Approximate methods to generate halo catalogs with modified gravity

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Future surveys → high precision data, tight constraints on cosmological parameters;

Test gravity on cosmological scales

Approximate methods

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PINOCCHIO code:

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

GOAL: extend PINOCCHIO to MG theories – f(R)

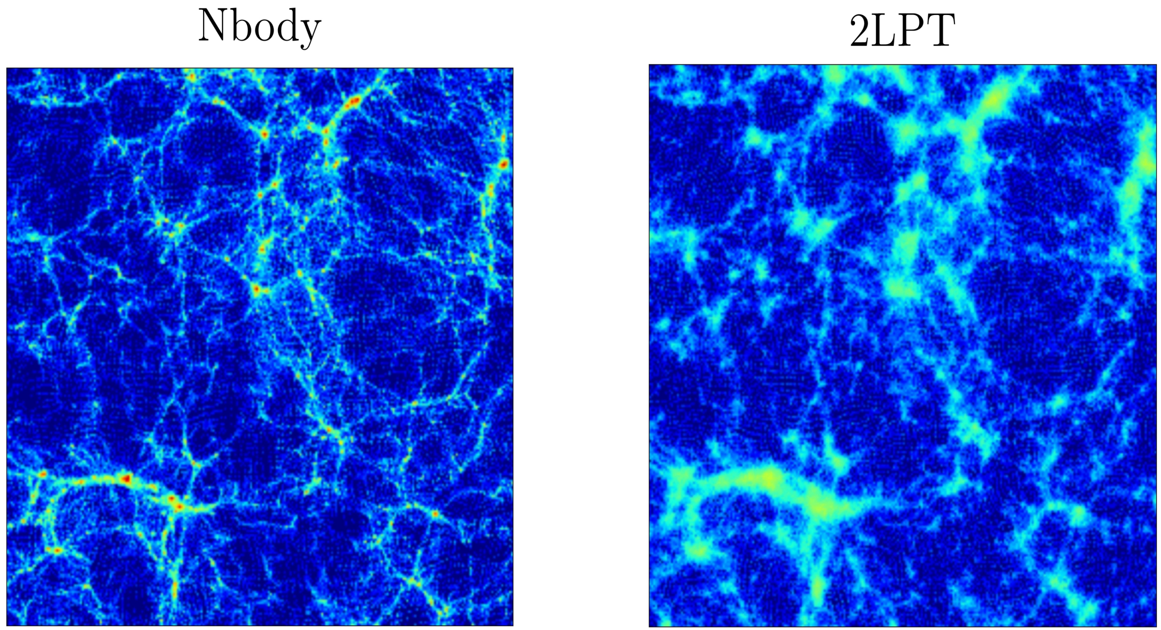
Formulating+implementing both LPT & ellipsoidal collapse for MG

Lagrangian perturbation theory

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

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

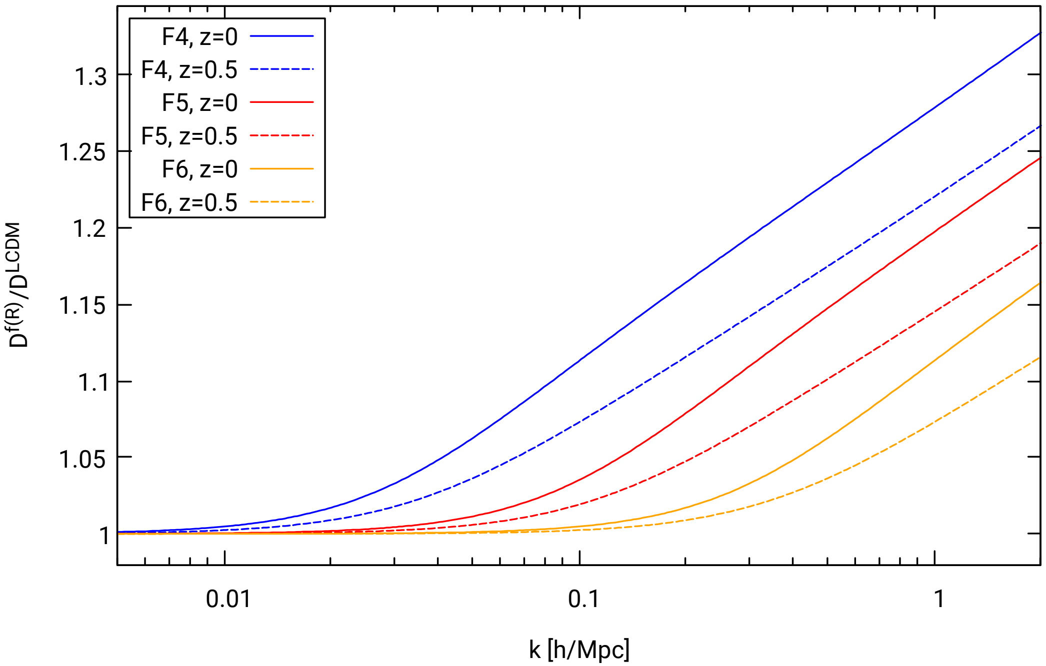
$$\left(\frac{\mathrm{d}^2}{\mathrm{d}t^2} + 2H\frac{\mathrm{d}}{\mathrm{d}t}\right) D_1(t) = -4\pi G\rho D_1(t)$$



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;



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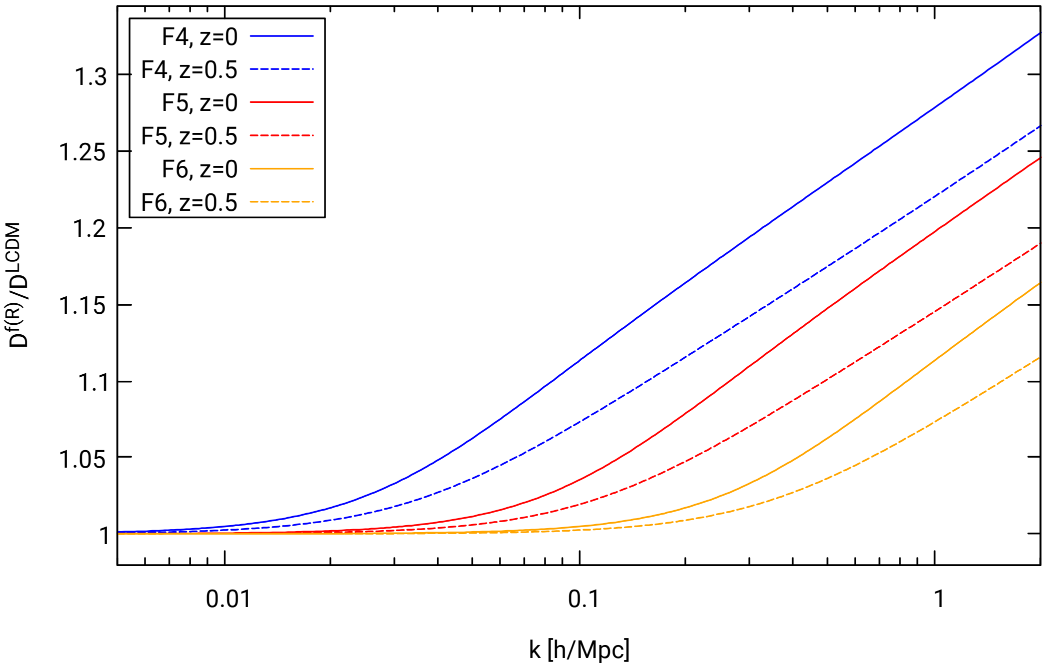
- **First order**: separate time for each Fourier mode;
- **Second order**: growth rate depends on triangle configurations in Fourier space



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

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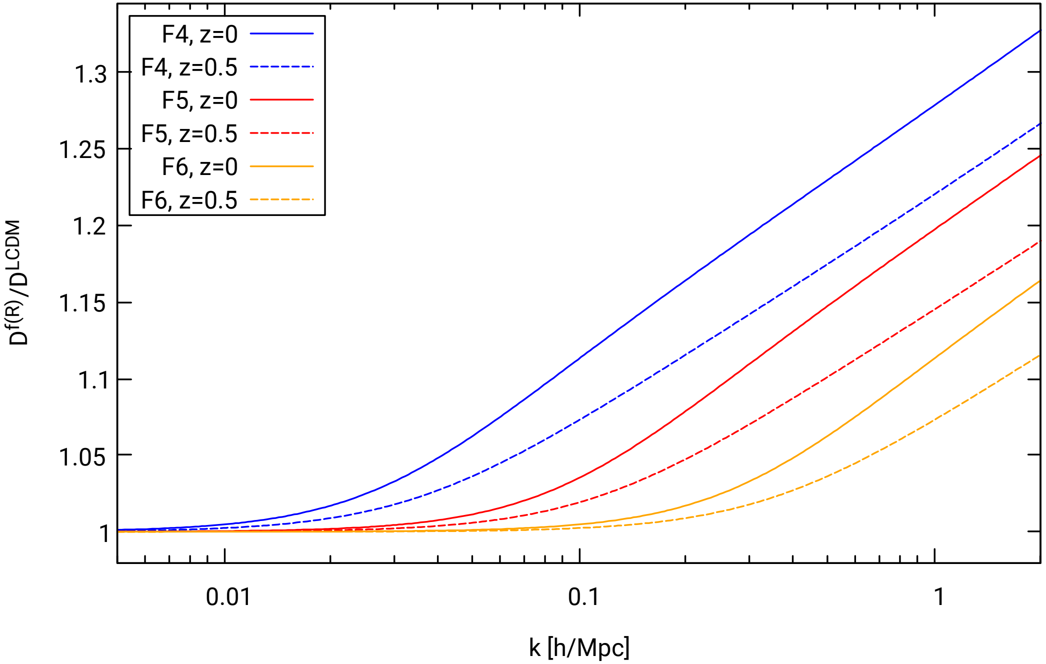

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Solve for all possible triangles

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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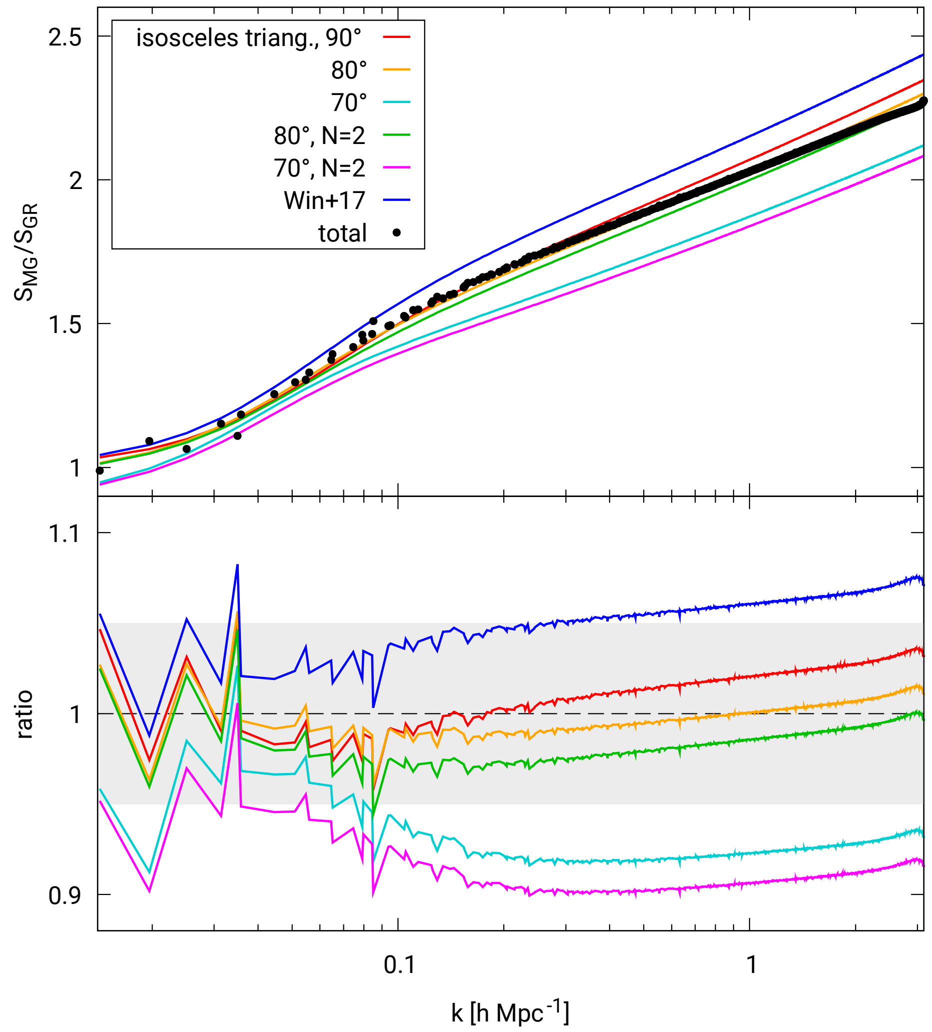

- Find D2(k,t):

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

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

Moretti+19, 1909.06282

Comparison with N—body simulations

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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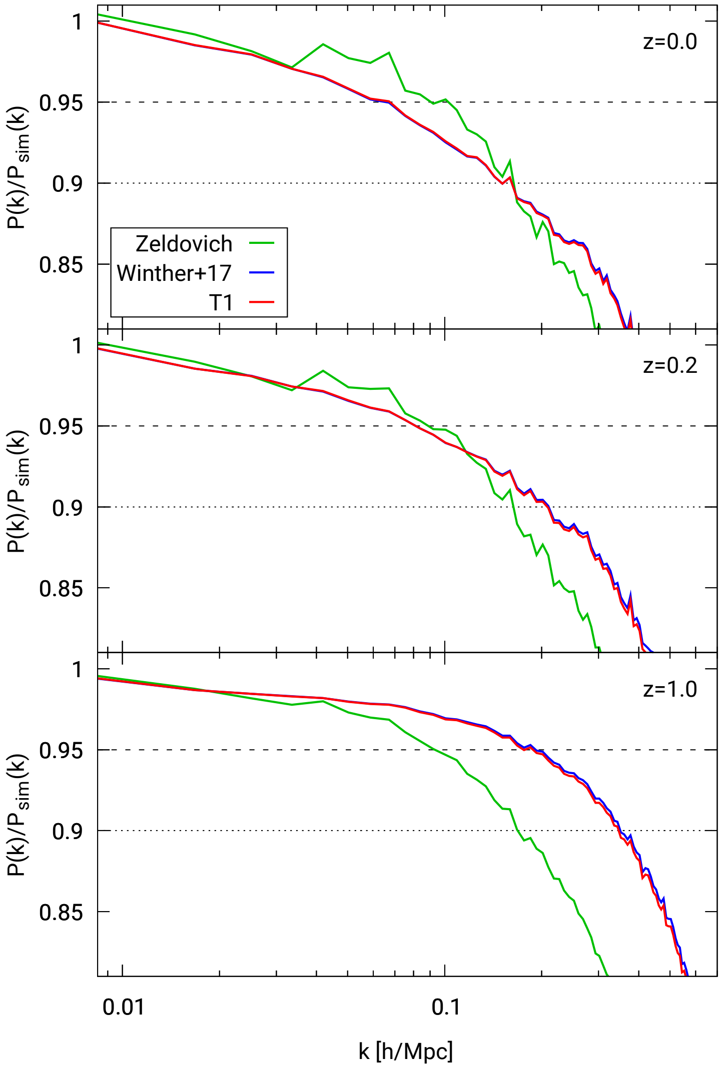

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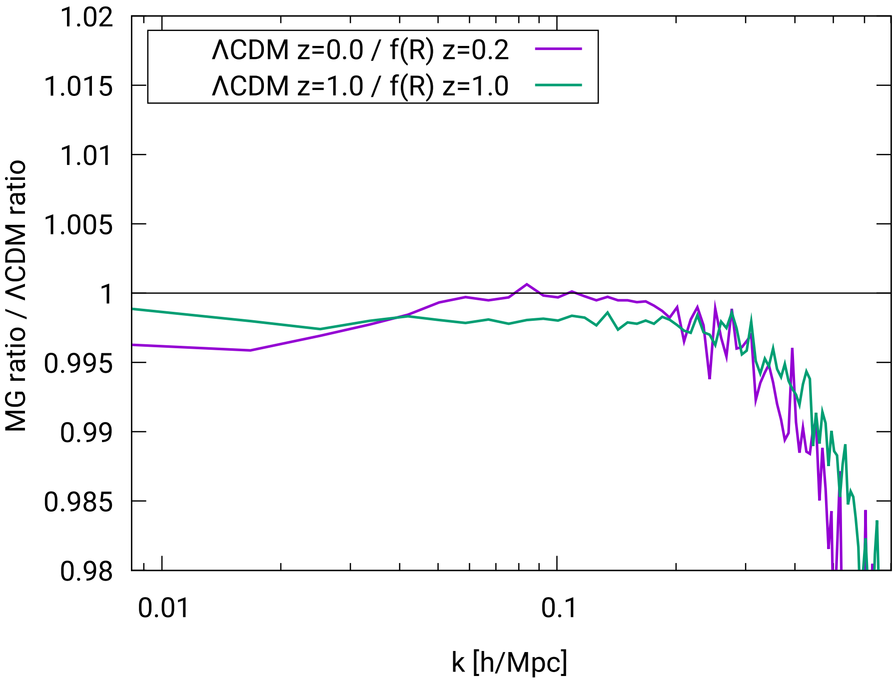

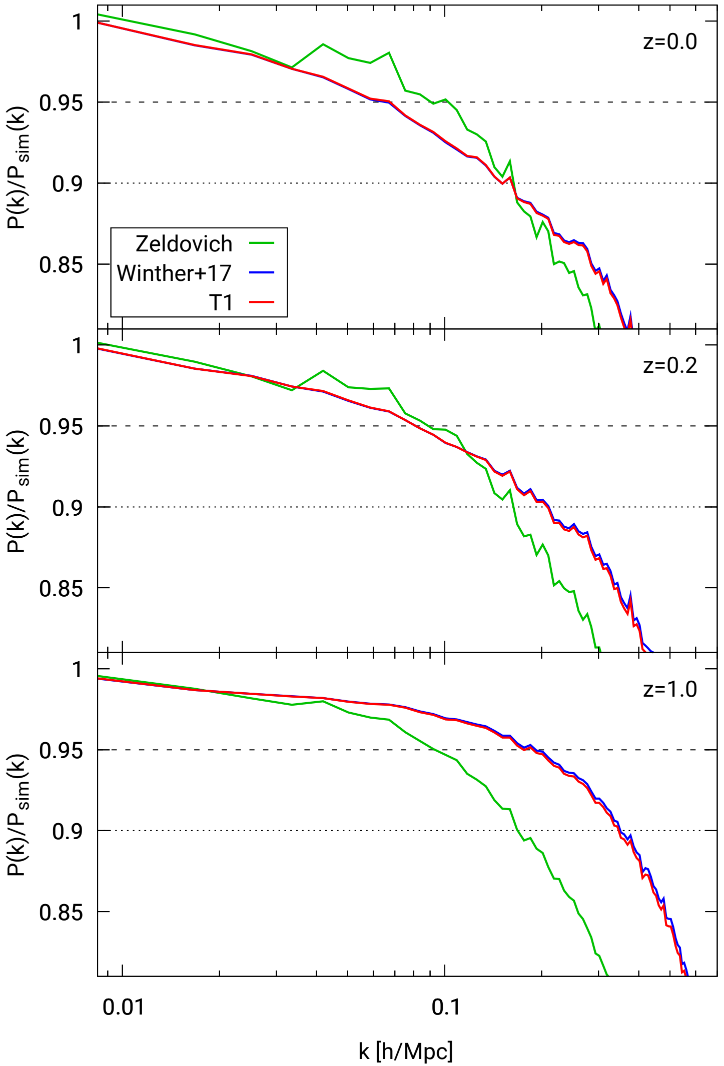

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Ellipsoidal collapse with MG

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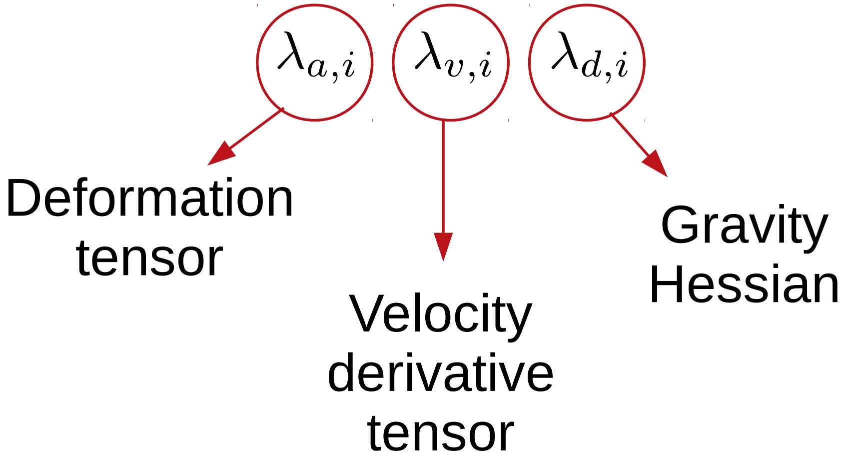
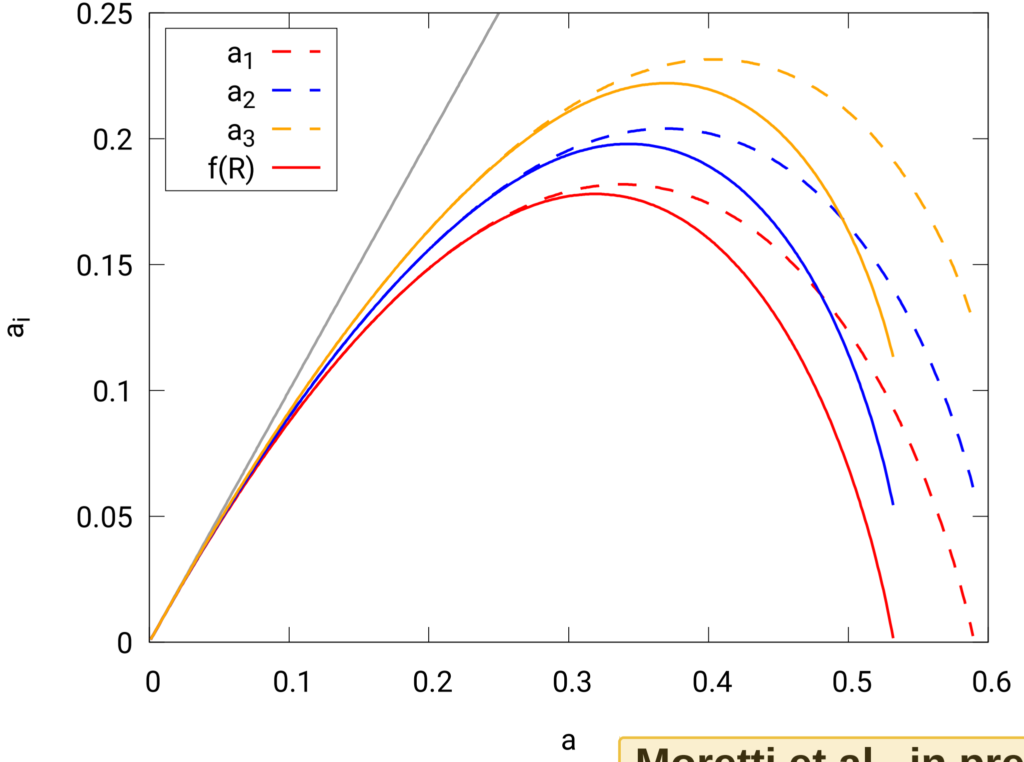
Include gravity enhancement + screening with $G_{eff} = G\,(1 + F)$:

$$a_i'' + \left(\frac{1}{a} - \frac{3}{2}\frac{\Omega_m(a)}{a}\right) a_i' = \left[-\frac{\Omega_\Lambda}{a^2} + \frac{1}{2}\frac{\Omega_m(a)}{a^2} + \frac{3}{2}\frac{\Omega_m(a)}{a^2} C_i(a)(1+F)\right] a_i$$

Ruan+19

Speed up computation → alternative description **(Nadkarni-Ghosh+16)**:





Moretti et al., in prep

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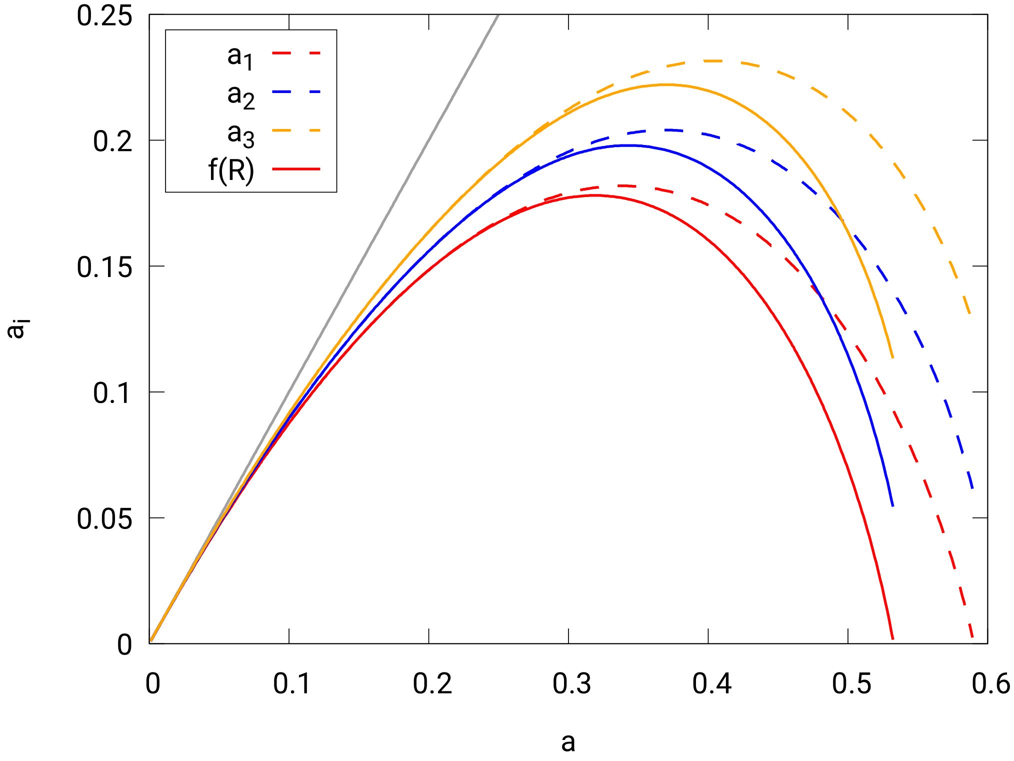

3 second order integro-differential equations ⟶ 9 first order differential equations

Moretti et al., in prep

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PINOCCHIO+MG can be used to produce many realizations, to compute cov. matrices → constrain beyond ΛCDM cosmologies