Neutrino Oscillation Workshop, 6th - 13th September 2008

Conca Specchiulla, Otranto, Italy

Earth Effects and Mass Hierarchy using Supernova Neutrinos

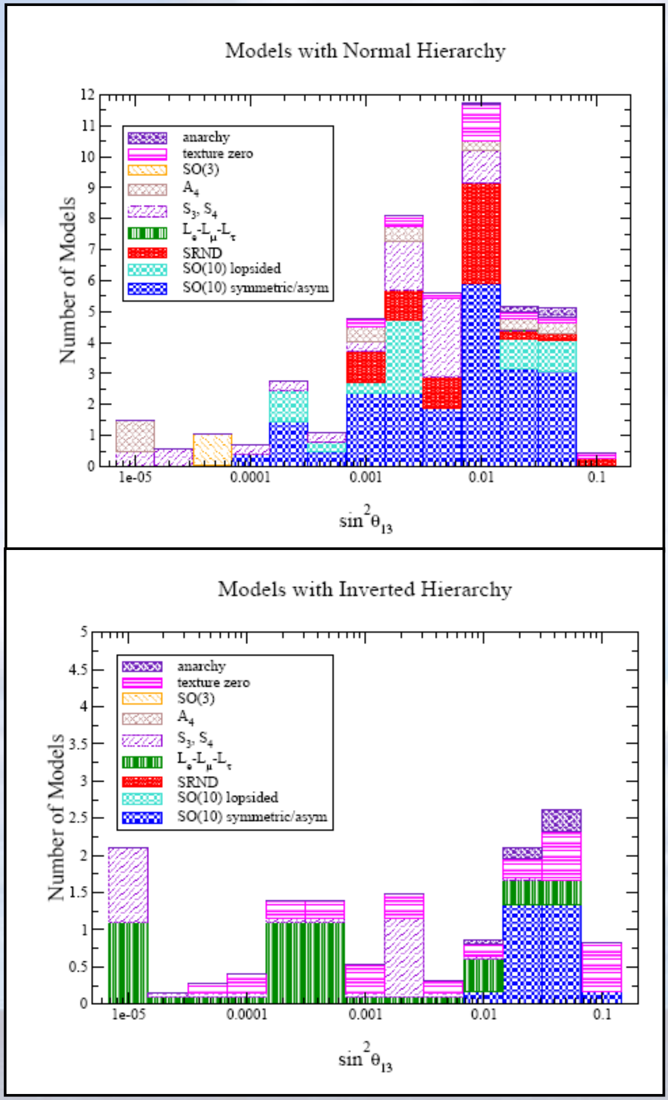
Basudeb Dasgupta

Tata Institute of Fundamental Research, Mumbai & Max Planck Institute for Physics, Munich

Hierarchy Sensitivity, θ_{13} and Models

- Mass Hierarchy remains an important unknown parameter of the mass matrix.
- Next-Generation expts for hierarchy determination.
- Sensitive if $\sin^2\theta_{13} > 10^{-3}$ to 10^{-4} .
- What happens for even smaller θ_{13} ?
- One could use other sub-dominant effects.
- 3σ determination with 23 yrs at NF + 0.5 MT scintillation detector: de Gouvea & Winter (2005).
- Hierarchy determination is a difficult task if θ_{13} is too small.
- However small θ_{13} is typically likely to be a sign of some symmetry and we could be missing out a valuable hint towards that new symmetry, if we can't determine the hierarchy…

So, what can be done about this problem?

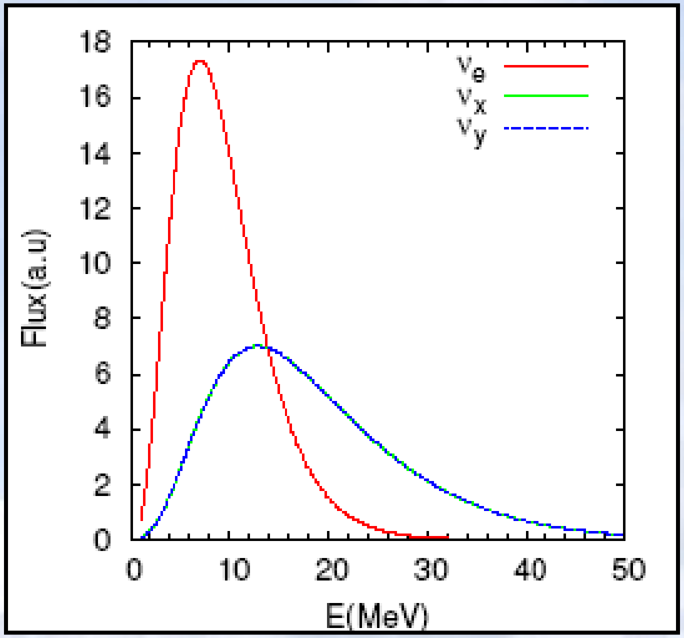


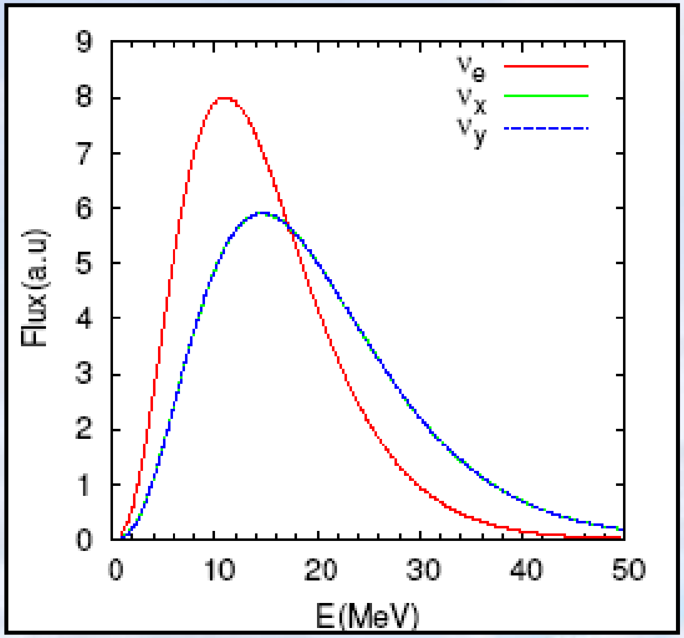
Albright and Chen (2006)

SN neutrinos to the rescue ?

- Claim: May be possible to determine the neutrino mass hierarchy even at extremely small θ_{13} using Earth matter effect on galactic SN neutrinos.
- Crucially dependent on collective effects in SN.
- Neutrino detection at a Liquid Argon detector.
- Antineutrino detection at water Cherenkov detectors.

Primary Fluxes from a SN





- $\nu_x = \cos\theta_{23}\,\nu_\mu + \sin\theta_{23}\,\nu_\tau$ (Similar for ν_y).
- Average energies: $E_e < E_{ebar} < E_{x,y}$.
- Mainly uncertainty in energy and luminosity of x and y “flavors”.
- Initial total fluxes: $\Phi_e > \Phi_{ebar} > \Phi_{x,y}$.

Collective Effects Redux

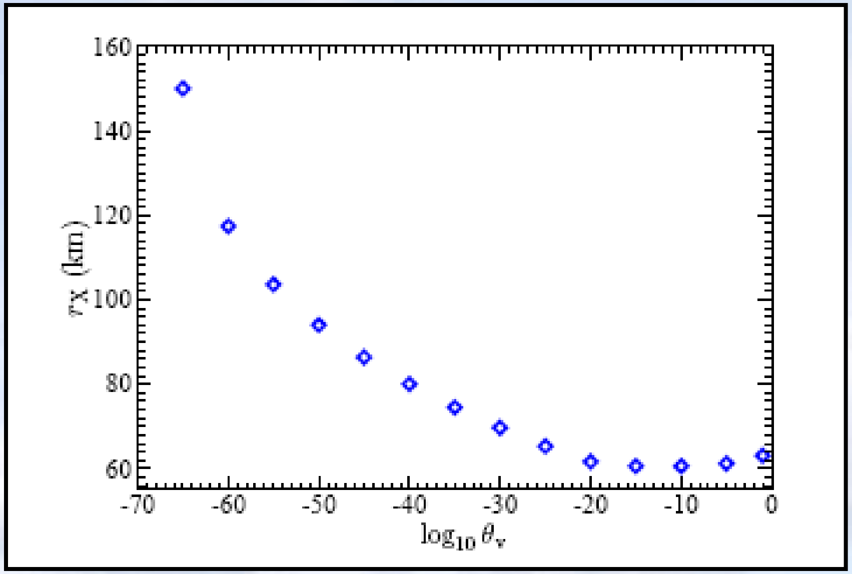
- For IH, exchange ν_e and ν_y above the E_c .
- For IH, exchange all anti-ν_e and anti- ν_y .
- For NH, no collective effects.

  Duan, Fuller, Carlson, Qian, Pastor, Raffelt, Semikoz, Hannestad, Sigl, Wong, Smirnov, Abazajian, Beacom, Bell, Esteban-Pretel, Tomas, Fogli, Lisi, Marrone, Mirizzi, Dasgupta, Dighe …

- How stable and robust is all this?
  - Small change in θ_{13} does not affect the result.
  - Nor do Multi-dimensional effects: Esteban-Pretel, Pastor, Raffelt, Sigl, Tomas (2007) and Fogli, Lisi, Marrone, Mirizzi (2007).
  - Mu-tau effects can be ignored in cooling phase: Esteban-Pretel, Pastor, Raffelt, Sigl, Tomas (2007).
  - Dense matter effects and decoherence: Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico, Sigl (2008).
  - Only if the ν_e and anti-ν_e spectra were identical, the answer is quite different…but that is unlikely: Raffelt&Sigl (2007).

Dependence on θ_{13}

- Allow enough time for conversions to take place: Duan, Fuller, Carlson, Qian (2007).



- Adiabaticity condition is expected to be satisfied quite well for θ_{13} at least as low as 10^{-10} but the strict lower bound needs to be calculated numerically from the neutrino density profile.

Collective Effects Redux

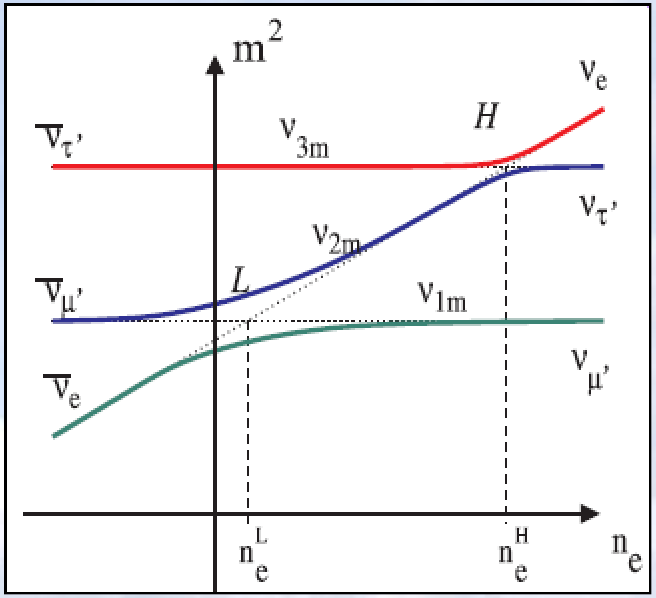
- For IH, exchange ν_e and ν_y above the E_c .
- For IH, exchange all anti-ν_e and anti- ν_y .
- For NH, no collective effects.

  Duan, Fuller, Carlson, Qian, Pastor, Raffelt, Semikoz, Hannestad, Sigl, Wong, Smirnov, Abazajian, Beacom, Bell, Esteban-Pretel, Tomas, Fogli, Lisi, Marrone, Mirizzi, Dasgupta, Dighe …

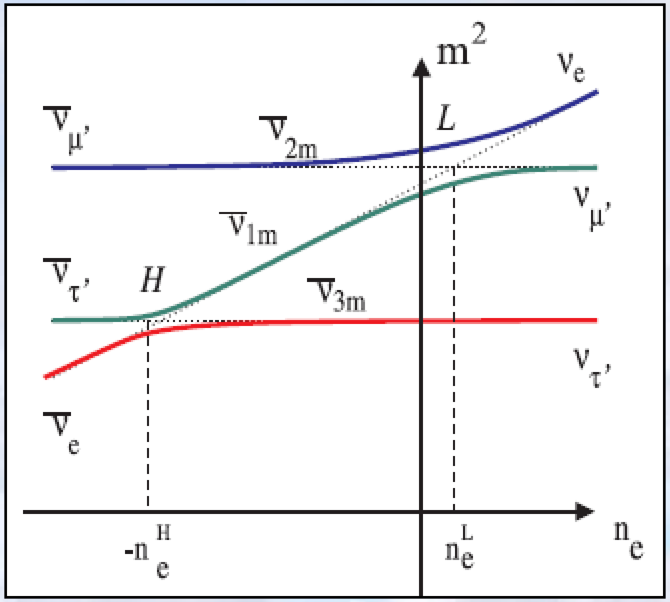
- How stable and robust is all this?
  - Small change in θ_{13} does not affect the result.
  - Nor do multi-dimensional effects: Esteban-Pretel, Pastor, Raffelt, Sigl, Tomas (2007) and Fogli, Lisi, Marrone, Mirizzi (2007).
  - Mu-tau effects can be ignored in cooling phase: Esteban-Pretel, Pastor, Raffelt, Sigl, Tomas (2007).
  - Dense matter effects and decoherence: Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico, Sigl (2008).
  - Only if the ν_e and anti-ν_e spectra were identical, the answer is quite different…but that is unlikely: Raffelt&Sigl (2007).

Standard MSW analysis for SN

Normal Hierarchy



Inverted Hierarchy



Dighe&Smirnov (2000)

- At small θ_{13} the H-resonance is completely non-adiabatic.
- The L-resonance is always adiabatic.

Mass Basis Fluxes reaching Earth from SN

Neutrinos

Flavor content in mass basis at	Normal Hierarchy	Inverted Hierarchy
Primary Flux	(F_x , F_x , F_e)	(F_x , F_e , F_x)
After Collective	(F_x , F_x , F_e)	$(F_x , F_e , F_x) \mid (F_x , F_x , F_e)$
After MSW (at Earth)	(F_x , F_e , F_x)	$(F_x , F_e , F_x) \mid (F_x , F_x , F_e)$

Antineutrinos

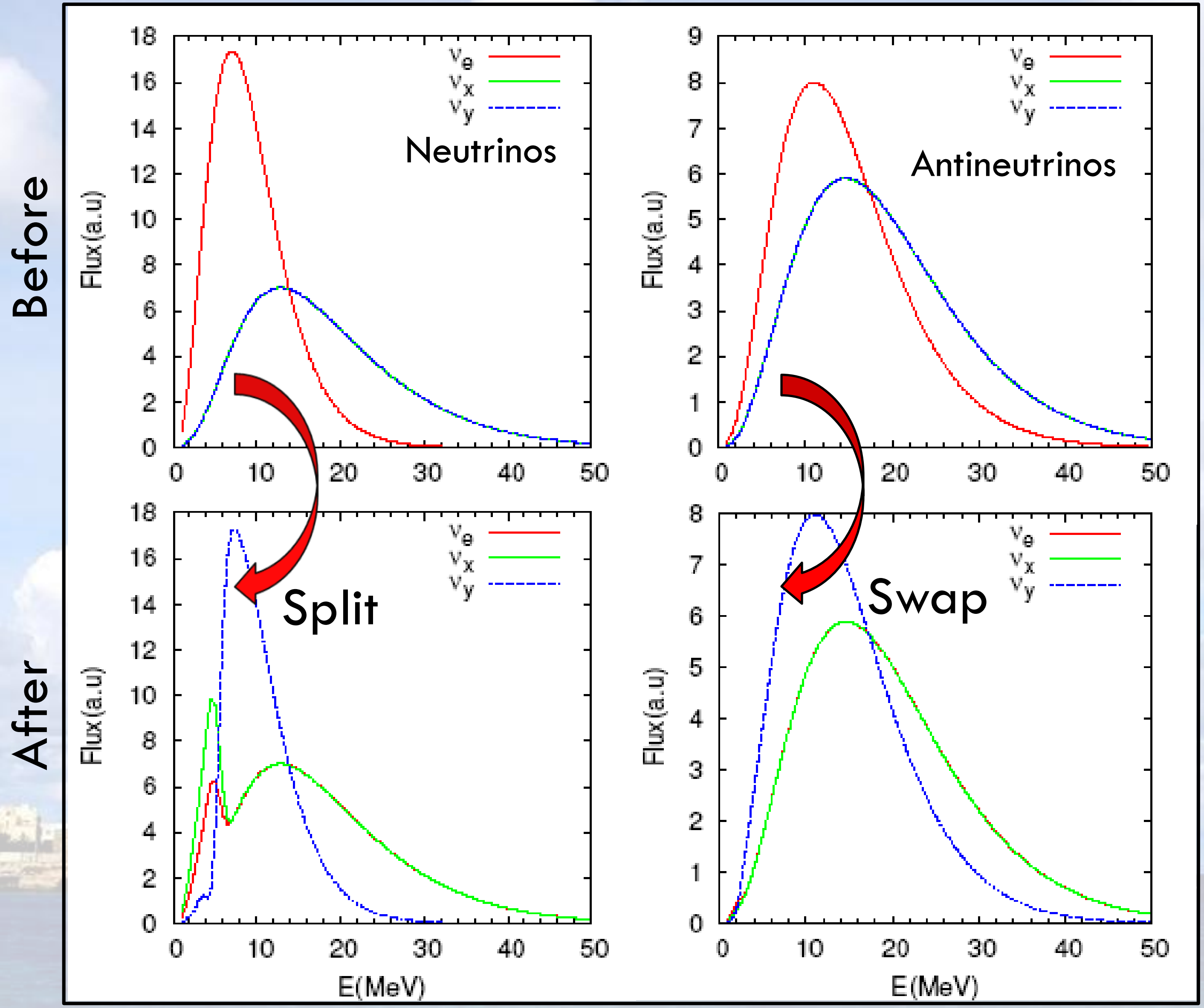
Flavor content in mass basis at	Normal Hierarchy	Inverted Hierarchy
Primary Flux	(F_e , F_x , F_x)	(F_x , F_x , F_e)
After Collective	(F_e , F_x , F_x)	(F_e , F_x , F_x)
After MSW (at Earth)	(F_e , F_x , F_x)	(F_x , F_x , F_e)

Dasgupta&Dighe (2007)

N.B: Electron flavor: $\nu_e = \cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2$

SN spectra at Earth

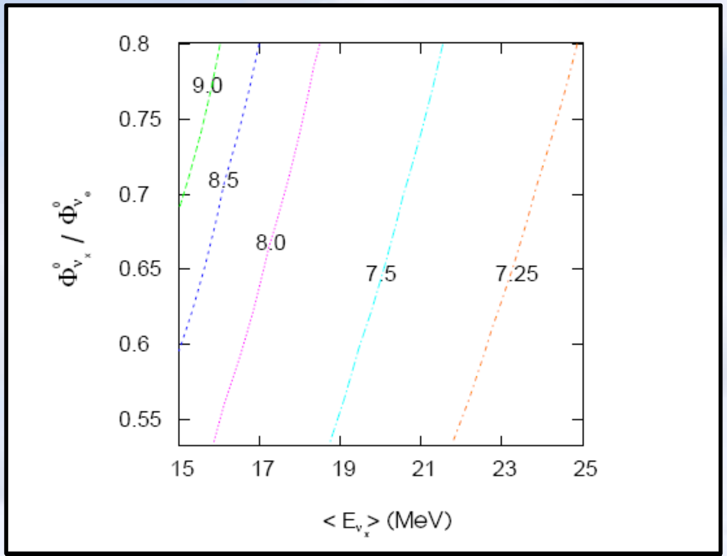
Dasgupta and Dighe(2007)

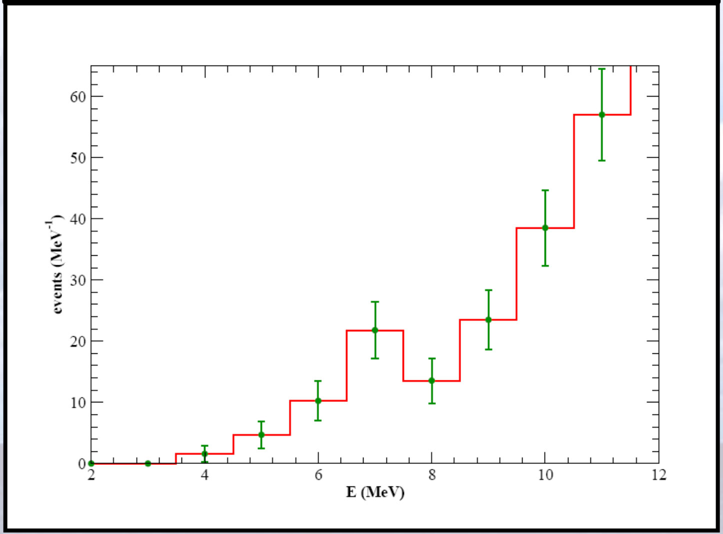


Antineutrino spectral split discussed by Fogli, Lisi, Marrone, Mirizzi, Tamborra in hep-ph/0808.0807

Spectral Split Signature in Neutrinos

- Spectral Split could be a signature for hierarchy determination at small θ_{13} : Duan, Fuller, Carlson Qian (2008).
- Spectral Split in neutrinos at $E_c \leq 10$ MeV.
- Challenging to observe even at a 100 Kt Liquid Argon detector.
- Main problem is that it appears at very low energy: Choubey, Dasgupta, Dighe, Mirizzi (to appear).





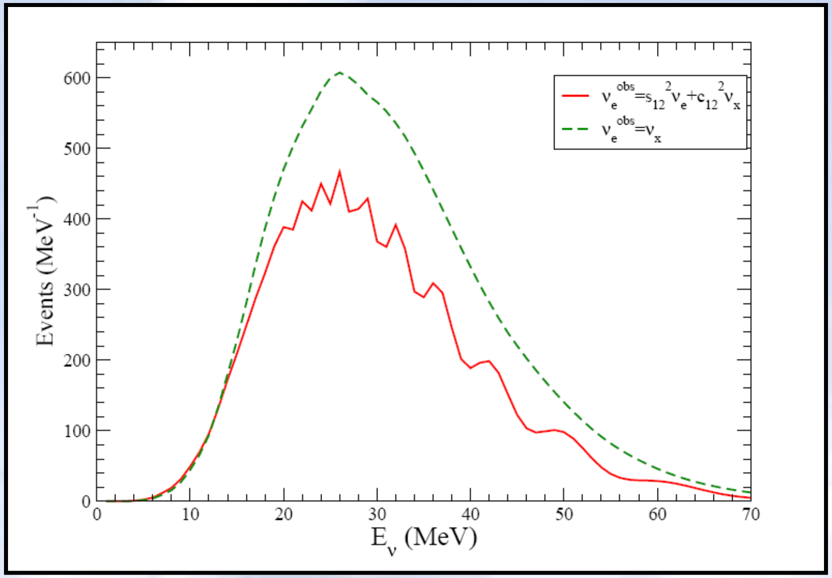
Earth Matter Effects

- Flux of electron neutrinos/antineutrinos at shadowed and unshadowed detector are different combinations of ν_1 and ν_2.
- In Earth, $\sin^2\theta_{12}$ replaced by $P_E = P(\nu_2 \text{ to } \nu_e)$ in the expression $F_e = \cos^2\theta_{12} F_1 + \sin^2\theta_{12} F_2$, and P_E is oscillatory in l/E.

Flavor content in mass basis at	Normal Hierarchy	Inverted Hierarchy
Primary Flux	(F_x, F_x, F_e)	(F_x, F_e, F_x)
After Collective	(F_x, F_x, F_e)	(F_x, F_e, F_x) | (F_x, F_x, F_e)
After MSW (at Earth)	(F_x, F_e, F_x)	(F_x, F_e, F_x) | (F_x, F_x, F_e)

- But for IH, it does not make any difference - both are “x” !
- $R = (F_e^{shadowed} - F_e^{unshadowed}) / F_e^{unshadowed}$.
- R is zero for IH, but not NH.
- This distinguishes NH from IH.

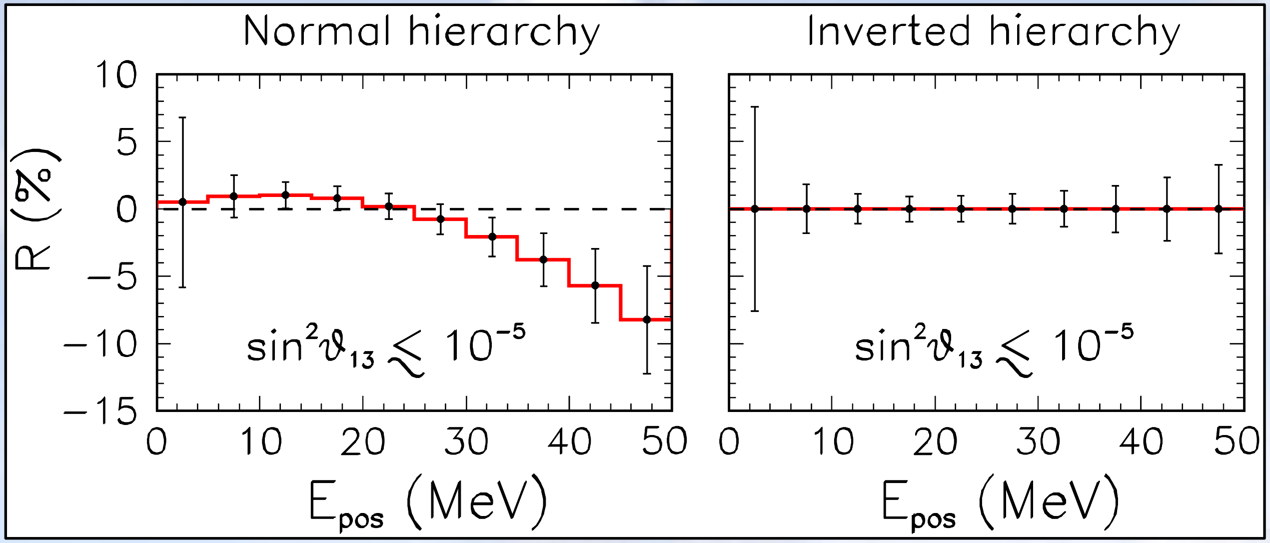
Earth Effect in Neutrino Signal



$\sin^2\theta_{13}=10^{-9}$
L=10kpc
Garching flux

- 100 kt Liq. Ar detector shadowed by 8000 km of Earth matter.
- Wiggles observable in NH; no wiggles in IH.
- Energy resolution is the key.
- Works for very small values of θ_{13} in contrast to previous literature and other experiments: Choubey, Dasgupta, Dighe, Mirizzi (to appear).
- Observation will establish NH and $\sin^2\theta_{13} < 10^{-3}$.

Earth Effect in Antineutrino Signal

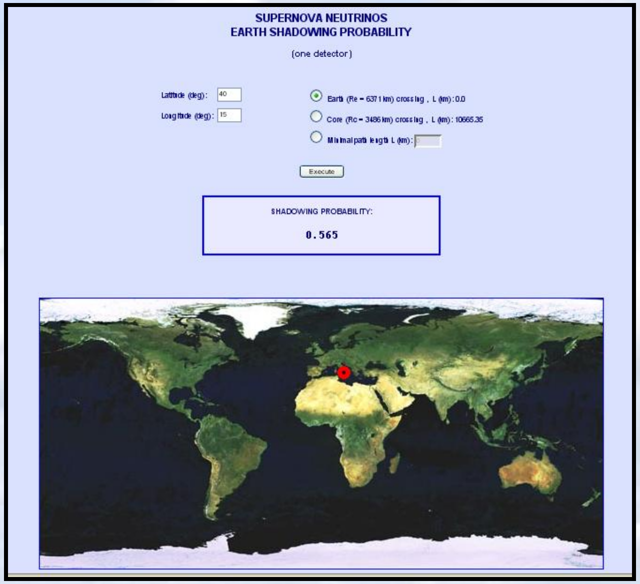


$\sin^2\theta_{13}=10^{-9}$
L=10kpc
Garching flux

- Two 0.4 MT water Cherenkov detectors – one shadowed, and other not shadowed by Earth.
- R= $(F_e^{\text{shadowed}} - F_e^{\text{unshadowed}}) / F_e^{\text{unshadowed}}$
- Significant "up-down asymmetry" for NH, and none for IH.
- Systematics and Statistics is the key.
- Signal is presence/absence (with a prior $\sin^2\theta_{13} < 10^{-5}$) of Earth effects: Dasgupta, Dighe, Mirizzi (2008).

Baseline dependence

- What happens at other “baselines” ?
- More than 8000 km: basically the same effect.
- Less: the effect is smaller.



- See the online tool by Mirizzi, Raffelt and Serpico at http://www.mppmu.mpg.de/supernova/shadowing

No Degeneracy between Scenarios

Neutrinos

	Hierarchy	θ_{13}	Earth Effects	Shock Effects	Burst Signal
A	NH	Large	No	Yes	No
B	IH	Large	No	No	Yes
C	NH	Small	Yes	No	Yes
D	IH	Small	No	No	Yes

Antineutrinos

	Hierarchy	θ_{13}	Earth Effects	Shock Effects
A	NH	Large	Yes	Yes
B	IH	Large	Yes	Yes
C	NH	Small	Yes	No
D	IH	Small	No	No

Concluding Remarks

- Earth Matter Effects are a robust and model-independent signature.
- Good sensitivity to hierarchy and ball-park estimate of θ_{13} .
- Spectral Split is challenging to observe.
- Turbulence and stochastic density fluctuations don't affect these results much (since θ_{13} is too small for ordinary matter effects to come into play).
- More interesting results could come out…collective efforts in progress!