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Prompt tidal disruption of stars as an electromagnetic signature of supermassive black hole coalescence

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ABSTRACT

A precise electromagnetic measurement of the sky coordinates and redshift of a coalescing black hole binary holds the key for using its gravitational wave (GW) signal to constrain cosmological parameters and to test general relativity. Here we show that the merger of $\sim 10^{6-7} M_{\odot}$ black holes is generically followed by electromagnetic flares from tidally disrupted stars. The sudden recoil imparted to the merged black hole by GW emission promptly fills its loss cone and results in a tidal disruption rate of stars as high as $\sim 0.1 \text{ yr}^{-1}$. The prompt disruption of a single star within a galaxy provides a unique electromagnetic flag of a recent black hole coalescence event, and sequential disruptions could be used on their own to calibrate the expected rate of GW sources for pulsar timing arrays or the proposed *Laser Interferometer Space Antenna*.

Key words: black hole physics – gravitational waves – galaxies: nuclei.

1 INTRODUCTION

Recently, general relativistic simulations demonstrated that the coalescence of a black hole binary is accompanied by the anisotropic emission of gravitational radiation, causing a typical recoil of hundreds of km s^{-1} for the black hole remnant (Pretorius 2005; Baker et al. 2006; Campanelli et al. 2006). Binaries of supermassive black holes (SMBHs) are a generic consequence of galaxy mergers (Escala et al. 2005; Mayer et al. 2007; Callegari et al. 2009; Colpi & Dotti 2009), and the resultant gravitational waves (GWs) are potentially detectable with the proposed *Laser Interferometer Space Antenna* (LISA)¹ or existing pulsar timing arrays (PTAs) such as NANOGrav.²

LISA would be most sensitive to binary mergers with a total mass $M_{\text{BH}} \sim 10^{6-7} M_{\odot}$ (McWilliams et al. 2010), whereas the PTA sensitivity peaks at $\sim 10^8 M_{\odot}$ (Sesana, Vecchio & Volonteri 2009). PTAs have a significantly poorer localization ability, with a typical uncertainty (Sesana & Vecchio 2010) of ~ 40 compared to $\lesssim 1 \text{ deg}^2$ for LISA. These positional errors limit the precise determination of the luminosity distance to merging binaries. An electromagnetic (EM) counterpart would greatly reduce the positional error to sub-arcsecond scales, and also determine the redshift of the source, which would enable its use as a ‘standard siren’ (independent of the cosmic distance ladder) for precision measurements of the dark

energy equation of state (Holz & Hughes 2005; Arun et al. 2009; Schutz 2009; Bode et al. 2010).

For these reasons, prompt EM signals are of primary importance for realizing the full potential of GW cosmology. The proposed prompt EM signals have so far all assumed the uncertain presence of a circumbinary accretion disc prior to coalescence. Dissipation of GW energy in the disc might result in a weak EM transient shortly after the merger (Kocsis & Loeb 2008), re-equilibration of the inner edge of the disc could create an X-ray brightening on a time-scale of $10\text{--}10^3 \text{ yr}$ (Milosavljević & Phinney 2005), and shocks produced by the GW-induced recoil might generate EM reverberations after the recoil (Lippai, Frei & Haiman 2008) which may take $\sim 10^4 \text{ yr}$ to dissipate as enhanced infrared luminosity (Schnittman & Krolik 2008). It is not obvious whether these EM signals could be distinguished from the much more abundant sources of temporal variability in single SMBH quasars. Moreover, the luminosity of any circumbinary disc is expected to be significantly reduced by the cavity associated with the decoupling of the binary from the inner edge of the disc in the final stage of inspiral (Milosavljević & Phinney 2005; Schnittman & Krolik 2008). The disc is not expected to refill the cavity and return to its full luminosity for a time $\sim 7(1+z)(M_{\text{BH}}/10^6 M_{\odot})^{1.32} \text{ yr}$ after coalescence (Milosavljević & Phinney 2005). On longer time-scales, the portion of the accretion disc that remains bound to the recoiled SMBH is expected to be detectable as a kinematically and eventually a spatially offset quasar (Loeb 2007; Bonning, Shields & Salviander 2007; Komossa, Zhou & Lu 2008; Shields & Bonning 2008; Comerford et al. 2009; Shields et al. 2009), although its lifetime is limited by the supply of gas that can remain gravitationally bound to it (Blecha & Loeb 2008).

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¹ <http://lisa.nasa.gov/>

² <http://nanograv.org/>

Here we show that the tidal disruption of stars provides a prompt EM flag that does not depend on the prior existence of a gaseous disc in the vicinity of the merging binary, and can result from mergers of gas-poor galaxies. Recent observations have demonstrated that tidal disruption events (TDEs) have a generic light curve and emission spectrum (Donley et al. 2002; Gezari et al. 2006, 2008, 2009; Esquej et al. 2007) that are distinguishable from normal quasar variability. Moreover, we find that SMBH recoil results in a sequence of TDEs over a time-scale of decades and potentially years, with a rate that is ~ 4 orders of magnitude higher than the typical TDE rate in normal galaxies (Donley et al. 2002). The existence of TDEs accompanying SMBH mergers has been studied in the past only for long time delays ($\sim 10^6$ – 10^9 yr) before (Ivanov, Polnarev & Saha 2005; Chen et al. 2009) or after (Komossa & Merritt 2008) the binary coalescence event. While previous studies have focused on mechanisms to slowly feed stars into an empty loss cone, here we show that GW recoil will instantaneously shift the loss cone to a non-empty region of phase space.

2 PHYSICS OF THE LOSS CONE

A star will be tidally disrupted by a SMBH of mass M_{BH} if it passes within the tidal distance,

$$r_t = r_* (\eta^2 M_{\text{BH}}/m_*)^{1/3}, \quad (1)$$

where m_* and r_* are the mass and radius of the star and η is a dimensionless constant of the order of unity (Diener et al. 1995). In our discussion we adopt $\eta = 1$ and assume an approximate main-sequence scaling law of $r_* \propto m_*^{0.8}$, which implies $r_t \propto m_*^{0.467}$ (Magorrian & Tremaine 1999). Tidal disruption does not occur if r_t is smaller than the event horizon radius r_h , in which case the star is swallowed intact by the black hole. For non-spinning black holes and solar mass stars, TDEs are therefore possible for $M_{\text{BH}} \lesssim 10^8 M_\odot$. A significant black hole spin can allow for (angle-dependent) TDEs by SMBHs with $M_{\text{BH}} \lesssim 7 \times 10^8 M_\odot$ (Beloborodov et al. 1992). During a TDE, approximately half of the star’s mass becomes unbound, while the rest flows on Keplerian trajectories, until the associated gas streams return to pericentre and collisionally shock each other (Rees 1988; Evans & Kochanek 1989). These gas streams return at a characteristic mass infall rate $\dot{M} \propto t^{-5/3}$ [roughly speaking; see Lodato, King & Pringle (2009) for a more thorough treatment] and form an accretion disc whose blackbody emission peaks in the ultraviolet (UV) or soft X-ray with luminosities comparable to a supernova (Loeb & Ulmer 1997; Strubbe & Quataert 2009). Other sources of emission include line radiation from the unbound debris (Kasen & Ramirez-Ruiz 2010), and a possible brief period of super-Eddington mass fallback. These features are useful for differentiating TDE flares from supernovae or quasar variability, and some have already been applied to candidate events (Komossa 2004).

In a spherical galaxy with a stationary SMBH, a star is tidally disrupted if its orbital angular momentum per unit mass falls below a critical value,

$$J^2 = |\mathbf{x} \times \mathbf{v}|^2 < J_{\text{crit}}^2 \approx 2GM_{\text{BH}}r_t, \quad (2)$$

where we have approximated the relevant orbit as nearly radial. Such orbits define the so-called loss cone. The rate of TDEs for a stationary SMBH is set by relaxational processes. Inwards of a certain galactocentric radius the loss cone is empty, but outside of it there is a ‘pinhole’ regime where the rate of scatter in and out of the loss cone is greater than the orbital frequency (Magorrian & Tremaine 1999).

Over the long orbital time-scale of stars, the impulsive GW-induced recoil of the SMBH remnant from a binary coalescence event yields a nearly instantaneous change in the black hole velocity relative to the stars (O’Leary & Loeb 2009). Viewed from the rest frame of the black hole, there is a sudden shift in the velocity of all stars, yielding a new loss cone defined by

$$J^2 = |\mathbf{x} \times (\mathbf{v} - \mathbf{v}_k)|^2 < J_{\text{crit}}^2 \approx 2GM_{\text{BH}}r_t, \quad (3)$$

where \mathbf{v}_k is the SMBH kick velocity.

As a first approximation, we parametrize the density of stars around a SMBH binary in the last stages of its inspiral with a power-law profile,

$$\rho = \rho_0(r/r_0)^{-\gamma}. \quad (4)$$

This density profile corresponds to an isotropic pre-kick distribution function of stars,

$$f(r, v) = C(2GM_{\text{BH}}/r - v^2)^{\gamma-3/2}, \quad (5)$$

where the normalizing constant is given by

$$C = \frac{(3-\gamma)(\gamma-0.5)\Gamma(\gamma+1)}{4\pi^{2.5}\Gamma(\gamma+0.5)} \frac{1}{r_{\text{inf}}^3} \left(\frac{r_{\text{inf}}}{2GM_{\text{BH}}} \right)^\gamma, \quad (6)$$

which in turn depends on the observationally calibrated radius of influence of the SMBH (inside of which the mass in stars is $2M_{\text{BH}}$). For a sample of galaxies taken from the ACS Virgo Cluster Survey (Côté et al. 2004; Merritt, Schnittman & Komossa 2009), this is

$$r_{\text{inf}} = 24(M_{\text{BH}}/10^8 M_\odot)^{0.51} \text{ pc}, \quad (7)$$

while for the core galaxies in that sample alone, it is

$$r_{\text{inf}} = 35(M_{\text{BH}}/10^8 M_\odot)^{0.56} \text{ pc}. \quad (8)$$

Stars will be bound to the black hole system of total mass M_{BH} before the binary coalescence if

$$v^2 < 2GM_{\text{BH}}/r, \quad (9)$$

and after coalescence if

$$(\mathbf{v} - \mathbf{v}_k)^2 < 2GM_{\text{BH}}/r. \quad (10)$$

The intersection of these two spheres in velocity space, with each other and with the loss cone, is the region of phase space containing bound stars which are tidally disrupted after the recoil. By performing a Monte Carlo integration of the appropriate distribution function over this region, we calculate the number of post-recoil TDEs. Through a separate integral, we find that the unbound stars provide $\lesssim 10$ per cent of the total number of TDEs and can be neglected. Another small correction to the total rate involves the net SMBH mass-loss by GW emission, which is typically $\lesssim 5$ per cent of the pre-merger mass (Campanelli et al. 2006). We have included the associated small reduction (by ~ 10 per cent) in the number of tidally disrupted stars. To evaluate the observability of the recoil-induced TDEs, we define the quantity $N_<(t)$ as the number of stars in the post-recoil loss cone which are tidally disrupted in t years. Since stars which fall into the new loss cone are near their apocentre in the rest frame of the kicked black hole, $N_<(100)$ is the number of stars with orbital periods below 200 yr.

The result of the Monte Carlo integral is sensitive to the innermost region of the distribution function, whose details are determined by the pre-merger dynamical environment. In particular, the SMBH binary will excavate a larger and more complex loss region than is given by equation (2). Below, we consider the innermost regions of phase space in gas-poor and gas-rich mergers, separately.

3 DRY MERGERS

In the absence of gas, $\gamma = 1.75$ is the dynamically relaxed (so-called Bahcall–Wolf) equilibrium state (Bahcall & Wolf 1976) of a stellar cluster around a SMBH. However, core galaxies are believed to be the end product of a binary inspiral, as the binary sheds angular momentum by ejecting stars. Numerical simulations of this process show that a binary hardening its orbit through scattering of stars will scour a core (Merritt 2006), but at some point depletion of the remaining stars in the binary loss cone (including in this context stars whose pericentres fall within twice the binary semimajor axis) will lead to a stalling of the binary and the so-called final parsec problem (Milosavljević & Merritt 2001). Without gas, the binary can only merge via a repopulation of its loss cone. Significant triaxiality of the galaxy potential (Merritt & Poon 2004) tends to repopulate the binary loss cone but preserve a core with $\gamma \approx 1$. Alternatively, collisional loss cone repopulation generates a central cusp of stars, though this method of binary hardening is only effective for binary masses $\lesssim 10^7 M_\odot$ (Merritt et al. 2009), and it may be modified in the presence of massive perturbers (Perets & Alexander 2008), such as infalling molecular clouds in gas-rich mergers. These gas-free scenarios lead us to consider both core galaxies, where $\gamma = 1$, and galaxies with a joint core-cusp density profile, where an inner $\gamma = 1.75$ profile meets an outer $\gamma = 1$ profile at a radius of $0.2 r_{\text{inf}}$ (Merritt et al. 2009). We use equation (8) as the fiducial radius of influence in these models, although use of equation (7) would not dramatically alter our results.

It is necessary to exclude the stars located in the pre-coalescence loss cone. The size of this region of phase space is somewhat uncertain. For collisional repopulation of the loss cone, numerical simulations (Merritt, Mikkola & Szell 2007) indicate the SMBH binary will decouple from a relaxed distribution of stars at a semimajor axis of $a_{\text{eq}} \sim 10^{-3} r_{\text{inf}}$, and coalesce before the stars can relax into the gap left behind. To model this cavity in energy space we remove all stars with semimajor axes less than this radius. However, because relaxation in angular momentum is faster than in energy, the resultant gap in angular momentum space will be partially refilled prior to the merger. The time-scale for filling up a gap in angular momentum space is given by (Merritt & Wang 2005),

$$T_{\text{gap}} = \frac{a}{r_{\text{inf}}} T_r, \quad (11)$$

where a is the semimajor axis of the SMBH binary taken to be the pericentre at which stars are ejected (Merritt & Wang 2005), and the system relaxation time at the radius of influence is (Merritt et al. 2009),

$$T_r \approx 8.0 \times 10^9 \text{ yr} \left(\frac{M_{\text{BH}}}{10^6 M_\odot} \right)^{1.54}. \quad (12)$$

Thus, a second cavity in the distribution function is created by removing all stars with pre-kick pericentres lower than the binary separation a at which T_{gap} equals the gravitational wave time-scale,

$$T_{\text{GW}} = \frac{5c^5 a^4}{256G^3 M_{\text{BH}}^2 \mu}, \quad (13)$$

with $\mu = M_1 M_2 / M_{\text{BH}}$ being the reduced mass of the binary and $M_{\text{BH}} = (M_1 + M_2)$. For simplicity, we adopt a flat J dependence for $f(E, J)$ with the cuts mentioned above. In the classical loss cone calculation, the steady-state solution of the orbit-averaged Fokker–Planck equation yields a distribution function that varies logarithmically with J at fixed E (Cohn & Kulsrud 1978). However, this solution may not apply to the innermost stars, for which the orbit-averaged assumption may break down and strong star–star

scatterings (which the Fokker–Planck approach does not account for, and which increase in rate with decreasing galactocentric radius as long as $\gamma > 0.5$) could be important. Furthermore, the loss cone of a binary SMBH is not the pure sink assumed for a single black hole, since stars may remain bound to the binary on low- J orbits. The use of a logarithmic instead of a flat distribution would have reduced $N_{<}(t)$ by a factor of ~ 2 – 4 .

We use these cuts in stellar energy and angular momentum as modifications to the joint core-cusp profile. Following Magorrian & Tremaine (1999), we generalize the results to a range of stellar masses using a mass function with a differential number of stars, $dN_*/dm_* \propto m_*^{-2.35}$, in the mass range $0.08 M_\odot < m_* < 1 M_\odot$. The number of disruptions is dominated by low-mass stars despite their smaller r_i ; switching to a mass range of $0.1 M_\odot < m_* < 100 M_\odot$ would reduce $N_{<}(100)$ by a factor ~ 1.5 , while using a top-heavy initial mass function (IMF), as is sometimes discussed in the context of galactic nuclei (Bartko et al. 2010), would reduce $N_{<}(100)$ by a factor of a few.

4 WET MERGERS

In gas-rich mergers, the pre-kick profile is likely to be different. On the one hand, rapid loss of angular momentum by the binary to dynamical friction on the gas can produce a core by denying stars the time needed to relax into a central cusp as described above (Merritt et al. 2009); but on the other hand, *in situ* star formation could rebuild a nuclear cusp while the binary orbit hardens. The possibility of star formation, and subsequent migration, in discs motivates us to consider values of $\gamma = 1.5, 1.75, 2$. Alternatively, stars formed elsewhere could be ‘ground down’ into orbits inside the disc (Syer, Clarke & Rees 1991), and then behave in a similar fashion. Although the details of star formation in discs fragmenting due to gravitational instability are quite complex (Shlosman & Begelman 1987; Alexander, Armitage & Cuadra 2008), we provide an approximate description of their potential to contribute to the post-kick loss cone here. If the Roche radius of the star in the disc exceeds the disc scale height and tidal coupling of the star to the disc is at least as effective as viscosity at transporting angular momentum, the star will open a gap in the disc (Syer et al. 1991) and migrate inwards on a viscous time-scale to the point where those conditions are no longer met, or to the disc’s inner edge (Goodman & Tan 2004), whichever is larger. Here we use equation (7) for the radius of influence, since we are considering galactic nuclei in the process of rebuilding their cusps.

We follow a similar procedure as with dry mergers, to approximate the size of the pre-merger loss cone. Assuming a thin disc, the radial size of the central cavity is determined by setting the viscous time-scale at the radius of marginal self-gravity (Goodman & Tan 2004),

$$T_{\text{vis}} = 4.2 \times 10^5 \text{ yr} \alpha_{0.3}^{-1/3} \kappa^{-1/2} \mu^{1/3} \left(\frac{\epsilon_{0.1}}{I_E} \right)^{1/6} M_8^{1/2}, \quad (14)$$

equal to T_{GW} . Here, κ is the opacity in units of electron-scattering opacity, μ is mean gas particle mass in units of the proton mass, $\alpha_{0.3}$ is the standard (Shakura–Sunyaev) viscosity parameter scaled to 0.3, $\epsilon_{0.1}$ is the radiative efficiency scaled to 10 per cent and I_E is the total radiated luminosity in units of the Eddington limit for the black hole mass $M_{\text{BH}} = M_8 \times 10^8 M_\odot$. Noting the weak power-law dependences in T_{vis} , we set all parameters except M_{BH} to their fiducial values (Goodman & Tan 2004). We remove any stars with pericentres interior to the radius at which the SMBH binary decouples from the accretion flow, and assume that the remaining

stars obtain a nearly spherical angular distribution [similarly to the innermost S-stars in the Milky Way nucleus (Ghez et al. 2008)] before the SMBH recoil. Because the details of star formation within the disc are highly uncertain and the TDE rate is dominated by low-mass stars, we assume for simplicity $m_* \sim 1 M_\odot$ in the wet merger case. We emphasize that in this case, accretion-induced alignment of SMBH spins prior to merger is expected to strongly suppress kicks over 200 km s^{-1} (Bogdanović et al. 2007; Dotti et al. 2010).

5 OTHER CONSIDERATIONS

Other processes could also partially refill the binary loss cone. In analogy to the problem of resonant capture during planetary migration (Yu & Tremaine 2001), mean-motion resonances could be capable of pulling stars inwards during the final stages of the SMBH merger, dramatically increasing the number of post-kick disruptions. The special case of the 1:1 Lagrange point resonance has recently been investigated (Schnittman 2010) and found capable of migrating stars to within tens of Schwarzschild radii from the system barycentre (Seto & Muto 2010). Higher integer ratio mean-motion resonances have been seen to affect stars (Madau, private communication) as a binary SMBH hardens, although their ability to drive resonant migration is less clear. A detailed study of resonant migration in SMBH binaries is beyond the scope of this paper, but this effect has the potential to dramatically expand the short-period population of the post-kick loss cone.

For a source at a redshift z , cosmological time dilation will stretch the duration of each TDE flare, delay the onset of the first post-kick flare and reduce the observed TDE rate all by the same factor of $(1+z)$. However, observations suggest that mean density of stars in high-redshift galaxies scales as $(1+z)^3$ (Oesch et al. 2010). This could lead to a net enhancement in the observed TDE rate $\propto (1+z)^2$ per galaxy, if the central regions of galaxies are self-similar. We set $z=0$ to ignore these possible cosmological effects in our calculated TDE rates.

6 RESULTS

For simplicity, our calculations assume binaries of equal mass black holes. An unequal mass would increase T_{GW} and increase $N_{<}(t)$ by allowing more time for refilling the binary loss cone, but it would also decrease the likely values of v_k . The latter change dominates only for mass ratios smaller than ~ 0.1 , so our results should be regarded as conservative for major mergers. Fig. 1 presents the velocity and mass dependences of our most realistic model (the joint core-cusp profile, for SMBH binaries that harden in dry mergers by scattering of stars), as well as a less realistic core-cusp model included for illustrative purposes. The first joint core-cusp model (labelled ‘Core’ for its radius of influence) removes stars from the binary loss cone and results in an interesting number of TDEs for $M_{\text{BH}} \lesssim 10^7 M_\odot$ and $200 \text{ km s}^{-1} \lesssim v_k \lesssim 1000 \text{ km s}^{-1}$. At low velocities, overlap with the pre-merger loss cone sharply suppresses $N_{<}(100)$, while at high velocities, the reduced size of the bound stellar population also shrinks $N_{<}(100)$. At higher masses, all short-period stars are scoured by the pre-merger binary loss cone. A related model (‘All’) shows the effect of using equation (7) instead of equation (8) for the influence radius. The last case in Fig. 1 (labelled ‘No LC’) replaces the loss cone of a binary with that of a single black hole. Interestingly, the dramatic increase in $N_{<}(100)$ here results from the addition of relatively few stars (~ 100 for $M_{\text{BH}} = 10^6 M_\odot$), indicating that resonant migration of a small population of stars could significantly boost $N_{<}(100)$. Finally, the

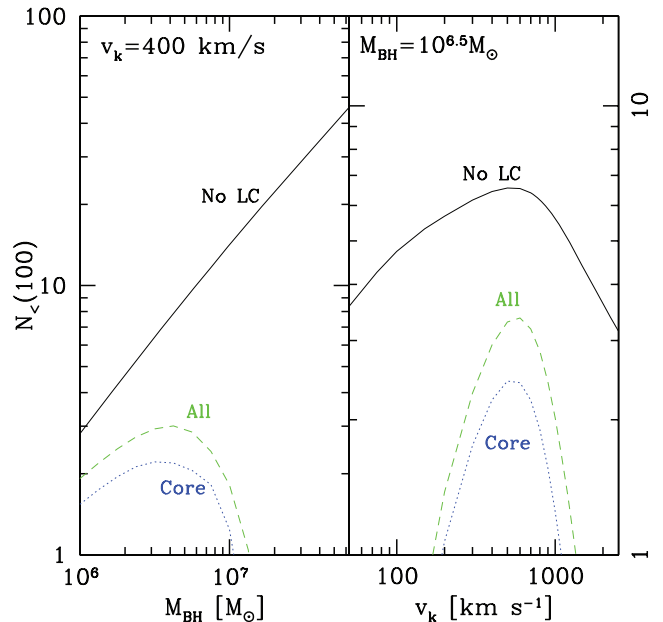


Figure 1. Expected number of stars disrupted in less than 100 yr, $N_{<}(100)$, in the dry merger, joint core-cusp case. Left-hand panel: black hole mass dependence for kick velocity $v_k = 400 \text{ km s}^{-1}$. The dashed green (‘All’) and dotted blue (‘Core’) lines represent the physically realistic binary loss cone discussed in the text (for galaxies following equations (7) and (8), respectively), whereas the black solid line (labelled ‘No LC’) accounts only for the loss cone of a single black hole. Right-hand panel: kick velocity dependence for a black hole mass $M_{\text{BH}} = 10^{6.5} M_\odot$, using the same line types.

$\gamma = 1$ (pure core) case does not have enough centrally located stars to produce post-kick tidal disruptions on < 100 yr time-scales.

The results for wet mergers are illustrated in Fig. 2. Although these rely on significantly more uncertain assumptions than the dry merger model, they show that star formation can produce interesting values of $N_{<}(100)$ in the $\gamma = 1.5$, 1.75 and 2 cases, with rates high enough that sequential TDEs could be observed in a single galaxy.

Fig. 3 shows how the delay until the first post-kick disruptions changes with black hole mass and kick velocity. Here we consider the joint core-cusp model (with removal of pre-merger loss cone by the binary, and fiducial radius of influence), and find that the first disruption is expected to occur between three and five decades after SMBH coalescence for black holes with masses between 10^6 and $10^7 M_\odot$, and kick velocities between 400 and 800 km s^{-1} . Fortunately, this region of parameter space falls within both the black hole mass range *LISA* is likely to observe and the range of physically plausible recoil velocities for dry mergers. In the most event-rich wet merger scenarios, the first TDEs could occur as soon as ~ 1 yr after coalescence.

7 SUMMARY

We find that merging galaxies with black hole masses $M_{\text{BH}} \lesssim 10^7 M_\odot$ are likely to produce a tidal disruption flare a few decades after coalescence in the case of a gas-poor merger. Multiple flares could possibly be seen on a time-scale of years if resonant migration is effective. For gas-poor mergers, the peak rate is therefore at least $\sim 10^4$ times higher than the typical TDE rate in galaxies (Donley et al. 2002). The total number of TDEs is maximized, and delay until the first TDE minimized, if the kick velocity is in the range of 200–1000 km s^{-1} .

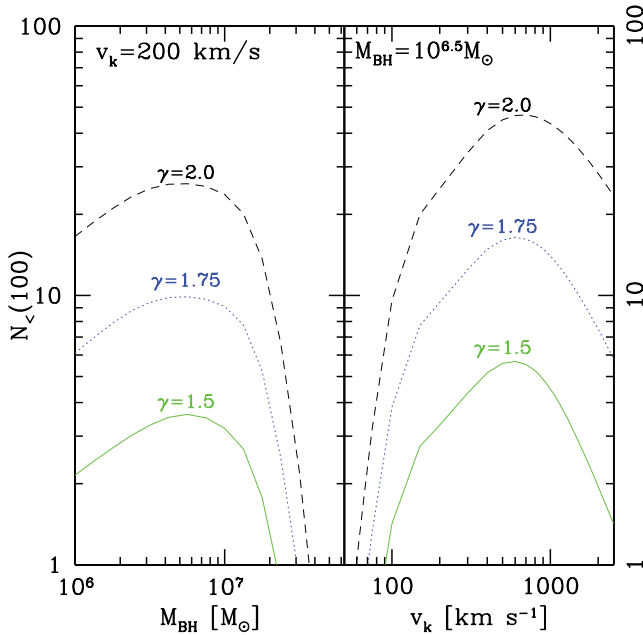


Figure 2. Expected number of stars disrupted in less than 100 yr, $N_{<}(100)$, in the wet merger scenario. Left-hand panel: mass dependence with $v_k = 200 \text{ km s}^{-1}$. The solid green line represents a $\gamma = 1.5$ cusp, the dotted blue $\gamma = 1.75$ and the dashed black $\gamma = 2.0$. Right-hand panel: velocity dependence with $M_{\text{BH}} = 10^{6.5} M_{\odot}$, and the same lines as in the left-hand panel.

Our minimal predictions concerning dry mergers could be dramatically enhanced if resonant migration increases the number and frequency of post-kick tidal disruptions, or if star formation and disc migration significantly increase the population of the post-kick loss cone. However, because the physics of wet mergers is substantially more complicated, a more detailed study of star–disc interactions around binary SMBHs is needed to make firm predictions in the gas-rich case.

Moderate to high kick velocities in dry mergers will provide a robust EM counterpart to the GW signature of black hole coalescence within the *LISA* band, enabling accurate identification of the host galaxy and a precise measurement of cosmological parameters (Holz & Hughes 2005) within a few decades of the initial GW signal. With the advent of massive transient surveys, such as PTF,³ Pan-STARRS,⁴ and LSST,⁵ it is possible that sequential tidal disruption flares could flag black hole recoil events without a GW signal, providing an independent test of the strong field regime of general relativity and a calibration of the expected event rate for *LISA* and PTAs.

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³ <http://www.astro.caltech.edu/ptf/>

⁴ <http://pan-starrs.ifa.hawaii.edu/public/>

⁵ <http://www.lsst.org/lsst>

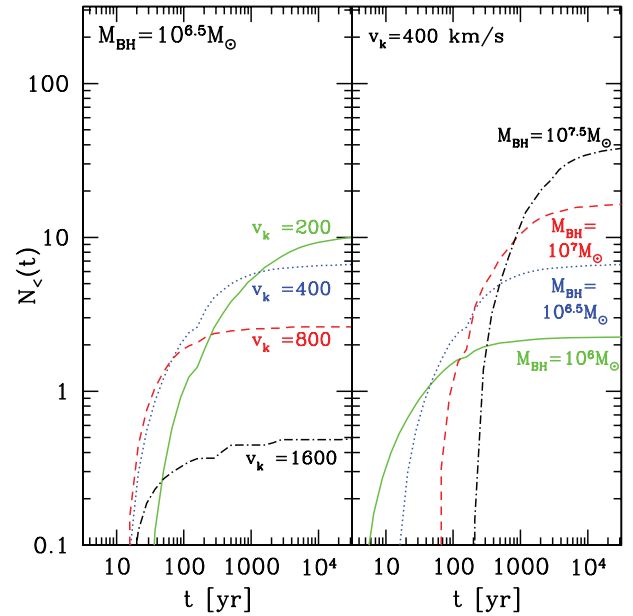


Figure 3. Left-hand panel: expected number of stars disrupted in less than t years, $N_{<}(t)$, for the dry merger (‘Core’) model and $M_{\text{BH}} = 10^{6.5} M_{\odot}$. The green solid line is for $v_k = 200 \text{ km s}^{-1}$, the blue dotted line is for $v_k = 400 \text{ km s}^{-1}$, the red dashed line is for $v_k = 800 \text{ km s}^{-1}$, and the black dot–dashed line is for $v_k = 1600 \text{ km s}^{-1}$. Right-hand panel: $N_{<}(t)$ for $v_k = 400 \text{ km s}^{-1}$ and varying masses. The green solid line is for $M_{\text{BH}} = 10^6 M_{\odot}$, the blue dotted for $M_{\text{BH}} = 10^{6.5} M_{\odot}$, the red dashed for $M_{\text{BH}} = 10^7 M_{\odot}$ and the black dot–dashed for $M_{\text{BH}} = 10^{7.5} M_{\odot}$.

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