On the interactions between dark energy and dark matter

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Introduction

- There is overwhelming observational evidence that the Universe is undergoing accelerated expansion.
- This late–time acceleration of the Universe must be driven by some unidentified energy source, generally referred to as dark energy (DE).
- The ΛCDM model is in an excellent agreement with these cosmological probes and its parameters have now been determined to a very good accuracy.
- From a theoretical viewpoint, this concordance cosmology is somewhat troubling:
- Rather than dealing directly with Λ, a number of alternative routes, such as quintessence, have been proposed which skirt around this thorny issue.

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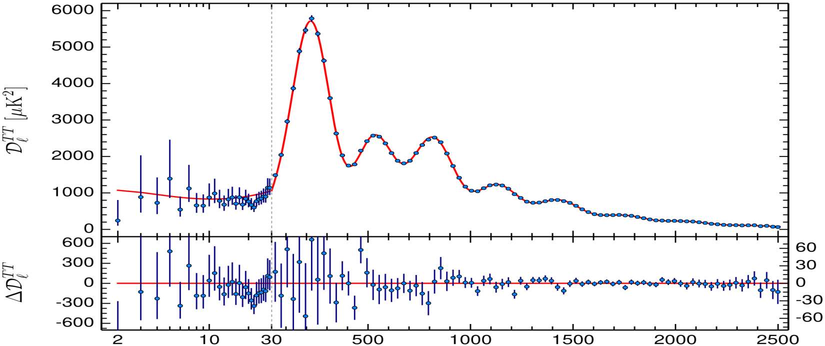

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  - the observed cosmological constant is surprisingly small

    $$\Lambda_{\text{obs.}} \sim \left(10^{-3}\text{eV}\right)^4 \sim \left(10^{-30} M_{\text{Pl}}\right)^4 \ ,$$

    when compared with the theoretical expectation of

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Theoretical Model

We consider the scalar–tensor theory described by the following action:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - V(\phi) + \mathcal{L}_{SM}\right] + \int d^4x\sqrt{-\tilde{g}}\tilde{\mathcal{L}}_{DM}\left(\tilde{g}_{\mu\nu},\psi\right),$$

where $\kappa^2 \equiv M_{\mathsf{Pl}}^{-2} \equiv 8\pi G$ together with

- R – Ricci scalar,
- ϕ – DE scalar field,
- $V(\phi)$ – potential of the scalar field,
- $\mathcal{L}_{SM}$ – Lagrangian which includes a relativistic component r, and a baryon component b.

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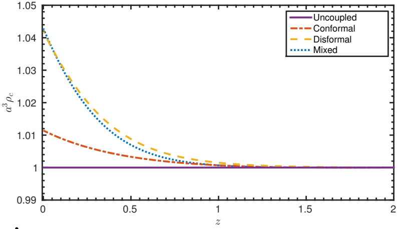
Particle quanta of the DM fields ψ, propagate on geodesics defined by the metric

$$\tilde{g}_{\mu\nu} = C(\phi)g_{\mu\nu} + D(\phi)\,\partial_\mu\phi\,\partial_\nu\phi\ ,$$

- $C(\phi)$ – conformal coupling
  - this is the well–known conformal transformation which characterises the Brans–Dicke class of scalar–tensor theories.
- $D(\phi)$ – disformal coupling
  - this appears in the Einstein frame formulation of any covariant theory involving an invariant other than R.

Theoretical Model – Background Evolution



In the standard flat FRW metric with conformal time τ, and scale factor $a(\tau)$, the Friedmann equations are given by

$$\mathcal{H}^2 = \frac{\kappa^2}{3}a^2\left(\rho_\phi + \rho_b + \rho_r + \rho_c\right) \ ,$$

$$\mathcal{H}' = -\frac{\kappa^2}{6}a^2\left(\rho_\phi + 3p_\phi + \rho_b + 2\rho_r + \rho_c\right) \ ,$$

where coupled DM is denoted by a subscript c, and $\mathcal{H} = a'/a$. The modified Klein–Gordon equation simplifies to

$$\phi'' + 2\mathcal{H}\phi' + a^2 V_{,\phi} = a^2 Q \ ,$$

and the fluid conservation equations reduce to

$$\rho_r' + 4\mathcal{H}\rho_r = 0, \quad \rho_b' + 3\mathcal{H}\rho_b = 0, \quad \rho_c' + 3\mathcal{H}\rho_c = -Q\phi',$$

with the coupling function

$$Q = -\frac{a^2 C_{,\phi} + D_{,\phi}\phi'^2 - 2D\left(\frac{C_{,\phi}}{C}\phi'^2 + a^2 V_{,\phi} + 3\mathcal{H}\phi'\right)}{2\left[a^2 C + D\left(a^2\rho_c - \phi'^2\right)\right]}\rho_c \ .$$

Theoretical Model – Evolution of Perturbations

- The matter growth rate function:

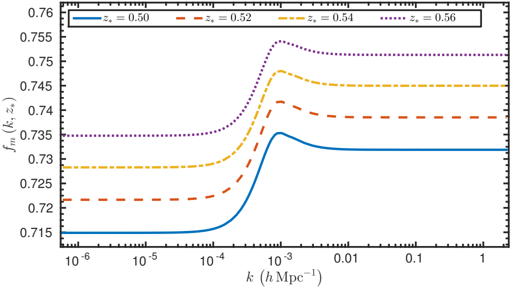
$$f_m = \frac{d\ln\delta_m}{d\ln a} = \frac{\delta_m'}{\mathcal{H}\delta_m}\,,$$

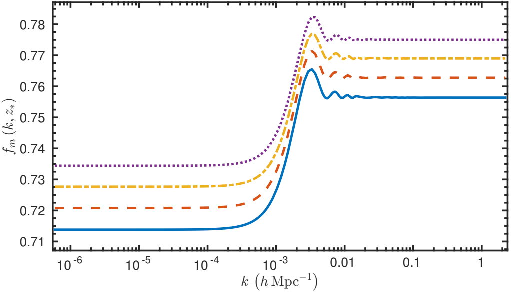
with

  - $\delta_m = \frac{\rho_b\delta_b+\rho_c\delta_c}{\rho_b+\rho_c}$ – matter density contrast
  - δ_b – baryon density contrast
  - δ_c – coupled DM density contrast

- On subhorizon scales DM experiences

$$\frac{\mathcal{H}_{\text{eff}}}{\mathcal{H}} = 1 - \frac{1}{\mathcal{H}}\frac{Q}{\rho_c}\phi'\,,$$
$$\frac{G_{\text{eff}}}{G} = 1 + \frac{2}{\kappa^2}\frac{Q^2}{\rho_c^2}\,.$$

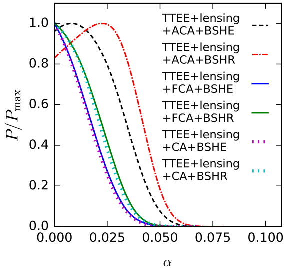


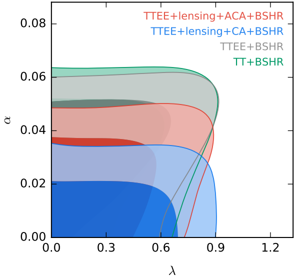


Parameter Constraints

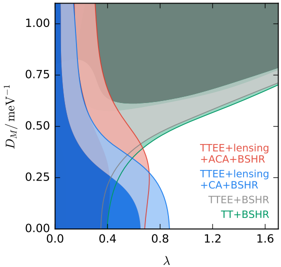
$$C(\phi) = e^{2\alpha\kappa\phi},\ D(\phi) = D_M^4,\ V(\phi) = V_0^4 e^{-\lambda\kappa\phi}$$

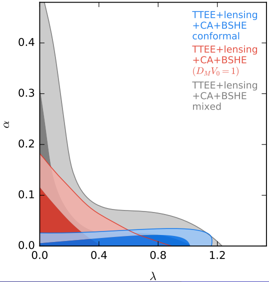
- Conformal Coupling





- Disformal & Mixed Couplings





Conclusions

- The cosmological characteristics of the conformal and disformal couplings were discussed.
- A disformal coupling leads to intermediate–scales time–dependent damped oscillations in the matter growth rate function.
- The conformal coupling is tightly constrained with the CMB, although the disformal coupling is able to evade this probe.
- These interacting DE models enhance the growth of small–scale perturbations, thus do not alleviate the claimed LSS tension.
- Forthcoming data of the LSS, CMB, and their cross-correlations should be able to place tighter constraints on DE couplings.

Thank You