Earth Effects and Mass Hierarchy using Supernova Neutrinos

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Hierarchy Sensitivity, $\theta_{13}$ 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 $\theta_{13}$?
- One could use other sub-dominant effects.
- $3\sigma$ determination with 23 yrs at NF + 0.5 MT scintillation detector: de Gouvea & Winter (2005).
- 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 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 $\theta_{13}$ 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 $\nu_y$).
- Average energies: $E_e < E_{e\text{bar}} < E_{x,y}$.
- Mainly uncertainty in energy and luminosity of $x$ and $y$ “flavors”.
- Initial total fluxes: $\Phi_e > \Phi_{e\text{bar}} > \Phi_{x,y}$.
Collective Effects Redux

• For IH, exchange $\nu_e$ and $\nu_\gamma$ above the $E_c$.
• For IH, exchange all anti-$\nu_e$ and anti-$\nu_\gamma$.
• 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 $\theta_{13}$ does not affect the result.
  ▪ 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).
Dependence on $\theta_{13}$

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

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

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

Dasgupta&Dighe (2007)
SN spectra at Earth

Before

Neutrinos

Antineutrinos

Split

Swap

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

Dasgupta and Dighe (2007)
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 \( E_c \leq 10 \text{ MeV} \).

- 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 $\nu_1$ and $\nu_2$.
- 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 $l/E$.

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- 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.
Earth Effect in Neutrino Signal

- 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 \( \theta_{13} \) in contrast to previous literature and other experiments: Choubey, Dasgupta, Dighe, Mirizzi (to appear).
- Observation will establish NH and \( \sin^2 \theta_{13} < 10^{-3} \).

\[ \sin^2 \theta_{13} = 10^{-9} \]

L=10kpc  
Garching flux
Earth Effect in Antineutrino Signal

- Two 0.4 MT water Cherenkov detectors — one shadowed, and other not shadowed by Earth.
- \( R = \frac{F_e^\text{shadowed} - F_e^\text{unshadowed}}{F_e^\text{unshadowed}} \)
- 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

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Concluding Remarks

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