PANDA: A TreePM N-body code to simulate Horndeski models with a phenomenological screening

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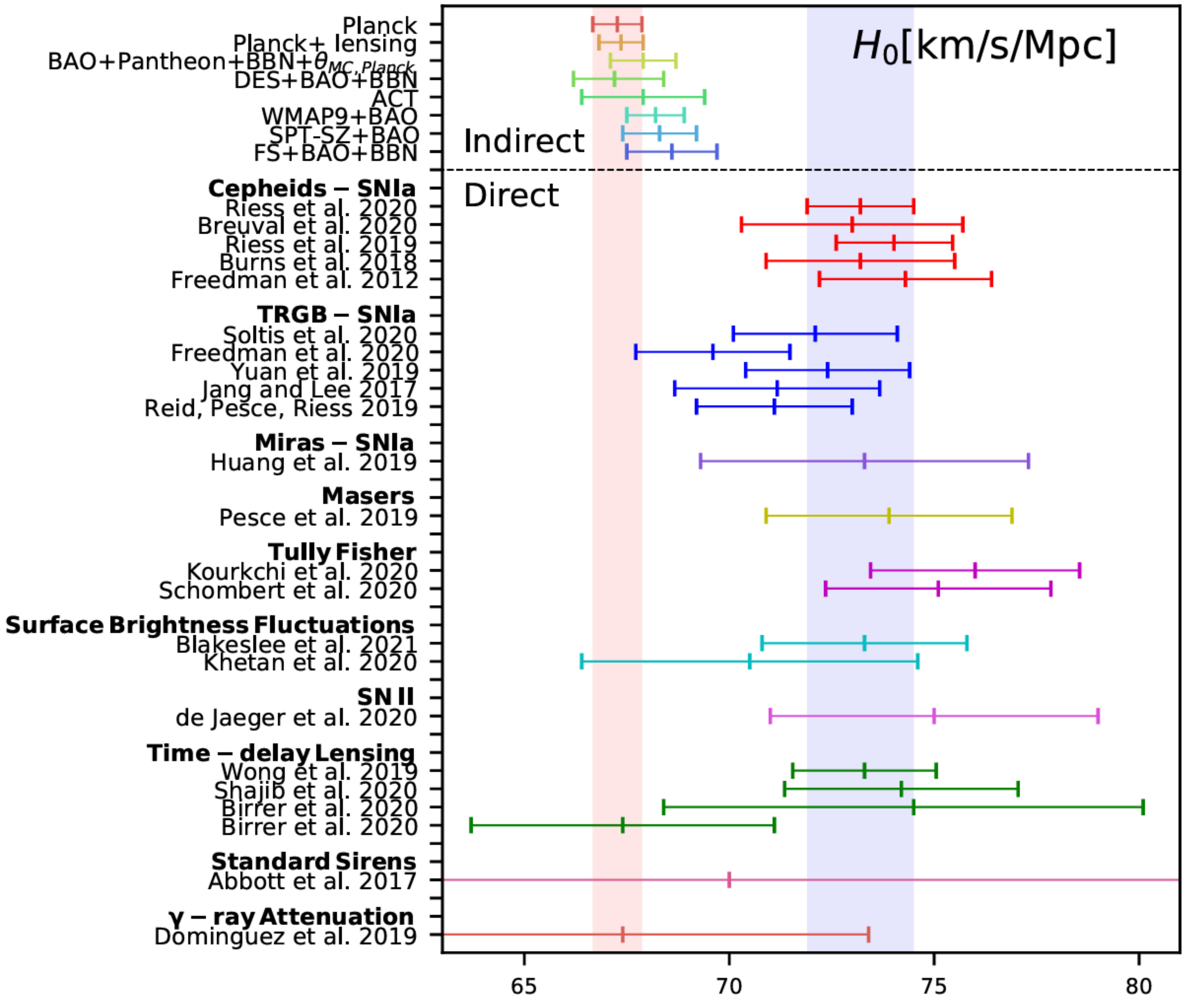
Why Modified Gravity?

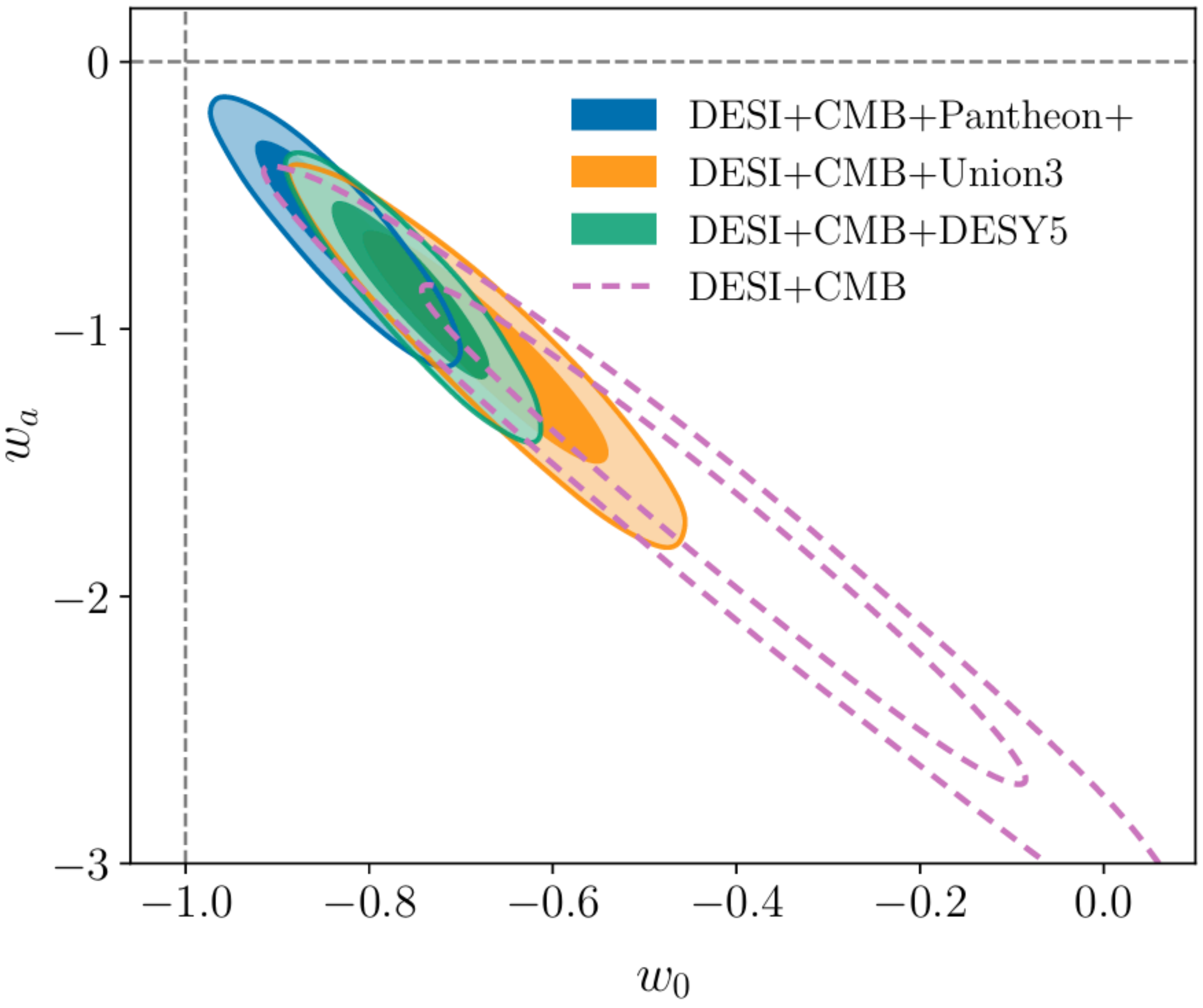
- Despite the success of LCDM describing cosmological observables, some inconsistencies arise:
    - Tensions on cosmological parameters, as H_0 (*Di Valentino et al. 2020*);
    - DESI results on DE (*Karim et al. 2025*);
    - …
- Which is the real cosmological nature of DE?

(*Di Valentino et al. 2020*)



Studying Modified Gravity theories becomes a natural path to follow, but **we need predictions on the cosmological observables**!

(*Karim et al. 2025*)



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How Modified Gravity has been simulated so far

We need predictions on the cosmological observables!

Linear Approach

Einstein Boltzmann (EB) solvers:

- H-EFTCAMB (*Hu et al. 2014, Ye et al. 2026*)
- Hi-Class (*Zumalacarregui et al. 2017*)

***Pros** and **cons**:*

- Very quick and general
- They solve only the linear limit of the theory

Non-Linear Approach

N-body solvers:

- MG-Gadget (*Puchwein et al. 2013*)
- ECOSMOG (*Li et al. 2011*)
- ECOSMOG-EFT (*Banjo et al. 2026*)
- RAMSES-EFT (*Woodcock et al. 2026*)

***Pros** and **cons**:*

- Accurate solution of the MG field down to fully non linear scales
- Usually slow and/or model specific [f(R),nDGP, cubic galileon, symmetron)

PANDA

Parametrised d**A**rk e**N**ergy and mo**D**ified gr**A**vity

P A N D A

PANDA is a modified version of the Newtonian N-body TreePM solver Gadget-4

1. ***(Casalino, Martinelli, Baldi in prep):*** Based on *(Lombriser et al. 2016)* parametrization. Generic non-linear parametric functional form describing the modified gravitational interaction. **Tested on f(R) and nDGP**
2. ***(Martinelli, Casalino, Baldi in prep):*** Based on the **linear parameterisation of Horndeski models** by Pogosian et al. 2016 plus a **phenomenological, model-dependent and environment-based screening function** proposed by Winther et al. 2015.

PANDA: key features of the implementation

PANDA is a modified version of the Newtonian N-body TreePM solver Gadget-4

PANDA is aimed to be…

Light:

- **Linear (costless) modifications** of Gravity added to the **non-linear GR implementation** of Gadget-4, in both the PM and Tree
- No solving of additional costly differential equations
- **Phenomenological effective screening** (*Winther et al. 2015)* based on local properties of the particles distribution already available in the simulation

General:

- The **linear MG kernel** we implemented in the PM is based on **EFT of DE**, from (*Pogosian et al. 2016)*
- The **phenomenological effective screening function** is the same for all the model under a certain type of screening

High-Resolution:

- Implementation of the **linear MG kernel also in real space** in the Tree
- Previously done only in the PM (*HI-Cola, Wright et al 2023, MG-evolution, Hassani et al. 2020, Ganjoo et al. 2026,…*)

PANDA: key features of the implementation

Inside PANDA we have **modified the Poisson equation** linearly as:

$$k^2\Phi = a^2 4\pi G\,\mu(\mathbf{k},\mathbf{a})\,\delta\rho_m \quad \rightarrow \quad 4\pi G\,\mu(\mathbf{k},\mathbf{a}) = \frac{f_1(a)+f_2(a)\frac{a^2}{k^2}}{f_3(a)+f_4(a)\frac{a^2}{k^2}} = \frac{A^*(a)}{4\pi G}\left(1+Y(a)\frac{k^2}{k^2+M^2(a)}\right)$$

In real space, for the **Tree implementation**: $\mathcal{F}^{-1}\left[4\pi G\frac{\mu(a,k)}{k^2}\right](r,a) = \frac{A^*(a)}{4\pi r}\left[1+Y(a)\,e^{-M(a)r}\right]$

We can simulate MG with **2 approaches;** a **physically-motivated** one, or a **phenomenological** one:

Setting of the **EFT functions**, or the **Horndeski G functions** using ***Hi-Class*** or ***H-EFTCAMB*** → Computation of the $\mathbf{A^*(a)}, \mathbf{Y(a)}, \mathbf{M^2(a)}$ parameters using the EB solver results → Creation of the input table and choice of the appropriate model-dependent phenomenological screening function → **SIMULATE!**

Direct postulation of $\mathbf{A^*(a)}, \mathbf{Y(a)}, \mathbf{M^2(a)}$ parameters as time dependent functions → Creation of the input table and choice of the appropriate model-dependent phenomenological screening function → **SIMULATE!**

PANDA: key features of the implementation

Most **MG N-body solvers** deal with screening solving computationally **expensive and/ or model specific differential equations.** (*MG-Gadget, Puchwein et al. 2013, ECOSMOG, Li et al. 2011, ECOSMOG/PySCo-EFT, Ganjoo et al. 2026*)

PANDA instead uses an **effective screening** function $\epsilon(\mathbf{a};\mathbf{env})$ (*Winther et al. 2015*), that naturally suppresses the fifth force.

$\epsilon(\mathbf{a};\mathbf{env})$'s functional form is **type-of-screening-dependent** , and **environment-dependent**

Chameleon:

$$\epsilon(\mathbf{a};\boldsymbol{\Phi}_{\mathbf{N}}) = Min\left[\frac{\boxed{\phi(a)}}{\boxed{2\sqrt{\frac{Y(a)}{2}}M_*(a)}\Phi_N}, 1\right]$$

$M_*(a) \equiv$ Eft of DE time dependent Planck Mass

$\phi(a) \equiv$ BG value of the scalar field

$\Phi_N \equiv$ Newtonian gravitational potential

Vainshtein:

$$\epsilon(\mathbf{a};\rho_{\mathbf{m}}) = 2\frac{\sqrt{1+\frac{\rho_m}{\boxed{\rho_{\rm crit}(a)}}}-1}{\frac{\rho_m}{\boxed{\rho_{\rm crit}(a)}}}$$

$\rho_{\rm crit}(a) \equiv$ Model-based critical density

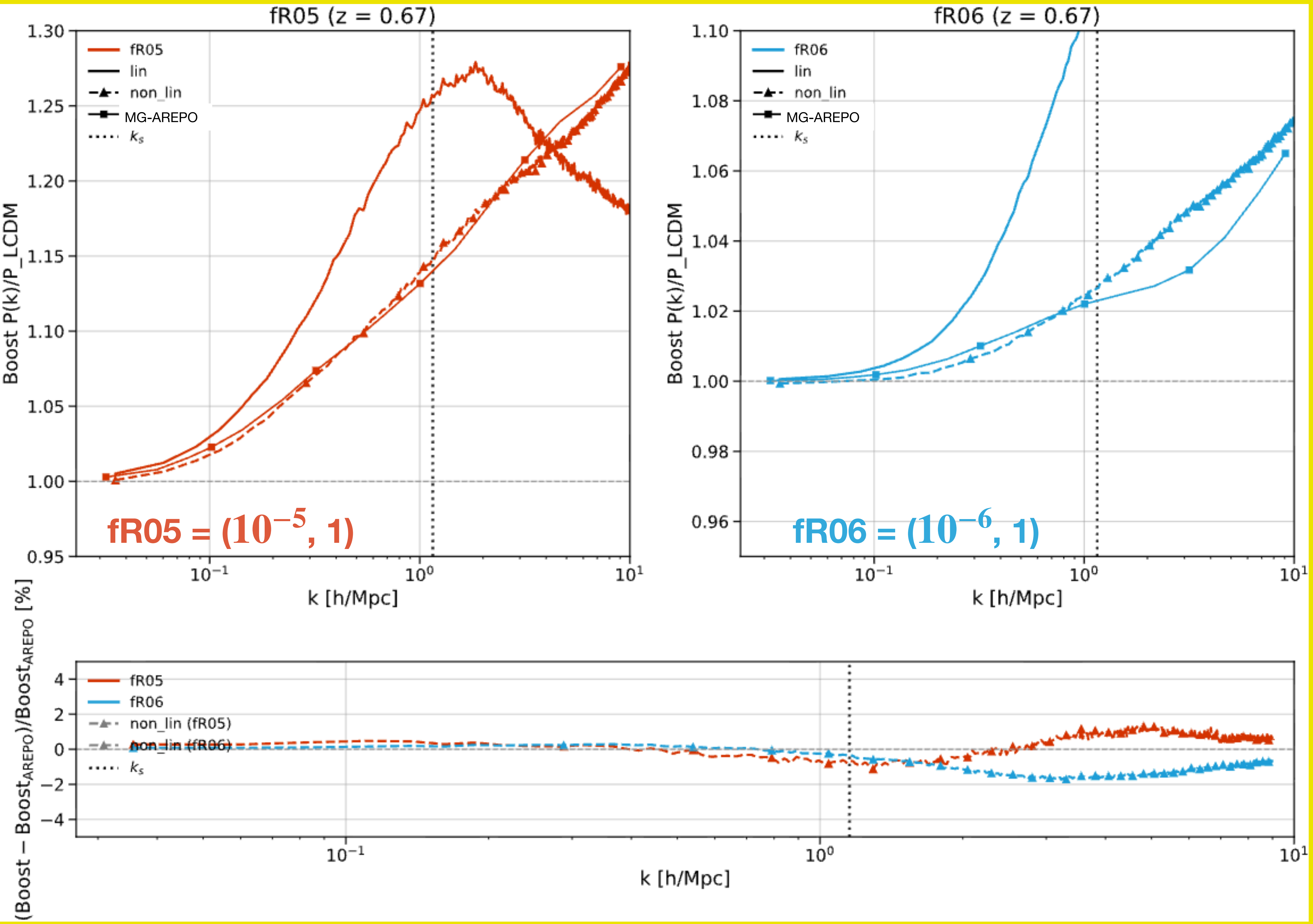
$\rho_m \equiv$ Matter density

PANDA: Preliminary results, fR, CHAMELEON

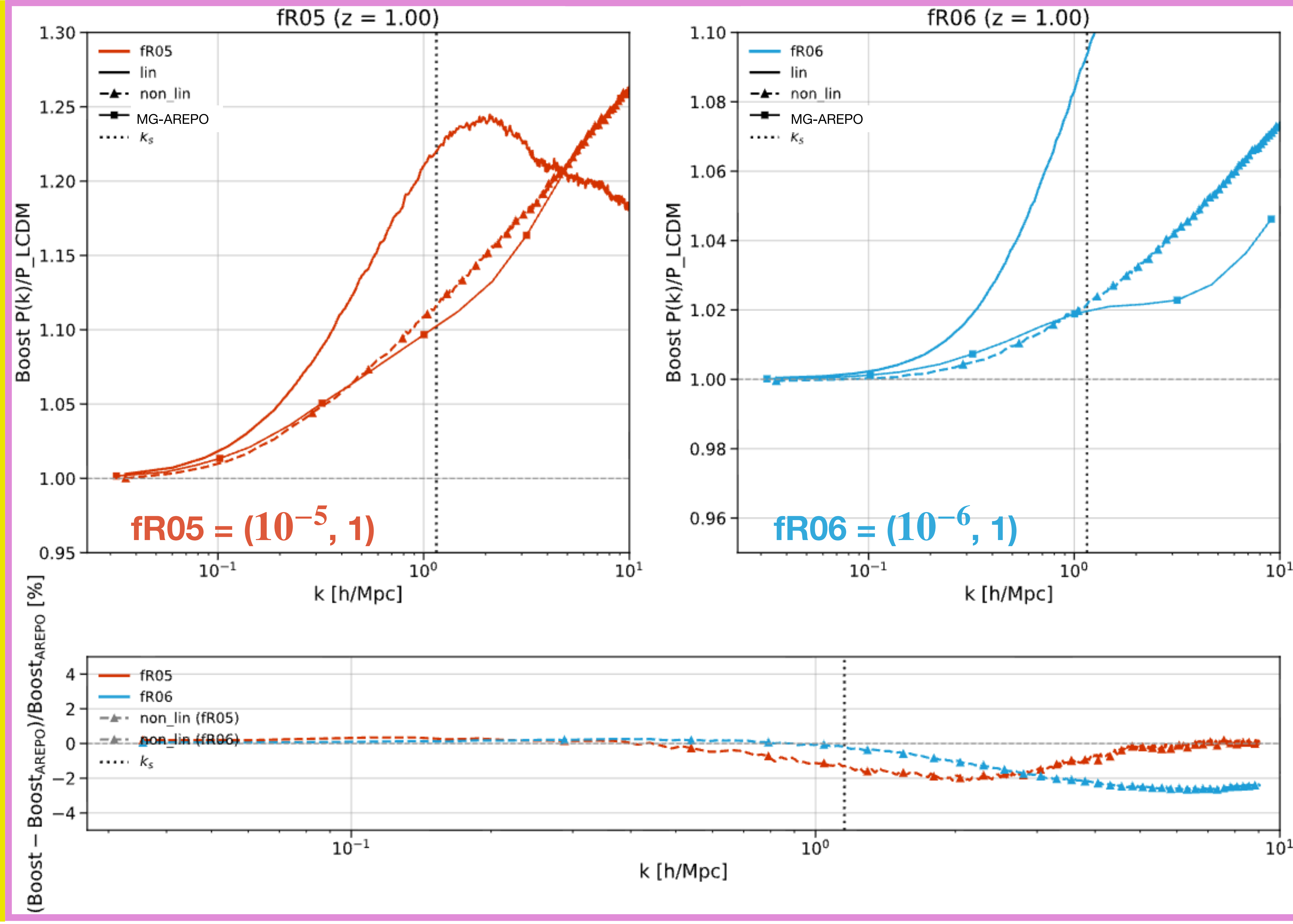
Testing our approach with known model **Hu-Sawicki** $\mathbf{f_{HS}(R)}$ $(\mathbf{f_R^0}, \mathbf{n})$ (*Hu, Sawicki 2007*) comparing it with the exact results of **MG-Arepo**, using the same ICs of (*Adamek et al. 2024*)

physically-motivated

z = 0.67



z = 1.00

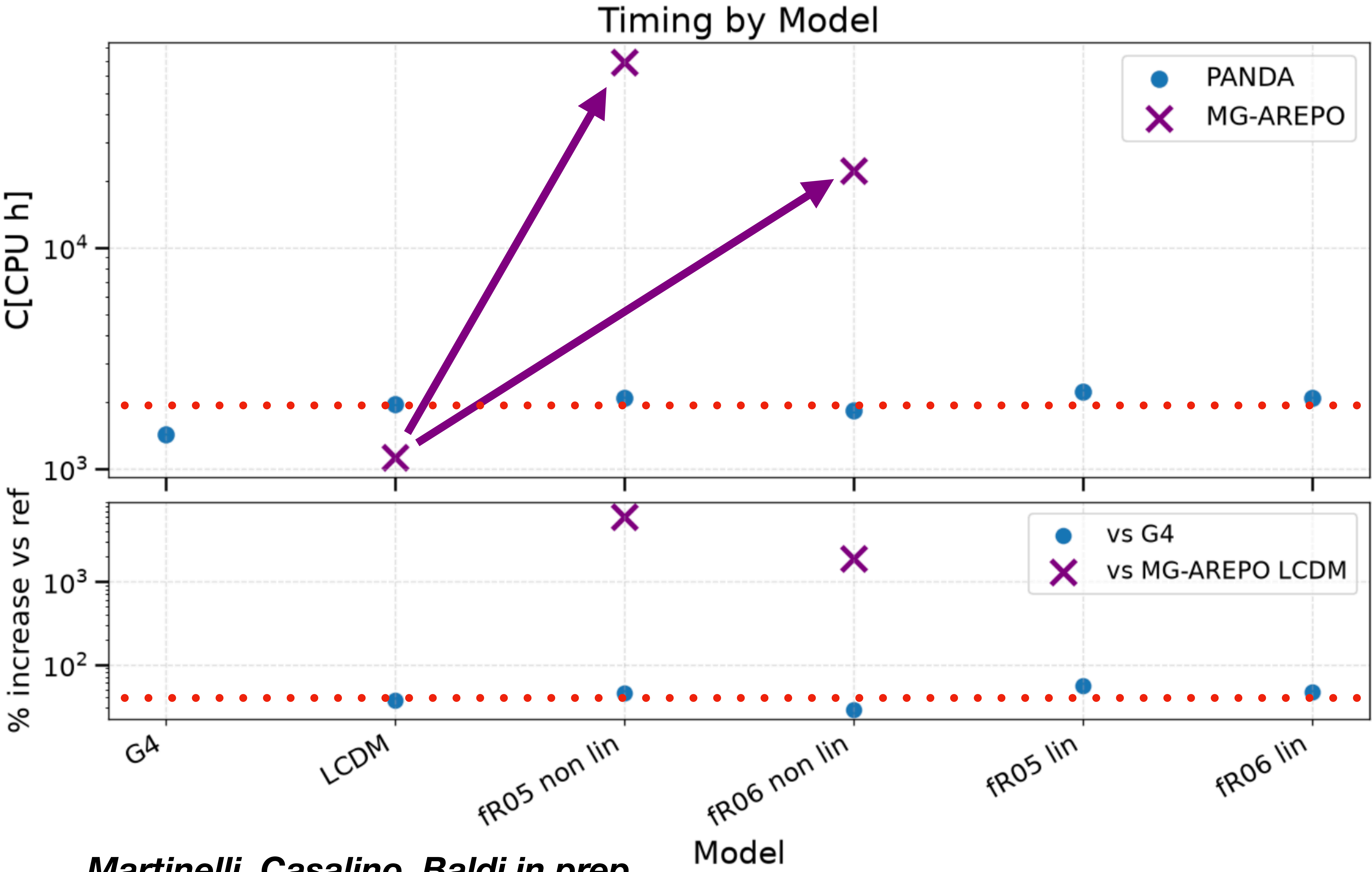


Martinelli, Casalino, Baldi in prep.

PANDA: Preliminary results, fR, CHAMELEON

As we can see, the **computational time cost** for these simulations are below **50% increase** wrt a standard Gadget4 simulation:

MG-Arepo has a **huge computational time cost increase** wrt its LCDM simulation



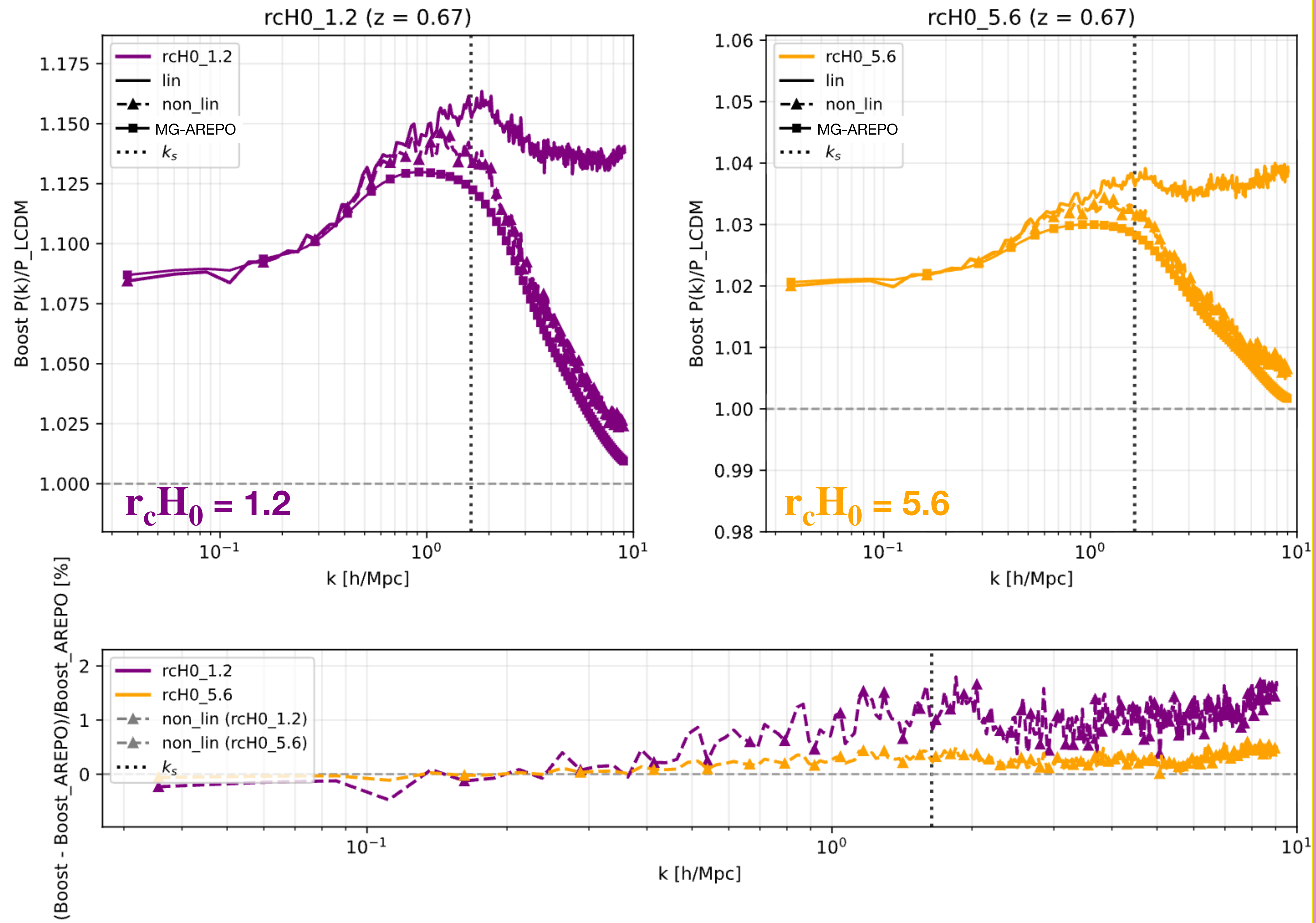
Martinelli, Casalino, Baldi in prep.

PANDA: Preliminary results, nDGP, VAINSHTEIN

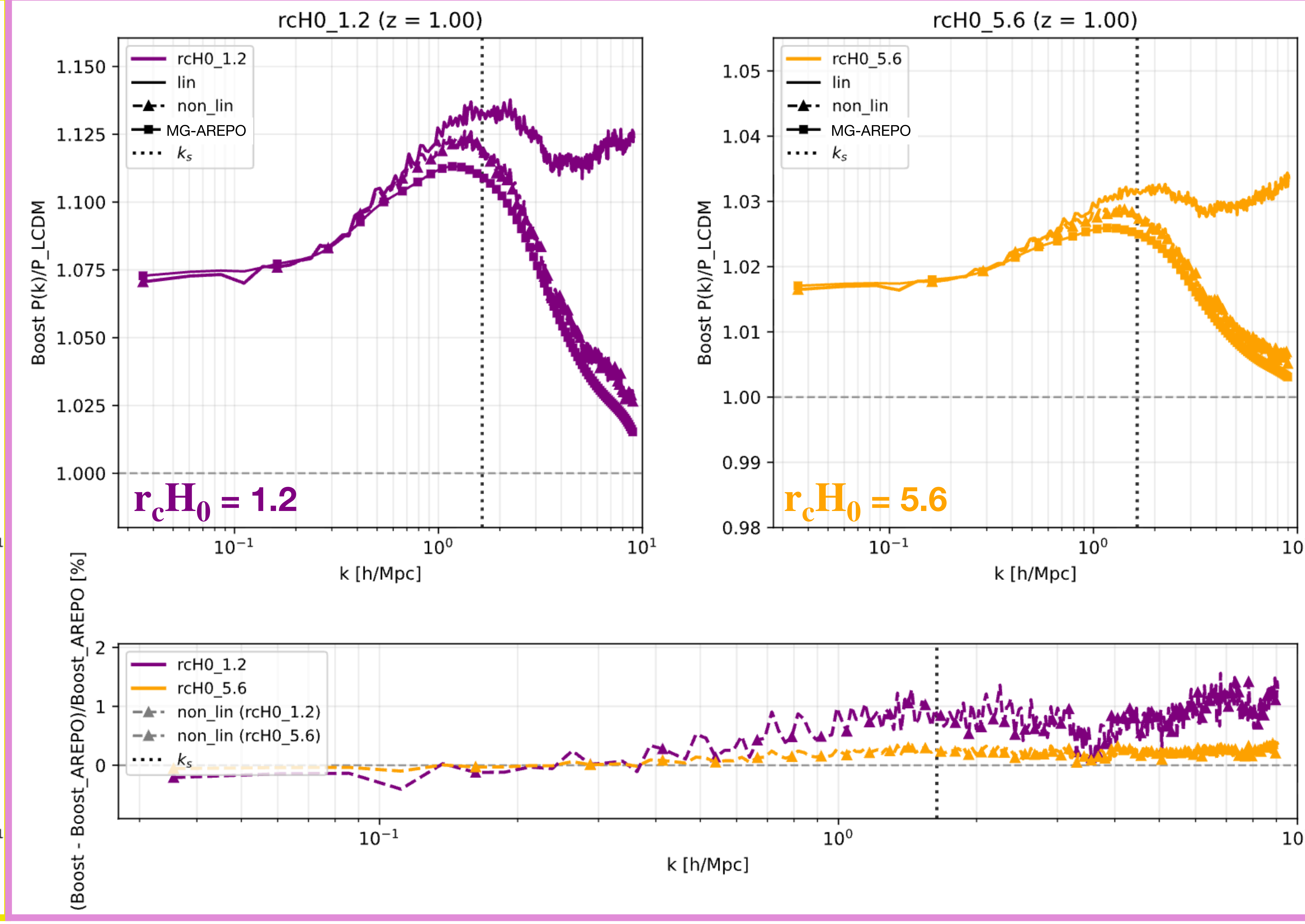
Testing our approach with known model **nDGP** (*Dvali et al. 2000*), ($\mathbf{r_c H_0}$), comparing it with the exact results of **MG-Arepo**, using the same ICs of (*Adamek et al. 2024*)

phenomenological

z = 0.67



z = 1.00



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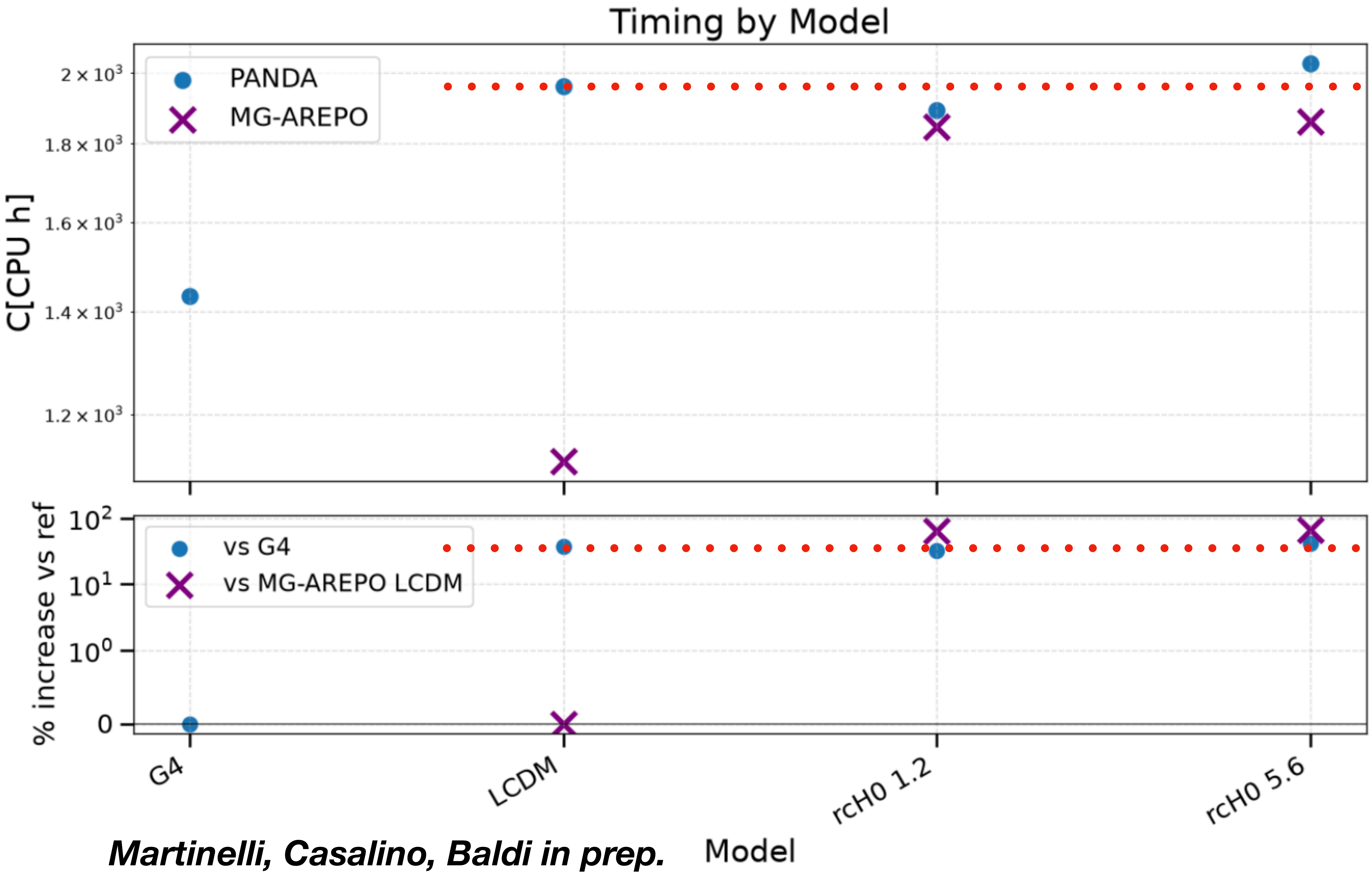
As we can see, the **computational time cost** for these simulations are below **50% increase** wrt a standard Gadget4 simulation:

MG-Arepo here has an **almost equal computational time cost increase** wrt its LCDM simulation as PANDA



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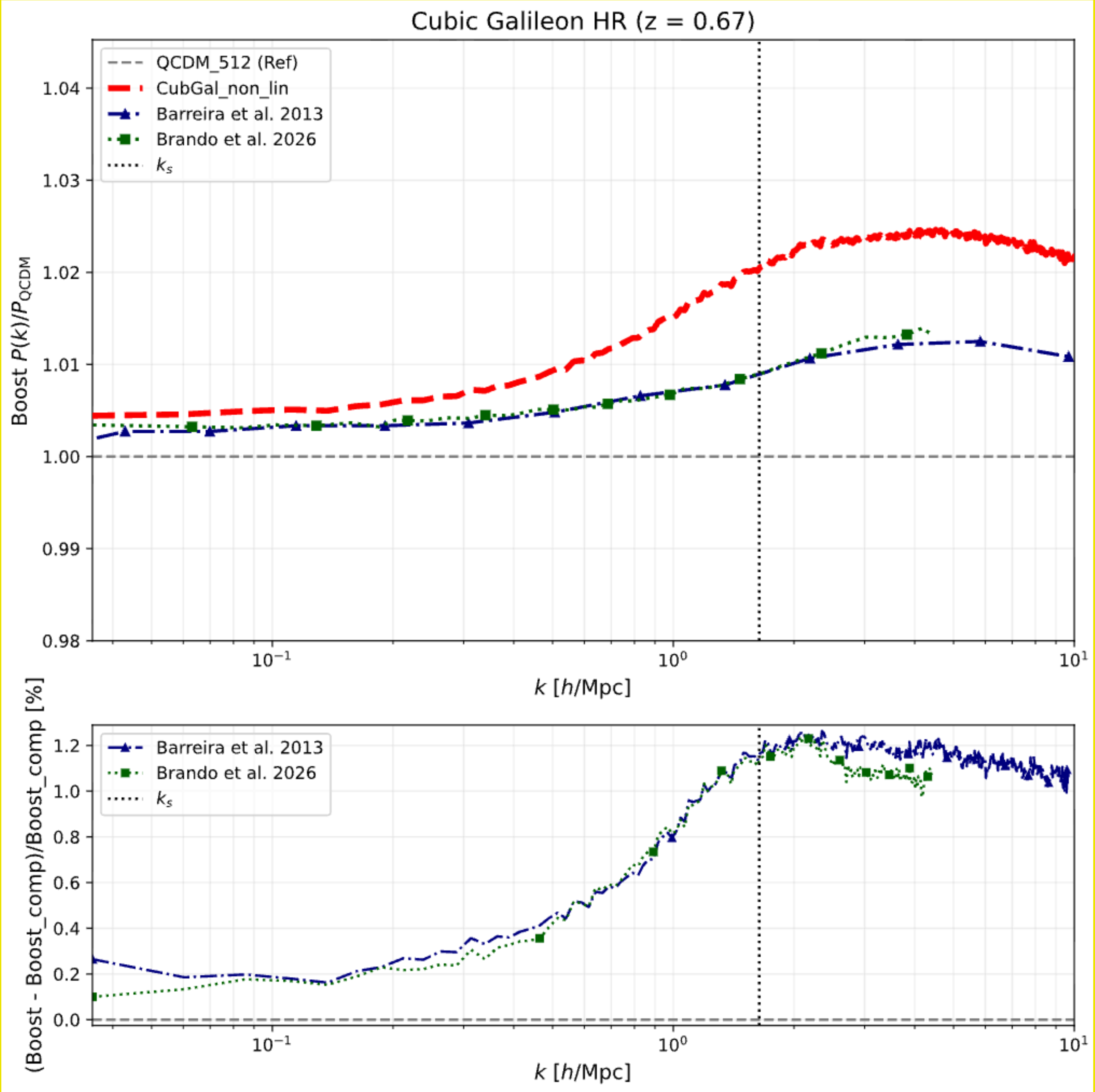
PANDA: Preliminary results, Cubic Galileon, VAINSHTEIN

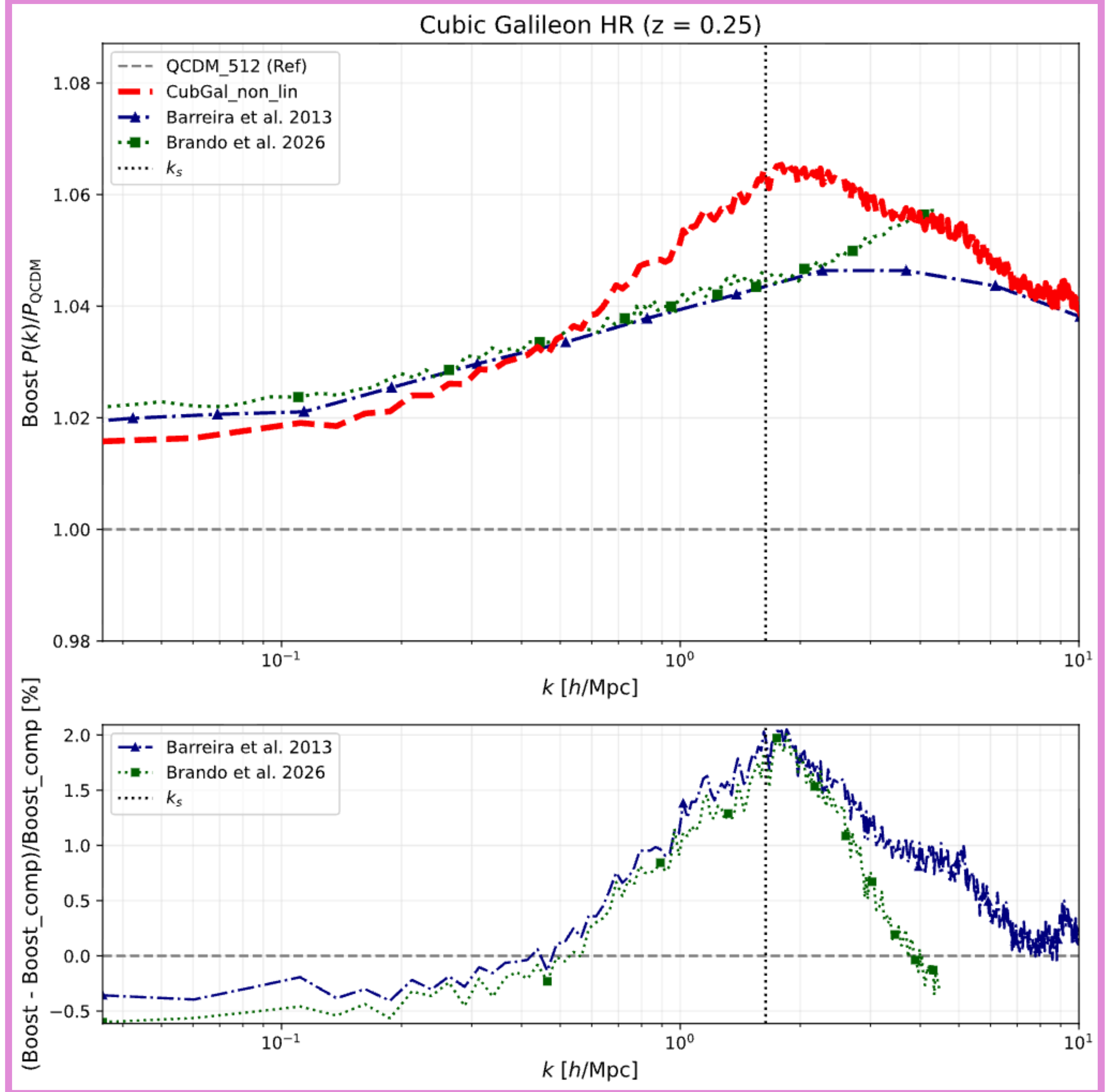
Testing our approach with known model **Cubic Galileon** (*Nicolis et al. 2009*), comparing it with the ***extracted results*** of **ECOSMOG** (*Barreira et al. 2013*) and **COLA** (*Brando et al. 2023*)

physically-motivated

z = 0.67



z = 0.25



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Conclusions & take-home messages

What's new?

- We implemented a **general linear MG kernel in both the PM and Tree solvers**, extending approximate MG simulations to smaller scales, with **up to 2% relative error** across a wide range of scales and redshifts. It supports **all Horndeski models with Chameleon and Vainshtein screening**;
- We introduced a **phenomenological screening function** that captures **Chameleon and Vainshtein screening** based on the **local gravitational potential and matter density**, avoiding the solution of computationally expensive differential equations;
- We can simulate a broad range of well-known and general MG models with only a **moderate computational overhead compared to GR**.

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