Usage Report for Fiscal Year 2022

**Project Title:**

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

**Name:**

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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.

The original purpose of this project was the investigation of HMNS remnants of neutron-star (NS) mergers. The computational budget was used also to perform simulations investigating BH-torus remnants [1,2] and large-scale outflows [3] emanating from NS mergers, as well as BH-tori formed in massive collapsing stars ("collapsars", [4]).

## 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. Results and conclusions

In [1] we investigated the impact of fast flavor conversions of neutrinos on the heavy elements created in BH-torus remnants of neutron-star mergers, as well as on the resulting kilonova light curve. To this end, we developed a criterion providing us with the approximate locations at which angular crossings of the so-called electron-lepton number occur. At those locations, we assume that the fast flavor instability leads to equipartition of all six neutrino flavors. Our simulations are among the first to include flavor conversions in time-dependent simulations. Our results suggest that fast flavor conversions make the outflows from BH-torus systems slightly more neutron rich and thereby increase the amount of heavy elements created. Due to the higher opacity caused by the larger amount of lanthanides in the ejected material, the kilonova light curve peaks at a slightly later time (see Fig. 1).

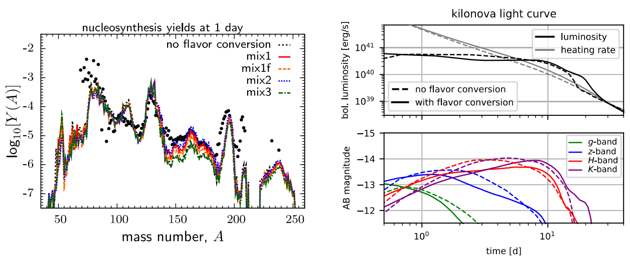


**Fig. 1:** Nucleosynthesis pattern (left) and kilonova light curves (right) resulting in BH-torus remnants in the case of fast-flavor conversion of neutrinos (from [1]).

For the study [2], in which kilonova light curves were calculated using a 3D Monte-Carlo radiative transfer scheme, we provided models of secular ejecta from BH-torus remnants of NS mergers. Study [2] is among the first to compute the kilonova signal based on multi-dimensional simulation data. Hence, it was an important step forward towards self-consistent kilonova modeling, which is required to reliably interpret future multi-messenger observations of NS mergers. Fig. 2 shows the bolometric light curves computed assuming only dynamical ejecta (which are released right during the merger) as well as the combination of dynamical and secular (BH-torus) ejecta, in comparison to the observed kilonova accompanying GW170817.

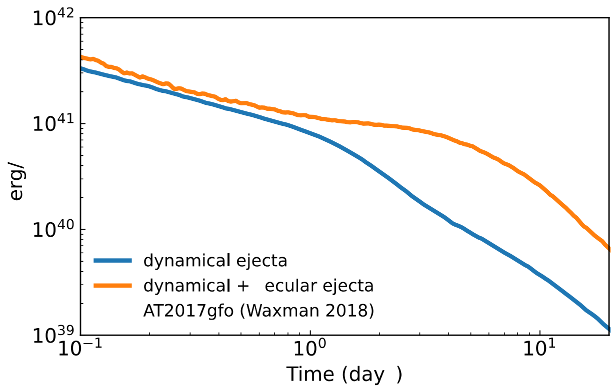


**Fig. 2:** Bolometric kilonova light curves calculated with a radiative transfer code using data from our BH-torus simulations ("secular ejecta") together with data from other simulations that provided dynamical ejecta (from [2]).

An important result found by D. Watson in 2019 was the appearance of the r-process element strontium in the spectra of the observed kilonova that accompanied GW170817. In the study [3], the absorption feature (called P-Cygni line) produced by strontium was investigated further in a way that allowed to constrain the geometric shape of the ejected material. Quite surprisingly, this analysis revealed that the ejecta have been spherically symmetric to a high degree, a result that appears to contradict most theoretical models of NS-merger ejecta. Our contribution to this project was to perform simulations of toy-models for the long-term expansion of merger ejecta, with the aim to identify a mechanism that could possibly make the ejecta spherical after their ejection. We designed and conducted several simulations of ejecta subject to late-time energy injection, however, none of our models could produce highly spherical ejecta (see Fig. 3). This negative result indicates that other, yet unknown mechanisms must operate that produce spherical kilonovae. Finding these mechanisms will be an important task for future models.

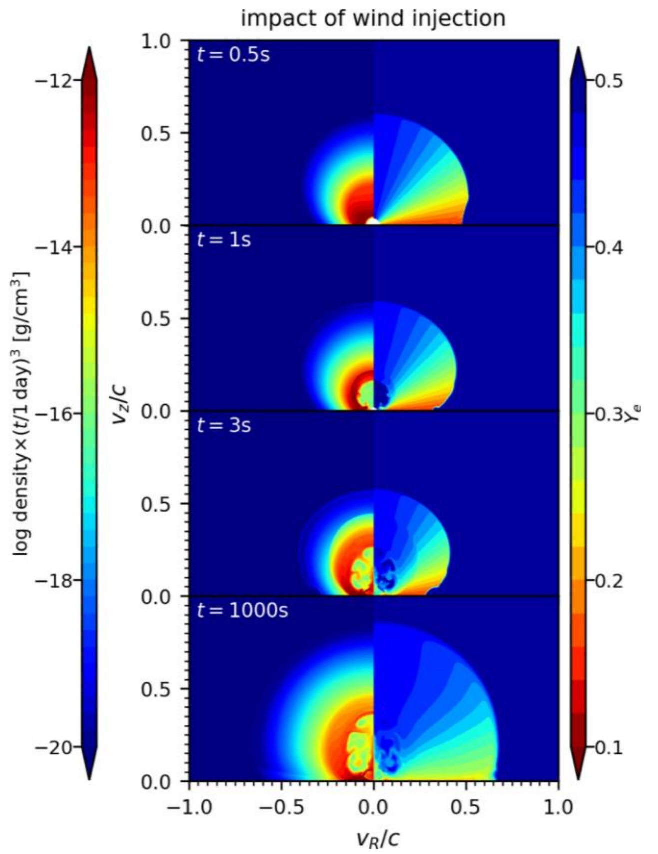


**Fig. 3:** Snapshots taken at different times of a toy model for late-time energy injection into expanding ejecta from NS mergers (from [3]). Late-time energy injection is unable to produce perfectly spherical ejecta.

In another work [4], we investigated the question whether outflows from BH-torus systems can be neutron rich enough to enable the r-process. Such collapsar disks have been discussed as r-process sites already for several decades. However, so far no global long-term evolution models resolving the innermost BH-torus system together with the imploding stellar mantle have existed. We constructed such global models in collaboration with the group of M. Aloy from University Valencia. Our models follow the collapse of the stellar mantle, the formation of the accretion disk, and the viscous disintegration of the disk. In our models the outflows launched from the disk are very powerful and can even explode the entire star, but they are not neutron rich enough to enable the r-process. Our models thus disfavor collapsars as prolific r-process sites and, therefore, indirectly support NS mergers as main sites of the r-process.

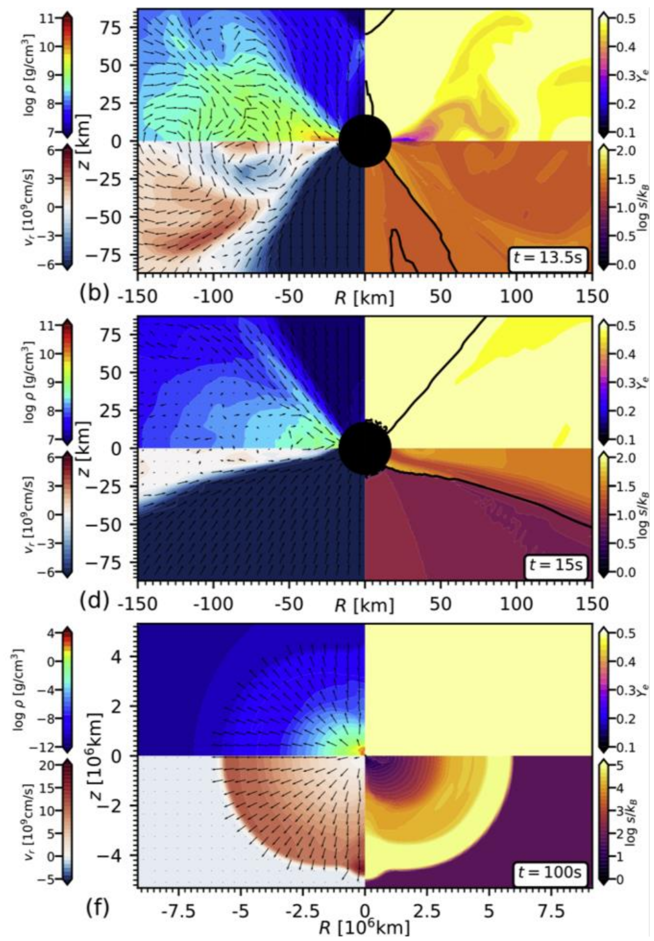


**Fig. 4:** Snapshots taken at different times of a model for a BH-torus system formed in a collapsing massive star (from [4]).

## 4. Schedule and prospect for the future

We recently also submitted a manuscript to ApJ Letters that reports simulations of HMNSs undergoing delayed collapse as well as the subsequent evolution of the BH-torus systems. Using these models, we intend to perform simulations of jets launched after the collapse of the HMNS. In contrast to our previous jet simulations, in which the ejecta-components were manually constructed, these new models evolve all ejecta components self-consistently and are therefore considerably more realistic.

## Fiscal Year 2022 List of Publications Resulting from the Use of the supercomputer

### [Paper accepted by a journal]

[1] Oliver Just, Sajad Abbar, Meng-Ru Wu, Irene Tamborra, Hans-Thomas Janka, and Francesco Capozzi, *"Fast neutrino conversion in hydrodynamic simulations of neutrino-cooled accretion disks"* Phys. Rev. D 105, 083024 (2022)

[2] Christine E. Collins, Andreas Bauswein, Stuart A. Sim, Vimal Vijayan, Gabriel Martínez-Pinedo, Oliver Just, Luke J. Shingles, Markus Kromer, *"3D radiative transfer kilonova modelling for binary neutron star merger simulations"* accepted for publication in Monthly Notices of the Royal Astronomical Society, eprint arXiv:2209.05246

[3] Albert Sneppen, Darach Watson, Andreas Bauswein, Oliver Just, Rubina Kotak, Ehud Nakar, Dovi Poznanski, Stuart Sim, *"Spherical symmetry in the kilonova AT2017gfo/GW170817"* Nature volume 614, pages 436–439 (2023)

[4] Oliver Just, Miguel A. Aloy, Martin Obergaulinger, Shigehiro Nagataki, *"R-process viable outflows are suppressed in global alpha-viscosity models of collapsar disks"* Astrophysical Journal Letter 934 L30 (2022)

### [Others (Book, Press release, etc.)]

[5] Press releases at GSI Darmstadt and University of Copenhagen based on paper [3],

URLs: https://www.gsi.de/en/start/news/details/2023/02/20/spherical-kilonova ,

https://news.ku.dk/all_news/2023/02/astrophysicists-discover-the-perfect-explosion-in-space