The origin of the heavy elements

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## Electromagnetic transients and heavy elements from compact object mergers and core-collapse supernovae

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### In Short


- The astrophysical origin of a large fraction of the periodic table, about half of the elements heavier than iron, remains an open question.
- Colliding neutron stars and black holes as observed through their gravitational-wave and electromagnetic radiation reveal important information about how such elements can be produced. However, there is mounting evidence that these events may not be the only sources of heavy elements in the universe.
- A suite of pioneering simulations on a wide array of astrophysical candidate systems is conducted to explore whether these systems can contribute to the cosmic synthesis of heavy elements. It continues to explore key open questions and implications of a previous project phase. The studied systems include double neutron-star and neutron-star-–black-hole collisions, the accretion-induced collapse (death) of white dwarfs, the collapse of massive rotating stars, and rapidly rotating protoneutron stars formed in core-collapse supernovae.


A fundamental and open question in physics and astrophysics pertains to the cosmic origin of roughly half of the elements heavier than iron, the so-called rapid neutron-capture ('r-process') elements. These include gold, silver, uranium, thorium, and many other well-known elements of the periodic table. As has been realized about 70 years ago, these elements must be synthesized in a highly neutron-rich astrophysical environment under extreme plasma densities. Yet identifying astrophysical systems that can give rise to these conditions has remained a challenge for both theory and observations.

The first detection of a collision of two neutron stars in a binary system by the gravitational-wave observatories LIGO and Virgo in 2017 (called GW170817) and its accompanying quasi-thermal electromagnetic emission from the radioactive decay of heavy elements synthesized in the merger debris—called a 'kilonova'—revealed that such collisions can indeed synthesize r-process elements. These spectacular observations inaugurated the field of multimessenger astronomy with gravitational waves, which combines gravitational signals, light, and high-energy particles to probe cosmic events in complementary and greater detail than ever before. Yet growing empirical and theoretical evidence suggests that such cosmic collisions may not be the only or even dominant source for r-process elements in the universe. This project explores by means of detailed supercomputer simulations the conditions for r-process nucleosynthesis over a wide array of astrophysical candidate sources.

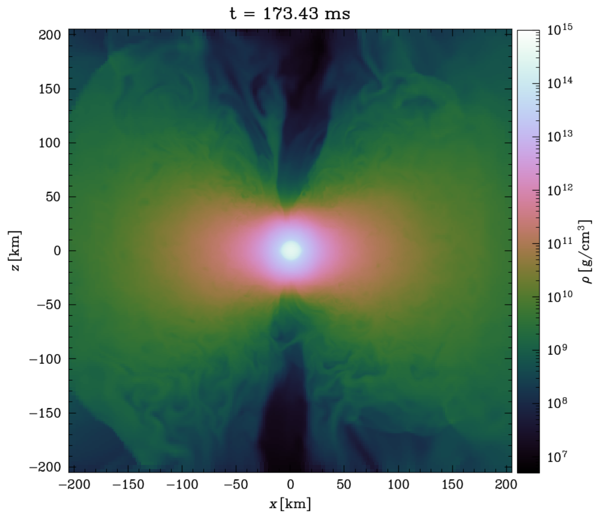


***Figure 1:** The collapse of a white dwarf triggered by accretion from a companion star leads to the formation of a rapidly, differentially rotating neutron star (white dot at center). We explore whether similar jet formation mechanisms as in [1] can be realized in this environment, which may have profound implications for r-process nucleosynthesis in the universe.*

*Double neutron-star collisions and the death of white dwarfs.* Simulations of double neutron-star collisions of the first and current project phase [1] demonstrated the first successful generation of an astrophysical jet from the remnant neutron star in such collisions. In the current project phase, we explore how universal this mechanism is and whether it could act in different astrophysical systems with similar physical environments. Figure 1 shows a test simulation of a white dwarf collapsing into a neutron star with similar physical conditions as in a post-merger phase. In this project phase, we explore the generation of jets in this environment, which can have profound implications for r-process nucleosynthesis by adding a new astrophysical production site.

*Neutron-star–black-hole collisions.* Depending on the magnitude and orientation of the black-hole spin vector, accretion streams onto the black hole generated by tidal disruption ('squeezing') of the neu-

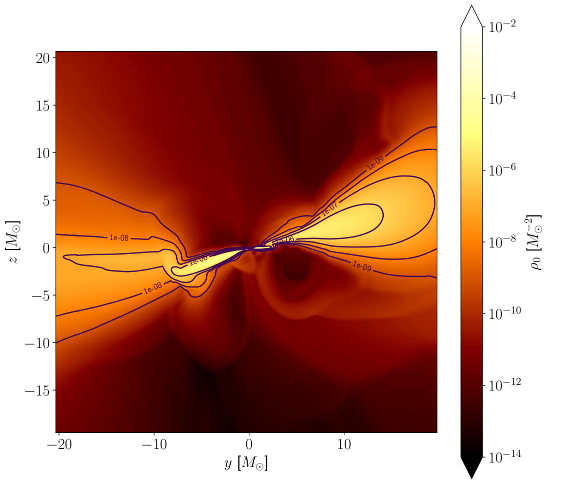


***Figure 2:** The merger of a neutron star and a black hole with tilted spin relative to the orbital plane (horizontal line at $z = 0$) leads to complex circularization of debris material around the final black hole (at center). Self-intersecting plasma streams cause heating that can drastically change the electromagnetic and nucleosynthetic signature of such systems.*

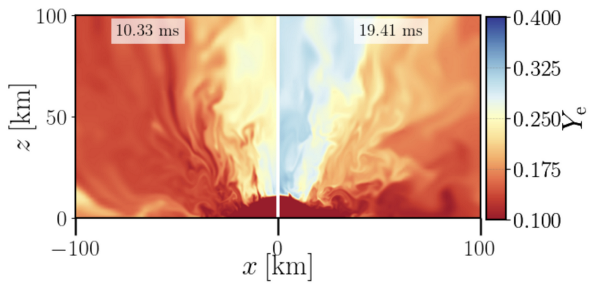


***Figure 3:** Snapshots at 10 and 20 ms after the onset of plasma winds from a hot proto-neutron star born in core-collapse supernovae (lower right and lower left corner, respectively). The combination of rapid rotation and strong magnetization generate favorable conditions for r-process nucleosynthesis in these winds, indicated here by the onset of requisite high neutron-richness (low proton fraction $Y_e$) in equatorial regions around the star.*

tron star 'warp' and self-intersect. Pioneering simulations in the previous and current project phase demonstrate for the first time the generation of light r-process elements and associated 'blue' kilonova emission as a result of self-intersecting plasma (cf. Fig. 2), traditionally thought to be absent in such mergers. Together with long-term follow-up simulations and widening up the parameter space of such systems in this project phase, we investigate whether such mergers can provide a consistent model of the GW170817 kilonova. Could GW170817 have been a neutron-star–black-hole collision after all?

*Massive collapsars.* This project phase explores with pioneering 3D GRMHD simulations in dynamical spacetime how accretion disks can be formed from the collapse of very massive ($\gtrsim 120 M_\odot$), rapidly rotating stars. Particular emphasis is on how magnetic field amplification upon collapse can trigger magnetic jets that may explode part of the infalling stellar envelope and unbind neutron-rich material. These simulations probe whether 'super-kilonovae' [2] that signal the birth of such massive black holes can be generated and whether these are observable with missions such as JWST or the Roman Space Telescope. Furthermore, such collapsars would naturally explain known extreme r-process enrichment events in low-metallicity environments.

*Proto-neutron stars.* A fraction of less than 10% of all isolated neutron stars born as a result of the core-collapse of massive stars at the end of their lives (in a core-collapse supernova) may be rapidly rotating and may possess strong magnetic fields. The previous project phase revealed that hot, strongly magnetized, and rapidly rotating proto-neutron stars are promising sources for r-process elements (cf. Fig. 3), much more so than the non-rotating systems of the first project phase [3]. Pioneering simulations of the current project phase explore whether upon neutrino cooling at lower temperatures, the conditions for r-process nucleosynthesis become even more favorable.

All simulations described above also have broader impact on how the universe chemically evolved from the first generation of stars until today. Expected deliverables such as elemental abundance distributions, ejecta/r-process yields, distributions of ejecta composition etc. from each astrophysical source directly inform modeling of cosmic chemical evolution. The project simulations will also help develop detailed models of kilonovae, which will be used to interpret future observations and constrain r-process nucleosynthesis in multimessenger events.

## WWW

https://physik.uni-greifswald.de/ag-siegel/

## More Information


[1] L. Combi & D. M. Siegel, *Phys. Rev. Lett.* **131**, 231402 (2023). doi:10.1103/PhysRevLett.131.231402

[2] D. M. Siegel, A. Agarwal, J. Barnes, et al., *The Astrophys. J.* **941**, 100 (2022). doi:10.3847/1538-4357/ac8d04

[3] D. K. Desai, D. M. Siegel & B. D. Metzger, *Astrophys. J.* **954**, 192 (2023). doi:10.3847/1538-4357/acea83


## Project Partners

Perimeter Institute for Theoretical Physics and the University of Guelph, Ontario, Canada; Columbia University, New York, USA.

## DFG Subject Area

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