# GPU-ACCELERATED SIMULATIONS: BLACK HOLES, SPAGHETTIFIED STARS, AND TILTED DISKS

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## EXECUTIVE SUMMARY

Stars approaching supermassive black holes (BHs) can be tidally disrupted, or spaghettified, by BH tidal gravity. A tidal disruption event (TDE) generally leads to a tilted accretion disk, with an axis misaligned relative to BH spin. However, how such a disk forms and how it evolves thereafter is not understood. Using our new GPU (graphics processing unit)-accelerated 3D general relativistic (GR) magnetohydrodynamic code H-AMR, we investigated both of these questions. We carried out the first GR hydrodynamic simulations of typical TDEs, with supermassive BHs disrupting Sun-like stars infalling from large distances. We discovered that as GR-induced precession causes the tidal stream to self-intersect, this can completely disrupt the stream and efficiently form the disk. We showed that our simulated tilted thick accretion disks launched twin magnetized relativistic jets that underwent Lense–Thirring precession together with the disk, demonstrating from first principles for the first time that jet precession can be used to probe strong-field gravity.

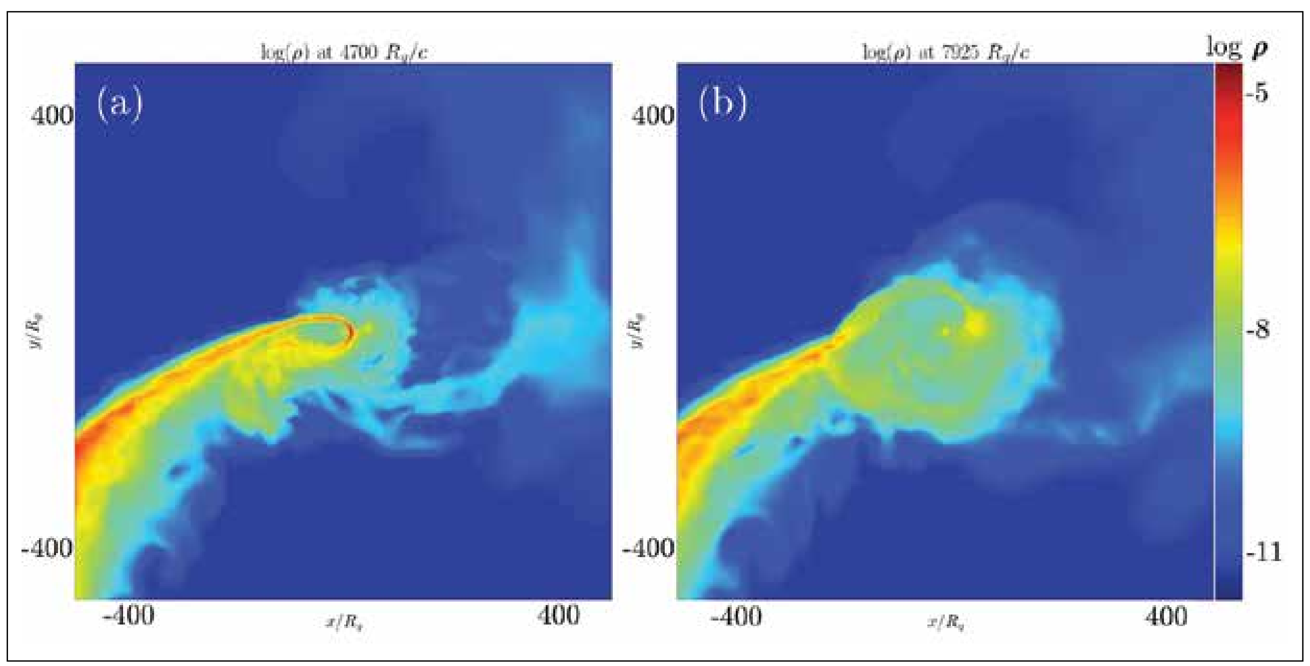


Figure 1: First general relativistic fluid dynamics simulation of typical stellar tidal disruption by supermassive black hole. It demonstrates that debris stream self-crossing can lead to its demise: complete disruption and efficient circularization into disk.



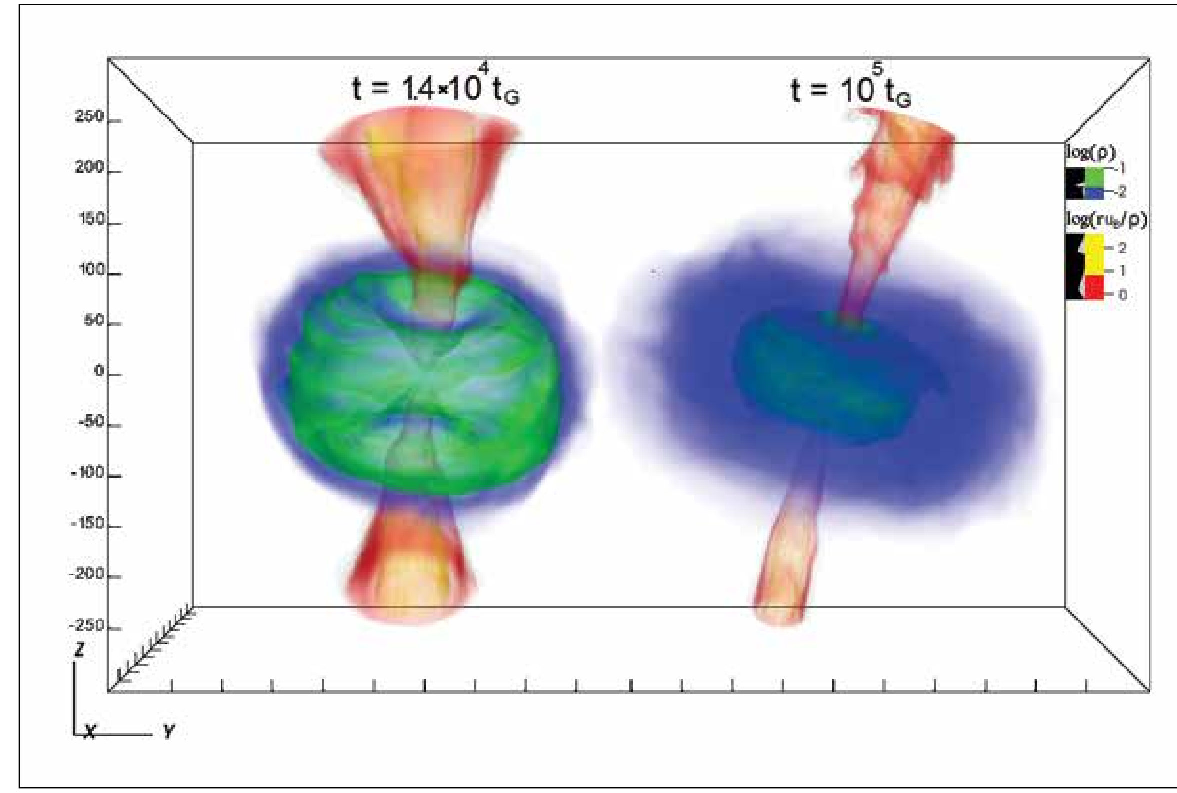


Figure 2: Our PRAC allocation allowed us to demonstrate for the first time that tilted precessing disks around BHs produce relativistic jets and that these jets precess together with the disk.

## RESEARCH CHALLENGE

Numerical simulations of TDEs of Sun-like stars by supermassive BHs are extremely challenging because it is difficult to numerically resolve the debris stream because it is very thin relative to the black hole. Tilted disk simulations require high resolution to properly resolve nonaxisymmetric turbulence in the tilted disks. Both are huge numerical challenges.

## METHODS & CODES

Using our new code H-AMR (pronounced "hammer"), which includes adaptive mesh refinement and efficiently runs on GPUs, we were able to overcome these challenges.

## RESULTS & IMPACT

Until now, many different simplifications have been adopted when simulating TDEs. For instance, to save computational time, (1) stars were sent in on closed, elliptic orbits (instead of parabolic ones) or (2) the BH-to-stellar ratio order of magnitude was assumed to be lower than in reality (e.g., 1,000 instead of $10^6$) [1,2]. The adaptive mesh capabilities of H-AMR and the high efficiency with which it runs on GPUs allowed us to properly resolve the thin debris stream for a typical encounter featuring both a parabolic orbit and a mass ratio of $10^6$.

The first simulations of tilted accretion disks were carried out a decade ago [3]. They demonstrated that tilted disks undergo Lense–Thirring precession. However, whether such disks are capable of producing relativistic outflows, or jets, and whether those jets point along the disk axis or the BH spin axis has remained a mystery. Our simulations for the first time established that such disks are indeed capable of producing jets and that the jets undergo precession together with the accretion disk. This is the first demonstration that jets can be used as probes of disk precession.

Blue Waters was instrumental in enabling our simulations, which are the highest resolution GRMHD simulations to date and set the new state of the art in the field. On a CPU (central processing unit) cluster, the effective simulation cost would have been 400-million CPU core-hours, accessible only on Blue Waters.

## WHY BLUE WATERS

Our simulations require a high degree of parallelism as they run on hundreds to thousands of GPUs in parallel.