Usage Report for Fiscal Year 2023

**Project Title:**

# Two- and three-dimensional neutrino-hydrodynamics simulations of hyper-massive neutron stars

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## 1. Background and purpose of the project, relationship of the project with other projects

If two neutron stars revolve around each other in the form of a binary, they continuously loose energy and angular momentum in the form of gravitational waves. They will very slowly approach each other and, ultimately, will fall into each other and merge to form a single object, a so-called hypermassive neutron-star (HMNS), which may either collapse into a black hole (BH) on timescales of milliseconds or longer or may remain indefinitely stable. The recent observation of the collision of two neutron stars in the event called GW170817 was the first of its kind and sparked tremendous attention within the scientific community. This is because very important questions are connected to neutron-star mergers: What is the origin of about half of the heavy elements heavier than iron, those produced by the so-called rapid neutron-capture (or r-) process? And, what is the origin of short gamma-ray bursts (sGRBs)?

Since GW170817 we now almost certainly know that a substantial fraction of heavy elements must have been created in the outflows of binary neutron-star mergers that occured during the past evolution of the Universe. This spectacular confirmation of existing theoretical models was possible, because material ejected in neutron-star mergers shines extremely bright and so could be observed in the form of a so-called Kilonova for several days after the merger. However, even though GW170817 was providing bright electromagnetic signals, it remains unclear how to exactly interpret these signals, particularly the red and blue kilonova. Lightcurve analyses of GW170817 predict that the bright blue kilonova is associated with ejected material of a few per-cent the mass of the sun and velocities of 10-30 per-cent the speed of light, while the red kilonova is believed to originate from another ejecta component with higher photon opacities. Although a growing number with exceedingly more sophisticated models of neutron-star mergers and their remnants already exists, a safe identification of the origin of each observed ejecta component is not possible at this moment. It is currently believed that the blue shining material is launched by a HMNS, but no available simulation is credible enough, yet, to scrutinize this hypothesis.

## 2. Specific usage status of the system and calculation method

For the hydrodynamical simulations we employ the code AENUS-ALCAR, which solves the Newtonian or special relativistic viscous hydrodynamics equations together with the M1 approximation of neutrino transport on a fixed, Eulerian mesh using Riemann-solver based finite-volume methods. The code was extensively tested and applied in a number of published studies. We typically run the code, which adopts a hybrid OpenMP + MPI parallelization, on 10-16 compute nodes.

## 3. Result

In [1] we performed the first coherent end-to-end simulations of neutron star mergers comprising a delayed collapse of the HMNS remnant. The term end-to-end indicates that all phases of substantial matter ejection are included, namely the dynamical merger phase (up to about 10ms after the stars collide), the HMNS phase (up to about 100-1000ms post merger), and the subsequent BH torus phase (up to 10 seconds post merger).

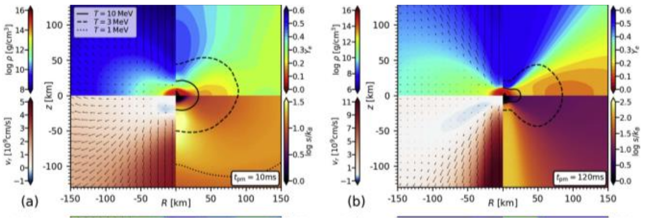

**Fig. 1:** Color maps showing the density (top left), electron fraction (top right), radial velocity (bottom left), and entropy (bottom right) at 150ms (left side) and 80s (right side) after the merger (from [1]).

Moreover, in order to obtain the final structure of the ejecta, which is important to know for a reliable prediction of the kilonova signal, we evolved the expanding ejecta for another 90 seconds. The resulting properties of the ejecta were post-processed to obtain the nucleosynthesis yields as well as an estimate of the kilonova bolometric light curve.

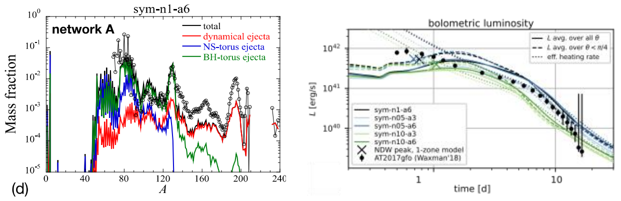

**Fig. 2:** Nucleosynthesis yields (left) and kilonova bolometric light curve (from [1]).

## 4. Conclusion

Our models are the first that provide a complete prediction of nucleosynthesis yields for delayed-collapse scenarios of neutron star mergers. An important finding of our study is that the kilonova observed with GW170817 is characteristically similar to the kilonova signals of our models, which is not the case for previous models by many other research groups that did not combine outflows of all phases of the merger. This result highlights the importance of end-to-end modeling, i.e. of including all evolutionary phases for predicting the kilonova lightcurve.

Second, since heavy elements with mass numbers of A>130-140 are underproduced compared to the solar pattern, our models also suggest that delayed-collapse systems are subdominant compared to events in which the NS remnant collapses to a BH promptly or briefly after the merger.

Moreover, our study suggests that symmetric mergers, i.e. mergers in which both NS masses are equal, exhibit a collapse somewhat later than asymmetric mergers.

Finally, our study also suggests that post-merger outflows produced by the remnant BH disks are all the more unfavorable for heavy r-process nucleosynthesis the longer the remnant NS survives before collapse. The reason for this is that the disk starts to expand and disintegrate already before BH formation, which causes its neutron richness to decrease well before the disk starts to launch outflows.

## Fiscal Year 2023 List of Publications Resulting from the Use of the supercomputer

### [Paper accepted by a journal]

[1] Oliver Just et al., *“End-to-end kilonova models of neutron star mergers with delayed black hole formation”,* The Astrophysical Journal Letters 951, L12 (2023)