Interacting Dark Energy in Hořava-Lifshitz Cosmology

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Abstract

In the usual Hořava-Lifshitz cosmological models, the scalar field is responsible for dark matter. Using an additional scalar field, Saridakis [1] has formulated Hořava-Lifshitz cosmology with an effective dark energy sector. In the paper [1] the scalar fields do not interact with each other, here we extend this work to the interacting case, where matter scalar field $\phi$ interact with dark energy scalar field $\sigma$. We will show that in contrast with [1], where $\sigma$-field is absent, we can obtain $w_{\text{d}}^{\text{eff}} < -1$, that is we result to an effective dark energy presenting phantom behaviour. This behaviour is pure effect of the interaction.
1 Introduction

Recent observations from type Ia supernovae [2] associated with Large Scale Structure [3] and Cosmic Microwave Background anisotropies [4] have provided main evidence for the cosmic acceleration. The combined analysis of cosmological observations suggests that the universe consists of about 70% dark energy, 30% dust matter (cold dark matter plus baryons), and negligible radiation. Although the nature and origin of dark energy are unknown, we still can propose some candidates to describe it, namely since we do not know where this dark energy comes from, and how to compute it from the first principles, we search for phenomenological models. The astronomical observations will then select one of these models. The most obvious theoretical candidate of dark energy is the cosmological constant $\lambda$ (or vacuum energy) [5, 6] which has the equation of state parameter $w = -1$. However, as it is well known, there are two difficulties that arise from the cosmological constant scenario, namely the two famous cosmological constant problems — the “fine-tuning” problem and the “cosmic coincidence” problem [7]. An alternative proposal for dark energy is the dynamical dark energy scenario. This dynamical proposal is often realized by some scalar field mechanism which suggests that the specific energy form with negative pressure is provided by a scalar field evolving down a proper potential. So far, a plethora of scalar-field dark energy models have been studied, including quintessence [8], K-essence [9], tachyon [10], phantom [11] and quintom [12], and so forth. An alternative way of explaining the observed acceleration of the late universe is to modify the gravitational theory and in the simplest case replace $R$ with $f(R)$ in the action which is well known as $f(R)$ gravity. Here $f(R)$ is an arbitrary function of scalar curvature (for recent reviews see [13, 14]). However, most of $f(R)$-gravity models do not manage to pass the observational and theoretical tests (solar system, neutron stars and binary pulsar constraints), giving also rise to an unusual matter dominated epoch and leading to significant fine-tunings [15].

Recently Hořava proposed a renormalizable gravity theory with higher spatial derivatives in four dimensions which reduces to Einstein gravity with a non-vanishing cosmological constant in IR but with improved UV behaviors [16, 17, 18]. It is similar to a scalar field theory of Lifshitz [19] in which the time dimension has weight 3 if a space dimension has weight 1, thus this theory is called Hořava-Lifshitz gravity. This theory is not invariant under the full diffeomorphism group of general relativity, but rather under a subgroup of it, manifest in the standard ADM splitting. The local symmetry usually puts constraint on the system and only the physical modes appear as propagating modes. However, since Hořava theory has not full diffeomorphism invariance, one can not obtain full constraint to restrict the possible modes to the physical modes. Various aspects of this theory have been investigated [20]-[48]. Motivated by these, in the present work we are interested in investigating interacting dark energy model in the framework of Hořava-Lifshitz cosmology.

2 Hořava-Lifshitz cosmology with interacting dark energy

In this section we obtain the equation of state for the dark energy when there is an interaction between energy density $\rho_d$ and a dark matter $\rho_m$. The dynamical variables of
Horava-Lifshitz gravity are the lapse and shift functions, \( N \) and \( N_i \) respectively, and the spatial metric \( g_{ij} \). Therefore we can write the metric as:

\[
\text{d}s^2 = -N^2 \text{d}t^2 + g_{ij}(\text{d}x^i + N^j \text{d}t)(\text{d}x^j + N^j \text{d}t),
\]

(1)

The scaling transformation of the coordinates reads \( (z=3) \):

\[
t \to t^3 t \quad \text{and} \quad x^i \to lx^i.
\]

(2)

Decomposing the gravitational action into a kinetic and a potential part as

\[
S_g = \int \text{d}t \text{d}^3x \sqrt{g} N (\mathcal{L}_K + \mathcal{L}_V)
\]

(3)

and under the assumption of detailed balance \[18\], which apart form reducing the possible terms in the Lagrangian it allows for a quantum inheritance principle \[16\], the full action of Horava-Lifshitz gravity is given by

\[
S_g = \int \text{d}t \text{d}^3x \sqrt{g} N \left\{ \frac{2}{\kappa^2} (K_{ij} K^{ij} - \lambda K^2) - \frac{\kappa^2}{2w^4} C_{ij} C^{ij} + \frac{\kappa^2 \mu}{2w^2} \sqrt{g} R_{il} \nabla_j R^i_k - \frac{\kappa^2 \mu^2}{8} R_{ij} R^{ij} + \frac{\kappa^2 \mu^2}{8(1 - 3\lambda)} \left[ \frac{1 - 4\lambda}{4} R^2 + \Lambda R - 3\Lambda^2 \right] \right\},
\]

(4)

where

\[
K_{ij} = \frac{1}{2N} (g_{ij} - \nabla_i N_j - \nabla_j N_i),
\]

(5)

is the extrinsic curvature and

\[
C_{ij} = \frac{\epsilon^{ijk}}{\sqrt{g}} \nabla_k (R^l_i - \frac{1}{4} R \delta^l_i)
\]

(6)

the Cotton tensor, and the covariant derivatives are defined with respect to the spatial metric \( g_{ij} \). \( \epsilon^{ijk} \) is the totally antisymmetric unit tensor, \( \lambda \) is a dimensionless constant and \( \Lambda \) is a negative constant which is related to the cosmological constant in the IR limit. Finally, the variables \( \kappa \), \( w \) and \( \mu \) are constants with mass dimensions \(-1, 0\) and \(1\), respectively.

In order to add the matter component (including both dark and baryonic matter) in the theory one can follow two equivalent approaches. The first is to introduce a scalar field \[20, 21\] and thus attribute to dark matter a dynamical behavior, with its energy density \( \rho_m \) and pressure \( p_m \) defined through the field kinetic and potential energy. In the second approach one adds a cosmological stress-energy tensor to the gravity field equations by demanding to recover the usual general relativity formulation in the low-energy limit \[35, 47\]. Similar to \[47\], where the author add a matter sector to the Hořava-Lifshitz action, we would like to add matter and dark energy sectors with the following properties: It must respect foliated diffeomorphism invariance, obey the principle of detailed balance and be nontrivial at the \( z = 3 \) critical point and Lorentz invariant in the infrared. So inserting a scalar field in the construction and imposing the corresponding symmetries
consistently, one results to the following action for the matter field \( \phi \) which has interaction with dark energy field \( \sigma \) (see \([20, 21]\) for non-interacting case):

\[
S_m = \int dt d^3 x \sqrt{g} N \left[ \frac{3\lambda - 1}{4} \frac{\dot{\phi}^2}{\dot{N}^2} + m_1 m_2 \phi \nabla^2 \phi - \frac{1}{2} m_2^2 \phi \nabla^4 \phi + \frac{1}{2} m_3^2 \phi \nabla^6 \phi - V_i(\phi, \sigma) \right],
\]

where \( V(\phi, \sigma) \) acts as a total potential term \([49]\):

\[
V_i(\phi, \sigma) = V(\phi) + B(\phi, \sigma),
\]

the interacting potential \( B(\phi, \sigma) \) is a function of both fields, and \( m_i \) are constants.

In usual Hořava-Lifshitz cosmological models, the scalar field is responsible for dark matter. However, in principle one could include additional scalars in the theory. In this work we will allow for one more, in which we attribute the dark energy sector \([1]\). Thus, we add a second scalar \( \sigma \), with action

\[
S_d = \int dt d^3 x \sqrt{g} N \left[ \frac{3\lambda - 1}{4} \frac{\dot{\sigma}^2}{\dot{N}^2} + h_1 h_2 \sigma \nabla^2 \sigma - \frac{1}{2} h_2^2 \sigma \nabla^4 \sigma + \frac{1}{2} h_3^2 \sigma \nabla^6 \sigma - V_i(\phi, \sigma) \right],
\]

where \( h_i \) are constants. Now, in order to focus on cosmological frameworks, we impose an flat FRW metric,

\[
N = 1, \quad g_{ij} = a^2(t) \gamma_{ij}, \quad N^i = 0.
\]

with

\[
\gamma_{ij} dx^i dx^j = dr^2 + r^2 d\Omega_2^2.
\]

We assume that the scalar fields are homogenous, i.e \( \phi \equiv \phi(t) \) and \( \sigma \equiv \sigma(t) \). By varying \( N \) and \( g_{ij} \), we obtain the equations of motion:

\[
H^2 = \frac{\kappa^2}{6(3\lambda - 1)} \left[ \frac{3\lambda - 1}{4} (\dot{\phi}^2 + \dot{\sigma}^2) + 2 V_i(\phi, \sigma) - \frac{3\kappa^2 \mu^2 \Lambda^2}{8(3\lambda - 1)} \right]
\]

\[
\dot{H} + \frac{3}{2} H^2 = - \frac{\kappa^2}{4(3\lambda - 1)} \left[ \frac{3\lambda - 1}{4} (\dot{\phi}^2 + \dot{\sigma}^2) - 2 V_i(\phi, \sigma) + \frac{3\kappa^2 \mu^2 \Lambda^2}{8(3\lambda - 1)} \right],
\]

where we have defined the Hubble parameter as \( H \equiv \frac{\dot{a}}{a} \). Finally, the equations of motion for the scalar fields read:

\[
\ddot{\phi} + 3H \dot{\phi} + \frac{2}{3\lambda - 1} (\frac{\partial V(\phi)}{\partial \phi} + \frac{\partial B(\phi, \sigma)}{\partial \phi}) = 0
\]

\[
\ddot{\sigma} + 3H \dot{\sigma} + \frac{2}{3\lambda - 1} \frac{\partial B(\phi, \sigma)}{\partial \sigma} = 0.
\]

Now we can define the energy density and pressure for the scalar fields. Concerning the dark matter, the corresponding relations are

\[
\rho_m = \frac{3\lambda - 1}{4} \dot{\phi}^2 + V(\phi)
\]

\[
p_m = \frac{3\lambda - 1}{4} \dot{\phi}^2 - V(\phi).
\]
Concerning the dark energy sector, we have

$$\rho_d \equiv \frac{3\lambda - 1}{4} \dot{\sigma}^2 + B(\phi, \sigma) - \frac{3\kappa^2 \mu^2 \Lambda^2}{8(3\lambda - 1)}$$

(17)

$$p_d \equiv \frac{3\lambda - 1}{4} \dot{\sigma}^2 - B(\phi, \sigma) + \frac{3\kappa^2 \mu^2 \Lambda^2}{8(3\lambda - 1)}.$$

(18)

The first parts of these expressions, namely \(\frac{3\lambda - 1}{4} \dot{\sigma}^2 \) and \(B(\phi, \sigma)\), correspond to the energy density and pressure of the \(\sigma\)-field, \(\rho_{\sigma}\) and \(p_{\sigma}\) respectively. The last constant term is just the explicit (negative) cosmological constant. Therefore, in expressions (17),(18) we have defined the energy density and pressure for the effective dark energy, which incorporates the aforementioned contributions. Using the above definitions, we can re-write the Friedmann equations (12),(13) in the standard form:

$$H^2 = \frac{\kappa^2}{6(3\lambda - 1)} \left[ \rho_M + \rho_{DE} \right]$$

(19)

$$\dot{H} + \frac{3}{2} H^2 = -\frac{\kappa^2}{4(3\lambda - 1)} \left[ p_M + p_{DE} \right].$$

(20)

Finally, note that using (14),(15) it is straightforward to see that the aforementioned interacting dark matter and dark energy quantities verify the following continuity equations

$$\dot{\rho}_m + 3H(\rho_m + p_m) = \dot{\rho}_m + 3H\rho_m(1 + w_m) = -\dot{\phi} \frac{\partial B(\phi, \sigma)}{\partial \phi} = Q$$

(21)

$$\dot{\rho}_d + 3H(\rho_d + p_d) = \dot{\rho}_d + 3H\rho_d(1 + w_d) = \dot{\phi} \frac{\partial B(\phi, \sigma)}{\partial \phi} = -Q.$$ 

(22)

The interaction is given by the quantity \(Q = \Gamma \rho_d\). This is a decaying of the dark energy component into dark matter with the decay rate \(\Gamma\). Taking a ratio of two energy densities as \(r = \rho_m/\rho_d\), the above equations lead to

$$\dot{r} = 3H \left[ w_d - \frac{1 + r \Gamma}{r 3H} \right]$$

(23)

If we define [50],

$$w_d^{\text{eff}} = w_d + \frac{\Gamma}{3H}, \quad w_m^{\text{eff}} = w_m - \frac{1}{r \Gamma 3H}. $$

(24)

Then, the continuity equations can be written in their standard form

$$\dot{\rho}_\Lambda + 3H(1 + w_d^{\text{eff}})\rho_d = 0,$$

(25)

$$\dot{\rho}_m + 3H(1 + w_m^{\text{eff}})\rho_m = 0$$

(26)

Define as usual

$$\Omega_m = \frac{\rho_m}{\rho_{cr}} = \frac{\kappa^2 \rho_m}{6(3\lambda - 1)H^2}, \quad \Omega_d = \frac{\rho_d}{\rho_{cr}} = \frac{\kappa^2 \rho_d}{6(3\lambda - 1)H^2}.$$ 

(27)

Now we can rewrite the first Friedmann equation as

$$\Omega_m + \Omega_d = 1.$$ 

(28)
Using Eqs.(27,28) we obtain following relation for ratio of energy densities $r$ as

$$r = 1 - \frac{\Omega_d}{\Omega_d}$$  \hspace{1cm} (29)$$

Here as in Ref.[51], we choose the following relation for decay rate

$$\Gamma = 3b^2(1 + r)H$$ \hspace{1cm} (30)$$

with the coupling constant $b^2$. Using Eq.(29), the above decay rate take following form

$$\Gamma = \frac{3b^2H}{\Omega_d}$$ \hspace{1cm} (31)$$

Substitute this relation into Eq.(24), one find

$$w^\text{eff}_d = w_d + \frac{b^2}{\Omega_d}, \quad w^\text{eff}_m = w_m - \frac{b^2}{1 - \Omega_d}$$ \hspace{1cm} (32)$$

where

$$w_d = \frac{3\lambda - 1}{4} \dot{\sigma}^2 + B(\phi, \sigma) + \frac{3b^2\mu^2\Lambda^2}{8(3\lambda - 1)}, \quad w_m = \frac{3\lambda - 1}{4} \dot{\phi}^2 - V(\phi) - \frac{3\lambda - 1}{4} \dot{\phi}^2 + V(\phi)$$ \hspace{1cm} (33)$$

Using Eqs.(17), and (27) we obtain following expression

$$w^\text{eff}_d = \frac{\kappa^2 \left( \frac{3\lambda - 1}{4} \dot{\sigma}^2 + B(\phi, \sigma) + \frac{3b^2\mu^2\Lambda^2}{8(3\lambda - 1)} \right) + 6(3\lambda - 1)b^2H^2}{\kappa^2 \left( \frac{3\lambda - 1}{4} \dot{\sigma}^2 + B(\phi, \sigma) - \frac{3b^2\mu^2\Lambda^2}{8(3\lambda - 1)} \right)}$$ \hspace{1cm} (34)$$

If $\dot{\sigma}^2 \leq -\frac{12b^2H^2}{\kappa^2}$, then $w^\text{eff}_d \leq -1$, therefore the interacting dark energy model in the framework of Hořava gravity exhibiting phantom behavior.

Now we consider the simplified case of the absence of the $\sigma-$filed. In this case we have

$$w^\text{eff}_d = \frac{-\kappa^2(B(\phi) - \frac{3b^2\mu^2\Lambda^2}{8(3\lambda - 1)}) + 6(3\lambda - 1)b^2H^2}{\kappa^2(B(\phi) - \frac{3b^2\mu^2\Lambda^2}{8(3\lambda - 1)})}$$ \hspace{1cm} (35)$$

Considering the case $3\lambda - 1 > 0$, if $B(\phi) < \frac{3b^2\mu^2\Lambda^2}{8(3\lambda - 1)}$, then $w^\text{eff}_d < -1$. However in flat space non-interacting case, where $b = 0$, $w^\text{eff}_d = w_d = 0$, so dark energy is a cosmological constant and equation of state can not cross over $-1$. This is big difference with the result of [1]. Surprisingly in the absence of the $\sigma-$filed, when there is an interaction between scalar matter fielded with cosmological constant we obtain $w^\text{eff}_d < -1$, that is we result to an effective dark energy presenting phantom behaviour. This behaviour is pure effect of the interaction, so we can ignore the $\sigma-$filed at first and only allow an interaction between matter fielded $\phi$ and cosmological constant to obtain the phantom-like behaviour. In this case the time evolution of equation of state control by the dynamics of filed $\phi$.

3 Conclusions

In order to solve cosmological problems and because the lack of our knowledge, for instance to determine what could be the best candidate for dark energy to explain the
accelerated expansion of universe, the cosmologists try to approach to best results as precise as they can by considering all the possibilities they have. Studying the interaction between the dark energy and ordinary matter will open a possibility of detecting the dark energy. It should be pointed out that evidence was recently provided by the Abell Cluster A586 in support of the interaction between dark energy and dark matter [52]. However, despite the fact that numerous works have been performed till now, there are no strong observational bounds on the strength of this interaction [53]. This weakness to set stringent (observational or theoretical) constraints on the strength of the coupling between dark energy and dark matter stems from our unawareness of the nature and origin of dark components of the Universe. May be the recent developments in Horawa gravity could offer a dark energy candidate with perhaps better quantum gravitational foundations. So in the present paper we have formulated Hořava-Lifshitz interacting dark energy model. We have considered two scalar fields, one responsible for dark matter fluid and one contributing to the dark energy sector. Our calculations show that the interacting dark energy model in the framework of Hořava gravity exhibiting phantom behavior.

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