Emulating the non-linear power spectrum in beyond-LCDM models

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Based on: 2203.11120 + 2303.09549

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Introduction

- The era of Stage-IV LSS surveys is finally arriving:

- And with it, the information on <u>small scales</u> will drastically increase

Introduction

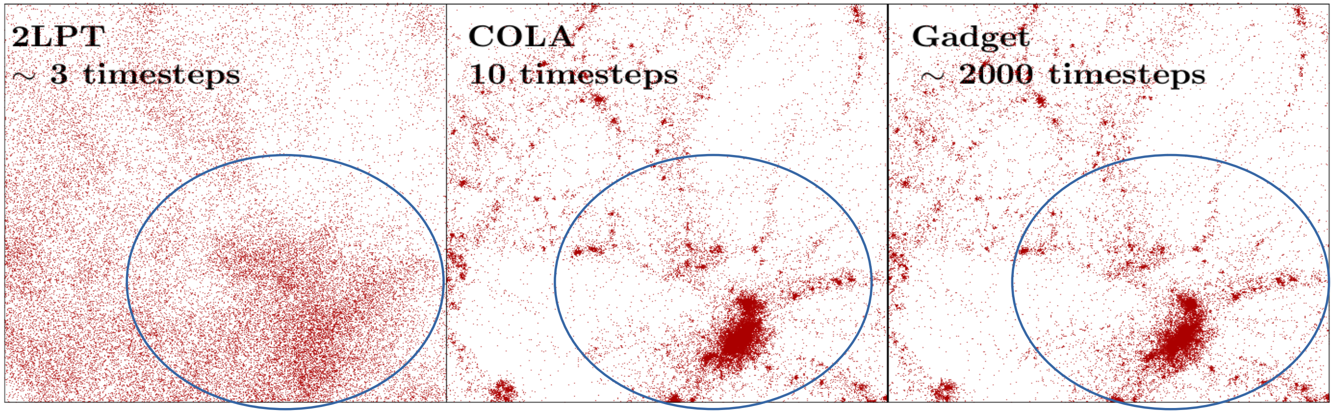
- The main quantity we want to get predictions on non-linear scales is the matter power spectrum

- One way of modelling this quantity in these scales is using N-Body simulations

- However:
  - 1) N-Body simulations are time consuming and computationally expensive
  - 2) Performing a full MCMC parameter estimation → need an order of 10^4-10^5 simulations
  - 3) The power spectrum measuered from these simulations is noisy → afftected by resolution issues
  - 4) All of this is worse in beyond-LCDM models

COLA

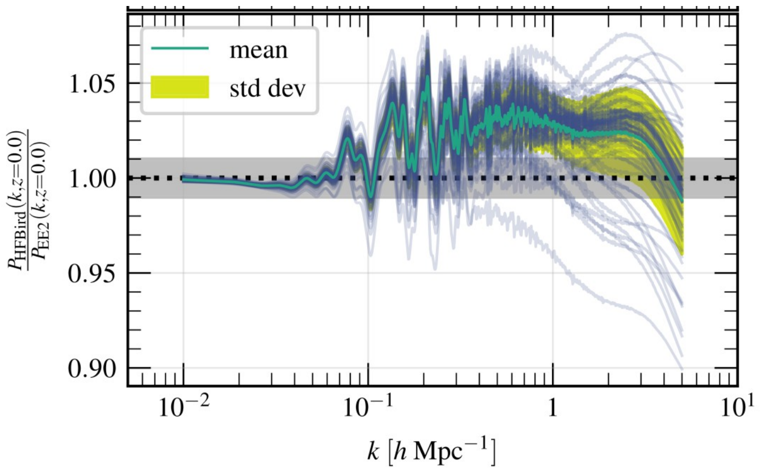
- Issue 1) To bypass the cost of running one N-Body sim we can use the COmoving Lagrangian Approximation method:
  - 2^{nd} Order Lagrangian Perturbation Theory + Particle-Mesh Algorithm
  - Effective decoupling of large scale modes (LPT) and small scale modes (PM)
  - Reduced number of time-steps at the cost of losing resolution at small scales



S. Tassev et al - 1301.0322

LCDM-Emulators

- <u>Issue 2)</u> Emulation techniques:
  - Instead of running 10^4 simulations we run ~10^2 simulations
  - Emulation methods then interpolate the results of cosmological simulations using machine learning
  - Example of emulators for the non-linear power spectrum in LCDM:
    - Euclid Emulator 2 (EE2): M. Knabenhans et al 2010.11288
      - N-Body simulations – PKDGRAV3
      - Approx 250 simulations
      - Emulation of the boost: $B\left(k,z\right)=\dfrac{P_{\mathrm{non}}\left(k,z\right)}{P_{\mathrm{lin}}\left(k,z\right)}$

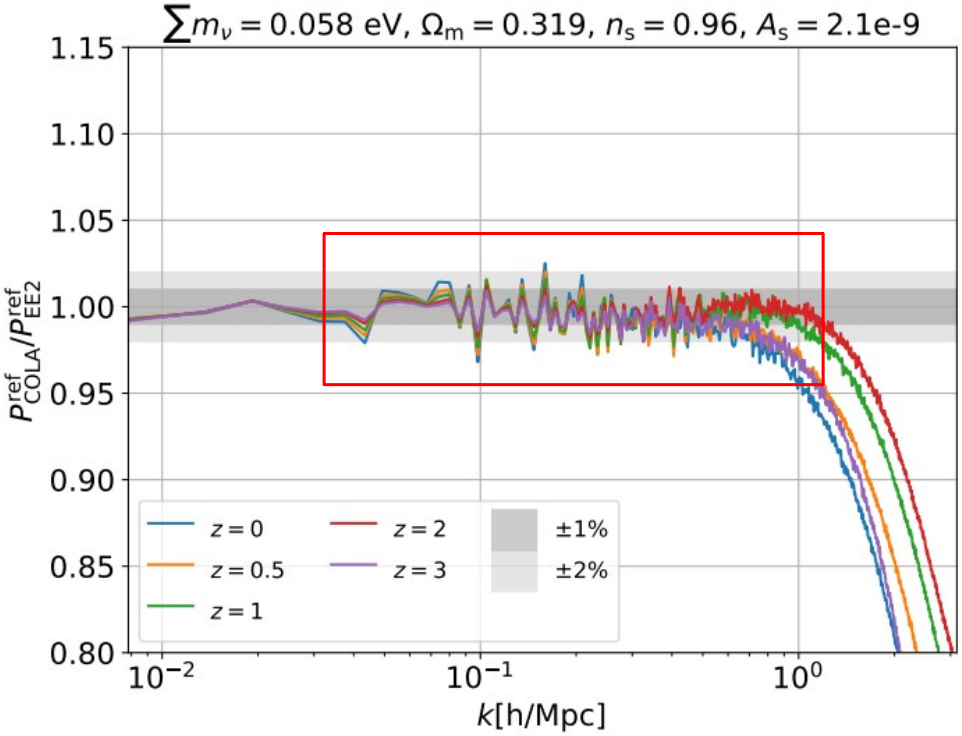


Parameter	min.	max.	Reference
Ω_m	0.24	0.40	0.319
Ω_b	0.04	0.06	0.049
n_s	0.92	1.0	0.96
A_s	1.7×10^{-9}	2.5×10^{-9}	2.1×10^{-9}
h	0.61	0.73	0.67

Table 1: Parameter space EE2

COLA vs EEZ2

- Issue 3) The issue:



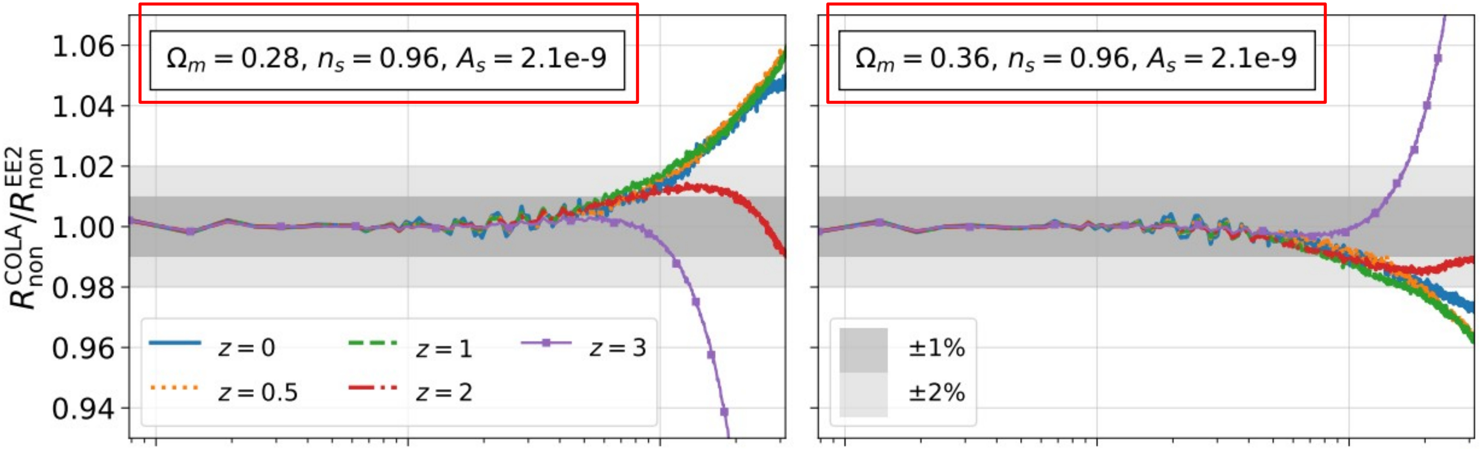
GB, B. Fiorini, et al: 2203.11120

COLA vs EE2

- Issue 3) To reduce the noise coming from resolution effects we can instead compare the non-linear response function, which is defined as:

$$R_{\rm non} = \frac{P_{\rm non}^{\rm case}}{P_{\rm non}^{\rm ref}}$$

Case cosmology: Case cosmology:



GB, B. Fiorini, et al: 2203.11120

COLA vs EE2

- Additionally, from the definition of the boost factor of a "case" cosmology (which can be any cosmology other than the reference one):

$$B^{\text{case}}(k,z) = \frac{P^{\text{case}}_{\text{non}}(k,z)}{P^{\text{case}}_{\text{lin}}(k,z)}$$

- We can rewrite it as:

$$B^{\text{case}}(k,z) = B^{\text{ref}}(k,z) \times \frac{R^{\text{case}}_{\text{non}}(k,z)}{R^{\text{case}}_{\text{lin}}(k,z)}$$

- Where we now see the Rnon function appearing explicitly

COLA vs EE2

- Additionally, from the definition of the boost factor of a “case” cosmology (which can be any cosmology other than the reference one):

$$B^{\rm case}\,(k,z) = \frac{P^{\rm case}_{\rm non}\,(k,z)}{P^{\rm case}_{\rm lin}\,(k,z)}$$

- We can rewrite it as:

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Quantity to be emulated

EE2 reference boost

Quantity computed using COLA

COLA & Modified Gravity

- To emulate the power spectrum for modified gravity we can use this prescription

- Where the main quantity we need to compute in COLA is the ratio (Rnon) of a case cosmology with respect to a reference one

- In MG theories this is simply: $\frac{P^{\mathrm{MG}}(k,z)}{P^{\mathrm{ref}}(k,z)}$

- So I will now present the MG theories we have created a fast way to run COLA simulations, and compare our results with available N-Body simulations in the literature

COLA & Modified Gravity

- We consider Hondeski gravity, whose action is big and messy:

$$S[g_{\mu\nu},\phi] = \int \mathrm{d}^4x\,\sqrt{-g}\left[\sum_{i=2}^{5}\frac{1}{8\pi G}\mathcal{L}_i[g_{\mu\nu},\phi] + \mathcal{L}_\mathrm{m}[g_{\mu\nu},\psi_M]\right]$$

- But can be made simpler:

$H(z)$	Fixes background
$\alpha_\mathrm{K}(z)$	Kineticity
$\alpha_\mathrm{B}(z)$	Braiding
$\alpha_\mathrm{M}(z)$	Running Planck Mass
$\alpha_\mathrm{T}(z)$	Tensor excess

→ Covariant Formulation

→ Parametrized Formulation

E. Bellini and I. Sawicki 1404.3713

COLA & Modified Gravity

- MG N-Body simulations solve:

N-Body:

$$\nabla^2\Phi = 4\pi G a^2 \delta\rho_{\rm m} + \frac{1}{2}\nabla^2\delta\phi,$$

$$\partial_\tau\delta + k\vec{v} = 0,$$

$$(\partial_\tau + \mathcal{H})\,\vec{v} = -\nabla\Phi,$$

$$\boxed{L[\delta\phi] = S(\delta\rho_{\rm m}, \delta\phi)}$$

Needs different solver:

Adds even more time and complexity

COLA:

$$\nabla^2\Phi = 4\pi G_{\rm eff} a^2 \bar{\rho}_{\rm m}\delta_{\rm m},$$

$$\partial_\tau\delta + k\vec{v} = 0,$$

$$[\partial_\tau + \mathcal{H}]\,v = -\nabla\Phi$$

$$\boxed{G_{\rm eff} = G_{\rm eff}\,(\alpha_{\rm B}, \alpha_{\rm M}, \alpha_{\rm T})}$$

One single time-dependent function

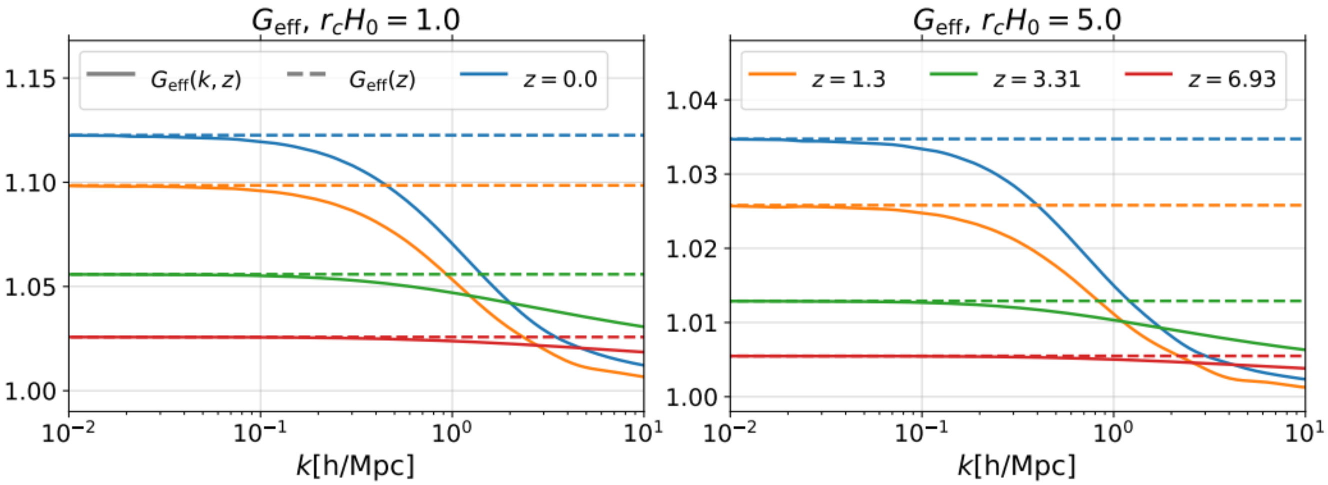
Linear theory

Screening

- In small scales, MG theories introduce an aditional force acting on particles, called 5th force. To shield this extra force we need to implement a screening mechanism in our simulations

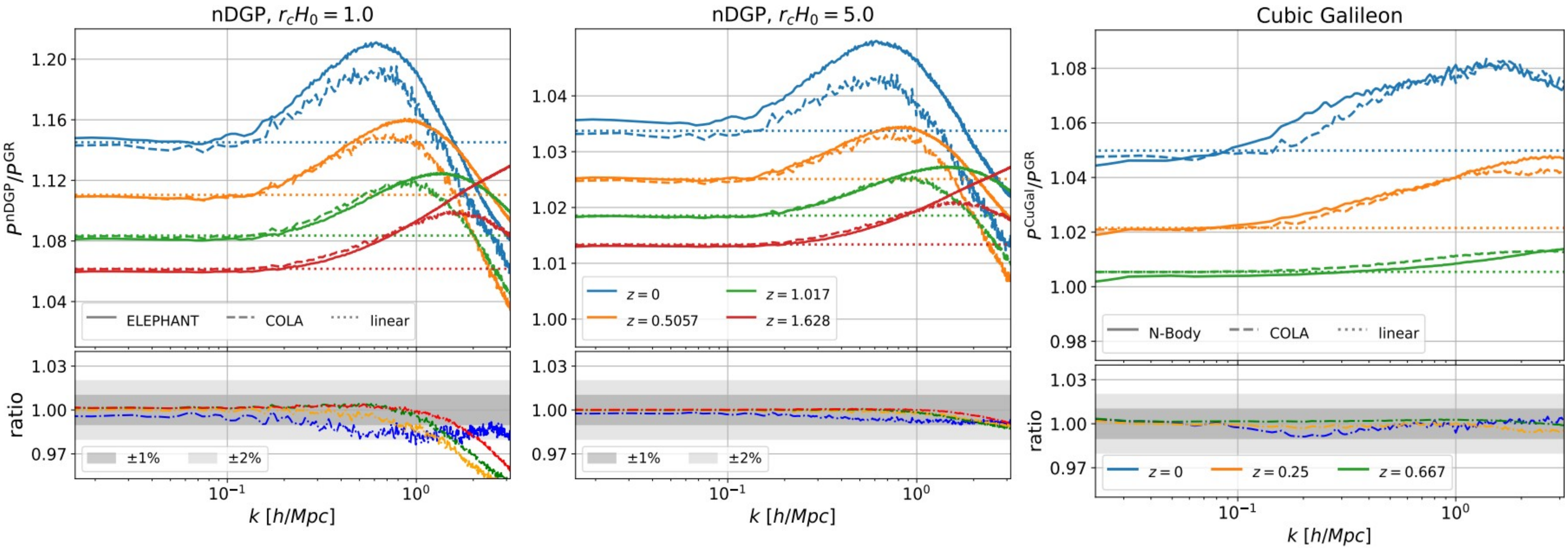
$$G_{\mathrm{eff}}\left(\alpha_{\mathrm{B}}\left(z\right),\alpha_{\mathrm{M}}\left(z\right),\alpha_{\mathrm{T}}\left(z\right)\right)\longrightarrow G_{\mathrm{eff}}\left(\mathbf{k},\alpha_{\mathrm{B}}\left(z\right),\alpha_{\mathrm{M}}\left(z\right),\alpha_{\mathrm{T}}\left(z\right)\right)$$

- In our COLA simulations we have implemented a numerical routine that numerically computes Geff as a function of scale, transitioning from its linear theory value to its GR one:



Screening

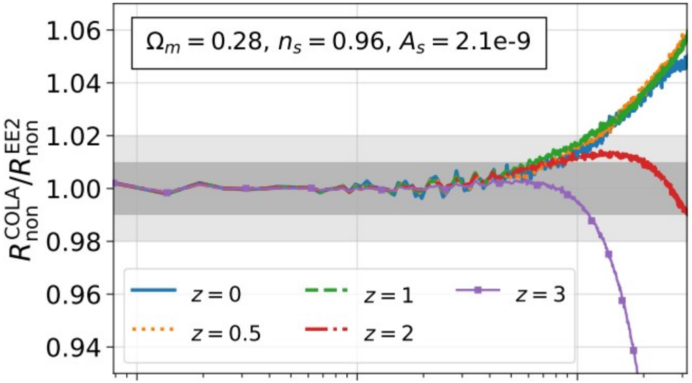
- Comparison with full N-Body simulations available in the literature

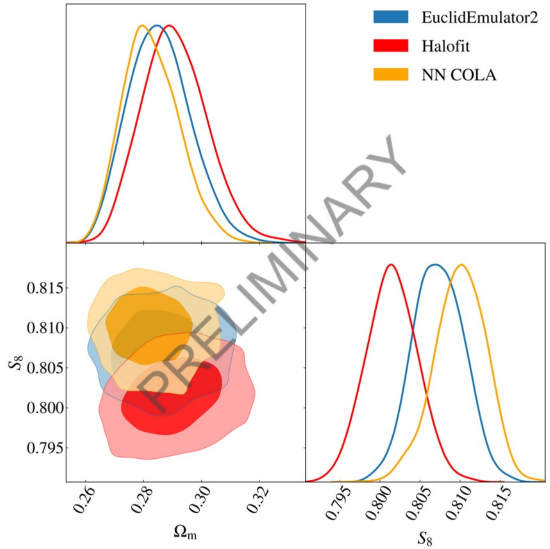


GB, K. Koyama, et al: 2303.09549

Conclusions

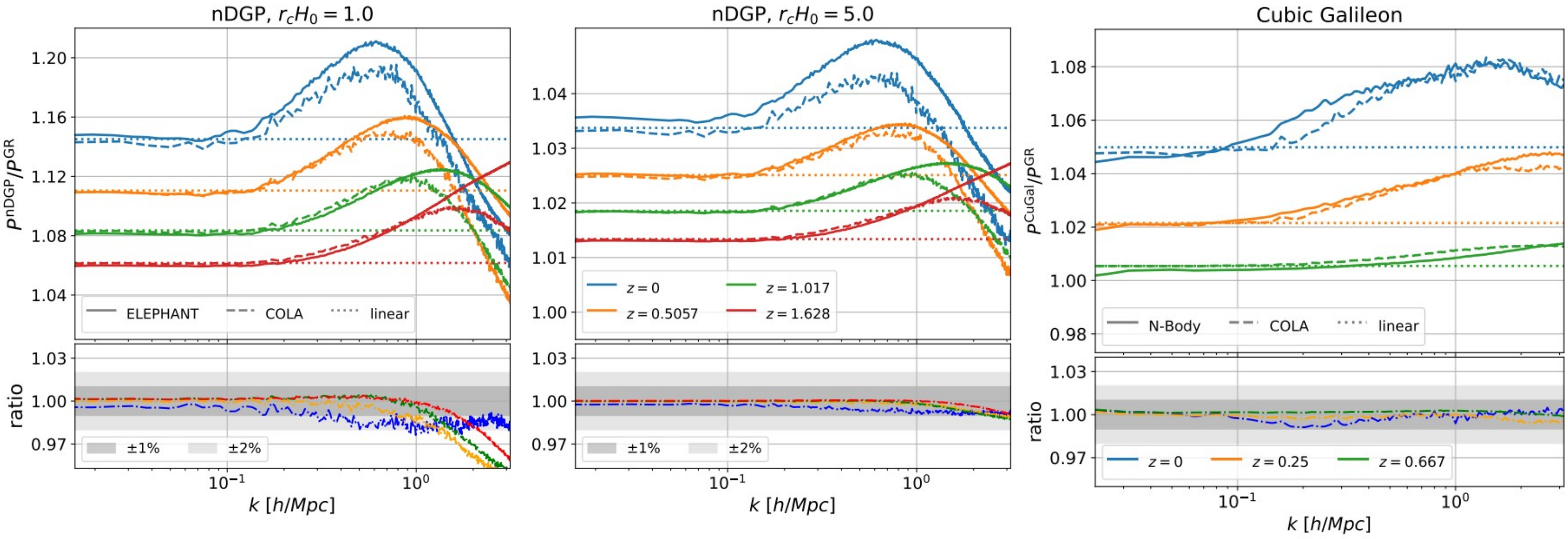
- Take aways:
  - COLA allows us to run faster simulations
  - Emulators reduce the number of required simulations
  - Emulating the Boost reduces resolution effects that worsen the agreement





Conclusions

- Modified gravity:
  - Fast pipeline to generate simulations in Horndeski theories



Thank you

Backup

- Our methodology to investigate beyond-LCDM models is given by:

$$B^{\mathrm{case}}(k,z) = B^{\mathrm{ref}}(k,z) \times \frac{R^{\mathrm{case}}_{\mathrm{non}}(k,z)}{R^{\mathrm{case}}_{\mathrm{lin}}(k,z)}$$

Quantity to be emulated

EE2 reference boost

Quantity computed using COLA

- As a proof of concept we created a Neural Network Emulator for:
  - LCDM with fixed sum of neutrino masses, 0.058 eV, and same parameter range as EE2
  - 400 COLA simulations

Backup

- We then performed a cosmic shear forecast analysis for an LSST-Y1 like survey