Time evolution of bias —
applying different methods

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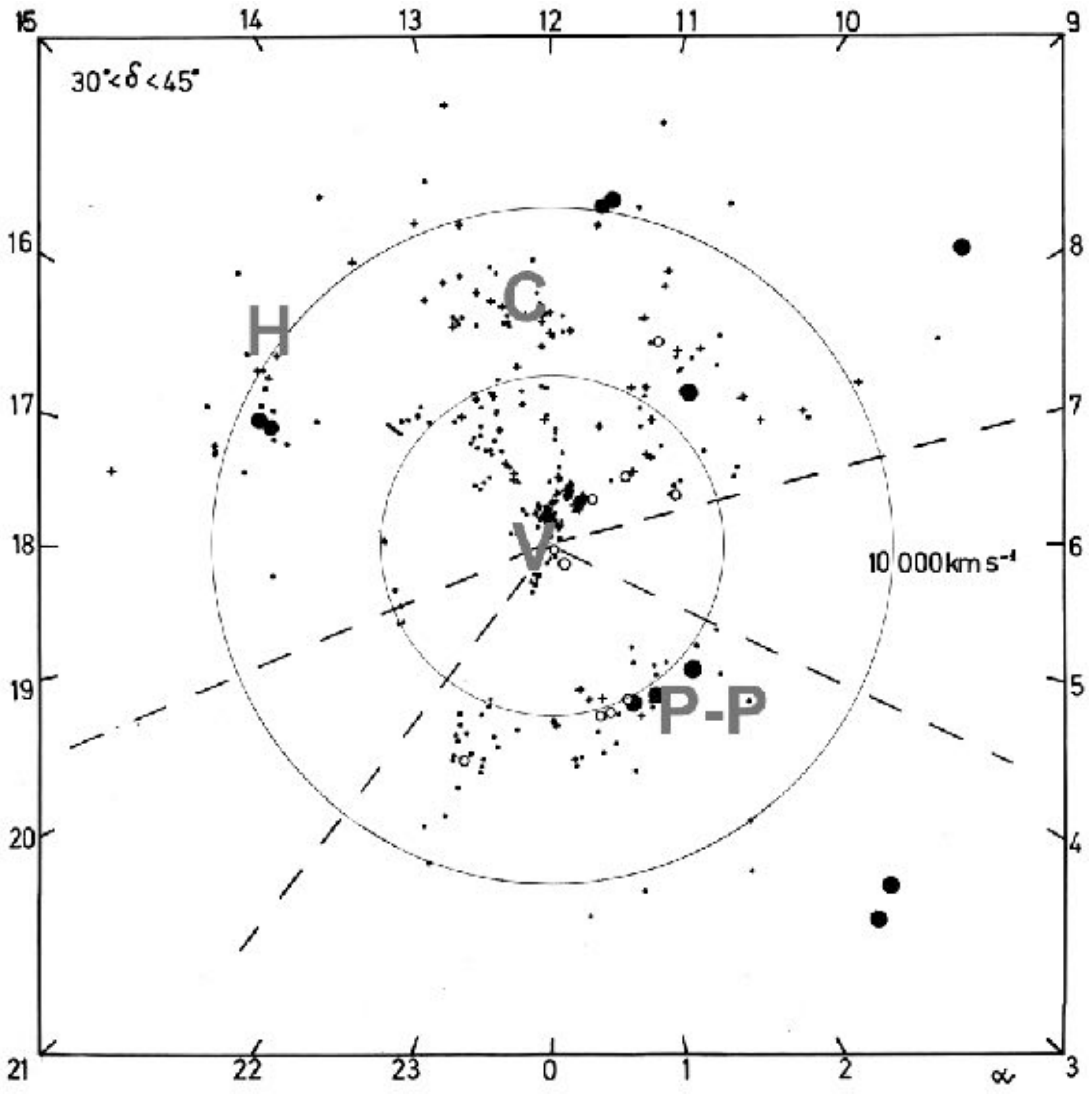
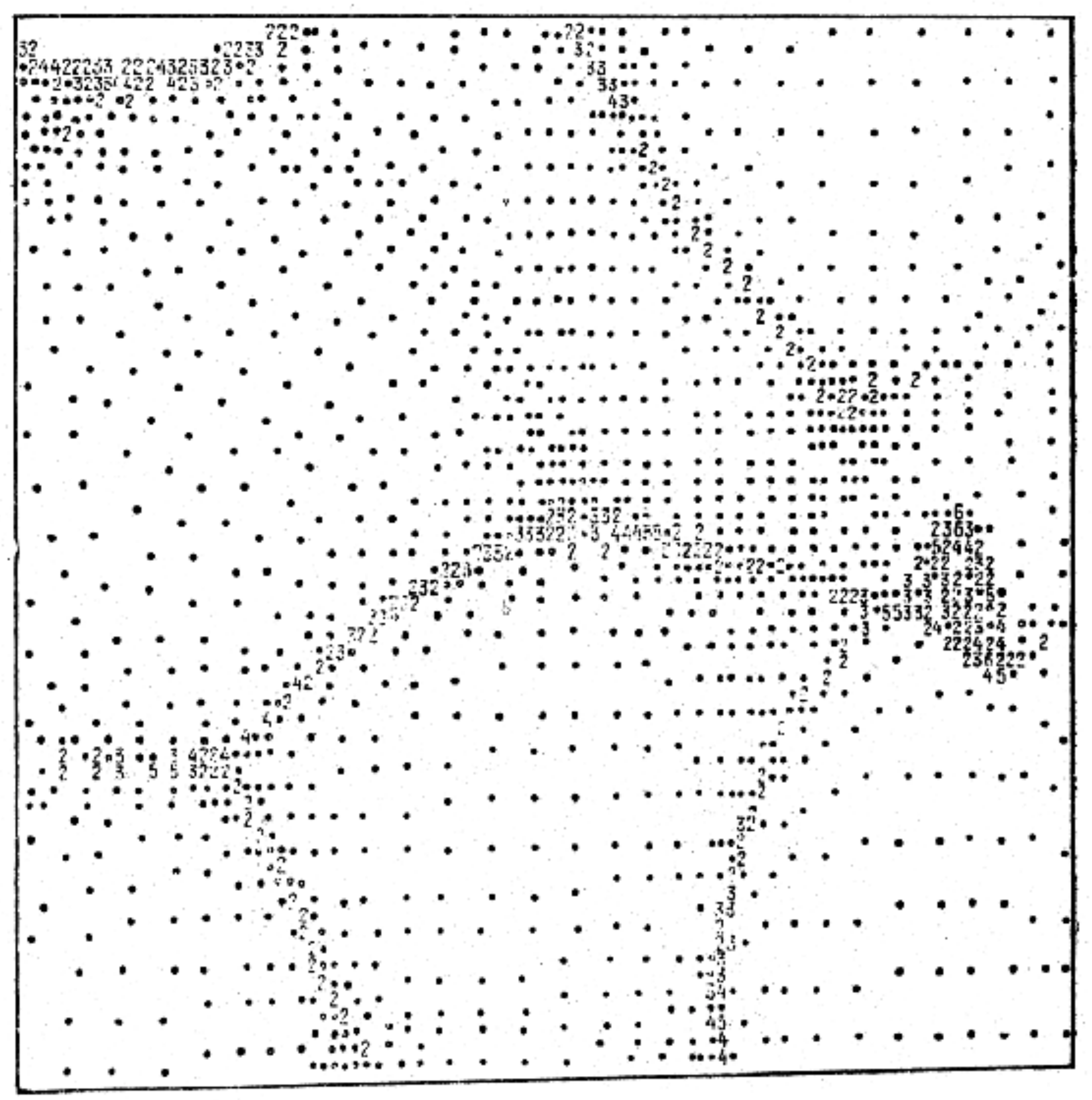
Observations vs simulations



Distribution of galaxies in Perseus-Pisces region Jõeveer, Einasto (1977)

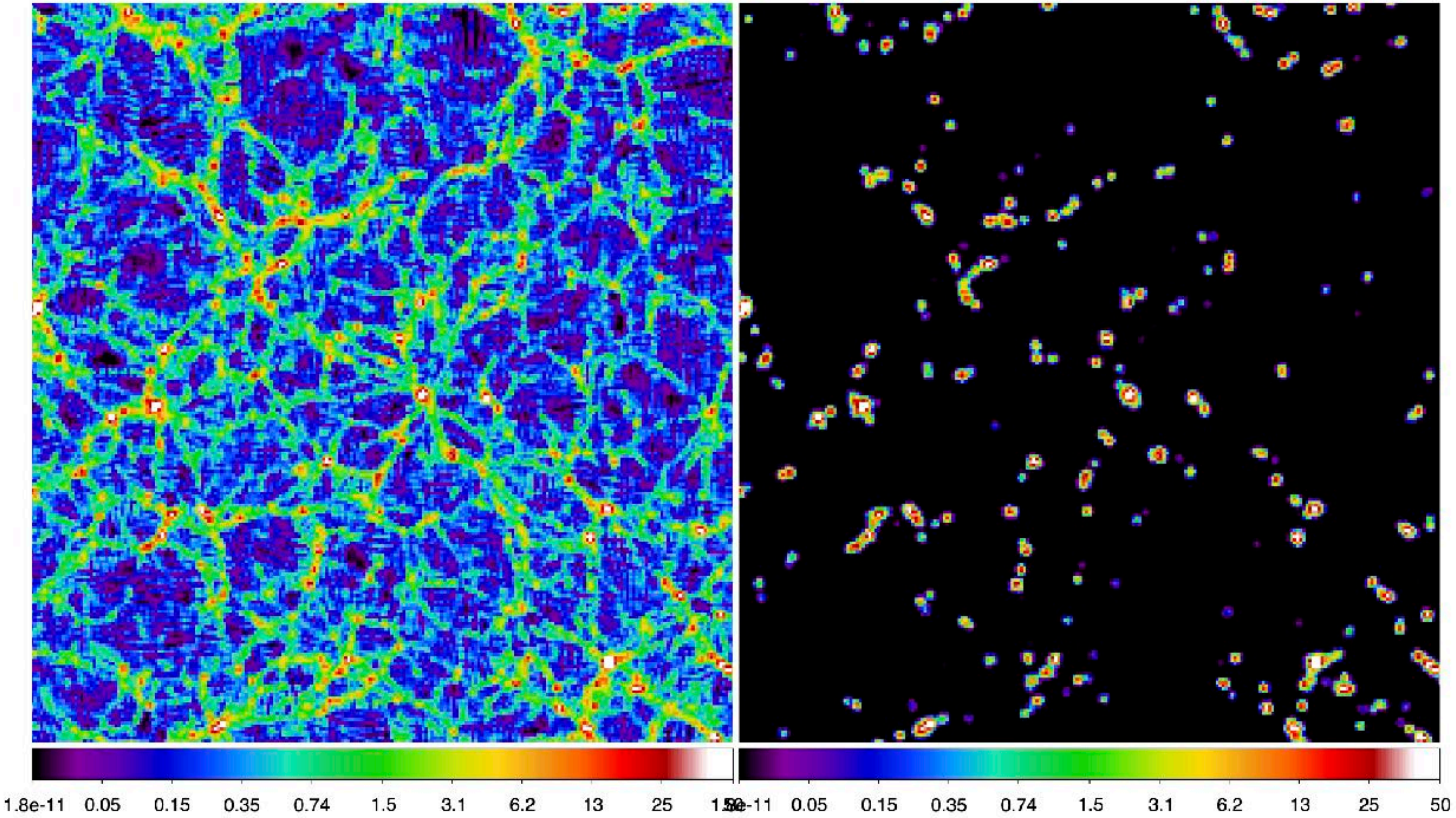


Doroshkevich, Shandarin simulation (1976)

Voids are not empty. Gravity works slowly - there must by dark matter in voids

Difference in the distribution of DM and galaxies, and galaxies of various luminosity is the **biasing phenomenon** (Bahcall, Soneira 1983, Kaiser 1984).

LCDM DM density fields with various particle density limits



3D slice of 512 Mpc/h density field, thickness 1 Mpc/h. Left with all DM particles.
Right with particles with densities $\rho \geq \rho_0 = 10$.Here most of the volume has zero density.

Measuring biasing

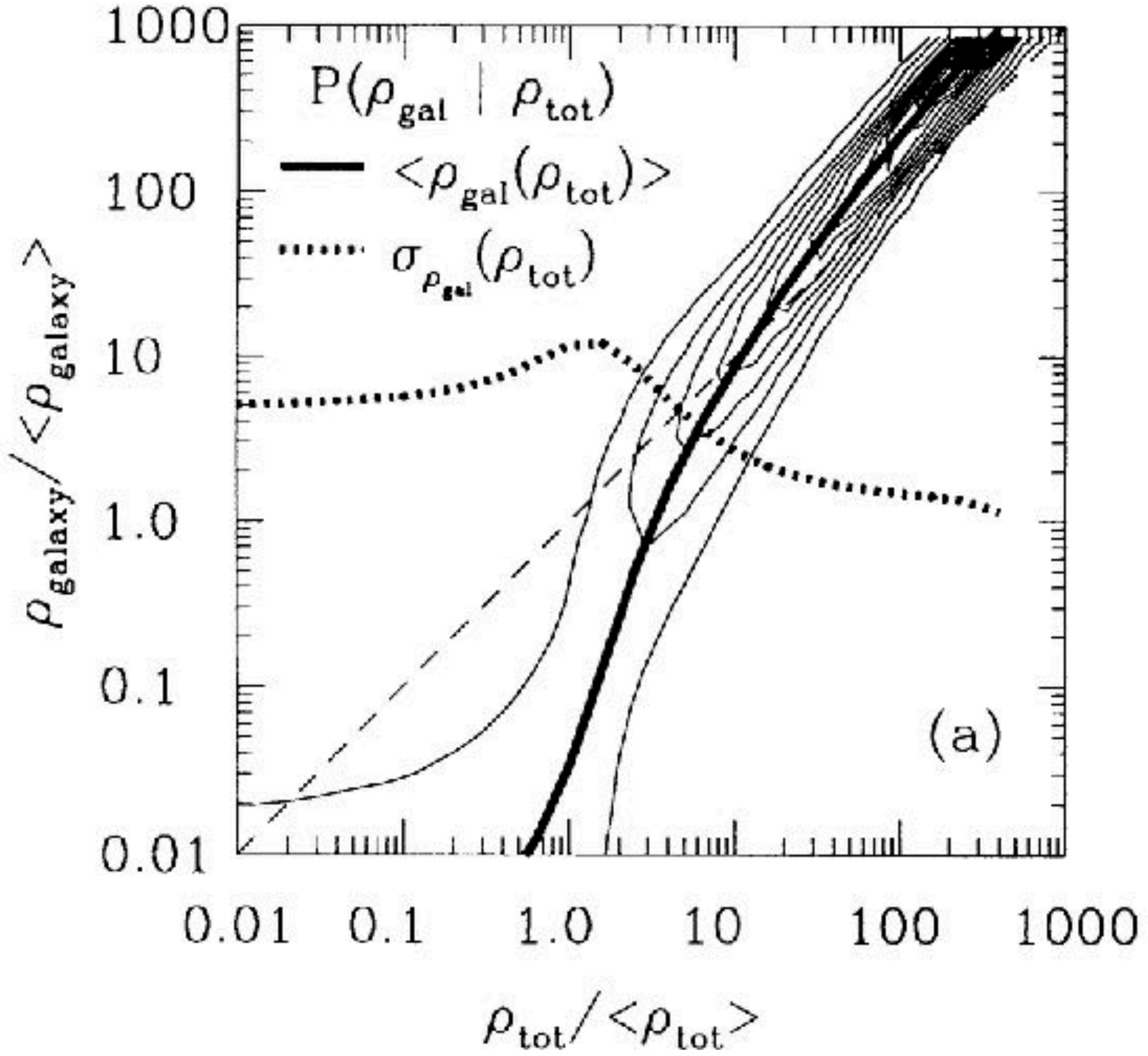
density fields $$b(x) = \delta_g(x)/\delta_m(x)$$

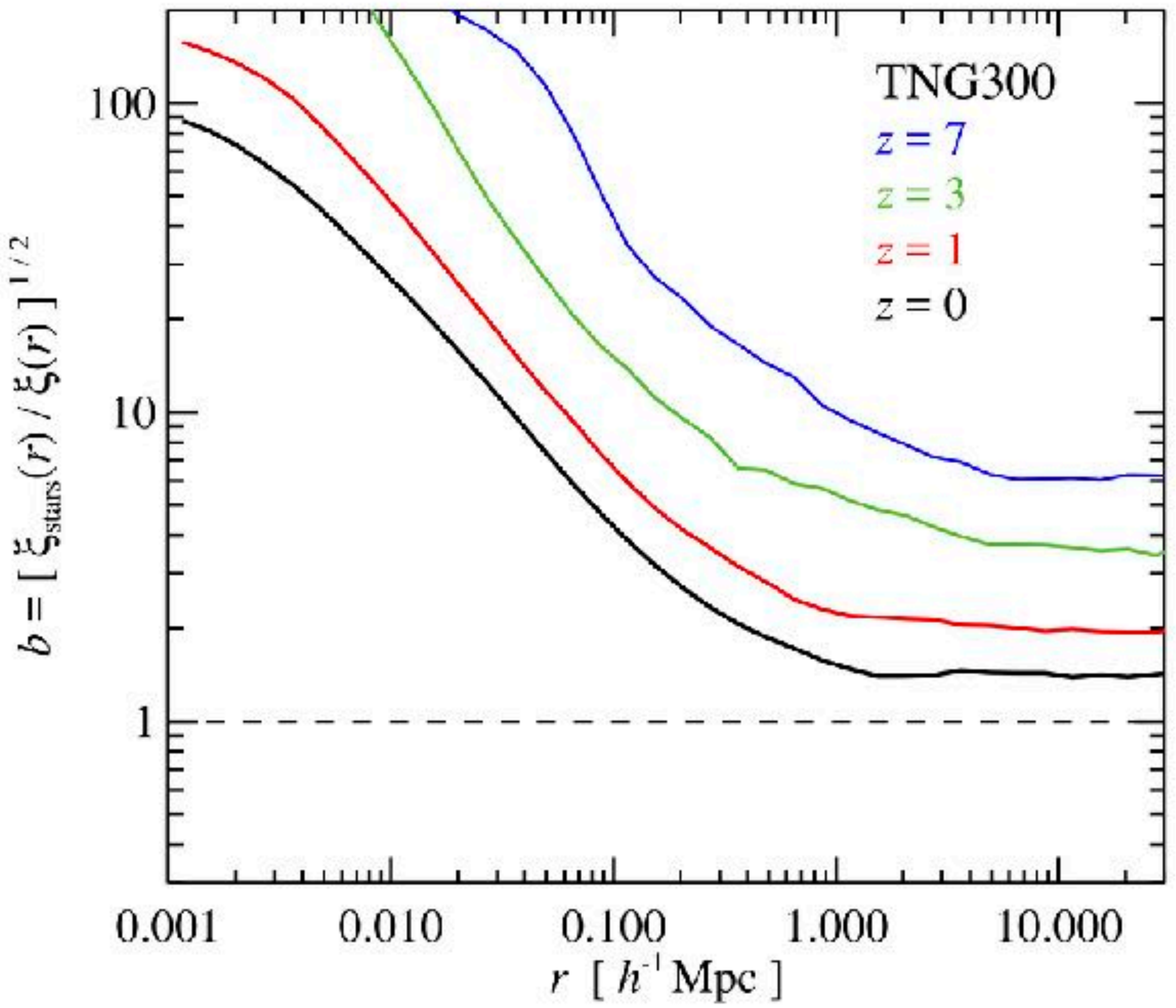
correlation functions $$b^2(r) = \xi_g(r)/\xi_m(r)$$

power spectra $$b^2(k) = P_g(k)/P_m(k)$$

All methods use density field, the first method has the difficulty that in real samples in a large fraction of the volume the density is zero. CF and power spectrum methods are favourable.

Results of early biasing studies





Left: Cen, Ostriker (1992) - Galaxies form only in high-density environment, $\rho \geq 1$, and matter in low-density regions does not contain galaxies. Bias parameter of galaxies at present epoch is $b \approx 1.6$.

Right: Springel et al. (2018) - bias parameter depends on age z, at present epoch $b \approx 1$, i.e. galaxies follow matter.

Why such discrepancy?

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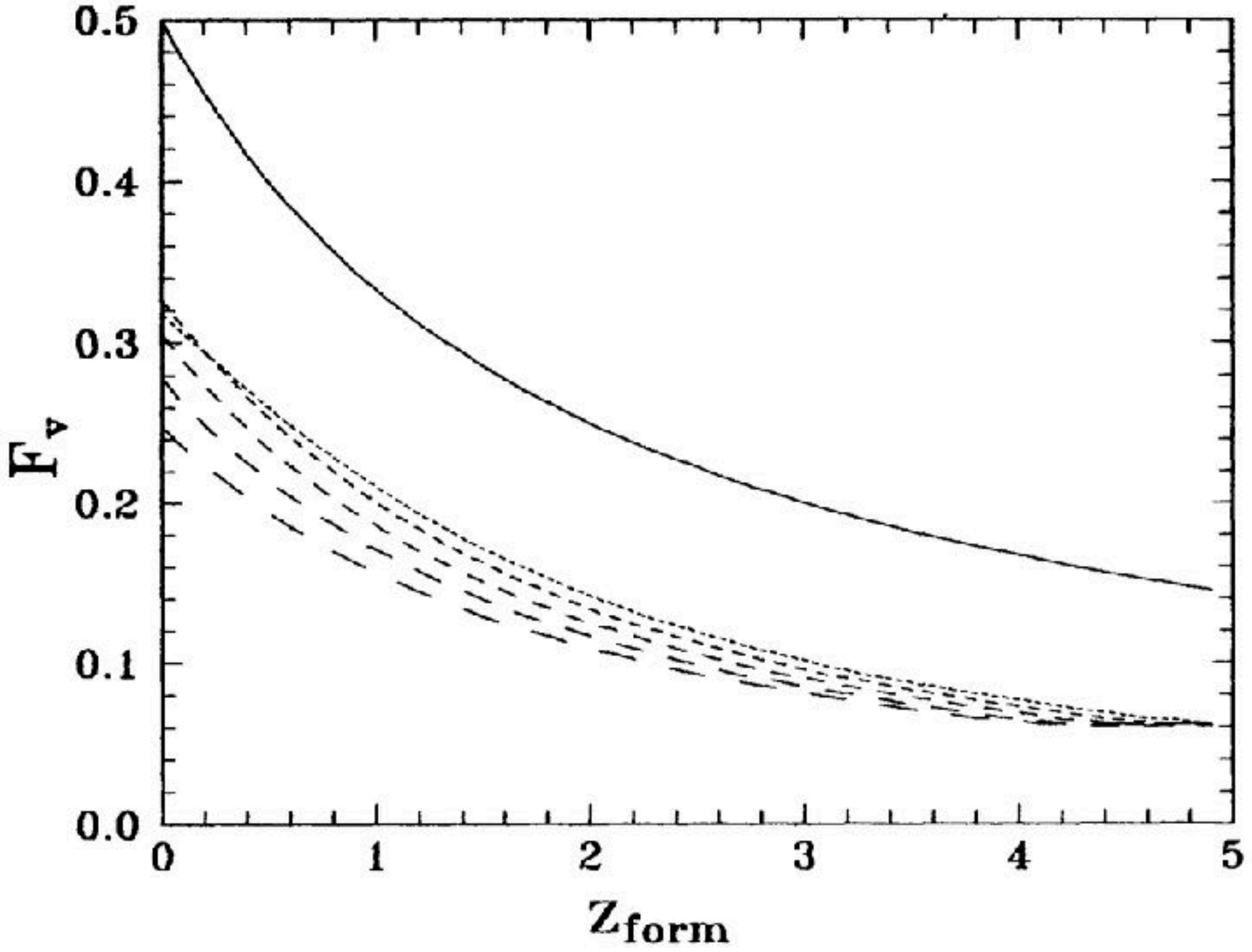
Bias parameter and fraction of matter in voids

Einasto, Saar et al (1994) investigated the evolution of the fraction of matter in voids. The fraction decreases with time and depends on the effective formation epoch z. The bias parameter is connected to the fraction of matter in high-density regions, F_c:

$b = 1/F_c$.

By definition $F_v = 1 - F_c$.



This study shows that the fraction of matter in voids decreases with time exponentially, but never reaches zero level. Thus $F_c < 1$ and $b > 1$ for all epochs z.

Fractions of matter in voids and in the clustered population can be followed by numerical simulations, and determined independently on bias values found from correlation function analysis.

Goals of the present study

- Study the evolution of bias parameters with time using IllustrisTNG numerical simulations TNG100 TNG300
- We apply correlation functions to investigate clustering properties of the cosmic web, using two kind of test objects - simulated galaxies and DM particles of the clustered population.
- Find bias functions for galaxies selected in the M_r band, and for DM particles in regions of local density $\rho \geq \rho_0$, where the density limit ρ_0 is selected using the whole density at given location (DM, stellar and baryonic gas).
- Find the evolution of bias parameters for galaxies and DM particles.
- Find the fraction of matter in the clustered population and compare with bias parameters found with both methods.

General goal: understanding bias evolution of galaxies and DM, focusing on differences between bias parameters of galaxies and clustered DM particles.

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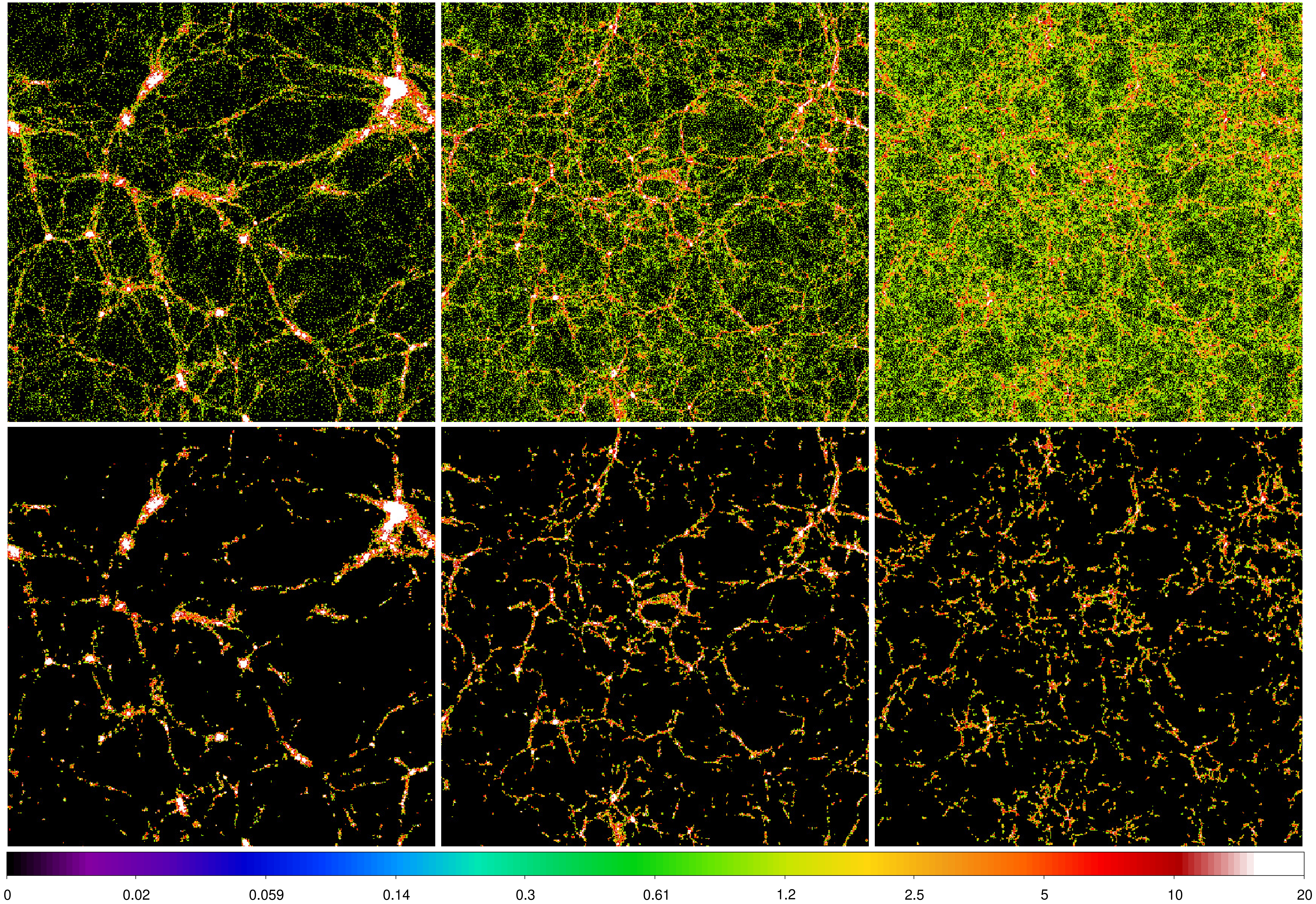
Density fields of DM and clustered population

TNG100 density fields
Top all DM,
Bottom clustered DM
$\rho \geq \rho_0$

Left to right z=0, 2, 5

In clustered density field over 90% of cells have zero density at all z, the fraction of filled cells F_c increases with time, due to outflow of non-clustered matter from voids.



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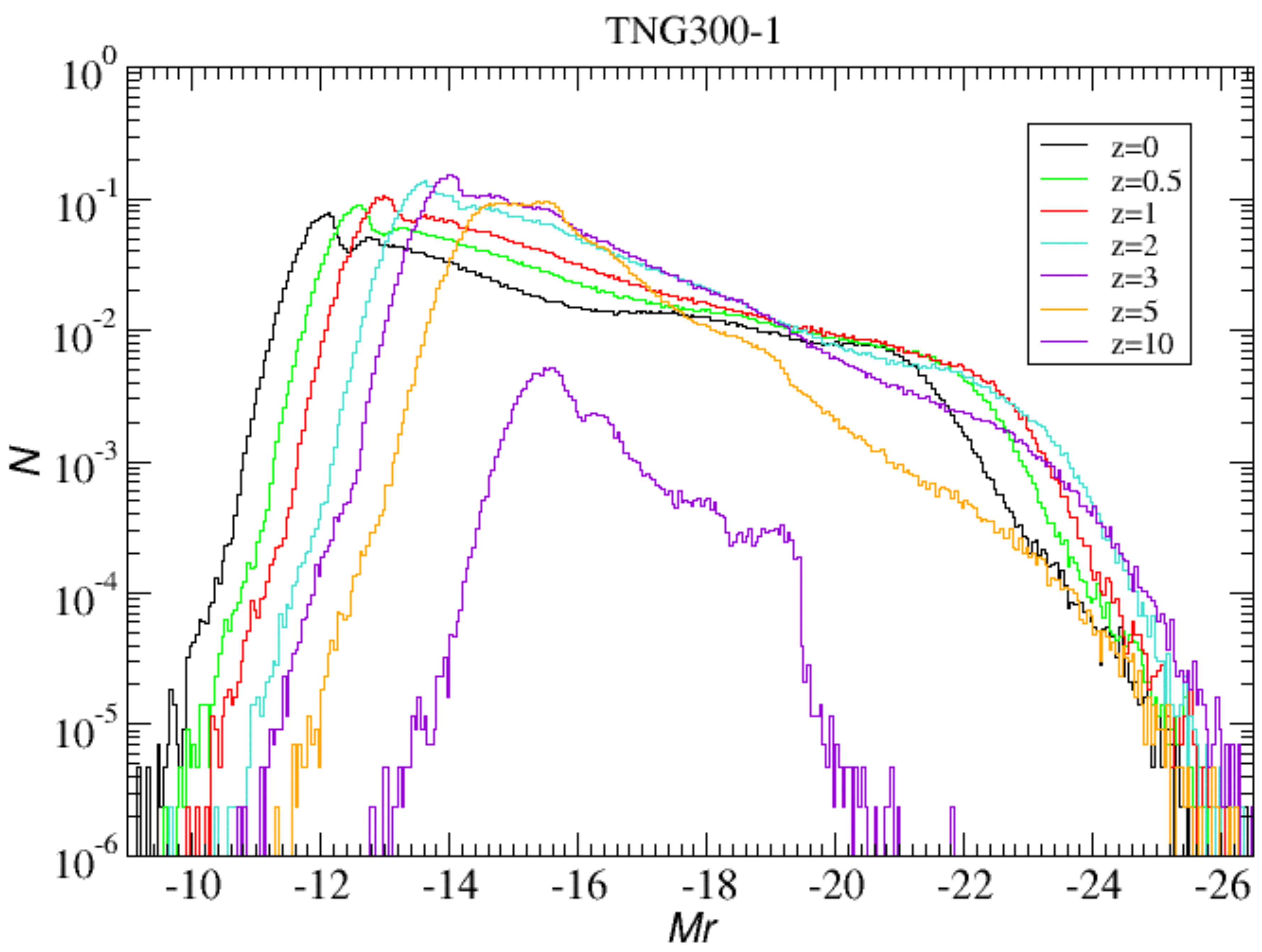
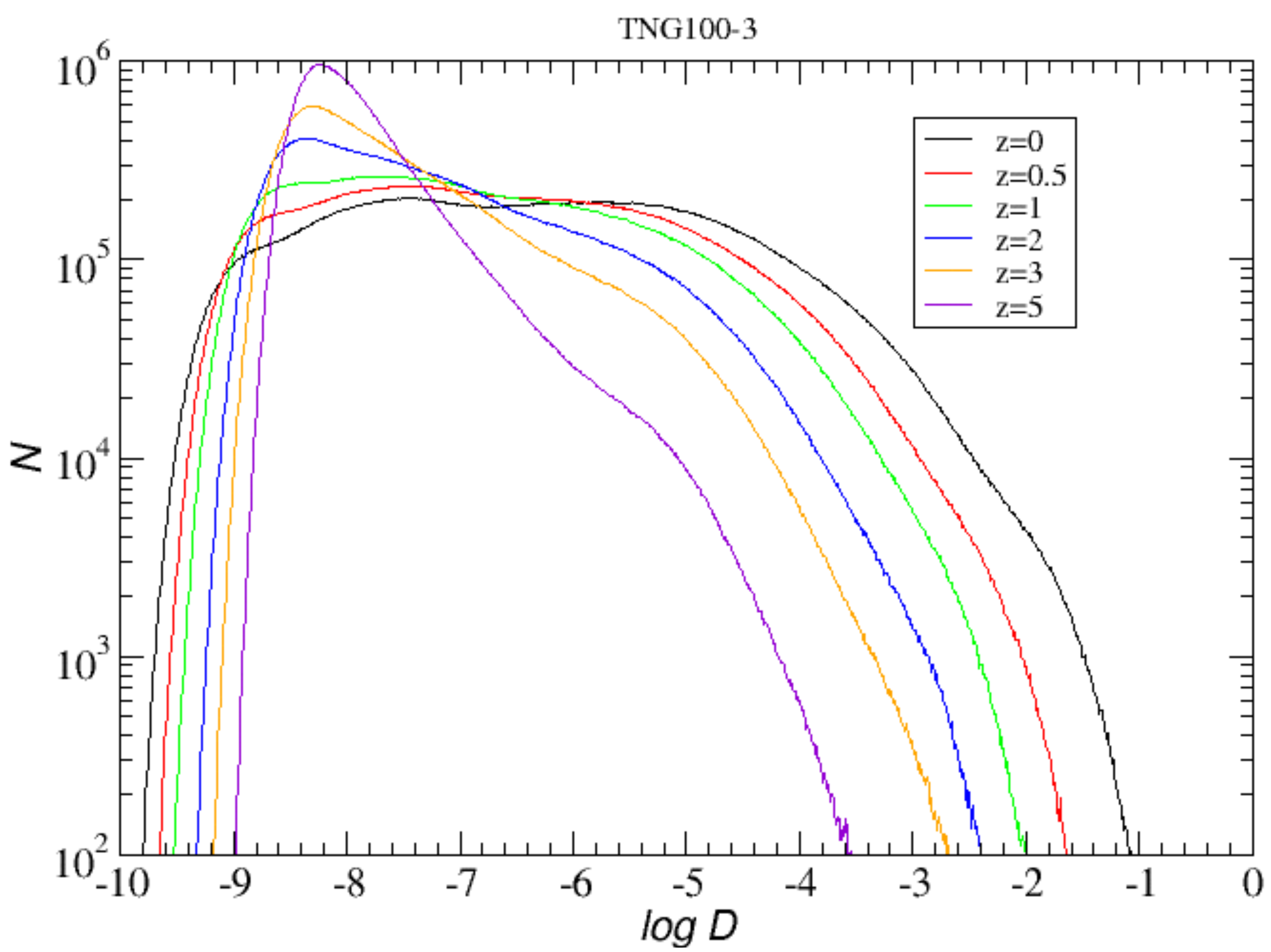
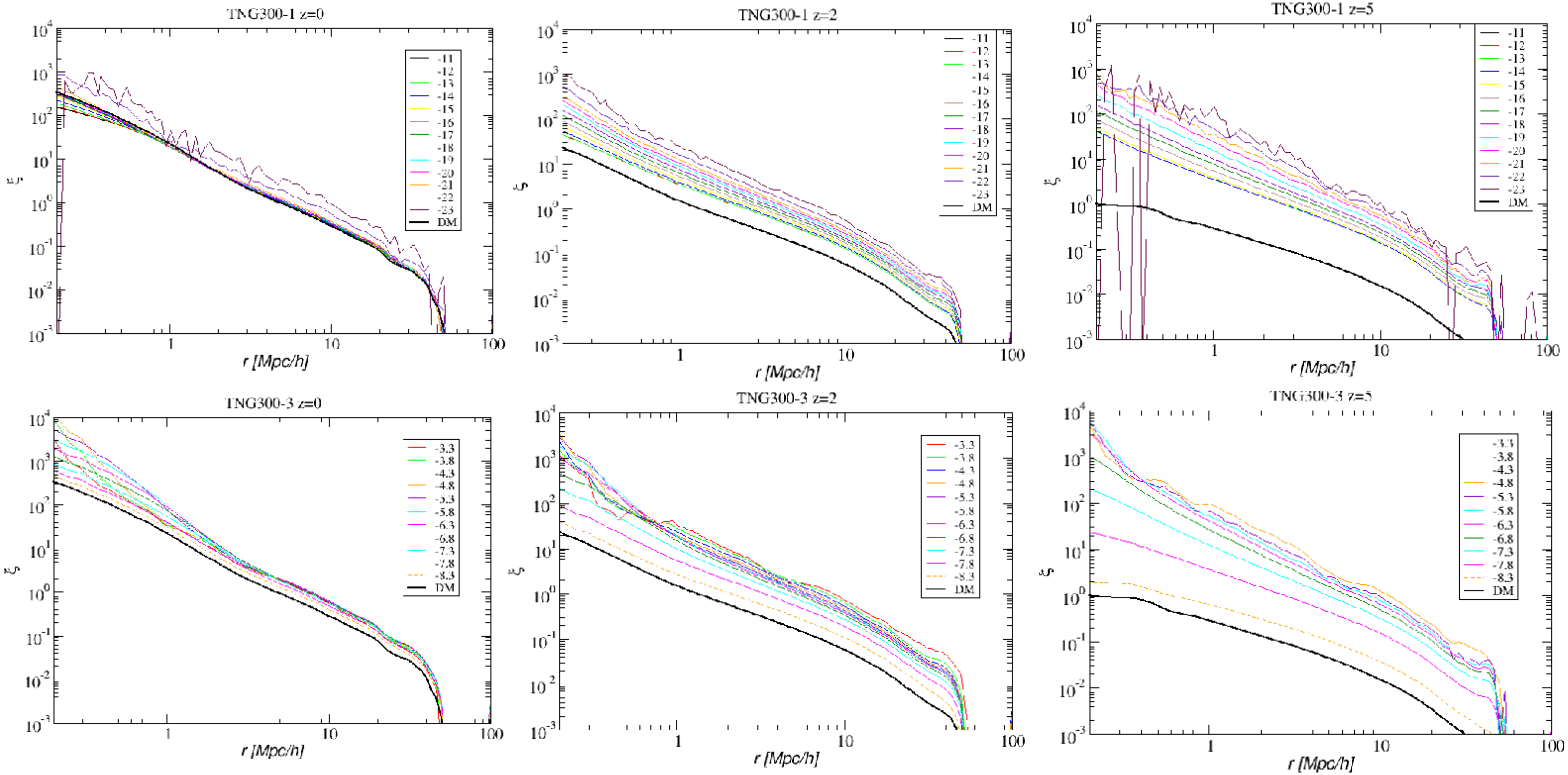
Distribution of luminosities and DM particle densities





Distributions of M_r magnitudes (left) and DM particle densities, log D, where density D is in units $10^{10} M_\odot\, kpc^{-3}$ (right), for TNG300-1 and TNG100-3 simulations at various z. Both distributions cover a large range of luminosities and densities, and have different shapes.

Correlation functions



Top: CFs of galaxies of TNG300-1. Bottom: CFs of clustered DM for TNG300-3. Differences are better seen in bias functions $b^2(r) = \xi_g(r)/\xi_m(r)$.

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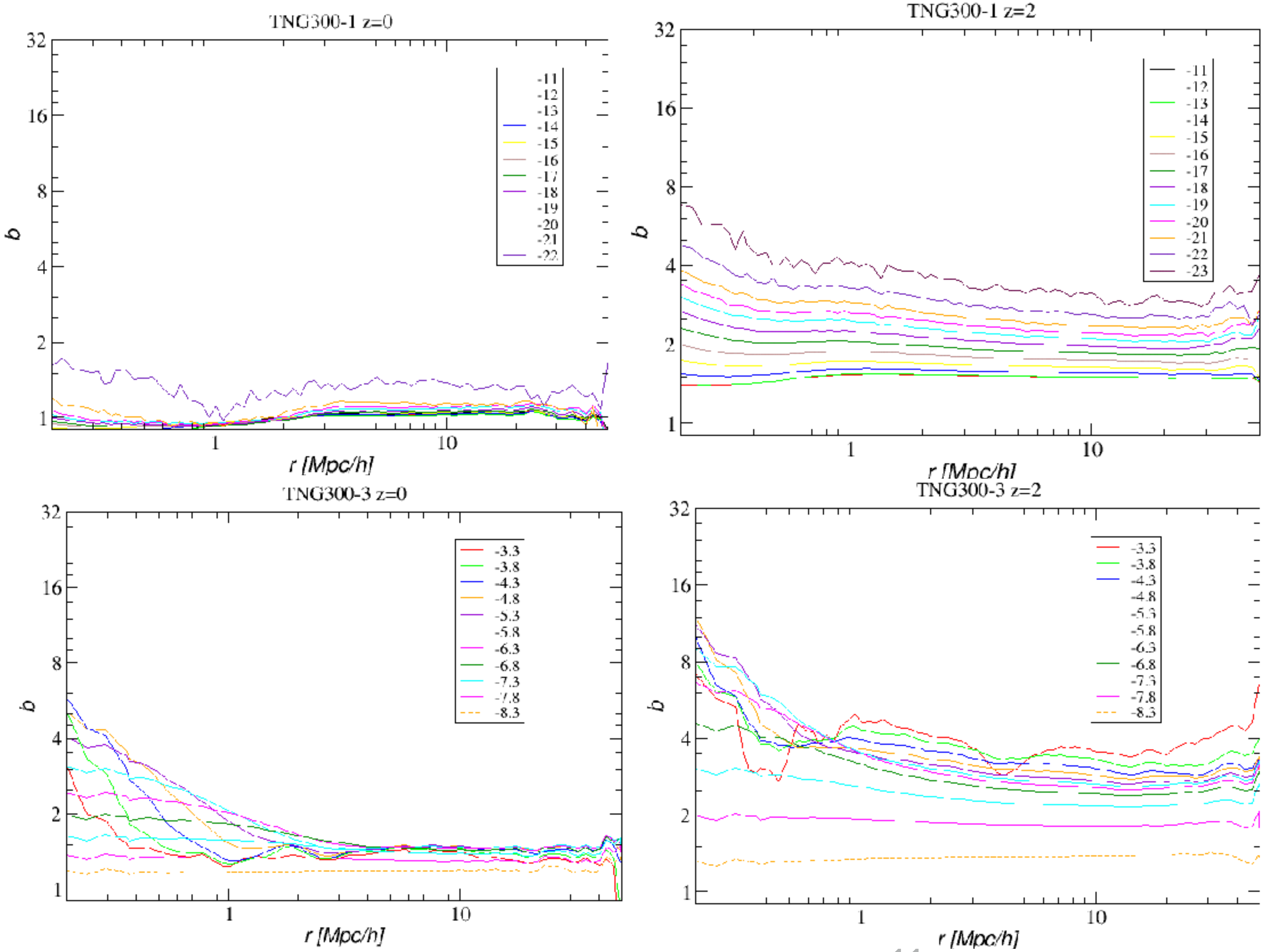
Bias functions

- On small separations bias functions (BF) are determined by properties of halos.
- To avoid influence of halos the value of BF at separation 10 Mpc/h is taken as bias parameter b.
- BFs of galaxies of low luminosity are identical.
- Amplitudes of BFs of low luminosity galaxies and density limited DM samples are different.
- With decreasing epoch z bias parameter b decreases.



- For galaxy samples TNG300-1 at $z = 0$ and small separation $b < 1$. Similar effect obtained by Springel et al. (2018) and from CFs of SDSS.

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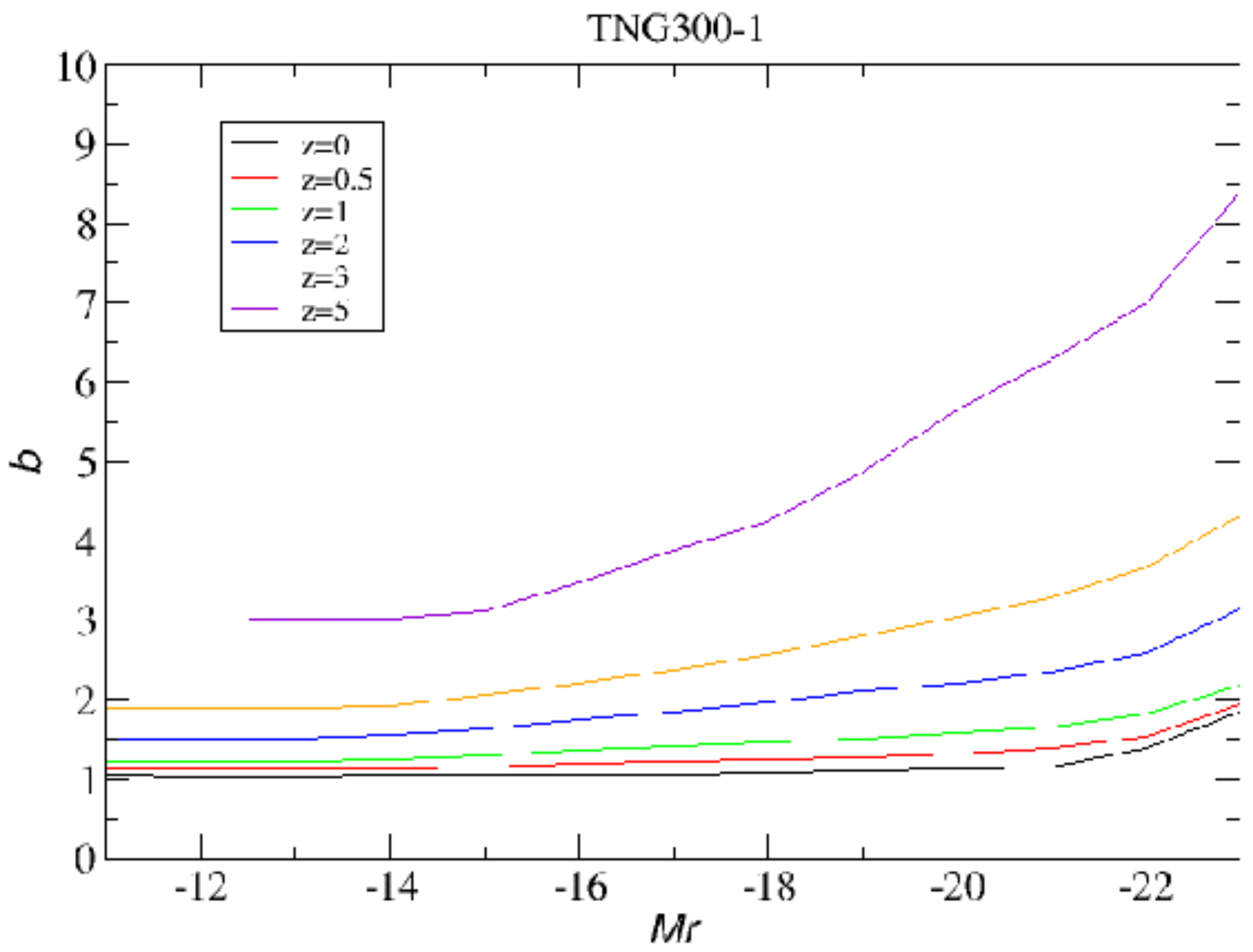
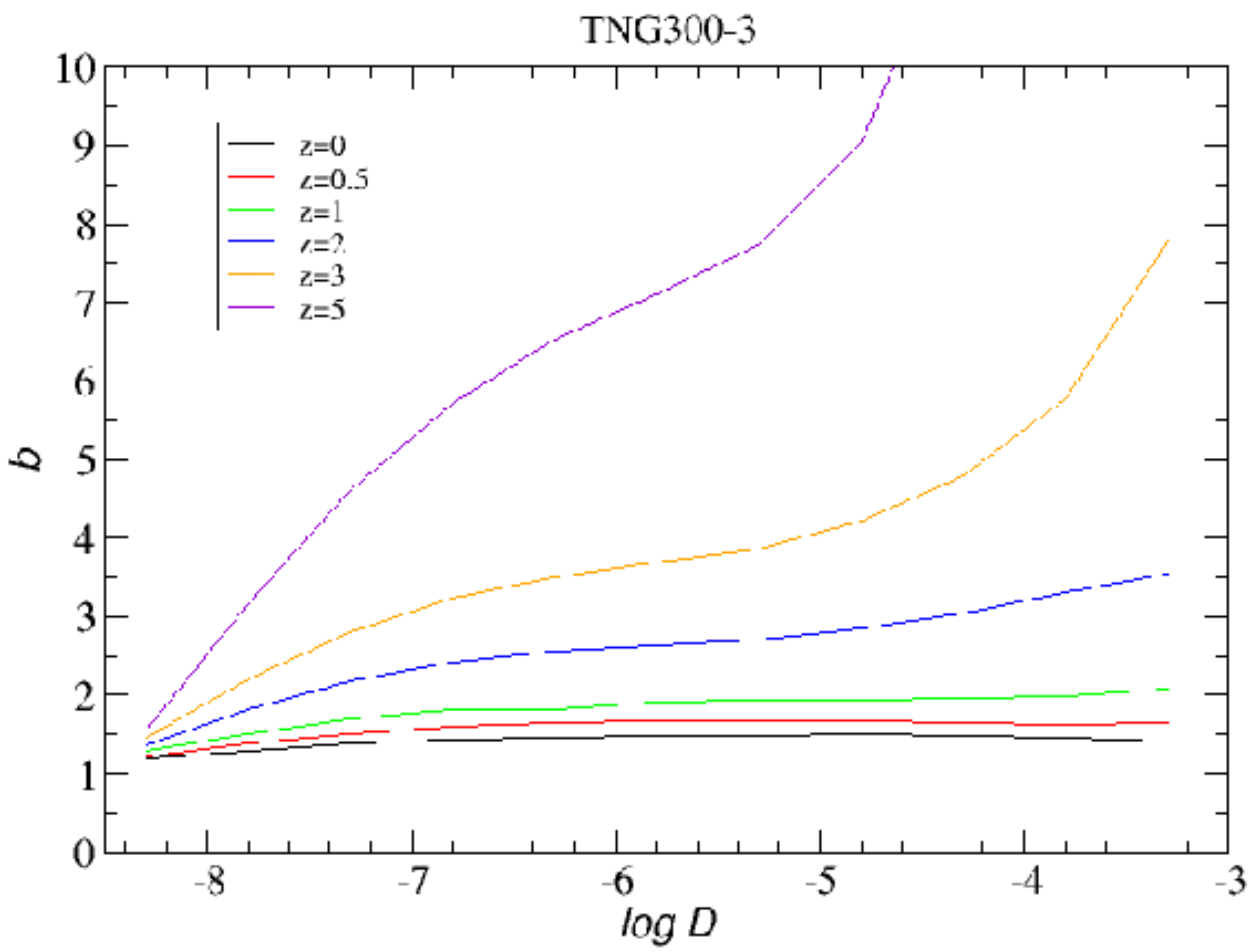
Bias parameters of galaxies of various luminosity





- Bias parameters of galaxies as functions of luminosity are flat at low luminosity. Bias value of low-luminosity galaxies, b_0, can be used as representative bias parameters instead of bias for $L_\star$ galaxies. This means that faint galaxies are located in the same halos as bright galaxies - there exists no population of field dwarf galaxies.
- Bias parameters of density limited DM samples increase continuously with density limit $\log D = \log \rho_0$. At low density limit $\log D \approx -9$ DM samples include all particles and bias parameter is by definition $b = 1$.

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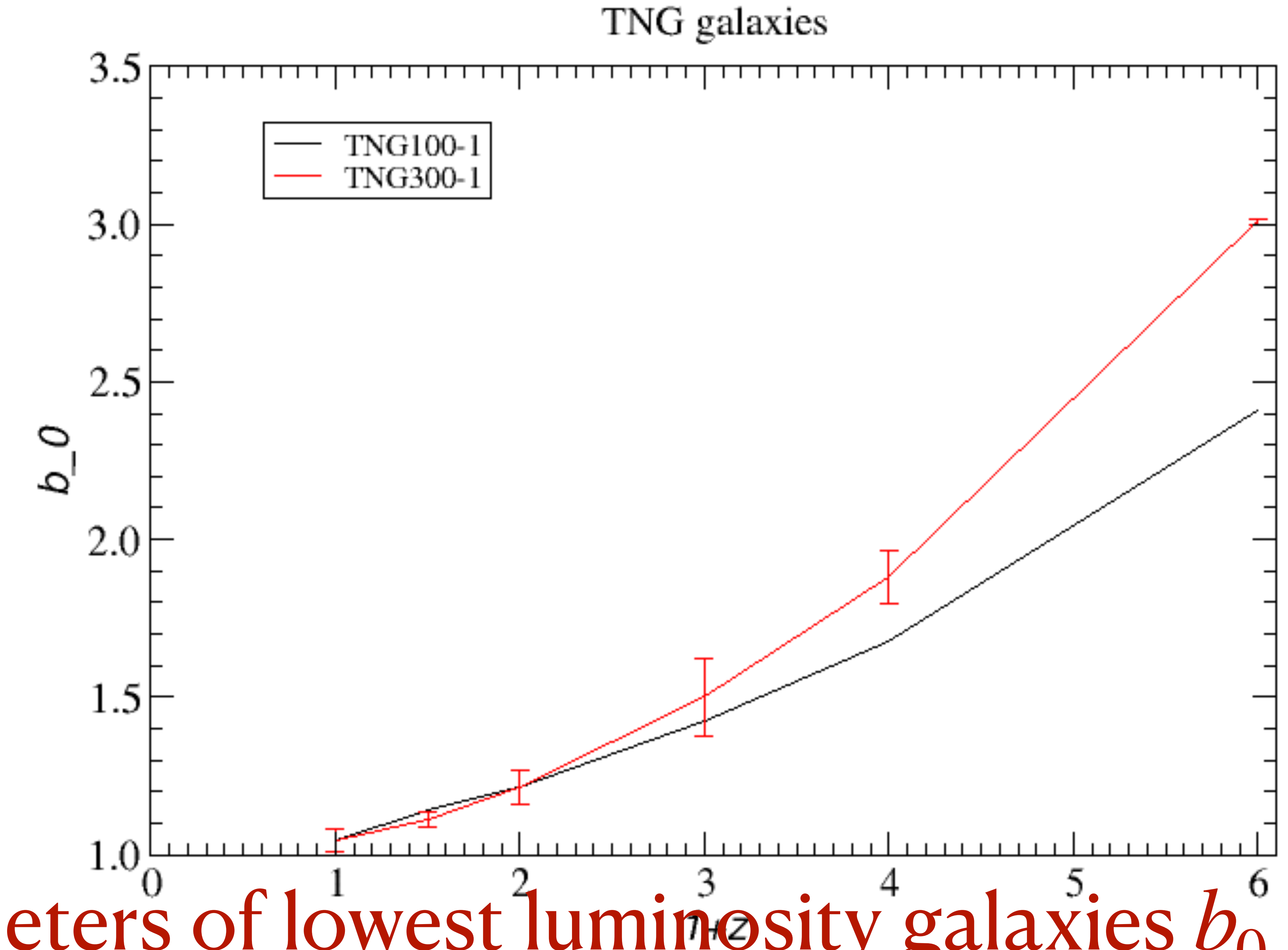
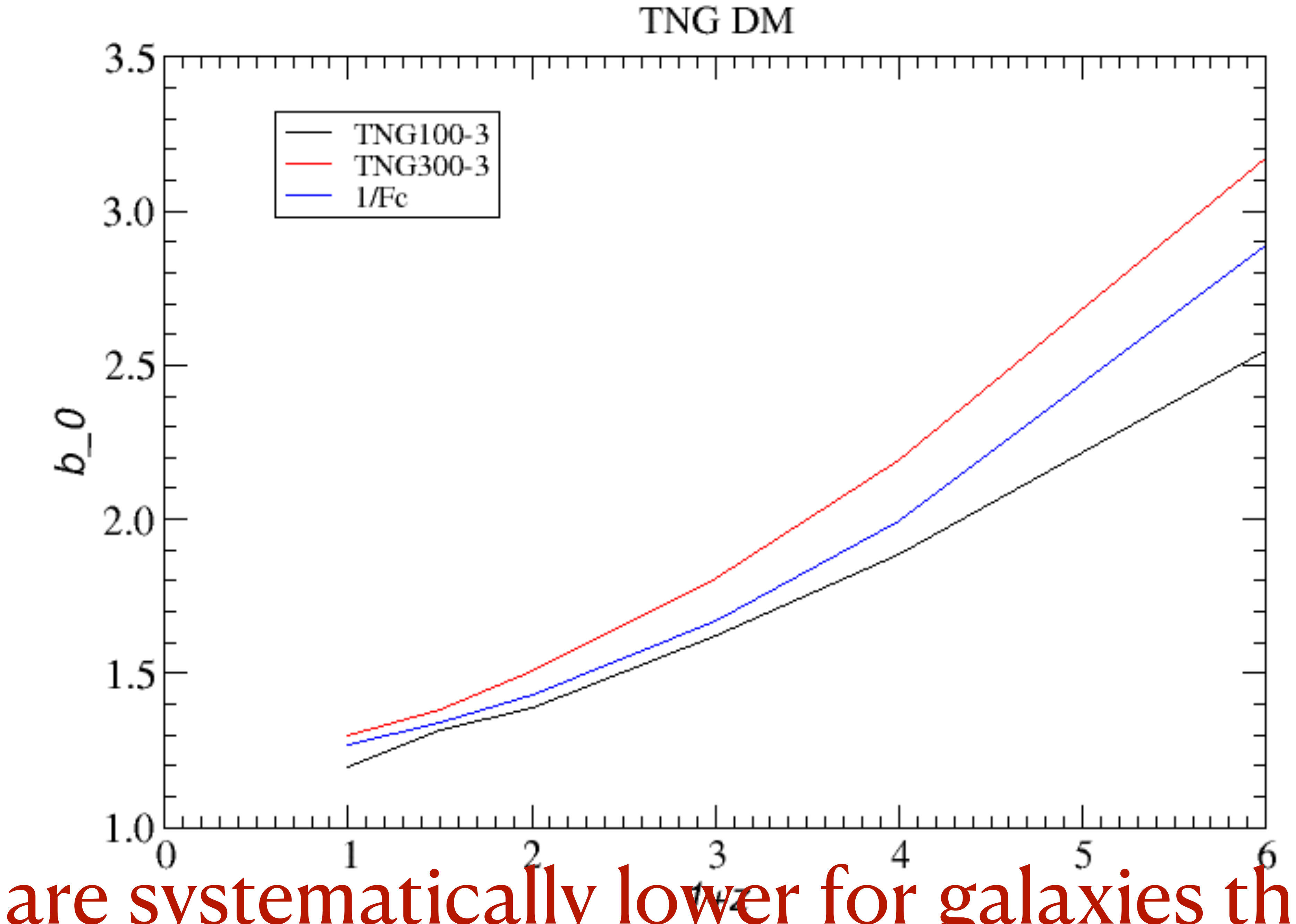
Evolution of bias for lowest luminosity galaxies b_0





- Bias parameters of lowest luminosity galaxies b_0 are systematically lower for galaxies than for clustered DM.
- Bias parameters b_0, found from CF of clustered DM, are in agreement with expected values from the outflow of particles from voids, measured by the fraction of particles in the clustered population, F_c: $b = 1/F_c$.
- Bias parameters of galaxies and DM describe different properties of the cosmic web.

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Conclusions

1. Bias parameters decrease during the evolution, confirming earlier results (Tegmark, Peebles 1998, Springer et al. 2005, 2018, Park et al. 2022).
2. Bias parameters of galaxies of low luminosity are equal. This means that faint galaxies are located in the same halos as bright galaxies - there exists no population of field dwarf galaxies.
3. Bias parameter of lowest luminosity galaxies b_0 is lower when found from CF of galaxies relative to CF of clustered DM.
4. Bias parameter b_0, found from CF of clustered DM is in agreement with expected values from the fraction of particles in the clustered population, F_c: $b = 1/F_c$.
5. Galaxy density field contains large number of cells with zero density, which increases the amplitude of the CF clustered matter over the amplitude of matter CF. **Thus the amplitude of CF of clustered matter is always higher than the amplitude CF of all matter, i.e. bias parameter must be *b>1.***
6. CFs of galaxies and clustered DM describe different properties of the cosmic web.

Why CFs of galaxies are in conflict with values, expected from the fraction of particles in voids F_v?