Extending approximate methods to generate halo catalogs with modified gravity

Chiara Moretti
Pierluigi Monaco

with S. Mozzon, E. Munari, M. Baldi, M. Raveri, B. Hu, A. Silvestri, G. Papadomanolakis

UNIVERSITÀ DEGLI STUDI DI TRIESTE

INAF ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTRONOMICO DI TRIESTE

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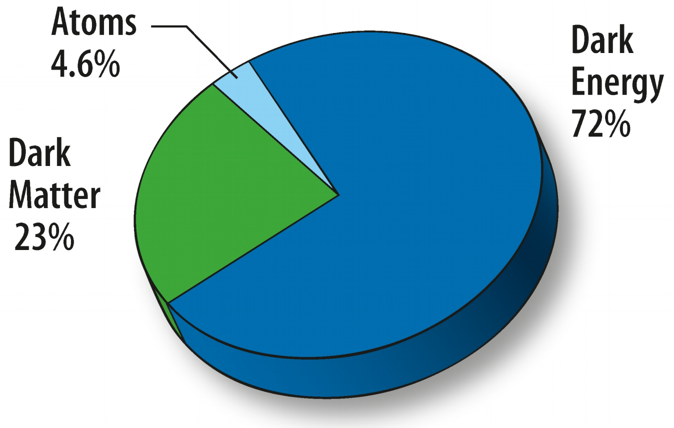
The standard cosmological model

ΛCDM model:
- based on GR;
- accelerated expansion = Λ
  - Λ (theory) >> Λ (observed).



TODAY

Alternative: GR is not the correct theory for gravity on cosmological scales →
Modified Gravity models

- specific signatures on cosmological observables;
- small effects (not yet detectable)

Largest scales: GR modified, expansion accelerates without need of Λ;

Intermediate scales: gravity modified by presence of fifth force;

Small scales: MG is screened, GR recovered

Approximate methods

Estimate cosmological parameters → need large number of simulated galaxy catalogs

- N-body simulations → model NL scales, but computationally expensive

- **Approximate methods** → fast, allow to explore cosmological parameter space and compute covariance matrices

PINOCCHIO code:
- LPT + ellipsoidal collapse
- ~10^3 times faster than full N-body simulation

GOAL: extend PINOCCHIO to MG theories

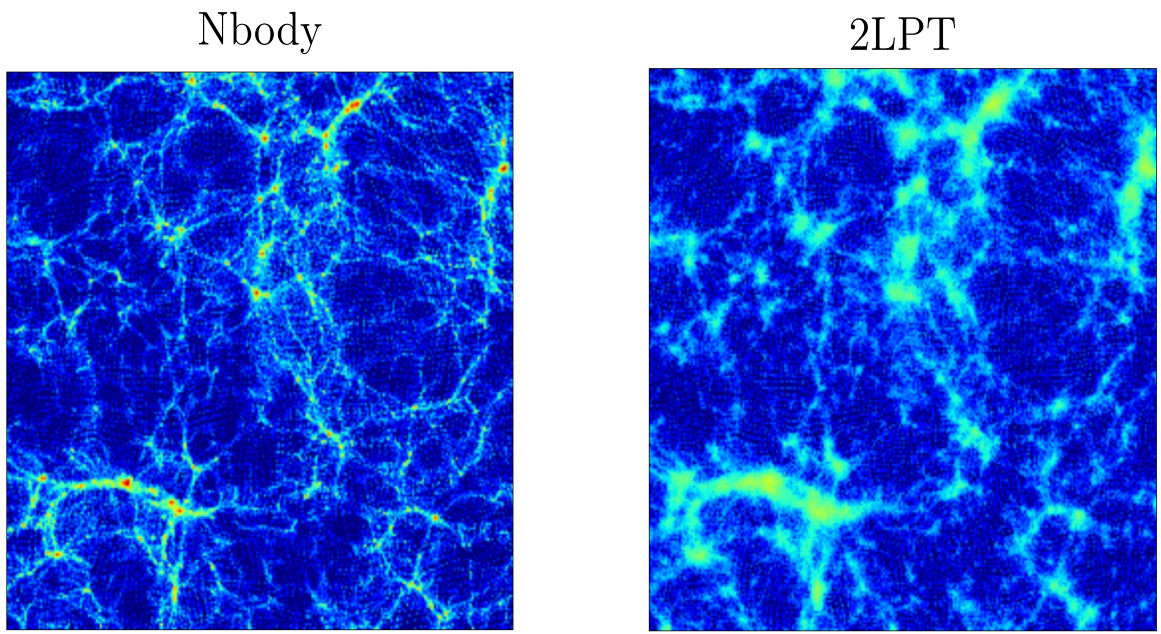
Formulating+implementing both LPT & ellipsoidal collapse for MG

Lagrangian perturbation theory

Used to displace particles: $\vec{x} = \vec{q} + \nabla\phi(\vec{q}, t)$

In GR time can be factored out: $\phi^{(1)}(\vec{q}, t) = D_1(t)\ \phi^{(1)}(\vec{q}, t_{in})$

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}t^2} + 2H\frac{\mathrm{d}}{\mathrm{d}t}\right) D_1(t) = -4\pi G\rho D_1(t)$$



Munari+17

LPT + Modified gravity

- Modified Poisson eq.:

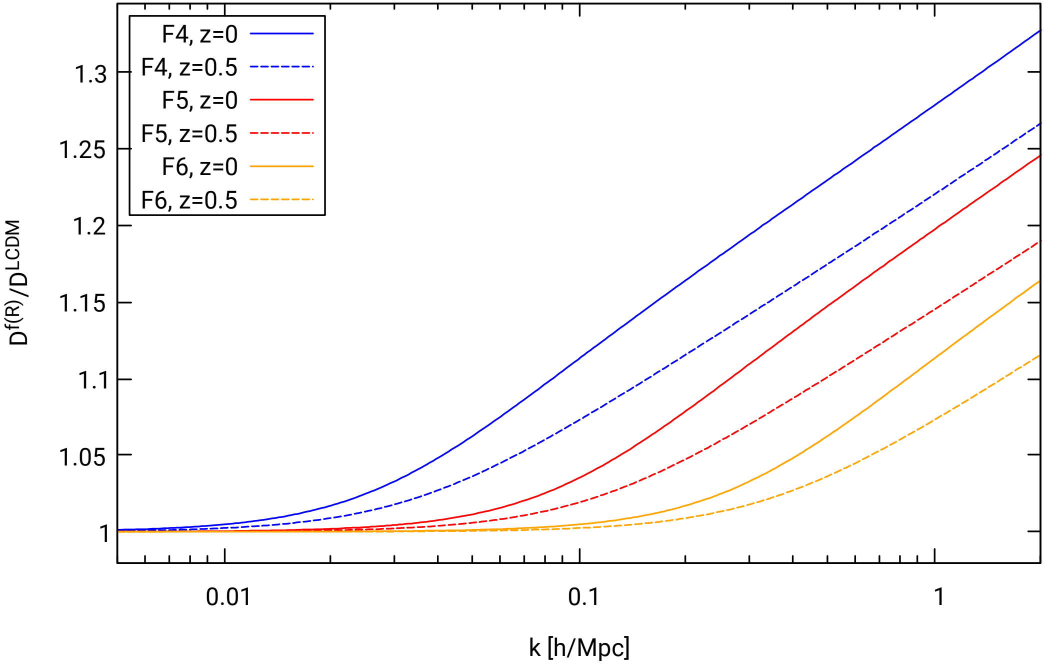
$$-\frac{k^2}{a^2}\Psi = 4\pi G\bar{\rho}\mu(k,a)\delta_k$$

- Growth rate becomes scale dependent:

$$\phi^{(1)}(\vec{k},t) = D_1(k,t)\phi^{(1)}(\vec{k},t_{in})$$

- **First order**: separate time for each Fourier mode;

- **Second order**: growth rate depends on triangle configurations in Fourier space



$$\phi^{(2)}(\vec{k},t) = -\frac{1}{2k^2}\int\frac{d^3k_1d^3k_2}{(2\pi)^3}\delta_D(\vec{k}-\vec{k}_{12})\delta^{(1)}(\vec{k}_1,t_{in})\delta^{(1)}(\vec{k}_2,t_{in})D_2(k,k_1,k_2,t)$$

Solve for all possible triangles

Find approximation for D2(k,a)

Second order: full solution

For f(R) we can take advantage of FFTs to compute the full solution:

$$\left(\frac{d^2}{dt^2} + 2H\frac{d}{dt} - 4\pi G\rho\mu(k,a)\right) \mathrm{FT}\left[\phi^{(2)}_{,ii}(\vec{q},a)\right](\vec{k},a) =$$

$$= 4\pi G\rho\, \mathrm{FT}\left[\phi^{(1)}_{,ij}\phi^{(1)}_{,ji} + \frac{1}{3a^2}\phi^{(1)}_{,ij}\left(\mathrm{IFT}\left[\frac{\delta^{(1)}(\vec{k},a)}{\Pi(k,a)}\right]\right)_{,ji}\right](\vec{k},a) +$$

$$- 2\pi G\rho\mu(k,a)\, \mathrm{FT}\left[\phi^{(1)}_{,ii}\phi^{(1)}_{,jj} + \phi^{(1)}_{,ij}\phi^{(1)}_{,ji}\right](\vec{k},a) +$$

$$+ \left(\frac{8\pi G\rho}{3}\right)^2 \frac{M_2(a)}{12}\frac{k^2/a^2}{\Pi(k,a)}\, \mathrm{FT}\left[\left(\mathrm{IFT}\left[\frac{\delta^{(1)}(\vec{k},a)}{\Pi(k,a)}\right]\right)^2\right](\vec{k},a) +$$

$$+ \frac{8\pi G\rho}{3}\frac{m^2(a)}{2a^2}\frac{1}{\Pi(k,a)}\, \mathrm{FT}\left[-2\phi^{(1)}_{,ij}\left(\mathrm{IFT}\left[\frac{\delta^{(1)}(\vec{k},a)}{\Pi(k,a)}\right]\right)_{,ij}\right.$$

$$\left. -\phi^{(1)}_{,iij}\left(\mathrm{IFT}\left[\frac{\delta^{(1)}(\vec{k},a)}{\Pi(k,a)}\right]\right)_{,j}\right](\vec{k},a)$$

Second order eq. of motion + Poisson

Scalar field self interaction (screening)

Frame lagging

LPT + Modified gravity: Second Order

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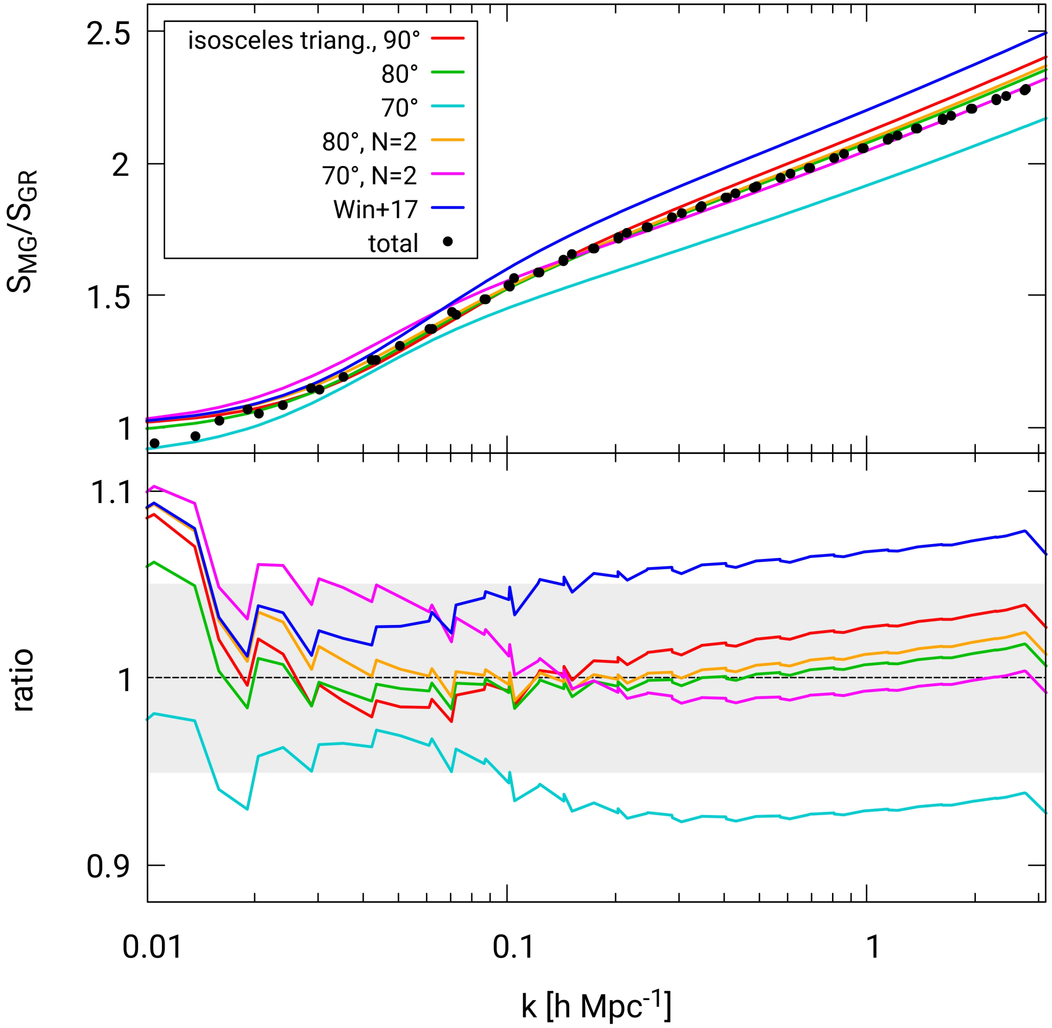

- Find D2(k,t):

$$\phi^{(2)}(\vec{k},t) = D_2(k,t)\phi^{(2)}(\vec{k},t_{in})$$

- Compute source term of differential eq. for the displacement field;
- Divide by GR source term to factor out dependence on $\vec{k}$;
- Compare to different triangle configurations → find the best match to the full solution.

Moretti+19, in prep.

Comparison with N—body simulations

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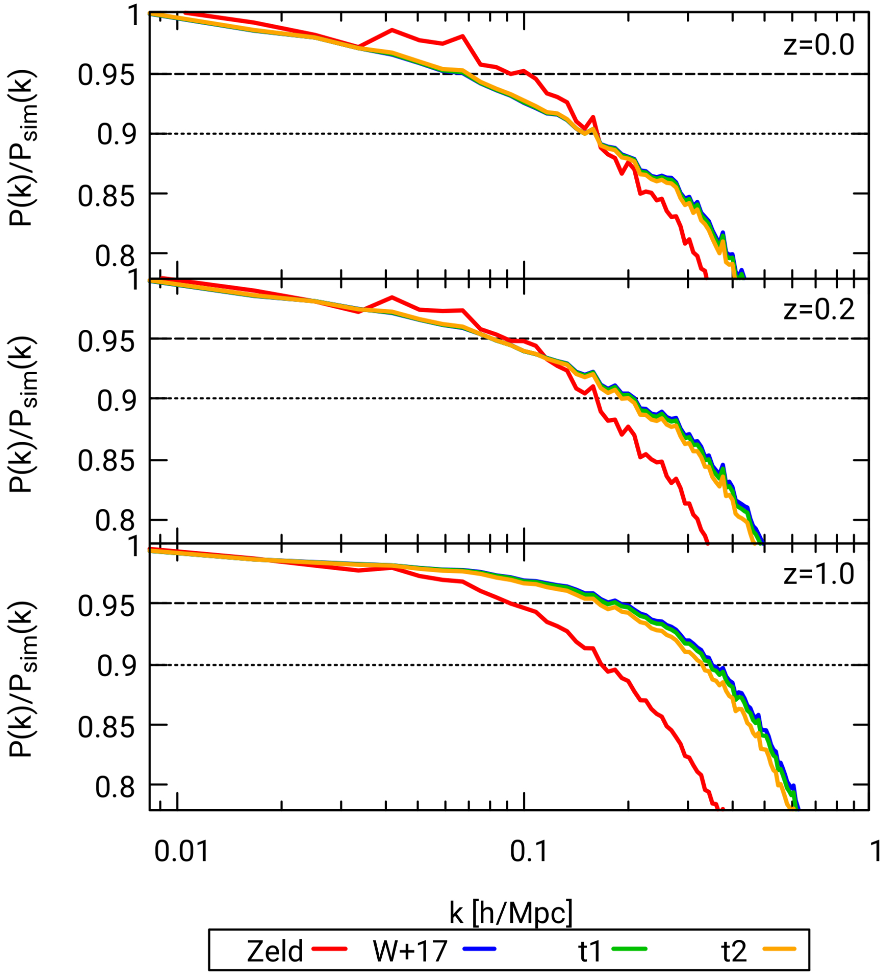
Test our approximation against N-body sim run with Hu-Sawicki f(R) (MG-GADGET, DUSTGRAIN pathfinder simulations, Giocoli+18)

L =750 Mpc/h
768^3 particles
Mp ~ 8 · 10^{10} Msun

Halos constructed using membership of the simulation (as in Munari+17)



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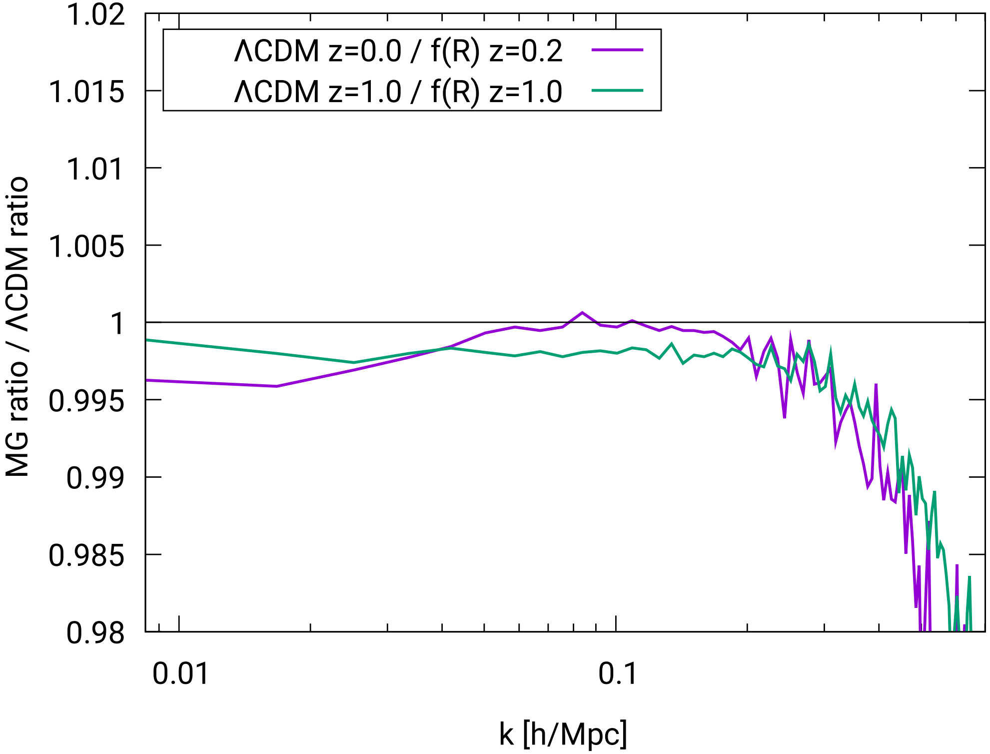

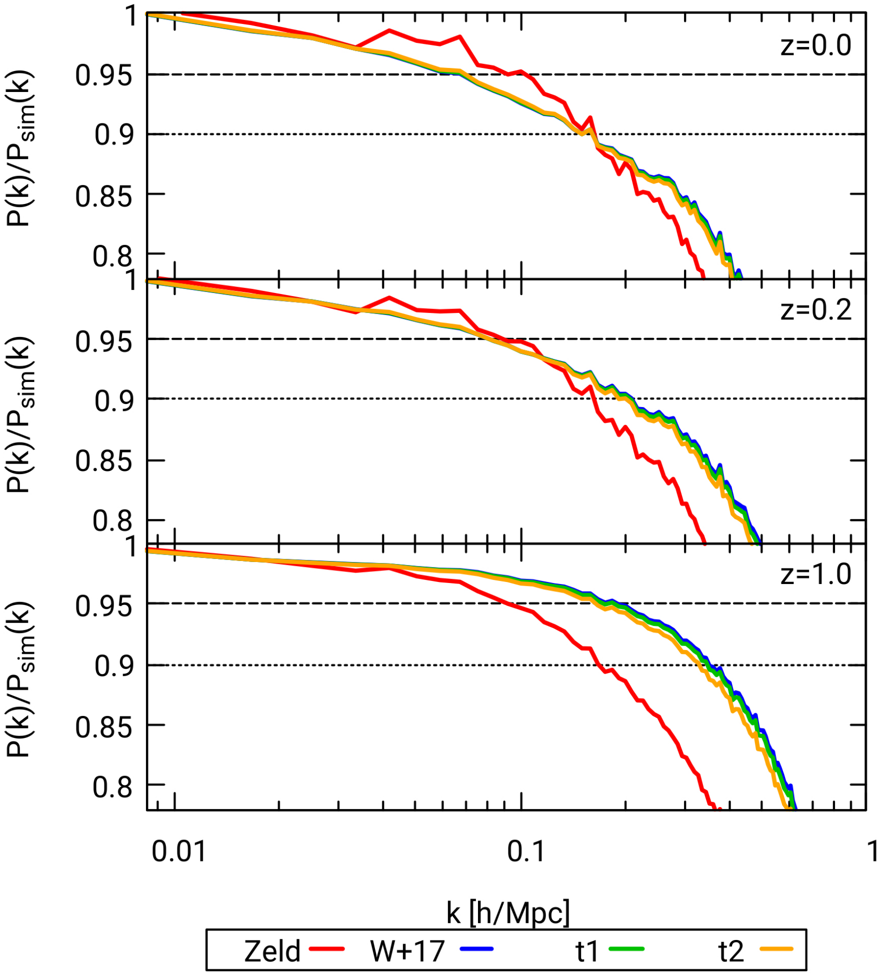

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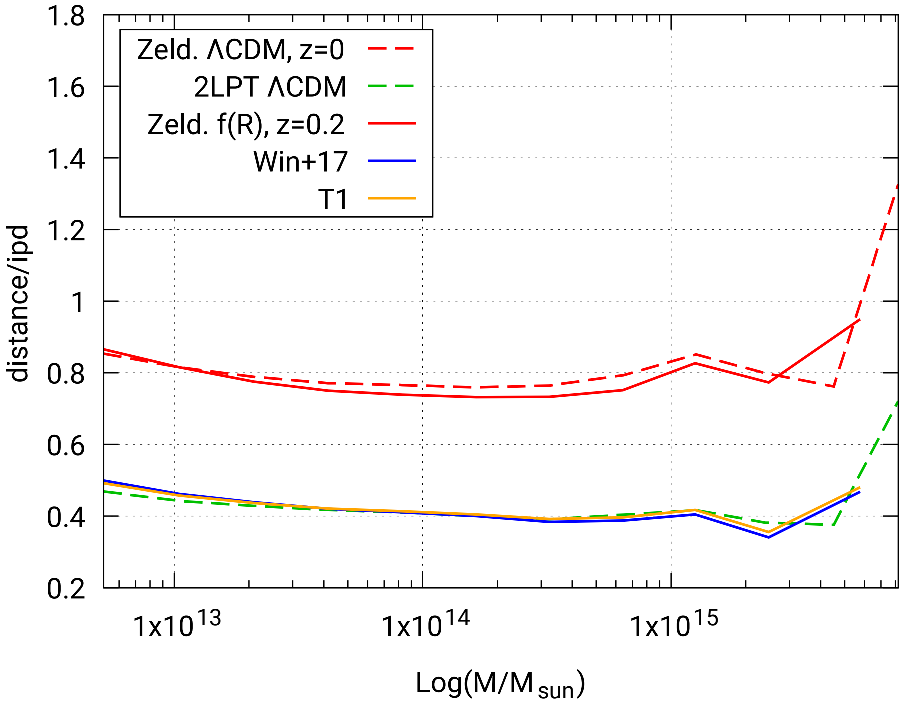

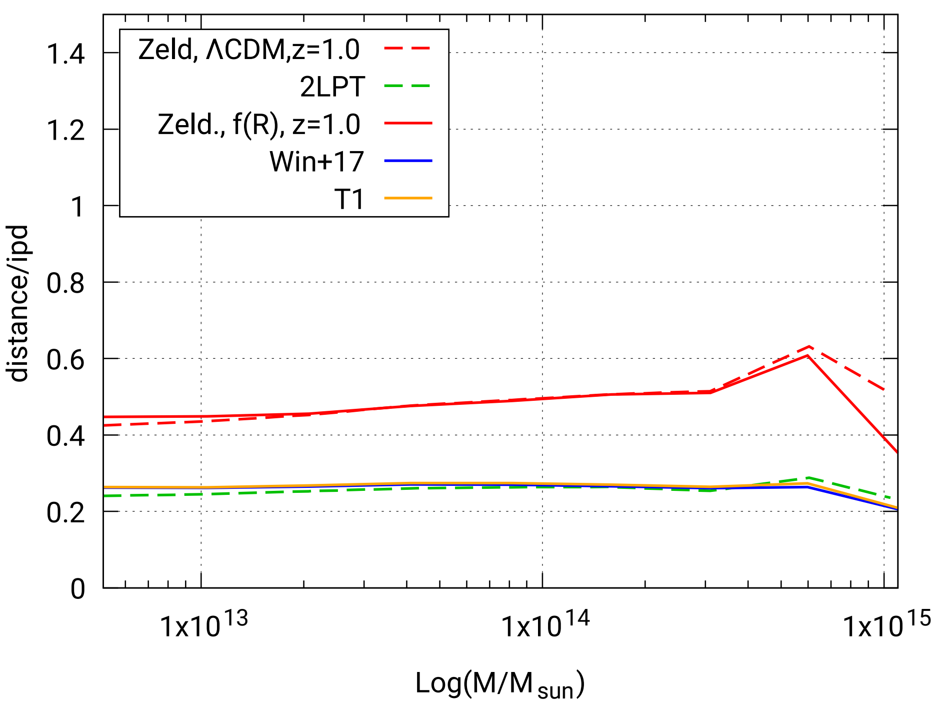

Summary & conclusions

- Extend PINOCCHIO to MG models, focus on f(R);
- New approach to compute full solution for 2LPT displacement field;
- Find best triangle configuration to match second order growth rate (+ quantify deviation from full solution).

  - We can recover halo P(k) within 10% up to mildly NL scales (k~0.2 h/Mpc);

    Moretti+19, in prep.

  - Halo positions recovered with same accuracy as in ΛCDM;
  - PINOCCHIO + MG can be used to produce many realizations, to compute covariance matrices and explore cosmological parameter space → constrain beyond ΛCDM cosmologies

Work in progress:

- ellipsoidal collapse → compute coll. time and group particles in halos
- third order LPT