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Testing Einstein's theory of gravity with simulations of tidal disruption events

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Although Einstein's theory of gravity has already passed many tests in the last century, it is still one of the most discussed theories in physics. Its strong-field regime can only be accessed through the study of ultra-compact objects like, e. g., black holes. In this report, we propose using black holes with metrics that deviate from the standard Kerr solution in order to probe the strong-field regime of gravity. For measuring the effects induced by the deviation, we study tidal disruption events from which large amounts of energy in electromagnetic and gravitational radiation are released. We developed an approach to implement arbitrary metrics that are not solutions of Einstein's equations into the framework of a fully general relativistic code. The results from our numerical simulations can then be compared with data from actual observed events and place constraints on the metric deviation parameters, hence assessing the validity of general relativity in gravity's very extremes.

1 Introduction

For over a century, Einstein's theory of relativity has been the best available theory of gravity and describes compact astrophysical objects like black holes (BHs) and

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neutron stars with high accuracy. Still, it does not fit perfectly with other major physical theories, e. g., it is not compatible with quantum field theory. Up to now, general relativity (GR) has easily passed all observational and experimental tests in the weak-field regime, i. e., within the solar system. In order to probe the strong-field regime, which is more difficult to access, one needs to study ultra-compact objects, the physical properties of which are not fully understood.

A popular test in the strong-field regime involves the so-called *no-hair theorem*, which states that BHs in GR are uniquely characterized by their masses, spins, and charges and are described by the Kerr-Newman metric. In the case of uncharged BHs, the Kerr metric is used for rotating BHs and the Schwarzschild metric for BHs without spin. One way of testing the theorem is via observations of phenomena in the vicinity of the Kerr metric and comparing them with those taking place near parametrically deviated metrics. These types of observations and measurements performed in the strong-field regime can put constraints on these deviations from the Kerr metric and thereby test GR itself.

Tidal disruptions of stars by BHs are fascinating and violent cosmic events that release large amounts of energy in electromagnetic radiation and are accompanied by gravitational wave (GW) emission in a broad range of frequencies. The radiation patterns provide information about both the BH and the internal structure of the disrupted star. As there is a huge variety of observational signals from these events, with the electromagnetic spectrum already being detectable for many years and the GW spectrum hopefully soon accessible, and as they involve compact objects tightly interacting with each other, tidal disruption events (TDEs) provide a perfect opportunity for testing the strong-field regime of GR.

In order to study complex astrophysical processes like TDEs, observations are not always sufficient to describe these processes with reasonable accuracy. Instead, we make use of numerical simulations which are necessary and useful tools for this type of research. TDEs involve compact objects and thus require the application of full GR, since Newtonian gravity is not enough. Therefore, the evolution of these objects is described by Einstein's equations. These evolution equations are complex tensor equations which are second order in time and describe the whole spacetime geometry at once. For the numerical implementation, we have to make some adjustments to these field equations in order to retrieve a set of equations that is more suitable for that purpose.

For our simulations we use a method developed in the Master thesis »Simulations of tidal disruption events with parametrically deformed black holes« (Hämmerling, 2017). With the help of a newly written code module, it is possible to perform simulations of tidal disruption using arbitrary metrics which are not solutions of Einstein's equations. The module is embedded in the framework of the fully general relativistic MAYA code, which is developed and maintained by the Atlanta group. Thereby, the MAYA code was extended as the deviated metrics are not a solution of Einstein's equations and thus do not obey the evolution equations.

The performance of the code has already been successfully tested in the Master thesis (Hämmerling, 2017). In this report, we will give an overview of the current status of the ongoing project.

2 Scientific background

The ongoing research is organized in two major topics: we want to probe GR in the strong-field regime by testing the no-hair theorem, which includes a) a thorough study of alternative theories of gravity and of the theorem itself, and b) the simulation of TDEs.

2.1 Testing the no-hair theorem

Although having successfully passed a large set of observational and experimental tests since its first formulation by Einstein in 1916 (Einstein, 1916), GR it is still one of the most discussed theories with a large variety of alternatives, for many of which there are good reasons to be seriously taken into account. Most of the tests that have been performed probed only the weak-field regime of gravity, as this can be very thoroughly tested through experiments in the solar system. Binary pulsar data and the recently discovered GWs from BHs (B. P. Abbott, R. Abbott, T. D. Abbott, Abernathy et al., 2016a; B. P. Abbott, R. Abbott, T. D. Abbott, Abernathy et al., 2016b; B. P. Abbott, R. Abbott, T. D. Abbott, Acernese et al., 2017b; B. P. Abbott, R. Abbott, T. D. Abbott, Acernese et al., 2017a; B. P. Abbott, R. Abbott, T. D. Abbott, Acernese et al., 2017c) and Neutron Stars (B. P. Abbott, R. Abbott, T. D. Abbott, Acernese et al., 2017d) allow for the first serious tests of the strong-field regime. In general, the physics and astrophysics of the objects involved here (BHs and neutron stars) are not completely understood and alternative candidates for ultra-compact objects have been seriously studied in the last decade. The most fundamental issue is that the astrophysical phenomena and objects associated with the strong-field regime have no counterparts in Newtonian gravity.

The so-called no-hair theorem states that astrophysical BHs are uniquely characterized by their masses, spins, and charges (Israel, 1967; Carter, 1971; Hartle et al., 1972). Their geometry is described by the Kerr-Newman metric (Newman, Couch et al., 1965), which reduces to the Kerr metric (Kerr, 1963) in the case of a rotating but uncharged BH. The latter should be the case for astrophysical black holes, because any residual electric charge would quickly neutralize. In other words, the Kerr metric is the only stationary, axisymmetric, asymptotically flat vacuum spacetime in GR that has an event horizon but no closed timelike curves outside the horizon.

In principle, if a deviation from the Kerr metric can be detected, there are two possible interpretations. Assuming the validity of GR, the object under investigation cannot be a BH, but rather a stable stellar configuration or a new exotic compact object, like a *gravastar* (Mazur et al., 2001; Visser et al., 2004) or a BH surrounded by a scalar field (C. A. R. Herdeiro et al., 2014; C. Herdeiro et al., 2016). There are already suggestions that some GW »echoes« may have already been seen in the post-merger data of black holes (Abedi et al., 2017; Westerweck et al., 2018; Maselli et al., 2017). On the other hand, if the no-hair theorem is violated, but the candidate shows features of an event horizon, then GR can only be *approximately* valid in the strong-field regime. The latter outcome naturally leads to the quest of finding a more complete and satisfactory theory of gravity.

Because of the no-hair theorem, all parametric deviations of the Kerr metric within GR have to violate at least one of the basic hypotheses of the theorem, leading to mathematical and physical issues. These spacetimes may contain either naked singularities (i. e., singularities without an event horizon) or regions with closed timelike curves outside the event horizon. Requiring that the new metric is free of these pathologies makes theses studies a very demanding task.

A variety of non-Kerr metrics have been developed in the past 7 years and many of them have already been tested in astrophysics, e. g., the approach by Johannsen and Psaltis (JP) (Johannsen and Psaltis, 2011a; Johannsen and Psaltis, 2011b; Johannsen, 2013a; Johannsen, 2013b). Here, the authors have parametrized strong-field deviations introducing polynomial corrections into the Schwarzschild metric of a nonrotating BH, showing that through the Newman-Janis algorithm (Newman and Janis, 1965) this procedure leads to a Kerr-like spacetime. The JP solution is regular and free of unphysical properties outside the event horizon, and it can be used to describe BHs spinning up to the maximum value of the angular momentum allowed by the deformation. This metric is therefore suitable to study astrophysical phenomena close to the event horizon and then provide genuine strong-gravity tests of the no-hair theorem.

A new approach deriving Kerr-like metrics has been proposed recently in (Papadopoulos et al., 2018), allowing for an easy way in constructing Kerr-like spacetimes that admit a Carter-like third constant of motion (Carter, 1968).

The JP metric used in this project so far has been improved even further by Johannsen (Johannsen, 2013a) in order to also include a Carter constant. For that purpose, Johannsen introduced several more deviating functions, resulting in a metric which can now also be mapped to known BH solutions in alternative theories of gravity.

The nonrotating case of the JP metric has been used in the work of Bambi et al. (Pei et al., 2015), studying the scattering of particles by these deformed BHs. They studied the excitation of axial quasinormal modes of deformed nonrotating BHs and compared the associated GW signal with that expected in GR from a standard Schwarzschild BH. As a result, they state that the measurement of the GW spectrum could in principle distinguish among different spacetimes and thus constrain the deviation parameter. Bambi is now investigating, among others, the Johannsen metric by studying the reflection spectrum of accretion disks around deformed BHs (Nampalliwar et al., 2018; Bambi et al., 2018).

Beside the JP approach, Konoplya et al. (Konoplya et al., 2016) have proposed another promising parametric framework. In this approach, deviations from GR are described by mixing continuous fraction and Taylor expansions of the radial and angular variables, which guarantee an excellent convergence of the metric to known solutions, as those given by the Einstein-Dilaton-Gauss-Bonnet (EDGB) BHs (Kanti et al., 1996; Kleihaus et al., 2016; Kokkotas et al., 2017).

In our research project we want to take the next step and investigate the strong-gravity tidal effect of the JP and EDGB-type metrics in a dynamical setup by considering the case of the tidal interaction between an intermediate-mass BH and different kinds of stars.

2.2 Tidal disruption events

TDEs are a powerful tool for the analysis of both the BH and the internal structure of the disrupted star. It is also an effective method for the detection of central BHs in quiescent massive galaxies, which are hard to detect due to a surrounding gas environment leading to no significant emissions. With the growing importance of GW detection, a deeper understanding and a thorough examination of tidal disruption events will facilitate the interpretation of measured GW signals and thus provide a new method for studying the nature of compact objects.

The modeling of TDEs was pioneered by Rees (Rees, 1988), Phinney (Phinney, 1989) and Evans & Kochanek (C. R. Evans et al., 1989) in the late 1980s. They proposed that the tidal disruption of a star closely passing by a massive BH provides a mechanism which may fuel a low-luminosity active galactic nucleus by leading to an intense accretion flare, whose signature might hint to the presence of a BH. In numerical calculations, they examined the distribution of debris orbits concentrating on post-disruption evolution. This requires detailed hydrodynamical calculations due to the complex balance between orbital circulation, cooling, viscous accretion, and debris infall. In these early years, numerical simulations including the calculation of the tidal disruption rate were already performed by various groups, including Shapiro and Marchant in 1978 (Shapiro et al., 1978), whereas important aspects of the physics of stellar disruption were first understood by Lacy, Townes and Hollenbach in 1982 (Lacy et al., 1982).

Observations of TDEs have the potential to unveil supermassive black holes (SMBHs) at the center of galaxies. In galaxies with quiescent BHs, accretion-powered nuclear activity is absent and tidal disruption signatures are principally easy to identify. In the last decade, observational evidence for TDEs has been presented in increasing numbers. Thanks to the huge variety of signals from these events and due to the fact that they involve compact objects hugely influencing the spacetime in the vicinity, TDEs are the ideal processes to probe the strong-field regime of GR by testing the no-hair theorem.

Summary The aim of our research project is to test the no-hair theorem by simulating TDEs, using BHs that are described by parametrically deviated metrics. The resulting observational data will be compared to measurements of actual events.

Thus, it will be possible to put constraints on these parameters and thereby test the validity of GR in the strong-field regime.

3 Numerical methods

As the process of a tidal disruption happens in the strong gravitational field of a SMBH, a general relativistic description and calculation of gravity is required. Thankfully, access and usage of the numerical relativity code MAYA is provided for the proposed project. The MAYA code has demonstrated excellent performance in handling fluid flows in the vicinity of BHs in the study of binary BH mergers (Bode, Shoemaker et al., 2008; Bode, Laguna et al., 2009; Bode, Bogdanović et al., 2011), tidal disruptions of white dwarfs by intermediate-mass BHs (Haas et al., 2012; Shcherbakov et al., 2013; Shcherbakov et al., 2012), and tidal disruptions of solar-type stars by SMBHs (C. Evans et al., 2015).

The MAYA code is based on the open source numerical relativity code `Einstein Toolkit` (Zilhão et al., 2013; Löffler et al., 2012), which is itself based on the `Cactus` framework (Goodale et al., 2002). Within this framework, the code is composed of several different modules called »thorns«, whereas each one has only one main functionality in order to sustain the modularity of the code. The `Einstein Toolkit` is developed by researchers from different institutions throughout the world and is in active continuous development. It uses the Baumgarte-Shapiro-Shibata-Nakamura (BSSN) formulation (Baumgarte et al., 1998; Shibata et al., 1995) for the spacetime evolution of Einstein's equations with a finite-volume general-relativistic hydrodynamics solver.

However, the ultimate goal of this research is to perform simulations of TDEs with parametrically deformed BHs that are *not* a solution of Einstein's equations. Therefore, an evolution of the BH spacetime with the BSSN formulation is impossible and an adapted approach for the numerical implementation of these modified metrics by programming a new thorn called `AddBH` has been developed in the Master thesis (Hämmerling, 2017).

Computational infrastructure The simulations proposed in this work will be performed on the computational resources bwUniCluster and BinAC, supported by the state of Baden-Württemberg through bwHPC and the German Research Foundation (DFG) with grant no. INST 39/963-1 FUGG. Additionally, the TAT group owns a 24 core machine for small runs and postprocessing routines.

For the purpose of our project, we have an allocation on the BinAC cluster for a computational project with a total of a million CPU hours per year. As it is only used by scientists in the field of bioinformatics and astrophysics, the queueing times are relatively short, which enables fast computation and quick results.

4 Status Report

In this report, we want to present the current status of our research project. The newly written code module `AddBH`, developed in (Hämmerling, 2017), has so far been tested by simulating TDEs with intermediate-mass BHs described by the standard Schwarzschild metric and the Kerr metric used for rotating black holes, which are both a solution of Einstein's equations.

4.1 First tests and troubleshooting

Throughout the testing phase, several problems have been encountered and solved. For example, the curvature singularity of the BH initially led to diverging data at its center. We solved this problem by introducing a smoothing function which overwrites the data within the event horizon with some predetermined values. As the overwriting happens well within the event horizon, no information about it can reach a possible observer, i. e., the observational signal of the tidal disruption event will not be influenced by that. The coordinate singularity at the event horizon is treated by transforming the respective metric to a more suitable coordinate system.

Additionally, putting the solar-type star into a parabolic orbit around the black hole turned out to be a huge problem. The first few simulations revealed that the perfect fluid of the star does not move very smoothly but starts to dissipate over a large area. This is caused by a faulty assignment of the star's velocity by the thorns which set the initial data for the hydrodynamical variables. For now, we decided to simply overwrite the data as a temporary solution, which leads to an acceptable amount of spreading of the stellar material. Nevertheless, this is not a permanent solution and we are currently addressing this problem in optimization runs.

4.2 Simulation parameters

Based on the study of ultra-close encounters of stars with intermediate mass black holes by (C. Evans et al., 2015), we also consider a black hole of mass $M_{\mathrm{BH}} = 10^5 M_\odot$ and a solar-type main sequence star. For the simulation of our compact objects, we used the parameters listed in table 1, by column: total system mass M_{sys}, black hole mass M_{BH}, mass of the star M_*, radius of the star R_*, central density of the star ρ_{c} and polytropic exponent Γ.

M_{sys}	M_{BH}	M_*	R_*	ρ_{c}	Γ
$1\,M_{\mathrm{sys}}$	$0.99999\,M_{\mathrm{sys}}$	$5.76 \times 10^{-6}\,M_{\mathrm{sys}}$	$3.85\,M_{\mathrm{sys}}$	$1.29 \times 10^{-6}\,M_{\mathrm{sys}}^{-2}$	$4/3$
$10^5\,M_\odot$	$\sim 10^5\,M_\odot$	$0.576\,M_\odot$	$0.82\,R_\odot$	$79.9\,\mathrm{g/cm^3}$	$4/3$

Table 1: Parameters used for the simulations in system units, which means geometrized units in addition to a scaling with the total system mass M_{sys}, and in CGS units beneath.

The star's mass, radius and central density is indeed comparable to the sun's properties.[1] In the following, we will only use the system units, i. e., we use geometrical units that are additionally scaled with the total system mass M_{sys}. The star is modeled as an ideal fluid described by the Tolman-Oppenheimer-Volkoff equations (Tolman, 1939; Oppenheimer et al., 1939), its equation of state is given by a polytrope with polytropic exponent $\Gamma = 4/3$. With initial velocities of $\texttt{velx} = -0.1133$, $\texttt{vely} = 0.0504$ and zero velocity in z-direction, the star takes a parabolic orbit around the black hole with an initial separation of $d = 130\,M_{\mathrm{sys}}$. The black hole in the rotating case has a spin parameter of $a = 0.5$.

Regarding the grid, we employ six levels of mesh refinements around the star and none around the black hole, as we are not interested in the evolution of the black hole. All but the coarsest mesh have 70^3 grid points, with the coarsest having 164^3. The resolution on the finest mesh is $R_*/30$.

4.3 Disruptions by standard black holes

Up until now, we tested the code by simulating TDEs with intermediate-mass BHs described by the standard Schwarzschild and Kerr metrics. The correct implementation of parametrically deformed metrics will be addressed in our future work.

[1] The central density of the sun is $\rho_{\mathrm{c}} \approx 160\,\mathrm{g/cm^3}$.

Schwarzschild black hole The simulations of the tidal disruption of a solar-type main sequence star by a standard Schwarzschild black hole were performed with the parameters for the compact objects displayed in table 1. In general, we are able to see the beginning of the tidal disruption process. Nevertheless, the simulations stop quite early and we cannot observe the whole disruption. As soon as the disrupted material of the star performs one circular orbit around the black hole and falls back onto its own tail, the hydrodynamical routines produce various errors. The main errors result from the star's fluid velocity exceeding the speed of sound. Additionally, certain routines have problems in the numerical transformation of hydrodynamical variables under these extreme conditions. All in all, the accumulation of errors finally results in an early termination of the simulation. In the future, we will optimize these routines so that the fluid variables are treated correctly near the event horizon and we are able to fully simulate the disruption process.

Figure 1 shows the rest mass density plots of the simulation. Each figure includes three snapshots of the tidal disruption and each panel depicts the xy-plane of the computational domain with a range of $[-160\,M_{\rm sys}, 160\,M_{\rm sys}]$ for both axes. The left panel shows the moment when matter first reaches the black hole, which is positioned in the center of the picture. The snapshot in the middle panel is taken shortly before the disruption sets in and the first material of the star is ejected outward. The right panel is the last iteration of the simulation and shows the instant when the disrupted debris falls back onto its own tail.

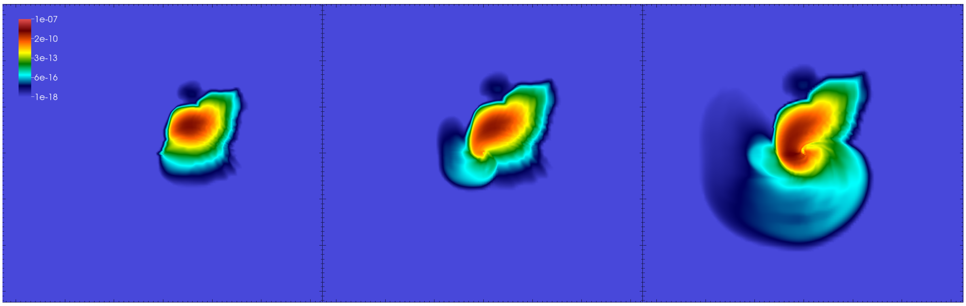

Figure 1: Rest mass density plots of a star moving on a parabolic orbit around a Schwarzschild black hole. The snapshots are taken when the stellar material first reaches the black hole (left panel), a few moments before the tidal disruption starts (middle panel) and at the end of the simulation (right panel).

Kerr black hole The simulations of the tidal disruption of a solar-type main sequence star by a standard Kerr black hole was performed with the parameters for the compact objects displayed in table 1 and an angular momentum parameter of $a = 0.5$. In fact, the simulations with the Kerr black hole are quite successful. In contrast to those with a Schwarzschild black hole, they don't stop when the disrupted debris falls back onto itself after one orbit around the black hole. Instead, the whole star gets disrupted and we can observe the formation of an accretion torus. Additionally, the tidal disruption produces a shockwave of debris that is ejected outward, in the end even reaching beyond the computational domain. Therefore, the statement by (Lacy et al., 1982), that nearly half of the debris is bound by the black hole in an accretion torus and the other half is ejected, seems to hold true for our simulation. If we compare the simulations between the disruptions by the Schwarzschild and by the Kerr black hole qualitatively, the only statement we can make is that the star seems to be spread over a larger area when reaching the black hole in the Kerr case. The reason for this is the increased gravitational pull of the Kerr black hole due to its rotation. The comparison of any other quantities is hardly possible as the simulations with the Schwarzschild black hole terminated early.

The rest mass density plots in the figures 2 and 3 show a succession of snapshots depicting this process.[2] Figure 2 shows the xy-plane of the computational domain in a range of $[-160\,M_{\mathrm{sys}}, 160\,M_{\mathrm{sys}}]$ for both axes, whereas the full domain of $[-460\,M_{\mathrm{sys}}, 460\,M_{\mathrm{sys}}]$ is shown in figure 3. In order to show the different dimensions of the figures, the right panel of figure 2 shows the same snapshot as the left panel of figure 3. Additionally, it is taken at a time comparable to the termination point of the simulations with the Schwarzschild black hole discussed before, i. e., it shows the moment when the debris performed one orbit around the black hole and falls back onto its own tail. The left panel of figure 2 shows the moment when the stellar matter first reaches the black hole, whereas the middle snapshot is taken just shortly after the estimated onset of tidal disruption.

Summary We are able to perform simulations of TDEs with intermediate-mass BHs described by the standard Schwarzschild and Kerr metrics using our alternative approach with promising results. It is possible to observe the disruption of the simulated main sequence, solar-type star and, in the Kerr case, the formation of

[2] For a video showing the full tidal disruption process see `https://drive.google.com/open?id=0B8Hmz8zgvMApZmFEbFV0UzAxX2c`.

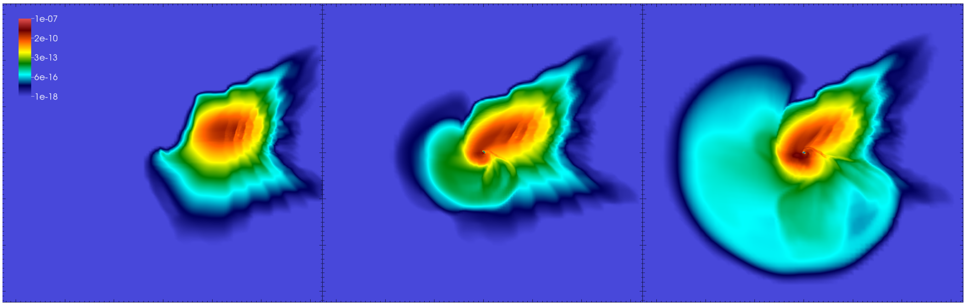

Figure 2: Rest mass density plots of a star moving on a parabolic orbit around a Kerr black hole with an angular momentum parameter of $a = 0.5$. The snapshots are taken when the stellar material first reaches the black hole (left panel), a few moments after the tidal disruption starts (middle panel) and when the debris falls back onto its own tail after one orbit around the black hole (right panel). The xy-plane of the computational domain is shown in a range of $[-160\,M_{\rm sys}, 160\,M_{\rm sys}]$.

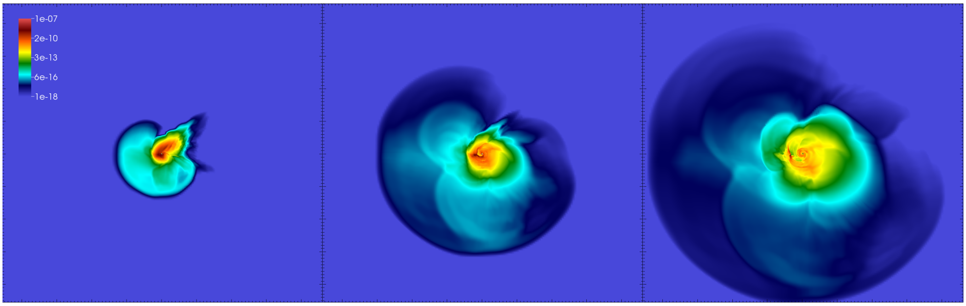

Figure 3: Continued rest mass density plots of 2 but shown in the full computational domain of $[-460\,M_{\rm sys}, 460\,M_{\rm sys}]$. The left panel is identical to the right panel of figure 2. The other two snapshots show the progress of the disruption. The star gets totally disrupted and an accretion torus forms around the Kerr black hole.

an accretion torus. Additionally, a shockwave of debris that is strongly ejected outwards becomes evident in the density plots. This supports the statement by ref. (Lacy et al., 1982), that nearly half of the debris is bound by the BH in an accretion torus and the other half is ejected.

There are many possible ways to improve the simulations. The optimization of the code and the actual implementation of the parametrically deviated BH metrics together with the calculation of observational data are all part of our planned work.

5 Outlook

With the help of the thorn `AddBH`, it is possible to perform simulations of tidal disruption with arbitrary metrics that are not a solution of Einstein's equations. This is the basis of our project titled »Testing Einstein's theory of gravity with simulations of tidal disruption events«.

The simulations performed with this module still require improvement. By testing various calculation and simulation parameters, it should be possible to further optimize the simulated TDEs. Possible approaches here are, for example, to check different stellar compositions, i. e., to not only simulate main sequence, solar-type stars but also white dwarfs.

The ultimate goal of this work is to probe the strong-field regime of GR by testing the no-hair theorem with simulations of TDEs containing parametrically deformed BHs. For that purpose, it is necessary to find a proper coordinate transformation for each meaningful alternative metric we will use in order to avoid diverging data at the event horizon. Then we can implement the metric in the code and be able to perform stable simulations.

We will not only study the JP and the Johannson metric, but also other metrics will be used. Actually, thanks to the framework developed in (Papadopoulos et al., 2018), meaningful deformations can be trivially constructed.

In order to evaluate the effect of the parametrically deviated metrics for the TDEs, the calculation of important observational data should complement the simulations in a postprocessing step. Only then will it be possible to tell the difference between a tidal disruption by a standard BH described by GR or by a deviated BH. For example, it is possible to calculate the rate of mass accretion onto the BH via measuring the flux through a spherical surface near the event horizon. Further post-disruption behavior can be studied by applying the Atlanta smoothed particle hydrodynamics code (Bogdanović et al., 2004). Then, the calculated mass accretion rate and light curves can be compared with measurements from actual observed TDEs.

Additionally, the GW emission can be calculated, although the signal is expected to be negligible with respect to amplitude and therefore detectability if compared to the already available electromagnetic spectrum.

To sum up, with our successfully developed code we possess the necessary tools to simulate TDEs, which will eventually enable us to test the no-hair theorem and thus probe the still largely unexplored strong-field regime of gravity.

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