Dark sector evolution in Horndeski models

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Feb 20 2019, Roma

Outline

Why and how to modify gravity

- Until very recently, the realm of modified gravity was relatively unconstrained: $w_{\rm de} \approx -1$, but many models can do this
- GR+Λ is the most general theory in 4D which contains only second derivatives of the metric tensor
- To go beyond, evade Lovelock's theorem: extra degrees of freedom, more dimensions, higher derivatives, non-locality, ...
- Here I consider an extra scalar degree of freedom $\longrightarrow$ Horndeski models

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Linear perturbations in Horndeski models

- Most general model with second order equations of motion
- It depends on four free functions (G_i) $\rightarrow$ rich phenomenology
- Parametrized frameworks provide a link between theory and observations
  - Solutions to the equations of motion $\longrightarrow$ (μ, η, Σ)
  - The action $\longrightarrow$ EFT, α parametrisation
  - The equations of motion $\longrightarrow$ PPF, Equations of State
- Perturbations described by H plus 4 free functions of time, $\alpha_{\rm K}$, $\alpha_{\rm B}$, $\alpha_{\rm M}$, $\alpha_{\rm T}$
- GW constraint implies $\alpha_{\rm T} \approx 0$. This rules out a large number of Horndeski models

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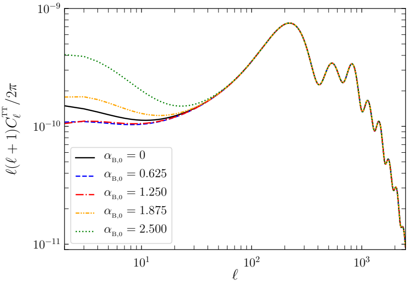
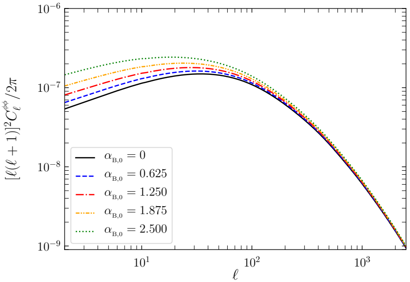
The Equation of State (EoS) approach

- Need equations of state to close the equations of motion for perturbations. Analogous to $P_{\rm ds} = w(a)\rho_{\rm ds}$ at background
- Treats any modification to standard GR as a non-trivial dark sector fluid i.e. $G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} + U_{\mu\nu}$
- Entropy perturbations $\Gamma^{\rm s}_{\rm ds} = \left(\frac{\delta P_{\rm ds}}{\delta\rho_{\rm ds}} - \frac{dP_{\rm ds}}{d\rho_{\rm ds}}\right)\delta_{\rm ds}$
- Anisotropic stress $\Pi^{\rm s}_{\rm ds}$
- Put the previous two terms in Einstein-Boltzmann code to get CMB and matter power spectra

CMB spectra for $\alpha_{\rm K}$ and $\alpha_{\rm B}$ non zero





Sub-percent agreement with Hi_class

FP, Battye, Bolliet, Trinh, in progress

Equations of state

Full expressions

- $\Gamma^{\rm s}_{\rm ds} = C_{\Gamma\Delta_{\rm ds}}\Delta_{\rm ds} + C_{\Gamma\Theta_{\rm ds}}\Theta_{\rm ds} + C_{\Gamma\Delta_{\rm m}}\Delta_{\rm m} + C_{\Gamma\Theta_{\rm m}}\Theta_{\rm m} + C_{\Pi\Gamma_{\rm m}}\Gamma_{\rm m}$
- $\Pi^{\rm s}_{\rm ds} = C_{\Pi\Delta_{\rm ds}}\Delta_{\rm ds} + C_{\Pi\Theta_{\rm ds}}\Theta_{\rm ds} + C_{\Pi\Delta_{\rm m}}\Delta_{\rm m} + C_{\Pi\Theta_{\rm m}}\Theta_{\rm m} + C_{\Pi\Pi_{\rm m}}\Pi_{\rm m}$

Simplified expressions

- $\Gamma^{\rm s}_{\rm ds} \approx C_{\Gamma\Delta_{\rm ds}}\Delta_{\rm ds} + C_{\Gamma\Delta_{\rm m}}\Delta_{\rm m}$
- $\Pi^{\rm s}_{\rm ds} \approx C_{\Pi\Delta_{\rm ds}}\Delta_{\rm ds} + C_{\Pi\Delta_{\rm m}}\Delta_{\rm m}$

$\Rightarrow$ Existence of an attractor ($\Delta_{\rm ds} = -\frac{\Omega_{\rm m}}{\Omega_{\rm ds}}\kappa_\Delta\Delta_{\rm m}$)
$\Rightarrow$ Possibility of understanding physics with relatively simple expressions

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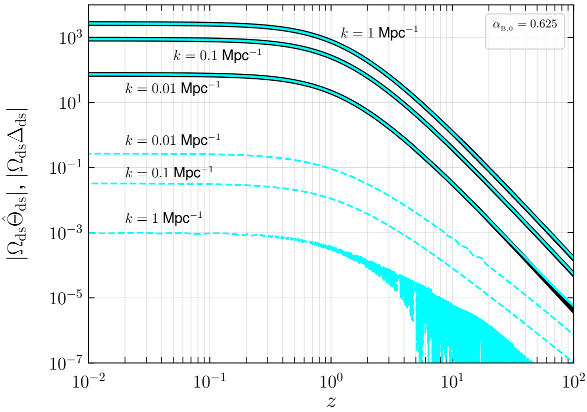

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Modified Gravity phenomenology

- In general, Poisson equation is modified and anisotropic stress arises: $-\frac{2}{3}\mathrm{K}^2 Z = \Omega_{\rm m}\Delta_{\rm m} + \Omega_{\rm ds}\Delta_{\rm ds}$, $\frac{1}{3}\mathrm{K}^2(Y - Z) = \Omega_{\rm m}\Pi_{\rm m} + \Omega_{\rm ds}\Pi_{\rm ds}$
- We can introduce 4 phenomenological functions to describe the phenomenology of modified gravity (only two independent): μ_Z, μ_Y, $\eta = \mu_Z/\mu_Y$, $2\Sigma = \mu_Z + \mu_Y = \mu_Y(1+\eta)$

$\mu_Z = \mu_Y = \eta = \Sigma = 1$ in ΛCDM

Usually, a function of time and scale

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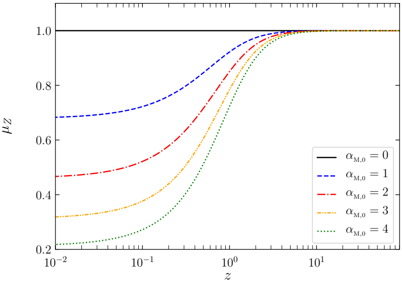
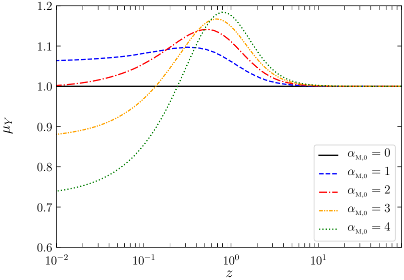
Modified Gravity phenomenology in the light of the EoS

$$
\begin{aligned}
\kappa_\Delta &= \frac{2C_{\Pi\Delta_\mathrm{m}} + 3C_{\Gamma\Delta_\mathrm{m}}}{3w_\mathrm{ds} + 2C_{\Pi\Delta_\mathrm{ds}} + 3C_{\Gamma\Delta_\mathrm{ds}}}\,, \\
\mu_Z &= 1 - \frac{\Omega_\mathrm{ds}}{\Omega_\mathrm{m}}\kappa_\Delta\,, \\
\mu_Y &= \mu_Z - 2\frac{\Omega_\mathrm{ds}\Pi_\mathrm{ds}}{\Omega_\mathrm{m}\Delta_\mathrm{m}}\,,
\end{aligned}
$$

Modified Poisson equations for $\alpha_{\rm K}$ and $\alpha_{\rm M}$ non zero





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EoS and the quasistatic approximation

- The EoS approach allows us to derive MG parameters (excellent agreement with numerical expectations)
- At the same time, one can get them using the quasistatic approximation or a semi-dynamical approach (Lombriser & Taylor, 2015)
- Except for k-essence, the expressions differ for more general models
- How does ignoring velocity perturbations compare with the quasistatic approximation? Are they equivalent?

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Summary and future work

- Horndeski models have a very rich phenomenology, despite GW constraints
- Perturbations described by four free functions with physical interpretation
- EoS formalism is a powerful tool to study linear perturbations
- The fluid approach gives a neat understanding of the physics involved
- Future work: which approach better recovers modified gravity phenomenology (Attractor, quasistatic, semi-dynamical)?