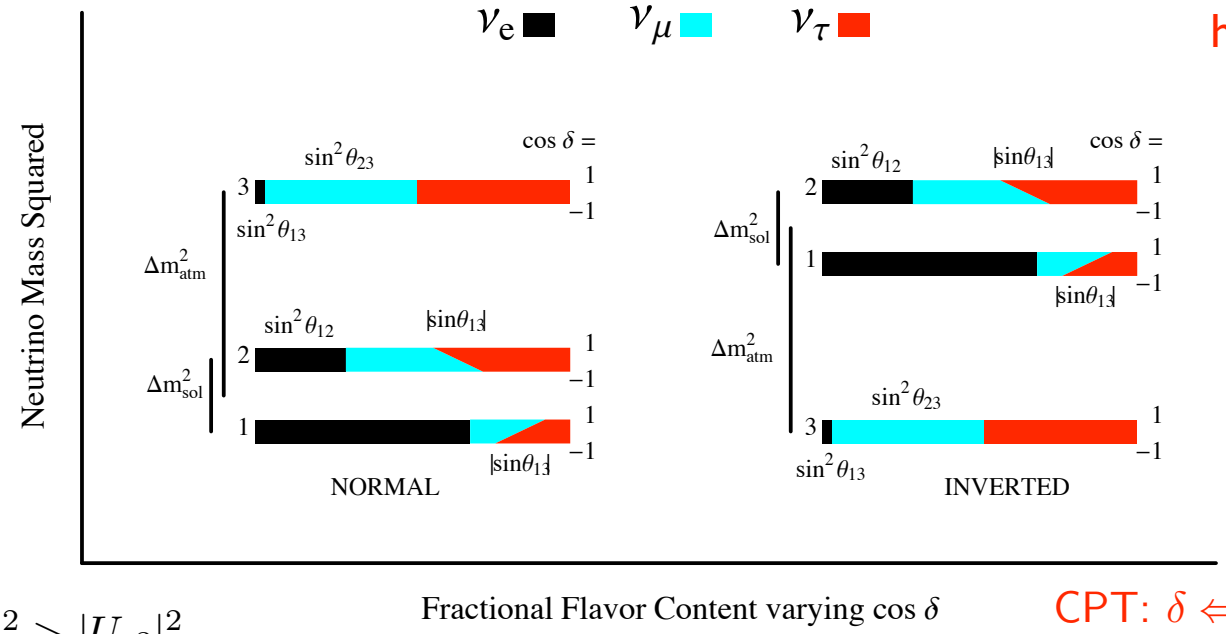
Ways to Determine the Neutrino Mass Hierarchy.

Stephen Parke - Fermilab

DOANOW: March 24, 2006

Mixings:

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



hep-ph/0312131

Less than 4% ν_e in the 3 state!

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

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

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

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

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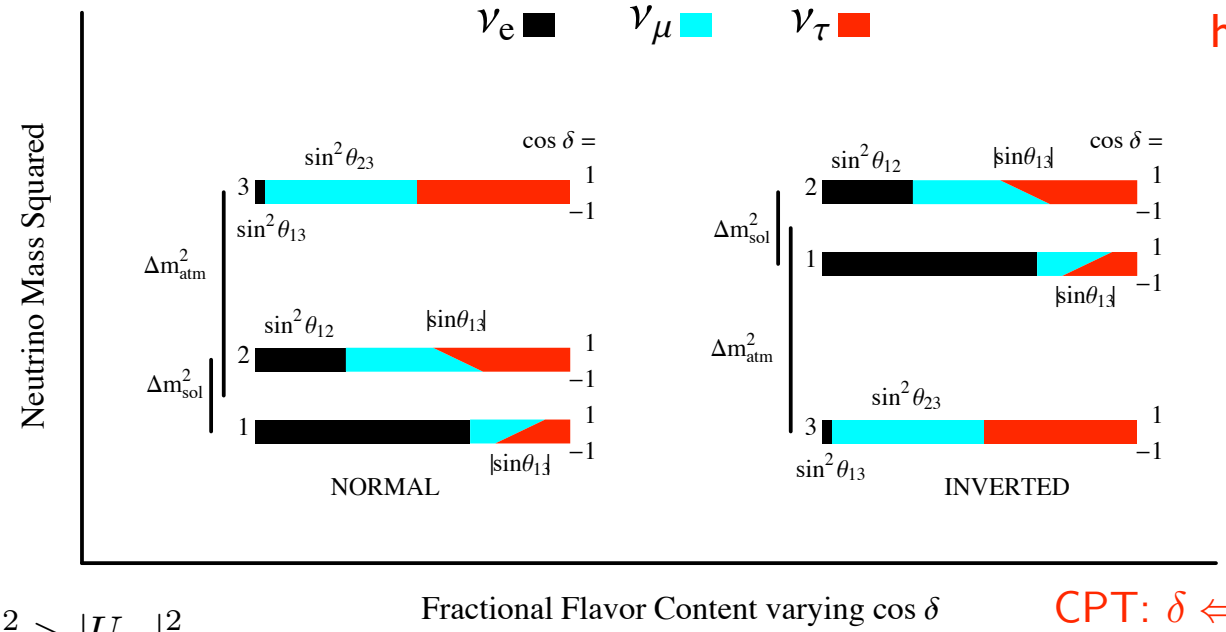

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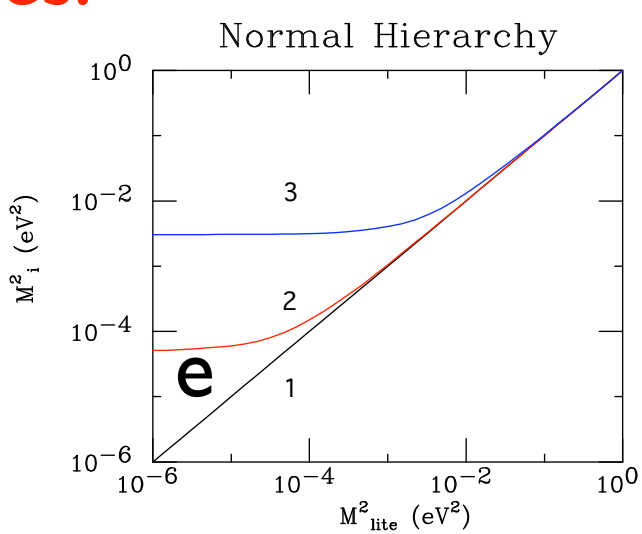
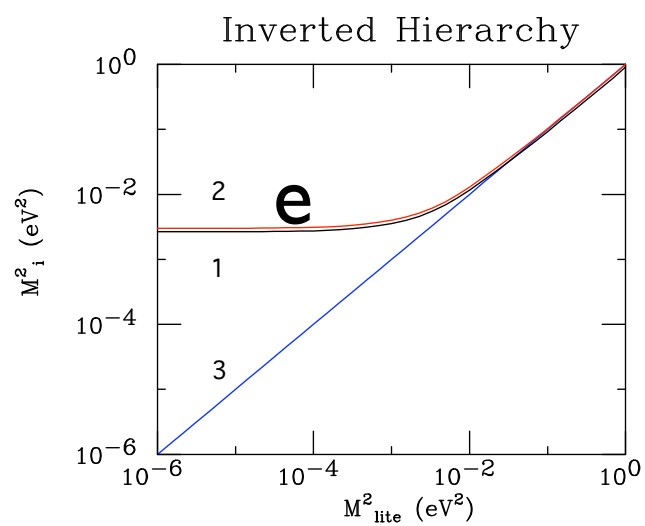
Masses:





States 1 and 2 are ν_e rich.

Long Baseline $\nu_\mu \longrightarrow \nu_e$ or $\nu_e \longrightarrow \nu_\mu$

- SUPERBEAMS: (0.4 to 4 MW)
  - Counting Expts (3 ways)
  - Spectrum Measurement
- NEW NEUTRINO BEAMS
  - Neutrino Factory (muon storage ring)
  - High Gamma Beta Beams

Counting Expts near First Osc. Max.

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

2.0, 2.5 or 3.0 deg

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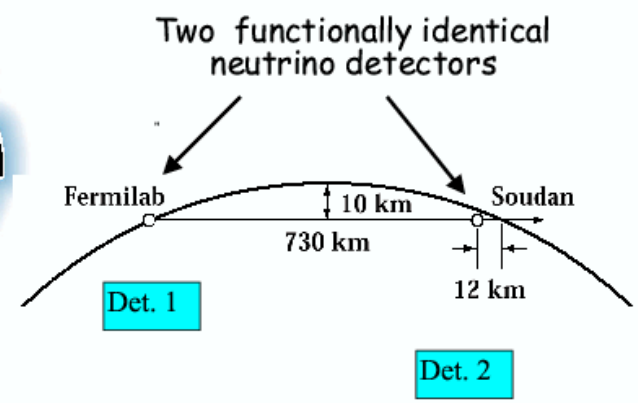
2.0, 2.5

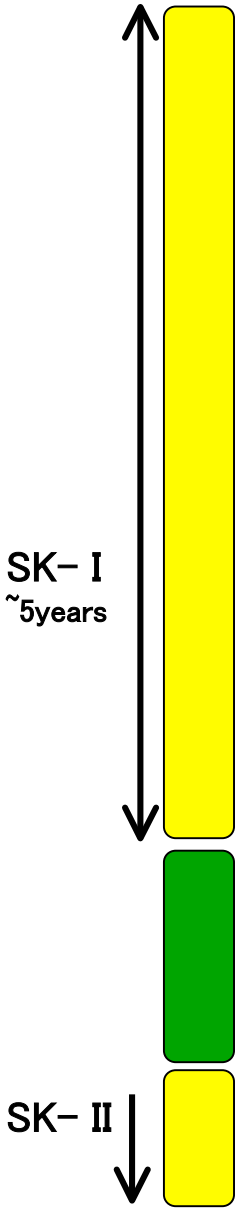
The NUMI Beamline

NOvA

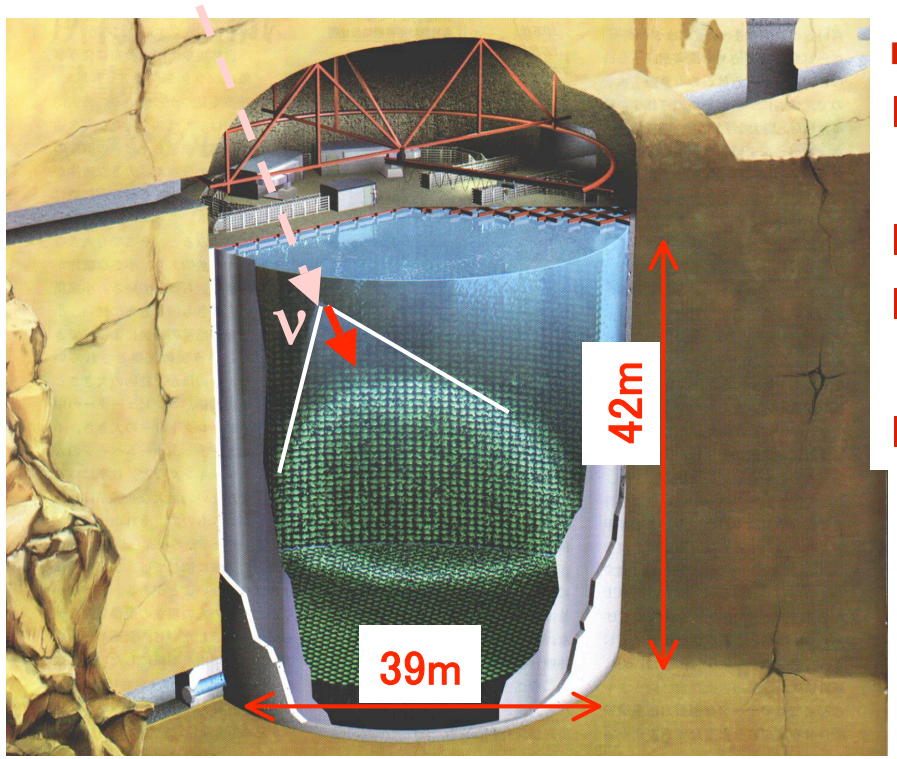


10, 12 14 km

Water Cherenkov detector



- 1996.4 Start data taking (SK- I)



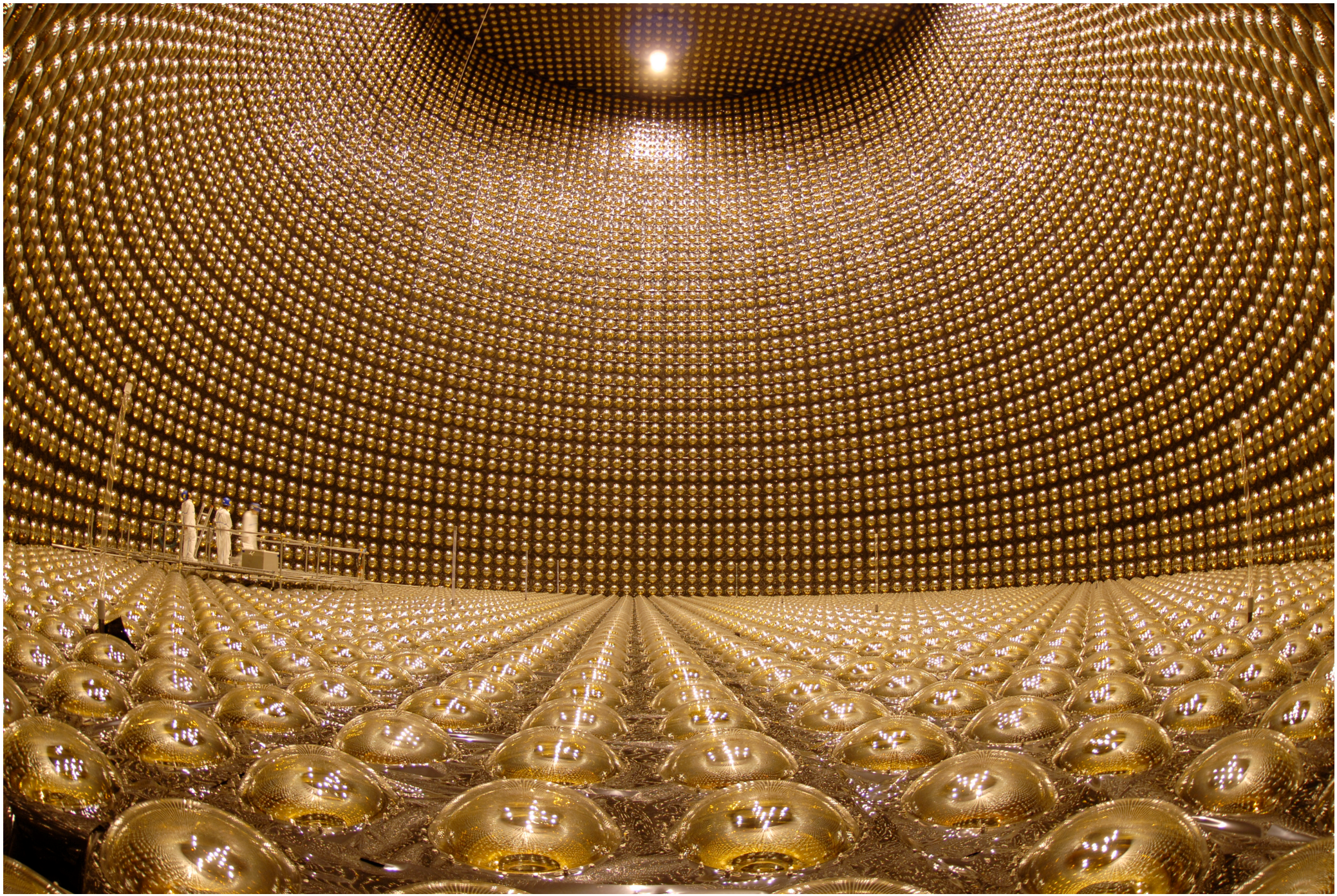
- 2001.7 Stop data taking for detector upgrade
- 2001.11 Accident (6777 inner PMTs, 1100 outer PMTs were destroyed)
  partial reconstruction of the detector

- 2002.10 Resume data taking (SK- II) mostly for K2K (photocathode coverage of 20%, 7MeV

- 2005.10 Start full recovery work

- 2700 w.e. overbuden
- 50,000 ton (22,500 ton fid.)
- 11,146 20 inch PMTs
- Photo cathode coverage: 40% of surface
- 1,885 anti-counter PMTs

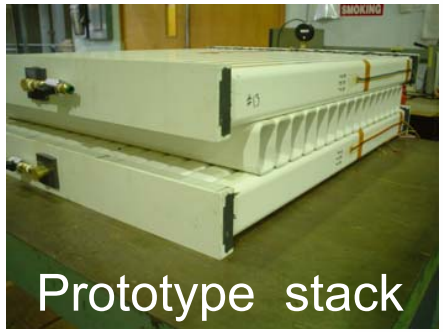
Acrylic + FRP vessel

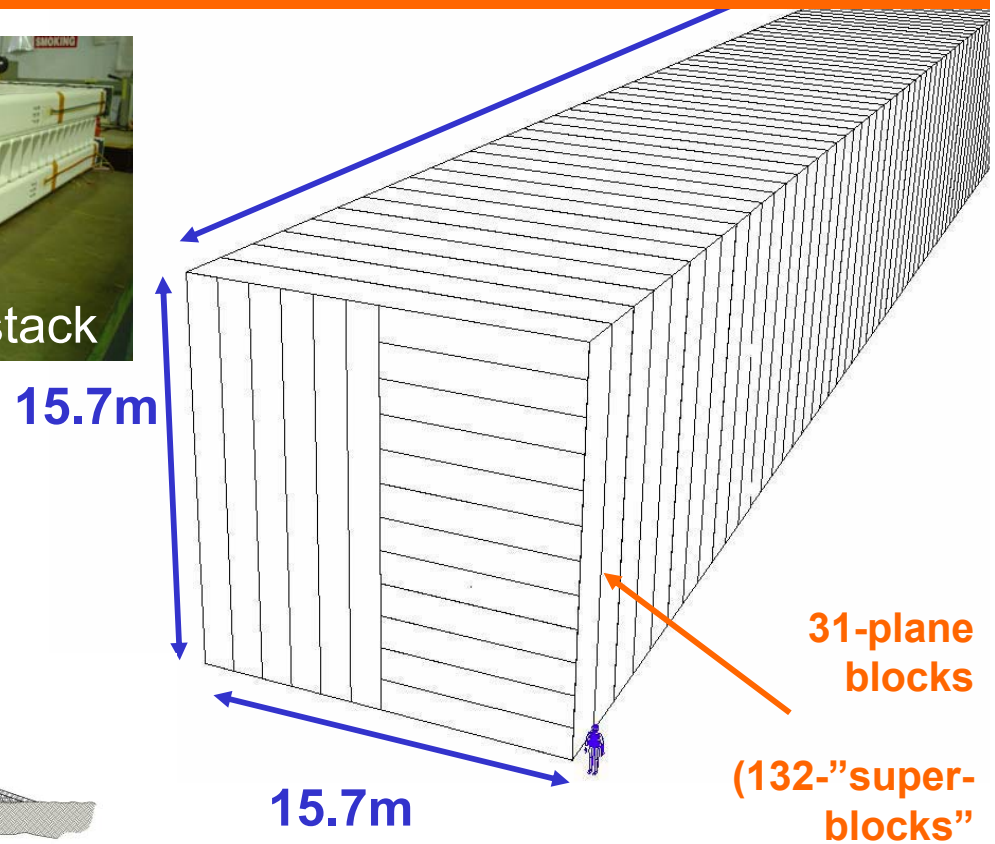


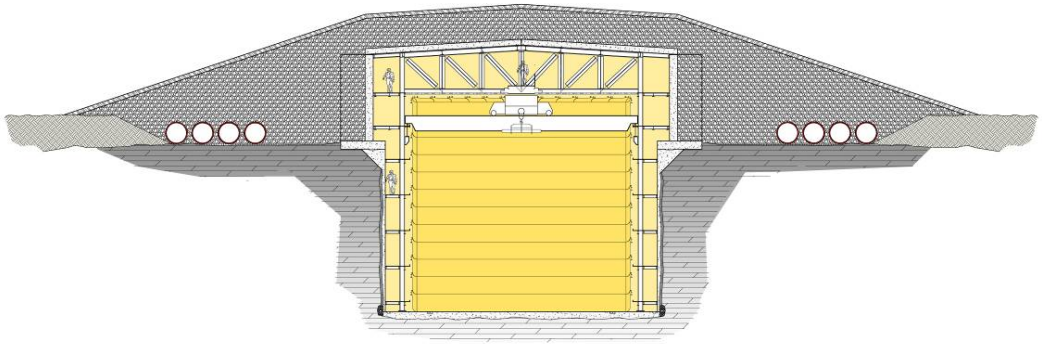
NOνA Far Detector we would like to build

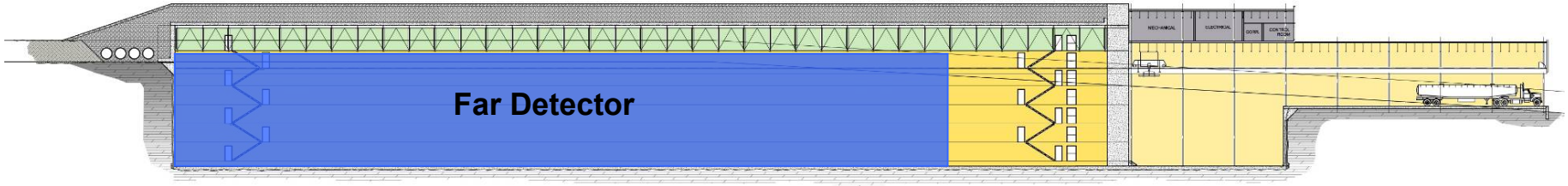
We will build as much of this as the funding will allow…

- TAD = Totally Active Detector
  - PVC = passive material
- mass N kT (N large)
  - ~80% scintillator
  - ~20% PVC extrusions
- Modular structure
  - 32 cells/extrusion
  - 12 extrusions/plane
  - 1984 planes
- Cell dimensions:
  - 3.9 cm x 6 cm x 15.7m
- U-shaped 0.7 mm WLS fiber into APD









$\nu_\mu \longrightarrow \nu_e$ with MATTER

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

$\nu_\mu \longrightarrow \nu_e$ 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 $\sin\Delta_{31}$

$\nu_\mu \longrightarrow \nu_e$ with MATTER

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in vac $\sin\Delta_{31}$

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

in vac $\sin\Delta_{21}$

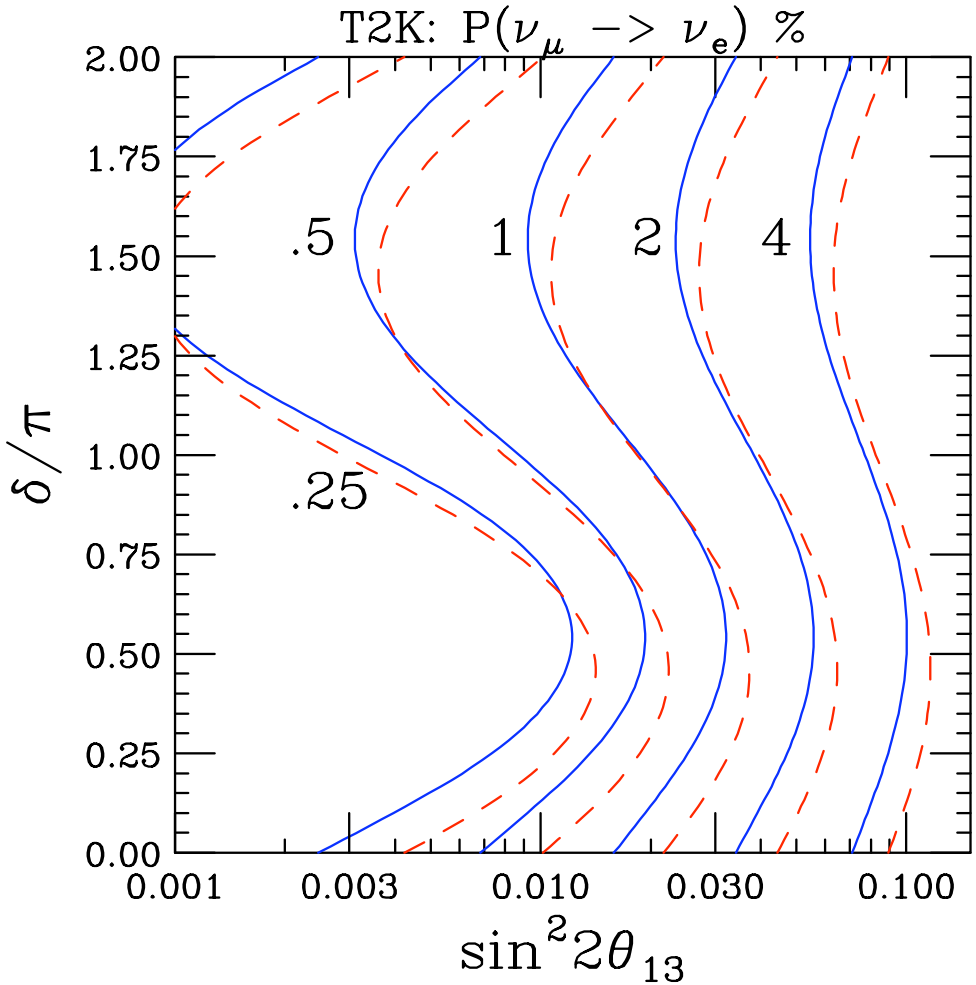
$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

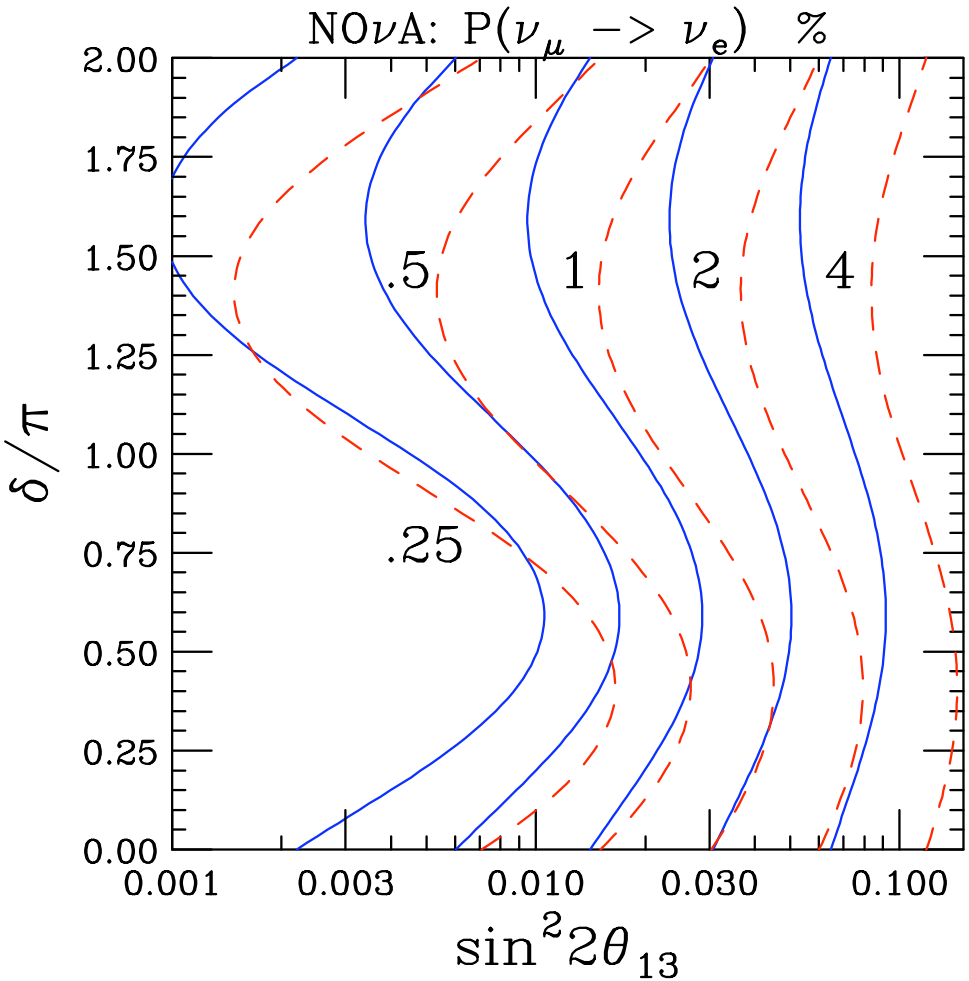
$$\pm = sign(\delta m^2_{31}) \qquad \Delta_{ij} = |\delta m^2_{ij}| L/4E$$

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

T2K:

NOvA:





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

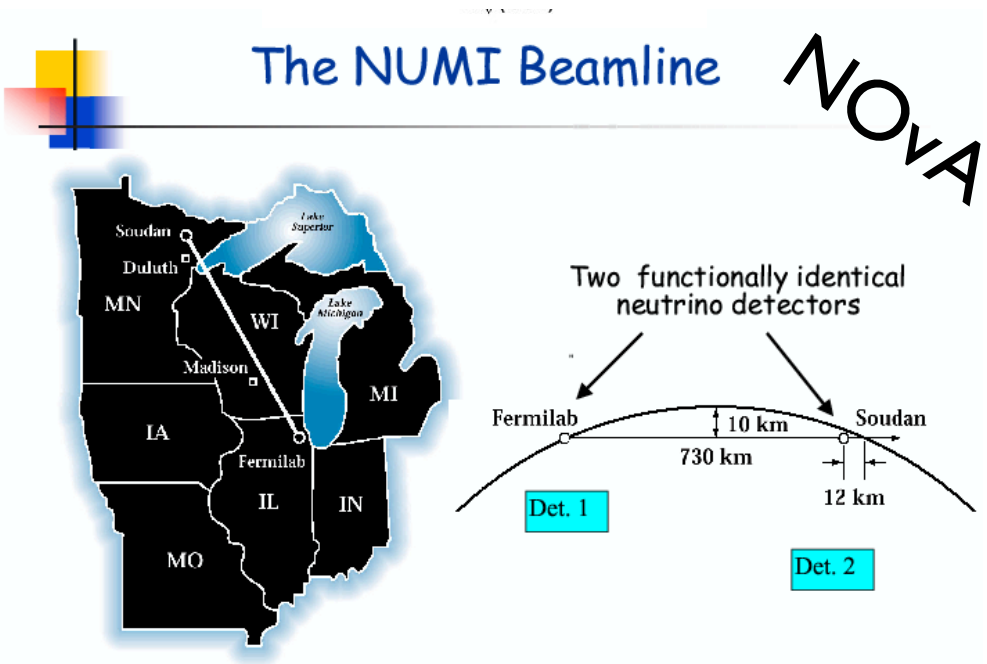
$\delta m^2_{31} < 0$

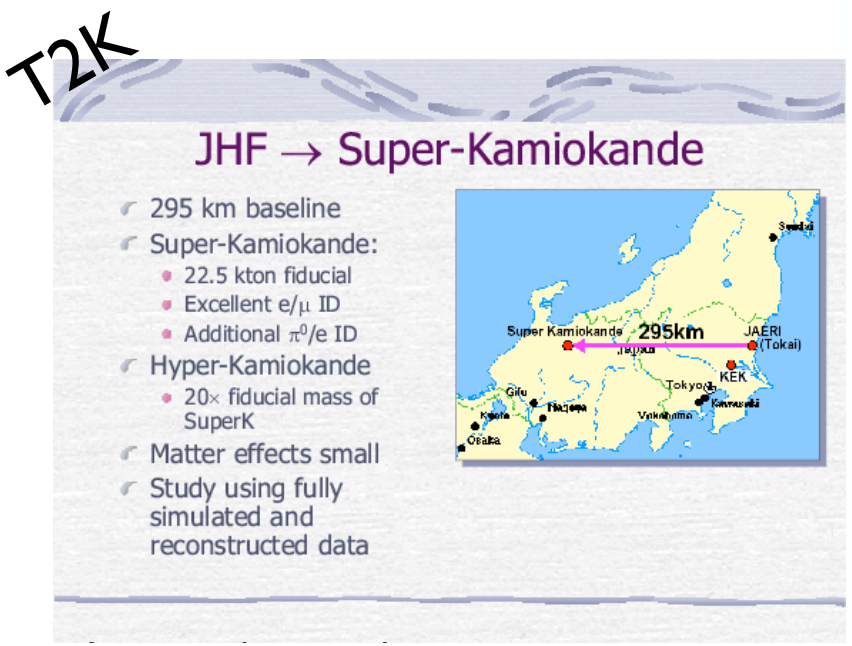
Phase I

Sensitivity approx 0.5%

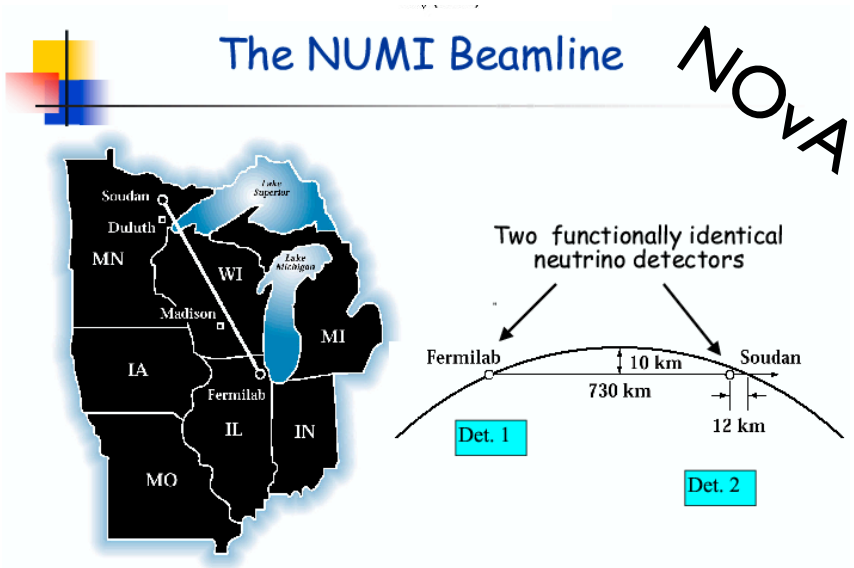
Counting Expts at First Osc. Max.

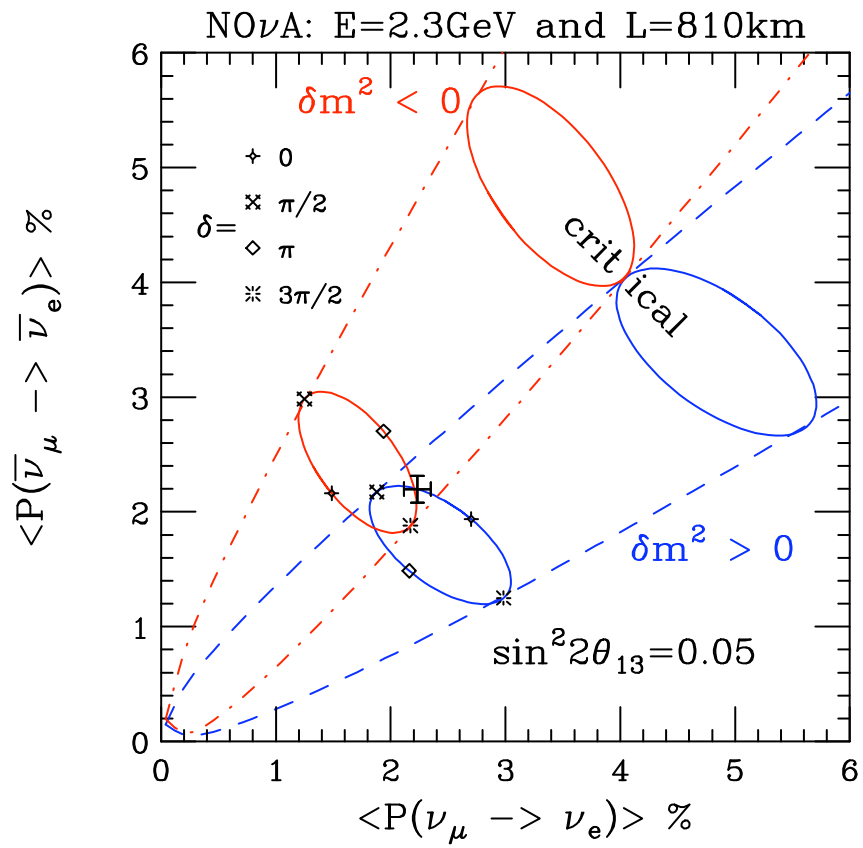
- Neutrino v Anti-Neutrino One Expt.
- Neutrino v Neutrino Two Expts Different L's and EQUAL E/L's
- Neutrino v Anti-Neutrino Two Expts Different L's





Neutrino v Anti-Neutrino One Expt.





in the overlap region

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

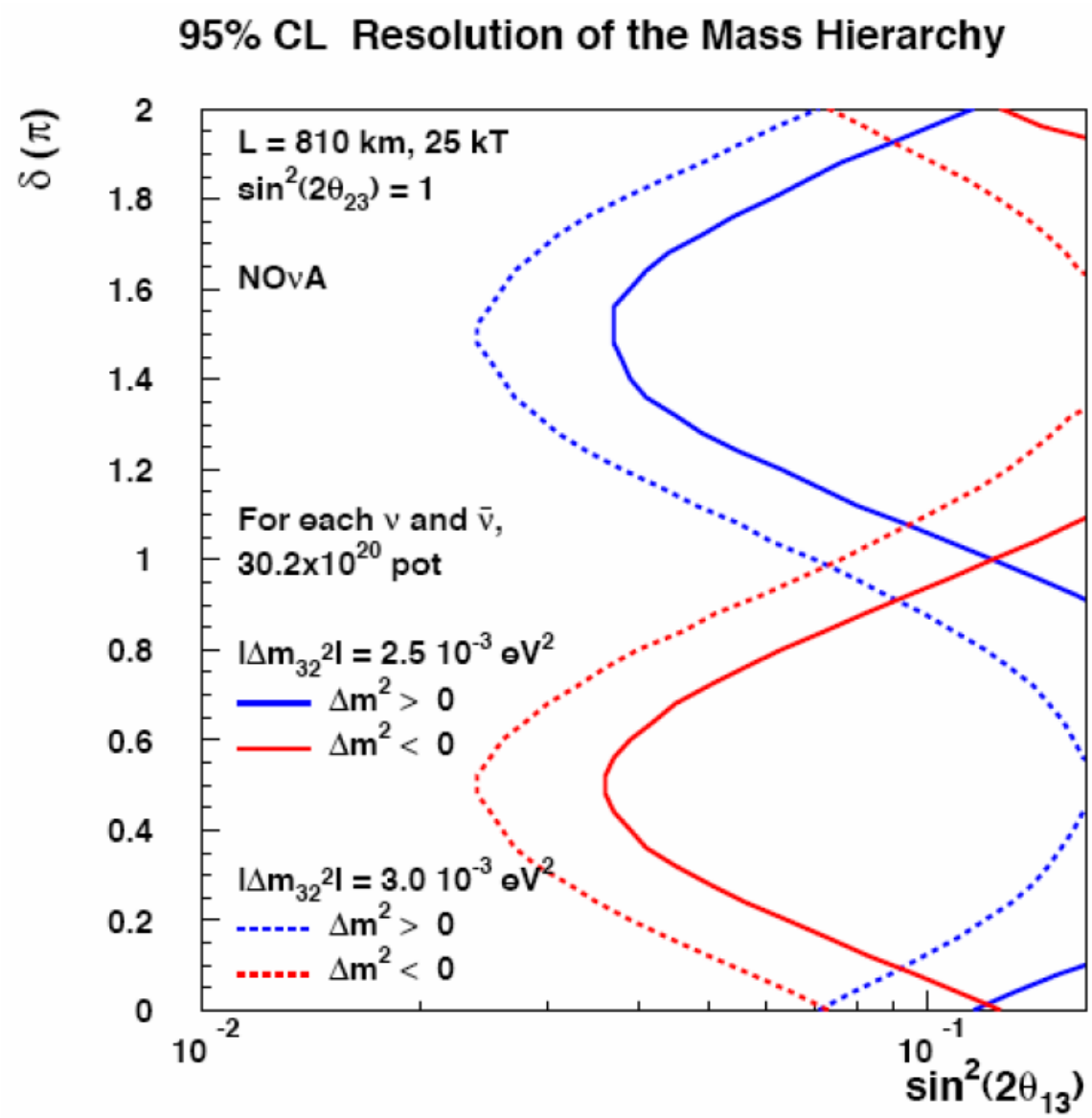
exact along diagonal --- approximately true throughout the overlap region!!!

$$\theta_{crit} = \frac{\pi^2}{8}\,\frac{\sin 2\theta_{12}}{\tan\theta_{23}}\,\frac{\delta m^2_{21}}{\delta m^2_{31}}\left(\frac{4\Delta^2/\pi^2}{1-\Delta\cot\Delta}\right)/(aL) \sim 1/6$$

i.e. $\sin^2 2\theta_{crit} = 0.10$

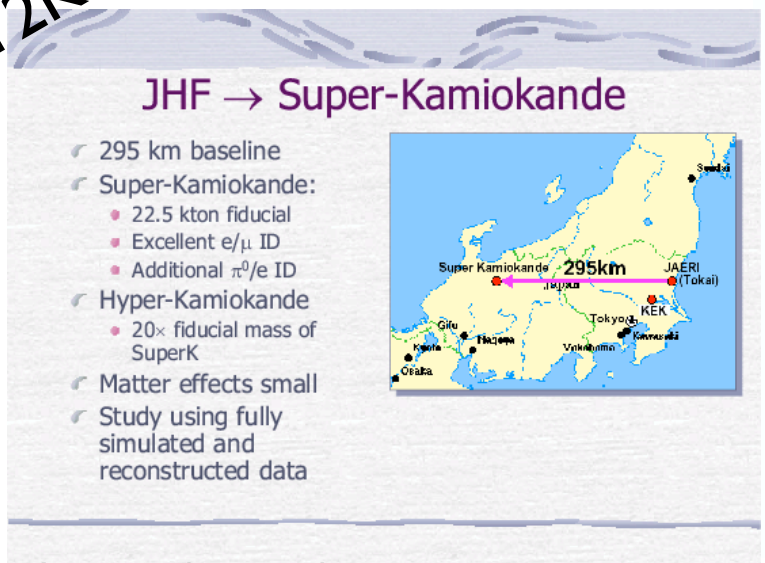
O. Mena + SP
hep-ph/0408070

NOvA:

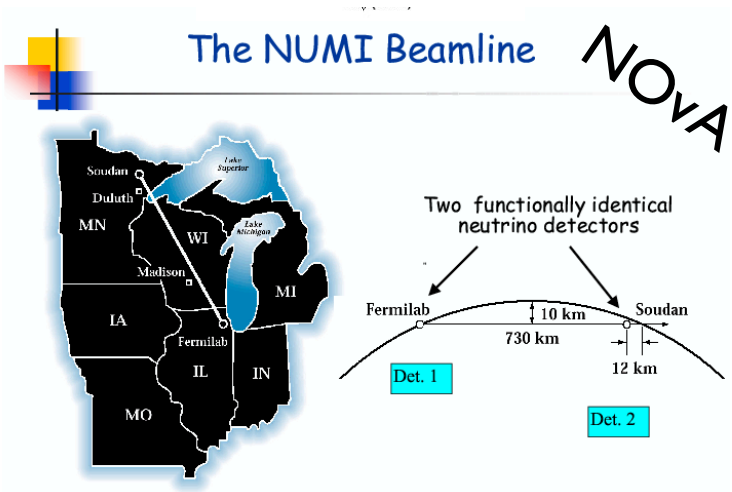

95% CL Resolution of the Mass Hierarchy
L = 810 km, 25 kT
sin²(2θ23) = 1
NOνA
For each ν and ν̄,
30.2x10²⁰ pot
|Δm32²| = 2.5 10⁻³ eV²
Δm² > 0
Δm² < 0
|Δm32²| = 3.0 10⁻³ eV²
Δm² > 0
Δm² < 0
δ (π)
sin²(2θ13)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10⁻²
10⁻¹

Neutrino v Neutrino Two Expts
Different L's and EQUAL <E>/L 's

T2K



NOvA



2.5 degrees and 14 km

or

2.0 degrees and 12 km

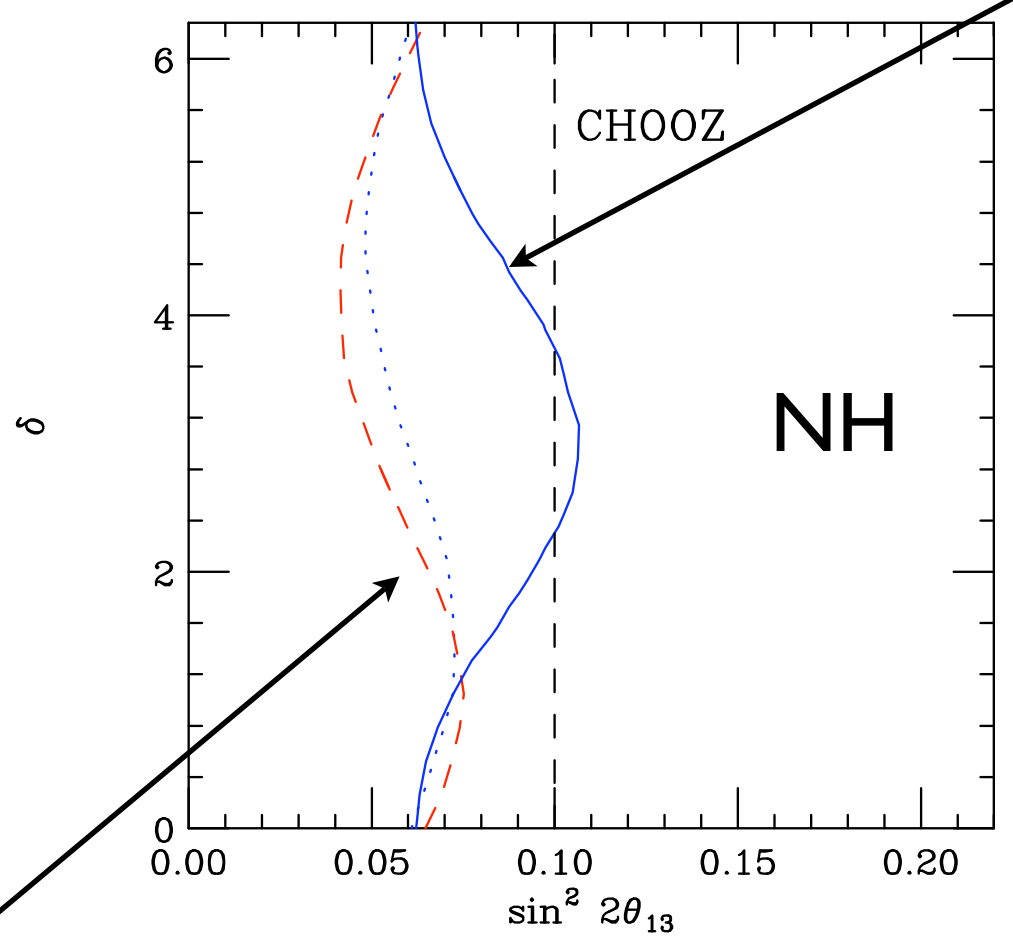
EQUAL <E>/L

but NOT

2.5 degrees and 12 km

Hierarchy Determination using 2 dof: 90% CL

2.5 deg & 12 km



2.5 deg & 14 km

2.0 deg & 12 km

(b) $\Delta m^2_{31} = +3.0 \times 10^{-3}$ eV^2

WHY 2 dof ????

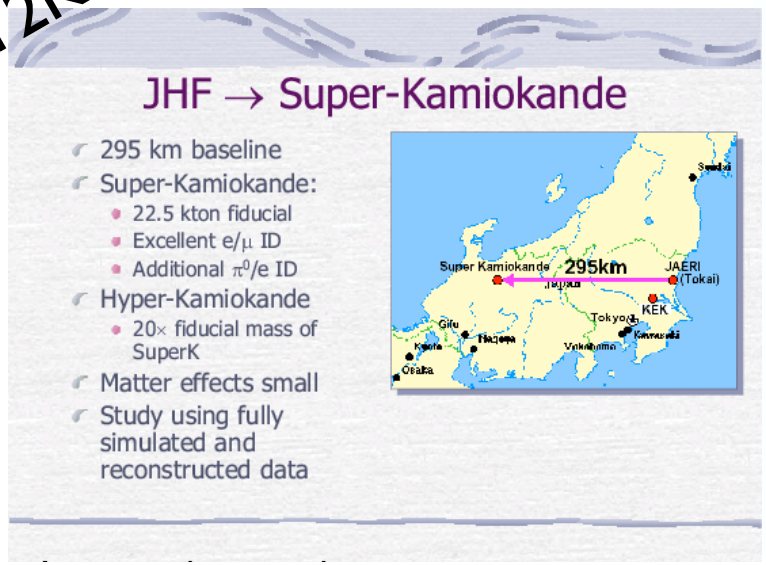
90% at 2 dof

approx

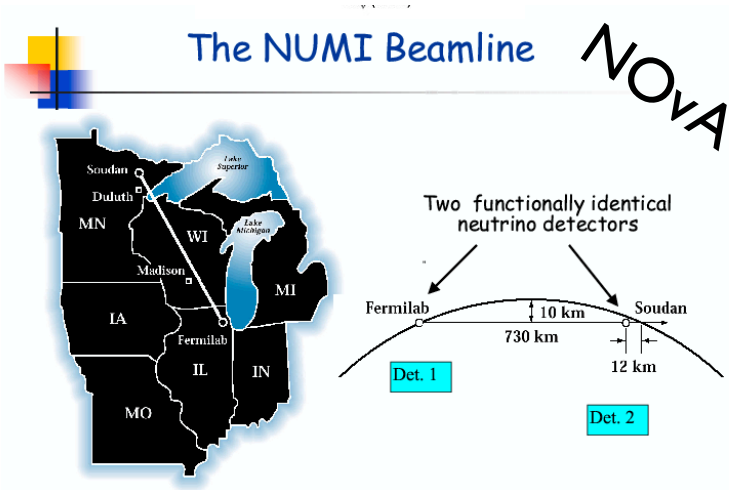
97% at 1 dof

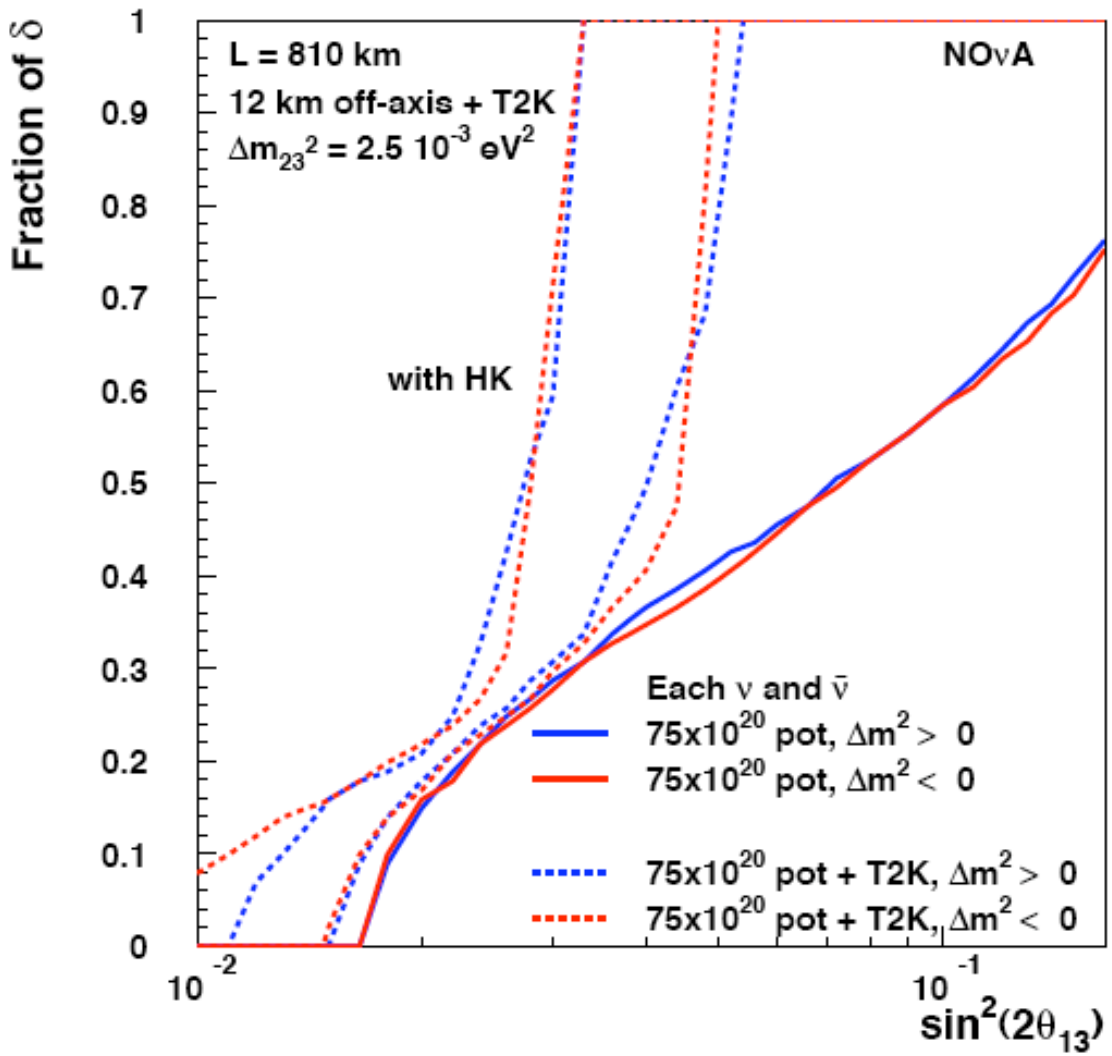
Neutrino v Anti-Neutrino
Two Expts. Different L's

T2K



NOvA





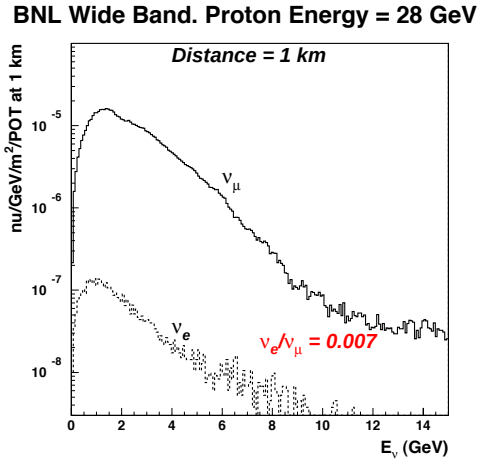
NOνA/PD with T2K Phase 2

Spectrum Measurements:

- On Axis
- Off Axis - 2nd Peak

On Axis Beams:

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

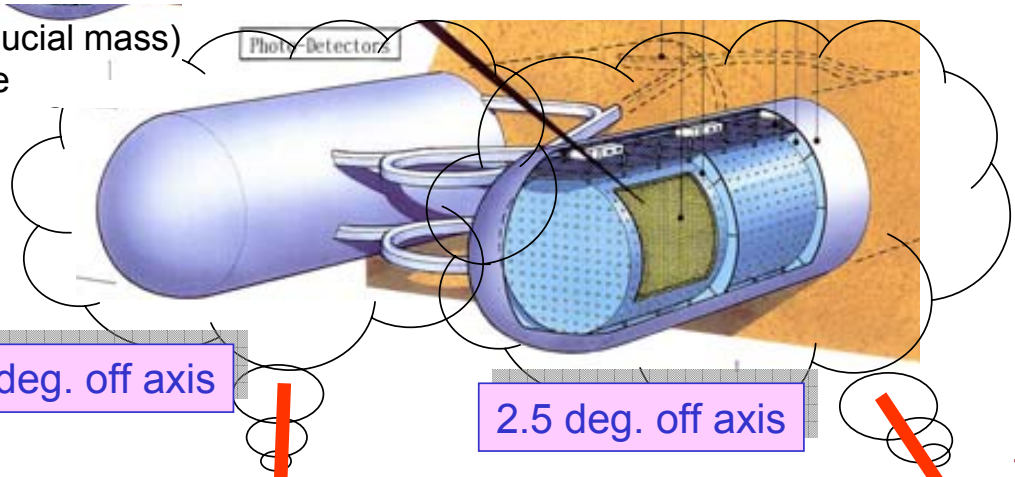


Brookhaven Proposal

Off Axis:

Some recent progress: detector in Korea

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande

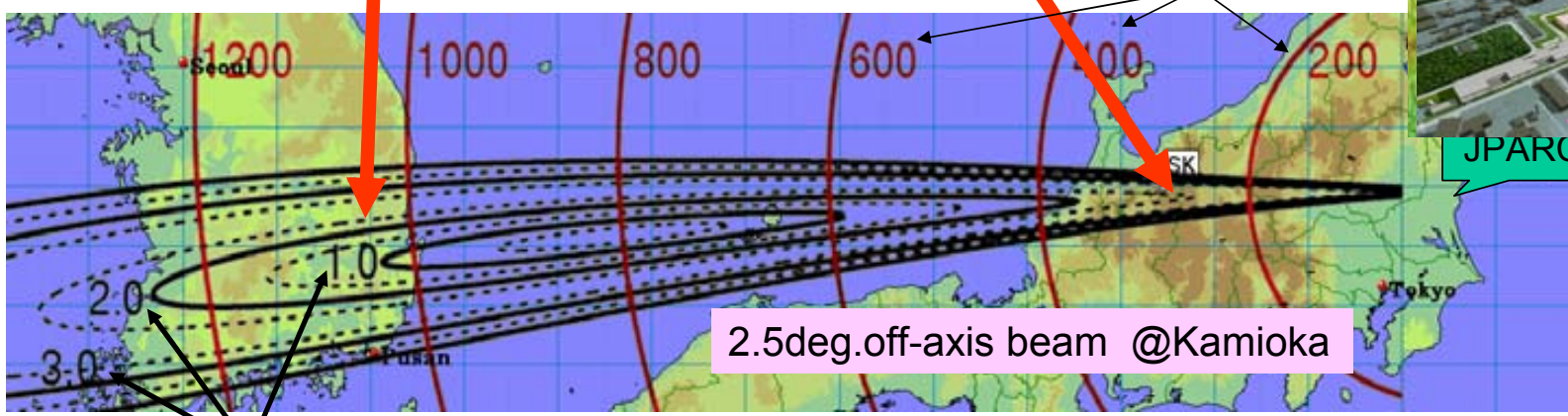


Total cost must be similar to the baseline design.

2.5 deg. off axis

2.5 deg. off axis

Distance from the target (km)



2.5deg.off-axis beam @Kamioka

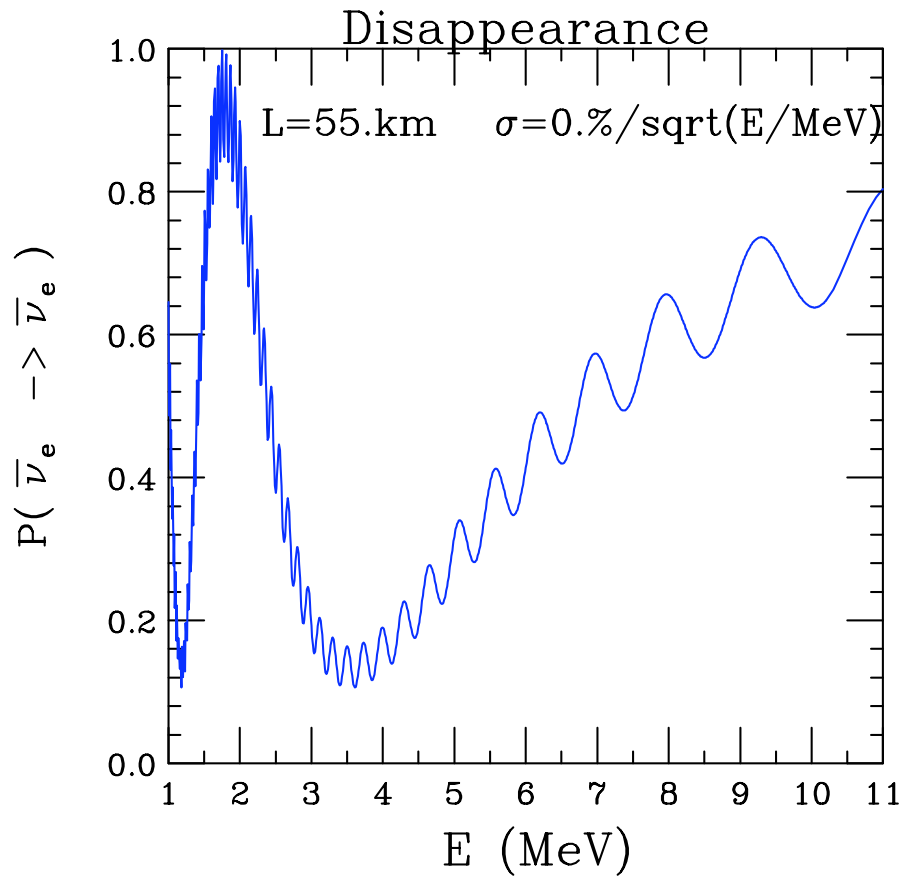
Off-axis angle

see Kajita talk:

$\bar{\nu}_e$ Disappearance

$$P(\nu_e \to \nu_e) \quad = \quad 1 - P_\odot - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32}\right]$$

$$P_\odot \equiv c_{13}^4 \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

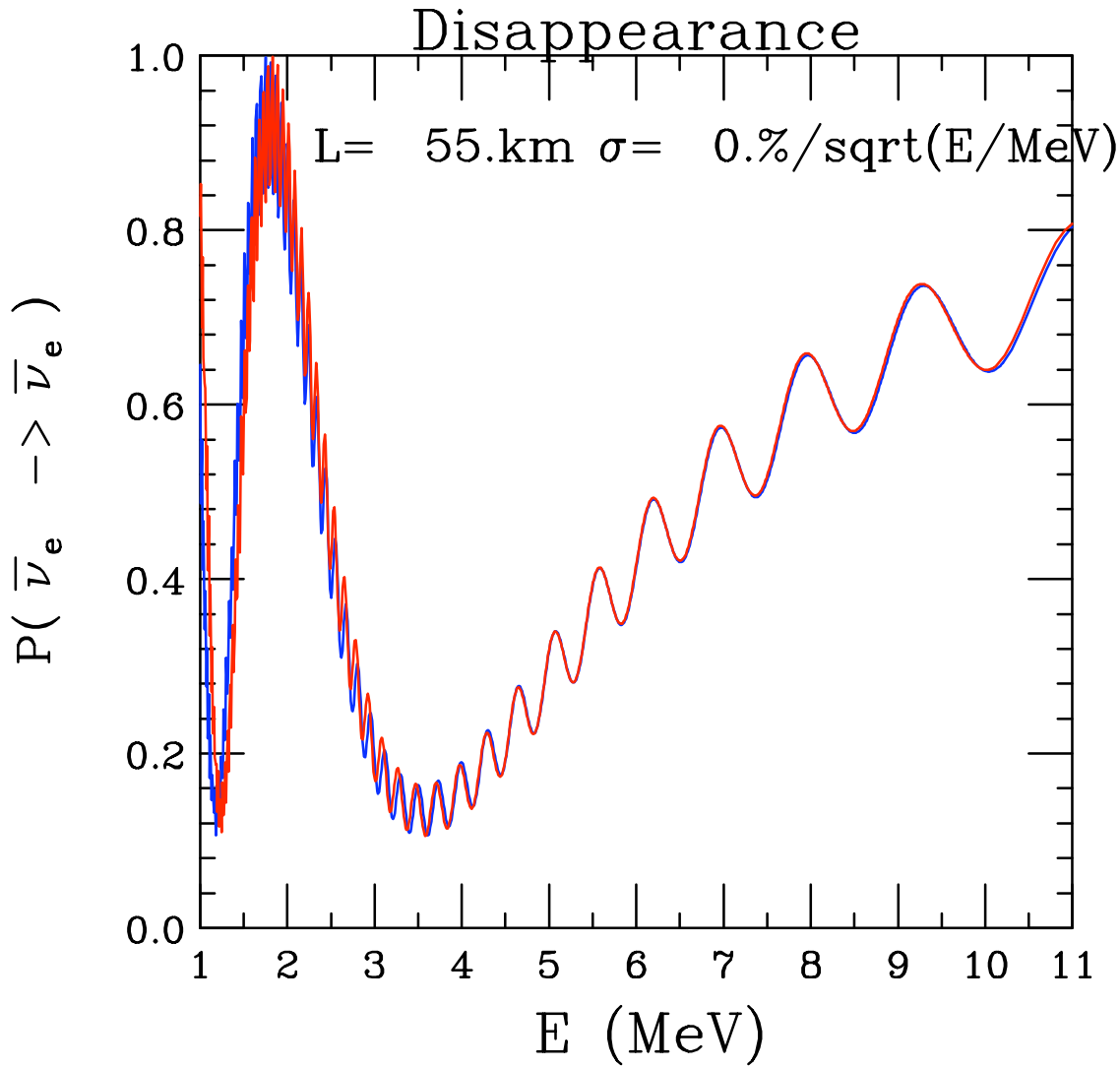


$$\Delta_{21} = \Delta_{31} - \Delta_{32}.$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4\hbar c E$$

$$(\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$

NH v IH :



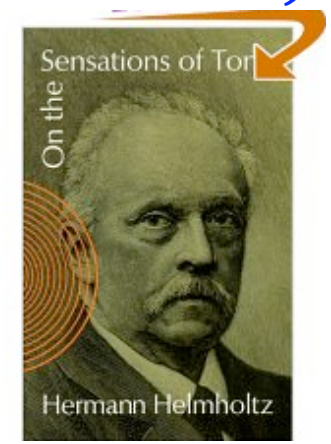
NH: $|\Delta m^2_{31}| > |\Delta m^2_{32}|$ $\quad (|\Delta_{31}| > |\Delta_{32}|)$

IH: $|\Delta m^2_{31}| < |\Delta m^2_{32}|$ $\quad (|\Delta_{31}| < |\Delta_{32}|)$

$$
\begin{aligned}
P(\nu_e \to \nu_e) &= 1 - P_\odot - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32}\right] \\
&= 1 - P_\odot \\
&\quad -\frac{1}{2}\sin^2 2\theta_{13}\left\{1 + \sqrt{(1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21})}\cos(2\bar{\Delta} + \bar{\phi})\right\}
\end{aligned}
$$

where $\bar{\Delta} = \frac{1}{2}(\Delta_{31} + \Delta_{32})$ and $\bar{\phi} = \arctan(\cos 2\theta_{12} \tan \Delta_{21})$

for small Δ_{21} $\Rightarrow$ $\bar{\phi} = \Delta_{21} \cos 2\theta_{12} + \mathcal{O}(\Delta_{21}^3)$



1875

Define $\phi \equiv \arctan(\cos 2\theta_{12} \tan \Delta_{21}) - \Delta_{21} \cos 2\theta_{12}$

then $\frac{d\phi}{dL}|_{L=0} = 0$

thus ϕ doesn't effect the atmospheric oscillation frequency at least for small L.

hep-ph/0701151

Rewrite $\cos(2\bar{\Delta} + \bar{\phi}) = \cos(2\Delta_{ee} + \phi)$ then

$$\Delta_{ee} \equiv \frac{1}{2}(\Delta_{31} + \Delta_{32} + \Delta_{21}\cos 2\theta_{21}) = c_{12}^2\Delta_{31} + s_{12}^2\Delta_{32}$$

since $\Delta_{21} = \Delta_{31} - \Delta_{32}$.

$$P(\nu_e \to \nu_e) = 1 - P_\odot - \frac{1}{2}\sin^2 2\theta_{13}\left\{1 + \sqrt{(1 - \sin^2 2\theta_{12}\sin^2\Delta_{21})}\cos(2\Delta_{ee} \pm \phi)\right\}$$

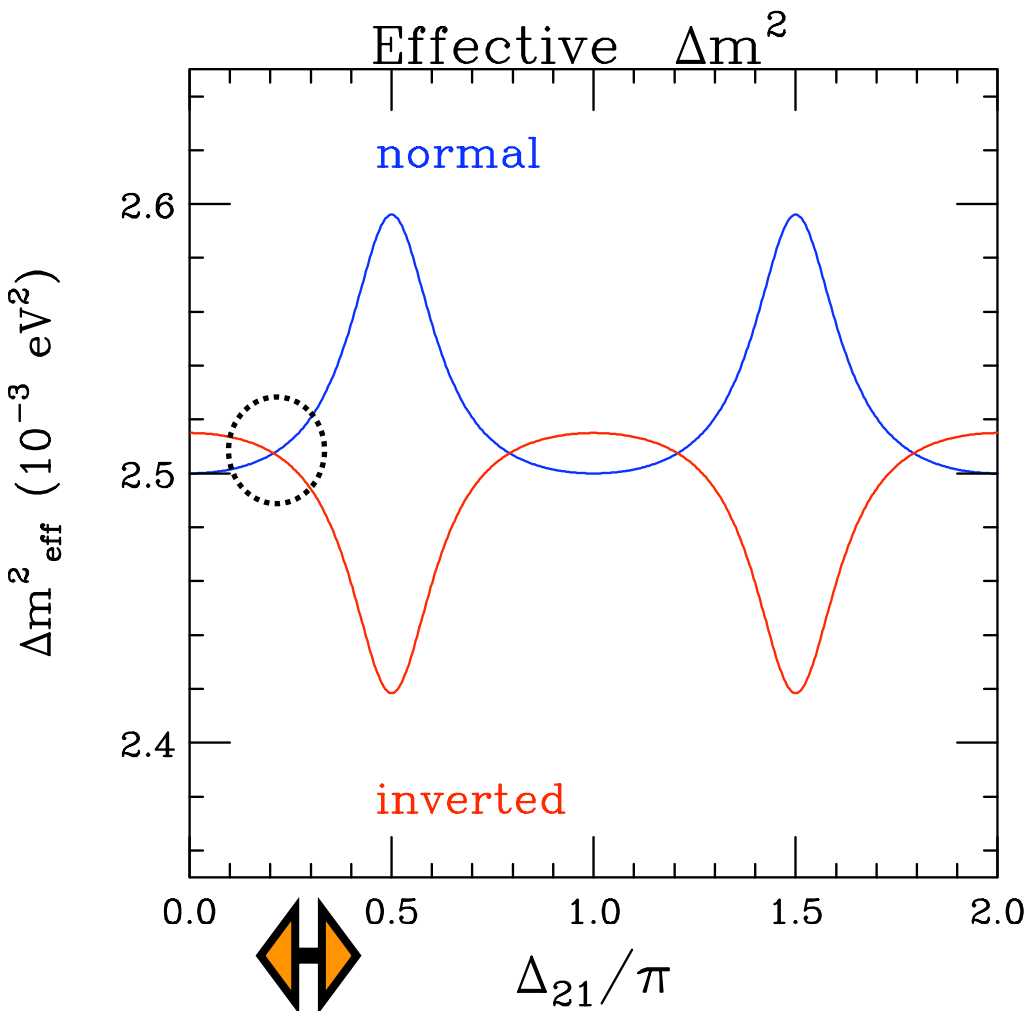
NH (+) and IH (-): $\Delta_{ee} \equiv \Delta m_{ee}^2 L/4E$, $\Delta m_{ee}^2 = c_{12}^2|\Delta m_{31}^2| + s_{12}^2|\Delta m_{32}^2|$

$$\phi \equiv \arctan(\cos 2\theta_{12}\tan\Delta_{21}) - \Delta_{21}\cos 2\theta_{12}$$

$$\Delta m_{eff}^2 \equiv \frac{d\ (2\Delta_{ee} \pm \phi_\odot)}{d\ L/2E}$$

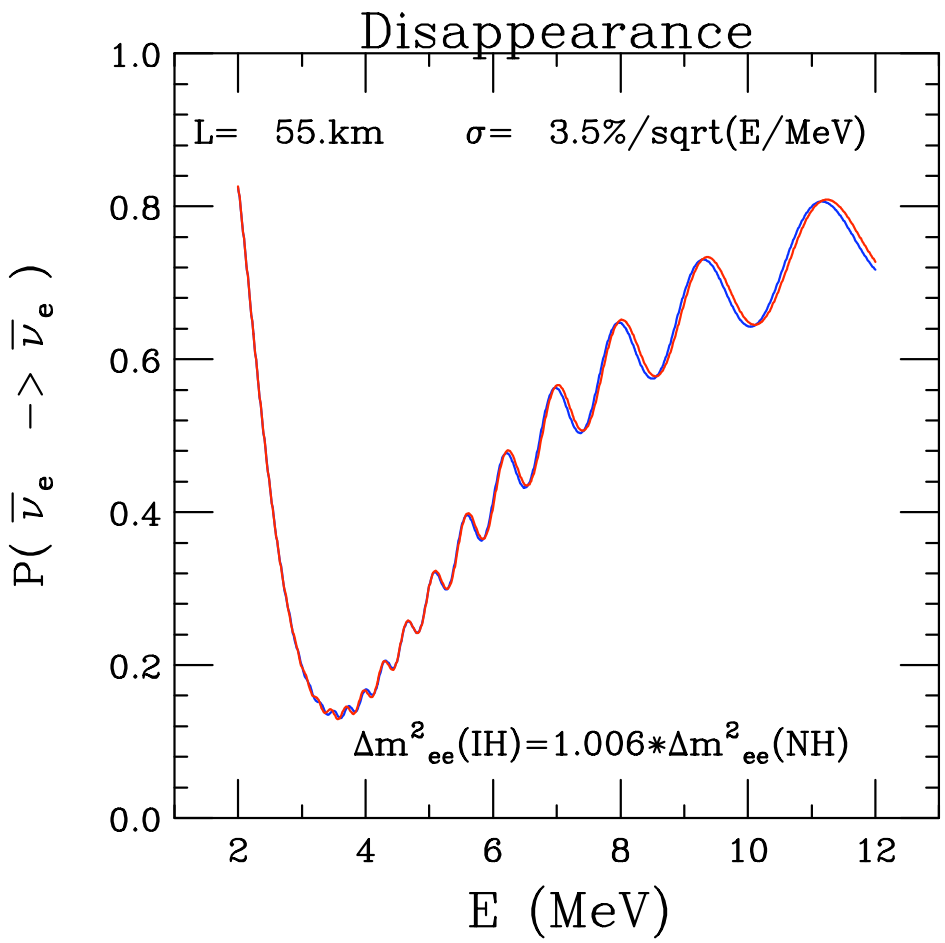
$$\Delta m^2_{eff} \equiv \frac{d\ (2\Delta_{ee} \pm \phi_\odot)}{d\ L/2E}$$

$$= \Delta m^2_{ee} \pm \frac{1}{2}\ \Delta m^2_{21} \cos 2\theta_{12}\ \frac{\sin^2 2\theta_{12} \sin^2 \Delta_{21}}{(1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21})}$$

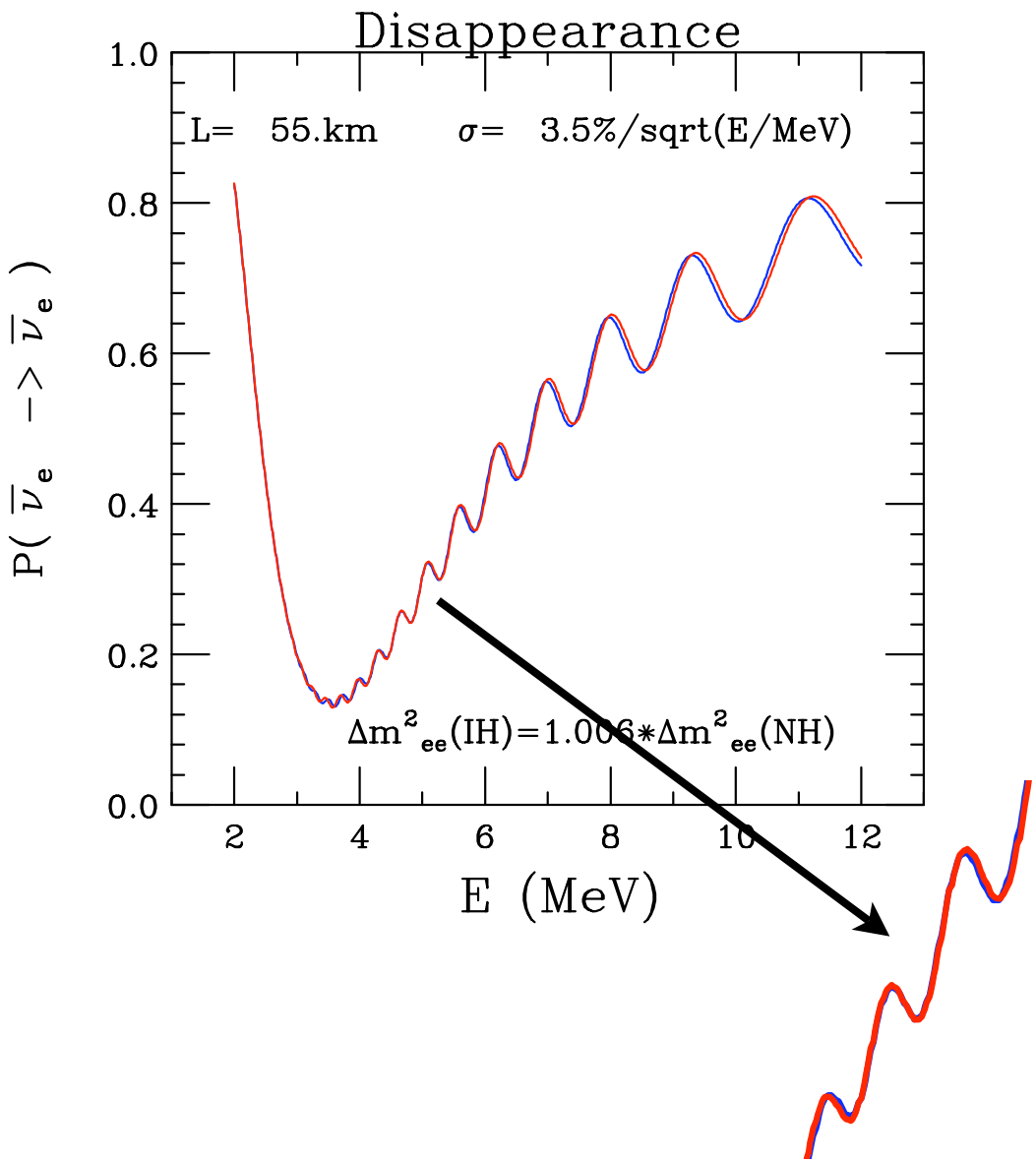


Hanohano

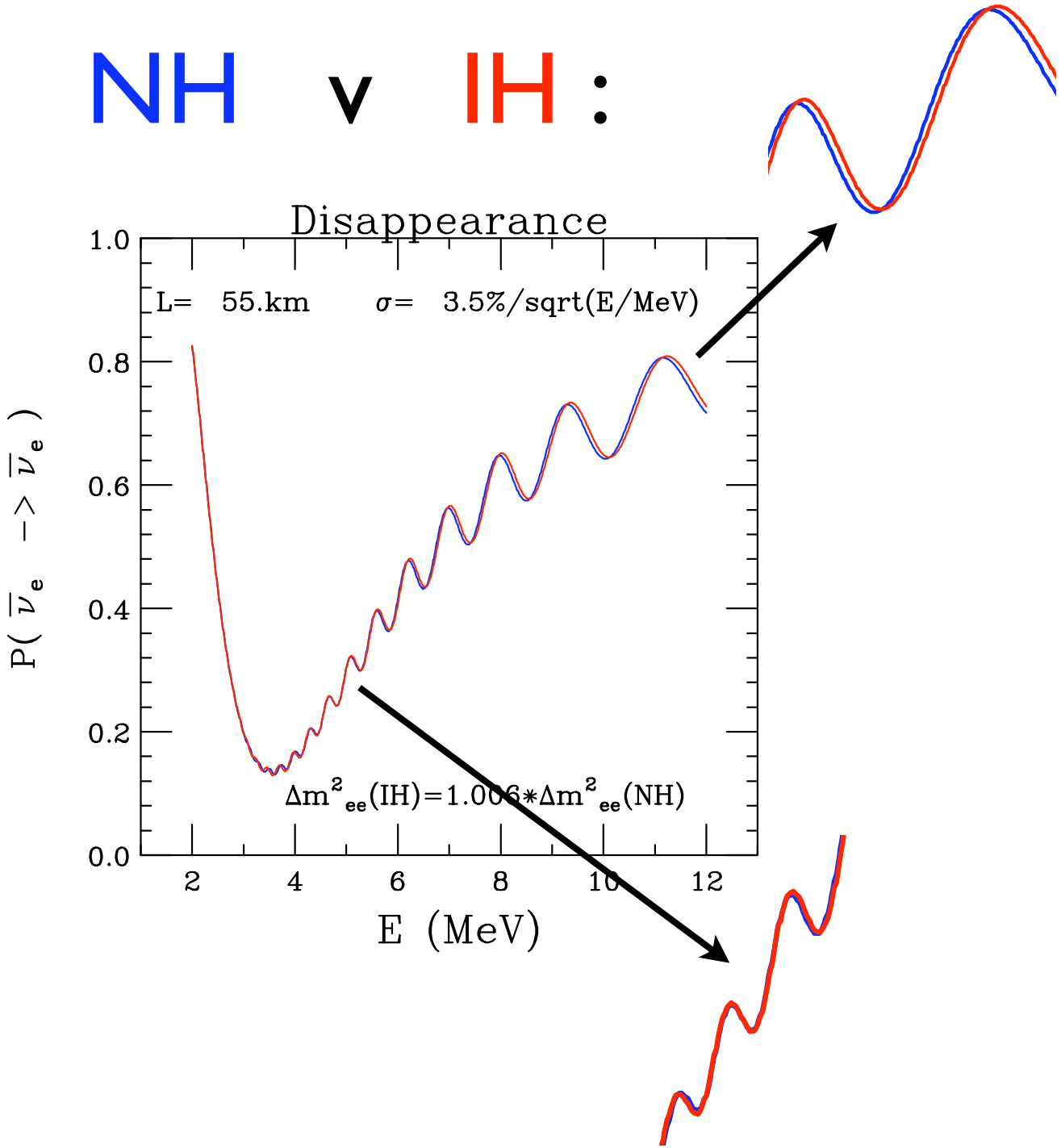
NH v IH :


Disappearance
L= 55.km
σ= 3.5%/sqrt(E/MeV)
Δm²ee(IH)=1.006*Δm²ee(NH)
P(ν̄e -> ν̄e)
E (MeV)
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12

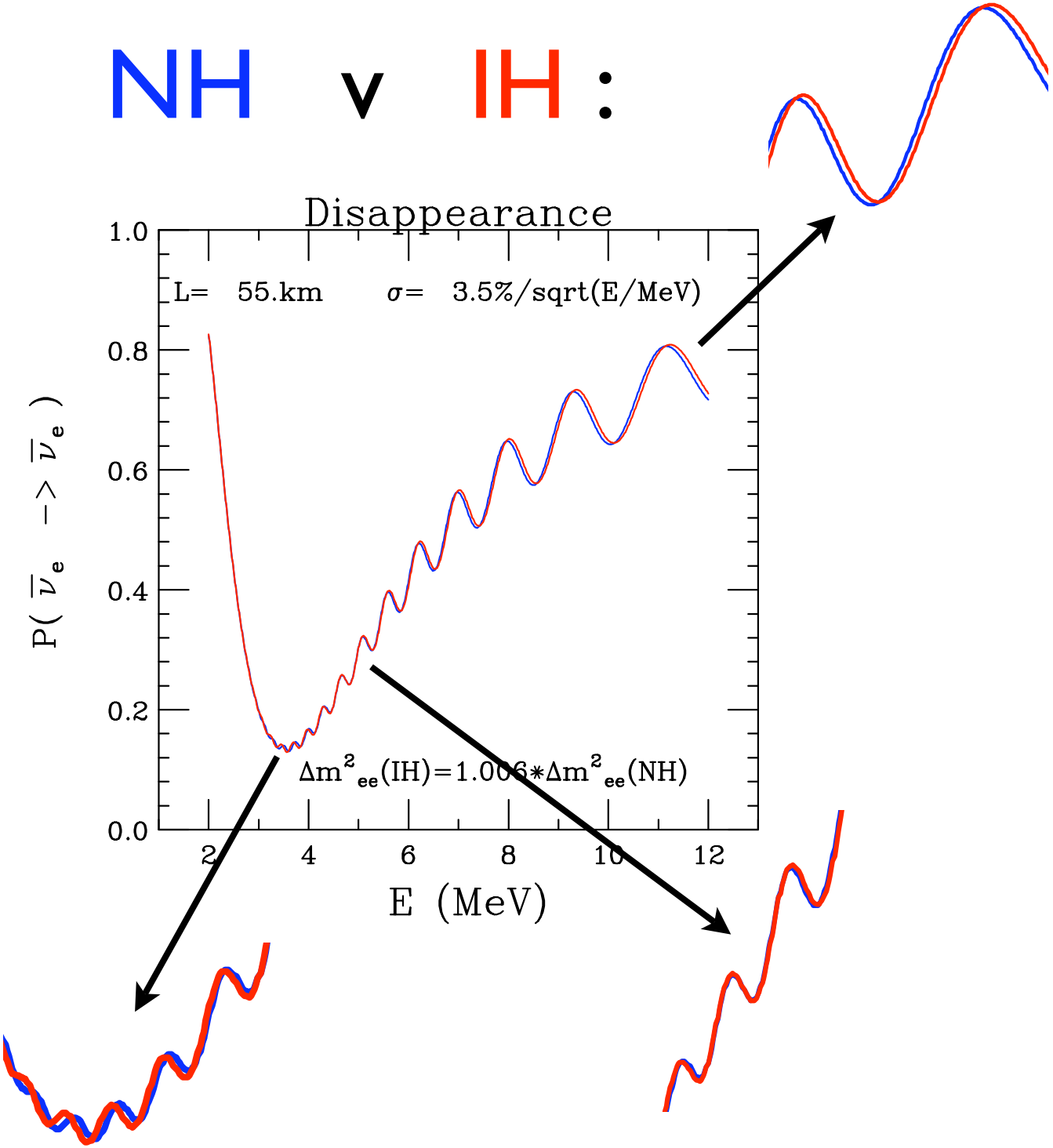
NH v IH :


Disappearance
L= 55.km
σ= 3.5%/sqrt(E/MeV)
Δm²ee(IH)=1.006*Δm²ee(NH)
P(ν̄e -> ν̄e)
E (MeV)
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12

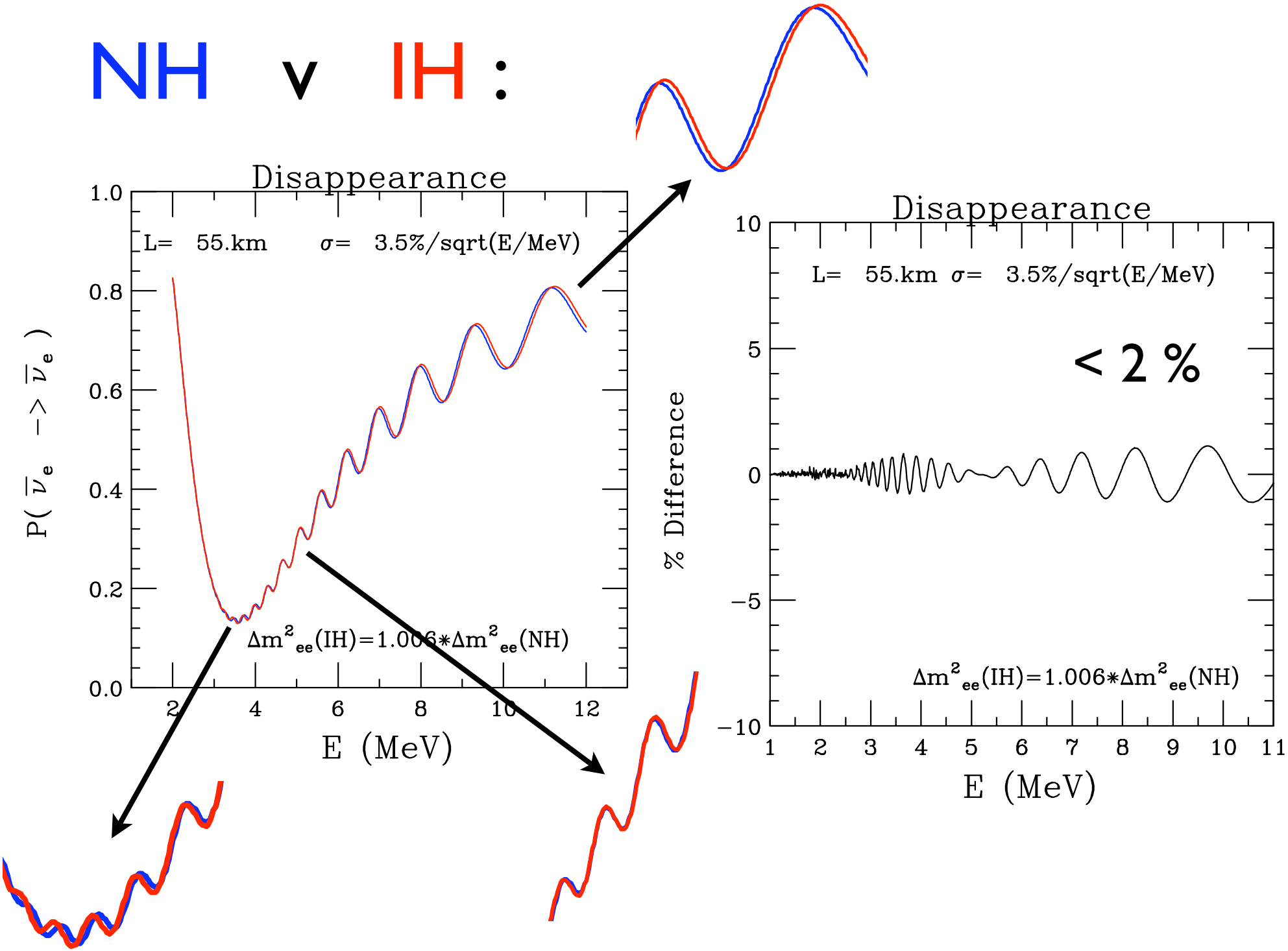
NH v IH :


Disappearance
L= 55.km
σ= 3.5%/sqrt(E/MeV)
Δm²ee(IH)=1.006*Δm²ee(NH)
P(ν̄e -> ν̄e)
E (MeV)
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12

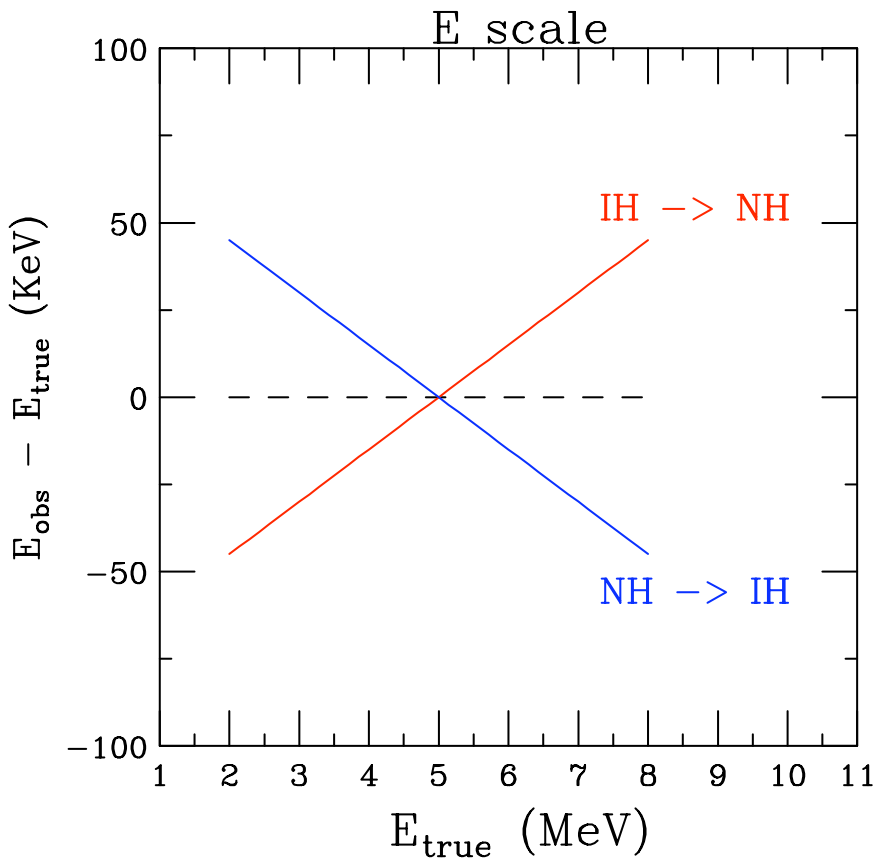
NH v IH :


Disappearance
L= 55.km
σ= 3.5%/sqrt(E/MeV)
Δm²ee(IH)=1.006*Δm²ee(NH)
P(ν̄e -> ν̄e)
E (MeV)
1.0
0.8
0.6
0.4
0.2
0.0
2
4
6
8
10
12

NH v IH :


Disappearance
L= 55.km σ= 3.5%/sqrt(E/MeV)
$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$
$\Delta m^2_{ee}(IH)=1.006*\Delta m^2_{ee}(NH)$
E (MeV)
Disappearance
L= 55.km σ= 3.5%/sqrt(E/MeV)
< 2 %
% Difference
$\Delta m^2_{ee}(IH)=1.006*\Delta m^2_{ee}(NH)$
E (MeV)

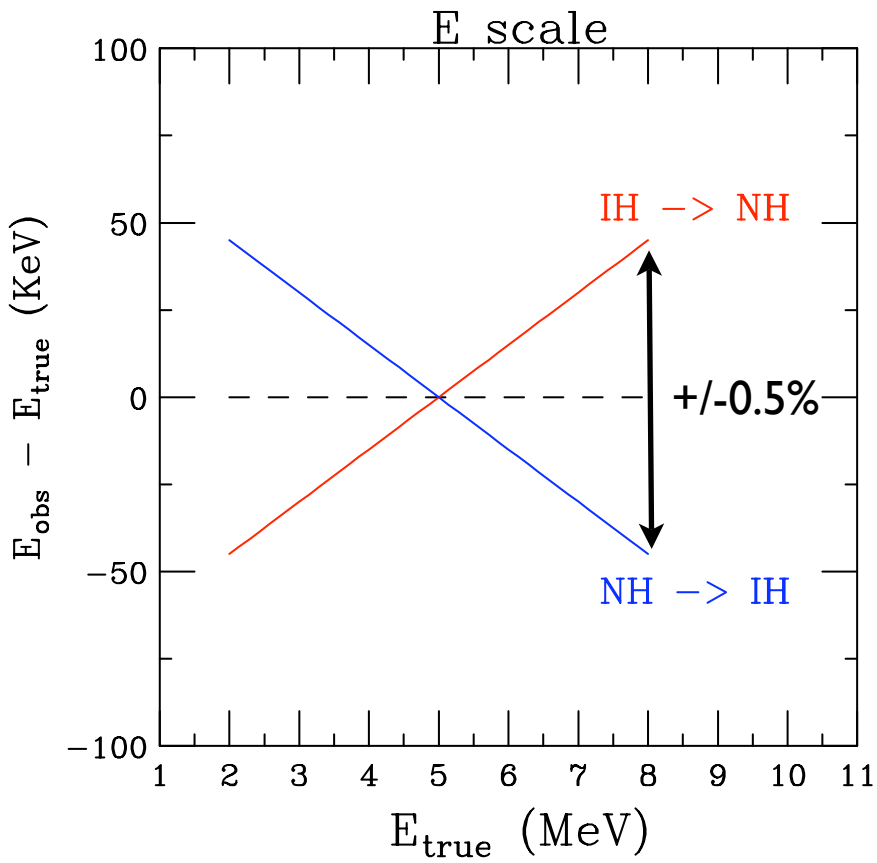
Uncertainty in E scale ???
between 2 and 8 MeV !!!



$$E_{obs} = E_{true} + 0.015 \times (E_{true} - 5)$$

$$E_{obs} = E_{true} - 0.015 \times (E_{true} - 5)$$

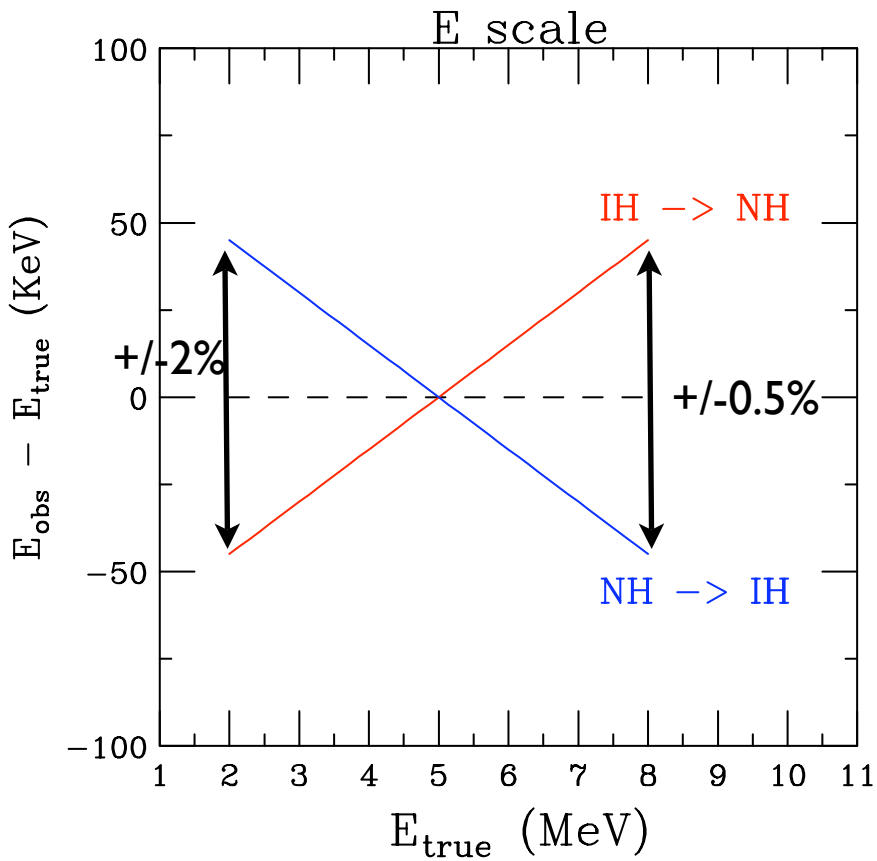
Uncertainty in E scale ???
between 2 and 8 MeV !!!



$$E_{obs} = E_{true} + 0.015 \times (E_{true} - 5)$$

$$E_{obs} = E_{true} - 0.015 \times (E_{true} - 5)$$

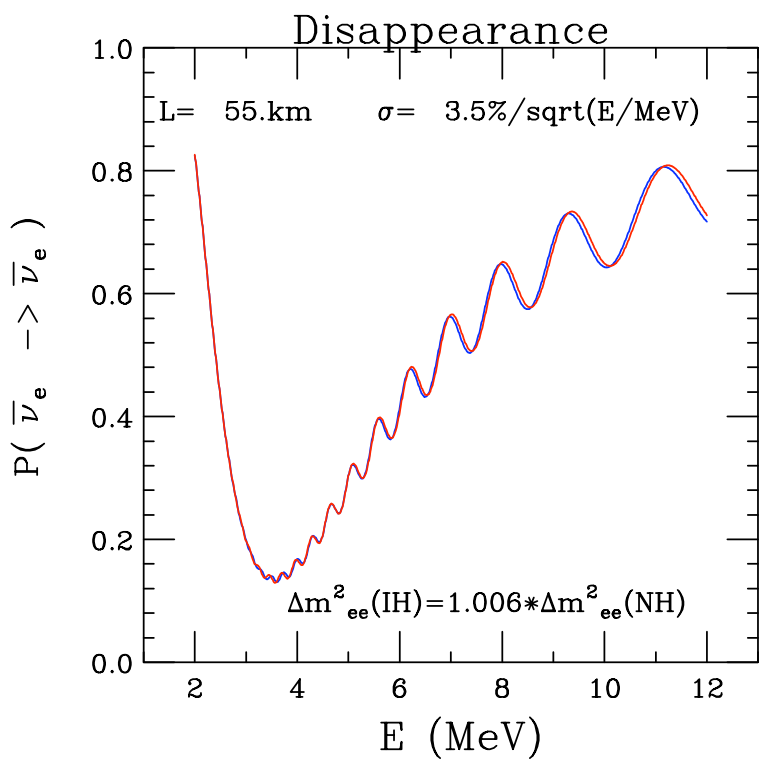
Uncertainty in E scale ???
between 2 and 8 MeV !!!



$$E_{obs} = E_{true} + 0.015 \times (E_{true} - 5)$$

$$E_{obs} = E_{true} - 0.015 \times (E_{true} - 5)$$

Distinguish NH from IH:

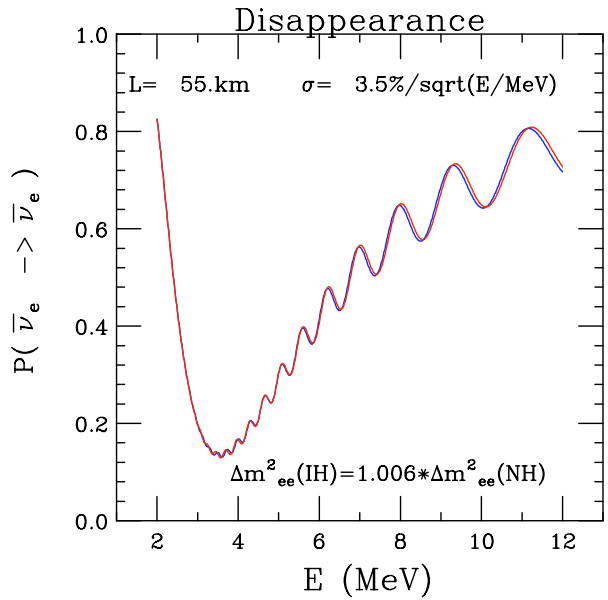


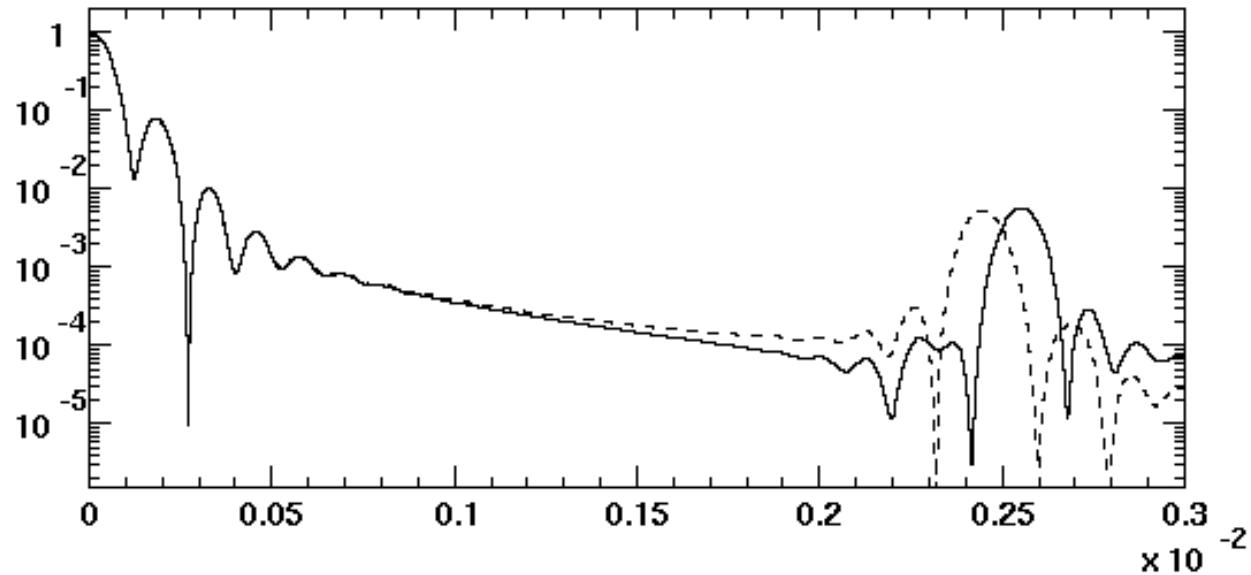
- Over 2 to 8 MeV Window
- High Quality data
- +
- Large Statistics

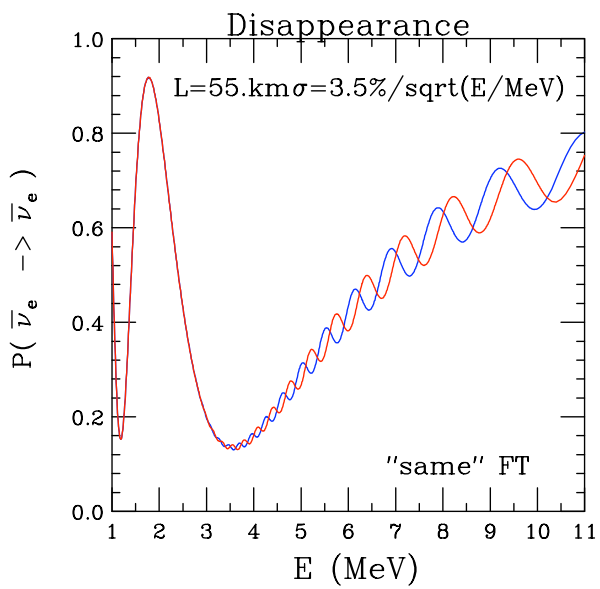
Magic of Fourier Transforms: JL talk

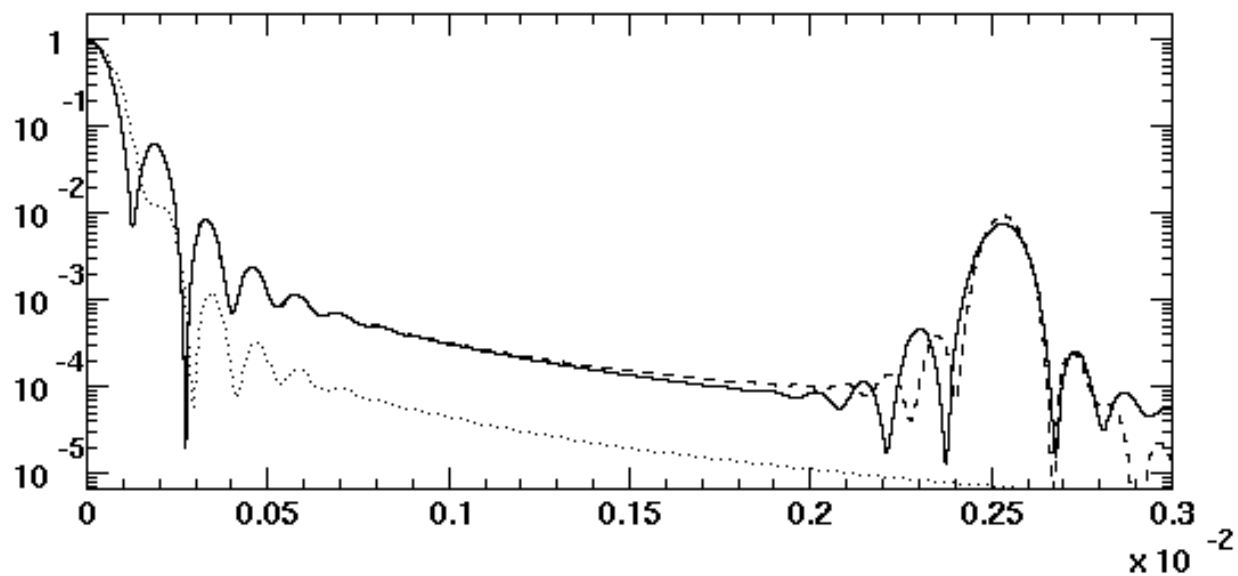
Conclusions:

- Determination of Hierarchy is Challenging
- NOvA and T2K statistics limited
- Help Needed!!!
- Large, High Quality data sets from Reactor - Hanohano
- Hanohano Limit independent of value of the CP violating phase.


Disappearance
L= 55.km σ= 3.5%/sqrt(E/MeV)
Δm²ee(IH)=1.006*Δm²ee(NH)
P(ν̄e -> ν̄e)
E (MeV)


x 10 -2


Disappearance
L=55.kmσ=3.5%/sqrt(E/MeV)
"same" FT
P(ν̄e -> ν̄e)
E (MeV)


x 10 -2