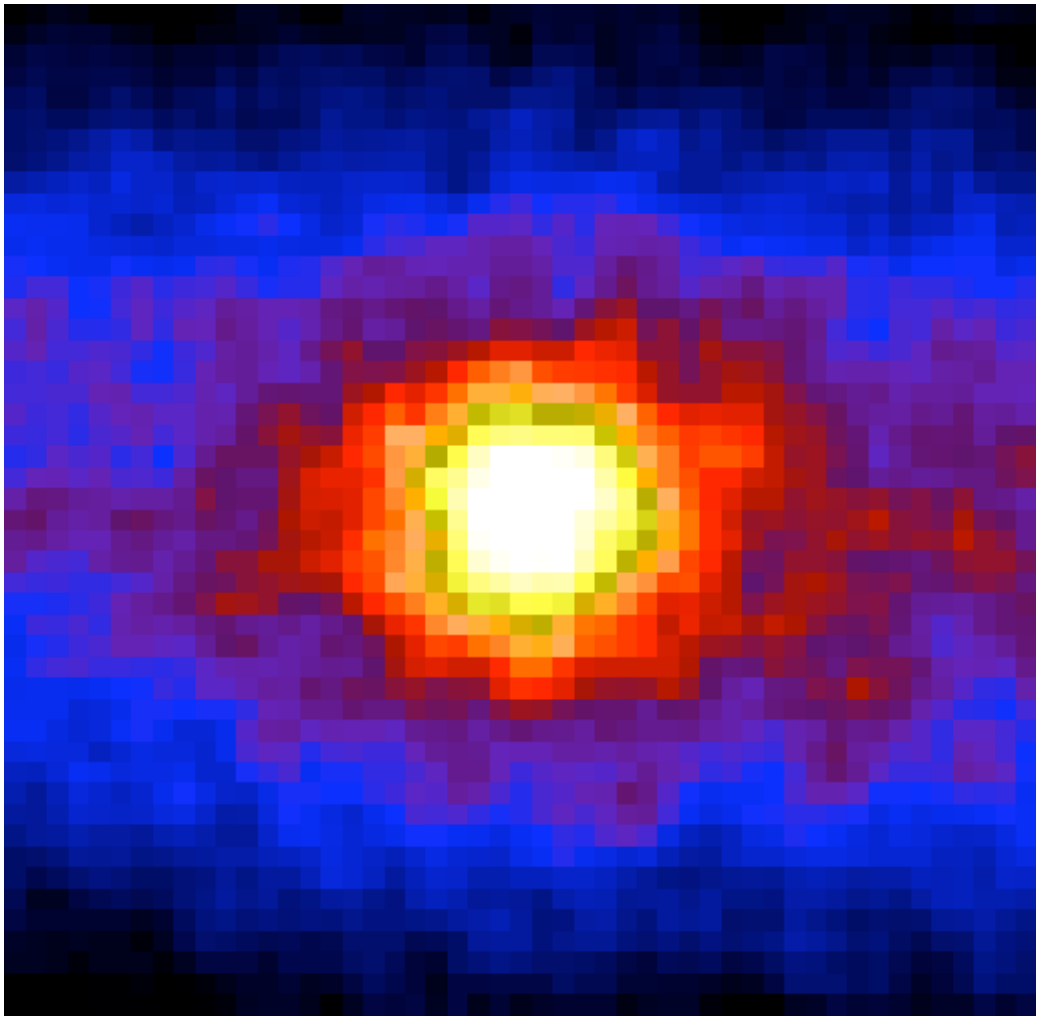
$\sim G_F N_e E_\nu$

MATTER EFFECTS CHANGE THE NEUTRINO MASSES AND MIXINGS

$pp, {}^7Be$ $\quad$ ^8B

MSW

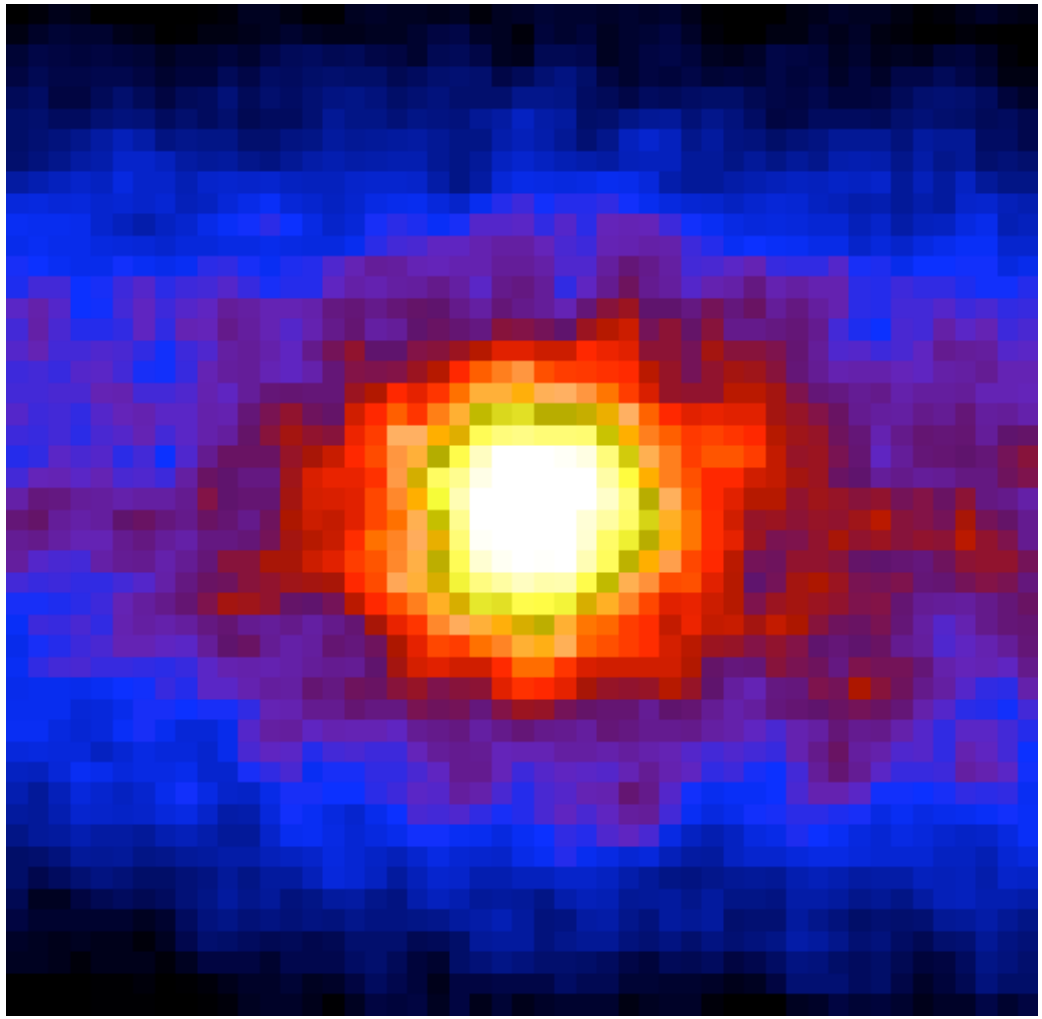
SuperK



$$\nu_? + e \rightarrow \nu + e$$

Which Neutrinos ?

SuperK

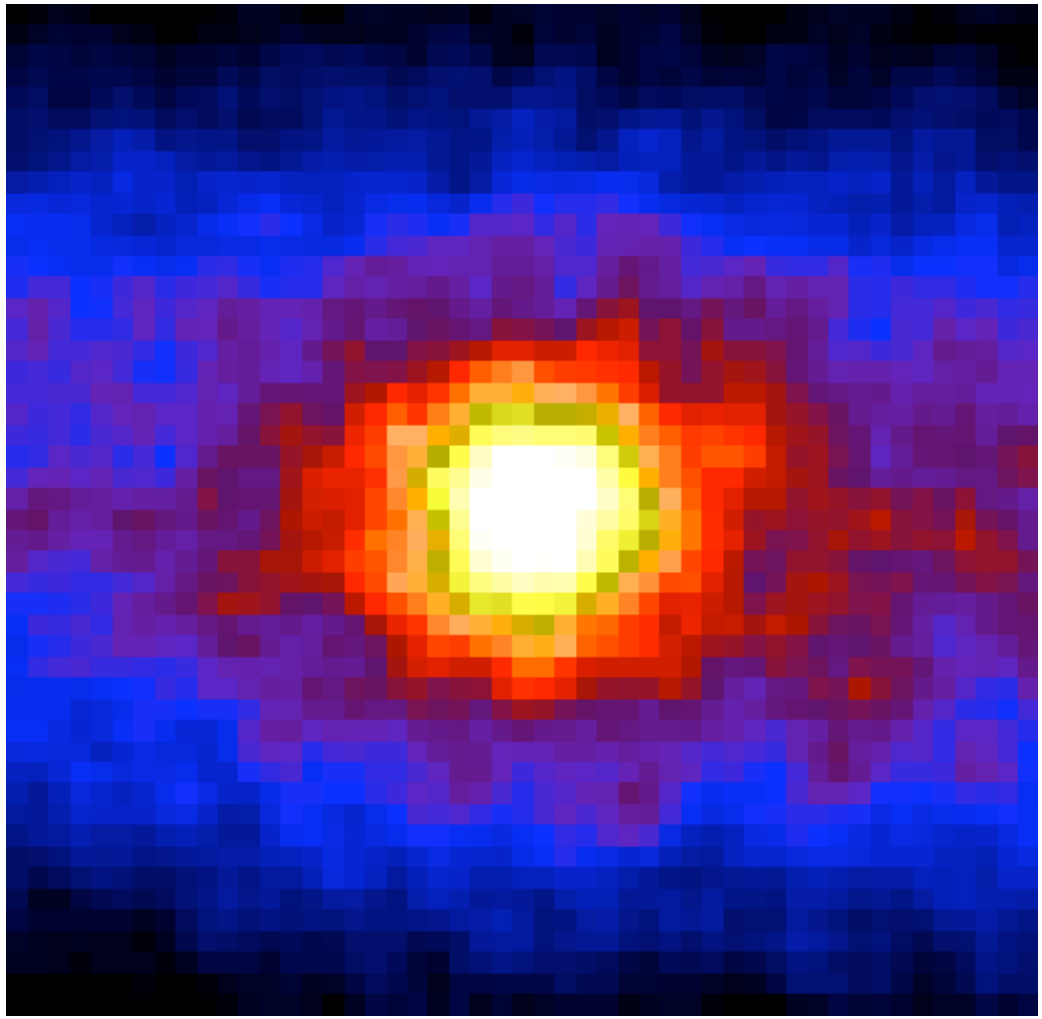


Flavor
Fraction
76% ν_e's

$$\nu_? + e \rightarrow \nu + e$$

Which Neutrinos ?

SuperK



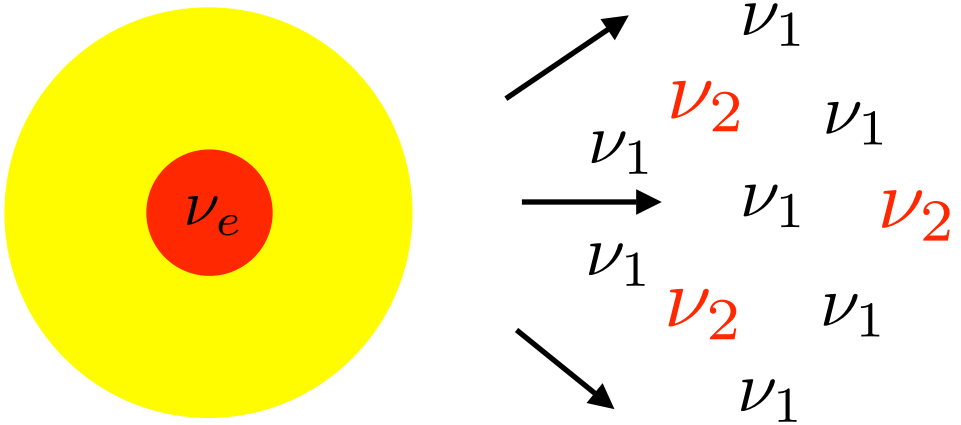
Flavor
Fraction
76% ν_e's

Mass E-state
Fraction
84% ν_2's

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

Which Neutrinos ?

pp and ^{7}Be



$$f_1 \sim \cos^2\theta_\odot \approx 68\%$$

$$f_2 \sim \sin^2\theta_\odot \approx 32\%$$

$$\langle P_{ee}\rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot \approx 0.6$$

$$f_3 = \sin^2\theta_{13} < 4\%$$

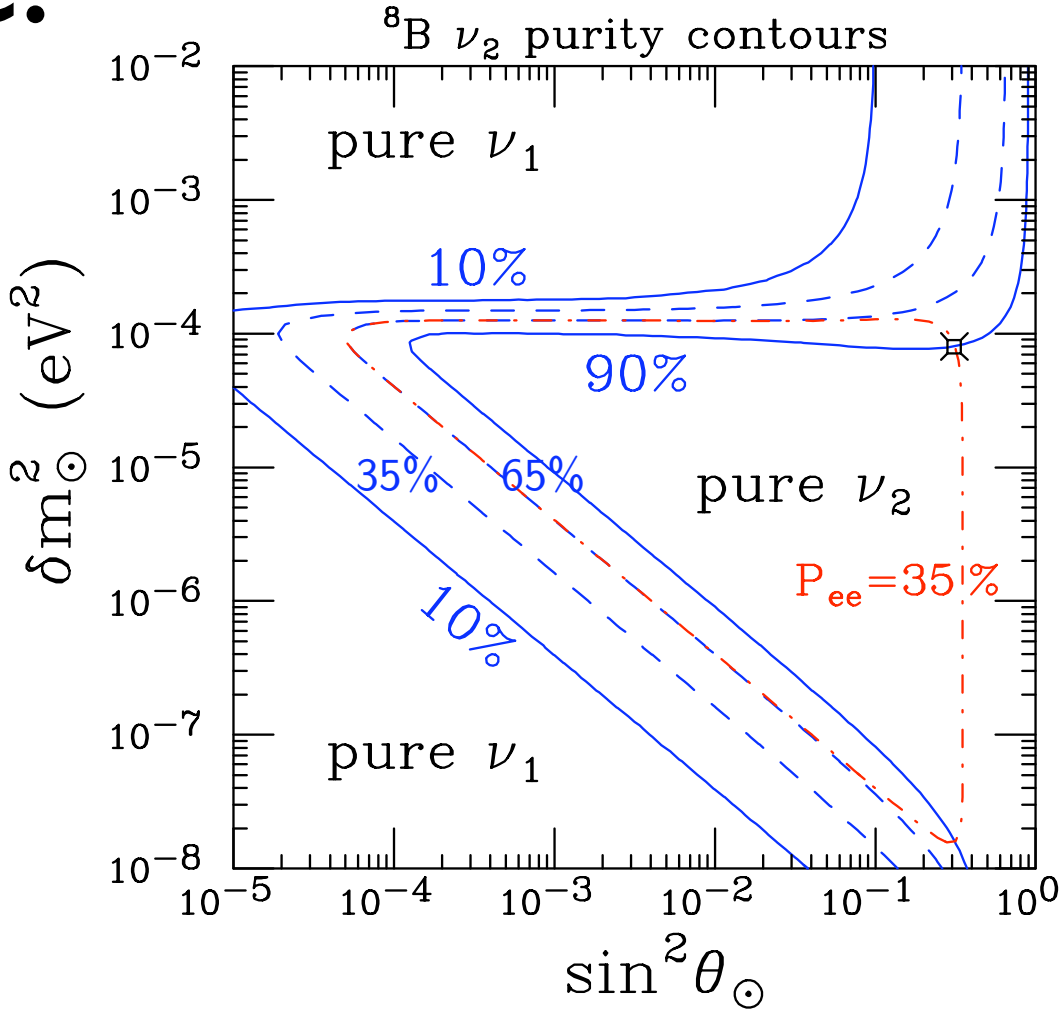
The Big Picture:

$$P_{ee} = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

$$f_1 = (1 - P_x)\cos^2\theta_\odot^N + P_x \sin^2\theta_\odot^N$$

$$f_2 = (1 - P_x)\sin^2\theta_\odot^N + P_x \cos^2\theta_\odot^N$$

P_x is the probability to jump from ν_2 to ν_1 (or ν_1 to ν_2) during MS-resonance crossing.



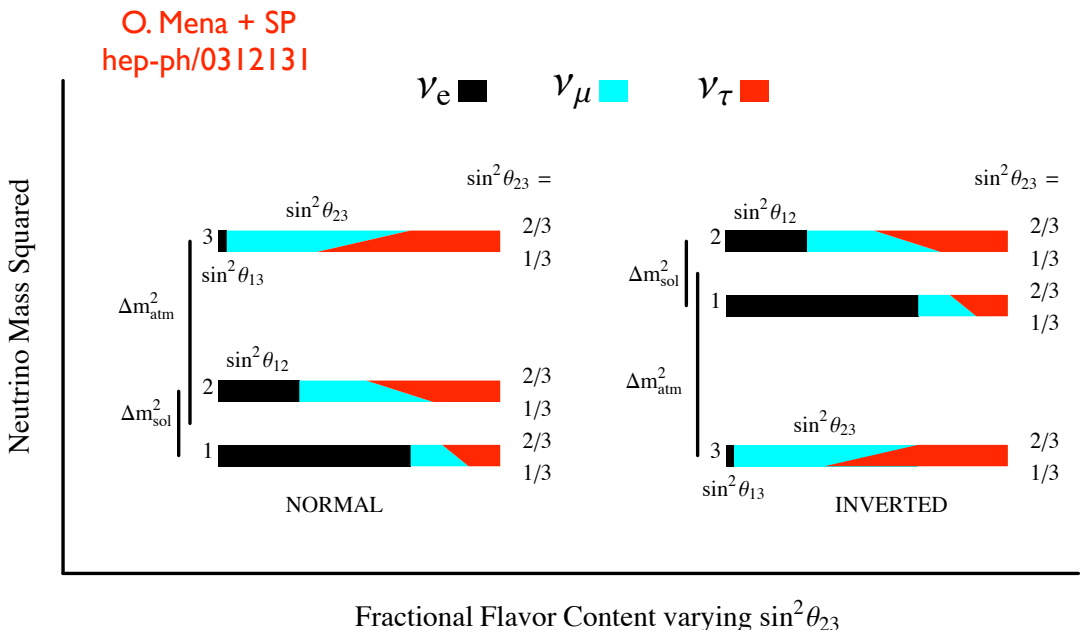
$$P_{ee} = \frac{1}{2} + \left(\frac{1}{2} - P_x\right)\cos 2\theta_\odot^N \cos 2\theta_\odot$$

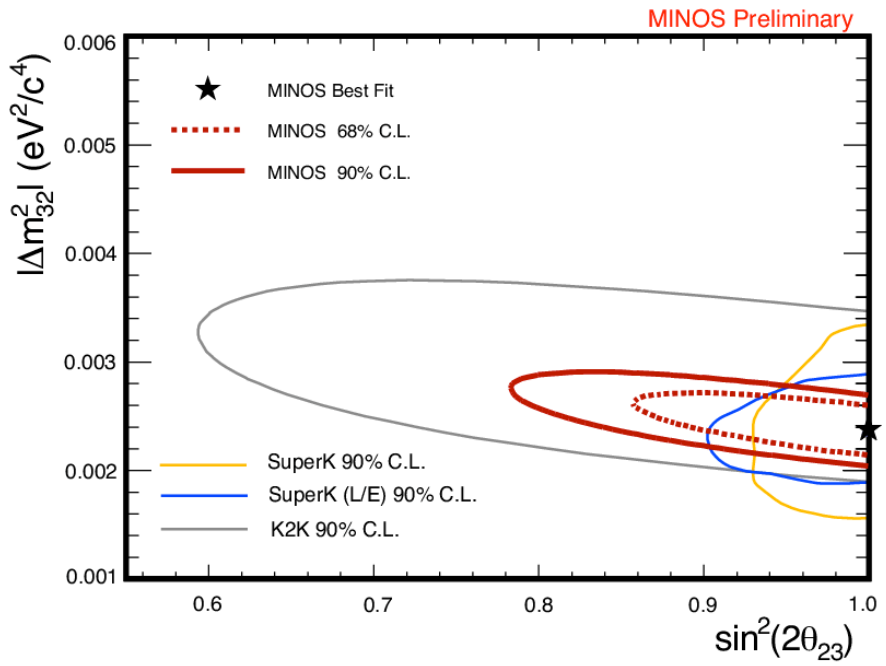
Jump Probability:

$$P_x \approx \exp\left(-\pi \frac{Width\ of\ Resonance}{Oscillation\ Length}\right)$$

SP PRL, 57, 1275 and 2322 (1986)

Atmospheric Sector: {23}





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

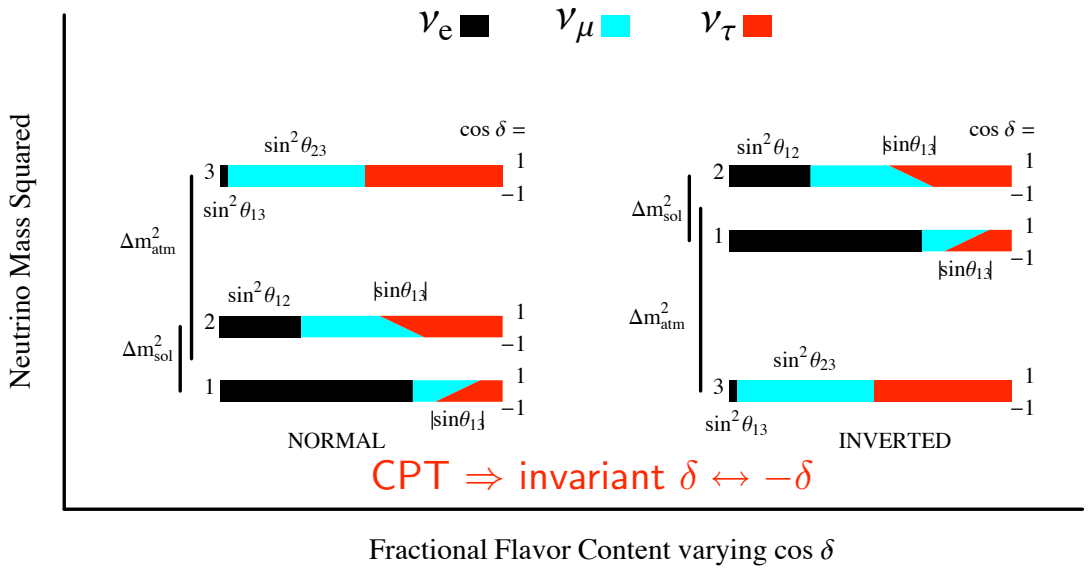
SuperK (90%)

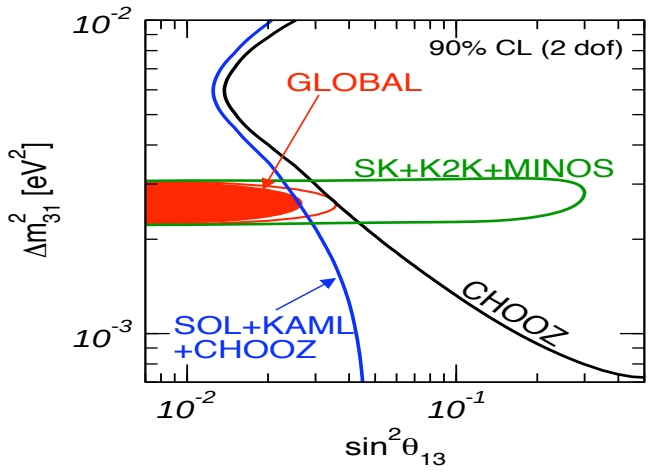
$$\delta m^2_{atm} = 2.38^{+0.20}_{-0.16} \times 10^{-3}\text{eV}^2$$

MINOS

Hierarchy?

Reactor/Accelerator Sector: {13}



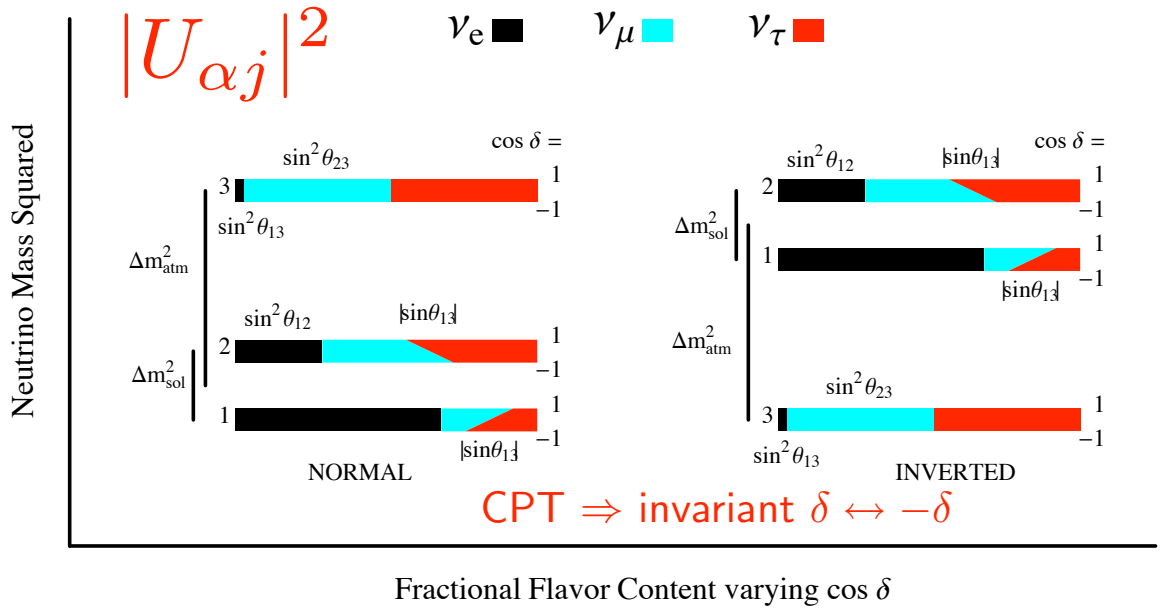


Maltoni etal

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

$$0 \leq \delta < 2\pi$$

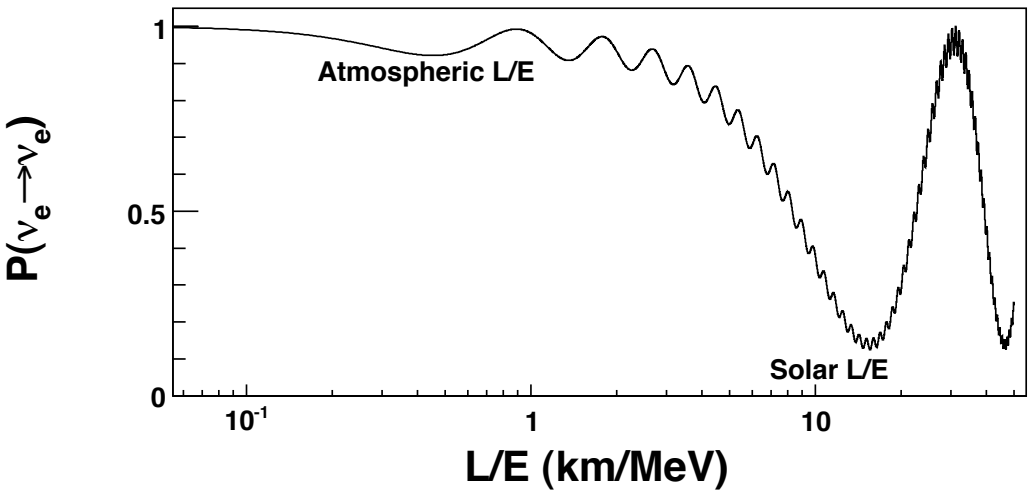
- Size of $|U_{e3}|^2$
- Hierarchy ?
- CPV ?
- Maximal $\{23\}$ Mixing ?
- .....
- New Interactions and Surprises !!!

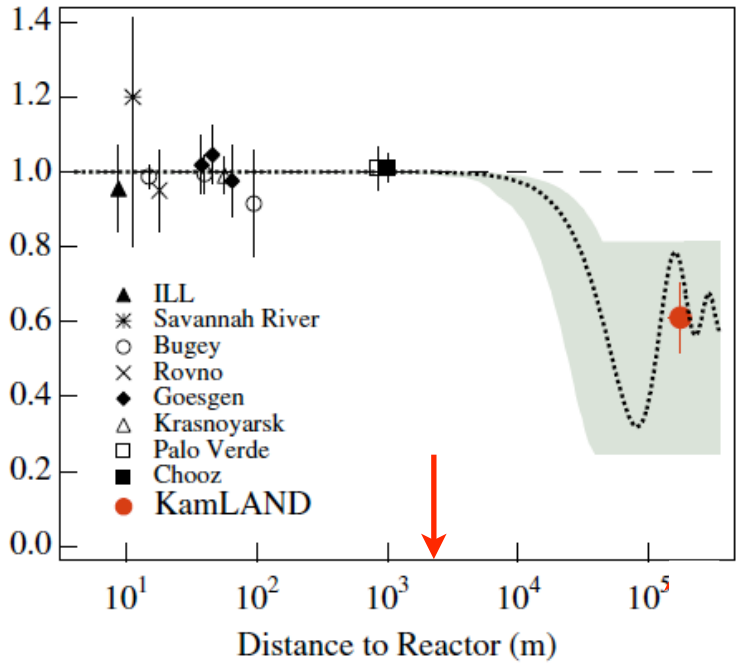


θ_{13} from Reactor Disappearance

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

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





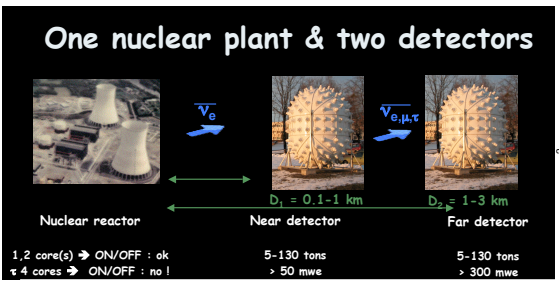
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

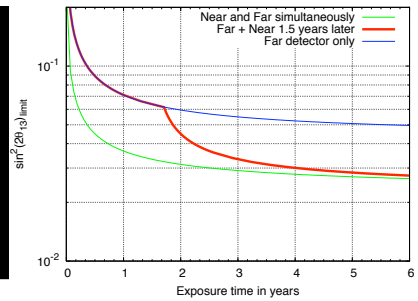
< 0.002

> 0.01

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

Double Chooz:

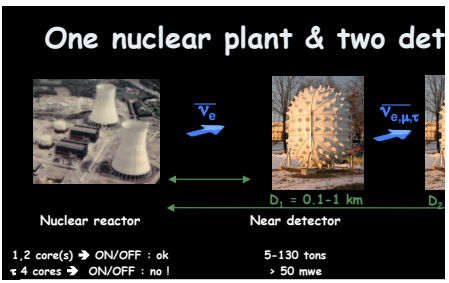




.03

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

Double Chooz:

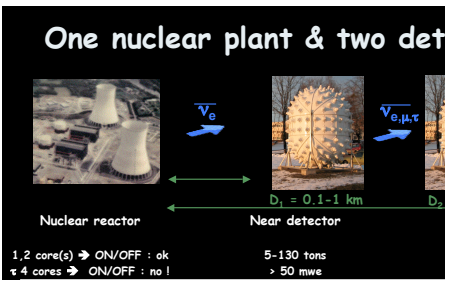


Daya Bay

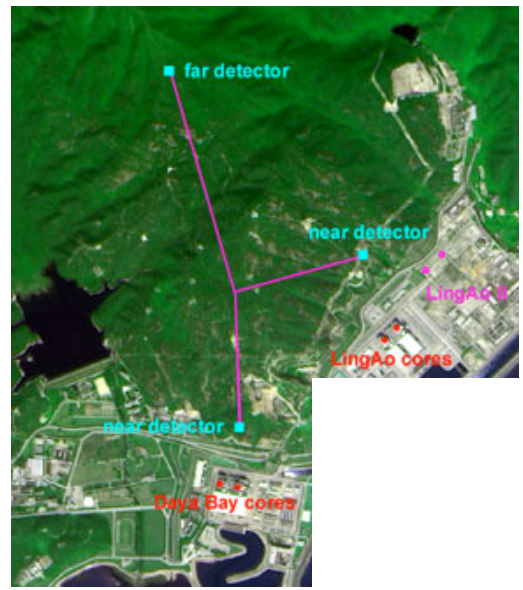
push the limit on

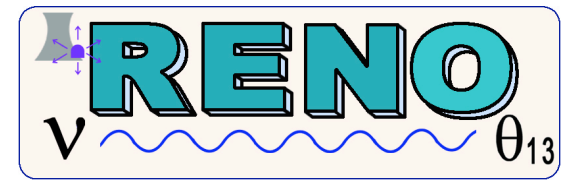
$$\sin^2 2\theta_{13} < 0.01$$

Double Chooz:



Daya Bay

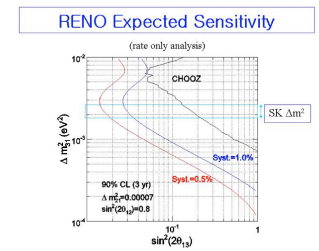




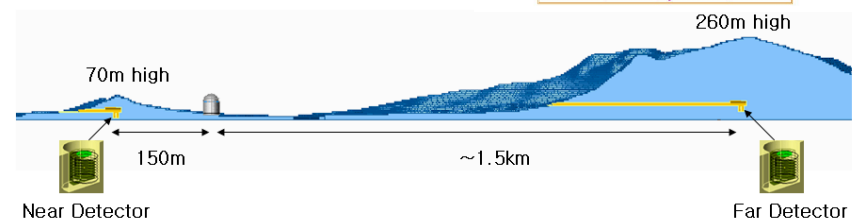
(Reactor Experiment for Neutrino Oscillation)

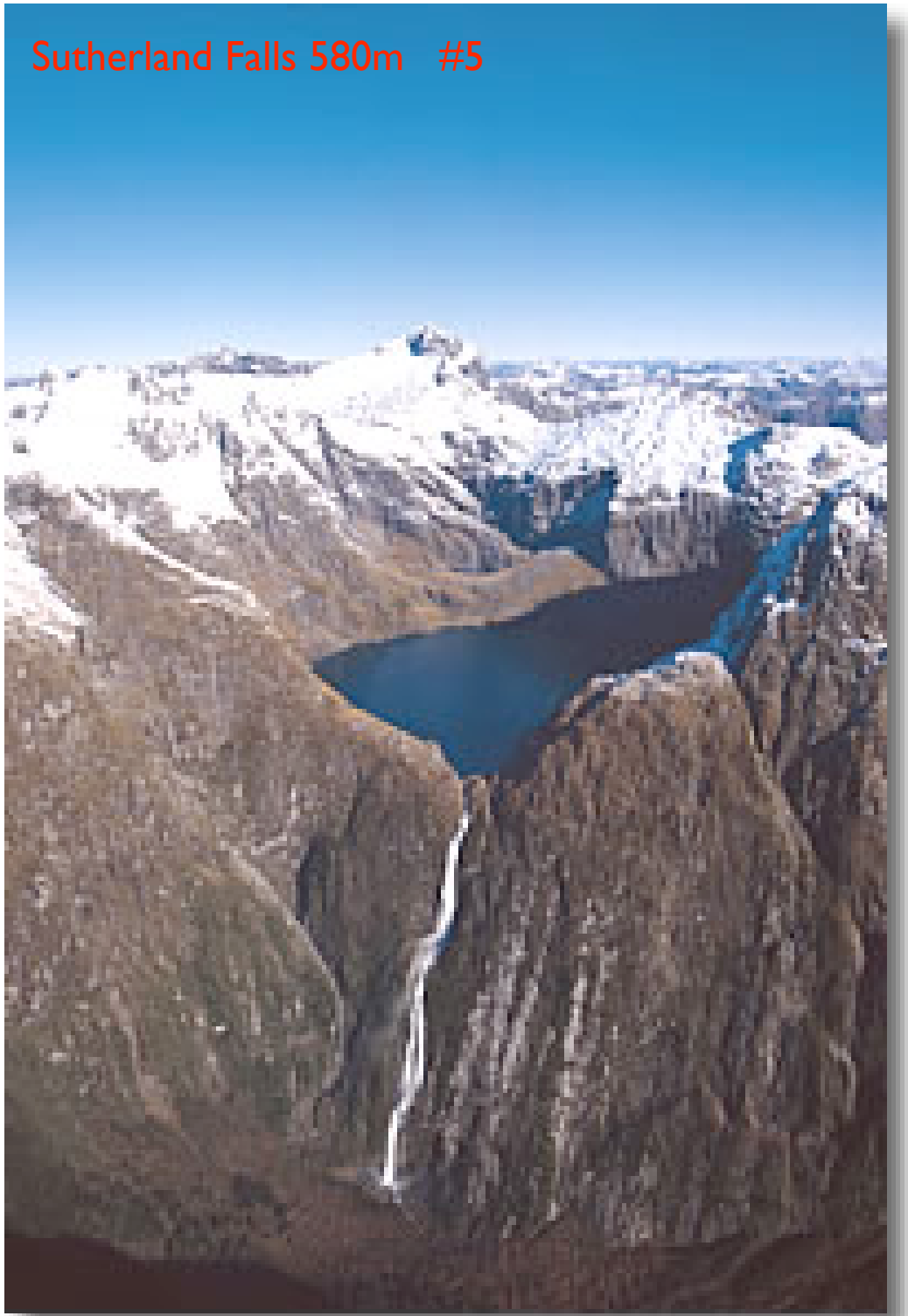
push the li

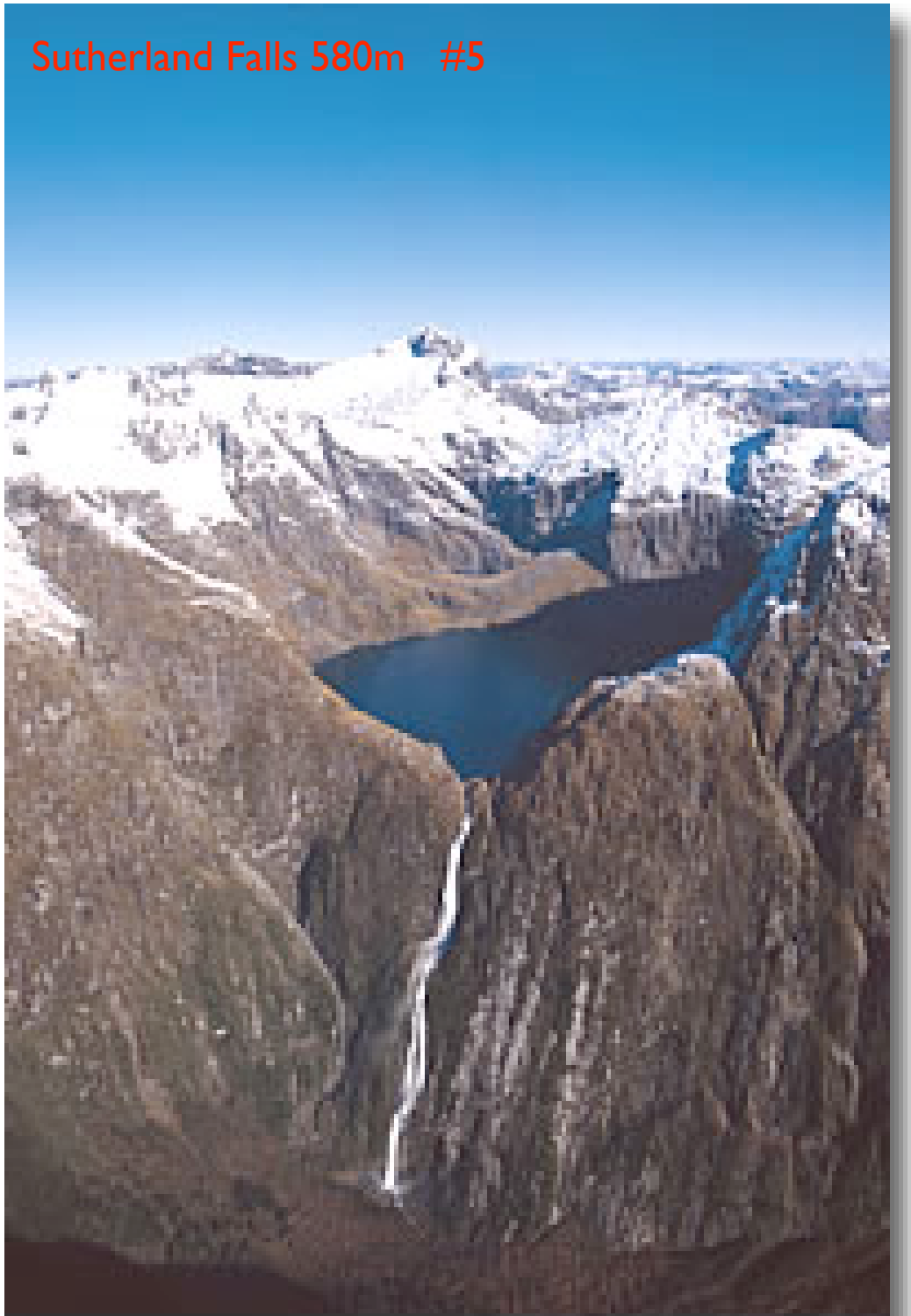
$\sin^2 2\theta_{13} <$



10x better sensitivity than current limit

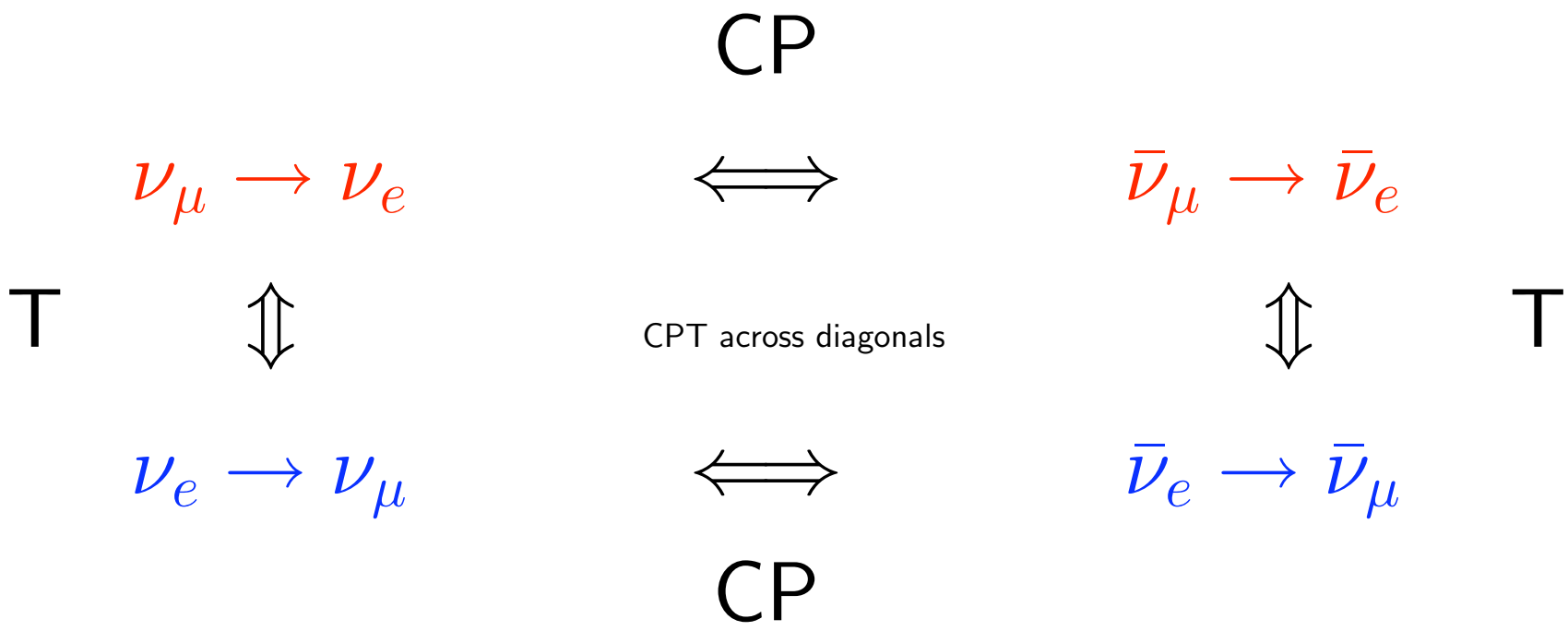



Sutherland Falls 580m #5



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

and related processes:



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

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

$$| \; U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} \; |^2$$

$\nu_\mu \longrightarrow \nu_e$

$$| \, U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} \, |^2$$

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

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

$\nu_\mu \longrightarrow \nu_e$

$$| \, U^*_{\mu 3} e^{-i m^2_3 L/2E} U_{e3} + U^*_{\mu 2} e^{-i m^2_2 L/2E} U_{e2} + U^*_{\mu 1} e^{-i m^2_1 L/2E} U_{e1} \, |^2$$

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

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

Atmospheric δm^2 — $\sqrt{P_{atm}}$

Solar δm^2 — $\sqrt{P_{sol}}$

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

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

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

CP violation !!!

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

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

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

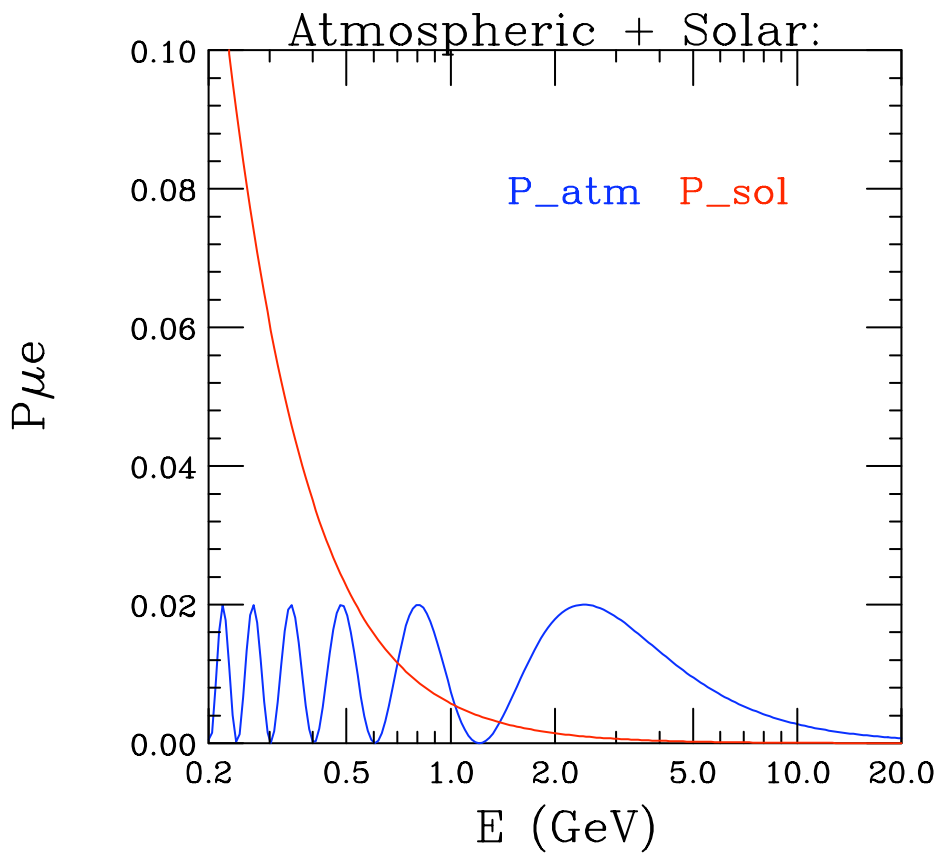
$$P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm} P_{sol}} \cos(\Delta_{32} \pm \delta) + P_{sol}$$

only CPV

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

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

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



x 3

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

For $L = 1200\ km$
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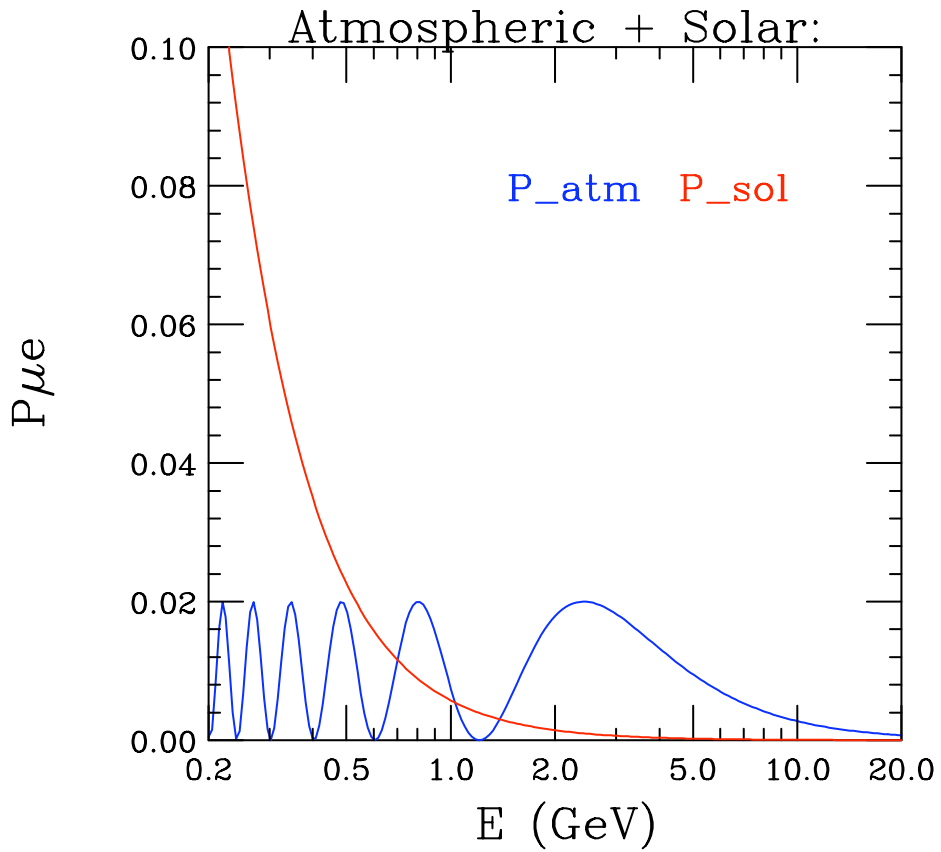
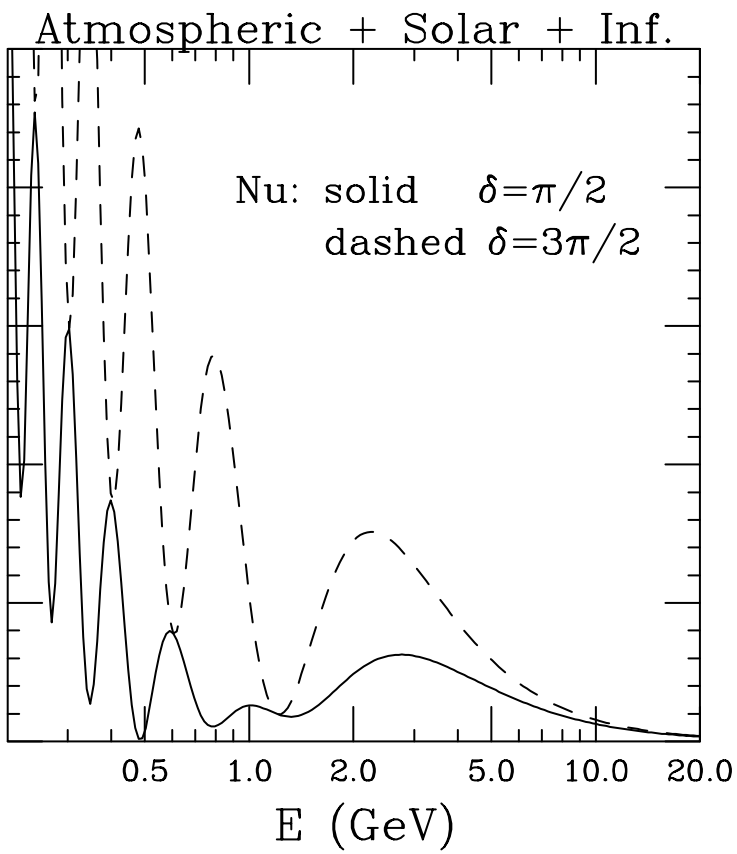


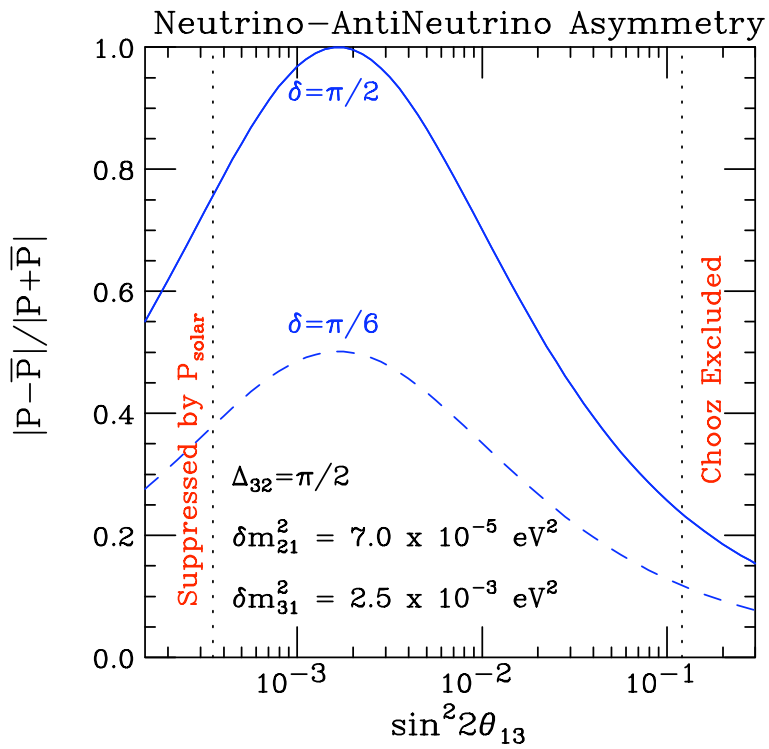
x 3



phase varies

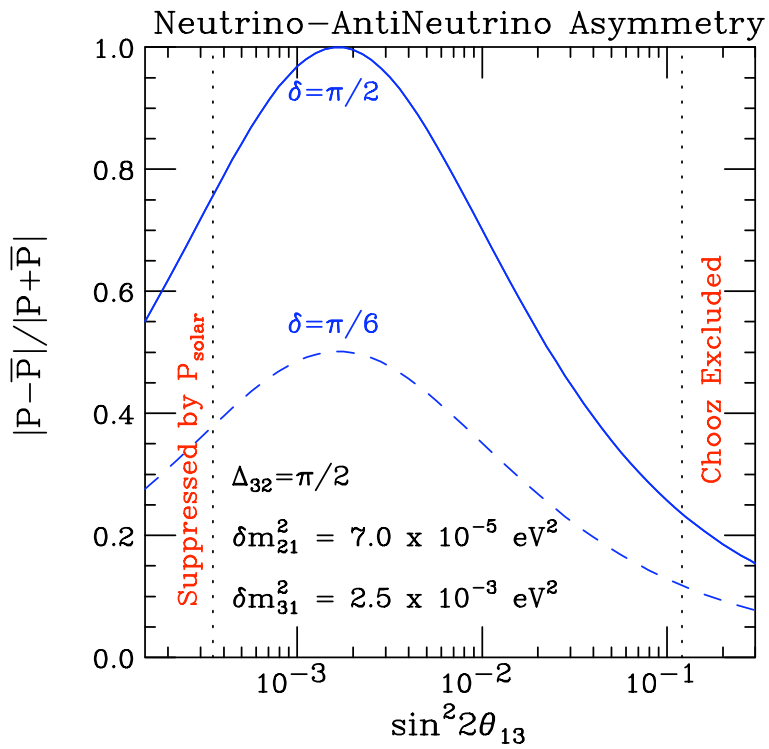
$$P_{\mu\to e} \approx \left| \sqrt{P_{atm}}\, e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

Asymmetry Peaks:



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

Asymmetry Peaks:



$$P_{atm} \leq P_{sol} \quad \text{when} \quad \sin^2 2\theta_{13} \leq \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}} \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \approx 0.001$$

In Matter:

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

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

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

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

In Matter:

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

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

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

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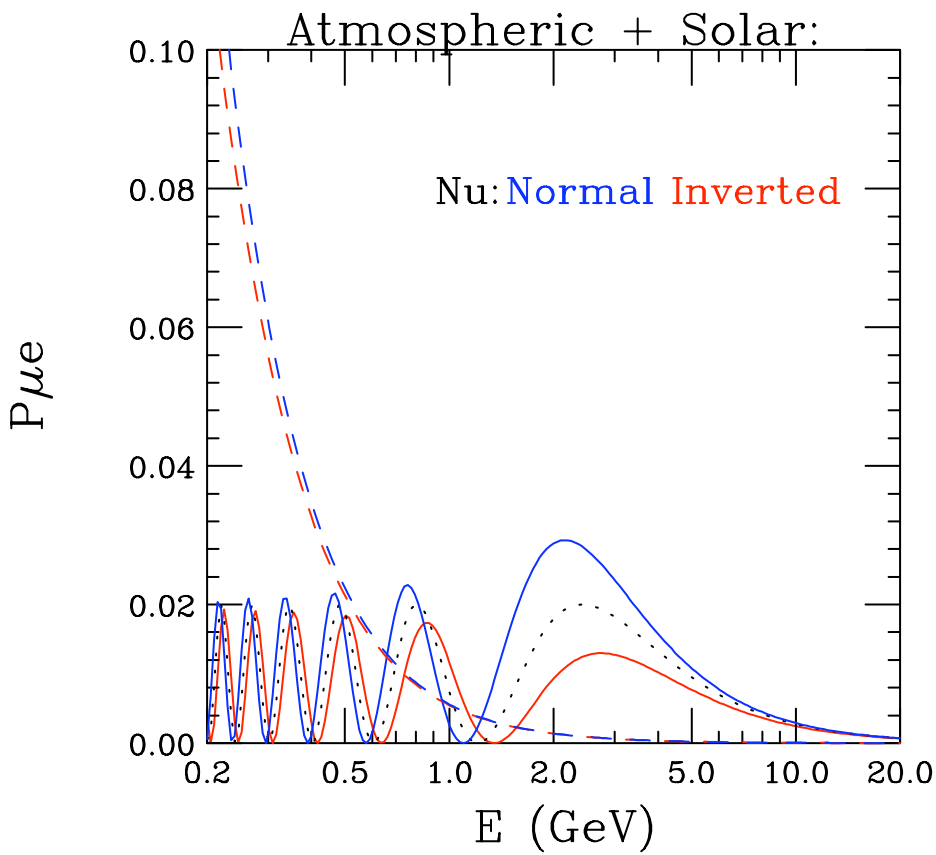

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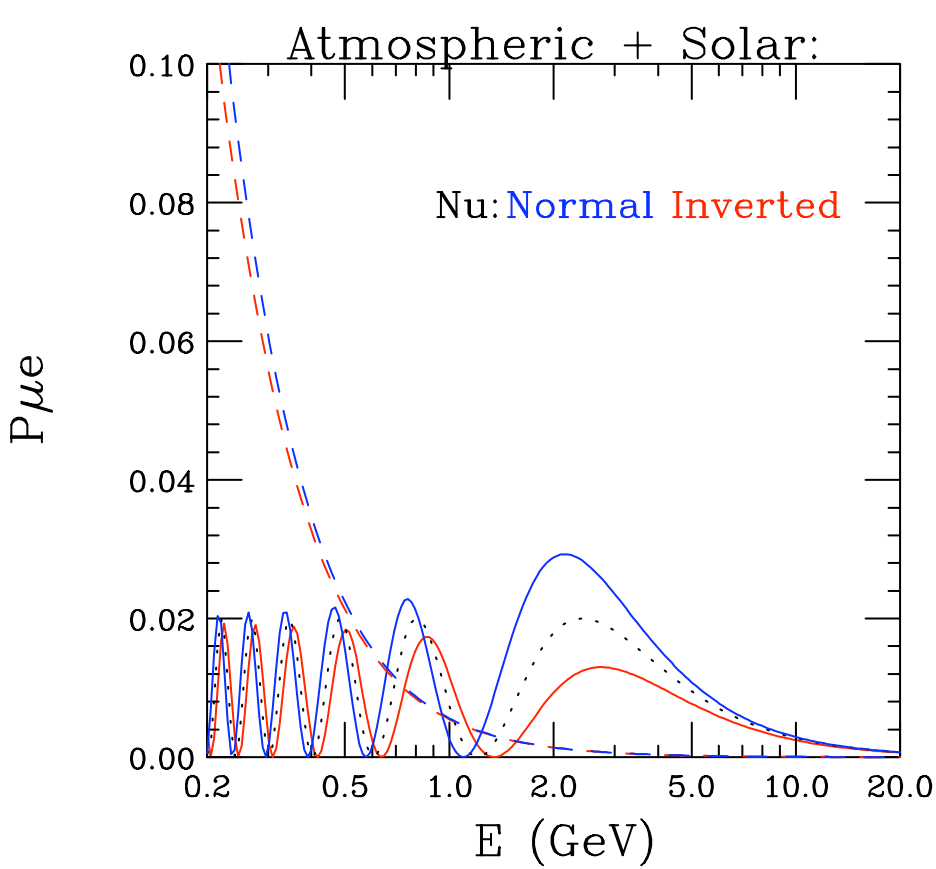
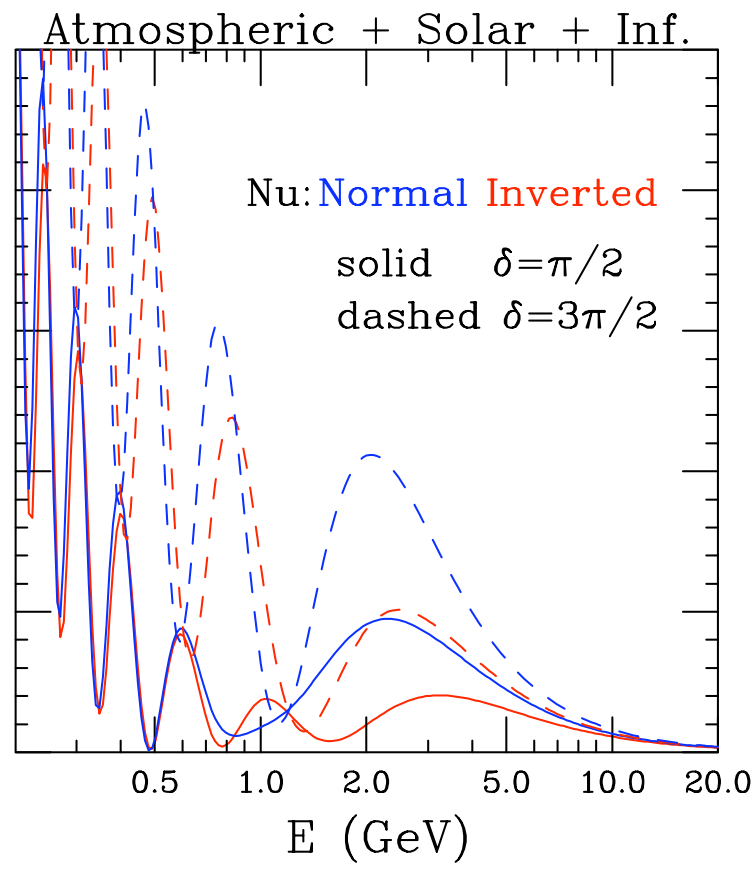
For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

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

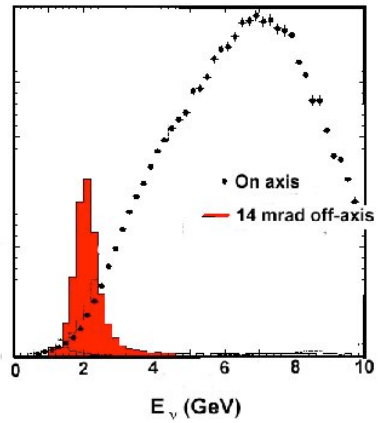
Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





Off-Axis Beams

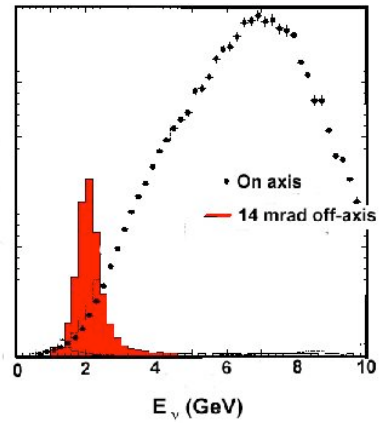
BNL 1994



π^0 suppression

Off-Axis Beams

BNL 1994



π^0 suppression

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

L=295 km and

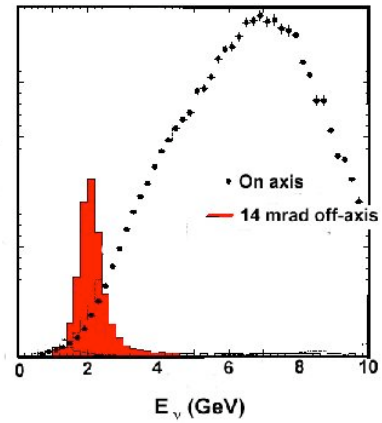
Energy at Vac. Osc. Max. (vom)

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

0.75 upgrade to 4 MW

Off-Axis Beams

BNL 1994



π^0 suppression

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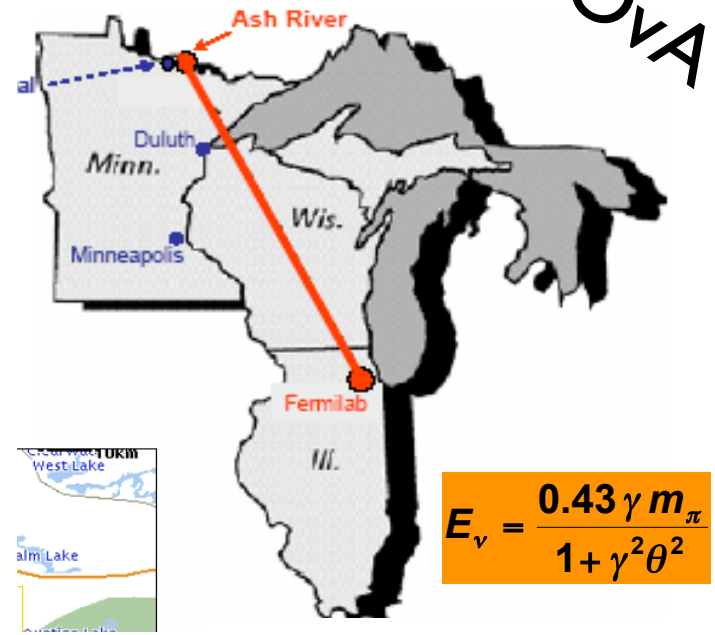
NOvA



$$E_\nu = \frac{0.43\,\gamma\, m_\pi}{1+\gamma^2\theta^2}$$

L=700 - 1000 km and

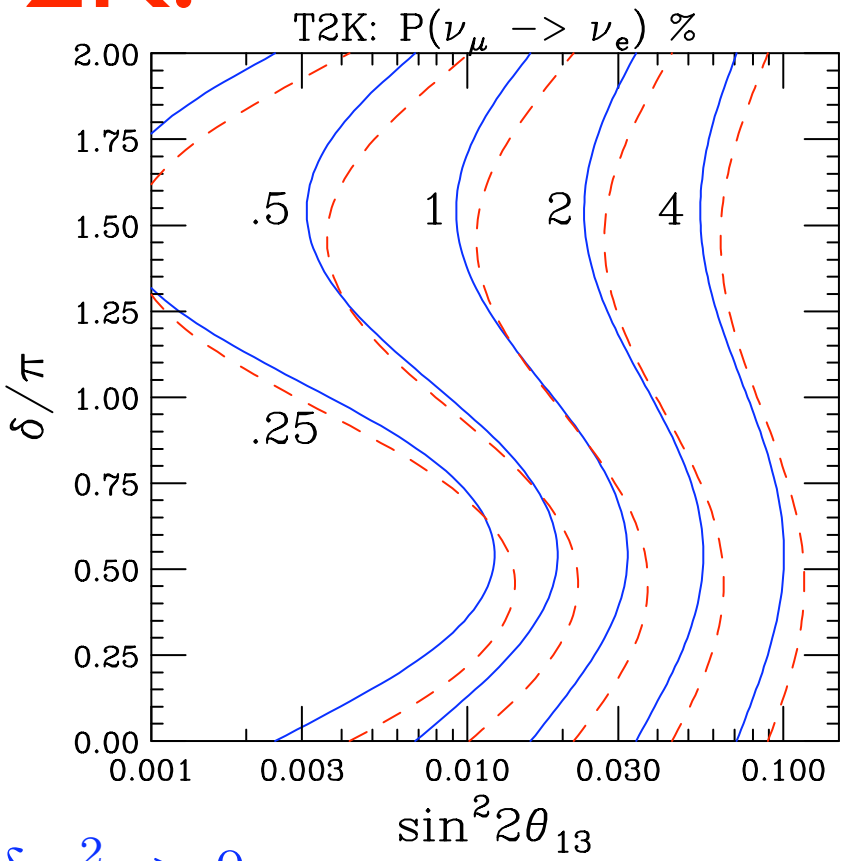
Energy near 2 GeV

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

0.4 upgrade to 2 MW

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

T2K:

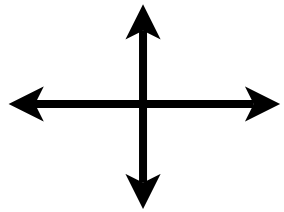


$\delta m^2_{31} > 0$

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

Beam 1%

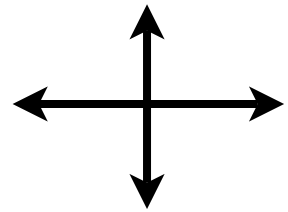
VOM: $\Delta_{31} \neq \pi/2$



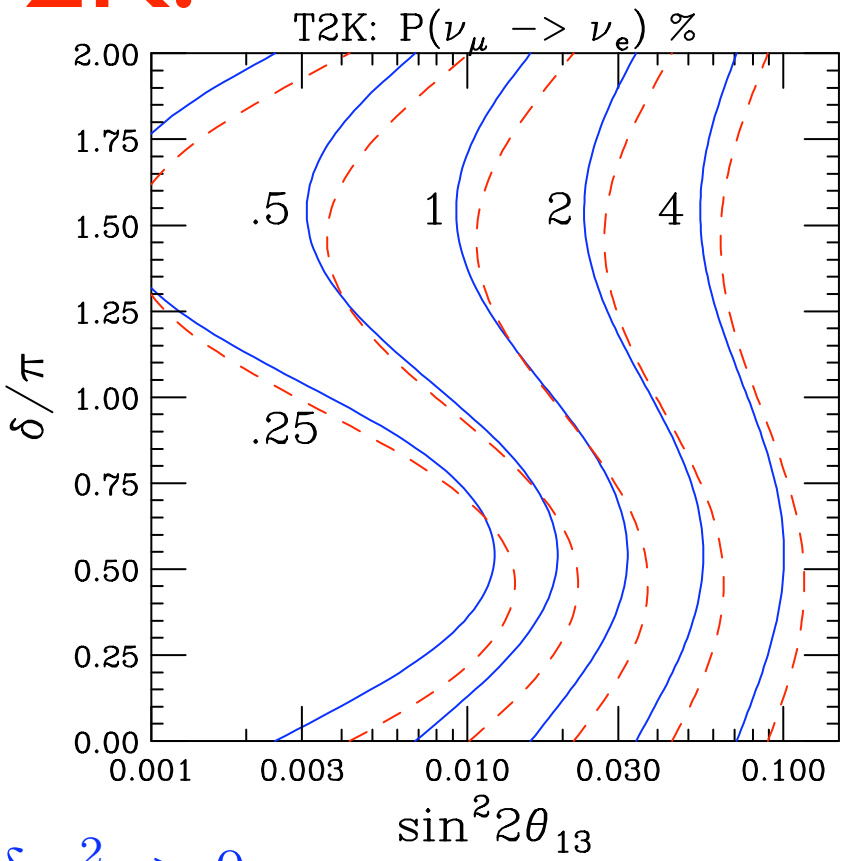
Matter Effect:

T2K:

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



Matter Effect:

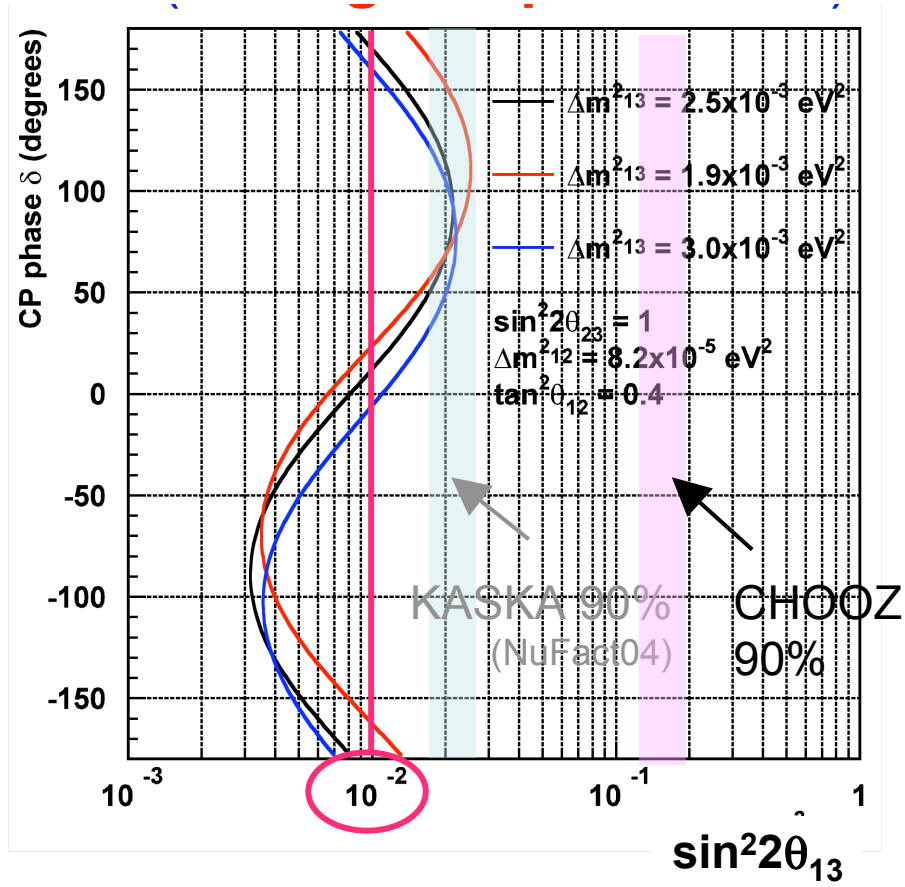


$\delta m^2_{31} > 0$

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

Beam 1%

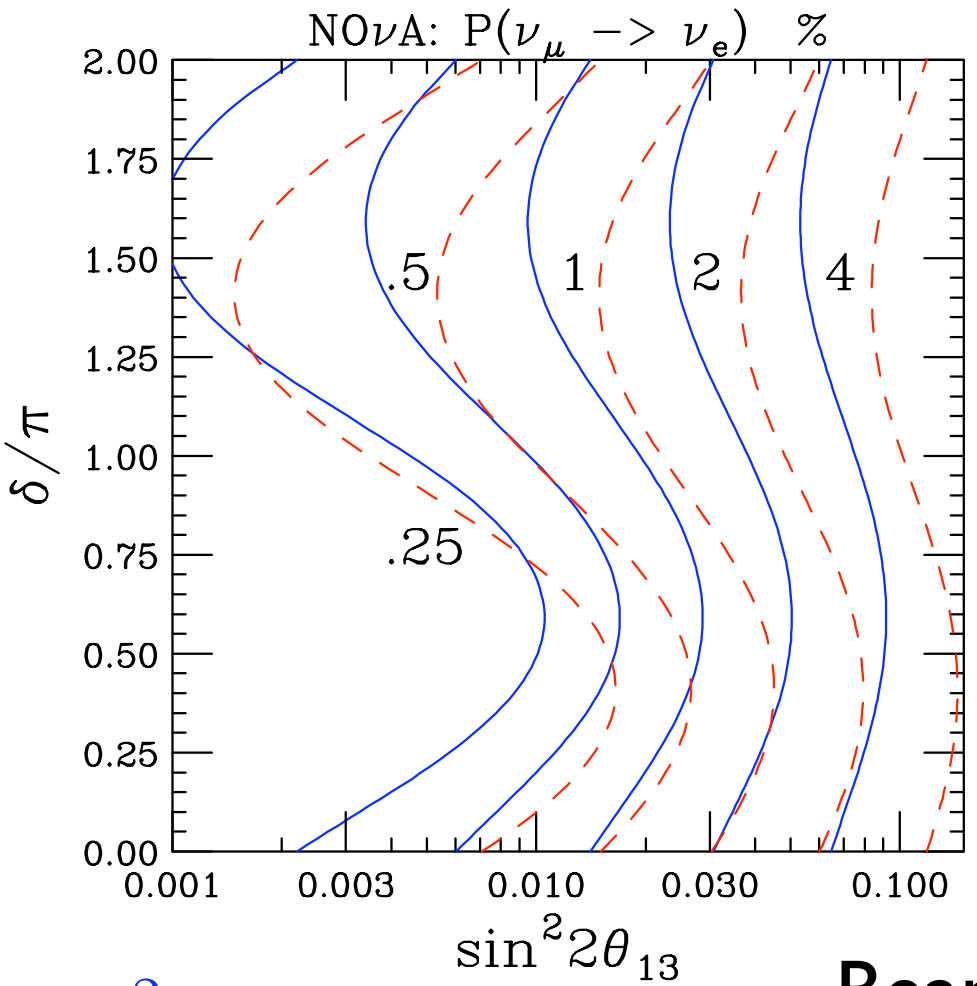
Aihara for T2K, P5 talk



Phase I

Sensitivity approx 0.5%

NOvA:

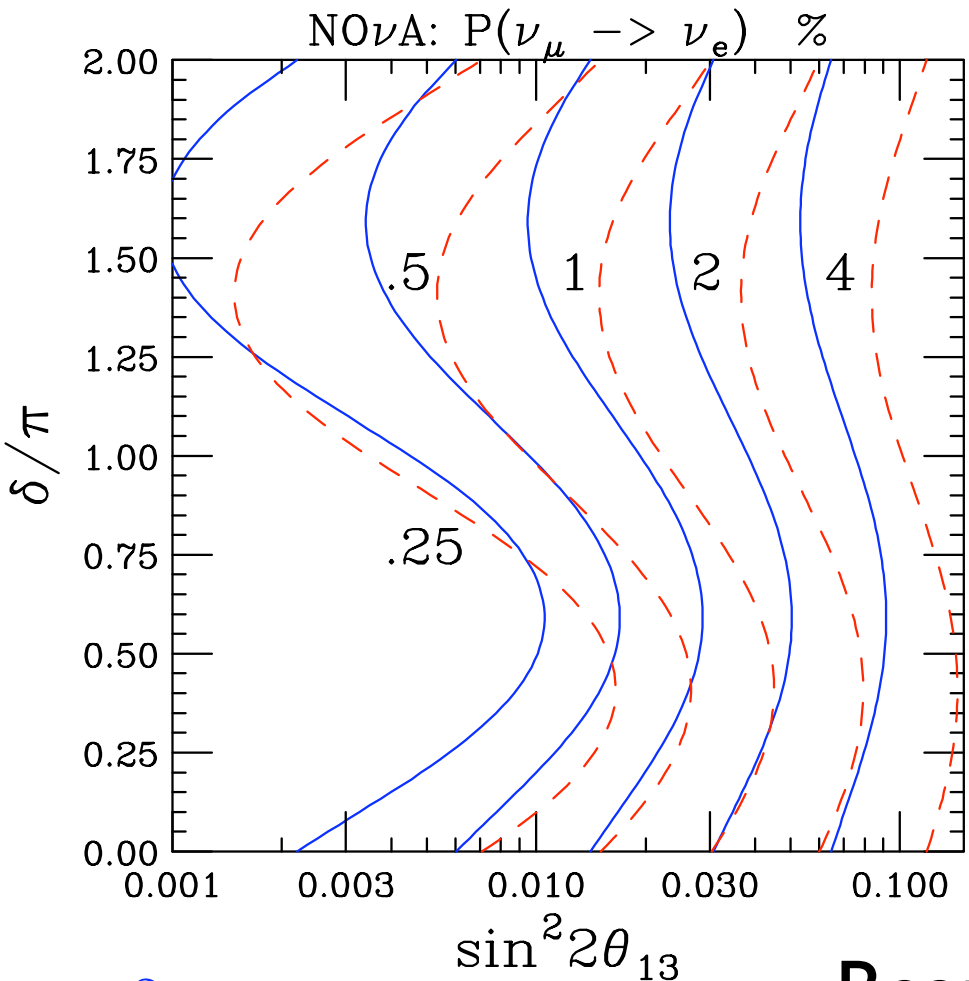


Beam 1%

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

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

NOvA:



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

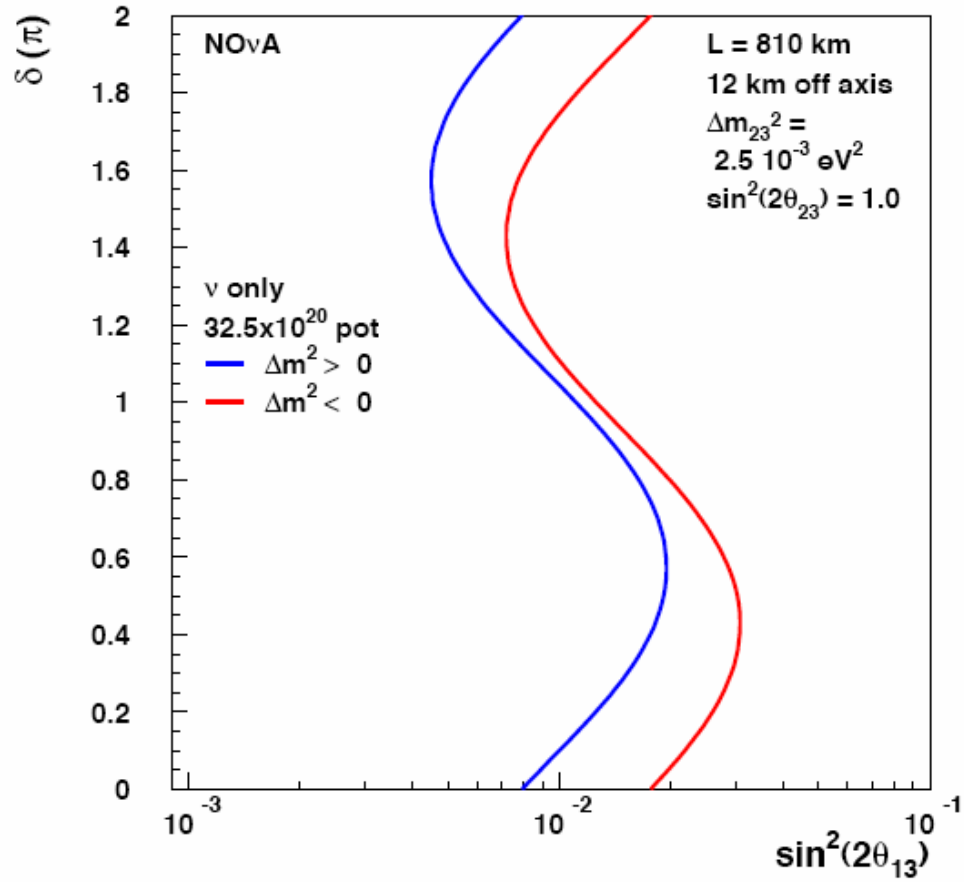
$\delta m^2_{31} < 0$

Beam 1%

Phase I

Sensitivity approx 0.5%

NOvA @ NO-VE 2007

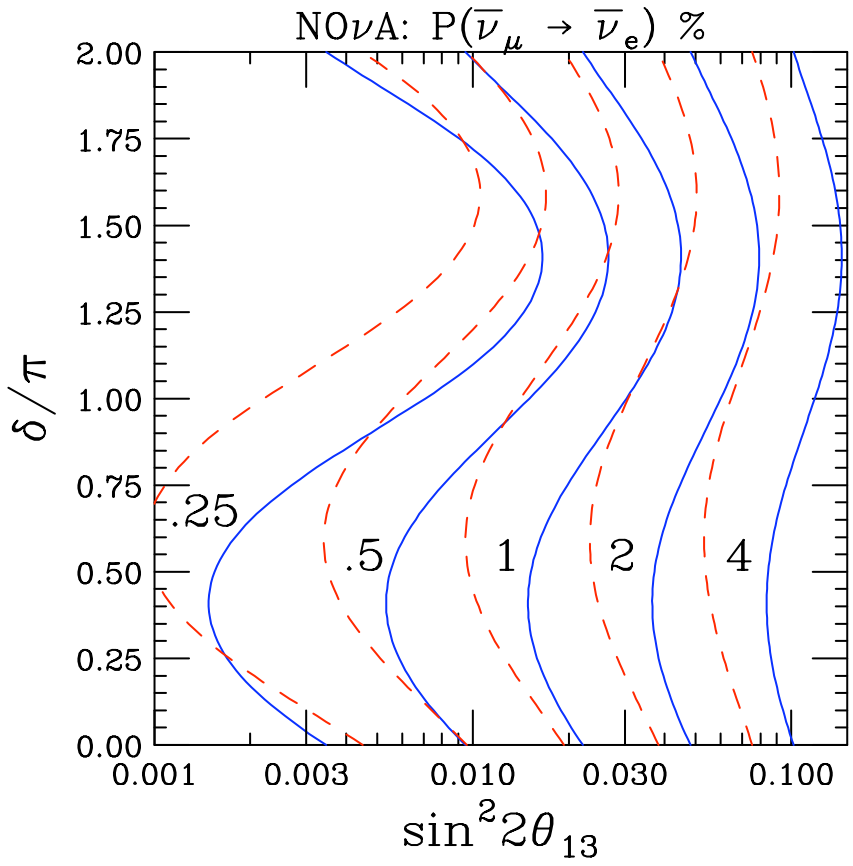


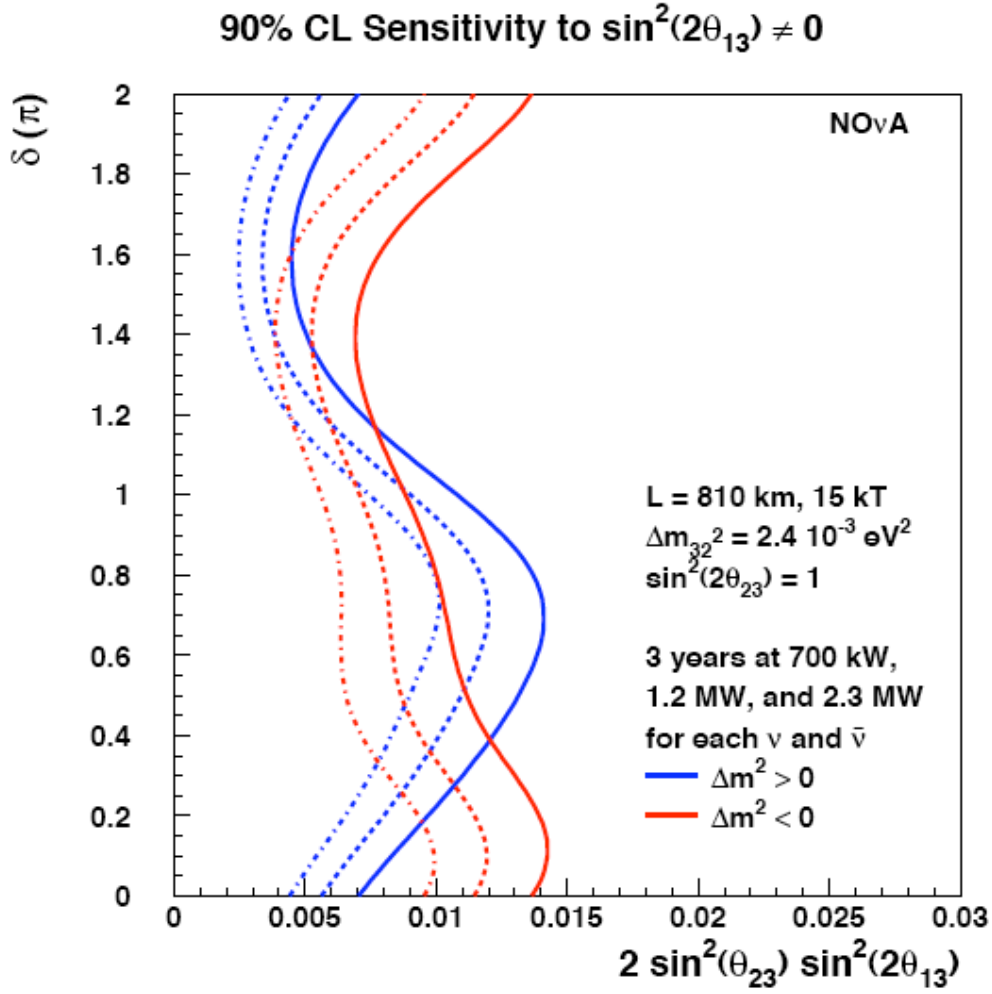
5 years with ν only run

NOvA:

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

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





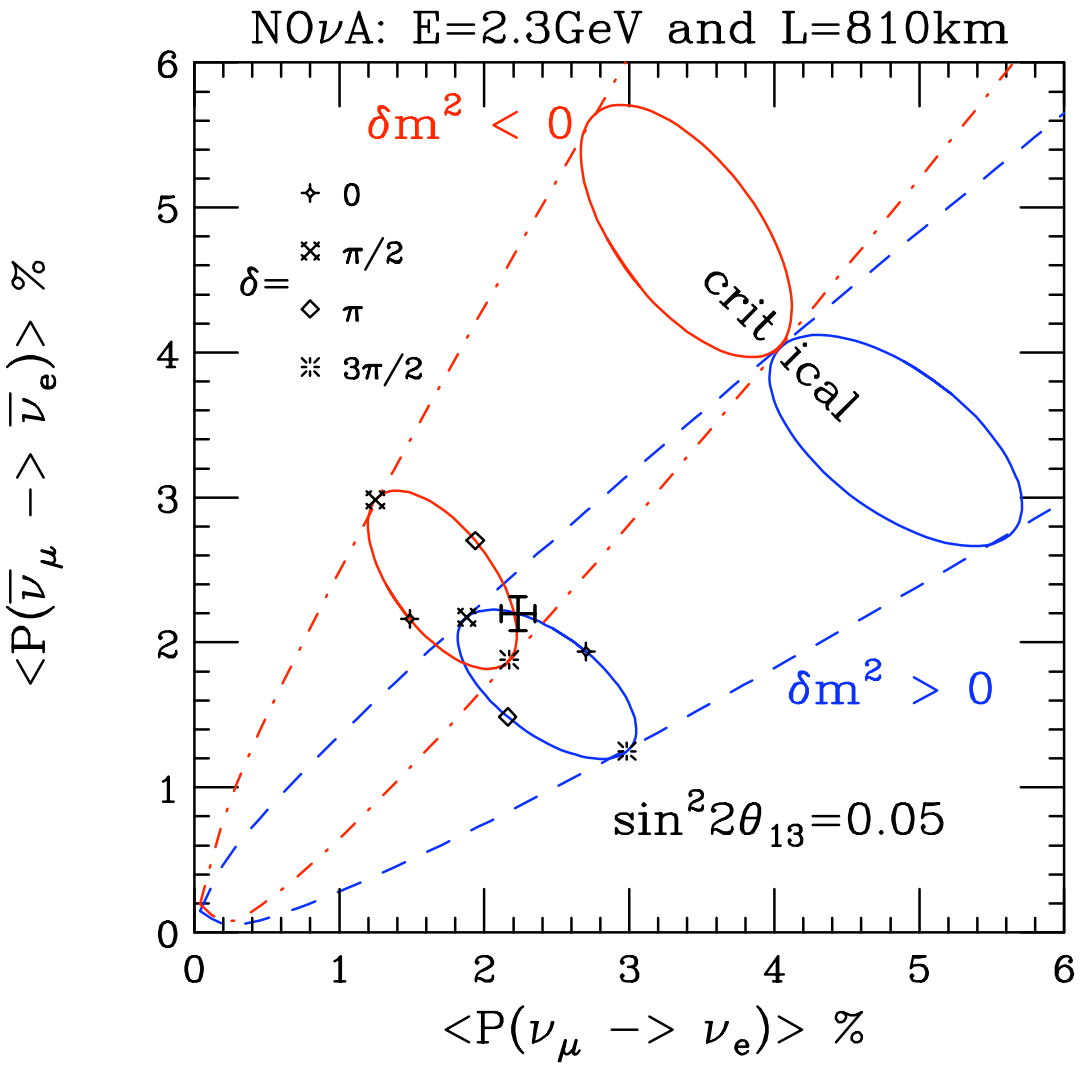
Beam ~1%

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

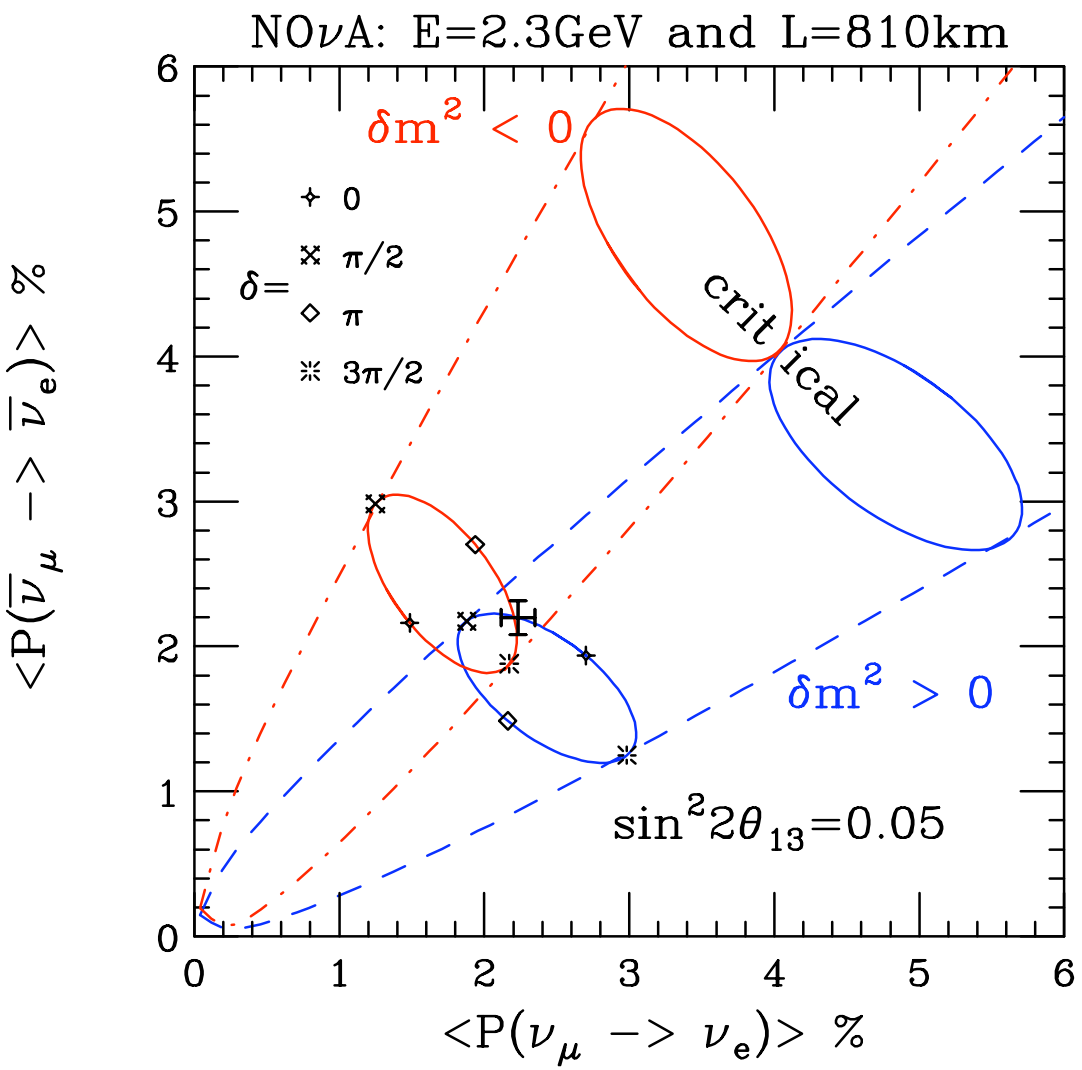
Correlations between

$$P(\nu_\mu \to \nu_e) \quad \text{and} \quad P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

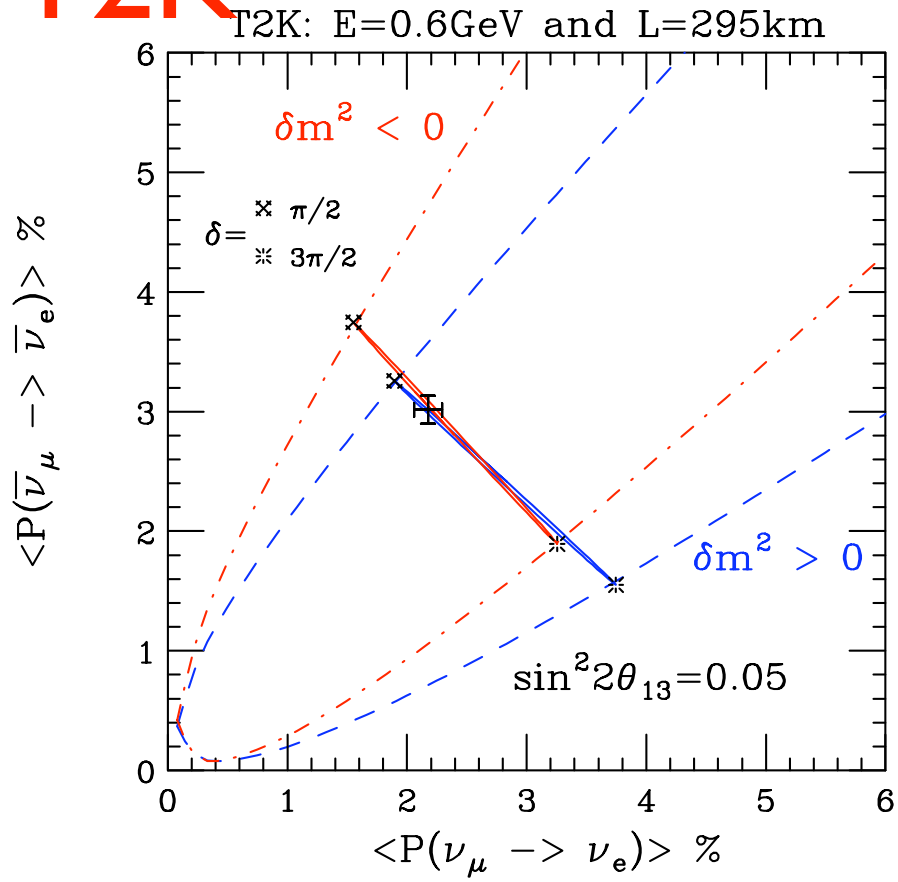
NOvA:


NOνA: E=2.3GeV and L=810km
δm² < 0
δm² > 0
critical
δ=
0
π/2
π
3π/2
sin²2θ13=0.05
<P(νμ -> νe)> %
<P(ν̄μ -> ν̄e)> %
0
1
2
3
4
5
6

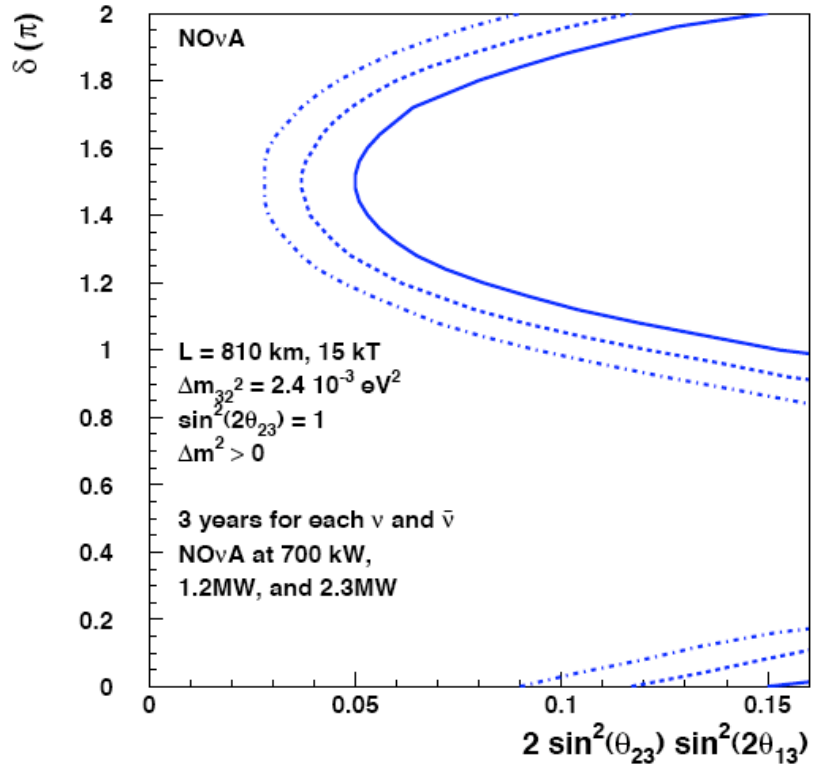
NOvA:


NOνA: E=2.3GeV and L=810km
δm² < 0
δm² > 0
critical
δ=
0
π/2
π
3π/2
sin²2θ13=0.05
<P(ν̄μ -> ν̄e)> %
<P(νμ -> νe)> %

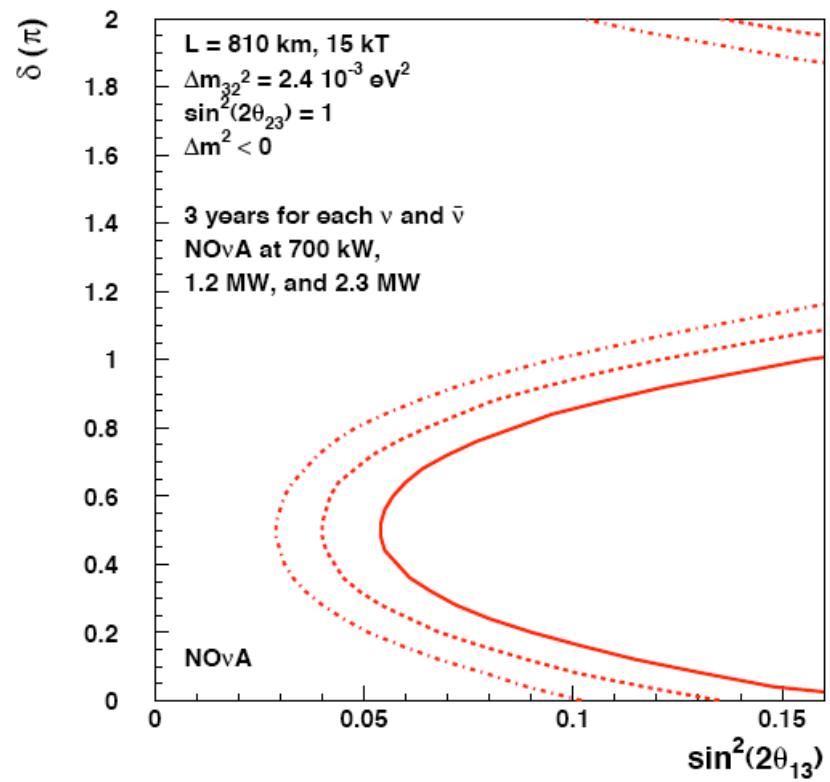
T2K


T2K: E=0.6GeV and L=295km
δm² < 0
δm² > 0
δ=
π/2
3π/2
sin²2θ13=0.05
<P(ν̄μ -> ν̄e)> %
<P(νμ -> νe)> %

95% CL Resolution of the Mass Ordering
NOνA Alone

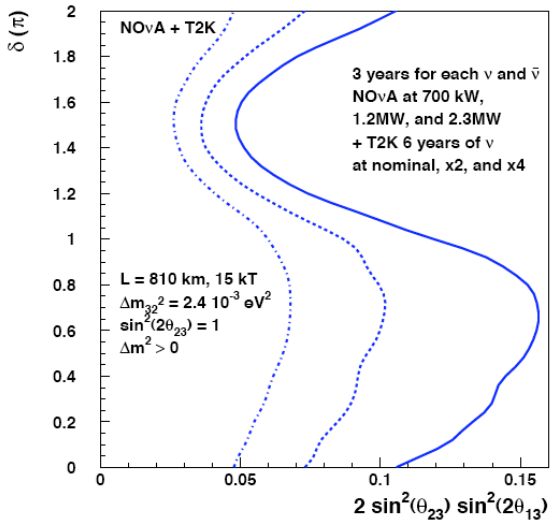


Normal Ordering

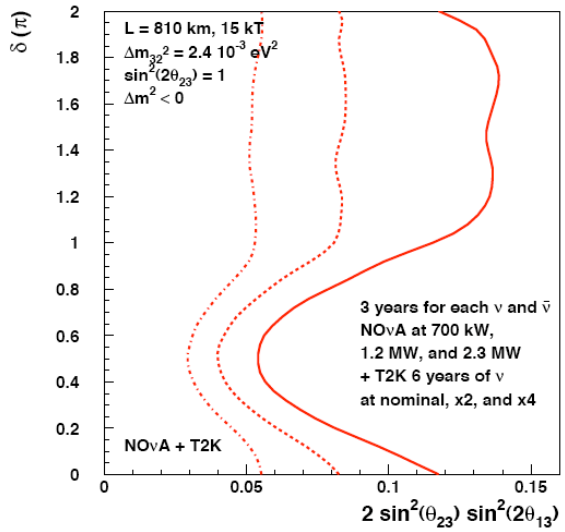


Inverted Ordering

95% CL Resolution of the Mass Ordering
NOνA Plus T2K

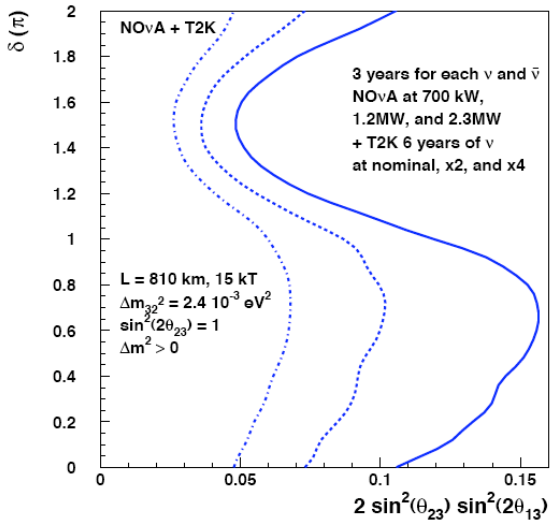


Normal Ordering

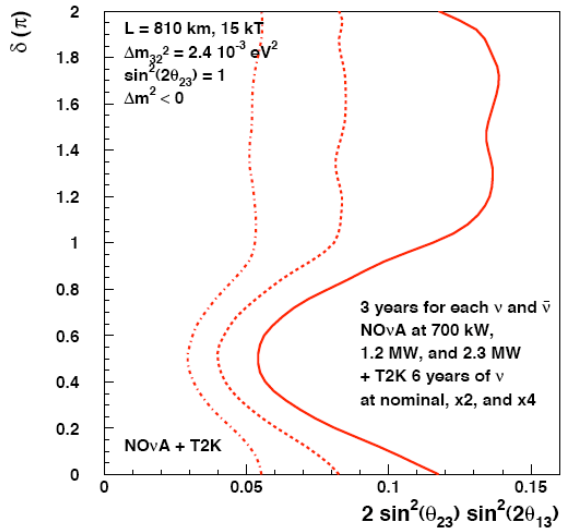


Inverted Ordering

95% CL Resolution of the Mass Ordering
NOνA Plus T2K



Normal Ordering

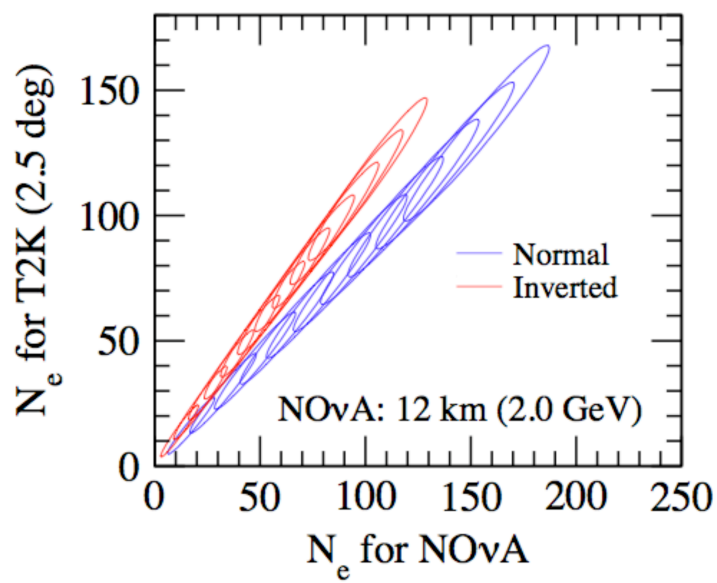


Inverted Ordering

T2K + NOνA, Neutrino Only, $\sin^2 2\theta_{13}$=0.01,0.02,..,0.1

T2K: 0.75 MW, 5 yrs, 22.5 kton

NOνA: 6.5e20 POT/yr, 5 yrs, 30 kton, 24%



Sensitivity to CP violation: $\sin\delta$

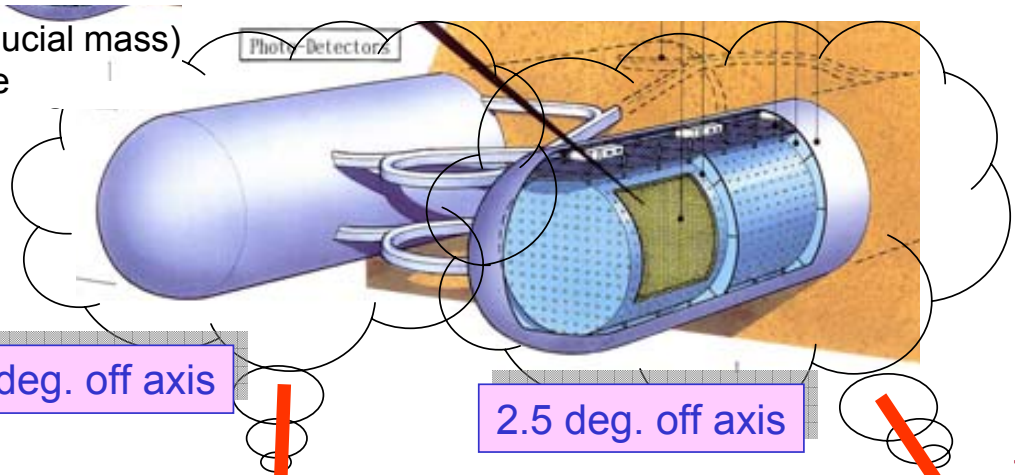
Events = efficiency * Fid. Mass * Protons on Target

(Power * Time)

Off Axis:

Some recent progress: detector in Korea

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande



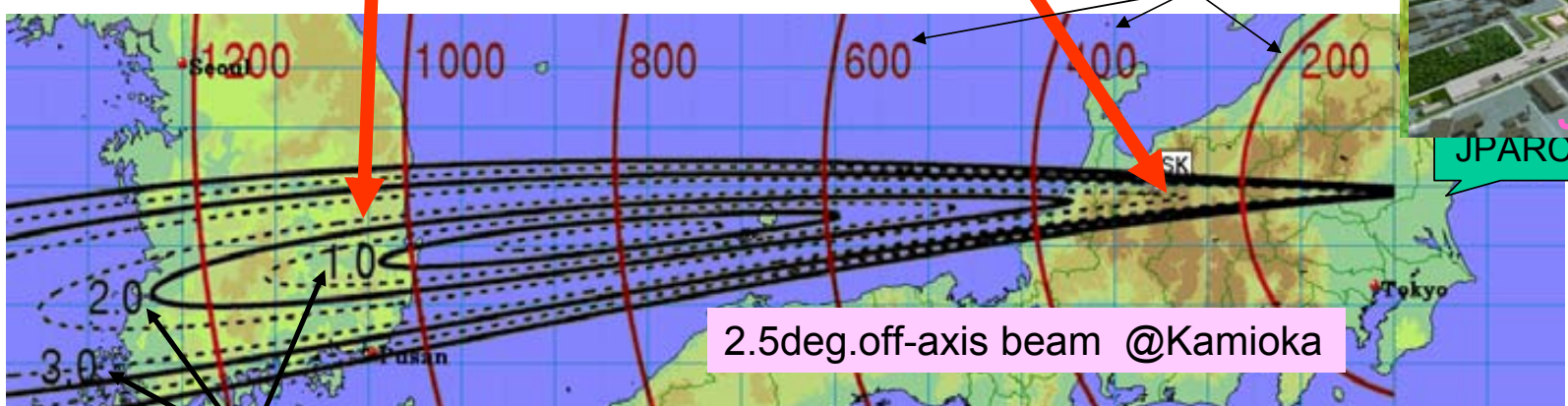
Total cost must be similar to the baseline design.

2.5 deg. off axis

2.5 deg. off axis

Distance from the target (km)

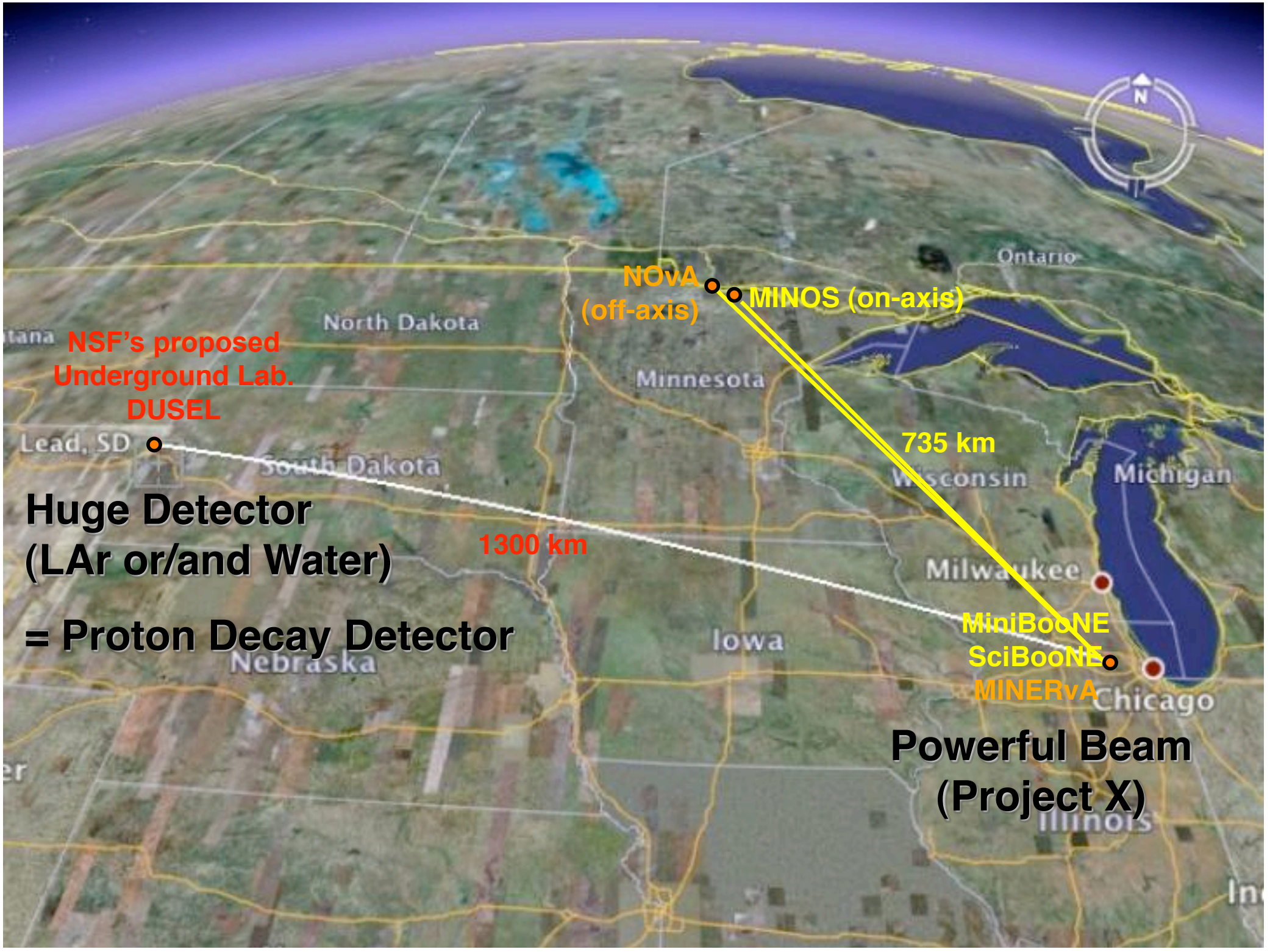
JPARC



2.5deg.off-axis beam @Kamioka

Off-axis angle

see Kajita talk:


NOvA
(off-axis)
MINOS (on-axis)
NSF's proposed
Underground Lab.
DUSEL
Lead, SD
735 km
1300 km
Huge Detector
(LAr or/and Water)
= Proton Decay Detector
MiniBooNE
SciBooNE
MINERvA
Powerful Beam
(Project X)
North Dakota
Minnesota
South Dakota
Nebraska
Iowa
Wisconsin
Michigan
Ontario
Milwaukee
Chicago
Illinois
N

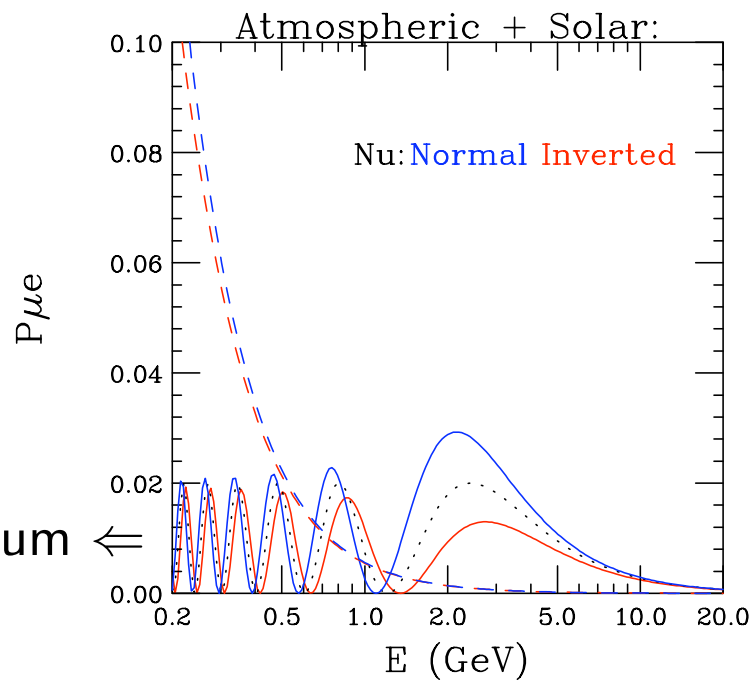
Narrow Band Beam: Same E, Longer L T2KK

Broadband Beam: Same L, Lower E Fermilab to DUSEL

In VACUUM the SAME but NOT in MATTER

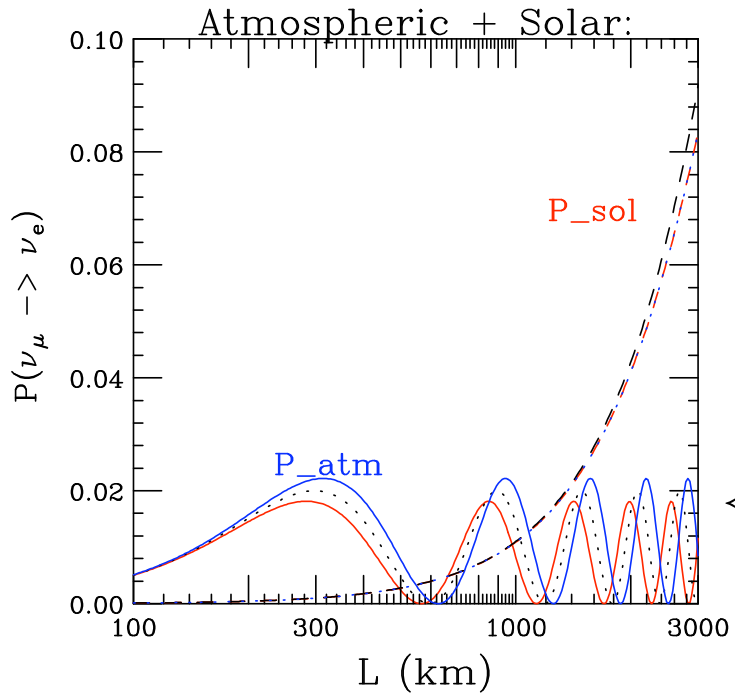
$$\sin^2 2\theta_{13} = 0.04$$

L=1200km



vacuum $\Leftarrow$

E=0.6 GeV



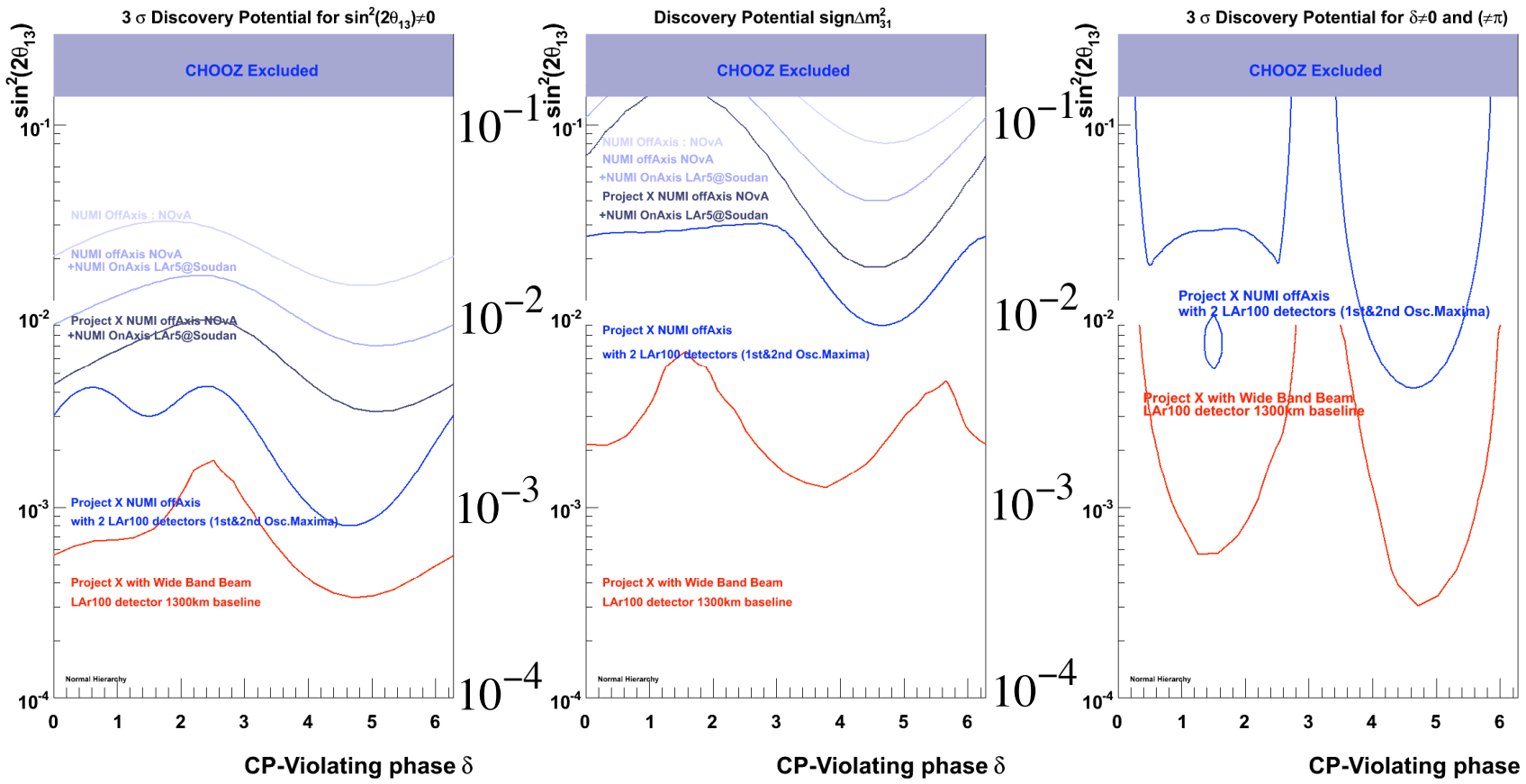
$\Leftarrow$ same height

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

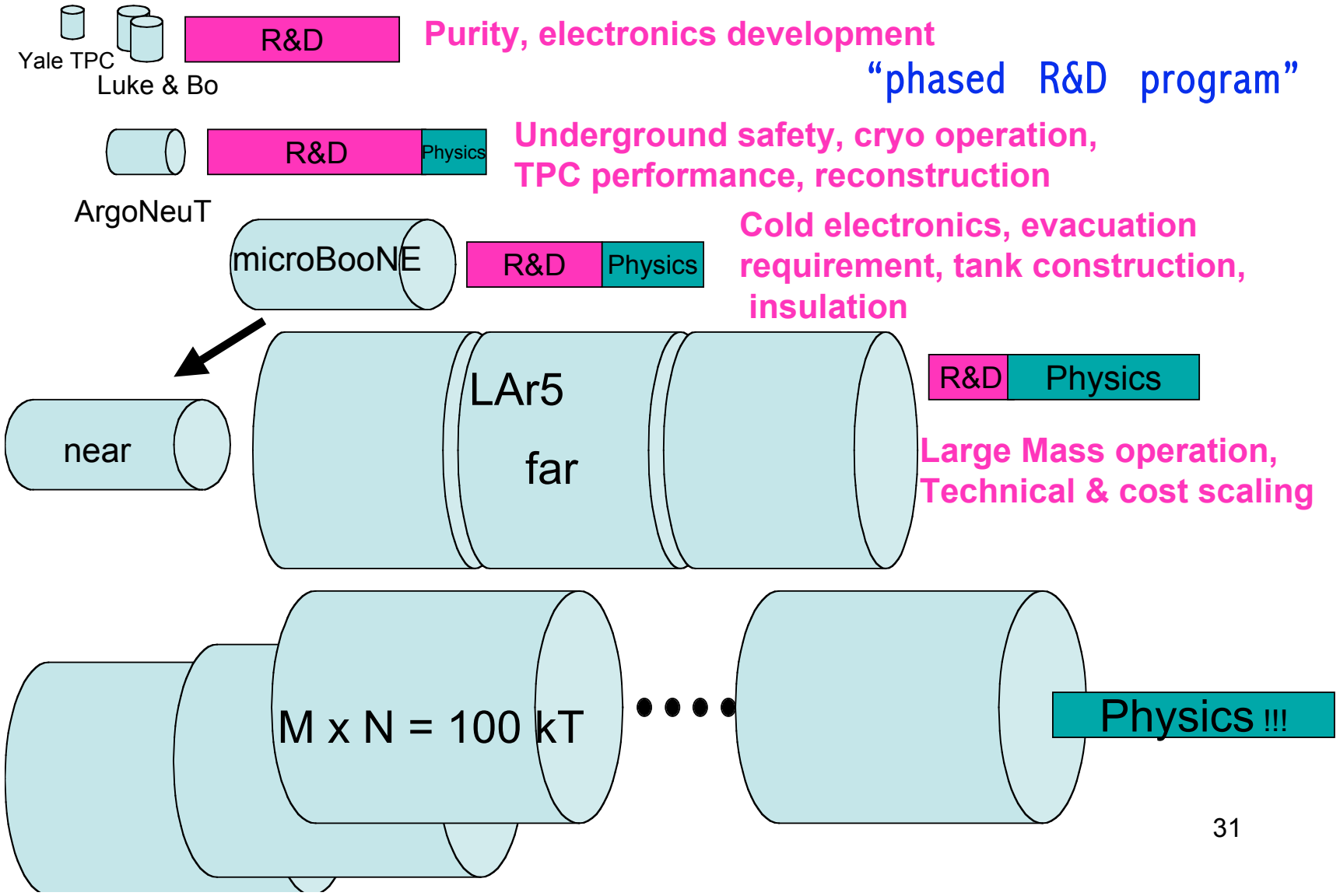
Fermilab to DUSEL (T2KK similar)

The 3σ Reach of the Successive Phases

$\sin^2 2\theta_{13}$ | Mass Ordering | CP Violation



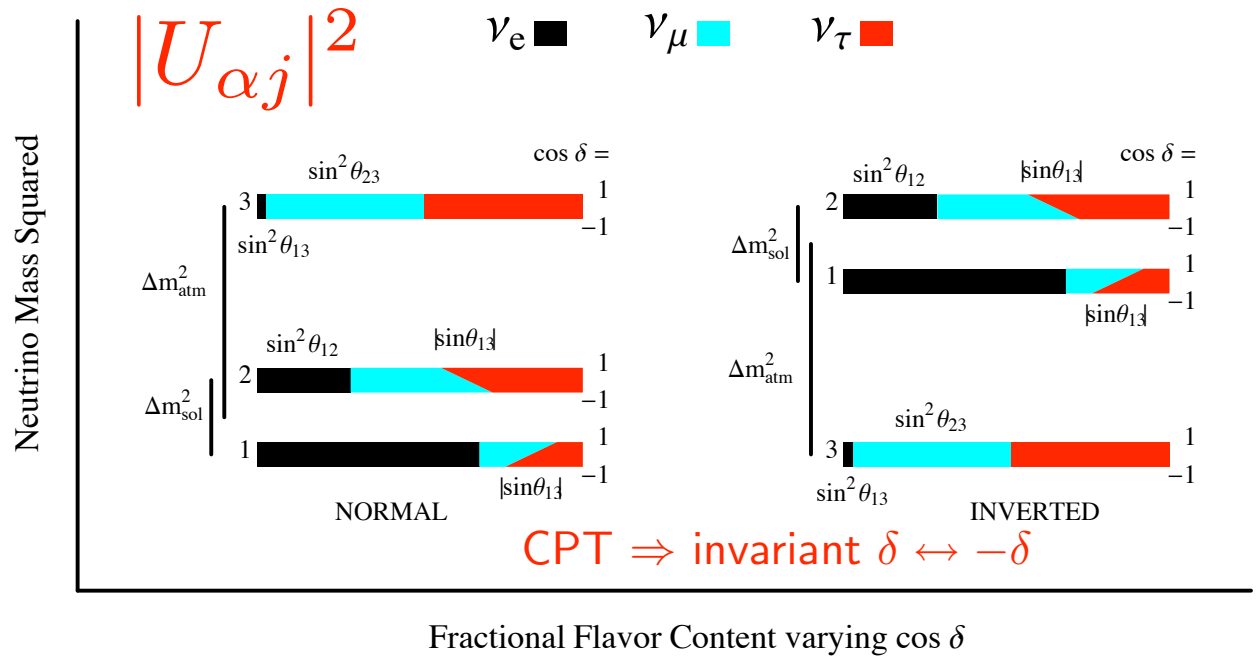
Evolution of the Liquid Argon Physics Program



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

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

Summary:



CP

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

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

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

CP

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

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

Neutrino 2008
May 25-31

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Antipodal NZ

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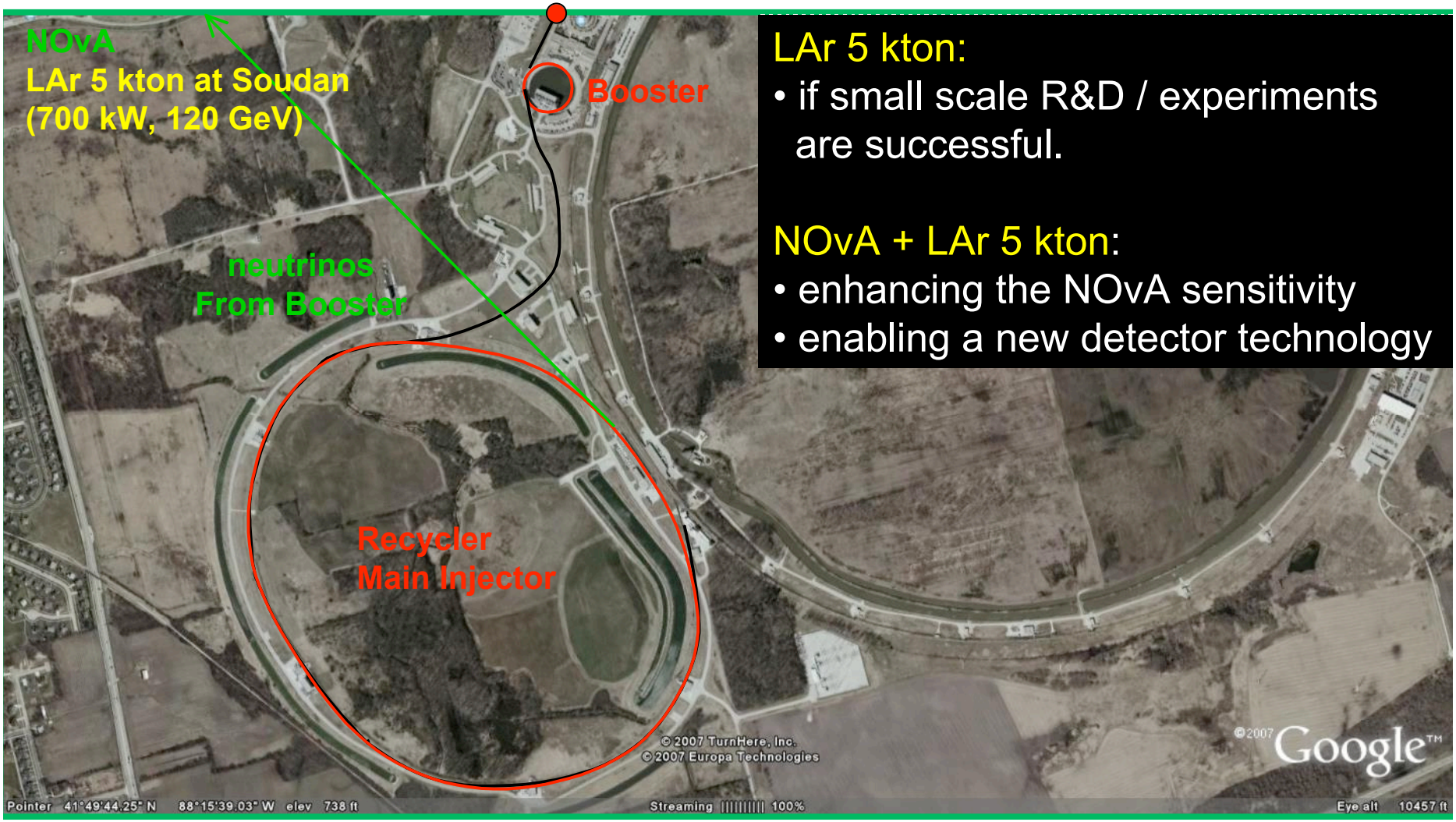
Phase 1.5:


NOvA
LAr 5 kton at Soudan
(700 kW, 120 GeV)
Booster
neutrinos
From Booster
Recycler
Main Injector
LAr 5 kton:
• if small scale R&D / experiments are successful.
NOvA + LAr 5 kton:
• enhancing the NOvA sensitivity
• enabling a new detector technology
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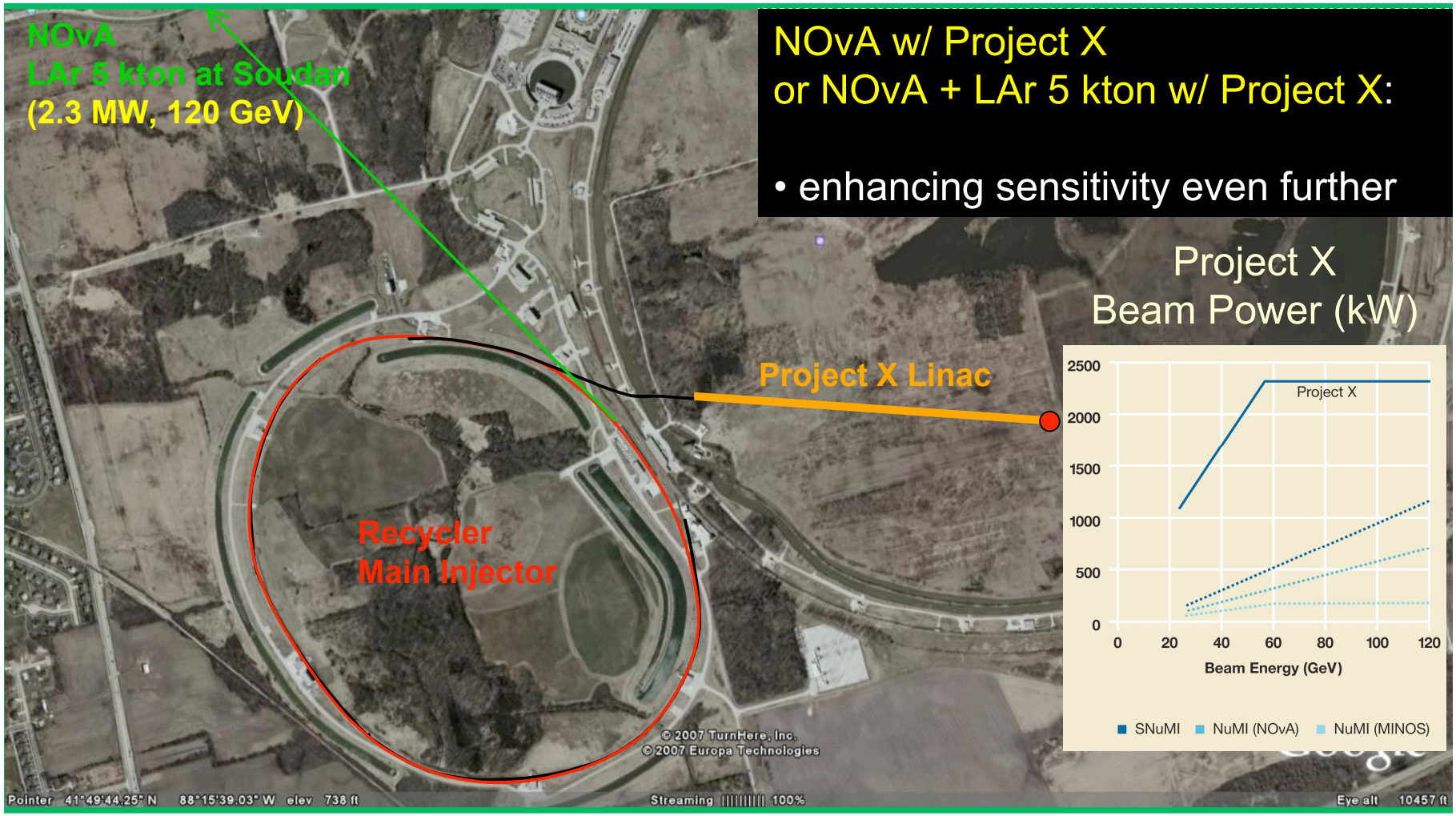
©2007 Google™
Pointer 41°49'44.25" N 88°15'39.03" W elev 738 ft
Streaming 100%
Eye alt 10457 ft

Phase 2:


NOvA
LAr 5 kton at Soudan
(2.3 MW, 120 GeV)
NOvA w/ Project X
or NOvA + LAr 5 kton w/ Project X:
• enhancing sensitivity even further
Project X Linac
Recycler
Main Injector
Project X
Beam Power (kW)
2500
2000
1500
1000
500
0
0
20
40
60
80
100
120
Project X
Beam Energy (GeV)
SNuMI
NuMI (NOvA)
NuMI (MINOS)
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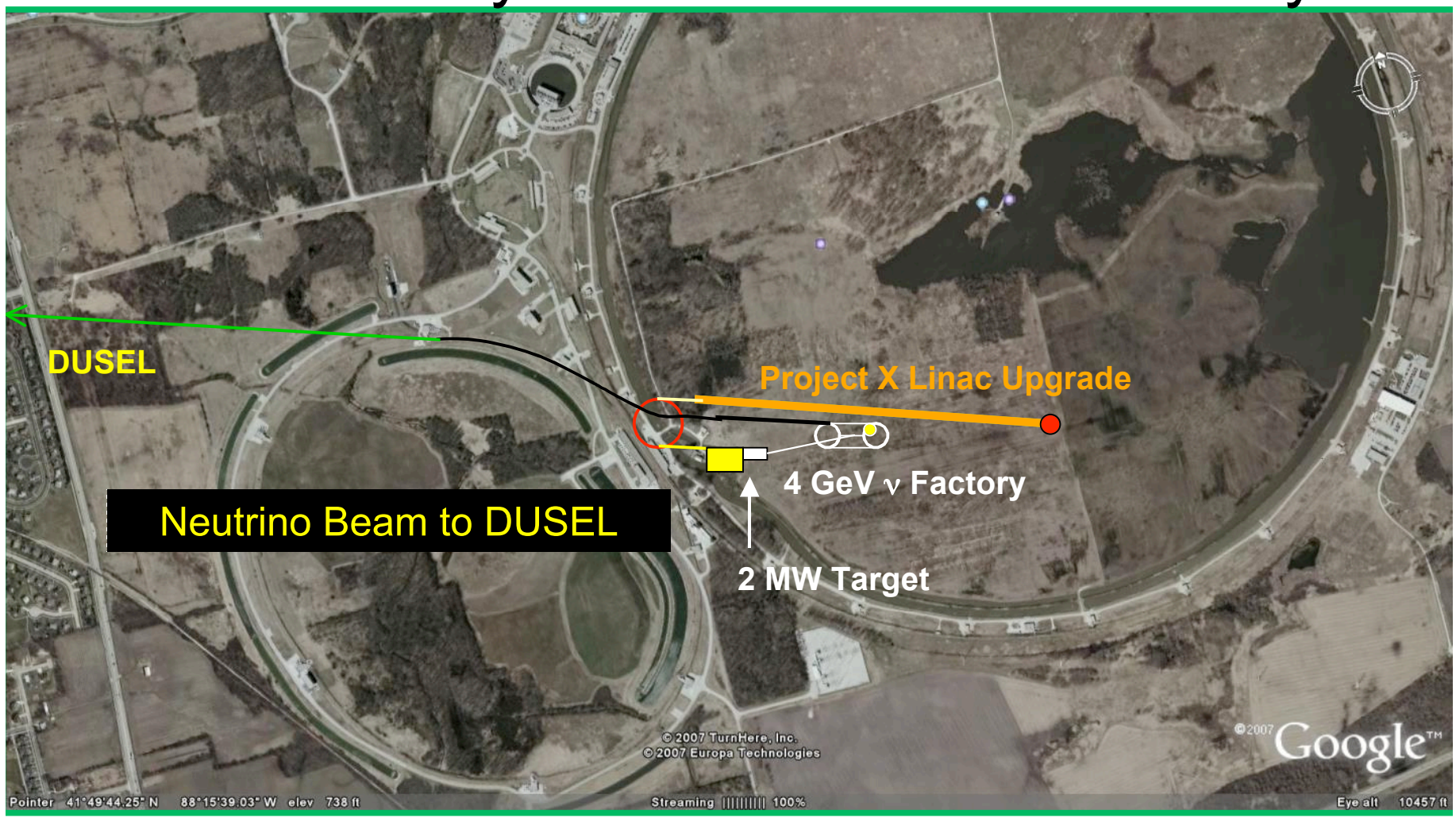
Pointer 41°49'44.25" N 88°15'39.03" W elev 738 ft
Streaming 100%
Eye alt 10457 ft

Toward "Proton Intensity Upgrade" Evolutionary Path to a Neutrino Factory



Evolutionary Path to a $\mu^+\mu^-$ Collider