The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2354-15

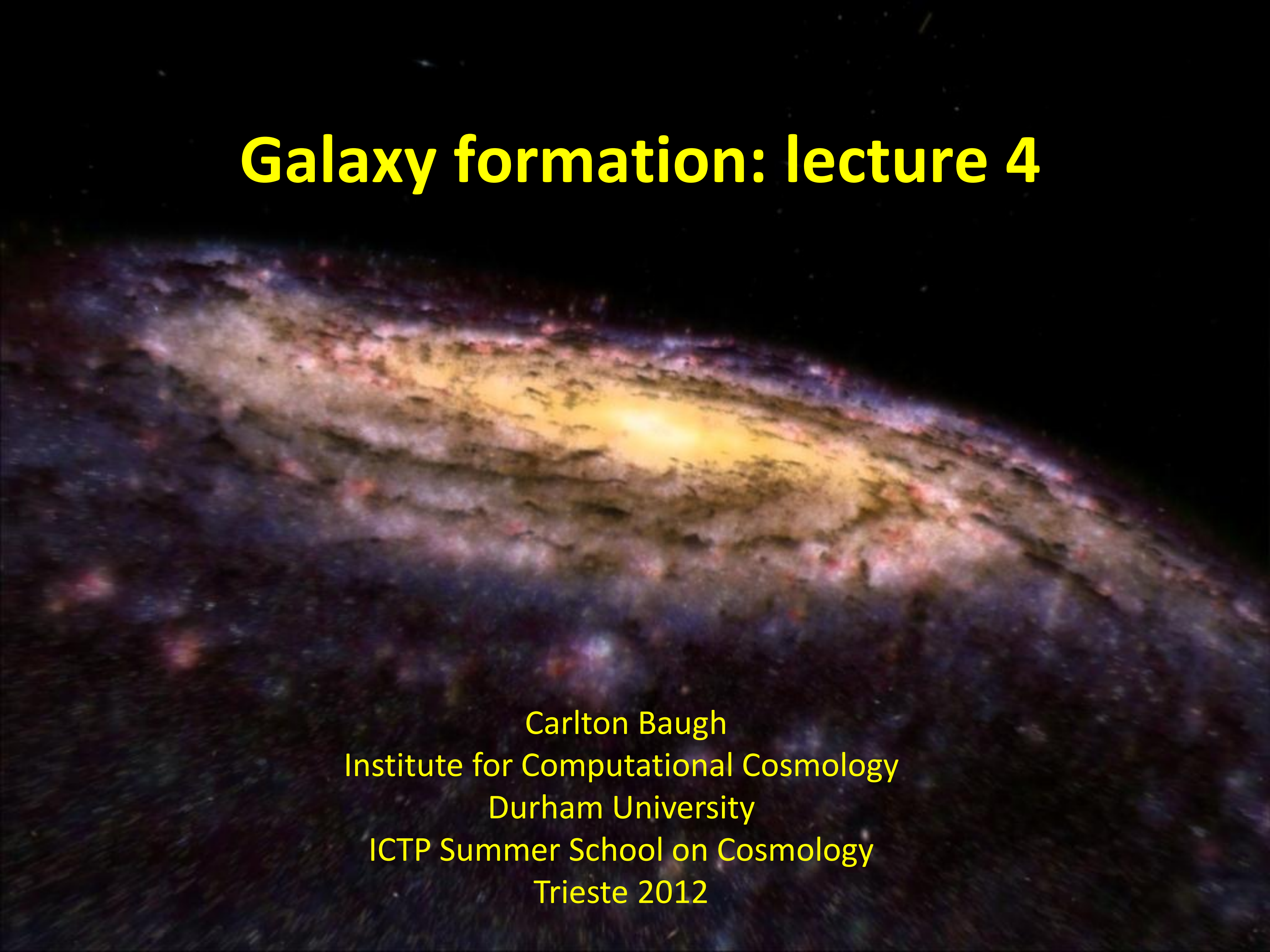
Summer School on Cosmology

16 - 27 July 2012

Galaxy formation - Lecture 4

C. Baugh
ICC, Durham U.

Galaxy formation: lecture 4

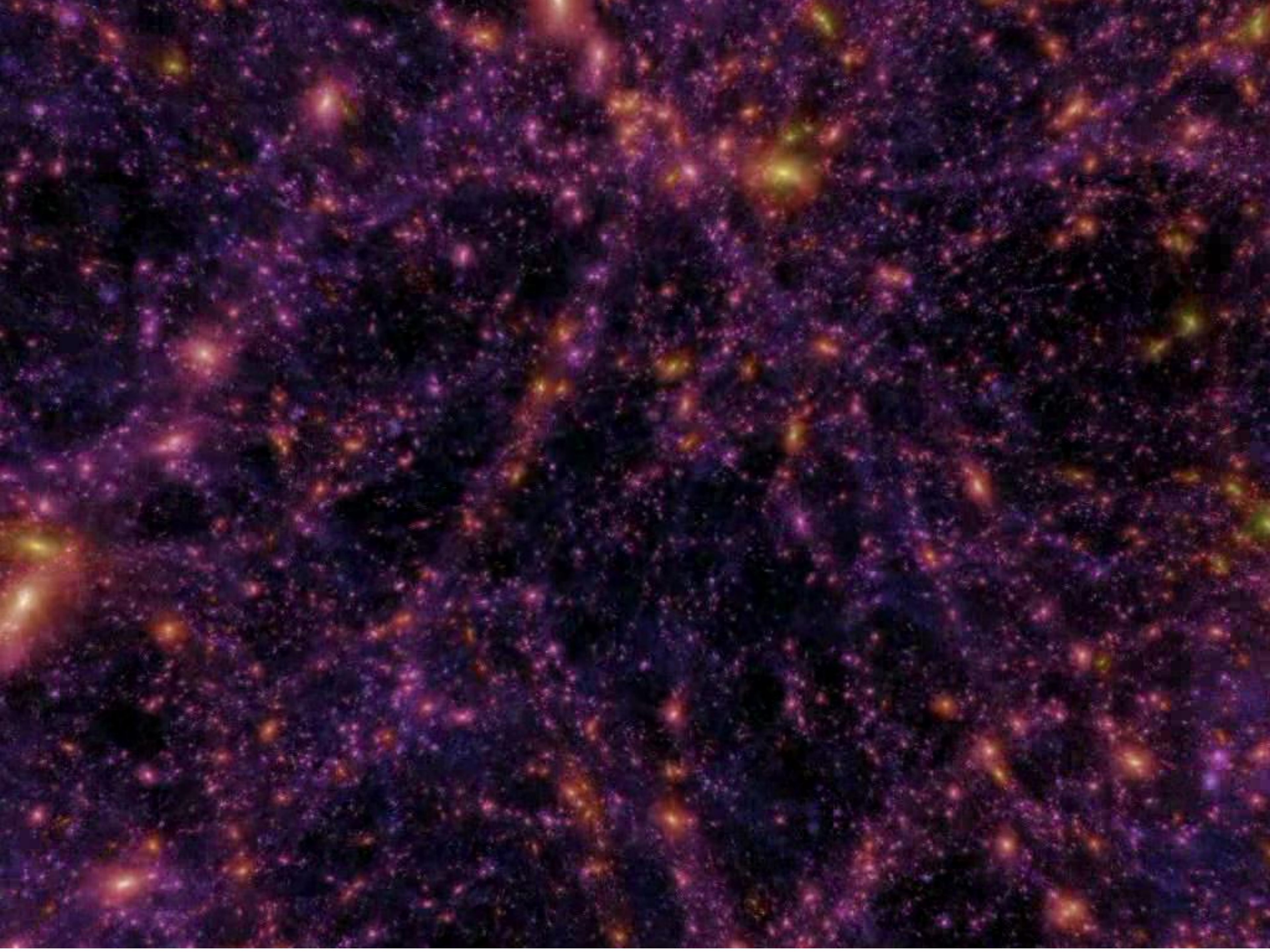


Carlton Baugh
Institute for Computational Cosmology
Durham University
ICTP Summer School on Cosmology
Trieste 2012

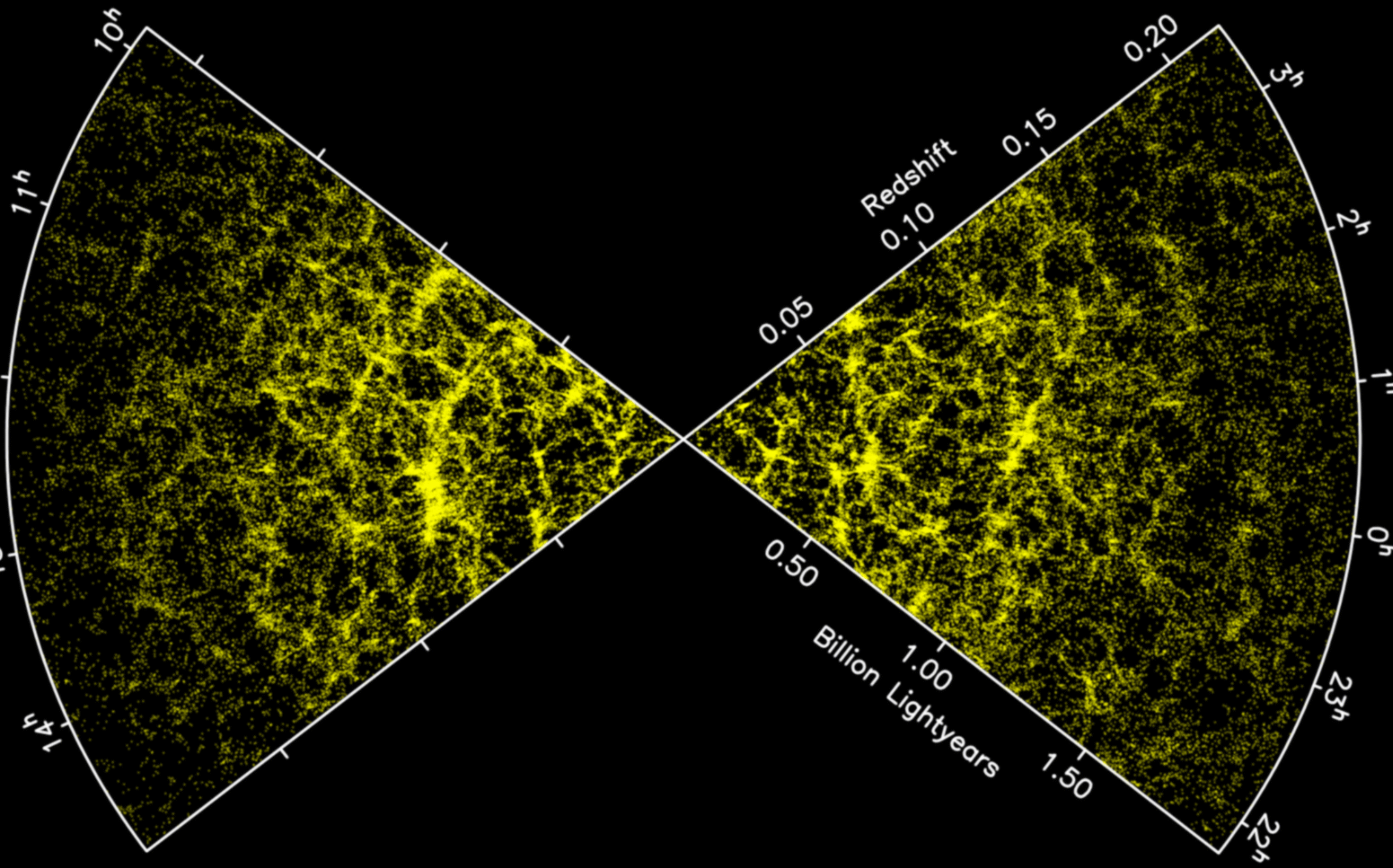
Lecture 4

- Bias: How do galaxies trace the dark matter?

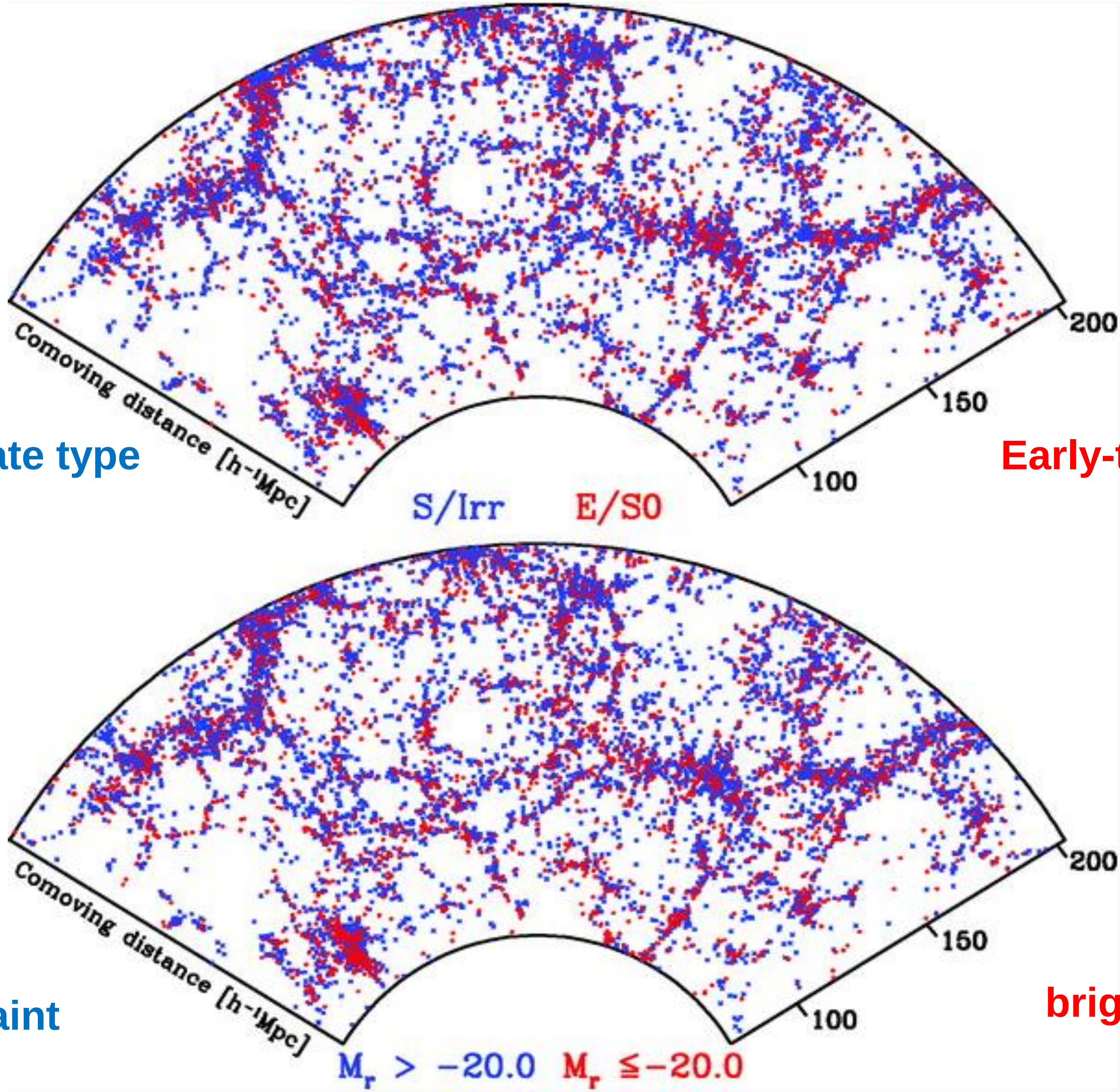
- Outstanding problems in galaxy formation



Two-degree Field Galaxy Redshift Survey



Sloan Digital Sky Survey



Late type

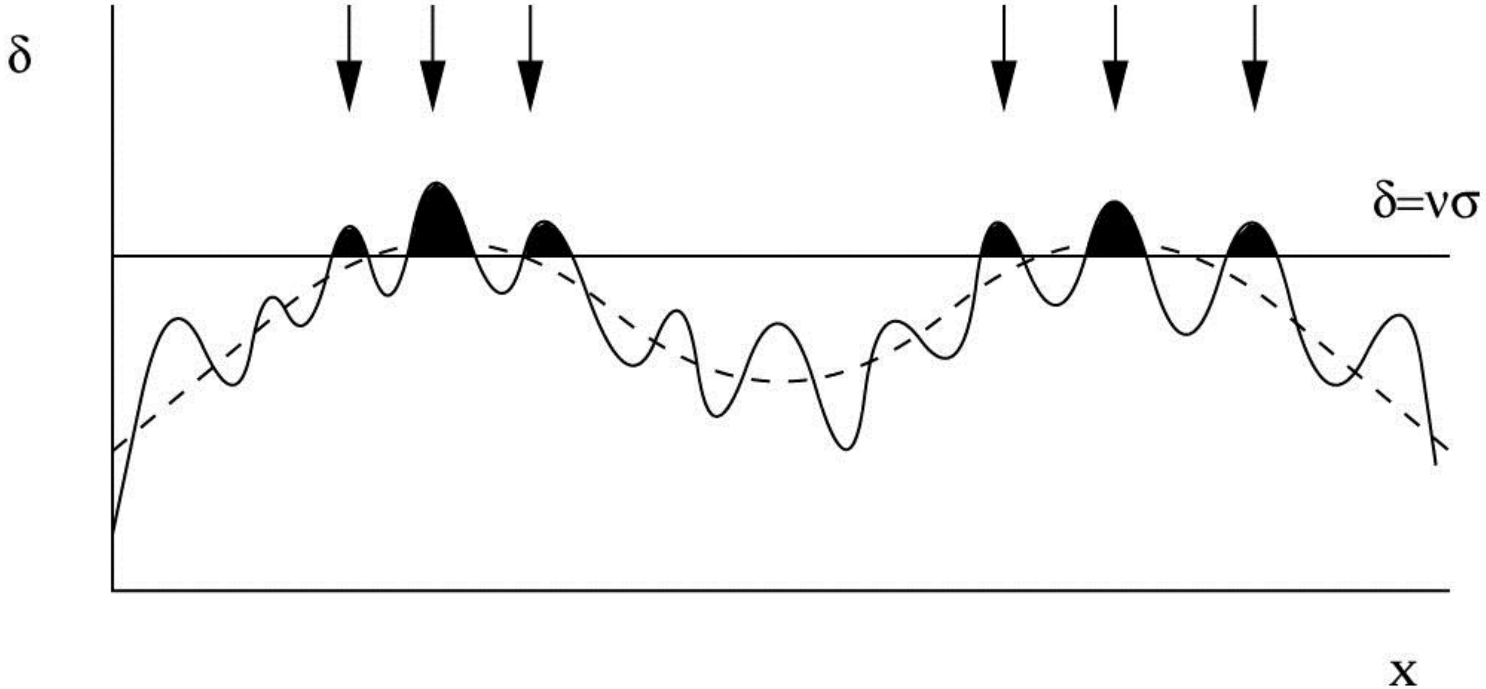
Early-type

faint

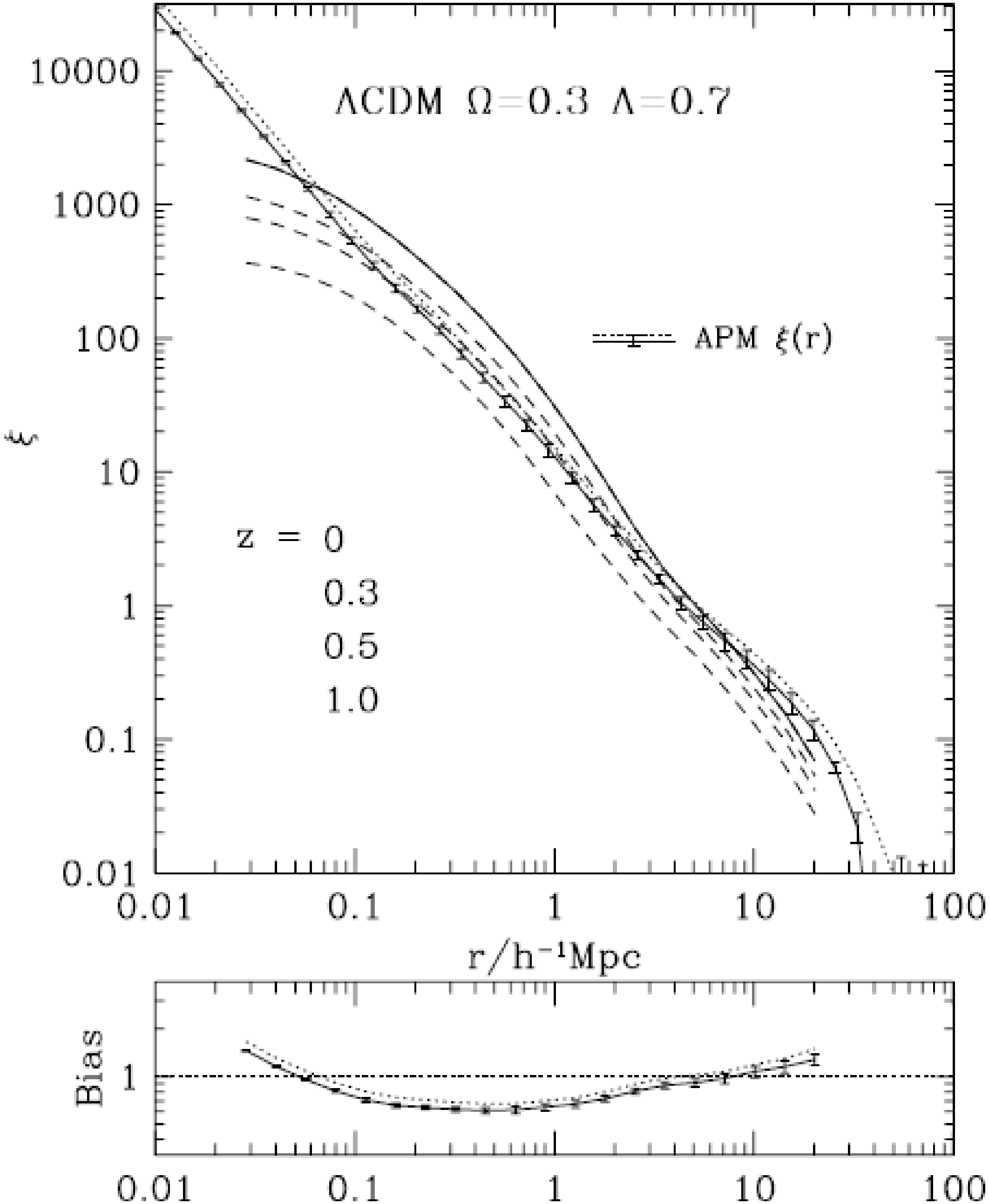
bright

Biased galaxy formation

Galaxies may trace DM distribution in a complicated way



Kaiser 1984 – originally derived to explain clustering of clusters
Clusters associated with high peaks in density field

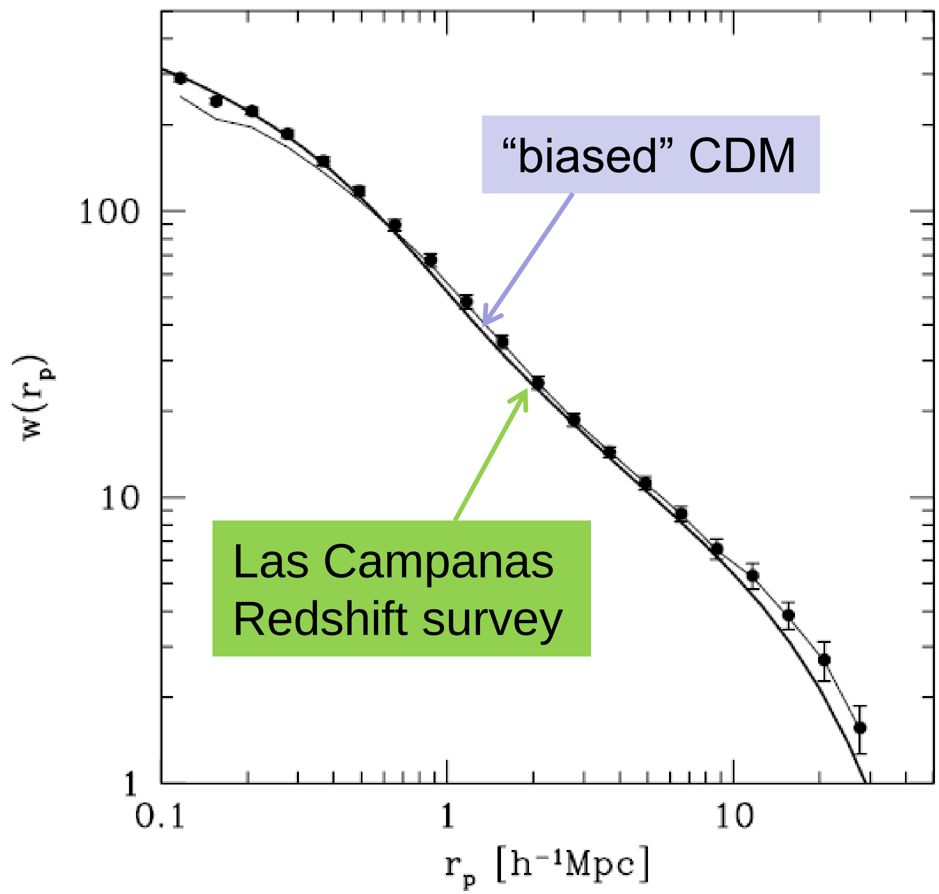


Galaxy clustering vs dark matter clustering

- Galaxy correlation function ~ power law over 3-4 decades in r
- DM correlation function not a power law
- Scale dependent bias

Jenkins et al. 1998

Associate galaxies with DM haloes instead of DM or peaks

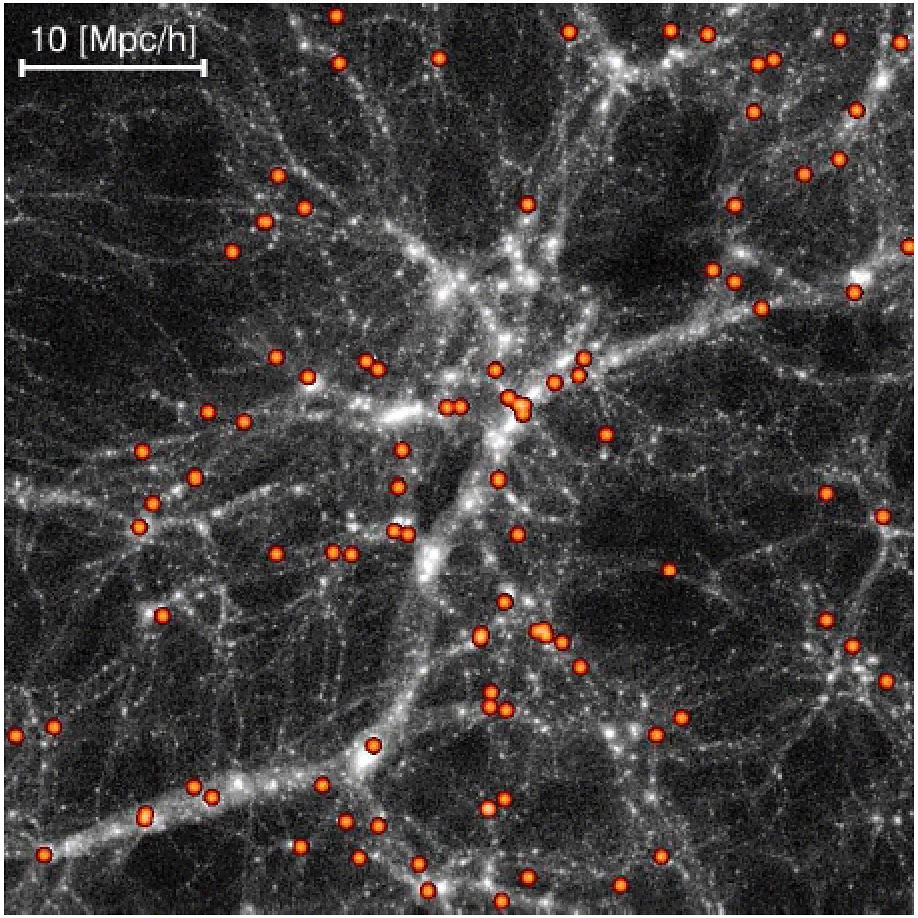


- First "Halo Occupation Distribution" model
- Scale dependent bias
- No low mass cut off
- No split between centrals and satellites

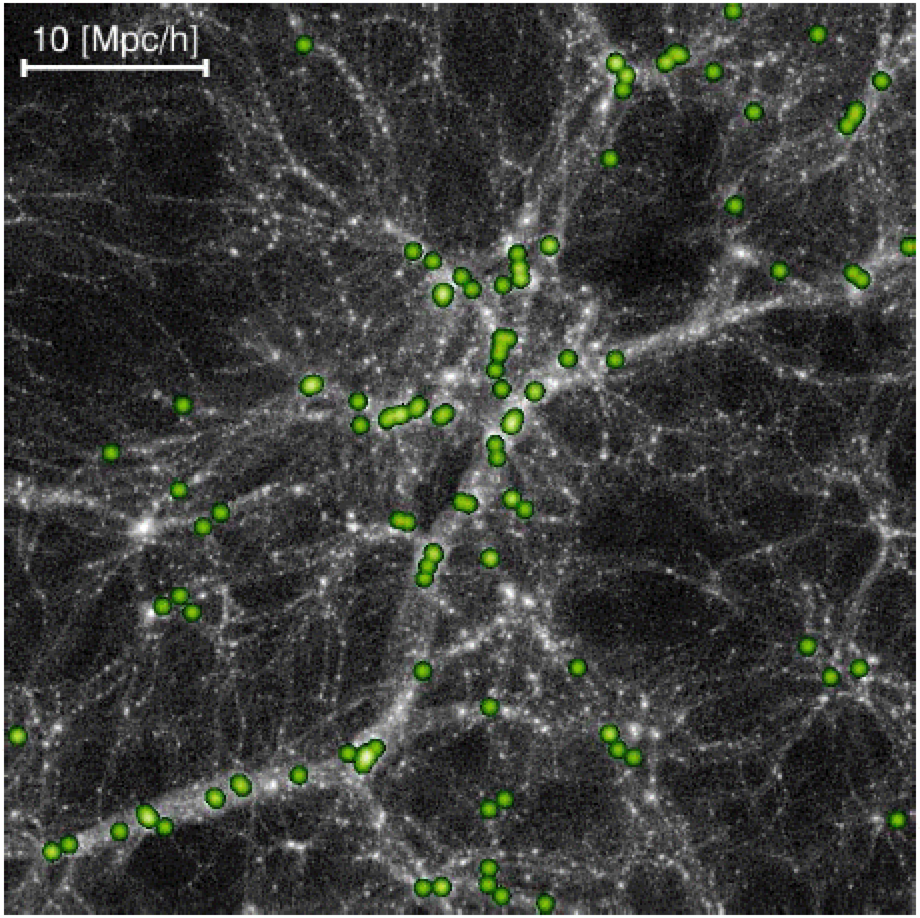
$$N/M \propto M^{-\alpha}$$

Jing, Mo & Boerner 1998

Predict connection between different galaxy samples and dark matter



H-α selection

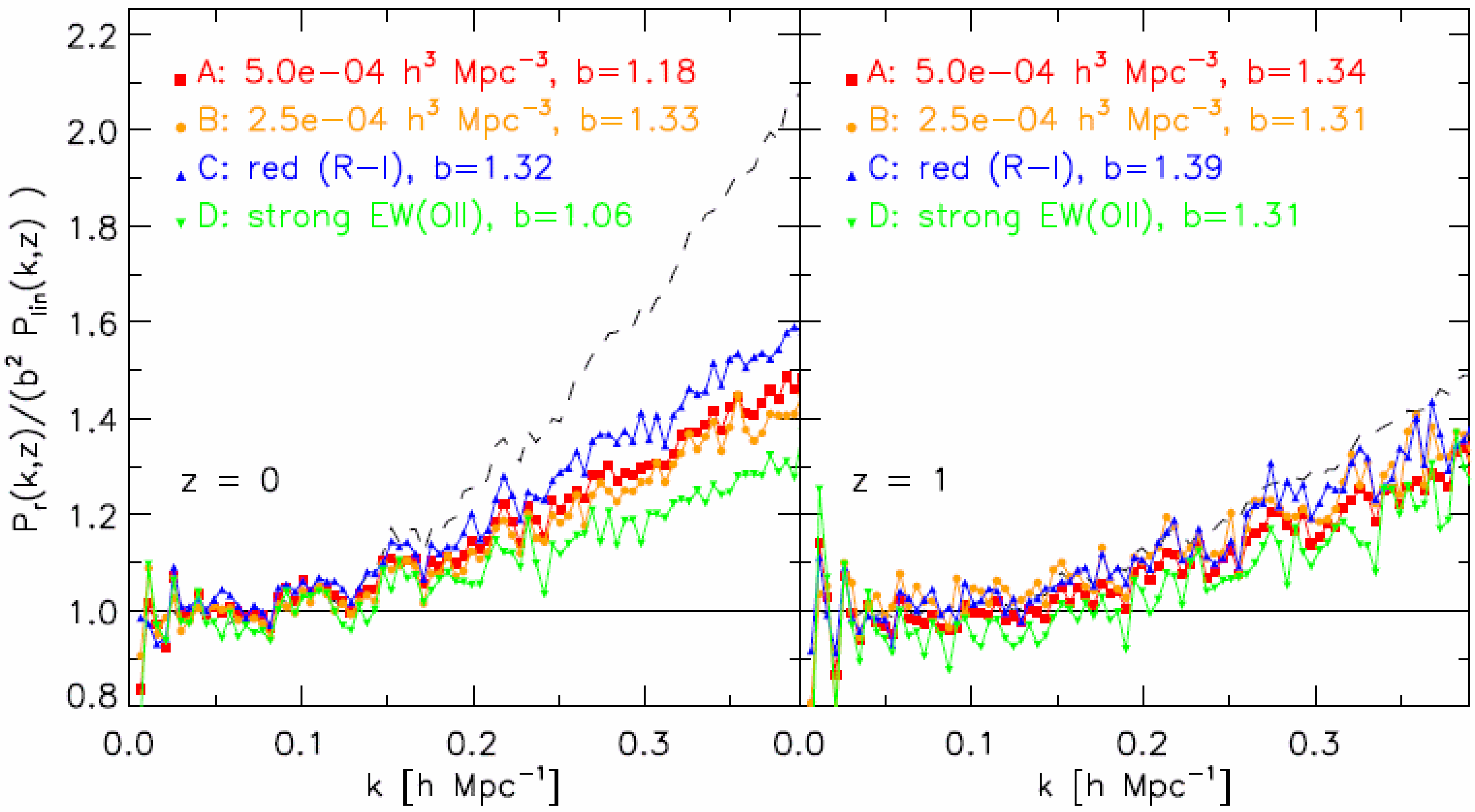


H-band selection

z=1

Orsi et al. 2009

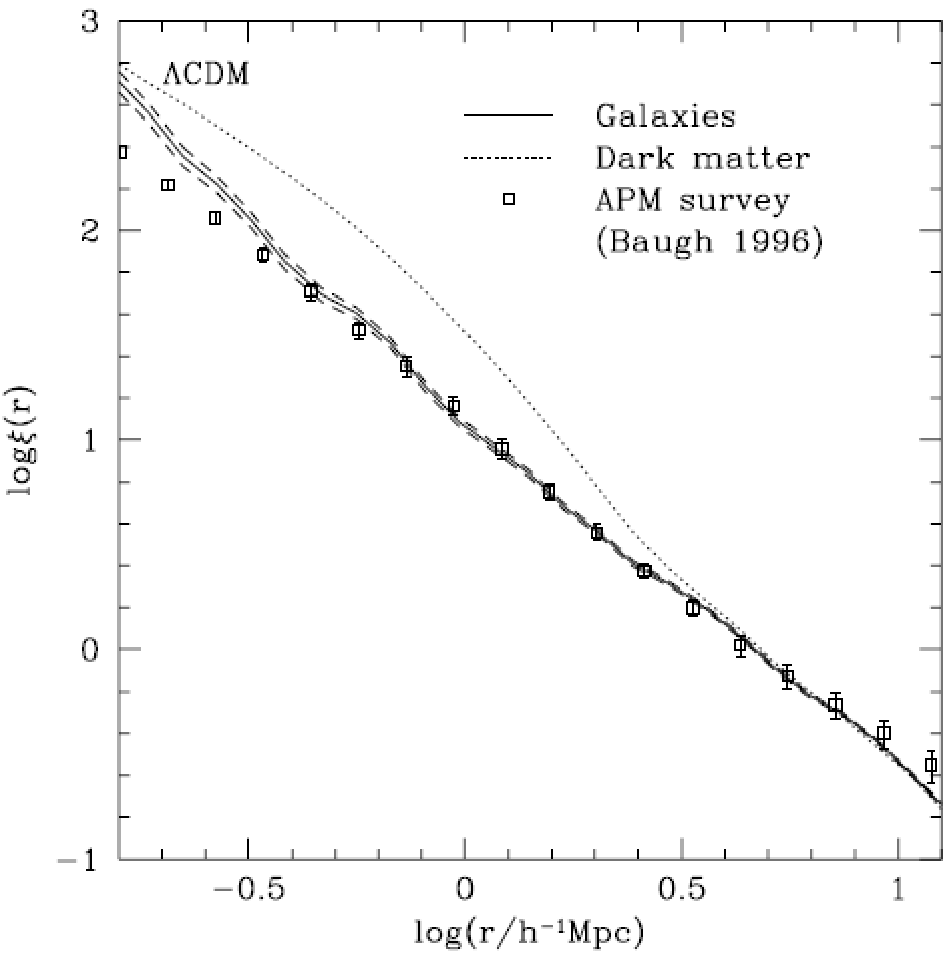
Bias for different galaxy samples



Driven by prediction for N(M) by following baryonic physics

Angulo et al. 2008

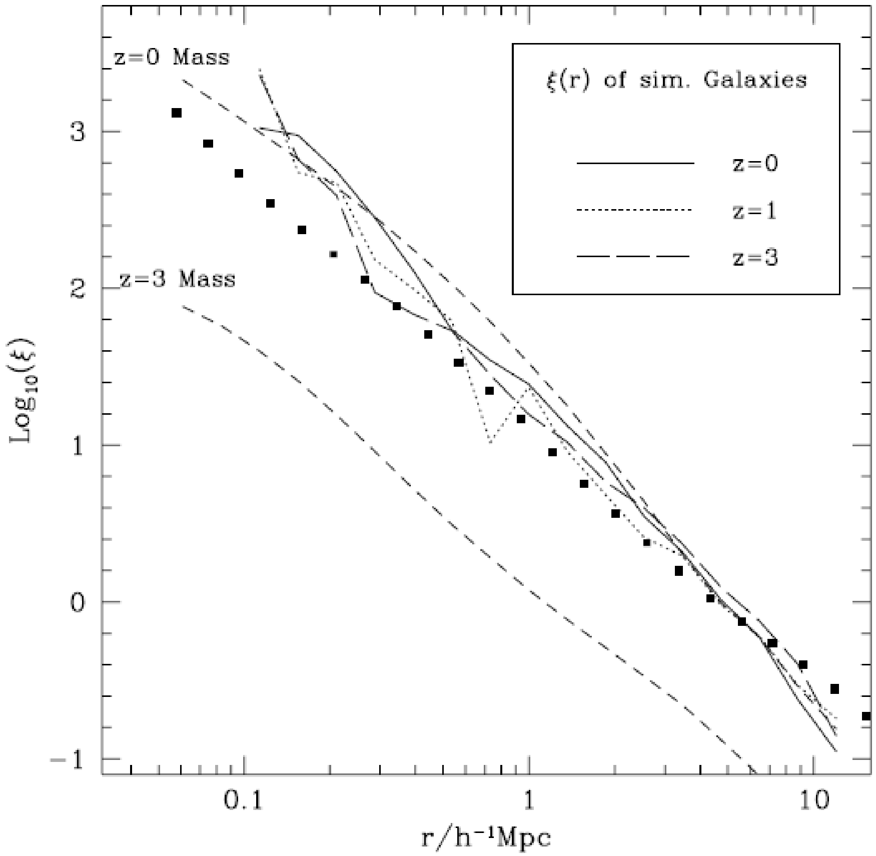
Galaxy clustering in SAMs



- Models that match LF give robust predictions for correlation function
- Can recover power-law simply by predicting number of galaxies per halo

Benson et al. 2000
Kauffmann et al. 1999a, b

Galaxy clustering from gas dynamics



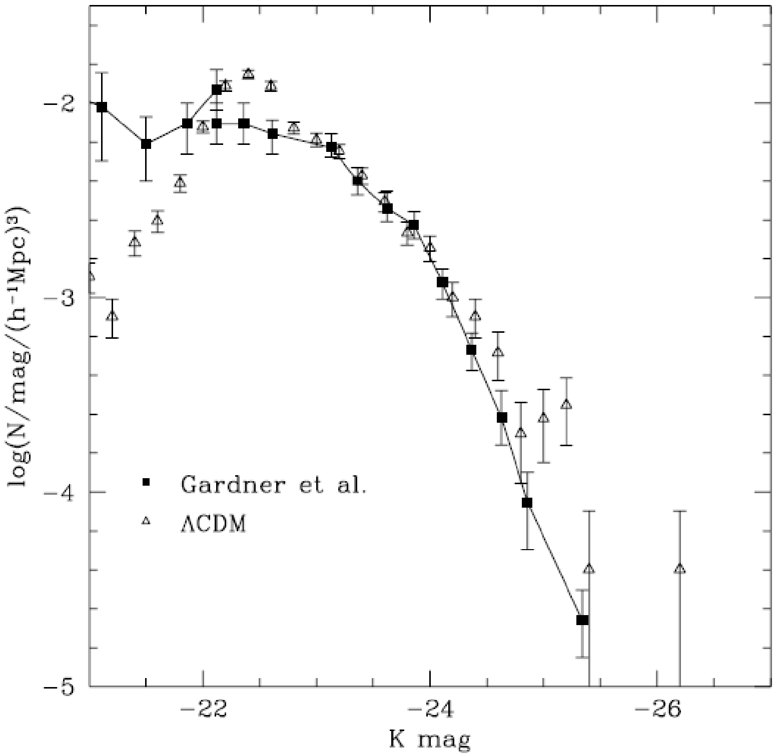
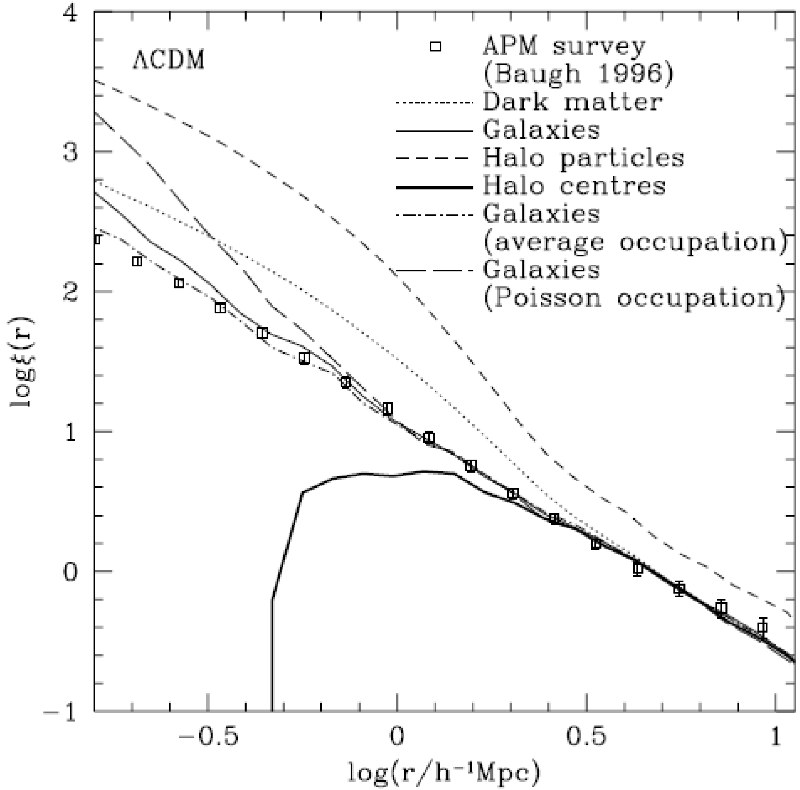
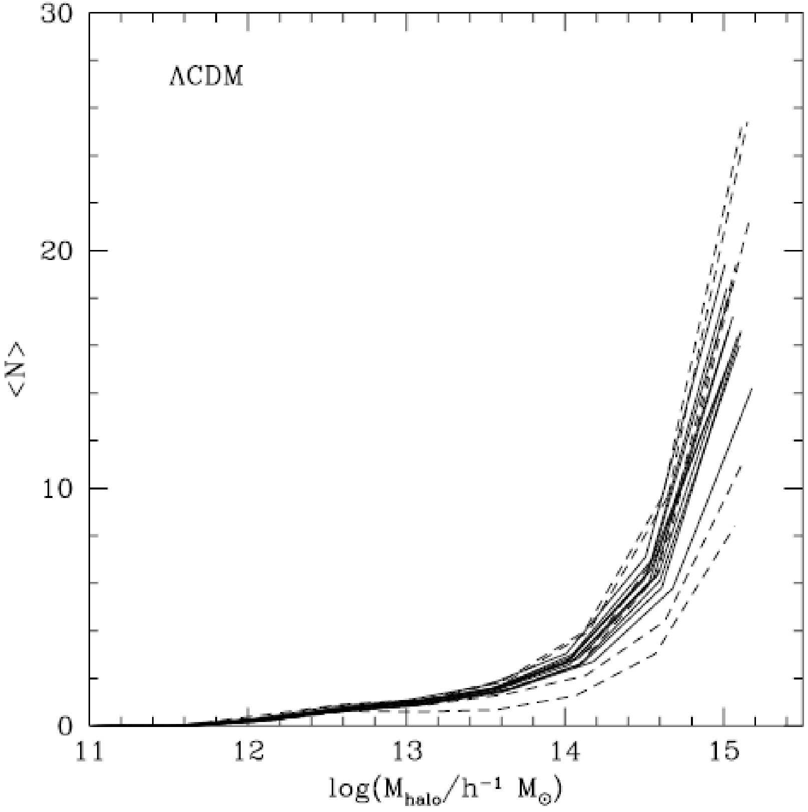


Fig. 3. A comparison between the K-band galaxy luminosity function in the simulation with observations. The simulation data are shown by open triangles and the data from Gardner *et al.* (1997) by filled squares. A luminosity normalization factor of $\Upsilon = 2.8$ has been assumed. Poisson errors are shown.

Pearce et al. 1999

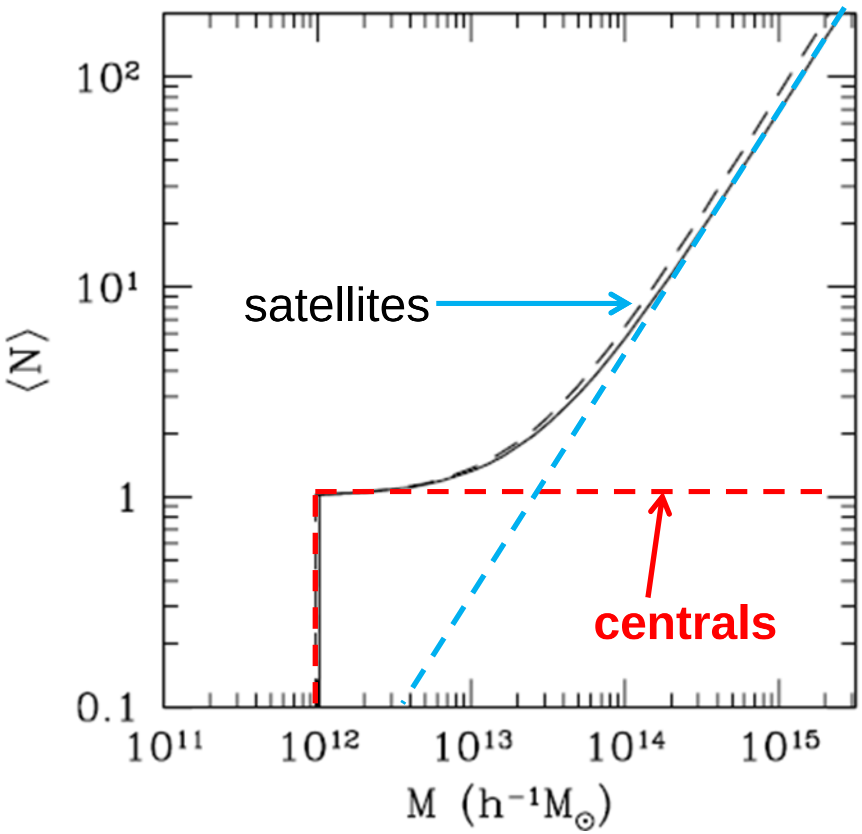
Explaining the form of the correlation function

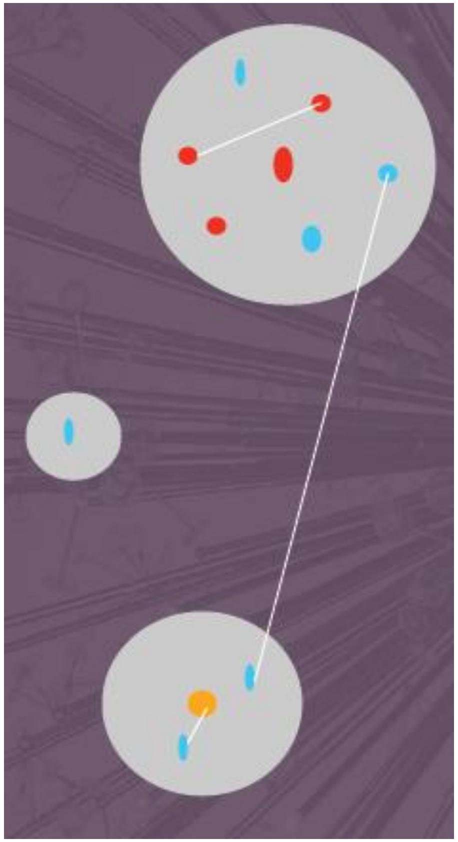




Benson et al. 2000

Halo Occupation Distribution



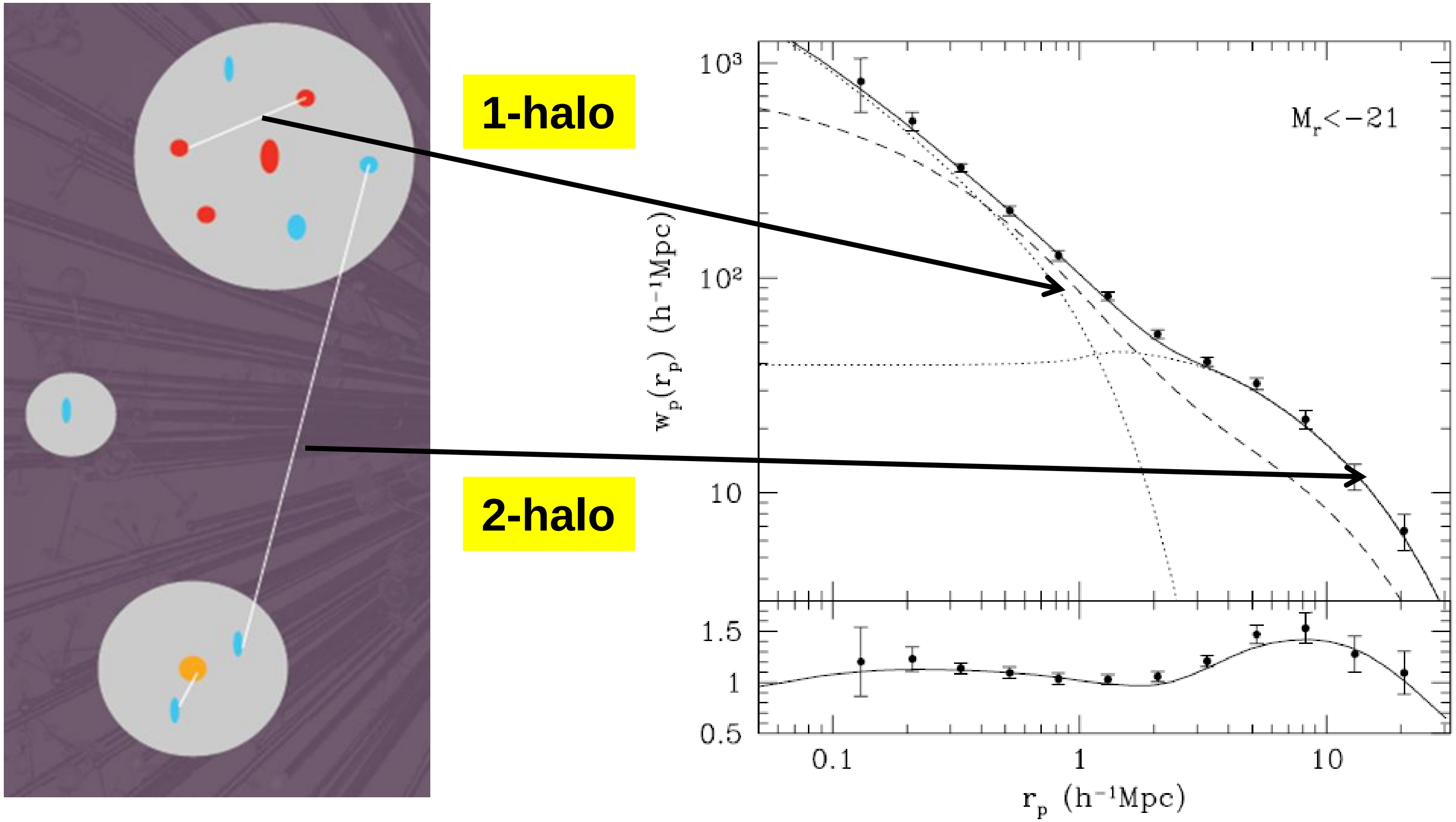


Break down galaxy clustering into contributions from pairs within same DM halo (1-halo term) and in different haloes (2-halo term)

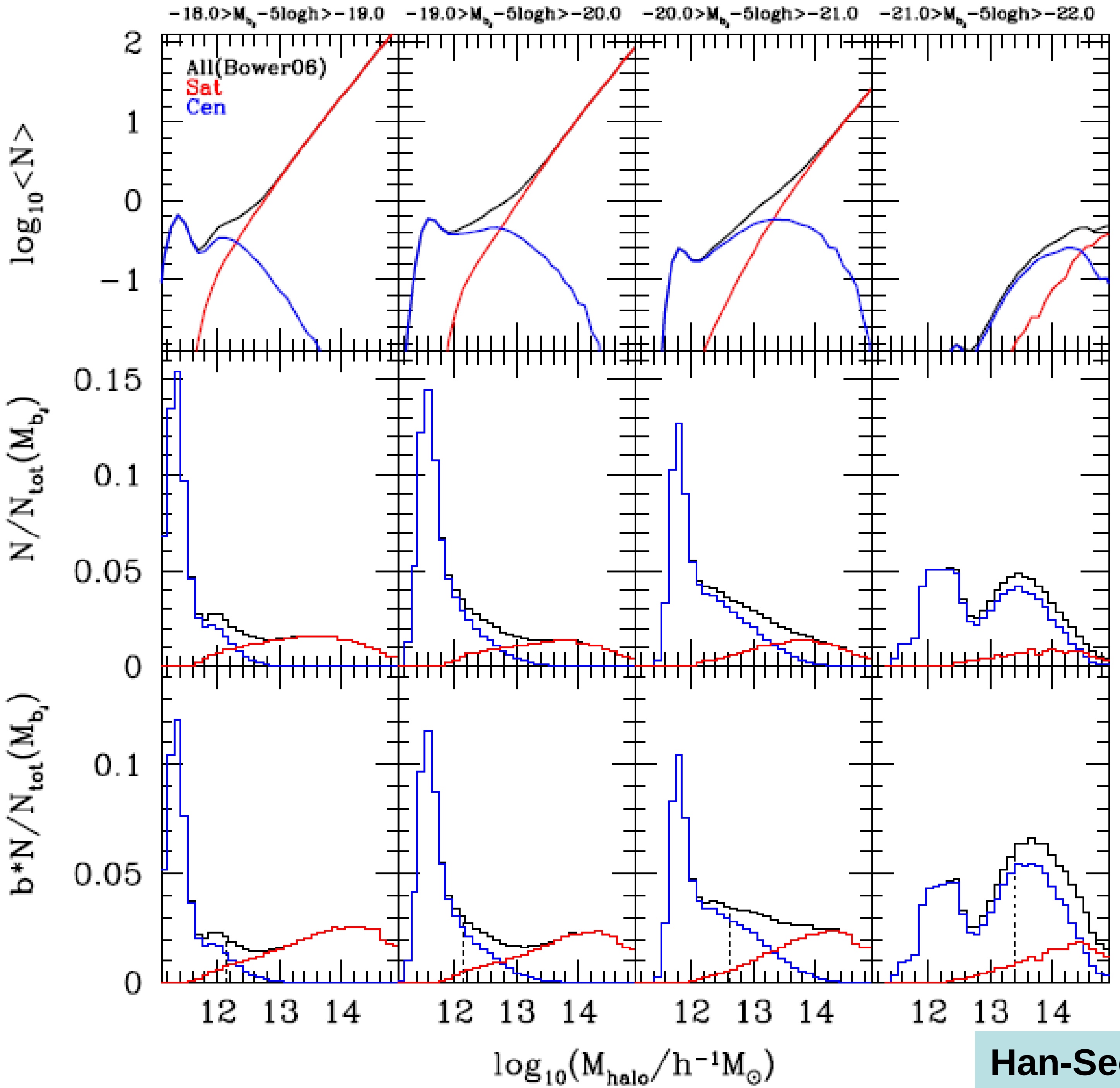
Zehvai et al. 2004, 2005; review by Sheth & Cooray 2002

David Weinberg

Halo Occupation Distribution



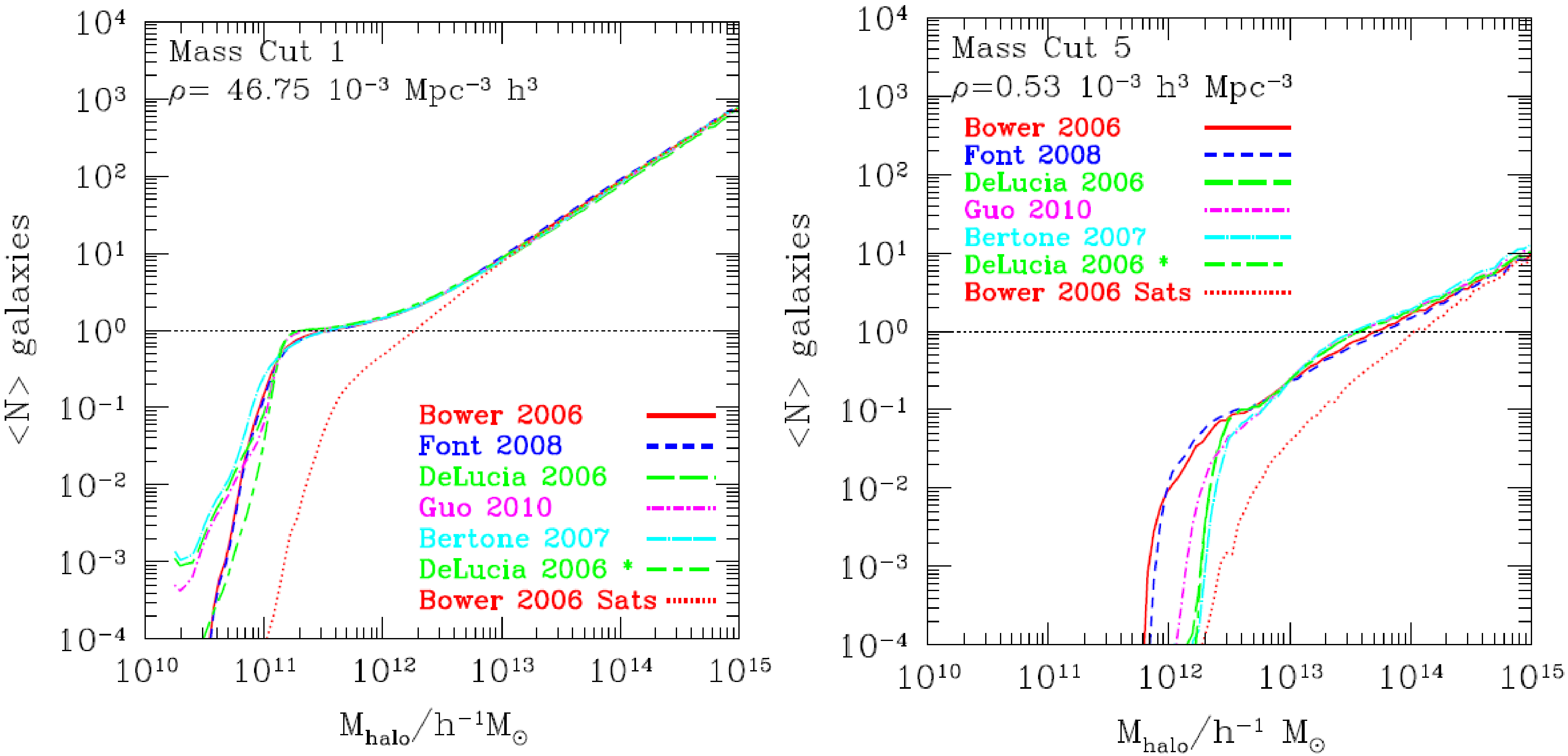
Zehvai et al. 2004, 2005; review by Sheth & Cooray 2002



Models predict HOD

Han-Seek Kim et al. 2009

How robust are the predictions from different SAMs?

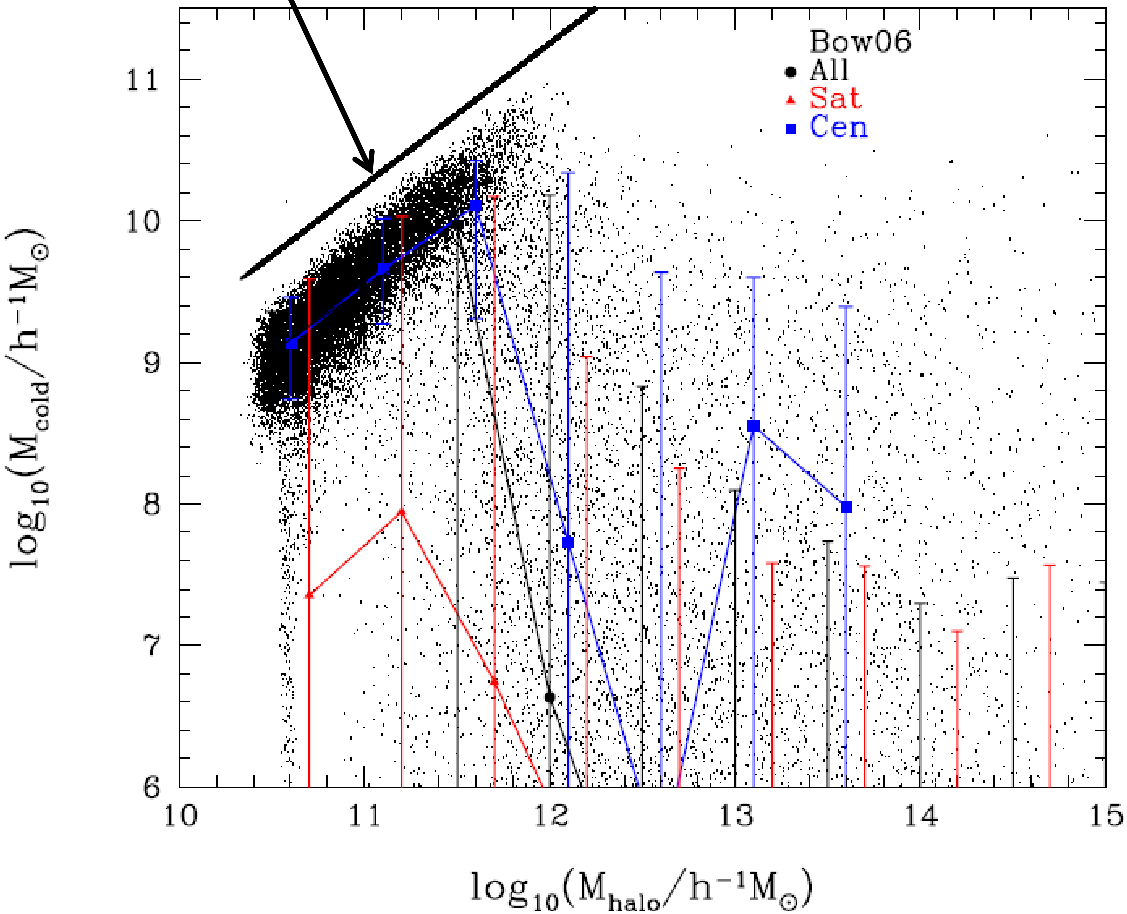


Contreras et al. 2012

Predict clustering for different selections: e.g. cold gas mass

Universal baryon fraction in cold gas in one object within halo

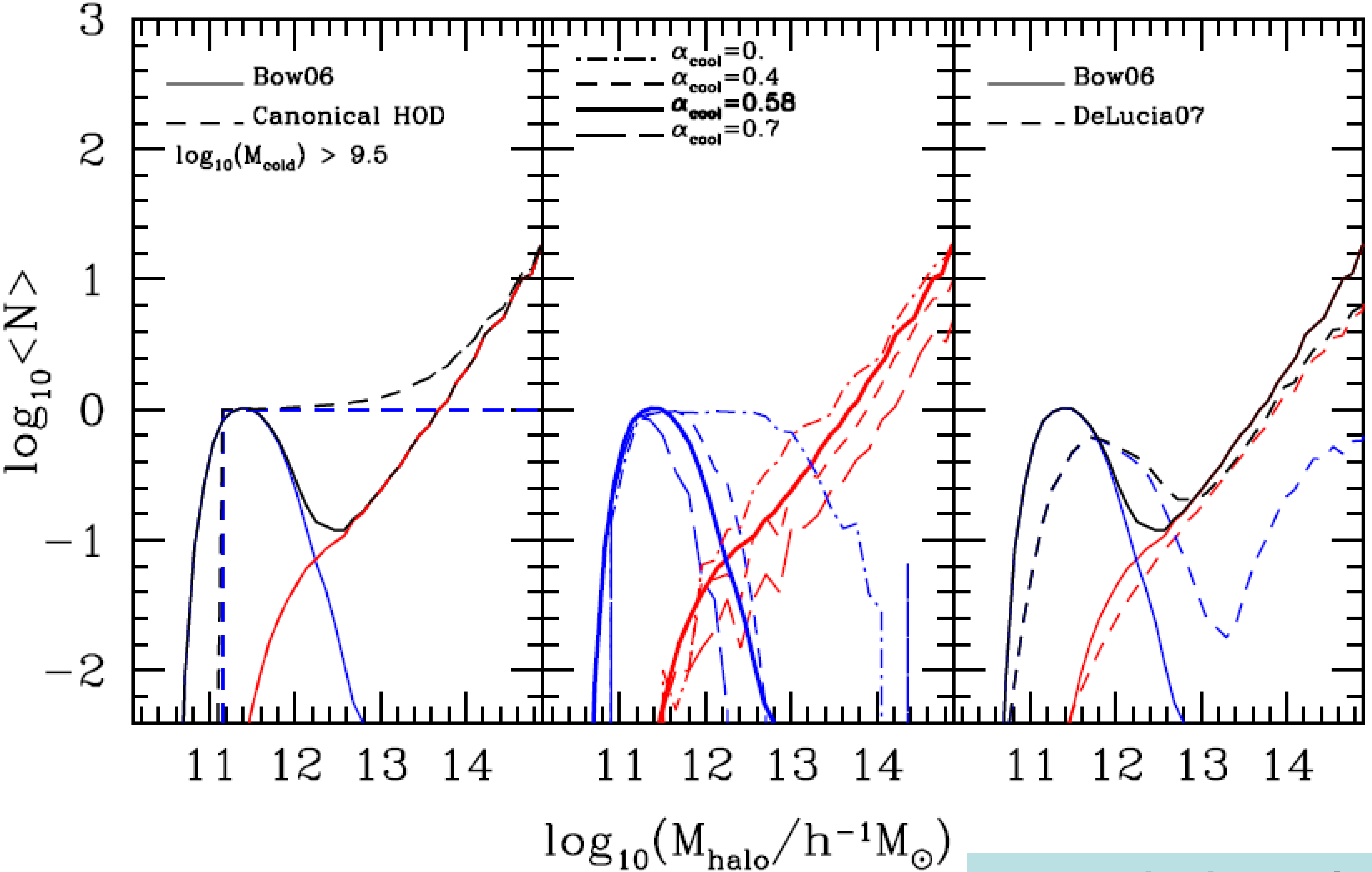
Galaxy cold gas mass



Mass of host DM halo

Han-Seek Kim et al. 2011

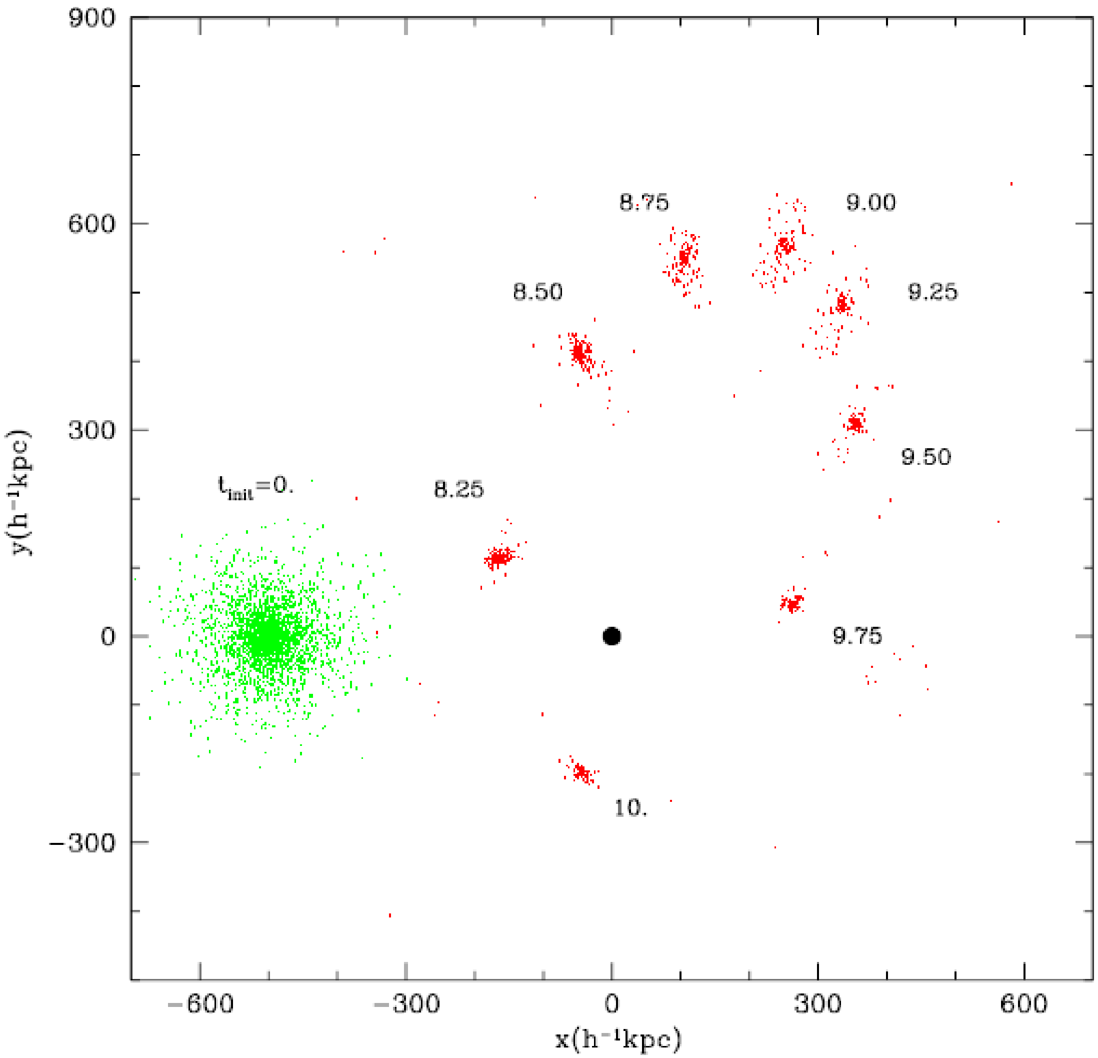
Predict HOD for cold gas samples



Han-Seek Kim et al. 2011

Associate galaxies with sub-haloes?

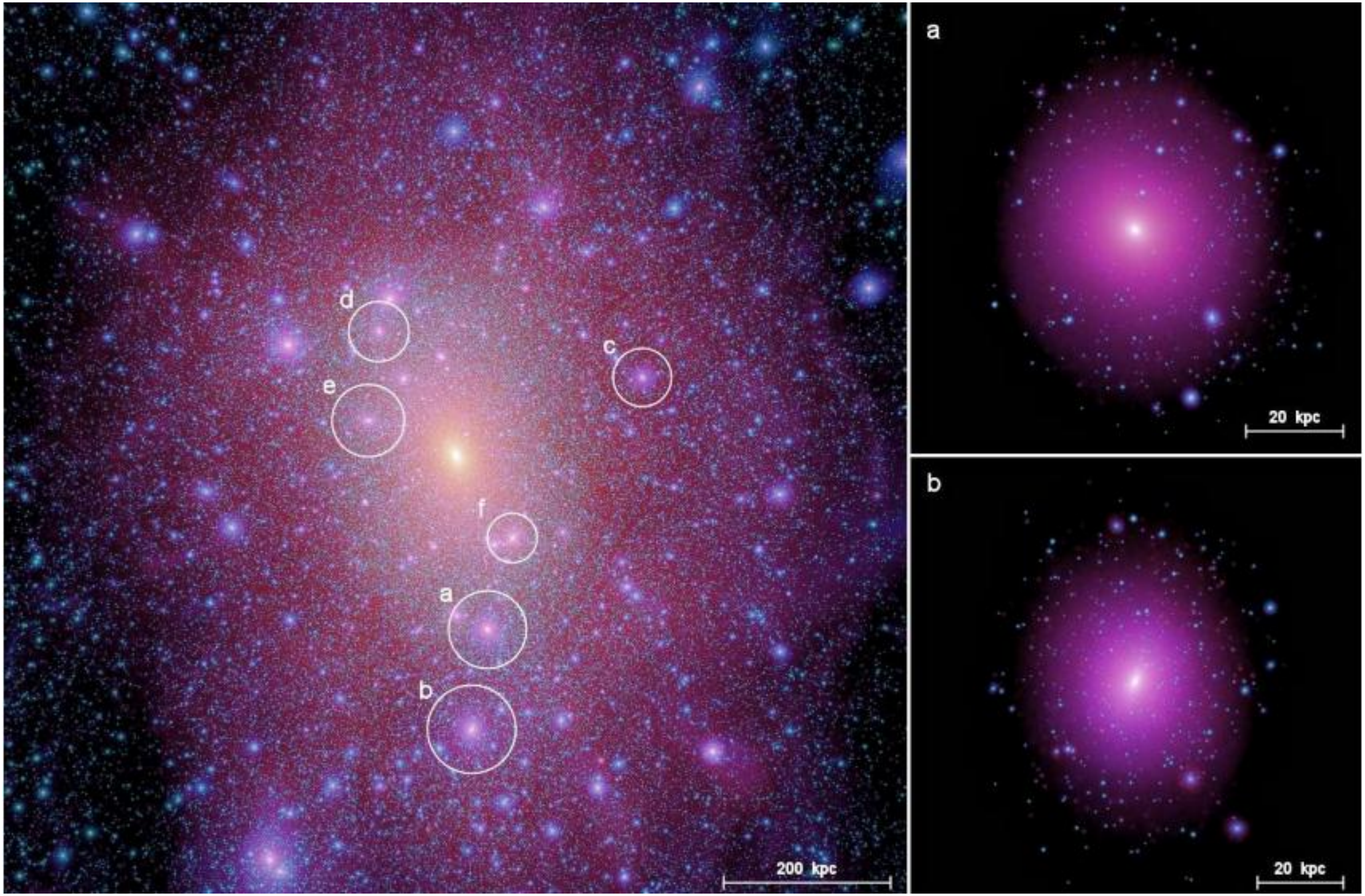
Avoiding "overmerging" of DM haloes



- Should we compare galaxies with haloes or subhaloes?
- Early simulations lacked mass & force resolution to follow subhalos

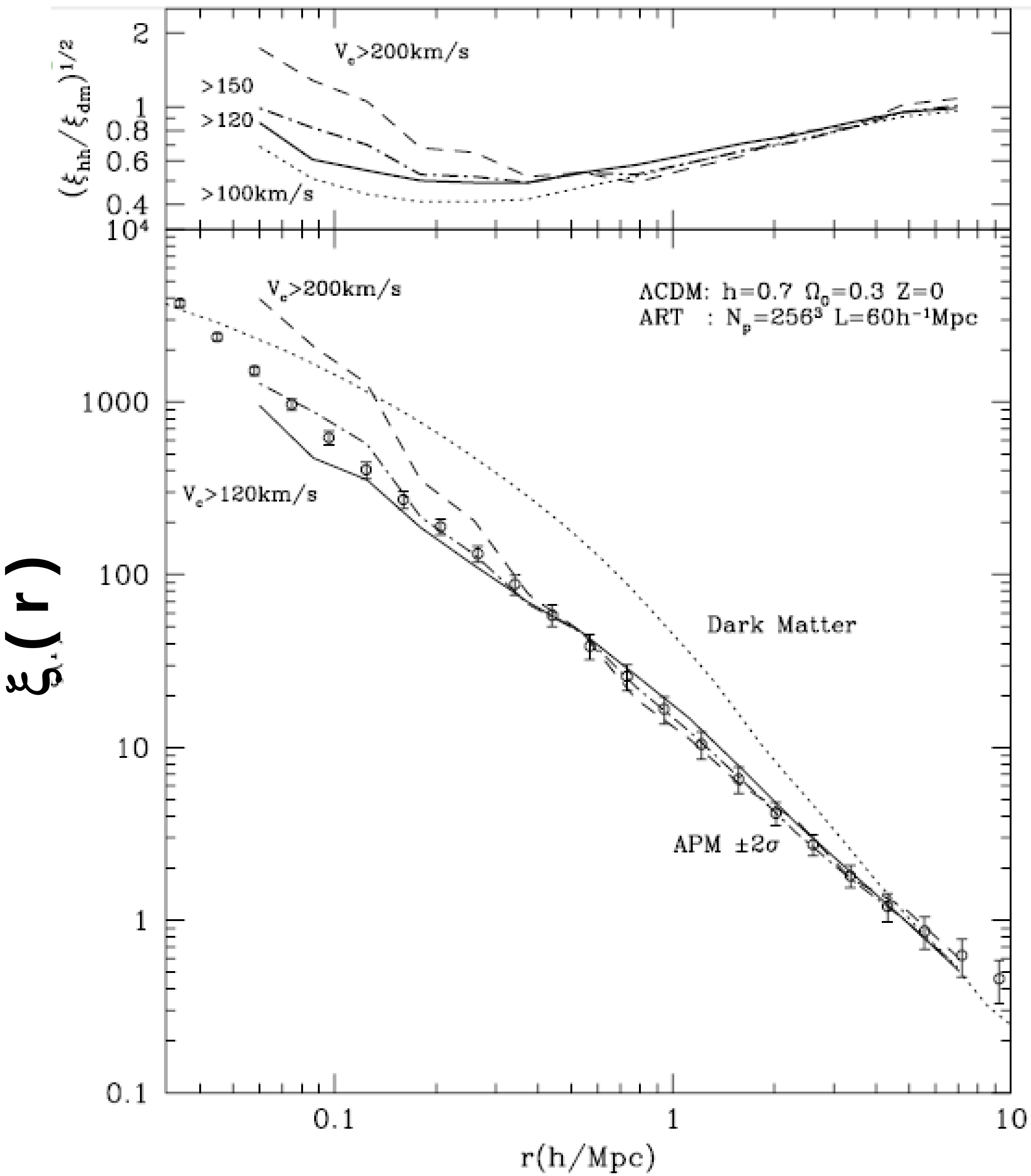
Klypin et al. 1999

Hierarchies of substructure



Springel et al 2008

Matching sub-haloes to "galaxies"



- Put cut on subhalo circular velocity
- Associate subhaloes with galaxies
- Early version of SHAM

Colin et al. 1999
Klypin et al. 1999
Kravtsov et al. 2004

SHAM – sub-halo abundance matching

KEY ASSUMPTIONS:

- Assume a monotonic relation between (sub)halo mass and galaxy luminosity

(Vale & Ostriker 2004; 2006; 2008)

$$n_S(> M_S) = n_H(> M_H)$$

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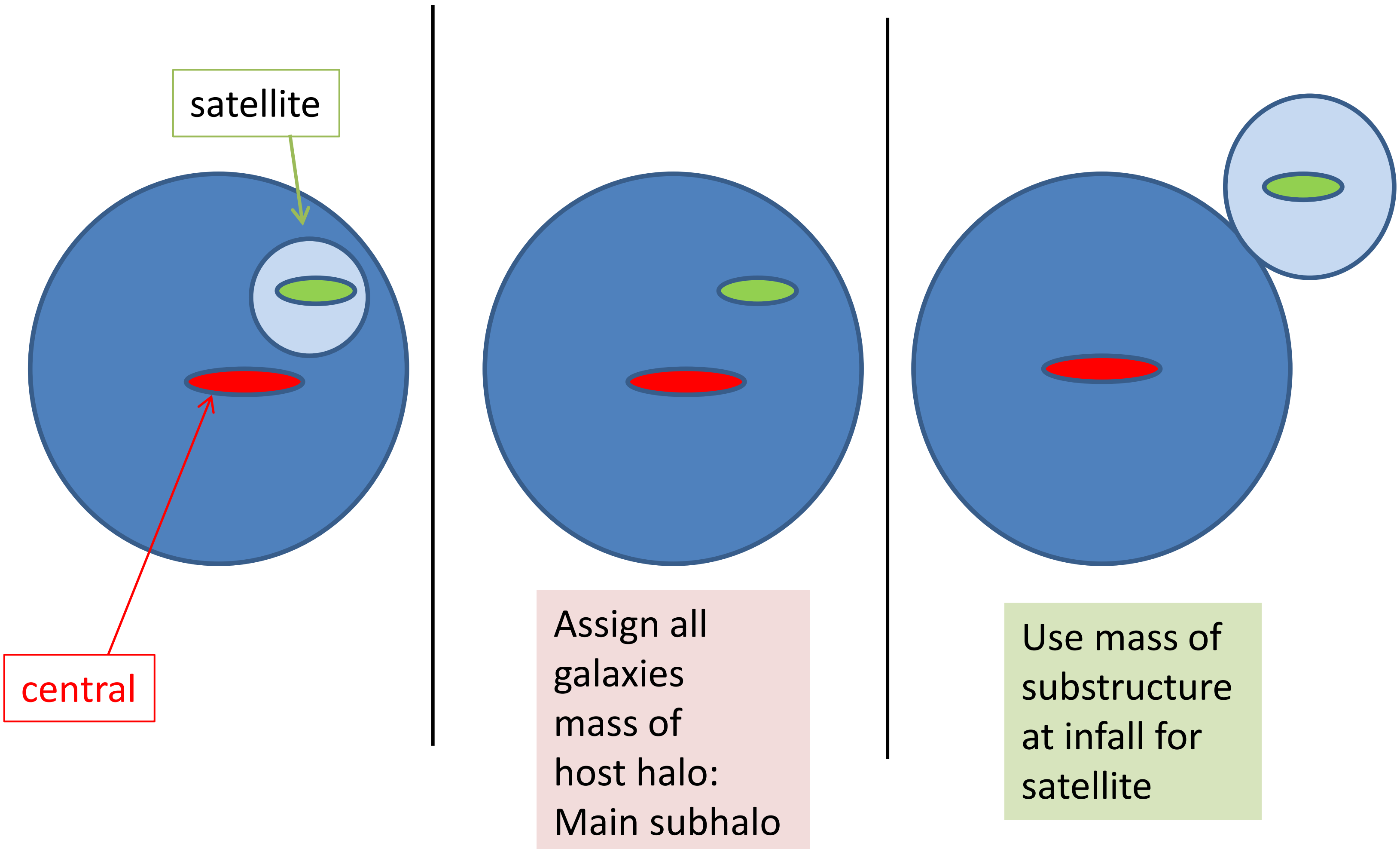
Which halo mass to assign?



SHAM – sub-halo abundance matching

KEY ASSUMPTIONS:

- Assume a monotonic relation between (sub)halo mass and galaxy luminosity

  (Vale & Ostriker 2004; 2006; 2008)

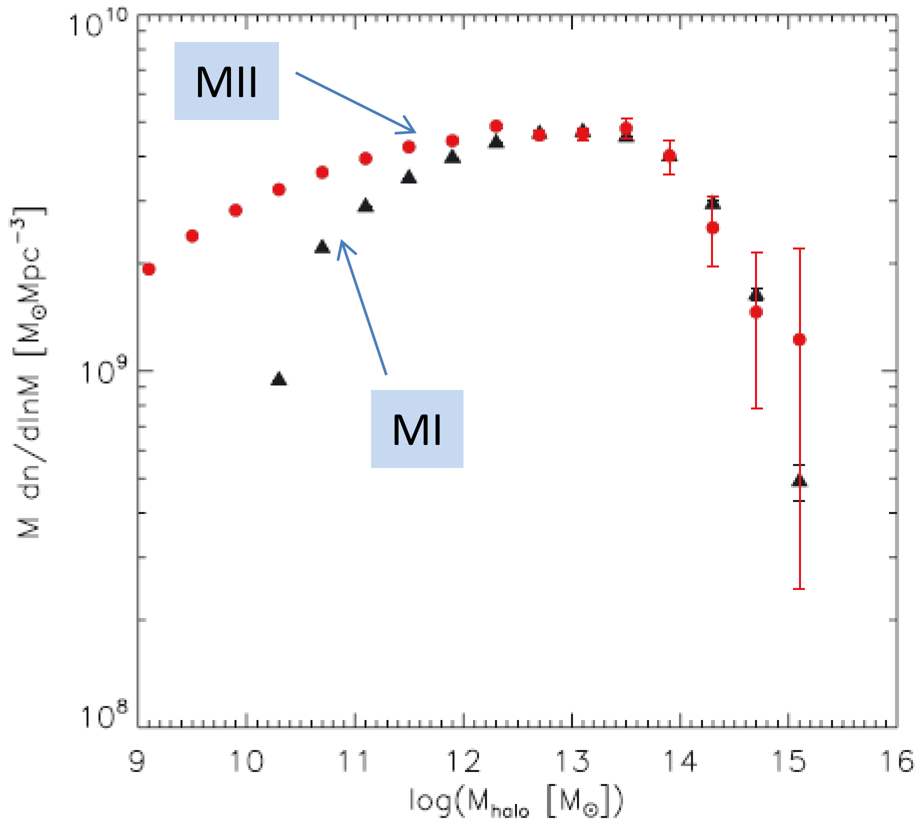
$$n_S(> M_S) = n_H(> M_H)$$

- For central galaxy, use host halo mass
- For satellite galaxies, use sub-halo mass at time of accretion (Kravtsov et al 2004; Nagai & Kravtsov 2005)

$$M_H = \begin{cases} M_{\rm halo}(z=0) & \text{for distinct halos,} \\ M_{\rm halo}(z=z_{\rm sat}) & \text{for subhalos,} \end{cases}$$

SHAM in action

(sub)halo mass function



- Use SDSS stellar mass function
- Use Millennium simulations (sub)halo mass functions
- Need to resolve subhalos
- Guo et al. 2010

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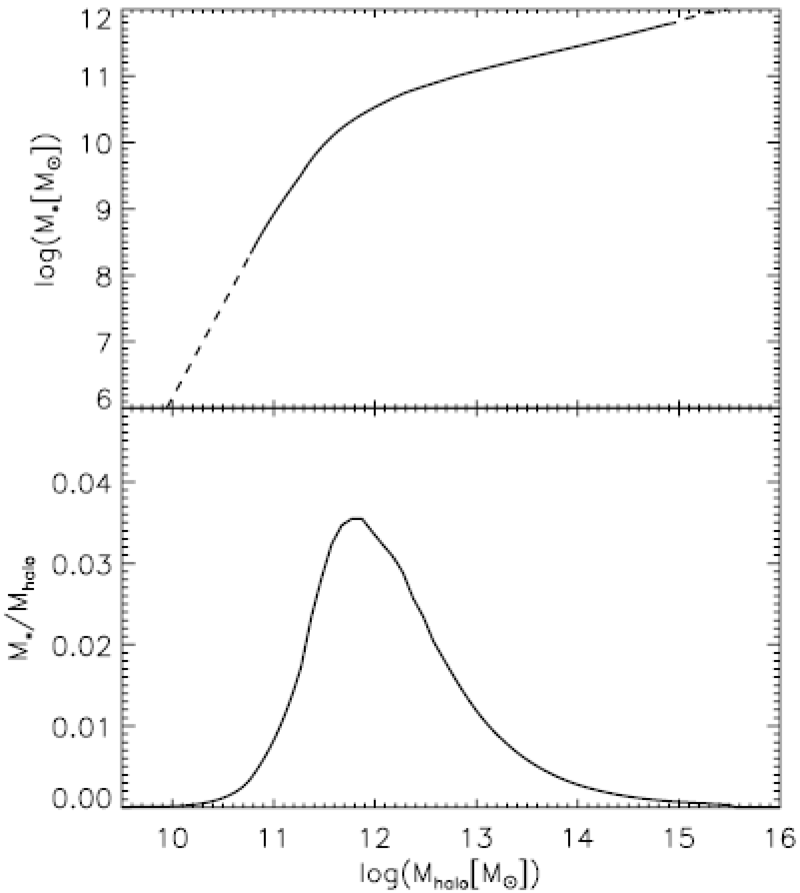
Which galaxies are in which halos?

Stellar mass

Stellar mass/halo mass



(sub)halo mass

- Match SDSS obs. stellar mass function to Millennium subhalos using SHAM
- Peak in M*/Mhalo
- Guo et al. 2010

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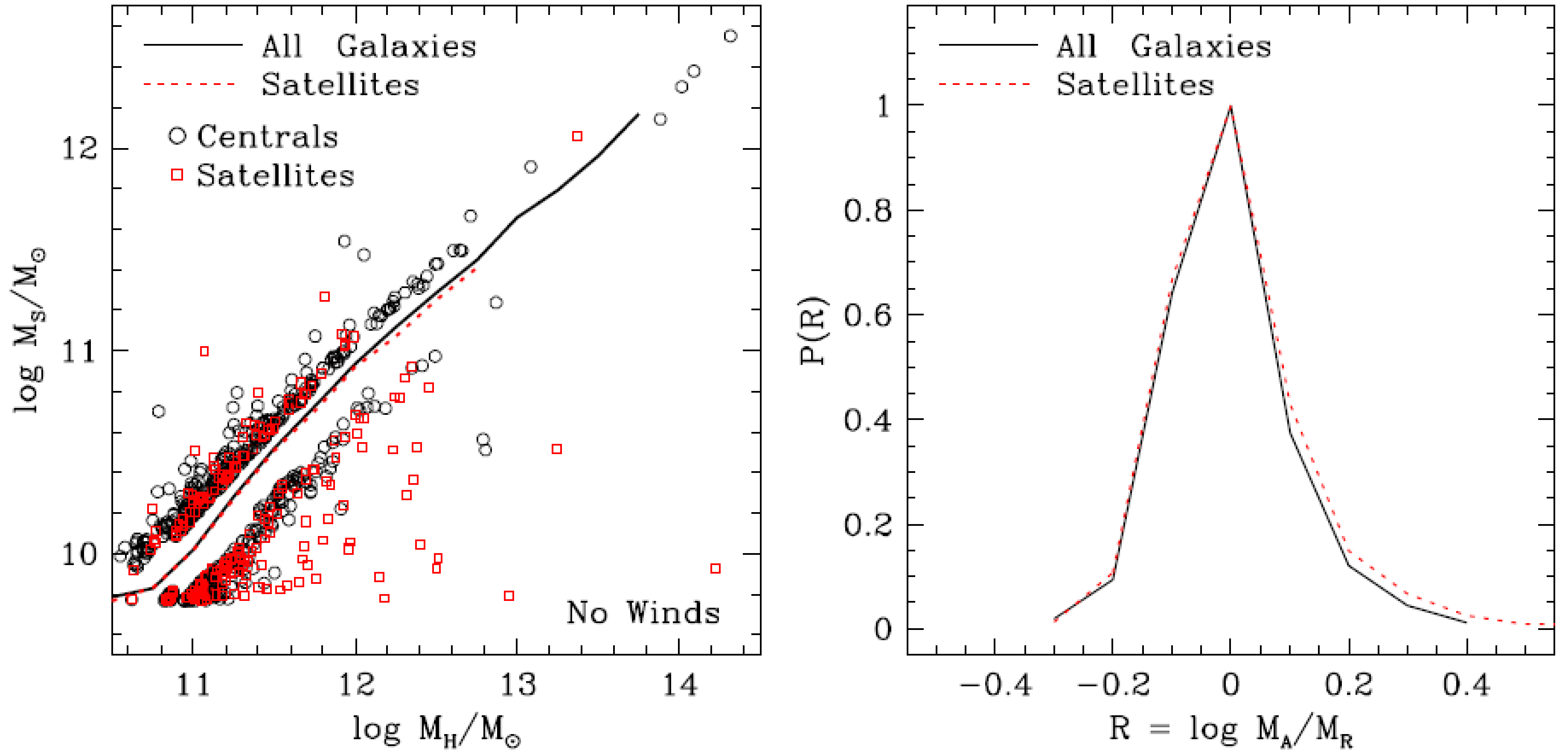
Testing SHAM with simulations



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SPH simulations Simha et al. 2011

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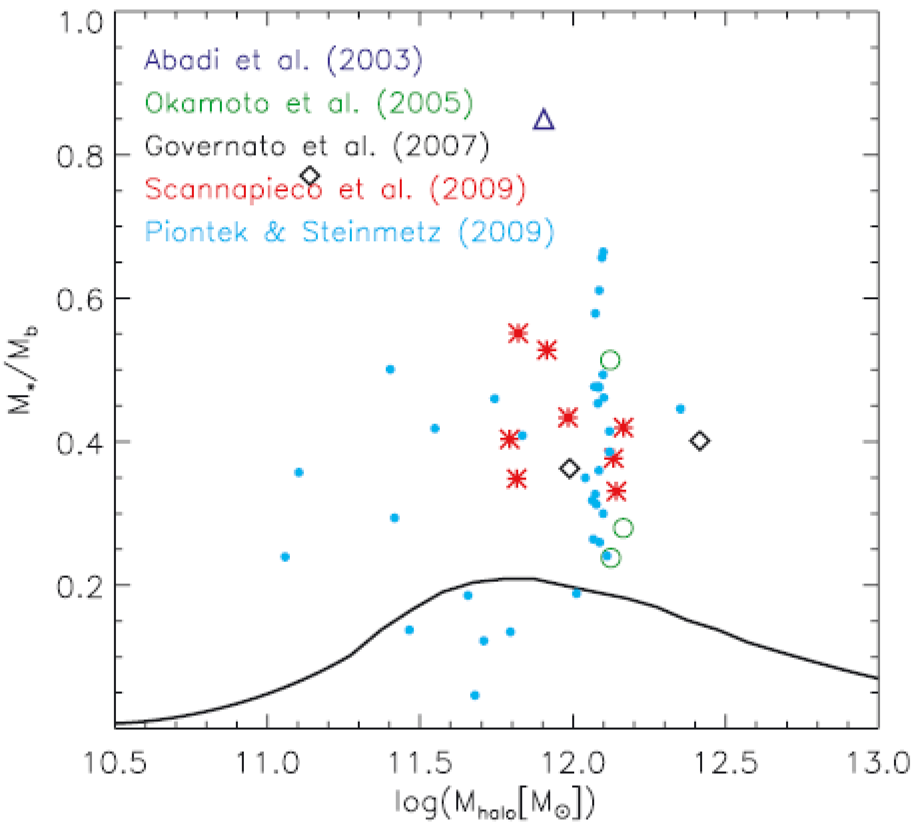
Stellar fraction in gas simulations

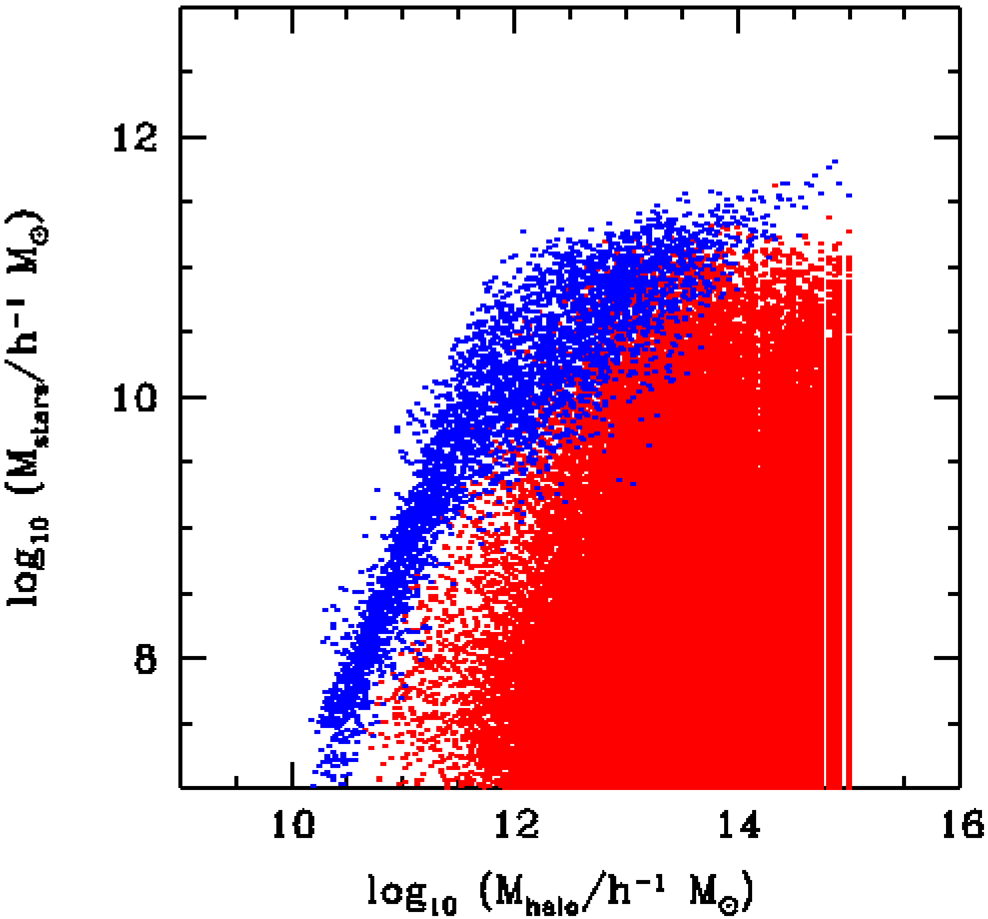


SPH runs tend to convert too many baryons to stars

Guo et al. 2010

SHAM in SAM
Stellar mass vs **host** halo mass

Stellar mass



centrals

satellites

Bower et al. 2006
z=0

Host halo mass

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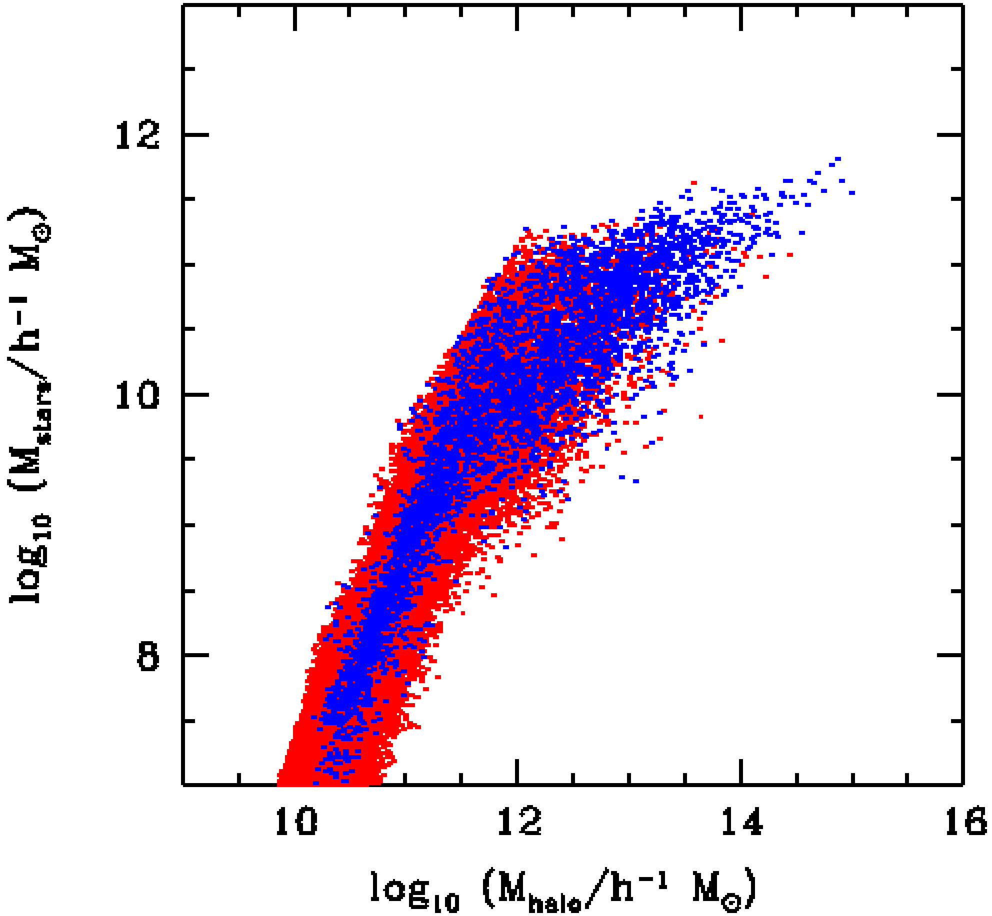
SHAM in SAM:
Stellar mass vs (sub)halo mass

Stellar mass



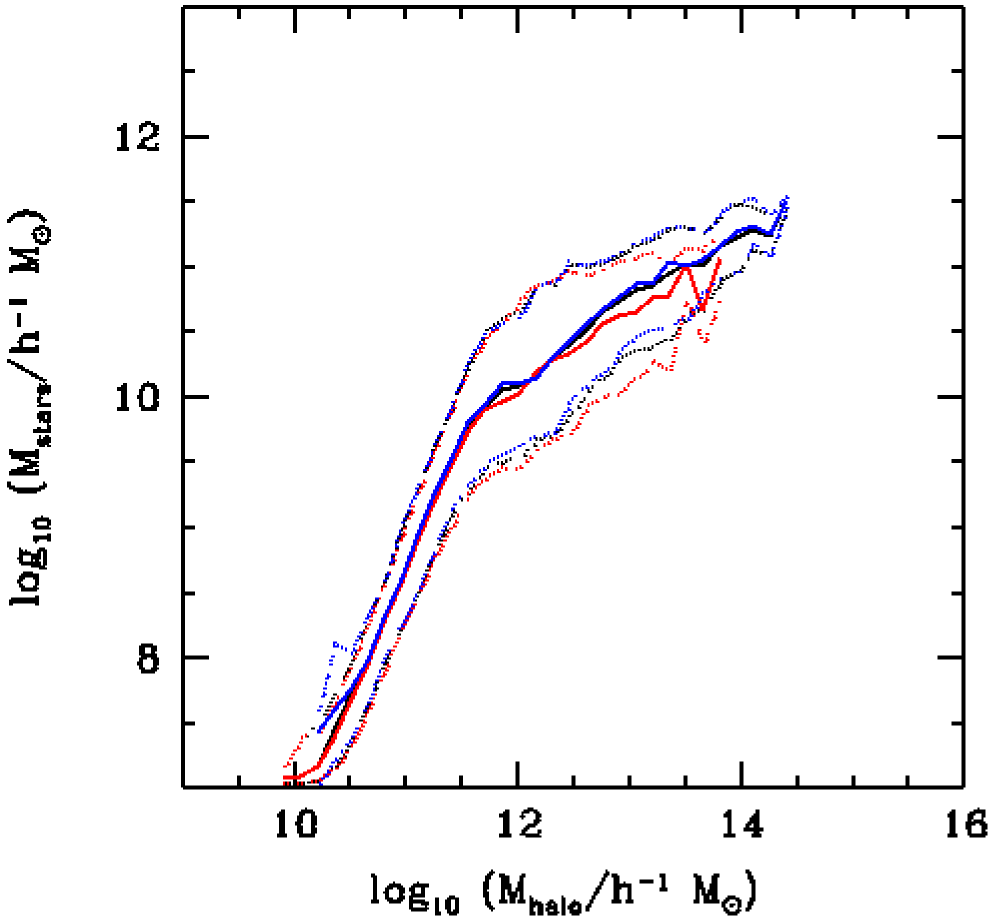
centrals

satellites

Bower et al. 2006
z=0

(sub)halo mass

SHAM in SAM:
Stellar mass vs (sub)halo mass



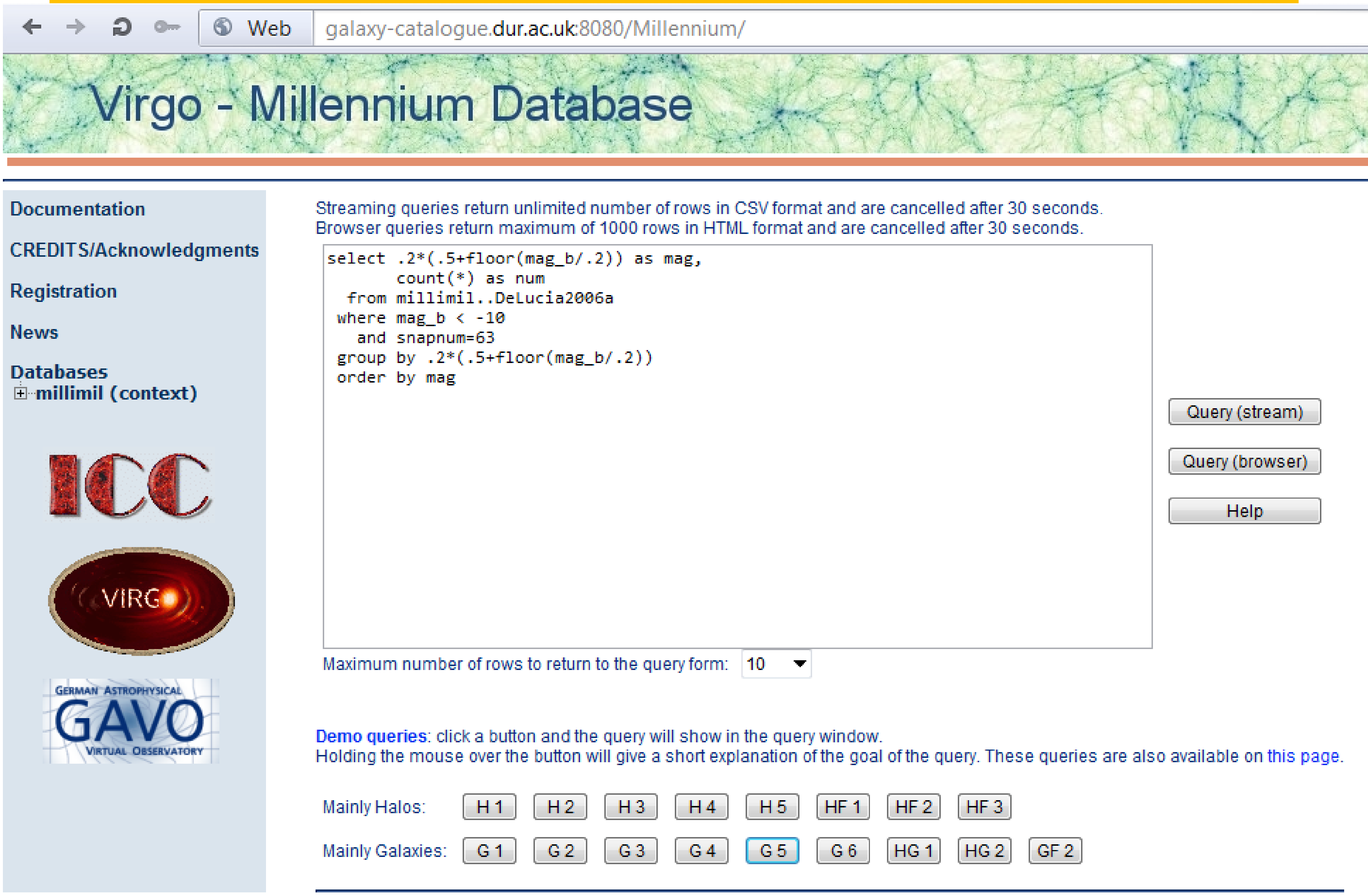
centrals

satellites

all galaxies

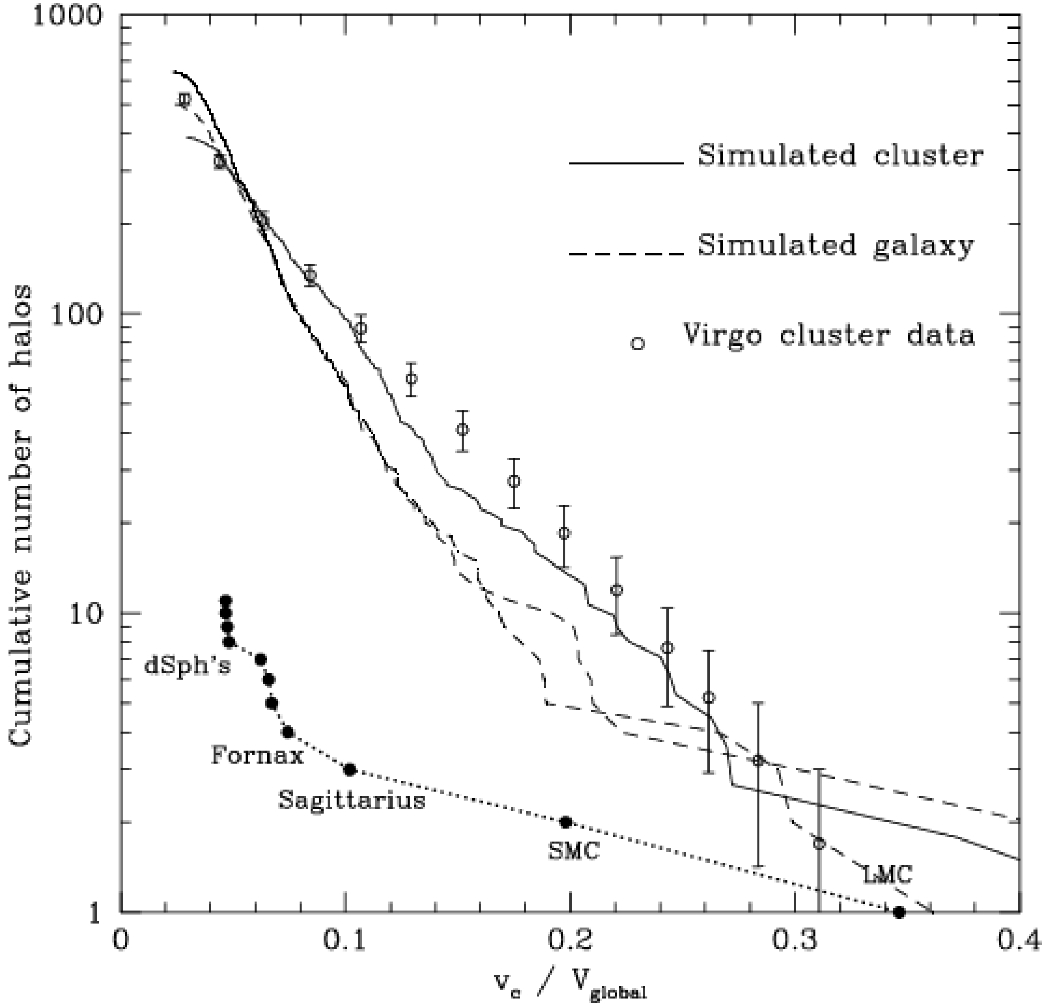
Medians, 10-90 percentile limits

http://galaxy-catalogue.dur.ac.uk:8080/Millennium/



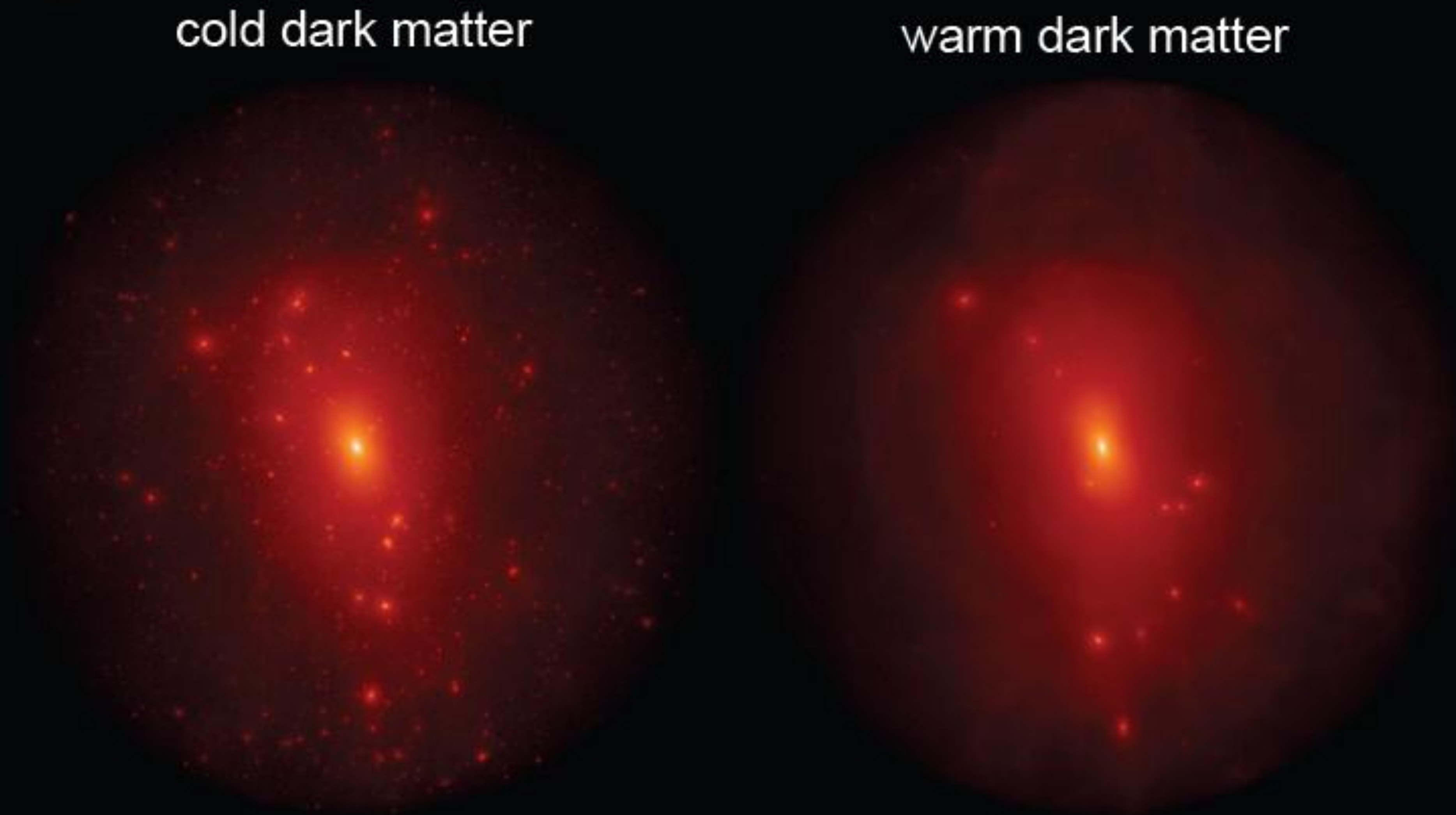
Some outstanding problems in galaxy formation

Is substructure a problem for CDM?



Moore et al 1999

Particle physics solution?



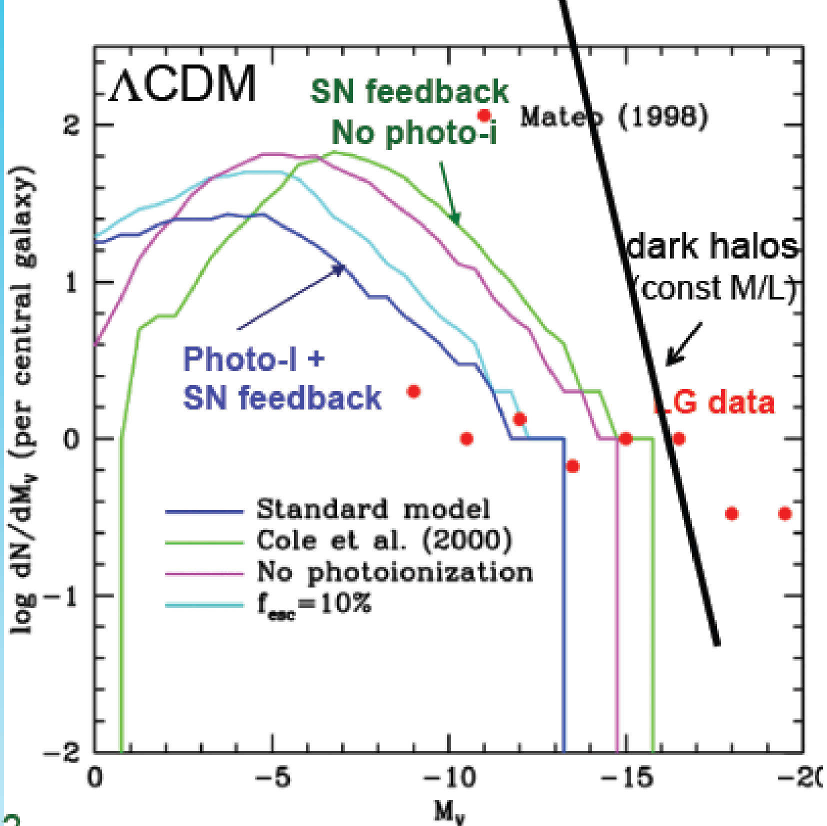
Lovell, Frenk, Gao et al 2011

Astrophysical solution?

University of Durham

Luminosity Function of Local Group Satellites

- Photoionization inhibits the formation of satellites
- Abundance of satellies reduced by large factor!
- Median model gives correct abundance of sats brighter than M_V=-9, V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites

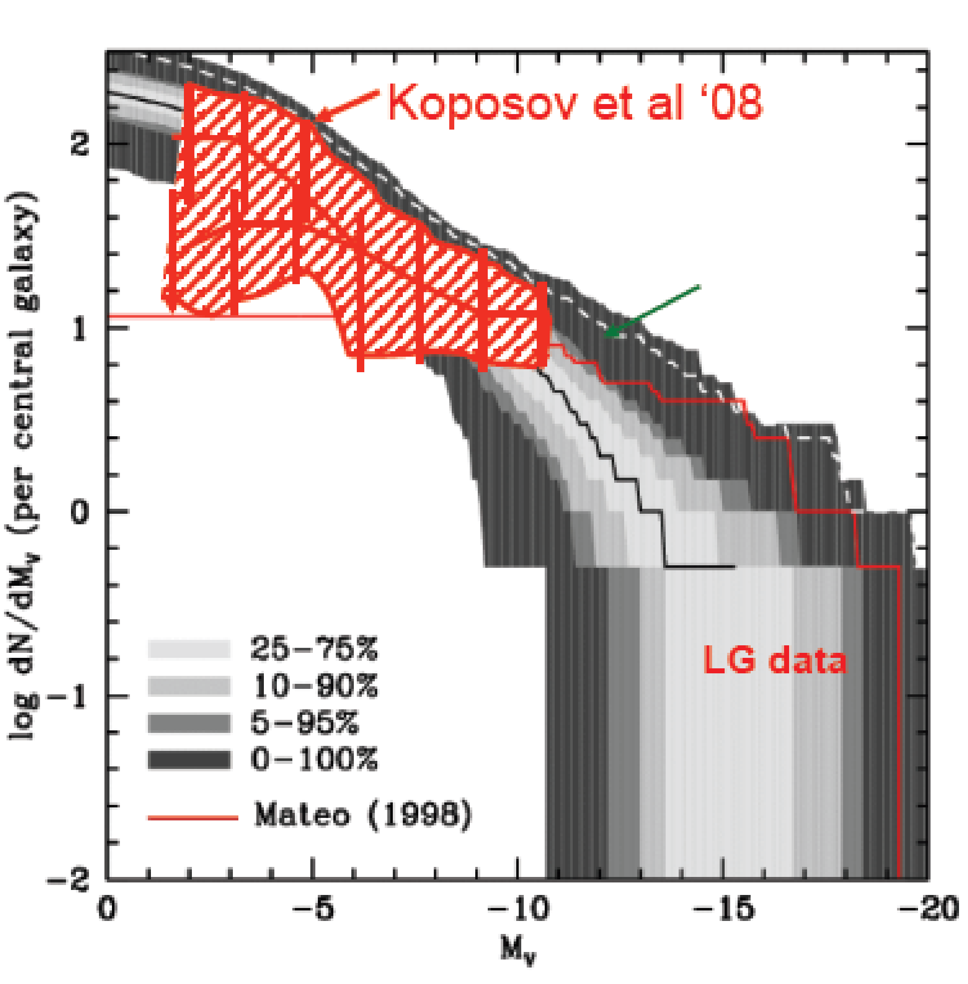


Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

Institute for Computational Cosmology

Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02

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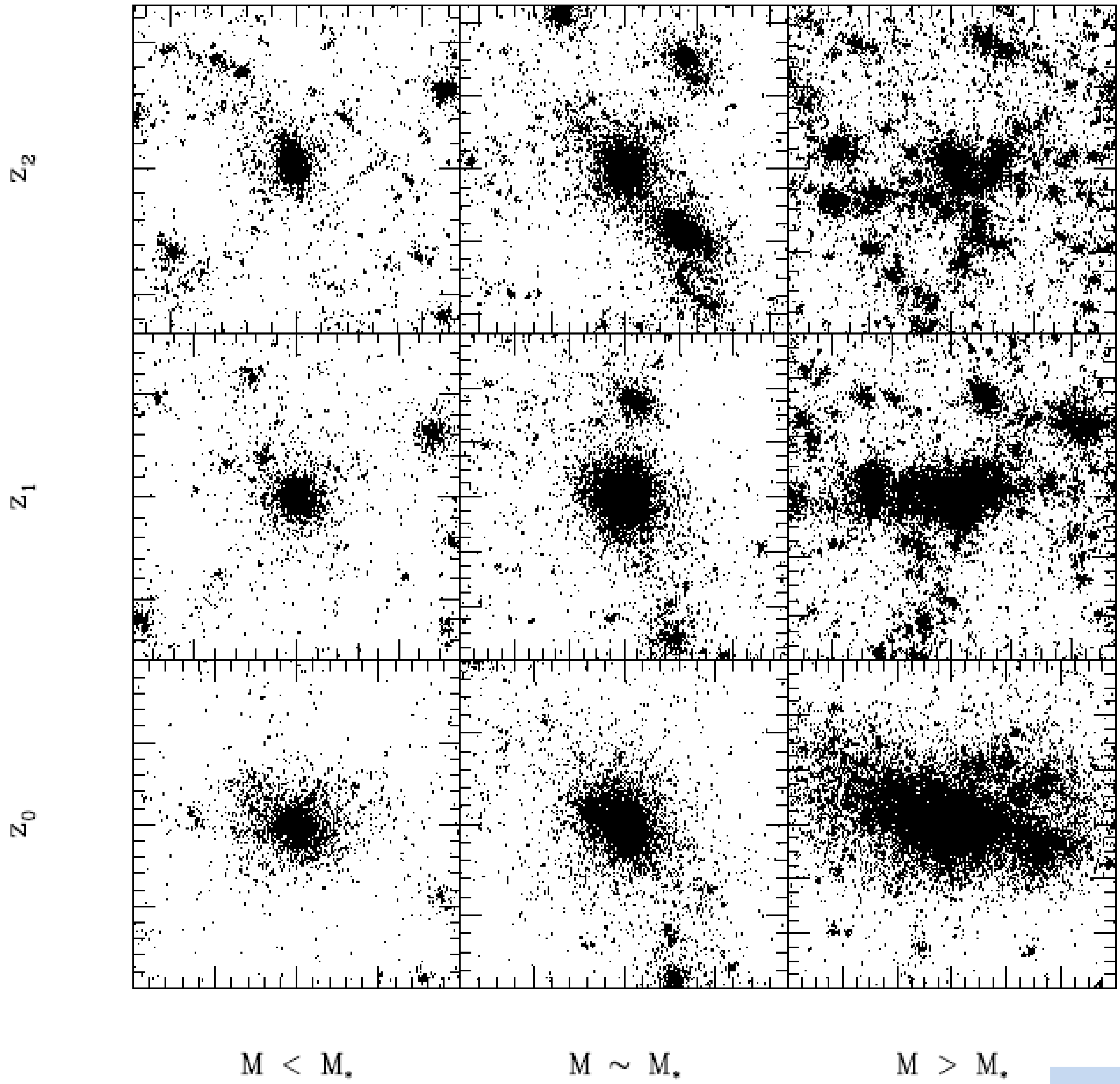
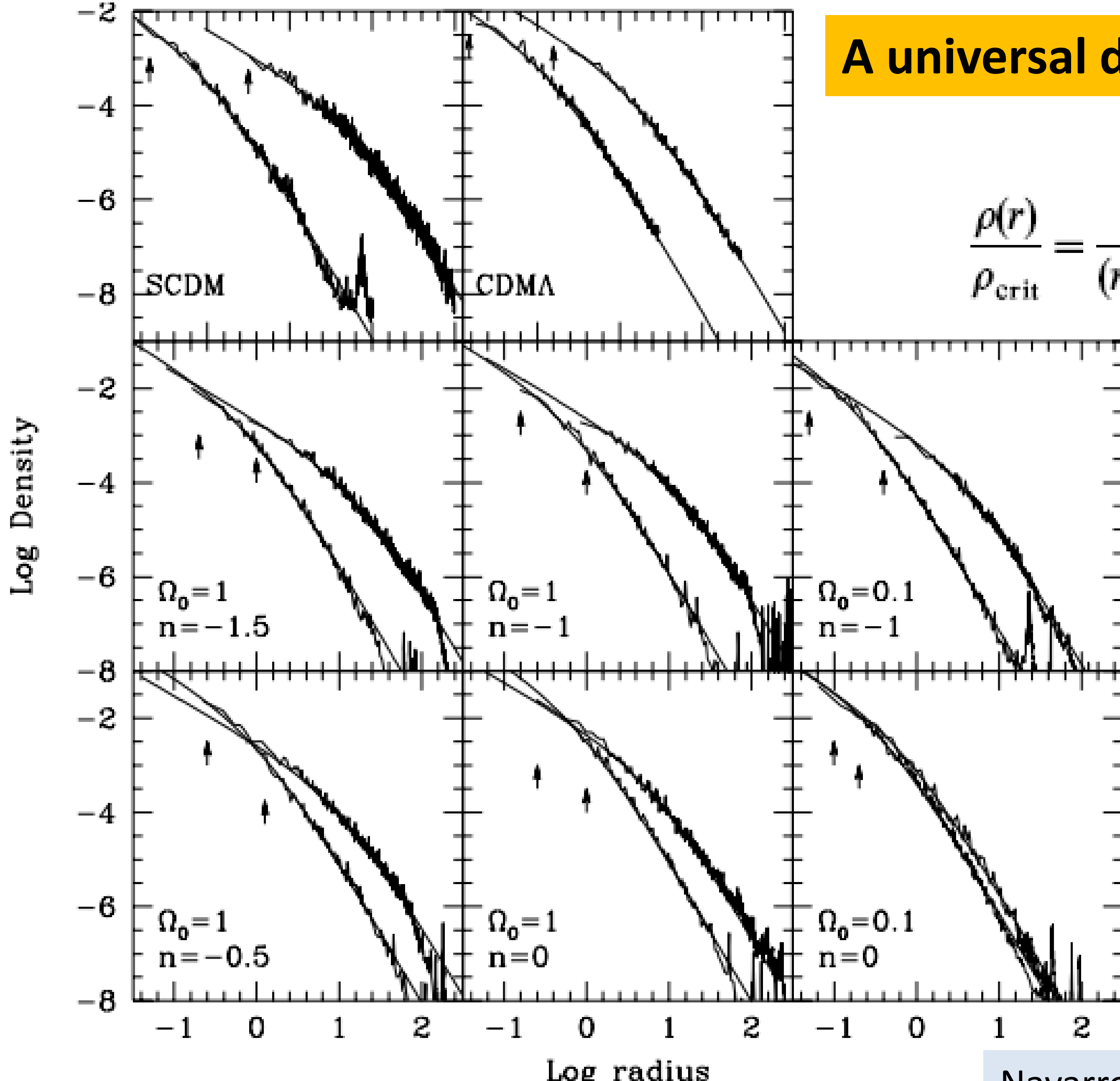


The assembly of DM Haloes

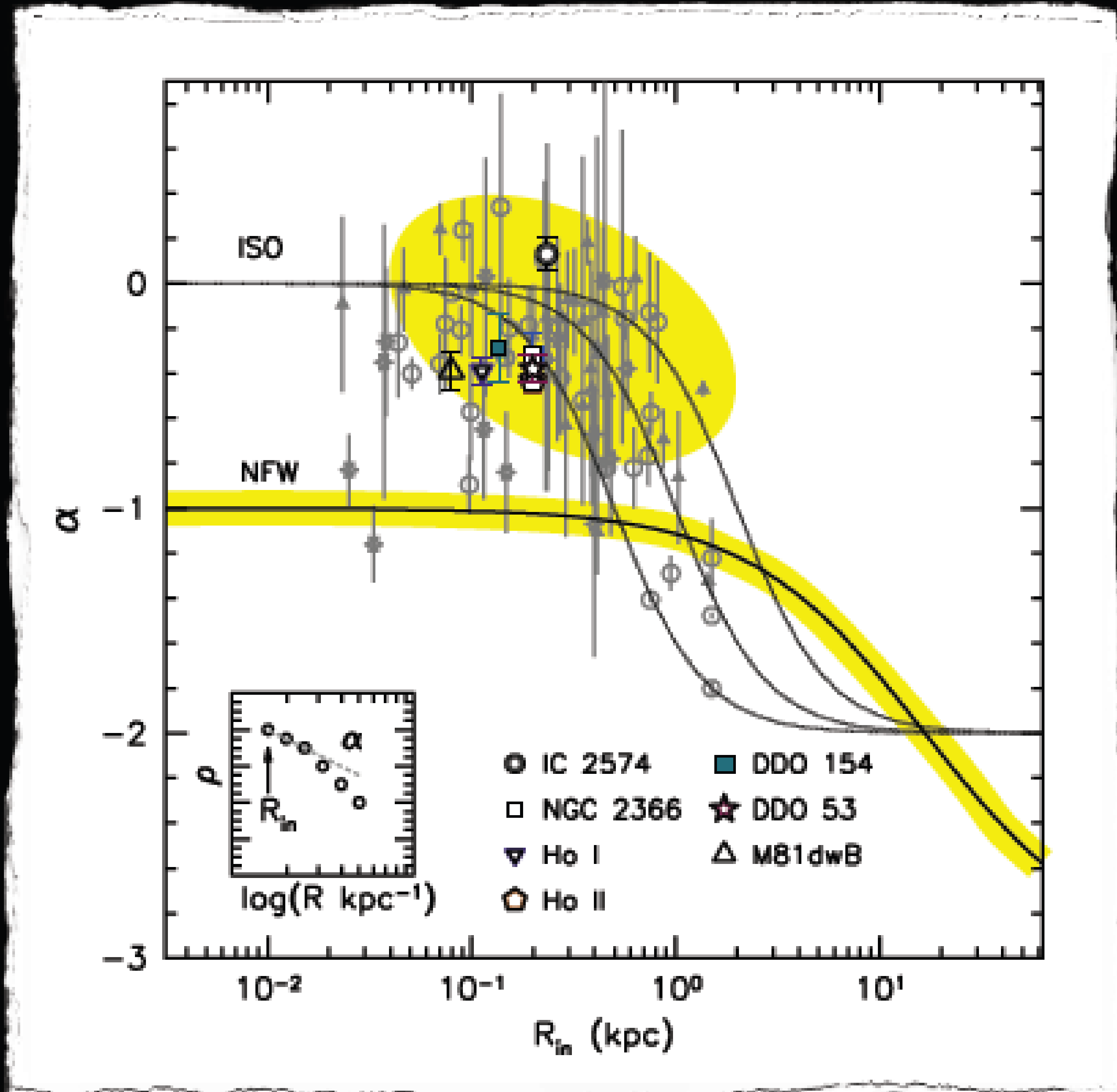
Navarro, Frenk & White 1997

A universal density profile?



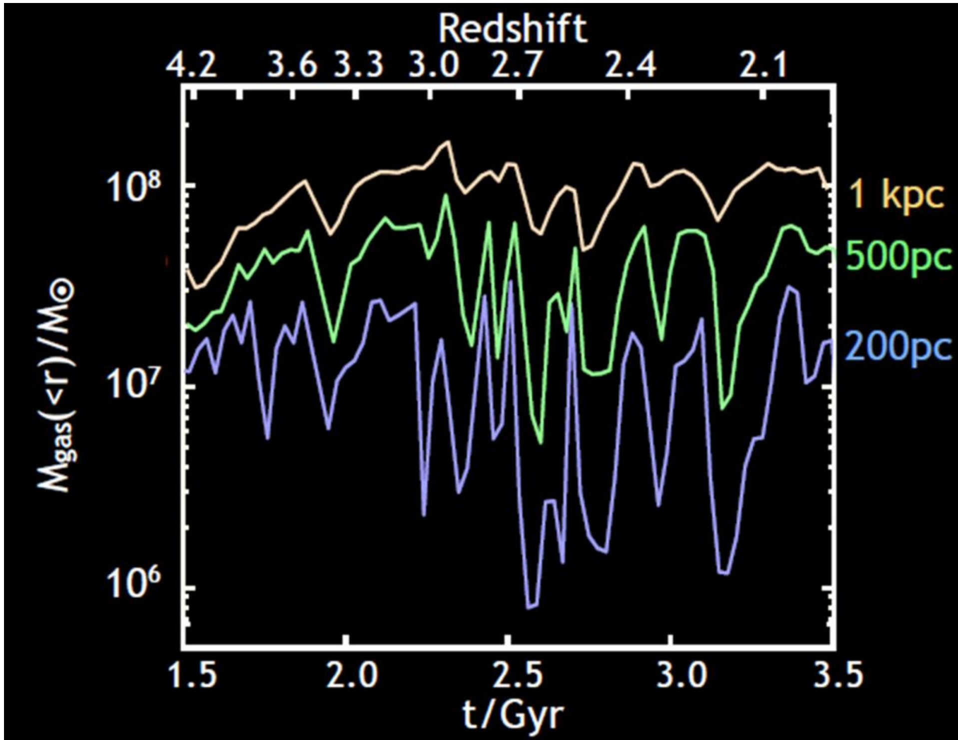
$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

Navarro, Frenk & White 1997



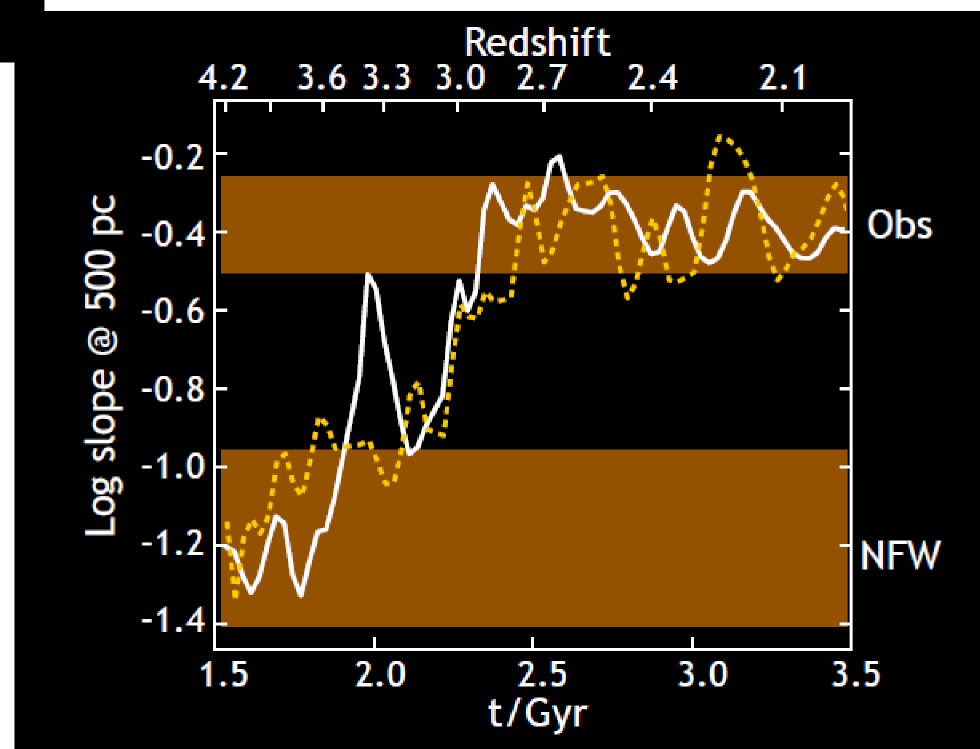
Oh et al 2011, AJ

Slide from Andrew Pontzen)



Multiple episodes of inflow and outflow
Shake up inner part of DM halo, softening cuspy core

Pontzen & Governato 2012
Governato et al. 2012



The satellites of the Milky Way

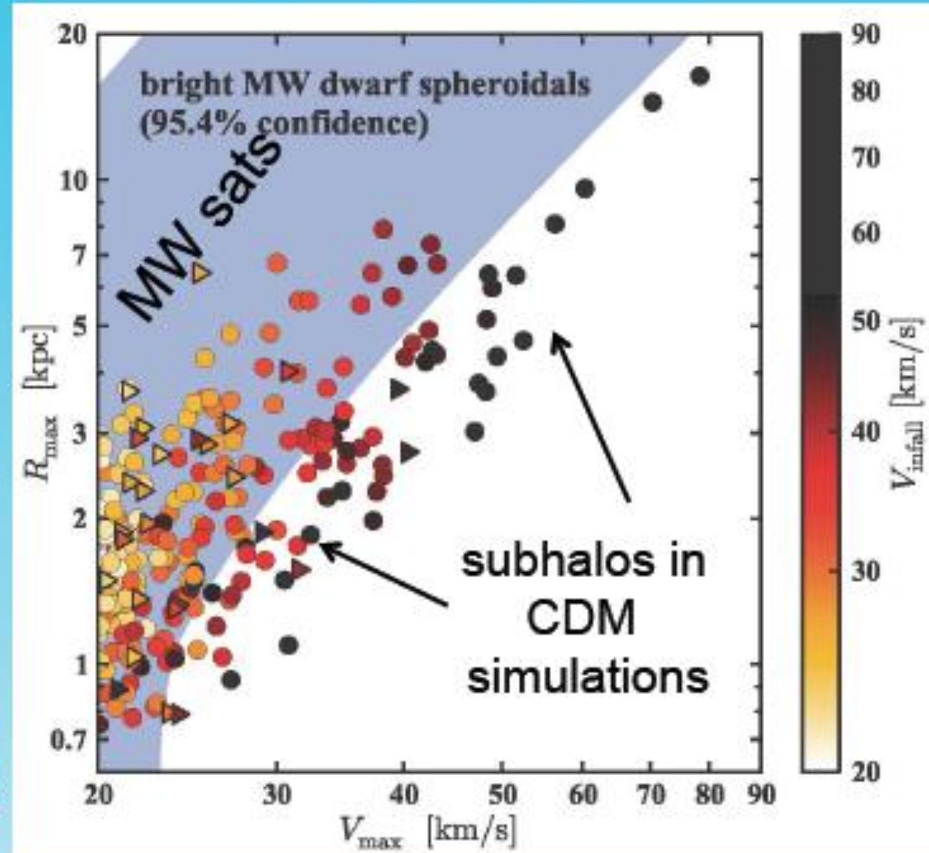
University of Durham

Boylan-Kolchin et al '11

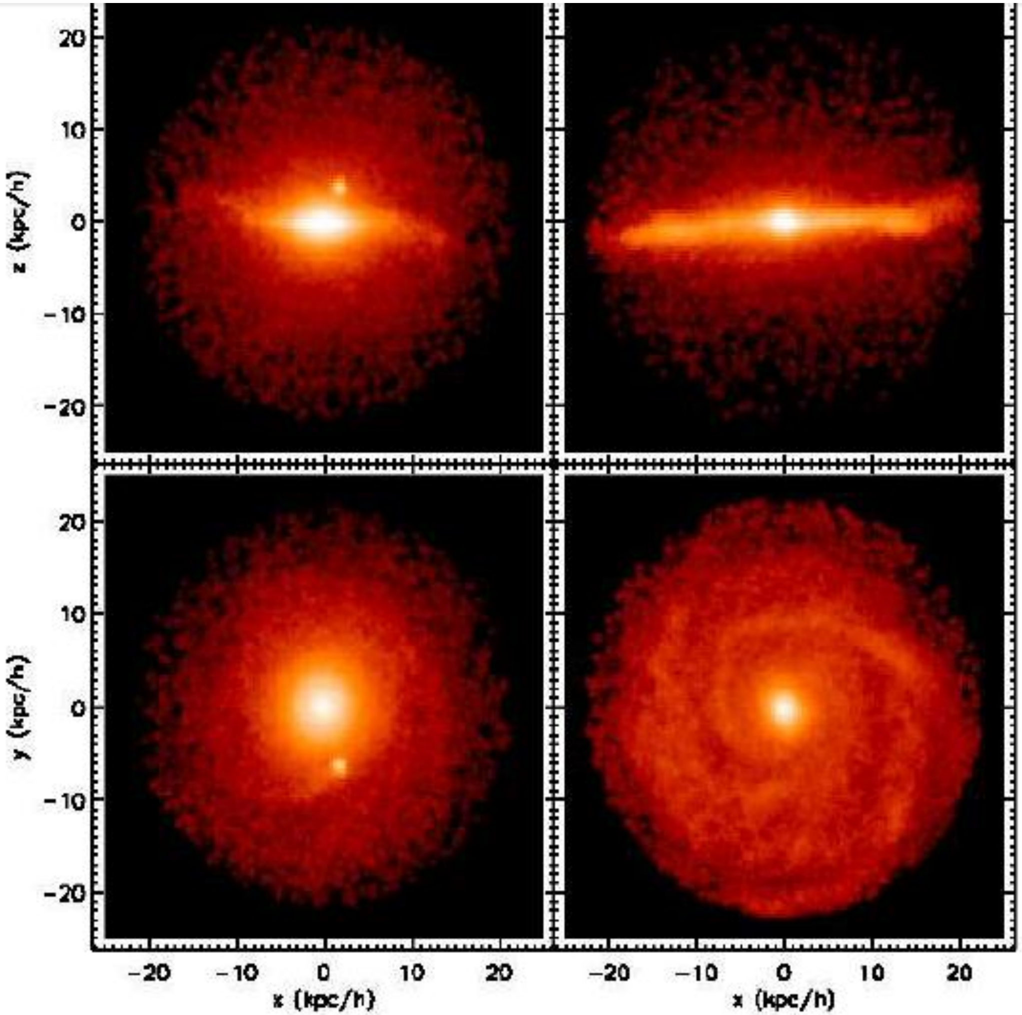
$$V_c = \sqrt{\frac{GM}{r}} \quad V_{max} = \max V_c$$

Allowed range of (V_{max}, R_{max}) inferred for each MW sat from $M(r<r_{hl})$ assuming NFW

Majority of most massive CDM subhalos are too dense to host any of the bright MW sats.



Forming realistic disks in CDM

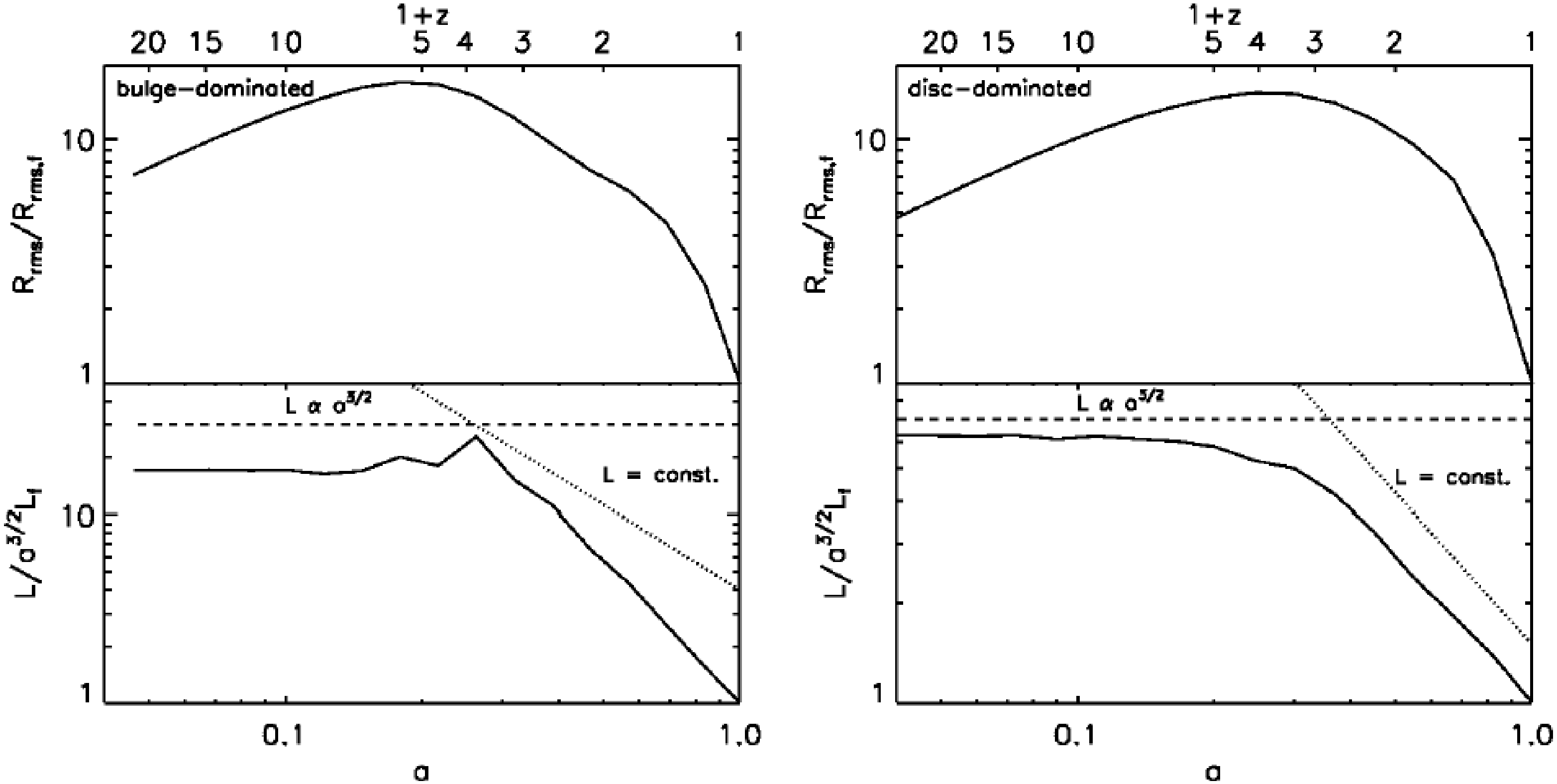


Bulge dominated

Disk dominated

- For a long time simulations failed to produce disks with the observed scale lengths
- Insufficient resolution?
- Insufficient sub-grid physics (feedback)
- Weil et al.
- Sales et al.
- Governato et al 20004, 2007
- Zavala et al 2008

Forming realistic disks in CDM

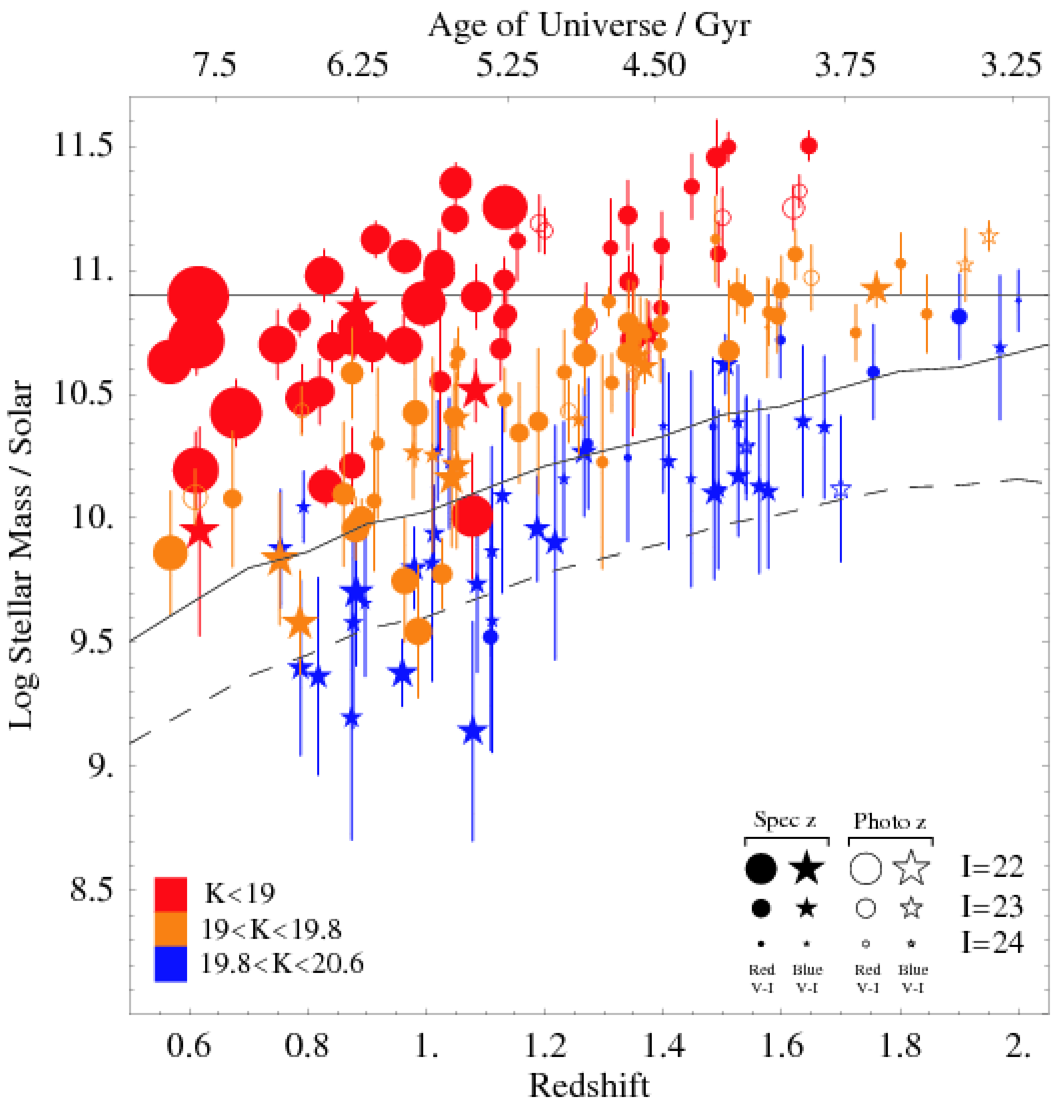


Weak feedback

Strong feedback

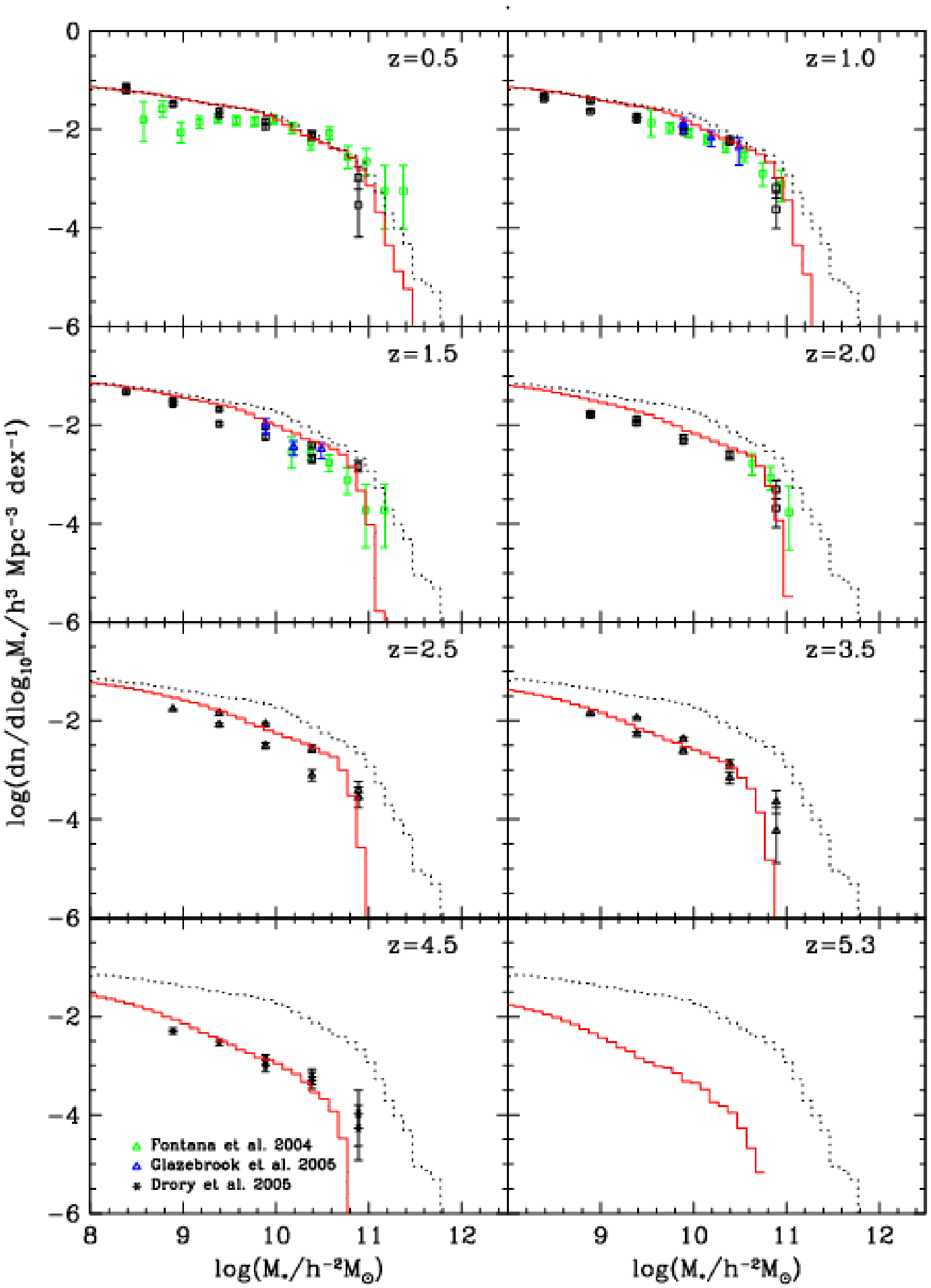
Zavala et al. 2008

Massive galaxies at z>0



Gemini Deep Deep Survey Glazebrook et al. 2004

Evolution of the stellar mass function

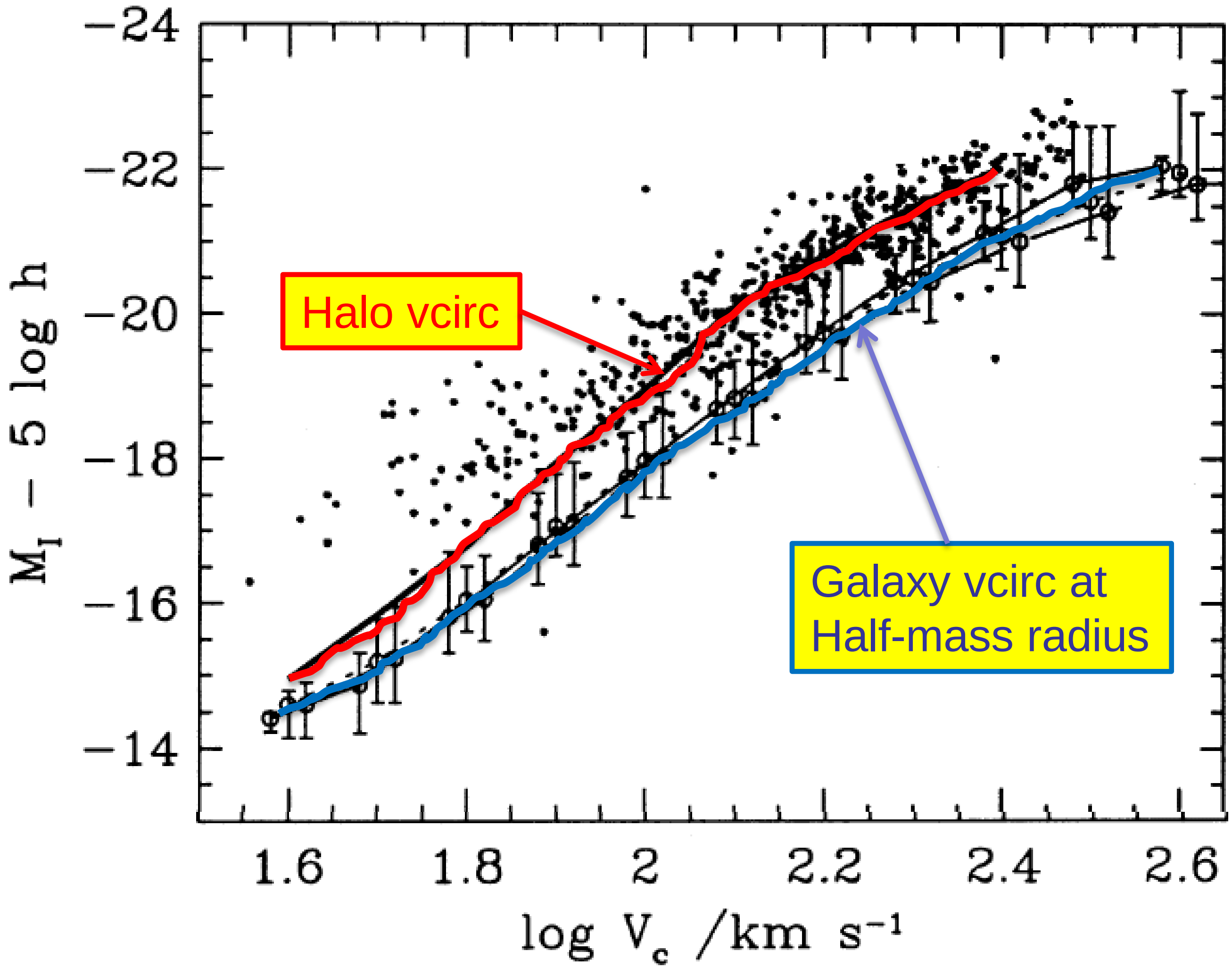


Interpretation relies on choice of IMF

Do analyses take into account scatter in M/L?

Bower et al. 2006

The Tully-Fisher relation



Summary

I will end with a quotation from Fred Hoyle's book *Galaxies, Nuclei and Quasars*, published in 1966:

> 'It is not too much to say that the understanding of why there are these different kinds of galaxy, of how galaxies originate, constitutes the biggest problem in present-day astronomy. The properties of the individual stars that make up the galaxies form the classical study of astrophysics, while the phenomena of galaxy formation touches on cosmology. In fact, the study of galaxies forms a bridge between conventional astronomy and astrophysics on the one hand, and cosmology on the other.'

This remains as true today as it was nearly fourty years ago.

Efstathiou 2003