The Origin of Galaxy Bimodality

What makes galaxies red & dead?

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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

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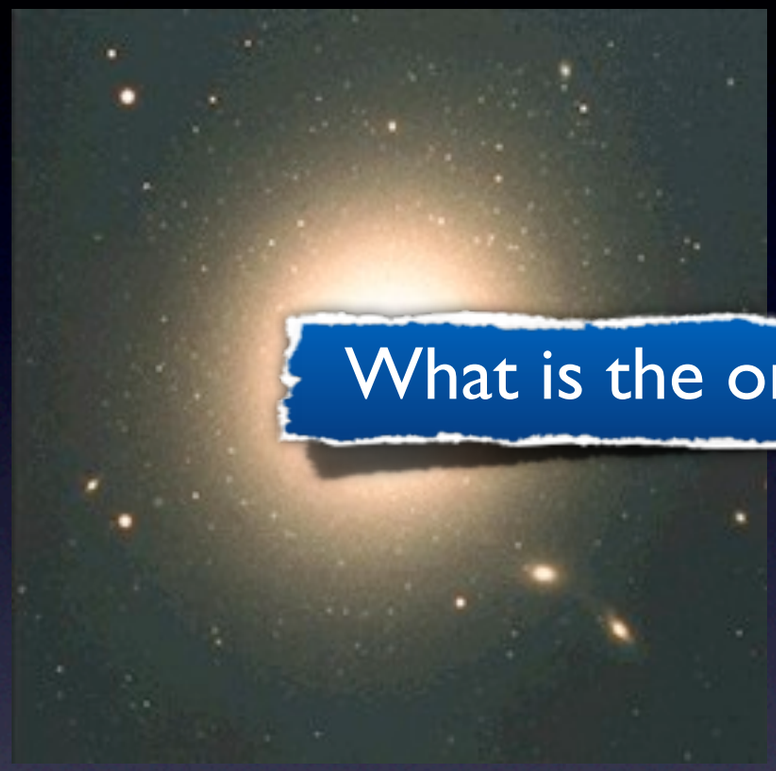

Late-Type

What is the origin of this bimodality?

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

Disk-Like Morphology
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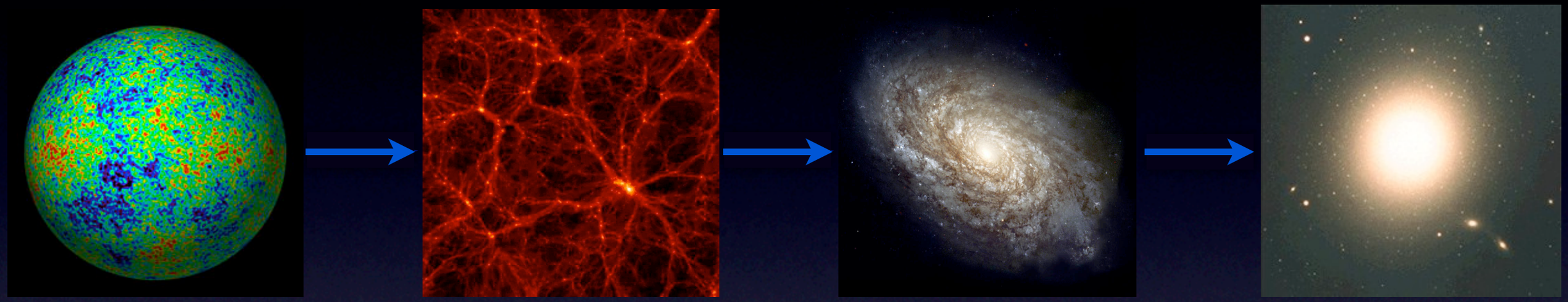
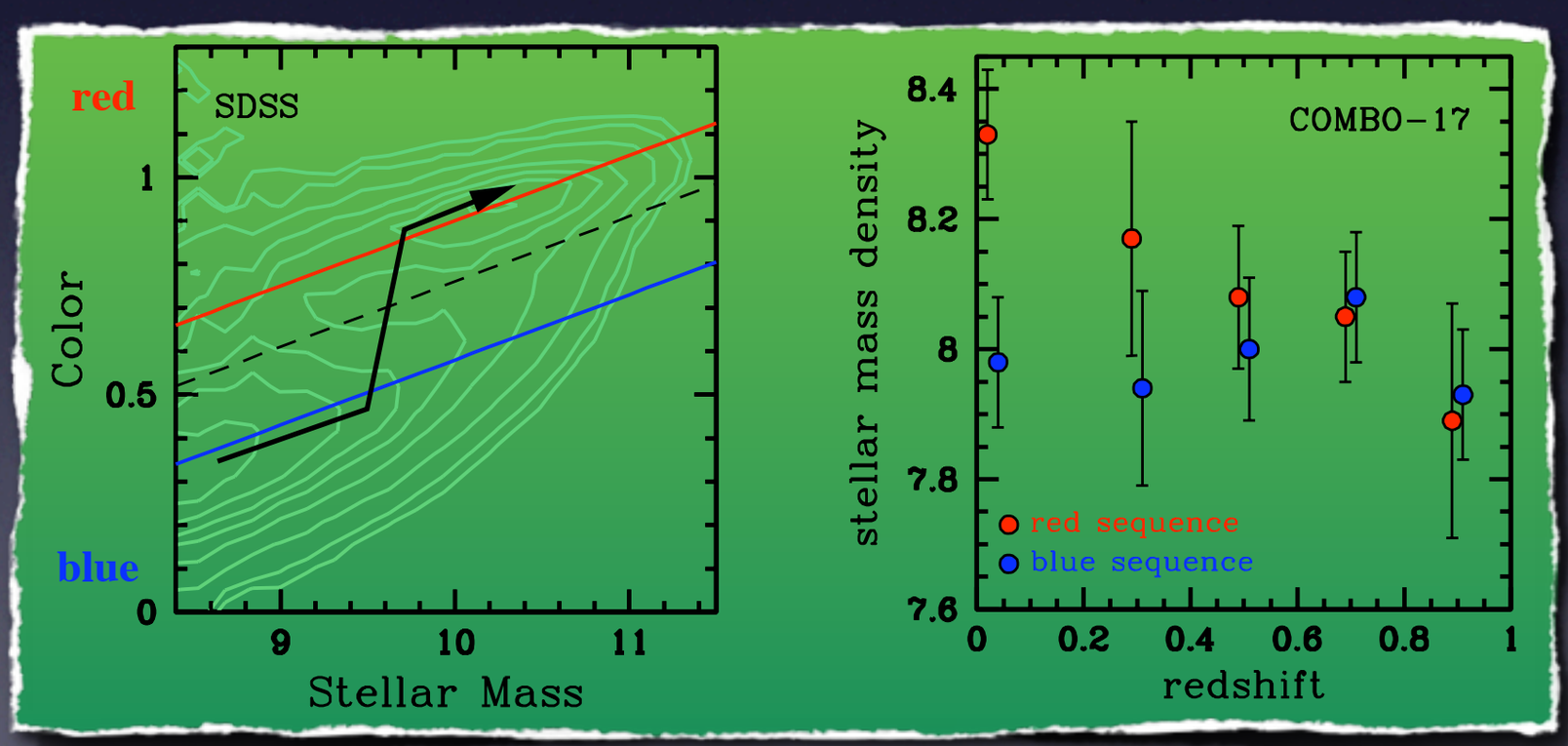
Blue colors

The Standard Paradigm

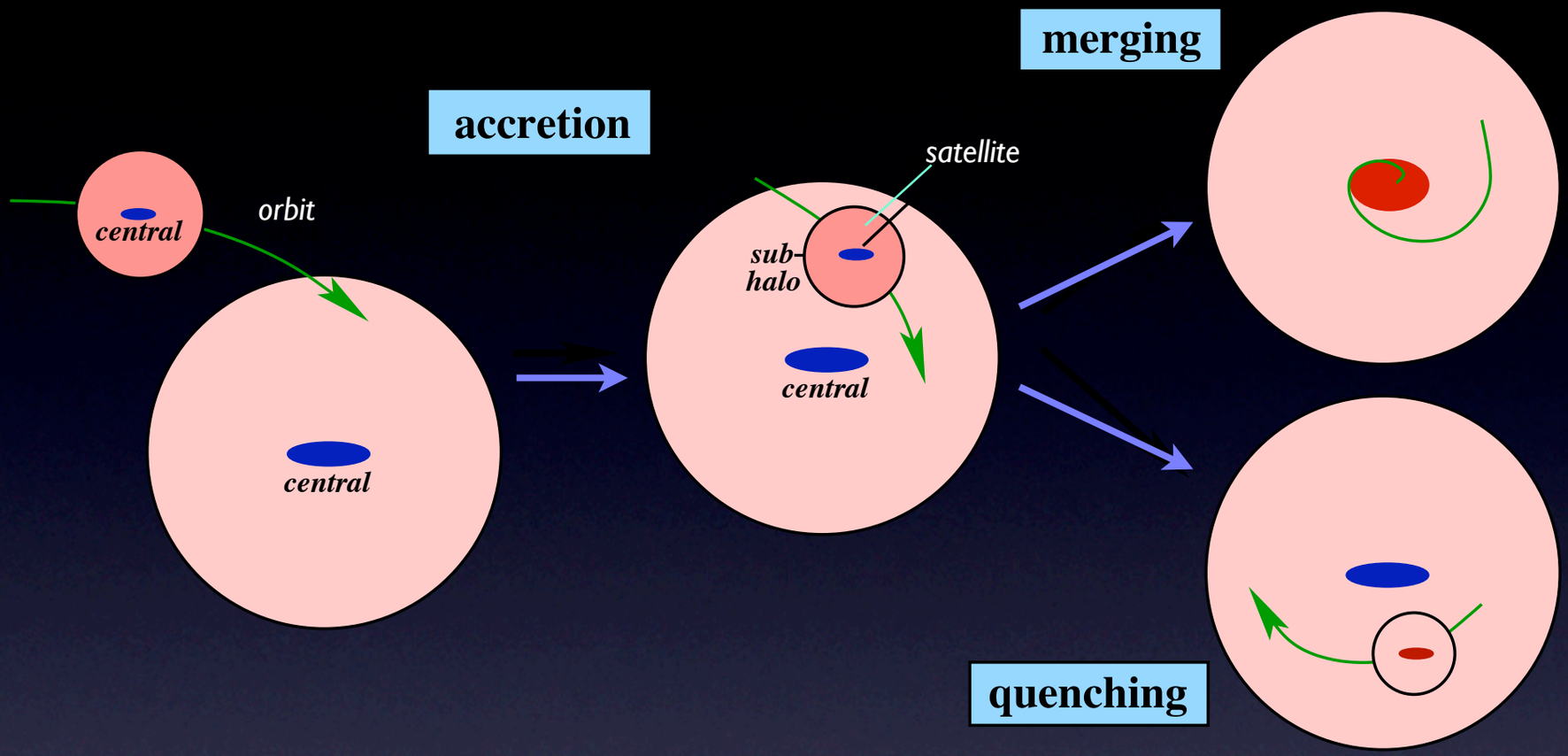
PARADIGM: All Galaxies Originally form as Central Disk Galaxies





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?

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- What fraction of the red-sequence satellites underwent their transformation as a satellite?
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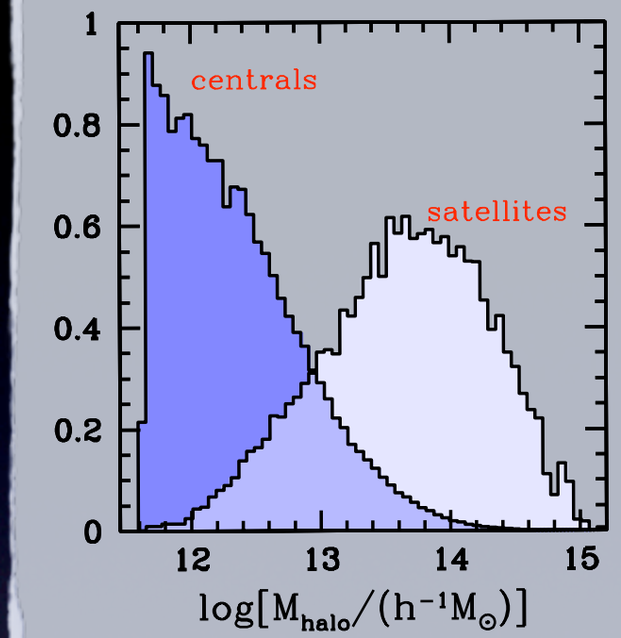
- To what extent are satellite-specific transformation processes responsible for environment dependence of galaxy population?

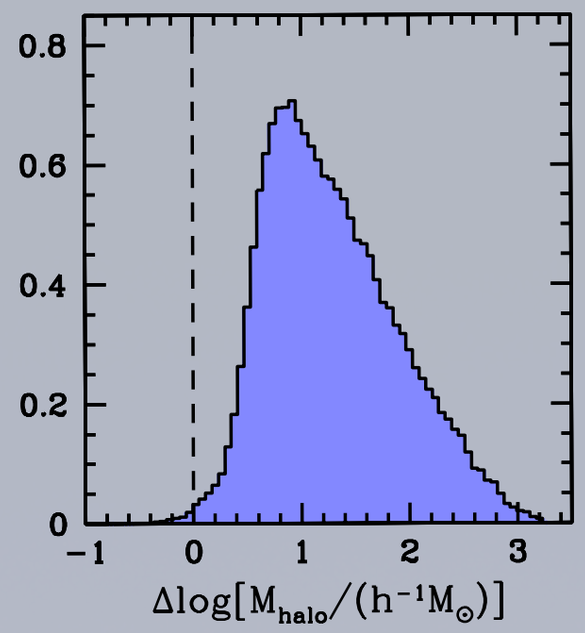
To address these questions, we constructed a large galaxy group catalogue from the SDSS *Yang et al. 2005, 2007*

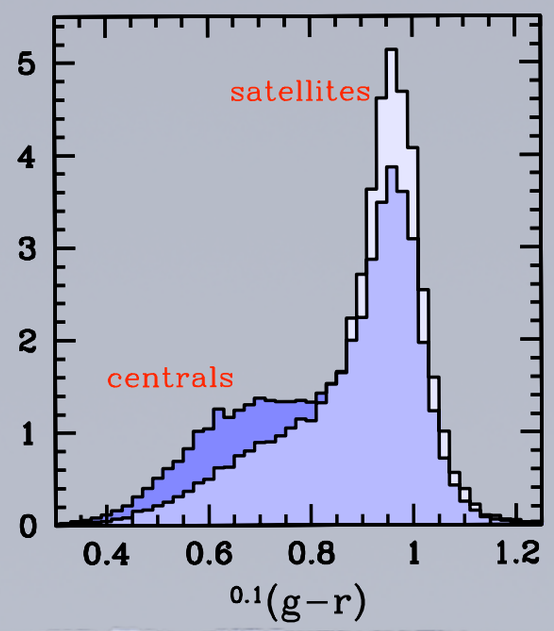
This allows us to split galaxy population in centrals and satellites, and to study galaxy properties as function of halo mass

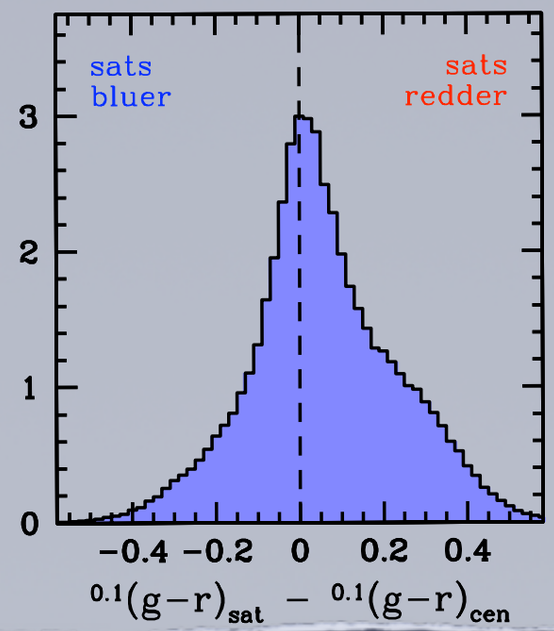
In particular, we study impact of satellite specific transformation processes by comparing satellites to centrals of the same stellar mass.

Centrals vs. Satellites





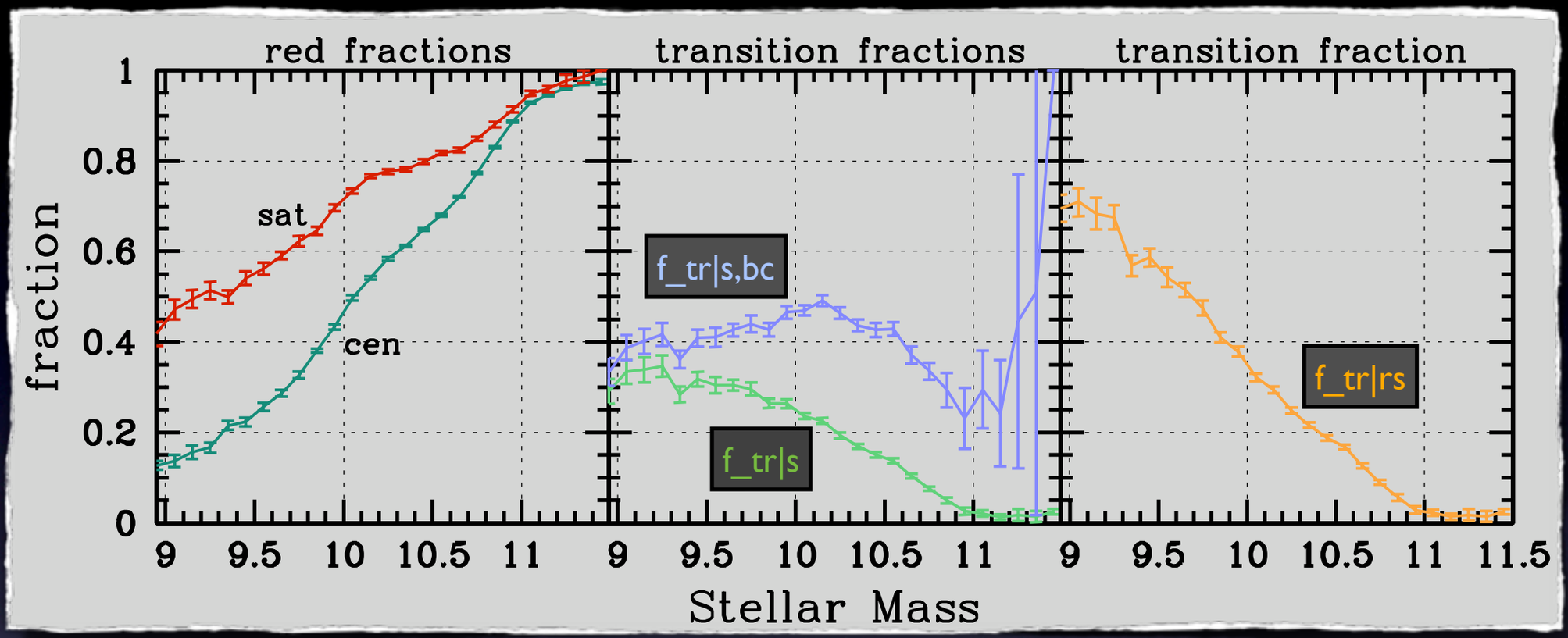




van den Bosch et al. (2008)

Sats are marginally redder than centrals of same stellar mass

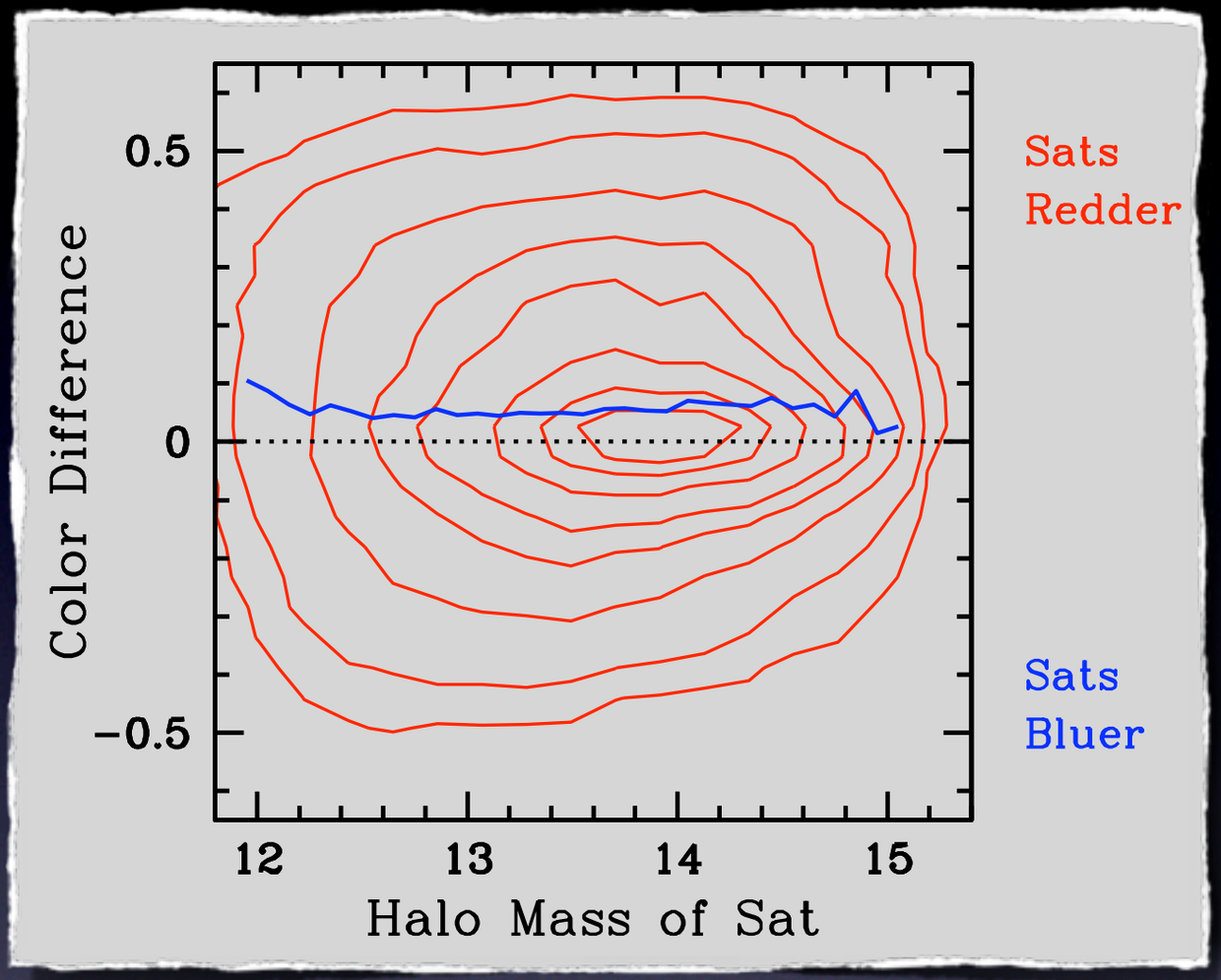
Blue-to-Red Transition Fractions



- 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)

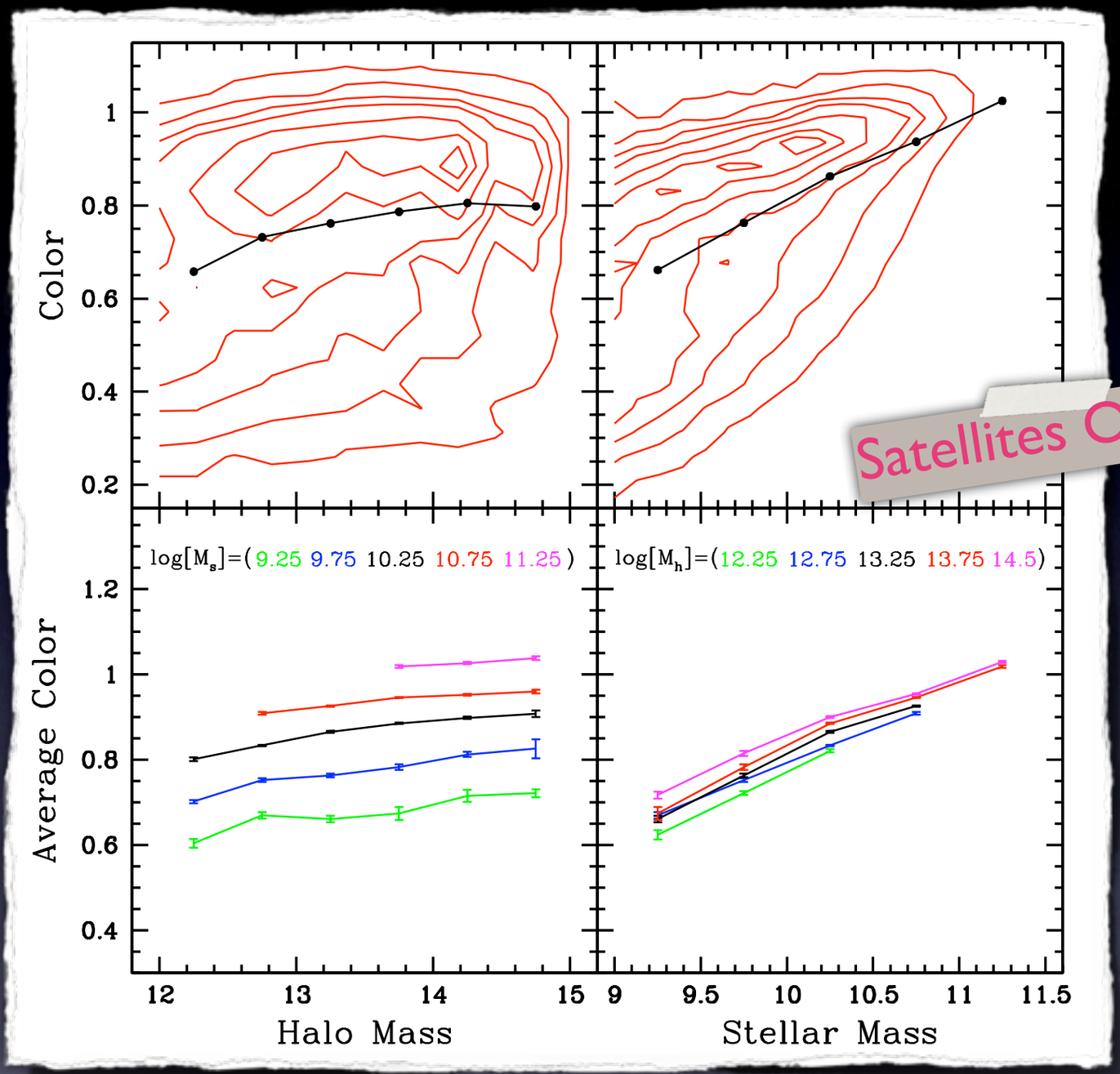
Dependence on Halo Mass



- 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)

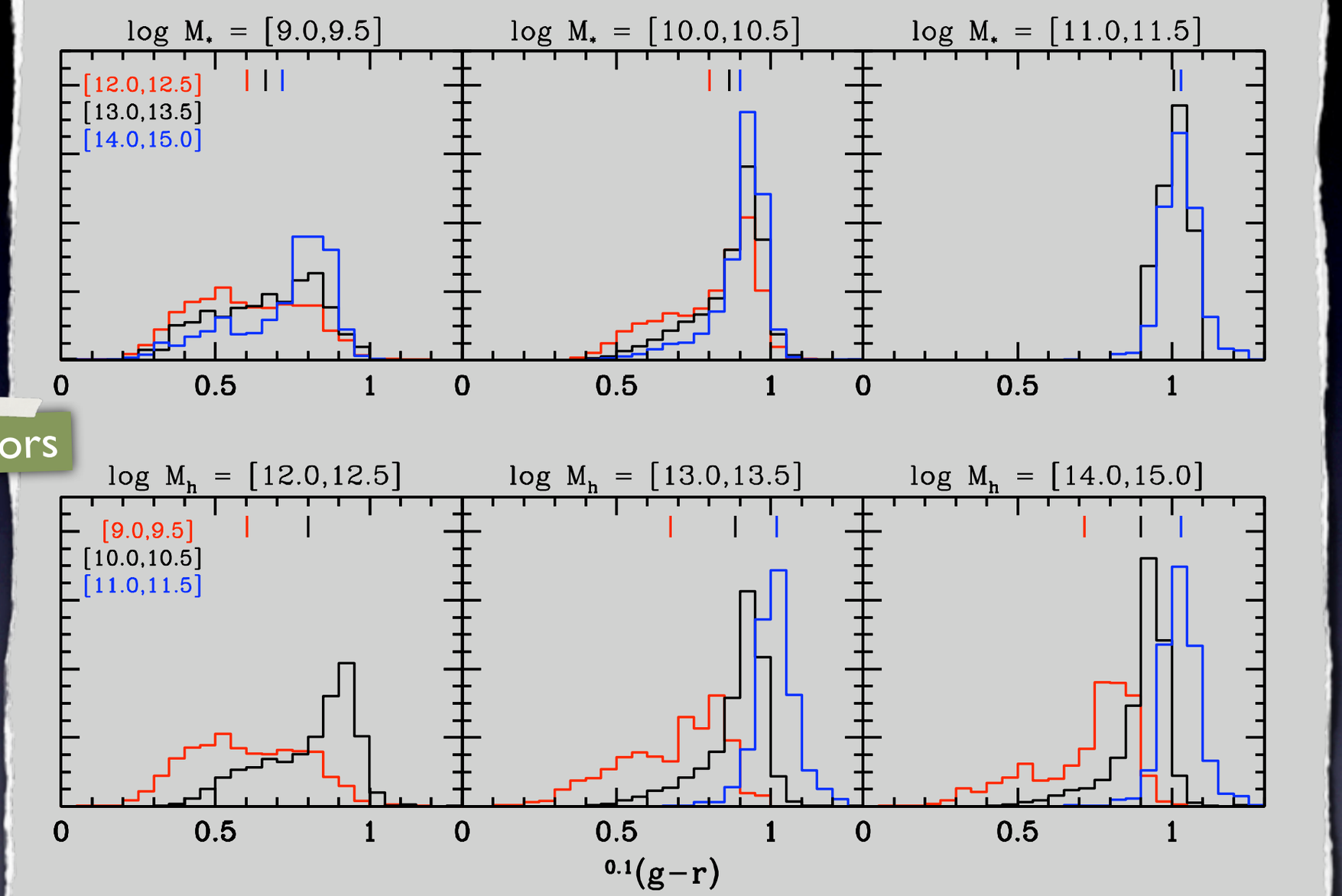
Satellite Ecology



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

van den Bosch et al. (2009)

The Dearth of Environment Dependence



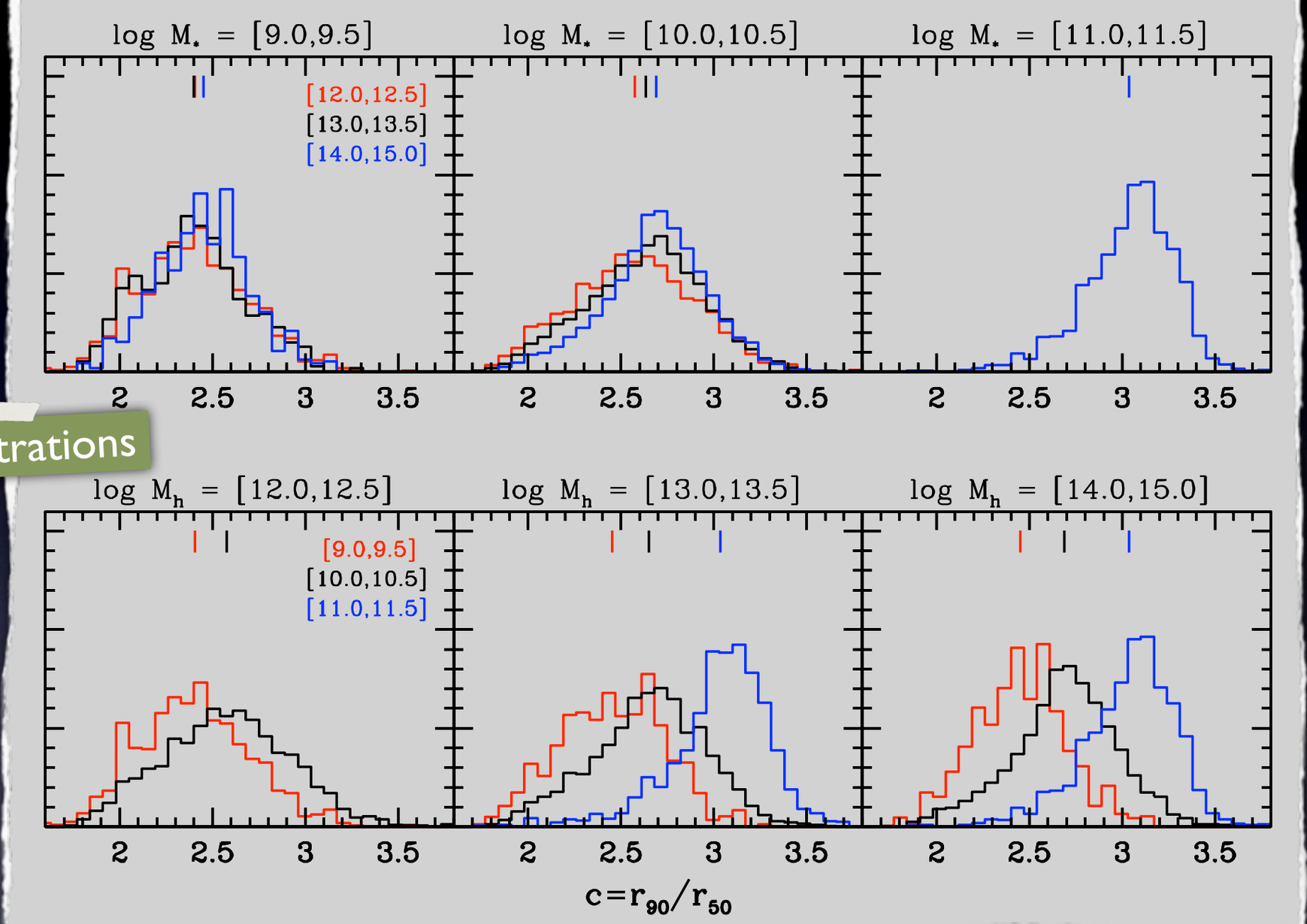
colors

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

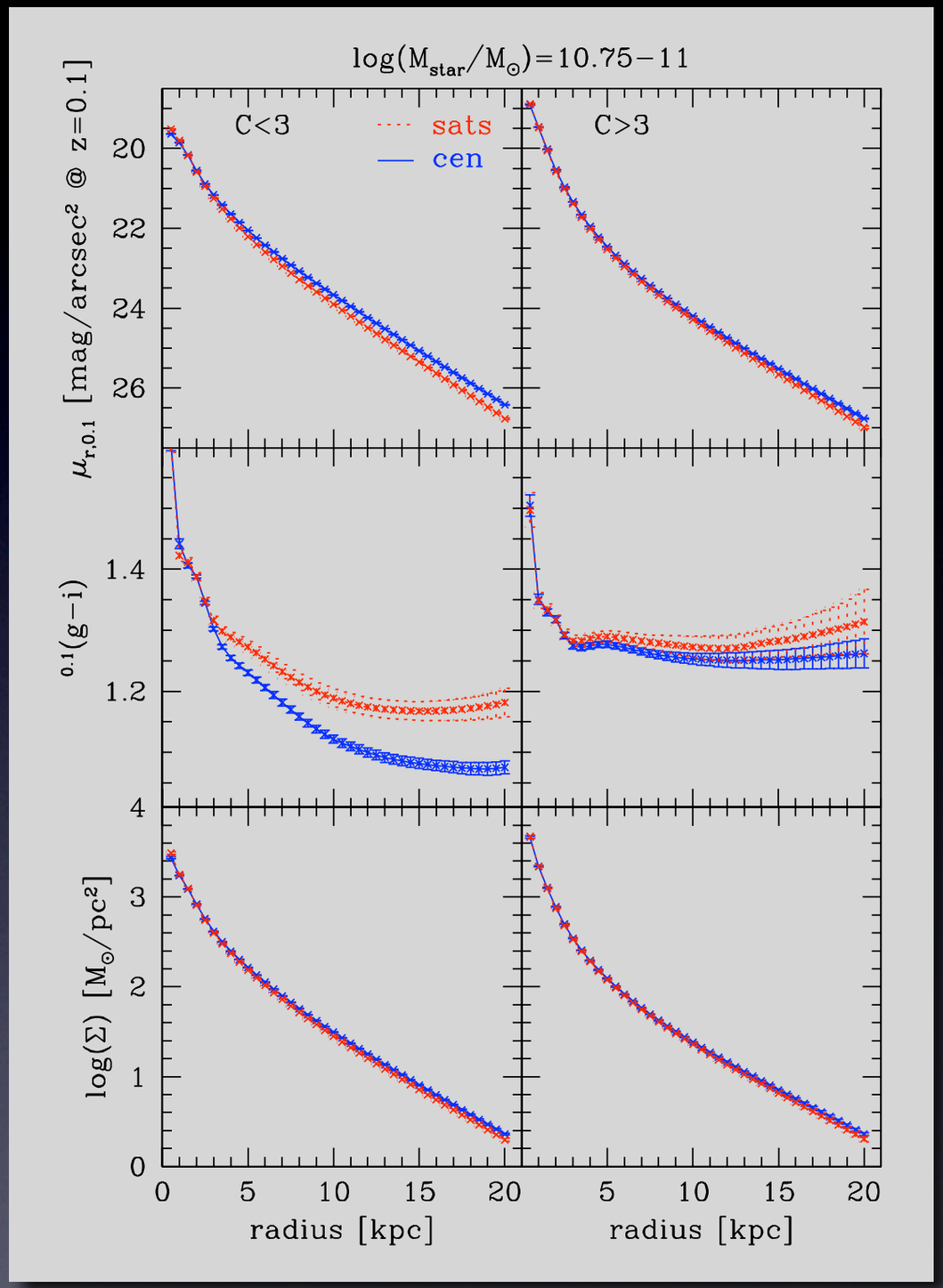
concentrations



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

van den Bosch et al. (2009)

Density distributions of centrals and satellites



low concentration systems:

Centrals are brighter and bluer, especially at larger radii.

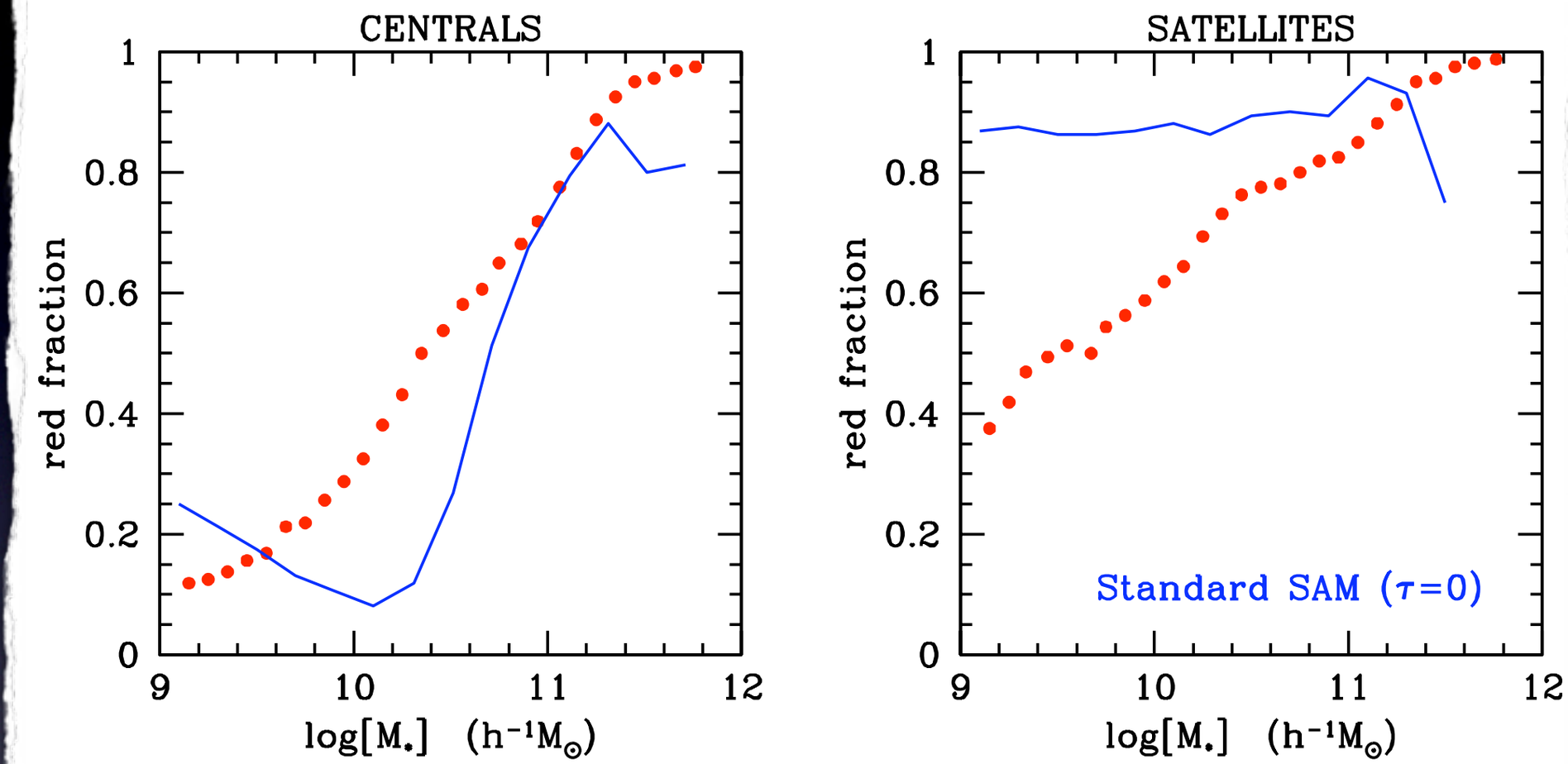
high concentration systems:

Surface photometry of centrals and satellites indistinguishable.

Independent of concentration, centrals and satellites have the same average stellar surface density, consistent with satellites being quenched centrals.

Weinmann et al. 2009

Modeling Strangulation

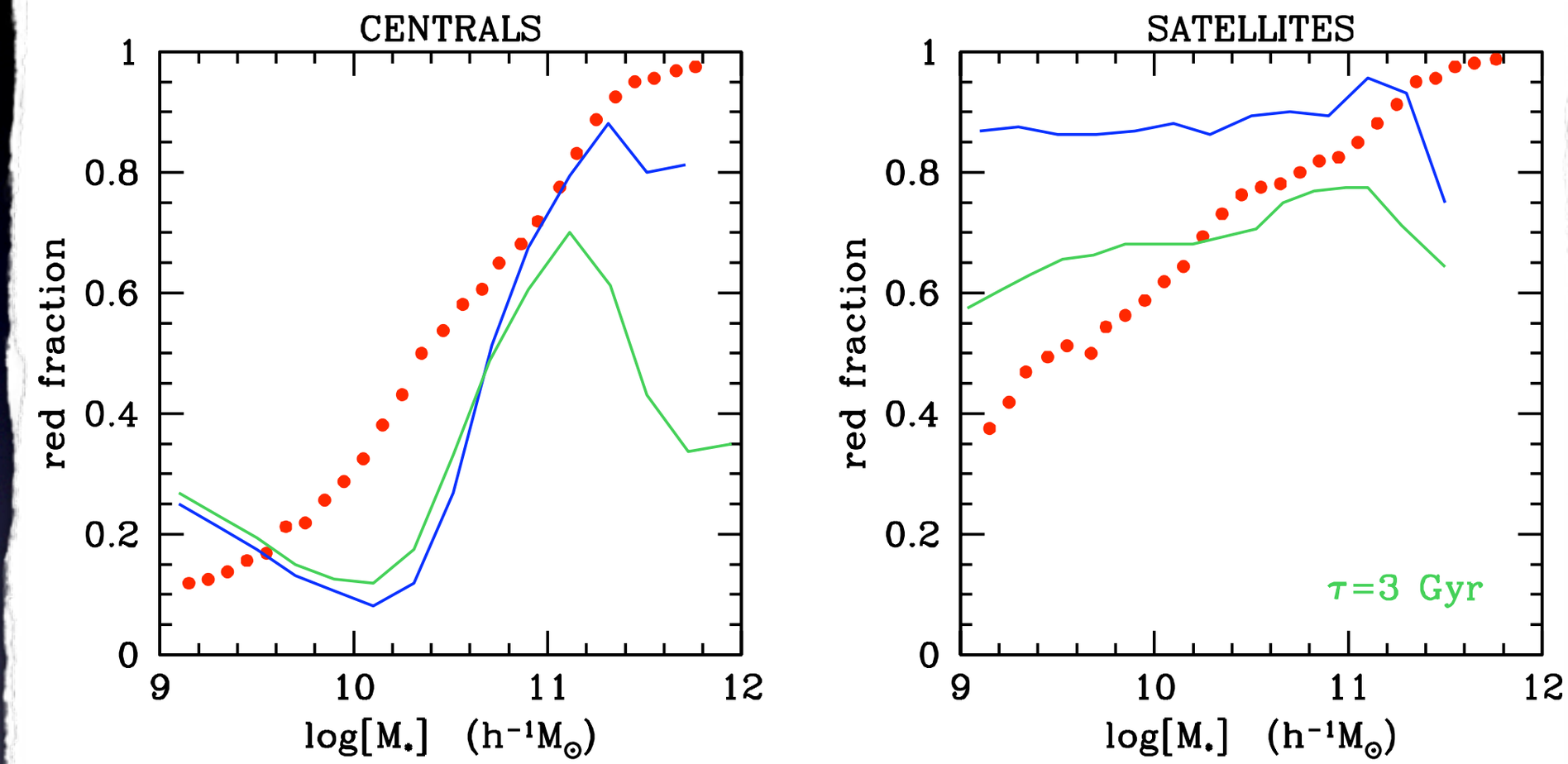


Kang & van den Bosch (2008)

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)

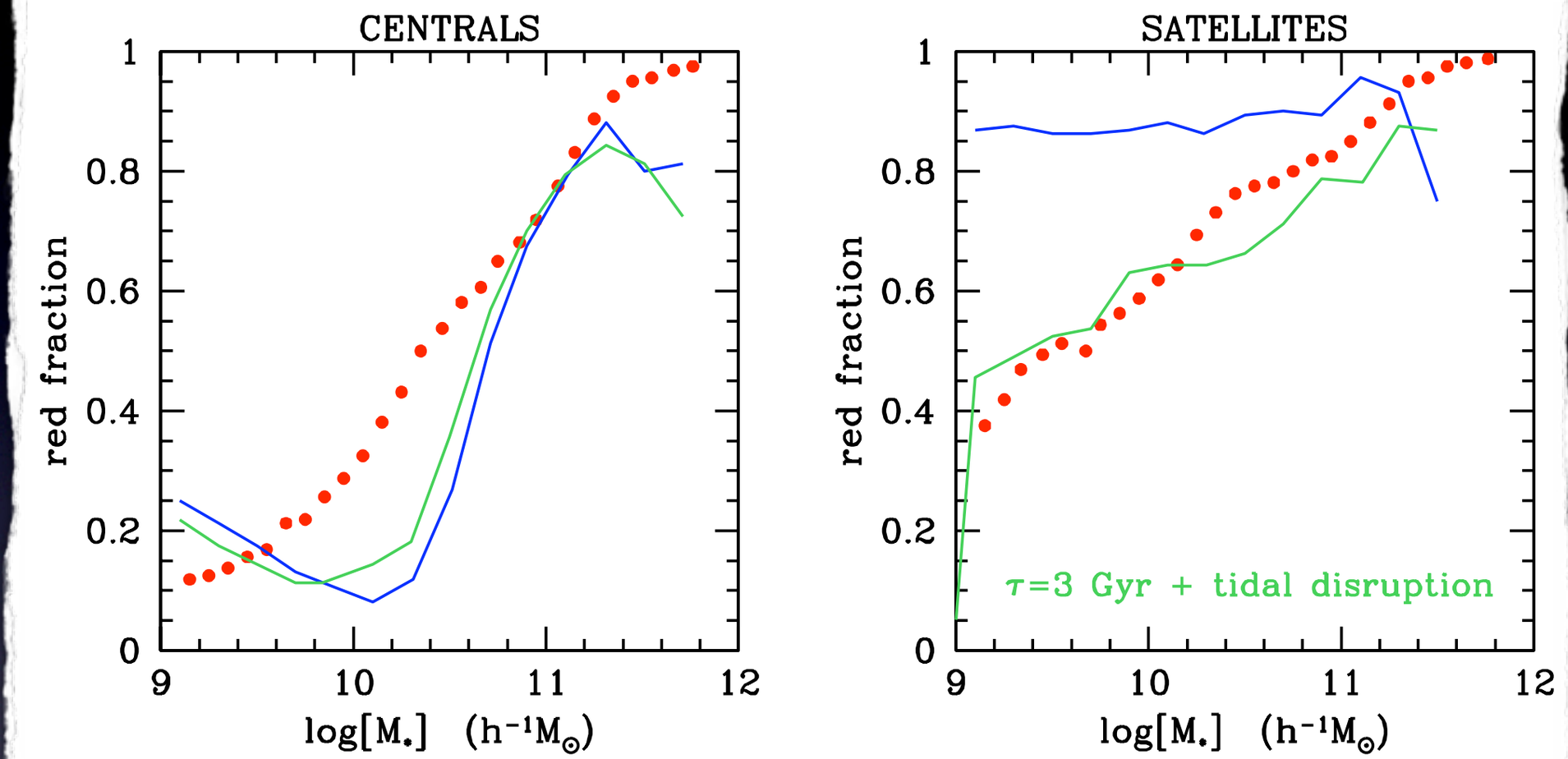
Modeling Strangulation



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

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

Modeling Strangulation

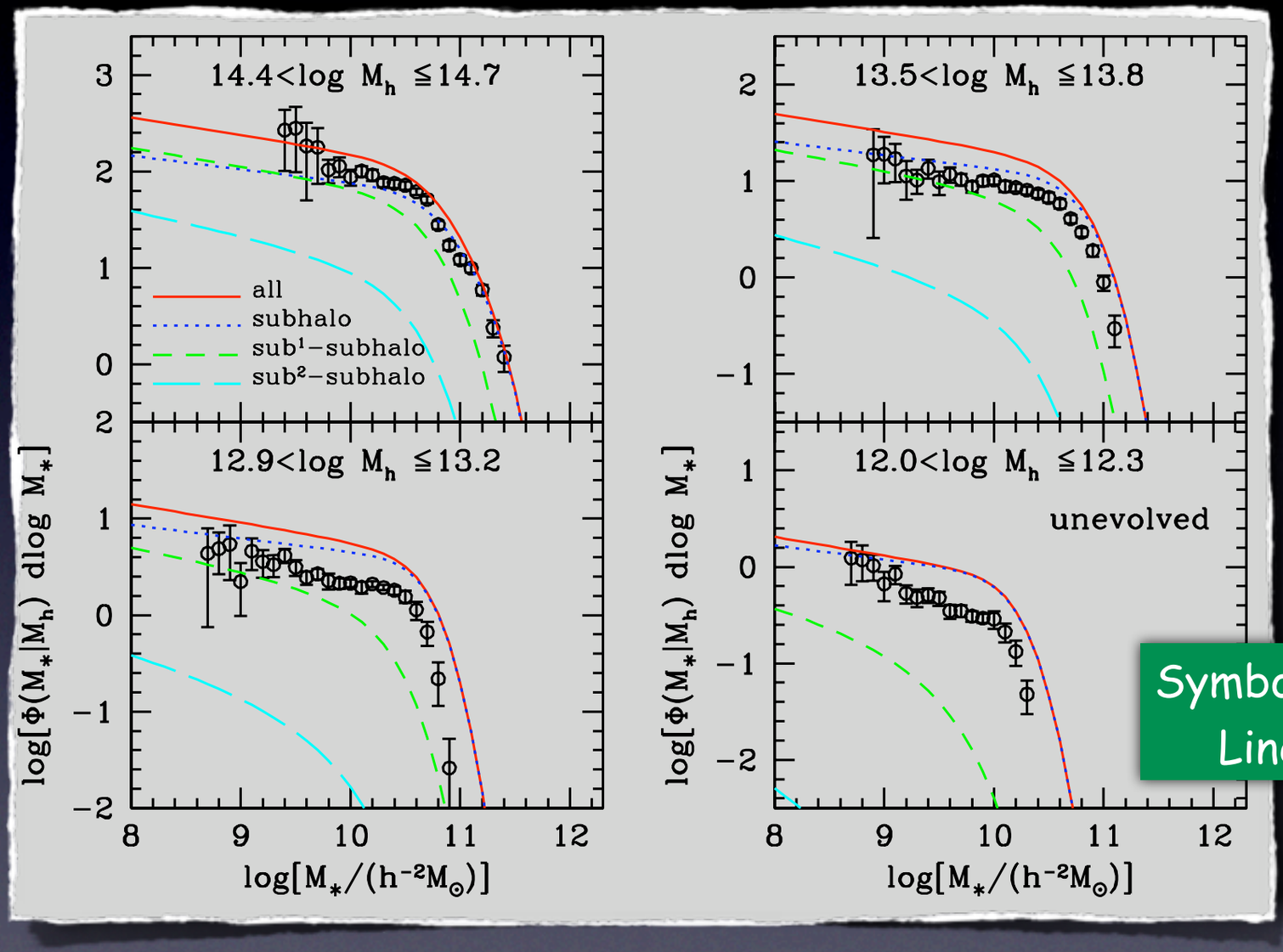


Half of orphans with $M_* < 10^{10} h^{-1} M_\odot$ tidally disrupted

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

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



Symbols: group catalogue
Lines: model predictions

Yang, Mo & vdB (2009)

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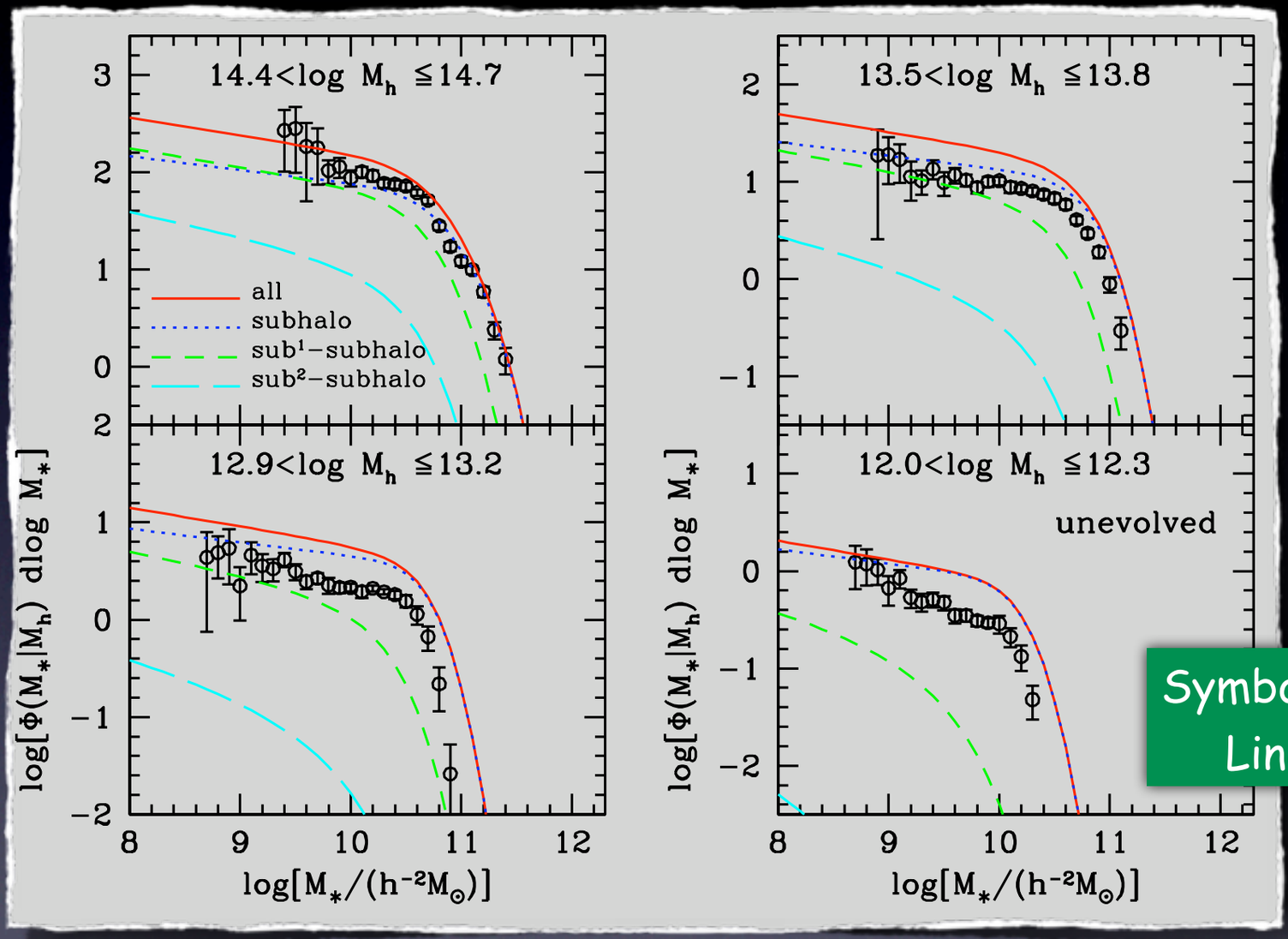

Symbols: group catalogue
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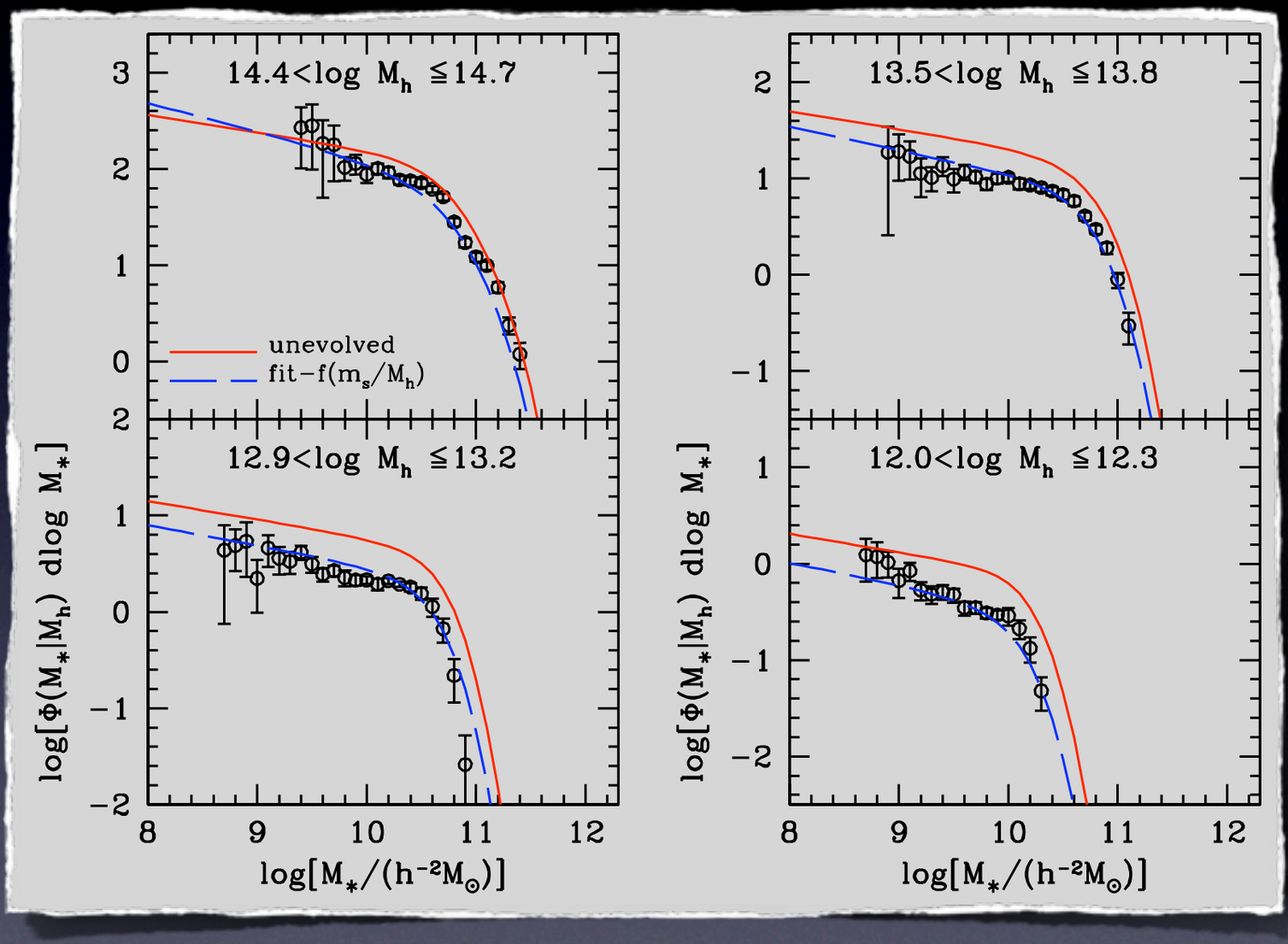
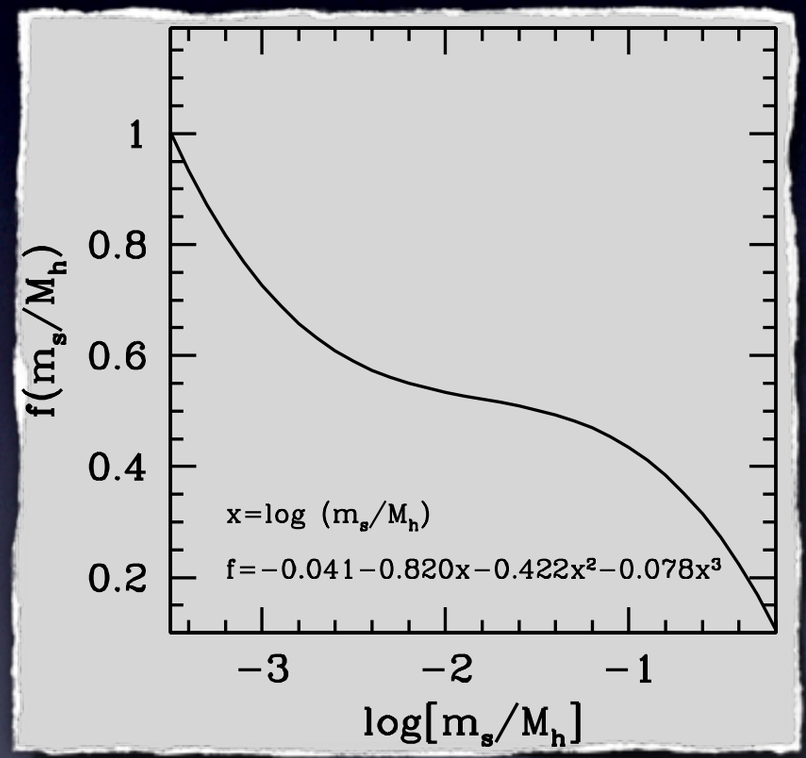
Model overpredicts number of satellites, especially in low mass haloes. Satellites have to be (tidally) destroyed, or be accreted by centrals.

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.





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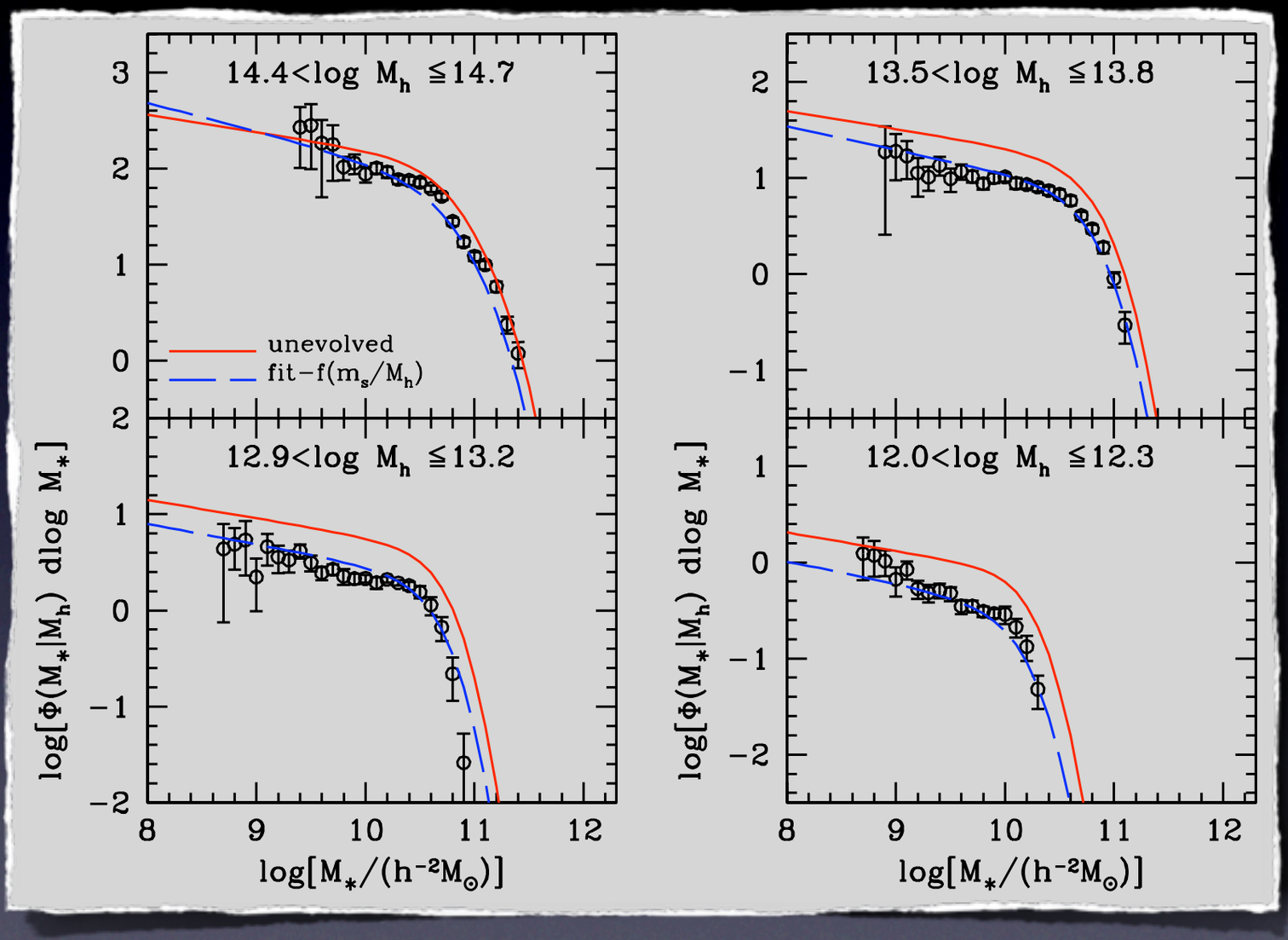
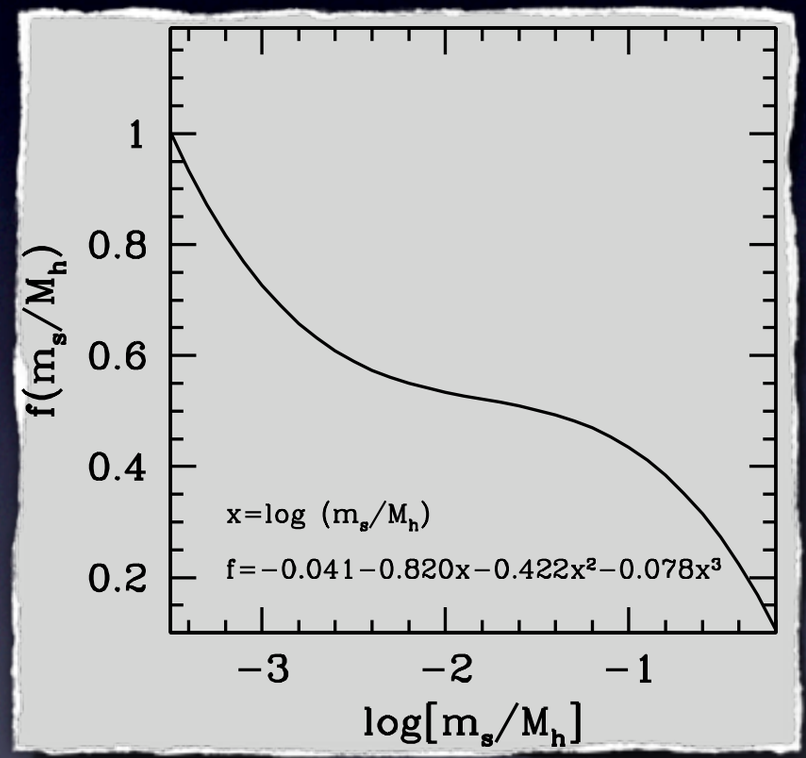


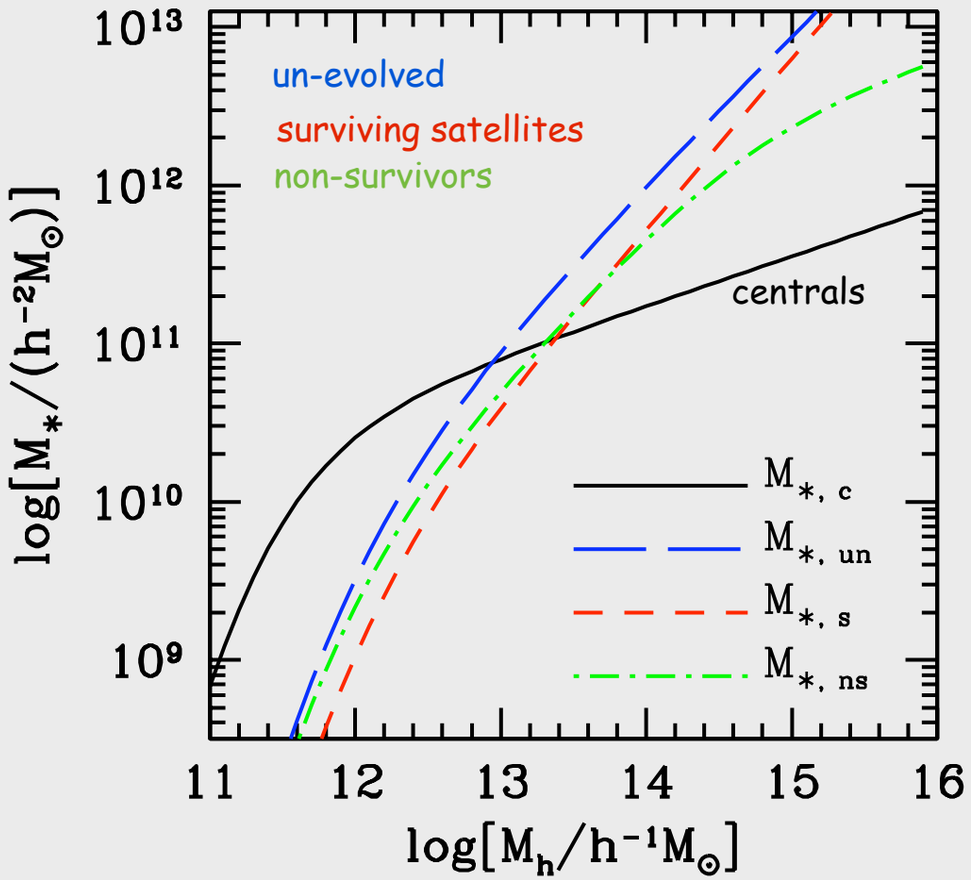


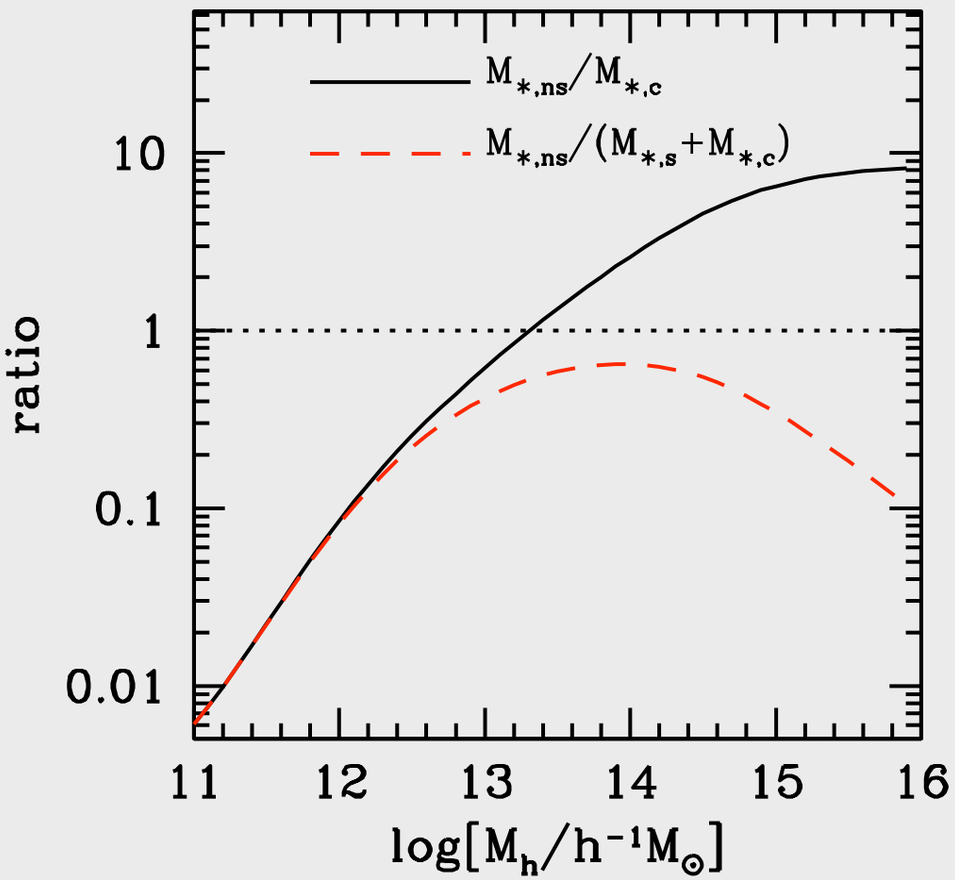
Yang, Mo & vdB (2009)

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

Frank van den Bosch *University of Utah*

The Fate of Disrupted Satellite Galaxies





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.

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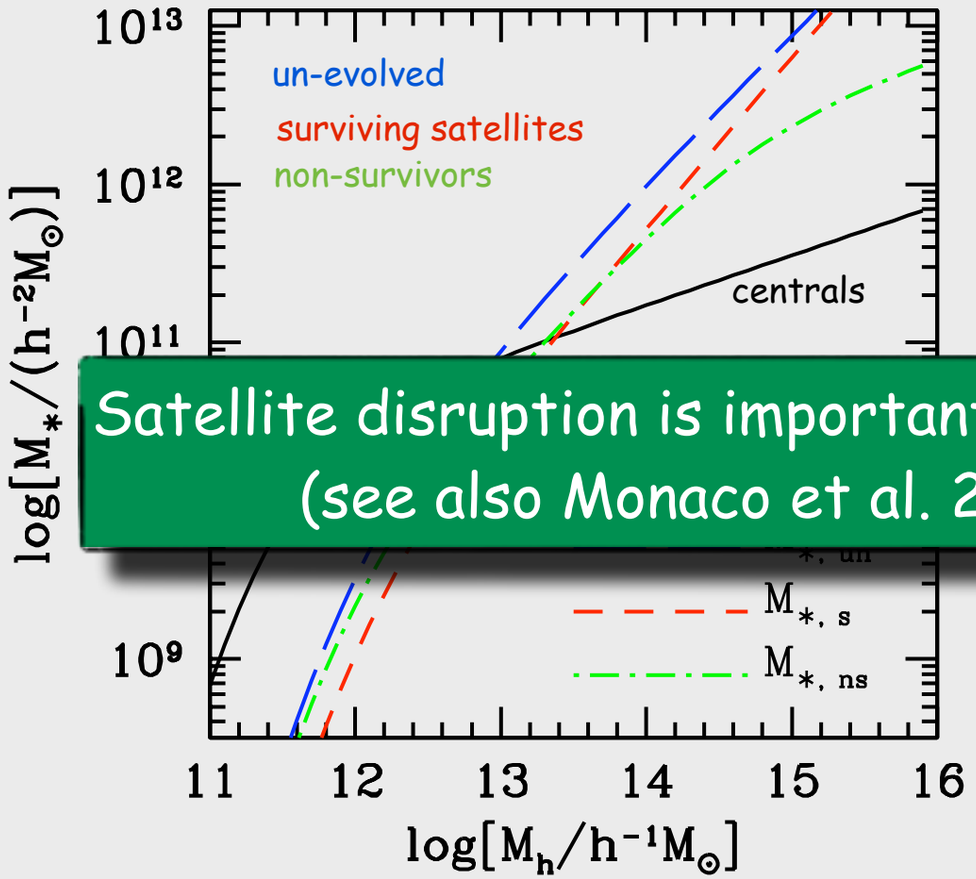

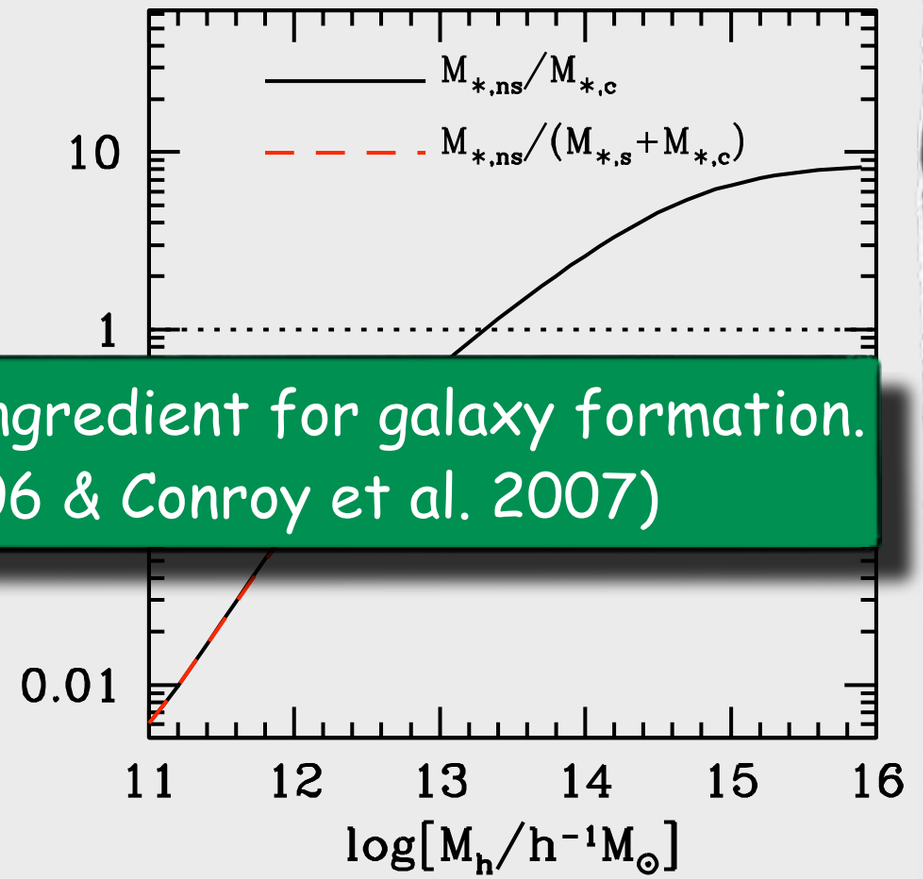

Satellite disruption is important ingredient for galaxy formation.
(see also Monaco et al. 2006 & Conroy et al. 2007)

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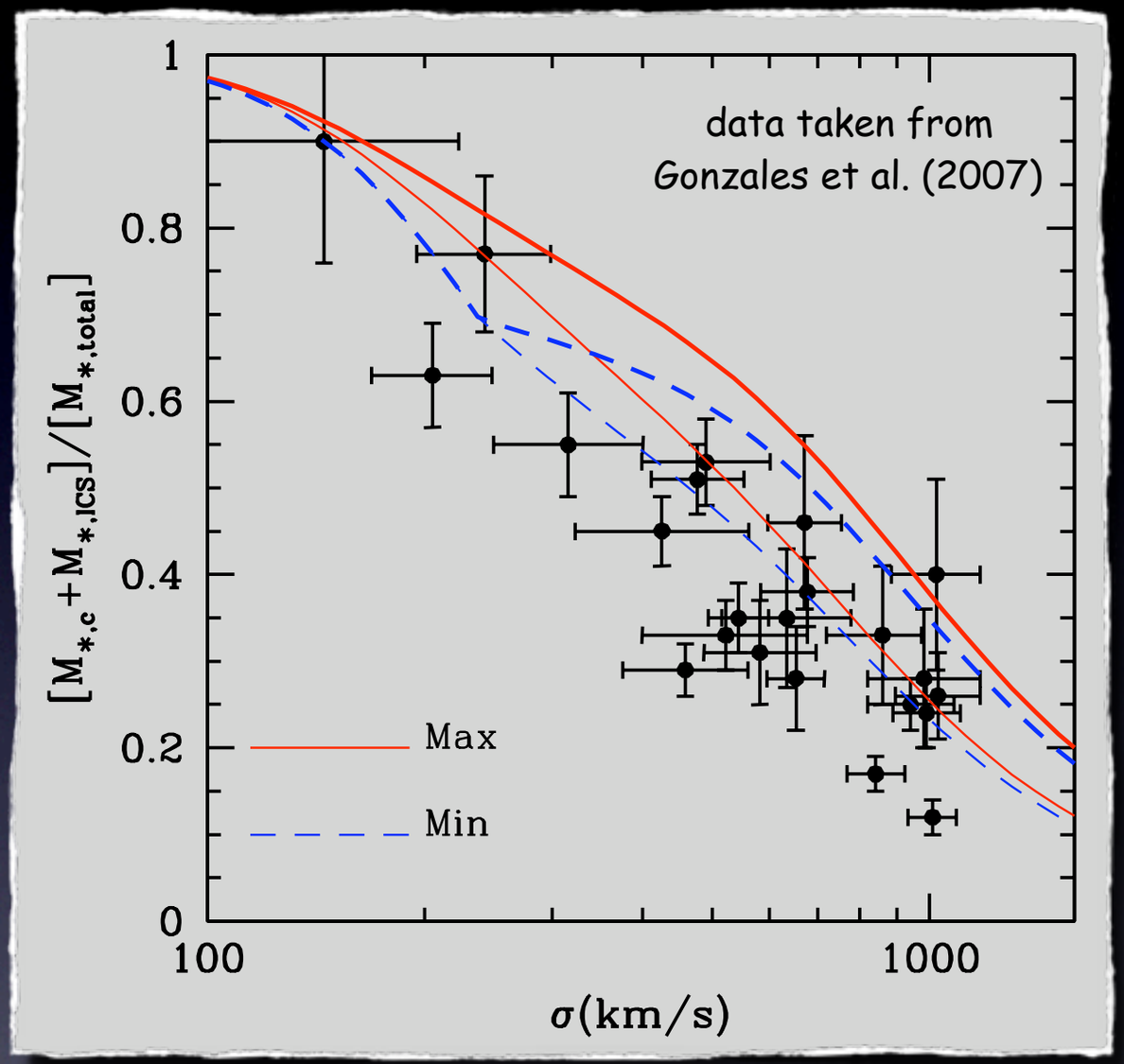
The Amount of Intra-Cluster Light



Predicted amount of ICL consistent with observations

Yang, Mo & vdB (2009)

Conclusions

- 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,
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  There is no environment dependence....

Frank's hot advice:

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Stop fiddling around with environment dependence; try to understand the stellar mass dependence of galaxy properties instead