A Study of Matter Outflows from a Binary Neutron Star Merger

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I. Introduction

In August 2017, LIGO detected gravitational waves (GW) from GW170817 [1]. This presented for the first time, GWs originating from a **neutron star – neutron star (NSNS) merger**. Studies of neutron star mergers are significant because the GW and electromagnetic wave signals can inform us on the nuclear physics of neutron stars and the creation of heavy elements in the universe. Matter outflows of kilonovae provide an ideal environment for such studies and are of interest to us.

- **Gravitational Waves:** The ripples of curved spacetime caused by massive moving objects. These ripples propagate at the speed of light.
- **Kilonovae:** Optical and infrared emission from radioactive decay in the matter outflow of neutron star mergers.

In this study we will be taking a look at the case of a NSNS merger. **Our goal is to recreate the matter density distribution at any arbitrary time using SpEC-Hydro** [2, 3], a relativistic hydrodynamics code.

II. Matter Outflows

1. The **neutron rich environment** of the NSNS outflows promotes neutron capture.
2. Early in the ejecta, **neutron capture (r-process)** occurs faster than radioactive decay and consequently, heavy elements are created.
3. From kilonova observations, what we detect on Earth are the **radioactive decays** of unstable elements into stable elements.

∴ Matter interactions in the matter outflow between particles lead to **nuclear reactions** that power emitted electromagnetic signals which can be detected on Earth.

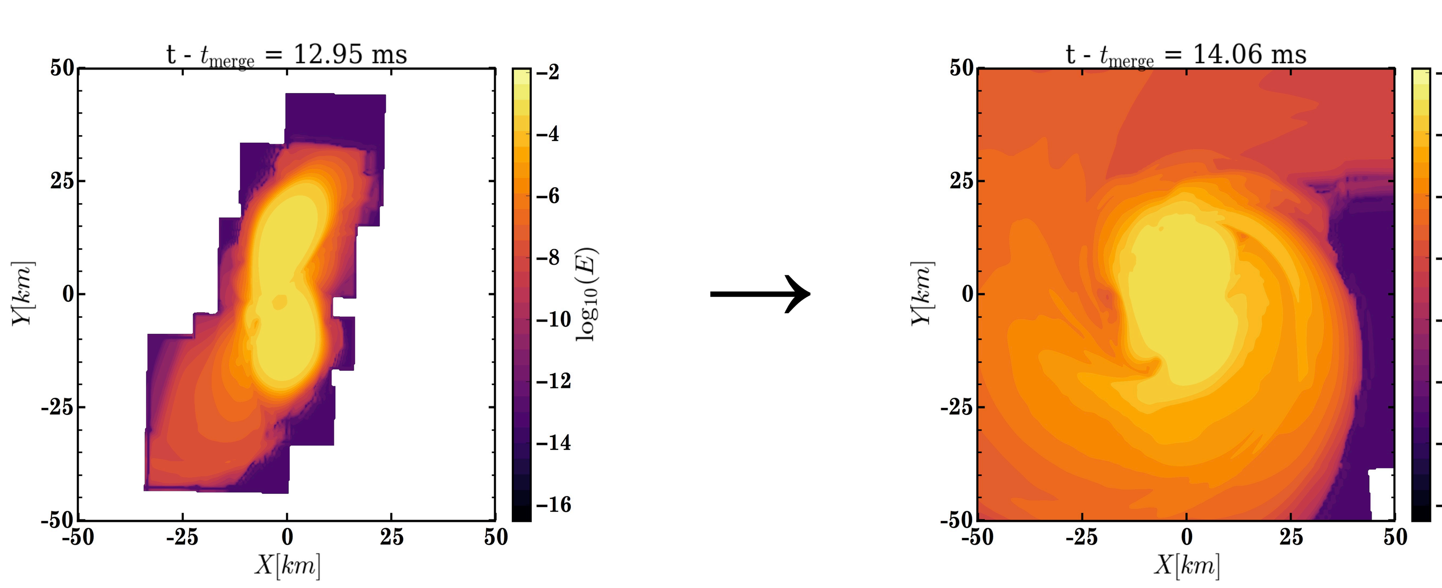

FIG 1. Matter density maps of our NSNS simulation.

HOWEVER… Matter is ejected from our NSNS system but it cannot be followed on SpEC-Hydro's set numerical grid. So **we sample the ejecta at the grid boundary and then evolve it…**

III. Merger Evolution

The time evolution of the NSNS system is of interest to us because **recreating the trajectories** of particles in the ejecta is necessary in modeling matter density distributions at any desired time.

III-A. Classical Particle Trajectories

We use **Newton's law of gravitation** to model the orbiting bodies of the NSNS system. Integrating this results in a 6-D coupled differential equation which is solved numerically.

$$\vec{F}_{grav} = m\ddot{\vec{r}} = \frac{-GMm}{r^3}\vec{r}$$

III-B. Relativistic Particle Trajectories

A linear transformation must be made to **ensure that energy is conserved** in our relativistic and classical simulations. We do this by including a term "A" in the energy conservation equation:

$$\epsilon = \frac{(Av)^2}{2} - \frac{GM}{r} = -U_t - 1 \qquad \begin{array}{l} \epsilon > 1, \text{ Unbound} \\ \epsilon < 1, \text{ Bound} \end{array}$$

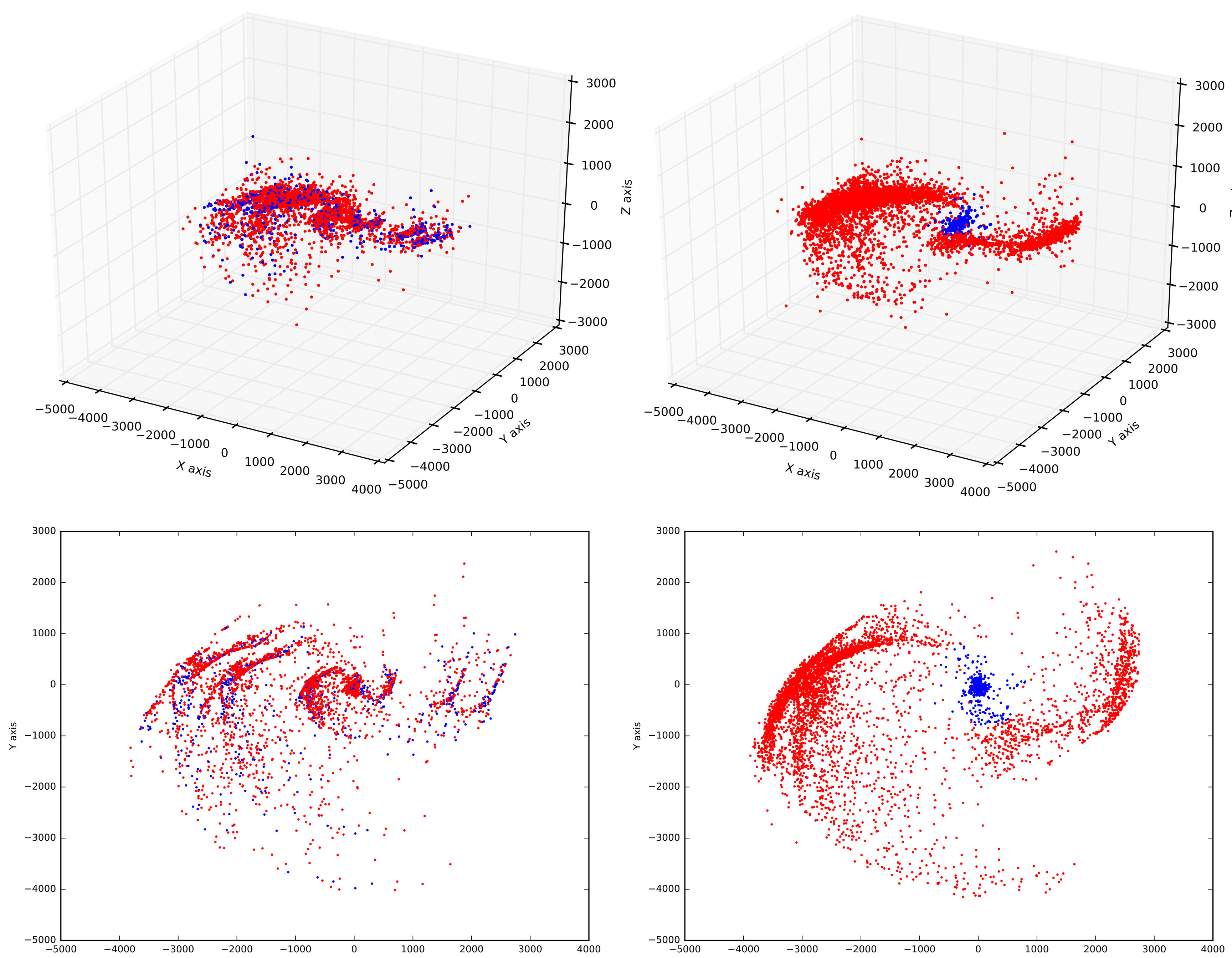

FIG 2. Subset of particles evolved over time. LHS: Particles 1 ms after merging. RHS: Particles 37 ms after merging.
Blue = Bound particles | Red = Unbound particles

IV. Data Analysis

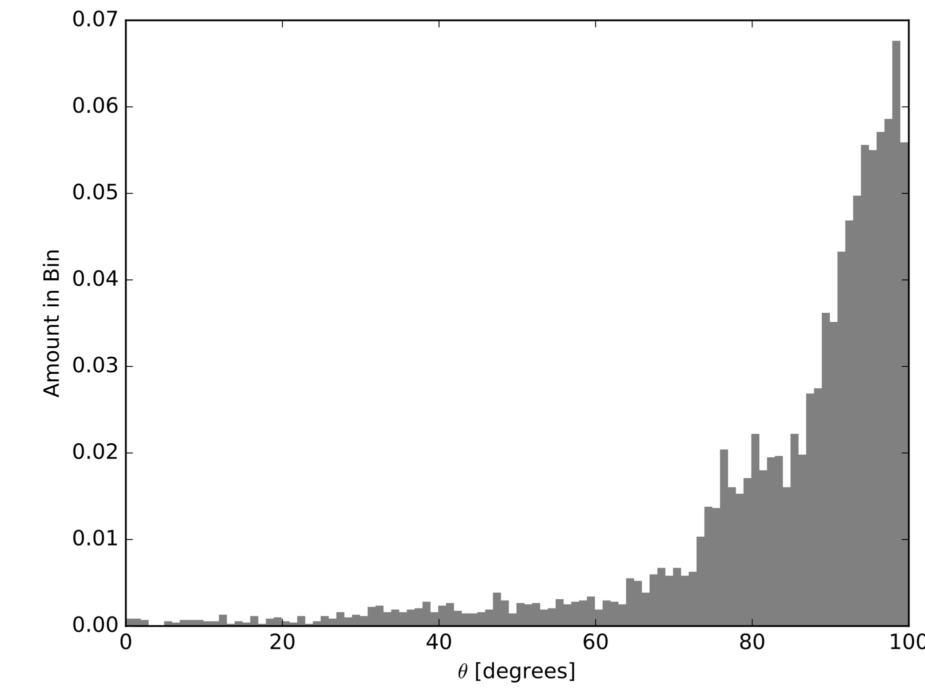

FIG 3. Angle distribution of particles leaving the merger system.

The polar angle is taken to be zero and the bins are normalized to the particle count.

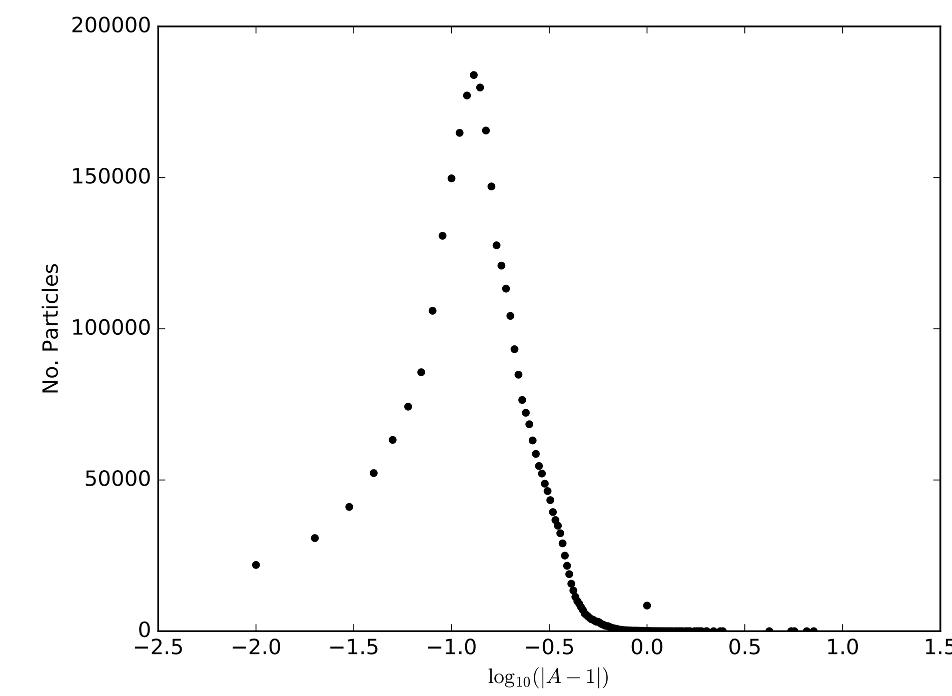

FIG 4. Analysis of error for relativistic corrections.

No. Particles	Average 'A'	No. of Unsolvable 'A'	Percentage of Unsolvable 'A'
10,000	1.53	0	0
100,000	1.46	3	0.003
1,000,000	1.31	992	0.099
2,533,255	1.19	42,377	1.672

V. Conclusions & Future Work

1. We have presented **a methodology to recreate the matter density distribution** of a NSNS merger at any arbitrary time using SpEC-Hydro and classical mechanics.
2. We have performed analysis on the properties of the particles leaving the merger system as well as the errors made by using non-relativistic simulations.
3. The methods presented here can also be applied to any generic merger system.

Acknowledgements & References:

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[1] Abbott et al. 2017, Phys. Rev. Lett. 119, 161101, (2017)
[2] Duez et al., Phys. Rev. D78, 104015, (2008)
[3] Foucart et al., Phys. Rev. D87, 084006, (2013)