Halo occupation models: motivation and results

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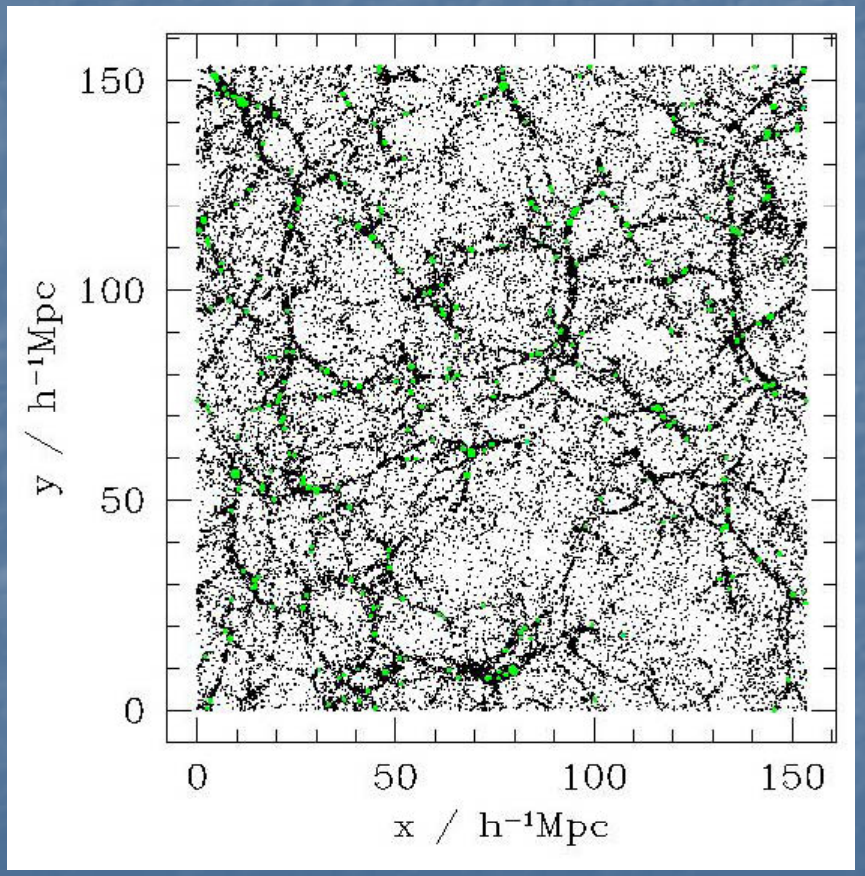
Dark Matter Halos

- Identify dark matter halos as regions of overdensity ~200.
- We are confident we can predict the distribution of dark matter on the scales of galaxy halos.
- Simulations are large enough to produce excellent statistics on these scales.



What is the Halo Occupation Distribution?

- The Halo Occupation Distribution (HOD) is a function of M, the mass of a dark matter halo.
- Describes how galaxies above some mass or luminosity threshold are biased with respect to the underlying dark matter.
- Can be split up into several components:
  - P(N|M) – the probability there are N galaxies in a halo of mass M
    - <N>(M) – the mean occupation function of a halo of mass M.
    - P(N|<N>)
  - Relative spatial distribution of galaxies in a halo
  - Relative velocity distribution of galaxies in a halo
- Defined for the whole galaxy population or for any subset.

Environmental dependence

- Simulations have suggested that treating the HOD as a function of halo mass only, independent of the large scale environment of the halo, is a good approximation (Lemson & Kauffman 1999, Berlind et. al. 2003).
- Environment is difficult to define and tests can be hard to interpret.
- More sensitive tests have recently been suggested.

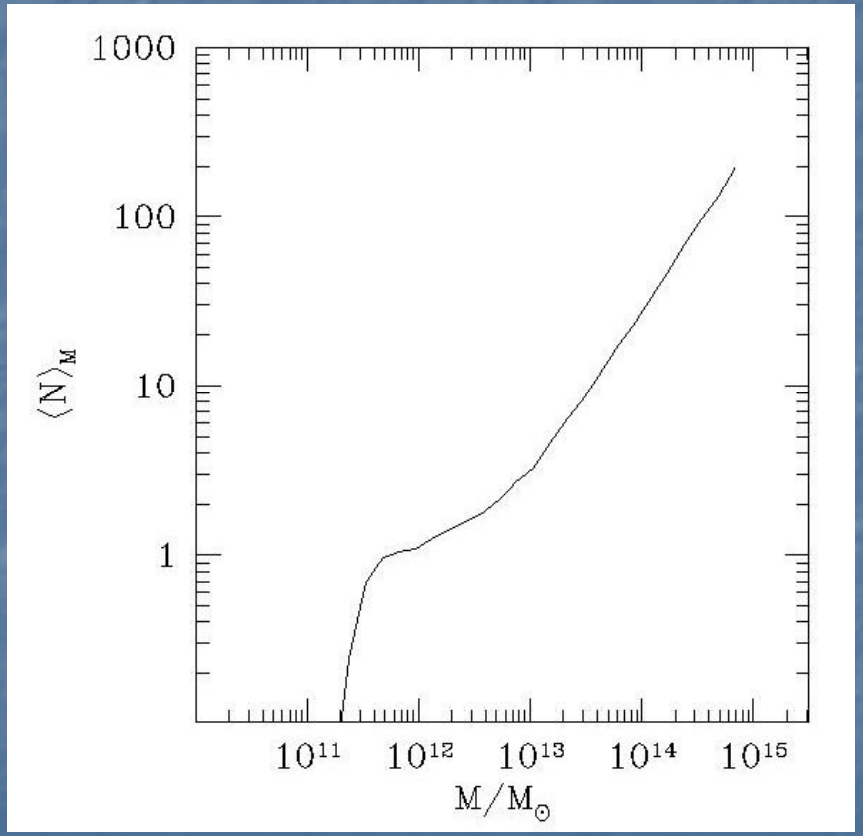
  Sheth & Tormen: astro-ph/0402237

Applications

- Halo Occupation Distribution (HOD) parameters and cosmological parameters have a non-degenerate effect on galaxy clustering statistics (n-point function, void probability function, pairwise velocity dispersion etc.).
- Agreement between SPH and semi-analytic predictions for the HOD suggests it can be used to constrain cosmology.
- A HOD can be defined for any subset of the galaxy population, and this can be used to constrain the physics of galaxy formation.
- The observed power-law form of the galaxy correlation function may place constraints on HOD or cosmological parameters.

Mean occupation function

- Relatively sharp cutoff at low M.
- Apparent power law for high M.
- Scatter around the mean is approximately Poisson at high M but narrower at low M.



Parametrisations

- Power law

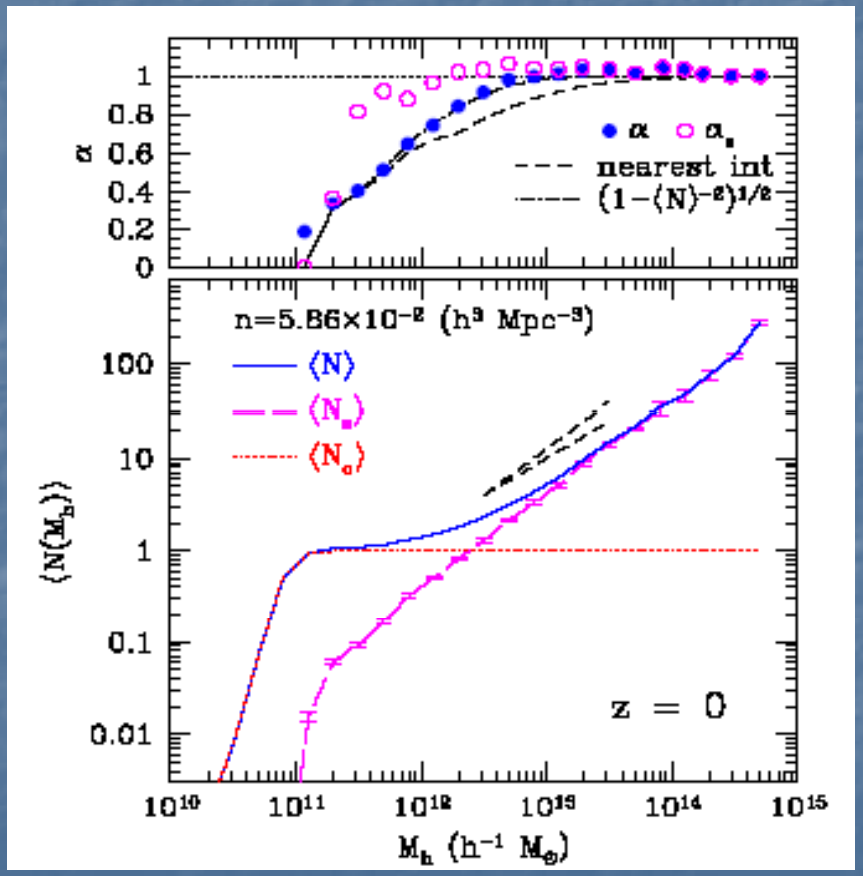
$$\langle N \rangle = \begin{cases} 0 & \text{if } M < M_{\text{min}} \\ (M / M_1)^{\alpha} & \text{otherwise} \end{cases}$$

- Broken power law

$$\langle N \rangle = \begin{cases} 0 & \text{if } M < M_{\text{min}} \\ (M / M_1)^{\alpha} & \text{if } M_{\text{min}} \leq M \leq M_{\text{crit}} \\ (M / M_1')^{\beta} & \text{otherwise} \end{cases}$$

Parametrisations

- Split into central and satellite galaxies suggests a parametrisation based on this split.
- Occupation function of satellite galaxies is power law with Poisson scatter over a much larger range than for the overall distribution.



Kravtsov et. al. 2003

Parametrisations – split between central and satellite galaxies

- Simple scheme (Kravtsov et. al. 2003)

$$\langle N_{\text{central}} \rangle = \begin{cases} 0 & M < M_{\min} \\ 1 & M \geq M_{\min} \end{cases} \qquad P\left(N \mid \langle N \rangle\right) \in \text{Nearest integer distribution}$$

$$\langle N_{\text{satellite}} \rangle = \begin{cases} 0 & M < M_{\min} \\ \left(\dfrac{M - M_{\min}}{M_1} \right)^{\alpha} & M \geq M_{\min} \end{cases} \qquad P\left(N \mid \langle N \rangle\right) \in \text{Poisson}$$

Parametrisations – split between central and satellite galaxies

- Zheng et. al. scheme

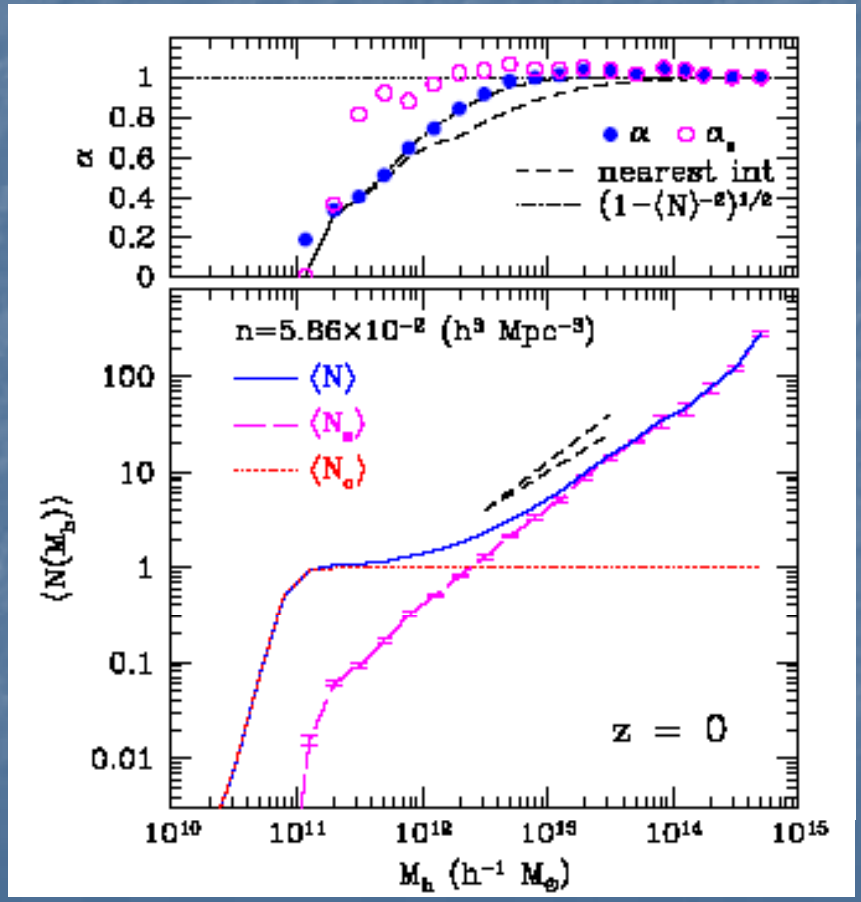
$$\langle N_{\text{central}} \rangle = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\lg M - \lg M_{\min}}{\sigma_M}\right)\right] \qquad P\left(N \mid \langle N \rangle\right) \in \text{Nint}$$

$$\langle N_{\text{satellite}} \rangle = \begin{cases} 0 & M < M_0 \\ \left(\frac{M - M_0}{M_1}\right)^{\alpha} & M \geq M_0 \end{cases} \qquad P\left(N \mid \langle N \rangle\right) \in \text{Poisson}$$

Parametrisations

$$\alpha^2 \equiv \frac{\langle N(N-1)\rangle}{\langle N\rangle^2}$$

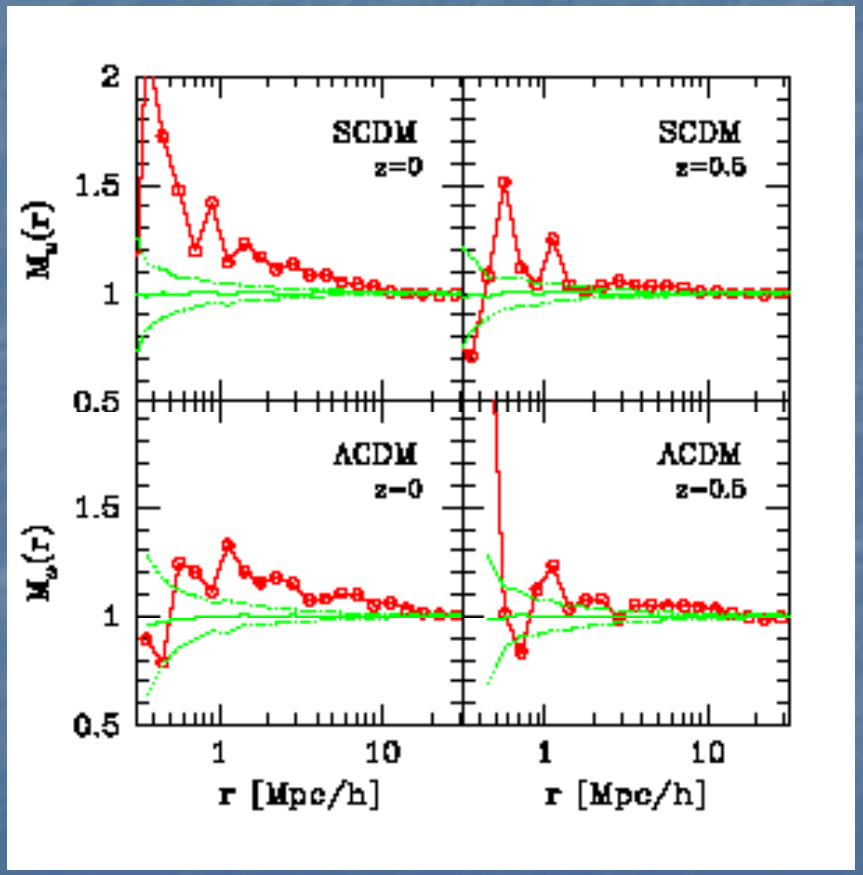
- α=1 for a Poisson distribution, and α<1 for a narrower distribution.
- Demonstrates a good fit to the new parametrisations.



Kravtsov et. al. 2003

Marked correlation function

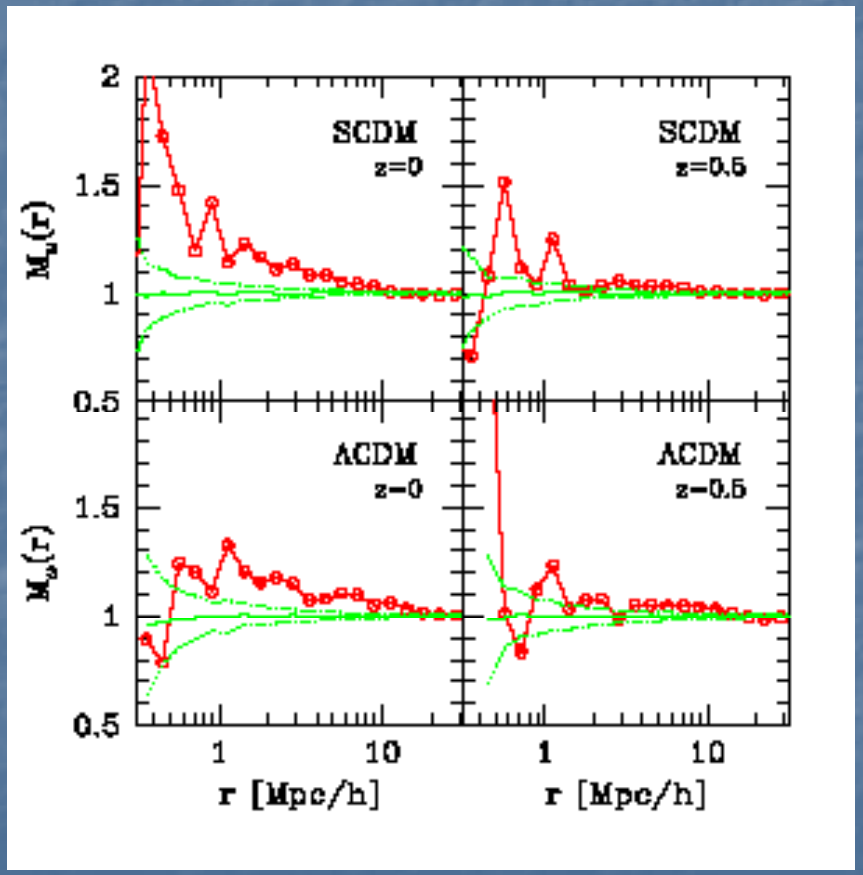
- Each object, i, is assigned a mark m_i.
- M(r) is the sum over pairs with separation r_{ij}=r weighted by $m_i m_j$, divided by the sum over the same pairs weighted by the mean mark squared.



Sheth and Tormen 2004

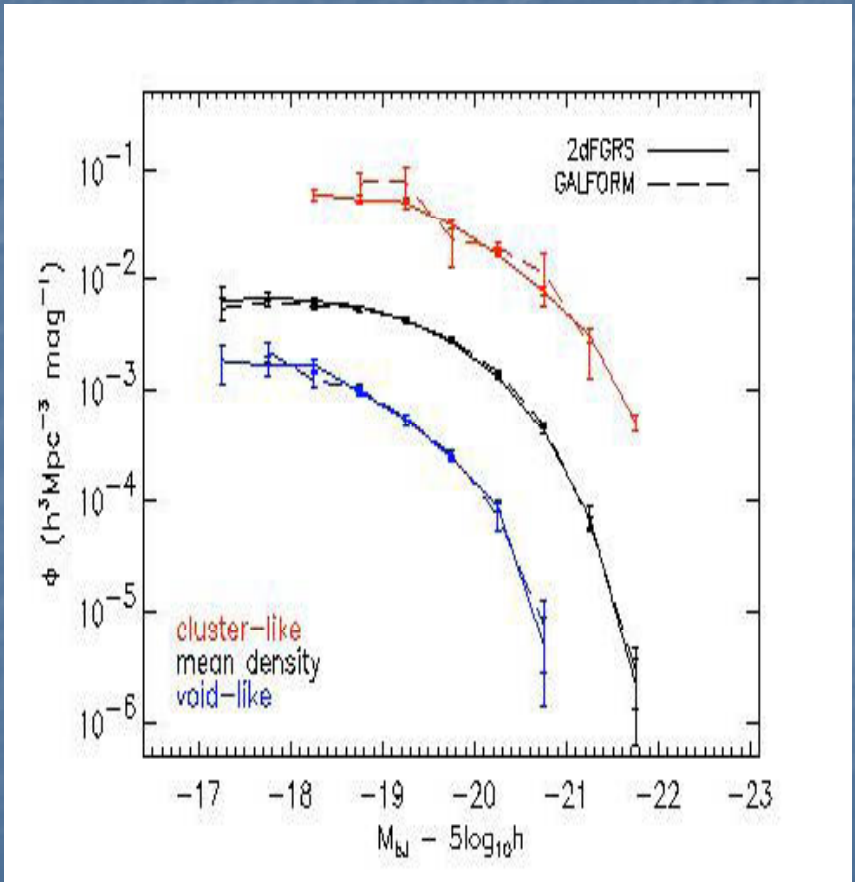
Marked correlation function

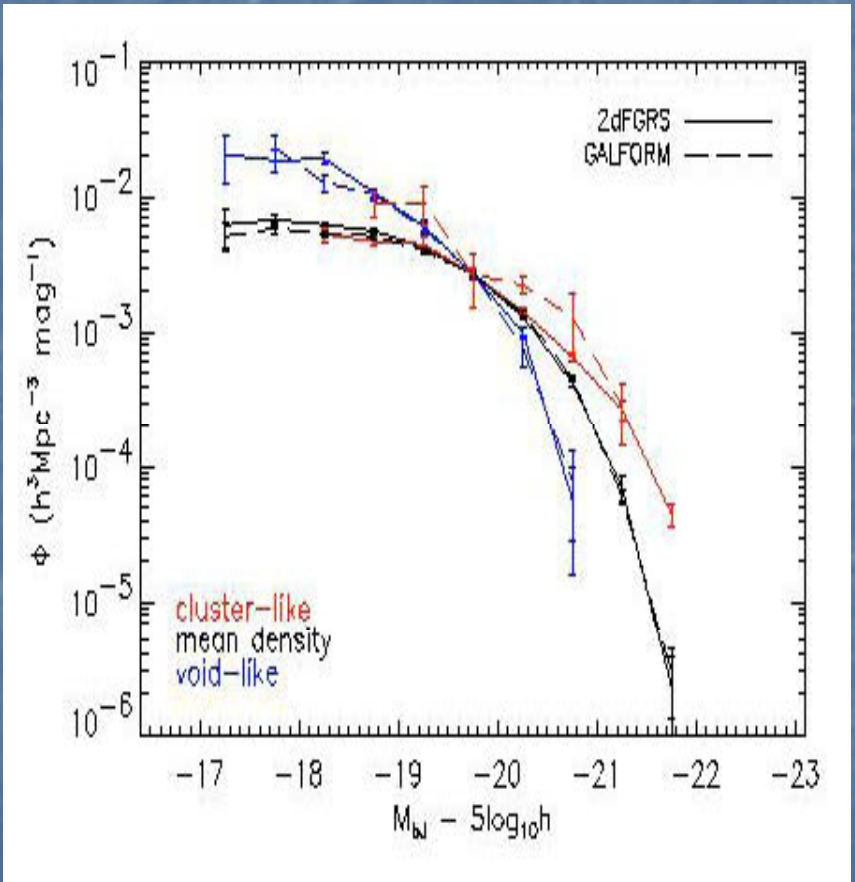
- Use scaled formation redshift as the mark.
- Shows environmental dependence of formation times without defining environment.
- Marginal evidence of dependence of formation time on environment



Sheth and Tormen 2004

Darren Croton's result





Constraining cosmological parameters using the HOD

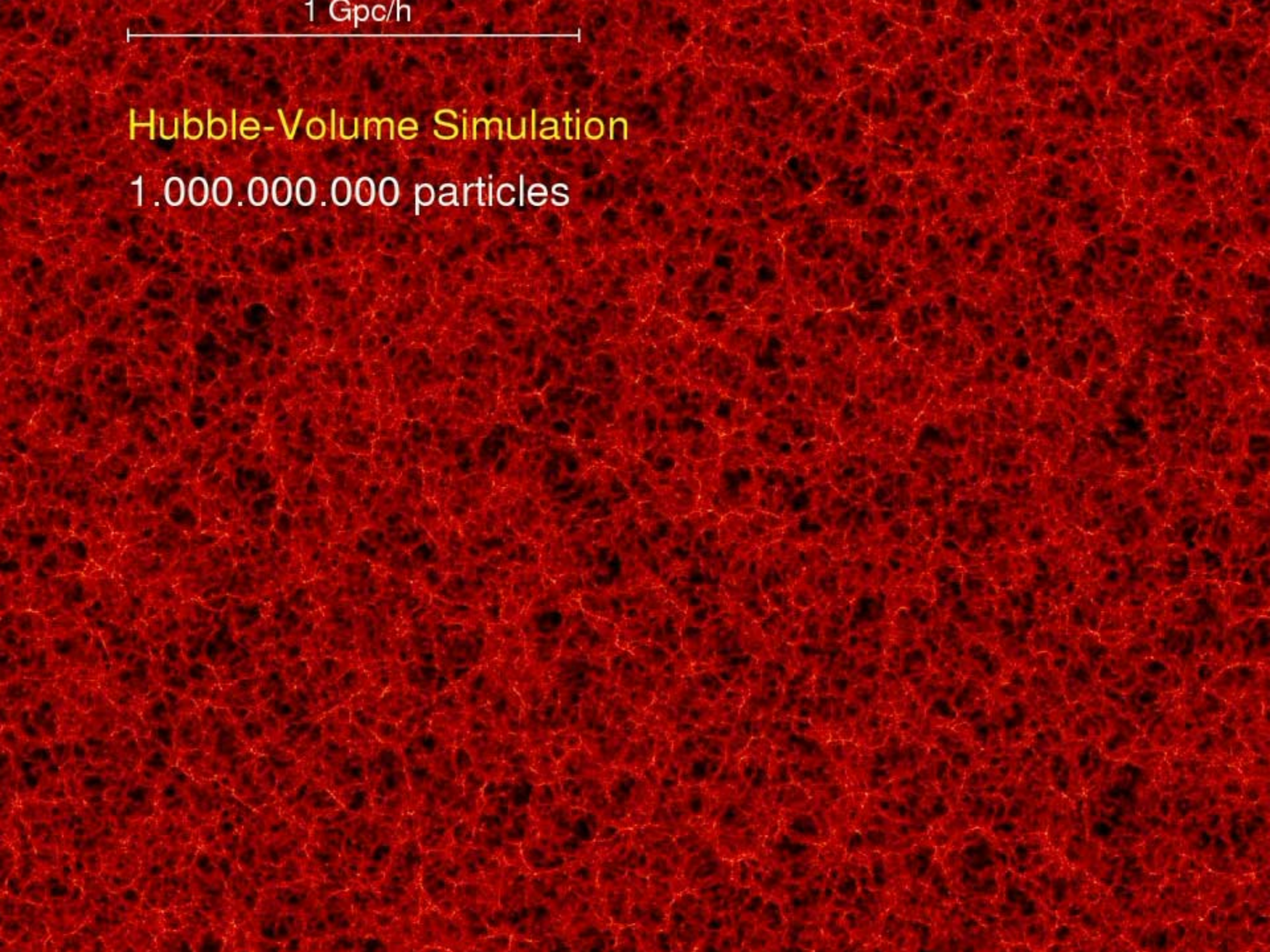
- Run simulations for a range of cosmologies.
- Use the degeneracies in cosmological parameters of Zheng et. al. 2003 to reduce the number of simulations required.
- Need a well-defined way of generating a reasonable GALFORM model for different cosmologies that fits low-redshift data.
- Populate simulations using the GALFORM HOD and use clustering statistics to constrain cosmology.

Constraining the physics of galaxy formation using the HOD

- Use simulations in the concordance cosmology.
- Generate a range of different GALFORM models which produce reasonable fits to low-redshift data.
- Populate simulations using the resulting HOD.
- Different models produce different HODs, which affects clustering statistics.
- Splitting the HOD into components for different populations of galaxies can provide more information.

Millennium Simulation

- Large simulation with high resolution and excellent dynamic range.
- Ideal to further the study of the environmental dependence of halo formation.
- Makes possible a more thorough marked correlation function analysis, with scaled formation redshift, number of halo substructures or concentration as the mark.
- Will enable measurement of clustering statistics to very high precision.


1 Gpc/h
Hubble-Volume Simulation
1.000.000.000 particles

Conclusions

- The HOD describes how the distribution of galaxies is related to the distribution of dark matter.
- Can provide constraints on cosmology or on the physics of galaxy formation.
- Finds applications in the study of clustering.
- Sensitive to the environmental dependence of halo formation and clustering.
- Work here is using dark matter simulations, semi-analytics and 2dF data.