

# HYDRODYNAMIC SIMULATIONS OF TIDAL DISRUPTION ENCORES

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We present hydrodynamic simulations with the moving-mesh code **AREPO** of Tidal Disruption Encores (TDEEs) in nuclear star clusters (NSCs). TDEEs arise when a stellar-mass black hole (sBH) disrupts a star within the NSC, producing debris that is unbound from the sBH but remains gravitationally bound to the central massive black hole (MBH), leading to a delayed secondary flare. We find that the morphology and thermodynamics of the fallback material depend sensitively on the disruption geometry, MBH mass, and sBH-MBH separation. We identify two distinct morphological outcomes: ring encores, where debris circularize into a torus, and direct encores, where streams plunge toward the MBH, with encore luminosities peaking at times corresponding to the freefall timescale and one orbital period, respectively. Across all simulated cases, we find these events exhibit luminosities of  $10^{40} - 10^{42}$  erg/s with lightcurves characteristic of their morphology. Our work greatly improves the predictions of TDEE lightcurves and empowers observations to probe into NSC dynamics and sBH population while providing possible explanations for anomalous TDE-like flares.

## I. INTRODUCTION

Nuclear star clusters (NSCs), made up of very dense concentrations of stars and the compact objects they leave behind, are often found in the central regions of galaxies surrounding the central massive black hole (MBH). In particular, the fraction of nucleated galaxies is found to be especially large,  $\sim 90\%$ , in early-type galaxies with masses  $\sim 10^9 M_\odot$ , albeit dropping at both the high and low end of the mass distribution [1]. The star density in NSCs is very high, possibly reaching  $\sim 10^6 M_\odot \text{ pc}^{-3}$  at a radial distance of  $\sim 0.1$  pc from the core and following a very steep profile,  $\propto r^{-1} - r^{-3}$  (see e.g. Neumayer *et al.* 2 for a comprehensive review). For our Galactic NSC, the stellar density is observed to be  $\sim 10^6 M_\odot \text{ pc}^{-3}$  even at a distance of 0.25 pc [3].

With about  $\sim 1\%$  of their mass in stellar-mass black holes (sBHs) [4], NSCs are ripe environments for close interactions between stars and sBHs. In some cases, the immense tidal forces exerted during such interactions can partially or completely disrupt the star, producing what are known as micro tidal disruption events (TDEs) [5–10]. The prefix “micro” distinguishes these events from “standard” TDEs, which involve the disruption of stars by MBHs in galactic nuclei [11, 12].

micro-TDEs in NSCs can lead to an interesting new phenomenology, which was uncovered by Ryu *et al.* [13]: For a subset of these events, the unbound debris to the sBH remains bound to the MBH, accreting at a later time, thus giving rise to a second flare, which they called a TDE Encore (TDEE). TDEE rates in galaxies with a NSC were found to vary between  $\sim 10^{-6} \text{ yr}^{-1} \text{ gal}^{-1}$  for a MBH of  $\sim 10^6 M_\odot$ , to  $\sim 10^{-3} \text{ yr}^{-1} \text{ gal}^{-1}$  for a

MBH of  $\sim 10^9 M_\odot$ , if the Bahcall-Wolf density profile [4] is extrapolated inward toward the MBH, down to the radius where at least one star and one BH are expected to be present.

Ryu *et al.* [13] studied the evolution of the TDEE analytically, assuming ballistic orbits for the stellar debris. They found that the temporal evolution of the fallback rate of the debris can vary between the standard  $t^{-5/3}$  power law to much steeper decays. If the first flare from the micro-TDE is missed, then the TDEE can show up as an ‘impostor’ among the more typical TDEs from MBHs. The variety of fallback rates exhibited by these encores may indeed provide a natural explanation for a wide range of decay slopes [ $t^{-1} - t^{-4}$ ; 14] of observed light curves of optical/UV TDE candidates which are in tension with the predictions of the classical TDE model [e.g., 15].

Motivated by the relatively high frequency of encores per NSC, and their potential importance both as contributors to the standard MBH TDEs as well as probes of the sBH population in NSCs [16], here we present hydrodynamic simulations of TDEEs, performed using the moving-mesh code **AREPO** [17–19], to investigate debris morphology and observables, accounting for non-linear hydrodynamical effects.

We find that TDEEs are broadly described by two morphologies which we call “direct encores” and “ring encores”, which display distinct observational signatures. In direct encores, the debris following the initial micro-TDE undergoes collisions with other streams, creating shocks on the freefall timescale and the resulting radiation is emitted on the photon diffusion time. For ring encores, the debris begins to reheat after a single period  $\mathcal{P}$  of the sBH’s orbit around the MBH and forms a mostly uniform ring after  $\approx 4\mathcal{P}$ . Rapid cooling then follows. Based on viscous timescale estimates, debris will make it into the relativistic regime of the MBH on the

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timescale of weeks to months for direct encores and years to decades for debris rings which would then produce a rebrightening in luminosity.

In Section II, we review the analytic theory of TDEEs outlined in [13] and describe the different morphology types. Section III details our use of the AREPO and MESA codes, along with the post-process analysis. We present the results for direct encore flares in Section IV, followed by the simulations of ring encores in Section V. Finally, in Section VI, we discuss the observational implications and the broader astrophysical context. We summarize and conclude in Section VII.

## II. ANALYTIC EXPECTATIONS - DIRECT ENCORE OR RING?

Ryu *et al.* [13] discussed how the unbound debris from micro-TDEs, which constitute approximately half the original stellar mass, can orbit within a larger gravitational well of a nearby MBH. To qualitatively discuss the final fate of the unbound debris “spilled” over to the MBH, it is convenient to introduce the characteristic orbital-energy width of debris produced in a micro-TDE relative to the sBH,

$$\Delta\epsilon = \frac{Gm_{\text{sBH}}R_{\star}}{R_{\text{t}}^2}, \quad (1)$$

where  $R_{\text{t}} = (M_{\text{MBH}}/M_{\star})^{1/3}R_{\star}$  is the tidal radius and  $M_{\star}$  ( $R_{\star}$ ) is the stellar mass (radius). If the original orbit of the star is parabolic relative to the sBH, the spilled debris’ orbital energy relative to the MBH can be approximated as  $E \simeq \epsilon_{\text{sBH}} + \Delta\epsilon$ , where  $\epsilon_{\text{sBH}} = -GM_{\text{MBH}}/2R_{\text{bin}}$  is the orbital energy of the sBH on a circular orbit relative to the MBH when their distance is  $R_{\text{bin}}$ .

We can thus consider three possible scenarios:

- 1) If  $|\epsilon_{\text{sBH}}| \gg \Delta\epsilon$  (or  $E \simeq \epsilon_{\text{sBH}}$ ), the energy change due to the micro-TDE is negligible and the spilled debris will essentially share the same circular orbit as the sBH. However, because of the internal energy spread within the debris, there will be a redistribution along the circular path, ultimately leading to a ring.
- 2) If  $|\epsilon_{\text{sBH}}|$  is comparable to, yet larger than  $\Delta\epsilon$ , the spilled debris remain bound ( $E < 0$ ). In this case,  $E$  can be significantly smaller than either of  $\Delta\epsilon$  or  $\epsilon_{\text{sBH}}$ , and the debris may follow a highly eccentric orbit around the MBH, falling into it on a free-fall timescale.
- 3) If  $|\epsilon_{\text{sBH}}| < \Delta\epsilon$  ( $E > 0$ ), the spilled debris are also unbound from the MBH and escape the binary black hole system.

To summarize, following the first TDE flare (Fig. 1a), the debris that do not fall into the sBH have three possible fates:

1. Falling into the MBH on a dynamical timescale and creating a second flare (Fig. 1c).
2. Retaining their original trajectory and forming a

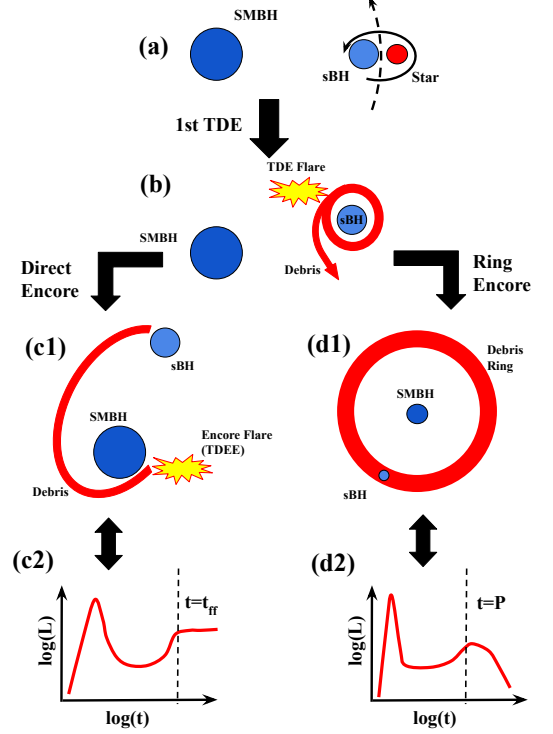


FIG. 1: Overview of the morphology types of TDEEs. (a) Initial three-body system of an MBH orbited by a sBH-star binary. (b) Star undergoes a micro-TDE onto the sBH while orbiting the MBH. Post micro-TDE, a direct encore (c1) or a debris ring (d1) ensue, with corresponding schematic lightcurves displayed in (c2) for a direct encore and (d2) for a ring.

ring which will accrete onto the MBH on a viscous timescale (Fig. 1d).

3. Escaping the binary BH system (not pictured).

Since direct encores follow ballistic debris trajectories, the closer the initial TDE is to the MBH, the more likely for a secondary flare. The angle  $\varphi$  subtended by the innermost stable circular orbit (ISCO) for massive particles around a Schwarzschild MBH is given by

$$\varphi = 2 \arcsin \left( \frac{6r_g}{R_{\text{bin}}} \right) \approx \frac{12GM_{\text{MBH}}}{R_{\text{bin}}c^2}, \quad (2)$$

where the approximation is for small angles  $\varphi$  and  $r_g = GM_{\text{MBH}}/c^2$  is the gravitational radius of the MBH.

The angle subtended is not intended to be an exact expression for the likelihood of the debris being disrupted again by the MBH since the width of the debris, gravitational attraction of the MBH, and existence of less direct debris trajectories all improve the chances of an encore. In part, this motivates our use of hydrodynamic

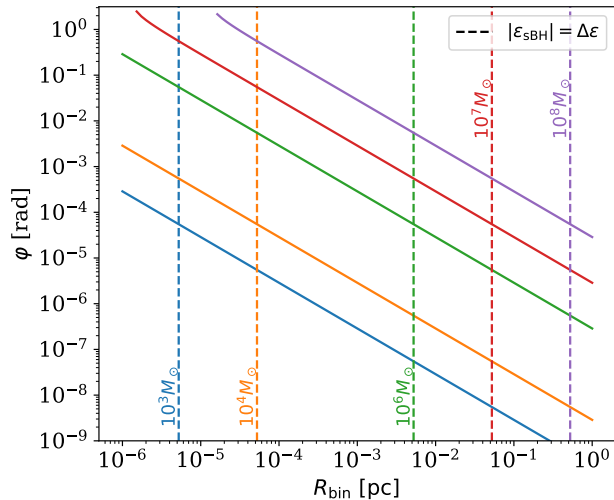


FIG. 2: Rings are likely to form to the left of the dashed vertical lines, where  $|\epsilon_{\text{sBH}}| > \Delta\epsilon$ . To the right of the lines, direct path encounters are possible depending on the specific orbital configuration of the three bodies.

simulations of the phenomenon across several initial angles. Nonetheless, the scaling displayed in Figure 2 is a helpful guide to the family of TDEE flares.

### III. NUMERICAL METHODS

#### A. Stellar model

We created a stellar model assuming near-solar metallicity ( $Z = 0.02$ ) using the stellar evolution code **MESA** [version r24.03.1; 20–22]. We followed the prescriptions for overshoot, convection, semiconvection, and thermohaline mixing from [23], and employed the Ledoux criterion [24] to identify the convective region boundary. We evolved a main-sequence star with a mass of  $1 M_{\odot}$  up to when the central hydrogen mass fraction reached 0.3. At that time, the star’s surface radius is  $1 R_{\odot}$  as anticipated. We show the density and Hydrogen mass fraction profiles of the stellar model in Appendix B.

In this first hydrodynamic investigation of TDEEs, we restrict our simulations to Sun-like stars. Although quantitative details such as energetics and timescales will depend on stellar mass, the main qualitative trends of TDEEs identified here are expected to remain robust. Fixing the stellar mass allows us to isolate and study the dependence on encounter geometry, MBH mass, and sBH–MBH separation.

#### B. Hydrodynamic simulations

We performed a suite of 3D hydrodynamic simulations of TDEEs using the moving-mesh magnetohydrodynamics code **AREPO** [17–19]. We employed an ideal gas equation of state accounting for radiation pressure assuming local thermodynamic equilibrium.

We first mapped a 1D **MESA** profile onto a 3D **AREPO** domain using the method by Ohlmann *et al.* [25], and then relaxed the star using  $N = 5 \times 10^5$  cells. This resolution was chosen after performing convergence tests for key quantities such luminosity, as discussed in Appendix A of Section VIII.

We initialized the simulation with the  $1 M_{\odot}$  star and two non-spinning point mass particles with masses  $M_{\text{MBH}}$  and  $m_{\text{sBH}}$  representing the MBH and sBH, respectively. These BH particles have no intrinsic angular momentum, interact with gas only via gravity, and have separate softening lengths based on the system’s scale.

In this work, we adopt the 2+1 body limit of the three-body problem to initialize the system. In this approximation, the dynamics are decomposed into a sub-binary, comprised of the sBH and the star, and an outer orbit in which the MBH moves relative to the center of mass (COM) of the sub-binary. This hierarchical treatment assumes a large separation between the MBH and the sBH–star pair compared to the binary’s internal separation, such that the gravitational influence of the MBH acts primarily as an external perturbation on the sub-binary. The 2+1 body limit thus allows the complex three-body configuration to be approximated as a coupled system of two Keplerian orbits: one describing the motion of the star about the sBH, and another describing the orbital motion of the sub-binary COM around the MBH.

All gas cells are initialized with identical initial velocities derived from this configuration. The sBH–star system is treated as a Keplerian sub-binary, while the MBH is set in a coplanar, prograde circular orbit around the COM of the sub-binary. The velocity field of the simulation is constructed by superposing the velocity contributions from the internal sub-binary motion and the outer orbital motion of the sub-binary COM about the MBH. All simulations are carried out in the center-of-mass frame of the full three-body system, which approximately coincides with the MBH position due to its dominant mass. A schematic representation of this 2+1 body setup is shown in Fig. 3, illustrating the hierarchical orbital structure and relative geometry of the system.

The specifics of the sBH–star binary orbit are held constant across the various simulations, except for the rotational orientation  $\theta$ , defined as the predicted angle at which the periapsis will occur. Owing to three body dynamics, this prediction is not exact, but it provides a good approximation in the  $2 + 1$  body limit.

Parameters of the sBH–star binary which are held constant are the masses, the eccentricity  $e$ , the initial separation  $R_{\text{sBH}} = 2 R_t$  (where  $R_t$  is defined with  $m_{\text{sBH}}$

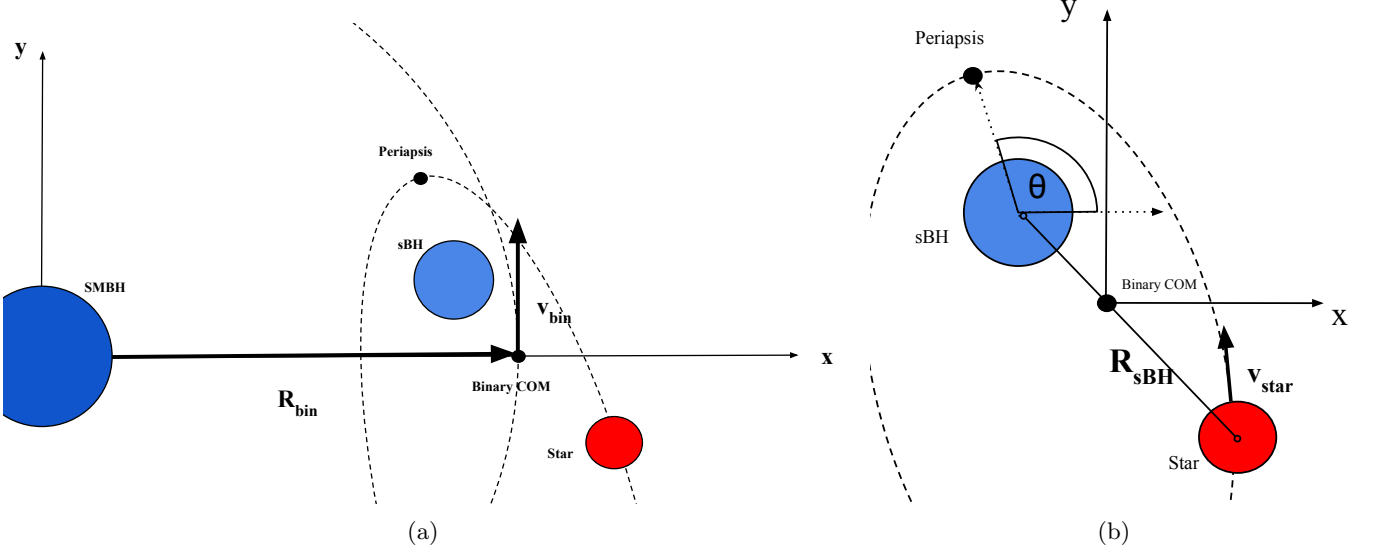


FIG. 3: Schematic depiction of the initial 3 body setup, not to scale: (a) Full 3-body system in the MBH rest frame; (b) Zoom on the sBH-star binary in the sBH rest frame.

and  $M_*$ ), and the distance to periapsis  $r_p = 0.25 R_t$ . We choose as fiducial values  $M_* = 1 M_\odot$ ,  $m_{\text{sBH}} = 10 M_\odot$  and  $1 - e = 10^{-3}$ .

In total, we performed 8 simulations in addition to those required for resolution testing. We detail in Table I the variable input simulation parameters, together with a key output for each, that is the (approximate) peak encore luminosity, computed as described in the following.

| TDEE Simulations              |                              |                       |                                 |
|-------------------------------|------------------------------|-----------------------|---------------------------------|
| $M_{\text{MBH}} (M_\odot)$    | $R_{\text{bin}} [\text{pc}]$ | $\theta [\text{Rad}]$ | $L_{\text{enc}} [\text{erg/s}]$ |
| <i>Direct Encore Outcomes</i> |                              |                       |                                 |
| $10^3$                        | $10^{-5}$                    | 0                     | $10^{40}$                       |
| $10^3$                        | $10^{-5}$                    | $\pi/4$               | $10^{40}$                       |
| $10^3$                        | $10^{-5}$                    | $\pi/2$               | $10^{41}$                       |
| $10^3$                        | $10^{-5}$                    | $3\pi/4$              | $10^{41}$                       |
| $10^3$                        | $10^{-5}$                    | $\pi$                 | $10^{41}$                       |
| $10^3$                        | $10^{-5}$                    | $3\pi/2$              | $10^{40}$                       |
| <i>Ring Encore Outcomes</i>   |                              |                       |                                 |
| $10^6$                        | $10^{-5}$                    | $3\pi/4$              | $*10^{42}$                      |
| $10^6$                        | $10^{-4}$                    | $3\pi/4$              | $10^{40}$                       |

TABLE I: List of the TDEE simulations. From left to right: MBH mass  $M_{\text{MBH}}$ , separation  $R_{\text{bin}}$  between sBH and MBH, argument of periapsis  $\theta$ , approximate peak luminosity of the second flare  $L_{\text{enc}}$ . \*For sufficiently compact ring formation, the distinction between micro-TDE and encore flares may become blurred.

### C. Bolometric Luminosity

Since our simulations did not include explicit radiation-transfer calculations, we estimated the luminosity from the radiation-pressure-dominated, optically thick debris in post-processing, following Ryu *et al.* [26, 27, 28]. We first constructed a cylindrical  $(r, \phi, z)$  virtual grid centred at the sBH with an exponential radial grid extending from  $R_\epsilon$  to  $3R_{\text{bin}}$  (i.e.  $\Delta r/r \simeq \log_{10}(3R_{\text{bin}}/R_\epsilon)/N_r \simeq 0.016$  where  $R_\epsilon = 10^{-3}\text{cm}$ ), a uniform azimuthal grid ( $\Delta\phi = 2\pi/N_\phi = 0.044$ ), and an exponential vertical grid ( $\Delta z/z \simeq 0.016$ ). The total bolometric luminosity is obtained by integrating the radiative flux  $F_{\text{rad}}(t, r, \phi)$  through each vertical column:

$$L(t) = \int_{R_\epsilon}^{3R_{\text{bin}}} dr \int_0^{2\pi} d\phi F_{\text{rad}}. \quad (3)$$

Considering the symmetry around  $z = 0$ , we explicitly calculated only the upward flux relative to the mid-plane. Downward flux was also calculated and found to be nearly identical verifying our symmetry assumptions. We computed the upward flux as:

$$F_{\text{rad}}(r, \phi) = \frac{\int_{z_\tau}^{z_{\text{ph}}} dz a T^4}{t_{\text{diff}}}, \quad (4)$$

where  $z_{\text{ph}}$  is the height above which  $t_{\text{diff}} < t$ , with  $t$  being the age of the system, and  $z_\tau$  is the height of the photosphere at  $\tau \simeq 1$ . Because only photons with  $t_{\text{diff}} < t$  can reach and escape the photosphere, we restricted the vertical integration to the range between  $z_{\text{ph}}$  and  $z_{\text{max}} = 3R_{\text{bin}}$ . To ensure that only radiation from the gas originating from the star is included, we applied a density

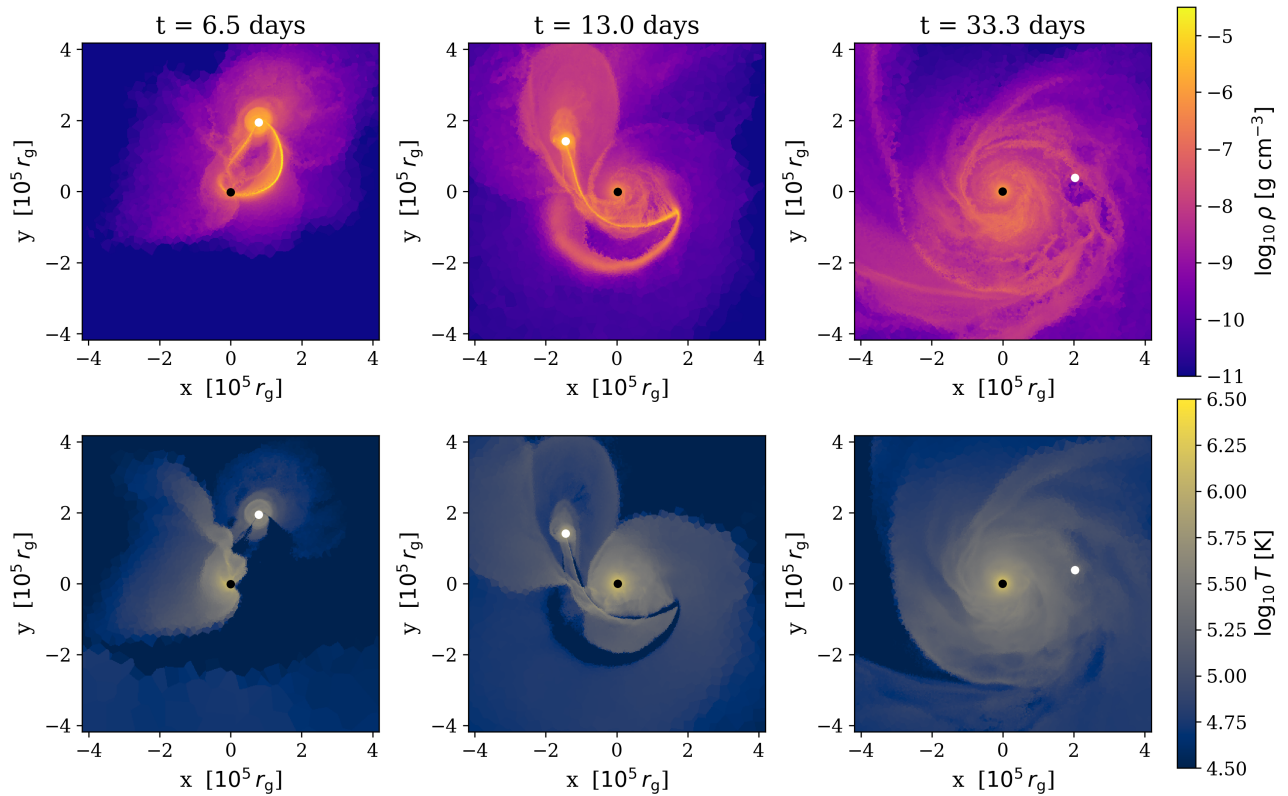


FIG. 4: Density (top) and temperature (bottom) evolution in a simulation of a direct encounter with  $M_{\text{MBH}} = 10^3 M_{\odot}$  (black dot in the center),  $m_{\text{sBH}} = 10 M_{\odot}$  (white dot),  $R_{\text{bin}} = 10^{-5} \text{ pc} \simeq 2 \times 10^5 r_g$ , and  $\theta = 3\pi/4$ . This is the highest luminosity encounter we simulated, but it shares many features with other members with the same TDEE morphology.

After a time  $t \sim t_{\text{ff}} \approx 6$  days, the star is destroyed by the sBH, resulting in an accretion flow near the sBH and a stream falling into the MBH. After a time  $t \sim 2t_{\text{ff}}$ , the tidal tail folds on itself, followed by more circular flows spreading even out to the distance of the sBH.

cut above  $10^{-15} \text{ g/cm}^3$ <sup>1</sup> when calculating the thermal energy within each column. We calculated the optical depth as

$$\tau(z) = - \int_{z_{\text{max}}}^z \kappa \rho dz, \quad (5)$$

where the opacity  $\kappa$  was obtained from the OPAL Rosse-land mean opacity table [29] for given local density  $\rho$  and temperature at each height. We ensured that  $z_{\text{max}}$  is sufficiently high to enclose the photosphere within the virtual grid. Accordingly, the photon diffusion time is

$$t_{\text{diff}}(t, r, \phi) \simeq \frac{H\tau(z=0)}{c}, \quad (6)$$

where  $H$  is the vertical density-weighted scale height at the given  $r$  and  $\phi$ . The diffusion time represents an “average” timescale across the entire vertical column, in the

sense that it does not depend on height. While this is admittedly an approximate estimate, it is robust against uncertainties in the exact photosphere location, which is a limitation inherent to estimates based on adiabatic hydrodynamical simulations.

#### D. Viscous Timescale

The viscous timescale is calculated using the  $H(r, \phi)$  values from our cylindrical virtual grid, adopting the  $\alpha$ -prescription [30]:

$$t_{\text{visc}}(r, \phi) \approx \frac{1}{\alpha} \left( \frac{r^3}{GM_{\text{MBH}}} \right)^{1/2} \left( \frac{H(r, \phi)}{r} \right)^{-2}, \quad (7)$$

where we take  $\alpha = 0.1$ . The mass distribution of the viscous timescale is calculated over  $r$  and  $\phi$  coordinates for masses  $M(r, \phi)$  and the corresponding  $t_{\text{visc}}(r, \phi)$ . For the purposes of Fig. 6, we average  $t_{\text{visc}}(r)$  over  $\phi$ , weighted by mass, that is  $t_{\text{visc}}(r) = \sum_{\phi} (t_{\text{visc}}(r, \phi) \cdot M(r, \phi)) / \sum_{\phi} M(r, \phi)$ , where  $M(r, \phi)$  is the cell mass at given  $r$  and  $\phi$ .

<sup>1</sup> Density is chosen such that the cut-off density is above the so called vacuum cells initialized but 2-3 orders of magnitude below the density of the main ring structure.

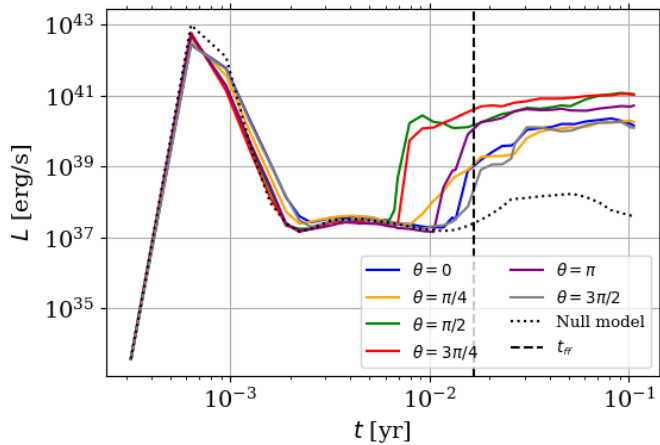


FIG. 5: Bolometric luminosity of the direct encore TDEEs for different initial debris orientations. The first peak corresponds to the micro-TDE around the SBH. Shocks corresponding to the encore begin at roughly the freefall timescale, which is marked. The first data point is manually added as  $1L_{\odot}$  at early times, since our virtual grid struggles to resolve an undisrupted star.

#### IV. DIRECT ENCORE RESULTS

In one limit of TDEEs, the debris has an orbital energy relative to the MBH that is negative but close to zero. Consequently, the debris trajectory can be strongly perturbed by the initial micro-TDE and redirected onto a highly eccentric orbit that plunges toward the MBH.

We performed simulations with  $M_{\text{MBH}} = 10^3 M_{\odot}$  and  $R_{\text{bin}} = 10^{-5}$  pc exploring a range of SBH–star orientations characterized by the projected periapsis angle  $\theta$ . We focused on varying  $\theta$  to assess how sensitively encore formation depends on the debris orientation.

We note that for our direct encore simulations, the MBH is best considered an intermediate-mass black hole or IMBH. Owing to computational limitations, a direct encore simulation for more typical SMBH masses is not feasible; however, MBHs of  $10^3 M_{\odot}$  are still valuable to explore the overall dynamics of TDEEs and are of worthwhile discussion on their own (more in Section VIB).

We show three snapshots of the TDEE simulation with  $\theta = 3\pi/4$  in Fig. 4. The top panels show the debris density, while the bottom ones the temperature. Past analytical models of Ryu *et al.* [13] envisioned debris of the micro-TDE as having direct ballistic paths to the MBH; however, Figure 4 displays nuanced hydrodynamics at play. Of great relevance to the TDEE phenomenology is the wake trailing the path of the SBH. This wake contains an appreciable fraction of the total debris mass (typically  $\approx 70\%$  of  $0.5M_{\star}$ ); it trails the SBH and is prone to freefall toward the MBH, creating shocks when supersonically-moving streams intersect each other.

We find that, while the orientation parameter  $\theta$  of the debris significantly affects their dynamics, the peak en-

core luminosity varies by less than an order of magnitude as shown in Figure 5. The primary cause for this variation is due to the amount of mass which falls onto the MBH following the micro-TDE. Figure 4 displays the debris tail which contains approximately half of the total stellar mass on a direct path, but other orientations  $\theta$  have longer trajectories and thus increase in luminosity later. The simulation with  $\theta = \pi/2$  is a special case where the stream self-interacts early and thus the luminosity has a local peak at  $t \sim 8 \times 10^{-3}$  yr. Other angles outside of  $\pi/2 < \theta < \pi$  do not display significant tidal tails; therefore, their luminosity is an order of magnitude lower. Shock-heating of the wake during freefall to the MBH further produces an observable luminosity  $\approx 10^{40}$  erg/s.

We report the highest encore luminosity of  $\approx 10^{41}$  erg/s, corresponding to roughly the Eddington limit for a  $10^3 M_{\odot}$  MBH, and the qualitatively most complex debris trajectories for  $\pi/2 \leq \theta \leq \pi$ . These TDEEs correspond to disruptions occurring closer to the MBH. Although our angle  $\theta$  has a slightly different definition than that of Ryu *et al.* [13], we confirm the most dramatic plunging angle for the debris to be  $\theta = 3\pi/4$ .

Because our version of AREPO does not include radiation transfer, the late time luminosity decay of our TDEE cannot be well predicted within simulations. However, we note that our simulation reach a rotationally stable disk by the end of an SBH orbital period. This final state motivates an understanding of late timescale TDEEs as being fuelled via viscous transfer of angular momentum.

In Fig. 6, we show the viscous timescale distribution for the encore debris as a proxy for the time they would reach the MBH. Accretion of this debris to the MBH can yield an additional source of luminosity on the freefall timescale. As an order of magnitude estimate, we can write  $L_{\text{acc}} \sim 5 \times 10^{44} \text{ erg s}^{-1} (\eta/0.1) (M_{\text{debris}}/0.1 M_{\odot}) (t_{\text{visc}}/1 \text{ yr})^{-1}$ , where  $\eta$  is an accretion efficiency factor. Accretion of the debris onto the MBH, depending on the efficiency, can therefore result in an hyper-Eddington accretion flow for  $M_{\text{MBH}} = 10^3 M_{\odot}$ , possibly driving an outflow/jet, and yield a rather brilliant encore flare.

#### V. RING ENCORE RESULTS

This scenario leaves the orbit of the stellar debris largely unchanged following the initial TDE flare, since their energy spread due to the micro-TDE is not large enough to significantly alter their path with respect to the initial trajectory of the star. It then follows that the debris form a disk in the shape of the original orbit as hypothesized by Ryu *et al.* [13].

Although the formation of a ring can be anticipated from an analytic comparison between  $\epsilon_{\text{SBH}}$  and  $\Delta\epsilon$ , such analytic estimates are insufficient to examine the detailed properties of the ring, due to the complex hydrodynamics and 3-body dynamics involved. Using our simulations,

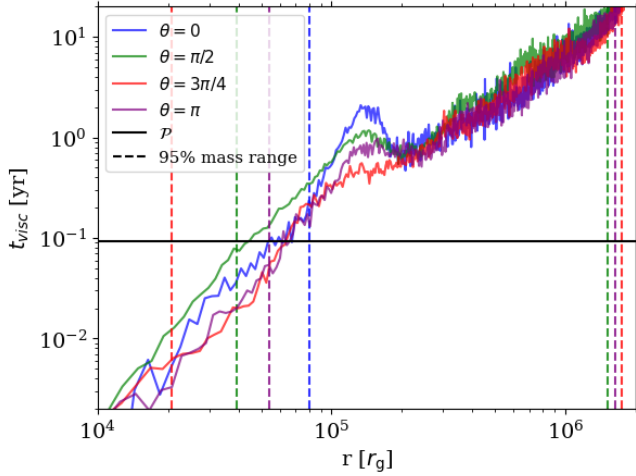


FIG. 6: Distribution of viscous timescales for the debris that reach the MBH in some of the direct encore cases. The dashed lines, sharing the same colors, indicate the range within which 95% of the debris mass is enclosed.

however, we can measure the thermodynamic properties of the ring debris, including their scale height and viscous timescale, as well as their observables, such as the bolometric luminosity.

We confirmed the formation of a ring from the debris in two simulations with  $R_{\text{bin}} = 10^{-5}$  pc and  $R_{\text{bin}} = 10^{-4}$  pc. All other parameters were kept the same:  $m_{\text{sBH}} = 10 M_{\odot}$ ,  $M_{\text{MBH}} = 10^6 M_{\odot}$ , and  $M_* = 1 M_{\odot}$ . For these parameters,  $\Delta\epsilon/\epsilon_{\text{sBH}} \simeq 10^{-2}(R_{\text{bin}}/10^{-4} \text{ pc}) \ll 1$ , which, according to our analytic estimates (see § II), corresponds to this ring-encore scenario.

As shown in Figure 7 for  $R_{\text{bin}} = 10^{-5}$  pc, the debris created in the micro-TDE closely track the orbit of the sBH. However, because of the energy spread within the debris ( $\simeq \Delta\epsilon$ ), each gas parcel follows a slightly different orbit, producing a crescent-shaped structure (left panels) that gradually evolves into an inspiral (middle panels), and eventually merges into an axisymmetric ring (right panels) over the course of roughly 20 orbital periods of the sBH. The structural transformation of the debris from a crescent to a ring qualitatively resembles the debris evolution in “extremely relativistic” TDEs [26] (see their Fig. 1), although the two events are entirely distinct in terms of their formation mechanisms, spatial and temporal scales, subsequent evolution of the ring, and resulting observables.

In the two subsections below, we focus on discussing relevant time and spatial scales for the ring (§ V A) and its luminosity (§ V B).

### A. Width and Timescale of the Ring

Our results indicate a disk aspect ratio of  $H/R_{\text{bin}} \approx 10^{-2}(R_{\text{bin}}/10^{-4} \text{ pc})$ , so  $H \propto R_{\text{bin}}^2$ . On the other hand,

the radial extent of the ring  $\Delta r$ , defined as the width enclosing 95% of the total mass in the ring, is approximately  $\Delta r/R_{\text{bin}} \simeq 65(\Delta\epsilon/\epsilon)$  so  $\Delta r \propto R_{\text{bin}}^2$ . This yields  $H/\Delta r \simeq 1.5 \times 10^{-3}$ , indicating that the vertical cross-sectional shape of the axisymmetric debris is more extended in the radial direction. The radial extent of the debris in the two simulations for the ring encore scenario is illustrated in Fig. 9. The dependence of  $\Delta r$  on  $R_{\text{bin}}$  can be understood from how wide the energy spread is within the debris, as indicated by the scaling factor  $(\Delta\epsilon/\epsilon)$ . We attribute the larger  $H$  at larger  $R_{\text{bin}}$  to weaker vertical gravity. If the debris are in vertical hydrostatic equilibrium,  $dP/dz \simeq GM_{\text{MBH}}z\rho/R_{\text{bin}}^3$ . If density and pressure share the same scale height ( $Pdz/dP \simeq \rho dz/d\rho$ ) for a given  $R_{\text{bin}}$ , and are virialized ( $P/\rho \propto R_{\text{bin}}^{-1}$ ), then  $Pdz/dP \propto (P/\rho)R_{\text{bin}}^3 \propto R_{\text{bin}}^2$ . This scaling relation  $P/\rho \propto R_{\text{bin}}^{-1}$  is indeed found in our simulations (see the bottom panels of Fig. 7 and 8).

For these spatial scales and their scalings, we can make two additional points: 1) The volume density scales as  $R_{\text{bin}}^{-5}$  because  $\rho \simeq M_*/[2\pi R_{\text{bin}} H \Delta r]$ , consistent with the simulations. The peak density is  $10^{-2} \text{ g cm}^{-3}$  for  $R_{\text{bin}} = 10^{-4} \text{ pc}$ , whereas it is  $10^{-7} \text{ g cm}^{-3}$  for  $R_{\text{bin}} = 10^{-5} \text{ pc}$ . 2) The very small  $H/\Delta r$  implies that photon diffusion is generally faster along the vertical direction.

While photons escape on the photon diffusion timescale  $t_{\text{diff}}$ , a fraction of the disk would gradually fall toward the MBH and finally accrete over the viscous timescale  $t_{\text{visc}}$ . If  $t_{\text{visc}} < t_{\text{diff}}$ , photons remain “frozen” into the debris and the luminosity is mostly determined by  $t_{\text{visc}}$ . On the other hand, if  $t_{\text{visc}} > t_{\text{diff}}$ , photons diffuse out before the gas accretes, so the prompt luminosity at early times is determined by  $t_{\text{diff}}$ . However, once the infalling debris begins accreting, the luminosity would arise from both accretion and radiative diffusion.

In Figure 10, we compare  $t_{\text{diff}}$  with  $t_{\text{visc}}$ , averaged over radial shells and weighted by mass, throughout the simulated rings. We find that  $t_{\text{visc}}$  is two to three orders of magnitude longer than  $t_{\text{diff}}$  in both cases, which suggests that the prompt luminosity is primarily powered by the thermal energy radiated away, rather than by accretion.

### B. Luminosity

Fig. 11 shows the luminosity, estimated following the procedure explained in § III C, for the two simulations with  $R_{\text{bin}} = 10^{-5}$  pc (blue) and  $10^{-4}$  pc (orange). As in the direct encore scenario, the first peak corresponds to the micro-TDE by the sBH. We remind that, because our simulations neglect physical viscosity and the viscous timescale for accretion onto sBHs is relatively short, the diffusive sBH luminosity presented here may not accurately represent the actual sBH flare, which is likely dominated by accretion luminosity (see, e.g., [5, 7, 8]).

Following the initial sBH flare, the subsequent plateau in the luminosity arises from the TDEE ring. The luminosity for  $R_{\text{bin}} = 10^{-5}$  pc is approximately two orders of

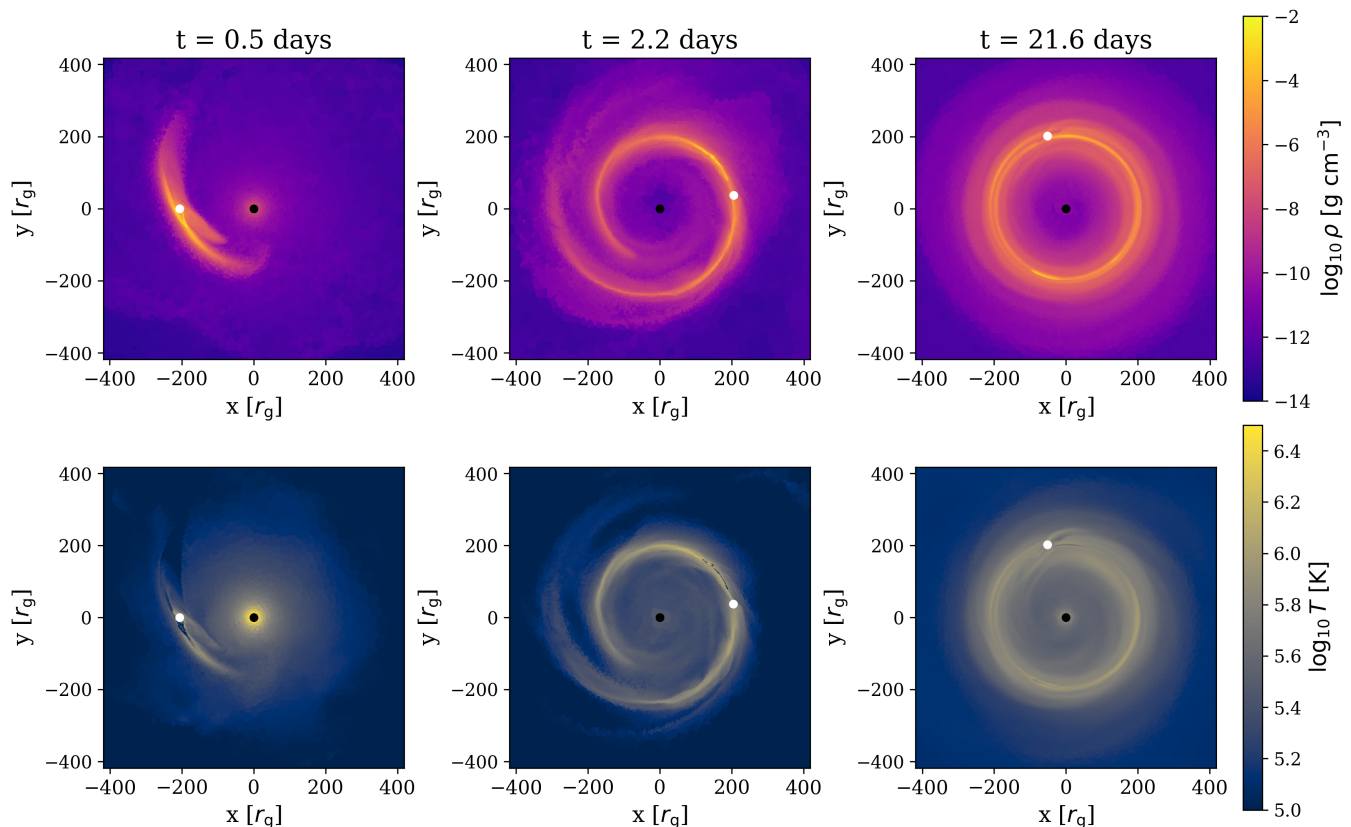


FIG. 7: Disk development and evolution around a central  $10^6 M_\odot$  MBH (black dot at  $x=y=0$ ) following a TDE of a  $1 M_\odot$  star by a  $10 M_\odot$  sBH (white dot). For this simulation,  $\mathcal{P} \approx 1.1$  days. The sBH-star sub system is initially set in a circular orbit around the MBH with initial separation  $R_{\text{bin}} = 10^{-5}$  pc =  $209 r_g$ . *Top panels*: Evolution of the disk’s density; *Bottom panels*: Evolution of the disk’s temperature.

magnitude higher than that for  $R_{\text{bin}} = 10^{-4}$  pc. We can understand this dependence on  $R_{\text{bin}}$  by deriving an approximate expression for the luminosity which relies on using the timescale considerations of the previous subsection. The vertical photon diffusion can be approximated as  $t_{\text{diff}} \simeq \kappa \rho H^2 / c$ , where  $\kappa$  is the Thomson opacity. The luminosity can then be estimated as

$$L \simeq \frac{aT^4 V}{t_{\text{diff}}} \propto \frac{T^4}{\rho^2 H^2} \propto R_{\text{bin}}^2, \quad (8)$$

where  $V \simeq M_*/\rho$  is the volume of the debris. Here, we have used  $T \propto R_{\text{bin}}^{-1}$ ,  $\rho \propto R_{\text{bin}}^{-5}$ , and  $H \propto R_{\text{bin}}^2$ . This scaling relation is consistent with our luminosity estimates from the simulations.

Based on our viscous timescale estimates (Fig. 10), the luminosity may rise again to  $\eta M_* c^2 / t_{\text{vis}} \simeq (1 - 5) \times 10^{43} (\eta/0.01) \text{ erg s}^{-1}$ , due to the accretion onset after  $\sim 10$  to  $50$  years since the micro-TDE, with the precise value depending on  $R_{\text{bin}}$ .

## VI. DISCUSSION

### A. Observational Implications

Our hydrodynamical simulations of TDEEs with AREPO have allowed us to study in detail this special phenomenon, characterize its morphological features, and estimate the expected luminosity.

For direct encores, our simulations show that debris stream self-intersections can occur as early as one week after the micro-TDE, scaling as  $(R_{\text{bin}}/10^{-5} \text{ pc})^{3/2} (M_{\text{MBH}}/10^3 M_\odot)^{-1/2}$ . This stage in the light curve corresponds to a sharp luminosity rise from shocks, observable in the optical/UV band (see Fig. 5). While the folding of debris streams into self-intersections near the MBH is complex and highly sensitive to initial conditions, the peak luminosity remains robust against these variations.

X-ray emission is expected both from the initial micro-TDE (e.g., [5]) and from subsequent accretion onto the MBH on the viscous timescale, with the X-ray fraction of the accretion luminosity generally increasing for lower-mass MBHs. The micro-TDE luminosity is roughly four orders of magnitude above the Eddington limit of a  $10 M_\odot$  sBH, which is likely to drive strong outflows and

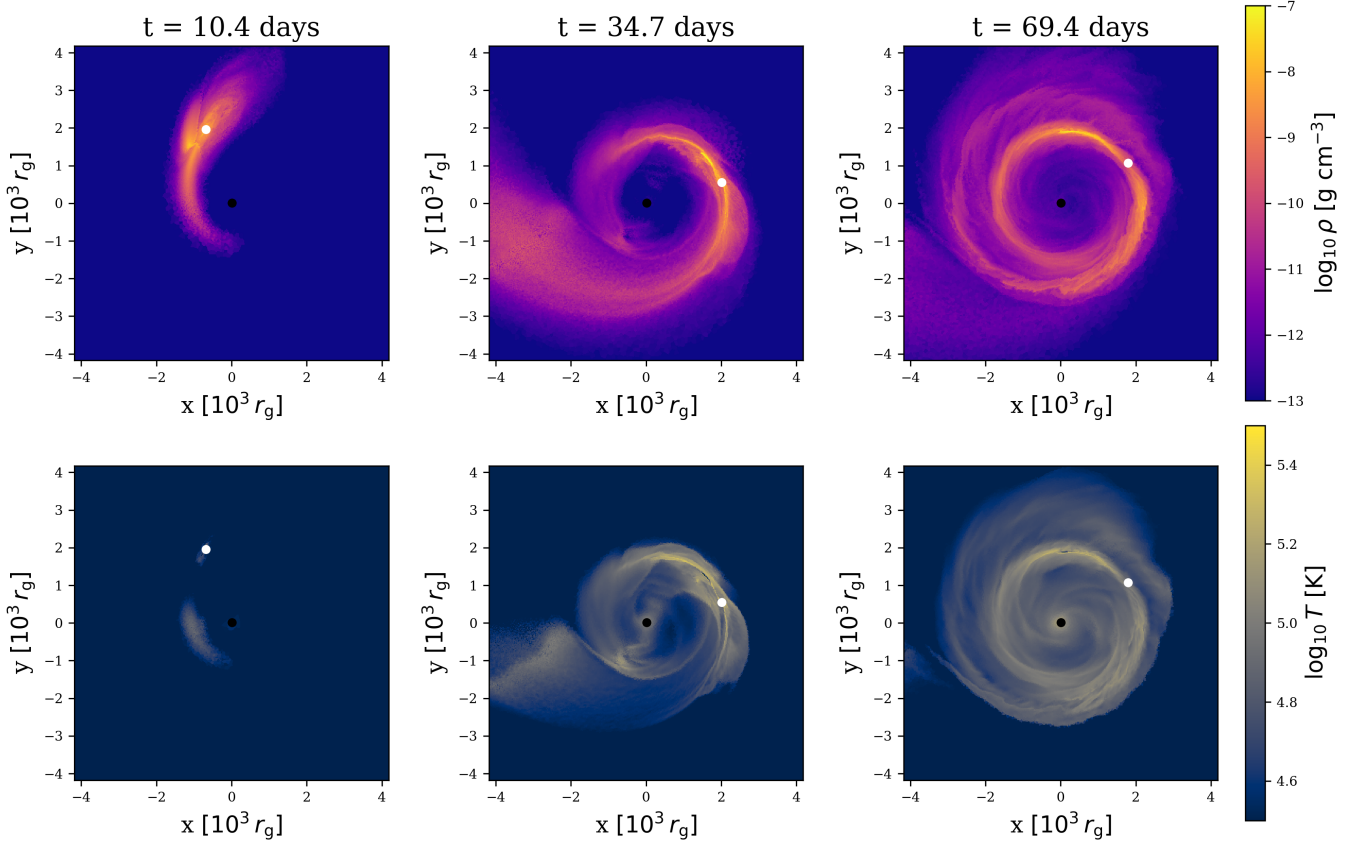


FIG. 8: Disk development and evolution around a central  $10^6 M_\odot$  MBH (black dot at  $x=y=0$ ) following a TDE of a  $1 M_\odot$  star by a  $10 M_\odot$  sBH (white dot). For this simulation,  $\mathcal{P} \approx 34$  days. The sBH-star sub system is initially set in a circular orbit around the MBH with initial separation  $R_{\text{bin}} = 10^{-4} \text{ pc} = 2.1 \times 10^3 r_g$ . *Top panels*: Evolution of the disk's density; *Bottom panels*: Evolution of the disk's temperature.

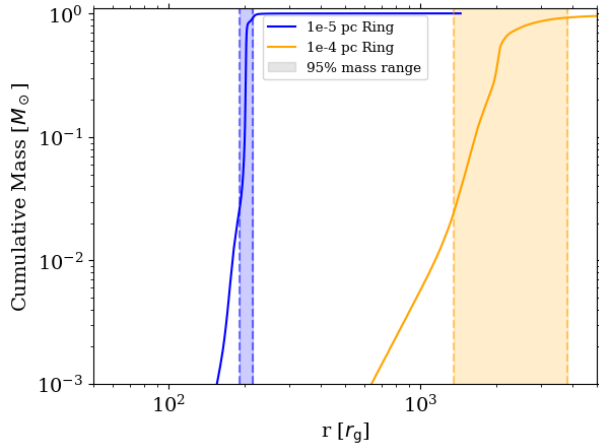


FIG. 9: Mass distribution in the TDEE rings, evaluated at  $t \approx 5\mathcal{P}$ . The radial extent of the debris containing 95% of the mass is  $\sim 26 r_g$  for the  $10^{-5}$  pc ring, and  $\sim 2.5 \times 10^3 r_g$  for the ring centred at  $10^{-4}$  pc.

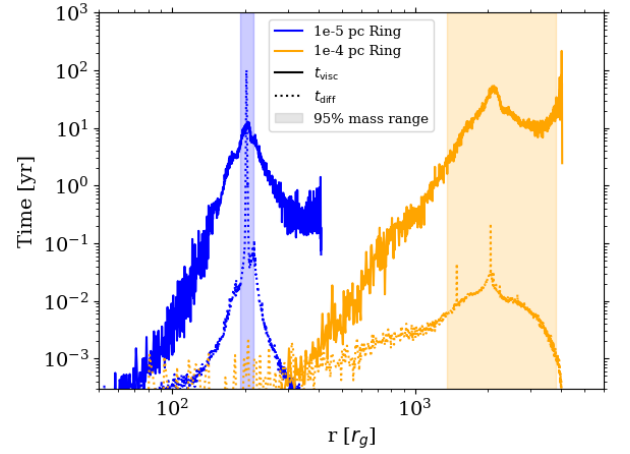


FIG. 10: Viscous and diffusive timescales calculated at  $t \approx 5\mathcal{P}$  for both ring simulations. Shaded regions enclose 95% of the debris mass, highlighting the areas of greatest significance.  $t_{\text{diff}}$  peaks at the tori centers, corresponding to the densest regions.

winds, making this initial event possibly appear like an

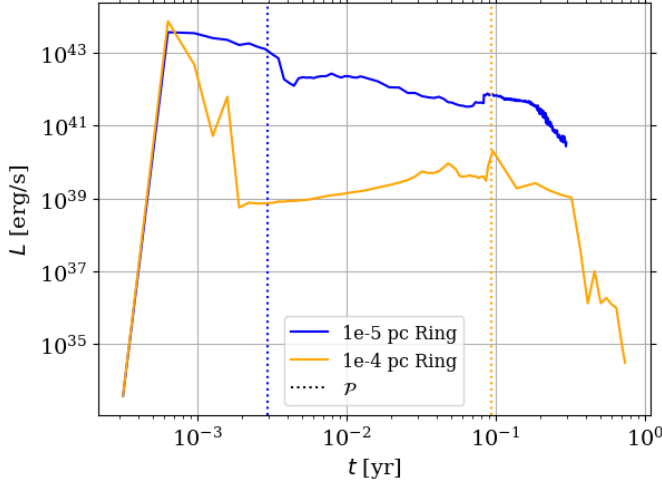


FIG. 11: Bolometric luminosity evolution of the TDEE in the two ring outcomes. The first simulation point has been manually set to  $1L_{\odot}$  since the virtual grid does not properly resolve the star prior to disruption. The vertical dotted lines indicate the one period timescale for each of the two cases. The first peak corresponds to the micro-TDE, which is not well distinct from the encore in the  $10^{-5}$  pc case.

X-ray rich, long-duration gamma-ray burst [5]. We find that for both morphologies of TDEEs, the two X-ray signatures are separated in time approximately by months to years.

Here we bring up the recent observations of AT 2023lli by Huang *et al.* [31] which show an optical/UV bump 2 months prior to the TDE's peak. Their observations show the early bump is two orders of magnitude smaller than the eventual global peak. This appears to align well with the peak interval and luminosity corresponding to a  $\approx 10^6 M_{\odot}$  TDEE where the micro-TDE is Eddington limited. In fact, their work also infers that the central BH mass is  $10^{6.4 \pm 0.47} M_{\odot}$ . In the perfectly circular sBH-MBH case, their separation would be  $R_{\text{bin}} \approx 4 \times 10^{-4}$  pc based on the time difference between the bump and the global peak of 50 days. Our results suggest that a TDEE of this configuration would have a encore luminosity peak at  $\approx 10^{41}$  erg/s.

Additionally, the delayed X-ray peak of AT 2023lli may be explained by the dynamics of TDEEs. Because the debris initially lie farther from the MBH than that in ordinary TDEs, the formation of an accretion disk—and thus the onset of X-ray emission—may be delayed due to an extended viscous timescale. The  $\sim 150$ -day lag between peak optical and peak X-ray luminosity in AT2023lli is consistent with the range expected from the viscous timescale of the debris structure's inner edge. While it is not yet certain that AT 2023lli is a TDEE, its properties align with several predicted features and merit further study.

## B. Encores as IMBH Probes

The existence of IMBHs in NSCs remains tentative, yet nuclear TDEs provide promising probes for their detection. Whereas most of the prior work of Ryu *et al.* [13] has concentrated on estimating TDE rates from IMBHs, the direct encore flares predicted here – lower luminosity in X-rays, followed by higher luminosity peak in optical/UV – offer an independent diagnostic for constraining IMBH masses in NSCs.

Since encore debris circularization begins at roughly the freefall timescale  $t_{\text{ff}}$ , the time delay between the micro-TDE and TDEE flares encodes information about  $M_{\text{MBH}}$  and  $R_{\text{bin}}$ , offering potential insights into the presence of IMBHs in NSCs. Furthermore, because both TDEE rates and their electromagnetic signatures depend on  $R_{\text{bin}}$  [13], their detection and characterization can be also informative of the properties of the innermost sBH population of the NSC, which is generally hard to probe by other means.

The time delay between the initial micro-TDE flare and its encore is very short, on the order of  $\sim$  week timescale for the specific IMBH mass ( $10^3 M_{\odot}$ ) and binary separation ( $10^{-5}$  pc) simulated here. It becomes longer for larger binary separations ( $\propto R_{\text{bin}}^{3/2}$ ), while it is shortened by larger central masses ( $\propto M_{\text{MBH}}^{-1/2}$ ). Because micro-TDEs are expected to be most prominent in high-energy X-rays/ $\gamma$ -rays, we encourage systematic follow-ups and cross-correlations of nuclear transients across multiple wavebands.

## C. General Relativistic Effects

Because most debris in our simulations for the encore flare remains sufficiently far from the MBH, the inclusion of relativistic effects is not expected to impact the overall evolution. The primary relativistic effect on tidal streams would be periapsis advance of the debris, given by  $\Delta\phi \simeq 1$  radian  $(r_p/10r_{\text{g,MBH}})^{-1}$  for highly eccentric geodesics [32], where  $r_p$  is the pericenter distance. For most simulations, we find that  $\Delta\phi < 10^{-3}$  radians relative to both BHs; however, certain debris trajectories ( $\pi/2 \leq \theta \leq 3\pi/4$ ) for our direct encore simulations have  $10^{-2} < \Delta\phi < 10^{-1}$ . In both cases, the expected relativistic effect is still small and thus expected to have a minor contribution in decreasing the circularization time of debris via stream self-crossing. From this post-process test, we therefore conclude that a Newtonian model for gravity is sufficient to characterize the observables predicted in this paper. However, relativistic effects eventually become important when the debris lose its orbital energy via shocks and accumulate in the vicinity of the MBH.

While our simulations are constrained to Newtonian mechanics, we can analytically predict the gravitational waves (GWs) emitted by the circular orbit of the sBH-MBH binary. With reduced mass  $\mu \approx M_{\text{MBH}}$ , chirp mass

$\mathcal{M} \approx M_{\text{MBH}}^{2/5} m_{\text{sBH}}^{3/5}$ , and distance to the observer  $R_{\text{obs}}$ , we derive that the GW strain from TDEE sources is

$$h \sim 2.3 \times 10^{-23} \left( \frac{m_{\text{sBH}}}{10 M_{\odot}} \right) \left( \frac{M_{\text{MBH}}}{10^6 M_{\odot}} \right) \times \left( \frac{R_{\text{bin}}}{10^{-5} \text{ pc}} \right)^{-1} \left( \frac{R_{\text{obs}}}{400 \text{ Mpc}} \right)^{-1} \quad (9)$$

and the frequency of the waves  $f_{\text{GW}} = 2/\mathcal{P}$  is

$$f_{\text{GW}} = 2.1 \times 10^{-5} \text{ Hz} \left( \frac{M_{\text{MBH}}}{10^6 M_{\odot}} \right)^{1/2} \left( \frac{R_{\text{bin}}}{10^{-5} \text{ pc}} \right)^{-3/2}. \quad (10)$$

In general, the expected strain from extreme mass ratio inspirals (EMRIs) forming TDEEs is too small to be detected corresponding to direct encores, and ring encores are tidally limited by the MBH. For the planned Laser Interferometer Space Antenna (LISA) sensitivity, most EMRIs would be outside expected sensitivities [33]. However, event rates from TDEEs offer valuable insight into BH populations in NSCs.

Inverting the equation for rates from Ryu *et al.* [13], we can obtain a lower bound on the radial distribution of sBHs in NSCs. A measurement of  $d\dot{N}_{\text{TDEE}}/dR_{\text{bin}}$  in the near vicinity of a MBH is possible via the use of TDEE's significant and measurable dependence on orbital period. Coupled with estimations of the mass of the MBH at the centre of a given galaxy such as those done by Huang *et al.* [31], values of  $R_{\text{bin}}$  can be extracted from light curve data.

Given a population of detections, we can then calculate

$$\frac{dN_{\text{sBH}}}{dR_{\text{bin}}} = \frac{d\dot{N}_{\text{TDEE}}}{dR_{\text{bin}}} (n_{\star}(R_{\text{bin}})v(R_{\text{bin}})\Sigma(R_{\text{bin}}))^{-1}, \quad (11)$$

where  $n_{\star}$  is the stellar number density,  $v$  is the maximal velocity, and  $\Sigma$  is the encounter cross section. While the range of distances for which TDEEs are more likely to occur is immediately unresolvable for upcoming space based missions, the BHs will eventually evolve into the LISA band as they radiate gravitational energy.

Meanwhile, the entire population of these unresolvable binaries will sum together and contribute to the stochastic GW background of space-based detectors. The background bolometric GW luminosity predicted by TDEE sources can be estimated as

$$L_{\text{GW, background}} = \int dR_{\text{bin}} dM_{\text{sBH}} \left[ \frac{dN_{\bullet}}{dR_{\text{bin}}} \phi(M_{\text{MBH}}) L_{\text{GW}}(M_{\text{MBH}}, R_{\text{bin}}) \right] \quad (12)$$

where  $\phi(M_{\text{MBH}})$  is the initial mass function of the central MBH. Although a single EMRI in the TDEE  $R_{\text{bin}}$  range is not detectable, their sum may be appreciable.

## VII. CONCLUSIONS AND OUTLOOK

In this work, we have carried out the first hydrodynamical simulations of tidal disruption encore events using the moving-mesh code **AREPO**. Our study focused on the disruption of Sun-like stars by stellar-mass BHs within the potential of a more massive BH, exploring the subsequent evolution of debris into encore flares. We identified two primary classes of encores: *direct encores*, in which debris streams plunge toward the MBH and produce shock-powered flares, and *ring encores*, in which debris circularize at larger radii, leading to delayed accretion and extended emission. The time delay between the primary flare from the micro-TDE onto the sBH and the encore onto the MBH is determined by the freefall timescale in the former case and the orbital period in the latter.

For the range of parameters studied here, we find that the delay between the micro-TDE and the encore flare can range from weeks to several decades, depending sensitively on the MBH mass and the sBH–MBH separation. The resulting light curves exhibit characteristic double-flare structures: a primary flare due to the micro-TDE, likely brighter in X-rays/ $\gamma$ -rays, followed by optical/UV emission powered by debris self-intersections, with contribution from viscous accretion onto the MBH. The latter, especially if the MBH is an IMBH, will likely emerge in X-rays. In some regimes, the accretion luminosity can exceed the Eddington limit for  $M_{\text{MBH}} \sim 10^3 M_{\odot}$ , raising the possibility of strong outflows or jet activity. These features position TDEEs as a novel class of nuclear transients, potentially explaining observed candidate TDE events with non-standard temporal decays and delayed rebrightenings.

Looking forward, several directions merit further exploration. Extending the simulations to a broader range of stellar masses and internal structures will elucidate how TDEE energetics and timescales scale with stellar properties. Incorporating radiation transport will provide more reliable predictions for spectra and observational diagnostics. Embedding our framework within cluster dynamical models will allow population-level predictions for TDEE rates and their connection to nuclear star cluster structure. From an observational perspective, wide-field optical/UV surveys (e.g., Rubin, ULTRASAT) combined with sensitive X-ray follow-up (e.g., eROSITA, Einstein Probe, Athena) are well positioned to identify candidate TDEEs through their distinctive double-flare light curves. Finally, in cases where sBHs inspiral toward MBHs, TDEEs may occur contemporaneously with extreme mass ratio inspirals detectable by LISA, offering a multi-messenger pathway to probe the dynamics of dense nuclear star clusters.

In summary, TDEEs open a new observational window onto the astrophysics of dense stellar environments. In particular, encore flares may provide an independent diagnostic for the long-sought population of intermediate-mass BHs in nuclear star clusters. As both time-domain

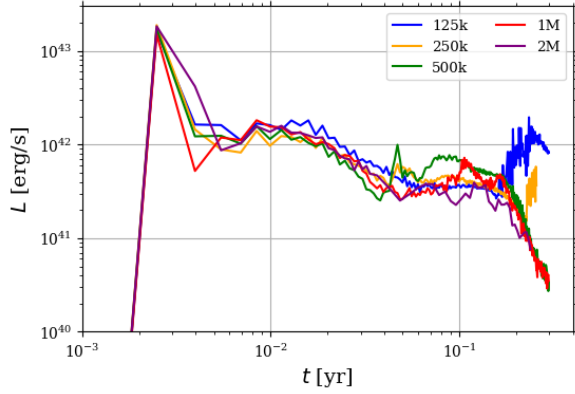


FIG. 12: Resolution test: Luminosity for the ring simulation with  $R_{\text{bin}} = 10^{-5}$  pc with relaxed MESA model stars of varied initial number of cells. We adopted the 500k resolution since values converge on the simulated timescale.

surveys and gravitational-wave observatories advance, TDEs may emerge as a complementary probe of BH demographics and strong-gravity astrophysics.

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#### VIII. APPENDIX A: RESOLUTION TESTS

Our simulations are run with a stellar model of 500k cells initially. This resolution was chosen after a series of simulations of increasing resolutions were performed until we had demonstrated the convergence of post-process values including luminosity and the relevant timescales.

As an illustrative example, Fig. 12 shows the results of our resolution test for one of the models, the ring-outcome simulation with  $R_{\text{bin}} = 10^{-5}$  pc. The figure presents the predicted luminosities obtained from relaxed MESA stellar models with initial mesh resolutions ranging from 125k to 2M cells. The results demonstrate that a resolution of 500k cells is sufficient, as it yields converged luminosities consistent with those at higher resolutions while minimizing computational cost.

#### IX. APPENDIX B: MESA STELLAR MODEL

As a reference, Fig. 13 shows the density and hydrogen mass fraction profiles of the  $1M_{\odot}$  star modeled with MESA and used in our simulations.

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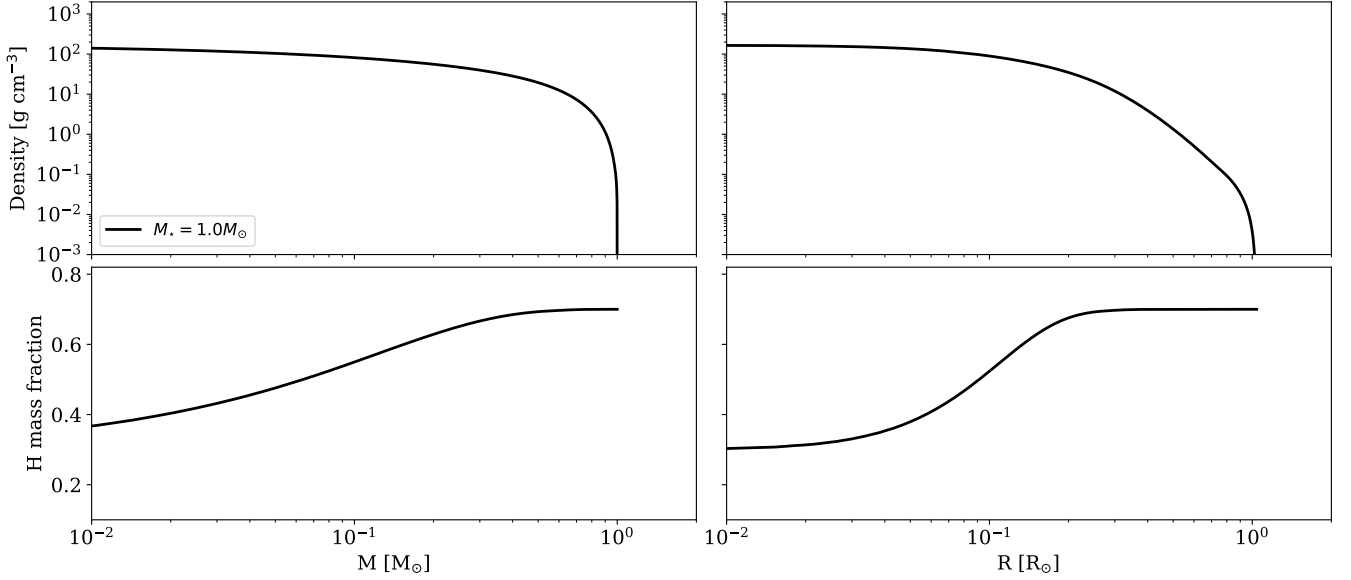


FIG. 13: Density and hydrogen mass fraction profiles of the  $1 M_{\odot}$  model consider. The left (right) panels depict the profile as a function of enclosed mass (radius).

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