Mass Hierarchy via Mossbauer Neutrinos and Reactor Neutrinos

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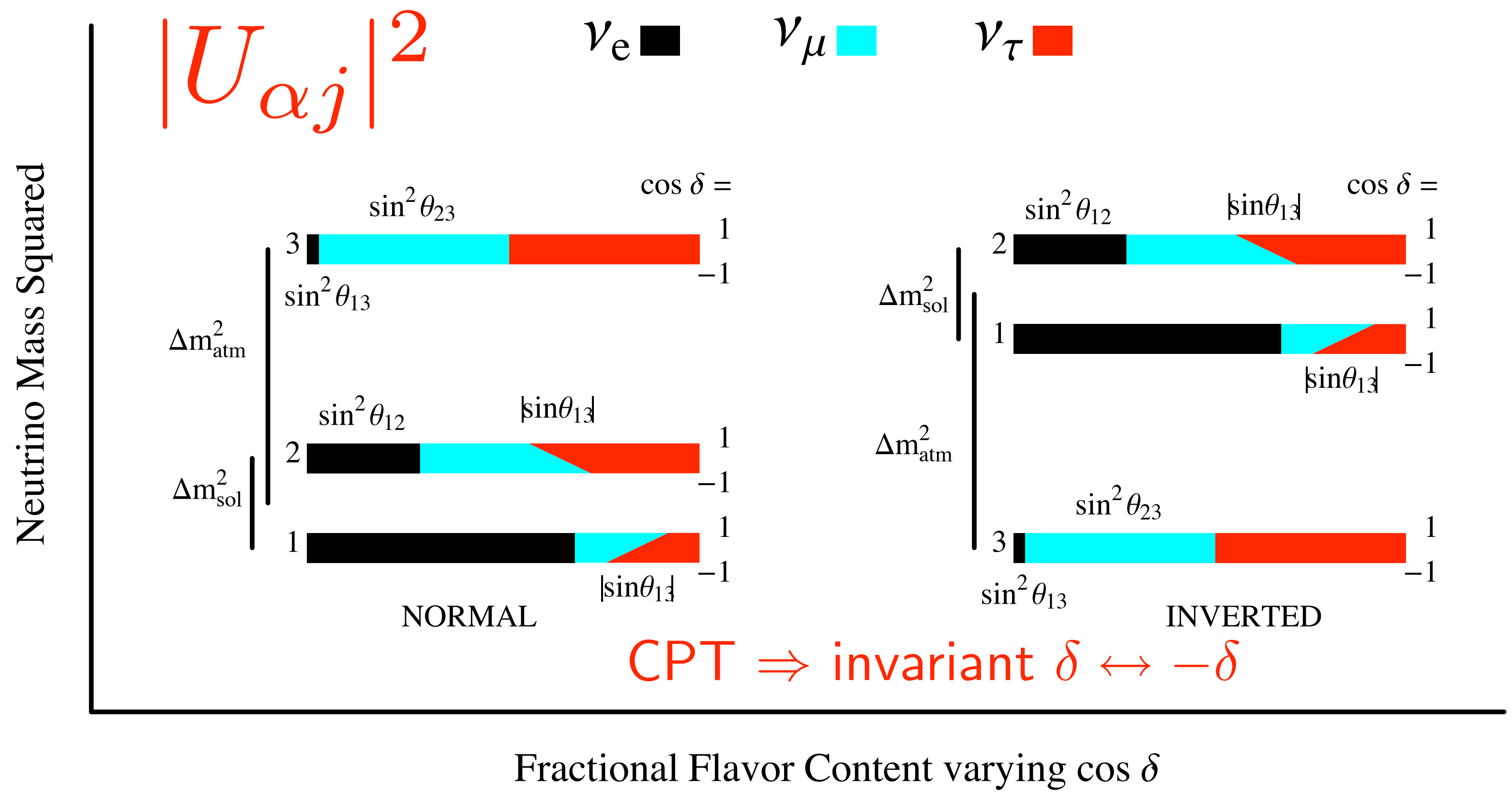
hep-ph/0701151

Minakata, Nunokawa, SP & Zukanovich Funchal

Atmospheric Neutrino Mass Hierarchy:



Mena + SP
hep-ph/0312131

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

Solar neutrino mass hierarchy (mass ordering of nu1 & nu2) was determined by SNO !

Mossbauer Neutrinos:

Mossbauer effect with Neutrinos in the $^3H -^3 He$ system:

Source: $^3H \longrightarrow (^3He + e^-_B) + \bar{\nu}_e$

Detector: $\bar{\nu}_e + (^3He + e^-_B) \longrightarrow^3 H$

$Q = 18.6$ keV and $\Gamma_{^3H} = 1.2 \times 10^{-24}$ eV

Various line broadening effects which significantly increase Γ_{eff}

Serious technical difficulties exist but it is not impossible (Raghaven, Potzel)

For $\Gamma_{eff} \sim 10^{-11}$ eV ($\Delta E/E \sim 10^{-15}$) then $\sigma \sim 10^{-33} cm^2$!!!

Do Mossbauer Neutrinos Oscillate? YES

(Akhmedov, Kopp, Lindner 0802.2513, 0803.1424)

(see also Bilenky, Feilitzsch, Potzel)

ν_e Disappearance

solar osc. (first min 270m)

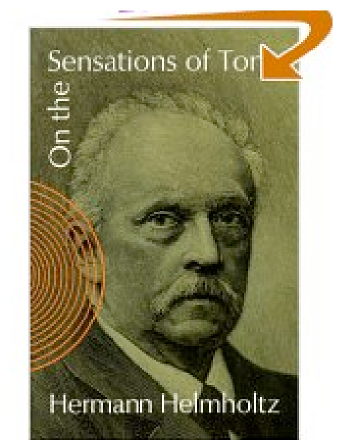
atm osc. (first min 9m)

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

$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$ (kinematic phase).

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

$$\cos^2\theta_{12} > \sin^2\theta_{12}$$



1875

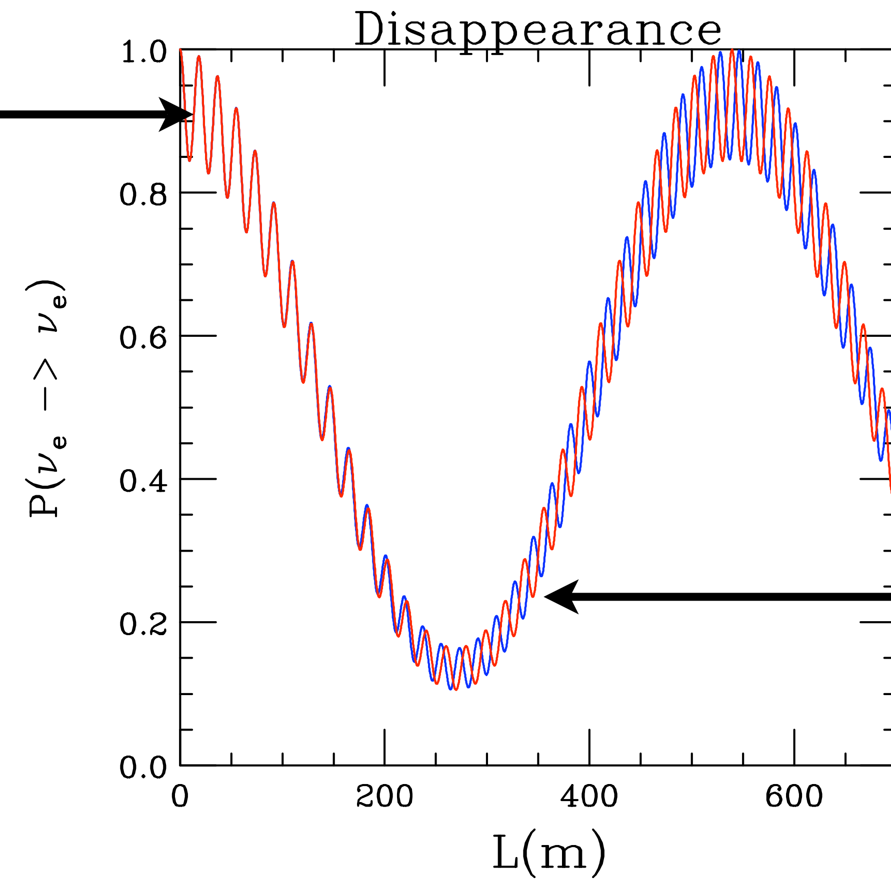
- for Normal Hierarchy (NH): $|\Delta_{31}| > |\Delta_{32}|$

  phase of atmospheric oscillation ADVANCES by $2\pi\sin^2\theta_{12}$ for every solar osc.

- for Inverted Hierarchy (IH): $|\Delta_{31}| < |\Delta_{32}|$

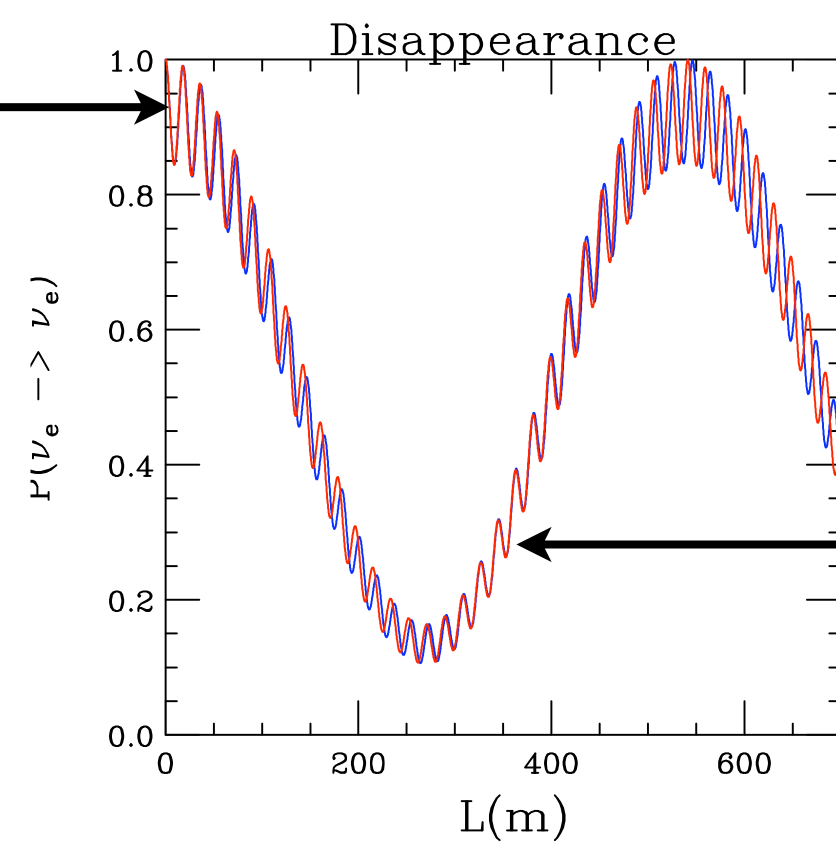
  phase of atmospheric oscillation RETARDED by $2\pi\sin^2\theta_{12}$ for every solar osc.

in phase



out of phase by pi/2

$\delta m^2_{IH} = 1.03 \times \delta m^2_{NH}$



in phase

Combining the Atm Osc:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$-\frac{1}{2}\sin^2 2\theta_{13}\left\{1 + \sqrt{(1-\sin^2 2\theta_{12}\sin^2\Delta_{21})}\cos(2\Delta_{ee} \pm \phi)\right\}$$

NH (+) and IH (-):

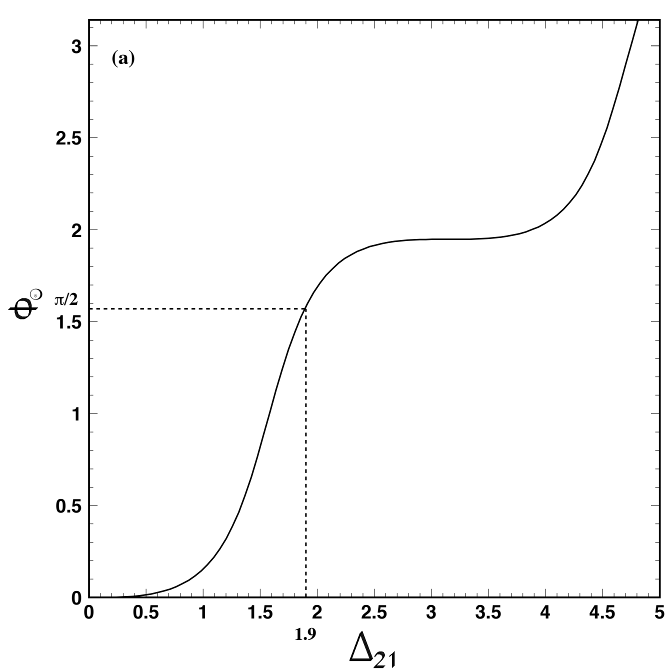
$$\Delta_{ee} \equiv \Delta m^2_{ee} L/4E$$

$$\Delta m^2_{ee} = c^2_{12}|\Delta m^2_{31}| + s^2_{12}|\Delta m^2_{32}| = |m^2_3 - (c^2_{12}m^2_1 + s^2_{12}m^2_2)|$$

ν_e weighted average of m^2_1 and m^2_2

everything else:

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

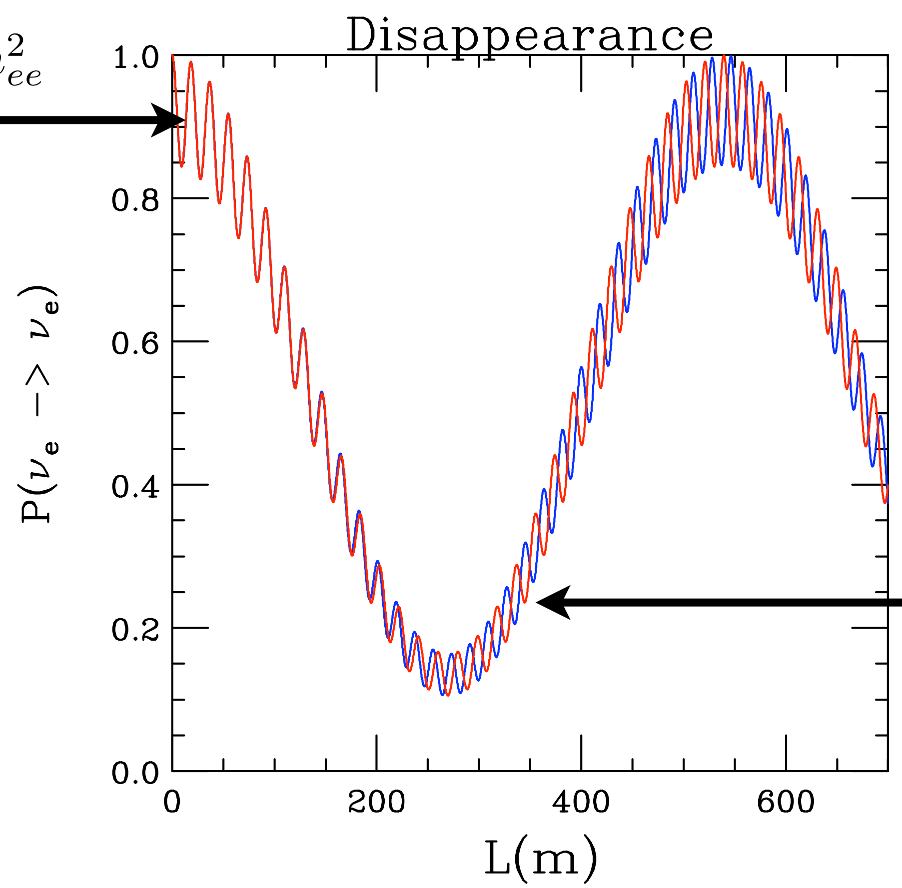


$$\phi_\odot(\Delta_{21}+\pi) = \phi_\odot(\Delta_{21}) + 2\pi\sin^2\theta_{12},$$

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

Strategy:

(I) Precision (<1%) measurement of δm^2_{ee} at L around 10 m

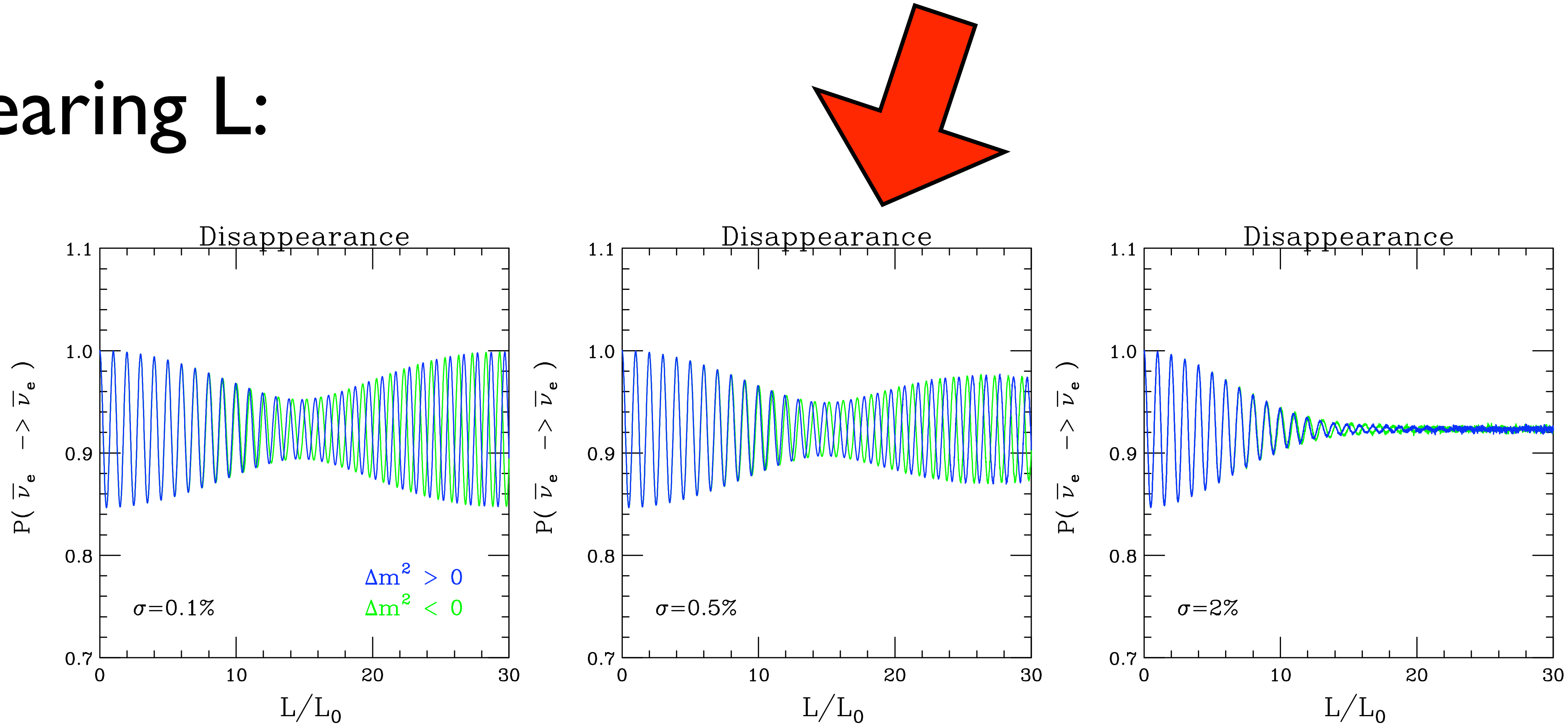


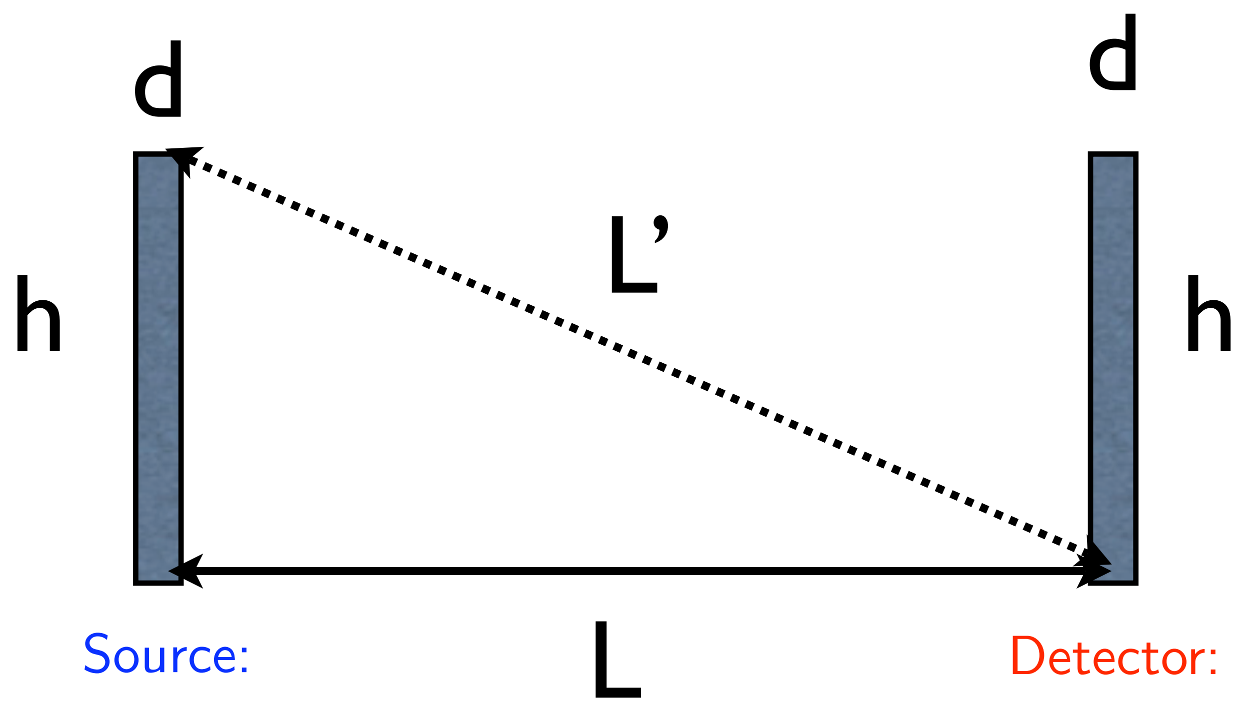
(II) determination of phase at L=350 m

But this is after 20 or so oscillation !!!
What about smearing in the L/E?

E ok, as $\Delta E/E \sim 10^{-15}$

Smearing L:





$$d < L/200$$

$L' \approx L(1 + \frac{1}{2}\frac{h^2}{L^2})$ so $h < L/10$

OK

Phase I: Measurement of δm^2_{ee}

(the atm δm^2 near the first osc. minima for a $\bar{\nu}_e$ disapp. exp.)

Event Rate:

$$R_{ench} = 3 \times 10^5 \left(\frac{S}{1MCi}\right)\left(\frac{M_T}{100g}\right)\left(\frac{L}{10m}\right)^{-2} day^{-1}$$

Minakata and Uchinami: hep/0602046

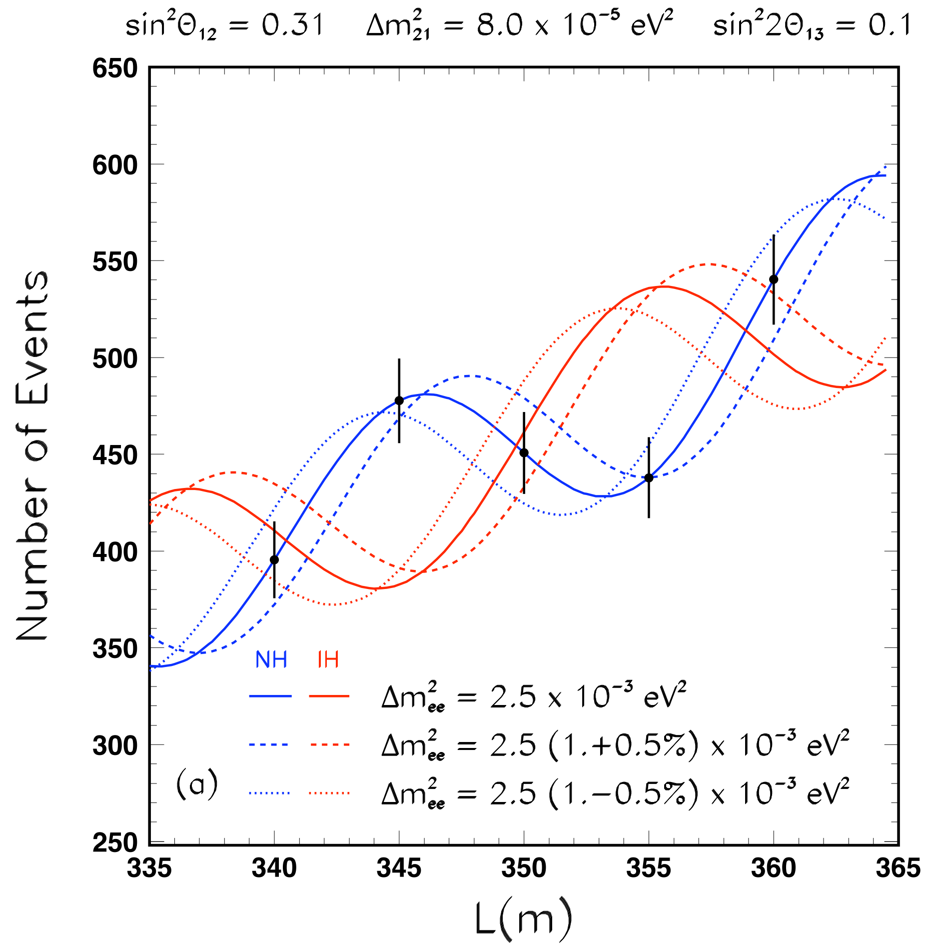
- Run IIB = 10 point measurement at (1/5, 3/5, $\cdots$ 19/5)L_{OM}
- 10^6 events each, $\sigma_{usys} = 0.2\%$, $\sigma_c = 10\%$
- Sensitivity in $\delta m^2_{ee} \approx 0.3 \left(\frac{\sin^2 2\theta_{13}}{0.1}\right)^{-1} \%$

Phase II: phase at 350 m

Event Rate:

$$R_{ench} = 2 \times 10^2 \left(\frac{S}{1MCi}\right) \left(\frac{M_T}{100g}\right) \left(\frac{L}{350m}\right)^{-2} day^{-1}$$

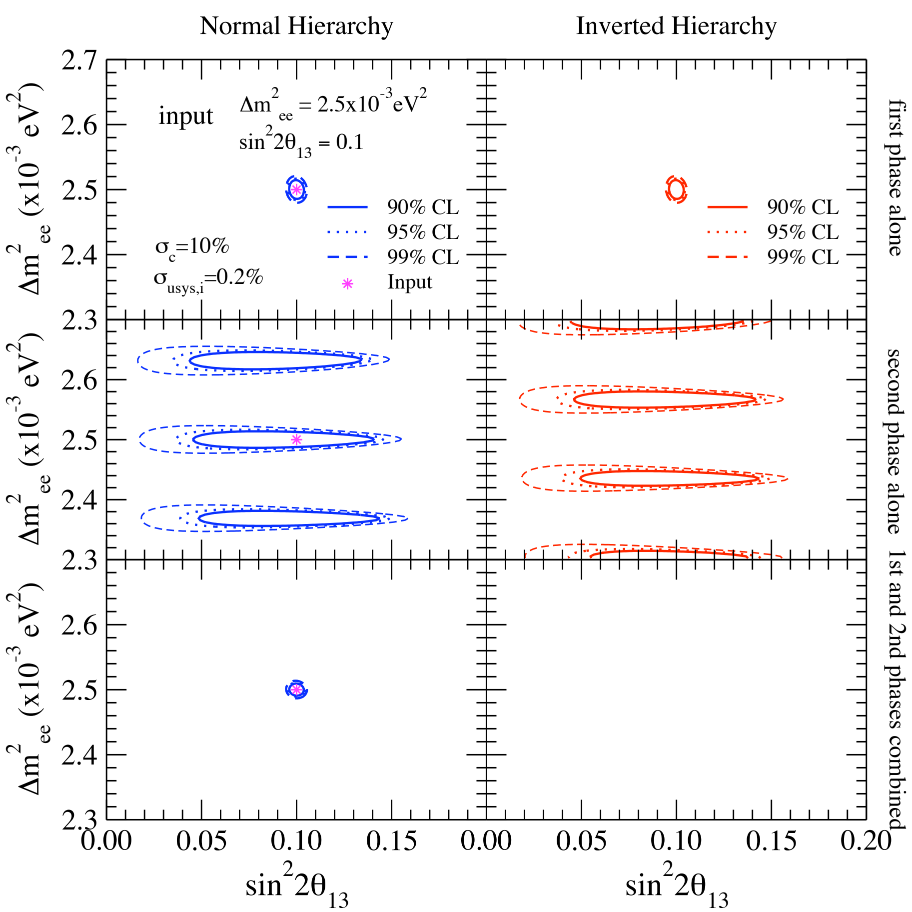
5 Baselines: $L = 350 \pm 5 \pm 10$ m



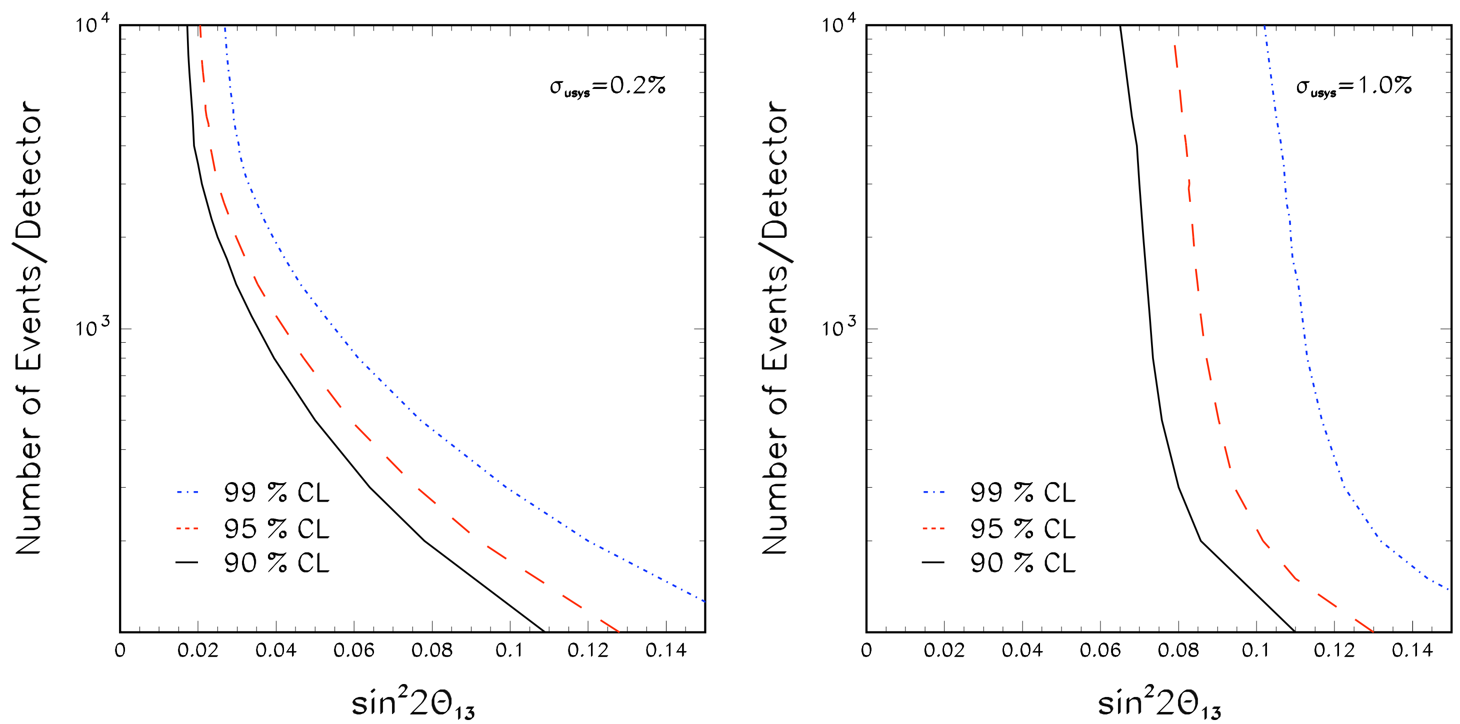
Phase I

Phase II

Phase I+II



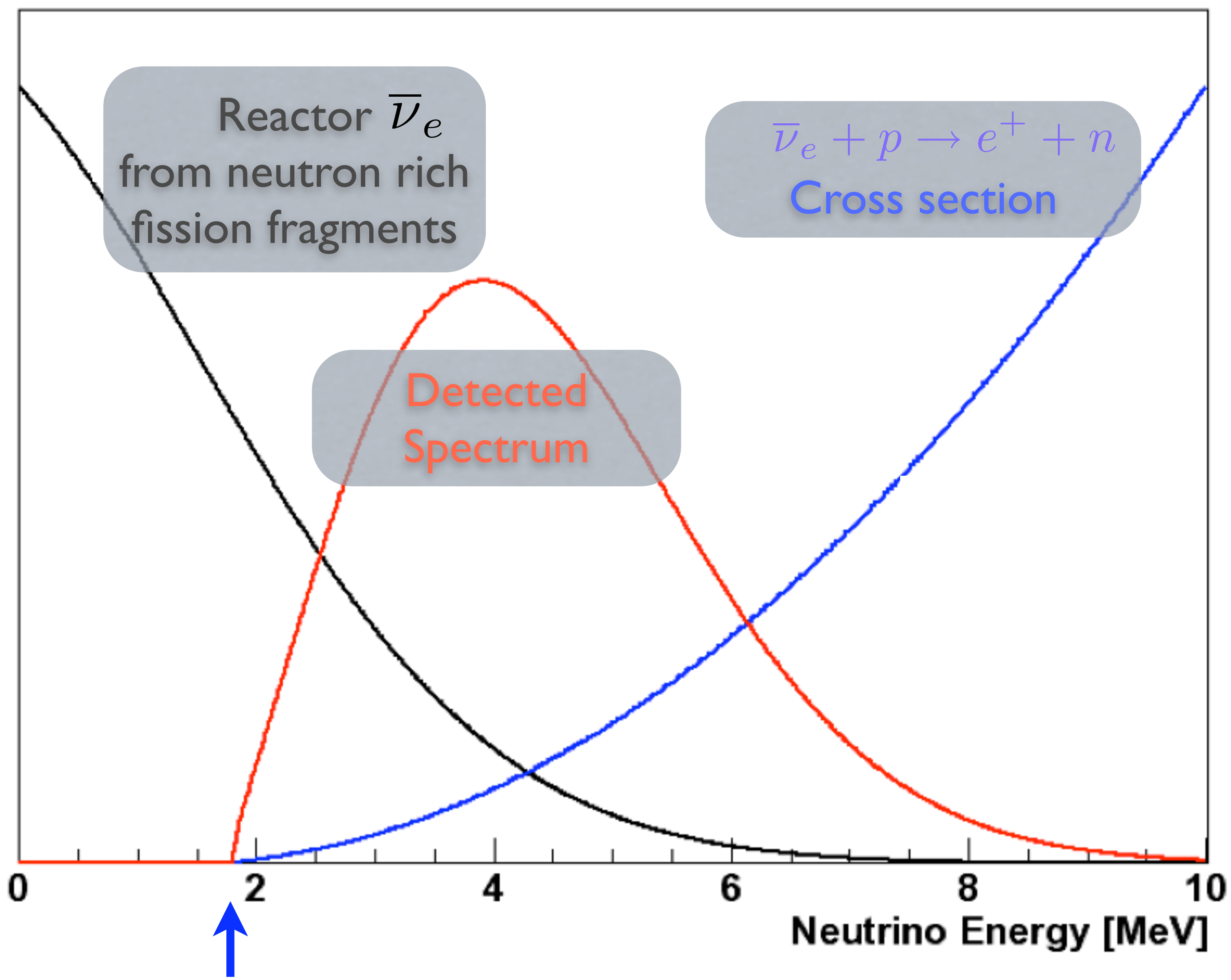
Sensitivity:



Reactor Neutrinos:

Reactor Neutrinos: Mass Hierarchy

Detected Spectrum



Hawaii Antineutrino Observatory
Hanohano

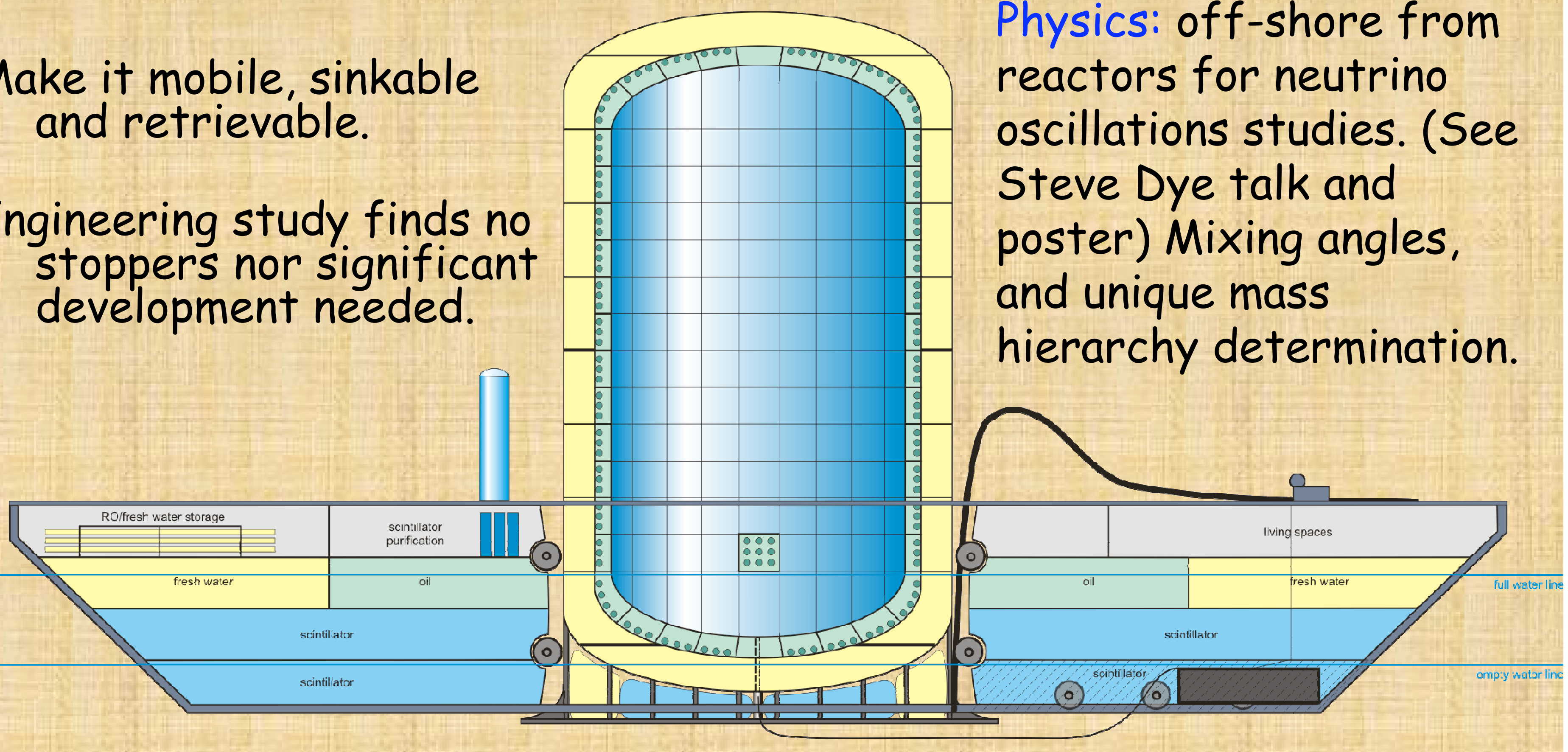
Idea: detector based on KamLAND technology adapted for deep ocean, but >10 x larger (for good counting rate)

Make it mobile, sinkable and retrievable.

Engineering study finds no stoppers nor significant development needed.

Geology: mid-Pacific and elsewhere for geo-neutrinos from mantle.

Physics: off-shore from reactors for neutrino oscillations studies. (See Steve Dye talk and poster) Mixing angles, and unique mass hierarchy determination.



Fourier Transforms: Hanohano

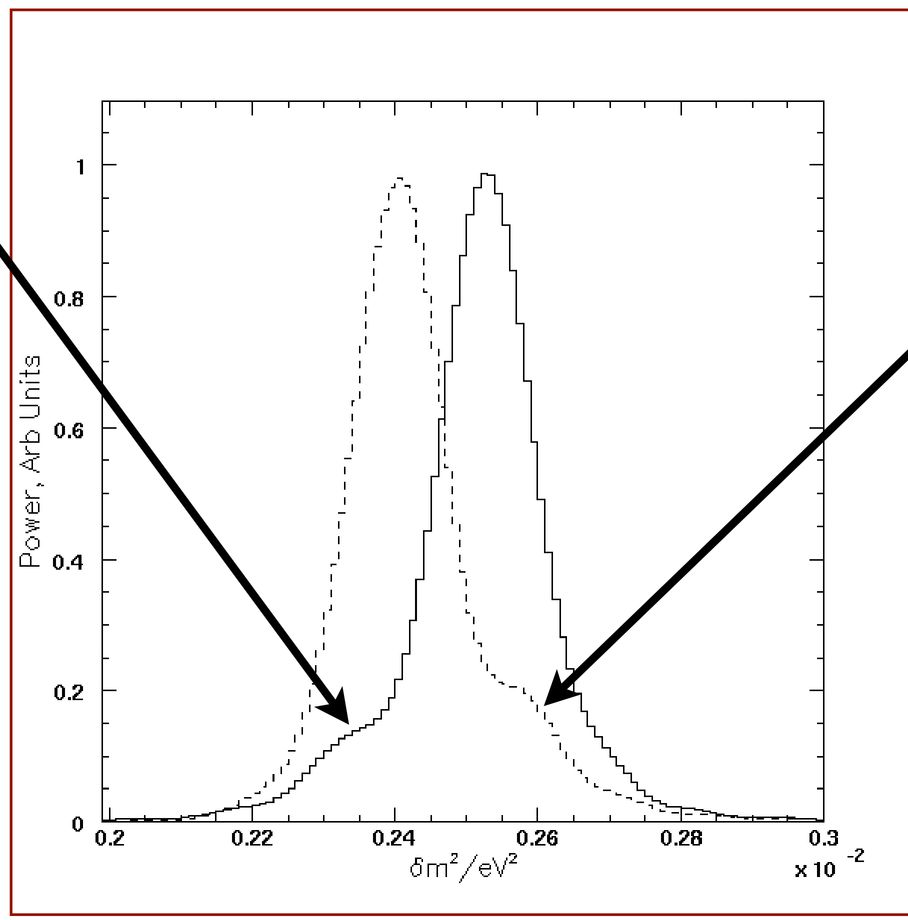
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$-\sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right]$$

dominant frequency

sub-dominant frequency
(1/5 the power)

NH:
shoulder at
smaller freq.



IH:
shoulder at
higher freq.

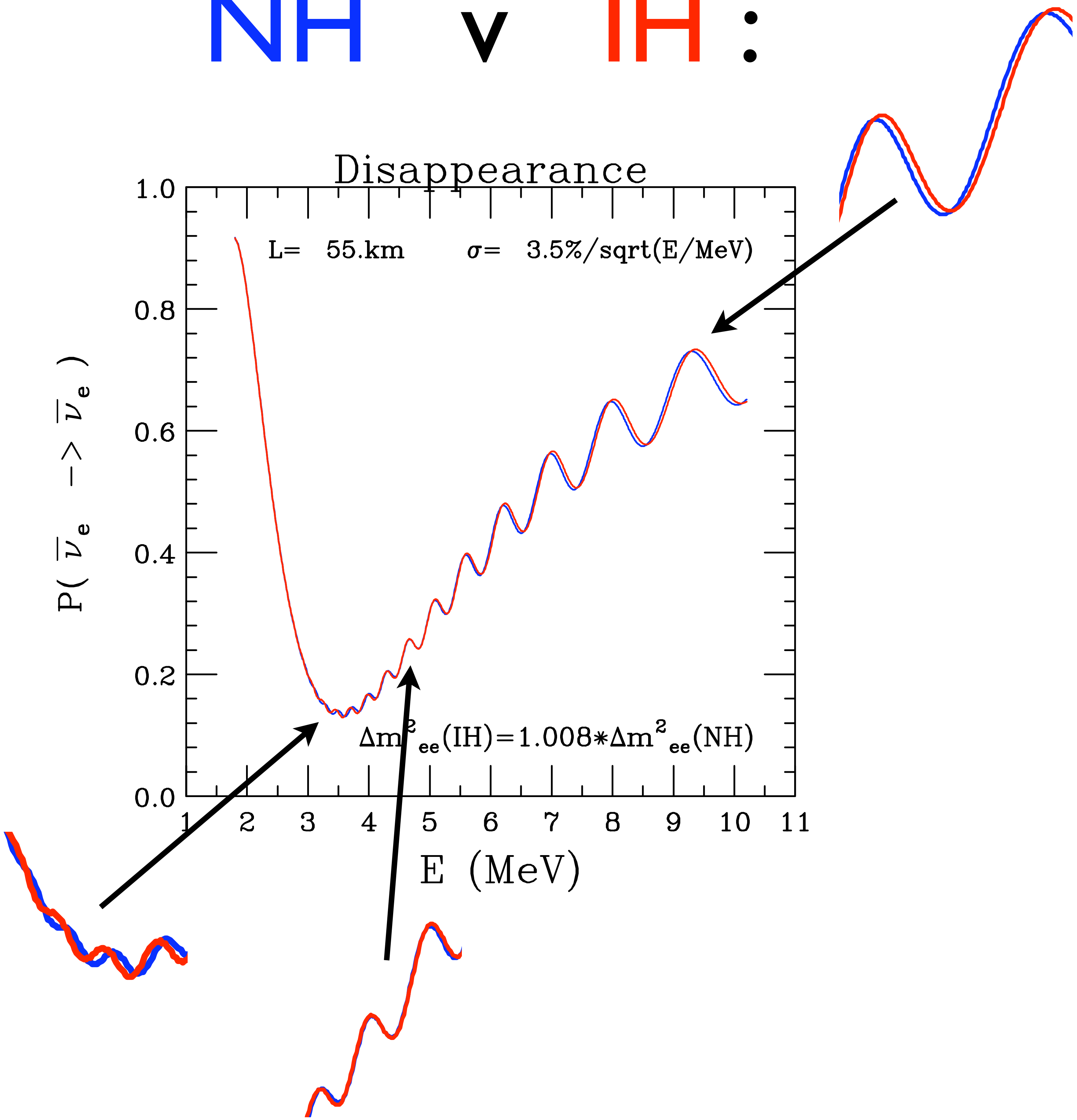
$\sin^2 2\theta_{13} > 0.05$ for 10 Kton-yr

$\sin^2 2\theta_{13} > 0.02$ for 100 Kton-yr

Learned, Dye, Pakvasa, and Svoboda, *hep-ex/0612022*

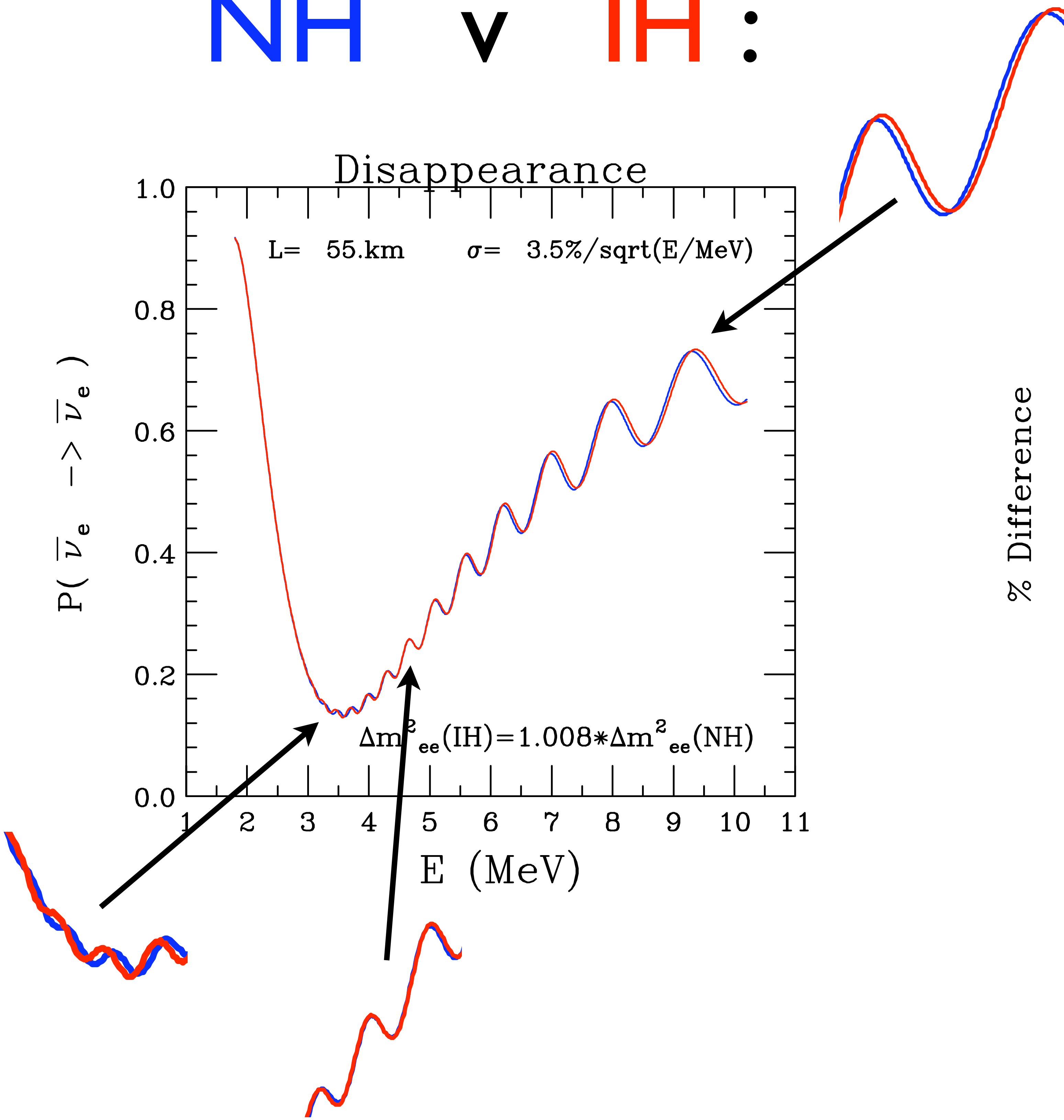
also L. Zhan, Y. Wang, J. Cao and L. Wen, arXiv:0807.3203

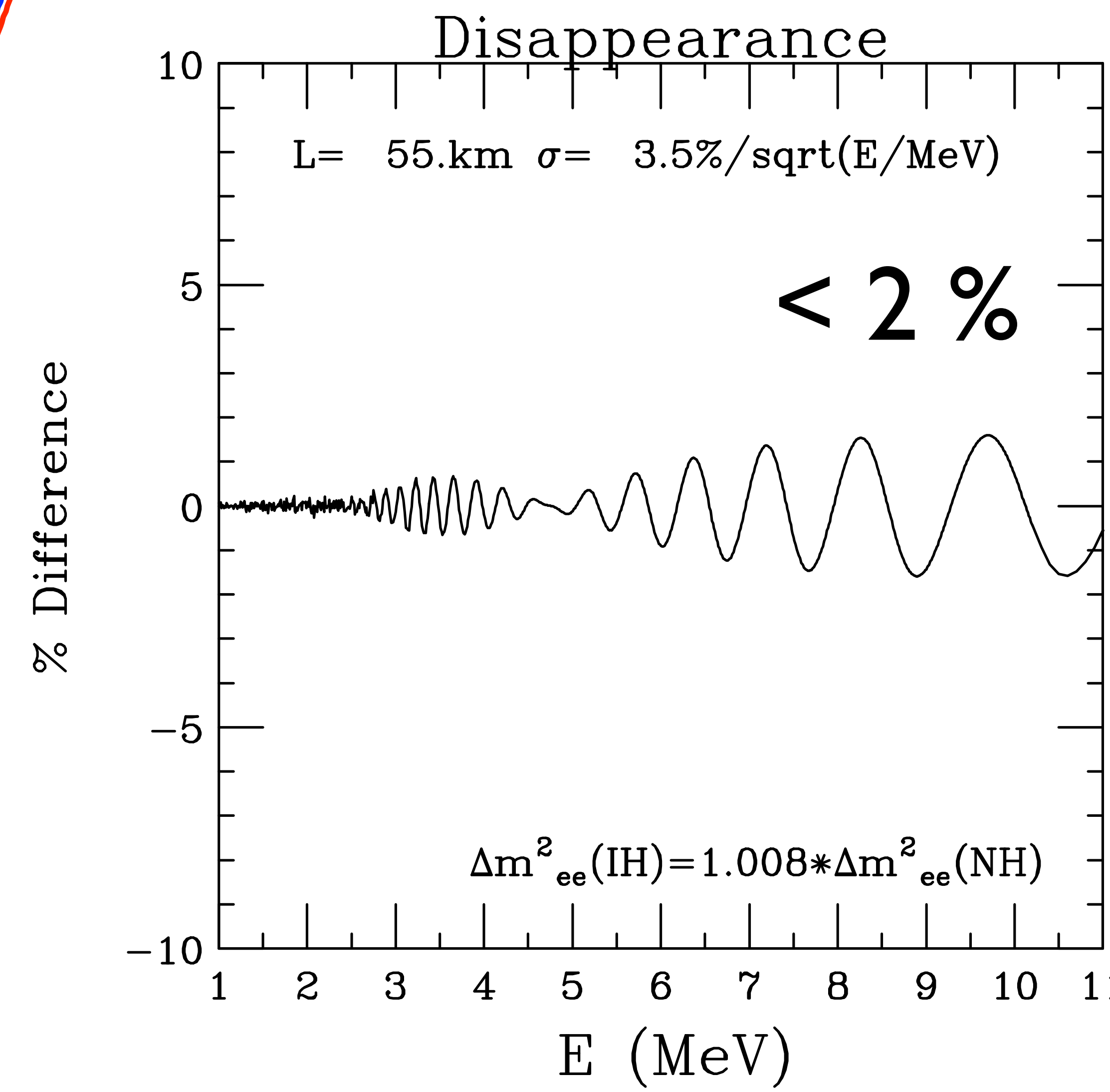
NH v IH :



Disappearance
L= 55.km
σ= 3.5%/sqrt(E/MeV)
Δm²ee(IH)=1.008*Δm²ee(NH)
P(ν̄e -> ν̄e)
E (MeV)
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
8
9
10
11

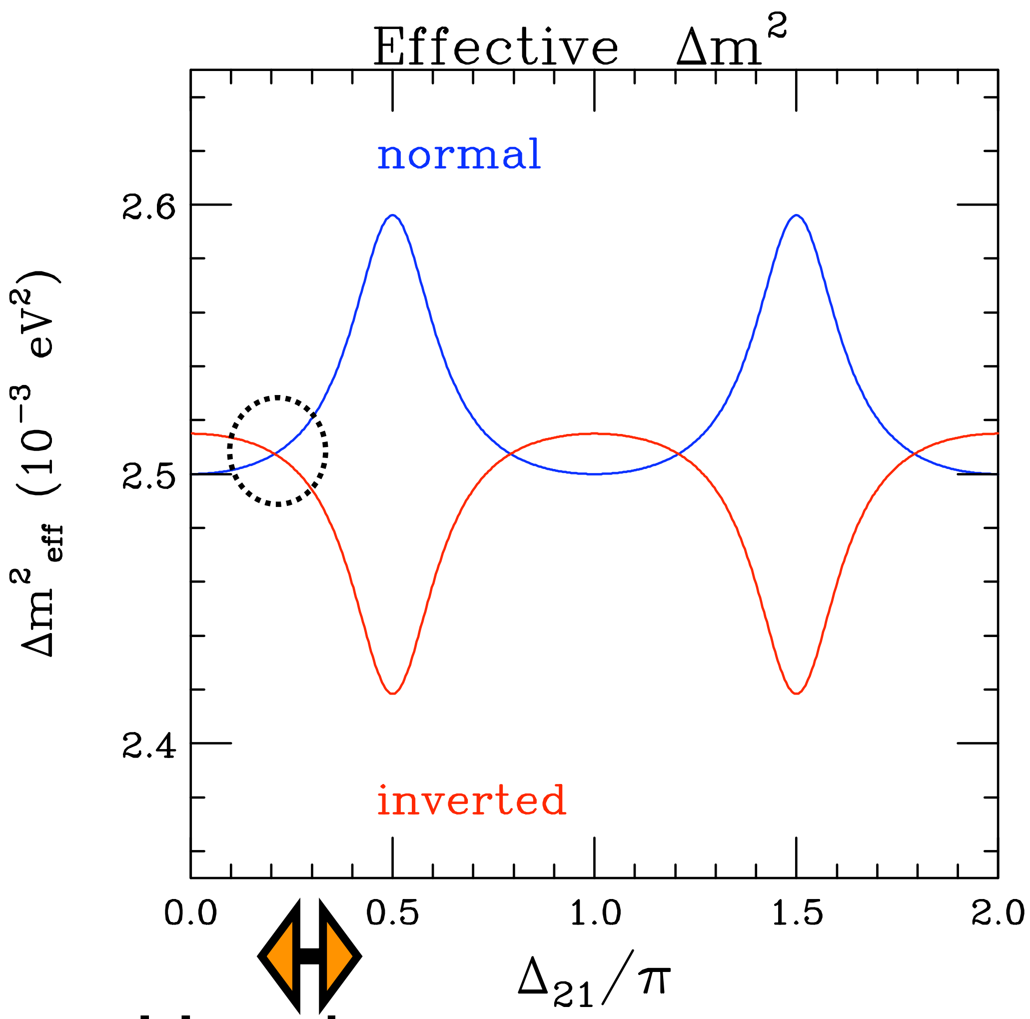
NH v IH :


Disappearance
L= 55.km σ= 3.5%/sqrt(E/MeV)
Δm²ee(IH)=1.008*Δm²ee(NH)
P(ν̄e -> ν̄e)
0.0
0.2
0.4
0.6
0.8
1.0
1 2 3 4 5 6 7 8 9 10 11
E (MeV)


Disappearance
L= 55.km σ= 3.5%/sqrt(E/MeV)
< 2 %
Δm²ee(IH)=1.008*Δm²ee(NH)
% Difference
−10
−5
0
5
10
1 2 3 4 5 6 7 8 9 10 11
E (MeV)

argument of the atm cosine term is $$2\Delta_{ee} \pm \phi_{\odot} \equiv \frac{1}{2}\int_0^{L/E} d\rho \; \delta m^2_{eff}(\rho)$$

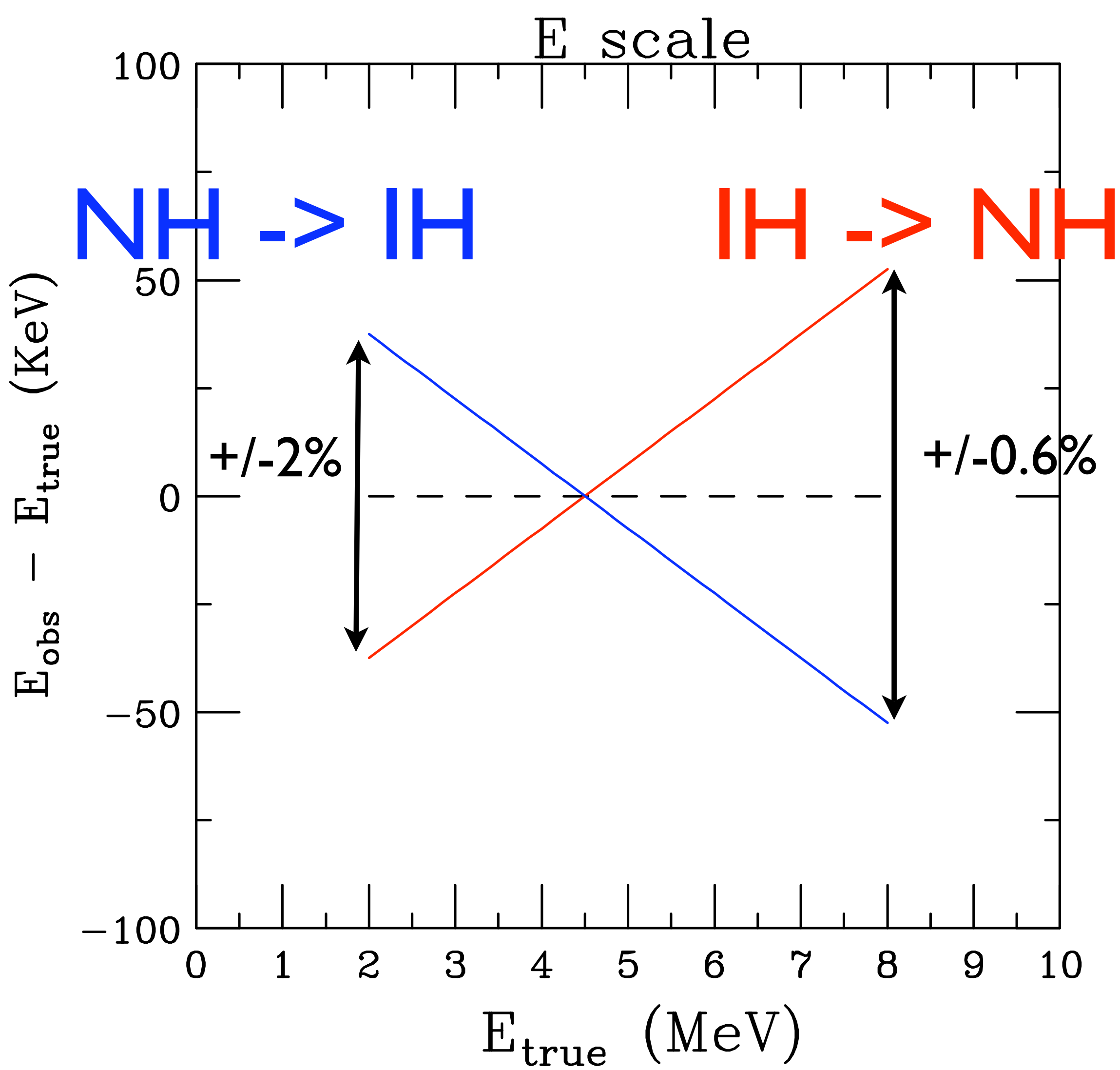
$$\delta m^2_{eff}(L/E) = \delta m^2_{ee} \pm \frac{1}{2}\,\delta m^2_{21}\cos 2\theta_{12}\,\frac{\sin^2 2\theta_{12}\sin^2\Delta_{21}}{(1-\sin^2 2\theta_{12}\sin^2\Delta_{21})}$$

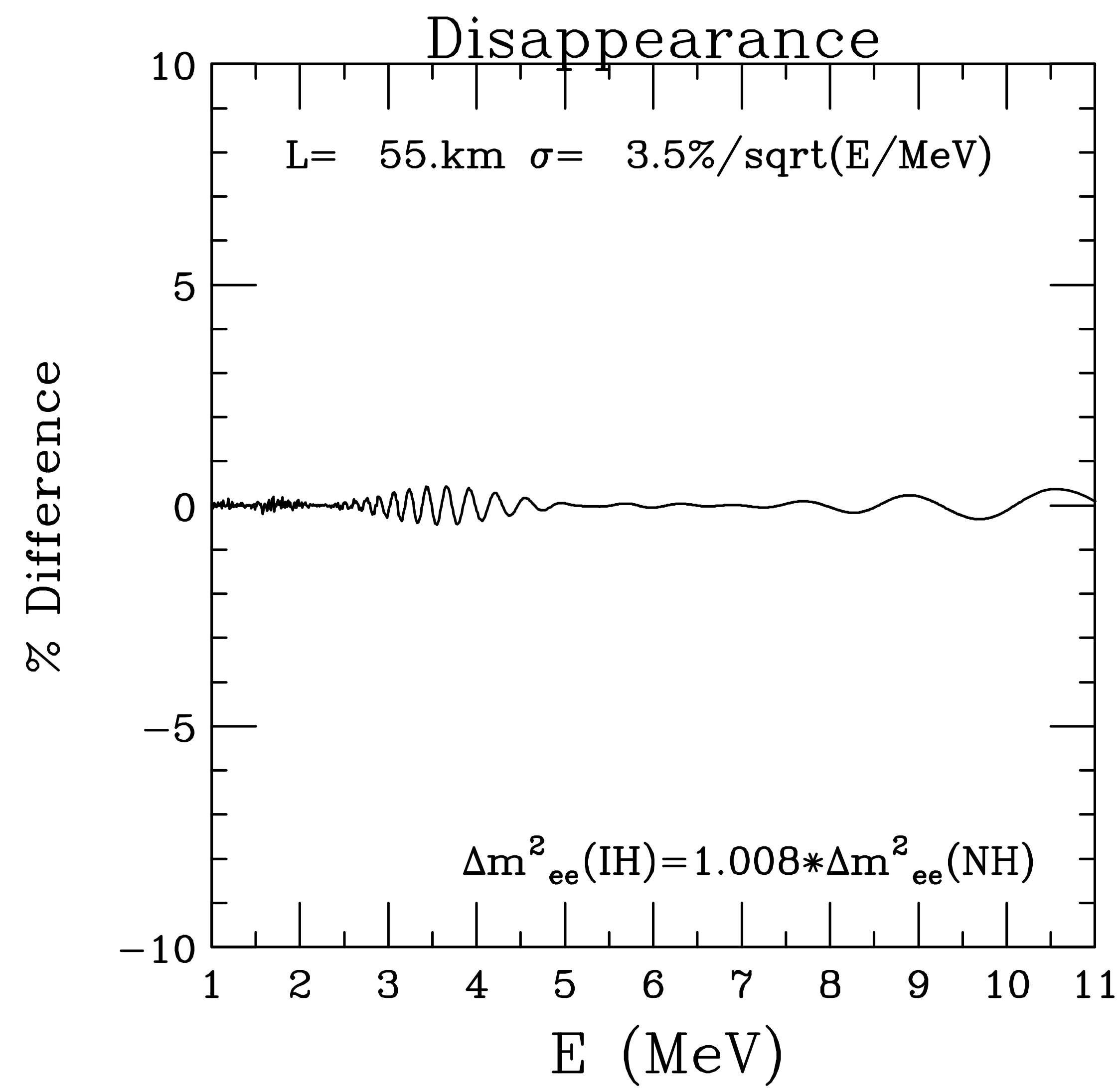


Hanohano

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

$$\frac{P_{IH}(E_{obs}) - P_{NH}(E_{true})}{P_{NH}(E_{true})}\%$$





$$E_{obs} = E_{true} + 0.015 \times (E_{true} - 4.5)$$

$$E_{obs} = E_{true} - 0.015 \times (E_{true} - 4.5)$$

Summary & Conclusions

The phase advancement or retardation of the atmospheric oscillation allows for the possibly determination of the neutrino mass hierarchy in $\bar{\nu}_e$ disappearance experiments:

- For monochromatic $\bar{\nu}_e$ beams this would require a high precision measurement of δm^2_{atm} around the first oscillation minimum as well as a determination of the phase 20 or so oscillations out ! Challenging, but the high event rate that maybe possible with Mossbauer neutrinos could make this possible with modest size detectors.

- Reactor neutrinos using multi-cycle analyses (Fourier) requires high precision relative determination of the neutrino energy from 2 to 8 MeV. What you call a 6 MeV neutrino must have twice the energy of what you call a 3 MeV to about 1%, otherwise the hierarchies can be confused. This requirement is very challenging for a large detector.