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Growth of Supermassive Black Holes in a Decaying Vacuum

Yuanxin Li *

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Growth of Supermassive Black Holes in a Decaying Vacuum

Yuanxin Li

Independent Researcher, China; yuanxinli31@gmail.com

Abstract

The appearance of supermassive black holes (SMBHs) within approximately the first 800 million years after the Big Bang remains subjects of intense scrutiny and debate. In this work, we investigate the growth of black holes in a decaying vacuum. This scenario may offer novel insights into the formation and growth of SMBHs.

Keywords: $\Lambda(t)$CDM model; vacuum energy; supermassive black holes

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1. Introduction

The discovery that the universe is undergoing an accelerated expansion has become one of the most profound results in modern cosmology. This acceleration is commonly attributed to a mysterious negative pressure component, known as dark energy. Many dark energy candidates for the dark energy have been put forward. However, most of the candidates suffer from the coincidence problem: it is unclear why the dark energy density happens to be of the same order of magnitude as that of matter in the current epoch. To cure such a drawback, a simple manner is to introduce a dynamical cosmological constant $\Lambda = \Lambda(t)$. For a definite model of $\Lambda(t)$CDM cosmology, we need to specify a vacuum decay law. A number of proposals of the vacuum decay law for describing a time-varying $\Lambda(t)$ have been proposed [1–5] even before the discovery of the accelerated expansion of the universe.

On the other hand, astronomical observations have revealed a number of black holes whose masses challenge the standard theoretical frameworks of formation and growth. In the early universe, supermassive black holes (SMBHs) with masses exceeding $10^9 M_\odot$ have been detected at redshifts $z \geq 7$ when the universe was less than a billion years old [6–9]. The rapid appearance of SMBHs is difficult to reconcile with conventional models. These observations suggest that our current understanding of the black hole evolution may be incomplete. In order to account for the emergence of observed SMBHs in the short time after the Big Bang, several scenarios have been proposed. In the early universe, some regions contained abundant gas and dust capable of sustaining rapid accretion. If a black hole seed formed in such an environment, the combination of dense surrounding material and its strong gravitational pull could in principle drive fast mass growth [10]. However, such high-density gas was not universally available, and feedback from the growing SMBHs could disrupt ongoing accretion [11]. A key criticism of this scenario is the challenge of sustaining the extremely high accretion rates needed to grow a 100 $M_\odot$ seed to $10^9 M_\odot$ within the limited cosmic time [12]. An alternative scenario proposes that the 100 $M_\odot$ seed rapidly accretes material to form a supermassive star, which can reach thousands of solar masses [13]. While theoretically feasible, the formation and long-term stability of such extremely massive stars remain controversial [12]. Finally, Modified Gravity (MOG) has also been proposed to address this issue, in which the gravitational interaction is effectively strengthened so that the accretion rate is consequently increased [14].

It should be noted that an important feature of the $\Lambda(t)$CDM model is that the stress-energy tensor of matter is not conserved due to coupling between matter and vacuum energy (most plausibly via gravity). It is natural to expect that a dynamical vacuum energy can also affect the growth of black holes. In this work, we will analyze the evolution of black holes in a decaying vacuum. Due to the

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direct energy exchange between the black hole and the vacuum, SMBHs with mass $10^9 M_\odot$ can be easily formed within the available time frame.

2. Time-Varying Cosmological Constant

Many purely phenomenological models have been proposed in the literature for describing a time-dependent Λ [15–19]. The evolution law for the vacuum energy can also de derived based on the dimensional argument [2] and Lagrangian formalism [20]. An alternative approach is to treat the Λ term as a running parameter in the quantum field theory in the curved spacetime [21,22].

We assume a coupling only between vacuum and matter particles. If vacuum is decaying into matter particles, the energy density of matter will dilute more slowly compared to its standard evolution, $\rho_m \propto a^{-3}$. We consider the deviation from the standard evolution characterized by a positive constant ϵ, i.e., [23,24]

$$\rho_m = \rho_{m0} a^{-3+\epsilon}, \tag{1}$$

where ρ_{m0} is the current energy density of matter. Let us consider a coupling only between the vacuum energy and matter. The energy conservation equation of matter takes an alternative form

$$\dot{\rho}_m + 3H(t)\rho_m = Q, \tag{2}$$

where $H(t) = \dot{a}/a$ is the Hubble parameter with $a(t)$ being the cosmic scale factor and $Q = -\dot{\rho}_\Lambda$ denotes the amount of vacuum energy converted into matter per unit time and per unit volume (the vacuum decay rate) with ρ_Λ being the vacuum energy density. Here, the dot denotes the derivative with respect to time t. Substituting Equation (1) into Equation (2) yields

$$\rho_\Lambda = \rho_{\Lambda 0} + \frac{\epsilon \rho_{m0}}{3-\epsilon} a^{-3+\epsilon}. \tag{3}$$

Then, one obtains the vacuum decay rate

$$Q = \epsilon H \rho_m. \tag{4}$$

The above equations for $\epsilon = 0$ reduces to the equations of the standard ΛCDM model. The value of ϵ has been observationally constrained to be less than 0.1 [16,17].

3. Growth of Black Holes in a Decaying Vacuum

We now investigate the rapid SMBH growth in the early universe and find the black hole mass as a function of time. Let us first consider the conventional accretion process. For spherical accretion onto a black hole, the Eddington limit on luminosity must be taken into account. The Eddington luminosity defines the maximum steady luminosity an accreting black hole can sustain before radiation pressure overcomes gravity. Beyond this limit, radiation drives a powerful outflow, preventing further infall of matter. Consider a fully ionized hydrogen gas (protons and electrons). We assume that radiation pressure acts on the electron via Thomson scattering. For a black hole of mass M and luminosity L, the expression for the Eddington luminosity is given by

$$L_{\rm Edd} = \frac{4\pi G M m_p}{\sigma_T}, \tag{5}$$

where $\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e}\right)^2$ denotes the Thomson scattering cross section and m_p denotes the proton mass. The luminosity generated by accretion comes from the conversion of gravitational potential energy into radiation. If the accretion process has a radiative efficiency η, then

$$L_{\rm acc} = \eta \dot{M}_{\rm acc}, \tag{6}$$

where the dot denotes the derivative with respect to time t. By using $\dot{M} = (1-\eta)\dot{M}_{\rm acc}$, the accretion rate can be written as

$$\dot{M} = \gamma f_{\rm Edd} M, \tag{7}$$

where $\gamma = \frac{1-\eta}{\eta\, t_E}$ with $t_E = \frac{\sigma_T}{4\pi G m_p} = 450\,\mathrm{Myr}$ being the Eddington time and $f_{\rm Edd} = \frac{L_{\rm acc}}{L_{\rm Edd}}$ is the Eddington fraction. The solution of Equation 7 is given by

$$M(t) = M_0 \exp(\gamma f_{\rm Edd}\, t), \tag{8}$$

where M_0 denotes the initial mass of the black hole. The value of η has now been observationally constrained to be about 0.1 [25]. Even if we adopt such a small value of η and choose $f_{\rm Edd} = 1$, an available time interval of 800 Myr is still inadequate for black holes to grow to SMBH masses ($\sim 10^9 M_\odot$) through conventional astrophysical processes. However, this is not an issue for $\Lambda(t)$CDM scenario as it allows for a direct exchange of energy between black holes and the decaying vacuum. The vacuum energy is constantly decaying into particles, the newly created particles beneath the black hole horizon lead to the growth of the black hole. For simplicity, we consider the coupling of vacuum to a Schwarzschild black hole. Since the Schwarzschild black hole is characterized solely by its mass, the black hole gains additional mass at the rate

$$\dot{M} = \kappa H M, \tag{9}$$

where the dimensionless parameter κ measures the efficiency with which vacuum energy is converted into black hole mass. We now obtain the modified accretion rate:

$$\dot{M} = (\gamma f_{\rm Edd} + \kappa H) M. \tag{10}$$

Since we are considering the formation of SMBHs at redshifts $z \geq 7$, i.e. the matter-dominated era, we have

$$H = \frac{2}{(3-\epsilon)t}. \tag{11}$$

Substituting Equation (11) into Equation (10), one obtains

$$\dot{M} = \gamma f_{\rm Edd} M + \frac{\kappa M}{t}, \tag{12}$$

where the numerical factor has been absorbed into κ. The second term M/t decays as t^{-1}, so for large t this term becomes negligible. For small t this term may dominate, allowing the black hole to accumulate mass rapidly. In Figure 1, we have plotted the black hole mass as a function of time for $\eta = 0.3$, $f_{\rm Edd} = 1$, $M_0 = 100 M_\odot$, and different values of κ. For values bigger than $\kappa = 2.78$, SMBHs with mass $10^9 M_\odot$ can be easily formed within 800 Myrs.

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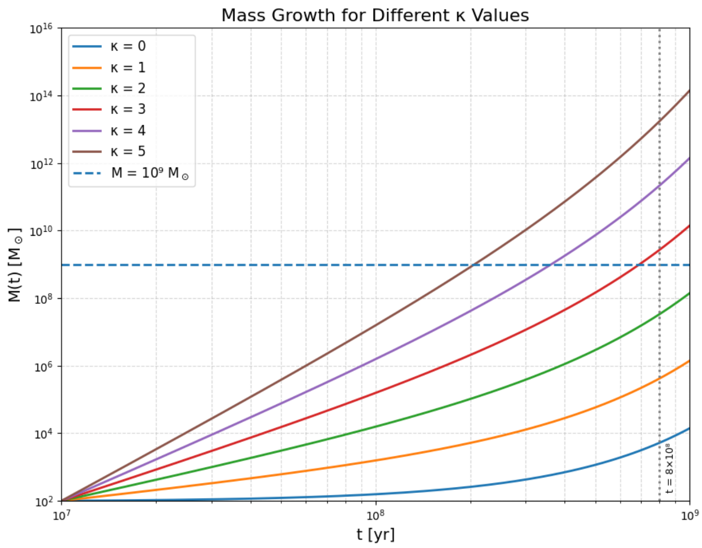

Figure 1. Plot of $M(t)$ vs t for $\eta = 0.3$, $f_{\rm Edd} = 1$, $M_0 = 100 M_\odot$, and various values of κ.

4. Conclusions

In this work, we investigate the evolution of black holes in a decaying vacuum cosmology. In this scenario, SMBHs with mass $10^9 M_\odot$ can be easily formed within 800 Myrs. Although the M/t term in Equation (12) can be neglected for large t, our results indicate a redshift dependence of the black hole mass. Thus, it would be interesting to explore a possible connection to a recent study by Farrah et al. [26]. The study finds that the black holes increase in mass over 6–9 Gyr by a factor of 8–20× relative to the stellar mass, with the growth factor increasing at higher redshifts. Such preferential growth is difficult to reconcile with standard galaxy assembly because SMBH growth via accretion in red-sequence ellipticals is insignificant and galaxy–galaxy mergers do not increase SMBH mass relative to stellar mass. On the other hand, the conventional ΛCDM cosmology is receiving a lot of setbacks due to recent results [27]. The proposal of the $\Lambda(t)$CDM is partially supported by recent results from the Dark Energy Spectroscopic Instrument (DESI) collaboration. When combined with CMB data, Type Ia supernovae, and weak lensing, the preference for a time-varying dark energy rises to approximately 3σ. This is widely interpreted as tentative evidence that dark energy density may be slowly decreasing with time. The theoretical analysis in this work could offer novel insights into the emergence of SMBHs in the early universe.

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