Gravitational recoils of supermassive black holes in hydrodynamical simulations of gas rich galaxies

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ABSTRACT

We study the evolution of gravitationally recoiled supermassive black holes (BHs) in massive gas-rich galaxies by means of high-resolution hydrodynamical simulations. We find that the presence of a massive gaseous disc allows recoiled BHs to return to the centre on a much shorter timescale than for purely stellar discs. Also, BH accretion and feedback can strongly modify the orbit of recoiled BHs and hence their return timescale, besides affecting the distribution of gas and stars in the galactic centre. However, the dynamical interaction of kicked BHs with the surrounding medium is in general complex and can facilitate both a fast return to the centre as well as a significant delay. The Bondi-Hoyle-Lyttleton accretion rates of the recoiling BHs in our simulated galaxies are favourably high for the detection of off-centred AGN if kicked into gas-rich discs – up to a few per cent of the Eddington accretion rate – and are highly variable on timescales of a few 10^7 yrs. In major merger simulations of gas-rich galaxies, we find that gravitational recoils increase the scatter in the BH mass – host galaxy relationships compared to simulations without kicks, with the BH mass being more sensitive to recoil kicks than the bulge mass. The BH mass can be lowered by a factor of a few due to a recoil, even for a relatively short return timescale, but the exact magnitude of the effect depends strongly on the BH binary hardening timescale and on the efficiency of star formation in the central regions. A generic result of our numerical models is that the clumpy massive discs suggested by recent high-redshift observations, as well as the remnants of gas-rich mergers, exhibit a gravitational potential that falls steeply in the central regions, due to the dissipative concentration of baryons. As a result, supermassive BHs should only rarely be able to escape from massive galaxies at high redshifts, which is the epoch where the bulk of BH recoils is expected to occur.

Key words: methods: numerical – black hole physics – cosmology: theory

1 INTRODUCTION

In the last couple of years, numerical relativity simulations of coalescing black hole (BH) binaries have opened a whole new window in our understanding of the BH properties in the merger aftermath (e.g. Pretorius 2007; González et al. 2007; Herrmann et al. 2007; Koppitz et al. 2007; Campanelli et al. 2007; Baker et al. 2008). These computations have established that for asymmetries in the mass and/or spin of the two merging BHs, net linear momentum will be carried away by the asymmetric emission of gravitational waves, imparting a gravitational recoil to the remnant BH. In the case of the spinning BHs, the recoil velocities can become very large – comparable to or even larger than the virial velocities of the most massive host systems. This is what makes this phenomenon astrophysically very interesting and relevant, and poses important questions to which we still do not have definite answers: How often do the recoils occur within the hierarchical structure formation scenario? What is the fraction of expelled BHs, and how fast can they sink back to the centre? What are the imprints of gravitationally recoiled BHs and why has it been difficult to detect them so far?

The importance of BH recoils in the astrophysical con-

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text has been realised in pioneering works early on (e.g. Bekenstein 1973; Blandford 1979; Kapoor 1985). More recently, analytical and numerical studies (e.g. Merritt et al. 2004; Boylan-Kolchin et al. 2004; Madau & Quataert 2004) have found that globular clusters and dwarf galaxies are the prime targets for getting depleted of their central BHs. Moreover, recoiled BHs which do not escape their host galaxies are likely to induce stellar cores through repeated passages close to the centre.

In the case of purely stellar systems, accurate N-body simulations (for a recent study see Gualandris & Merritt 2008) have led to a good understanding how gravitationally recoiled BHs orbit in spherical systems and what their typical return timescales for different kick velocities are. For systems with gas, however, only a handful of numerical studies (e.g. Kornreich & Lovelace 2008; Devecchi et al. 2009; Guedes et al. 2010) are available which computed the trajectories of recoiled BHs and accounted for their possible interaction with the surrounding gas. Adopting a semi-analytical approach, BH luminosities during the wandering phase have nevertheless been estimated (e.g. Volonteri & Perna 2005; Blecha & Loeb 2008; Fujita 2009; Guedes et al. 2010). While observationally several candidates for recoiled BHs have been proposed (Komossa et al. (2008); Civano et al. (2010), but see Shields et al. (2009); Heckman et al. (2009)), there is scarce evidence for luminous recoiled quasars, at least in the case of large kinematic offsets (Bonning et al. 2007).

For galaxies containing gas, the evolution of recoiled BHs can possibly vary significantly depending on the mass fraction of the gas, and its spatial distribution and thermodynamic state. This situation presents a much more complex problem than for purely stellar systems. For example, recoiled BHs might accrete some of the interstellar gas which could in return affect their trajectory. Also, if BH feedback effects associated with accretion are not negligible, they could provide distributed heating throughout the galaxy. It is clear that a full understanding of these possibilities will require the exploration of a large parameter space.

At redshifts of $z \sim 2 - 3$, galaxy mergers are much more common in the hierarchical structure formation scenario than at the present day, and it is believed that many galaxies are gas-rich, with gas fractions of up to 50% (Förster Schreiber et al. 2009, and references therein). Massive compact ellipticals at $z \sim 2$ with much smaller sizes and higher stellar densities than their local counterparts (e.g. van Dokkum et al. 2008) are likely to be the end products of gas-rich mergers where remnant BHs would reside. This epoch also corresponds to the peak of the quasar space density, indicating that BHs are accreting gas supplied by their hosts efficiently. This is hence an extremely important and interesting regime, where BH mergers and recoils are expected to occur frequently and at the same time the gas component in the host systems cannot be neglected.

In this paper, we present an exploratory study of the properties of recoiled BHs in gas-rich galaxies, where BH accretion and feedback processes are followed self-consistently. We first focus on studying an isolated spiral galaxy, simulated at a high resolution to understand how the inclusion of gas accretion or additional BH feedback affects the orbits of recoiled BHs, their return timescale to the centre, and their imprints on the host galaxy. We simulate kicks
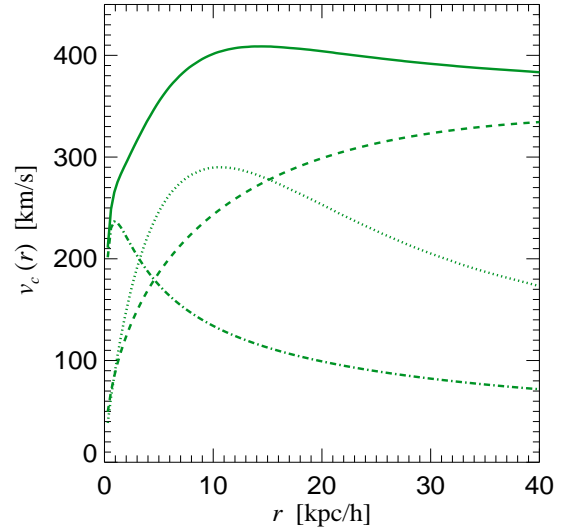

Figure 1. Circular velocity curves of the isolated galaxy with $v_{200} = 300 \, \mathrm{km \, s^{-1}}$ for different components: bulge (dot-dashed line), disc (dotted line), dark matter halo (dashed line), and total (continuous line).

of different magnitude, both in the plane and perpendicular to the plane of the galaxy, to gauge the dependence of the AGN luminosity on the kick orientation and on the assumed equation of state for the interstellar gas. We then perform a major merger simulation of two gas-rich galaxies, each containing a supermassive BH in its centre. After BH coalescence, we follow the evolution of the gravitationally recoiled BH and study how its growth is affected by the kick, and which consequences this has for the scatter in the BH mass-host galaxy scaling relations. Note that a systematic study of recoiled BHs in merging galaxies is underway (Blecha & Loeb 2010, private communication).

The paper is organised as follows. In Section 2, we outline the numerical methods we adopted. Most of our results are presented in Section 3, where we discuss isolated spiral galaxies with uniform or clumpy discs (Section 3.1), and major mergers of two gas-rich galaxies (Section 3.2). In Section 4, we discuss our findings and draw our conclusions.

2 METHODOLOGY

2.1 The numerical code

In this work we perform hydrodynamical simulations with the massively parallel Tree-SPH code GADGET-3 (last described in Springel 2005). The code computes gravitational forces acting on dark matter, gas, star and BH particles, as well as the hydrodynamical forces that affect the baryons. Gas is modelled as an optically thin plasma of hydrogen and helium, which can radiatively cool and heat. Star formation and supernova feedback is implemented adopting a sub-resolution multi-phase model (Springel & Hernquist 2003), while BH growth and feedback is modelled as described in Di Matteo et al. (2005); Springel et al. (2005); Sijacki et al. (2007, 2009). For completeness, we briefly summarise this model below.
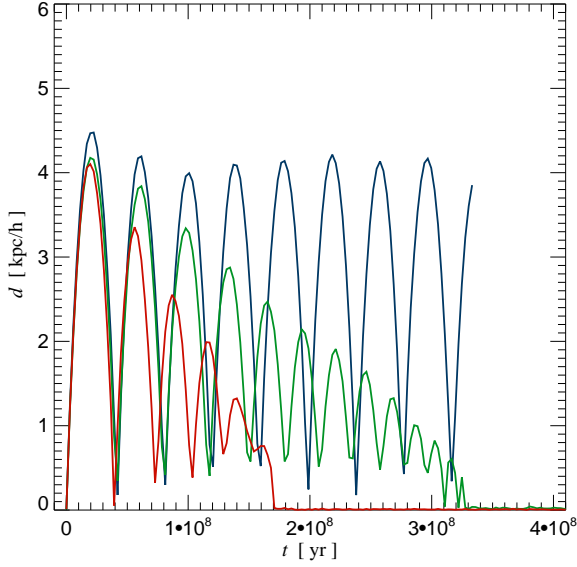
Figure 2. BH distance from the minimum of the potential as a function of time for simulations where the BH is (a) not subject to dynamical friction forces (blue line), (b) experiences dynamical friction from stars only (green line), and (c) additionally is subject to dynamical friction from the gas in the disc (red line).

	uniform disc [km s^{-1}]	clumpy disc [km s^{-1}]	major merger [km s^{-1}]
v_{200}	300	300	378
$v_{\mathrm{esc}}(0)$	1450	1980	3510
v_{kick}	375	1000	3253
v_{kick}	700	1600	3535

Table 1. Virial and central escape velocities for the isolated spiral galaxy with a smooth and a clumpy disc, and for the gas-rich major merger remnant (rows one and two). Recoil velocities imparted to the central BHs are summarised as well (rows three and four).

2.2 BH model

In the simulation code, BHs are treated as collisionless sink particles. Starting out with a certain seed mass, BHs can grow in time by gas accretion, or by merging with other BHs that happen to be sufficiently close (within each others smoothing lengths) and that have small relative velocities (less than the local gas sound speed). The accretion rate is parametrised in terms of a spherically symmetric Bondi-Hoyle-Lyttleton type accretion flow (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Bondi 1952), i.e.

$$\dot{M}_{\mathrm{BH}} = \frac{4\pi\alpha G^2 M_{\mathrm{BH}}^2 \rho}{\left(c_s^2 + v^2\right)^{3/2}}, \qquad (1)$$

where α is a dimensionless parameter, ρ is the gas density, c_s the sound speed of the gas, and v is the velocity of the BH relative to the gas. Here, as a default value we fix α to 100, as in all of our previous work, because the multiphase model for star formation gives a comparatively high

mean gas temperature as a result of supernova feedback. A volume-average of the Bondi-rates for the sub-grid cold and hot phases of the interstellar medium recovers a value of α close to 100. We have however found that our results are relatively insensitive to the adopted value for the α parameter (see the tests in Appendix A). The maximum BH accretion rate is limited to the Eddington rate. BH feedback associated with the accretion is injected in thermal form, where a small fraction (5%) of the bolometric luminosity is isotropically coupled to the surrounding gas.

2.3 Gravitational recoils of BHs

BH merger remnants are subject to a gravitational recoil due to the anisotropic emission of gravitational waves, which carry away net linear momentum. In Sijacki et al. (2009), we have implemented a simple method to represent this effect in our simulations. At the moment of a BH binary merger, the involved BH masses and spins[*] are known in the simulation. By making assumptions about the orientation of the spins with respect to the orbital angular momentum of the BH binary, it is then possible to compute the expected gravitational kick velocities accurately based on fitting formulae that are calibrated against numerical relativity simulations (for a review see Pretorius 2007). In particular, for non-spinning BHs we use Fitchett's formula (Fitchett 1983), calibrated as in González et al. (2007). In the case of spinning BHs, both when spins are (anti-)aligned or are randomly distributed, we adopt relations from Campanelli et al. (2007) (see also Herrmann et al. 2007; Koppitz et al. 2007; Baker et al. 2008).

2.4 Galaxy models

We first consider an isolated, massive, gas-rich galaxy, that we simulate at high numerical resolution. The initial conditions of this galaxy are set-up as described in detail in Springel et al. (2005). Specifically, the total mass of the galaxy is $M_{200} = 6.28 \times 10^{12}\,h^{-1}\mathrm{M}_\odot$, its virial velocity is $v_{200} = 300\,\mathrm{km\,s^{-1}}$, the dark matter halo concentration is $c = 9$, and the spin parameter is $\lambda = 0.033$. The fraction of the total mass in the disc is $m_{\mathrm{d}} = 0.041$, while the bulge mass fraction amounts to $m_{\mathrm{b}} = 0.008$. The galactic disc scale length is $4.8\,h^{-1}\,\mathrm{kpc}$. The disc is gas-rich, with a gas fraction of $f_{\mathrm{gas}} = 0.6$, while the remaining 40% are in stars. Circular velocity curves for the different galactic components are shown in Figure 1.

We select the numerical parameters of the multiphase model for star formation such that the gas consumption time-scale is long, specifically we adopt $t_*^0 = 12.6\,\mathrm{Gyrs}$, $A_0 = 6000$, $T_{\mathrm{SN}} = 6 \times 10^8\,\mathrm{K}$ (in the notation of Springel & Hernquist 2003), and we assume a softer equation of state with $q_{\mathrm{EOS}} = 0.5$. This choice of parameters assures that during the simulated time-span (which can be a considerable fraction of the Hubble time) the galaxy stays comparatively gas-rich and the gaseous disc is stable. We

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[*] Note that in our simulations BH spins change only when BHs merge, and any possible spin-up/down due to the gas accretion is neglected.
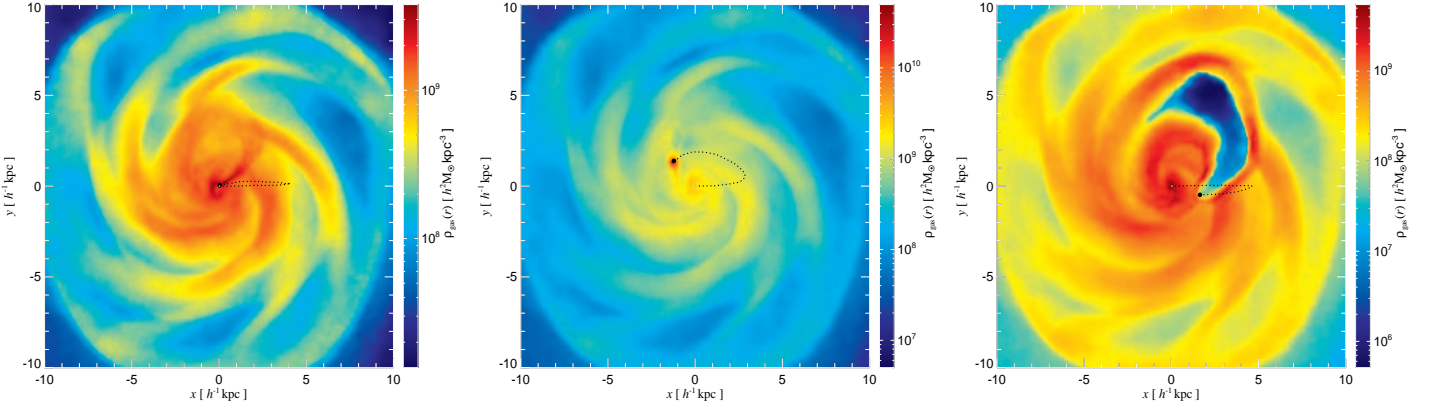
Figure 3. Projected mass-weighted gas density maps of the isolated galaxy at time $t = 3.92 \times 10^7$ yrs after BH recoil. The three panels show simulation results where the BH does not accrete nor exerts feedback (left-hand panel), where the BH accretes but has zero feedback efficiency (central panel), and where the BH is allowed both to accrete and inject feedback energy (right-hand panel). The dotted lines show the BH orbits from the start of the simulation. Note that the colour maps display different density ranges, as given by the individual colour bars.

additionally perform runs where the equation of state parameter is much smaller, 0.05, corresponding to a nearly isothermal equation of state and resulting in a very clumpy disc. The galaxy is simulated with 300000 dark matter particles in the halo, 200000 star particles in the disc, 200000 gas particles in the disc and 50000 star particles belonging to the bulge. The gravitational softening of the disc and bulge is set to $60\,h^{-1}$ pc, and of the dark matter halo to $2\,h^{-1}$ kpc.

2.5 Numerical setup

We first evolve the isolated gas-rich galaxy for 2.8×10^8 yrs without a central BH, until the gas disc develops a well defined spiral structure which is long lived. Thus, during the simulated time of the central BH the gaseous disc will be in a stable, quasi stationary state. We then introduce a BH particle in the centre of the galaxy, assuming that such a gas-rich galaxy should already contain a supermassive BH. The initial mass of the BH is $5 \times 10^8\,h^{-1}\mathrm{M}_\odot$ in most of our calculations, but we have also considered a lower mass BH of $5 \times 10^7\,h^{-1}\mathrm{M}_\odot$ (corresponding to $\sim 10^{-3}M_{\rm bulge}$). Given that we want to track dynamical friction forces acting on the BH as accurately as possible, we do not perform simulations with a lower mass BHs here, because then the mass ratio between the BH and the gas or star particles would not be sufficiently large. Also, by simulating a more massive BH we are in a more advantageous regime for spatially resolving regions close to the Bondi radius.

Once the BH particle is introduced in the centre we let it evolve for an additional 1.4×10^7 yrs[†] after which the BH is imparted a certain recoil velocity, with the direction either parallel to the galactic disc or perpendicular to it. Table 1 summarises virial and central escape velocities of our simulated galaxies, as well as BH recoil velocities. For comparison, we also carried out runs where the BH stays in

[†] This delay time is introduced such that the BH orbit is not artificially altered by initial accretion caused by the introduction of the BH into very gas-rich and dense material.

the centre of the galaxy, and is not subject to any gravitational recoil. The simulations with the stationary BH permit us to verify that the BH position always coincides with the minimum of the gravitational potential within the spatial resolution of the simulation, hence the resolution is sufficiently high to reduce two-body noise acting on the BH to negligible levels.

Most of our simulations were performed with BH accretion and feedback included, but we also considered cases where BH accretion, or selectively only BH feedback, was switched-off. This allows us to disentangle purely dynamical processes acting on a recoiled BH from the additional effects due to BH accretion and feedback, which can affect the properties of the surrounding gas and thus possibly alter the BH dynamics.

3 RESULTS

3.1 Isolated galaxies

3.1.1 *Importance of the stellar and gas dynamical friction*

We first want to assess the importance of dynamical friction forces acting on the BH as it moves trough the simulated galaxy. For this purpose, we consider the BH to be a collisionless particle which does not accrete, and has a constant mass of $5 \times 10^8\,h^{-1}\mathrm{M}_\odot$. Just before the BH is imparted the kick, we estimate the central escape velocity from the halo based on the minimum of the gravitational potential, which yields $v_{\rm esc}(0) = \sqrt{2\,\Phi(r=0)} \sim 1450\,{\rm km\,s^{-1}}$. Note that the central escape velocity is rather high, $v_{\rm esc}(0) \sim 4.8\,v_{200}$, due to the presence of a central stellar bulge. Using instead the often adopted equation $v_{\rm esc} = \sqrt{2\,f(c)}\,v_{200}$, where $f(c) = c\,(\ln(1+c) - c/(1+c))^{-1}$ is only a function of the concentration parameter, one would obtain a significantly lower estimate of $v_{\rm esc}(0) \sim 3.6\,v_{200}$, as this considers only the distribution of the dark matter.

We then impart a gravitational recoil velocity to the BH of $700\,{\rm km\,s^{-1}}$ ($\sim 0.5\,v_{\rm esc}$) along the x-axis in the plane
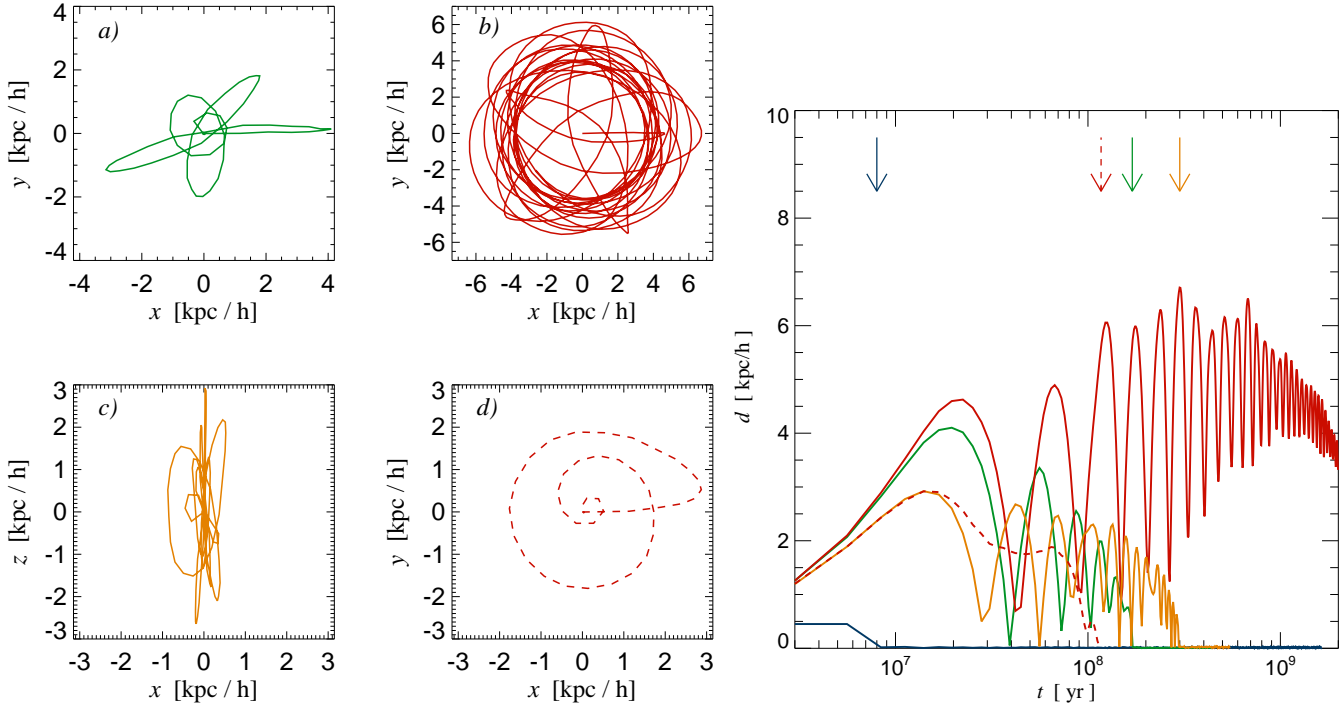
Figure 4. *Four left-hand panels:* Orbits of BHs over the course of the simulated time-span, for different cases. Panel a) $v_{\rm kick} = 700\,{\rm km\,s^{-1}}$ ($\sim 0.5\,v_{\rm esc}$) in the galactic plane without BH accretion; Panel b) $v_{\rm kick} = 700\,{\rm km\,s^{-1}}$ in the galactic plane with BH accretion and feedback; Panel c) $v_{\rm kick} = 700\,{\rm km\,s^{-1}}$ perpendicular to the galactic plane with BH accretion and feedback; Panel d) $v_{\rm kick} = 700\,{\rm km\,s^{-1}}$ in the galactic plane with BH accretion but no feedback. *Right-hand panel:* BH distance from the minimum of the potential as a function of time for the same simulations as in left-hand panels. The additional blue line is for an initial recoil of $375\,{\rm km\,s^{-1}}$ ($\sim 0.26\,v_{\rm esc}$) in the galactic plane. The arrows indicate when the BHs return to the centre of the galaxy.

of the disc. Figure 2 shows the resulting distance of the BH from the minimum of the potential as a function of time for three different runs. The blue line is for a simulation where the BH particle is massless, and thus is not subject to dynamical friction forces. The red line is for our default case where the galactic disc is gas-rich, while the green line is for a simulation where we have set-up a galaxy with exactly the same structure, only that the galactic disc is made up entirely of stars. In the case where dynamical friction is not acting on the BH particle, the apocentric distances reached during the simulated time-span stay roughly constant. The BH simple simply oscillates through the nearly static potential of the galaxy. However, as expected, dynamical friction from stars, and even more so from the gas, leads to the systematic reduction of the apocentric distance with time. Dynamical friction already reduces the first apocentric distance reached, and the effect becomes more pronounced with further passages of the BH through the innermost regions. From Figure 2 we infer that the BH returns to the centre[‡] after $\sim 3.3 \times 10^8$ yrs due to the dynamical friction

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[‡] Throughout the paper we define that the BH has returned to the centre if its position coincides with the minimum of the potential within the gravitational softening length of the simulation. Note that due to the limited spatial resolution achieved we cannot track BH-galaxy core oscillations (Gualandris & Merritt 2008) which may further prolong BH settling to the centre, at least in the case with only stars and no gas at the centre.

from a fully stellar disc. When the host galaxy has instead a substantial fraction of the disc mass in gas, but otherwise the same structure and potential shape, the BH return time is almost halved.

3.1.2 Properties of recoiled BHs

In Figure 3, we show three illustrative examples of recoiled BH orbiting in the gas-rich galactic disc after $t = 3.92 \times 10^7$ yrs. In all three simulations, the initial BH mass is $5 \times 10^8\,h^{-1}{\rm M}_\odot$ and the recoil velocity is $700\,{\rm km\,s^{-1}} \sim 0.5\,v_{\rm esc}$ along the x-axis. In the left-hand panel we show the case where the BH is not accreting, in the central panel we present the case where BH accretion is switched-on but there is no feedback, while in the right-hand panel we illustrate the case where both BH accretion and feedback are followed. As can been seen from the left-hand panel, the motion of the BH through the high density gas creates a density enhancement in its wake that propagates outwards, as has been previously reported (e.g. Escala et al. 2004, 2005). We further found that the local potential of the stellar disc at the position of the BH becomes notably deeper, over a typical size of order $\le 500\,h^{-1}$ pc. The shape of the stellar potential deformation is roughly spherical, but shows a tendency to be more elongated behind the BH for a fraction of the time.

When we allow the BH to accrete, the BH orbit is considerably different (central panel). Even though the BH is moving with a high relative velocity with respect to the

surrounding gas, it does manage to accrete a substantial amount of gas, allowing it to almost double its mass to $M_{\rm BH} = 9.1 \times 10^8 \, h^{-1} {\rm M_\odot}$ at $t = 3.92 \times 10^7$ yrs after the kick. The larger dynamical mass this implies and the considerable drag force from gas accretion act in the same direction and prevent the BH from reaching similar apocentric distances as in the case without accretion. The orbit quickly starts to circularise in the direction of gas rotation. While initially the accreting BH also generates a high density wake, after it has gained enough mass some of the gas particles actually become bound to it and create a high density blob around the BH.

If in addition to BH accretion we include BH feedback, the BH orbit is again different (right-hand panel). Instead of a high density wake, we now observe a low density wake, which similarly propagates outwards from the BH orbit. This low density wake is due to the BH feedback, which creates a hot expanding gas plume. Whereas the gas drag from accretion tends to bend the BH orbit in the prograde direction from the initially radial orbit, the BH orbit is here deflected in the retrograde direction after reaching the apocentre (opposite to the rotation of the galaxy). Note also that due to the BH feedback the BH does not grow much in mass, reaching only $M_{\rm BH} = 5.1 \times 10^8 \, h^{-1} {\rm M_\odot}$ at $t = 3.92 \times 10^7$ yrs. As a result, the gas drag from accretion is much smaller than in the previous case. The effect of the hot, expanding density plume on the evolution of the BH orbit turns out to be very important, as we discuss in detail below.

In Figure 4, we show the BH orbits and distances from the centre of the host galaxy during the simulated time-span for four different runs. In panel (a) the case with $v_{\rm kick} = 700 \, {\rm km \, s^{-1}}$ in the galactic plane without BH accretion is shown. The BH orbit is initially radial, and after the BH reaches the apocentre, its trajectory is bent in the prograde direction due to gravitational drag. The BH describes four precessing loops with decreasing apocentric distances and then quickly spirals inwards reaching the minimum of the gravitational potential at $\sim 1.7 \times 10^8$ yrs after the kick. The orbit is essentially completely contained in the galactic disc, with excursions in the z-direction of less than $100 \, h^{-1}$ pc.

When BH accretion but no feedback is included [panel (d)], the BH returns to the galactic centre on an even shorter timescale, in only $\sim 1.2 \times 10^8$ yrs. Without self-regulating feedback the BH mass grows rapidly, making dynamical friction more effective. Moreover, the drag force the BH is experiencing from accreted gas particles is efficiently circularising the BH orbit and causing it to co-rotate with the galactic disc. These two processes acting together lead to rapid spiralling in.

BH feedback can nonetheless have an impeding impact on the return timescale of gravitationally recoiled BHs [panel (b)]. As anticipated above, the BH heats the surrounding gas, which then forms a hot plume that propagates outwards and expands, compressing the gas in a thin rim and generating a low density wake within. To understand in more detail the nature of the resulting BH orbit, Figure 5 shows unsharp masked maps of the gravitational potential of the gas at the moment when the BH reaches the apocentre for the first time. The unsharp masking has been performed by subtracting from the initial potential a version smoothed on a scale of $\sim 600 \, h^{-1}$ pc. As can be seen in the top panel, for
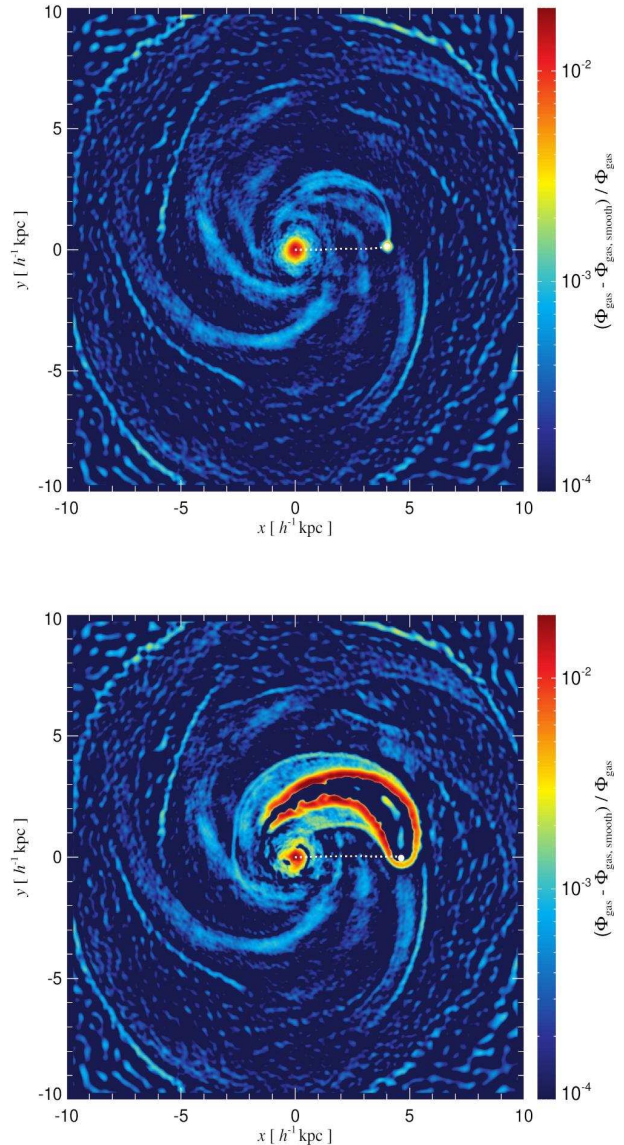

Figure 5. Projected unsharp masked map of the gravitational potential of the gas (absolute value), for a simulation without BH accretion (top panel), and with BH accretion and feedback (bottom panel). The displayed snapshots correspond to the moment when the BHs reach the apocentres for the first time.

the case without BH accretion, the high density wake exerts gravitational drag on the BH and the net gravitational force from the surrounding gas acting on the BH is directed prograde along the y-axis. In the case with BH accretion and feedback, the situation is more complex, as shown in the bottom panel. Here the BH is located within the dip associated with high density compressed gas, while above the BH a hot low density plume is expanding away from the BH. The net gravitational force acting on the BH from this gas distribution is pointing retrograde along the y-axis, and thus the BH experiences a gravitational drag in the opposite direction than in the top panel. Moreover, cold gas in the galactic disc, which approaches the hot gas plume due to the rotation of the galaxy, is compressed and transfers

its angular momentum to the gas in the plume. This effect further reduces the effective drag force onto the BH from gas accretion.

The BH describes a precessing elliptical trajectory, and with each passage the ellipses widen such that after five relatively close passages to the galactic centre (after about 3×10^8 yrs) the orbit starts to circularise, but with a BH that is counter-rotating, even though it started out with the same radial motion. Due to the feedback a ring of hot, low density gas forms, within which the BH orbits, partially decoupled from the rest of the galaxy. The BH trajectory is loop-like, with $\pm 500\,h^{-1}$ pc excursions from the plane. For the rest of the simulated time of $\sim 1.7 \times 10^9$ yrs, the BH remains at a considerable distance from the galactic centre, in the range of $3.5 - 6.5\,h^{-1}$ kpc, even though $\sim 7 \times 10^8$ yrs after the kick, the apocentric distance starts to decay, indicating that the BH will eventually return to the centre (see also Appendix A).

The case where the BH is kicked perpendicular to the plane of the galaxy is shown in panel (c) of Figure 4. During the first $\sim 3 \times 10^8$ yrs, the BH describes about a dozen orbits before it returns to the galactic centre. In this case, the BH feedback does not significantly delay the return timescale because the BH accretes only during short passages through the galactic plane, due to the mostly radial orbit along the z-axis. Note also that the maximum distance reached by the BH at the first apocentre is lower than for the BH kicked in the plane of the galaxy, as a result of the larger gravitational force exerted from the disc of the galaxy in this direction (see panel on the right).

Finally, in the right-hand panel of Figure 4, we also show a case where the kick velocity is much lower, equal to $375\,\mathrm{km\,s}^{-1}$ (blue line). Here the BH briefly leaves the minimum of the potential and reaches a radial distance of $500\,h^{-1}$ pc, but then returns to the centre within 7×10^6 yrs.

In Figure 6 we show the BH mass (top panel) and bolometric luminosity (middle panel) as a function of time, as well as the time evolution of the total star formation rate (SFR) of the host galaxy (bottom panel) for different cases. The green lines are for the case where the BH does not experience a gravitational recoil, while the red and orange lines are for $v_{\mathrm{kick}} = 700\,\mathrm{km\,s}^{-1}$ parallel and perpendicular to the plane of the galaxy, respectively. From the top panel it can be seen that the BH which does not experience any recoil increases its mass moderately, by $\sim 8.5 \times 10^7\,h^{-1}\mathrm{M}_\odot$ over 2 Gyrs. This is due to secular processes which gradually transport some gas towards the inner regions, fuelling BH accretion. The bolometric luminosity[§] is initially around $10^{45}\,\mathrm{erg\,s}^{-1}$ and slowly decreases with time, but we note that after ~ 0.5 Gyrs the BH accretion falls below 0.01 of the Eddington rate, as indicated by the continuous lines (becoming probably radiatively inefficient). Thus, for most of the time this AGN would be optically dim, exhibiting only very few, brief luminous episodes.

In contrast, the BH kicked in the plane of the galaxy initially grows more as it encounters a larger supply of material on its orbit through the the gas-rich galactic disc. Consequently, its bolometric luminosity is up to an order
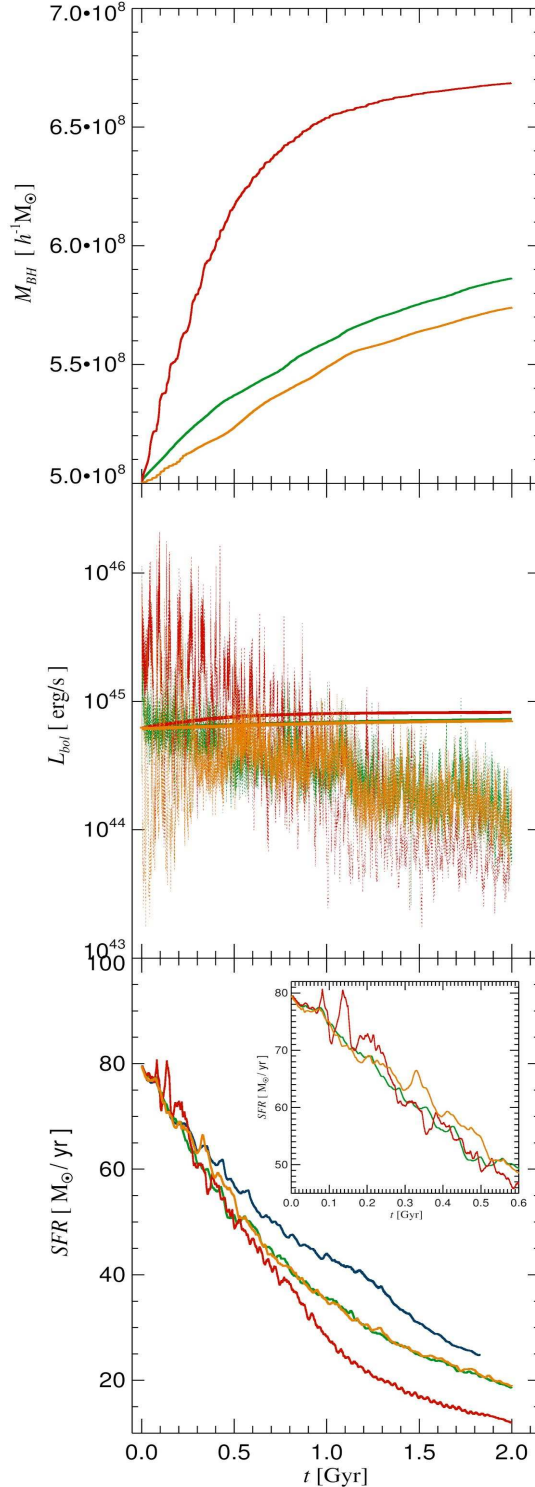

Figure 6. BH mass (top panel), bolometric luminosity (central panel) and total SFR (bottom panel) as a function of time. The green lines are for the run where the BH is always at the centre of the galaxy. Cases where the BH experiences a gravitational recoil of $700\,\mathrm{km\,s}^{-1}$ in the plane of the galaxy or perpendicular to the galactic plane are denoted with red and orange lines, respectively. The blue line (only in the bottom panel) is for the simulation without a BH. Continuous lines in the middle panel denote an accretion rate equal to 0.01 of the Eddington rate.

[§] For the computation of the bolometric luminosity a radiative efficiency of 0.1 is assumed throughout the paper.

of magnitude higher than that of the BH which never leaves the centre. Once the BH orbit circularises in a ring of low density material formed by feedback, its accretion is even more sub-Eddington than that of the BH which stays in the galactic centre. Note however that the AGN bolometric luminosity obtained in this case should be an upper limit for several reasons. First, it is probably not very common that the BH is gravitationally recoiled exactly within the disc, as assumed here, given that at present there is no evidence for a correlation between the spin orientations of the BH and of the host galaxy. Second, during a galaxy merging event, which is a much more realistic setting for the occurrence of a gravitationally recoiled BH, the largest amount of gas available for accretion will be in central regions, meaning that a kicked BH will be biases towards accreting less gas (see Section 3.2). Finally, the BH accretion rate estimated from equation (1) should be considered as an upper limit if the gas surrounding the BH is not multiphase, and the BH feedback is not strong enough to self-regulate the BH growth. While for a stationary BH in the centre of the host galaxy this is unlikely to occur, for a recoiled BH the actual accretion rate may well be lower if it leaves the dense multiphase medium. We explore this issue in detail in Appendix A. Nonetheless, our findings suggest that the recoiled AGN could have accretion rates up to a few percent of the Eddington rate on timescales of a few 10^7 yrs, if their orbits are approximately contained within the gas-rich galactic disc.

Gravitational recoil of the BH perpendicular to the galactic disc significantly suppresses BH accretion, but it does not truncate it all together. As the BH orbit decays towards the centre, the accretion rate increases as the BH experiences more and more passages through the disc. Eventually, once back in the centre the accretion rate is very similar to the case of the stationary BH, and the difference between the final masses is not very large, i.e. $\sim 10^7 \, h^{-1} \mathrm{M_\odot}$. This is, however, very likely a lower limit to the mass difference between a recoiled and a stationary BH, given the quiescent nature of the host galaxy. In a more realistic scenario, where the progenitor BHs merge during a merger of two galaxies, a large amount of gas will be funnelled towards the central regions. This gas will form a copious reservoir for BH accretion and it will thus make a much bigger difference for BH growth whether the remnant BH stays in the centre or is gravitationally recoiled, as we discuss in Section 3.2.

3.1.3 *Impact of recoiled BH on the host galaxy*

In the bottom panel of Figure 6, we show the total SFR of the simulated galaxy, where the blue line denotes the simulation result without a BH, for comparison. The feedback from the stationary BH reduces the SFR of the host galaxy in the central regions during the simulated time span. In the case where the BH undergoes a gravitational recoil perpendicular to the galactic disc, the SFR of the host galaxy is similarly diminished as in the case where the BH is stationary, because the recoiled BH returns relatively quickly back to the centre. On the other hand, a BH which is kicked in the plane of the galaxy is found to have a sizable impact on the amount of stars produced, both because the BH then grows more in mass (feedback effects are hence stronger) and also because the BH can affect larger portions of the star-forming disc on its orbit.

We do however find that the motion of the BH through the galaxy triggers brief local bursts of star formation. These are highlighted in the inset plot, where we show the evolution of the SFR during the first 0.6 Gyrs after the kick. Feedback from recoiling BHs generates expanding plumes of hot gas, which push the surrounding material and induce localised bursts of star formation with rates of several $\mathrm{M_\odot \, yr^{-1}}$.

In Figure 7, we show radial density profiles of stars in the bulge (continuous lines), stars in the disc (dashed lines) and gas in the disc (triple dot-dashed lines). The results for the simulations without BH and for the gravitationally recoiled BH are denoted with green and red colour, respectively. In the left-hand panels we illustrate the case where the recoiled BH was not allowed to accrete, and the profiles are computed once the BH has returned to the centre of the galaxy. During the simulated time-span, the density of stars in the bulge decreases systematically in the case with recoiled BH, as can be seen more clearly in the lower panel, where the ratio of the profiles is shown. This result agrees well with those from N-body simulations of recoiled BHs in stellar cores (see Gualandris & Merritt 2008, and references therein), where the BH scatters the surrounding stars transferring some of its kinetic energy. In the particular case studied here, the central bulge mass deficit (evaluated within $1 \, h^{-1}$ kpc) is of the order of the BH mass once the BH returns to the centre. Moreover, we find that the stars in the galactic disc are also perturbed by the orbiting BH, but there is no clear systematic trend with the radial distance from the centre as a function of time. Interestingly, however, the high density gas in the wake of the BH follows the BH all the way to the centre, creating a large density enhancement.

In the right-hand panels of Figure 7, we show density profiles for the case where BH accretion and feedback have been switched-on. Here, as discussed above, the BH does not return to the centre, but instead describes a loop-like orbit, counter-rotating with respect to the disc. The BH spends considerable amount of time away from the central regions, as indicated by the coloured symbols, and transfers kinetic energy to the stars which are not in the centre. Examining the ratios of the density profiles, shows a clear dip in the density of stars in the bulge for $0.5 - 3 \, h^{-1}$ kpc. Stars which are scattered-away from this region create density enhancements on both sides, towards the centre and away from it. Thus, instead of a mass deficit the bulge mass within $1 \, h^{-1}$ kpc is increased by $\sim 0.7 \times M_{\mathrm{BH}}$. In this case there is also a systematic reduction of the density of stars in the galactic disc in the region of the disc where the BH spends considerable amount of time (pink symbols). The bulge density declines more steeply than the disc density, and thus for radii $\geq 1 \, h^{-1}$ kpc the BH is more likely to transfer its kinetic energy to the stars in the disc. Additionally, due to the BH feedback in this region a ring of hot, low density gas creates a local perturbation in the gravitational potential, which is felt by the stars in the disc. A dip in the density distribution of the disc stars is formed.

While we have seen that the recoiling BH which returns to the centre (left-hand panels of Figure 7) leads to a moderate mass deficit of the bulge, of the order of the BH mass, in some cases the mass deficit can be substantially bigger. In the simulation where the BH is recoiled perpendicular to the galactic disc, and passes many more times close to
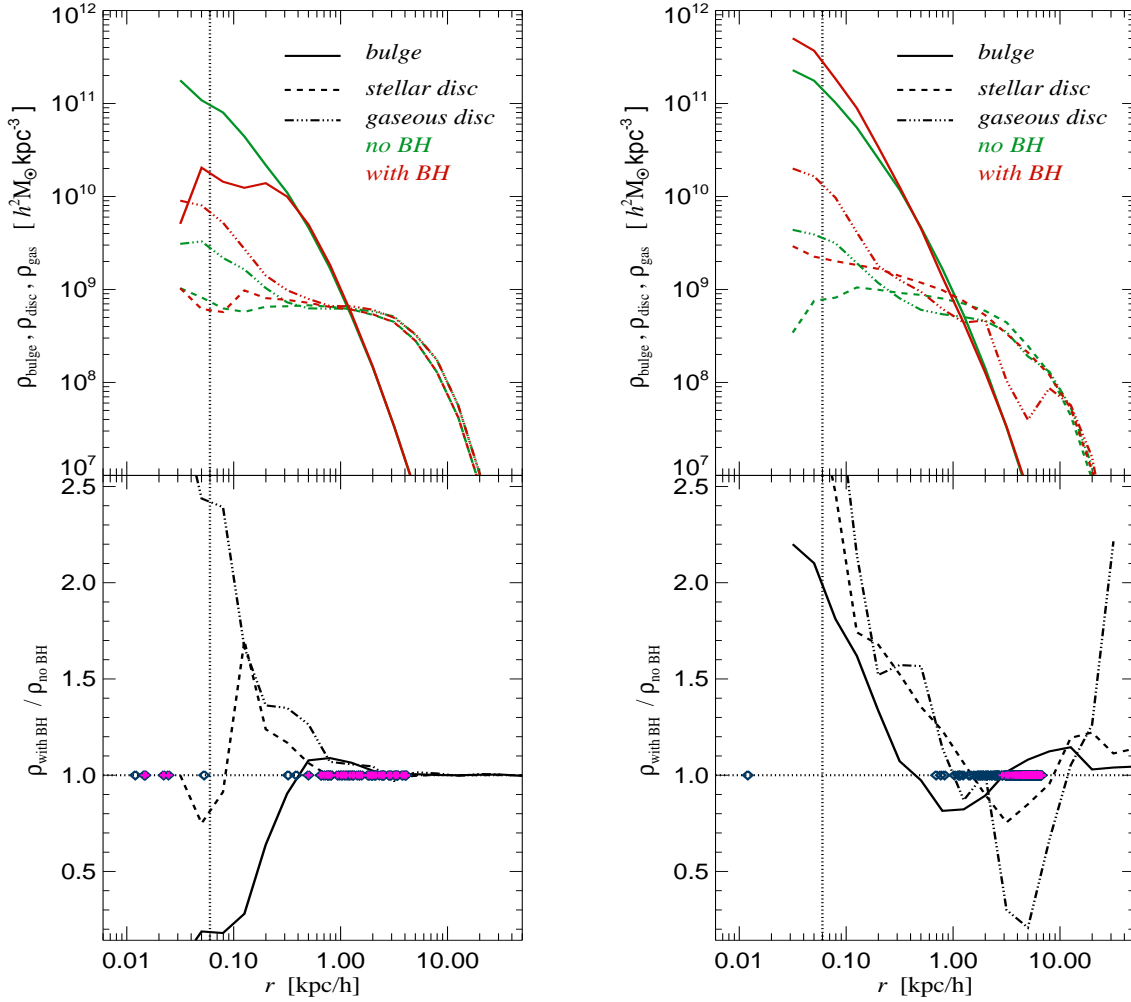
Figure 7. Mass density profiles of the stellar bulge (continuous lines), stellar disc (dashed lines) and gaseous disc (triple dot-dashed lines) are shown in the upper panels for simulations with recoiled BHs (red colour) and without BHs (green colour). The ratio of these density profiles for each galactic component (same line styles) is plotted in the bottom panels. The BH is subject to an initial recoil of $700\,\mathrm{km\,s^{-1}}$ in the galactic plane. Results for a BH without (with) gas accretion are shown in the left-hand panel (right-hand panel). Blue diamond symbols denote the BH distance from the minimum of the potential, while the pink crosses indicate those distances where the BH velocity is less than $400\,\mathrm{km\,s^{-1}}$.

the galactic centre, the mass deficit becomes of the order of $\sim 3.5 \times M_{\mathrm{BH}}$ when the BH finally returns to the centre.

3.1.4 Clumpy discs

At present the spatial distribution of stars and gas in high redshift galaxies are still rather uncertain, yet this is the regime where BH mergers and thus gravitational recoils should be most frequent. Recent observational studies suggest that there is a significant population of high redshift galaxies that have gas-rich, thick and clumpy discs (Förster Schreiber et al. 2009, and references therein). To numerically explore this scenario, we now discuss cases where the galactic disc is very clumpy instead of stable and quasi-stationary.

Even though in the model we consider the total galaxy mass and virial radius are the same, the clumpy disc has

a deeper central potential with a central escape velocity $v_{\mathrm{esc}} \sim 1980\,\mathrm{km\,s^{-1}} \sim 6.6\,v_{200}$, as a result of more efficient radiative cooling in the innermost regions. While in the case of a smooth disc a BH with kick velocity $\geq 0.3\,v_{\mathrm{esc}}$ can leave the innermost regions, here a larger kick velocity of $> 0.5\,v_{\mathrm{esc}}$ is needed to displace the BH from the central region at all. Also, the maximum distance reached at the first apocentre is affected by the structure of the gaseous disc: if the disc is relatively smooth, a BH recoiled with $\sim 0.5\,v_{\mathrm{esc}}$ reaches $\sim 4.6\,h^{-1}\,\mathrm{kpc}$, while if the disc is clumpy a BH with initial kick velocity of $\sim 0.8\,v_{\mathrm{esc}}$ does not reach a distance further than $3\,h^{-1}\,\mathrm{kpc}$ from the centre. To the extent that clumpy discs are accompanied by elevated deposition rates of baryons in the centre, as it happens in our simulation, BHs are more likely to stay in the centre, or leave only for brief periods of time, when they experience merger kicks.
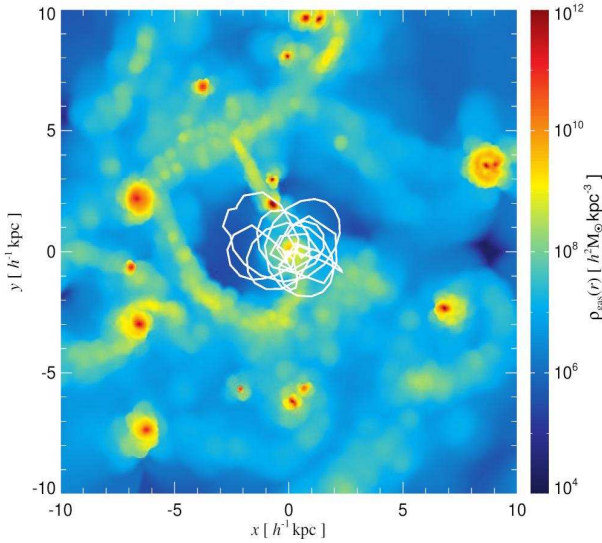
Figure 8. Projected mass-weighted gas density map of the isolated galaxy with a very clumpy disc. The over-plotted white line shows the BH orbit from the beginning of the simulation to the moment when it returns to the galaxy centre.

This may contribute to explain the very scarce observational evidence for off-centred quasars (Bonning et al. 2007).

An example of a gravitationally recoiled BH with $v_{\rm kick} = 1600\,{\rm km\,s^{-1}}$ ($\sim 0.8\,v_{\rm esc}$) in the plane of the clumpy disc is shown in Figure 8. The BH orbit (denoted with a white line) is plotted on top of the projected density map, where the clumpy nature of the disc can be clearly seen. Regardless of gas accretion and feedback processes, the BH returns to the minimum of the potential in 3×10^8 yrs. The BH trajectory is completely contained in the disc, with $|z| < 100\,h^{-1}$ pc, and soon after reaching the first apocentre the BH starts co-rotating with the galactic disc. During its orbit through the clumpy disc, the BH accretes a relatively small amount of gas. By the time the BH returns to the centre, the BH mass has increased by $\sim 3.6 \times 10^7\,h^{-1}{\rm M_\odot}$. Most of the mass gain happens when the BH is on its way back to the innermost regions, passing through a dense central lump of gas. The bolometric luminosity of the BH moving through a clumpy disc is on average lower than that of the BH passing though a more uniform gas distribution: in fact, the bolometric luminosity is reduced by at least one order of magnitude with respect to the values shown in Figure 6. During most of the 3×10^8 yrs while displaced from the centre, the BH should be in the radiatively inefficient accretion regime with only a few brief bursts of typical duration $< 10^7$ yrs when passing through a dense gas lump.

When the BH finally approaches the centre, its accretion rate increases, making the AGN optically bright for $\sim 5 \times 10^7$ yrs, after which the accretion rate drops again due to ensuing feedback. This suggests an interesting possibility for spectroscopically detecting a recoiled BH on its way back to the centre of a galaxy, given that its relative velocity during the luminosity maximum is still sufficiently large ($\sim 500\,{\rm km\,s^{-1}}$) to discriminate it from a stationary BH. However, it is possible that the BH accretes the gas with a

significant time delay compared to our model estimates, in which case it might become optically bright only when it has already settled into the minimum of the potential.

In the case of a clumpy disc we do not see any clear evidence for the impact of BH feedback on the surrounding gas, e.g. in the form of a low density wake in the gas as we witnessed for the smooth disc. We conclude that while BH feedback can alter the local gas density distribution and thus influence the BH dynamics, these feedback effects are not universal and depend sensitively on the thermodynamic state and the spatial distribution of the local gas.

3.2 Merging galaxies

The simulations presented in Section 3.1 have been instructive for understanding the complex interaction of gravitationally recoiled BHs with host galaxies that have pure stellar disc or gas-rich discs with different equations of state. However, these models considered isolated, unperturbed systems, which is not very realistic for the most commonly expected BH mergers, and this simplification may hide important aspects of the evolution of the recoiled BHs.

In order to illustrate the changes expected in a more realistic case, we now consider a simulation of the major merger of two equal mass galaxies. The two merging galaxies have been set-up initially in exactly the same way as described for the isolated gas-rich galaxies, with each of them containing a central BH with a mass of $5 \times 10^7\,h^{-1}{\rm M_\odot}$. The galaxies collide on a prograde parabolic orbit, break due to dynamical friction of their dark matter halos, and eventually coalesce to form a spheroidal remnant system. When the galaxy cores merge, their central BHs merge as well, leading to the recoil of the BH merger remnant.

In Figure 9, we show the time evolution of the gas density during the major merger of the two gas-rich galaxies. The left-hand panels correspond to times prior to the BH coalescence, while in the right-hand panels we illustrate snapshots after the remnant BH has been gravitationally kicked with $v_{\rm kick} \sim 3535\,{\rm km\,s^{-1}}$. In this particular case, we deliberately selected an initial BH trajectory that should maximise the possible interaction with the dense gaseous arms which are falling towards the core. The top right-hand panel shows a wake of low density, hot gas behind the BH, similarly to the case of the isolated galaxy with a smooth disc. However, the occurrence of feedback-generated hot gas is short lived and is present for only $\sim 5 \times 10^7$ yrs, as a result of the rapidly changing gas distribution in the significantly disturbed system. After reaching the apocentre, the BH passes trough the dense disc-like structure which is forming around the galactic core (bottom right-hand panel). Here BH feedback leads again to the formation of a low density wake. Thus, if BH accretion and feedback processes are not significantly suppressed compared to our numerical model, and if the gas discs are sufficiently smooth, such wakes of hot, low density gas may be ubiquitous in post merger systems, albeit short-lived.

We note that the recoil velocity of $v_{\rm kick} \sim 3535\,{\rm km\,s^{-1}}$ imparted on the remnant BH is extremely high. At present it is unclear whether such kicks are attainable (Campanelli et al. 2007; Baker et al. 2008), but it seems certain that they should be very rare. The estimated central escape velocity from our merging system at the moment of
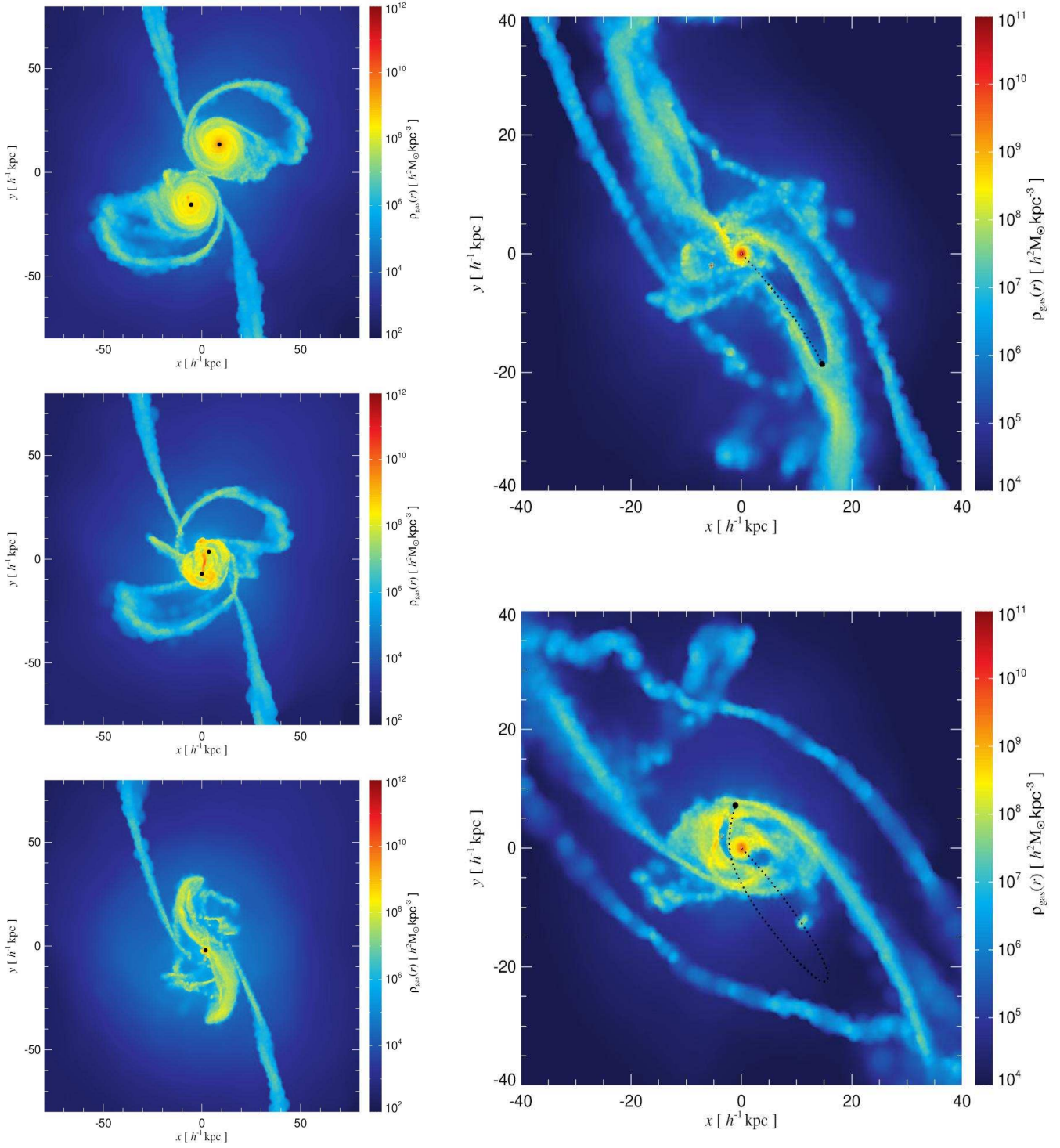
Figure 9. Projected mass-weighted gas density maps of two gas-rich merging galaxies, each containing a supermassive BH in the centre. The left-hand panels show a time sequence at $t = 1.55$, 1.62 and 1.69 Gyrs from the beginning of the simulation. At 1.69 Gyrs, the two BHs coalesce. In the right-hand panels we show the orbit of the gravitationally recoiled BH at times $t = 1.75$ and 1.89 Gyrs, which at the moment of the merger was kicked with a recoil velocity of $2500\,\mathrm{km\,s^{-1}}$ along the x-axis and $-2500\,\mathrm{km\,s^{-1}}$ along the y-axis.

BH coalescence is $v_{esc} \sim 3510 \, \mathrm{km \, s^{-1}}$. This is also a strikingly large value, caused here by the fact that we consider comparably massive galaxies in which substantial baryonic dissipation has created a massive central stellar bulge. For recoil velocities $\leq 0.8 \, v_{esc}$, the remnant BH does not leave the innermost regions, making it highly unlikely for the BH to ever get kicked out from the centre. To illustrate why recoil velocities $\leq 0.8 \, v_{esc}$ are not sufficient for the BH to leave the galactic core, in Figure 10 we show radial profiles of the gravitational potential for our merging system as well as for isolated galaxies with smooth and clumpy discs, for comparison. Clearly, already in the case of the clumpy disc, the gravitational potential is not only almost twice deeper with respect to the galaxy with a smooth disc, but it is also much steeper in the inner parts, which explains why the BH needs to have a larger fraction of the central escape velocity to leave the innermost regions. For the merging system, the central potential is almost six times deeper. Much of this depth arises in the steep part within $r < 1 \, h^{-1} \, \mathrm{kpc}$, so that the BH indeed has to have a recoil velocity comparable with the escape speed to leave the core. Similar results have been found for a variety of gas-rich mergers, extending to lower mass systems Blecha & Loeb (2010).

In order to explore the imprints of strong gravitational recoils in this system, we hence consider very high kick velocities: $v_{kick} \sim 3253 \, \mathrm{km \, s^{-1}} \sim 0.9 \, v_{esc}$ and $v_{kick} \sim 3535 \, \mathrm{km \, s^{-1}} \sim v_{esc}$, which could be achieved if the BHs are maximally spinning, are of comparable mass, and have anti-aligned spins in the orbital plane, as we assume here. The BH orbits for the two kick velocities turn out to be rather different due to the shape of the gravitational potential. For $v_{kick} \sim 0.9 \, v_{esc}$ the BH reaches only $1.5 \, h^{-1} \, \mathrm{kpc}$ at the first apocentre. After experiencing several mostly radial-type passages close to the centre, it returns back in 10^8 yrs. Instead, the BH kicked with $v_{kick} \sim v_{esc}$ leaves the central region all together. Along its way towards the outskirts it experiences drag forces from the infalling dense gaseous arms, such that it only reaches an apocentric distance of $\sim 27 \, h^{-1} \, \mathrm{kpc}$. Thereafter, the BH describes a precessing elliptical trajectory, and after reaching each apocentre, the BH moves retrograde with respect to the forming circumnuclear disc (similar to the simulation findings in the case of the uniform isolated disc). This will likely increase the time needed for the BH to return to the centre. In fact, at time $\sim 10^9$ yrs after the recoil event the apocentric distances are still very large, $\geq 20 \, h^{-1} \, \mathrm{kpc}$, implying that this BH will be wandering within the host galaxy for several Gyrs before returning to the centre.

In Figure 11, we show the time evolution of BH mass, bolometric luminosity and SFR of the merging system. The selected time sequence starts before the two BHs merge, which happens at ~ 1.69 Gyrs. In each panel, the blue continuous lines denote the case where the remnant BH does not experience a gravitational recoil, while the green dashed lines and the red triple dot-dashed lines are for the simulations where the remnant BH is kicked with $\sim 0.9 \, v_{esc}$ and $\sim v_{esc}$, respectively. A number of interesting features can be seen in this figure: *i)* Prior to coalescence, both BHs grow rapidly, reaching the Eddington limit; *ii)* During this period, the merging system also enters into a starburst phase, with a SFR peaking at $4000 \, \mathrm{M_\odot \, yr^{-1}}$; *iii)* Once the remnant BH is gravitationally recoiled its accretion rate drops,
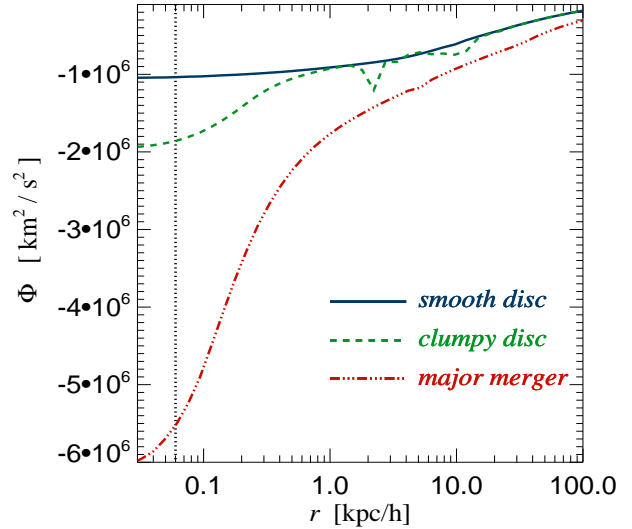

Figure 10. Radial profiles of the gravitational potential for the isolated galaxy with a smooth disc (blue continuous line), for the isolated galaxy with a clumpy disc (green dashed line), and for the system undergoing a major merger of two gas-rich galaxies (red triple dot-dashed line). The potential in the central regions is progressively both deeper and steeper in these three cases.

especially in the case where the BH leaves the dense central regions (i.e. for $v_{kick} \sim v_{esc}$), implying that the AGN will have a much lower bolometric luminosity and will grow less in mass; *iv)* Because the remnant BH is wandering away from the centre, it becomes much less efficient in regulating the central properties of the host galaxy. Thus, in the case of recoiled BHs, the central starburst activity will be prolonged, with more young stars formed in situ; *v)* The extended star formation activity has a direct impact on the BH growth once it returns to the centre: more stars have already formed, leaving less gas to fuel further BH accretion. This explains why the BH mass in the case of the $\sim 0.9 \, v_{esc}$ kick stays much lower and cannot catch-up with that of the stationary BH, even though it returns to the centre already after 10^8 yrs; *vi)* While the amount of stars formed has a large impact on the BH growth, it does not significantly affect the total stellar mass, which changes by a few percent at most. We hence find that the gravitational recoil for a single merger could in principle introduce more scatter in the BH mass (by up to factor of ~ 2) than in the bulge mass when considering BH mass - bulge mass scaling relation (see Blecha & Loeb (2010) for a comprehensive study of the scatter in the BH mass - host galaxy scaling relations for different merging systems).

While the findings discussed above should reflect the general characteristics of gas-rich mergers of galaxies, we would however like to stress that the quantitative details will be very sensitive to the physics of BH binary hardening, as well as to star formation and feedback. In our simulations, we cannot follow the BH binary hardening due to insufficient spatial resolution. Instead, we simply assume that the BH coalescence happens rapidly in a gas-rich environment. This is plausible assumption, but obviously not
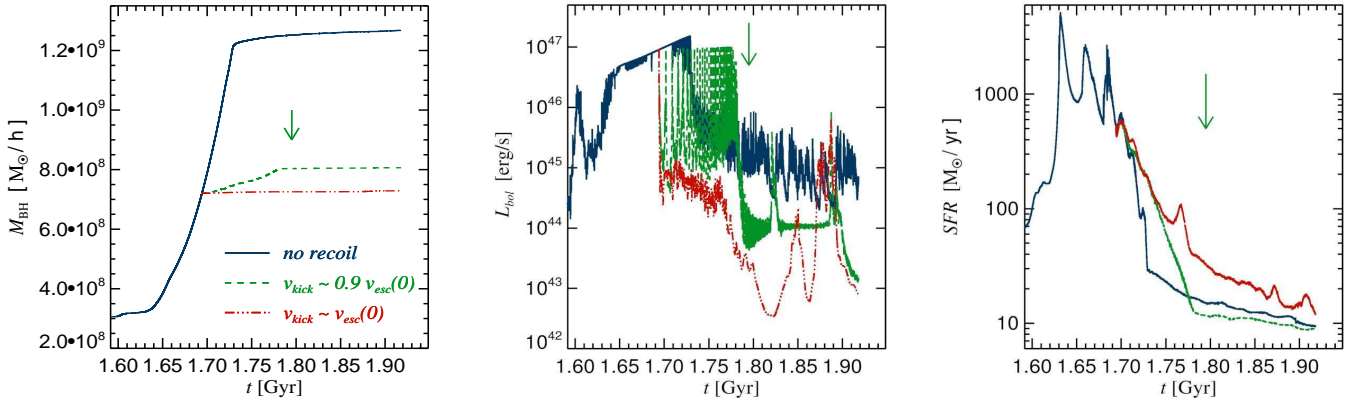
Figure 11. BH mass (left-hand panel), bolometric luminosity (central panel) and total SFR (right-hand panel) as a function of time during a major merger of two gas-rich galaxies. The blue continuous lines are for the run where after the BH coalescence no recoil is imparted on the remnant BH. Green dashed and red triple dot-dashed lines are for the simulations where the remnant BH is kicked with $v_{\rm kick} \sim 3253\,{\rm km\,s^{-1}} \sim 0.9\,v_{\rm esc}$ and $v_{\rm kick} \sim 3535\,{\rm km\,s^{-1}} \sim v_{\rm esc}$, respectively. The green arrows indicate when the gravitationally recoiled BH returns to the centre in the case of lower kick velocity.

guaranteed to be the case. If the final BH binary hardening should take longer, this would have a significant impact on the results. From the right-hand panel of Figure 11, we can infer that during a very short time interval of the order of $\leq 5 \times 10^7$ yrs, from the merger of the galactic cores to the moment where the BH growth becomes self-regulated, the BH grows rapidly. Thus, a delay in the BH coalescence relative to what we have assumed here, and hence a delay in the moment the recoil occurs, can significantly reduce the mass difference between a stationary and a recoiled BH. Similarly, the efficiency of star formation in the innermost regions will affect the amount of gas that is still available for accretion once the BH returns to the centre.

4 DISCUSSION AND CONCLUSIONS

In this study, we have used numerical simulations to discuss the complex interplay between the baryonic component of gas-rich galaxies and the dynamics of supermassive BHs recoiling due to a gravitational wave induced binary merger. Our analysis has focused on understanding how BH accretion and feedback processes can possibly modify the orbit and return timescale of recoiled BHs. This question has important implications both for the assembly history of the population of supermassive BHs as well as possible detections of displaced AGN in galaxies.

In our simulations, we have deliberately chosen massive and gas-rich systems, which could be representative of high redshift progenitors of present day ellipticals and brightest cluster galaxies. Using isolated disc galaxies, we were able to study the orbital evolution of kicked BHs for a variety of different assumptions about BH accretion and feedback, and about the treatment of the interstellar gas. We have then extended the analysis with simulation models of major galaxy mergers, yielding a more realistic accounting of the perturbed state of the systems that are expected to host merger recoil events of BHs. Our main conclusions from these simulations are as follows:

• At the centre of galaxies, the gravitational potential is strongly dominated by the baryonic component. The expected escape velocity will thus generally be significantly larger than that from the dark matter alone. It will depend on the detailed assumptions for the spatial distribution and dynamical evolution of the baryonic component at the host galaxy centre, which in turn can be affected by BH feedback as well as dynamical heating by the motion of the BH. For the compact remnants of galaxy mergers the escape velocity will be larger by a factor of a few, and the kick velocities required for a significant displacement of the supermassive BHs will need to be comparable to the central escape velocity, due to the steepness of the potential.

• Recent claims that massive high-redshift galaxy spheroids and discs are significantly more compact than their low-redshift counterparts should thus have a large effect on the expected trajectory of recoiling BH merger remnants. For all but the most extreme and rather unlikely values of the kick velocities, supermassive BHs should thus not be removed from the rather massive galaxies which appear to host the bulk of the supermassive BH population and the displacements should be mostly moderate (less than a few kpc) and rather short-lived.

• During mergers of gas-rich systems, where it is very likely that the BHs will grow rapidly due to large amounts of gas being funnelled towards the centre, gravitational recoils increase the scatter in BH mass - host galaxy scaling relationships predicted by the simulations. In particular, the BH mass is very sensitive to the occurrence of recoil, and can be lower by up to a factor of a few in respect to the mass of a BH which does not experience any kick. We note however that the exact amount of BH mass reduction is very dependent on the BH binary hardening timescale and also on the efficiency of the starburst to consume the central gas supplies.

• Unfortunately, the strong sensitivity of the dynamics of a recoiling BH on the detailed spatial distribution and thermal state of the baryonic component, which in turn depends on the details of the feedback of the accreting BHs, adds another level of complexity to predictions of the ex-

pected distribution of the luminosity and the displacement of off-centred AGN.

• The overall amount of accretion and therefore also the luminosity of a recoiling BH depends sensitively on the distribution and thermal state of gas down to scales smaller than can be resolved by our simulations. As in previous work, we have thus parametrised the accretion rate as Bondi-Hoyle-Lyttleton accretion with a parameter α to take into account that the simulations cannot fully resolve the multi-phase medium of the interstellar gas. If the recoiling BH leaves the dense multi-phase gas $\alpha = 100$ probably over-estimates the accretion rate somewhat. We have thus also tested what happens if we assume $\alpha = 1$, i.e. Bondi-Hoyle-Lyttleton accretion as derived from the actual density and temperature distribution of the gas in the simulation. This should now underestimate the actual accretion rate. The corresponding reduction of the accretion rate and luminosity is about a factor five – much weaker than linear because of the self-regulating effect of the feedback on the accretion rate. In reality, the accretion rates and the corresponding luminosities should lie somewhere in between. The generally rather large accretion rates of BHs if recoiled within gas-rich discs predicted by our simulations would bode well for the possibility to detect off-centred AGN, and may give added confidence in the recent claims of such detections.

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APPENDIX A: NUMERICAL ISSUES

If the gravitationally recoiled BH leaves the dense multiphase medium while on its orbit through the galaxy, the accretion rate might be overpredicted by equation (1) when $\alpha = 100$ is used (see also Booth & Schaye 2009). A lower gas accretion rate and hence a lower associated BH feedback
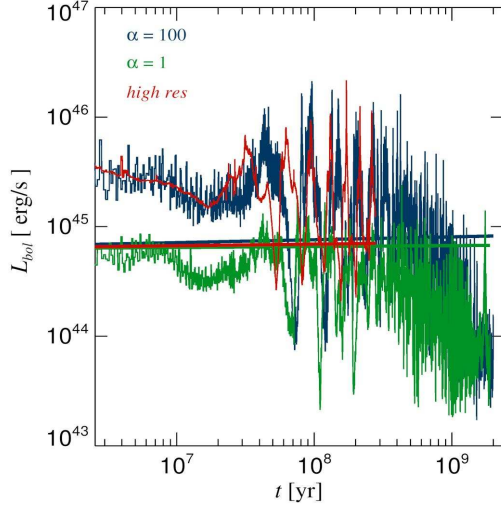
Figure A1. Bolometric luminosity as a function of time for simulations with two different values for the α parameter in equation (1): $\alpha = 100$ (blue line) and $\alpha = 1$ (green line). The same galaxy has also been simulated with twice as high spatial resolution and $\alpha = 100$ (red line).

Figure A2. BH distance from the minimum of the potential as a function of time for the simulations where $\alpha = 100$ in equation (1) (blue continuous line) and where $\alpha = 1$ (green dashed line). The same galaxy has also been simulated with twice as high spatial resolution and $\alpha = 100$ (red triple dot dashed line).

may then possibly change the impact of the recoiled BH on its surroundings, which in turn then leads to a different BH trajectory.

To explore these issues and test the robustness of our results, we have performed two additional simulation studies. In one run we reduce the α parameter to 1, thereby providing a lower limit to the expected accretion. In the other we increase the numerical resolution by a factor of 8 in particle number for each galactic component, resulting in twice better spatial resolution per dimension, equal to $30\,h^{-1}$ pc for the bulge and the disc, and of $1\,h^{-1}$ kpc for the dark matter halo.

In Figure A1 we show the bolometric luminosity of a BH which has been kicked in the plane of the galaxy with $700\,\mathrm{km\,s^{-1}}$. The blue line is for our default simulation, as shown in the central panel of Figure 6. The green line is for a test run performed with $\alpha = 1$, and the red line is the result of our higher resolution simulation. For the case of $\alpha = 1$ the accretion rate and thus the bolometric luminosity is lower than for the simulation with $\alpha = 100$, with the bolometric luminosity being reduced by a factor of ~ 5 on average. We note, however, that $\alpha = 1$ provides clearly a lower limit of the expected Bondi-Hoyle-Lyttleton rate, given that the recoiled BH trajectory is confined mostly within the dense gaseous disc, which has a multi-phase structure. In either case we expect that the recoiled BH can still have several radiatively efficient episodes while it travels through the gas-rich disc, but these will occur during shorter time intervals of a few 10^7 yrs. From Figure A1 it can also be seen that the bolometric luminosity for our lower resolution run is in excellent agreement with the finding of the higher resolution simulation. This indicates that our subresolution model for BH growth and feedback gives numerically robust and convergent results.

Figure A2 shows the BH distance from the minimum of the potential for the same set of simulations as in Figure A1. Initially the BH orbits for $\alpha = 1$ and $\alpha = 100$ are
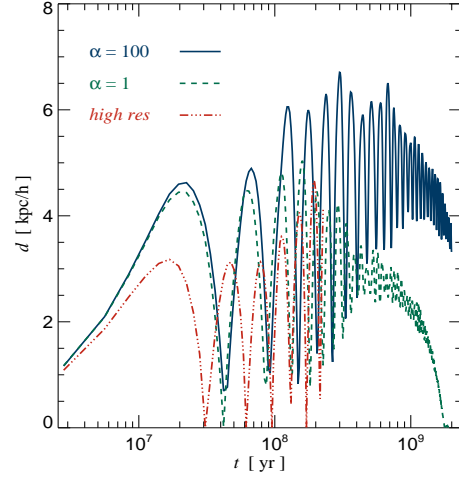
very similar, but after 10^8 yrs the recoiled BH in the case of $\alpha = 1$ reaches smaller apocentric distances. Nonetheless, we observe that also in the case of $\alpha = 1$ a plume of hot, low density gas develops in the wake of the BH, which forces the BH into a retrograde orbit with respect to the galactic disc. Given that the BH accretion rate is lower, the magnitude of this effect is somewhat diminished and thus the BH returns to the centre on a shorter timescale, which is however still rather long $\sim 1.6 \times 10^9$ yrs. Note that this findings means that our qualitative findings are very robust regardless of the exact value of the α parameter, which is very encouraging.

The BH orbit for the higher resolution simulation is more different than perhaps may have been expected, given that the BH mass growth is very similar. The reason for this can be attributed to the detailed shape of the gravitational potential, which is resolved down to smaller scales in the higher resolution run. As a result, the central potential is about 10% deeper than in the lower resolution simulation. This difference is sufficient for the recoiled BH to reach only $\sim 3.2\,h^{-1}$ kpc instead of $\sim 4.6\,h^{-1}$ kpc at the first apocentre.