CP Violation in the Neutrino Sector

FPCP 2008:

Stephen Parke
Fermilab

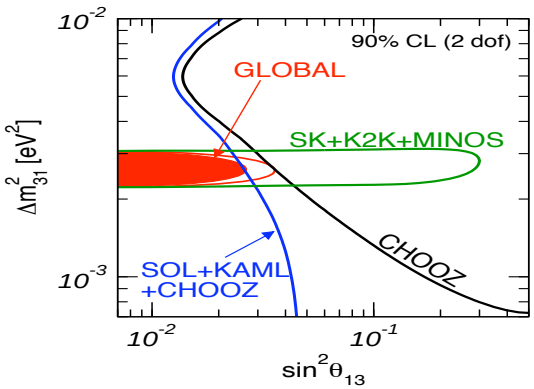
$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

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

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

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



Maltoni etal hep-ph/0405172v5

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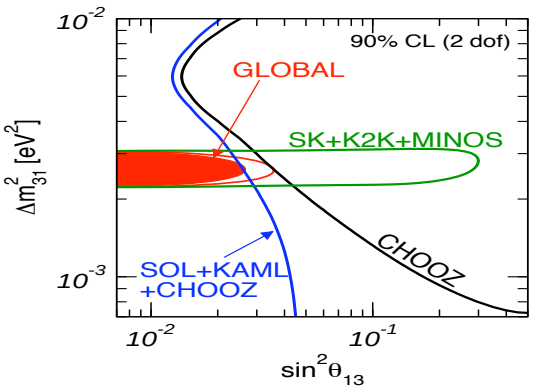

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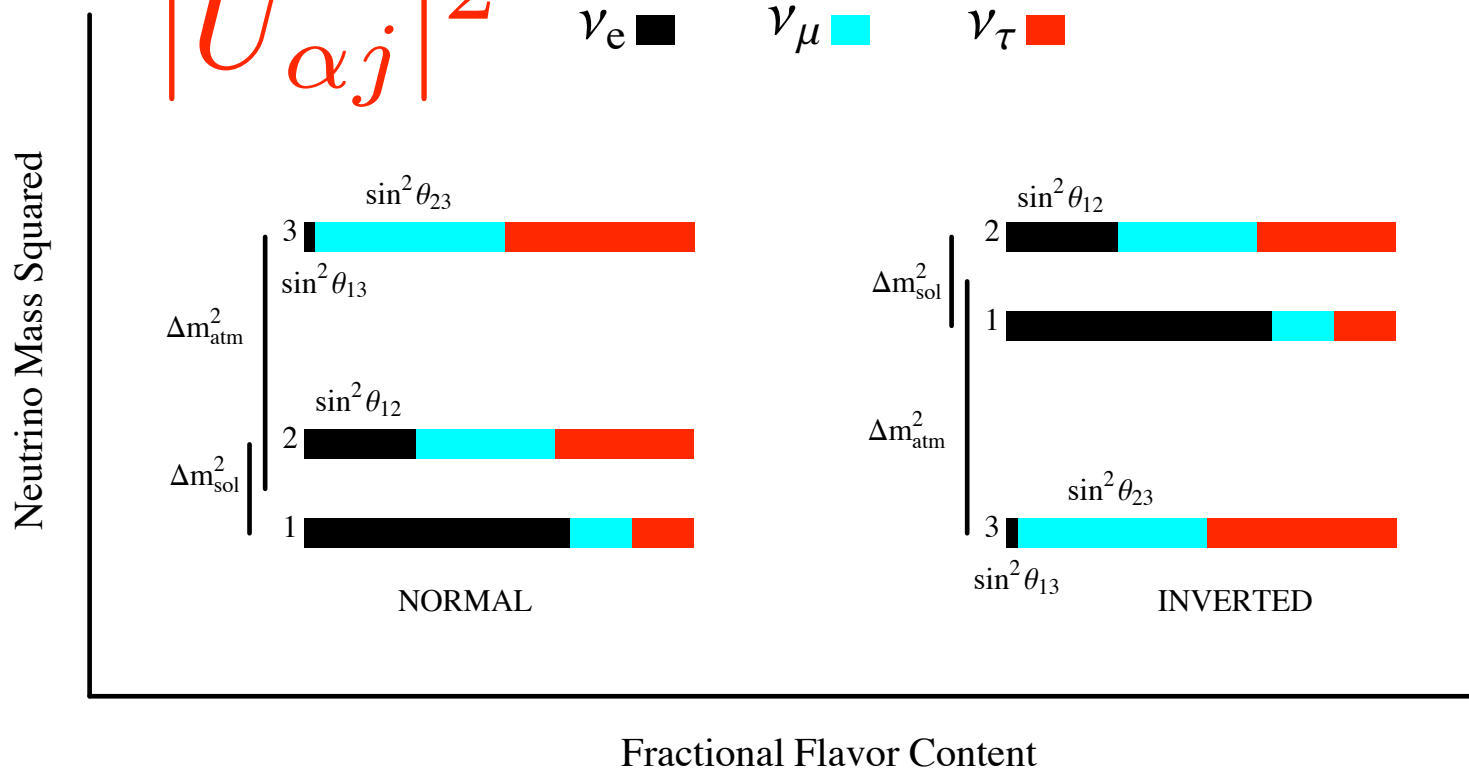
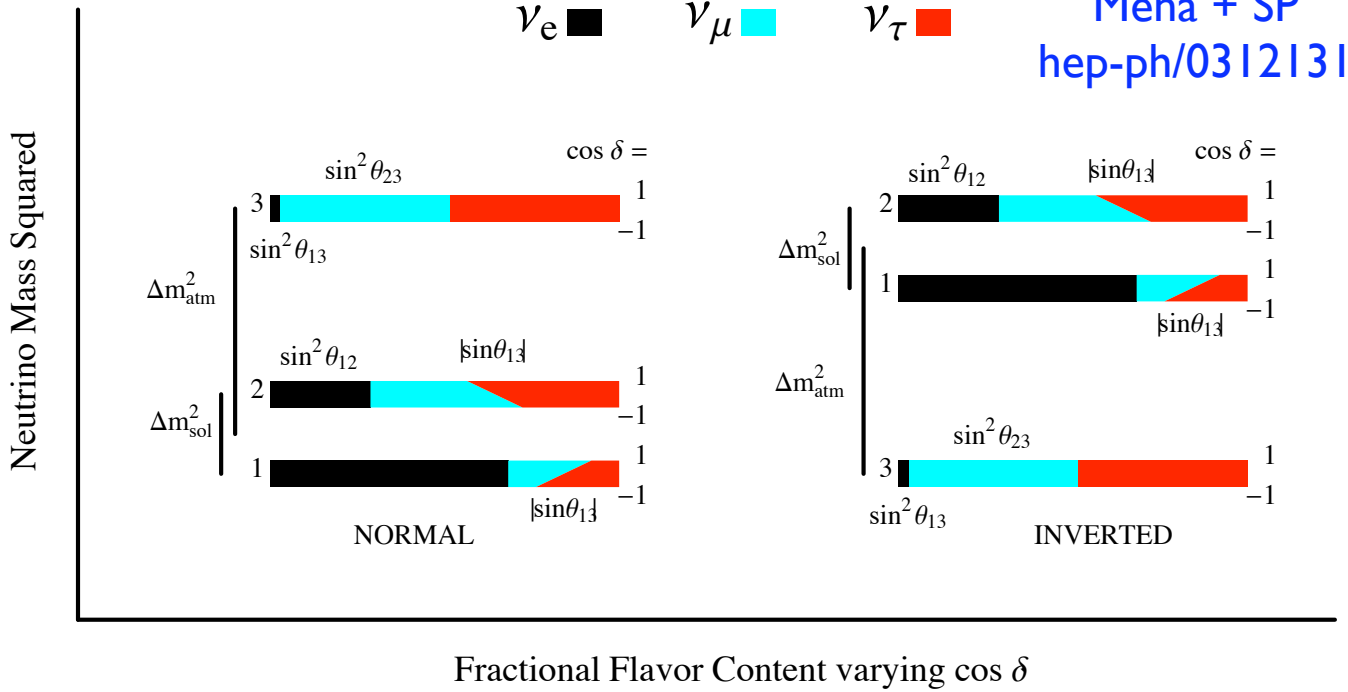
$|U_{\alpha j}|^2$ ν_e ν_μ ν_τ



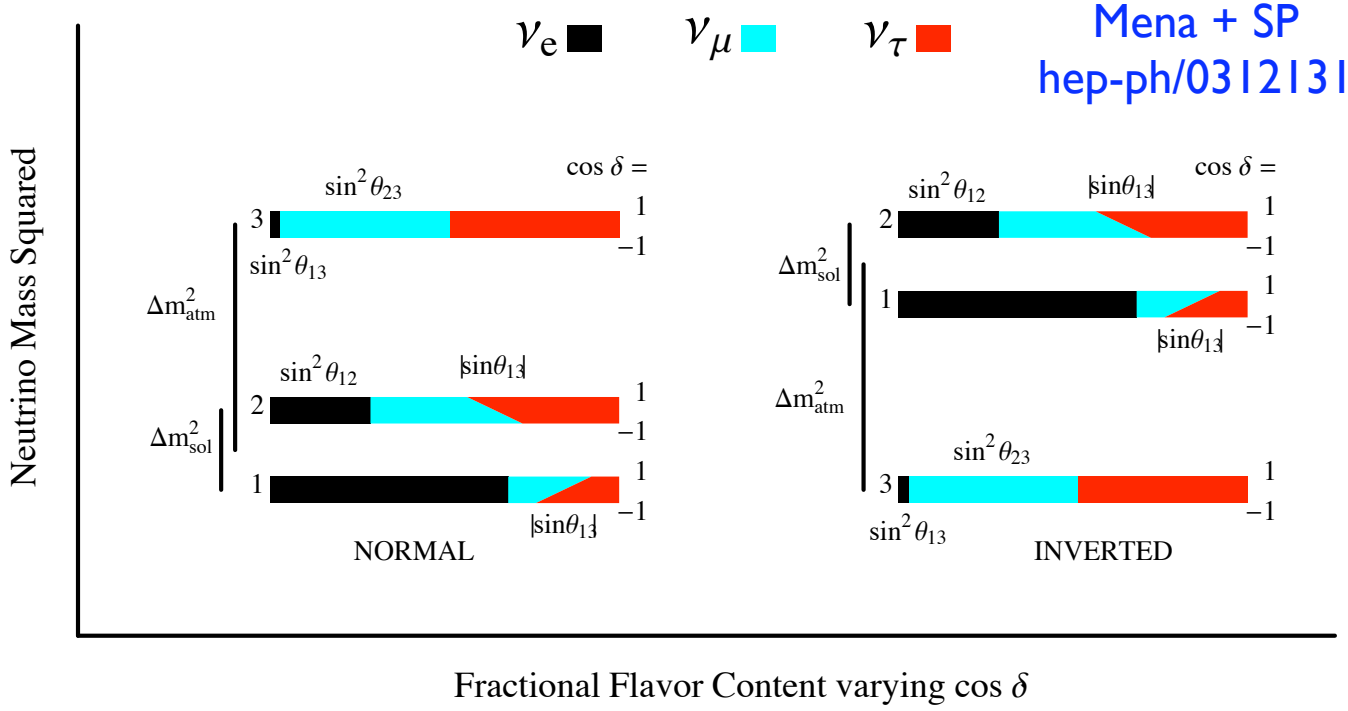
Sine/Signs



States 1 and 2 are ν_e rich.

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

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

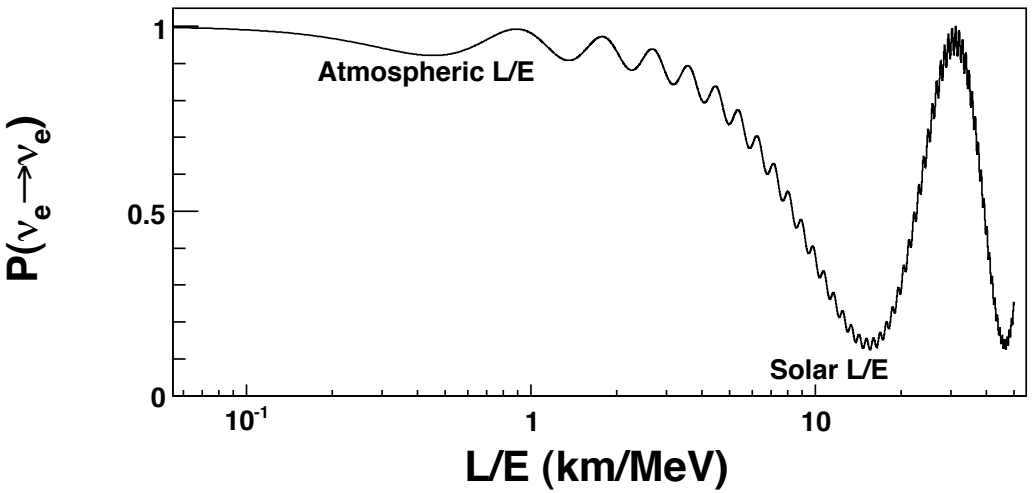
States 1 and 2 are ν_e rich.

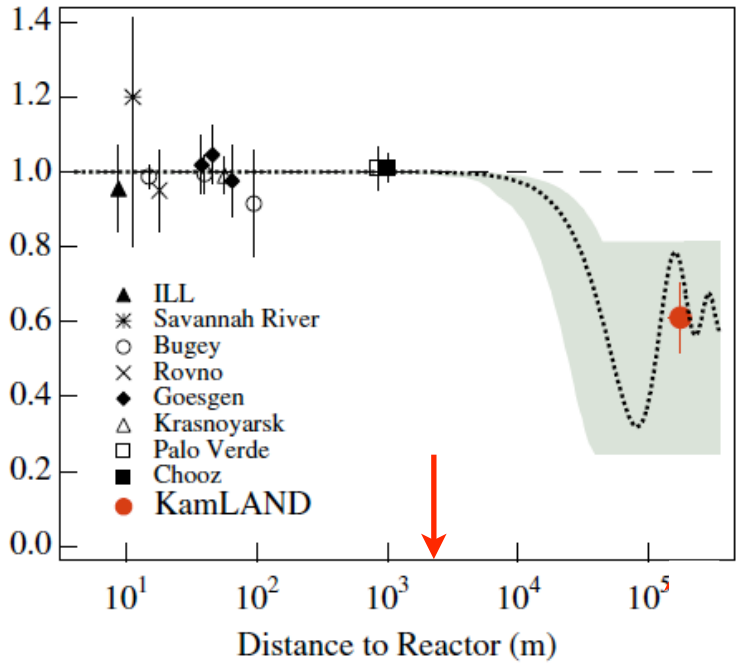
CPT: $\delta \Leftrightarrow -\delta$ Invariant!

θ_{13} from Reactor Disappearance

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

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





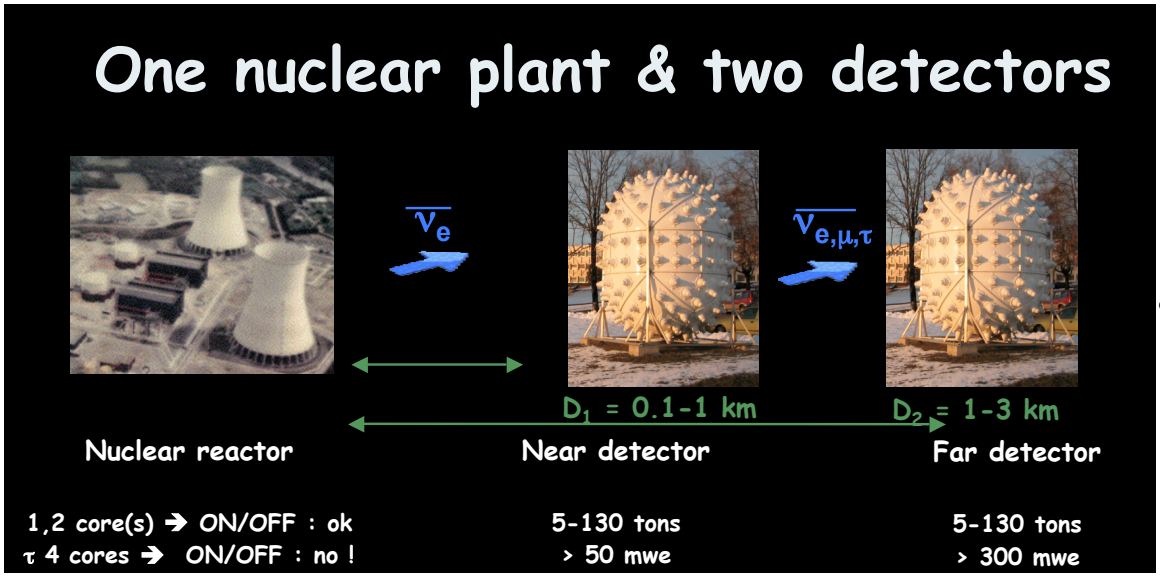
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

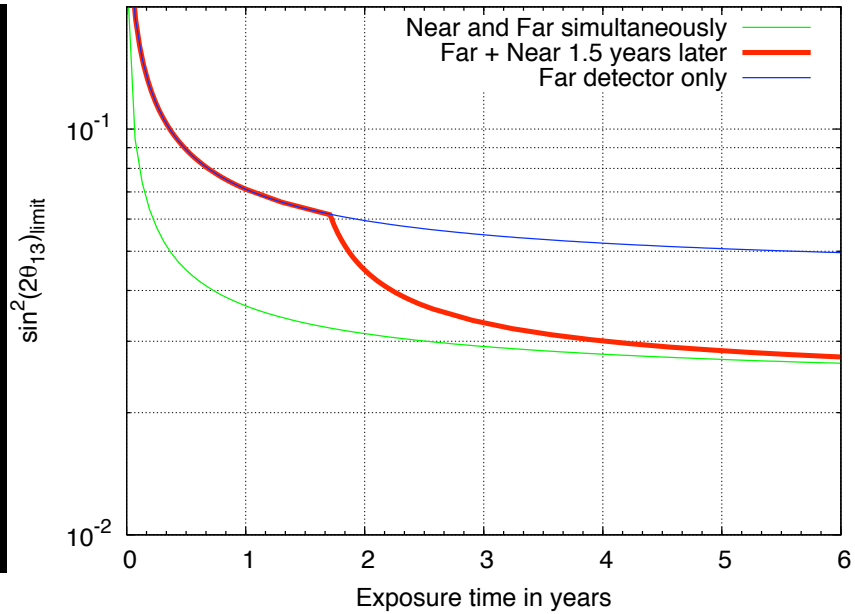
< 0.002

> 0.01

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

Double Chooz:

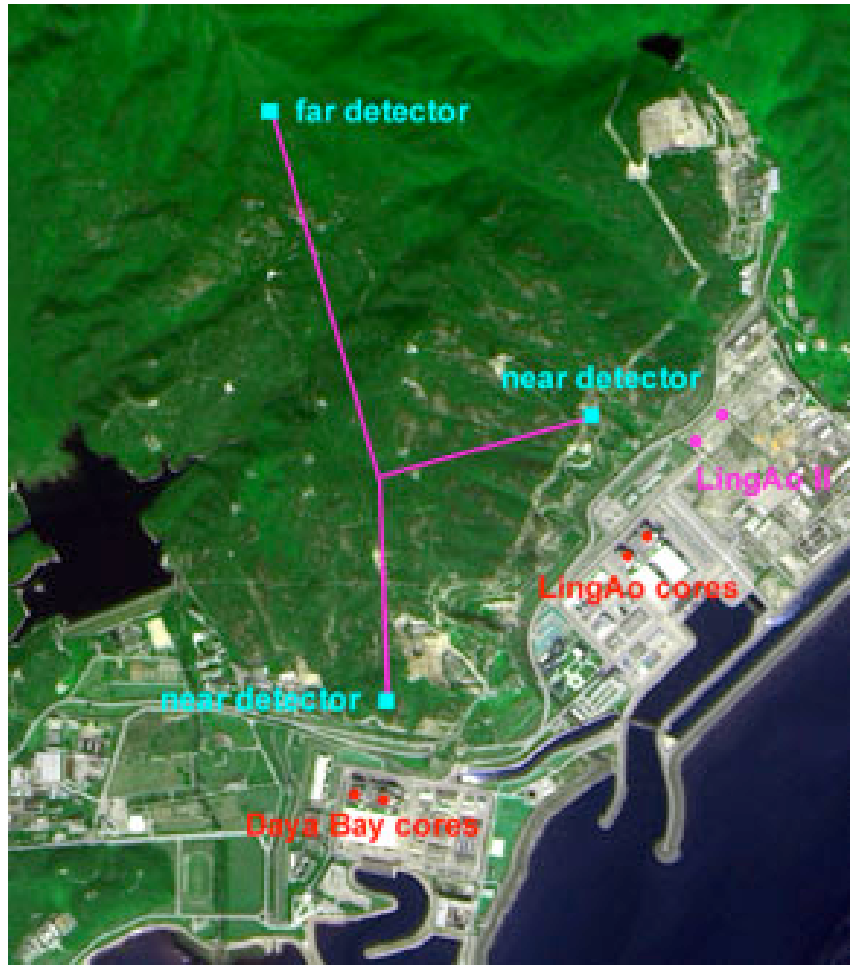




.03

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

Daya Bay



push the limit on

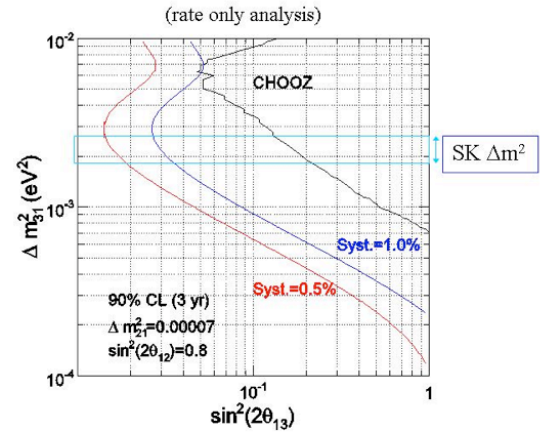
$\sin^2 2\theta_{13} < 0.01$

RENO

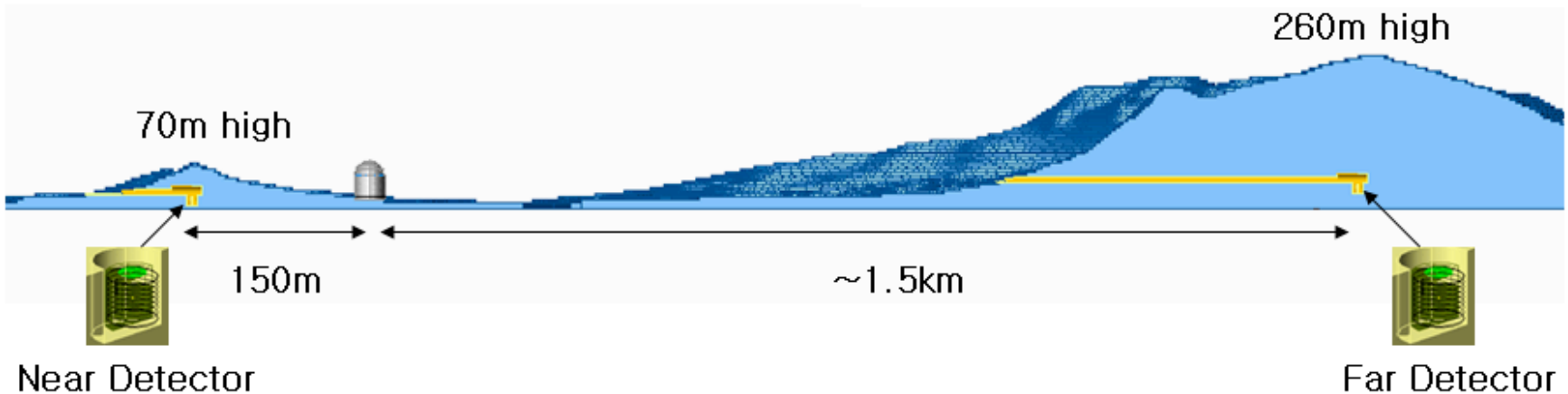
ν θ_{13}

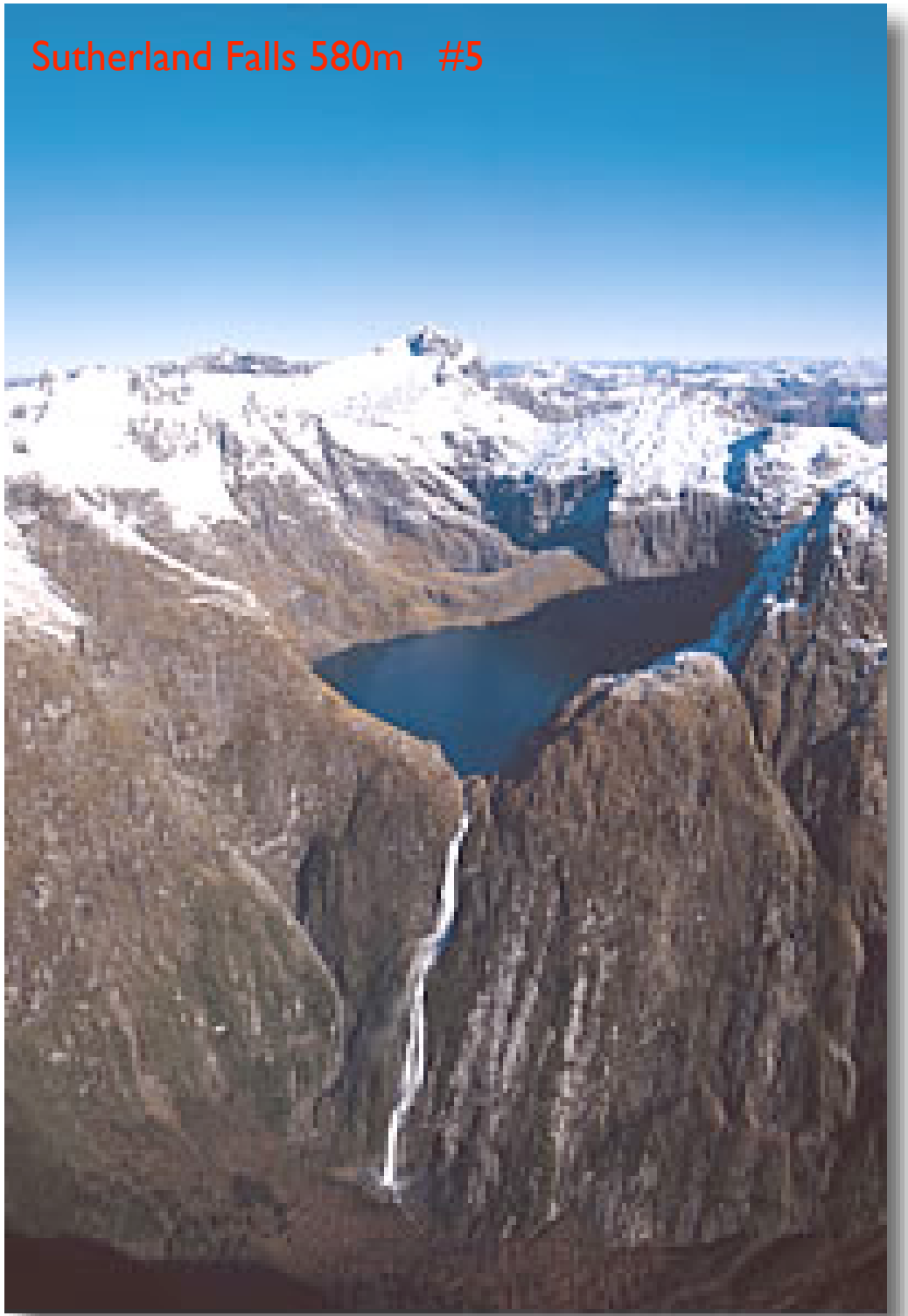
(Reactor Experiment for Neutrino Oscillation)

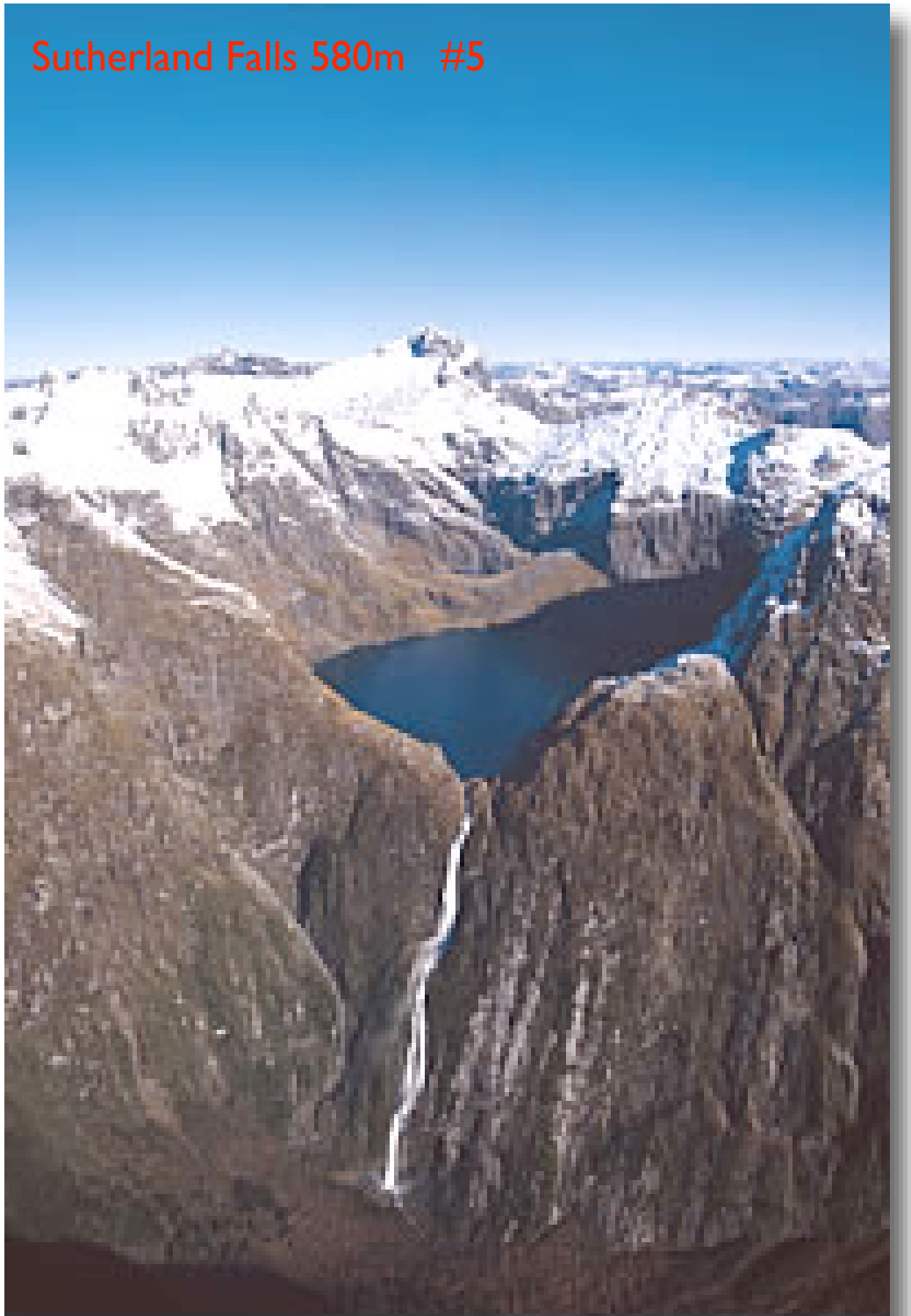
RENO Expected Sensitivity



10x better sensitivity than current limit

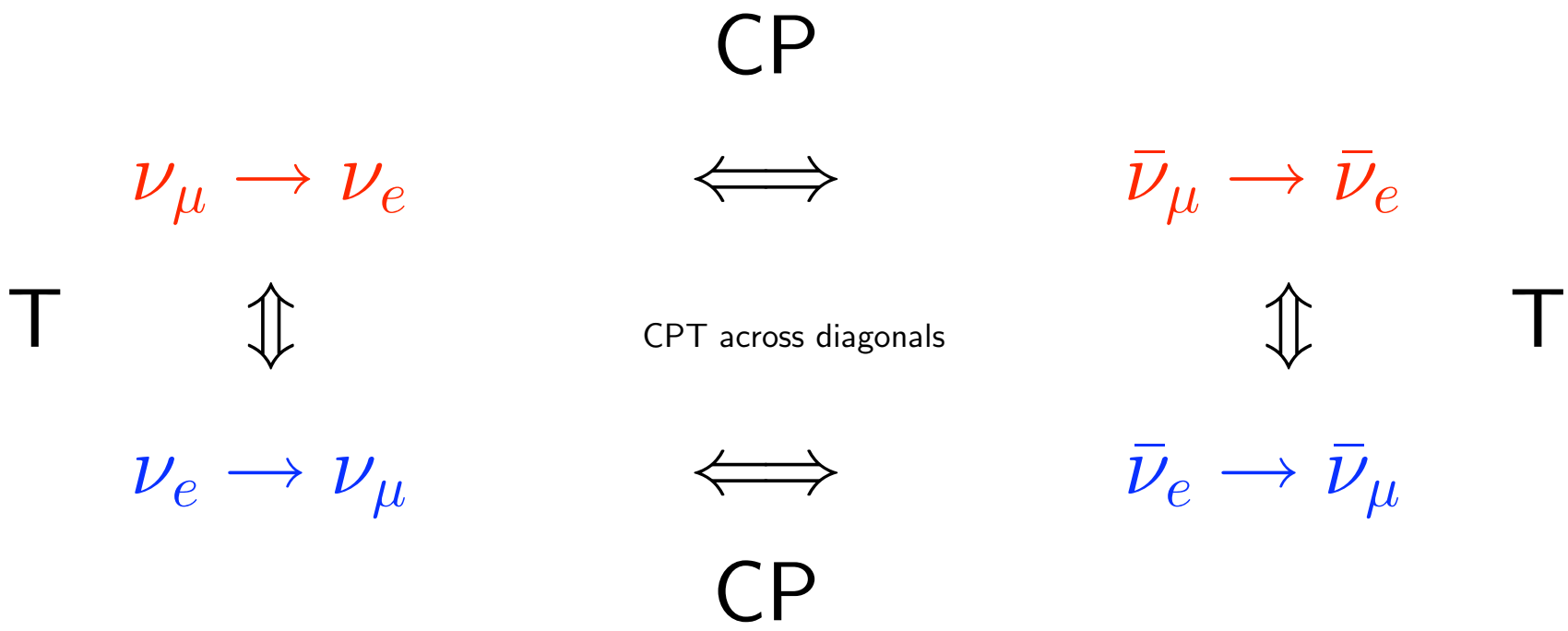



Sutherland Falls 580m #5



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

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:

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

$\nu_\mu \longrightarrow \nu_e$

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

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Atmospheric δm^2 Solar δm^2

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

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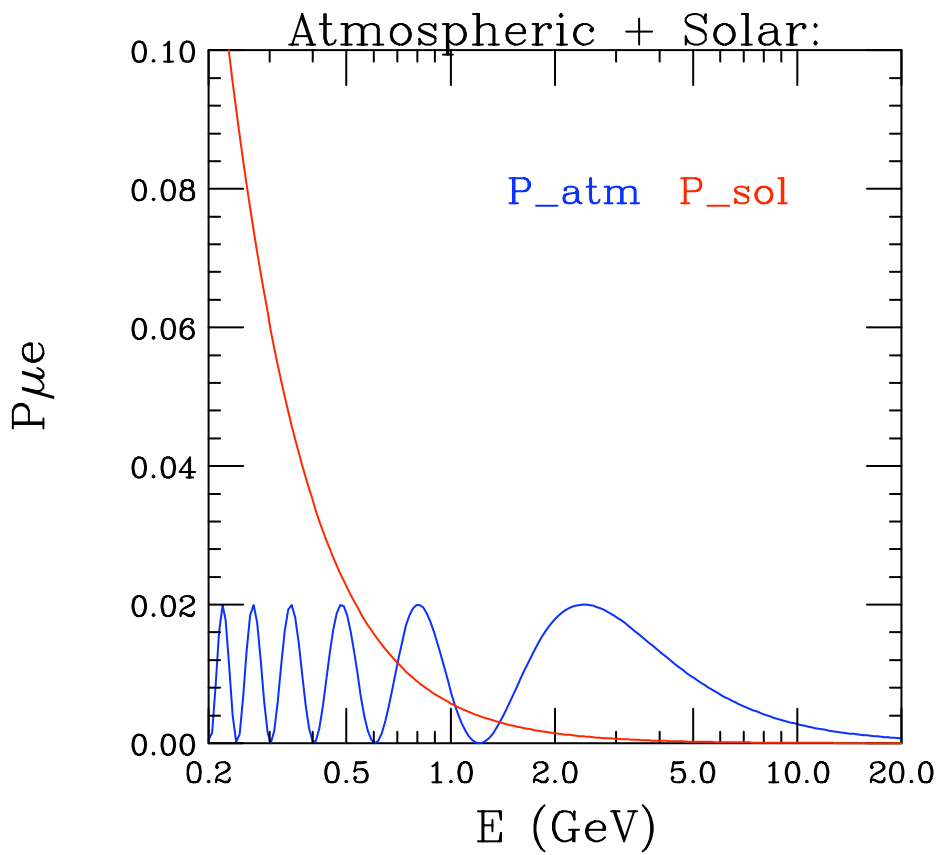
$$P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm} P_{sol}} \cos(\Delta_{32} \pm \delta) + P_{sol}$$

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

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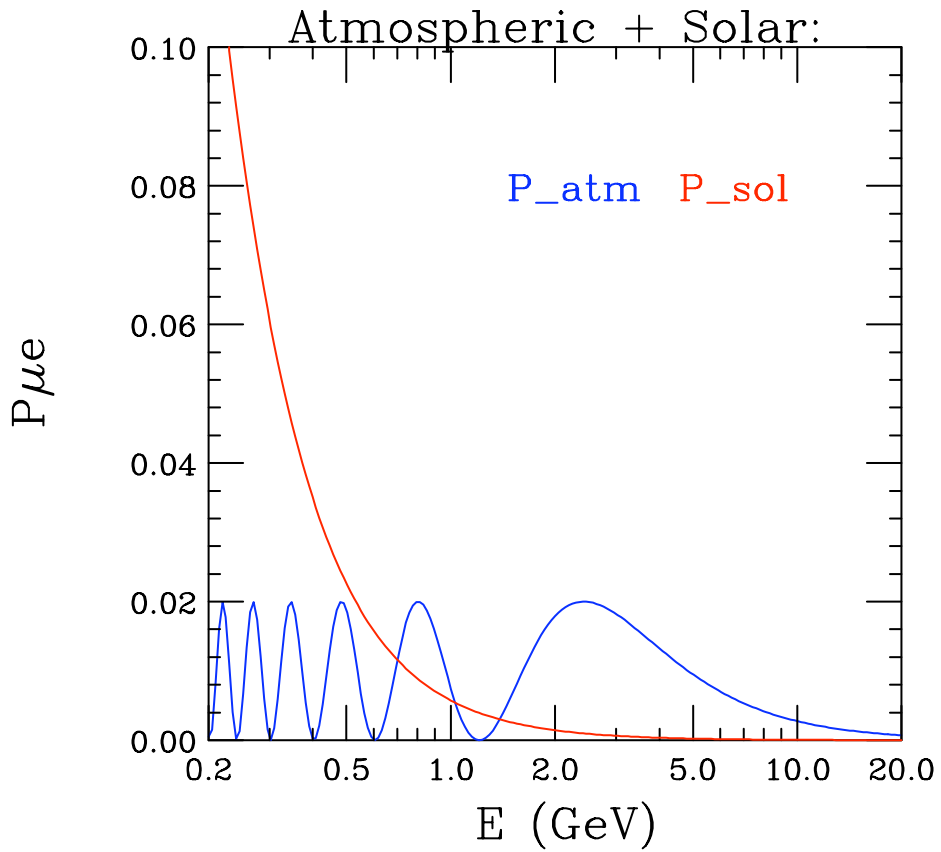

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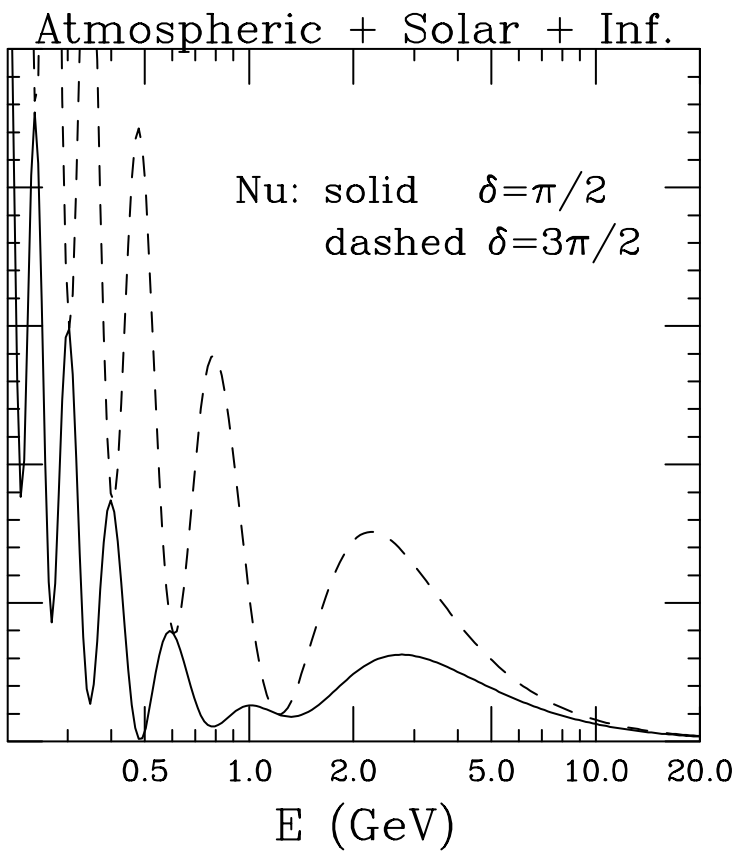
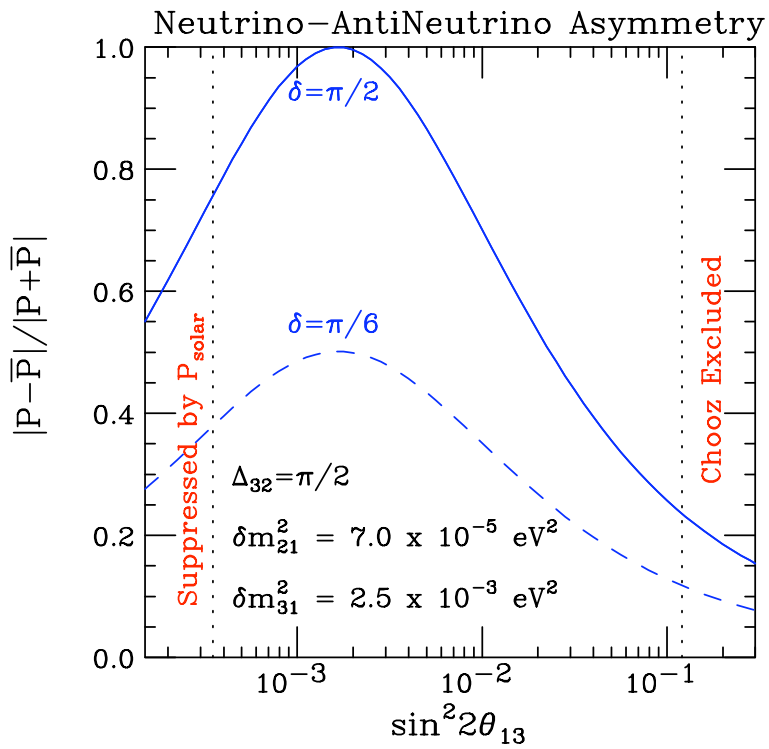


phase varies

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

Asymmetry Peaks:



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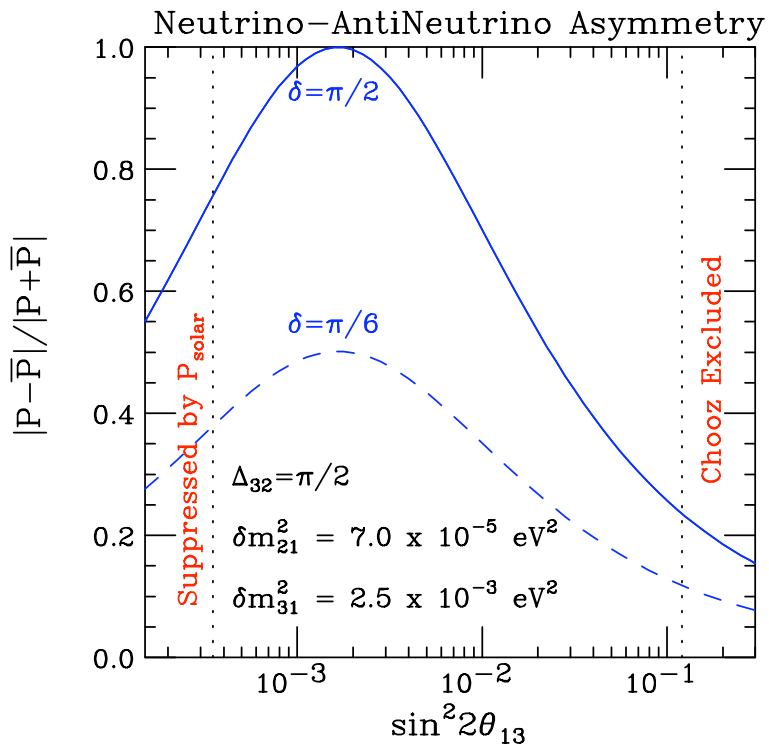

$$P_{atm} \leq P_{sol} \quad \text{when} \quad \sin^2 2\theta_{13} \leq \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}} \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \approx 0.001$$

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

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

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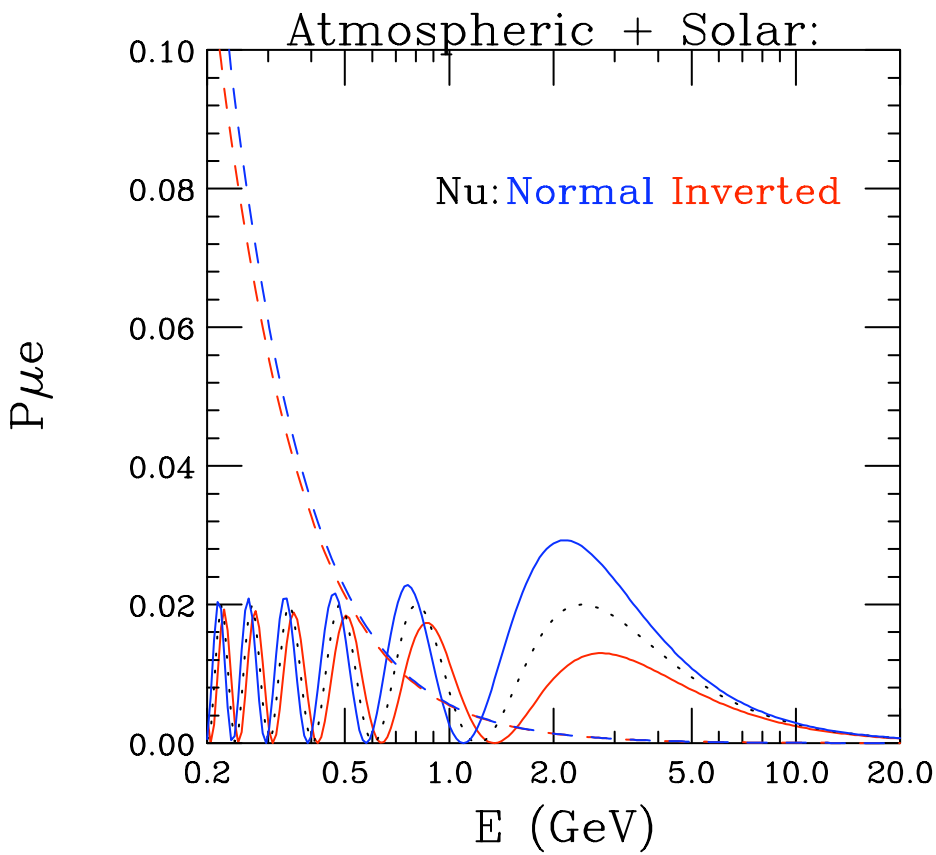

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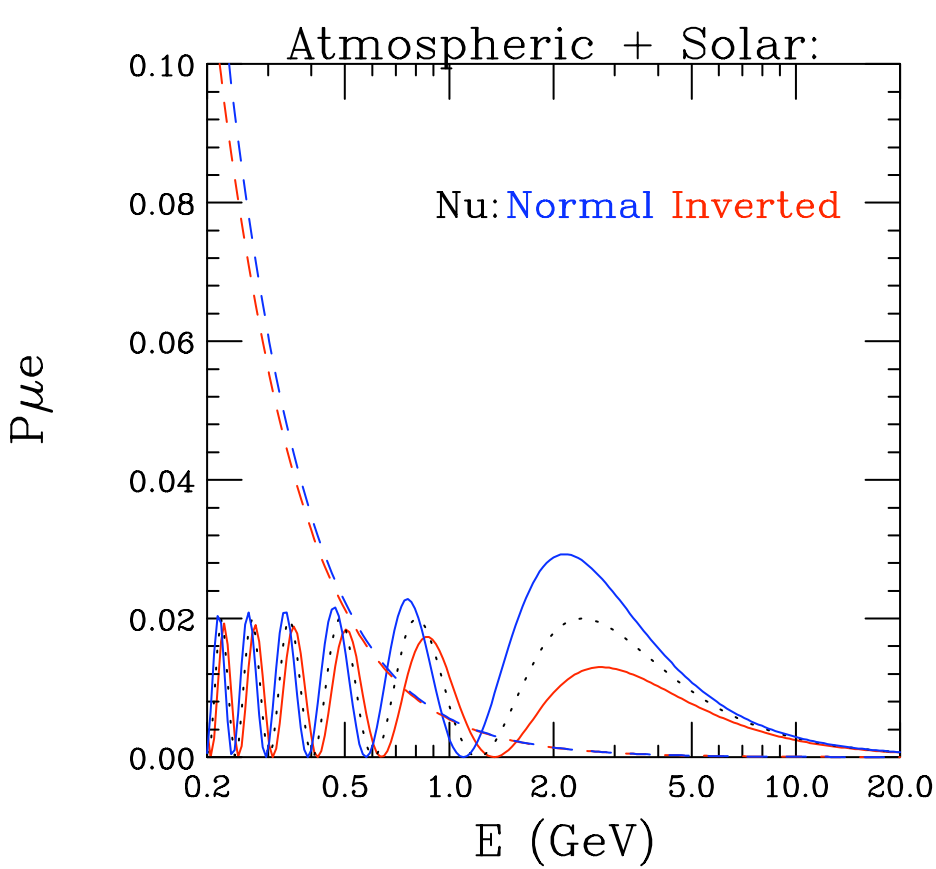
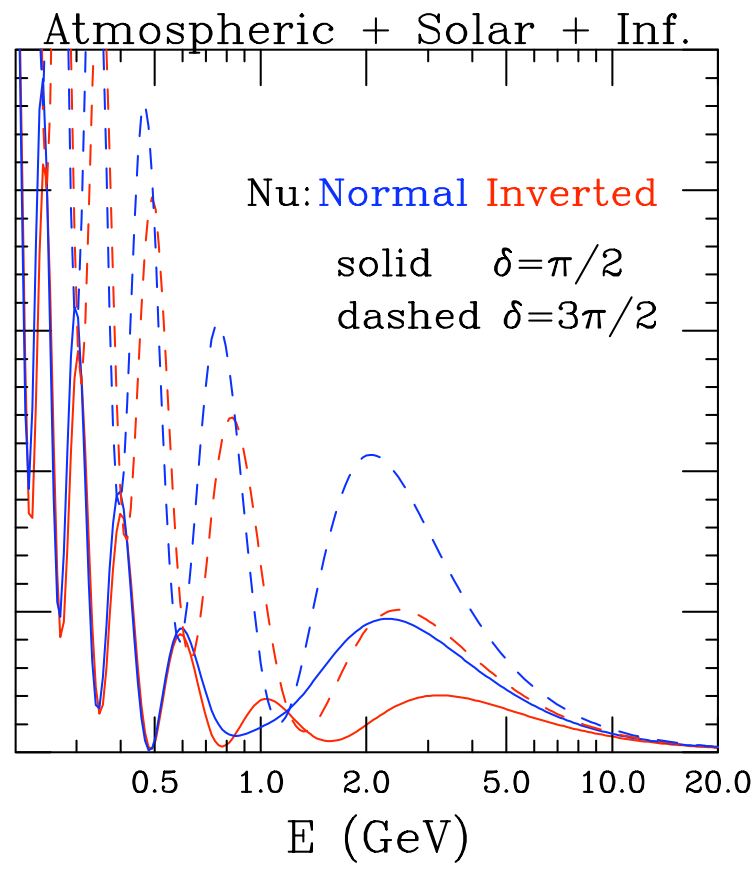
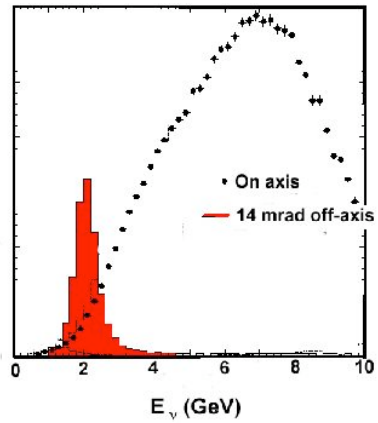
Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





Off-Axis Beams

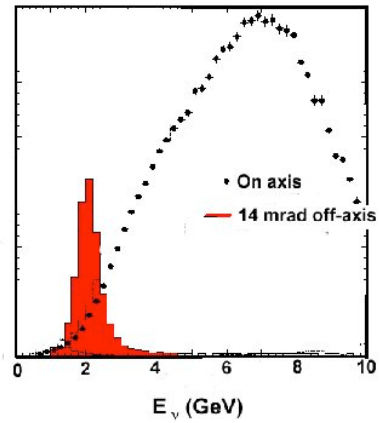
BNL 1994



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

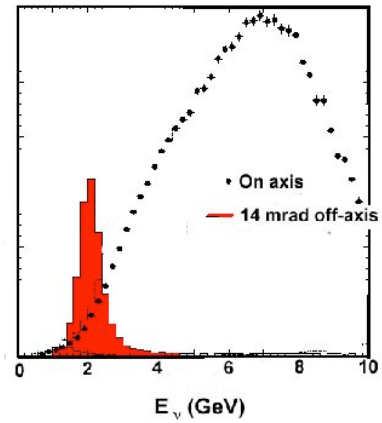
Energy at Vac. Osc. Max. (vom)

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

0.75 upgrade to 4 MW

Off-Axis Beams

BNL 1994



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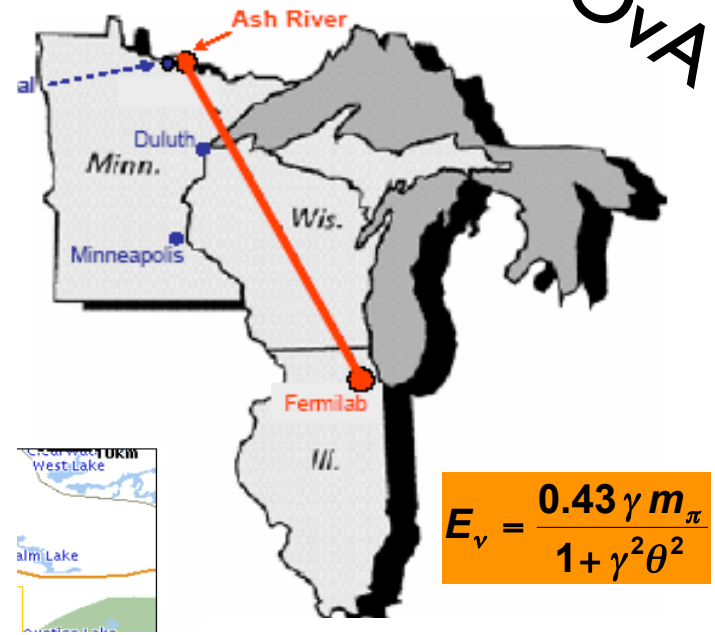
NOvA



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

L=700 - 1000 km and

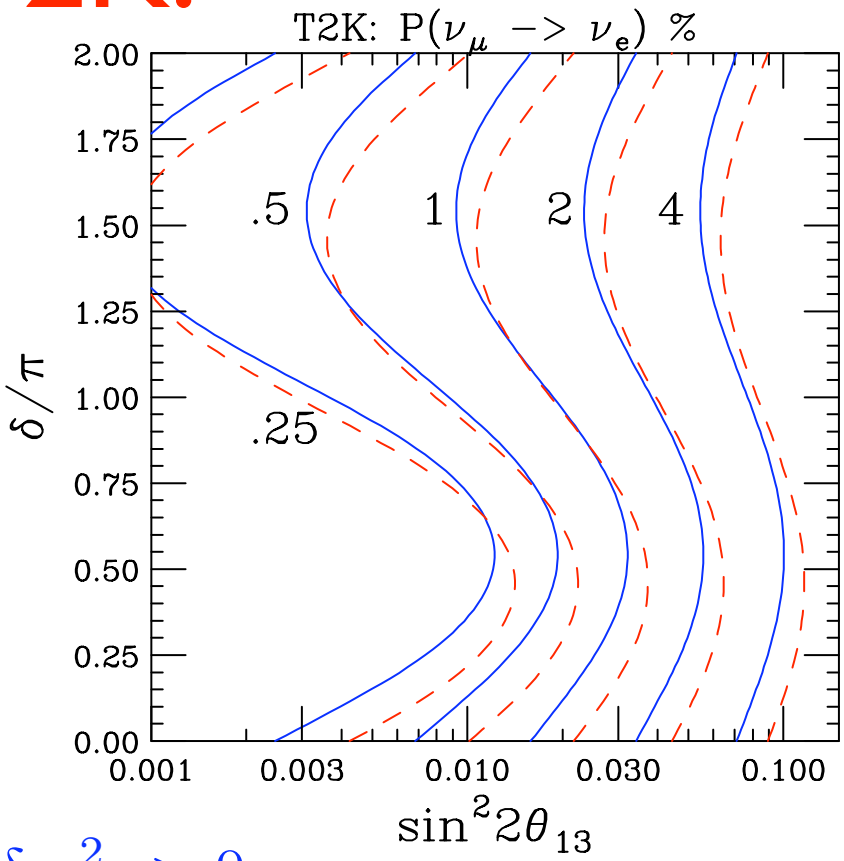
Energy near 2 GeV

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

0.4 upgrade to 2 MW

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

T2K:

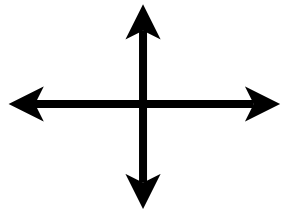


$\delta m^2_{31} > 0$

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

Beam 1%

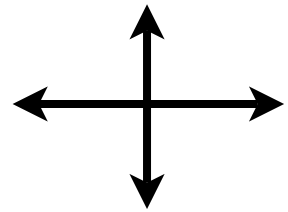
VOM: $\Delta_{31} \neq \pi/2$



Matter Effect:

T2K:

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



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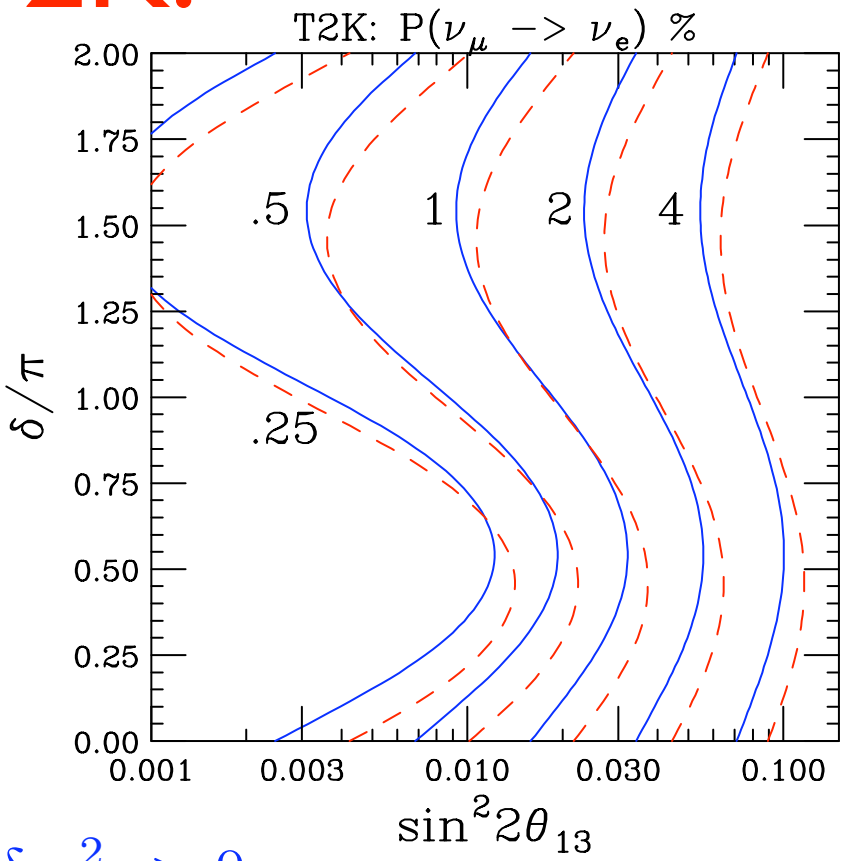

$\delta m^2_{31} > 0$

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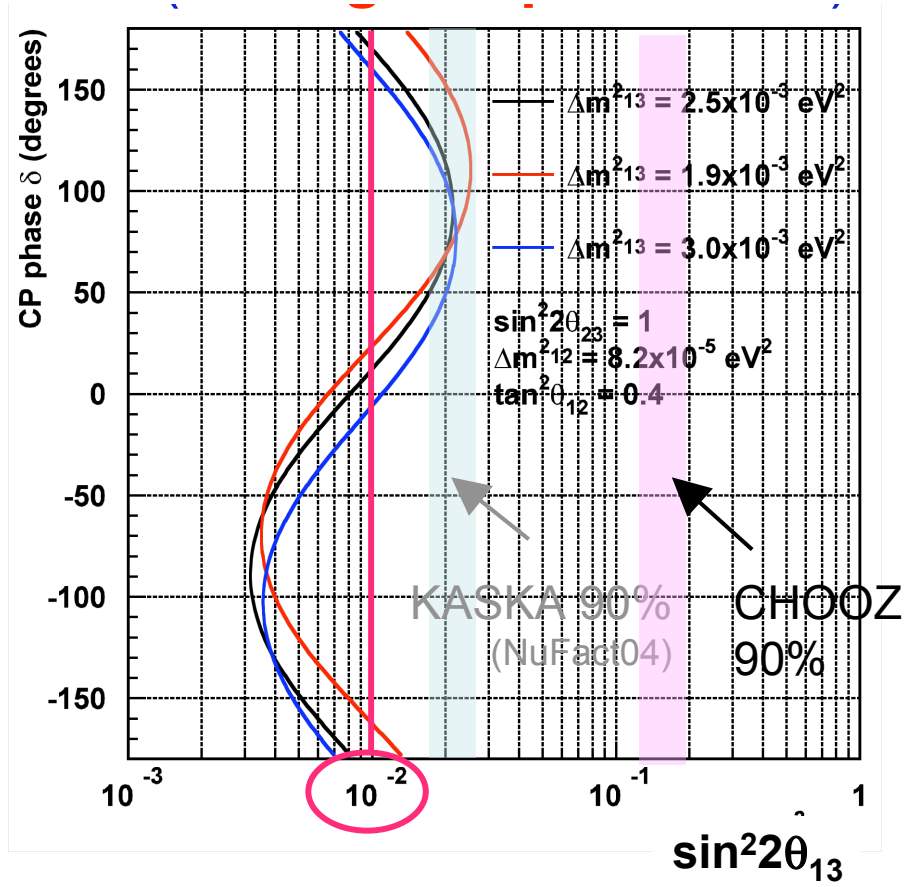
Beam 1%

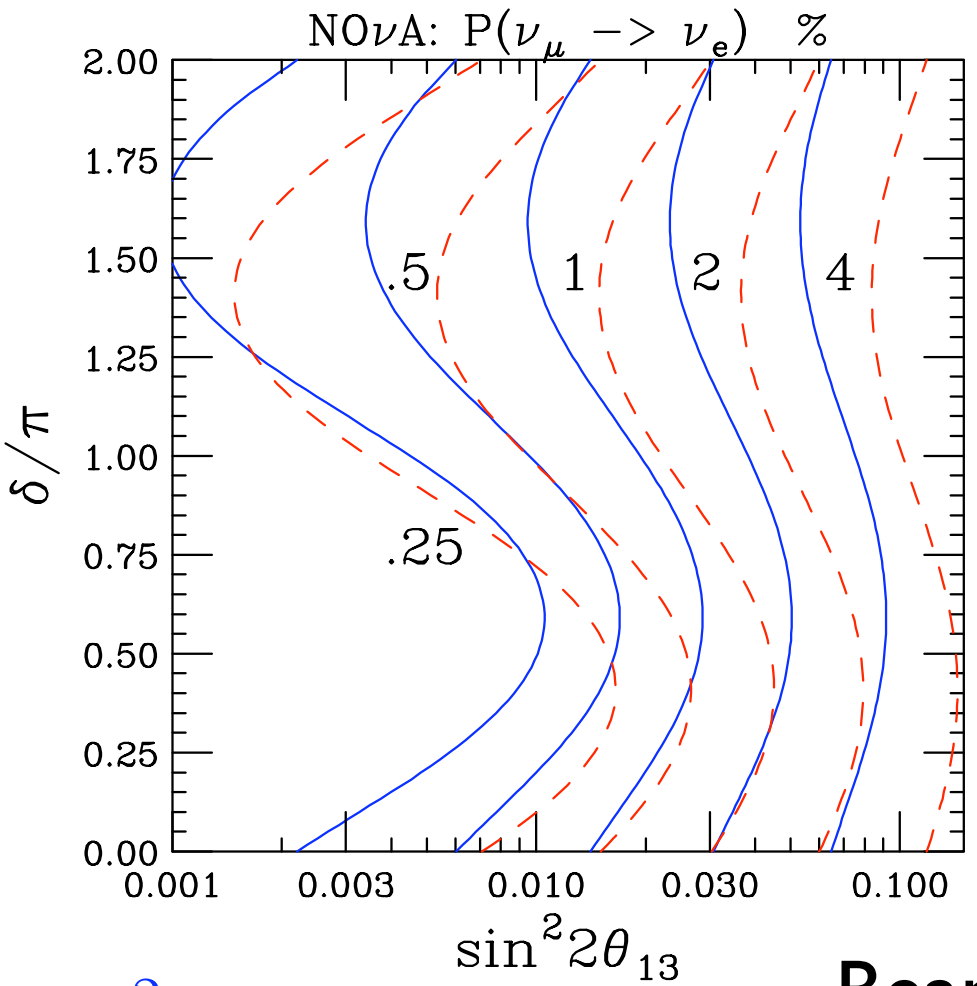
Aihara for T2K, P5 talk



Phase I

Sensitivity approx 0.5%

NOvA:



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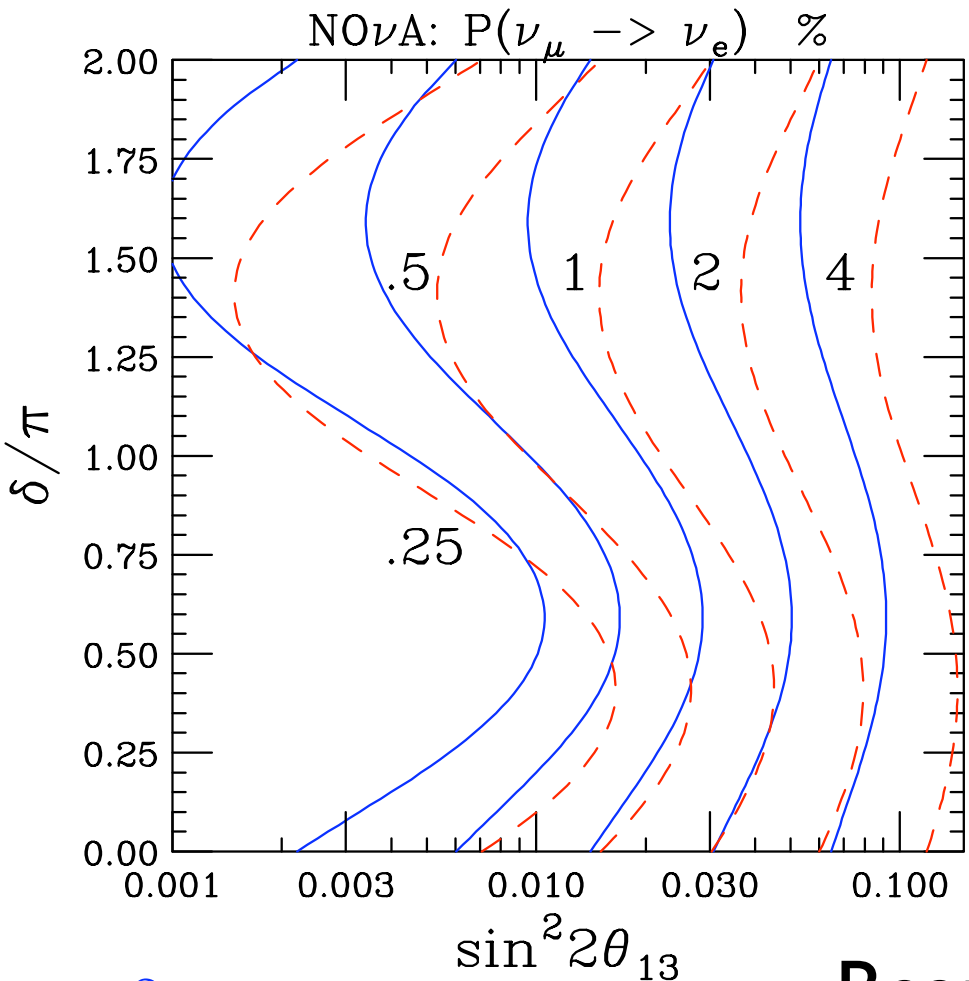
$\delta m^2_{31} < 0$

NOvA:



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

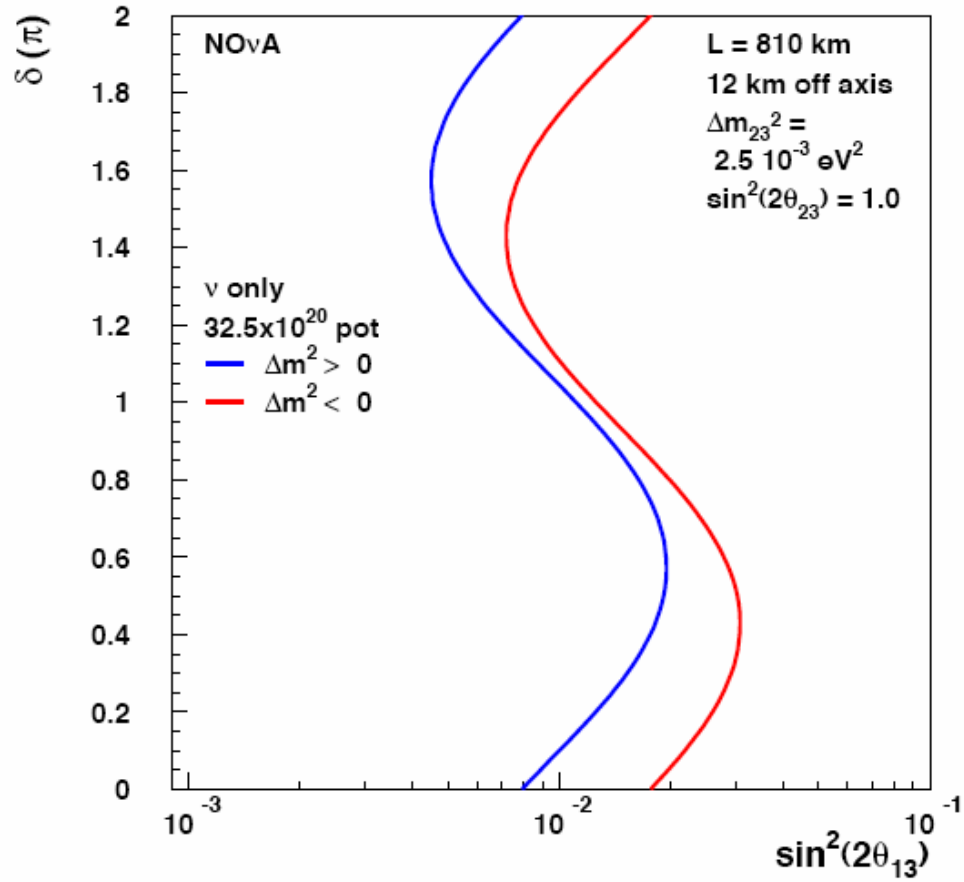
$\delta m^2_{31} < 0$

Beam 1%

Phase I

Sensitivity approx 0.5%

NOvA @ NO-VE 2007

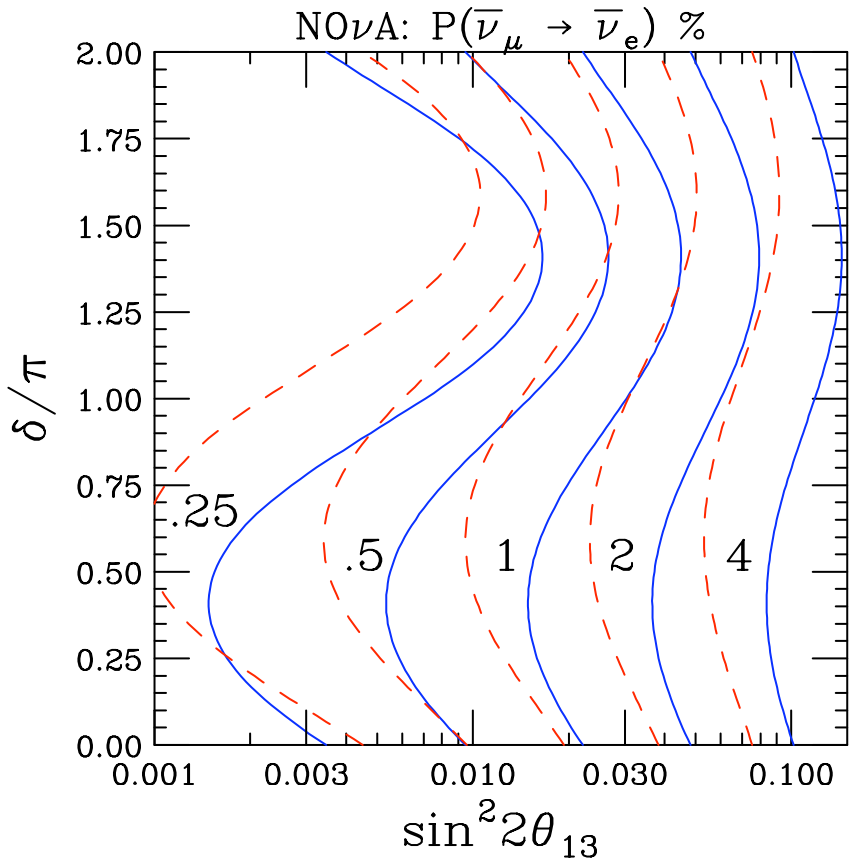


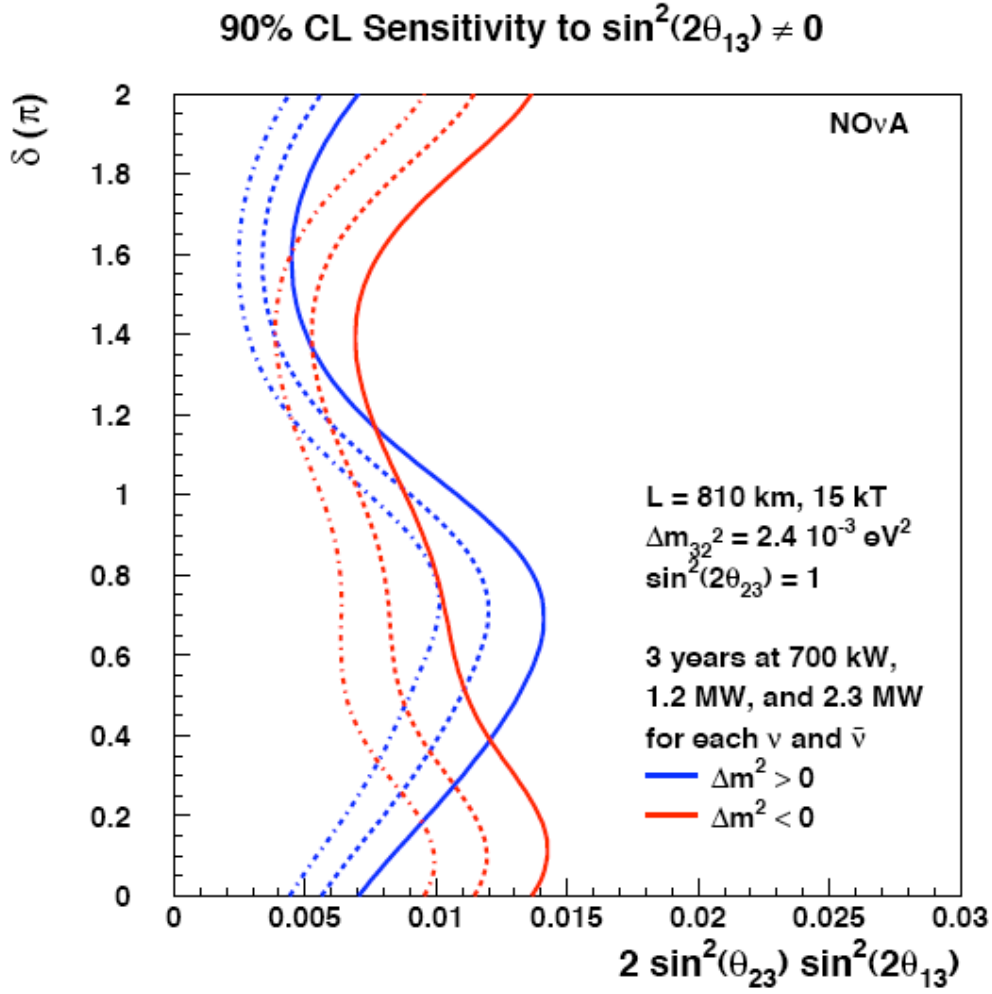
5 years with ν only run

NOvA:

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

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





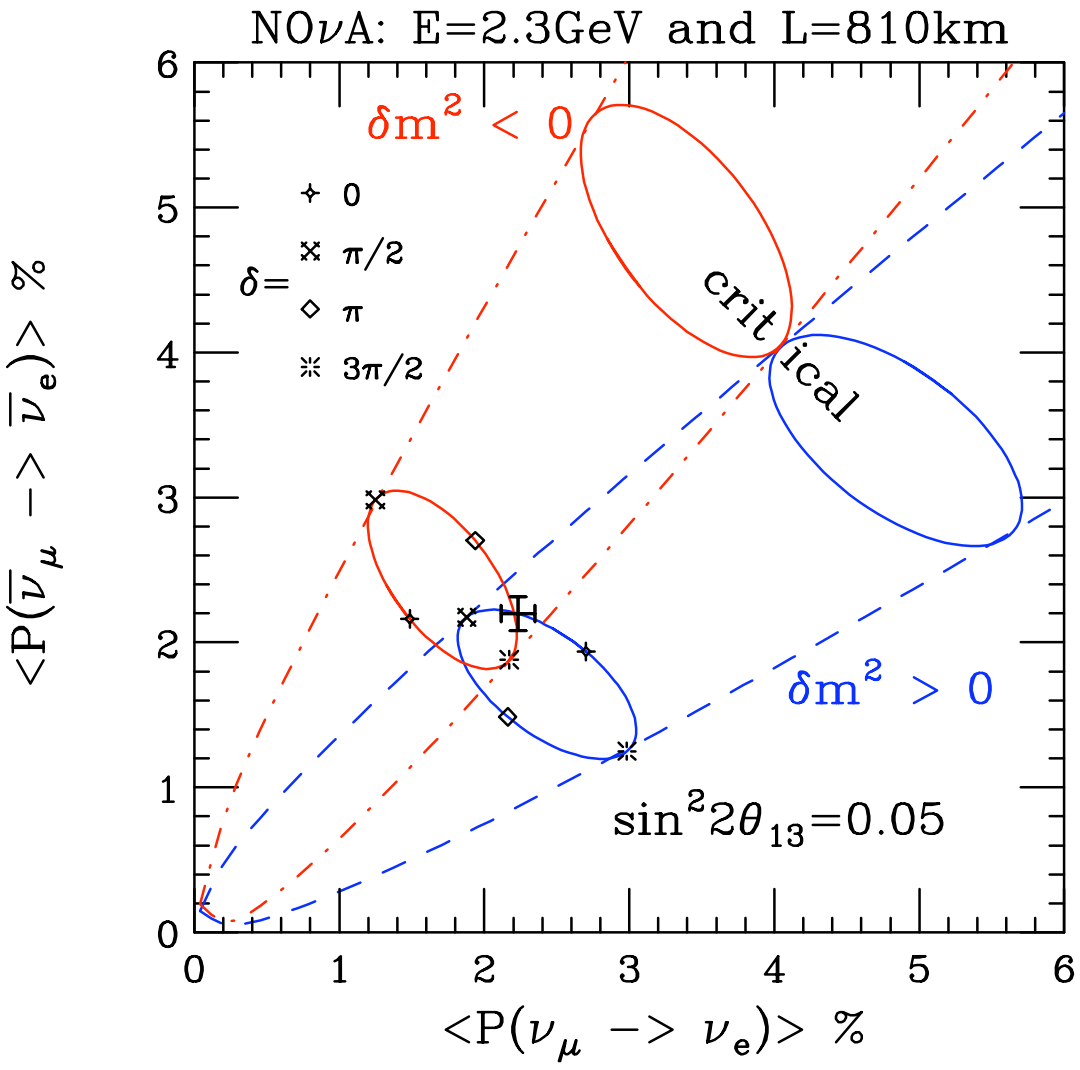
Beam ~1%

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

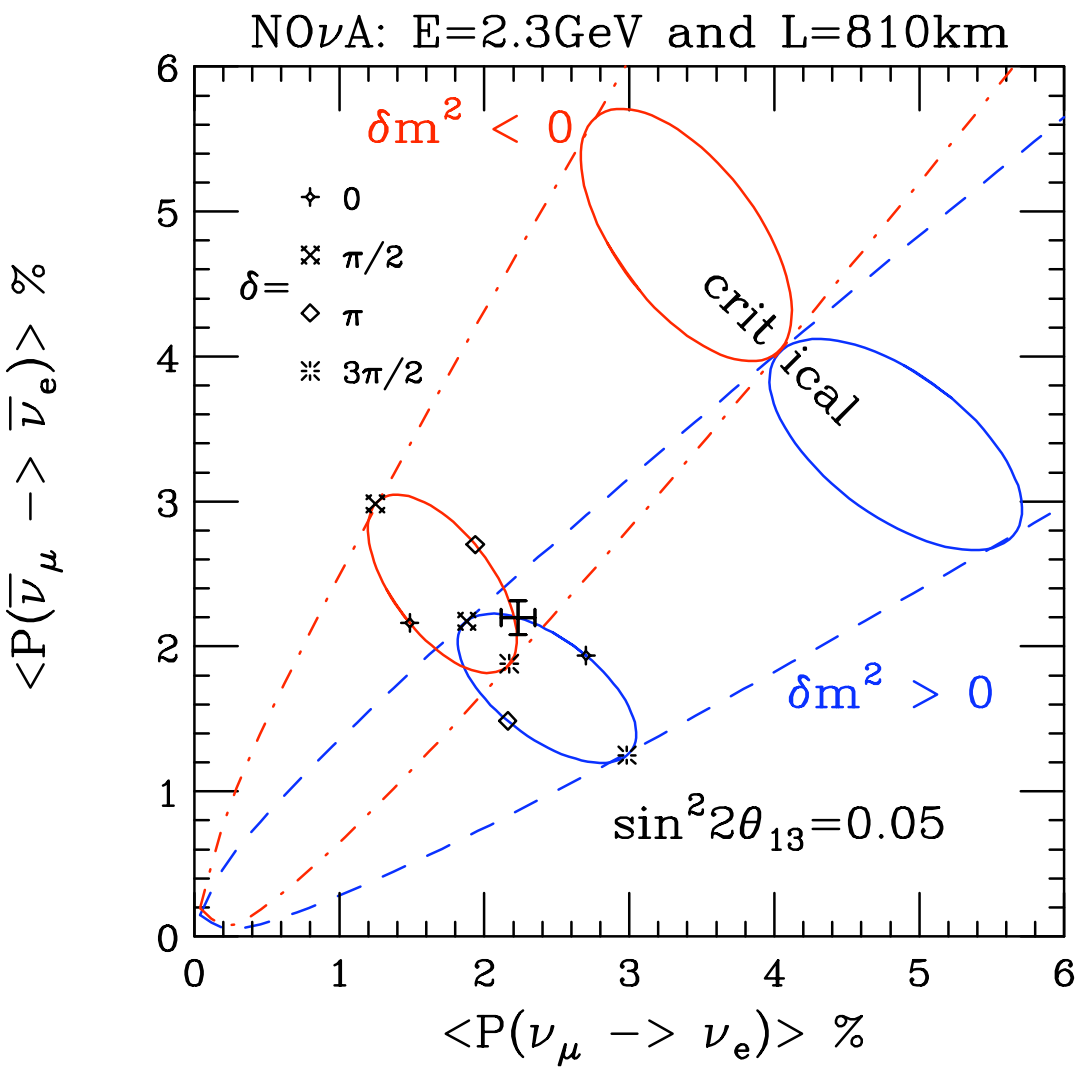
Correlations between

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

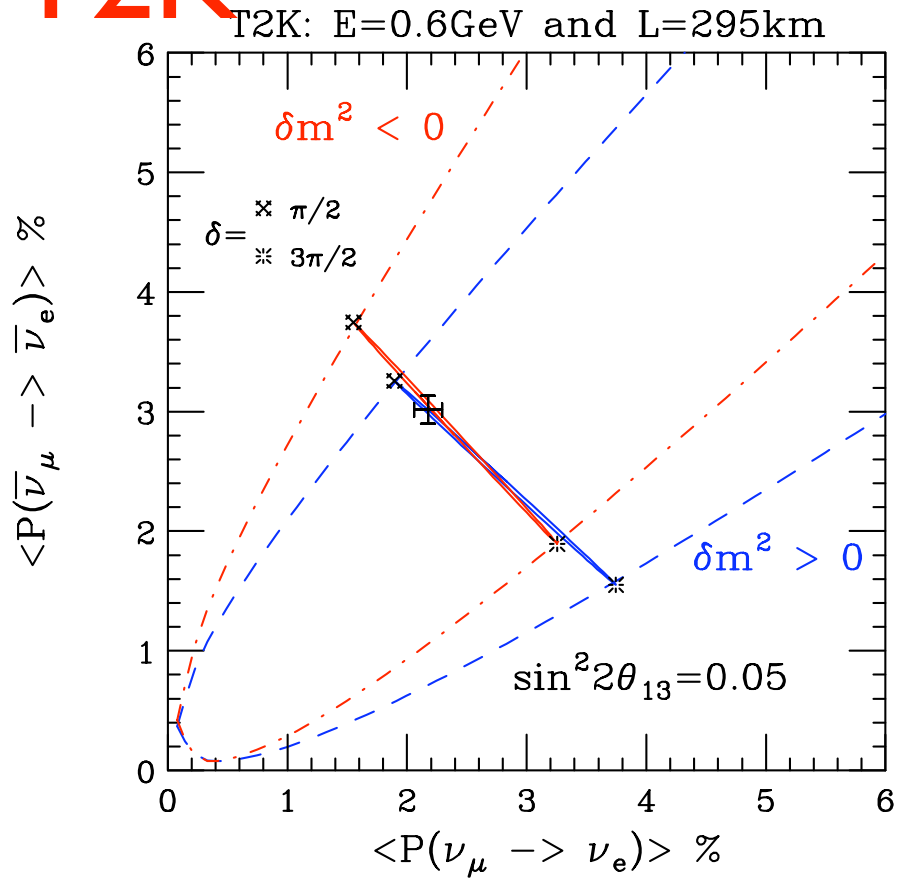
NOvA:


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

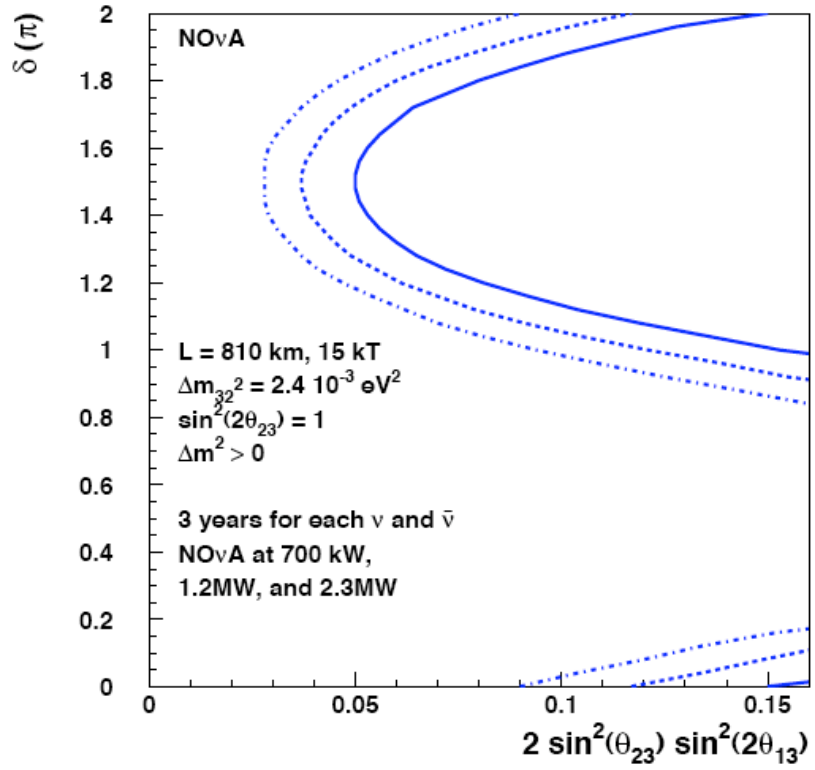
NOvA:


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)> %

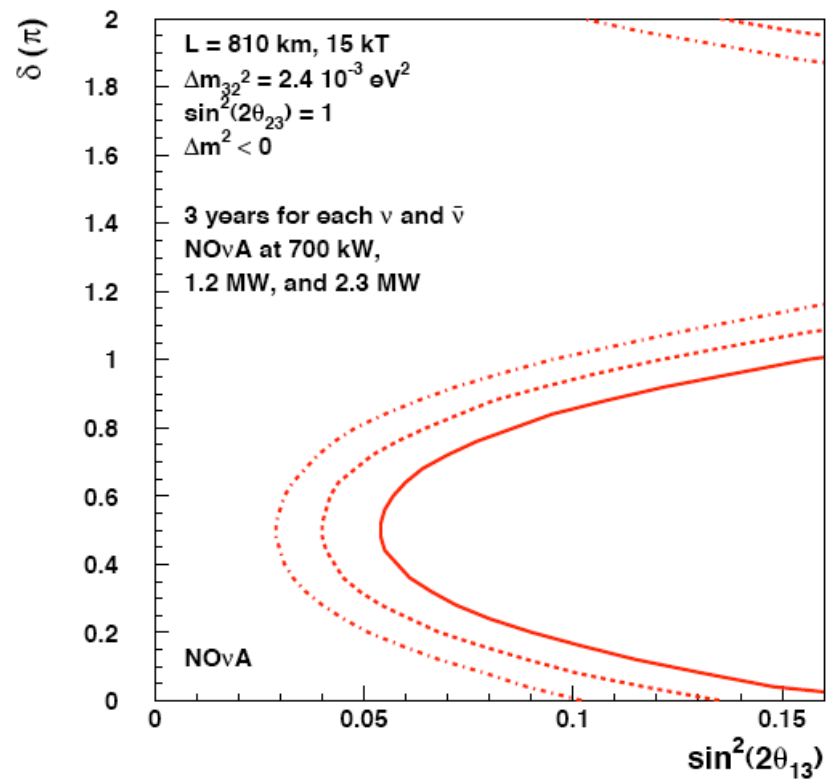
T2K


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

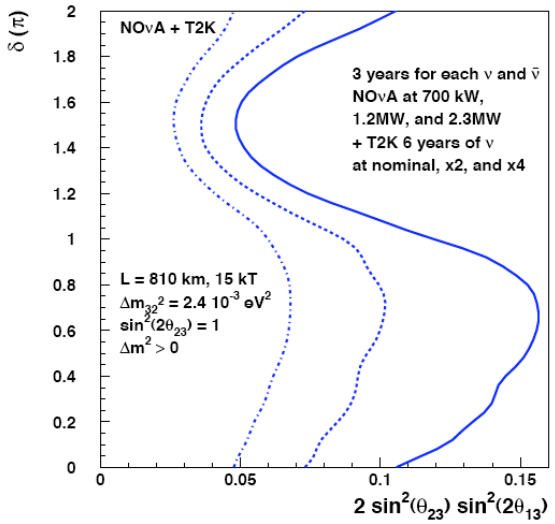


Normal Ordering

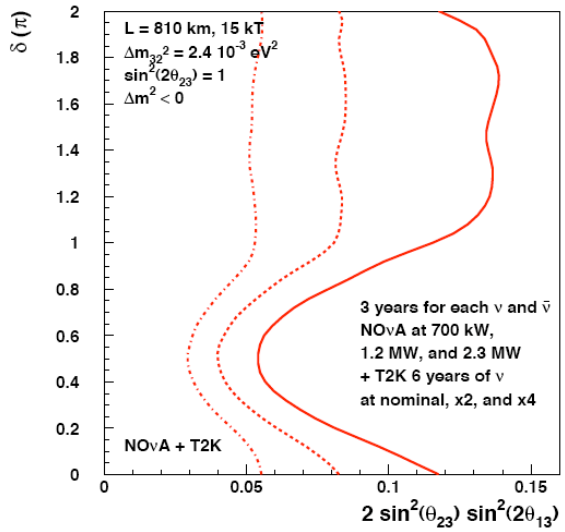


Inverted Ordering

95% CL Resolution of the Mass Ordering
NOνA Plus T2K

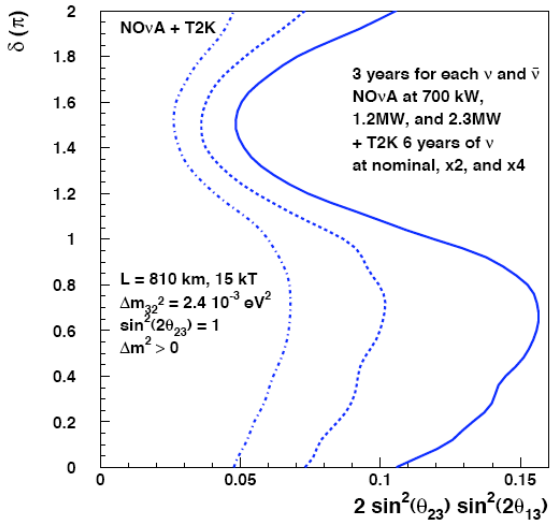


Normal Ordering

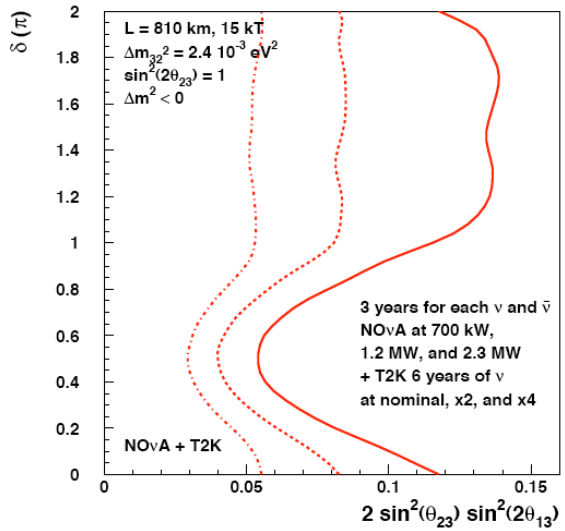


Inverted Ordering

95% CL Resolution of the Mass Ordering
NOνA Plus T2K



Normal Ordering

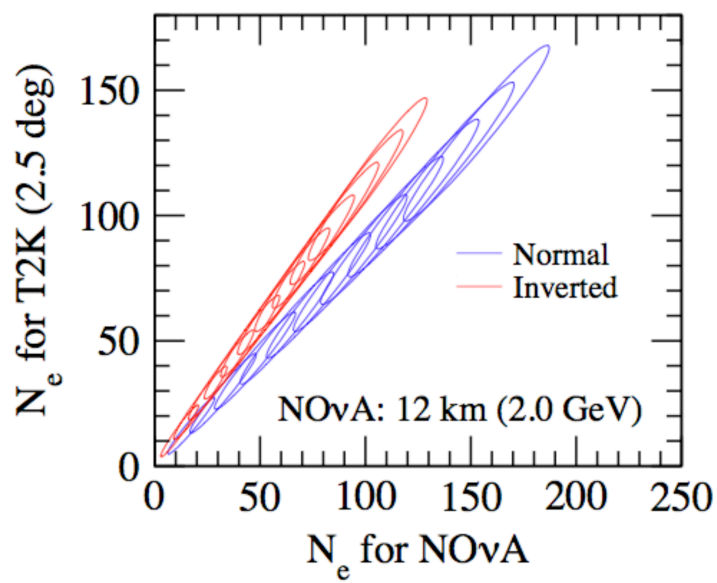


Inverted Ordering

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: $\sin\delta$

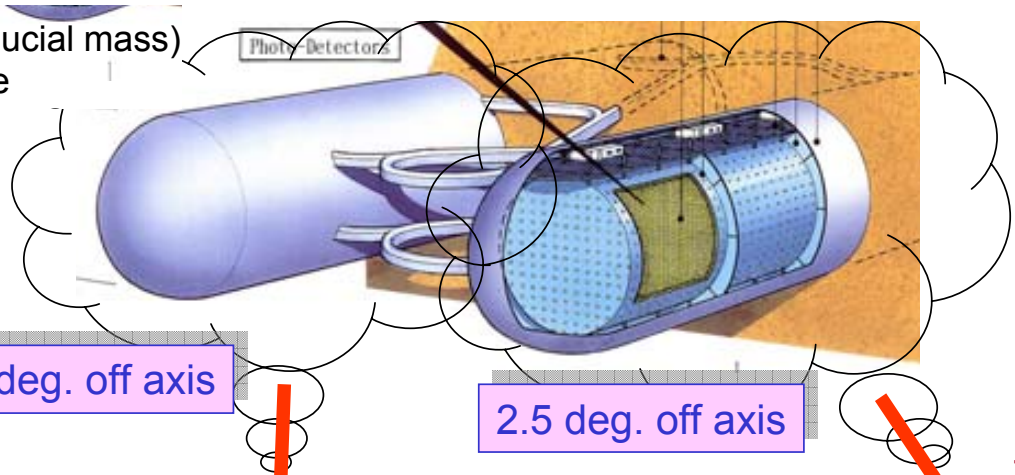
Events = efficiency * Fid. Mass * Protons on Target

(Power * Time)

Off Axis:

Some recent progress: detector in Korea

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande



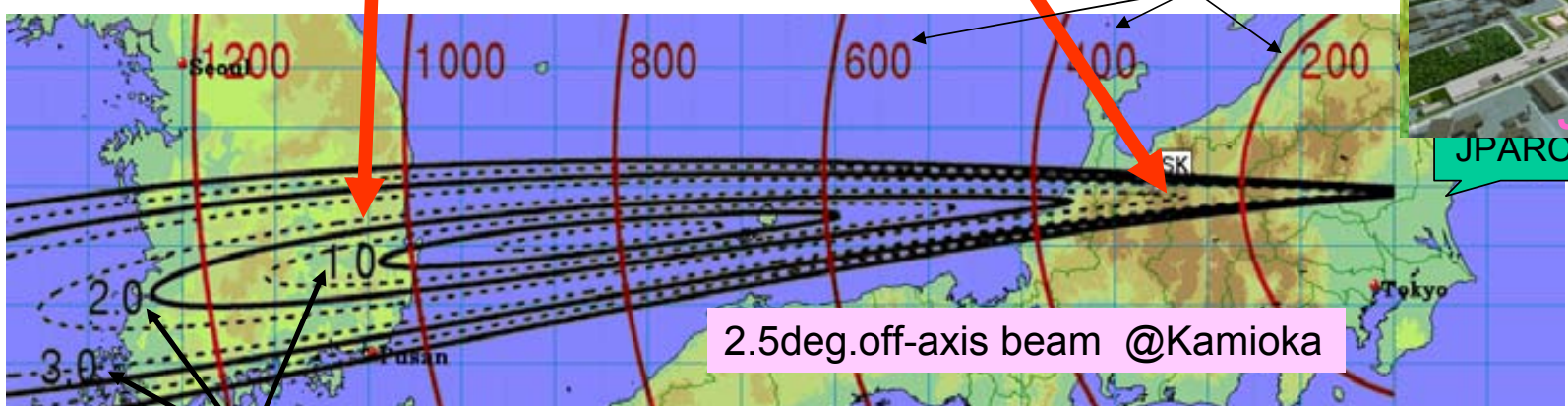
Total cost must be similar to the baseline design.

2.5 deg. off axis

2.5 deg. off axis

Distance from the target (km)

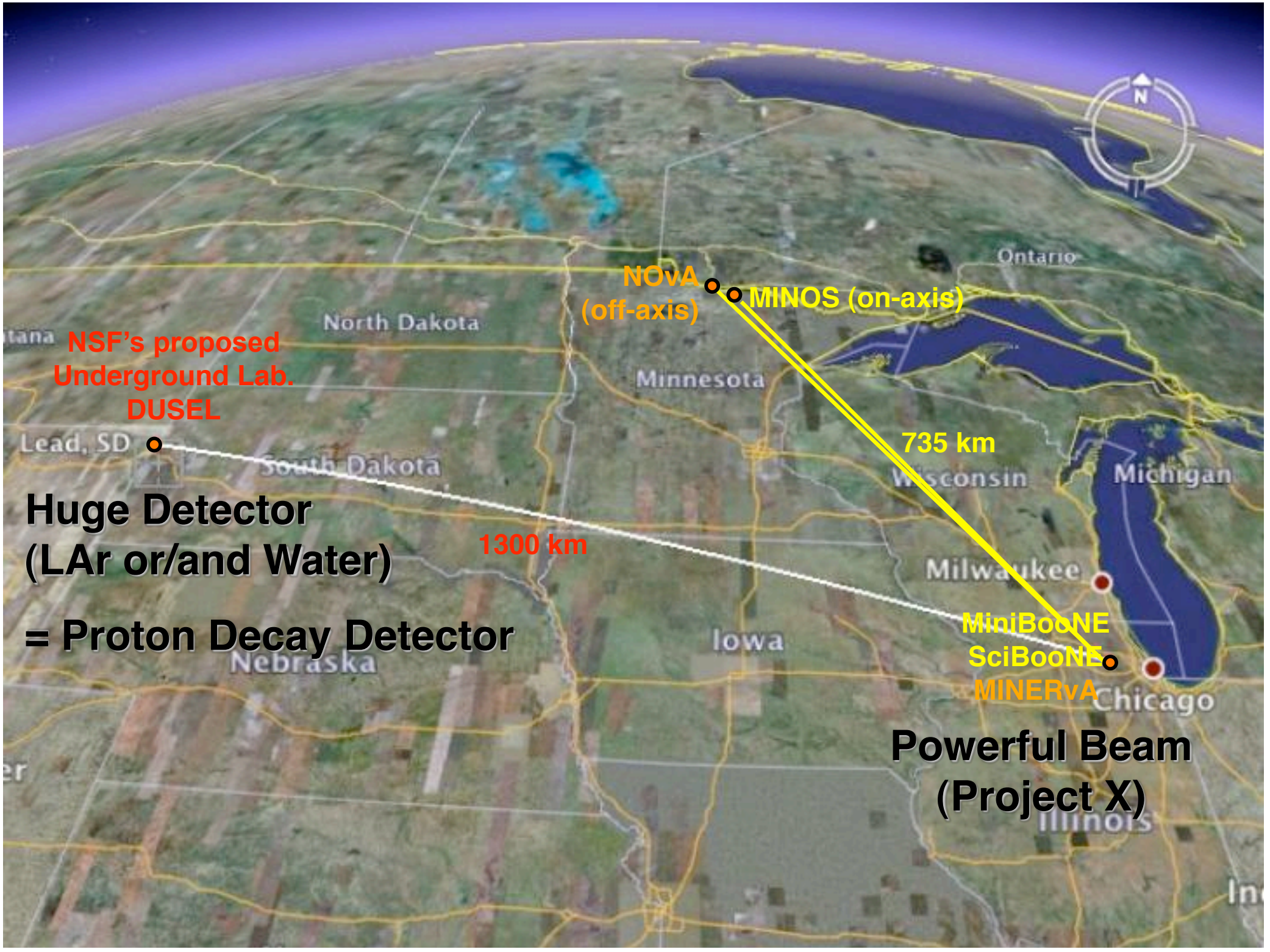
JPARC



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

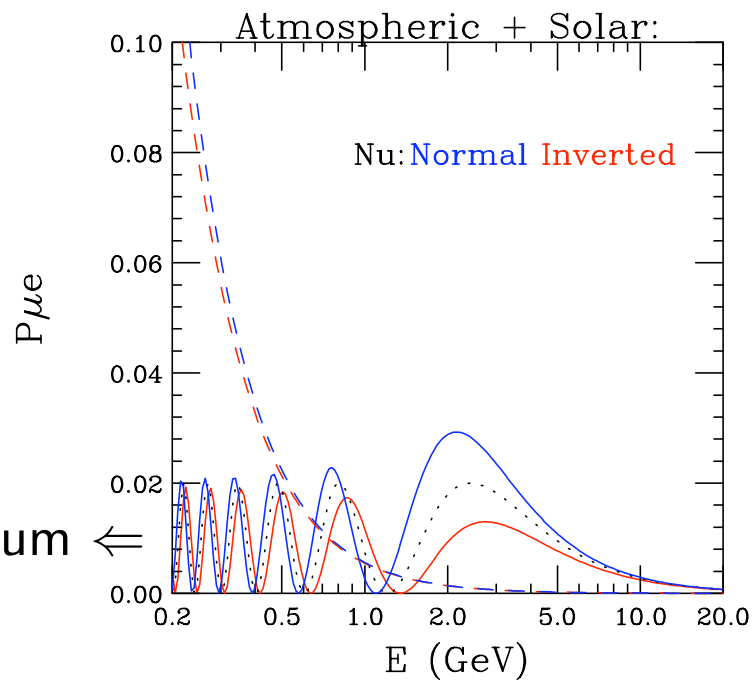
Narrow Band Beam: Same E, Longer L T2KK

Broadband Beam: Same L, Lower E Fermilab to DUSEL

In VACUUM the SAME but NOT in MATTER

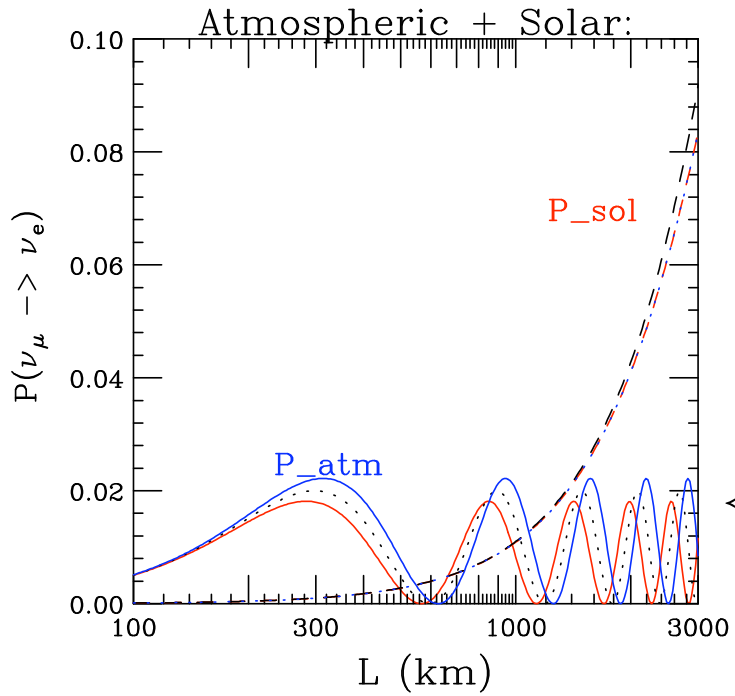
$$\sin^2 2\theta_{13} = 0.04$$

L=1200km



vacuum $\Leftarrow$

E=0.6 GeV



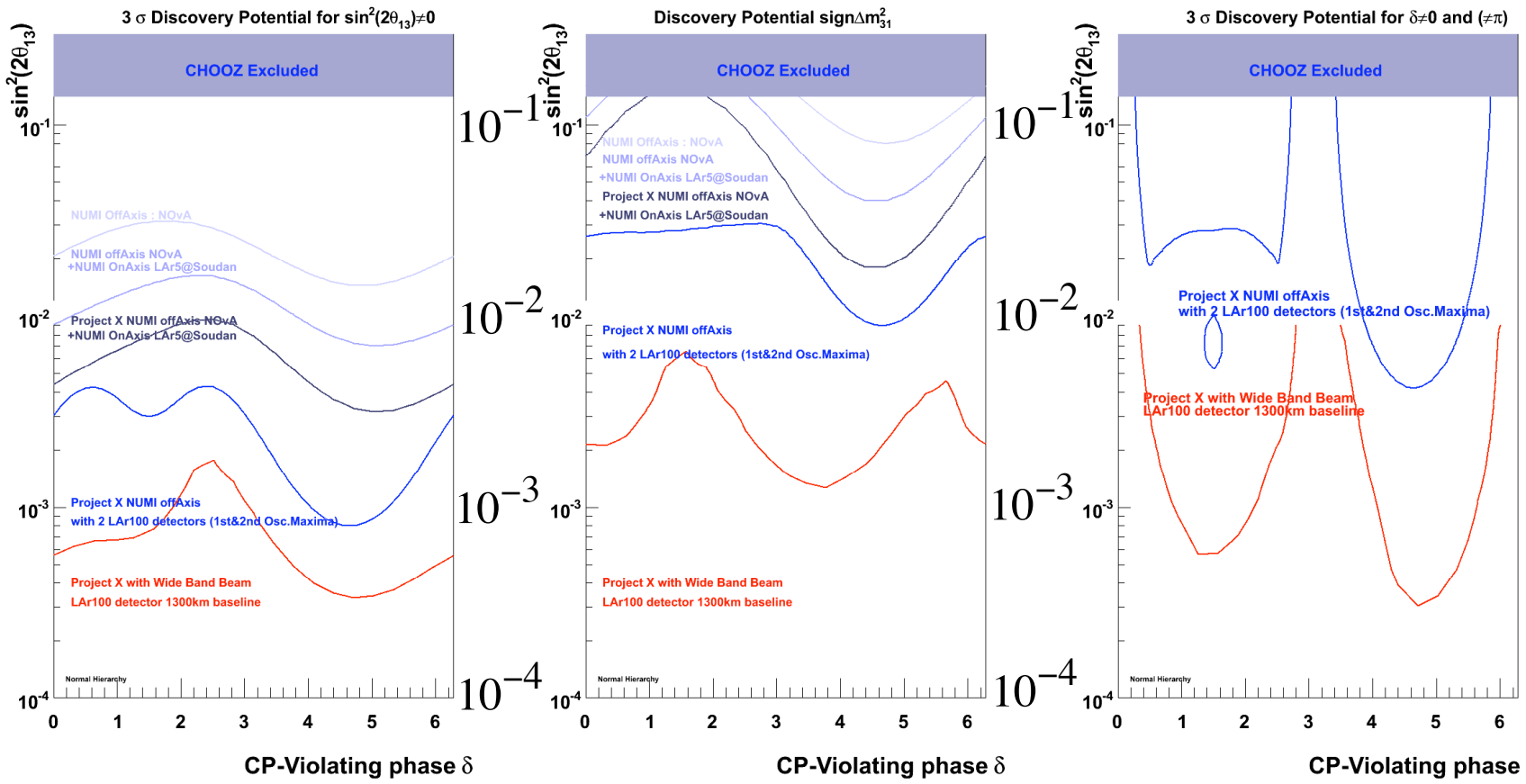
$\Leftarrow$ same height

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

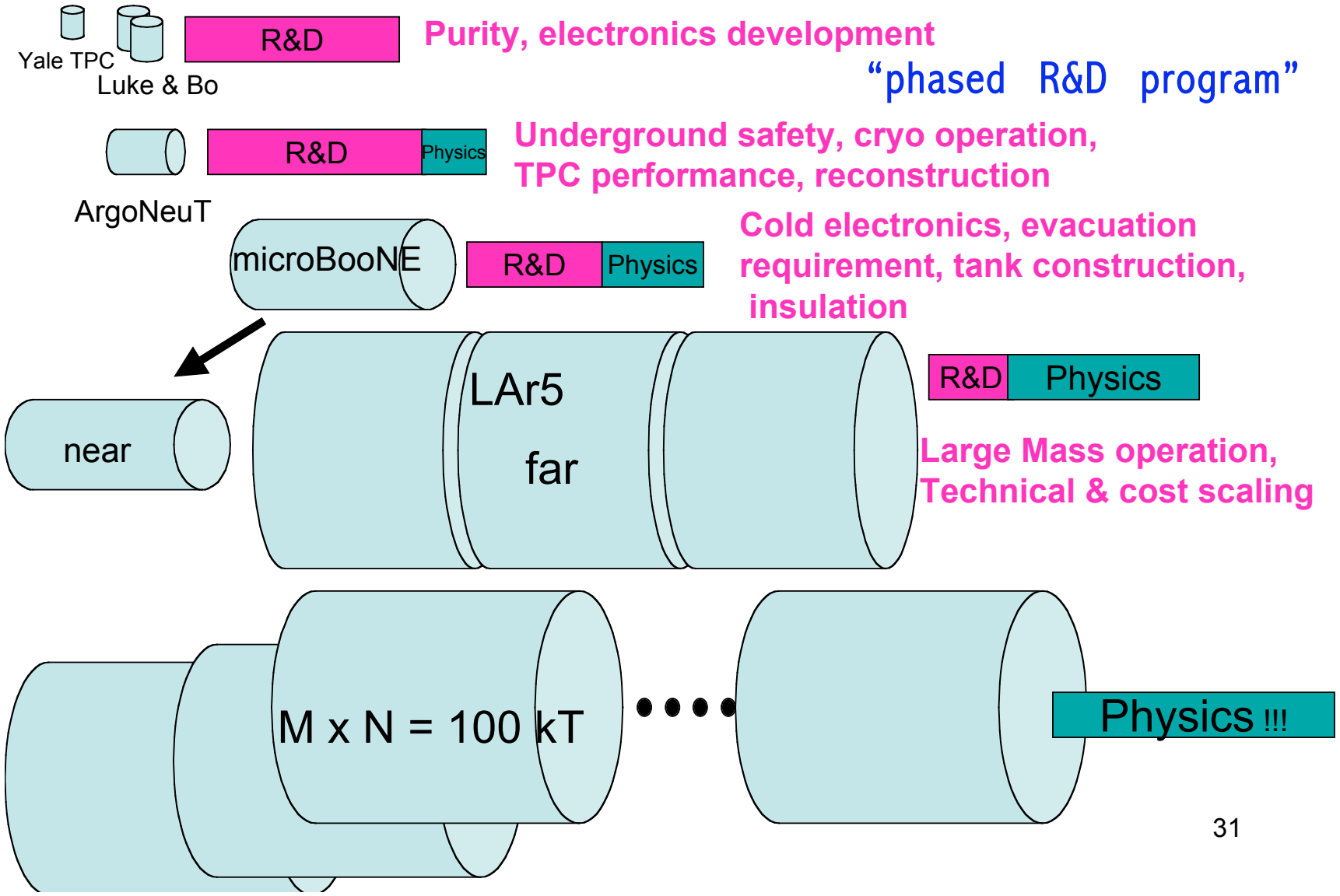
Fermilab to DUSEL (T2KK similar)

The 3σ Reach of the Successive Phases

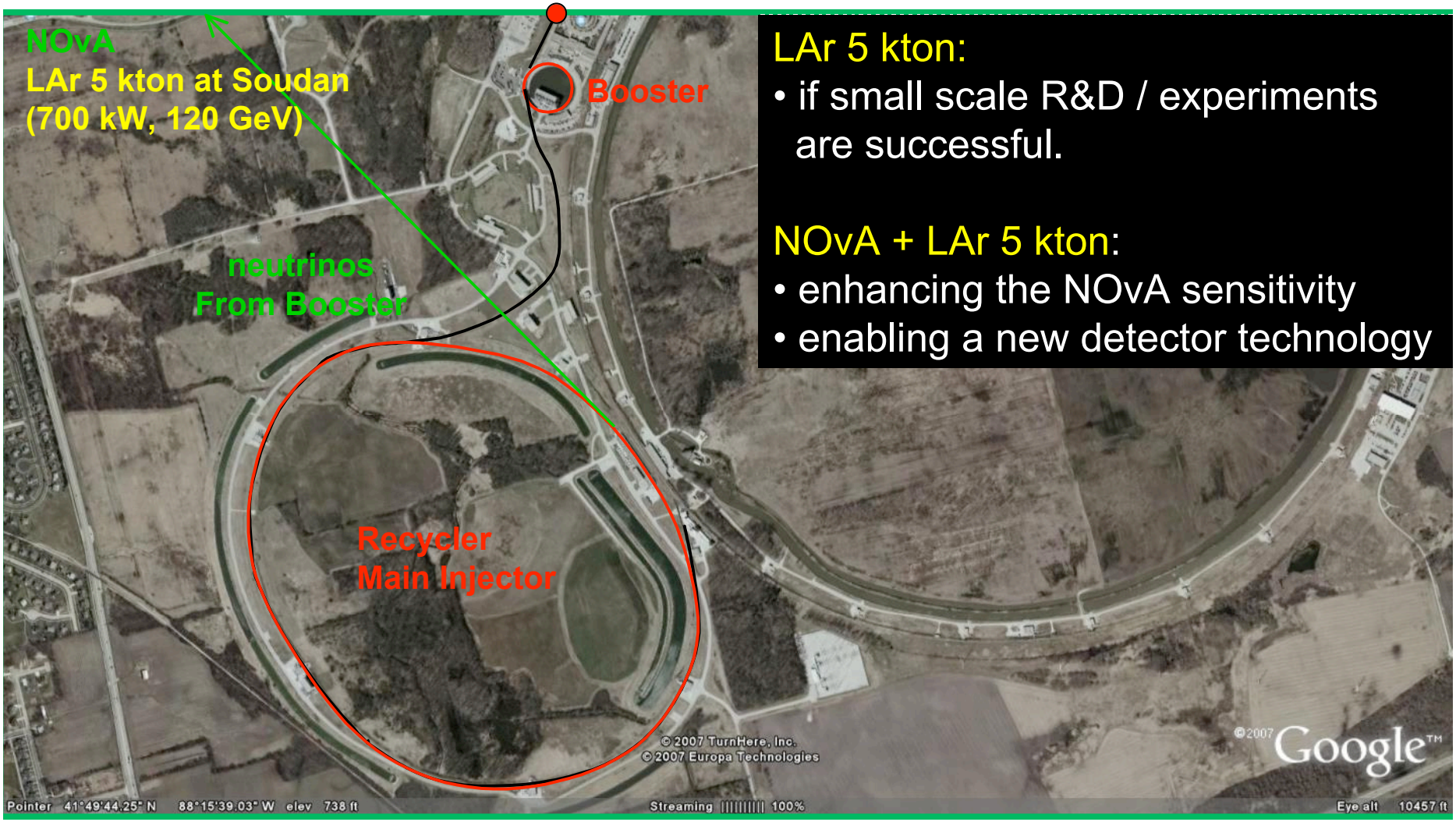
$\sin^2 2\theta_{13}$ | Mass Ordering | CP Violation



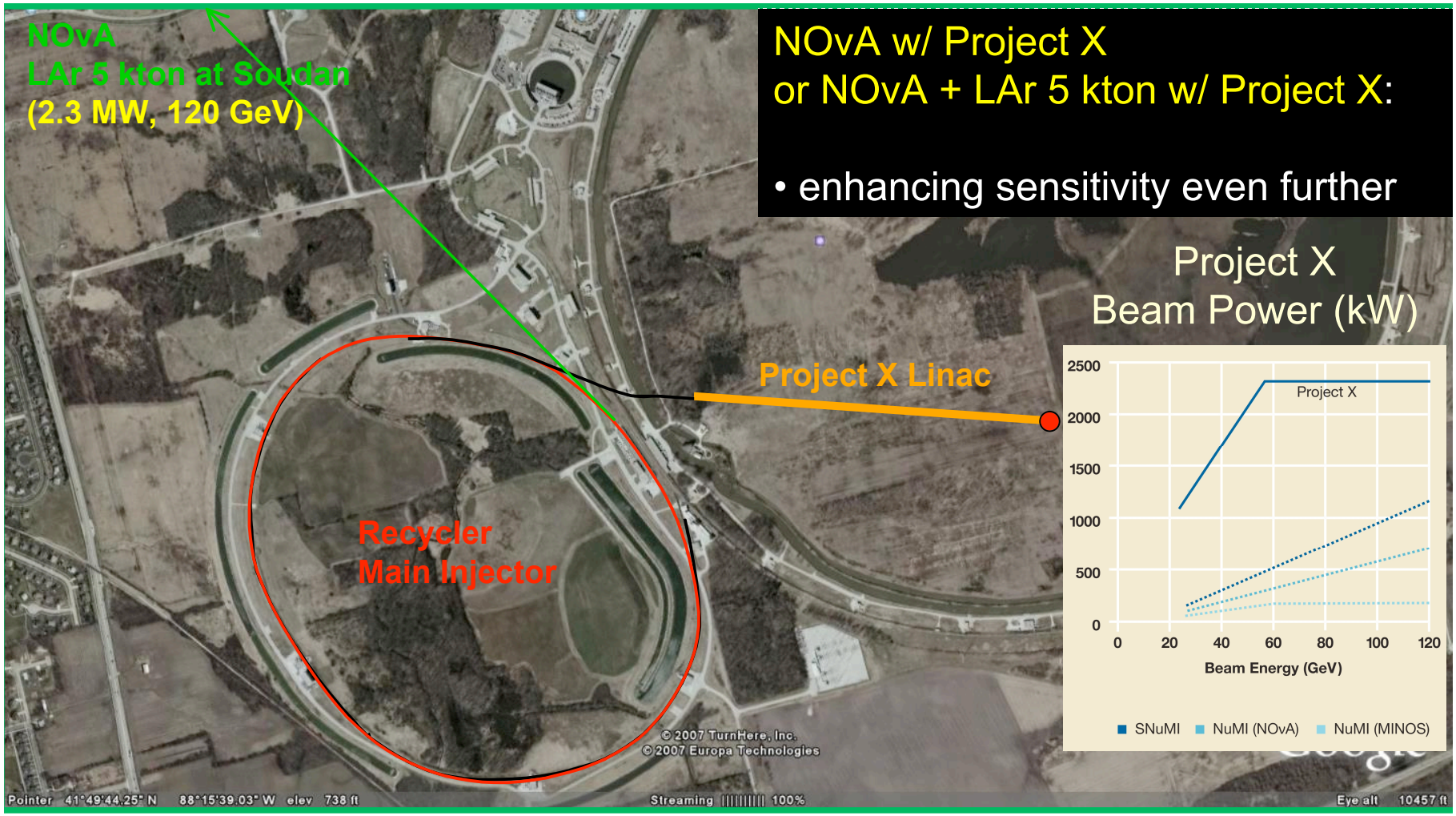
Evolution of the Liquid Argon Physics Program



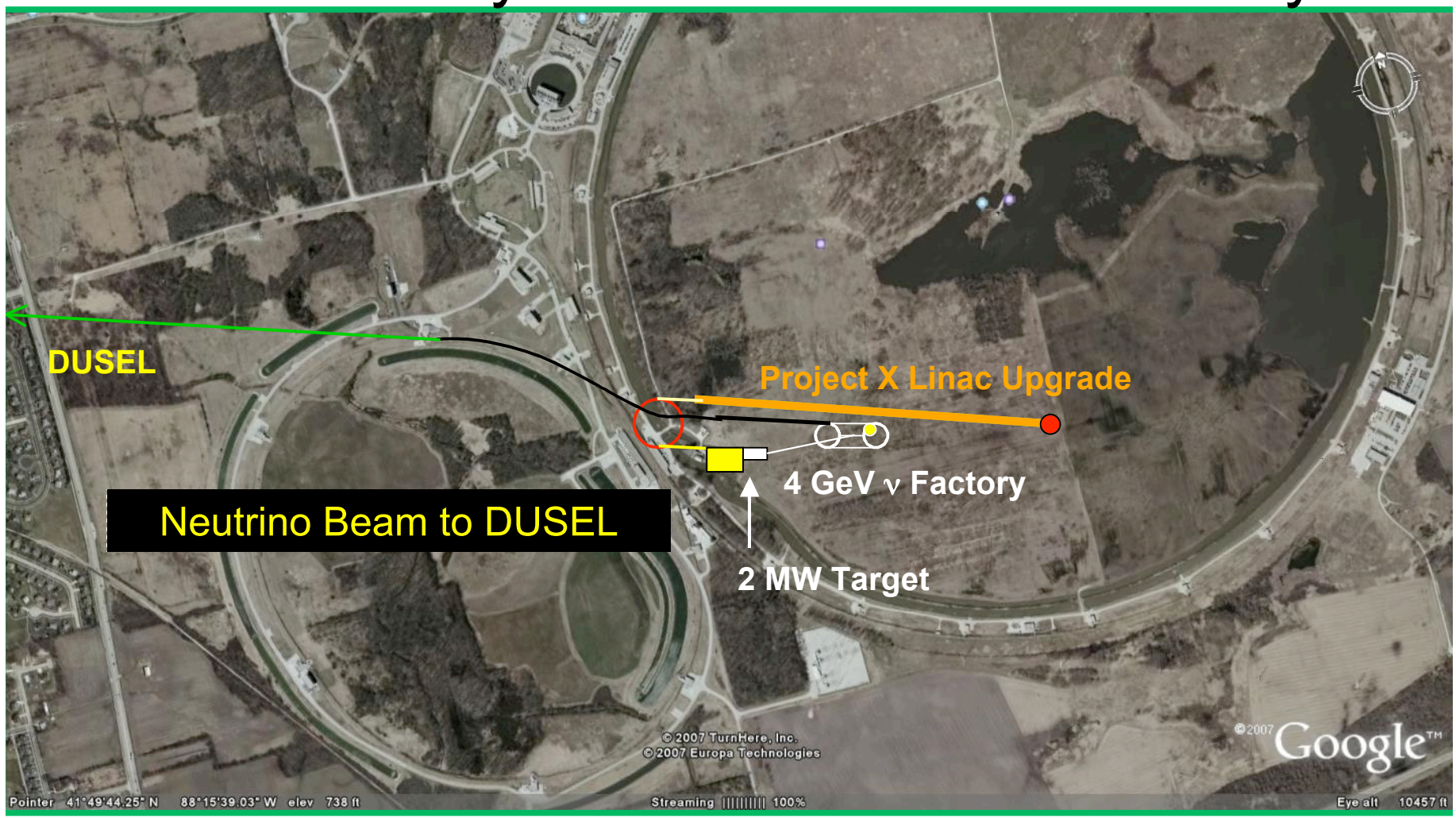
Phase 1.5:


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
© 2007 TurnHere, Inc.
© 2007 Europa Technologies
©2007 Google™
Pointer 41°49'44.25" N 88°15'39.03" W elev 738 ft
Streaming 100%
Eye alt 10457 ft

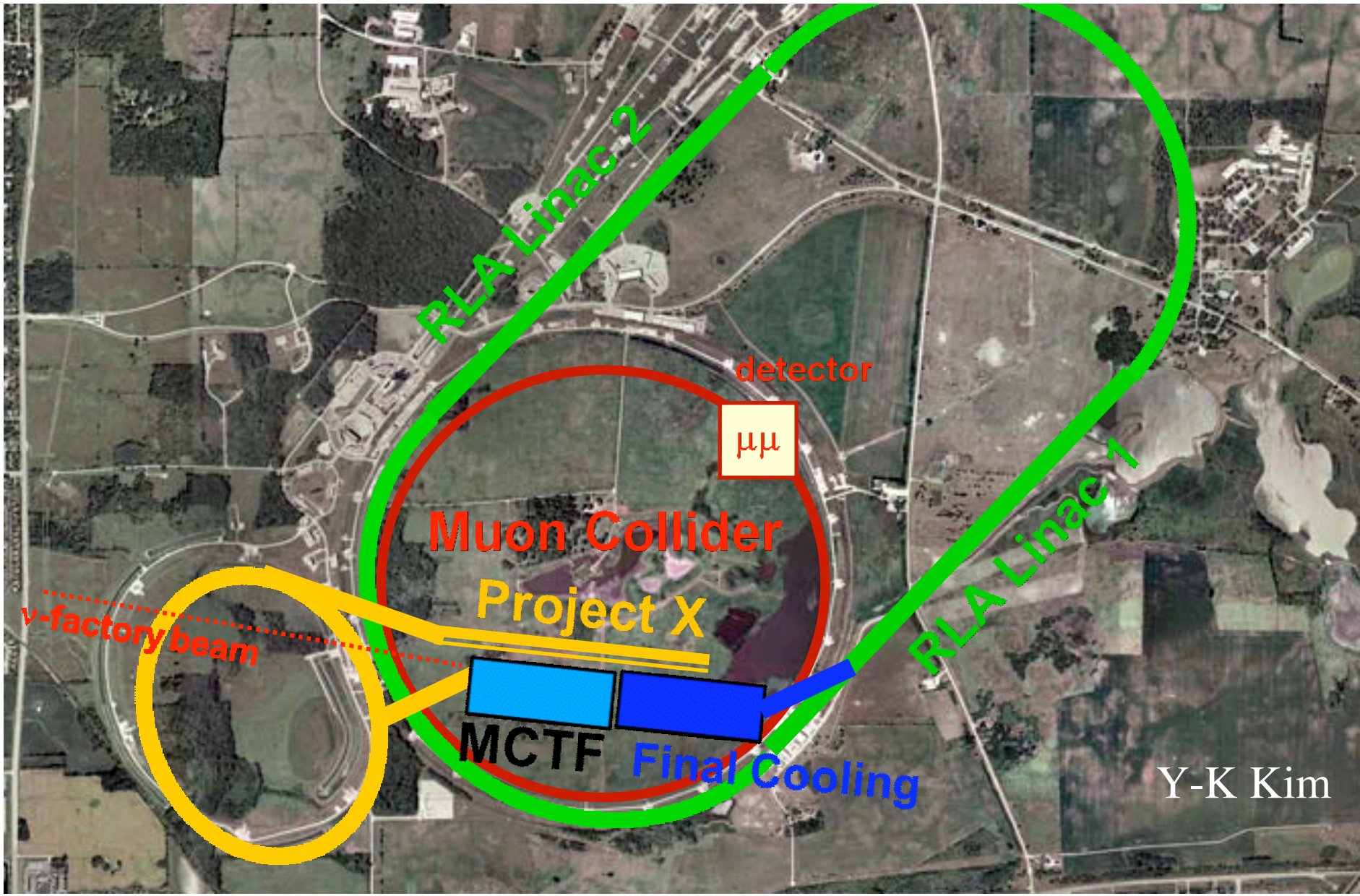
Phase 2:


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)
© 2007 TurnHere, Inc.
© 2007 Europa Technologies
Pointer 41°49'44.25" N 88°15'39.03" W elev 738 ft
Streaming 100%
Eye alt 10457 ft

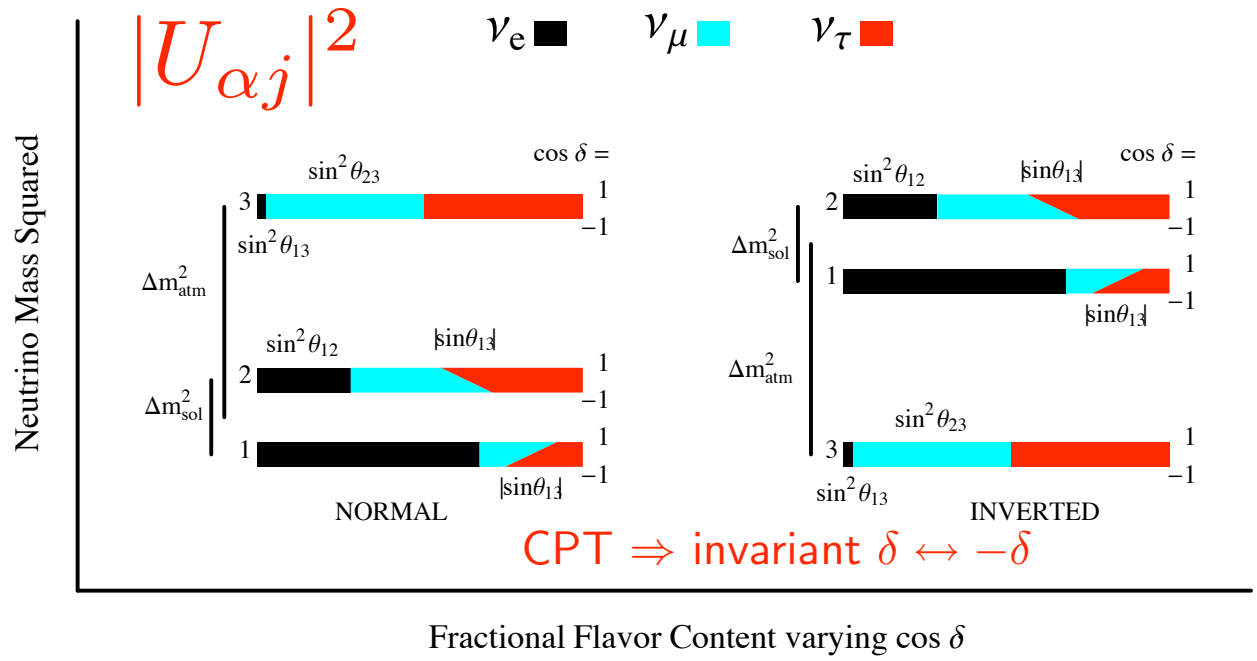
Toward "Proton Intensity Upgrade" Evolutionary Path to a Neutrino Factory



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



Summary:



CP

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

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

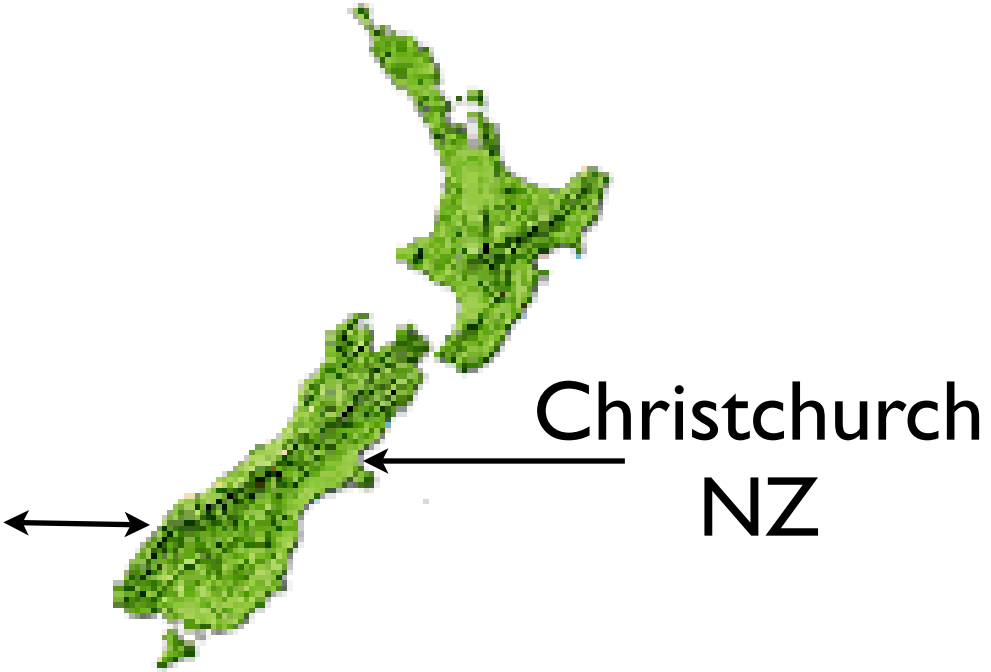
$\nu_e \longrightarrow \nu_\mu$ $\Longleftrightarrow$ $\bar{\nu}_e \longrightarrow \bar{\nu}_\mu$

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



www.neutrino2008.co.nz