Energy input from quasars regulates the growth and activity of black holes and their host galaxies

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In the early Universe, while galaxies were still forming, black holes as massive as a billion solar masses powered quasars. Supermassive black holes are found at the centers of most galaxies today[1,2,3], where their masses are related to the velocity dispersions of stars in their host galaxies and hence to the mass of the central bulge of the galaxy[4,5]. This suggests a link between the growth of the black holes and the host galaxies [6,7,8,9], which has indeed been assumed for a number of years. But the origin of the observed relation between black hole mass and stellar velocity dispersion, and its connection with the evolution of galaxies have remained unclear. Here we report hydrodynamical simulations that simultaneously follow star formation and the growth of black holes during galaxy-galaxy collisions. We find that in addition to generating a burst of star formation[10], a merger leads to strong inflows that feed gas to the supermassive black hole and thereby power the quasar. The energy released by the quasar expels enough gas to quench both star formation and further black hole growth. This determines the lifetime of the quasar phase (approaching 100 million years) and explains the relationship between the black hole mass and the stellar velocity

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dispersion.

A large fraction of the black hole mass in galaxies today is thought to have been assembled during the peak of quasar activity in the early Universe[11,12], when large amounts of matter were available for accretion onto central black holes. Interactions and mergers between galaxies are known to trigger large-scale nuclear gas inflows[13,14], which is a prerequisite for the growth of central black holes by accretion. Also, hierarchical models of galaxy formation imply that mergers of galaxies form elliptical galaxies or spheroidal components in galaxies, by destroying stellar disks and triggering nuclear starbursts.

This led to suggestions that the $M_{\rm BH} - \sigma$ relation (where $M_{\rm BH}$ is the black hole mass and σ is the velocity dispersion of stars in the bulge of galaxies) could arise in galaxy mergers, provided strong outflows are produced in response to major phases of accretion, capable of halting further black hole growth[15,16,17,8]. Indeed, observations point to the existence of strong outflows in bright quasars[18,19,20]. In this picture, black hole accretion is expected to have a crucial impact on the evolution of the host galaxy. However, the coupling of star formation with black hole growth in the context of galaxy evolution is difficult to treat on the basis of analytical estimates alone.

We have, therefore, performed detailed numerical simulations of galaxy mergers that include radiative cooling, star formation, black hole growth, energetic feedback from supernovae and accretion onto black holes, as well as the gravitational dynamics of gas, stars, and dark matter (see Supplementary Information and further details in ref. 21). As described in the supplementary information, we include a novel treatment of gas accretion onto supermassive black holes and its associated feedback in the centres of merging galaxies. We describe black holes using collisionless "sink" particles that can grow in mass by accreting gas from their surroundings. The accretion rate is estimated by relating the small-scale, unresolved flow around the black hole to the large-scale, resolved gas properties using a spherical Bondi-Hoyle[22] model. We further assume that a small fraction f of the radiated luminosity L couples thermodynamically to the surrounding gas. This gives an effective heating rate, $\dot{E}_{\rm feed} = fL = f\eta \dot{M}c^2$, where we fix the radiative efficiency to $\eta = 0.1$, the typical value derived from Shakura-Sunyaev[23] accretion models onto a non-rotating black hole. We further assume $f = 0.05$, so that $\sim 0.5\%$ of the accreted rest mass energy is available to heat the gas.

To illustrate the impact of central, supermassive black holes on mergers of two disk galaxies, we compare the gas evolution between two simulations with galaxies which have roughly the size of the Milky Way (Fig. 1). Star formation and supernova feedback are included in both simulations, but we add our black hole growth and feedback in one (top four panels of Fig. 1, see also the corresponding Supplementary Video) and neglect it in the other (bottom four panels). The first image ($t = 1.1$ Gyr) shows the galaxies soon after their first encounter, when strong gravitational forces have spawned extended tidal tails. At this time, the black holes in the centres of each galaxy (top) have already grown significantly from their initial masses and are accreting at a moderate level. However, the overall star formation rate is essentially unaffected by the presence of the black holes, as indicated by Figure 2, which plots the star formation rate (in both cases), black hole accretion rate, and black hole mass (for the top panels), as a function of time.

The second snapshot ($t = 1.4$ Gyr) in Fig. 1 shows the galaxies when they begin to coalesce. Here, the tidal interaction has distorted the disks into a pair of bi-symmetric spirals, and gas is shocked between the two galaxies. The tidal response drives gas into the central regions of each galaxy. While only weak starbursts and accretion events are triggered at this time, it is already evident that black hole feedback alters the thermodynamic state of the gas, as indicated by the relatively lower density and higher temperature of the gas surrounding the galaxies in the simulation with black holes. In fact, a significant wind has started to flow out of the centres.

When the galaxies finally merge, as shown in the third image ($t = 1.6$ Gyr), much of the gas is quickly converted into stars in intense bursts of star formation[10]. Owing to the enhanced gas density, the black holes, which also merge to form one object, experience a rapid phase of accretion close to the Eddington rate resulting in significant mass growth. Also, the morphologies of the remnants in the two simulations begin to differ significantly. In the model without black holes, most of the gas is still inflowing in a comparatively cool phase. In contrast, the simulations with black holes exhibit a significant change in the thermodynamic state of the circumnuclear gas, which is heated by the feedback energy provided by the accretion and partly expelled in a powerful wind. During this strong accretion phase and for this interval of time, the object would be a bright quasar with a specific lifetime.

Differences persist as the remnants settle into a relaxed state (fourth panels in Fig. 1). The remnant without black holes retains a large amount of dense cold gas, yielding prolonged star formation at a steady rate. However, in the simulation with supermassive black holes, nearly all the gas is expelled from the centre, quenching star formation and black hole accretion itself. Consequently, the black hole mass saturates, quasar activity stops, and star formation is inhibited, so that the remnant resembles a "dead" elliptical galaxy whose stellar population quickly reddens[25]. In the particular example we show, the remnant of this major merger is an elliptical galaxy. In the hierarchical model of galaxy formation, a new disk can grow around this spheroid, turning it into the bulge component of a spiral galaxy. In very gas-rich mergers, a disk component may even survive directly[26] (an example of this is shown in a Supplementary Figure). We therefore expect black holes in bulges of spiral galaxies to be assembled in a manner similar to those in ellipticals. Our results should also apply for cases involving minor mergers.

The evolution of star formation rate, black hole accretion rate, and black hole mass for mergers when the progenitor galaxy mass is varied (including the model shown in Fig. 1) are shown in Figure 2. Models with different mass qualitatively reproduce the key features of the evolution shown in Figure 1: the star formation and black hole accretion rates are both quenched in the remnant, and black hole growth saturates owing to feedback provided by accretion energy. However, the damping of star formation and black hole activity is more abrupt in the more massive systems. Here, the total gas supply for accretion is larger, and the gravitational potential well is deeper, and so the black hole has to grow much more before its released energy is sufficient to expel the gas in a quasar driven wind, which then terminates further nuclear accretion and star formation. For the same reasons, the initial growth of the black holes, which is regulated by the properties of nearby gas, depends on the total mass. It is faster in more massive systems, which can therefore reach the exponential, Eddington-limited growth phase more easily. The lifetime of the active black hole phase, however, increases for smaller black hole masses, implying that low-luminosity quasars should be more numerous than bright ones. This is consistent with them residing in smaller galaxies and with what has been found in recent surveys[27,28].

The dependence of black hole growth on galaxy mass yields a relation between the stellar spheroid of the remnant and its central black hole. Figure 3 shows the black hole mass versus the stellar velocity dispersion of the merger remnants from our simulations, compared with observations. We show simulations with six different galaxy masses, each of which has been run with three different initial gas mass fractions of the galaxies' disks. Remarkably, our simulations reproduce the observed $M_{\rm BH}$–σ correlation very well. Note that black holes in more gas-rich mergers reach somewhat larger masses than those growing in gas-poorer environments (which is expected from our prescription for the accretion rate), but this is partly compensated by an increase in the velocity dispersion of the corresponding bulges, maintaining a comparatively tight $M_{\rm BH}$–σ relation. However, this suggests that part of the intrinsic scatter in the observed relation can be ascribed to different gas fractions of the galaxies during black hole growth. Our lowest mass galaxy models probe a region of the $M_{\rm BH}$–σ relation where few measurements are available and predict that this correlation should hold towards small black hole masses and velocity dispersions, in tentative agreement with recent observations[30].

Black hole growth is self-regulated in our models. As galaxies merge to form spheroids, the dynamical response of the gas to the energy supplied by accretion halts further growth once the black holes have reached a critical size for the gravitational potential of the bulge. At this saturation point, the active galactic nuclei (AGN) generate outflows that drive away gas and inhibit further star formation. Our simulations are the first self-consistent models to demonstrate that self-regulation can quantitatively account for the principle observational facts known for the local population of supermassive black holes, most notably the $M_{\rm BH}$–σ relation. Moreover, self-regulation in our hydrodynamical simulations predicts a specific duration of the luminous episode of a black hole in a given galaxy, thereby explaining the origin of quasar lifetimes. We note that the final black hole masses we obtain are roughly proportional to the inverse of the value assumed for the feedback efficiency, f. Interestingly, our choice of $f = 5\%$ is consistent with the value required in semi-analytic models[8] to explain the evolution of the number density of quasars.

The black hole accretion activity also has a profound impact on the host galaxy. The remnant spheroid is gas-poor and has low residual star formation, so it evolves to a red stellar colour on a short timescale. The simulations shown here make it possible to draw firm conclusions on this and other links between black hole growth, quasar activity, and properties of the galaxy population. Our novel approach can also be implemented in cosmological simulations of hierarchical structure formation in representative pieces of the Universe. Such simulations will allow us to study directly why quasars were much more numerous in the early Universe than they are today, and how black holes and galaxies influence each other throughout cosmic history.

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Fig. 1.— Snapshots of the simulated time evolution in mergers of two galaxies with and without black holes. The model with black holes is shown in the top panels. The full time sequence for this simulation can be viewed in the Supplementary Video. The bottom row shows the corresponding simulation without the inclusion of black holes. In both cases, four snapshots at different times in the simulations are shown. The images visualise the projected gas distribution in the two galaxies, colour-coded by temperature (blue to red). The colliding galaxies have the same initial mass corresponding to a 'virial velocity' of $V_{\rm vir} = (M_{\rm tot} \times 10GH_0)^{1/3} = 160$ km/s, and consist of an extended dark matter halo, a stellar bulge, and a disk made up of stars and 20% gas. Each individual galaxy in the simulations is represented with 30000 particles for the dark matter, 20000 for the stellar disk, 20000 for the gaseous disk, and 10000 for the bulge component. Two such galaxies were set up on a parabolic, prograde collision course, and then evolved forward in time numerically with GADGET-2[24], a parallel TreeSPH simulation code. The first snapshot ($t = 1.1$ Gyr) shows the systems after the first passage of the two galaxies. The second snapshot ($t = 1.4$ Gyr) depicts the galaxies distorted by their mutual tidal interaction, just before they merge. The peak in the star formation and black hole accretion (see also Fig. 2) is reached at the time of the third snapshot ($t = 1.6$ Gyr), when the galaxies finally coalesce. At this time, a strong wind driven by feedback energy from the accretion expels much of the gas from the inner regions in the simulation with black holes. Finally, the last snapshots show the systems after the galaxies have merged ($t = 2.5$ Gyr), leaving behind quasi-static spheroidal galaxies. In the simulation with black holes, the remnant is very gas poor and has little gas left dense enough to support ongoing star formation. This highlights that the presence of supermassive black holes, which accrete from the surrounding gas and heat it with the associated feedback energy, dramatically alters the merger remnant.

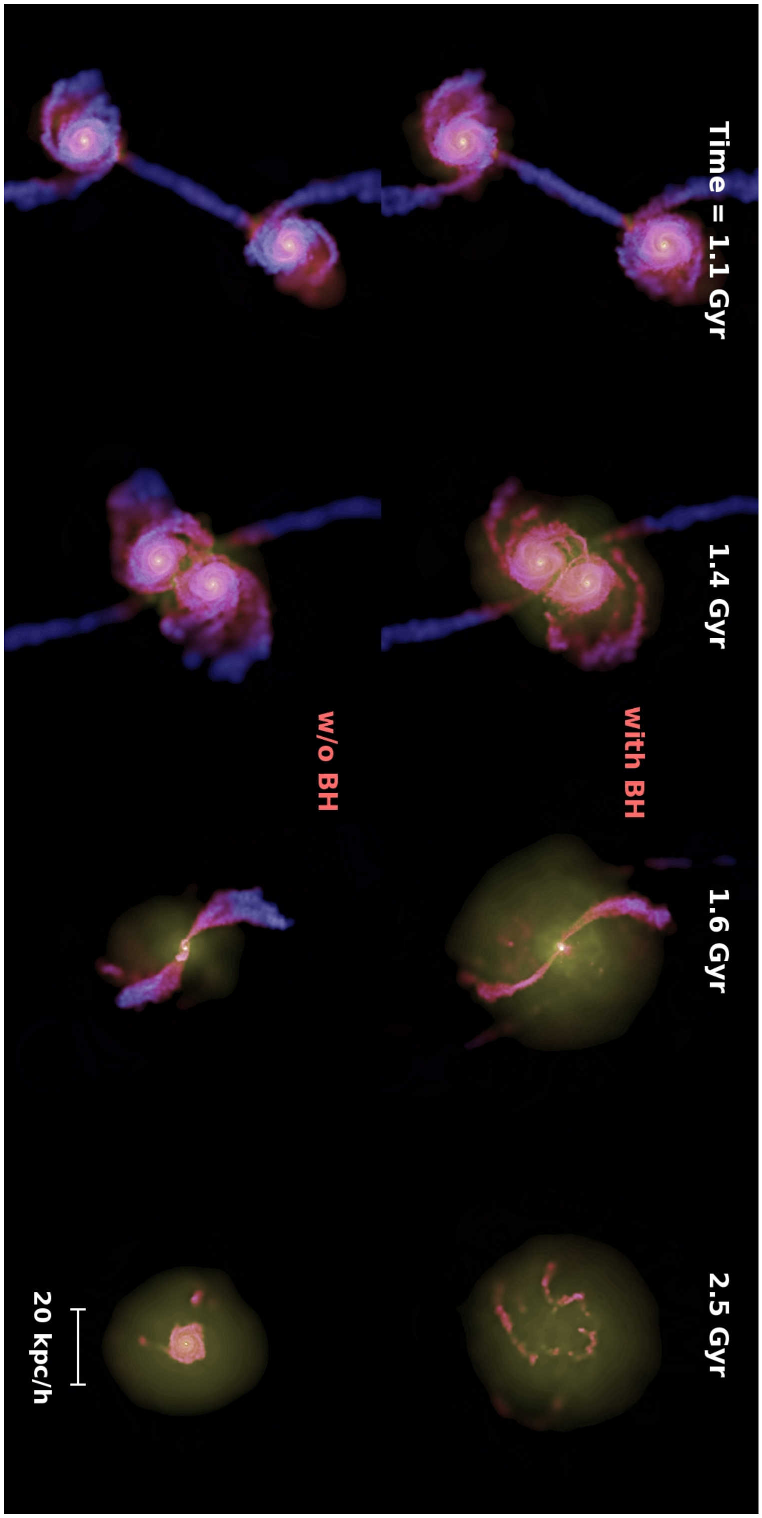

Time = 1.1 Gyr
1.4 Gyr
1.6 Gyr
2.5 Gyr
with BH
w/o BH
20 kpc/h

Fig. 2.— Black hole activity, star formation and black hole growth plotted as a function of time during a galaxy-galaxy merger. The star formation rate (SFR) and black hole accretion rate (BHAR) are shown in the top and middle panels, respectively, and are given in units of solar masses per year. The black hole mass ($M_{\rm BH}$). is given in units of solar masses. The three lines in each panel correspond to models with galaxies of virial velocity $V_{\rm vir} = 80$, 160, and 320 km/s, (bottom to top lines in each panel, also labelled in the bottom panel). For comparison, we also show the evolution of the star formation rate for the model without a black hole that is shown in Fig. 1 (dashed line – for the $V_{\rm vir} = 160$ km/s galaxy). We note, in particular, that owing to AGN feedback, the peak amplitude of the starburst during the merger is lowered by a significant factor. The black solid circles in the individual panels identify the times of the corresponding snapshots shown in Figure 1.

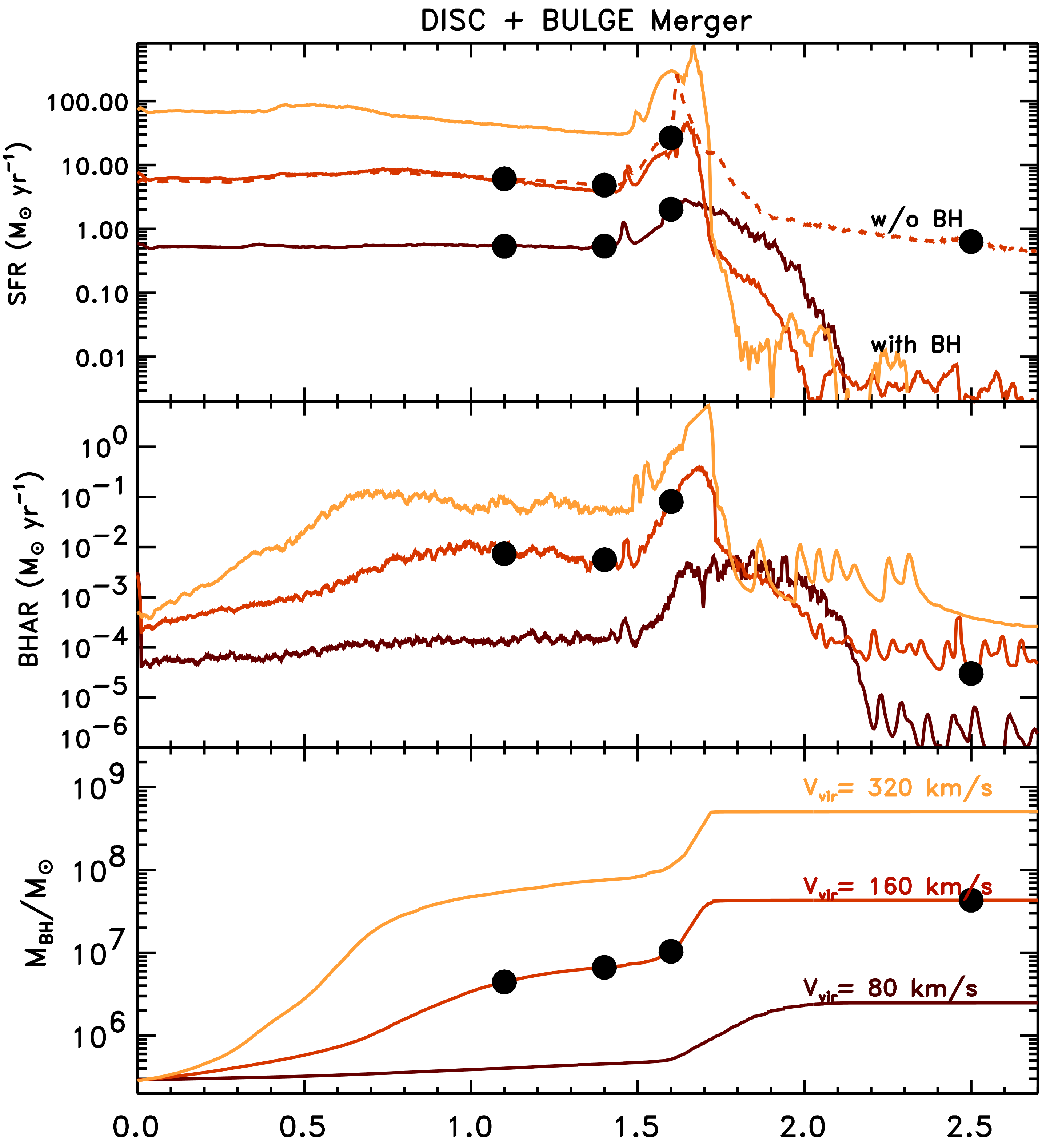
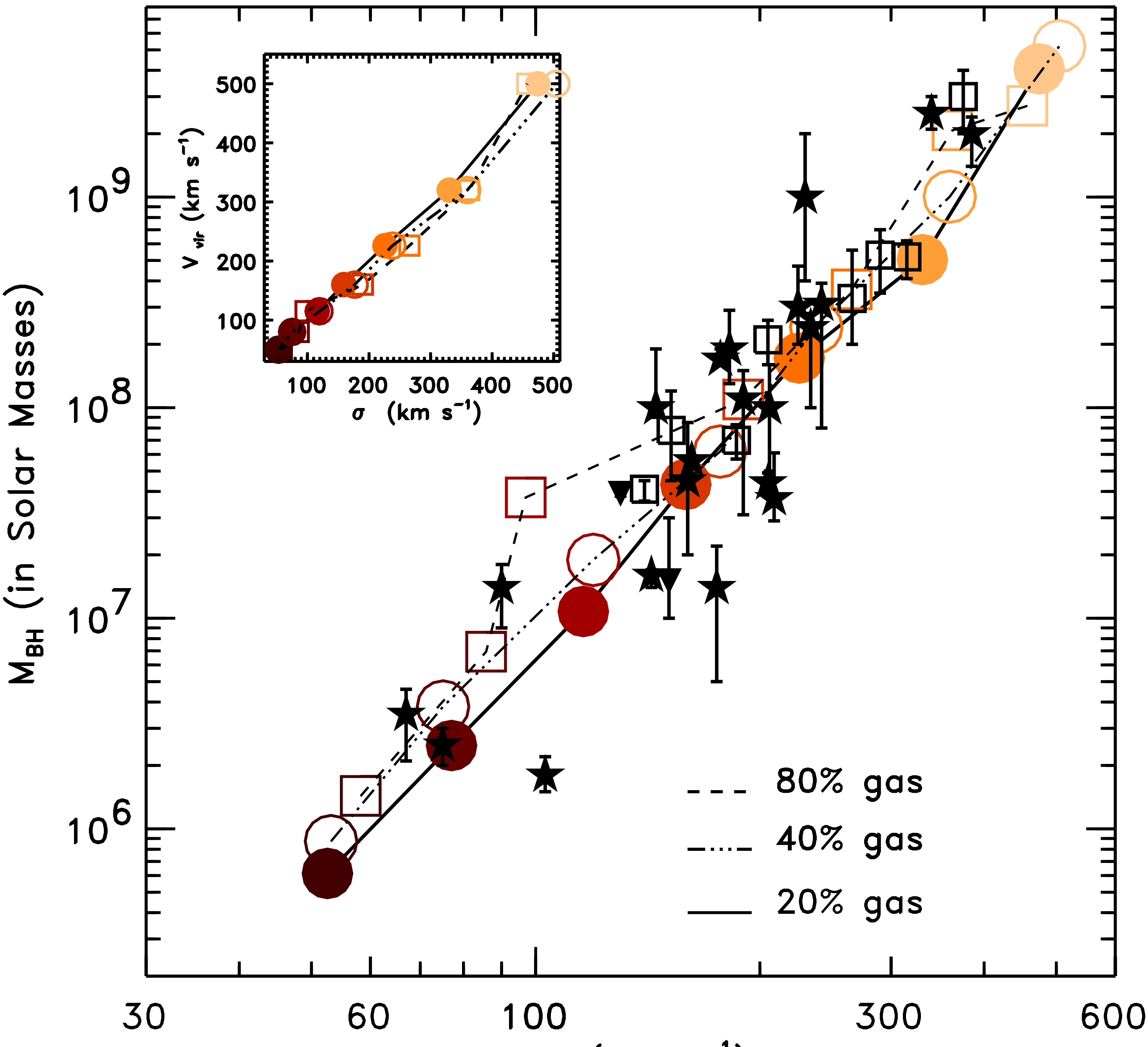

DISC + BULGE Merger
SFR (M⊙ yr⁻¹)
100.00
10.00
1.00
0.10
0.01
w/o BH
with BH
BHAR (M⊙ yr⁻¹)
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
M_BH/M⊙
10⁹
10⁸
10⁷
10⁶
V_vir= 320 km/s
V_vir= 160 km/s
V_vir= 80 km/s
0.0
0.5
1.0
1.5
2.0
2.5
t (Gyr)

Fig. 3.— The relation between the final black hole mass, $M_{\rm BH}$, and the velocity dispersion of stars, σ, of our galaxy merger simulations compared with observational measurements. The solid circles show the masses of the black holes and the bulge velocity dispersions measured for the final remnants of six merger simulations of galaxies with disk gas fraction of 20%, but different total mass, parameterised by virial velocities of $V_{\rm vir} = 50$, 80, 160, 320, and 500 km/s (shown by the dark to light red, from low to high mass galaxies respectively). Open circles and open squares with the same colour give results for gas fractions of 40% and 80%, respectively. We have also checked that our results are insensitive to the orbits of the galaxy collisions. Mimicking the observational data, we calculate σ as the line-of-sight stellar velocity dispersion of stars in the bulge within the effective radius, R_e, of the galaxy. Black symbols show observational data for the masses of supermassive black holes and the velocity dispersions of their host bulges. Measurements based on stellar kinematics are denoted by filled stars, those on gas kinematics by open squares, and those on maser kinematics by filled triangles. Details for all the displayed measurements are given in ref. 3 and 28. The observed BH sample has been fit by a power law relation, yielding[29]: $M_{\rm BH} = (1.5 \pm 0.2) \times 10^8 {\rm M}_\odot (\sigma / 200\,{\rm km/s})^{4.02 \pm 0.32}$. The inset shows the relation between the circular velocity $V_{\rm vir}$ and σ measured for the merger remnants in the simulations. The same colour coding is used as in the main panel to indicate corresponding mass objects.



M_{BH} (in Solar Masses)
10^9
10^8
10^7
10^6
30
60
100
300
600
σ (km s^{-1})
80% gas
40% gas
20% gas
V_{vir} (km s^{-1})
500
400
300
200
100
100
200
300
400
500
σ (km s^{-1})