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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In collaboration with Amol Dighe and Alessandro Mirizzi: hep-ph/0802.1481
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)
• 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.
- $E_e < E_{\bar{e}} < E_{x,y}$
- Mainly uncertainty in energy and luminosity of $x$ and $y$ “flavors”.
- $F_e$, $F_{\bar{e}}$, $F_{x,y}$ are the initial fluxes.
Collective Effects Redux

- For IH, exchange \( \nu_e \) and \( \nu_\gamma \) above the \( E_c \): Raffelt&Smirnov (2007).
- For IH, exchange all anti-\( \nu_e \) and anti- \( \nu_\gamma \).
- 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.
  - 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).
• At small $\theta_{13}$ the H-resonance is completely non-adiabatic.
• The L-resonance is always adiabatic.

Dighe & Smirnov (2000)
## Mass Basis Fluxes reaching Earth from SN

### Neutrinos

<table>
<thead>
<tr>
<th>Flavor content in mass basis at</th>
<th>Normal Hierarchy</th>
<th>Inverted Hierarchy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Flux</td>
<td>((F_x, F_x, F_e))</td>
<td>((F_x, F_e, F_x))</td>
</tr>
<tr>
<td>After Collective</td>
<td>((F_x, F_x, F_e))</td>
<td>((F_x, F_e, F_x) \parallel (F_x, F_x, F_e))</td>
</tr>
<tr>
<td>After MSW (at Earth)</td>
<td>((F_x, F_e, F_x))</td>
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### Anti-Neutrinos

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

Dasgupta & Dighe (2007)
SN spectra at Earth

Before

Split

After

Neutrinos

Antineutrinos
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 $\nu_2$.

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- But for IH it does not make any difference, both are “x”!
- $R = \frac{(F_e^{\text{shadowed}} - F_e^{\text{unshadowed}})}{F_e^{\text{unshadowed}}}$.
- $R$ 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).

\begin{align*}
n_{13} & \leq 10^{-9} \\
L & = 10 \text{kpc} \\
2 \times 0.4 \text{ MT WC} \\
\text{Garching flux}
\end{align*}
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

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<th>Earth Effects</th>
<th>Shock Effects</th>
<th>Burst Signal</th>
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<td>Large</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>B IH</td>
<td>Large</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>C NH</td>
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<td>No</td>
<td>Yes</td>
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<tr>
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