Cosmology in the Dark Sector with Sign-Changeable Interactions

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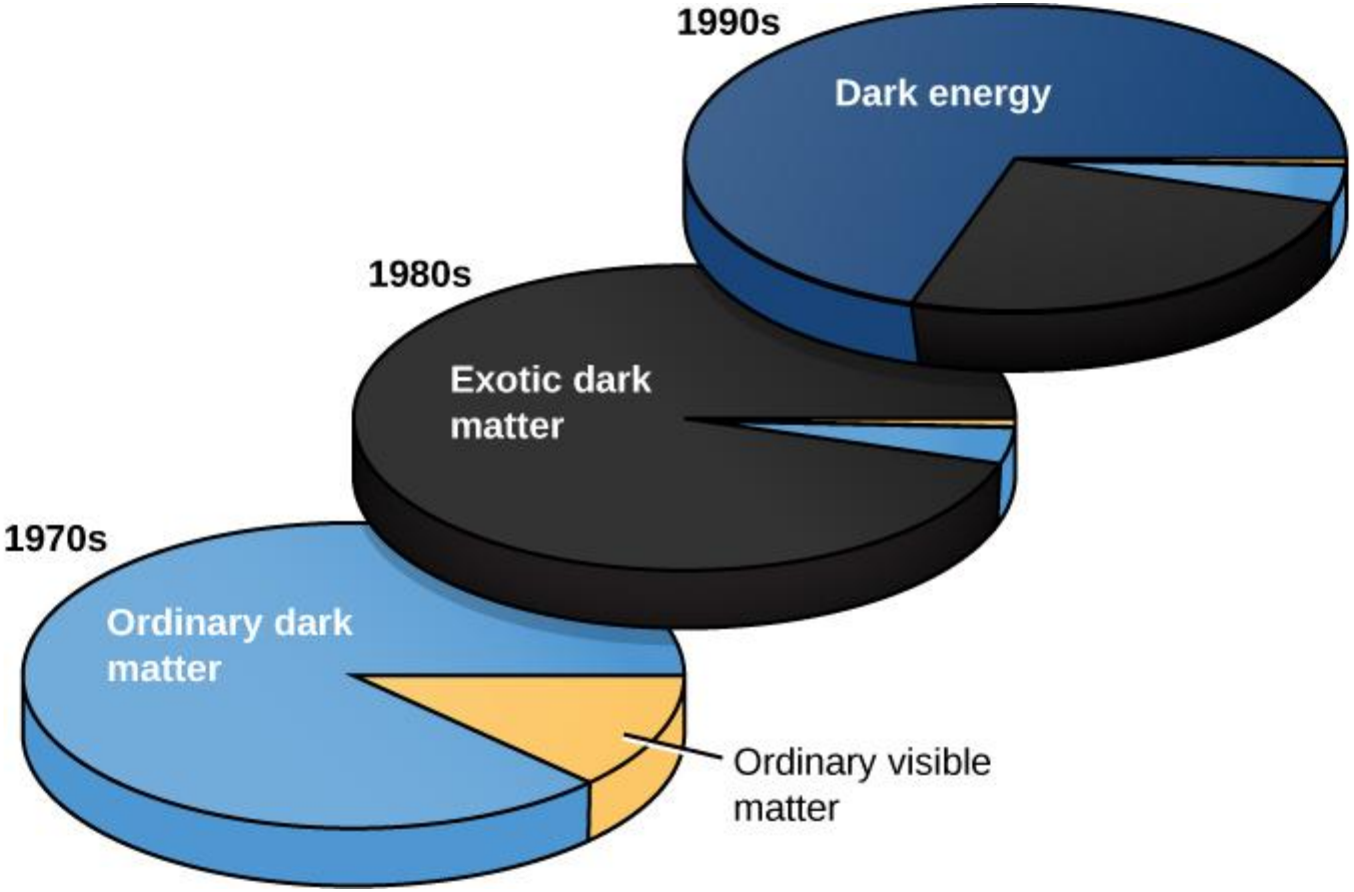
Outline

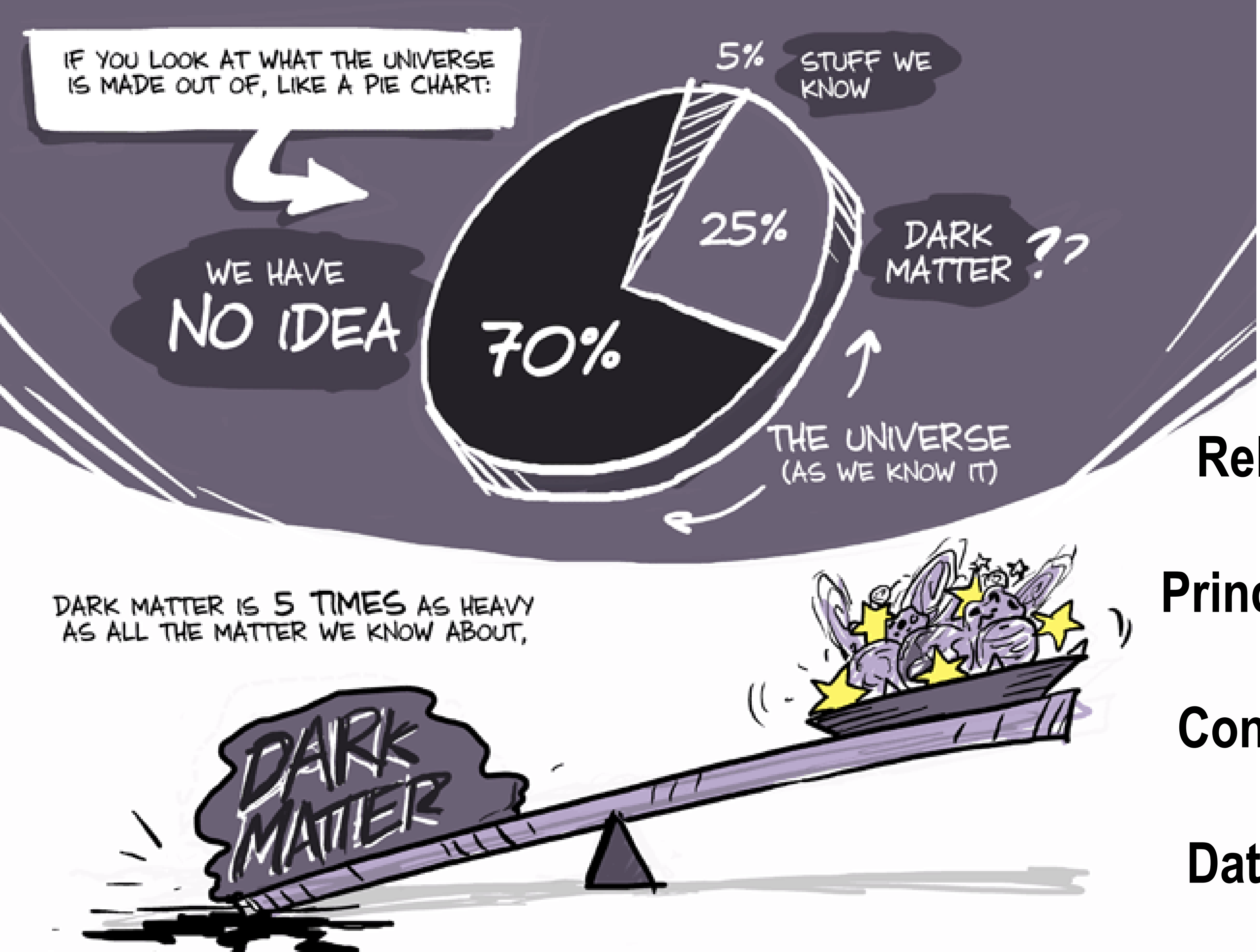
1. Cosmology in the Dark Sector

2. Cosmological Interactions

3. Constraints

1. Cosmology in the Dark Sector





Relatividad General

+

Principio Cosmológico

+

Contenido de Materia

+

Datos Astronómicos

Relatividad General

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

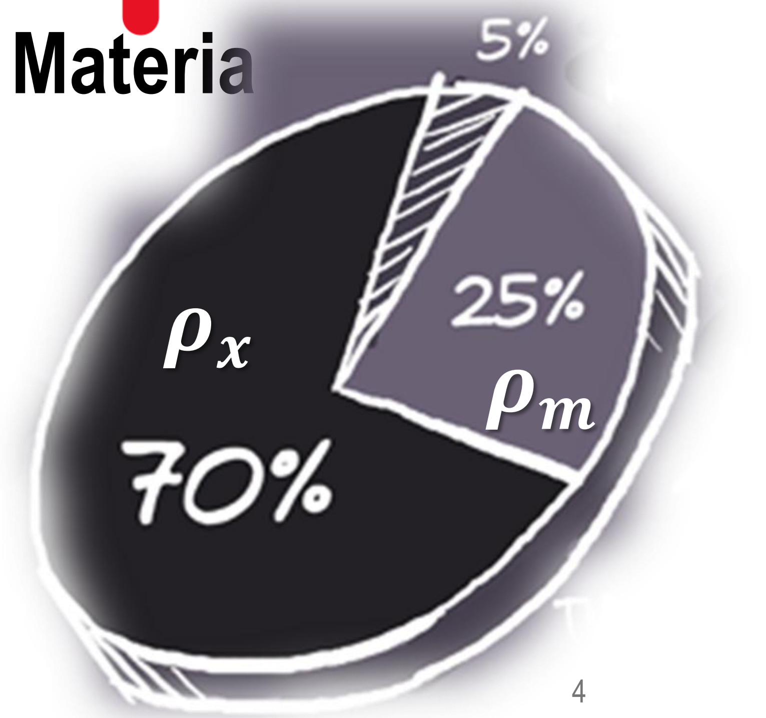
geometría del espaciotiempo

distribución de materia y energía

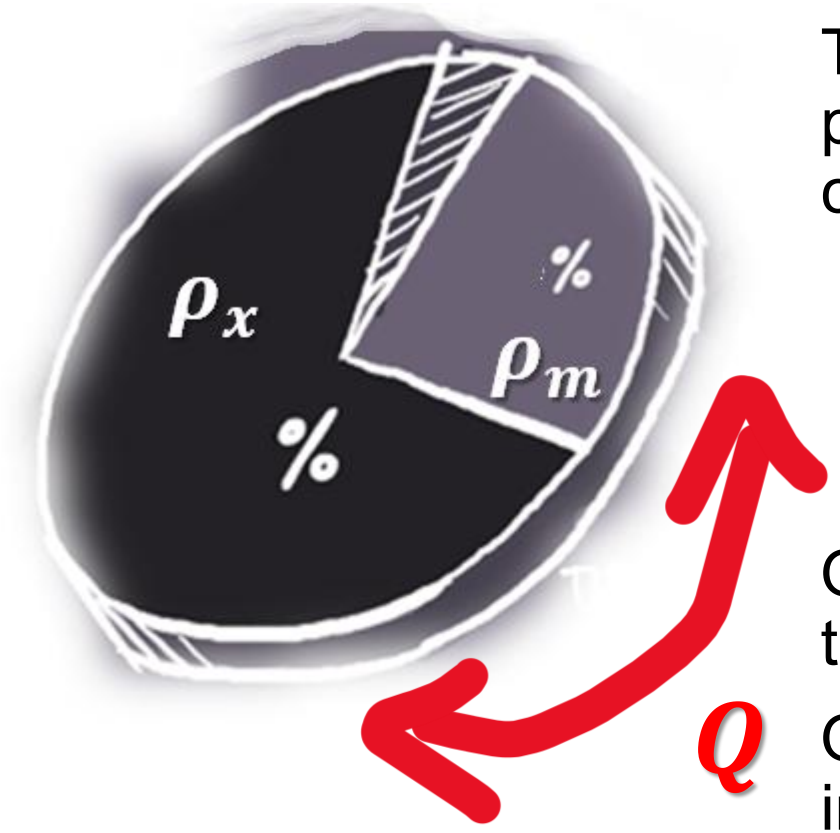
@jsdiaz_

Principio Cosmológico **Contenido de Materia**

Datos Astronómicos



2. Cosmological Interactions



The unknown nature of the dark sector allows us to explore possible cosmological interactions between its components.

$$\dot{\rho}_m + 3H\rho_m = Q,$$
$$\dot{\rho}_x + 3H(1+w)\rho_x = -Q,$$

Question 1: Should such interactions involve energy transfer in only one direction?

Question 2: Can we obtain constraints on these interactions from a thermodynamic perspective?

We review various models from different origins in an attempt to answer these questions.

2. Cosmological Interactions

The CosmoVerse White Paper: Addressing observational tensions in cosmology with systematics and fundamental physics

CosmoVerse Network Collaboration • Eleonora Di Valentino (Sheffield U.) Show All(543)

Apr 2, 2025

416 pages

Published in: *Phys.Dark Univ.* 49 (2025) 101965

- **Interacting Dark Matter and Dark Energy (IDE) Models**: Interacting Dark Matter and Interacting Dark Energy (IDE) models (Sec. 4.2.3) propose a non-trivial energy exchange between DM and DE, modifying both the cosmic expansion rate and structure growth. This interaction, described by a coupling function Q, allows energy to transfer from one component to the other. Depending on the direction and strength of the coupling, IDE can either slow down or accelerate the expansion rate. IDE models can increase H_0 estimates while modifying the growth of structure, offering a way to reduce the S_8 tension simultaneously. However, strong constraints from CMB lensing and BAO measurements limit the parameter space of IDE models, and they often require fine-tuning to remain consistent with multiple datasets.

In order for IDE models to be viable candidates for addressing the H_0 and σ_8 tensions, special attention must be given to the physicality of the parameter space [2947]. In these models, there is not always a mechanism to halt the energy transfer when either the DM or DE density becomes zero (i.e., $Q \neq 0$ in Eq. (4.15) when $\rho_{\mathrm{DE/DM}} = 0$), which can lead to negative energies. The case of $Q > 0$ corresponds to an energy transfer from DE to DM. It has been reported that CMB observations seem to favor an energy transfer from DE to DM, WL measurements and thermodynamical considerations suggest an energy transfer from DM to DE [2050, 2948–2950].

2. Cosmological Interactions

Interaction Q
$3H(\delta_{\rm dm}\rho_{\rm dm} + \delta_{\rm de}\rho_{\rm de})$
$3H\delta(\rho_{\rm dm} + \rho_{\rm de})$
$3H\delta(\rho_{\rm dm} - \rho_{\rm de})$
$3H\delta\rho_{\rm dm}$
$3H\delta\rho_{\rm de}$
$3H\delta\left(\frac{\rho_{\rm dm}\rho_{\rm de}}{\rho_{\rm dm}+\rho_{\rm de}}\right)$
$3H\delta\left(\frac{\rho_{\rm dm}^2}{\rho_{\rm dm}+\rho_{\rm de}}\right)$
$3H\delta\left(\frac{\rho_{\rm de}^2}{\rho_{\rm dm}+\rho_{\rm de}}\right)$

$$\dot\rho_{\rm DM} + 3H\rho_{\rm DM} = \frac{\gamma}{a^3}, \quad \dot\rho_\Lambda = -\frac{\gamma}{a^3},$$

as $\sim a^{-3}$ since the current is covariantly conserved.

III. Interacting Dark Energy: Summary of Models, Pathologies, and Constraints

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(Dated: October 20, 2025)

We present an overview of the main results from our two companion papers that are relevant for observational constraints on interacting dark energy (IDE) models. We provide analytical solutions for the dark matter and dark energy densities, $\rho_{\rm dm}$ and $\rho_{\rm de}$, as well as the normalized Hubble function $h(z)$, for eight IDE models. These include five linear IDE models, namely $Q = 3H(\delta_{\rm dm}\rho_{\rm dm} + \delta_{\rm de}\rho_{\rm de})$ and four special cases: $Q = 3H\delta(\rho_{\rm dm} + \rho_{\rm de})$, $Q = 3H\delta(\rho_{\rm dm} - \rho_{\rm de})$, $Q = 3H\delta\rho_{\rm dm}$, and $Q = 3H\delta\rho_{\rm de}$, together with three non-linear IDE models: $Q = 3H\delta\left(\frac{\rho_{\rm dm}\rho_{\rm de}}{\rho_{\rm dm}+\rho_{\rm de}}\right)$, $Q = 3H\delta\left(\frac{\rho_{\rm dm}^2}{\rho_{\rm dm}+\rho_{\rm de}}\right)$, and $Q = 3H\delta\left(\frac{\rho_{\rm de}^2}{\rho_{\rm dm}+\rho_{\rm de}}\right)$. For these eight models, we present conditions to avoid imaginary, undefined, and

[2966]. Other model types, such as exponential models $Q = 3H\xi\rho_{\rm DE}\exp(\rho_{\rm DE}/\rho_{\rm DM} - 1)$
s $Q = 3H\xi\rho_{\rm DE}\log(\rho_{\rm DE}/\rho_{\rm DM})$ and $Q = 3H\xi\rho_{\rm DE}\log(\rho_{\rm DM}/\rho_{\rm DE})$ [2968], were studied but s
g results.
ms $Q = 3H\xi\rho_{\rm DE}\sin(\rho_{\rm DE}/\rho_{\rm DM} - 1)$ and $Q = 3H\xi\rho_{\rm DE}[1 + \sin(\rho_{\rm DE}/\rho_{\rm DM} - 1)]$ have

Q = 3Hξ F(ρDE, ρDM)

Q = 3HξρDM^p ρ DE^s (ρDM+ρDE)^ r

Q = 3Hξ (ρDM + ρDE + ρDMρDE /(ρDM+ρDE))

1. **The cosmological constant problem:** The predicted energy density of a cosmological constant Λ is approximately 120 orders of magnitude smaller than the predicted value. [3]. This does not directly motivate research into IDE models, but provides a reason to consider DE models beyond the ΛCDM model.
2. **The coincidence problem:** The densities of DM and DE are observed to have the same order of magnitude today, even though they are predicted to differ by many orders of magnitude in both the past and the future [4–16]. This provided the initial motivation to specifically study IDE models.
3. **The Hubble tension:** The $4\sigma - 6\sigma$ discrepancy in the estimation of the present expansion rate H_0 from late-time probes such as Type Ia Supernova and early-time probes such as CMB. The potential of IDE models to address this tension has caused a resurgence in their popularity in recent years [17–64].
4. **The S_8 discrepancy:** The $2\sigma - 5\sigma$ discrepancy between early-time and late-time measurements of the parameter S_8, which is related to the clumping of matter on cosmological scales. IDE models have been investigated to possibly alleviate this tension along with the H_0 tension [19, 21, 50, 51, 56, 60–62, 65–69].
5. **Hints of dynamical dark energy**: Recent measurements from DESI collaboration of baryonic acoustic oscillations (BAO) provide a $2.8\sigma - 4.2\sigma$ preference for dynamical DE over the ΛCDM model [70–73] (see also [74–125]). IDE models provide a natural mechanism for the dynamical behavior of DE, thus reinvigorating the interest in these models.

What about cosmological interactions that change sign?

On the other hand, the authors of Ref.[10] use observational data to analyze a generic type of cosmological interaction and find that its sign changes during the evolution of the universe. Later, motivated by Ref.[10], the authors of Ref.[11] find a sign change in the cosmological interaction which is described by a running coupling in the cosmic interaction between dark energy and dark matter. Ref.[12] proposes a model consistent with thermodynamics and observational constraints, where interaction is proportional to the difference between the energy densities of dark components. In the context of this model, there is a natural change in the interaction sign which coincides with the time when dark energy starts to dominate over dark matter during evolution. This change in sign is explored further in [13] where they analyze a parametrization of the cosmological interaction that changes sign as the scale factor evolves.
In Ref.[14] a dynamical system analysis was performed for a type of cosmological interaction proportional to the deceleration parameter with the dark energy component modeled by a scalar field, a sign change was naturally induced in the interaction term when the sign of the deceleration parameter changes in the transition from a decelerated universe to an accelerated one, finally the authors find that some scaling attractors could alleviate the cosmological coincidence problem. Other examples of cosmological interaction proportional to the deceleration parameter are found in the literature [15, 16, 17, 18].

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Observational constraints on sign-changeable interaction models and alleviation o the H_0 tension

Supriya Pan (Presidency U., Kolkata), Weiqiang Yang (Liaoning Normal U.), Chiranjeeb Singha (IISER, Kolkat Mohanpur), Emmanuel N. Saridakis (Natl. Tech. U., Athens and USTC, Hefei) (Mar 26, 2019)

Published in: *Phys.Rev.D* 100 (2019) 8, 083539 • e-Print: 1903.10969 [astro-ph.CO]

pdf DOI cite claim reference search 13

Non-linear interactions in cosmologies with energy exchange

John D. Barrow, Georgia Kittou

Jul 15, 2019

15 pages

Published in: *Eur.Phys.J.C* 80 (2020) 2, 120

Phase space analysis of sign-shifting interacting dark energy models

Sudip Halder (Presidency U., Kolkata), Jaume de Haro (Barcelona, Polytechnic U.), Tapan Saha (Presidency U., Kolkata), Supriya Pan (Presidency U., Kolkata and DUT, Durban)

Mar 3, 2024

30 pages

Published in: *Phys.Rev.D* 109 (2024) 8, 083522

Dark Energy Is Not That Into You: Variable Couplings after DESI DR2 BAO

Weiqiang Yang (Liaoning Normal U.), Sibo Zhang (Liaoning Normal U.), Olga Mena (Valencia U., IFIC), Supriya Pan (Presidency U., Kolkata and DUT, Durban), Eleonora Di Valentino (U. Sheffield (main))

Aug 26, 2025

16 pages

e-Print: 2508.19109 [astro-ph.CO]

View in: ADS Abstract Service

On sign-changeable interaction in FLRW cosmology

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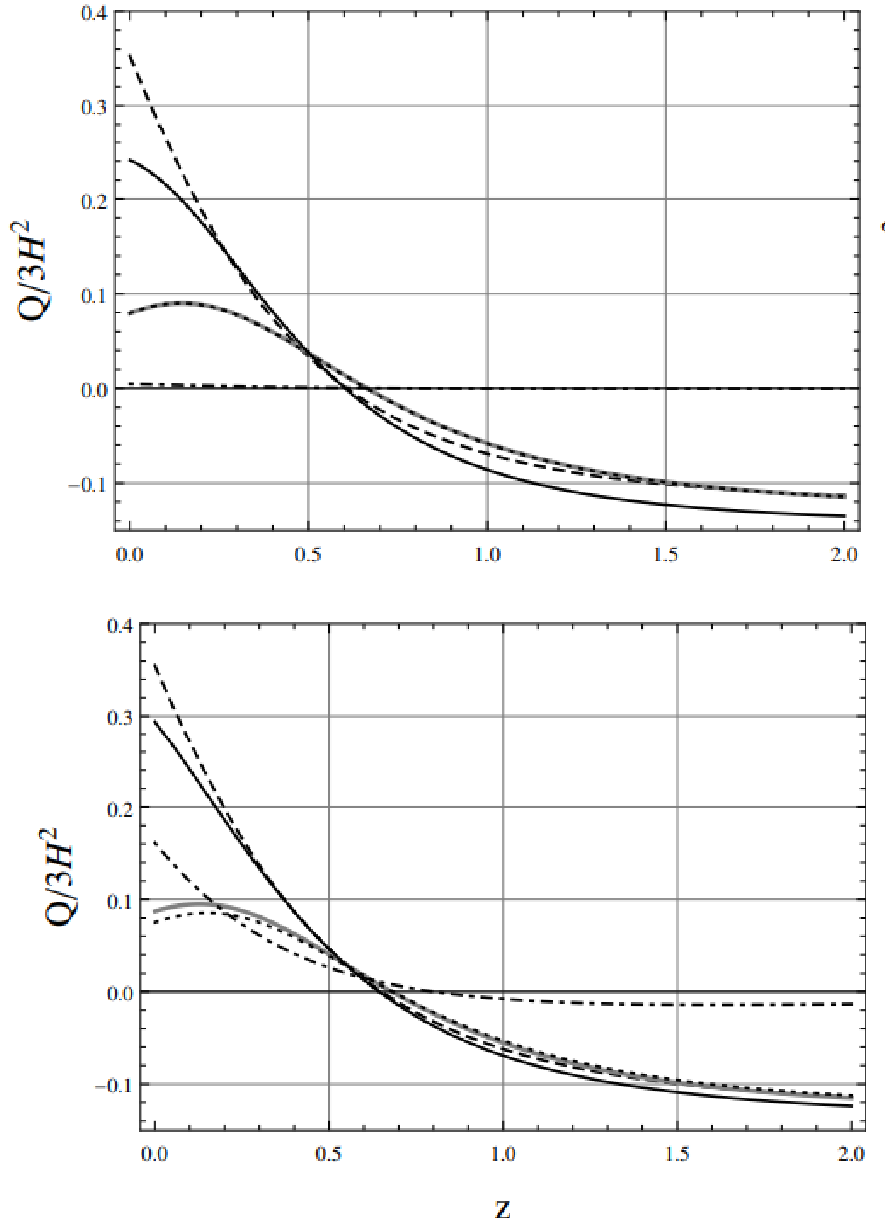
January 15, 2019

sign-changeable interaction depend

e form, $Q(\rho,\rho') = \rho[q_1 + q_2 q + q_3 q^2]$.

Interactions	$Q(\rho,\rho')$
$\alpha_1\,\rho\,q$	$Q_1 = -\alpha_1\,\rho\left(1+\frac{3}{2}\frac{\rho'}{\rho}\right)$
$\alpha_2\,\rho'\,q$	$Q_2 = -\alpha_2\,\rho\left(\frac{\rho'}{\rho}+\frac{3}{2}\left[\frac{\rho'}{\rho}\right]^2\right)$
$\alpha_3\,\rho_m\,q$	$Q_3 = \frac{\alpha_3}{\Delta}\,\rho\left(\gamma_x+\left(1+\frac{3}{2}\gamma_x\right)\frac{\rho'}{\rho}+\frac{3}{2}\left[\frac{\rho'}{\rho}\right]^2\right)$
$\alpha_4\,\rho_x\,q$	$Q_4 = -\frac{\alpha_4}{\Delta}\,\rho\left(\gamma_m+\left(1+\frac{3}{2}\gamma_m\right)\frac{\rho'}{\rho}+\frac{3}{2}\left[\frac{\rho'}{\rho}\right]^2\right)$
$(\alpha\,\rho+\beta\,\rho')q$	$Q = -\rho\left(\alpha+\left(\beta+\frac{3}{2}\alpha\right)\frac{\rho'}{\rho}+\frac{3}{2}\beta\left[\frac{\rho'}{\rho}\right]^2\right)$



action term. The left panel corresponds to
figures consider the analysis JLA+H_0+H(z).

Dynamics and statefinder analysis of a class of sign-chan
interacting dark energy scenarios

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Received: date / Accepted: date

Abstract We revise the dynamical properties of a class of cosmological models where
interacts through an interacting term that changes sign during evolution. In partic
the critical points and we investigate the existence and stability conditions for cosmolo
describing radiation, matter and dark energy dominated eras. We find that all the
admit a stable critical point corresponding to an accelerated phase. We use background data to find
the best fit parameters for one of the studied models, resulting an interacting
definite sign within 1σ confidence level, consistent with the results of the dynami
We also compute the statefinder parameters and plot the $r-q$ and $r-s$ planes
different trajectories when we vary the interaction parameter for a specific model
the interacting scenario. We can in this sense distinguish among models, incl

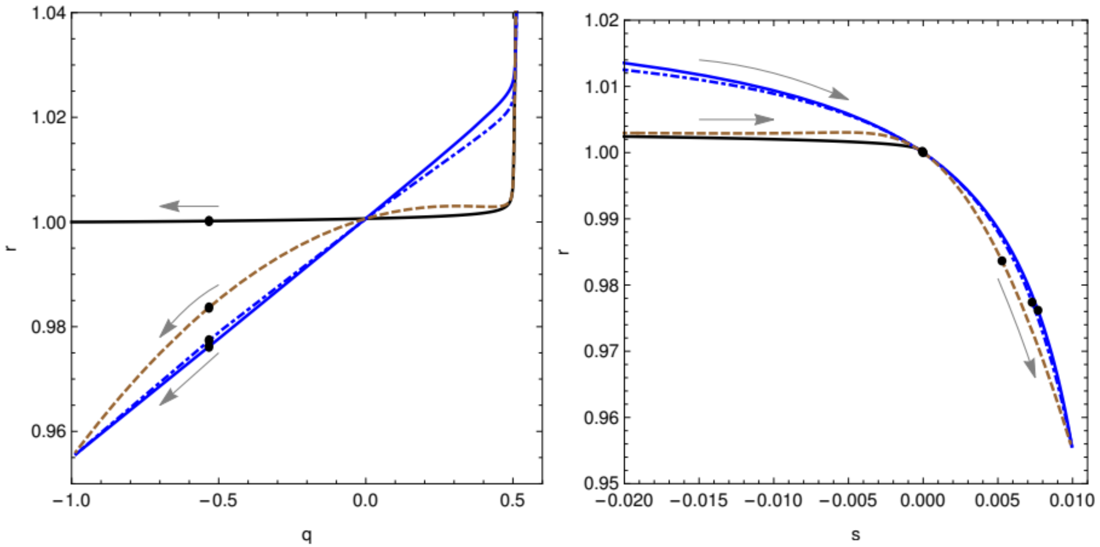

Fig. 12 The figure shows the planes $r-q$ (left) and $r-s$ (right) for the Γ_{1T}, Γ_{1d} and Γ_{1x} models in the case $\alpha = 0.01$. Black dots indicate current values and gray arrows the evolution's direction. The solid black line represents ΛCDM, meanwhile, blue solid, blue dot-dashed and brown lines indicate Γ_{1T}, Γ_{1d} and Γ_{1x}, respectively.

$$\Gamma_{1i} = \alpha_{1i}\, q\, \rho_i, \qquad i = T, d, c, x$$
$$\Gamma_{2j} = \alpha_{2j}\, q\, \rho_j', \qquad j = T, d, c$$

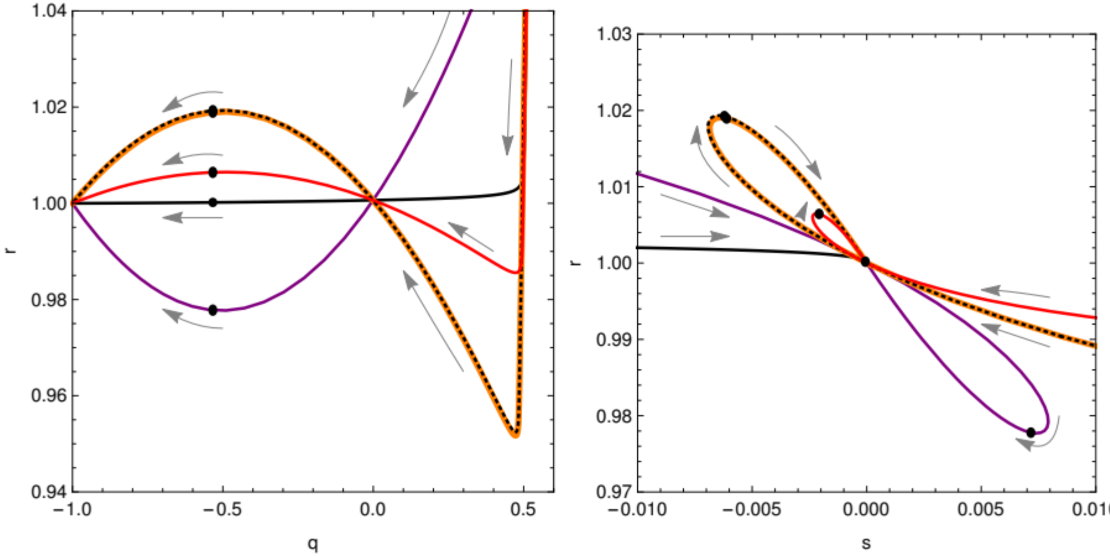

Fig. 13 The figure shows the planes $r-q$ (left) and $r-s$ (right) for the models Γ_{2T} and Γ_{1c} in the case $\alpha = -0.01$ and models Γ_{2c} and Γ_{2d} in the case $\alpha = 0.01$. Black dots indicate current values and gray arrows the evolution's direction. The solid black line represents ΛCDM, meanwhile, purple, red, orange and black dotted lines correspond to models Γ_{2T}, Γ_{1c}, Γ_{2d} and Γ_{2c}, respectively.

Physics of the Dark Universe 50 (2025) 102155

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Physics of the Dark Universe

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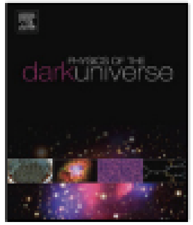

Full length article

On the Gaussian assumption in the estimation of parameters for dark energy models

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[b] Universidad del Bío-Bío, Departamento de Estadística, Concepción, 4051381, Región del Bío-Bío, Chile

ARTICLE INFO

Keywords:
Distribution
Supernovae
Bimodal

ABSTRACT

The assumption of Gaussian distribution in Type Ia supernova data underlies most cosmological parameter estimates and led to the discovery of late acceleration. In this work, we assess the validity of this assumption using the Pantheon+ dataset and analyze its impact on parameter estimation for dark energy cosmological models.

We perform a comprehensive statistical, analysis including the Lilliefors and Jarque–Bera tests, to assess the normality of both the data and model residuals. We find that the Gaussianity assumption is untenable and that the redshift distribution is more accurately described by a t-distribution, as indicated by the Kolmogorov Smirnov test.

These statistical findings are explored within the framework of a nonlinear cosmological interaction for the dark sector. Free parameters are estimated using multiple methods, and bootstrap confidence intervals are constructed for them. Our results suggest that standard Gaussian assumptions may underestimate uncertainties in cosmological inference, and we advocate for incorporating more flexible statistical models in future analyses.

$$\alpha\dot{\rho}_x + 3\beta H\rho_x\right) = q\left(\alpha\rho'_x + \beta\rho_x\right), \quad (5)$$

ınd β are constants. If both these constants are null, it implies
: is no cosmological interaction present. These interactions naturally undergo a sign change at some point during their evolution, due to the q term. By focusing in a particular case for Q, $\alpha = \frac{2}{3\gamma_m - 2}$, we can obtain a solution for (4) using the methods described in [21]. We then obtain the total energy density as:

$$\rho = c_1 a^{3/4\lambda_+} + c_2 a^{3/4\lambda_-}, \quad (6)$$

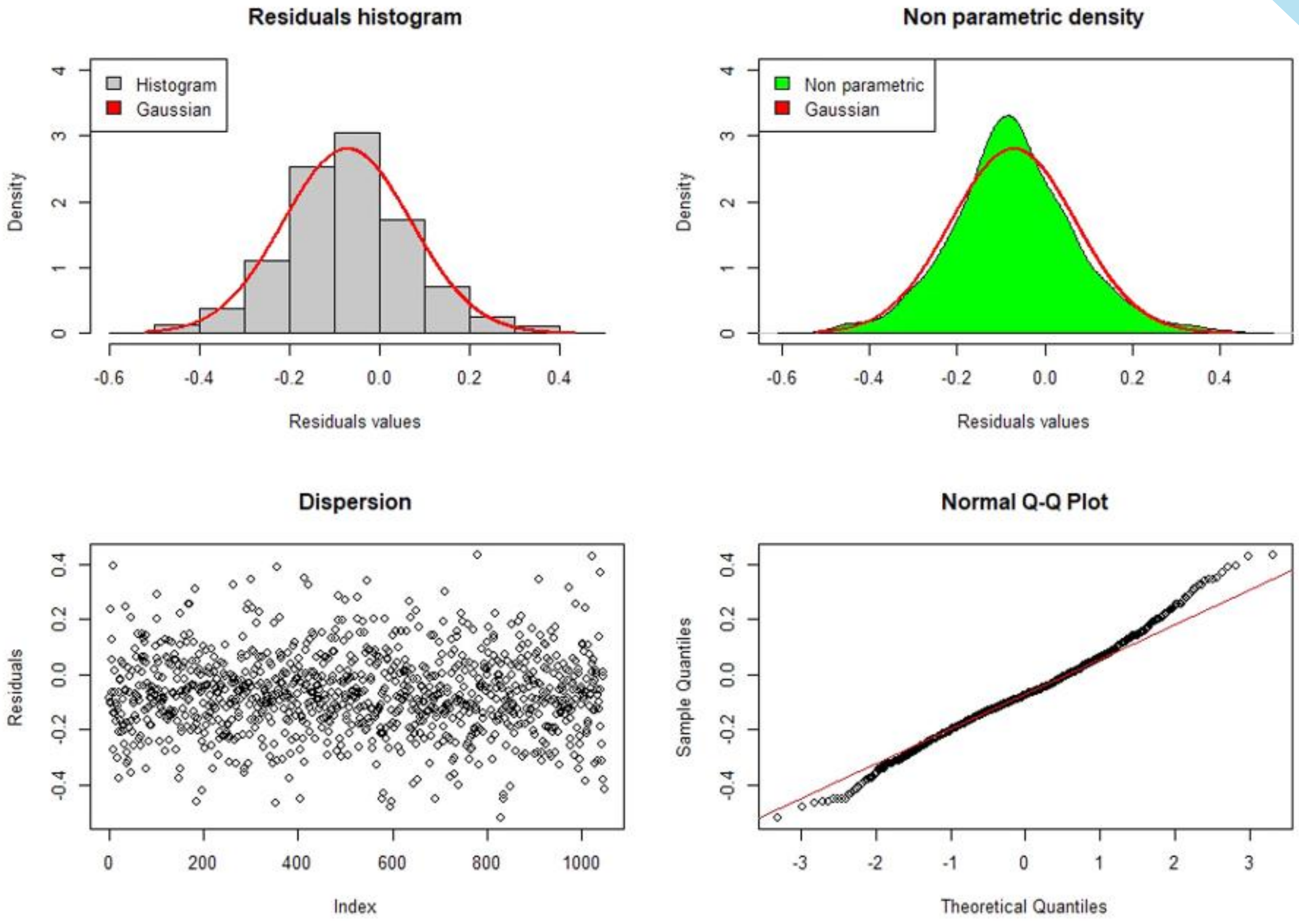

Fig. 2. Analysis of the density of the residuals of the fitted model.

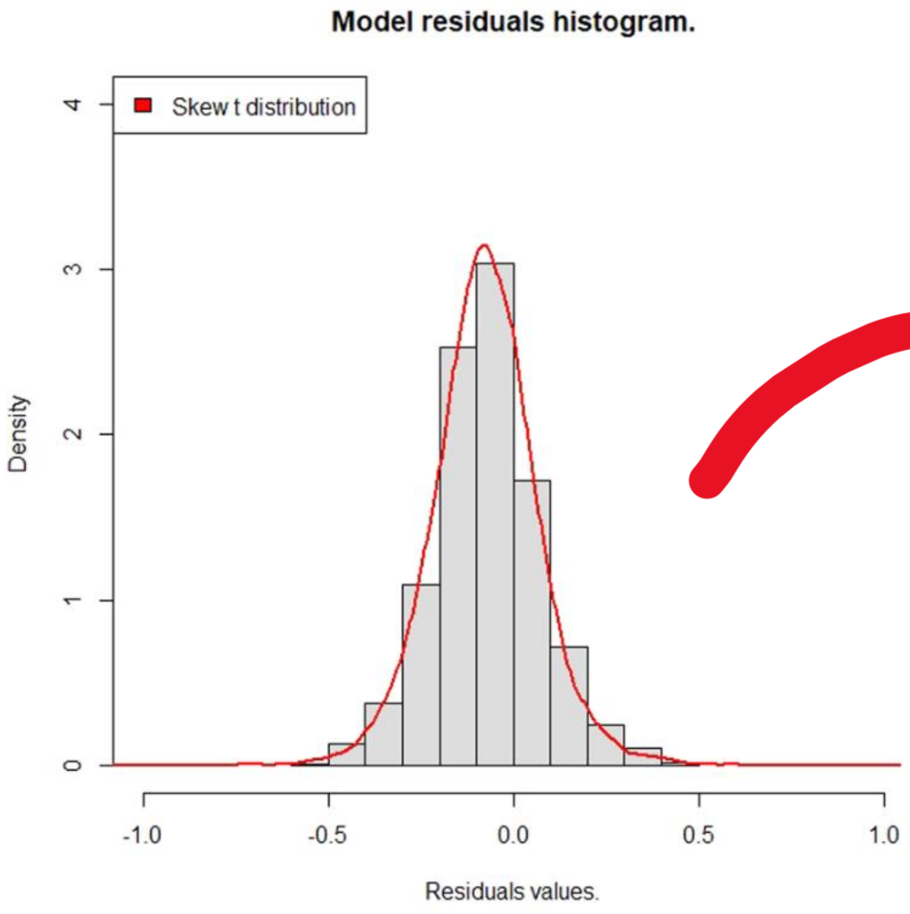

Fig. 3. Fitted Skew t Distribution.

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Table 2
Results from the analysis with different methods, Grid, EM and GRadient, for interaction Q. Fixed a priori parameters are denoted with
refers to the minimum sum of squares for the Grid and Gradient methods and to the maximum for the EM algorithm.

	Ω_m	H_0	γ_m	γ_x	β
I	0.34	0.74	1.12	−0.28	0.15*
	0.32	0.74	1.14	−0.24	0.15*
	0.3371	0.7449	1.1239	−0.2760	0.15*
II	0.34	0.66	1*	−0.11	0.15*
	0.35	0.68	1*	−0.13	0.15*
	0.3485	0.7294	1*	−0.1241	0.15*
III	0.26	0.74	1.19	−0.151*	0.15*
	0.25	0.72	1.22	−0.151*	0.15*
	0.2576	0.7451	1.1940	−0.151*	0.15*
IV	0.34	0.66	1*	−0.115*	0.15*
	0.35	0.73	1*	−0.115*	0.15*
	0.3482	0.6626	1*	−0.115*	0.15*
V	0.26	0.74	1.2*	−0.13*	0.15*
	0.26	0.68	1.2*	−0.13*	0.15*
	0.2602	0.7456	1.2*	−0.13*	0.15*
VI	0.25	0.67	1*	0*	−0.45
	0.25	0.67	1*	0*	−0.42
	0.2517	0.6688	1*	0*	−0.4471

F. Arevalo et al.

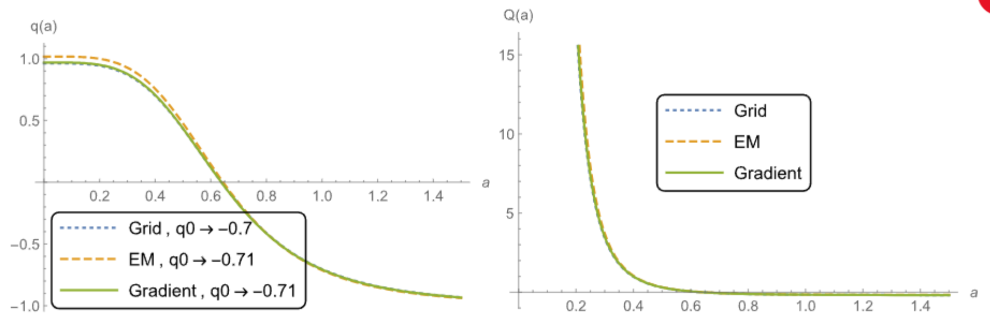

Fig. 4. The deceleration parameter and the interaction are plotted using the results of Table 1, case I, 4 free parameters.

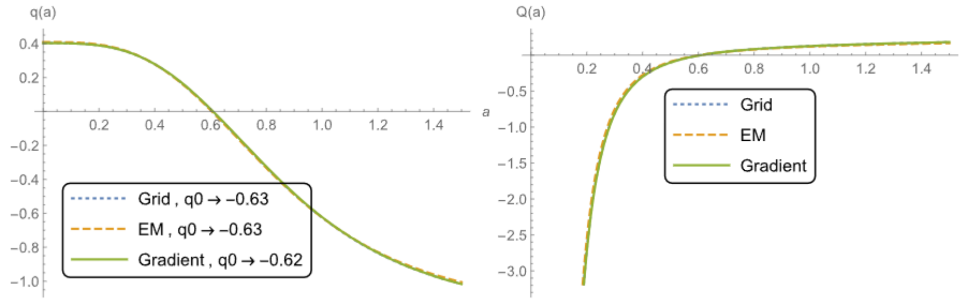

Fig. 5. The deceleration parameter and the interaction are plotted using the results of Table 1, case VI, 3 free parameters for $\gamma_x = 0$ and $\gamma_m = 1$.

3. Constraints

Thermodynamics of interacting holographic dark energy

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January 5, 2016

Abstract

The thermodynamics of a scheme of dark matter-dark energy interaction is studied considering a holographic model for the dark energy in a flat Friedmann-Lemaitre-Robertson-Walker background. We obtain a total entropy rate for a general horizon and we study the Generalized Second Law of Thermodynamics for a cosmological interaction as a free function. Additionally, we discuss two horizons related to the Ricci and Ricci-like model and its effect on an interacting system.

3 Horizons and Dark Energy

In flat FRW, if the horizon is related to the length scale L, the dark energy proposed written as

$$\rho_{DE} \equiv \frac{3c^2}{L^2},$$

where c is a positive constant that fulfill $c^2 < 1$ [46, 47, 48]. In this context, we can

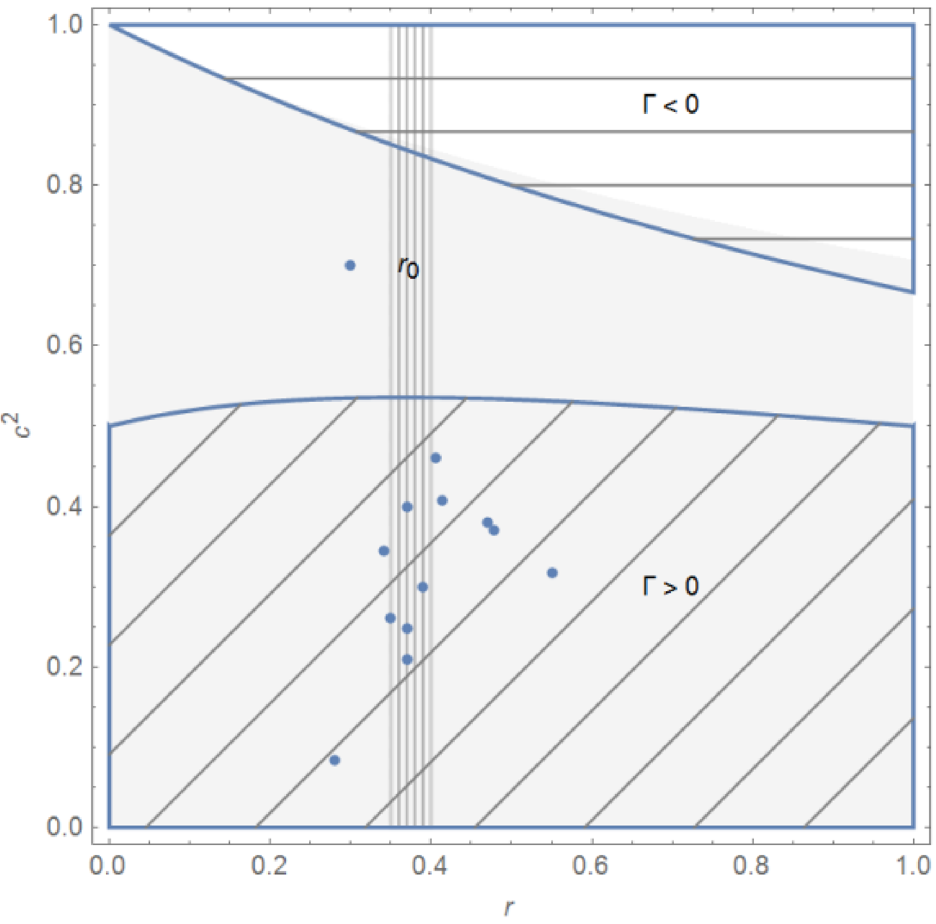
$$\dot{S}_{tot} = \dot{S}_{DE} + \dot{S}_{DM} + \dot{S}_h = 16\pi^2 L\dot{L} - 16\pi^2 L^3 \left(\dot{L} - HL\right) \dot{H},$$

$$\frac{S'_{tot}}{4\pi^2 L^2} = 4 + (2 + 3H^2L^2 + p_{DE}L^2) \times \left[1 + \frac{L^2}{3c^2}\left(3p_{DE} + \frac{Q}{H}\right)\right]$$

El horizonte delimita rango de la interacción

The Ricci dark energy density is

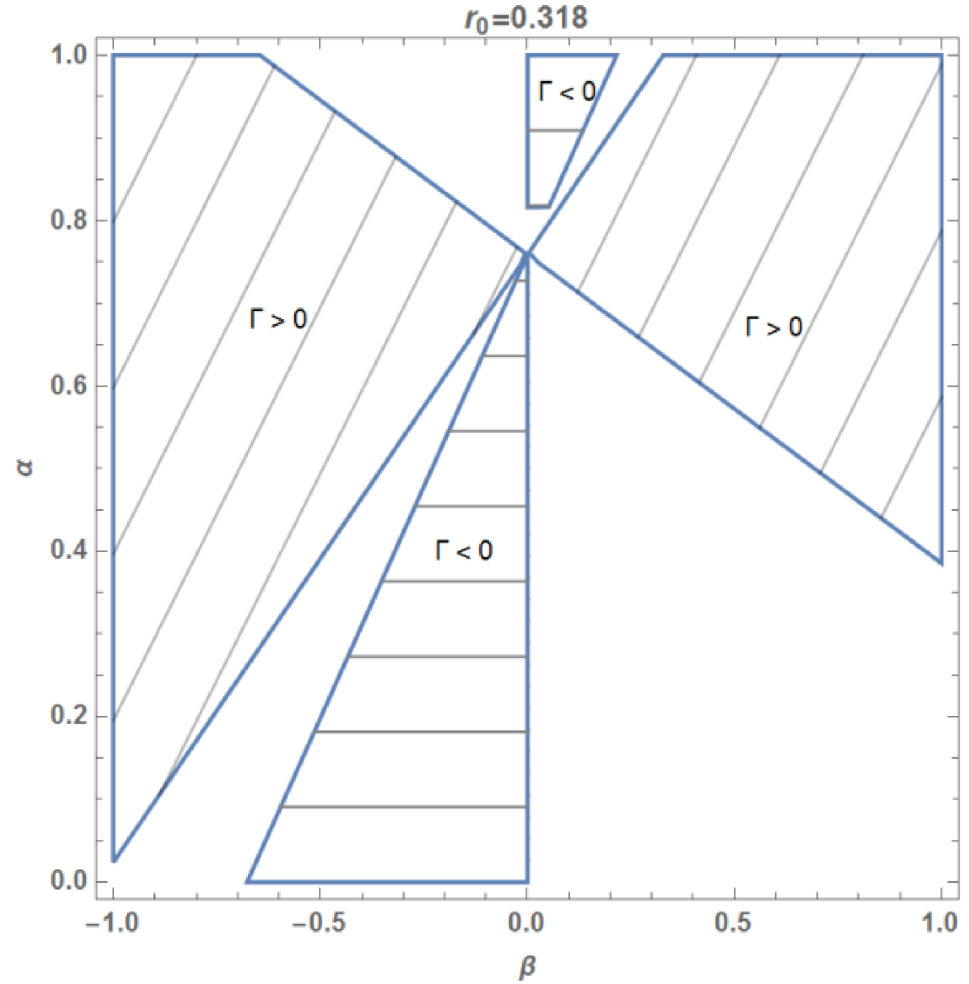
$$\rho_{DE} \equiv 3c^2(2H^2 + \dot{H}),$$



f (r, c^2) considering zones where the interaction Q respects the GSL
shaded area is where the pressure is negative at late times. The dots

Ricci-like dark energy density is given by

$$\rho_{DE} \equiv 3(\alpha H^2 + \beta \dot{H})$$



on the bottom represents the relation between the G
phase space of (α, β) and the graph on the center is t

3. Constraints

New Perspectives from Matter Creation Cosmologies to Dark Sector Interactions

Fabiola Arévalo[1], Antonella Cid[2,3], Victor Cardenas[4], and Patricio Mella[5]

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Received: date / Revised version: date

Abstract We investigate a cosmological model based on matter creation in a single-component universe, its late time behavior and observational constraints derived from type Ia supernova data. Furthermore, we explore the equivalence between this framework and interacting dark sector models, which establishes a connection between the matter creation rate and cosmological interactions. We first focus on the case of a constant equation of state parameter, where both known and novel interaction terms naturally emerge from matter creation, numerous of them exhibiting a sign-changeable behavior. The analysis is then extended to a time-dependent equation of state by using dynamical systems techniques.

The effect of matter creation is characterized by the introduction of a term Γ into the particle number conservation equation [31,32,33]

$$N^a_{;a} = n\Gamma, \qquad (1)$$

where $N^a = nu^a$, n is the number density and u^a is the four-velocity. If $\Gamma > 0$, we have par-

$$\Gamma = \frac{2\dot{H}}{H} + 3H,$$

$$\dot{\rho} + 3H\rho = \rho\Gamma.$$

One fluid

$$w_{\rm eff} = -\frac{\Gamma}{3H},$$

$$w_{\rm eff} = w\frac{\rho_x}{3H^2},$$

$$\Gamma = -\frac{\rho_x w}{H}.$$

two fluids

New Perspectives from Matter Creation Cosmologies to Dark Sector Interactions

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Comparing Eq. (18) with Eq. (12), we obtain Γ related to the dark energy as

$$\Gamma = -\frac{\rho_x w}{H}. \tag{19}$$

Since the dark energy density depends on the matter creation rate Γ, Eq. (19) implies that the interaction term Q in (20) is directly related to Γ by

$$\frac{Q}{H} = -\left(\frac{\Gamma}{w}\right)^{\cdot} + \frac{\Gamma}{2w}\left(\Gamma - 3H + 6(1+w)\right). \tag{21}$$

This general result leads to an interaction in terms of Γ, H, w and their derivatives. From Eq. (11), the interaction can be expressed as $Q = Q(q, \dot{q})$, and from Eq. (12) as $Q = Q(w_{\mathrm{eff}}, \dot{w}_{\mathrm{eff}})$. A related connection was previously established for holographic dark energy in Ref. [70], although

3 General Γ Model

In this section we consider a general model given by,

$$\Gamma = 3\gamma H_0 \left(\frac{H}{H_0}\right)^{\delta}, \tag{14}$$

where γ and δ are constants and H_0 is the current value of the Hubble-Lemaître parameter.

$$Q = -\rho_x \left(\frac{\dot{H}}{H}(1+\delta) - \frac{\dot{w}}{w} + 3H(1+w)\right) \tag{25}$$

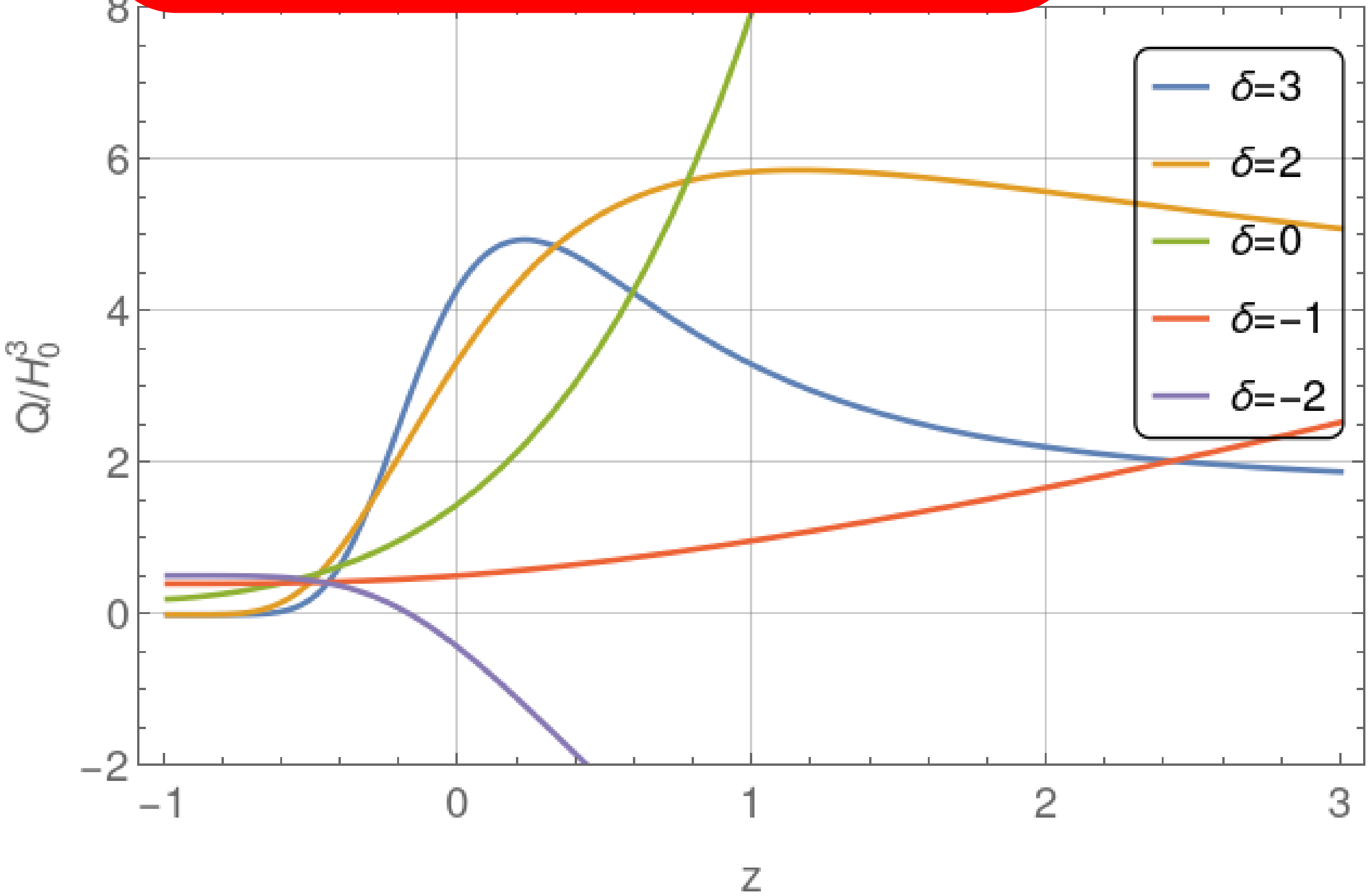
The **sign change is a natural consequence of the matter creation equivalence** and it connects with previous results where the interaction was an ansatz of the deceleration parameter, see for example Refs. [73] and [74]. Notice we can write the interaction (27) in terms of the deceleration parameter,

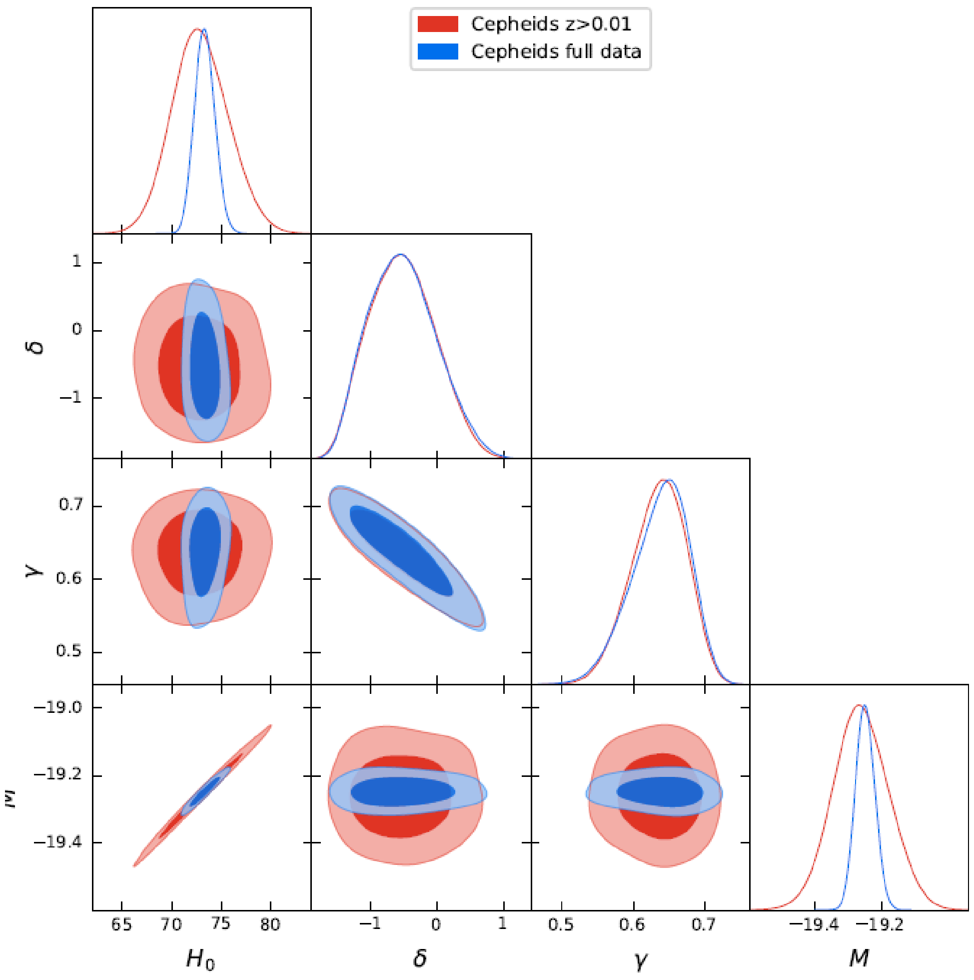
$$Q = 2H^3 \frac{(q - \frac{1}{2})(\delta + (\delta+1)q - 3w - 2)}{w} \tag{28}$$

where we observe that Q changes sign at $q = 1/2$ and $q = -1 + 3\left(\frac{w+1}{\delta+1}\right)$ for $\delta \neq -1$.

$$Q = 3H\left(\frac{1}{2}(\delta - 2w - 1)\rho_x + \frac{(\delta+1)w}{2}\frac{\rho_x^2}{\rho}\right). \quad (27)$$

$$Q = 2H^3\frac{(q-\frac{1}{2})(\delta + (\delta+1)q - 3w - 2)}{w}, \quad (28)$$





Final Remarks

Interactions appear not bound to a especific direction of matter transfer and can be applied to cosm. tension.

Applying thermodynamics to simple models can offer information about the nature of Dark Sector behaviour

Modifying the statistics of data analysis can provide questions about previous results

Thank you for your attention

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Questions?