Neutrino-Matter Interactions in Neutron Star Mergers

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Physical Setup

Movie from Lovelace et al. 2013
Where do neutrinos matter?

- Neutrinos:
  - Cool the remnant accretion disk (under control)
  - Drive disk winds (maybe not that important?)
  - Set the composition of the ejecta, and thus
    - the outcome of \textit{r-process nucleosynthesis}
    - the color/amplitude/duration of \textit{kilonovae}
  - Deposit energy in low-density region (SGRB?)
The neutrino problem

The full problem:
Boltzmann equations

\[ p^\alpha \left[ \frac{\partial f_{(\nu)}}{\partial x^\alpha} - \Gamma^\beta_{\alpha \gamma} p^\gamma \frac{\partial f_{(\nu)}}{\partial p^\beta} \right] = \left[ \frac{df_{(\nu)}}{d\tau} \right]_{\text{coll}} \]

with collision terms including emission / absorption / scattering

High cost: \((6+1)D\) problem
\[ f_{(\nu)} = f(t, x^i, p^\alpha) \]

and complex collision terms, e.g.
Inelastic scattering
Neutrino-antineutrino annihilation
Approximate Methods

- Cooling function: only in optically thin regime
- Leakage: good in optically thin regime, order of magnitude accurate otherwise
- **Moment formalism**: good in optically thick and semi-transparent regime. In the grey regime, lack of spectral information is an issue
- Beyond moments: **Monte-Carlo**, full transport
Moment formalism (M1)

Relatively cheap, **approximate transport** method.

See Shibata et al. 2011, Foucart et al. 2015

Define moments (fluid frame):

\[
J = \int d\nu \nu^3 \int d\Omega f(\nu)(x^\alpha, \nu, \Omega)
\]

\[
H^\mu = \int d\nu \nu^3 \int d\Omega f(\nu)(x^\alpha, \nu, \Omega) l^\mu
\]

Approximate closure

\[
K^{\mu\nu} = \alpha K^{\mu\nu}_{\text{thick}} + (1 - \alpha) K^{\mu\nu}_{\text{thin}}
\]

using optically thin/thick limits

Transform to inertial frame:

\[
T^{\mu\nu} = J u^\mu u^\nu + H^\mu u^\nu + H^\nu u^\mu + P^{\mu\nu}
\]

\[
T^{\mu\nu} = En^\mu n^\nu + F^\mu n^\nu + F^\nu n^\mu + K^{\mu\nu}
\]

Sources include:

- Curvature/redshift terms
- Emission/Absorption/Scattering

Exact evolution equations:

\[
\partial_t \tilde{E} + \partial_j \tilde{F}^j = \text{sources}
\]

\[
\partial_t \tilde{F}_i + \partial_j \tilde{P}^j_i = \text{sources}
\]

Improvement:

**Evolve number density.**
Provides information about \(\nu\)

See Foucart et al. 2016b
Qualified Success: NSNS mergers

1.2M⊙ + 1.2M⊙, LS220 EoS (Foucart+ 16,17)

Density and temperature of the remnant are reliable even with leakage
Qualified Success: NSNS mergers

$1.2M_\odot + 1.2M_\odot$, LS220 EoS (Foucart+ 16,17)

Electron fraction and polar outflows are unreliable when using leakage
Qualified Success: NSNS mergers

$1.2M_\odot + 1.2M_\odot$, LS220 EoS (Foucart+ 16,17)

Compare **different energy estimates** in M1:

Outflow mass, composition of equatorial outflows now converge. **Composition of polar outflows** is uncertain.
Pair annihilation

- Neutrino-Antineutrino annihilation can deposit \( \sim (0.001-0.01) \, \text{L}_\nu \) in polar regions.
- Annihilation rate depends on neutrino orientations, which is unknown in M1 scheme.
- Post-processing with transport codes provides information about energy deposition.
- Back-reaction on fluid/jet requires on-the-fly computation!

Image: Fujibayashi et al. 2017
Can we go further?

• One possibility: Monte-Carlo (MC) as closure
  • Too expensive to run MC with high-accuracy at all times
  • Noise in low-resolution MC simulation could be an issue
  • Could run MC rarely on time-independent snapshots
  • **Could run MC with low number of particles** and get a time-averaged distribution function
  • **No need to do MC in optically thick regions!**
  • Can provide information needed for pair annihilation
Proof of principle: two beams problem

MC vs M1

M1 closure causes radiation shock

MC closure (nearly) avoids interactions

(Foucart, in prep)
Proof of principle
Composition after 8ms of evolution of a core-collapse profile
Very low resolution simulations (dx~6km)

M1 vs M1+MC

Different M1 methods

MC also provides spectral information,
in good agreement with spectral M1

(Foucart, in prep)
Pitfalls and limitations

- Time averaging could introduce artifacts for low number of particles.
- Choices made at the interface between optically thick regions (where MC is not active) and regions in which MC is active has to be studied.
- Parallelization will be non-trivial (and hasn’t been done).
- M1 and MC can get out of sync, leading to closure inconsistent with M1 evolution.

For ~50 part./cell at peak E
(Foucart, in prep)
Conclusions

- Neutrino-matter interactions are important but expensive to compute
- How much to spend depends on the question asked
  - Remnant properties captured by leakage
  - Outflow masses captured with any M1 scheme
  - Outflow composition needs spectral information
  - Pair annihilation requires MC or full transport
    - To get energy deposition, post-processing is good enough