Galaxy Ecology

an Environmental Impact Assessment

Frank van den Bosch (MPIA)

in collaboration with

Xiaohu Yang (SHAO), Houjun Mo (UMass), Simone Weinmann (Zürich)

Anna Pasquali (MPIA), Daniel Aquino (MPIA)

Outline of this Talk

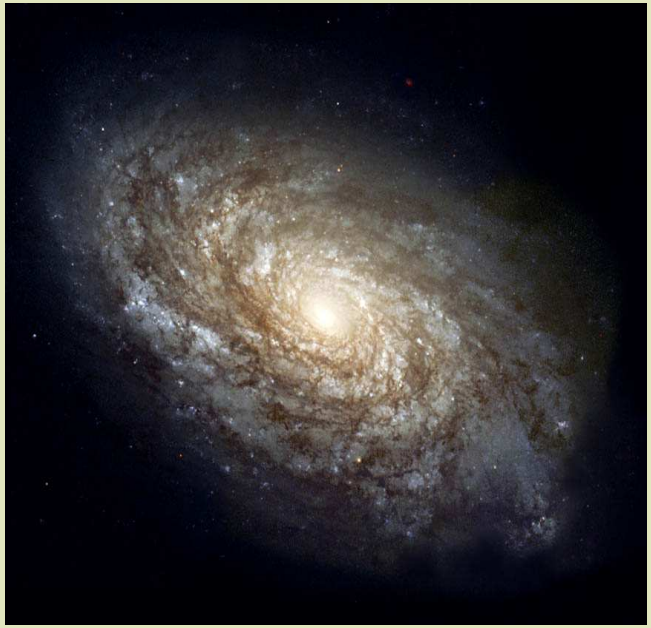
ECOLOGY

1. a branch of science concerned with the interrelationship of organisms and their environments
2. the totality or pattern of relations between organisms and their environment

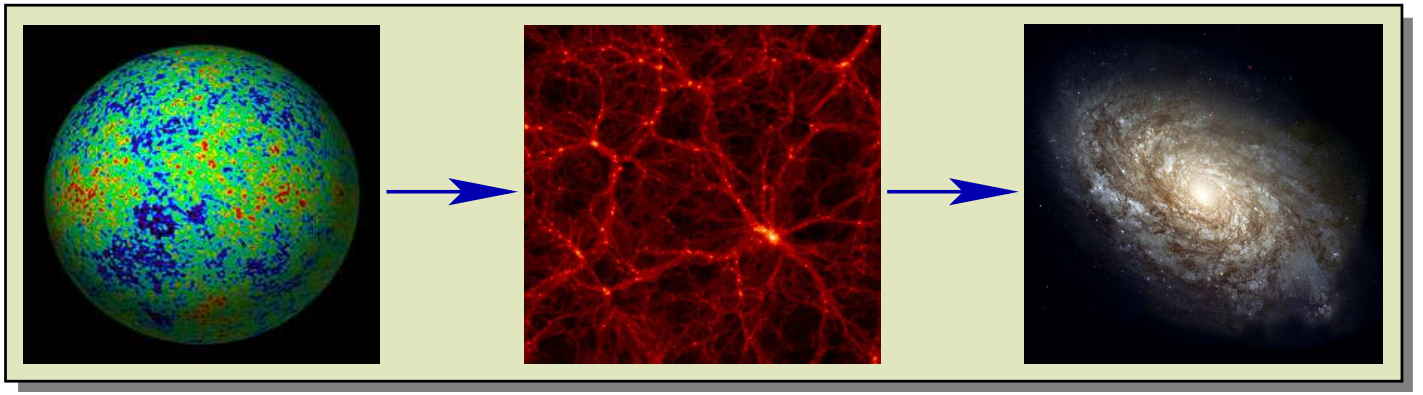
(Merriam-Webster's Dictionary)

- Brief Overview of Galaxy Formation
- Overview of Observational Evidence for Environment Dependence
- Studying Galaxy Ecology with SDSS Group Catalogues
- Galaxy Fractions as function of Halo Mass
- Comparison with Semi-Analytical Models of Galaxy Formation
- Starformation and AGN Activity as function of Halo Mass
- The Dearth of Environment Dependence?
- Conclusions

The Bi-Modal Distribution of Galaxies

Early-Types	Late-Types
	
Spheroidal Morphology	Disk-like Morphology
Old Stellar Populations	Young Stellar Populations
No or Little Cold Gas	Abundant Cold Gas
Red Colors	Blue colors

Galaxy Formation in a Nutshell

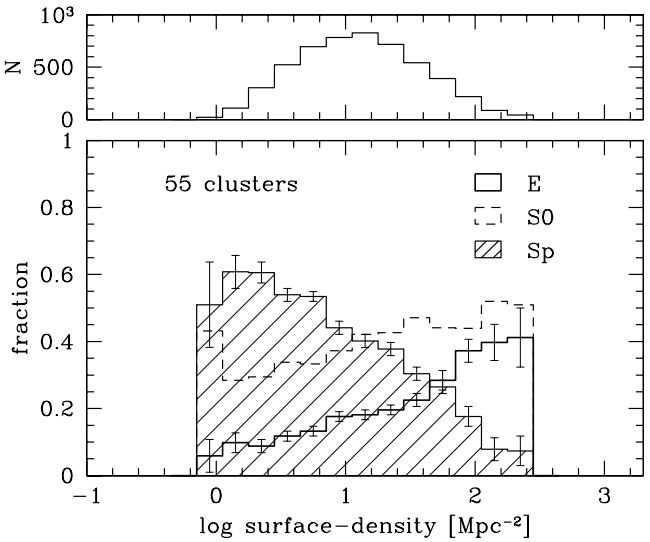


- Quantum fluctuations during inflation create density perturbations
- Perturbations grow due to gravitational instability and collapse to produce (virialized) dark matter halos
- Baryons cool, accumulate at center, and form stars $\Rightarrow$ galaxy
- Mergers between haloes create satellite galaxies that orbit halo
- Dynamical friction causes galaxies to merge $\Rightarrow$ transformation

Satellite galaxies are subject to number of **transformation processes**:

- **Tidal stripping & heating** — due to tidal field of parent halo
- **Strangulation** — stripping of hot gas atmosphere
- **Ram-pressure stripping** — stripping of cold gas
- **Galaxy Harassment** — impulsive encounters with other satellites

The Morphology-Density Relation

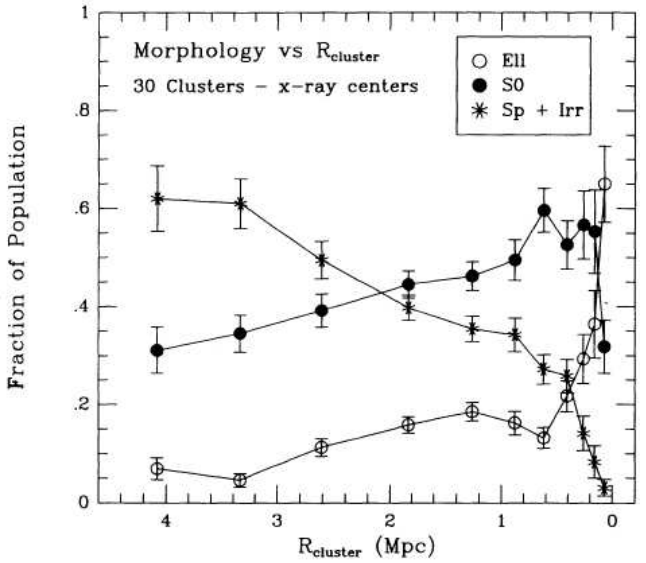


Elliptical galaxies are preferentially found in dense environments (clusters), while spiral galaxies reside predominantly in low density environments (the field).

(Dressler 1980)

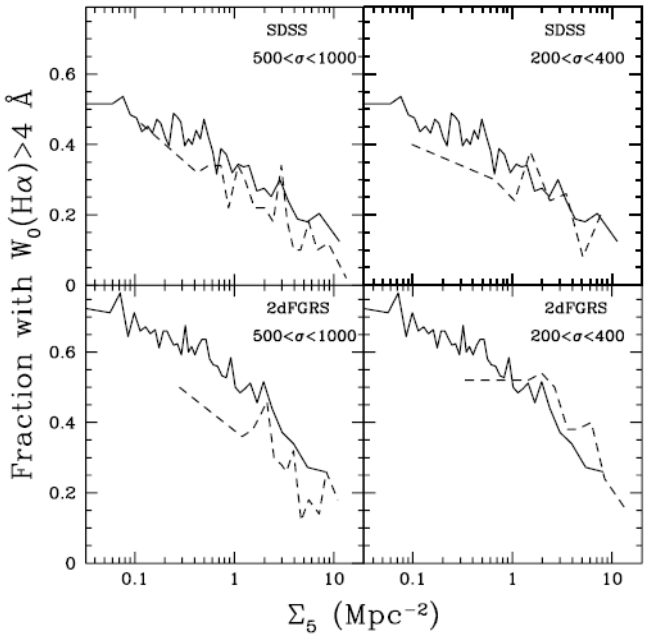
Galaxy Morphologies depend on cluster-centric radius: the spiral fraction is larger at cluster outskirts than at center.

(Whitmore, Gilmore & Jones 1993)



Both trends also clearly present in SDSS (Goto et al. 2003)

Environment Dependence of Star Formation

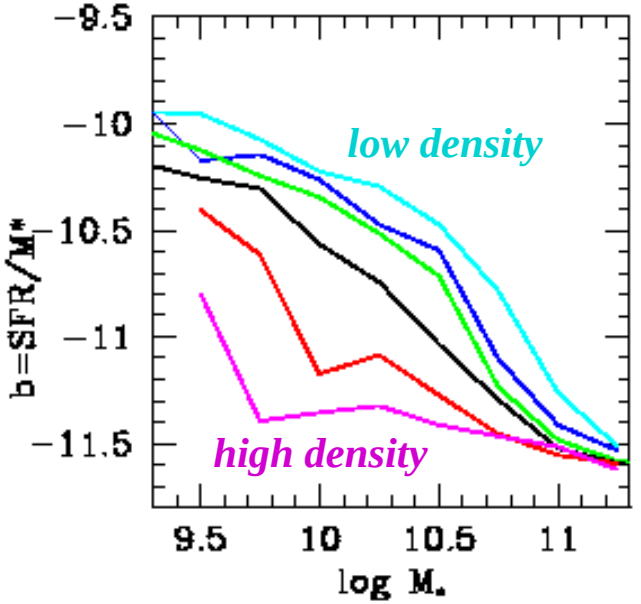


The fraction of star forming galaxies decreases with increasing density of the environment.

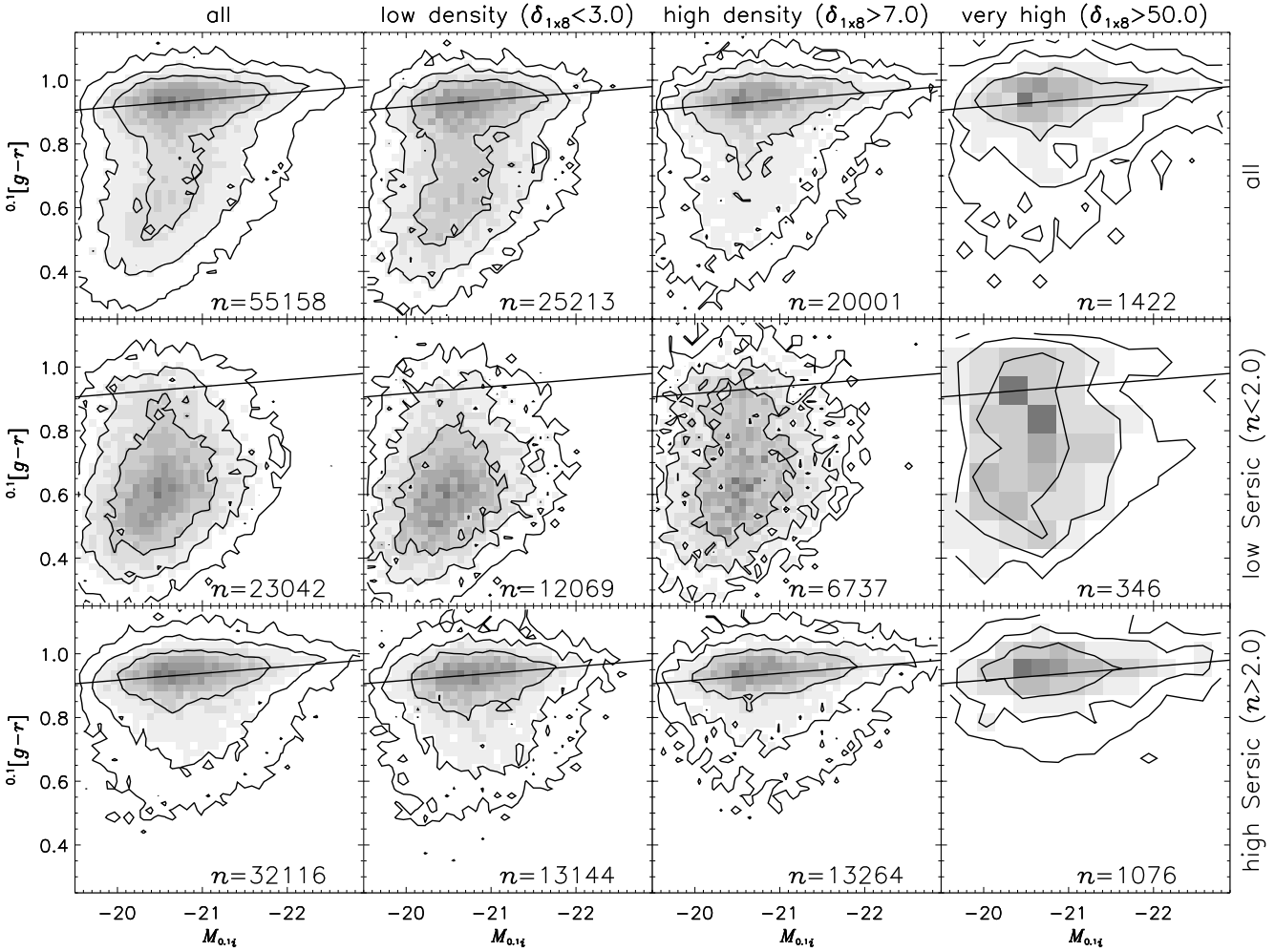
(Balogh et al. 2004)

At fixed stellar mass, galaxies in denser environments have lower (median) specific star formation rates.

(Kauffmann et al. 2004)



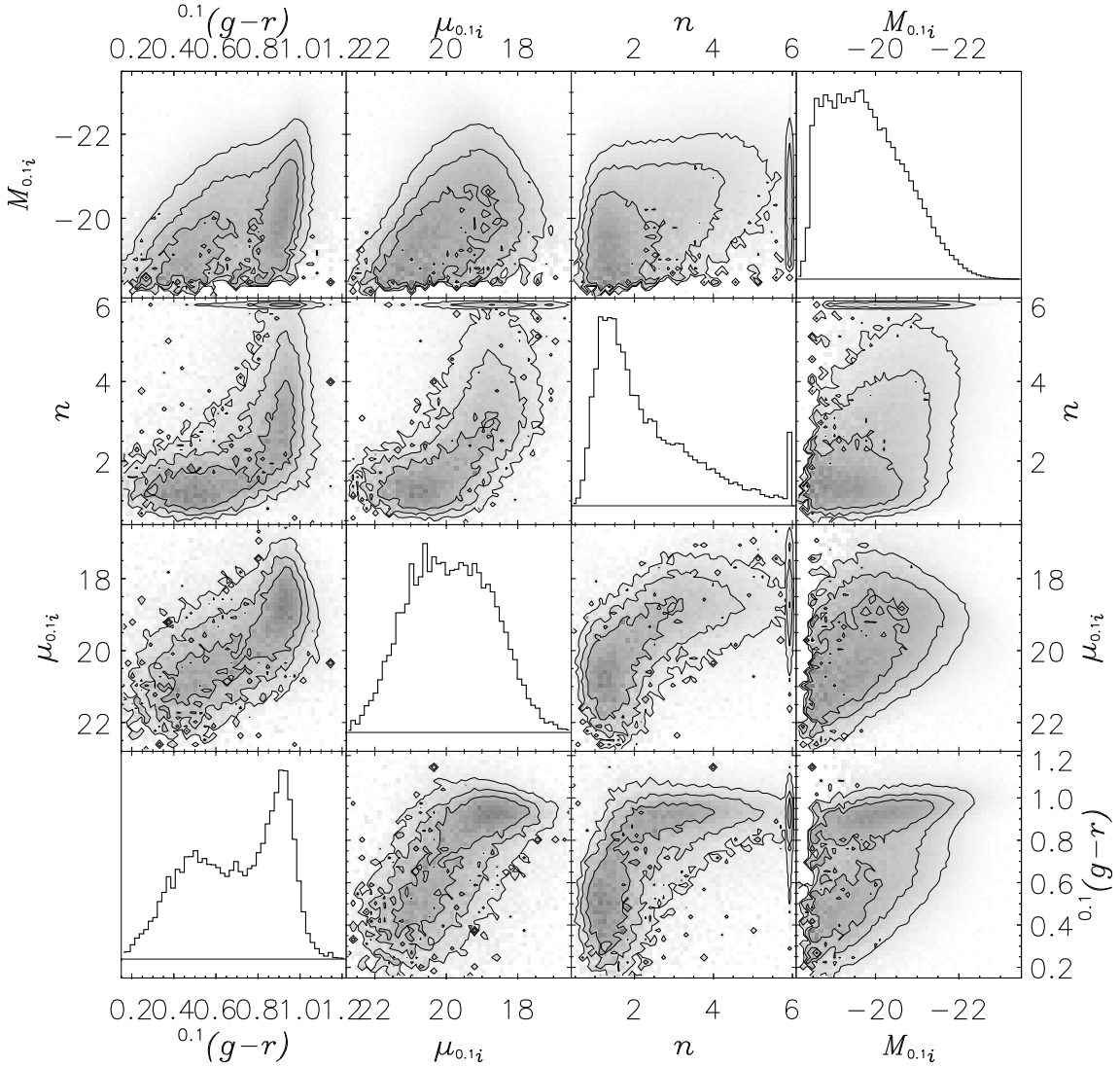
Environment Dependence of Galaxy Colors



The Color-Magnitude relation is strongly environment dependent

(Hogg et al. 2004)

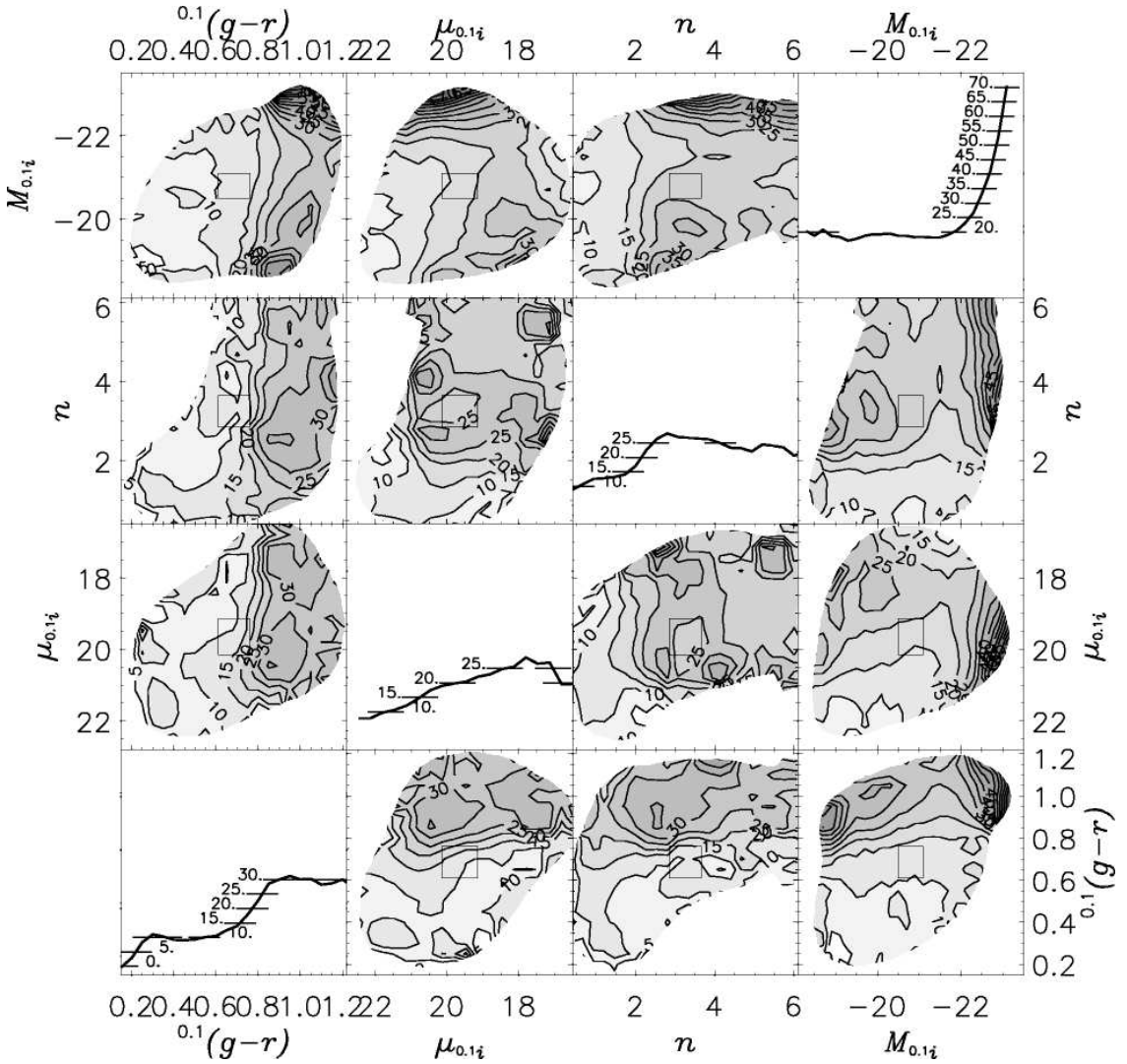
Correlations of Galaxy Properties



Color, Surface density, concentration and luminosity are all interrelated

(Blanton et al. 2005)

Mean Local Overdensities



Galaxies with Different Properties live in Different Environments

(Blanton et al. 2005)

Galaxy Ecology

Galaxies in dense environments are more massive, older, redder, and more concentrated than galaxies in less dense environments

OUTSTANDING QUESTIONS

- **Which galaxy properties are most directly related to which environment indicator; which relations are causal?**
- **What is the characteristic scale of environment dependence?**
- **What is the physical origin: Nature *vs.* Nurture**

These questions can be addressed by confronting data from the SDSS with galaxy formation models and numerical simulations

How to Quantify Environment?

The environment of a galaxy can be specified in different ways:

Σ_R: Projected number density in circular aperture of radius R
Σ_n: Projected number density out to $n^{\rm th}$ nearest neighbour
$R_{\rm proj}$: Projected distance from group/cluster center
$M_{\rm vir}$: Virial mass of dark matter halo (group)
δ_R: Three-dimensional matter overdensity in sphere of radius R

Latter two are preferred from theoretical point of view, but are very difficult to measure

Former two are observationally accessible, but their physical interpretation is environment dependent:

- In clusters Σ_n measures environment on scales $R < R_{\rm vir}$
- In field Σ_n measures environment on scales $R > R_{\rm vir}$

The halo virial radius is the most natural scale to consider

e.g., Mo et al. 2004; Kauffmann et al. 2004; Blanton et al. 2006

Constructing Galaxy Groups Catalogues

Galaxy-Dark Matter connection can be studied more directly by measuring the occupation statistics of galaxy groups.

Potential Problems: interlopers, (in)completeness, mass estimates

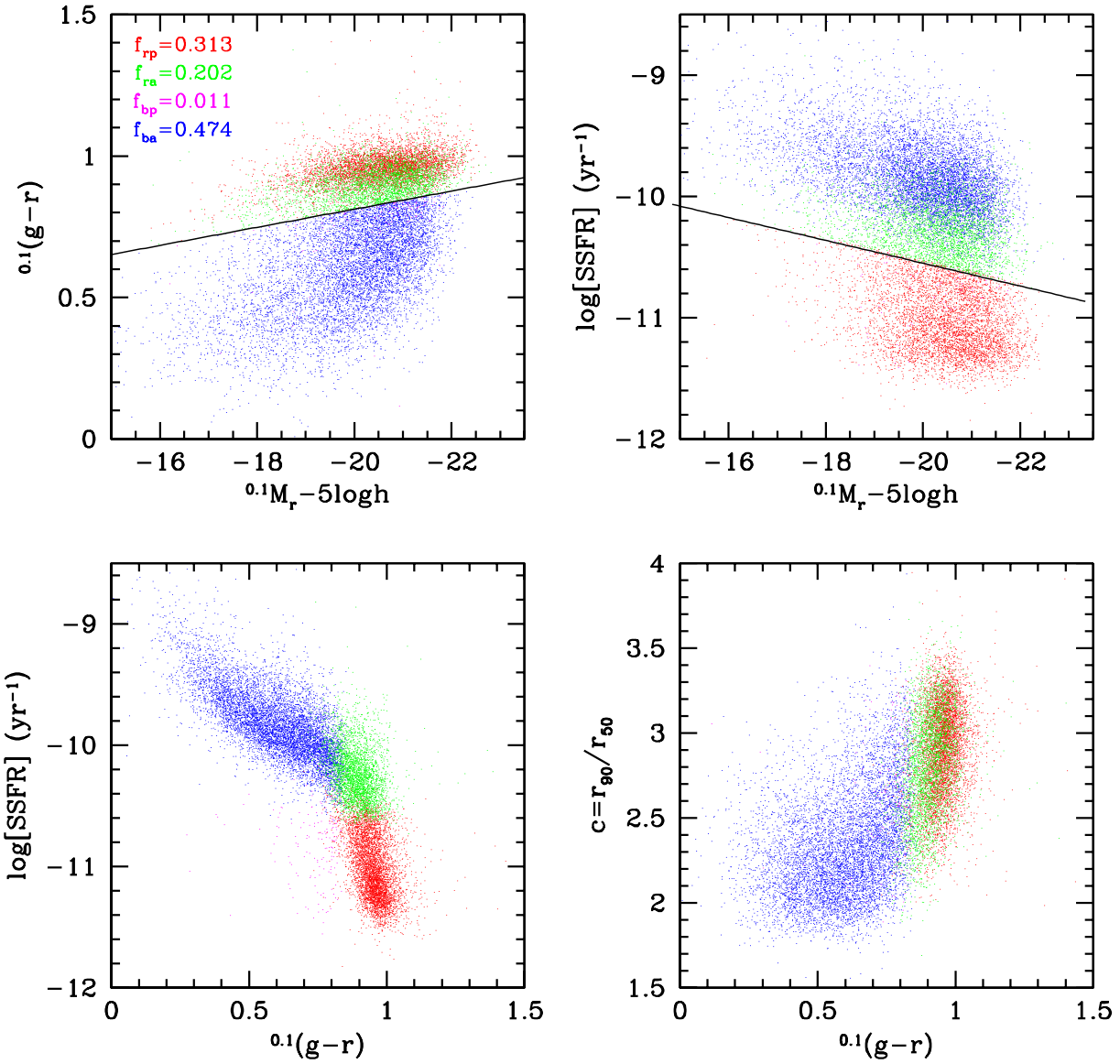
We have developed a new, iterative group finder which uses an adaptive filter modeled after halo virial properties

Yang, Mo, vdB, Jing 2005, MNRAS, 356, 1293

- **Calibrated & Optimized with Mock Galaxy Redshift Surveys**
- **Low interloper fraction ($\lesssim 20\%$).**
- **High completeness of members ($\gtrsim 90\%$).**
- **Masses estimated from group luminosities/stellar masses. More accurate than using velocity dispersion of members.**
- **Can also detect "groups" with single member**
  - ▷ **Large dynamic range ($11.5 \lesssim \log[M/\,\mathrm{M}_\odot] \lesssim 15$).**

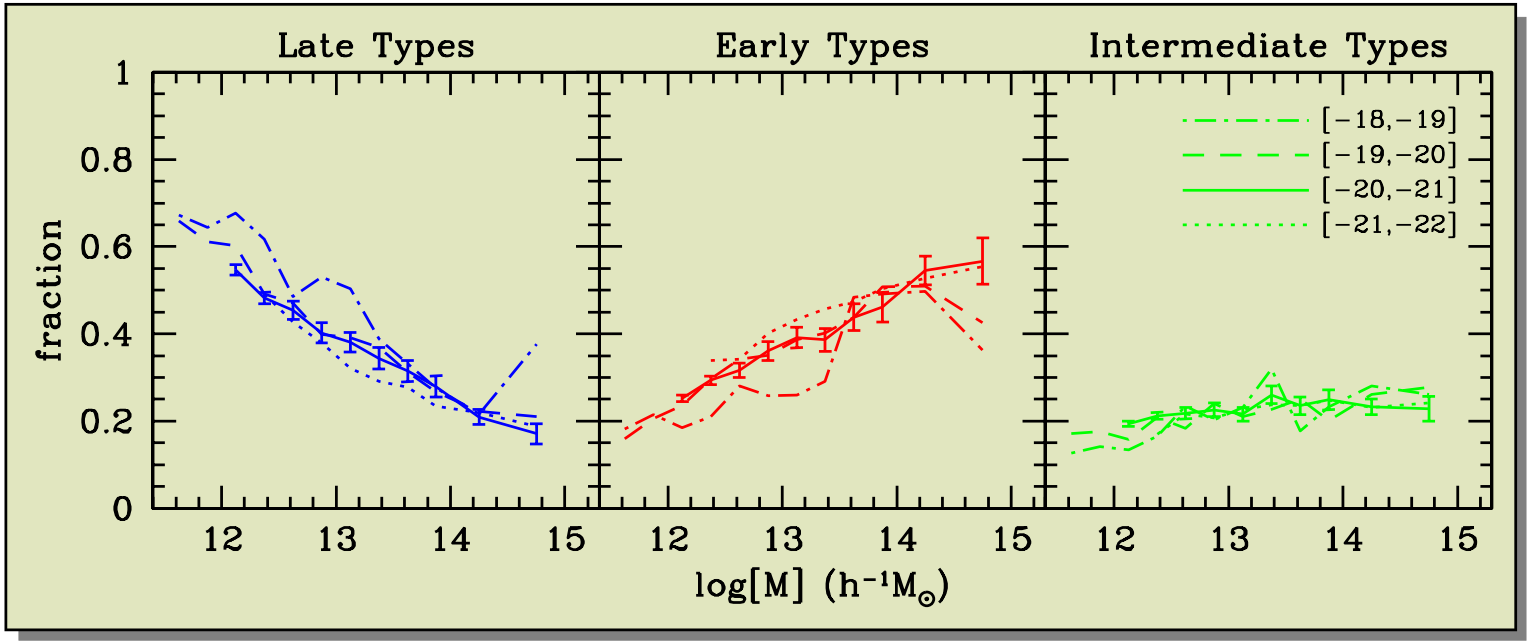
Group finder has been applied to both the 2dFGRS (completed survey) and to the SDSS (NYU-VAGC DR2 + DR4; Blanton et al. 2005)

Defining Galaxy Types



SDSS-DR2 data from NYU-VAGC (Blanton et al. 2005)
SSFRs from Kauffmann et al. (2003) and Brinchmann et al. (2004)

Halo Mass Dependence



The fractions of early and late types depend strongly on halo mass.

At fixed halo mass, there is virtually no luminosity dependence.

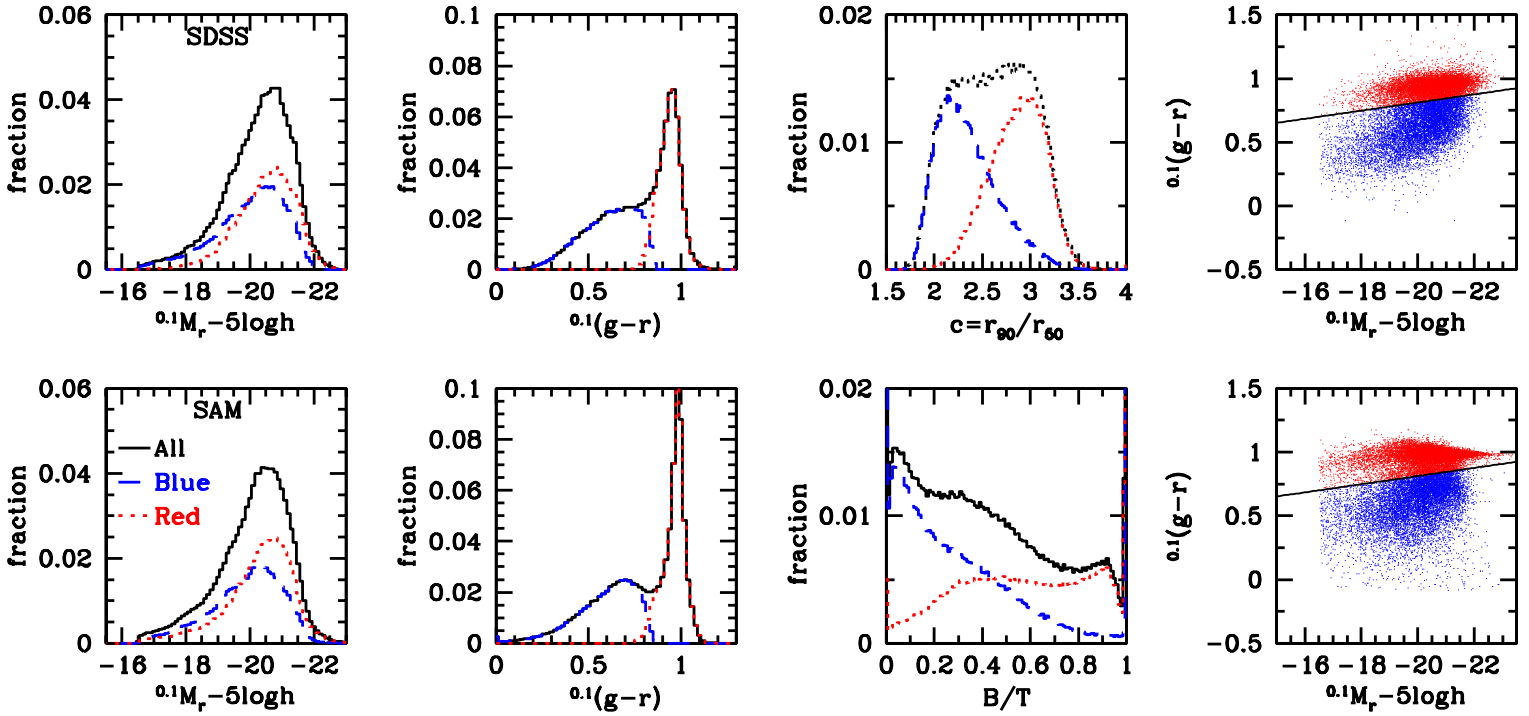
The mass dependence is smooth: there is no characteristic mass scale

The intermediate type fraction is independent of luminosity and mass.

(Weinmann, vdB, Yang & Mo, 2006)

Comparison with Semi-Analytical Model

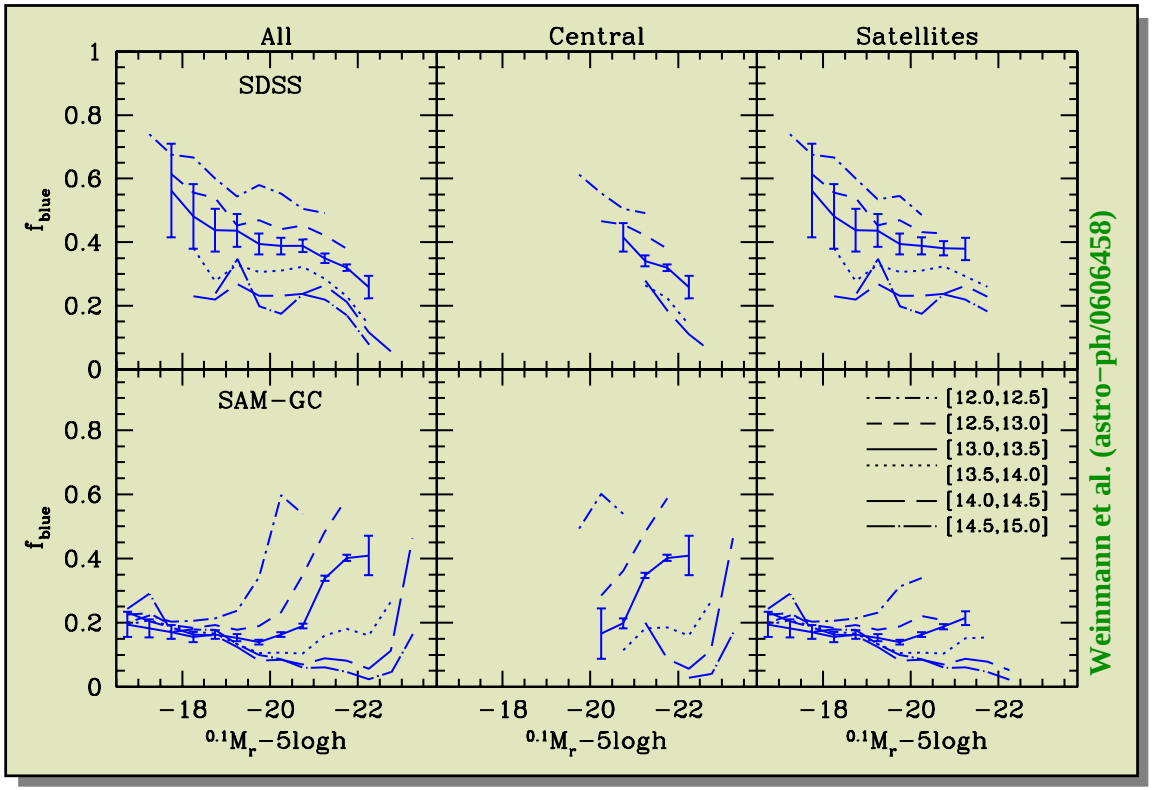
Comparison of Group Occupation Statistics with Semi-Analytical Model of Croton et al. 2006. Includes 'radio-mode' AGN feedback.



- SAM matches global statistics of SDSS
- LF, bimodal color distribution, and overall blue fraction
- But what about statistics as function of halo mass?

Constraining Star Formation Truncation

To allow for fair comparison, we run our Group Finder over SAM.



Satellites: red fraction too large: ▷ strangulation too efficient

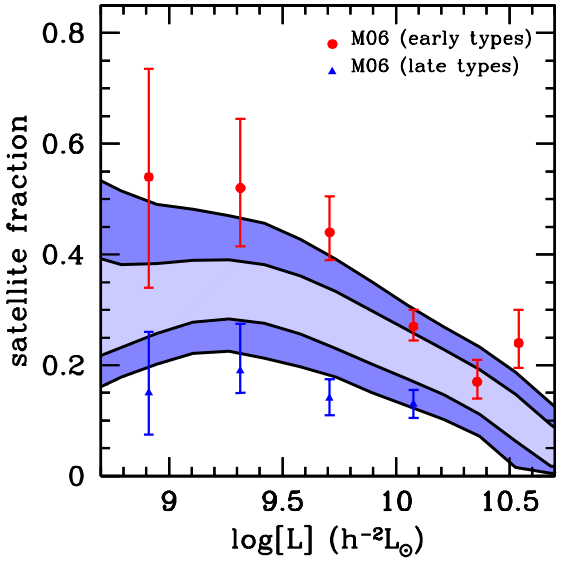
Centrals: $f_{\rm blue}(L|M)$ wrong: ▷ Problem with AGN feedback or dust

$f_{\rm blue}(L, M)$ useful to constrain SF truncation mechanism

Satellite Ecology

Most transformation mechanisms only work on satellite galaxies:

Strangulation, Ram-pressure stripping, harassement, tidal stripping & heating



Satellite galaxies only account for 20 to 40 percent of entire galaxy population.

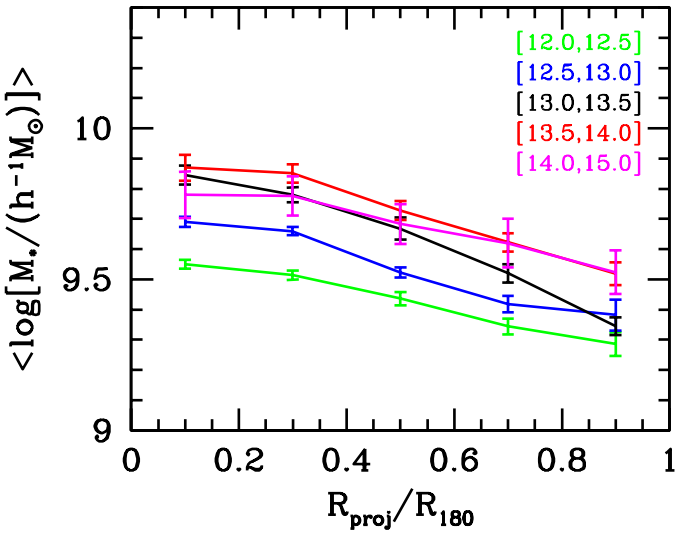
Central galaxies can wash away environment signal

(vdB et al. 2007, MNRAS, 376, 841)

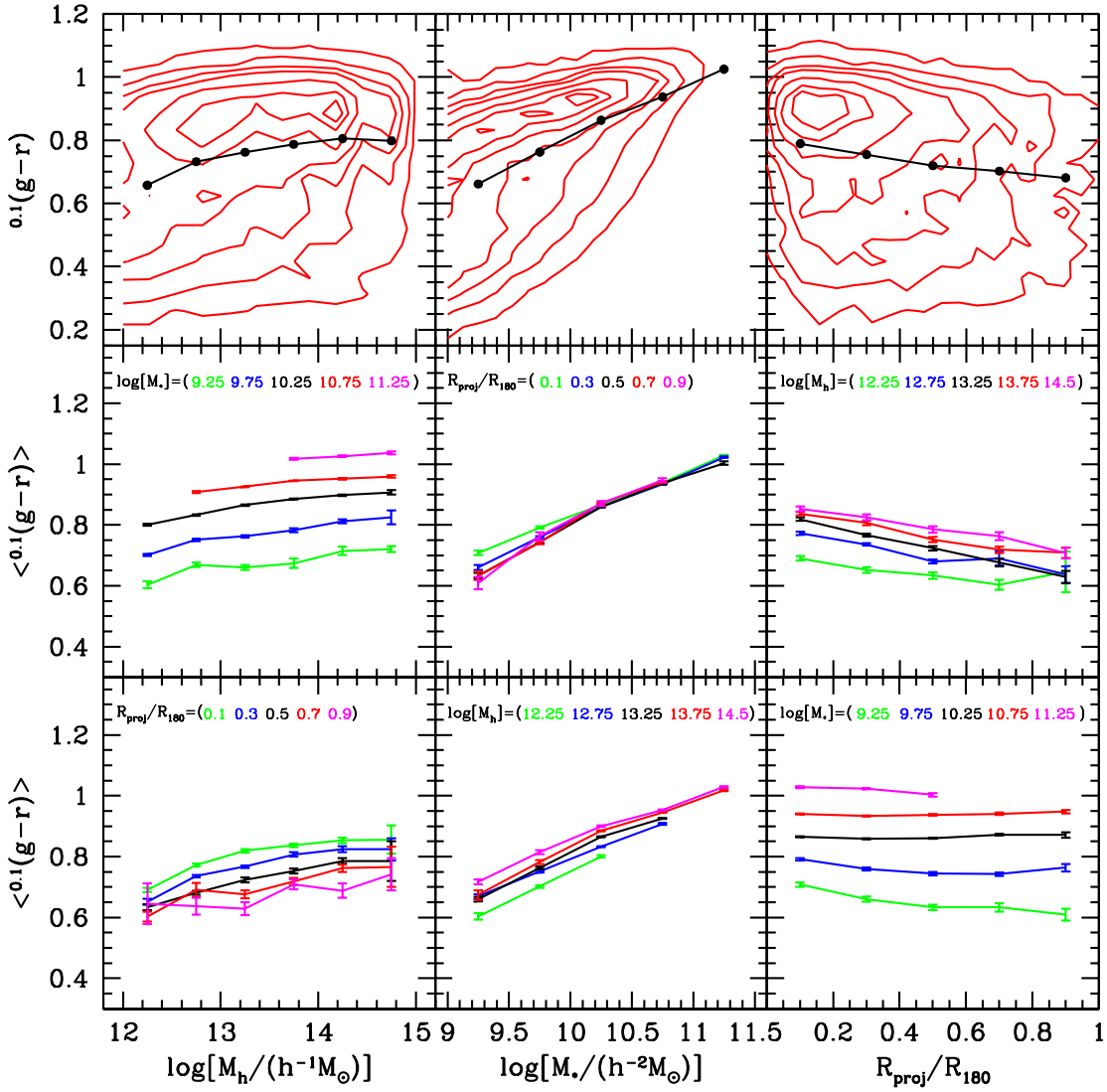
Use group catalogue to only select satellite galaxies

Study color and concentration as function M_h, M_*, and $R_{\rm proj}$

(vdB et al. 2007, in preparation)

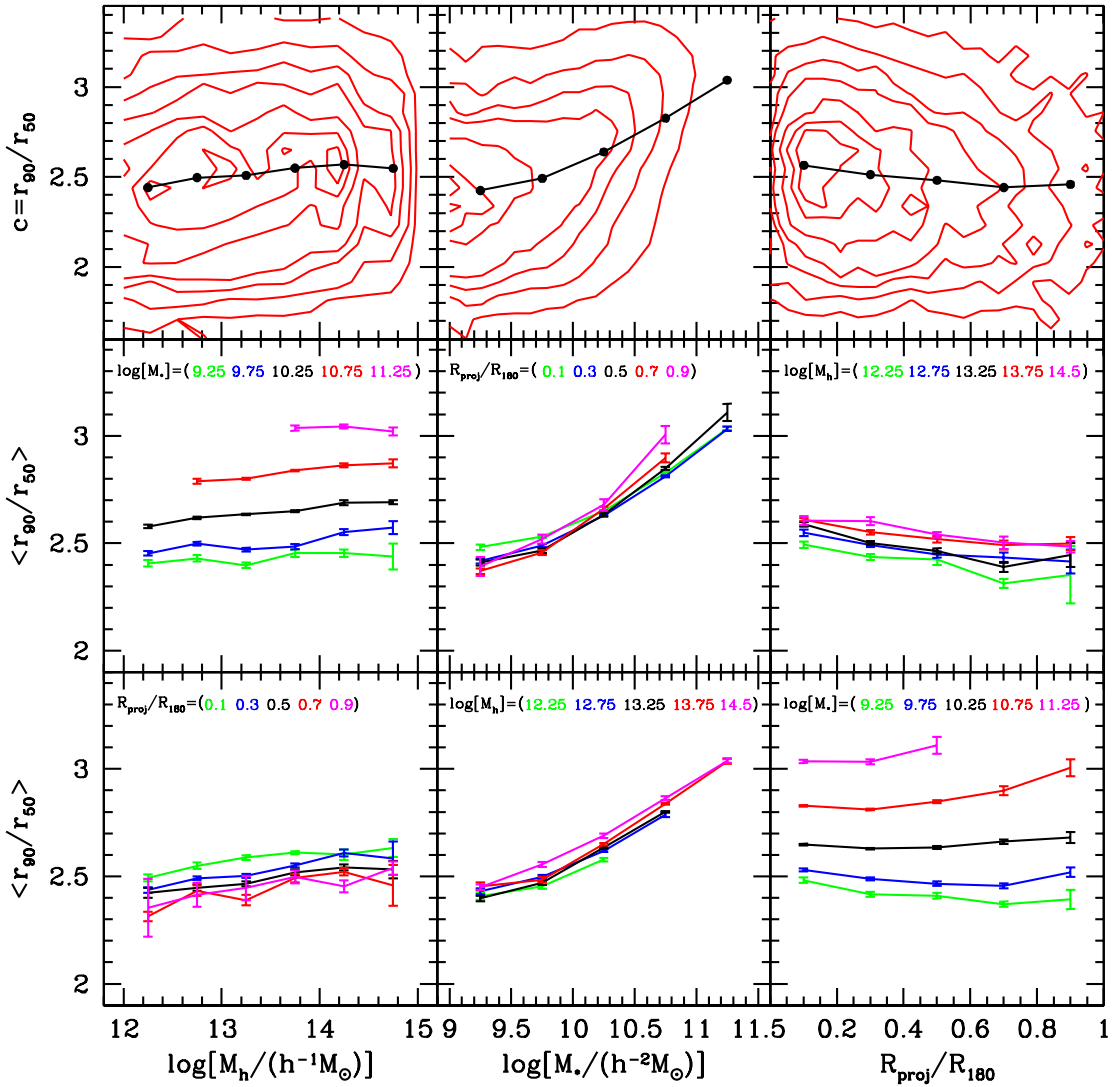


Average Colors of Satellite Galaxies



At fixed M_*, average satellite color independent of environment

Average Satellite Concentrations

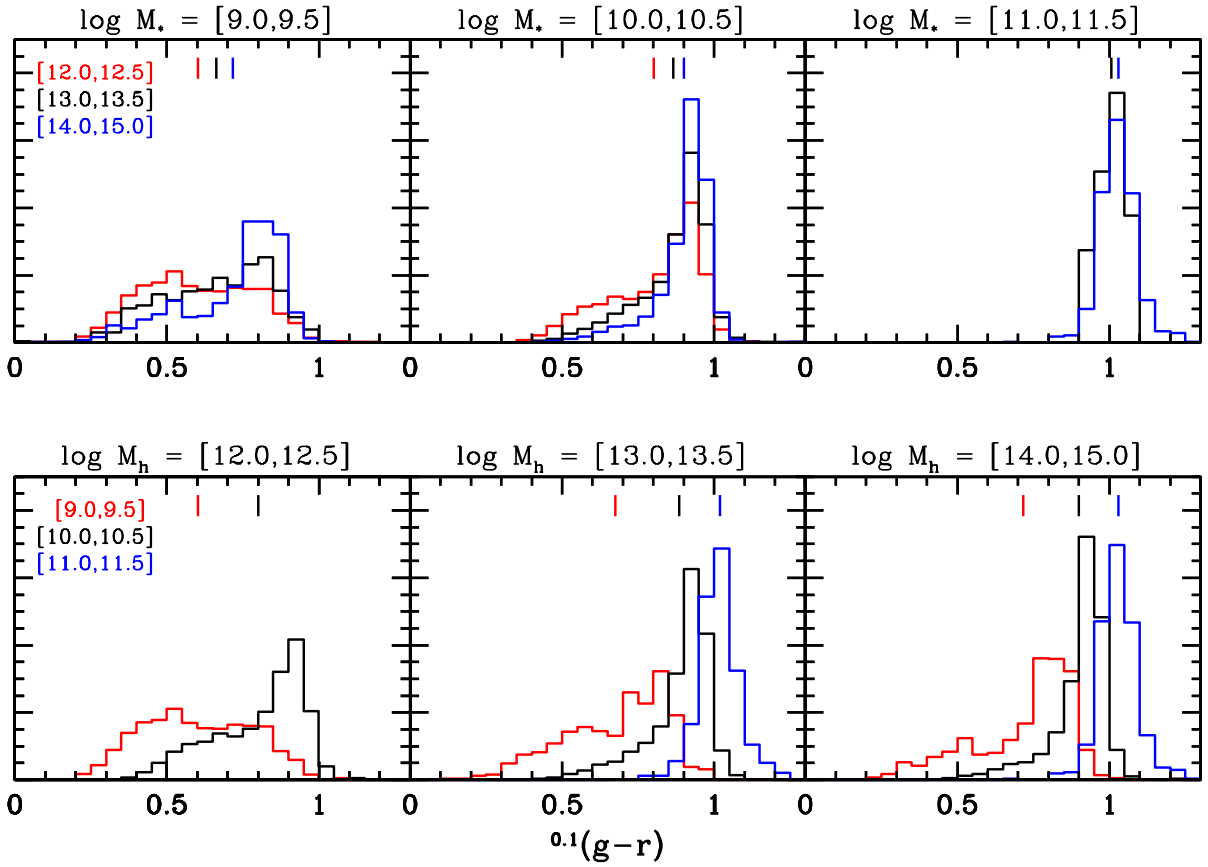


At fixed M_*, average satellite concentration independent of environment

The Dearth of Environment Dependence

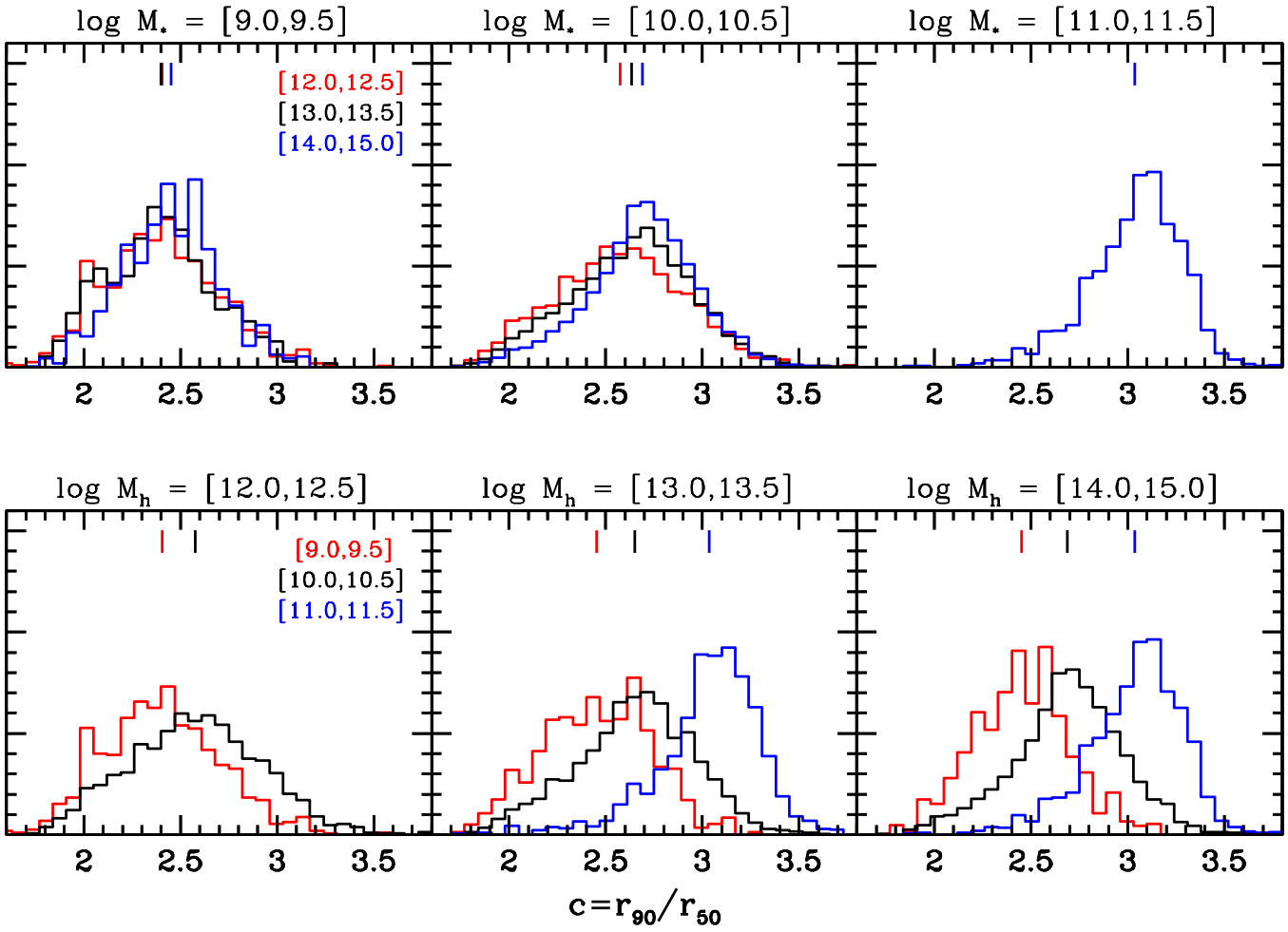
How can these results be reconciled with previous findings?

For example, recall that $f_{\rm red}$ depends strongly on M_h at fixed M_*.



Fractions are mainly sensitive to skewness of distribution

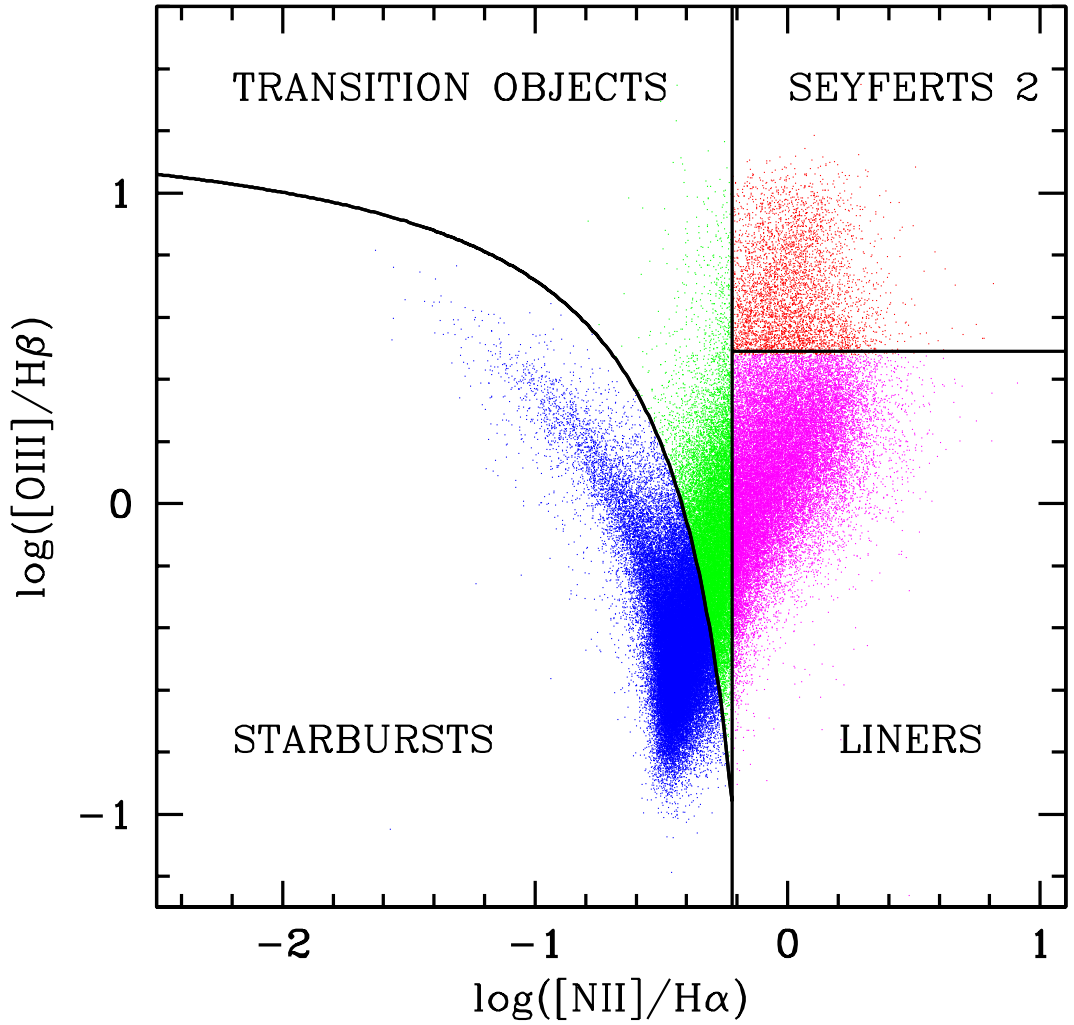
The Dearth of Environment Dependence



Satellite concentrations are independent of environment

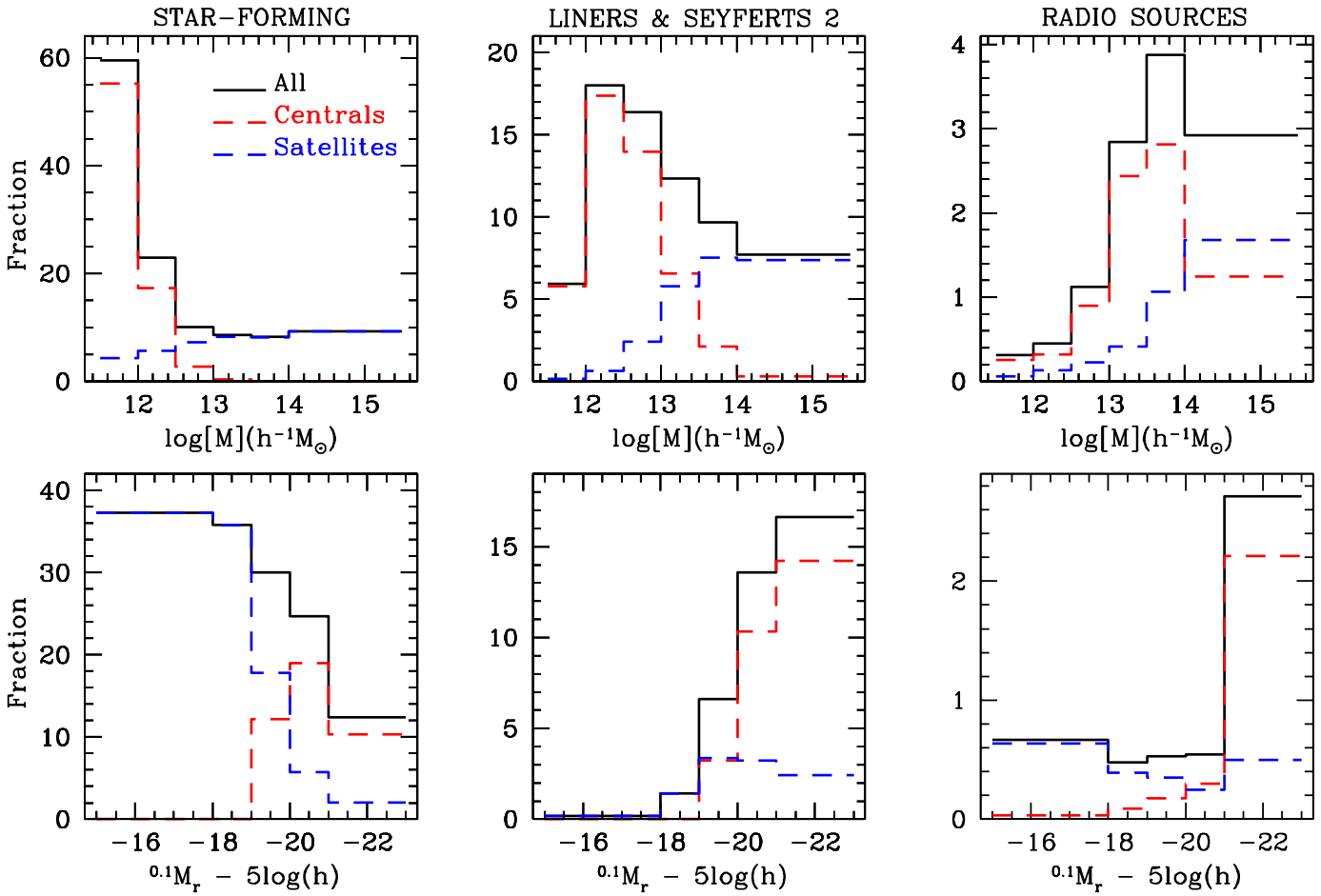
Defining Activity Classes

Galaxies can be classified in Seyferts, Liners and Starbursts using emission line ratios. We also use Radio detections (FIRST+NVVS).



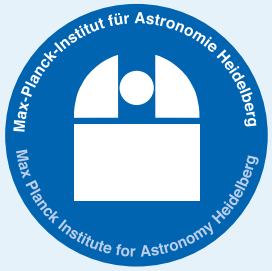
Pasquali, vdB, et al. 2007, in prep.

Ecology of AGN and Starbursts



- Central **SB** activity truncated at $M \sim 10^{12} h^{-1}\,\mathrm{M}_{\odot}$
- Central **AGN** activity peaks at $M \sim 3 \times 10^{12} h^{-1}\,\mathrm{M}_{\odot}$
- **Radio-mode** AGN activity peaks at $M \sim 10^{14} h^{-1}\,\mathrm{M}_{\odot}$

Pasquali, vdB, et al. 2007, in prep.



Conclusions

- The ecology of **galaxies** yields useful constraints on physics of galaxy formation.
- From **theoretical** point of view, most natural environment indicators are $M_{\rm halo}$ and $R_{\rm proj}$
- These are accessible with modern galaxy **group catalogues**
- Galaxies in denser environments (more massive halos) are more massive, redder, and more concentrated
- This mainly owes to fact that more massive haloes contain more massive galaxies and to **mass segregation**
- Colors and concentrations of satellite galaxies reveal no significant **environment dependence**
- The ecology of **AGN** agrees with a “cold-mode” to “hot-mode” transition at $M \simeq 10^{12} - 10^{13} h^{-1}\,{\rm M}_\odot$