Traveling through turbulence

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INT Program 12-2a ”Core-Collapse Supernovae: Models and Observable Signals ”
July 16th – July 20th, 2012
Neutrino emission from ccSN

- Neutrinos produced at PNS surface.
- Amount and energies varies during accretion and cooling phases.
- Correct interpretation of observed neutrinos → Need to know all about ν's.

[Fischer et al., 2010]
Effects affecting neutrinos

- Self-interactions
- Turbulence
- Shock wave
- MSW

Diffusion

Flavor conversion inside the star

Propagation in vacuum

Oscillations Inside the Earth
Focus of this project

- Interplay of MSW, νν self-interaction and turbulence.
- Impact of turbulence - 2 regions.
- Investigate shock hitting MSW L resonance.
- Use numerically realistic density profiles.

[www.particlezoo.net]
Density profiles

- Ideally multi-D simulations, but does not go long enough.
- 1D simulation of $10.8 \, M_\odot$ progenitor, $(8.8 \, \text{and} \, 18.0 \, M_\odot)$.
- Provided by Basel group.
- 10.7 s post bounce duration.
- Develop contact discontinuity, forward and reverse shocks.
MSW resonances

- Neutrino flavor changes at two resonance densities:

\[ \rho_{\text{res}} \sim 1.4 \times 10^6 \text{ g/cc} \left( \frac{\Delta m^2}{1 \text{ eV}^2} \right) \left( \frac{10 \text{ MeV}}{E} \right) \left( \frac{0.5}{Y_e} \right) \cos 2\theta \]

- \( \rho_H \) corresponding to

\[ \Delta m^2_{13} \approx 2.43 \times 10^{-3} \text{ eV}^2 \text{ and } \theta_{13} = 9^\circ \]

- \( \rho_L \) corresponding to

\[ \Delta m^2_{12} = 7.56 \times 10^{-5} \text{ eV}^2 \text{ and } \theta_{12} = 34^\circ \]

- Position of \( \rho_{\text{res}} \) and derivative of density there important.
Resonance transitions

- General propagation is adiabatic.
- Need diabatic at shock.

[Dighe & Smirnov, 2000]
Shock morphology

- Numerical soft shocks.
- When $\theta_\text{13}$ is big, only adiabatic transitions happen: $\gamma \gg 1$, $\gamma \propto n_e / (dn_e / dr)$
- Need diabatic at shock.
- Partially steepend by hand.
Collective effects

- Flavor changes from background neutrinos.
- When $n_\nu$ is high enough.
- Usually before MSW and turbulence.
Turbulence

- Turbulence by hand on 1D.
- 2 different turbulence areas.
- From Kneller & Volpe, we have the equations for adding turbulence:

\[ V(r) = (1 + F(r)) \langle V \rangle(r) \]

- Where \( F(r) \) is given by:

\[
F(r) = \frac{C_*}{\sqrt{N_k}} \tan \left( \frac{r - r_T}{\lambda} \right) \tan \left( \frac{r_s - r}{\lambda} \right) \times \sum_{n=1}^{N_k} \left\{ A_n \cos \left[ k_n (r - r_T) \right] + B_n \sin \left[ k_n (r - r_T) \right] \right\}
\]

- \( C_* = 0.03 \)
- \( N_k = 10^3 \)
Tests

- Kolmogorov spectrum.
- Decades and number of wave modes.
Tests

- Results reported in the following will be for
  - $C_\ast = 0.03$
  - $N_k = 10^3$

- Kolmogorov spectrum.
- Decades and number of wave modes.
Results for $t = 9$ s

- **MSW:**
  - H: $\nu_3 \leftrightarrow \nu_2$, NH
  - L: $\nu_1 \leftrightarrow \nu_2$, both

- **Collective:**
  - NH: nothing
  - IH: $\nu_3 \leftrightarrow \nu_{1,2}$, split
  - IH: $\bar{\nu}_3 \leftrightarrow \bar{\nu}_{1,2}$, swap
Collective effects

\[ <E_e> = 10 \text{ MeV} \]
\[ <E_x> = 24 \text{ MeV} \]

\[ <\bar{E}_e> = 15 \text{ MeV} \]
\[ <\bar{E}_x> = 24 \text{ MeV} \]

[Ref.: Fogli et al., 2003, 2006]
Comment on collective effects only

- Cooling phase, so $L_x \geq L_e$
- 70 – 1000 km.
- Multiple splits observed.
- No exact match.
- Highly non-linear problem.
MSW and $\nu\nu$ – NH and $\nu$'s

Collective only

MSW only

Collective and MSW
MSW and $\nu \nu$ – NH and $\nu$'s

Collective only

MSW only

Collective and MSW

L resonance
MSW and $\nu \nu$ – NH and $\nu$'s

Collective only

MSW only

Collective and MSW
MSW and $\nu \nu$ – NH and $\bar{\nu}$'s

Collective only

MSW only

Collective and MSW
MSW and $\nu \nu$ – IH and $\nu$'s

Collective only

MSW only

Collective and MSW
MSW and $\nu\nu$ – IH and $\bar{\nu}$'s

Collective only

MSW only

Collective and MSW
Phase effects

- Oscillations due to phase effects.
- Distance between 2 MSW resonances points depends on neutrino energy.
- $\theta_{13} \approx 5.7^\circ$. 
Multiple passings
Adding turbulence – NH and ν's

- Detailed differences.
Adding turbulence – NH and ν's
Adding turbulence – NH and $\nu$'s
Adding turbulence – NH and $\nu$'s

- Detailed differences.
- Multiple realisations.
- Bigger amplitudes.
- Collective and MSW features survive.
Adding turbulence – NH and $\nu$'s

- Wash out by energy resolution of detectors.
- Some collective and MSW features survive – future work.
Time dependent probabilities
Case of t = 4 s

- Low E one pass of H, high E multiple passes.
- Transition probabilities for L resonance not shown.
Accretion phase 93 ms

- Collective effects only.
- Adiabatic transversal of H and L.
Conclusions and future challenges

- Features not washed out by turbulence.
- Need both anti-ν and ν detectors.
- Energy resolution.

Future:

- Better understanding of collective effects.
- Ensemble averages.
- More profiles and progenitors.
- Observability in detectors.