Explorations based on Galaxy Group Catalogues

On strangulation, tidal stripping, assembly bias
galaxy alignment and halo occupation statistics

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In collaboration with:
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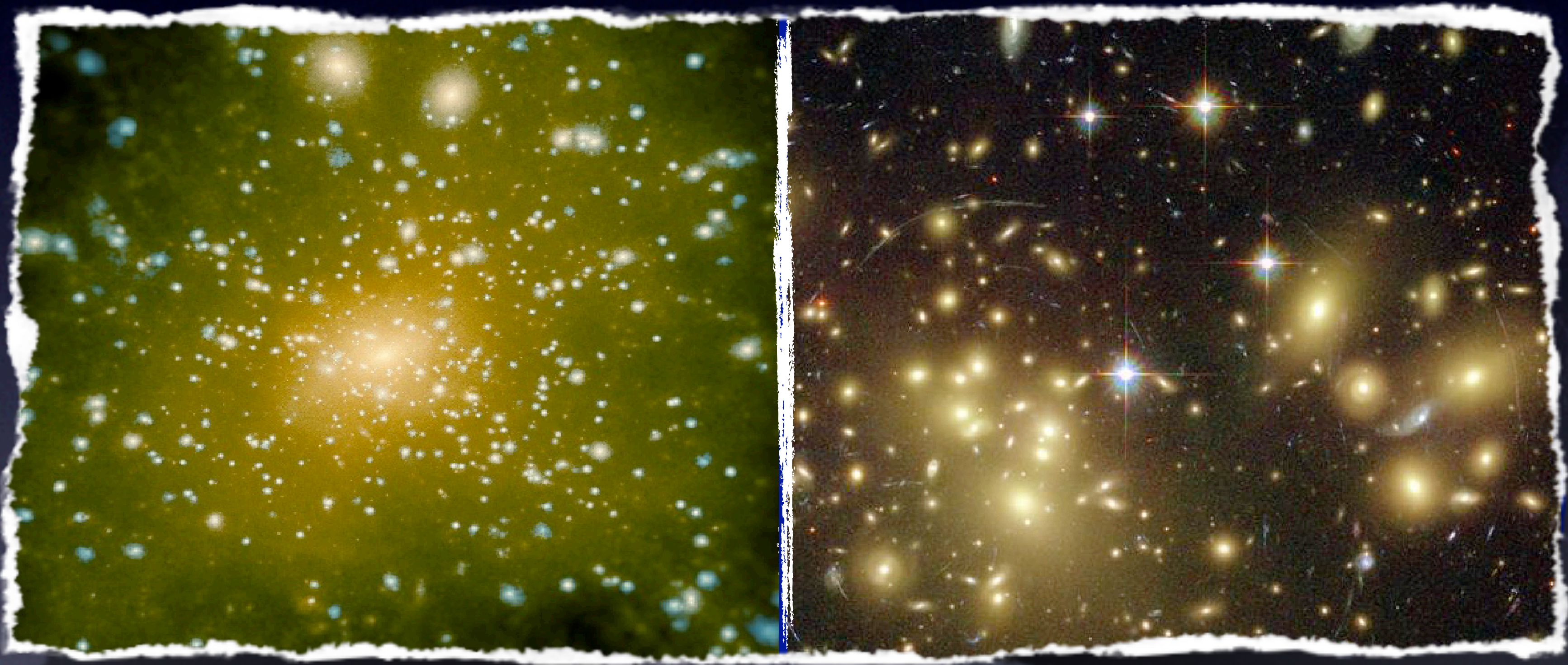
Introduction: Motivation & Goal

Our main goal is to study the Galaxy-Dark Matter connection;
i.e., what galaxy lives in what halo?

- To constrain the physics of Galaxy Formation
- To constrain cosmological parameters



Four Methods to Constrain Galaxy-Dark Matter Connection:

- Large Scale Structure
- Galaxy-Galaxy Lensing
- Satellite Kinematics
- Group Catalogues

Constructing Galaxy Group Catalogues

Galaxy Group catalogues are ideal to probe galaxy dark matter connection:

- each **individual** galaxy is linked to a halo mass
- allows separation in **central** and **satellite** galaxies
- allows direct measurement of halo-halo clustering
- can be used to measure halo shapes and halo-galaxy alignment

We have developed a new, iterative group finder which uses an adaptive filter modeled after halo virial properties.

- Calibrated & Optimized using mock galaxy redshift surveys
- Low interloper fraction (<15%) & high completeness of members (>90%)
- Masses estimated from total group luminosity/stellar mass; more accurate than using velocity dispersion of members!
- Can also detect \`groups' with single member; large dynamic mass range

For details see Yang et al. (2005) and Yang et al. (2007).

Part I

Constraining the Physics of Galaxy Formation

The Bi-Modal Distribution of Galaxies

Early-Type

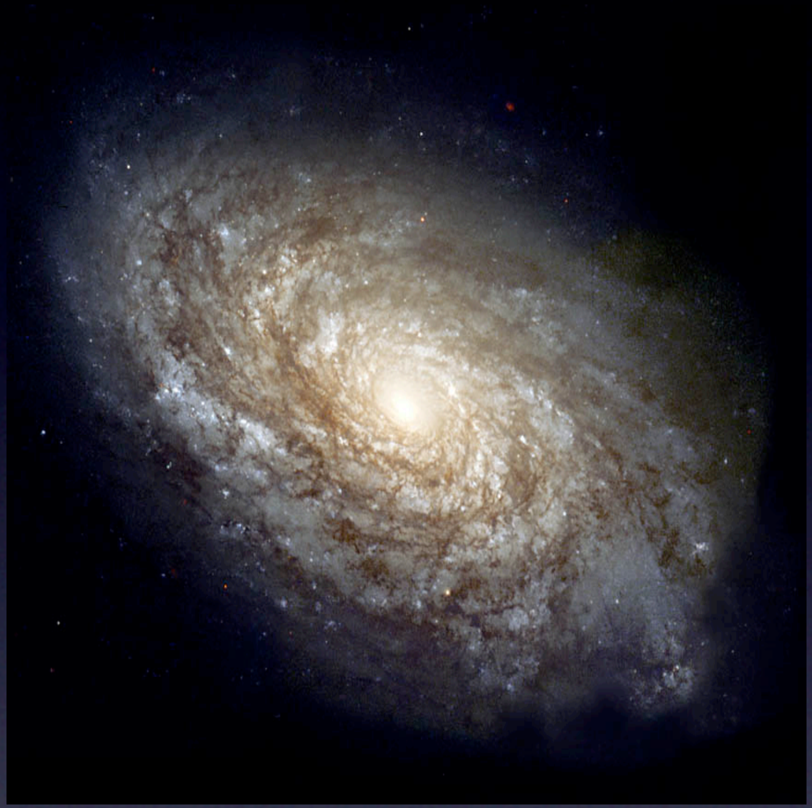
Spheroidal Morphology

Old Stellar Populations

No or Little Cold Gas

Red Colors

Late-Type



Disk-Like Morphology

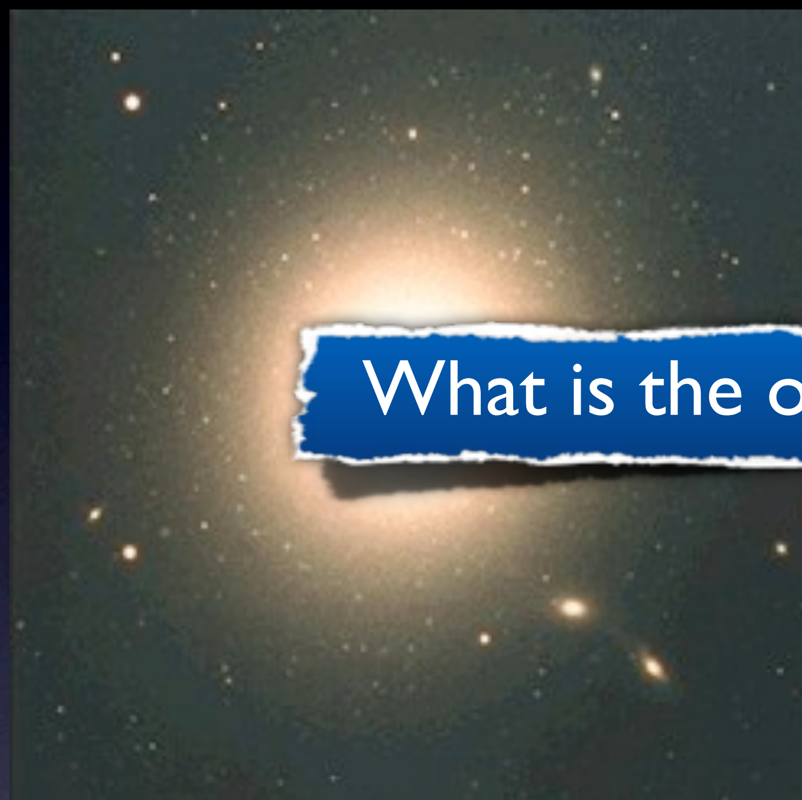
Young Stellar Populations

Abundant Cold Gas

Blue colors

The Bi-Modal Distribution of Galaxies

Early-Type



Late-Type

What is the origin of this bimodality?

Spheroidal Morphology

Old Stellar Populations

No or Little Cold Gas

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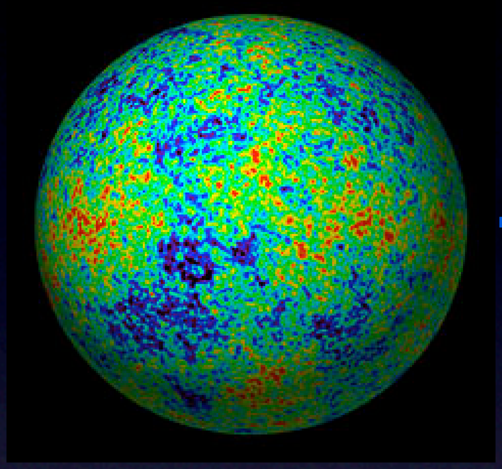
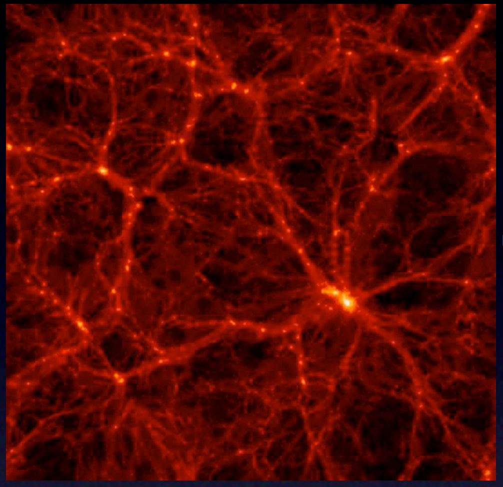
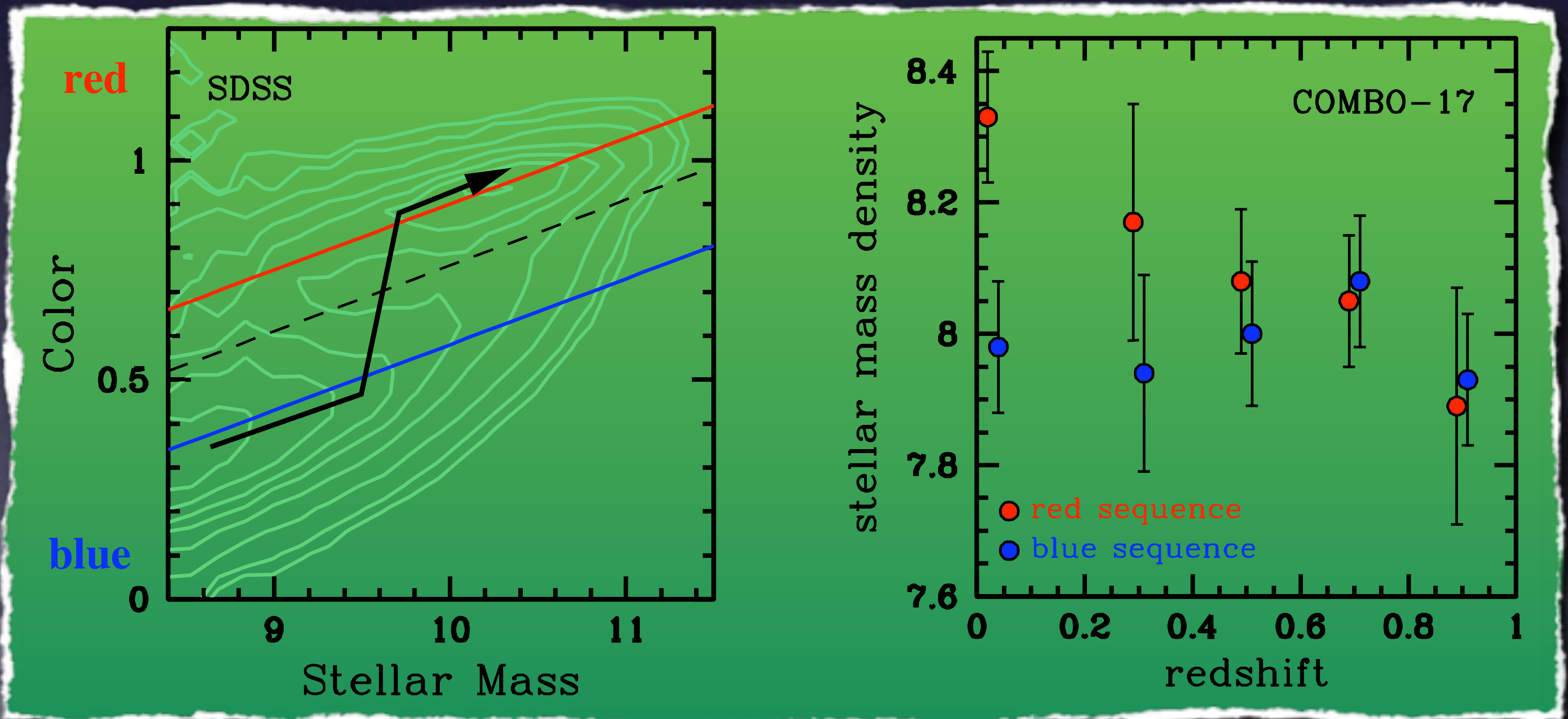
The Standard Paradigm

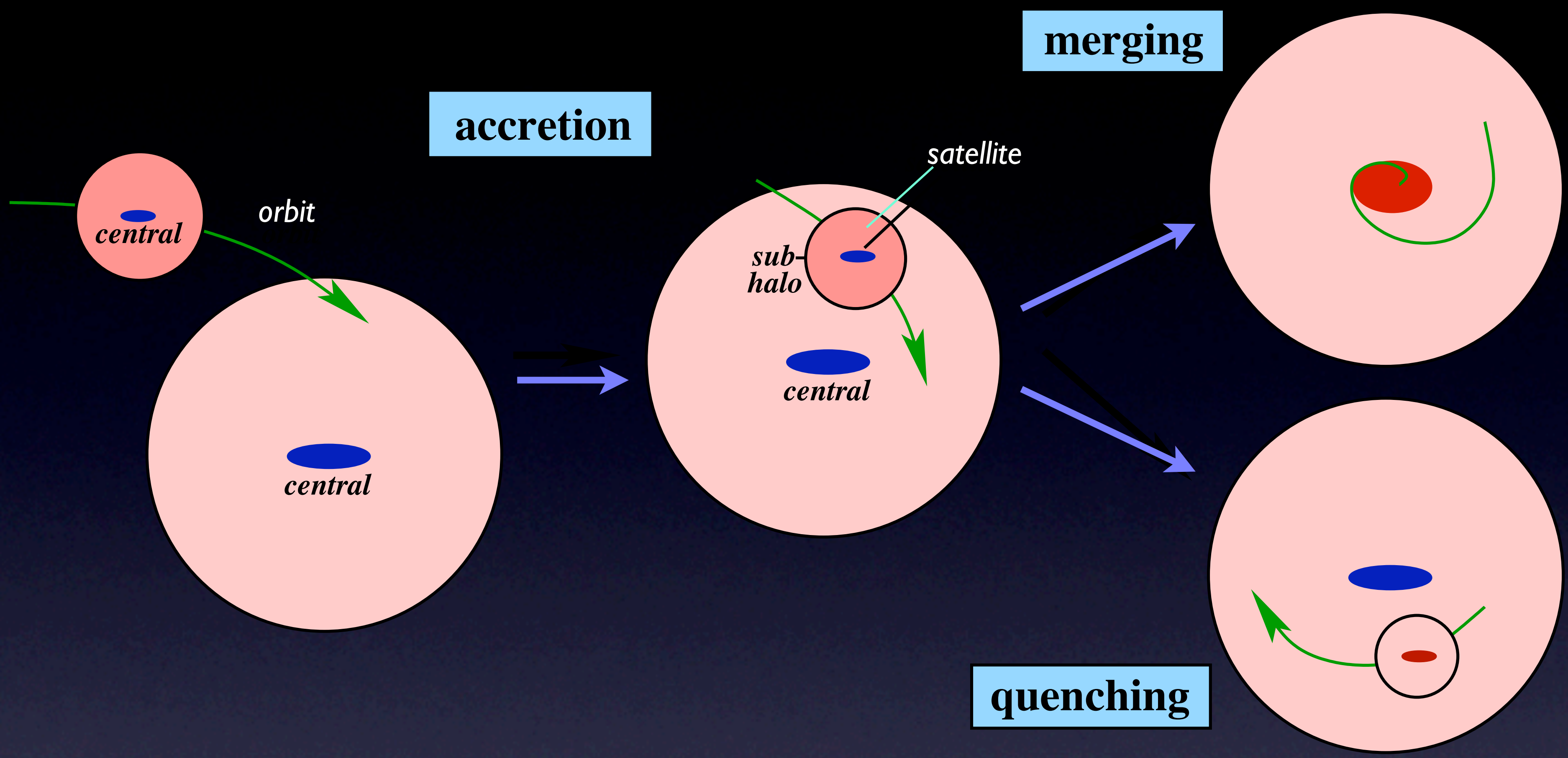
PARADIGM: All Galaxies Originally form as Central Disk Galaxies



Wolf et al. 2003; Bell et al. 2004; Borch et al. 2006

Galaxy Transformations



In LCDM cosmology dark matter haloes grow hierarchically

A major merger between disk galaxies results in an early-type remnant

There are also several satellite-specific transformation processes

- ✶ Strangulation *(stripping of hot gas atmosphere)*
- ✶ Ram-pressure stripping *(stripping of cold gas)*
- ✶ Galaxy harassment *(impulsive encounters with other satellites)*

Outstanding Questions

- What fraction of the red-sequence satellites underwent their transformation as a satellite?
- Which transformation process is most important?
- In what environment (dark matter halo) do galaxies undergo their transformation?
- To what extent are satellite-specific transformation processes responsible for environment dependence of galaxy population?

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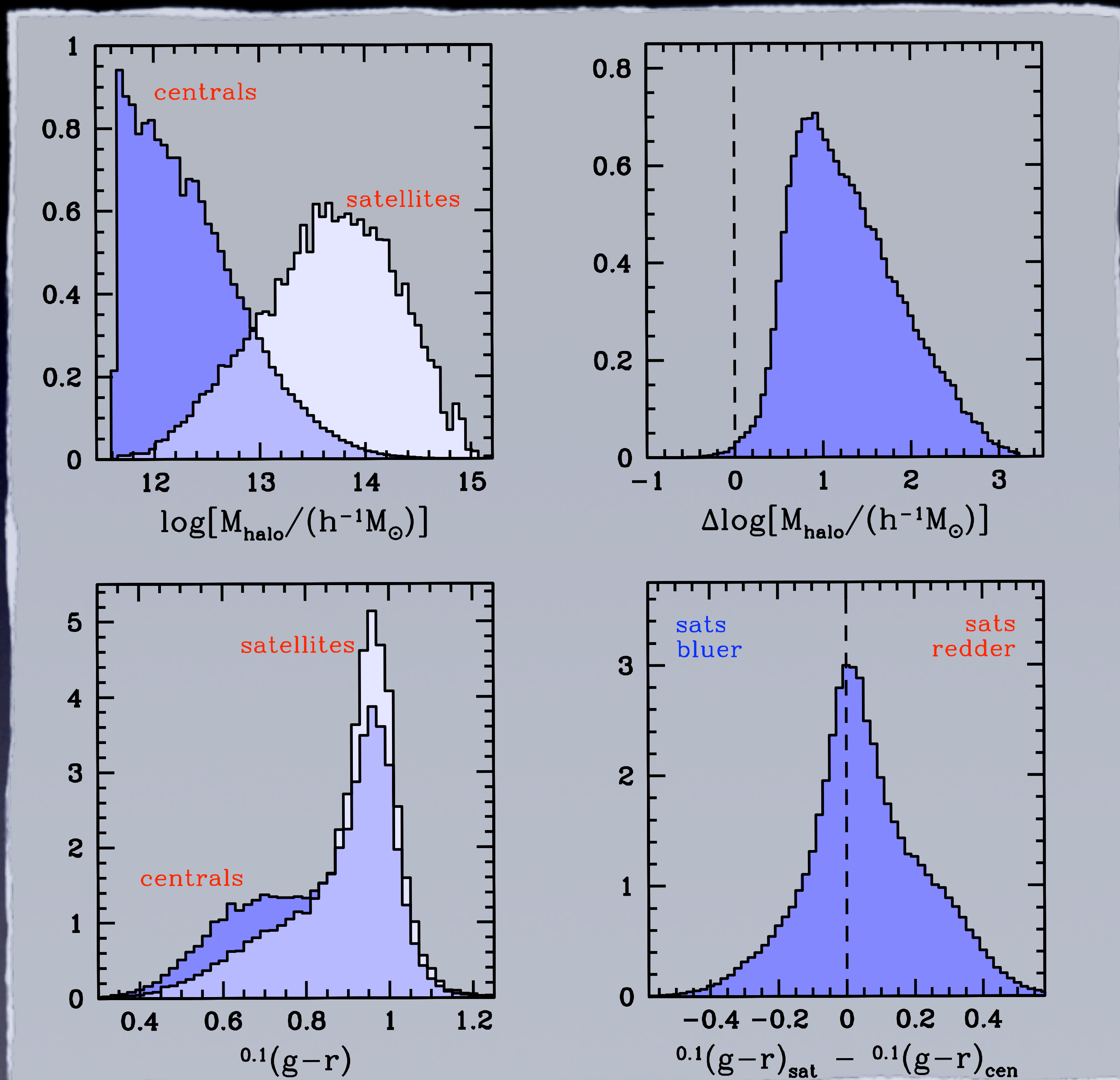
We address these questions, using SDSS galaxy group catalogue.

In particular, we study impact of satellite specific transformation processes by comparing satellites to centrals of the same stellar mass.

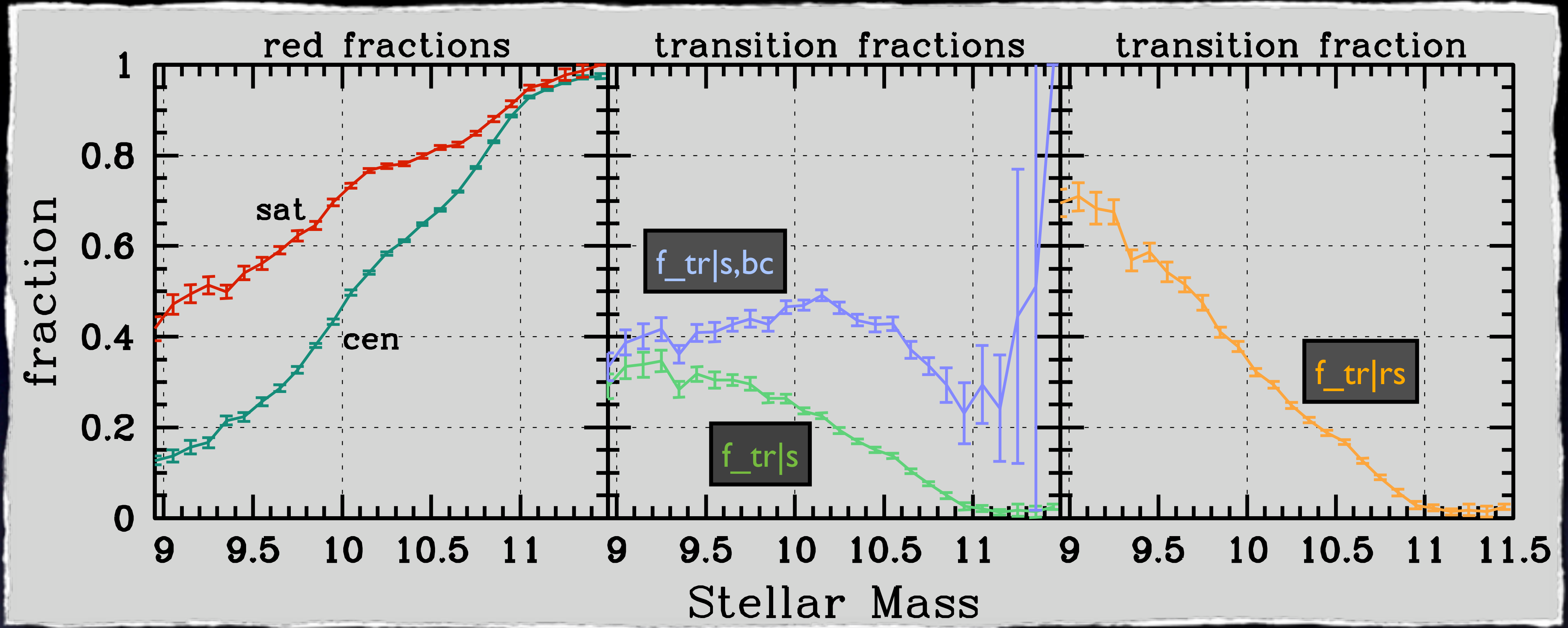
Centrals vs. Satellites



van den Bosch et al. (2008)

Sats are marginally redder than centrals of same stellar mass

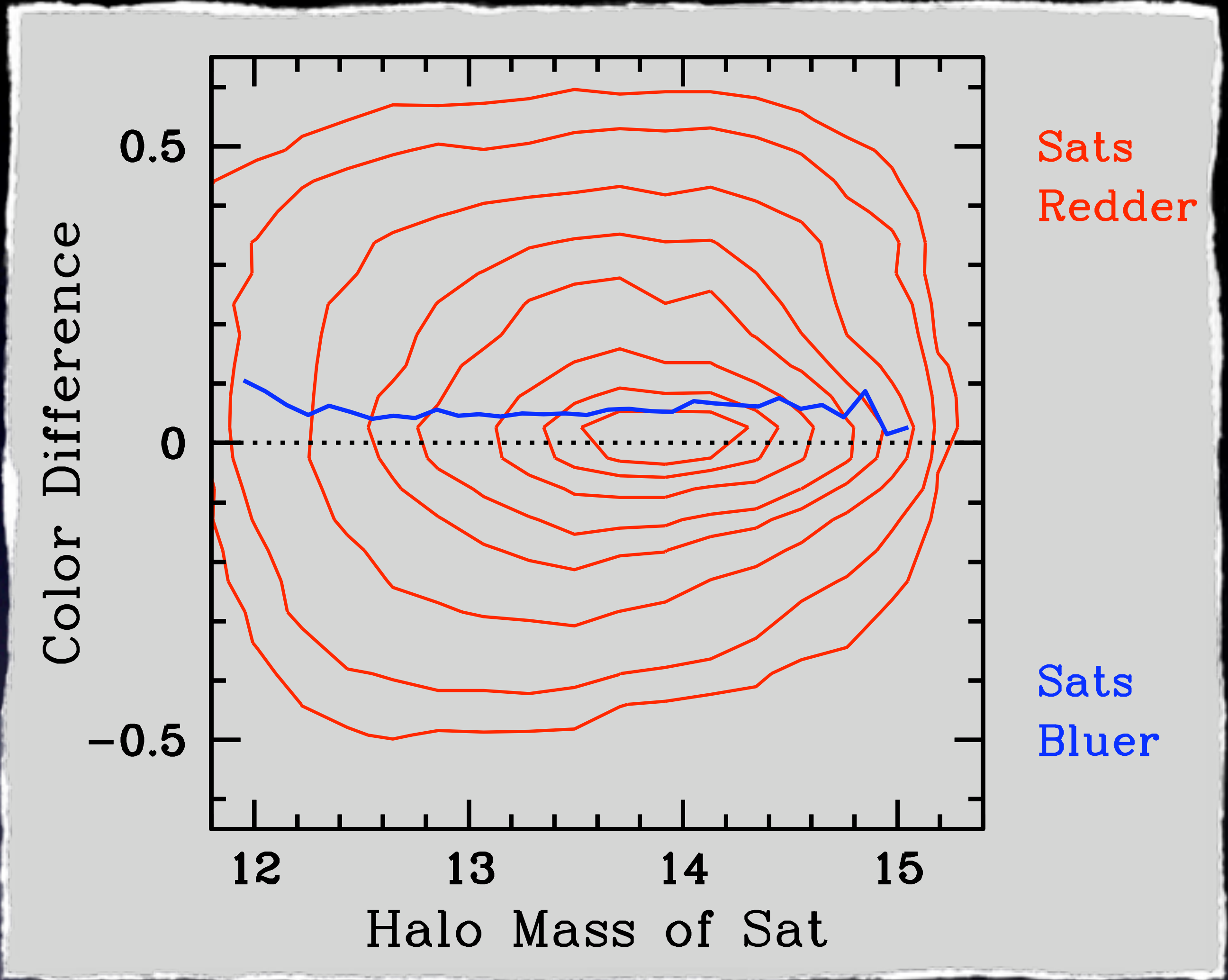
Blue-to-Red Transition Fractions



- The red fraction of sats is higher than that of centrals of same M_star
- Roughly 40% of sats that are blue at accretion undergo transition
- Above 10^{10} h^{-2} Msun majority of sats were already red at accretion
- Satellite transformation processes are only important at low M_star

van den Bosch et al. (2008)

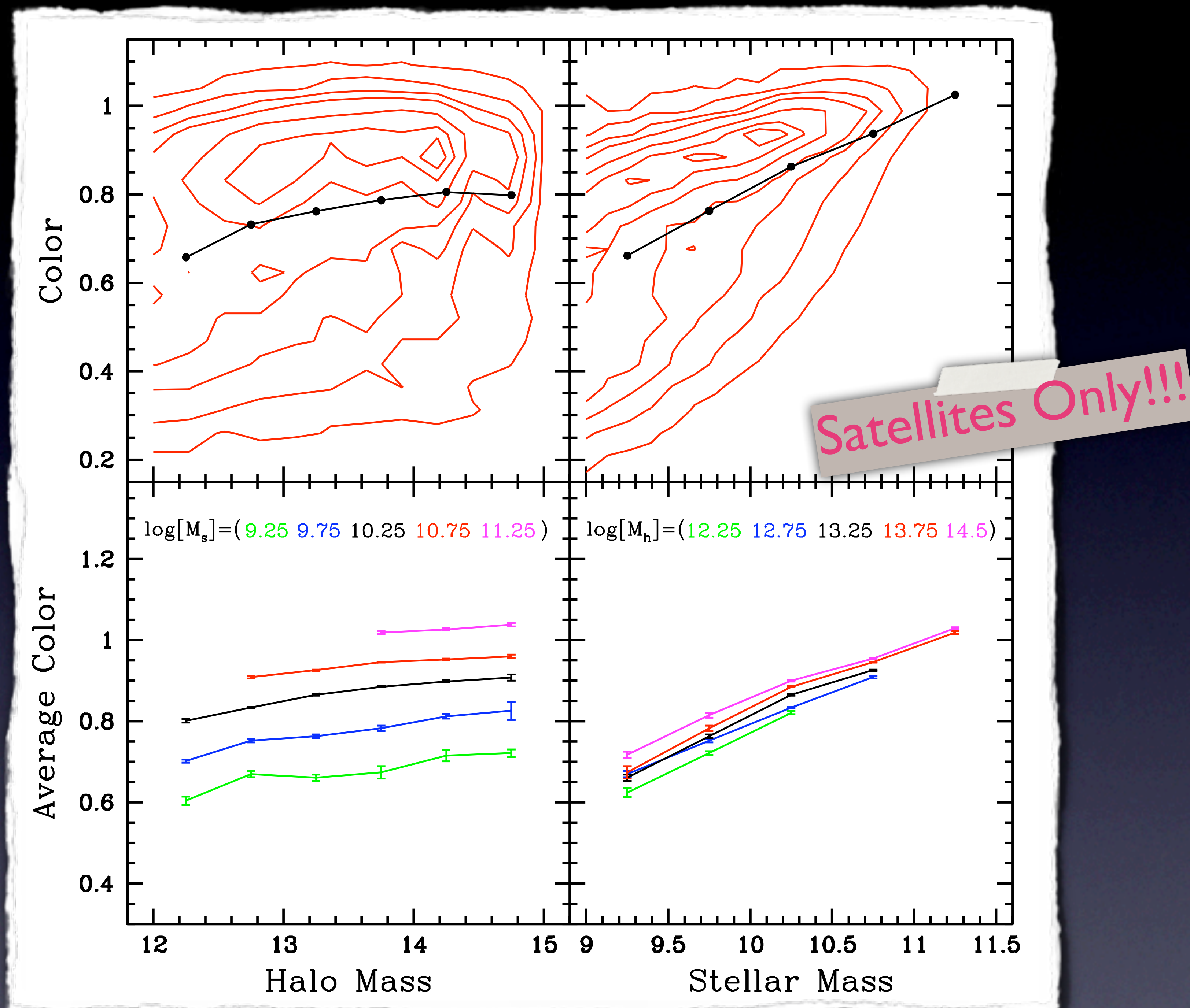
Dependence on Halo Mass



- Color Difference is independent of halo mass of satellite
- Transformation efficiency is independent of halo mass of satellite
- Strangulation is main satellite-specific transformation process

van den Bosch et al. (2008)

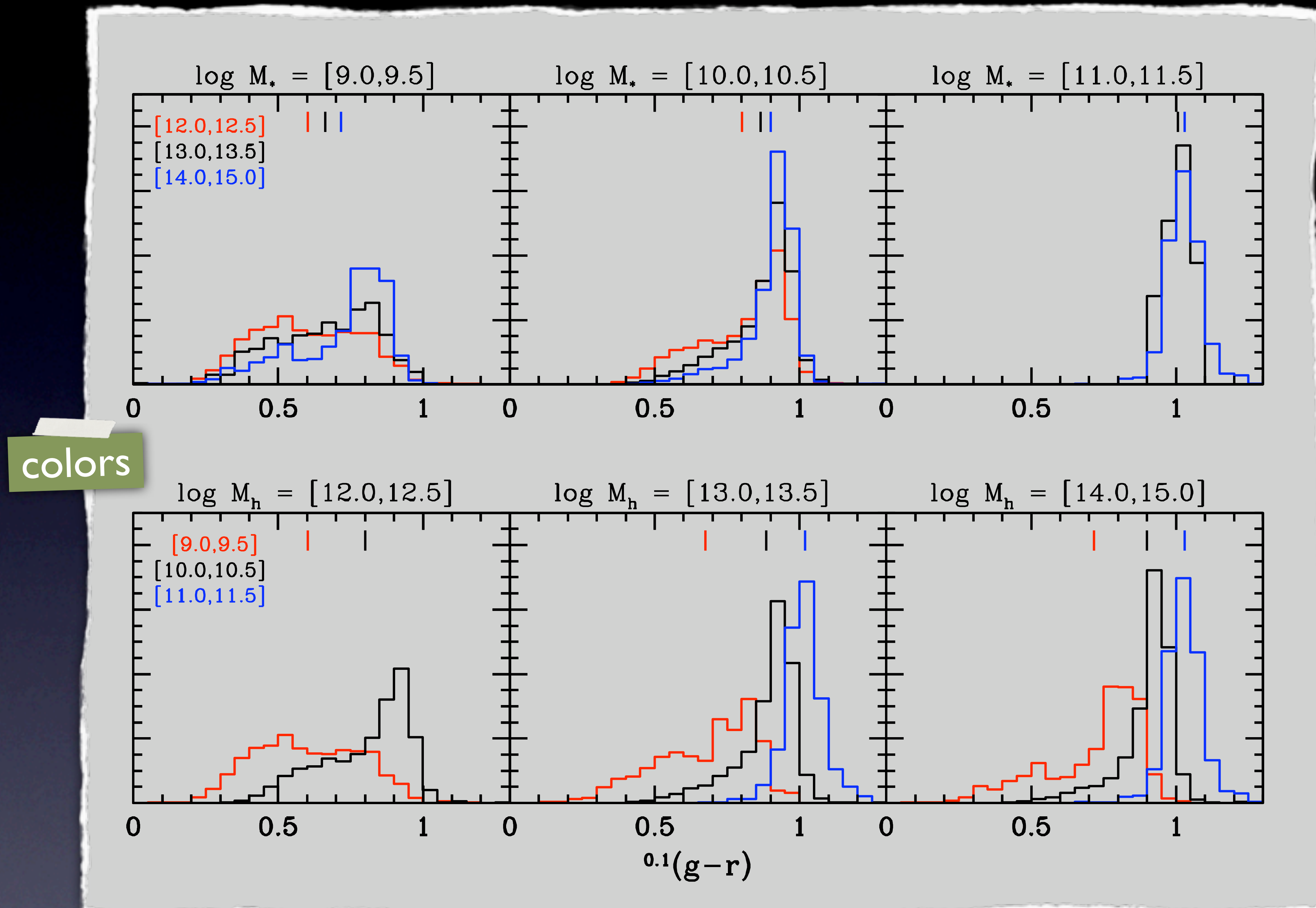
Satellite Ecology



At fixed stellar mass the average satellite color is independent of halo mass

van den Bosch et al. (2009)

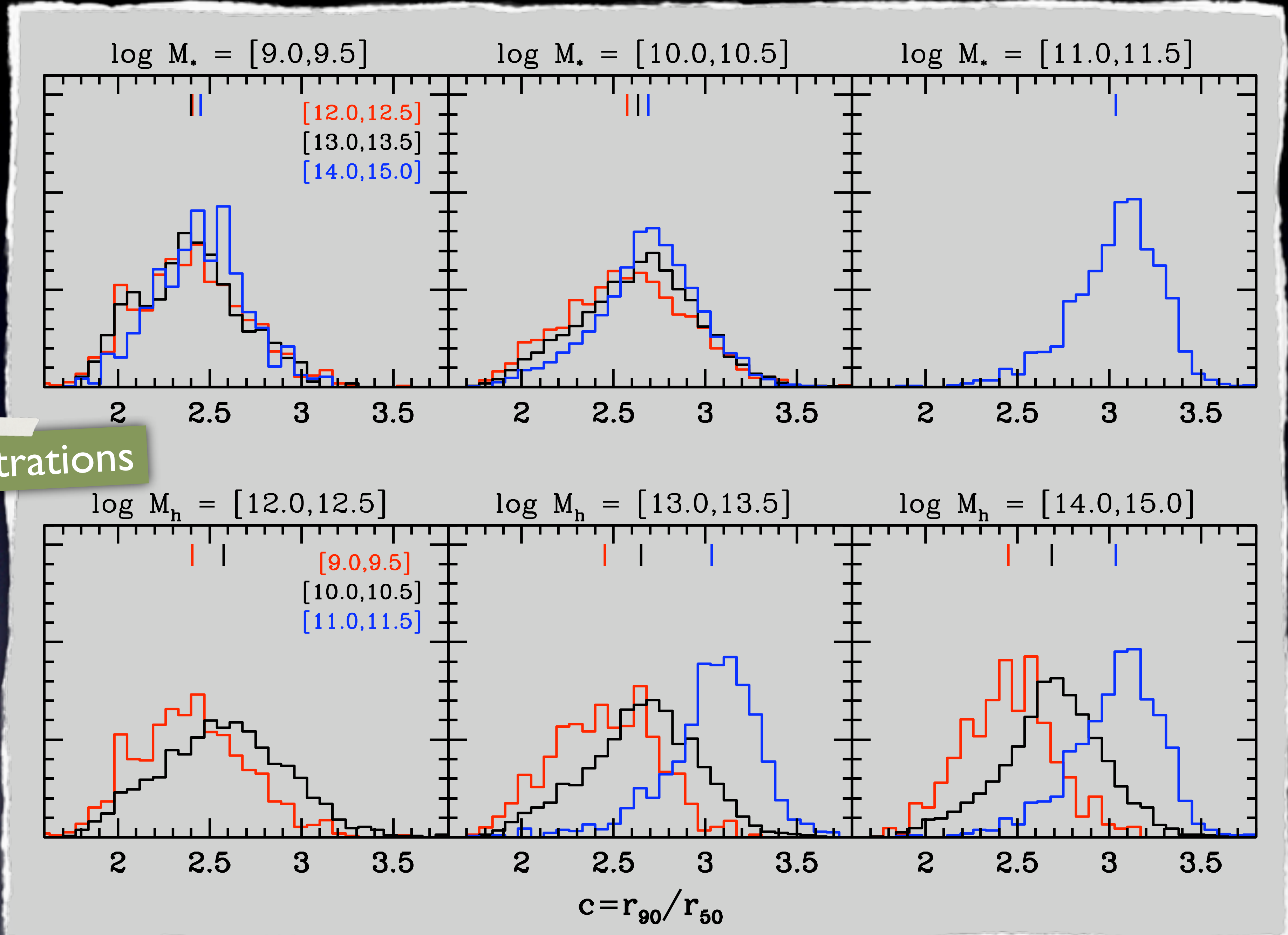
The Dearth of Environment Dependence



Satellite color distribution depends strongly on stellar mass, but only very weakly on halo mass (environment)

van den Bosch et al. (2009)

The Dearth of Environment Dependence

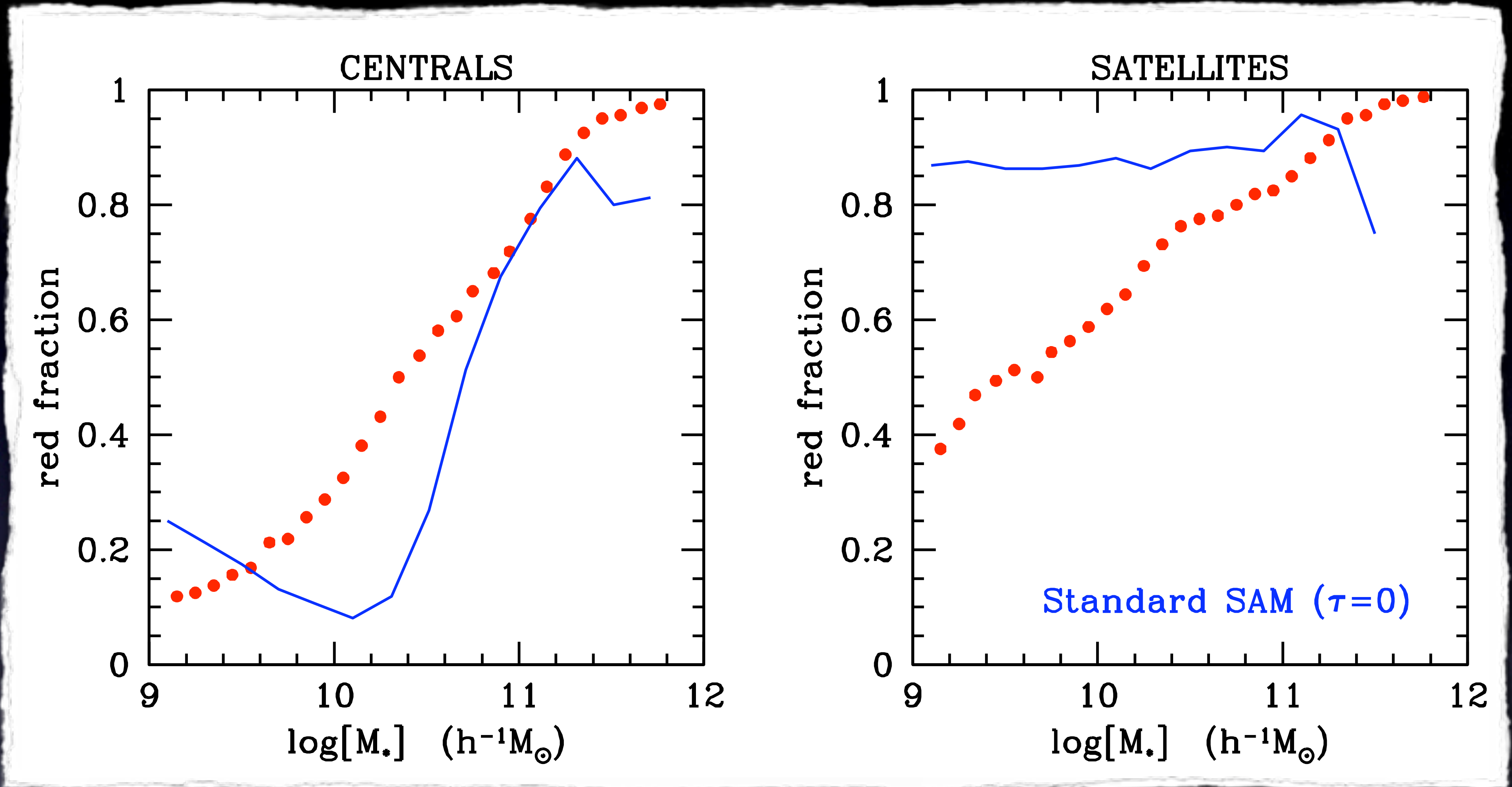


concentrations

Satellite concentration distribution depends strongly on stellar mass, but is virtually independent of halo mass (environment)

van den Bosch et al. (2009)

Modeling Strangulation

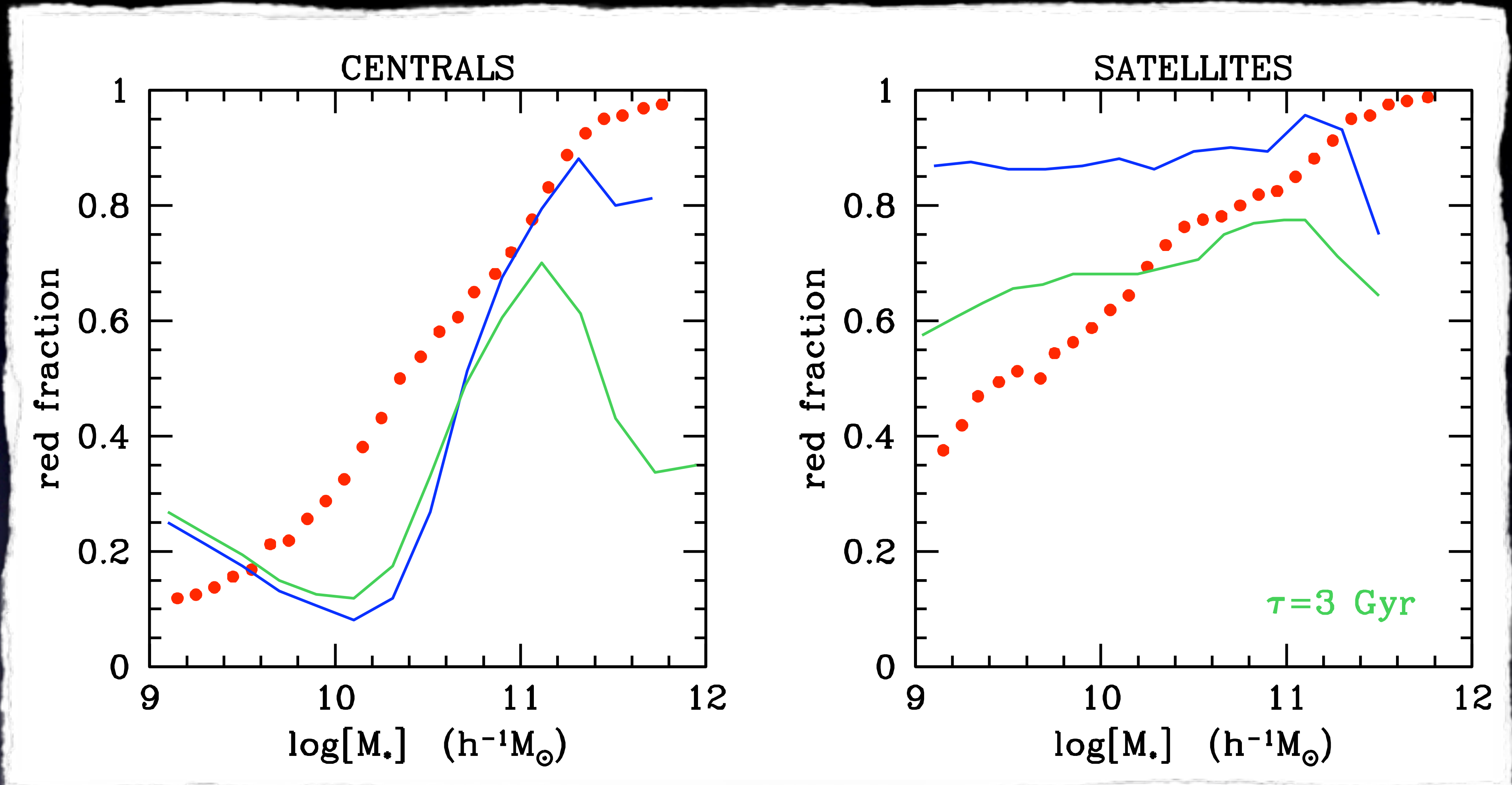


Kang & van den Bosch (2008)

In standard SAMs, hot halo is instantaneously removed; results in red satellite fraction that is too large...

see also Weinmann et al. (2006) and Baldy et al. (2006)

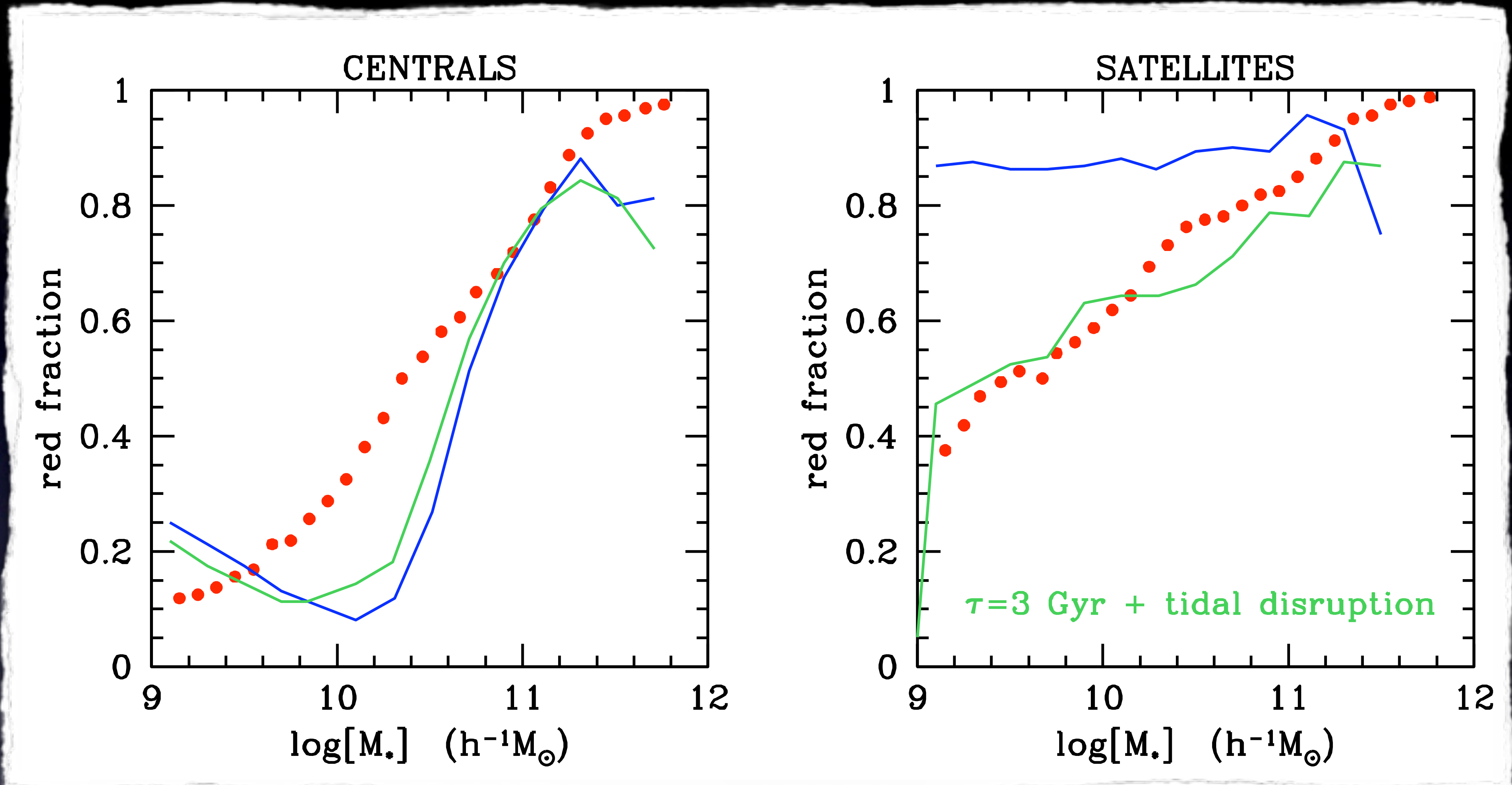
Modeling Strangulation



$$M_{\rm hot}(t) = M_{\rm hot}(t_{\rm acc})e^{-(t-t_{\rm acc})/\tau}$$

Delaying hot gas removal reduces red satellite fraction, but increases blue fraction of massive centrals.....

Modeling Strangulation



Half of orphans with $M_* < 10^{10} h^{-1} M_\odot$ tidally disrupted

If significant fraction of low mass satellites is tidally disrupted before being accreted by central, data can be fit satisfactory

Conclusions Part I

- What fraction of the red-sequence satellites underwent their transformation as a satellite?

- Which transformation process is most important?

- In what environment (dark matter halo) do galaxies undergo their transformation?

- To what extent are satellite-specific transformation processes responsible for environment dependence of galaxy population?

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  From 70% for satellites with M_star = 10^9 Msun,
  to 0% for the most massive satellites

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  Strangulation...but needs to be better understood.
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  In all halos of all masses...

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  There is no environment dependence....

Part II

The Clustering of Dark Matter Halos

Clustering of Galaxy Groups

Clustering of groups probes clustering of Dark Matter Haloes.

Prediction from hierarchical models:
More massive haloes are more strongly clustered

Wang et al. (2008)

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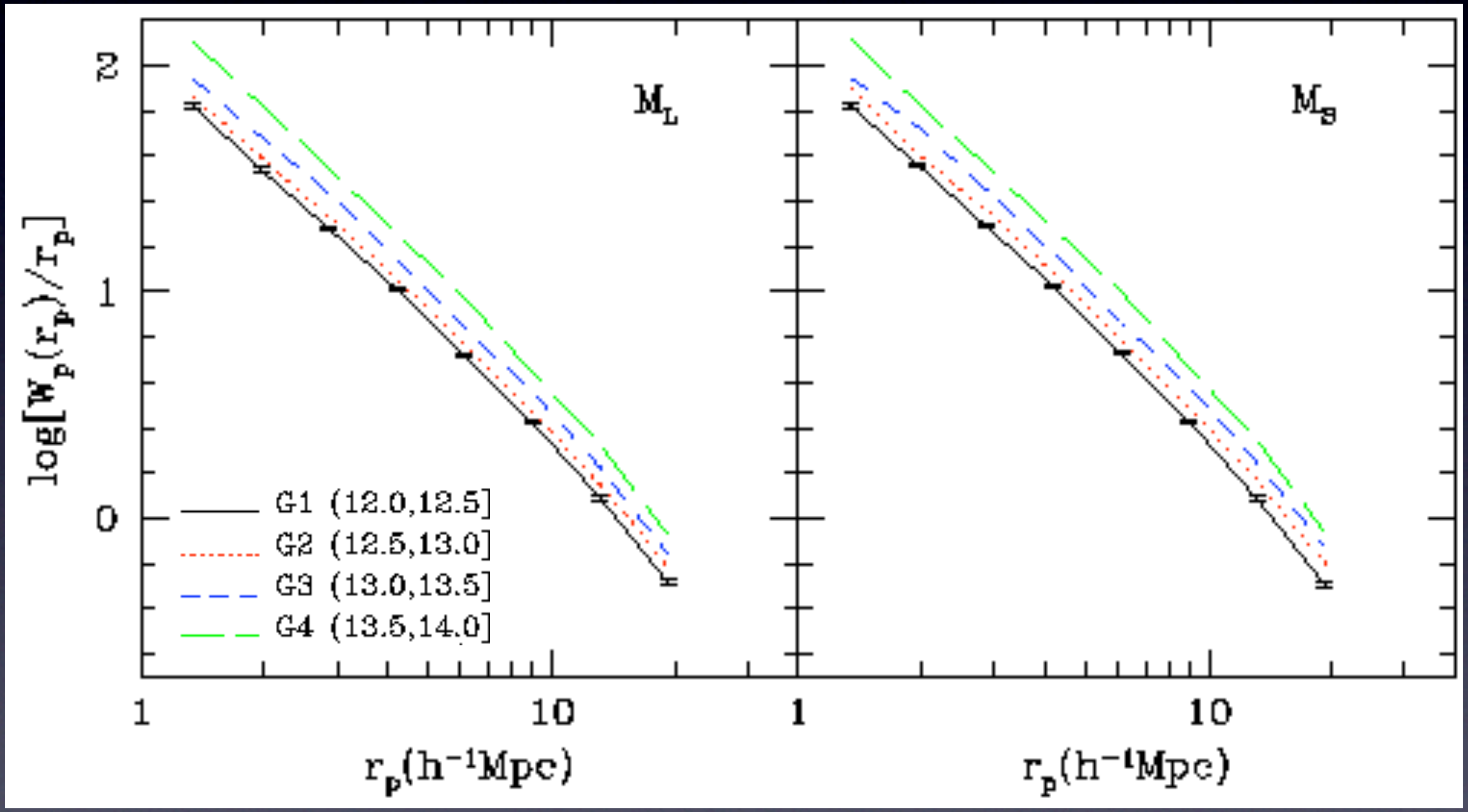
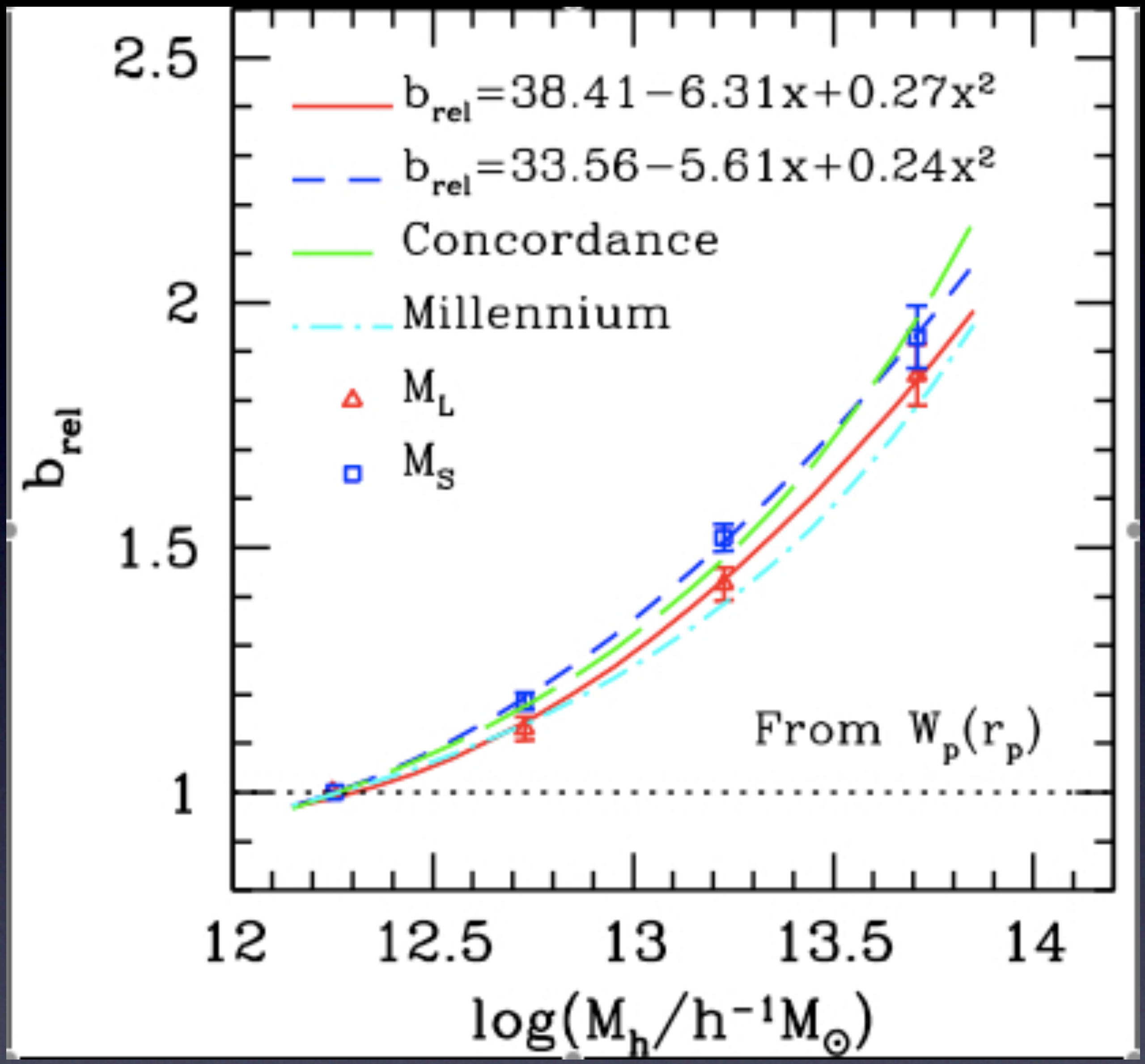


Galaxy-Group Cross Correlation confirms prediction!
Results independent of halo-mass indicator.

Wang et al. (2008)

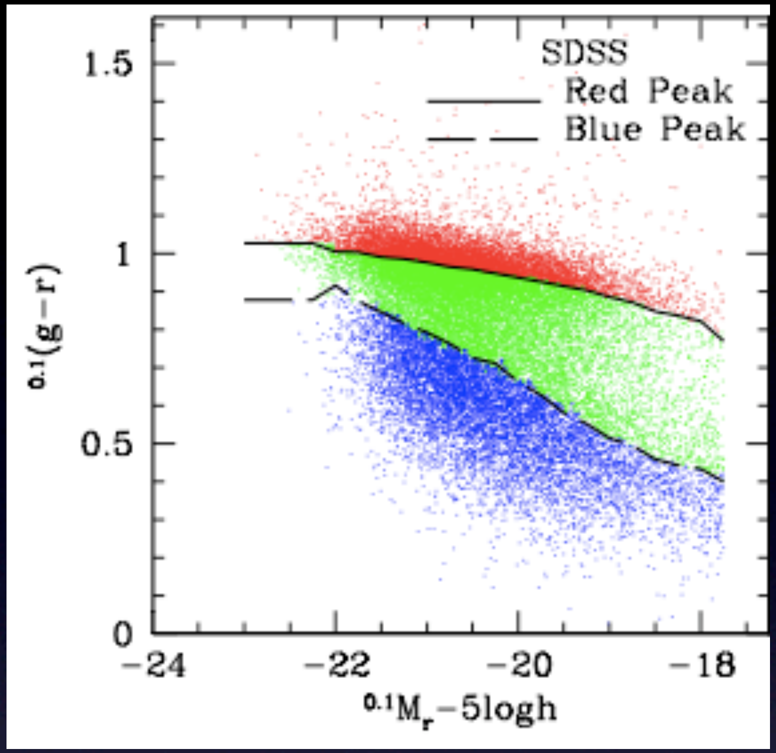
Mass Dependence of Halo Bias



Wang et al. (2008)

Halo Bias in good agreement with predictions for concordance cosmology

Color Dependence of Halo Bias



We split groups according to color of central galaxy, and look for color dependence of halo/group bias.

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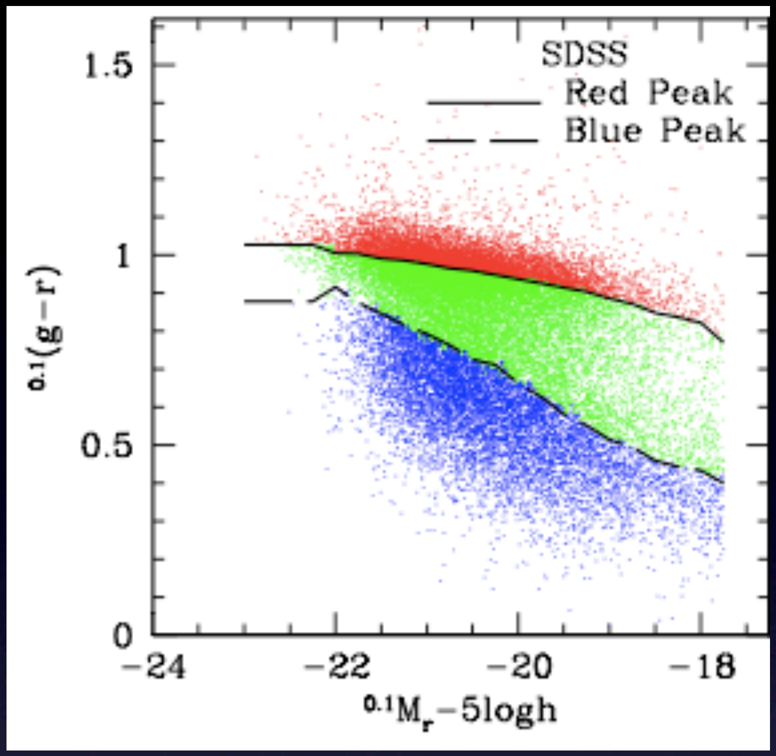

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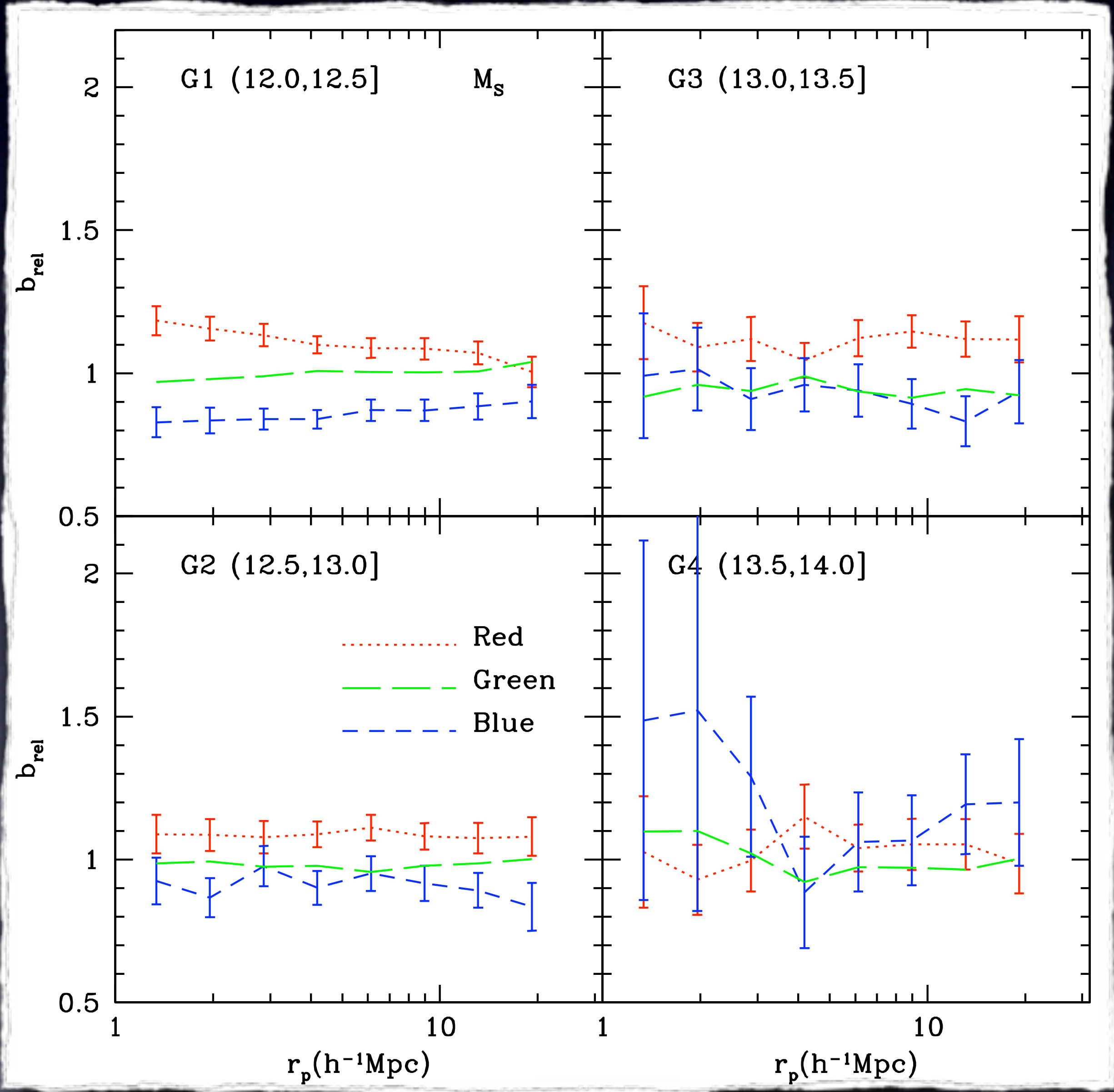
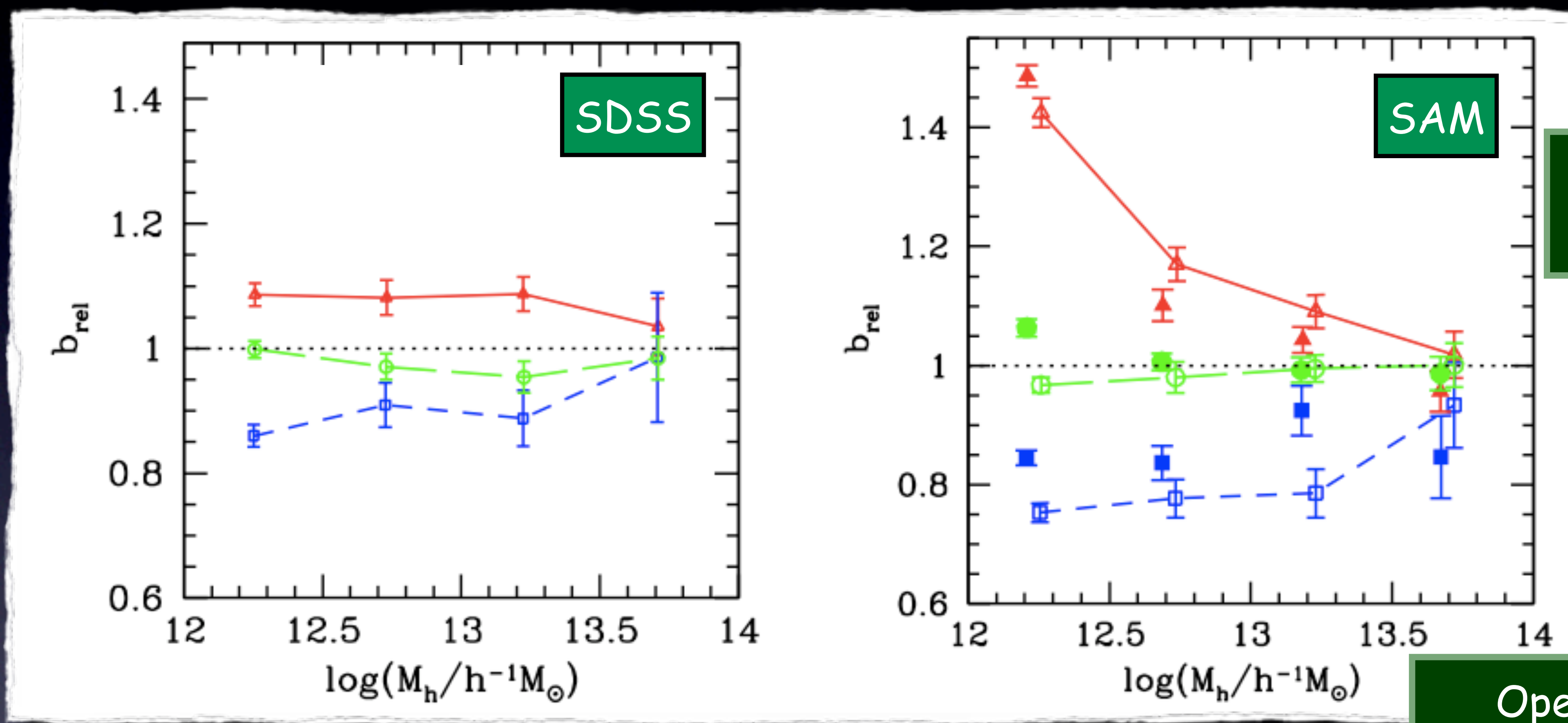


Groups with red centrals are more strongly clustered than groups of same mass but with blue centrals.

Effect is weak, and limited to low mass haloes only!!

Tests with Mock Galaxy Redshift Survey

We construct MGRS from semi-analytical model (SAM) of Croton et al. (2006) crafted on Millenium simulation.



Solid symbols: intrinsic

Open symbols: mock group catalogue

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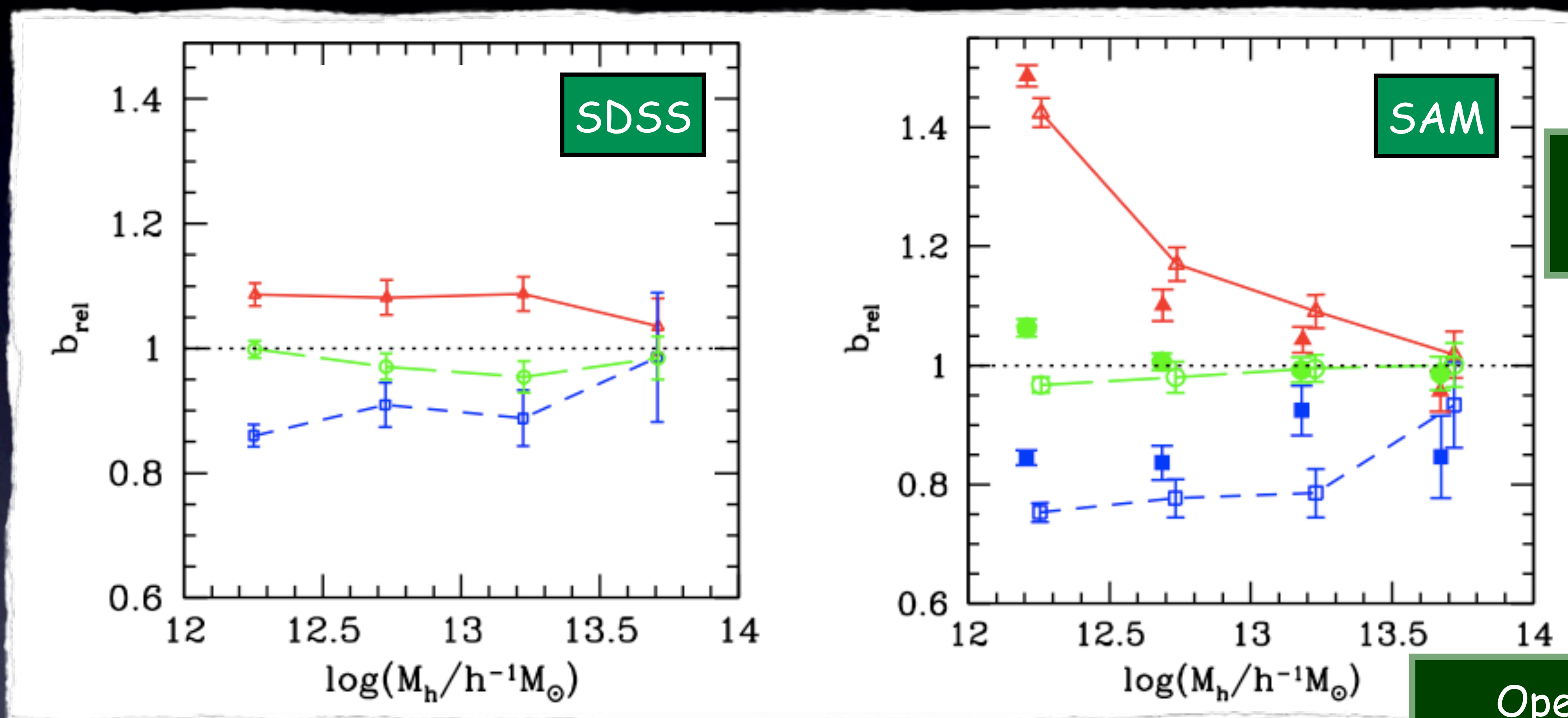
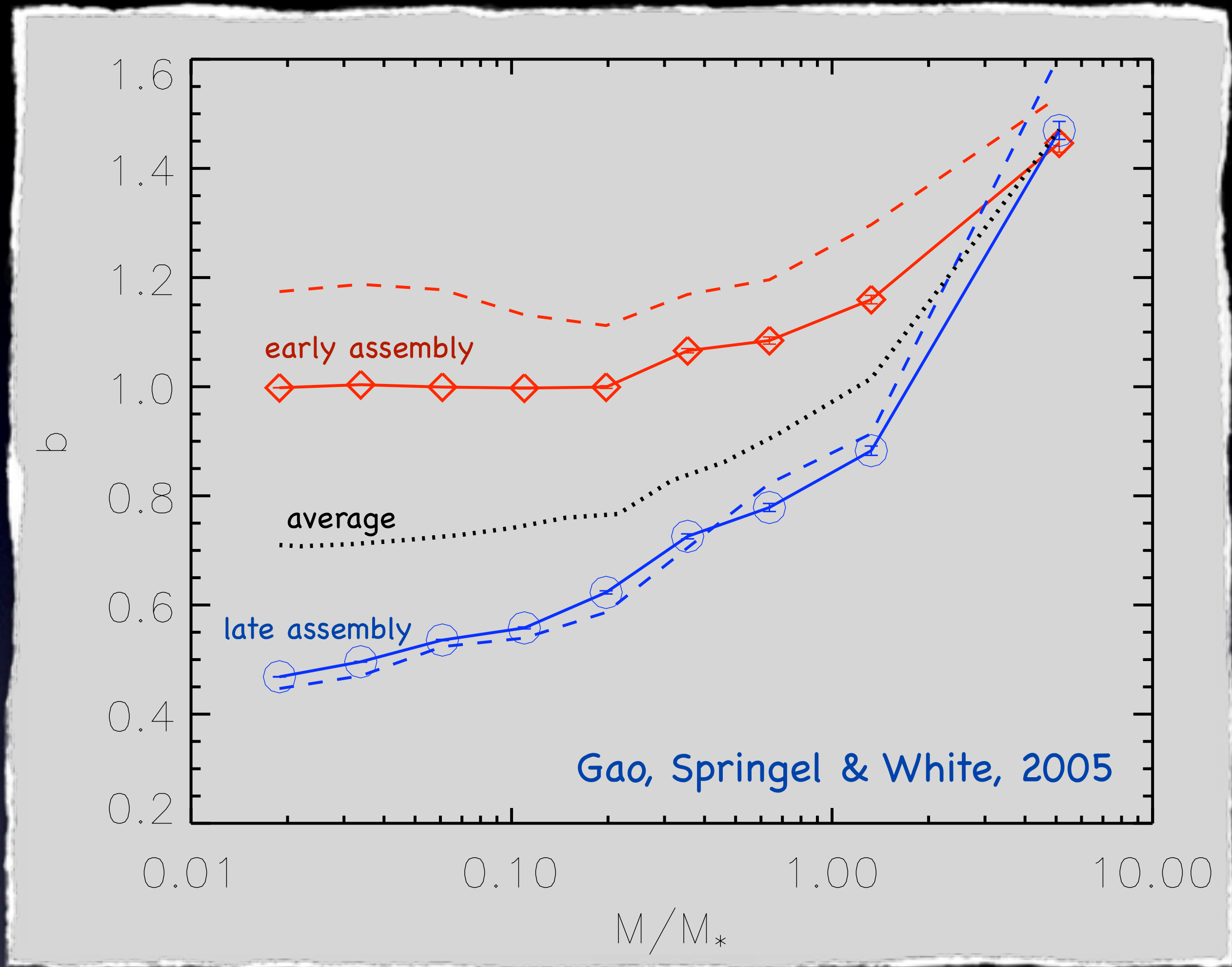


Solid symbols: intrinsic

Open symbols: mock group catalogue

- Group finder does not introduce spurious results.
- SAM predicts much stronger color dependence.

Relation to Halo Assembly Bias



Linear theory predicts that halo bias is a function of halo mass only.

However, simulations have shown that halo bias also depends on assembly time.

Low mass halos that assemble earlier are more strongly clustered than haloes of the same mass that assemble later.

e.g. Gao et al. 2005, Wechsler et al. 2006

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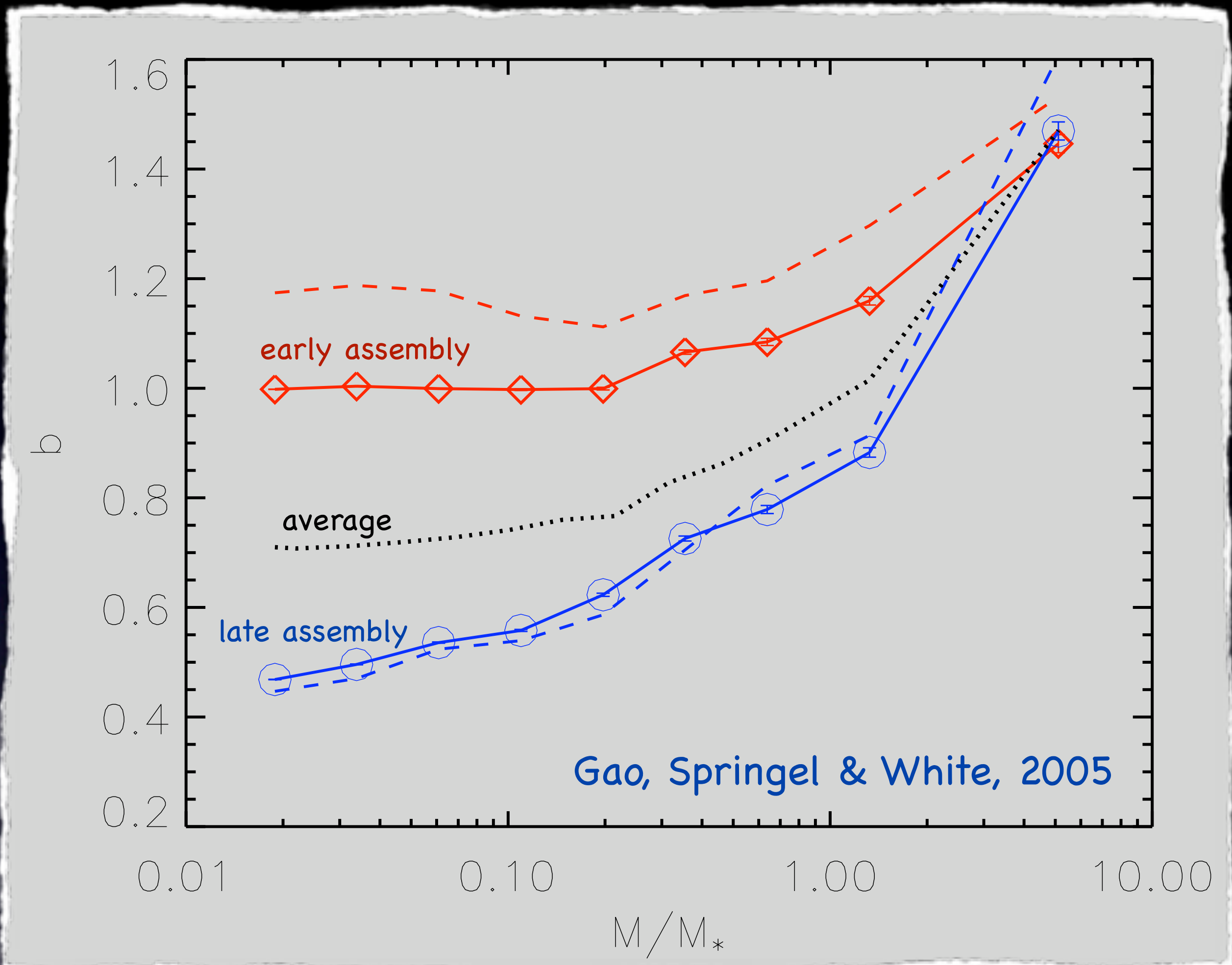

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Naive interpretation: haloes that assemble earlier contain redder galaxies.

However, this would result in an inverted color-magnitude relation.

More likely solution: haloes that form earlier contain redder galaxies.

Neistein, vdB & Dekel, 2006

Conclusions Part II

- Mass dependence of halo bias in good agreement with predictions for LCDM concordance cosmology
- Groups with red centrals are more strongly clustered than groups of same mass but with blue central
- Can be understood qualitatively if star formation history of central galaxies is correlated with formation history (NOT assembly history) of host halo.
- Semi-analytical models reproduce observed trend qualitatively, but predicted effect is much stronger than observed.

Part III

The Alignment between Galaxies and Dark Matter Halos

Galaxy-Halo Alignment: the Holmberg effect

In 1969 Holmberg noted that satellites galaxies are preferentially located along the minor axis of disk galaxies (analysis restricted to r<50 kpc).

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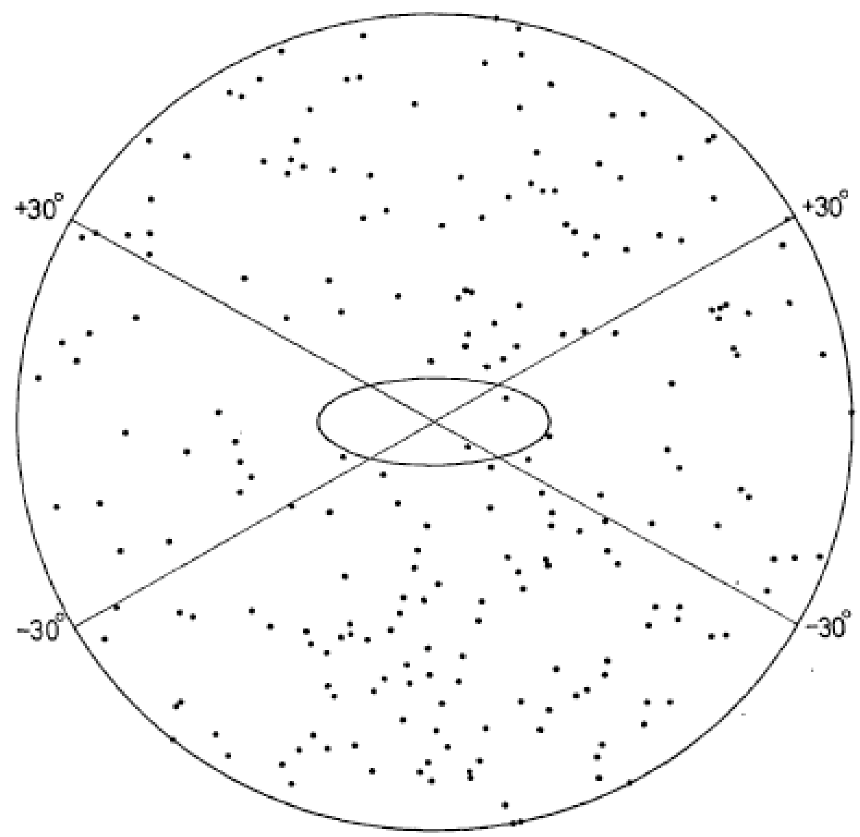

Fig. 3. Combined distribution of 218 galaxies in 58 survey areas around spiral systems of class *A* (edgewise orientation). The ellipse shows the average size of the central system.

Subsequent studies by Hawley & Peebles (1975), Sharp, Lin & White (1979) and MacGillivray et al. (1982) were unable to confirm this Holmberg effect....

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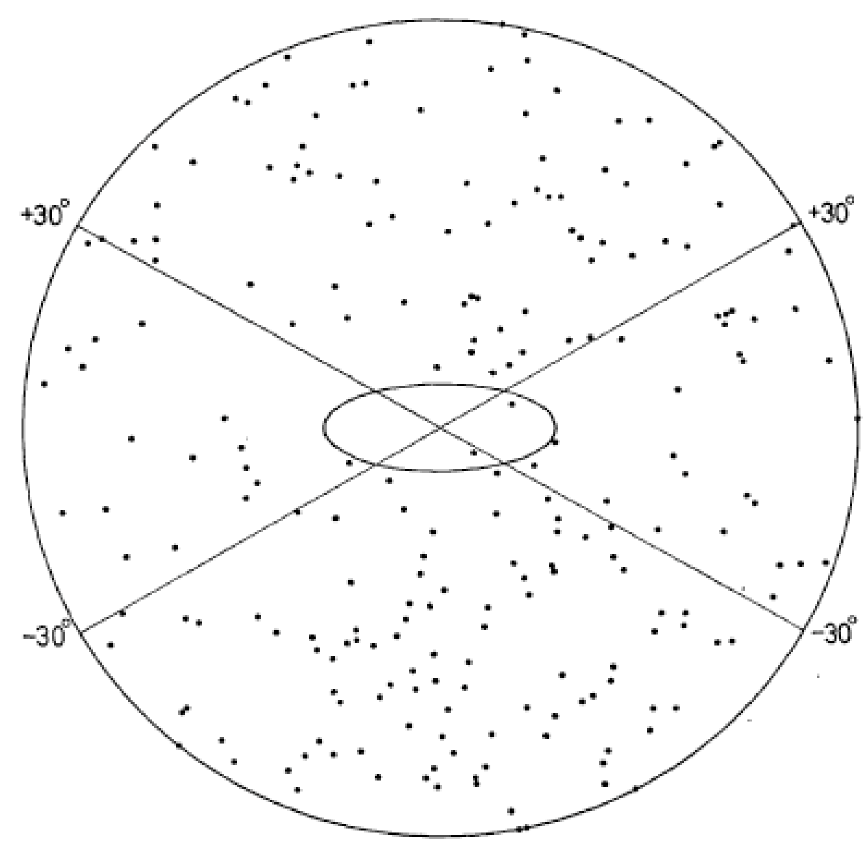

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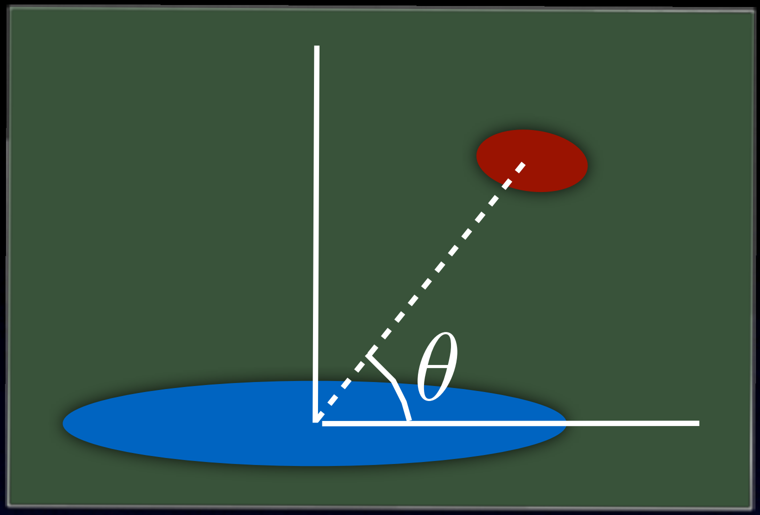
Subsequent studies by Hawley & Peebles (1975), Sharp, Lin & White (1979) and MacGillivray et al. (1982) were unable to confirm this Holmberg effect....

But, in 2005, Brainerd found strong evidence for opposite effect in SDSS....

Testing for Holmberg effect in Group Catalogue



For each central-satellite pair, measure angle θ.

Count $N(\theta)$ from groups and from 100 realizations, in which orientation of centrals is randomized.

Compute $f_{\rm pair}(\theta) = \frac{N(\theta)}{\langle N_R(\theta) \rangle}$

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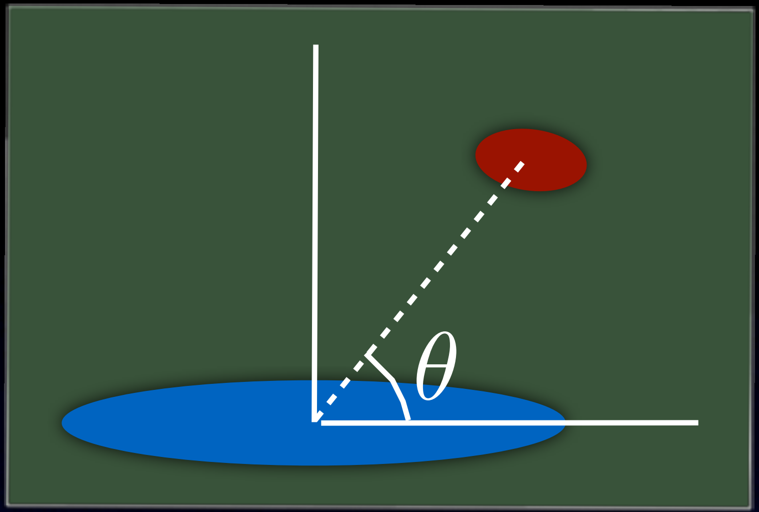

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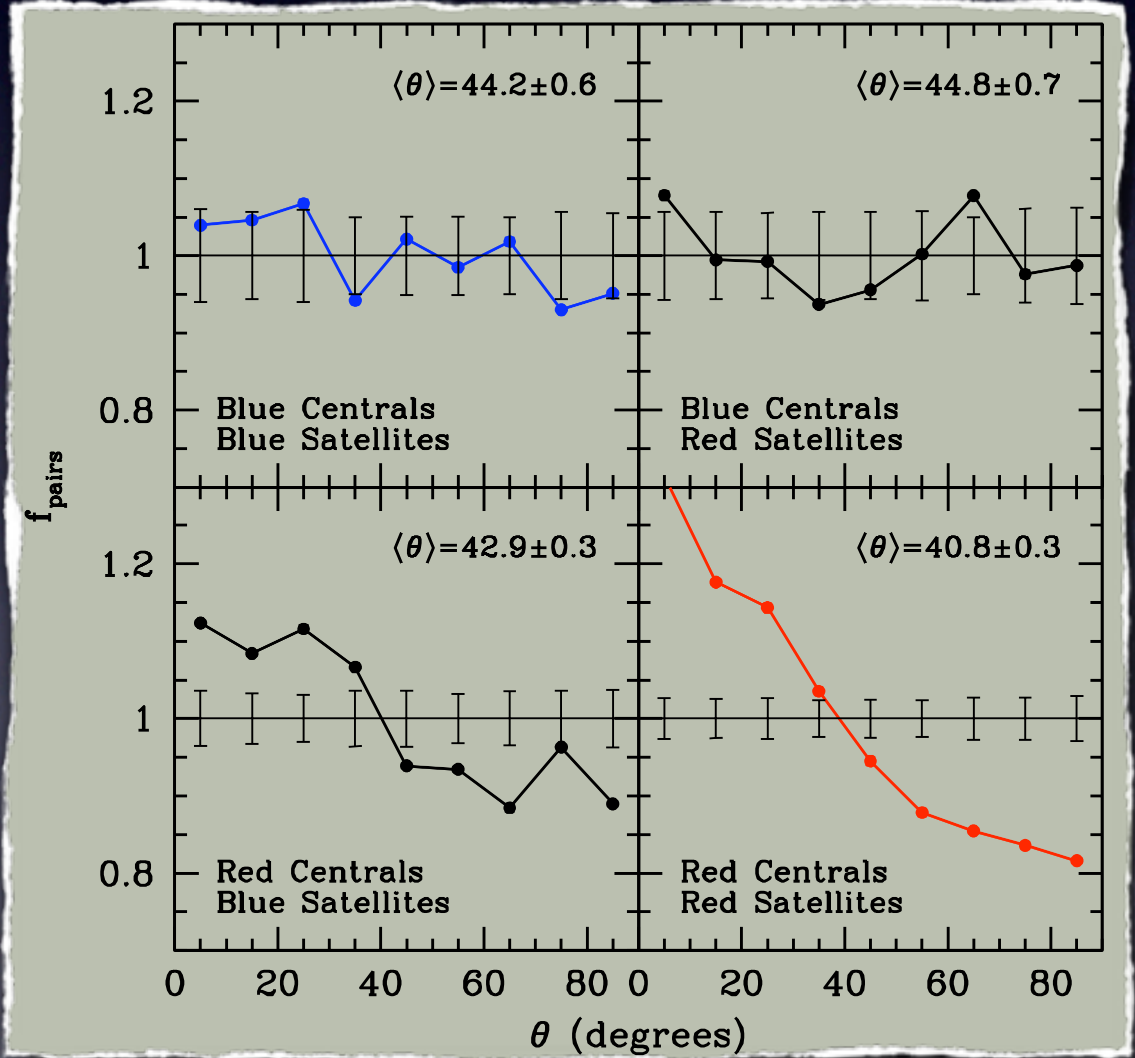
Compute $f_{\rm pair}(\theta) = \frac{N(\theta)}{\langle N_R(\theta) \rangle}$

No Holmberg effect around blue centrals

Strong, inverted Holmberg effect around red centrals, confirming Brainerd (2005).

Alignment stronger for red satellites...



Brainerd (2005), Sales & Lambas (2005), Yang et al. (2006), Faltenbacher et al. (2007), Azzaro et al. (2007), Wang et al. (2008)

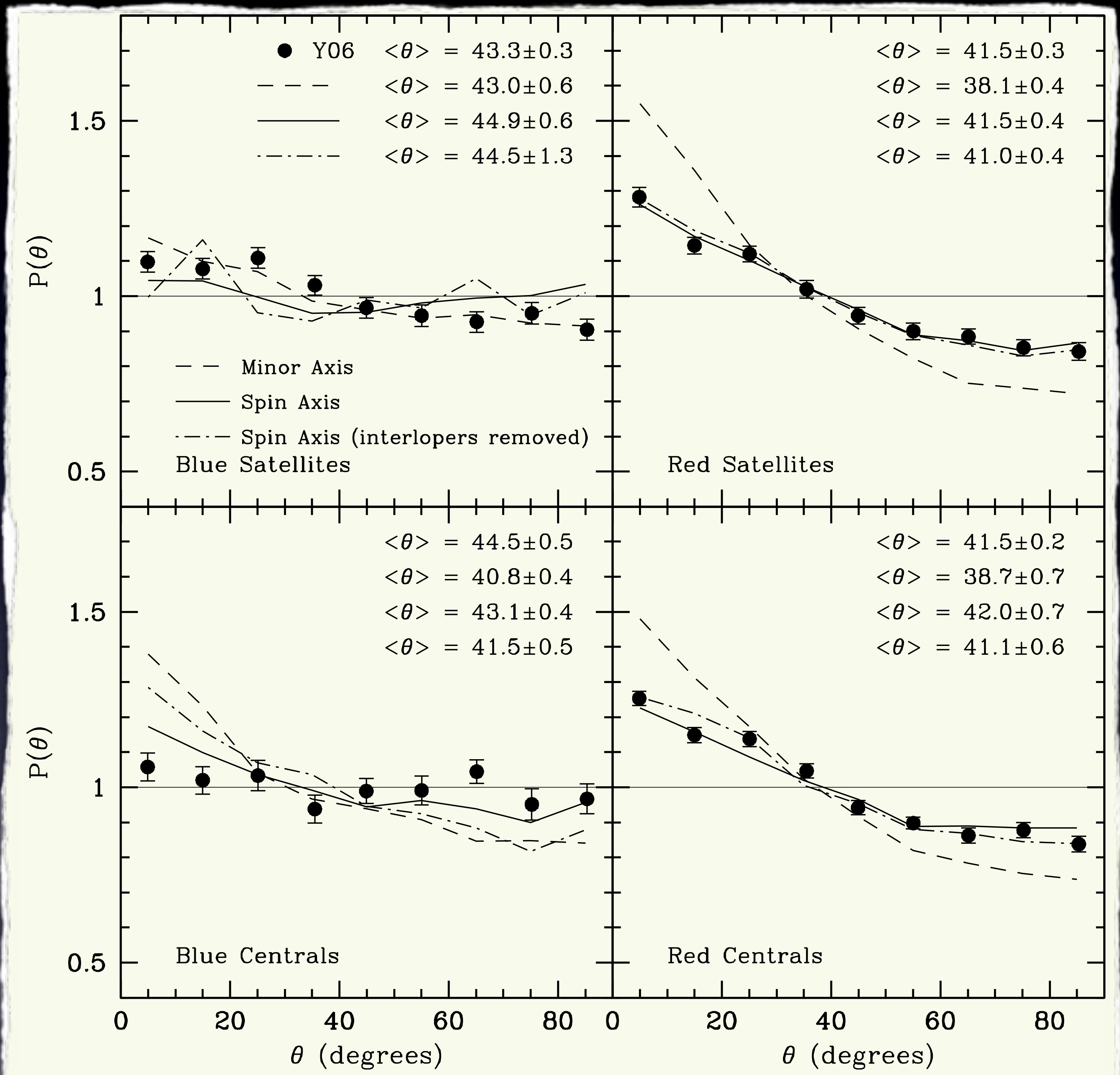
Interpretation of Alignment

Alignment arises naturally if:
(i) satellites trace halo shape
(ii) centrals are aligned with halo

Modeling with Numerical Simulation +Semi-Analytical Model

- Satellites are associated with dark matter subhaloes.
- Minor axis of centrals aligned with (i) minor axis of host halo, or (ii) spin axis of host halo.
- Create mock SDSS, apply group finder, analyze as real data.

Interpretation of Alignment



Minor axis model predicts alignment that is much too strong

Spin axis model predicts alignment in good agreement with data

Model even reproduces dependence on color of satellite galaxies

Weaker alignment around blue centrals partially due to interlopers

Kang et al. (2007), see also Agustsson & Brainerd (2006)

Note: spin axis & minor axis of CDM haloes have average misalignment of 40 deg.

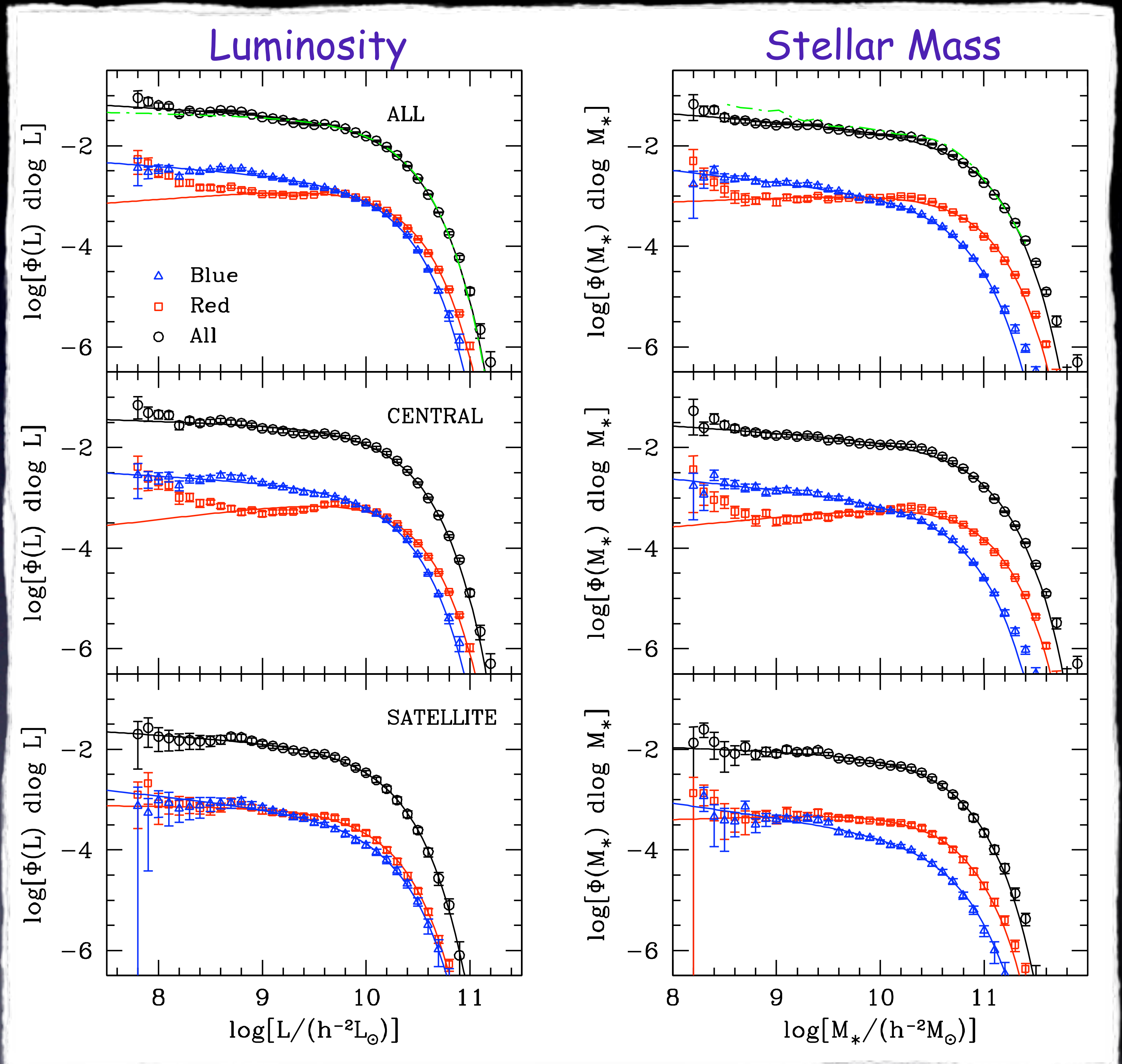
Conclusions Part III

- The distribution of satellite galaxies around red centrals is preferentially aligned with the major axis of the central.
- Alignment strongest for red satellites.
- No satellite alignment detected around blue centrals.
- These alignments can be reproduced in semi-analytical models for galaxy formation, if minor axis of centrals is aligned with spin axis of host halo.
- Absence of alignment around blue centrals may partially be an artifact due to interlopers.

Part IV

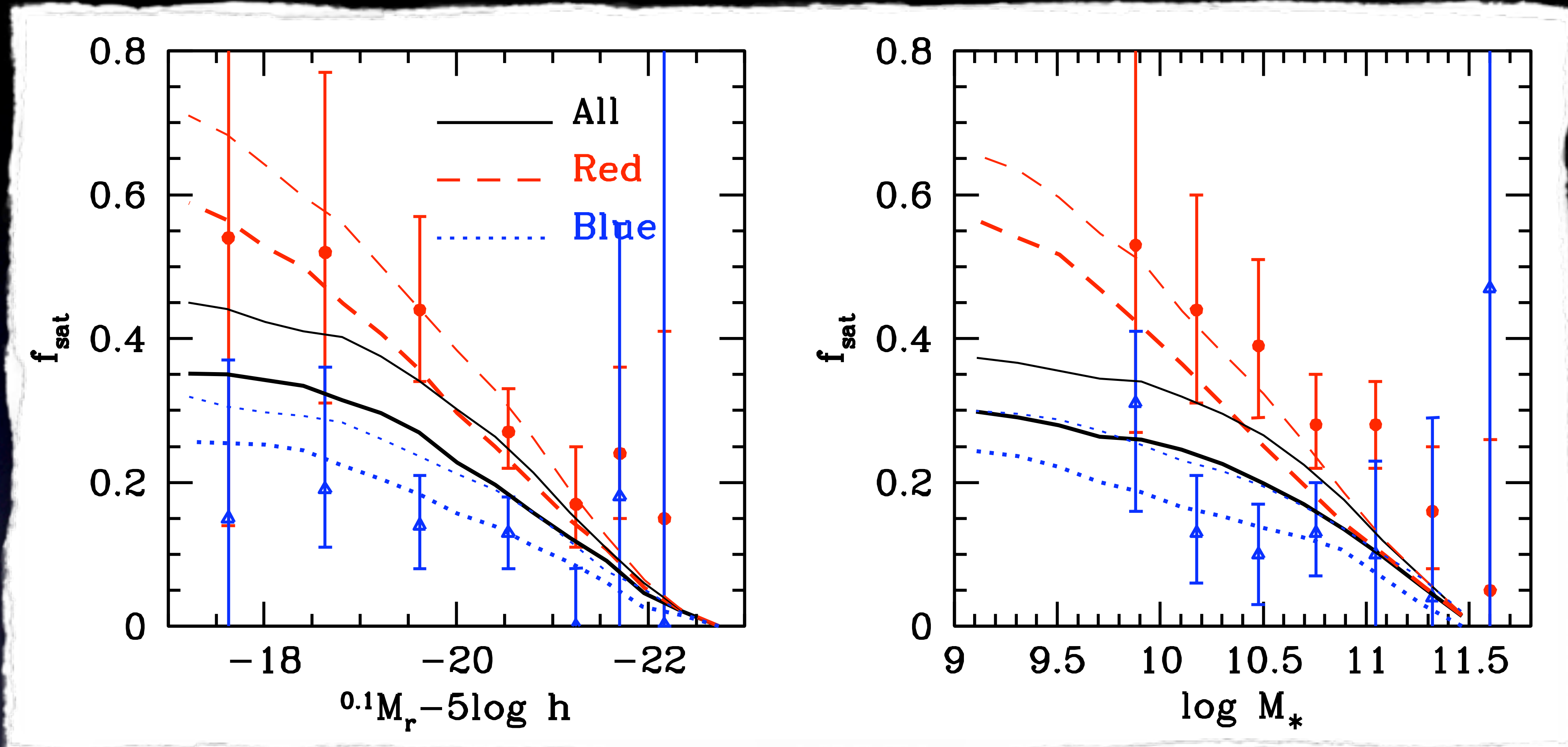
Halo Occupation Statistics

Luminosity and Stellar Mass Functions



Yang, Mo & vdB (2009)

Satellite Fractions



- Satellite fractions decrease with increasing luminosity/stellar mass
- Red galaxies have larger satellite fraction than blue galaxies
- Overall satellite fraction is small; centrals dominate galaxy population
- Good agreement with results from galaxy-galaxy lensing (Mandelbaum et al.2006)

Conditional Luminosity Function

- Describes occupation statistics of dark matter haloes
- Is direct link between galaxy luminosity function and halo mass function
- Contains information on average relation between light and mass

$$\Phi(L) = \int \Phi(L|M)\, n(M)\, \mathrm{d}M$$

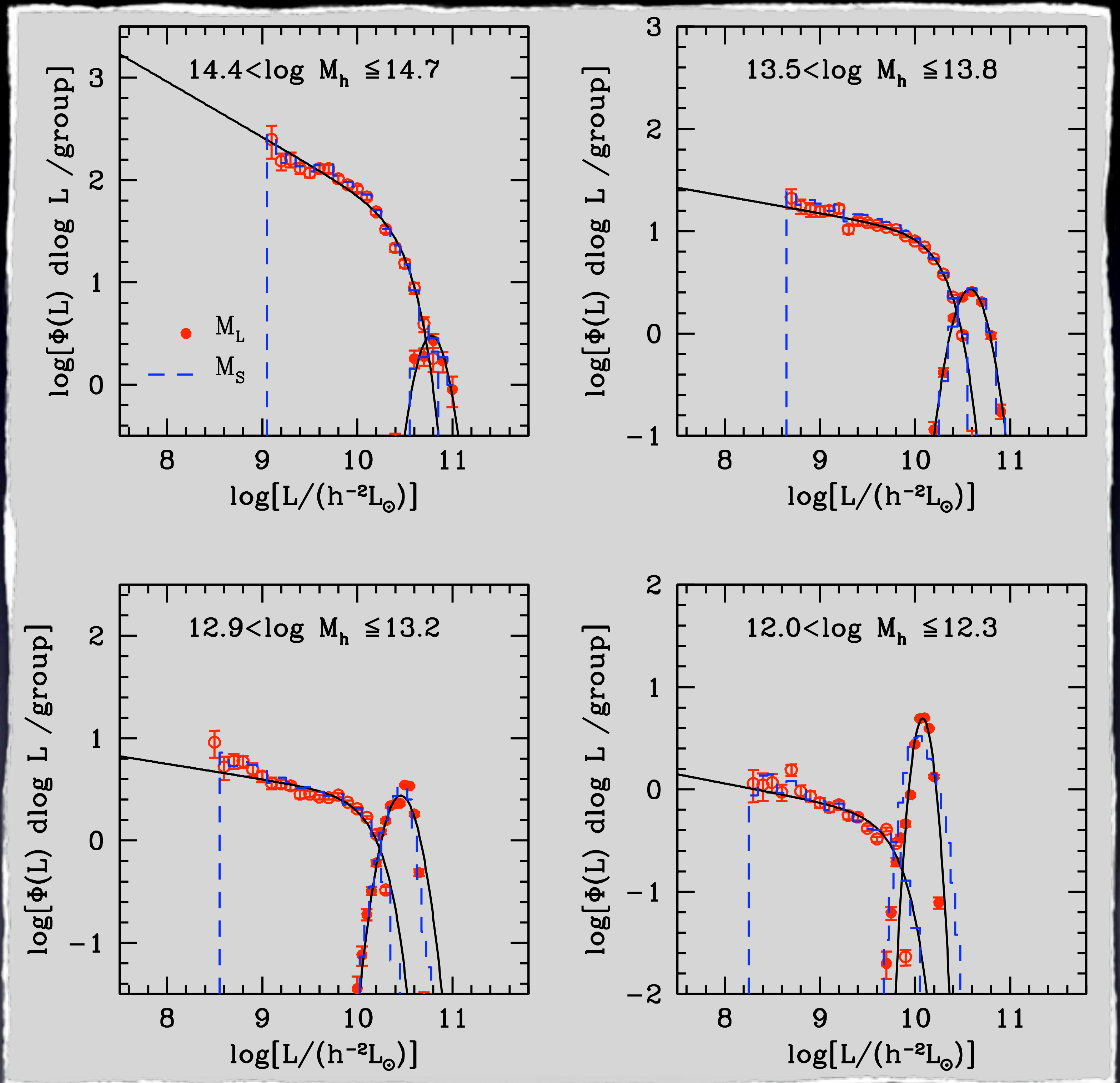
$$\langle L \rangle_M = \int \Phi(L|M)\, L\, \mathrm{d}L$$

$$\langle N \rangle_M = \int_{L_{\rm min}}^{\infty} \Phi(L|M) \mathrm{d}L$$

CLF can be constrained using:

- Galaxy Clustering: *Yang, Mo & vdB, 2003; vdB, Yang & Mo 2003, vdB et al 2007*
- Galaxy-Galaxy Lensing: *Cacciato et al. 2009*
- Satellite Kinematics: *vdB et al. 2004; More et al. 2009a.b*
- Galaxy Group Catalogue: *Yang et al. 2005; Yang, Mo & vdB 2008a,b*

Conditional Luminosity Function



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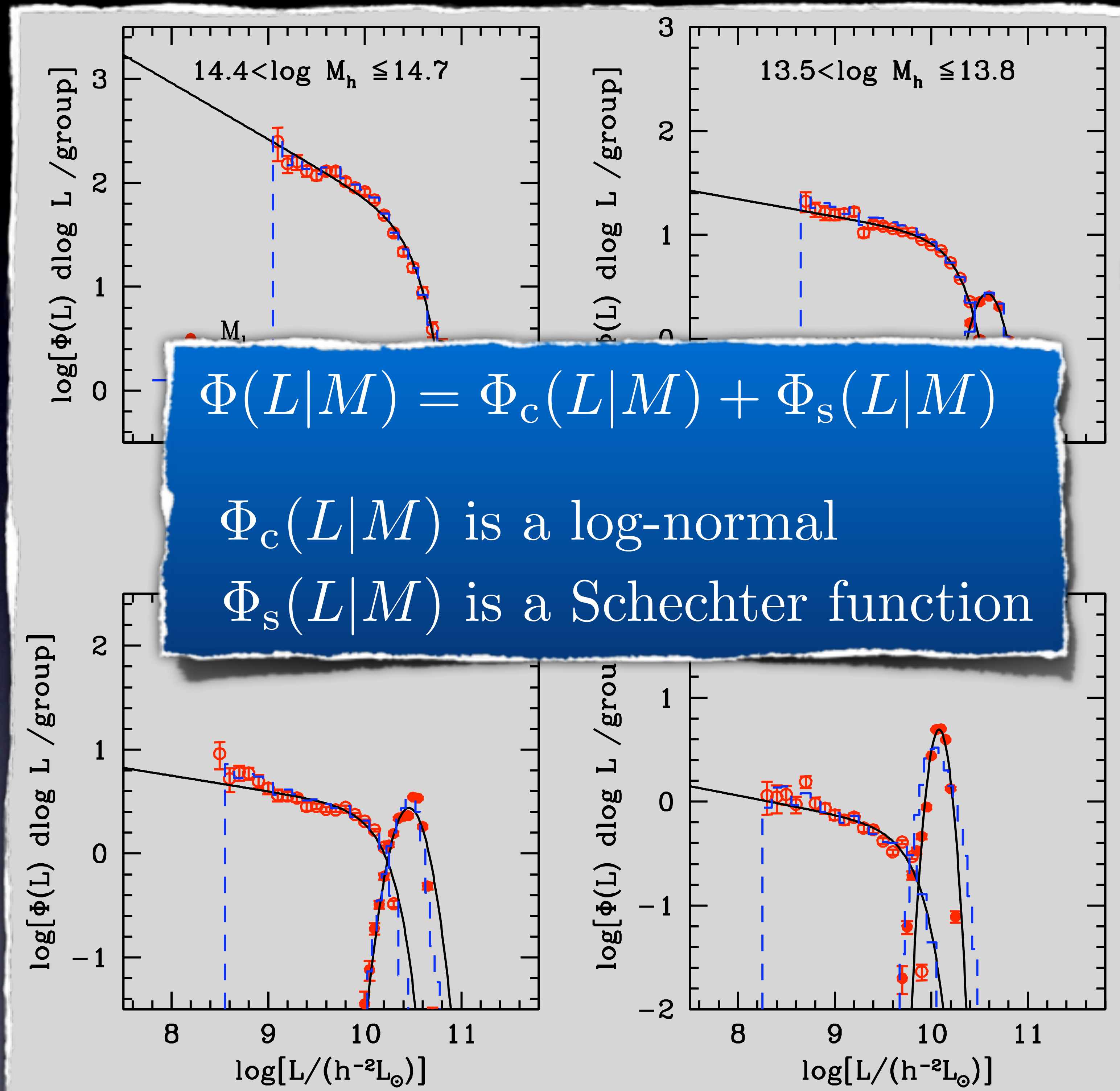


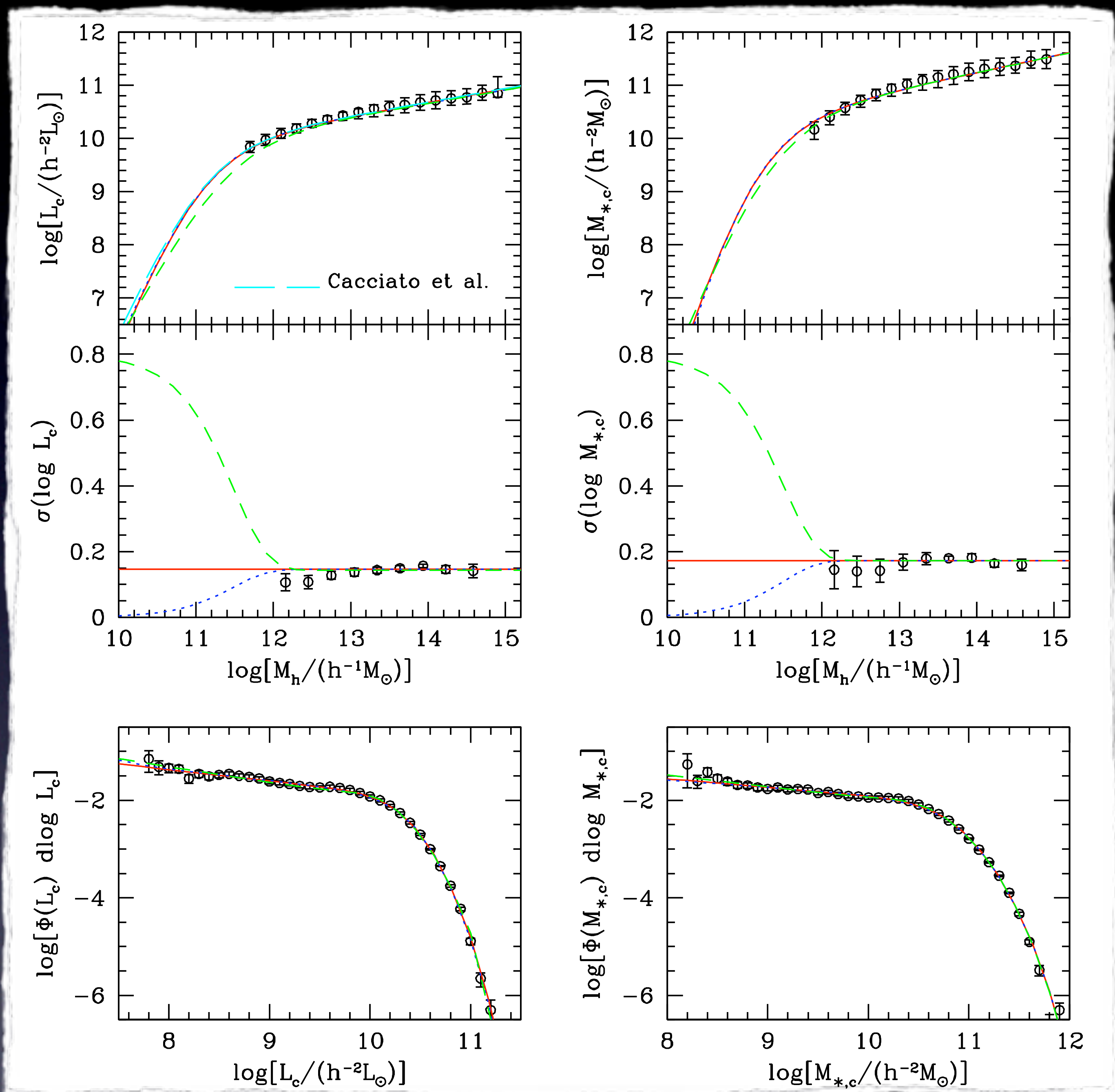
$$\Phi(L|M) = \Phi_{\rm c}(L|M) + \Phi_{\rm s}(L|M)$$

$\Phi_{\rm c}(L|M)$ is a log-normal

$\Phi_{\rm s}(L|M)$ is a Schechter function

Yang, Mo & vdB (2008)

Halo Mass dependence of Central Galaxies



Fit relation with following form:

$$L_{\rm c} = L_0 \frac{(M_{\rm h}/M_1)^{\alpha+\beta}}{(1+M_{\rm h}/M_1)^{\beta}}$$

Constrain faint-end using:

$$\Phi(L_{\rm c}) = \int_0^{\infty} \Phi_{\rm c}(L|M_{\rm h})\, n(M_{\rm h})\, {\rm d}M_{\rm h}$$

Results are very insensitive to scatter in relation.

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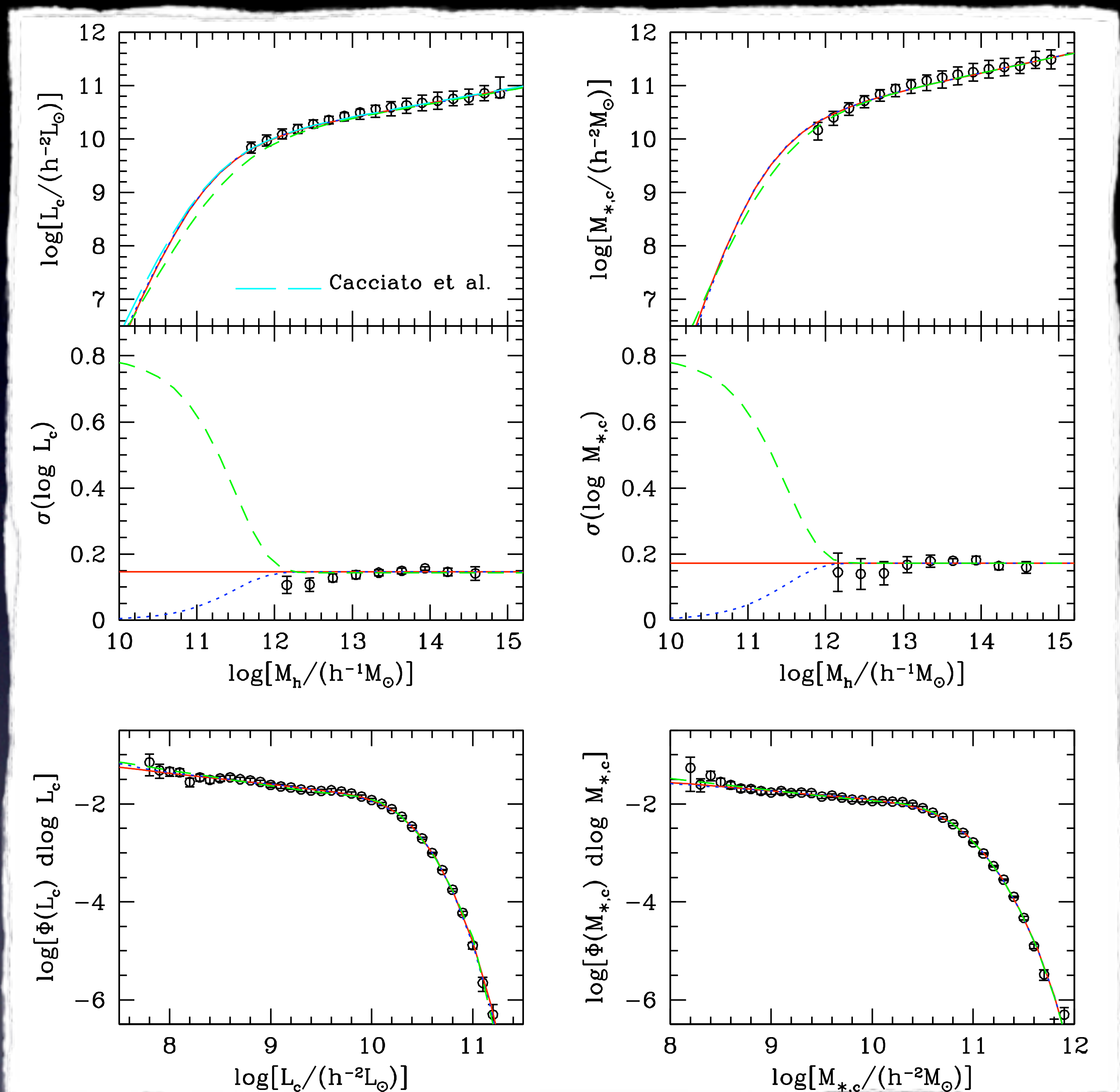

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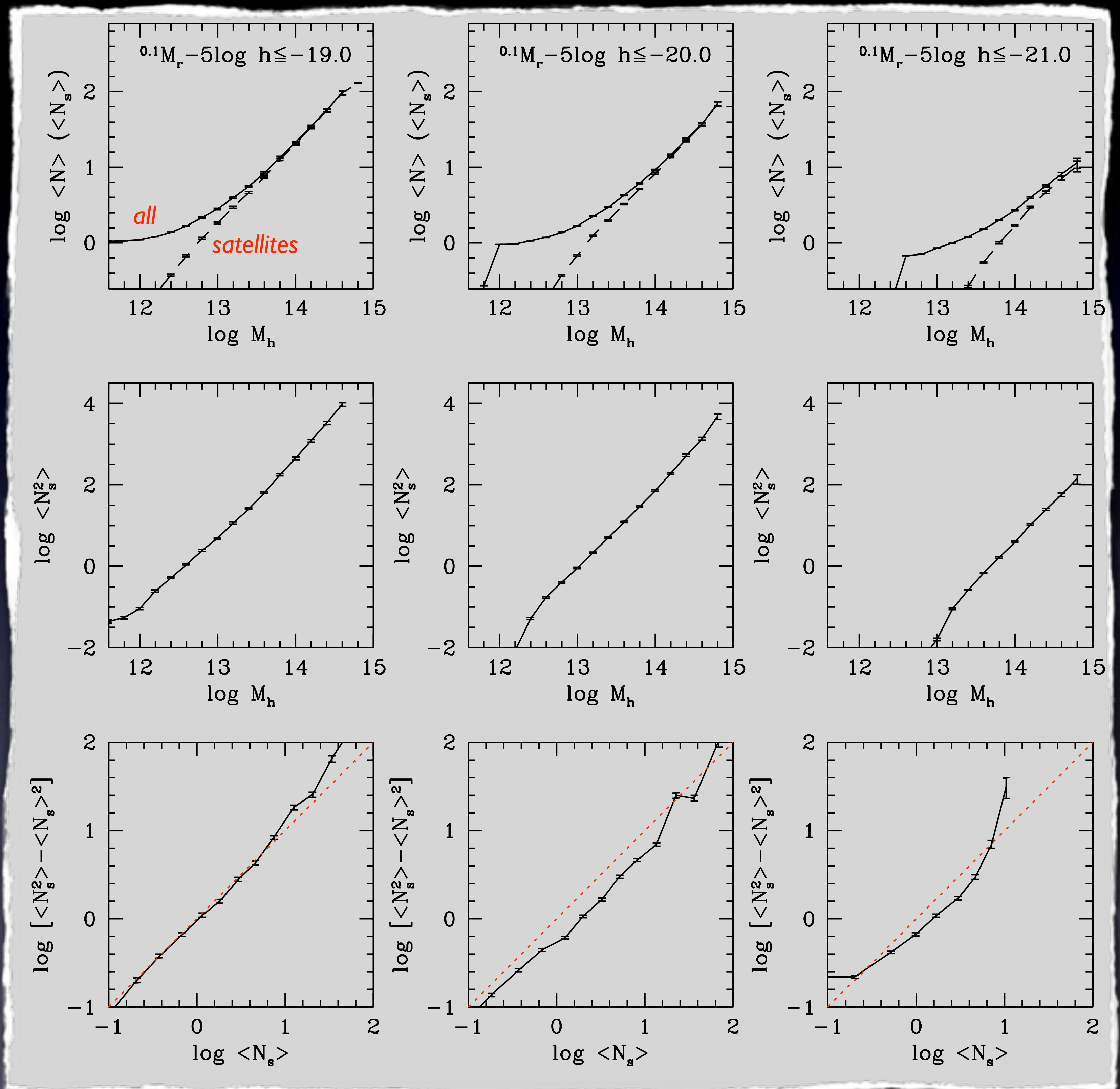
Constrain faint-end using:

$$\Phi(L_c) = \int_0^{\infty} \Phi_c(L|M_h)\, n(M_h)\, dM_h$$

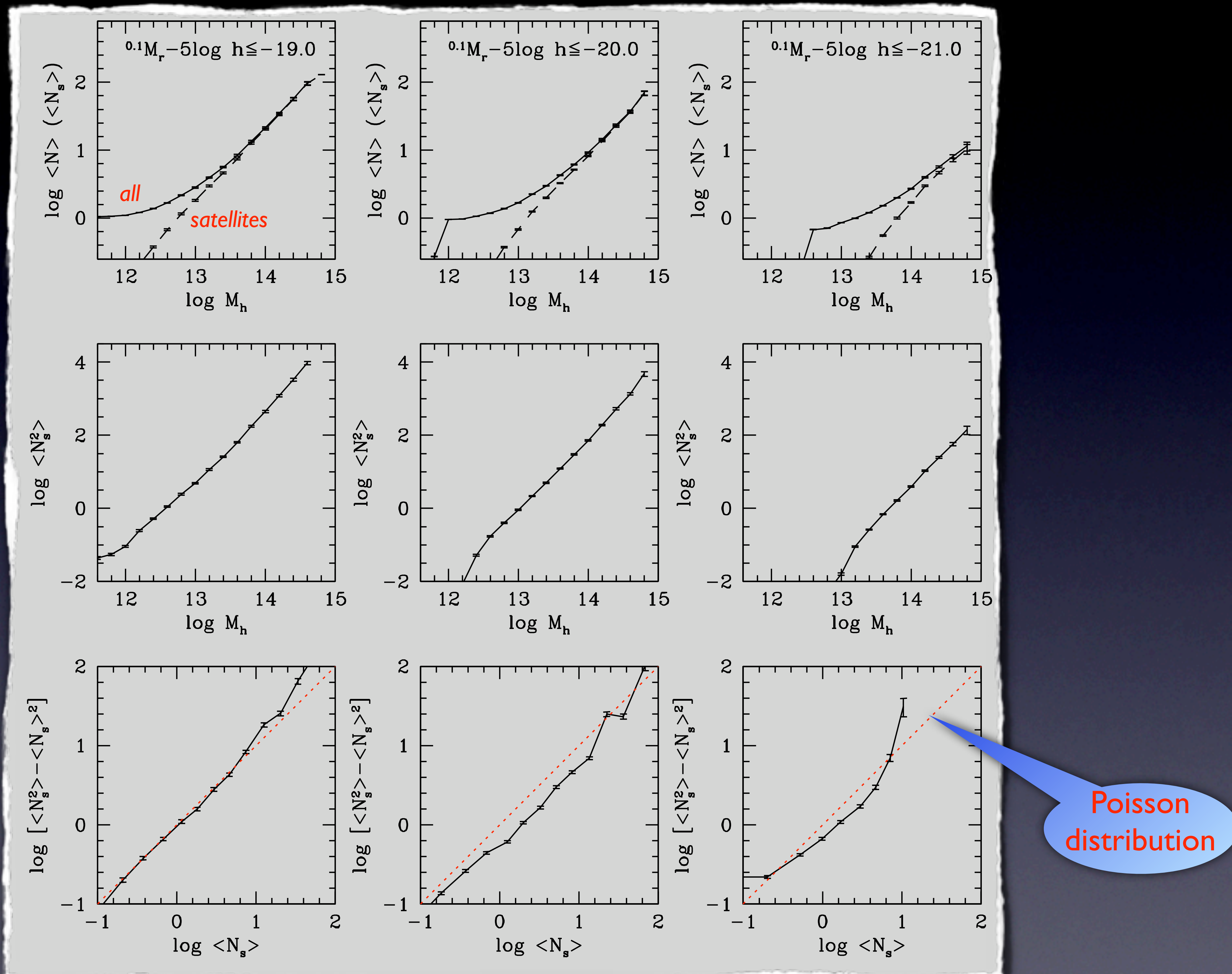
Results are very insensitive to scatter in relation.

We obtain tight constraints on relations between luminosity or stellar mass of central galaxy and the mass of the halo it inhabits

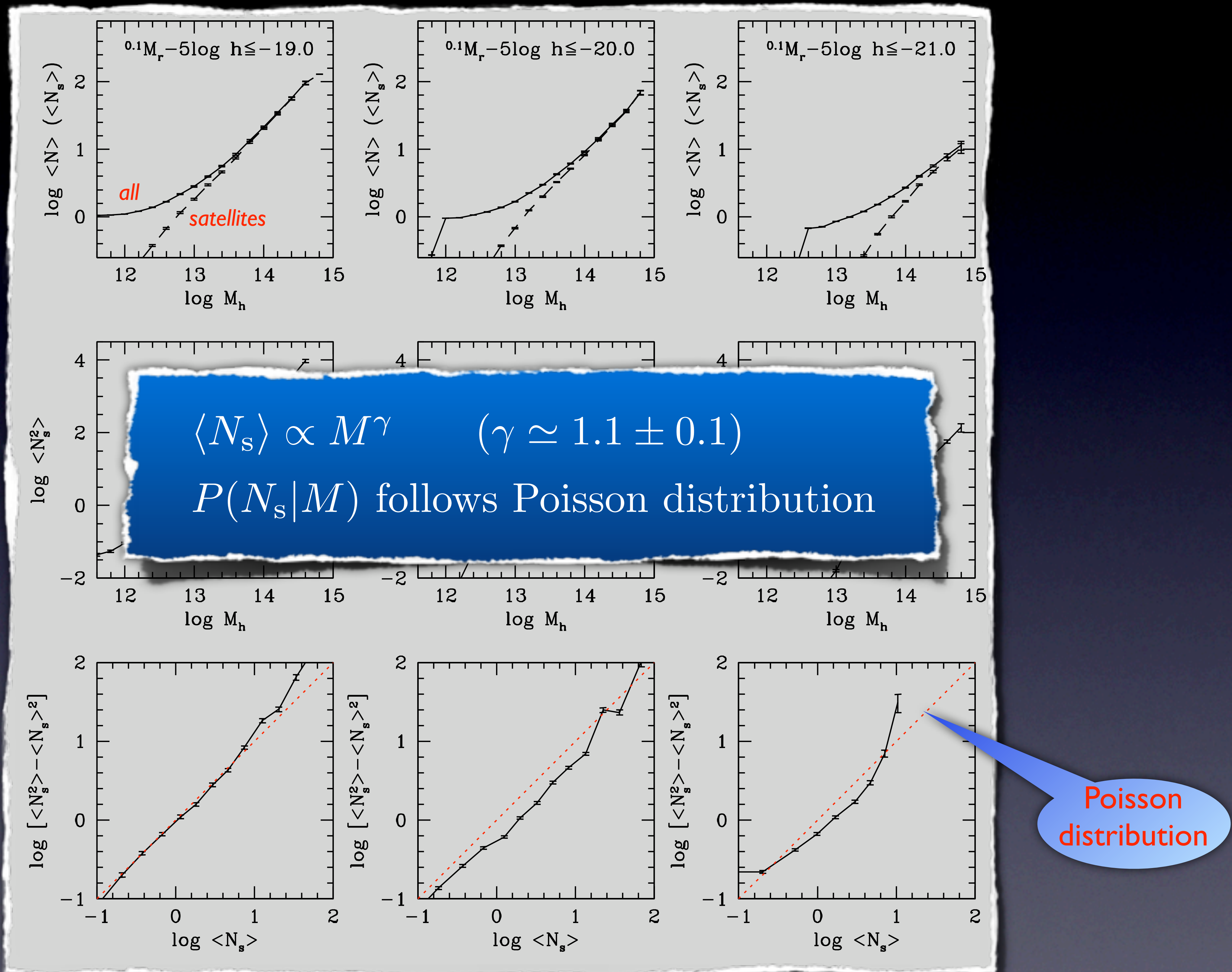
Halo Occupation Statistics



Halo Occupation Statistics



Halo Occupation Statistics



$\langle N_{\rm s}\rangle \propto M^{\gamma} \qquad (\gamma \simeq 1.1 \pm 0.1)$

$P(N_{\rm s}|M)$ follows Poisson distribution

Conclusions Part IV

- Galaxy Group Catalogues yield tight constraints on halo occupation statistics and CLF in particular.
- Ideally suited to split galaxies in centrals and satellites.
- Faint-end upturn in LF of red galaxies due to centrals; most likely an environmental effect...
- Relation between halo mass and luminosity/stellar mass of centrals tightly constrained down to faint/low mass end
- Satellite occupation statistics follow Poisson distribution with <Nsat> proportional to halo mass.

The End