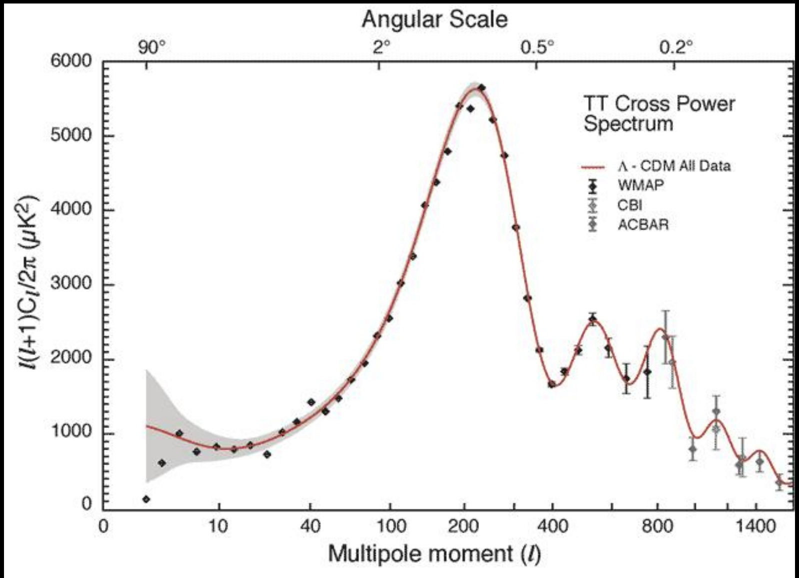
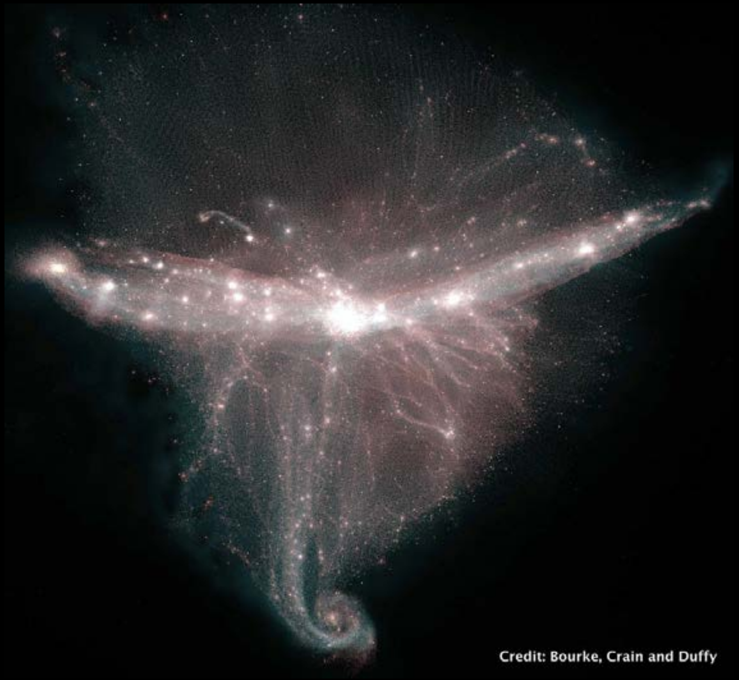
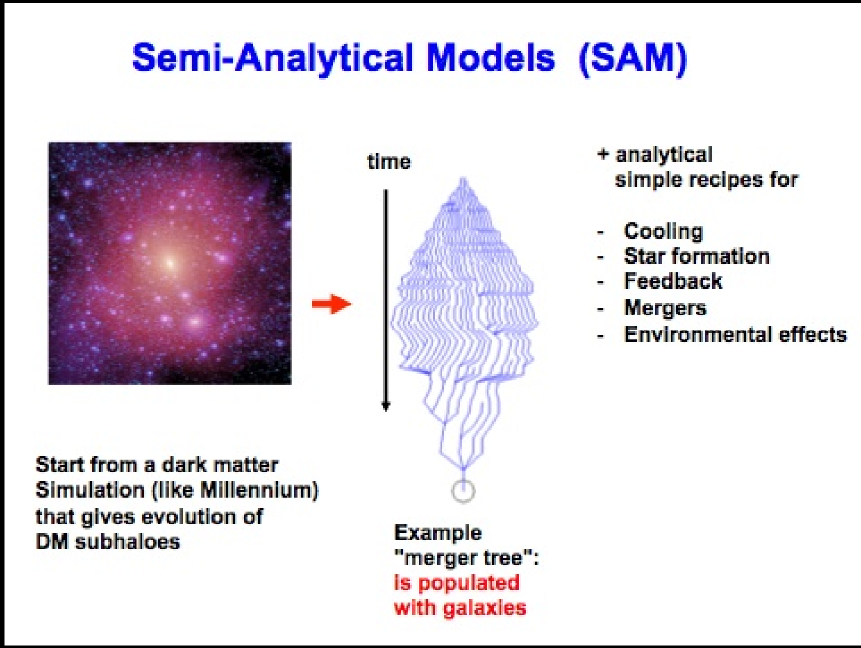
What does galaxy formation tell us about the Universe?

Christopher J. Conselice

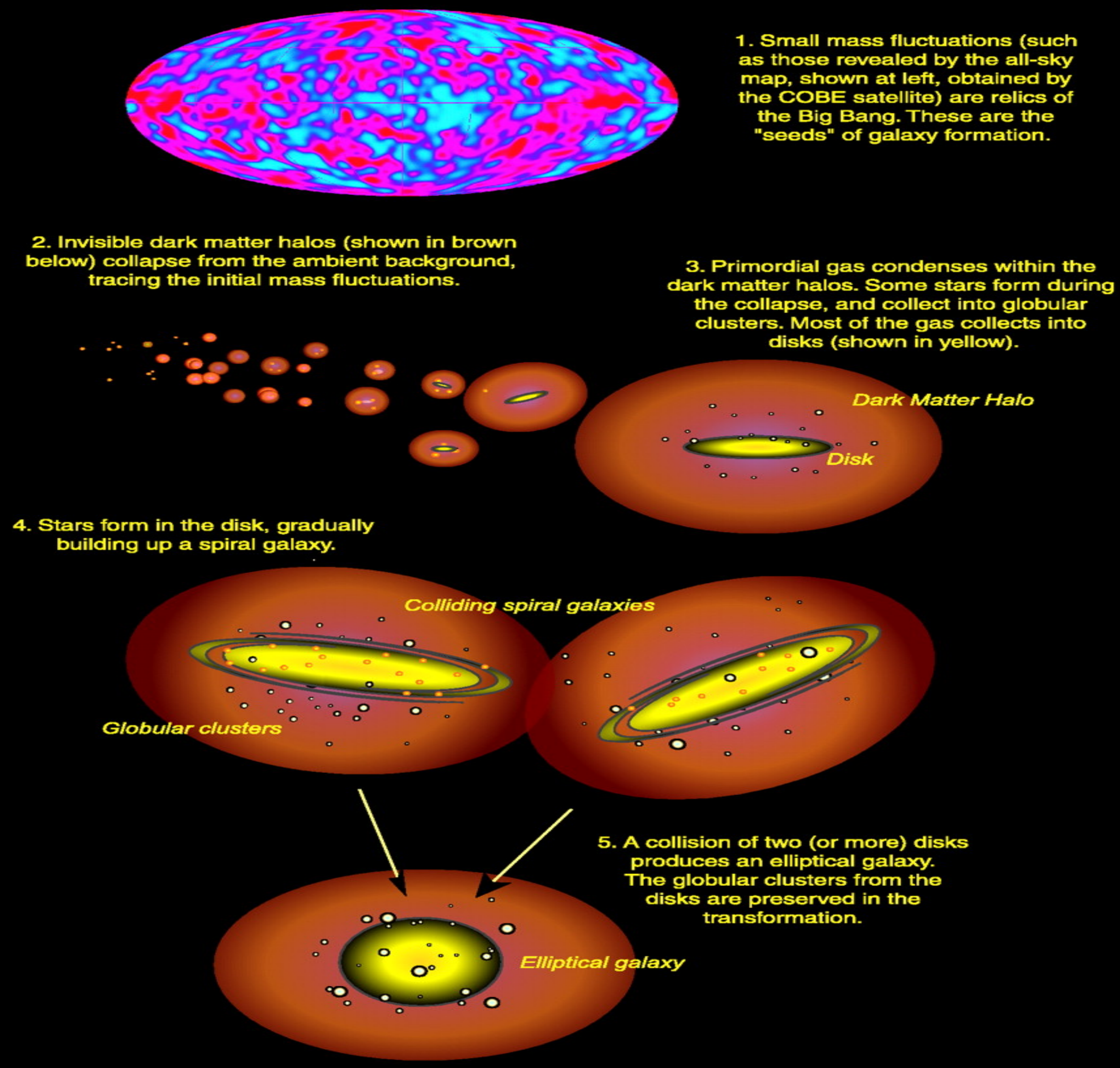


Galaxy Formation with Cold/Warm dark matter predicts a hierarchical formation of structure and galaxies

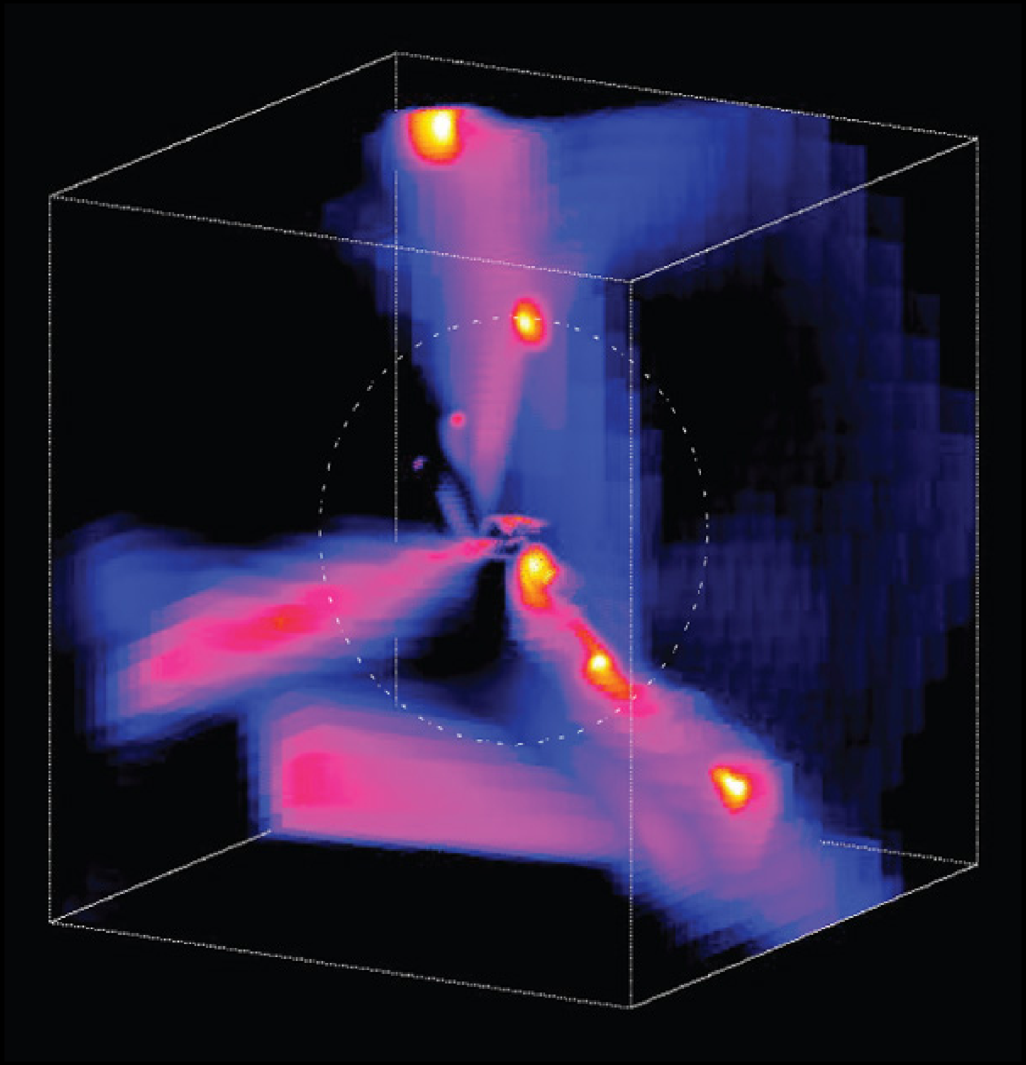




Traditional Idea for How Galaxies Form



Cold gas accretion is a popular theoretical idea – but little obs. evidence



Dekel et al. 2008

Monolithic collapse – earliest idea from Eggen et al. (1962)

EVIDENCE FROM THE MOTIONS OF OLD STARS
THAT THE GALAXY COLLAPSED

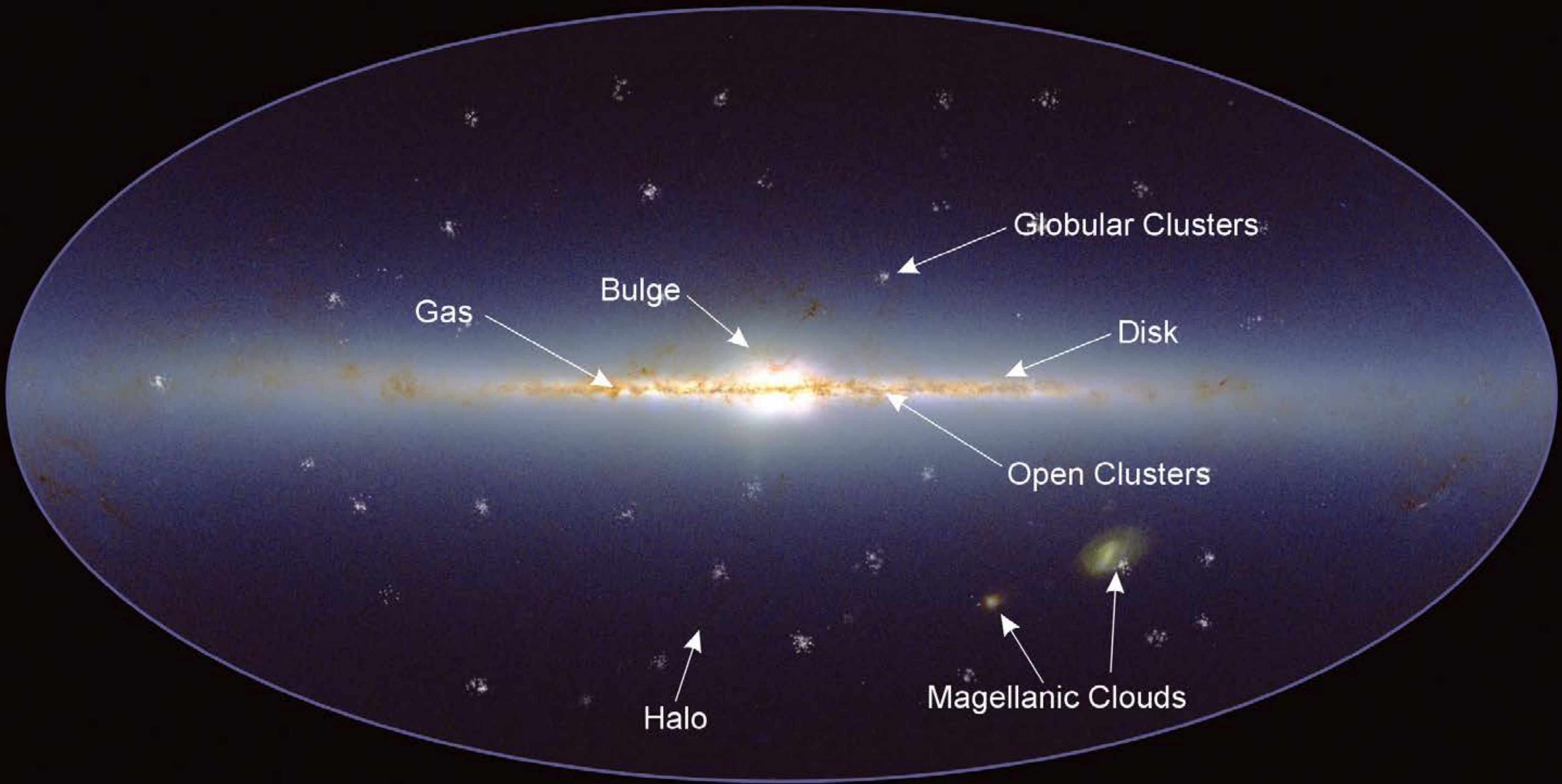
O. J. EGGEN, D. LYNDEN-BELL,* AND A. R. SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received May 17, 1962

ABSTRACT

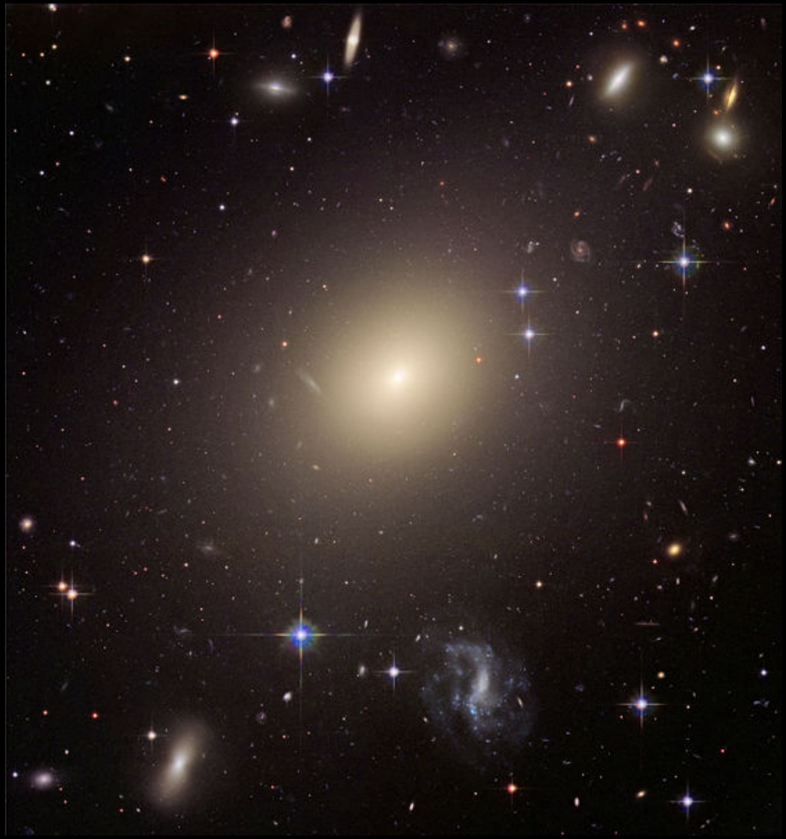
The (U, V, W)-velocity vectors for 221 well-observed dwarf stars have been used to compute the eccentricities and angular momenta of the galactic orbits in a model galaxy. It is shown that the eccentricity and the observed ultraviolet excess are strongly correlated. The stars with the largest excess (i.e., lowest metal abundance) are invariably moving in highly elliptical orbits, whereas stars with little or no excess move in nearly circular orbits. Correlations also exist between the ultraviolet excess and the W-velocity. Finally, the excess and the angular momentum are correlated; stars with large ultraviolet excesses have small angular momenta.

These correlations are discussed in terms of the dynamics of a collapsing galaxy. The data require that the oldest stars were formed out of gas falling toward the galactic center in the radial direction and collapsing from the halo onto the plane. The collapse was very rapid and only a few times 10^8 years were required for the gas to attain circular orbits in equilibrium (i e., gravitational attraction balanced by centrifugal acceleration). The scale of the collapse is tentatively estimated to be at least 10 in the radial direction and 25 in the Z-direction. The initial contraction must have begun near the time of formation of the first stars, some 10^{10} years ago.

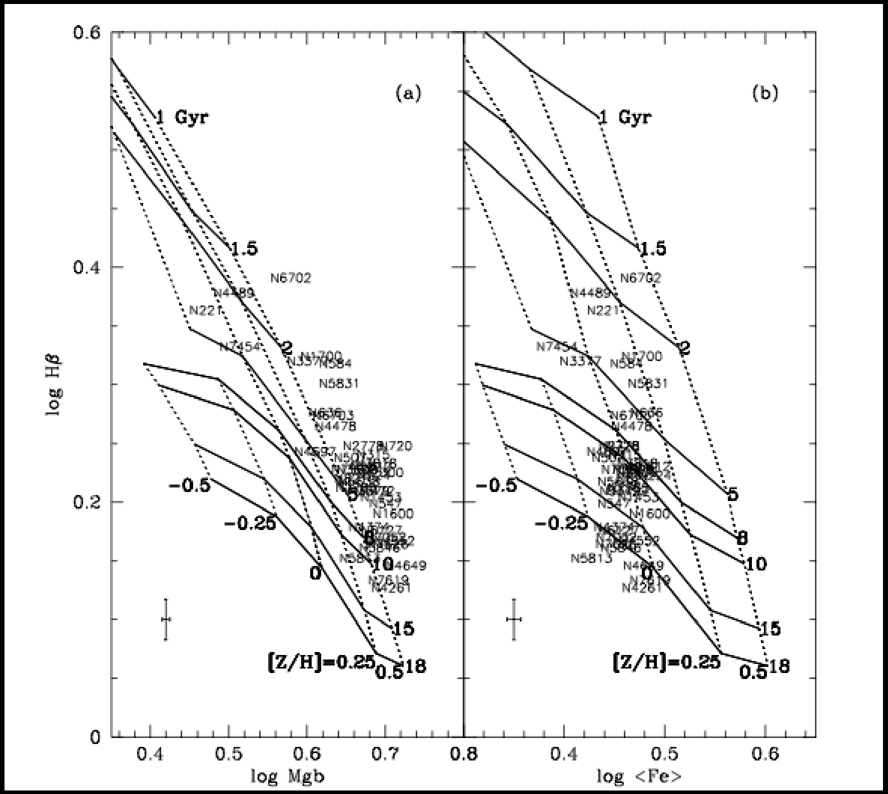
Milky Way


Globular Clusters
Bulge
Gas
Disk
Open Clusters
Magellanic Clouds
Halo

What about the most massive galaxies?



Stellar populations show the stars in these galaxies are very old



How do massive galaxies form?

Ideas

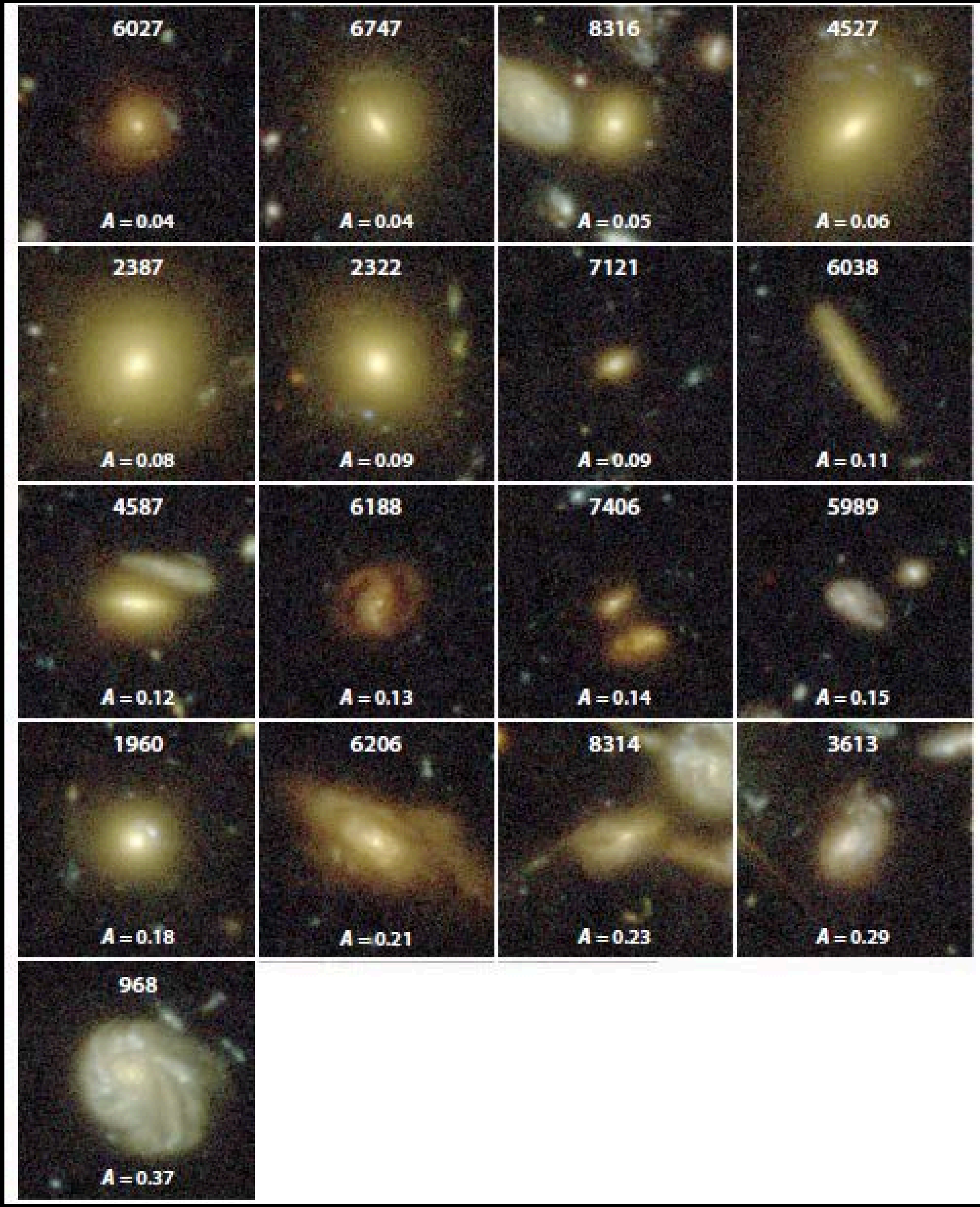
Major mergers

Minor mergers

Gas accretion

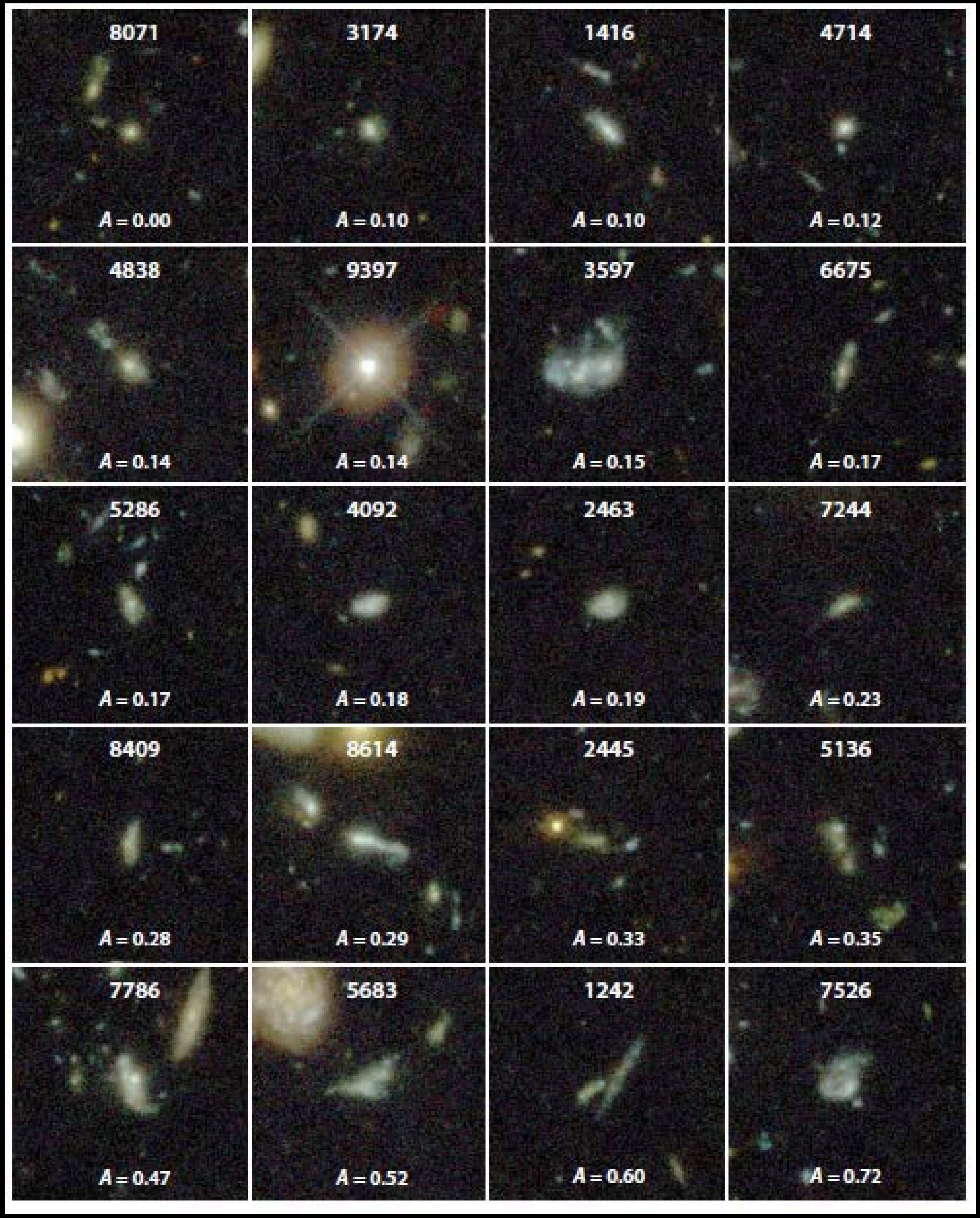
Monolithic collapse

Can test ideas by looking at distant galaxies



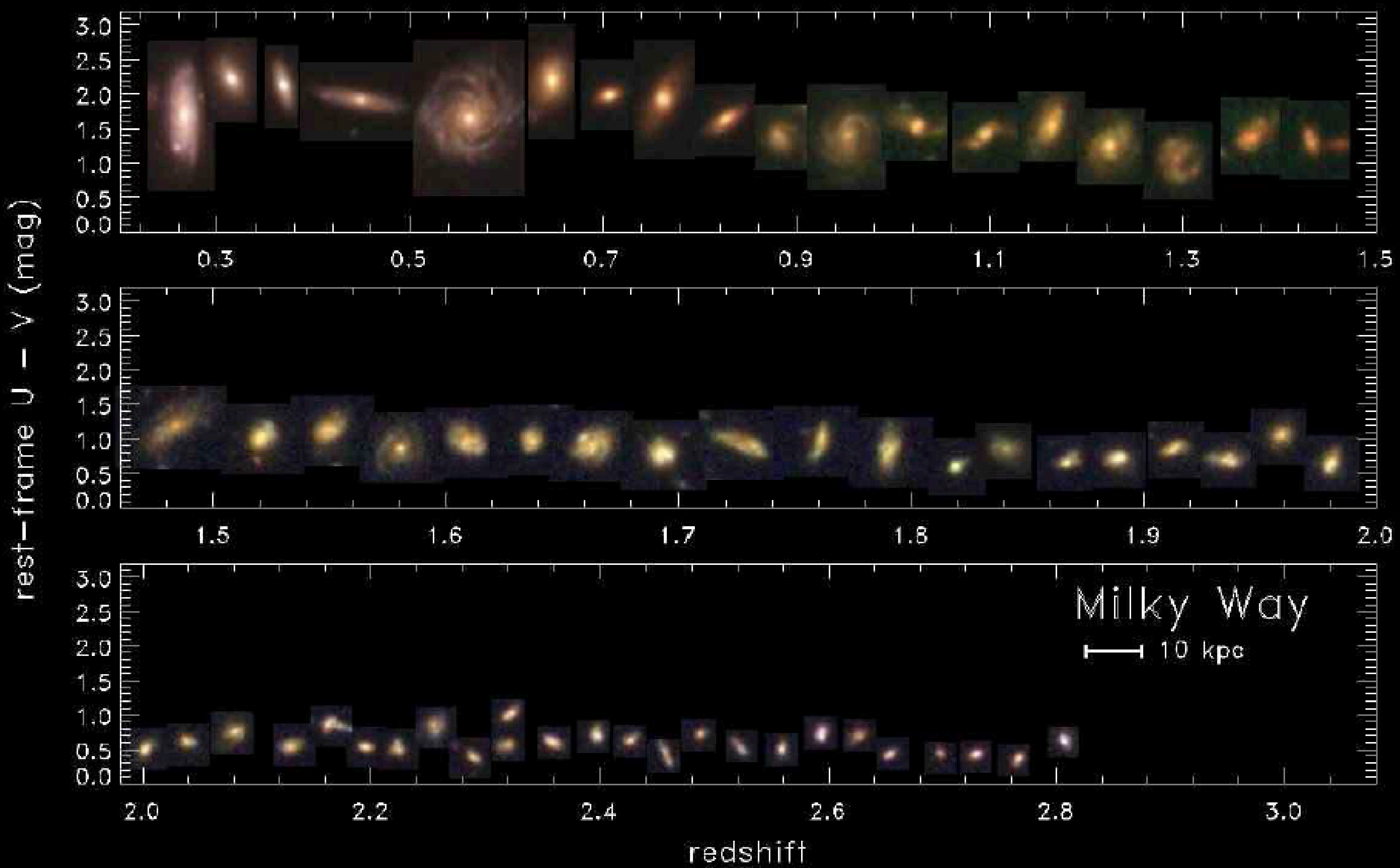
Disk/elliptical/peculiar evolution – visual morphologies

$z < 1$ massive Galaxies in Hubble Ultra Deep Field (UDF)

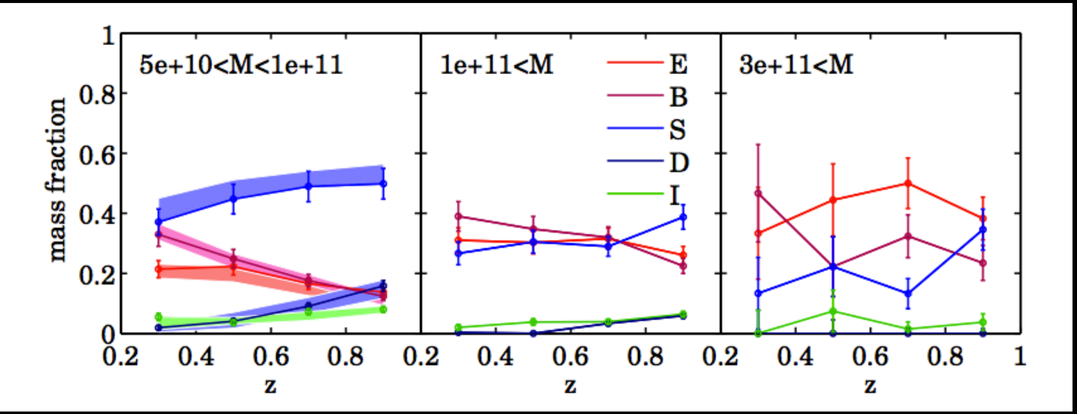


z > 1 massive
Galaxies in UDF

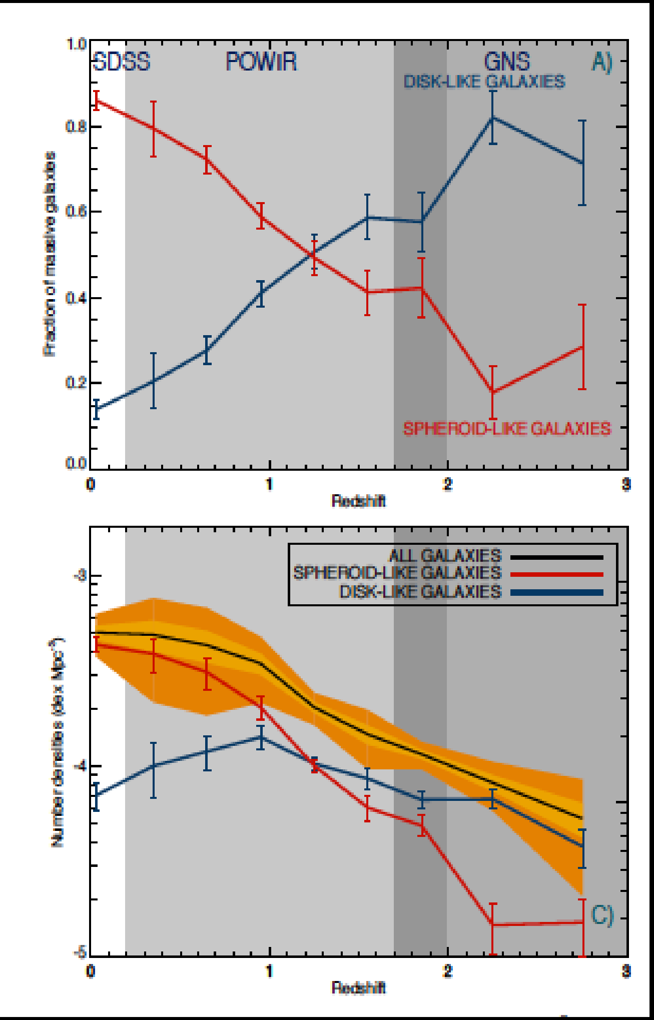
Milky Way mass progenitors



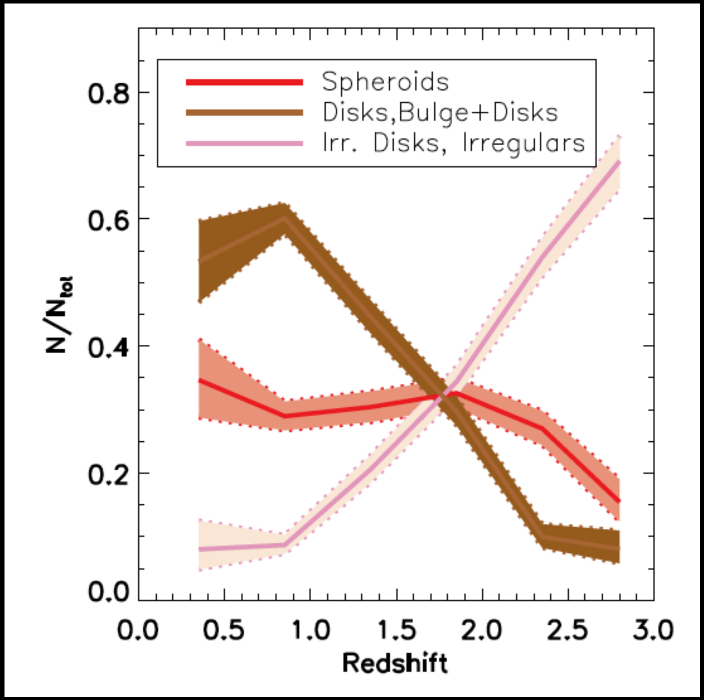
Massive galaxies become more disky/peucliar at higher redshifts



Oesch+10

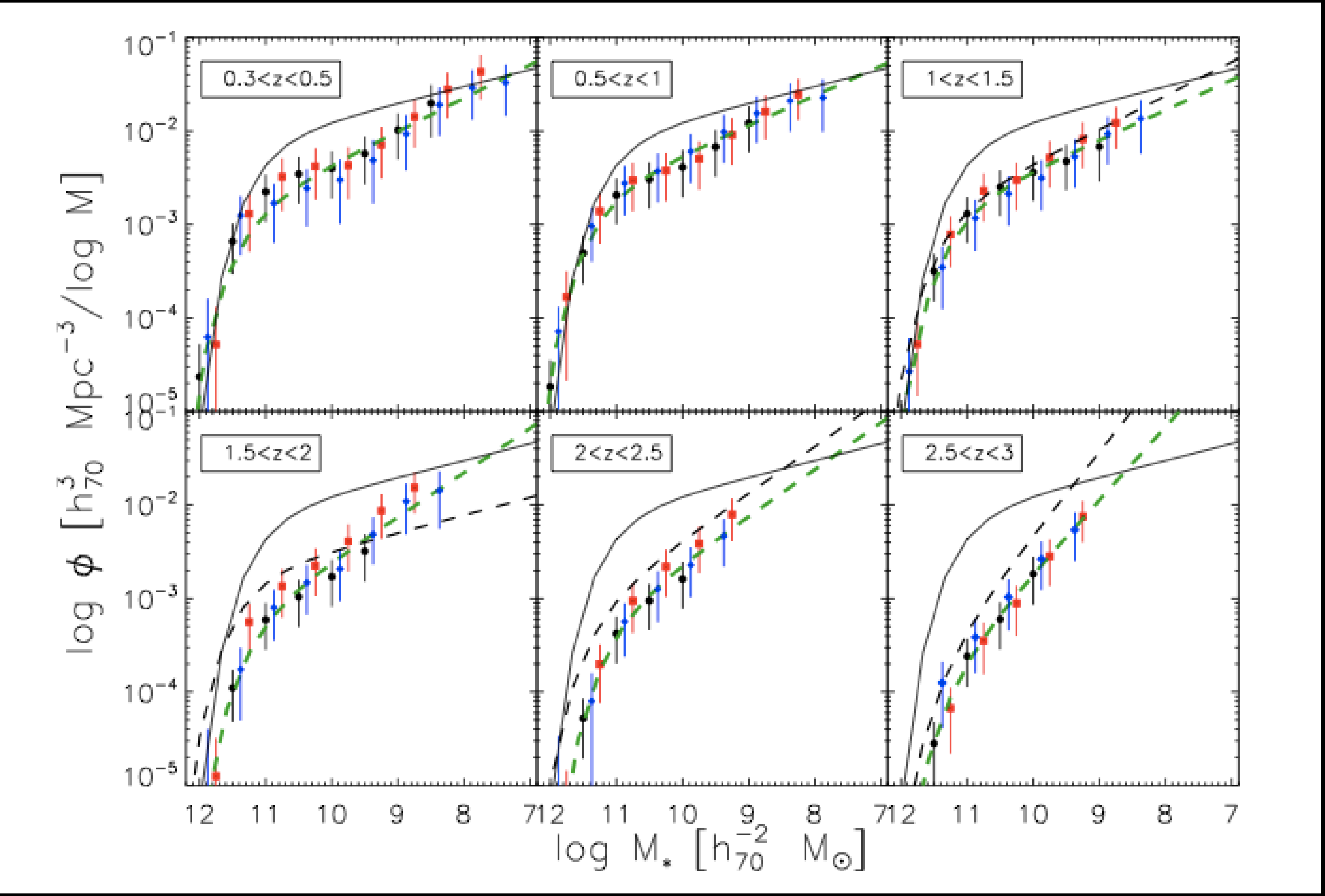


Buitrago+13



Huertas-Company+15

Mass function also shows that massive galaxies form quick



Mortlock, CJC, et al. (2013)

Most massive galaxies are formed by z = 1 but not z = 3

How do massive ellipticals form?

Ideas

Major mergers

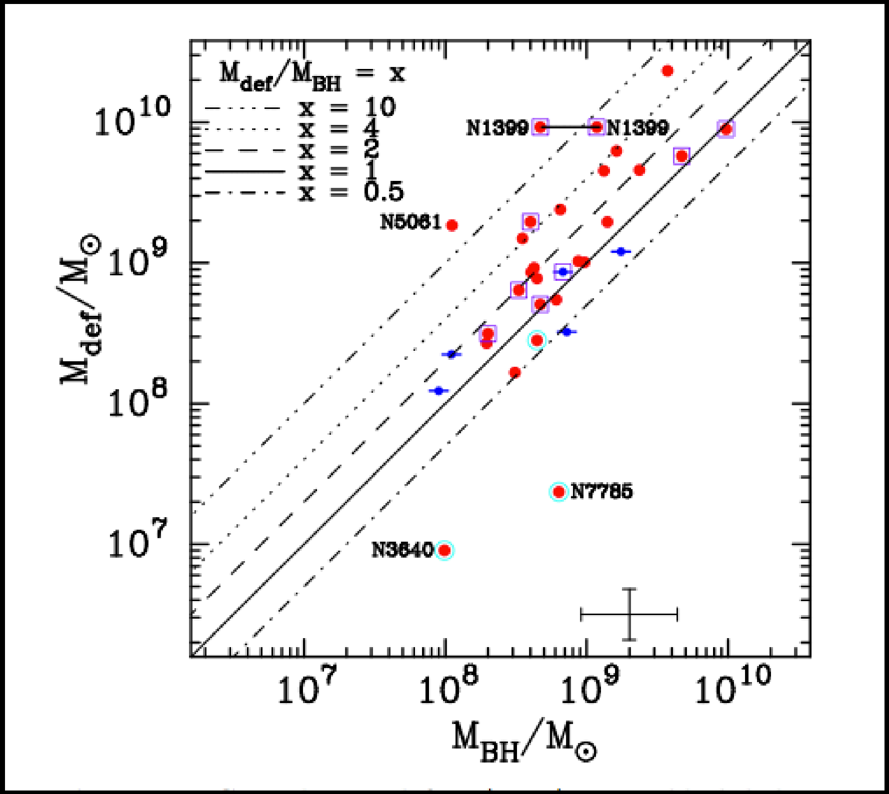
Minor mergers

Gas accretion

Monolithic collapse

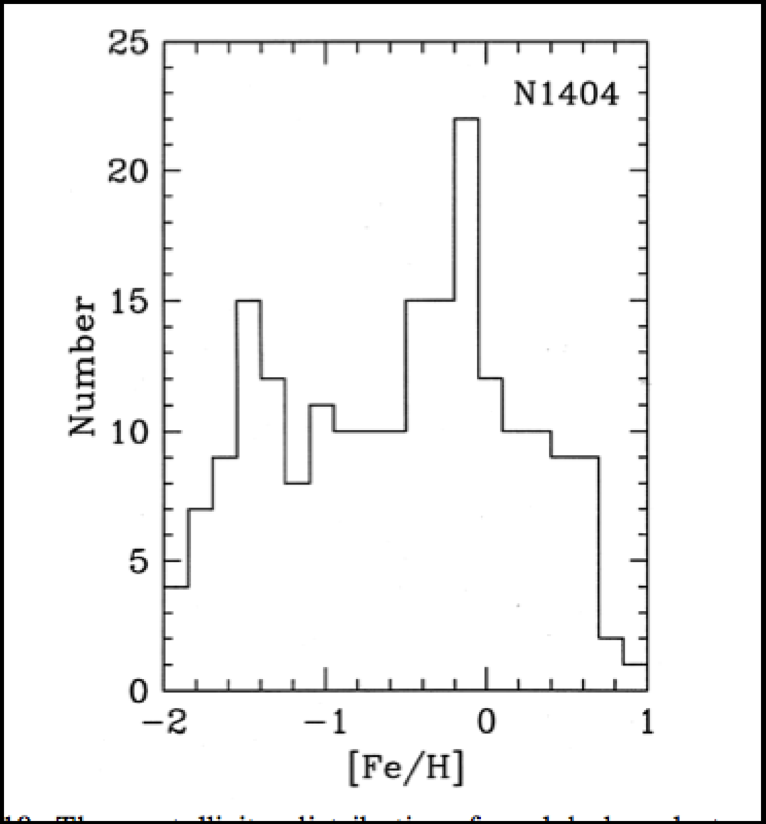
Do mergers form massive galaxies?

Black holes



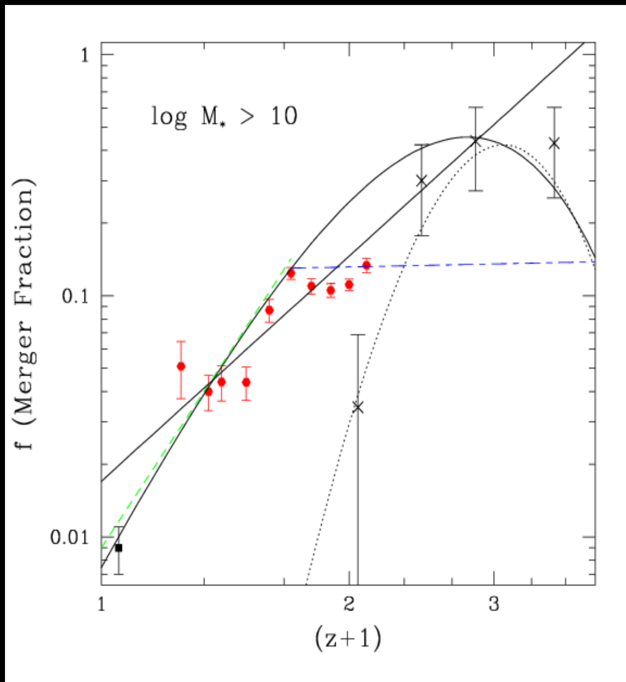
Dullo & Graham 2013

Globular clusters

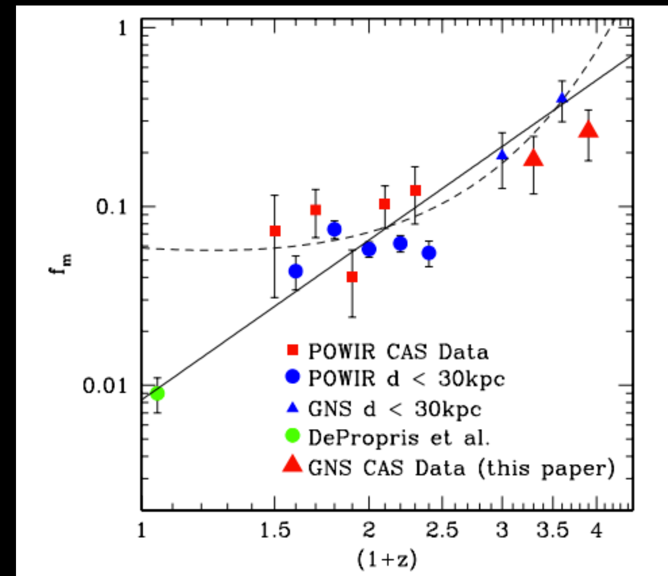


Forbes et al. (1998)

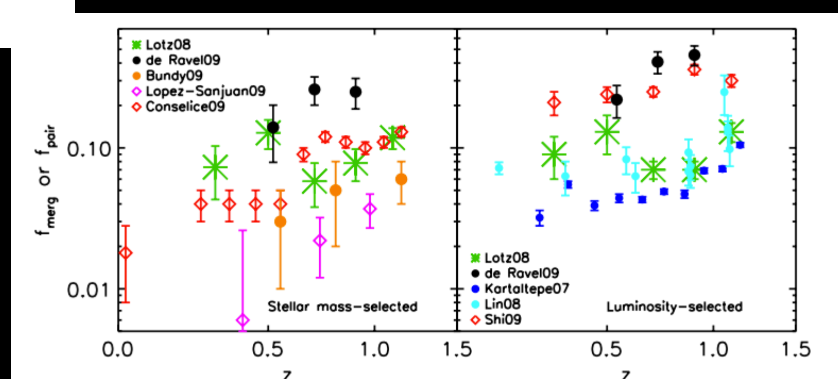
Major mergers – measure with structure



Conselice+09



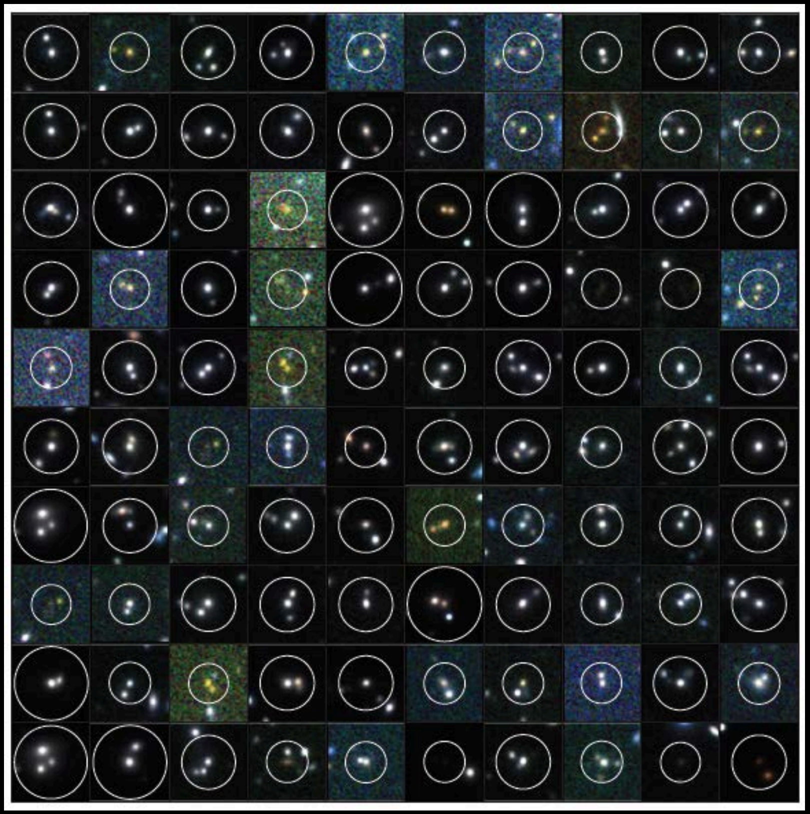
Bluck+12



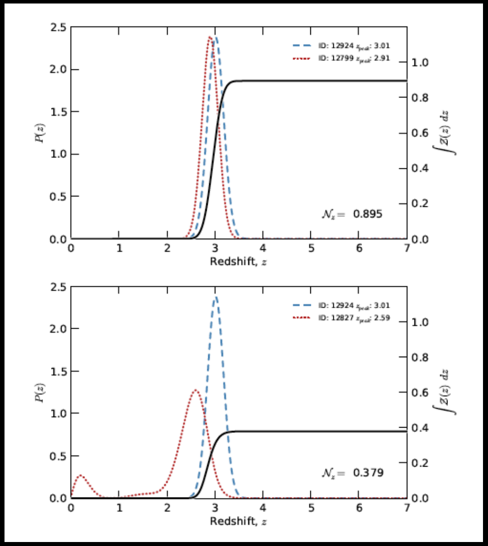
Lotz+11

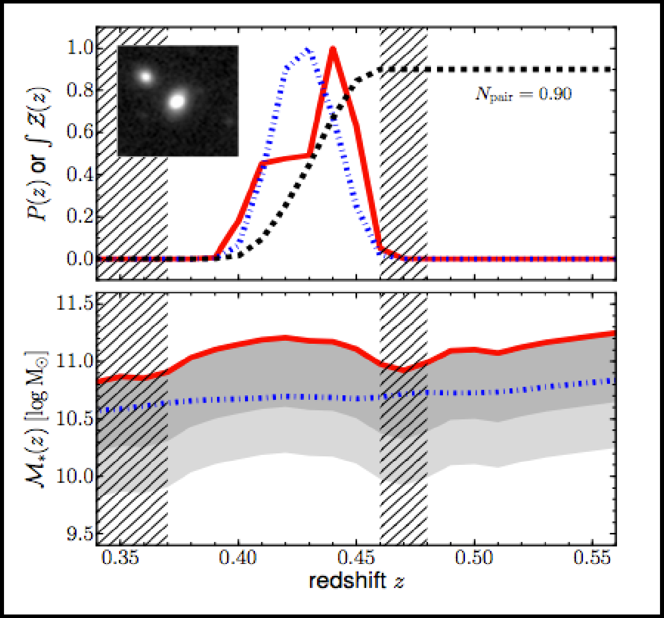
Mergers evolve as $(1+z)^{1\text{-}3}$ to z = 3

Mergers – though pair counts



Find galaxy pairs using the P(z) values for each galaxy

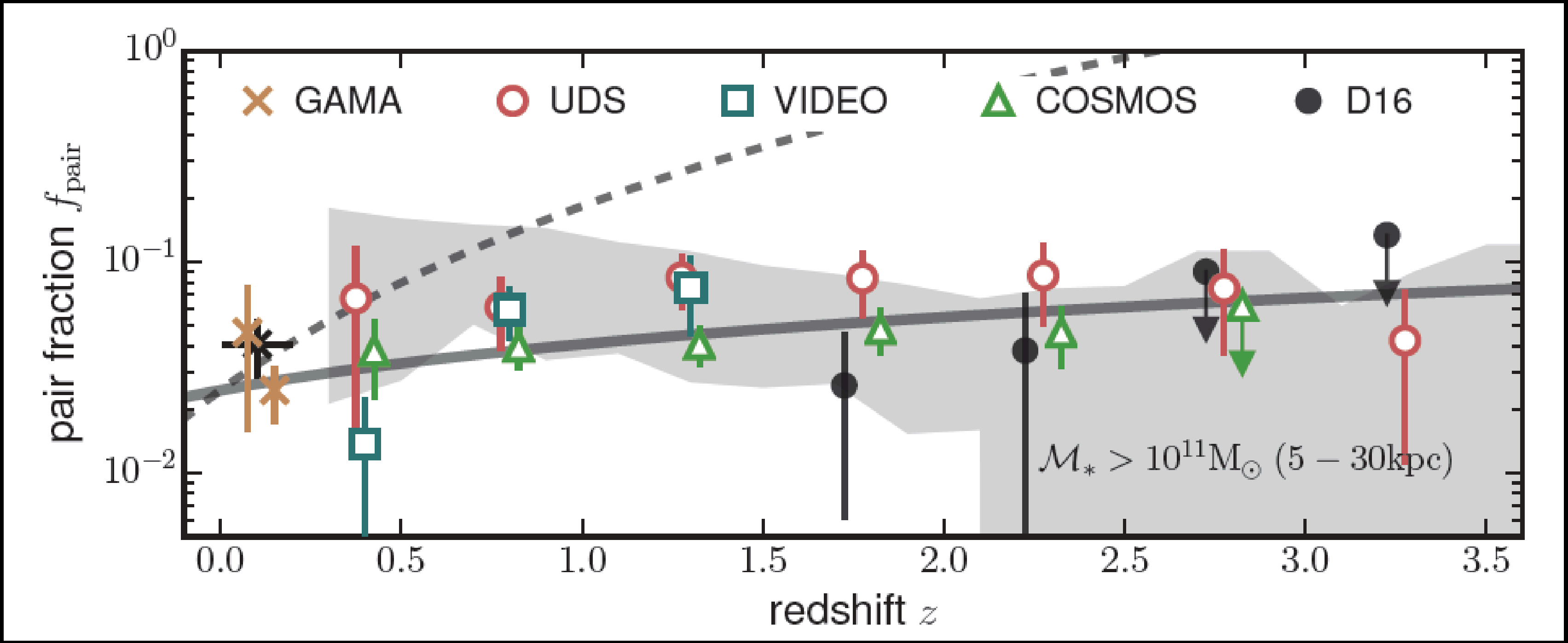




$$\mathcal{Z}(z) = \frac{2 \times P_1(z) \times P_2(z)}{P_1(z) + P_2(z)} = \frac{P_1(z) \times P_2(z)}{N(z)}.$$

New Results

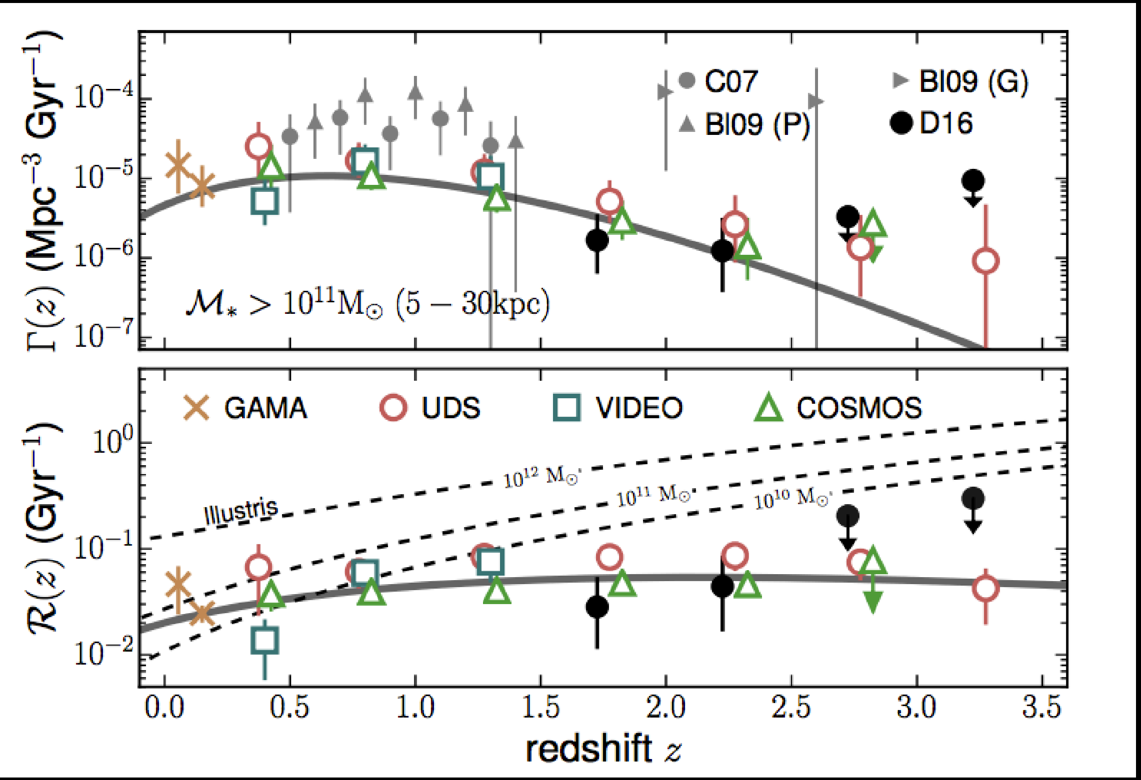
Pair fraction evolution for log M > 11, < 30kpc, < ¼ mass ratio



Pair Fractions from three 1 degree sq. deep imaging surveys
VIDEO, UDS, COSMOS and GAMA (for z ~ 0)

Merger rates, harder to infer – need time-scales

$$\Gamma_{\mathrm{merg}}(z) = \frac{\phi_{\mathrm{merg}}(z)}{\langle T_{\mathrm{obs}}\rangle} = \frac{f_{\mathrm{merg}}(z) n_1(z)}{\langle T_{\mathrm{obs}}\rangle}, \quad [\mathrm{Mpc}^{-3}\ \mathrm{Gyr}^{-1}]$$



$$\mathcal{R}_{\mathrm{merg}}(z) = \frac{f_{\mathrm{merg}}(z)}{\langle T_{\mathrm{obs}}\rangle}, \quad [\mathrm{Gyr}^{-1}]$$

Results show a merger rate which is lower than previous work

<u>Gives ~1 major merger per galaxy at z < 3</u>

How do massive ellipticals form?

Ideas

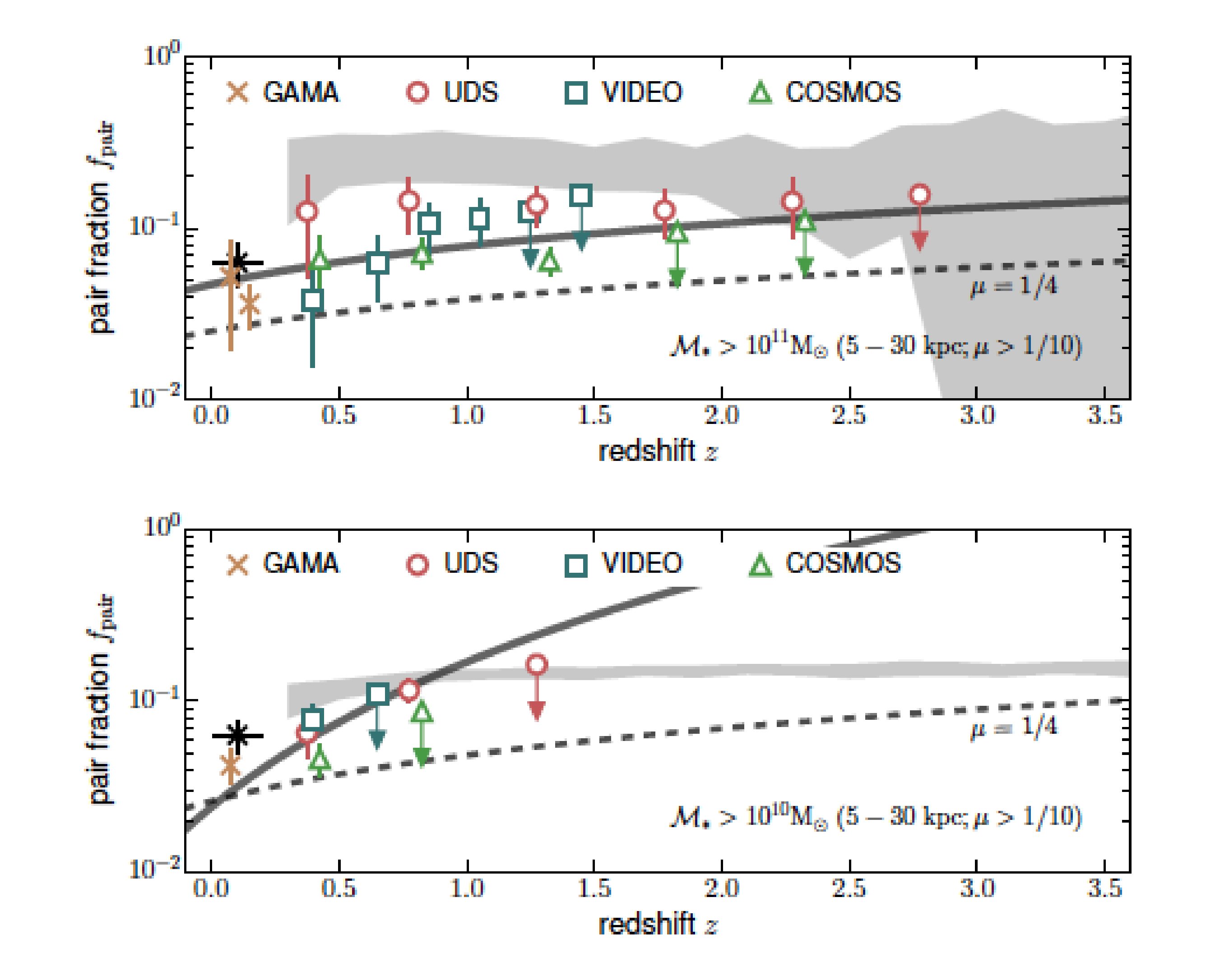
Major mergers

Minor mergers

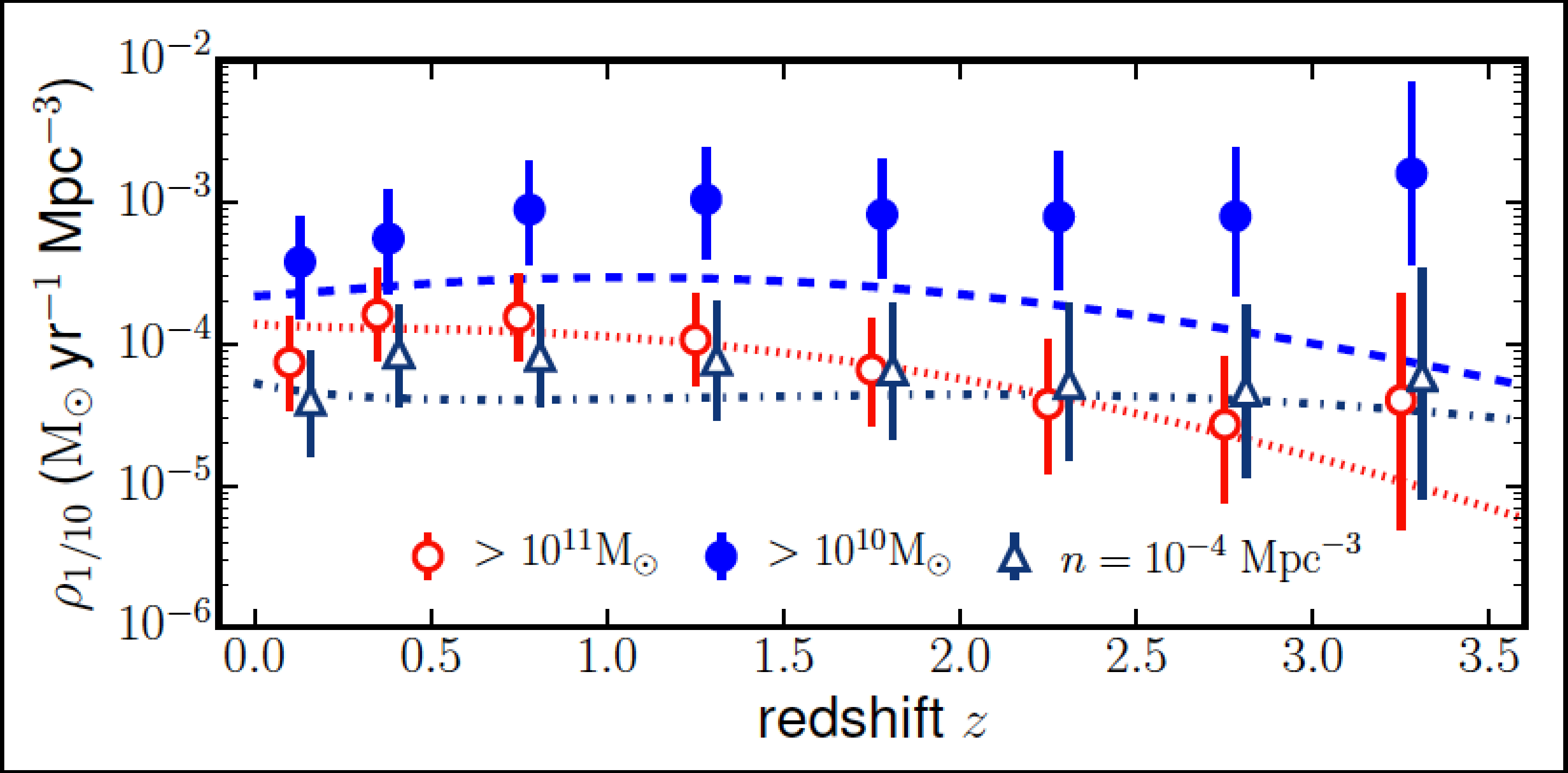
Gas accretion

Monolithic collapse

Minor Merger Pair Fraction - ratio > 1/10



Mass accretion rate due to minor mergers



About the same level as the mass accretion from major mergers

How do massive ellipticals form?

Ideas

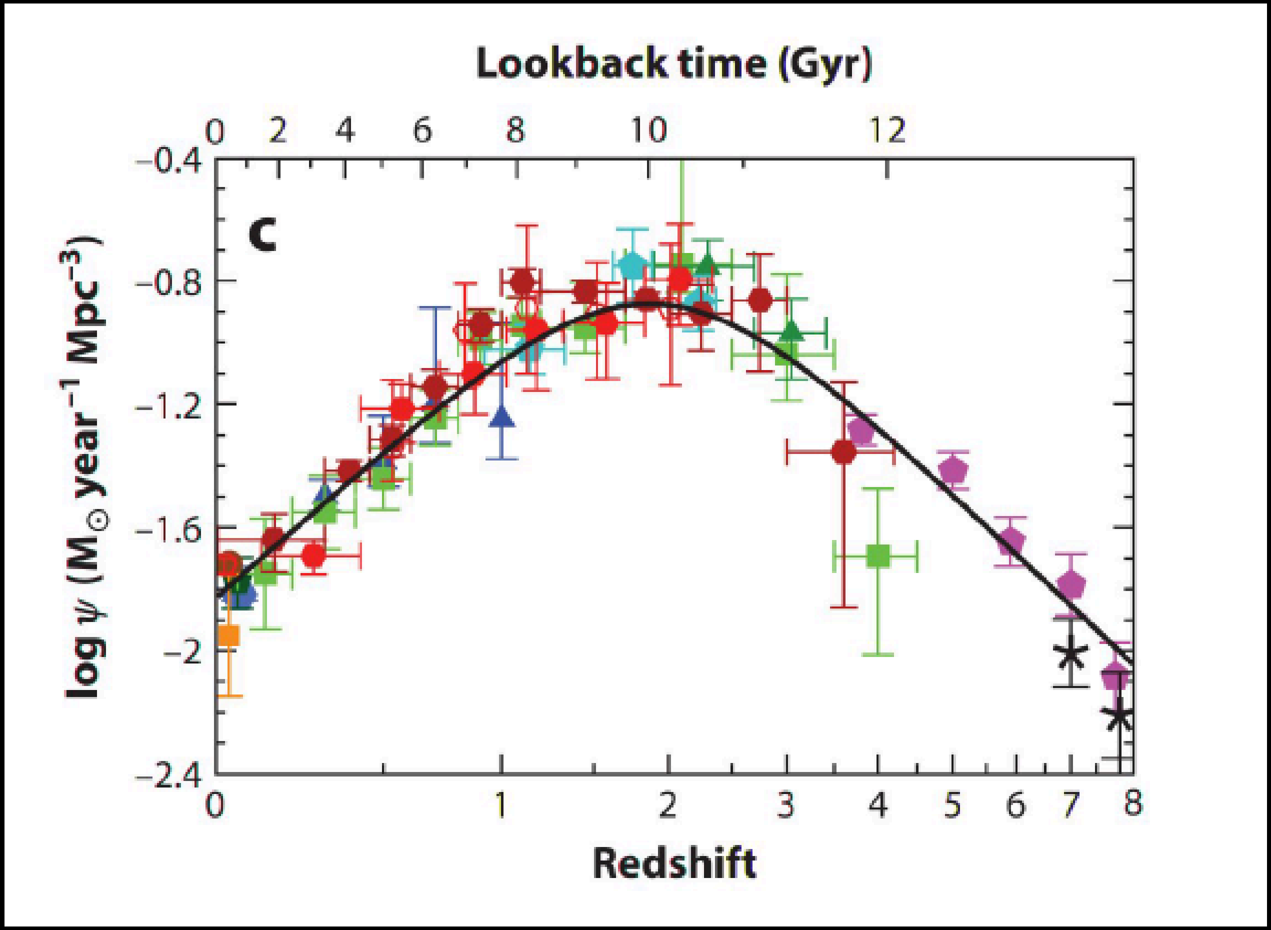
Major mergers

Minor mergers

Gas accretion

Monolithic collapse

Can compare with star formation history



<u>At z = 2 SFR Peak</u>

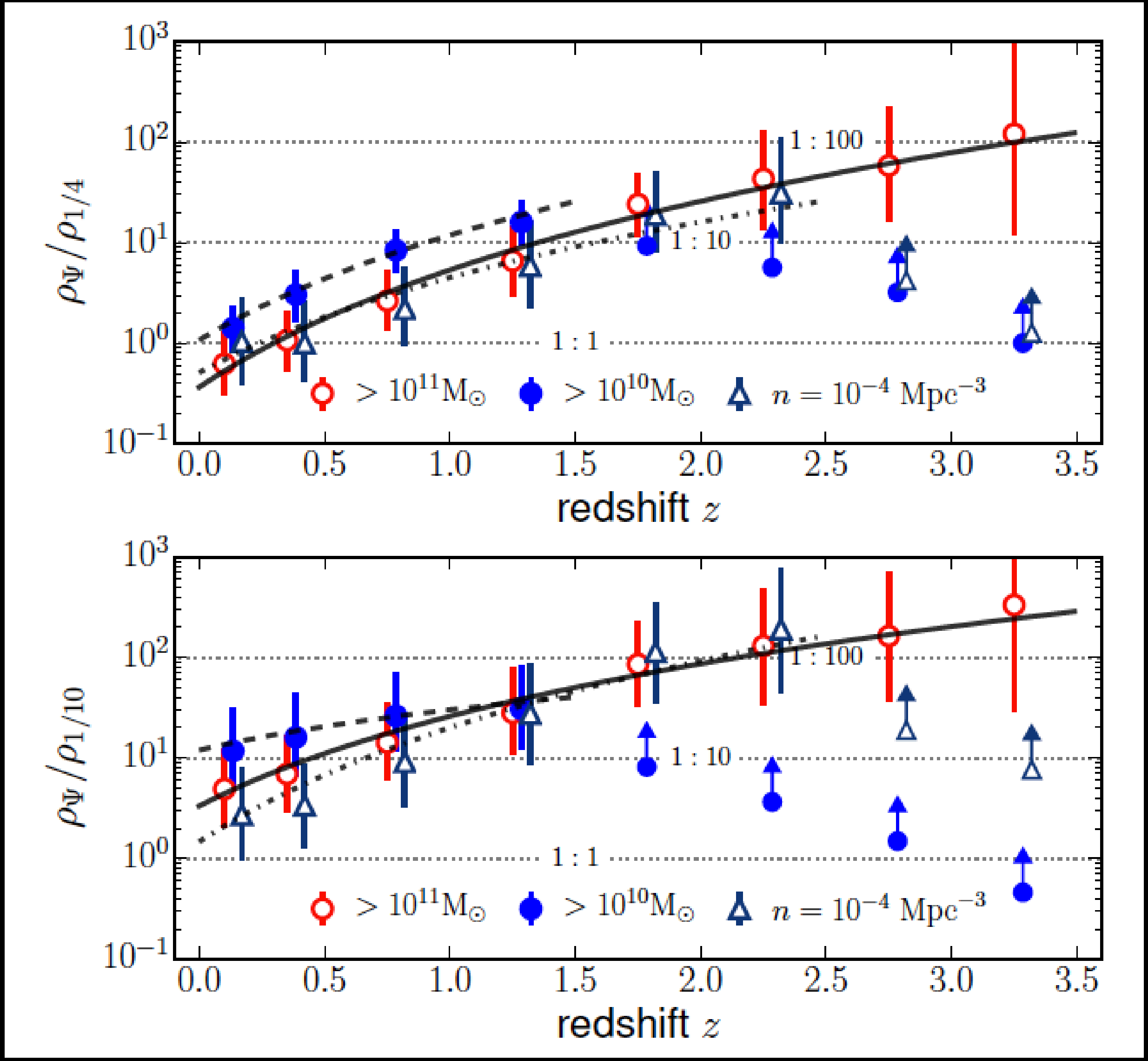
SFR ~ 0.1

Mergers ~ 0.005

<u>But mergers only for log M > 10, SF integrated over all masses</u>

Madau & Dickinson 2014

Ratio of SFR to mass accretion rate due to major mergers



SFR more important at z > 0.5, equal at z ~0.5

Do we have a consensus about how massive galaxies form at 1.5 < z < 3?

$$M_*(t) = M_*(0) + M_{*,M}(t) + <\psi> \delta t$$

Stellar mass evolution

$$M_g(t) = M_g(0) + M_{g,M}(t) + M_{g,A}(t) - <\psi> \delta t$$

Gas mass evolution

$$\frac{M_g(t)}{M_*(t)} \sim \frac{M_g(0)}{M_*(0)}$$

Observed condition

$$M_{g,A}(t) = (1.18 \pm 0.21) \times M_g(0) + <\psi> \delta t - M_{g,M}(t)$$

Amount of gas accreted

Integrate: Mass added from SF ~ Mass added from major merging

However - gas mass fraction for log M > 11 is less than 0.2

The amount of gas added from accretion (or <u>very</u> minor mergers)

$$\mathrm{M_{g,A}}(t) = (1.18 \pm 0.21) \times \mathrm{M_g}(0) + < \psi > \delta t - \mathrm{M_{g,M}}(t)$$

$$\frac{\mathrm{M_{g,A}}(t)}{\mathrm{M_*}} = \frac{(1.18 \pm 0.21) \times \mathrm{M_g}(0)}{\mathrm{M_*}} + \frac{< \psi > \delta t}{\mathrm{M_*}} - \frac{\mathrm{M_{g,M}}(t)}{\mathrm{M_*}}$$

$$\mathrm{M_{g,A}}/\mathrm{M_*}(0) = 0.83 \pm 0.37$$

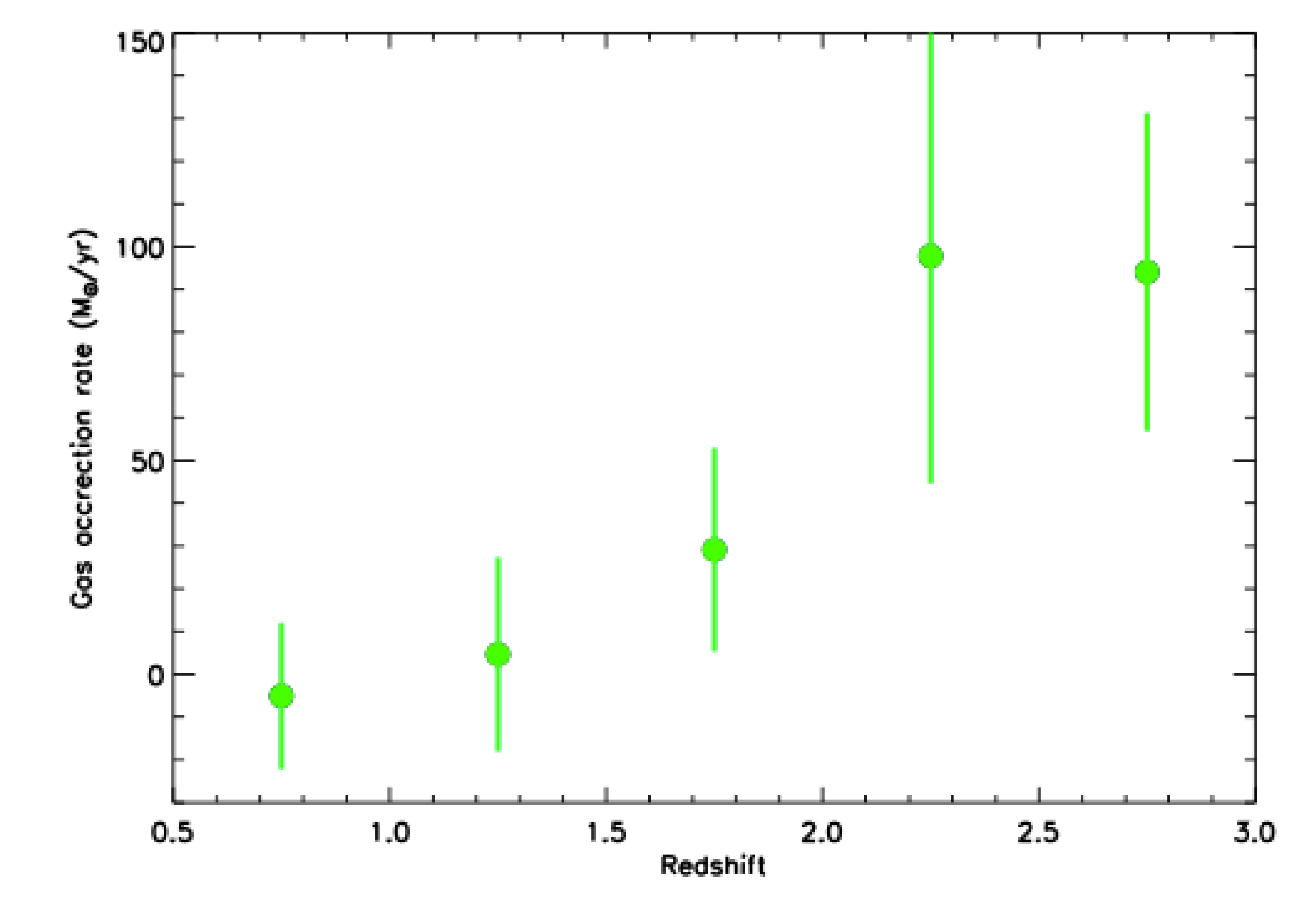
Over $1.5 < z < 3$ (2.16 Gyr)

$$(1.6 \pm 0.5) \times 10^{11}\ \mathrm{M_\odot}$$

Average amount of gas accreted

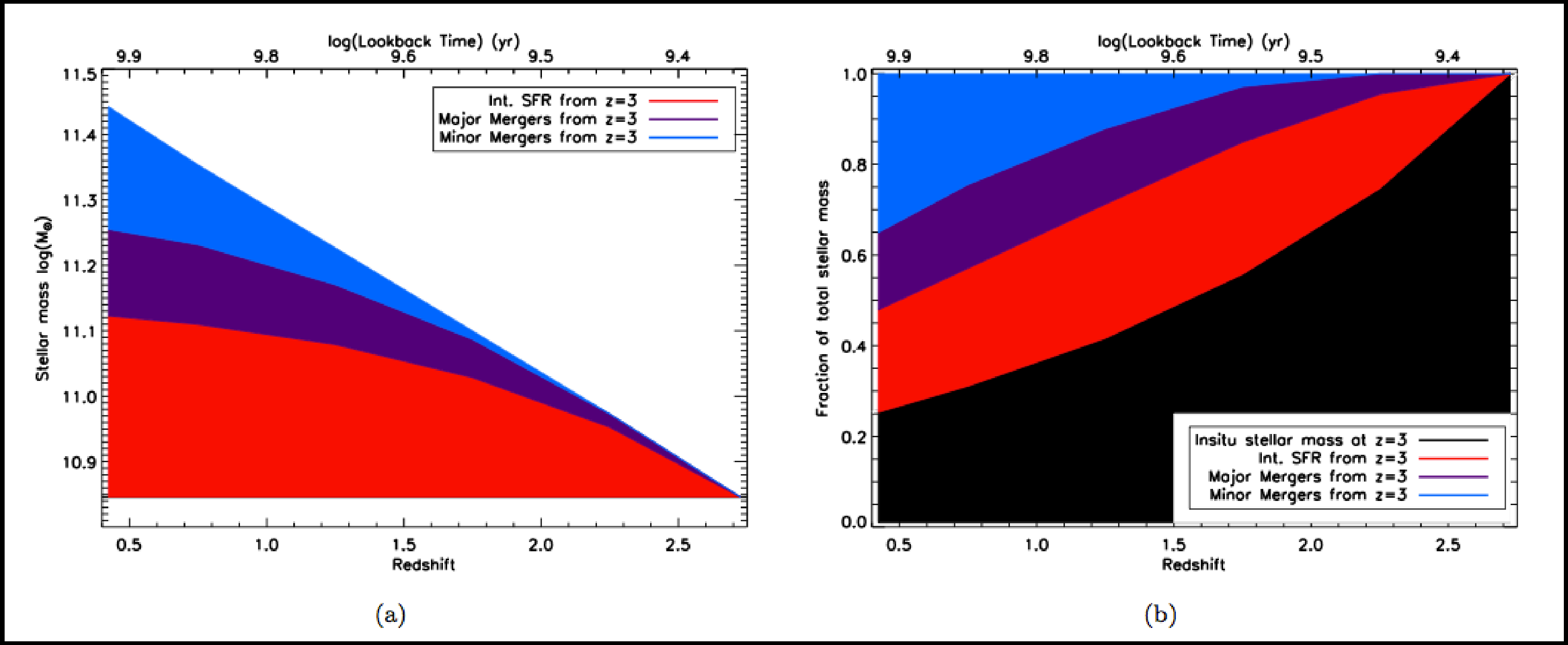
Results in accretion rate of $$\frac{\mathrm{dM_{g,A}}(t)}{\mathrm{dt}} = \dot{\mathrm{M}}_{\mathrm{g,A}} = (83 \pm 36)\, \mathrm{M_\odot\, yr^{-1}}$$

Gas accretion rate history for massive systems over cosmic time



Ownsworth,CC,+14

Can determine the relative contributions to massive galaxy formation from z = 3



All mergers ~50% of formation of stellar mass since z ~3

Star formation is not the only way to build mass in galaxies

How do massive ellipticals form?

Ideas

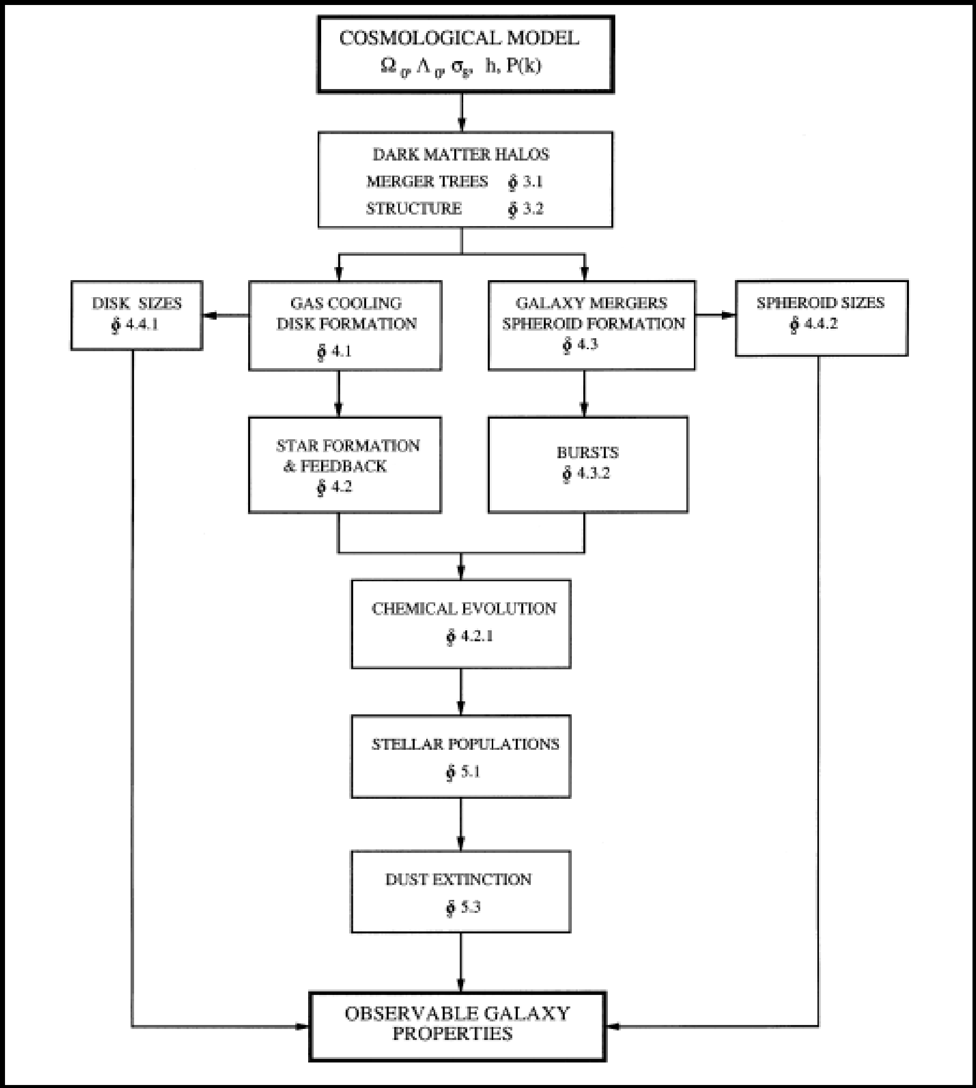
Major mergers ✓

Minor mergers ✓

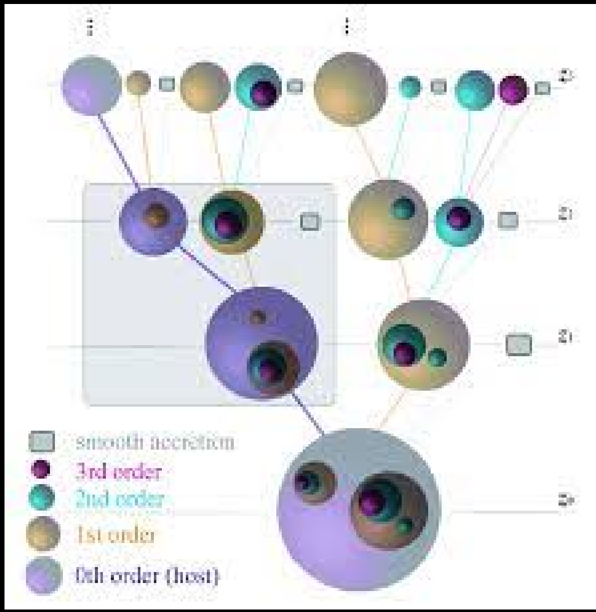
Gas accretion ✓

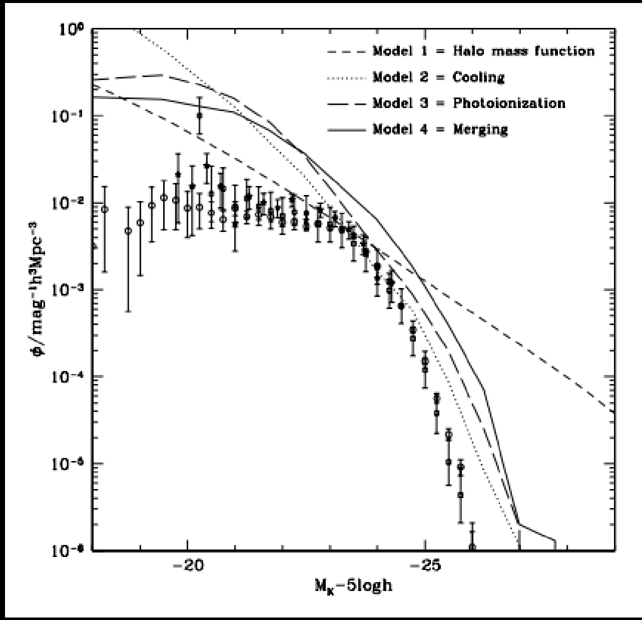
Monolithic collapse ✗

Details matter! Test with models

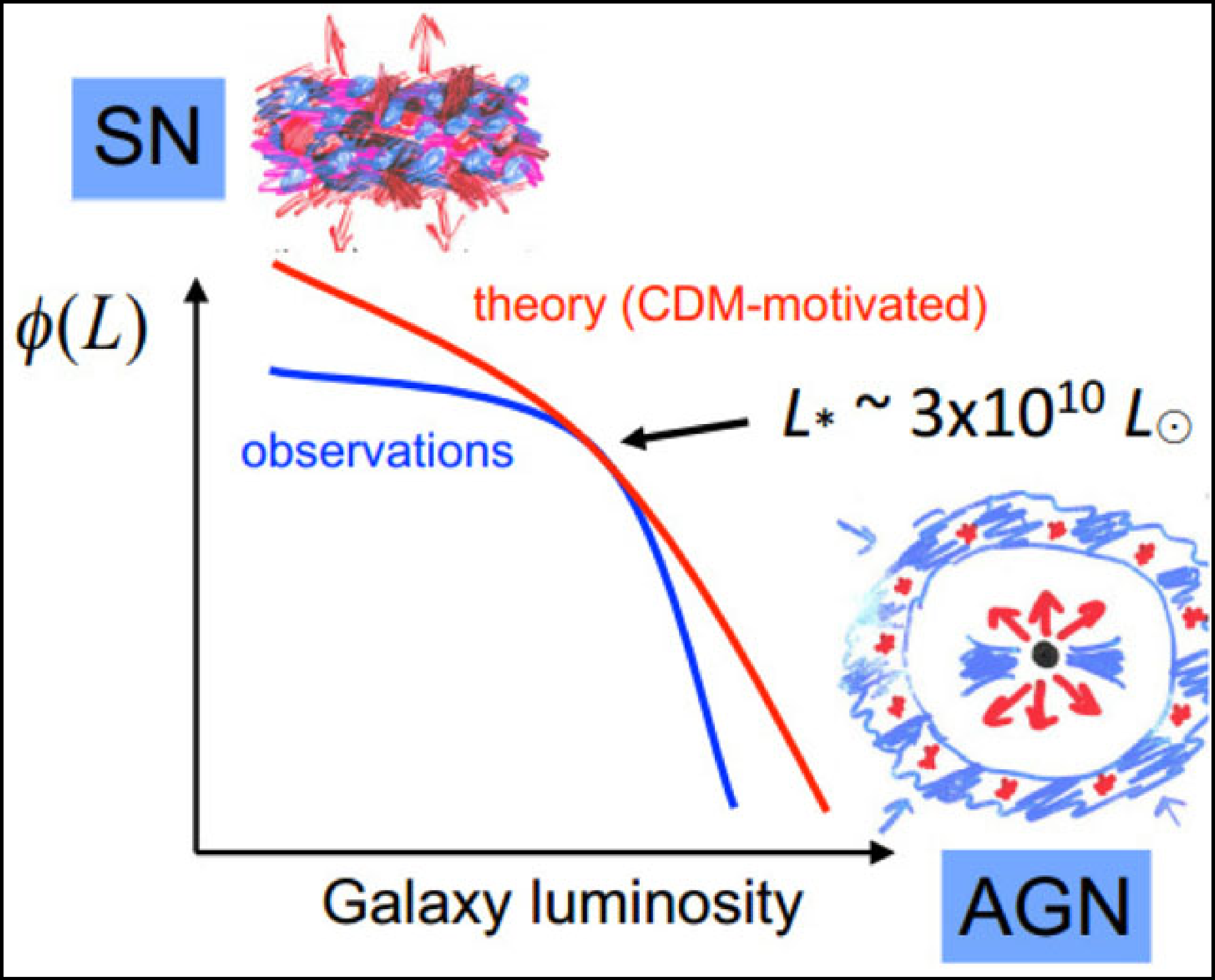


Cole et al. 2000

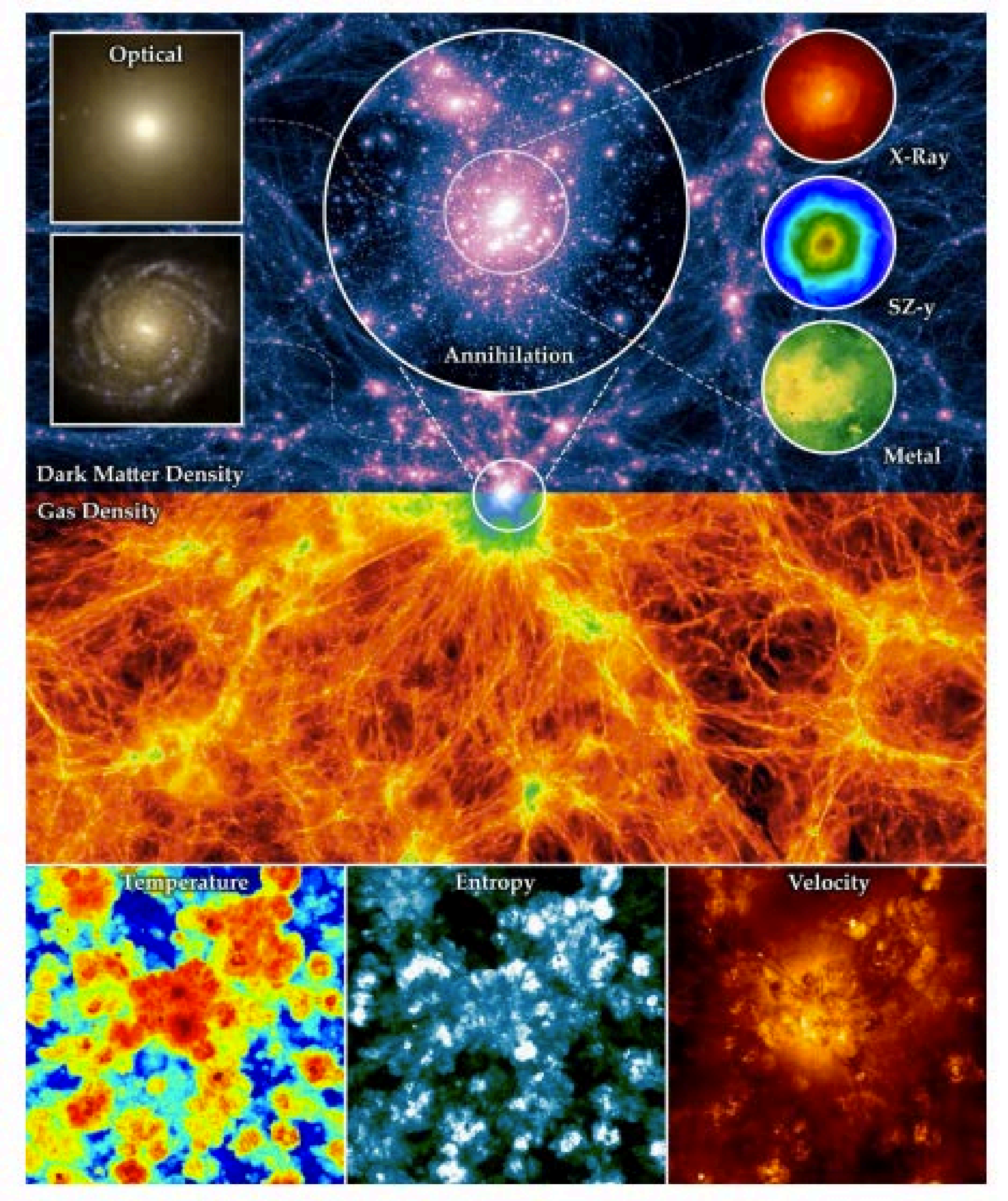




Benson+03



Silk & Mamon 2015

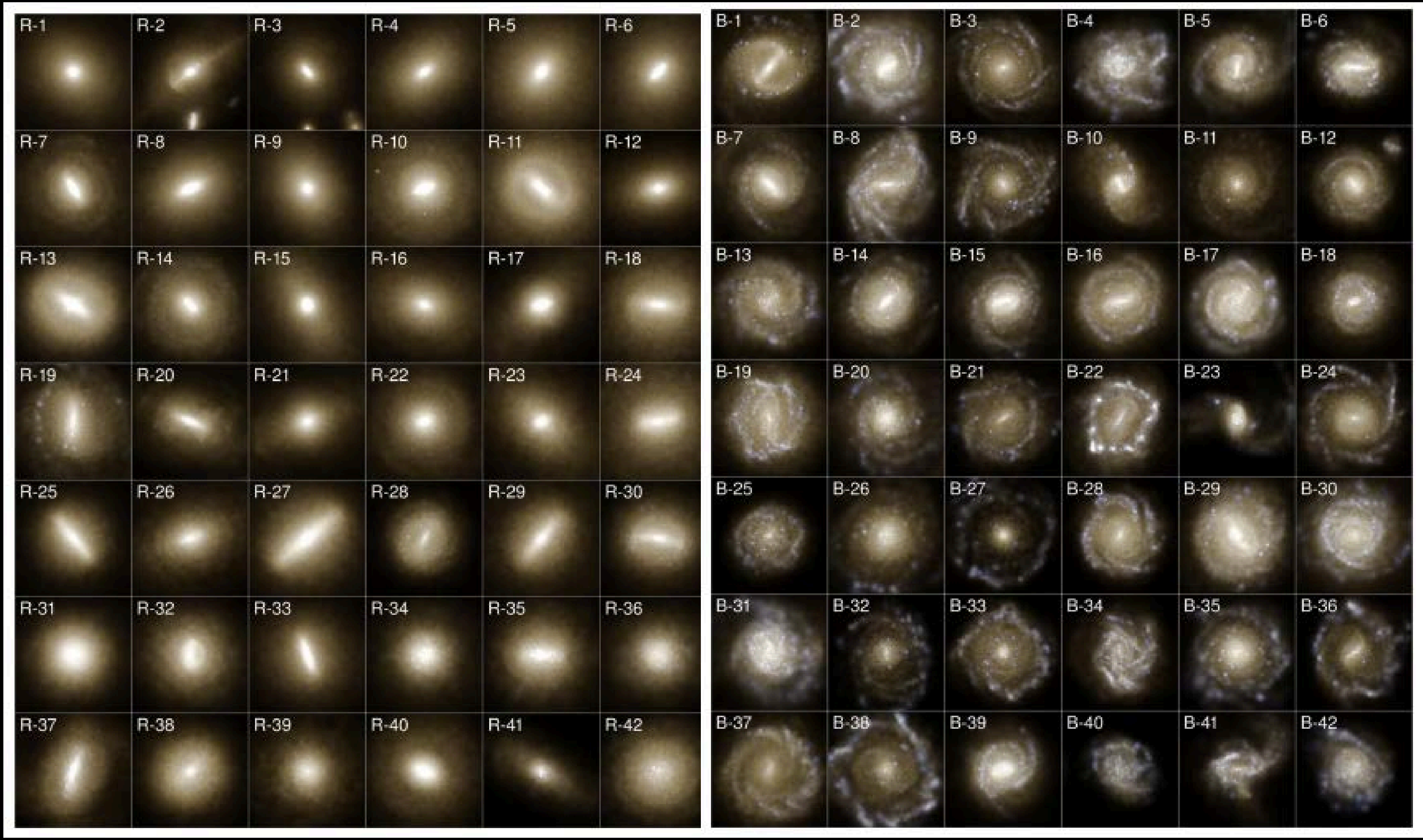


Illustris simulation

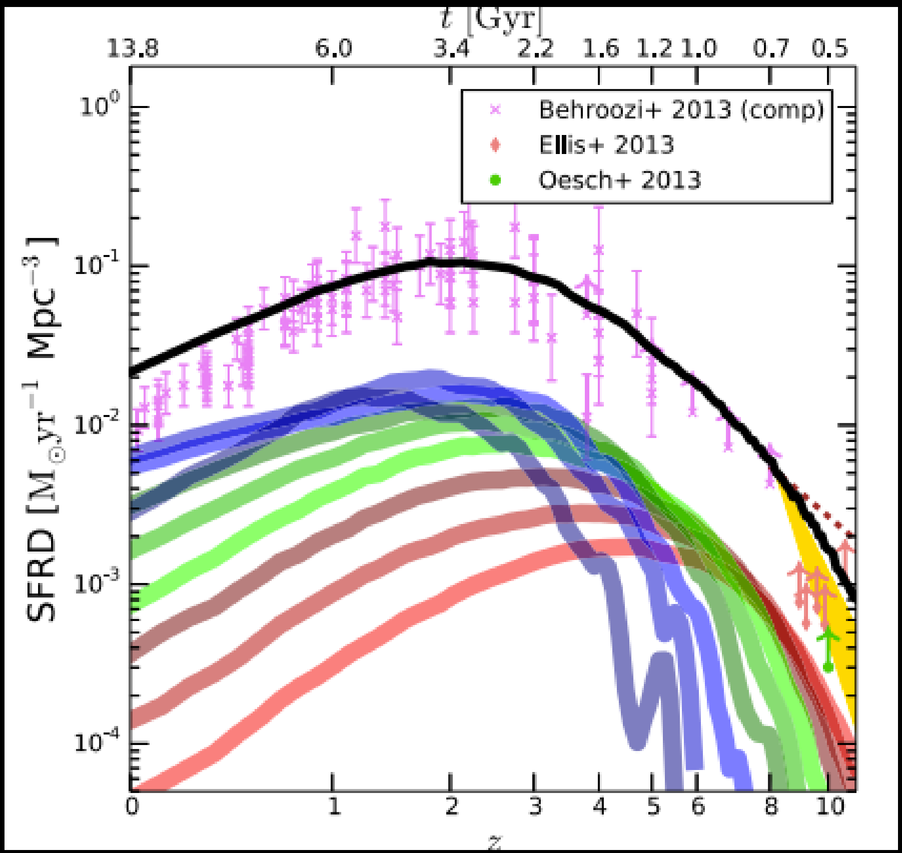
Hydrodynamical

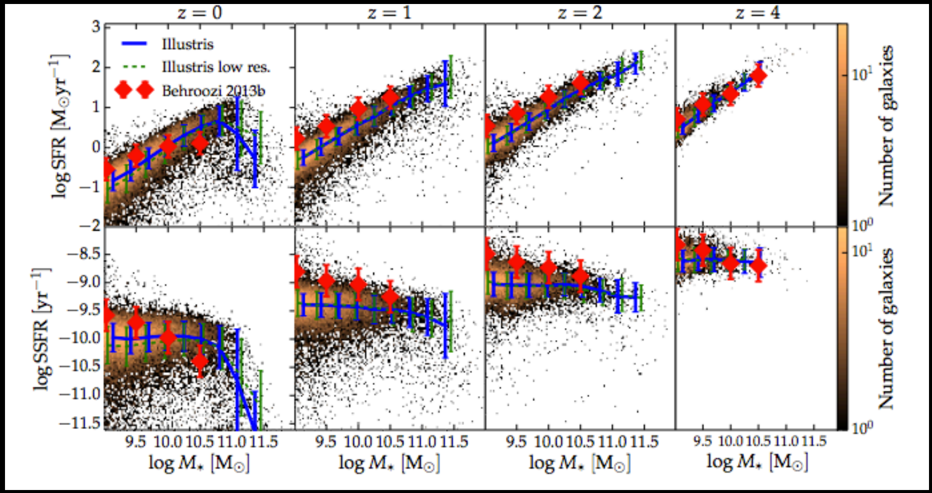
106.5 Mpc^3

Resolved simulated images



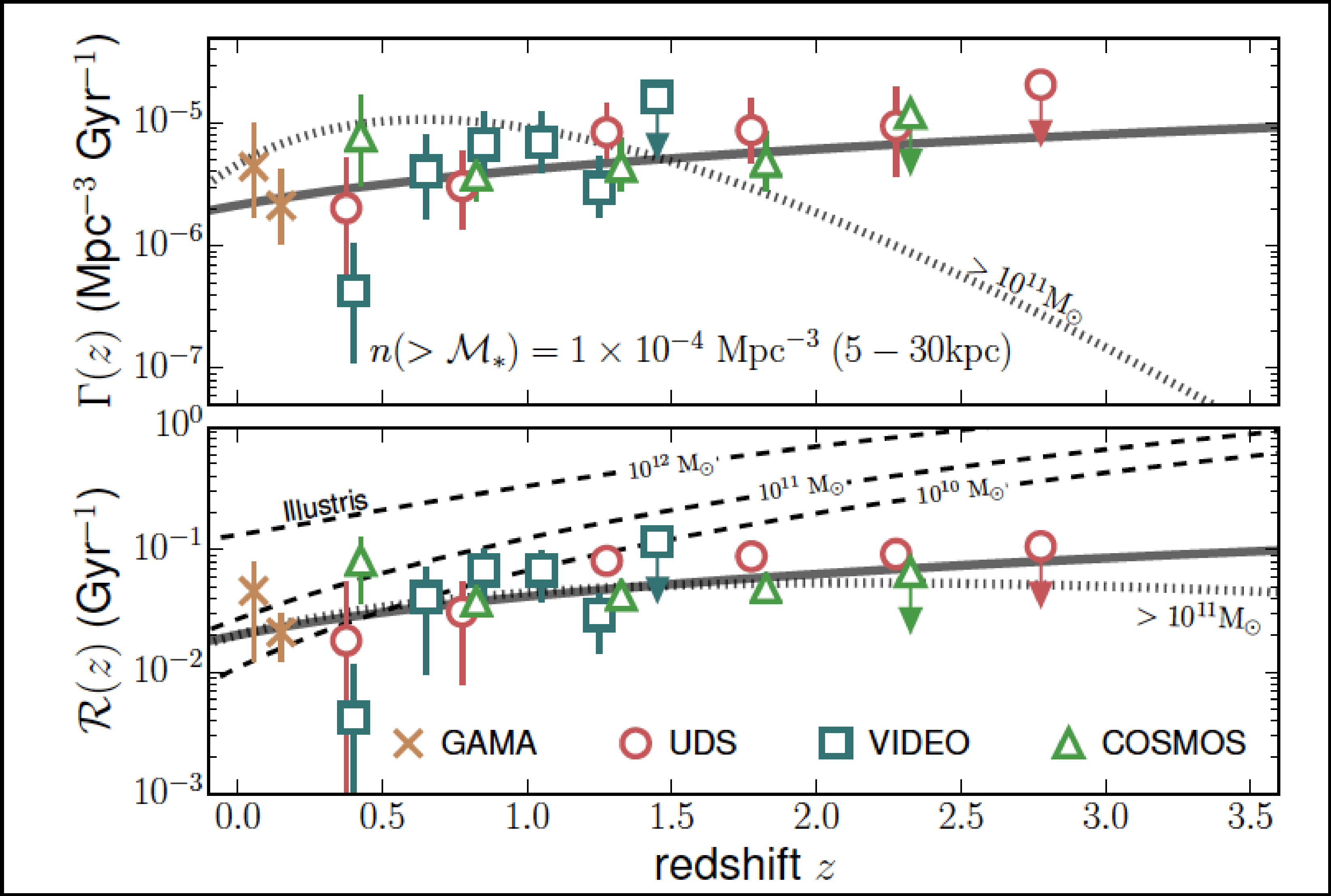
Fairly good agreement with star formation (but not merger rate)





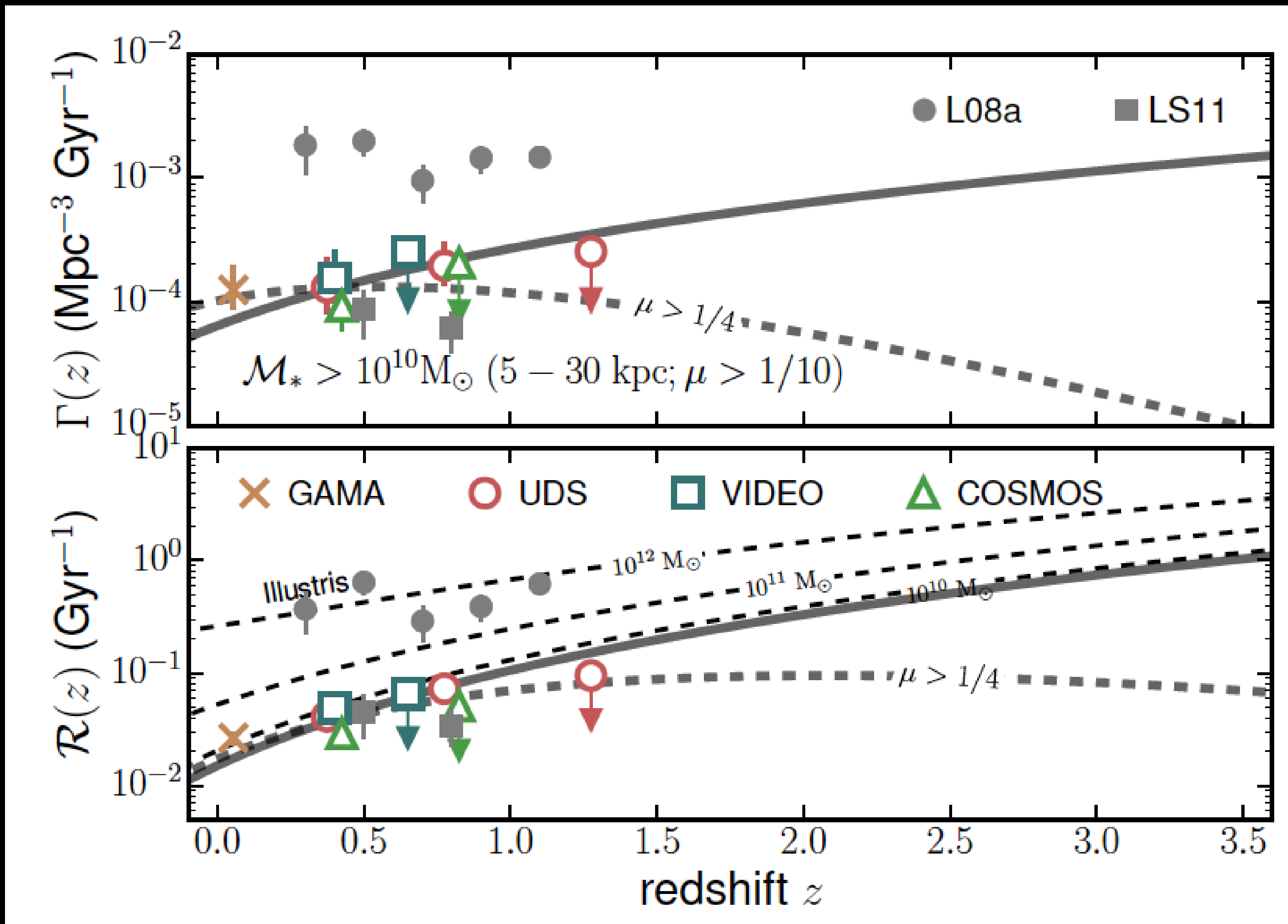
Illustris simulation results- Sparre+15, Vogelsberger+14

Comparison to Models – not good agreement



Mundy, CC+17 submitted

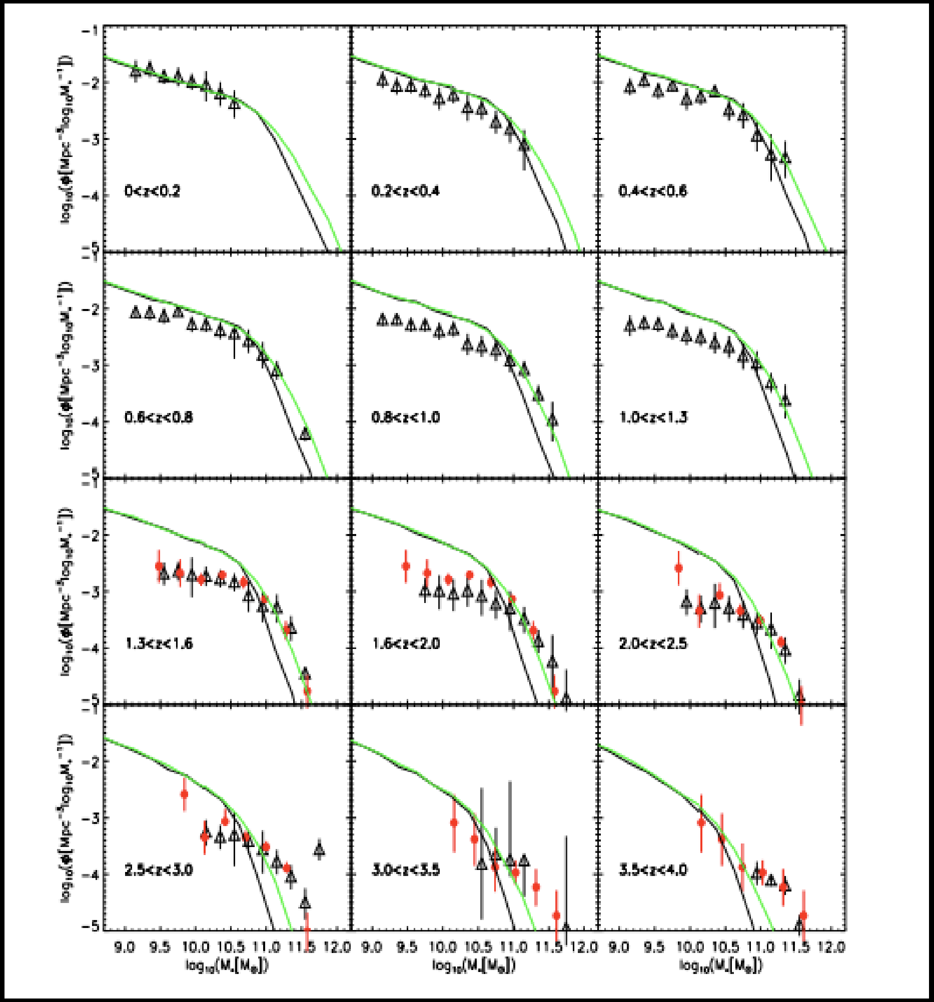
Minor merger comparison



Mundy, CC+17 submitted

Galaxy formation models in Lambda CDM

Traditional method: Make a model to predict or match observations



CDM does a very poor job at predicting galaxy evolution and properties of distant galaxies

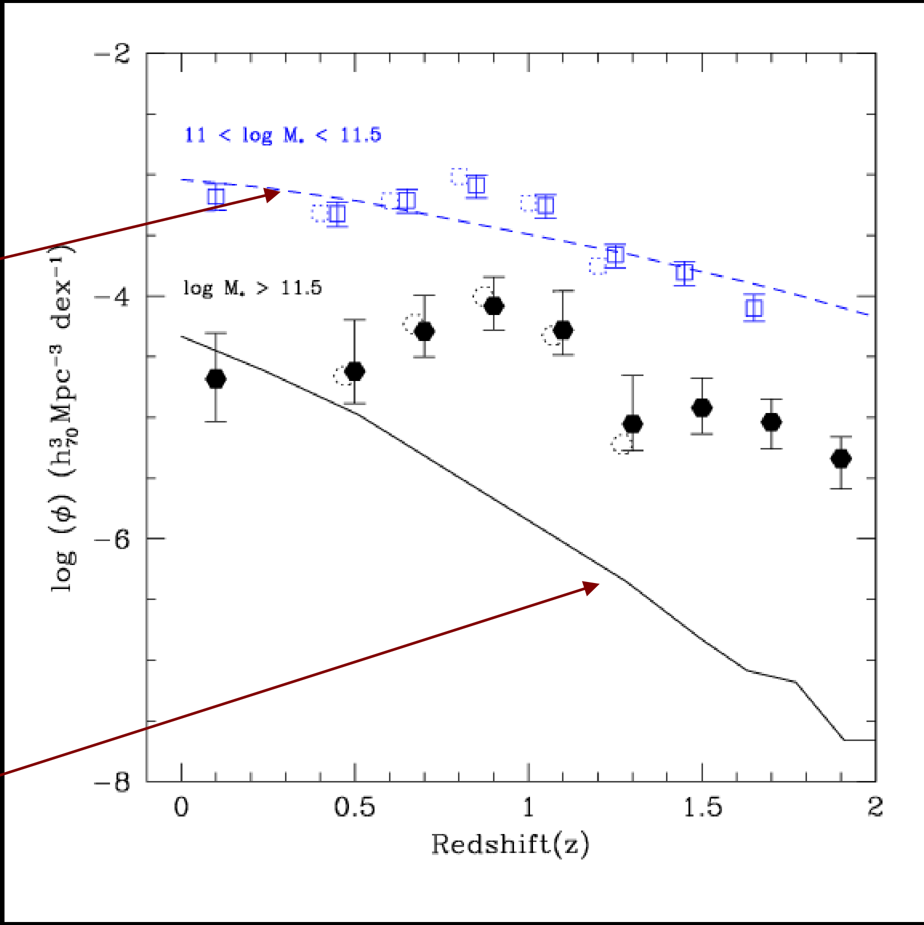
Problems at high-z: Guo et al. (2010)

Also, there are too many distant massive galaxies in LCDM

Millennium simulation

Prediction for 11 < log M < 11.5

Prediction for log M > 11.5



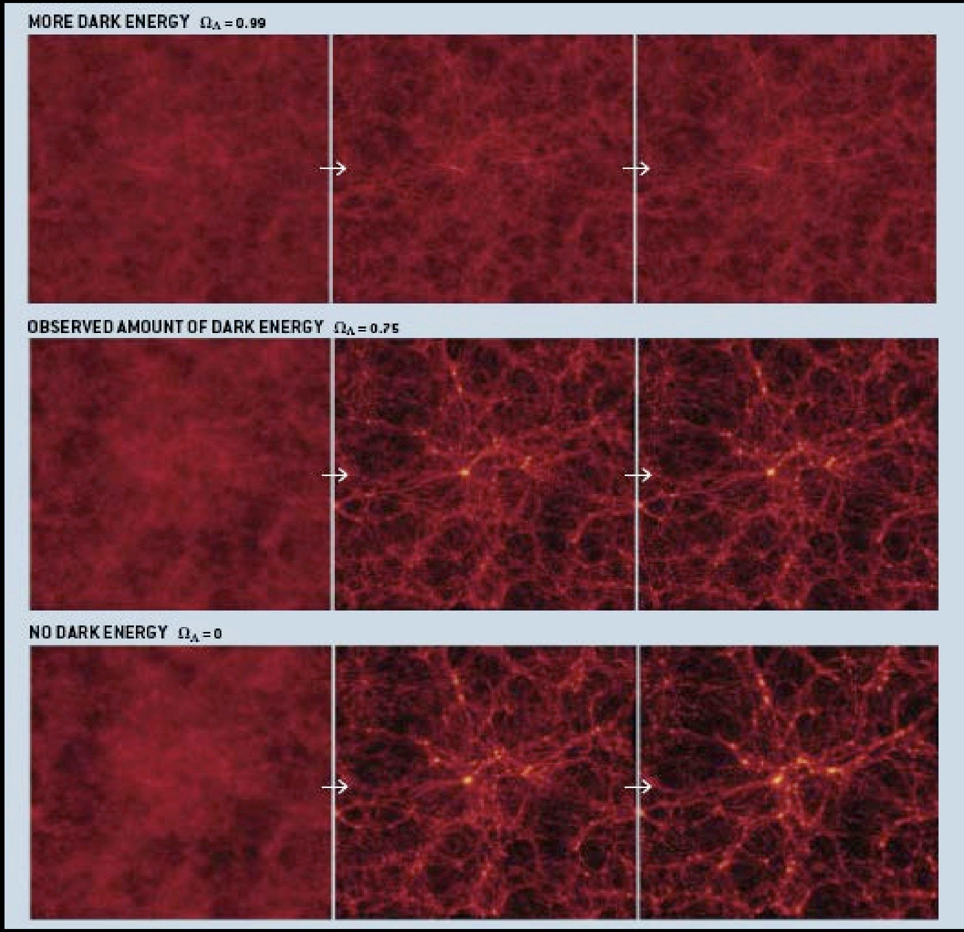
Vast under prediction in models compared to observations

Galaxy formation appears to be 'top-down' at small scales – Directly opposite to CDM predictions of 'bottom-up'

e.g., Conselice et al. (2007)

Galaxy Formation and Cosmology

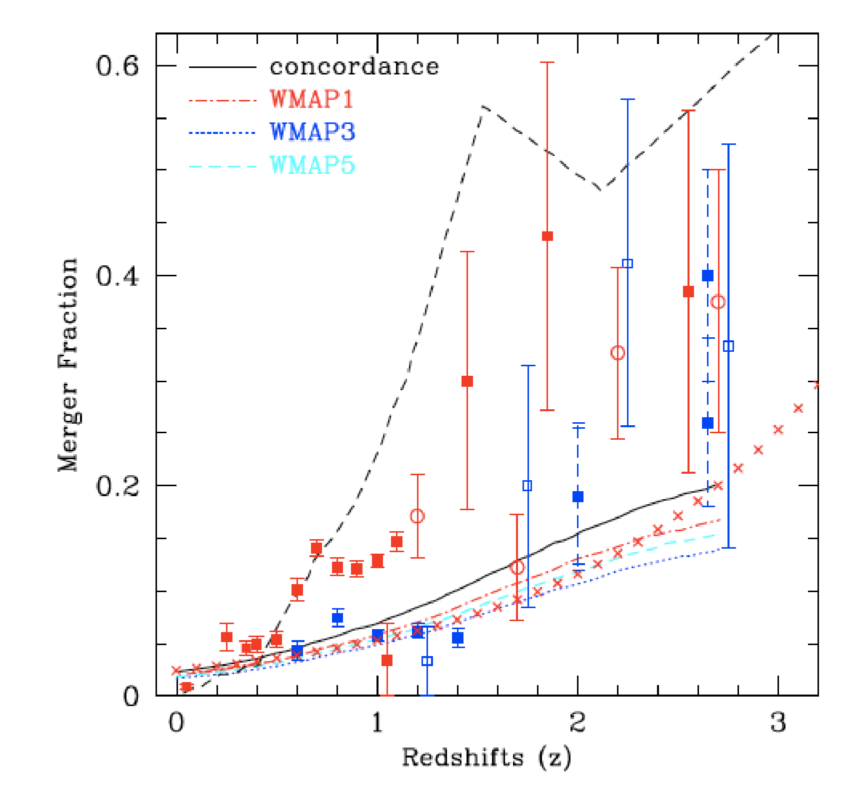
High-z Today

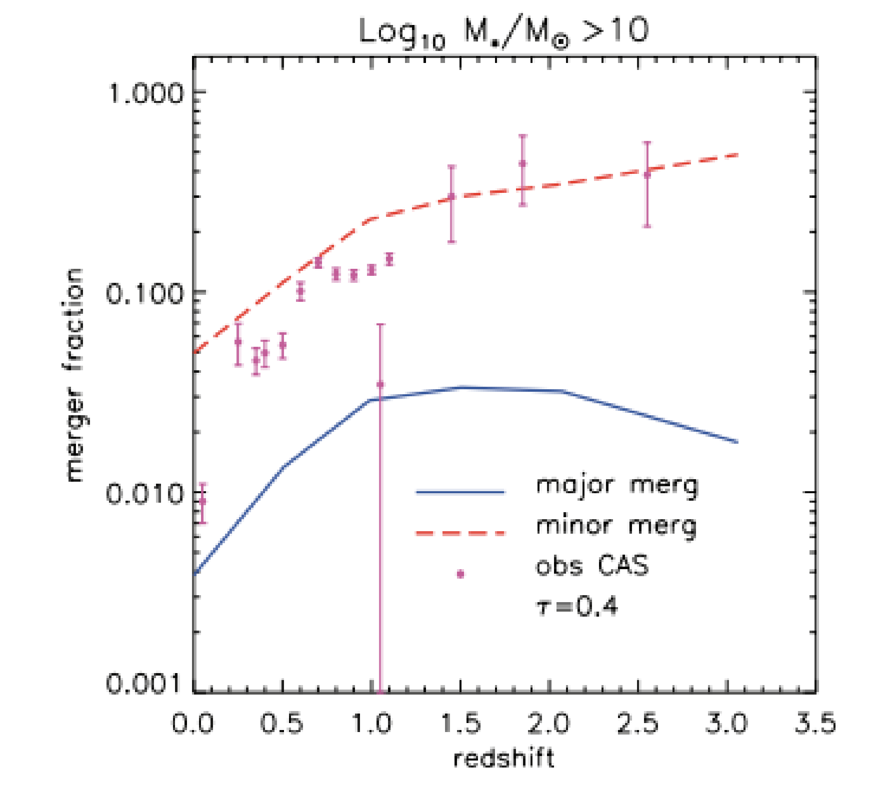


Observations of how structure formation occurs can perhaps help reveal cosmological features

Conselice, Feb 2007 Scientific American

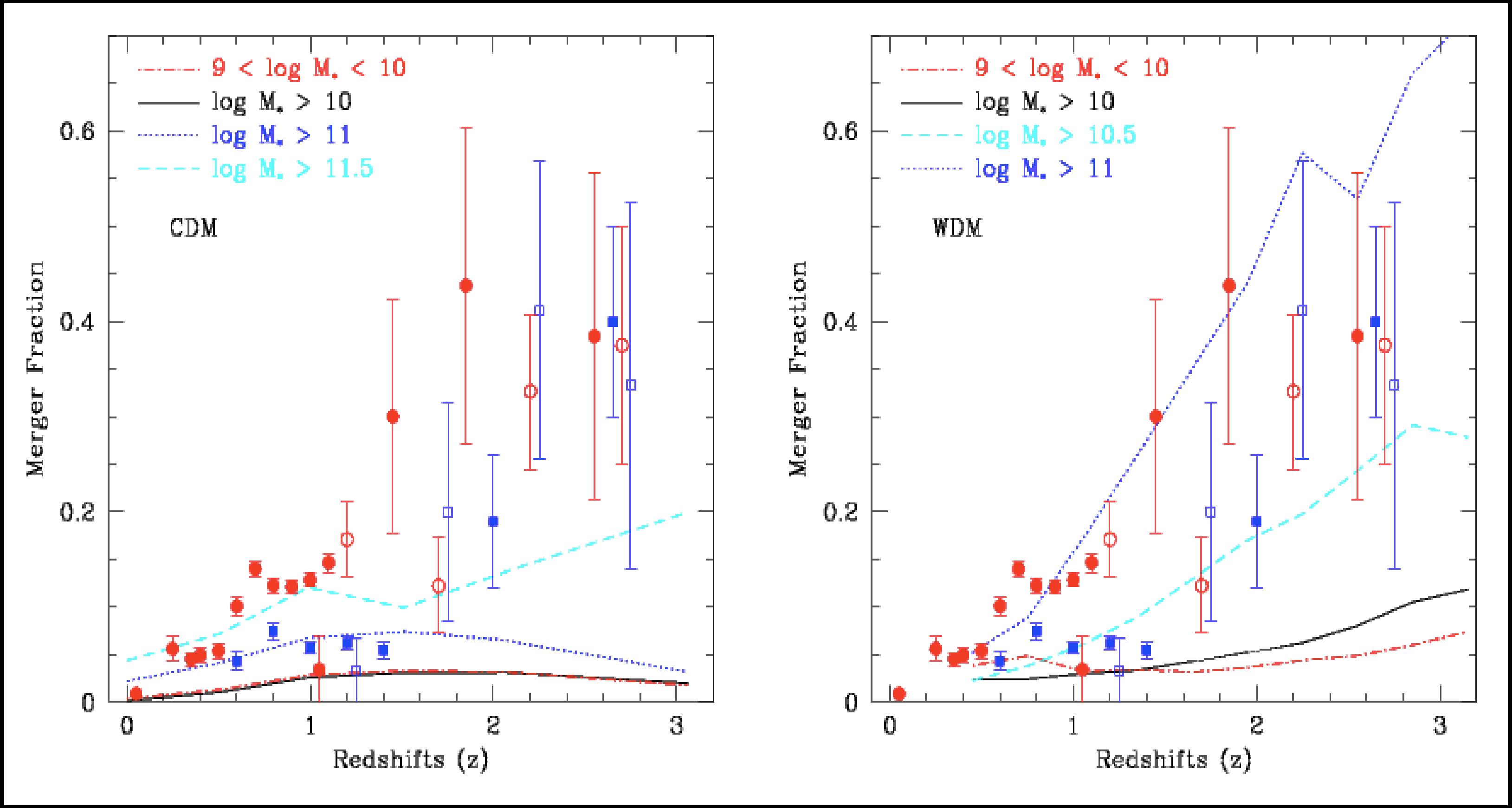
Different ΛCDM model predictions of the merger rate





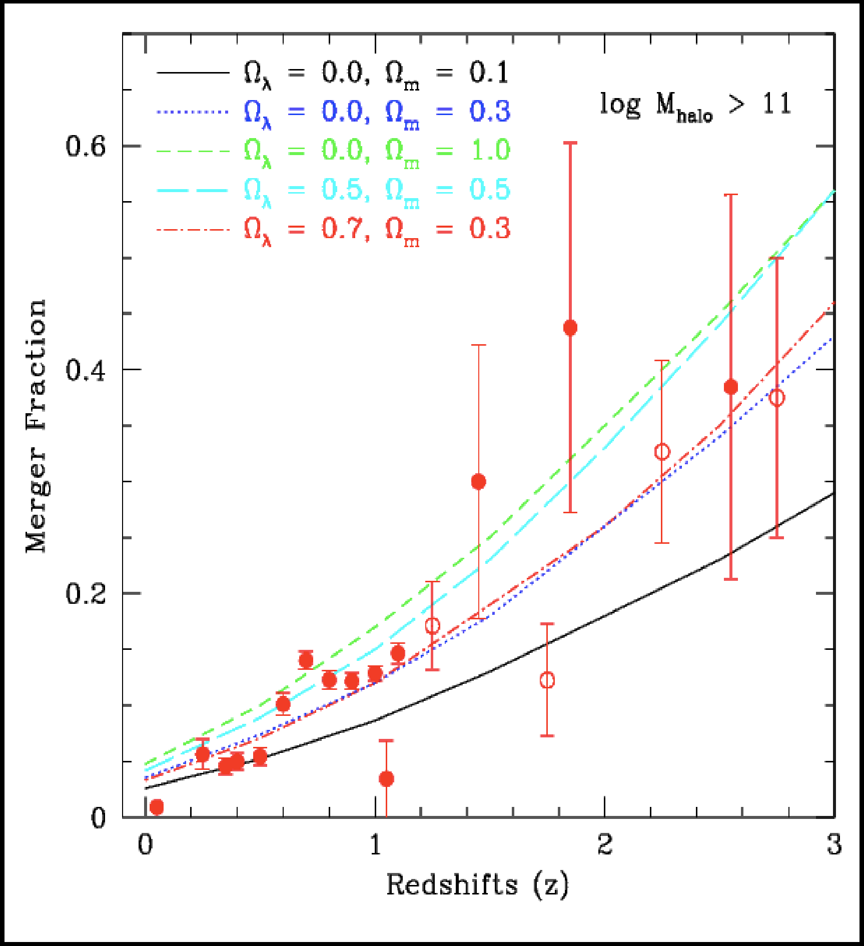
Maller et al. (2006); Bertone & Conselice (2009); Hopkins et al. (2010)

While merger history is not predicted well by CDM better by WDM



Warm dark matter fits much better

Better agreement between dark matter halo mergers

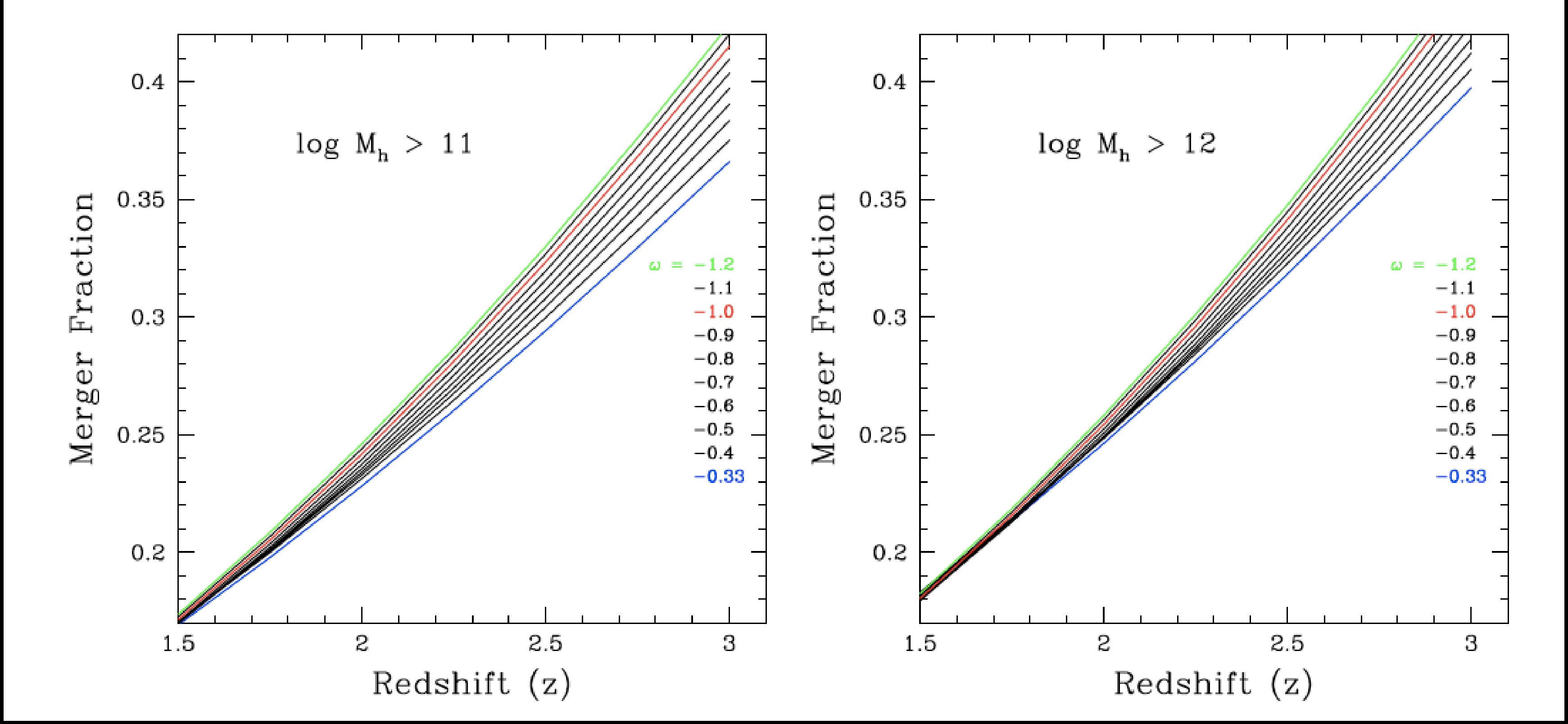


Best fitting model is standard cosmology

Higher merger fractions at higher matter densities

Issue(s) with baryonic physics driving stellar mass formation or cosmological assumptions?

Some variation with ω however, very small differences



Need a survey of > 10 deg^2 with accurate mergers to z=3 to use as a test of cosmology

Summary

1. Very deep observations needed to study galaxies at $z > 2$ to connect with galaxies at $z < 1.5$ and to use as a cosmological probe – can in principle give cosmological information and dark matter info.

2. Examination of the major merger history shows mergers are an important, but not the only process of galaxy formation, even for the most massive systems.

3. Minor mergers are about as equally as important as major mergers in forming massive galaxies from $1 < z < 3$.

4. Gas accretion from the intergalactic medium can account for roughly half of the baryonic formation of massive galaxies. We now getting roughly a complete census of massive galaxy formation at $z < 3$.

5. Models still need work to explain evolution and abundances of galaxies in LCDM – neither or which fit current simulations. WDM appears to do better.