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Impact of r-Process Heating on Disk Outflow from Neutron Star Mergers

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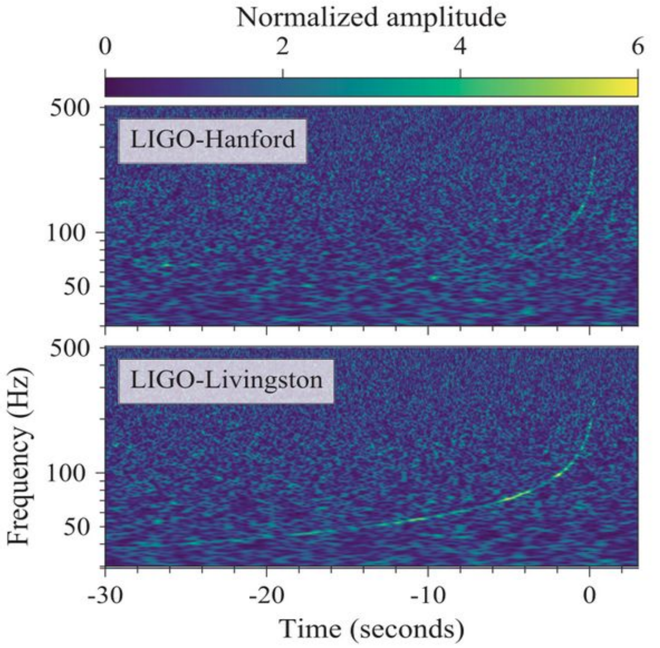
Theory - Outflows from Binary Neutron star Mergers

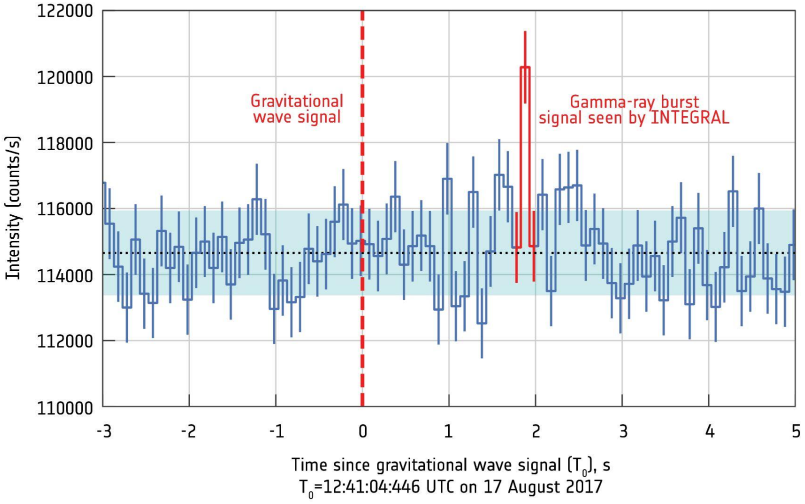
- During the merges, mass ejection occurs on dynamical timescales due to tidal force, producing ~10^{-4} to 10^{-2} $M_{\odot}$ of material with escape velocities of ~0.1-0.3c. (Metzger et al. 2014)
- After the merger, some of the material is still gravitationally bound and can form an accretion disc of up to 0.3 $M_{\odot}$ that expand slower and evolves on longer timescales.
- The ejected material rapidly decompress from nuclear densities, then went through r-process nucleosynthesis which produce unstable nuclei and power the kilonova. (Ruffert & Janka 1999; Stephens et al. 2008)

Observation – GW170817 / GRB170817A

Binary neutron star merger (1.3 / 1.5 Msun) , at ~40 Mpc

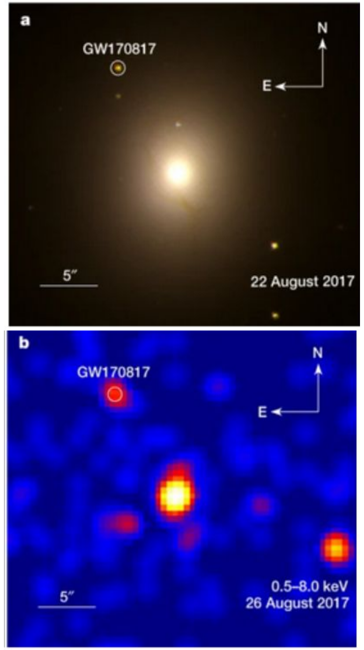


Abbottetal et al. 2017

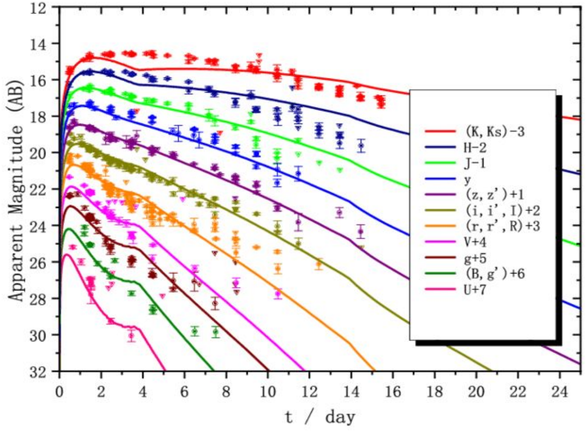


Savchenko et al. 2017

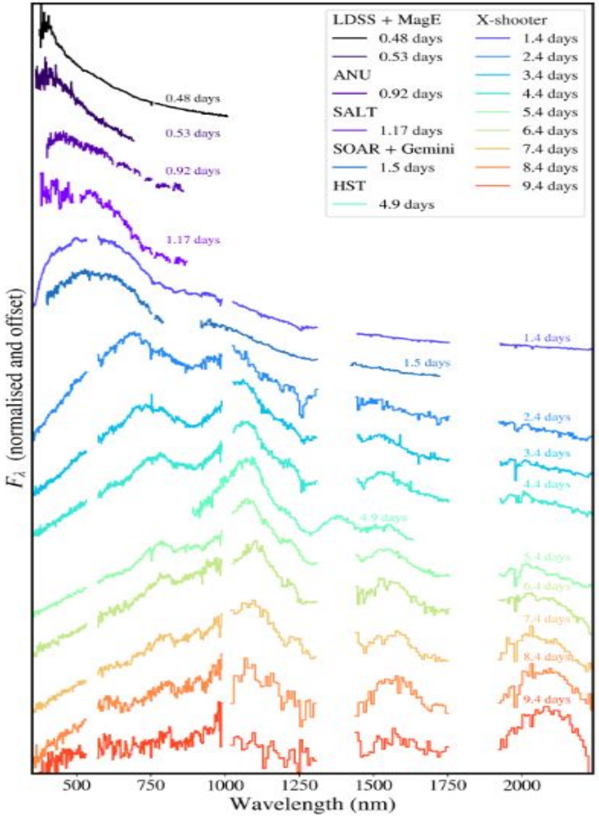
Observation – AT2017gfo



Troja et al. 2017



Arcavi et al. 2017



Sneppen et al. 2023

Motivation and previous studies

- Feedback of r-process nuclear energy can alter the outflow properties.
- Most of the numerical studies separate hydrodynamical simulations and post-process nuclear networks. Therefore the feedback of r-process heating is not considered in the hydro simulations.
- Recently, several works have considered the heating feedback in the hydrodynamic simulation by different attempts with various simplifications. (H. Klion, 2021; F. Foucart, 2021; M. Haddadi, 2022; I. Kullmann, 2022)

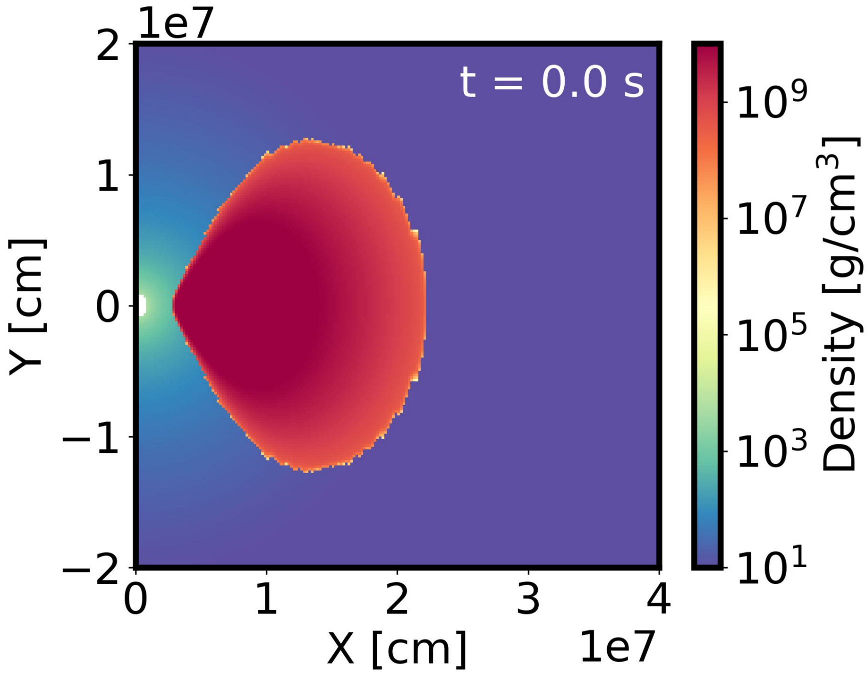
This project

- Perform viscous hydrodynamic simulations with self-consistent heating treatment to investigate the heating feedback on the post-merger disk.

Simulation setup

Disk model (Fernàndez et al. 2013):

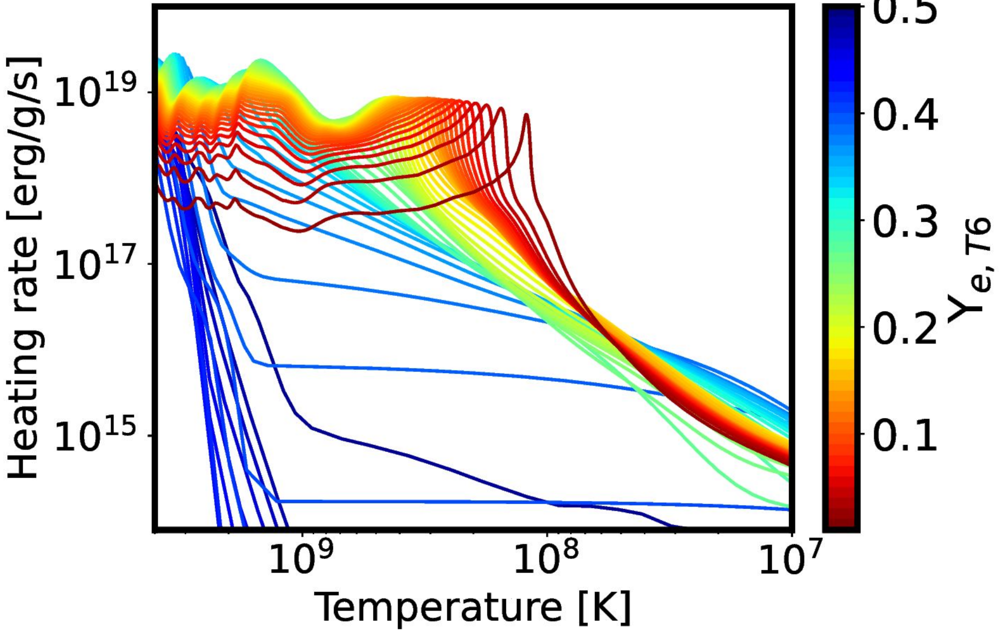
- FLASH (Eulerian Grid based code)
- Spherical coordinate in 2D
- Viscosity: α-disk
- Neutrino scheme:
  leakage scheme for cooling
  lightbulb scheme for absorption
- Passive tracers for data recording
  and providing heating informations.



Initial condition:

- central BH: mass=2.65 $M_\odot$, spin=0.8
- equilibrium torus: constant s = 8 kb/baryon, Ye = 0.1, mass = 0.1 $M_\odot$, Rd = 50 km

Nuclear heating Implementation



Wu et al. 2019

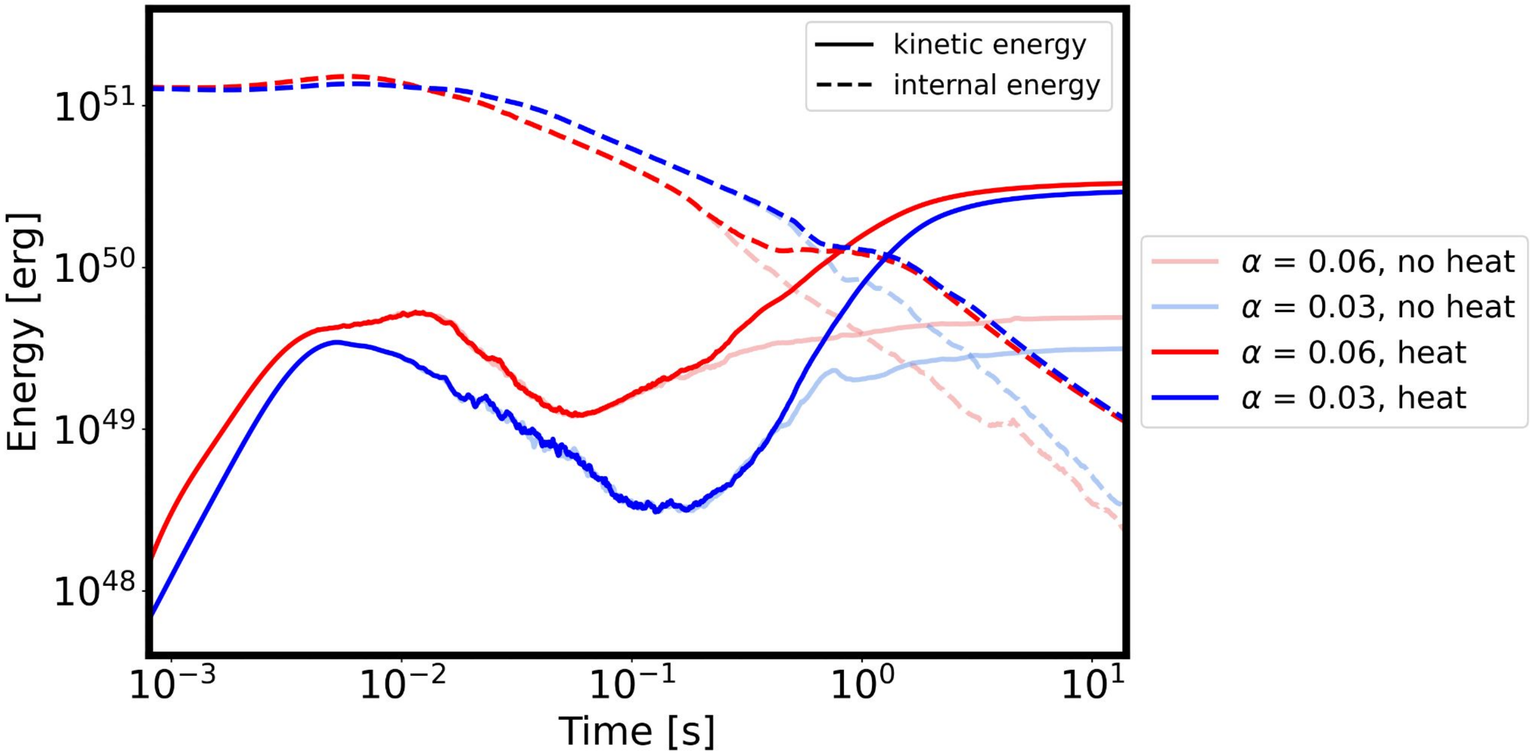
r-process heating rate is based on the initial electron fraction (Ye) and temperature.

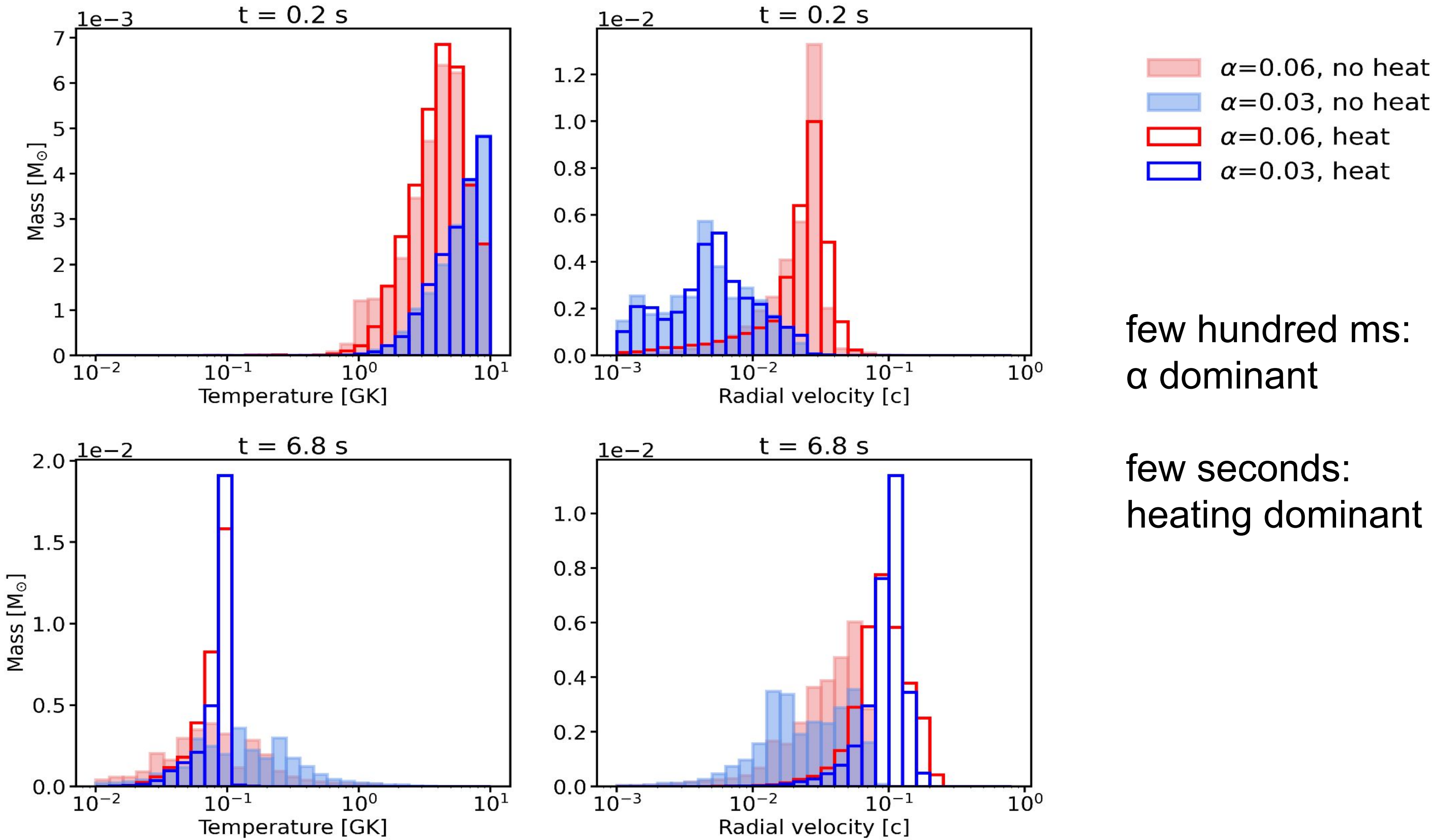
Local condition to add heating:
(1) Temperature < 4GK
(2) Radial velocity > 0

Parametertized nuclear heating based on

- Initial Ye:
  Ye value when tracer temperature first drops below 6GK.
- Local fluid temperature

Energy evolution

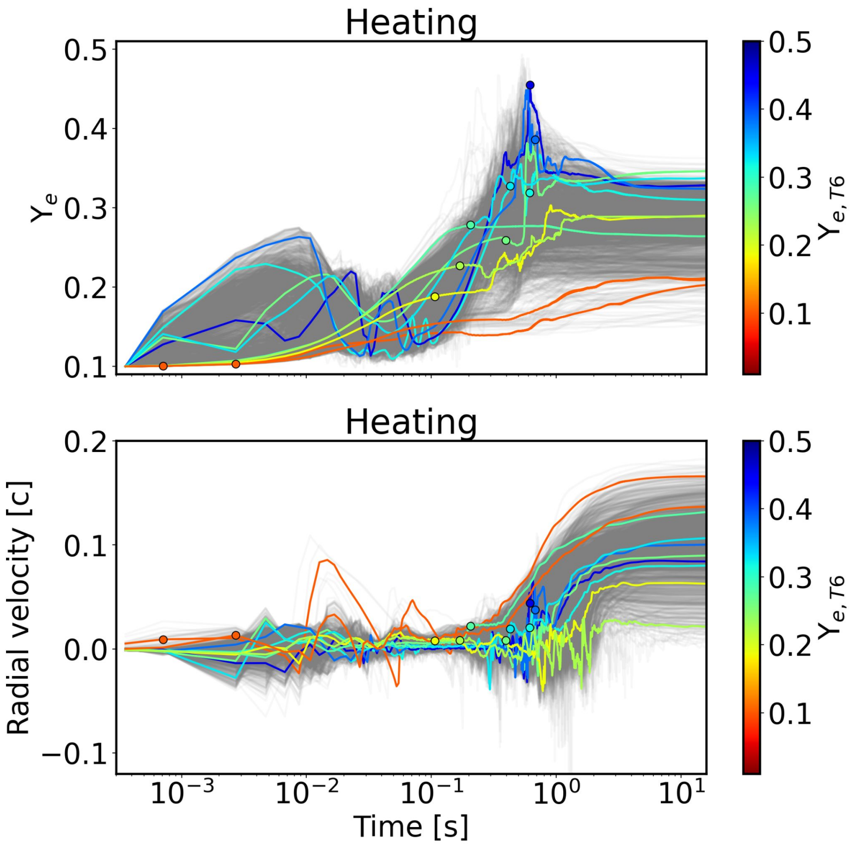




few hundred ms:
α dominant

few seconds:
heating dominant

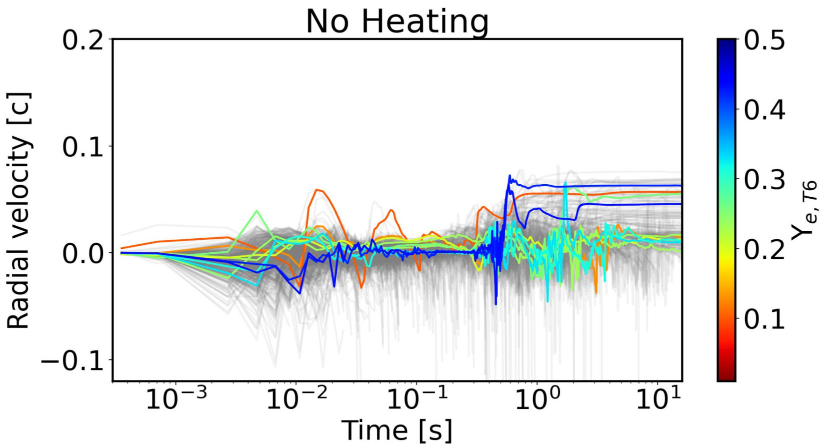
Ejecta radial velocity

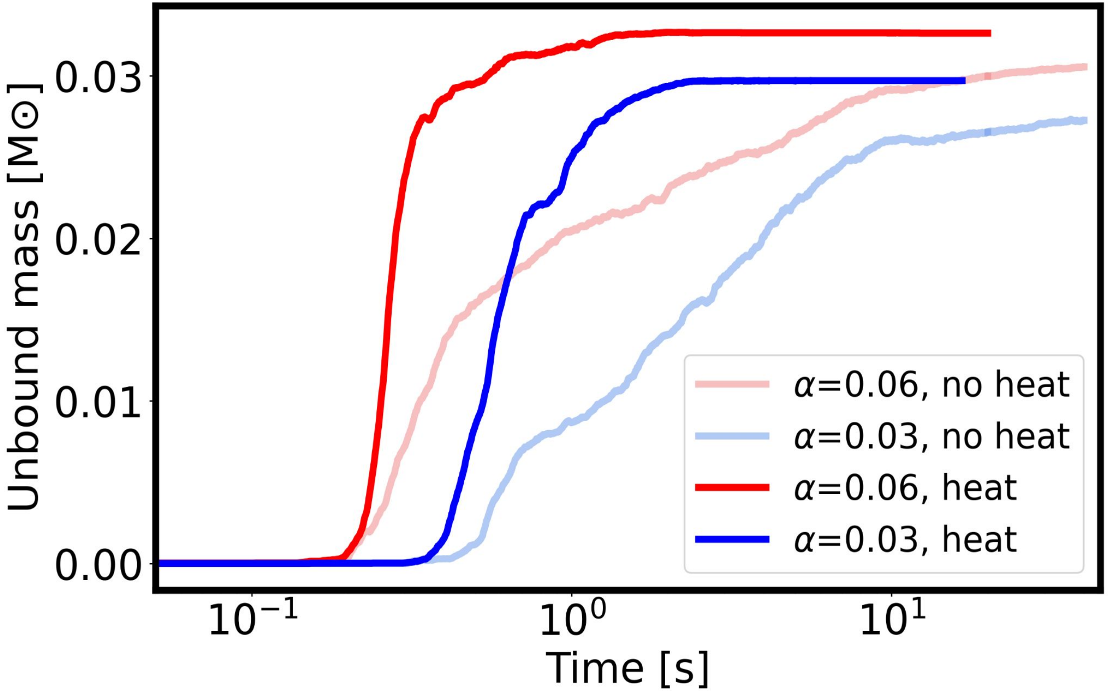


Initially low Ye component remain low Ye value.

Contribute higher heating rate and start heating earlier.

⇒ fast component

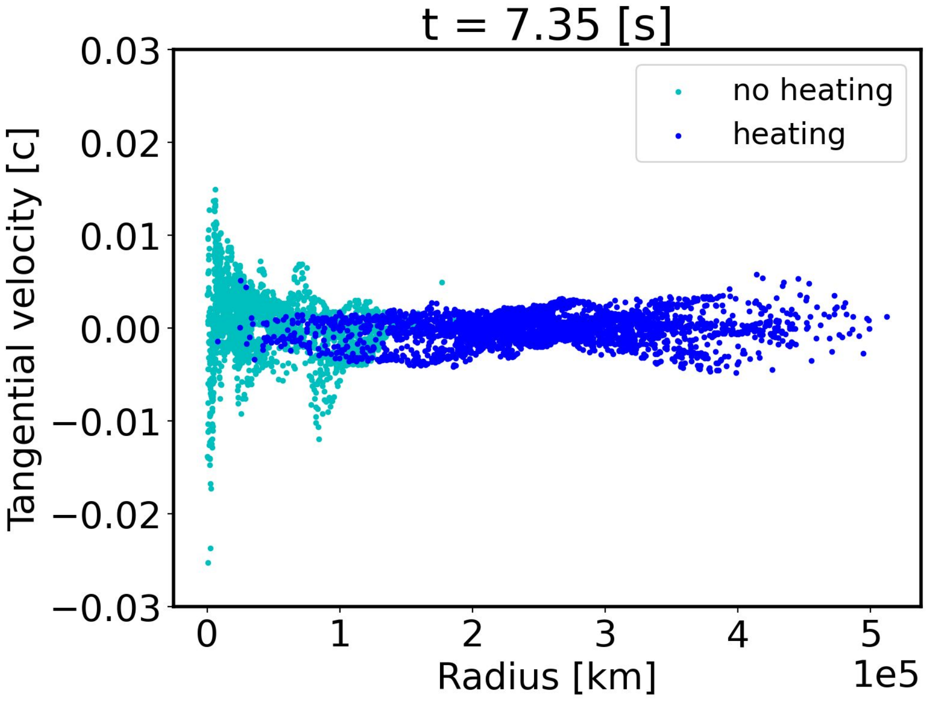


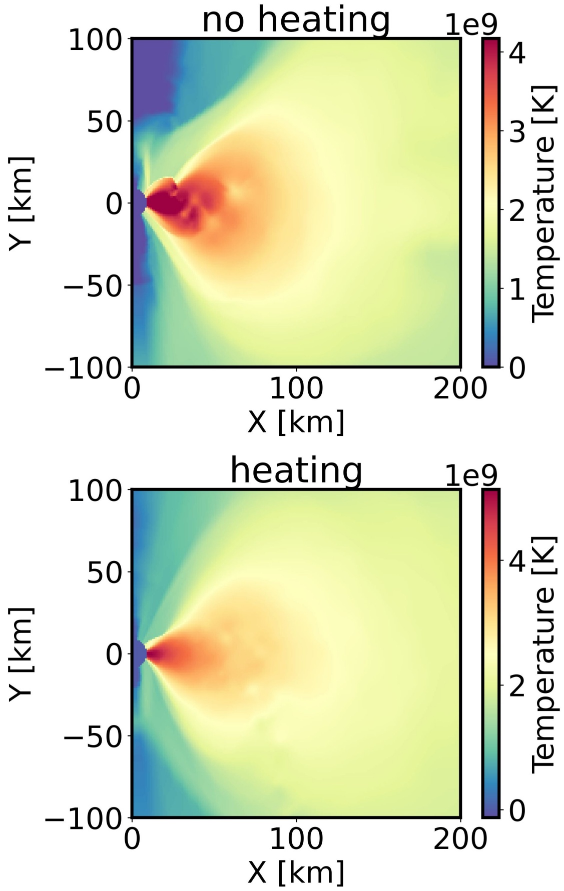


With the nuclear heating feedback:

- ➔ material get unbound earlier
- ➔ unbound mass increases by ~10%

Effect on convection





Summary

- We investigate the r-process heating feedback on the outflow properties by implementing parameterized heating energy in the viscous hydrodynamic simulations.
- Viscosity dominates the evolution at earlier phases, and r-process heating dominates later evolution.
- Nuclear heating increases the ejecta mass by ~10%.
- Without heating feedback, the mass unbound time is significantly delayed.
- Nuclear heating suppresses the convection at the inner region and increases radial velocity by a factor of 2.