Challenging ΛCDM with scalar-tensor gravity and thermodynamics of irreversible matter creation

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Motivation

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General Relativity (GR) is currently facing many theoretical and experimental challenges...

Some failures of GR are:

- ✗ The inability to explain the nature of dark matter and dark energy;
- ✗ The incompatibility between another well-established theories;
- ✗ Its lack of uniqueness.

Motivation

But there is
more...

- Einstein field equations are adiabatic and reversible, as they set an equivalence between the geometry of space-time and matter.

- The entropy of the Universe is always increasing, and therefore being a system where irreversible processes occur.

- Einstein's equations are unable to provide an explanation for the increase in entropy that accompanies the production of matter.

Is GR the true fundamental theory of gravitation?

Motivation

- Motivated by these problems left unanswered by GR, we investigate the possibility of gravitationally generated particle production in **scalar-tensor gravity**.

- In this theory the covariant divergence of the matter energy-momentum tensor does not vanish.

- We explored both physical and cosmological implications of this property by using the formalism of irreversible thermodynamics of open systems in the presence of matter creation/annihilation.

Introduction

Thermodynamics of Open Systems (Prigogine and Geheniau, PNAS 1986, 1988)

Let us consider an open system with Volume containing particles

Thermodynamic Conservation Equation: $d(\varrho V) = dQ - pdV + \frac{h}{n} d(nV)$

$\varrho = \frac{E}{V}$ Energy Density

$n = \frac{N}{V}$ Number Density

$h = \varrho + p$ Enthalpy (per unit volume)

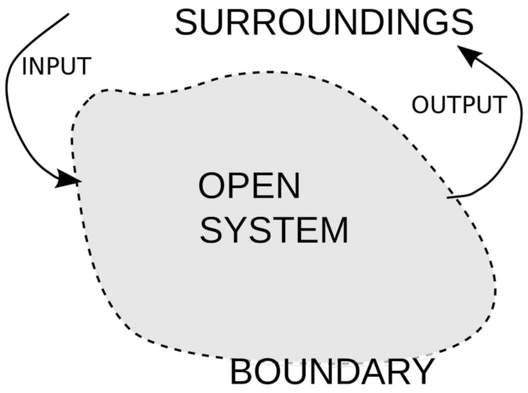

Fig.1 – Open system

Adiabatic Transformations: $d(\varrho V) + pdV - \frac{h}{n} d(nV) = 0$

The "heat" received by the system is due to the variation in the number of particles!

2nd Law of Thermodynamics: $dS = d_e S + d_i S \geq 0$

Entropy Flow   Entropy Creation

Introduction

Thermodynamics of Open Systems (Prigogine and Geheniau, PNAS 1986, 1988)

Total Differential of the Entropy: $\mathcal{T}\, dS = d(\varrho V) + p dV - \mu\, d(nV)$

Chemical Potential $\mu \geq 0$

Entropy Density $s = \frac{S}{V} \geq 0$

- By using the energy conservation equation and the relation we can write the expression above in a more convenient way:

$$\mathcal{T}\, dS = dQ + \mathcal{T}\, \frac{s}{n} d(nV)$$

$$d_e S = \frac{dQ}{\mathcal{T}} \qquad d_i S = \frac{s}{n} d(nV)$$

$$\mathcal{T}\, dS = \mathcal{T}\, d_e S + \mathcal{T}\, d_i S$$

- Considering an homogeneous system: $d_e S = 0 \quad \Longrightarrow dS = d_i S = \frac{s}{n} d(nV) \geq 0 \qquad d_e S = 0 \Longrightarrow dQ = 0$

In homogeneous systems we expect adiabatic processes to occur and matter creation is the only contribution to entropy production!

In the cosmological context this implies that gravitational fields can produce matter (but the inverse process is forbidden)!

Alternative Cosmology
The Universe as an Open System

Comoving frame of reference

Let us consider a flat homogeneous and isotropic Universe:

$$ds^2 = -dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$$

Flat FLRW metric

Its energy-momentum tensor corresponds to a perfect fluid:

$$T_{\mu\nu} = (\varrho + p) u_\mu u_\nu + p g_{\mu\nu}$$

$$u^\mu = (-1, \vec{0})$$ 4-Velocity

Because of homogeneity $p = p(t)$ $\varrho = \varrho(t)$

Normalization condition $u_\mu u^\mu = -1$

$$V = a^3(t)$$

- The Universe being homogeneous means that and therefore:

$$\frac{d}{dt}(\varrho a^3) + p \frac{d}{dt} a^3 = \frac{h}{n} d(n a^3) \Longrightarrow \dot{\varrho} + 3H(\varrho + p) = 1 \frac{\rho + p}{n}(\dot{n} + 3Hn)$$

Particle Creation Rate

$$\Gamma n = (\dot{n} + 3Hn)$$

- For adiabatic transformations describing irreversible particle creation in an open thermodynamic systems, the energy conservation equation can be rewritten as an effective energy conservation equation

$$\frac{d}{dt}(\varrho a^3) + (p + p_c) \frac{d}{dt} a^3 = 0 \Longrightarrow \dot{\varrho} + 3H(\varrho + p + p_c) = 0$$

$$p_c = -\frac{\varrho + p}{3H} \Gamma$$

Creation Pressure

gravity

Geometrical Representation (Harko, Lobo, Odintsov, Nojiri, PRD 2011)

The gravity action takes the following form: $S=\frac{1}{2\kappa^2}\int_{\Omega}\sqrt{-g}\,f(R,T)\,d^4x+\int_{\Omega}\sqrt{-g}\,\mathcal{L}_m\,d^4x$ $\kappa^2=8\pi G/c^4$

$R=g^{\mu\nu}R_{\mu\nu}$ $T=g^{\mu\nu}T_{\mu\nu}$ ⟹ There is a non-minimal curvature-matter coupling!

$$T_{\mu\nu}\equiv-\frac{2}{\sqrt{-g}}\frac{\delta\left(\sqrt{-g}\,\mathcal{L}_m\right)}{\delta g^{\mu\nu}}$$

- By varying this action with respect to the metric tensor we obtain the field equation

$$f_R(R,T)R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}f(R,T)+\left(g_{\mu\nu}\nabla^{\sigma}\nabla_{\sigma}-\nabla_{\mu}\nabla_{\nu}\right)f_R(R,T)=\kappa^2T_{\mu\nu}-f_T(R,T)\left(T_{\mu\nu}+\Theta_{\mu\nu}\right).$$

$$\Theta_{\mu\nu}\equiv g^{\varrho\sigma}\frac{\delta T_{\varrho\sigma}}{\delta g^{\mu\nu}}$$

- By taking the covariant divergence of the field equation we get the conservation equation

$$\left(\kappa^2-f_T\right)\nabla^{\mu}T_{\mu\nu}=\left(T_{\mu\nu}+\Theta_{\mu\nu}\right)\nabla^{\mu}f_T+f_T\nabla^{\mu}\Theta_{\mu\nu}+f_R\nabla^{\mu}R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}\nabla^{\mu}f\,.$$

Unlike in GR, the covariant divergence of does not vanish in this theory!

gravity
Scalar-tensor Representation

We will use this representation throughout our work!

In the scalar-tensor rep. the action takes the form:
$$S=\frac{1}{2\kappa^2}\int_\Omega \sqrt{-g}\left[\varphi R+\psi T-V(\varphi,\psi)\right]d^4x+\int_\Omega \sqrt{-g}\,\mathcal{L}_m d^4x$$

Scalar Fields $\varphi\equiv\frac{\partial f}{\partial R}$ $\psi\equiv\frac{\partial f}{\partial T}$

Scalar Interaction Potential $V(\varphi,\psi)\equiv\varphi\alpha+\psi\beta-f(\alpha,\beta)$

- By varying the action with respect to the metric and to the scalar fields and we obtain, respectively

$$\varphi R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}(\varphi R+\psi T-V)+\left(g_{\mu\nu}\nabla^\sigma\nabla_\sigma-\nabla_\mu\nabla_\nu\right)\varphi=\kappa^2 T_{\mu\nu}-\psi(T_{\mu\nu}+\Theta_{\mu\nu}),\qquad V_\varphi=R,\qquad V_\psi=T.$$

gravity
Cosmological Equations

- Using the FLRW metric and the field equations one can obtain the modified cosmological equations for the scalar-tensor gravity

Modified Friedmann Equation

Modified Raychaudhuri Equation

$$V_{\varphi}=6\left(\dot{H}+2H^2\right),\quad V_{\psi}=3p-\varrho$$

Equations of motion for the scalar fields

gravity
Cosmological Equations

- By taking the covariant divergence of the field equation we get the conservation equation

$$(\kappa^2-\psi)\nabla^\mu T_{\mu\nu}=(T_{\mu\nu}+\Theta_{\mu\nu})\nabla^\mu\psi+\psi\nabla^\mu\Theta_{\mu\nu}-\frac{1}{2}g_{\mu\nu}\left[R\nabla^\mu\varphi+\nabla^\mu(\psi T-V)\right]$$

- Fixing gives us the cosmological energy conservation equation

$$\dot\varrho+3H(\varrho+p)=\frac{3}{8\pi}\left\{-\frac{\dot\psi}{2}\left(\varrho-\frac{p}{3}+\frac{V_\psi}{3}\right)-\psi\left[H(\varrho+p)+\frac{1}{2}\left(\dot\varrho-\frac{\dot p}{3}\right)\right]\right\}.$$

- Comparing the equation above with , where , we obtain

$$\psi\equiv\frac{\partial f}{\partial T}$$

We conclude that non-minimal curvature-matter couplings induce particle production!

Cosmological Evolution

Entropy evolution

Second law of thermodynamics: $dS = d_e S + d_i S \geq 0$

- The condition of homogeneity implies . One can obtain the following expression for the entropy temporal evolution

$$\frac{dS}{dt} = \Gamma S > 0 \,,$$

whose general solution is $S(t) = S_0 \exp\left[\int_0^t \Gamma(t')\, dt'\right], \quad S_0 = S(0)\,.$

- The entropy temporal evolution in the scalar-tensor gravity assumes the following form

Cosmological Evolution

Entropy evolution

The entropy flux 4-vector is defined as

$$S^{\mu} = n \sigma u^{\mu} ,$$

(M. O. Calvao, J. A. S. Lima and I. Waga, Phys. Lett. A 1992)

where is the characteristic entropy.

- Since must obey the 2nd law of thermodynamics then we have the following condition

$$\nabla_{\mu} S^{\mu} \geq 0.$$

- Using the Gibbs relation in combination with the definition of chemical potential yields

$$\nabla_{\mu} S^{\mu} = \Gamma s .$$

- The entropy production rate in the scalar-tensor gravity assumes the following form

Cosmological Evolution

Temperature evolution

A thermodynamic system is fundamentally described by the number density and the temperature. In the thermodynamic equilibrium, the energy density and the pressure are determined from the equilibrium equations of state, given in a parametric form as

$$\varrho=\varrho(n,\mathcal{T}), \qquad p=p(n,\mathcal{T}).$$

- Hence, the energy conservation equation becomes

$$\left(\frac{\partial\varrho}{\partial n}\right)_{\mathcal{T}}\dot{n}+\left(\frac{\partial\varrho}{\partial\mathcal{T}}\right)_{n}\dot{\mathcal{T}}+3(\varrho+p)H=(\varrho+p)\Gamma\,.$$

- We write the differential of the characteristic entropy and use the fact that it is an exact differential in order to obtain an useful thermodynamical relation

$$\left(\frac{\partial\varrho}{\partial n}\right)_{\mathcal{T}}=\frac{\varrho+p}{n}-\frac{\mathcal{T}}{n}\left(\frac{\partial\varrho}{\partial\mathcal{T}}\right)_{n}.$$

Cosmological Evolution

Temperature evolution

- By using the previous relation we then achieve an expression for the temperature evolution due to the nonminimal curvature-matter coupling

$$\frac{\dot{\mathcal{T}}}{\mathcal{T}} = c_s^2 \frac{\dot{n}}{n} = c_s^2 (\Gamma - 3H)$$

whose general solution is

$$\mathcal{T}(t) = \mathcal{T}_0 \exp\left\{ c_s^2 \int_0^t \left[\Gamma(t') - 3H(t') \right] dt' \right\},$$

where is the speed of sound.

- The temperature of the newly created particles in scalar-tensor gravity is given by

Particular Cosmological Models

The de Sitter solution with constant density

$$H = H_0 = constant$$

$$\varrho = \varrho_0 = constant$$

Matter – Pressureless dust

$$p = 0$$

Under these assumptions it is possible to get analytical solutions

$$V(\varphi, \psi) = 12 H_0^2 \varphi - \varrho_0 \psi + \Lambda_0$$

$$\psi(t) = e^{-3 H_0 t}\left[\psi_0 - 8\pi\left(1 - e^{3 H_0 t}\right)\right] \qquad \psi_0 = \psi(0)$$

$$\varphi(t) = \frac{1}{12 H_0^2}\left[e^{H_0 t}\left(12 H_0^2 \varphi_0 + 2\Lambda_0 + \varrho_0 \psi_0 + 56\pi \varrho_0\right) - 2\left(\Lambda_0 + 32\pi \varrho_0\right) - \varrho_0 e^{-3 H_0 t}\left(8\pi - \psi_0\right)\right] \qquad \varphi_0 = \varphi(0)$$

$$\Gamma = \frac{3 H_0 (\psi_0 - 8\pi)}{8\pi\left(2 e^{3 H_0 t} - 1\right) + \psi_0} \qquad p_c = -\frac{\varrho_0 (\psi_0 - 8\pi)}{8\pi\left(2 e^{3 H_0 t} - 1\right) + \psi_0}$$

The scalar-tensor gravity admits a de Sitter type solution **without** resorting to the presence of dark energy!

Particular Cosmological Models

The de Sitter solution with time varying density

$H = H_0 = constant$

Matter – Pressureless dust

$p = 0$

We assume the interaction potential has the following form: $V(\varphi, \psi) = 12 H_0^2 \varphi - \frac{1}{2\beta}\psi^2$

Then, it is possible to obtain an expression for each scalar in terms of the matter density: $\psi = \beta\rho$

$$\varphi(\rho) = -\frac{1}{11220\beta H_0^2}\left[\frac{55\beta}{\sqrt[3]{\rho}}\left(25\beta\rho^{7/3} - \frac{204 c_1 H_0^2}{\sqrt{\beta\rho + 8\pi}}\right) - \frac{27648\pi^{5/2}}{\sqrt{\frac{\beta\rho}{2} + 4\pi}}\, {}_2F_1\left(\frac{1}{3}, \frac{1}{2}; \frac{4}{3}; -\frac{\beta\rho}{8\pi}\right) + 13824\pi^2 + 6400\pi\beta\rho\right]$$

where ${}_2F_1(a, b; c; z) = \sum_{k=0}^{\infty} ((a)_k (b)_k / (c)_k) \left(z^k / k!\right)$ is the hypergeometric function.

The first order nonlinear differential equation for the density that was found and used to obtain the above expression is

$$\left(1 + \frac{5\beta}{16\pi}\rho\right)\dot{\rho} + 3H_0\rho = -\frac{3\beta H_0}{8\pi}\rho^2$$

which has the following general solution

$$\rho\left(\beta\rho + 8\pi\right)^{3/2} = e^{-3H_0(t - t_0)}$$

Particular Cosmological Models

The de Sitter solution with time varying density

$H = H_0 = constant$

Matter – Pressureless dust

$p = 0$

The particle creation rate can be obtained as:

$$\Gamma = -\frac{3}{2}\frac{\beta\rho}{\beta\rho + 8\pi}\frac{\dot{\rho}}{\rho} = \frac{9H_0\beta}{2}\frac{\rho\left[1 + (\beta/8\pi)\,\rho\right]}{(\beta\rho + 8\pi)\left[1 + (5\beta/16\pi)\,\rho\right]}$$

Finally, we explored the following limits:

$\beta\rho \ll 8\pi$	$\beta\rho \gg 8\pi$
$\rho(t) \sim e^{-3H_0(t-t_0)}$	$\rho(t) \sim e^{-(6/5)H_0(t-t_0)}$
$\Gamma \approx (9H_0/16\pi)\, e^{-3H_0(t-t_0)}$	$\Gamma \approx (9/5)H_0$

Conclusions

- The scalar-tensor gravity can provide a (macroscopical) phenomenological description of particle production in the cosmological fluid filling the Universe - and ;

- The creation rate and creation pressure only depend on the scalar field associated with the trace of the energy-momentum tensor - and with ;

- Non-minimal curvature-matter couplings induce particle production - ;

- We have a cosmology in which the Universe gradually builds up entropy as particles are created;

- The scalar-tensor gravity can explain the late time acceleration without dark energy.

- The de Sitter solution can either describe a constant matter density Universe or a Universe in which the density decreases asymptotically as an exponential.

Thanks for your attention!
Questions?

(If you do have some question please send me an e-mail: **mapinto@fc.ul.pt**)