Dark Matter:
Halo Mergers
in ΛCDM Cosmology

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Lecture Outline

1. Halo merger rate from Millennium simulation
   - "Universal" global rate
   - Environmental dependence

2. Theoretical merger models:
   - Extended PS
   - Coagulation equation

3. Mass accretion history

Merging Spiral Galaxies

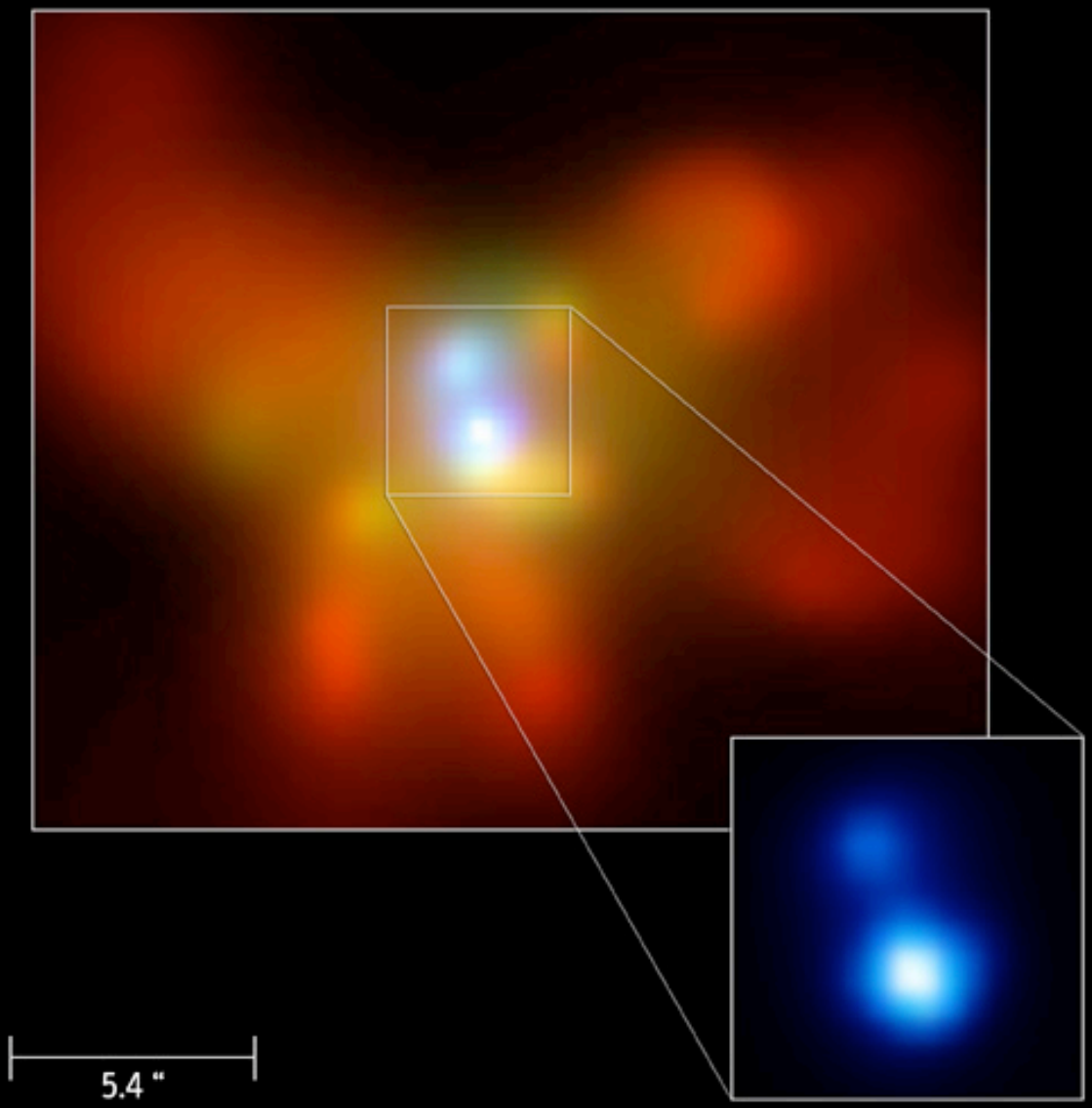
MS 1054 (z=0.83):

Evidence for pairs/mergers of ellipticals in clusters

Tran et al. (2005)

40 kpc

NGC 6240:
Two Supermassive Black Holes



The Millennium Simulation

Springel et al. (2005)

Particle number: 2160^3

Particle mass: $8.6 \times 10^8\ h^{-1}\ M_{sun}$

Box size: $500\ h^{-1}$ Mpc

Dark matter halos:

~ 18 million (from z=127 to 0)

~ 300,000 with $M > 2 \times 10^{12}\ M_{sun}$ at z=0

Halo merger trees:

constructed from 46 outputs from z=6.2 to 0

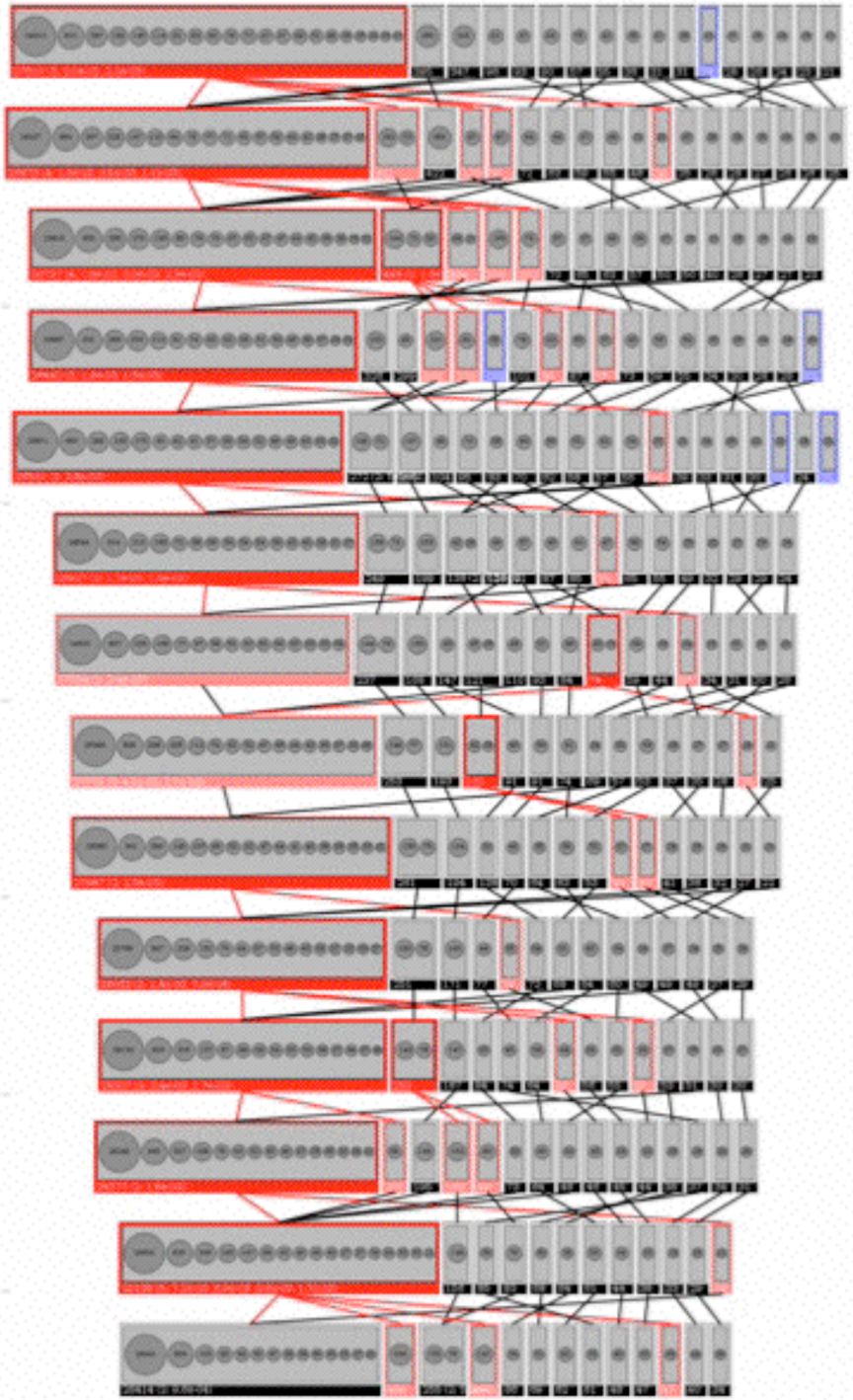
(Δz=0.02 at low z)

Millennium Merger Statistics

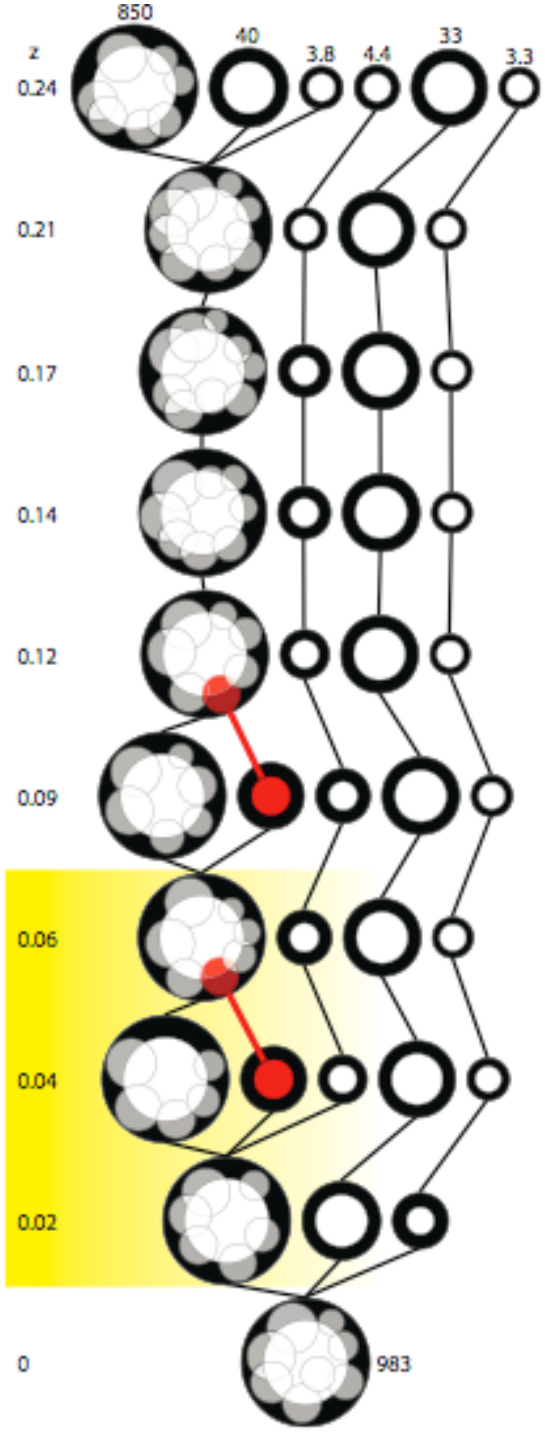
Fakhouri & Ma (2008)

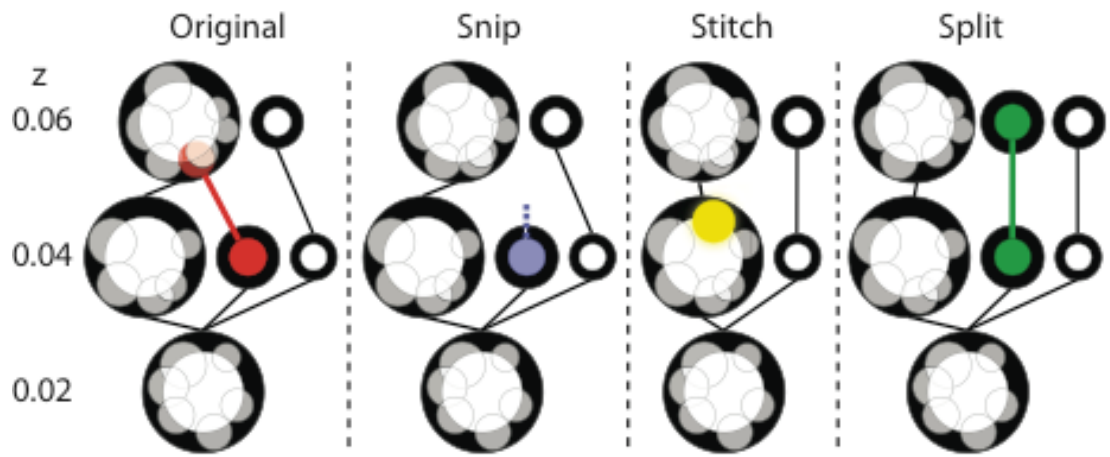
z_P:z_D	Galaxy-Scale			Group-Scale			Cluster-Scale		
	$N_p = 1$	$N_p = 2$	$N_p > 2$	$N_p = 1$	$N_p = 2$	$N_p > 2$	$N_p = 1$	$N_p = 2$	$N_p > 2$
0.06:0	188,400	65,711	27,939	1,063	2,418	13,256	3	25	5,356
0.56:0.51	189,351	61,718	22,031	1,212	2,468	9,374	6	18	3,014
1.08:0.99	145,779	68,467	35,426	325	878	7,630	0	2	1,308
2.07:1.91	76,298	52,525	39,097	31	77	2,225	0	0	129
3.06:2.83	30,641	26,675	25,072	0	4	343	0	0	4

1-1 binary mergers multiple progenitors



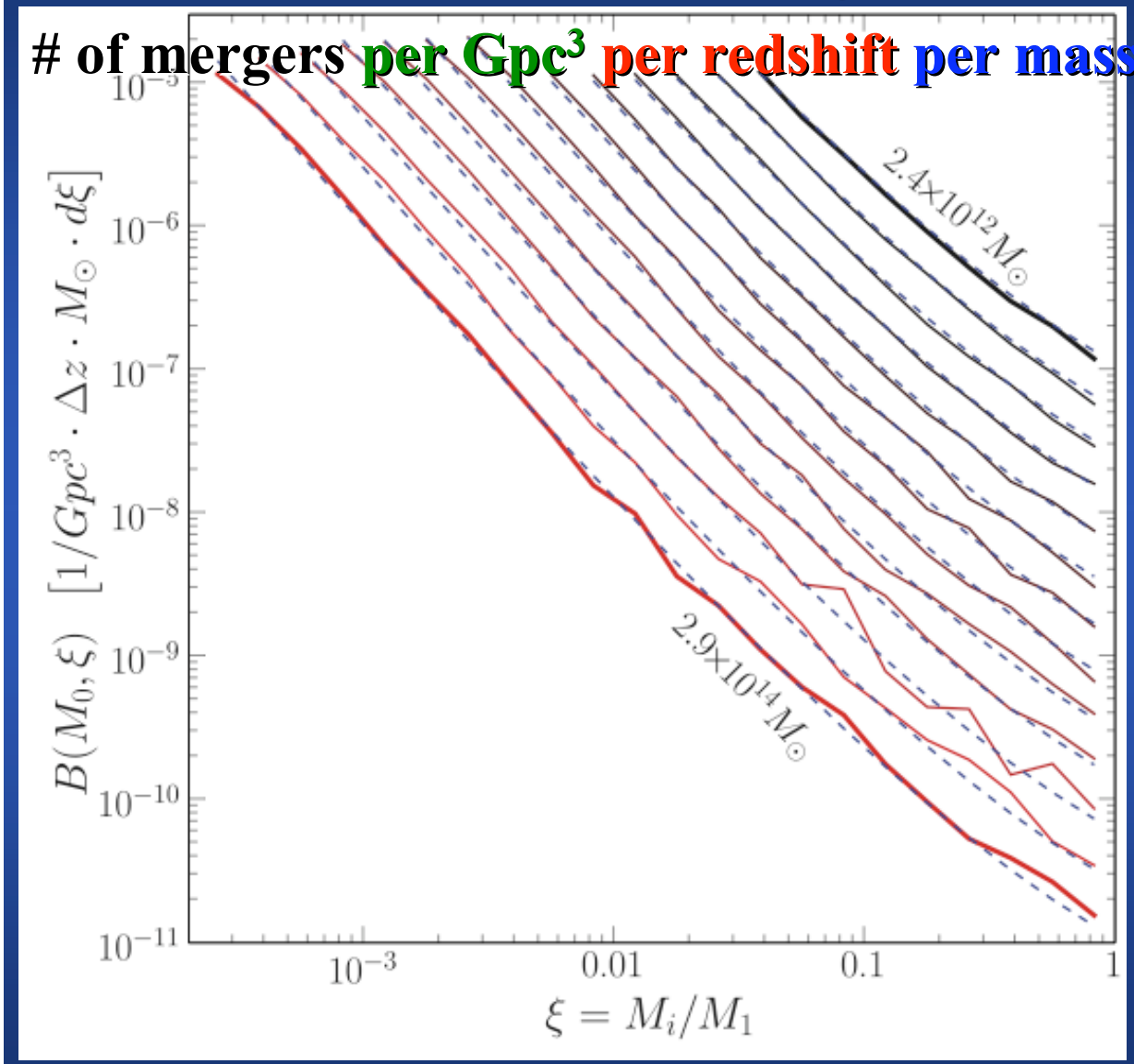
Merger Tree Construction





Fakhouri & Ma (2008,2009)

ΛCDM Merger Rate (z=0)

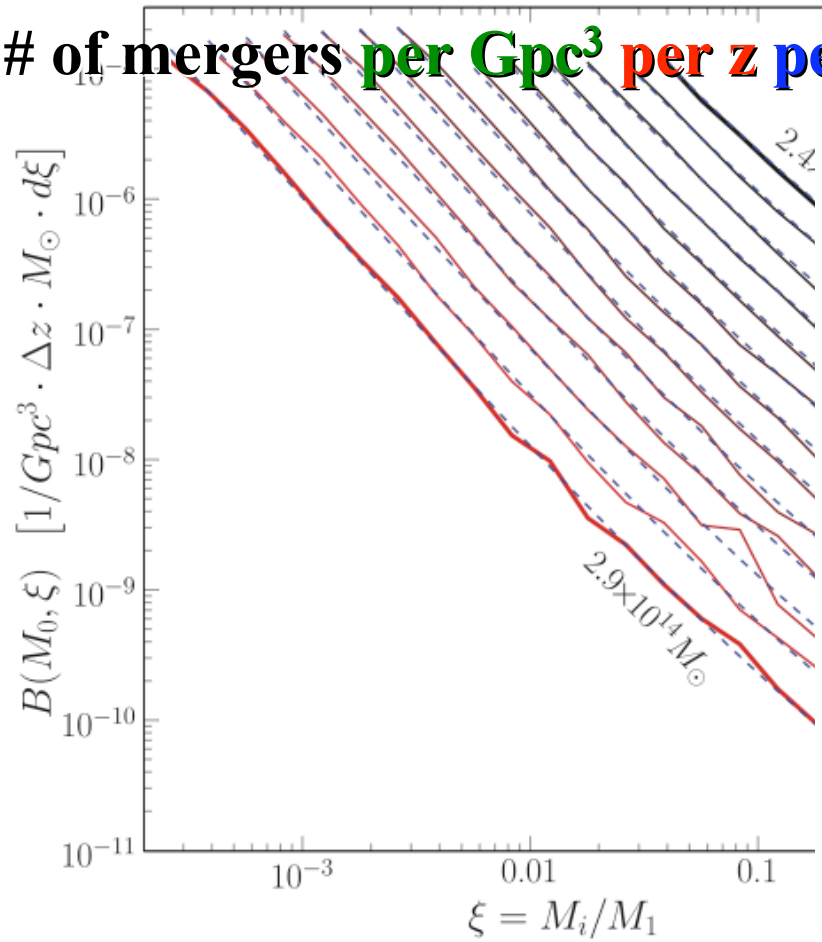


Solid: N-body
Dashed: our fit

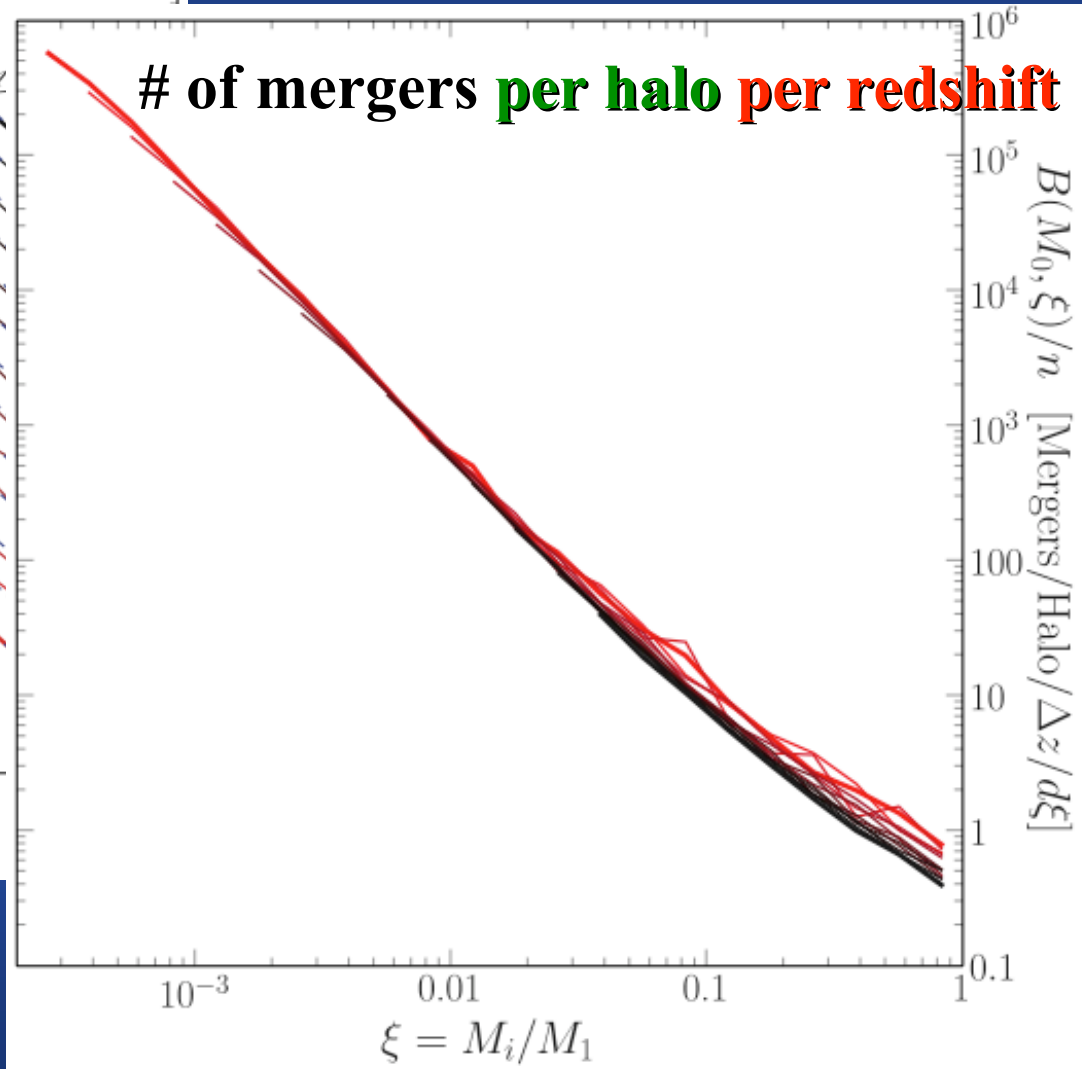
minor → **major mergers**

ΛCDM Merger Rate (z=0)

of mergers per Gpc^3 per z per mass

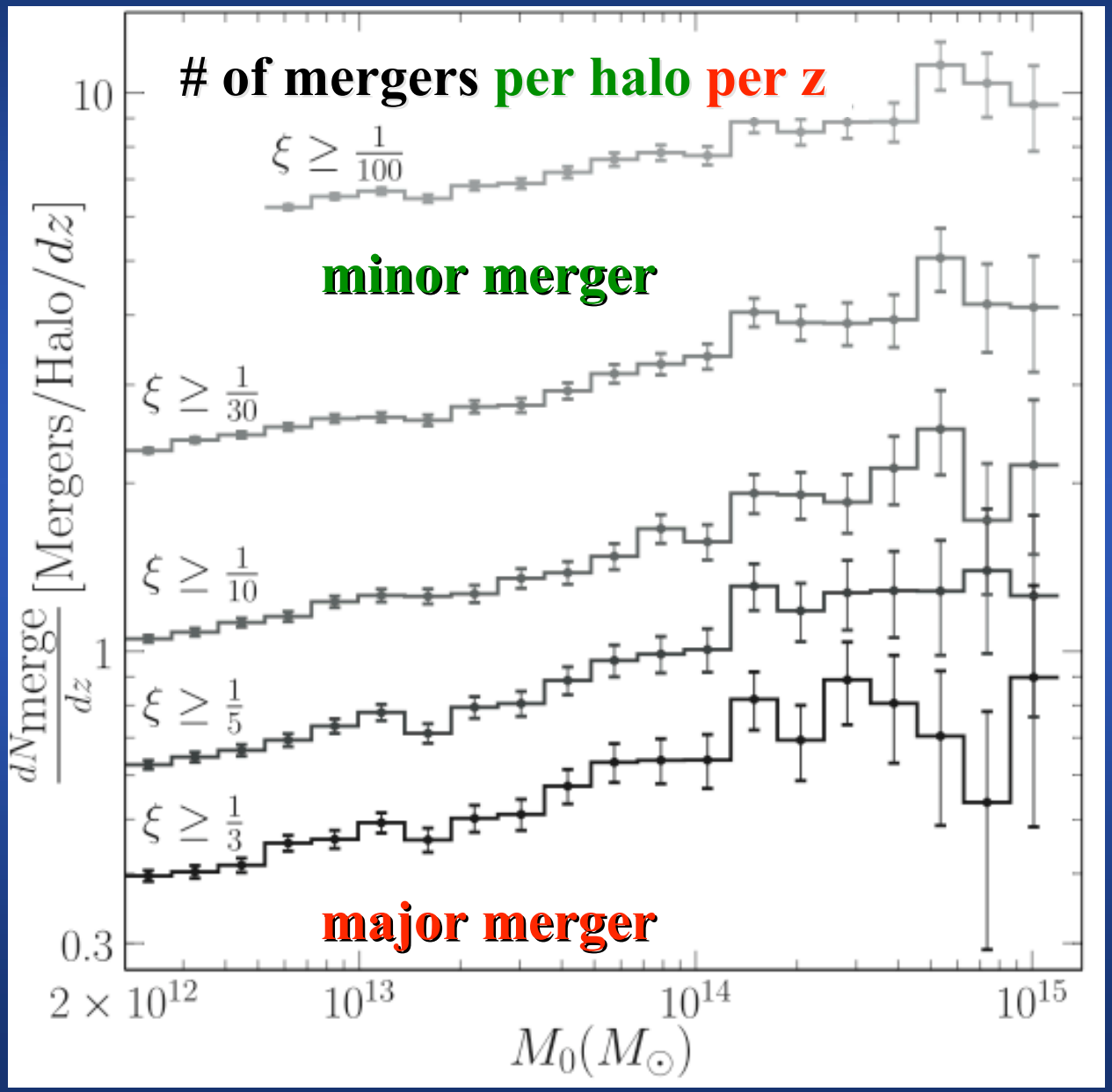


# of mergers per halo per redshift

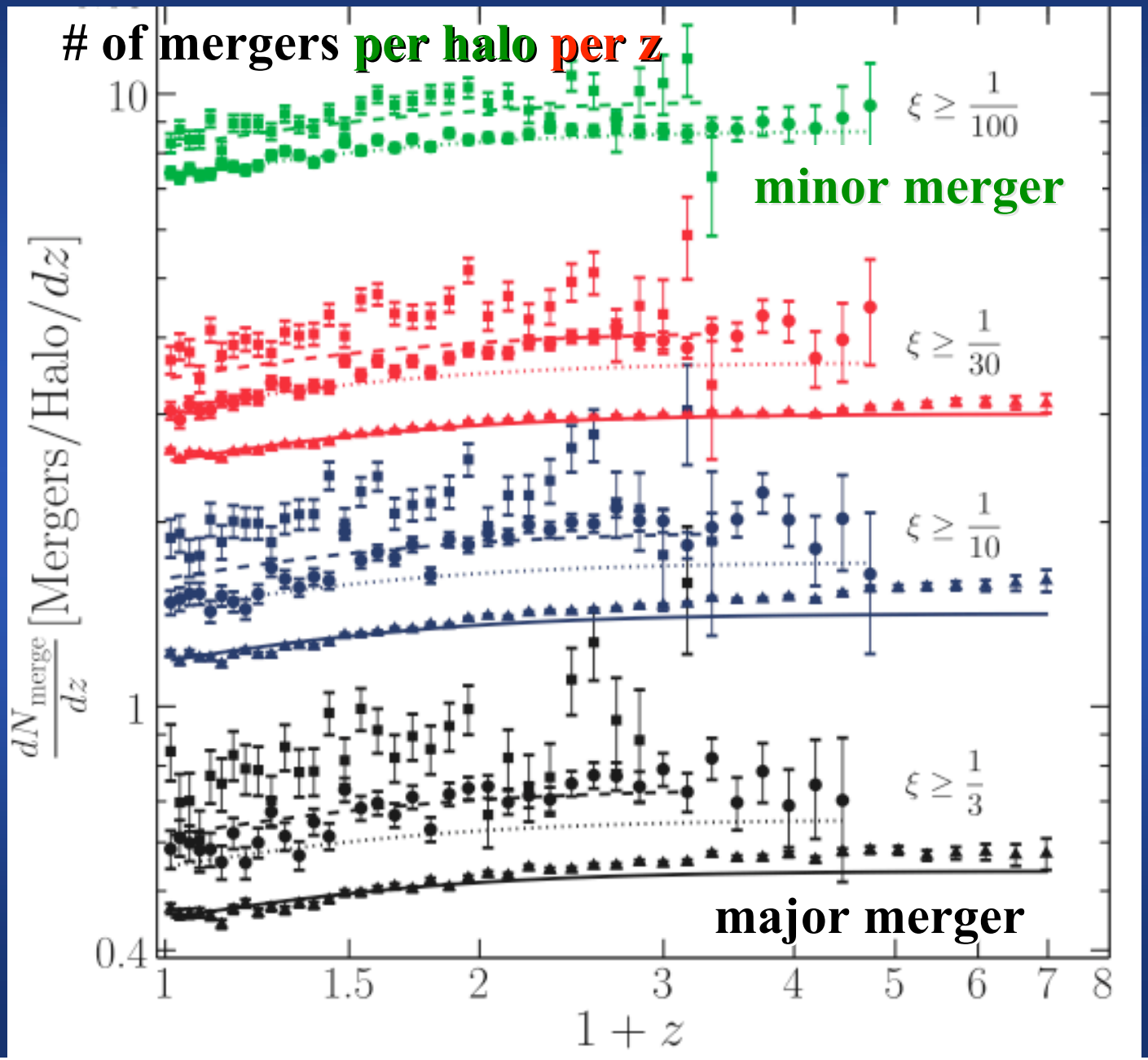


minor → major mergers

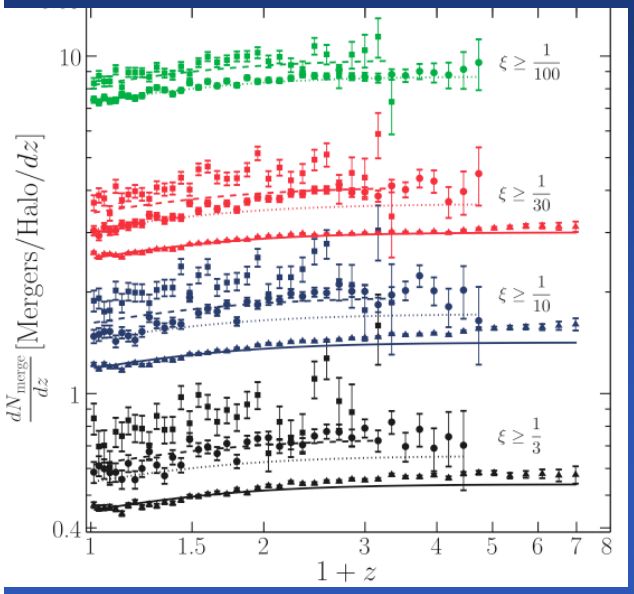
Weak Mass Dependence

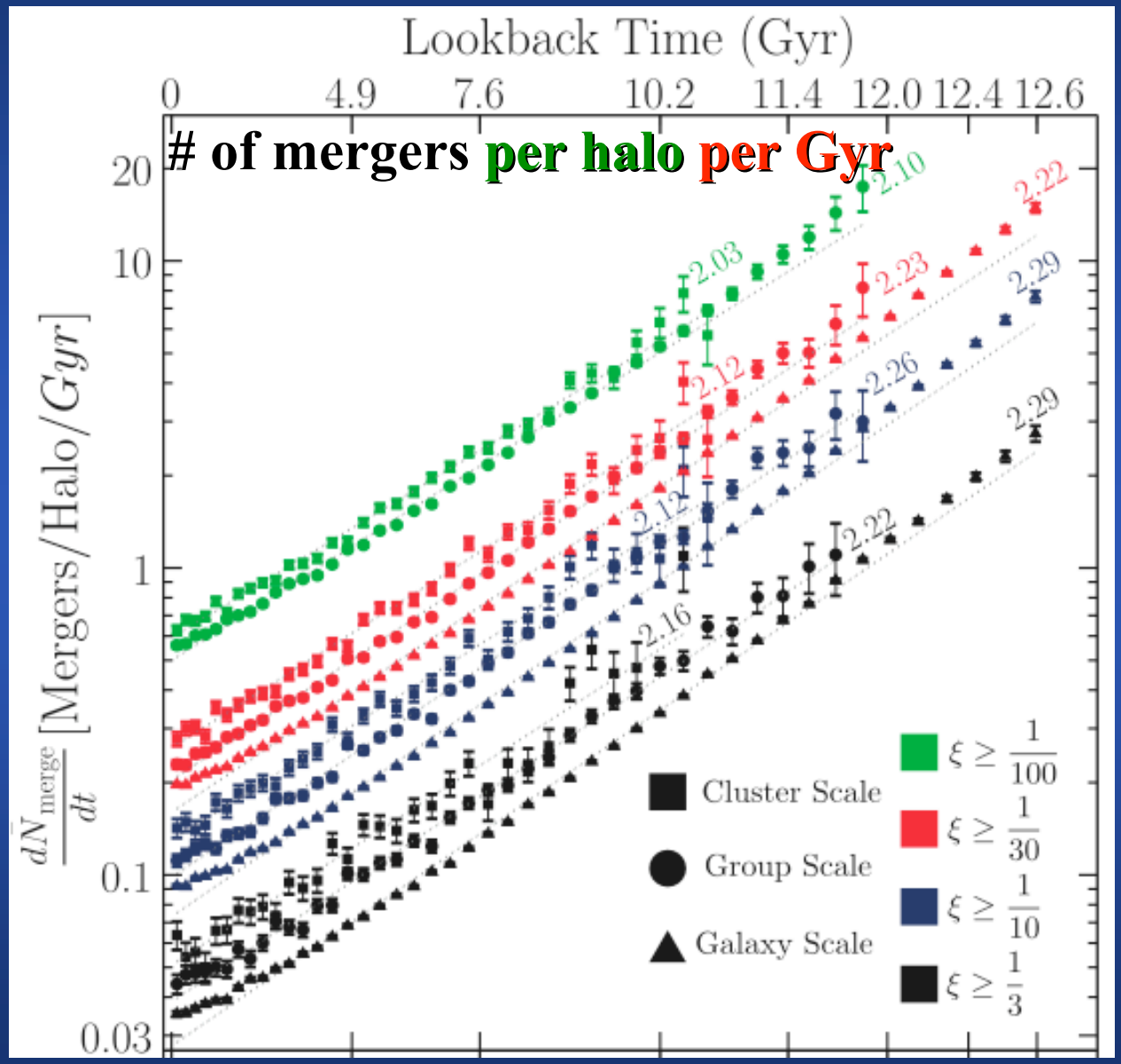


Weak Redshift Dependence



Redshift Dependence





Universal Merger Rate

Fakhouri & Ma (2008)

Mean merger rate per halo

$$\frac{B(M_0,\xi,z)}{n(M_0,z)} \propto M_0^{\alpha}\ \xi^{\beta}\ e^{\xi^{\gamma}}\ f(D(z))$$

Descendent halo mass

Progenitor mass ratio

Linear growth factor

$\alpha \approx 0.08$ $\beta \approx -2$ $\gamma \approx 0.4$

Halo Mergers ≠ Galaxy Mergers

Guo & White (2008) Stewart et al (2008)
Bundy et al (2008) Hopkins et al (2009)

M_{halo} growth ≠ M_* growth

Small galaxies: stellar growth dominated by **star formation**

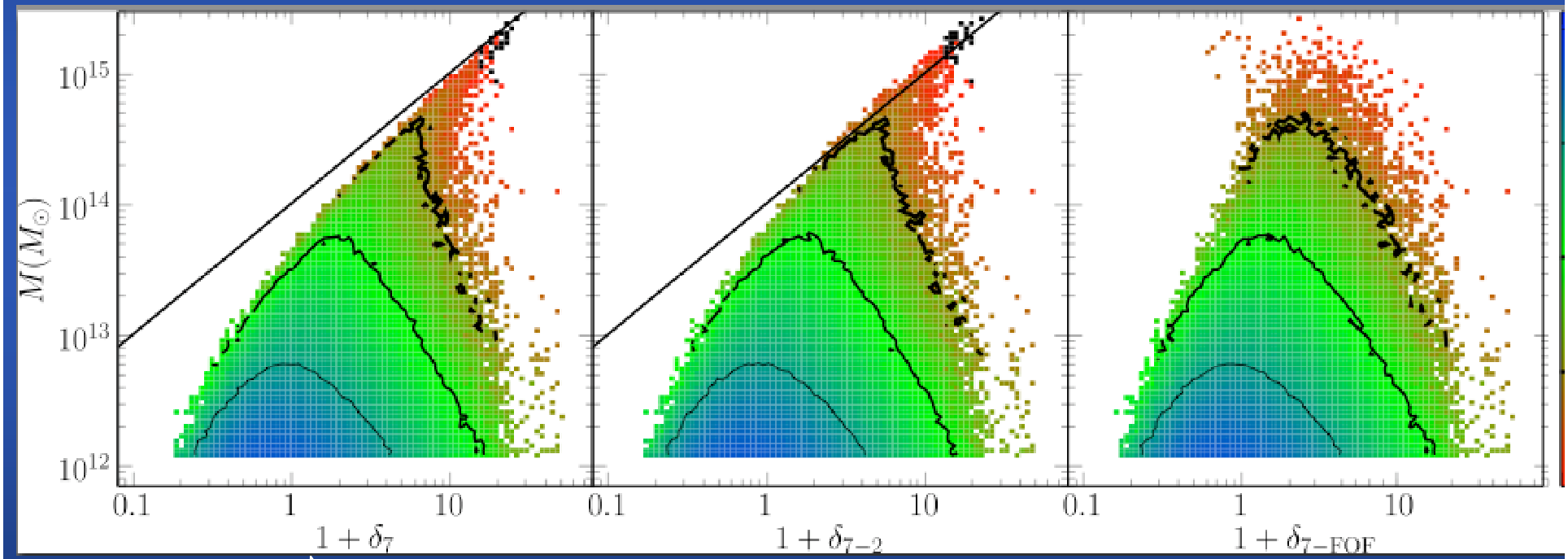
Massive galaxies: growth dominated by **mergers,** with additional merger physics (e.g. **dynamical friction**)

(See Boylan-Kolchin et al 2008:
standard merger timescale is too short)

Environmental Dependence

Fakhouri & Ma (2009a)

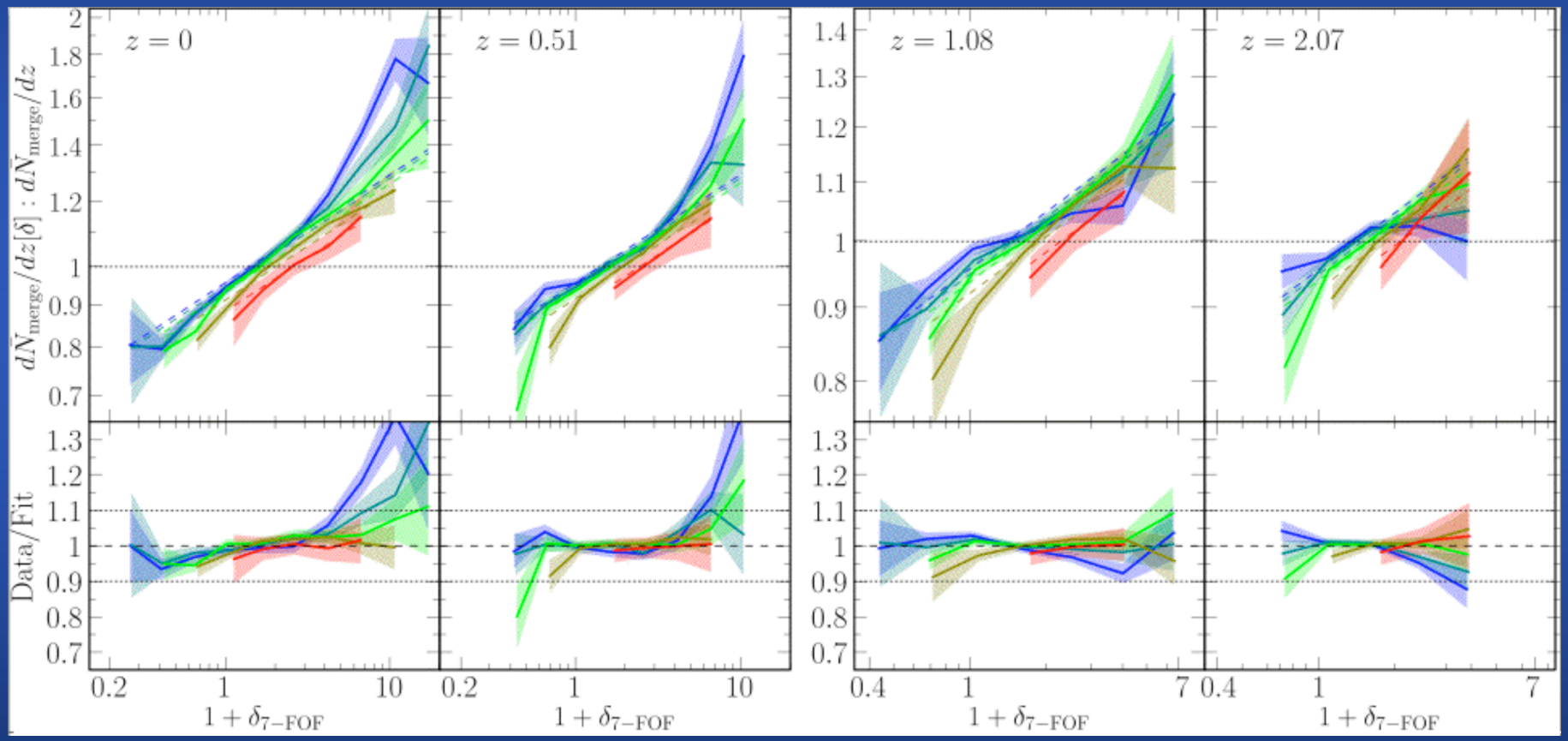
Three measures of local density



void → dense

Environmental Dependence

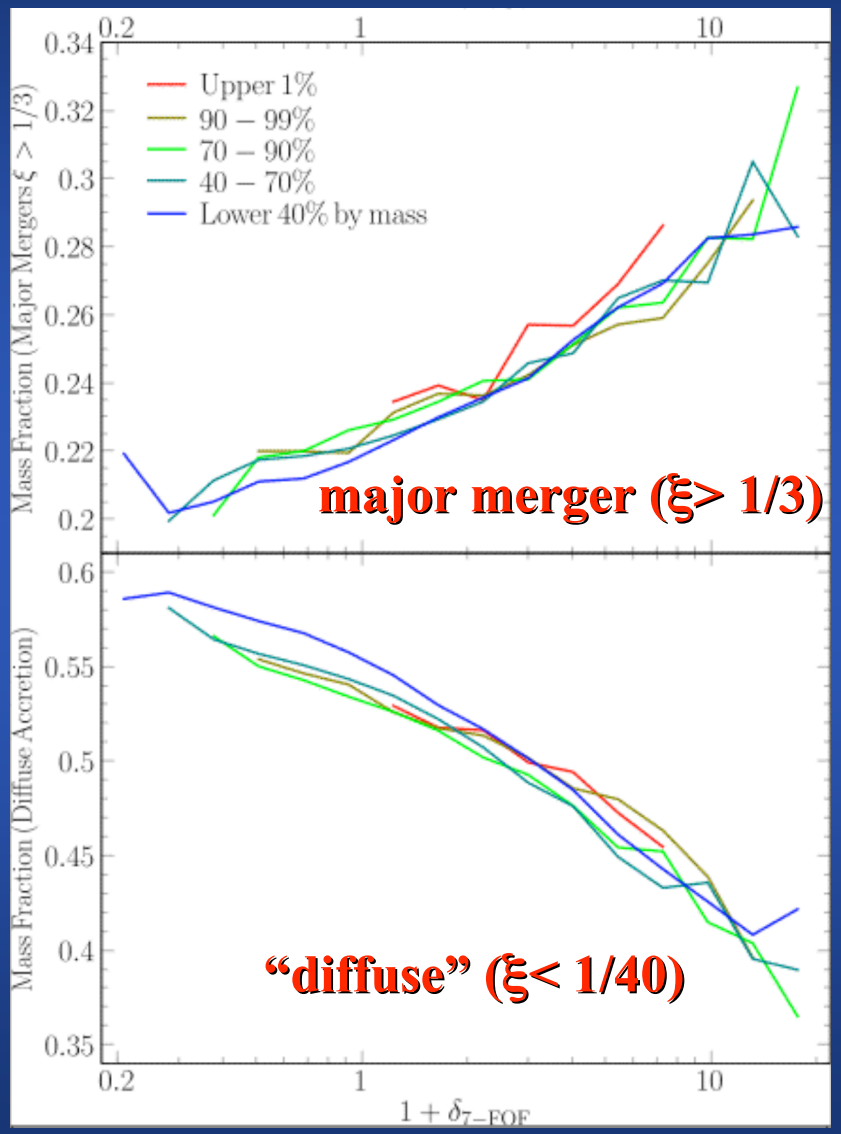
Higher merger rates in denser environments



void → dense

Fakhouri & Ma (2009a)

Environmental Dependence

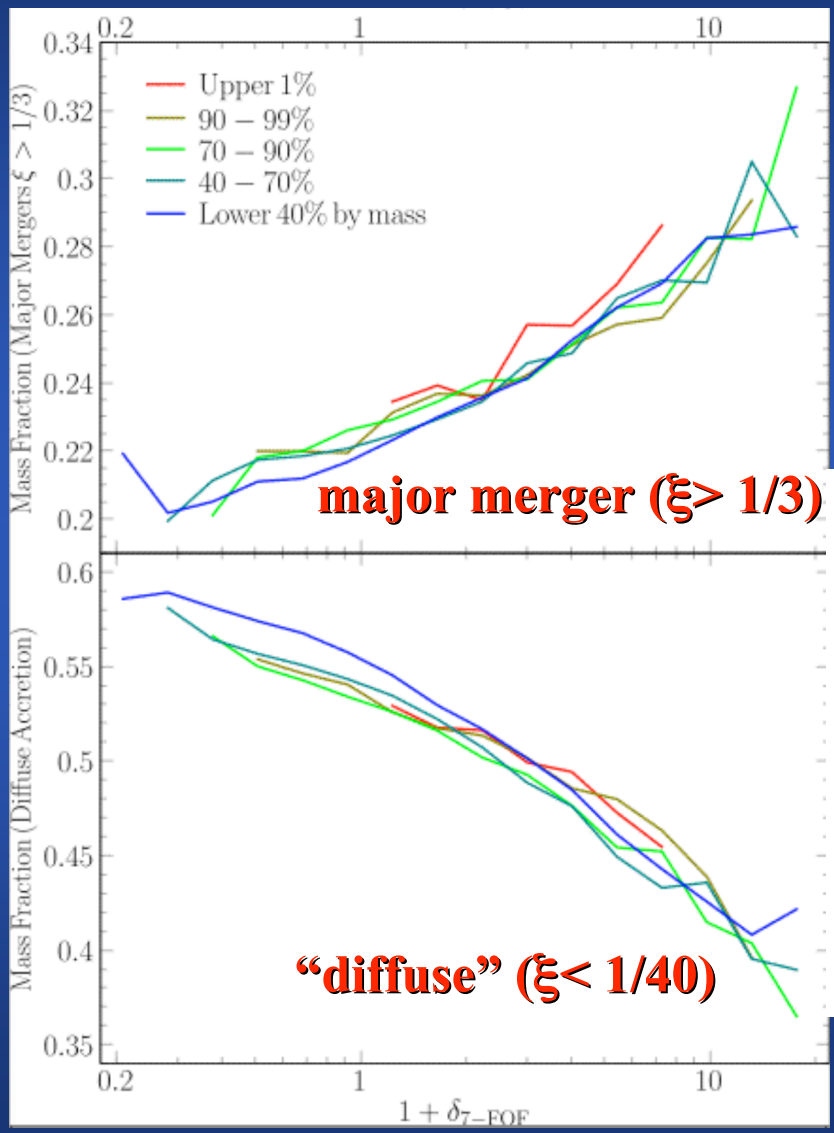


void → dense

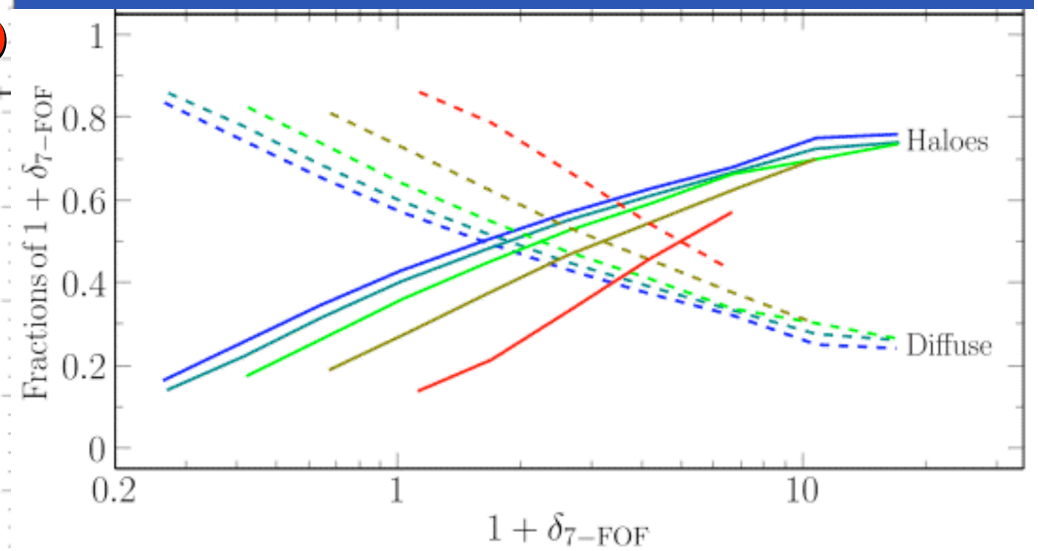
In denser environments,
a higher fraction of
a halo's final mass
is gained via major mergers.

Fakhouri & Ma (2009b)

Environmental Dependence



In **denser** environments, a **higher** fraction of the **mass reservoir** surrounding a halo is in halos.

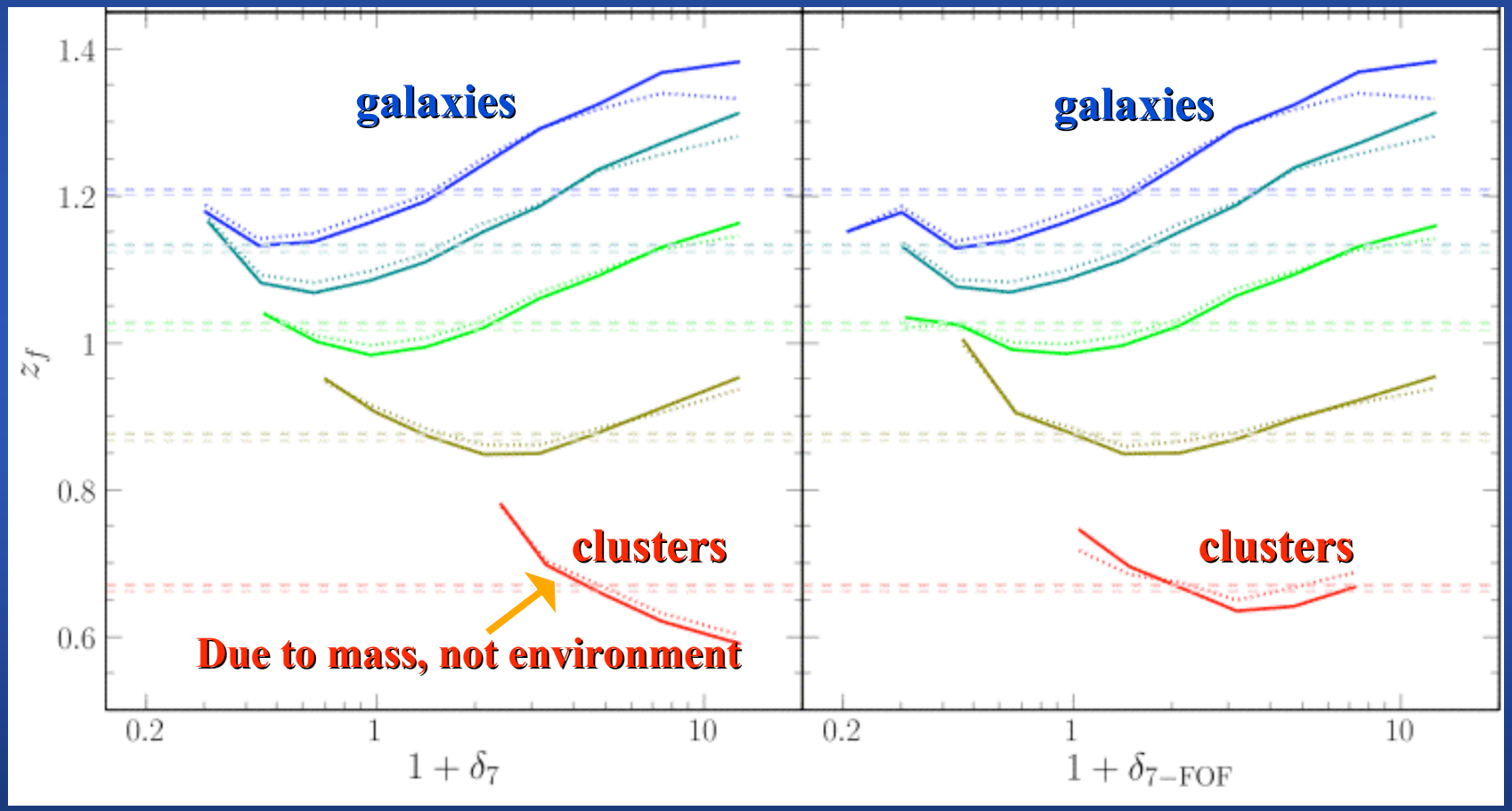


void → **dense**

Fakhouri & Ma (2009b)

Environmental Dependence

Formation redshift: older halos live in denser environment (at a give mass)



void → dense

Fakhouri & Ma (2009b)

Summary

We've measured halo merger rates from the Millennium simulation.

The global mean rate of mergers is well fit by a simple universal form as a function of m_0, m_2/m_1, redshift

⇒The rate (per unit z) depends weakly on m_0 and redshift

⇒The rate (per Gyr) increases as (1+z)^p, p~2 to 2.3

Merger rates also depend on halo environment.

⇒ Higher merger rates in denser regions

Halos gain mass by mergers and "diffuse" accretion

⇒ Lower accretion rates in denser regions

⇒ Higher formation redshifts (i.e. older halos) in denser regions