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.

Electron-Neutrino Burst

Accretion Luminosity
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.

⇒ Zeroth-order shell model (nucleons independent), electron capture on nuclei is blocked for N>40.
When Micro and Macro Worlds Collide


- No correlations.
- With correlations.

Significant change in shock formation mass.
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:

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

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

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

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

\[ \psi^1 \rightarrow -\lambda \frac{\partial \psi^0}{\partial r} \]  \hspace{1cm} \text{Diffusion Limit: Fick’s Law}

\[ \psi^1 \rightarrow -\frac{\lambda}{3} \frac{\partial \psi^0}{\partial r} \]  \hspace{1cm} \text{Free Streaming Limit}

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

\[
\int d\mu \left[ \frac{\partial f}{\partial t} = L[f] \right] \Rightarrow \frac{\partial \psi^0}{\partial t} = \ldots \quad \psi^0 = \frac{1}{2} \int d\mu f
\]

\[
\int d\mu \int d\mu \left[ \frac{\partial f}{\partial t} = L[f] \right] \Rightarrow \frac{\partial \psi^1}{\partial t} = \ldots \quad \psi^1 = \frac{1}{2} \int d\mu \mu f \]

\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.
Ongoing 2D Multi-Physics Supernova Models

Simulation Building Blocks

 обязуемое “RbR-Plus” MGFLD Neutrino Transport

 • $O(\nu/c)$, GR time dilation and redshift, GR aberration (in flux limiter)

 обязуемое 2D PPM Hydrodynamics

 • GR time dilation, effective gravitational potential, adaptive radial grid

 обязуемое Lattimer-Swesty EOS

 • 180 MeV (nuclear compressibility), 29.3 MeV (symmetry energy)

 обязуемое Nuclear (Alpha) Network

 • 14 alpha nuclei between helium and zinc

 обязуемое 2D Effective Gravitational Potential


 обязуемое Neutrino Emissivities/Opacities

 • “Standard” + Elastic Scattering on Nucleons
  + Nucleon–Nucleon Bremsstrahlung

 “Ray-by-Ray-Plus” Approximation

 • Radial transport allowed.
 • Lateral transport suppressed.

Impact of Energy Exchange in Neutrino Scattering on Nucleons

Schematic Layout of Neutrinospheres in PNS

New Weak Interaction Physics and Its Ramifications:

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
• 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?

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 $\times$ 76 $\times$ 152 $\Rightarrow$ 11,552 processors
- 576 $\times$ 96 $\times$ 192 (recently launched) $\Rightarrow$ 18,432 processors
- 512 $\times$ 256 $\times$ 512 $\Rightarrow$ 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]
<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>
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<td>RbR MGFLD</td>
<td>CHIMERA</td>
<td>Approximate</td>
<td>Alpha, Full</td>
<td>2-20 PF</td>
<td>2010-2015</td>
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<tr>
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