

# Determining the Neutrino Mass Hierarchy even if $\theta_{13}$ is too small

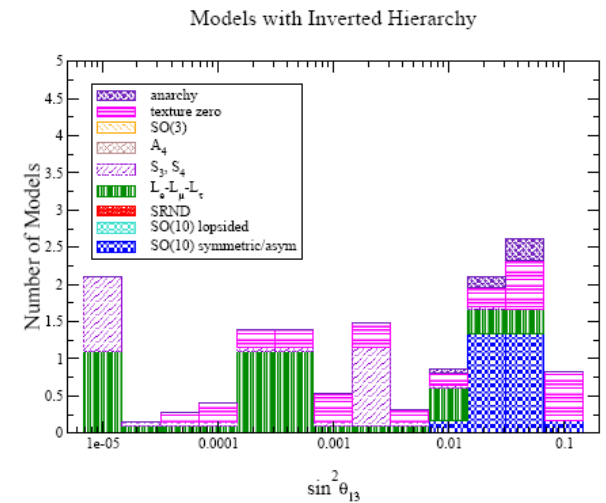
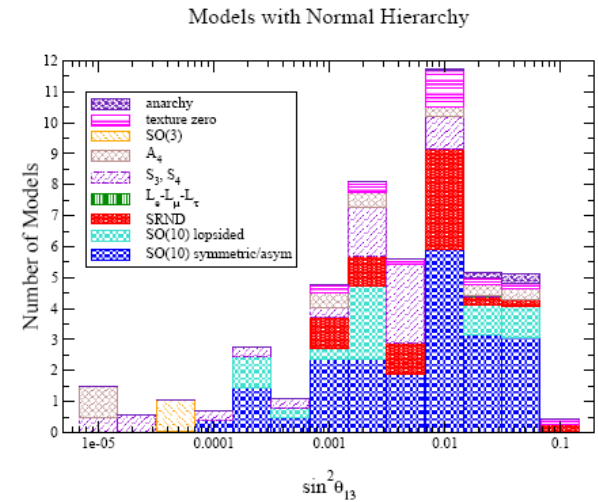
:: *An interplay of collective effects and Earth matter effects on SN neutrinos* ::

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# Hierarchy Sensitivity, $\theta_{13}$ and Models

- Mass Hierarchy remains an important unknown parameter.
- Sensitivity of Next-Generation experiments like Neutrino Factory for hierarchy determination:  $\sin^2 \theta_{13} > 10^{-3}$  to  $10^{-4}$
- What happens for even smaller  $\theta_{13}$  ?
- One could use other sub-dominant effects...
- $3\sigma$  determination with 23 years of data at a NF + 0.5 MT scintillation detector: [de Gouvea & Winter \(2005\)](#).
- With a very precise ( $\sim 2\%$ ) measurement of  $\Delta_{31}$  and 1MTyr data of atmospheric neutrinos HK can give a  $2\sigma$  signal: [Gandhi, Ghoshal, Goswami and Sankar \(2008\)](#).
- Hierarchy determination is a difficult task if  $\theta_{13}$  is too small.
- However small  $\theta_{13}$  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 ?

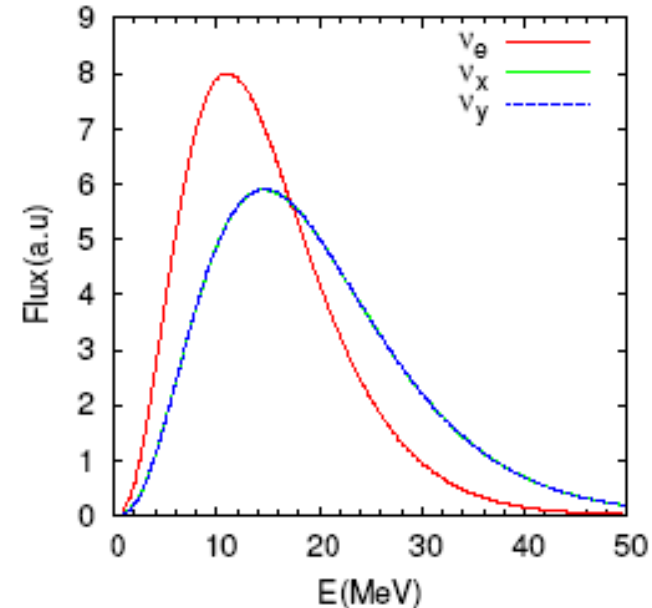
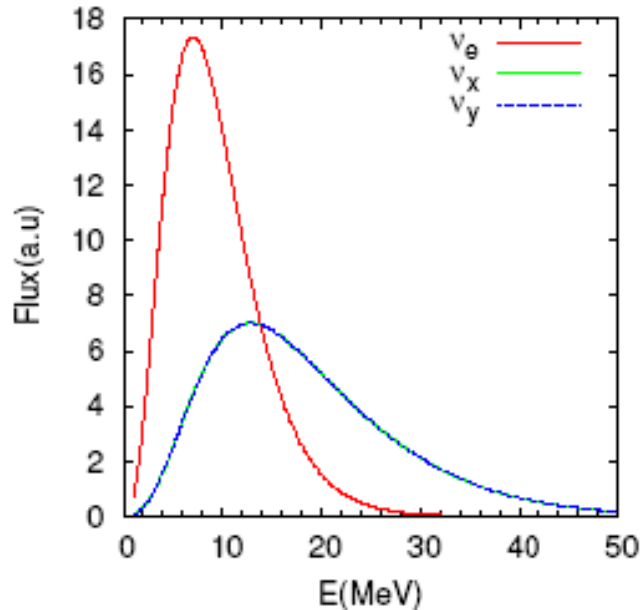


[Albright and Chen \(2006\)](#)

# SN neutrinos to the rescue ?

- **Claim: May be possible to determine the neutrino mass hierarchy at extremely small  $\theta_{13}$  using galactic SN neutrinos.**
- Crucially dependent on collective effects in SN.
- Neutrino detection a Liquid Argon Detector: Spectral Split.
- Antineutrino detection at two Water Cherenkov detectors: Earth Matter Effects.

# Primary Fluxes from a SN



- $\nu_x$  and  $\nu_y$  are linear combinations :  $\cos \theta_{23} \nu_\mu + \sin \theta_{23} \nu_\tau$  etc.
- $E_e < E_{\text{ebar}} < E_{x,y}$
- Mainly uncertainty in energy and luminosity of x and y “flavors”.
- $F_e, F_{\text{ebar}}, F_{x,y}$  are the initial fluxes.

# Collective Effects Redux

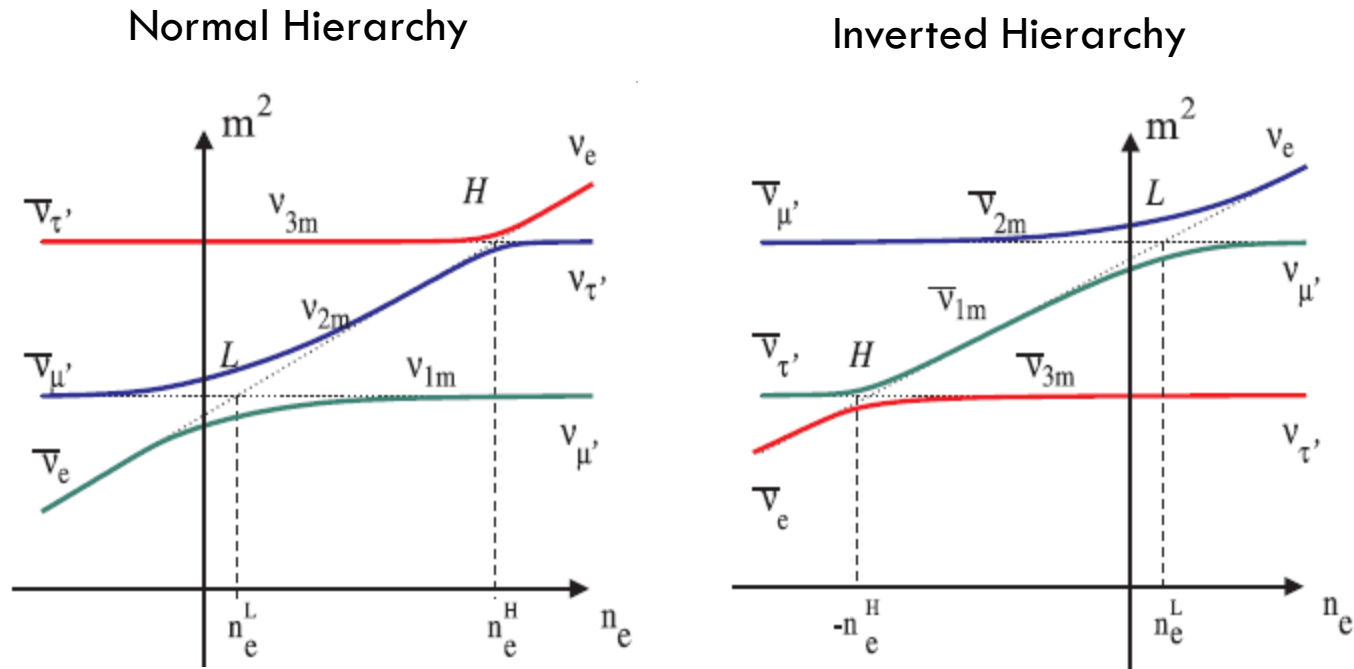
- For IH, exchange  $\nu_e$  and  $\nu_y$  above the  $E_c$  : Raffelt&Smirnov (2007).
- For IH, exchange all anti- $\nu_e$  and anti-  $\nu_y$  .

- No collective effect for NH .

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 this answer?
  - Small change in  $\theta_{13}$  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).
  - Only if the  $\nu_e$  and anti- $\nu_e$  spectra were identical, the answer is quite different...but that is unlikely: Raffelt&Sigl (2007).

# Standard MSW analysis



Dighe&Smirnov (2000)

- At small  $\theta_{13}$  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	$(F_x, F_x, F_e)$	$(F_x, F_e, F_x)   (F_x, F_x, F_e)$
After MSW (at Earth)	$(F_x, F_e, F_x)$	$(F_x, F_e, F_x)   (F_x, F_x, F_e)$

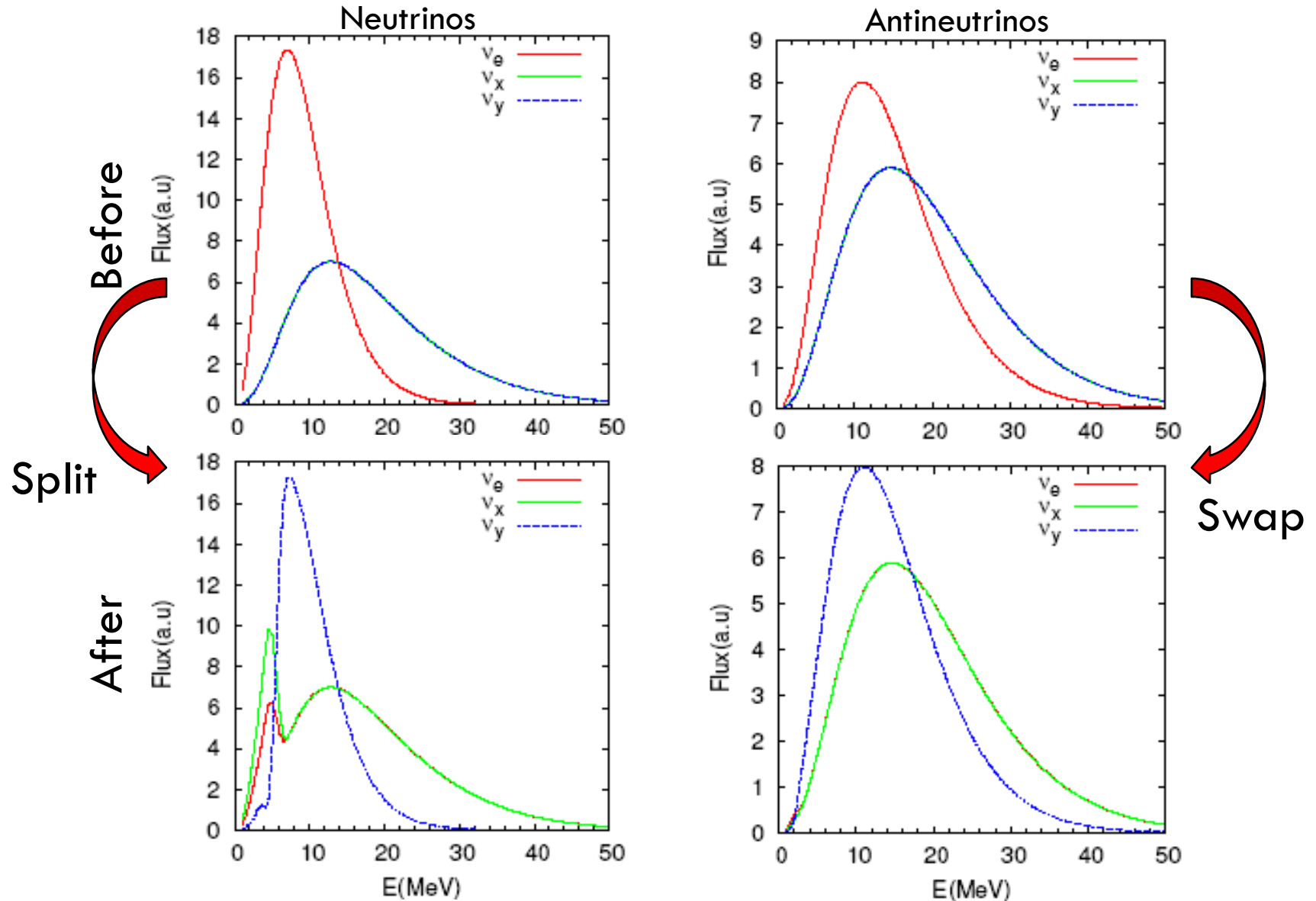
## Anti-Neutrinos

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)

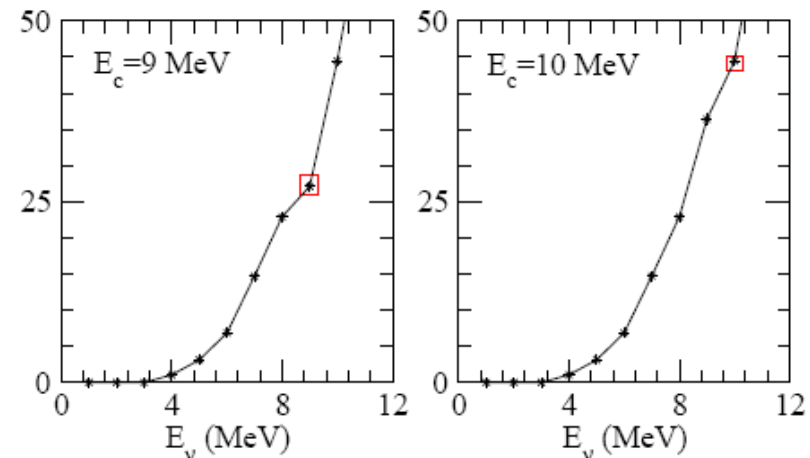
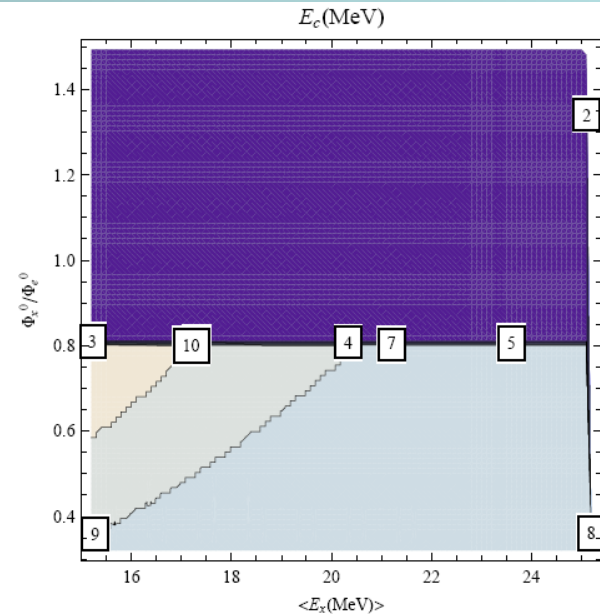
**Electron flavor:  $\nu_e = \cos \theta_{12} \nu_1 + \sin \theta_{12} \nu_2$**

# SN spectra at Earth



# Spectral Split Signature in Neutrinos

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



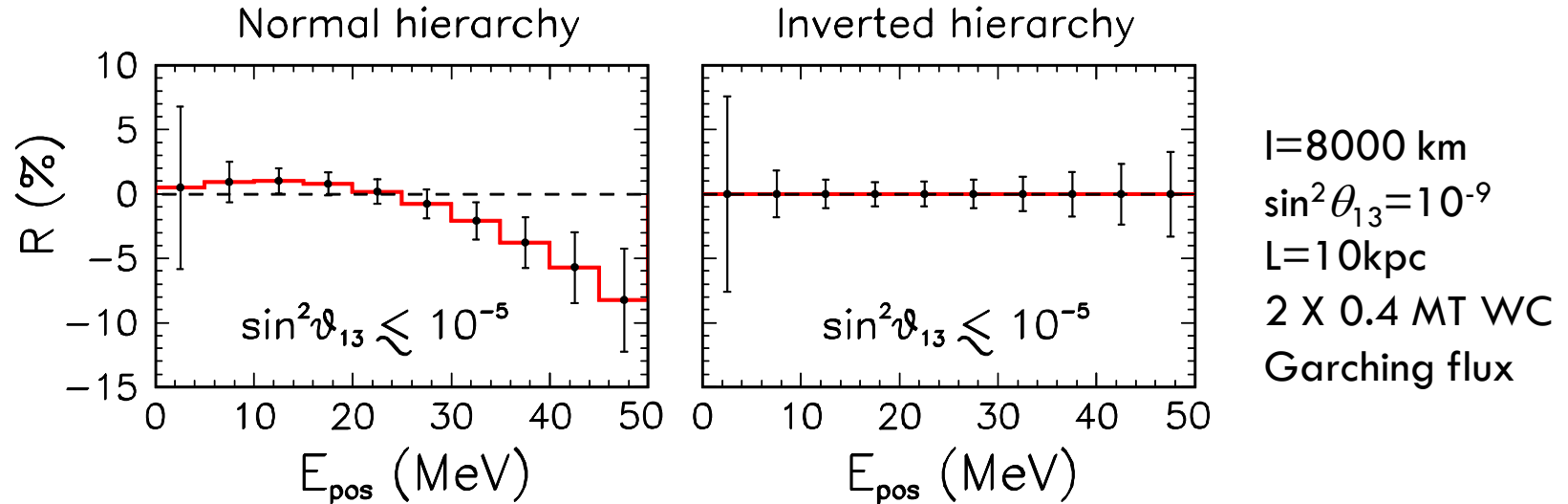
# Earth Matter Effects

- Flux of electron antineutrinos at shadowed and unshadowed detector are different combinations of  $\nu_1$  and  $\nu_2$ .

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)	$(F_e, F_x, F_x)$	$(F_x, F_x, F_e)$

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

# Mass hierarchy at very small $\theta_{13}$



- Two 0.4 MT water Cherenkov detectors – one shadowed, and other not shadowed by Earth
- Significant difference in events for NH, and none for IH.
- Works for arbitrarily small values of  $\theta_{13}$  in contrast to previous literature, and vis-à-vis other experiments : [Dasgupta, Dighe, Mirizzi \(2008\)](#).

# Some concluding remarks

- Earth Matter Effects are a robust and model-independent signature.
- Sensitivity in hierarchy and only “ball-park” estimate of  $\theta_{13}$ .
- Spectral Split is quite challenging to observe.
- Even turbulence and stochastic density fluctuations don't affect these results (since  $\theta_{13}$  is too small for ordinary matter effects to come into play).

# No Degeneracy between Scenarios

## Neutrinos

	Hierarchy	$\theta_{13}$	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

## Anti-Neutrinos

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