N-Body Simulations of the EFT of Dark Energy with PySCo and RAMSES

25th November 2025, RAMSES SNO Days, Paris

Himanish Ganjoo,
LUX, Observatoire de Paris
For the **ProGraceRay ANR Project,**
with Yann Rasera, Michel-Andrès Breton and Emilio Bellini

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Large-scale surveys and lensing measurements can probe the nature of gravity

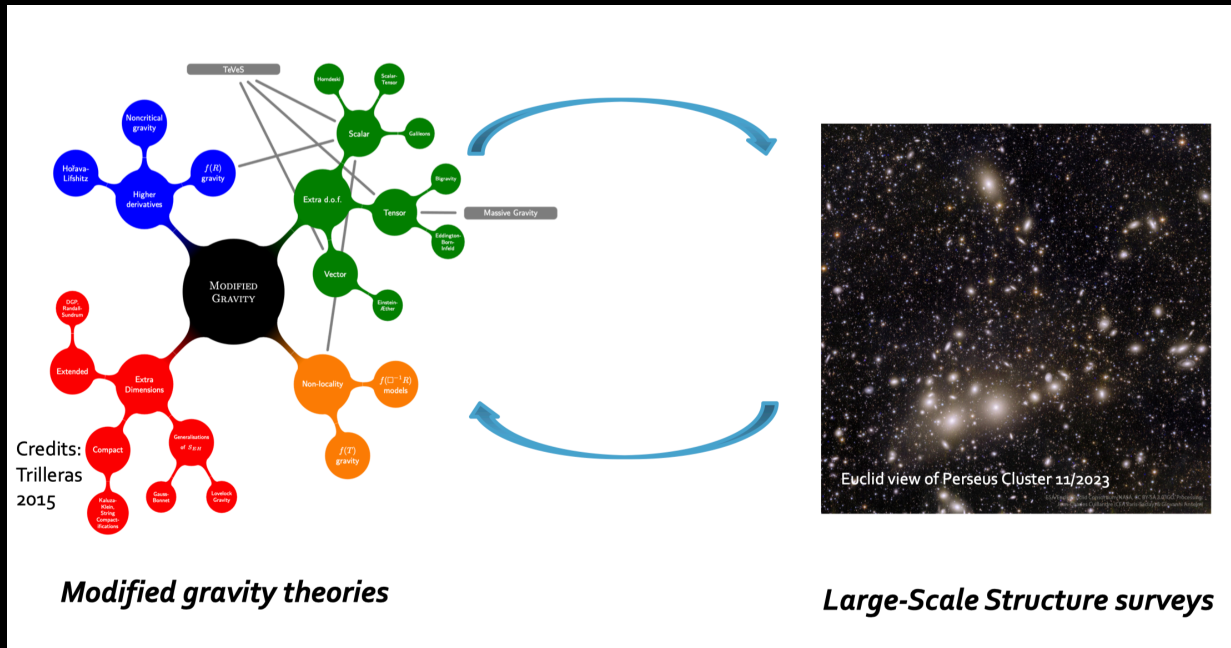
PROGRACERAY ANR PROJECT:

Run N-body simulations to predict structure formation and lensing on cosmological scales in modified gravity theories

Tool of choice: EFT of DE, which unifies dark energy and modified gravity models in one framework and expresses a wide variety of models using a few parameters.

AIM

Implement EFT of DE in RAMSES



The Program

Solving for the additional field

- Choice of model: **cubic screening**. Simplest non-trivial model satisfying GW constraints.

- Additional scalar field χ: acts as DE component.

- Deviation from GR can be parametrised by two numbers:

  - α_{B0}: mixing of scalar field χ with the metric.

  - α_{M0}: variation of G over time.

- Gives a separate equation for the scalar field χ.

Solution Strategy

Solving on a Grid: The Cubic Screening Model

Step 1: Solve for χ

$$p\,\nabla^2\chi + q[4\pi G_{\rm eff}(a)\,a^2\bar{\rho}\delta] + r\left[(\nabla^2\chi)^2 - \partial_i\partial_j\chi\,\partial^i\partial^j\chi\right] = 0$$

Discretise and solve

$$\chi_{ijk} = \frac{-q \pm \sqrt{q^2 - 4pr}}{2p}$$

Step 2 : Add effect of χ to gravity

Solve the modified Poisson equations for Φ, Ψ

$$\nabla^2\Phi = 4\pi G_{\rm eff}(a)\,a^2\bar{\rho}\delta + (\alpha_B - \alpha_M)\,\nabla^2\chi$$

$$\nabla^2\Psi = 4\pi G_{\rm eff}(a)\,a^2\bar{\rho}\delta + \alpha_B\,\nabla^2\chi$$

Major Modifications

Computing EFT parameters at each time step

Writing the quadratic solver logic

Adding the quadratic solver to the multigrid logic to compute χ

Adding the force from the additional field to gravity $\vec{F} = -\nabla\Phi - (\alpha_B - \alpha_M)\nabla\chi$

Stage I - PySCo

- PySCo - fast particle-mesh based N-body simulations in Python, using multigrid or FFT solvers, including various MG models like f(R) and parametrised gravity (Breton 2024, 2410.20501).

- 512^3 particle simulation in ~1 CPU hour: ideal for quickly exploring the parameter space.

- Implemented the quadratic solver for the additional field in PySCo, solved using Full-Approximation-Scheme multigrid

- Since PySCo uses the same solver and conventions as RAMSES, transposing the solver to RAMSES is made easier once tested in PySCo.

Stage II - RAMSES

- We modified RAMSES (**ECOSMOG-CVG, Becker et al** described in 2007.03042) to now solve the field equation in our EFT formalism.

- This gives us the ability to run full AMR simulations with the extra field solver.

- The RAMSES solver is slightly different from the PySCo version — it solves the quadratic equation for $\nabla^2\chi$ (instead of χ), using the operator splitting formalism.

Comparisons
RAMSES vs PySCo

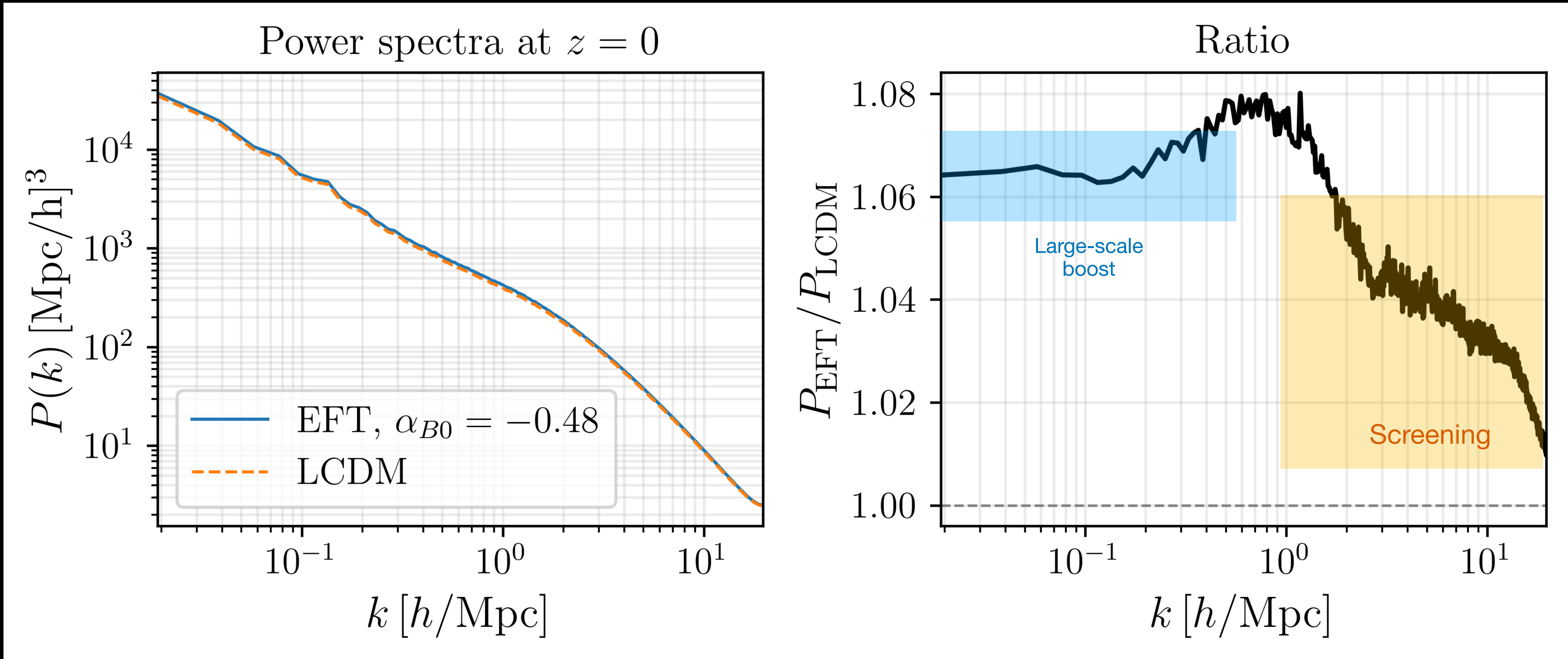
- Preliminary testing: we ran PM simulations (no refinements) with the modified RAMSES.

- ICs generated by MUSIC and converted to a format read by PySCo.

- This enables direct comparison of power spectra from the two codes.

Power Spectra and Ratios

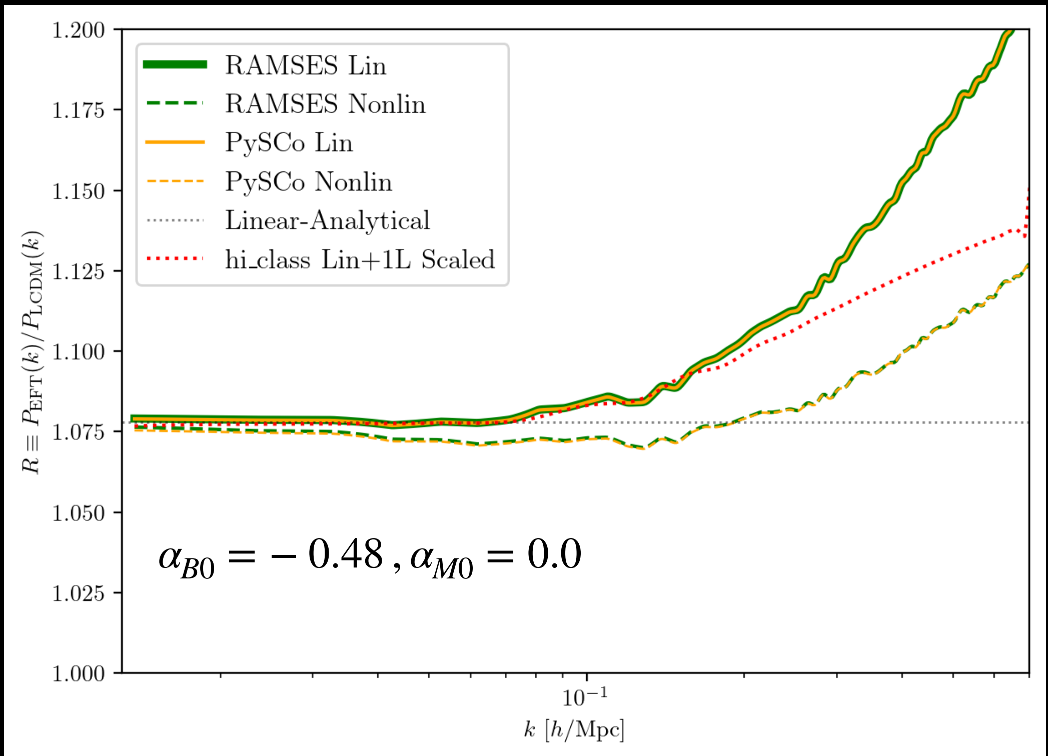
We are interested in the ratio of the EFT to LCDM power spectra to encode the effects of the scalar field

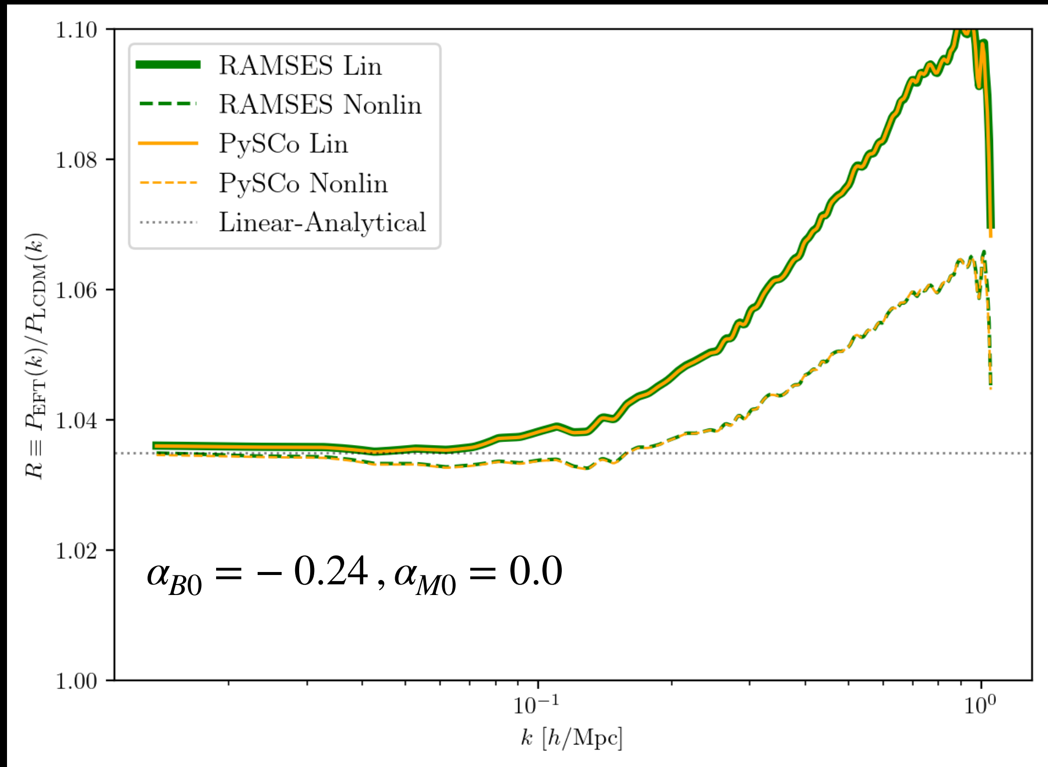


Comparisons
RAMSES vs PySCo

Linear versions agree almost perfectly with each other and are within 0.5% of linear prediction.

Nonlinear versions also agree closely between RAMSES and PySCo.

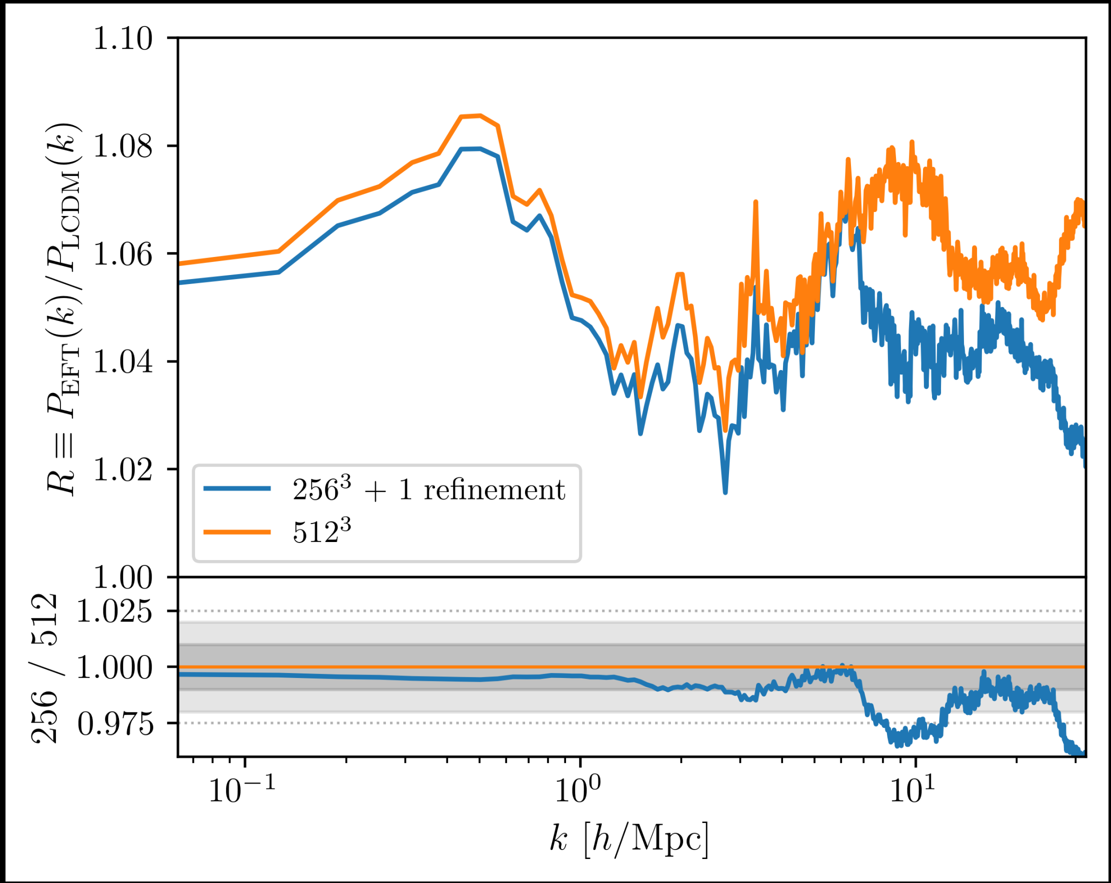




RAMSES Tests

Refinement Testing

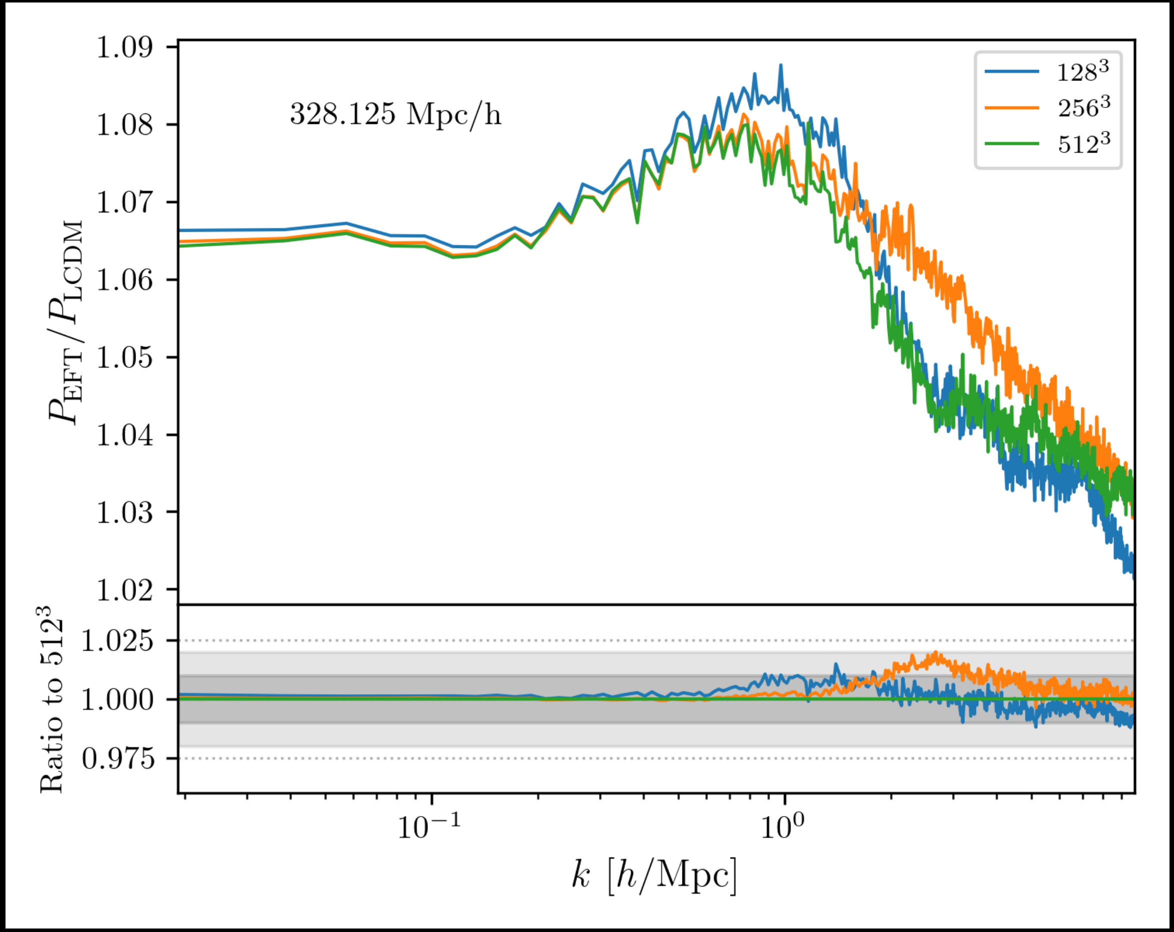
- 100 Mpc/h box evolved from $z = 25$.
- Different resolutions and one AMR level.
- The ratio of the EFT to LCDM power spectra stays within 1% at $k \lesssim 7h/\mathrm{Mpc}$



RAMSES Convergence Tests

Mass Resolution

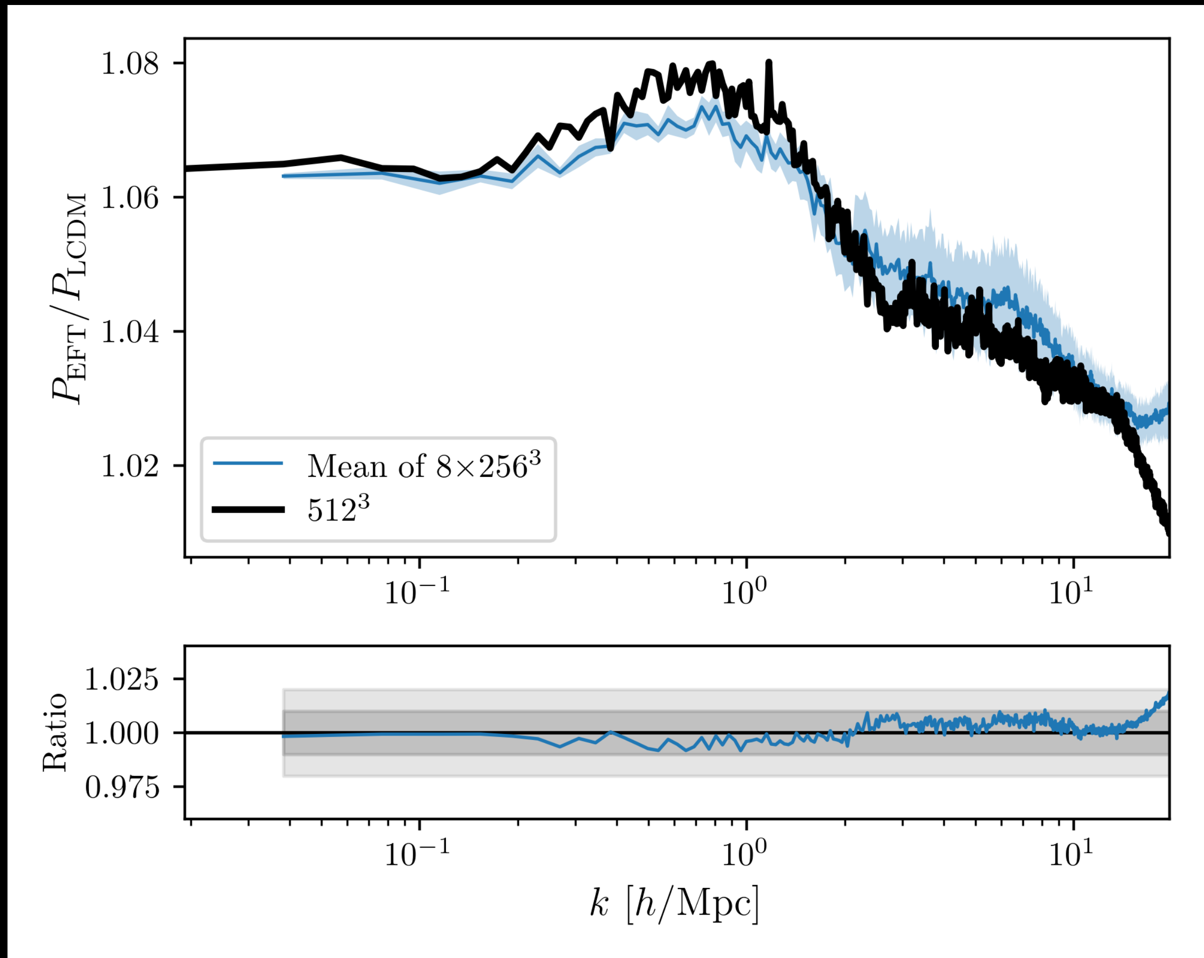
- We ran 328.125 Mpc/h boxes with different resolutions.
- Ratios are within 1% for $k < 2h/\mathrm{Mpc}$ and within 2% for $k < 9h/\mathrm{Mpc}$.



RAMSES Convergence Tests

Boxsize

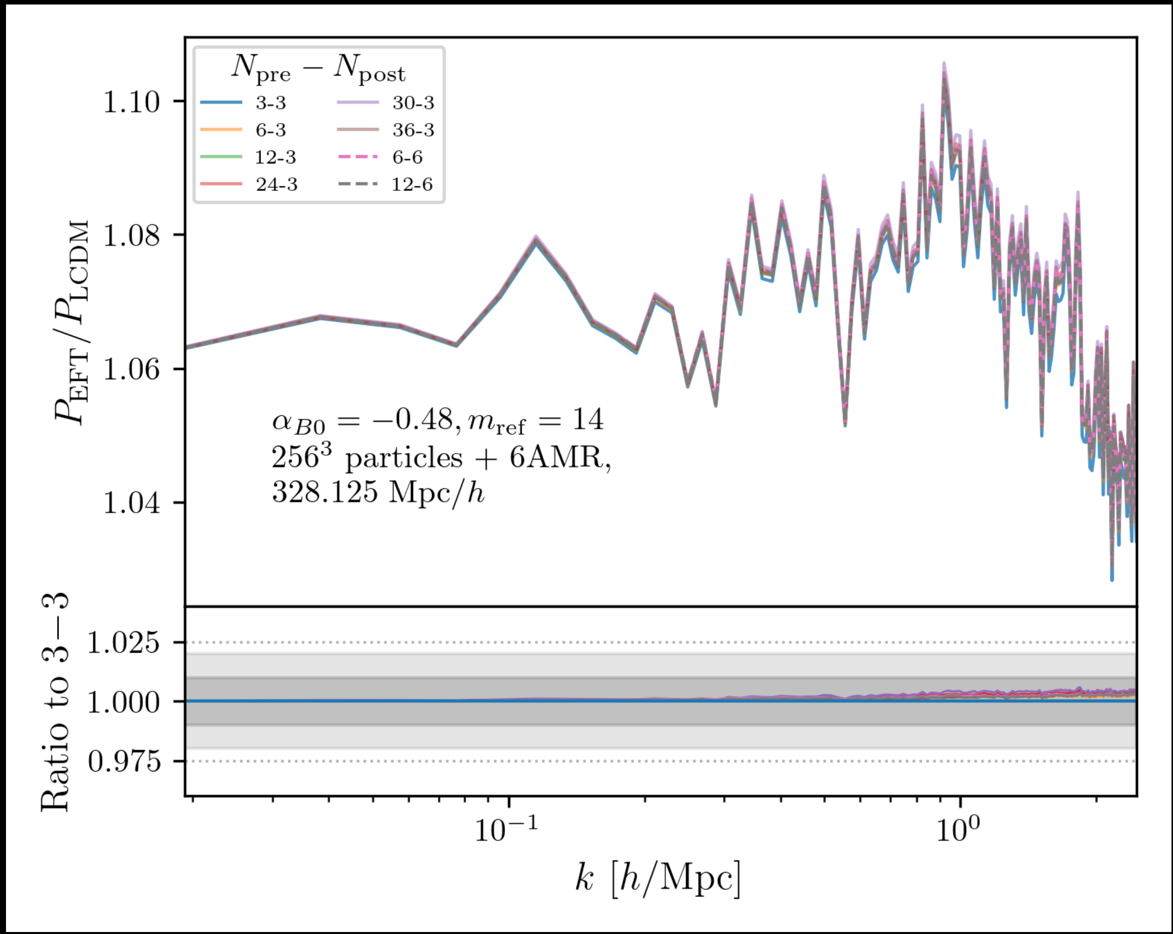
- We ran one 512^3 particle simulation, then split the ICs into 8 256^3 boxes and ran those. Both with 6 AMR levels.
- The ratio stays within 1% up to $k \sim 10\,h/\mathrm{Mpc}$.
- Agreement to within 0.7% on scales with $k < 1h/\mathrm{Mpc}$.



RAMSES Convergence Tests

Pre and Post Smoothing Cycles

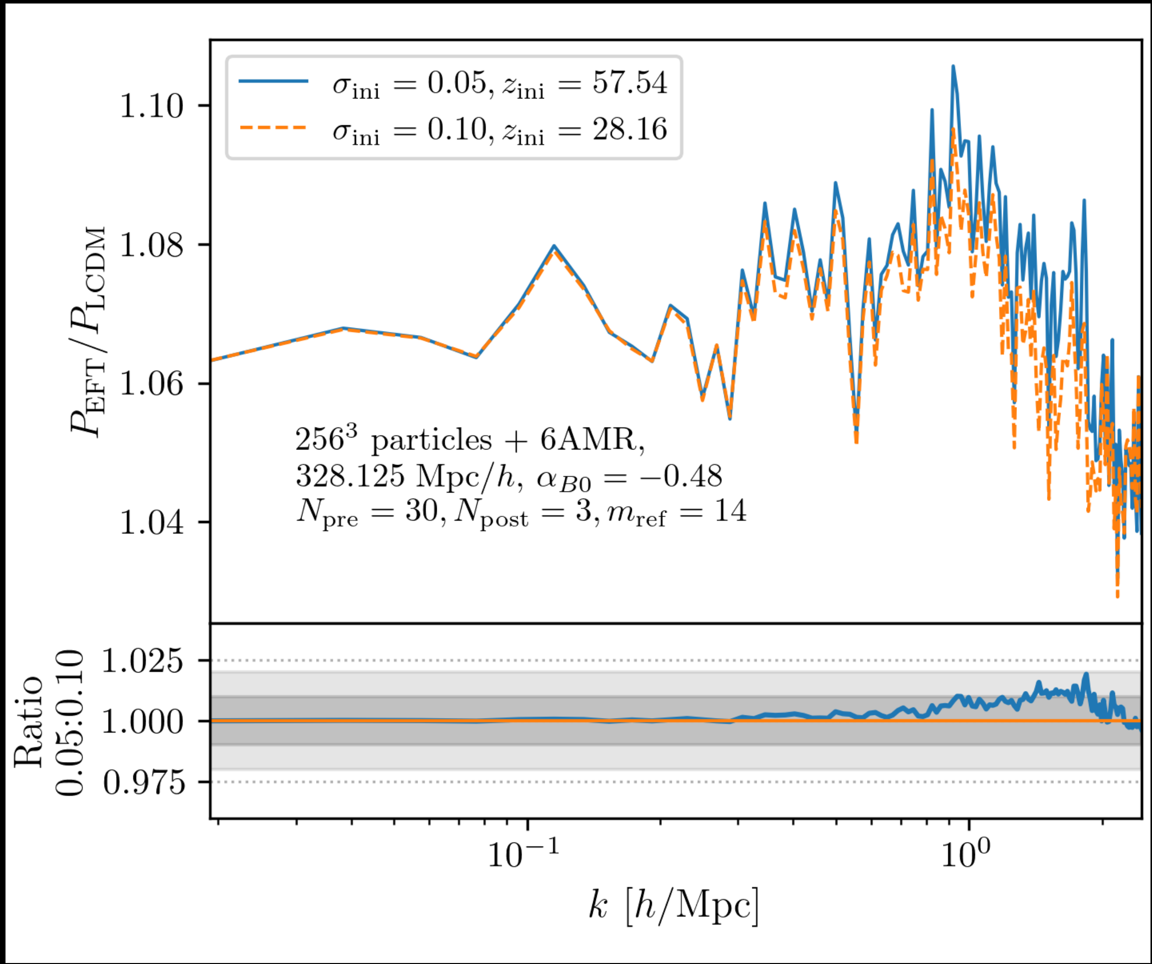
- Range of simulations with different pre- and post-smoothing for the multigrid.
- Agreement within 0.5% up to $k_{\rm Nyquist}/2$ (x-axis limit).



RAMSES Convergence Tests

Start Time

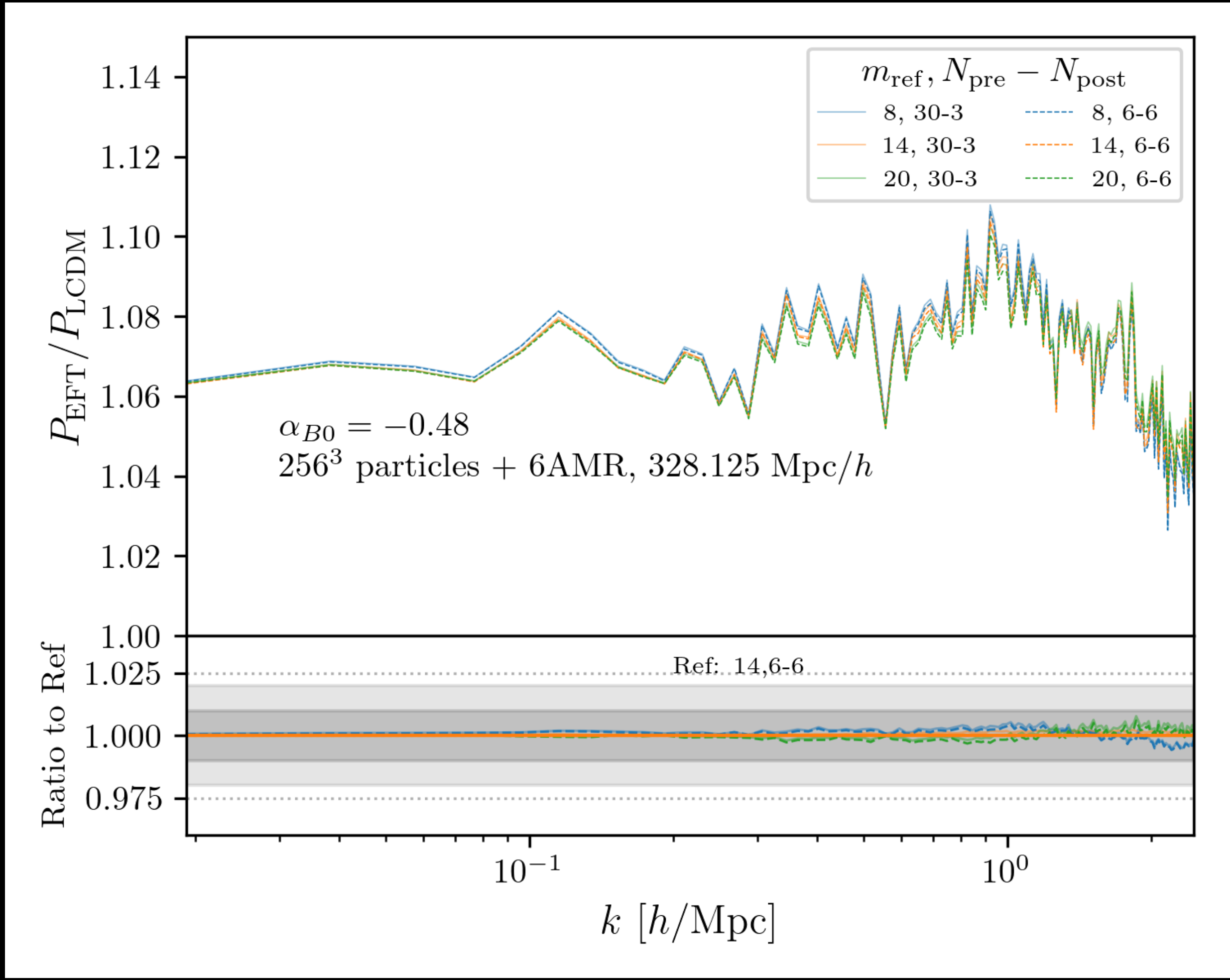
- Pair of simulations with different start times based on σ_{grid} at start time.
- Ratio is within 1% up to $k \sim 1h/\text{Mpc}$ and within 2% for $k < k_{\text{Nyquist}}/2$.



RAMSES Convergence Tests

Refinement Threshold

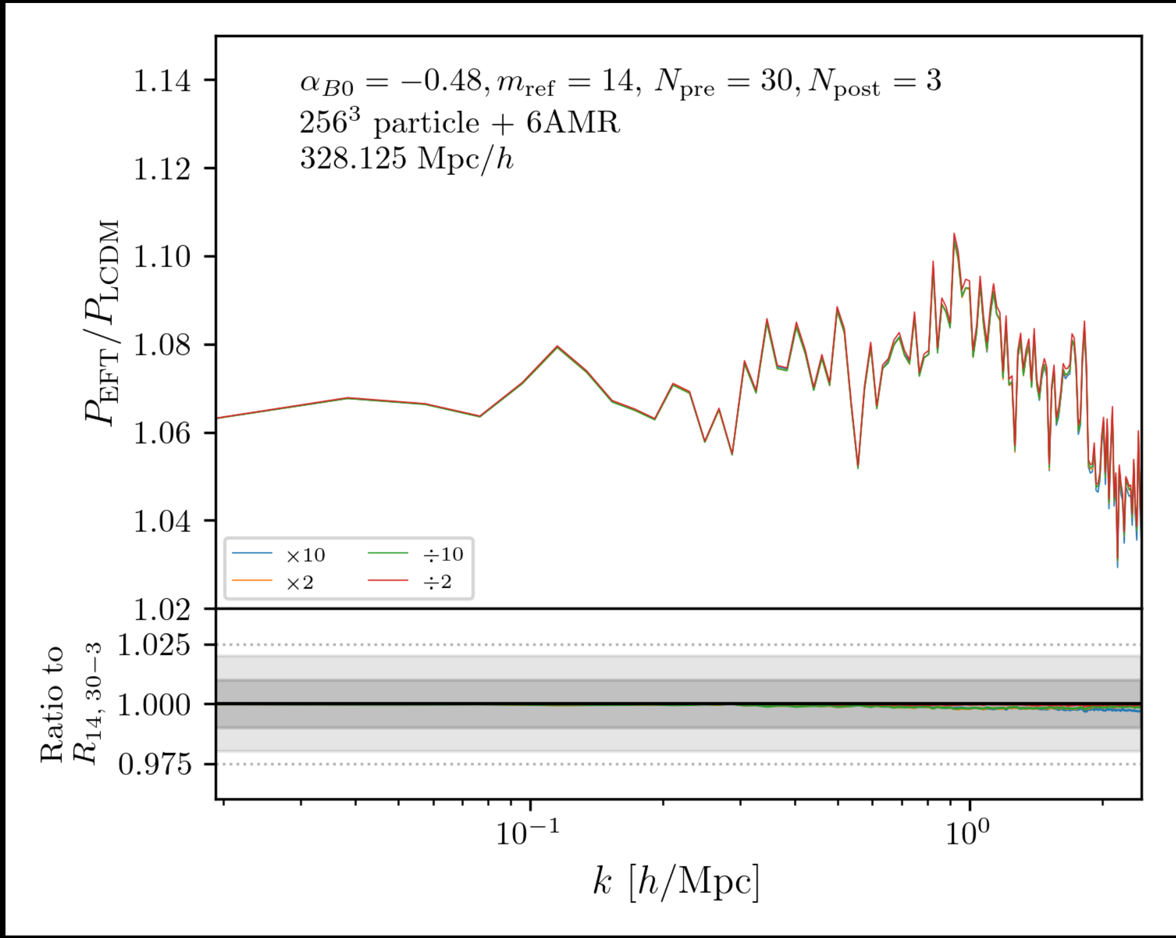
- Three different mass thresholds for refinement, run with two different $N_{\text{pre}} - N_{\text{post}}$ combinations.
- Ratios to the reference all well within 1% for $k < k_{\text{Nyquist}}/2$.



RAMSES Convergence Tests

Chi Solver Residual Criterion

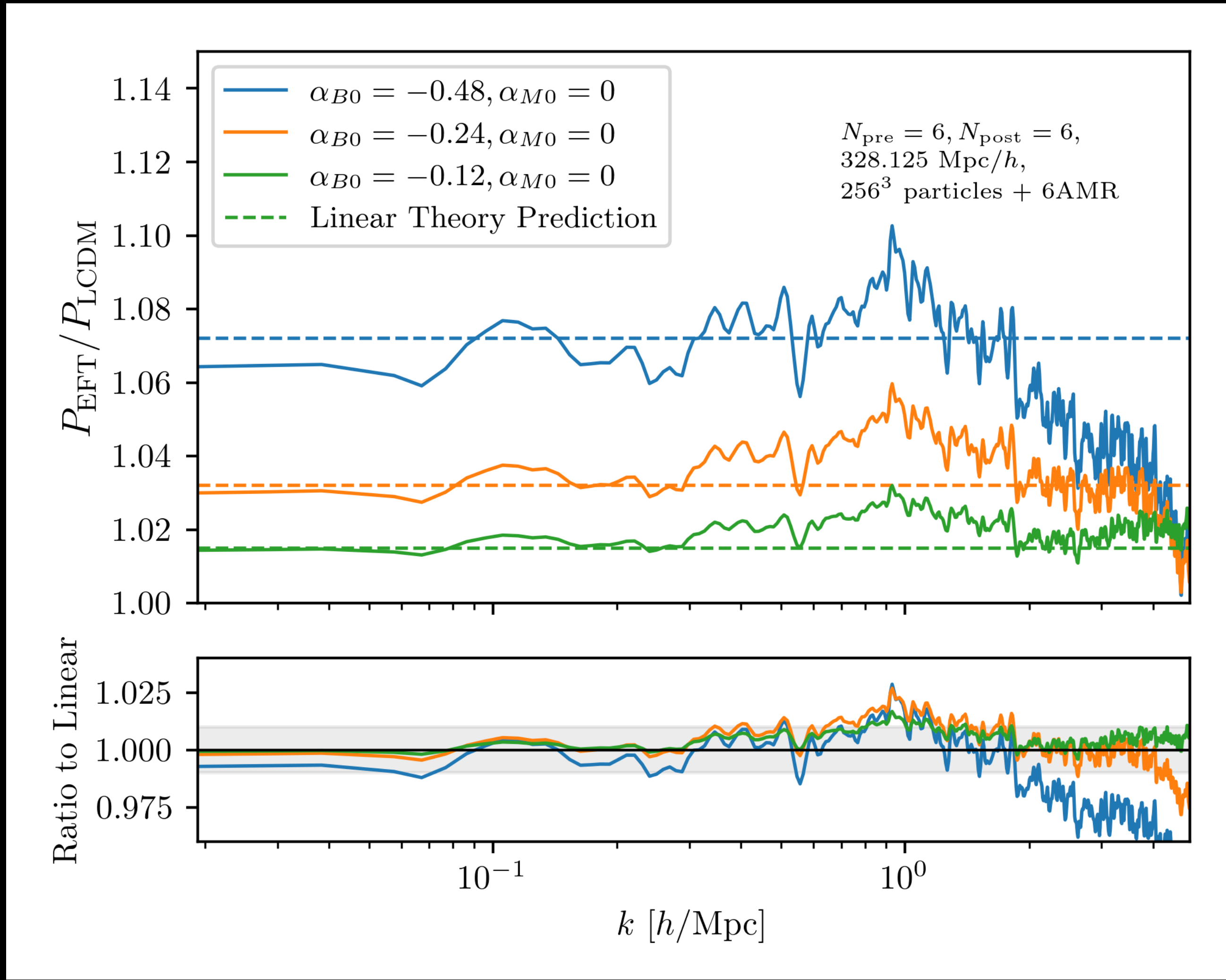
- The scalar field solver decides "convergence" based on the residual error in the multigrain cycle.
- We changed this "stopping" criterion: Baseline residual $< 10^{-9}$
- Ratios to the reference all well within 0.2% for $k < k_{\rm Nyquist}/2$.



Results

Impact of Varying α_{B0}

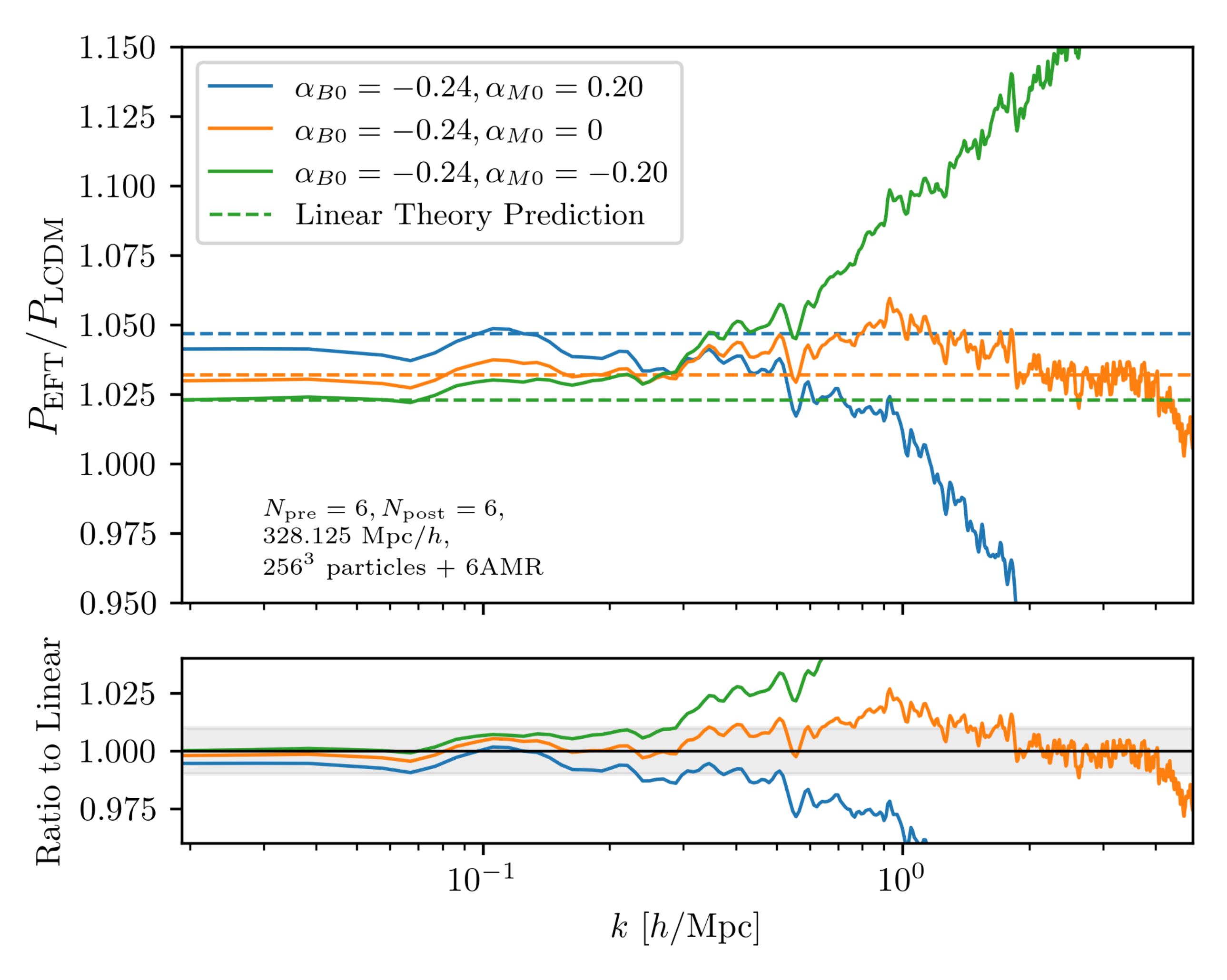
- The coupling between the scalar field and the metric is controlled by α_{B0}.
- Decreasing it increases the screening effect on small scales.



Results

Impact of Varying α_{M0}

- The time variation of the gravitational "constant" G is controlled by α_{B0}.
- Decreasing it increases the effective "G" on small scales, overcoming the effect of screening and leading to increased small-scale structure.



Conclusions

- We have developed PySCo-EFT and RAMSES-EFT to run **simulations of cosmologies with the EFT of DE**, solving the **full nonlinear equations** for the scalar field.

- The full nonlinear solver yields power spectra ratios that are **within 1% of the linear theory predictions at large (linear) scales** for α_{B0} as high in magnitude as 0.48.

- Computational cost: **8-10 times** the LCDM simulations for nonlinear. Of the order of LCDM for linear.

Ongoing Work

- Exploration of the $\alpha_{B0} - \alpha_{M0}$ parameter space.
- Generation of power spectrum emulators and mass functions.
- More generic EFT models.
- Output of the three fields at particle positions for constructing lensing maps.
- Testing $w_0 - w_a$ cosmologies.

Perspective

Aim: solver for the EFT of dark energy integrated into RAMSES.

Pros: Enables deep exploration of the parameter space using full N-body simulations, covering a wide array of MG+DE theories.

Challenges: The solver will be slower than the standard Newtonian Poisson equation multigrid solver, and might not always converge. Nonlinear solutions not always possible.