

Explorations based on Galaxy Group Catalogues

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

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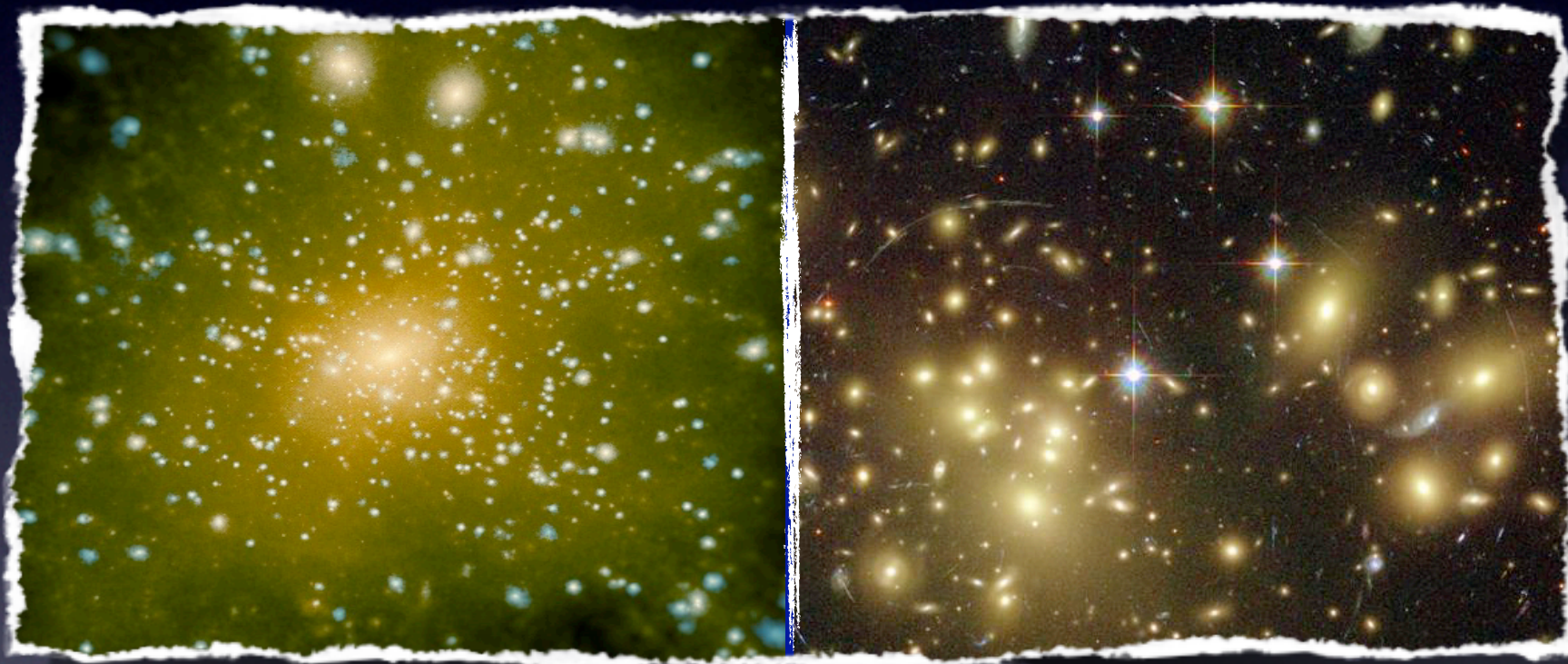
In collaboration with:

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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

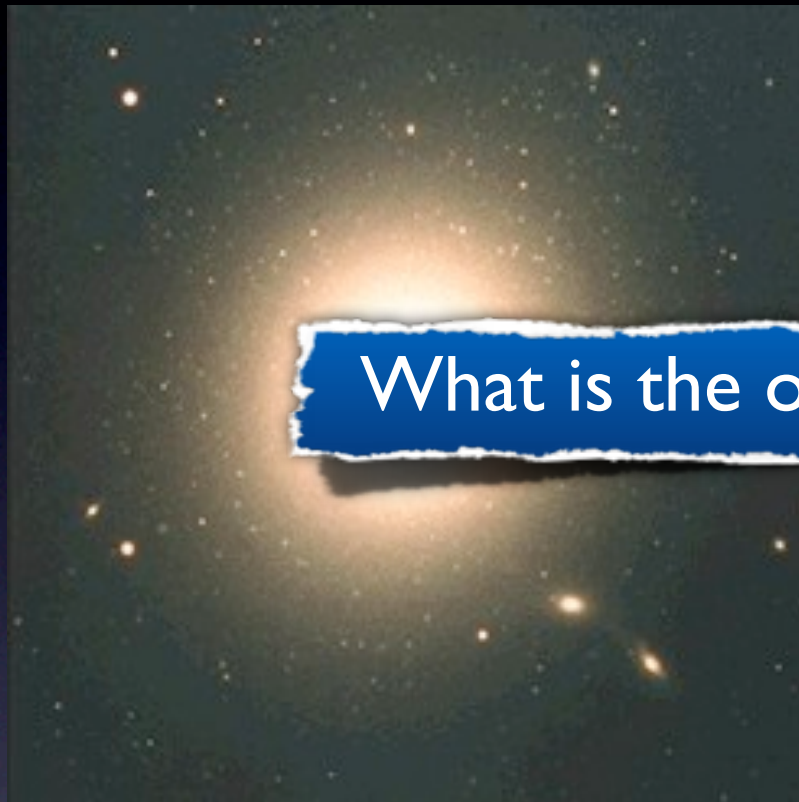
For details see Yang et al. (2005) and Yang et al. (2007).

Part I

Constraining the Physics
of Galaxy Formation

The Bi-Modal Distribution of Galaxies

Early-Type



Late-Type



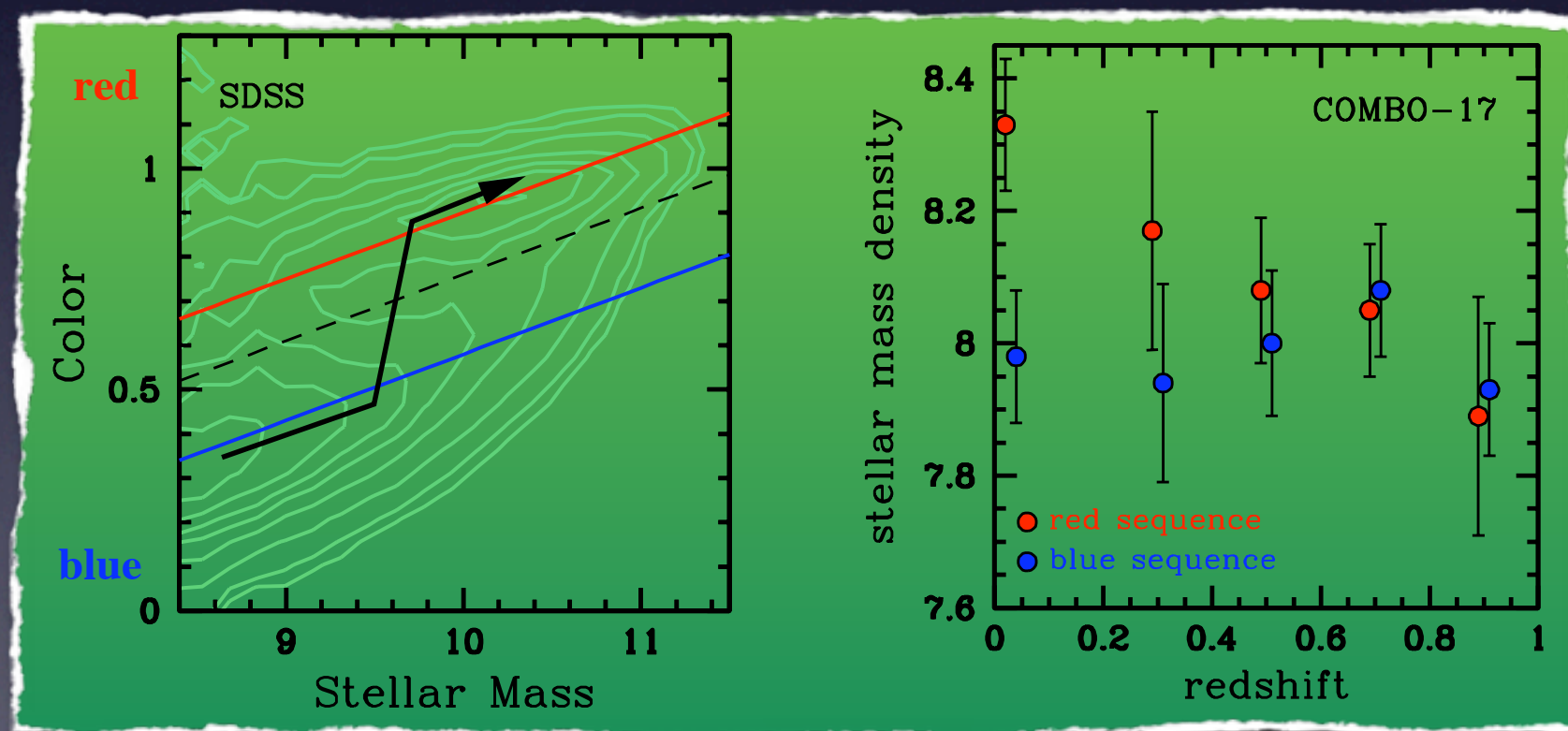
What is the origin of this bimodality?

Spheroidal Morphology
Old Stellar Populations
No or Little Cold Gas
Red Colors

Disk-Like Morphology
Young Stellar Populations
Abundant Cold Gas
Blue colors

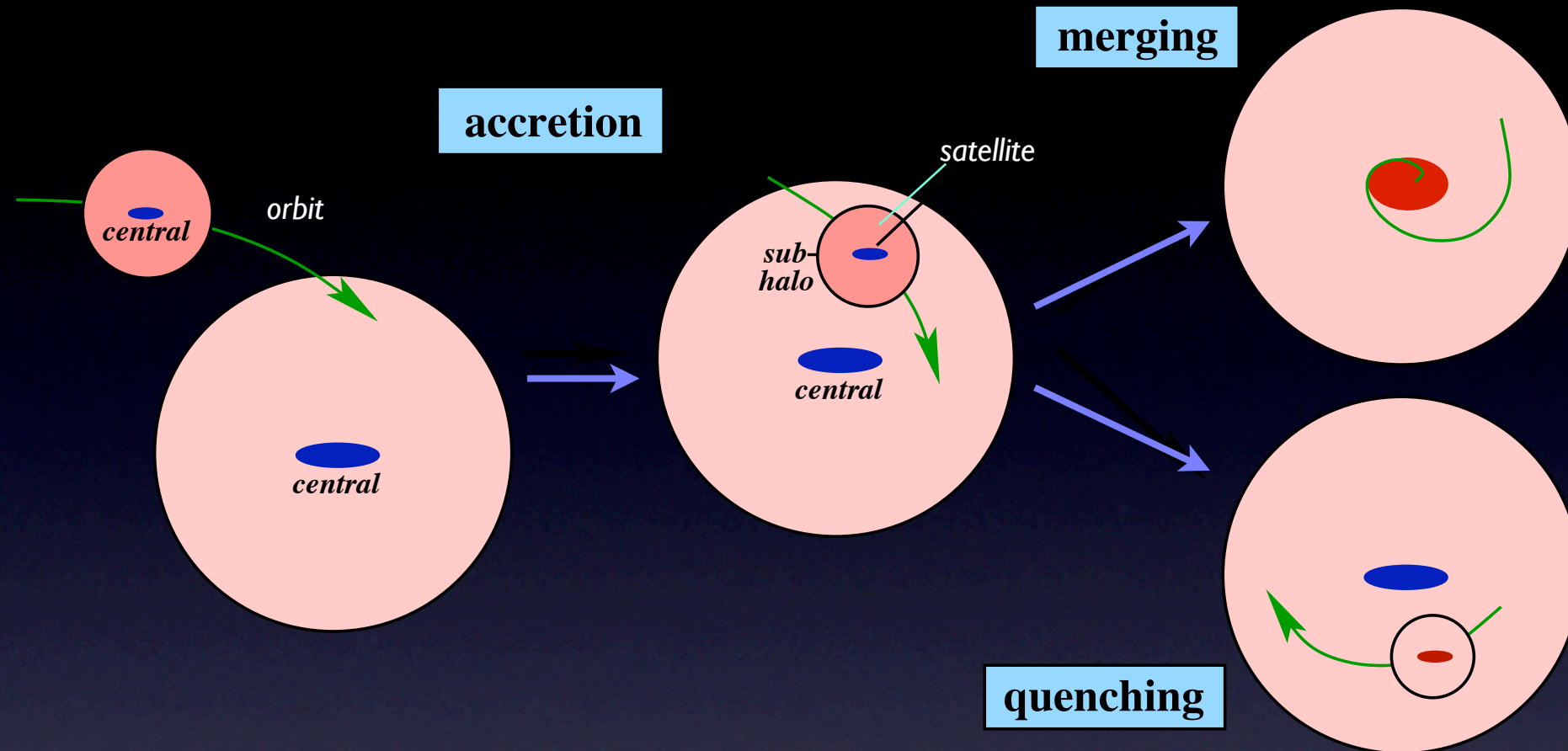
The Standard Paradigm

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)*

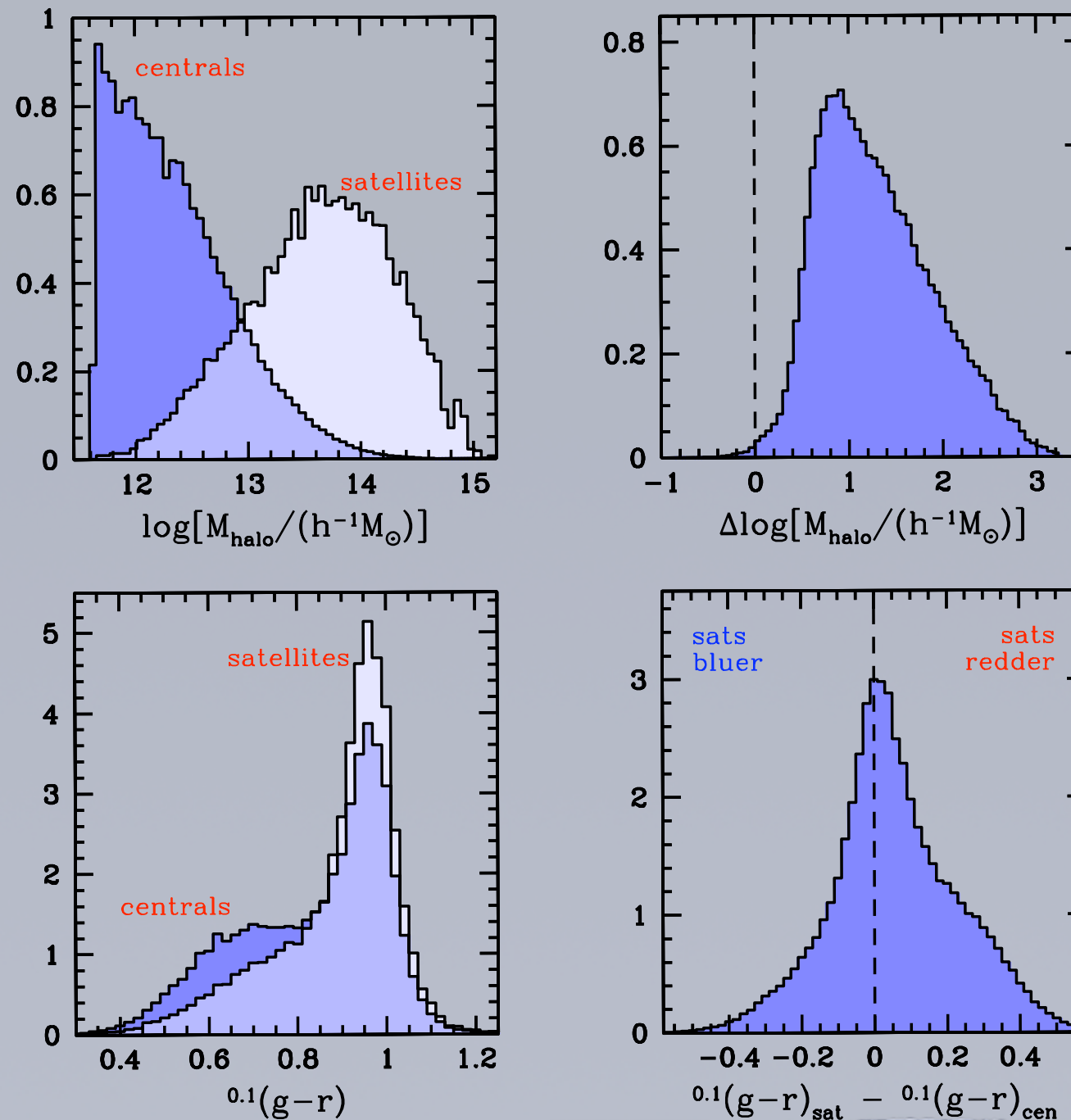
Outstanding Questions

- 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?

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.

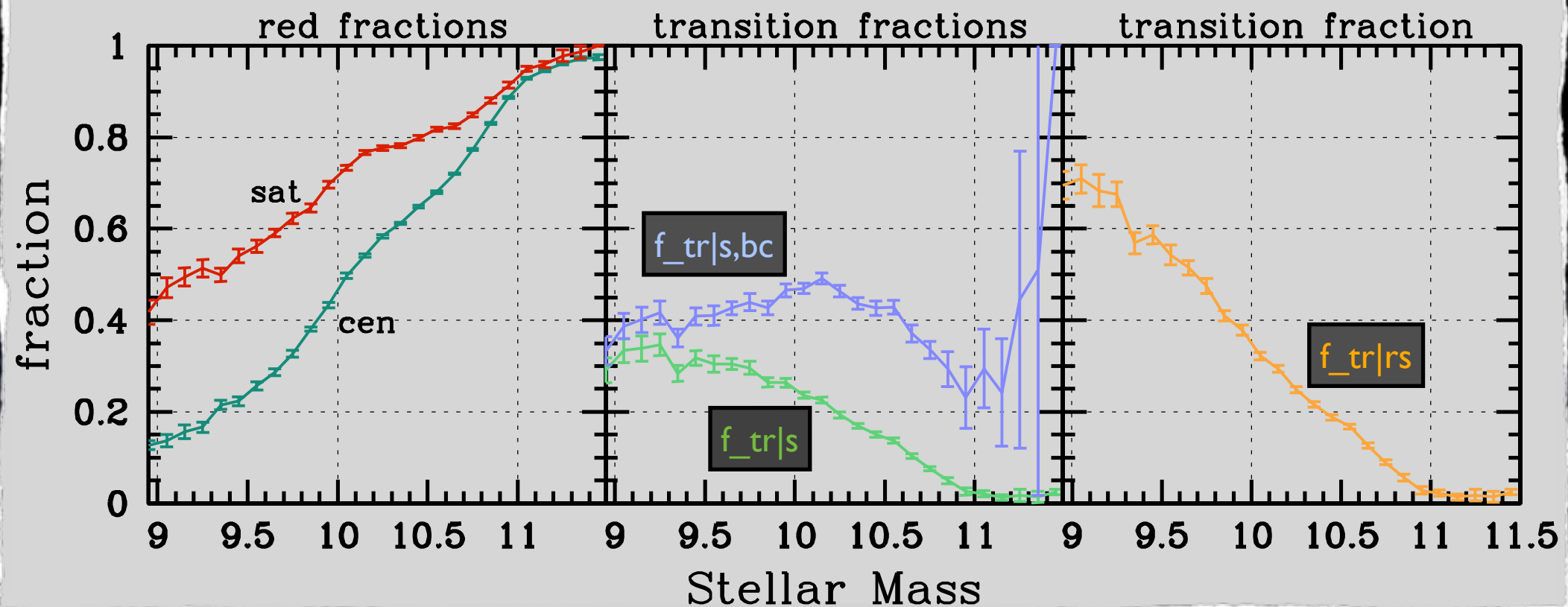
Centrals vs. Satellites



van den Bosch et al. (2008)

Sats are marginally **redder** than centrals of same stellar mass

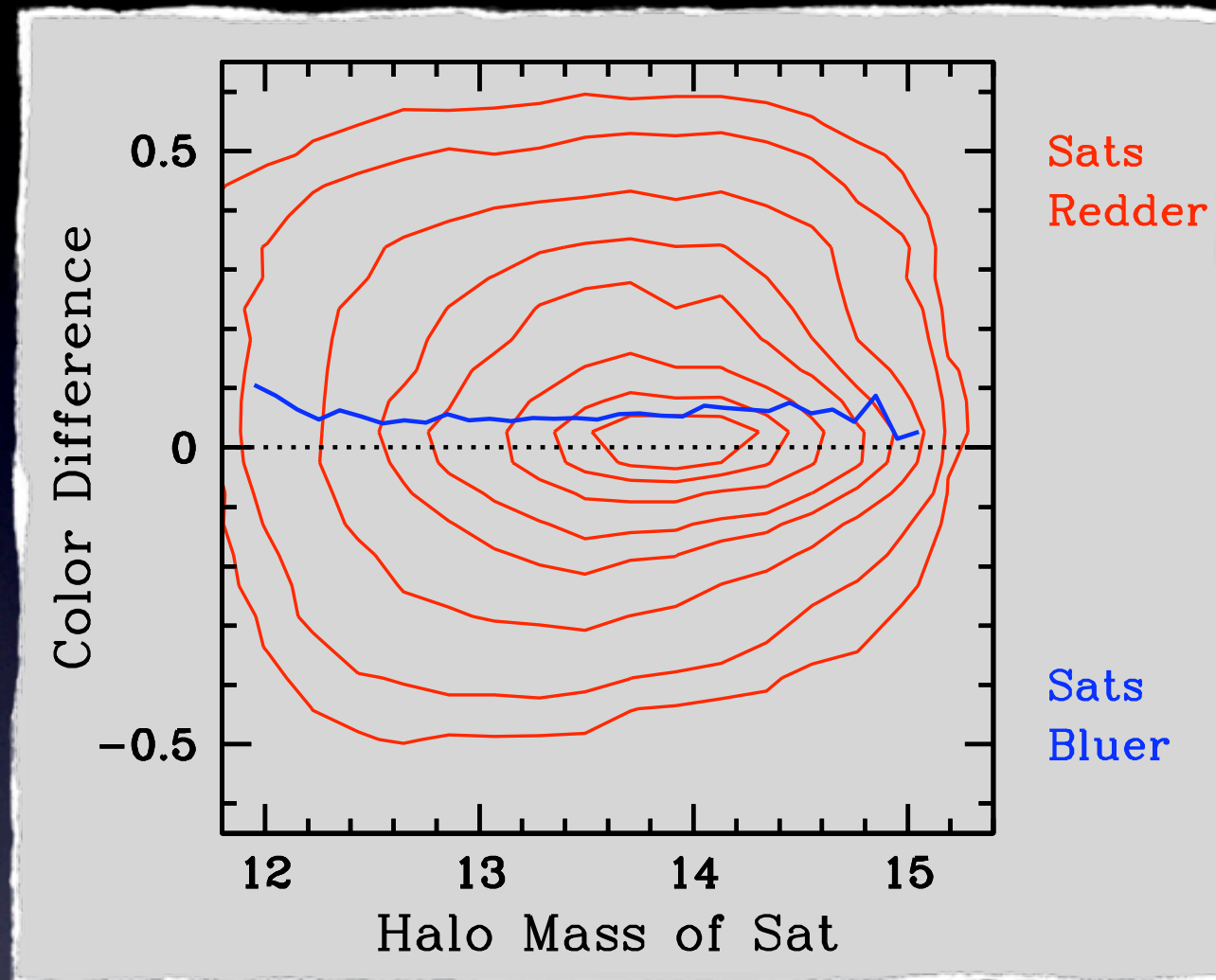
Blue-to-Red Transition Fractions



- 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 $10^{10} h^{-2} M_{\text{sun}}$ majority of sats were already red at accretion
- Satellite transformation processes are only important at low M_{star}

van den Bosch et al. (2008)

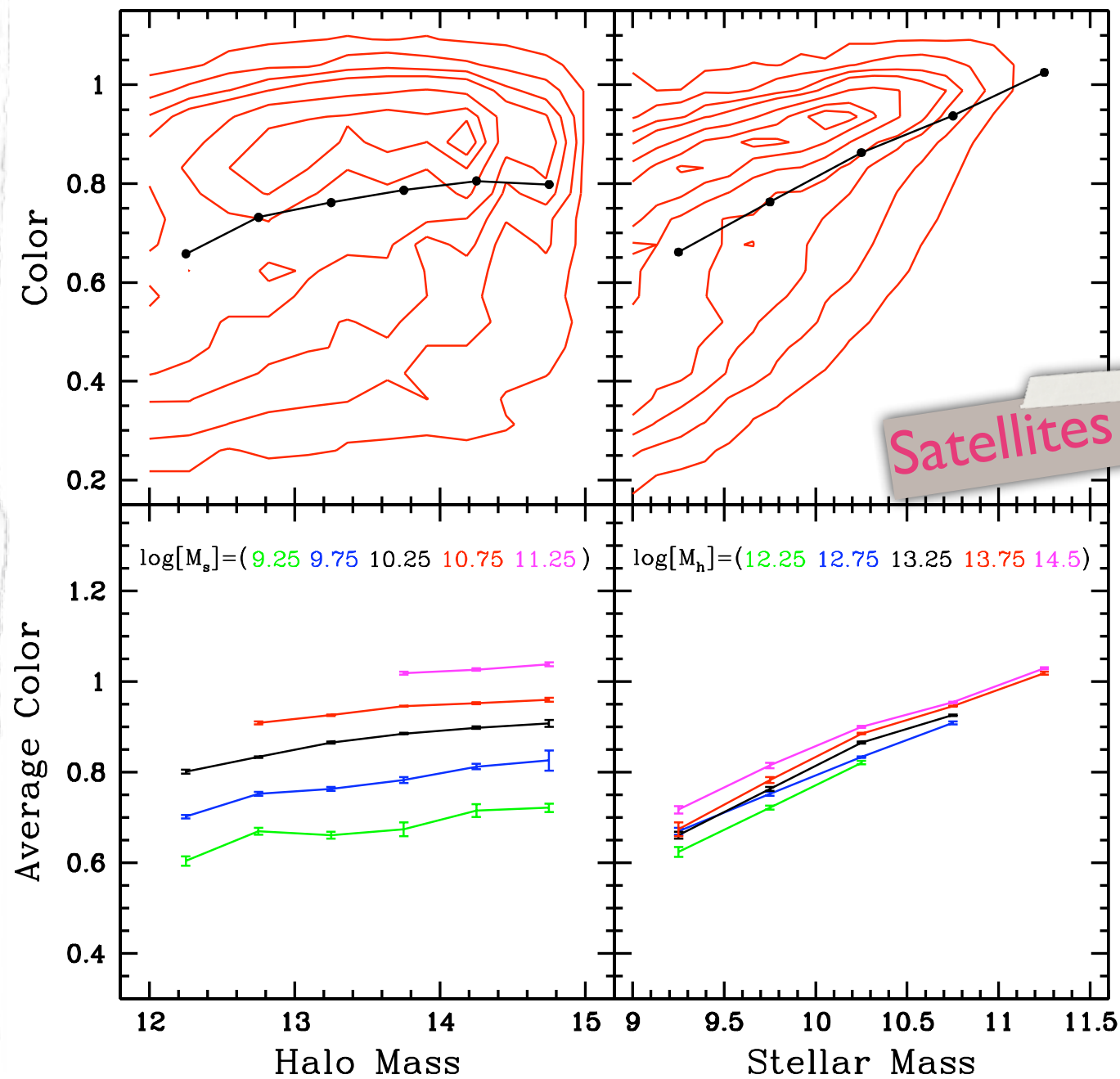
Dependence on Halo Mass



- 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

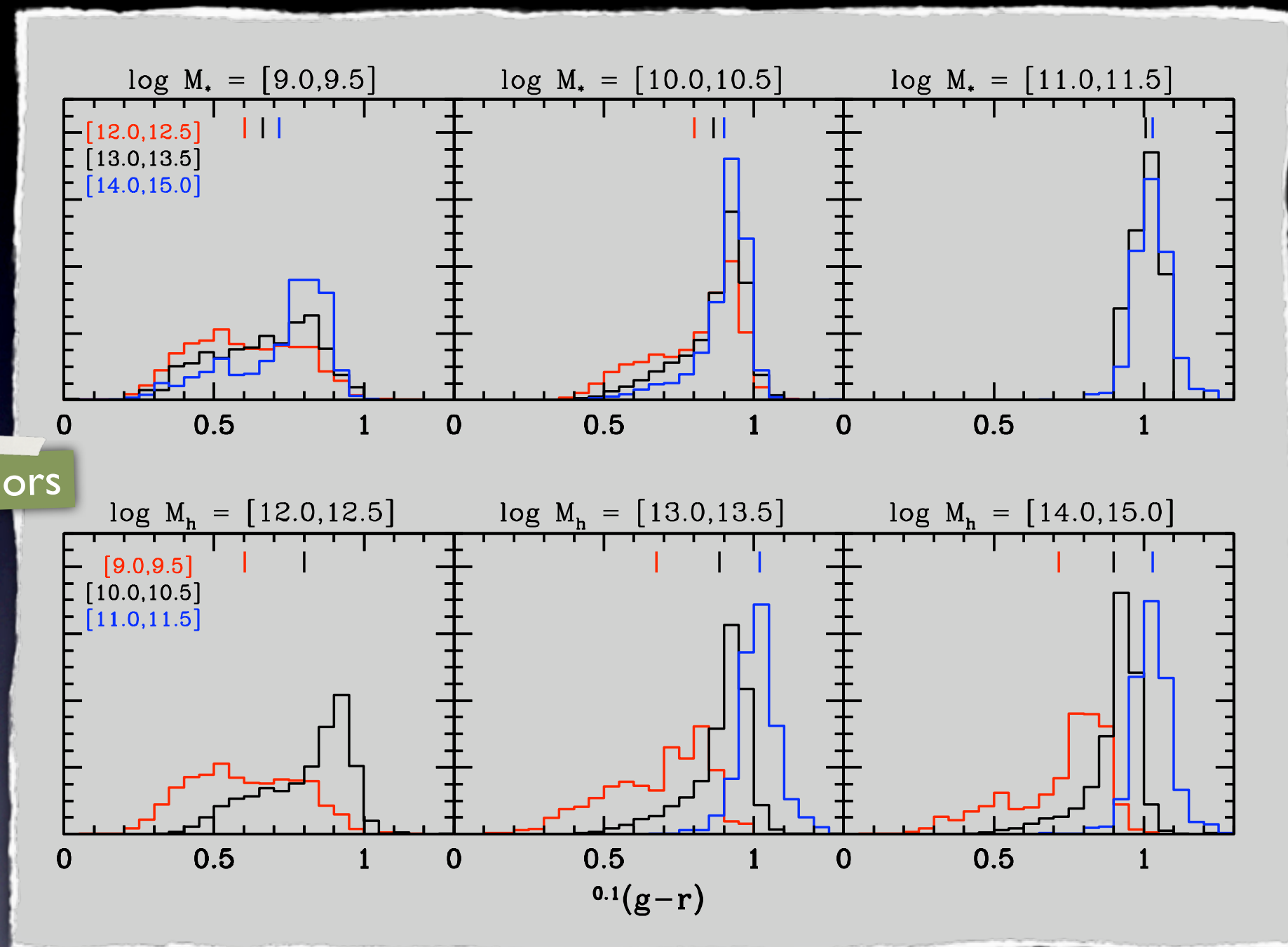


At fixed stellar mass the average satellite color is independent of halo mass

van den Bosch et al. (2009)

The Dearth of Environment Dependence

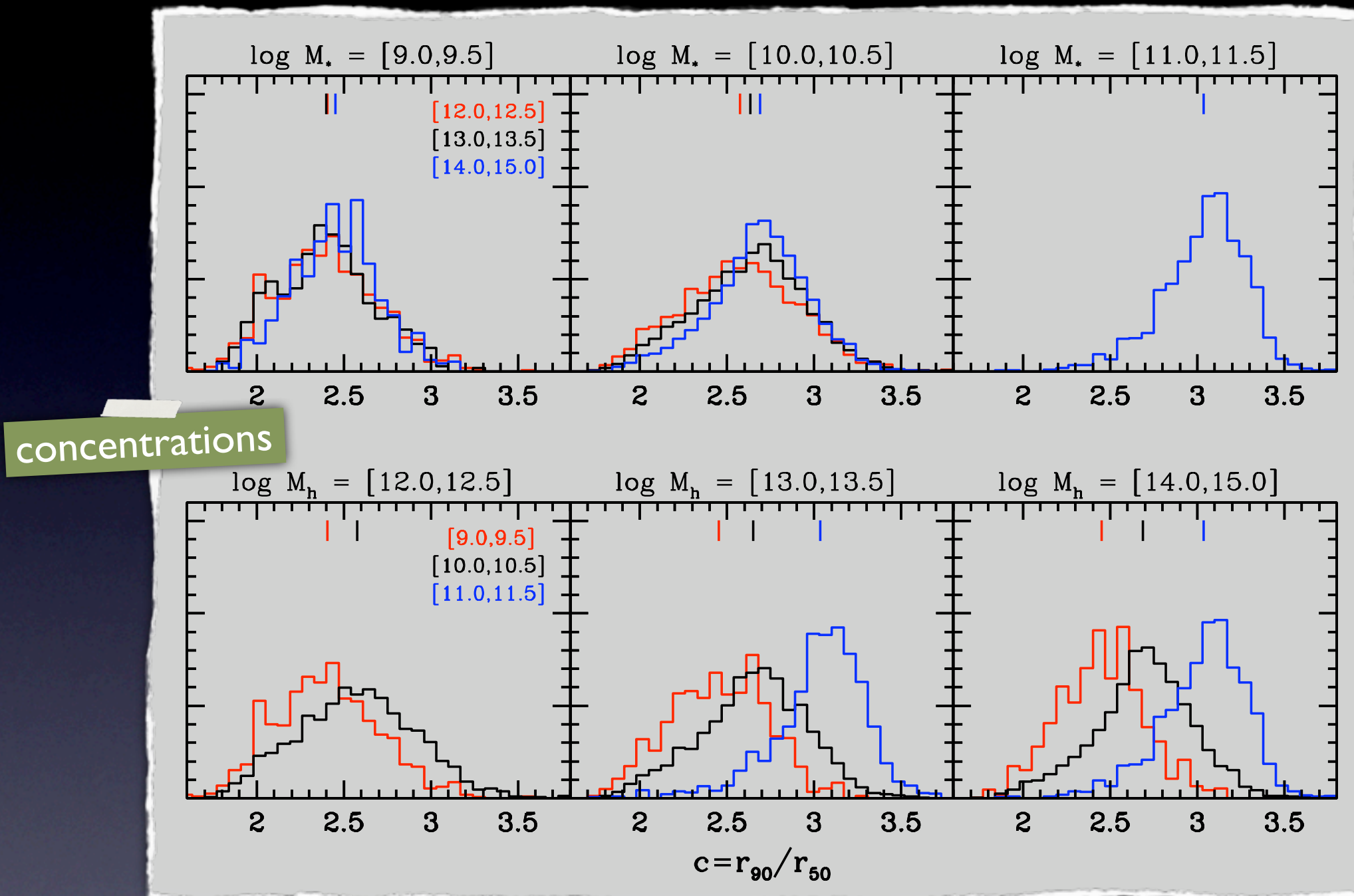
colors



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



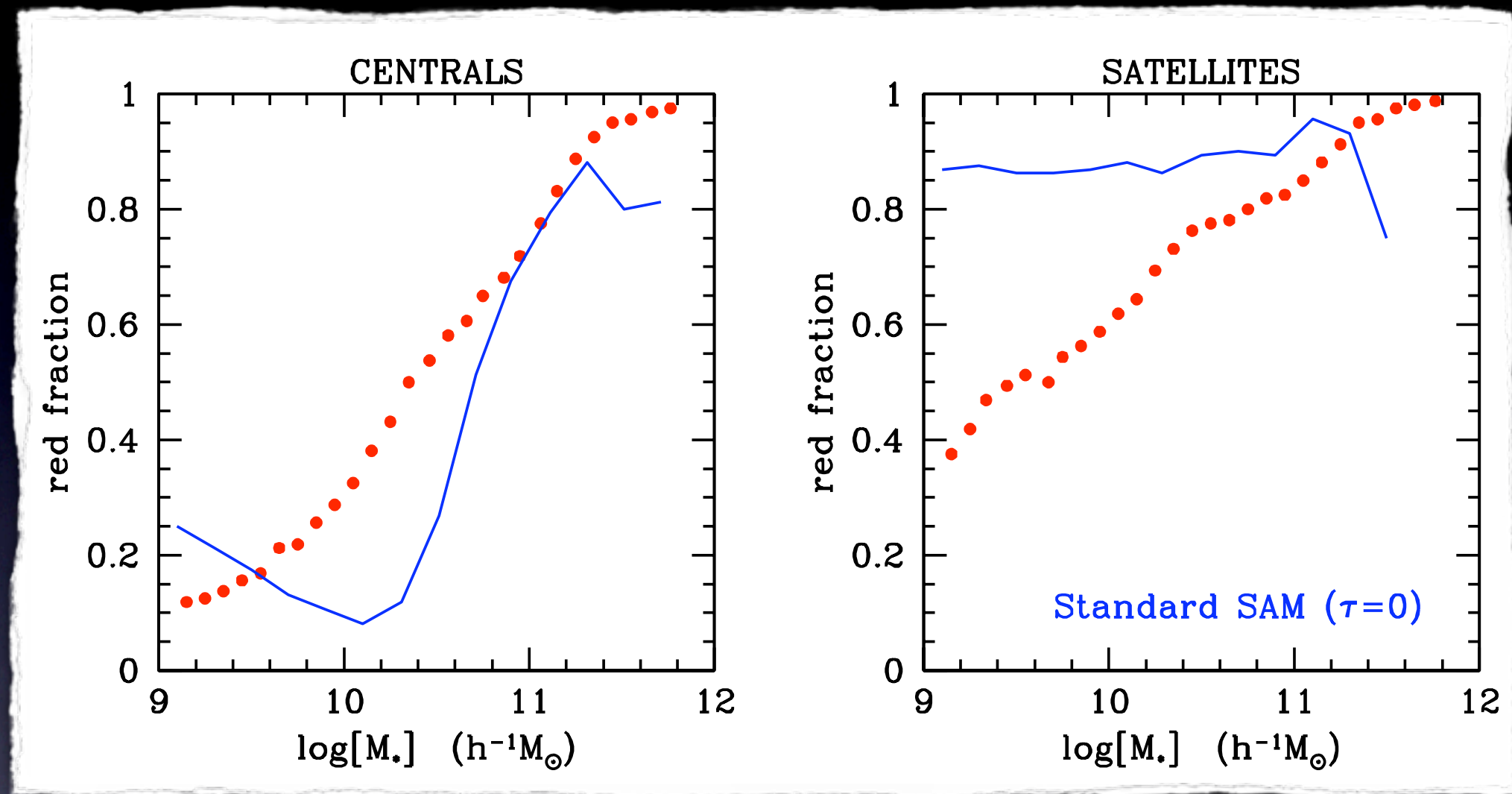
Satellite concentration distribution depends strongly on stellar mass, but is virtually independent of halo mass (environment)

van den Bosch et al. (2009)

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University of Utah

Modeling Strangulation

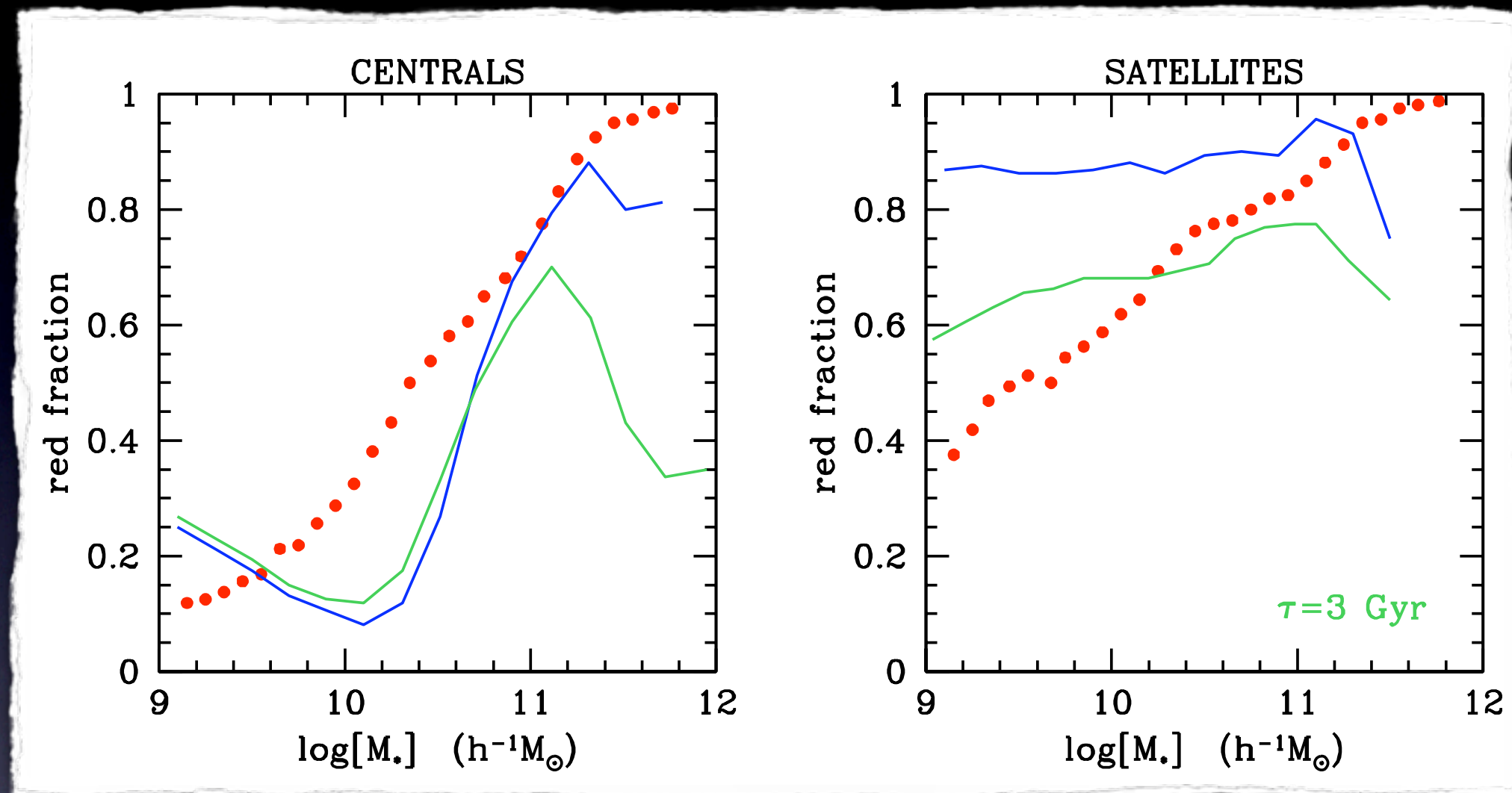


Kang & van den Bosch (2008)

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)

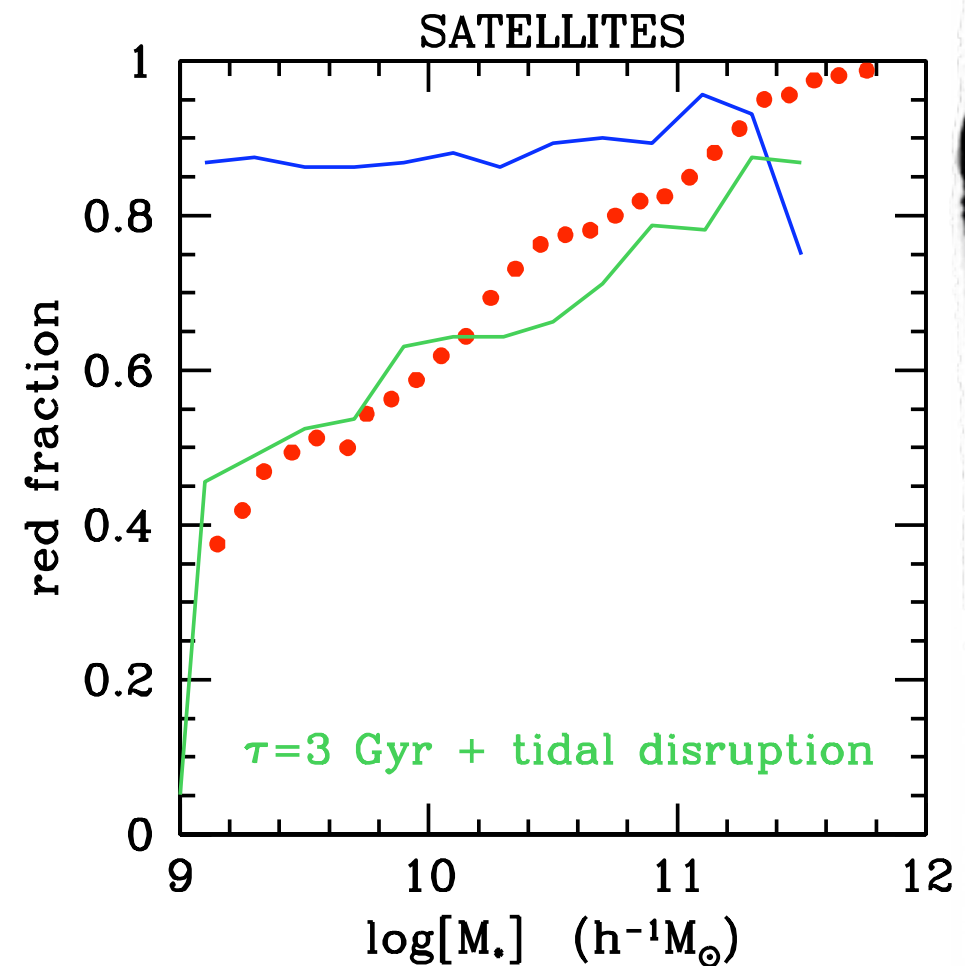
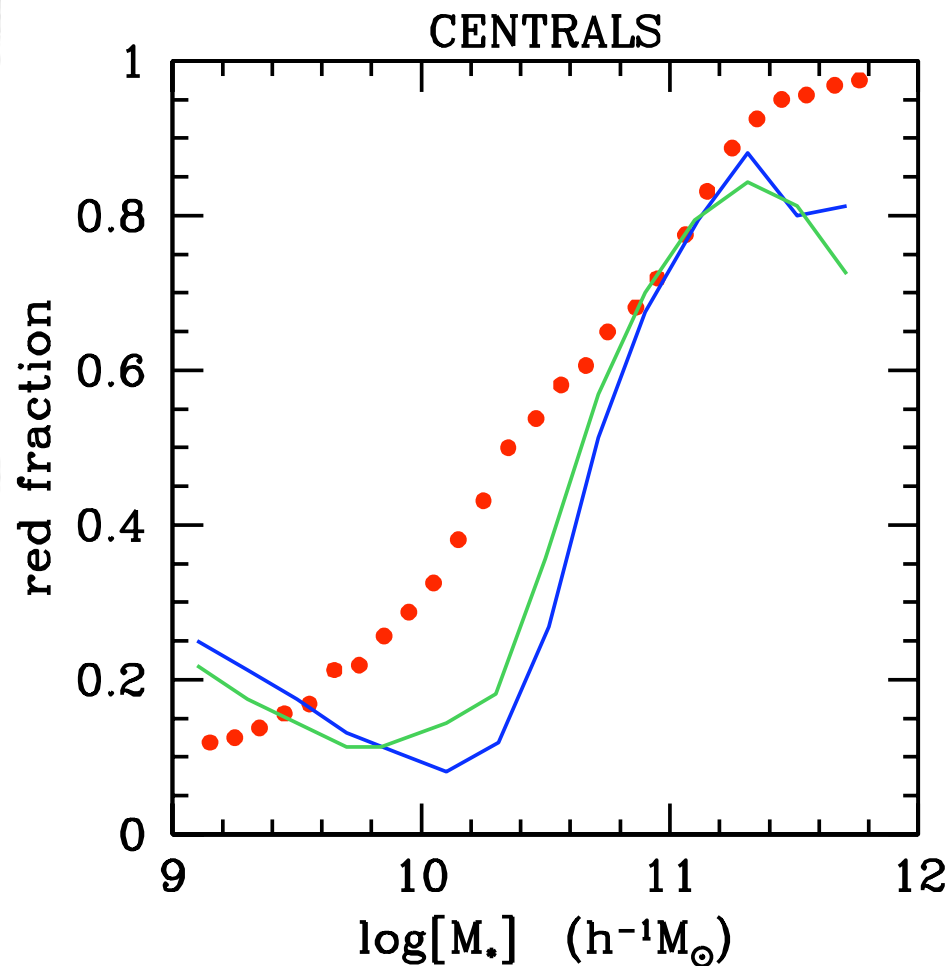
Modeling Strangulation



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

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?
From 70% for satellites with $M_{\text{star}} = 10^9 M_{\text{sun}}$,
to 0% for the most massive satellites
- Which transformation process is most important?
Strangulation...but needs to be better understood.
Also, tidal disruption seems to be important...
- In what environment (dark matter halo) do galaxies undergo their transformation?
In all halos of all masses...
- To what extent are satellite-specific transformation processes responsible for environment dependence of galaxy population?
There is no environment dependence....

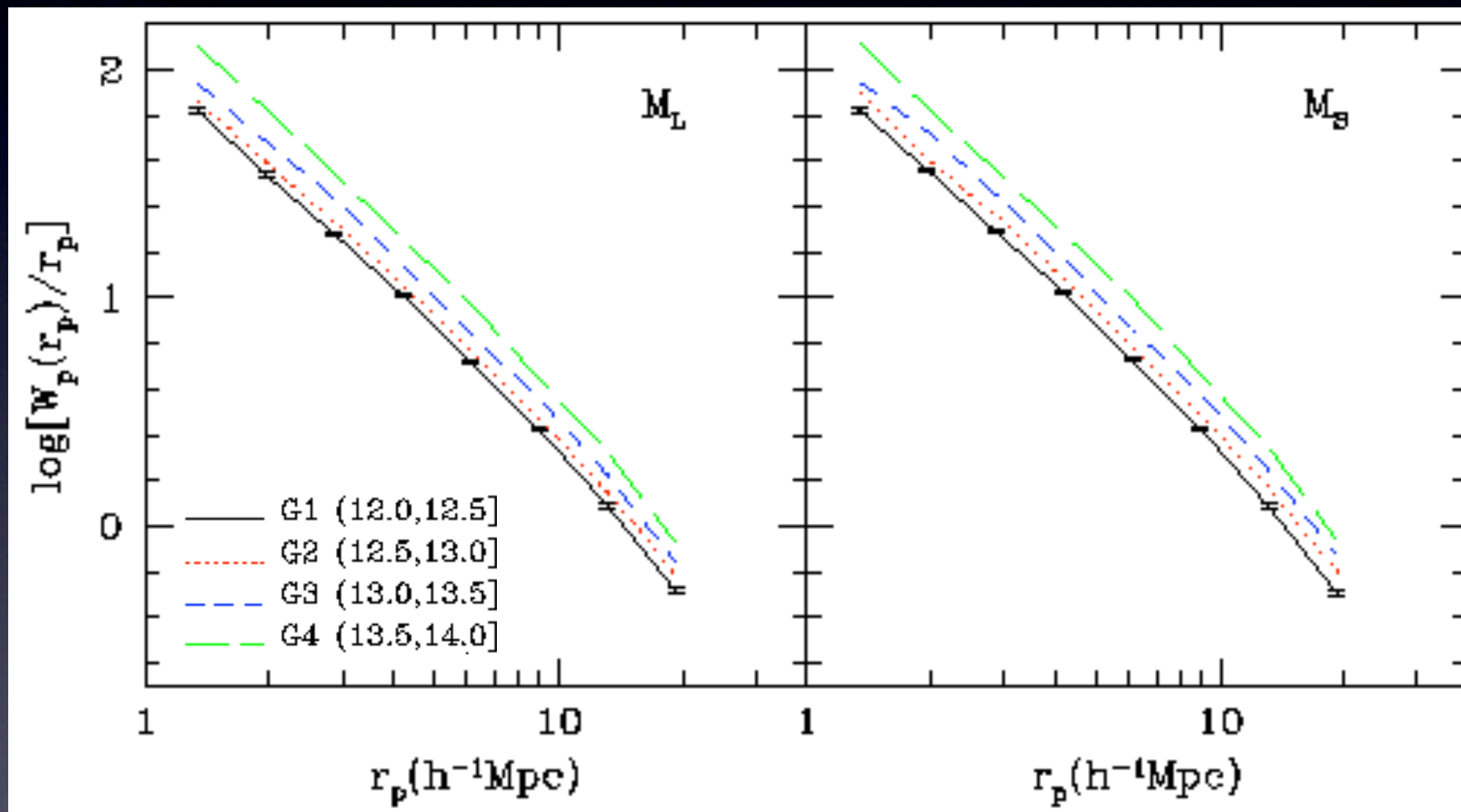
Part II

The Clustering of Dark Matter Halos

Clustering of Galaxy Groups

Clustering of groups probes clustering of Dark Matter Haloes.

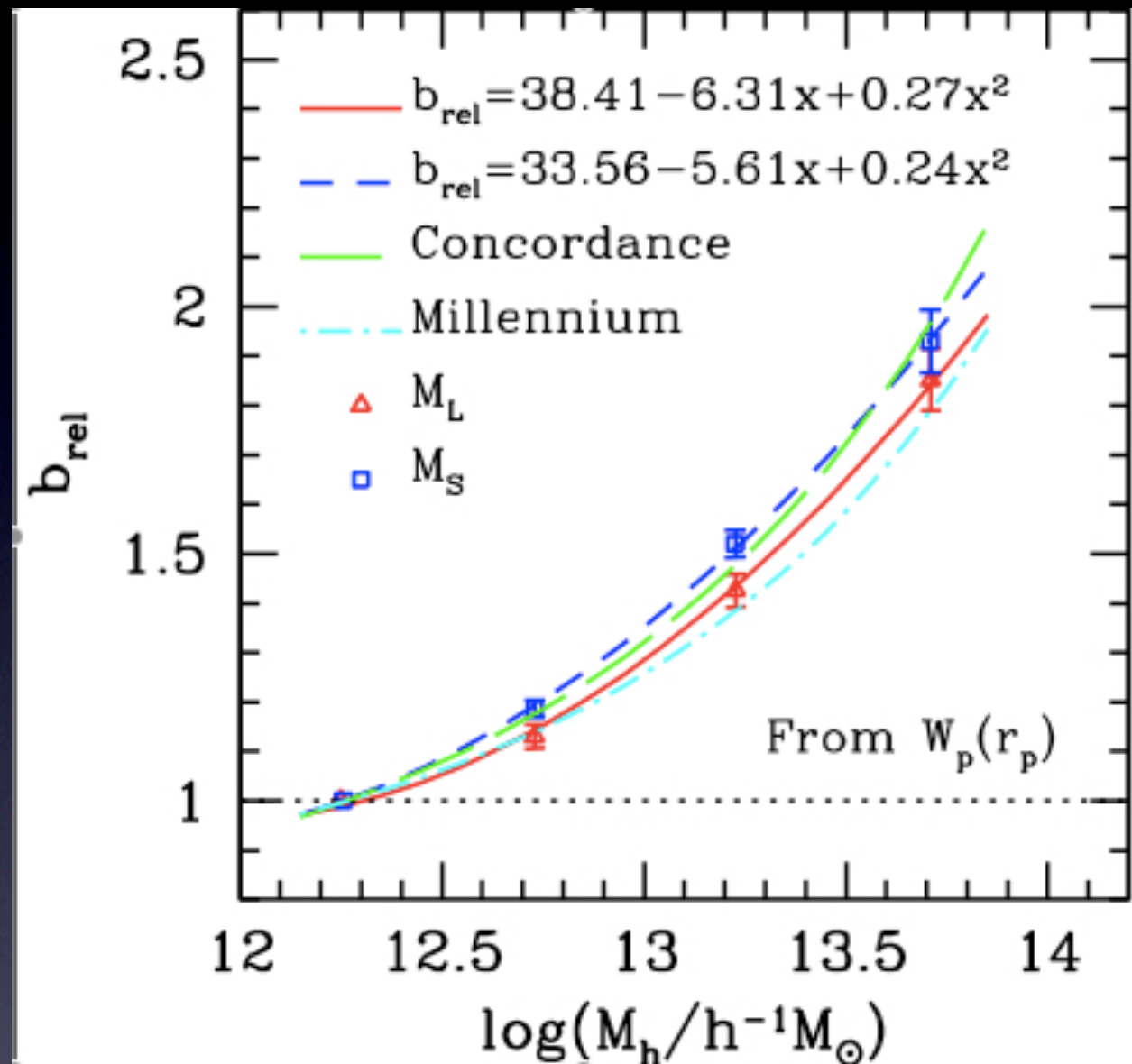
Prediction from hierarchical models:
More massive haloes are more strongly clustered



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

Wang et al. (2008)

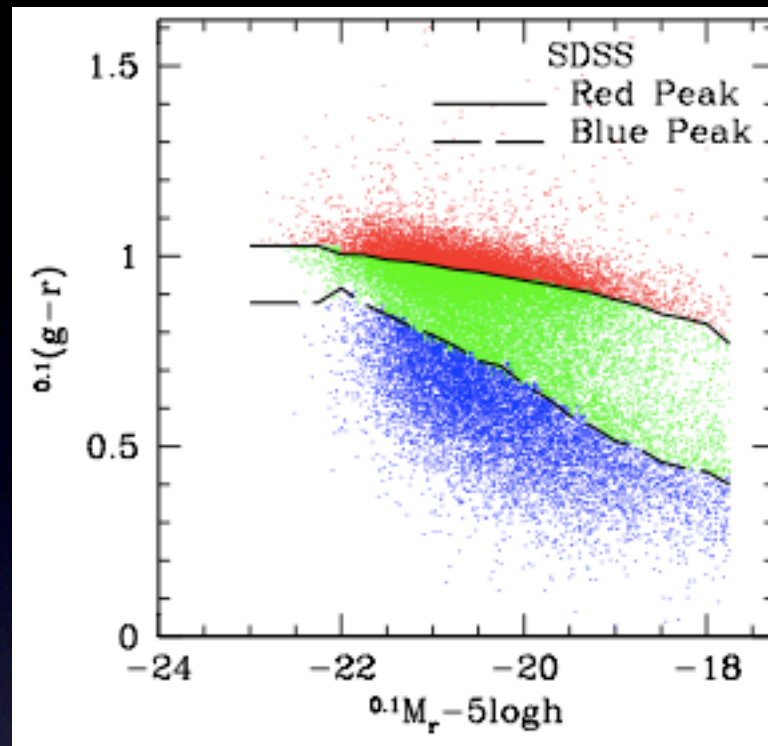
Mass Dependence of Halo Bias



Wang et al. (2008)

Halo Bias in good agreement with predictions for concordance cosmology

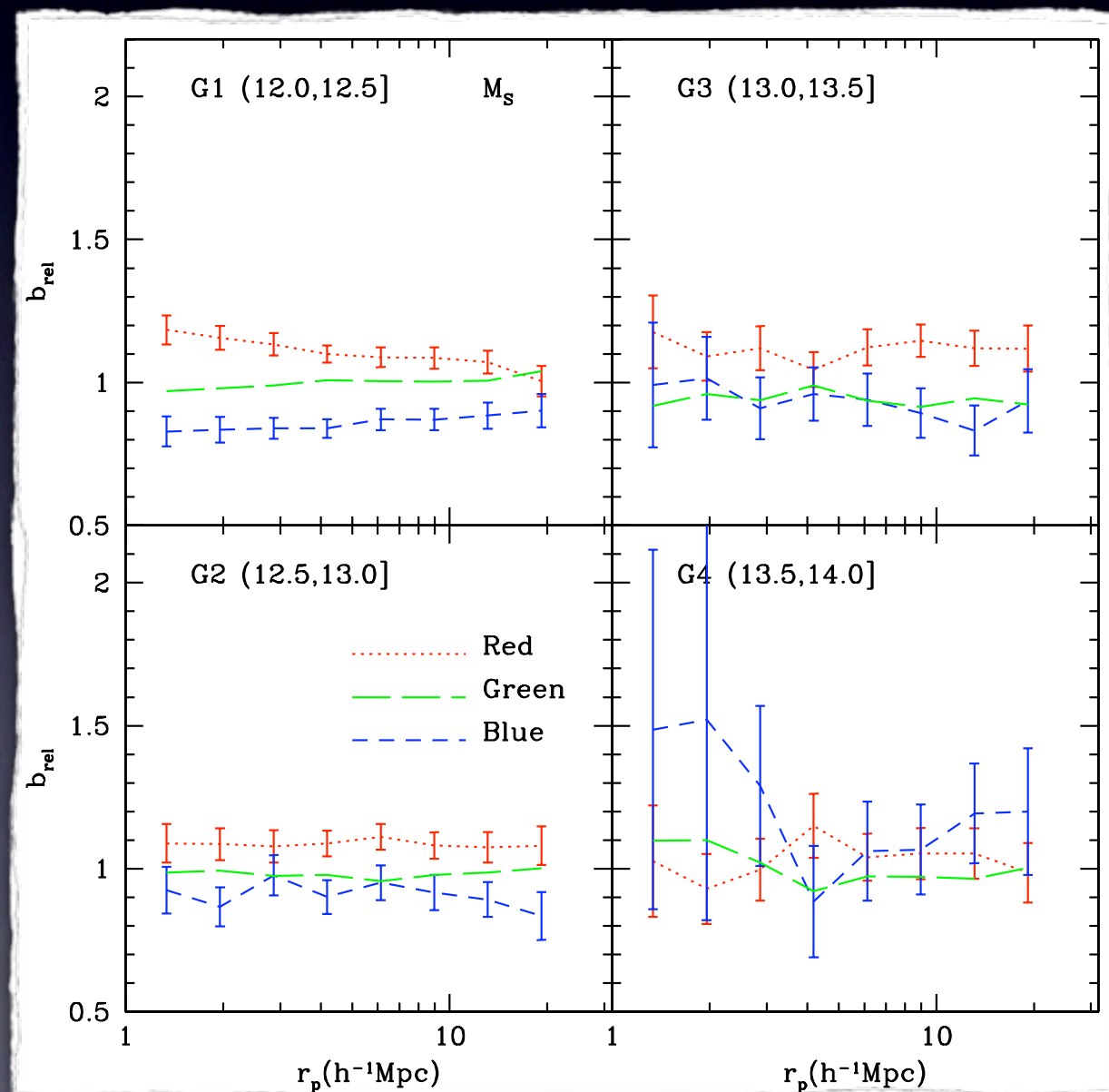
Color Dependence of Halo Bias



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

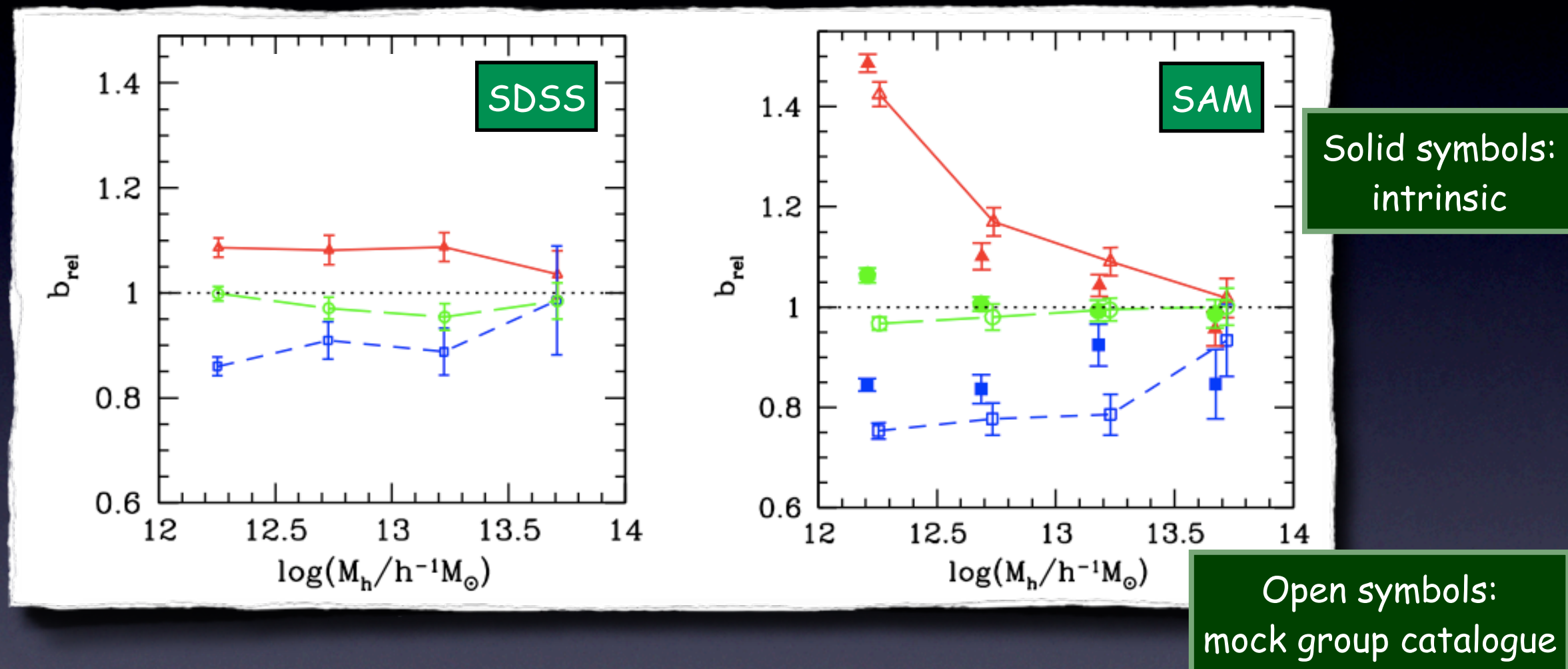
Groups with red centrals are more strongly clustered than groups of same mass but with blue centrals.

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



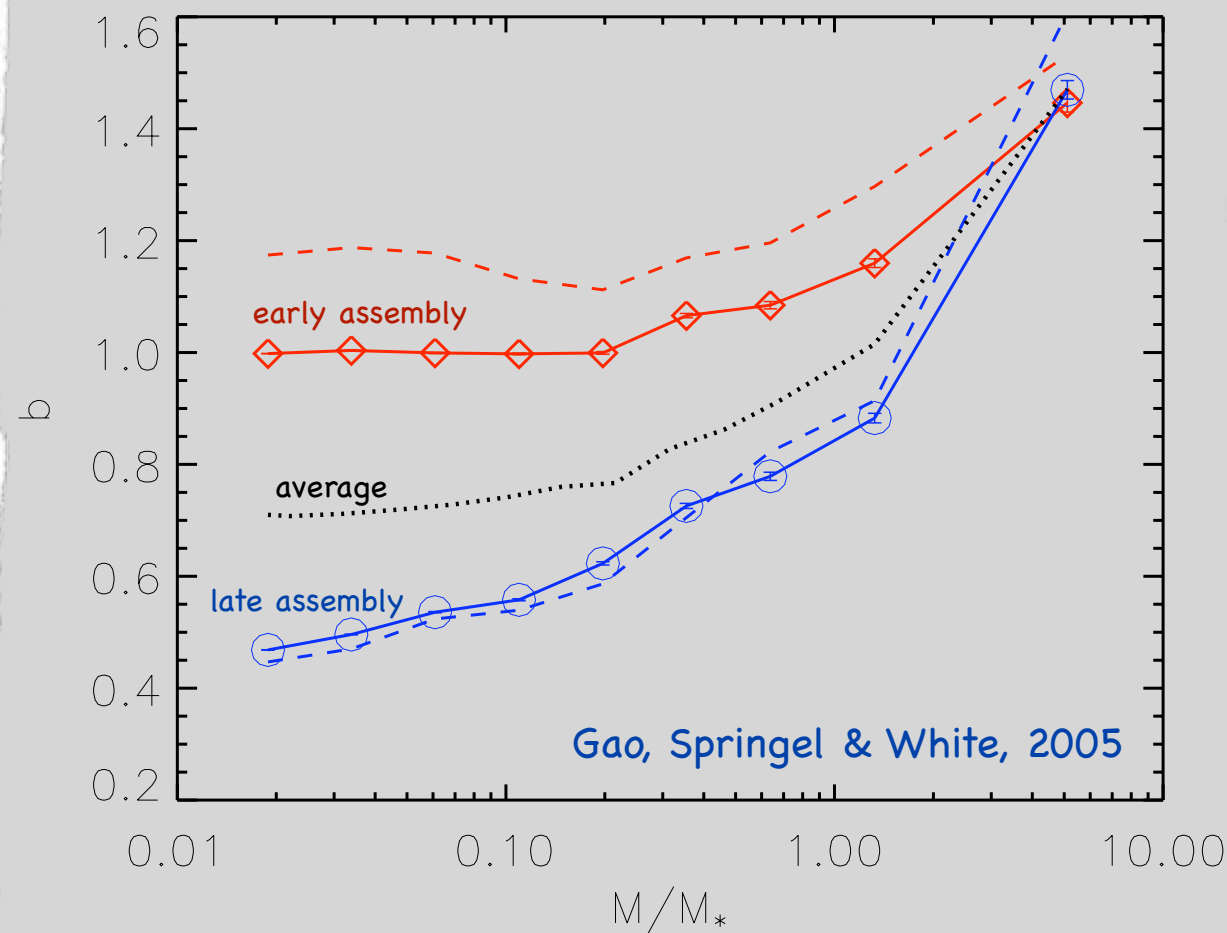
Tests with Mock Galaxy Redshift Survey

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



- 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

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

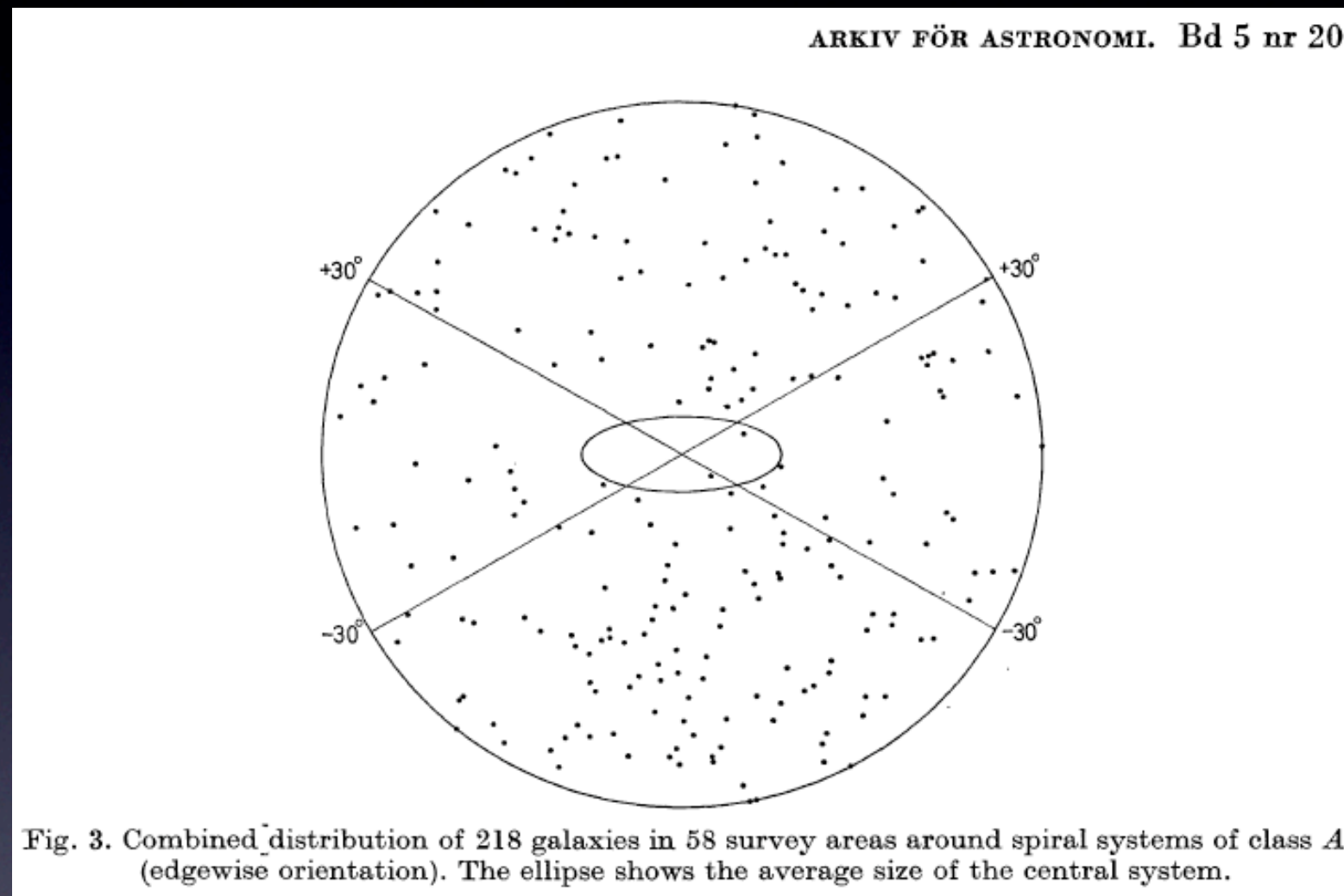
- Mass dependence of halo bias in good agreement with predictions for LCDM concordance cosmology
- Groups with red centrals are more strongly clustered than groups of same mass but with blue central
- Can be understood qualitatively if star formation history of central galaxies is correlated with formation 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

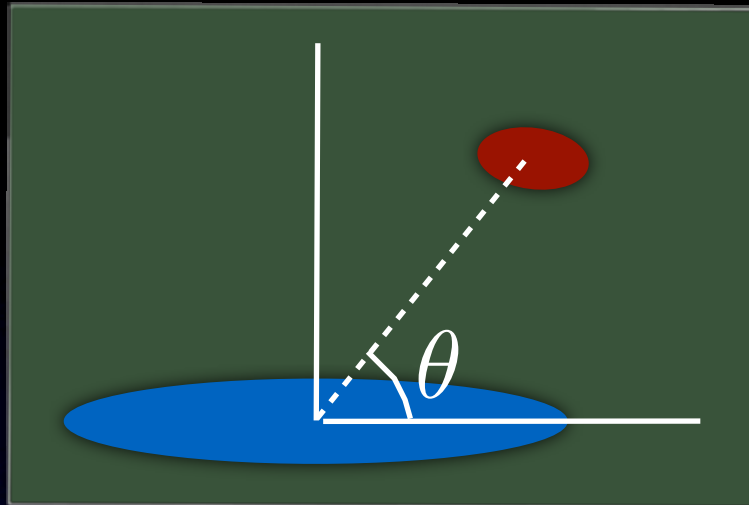
In 1969 Holmberg noted that satellites galaxies are preferentially located along the minor axis of disk galaxies (analysis restricted to $r < 50$ kpc).



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 .

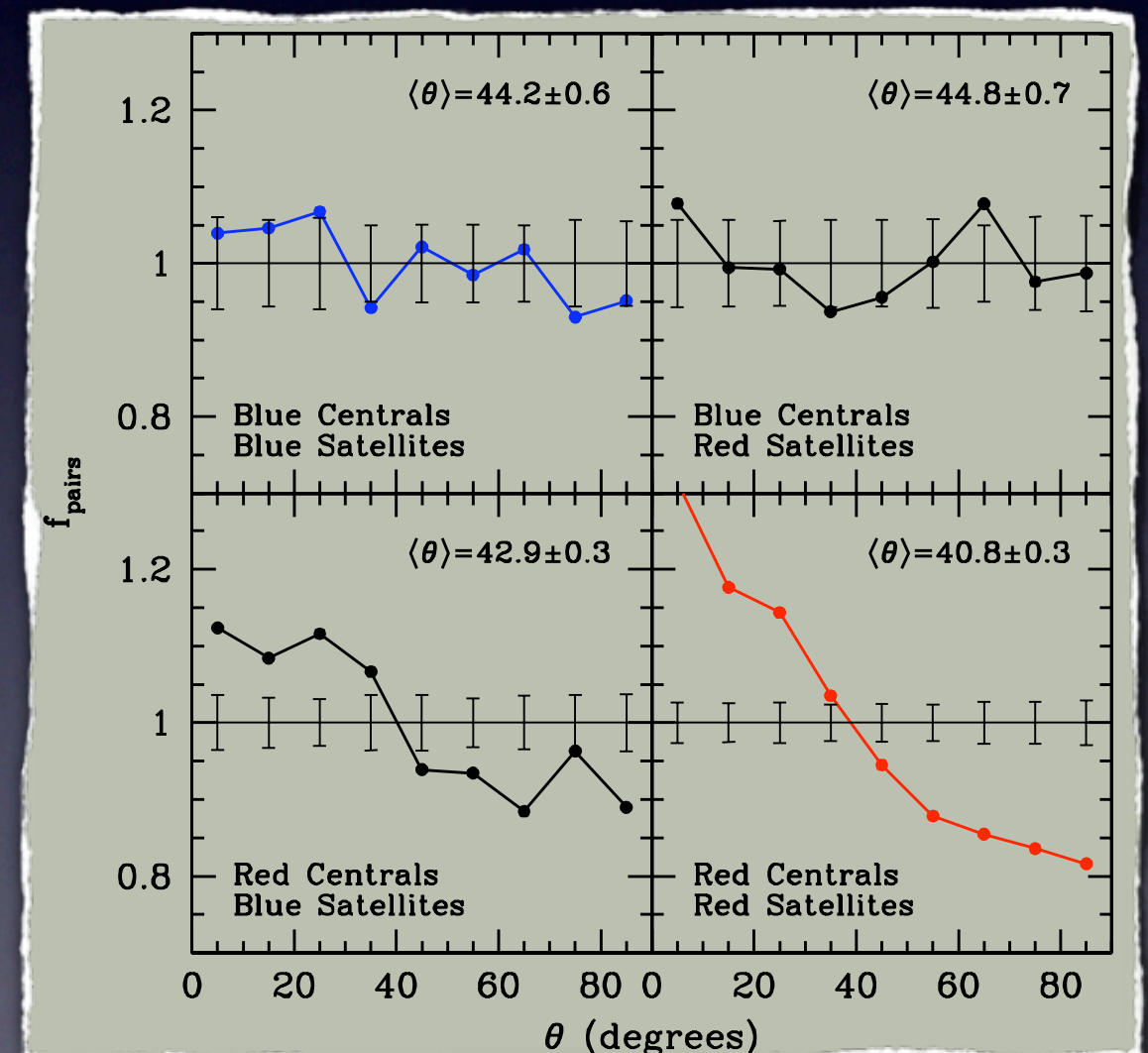
Count $N(\theta)$ from groups and from 100 realizations, in which orientation of centrals is randomized.

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

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)

Yang et al. (2006)

Interpretation of Alignment

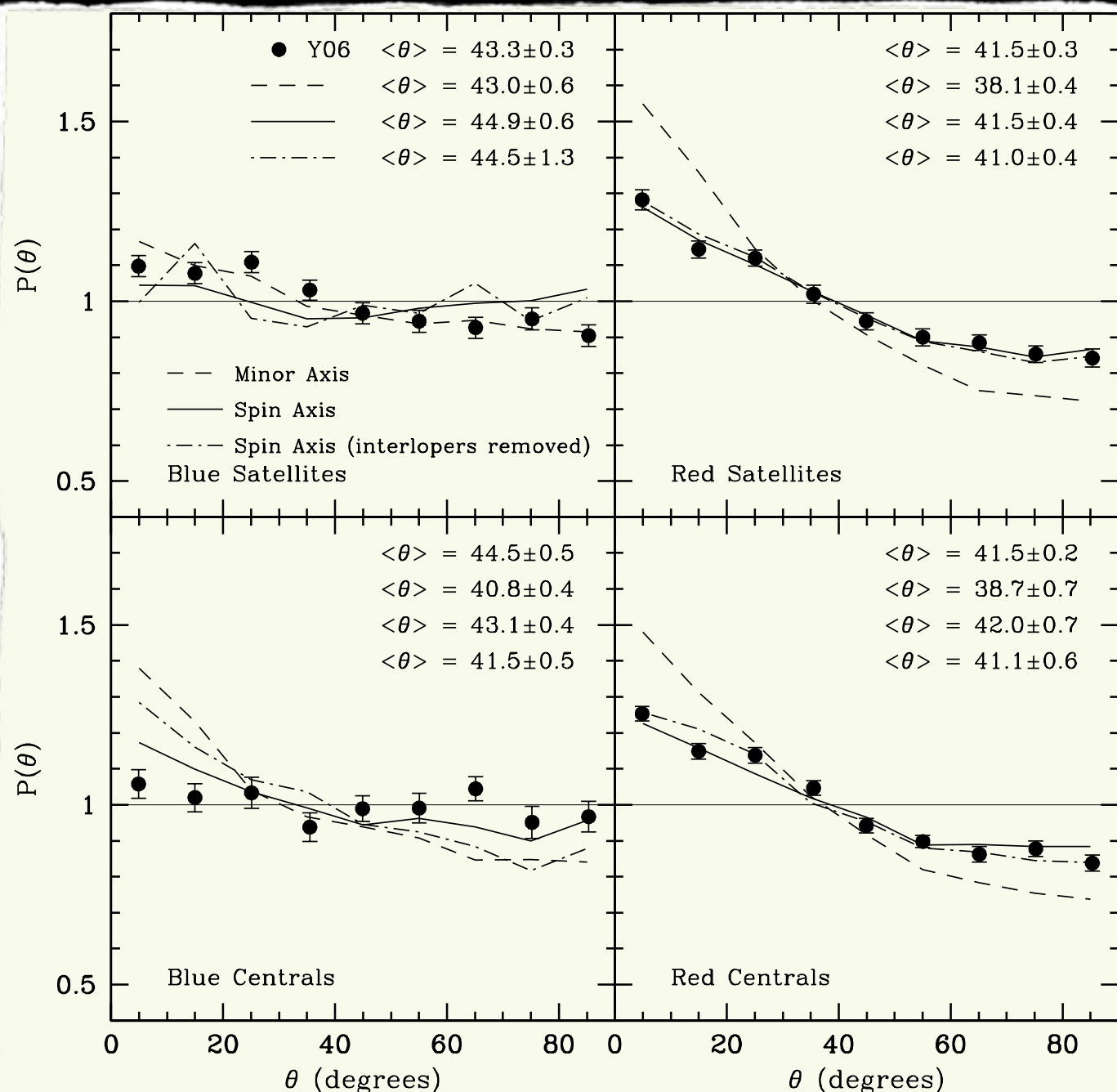
Alignment arises naturally if:

- (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.

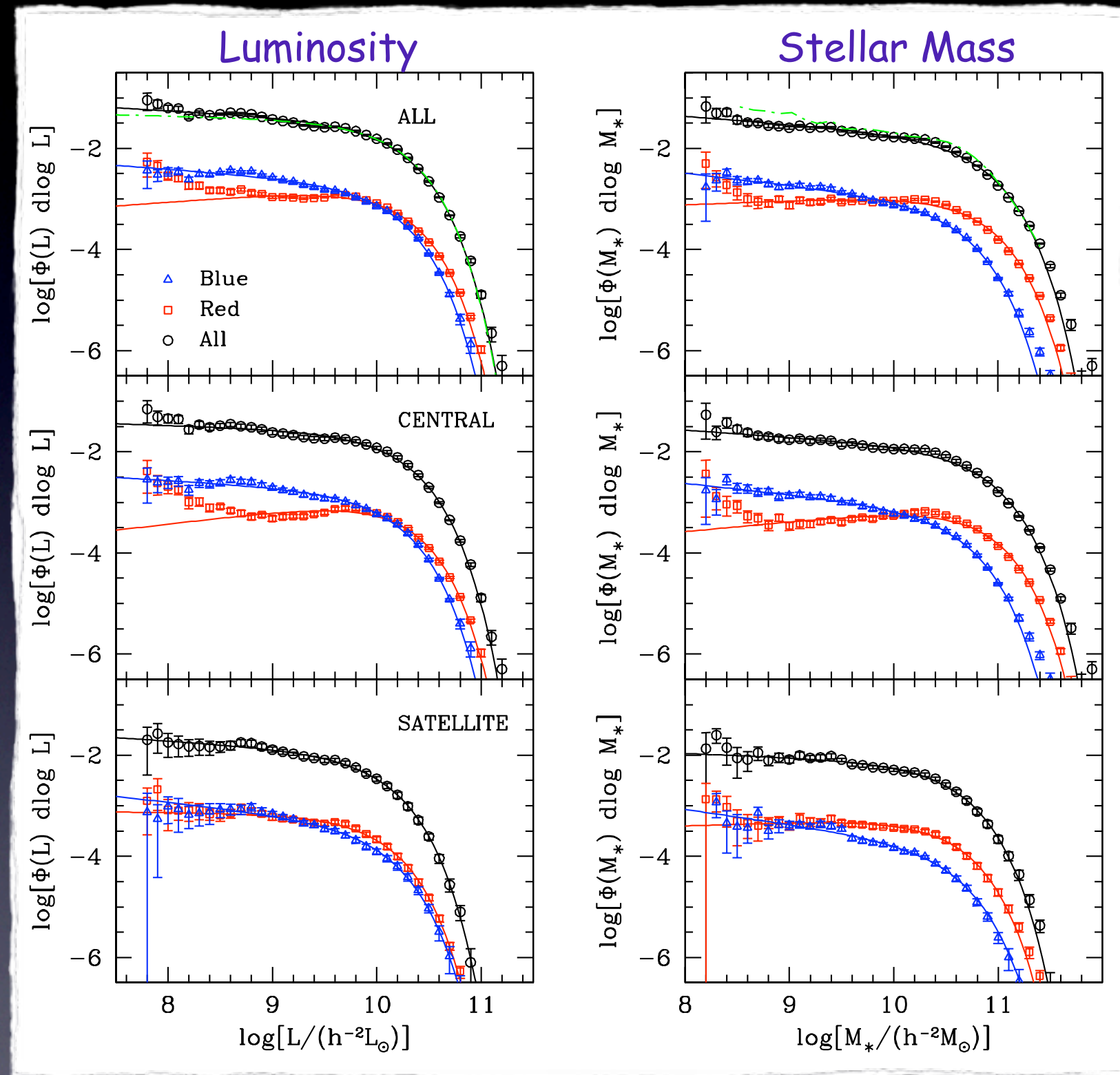
Conclusions Part III

- 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

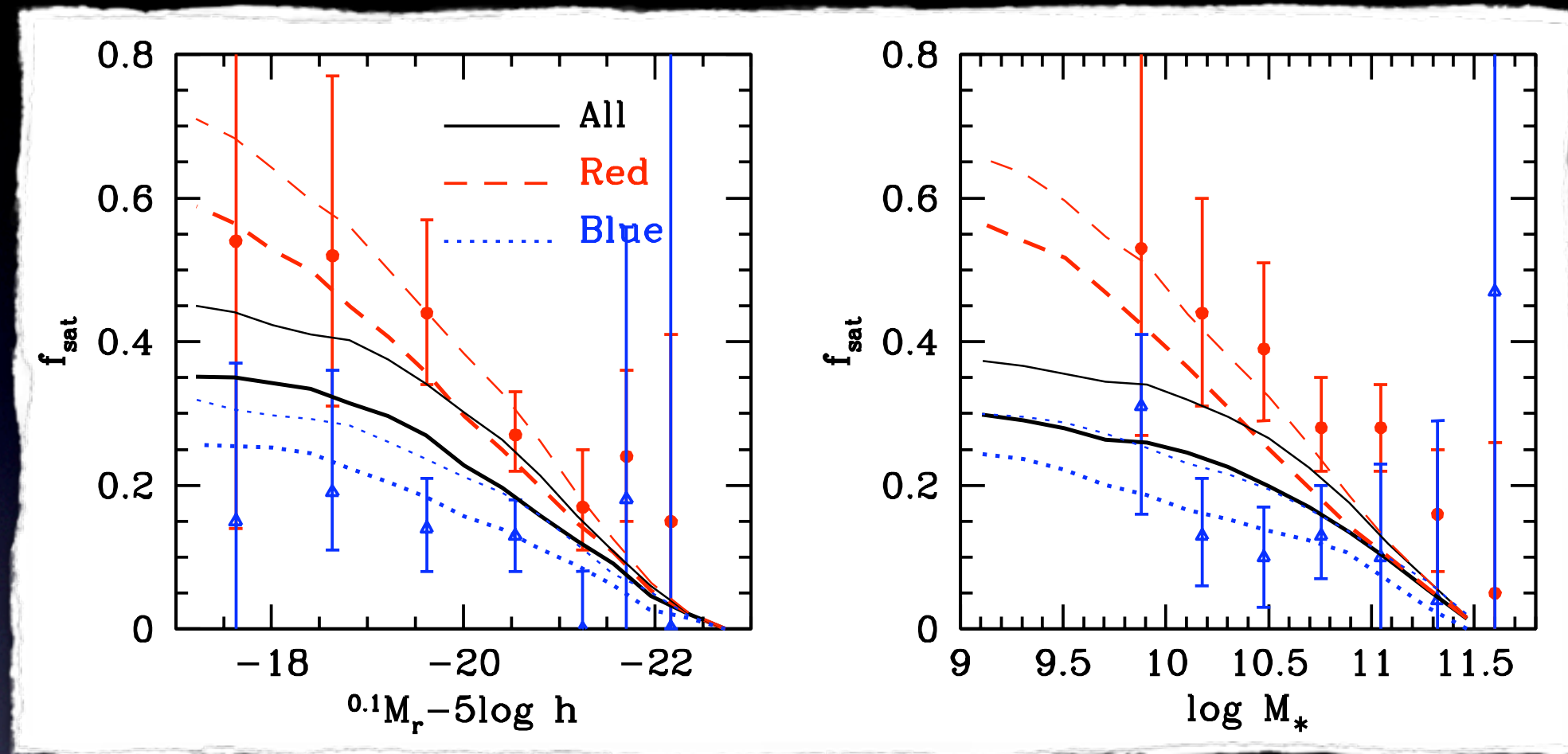
Halo Occupation Statistics

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

$$\Phi(L) = \int \Phi(L|M) n(M) dM$$

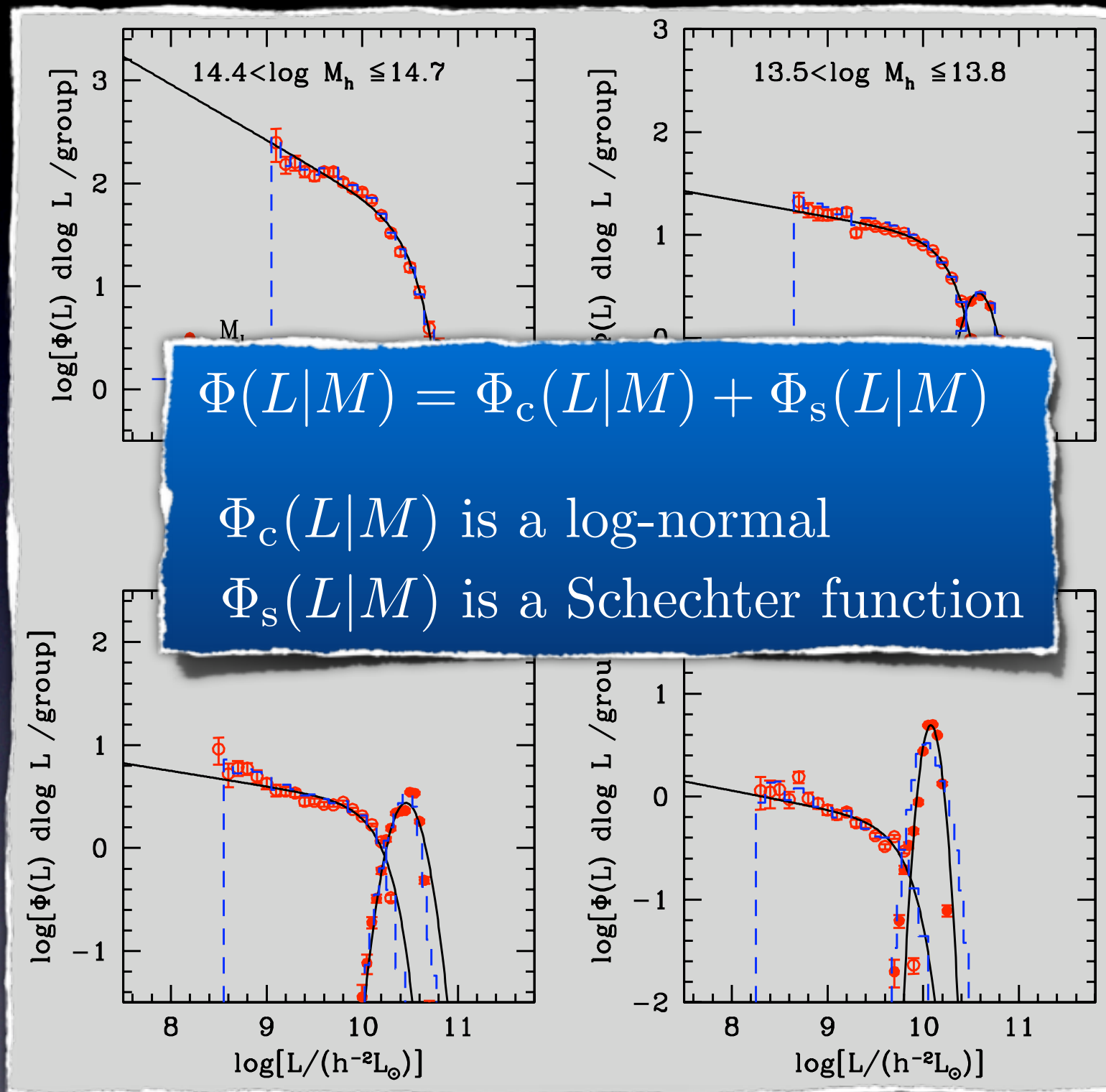
$$\langle L \rangle_M = \int \Phi(L|M) L dL$$

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

CLF can be constrained using:

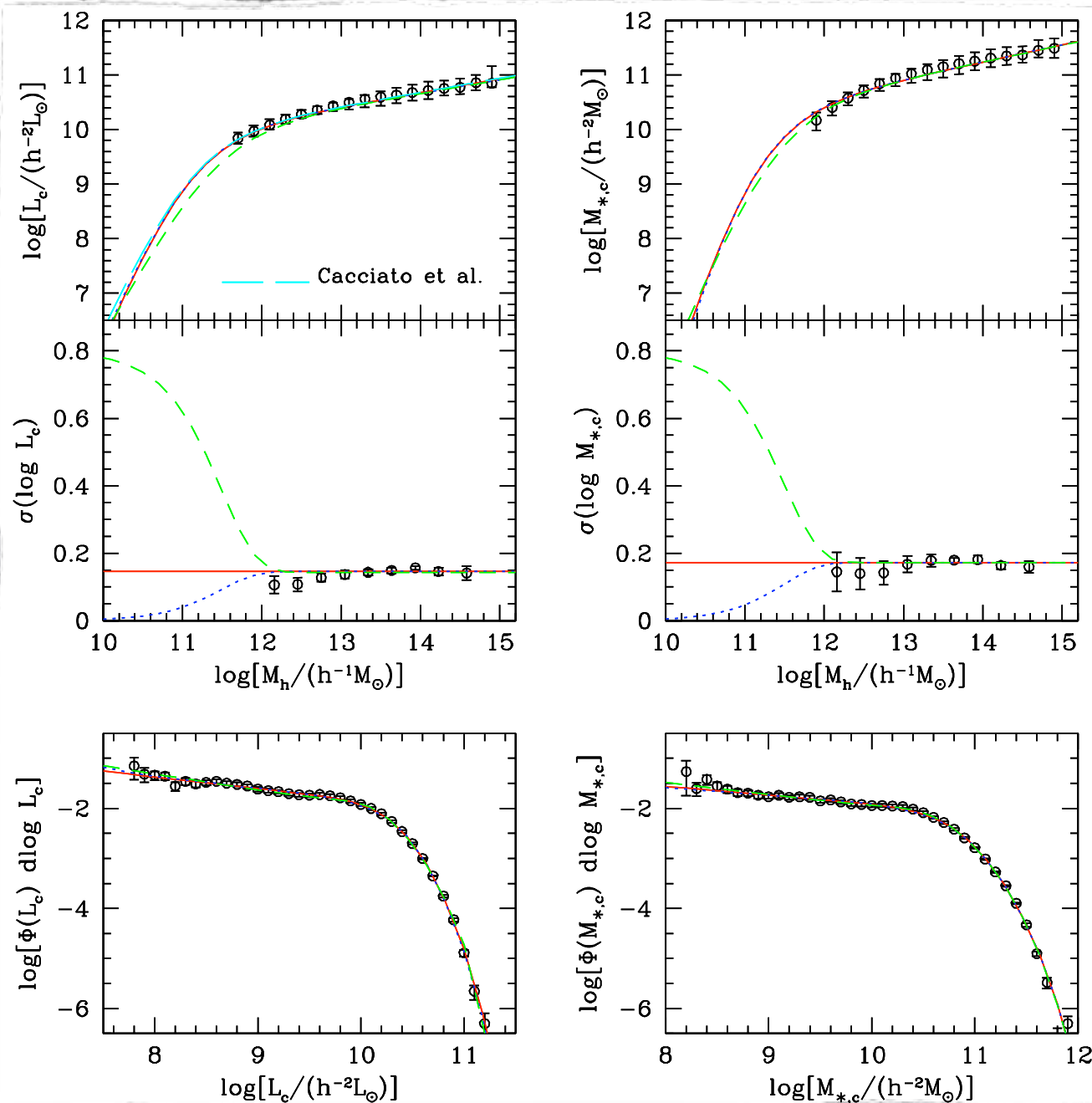
- Galaxy Clustering: *Yang, Mo & vdB, 2003; vdB, Yang & Mo 2003, vdB et al 2007*
- Galaxy-Galaxy Lensing: *Cacciato et al. 2009*
- Satellite Kinematics: *vdB et al. 2004; More et al. 2009a,b*
- Galaxy Group Catalogue: *Yang et al. 2005; Yang, Mo & vdB 2008a,b*

Conditional Luminosity Function



Yang, Mo & vdB (2008)

Halo Mass dependence of Central Galaxies



Fit relation with following form:

$$L_c = L_0 \frac{(M_h/M_1)^{\alpha+\beta}}{(1 + M_h/M_1)^\beta}$$

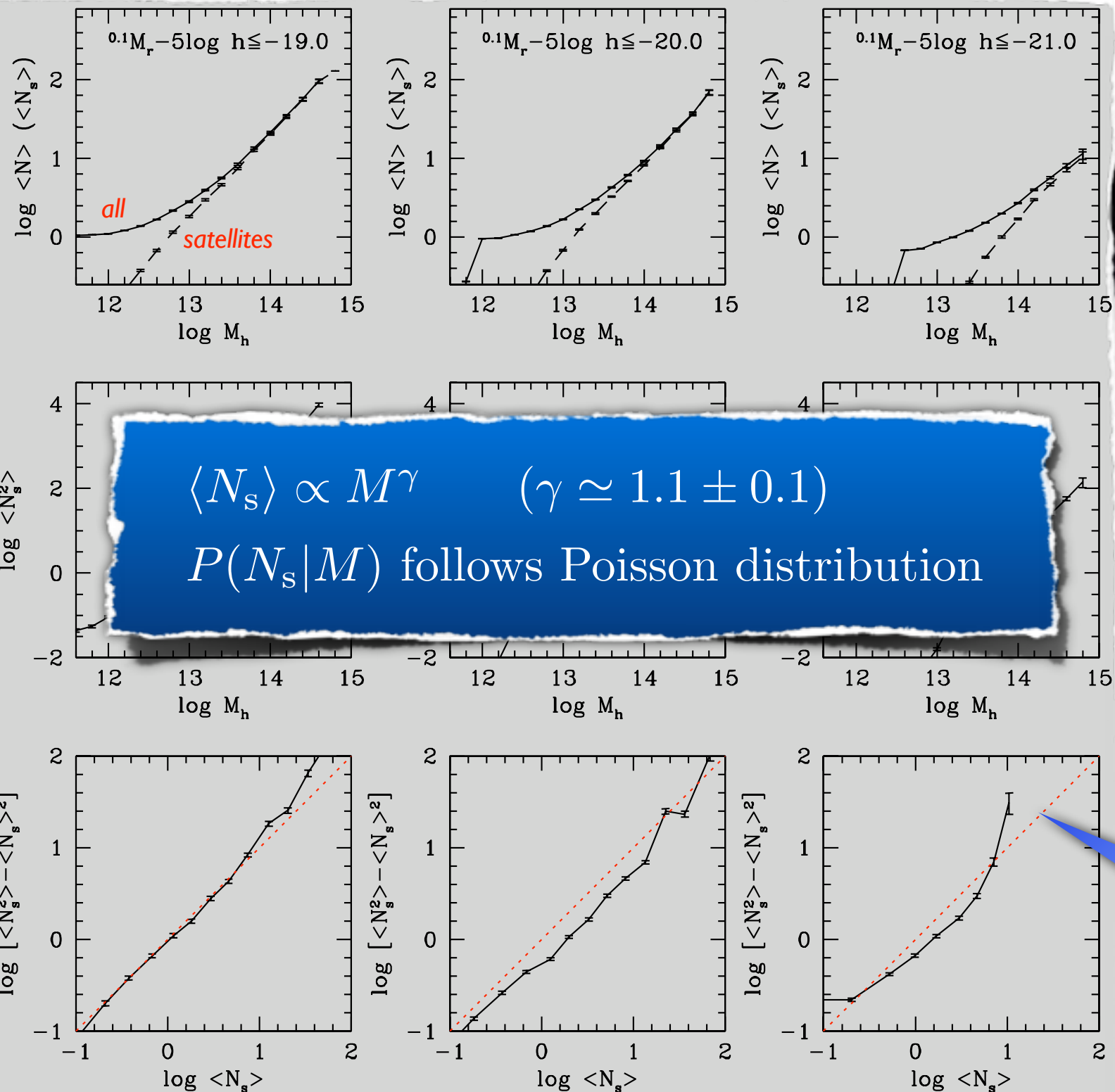
Constrain faint-end using:

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

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



Conclusions Part IV

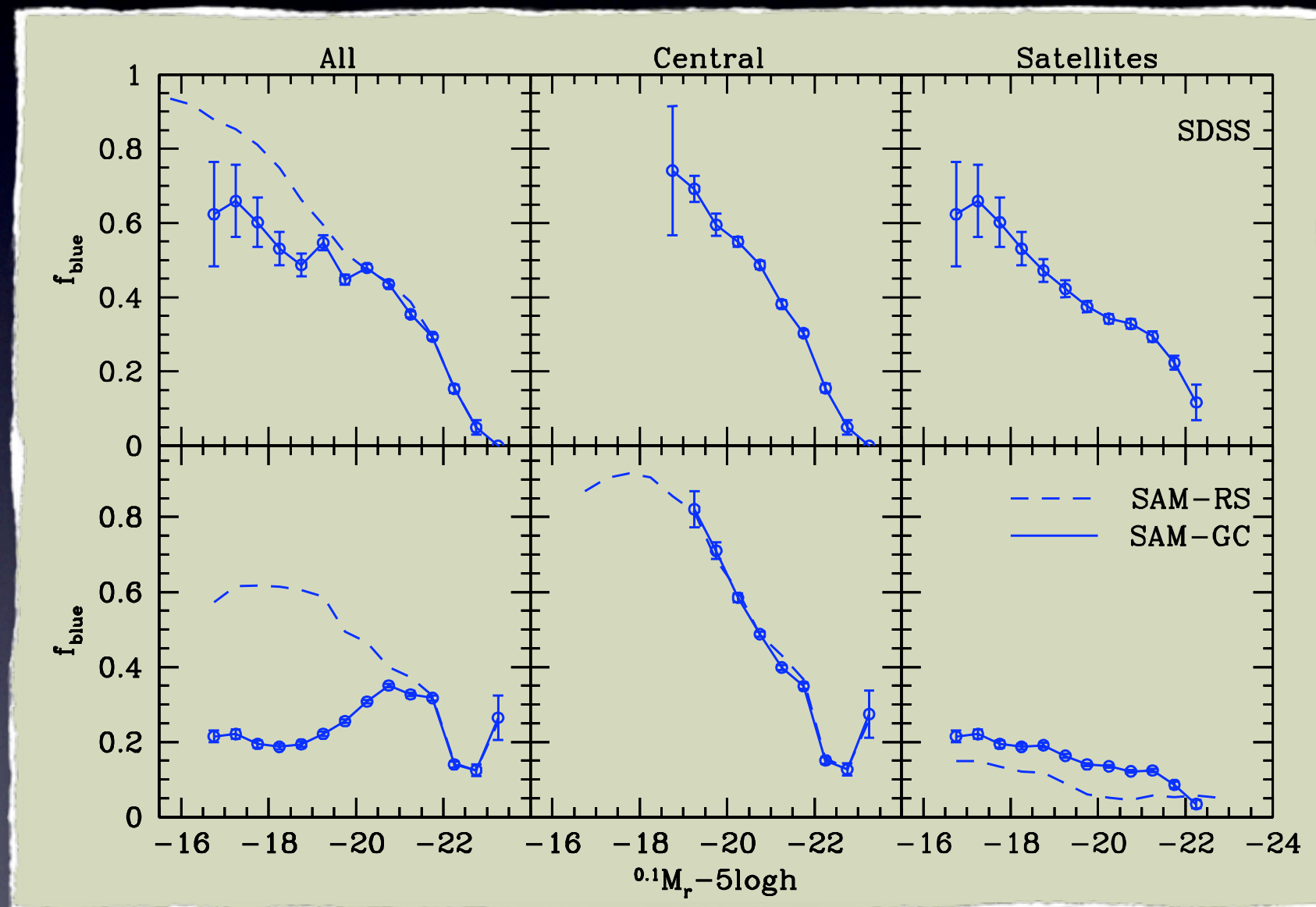
- Galaxy Group Catalogues yield tight constraints on halo occupation statistics and CLF in particular.
- Ideally suited to split galaxies in centrals and satellites.
- Faint-end upturn in LF of red galaxies due to centrals; most likely an environmental effect...
- Relation between halo mass and luminosity/stellar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

The End

Modeling Strangulation

Strangulation is a standard ingredient in semi-analytical models of galaxy formation.

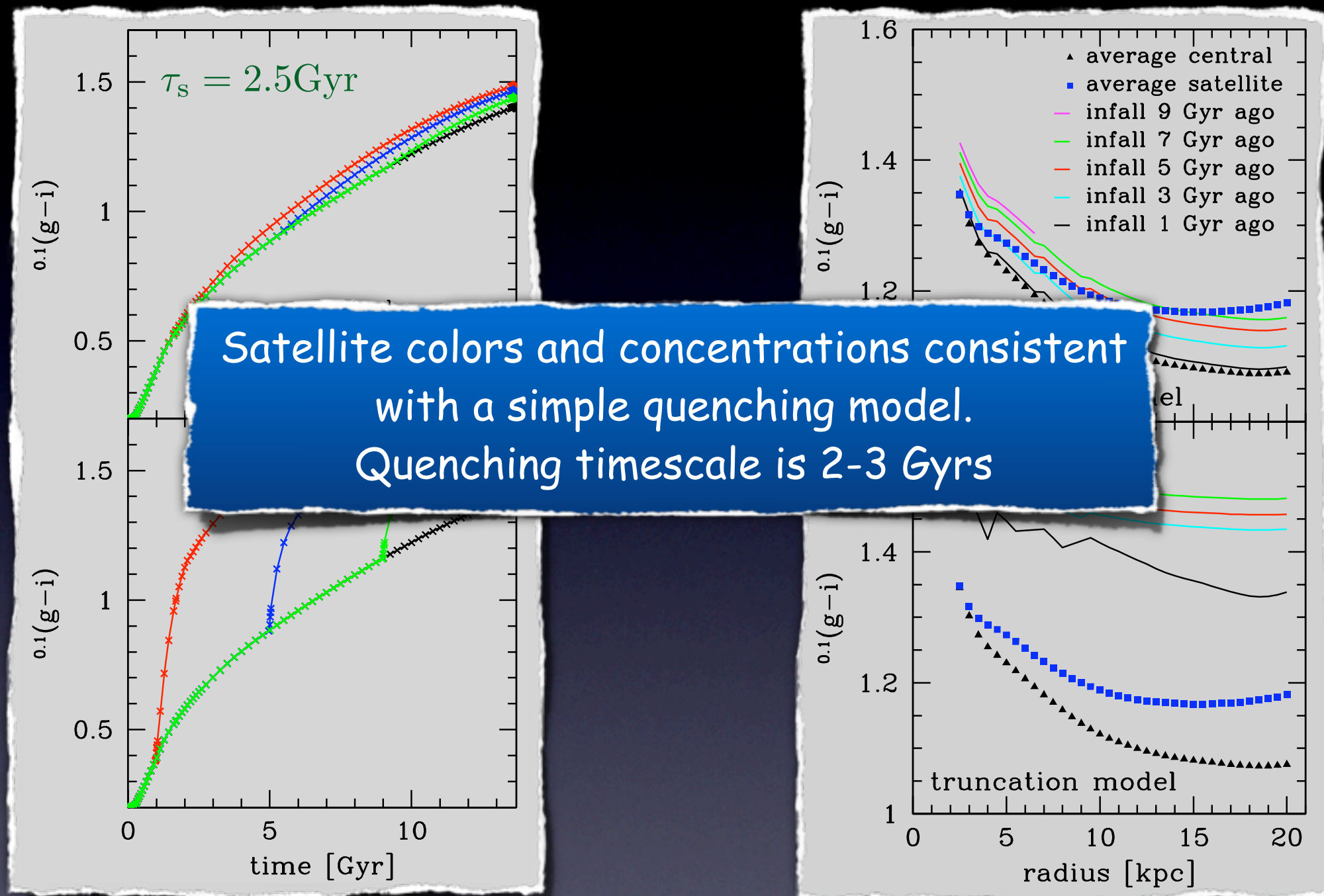
It is typically assumed that satellites are *instantaneously* stripped of their hot gas upon accretion



Weinmann et al. 2006

But this results in a red satellite fraction that is too large....

Quenching Timescale



$$\text{SFR}(t) = e^{-t/\tau_c}$$

centrals

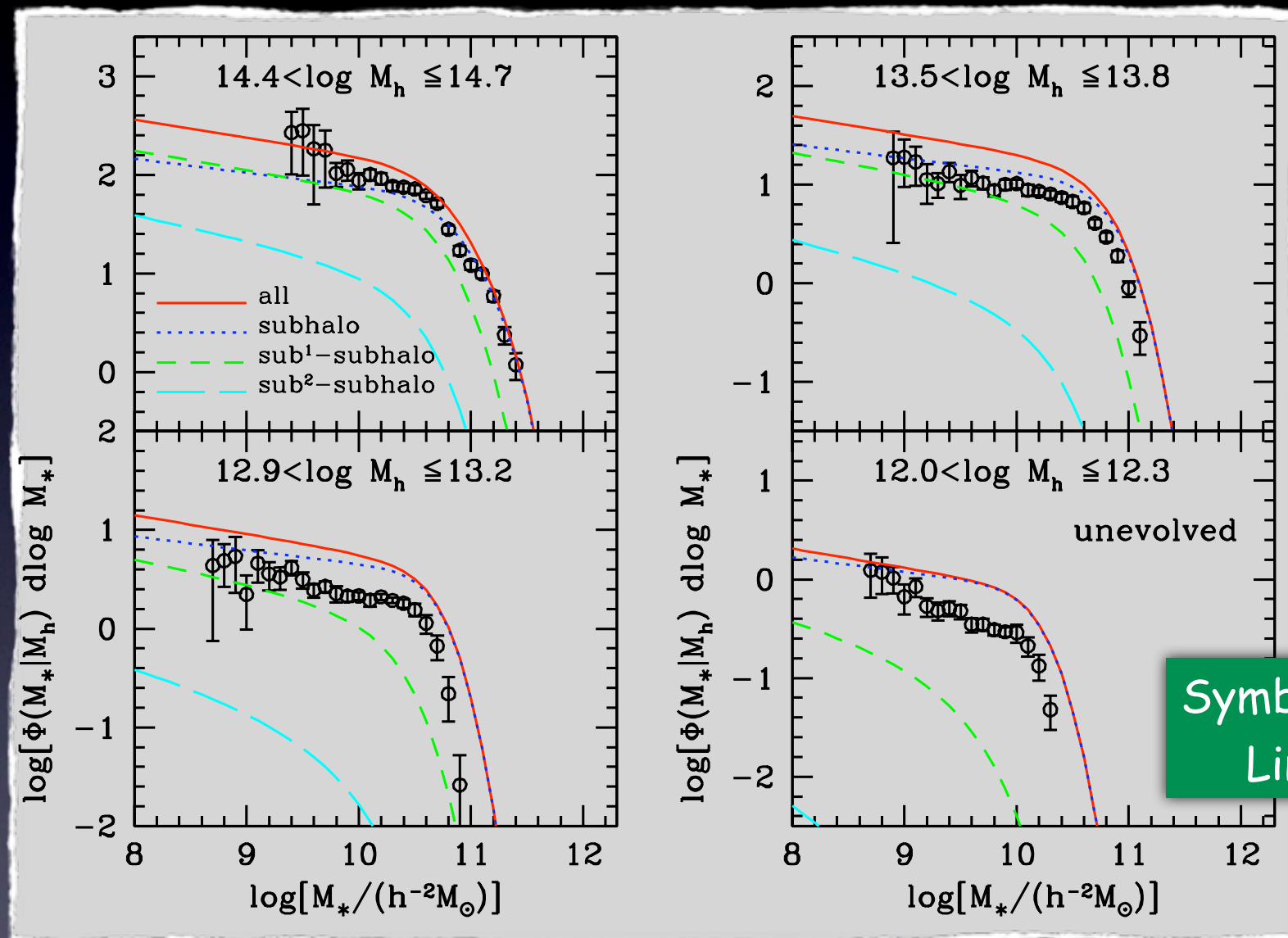
$$\text{SFR}(t) = e^{-t_{\text{acc}}/\tau_c} e^{-(t-t_{\text{acc}})/\tau_s}$$

satellites

Weinmann et al. 2009

The Fate of Satellite Galaxies

Use unevolved subhalo mass function to predict CLF of satellites, under the assumption that CLF of centrals does not evolve with redshift

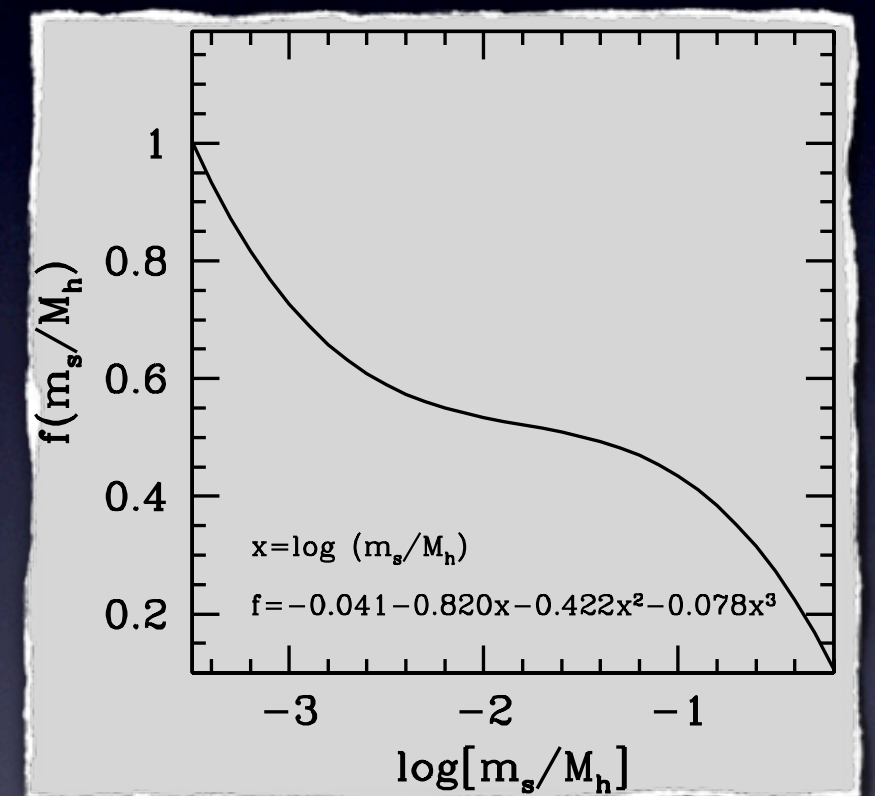
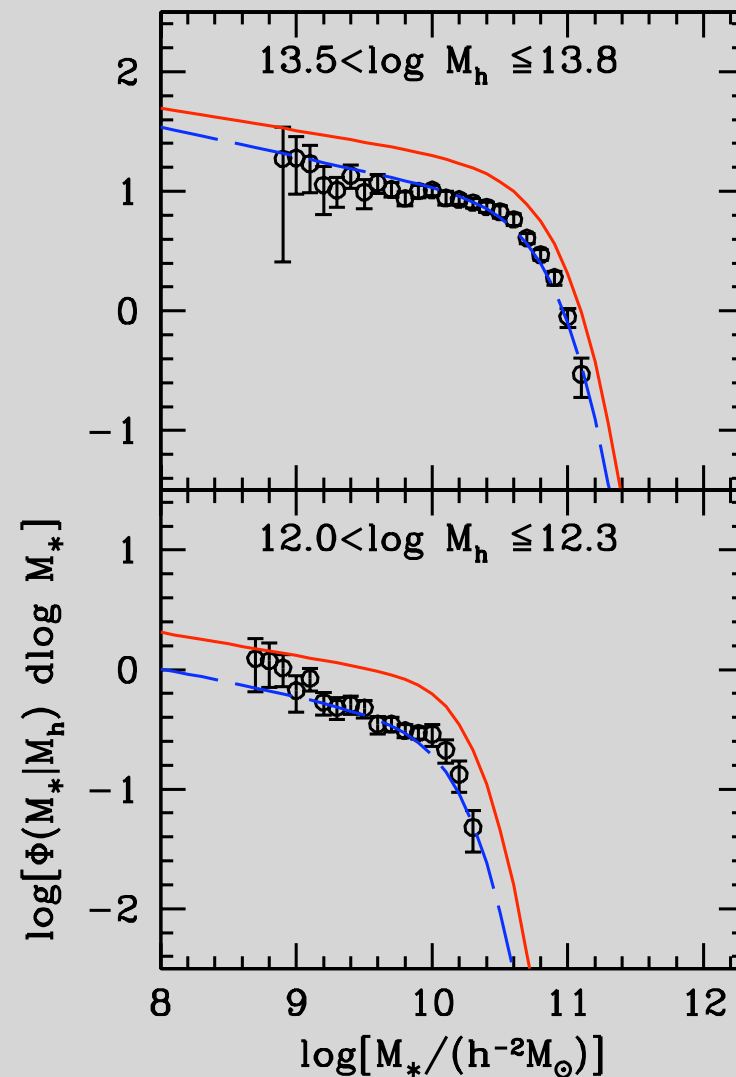
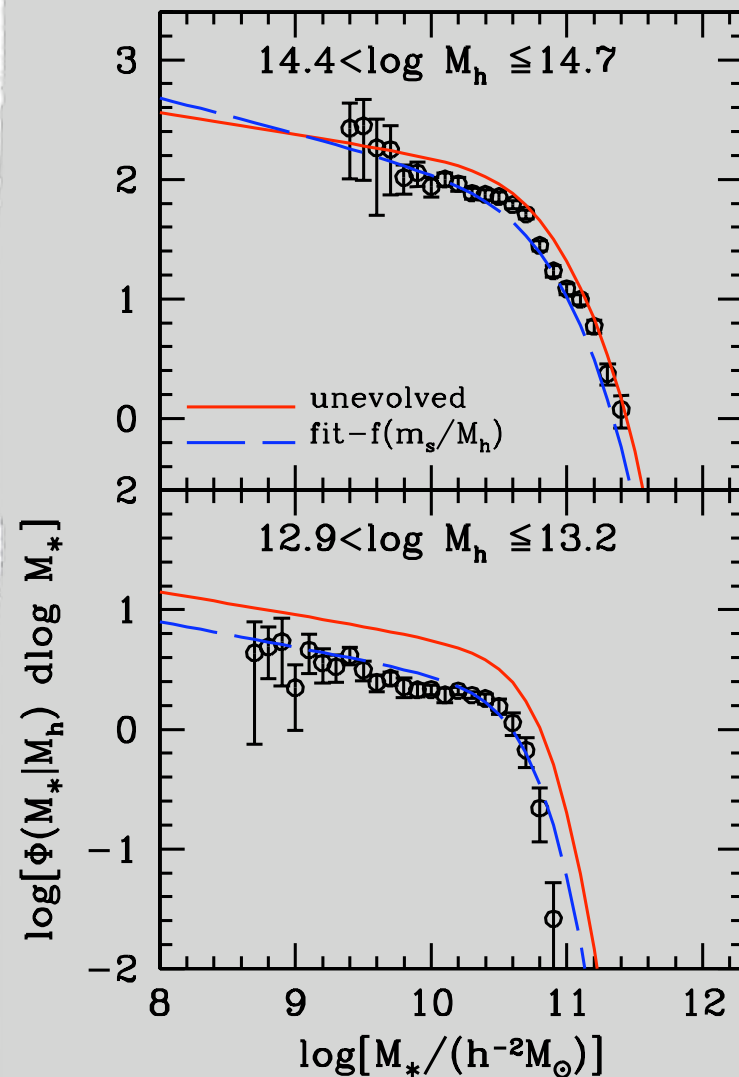


Yang, Mo & vdB (2009)

Model overpredicts number of satellites, especially in low mass haloes. Satellites have to be (tidally) destroyed, or be accreted by centrals.

The Fate of Satellite Galaxies

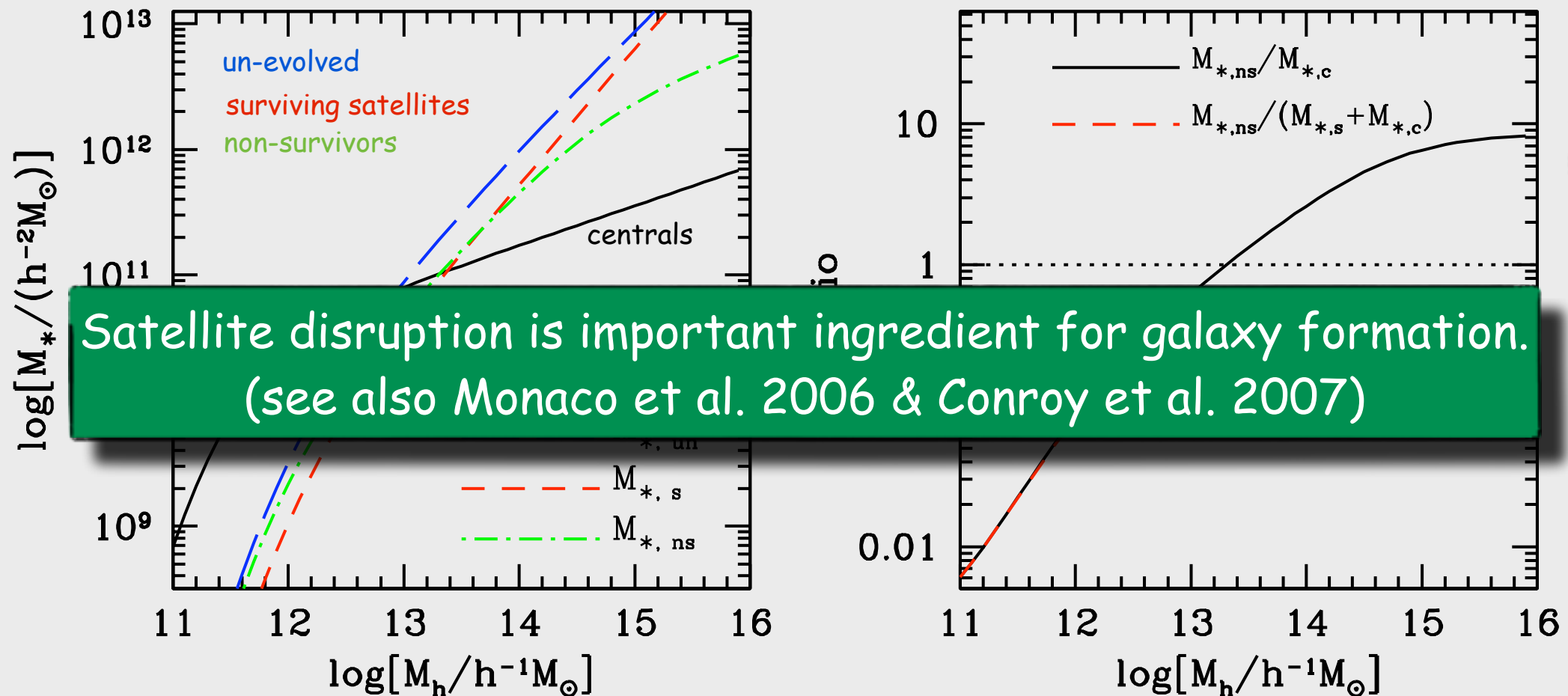
We fit CLF of satellites assuming a survival fraction that only depends on ratio of subhalo mass (at time of accretion) and halo mass.



Yang, Mo & vdB (2009)

More massive subhaloes (and their satellites) are less likely to survive.
Consistent with dynamical friction efficiency increasing with subhalo mass.

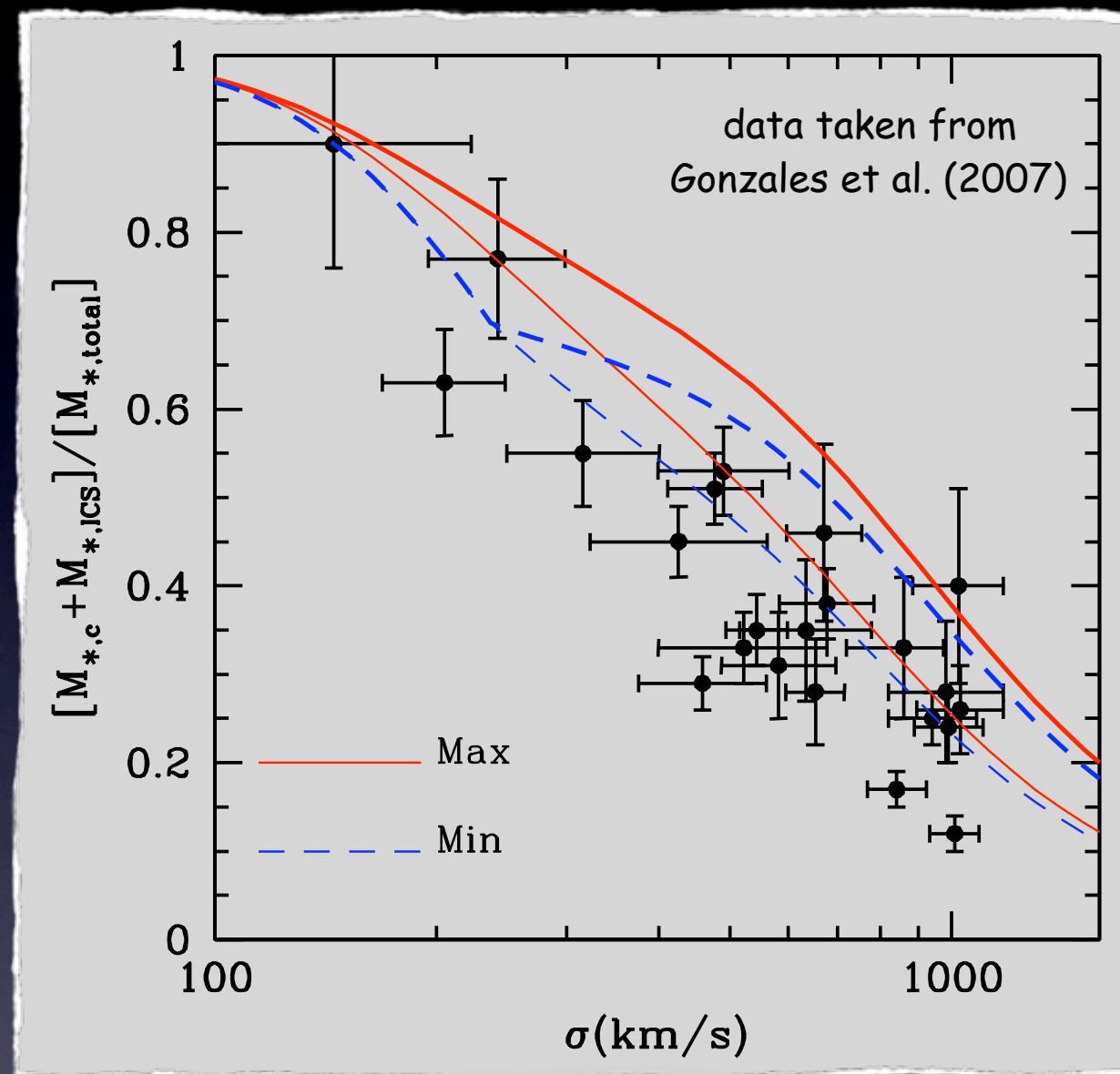
The Fate of **Disrupted** Satellite Galaxies



Satellite disruption is important ingredient for galaxy formation.
(see also Monaco et al. 2006 & Conroy et al. 2007)

In massive haloes, the stellar mass in non-surviving satellites is several times larger than stellar mass of central galaxy. Consequently, most of the non-surviving satellites have to be disrupted, giving rise to a significant stellar halo.

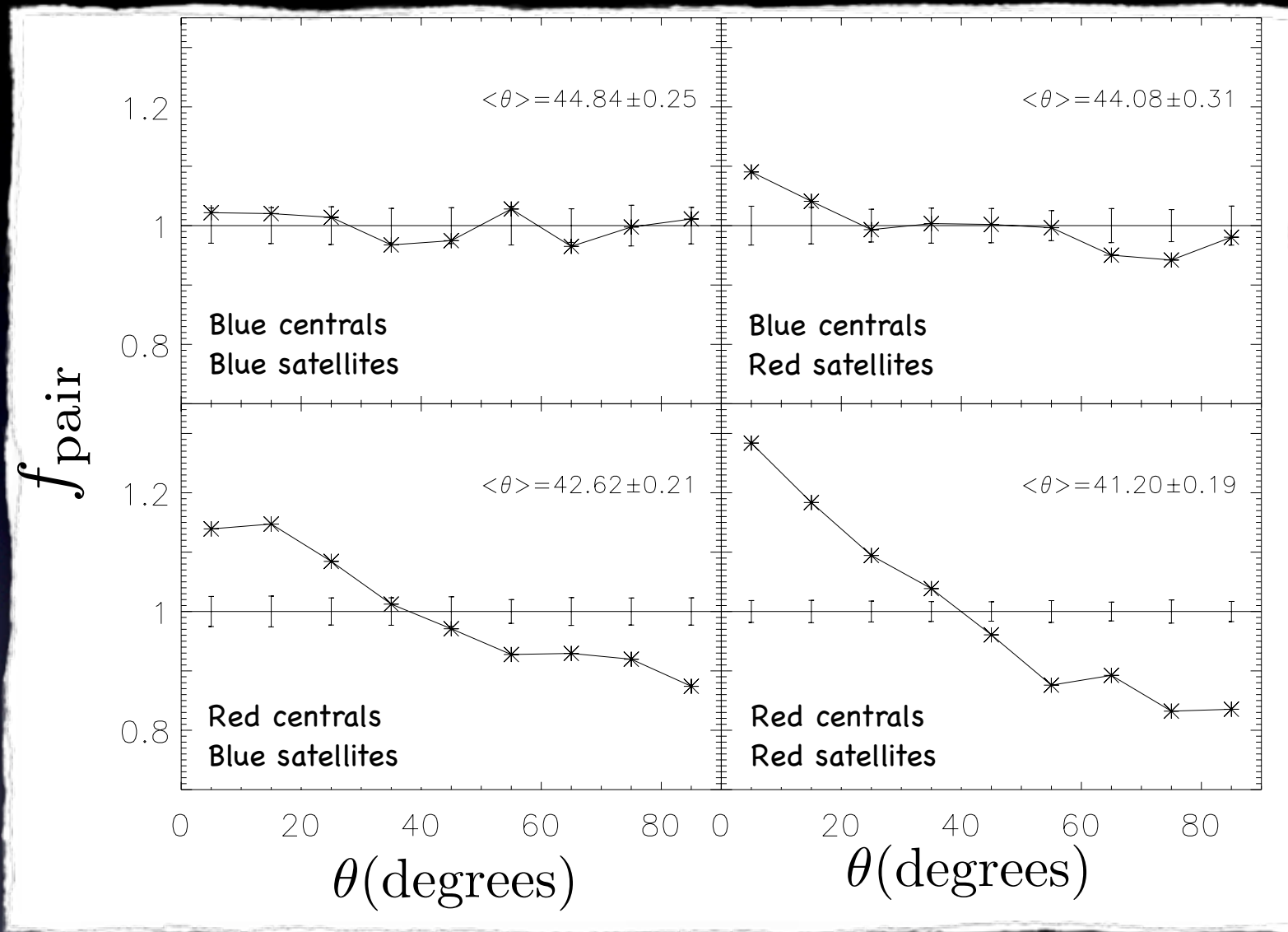
The Amount of Intra-Cluster Light



Predicted amount of ICL consistent with observations

Yang, Mo & vdB (2009)

Alignment Results



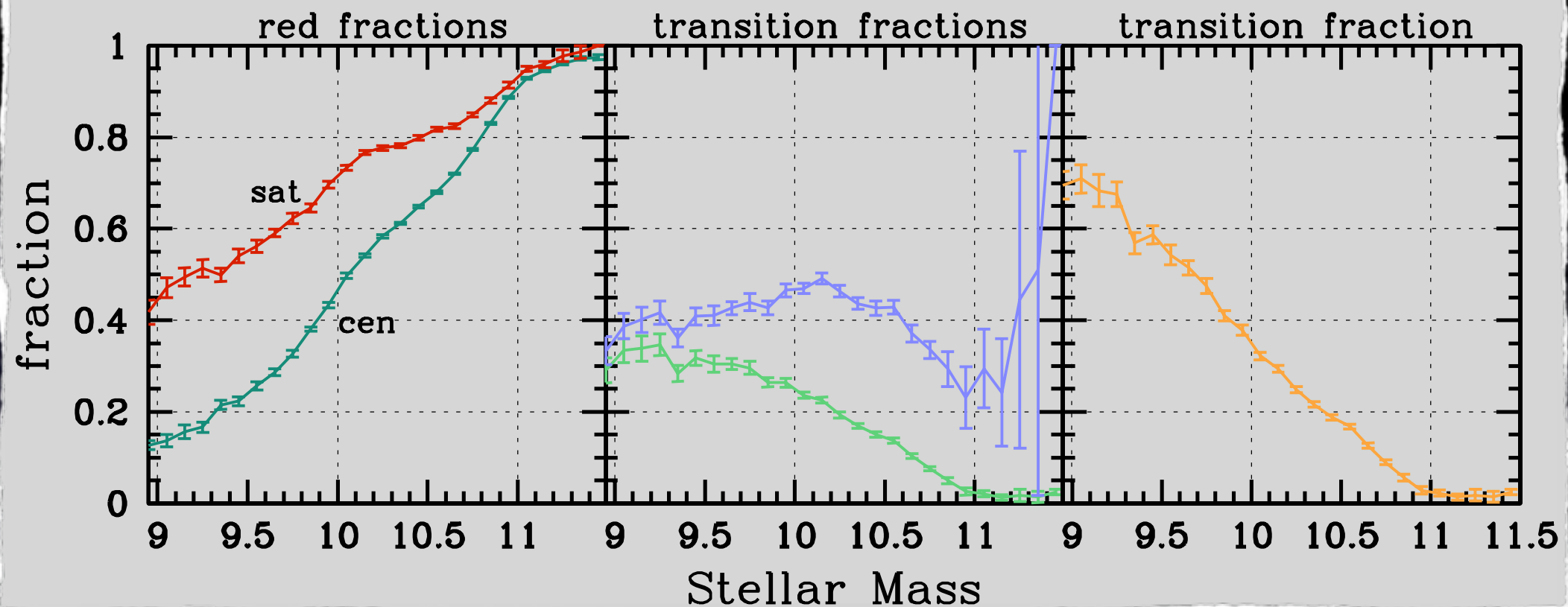
Wang et al. (2008)

- Satellites around red centrals preferentially aligned with major axis.
- Alignment stronger for red satellites than for blue satellites.
- Satellites around blue centrals show no significant alignment.

see also: Brainerd (2005); Yang et al. (2005); Azzaro et al. (2007)



Blue-to-Red Transition Fractions

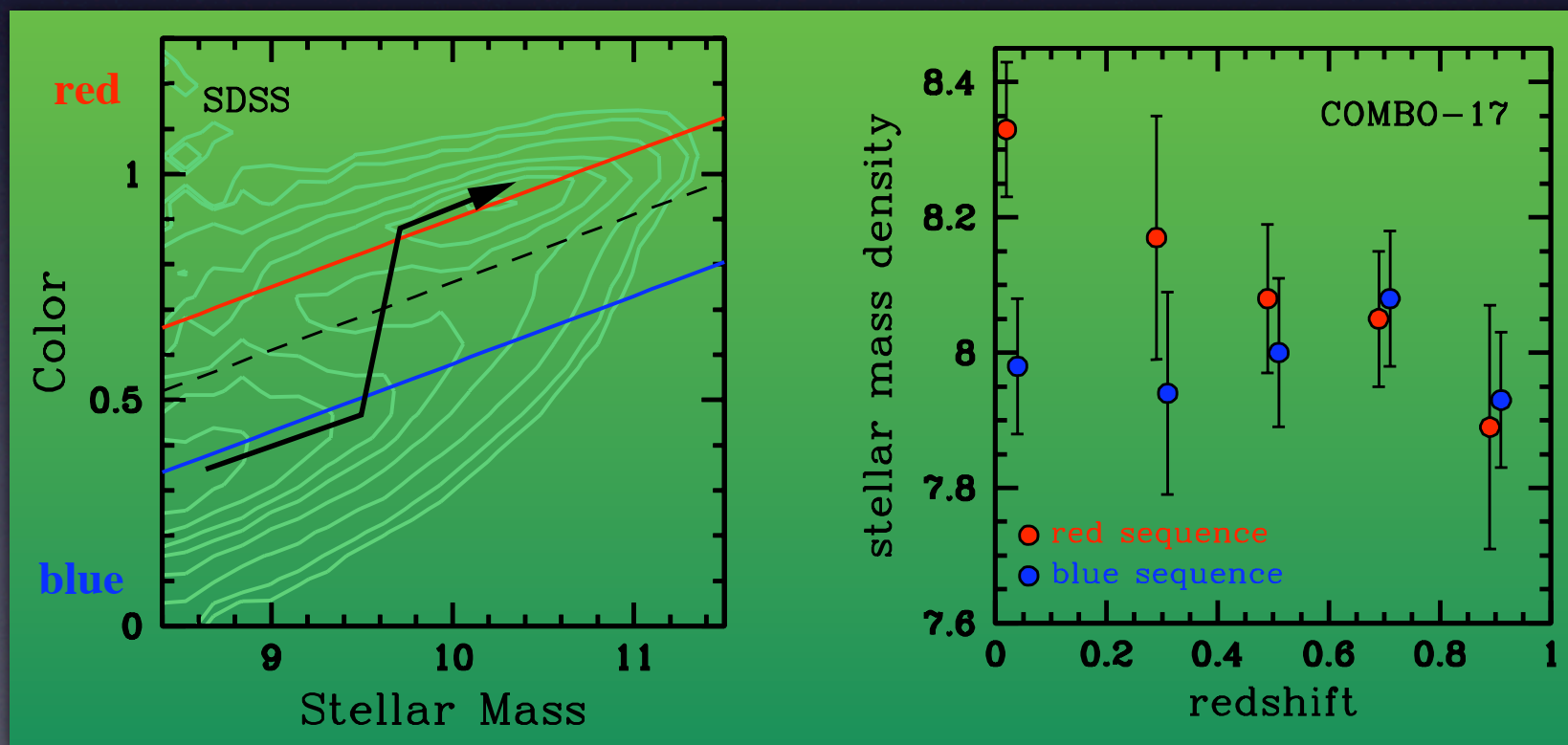
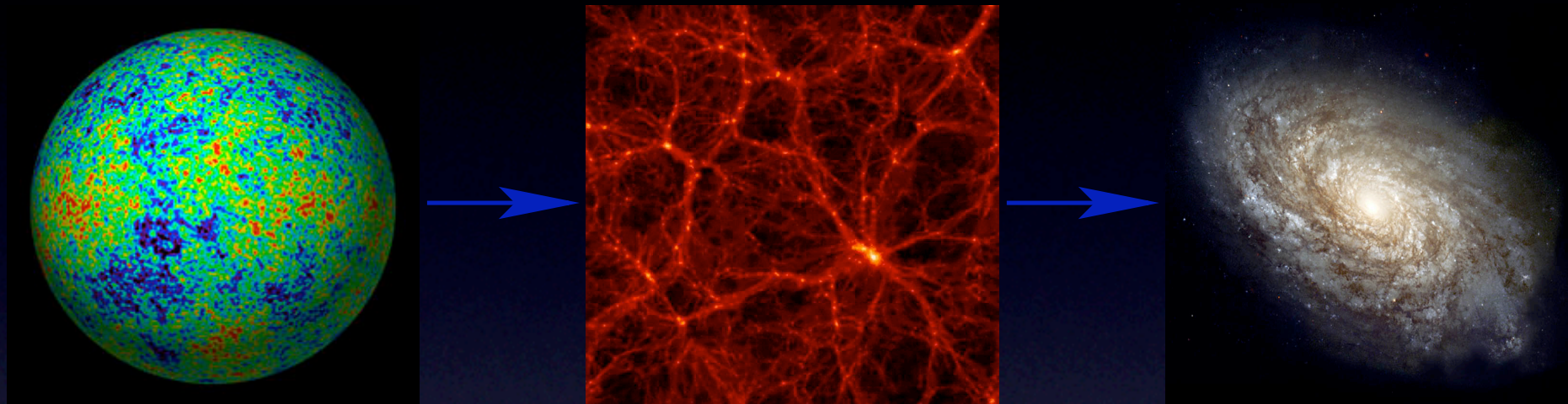


- The red fraction of sats is higher than that of centrals of same M_{star}
- Roughly 40% of sats that are blue at accretion undergo transition
- Above $10^{10} h^{-2} M_{\text{sun}}$ majority of sats were already red at accretion
- Satellite transformation processes are only important at low M_{star}

van den Bosch et al. (2008)

The Standard Paradigm

PARADIGM: All Galaxies Originally form as Central Disk Galaxies



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