8/5/10

Large positron population. Neutrino production via:

\[ e^- + p \rightarrow \nu_e + n \]
\[ e^+ + n \rightarrow \bar{\nu}_e + p \]
\[ e^- + e^+ \rightarrow \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \]
\[ N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \]
\[ \nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \]

Low positron population. Neutrino production via:

\[ e^- + p \rightarrow \nu_e + n \]
\[ N + N \leftrightarrow N + N + \nu_{e,\mu,\tau} + \bar{\nu}_{e,\mu,\tau} \]
\[ \nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau} \]
Anatomy of Neutrino Luminosities

Increase in neutrino rms energies as PNS initially contracts.

Three-Flavor Neutrino Luminosities and Mean Energies

Initial shock location/strength depend on amount of electron capture on nuclei (and protons) during stellar core collapse.

Electron capture on stellar core nuclei depends on energy levels in the nucleus and how the nucleons populate them.

$e^- + p, A \leftrightarrow \nu_e + n, A'$

Zeroth-order shell model (nucleons independent), electron capture on nuclei is blocked for $N>40$. 

$(Z,A)$
When Micro and Macro Worlds Collide

Significant change in shock formation mass.


No correlations.

With correlations.
Multigroup Flux-Limited Diffusion

The Boltzmann equation contains the same information as an infinite hierarchy of equations for the angular “moments” of the neutrino distribution function:

\[ \int d\mu \left[ \frac{\partial f}{\partial t} = L[f] \right] \Rightarrow \frac{\partial \psi^0}{\partial t} = ... \]

\[ \psi^0 = \frac{1}{2} \int d\mu f \]

\[ \int d\mu \mu \left[ \frac{\partial f}{\partial t} = L[f] \right] \Rightarrow \frac{\partial \psi^1}{\partial t} = ... \]

\[ \psi^1 = \frac{1}{2} \int d\mu \mu f \]

... 

Approximation:

• Truncate hierarchy at the level of the “zeroth” moment (neutrino energy density).
• Closure: Relate the first moment (momentum density/flux) to the energy density so as to satisfy known limits:

\[ \psi^1 = -\Lambda \left( \frac{\partial \psi^0}{\partial r} \right) \]

\[ \Lambda = \frac{1}{3} \frac{1}{\frac{1}{\lambda} \frac{\partial \psi^0}{\partial r}} \]

\[ \text{Diffusion Limit: Fick’s Law} \]

\[ \psi^1 \rightarrow -\frac{\lambda}{3} \frac{\partial \psi^0}{\partial r} \]

\[ \text{Free Streaming Limit} \]

\[ \psi^1 \rightarrow \psi^0 \]
The Boltzmann equation contains the same information as an infinite hierarchy of equations for the angular “moments” of the neutrino distribution function:

\[
\int d\mu \frac{\partial f}{\partial t} = L[f] \Rightarrow \frac{\partial \psi^0}{\partial t} = \ldots
\]

\[
\frac{\psi^0}{2} = \int d\mu f
\]

\[
\int d\mu \mu \frac{\partial f}{\partial t} = L[f] \Rightarrow \frac{\partial \psi^1}{\partial t} = \ldots
\]

\[
\frac{\psi^1}{2} = \int d\mu \mu f
\]

\ldots

**Approximation:**

- Truncate hierarchy at level of “first” moment (neutrino momentum density).
- **Closure:** Relate the second (and third) moments to the zeroth moment using “Eddington factors,” which are the ratio of these higher moments to the zeroth moment.

Eddington factors can be computed at different levels of approximation:

- “Prescribed” closure (e.g., maximum entropy closure).
- Approximate Boltzmann solution.
- Exact Boltzmann solution.
Simulation Building Blocks

- **“RbR-Plus” MGFLD Neutrino Transport**
  - $O(v/c)$, GR time dilation and redshift, GR aberration (in flux limiter)

- **2D PPM Hydrodynamics**
  - GR time dilation, effective gravitational potential, adaptive radial grid

- **Lattimer-Swesty EOS**
  - 180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)

- **Nuclear (Alpha) Network**
  - 14 alpha nuclei between helium and zinc

- **2D Effective Gravitational Potential**

- **Neutrino Emissivities/Opacities**
  - “Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung
Impact of Energy Exchange in Neutrino Scattering on Nucleons

Schematic Layout of Neutrinospheres in PNS

\[ R_{\nu_e} \]
\[ R_{\nu_{\mu,x}} \]

New Weak Interaction Physics and Its Ramifications:

\( \Rightarrow \) Muon/tau neutrino elastic scattering on nucleons leads to heating of electron neutrinospheres.
• Variations with angle due to highly nonspherical flow in postshock region, induced by convection and SASI.
• Variations are angle and time dependent.
SASI: A Case Study for 3D
Anatomy of a Mach Reflection

- Symmetry of Mach reflection broken in three dimensions.
- Internal shock (orthogonal to supernova shock) leads to two counter-rotating flows.
Ramifications...

**SASI-induced counter rotating flows.**

*Inner flow capable of spinning up remnant NS to 50 ms periods, even beginning with spherically symmetric initial conditions.*

Implications for
- the growth of B fields?
- the supernova mechanism?
- supernova observables?

Ongoing 3D Multi-Physics Simulations

Simulation Building Blocks

- “RbR-Plus” MGFLD Neutrino Transport
  • $O(v/c)$, GR time dilation and redshift, GR aberration (in flux limiter)

- 3D PPM Hydrodynamics
  • GR time dilation, effective gravitational potential, adaptive radial grid

- Lattimer-Swesty EOS
  • 180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)

- Nuclear (Alpha) Network

- 3D Effective Gravitational Potential

- Neutrino Emissivities/Opacities
  • “Standard” + Elastic Scattering on Nucleons + Nucleon–Nucleon Bremsstrahlung


Resolution

- 304 X 76 X 152
  ⇒ 11,552 processors
- 576 X 96 X 192 (recently launched)
  ⇒ 18,432 processors
- 512 X 256 X 512
  ⇒ 131,072 processors
15 M\(_\odot\) Heger

- Shock Radius 1D
- Min/Mean/Max Shock Radius 2D
- Min/Mean/Max Shock Radius 3D

Shock Radius [km]

Time from Bounce [s]
### 3D Models: Path Forward

<table>
<thead>
<tr>
<th>Neutrino Transport Approach</th>
<th>Code</th>
<th>GR</th>
<th>Network</th>
<th>Platform</th>
<th>Time Frame</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>RbR MGFLD</td>
<td>CHIMERA</td>
<td>Approximate</td>
<td>Alpha, Full</td>
<td>2-20 PF</td>
<td>2010-2015</td>
<td>CCSNe</td>
</tr>
<tr>
<td>MGFLD</td>
<td>CHIMERA</td>
<td>Approximate</td>
<td>Alpha, Full</td>
<td>100 PF – 1 EF</td>
<td>2015-2020</td>
<td>CCSNe</td>
</tr>
<tr>
<td>MGVET</td>
<td>GenASiS</td>
<td>BSSN</td>
<td>Alpha, Full</td>
<td>100 PF – 1 EF</td>
<td>2015-2020</td>
<td>CCSNe, Hypernovae</td>
</tr>
<tr>
<td>Boltzmann</td>
<td>GenASiS</td>
<td>BSSN</td>
<td>Alpha, Full</td>
<td>&gt; 10 EF</td>
<td>&gt; 2020</td>
<td>CCSNe, Hypernovae</td>
</tr>
</tbody>
</table>