Evolution of structures in shift-symmetric Galileon models

Francesco Pace

University of Torino & INFN, Italy

Jul 9 2024, MG17, Pescara

based on I. Albuquerque, N. Frusciante, F. Pace, C. Schimd, PRD, 109, 023535

Galileon models: generic features

- Lagrangian: $\mathcal{L} = G_2(X) + G_3(X)\Box\phi + \frac{1}{2}M_{\mathrm{pl}}^2 R$
- Linear perturbations in the quasi-static regime described by two functions, μ^{L} and Σ^{L}
- $-k^2\Psi = 4\pi G_{\mathrm{N}} a^2 \mu^{\mathrm{L}}(a,k)\bar{\rho}_{\mathrm{m}}\delta_{\mathrm{m}}$, $-k^2(\Psi + \Phi) = 4\pi G_{\mathrm{N}} a^2 \Sigma^{\mathrm{L}}(a,k)\bar{\rho}_{\mathrm{m}}\delta_{\mathrm{m}}$
- Linear perturbations: $\mu^{\mathrm{L}} = \Sigma^{\mathrm{L}} = 1 + \frac{2\alpha_{\mathrm{B}}^2}{\alpha c_{\mathrm{s}}^2}$
- Nonlinear Vainshtein screening
- Everything can be written in terms of the EFT functions α_{K} and α_{B}

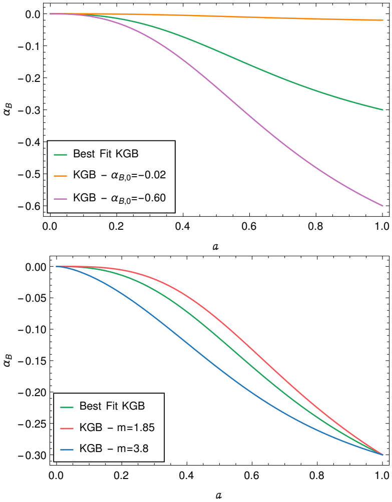
EFT functions for linear perturbations

- $H(t)$ [$w_{\rm ds}(t)$]: background evolution
- $\alpha_{\rm K}(t)$: "kineticity" - kinetic energy, large $\alpha_{\rm K} \to$ small $c_{\rm s}^2$
- $\alpha_{\rm B}(t)$: "braiding" - mixing of kinetic terms and metric, contributes to DE clustering
- $\alpha_{\rm M}(t)$: "running rate of the Planck mass" $M^2(t)$ - $H\alpha_{\rm M} = {\rm d}\ln M^2 {\rm d}t$, contributes to the anisotropic stress
- $\alpha_{\rm T}(t)$: "tensor speed excess" - $c_{\rm gw}^2/c^2 = 1 + \alpha_{\rm T}$, contributes to the anisotropic stress
- $\alpha_{\rm H}(t)$: "beyond Horndeski" - higher order terms that cancel in the e.o.m.
- Stability conditions: $c_{\rm s}^2 > 0$, $c_{\rm T}^2 > 0$, $\alpha = \alpha_{\rm K} + 6\alpha_{\rm B}^2 > 0$

Bellini & Sawicki, 2014; Gleyzes et al., 2014, 2015

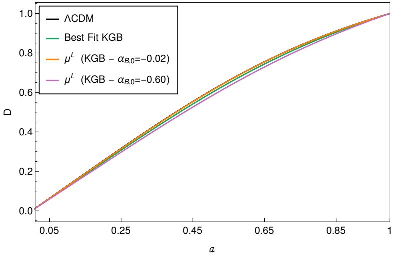
- We need to specify G_2 and G_3 to fix α_{K} and α_{B}
- Here we pursue a more general approach not specifying the G functions
- KGB features are encoded in $w_{\mathrm{de}}(a)$ and $\alpha_{\mathrm{B}}(a)$
- This modelling fits more than 98% of the randomly generated models (Traykova et al., 2021)
- $w_{\mathrm{de}}(a) = w_0 + w_a(1-a)$, $\alpha_{\mathrm{B}}(a) = \alpha_{\mathrm{B},0}\left(\frac{H_0}{H(a)}\right)^{4/m}$, $\alpha_{\mathrm{K},0} = 10$
- The baseline model is $\{w_0, w_a, \alpha_{\mathrm{B},0}, m\} = \{-0.97, -0.11, -0.30, 2.4\}$

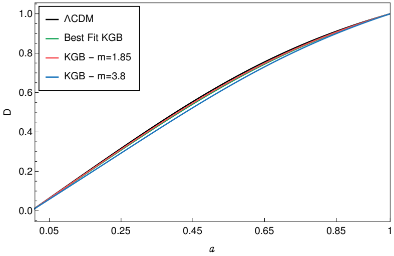
Evolution of α_B



How do linear perturbations evolve?

$$\ddot{\delta}_{\rm m} + 2H\dot{\delta}_{\rm m} - 4\pi G_{\rm N}\bar{\rho}_{\rm m}\,\mu^{\rm L}(a)\delta_{\rm m} = 0$$



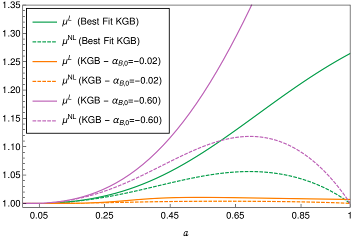


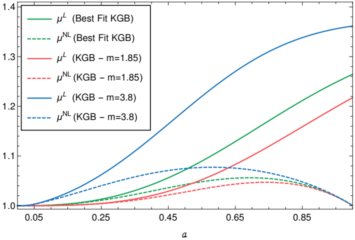
Fisica Torino

INFN Istituto Nazionale di Fisica Nucleare

Effective gravitational constant

Recall the definition of the linear effective gravitational constant $\mu^{\mathrm{L}} = 1 + \frac{2\alpha_B^2}{\alpha c_s^2}$

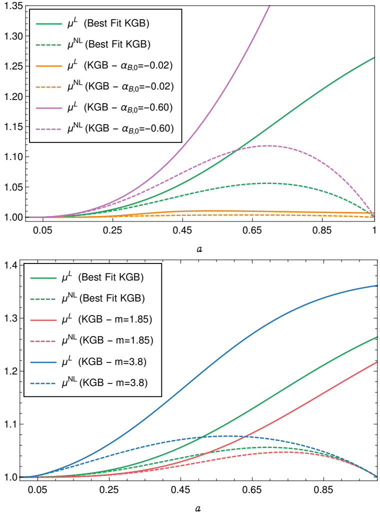




How can we compute nonlinear perturbations?

- Assume the validity of the quasi-static approximation
- Poisson equation: $\nabla^2\Psi = \frac{\bar{\rho}_\mathrm{m}\delta_\mathrm{m}}{2M_\mathrm{pl}^2} + \alpha_\mathrm{B} H \nabla^2\chi$
- Evolution of the scalar field: $\nabla^2\chi + \lambda^2\left[(\nabla_i\nabla_j\chi)^2 - (\nabla^2\chi)^2\right] = -\frac{\lambda^2}{2M_\mathrm{pl}^2}\bar{\rho}_\mathrm{m}\delta_\mathrm{m}$
- Consider spherical symmetry
- Nonlinear effective gravitational constant
  $\mu^\mathrm{NL} = 1 + 2(\mu^\mathrm{L} - 1)\left(\frac{R}{R_\mathrm{V}}\right)^3\left(\sqrt{1 + \frac{R^3}{R_\mathrm{V}^3}} - 1\right)$
- Vainshtein radius $R_\mathrm{V}^3 = 8\lambda^4 G_\mathrm{N} M$ $\quad\left(\lambda^2 \equiv -\frac{2\alpha_\mathrm{B}^2}{H\alpha c_\mathrm{s}^2}\right)$
- Nonlinear Poisson equation: $\nabla^2\Psi = 4\pi G_\mathrm{N}\mu^\mathrm{NL}(a, R)a^2\bar{\rho}_\mathrm{m}\delta_\mathrm{m}$

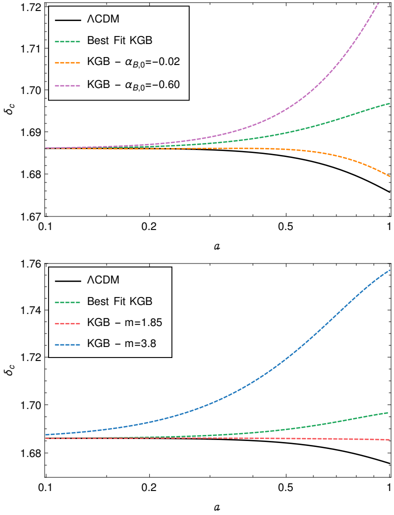
Nonlinear effective gravitational constant



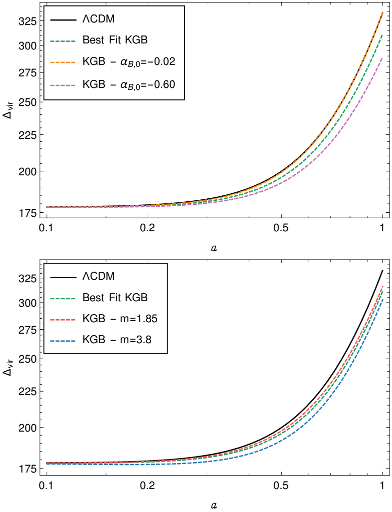
Evolution of nonlinear perturbations

- Use the spherical collapse model:
  $\ddot{\delta}_{\rm m} + 2H\dot{\delta}_{\rm m} - \frac{4}{3}\frac{\dot{\delta}_{\rm m}^2}{1+\delta_{\rm m}} - 4\pi G_{\rm N}\mu^{\rm NL}\bar{\rho}_{\rm m}\delta_{\rm m}(1+\delta_{\rm m}) = 0$
- A stable perturbation satisfies the virial theorem $T + \frac{1}{2}U = 0$
- Energy conservation is not strictly satisfied in modified gravity models, so we use it to find the virialization time
- Virial overdensity: $\Delta_{\rm vir} = [1+\delta_{\rm m}(R_{\rm vir})]\left(\frac{a_{\rm coll}}{a_{\rm vir}}\right)^3$

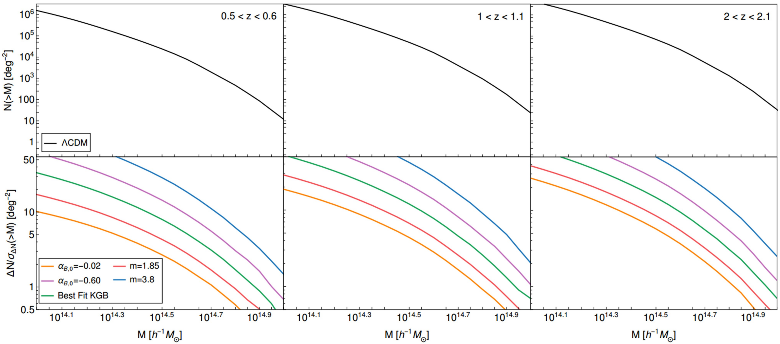
Linearly extrapolated overdensity



Virial overdensity



Halo number counts



Conclusions

- Structures grow differently from standard scenario
- This is true both at linear and nonlinear perturbations
- The Vainshtein mechanism is such that KGB models satisfy solar system constraints
- Differences are clearly observable in the halo mass function
- Future work
  - study lensing effects
  - application to voids