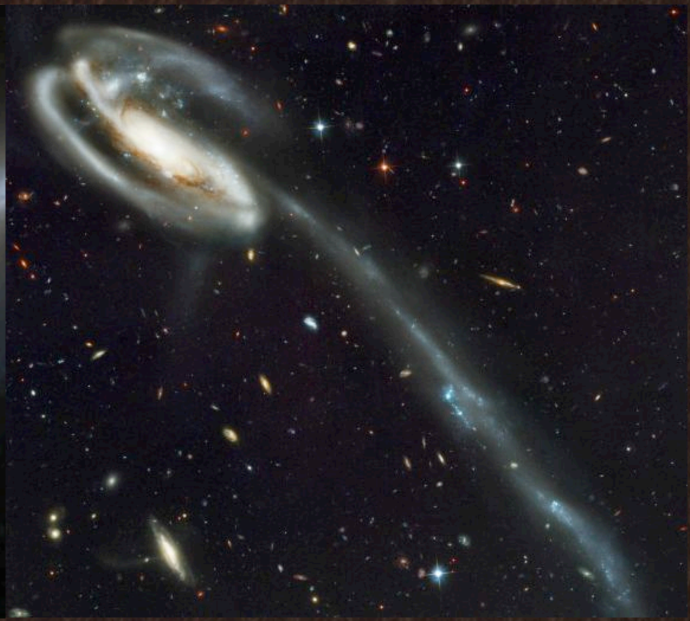
Satellite Galaxies in ΛCDM: Orbits, Merging & Disruption

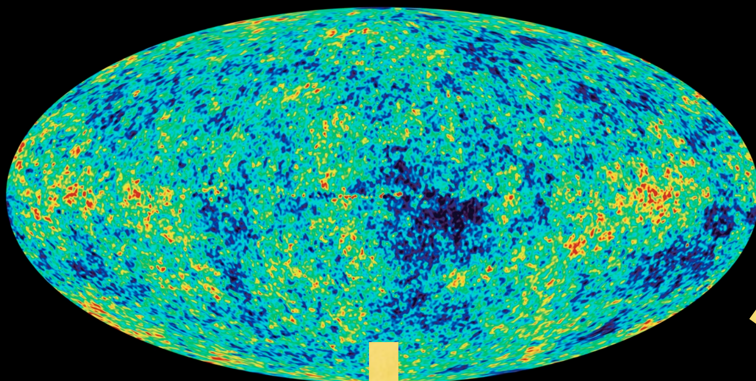


Fermilab, October 29, 2009

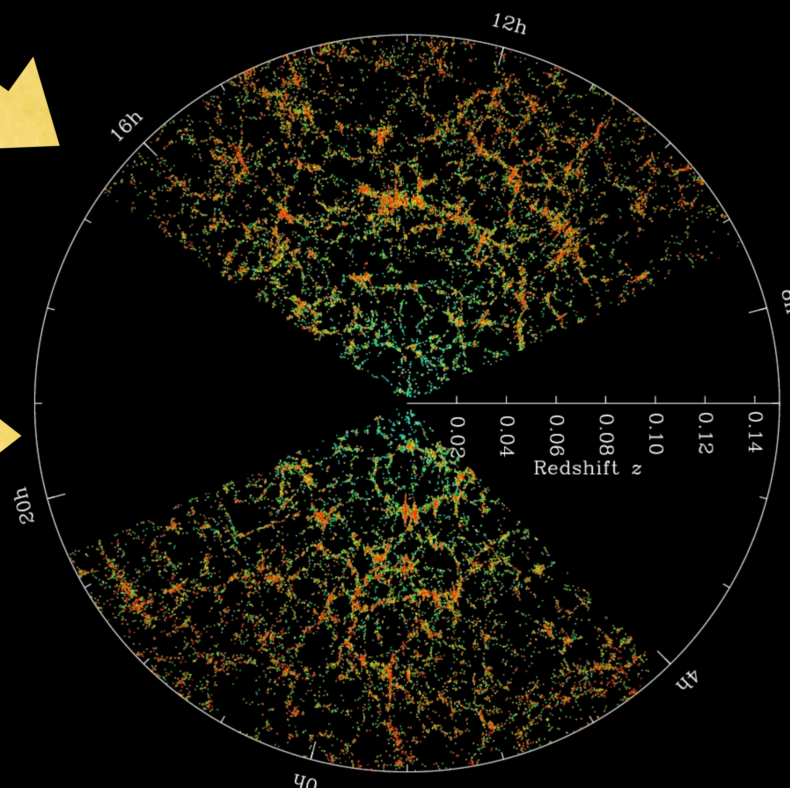
Andrew Wetzel
Martin White
UC Berkeley

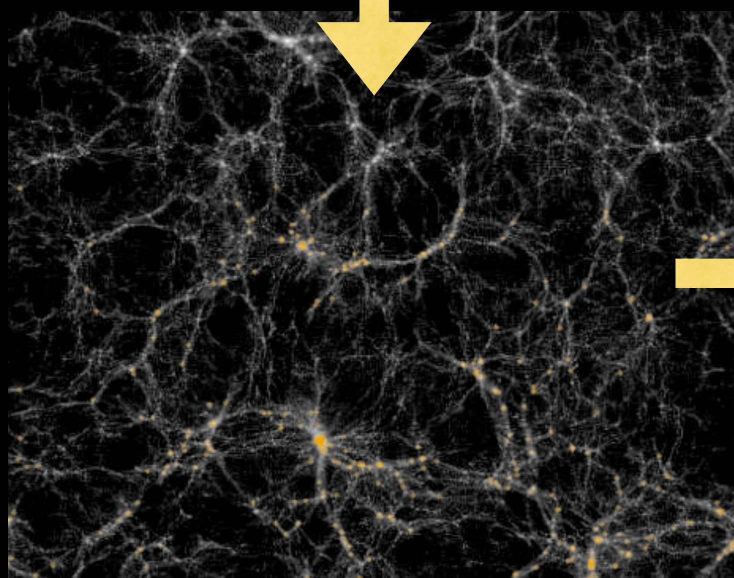
Connecting Cosmology to Galaxy Evolution

Cosmic Microwave Background (WMAP)

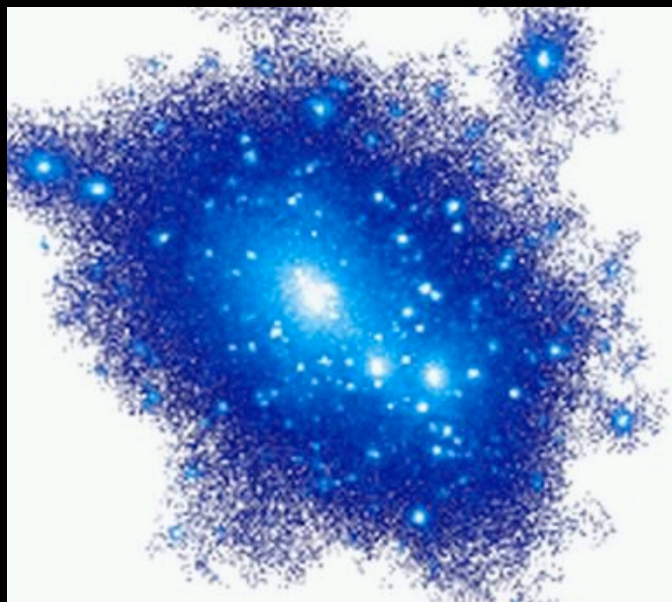


Local Galaxy Distribution (SDSS)





Cosmological *N*-body Simulations



Connecting galaxies to dark matter subhalos permits the study of galaxy evolution in a cosmological context

Importance of galaxy mergers in driving galaxy evolution

Galaxy mass assembly

Morphological evolution: Spirals → Ellipticals

Toomre & Toomre 76, Hausman & Ostriker 78, White 78, Hernquist 92, Hopkins et al. 08

Trigger rapid star formation

Barnes & Hernquist 91, Mihos & Hernquist 94, Cox et al. 08

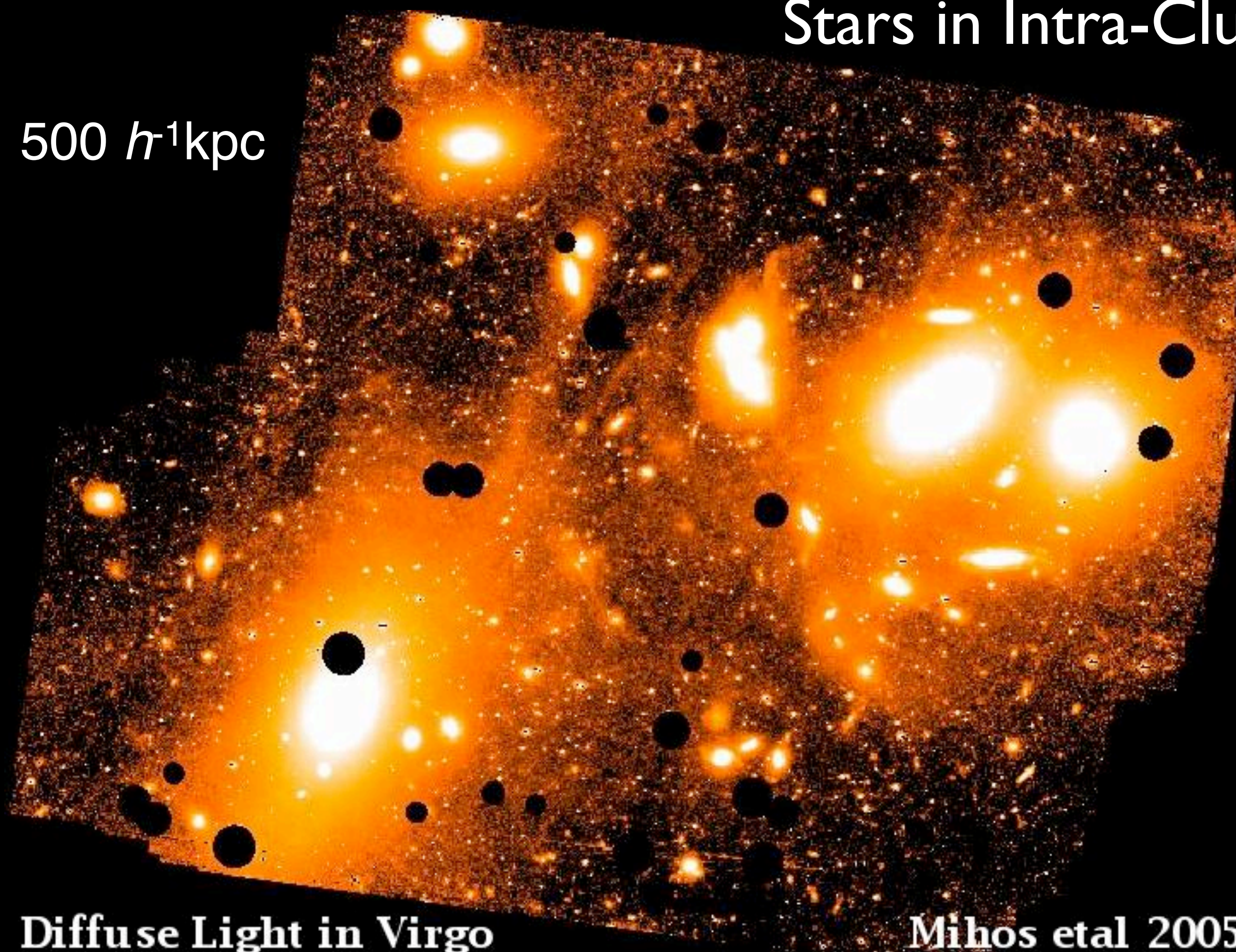
Trigger supermassive black hole growth & quasars

Carlberg 90, Kauffman & Haehnelt 00, Wyithe & Loeb 02, Di Matteo et al. 05

Evolution of galaxies in a cluster environment

Galaxy Clusters Contain 5-50% of Stars in Intra-Cluster Light (ICL)

500 h^{-1}kpc



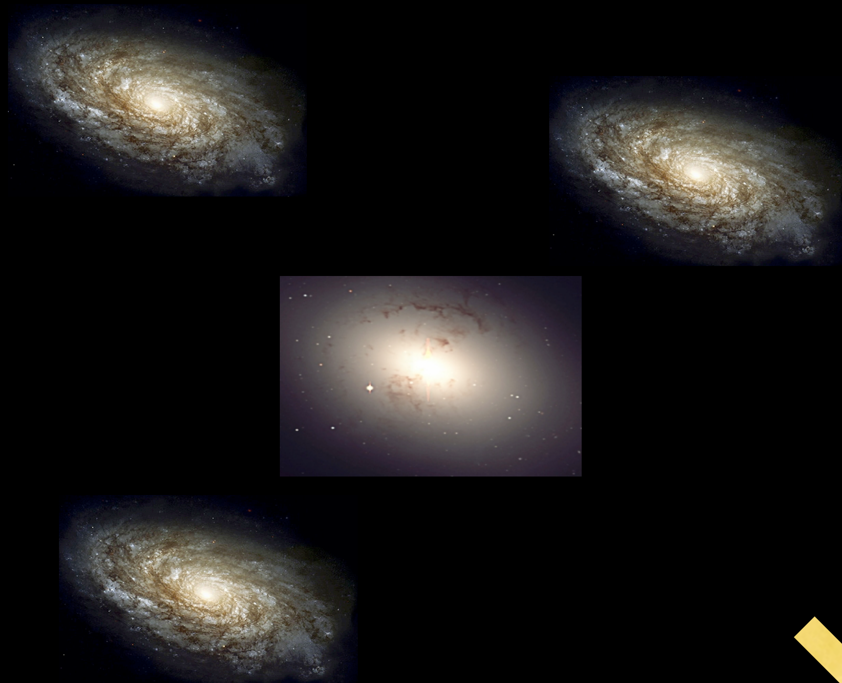
also:

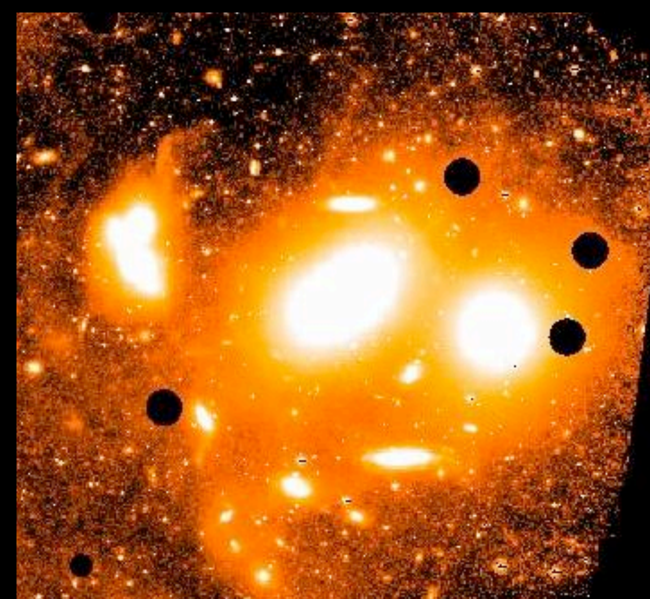
Lin & Mohr 04

Zibetti et al. 05

Gonzalez et al. 07

Krick & Bernstein 07





Satellite galaxy evolution in a cosmological context

Outline

- Connecting galaxies to halo substructure
- Model for satellite galaxy merging/disruption
- Quantitative comparisons with observations
- Analytic model for satellite infall time
- Orbits of infalling satellites

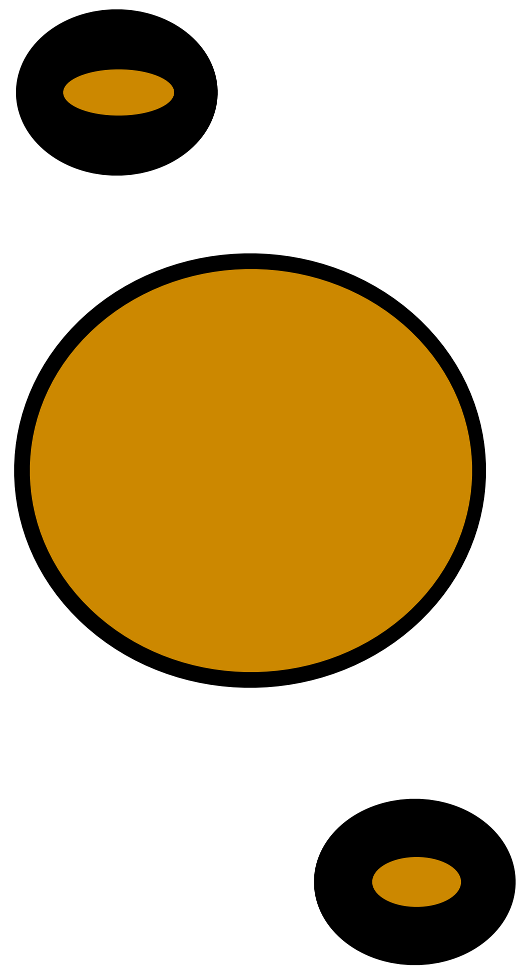
Galaxies Reside in Subhalos

A galaxy forms in the dense, central region of a halo
Rees & Ostriker 77, White & Rees 78

Halos merge, becoming subhalos of larger halos
Moore et al. 99, Tormen et al. 98, Klypin et al. 99

Halo merger ≠ galaxy merger

Halos can host multiple galaxies



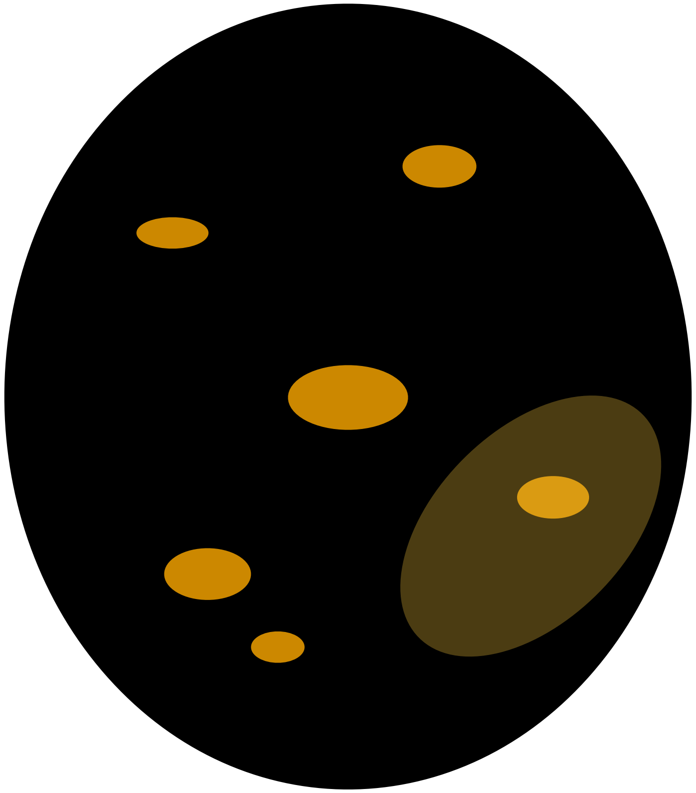
Possible Fates of Satellite Galaxies

(1) Eject

(2) Merge with a satellite

(3) Merge with the central

(4) Tidally disrupt into
Intra-Cluster Light



Goal: constrain (3) & (4)

High-Resolution, Cosmological Volume N-body Simulation

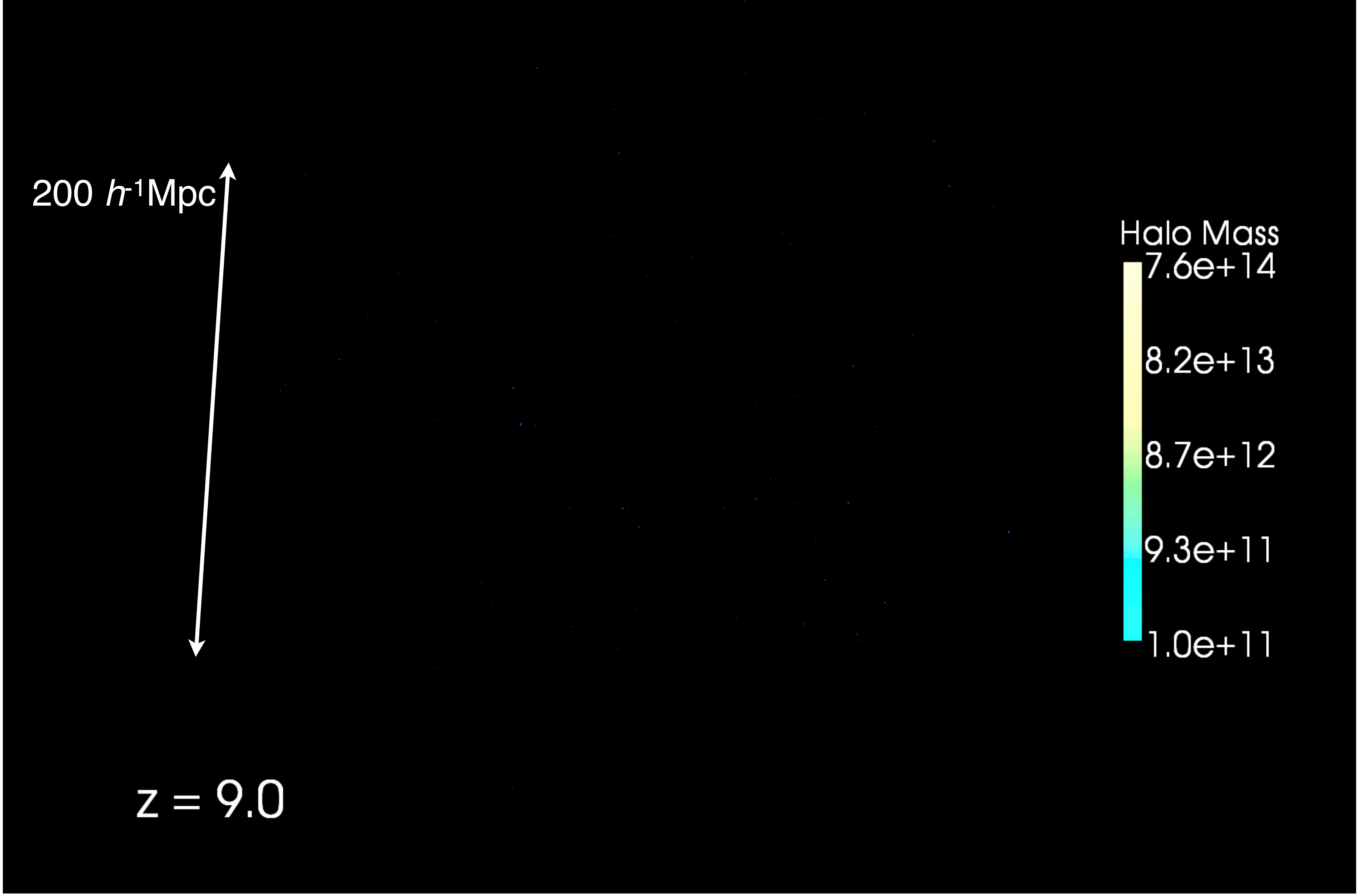
Robustly tracking subhalos within halos requires high resolution

- Particle mass: $1.6\text{x}10^8\ h^{-1}M_\odot$ (>2000 particles at infall)
- Force resolution: $3\ h^{-1}$kpc
- Particles: $1500^3 = 3.4$ billion

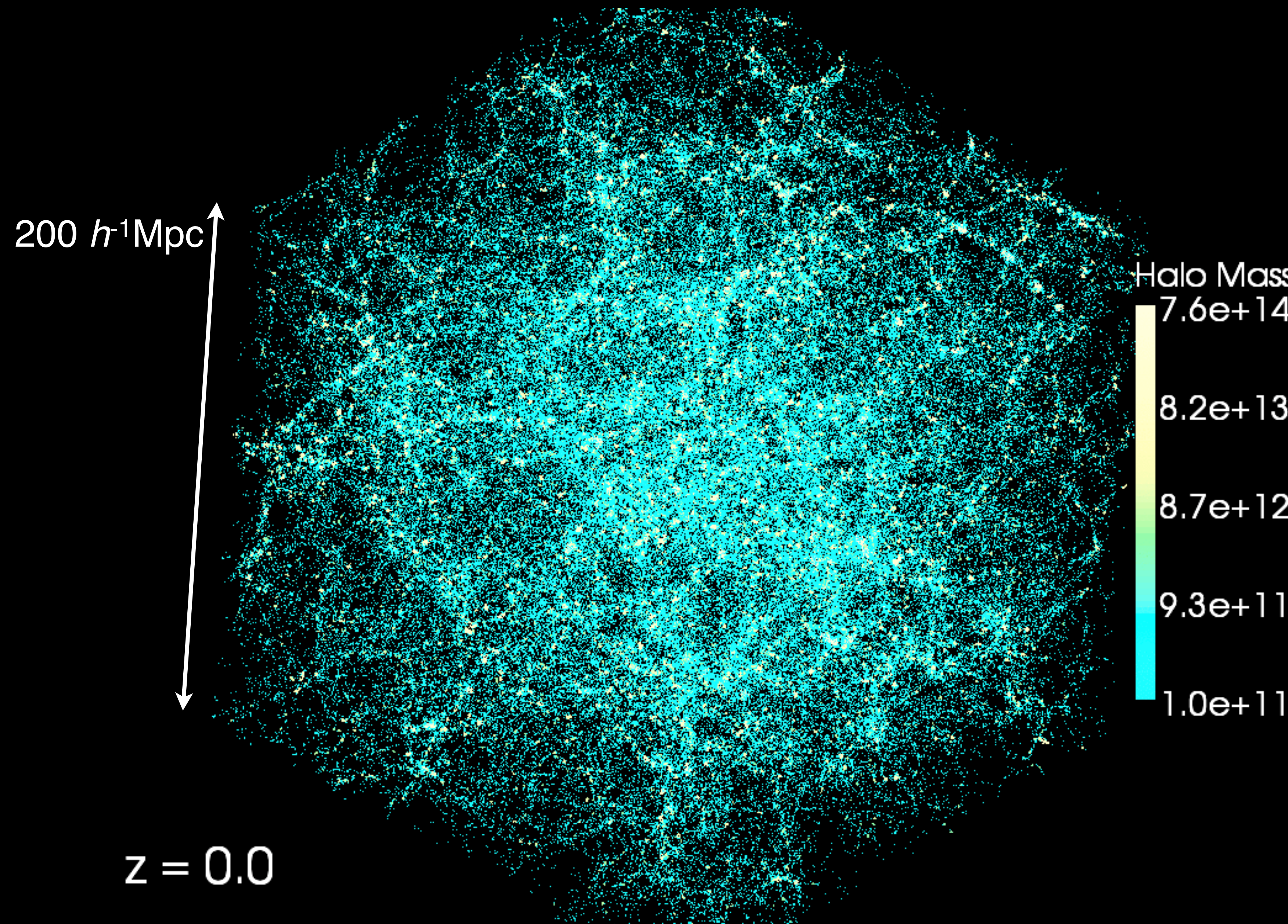
Accurate spatial clustering measure requires significant volume

- Box size: $200\ h^{-1}$Mpc
- Smaller simulation sizes do not accurately represent large-scale structure

Growth of subhalos



Massive subhalos are rarer & more clustered



Identifying Halo Substructure

Halos

FoF, linking length=0.168

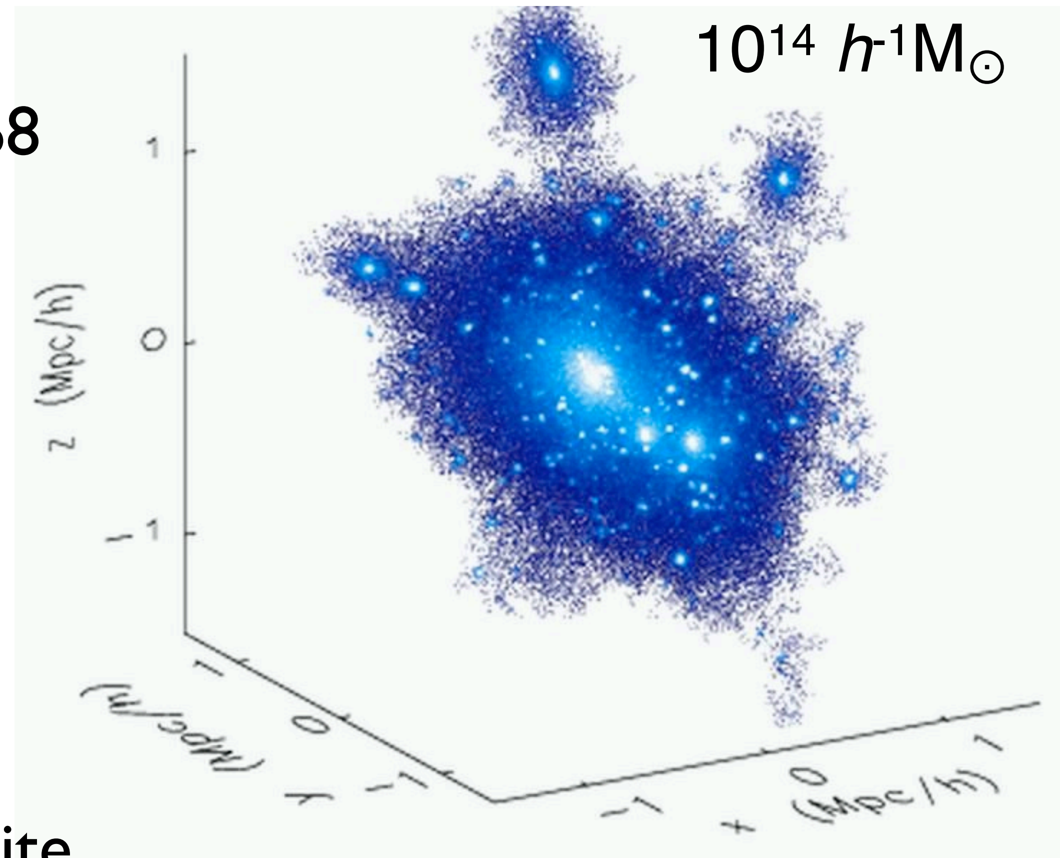
Davis et al. 85

Subhalos

SUBFIND Springel et al. 01

Self-bound group
around density peak

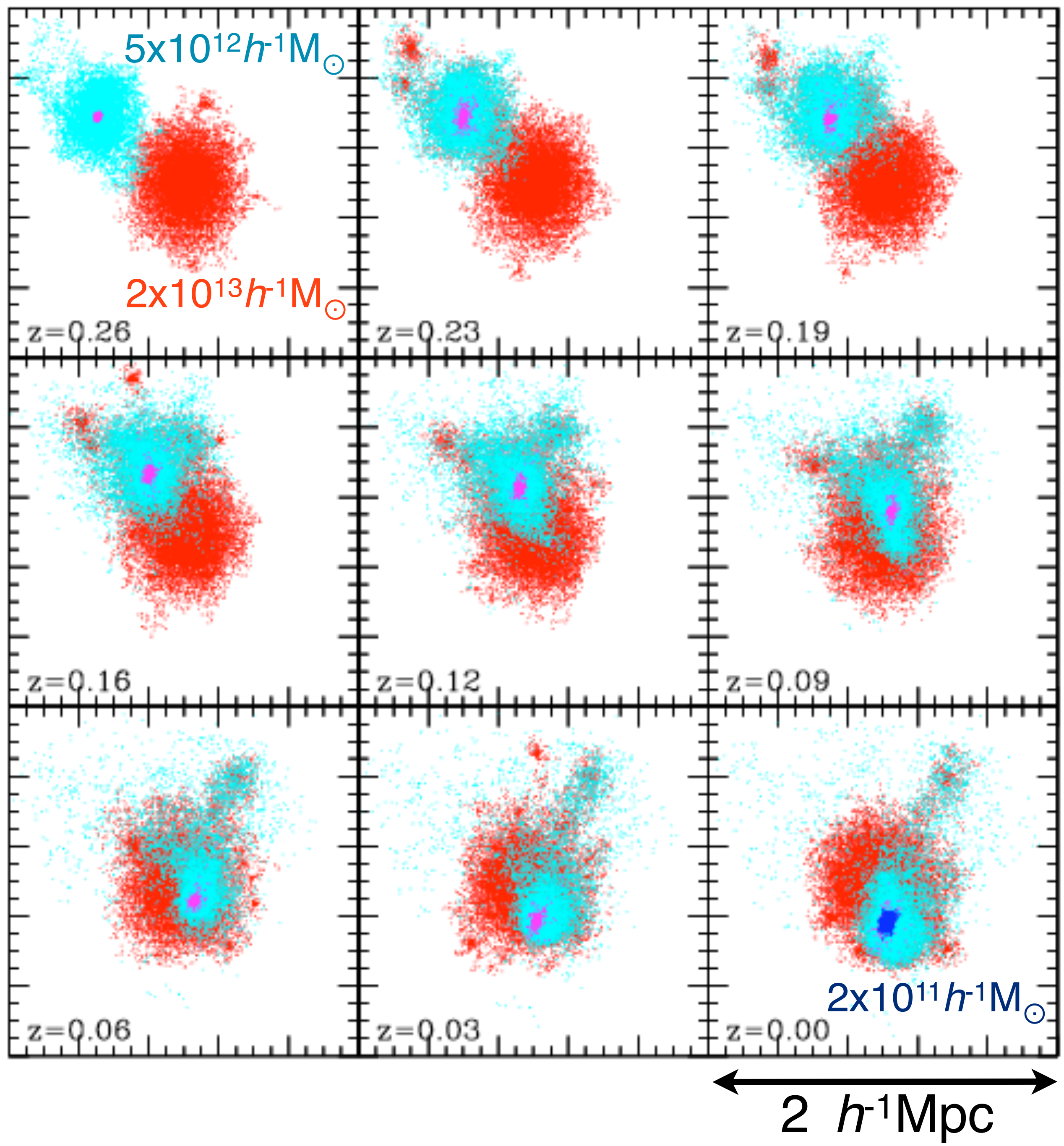
Can be central or satellite



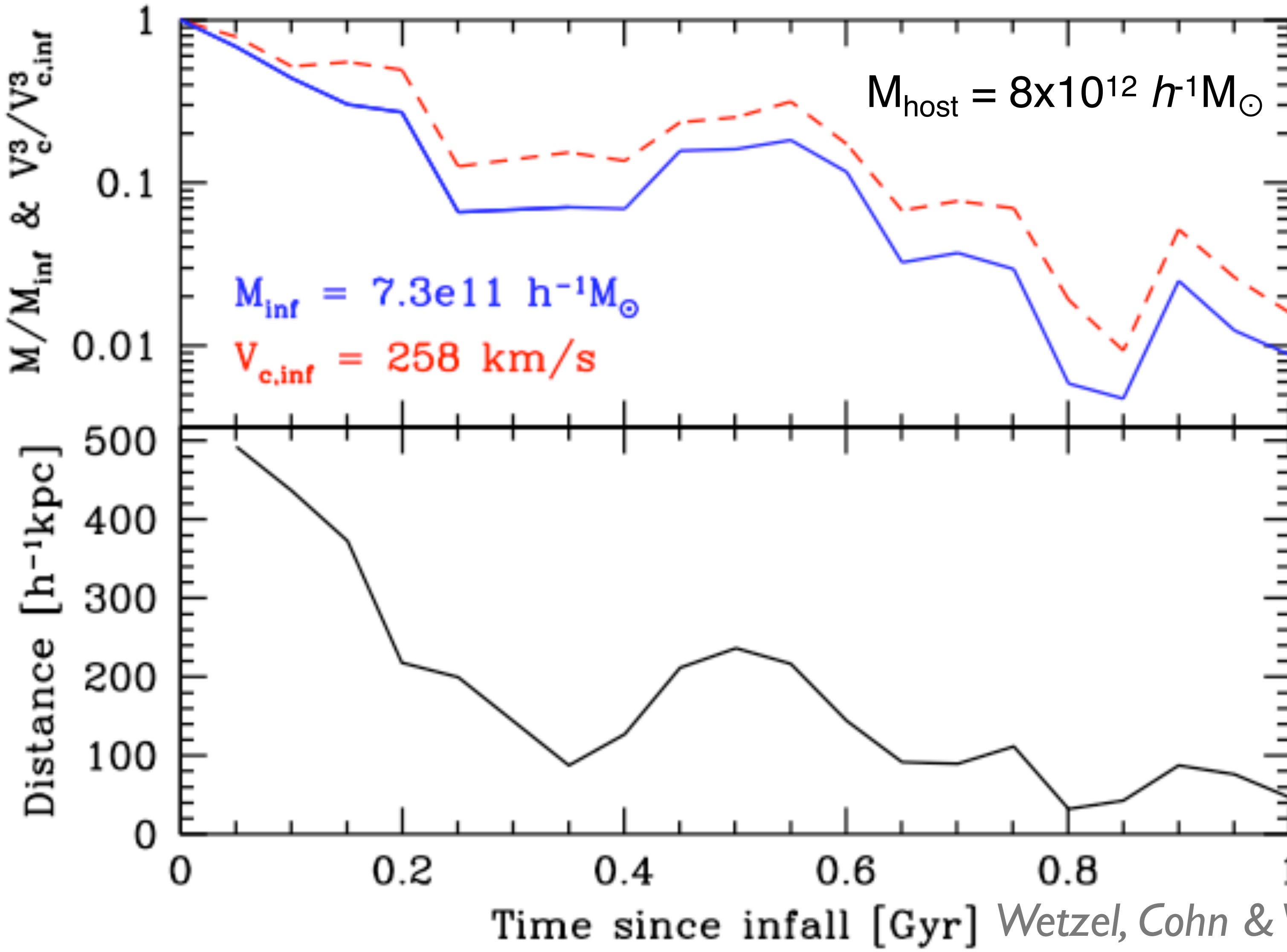
Satellite Subhalo Mass Stripping

Occurs from the outside-in

The most bound mass remains self-bound



Subhalos undergo severe mass stripping



Wetzel, Cohn & White 09b

Subhalo infall mass, M_{inf}

Satellite subhalo bound mass severely stripped after infall

Compact galaxy stellar mass remains intact longer

Satellite subhalos mass at infall best correlates with galaxy stellar mass

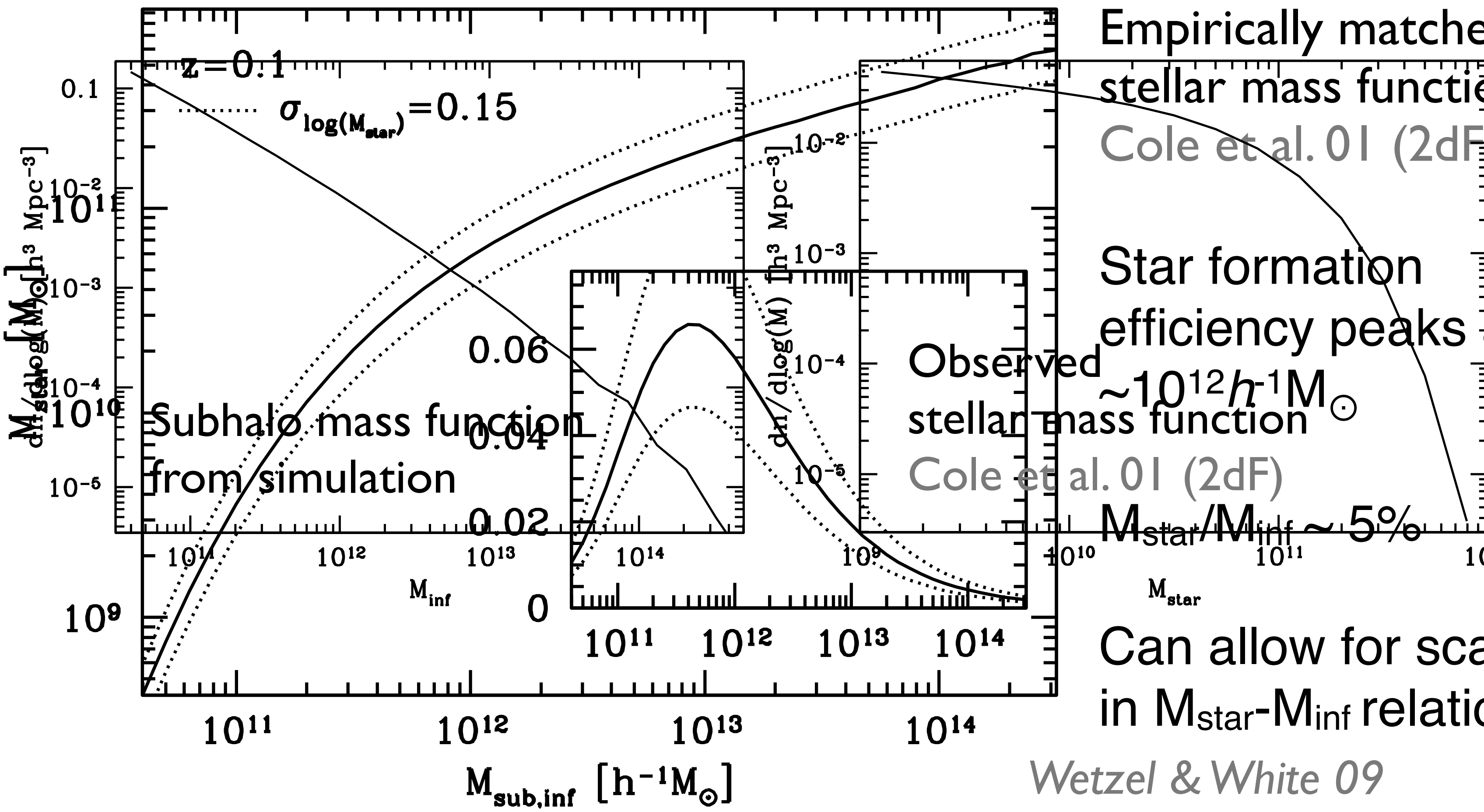
Subhalo infall mass agrees with hydrodynamic simulations & correlates with observations ($z < 1$)

Central subhalo assigned M_{inf} as its current bound mass, ~90% of halo mass

Hydro: Nagai & Kravtsov 05, Weinberg et al. 08
Observations: Vale & Ostriker 06, Conroy, Wechsler & Kravtsov 06, Berrier et al. 06, Shankar et al. 06, Wang et al. 06, Marin et al. 08

Stellar mass assigned via subhalo abundance matching

$$n_{sub}(>M_{inf}) = n_{gal}(>M_{star})$$



Empirically matched to stellar mass function of Cole et al. 01 (2dF)

Star formation efficiency peaks at $\sim 10^{12} h^{-1} M_\odot$

$M_{star}/M_{inf} \sim 5\%$

Can allow for scatter in M_{star}-M_{inf} relation

Wetzel & White 09

Connecting Light to Mass: Summary

Satellite subhalo dark mass stripped rapidly (outside-in), but stellar mass remains intact

Stellar mass/luminosity correlates with subhalo infall mass

Stellar mass/luminosity assigned *empirically* by abundance matching to observed stellar mass/ luminosity function

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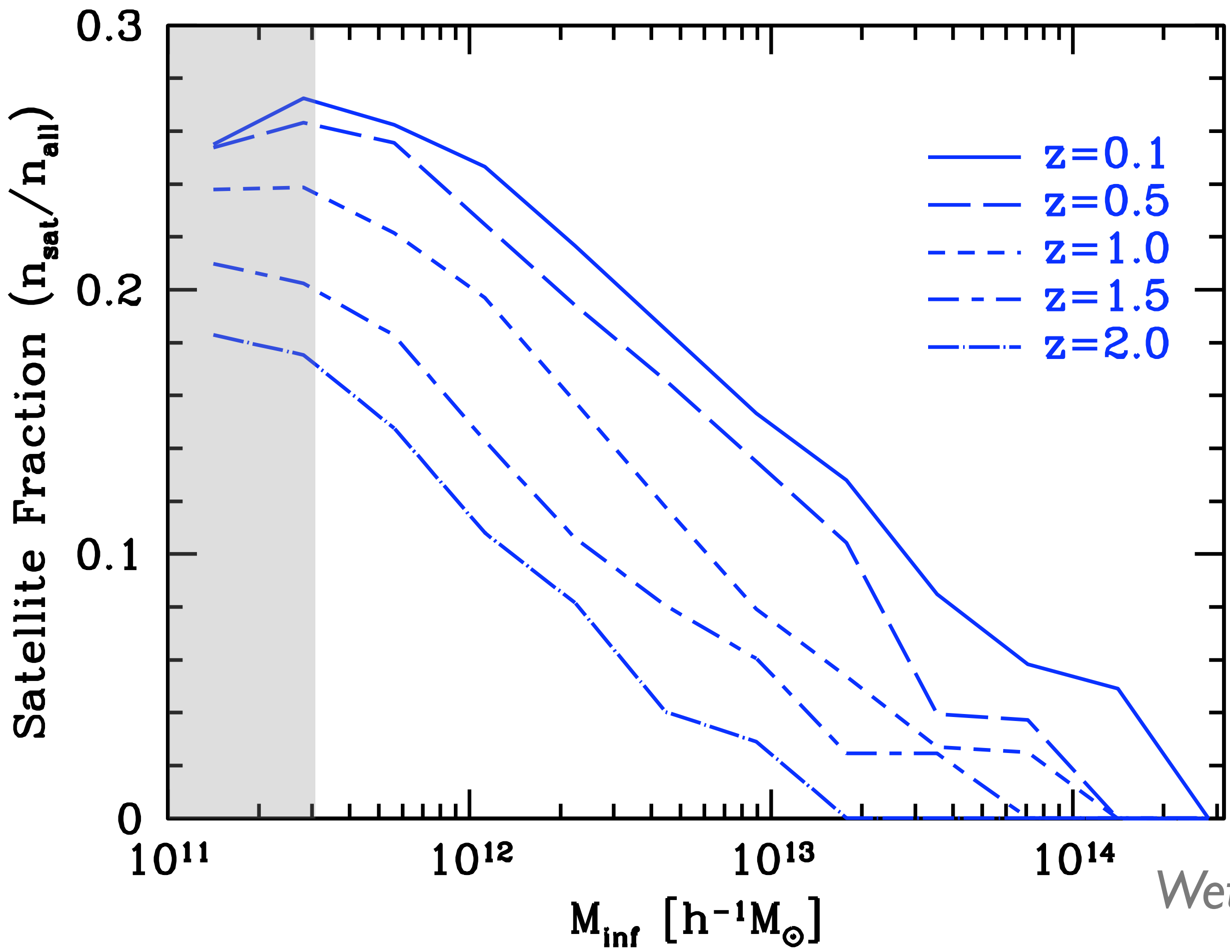
Satellites comprise ~25% of ~L* galaxies at z~0



Wetzel & White 09

Artificial numerical disruption for $M_{inf} < 10^{11.5}\ h^{-1}\ M_\odot$

Satellite Merging/Disruption Criteria

Ansatz: galaxy merging/disruption is determined by subhalo dark mass stripping

Satellite removed if subhalo's bound mass - infall mass ratio falls below given threshold

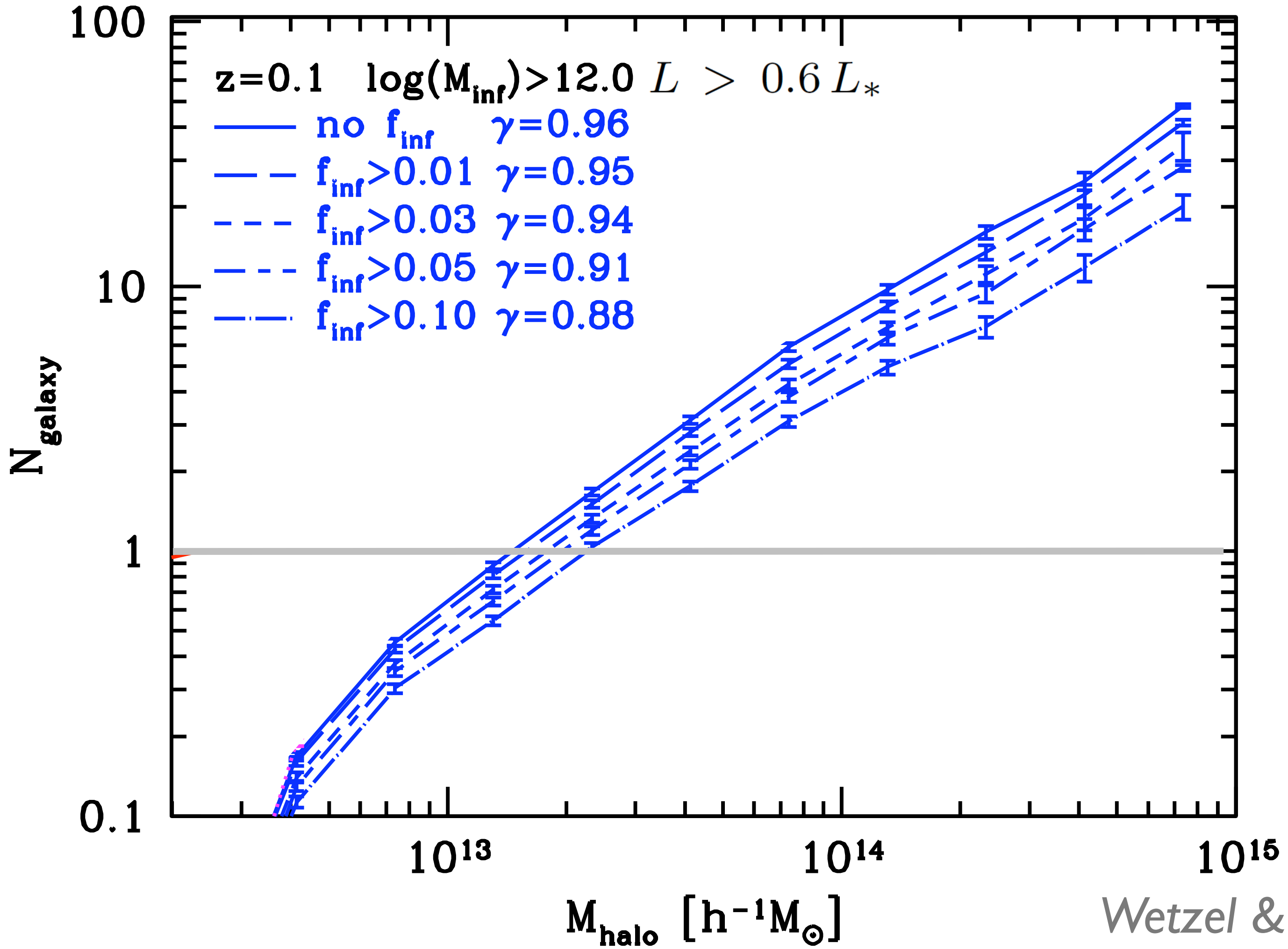
$$f_{\rm inf} = M_{\rm bound}/M_{\rm inf}$$

Consider threshold range: f_{inf} = 0.01-0.1

Criteria other than infall mass fraction give poorer match to observations

Halo Occupation Distribution (HOD)

$f_{\rm inf} = M_{\rm bound}/M_{\rm inf}$

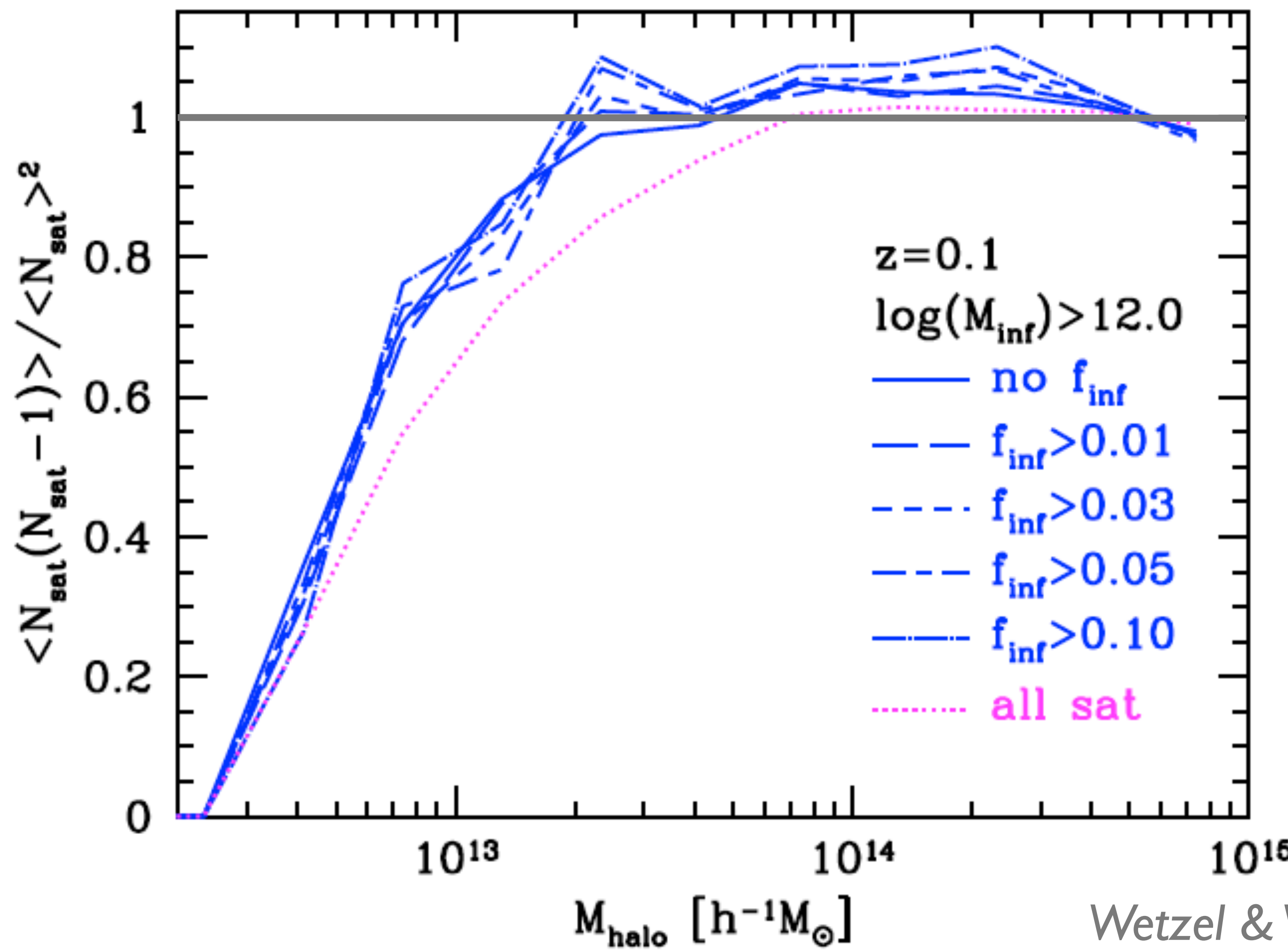


Wetzel & White 09

Modeling satellite merging/disruption most critical in high mass halos

HOD 2nd Moment: $\langle N_{\rm sat}(N_{\rm sat}-1)\rangle / \langle N_{\rm sat}\rangle^2$

$f_{\rm inf} = M_{\rm bound}/M_{\rm inf}$



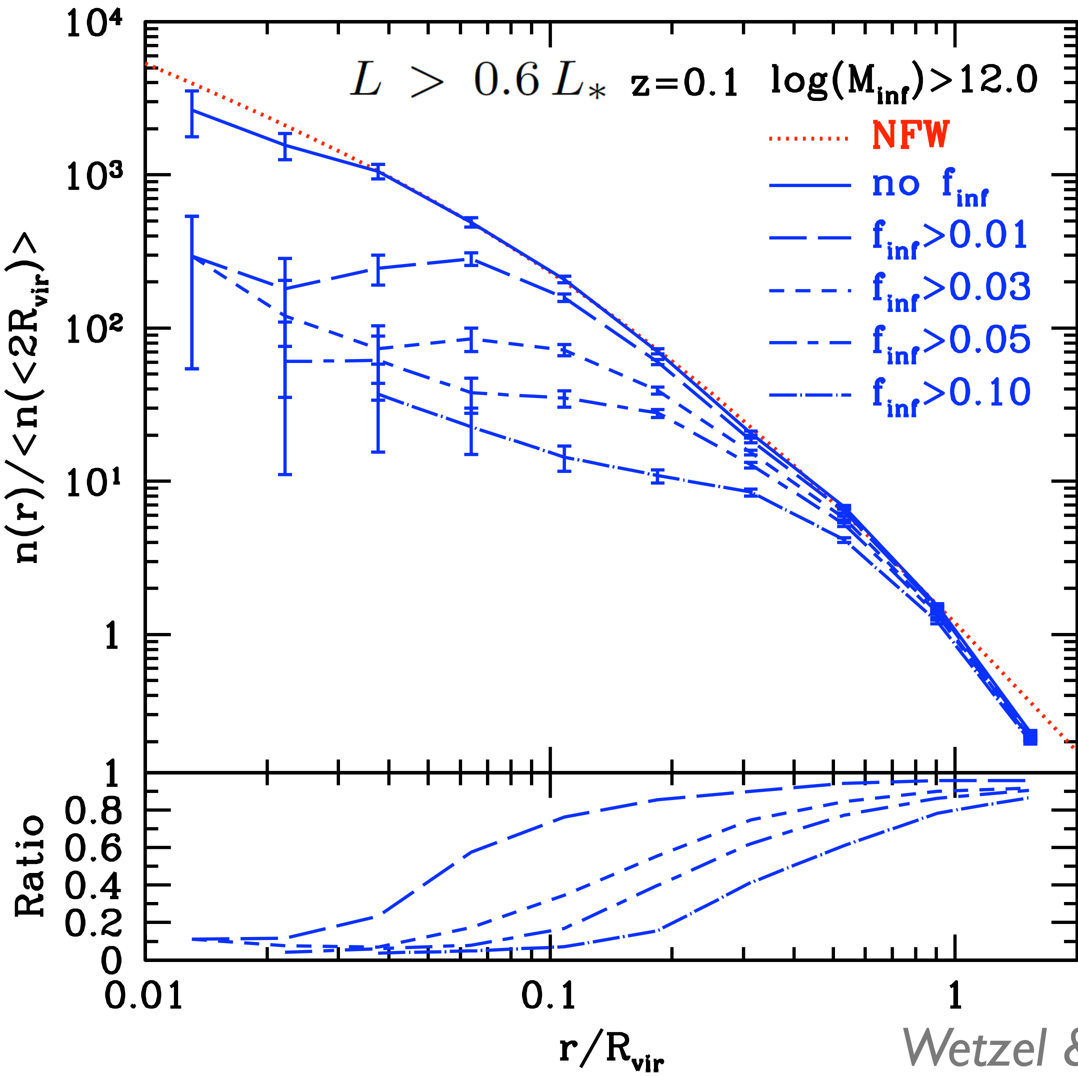
Wetzel & White 09

Super-Poisson satellite HOD from correlated infall

also: Kravtsov et al. 04

Satellite Radial Distribution Profile

$$f_{\rm inf} = M_{\rm bound}/M_{\rm inf}$$



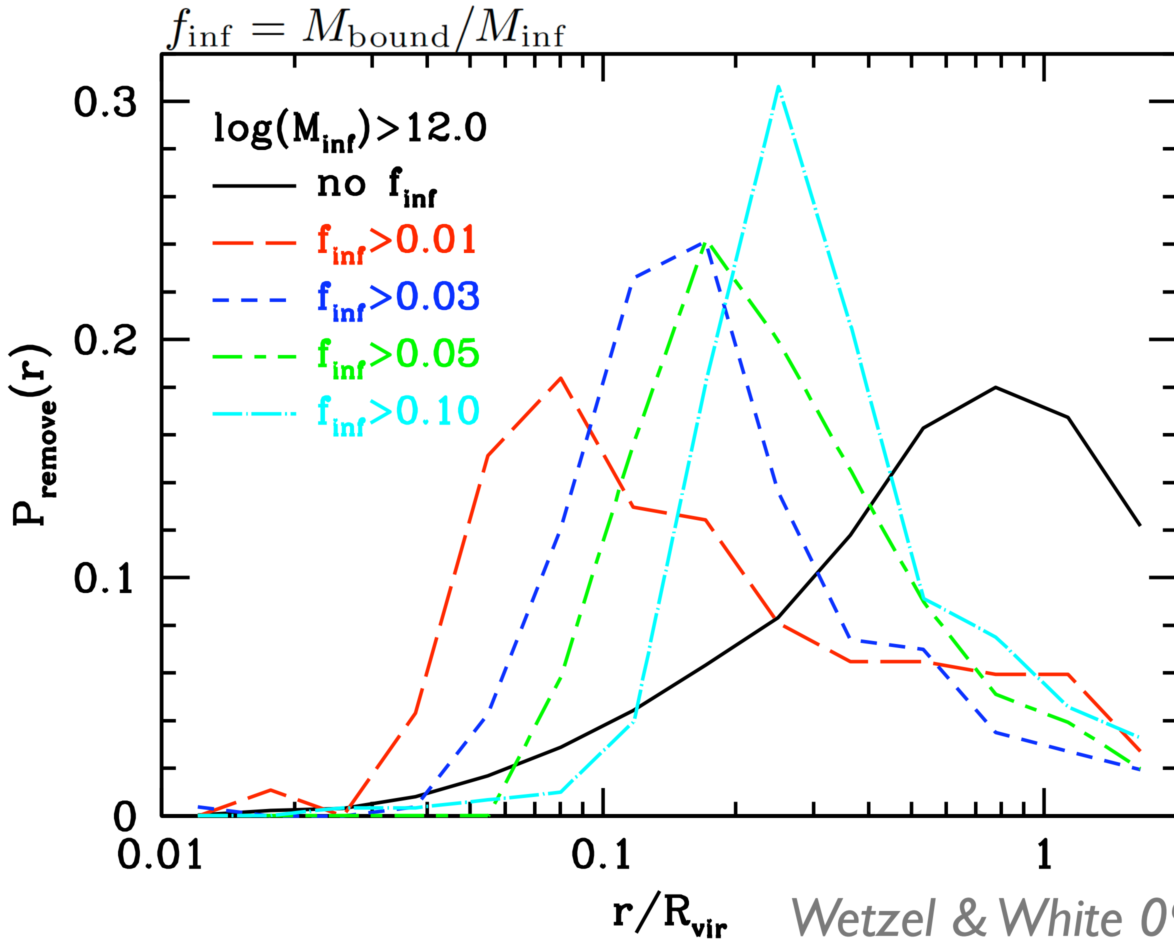
Wetzel & White 09

Resolved subhalos trace NFW profile

Merging/disruption occurs toward halo center

Some disruption occurs out to R_{vir}

Merger vs Disruption: Radius at Removal



Wetzel & White 09

Satellite mass stripping correlates with radius, but with large scatter

Velocities only mildly radial $v_r/v_t = 1.1\text{-}1.5$

45% of satellites moving outward regardless of stripping threshold

Many satellite galaxies tidally disrupt into ICL instead of merging with central galaxy

Monaco et al. 06
Conroy, Ho & White 07
Purcell, Bullock & Zentner 07
M. White et al. 07

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Robust comparison with observation via spatial clustering

$$w_p(r_p) = \int_{-\pi_{\max}}^{\pi_{\max}} d\pi \, \xi(r_p, \pi) \qquad P(r) = n dV[1+\xi(r)]$$

Direct observable

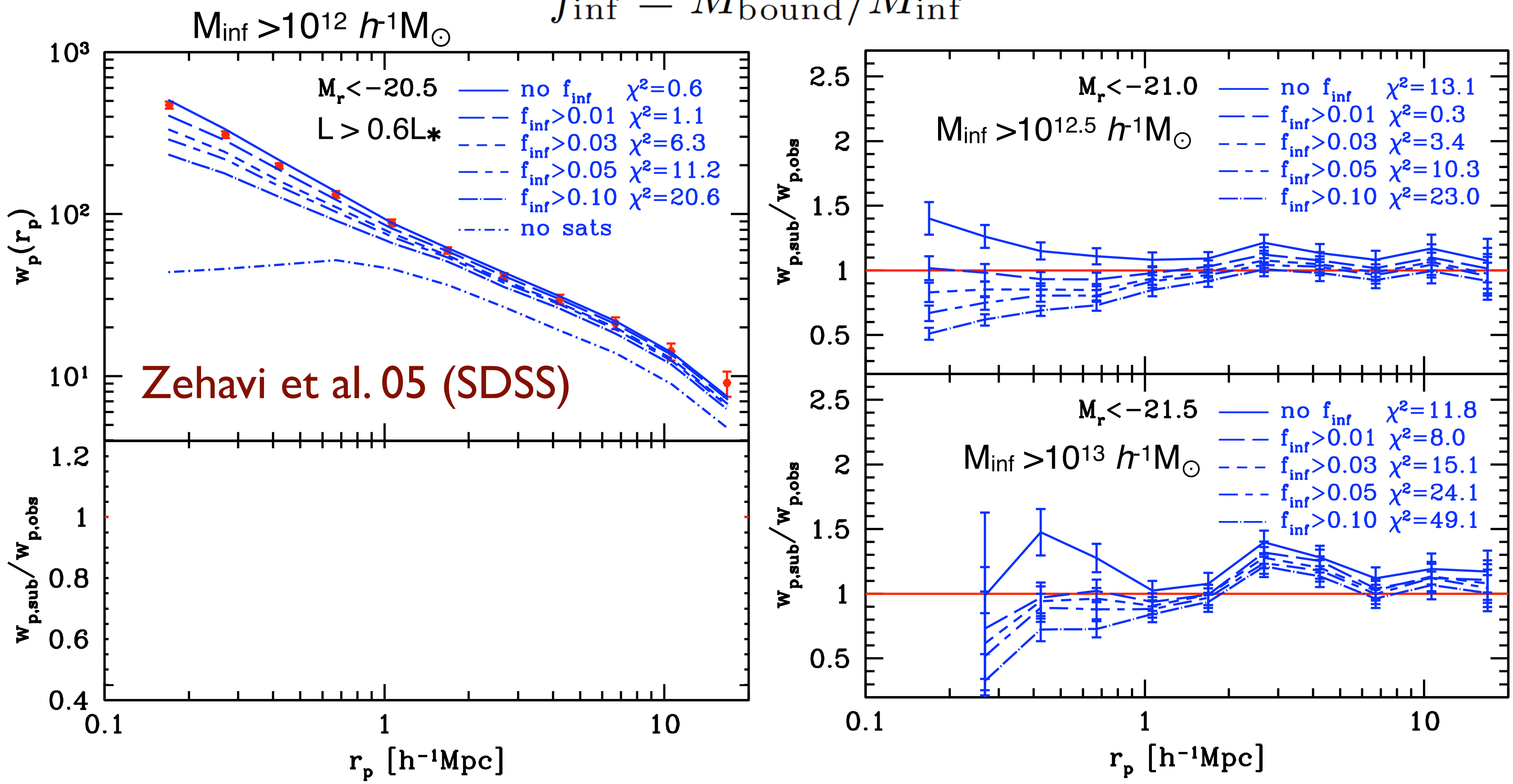
Scale-dependent test of subhalo-galaxy relation

Lower threshold for removal → higher satellite fraction → increased large- and small-scale clustering amplitude

Abundance match to luminosity threshold samples from SDSS Zehavi et al. 05

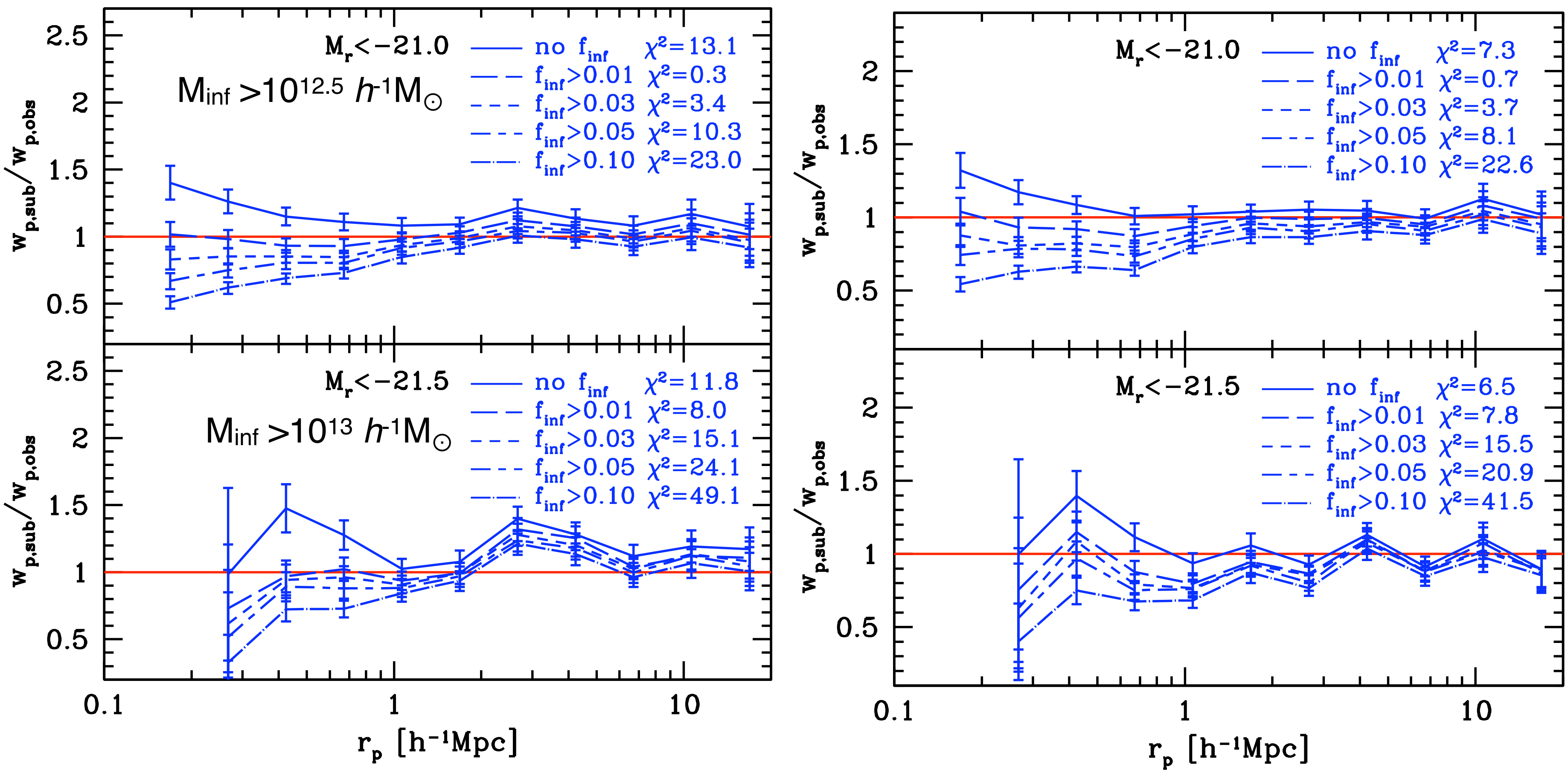
Excellent agreement using $f_{inf} \approx 0.01$

$$f_{\rm inf} = M_{\rm bound}/M_{\rm inf}$$



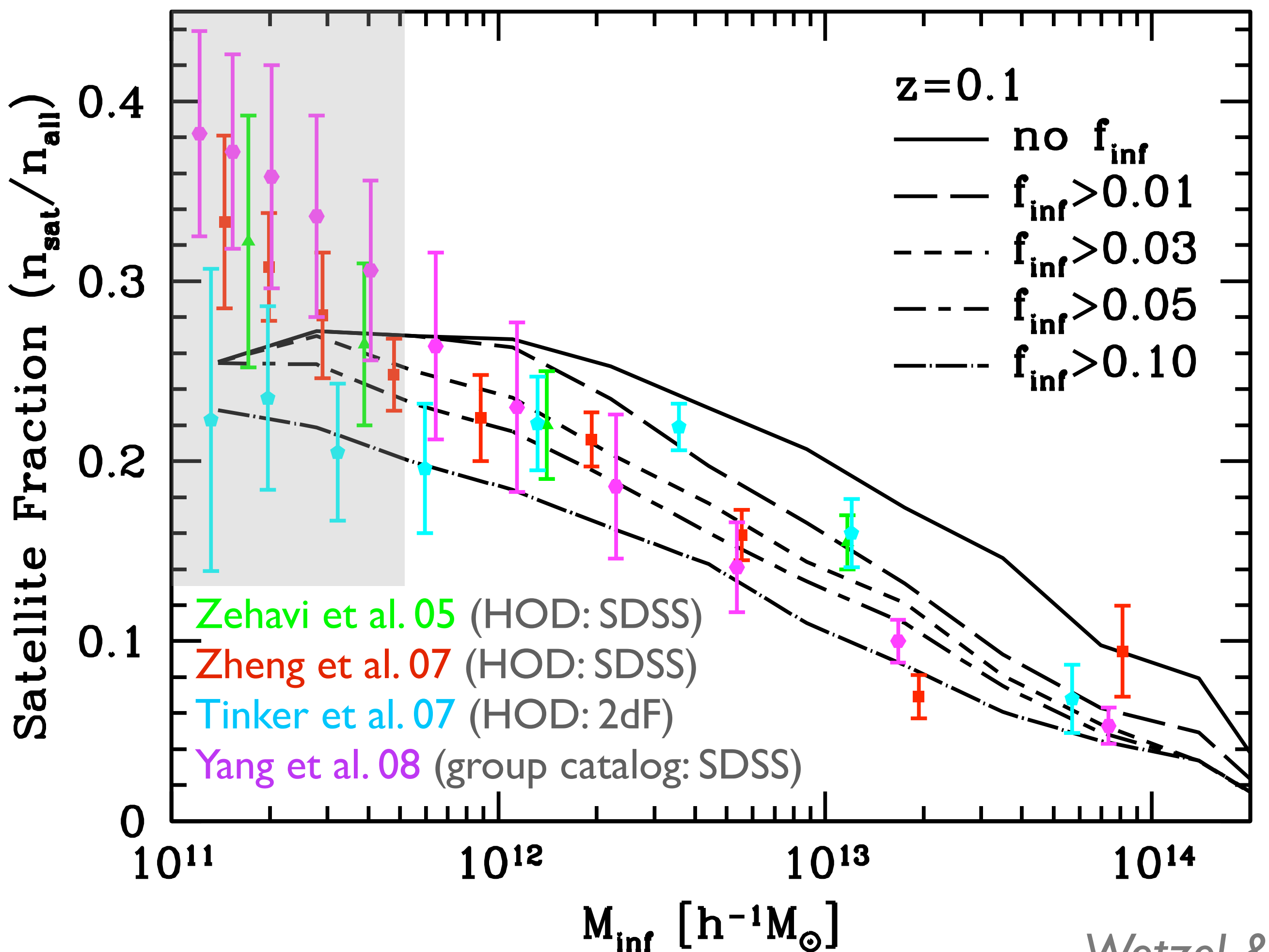
Consistent with L_r-M_{inf} scatter

no scatter $f_{\rm inf} = M_{\rm bound}/M_{\rm inf}$ 0.2 dex scatter



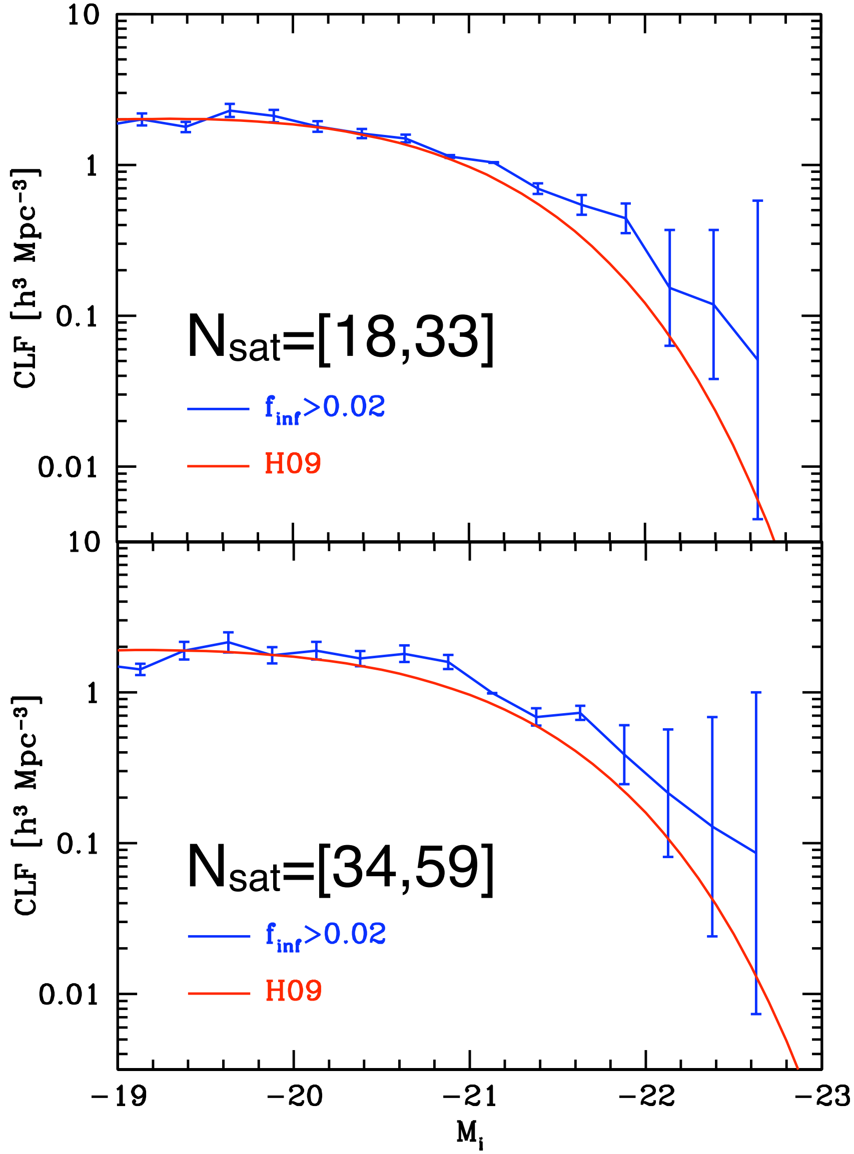
Consistent with observed satellite fractions

$$f_{\rm inf} = M_{\rm bound}/M_{\rm inf}$$



Wetzel & White 09

Consistent with observed galaxy cluster satellite luminosity function



Abundance matched to Sheldon et al. 08 luminosity function z=0.25 (SDSS)

Cluster Luminosity Function from Hansen et al. 09

Model robust even in dense galaxy cluster environment

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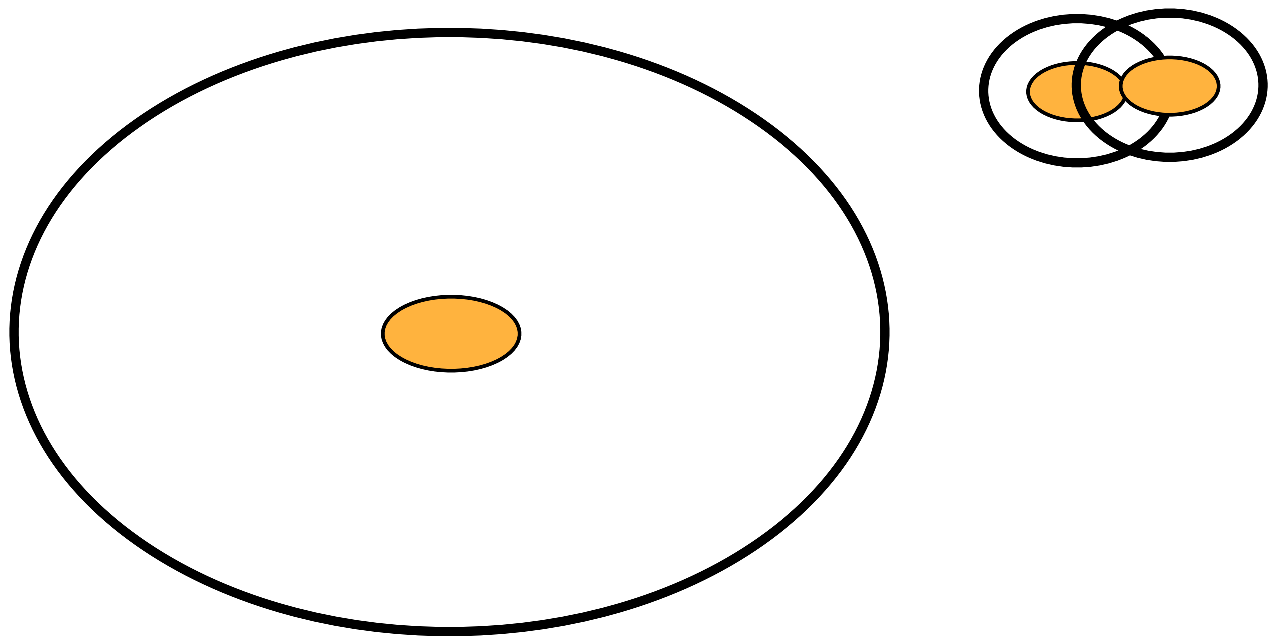
Dynamical Friction Infall Time



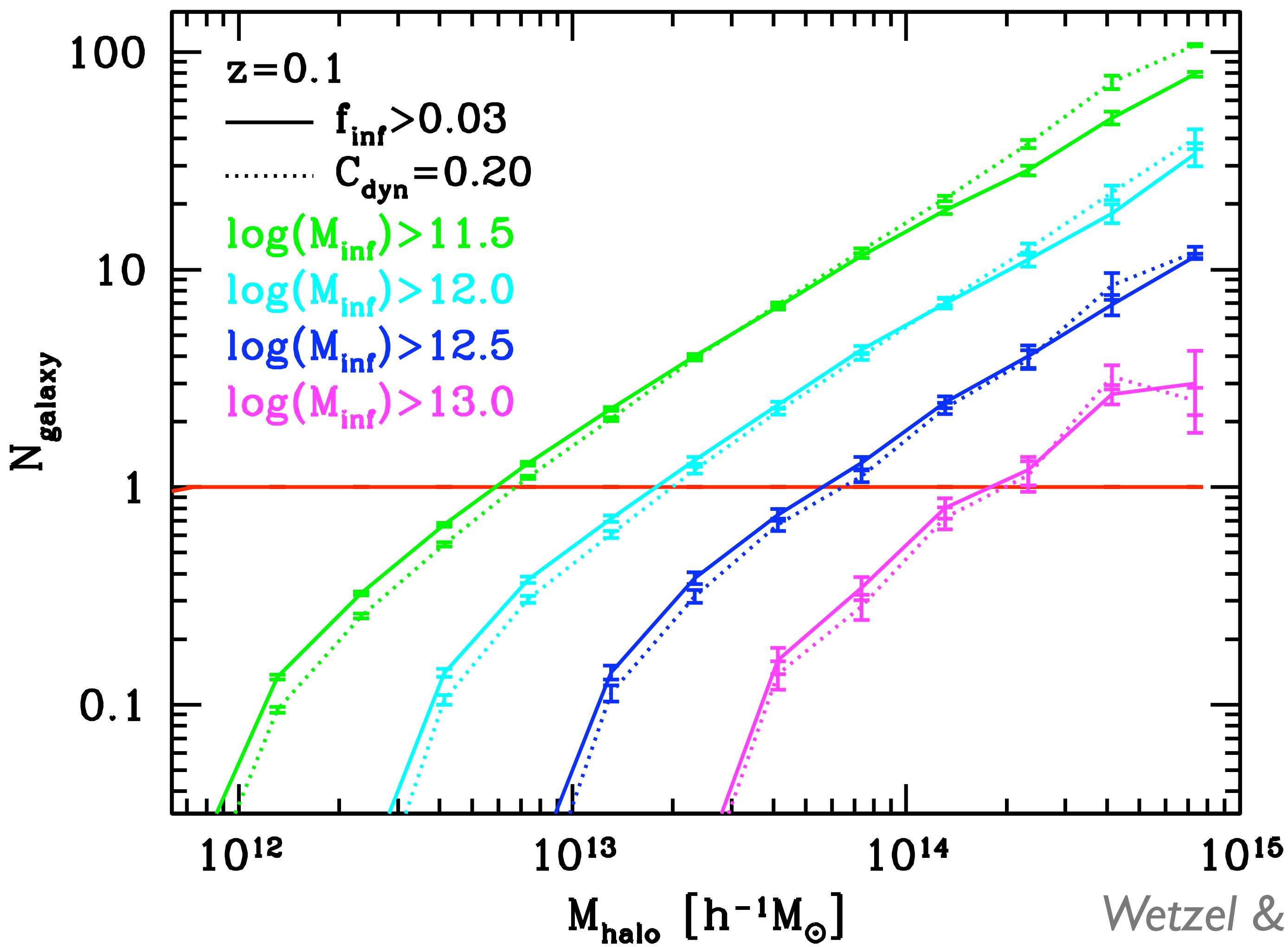
$$t_{\rm dyn} = C_{\rm dyn} \; \frac{M_{\rm halo}/M_{\rm sat,inf}}{\ln(1 + M_{\rm halo}/M_{\rm sat,inf})} \; t_{\rm Hubble}$$

Chandrasekhar 43, Jiang et al. 08, Boylan-Kolchin et al. 08

Ingredient to many semi-analytic models

Analytic model agrees with subhalo catalog

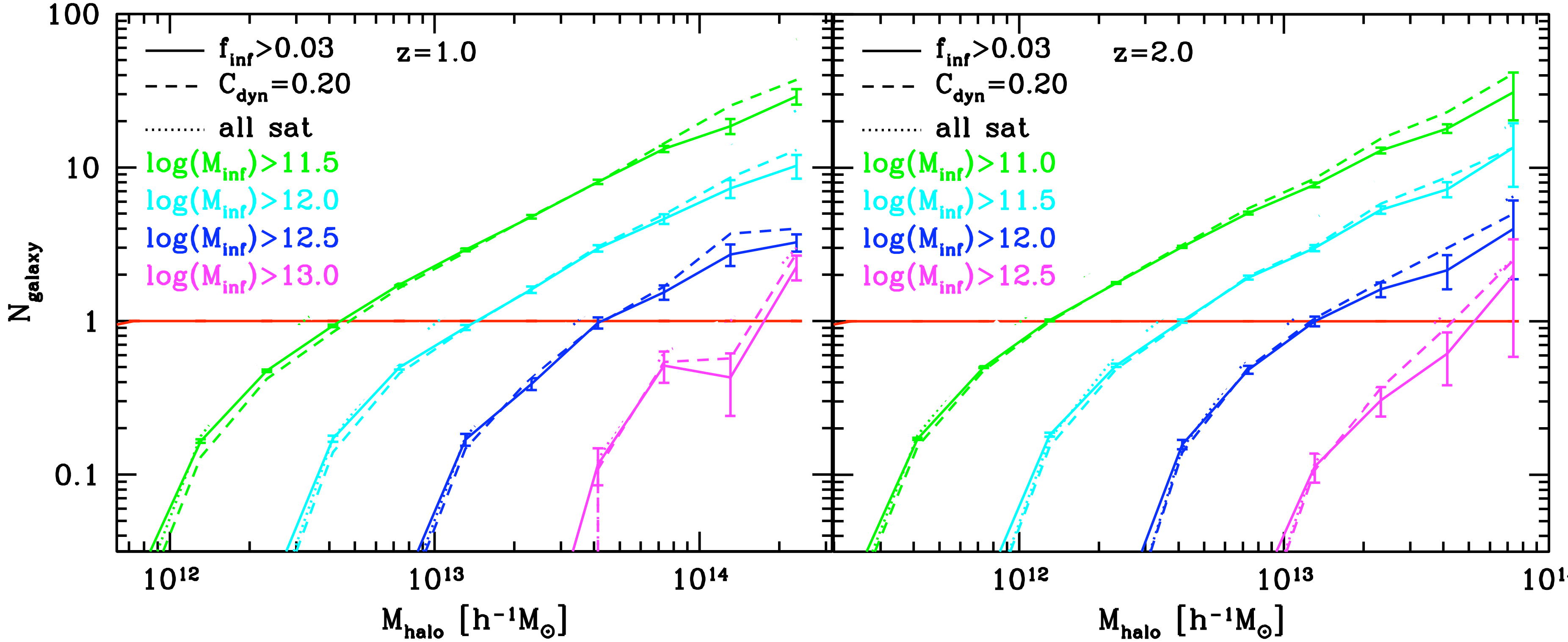
$$t_{\rm dyn} = C_{\rm dyn}\ \frac{M_{\rm halo}/M_{\rm sat,inf}}{\ln(1+M_{\rm halo}/M_{\rm sat,inf})}\ t_{\rm Hubble}$$



Wetzel & White 09

Analytic model agrees with subhalo catalog at high z

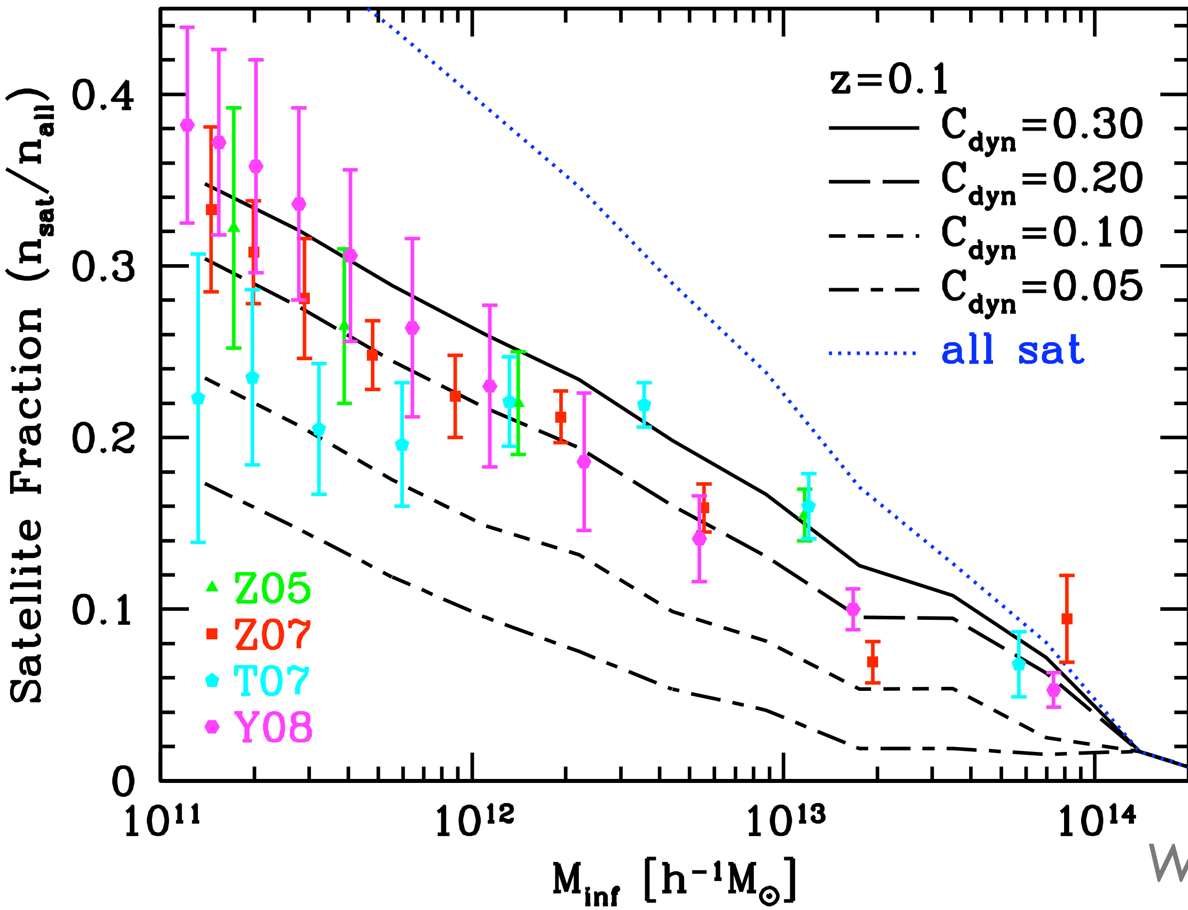
$$t_{\rm dyn} = C_{\rm dyn}\ \frac{M_{\rm halo}/M_{\rm sat,inf}}{\ln(1 + M_{\rm halo}/M_{\rm sat,inf})}\ t_{\rm Hubble}$$



Wetzel & White 09

Analytic model agrees with observations

$$t_{\rm dyn} = C_{\rm dyn} \frac{M_{\rm halo}/M_{\rm sat,inf}}{\ln(1 + M_{\rm halo}/M_{\rm sat,inf})} t_{\rm Hubble}$$



Wetzel & White 09

C_{dyn} = 0.25 gives significantly longer infall times than fits of Jiang et al. 08, Boylan-Kolchin et al. 08

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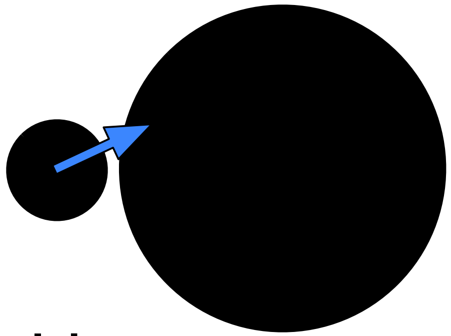
Orbital Parameters of Infalling Halos

(in prep.)



Halo evolution

Mass assembly & angular momentum build-up

Satellite subhalo evolution

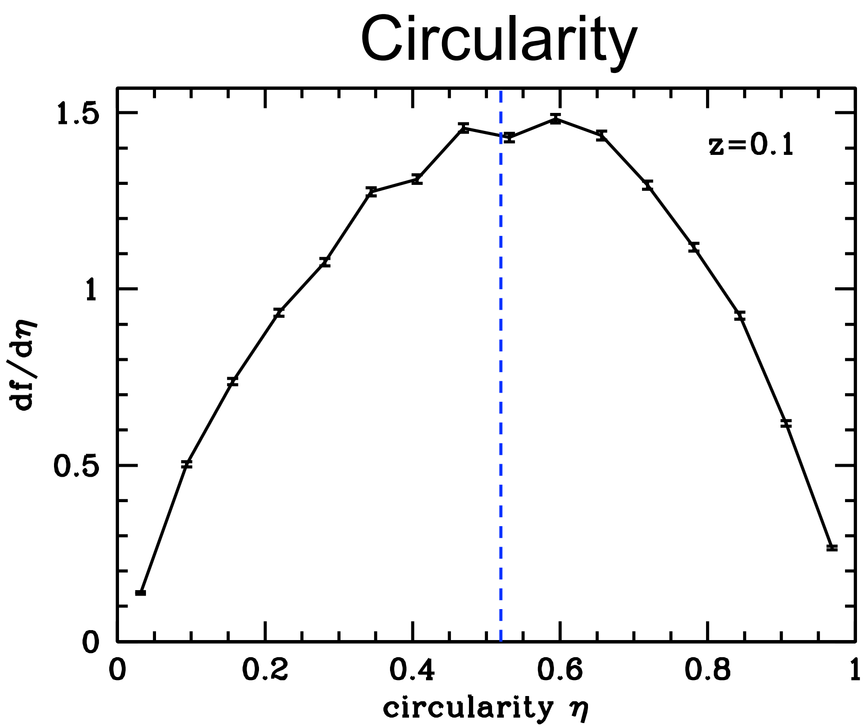
Initial conditions for analytic satellite infall timescales & mass stripping

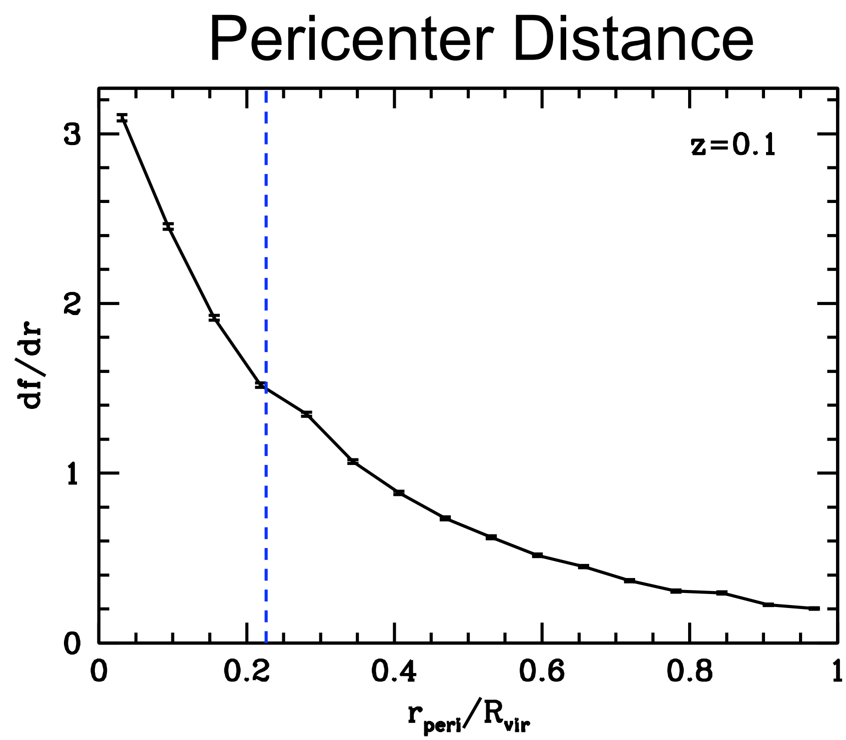
Galaxy evolution

Galaxy merger rate

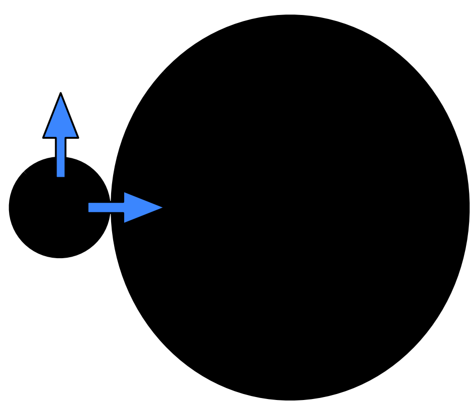
Quenching of satellite star formation after infall

Satellite infall orbital distribution at z~0





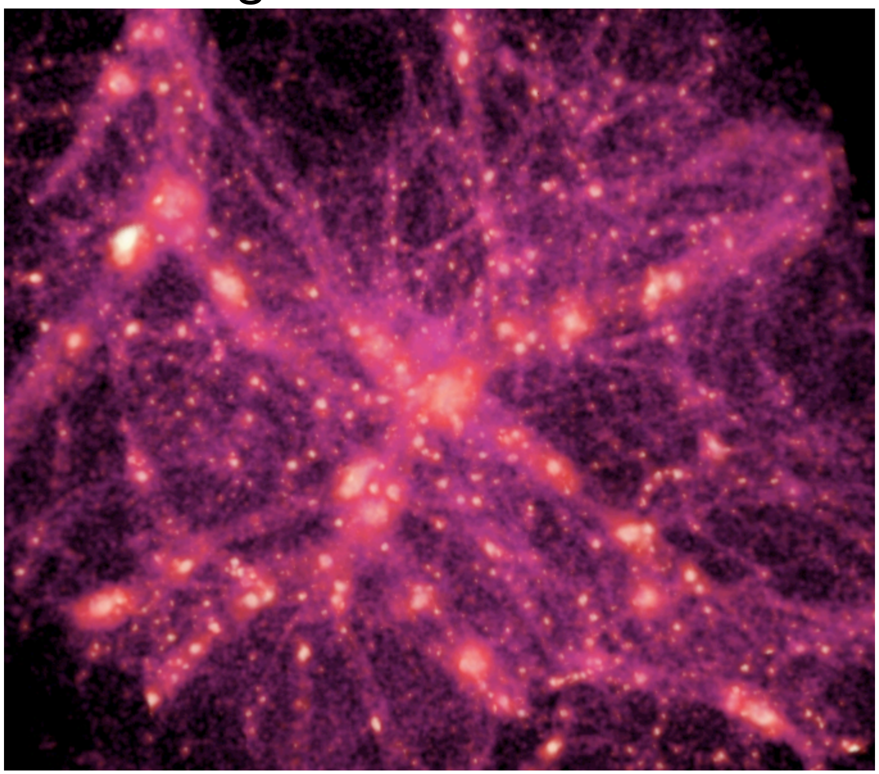
Wetzel in prep.



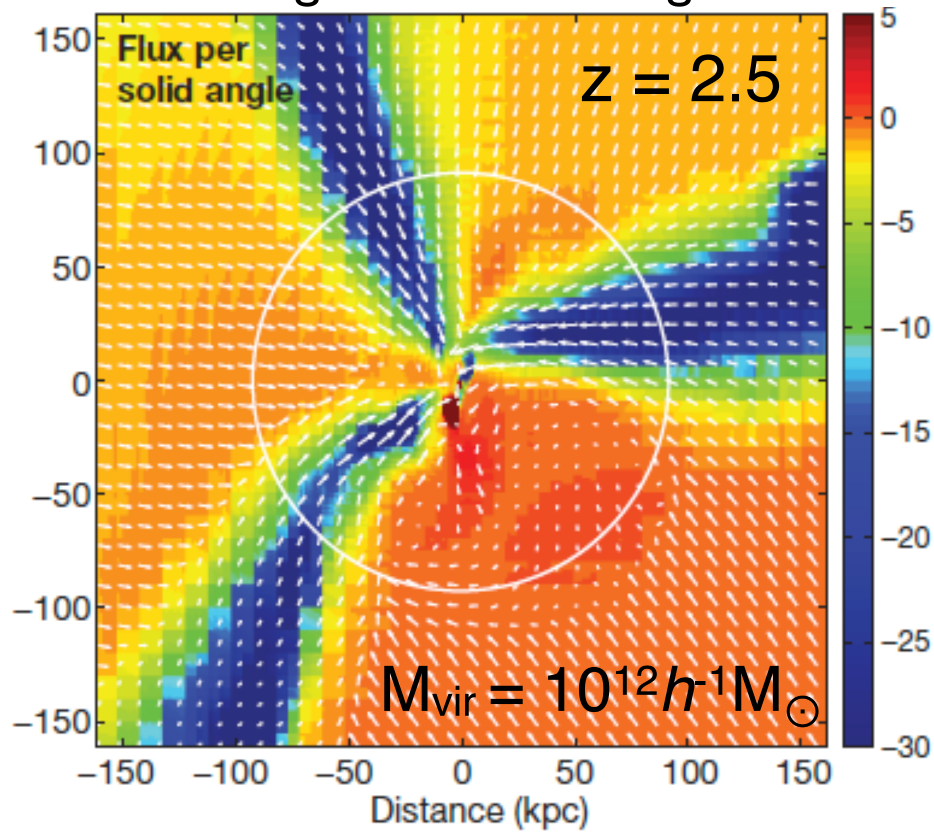
also:
Zentner et al. 05, Benson 05,
Wang et al. 05, Khochfar & Burkert 06

Does matter infall become more radial at higher mass or higher redshift?

Clusters at intersection of filaments
Field galaxies within filaments

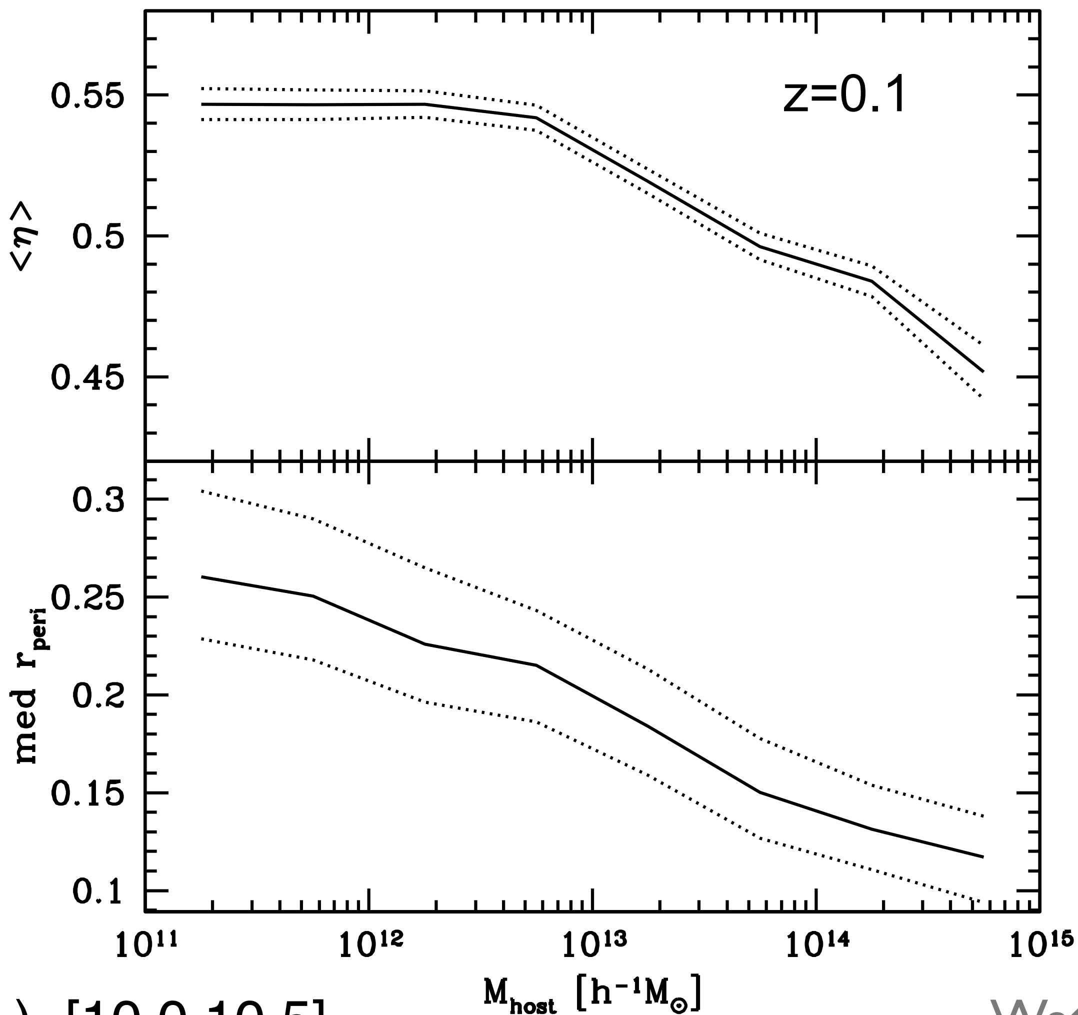


Galaxy formation via highly radial cold gas streams at high z



Dekel et al. 09

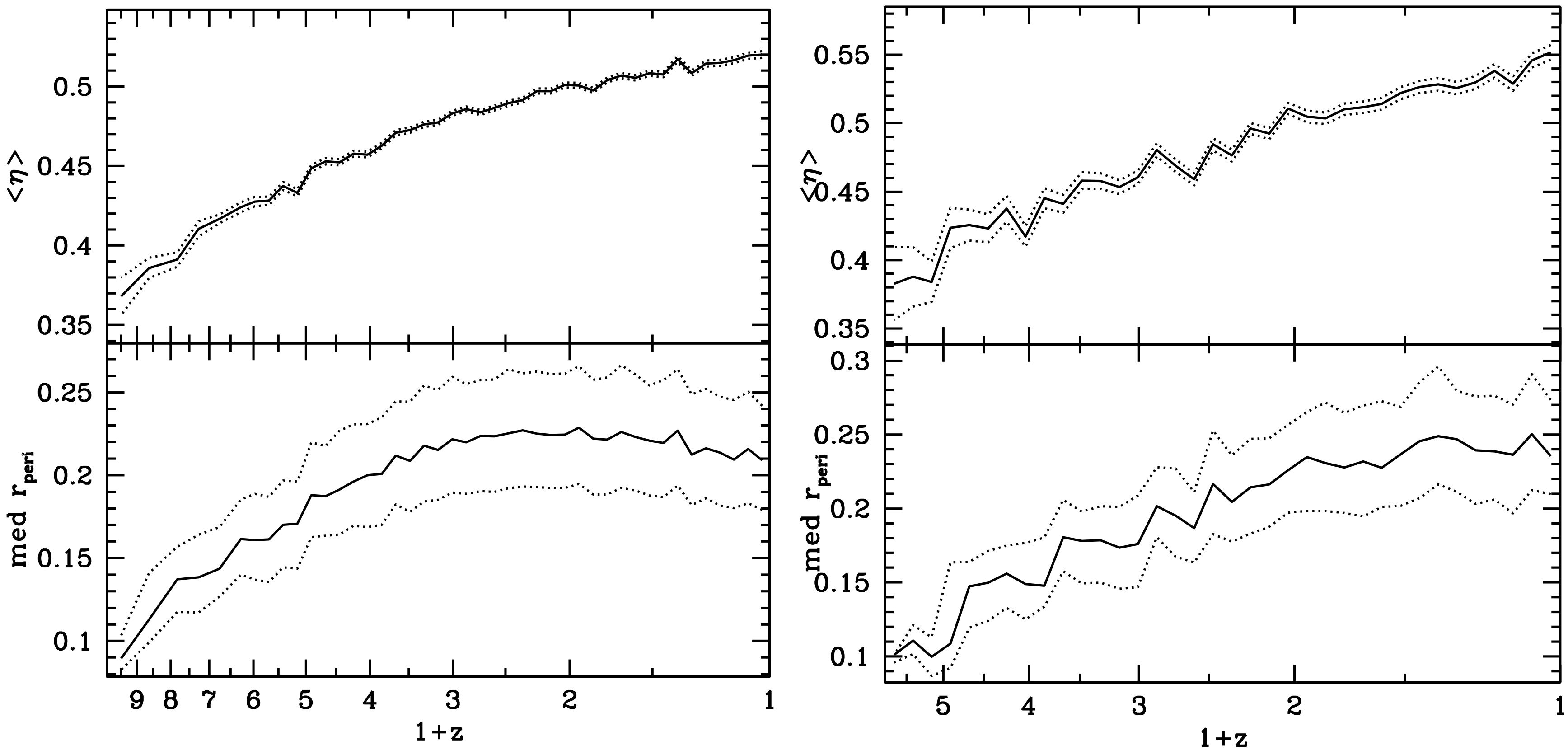
Satellite orbits are more radial & penetrate deeper at higher host halo mass



$\log(M_{sat})=[10.0,10.5]$

Wetzel in prep.

Satellite orbits are more radial & penetrate deeper at higher redshift



log(M_{halo}) > 10

Wetzel in prep.

log(M_{host}) = [12,13]

log(M_{sat}) = [10,11]

No redshift evolution at constant M/M*

Connecting galaxies to subhalos

- Galaxies are in 1-1 correspondence with subhalos
- Abundance matching $n_{sub}(>M_{infall}) = n_{gal}(>M_{star})$ to assign stellar mass/luminosity reproduces observed
  - Spatial clustering
  - Satellite fraction
  - Cluster satellite luminosity function
- Improved agreement with model for merging/disruption

Satellite galaxy merging & disruption

- What determines satellite galaxy merging/disruption?
  - Satellite subhalos must be resolved down to ~1% of infall mass, after which galaxy merging/disruption occurs
- What are the fates of satellite galaxies?
  - Most satellite galaxies merge onto central galaxy, but a *significant* fraction are tidally disrupted into Intra-Cluster Light
- Can a simple analytic model for satellite infall reproduce simulated subhalo populations and observed galaxy samples?
  - Yes, but requires significantly longer infall times
- Is there evolution in the nature infalling satellite orbits?
  - Yes, satellite orbits become more radial and penetrating at higher host halo mass and higher redshift