The Role of Black Holes in Galaxy Mergers

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Abstract

In the paper “Black Holes in Galaxy Mergers: The Formation of Red Elliptical Galaxies”[1], researchers use a new model and show that growing black holes release a blast of energy that fundamentally regulates galaxy formation and black hole growth itself. The model assumes that a fraction of bolometric luminosity from an accreting black holes couples to the surrounding gas and provides a feedback mechanism that regulates black hole growth. This feedback shortens the timescale of starburst and black hole accretion. It accounts for the bimodal color distribution of galaxies in the universe. There’s another paper “Energy input from quasars regulates the growth and activity of black holes and their host galaxies”[2], which use the same model and comments on the growth relation between BHs and host galaxies as well as the relation between BH masses and the velocity dispesion.

Introduction

After the Big Bang, the universe had a period when it was remarkably homogeneous, as can be observed in the Cosmic Microwave Background, the fluctuations of which were less than one part in one hundred thousand. The most accepted view is that all the structure we observe today was formed as a consequence of the growth of primordial fluctuations by gravitational instability. Gravity slowed the expansion of high-density regions more rapidly than that of low-density regions, so the contrast between high- and low-density regions steadily increased. After that, all the structures in universe were gradually formed, including the galaxy.

In the standard scenario of galaxy formation, one of the most important ways is through interaction with other galaxies. Gravity is pulling neighbor galaxies together. The halos of dark matter then merge to form a similar but more massive dark halo, and the gas disks merge to form a more massive disk. The central black holes, if they have, will also merge, generating a stunning release of energy, mostly in the form of neutrinos and gravitational waves. As the gas disks merge, a significant fraction of their gas will have crashed down on the central black hole. Other gas will have been catalyzed into forming stars.

Fully consistent numerical models have demonstrated that interactions and mergers of spiral galaxies can produce remnants with properties similar to large elliptical galaxies. The spiral structure is associated with active star-forming regions. The spiral arms of these galaxies are so prominent, because there are many hot young blue and blue-white stars there, making the spiral arms extremely visible. Also, spiral galaxies are rich in gas and dust.

Observations have shown bimodal color distribution at fixed luminosity in the process of merger. The mean and variance of these two distributions do not depend on the environment. However, if mergers of galaxies really generate red elliptical galaxies from the collision of blue, star-forming spiral galaxies, it requires a very short timescale for the color to transform from blue to red. Long time transform may obscure the gap between these two distributions. If so, it is required to consume up all the gas in the blue spiral galaxies immediately after the merger so that there are no stars born in the new merged galaxy. Starburst can consume a considerable amount of gas. However, even very little remaining gas can lead to departure from the extremely red color [1]. Now there comes the question: how could the new galaxy exhaust all the gas in a very short time?

In recent years, scientists have begun to appreciate that the total mass of stars in today's galaxies corresponds directly to the size of a galaxy's black hole [6], but until now, no one could account for this observed relationship.

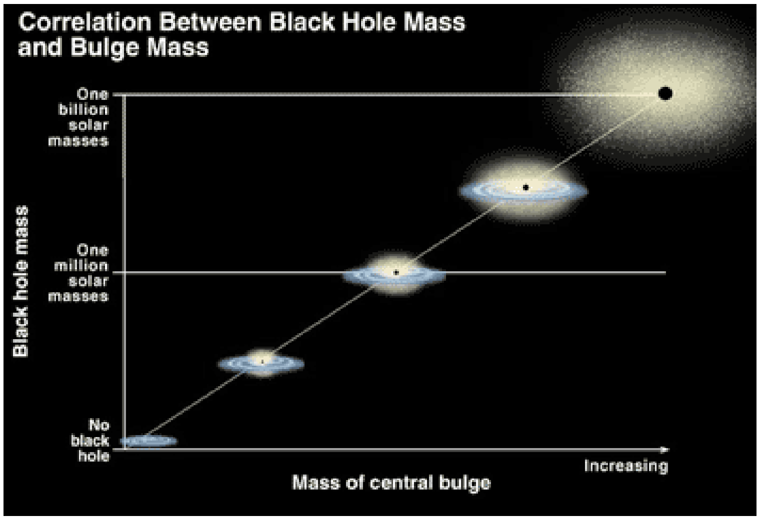

Fig1. The relation between BH mass and central bulge mass

Results from a NASA Hubble Space Telescope census of more than 30 galaxies with its powerful black hole hunting spectrograph show a close relationship between the black hole mass and the stars that comprise an elliptical galaxy or the central bulge stars of a spiral galaxy. Black holes did not precede a galaxy's birth but instead co-evolved with the galaxy by trapping a surprisingly exact percentage of the mass of stars and gas in a galaxy. So, the final mass of a black hole is not primordial; it is determined during the galaxy formation process. In most cases the black holes not only bulked up through the accretion of gas in isolated galaxies, but also through the mergers of galaxies where pairs of black holes combined. So, there comes a guess, the remarkable connection between galaxy formation and supermassive black hole could cast light on the solution to the "merger problem" we mentioned before.

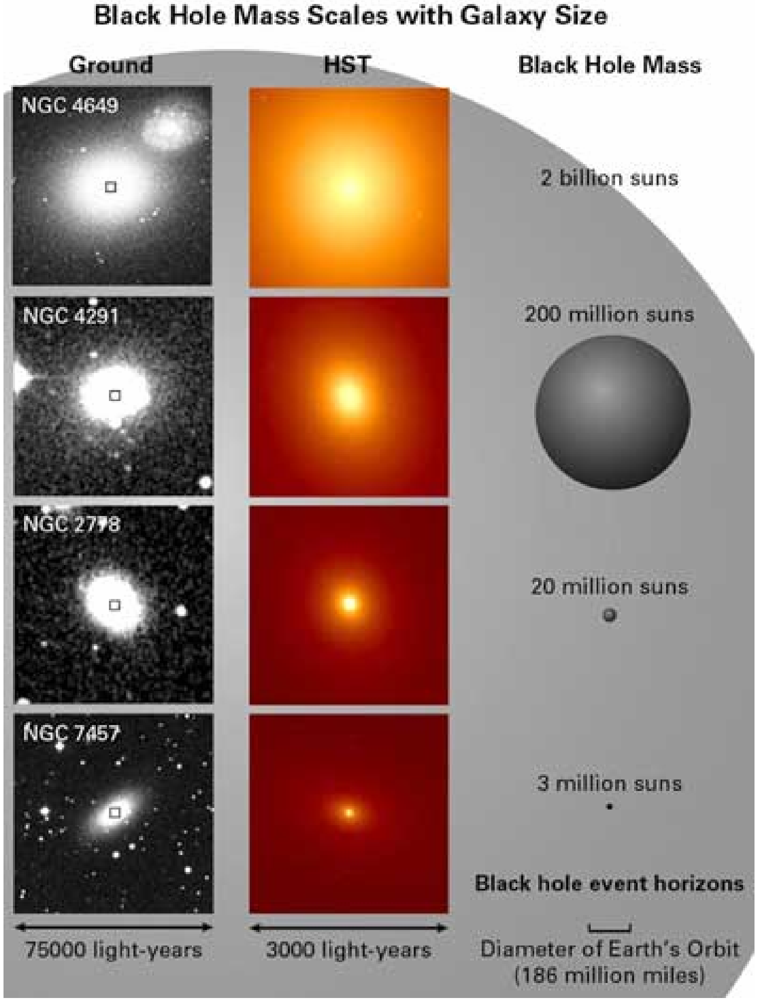

Fig2. The spectrograph about the relation between BH mass scale and galaxy size form the NASA Hubble space Telescope. (Hubble Release STScI-2000-22)

Fig3. A way to grow a black hole: Two disk galaxies with their own black holes fall toward each other. The merge yields a giant elliptical galaxy with a central black hole grown proportionally more massive. (Hubble Release STScI-2000-22)

As we know, the variation of speed and direction of stars near the core of galaxies is called velocity dispersion. The motions of stars in the inner space of the galaxy are chaotic. The gravitational fields make stars have varied speeds and directions of their orbital motions, which is what we mean by velocity dispersion. On the other hand, the effects on galaxy formation differ depending on whether the dark matter is hot, warm, or cold. These refer to its velocity dispersion relative to the normal matter. In some papers, the connection between galaxy formation and supermassive BHs is also indicated. For example, observations of nearby galaxies reveal a strong correlation between the mass of the central dark object and the velocity dispersion of the host galaxy [3]. This also leads to the conjecture whether the BH functions in the process of galaxy merger.

The key of this paper was incorporating black hole dynamics into a computational model of galaxy formation. In some galaxies, known as "active galactic nuclei" (AGN), the nucleus produces more radiation than the entire rest of the galaxy. Current theory suggests that there is a super massive black hole at the center of AGN. Although the black hole itself is invisible, gas accreting, or falling, onto a black hole becomes hot and some of this energy escapes for us to see.

The gas which falls into a black hole doesn't plunge in directly. Instead, it tries to move around the black hole in an orbit, forming what is known as an accretion disk. Material in the accretion disk slowly spirals inward as it loses energy due to friction. The huge gravitational tides near the black hole are excellent at ripping apart this material and heating it to high temperatures. The inner disks of super massive black holes (MBH) reach thousands of degrees Kelvin, while smaller black holes can heat their disks to millions of degrees, where they emit in the x-ray part of the spectrum. Black holes, therefore, are some of the brightest objects around.

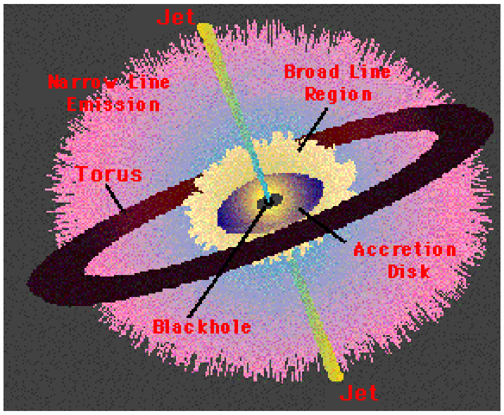

Fig4. Model of the active galactic nuclei

In about 10% of the AGN, the MBH and the accretion disk somehow can create jets of charged particles when matter falling towards them, and eject them outward in opposite directions away from the disk along strong magnetic fields. These are the radio jets at nearly the speed of light. The processes by which these jets are formed require magnetic fields, whose presence causes instabilities in the accretion disk that allow material to fling upwards. Radio galaxies, quasars, and blazars are AGN with strong jets, which can travel outward into large regions of intergalactic space. In this paper, the authors include quasar state of BH in the process of merger and the feedback energy of the BH is injected into the gas.

Methods

The colliding galaxies in their merger simulations consist of a dark matter halo, a disk of gas and stars, and a central bulge. The dominant mass component is in the form of collisionless dark matter, resulting in halo density profile with a central cusp. The dark matter and stellar components are modeled as collisionless fluids, governed by the Boltzmann equation coupled to self-gravity described by the Poisson equation. The baryonic component is followed as an ideal, monoatomic, optically thin gas, subject to radiative cooling and heating processes. The cooling processes they include are bremsstrahlung and line radiation of a primordial mix of Helium and Hydrogen, while photoheating occurs due to an imposed ionizing UV background [1].

Star formation and associated feedback processes are described by a multi-phase model. A thermal instability is assumed to operate above a critical density threshold, producing a two phase medium consisting of cold clouds at pressure equilibrium. Stars form from the cold clouds, and short-lived stars supply energy to the surrounding gas when they die as supernovae. This energy heats the diffuse phase and evaporates cold clouds, thereby establishing a self-regulation cycle for star formation.

This simple model reduces to an effective equation of state (EOS) for dense gas above a critical density threshold for star formation [2]. This EOS is given by:

$$P = P(\rho) = (\gamma - 1)(\rho_h u_h + \rho_c u_c)$$

where ρh and ρc are the average densities of hot and cold phases, while uh and uc denote their corresponding thermal energies per unit mass. γ is the adiabatic index. The star formation rate is parameterized as:

$$\frac{\mathrm{d}\rho_\star}{\mathrm{d}t} = (1-\beta)\frac{\rho_c}{t_\star}$$

where the star formation timescale $t_\star$ is set proportional to the local dynamical time, $t_\star = \hat{t}_\star(\rho/\rho_{\mathrm{th}})^{-1/2}$, and β is the mass fraction of stars that explode as supernovae, and The parameter $\hat{t}_\star$ is fixed by requiring that the model reproduces the star formation rates observed in isolated spiral galaxies, while ρth is determined self-consistently in the model by requiring that the EOS is continuous at the onset of star formation. The cloud evaporation process and the cooling function of the gas then determine the temperature and the mass fractions in the two phases.

The super massive black holes at the centers of galaxies as collisionless sink particles and can accrete gas from their surroundings. They relate the accretion onto the black hole (BH) to the large-scale gas distribution using a Bondi-Hoyle-Lyttleton parameterization [2]. In this description, the accretion rate onto the black hole is given by:

$$\dot{M}_{\rm B} = \frac{4\pi\,\alpha\,G^2 M_{\rm BH}^2\,\rho}{(c_s^2 + v^2)^{3/2}}$$

Where ρ and Cs are the density and sound speed of the gas, respectively, α is a dimensionless parameter, and v is the velocity of the black hole relative to the gas. They also assume that the accretion rate is limited to the Eddington rate [4]:

$$\dot{M}_{\rm Edd} \equiv \frac{4\pi\,G M_{\rm BH}\,m_{\rm p}}{\epsilon_{\rm r}\,\sigma_{\rm T}\,c}$$

where mp is the proton mass, σT is the Thomson cross-section, and εr is the radiation efficiency.

They further assume that a small fraction (εf) of the energy released by the black hole couples to the surrounding gas. For simplicity, they assume thermal and isotropic coupling, for example, the accreting black hole heats the surrounding gas at a rate:

$$\dot{E}_{\rm feed} = \epsilon_{\rm f}\,\epsilon_{\rm r}\,\dot{M}_{\rm BH}\,c^2$$

In the final stages of their merger simulations, the cores of the galaxies coalesce to form a single stellar system. It is also leads to the formation of a central binary system of two supermassive black holes. They assume that supermassive black holes merge efficiently.

Numerically [2], they use the N-body method to solve the collisionless dynamics of stars and dark matter. The mass distribution is discrete in terms of particles. Following the equations of motion of these particles gives then an approximate solution to the Boltzmann equation. Radiative cooling and heating processes are solved on a per-particle basis assuming collision ionization equilibrium. Star formation is modeled with the multi-phase model, where highly overdense gas is pressurized by an effective equation of state. Independent collisionless star particles are spawned stochastically out of the gas, with a rate that follows (on average) the estimated local star formation rate. Similarly, accretion onto supermassive massive black holes is treated in terms of sink particles. Gas particles from the smoothing region are absorbed stochastically by the black hole in accordance with its estimated accretion rate. The feedback energy of the black hole is injected into the gas in the local smoothing region.

Result

From the graph we can find when the two galaxies come together, they collide and cause a nuclear flow of gas and trigger the accretion of BHs. The accretion of the BH consumes the surrounding gas, increase its own mass. Thus decreasing gas slows the starburst after the collision. But this activity was self-limiting. When the accretion rate reaches its upper limit, that is the Eddington rate we mentioned before, it powered a luminescent quasar state. If we compare the morphologies of the remnants in the two simulations, they differ significantly. In the model without black holes, most of the gas is still inflowing in a comparatively cool phase. With the large amount of dense cold gas, the remnant has a prolonged star formation at a almost steady rate. In contrast, the simulations with black holes exhibit a significant change in the thermodynamic state of the circumnuclear gas. The quasar energized the surrounding gas to such a level that it was blown away from the vicinity of the supermassive black hole to the outside of the galaxy. In this way, gas no long available to form new stars. We can see in the figure, there is almost no new star born a short time after the collision.

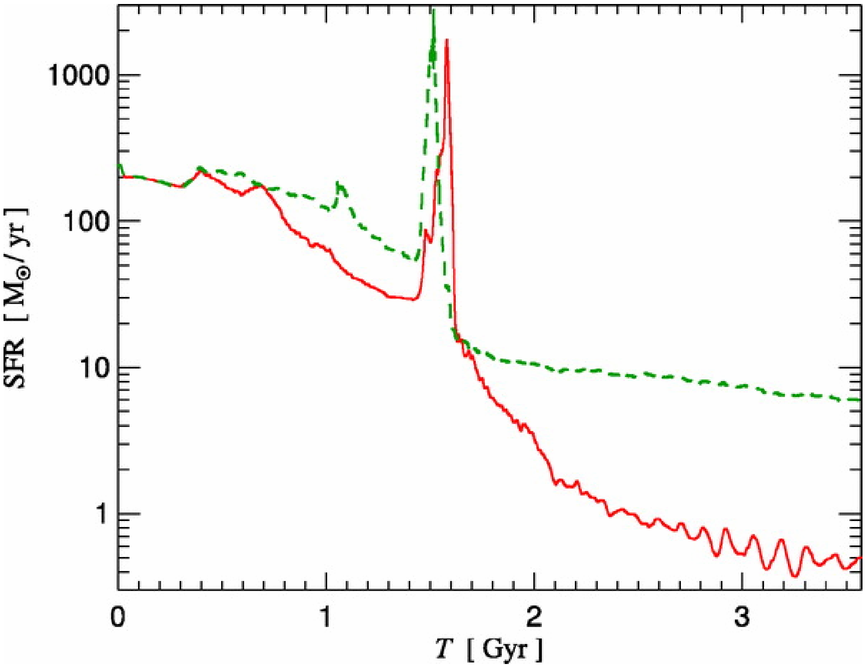

Fig5. Comparison of the star formation rate history of two colliding gas-rich spiral galaxies with (solid) and without (dashed) central supermassive BHs. The merger triggers a powerful starburst at time ~ 1.5 Gyr. The feedback energy from accretion blows away the gas surrounding the BHs, nearly terminating star formation in the remnant and stalling further growth of the BHs [1].

With respect to the temporal evolution of colors, it's found there's a brief shift to the extreme blue during the starburst (about 1.5 Gyr). Both remnants without and with BHs begin to redden. But the curve with BHs is more consistent with the fiducial color evolution when there are no stars forming at all. It means the remnants after merger becomes extreme red colors characteristic of many elliptical galaxies.

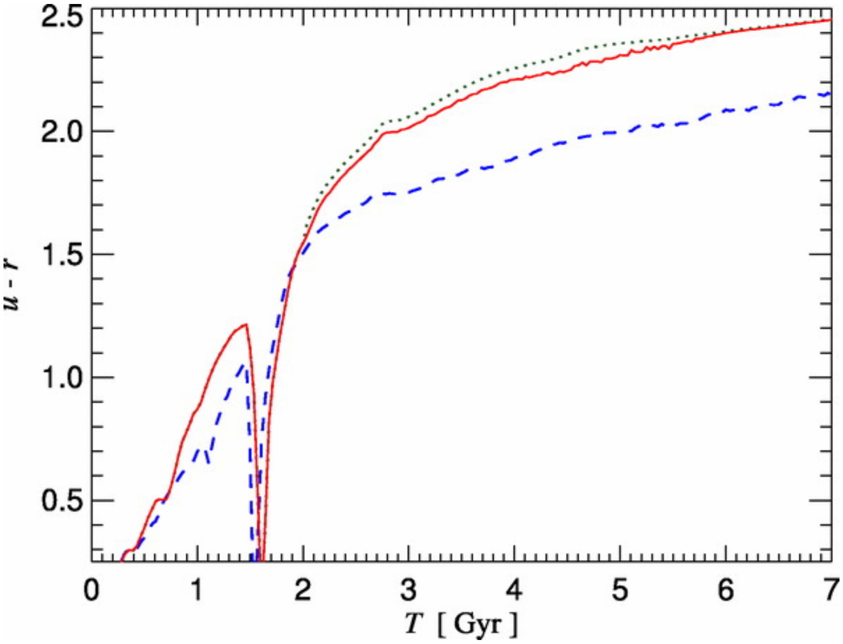

Fig6. Comparison of the color evolution of the merger of two colliding gas-rich spiral galaxies with (solid) and without (dashed) central supermassive BHs. The thin dotted line marks a fiducial color evolution when it is assumed that no stars are formed after T=2 Gyr [1].

In another paper from the same group [2], they also use the same model to explain the relation between the masses of galaxies and the BHs they hold. Without nearby gas, the galaxy's supermassive black hole could not accrete. This process inhibits further black hole growth and shuts off the quasar, just as star formation stops inside a galaxy. In a large galaxy, the black hole can reach a greater size, before it reaches the accrete rate limit and its surrounding gas is energized enough to stop falling in. With their gas quickly spent, smaller galaxies make fewer stars. With a longer-lived pool of gas, larger galaxies make more stars. These findings match the observed relation between black hole size and the total mass of stars in galaxies.

Also, the star formation and black hole activity is damped more abrupt in the more massive systems. It means the black holes in larger galaxies self-limit their growth more quickly than in those in larger galaxies. The initial growth of the black holes is faster in more massive systems, which can therefore reach the 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 a greater number of smaller galaxies and with what has been found in recent surveys.

As for the velocity dispersion, they also 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, the simulations reproduce the MBH-velocity dispersion correlation that matches the observed results very well.

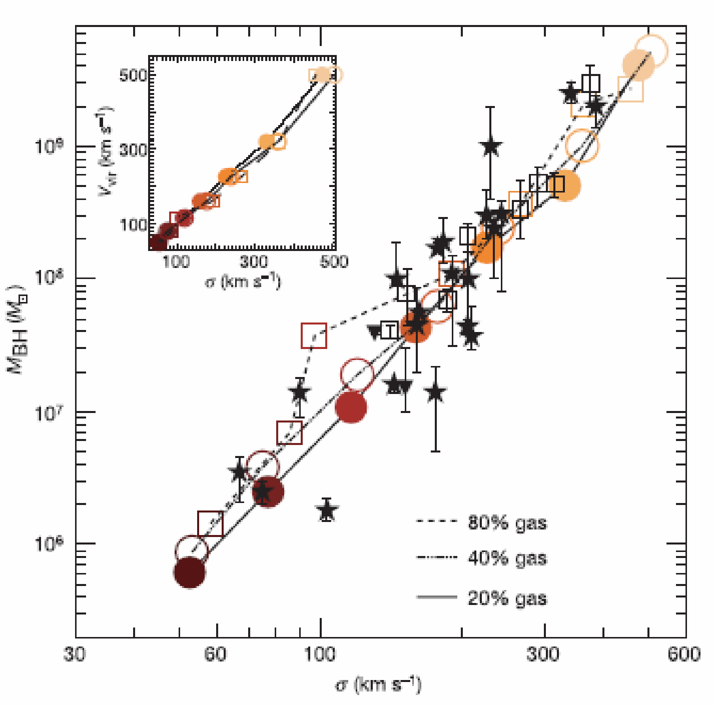

Fig7. The relation between the final black hole mass and the velocity dispersion of stars of the galaxy merger simulations compared with observational measurements. Filled circles are for the initial disk gas fraction of 20%. Open circles and open squares with the same color give results for gas fractions of 40% and 80%. 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 black filled stars, those on gas kinematics by black open squares, and those on maser kinematics by black filled triangles. The inset shows the relation between the virial velocity and velocity dispersion [2].

Discussion

The key to the model is to incorporate the BH dynamics of galaxy formation. BH growth is self-regulated. After the accretion rate of BH reaches the limit, it gives out energy and the response of the surrounding gas to the energy prevents the further growth of the BH as well as the star formation. These two papers explain the links between black hole growth, evolution, quasar activity and properties of the host galaxy population.

Moreover, a later paper about the rapid growth of black holes in massive star-forming galaxies gives support to this simulation [5]. In that paper, they report ultra-deep x-ray observations of a set of distant star-forming galaxies that are bright at submillimeter wavelength. It is found that the BHs are growing almost continuously throughout the intense star-formation phase of these galaxies. The BHs and galaxy spheroids are growing concordantly in submillimeter galaxies (SMG). It indicates there should be an abundance of available fuel and the accretion may occur sufficiently. Also, the majority of AGNs are obscure, which is also consistent with the prediction that BHs undergo efficient growth.

We know the BH growth from SMGs can be calculated by integrating the average accretion density over the SMG red shift. 80% of the observed SMGs have a red shift interval between z=1.8-3.0. In this way, it is found the growth of BH is from ~107 $M_{\odot}$ to ~108 $M_{\odot}$, before a high-accretion-rate quasar phase, the growth rate of which is from ~108 $M_{\odot}$ to ~8*108 $M_{\odot}$. So it means the rapid growth of both BHs in star-forming galaxies is the pre-quasar state.

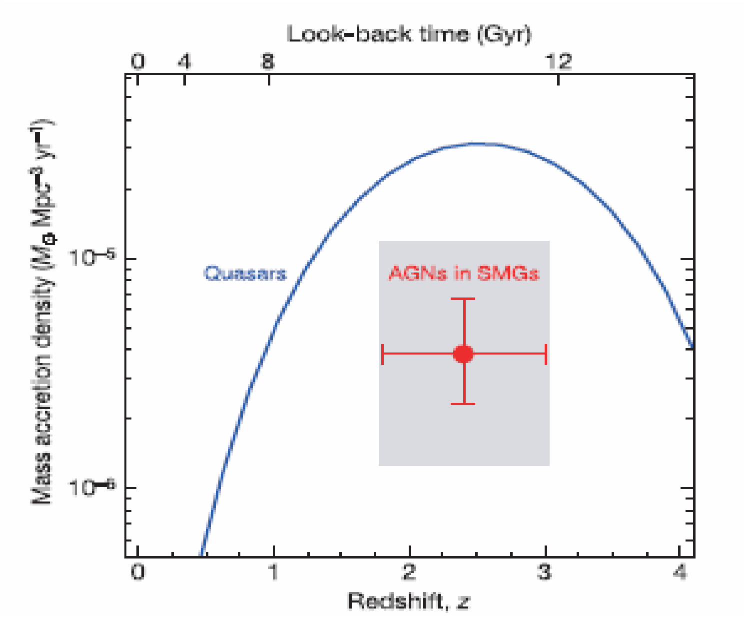

Fig.7 Cosmological black hole accretion density

This experimental result agrees with theoretical model and simulation result in the previous two papers. After the merger of two galaxies, the BH stays in the pre-quasar phase, which is exactly characterized by the starburst in the galaxies and rapid gas accretion of the BH [5].

Reference:

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