Current status of an interacting dark sector with cosmological observations

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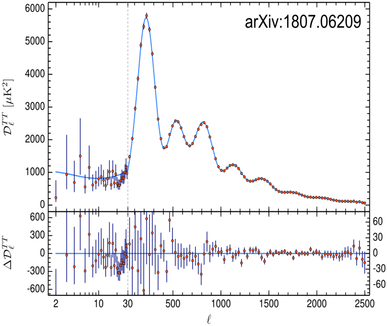
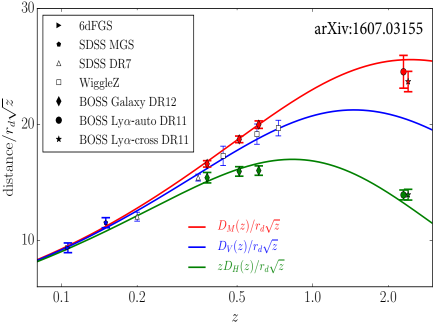
Outline

- 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.





Introduction

- From a theoretical viewpoint, this concordance cosmology is somewhat troubling
  - the observed cosmological constant is surprisingly small

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

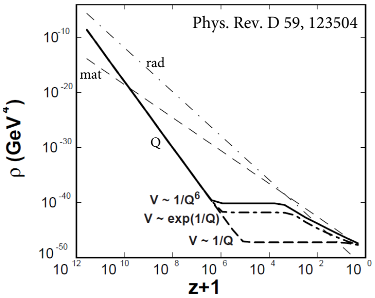
    when compared with the theoretical expectation of the cosmological constant

    $$\Lambda_{\text{theory}} \sim (\text{TeV})^4 \sim 10^{-60} M_{\text{Pl}}^4 .$$

- Rather than dealing directly with the cosmological constant, a number of alternative routes have been proposed which skirt around this thorny issue.

Introduction

- Quintessence models invoke an evolving canonical scalar field with a potential and make use of the scaling properties and tracking nature of such scalar fields evolving in the presence of other background matter fields.



- It is often simply assumed that the components of the dark sector are independent and do not interact directly with each other.
- However, there is no fundamental principle which forbids some form of interplay between dark matter (DM) and DE.
- Indeed, whereas new forces between DE and normal matter particles are heavily constrained by observations (for e.g. by solar system tests), this is not the case for DM particles.

Theoretical Framework

We consider the scalar–tensor theory described by the following action, expressed in the Einstein frame:

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

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

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

[JCAP **1504** (2015) 036, JCAP **1711** (2017) 001]

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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
- $D(\phi)$ – disformal coupling

[Phys. Rev. **D48** (1993) 3641]

Theoretical Framework - Field Equations

- The dark sector coupling leads to the non-conservation of $T^{\phi}_{\mu\nu}$:

$$\Box\phi = V_{,\phi} - Q \ ,$$

where

$$Q = \frac{C_{,\phi}}{2C} T_{DM} + \frac{D_{,\phi}}{2C} T^{\mu\nu}_{DM} \nabla_\mu \phi \nabla_\nu \phi - \nabla_\mu \left[\frac{D}{C} T^{\mu\nu}_{DM} \nabla_\nu \phi \right] \ ,$$

and T_{DM} is the trace of $T^{\mu\nu}_{DM}$, which satisfies a modified conservation equation

$$\nabla^\mu T^{DM}_{\mu\nu} = Q \nabla_\nu \phi \ .$$

- The uncoupled SM particles are governed by the standard conservation equation

$$\nabla^\mu T^{SM}_{\mu\nu} = 0 \ .$$

Theoretical Framework - Background Evolution

- Consider the spatially–flat FLRW line-element:

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = a^2(\tau)\left[-\mathrm{d}\tau^2 + \delta_{ij}\mathrm{d}x^i \mathrm{d}x^j\right] \,,$$

with conformal time τ, and scale factor $a(\tau)$.

- The Friedmann equations are given by

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

- The evolution equations of radiation and baryons are respectively given by

$$\rho_r' + 4\mathcal{H}\rho_r = 0 \,, \qquad \rho_b' + 3\mathcal{H}\rho_b = 0 \,,$$

where we denote a conformal time derivative by a prime, and the conformal Hubble parameter by $\mathcal{H} = a'/a$.

Theoretical Framework - Background Evolution

- The modified Klein-Gordon equation simplifies to

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

and the DM conservation equation reduces to

$$\rho_c' + 3\mathcal{H}\rho_c = -Q\phi' \; ,$$

with the coupling function

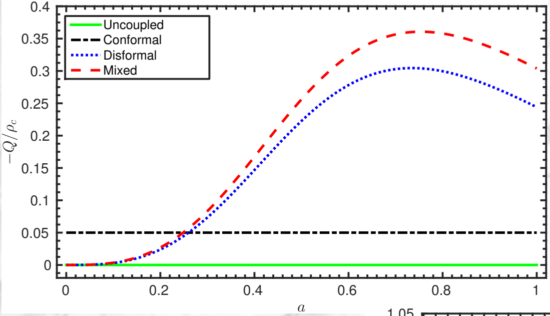
$$Q = -\frac{a^2 C_{,\phi} + D_{,\phi}\phi'^2 - 2D\left(\frac{C_{,\phi}}{C}\phi'^2 + a^2 V_{,\phi} + 3\mathcal{H}\phi'\right)}{2\left[a^2 C + D\left(a^2\rho_c - \phi'^2\right)\right]}\rho_c \; .$$

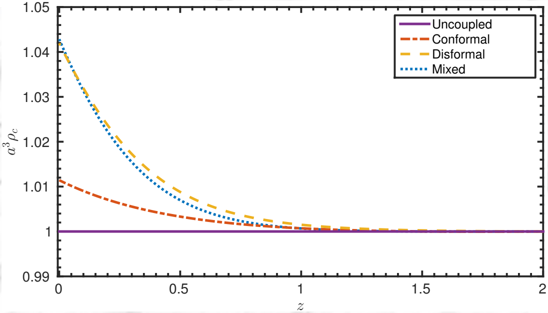
- This simplifies considerably in the pure conformal case to

$$Q^{(c)} = -\frac{1}{2}\left(\ln C\right)_{,\phi}\rho_c \; .$$

[JCAP **1711** (2017) 001]

Theoretical Framework - Background Evolution





Growth History

- Using the conformal Newtonian gauge line-element

$$\mathrm{d}s^2 = a^2(\tau)\left[-\left(1+2\Psi\right)\mathrm{d}\tau^2 + \left(1-2\Phi\right)\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j\right] \ ,$$

  we get the perturbed continuity and Euler equations of the coupled DM:

$$\delta_c' = -\left(\theta_c - 3\Phi'\right) + \frac{Q}{\rho_c}\phi'\delta_c - \frac{Q}{\rho_c}\delta\phi' - \frac{\phi'}{\rho_c}\delta Q \ ,$$

$$\theta_c' + \mathcal{H}\theta_c = k^2\Psi + \frac{Q}{\rho_c}\phi'\theta_c - \frac{Q}{\rho_c}k^2\delta\phi \ .$$

- The evolution of the perturbed scalar field is governed by

$$\delta\phi'' + 2\mathcal{H}\delta\phi' + \left(k^2 + a^2 V_{,\phi\phi}\right)\delta\phi = \left(\Psi' + 3\Phi'\right)\phi' - 2a^2 V_{,\phi}\Psi + a^2\delta Q + 2a^2 Q\Psi \ .$$

[JCAP **1711** (2017) 001]

Growth History

- The generic perturbed coupling function reads as follows

$$\delta Q = \frac{-\rho_c}{a^2 C + D\left(a^2\rho_c - \phi'^2\right)}\left(\widetilde{\mathfrak{B}}_1\delta_c + \widetilde{\mathfrak{B}}_2\Phi' + \widetilde{\mathfrak{B}}_3\Psi + \widetilde{\mathfrak{B}}_4\delta\phi' + \widetilde{\mathfrak{B}}_5\delta\phi\right)$$

- We consider the matter growth rate function defined by

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

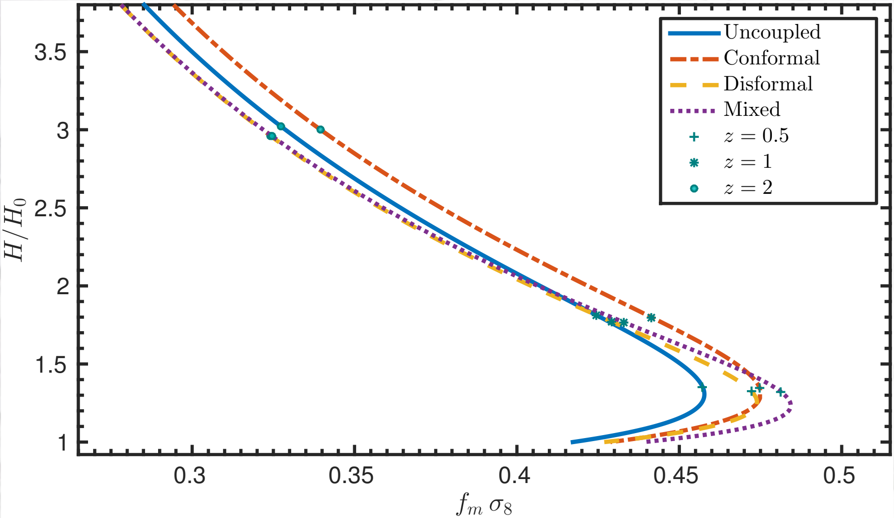
where we define the matter density contrast by

$$\delta_m = \frac{\rho_b\delta_b + \rho_c\delta_c}{\rho_b + \rho_c}\ ,$$

with δ_b, δ_c being the baryon and coupled DM density contrasts, respectively.

[JCAP **1711** (2017) 001]

Growth History



$\alpha = 0.05$, $D_M = 0.43\,\text{meV}^{-1}$, and $\lambda = 1$.

[JCAP **1711** (2017) 001]

Growth History

- The DM density contrast evolution on the small–scales is governed by

$$\delta_c'' + \mathcal{H}_{\mathsf{eff}}\, \delta_c' - \frac{3}{2}\mathcal{H}^2\, \frac{G_{\mathsf{eff}}}{G}\, \Omega_c \delta_c = \frac{3}{2}\mathcal{H}^2\, (\Omega_b \delta_b + \Omega_r \delta_r)\ ,$$

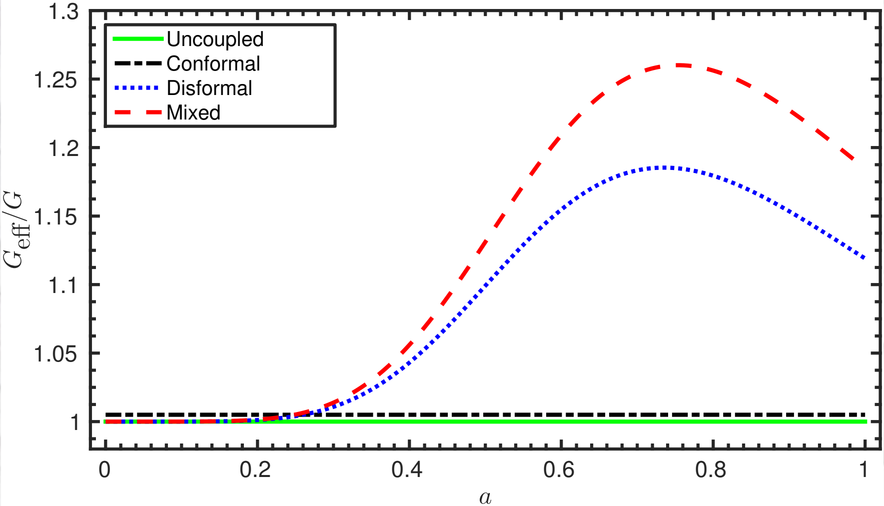
  with

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

- Coupled models are characterised by an enhancement in the growth rate function on the small–scales when compared with the large–scales.
- In disformally coupled models, it is the increase in the effective gravitational constant which gives rise to this enhanced growth.

[JCAP **1711** (2017) 001]

Growth History



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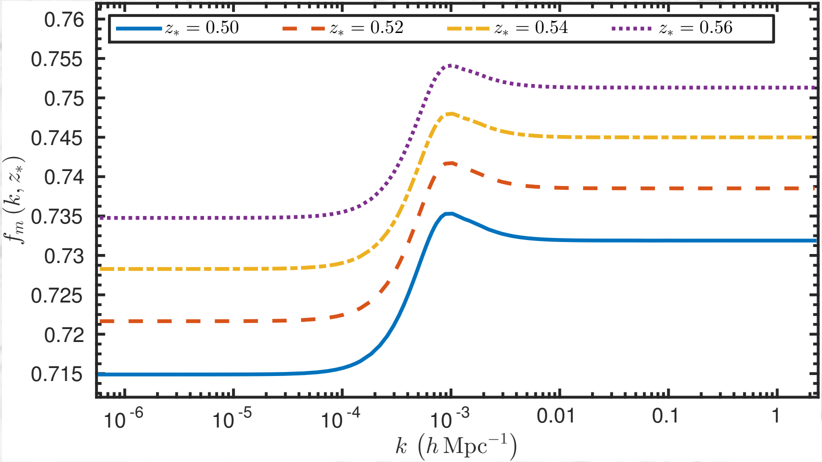
Growth History

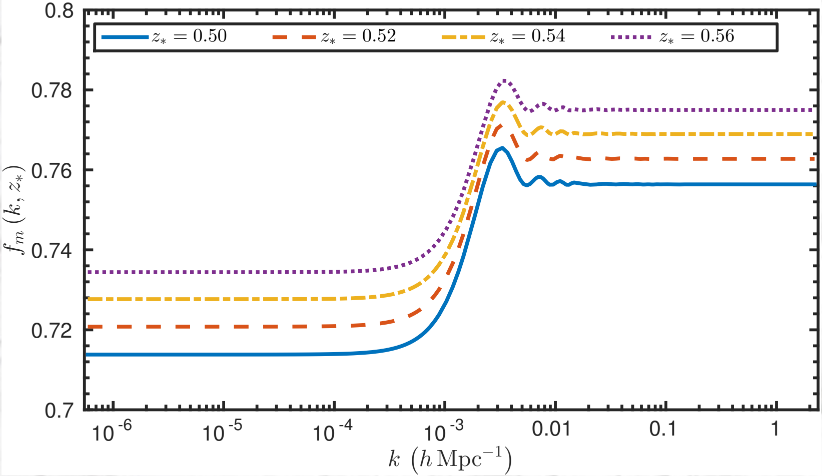
Conformal Coupling



[JCAP **1711** (2017) 001]

Growth History

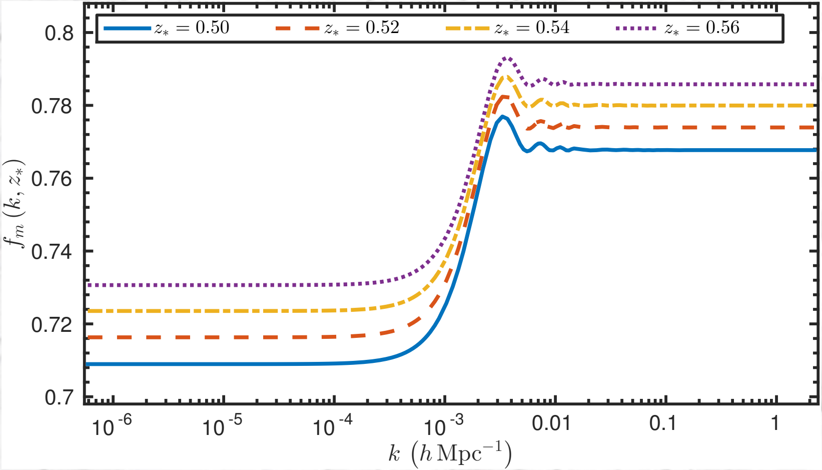
Disformal Coupling



[JCAP **1711** (2017) 001]

Growth History

Mixed Coupling



[JCAP **1711** (2017) 001]

Growth History

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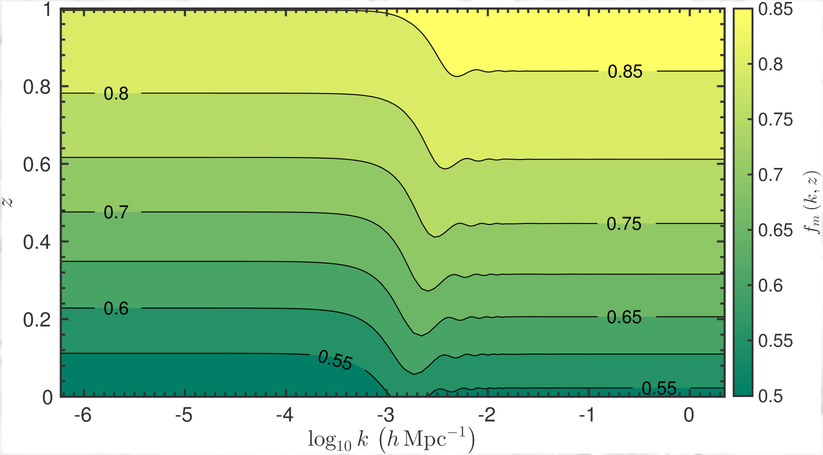


[JCAP **1711** (2017) 001]

The ISW Effect

- Measurements of the ISW effect provide a powerful method to probe DE as this effect is sensitive to the time evolution of the gravitational potential sourced by the LSS.
- It is too small to be directly detected in the CMB spectrum (~ 10 times less than TT).
- It is more pronounced through the correlation between the CMB anisotropies and the LSS.
- The cross–correlation angular power spectrum is given by

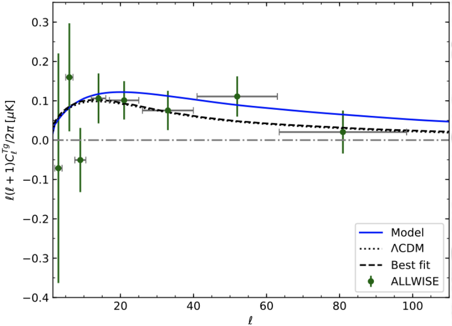
$$C_\ell^{Tg} = 4\pi T_{\rm CMB} \int \Delta_\ell^T(k)\Delta_\ell^g(k)\mathcal{P}_\mathcal{R}(k)\frac{\mathrm{d}k}{k}$$

where the weight functions for the tracer overdensity and the ISW effect are respectively denoted by $\Delta_\ell^g(k)$ and $\Delta_\ell^T(k)$, and $\mathcal{P}_\mathcal{R}(k)$ is the primordial curvature power spectrum.

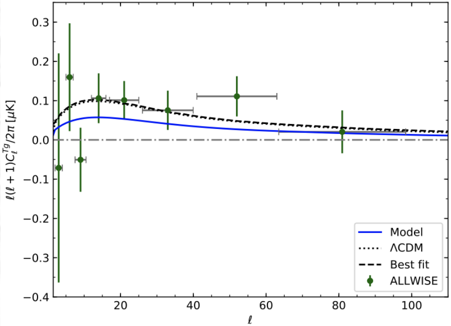
[In preparation]

The ISW Effect

Conformal Coupling



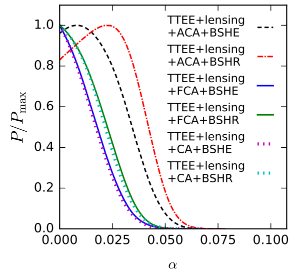
Disformal Coupling

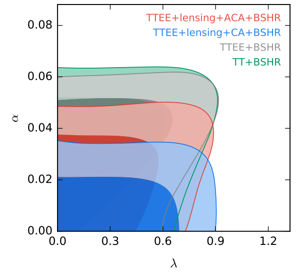


[In preparation]

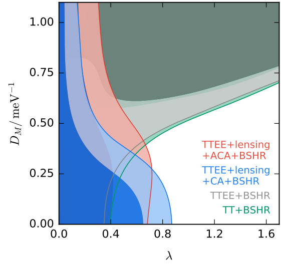
Parameter Constraints

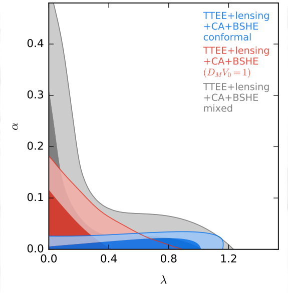
- Conformal Coupling





- Disformal & Mixed Couplings



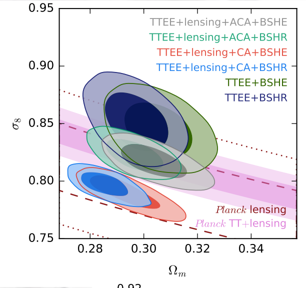


$C(\phi) = e^{2\alpha\kappa\phi},\ D(\phi) = D_M^4,\ V(\phi) = V_0^4 e^{-\lambda\kappa\phi}$

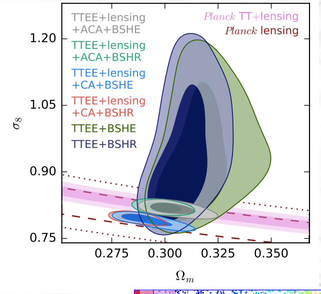
[Phys. Rev. **D97** (2018) 023506]

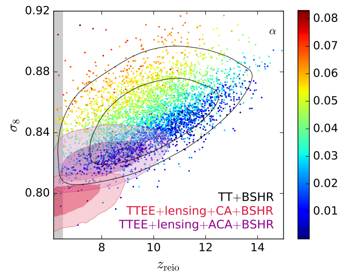
Parameter Constraints

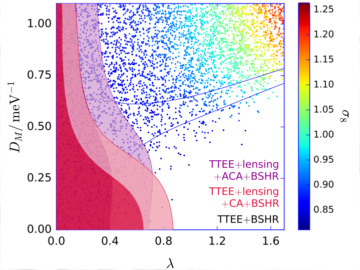
- Conformal Coupling



- Disformal Coupling







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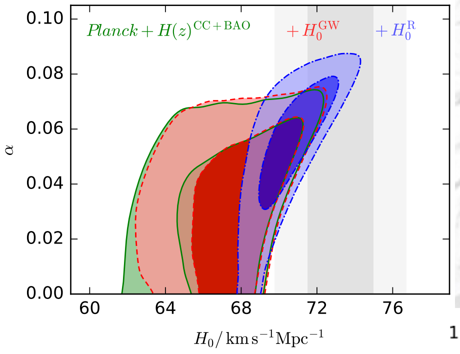
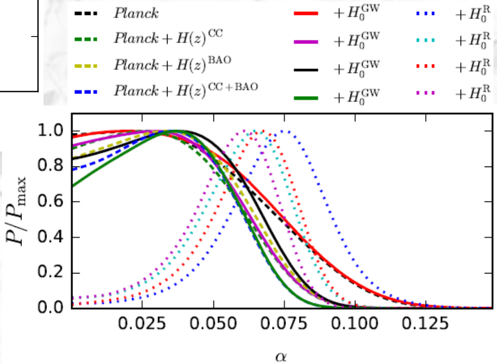
[Phys. Rev. **D97** (2018) 023506]

Parameter Constraints - H_0 from GW170817





[MNRAS **487** (2019) 900]

Conclusion

- Interacting DE models give an enhanced growth on the small–scales, particularly in the disformal case.
- A disformal dark sector coupling leads to intermediate–scale damped oscillations in the matter growth rate function; a unique signature of the disformal coupling.
- The conformal coupling is found to be tightly constrained with CMB data, although the disformal coupling is able to evade this probe.
- A better understanding of the non–linear cosmic evolution of perturbations should be able to shed light on the still hidden features of these coupled quintessence models.
- Other distinctive signatures of dark sector interactions might be indirectly detected through observations of the tidal tails of a disrupting satellite galaxy.

Thank You