Applications of the EoS formalism to f(R) models

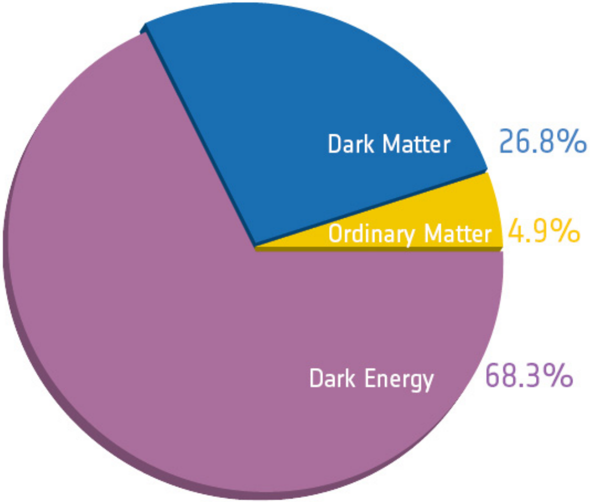
Francesco Pace

& Boris Bolliet, Richard Battye

JBCA, University of Manchester

25th April 2017, PONT2017, Avignon

Outline


Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%

Motivations

- Accelerated expansion can be explained by dark energy or modifications of gravity
- Simplest model: ΛCDM, but it has problems
- Simple modified gravity model is $f(R)$
- Here we consider designer $f(R)$ models
- We parametrize them via $B_0 = \frac{f_{RR}}{1+f_R} R' \frac{H}{H'}\Big|_{a=1}$
- Ground test for Horndeski models

Perturbations

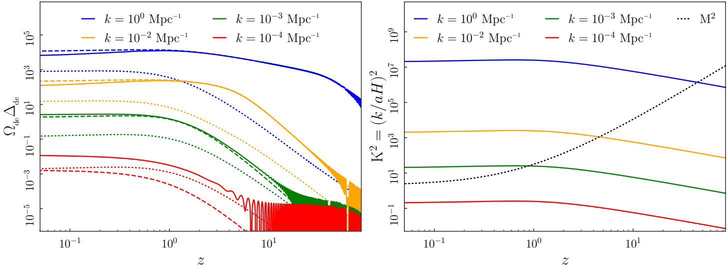
- Designer models have a ΛCDM background with differences at the perturbation level
- Perturbations studied with the EFT and the EoS framework (see Vernizzi, Mancarella & Trinh)
- Implemented in class_eos
- Equations of state:

$$
\begin{aligned}
w_{\rm de}\Pi_{\rm de} &= c_{\Pi\Delta_{\rm de}}\Delta_{\rm de} + c_{\Pi\Theta_{\rm de}}\hat{\Theta}_{\rm de} + c_{\Pi\Delta_{\rm m}}\Delta_{\rm m} + c_{\Pi\Theta_{\rm m}}\hat{\Theta}_{\rm m} + c_{\Pi\Pi_{\rm m}}\Pi_{\rm m}\ , \\
w_{\rm de}\Gamma_{\rm de} &= c_{\Gamma\Delta_{\rm de}}\Delta_{\rm de} + c_{\Gamma\Theta_{\rm de}}\hat{\Theta}_{\rm de} + c_{\Gamma\Delta_{\rm m}}\Delta_{\rm m} + c_{\Gamma\Theta_{\rm m}}\hat{\Theta}_{\rm m} + c_{\Gamma\Gamma_{\rm m}}\Gamma_{\rm m}\ .
\end{aligned}
$$

Evolution of perturbations

$$\Delta_{\rm m}'' + (2-\epsilon_{\rm H})\Delta_{\rm m}' - \frac{3}{2}\Omega_{\rm m}\Delta_{\rm m} = -\frac{3}{2}\Omega_{\rm de}\Delta_{\rm de}\,,$$

$$\Delta_{\rm de}'' + (2-\epsilon_{\rm H})\Delta_{\rm de}' + ({\rm K}^2+{\rm M}^2)\Delta_{\rm de} = -\frac{1}{3}\frac{\Omega_{\rm m}}{\Omega_{\rm de}}{\rm K}^2\Delta_{\rm m}\,.$$

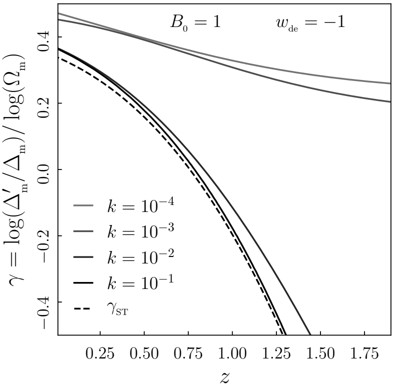


Battye, Bolliet, Pace, 2017; in preparation

- Frequency of oscillations $\omega = H\sqrt{\mathrm{K}^2 + \mathrm{M}^2}$
- $\Delta_{\mathrm{de}} = \Delta_{\mathrm{de},0} a^{-1} \frac{1}{\sqrt{\omega}} \cos\left(\int \omega dt\right)$
- $\Omega_{\mathrm{de}}\Delta_{\mathrm{de}} = -\frac{1}{3}\frac{\mathrm{K}^2}{\mathrm{K}^2+\mathrm{M}^2}\Omega_{\mathrm{m}}\Delta_{\mathrm{m}} = \frac{1}{3}\frac{2\mathrm{K}^2}{2\mathrm{K}^2+3\mathrm{M}^2}\mathrm{K}^2 Z \Rightarrow \frac{G_{\mathrm{eff}}}{G_{\mathrm{N}}} = G \equiv \frac{4\mathrm{K}^2+3\mathrm{M}^2}{3(\mathrm{K}^2+\mathrm{M}^2)}$
- Oscillations do not transfer to the potential $Z = -\frac{1}{2}\frac{2\mathrm{K}^2+3\mathrm{M}^2}{\mathrm{K}^2(\mathrm{K}^2+\mathrm{M}^2)}\Omega_{\mathrm{m}}\Delta_{\mathrm{m}}$

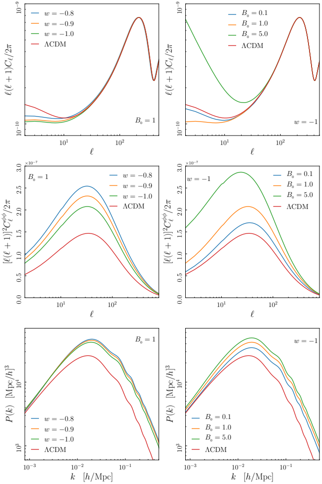
Growth index

$$\gamma(a,k) = \frac{3(G-w_{\rm de})}{2-6w_{\rm de}+3G} - \frac{3(G-1)}{2+3G}\frac{1}{\Omega_{\rm de}}$$



Battye, Bolliet, Pace, 2017; in preparation

Observables



Battye, Bolliet, Pace, 2017; in preparation

Conclusions

- The EoS/EFT approach is very suitable for implementation in Boltzmann codes
- Our code delivers robust results
- On small scales, equations of state can be simplified to

$$
\begin{aligned}
w_{\rm de}\Pi_{\rm de} &= \Delta_{\rm de}\ , \\
w_{\rm de}\Gamma_{\rm de} &= \left\{\frac{1}{3} - w_{\rm de} + \frac{\mathrm{M}^2}{\mathrm{K}^2}\right\}\Delta_{\rm de} + \frac{1}{3}\frac{\Omega_{\rm m}}{\Omega_{\rm de}}\Delta_{\rm m}
\end{aligned}
$$

- Easily extended to Horndeski class

Future work

- Comparison with other codes (i.e. EFTCAMB, HiClass)
- Parameter constraints