3D Visualization of Supermassive and Hypermassive Binary Neutron Star Mergers

Yinuan Liang · Rohan Narasimhan · Stuart L. Shapiro · Antonios Tsokaros · James Bamber

Department of Physics · Urbana, IL

Abstract

What we are studying: Binary Neutron Star Mergers

- A binary pair of 2 identical neutron stars can collapse into supermassive and hypermassive remnants depending on the mass of the stars

How we study them: Numerical Relativity

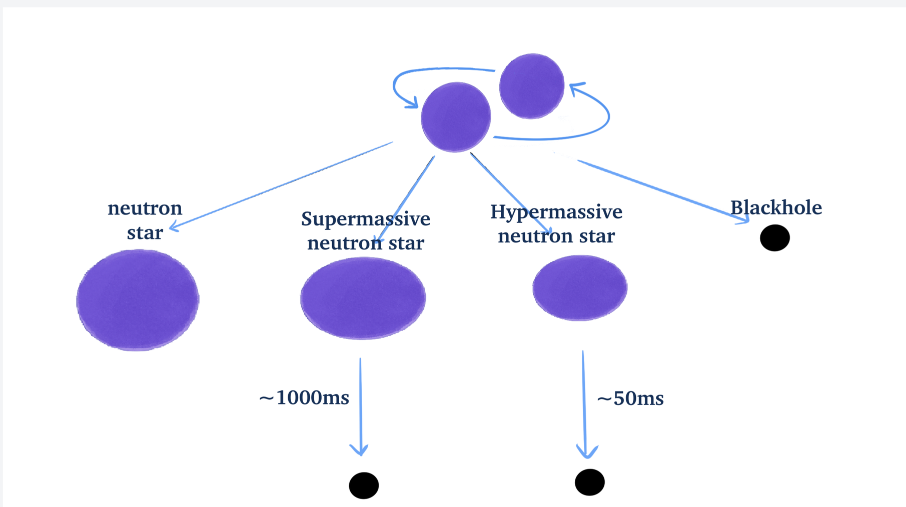
- Einstein's equations are decomposed into 3+1 dimensions using Baumgarte-Shapiro-Shibata-Nakamura formalism. Space and time are separated allowing the time evolution of an initial spatial slice.[1]
- General relativistic magnetohydrodynamics (GRMHD) combine Einstein's equations with Maxwell's equations and fluid dynamics to allow study of systems such as binary neutron stars.[1]

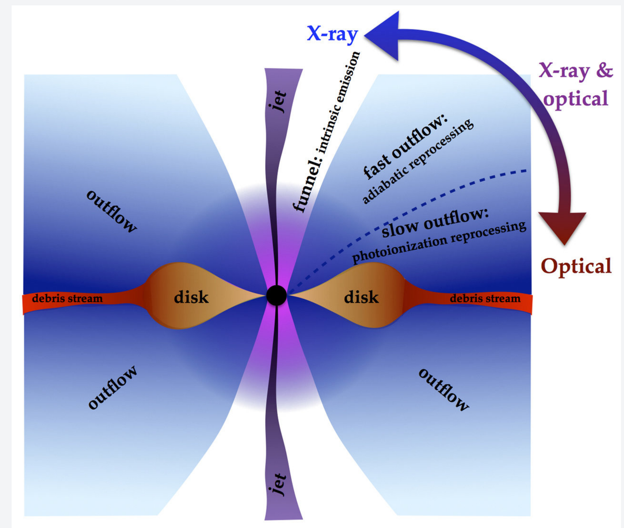
Goal of the study: In search of a relativistic jet for evidence of gamma-ray burst

- It is known that black holes and hypermassive neutron star remnants (once collapsed into a black hole) can produce a jet of ionized matter at relativistic speed around its poles due to the accretion of magnetized matter; however, if supermassive remnants produce the same kind of jet is still unknown. [2]

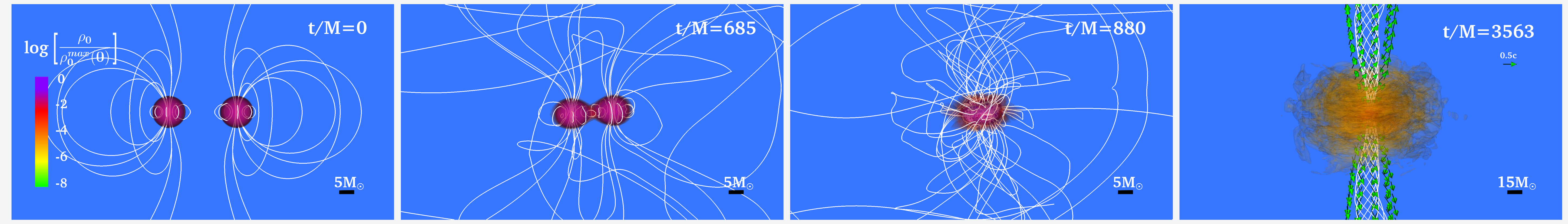
Our Cases

- Irrotational binary neutron stars with total gravitational mass 2.40, 2.51, 2.54, 2.57, and 2.70 $M_\odot$
- Spinning binary neutron stars with total gravitational mass 2.40, 2.51, 2.54, and 2.57 $M_\odot$
- the IR and SP neutron stars of mass 2.40, 2.51, 2.54, and 2.57 will form hypermassive remnants, and later form supermassive remnants, while the 2.70 case will form hypermassive neutron stars and later collapse into a black hole.

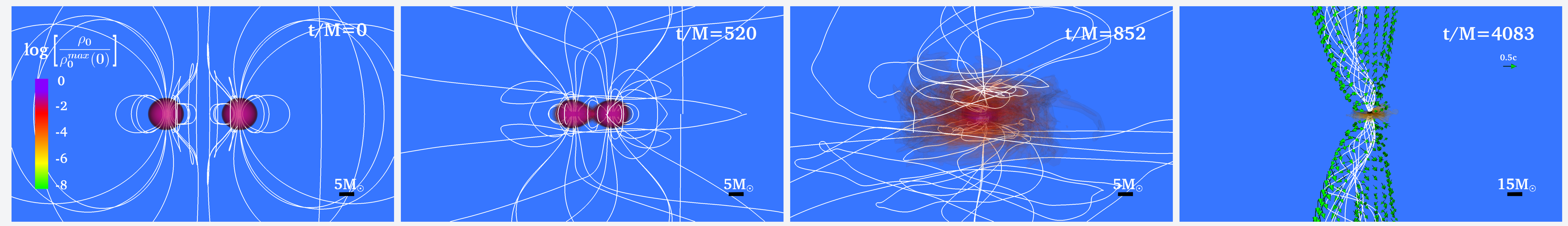




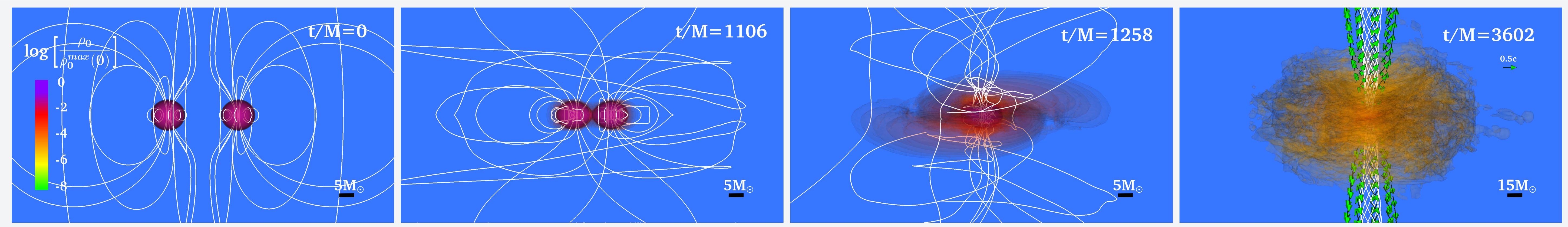
IR2.40



IR2.70



SP2.40



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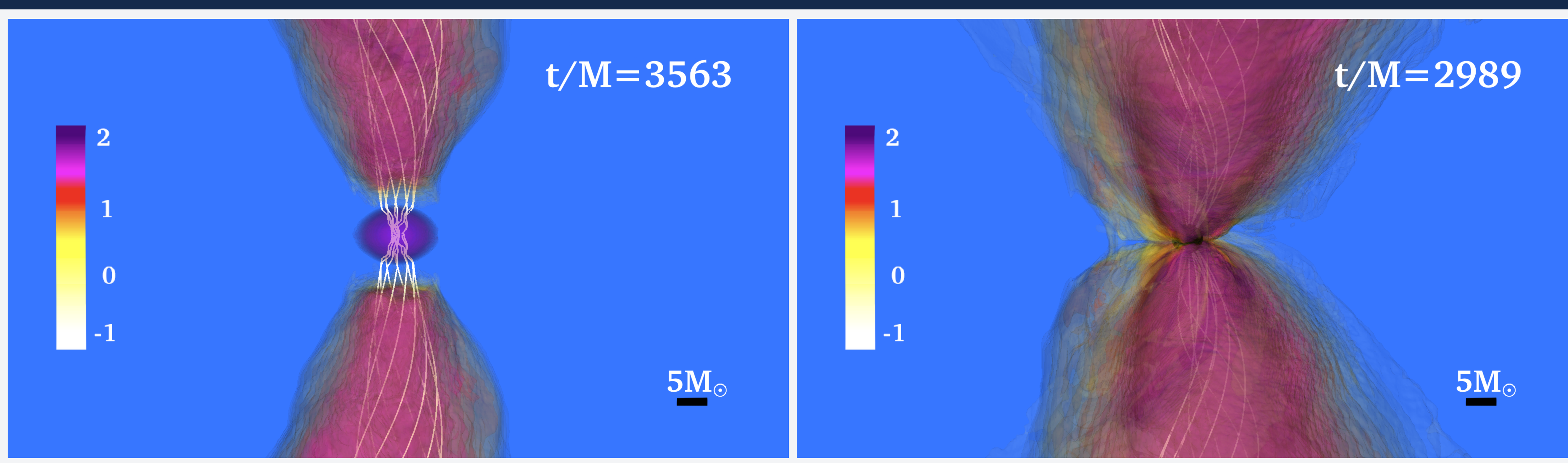
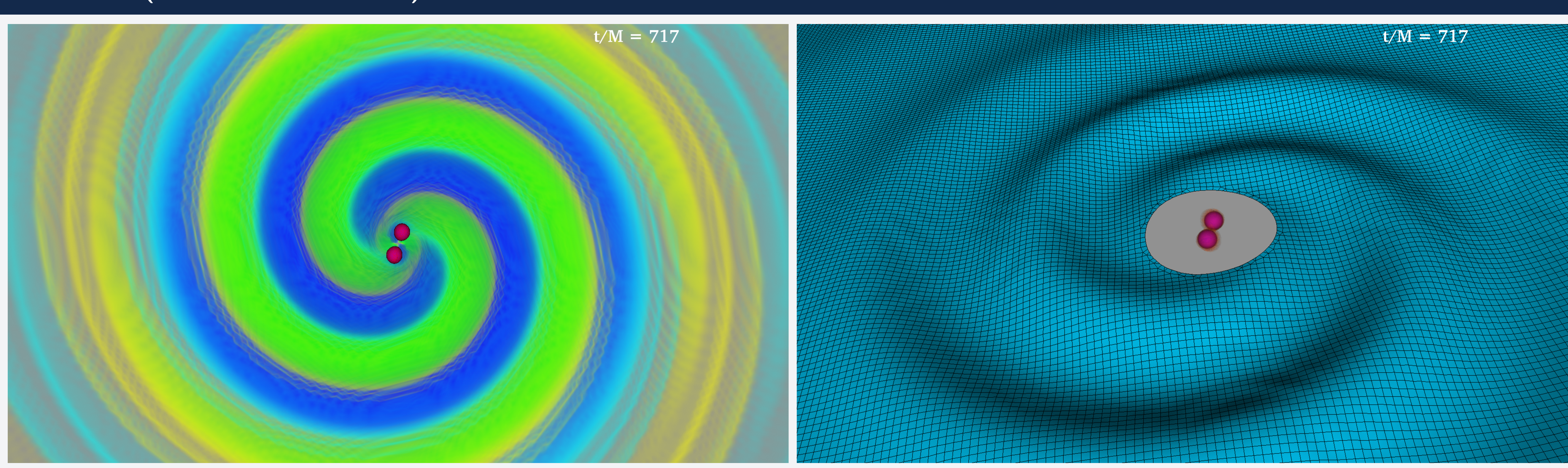
Bsq2r $\frac{b^2}{2\rho}$ comparison



Gravitational Waves (3D and Contour Plot)



Results

We use the well-tested IllinoisGRMHD code to generate the evolution data for the NSNS cases.

Evolution of stars

- In both the neutron star cases, the stars collapse into remnants and show tightly collimated magnetic field lines some time after merger.
- The 2.70M case forms an unstable remnant which eventually collapses to a black hole, while the 2.40M case forms a stabilized remnant.
- The accretion disk around the black hole is much smaller than that of the supermassive neutron star remnant due to its larger mass and gravitational pull.

Bsq2r $\frac{b^2}{2\rho}$ comparison: IR2.40 vs IR2.70

- At the end of the evolution of the 2.70M case, we observe collimated magnetic field lines and a high $\frac{b^2}{2\rho}$ density around the funnel, indicating an outflow of matter, which is a necessary requirement for detectable gamma-ray bursts.
- The 2.40 case similarly has collimated field lines, but a much lower density of $\frac{b^2}{2\rho}$. This case also has a lot more gas polluting the funnel region, and we cannot be sure that it can overcome the gas and accelerate plasma to relativistic speeds. So we cannot conclusively say that there is a relativistic jet.

Gravitational Waves

- The gravitational wave plots shown on the left are from the spinning 2.57M case. We generally show two types of plots, the left one is a 3D visualization to show the quadrupole nature of the waves, while the one on the right is a contour visualization of the wave.
- We extract the gravitational wave data at seven different extraction radii and convert the values into $h_{+/x}$ polarization. We then plot them at a retarded time with respect to the neutron stars.

References and Acknowledgements

[1] L. Sun, M. Ruiz, S. L. Shapiro, and A. Tsokaros, "Jet Launching from Binary Neutron Star Mergers: Incorporating Neutrino Transport and Magnetic Fields" *Phys. Rev. D*, vol. 105, p. 104028, 2022.

[2] J. Bamber, A. Tsokaros, M. Ruiz, S. L. Shapiro, "Jet-like structures in low-mass binary neutron star merger remnants", 2024

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Rohan Narasimhan (rohann4@illinois.edu)
Yinuan Liang (yinuanl@illinois.edu)

Movies SP2.51

Movies IR2.70

Movies IR2.40

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