Looking for interactions in the dark sector: An update

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A perfect fluid

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu - pg^{\mu\nu}$$

can always be decomposed as

$$T^{\mu\nu} = \rho_m u^\mu u^\nu + \Lambda g^{\mu\nu}$$

with

$$T^{\mu\nu}_{m;\nu} \; = \; Q^\mu,$$

$$T^{\mu\nu}_{\Lambda;\nu} \; = \; -Q^\mu$$

where

$$Q^\mu \; = \; Qu^\mu + \bar{Q}^\mu, \qquad \bar{Q}^\mu u_\mu \; = \; 0$$

Zimdahl, Wands, Maartens, Fabris, Waga, Alcaniz…

Background

$$Q = -\Lambda_{,\nu} u^{\nu},$$

$$\bar{Q}^{\mu} = \Lambda_{,\nu}(u^{\mu} u^{\nu} - g^{\mu\nu})$$

Perturbations

$$\delta Q = \delta \bar{Q}^{0} = 0,$$

$$\delta \bar{Q}_i = (\delta\Lambda + \dot{\Lambda}\theta)_{,i} \equiv \delta\Lambda^{c}_{,i}$$

If dark matter is cold, dark energy is homogeneous, and vice-versa.

SC, Borges, JCAP 1406 (2014) 010
Zimdahl, Borges, SC, Fabris, Hipolito-Ricaldi, JCAP 1104 (2011) 028

Friedmann equations

$$3H^2 = \rho_m + \Lambda,$$

$$\dot{\rho}_m + 3H\rho_m = \Gamma\rho_m = -\dot{\Lambda}$$

Parametrising the interaction

$$\Lambda = \sigma H^{-2\alpha},$$

$$\Gamma = -\alpha\sigma H^{-(2\alpha+1)}$$

Non-adiabatic Chaplygin gas

$$H^2(z) = H_0^2\left[1 - \Omega_{m0} + \Omega_{m0}(z+1)^{3(1+\alpha)}\right]^{\frac{1}{1+\alpha}}$$

Borges, SC, Fabris, Zimdahl, Phys. Lett. B 727 (2013) 37

Matter power spectrum

$$P(k) = P_0 k^{n_s} T^2(k/k_{eq}),$$

Matter-radiation equality

$$\rho_m(z) = 3H_0^2\,\Omega_{m0}^{\frac{1}{1+\alpha}}\,z^3 \quad (z \gg 1)$$

$$k_{eq} = \frac{H(z_{eq})}{z_{eq}} = 0.073\,\mathrm{Mpc}^{-1} h^2\,\Omega_{m0}^{\frac{1}{1+\alpha}}$$

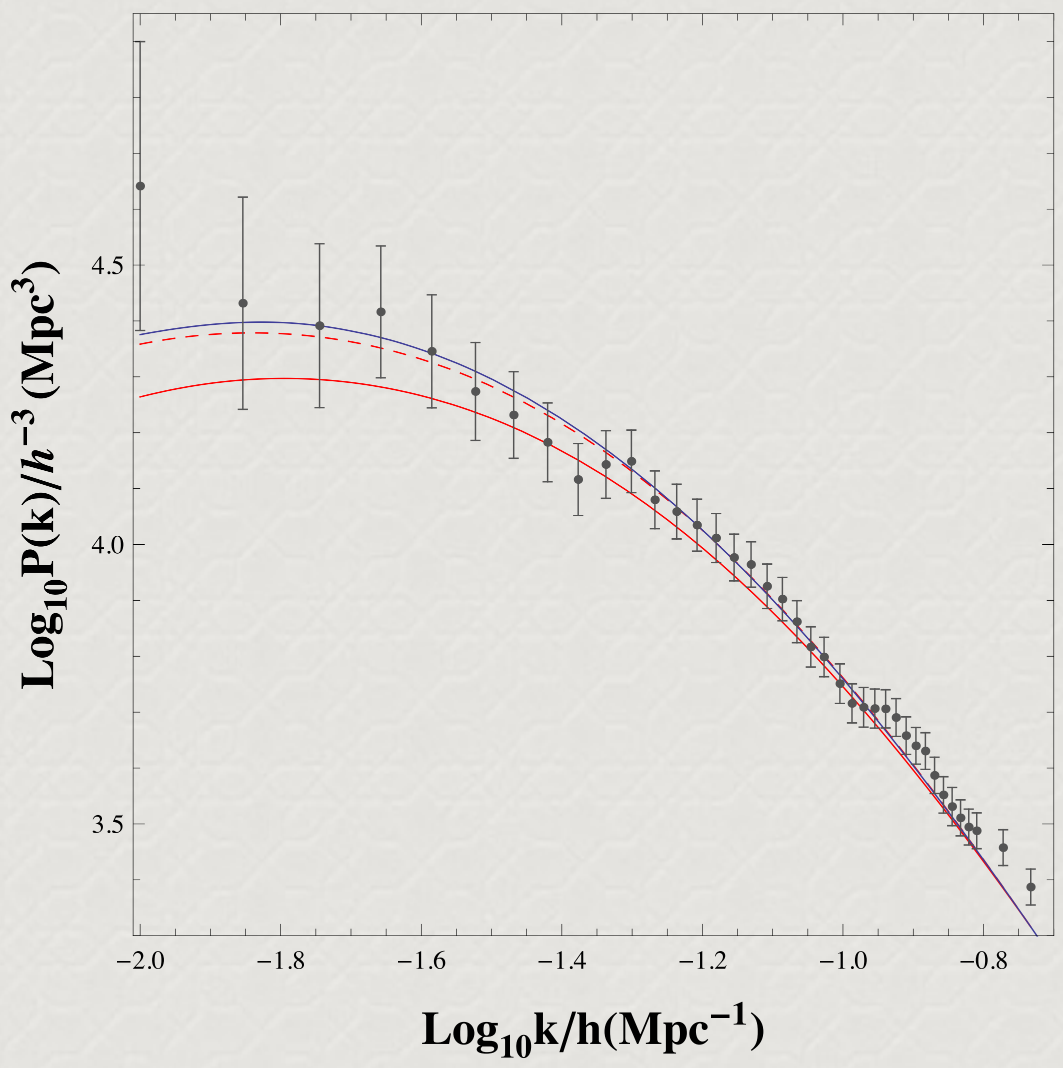


FIG. 1: The linear power spectrum for $\alpha = -1/2$ and $\Omega_{m0} = 0.45$ [18]. The blue line was obtained by a direct integration of the perturbation equations [25]. The dashed red line corresponds to the use of (14) and (18). The solid red line corresponds to the concordance ΛCDM model. Data come from the 2dFGRS catalogue [7].

Alcaniz, Borges, SC, Fabris, Pigozzo, Zimdahl, Phys. Lett. B 716 (2012) 165

Redshift space distortions

$$f_b(z) = \frac{\delta_b'(z)}{Ha\delta_b(z)},$$

$$f_{rsd}(z)\sigma_8(z) = f_b(z)\sigma_8 D_{b+}^N(z)$$

Perturbation equations

$$\begin{aligned} a^2H^2\delta_m'' + aH\left(aH' + 3H + \Gamma\right)\delta_m' + 2\Gamma H\delta_m &= \frac{\rho_m\delta_m}{2} \\ a^2H^2\delta_b'' + aH\left(aH' + 3H\right)\delta_b' &= \frac{\rho_m\delta_m}{2} \end{aligned}$$

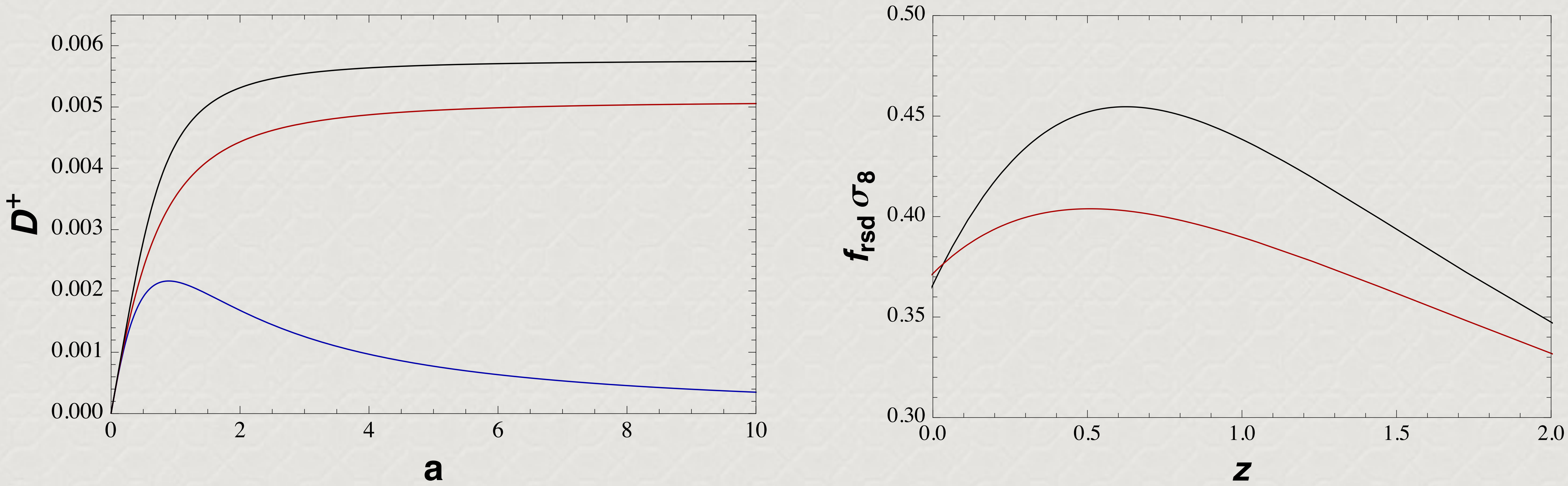


FIG. 2: **Left panel:** Evolution of the matter contrast in the ΛCDM model (black curve), and of the total matter (blue) and baryonic (red) contrasts for $\alpha = -1/2$ [27]. **Right panel**: Evolution of the baryonic $f_{rsd}\sigma_8$ for ΛCDM (black) and for $\alpha = -1/2$ (red).

Velten, Borges, SC, Fazolo, Gomes, MNRAS 452 (2015) 2220
SC, Borges, Gen. Rel. Grav. 50 (2018) 1

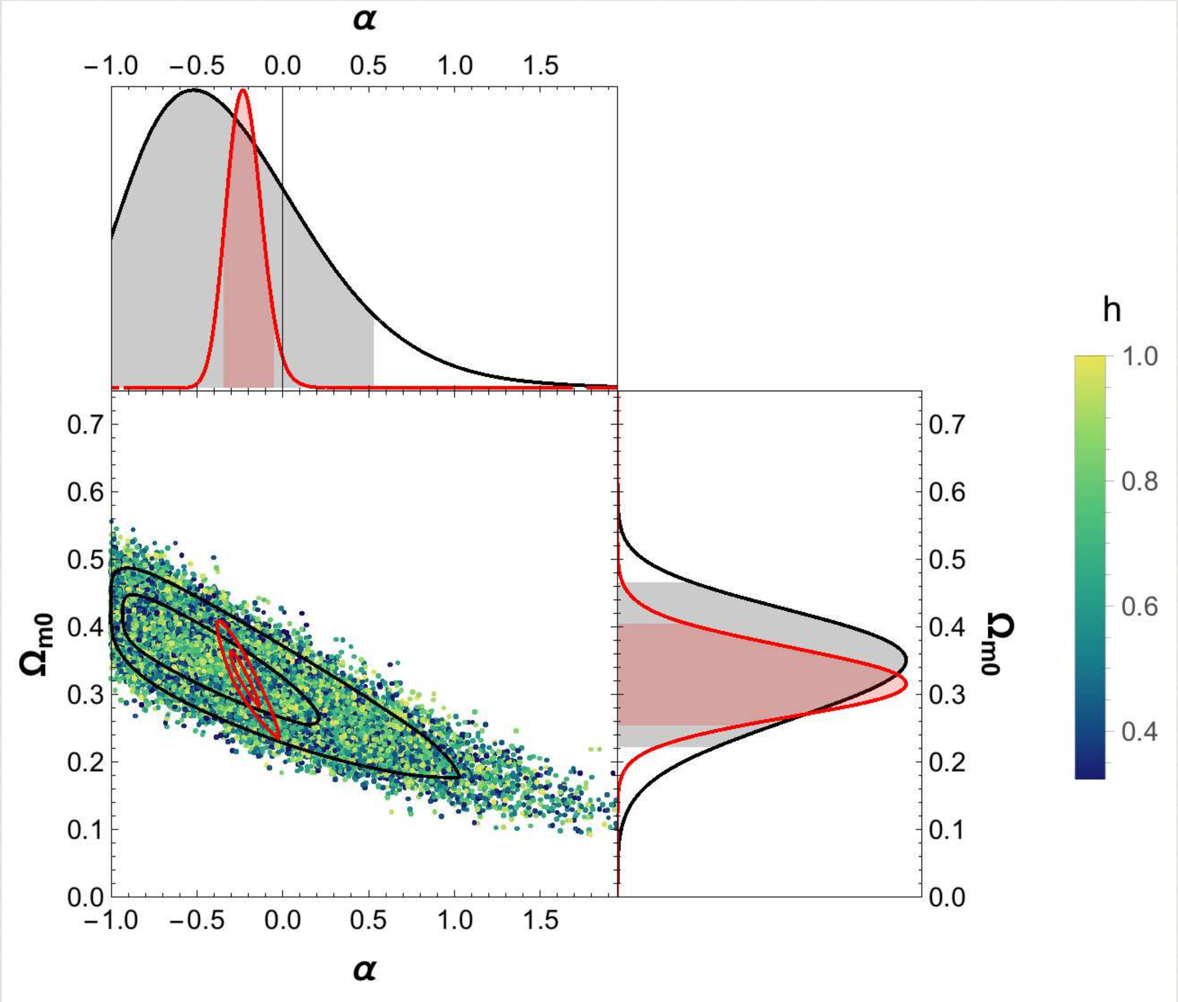


FIG. 3: Likelyhoods for the interaction parameter and the matter density parameter from the joint analysis of SNe Ia (JLA) + LSS (2dFGRS) + l_1 (red) [20]. The black lines are PDFs for just JLA supernovae. The confidence regions in the $\alpha \times \Omega_{m0}$ plane are also shown.

Pigozzo, SC, Alcaniz, Borges, Fabris, JCAP 1605 (2016) 022
Pigozzo, SC, Fabris, Phys. Dark. Univ. 28 (2020) 100486

CMB - full

Background

$$\rho_m = 3H_0^2\left[\Omega_{m0}^2(z+1)^3 + \Omega_{m0}(1-\Omega_{m0})(z+1)^{3/2}\right]$$

$$\rho_b = 3H_0^2\Omega_{b0}(z+1)^3 \qquad \rho_{dm} = \rho_m - \rho_b \qquad \rho_R = 3H_0^2\Omega_{R0}(z+1)^4$$

$$H(z) = H_0\left\{\left[1-\Omega_{m0}+\Omega_{m0}(z+1)^{3/2}\right]^2 + \Omega_{R0}(z+1)^4\right\}^{1/2}$$

Perturbations

$$\theta'_{dm} = -aH\theta_{dm} + k^2\phi,$$

$$\delta'_{dm} = -\theta_{dm} + 3\phi' + \Gamma a\left(\frac{\rho_m}{\rho_{dm}}\right)(\phi - \delta_{dm})$$

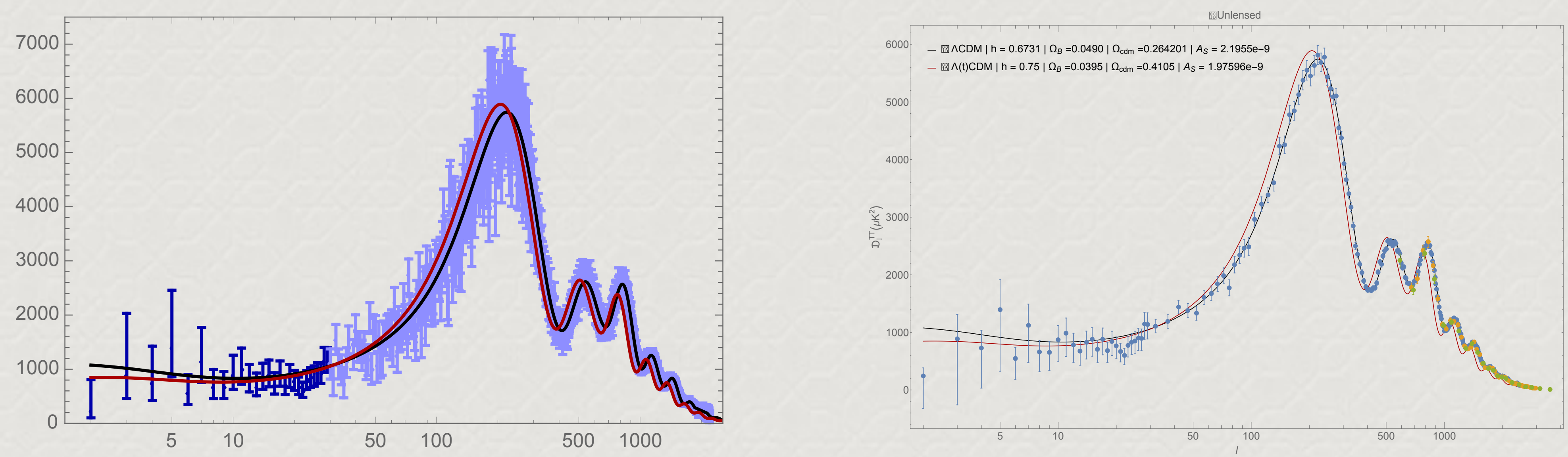


FIG. 4: The CMB anisotropy spectra for the ΛCDM model ($\alpha = 0$, black) and for the model with constante matter-creation rate ($\alpha = -1/2$, red), superposed to the unbinned (left) and binned (right) Planck data. For the standard model we have adopted $\Omega_m = 0.31$ and $h = 0.67$, while for the interacting model we have used $\Omega_m = 0.45$ and $h = 0.75$.

Perturbations (general case)

$$\theta'_{dm} + \mathcal{H}\theta_{dm} - k^2\Phi = 0,$$

$$\delta'_{dm} - 3\Phi' + \theta_{dm} = -\frac{aQ}{\rho_{dm}}\left[\delta_{dm} - \frac{1}{k^2}\left(k^2\Phi + \frac{Q'}{Q}\theta_{dm}\right)\right],$$

$$-k^2\Phi = \frac{a^2}{2}(\rho_{dm}\delta_{dm} + \rho_b\delta_b) - \left(\frac{a^3Q}{2} - \frac{3a^2}{2}\mathcal{H}\rho_m\right)\frac{\theta_{dm}}{k^2},$$

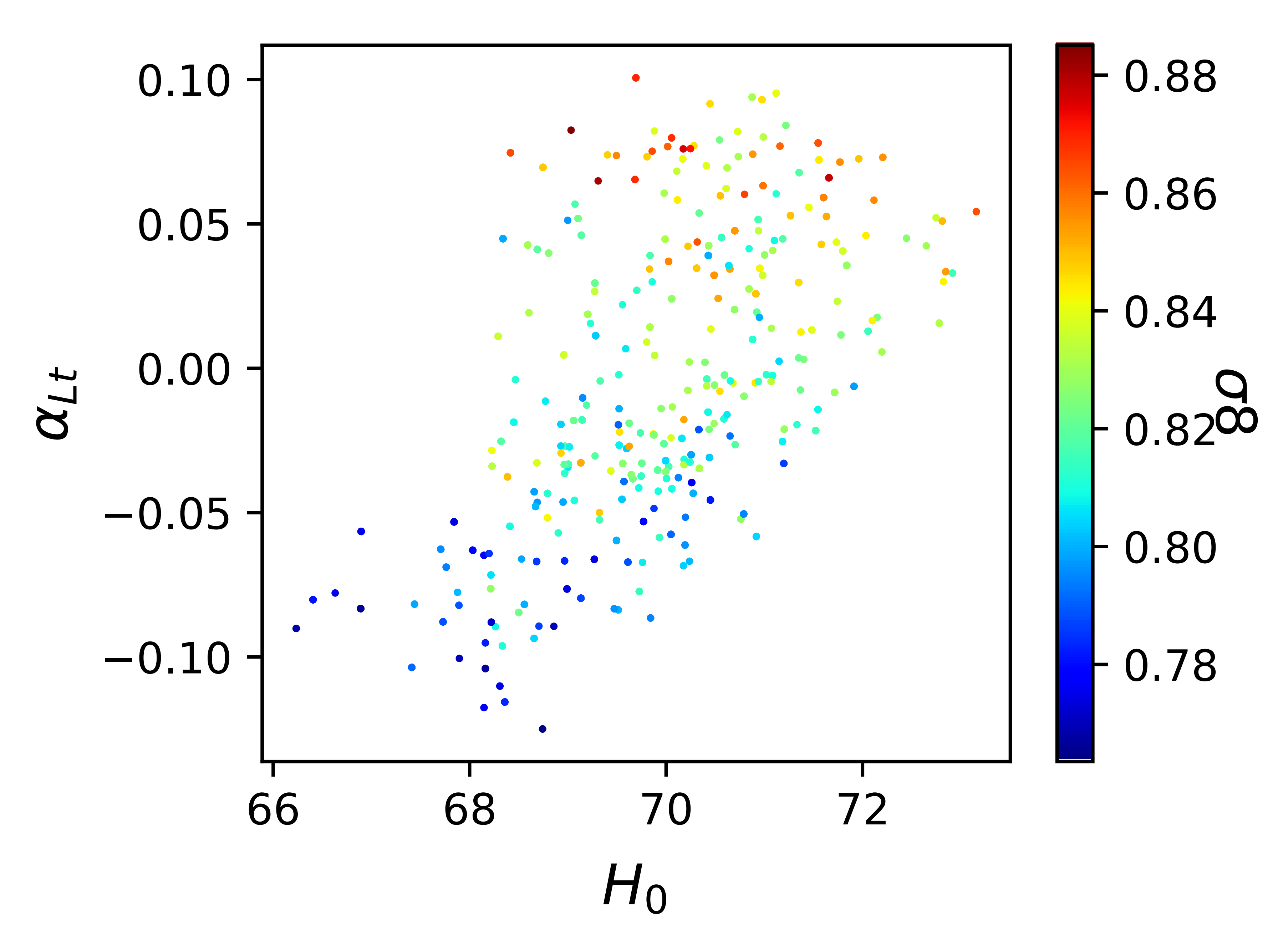
$$\delta\Lambda = -aQ\theta_m/k^2 \text{ and } \delta Q = Q'\theta_m/k^2,$$

Sub-horizon limit

$$\theta'_{dm} + \mathcal{H}\theta_{dm} - k^2\Phi = 0,$$

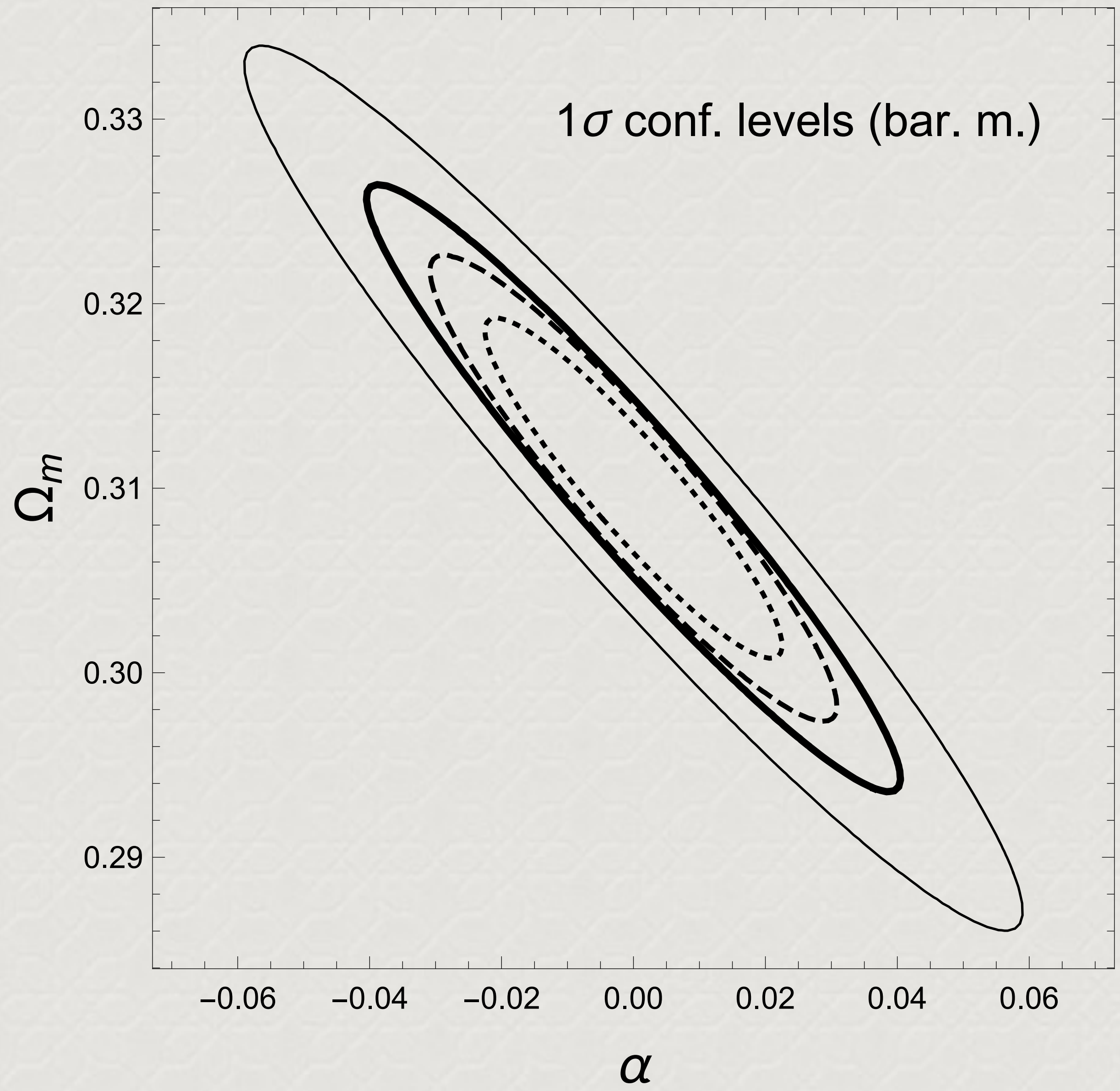
$$\delta'_{dm} + \theta_{dm} = -\frac{aQ}{\rho_{dm}}\delta_{dm},$$

$$-k^2\Phi = \frac{a^2}{2}(\rho_{dm}\delta_{dm} + \rho_b\delta_b).$$



Benetti, Miranda, Borges, Pigozzo, SC, Alcaniz, JCAP 1912 (2019) 023

Forecasts



Salzano et al. [J-PAS collaboration], to appear.

Thanks