A gradient based method for modeling baryons and matter in halos

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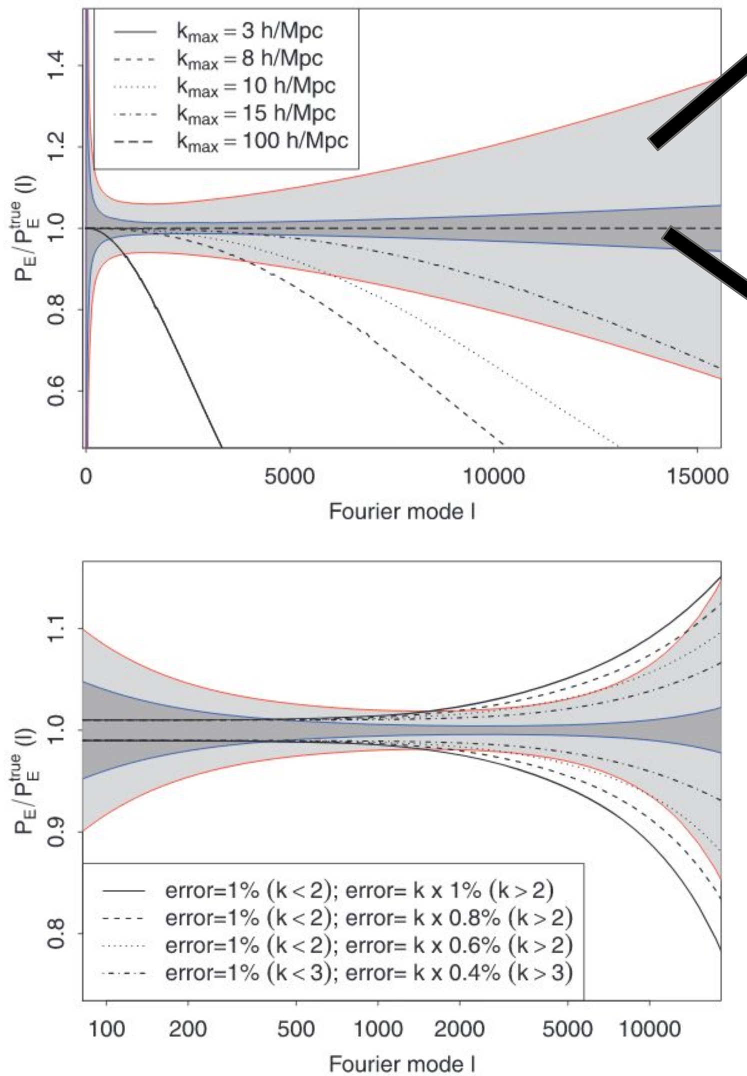
Outline

- Introduction
- Models
  - Potential Gradient Descent
  - Enthalpy Gradient Descent
- Example Application
  - Visual Inspection
  - Matter Power Spectrum
  - Halo Mass Profile
- Conclusions

Introduction

- To take full advantage of future weak lensing surveys, the accuracy with which we model the matter power spectrum will have to be improved to the few percent level.



Statistical error in a DES-like survey

Statistical error in a LSST-like survey

Figure 3 in Eifler 2011

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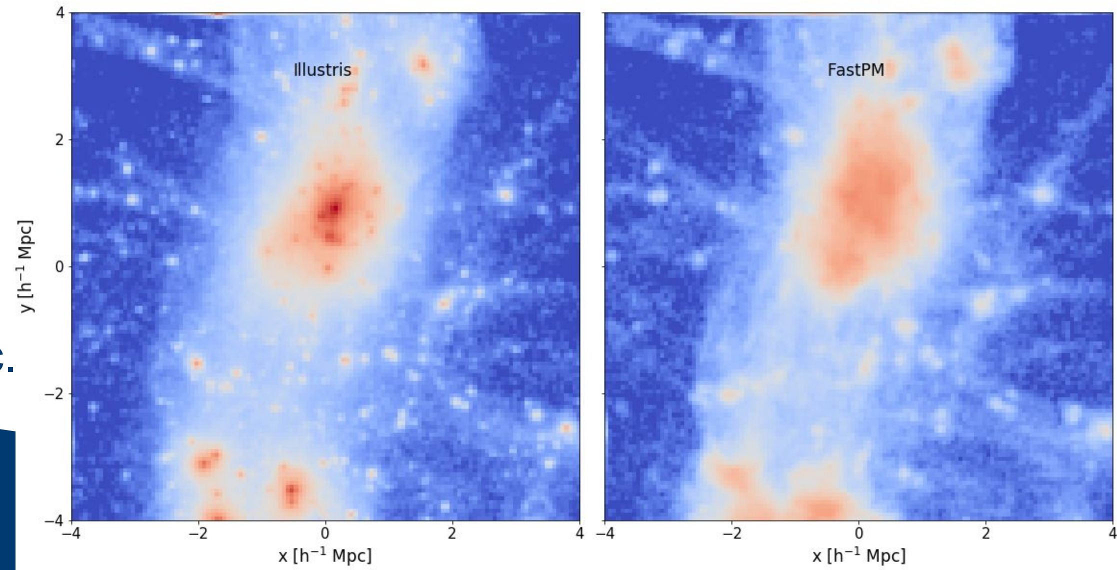
Introduction

- Hydrodynamical simulation:
  - Expensive
  - Different baryon models do not agree
- Fast N-body PM simulation (such as FastPM and COLA):
  - Fast (limited number of time steps while enforcing the correct linear growth)
  - Cannot give accurate halo matter profiles or matter power spectrum
- Full N-body simulation:
  - Lacks baryonic effect, which can changes the matter power spectrum by more than 10% for $1 < k < 30$ h/Mpc.



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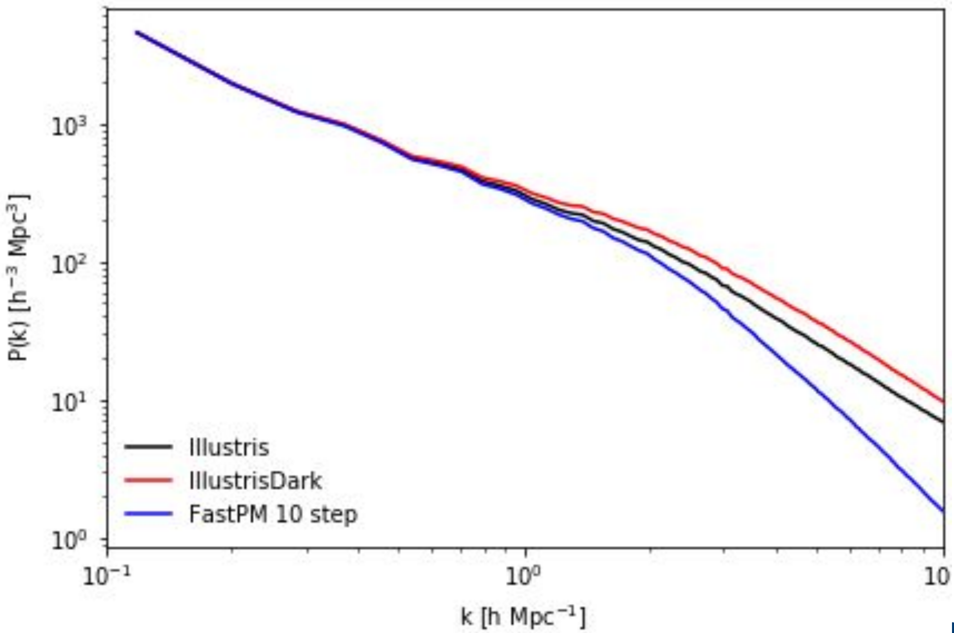

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Models

- The basic goal: mimics the physics that is missing
    - Halo virialization
    - Baryonic physics (pressure, AGN feedback, supernovae feedback)

- Correction preformed on particles in configuration space
    - Ideally additional displacement

- Flexible & few free parameters

- Computationally cheap

Models - Potential Gradient Descent (PGD)

- Quasi N-body simulations: the halos are not fully virialized
  - Add additional displacements to sharpen the halos
- The direction of the displacements should be pointing towards the halo center (local potential minimum), similar to the gravitational force.
- The gravitational force:

$$\mathbf{F} = -\nabla\phi$$

- The PGD correction displacement:

$$\mathbf{S} = -\alpha\nabla\hat{\mathbf{O}}_{\mathbf{h}}\hat{\mathbf{O}}_{\mathbf{l}}\phi$$

- High pass filter $\hat{\mathbf{O}}_{\mathbf{h}}$ prevents the large scale growth, low pass filter $\hat{\mathbf{O}}_{\mathbf{l}}$ reduces the numerical effect

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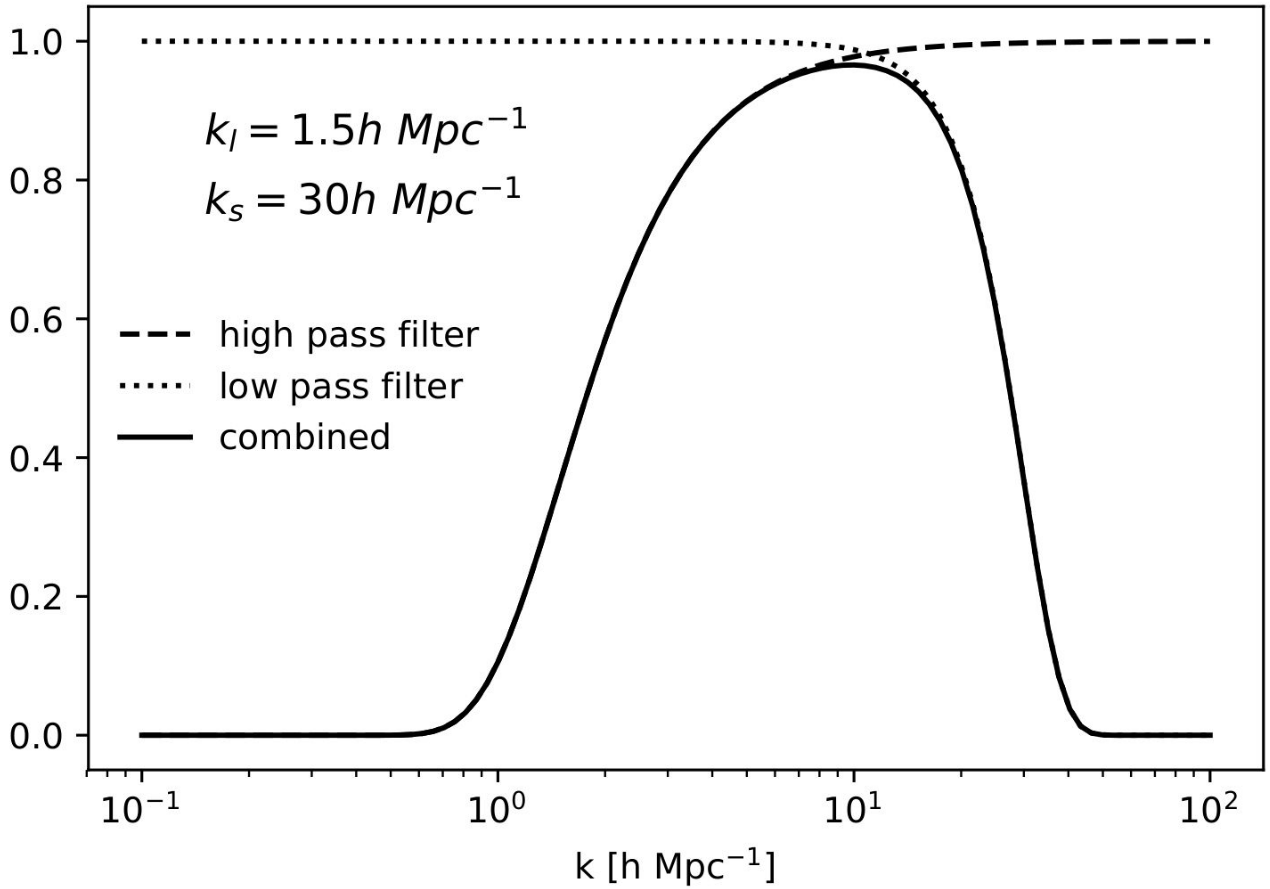
Models - Potential Gradient Descent (PGD)



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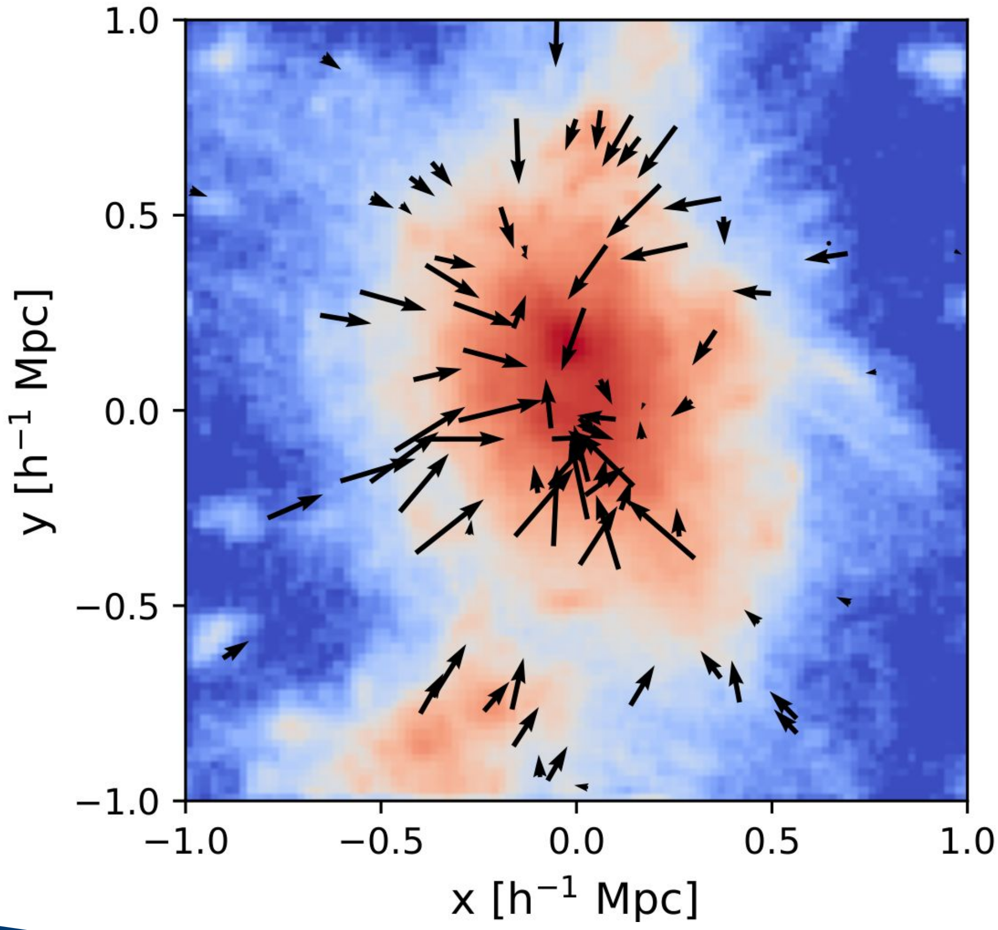
Models - Potential Gradient Descent (PGD)



Models - Enthalpy Gradient Descent (EGD)

- Goal: mimics the effect of AGN and supernovae feedback
  - Move particles out of the halo
- Consider the equation of motion for a gas element:

$$\frac{d\mathbf{v}}{dt} + H\mathbf{v} = -\nabla\phi - \frac{1}{\rho}\nabla P$$

- The EGD correction displacement:

$$\mathbf{S} = -\beta\frac{1}{\rho}\nabla P = -\beta\nabla\mathcal{H}$$

- The specific enthalpy:

$$\mathcal{H} = \frac{P(\rho)}{\rho} + \int_1^\rho \frac{P(\rho')}{\rho'}\frac{d\rho'}{\rho'}$$

- Assumed baryon traces dark matter, and a power law equation of state:

$$T(\delta_b) = T_0(1+\delta_b)^{\gamma-1}$$

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From N-body to Hydro

- As an example, we calibrate 2 ”inaccurate” simulations against Illustris hydrodynamical simulations (Vogelsberger et al. 2014):
  - FastPM with 10 steps (Feng et al. 2016) -> PGD
  - Full N-body simulation (IllustrisDark) -> EGD

- The calibrations are based on minimizing the discrepancies of the power spectra:

$$p(P_{\mathrm{ref}}(k)|\theta) = \prod_{k<10\mathrm{h\ Mpc}^{-1}} \frac{1}{\sqrt{2\pi\sigma_k^2}} \exp\left[\frac{(P_{\mathrm{ref}}(k) - P_{\mathrm{calib}}(k))^2}{2\sigma_k^2}\right]$$

- Free parameters: α, k_l, k_s in PGD and β, γ in EGD

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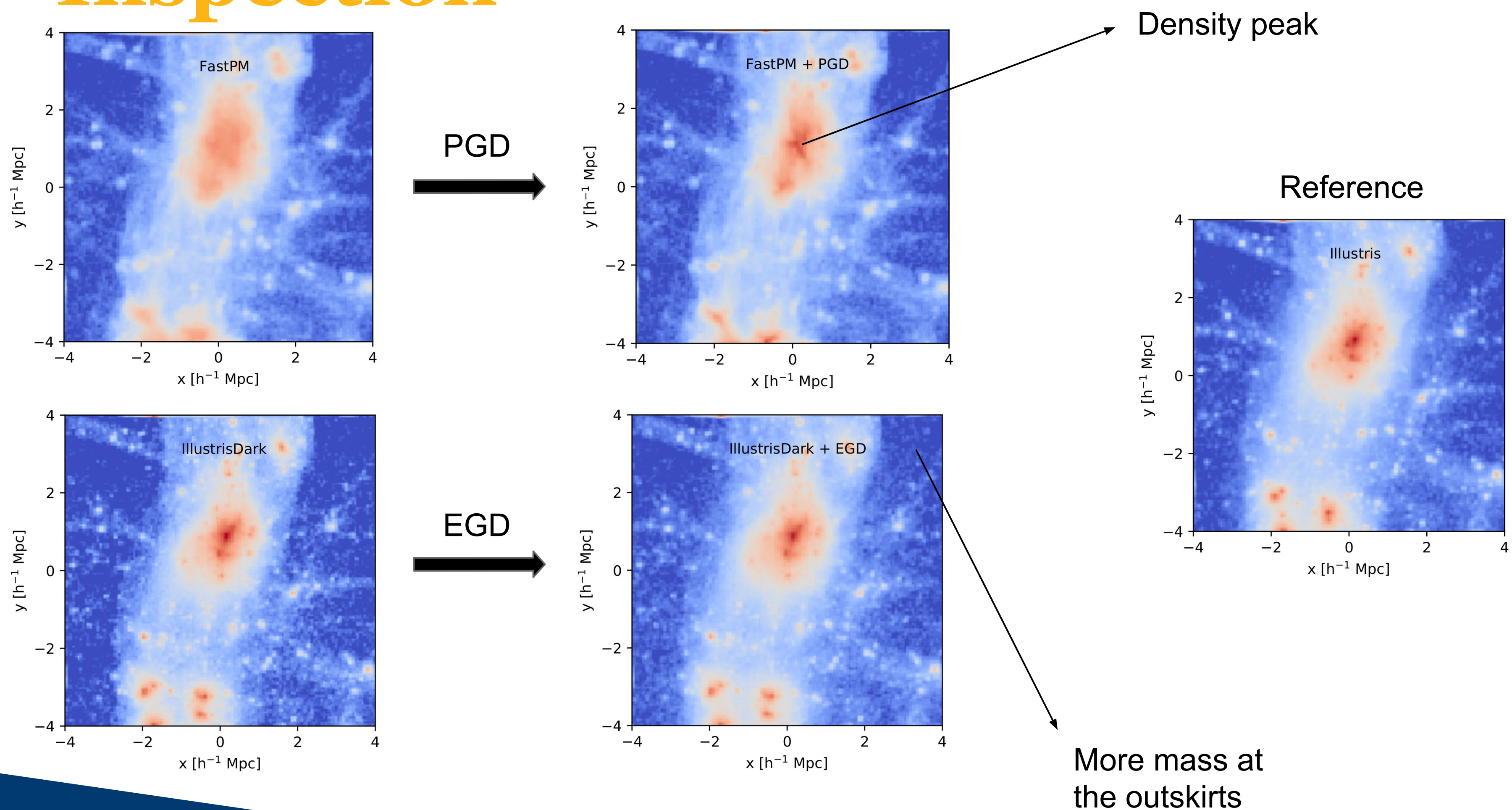
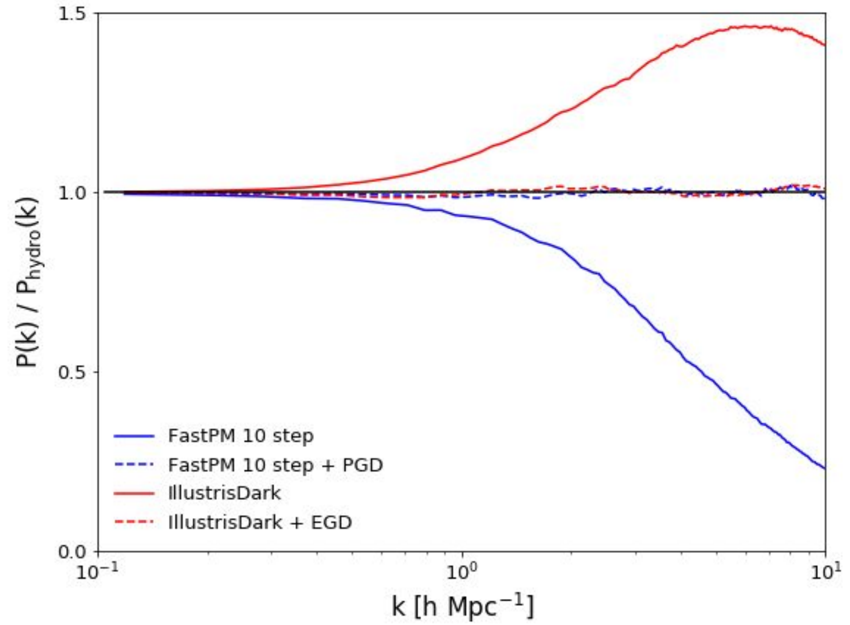
From N-body to Hydro - Visual Inspection

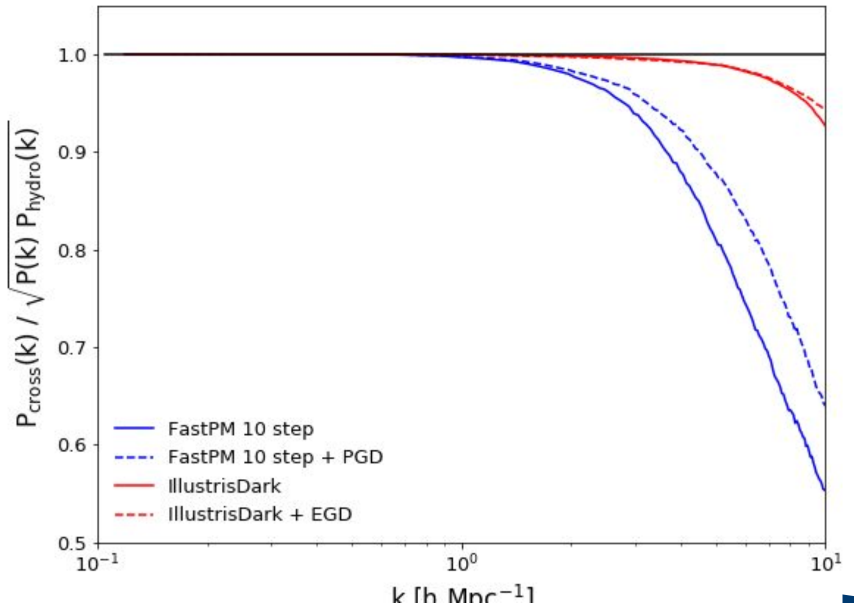


From N-body to Hydro - Matter Power Spectrum

- Matter power spectrum close to hydro after calibration

- Cross correlation coefficient improves





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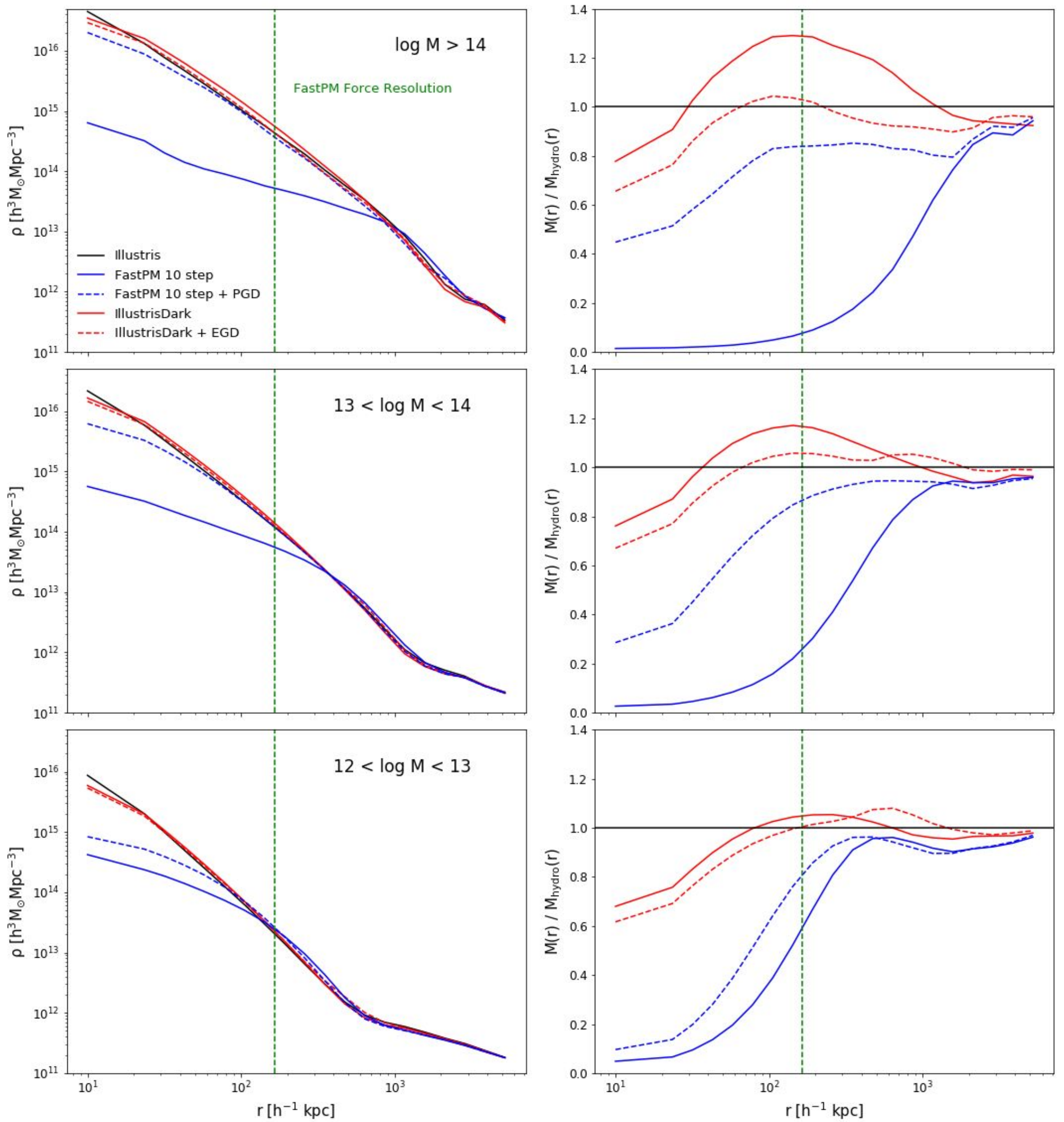
From N-body to Hydro - Halo Mass Profile

- PGD increases the mass at the halo center
- EGD moves mass to the outskirts of the halos
- Effects are stronger at larger halos



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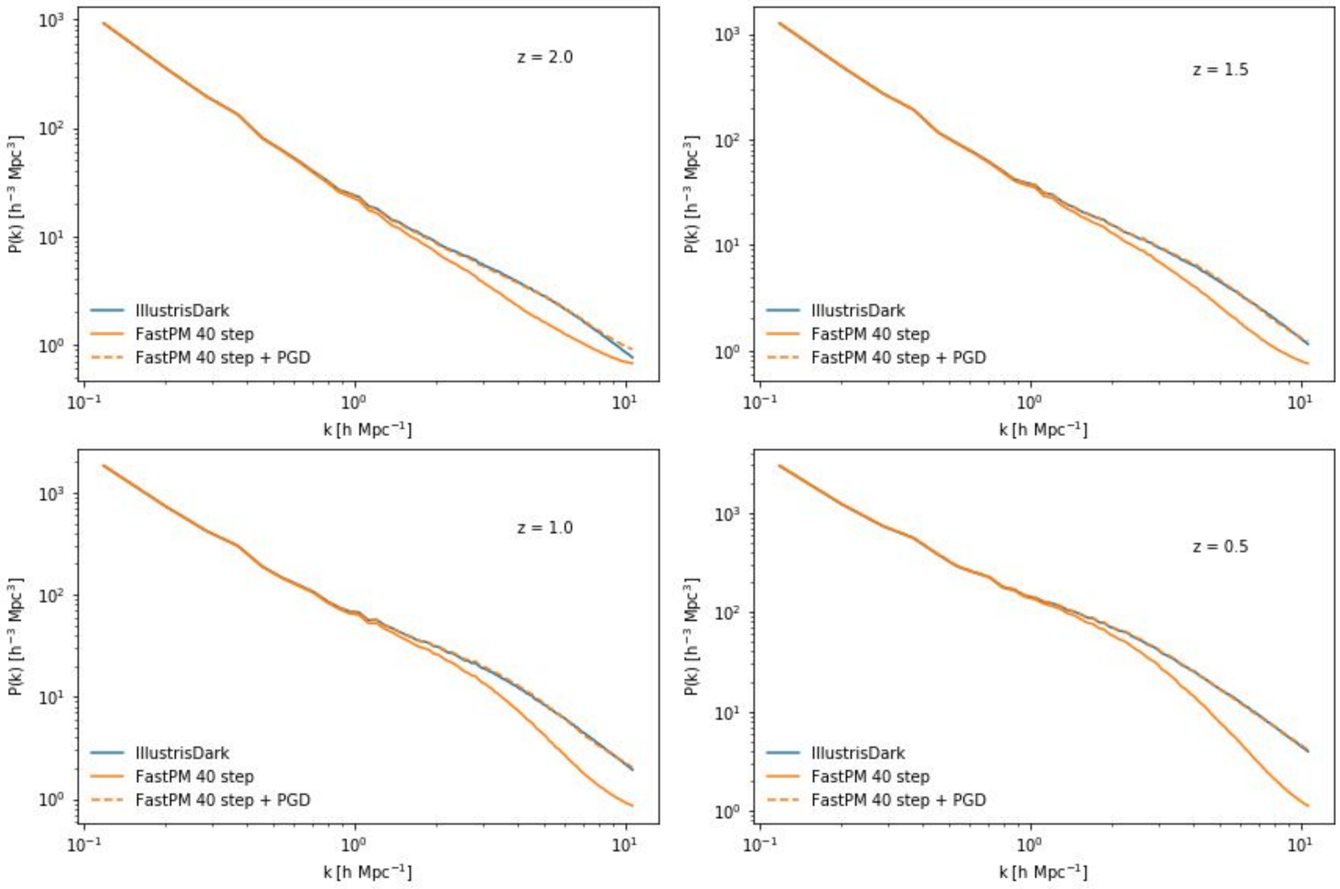
Conclusions

- PGD helps virialize the halos in quasi N-body simulations.
- EGD effectively models the feedback from AGN and supernovae.
- Both of them are able to improve the halo profiles and small scale power spectra.
- The corrections are preformed on particles in configuration space (expect improvement on non-gaussian statistics).
- They are fast, flexible and differentiable (useful for reconstruction of initial conditions (Seljak et al. 2017)). The parameters can be marginalized in data analysis.
- They can be used to improve weak lensing maps (currently working on embedding the model to every time step for light-cone simulation).

Matching High Redshift



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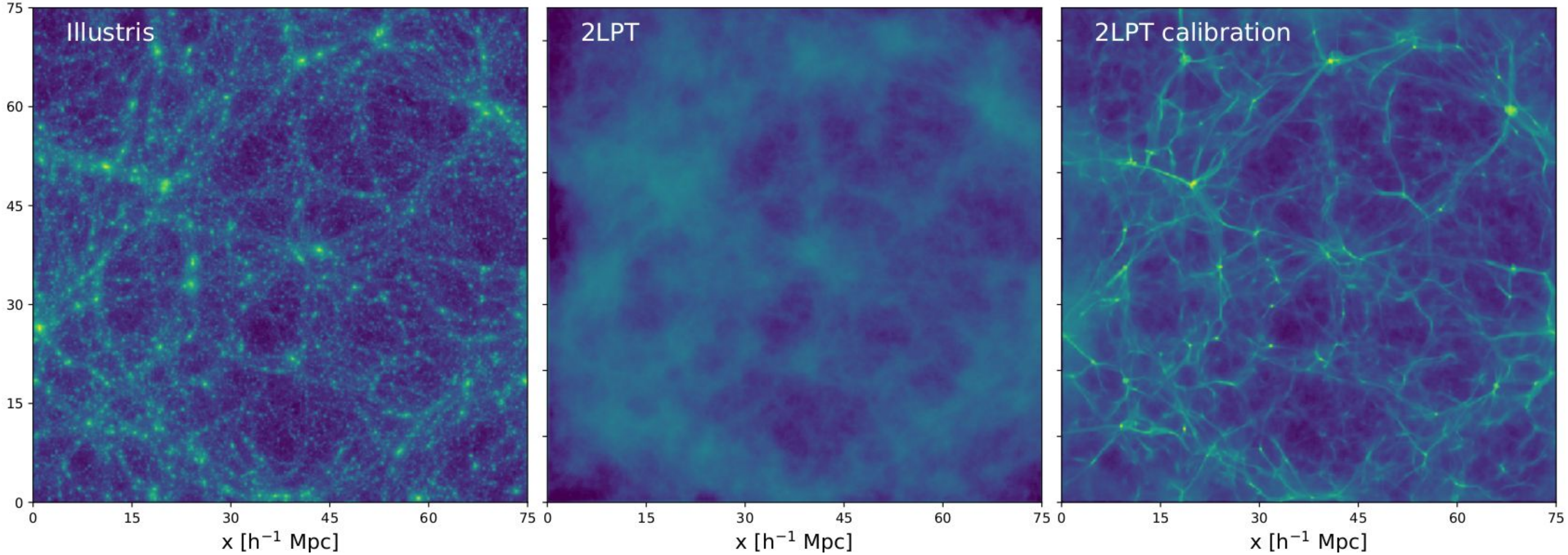
For Fun!



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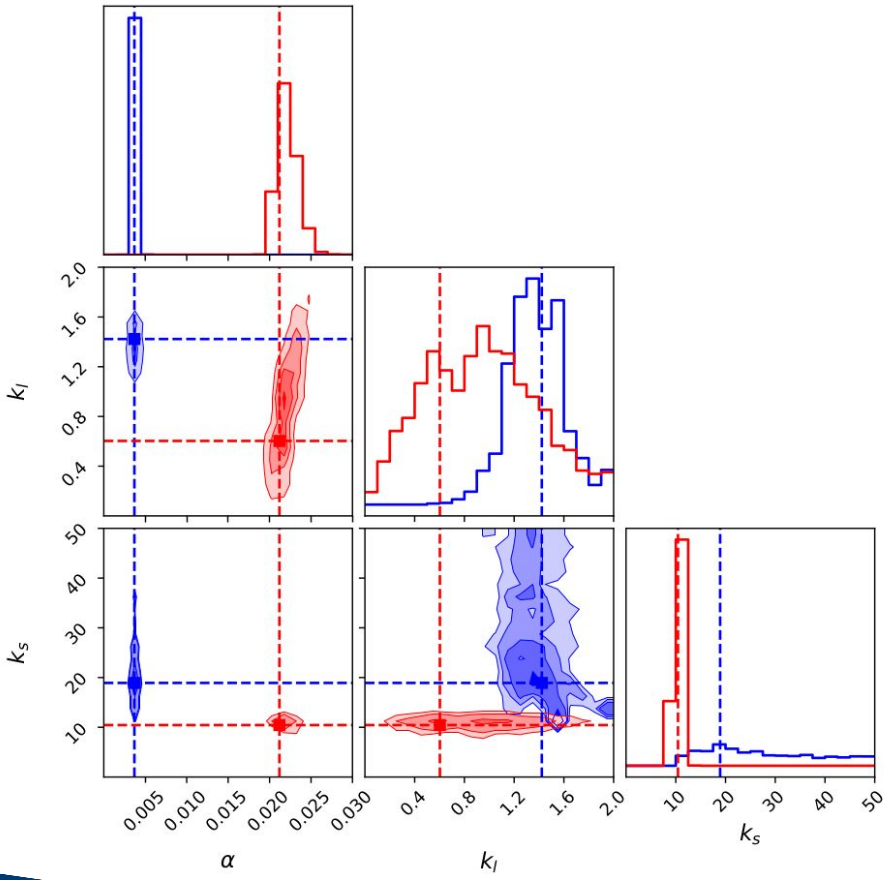
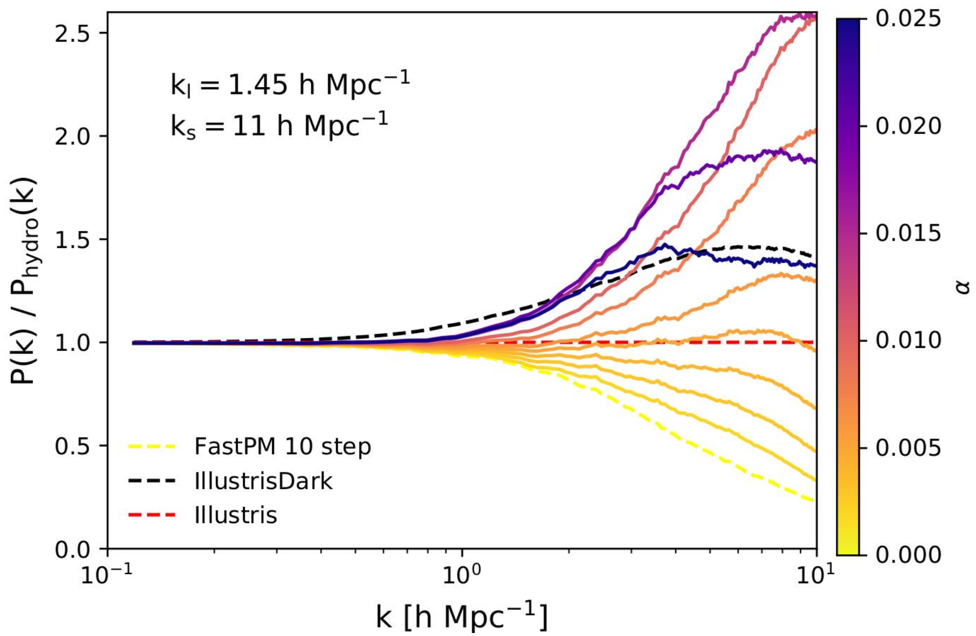
Parameters of PGD





$$\mathbf{S} = -\alpha \nabla \hat{\mathbf{O}}_\mathbf{h} \hat{\mathbf{O}}_\mathbf{l} \phi$$

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Simulation Data Sets

A.1 Illustris-3/IllustrisDark-3

Illustris [13, 22–24] is a series of cosmological hydrodynamic simulations, carried out with the moving-mesh code AREPO [30]. Each simulation evolved a periodic volume 106.5 Mpc on a side, over the redshift range $z = 127$ to the present in a ΛCDM cosmology($\Omega_M = 0.2726$, $\Omega_b = 0.0456$, $H_0 = 70.4\mathrm{km\ s^{-1}\ Mpc^{-1}}$, $n_s = 0.963$, $\sigma_8 = 0.809$). Illustris follows the evolution of the dark matter, cosmic gas, stars and supermassive black holes, with a full set of physical models including primordial and metal-line gas cooling, star formation and evolution, gas recycling, chemical enrichment, supernova feedback and AGN feedback (for more details see [31, 32]).

Illustris has three runs (Illustris-1,2,3) at different resolutions. Since the scale we are interested in this study is larger than $k = 10hMpc^{-1}$, we focus on Illustris-3, which has a mass resolution $m_{\mathrm{DM}} = 2.8 \times 10^8 h^{-1} M_\odot$, $\bar{m}_{\mathrm{baryon}} = 5.7 \times 10^6 h^{-1} M_\odot$ and a force resolution $\epsilon_{\mathrm{DM}} = 5.68\mathrm{kpc}$, $\epsilon_{\mathrm{baryon}} = 2.84\mathrm{kpc}$. As a comparison, we also make use of Illustris-3-Dark, a dark-matter-only analog of Illustris-3.

A.2 FastPM

FastPM is a quasi N-body particle-mesh (PM) solver, in which the drift and kick factors are modified following the Zel'dovich equation of motion so that the correct linear theory growth at large scale can be produced at a limited number of steps. We generate the initial condition with the same random seed and linear power spectrum as Illustris, starting at $z = 9$ and using the second order Lagrangian perturbation theory. However, for simulations with a small volume ($75\mathrm{h}^{-1}\mathrm{Mpc}$) the contribution to the large scale growth due to non-linear evolution at the box scale becomes significant (percent level), which is why the ratio of large scale power in Figure 5 and 12 is a little smaller than 1. In this paper all FastPM simulations have the same resolution as Illustris-3 ($N_{\mathrm{particle}} = 455^3$).

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