Cosmology and Non-Standard Equations of State

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ABSTRACT

We assess an **Early Dark Energy (EDE)** model of cosmology using the **Cosmological Linear Anisotropy Solving System (CLASS)** and the Markov chain Monte Carlo code **MontePython** via the extraction of various cosmological parameters.

As observations of earlier epochs of the Universe become possible, it may be that the Universe is better modeled by something other than a standard ΛCDM cosmological model. We use MontePython to test a nonstandard cosmological model which proposes a transition in a fluid dark energy in the Early Universe. One of our motivations is to explore whether such cosmologies can alleviate Hubble tension.

Evaluation using MontePython has been carried out on both the standard ΛCDM and EDE models, using the likelihoods of the latest public versions of CMB data. We additionally provide triangle plots of the convergence results for both models for the main cosmological density parameters as well as baryon density using the BAO BOSS DR12 and BAO smallz datsets.

BACKGROUND

Robertson-Walker Metric

$$(ds)^2 = (c\,dt)^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right]$$

Friedmann Equations for Scale Factor $a(t)$

$$\left(\frac{\dot a}{a}\right)^2 + \frac{kc^2}{a^2} = \frac{8\pi}{3}G\rho + \frac{\Lambda c^2}{3}$$

$$2\frac{\ddot a}{a} + \left(\frac{\dot a}{a}\right)^2 + \frac{kc^2}{a^2} = -\frac{8\pi}{c^2}G\rho + \Lambda c^2$$

Scale Factor vs Time

$$\dot a^2(t) + k = \frac{8\pi G}{3}\rho_c a^2(t)$$

Vacuum Energy

$$\Lambda = \rho_{vac}\frac{8\pi}{c^2}G$$

DENSITY EVOLUTIONS

Density Evolution

$$\rho_i(a) = \rho_{i,0}\,\exp\left[\int_a^{a_0} da'\,\frac{3}{a'}(1 + w_i(a'))\right]$$

Standard ΛCDM Model ($k = 0$)

$$\rho_c = \rho_m + \rho_r + \rho_\Lambda = \frac{1}{a^3}\rho_{m,0} + \frac{1}{a^4}\rho_{r,0} + \rho_{\Lambda,0}$$

Non-Standard Model

In some non-standard cosmological models, the role of vacuum energy is played a (fluid) **general dark energy** which is not necessarily constant with respect to the expansion of the Universe. That is,

$$\rho_c = \frac{1}{a^3}\rho_{m,0} + \frac{1}{a^4}\rho_{r,0} + \rho_{fld}(a).$$

An example of such a non-standard model is one which involves a late-time **phase transition** in the vacuum energy:

$$\rho_c = \frac{1}{a^3}\rho_{m,0} + \frac{1}{a^4}\rho_{r,0} + \rho_{fld}(a) \qquad (a \ll a_c)$$

$$\rho_c = \frac{1}{a^3}\rho_{m,0} + \frac{1}{a^4}\rho_{r,0} + \rho_\Lambda + \left(\frac{a_c}{a}\right)^4(\rho_{fld} - \rho_\Lambda) \qquad (a \gg a_c)$$

EDE EQUATION OF STATE

We can produce the desired non-standard behavior of the dark energy via a modified equation of state. One such formulation is shown below.

$$w_{fld}(a) = \frac{1+w_n}{1+(a_c/a)^{3(1+w_n)}} - 1, \qquad w_n = \frac{n-1}{n+1}$$

When $n = 2$, we have that $w_n = 1/3$. From the above expression, we obtain

$$w_{fld}(a) \to -1 \qquad (a \ll a_c)$$

$$w_{fld}(a) > 1/3 \qquad (a \gg a_c).$$

That is, the fluid dark energy behaves as regular vacuum energy for early times and redshifts away more or less as radiation $\sim a^{-4}$ at late times.

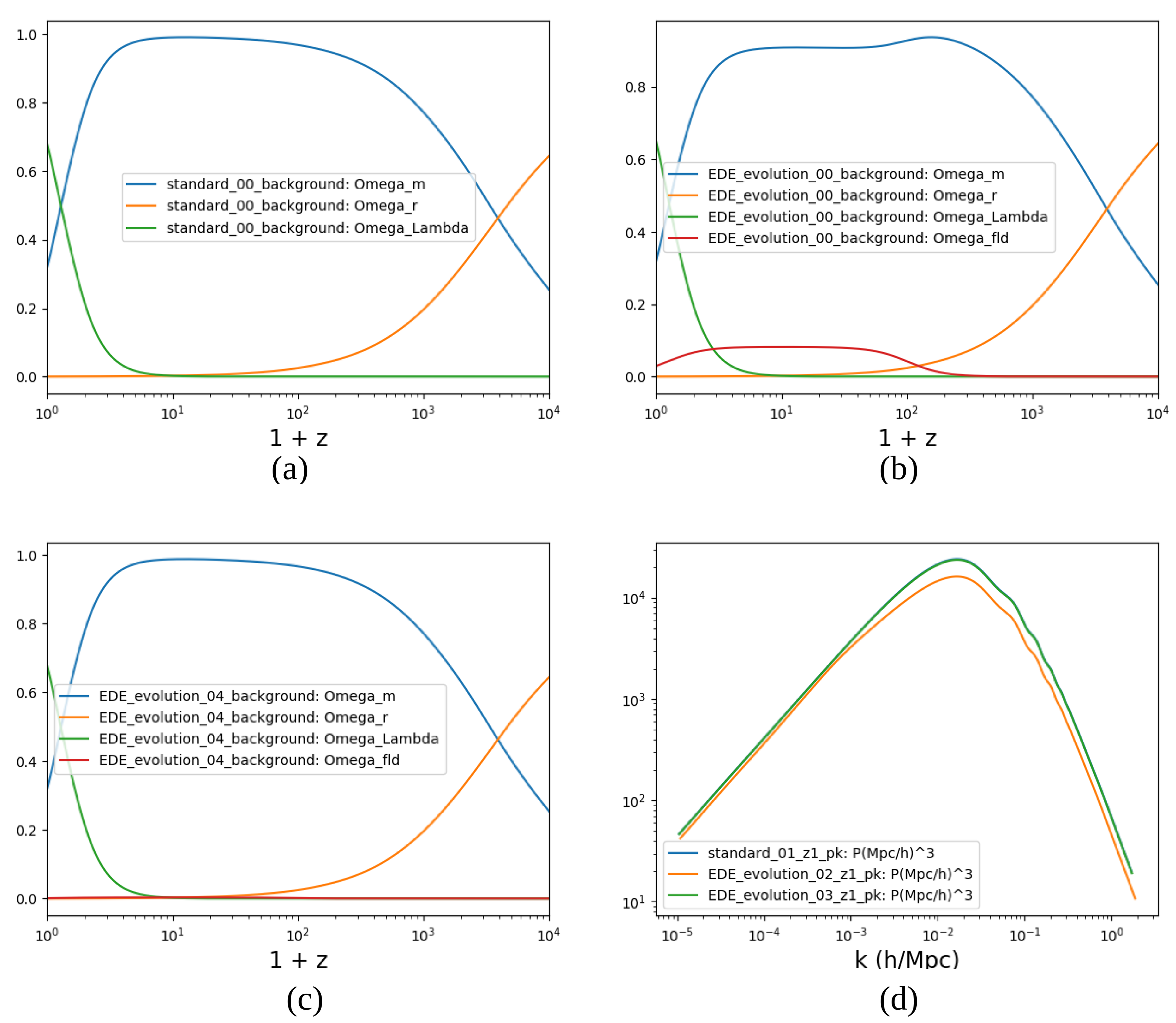
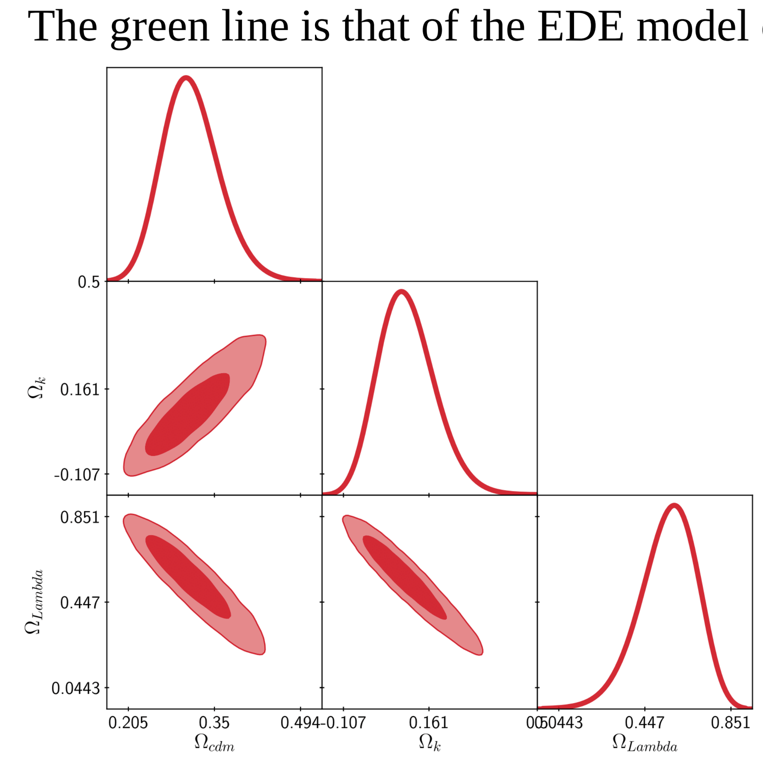
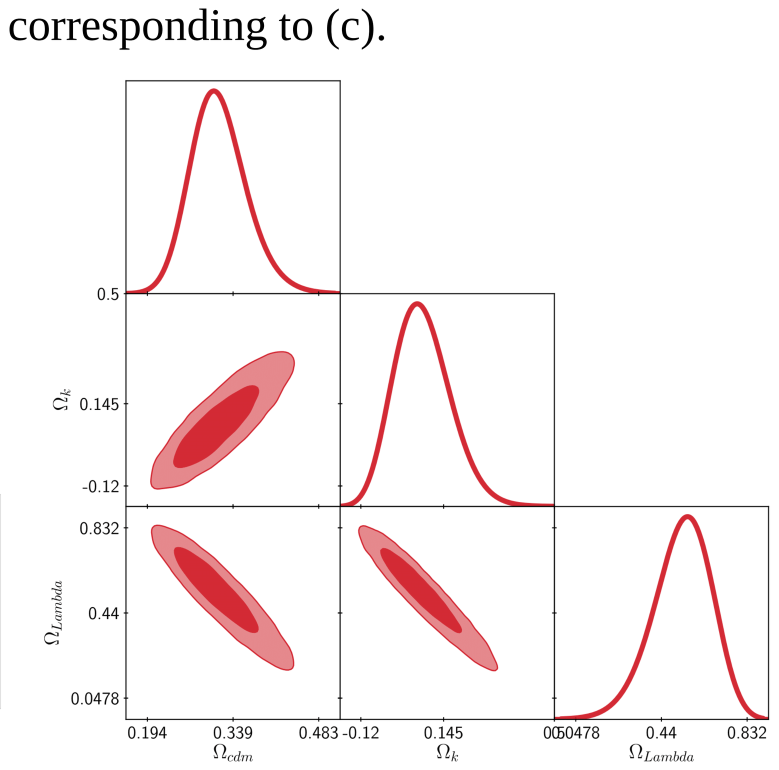


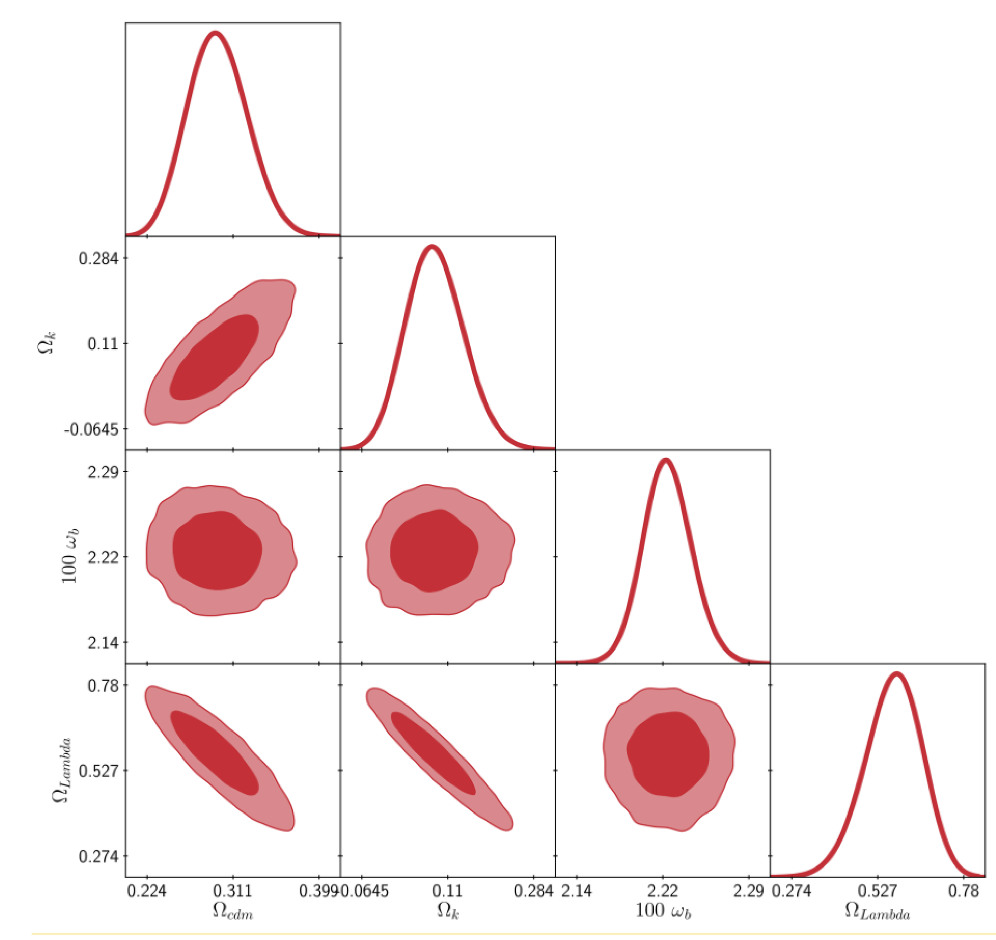
Figure 1: Evolution of closure fractions of the energy density parameters for the (a) standard ΛCDM model and two cases (b) and (c) for the non-standard EDE model, and (d) matter power spectrums for the two models at a redshift of $z = 1$. We have used the present-day values $\Omega_{m,0} = 0.31$ and $\Omega_{\Lambda,0} = 0.69$ for the ΛCDM model. Note the additional energy component Ω_{fld} in the two non-standard models, where we have used $\Omega_{fld,0} = 0.0286864$ for (b) and $\Omega_{fld,0} = 0.001$ for (c). In both cases, we have used $a_c = 0.01$. The additional component of the general dark energy induces the desired nonstandard behavior. In (d), the orange line is the matter power spectrum of the EDE model corresponding to (b). The green line is that of the EDE model corresponding to (c).



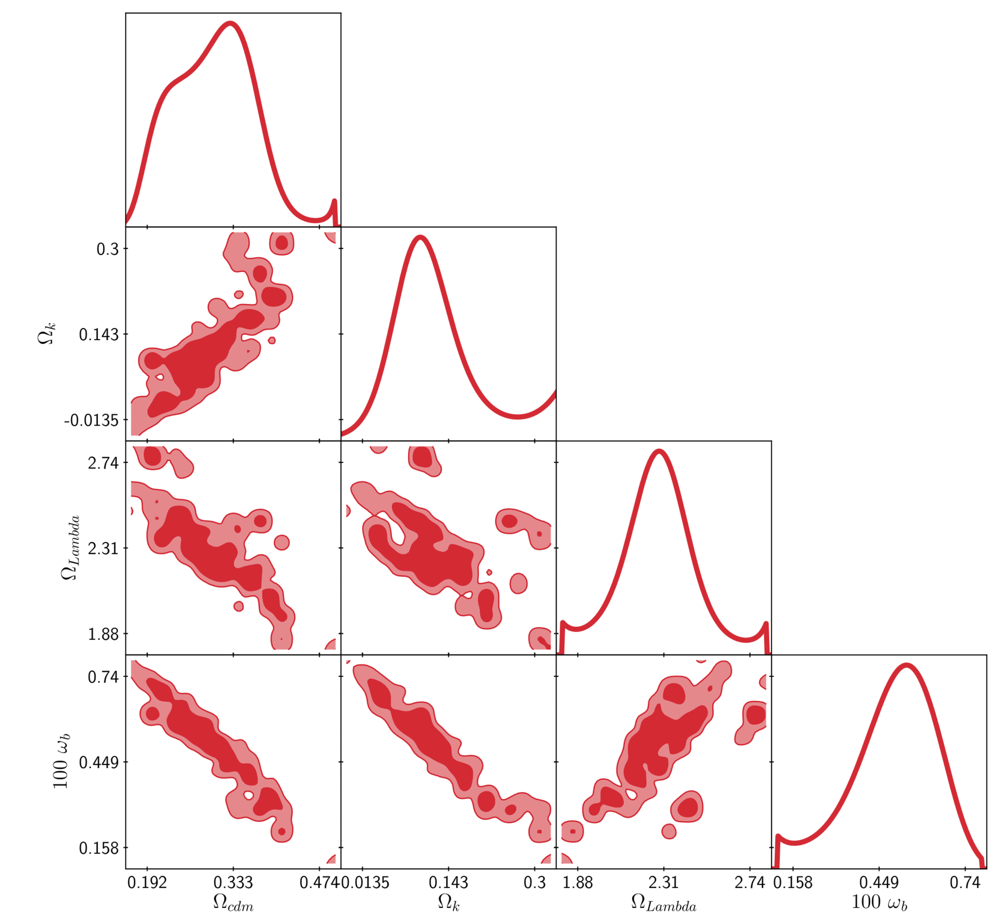
(a)



(b)



(c)



(d)

Figure 2: Triangle plots of the convergence results from MontePython for the (a) ΛCDM and (b) EDE models for the main cosmological closure fractions. Triangle plots for the (c) ΛCDM and (d) EDE models with an additional parameter, ω_b. All convergence results are with 10,000 runs. We have used the fixed values $\Omega_{fld,0} = 0.0286864$ and $a_c = 0.01$.

ACKNOWLEDGEMENTS

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