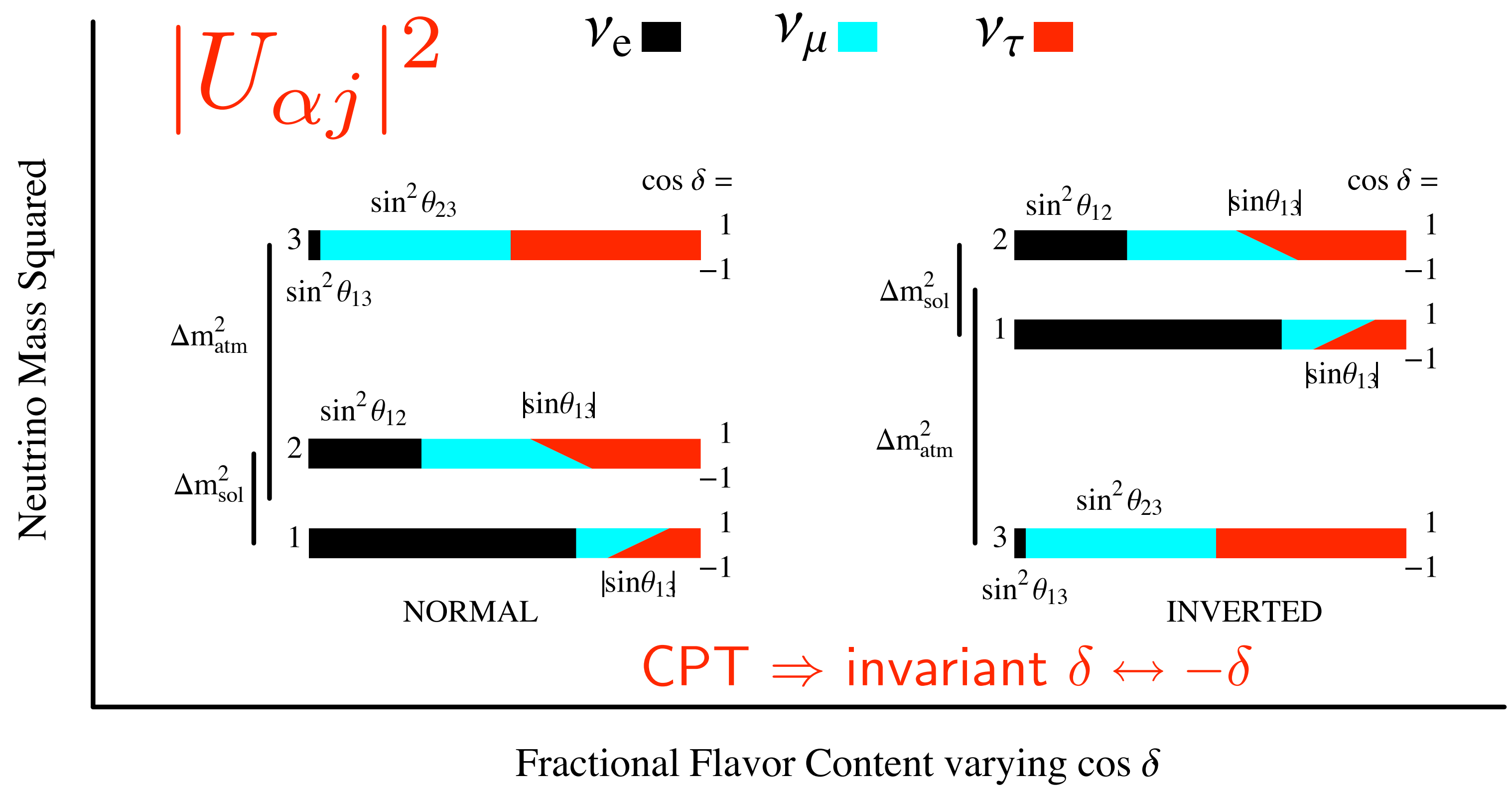
Physics case for long-baseline oscillation measurements:

Stephen Parke
Fermilab

Nu Standard Model:

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



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2 \qquad \sin^2\theta_{12} \sim \frac{1}{3}$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2 \qquad 0 \leq \delta < 2\pi \qquad \sin^2\theta_{23} \sim \frac{1}{2}$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03 \qquad \sin^2\theta_{13} \sim 0.02$$

Except: LSND, miniBooNE, reactor anomaly, gallium anomaly.

Neutrino Mixing Matrix: PMNS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

smaller ν_e content

$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

Neutrino Mixing Matrix: PMNS

SNO CC
KamLAND
$|U_{e2}|^2$

Reactor/LBL
$|U_{e3}|^2(1-|U_{e3}|^2)$

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Atm Nus/LBL
$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

Neutrino Mixing Matrix: PMNS

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SK & OPERA Tau's
$|U_{\tau 3}|^2$

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$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

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SNO NC $|U_{e2}|^2+|U_{\mu 2}|^2+|U_{\tau 2}|^2$

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$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

No Information!

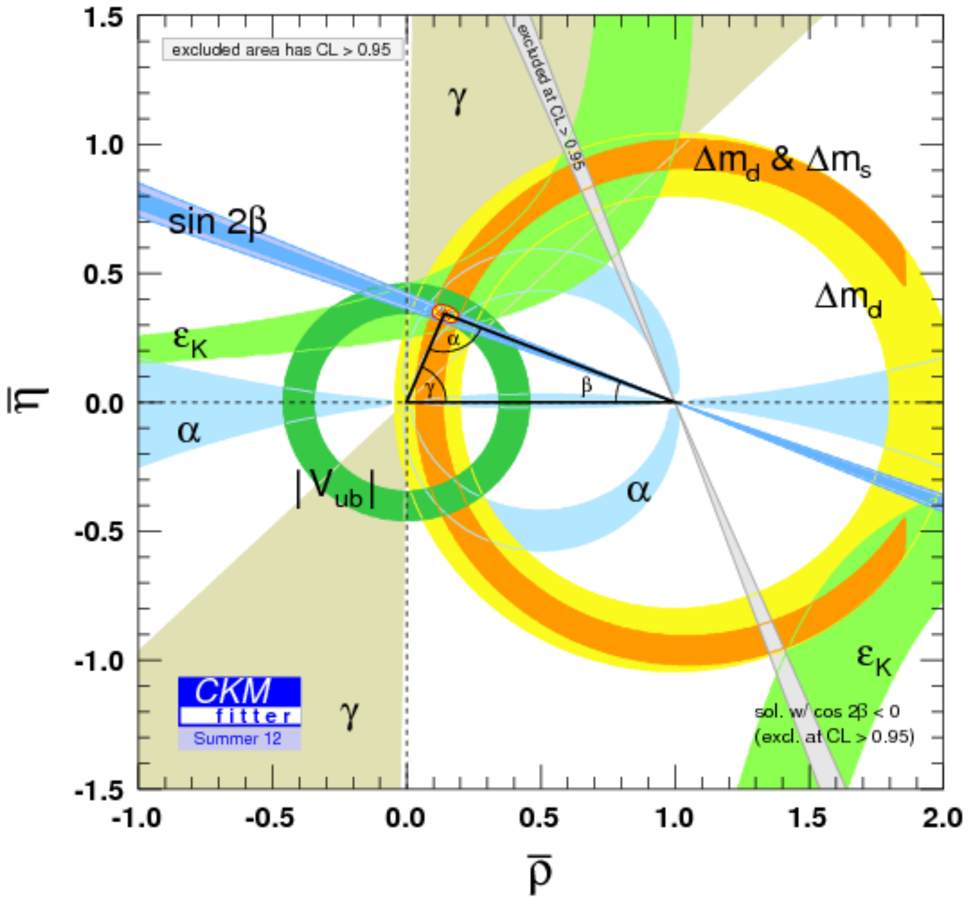
SNO NC $|U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2$

SK & OPERA Tau's $|U_{\tau 3}|^2$

Atm Nus/LBL $|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$

Quark & lepton Unitarity Triangles:

Quark Triangle:



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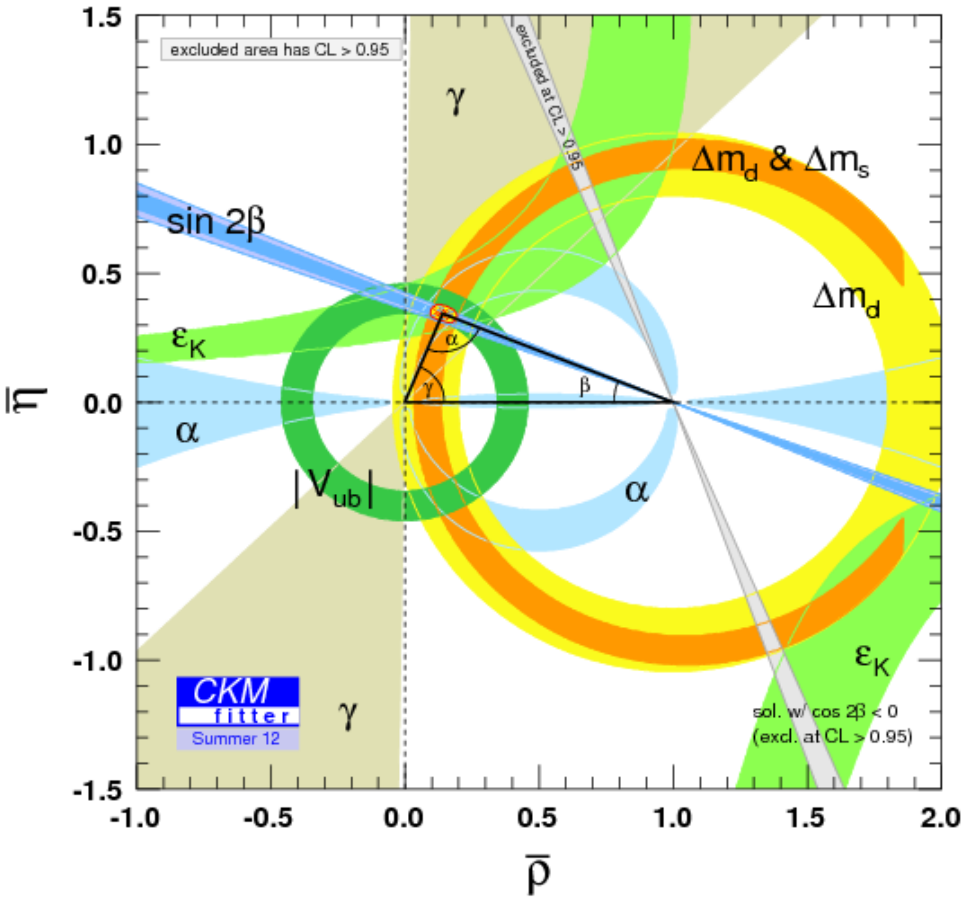
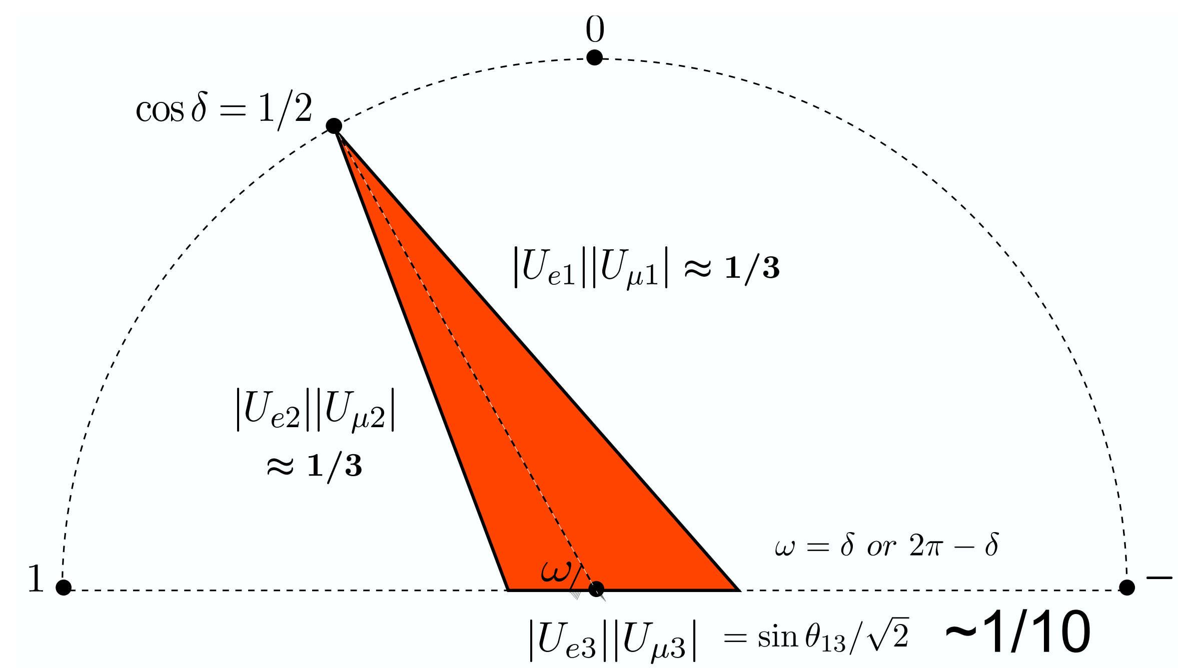


Neutrino Triangle:

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

only Unitarity triangle that doesn't involve ν_τ !

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



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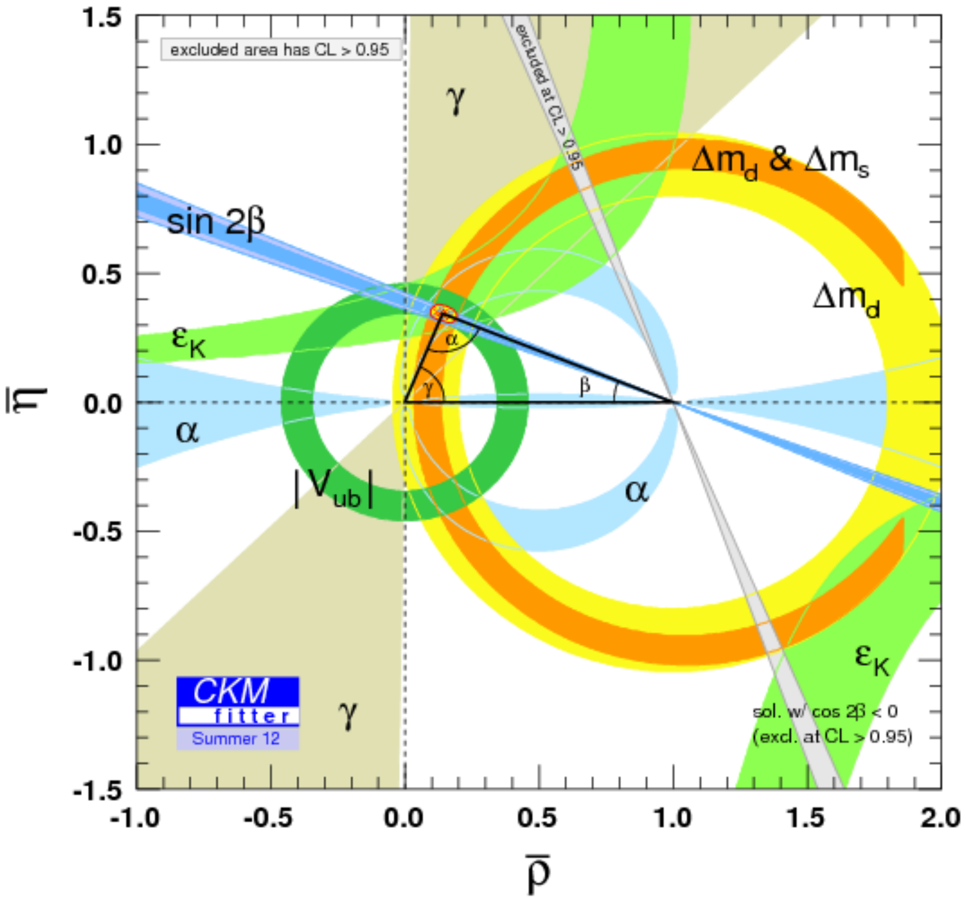

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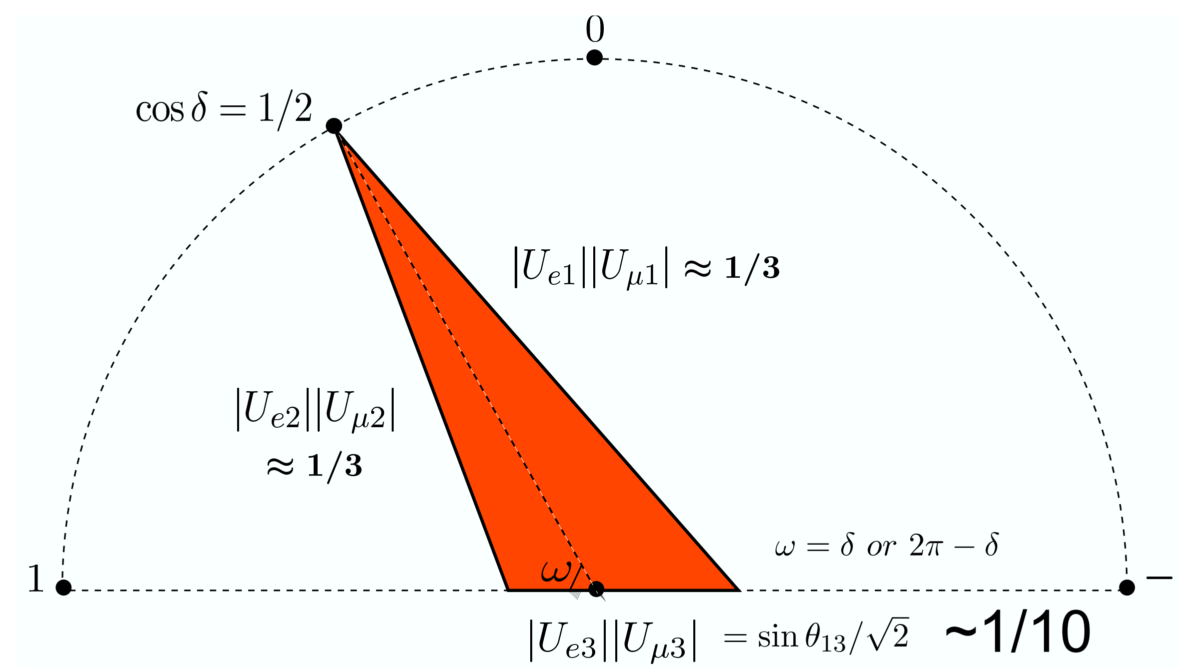

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How to measure $|U_{\mu 1}|^2$ and $|U_{\mu 2}|^2$ separately ? ? ?

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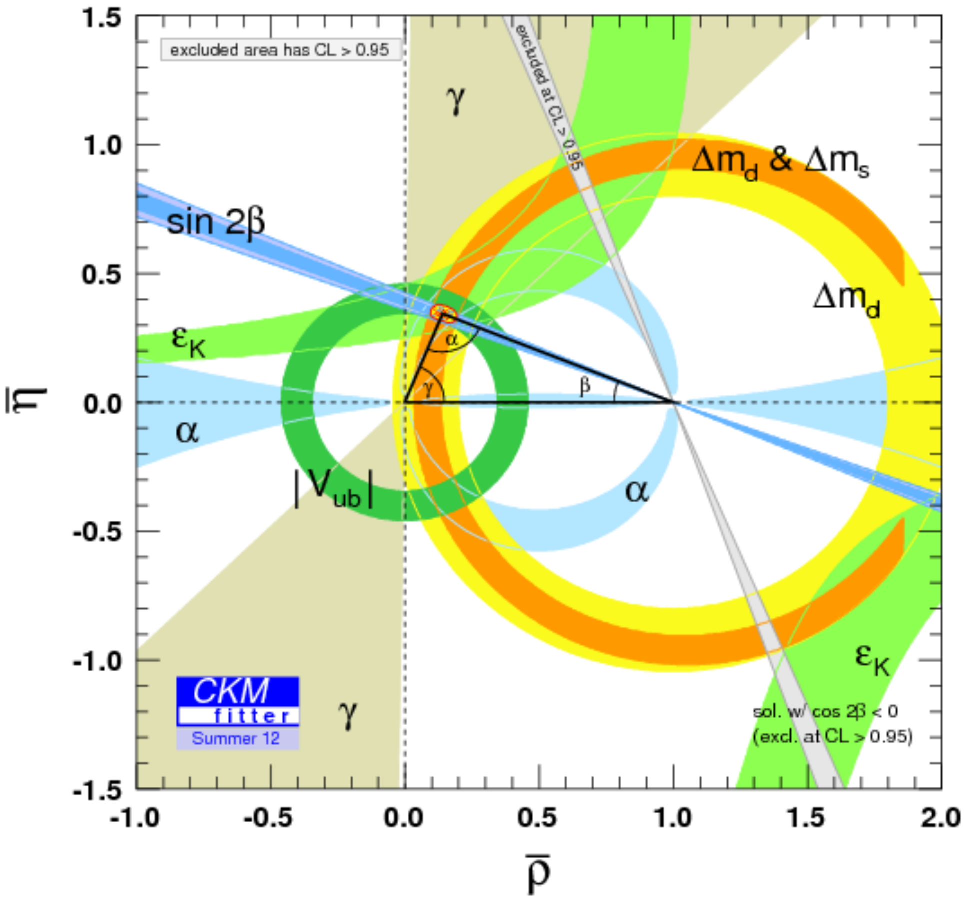

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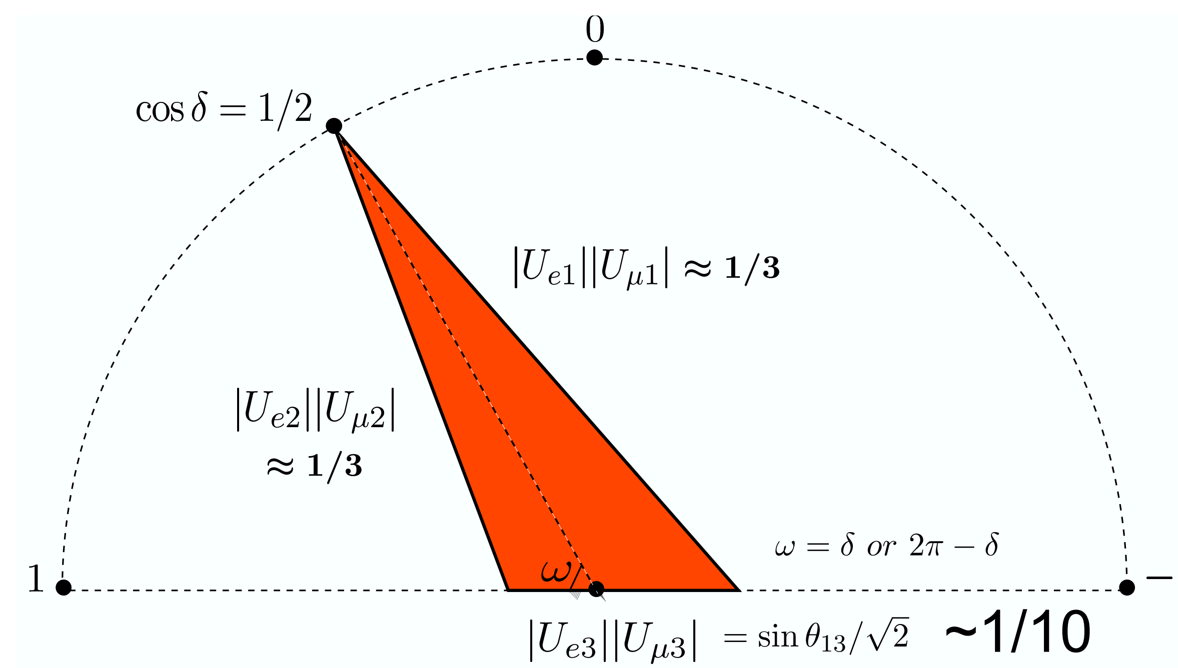

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Neutrino Factory to detector in geo-synchronous orbit ! ! !

Unanswered Questions !

ν Standard Model

- Nature of Neutrino: Majorana (2 comp) or Dirac (4 comp) fermion?
- CPV in Neutrino Sector: determination Dirac phase δ ?
- Ordering of mass eigenstates: Atmos. mass hierarchy, sign of δm^2_{31} ?
- Is ν_3 more ν_μ or more ν_τ: $|U_{\mu 3}|^2 > \text{or} < |U_{\tau 3}|^2$ or $\theta_{23} > \text{or} < \pi/4$
- Majorana Phases: 2 additional phases
- Absolute Neutrino Mass: m_{lite}

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} ***Credibility of Leptogenesis !!***

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- What is the mass of the Sterile Neutrinos: light? or Superheavy?
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Leptons v Quarks:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Very Different !!!

Flavors & quark-lepton unification

Quarks CKM matrix = **1** + (Cabibbo) effects

Leptons' MNSP matrix = **X** + (Cabibbo?) effects

↖ contains two large angles

Cabibbo effects as deviation from **X**

example: $\theta_{13} \simeq \theta_c/\sqrt{2}$ deviation from zero?

speculate: $\theta_{atm} \simeq \pi/4 + O(\theta_c)$ deviation from $\pi/4$?

Masses & Mixings (conti.)

- Quark-Lepton Complementarity $\theta_{12} + \theta_C = 45^o$
- Solar sum rules
  - Bimaximal $\theta_{12} = 45^o + \theta_{13} \cos\delta$
  - Tri-bimaximal $\theta_{12} = 35^o + \theta_{13} \cos\delta$
  - Golden Ratio $\theta_{12} = 32^o + \theta_{13} \cos\delta$

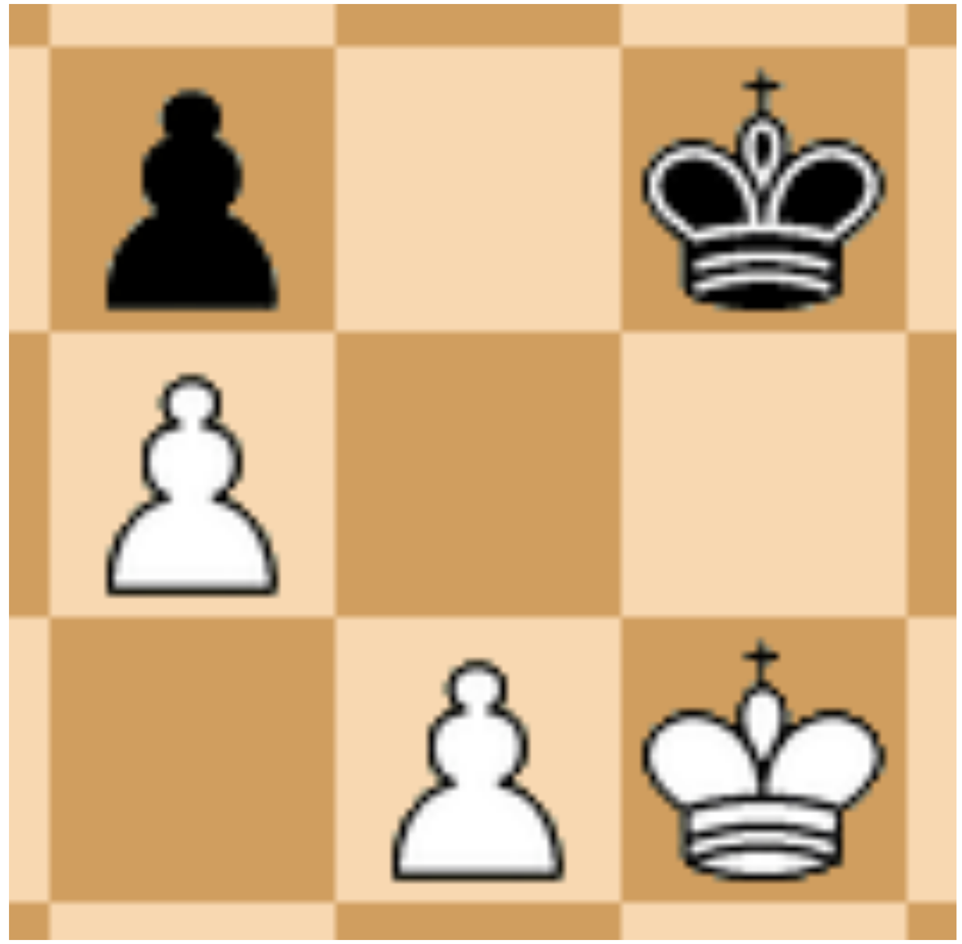
Plus HO corrections...

- Atm. sum rules
  - Tri-bimaximal-Cabibbo $\theta_{12} = 35^o \quad \theta_{23} = 45^o$, $\theta_{13} = \theta_C/\sqrt{2} = 9.2^o$
  - Trimaximal1 $\theta_{23} = 45^o + \sqrt{2}\theta_{13} \cos\delta$
  - Trimaximal2 $\theta_{23} = 45^o - \frac{\theta_{13}}{\sqrt{2}} \cos\delta$

Plus Charged Lepton Corrections...

Now that θ_{13} is measured these predict $\cos\delta$

Given this end game:



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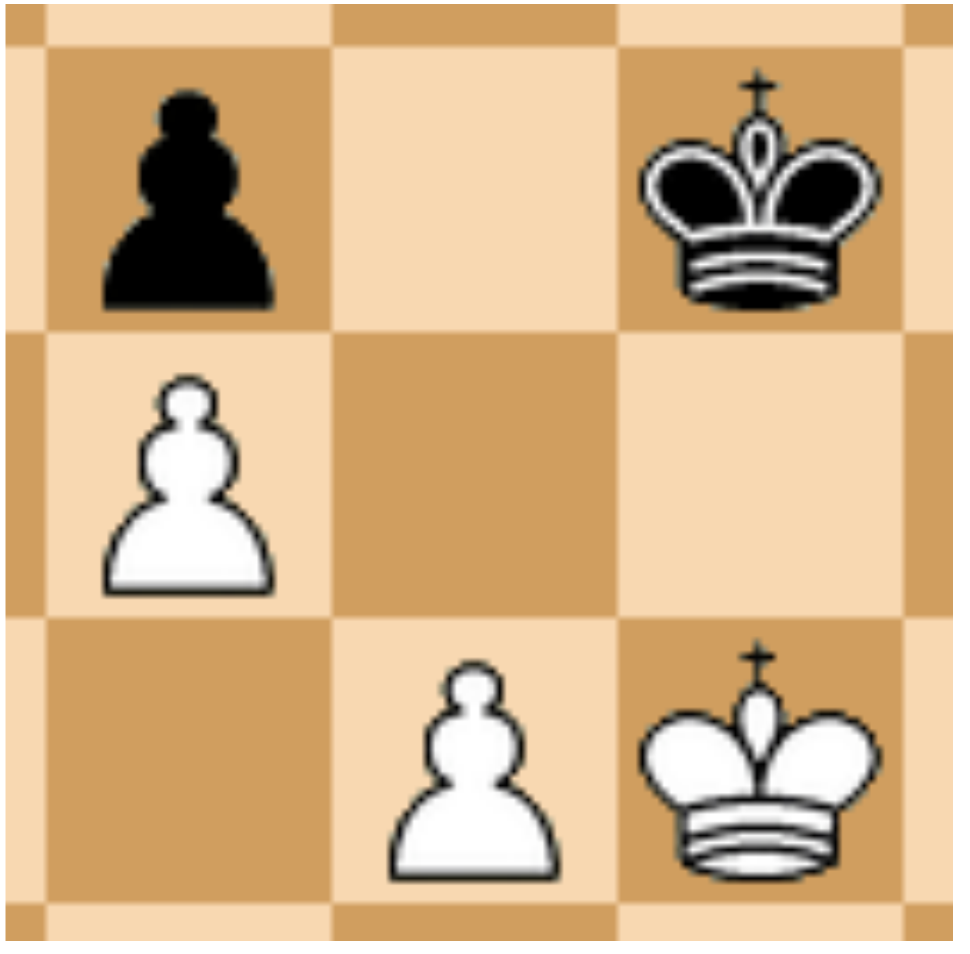

Deduce the rules of chess!!!

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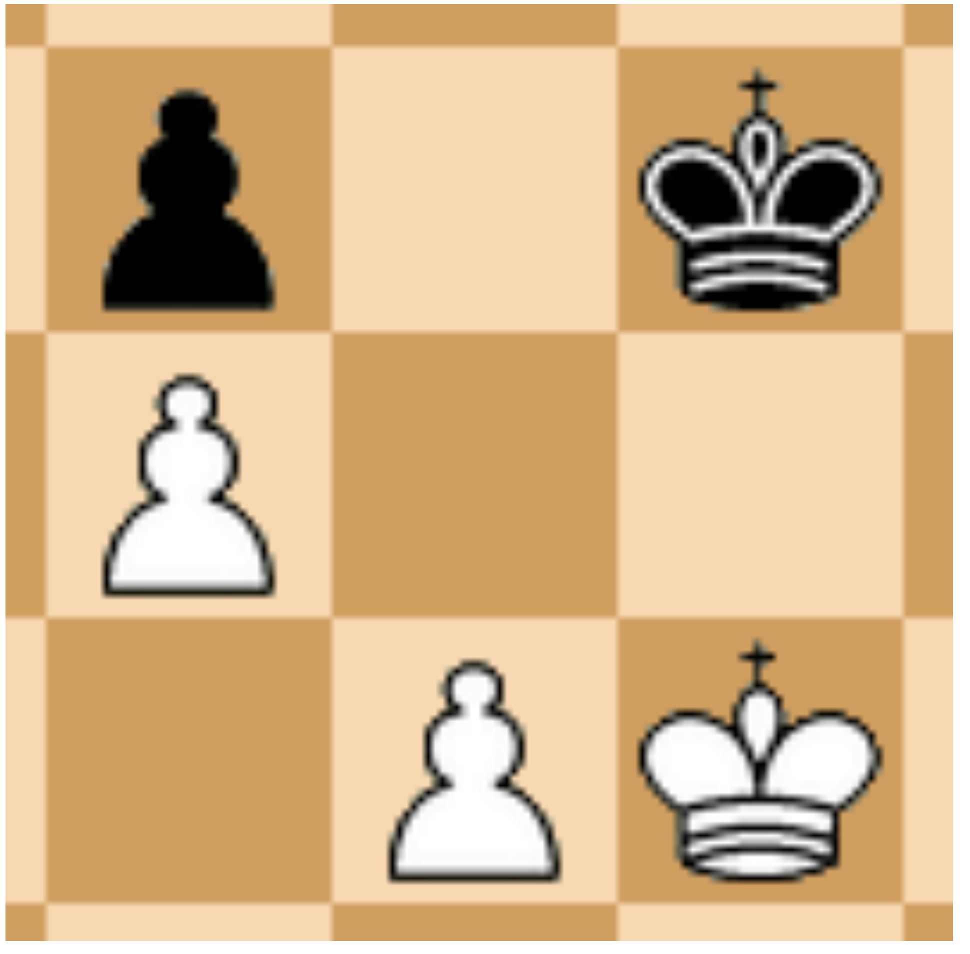

Deduce the rules of chess!!!

theorists need more hints !

Precision Measurements:

Appearance Experiments:

CP

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

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

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

CP

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

$\boldsymbol{\nu_\tau}$ at Neutrino Factory

Vacuum LBL:

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

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

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

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

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

only CPV

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

$$\Delta P_{cp} = 2\sin\delta\sin 2\theta_{13}\ \sin 2\theta_{23}\sin 2\theta_{12}\cos\theta_{13}\ \sin\Delta_{21}\sin\Delta_{31}\sin\Delta_{32}$$

$\nu_\mu \longrightarrow \nu_e$

In Matter:

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

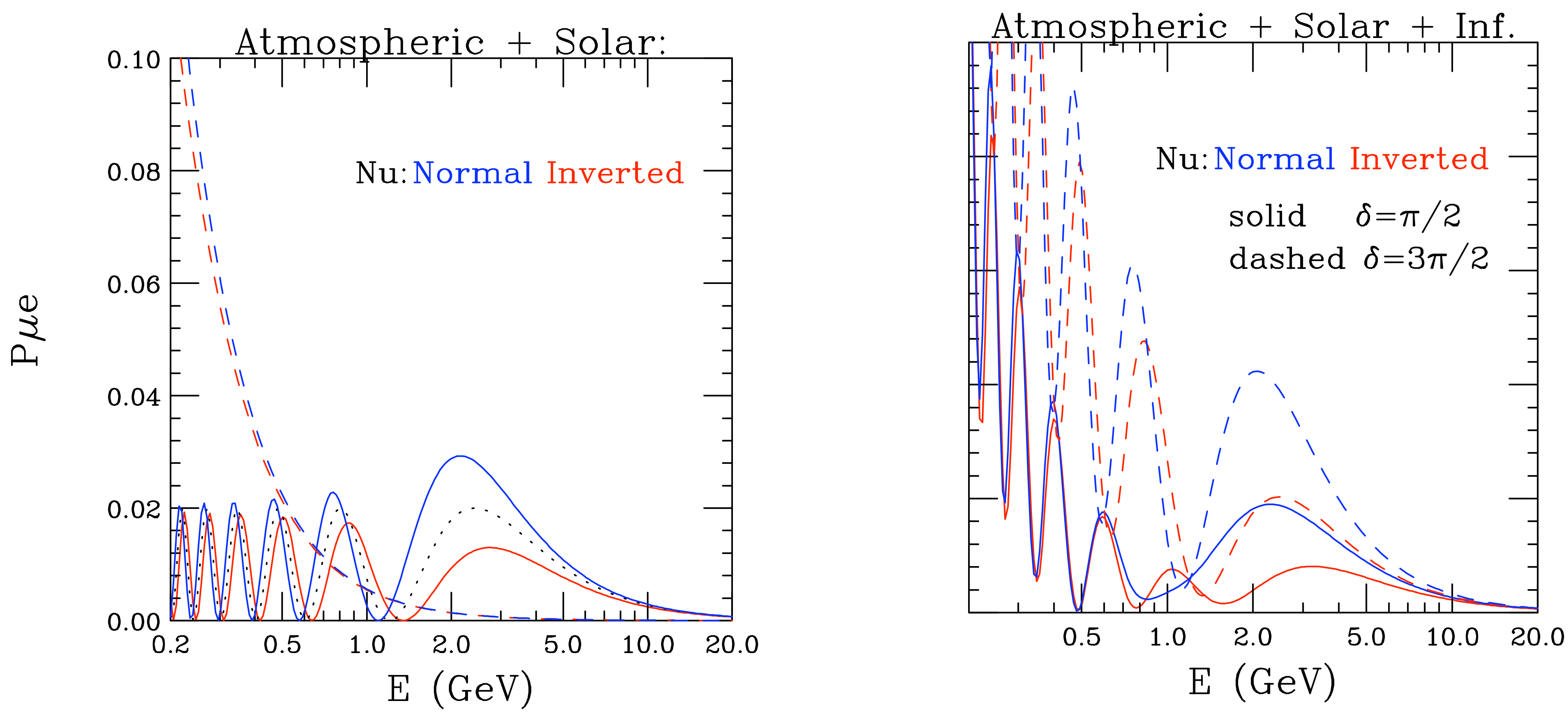
where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\, \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\, \Delta_{31}$

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

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 $\delta = 3\pi/2$



1st Oscillation Maximum

At 1st Oscillation Maximum: $\Delta_{31} = \pi/2$:

In vacuum,

Reactor:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \pm P(\nu_\mu \to \nu_e) = \begin{cases} 2\,\sin^2\theta_{23}\;\sin^2 2\theta_{13} & \Rightarrow \theta_{23} \text{ ``octant''} \\ \frac{\pi}{30}\,\sin\delta\; J_r & CPV \end{cases}$$

where $J_r = \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \approx 0.3$

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where $J_r = \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \approx 0.3$

In Matter:

- sum, corrections are small – matter*CPV ! ! !
- difference can give Mass Hierarchy,
  if matter effects large enough and/or δ favourable

Current Experiments:

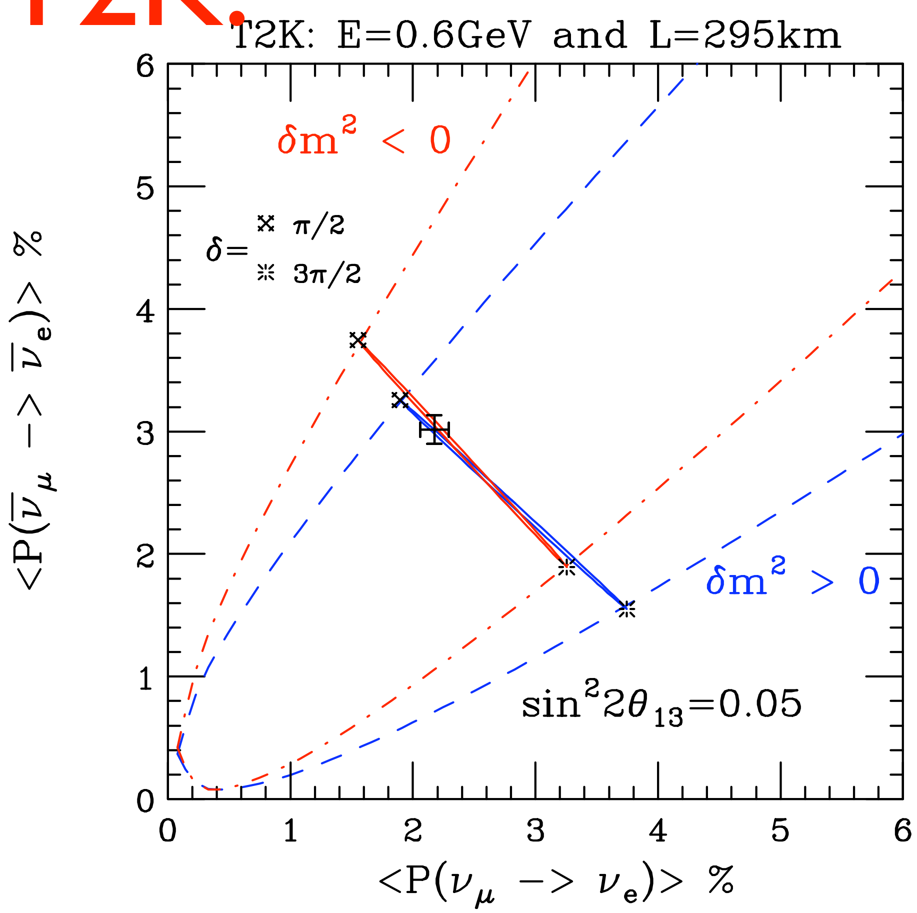
- Near 1st Oscillation Maximum: L/E= 500 km/GeV

Off Axis beams:

T2K L=295km, $\langle E \rangle = 0.65$ GeV, 2.5°

NOνA: L=810km, $\langle E \rangle = 2.0$ GeV, 14 mrad

T2K:



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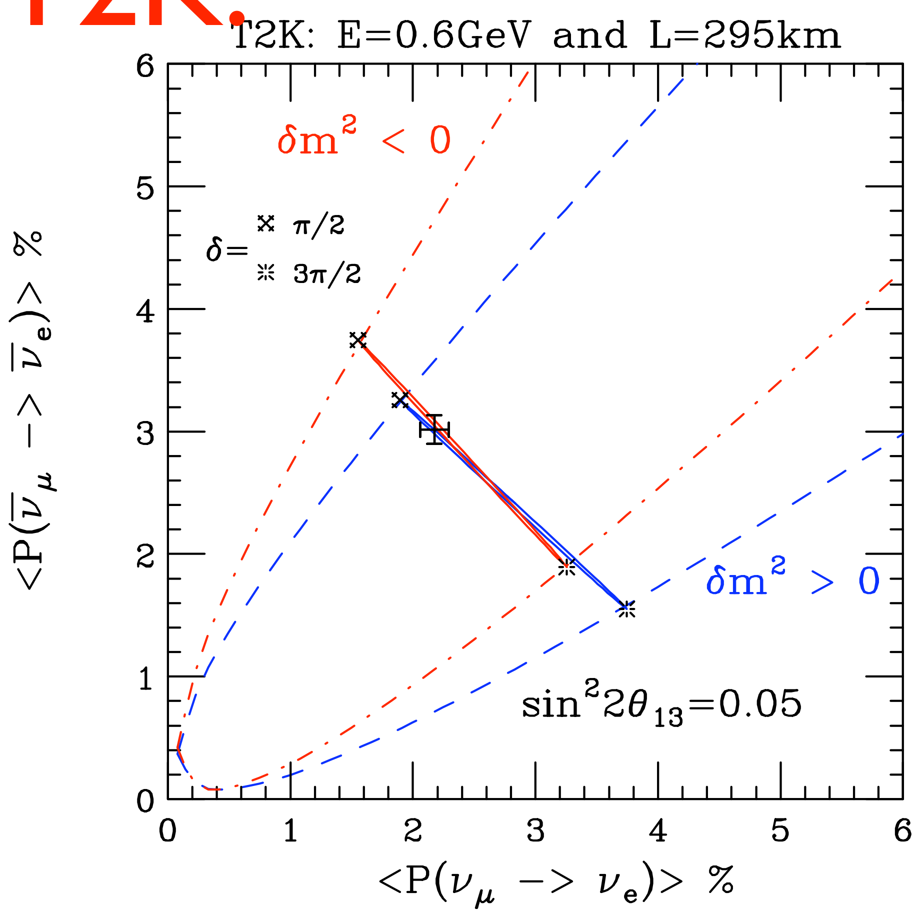
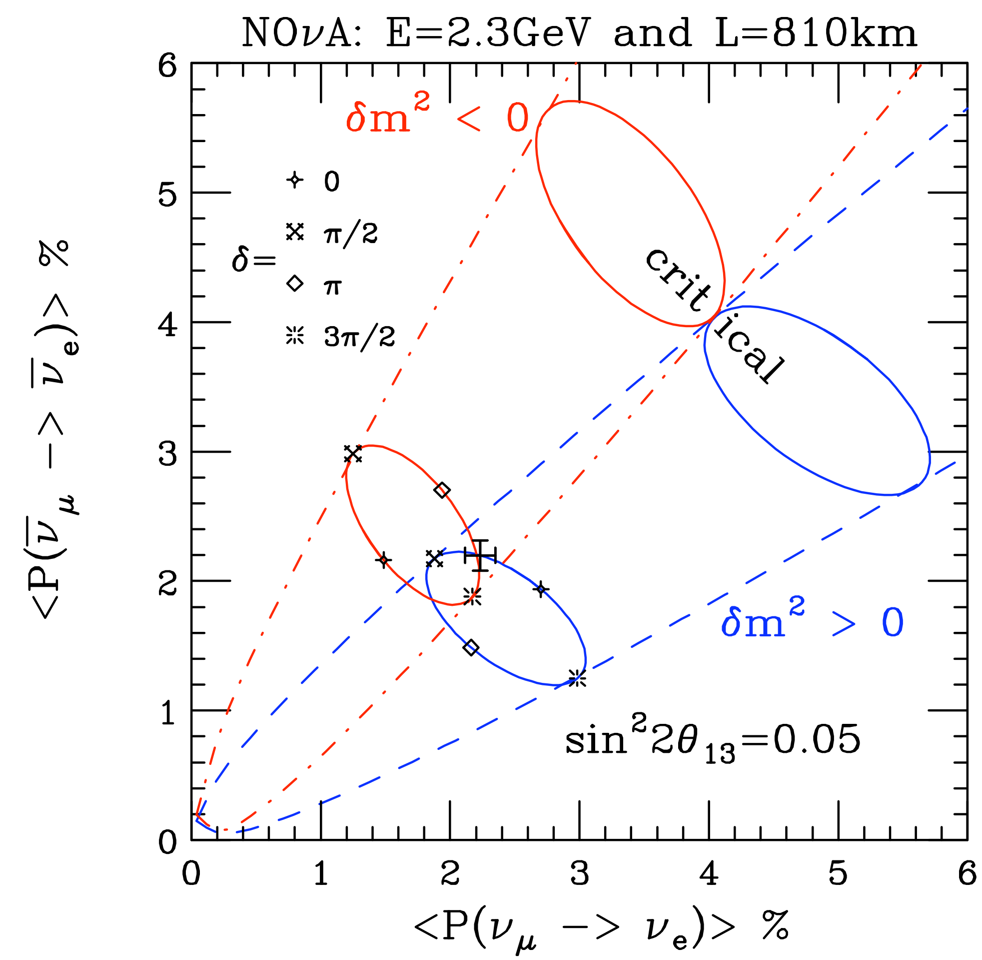
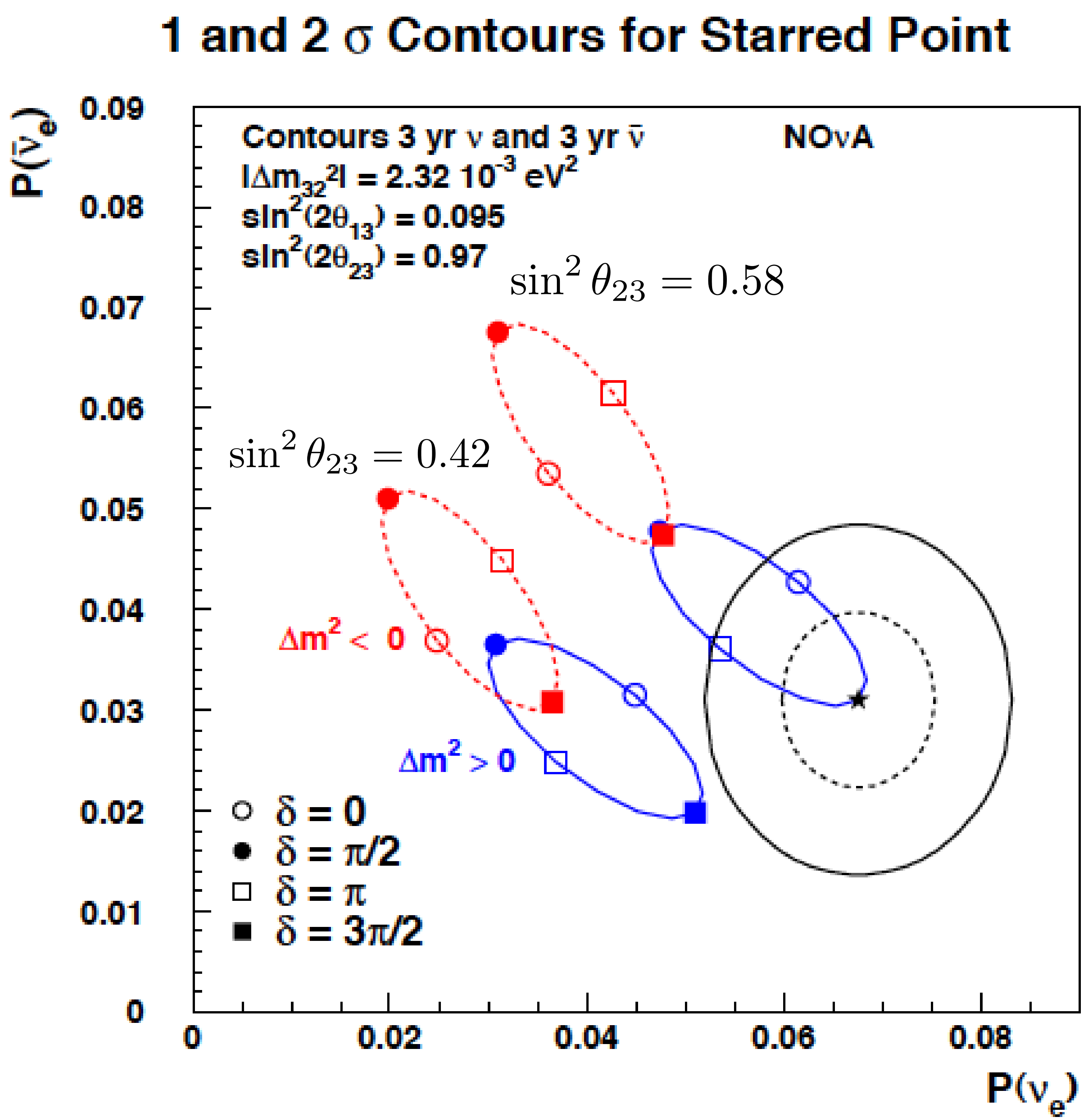




$$\theta_{crit} \approx \frac{\pi^2}{8} \frac{\sin 2\theta_{12}}{\tan\theta_{23}} \frac{\delta m^2_{21}}{\delta m^2_{31}} \left(\frac{4\Delta^2_{31}/\pi^2}{1-\Delta_{31}\cot\Delta_{31}} \right) /(aL)$$

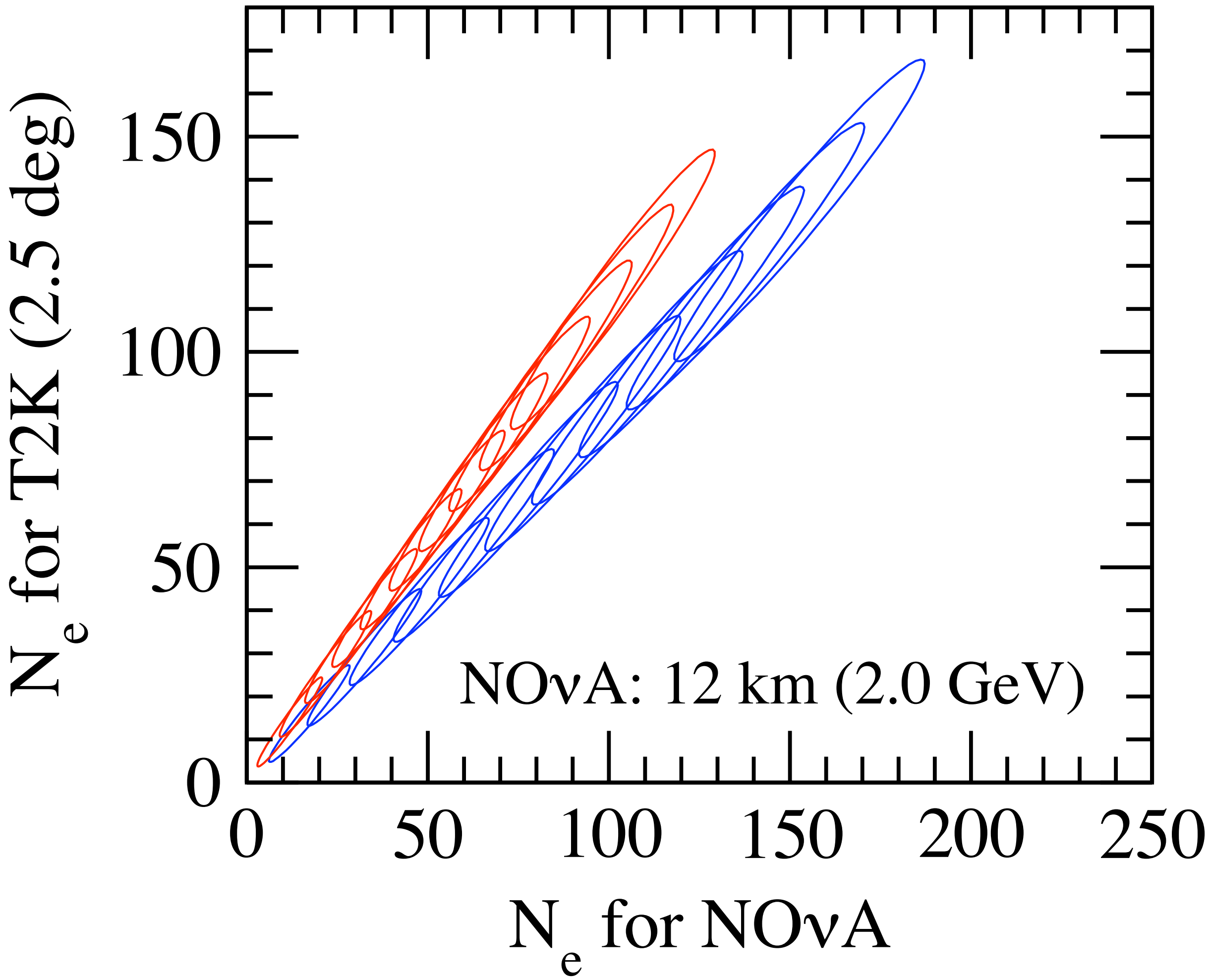
NOvA

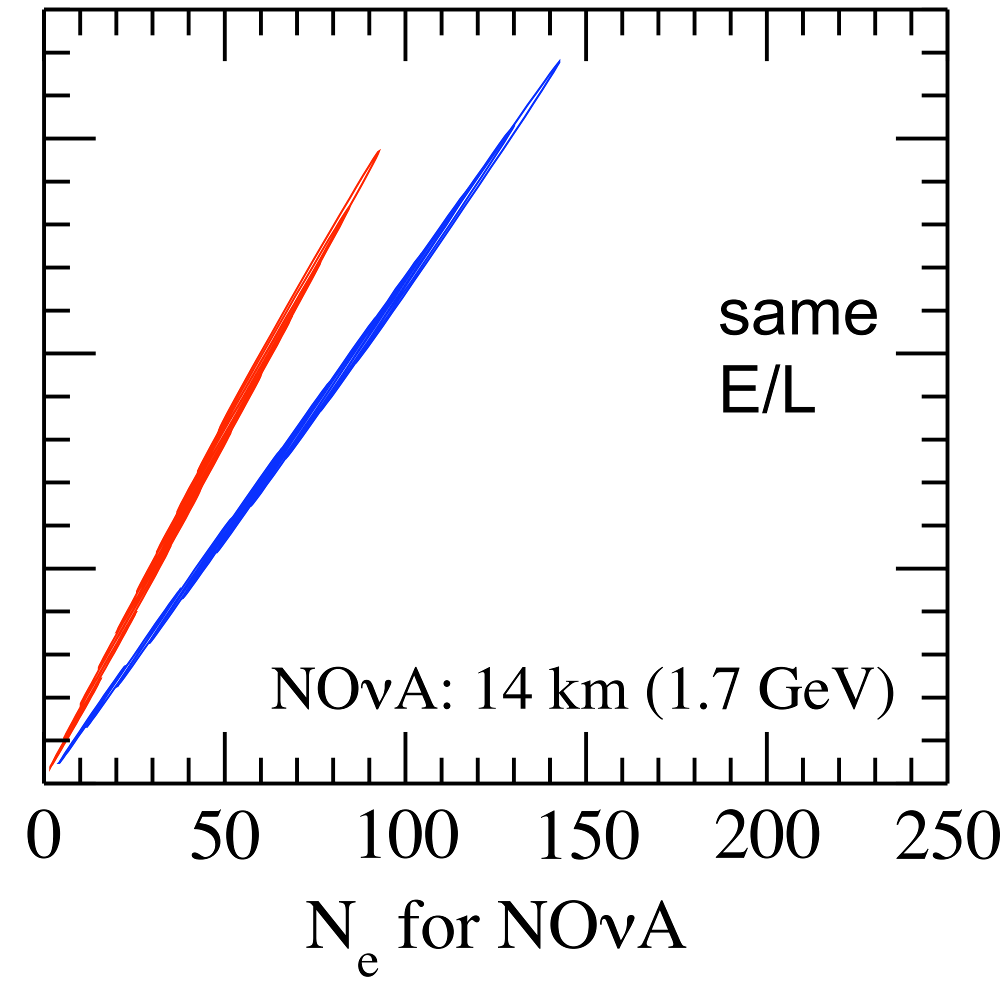


1 and 2 σ Contours for Starred Point
Contours 3 yr ν and 3 yr ν̄
NOvA
|Δm$_{32}^2$| = 2.32 10^{-3} eV^2
sin^2(2θ$_{13}$) = 0.095
sin^2(2θ$_{23}$) = 0.97
$\sin^2\theta_{23} = 0.58$
$\sin^2\theta_{23} = 0.42$
Δm^2 < 0
Δm^2 > 0
δ = 0
δ = π/2
δ = π
δ = 3π/2
P(ν̄$_e$)
P(ν$_e$)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09

What about combining T2K and NOvA?

Neutrinos Only





Mena, Nunokawa + SP: hep-ph/0609011

Future Experiments:

- Near 1st Oscillation Maximum: L/E= 500 km/GeV

T2HK L=295km, $\langle E \rangle = 0.65$ GeV, off axis 2.5°

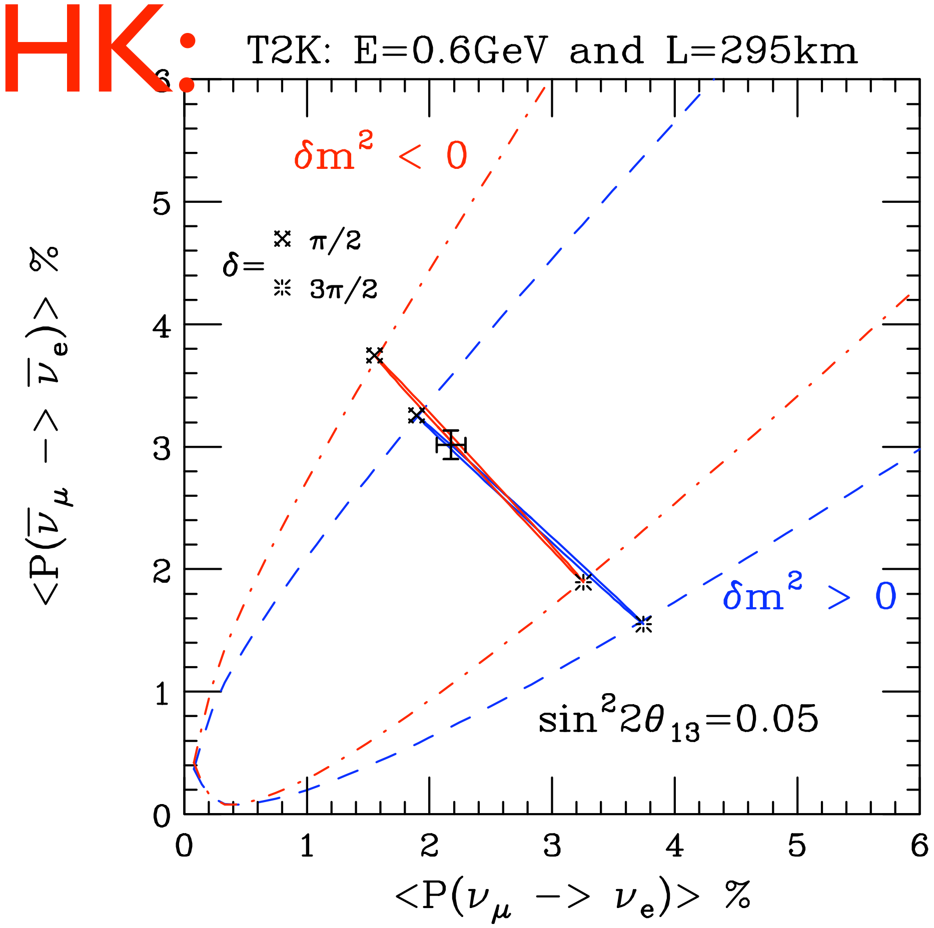
LBNE: L=1300km, E = 1 to 5 GeV, broad band beam

LENF L=1300km $\langle E \rangle = 2.5$ GeV

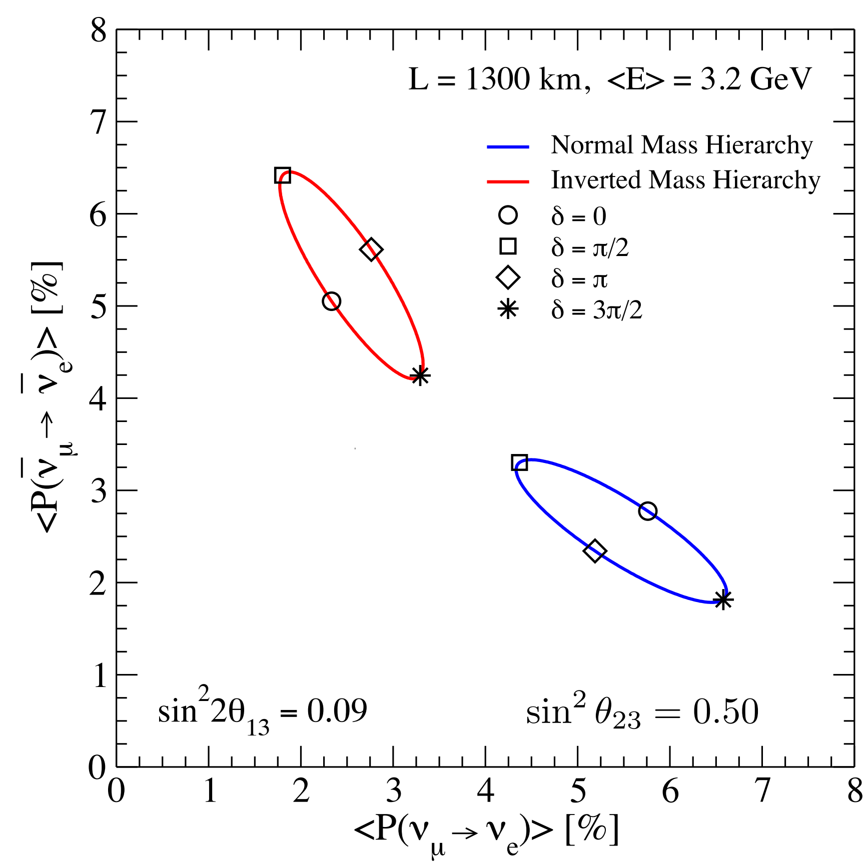
- Near the 2nd Oscillation Maximum: L/E= 1500 km/GeV

ESS to Garpenberg (540km) E= 200 to 400 MeV, broad band beam

T2HK:



LBNE:
@ same L/E as NOvA

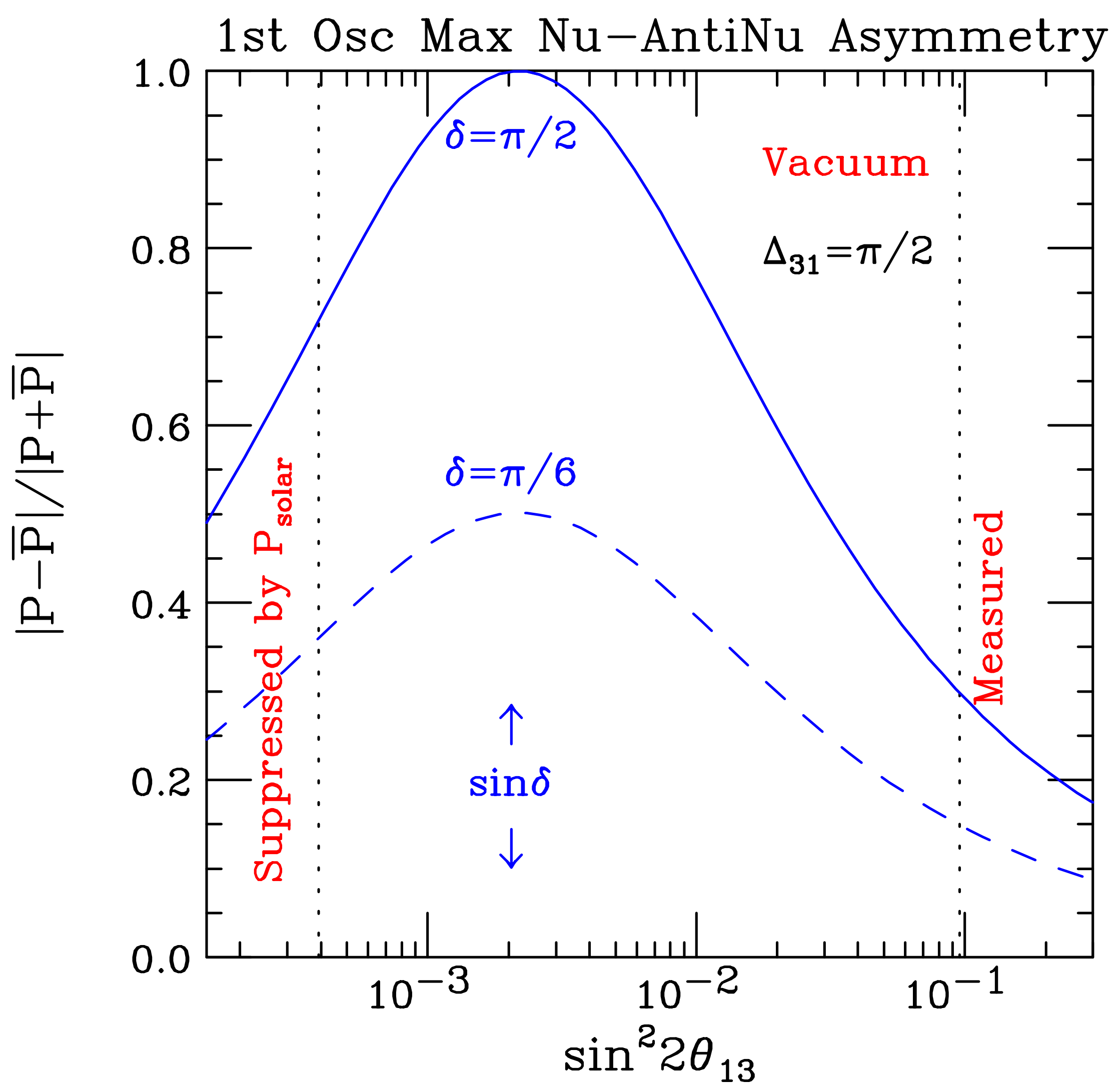


CPV & Neutrino Anti-Neutrino Asymmetry:

In Vacuum, at 1st Oscillation Maximum:

$$A_{vac} \equiv \frac{|P-\bar{P}|}{|P+\bar{P}|} \approx \frac{1}{11}\frac{\sin 2\theta_{13} \sin\delta}{(\sin^2 2\theta_{13}+0.002)} = 0.3\ \sin\delta$$

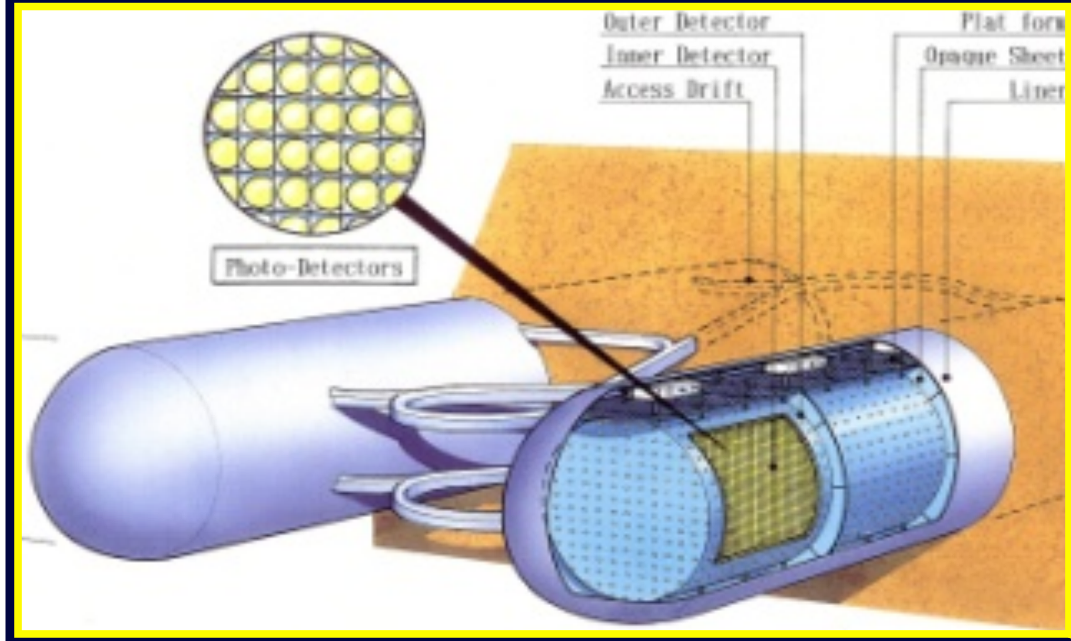
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ ranges is between $\frac{1}{2}$ and 2 times $P(\nu_\mu \to \nu_e)$!!!



Future LBL plans using J-PARC

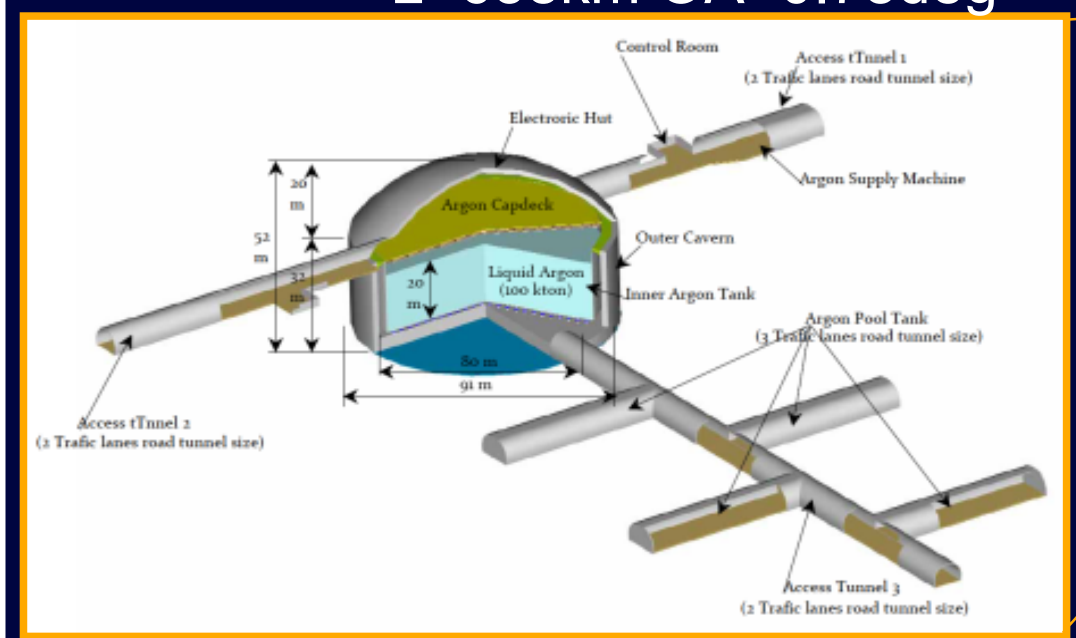
Current: T2K
J-PARC ~0.75MW
+ 50kt WC @ 295km 2.5°

J-PARC+HK @ Kamioka
L=295km OA=2.5deg



LoI: The Hyper-Kamiokande Experiment
arXiv:1109.3262v1

J-PARC+LAr @ Okinoshima
L=658km OA=0.78deg



J-PARC P32 (LAr TPC R&D), arXiv:0804.2111

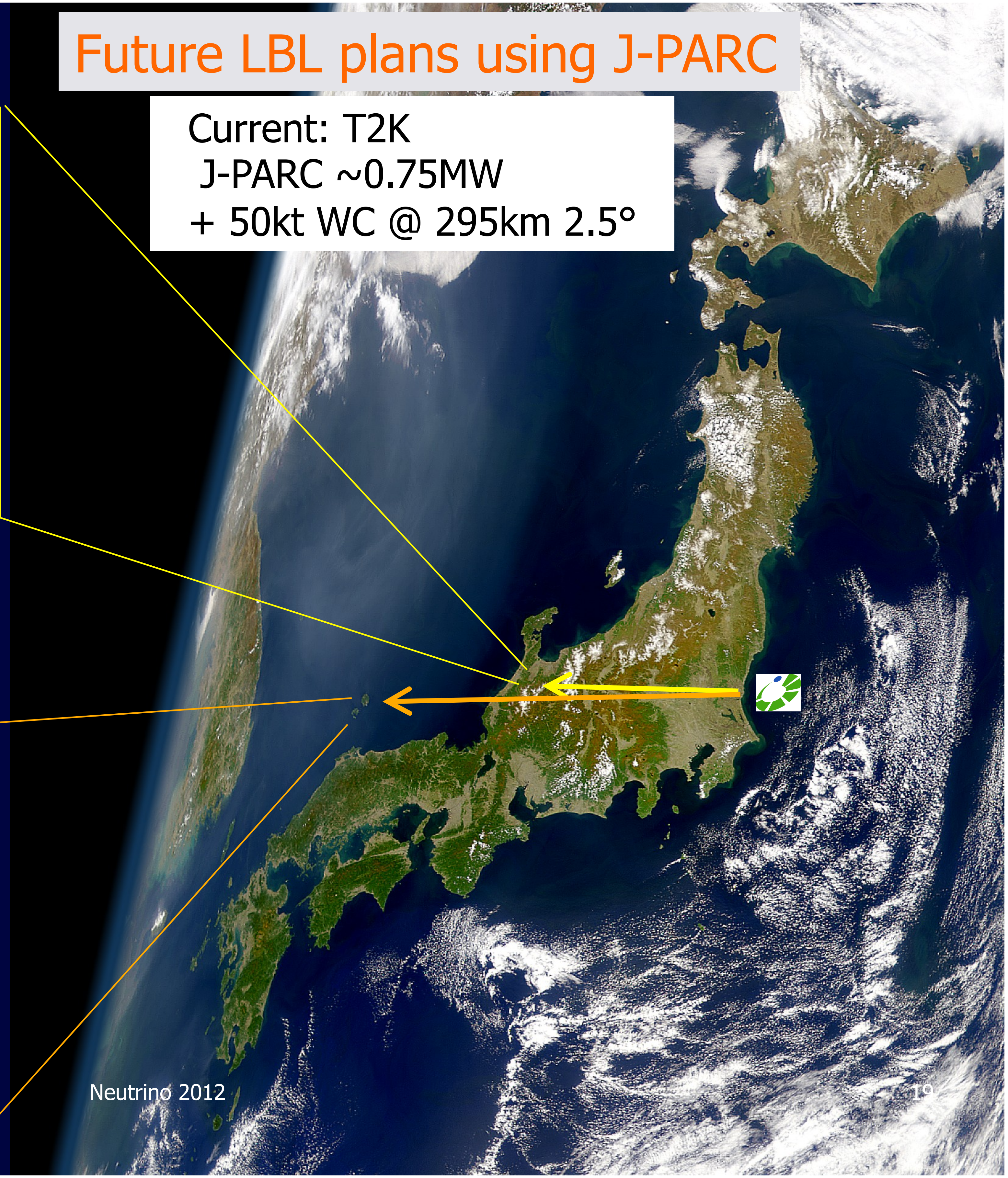
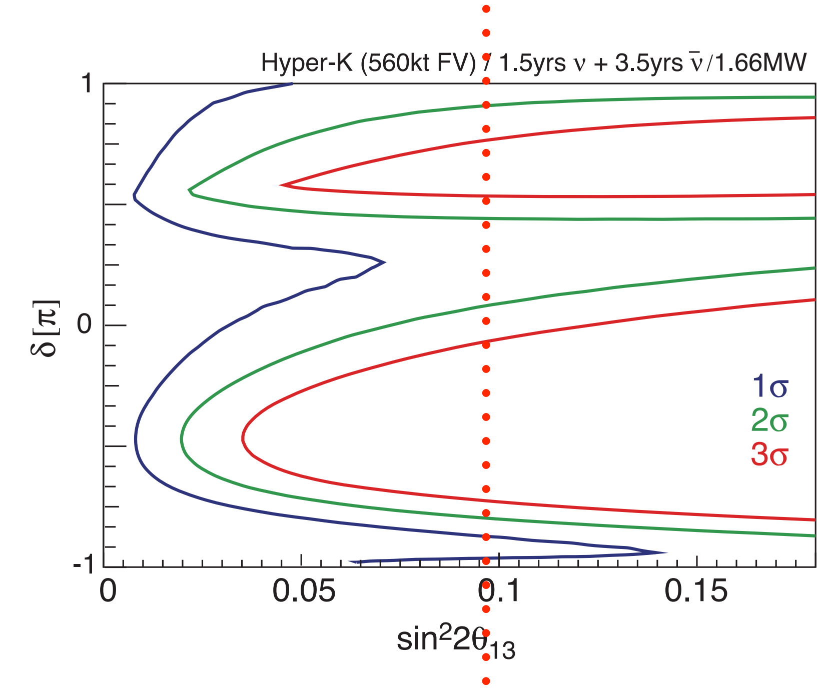


TABLE I. Detector parameters of the baseline design.

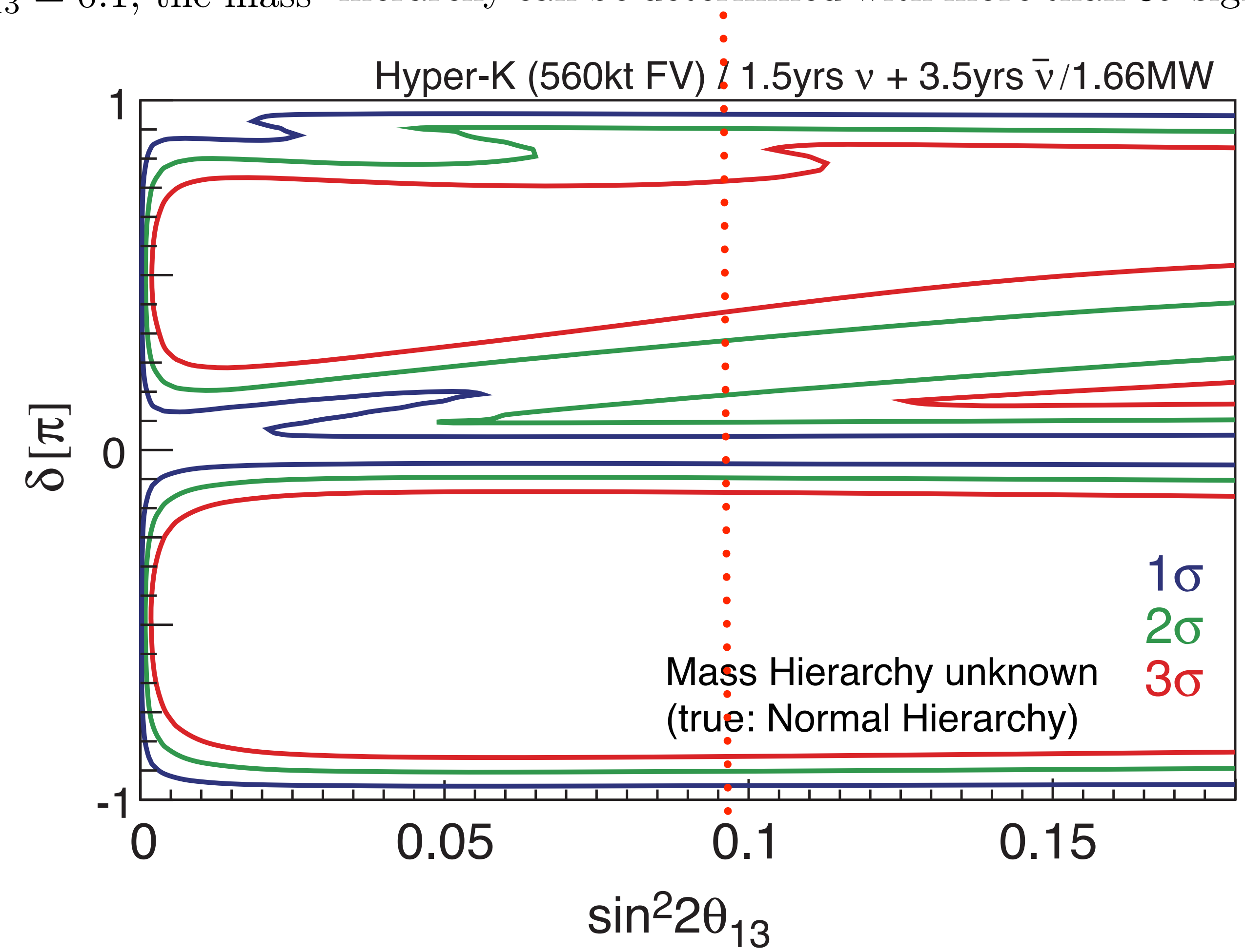
Detector type		Ring-imaging water Cherenkov detector
Candidate site	Address	Tochibora mine
		Kamioka town, Gifu, JAPAN
	Lat.	36°21′08.928″N
	Long.	137°18′49.688″E
	Alt.	508 m
	Overburden	648 m rock (1,750 m water equivalent)
	Cosmic Ray Muon flux	$1.0 \sim 2.3 \times 10^{-6}$ $\mathrm{sec^{-1}cm^{-2}}$
	Off-axis angle for the J-PARC ν	2.5° (same as Super-Kamiokande)
	Distance from the J-PARC	295 km (same as Super-Kamiokande)
Detector geometry	Total Volume	0.99 Megaton
	Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
	Outer Volume	0.2 Megaton
Photo-multiplier Tubes	Inner detector	99,000 20-inch ϕ PMTs
		20% photo-coverage
	Outer detector	25,000 8-inch ϕ PMTs
Water quality	light attenuation length	> 100 m @ 400 nm
	Rn concentration	< 1 mBq/$\mathrm{m^3}$

Mass Hierarchy:



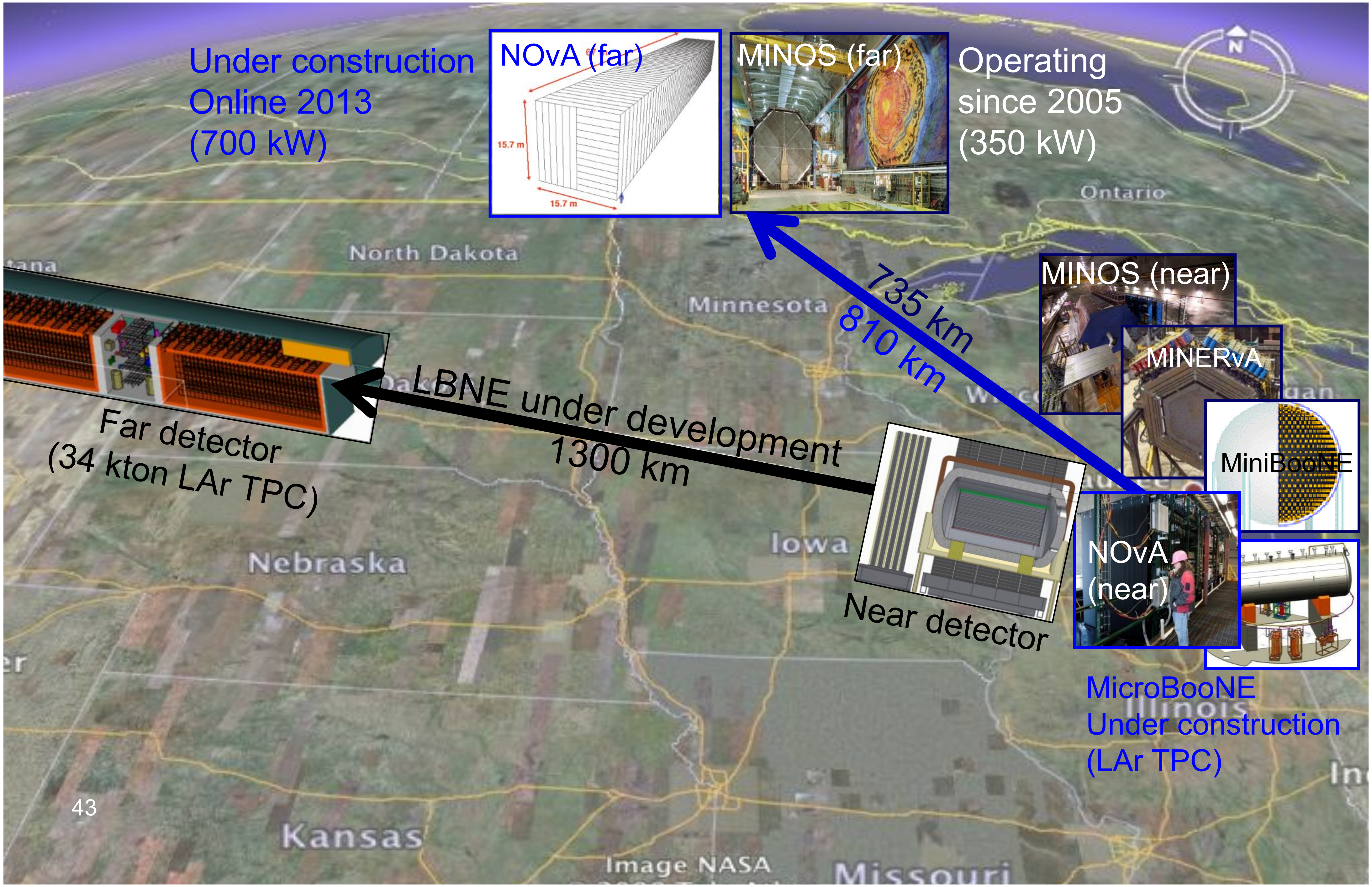
For $\sin^2 2\theta_{13} = 0.1$, the mass hierarchy can be determined with more than 3σ significance for 46% of the δ parameter space.

CPV:



MH from Atm Nus:

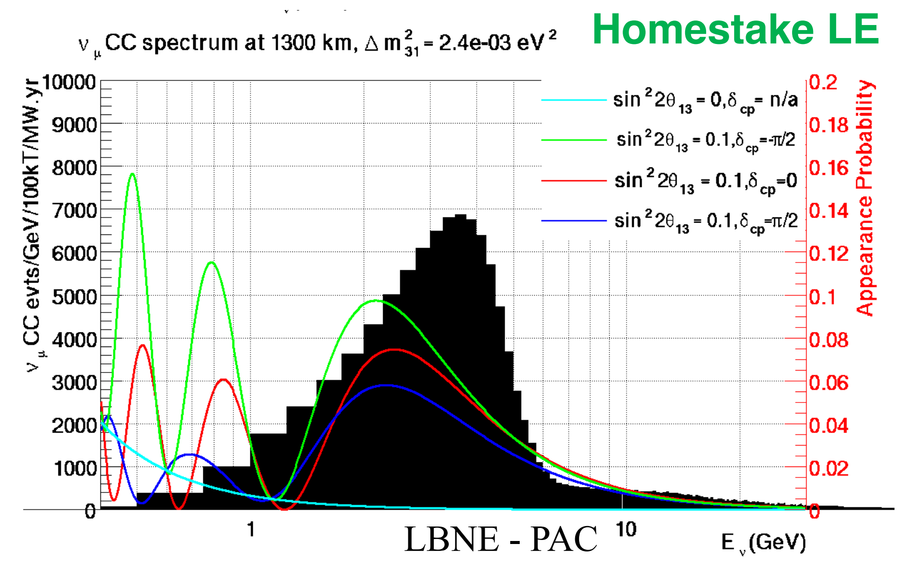
LBNE

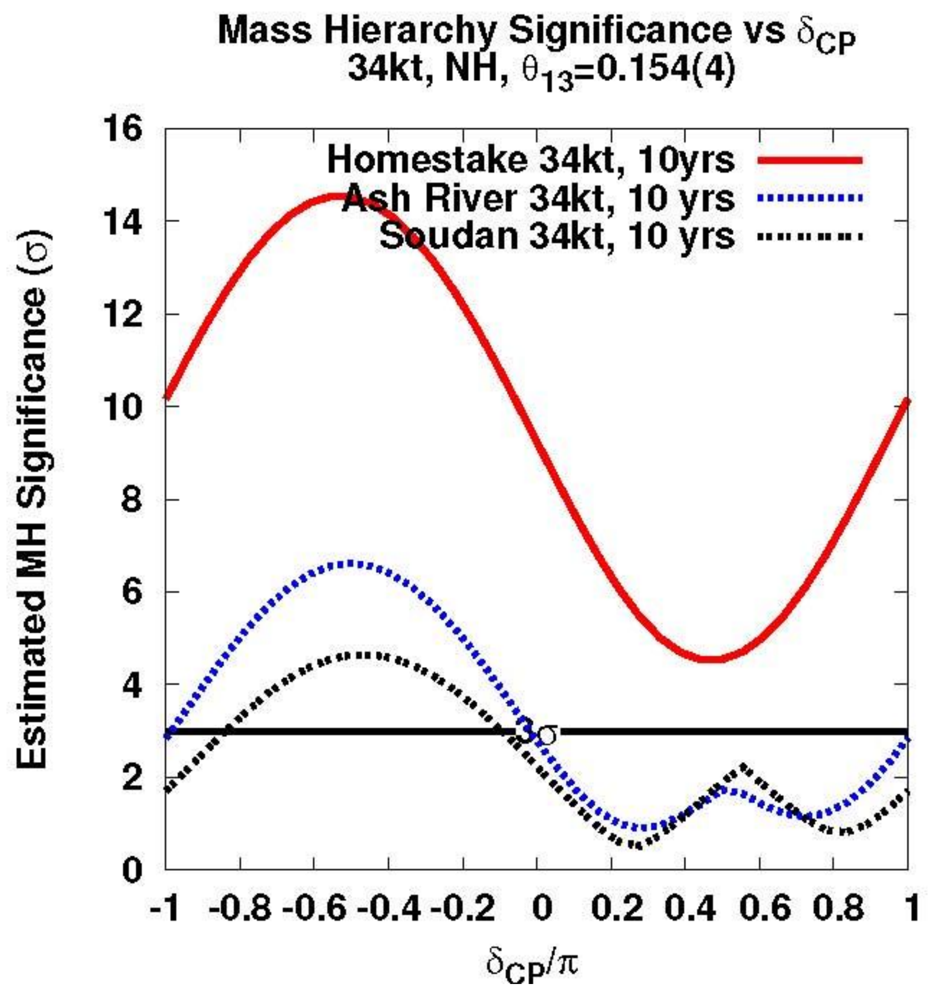


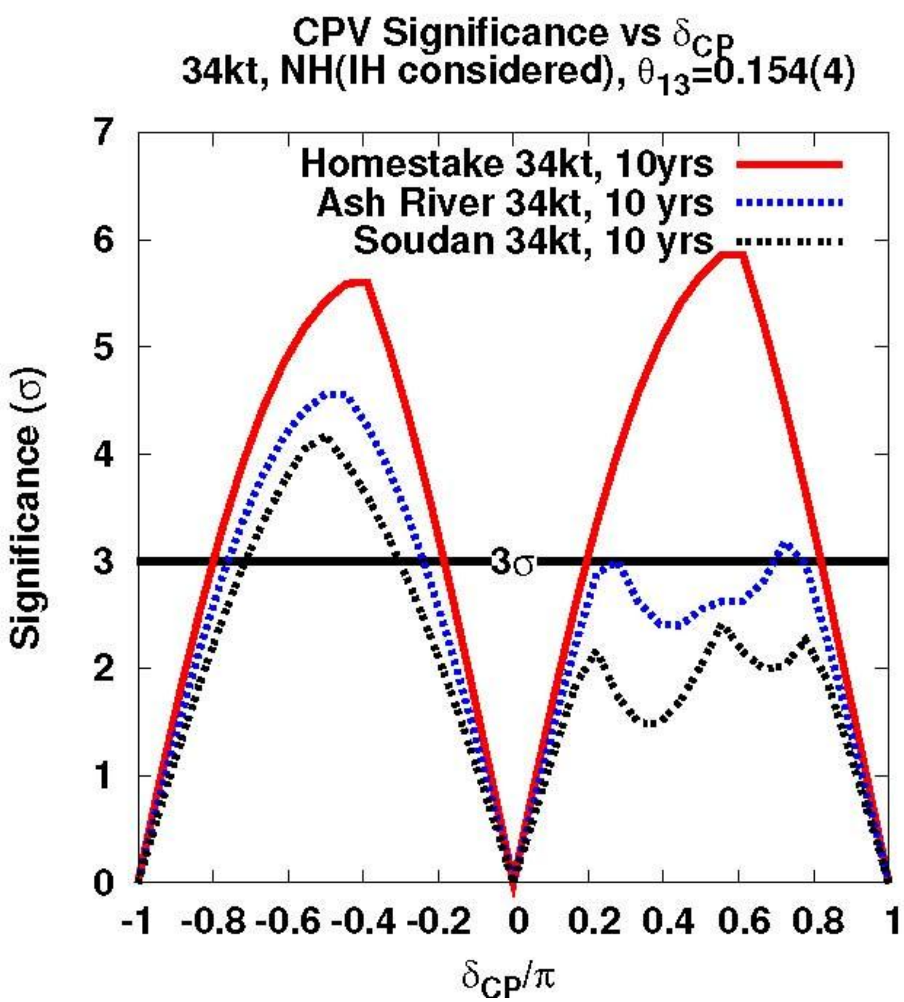
Under construction
Online 2013
(700 kW)
NOvA (far)
MINOS (far)
Operating
since 2005
(350 kW)
Ontario
North Dakota
Minnesota
735 km
810 km
MINOS (near)
MINERvA
MiniBooNE
LBNE under development
1300 km
Far detector
(34 kton LAr TPC)
Near detector
Iowa
Nebraska
NOvA
(near)
MicroBooNE
Under construction
(LAr TPC)
43
Kansas
Image NASA
Missouri

LBNE original

- LBNE:
  - Beamline @ Fermilab: 1-5 GeV, 700 kW ---> 2.1 MW
  - Baseline: 1300 km on-axis, Fermilab to Homestake
  - Detector: 34 ktons LAr @ 4300 mwe in Homestake







Staging??? LBNO+LBNE=LBNU

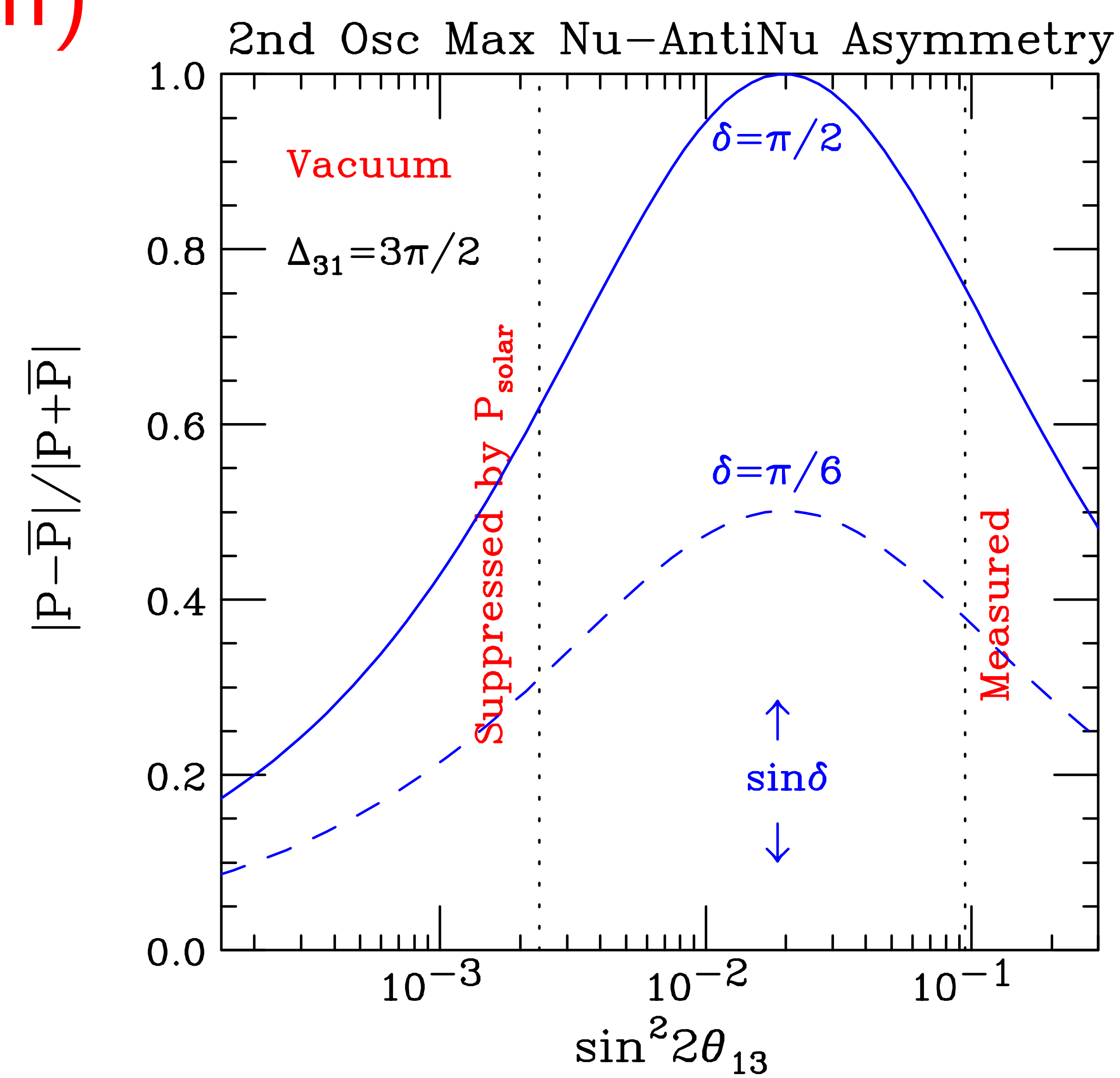
2nd Oscillation Max:

ESS to Garpenburg (540km)

$$\boldsymbol{A_{vac} \approx 0.75 \sin\delta}$$

$A_{vac}(2^{nd}\ \mathrm{OM}) \approx$ 2.5 $A_{vac}(1^{st}\ \mathrm{OM})$

(9/11 of 3)

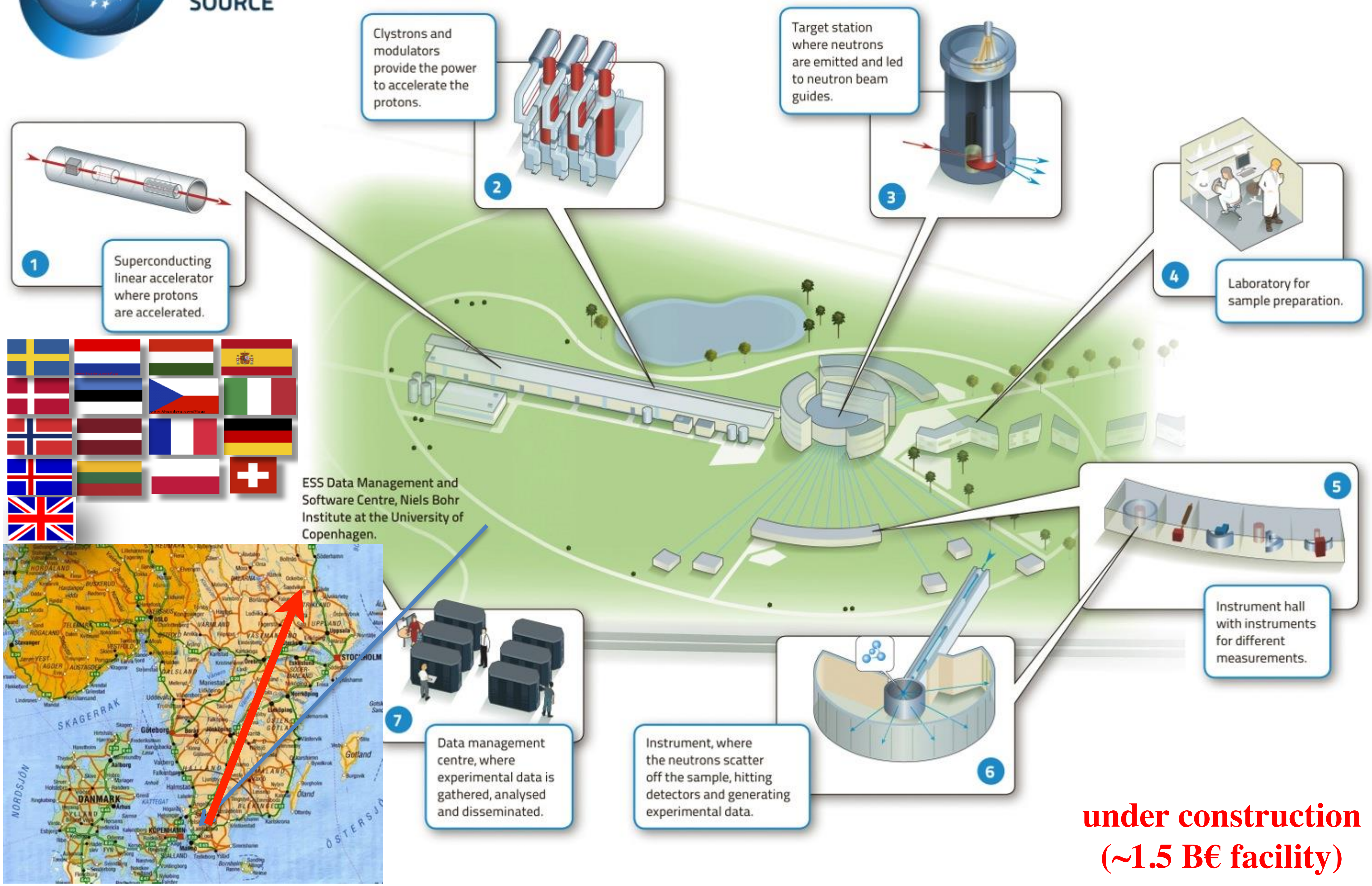


$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ ranges is between $\frac{1}{7}$ and 7 $P(\nu_\mu \to \nu_e)$

Appearance Probabilities more dynamic near 2nd Osc. Max. than 1st. OM

European Spallation Source

from Wildner's talk

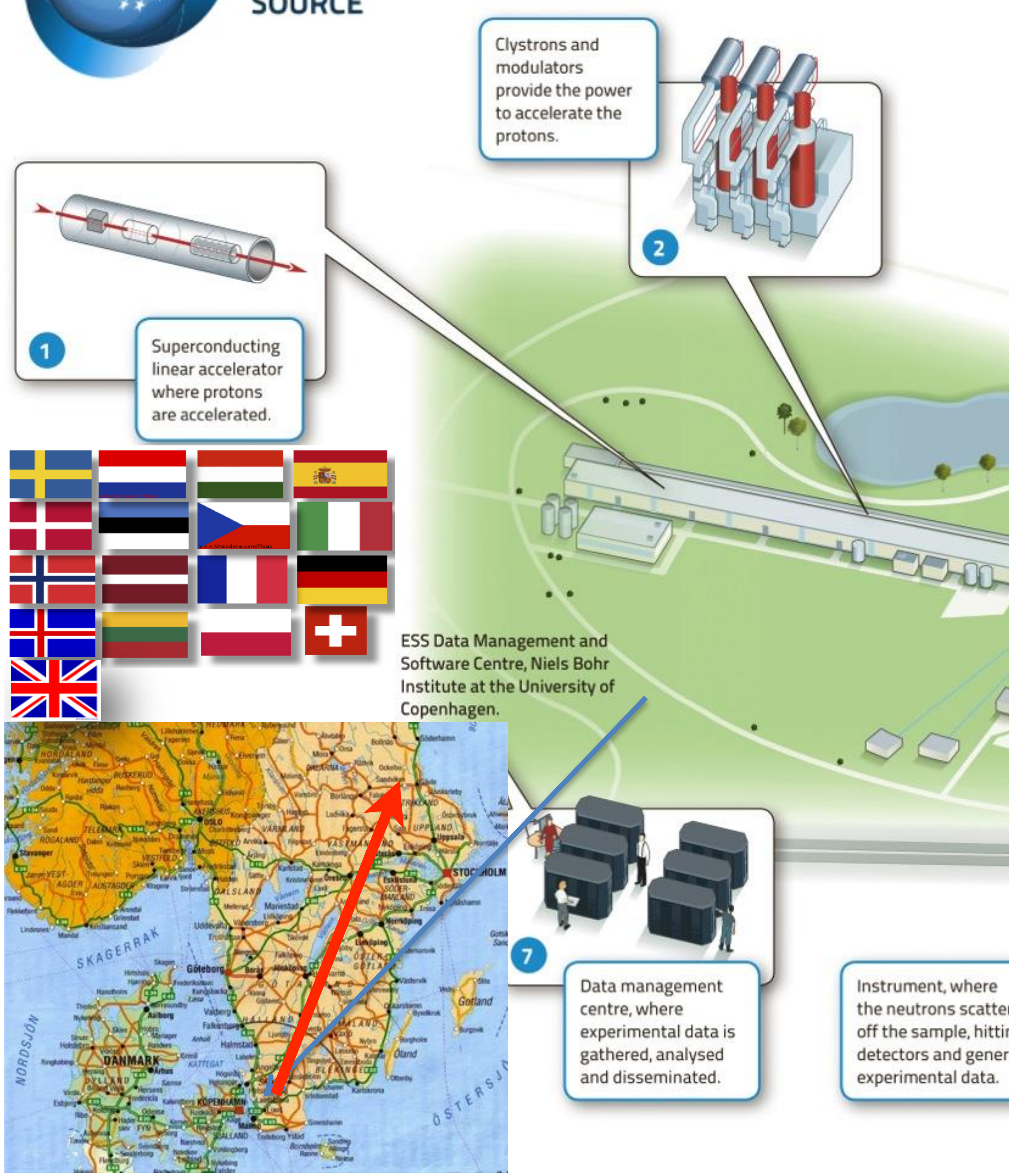


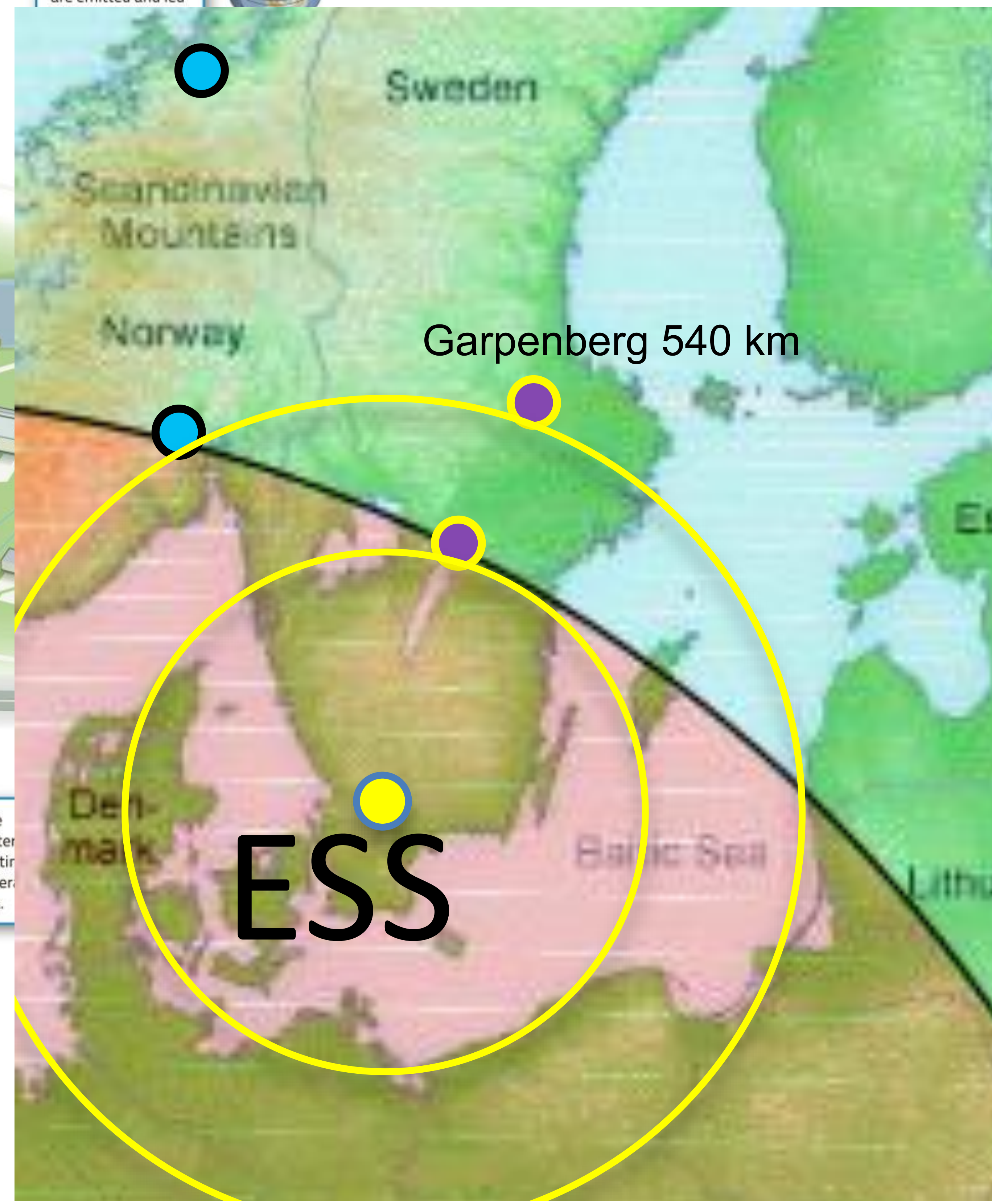
under construction
(~1.5 B€ facility)

Detector: 500kt WC, MEMPHYS

European Spallation Source

from Wildner's talk

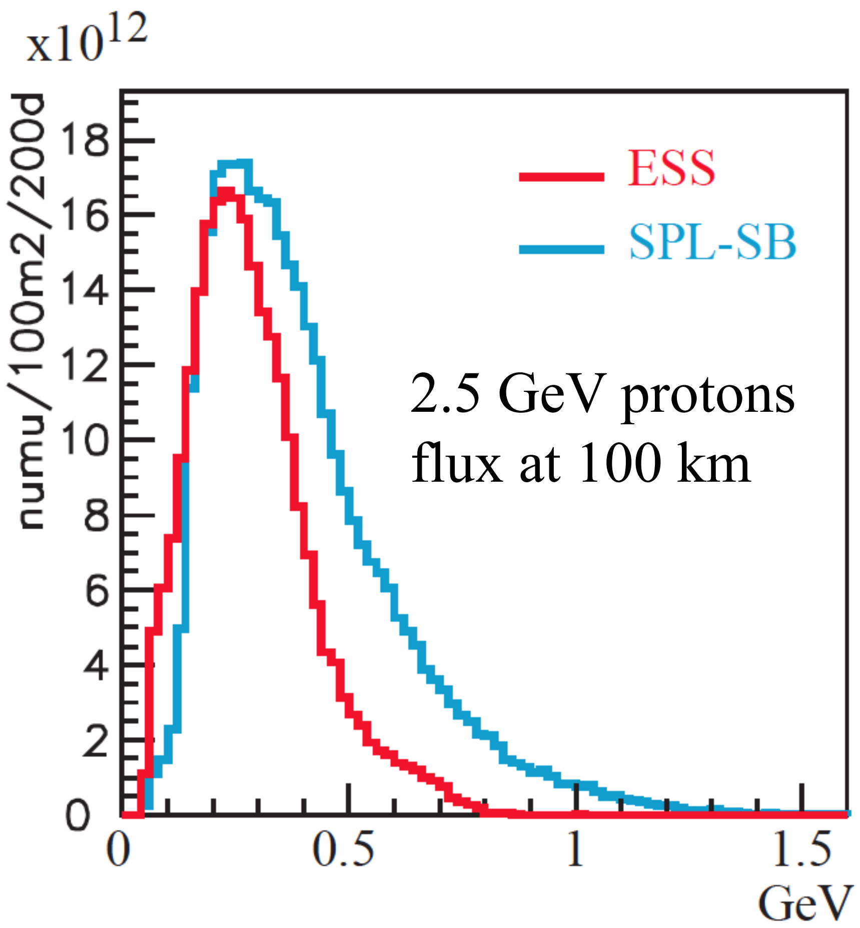




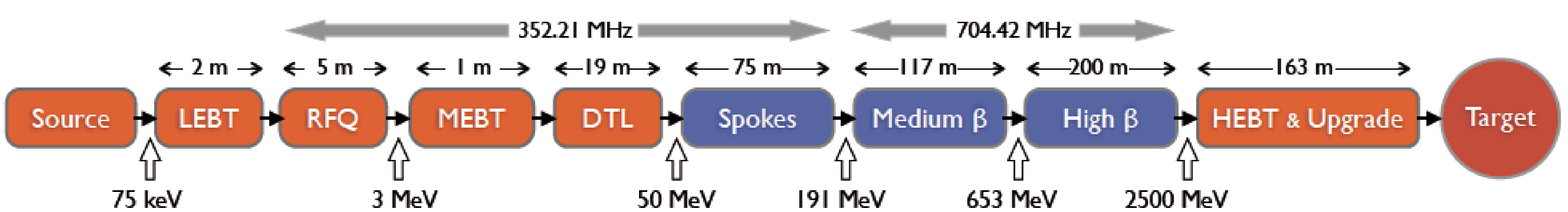
Detector: 500kt WC, MEMPHYS

How to add a neutrino facility?

- 2 GeV protons: ~300 MeV neutrinos
- No perturbation of the neutron facility
- Close technical collaboration at early stage
- Acceptable cost

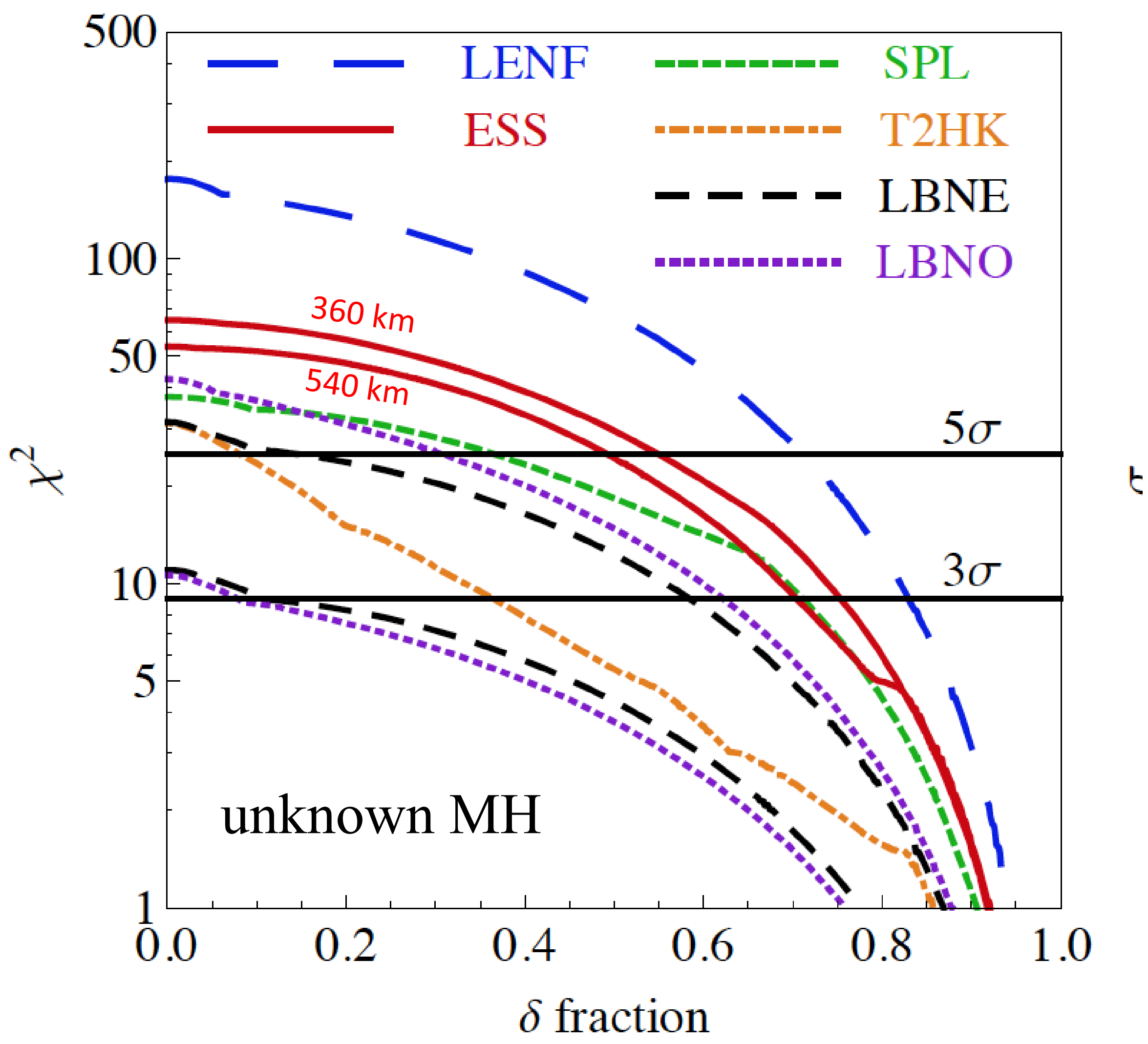


- **Linac modifications**:
  - double the rate (14 Hz → 28 Hz), one pulse for neutrinos and one pulse for neutrons (5 MW each)
  - additional RF power to drive the two beams (for neutrons and neutrinos)
  - install upgradable power sources
  - or double the power sources (free space has to be foreseen since now)



- ***For a fraction of the cost we can get a 5MW proton driver for Neutrino Physics***

CPV



- LBNE: 5+5 years, 0.7 MW, 10/35 kt LAr
- T2HK: 3+7 years, 0.75 MW, 500 kt WC (5%/10% syst. errors)
- SPL: 2+8 years, 4 MW, 500 kt WC (130 km, 5%/10% syst. errors)
- ESS: 2+8 years, 5 MW, 500 kt WC (2 GeV, 360/540 km, 5%/10% syst. errors)
- C2Py: 20/100 kt LAr, 0.8 MW, 2300 km

another possibility: Daedalus

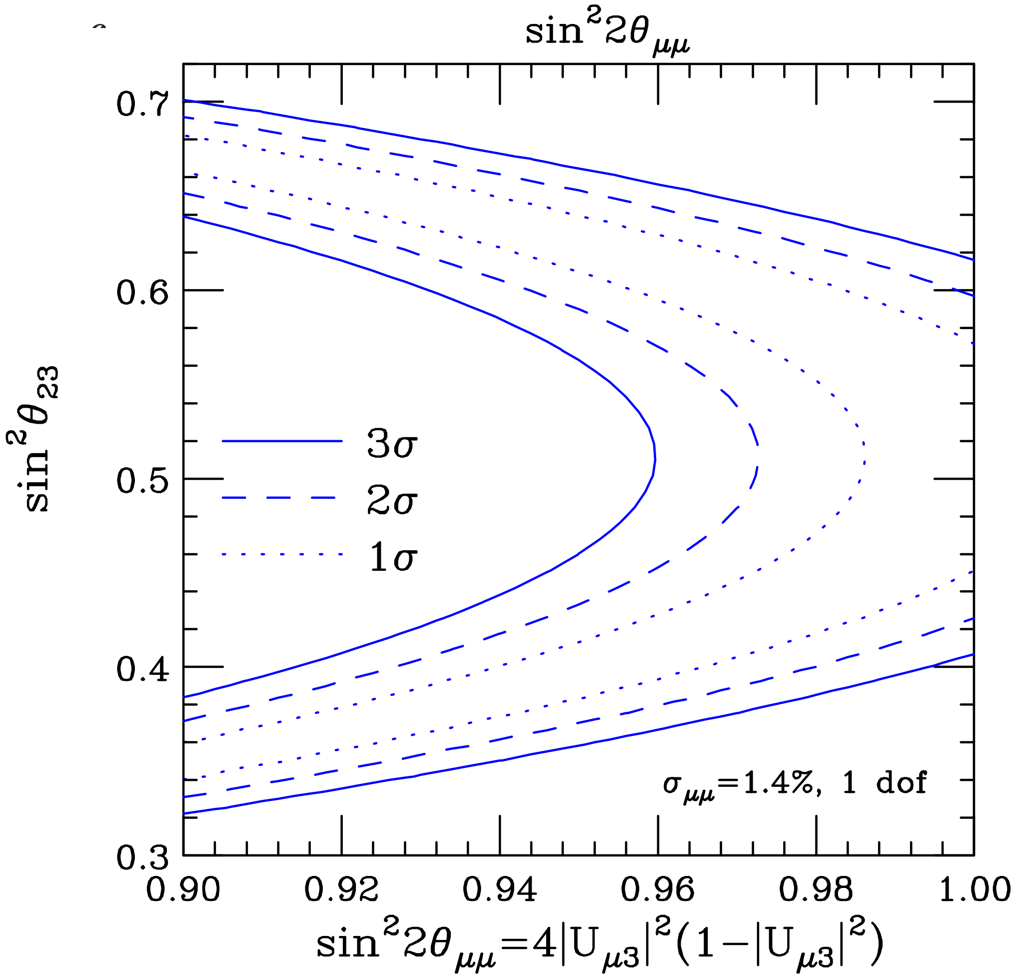
nu_mu Disappearance:

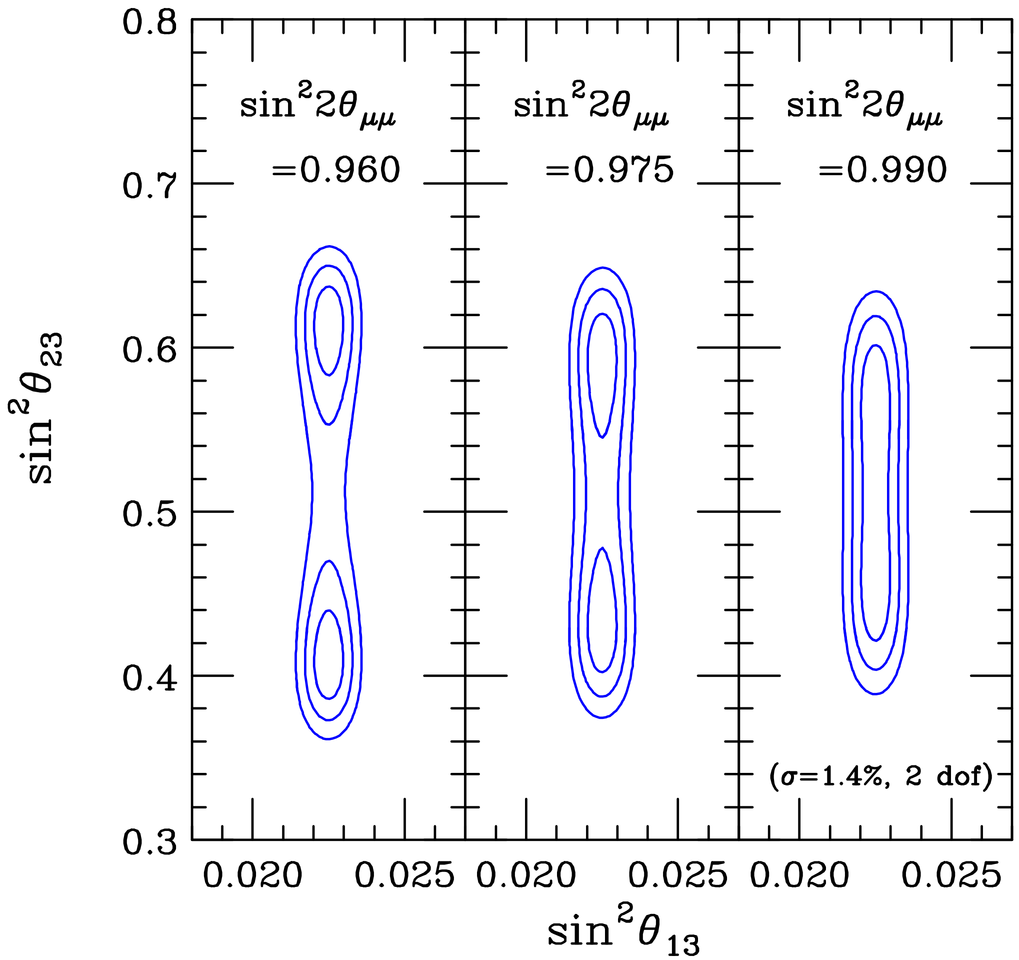
$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2$$

23 - Modified Octant Degeneracy:

$$\sin^2\theta_{23}^{(1)} = \sin^2\theta_{\mu\mu}/\cos^2\theta_{13} \approx \sin^2\theta_{\mu\mu}(1+\sin^2\theta_{13}),$$
$$\sin^2\theta_{23}^{(2)} = \cos^2\theta_{\mu\mu}/\cos^2\theta_{13} \approx \cos^2\theta_{\mu\mu}(1+\sin^2\theta_{13}),$$

$$\theta_{\mu\mu} \leq \frac{\pi}{4}$$





$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2) = 0.975$$

$$\sigma_{\mu\mu} = 1.4\%$$

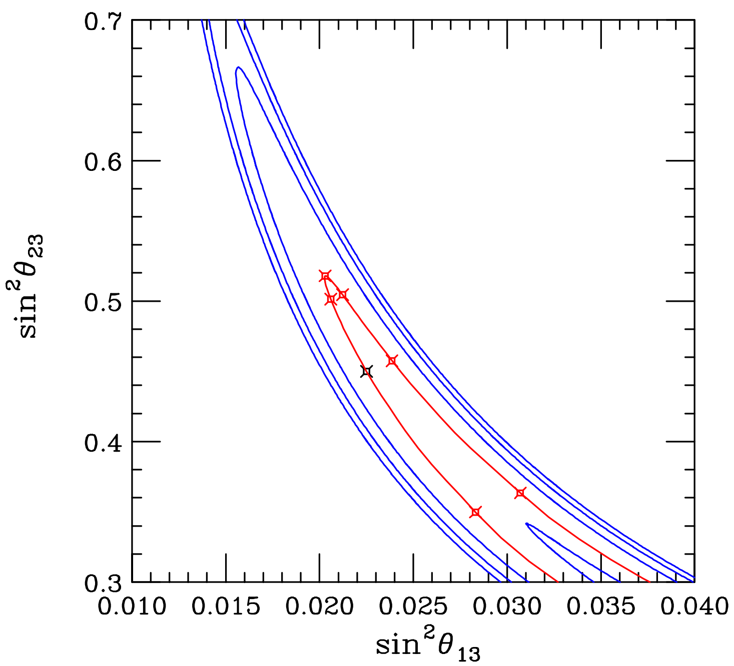
Coloma, Minakata and Parke
arXiv:2014.????

Generalized Intrinsic Degeneracy: (Coloma, Minakata and SP)

Assume θ_{13}, θ_{23} and δ unknown:

ν_e-Appearance

$P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



$\delta =$ 60, 70, 80, 90, 100, 110, 120 degrees

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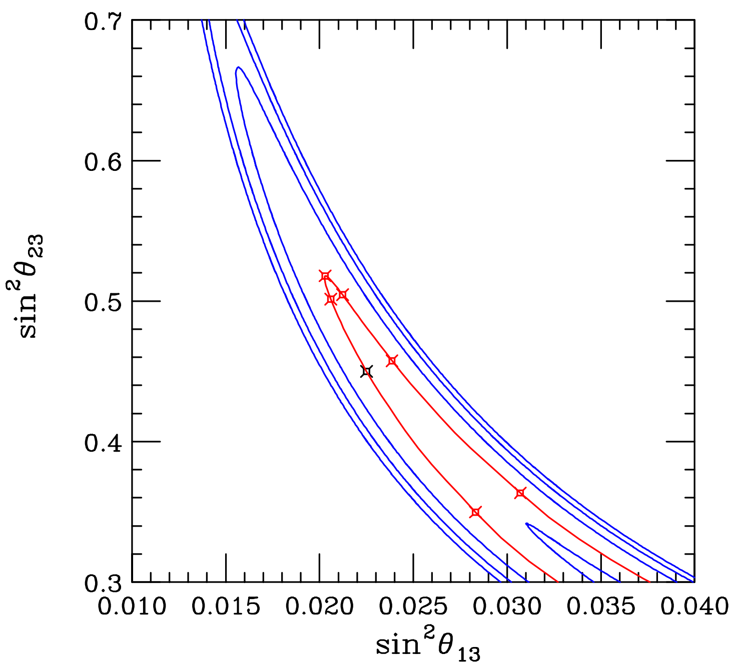

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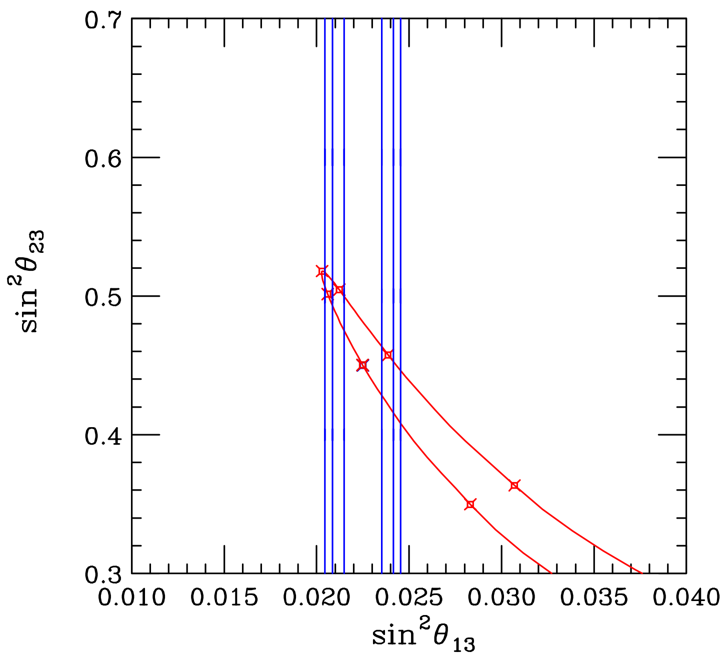

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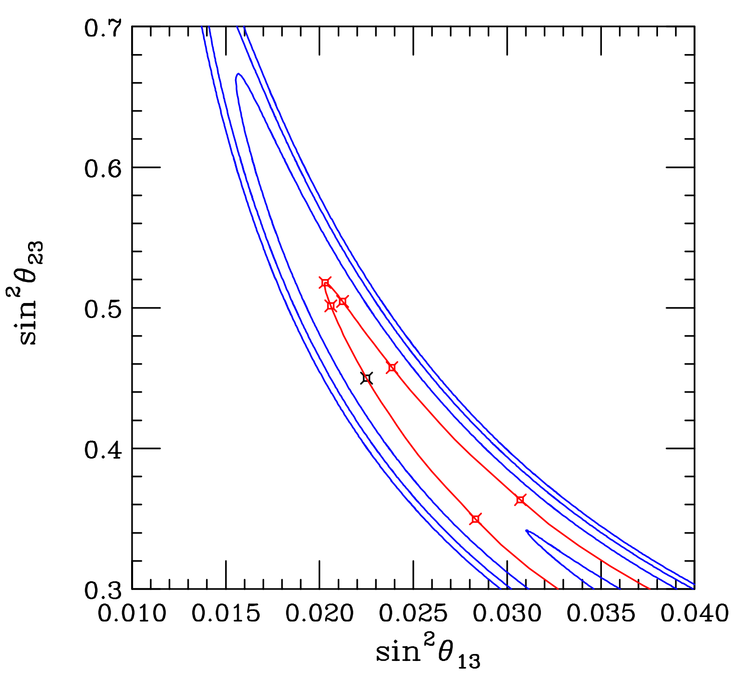

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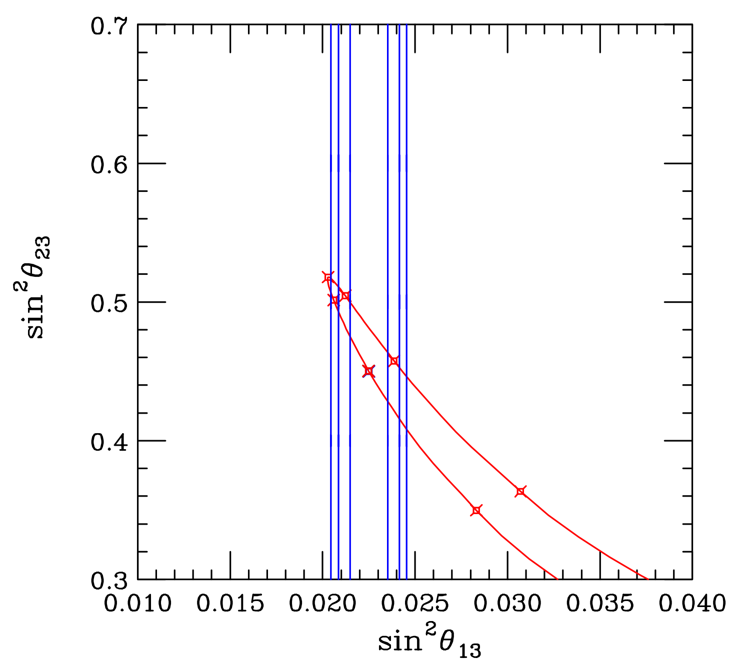
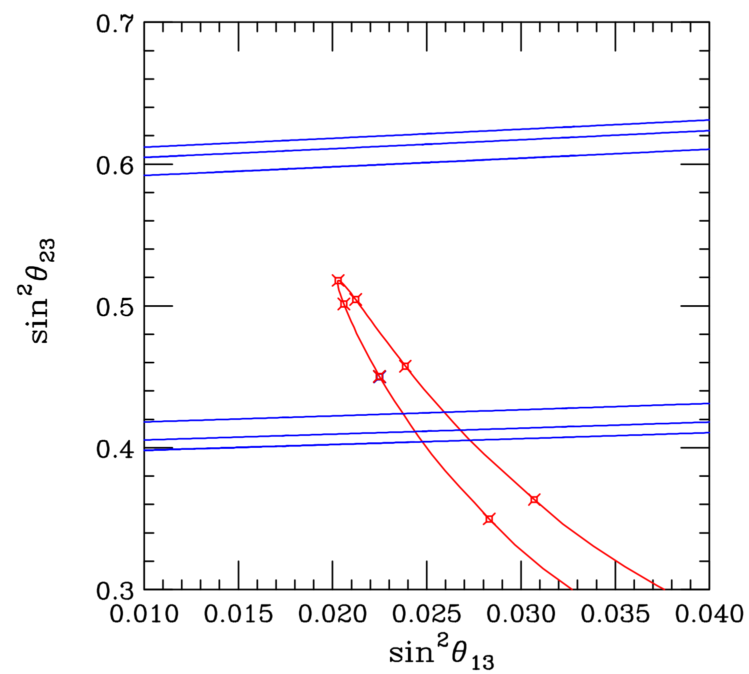


ν_μ-Disappearance

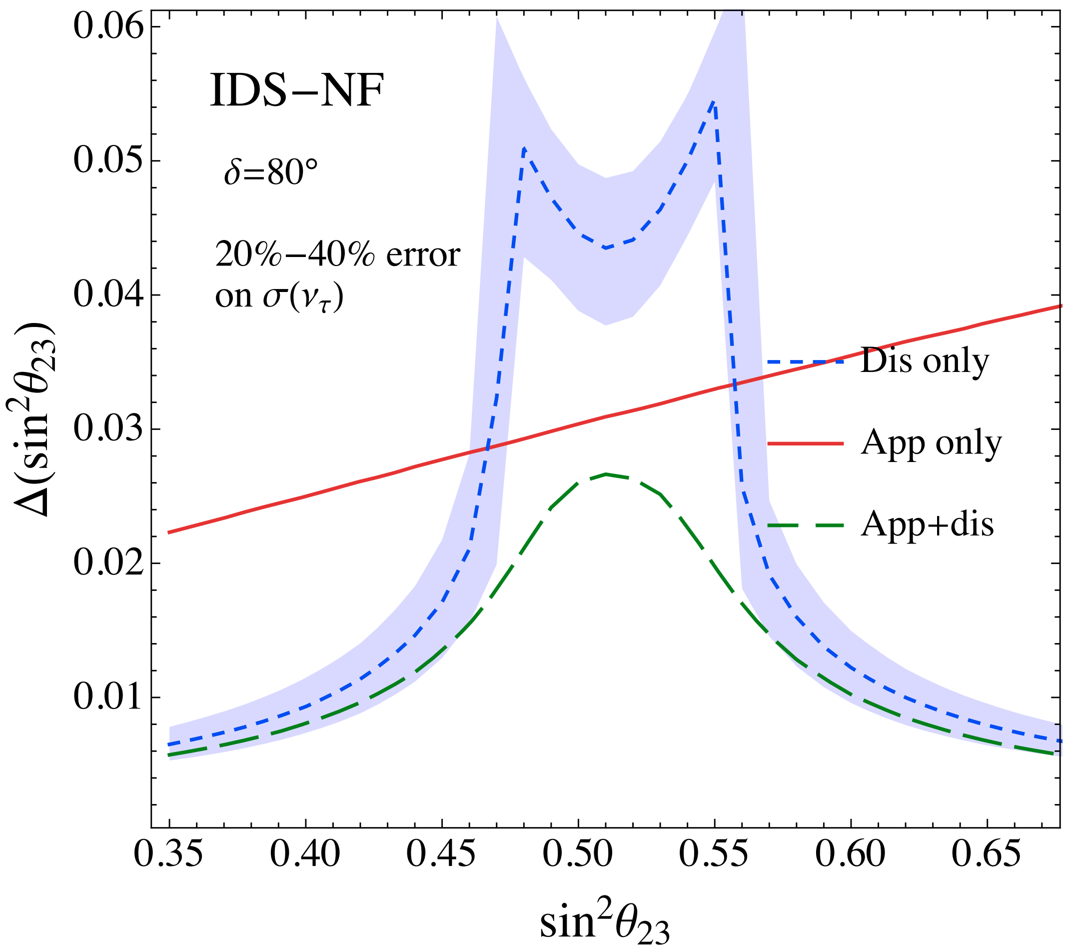
$P(\nu_\mu \to \nu_\mu)$



$\delta =$ 60, 70, 80, 90, 100, 110, 120 degrees

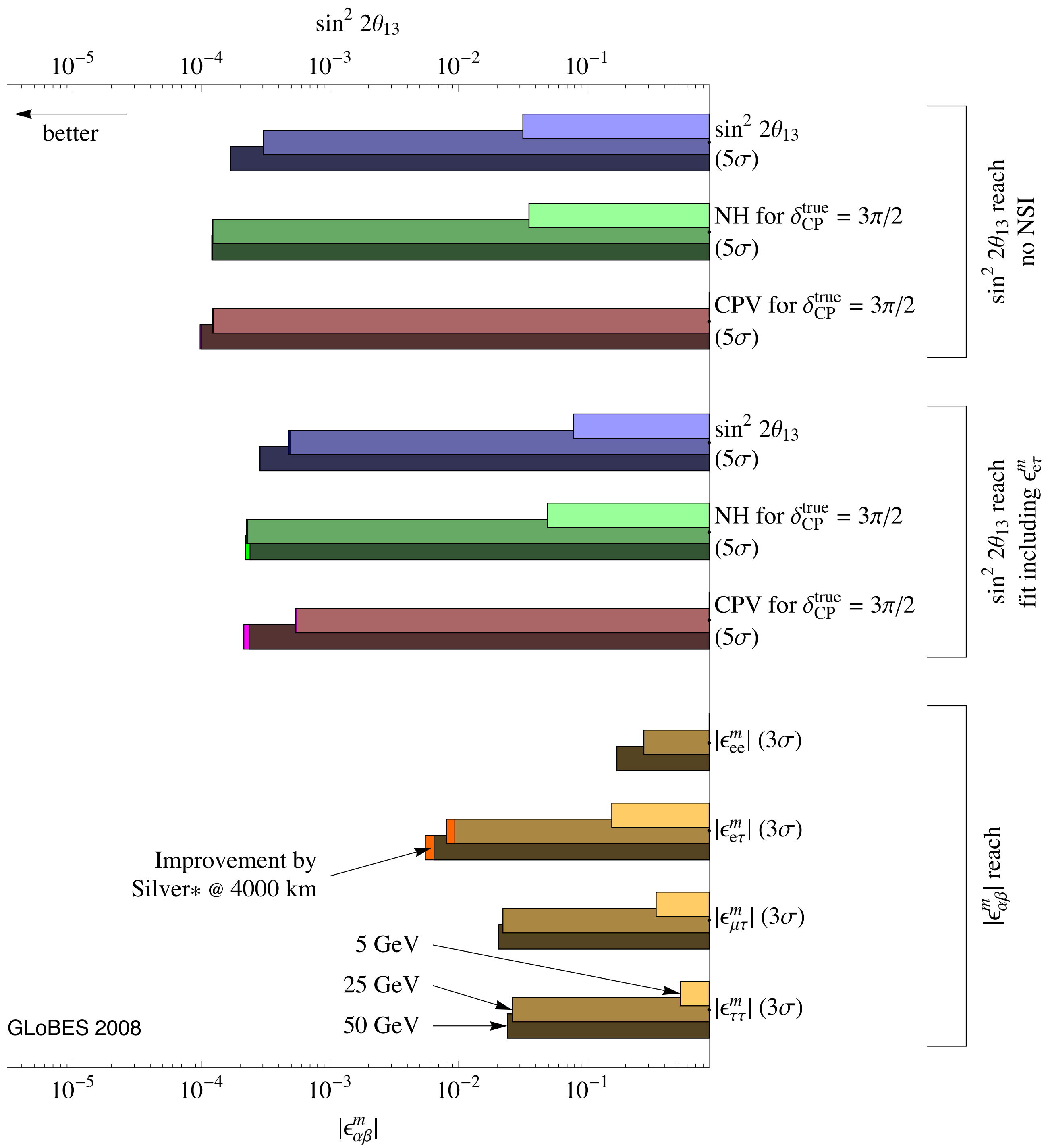
Spectral information can help break this degeneracy

Uncertainty on Theta23 for NF:



Coloma, Minakata and Parke
arXiv:2014.????

Non-Standard Interactions:



Conclusions:

- To Be Majorana or Not To Be Majorana?

- We know ($|U_{e2}|^2$, $|U_{e3}|^2$, $|U_{\mu 3}|^2$) with precision of (5,10,15)% but have little information on the other 6 elements of the PMNS matrix without assuming Unitarity. Stringent tests of the νSM Paradigm needed.

- Determining the Mass Hierarchy & measuring CPV are the next steps. Tau's?

- m_{lite}, if $\ll \delta m^2_{21}$, a new scale to explain !

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- Are there lite Sterile neutrinos?

Can we exclude $|U_{e4}|^2$ and $|U_{\mu 4}|^2 > 0.01$, say, for $\delta m^2 \sim 1 eV^2$

- Solving the Neutrino Masses and Mixing pattern is difficult challenge for Theory! Need hints.

- Where are there further "SURPRISES" in the Neutrino Sector?

We haven’t got the money,

so we’ll have to think!

E. Rutherford