Universe and Holography

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Outline

Current content of the Universe

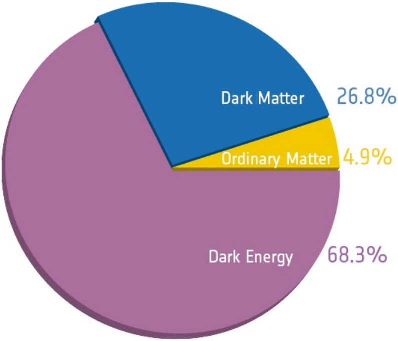

Figure: The content of the Universe, according to results from the Planck Satellite (2013). [arXiv:1303.5076v3]

General Relativity ⟷ Symmetries: homogeneity and isotropy

⇓

$$G^{\mu}_{\nu} = R^{\mu}_{\nu} - \frac{1}{2} g^{\mu}_{\nu} R = \kappa T^{\mu}_{\nu}$$

⇓

relate

↙ ↘

Dynamics of the Universe ⟷ Content of energy-momentum

General Relativity $\longleftrightarrow$ Symmetries: homogeneity and isotropy

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$$G^{\mu}_{\nu} \equiv R^{\mu}_{\nu} - \frac{1}{2} g^{\mu}_{\nu} R = \kappa T^{\mu}_{\nu}$$

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Dynamics of the Universe $\longleftrightarrow$ Content of energy-momentum

General Relativity $\longleftrightarrow$ Symmetries: homogeneity and isotropy

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Dynamics of the Universe $\longleftrightarrow$ Content of energy-momentum

Holographic Dark Energy (HDE)

In this work our aim is to investigate a dark energy in the context of the holographic principle.

Holographic Principle

The number of degrees of freedom in a bounded system should be finite and is related to the area of its boundary. The phenomena within a volume can be explained by the set of degrees of freedom residing on its border, and the degrees of freedom are determined by the area of the border instead of the volume. This idea is based on reality, on the entropy of the limited black hole.

Gerard ’t Hooft[1], Leonard Susskind[2], and Jacob D. Bekenstein[3] .

[1] G. ’t Hooft, “Dimensional Reduction In Quantum Gravity” in Salamfest 93, p. 284, gr-qc/9310026
[2] L. Susskind, J. Math. Phys. 36, 6377 (1995).
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In the literature, commonly the energy density of HDE is parametrized as $\rho_\Lambda = 3c^2 M_p^2 L^{-2}$. In the holographic Ricci dark energy model[4], L is given by the average radius of the Ricci scalar curvature $|\mathcal{R}|^{-1/2}$, so in this case the density of the HDE is $\rho_x \propto \mathcal{R}$. In a spatially flat FLRW universe, the Ricci scalar of the spacetime is given by $|\mathcal{R}| = 6(\dot{H} + 2H^2)$, this model works fairly well in fitting the observational data, and it alleviates the cosmic coincidence problem[5].

Model

A generalization of the holographic Ricci dark energy model is proposed[6]

$$\rho_x = 3(\alpha H^2 + \beta \dot{H}) \quad (1)$$

where α and β are constants to be determined.

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[5] C. Gao, F. Q. Wu, X. Chen and Y. G. Shen, Phys. Rev. D 79, 043511 (2009); Zhang, X. Phys. Rev. D 79, 103509 (2009); C. -J. Feng and X. Zhang, Phys. Lett. B 680 (2009) 399; T. F. Fu, J. F. Zhang, J. Q. Chen and X. Zhang, Eur.Phys. J. C 72, 1932 (2012).

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Spatially flat FLRW universe

In the framework of General Relativity and a homogeneous, isotropic and flat universe, the Friedmann-Lematre-Robertson-Walker (FLRW) metric

$$\boxed{ds^2 = dt^2 - a^2(t)[dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)]}\,, \tag{2}$$

where $a(t)$ is the scale factor and (t, r, θ, ϕ) are comoving coordinates. Then, from Einstein's Equation, we get

$$3\,H^2 = \rho\,, \tag{3}$$
$$2\,\dot{H} + 3\,H^2 = -\,p\,, \tag{4}$$

these are the so-called Friedmann equations. Also, the conservation of the energy-momentum tensor

$$\nabla_\mu T^{\mu\nu} = 0 \quad \Rightarrow \quad \dot{\rho} + 3H(\rho + p) = 0\,, \tag{5}$$

where ρ is the total energy density, p is the total pressure, and $8\pi G = c = 1$ is assumed. Also, $p = \omega\rho$.

HDE scenarios

No interaction

$$\left.\begin{array}{c} 3H^2 = \rho_1 + \rho_x \\ \dot{\rho}_1 + 3H\rho_1(1+\omega_1) = 0 \\ \dot{\rho}_x + 3H\rho_x(1+\omega) = 0 \\ \rho_x = 3(\alpha H^2 + \beta \dot{H}) \end{array}\right\} \longrightarrow \left\{\begin{array}{c} \text{with } \omega_1 \text{ constant} \\ \text{variables: } a,\ \rho_1, \rho_x \\ \Downarrow \\ \omega \text{ variable} \end{array}\right.$$

Interaction[7] [8]

$$\left.\begin{array}{c} 3H^2 = \rho_1 + \rho_x \\ \dot{\rho}_1 + 3H\rho_1(1+\omega_1) = -Q \\ \dot{\rho}_x + 3H\rho_x(1+\omega) = Q \\ \rho_x = 3(\alpha H^2 + \beta \dot{H}) \end{array}\right\} \longrightarrow \left\{\begin{array}{c} \text{with } \omega_1 \text{ constant} \\ \text{variables: } a,\ \rho_1, \rho_x \\ \text{given a } Q(\rho_1, \rho_x) \Rightarrow \omega \text{ variable} \\ \omega \text{ constant} \Rightarrow Q \text{ variable function} \end{array}\right.$$

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General analysis

We consider besides the Friedmann equation (3) and the conservation equation (5),

- the total density: $\rho = \rho_b + \rho_r + \rho_c + \rho_x$,
- the total pressure: $p = p_b + p_r + p_c + p_x$,
- dark sector: $\rho_d := \rho_c + \rho_x$,
- barotropic state equation: $p_i = \omega_i \, \rho_i$ with $\omega_b = 0$, $\omega_r = 1/3$, $\omega_c = 0$ and $\omega_x = \omega$.

We include a phenomenological interaction in the dark sector through

$$\rho_c' + \rho_c = -\Gamma \qquad \text{and} \qquad \rho_x' + (1+\omega)\,\rho_x = \Gamma\,. \tag{6}$$

where Γ is a function defining the interaction.

For the HDE (1) we obtain:

$$\boxed{\rho_x = \alpha\,\rho + \frac{3\beta}{2}\,\rho'}\,. \tag{7}$$

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In our scenario we have for baryons and radiation, respectively,

$$\rho_b = \rho_{b0}\, a^{-3} \quad \text{and} \quad \rho_r = \rho_{r0}\, a^{-4}\,. \tag{8}$$

The combining equations (6) - (8) we obtain

$$\boxed{\frac{3\beta}{2}\,\rho_d'' + \left(\alpha + \frac{3\beta}{2} - 1\right)\,\rho_d' + (\alpha - 1)\,\rho_d + \frac{1}{3}(2\beta - \alpha)\,\rho_{r0}\, a^{-4} = \Gamma} \tag{9}$$

The equation (9) can be easily solve when $\Gamma = \Gamma(\rho_d, \rho_d', \rho, \rho')$.

In our work we consider the following linear interactions[9] [10]:

$$\boxed{\Gamma_1 = \alpha_1\rho_c + \beta_1\rho_x, \quad \Gamma_2 = \alpha_2\rho_c' + \beta_2\rho_x' \quad \text{and} \quad \Gamma_3 = \alpha_3\rho_d + \beta_3\rho_d'.}$$

[9] F. Arevalo, A. Cid, and J. Moya, Eur. Phys. J. C77, 565 (2017).

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The energy density of the dark sector ρ_d

Notice that by rewriting equation (9) we get

$$\boxed{\rho_d'' + b_1\,\rho_d' + b_2\,\rho_d + b_3\,a^{-3} + b_4\,a^{-4} = 0}\,, \tag{10}$$

where b_1, b_2, b_3, b_4 are parameters representing each interaction such that

	$\Gamma_1 = \alpha_1\,\rho_c + \beta_1\,\rho_x$	$\Gamma_2 = \alpha_2\,\rho_c' + \beta_2\,\rho_x'$	$\Gamma_3 = \alpha_3\,\rho_d + \beta_3\,\rho_d'$
b_1	$1+\alpha_1-\beta_1-\frac{2}{3\beta}(1-\alpha)$	$\frac{2\alpha-3\beta-2-2\alpha_2-2\alpha(\beta_2-\alpha_2)}{3\beta(1-\beta_2+\alpha_2)}$	$\frac{2}{3\beta}\left(\alpha+\frac{3\beta}{2}-1-\beta_3\right)$
b_2	$\frac{2}{3\beta}(\alpha(1-\beta_1+\alpha_1)-1-\alpha_1)$	$\frac{2(\alpha-1)}{3\beta(1-\beta_2+\alpha_2)}$	$\frac{2}{3\beta}(\alpha-1-\alpha_3)$
b_3	$(\beta_1-\alpha_1)\left(1-\frac{2\alpha}{3\beta}\right)\rho_{b0}$	$\frac{(2\alpha-3\beta)(\beta_2-\alpha_2)}{3\beta(1-\beta_2+\alpha_2)}\rho_{b0}$	0
b_4	$\frac{2}{3\beta}\left(\frac{1}{3}(2\beta-\alpha)-(\beta_1-\alpha_1)(\alpha-2\beta)\right)\rho_{r0}$	$\frac{2(2\beta-\alpha)-8(2\beta-\alpha)(\beta_2-\alpha_2)}{9\beta(1-\beta_2+\alpha_2)}\rho_{r0}$	$\frac{2}{9\beta}(2\beta-\alpha)\rho_{r0}$

The general solution of equation (10) has the form

$$\boxed{\rho_d(a) = A\,a^{-3} + B\,a^{-4} + C_1\,a^{3\,\lambda_1} + C_2\,a^{3\,\lambda_2}}\,, \tag{11}$$

where the integration constants are given by

$$C_1 = \frac{-3A(1-\lambda_2) - B(4-3\lambda_2) - 9H_0^2\left((\lambda_2-1)\,\Omega_{c0} + (\lambda_2-\omega_0-1)\Omega_{x0}\right)}{3\,(\lambda_1-\lambda_2)}\,,$$

$$C_2 = \frac{3A(1-\lambda_1) + B(4-3\lambda_1) + 9\,H_0^2\left((\lambda_1-1)\Omega_{c0} + (\lambda_1-\omega_0-1)\Omega_{x0}\right)}{3\,(\lambda_1-\lambda_2)}\,, \tag{12}$$

and the coefficients in (11) are

$$A = \frac{b_3}{b_1-b_2-1} \quad \text{and} \quad B = \frac{9b_4}{12b_1-9b_2-16}\,, \tag{13}$$

as well as

$$\lambda_{1,2} = -\frac{1}{2}\left(b_1 \pm \sqrt{b_1^2-4b_2}\right) \tag{14}$$

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The state parameter of the HDE

The state parameter of the HDE corresponds to the ratio $\omega = \frac{p_x}{\rho_x}$.

Using the expression (7) in equation (6), and the linear interactions Γ_i, we find

$$\omega(a) = \frac{D_1\, a^{-3} + D_2\, a^{-4} + D_3\, a^{3\,\lambda_1} + D_4\, a^{3\lambda_2}}{\tilde{A}\, a^{-3} + \tilde{B}\, a^{-4} + \tilde{C}_1\, a^{3\,\lambda_1} + \tilde{C}_2\, a^{3\lambda_2}}, \qquad (15)$$

where $\tilde{A} = (2\alpha - 3\beta)(A + \rho_{b_0})$, $\tilde{B} = 2(\alpha - 2\beta)(B + \rho_{r_0})$ and $\tilde{C}_{1,2} = C_{1,2}(3\beta\lambda_{1,2} + 2\alpha)$.

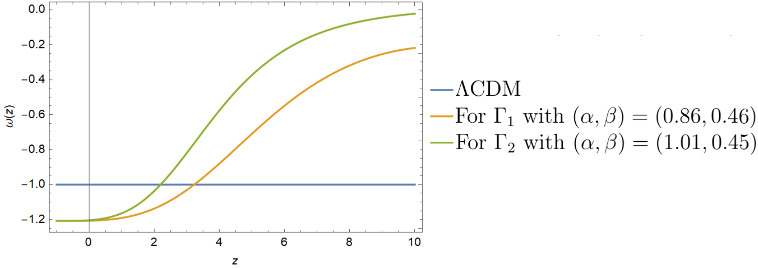
	$\Gamma_1 = \alpha_1\,\rho_c + \beta_1\,\rho_x$	$\Gamma_2 = \alpha_2\,\rho_c' + \beta_2\,\rho_x'$	$\Gamma_3 = \alpha_3\,\rho_d + \beta_3\,\rho_d'$
D_1	$2\alpha_1 A + (2\alpha - 3\beta)(\beta_1 - \alpha_1)(A + \rho_{b0})$	$-2\alpha_2 A + (3\beta - 2\alpha)(\beta_2 - \alpha_2)(A + \rho_{b0})$	$2(\alpha_3 + \beta_3)A$
D_2	$2\alpha_1 B + 2(\alpha - 2\beta)\left(\frac{1}{3} - \alpha_1 + \beta_1\right)(B + \rho_{r0})$	$-\frac{8}{3}\alpha_2 B + \frac{2}{3}(2\beta - \alpha)(-1 - \alpha_2 + \beta_2)(B + \rho_{r0})$	$2\left(\alpha_3 - \frac{4}{3}\beta_3\right)B + \frac{2}{3}(\alpha - 2\beta)(B + \rho_{r0})$
D_3	$C_1(2\alpha_1 + (2\alpha + 3\beta\lambda_1)(\beta_1 - \alpha_1 - 1 - \lambda_1))$	$C_1(2\alpha_2\lambda_1 - (2\alpha + 3\beta\lambda_1)(1 + \lambda_1(1 + \alpha_2 - \beta_2)))$	$C_1(2(\alpha_3 + \beta_3\lambda_1) - (2\alpha + 3\beta\lambda_1)(1 + \lambda_1))$
D_4	$C_2(2\alpha_1 + (2\alpha + 3\beta\lambda_2)(\beta_1 - \alpha_1 - 1 - \lambda_2))$	$C_2(2\alpha_2\lambda_2 - (2\alpha + 3\beta\lambda_2)(1 + \lambda_2(1 + \alpha_2 - \beta_2)))$	$C_2(2(\alpha_3 + \beta_3\lambda_2) - (2\alpha + 3\beta\lambda_2)(1 + \lambda_2))$

The state parameter of the HDE

Current values of the parameters[11]: $\Omega_{b0} = 0.0484$, $\Omega_{r0} = 1.25 \times 10^{-3}$, $\Omega_{c0} = 0.258$, $\Omega_{x0} = 0.692$, $H_0 = 67.8\ km\, s^{-1}\ Mpc^{-1}$, and $\omega_\Lambda = -1$.

For the linear interaction models, some reference values are[12]: $(\alpha_1, \beta_1) = (-0.0076, 0)$ and $(\alpha_2, \beta_2) = (0.0074, 0)$.

For the HDE scenario, some reference values are given[13] [14]. Also, we consider $a = (1+z)^{-1}$.



[11] P. A. R. Ade et al. [Planck Collaboration], Astron. Astrophys. 594, A13 (2016).
[12] A. Cid, B. Santos, C. Pigozzo, T. Ferreira, J. Alcaniz. (2018). arXiv: 1805.02107[astro-ph.CO].
[13] S. Lepe and F. Peña, Eur. Phys. J. C 69, 575 (2010).
[14] F. Arévalo, P. Cifuentes, S. Lepe and F. Peña. Interacting Ricci-like holographic dark energy. (2014).

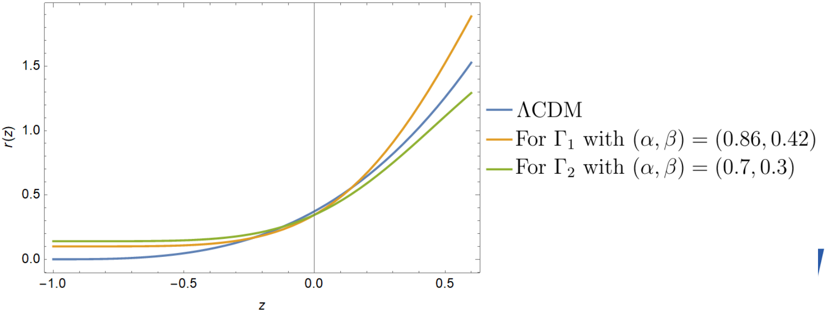
The coincidence parameter

To examine the problem of cosmological coincidence, we define $r \equiv \rho_c/\rho_x$.

In our work

$$r = \frac{\rho_d}{\left(\alpha - \frac{3\beta}{2}\right)\rho_b + (\alpha - 2\beta)\rho_r + \alpha\rho_d + \frac{3\beta}{2}\rho_d'} - 1\,. \tag{16}$$

We use (8) and (11) in the previous expression and obtain $r = r(a)$.
Then $r(a \to \infty) = \frac{2}{2\alpha + 3\beta\lambda_i} - 1$, where $\lambda_i = \text{máx}\{\lambda_1, \lambda_2\}$ for $\lambda_i > 0$.

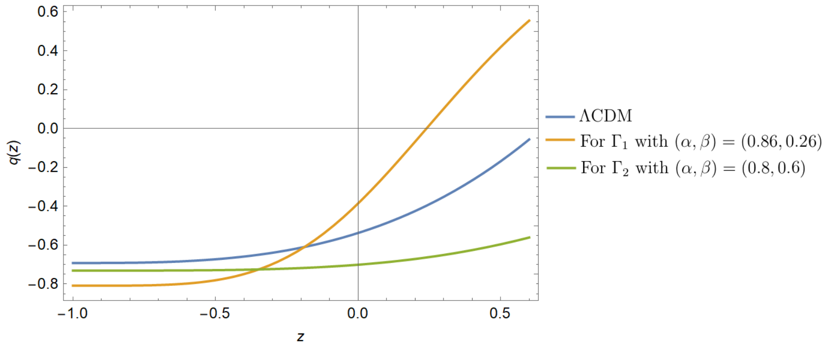


The deceleration parameter

The deceleration parameter q is a dimensionless measure of the cosmic acceleration in the evolution of the universe. It is defined by $q \equiv -\left(1 + \frac{\dot{H}}{H^2}\right) = -\left(1 + \frac{3\rho'}{2\rho}\right)$.

Using (11), we obtain

$$q(a) = -\left(1 + \frac{-3(\rho_{b0} + A)a^{-3} - 4(\rho_{r0} + B)a^{-4} + 3(C_1\lambda_1 a^{3\lambda_1} + C_2\lambda_2 a^{3\lambda_2})}{2(\rho_{b0} + A)a^{-3} + 2(\rho_{r0} + B)a^{-4} + 2(C_1 a^{3\lambda_1} + C_2 a^{3\lambda_2})}\right) \quad (17)$$



Conclusions and Perspectives.

- A theoretical model was developed according to the current components of the universe, such as baryons, radiation, dark dark cold and HDE, with interaction in the dark sector, obtaining for the HDE, the functions $\omega(z)$, $r(z)$ and $q(z)$.
- The proposed model was compared graphically ΛCDM, using the referential values for the HDE parameters and the given interactions.
- In the near future we expect to contrast the present scenarios with the observational data (SNe Ia, CC, BAO, CMB), using Bayesian statistics.
- We will also obtain the best fitting values for the model parameters and the use bayesian model selection criteria to compare these modells to ΛCDM.

Conclusions and Perspectives.

- A theoretical model was developed according to the current components of the universe, such as baryons, radiation, dark dark cold and HDE, with interaction in the dark sector, obtaining for the HDE, the functions $\omega(z)$, $r(z)$ and $q(z)$.
- The proposed model was compared graphically ΛCDM, using the referential values for the HDE parameters and the given interactions.
- In the near future we expect to contrast the present scenarios with the observational data (SNe Ia, CC, BAO, CMB), using Bayesian statistics.
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Universe with holographic dark energy(Article)(Open Access)

[Universo con energía oscura holográfica]

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Abstract

In this work we explore a Holographic Dark Energy Model in a flat Friedmann-Lemaître-Robertson-Walker Universe, which contains baryons, radiation, cold dark matter and dark energy within the framework of General Relativity. Furthermore, we consider three types of phenomenological interactions in the dark sector. With the proposed model we obtained the algebraic expressions for the cosmological parameters of our interest: the deceleration and coincidence parameters. Likewise, we graphically compare the proposed model with the ΛCDM model.

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Bayesian comparison of interacting modified holographic Ricci dark energy scenarios

Antonella Cid, Carlos Rodriguez-Benites, Mauricio Cataldo & Gonzalo Casanova

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Abstract

We perform a Bayesian model selection analysis for interacting scenarios of dark matter and modified holographic Ricci dark energy (MHRDE) with linear interacting terms. We use a combination of some of the latest cosmological data such as type Ia supernovae, cosmic chronometers, the local value of the Hubble constant, baryon acoustic oscillations measurements and cosmic microwave background through the angular scale of the sound horizon at last scattering. We find moderate/strong evidence against all the MHRDE interacting scenarios studied with respect to ΛCDM when the full joint analysis is considered.

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