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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 evolution of black holes in such a background with a decaying vacuum. The black hole accretion rate is estimated for a simple model.

Keywords: $\Lambda(t)$CDM model; vacuum energy; black hole evolution

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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 have been detected at redshifts $z \geq 6$ when the universe was less than a billion years old [6–8]. The rapid appearance is difficult to reconcile with conventional models. These observations suggest that our current understanding of black hole evolution may be incomplete.

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 therefore natural to expect that a black hole may interact with vacuum energy in a way that enables an exchange of energy between them. A dynamical vacuum energy can also affect the evolution of black holes. In this work, we will analyze the evolution of black holes in a decaying vacuum for a simple model.

2. Growing Black Holes in a Decaying Vacuum

Many purely phenomenological models have been proposed in the literature for describing a time-dependent Λ [2,9–13]. We consider here the Λ term as a running parameter in the quantum field theory in the curved spacetime. Following [14,15], there should exist a corresponding renormalization group equation of this form

$$16\pi^2 \frac{d\rho_\Lambda}{d\ln\mu} = \sum_{n=1}^{\infty} A_n \mu^{2n}, \qquad (1)$$

where ρ_Λ is the vacuum energy density and μ is the renormalization scale. By choosing $\mu = H(t)$, all terms with $n > 1$ can be neglected due to the expansion involving powers of the small quantities.

Here, $H(t) = \dot{a}/a$ is the Hubble parameter with $a(t)$ being the cosmic scale factor. The $n = 0$ term can also be discarded because it leads to an extremely fast evolution. Thus, Equation 1 reduces to

$$\frac{d\rho_\Lambda}{d\ln H} = \frac{\kappa}{16\pi^2} M_P^2 H^2 \tag{2}$$

with

$$\kappa = \frac{s M_U^2}{M_P^2}, \tag{3}$$

where M_U denotes the GUT mass scale, M_P denotes the Planck mass and $s = \pm 1$ are associated with bosons and fermions respectively. The solution of Equation 2 takes the following form

$$\rho_\Lambda = c_0 + \epsilon M_P^2 H^2, \tag{4}$$

where c_0 is an integration constant and we have introduced a dimensionless parameter $\epsilon = \kappa/32\pi^2$. The matter will dilute in a smaller rate compared with the standard relation $\rho \propto a^{-3}$ because the vacuum energy is constantly decaying into the matter. Since new matter is created from the decaying vacuum, the matter density can be written as [16,17]

$$\rho = \rho_0 a^{-3+\epsilon}. \tag{5}$$

We now analyze the evolution of black holes in a background of decaying vacuum. We consider an isotropic and low-density pressureless particle production background around an isolated black hole with mass M. We assume that particles are collisionless and at rest at infinity. Therefore, every particle follows a radial free-fall geodesic independently. In the case of steady and spherically symmetric flows, the following relation holds

$$4\pi r^2 \rho u^r = \dot{M} = \text{constant}. \tag{6}$$

For particles released from rest at infinity, the radial component of velocity is

$$u^r = \sqrt{\frac{2M}{r}}. \tag{7}$$

Thus the accretion rate is given by

$$\dot{M} = 4\pi r^2 \rho(r) \sqrt{\frac{2M}{r}}. \tag{8}$$

Substituting Equation (5) into Equation (8) yields

$$\dot{M} = 16\pi \rho_0 M^2 a^{-3+\epsilon}. \tag{9}$$

The accretion rate can also be written as a function of the redshift:

$$\dot{M} = 16\pi \rho_0 M^2 (1+z)^{\epsilon-3}. \tag{10}$$

Even in the absence of local structures such as galaxies, halos, or accretion disks, a black hole will still grow, and the source of this growth is the vacuum energy.

3. Conclusions

In this work, we investigate the evolution of black holes in a decaying vacuum cosmology. Although this is a very ideal case, it still captures the main features of the evolution of black holes in a coupled decaying vacuum. Here, we adopt quadratic evolution law ($\rho_\Lambda \propto H^2$) for the vacuum energy, following the conventional choice made in numerous prior studies. In the absence of a fundamental underlying theory, we consider a homogeneous and isotropic 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. [18,19]. On the other hand, the conventional ΛCDM cosmology is receiving a lot of setbacks due to recent results [20]. 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 shed light on the mass origin of the supermassive black holes in the early universe. The mass of the black hole may increase as a result of its gravitational coupling to the decaying dark energy. Furthermore, it would be interesting to explore a possible connection to the results of Ref. [21–23], despite differing underlying mechanisms.

References

1. Özer, M.; Taha, M. A possible solution to the main cosmological problems. *Physics Letters B* **1986**, *171*, 363–365.
2. Carvalho, J.; Lima, J.; Waga, I. Cosmological consequences of a time-dependent Λ term. *Physical Review D* **1992**, *46*, 2404.
3. Lima, J.; Maia, J. Deflationary cosmology with decaying vacuum energy density. *Physical Review D* **1994**, *49*, 5597.
4. Lima, J.; Trodden, M. Decaying vacuum energy and deflationary cosmology in open and closed universes. *Physical Review D* **1996**, *53*, 4280.
5. Freese, K.; Adams, F.C.; Frieman, J.A.; Mottola, E. Cosmology with decaying vacuum energy. *Nuclear Physics B* **1987**, *287*, 797–814.
6. Jeon, J.; Liu, B.; Taylor, A.J.; Kokorev, V.; Chisholm, J.; Kocevski, D.D.; Finkelstein, S.L.; Bromm, V. The Emerging Black Hole Mass Function in the High-Redshift Universe. *arXiv preprint arXiv:2503.14703* **2025**.
7. Kroupa, P.; Subr, L.; Jerabkova, T.; Wang, L. Very high redshift quasars and the rapid emergence of supermassive black holes. *Monthly Notices of the Royal Astronomical Society* **2020**, *498*, 5652–5683.
8. Bromley, J.M.; Somerville, R.; Fabian, A. High-redshift quasars and the supermassive black hole mass budget: constraints on quasar formation models. *Monthly Notices of the Royal Astronomical Society* **2004**, *350*, 456–472.
9. Elizalde, E.; Nojiri, S.; Odintsov, S.D.; Wang, P. Dark energy: Vacuum fluctuations, the effective phantom phase, and holography. *Physical Review D—Particles, Fields, Gravitation, and Cosmology* **2005**, *71*, 103504.
10. Wang, P.; Meng, X.H. Can vacuum decay in our universe? *Classical and Quantum Gravity* **2004**, *22*, 283.
11. Costa, F.; Alcaniz, J.; Maia, J. Coupled quintessence and vacuum decay. *Physical Review D—Particles, Fields, Gravitation, and Cosmology* **2008**, *77*, 083516.
12. Cai, R.G.; Wang, A. Cosmology with interaction between phantom dark energy and dark matter and thecoincidence problem. *Journal of Cosmology and Astroparticle Physics* **2005**, *2005*, 002.
13. Overduin, J.; Cooperstock, F. Evolution of the scale factor with a variable cosmological term. *Physical Review D* **1998**, *58*, 043506.
14. Shapiro, I.L.; Sola, J. On the possible running of the cosmological "constant". *Physics Letters B* **2009**, *682*, 105–113.
15. Shapiro, I.L.; Sola, J. Cosmological constant problems and the renormalization group. *Journal of Physics A: Mathematical and Theoretical* **2007**, *40*, 6583.
16. Alcaniz, J.S.; Lima, J.A.S.d. Interpreting cosmological vacuum decay. *Physical Review D—Particles, Fields, Gravitation, and Cosmology* **2005**, *72*, 063516.
17. Alcaniz, J.S. Dark energy and some alternatives: a brief overview. *Brazilian Journal of Physics* **2006**, *36*, 1109–1117.
18. Farrah, D.; Croker, K.S.; Zevin, M.; Tarlé, G.; Faraoni, V.; Petty, S.; Afonso, J.; Fernandez, N.; Nishimura, K.A.; Pearson, C.; et al. Observational evidence for cosmological coupling of black holes and its implications for an astrophysical source of dark energy. *The Astrophysical Journal Letters* **2023**, *944*, L31.
19. Croker, K.S.; Zevin, M.; Farrah, D.; Nishimura, K.A.; Tarle, G. Cosmologically coupled compact objects: A single-parameter model for LIGO–Virgo mass and redshift distributions. *The Astrophysical Journal Letters* **2021**, *921*, L22.
20. Karim, M.A.; Aguilar, J.; Ahlen, S.; Alam, S.; Allen, L.; Prieto, C.A.; Alves, O.; Anand, A.; Andrade, U.; Armengaud, E.; et al. DESI DR2 results. II. Measurements of baryon acoustic oscillations and cosmological constraints. *Physical Review D* **2025**, *112*, 083515.

21. Cadoni, M.; Sanna, A.; Pitzalis, M.; Banerjee, B.; Murgia, R.; Hazra, N.; Branchesi, M. Cosmological coupling of nonsingular black holes. *Journal of Cosmology and Astroparticle Physics* **2023**, *2023*, 007.
22. Cadoni, M.; Murgia, R.; Pitzalis, M.; Sanna, A.P. Quasi-local masses and cosmological coupling of black holes and mimickers. *Journal of Cosmology and Astroparticle Physics* **2024**, *2024*, 026.
23. Cadoni, M.; Pitzalis, M.; Rodrigues, D.C.; Sanna, A.P. Cosmological coupling of local gravitational systems. *Journal of Cosmology and Astroparticle Physics* **2024**, *2024*, 045.