Impact of M1 neutrino transport in BNS mergers

Pedro Luis Espino

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Outline

01 Background

- Neutrinos in BNS mergers
- Neutrino transport in GRHD codes

02 Methods

- `THC_M1`
- Simulations overview

03 Simulation results

- Dynamics overview
- Neutrino luminosity
- Ejecta
- Nucleosynthesis and Kilonovae
- Out-of-equilibrium effects

04 Conclusion

01 Introduction

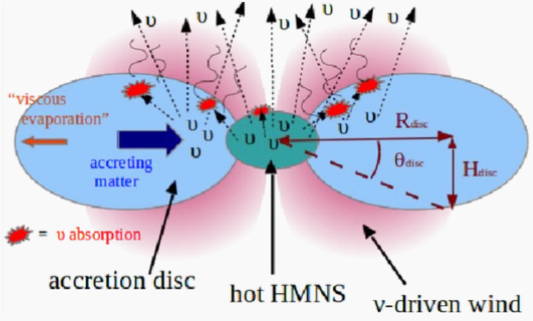
- Neutrinos in BNS mergers
- Neutrino transport in GRHD codes

The role of neutrinos in BNS mergers

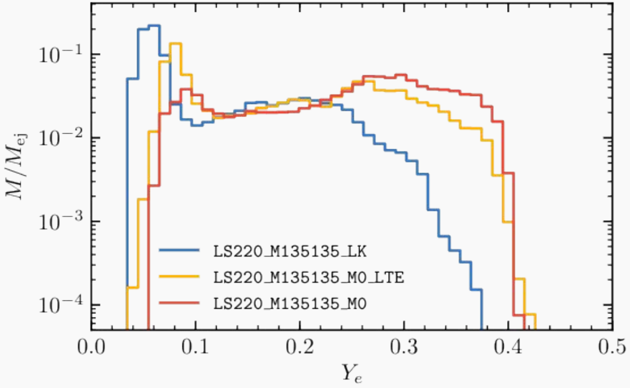
Neutrinos are expected to play an important role in the physics of BNS mergers

Neutrinos interact with matter in the post-merger environment at different length scales depending on the local matter conditions

Perego et al., Mon.Not.Roy.Astron.Soc.443 (2014)



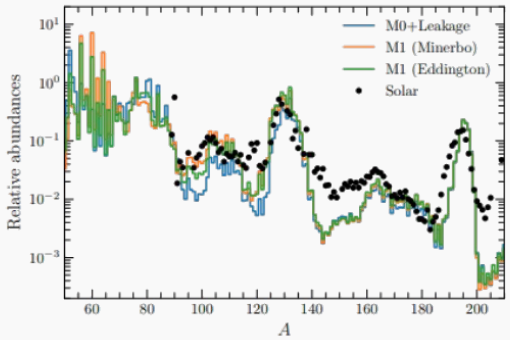
These interactions may alter the properties and amount of ejecta



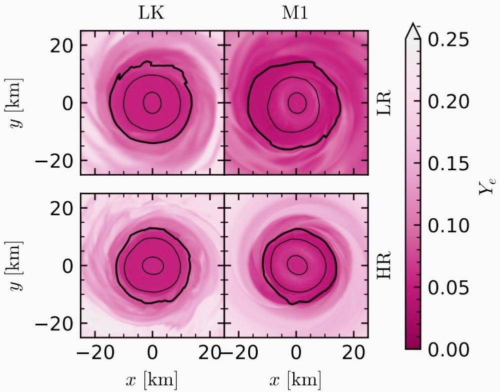
Radice et al., Astrophys.J. 869 (2018)

This may in turn affect phenomena associated with BNS mergers such r-process nucleosynthesis and kilonovae

Radice et al., Mon.Not.Roy. Astron.Soc. 512 (2022)



The accuracy of these interactions depends strongly on the radiation transport scheme used



Zappa et al., Mon. Not. Roy. Astron. Soc., 520, (2023)

Neutrino transport in BNS mergers

- Neutrino transport, in-principle, requires a solution to the **Boltzmann equations**

$$p^\alpha \left[\frac{\partial f_\nu}{\partial x^\alpha} - \Gamma^\beta_{\alpha\gamma} p^\gamma \frac{\partial f_\nu}{\partial p^\beta} \right] = \frac{\partial f_\nu}{\partial \tau} \qquad f_\nu = f_\nu(x^\alpha, p^\alpha)$$

- Numerical methods have been developed for solving these equations in the context of BNS mergers. **However full solutions remain a computationally expensive problem**.

- Instead, one can consider approximations to the problem, by considering how **macroscopic** properties of the neutrinos.

- Moment-based schemes evolve moments of the distribution function:

$$J = \int_0^\infty d\nu \nu^3 \int d\Omega f_\nu$$

$$H^\mu = \int_0^\infty d\nu \nu^3 \int d\Omega f_\nu l^\mu$$

$$S^{\mu\nu} = \int_0^\infty d\nu \nu^3 \int d\Omega f_\nu l^\mu l^\nu$$

$$l^\alpha = p^\alpha / \nu - u^\alpha$$

Fluid rest frame

$$T^{\mu\nu}_{\rm rad} = J u^\mu u^\nu + H^\mu u^\nu + H^\nu u^\mu + S^{\mu\nu}$$

Inertial frame

$$T^{\mu\nu}_{\rm rad} = E n^\mu n^\nu + F^\mu n^\nu + F^\nu n^\mu + P^{\mu\nu}$$

$$\nabla_\nu T^{\mu\nu}_{\rm rad} = -\nabla_\nu T^{\mu\nu}_{\rm hydro}$$

Evolution equations for **first two moments** E, F^i

Approximation: introduce an analytic **closure** which relates the inertial frame stress-tensor to the first two moments

$$P^{ik} = f(E, F^i)$$

02 Methods

- THC_M1 code
- Simulations overview

THC_M1

- **THC_M1** is an extension of the well-tested **WhiskyTHC** code for general relativistic hydrodynamics (GRMHD)
- Implements M1 neutrino transport with use of the **Minerbo closure**, which is exact in the optically thick and optically thin (assuming the neutrino propagation direction) limits

$$P_{\alpha\beta} = \frac{3\chi - 1}{2} P^{\text{thin}}_{\alpha\beta} + \frac{3(1-\chi)}{2} P^{\text{thick}}_{\alpha\beta}$$

- We also evolve the number density of neutrinos, to capture potential changes in the lepton number of the fluid introduced by weak interactions. We consider the evolution of three neutrino species, $\bar{\nu}_e, \nu_e, \nu_x$

$$\nabla_\alpha N^\alpha = \sqrt{-g}(\eta^0 - \kappa^0_a n) \qquad N^\alpha = N^\alpha(H, J^\alpha)$$

Main assumptions:

- ❑ Closure on the pressure tensor $P_{\alpha\beta}$
- ❑ Closure on neutrino number flux N_α
- ❑ Simplified treatment of the energy dependence of neutrino absorption and scattering opacities
- ❑ Neglect of neutrino oscillations are the only modeling assumptions in THC_M1

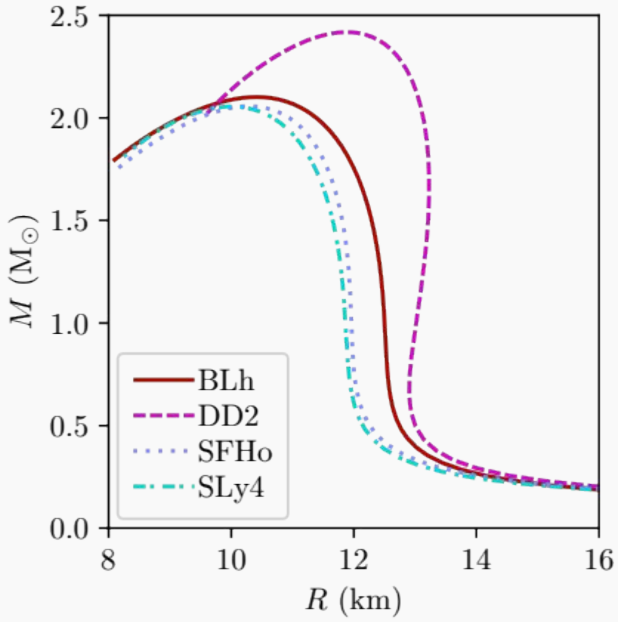
Benefits:

- ❑ Relatively computationally inexpensive
- ❑ Well suited to systematic studies with a large number of simulations

Simulations overview

We run a series of state-of-the-art 3D GRHD simulations of BNS mergers using M1 neutrino transport within the `THC_M1` code.
We construct equal-mass and non-equal mass binaries with the `Lorene` code and utilize the `CTGamma` code for the spacetime evolution.

EOS	h_c	q	$M(M_\odot)$	$M_b(M_\odot)$	Res.
BLh	0.125	1.0	2.68	2.95	LR/SR/HR
BLh	0.125	1.2	2.68	2.95	LR/SR/HR
DD2	0.125	1.0	2.68	2.94	LR/SR/HR
DD2	0.125	1.2	2.68	2.94	LR/SR/HR
SFHo	0.125	1.0	2.68	2.96	LR/SR/HR
SFHo	0.125	1.2	2.68	2.96	LR/SR/HR
SLy	0.125	1.0	2.68	2.97	LR/SR/HR
SLy	0.125	1.2	2.68	2.97	LR/SR/HR



Finest-level grid resolutions

LR: ~0.25 km (~50 points covering R)

SR: ~0.125 km (~64 points covering R)

HR: ~0.083 km (~96 points covering R)

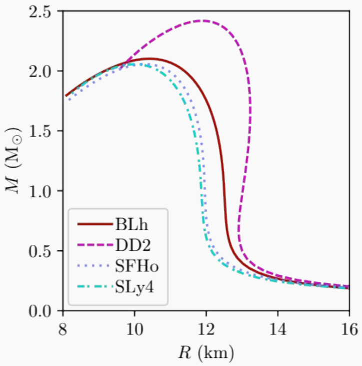
03 Simulation results

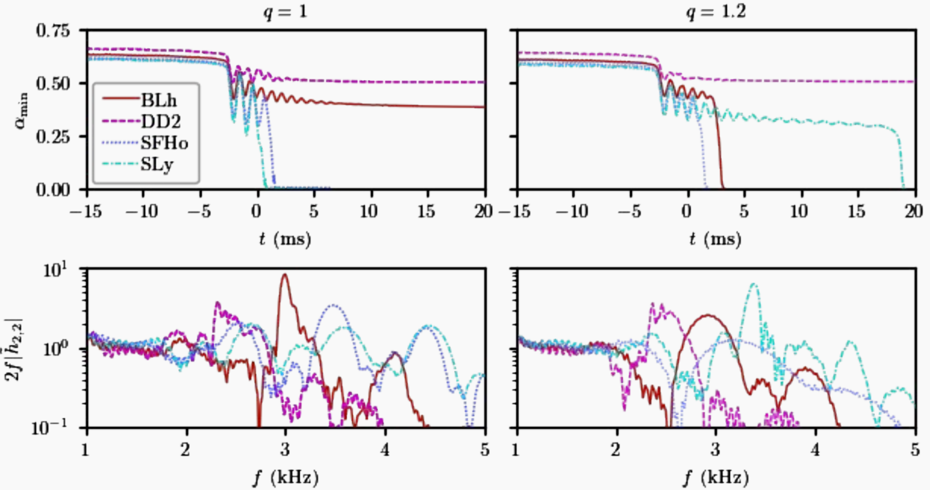
- Dynamics overview
- Neutrino luminosity
- Ejecta
- Nucleosynthesis and Kilonovae
- Out-of-equilibrium effects

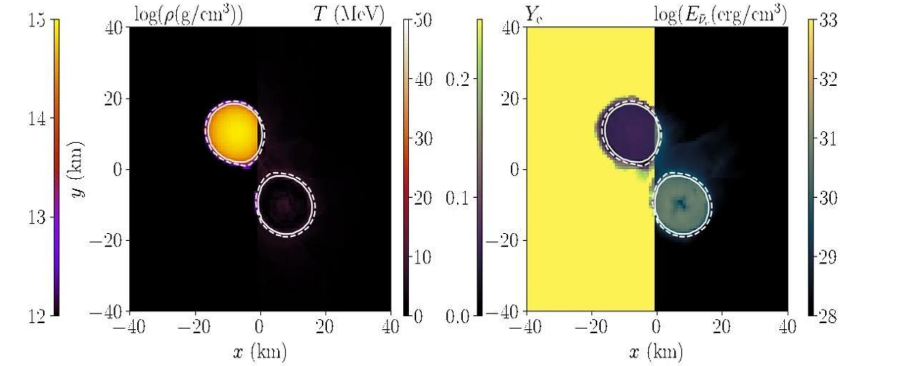
03a General dynamics

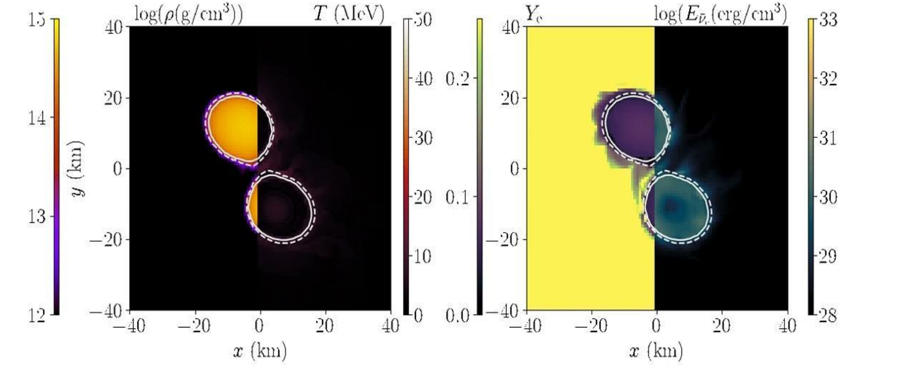
General dynamics

EOS	h_c	q	$M(M_\odot)$	$M_b(M_\odot)$	Res.
BLh	0.125	1.0	2.68	2.95	LR/SR/HR
BLh	0.125	1.2	2.68	2.95	LR/SR/HR
DD2	0.125	1.0	2.68	2.94	LR/SR/HR
DD2	0.125	1.2	2.68	2.94	LR/SR/HR
SFHo	0.125	1.0	2.68	2.96	LR/SR/HR
SFHo	0.125	1.2	2.68	2.96	LR/SR/HR
SLy	0.125	1.0	2.68	2.97	LR/SR/HR
SLy	0.125	1.2	2.68	2.97	LR/SR/HR









03b Neutrino luminosities

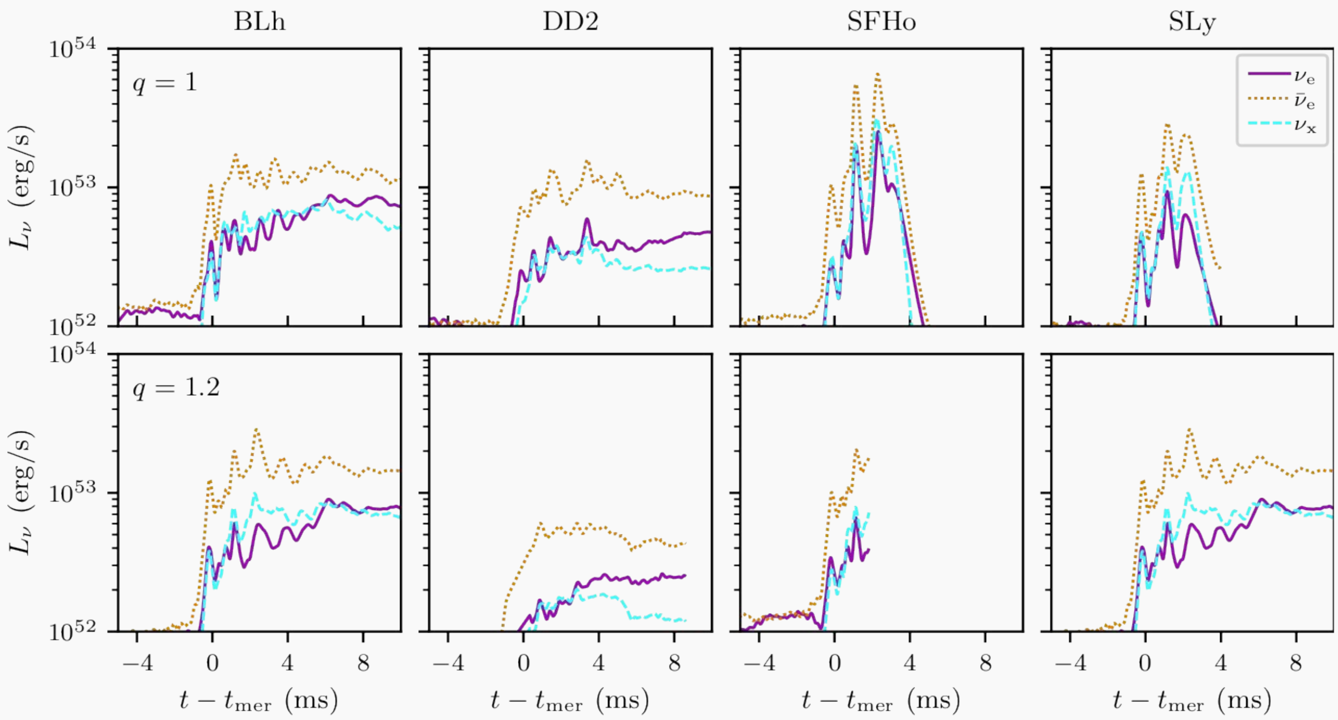
Neutrino luminosities

★ **M1 neutrino luminosities are consistent with other neutrino transport schemes** (e.g., M0 and MC-based schemes)

★ Typical luminosities of 1e53 erg/s

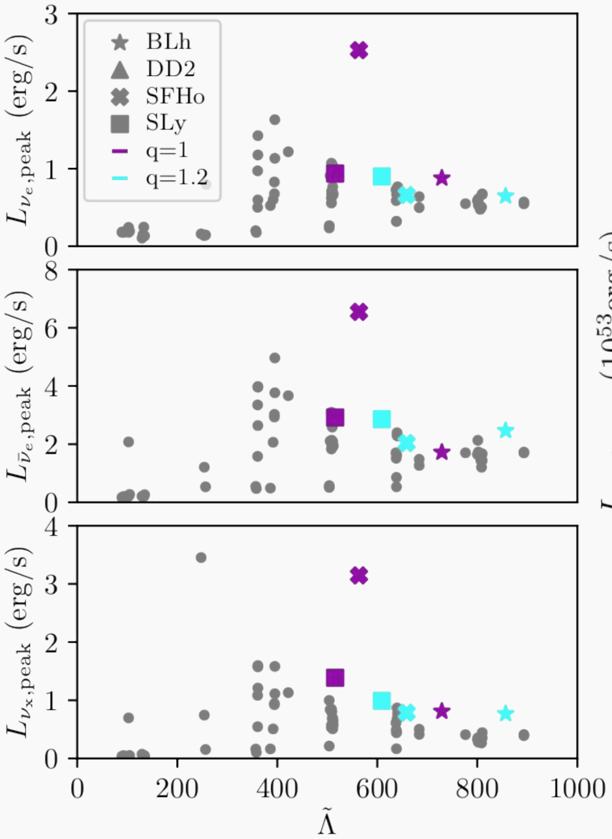
★ **Peak luminosity is reached within a few ms after the merger** and either plateaus (if RMNS is present) or sharply decreases (if BH is present)

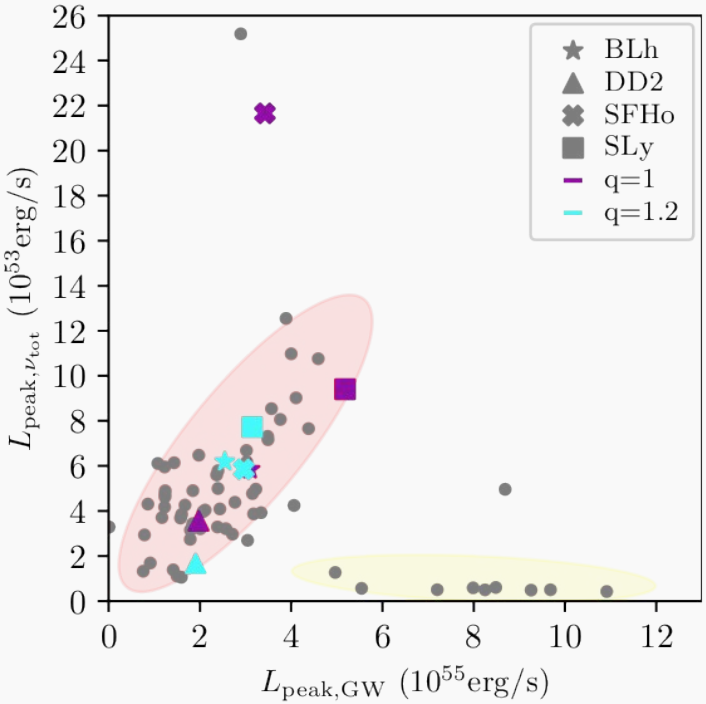
★ **The electron anti-neutrino is the brightest species**



Neutrino luminosities

- ★ The more compact the binary components, the more "violent" the merger (i.e., the louder the GWs)
- ★ The more "violent" the merger, the brighter the neutrino emission
- ★ **M1 simulations (color) predict similar correlations between neutrino and GW luminosities to M0 simulations (gray)**





see Cusinato et al., Eur. Phys. Jour. A, 58 (2022) for additional correlations

03C Ejecta

Ejecta

RMNS

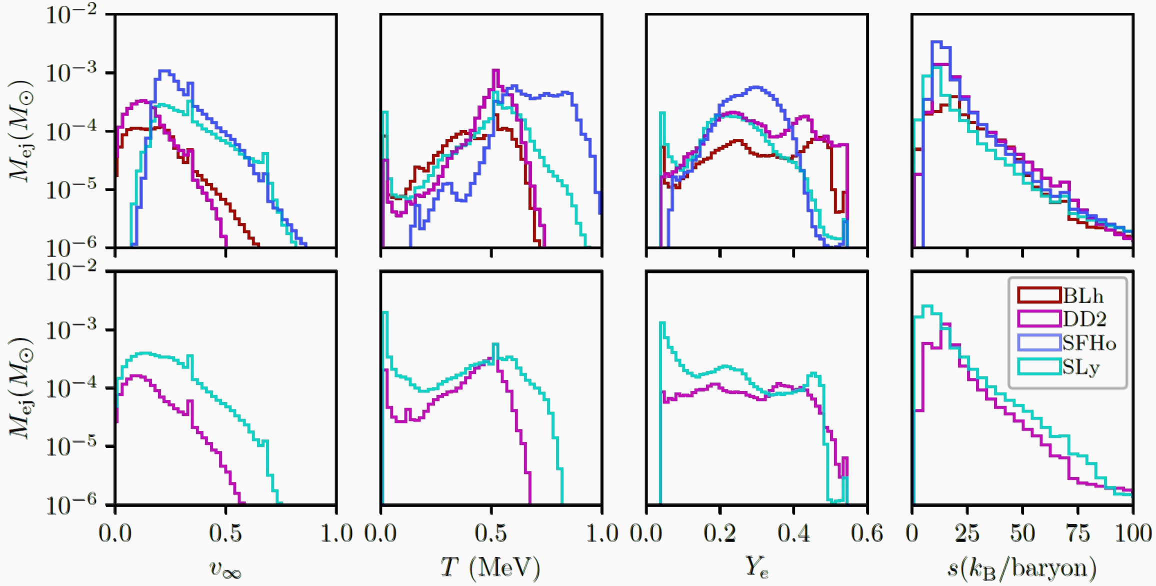
no RMNS

EOS	q	$\delta t_{\rm AH}$ (ms)	$M_{\rm ej,tot}$ ($10^{-2} M_\odot$)	$E_{\rm kin}$ (10^{50}erg)	$\langle v_\infty \rangle$	$\langle Y_e \rangle$	$\langle s \rangle$ (k_B/baryon)	$\langle T \rangle$ (MeV)	$M_{\rm ej}^{v\geq0.6}$ ($10^{-2} M_\odot$)	$M_{\rm ej}^{Y_e\geq0.4}$ ($10^{-2} M_\odot$)	$M_{\rm ej}^{s\geq150}$ ($10^{-2} M_\odot$)
BLh	1.0	21.745	0.188	0.605	0.145	0.309	23.747	0.418	5.949×10^{-4}	0.061	5.603×10^{-4}
DD2	1.0	40.096	0.508	0.673	0.079	0.308	19.182	0.509	3.504×10^{-8}	0.144	2.277×10^{-4}
SFHo	1.0	1.762	0.819	6.807	0.287	0.283	16.761	0.697	1.407×10^{-2}	0.017	9.041×10^{-4}
SLy	1.0	0.792	0.342	3.765	0.324	0.230	16.190	0.498	1.993×10^{-2}	0.013	1.219×10^{-3}
DD2	1.2	31.181	0.363	0.530	0.071	0.266	18.494	0.400	1.069×10^{-4}	0.068	2.220×10^{-4}
SLy	1.2	19.179	0.871	3.525	0.152	0.187	13.562	0.327	8.315×10^{-3}	0.101	8.168×10^{-4}

★ Simulations that produce **remnant massive neutron stars (RMNSs)** after the merger result in **systematically higher values of Ye** when compared to simulations that result in BH formation

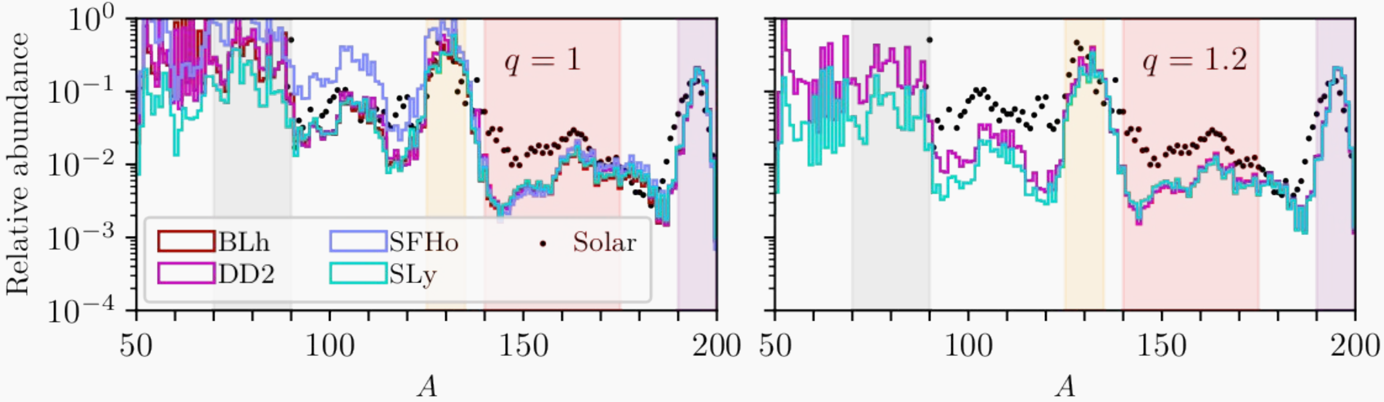
★ These simulations may also result in **significantly higher amounts of proton-rich (Ye > 0.4) rich ejecta**

★ The **RMNS continuously irradiates the surrounding disk with neutrinos**, which may be absorbed onto the neutron-rich environment and produce proton-rich ejecta



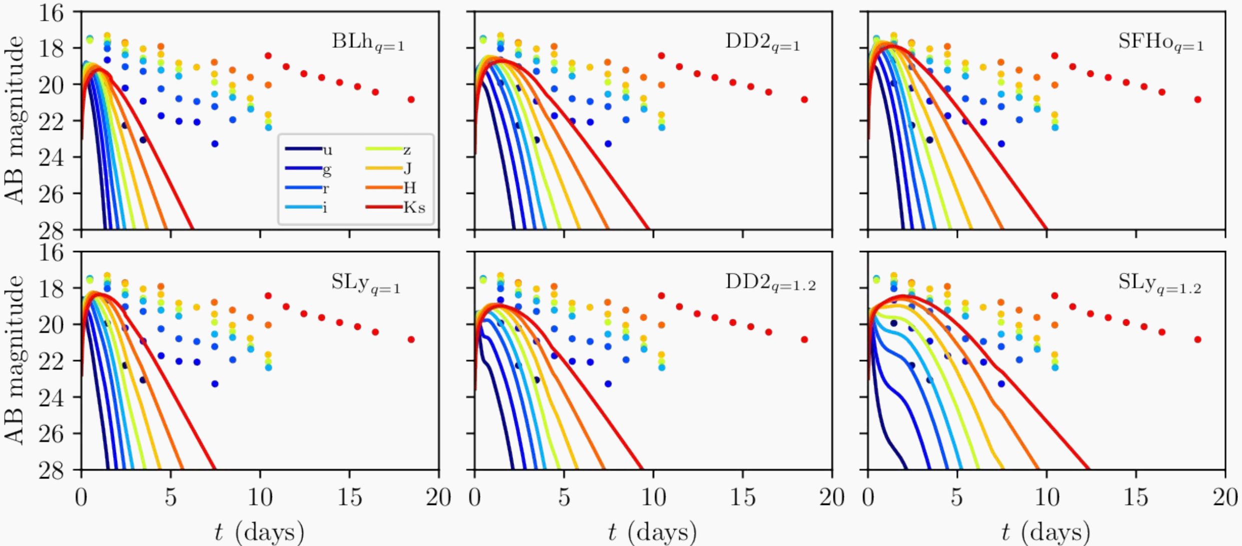
03d Nucleosynthesis

Nucleosynthesis and Kilonovae



★ Despite significant differences in the amount of proton-rich material between cases that produce relatively long-lived RMNSs and those that do not, **no clear trends emerge in the nucleosynthetic patterns**

★ As a result, no clear trends are seen in the KN lightcurves resulting from these dynamical ejecta



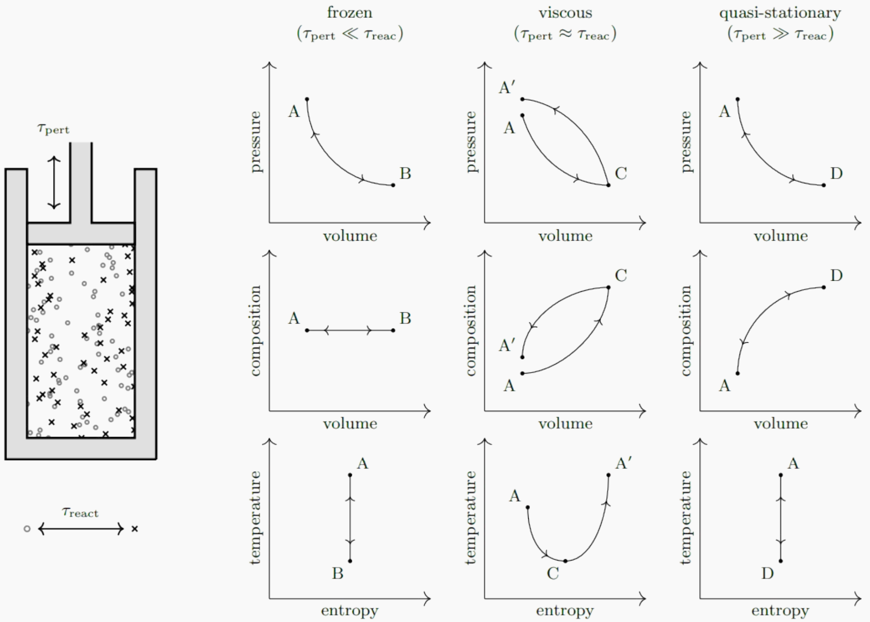
03e Out-of-equilibrium effects

What is the size of bulk viscosity in BNS mergers?

Bulk viscosity is typically calculated using the dimensionless parameter

$$\mathcal{A} = \frac{\mu_\Delta}{T}.$$

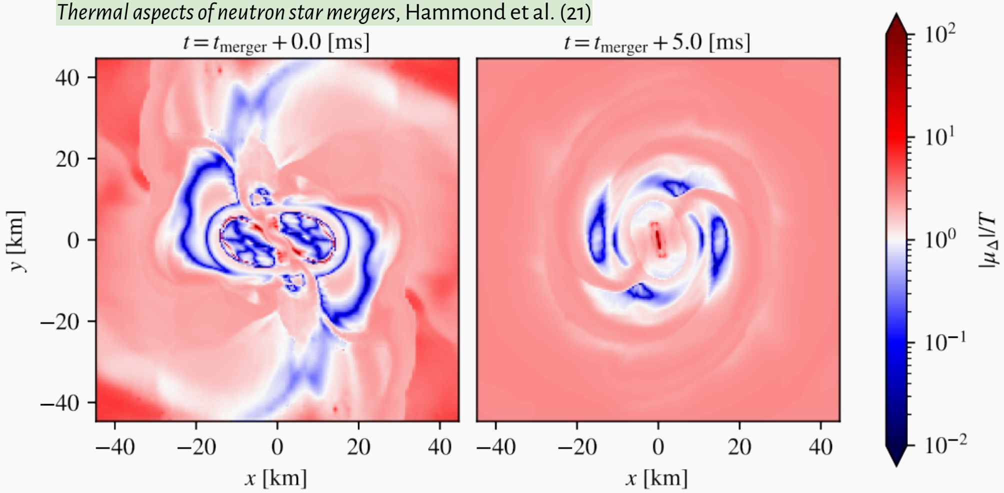
Simulating bulk viscosity in neutron stars I: formalism, Camelio et al. (22)



The calculations is carried out using different techniques depending on the size of the parameter

$\mathcal{A} \ll 1$	Leading order, perturbative regime
$\mathcal{A} \gg 1$	Suprathermal and general solution

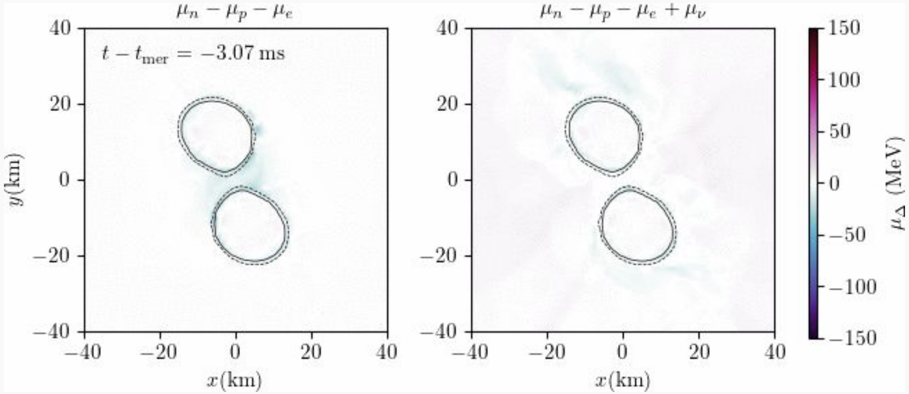
Thermal aspects of neutron star mergers, Hammond et al. (21)

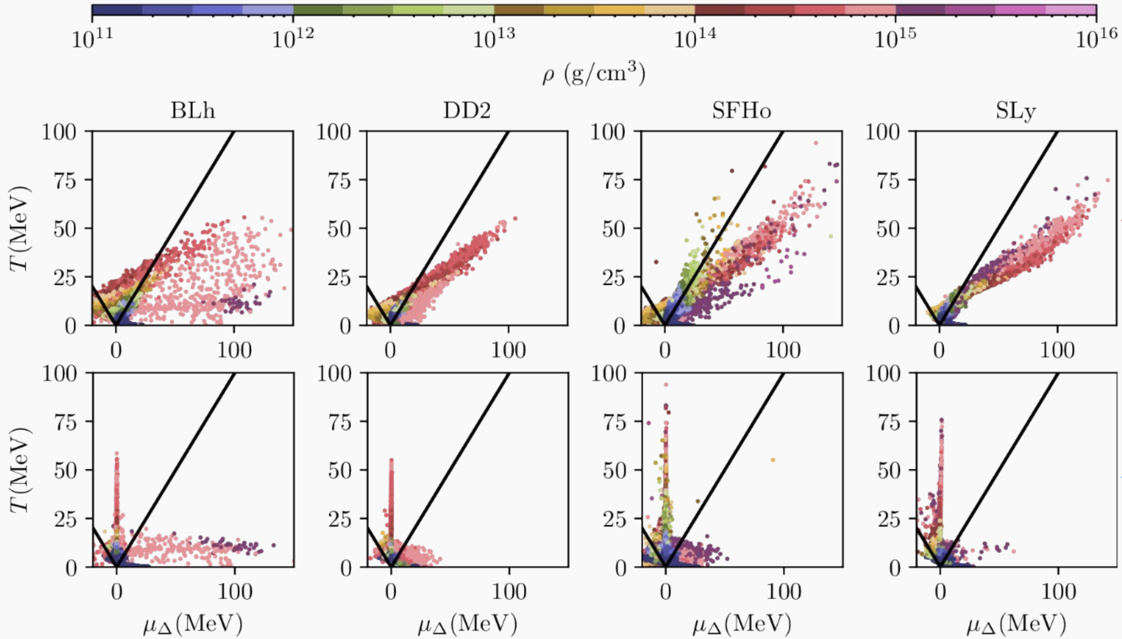


*** Crucially missing from simulations that do not include neutrino transport is the impact of trapped neutrinos. If neutrinos are sufficiently trapped, they may allow for the proper Urca processes to take place in equilibrium**

Out-of-equilibrium effects

- ★ When accounting for trapped neutrinos, the matter appears to remain close to local weak equilibrium.
- ★ In this regime bulk viscosity may be small enough to be treated perturbatively





Assume no neutrino trapping

Account for neutrino trapping by considering local neutrino fraction

Out-of-equilibrium effects

Hydrodynamics timescales

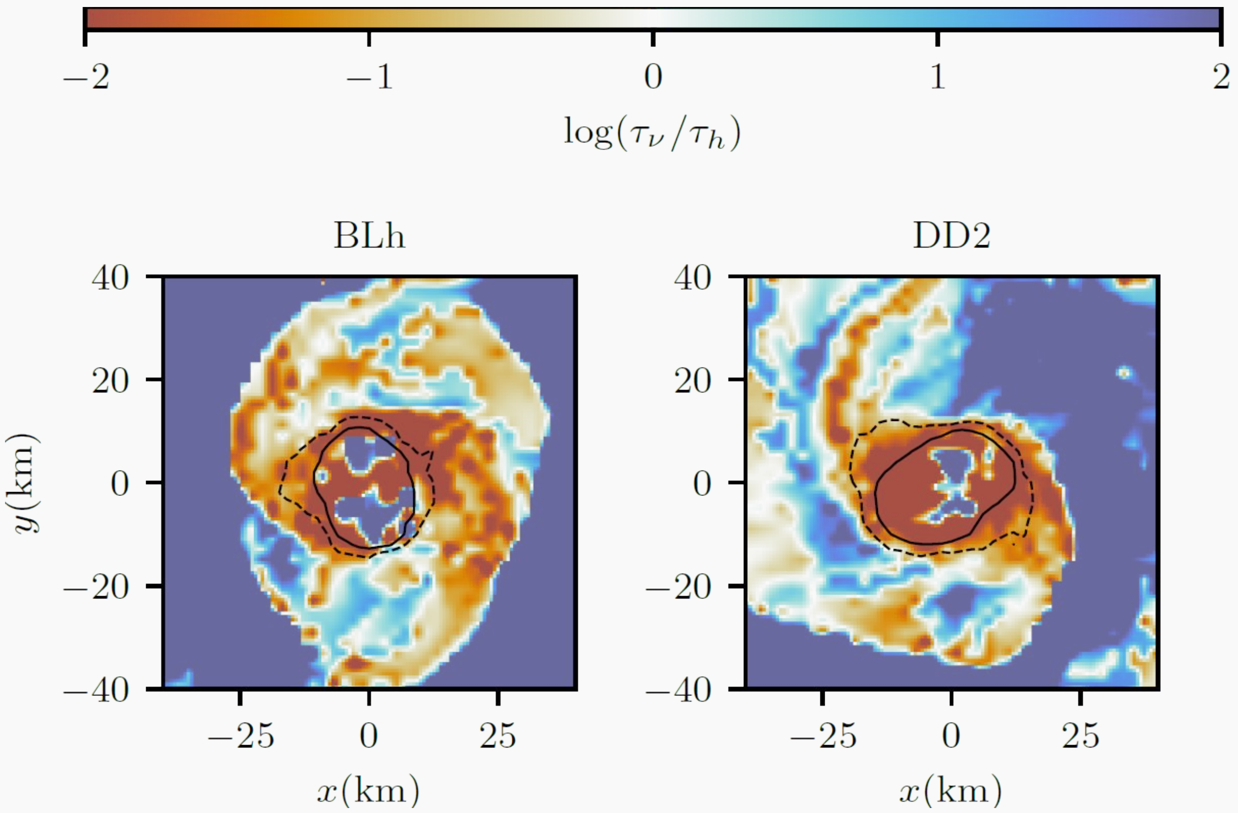
$$\tau_h = -\nabla_\mu u^\mu \approx \frac{D}{\dot{D}}$$

$$\tau_h \approx \frac{\rho W \sqrt{\gamma}}{\partial_k(\sqrt{\gamma}\rho W \omega^k)}$$

Neutrino interaction timescales

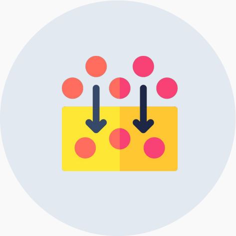
$$\tau_\nu = \frac{1}{\sqrt{\kappa_{\rm abs}(\kappa_{\rm abs} + \kappa_{\rm scat})}}$$

- ★ An approximate comparison of the timescales relevant to bulk viscosity reveals that for the bulk of the matter **the neutrino interaction timescales are significantly smaller than hydrodynamics timescales**, suggesting neutrinos are in weak equilibrium there
- ★ **There are few regions where the two relevant timescales are commensurate**



04 Conclusion

Conclusion

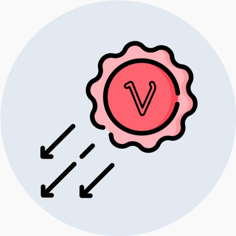


Neutrino absorption is key

- **Our M1 scheme accurately captures neutrino trapping and reabsorption**, which leads to many interesting effects

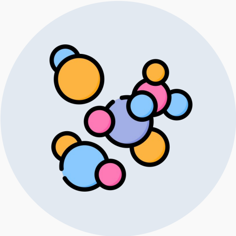
Ejecta properties are significantly affected

- The combined effect of the EOS (which largely determines the remnant lifetime) and our M1 scheme leads to **systematically higher ejecta electron fractions for longer-lived RMNSs**
- This does not strongly appear to affect nucleosynthetic patterns and KN lightcurves



Neutrino luminosities are consistent with other schemes

- **Luminosities largely consistent with other schemes/methods**
- Good agreement in trends established for M0



Out of equilibrium effects

- The significant neutrino trapping and reabsorption allows the medium to **remain near local weak equilibrium**
- **This may mitigate the impact of bulk viscosity in the post-merger environment** (more quantitative analyses remain to be done)

Thanks!

Questions?

To reach out to me, email:
pespino@berkeley.edu