Cosmological Simulations

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26th May 2009

Outline

Initial Conditions

Initial distribution $\vec{q}$

Initial grid or glass distribution.

Zel'dovich approximation

$$\vec{x}(\vec{q}, a) = \vec{q} + \vec{\Psi}(\vec{q}, a),$$

where $a(t)$ is usual scale factor and $\vec{\Psi}(\vec{q}, a) = b(a)\vec{\Psi}(\vec{q}, a = 1)$; $\vec{\Psi}(\vec{q}, a = 1)$ is the linear gravitational field at the present epoch and is linked to the power spectrum today $P(k, a = 1)$.

Lagrange perturbation theory

Use of higher order approximations[a].

[a] 2LPT initial conditions: R. Scoccimarrio, *Transients from Initial Conditions: A Perturbative Analysis*, arXiv:astro-ph/9711187v1

Transfer function

Power spectrum today

Generate transfer function $T(k; \Omega_m, \Omega_\Lambda, h, \Omega_\nu, T_{CMB}, ...)$[a]
Power spectrum at late times:

$$P(k, a) \propto k^n T^2(k) \left(\frac{D_1(a)}{D_1(a=1)} \right)^2,$$

where n is spectral index and $b(a) = \frac{D_1(a)}{D_1(a=1)}$ is normalized linear growth factor.

[a] using CMBFAST: U. Seljak & M. Zaldarriaga, *A line of sight approach to Cosmic Microwave Background anisotropies*, ApJ 469:437-444,1996

Time integration

Gadget-2 code

Gadget-2 integration code is freely available:
`http://www.mpa-garching.mpg.de/gadget/`

- TreeSPH code: a N-body collisionless fluid and an ideal gas
- Different particle types (i.e. gas, dark matter, halo, disk, buldge, stars, ...)
- Cosmological expansion
- Massively parallel
- ...

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Time consumption

In 500 Mpc/h boxsize.

# of particles	time $[min]$	# of processors
128^3	200	4^a
128^3	112	8^b
256^3	1500	8

[a] AMD Opteron(tm) Processor 275 2199 MHz; (pavla)
[b] Intel(R) Xeon(R) X5365 3 GHz; (krasner)

Visualization

visualization software

- SPLASH (by Daniel Price)
- IFRIT (by Nick Gnedin)

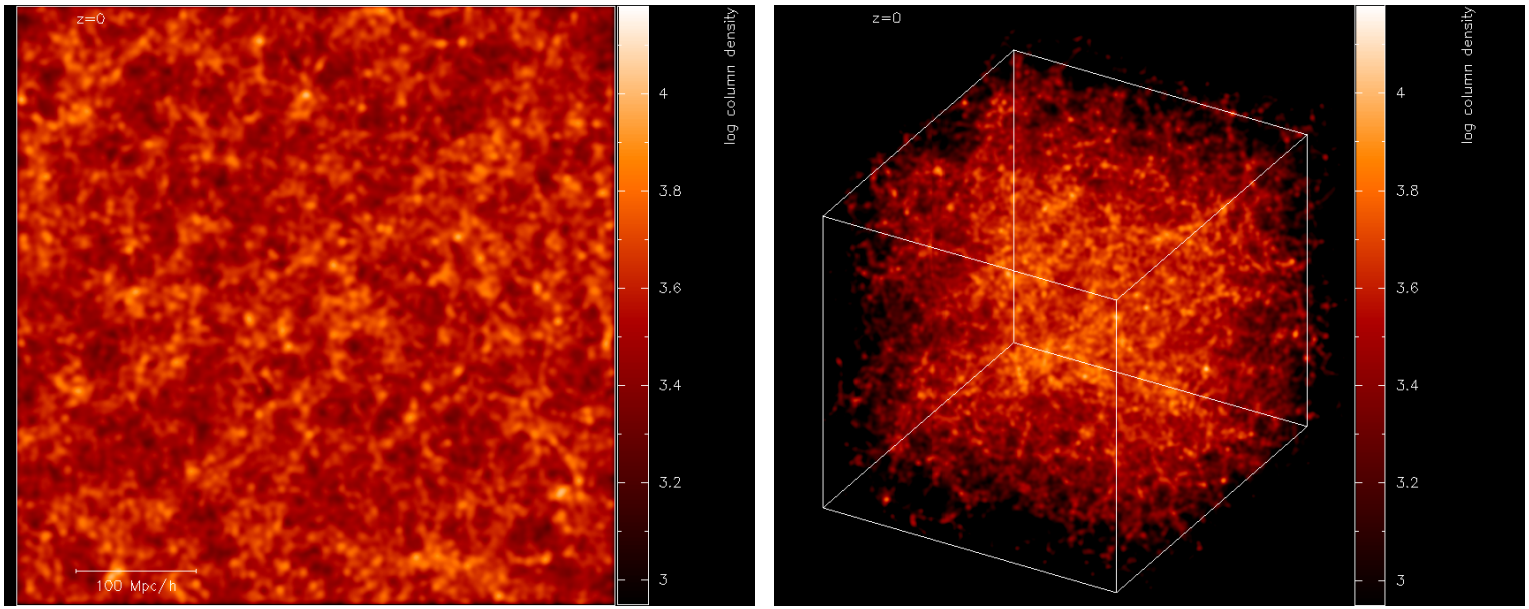

Figure: cosmologcial simulations with boxsize 500 Mpc/h and 256^3 particles. Images created with SPLASH: Price (2007), PASA, 24, 159-173 (arXiv:0709.0832)

Physics

Physics of results

- Structure and sub-structure evolution
- Power spectrum test
- Mass function
- Halo's density profiles
- Halo's angular momentum
- Cluster formation (and galaxy formation on smaller scales)
- Lyman α forest and study of IGM
- Peculiar velocities
- Weak lensing and polarization

Physics

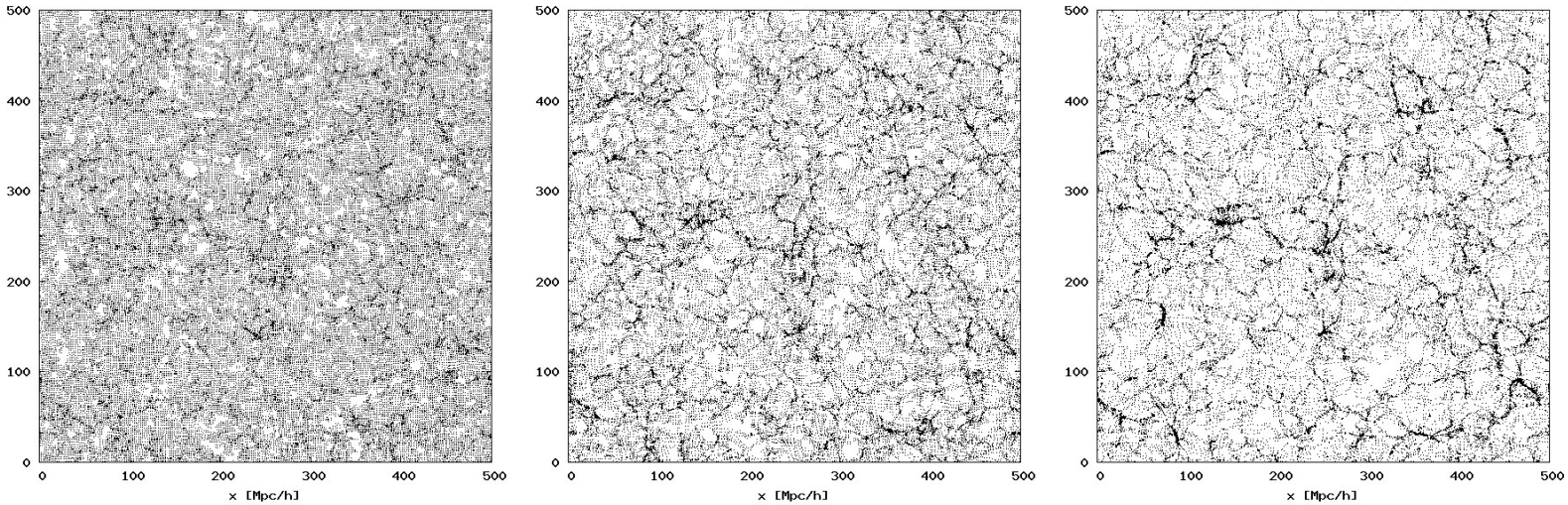

Figure: slice through simulation at 250 Mpc/h, 2 Mpc/h thick. Structure evolution $z = 4.3$ (*left*), $z = 1.02$ (*middle*) and $z = 0$ (*right*). Simulations was in a 500 Mpc/h box size with 128^3 dark matter particles.

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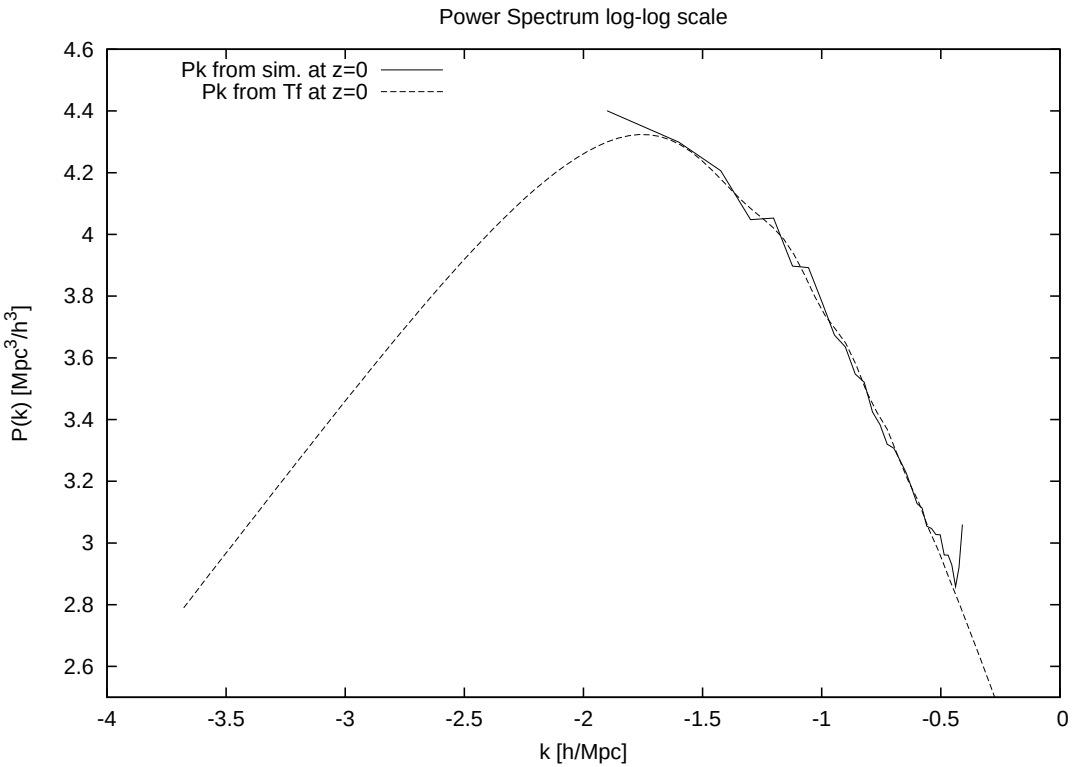

$$k_{eq} = \sqrt{\frac{2\Omega_m H_0^2}{a_{eq}}}$$

Figure: Power spectrum from simulation with box size 500 Mpc/h and 128^3 particles.

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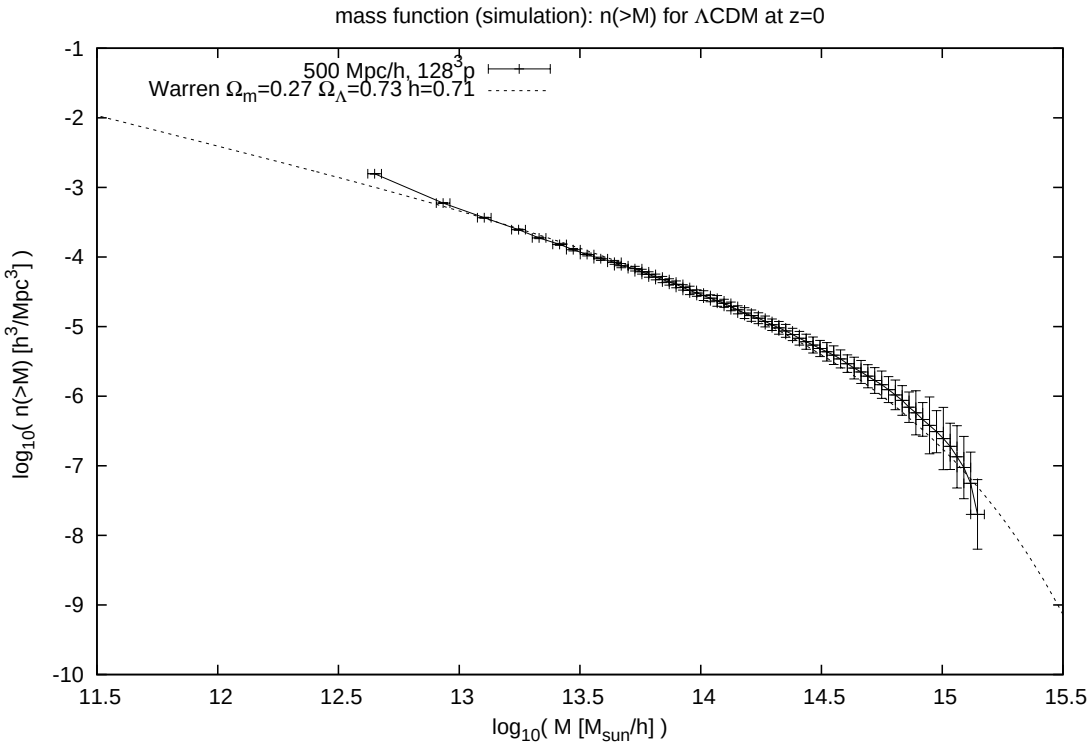

$$\delta(\vec{r}) = \frac{\rho(\vec{r}) - \rho_c}{\rho_c},$$
$$\delta_c = 1.689,$$

for spherical collapse. $\delta(\vec{r}) > \delta_c$ $\longrightarrow$ virialised object Press-Schechter theory of gaussian distribution.

Figure: Mass function from simulation with box size 500 Mpc/h and 128^3 particles with theoretical prediction Warren et al.

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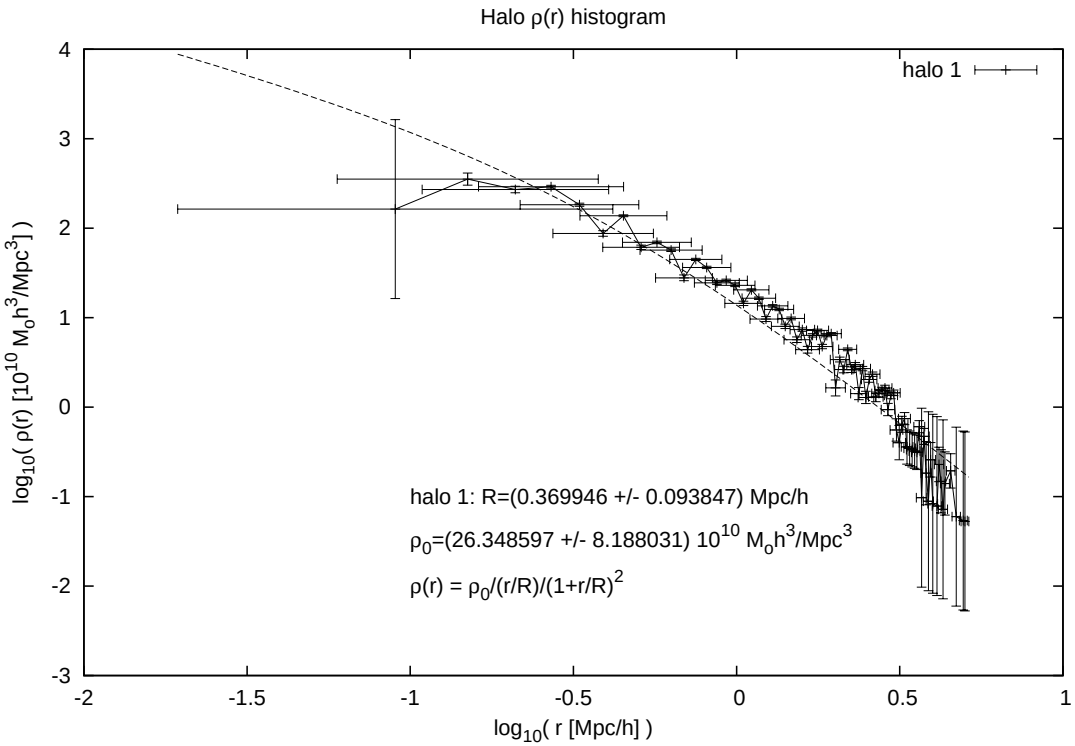

Navarro-Frenk-White (NFW)

$$\rho(r) = \frac{\rho_0}{\frac{r}{R}\left(1+\frac{r}{R}\right)^2}$$

Figure: Density profile of largest halo in 500 Mpc/h boxsize and 128^3 simulation compared to NFW profile.

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- R. Scoccimarrio, *Transients from Initial Conditions: A Perturbative Analysis*, arXiv:astro-ph/9711187v1
- V. Springel, *The cosmological simulation code GADGET-2*, Mon. Not. R. Astron. Soc. **364**, 1105–1134 (2005)
- D. Price, *SPLASH: An interactive visualisation tool for Smoothed Particle Hydrodynamics simulations*, Publ. Astron. Soc. Aust., **24**, 159-173, 2007
- R. E. Smith et al. (The Virgo Consortium), *Stable clustering, the halo model and nonlinear cosmological power spectra*, arXiv:astro-ph/0207664v2, 11 Jun, 2003
- S. Dodelson, *Modern Cosmology*, Academic Press, ISBN-13: 978-0-12-219141-1