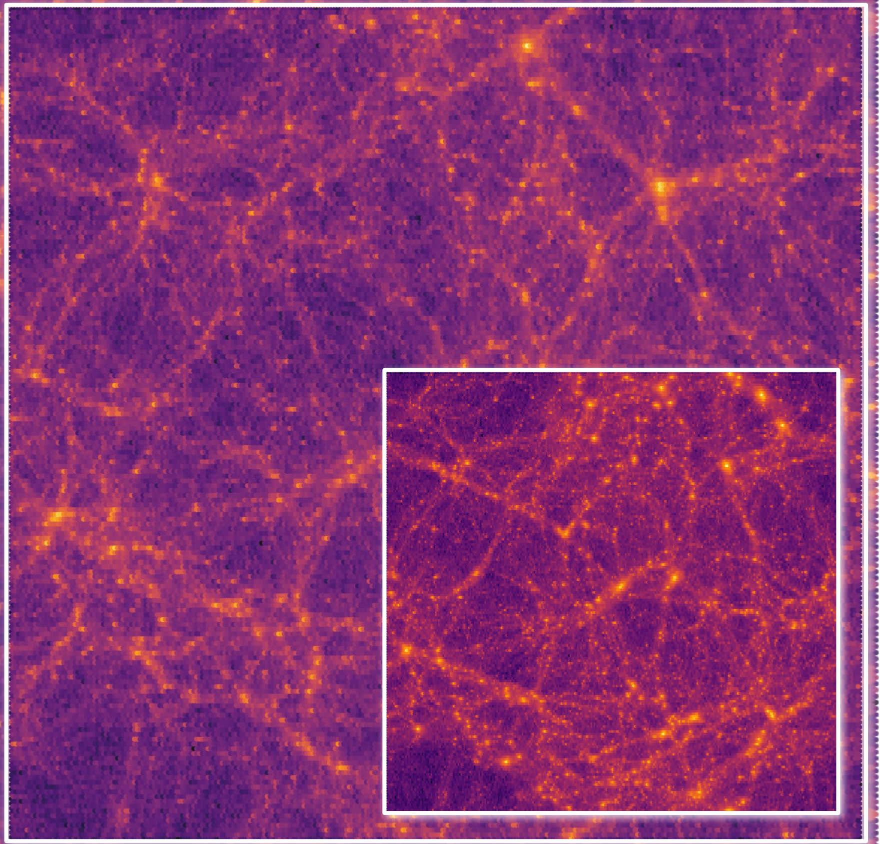
Convergence of Cosmological N-body Simulations



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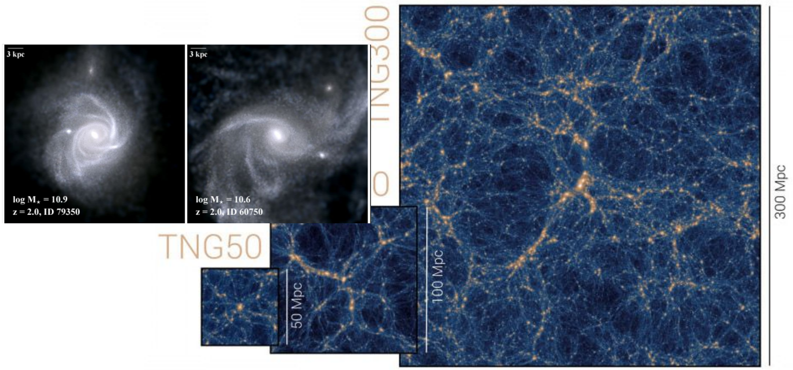
May 4, 2022

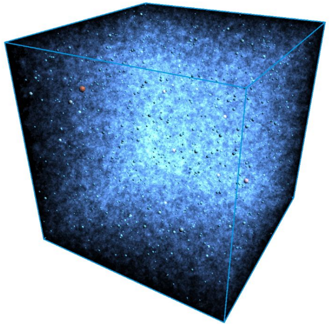
Cosmological Simulations

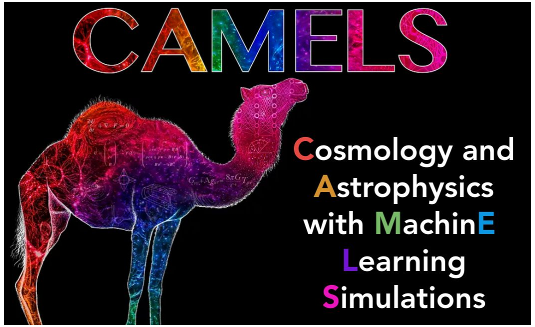
- ***Linear*** structure formation (early times or large scales) - very easy to predict analytically
- ***Non-linear*** structure (late times, small scales) - practically impossible without direct simulation

→ Need very large N-body simulations to study anything < ~10 Mpc



IllustrisTNG collaboration


Outer Rim simulation
Heitmann+ 2019



Villaescusa-Navarro+ 2021

Initial Conditions

Use info from CMB to generate initial conditions

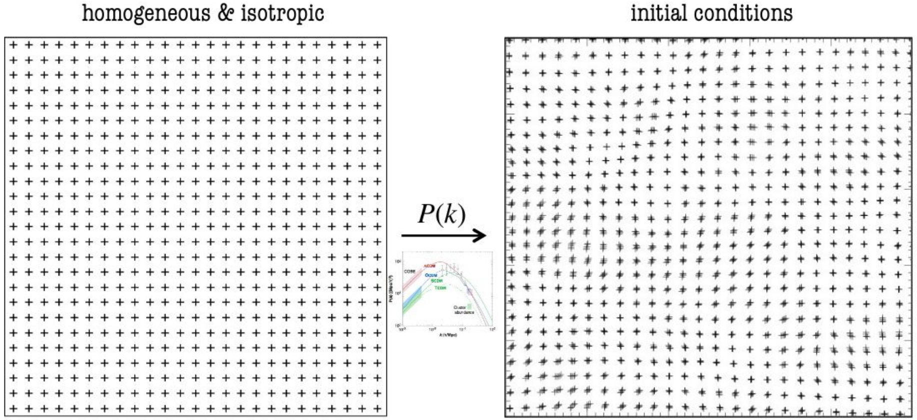


Image from lecture by Alexander Knebe

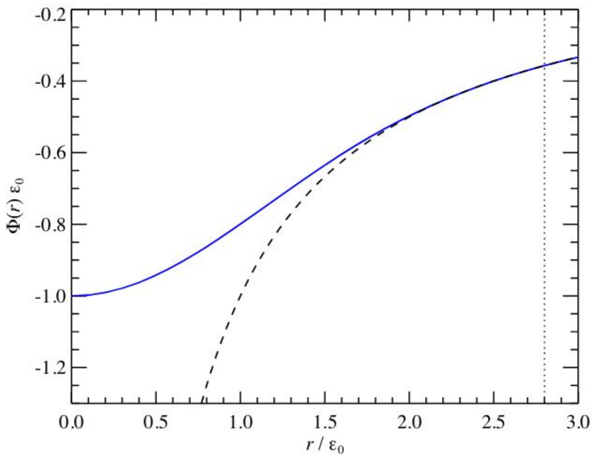
- Zel’dovich Approximation (ZA) - only linear order
- Second-order Lagrangian perturbation theory (2LPT)

Generate initial particle displacements and velocities from an initial power spectrum

Discretization Parameters

- Number of particles *(N)* and box length *(L)* directly control the mass resolution *(m_p)* of the simulation
  - Computational cost directly related to *N*
  - Trade-off between needing large *L* and small m_p

- Softening length *(ϵ)* - very important to avoid artificial close encounters, but puts limit on length resolution
  - Typically specified as a fraction of $L / N^{1/3}$



Gravitational softening in GADGET (Springel+ 2021)

Simulation Runs

Simulations run with GADGET-4

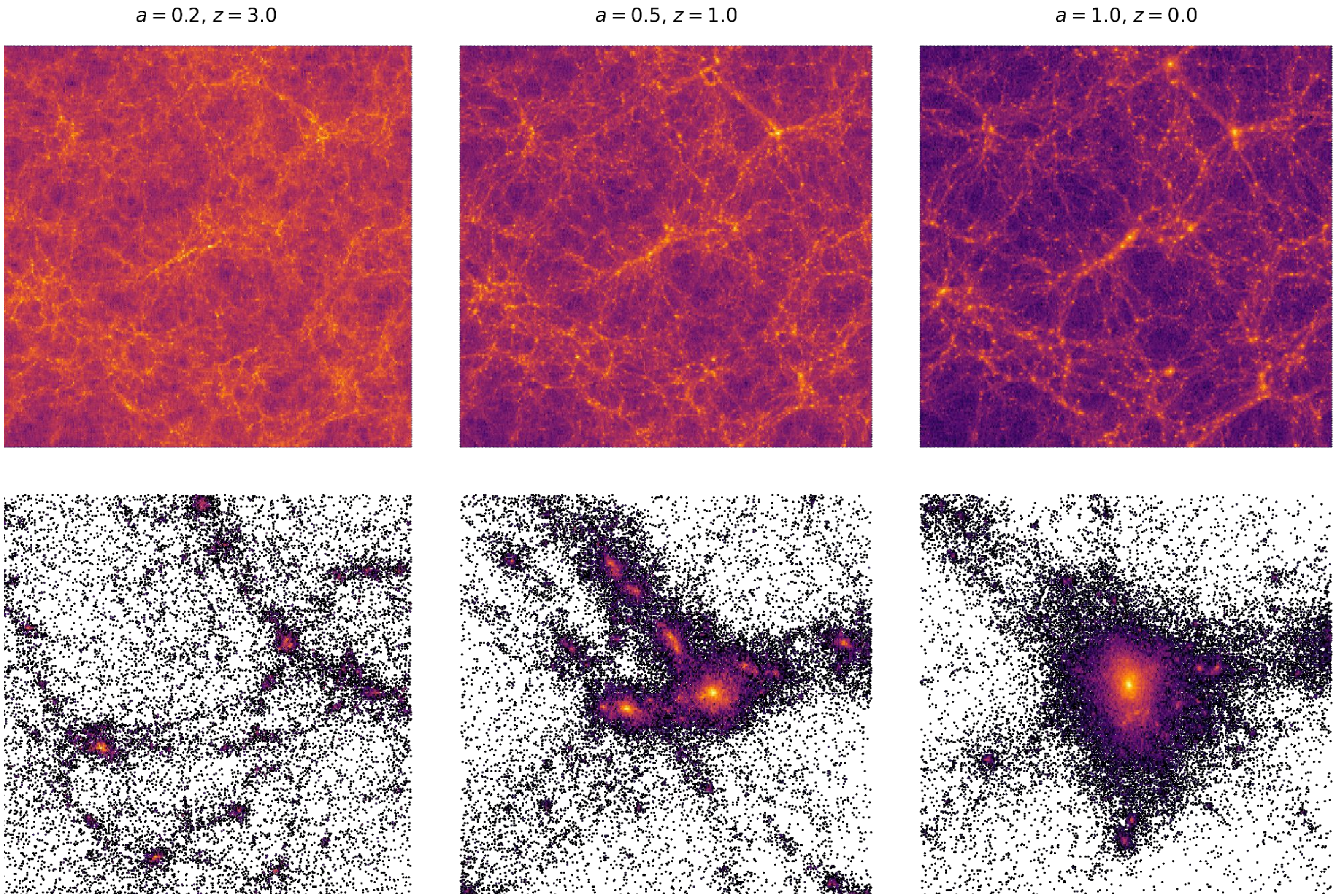
DM only - no hydro

Assume Planck 2018 cosmology ar
same random seed for each run

Simulation outputs: particle snapshots and halo catalogs (FoF and subhalos)

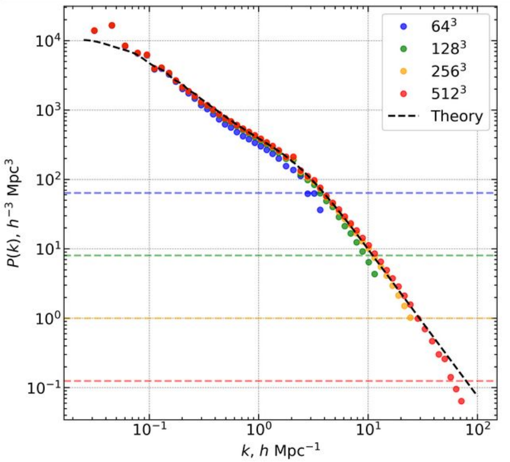
Table 1. Run parameters of the N-body simulations. Parameters that are not listed (e.g. the cosmology) are listed in the text and are kept constant between all of the runs.

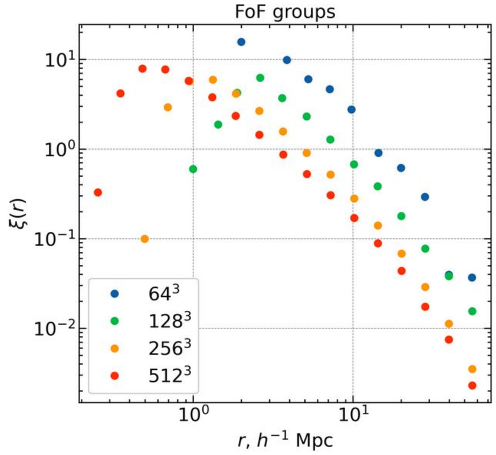
Run #	$L(h^{-1}$ Mpc)	N	$m_p(h^{-1}\ \mathrm{M}_\odot)$	IC type	$\epsilon\ (L/N^{1/3})$	$\epsilon\ (h^{-1}$ kpc)
1	256	64^3	5.6×10^{12}	2LPT	1/42	95
2	256	128^3	7.0×10^{11}	2LPT	1/42	48
3	256	256^3	8.7×10^{10}	2LPT	1/42	24
4	256	512^3	1.1×10^{10}	2LPT	1/42	12
5	256	64^3	5.6×10^{12}	ZA	1/42	95
6	256	128^3	7.0×10^{11}	ZA	1/42	48
7	256	256^3	8.7×10^{10}	ZA	1/42	24
8	256	256^3	8.7×10^{10}	2LPT	1/200	5
9	256	256^3	8.7×10^{10}	2LPT	1/67	15
10	256	256^3	8.7×10^{10}	2LPT	1/29	35
11	256	256^3	8.7×10^{10}	2LPT	1/22	45
13	512	256^3	7.0×10^{11}	2LPT	1/42	48
14	128	256^3	1.1×10^{10}	2LPT	1/42	12
15	64	256^3	1.4×10^{9}	2LPT	1/42	6

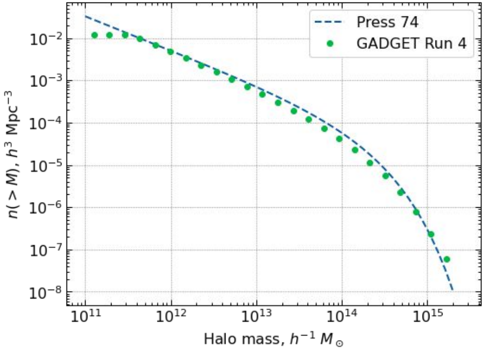

$a = 0.2,\ z = 3.0$
$a = 0.5,\ z = 1.0$
$a = 1.0,\ z = 0.0$

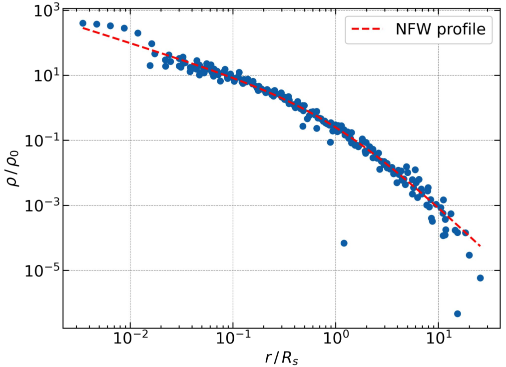
Summary Statistics

- Power spectra
    - Compare to predictions using LSSTDESC Core Cosmology Library
- Correlation functions
- Halo mass functions (HMFs)
    - Compare to Press-Schechter HMF
- Halo density profiles
    - Fit to NFW profile

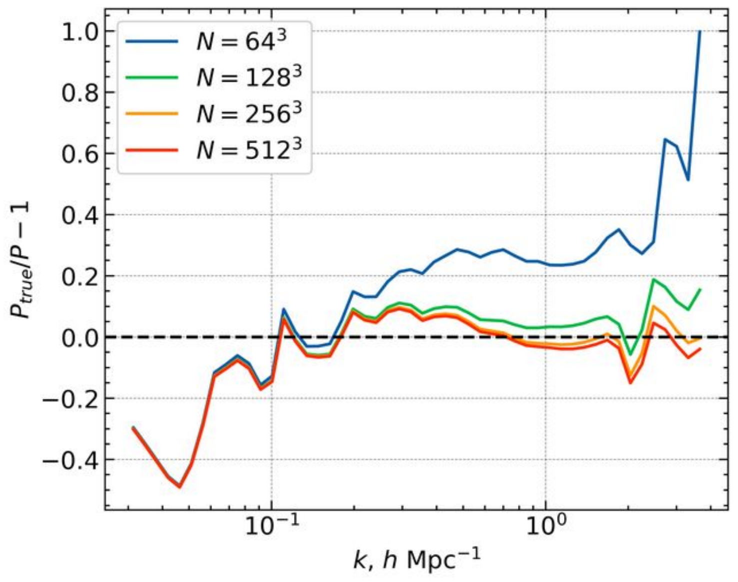




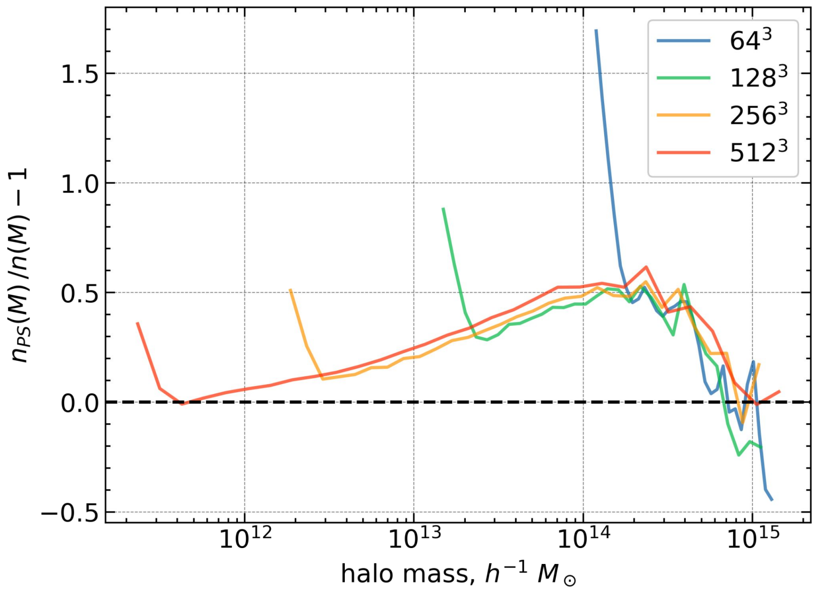




Results: Mass Resolution



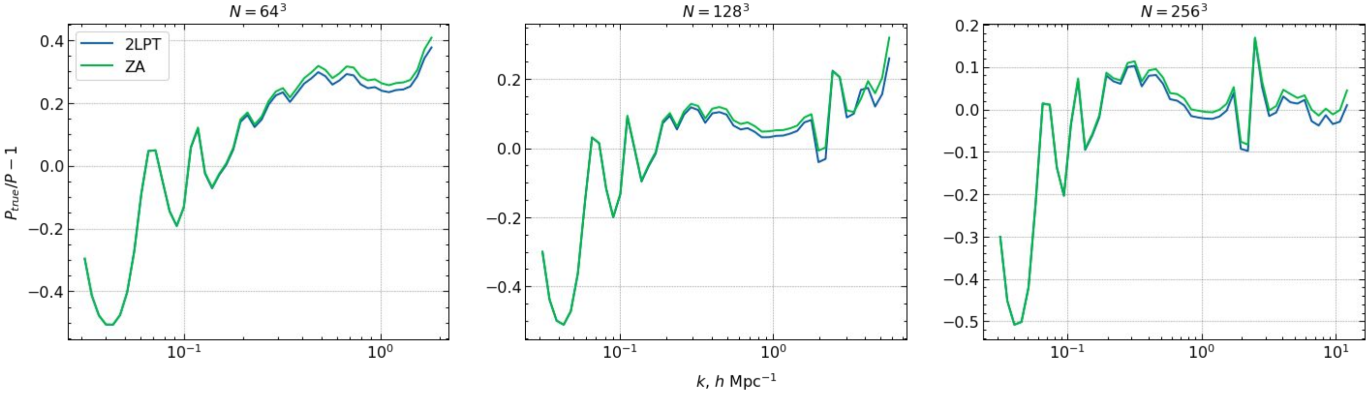
Power spectra



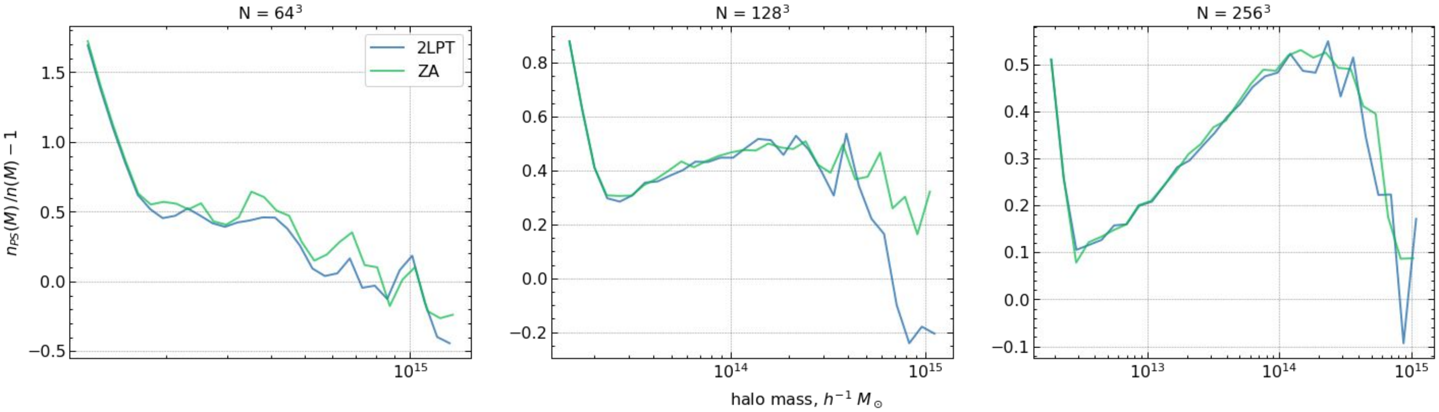
HMFs

Results: Initial Conditions

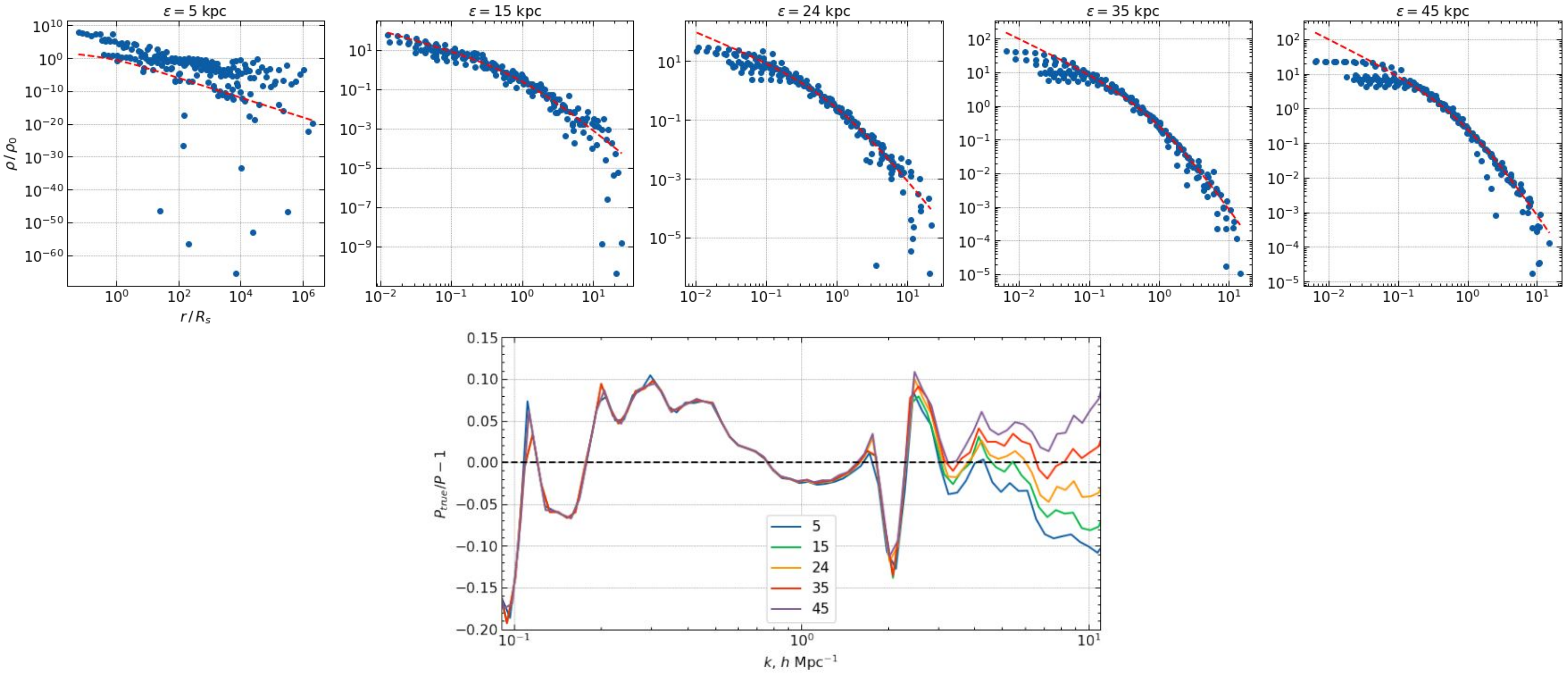
Power spectra



HMFs



Results: Softening Length



Conclusions

- Parameter choices for cosmological simulations:
  - Use 2LPT instead of ZA to generate initial conditions
  - *N* and *L* directly affect the regimes the simulation can probe, secondary concern: accuracy
  - Softening length should usually be ~ 1/40 to 1/30 x mean interparticle separation

- For current and upcoming surveys, huge computational effort is required to produce simulations that can be compared to observations