Non-linear structure formation in Horndeski gravity

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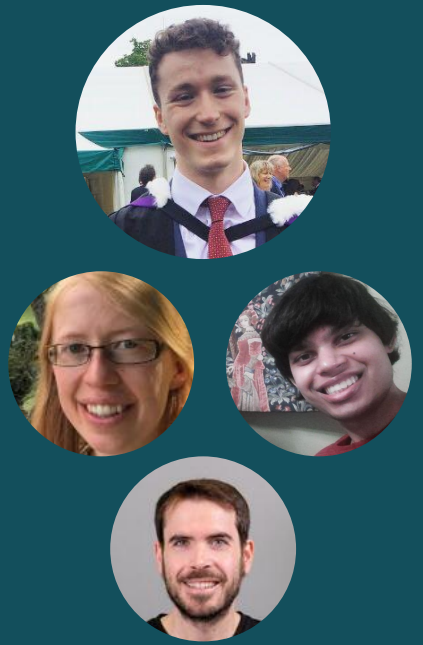


A Big Problem

In Horndeski gravity:

Linear
Structure Formation

Non-linear
Structure Formation

Big Problem for upcoming surveys as majority of constraining power comes from non-linear regime

Either:

a) linear constraints in Horndeski
b) non-linear constraints on a few individual theories

Non-linear structure formation in Horndeski gravity

1. What is Horndeski gravity?

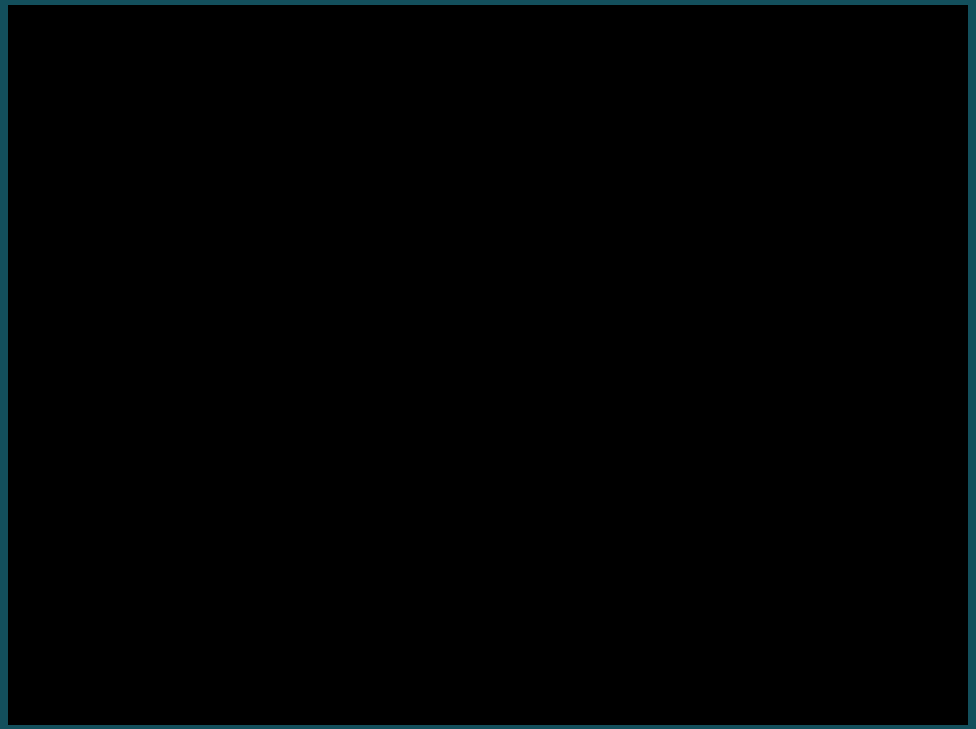
2. What is non-linear structure formation?

Horndeski Gravity

$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\sum_{i=2}^{5} \mathcal{L}_i + \mathcal{L}_\mathrm{m}[g_{\mu\nu}] \right]$$

$$\begin{aligned}
\mathcal{L}_2 &= K(\phi, X) \\
\mathcal{L}_3 &= -G_3(\phi, X)\Box\phi \\
\mathcal{L}_4 &= G_4(\phi, X)R + G_{4X}(\phi, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right] \\
\mathcal{L}_5 &= G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]
\end{aligned}$$

Non-linear structure formation



Credit: Volker Springel (MPA)

$$\delta = \frac{\rho}{\bar{\rho}} - 1$$

Linear: $\delta \ll 1$

Simple equations

Non-linear: $\delta \geq 1$

Difficult equations

Use *N*-body

Non-linear structure formation in Horndeski

Well understood via EFT functions (Bellini & Sawicki 2014)

EFT functions derived from linearised field equations:

$$\{H, \alpha_M, \alpha_B, \alpha_K, \alpha_T\}$$

Hubble factor | Running of Planck mass | Braiding | Kineticity | Tensor speed excess

Linear observables can be computed with hi_class or EFTCAMB

Reminder: A Big Problem

No Horndeski *N*-body simulation codes exist

Big Problem for upcoming surveys as majority of constraining power comes from non-linear regime

Either:

a) linear constraints in Horndeski
b) non-linear constraints on a few individual theories

Others are tackling this problem too (Hassani & Lombriser 2020, Thomas 2020)

Simulations in Horndeski

Need to compute screened fifth force

Do this via screening factor & coupling:

$$F_{5\mathrm{th}} = F_{\mathrm{GR}} \times \frac{G_{\mathrm{eff}}}{G_{\mathrm{GR}}} \times [1 + \mathrm{coupling} \times \mathrm{screening\ factor}]$$

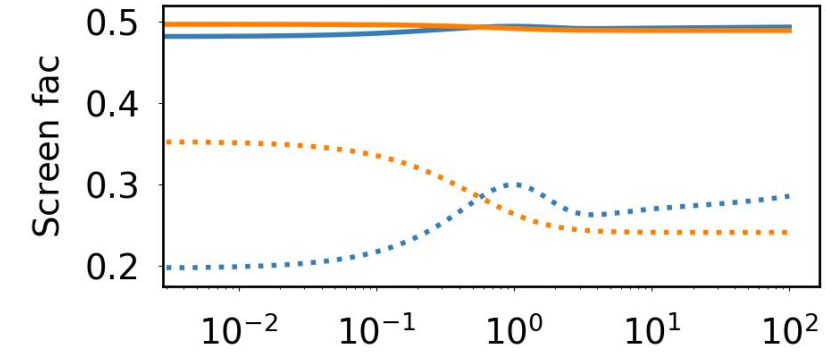
Screening factor is density-dependent

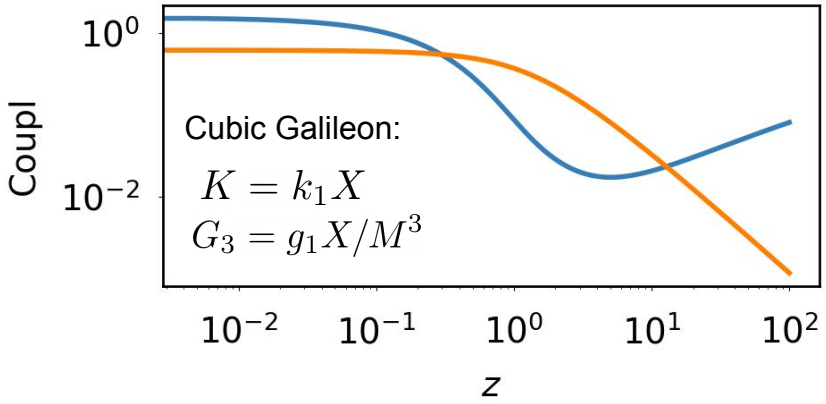
Compute screening factor & coupling from background solutions

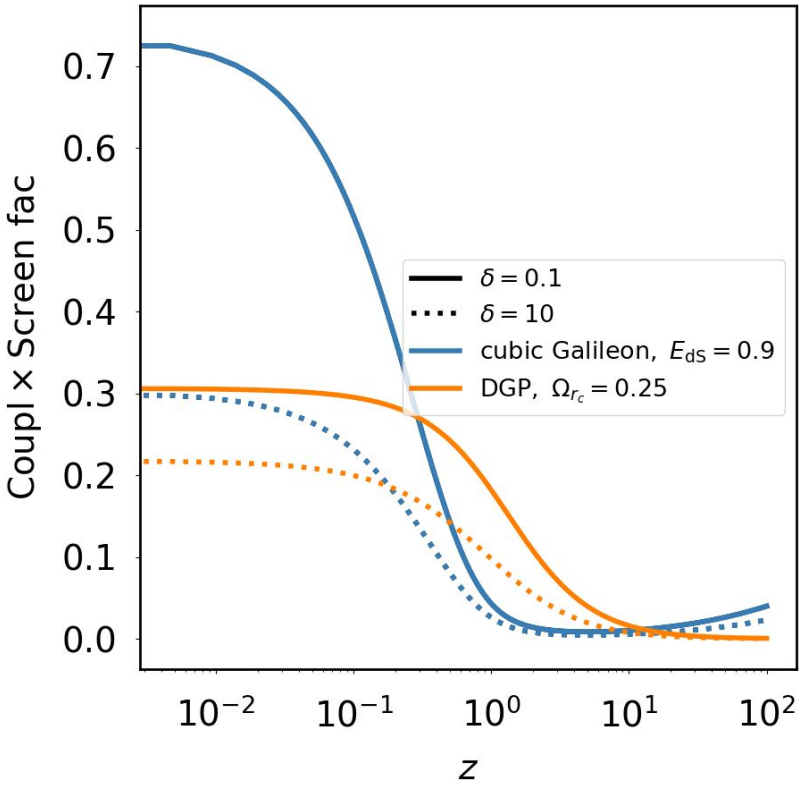
Solve for full background rather than assuming LCDM expansion history

Implement screened fifth force in approximate COLA simulation code = HiCOLA

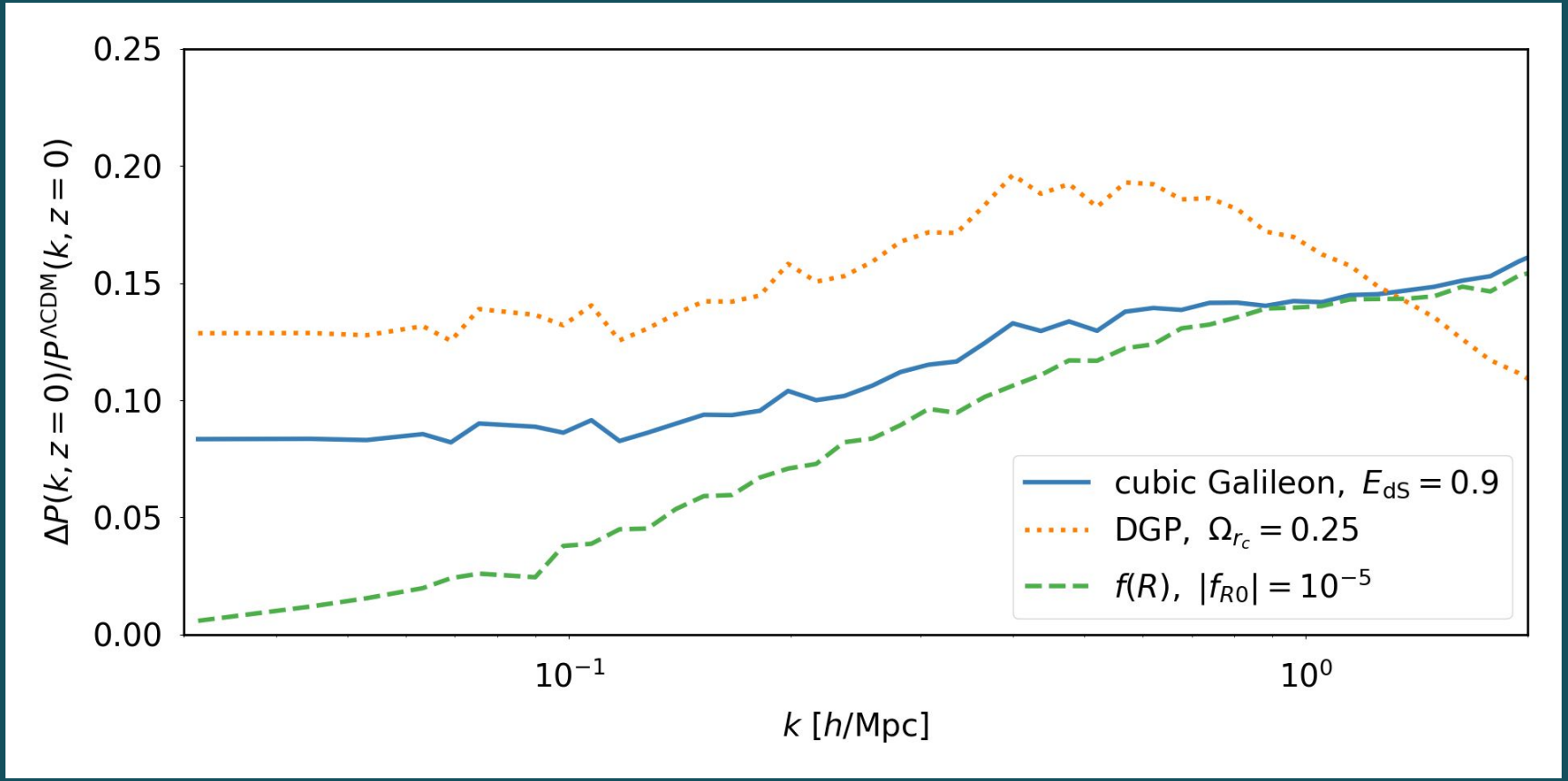
Screening factor & coupling







Non-linear matter power spectrum



Take-home points

1. Constraining Horndeski instead of individual theories is efficient
2. Currently can’t compute non-linear structure formation in Horndeski
3. This is a Big Problem because most of upcoming LSS data is non-linear
4. N-body simulations in Horndeski are required
5. We can compute screened fifth force for general Horndeski with full background
6. Implemented in HiCOLA, an approximate COLA simulation code

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