ESO ASTROPHYSICS SYMPOSIA

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GROWING BLACK HOLES: ACCRETION IN A COSMOLOGICAL CONTEXT

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Growing Black Holes: Accretion in a Cosmological Context

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Growing Black Holes: Accretion in a Cosmological Context

Proceedings
of the MPA/ESO/MPE/USM Joint Astronomy Conference
Held at Garching, Germany, 21-25 June 2004

Springer

A Physically Motivated Toy Model for the BH-Spheroid Coevolution

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Abstract. We present a summary of the results obtained with a time-dependent, one-zone toy model aimed at exploring the importance of radiative feedback on the co-evolution of massive black holes (MBHs) at the center of stellar spheroids and their stellar and gaseous components. We consider cosmological infall of gas as well as the mass and energy return for the evolving stellar population. The AGN *radiative* heating and cooling are described by assuming photoionization equilibrium of a plasma interacting with the average quasar SED. Our results nicely support a new scenario in which the AGN accretion phase characterized by a very short duty-cycle (and now common in the Universe) is due to radiative feedback. The establishment of this phase is recorded as a fossil in the Magorrian and $M_{\rm BH} - \sigma$ relations.

1 A simple scenario

In [1,2,3] we discuss the importance of radiative feedback on the co-evolution of MBHs at the center of spheroidal galaxies and that of their stellar and gaseous components. After assessing the energetics of the radiative feedback by using the results in [4], in [1,3] we demonstrate that the observed relation between the MBH mass and the stellar velocity dispersion can be the natural consequence of the MBHs growth at early times in the galaxy history and the gas depletion of the galaxy gaseous content due to star formation. In particular, in [1] we show that *radiative feedback from the central AGN is effective in halting accretion* when the gas temperature is $> 3 \times 10^4$ K, and the mass of the MBH has grown to a critical value:

$$\frac{M_{\rm BH}^{\rm crit}}{10^{11} M_{\odot}} \simeq \left(\frac{\sigma_*}{200 {\rm km/s}}\right)^4 \frac{L_{\rm Edd}}{L_{\rm BH}} \frac{M_{\rm gas}}{M_{\rm gal}} \tag{1}$$

where σ_* is the stellar velocity dispersion in the spheroid, $M_{\rm gal}$ is its mass, $L_{\rm BH}$ is the accretion luminosity. Under the assumption that $L_{\rm BH} \simeq L_{\rm Edd}$ during the phases of significant growth of the central MBH (e.g., [5,6,7]), one can derive a condition on $M_{\rm gas}/M_{\rm gal}$ in order to satisfy the $M_{\rm BH} - \sigma$ relation observed today (e.g., see [8,9,10]):

$$\frac{M_{\rm gas}}{M_{\rm gal}} \simeq 10^{-3} \frac{L_{\rm BH}}{L_{\rm Edd}}. \tag{2}$$

In [1,3], with the aid of a simple yet physically motivated toy model, we show that such low-density, hot-temperature phases for the ISM are established early in the lifetime of stellar spheroids as a natural consequence of galaxy formation.

In our simulations we always find that at the epoch of the transition between cold and hot solutions $10^{-3} < M_{\rm gas}/M_{\rm gal} < 10^{-2}$, in very good agreement with the request of Eq. (2). Remarkably, if in our toy model we adopt duty-cycles of the order of those obtained in numerical hydrodynamical simulations and also derived from observations ($\sim 10^{-3}$, see [5,6,7]), we obtain present-day MBHs that follow the observed scaling relations. Substantially longer duty-cycles with (very) low accretion efficiencies are not a viable alternative, because in this case accretion would be dominated by Bondi accretion, resulting in too massive MBHs. Gas heating due to the evolving galaxy stellar component in its various forms (stellar winds thermalization, SNII and SNIa explosions), is confirmed to be an important ingredient in galaxy evolution. Due to their shallower potential well, low mass galaxies host stronger galactic winds than more massive galaxies. In the toy model AGN heating is not sufficient "per se" to produce galaxy degassing, even though is able to maintain the ISM temperature near to the galaxy virial temperature.

Thus, a plausible (and observationally supported) scenario for the coevolution of MBHs and stellar spheroids, is the following: at early times in the galaxy life, when the protogalactic gas was dense and cold, star formation and MBH growth were approximately parallel [7]. Later on, due to the MBH growth on one side and the gas depletion (due to star formation and reduced cosmological infall) on the other, $M_{\rm BH}$ reaches the value $M_{\rm BH}^{\rm crit}$. After this, accretion is characterized by a short duty cycle, of the order of 10^{-3}, with only a marginal growth of the central BH, even in presence of the non negligible stellar mass losses of the passively evolving stellar population [11].

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Radiative Feedback from Quasars and the Growth of Supermassive Black Holes

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Abstract. We discuss the role of feedback via photoionization and Compton heating in the co-evolution of massive black holes at the center of spheroidal galaxies and their stellar and gaseous components. We first assess the energetics of the radiative feedback from a typical quasar on the ambient interstellar gas. We then demonstrate that the observed $M_{\rm BH}$–σ relation could be established at a relatively early epoch in galactic evolution when the formation of the stellar bulge was almost completed and the gas-to-stars mass ratio was reduced to a low level $\sim$0.01 such that cooling could not keep up with radiative heating. A considerable amount of gas was expelled at that time and black hole accretion proceeded at a much lower rate thereafter.

1 General Picture

Most elliptical galaxies are poor with respect to interstellar gas. Also, elliptical galaxies invariably contain central massive black holes (BHs), and there exists a tight relationship between the characteristic stellar velocity dispersion σ and the BH mass $M_{\rm BH}$ [4,2], and between $M_{\rm BH}$ and the host spheroid mass in stars, M_* [3]. Are these two facts related? Here we focus on a scenario in which the mass of the central BH grows within gas rich elliptical progenitors until star formation has reduced the gas fraction in the central regions to of order 1% of the stellar mass. Then radiative feedback during episodes when the BH luminosity approaches its Eddington limit drives much of the gas out of the galaxy, limiting both future growth of the BH and future star formation to low levels.

Many works already recognized the importance of feedback as a key ingredient of the mutual BH and galaxy evolution [4–16]. What is new about this work is the stress on one component of the problem that has had relatively little attention: the radiative output of the central BH is not conjectural – it must have occured – and the high energy component of that radiative output will have a dramatic and calculable effect in heating the gas in ellipticals.

Using the average quasar spectral output derived in [17], we show below and in more detail in [18] that the limit on the central BH produced by the above argument coincides accurately with the observed $M_{\rm BH}$–σ relation. Not only the slope, but also the small normalization factor is nicely reproduced.

The present work is complementary to [5,8] in that, while it does not attempt to model the complex flaring behavior of an accreting BH with an efficient hydrodynamical code, it does do a far more precise job of specifying the input spectrum and the detailed atomic physics required to understand the interaction between that spectrum and the ambient interstellar gas in elliptical galaxies.

2 Radiative Heating of ISM in Spheroids

Below we assess the conditions required for the central BH radiation to significantly heat the ISM over a substantial volume of the galaxy. In this section we shall *assume* that the central BH has a mass as given by the observed $M_{\rm BH}$–σ relation for local ellipticals and bulges [2]:

$$M_{\rm BH} = 1.5 \times 10^8 M_\odot \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^4 . \tag{1}$$

This assumption will be dropped in §3, where we *predict* the $M_{\rm BH}$–σ relation.

In [17] we computed for the average quasar spectrum the equilibrium temperature $T_{\rm eq}$ (at which heating due to Compton scattering and photoionization balances cooling due to line and continuum emission) of gas of cosmic chemical composition as a function of the ionization parameter $\xi \equiv L/nr^2$, where L is the BH bolometric luminosity. In the range 3×10^4–10^7 K,

$$T_{\rm eq}(\xi) \simeq 2 \times 10^2 \xi \,\text{K}, \tag{2}$$

while at $\xi \ll 10^2$ and $\xi \gg 10^5$, $T_{\rm eq} \approx 10^4$ K and 2×10^7 K, respectively. On the other hand, the galactic virial temperature is given by

$$T_{\rm vir} \simeq 3.0 \times 10^6 \,\text{K} \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^2 . \tag{3}$$

We can then find the critical density $n_{\rm crit}$ defined by

$$T_{\rm eq}(L/n_{\rm crit}r^2) = T_{\rm vir} \tag{4}$$

as a function of distance r from the BH. Gas with $n < n_{\rm crit}(r)$ will be heated above $T_{\rm vir}$ and expelled from the galaxy. We show in Fig. 1 the resulting (r, n) diagrams for a small and large BH/galaxy.

In reality, provided that $T_{\rm eq} > T_{\rm vir}$, significant heating will take place only out to a certain distance that depends on the luminosity and duration of the quasar outburst. Since the BH releases via accretion a finite total amount of energy, $\epsilon M_{\rm BH} c^2$, there is a characteristic limiting distance:

$$R_{\rm C} = \left(\frac{\sigma_{\rm T} \epsilon M_{\rm BH}}{3\pi m_{\rm e}}\right)^{1/2} = 400 \,\text{pc} \left(\frac{\epsilon}{0.1}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)^{1/2} . \tag{5}$$

Inside this radius, a low density, fully photoionized gas will be heated to the Compton temperature $T_{\rm C} \approx 2\,\text{keV}$ characteristic of the quasar spectral output.

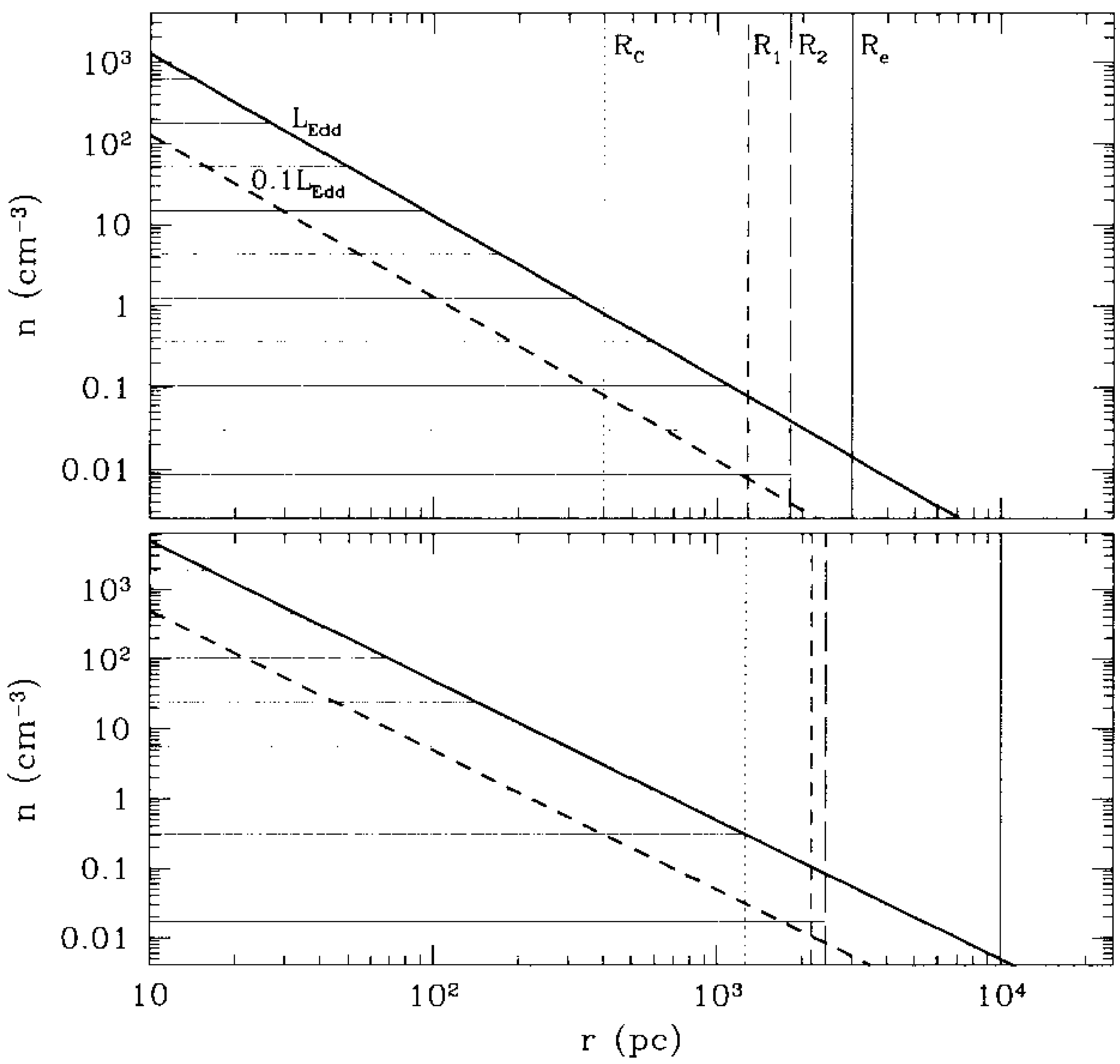

Fig. 1. The (r, n) plane for a galaxy with $\sigma = 180\,\mathrm{km\,s^{-1}}$ ($T_{\rm vir} = 2.4 \times 10^6\,\mathrm{K}$, $M_{\rm BH} = 10^8 M_\odot$, upper panel), and with $\sigma = 320\,\mathrm{km\,s^{-1}}$ ($T_{\rm vir} = 7.7 \times 10^6\,\mathrm{K}$, $M_{\rm BH} = 10^9 M_\odot$, lower panel). In the dashed area, gas can be heated above $T_{\rm vir}$ by radiation from the central BH emitting at the Eddington luminosity. The upper boundary of this area scales linearly with luminosity. Vertical boundaries are R_C, R_1, R_2 and R_e.

More relevant for the problem at hand is the distance out to which low density gas will be Compton heated to $T \gtrsim T_{\rm vir}$:

$$R_1 = R_C \left(\frac{T_C}{T_{\rm vir}}\right)^{1/2} = 1{,}300\,\mathrm{pc} \left(\frac{\epsilon}{0.1}\right)^{1/2} \frac{\sigma}{200\ \mathrm{km\ s^{-1}}}. \tag{6}$$

Yet another characteristic radius is out to which gas of critical density $n_{\rm crit}$ will be heated to $T \gtrsim T_{\rm vir}$ via photoionization and Compton scattering:

$$R_2 = R_1 [\Gamma(n_{\rm crit})/\Gamma_C]^{1/2}, \tag{7}$$

where Γ_C and Γ are the Compton and total heating rates, respectively. Depending on gas density ($0 < n < n_{\rm crit}$), the outer boundary of the "blowout region" will be located somewhere between R_1 and R_2. The size of the heating zone can be compared with the galaxy effective radius

$$R_e \sim 4{,}000\,\mathrm{pc} \left(\frac{\sigma}{200\ \mathrm{km\ s^{-1}}}\right)^2. \tag{8}$$

The different characteristic distances defined above are shown as a function of $M_{\rm BH}$ in Fig. 2. One can see that a BH of mass $< 10^7 M_\odot$ should be able to unbind the ISM out to several R_e. In the case of more massive BHs/galaxies with $M_{\rm BH} \sim 10^8$–$10^9 M_\odot$, the heating will be localized to innermost $\sim$0.3–0.5R_e.

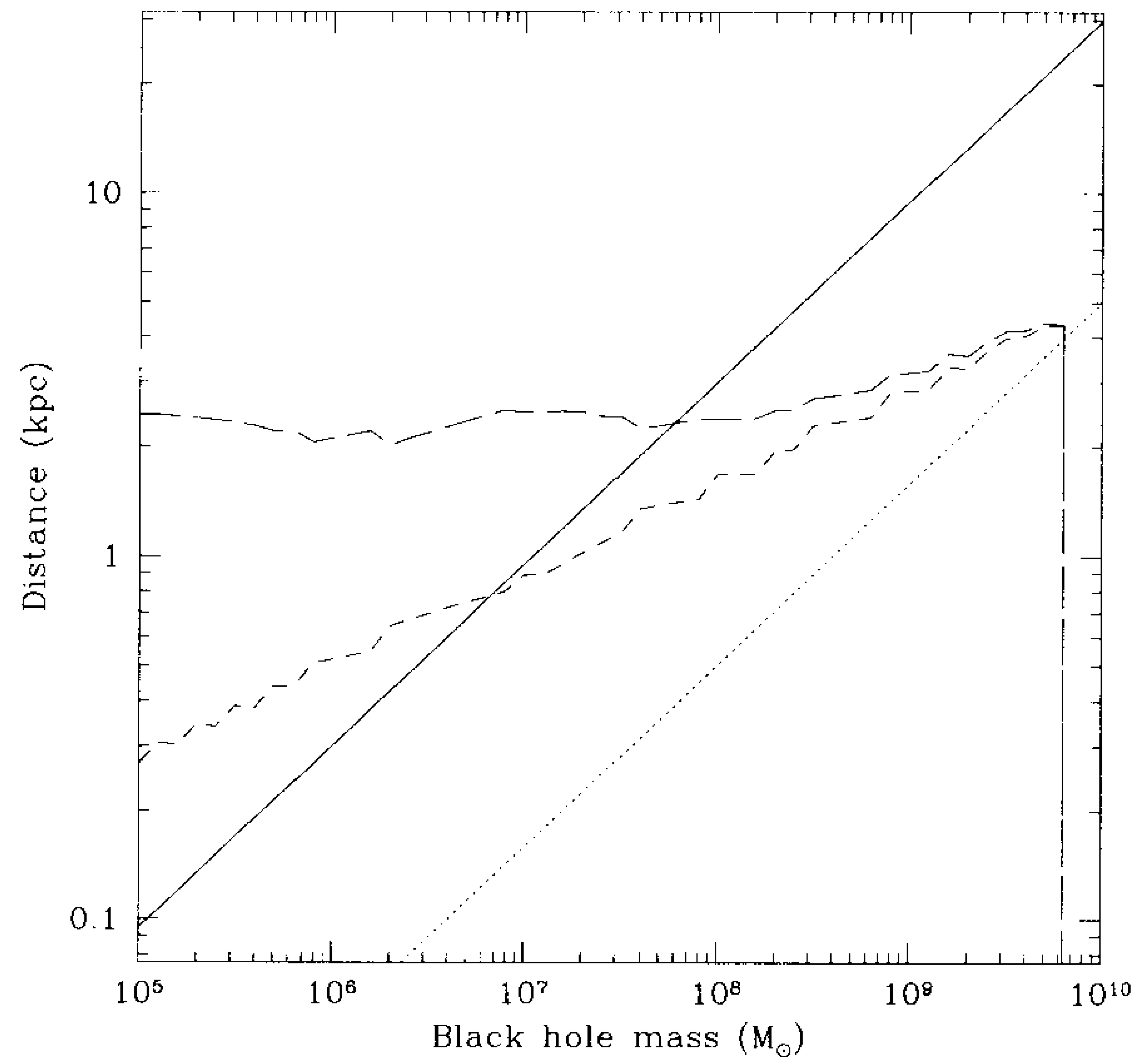

Fig. 2. Different heating radii: R_C (dotted line), R_1 (short-dashed line), and R_2 (long-dashed line), and the galactic effective radius (solid line), as a function of M_{BH}.

3 Possible Origin of the M_{BH}–σ Relation

We now consider the following general idea. Before the BH grows to a certain critical mass, $M_{BH,crit}$, its radiation will be unable to efficiently heat the ambient gas, and the BH will accrete gas efficiently. Once the BH has grown to $M_{BH,crit}$, its radiation will heat and expell a substantial amount of gas from the central regions. Feeding of the BH will then become self-regulated on a time scale of order the cooling time of the low density gas. Subsequent central activity will be characterized by a very small duty cycle (~0.001), as predicted by hydrodynamical simulations [5,8] and suggested by observations [14]. BH growth will be essentially terminated.

Suppose that the galaxy density distribution is that of a singular isothermal sphere, with the gas density following the total density:

$$\rho_{gas}(r) = \frac{M_{gas}}{M}\frac{\sigma^2}{2\pi G r^2}. \tag{9}$$

Here M_{gas} and M are the gas mass and total mass within the region affected by radiative heating. The size of the latter is uncertain but is less than a few kpc (see §2), so that M is dominated by stars rather than by dark matter.

Radiation from the central BH can heat the ambient gas up to

$$T_{eq} \approx 6.5 \times 10^3\,\mathrm{K}\frac{L}{L_{Edd}}\left(\frac{M_{gas}}{M}\right)^{-1}\frac{M_{BH}}{10^8 M_\odot}\left(\frac{200\,\mathrm{km\,s^{-1}}}{\sigma}\right)^2, \tag{10}$$

this approximate relation being valid in the range 3×10^4–10^7 K. Remarkably, T_{eq} does not depend on distance for the adopted r^{-2} density distribution. We then associate the transition from rapid BH growth to slow, feedback-limited BH growth with the critical condition

$$T_{\rm eq} = \eta_{\rm esc} T_{\rm vir}, \tag{11}$$

where $\eta_{\rm esc} \gtrsim 1$ and $T_{\rm vir}$ is given by (3). Once heated to $T_{\rm eq} \gtrsim T_{\rm vir}$, the gas will stop feeding the BH. The condition (11) will be met for

$$M_{\rm BH,crit} = 4.6 \times 10^{10} M_\odot \eta_{\rm esc} \left(\frac{\sigma}{200\,{\rm km\ s^{-1}}}\right)^4 \frac{L_{\rm Edd}}{L}\frac{M_{\rm gas}}{M}. \tag{12}$$

Therefore, for fixed values of $\eta_{\rm esc}$, $L/L_{\rm Edd}$ and $M_{\rm gas}/M$ we expect $M_{\rm BH,crit} \propto \sigma^4$, similarly to the observed $M_{\rm BH}$–σ relation. Equally important is the normalization of the $M_{\rm BH}$–σ relation. By comparing (12) with (1) we find that the observed correlation will be established if

$$M_{\rm gas}/M = 3 \times 10^{-3} \eta_{\rm esc}^{-1} L/L_{\rm Edd}. \tag{13}$$

The gas-to-stars ratio is thus required to be low and approximately constant for spheroids of different mass at a certain stage of their evolution. As for the Eddington ratio, it is reasonable to expect $L/L_{\rm Edd}$ ~0.1–1 during quasar outbursts.

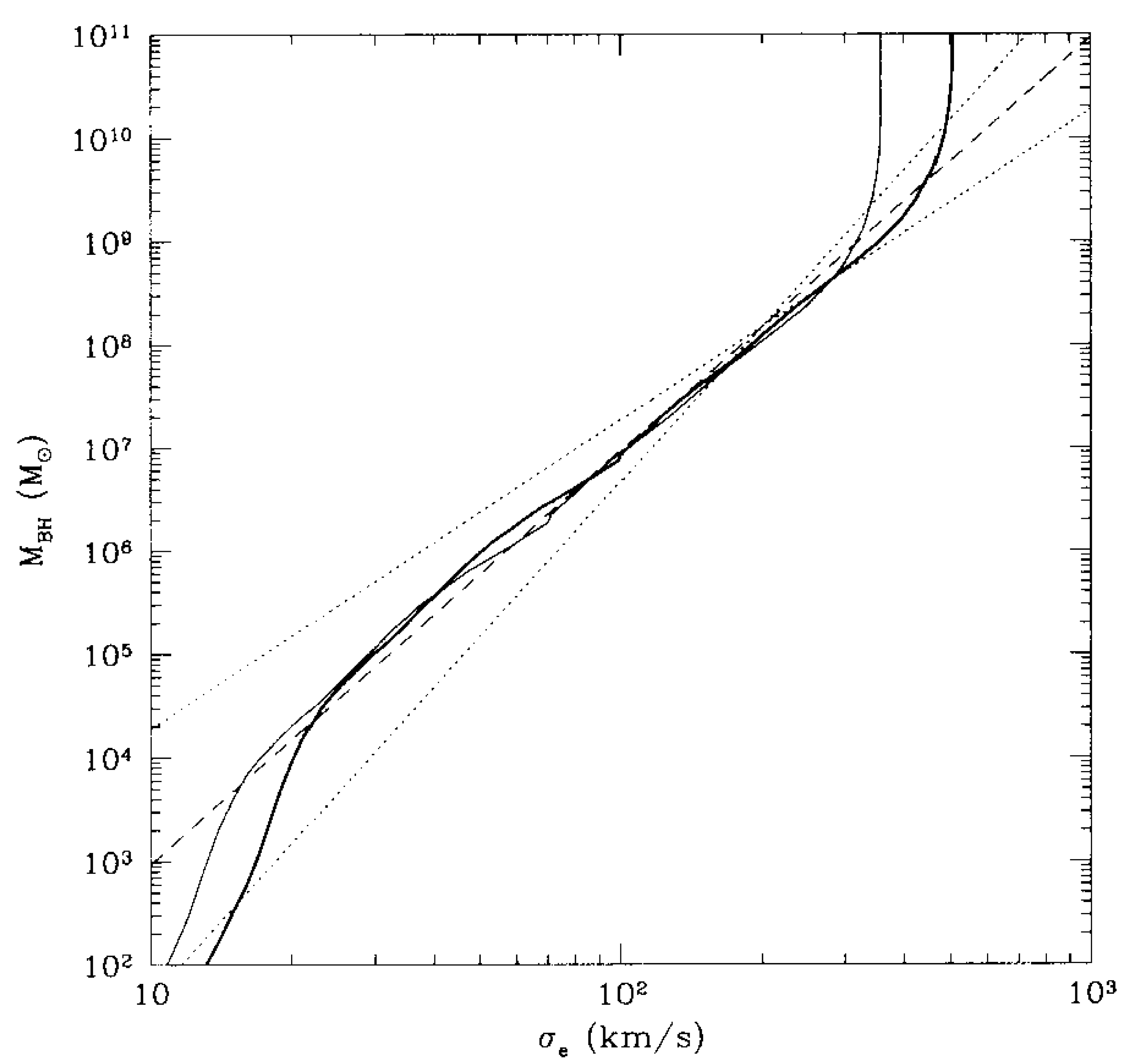

Fig. 3. Thick solid line shows the predicted $M_{\rm BH}$–σ correlation resulting from heating of the ISM by the radiation from the central BH assuming $M_{\rm gas}(R_{\rm e})/M = 0.003$ and $\eta_{\rm esc} = 1$. Thin solid line corresponds to $M_{\rm gas}(R_{\rm e})/M = 0.0015$ and $\eta_{\rm esc} = 2$. Dashed line is the observed $M_{\rm BH} \propto \sigma^4$ correlation in the range 10^6–a few $10^9 M_\odot$, extrapolated to lower and higher BH masses. Dotted lines are $M_{\rm BH} \propto \sigma^3$ and $M_{\rm BH} \propto \sigma^5$ laws.

The approximately linear $T_{\rm eq}(\xi)$ dependence [see (2)] was crucial to the above argument leading to the $M_{\rm BH,crit} \propto \sigma^4$ result. However, the $T_{\rm eq}(\xi)$ function becomes nonlinear outside the range $3 \times 10^4\,\mathrm{K} < T_{\mathrm{eq}} < 10^7\,\mathrm{K}$ [17]. In Fig. 3 we show the predicted correlation between $M_{\mathrm{BH,crit}}$ and σ for $L/L_{\mathrm{Edd}} = 1$ and $M_{\mathrm{gas}}/M = 3 \times 10^{-3}$. It can be seen that the $M_{\mathrm{BH}} \propto \sigma^4$ behavior is expected to break down for $M_{\mathrm{BH}} < 10^4 M_{\odot}$ and for $M_{\mathrm{BH}} \gtrsim$ a few $10^9 M_{\odot}$. It is perhaps interesting that the range of masses shown in Fig. 3 for which $M_{\mathrm{BH}} \propto \sigma^4$ is obtained from considerations of atomic phyisics (and the observed AGN spectra) corresponds closely with the range of masses for which this power law provides a good fit to the observations. Exploring the M_{BH}–σ relation observationally near $10^9 M_{\odot}$ would be a sensitive test of the importance of radiative feedback.

4 Detailed Modelling of the BH-Galaxy Co-evolution

In [18–20] we addressed in a more quantitative way the BH growth in the context of the parent galaxy evolution. We adopted a physically-motivated one-zone model, taking into account the mass and energy return from the evolving stellar population. This model predicts that after an initial "cold" phase dominated by gas infall, once the gas density becomes sufficiently low the gas heating dominates and the galaxy switches to a "hot" solution. The gas mass/stellar mass ratio at that epoch (~0.003) is remarkably close to the value inferred above from the argument leading to the right M_{BH}–σ relation. Other predictions of the toy model are also in satisfactory agreement with observations. The "cold" phase would probably be identified observationally with the Lyman Break and SCUBA galaxies, while the "hot" phase with normal, local ellipticals.

A proper investigation of the importance of radiative heating on the BH/galaxy co-evolution, based on hydrodynamical numerical simulations, is now in progress.

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