# Dark Matter Substructure and their associated Galaxies

**Frank C. van den Bosch (MPIA)**

# Outline

**PART I:** The Subhalo Mass Function

**(van den Bosch, Tormen & Giocoli, 2005)**

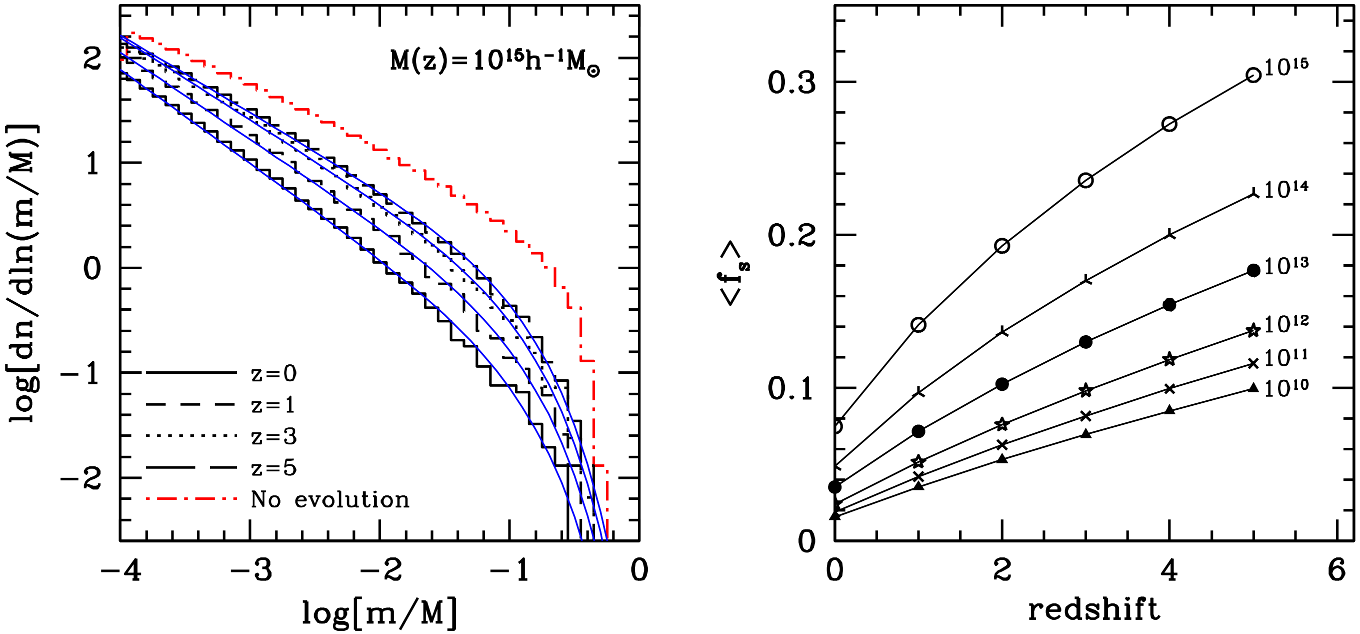
**PART II:** Statistical Properties of Satellite Galaxies
Evidence for Galactic Conformity

**(Weinmann, van den Bosch, Yang & Mo, 2005)**

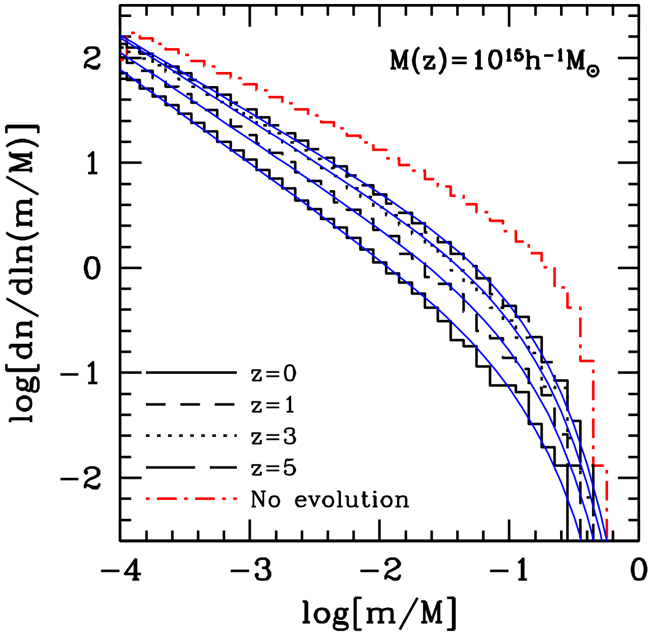
# Substructure: Why Bother?

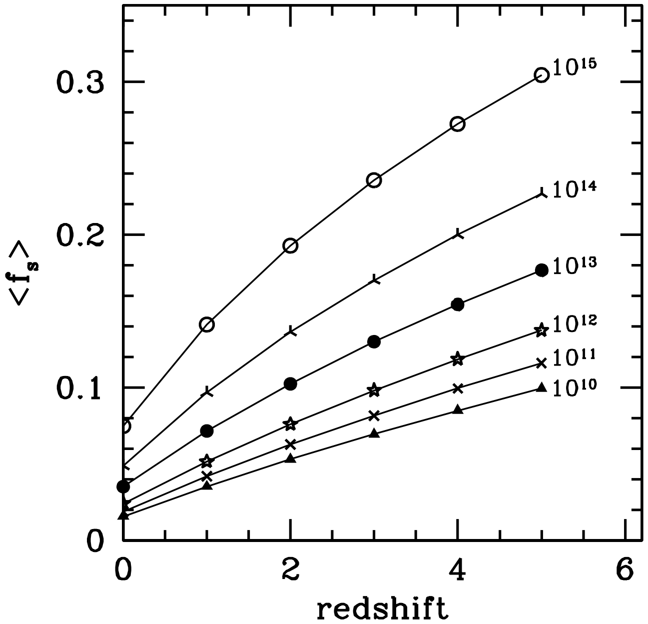
- **Satellite Galaxies:** Dark matter subhaloes are thought to be associated with satellite galaxies
- **Cosmology:** Abundance of subhaloes is cosmology dependent, and may provide constraints on the power-spectrum on small scales
- **Dark matter annihilation:** Because of high phase-space densities, subhaloes are expected to be sites of pronounced gamma-ray emission from neutralino annihilations
- **Gravitational Lensing:** Substructure may explain flux-ratio anomalies
- **Dynamics:** Subhaloes are associated with interesting dynamical processes, such as dynamical friction, tidal stripping, and tidal heating
- **Disk Formation:** The presence of dark matter substructure may have important implications for formation and structure of disk galaxies (disk heating and onset of bar instabilities through impulsive encounters)

# Part One: The Subhalo Mass Function

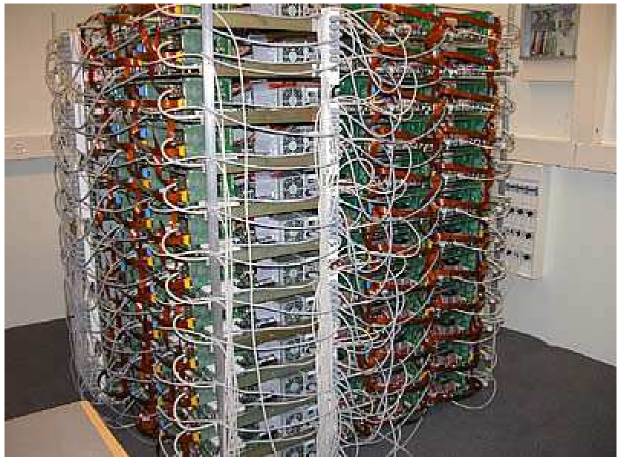


# Part One: The Subhalo Mass Function




or

**How**  **&**  **beat(s)** 

# Simulations: Handy Tool or HandiCap?

Because of complex, non-linear processes involved, the statistics and properties of subhaloes are typically investigated using $N$-body Simulations.

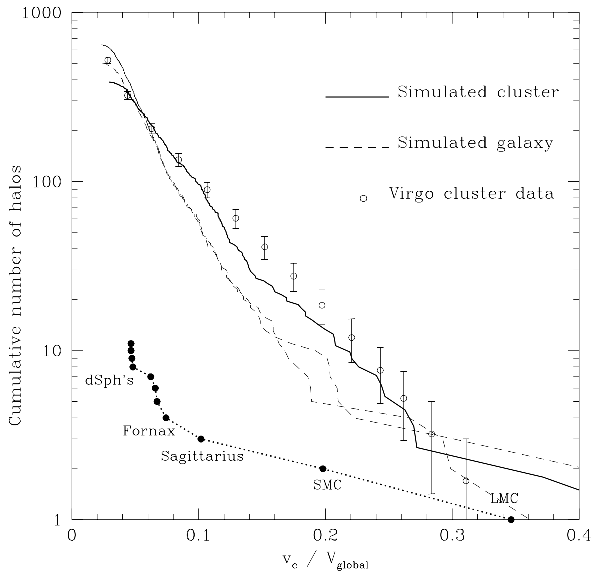
**Problems with Simulations**

- **Resolution:** It took until 1997-1998 before substructure appeared. Ghigna et al. (1998), Klypin et al. (1999), Moore et al. (1999)
- **Identification:** A plethora of subhalo finders is available, but they often yield conflicting results. See Kravtsov's talk
- **Expensive:** Many CPU cycles and students are required to produce (statistically relevant) results

**Advantages of Simulations**

- **All the relevant Physics is (in principle) included:** Merger histories (progenitor masses & accretion times), orbital properties, dynamical friction, tidal stripping and heating, non-sphericity of haloes, subhalo-subhalo mergers
- **Pretty Pictures:** The "Whoaaahh-that-looks-so-cooool-effect"

# Many CPU cycles later...Self-Similarity

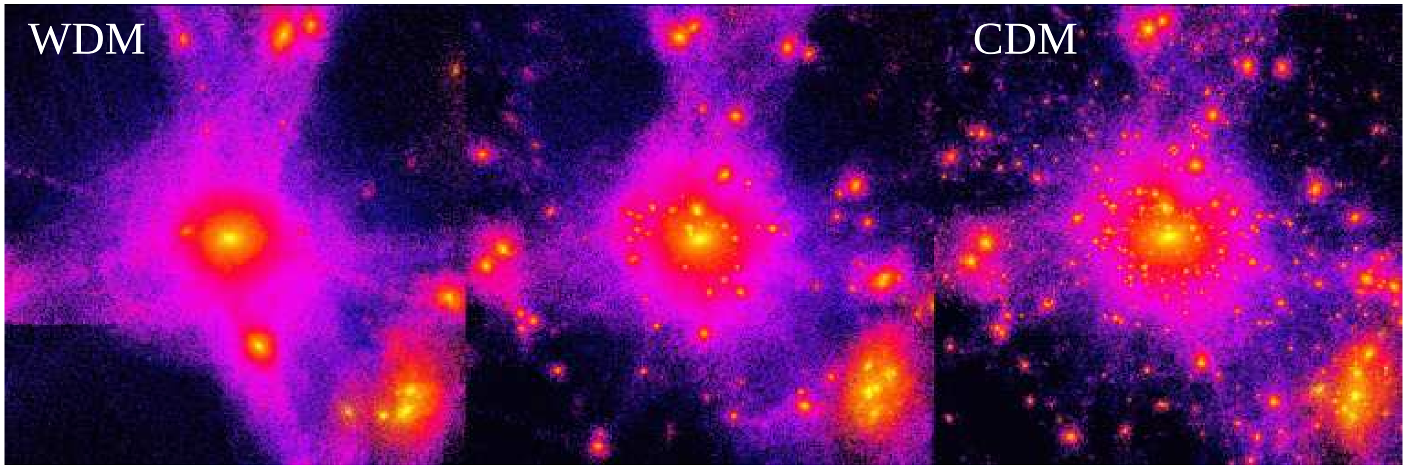



**In terms of substructure, haloes of widely different masses look self-similar:**

**subhalo mass function is universal**

$\Rightarrow$ **Only cosmology dependence**
**no mass dependence**

$\Rightarrow$ **Missing Satellite Problem**




**Problems:**
- **Ghao et al. (2004) finds weak trend for mass dependence**
- **Disagreement on subhalo mass function; $6\% \lesssim f_s \lesssim 100\%$**
- **Poor statistics because of heavy CPU requirements**

# Uncle SAM to the rescue

Several studies used semi-analytical methods as alternative

Zentner & Bullock 2003; Oguri & Lee 2004; Taylor & Babul 2004

**Ingredients**

- Merger trees (PS formalism)
- Orbit Integration (Spherical Haloes)
- Dynamical Friction (Chandrasekhar 1943)
- Tidal Stripping & Heating

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- Many of these ingredients are poorly understood (difficult to model)
- Simulations provide little help because of resolution dependence
- Integration of individual orbits $\longrightarrow$ code is complicated & relatively slow
- Orbits do not adjust adiabatically to (violent) major mergers...
- Predictions for Subhalo Mass Function:

  Taylor & Babul do not discuss subhalo mass function

  Zentner & Bullock discuss cosmology- but not mass-dependence

  Oguri & Lee subhalo mass functions are self-similar

# Solution: Less Physics

Parent haloes have self-similar NFW potentials: $c(M)$ is weak compared to scatter in $P(c|M)$

$\Rightarrow$ Orbital eccentricity distributions $P(\varepsilon)$ independent of parent halo mass

$\Rightarrow$ Consider the average orbit only; focus on average mass loss rate, averaged over all individual orbits, weighted by $P(\varepsilon)$

This average mass loss rate is only a function of the mass ratio $\psi = m/M$

$$\frac{1}{m}\frac{\mathrm{d}m}{\mathrm{d}t} = -\frac{1}{\tau}\psi^{\zeta}$$

The characteristic time $\tau$ is proportional to dynamical time $t_{\rm dyn} \propto 1/\sqrt{\rho}$

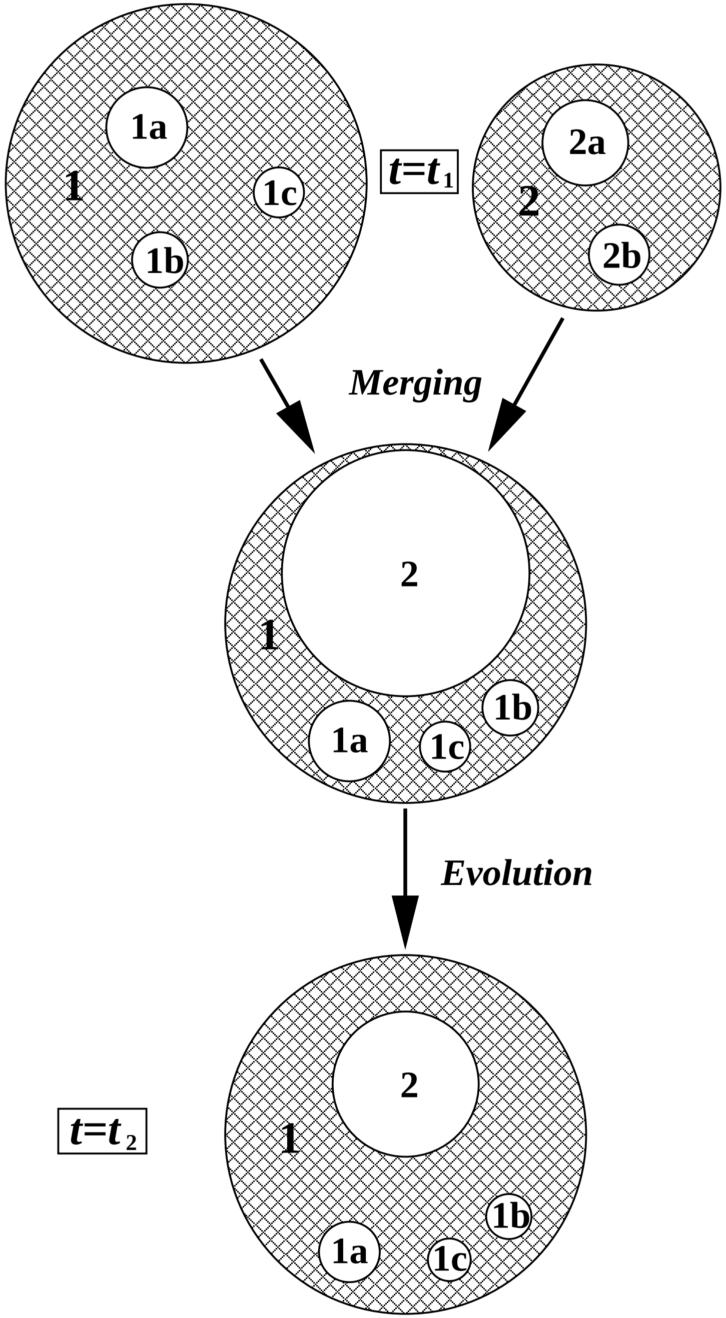
$$\tau = \tau(z) = \tau_0 \left(\frac{\Delta_{\rm vir}(z)}{\Delta_{\rm vir}(0)}\right)^{-1/2} \left(\frac{H(z)}{H_0}\right)^{-1}$$

The two free parameters, $\tau_0$ and $\zeta$ capture the physics of dynamical friction, tidal stripping, and tidal heating

Calibrate $\tau_0$ and $\zeta$ at a fixed parent mass using numerical simulations

The only property that is dependent on parent mass is mass assembly history, which can be modelled with EPS formalism

# Diagrammatica




⇐ **Merger trees from EPS formalism**

⇐ $\dot{m} = -\frac{m}{\tau}\psi^{\zeta}$

⇒ **Subhalo Mass Function at $t = t_2$**

# The Pros and Cons of Simplicity

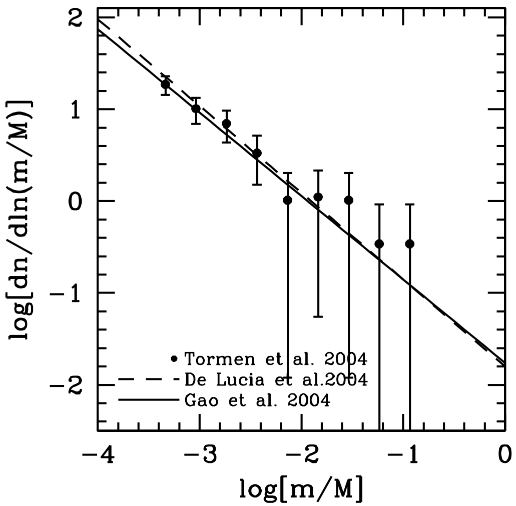
## Advantage

- **Extremely fast** **Subhalo mass function of individual halo is a matter of seconds on modern wristwatch**
- **Parameter Space** **Allows detailed study of mass dependence, cosmology dependence, redshift dependence, and scatter**

## Disadvantage

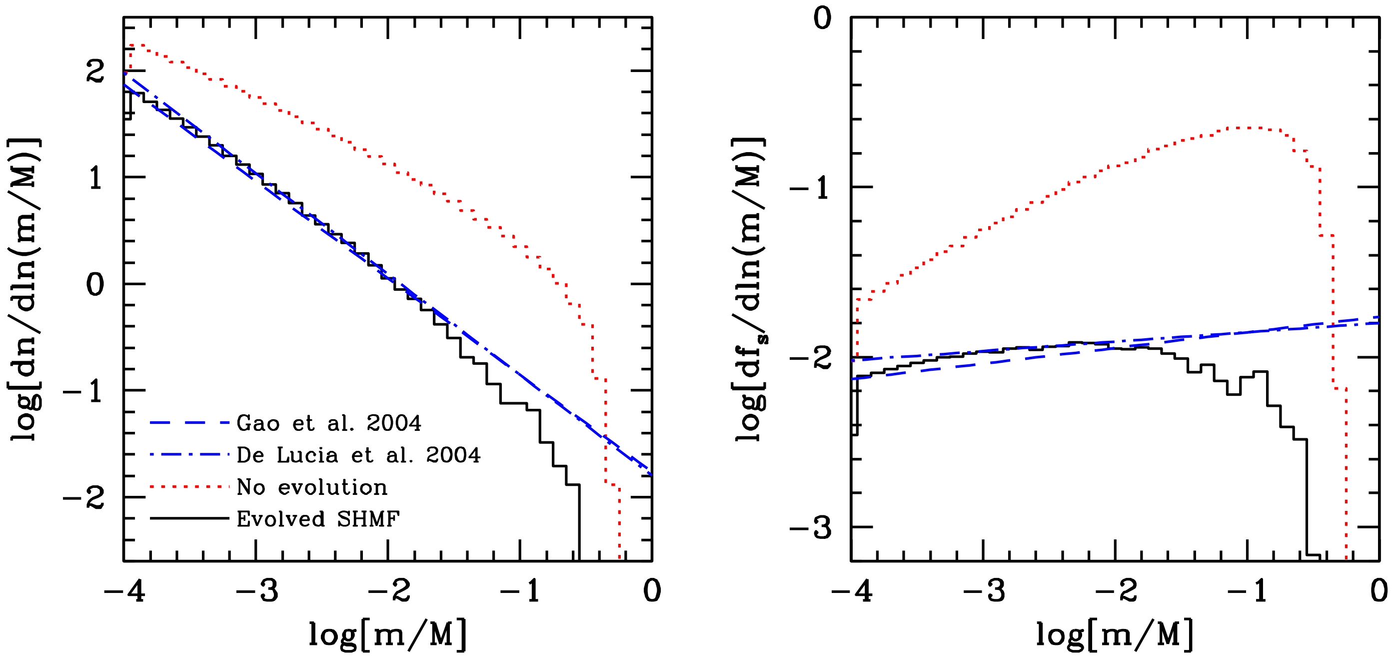
- **No Phase-Space Info** **Because no individual orbits are followed, no predictions can be made regarding the spatial or kinematic distribution of subhaloes**

# A Matter of Tuning



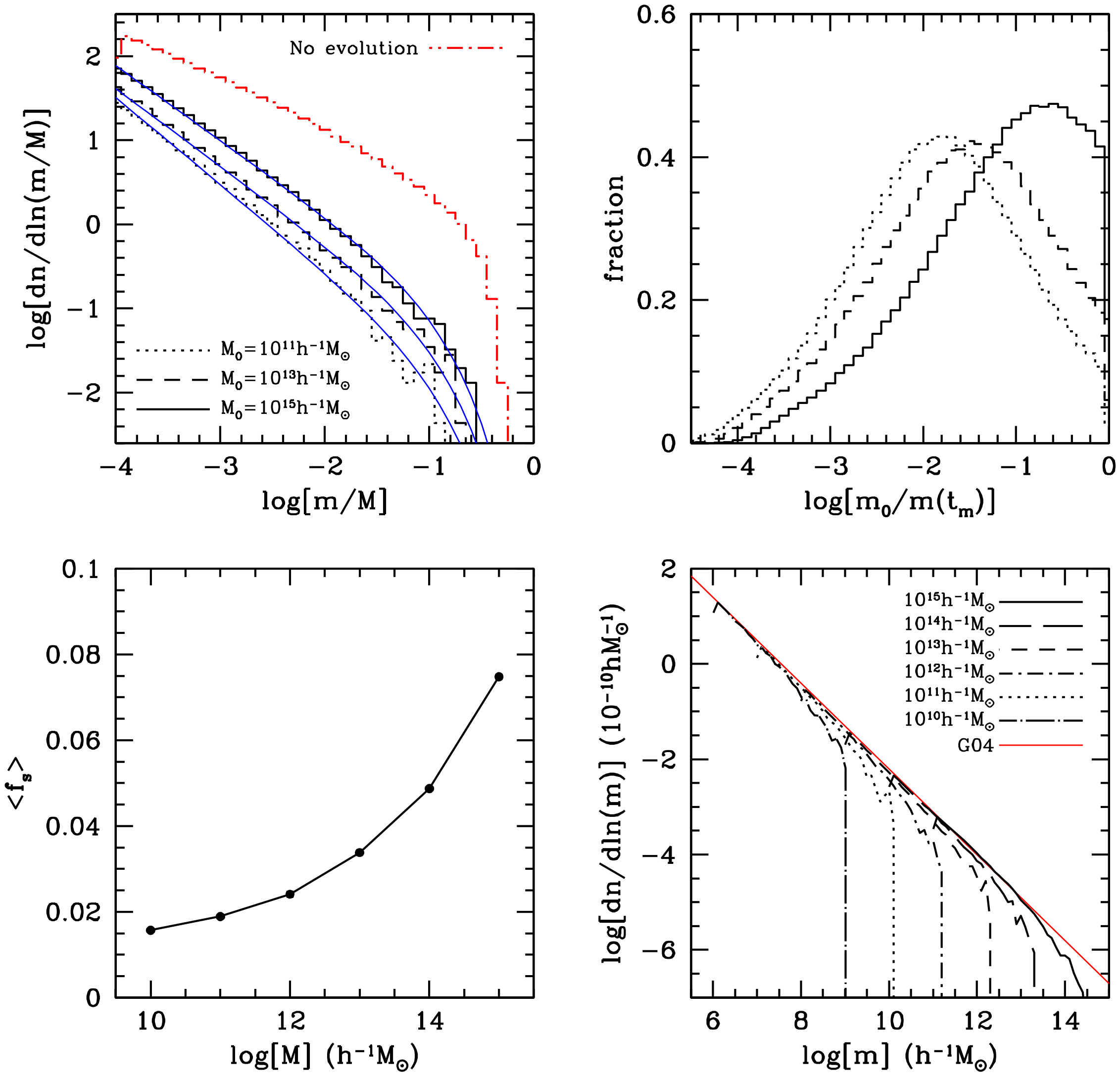

**Data used for calibration:** the subhalo mass function of massive clusters $(M_0 \simeq 10^{15} h^{-1}\,\mathrm{M}_\odot)$ from three independent $N$-body sources

We tune $\tau_0$ and $\zeta$ by reproducing these results.
$\Rightarrow$ $\tau_0 = 0.13$ Gyr and $\zeta = 0.36$




$dn/d\psi \propto \psi^{-1.9}$ $\Rightarrow$ mass budget dominated by most massive subhaloes, but only marginally so. Also, note the high mass cut-off (as expected)

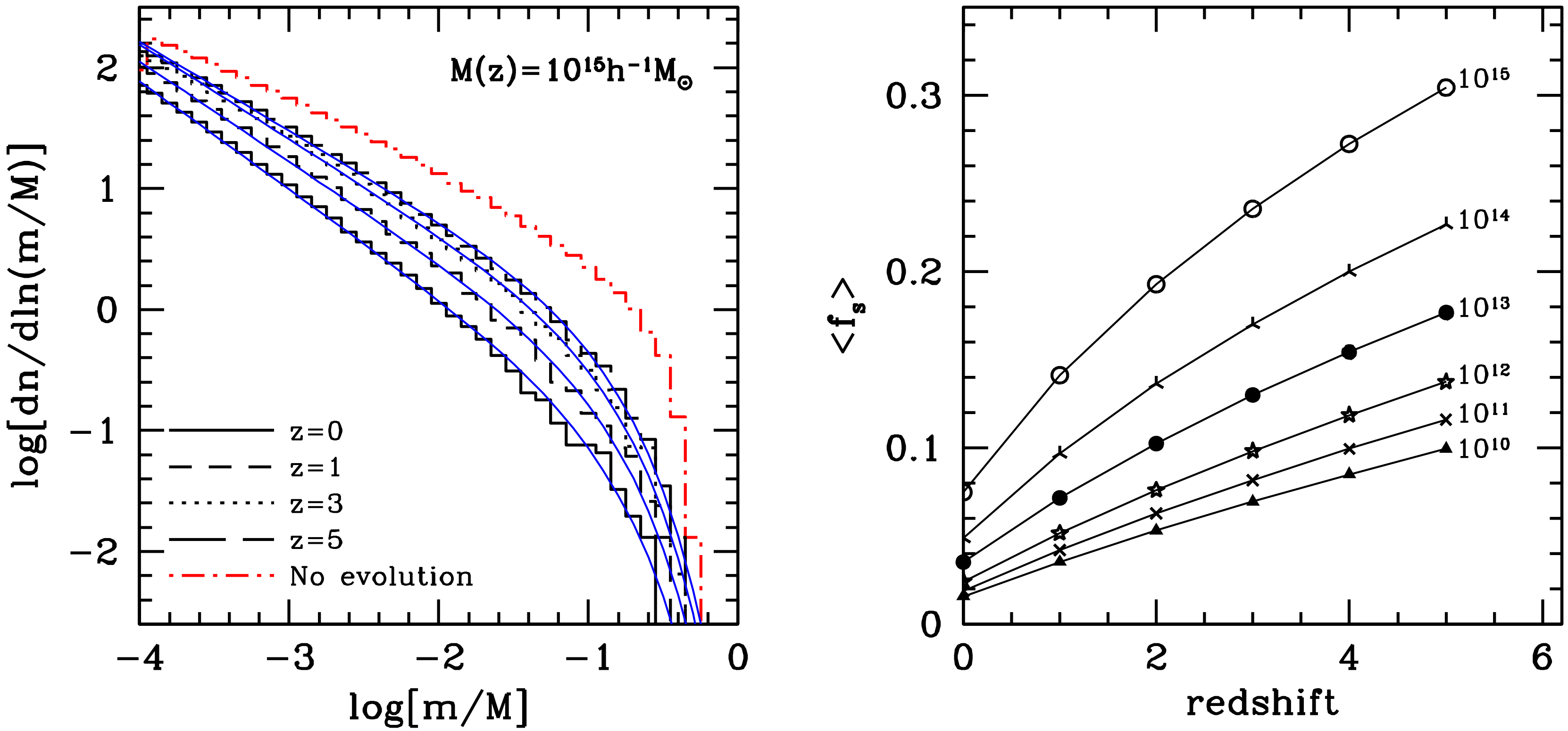
# SHMFs are NOT self-similar




**More massive haloes assemble later ⇒ less time for mass loss to operate ⇒ larger subhalo mass fraction.**

**Our results accurately match the simulation results of Gao et al. (2004)**

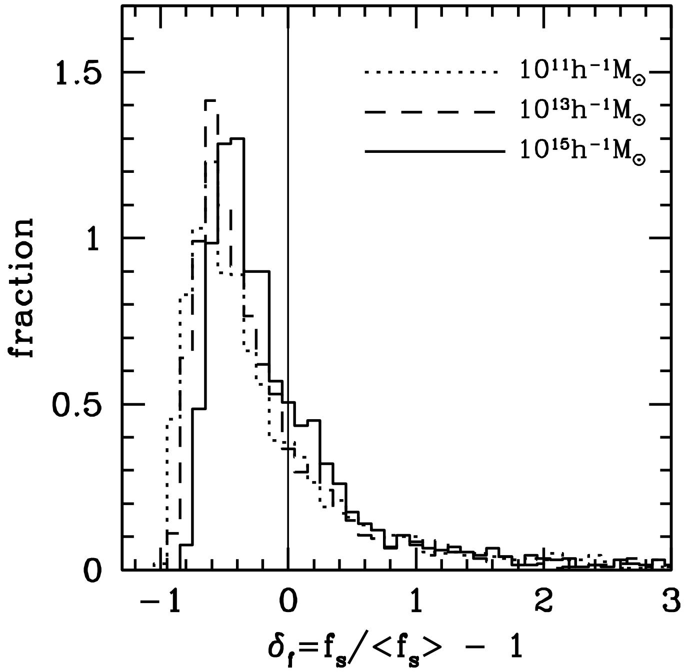
# Haloes grow, Subhaloes shrink




**At** **higher** **redshifts, haloes have a** **larger** **subhalo mass fraction**

**This is a reflection of the fact that the** **time-scale for subhalo mass loss**, $\tau$, **is always smaller than the** **mass accretion time-scale** **on which new subhaloes are accreted**

# Halo-to-Halo Variance




**The Subhalo Mass Fraction**

**Define:** $f_s \equiv \int_{10^{-4}}^{1} \psi \frac{dn}{d\psi} d\psi$

**and** $\delta_f \equiv \frac{f_s - \langle f_s \rangle}{\langle f_s \rangle}$

**Note that $P(\delta_f)$ is extremely skewed and broad.**

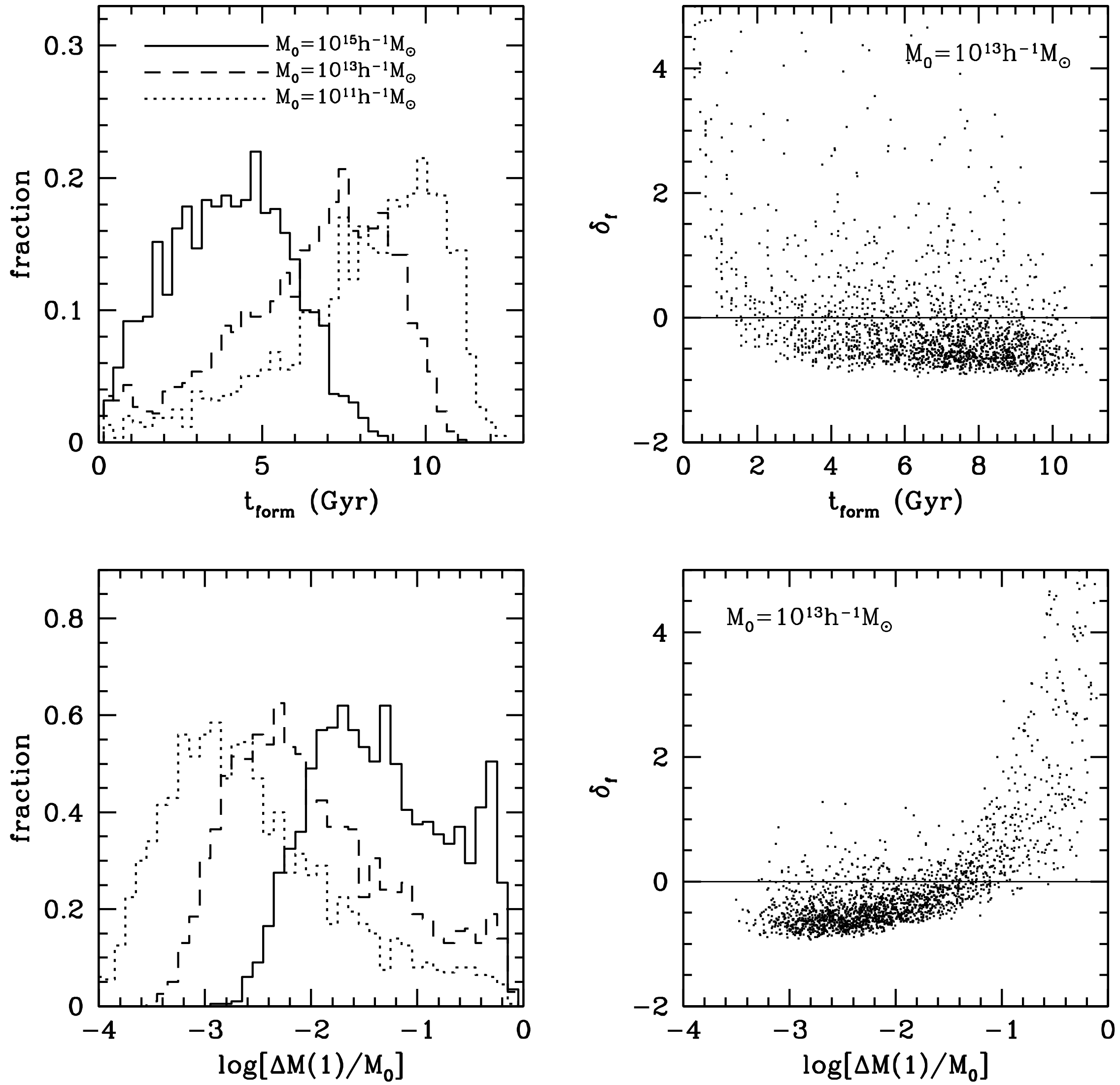
**This scatter in $f_s$ owes entirely to scatter in the mass assembly histories.**
**Scatter in $P(\varepsilon)$, not modelled here, will only make true scatter larger**

**To obtain an accurate, average subhalo mass function, one needs to average over many individual haloes**

$\Rightarrow$ **Trends predicted are difficult to test with $N$-body simulations**

$\Rightarrow$ **Constraining cosmology with flux-ratio anomalies is virtually impossible.**

# Origin of the Variance




**Scatter is virtually uncorrelated with the halo assembly time...**

**but $\delta_f$ is strongly correlated with the mass fraction that has been accreted in the last Gyr.**

**Present-Day Subhaloes have been accreted fairly recently**

# Conclusions Part I

- As long as $P(\varepsilon)$ does not significantly depend on halo mass, one expects the average mass loss rate of subhaloes to only depend on the instantaneous mass ratio $\psi = m/M$
- In this case the only mass dependence of the subhalo mass function originates from the mass dependence of the halo assembly histories
- The subhalo mass function is not self-similar or universal
- A halo of $10^{11} h^{-1}\,\mathrm{M}_{\odot}$ has, on average, a suhalo mass fraction that is a factor 4 lower than a halo of $10^{15} h^{-1}\,\mathrm{M}_{\odot}$.
- Haloes of the same mass have a larger subhalo mass fraction at higher redshifts.
- Large halo-to-halo variance; correlated with mass fraction that has been accreted recently $(\lesssim 1\mathrm{Gyr})$.
- Present day subhaloes have been accreted recently
- All these results are in excellent agreement with the numerical simulations of Gao et al. (2004).

# Part II: Galaxy Ecology

Many studies have investigated the relation between various galaxy properties (morphology/SFR/colour) and environment

(e.g., Oemler 1974; Dressler 1980; Postman & Geller 1984; Dominguez et al. 2002; Kauffmann et al. 2004; Balogh et al. 2004; Goto et al. 2003; Gomez et al. 2003; Hogg et al. 2004; Tanaka et al. 2004)

Environment estimated using galaxy overdensity (projected) to $n$th nearest neighbour, $\Sigma_n$ or using fixed, metric aperture, $\Sigma_R$.

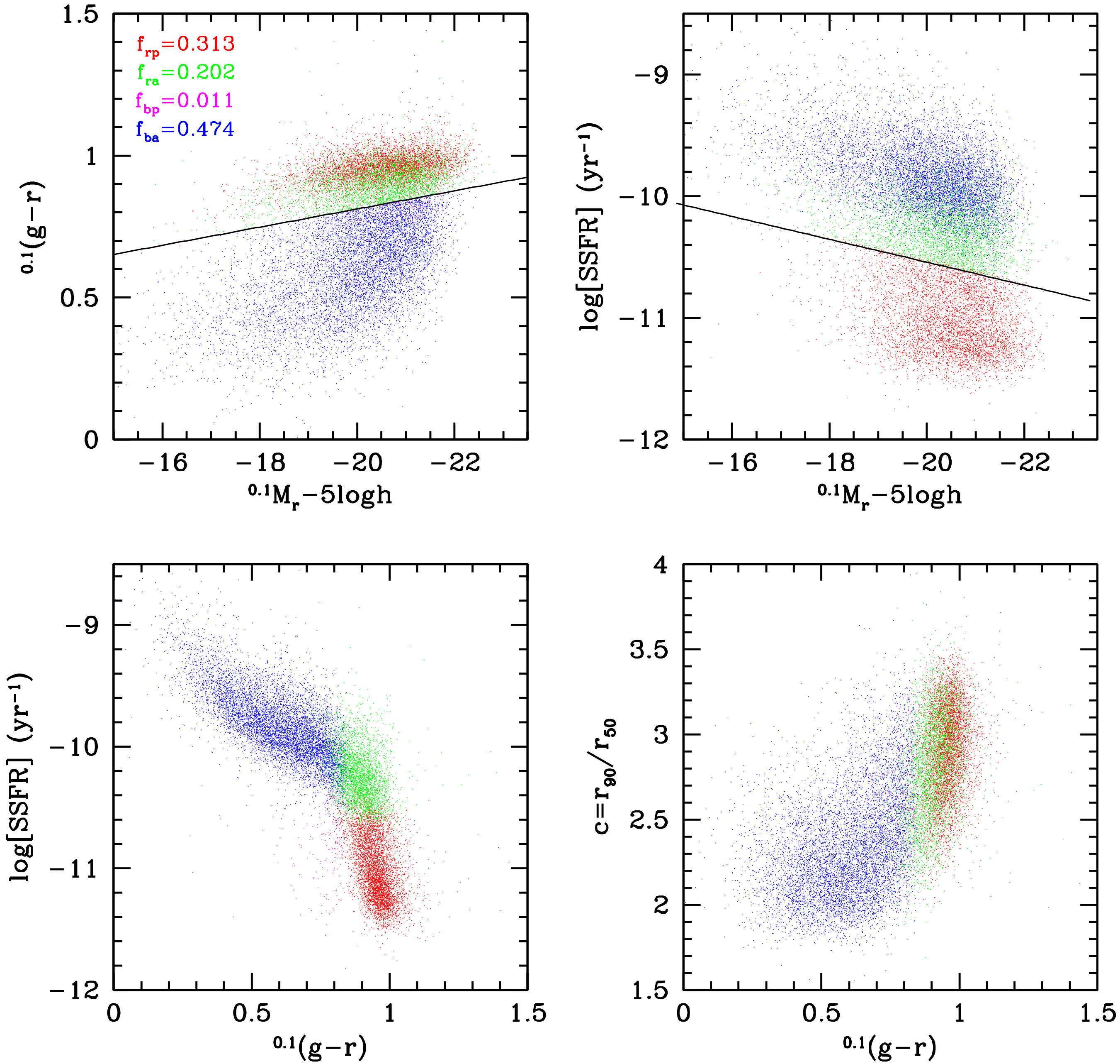
- Fraction of early types increases with density
- There is a characteristic density ($\sim$ group-scale) below which environment dependence vanishes
- Groups and Clusters also reveal radial dependence: late type fraction increases with radius
- No radial dependence in groups with $M \lesssim 10^{13.5} h^{-1}\,\mathrm{M}_\odot$

Danger: Physical meaning of $\Sigma_n$ and $\Sigma_R$ depends on environment.

Physically more meaningful to investigate halo mass dependence of galaxy properties. This requires galaxy group catalogues.

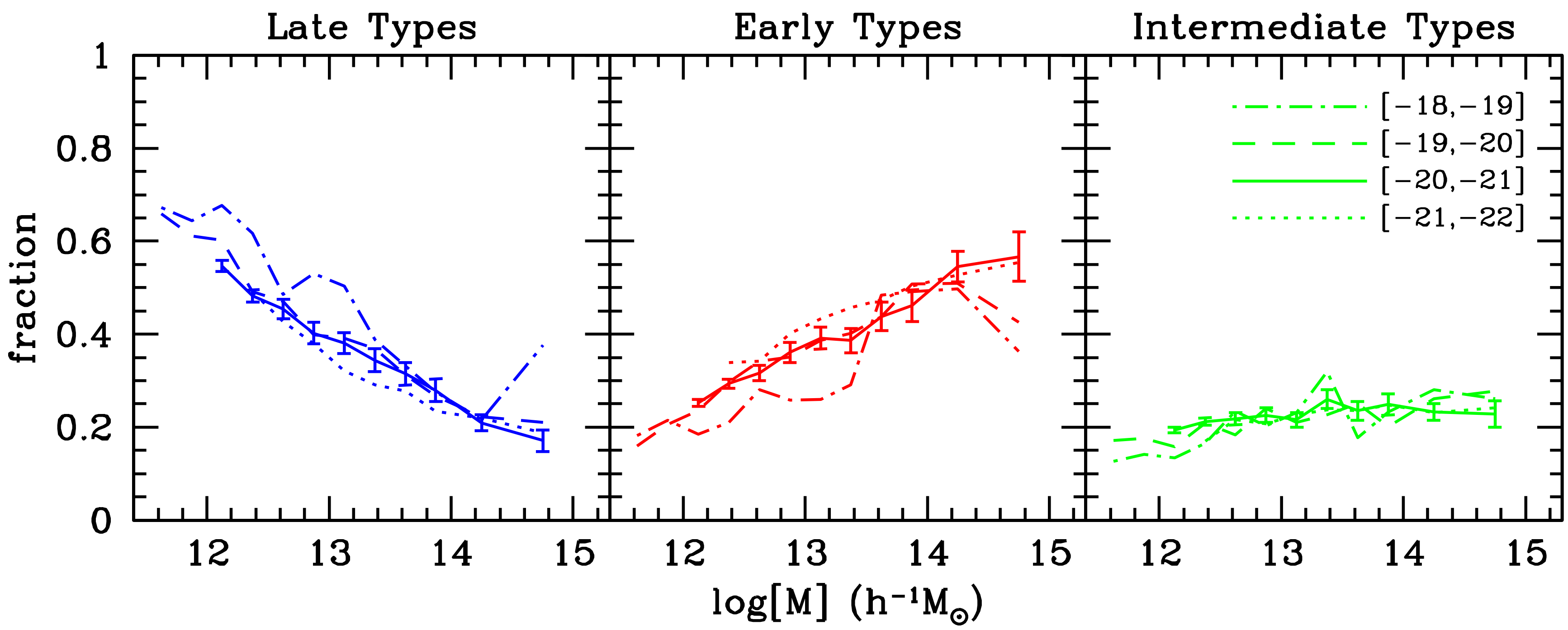
Important: Separate luminosity dependence from halo mass dependence.

# Defining Galaxy Types




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 type galaxies depend strongly on halo mass.**

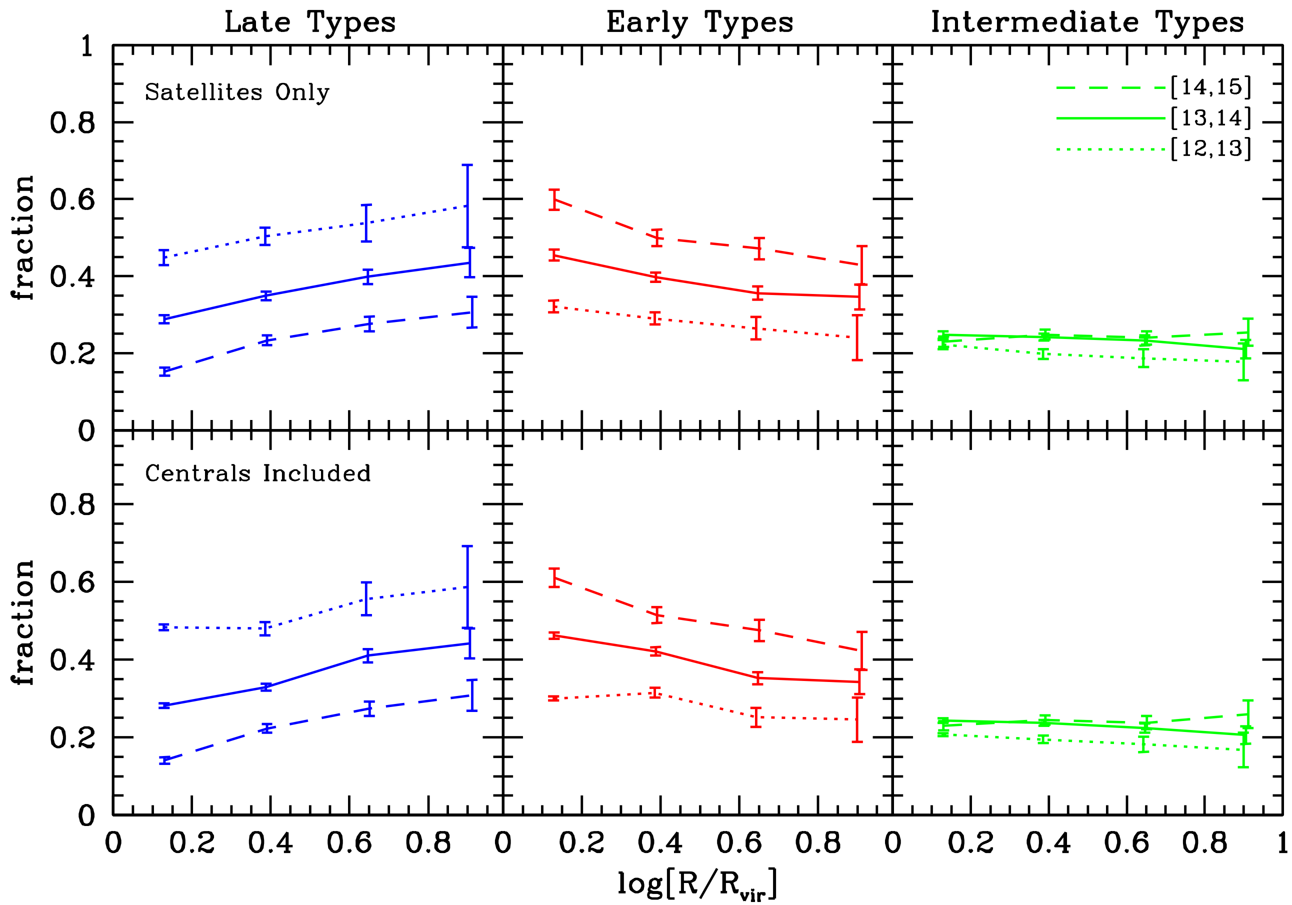
**At fixed halo mass, there is virtually no luminosity dependence.**

**The mass dependence is smooth: there is no characteristic mass scale; i.e., no indication that something special happens at the group or cluster scales.**

**The intermediate type fraction is independent of luminosity and mass.**

**(Weinmann, vdB, Yang & Mo, 2005)**

# Dependence on Group-centric Radius



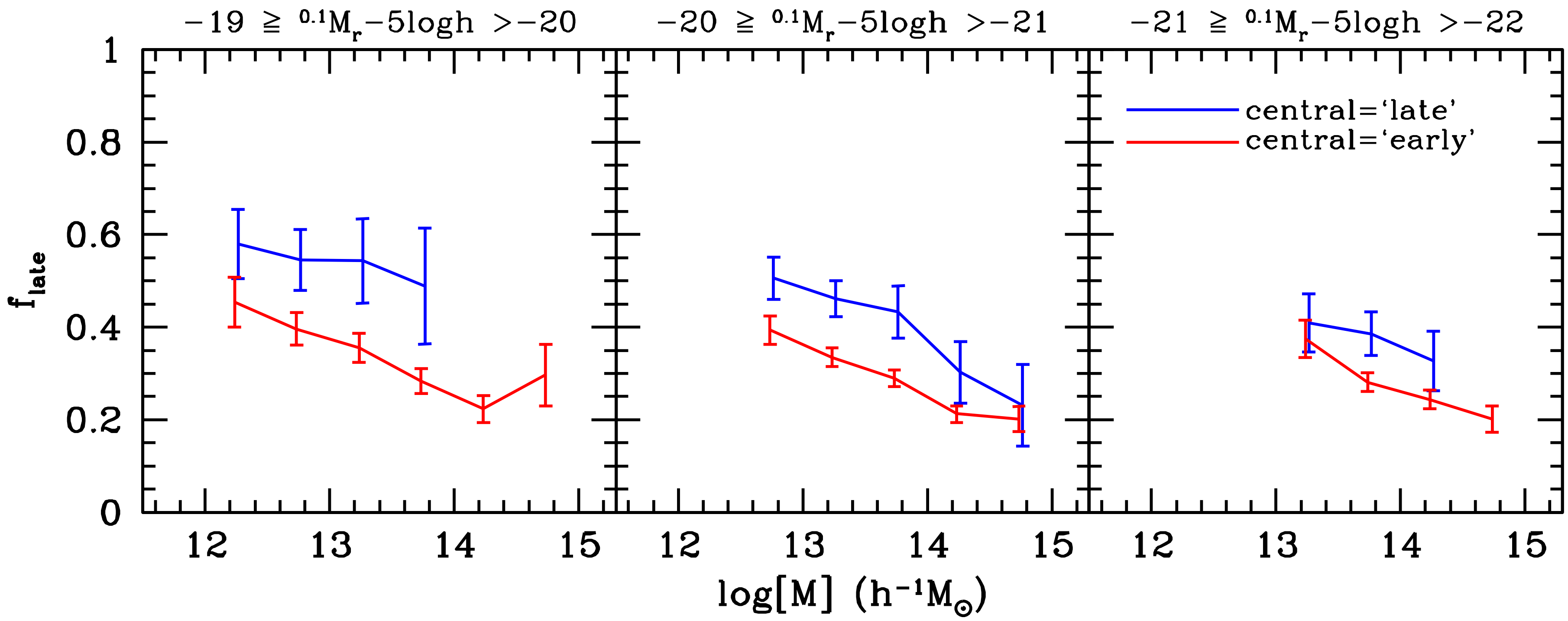

**As noticed before, the late type fraction of satellites increases with radius.**
**This trend is independent of halo mass!**

**Inconsistent with previous studies, but these included central galaxies.**

**Our results rule out group- and cluster-specific processes such as ram-pressure stripping and harassment: nature rather than nurture!**

**(Weinmann, vdB, Yang & Mo, 2005)**

# Galactic Conformity




**Satellite galaxies 'adjust' themselves to properties of their central galaxy: late type 'centrals' have preferentially late type satellites, and vice versa.**

**This has been noticed before, but only for small samples of loose groups**

**(Wirth 1983; Ramella et al. 1987; Osmond & Ponmon 2004).**

**Our results indicate that this Galactic Conformity is present over large ranges in luminosity and halo mass.** **(Weinmann, vdB, Yang & Mo, 2005)**

# Conclusions Part II

- Galaxy properties scale smoothly with halo mass. There is no indication for a specific transition at either group or cluster scale.
- Galaxy type (early vs. late) is determined by the mass of the halo in which the galaxy lives. Not by the mass (or luminosity) of the galaxy.
- Late type fractions increase with halo-centric radius, independent of halo mass.
- Satellite galaxies 'adjust' their properties to those of their central galaxy: Galactic Conformity (Weinmann, vdB, Yang & Mo 2005)