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Parametrised methods for Modified Gravity N-Body Simulations

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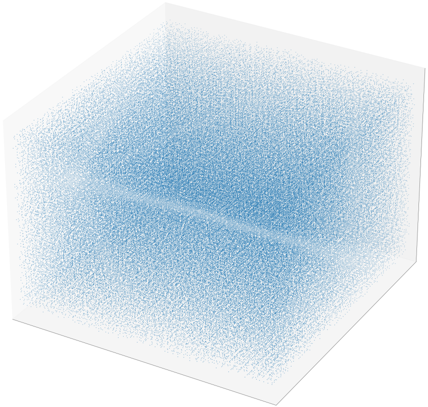
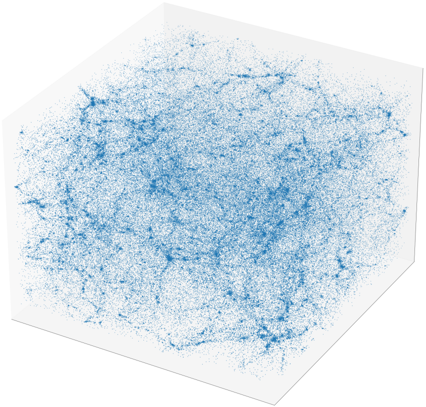
Outline

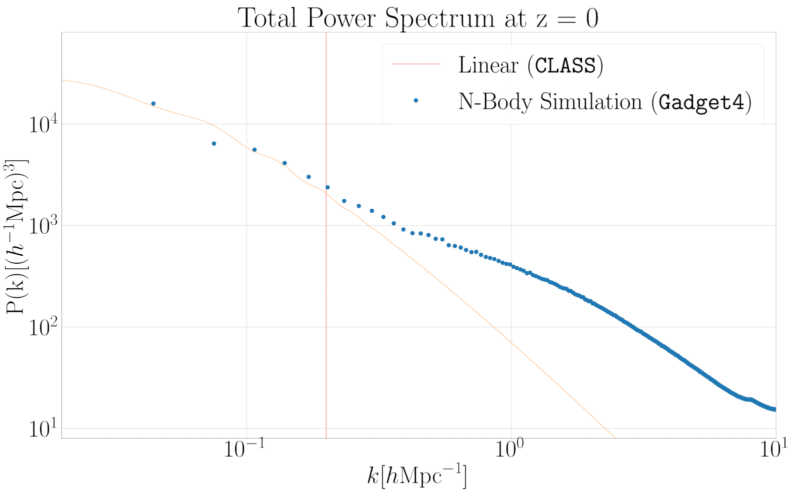
- (Brief) introduction to N-Body Simulations.
- Modified Gravity.
- Model-independent approaches.
- (Preliminary) results and conclusions.

Why N-Body Simulations?



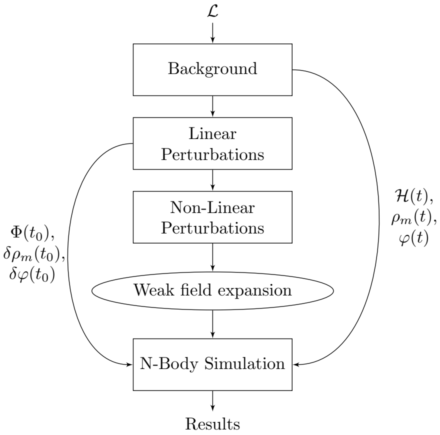


Why N-Body Simulations?

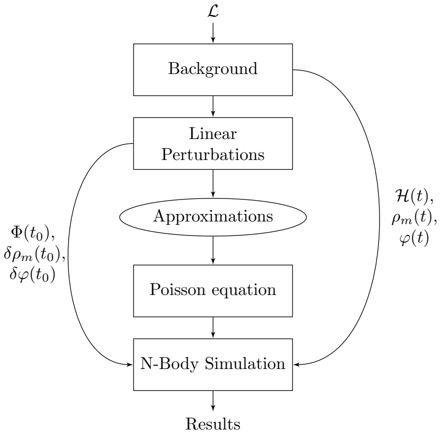


N-Body Simulations

Relativistic



Newtonian



Particle evolution

Large scales

- Linear perturbations.
- Description with Fourier modes.

$$\downarrow$$

Particle Mesh (PM)

$$k^2\Phi(k) = -4\pi G a^2 \delta\rho_m$$

- Fixed grid.
- Need finer grid to probe smaller scales.

Small scales

- Non-linear interaction.
- Local force.

$$\downarrow$$

Direct Force

$$\Phi(r) = -G\Sigma_i \frac{m_i}{|r - r_i|}$$

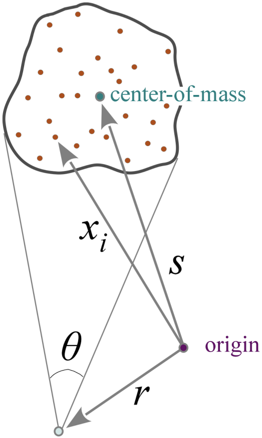
- Precise by definition.
- Huge number of interactions.

TreePM

- PM at large scales.
- Multipole expansion (Tree) at small scales.
- Merge with

$$\Phi(k) = \Phi^{\text{long}} + \Phi^{\text{short}}$$
$$= e^{-k^2 r_s^2}\Phi(k) + \left(1 - e^{-k^2 r_s^2}\right)\Phi(k)\,.$$

- Code: `Gadget4` (full `MPI`).[a]



[a] S. Volker et al, Mon.Not.Roy.Astron.Soc. **506** (2021) 2, 2871-2949.

Modified Gravity

Lagrangian includes new degrees of freedom

$$\mathcal{L} = R + \mathcal{L}_m \qquad \longrightarrow \qquad \mathcal{L} = f(R, \varphi, \dots)\,,$$

where f can be any function of R, scalar fields, etc.

For one additional (scalar) degree of freedom:

- new Klein-Gordon equation to solve (CPU);
- new field to store (memory);
- additional contribution to Poisson equation and force.

Parametrization Methods

- Spherical collapse: modification by fifth force.
- Fix parametrisation as function of k (and r), e.g.,

$$k^2\Phi(k) = -4\pi G_{\text{eff}}(k)a^2\delta\rho_m\,. \tag{1}$$

- Find constant parameters of parametrisation.
- Simulate.

Parametrisation Method I

- "**Non-local**" parametrisation for non-linear interactions.
- Effective Newton constant proposal[1]

$$\frac{G_{eff}}{G}(r) = A + \sum_i^{N_0} B_i \prod_j^{N_i} b_{ij} \left(\frac{r}{r_{0ij}}\right)^{a_{ij}} \left\{ \left[1 + \left(\frac{r_{0ij}}{r}\right)^{a_{ij}}\right]^{1/b_{ij}} - 1 \right\} ,$$

$$\frac{G_{eff}}{G}(k) = A + \sum_i^{N_0} B_i \prod_j^{N_i} b_{ij} \left(\frac{k}{k_{0ij}}\right)^{-a_{ij}} \left\{ \left[1 + \left(\frac{k_{0ij}}{k}\right)^{-a_{ij}}\right]^{1/b_{ij}} - 1 \right\} .$$

- Already studied in the PM (large scale) part[2].

[1] L. Lombriser, JCAP **11** (2016), 039

[2] F. Hassani and L. Lombriser, Mon. Not. Roy. Astron. Soc. **497** (2020) no.2, 1885-1894

Yukawa Interaction

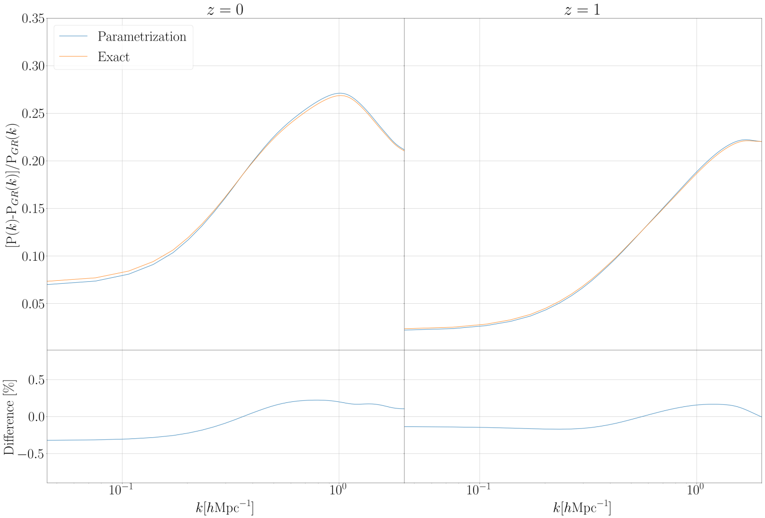
Simple Yukawa model

$$\tilde{\Phi}(k) = 4\pi G \frac{1}{k^2}\left(1 + \frac{1}{3}\frac{k^2}{k^2 + a^2\mu^2}\right) a^2 \delta\tilde{\rho}_{\mathrm{m}}(\vec{k}, a)\,,$$

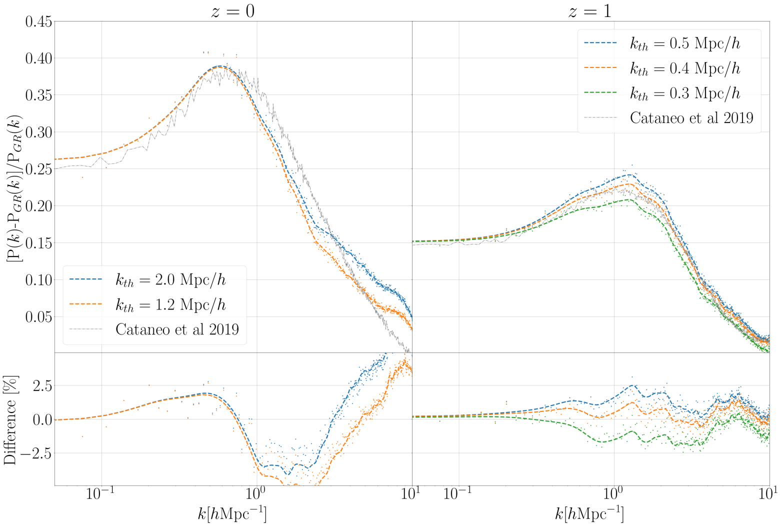
$$\Phi(r) = -\frac{Gm}{r}\left(1 + \frac{1}{3}e^{-\mu a r}\right)\,,$$

Matching parametrisation and model limits ($r \to 0$, $r \to \infty$), we obtain the parametrisation parameters.

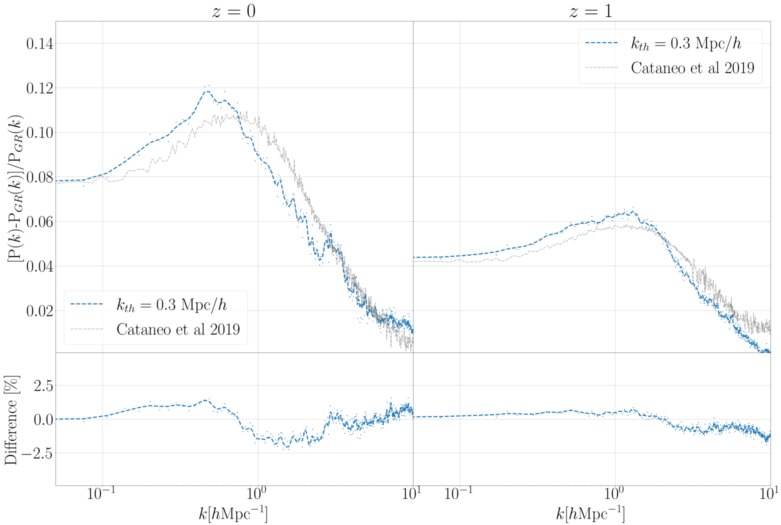
Yukawa Interaction



nDGP $r_c\mathcal{H}_0 = 0.5$



nDGP $r_c\mathcal{H}_0 = 2$



Parametrisation Method II

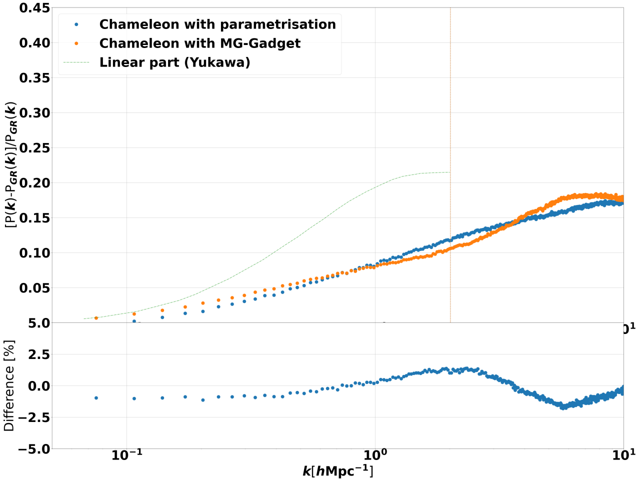
- "**Local**" parametrisation for non-linear interactions.
- Effective mass proposal (Chameleon screening)[3]

$$m_{\text{eff}} = m\frac{3\,|f_{R\,0}|}{2\,|\Phi|}\frac{\Omega_m + 4\Omega_\Lambda}{\Omega_m a^{-3} + 4\Omega_\Lambda}\,. \tag{2}$$

- Already studied in the PM (large scale) part.

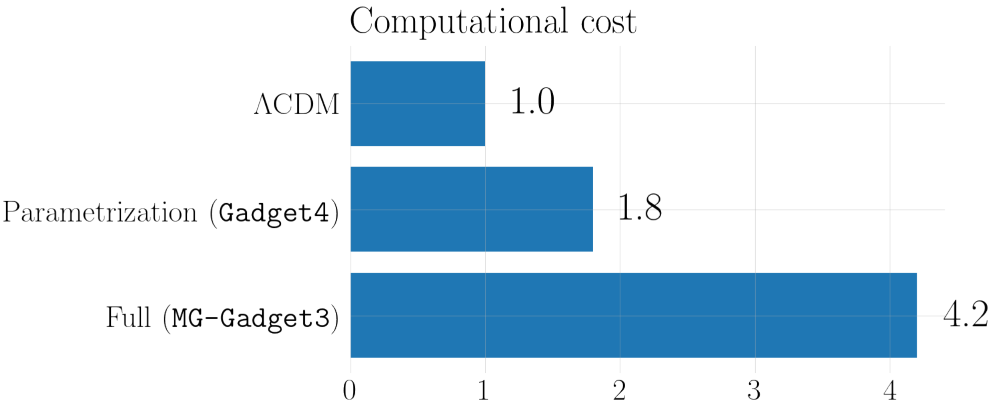
[3] H. A. Winther et al, Phys. Rev. D **91**, 123507 (2015).

Chameleon



Chameleon with parametrisation
Chameleon with MG-Gadget
Linear part (Yukawa)
[P(k)-P_GR(k)]/P_GR(k)
Difference [%]
k[hMpc⁻¹]
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
5.0
2.5
0.0
−2.5
−5.0
10⁻¹
10⁰
10¹

Why Parametrization Methods?



Conclusions

- N-body simulations captures non-linear structure formation.
- Modified Gravity with N-body simulations might be very expensive..
- .. but alternative approaches are available.

Thank you for your attention!