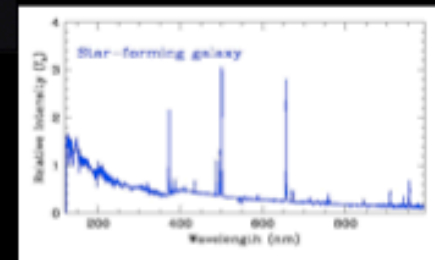
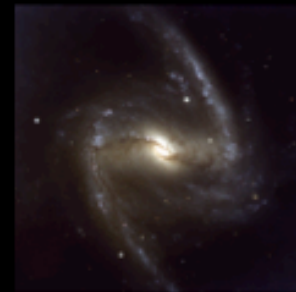
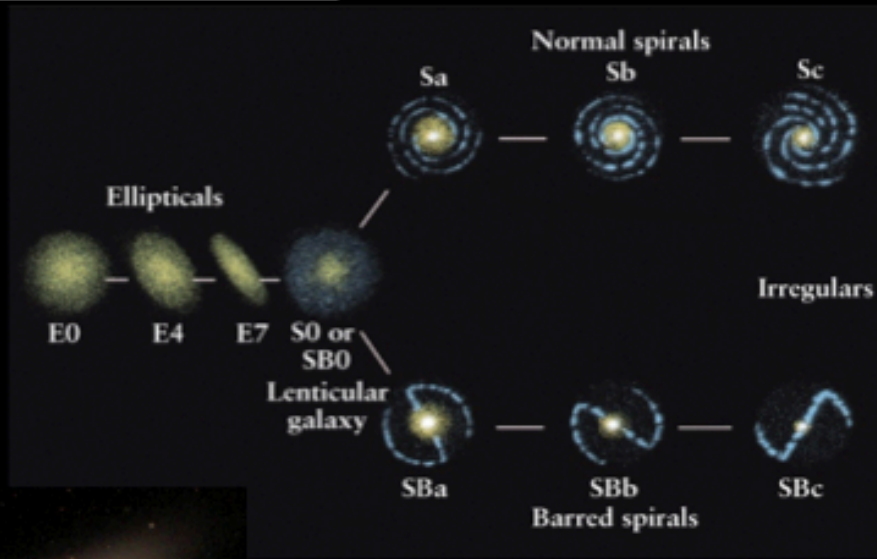
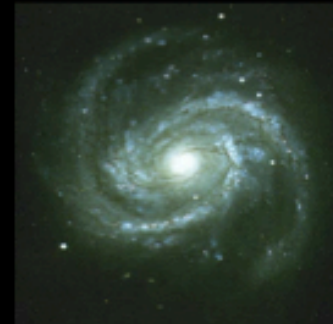
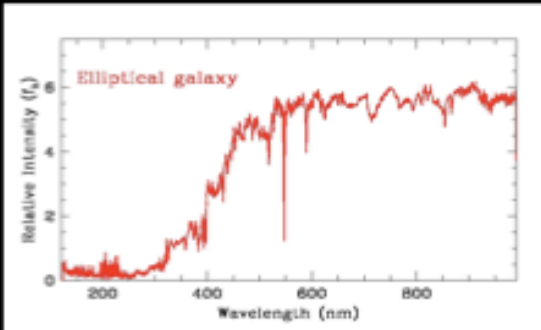


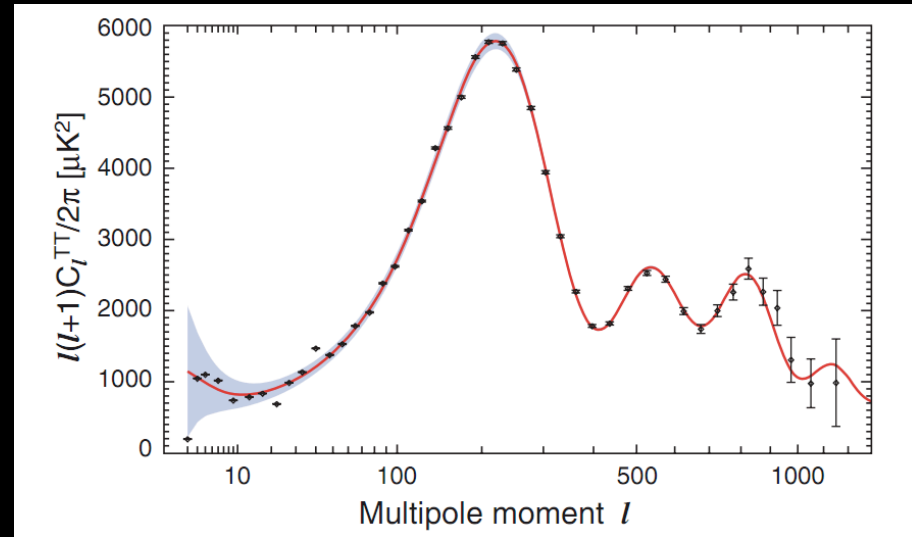
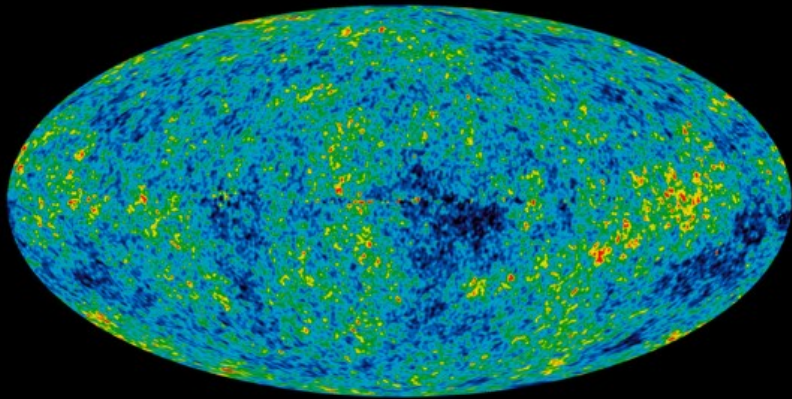
Galaxies formation and evolution: An overview

Christopher J. Conselice

(University of Nottingham)

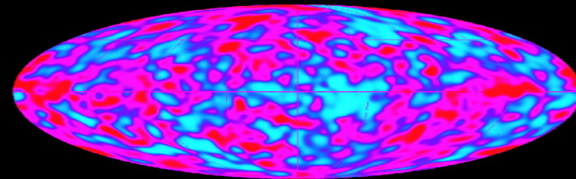


Cosmic Background Radiation – cosmological parameters



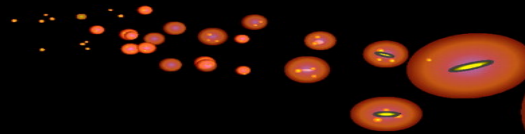
WMAP7

Traditional Idea for How Galaxies Form

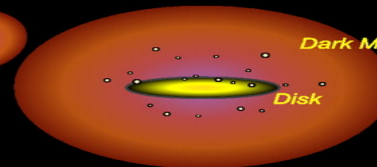


1. Small mass fluctuations (such as those revealed by the all-sky map, shown at left, obtained by the COBE satellite) are relics of the Big Bang. These are the "seeds" of galaxy formation.

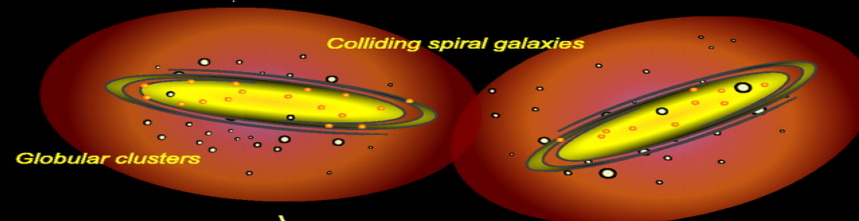
2. Invisible dark matter halos (shown in brown below) collapse from the ambient background, tracing the initial mass fluctuations.



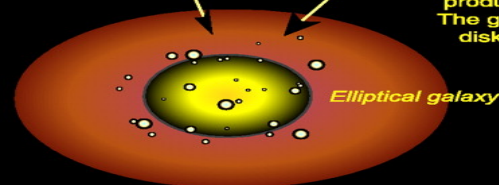
3. Primordial gas condenses within the dark matter halos. Some stars form during the collapse, and collect into globular clusters. Most of the gas collects into disks (shown in yellow).



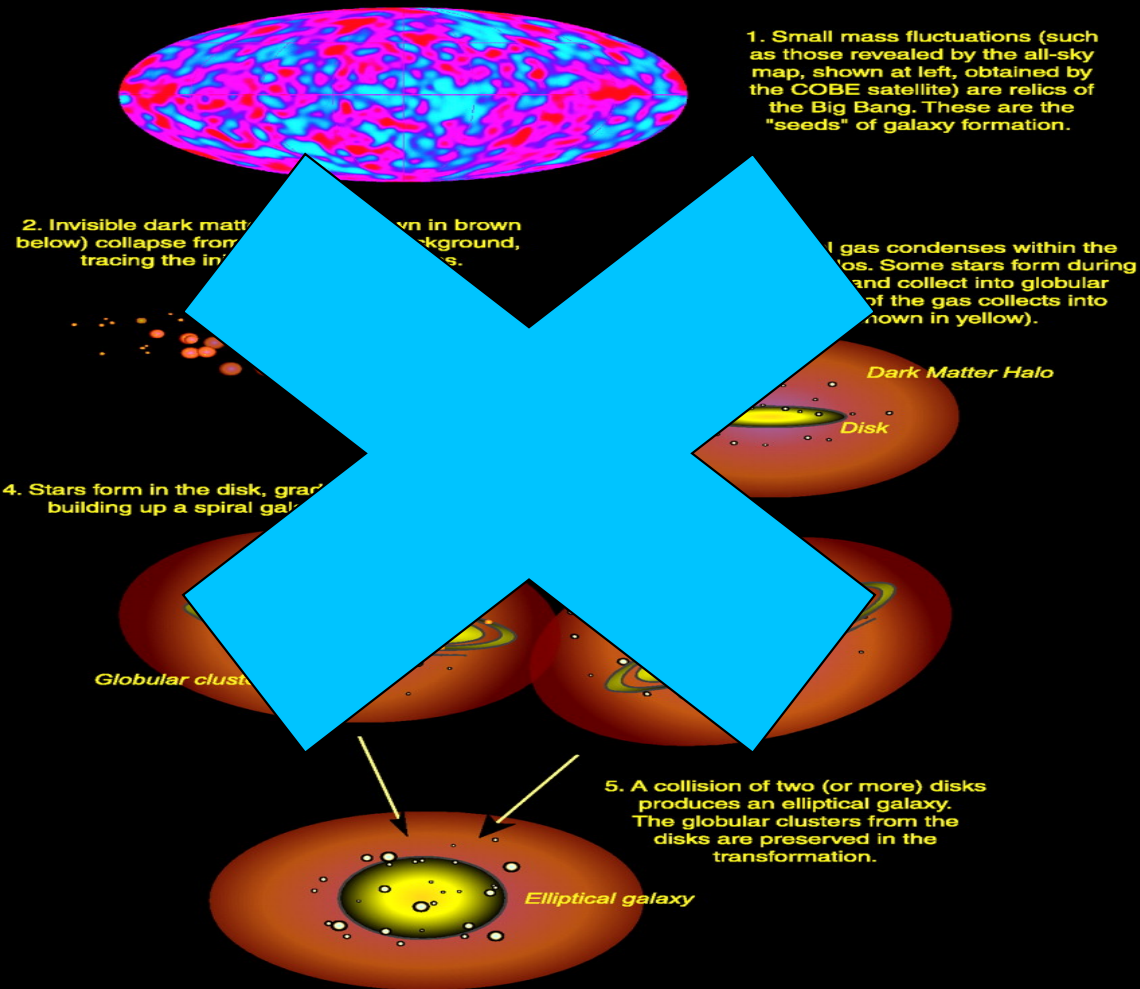
4. Stars form in the disk, gradually building up a spiral galaxy.



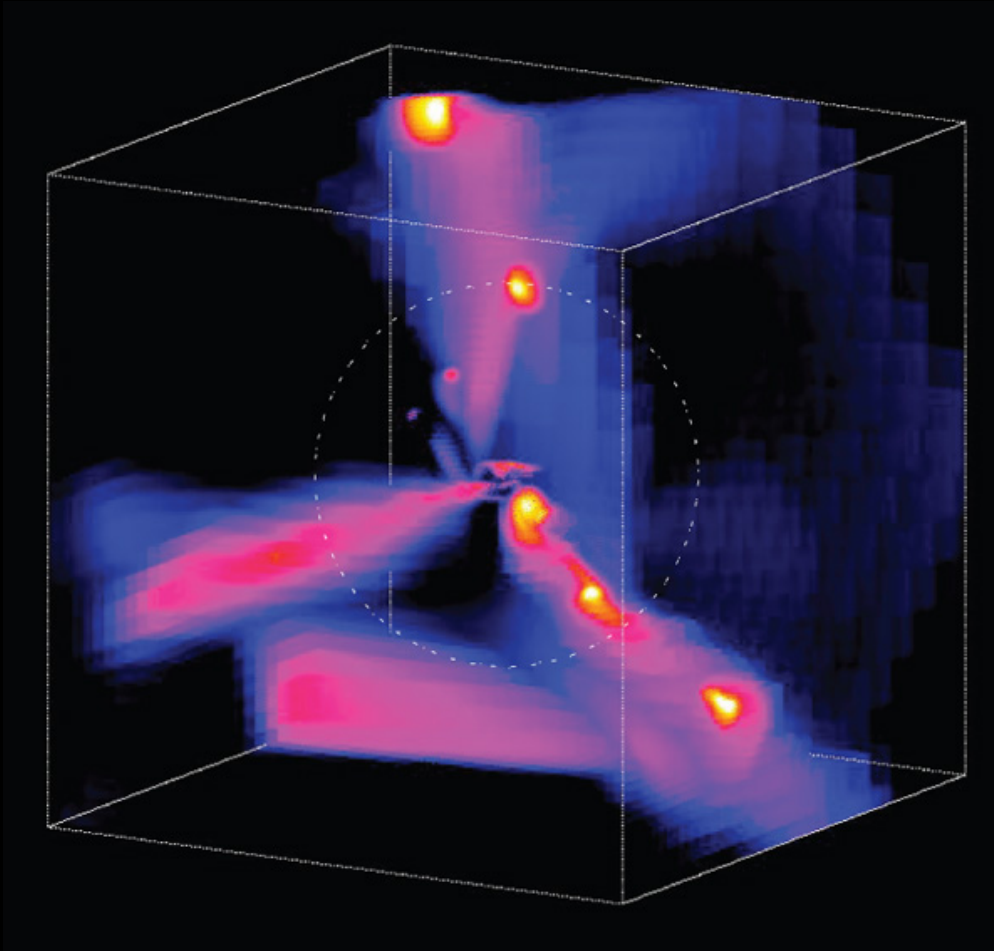
5. A collision of two (or more) disks produces an elliptical galaxy. The globular clusters from the disks are preserved in the transformation.



Traditional Idea for How Galaxies Form

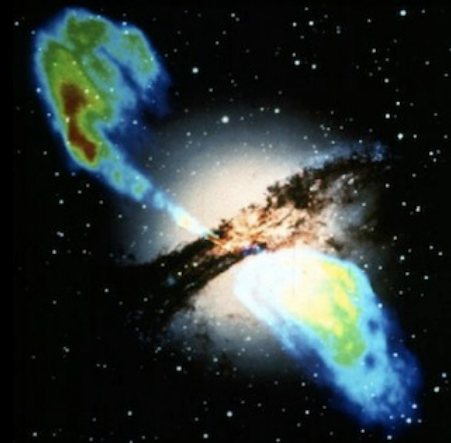


Cold gas accretion is a popular theoretical idea – but little obs. evidence



Dekel et al. 2008

Feedback – e.g., AGN



Certainly occurs, but exact role uncertain

Galaxy Formation: How can we address this problem?

1. Observationally – scaling relations, and counting (i.e., mass and luminosity functions), star formation rates, mass evolution, dark matter properties as a function of time (redshift) (history not physics)

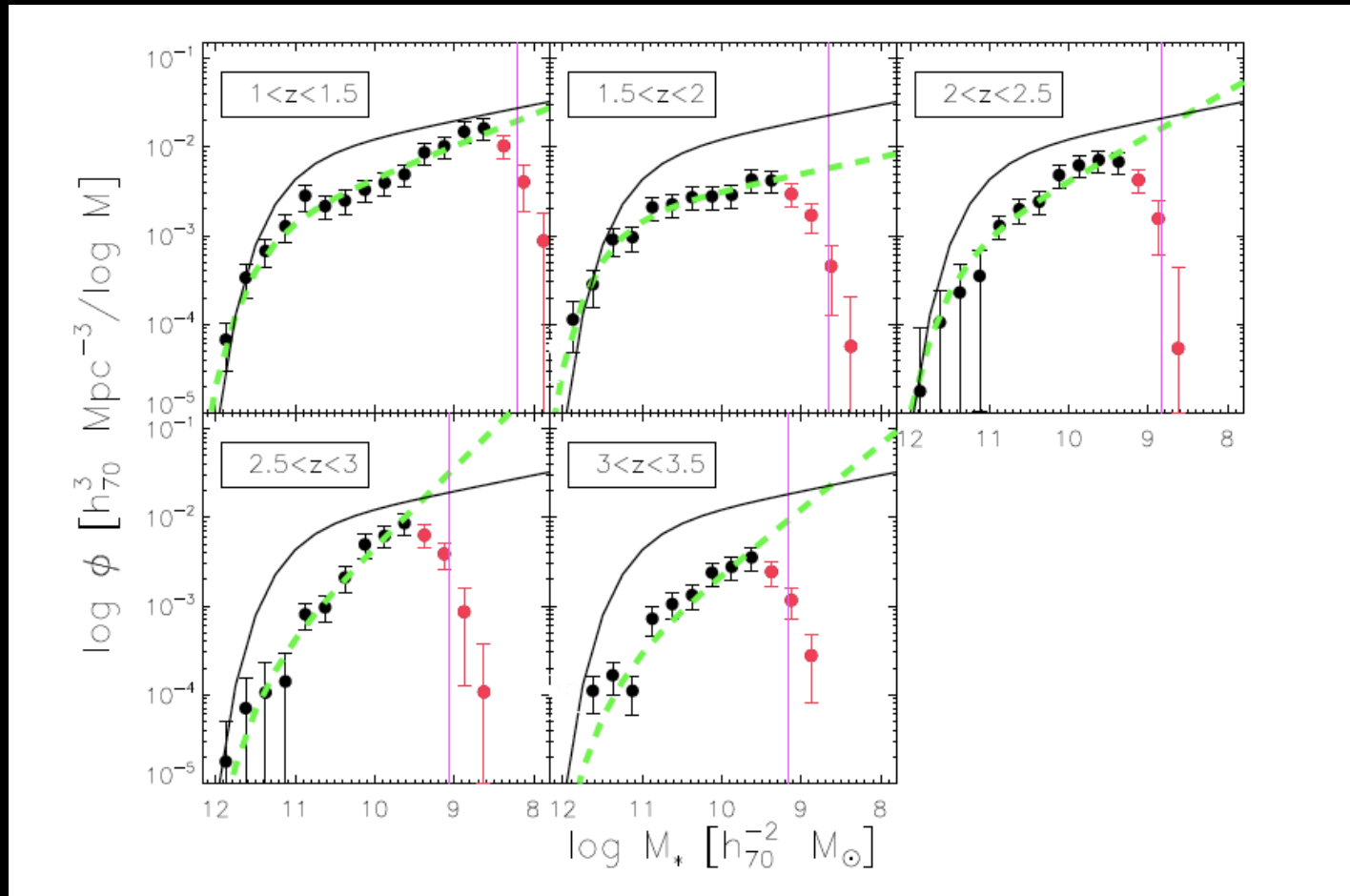
Galaxy Formation: How can we address this problem?

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Galaxy Formation: How can we address this problem?

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2. Theory - simulations of galaxy formation i.e., numerical, SPH, semi-analytical, etc. Try to match the observations with ‘physics’ – cosmological model with gas physics included
3. Identification of physical processes from observations that drive evolution and trace through time looking at similar galaxies at different redshifts
 - a. Interactions+Mergers, gas accretion, feedback (SN, AGN, etc)
 - b. Environmental process – what are consequences of galaxies living in a variety of environments on their formation/evolution?

A first attempt to solve this problem is with massive galaxies



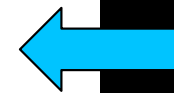
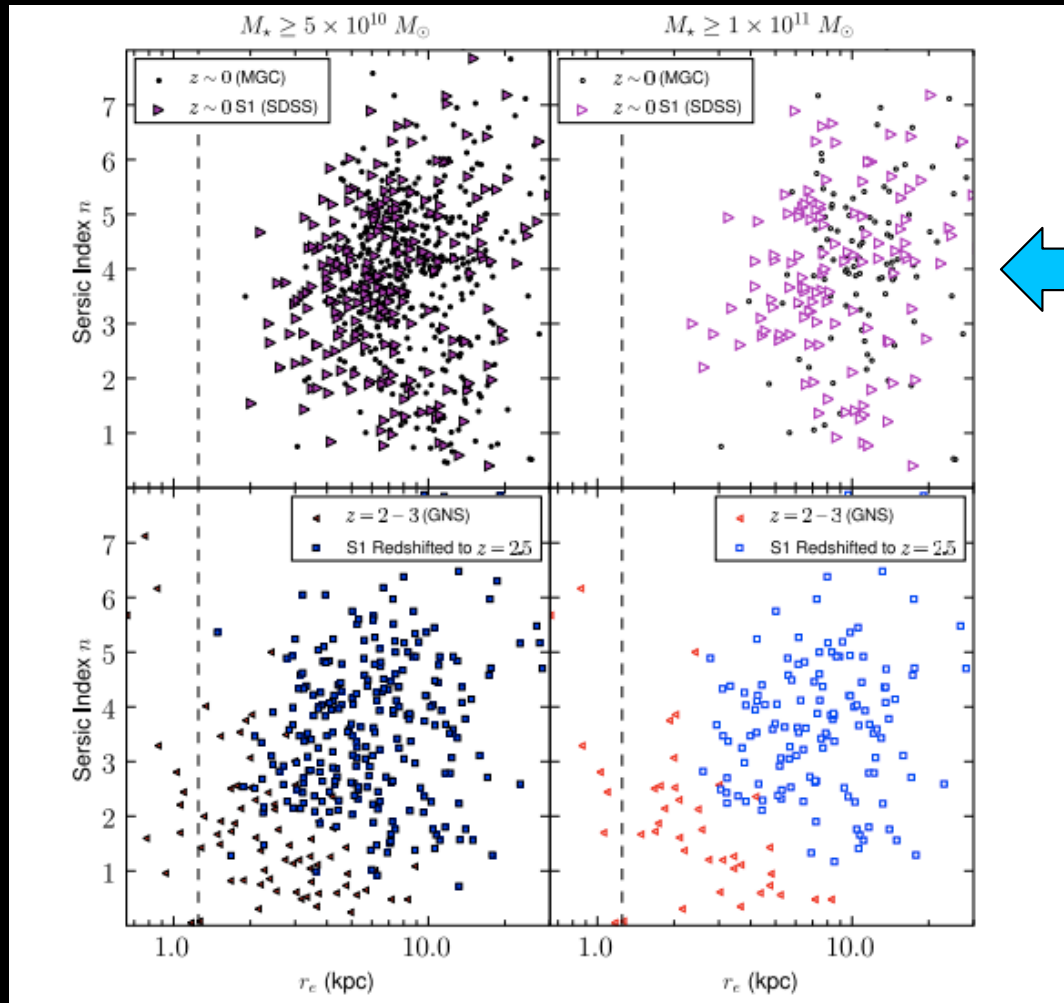
Mortlock et al. (2010)

Most massive galaxies are formed by $z = 1$



Example of nearby massive galaxy

Galaxies at $z = 2.5$ --- different from nearby massive galaxies

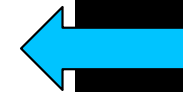
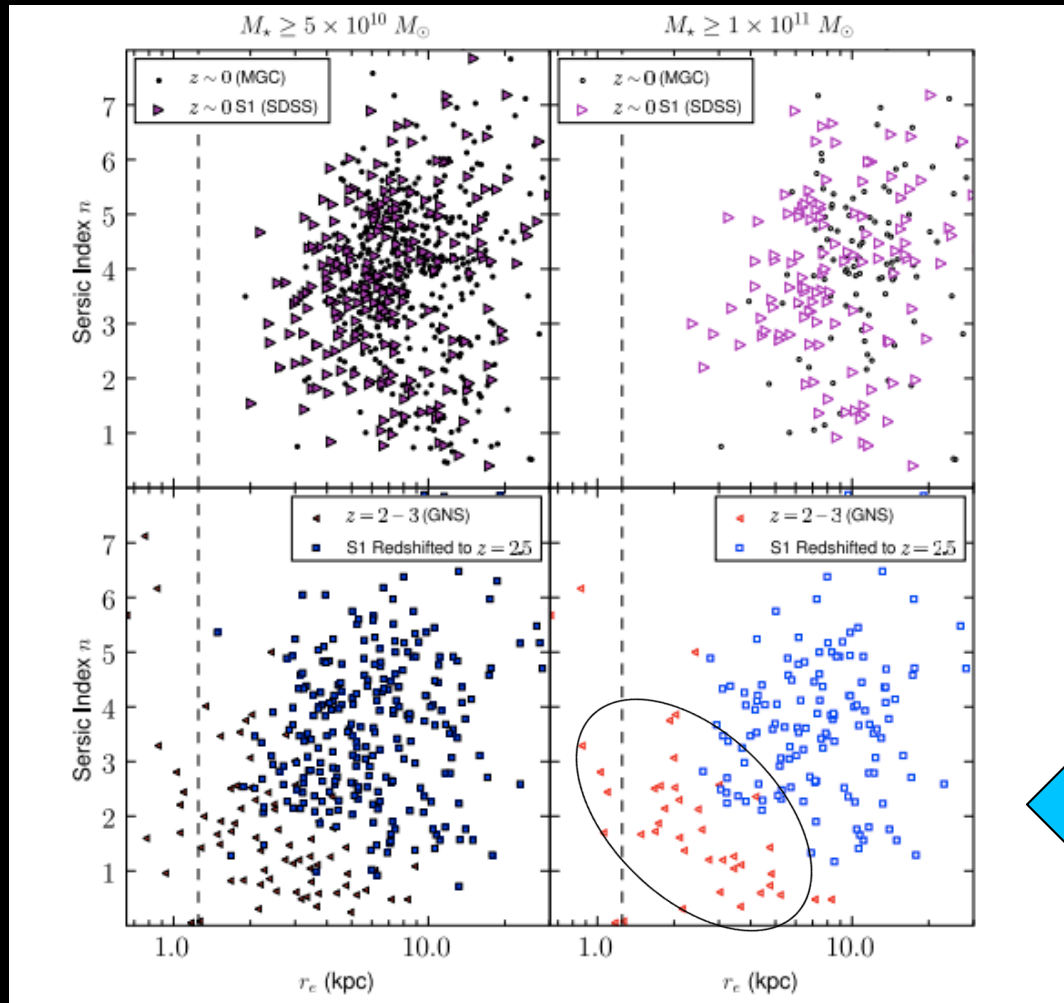


Nearby massive galaxies

Weinzirl et al. (2011)



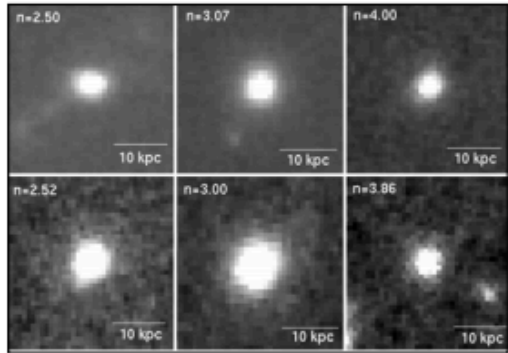
Galaxies at $z = 2.5$ --- different from nearby massive galaxies



Same mass
but at $z > 1$

Massive Galaxies at $z > 1.5$

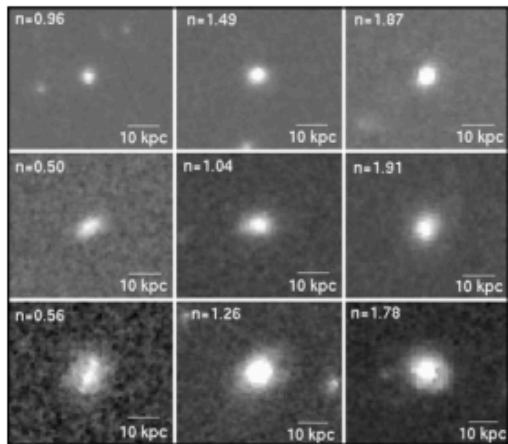
$n > 2$ Systems



$r_e \leq 2$ kpc

$2 < r_e \leq 4$ kpc

$n \leq 2$ Systems

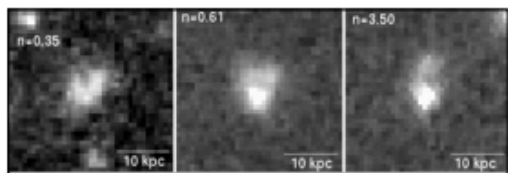


$r_e \leq 2$ kpc

$2 < r_e \leq 4$ kpc

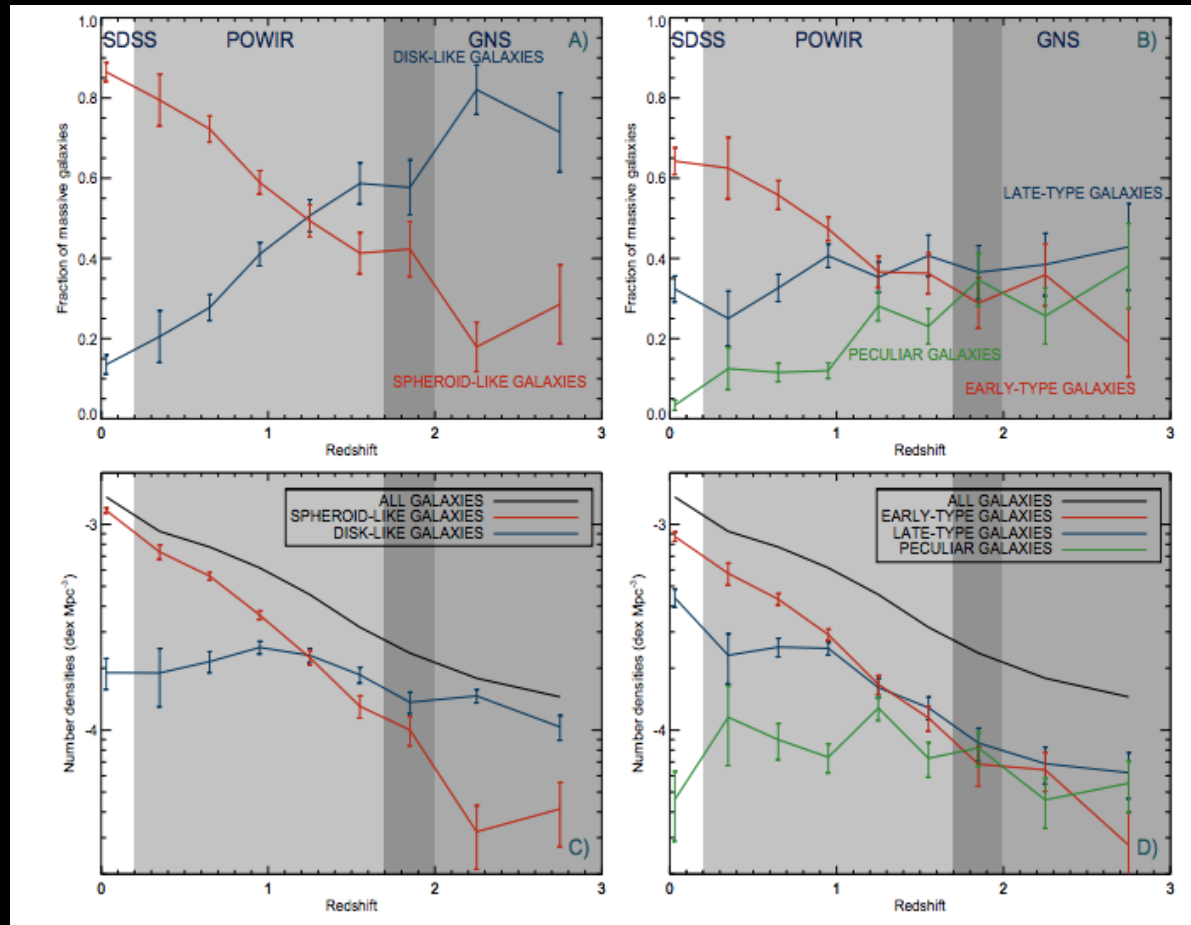
$4 < r_e \leq 8$ kpc

Irregular/Disturbed Systems



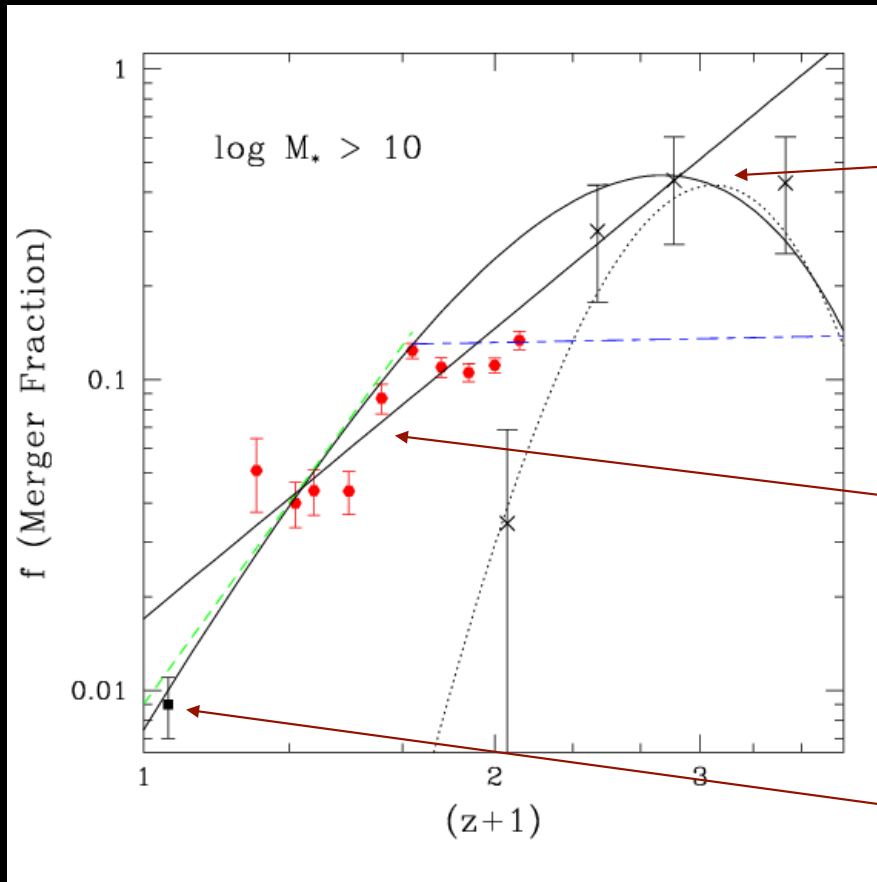
$2.7 \leq r_e \leq 3.6$ kpc

Massive galaxies become more disk like at higher redshifts



Buitrago et al. (2011)

Do mergers form galaxies?



UDF+HDF
(z = 1 - 3)

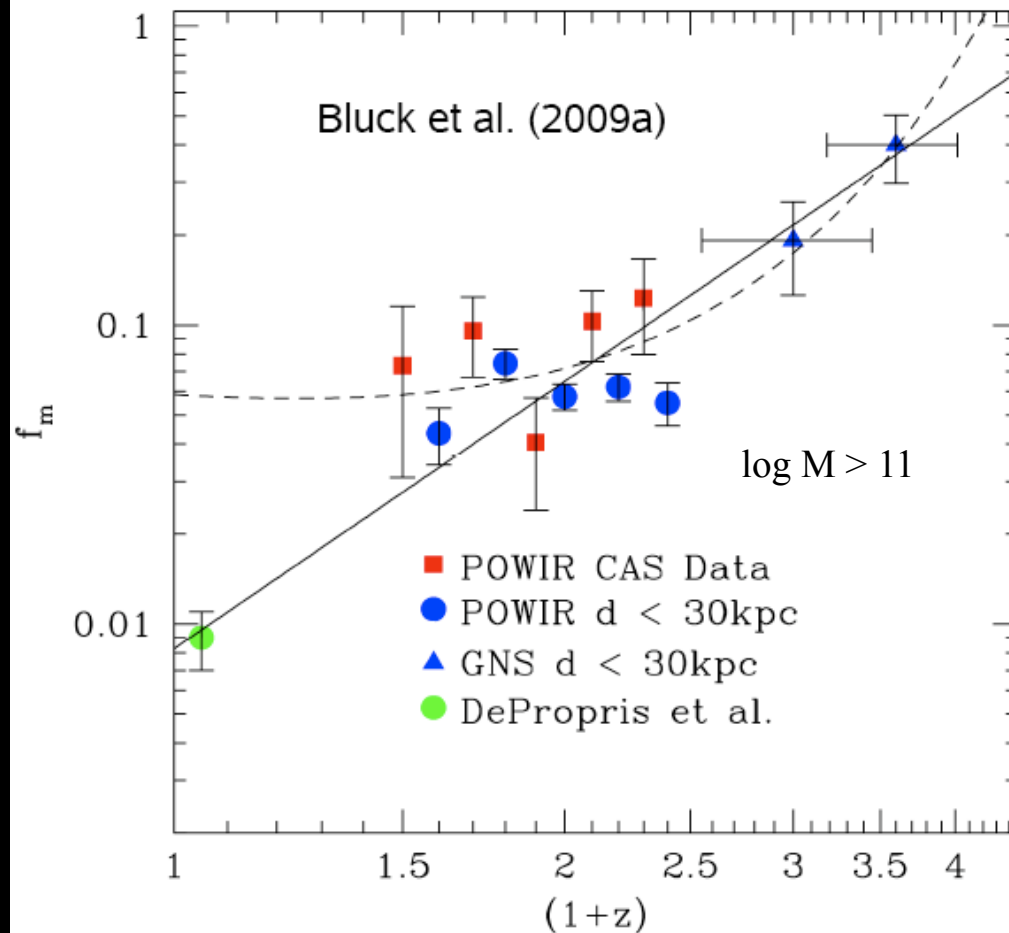
EGS+COSMOS
(z = 0.2 - 1.2)

Millennium Galaxy
Catalog (z = 0)

Evolves as $(1+z)^3$ to $z = 1.5$

Conselice et al. (2009)

Results – Merger Fraction Evolution



This plot shows the redshift evolution of the merger fraction for massive galaxies.

The solid line is a best fit power law approach:

$$f(z) = f(0) \times (1+z)^\alpha$$

Dotted line is Press-Schechter power law exp:

$$f(z) = f(0)(1+z)^\alpha \exp(\beta(1+z)^2)$$

Number of Major Mergers



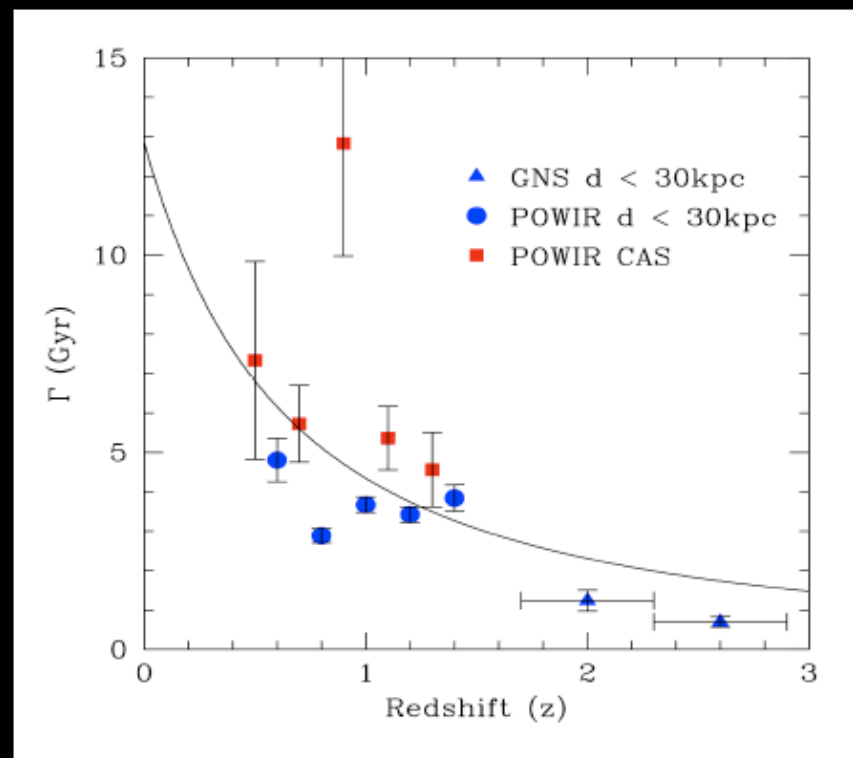
The number of mergers an average massive galaxy will undergo from $z = 3$ to $z = 0$ can be calculated via:

$$N_m = \int_{t_1}^{t_2} \frac{1}{\Gamma(z)} dt = \int_{z_1}^{z_2} \frac{1}{\Gamma(z)} \frac{t_H}{(1+z)} \frac{dz}{E(z)}$$

For our best fit for $\Gamma(z)$, integrating over the redshift range of our galaxies we obtained:

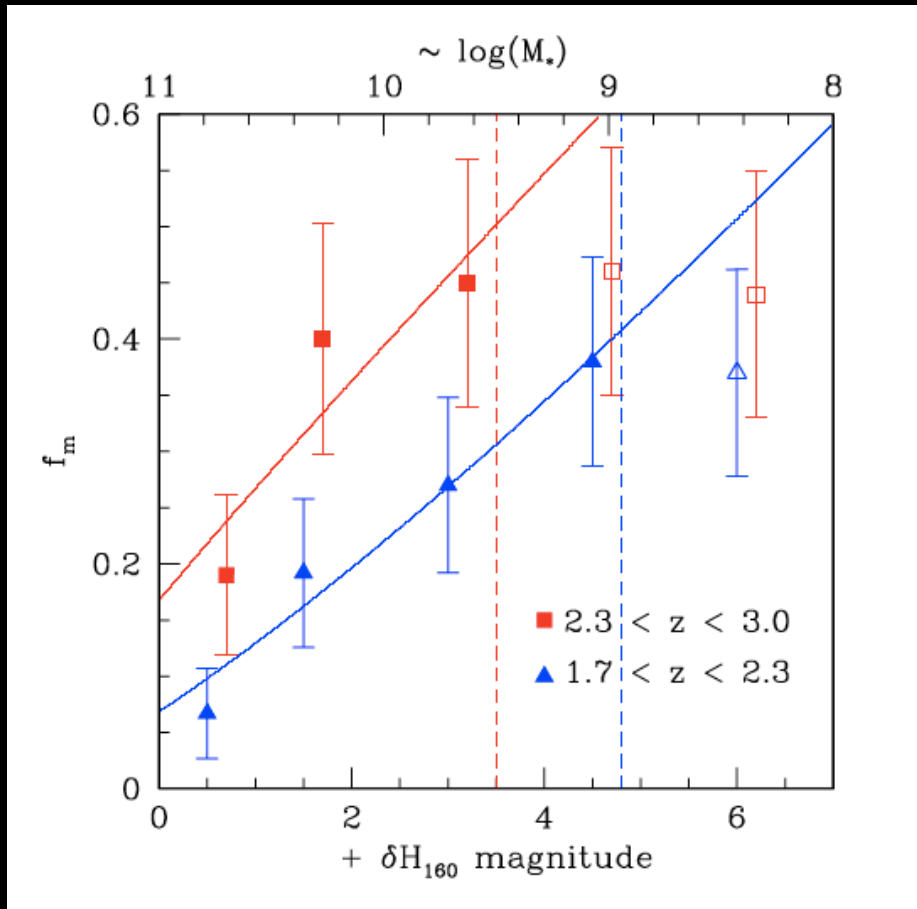
$$N = 1.7 \pm 0.5$$

(Major mergers / Galaxy)



Roughly doubles the stellar masses of galaxies

Role of minor mergers



More minor mergers – however,
add less mass than major mergers

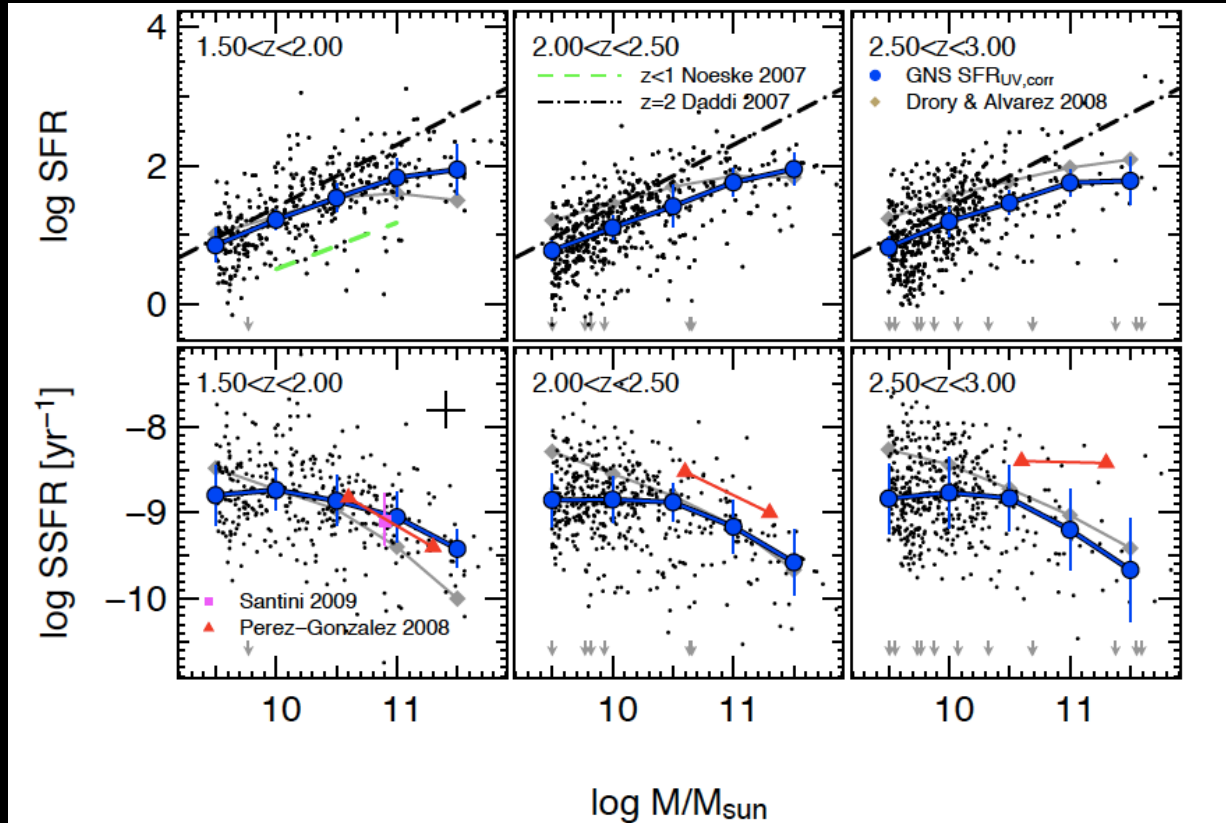
Total amount from mergers:

$$M_{*,M}/M_{*,0} = 0.51 \pm 0.2$$

Bluck, Conselice et al. (2011)



The star formation rates as a function of stellar mass



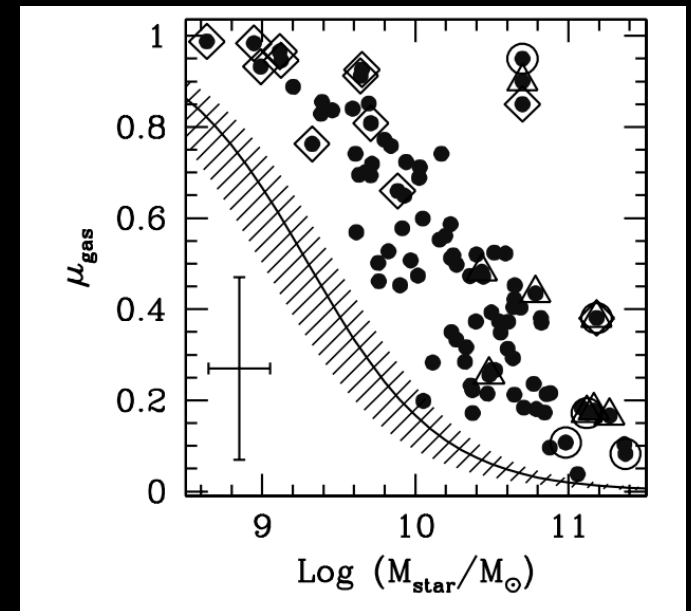
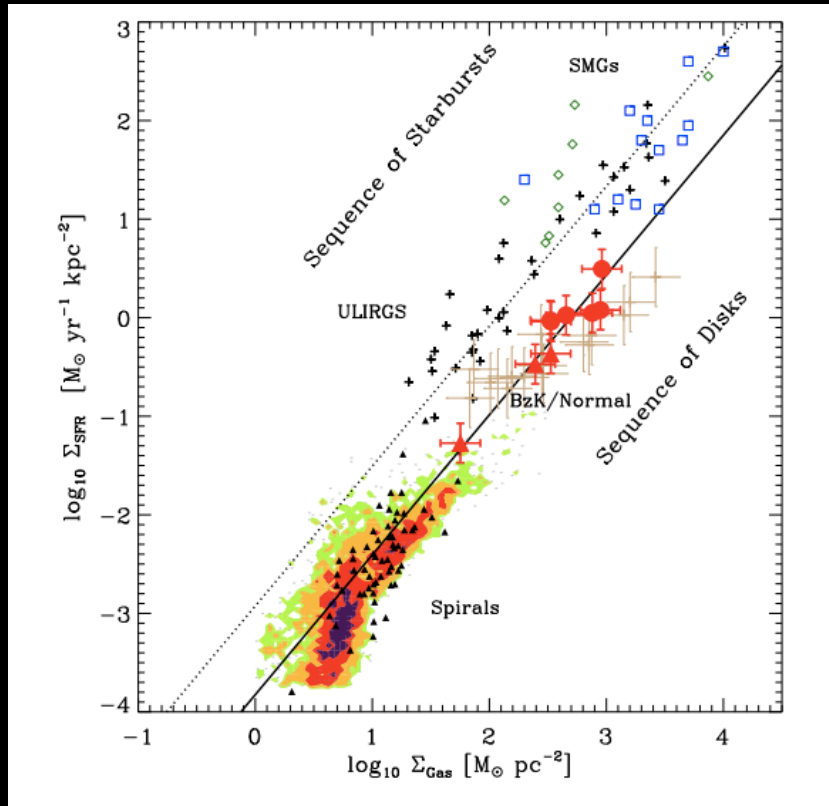
More massive galaxies have higher star formation rates at $z > 1$

Stellar mass added by star formation

$$(\psi \delta t / M_0) = 0.67 \pm 0.08$$

Bauer, Conselice, et al. (2011)

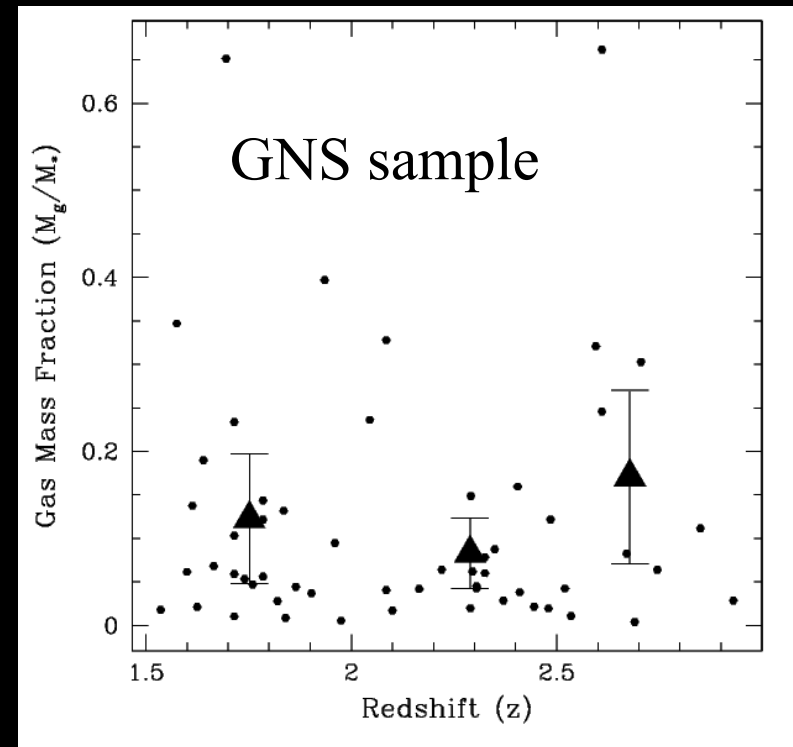
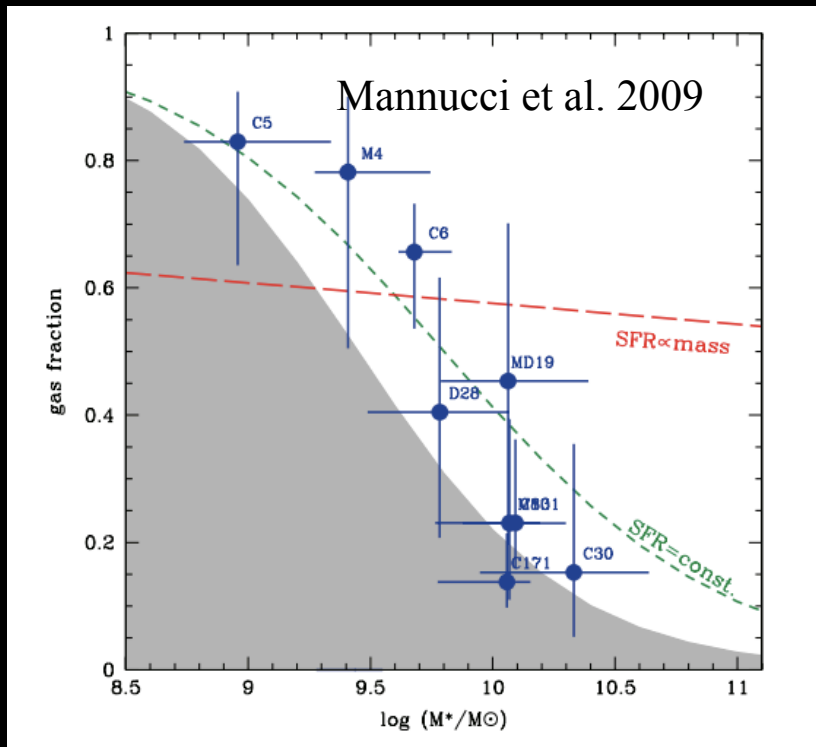
Gas mass fractions from Inverse Schmidt-Kennicutt



Erb et al. (2006)

Cold gas fraction for $\log M > 11$ is $\sim 0.1-0.2$ in GNS

Gas mass fractions



$$\Sigma_{\text{SFR}} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\text{gas}}}{1 M_\odot \text{pc}^{-2}} \right) M_\odot \text{yr}^{-1} \text{kpc}^{-2}$$

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

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

Stellar mass evolution

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

Gas mass evolution

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

Observed condition

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

Amount of gas accreted

Integrate: Mass added from SF \sim Mass added from major merging

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

 *Evidence for cold gas accretion?*

The amount of gas added from accretion (or very minor mergers)

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

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

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

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

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

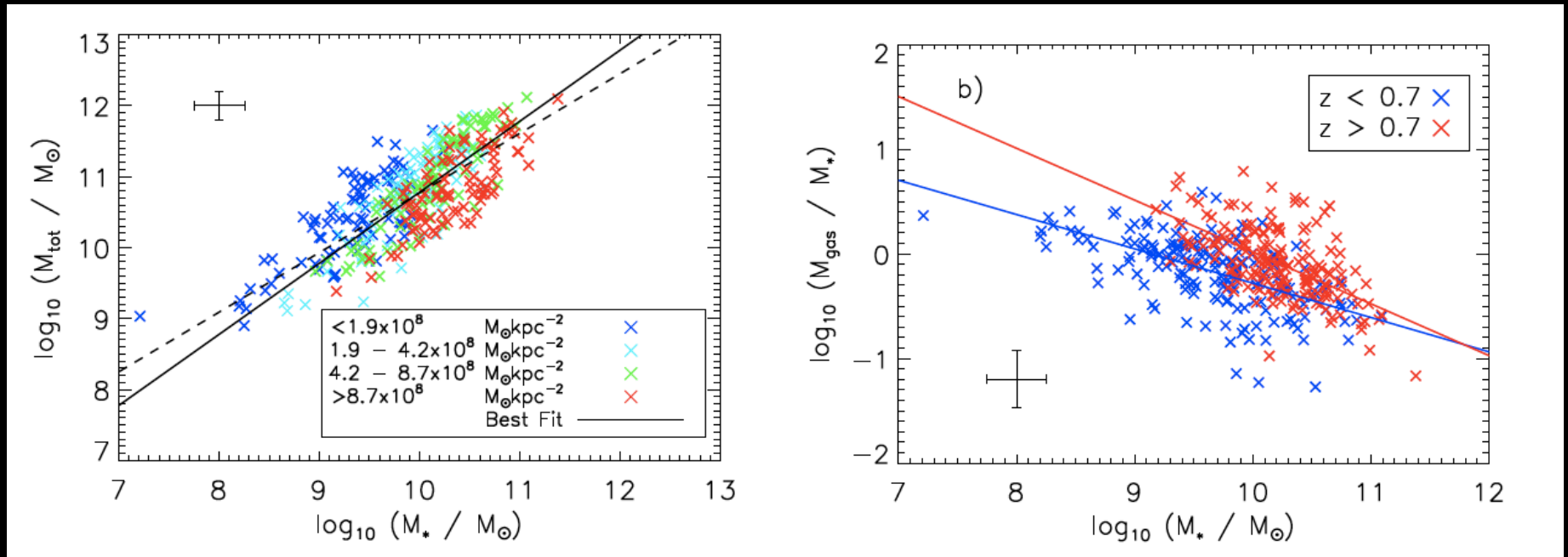
Average amount of gas accreted

Results in accretion rate of

$$\frac{dM_{g,A}(t)}{dt} = \dot{M}_{g,A} = (83 \pm 36) M_\odot \text{ yr}^{-1}$$

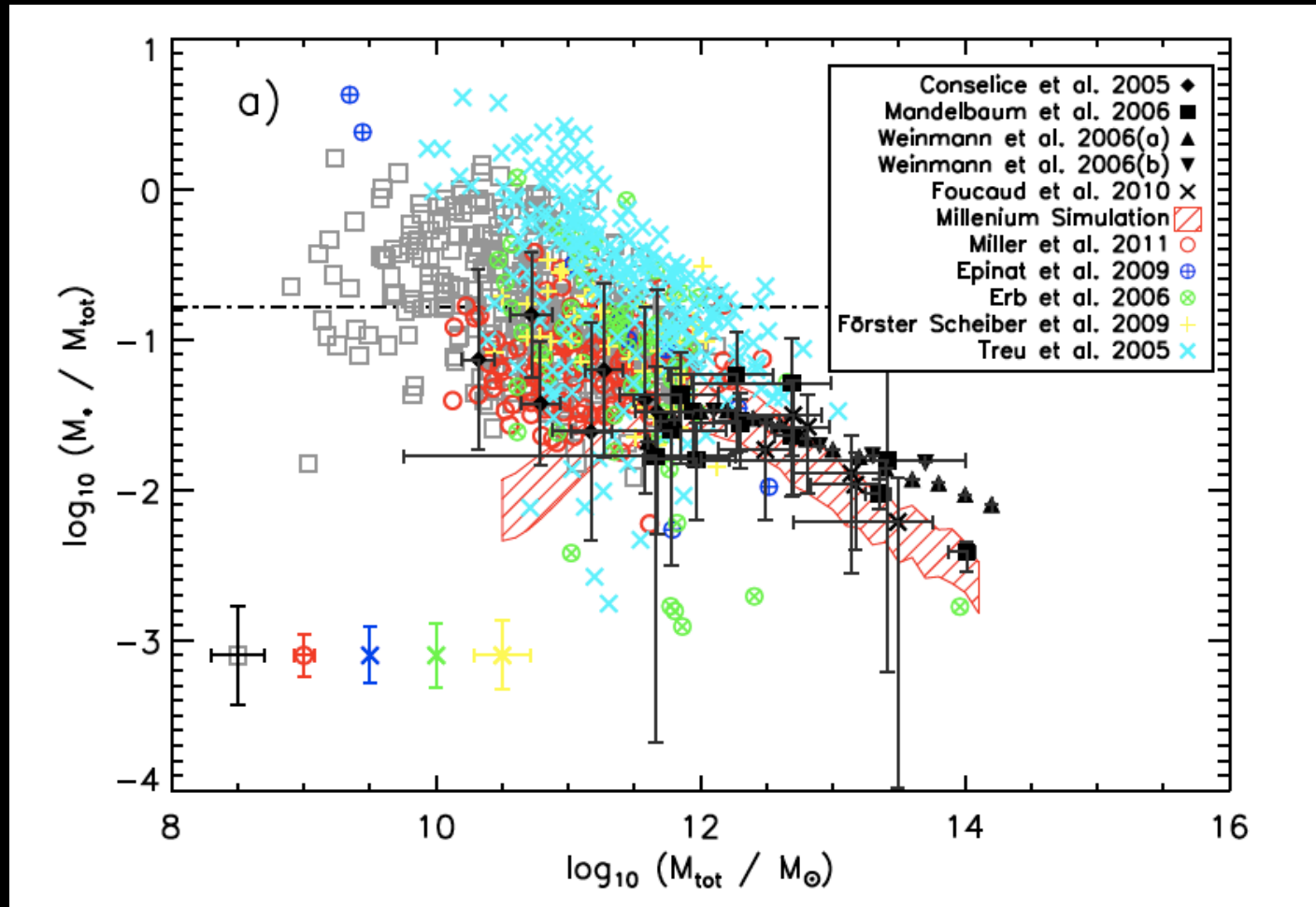
Dekel et al. (2009) predict 200 M/yr at $z = 2.2$ for $\log M = 12$ galaxy

How do these components form together in galaxies?

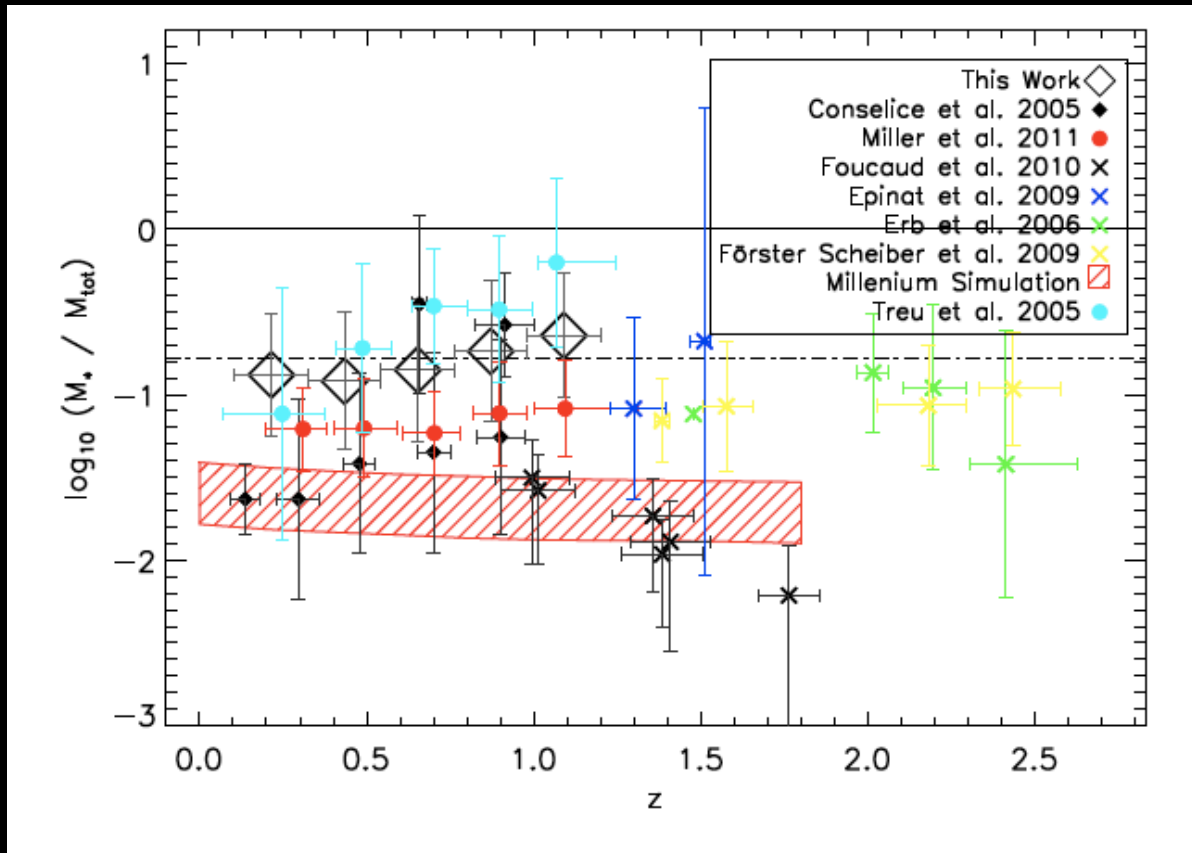


Find a good correlation between various forms of mass – stellar, dark and gaseous up to $z = 1.5$

Stellar mass vs. total mass for galaxies



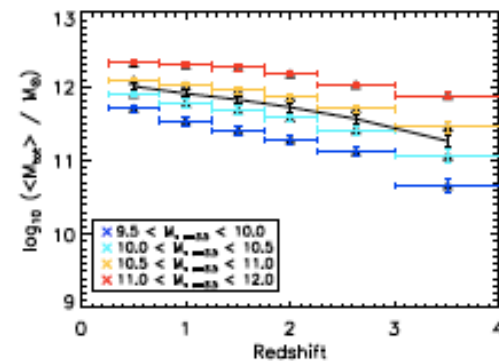
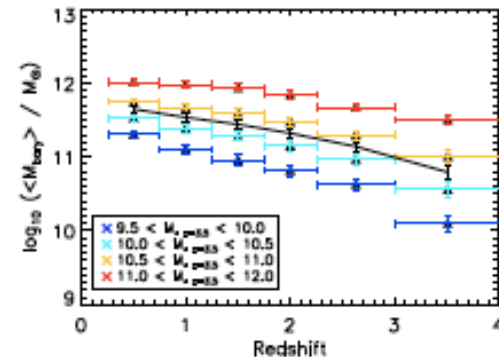
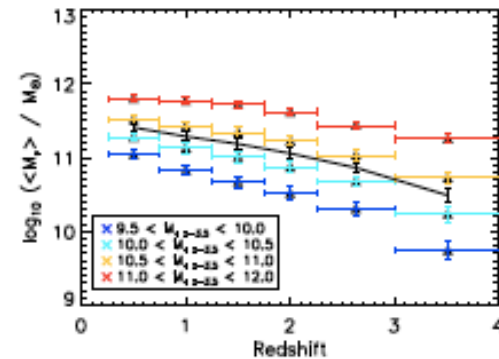
Evolution with redshift of the ratio of stellar to total mass



Does not show much evolution for typical M^* galaxies

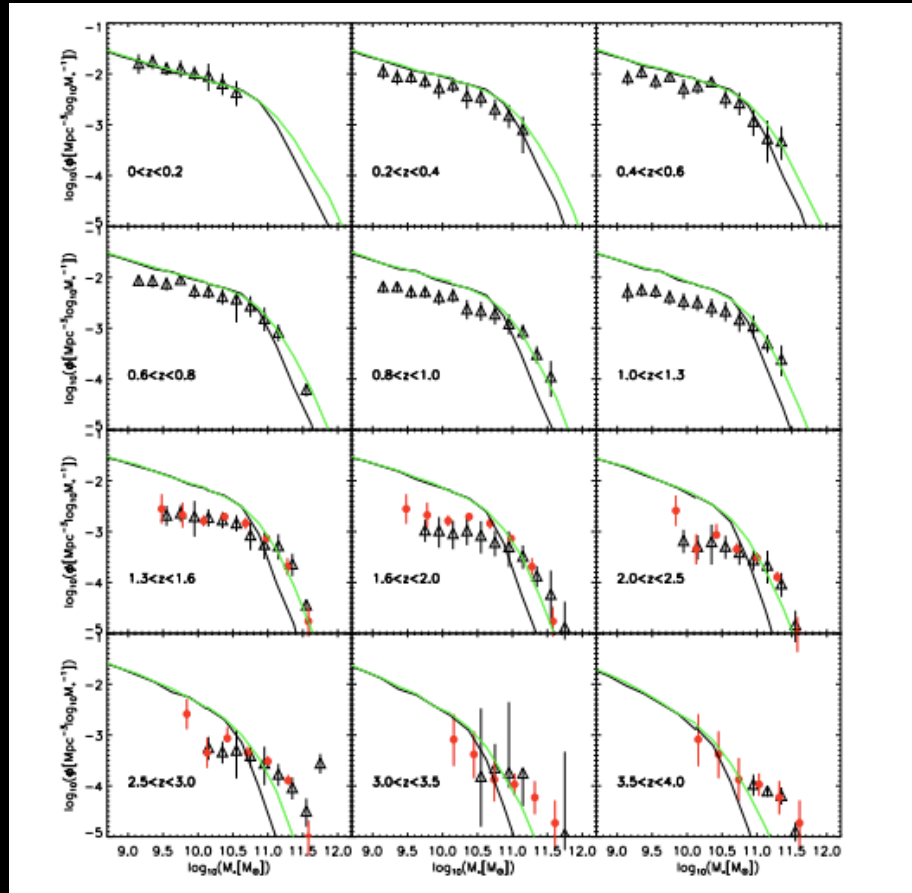
Can use relations between stellar mass and gas mass and total mass to see how these have evolved over time using Well measured stellar mass functions

The build up of mass in the stellar, gaseous and dark matter are similar, but not exactly the same – showing a hierarchical and moderated formation mechanism



Galaxy formation models in Lambda CDM

Traditional method: Make a model to predict or match observations



Need a complementary approach for understanding galaxy formation

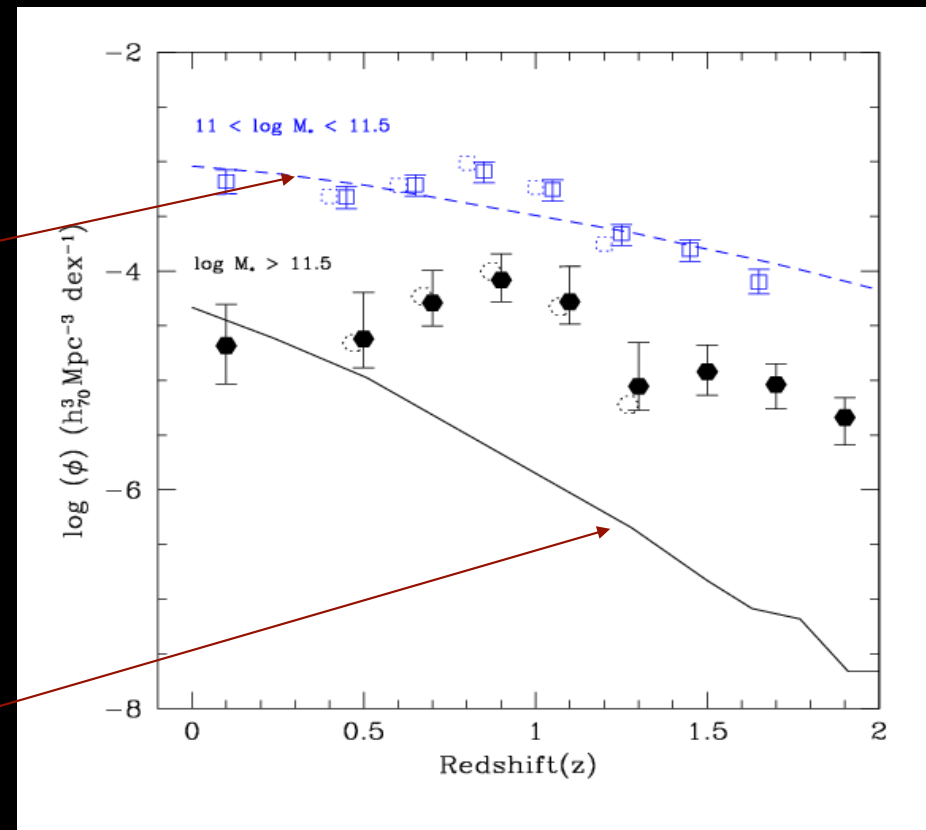
problems at high-z: Guo et al. (2010)

Also, there are too many massive galaxies in comparison to models

Millennium simulation

Prediction for $11 < \log M < 11.5$

Prediction for $\log M > 11.5$

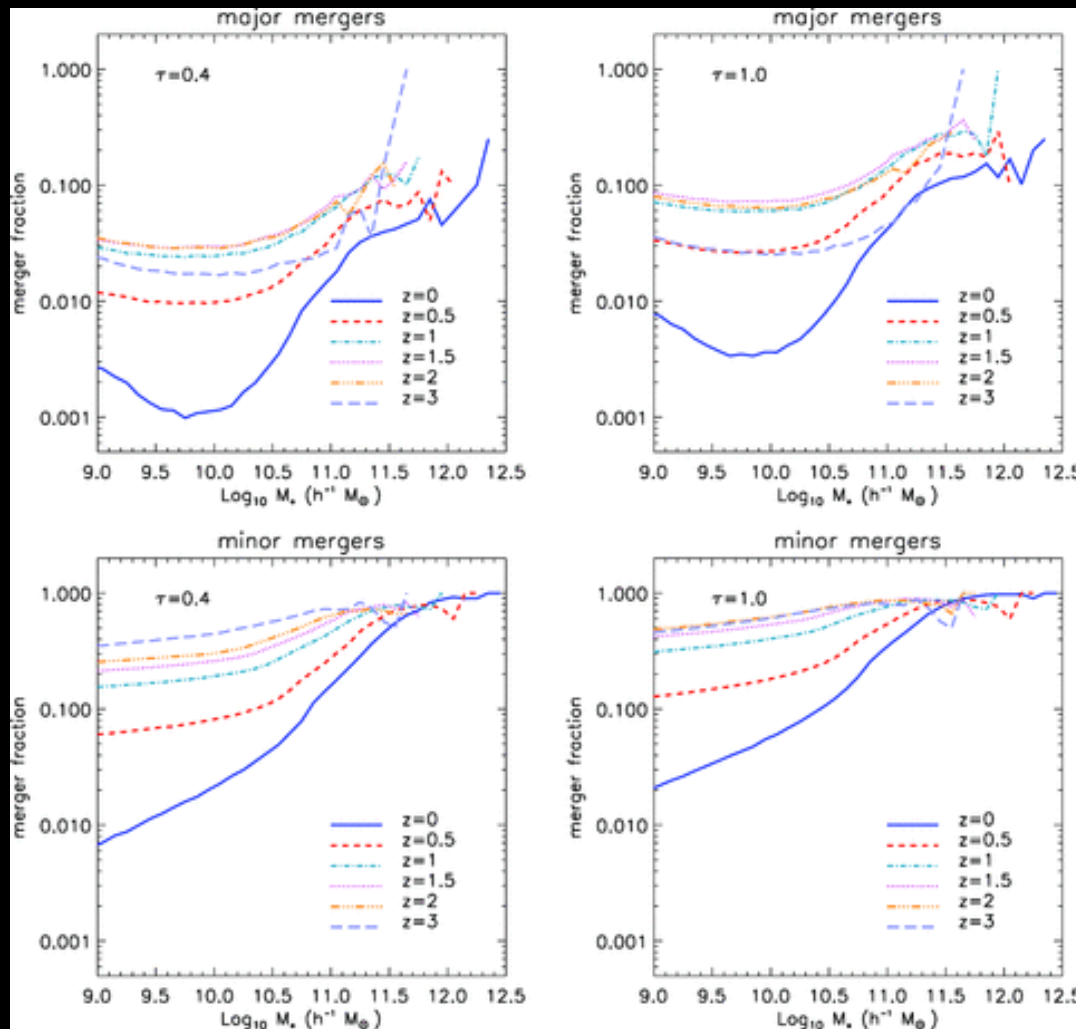


Conselice et al. (2007)

Vast under prediction in models compared to observations

Must go to higher redshifts to study their formation

Examine the physics behind CDM Simulations - merging

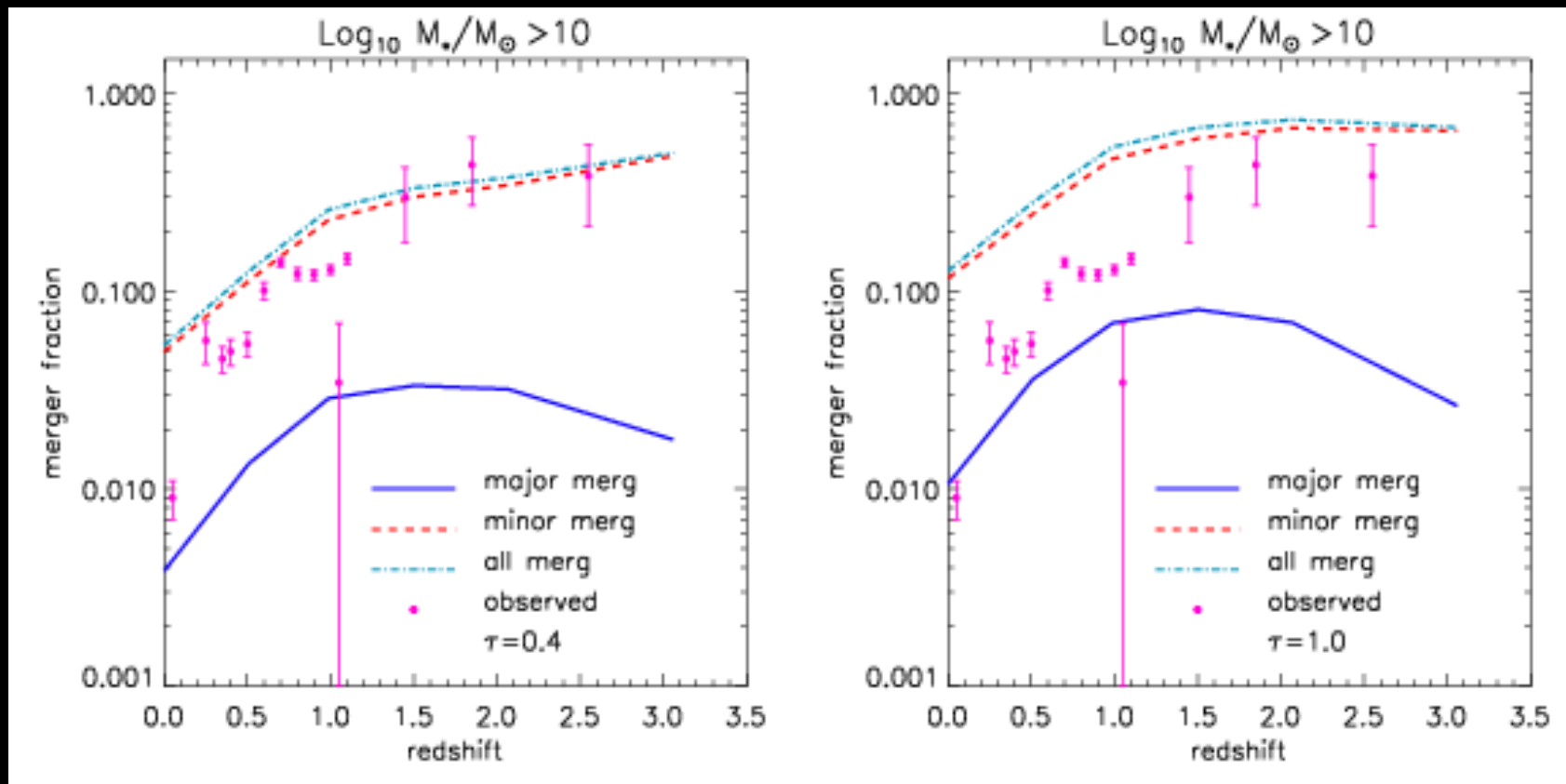


Major mergers are:
Stellar mass
ratio > 0.3

Minor mergers are:
Stellar mass
 $0.01 < \text{ratio} < 0.3$

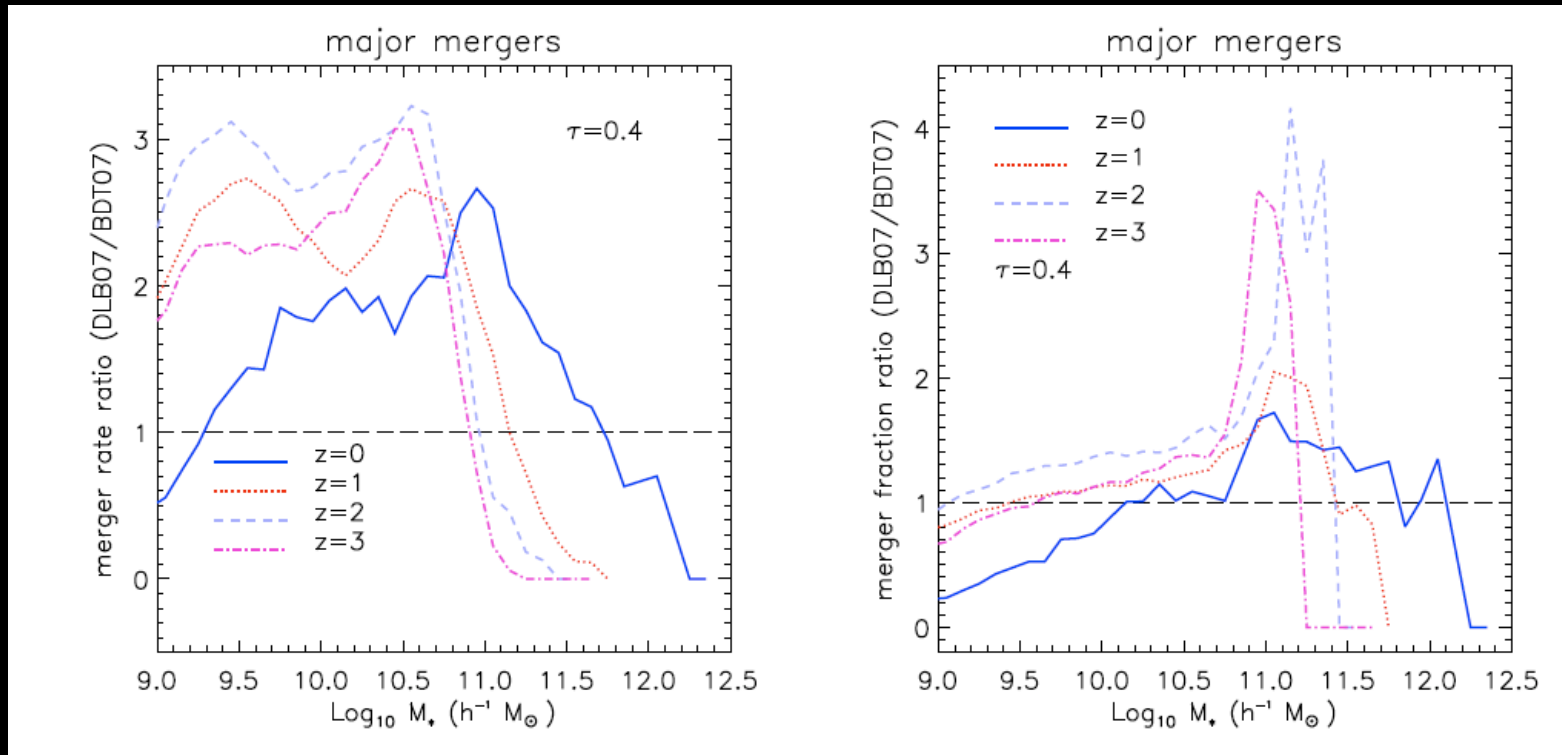
Must also assume
a time-scale for
mergers - 1 Gyr,
0.4 Gyr

Different Lambda+CDM model predictions of the merger rate



Bertone & Conselice (2009)

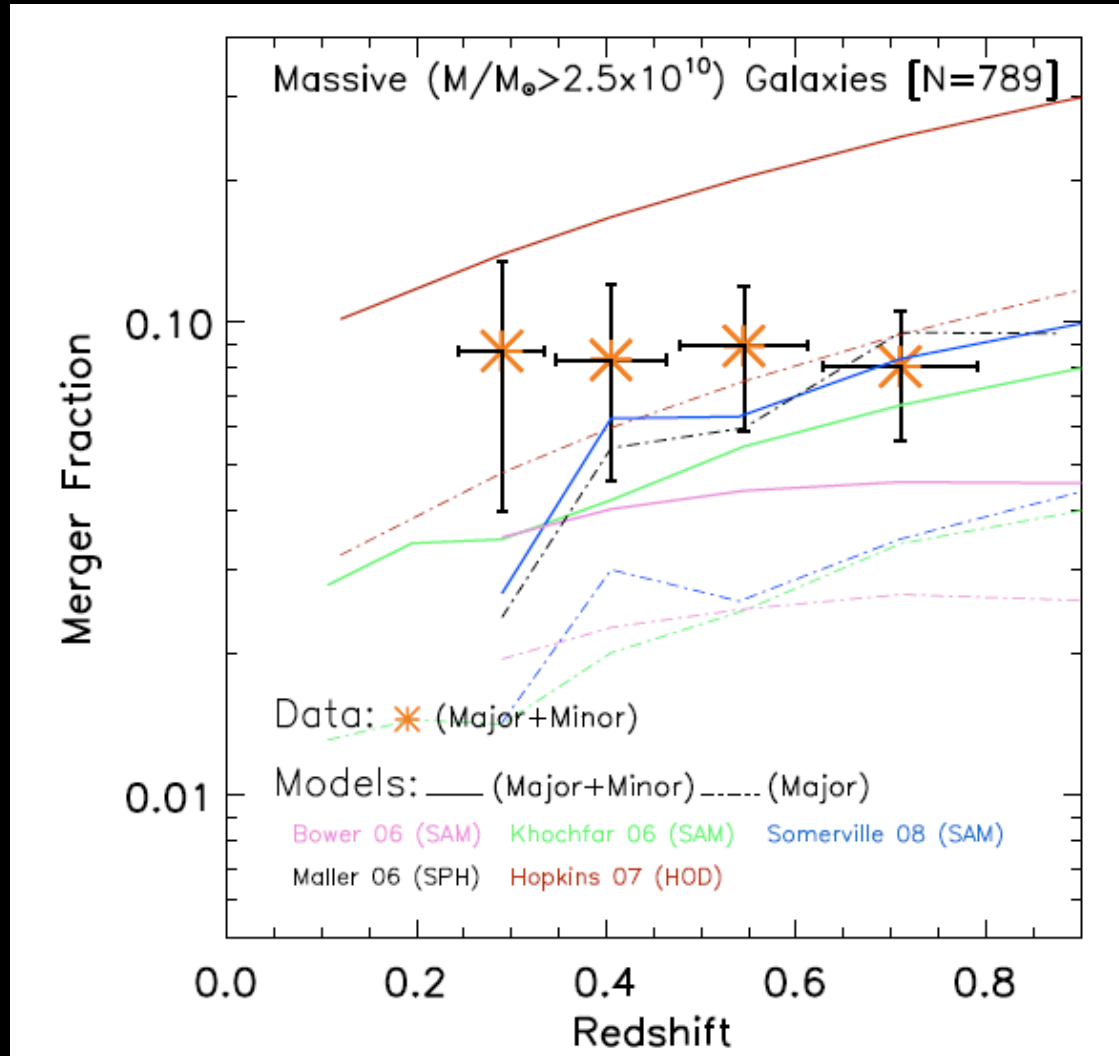
Different star formation physics, give different merger histories



Bertone & Conselice (2009)

Ratio of merger rates and fractions for De Lucia et al. (2007) and Bertone et al. (2007). Both use the Millennium simulation, and only differ in terms of how SN feedback is implemented.

Merger fractions based on visual measures - find similar results

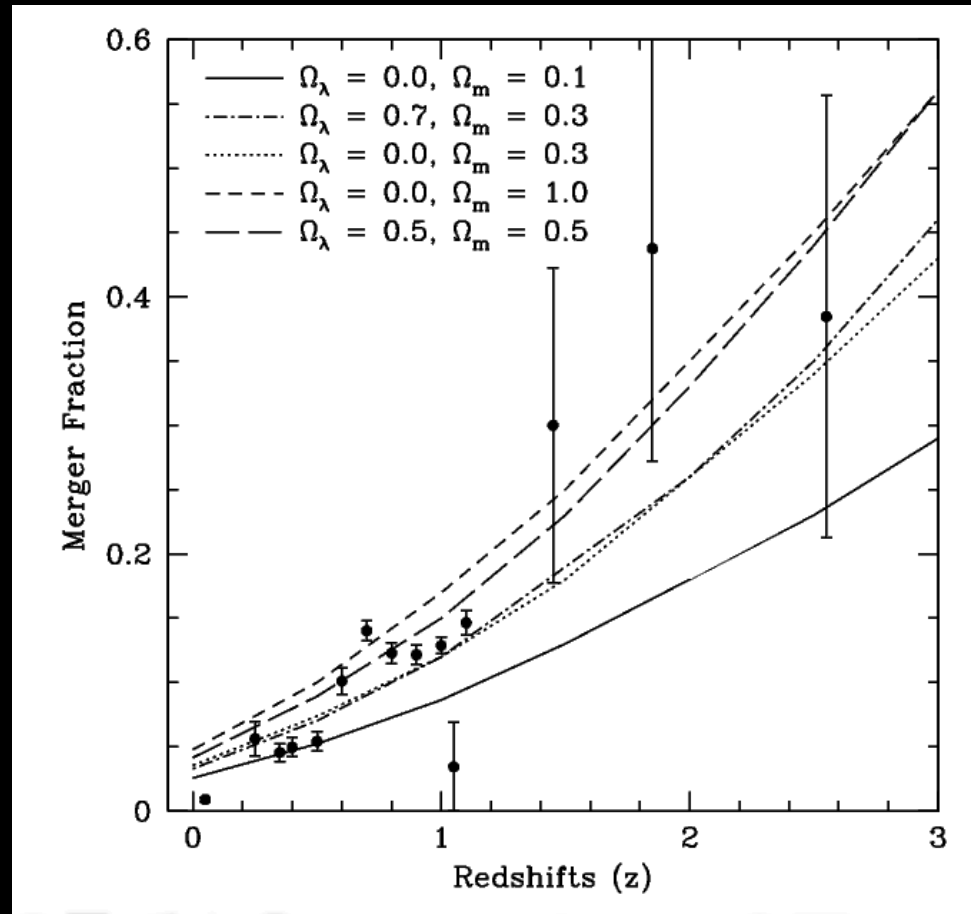


Galaxy sims do not predict enough mergers

LCDM models cannot reproduce either galaxy evolution or abundances

Jogee et al. (2009)

Better agreement between dark matter halo mergers



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

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
2. Examination of the major merger history shows mergers are an important, but not the only process of galaxy formation
3. Minor mergers are equally as important as major mergers in forming massive galaxies
4. Gas accretion from the intergalactic medium can account for roughly half of the formation – a complete census of galaxy formation?
5. All forms of matter grow at similar rates in the universe – gaseous, dark and stellar
6. Models still need work to explain evolution and abundances of galaxies in LCDM – neither or which fit current simulations