Non-linear Horndeski analysis with Hi-COLA



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In a nutshell

Hi-COLA is a fast, approximate simulation package that can provide results valid on mildly non-linear scales for a wide class of Horndeski modified gravity theories for the first time

Outline

1. Motivation for developing Hi-COLA
2. What Hi-COLA is
3. The theories it computes predictions for - reduced Horndeski class
4. Use of Hi-COLA on an example theory - the cubic Galileon
    a. Overview of how Hi-COLA works
    b. Some of the physics we have found through Hi-COLA
5. Another example - the Extended Shift Symmetric model

The purpose of Hi-COLA

- ΛCDM has been shown to hold to high precision in Solar System tests [1]
- Modified Gravity (MG) theories with screening mechanisms can satisfy constraints from such tests
- Screening mechanisms manifest on non-linear scales
    - Nonlinear analyses of theories typically done through computationally expensive N-body simulations

[1] Bertotti, B., Iess, L. & Tortora, P. A test of general relativity using radio links with the Cassini spacecraft. *Nature* **425,** 374–376 (2003).

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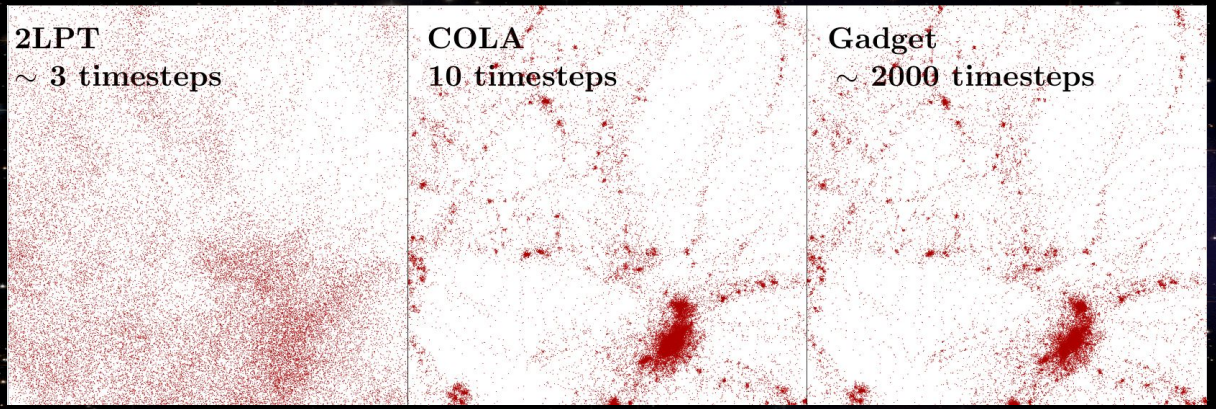
- Modified Gravity (MG) theories with screening mechanisms can satisfy constraints from such tests
- Screening mechanisms manifest on non-linear scales
    - Nonlinear analyses of theories typically done through computationally expensive N-body simulations
- Hi-COLA is a fast, approximate simulation package for theories with screening as it is valid on mildly non-linear scales, giving predictions to compare with upcoming galaxy survey data to constrain this theory space.

[1] Bertotti, B., Iess, L. & Tortora, P. A test of general relativity using radio links with the Cassini spacecraft. *Nature* **425,** 374–376 (2003).

What is Horndeski-in-COLA (Hi-COLA)?

- COLA = Co-moving Lagrangian Acceleration, a hybrid N-body code
- Uses Lagrangian Perturbation Theory on large scales, N-body on small scales, giving mildly non-linear results in less time steps than traditional N-body codes
- Can incorporate and compute predictions for theories with *screening mechanisms* by encoding MG as a *fifth force effect*



Tassev, S., Zaldarriaga, M., and Eisenstein, D. J., "Solving large scale structure in ten easy steps with COLA", *Journal of Cosmology and Astroparticle Physics*, vol. 2013, no. 6, 2013.

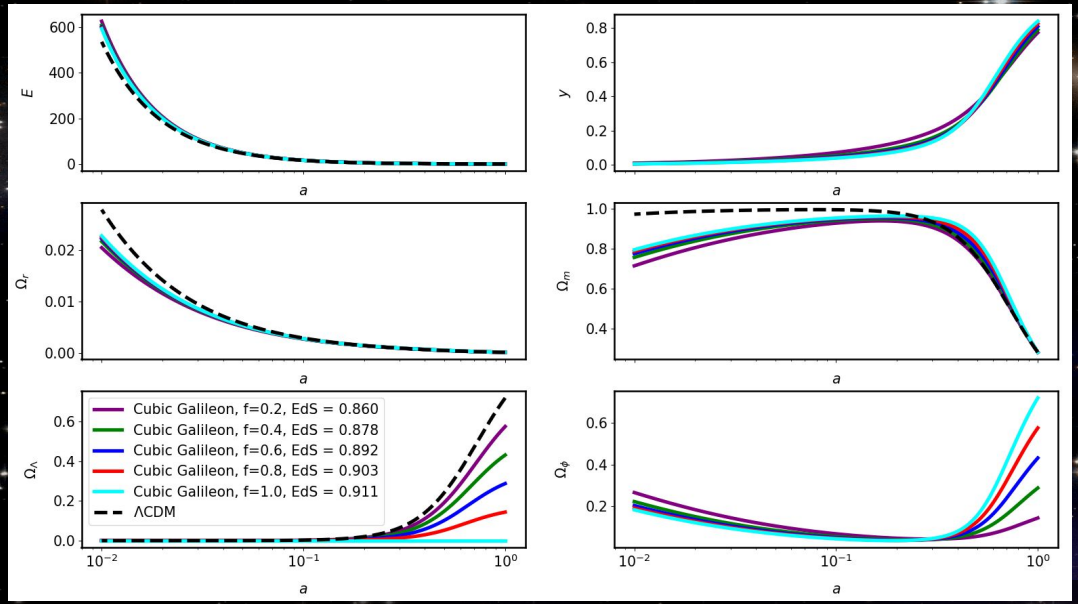
Reduced Horndeski (rH) Action

$$S = \int d^4x\sqrt{-g}\,(G_4(\phi)R + K(\phi, X) - G_3(\phi, X)\Box\phi + \mathcal{L}_m)$$

$$X = (-1/2)(\partial_\mu\phi)\partial^\mu\phi$$

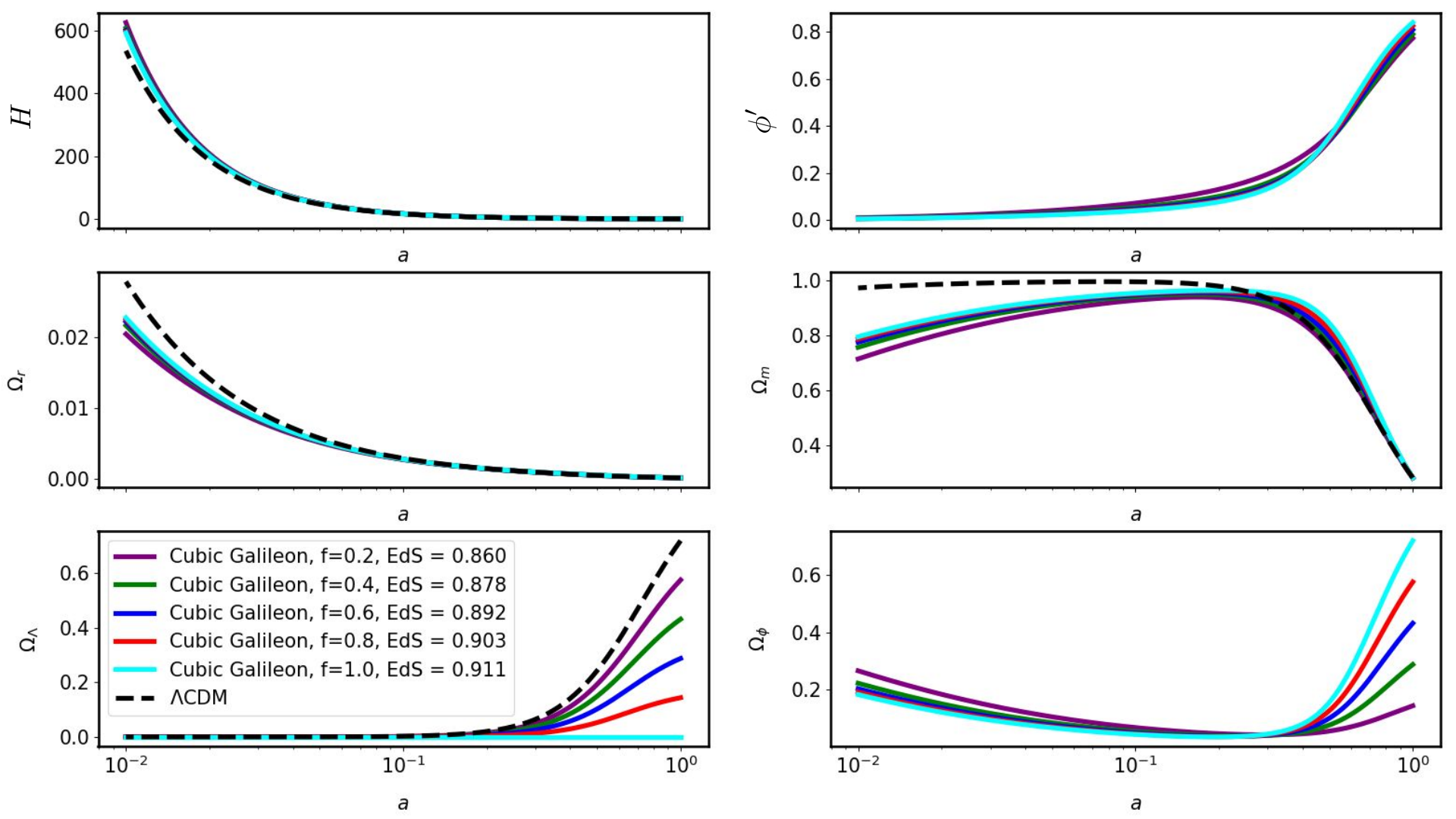
- ϕ is the extra scalar degree of freedom not present in GR
- GR-like piece
- Kinetic term for ϕ
- Non-linear interaction term that gives rise to screening
- HiCOLA has been designed to be applicable to ***any*** rH model
- K, G_3, G_4 are free functions that need to be specified

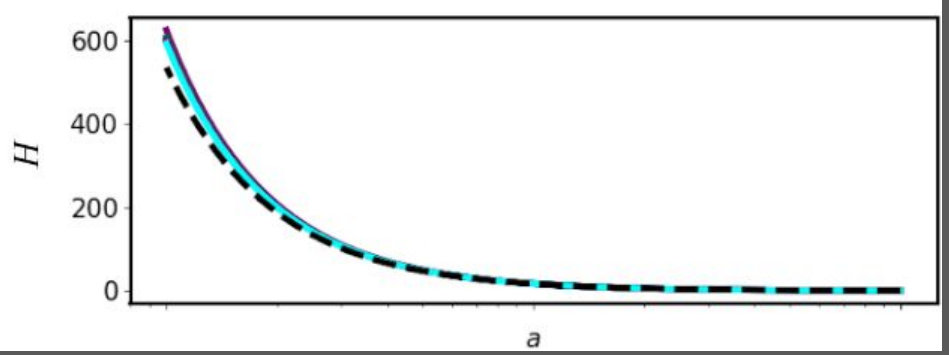
Background solutions for Cubic Galileon



- A useful test case, even if ruled out [2]
- Specified by: $K = k_1 X$ $G_3 = g_{31} X$ $G_4 = 0.5$
- f and E_{dS} are initial condition parameters for the Cubic Galileon

[2] Renk, Janina, Zumalacárregui, Miguel, Montanari, Francesco, and Barreira, Alexandre. 2017. "Galileon gravity in light of ISW, CMB, BAO and H {sub 0} data".


H
a
ϕ'
a
Ω_r
a
Ω_m
a
Ω_Λ
a
Ω_ϕ
a
Cubic Galileon, f=0.2, EdS = 0.860
Cubic Galileon, f=0.4, EdS = 0.878
Cubic Galileon, f=0.6, EdS = 0.892
Cubic Galileon, f=0.8, EdS = 0.903
Cubic Galileon, f=1.0, EdS = 0.911
ΛCDM


H
600
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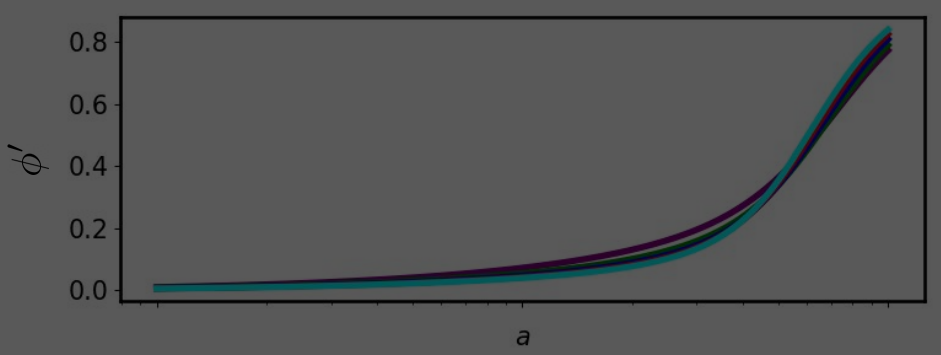
ϕ'
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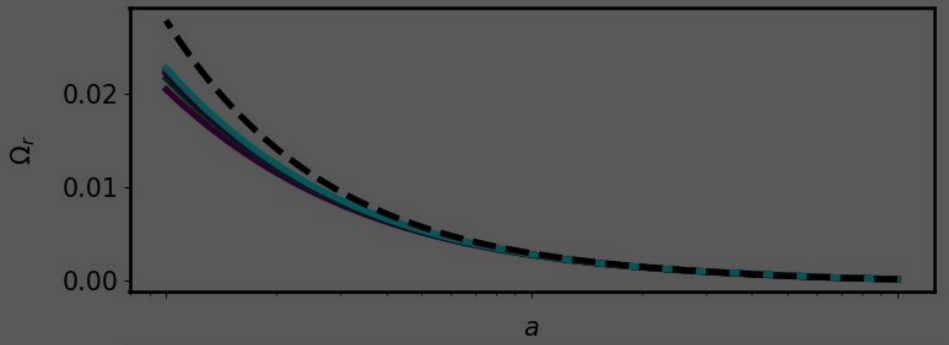
0.6
0.4
0.2
0.0
a


Ω_r
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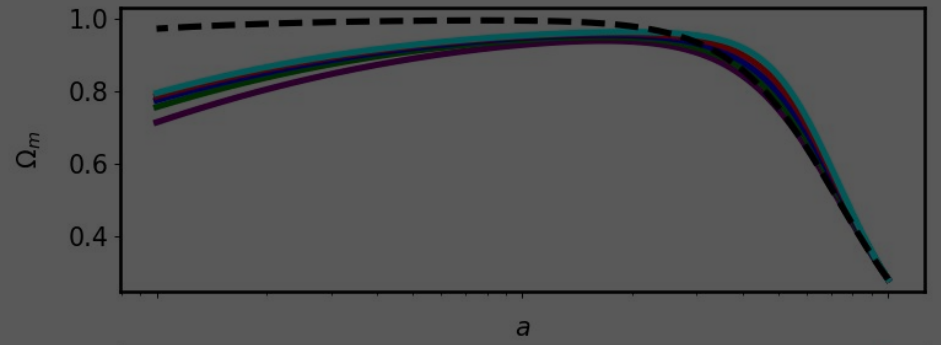
Ω_m
1.0
0.8
0.6
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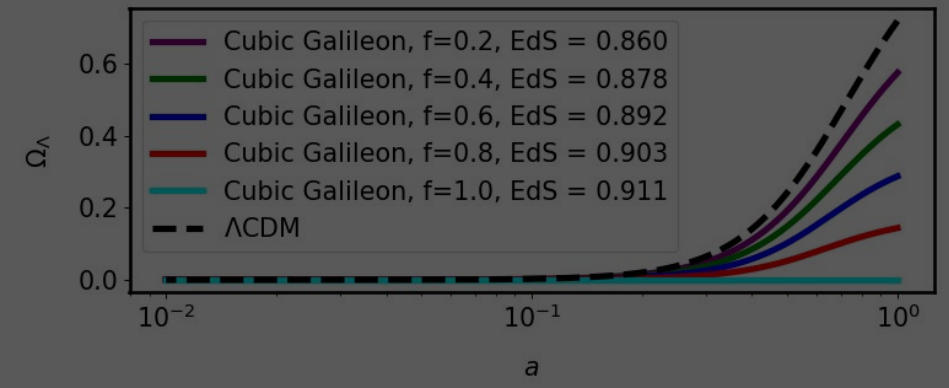
Ω_Λ
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10^{-2}
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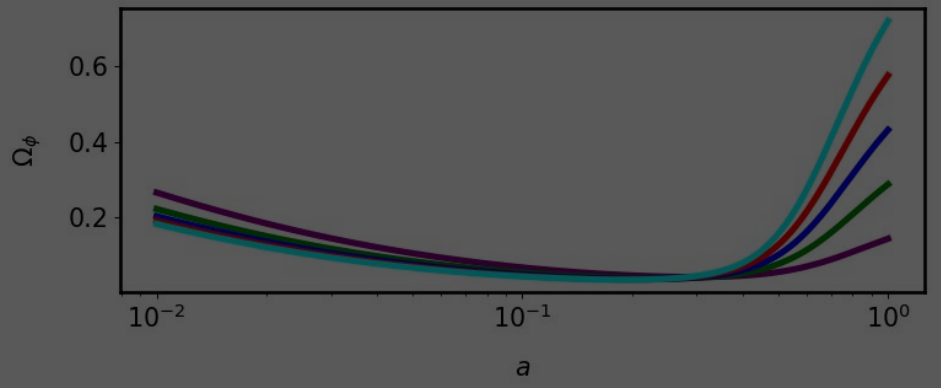
Ω_ϕ
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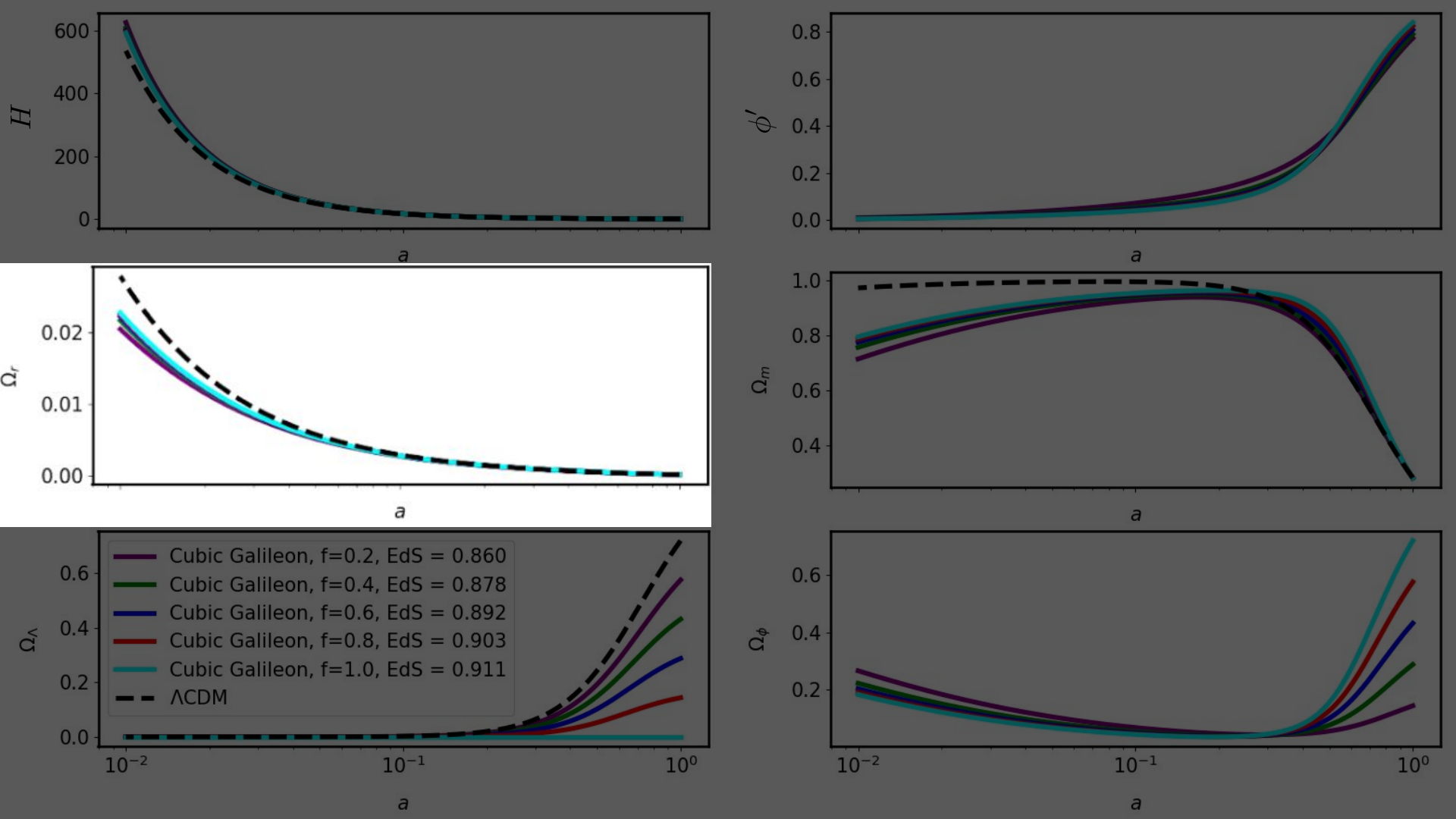
10^{-1}
10^{0}
a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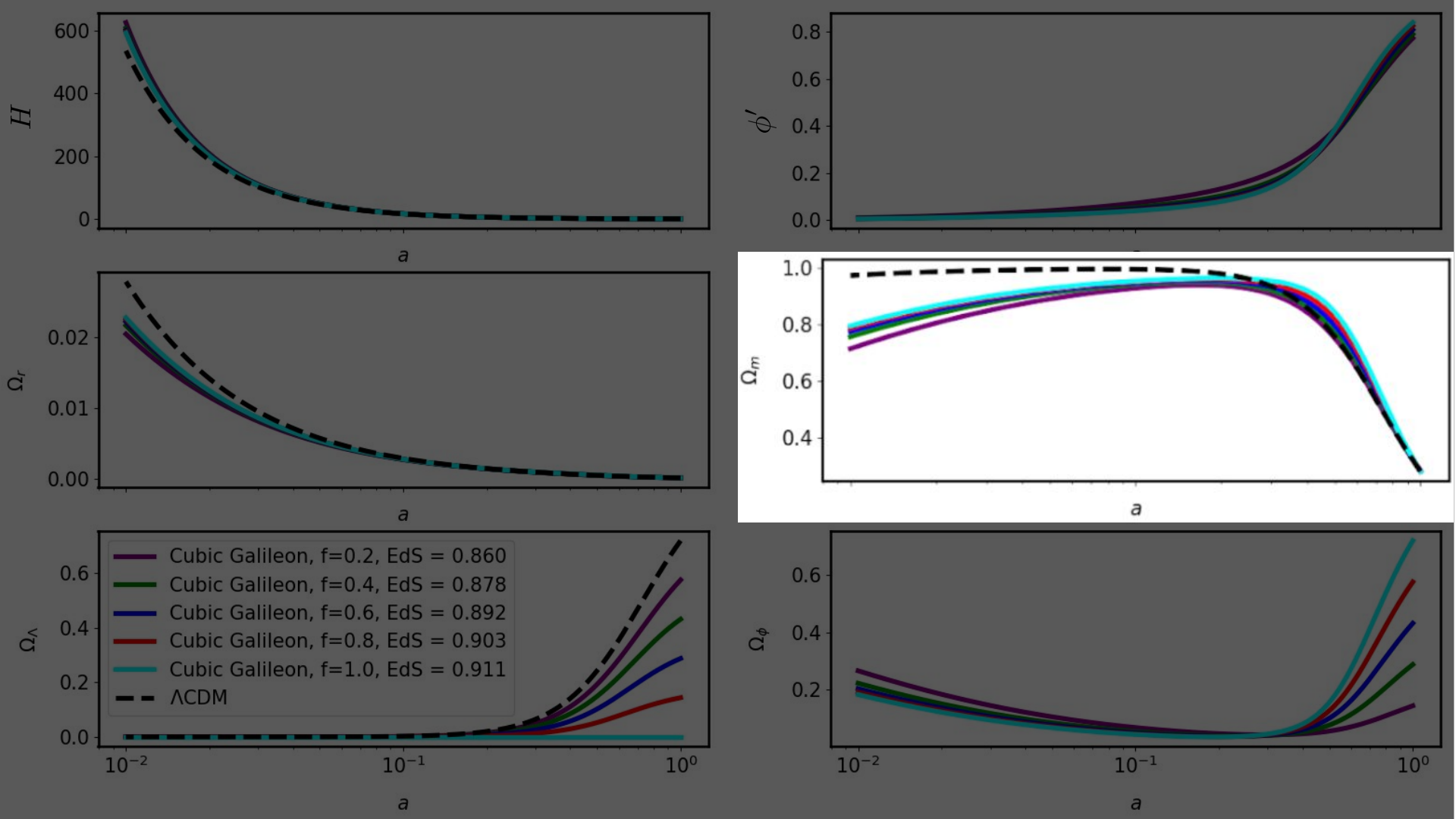
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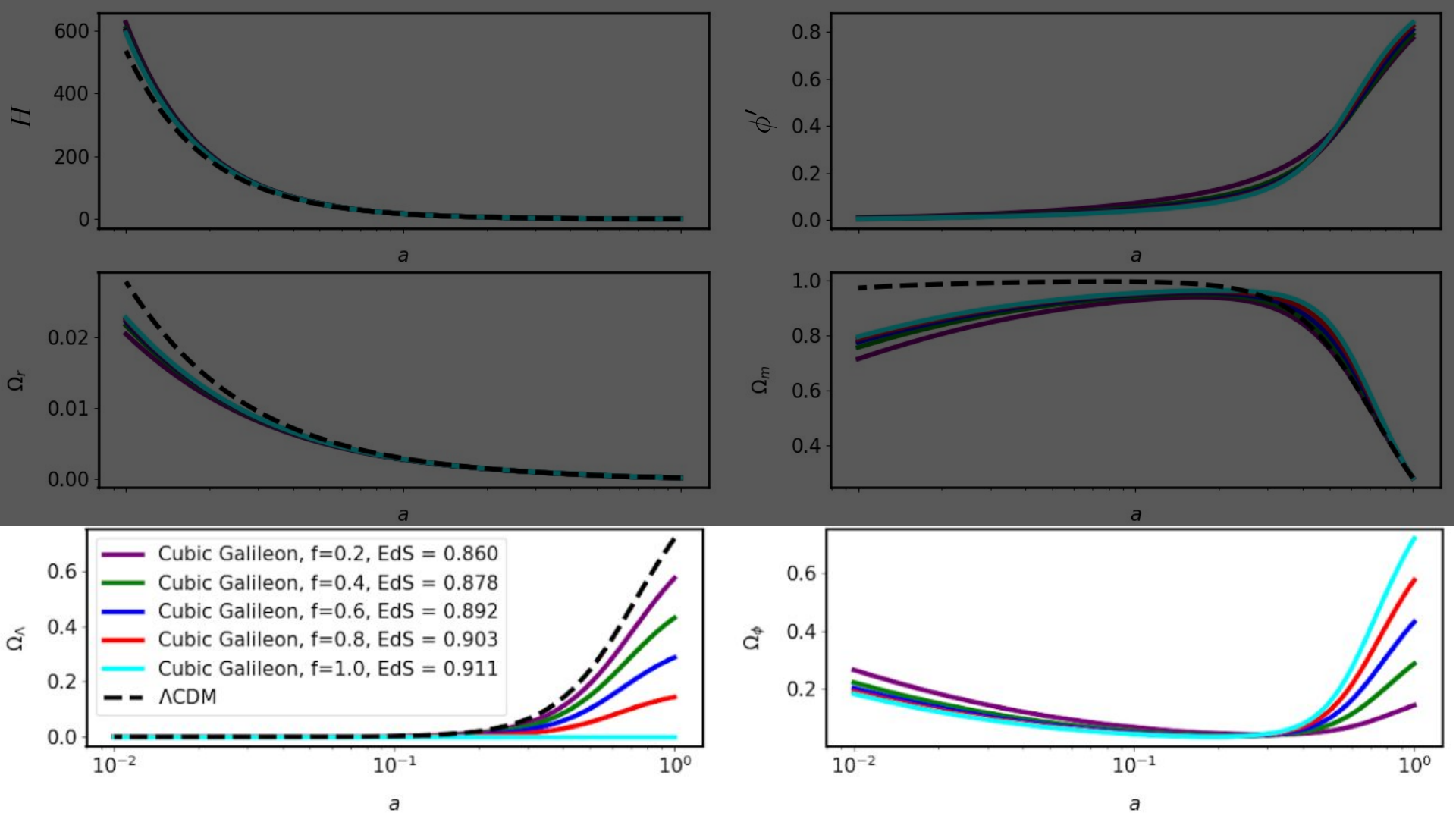
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ΛCDM

The Fifth Force

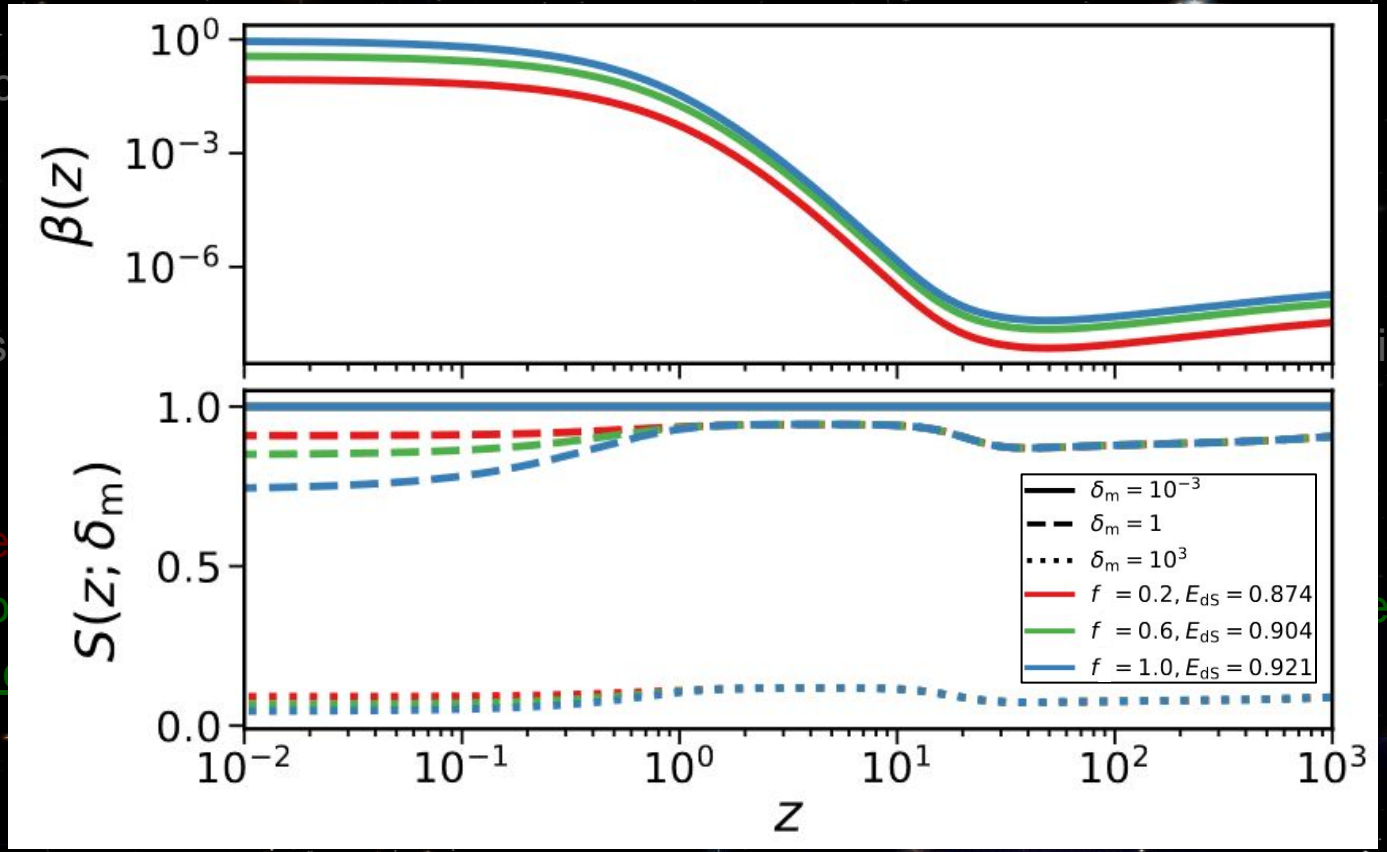
- 3 components needed to complete a Hi-COLA run:
  - Modified background (just seen)
  - Modified growth factors (detailed in our paper!)
  - Modified forces between particles
- Using Quasi-Static Approximation and Spherical Approximation, we derive:

$$F_{\text{total}} \propto F_N(1 + \beta S)$$

- Determines total strength of fifth force, depends only on background
- Controls when force approaches full strength or fully-screened limits, depends on background and local density

The Fifth Force

- 3 c
- Us ive:
- De
- Co epends on
  bac



The Fifth Force

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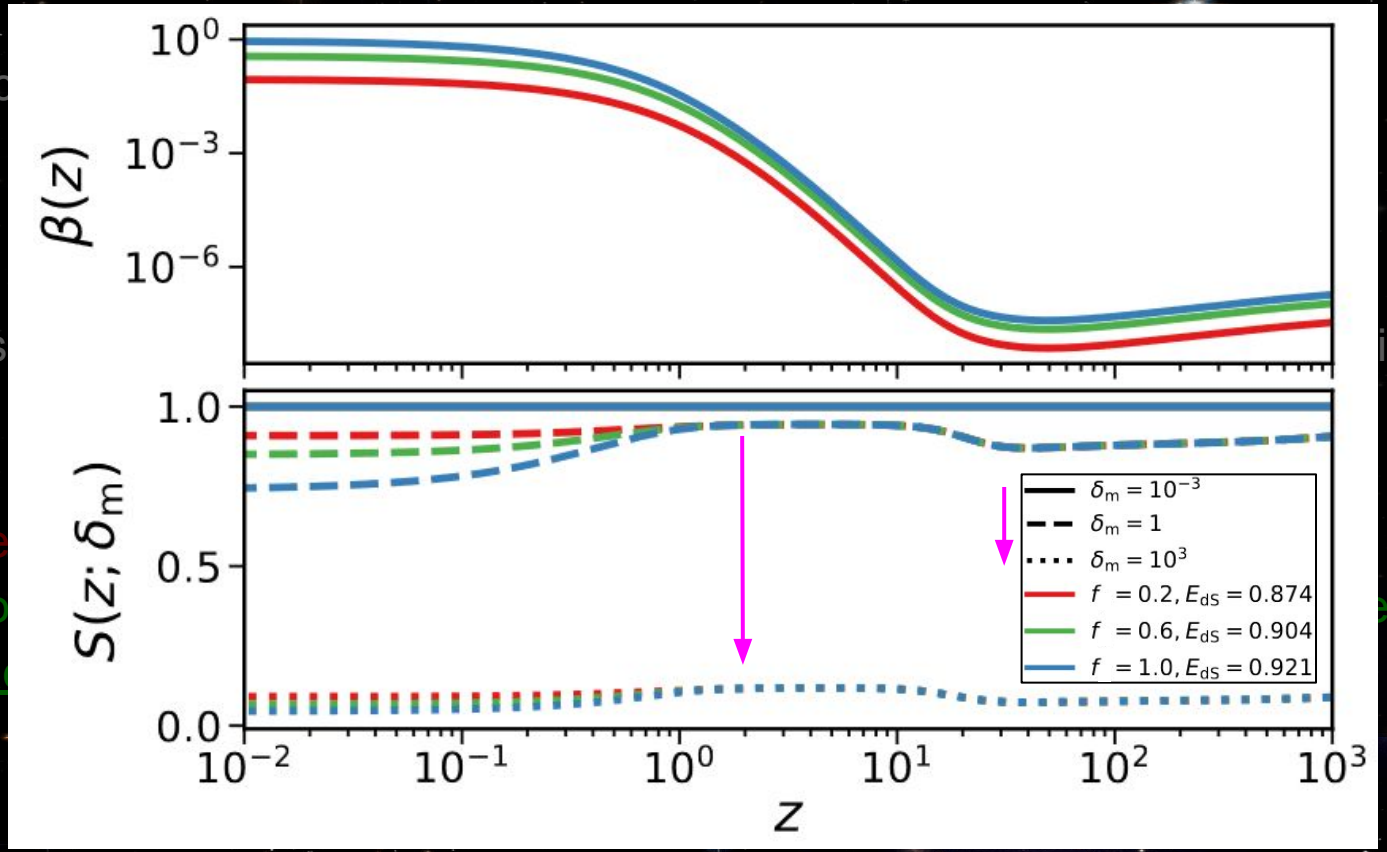
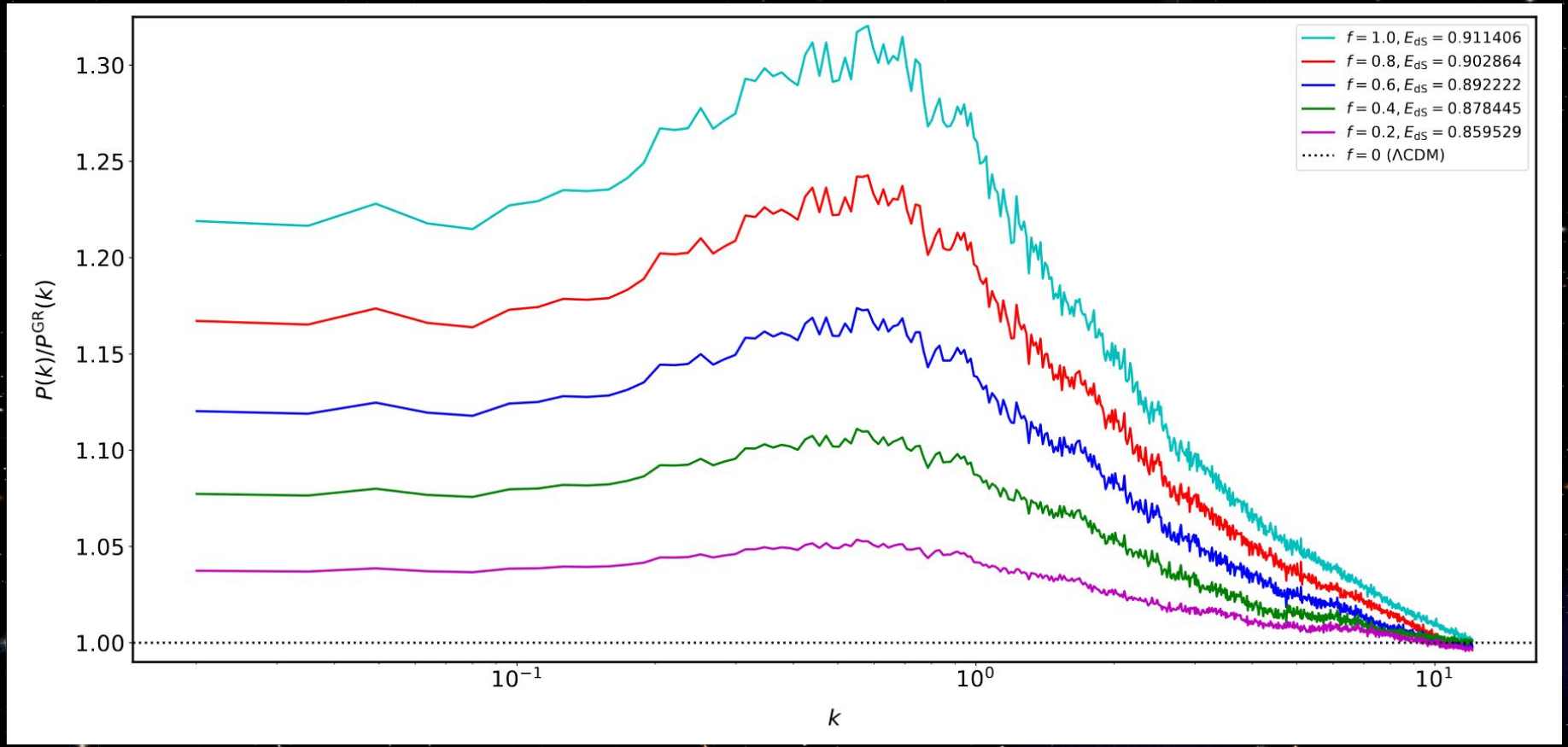
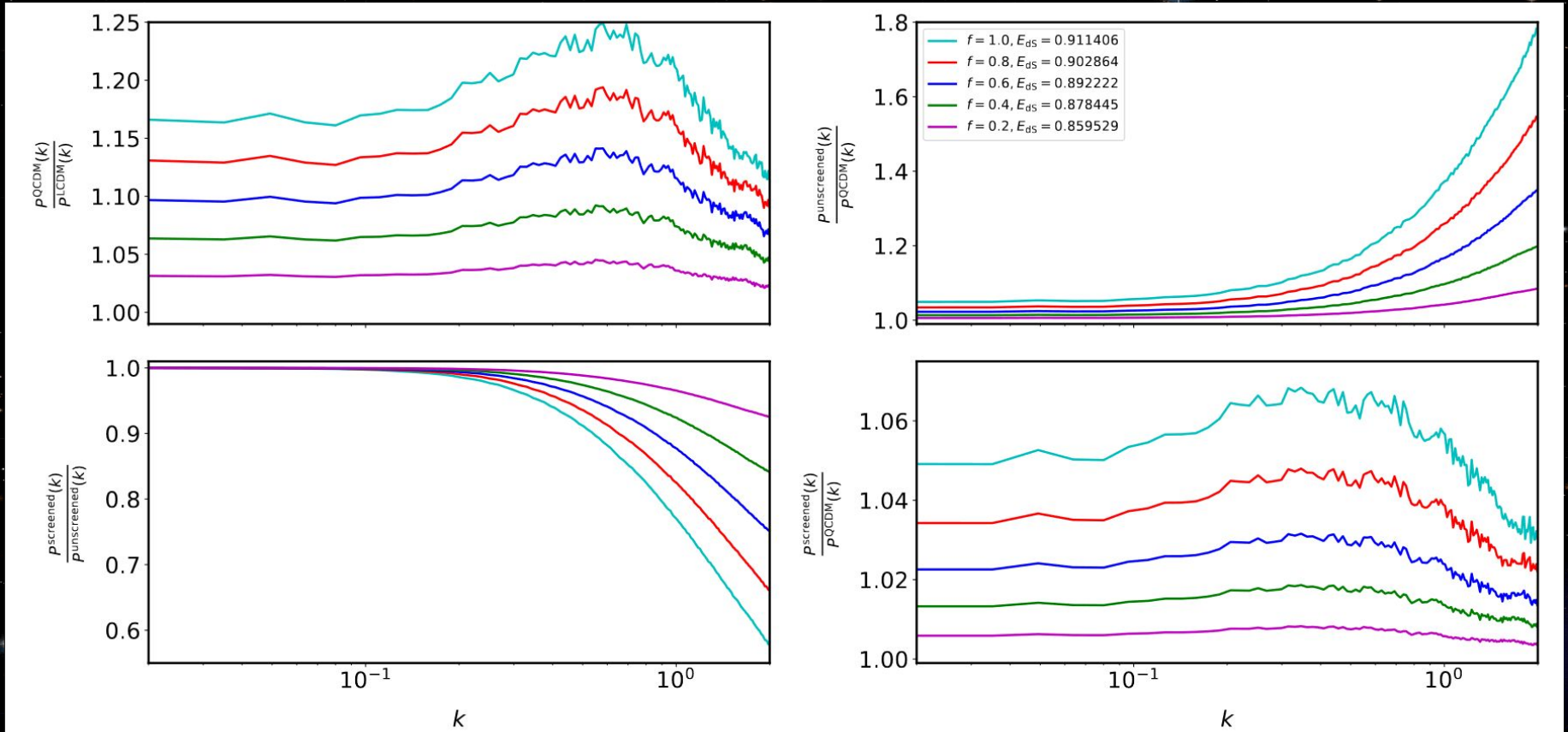
  bac



Cubic Galileon Power Spectra relative to GR



Breaking down the power spectra



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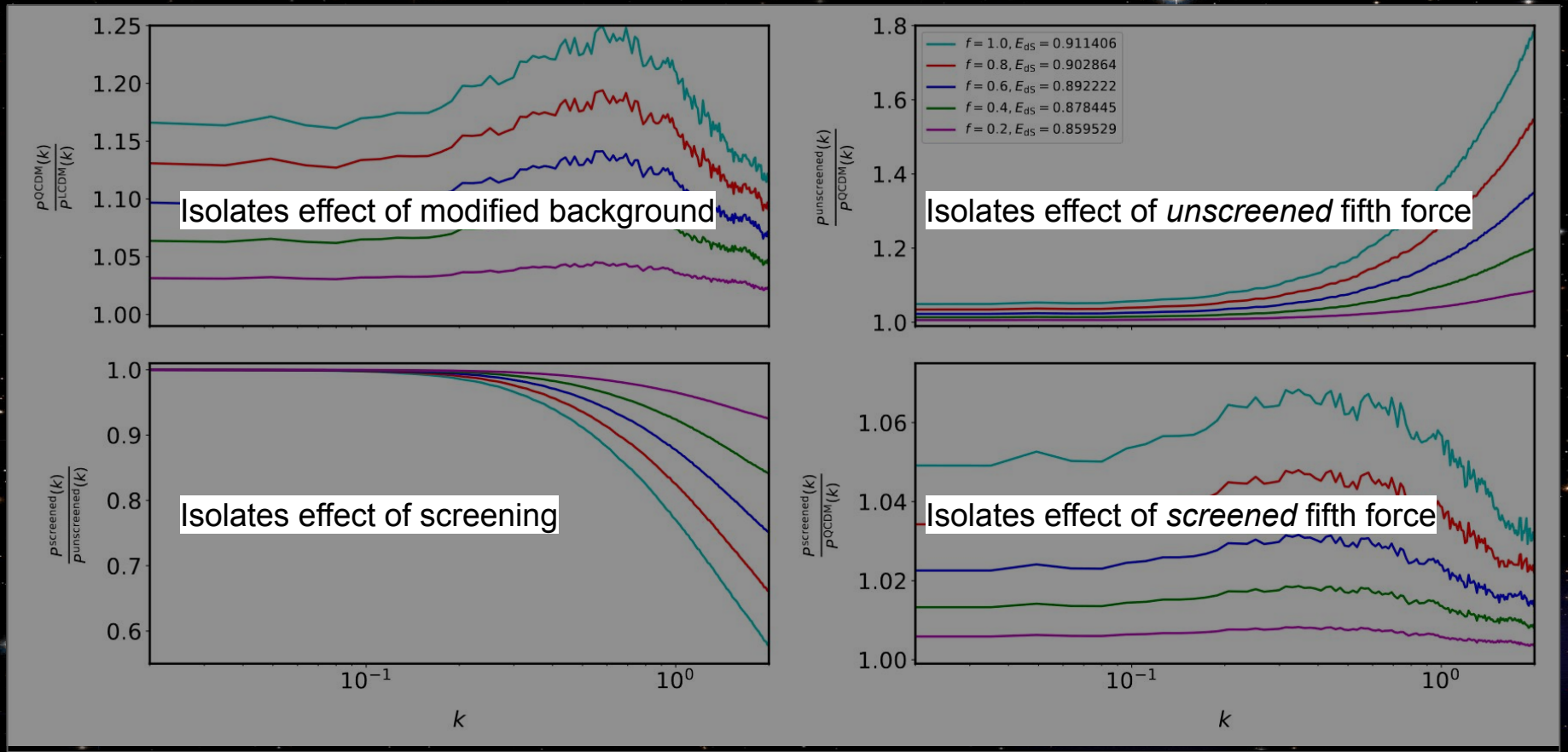

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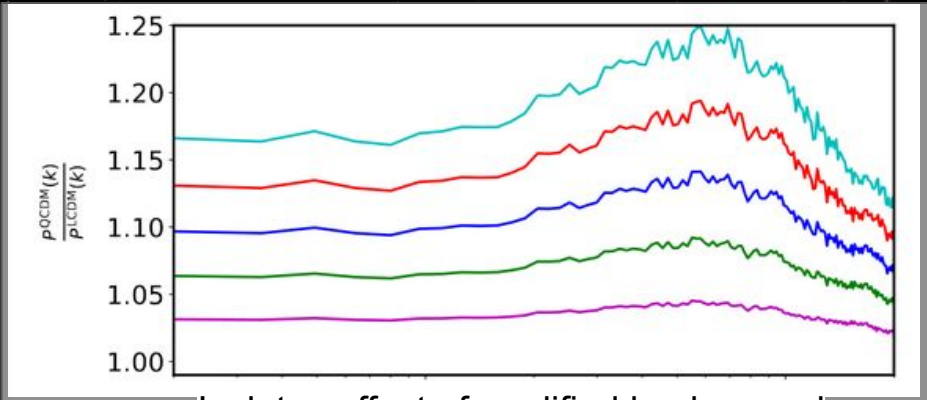
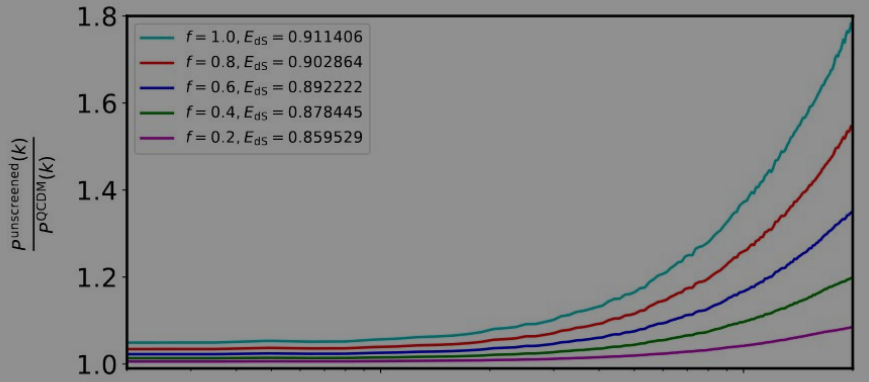
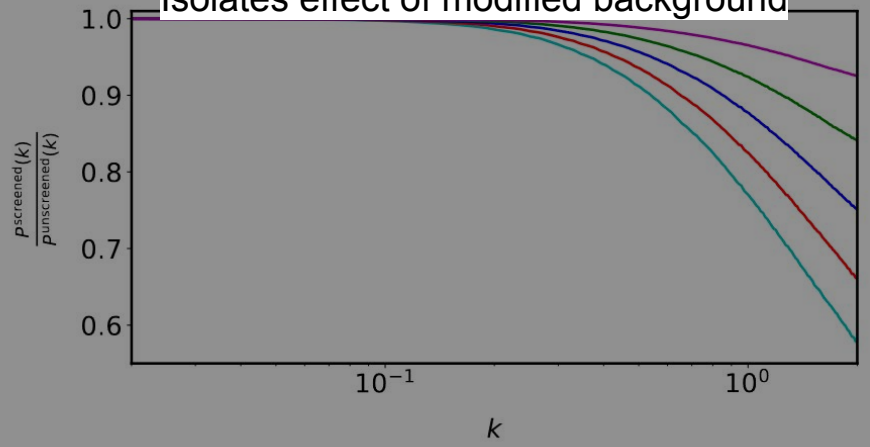
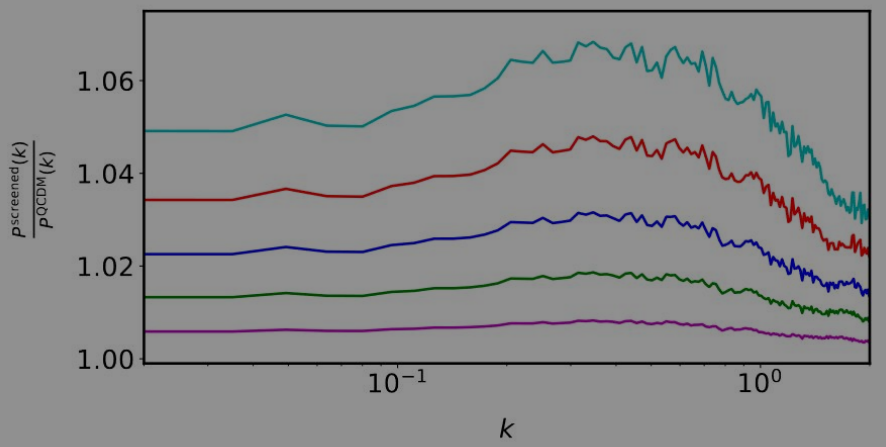


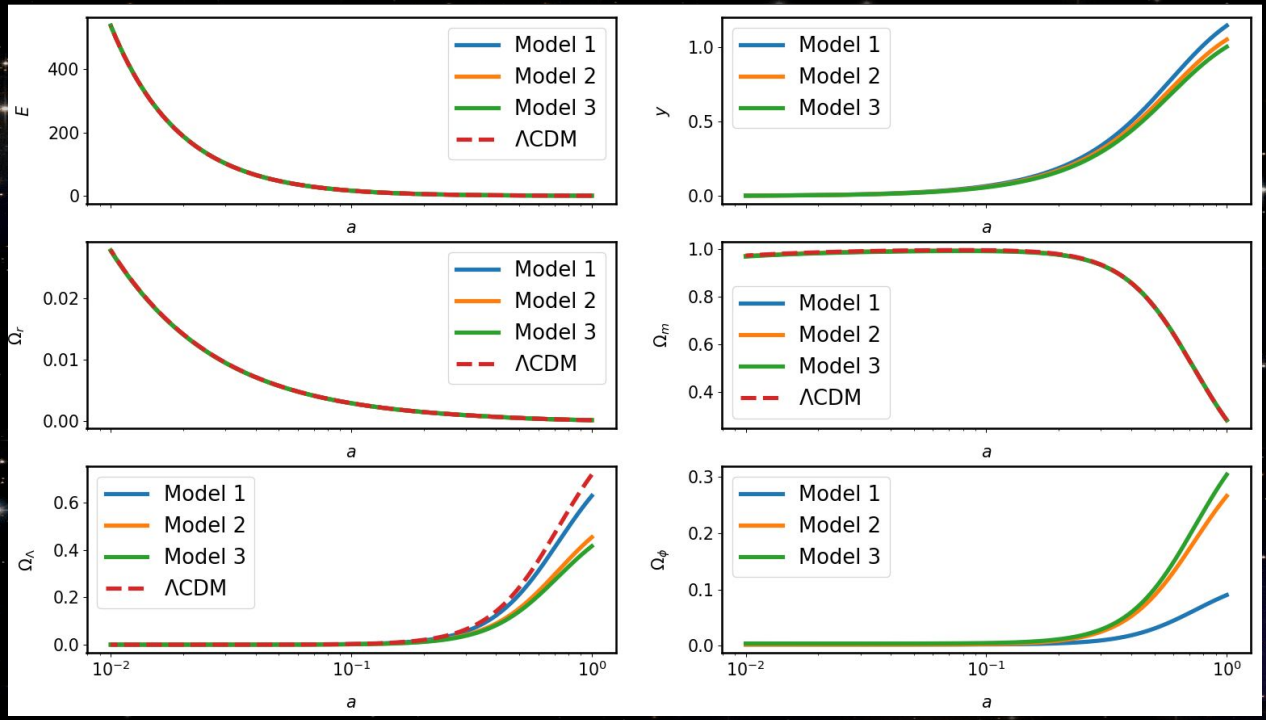
Isolates effect of modified background







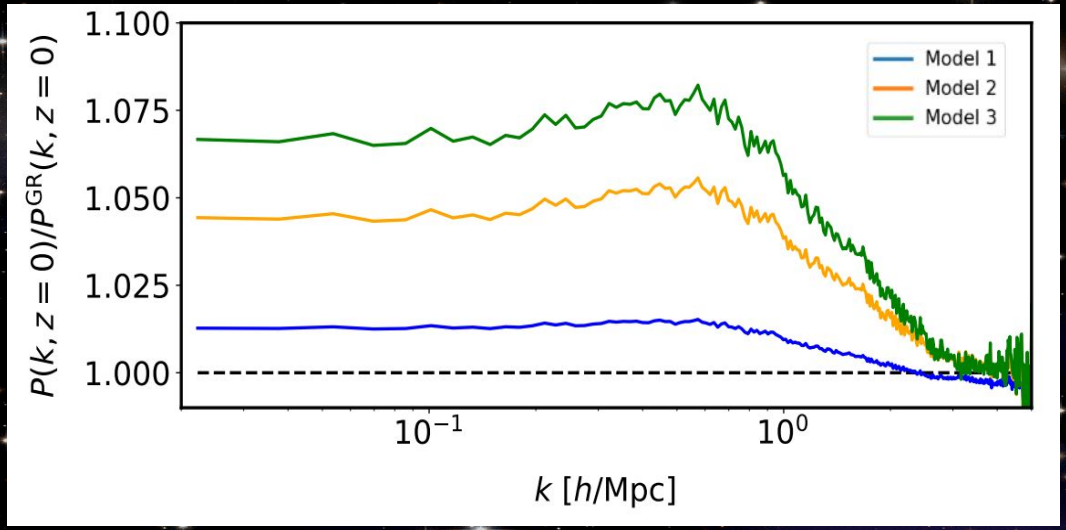
Background solutions for Extended Shift Symmetric models



- ESS specified by: $K = k_1 X + k_2 X^2$ $G_3 = g_{31} X + g_{32} X^2$ $G_4 = 0.5$

Traykova, D., Bellini, E., Ferreira, P. G., García-García, C., Noller, J., and Zumalacárregui, M., "Theoretical priors in scalar-tensor cosmologies: Shift-symmetric Horndeski models", *Physical Review D*, vol. 104, no. 8, 2021.

ESS power spectra relative to GR



- Even while satisfying criteria to show ΛCDM-like behaviour, there are still visible differences in the power spectra
- Can see the varied linear enhancements, and suppression back to GR due to screening

Takeaway messages

- Hi-COLA produces fast, approximate nonlinear matter power spectra for a *wide* class of Horndeski models. Will enable first tests of Horndeski family on non-linear scales with surveys like LSST.

- Including the *modified* background is important as its effects are significant on power spectra.

- Even while satisfying criteria to show ΛCDM-like behaviour, there are still visible differences in the power spectra. Potentially rich theory spaces to study and constrain with upcoming galaxy surveys.

Paper outlining results and methodology in collaboration review, stay tuned!