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Growing Black Holes in a Decaying Vacuum

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Abstract

In cosmological models with a time-varying cosmological constant, the stress-energy tensor of matter is not conserved due to coupling between matter and vacuum energy. This non-conservation leads to the possibility of an energy transfer from the vacuum energy to ordinary matter. It is therefore natural to expect that a dynamical vacuum energy can also affect the evolution of black holes. In this work, we investigate the growth of black holes in such a background of a decaying vacuum. Allowing a direct exchange of energy between black holes and the decaying vacuum enables supermassive black holes (SMBHs) to form easily in the early universe.

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

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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 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].

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

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

The above equations for $\epsilon = 0$ reduces to the equations of the standard ΛCDM model.

3. Growing 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

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

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 an efficiency η, then

$$L_{\rm acc} = \eta \dot{M}_{\rm acc}. \tag{5}$$

By using $\dot{M} = (1-\eta)\dot{M}_{\rm acc}$, the accretion rate can be written as

$$\dot{M} = \gamma f_{\rm Edd} M, \tag{6}$$

where $\gamma = \frac{1-\eta}{\eta\, t_E}$ with $t_E = \frac{\sigma_T}{4\pi G m_p} = 450\,\text{Myr}$ being the Eddington time and $f_{\text{Edd}} = \frac{L_{\text{acc}}}{L_{\text{Edd}}}$ is the Eddington fraction. The solution of Equation 6 is given by

$$M(t) = M_0 \exp(\gamma f_{\text{Edd}}\, t), \tag{7}$$

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 $f_{\text{Edd}} = 1$, 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 model as it allows for a direct exchange of energy between black holes and the decaying vacuum. Using Equations 1, 2 and 3 and assuming the spatial flatness, the Friedamnn equation of the $\Lambda(t)$CDM model reads

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_\Lambda) = H_0^2\left(\frac{3\Omega_{m0}}{3-\epsilon}a^{-3+\epsilon} + \tilde{\Omega}_{\Lambda 0}\right), \tag{8}$$

where $\Omega_{m0} = \rho_{m0}/\rho_{c0}$, $\tilde{\Omega}_{\Lambda 0} = \tilde{\rho}_{\Lambda 0}/\rho_{c0}$ and $\rho_{c0} = 3H_0^2/8\pi G$ is the current critical energy density. Since we are considering the formation of SMBHs at redshifts $z \geq 7$, i.e. the matter-dominated era, we have

$$H = \frac{2}{(3-\epsilon)t} \tag{9}$$

and the scale factor evolves as

$$a(t) = \left[\frac{3-\epsilon}{2}\left(\frac{8\pi G \rho_{m0}}{3}\right)^{1/2} t\right]^{\frac{2}{3-\epsilon}}. \tag{10}$$

Substituting Equations (1), (9) and (10) into Equation (2), one obtains the vacuum decay rate

$$Q = \epsilon H \rho_m = \frac{3\epsilon}{\pi(3-\epsilon)^3 G t^3}. \tag{11}$$

Hence, the black hole gains additional mass at the rate

$$\dot{M} = \frac{4\pi}{3}(2GM)^3 Q = \frac{32\epsilon G^2 M^3}{(3-\epsilon)^3 t^3}. \tag{12}$$

We now obtain the modified accretion rate:

$$\dot{M} = \gamma f_{\text{Edd}} M + \kappa M^3 t^{-3}, \tag{13}$$

where $\kappa = 32\epsilon G^2/(3-\epsilon)^3$ measure the efficiency with which vacuum energy is converted into black hole mass. The second term M^3/t^3 decays as t^{-3}, so for large t this term becomes negligible. For small t this term may dominate, allowing the black hole to accumulate mass rapidly. The solution of Equation (13) does not have a closed-form expression. Numerical analysis reveals that for $\eta = 0.3$ and $f_{\text{Edd}} = 1$, the minimum value of κ necessary for M to grow from $100 M_\odot$ to $10^9 M_\odot$ within 800 Myrs is about 10^{-9}.

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. However, the present work has several limitations. We consider solely the coupling between vacuum energy and matter particles. Similarly, one can also consider the coupling of vacuum energy to radiation and to dark matter. Nevertheless, in the absence of a fundamental underlying theory, we do not yet know the exact form of the coupling between vacuum energy and black holes. Therefore, the parameter κ in Equation (13) can only be regarded as a phenomenological quantity that characterizes the efficiency

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of vacuum energy conversion into black hole mass. The drawback is that this prevents us from comparing the value of κ in our model with the value given by observational constraints of the $\Lambda(t)$CDM universe. Furthermore, the parameter κ may take different values for conventional black holes with a singularity and nonsingular black holes with a regular de Sitter core [26,27]. Here, we further assume a homogeneous and isotropic decaying vacuum background for black holes. Although this is a very ideal case, it still captures the main features of the evolution of black holes in a coupled decaying vacuum. Further exploration of the coupling between black holes and vacuum energy would be of interest. Notably, our theory is local, in contrast to the non-local cosmological coupling proposed in Ref. [28,29]. It is worth noting that we consider a first-generation stellar collapse black hole with mass $100M_\odot$ as the seed. It is also interesting to investigate the evolution of primordial black holes in a decaying vacuum. On the other hand, the conventional ΛCDM cosmology is receiving a lot of setbacks due to recent results [30]. 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. The mass of black holes may increase as a result of its gravitational coupling to the decaying dark energy. Finally, it would be interesting to explore a possible connection to the results of Ref. [31–33], despite differing underlying mechanisms.

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