Observational Overview of Galaxy Formation and Evolution in a Cosmological Context

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Ecole Internationale Daniel Chalonge

18th Paris Cosmology Colloquium 2014

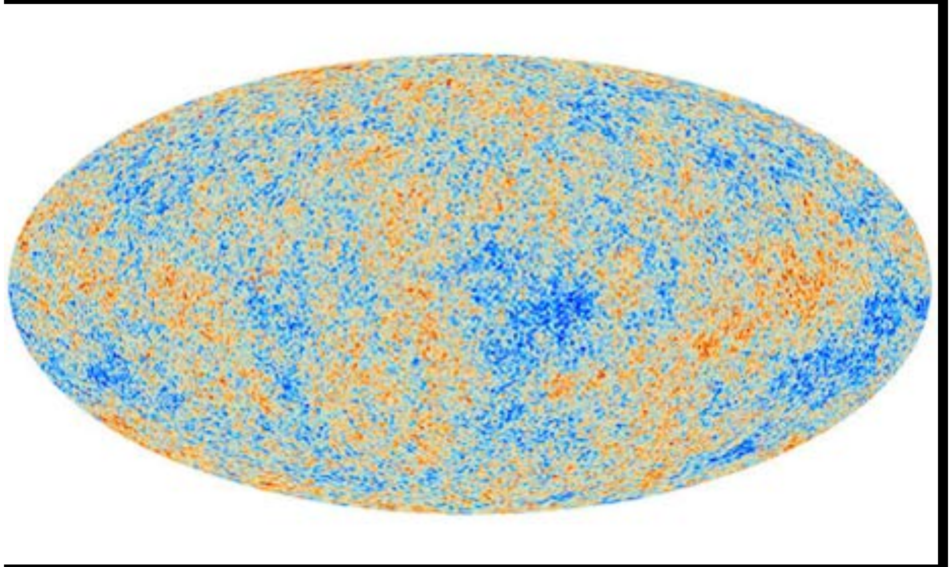
LATEST NEWS FROM THE UNIVERSE :
LAMBDA WARM DARK MATTER (ΛWDM), CMB, DARK MATTER,
DARK ENERGY, NEUTRINOS AND STERILE NEUTRINOS

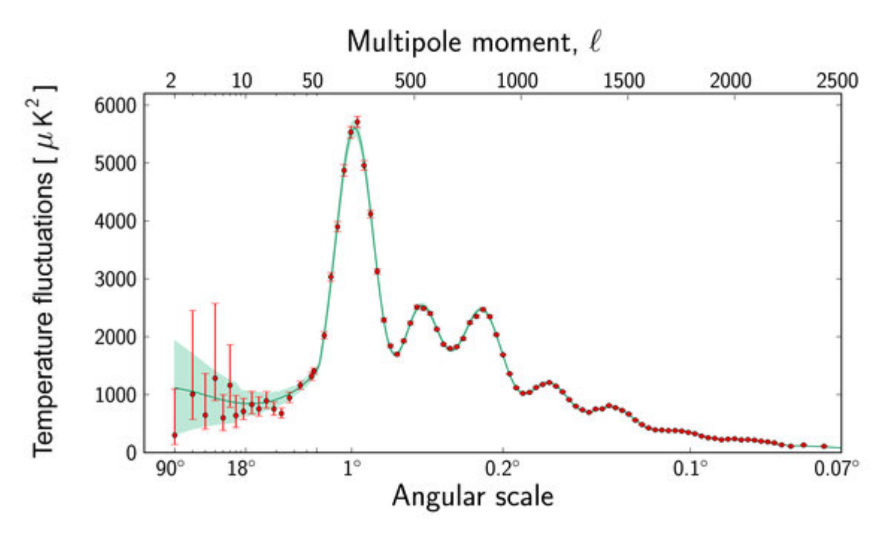
The International School Daniel Chalonge : 23 Years of Activity

Observatoire de Paris, Paris campus

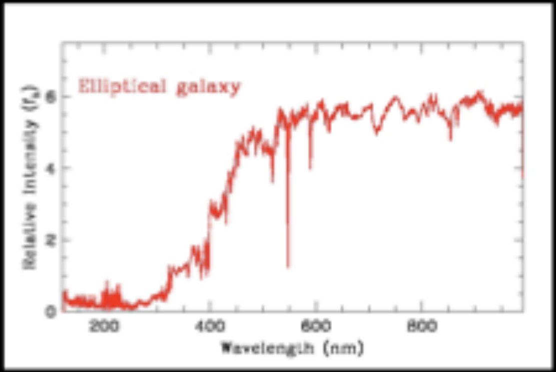
23, 24 and 25 July 2014

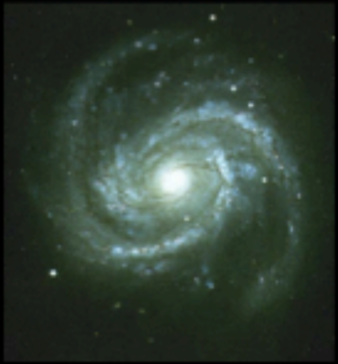
Cosmic Background Radiation – cosmological parameters

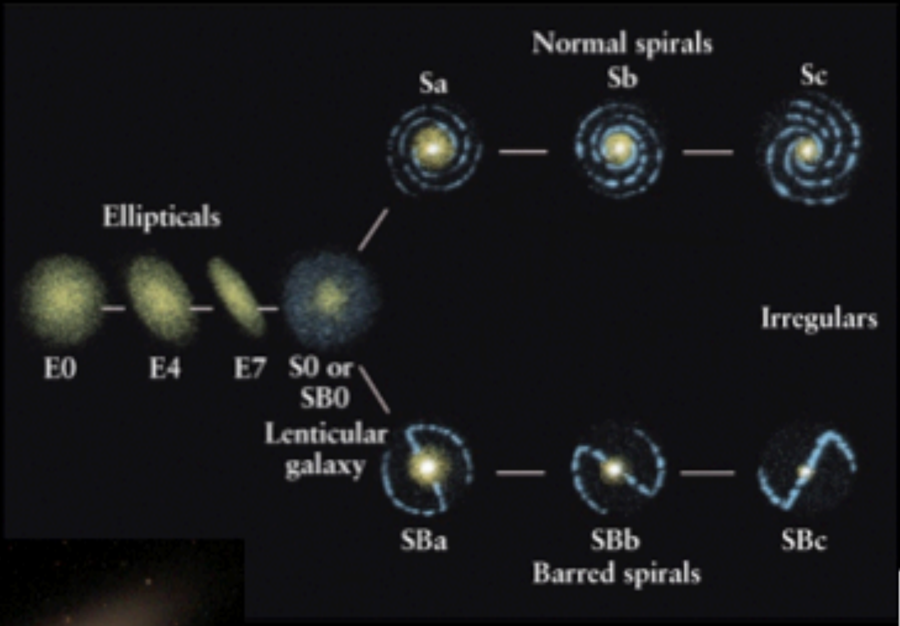


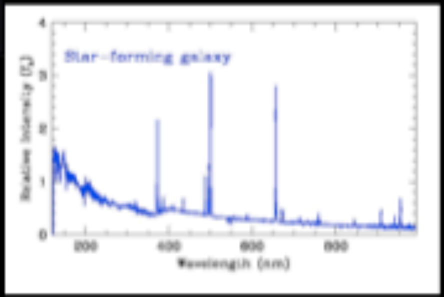


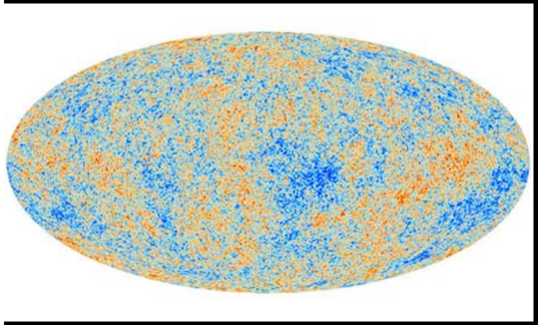
Planck collaboration results 2013


Elliptical galaxy
Relative Intensity (f_λ)
0
2
4
6
200
400
600
800
Wavelength (nm)

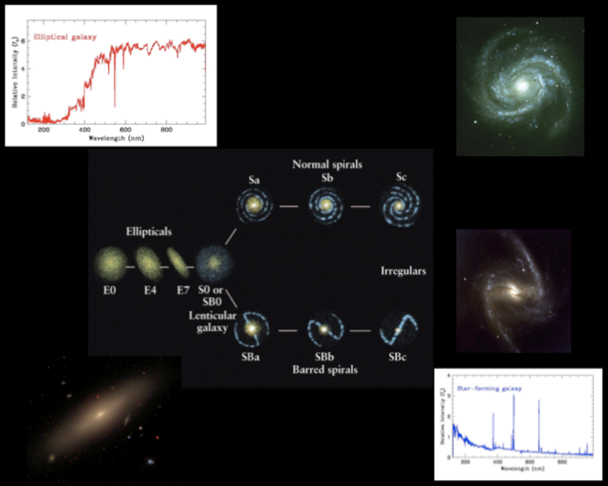



Normal spirals
Sa
Sb
Sc
Ellipticals
E0
E4
E7
S0 or SB0
Lenticular galaxy
Irregulars
SBa
SBb
SBc
Barred spirals


Star-forming galaxy
Relative Intensity (f_λ)
0
1
2
3
4
200
400
600
800
Wavelength (nm)



?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Irregulars
SBa
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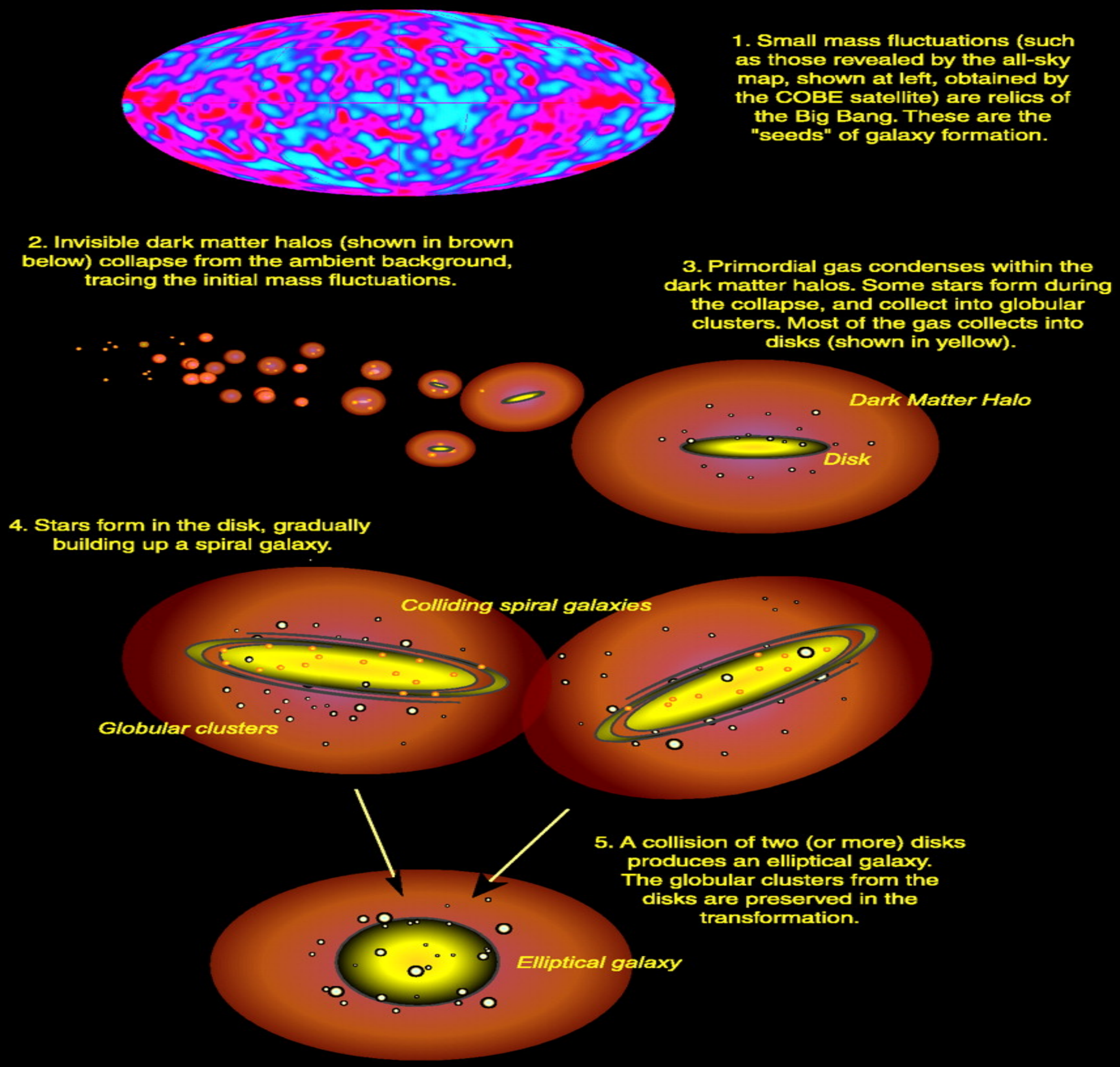
Star-forming galaxy

Basic 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.

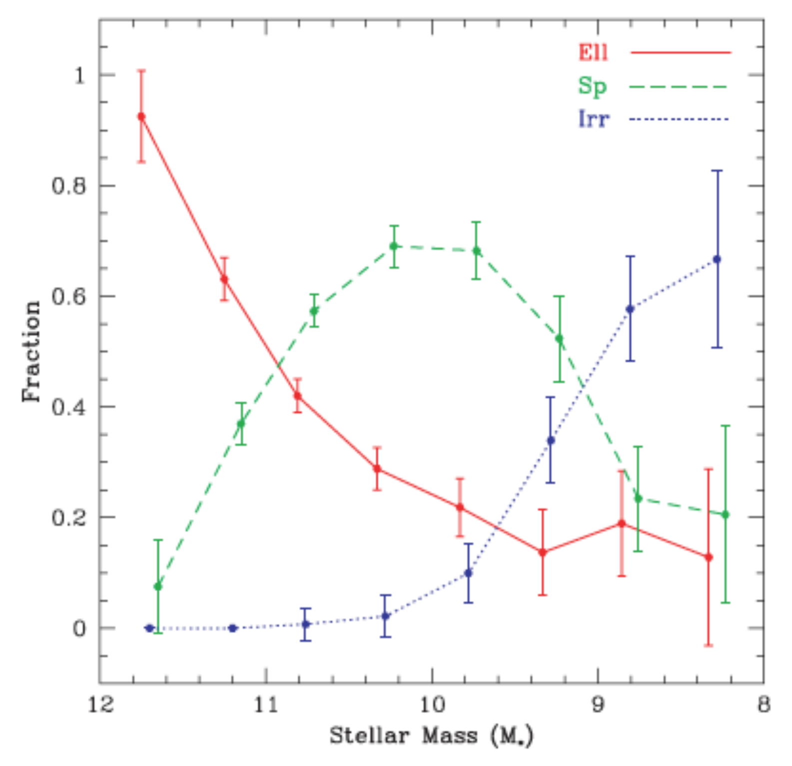
2. Invisible dark matter halos (shown in brown below) collapse from the ambient background, tracing the initial mass fluctuations.

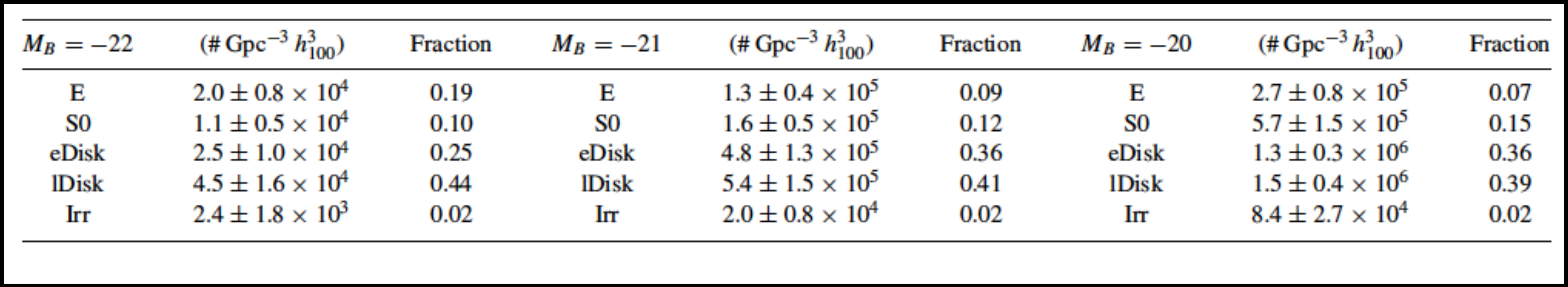
3. Primordial gas condenses within the dark matter halos. Some stars form during the collapse, and collect into globular clusters. Most of the gas collects into disks (shown in yellow).

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.

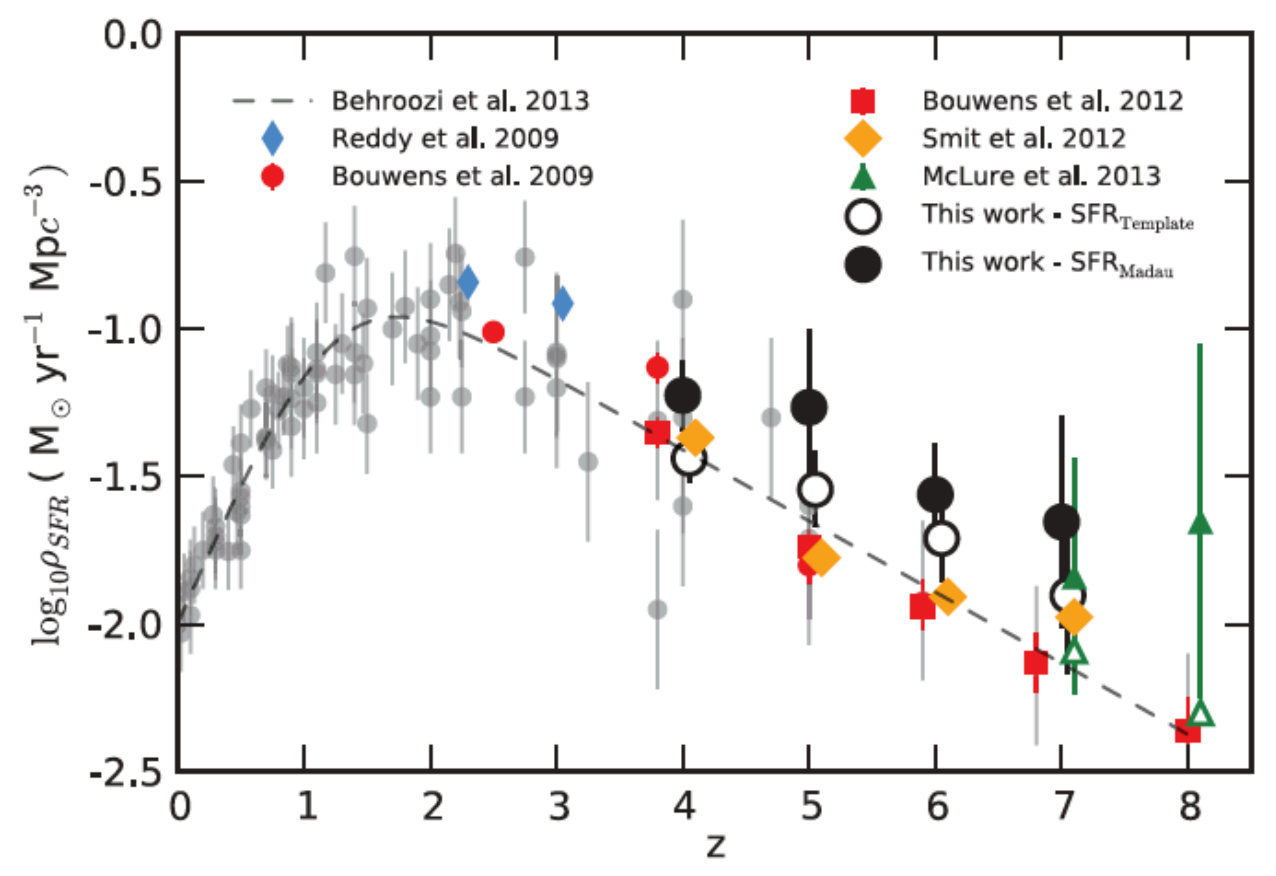
End product of galaxy formation highly regulated and dependent on stellar mass for reasons that are not understood





$M_B = -22$	(# Gpc^{-3} h^3_{100})	Fraction	$M_B = -21$	(# Gpc^{-3} h^3_{100})	Fraction	$M_B = -20$	(# Gpc^{-3} h^3_{100})	Fraction
E	$2.0 \pm 0.8 \times 10^4$	0.19	E	$1.3 \pm 0.4 \times 10^5$	0.09	E	$2.7 \pm 0.8 \times 10^5$	0.07
S0	$1.1 \pm 0.5 \times 10^4$	0.10	S0	$1.6 \pm 0.5 \times 10^5$	0.12	S0	$5.7 \pm 1.5 \times 10^5$	0.15
eDisk	$2.5 \pm 1.0 \times 10^4$	0.25	eDisk	$4.8 \pm 1.3 \times 10^5$	0.36	eDisk	$1.3 \pm 0.3 \times 10^6$	0.36
lDisk	$4.5 \pm 1.6 \times 10^4$	0.44	lDisk	$5.4 \pm 1.5 \times 10^5$	0.41	lDisk	$1.5 \pm 0.4 \times 10^6$	0.39
Irr	$2.4 \pm 1.8 \times 10^3$	0.02	Irr	$2.0 \pm 0.8 \times 10^4$	0.02	Irr	$8.4 \pm 2.7 \times 10^4$	0.02

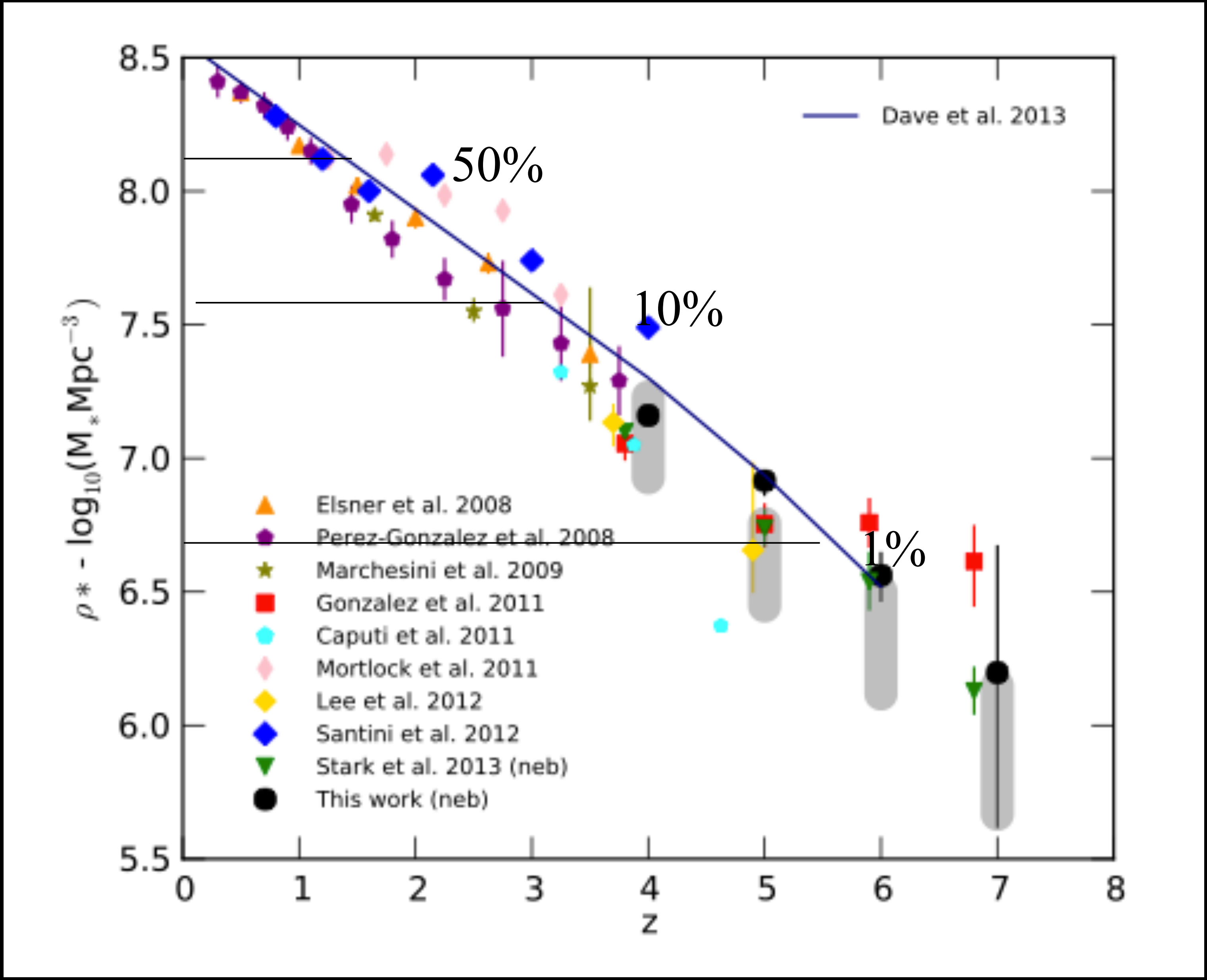
Star formation rate integrated density – factor of > 10 variation



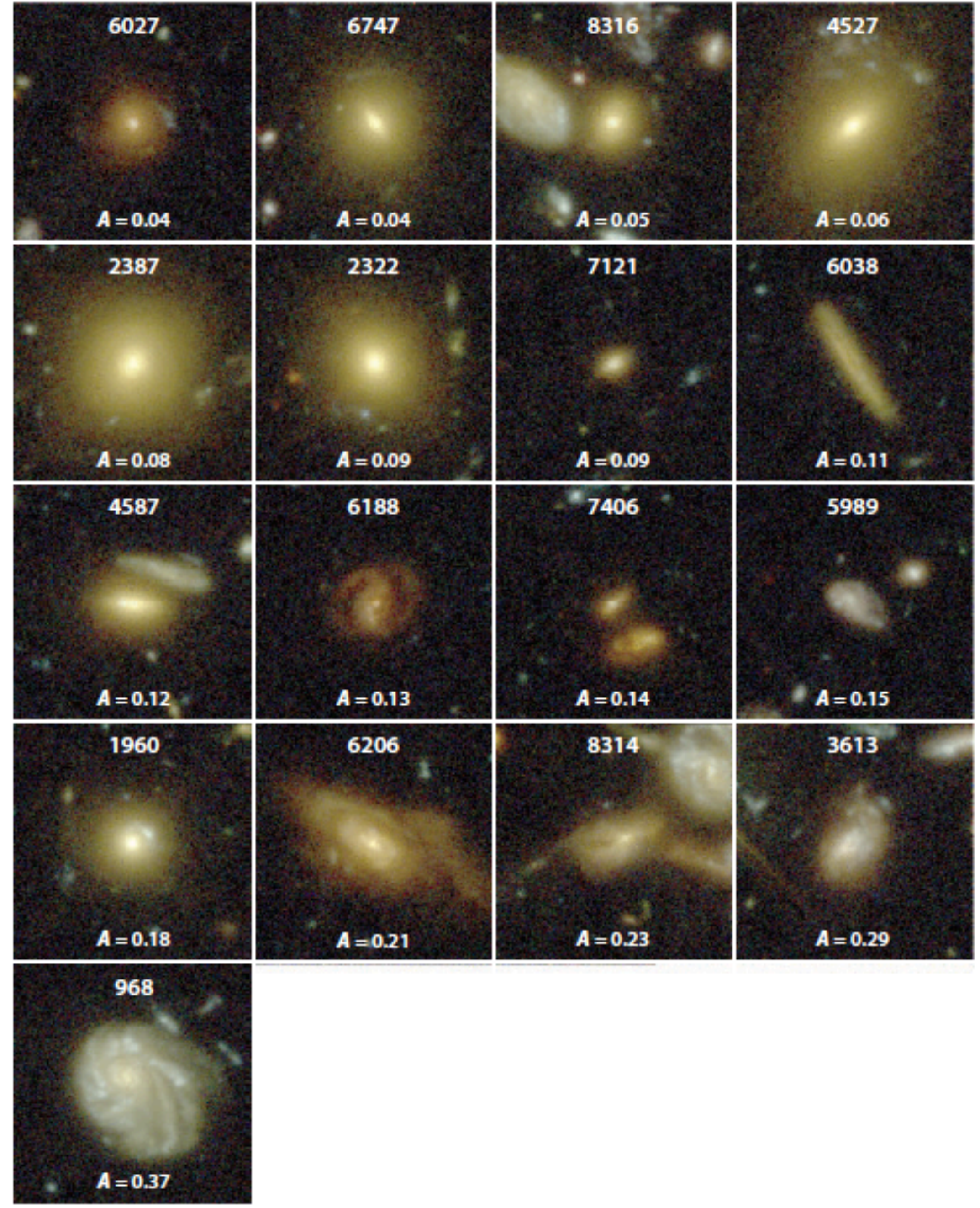
Star formation rate density peaks at z~2

Duncan et al. (2014)

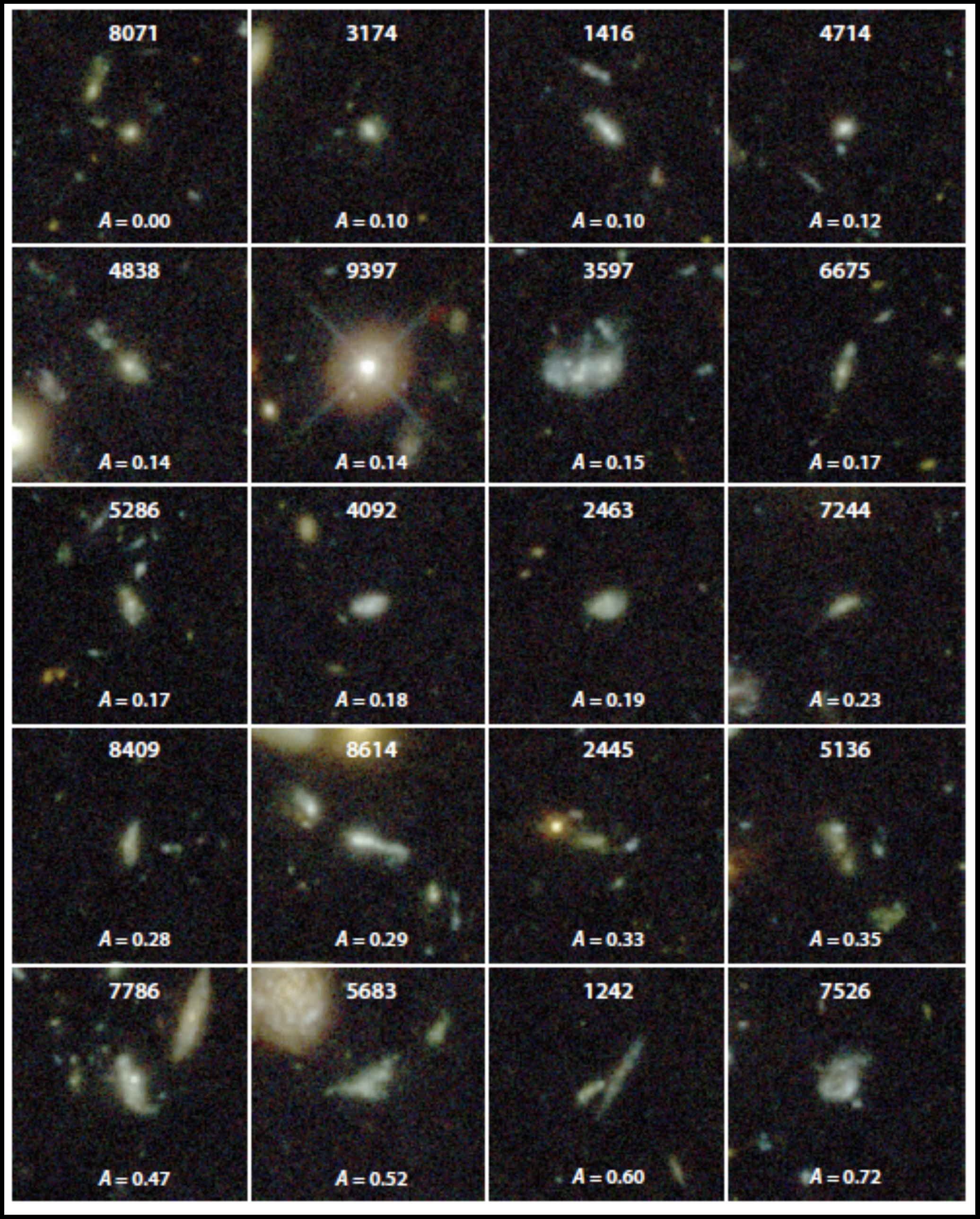
The formation of stellar mass – direct measures



Observed integrated stellar mass density vs. redshift



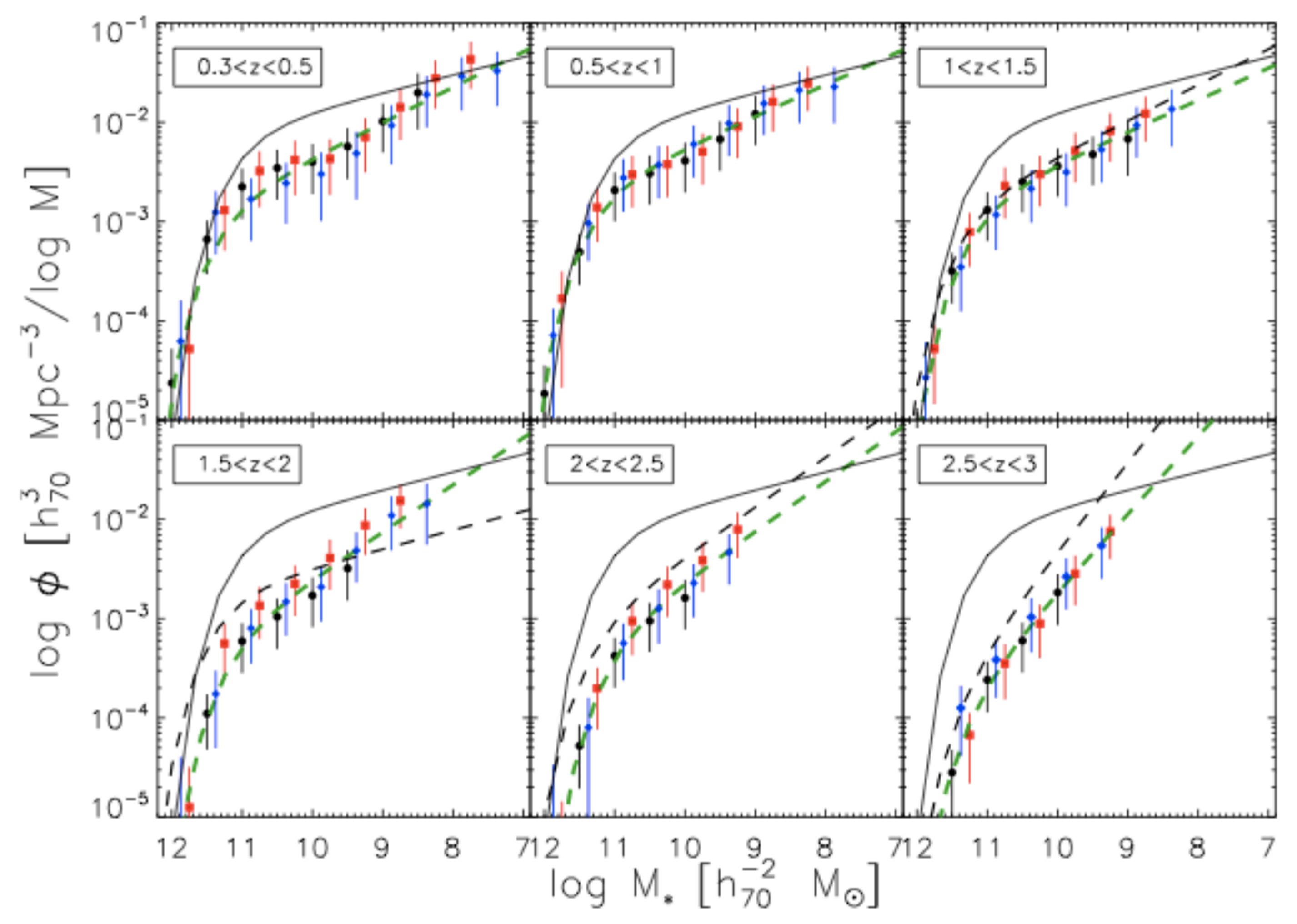
z < 1 massive
Galaxies in UDF



$z > 1$ massive
Galaxies in UDF

More peculiar, bluer,
higher SF, higher sSFR,
and smaller size

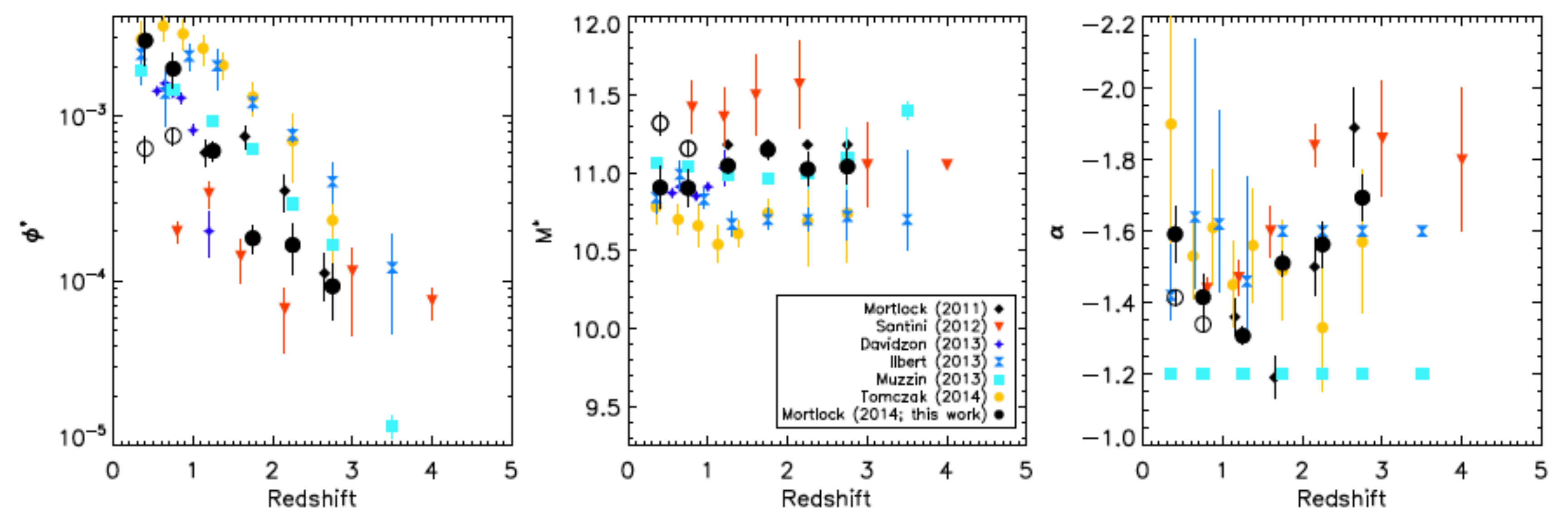
A first attempt to solve this problem is with massive galaxies



Mortlock, CJC, et al. (2014)

Most massive galaxies are formed by z = 1

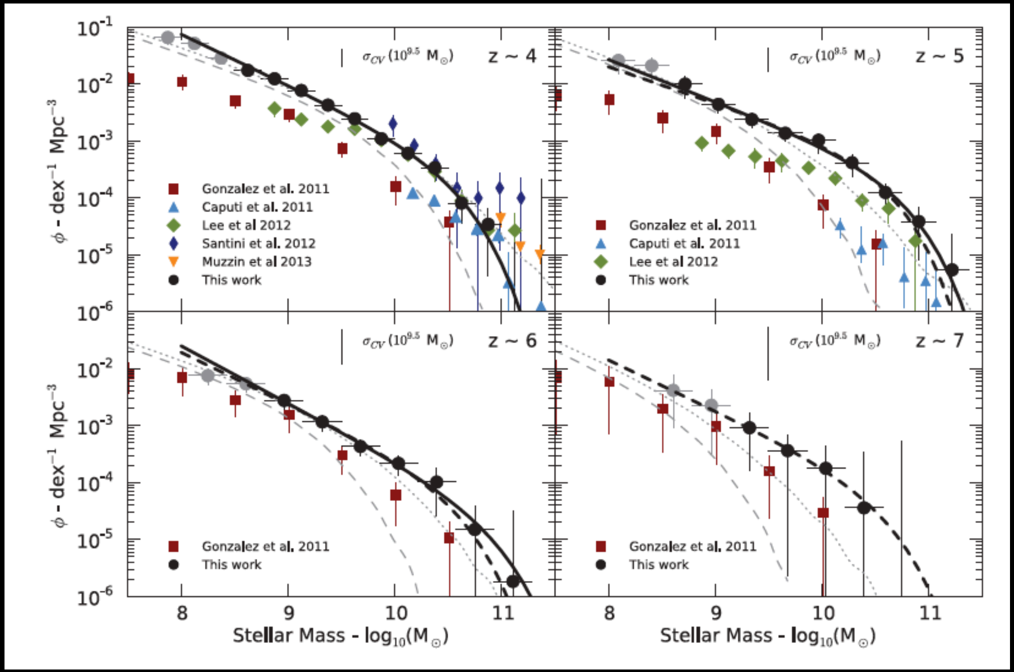
Traditional way is to examine the change in the stellar mass function

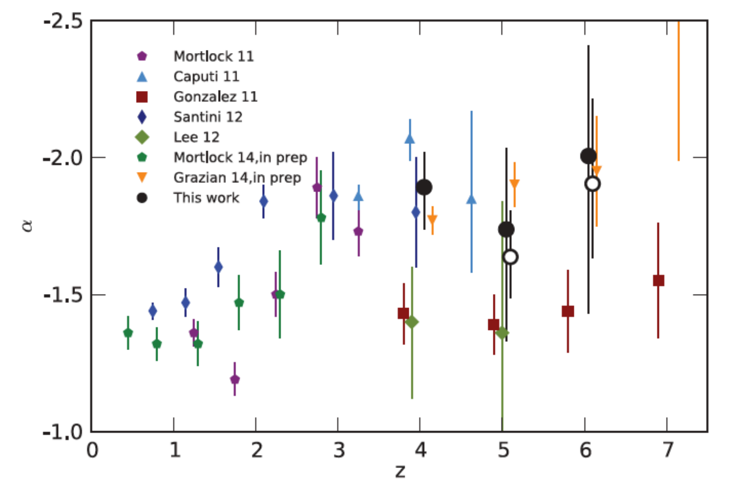


Mortlock et al. (2014)

Φ declines with time, α goes up (?) and M* is roughly constant

Can now measure mass functions up to z~7



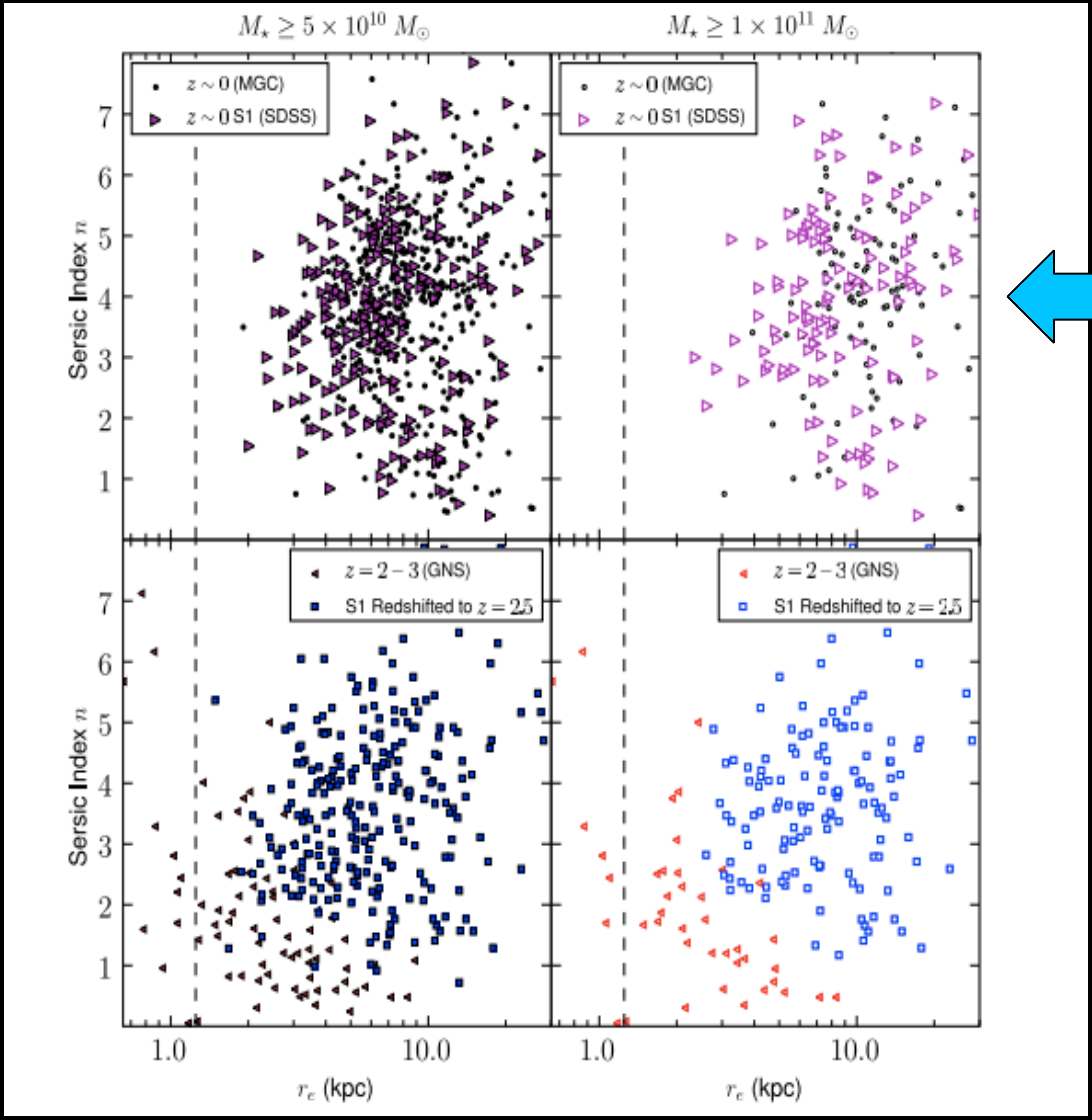


Power-law form at z ~7? Closer to dark matter mass function?

Also, faint end slope α is very step, near α = -2 at z > 6

Duncan, CC, et al. 2014

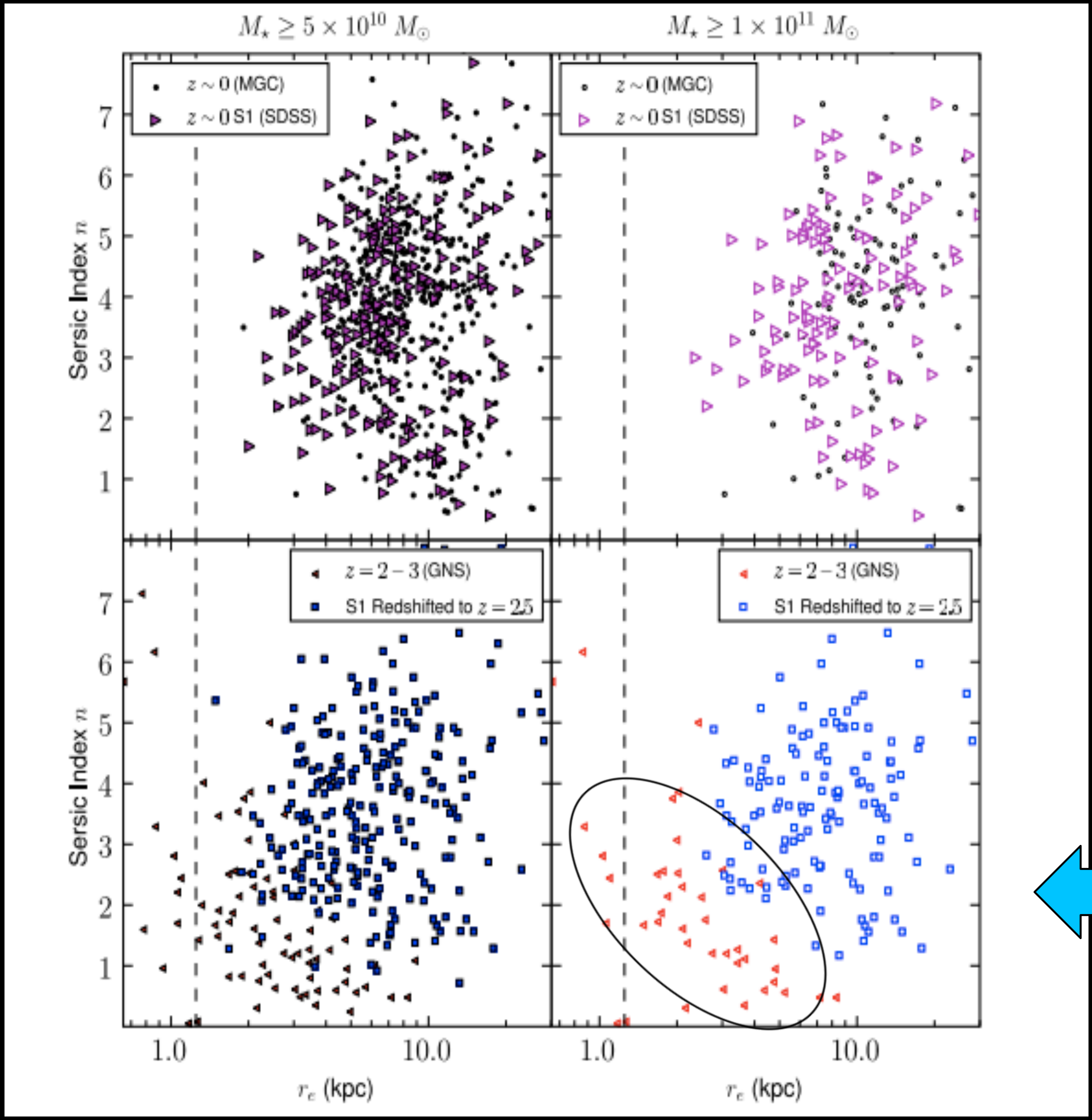
Galaxies at z = 2.5 --- different from nearby massive galaxies



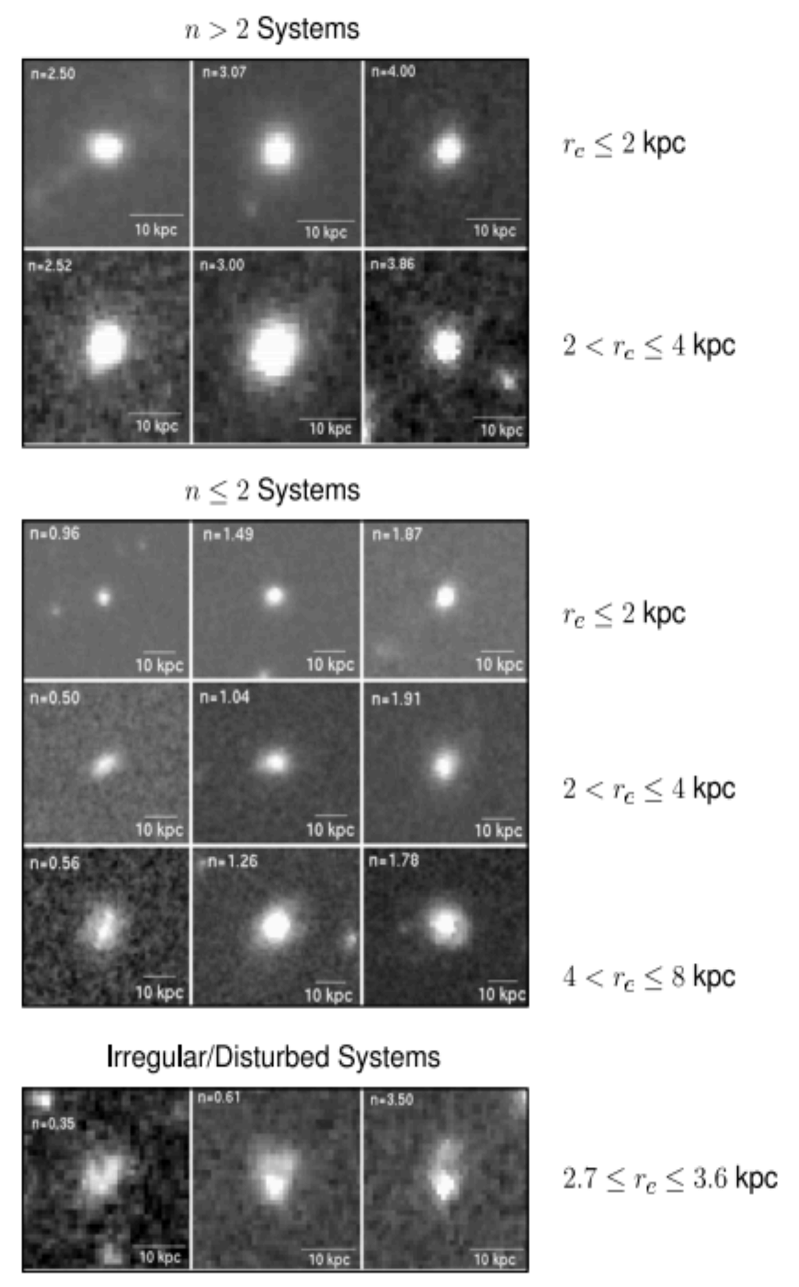
Nearby massive galaxies

Weinzirl et al. (2011)

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



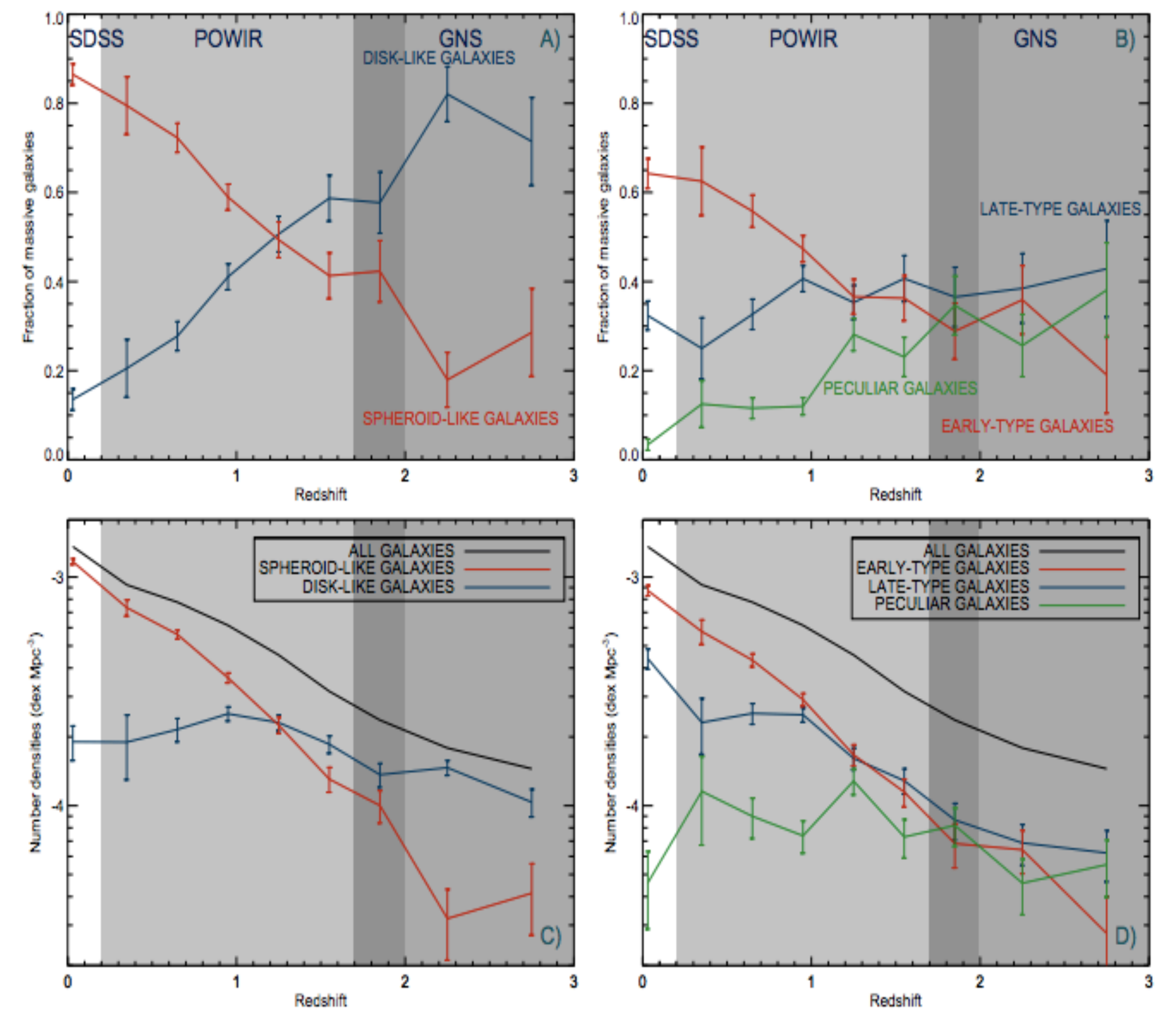
Same mass
but at z > 1



Massive Galaxies at z > 1.5

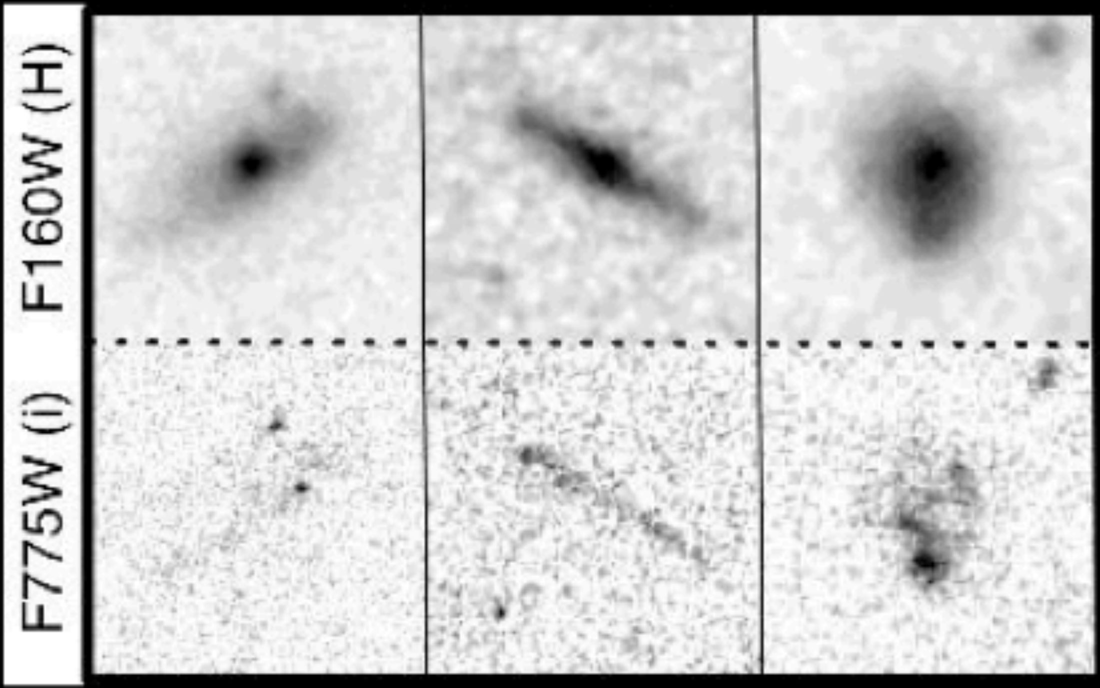
Mixture of morphologies

Massive galaxies become more disk like at higher redshifts



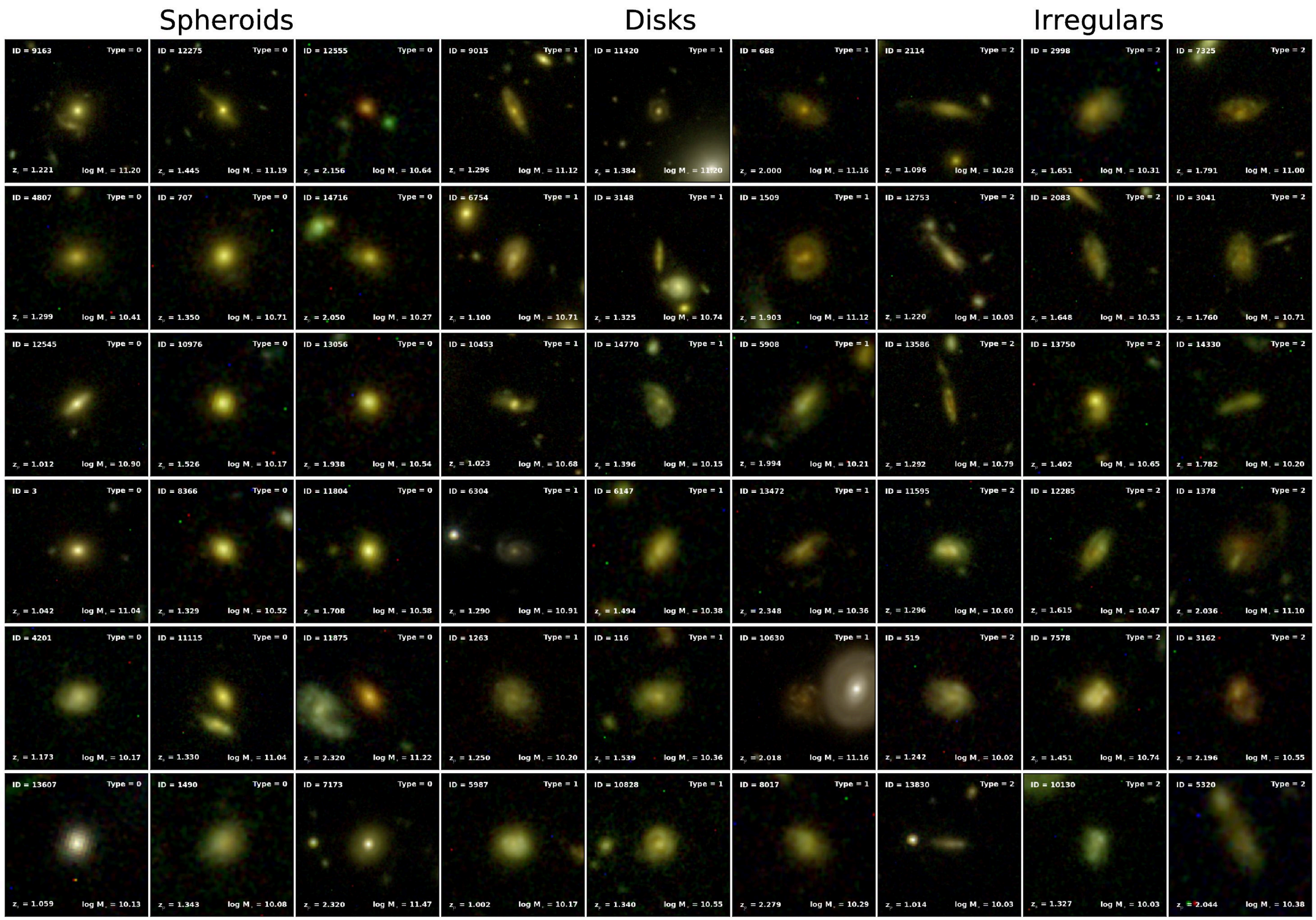
Buitrago et al. (2013)

CANDELS survey imaging – Hubble Sequence at z > 1



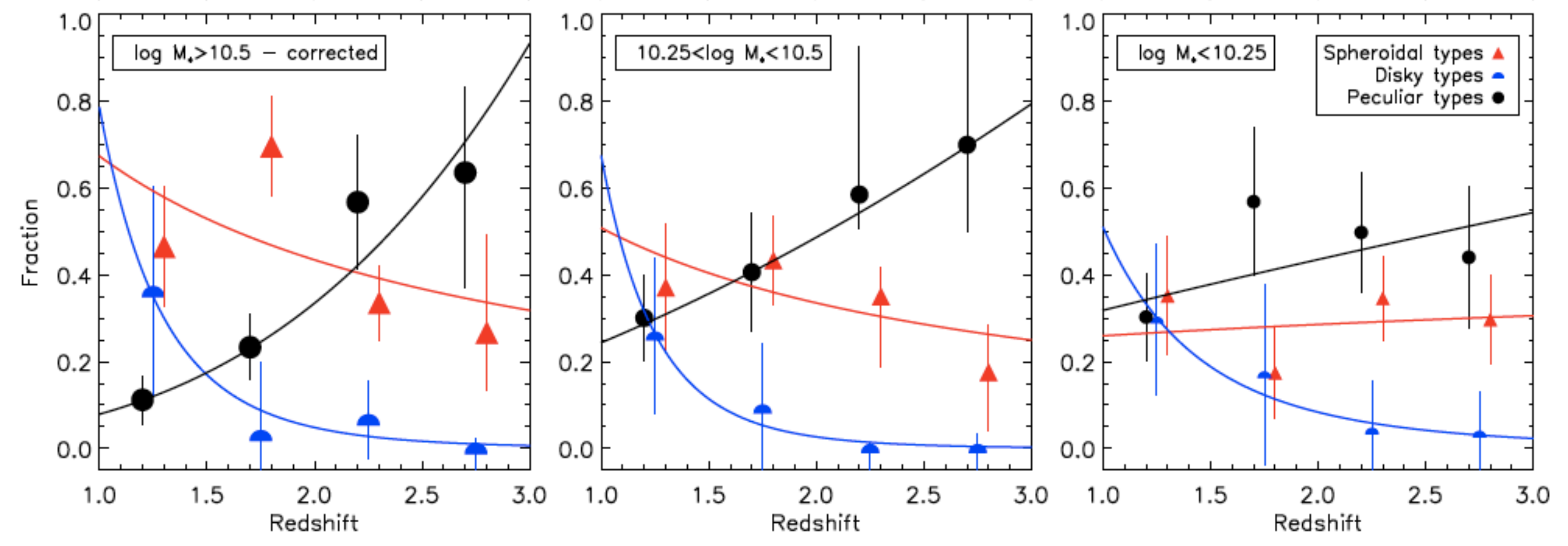
The CANDELS Survey – 900+ Hubble orbits to study high the resolution NIR Universe in five fields. Gives rest-frame optical structures for galaxies at z=1-3

Galaxy morphologies in CANDELS



Mortlock et al. (2013); Hilton et al. (2013)

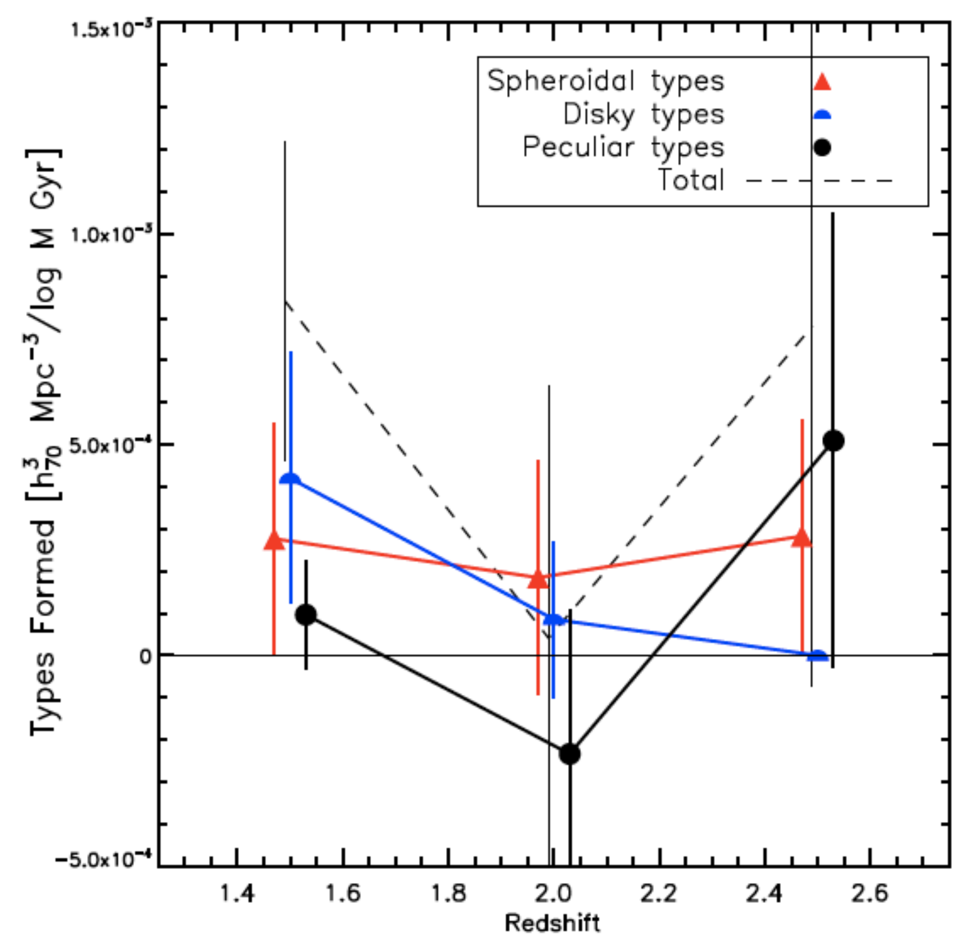
There is a dependence on stellar mass on morphological evolution



More massive systems become ‘Hubble-types’ before lower masses

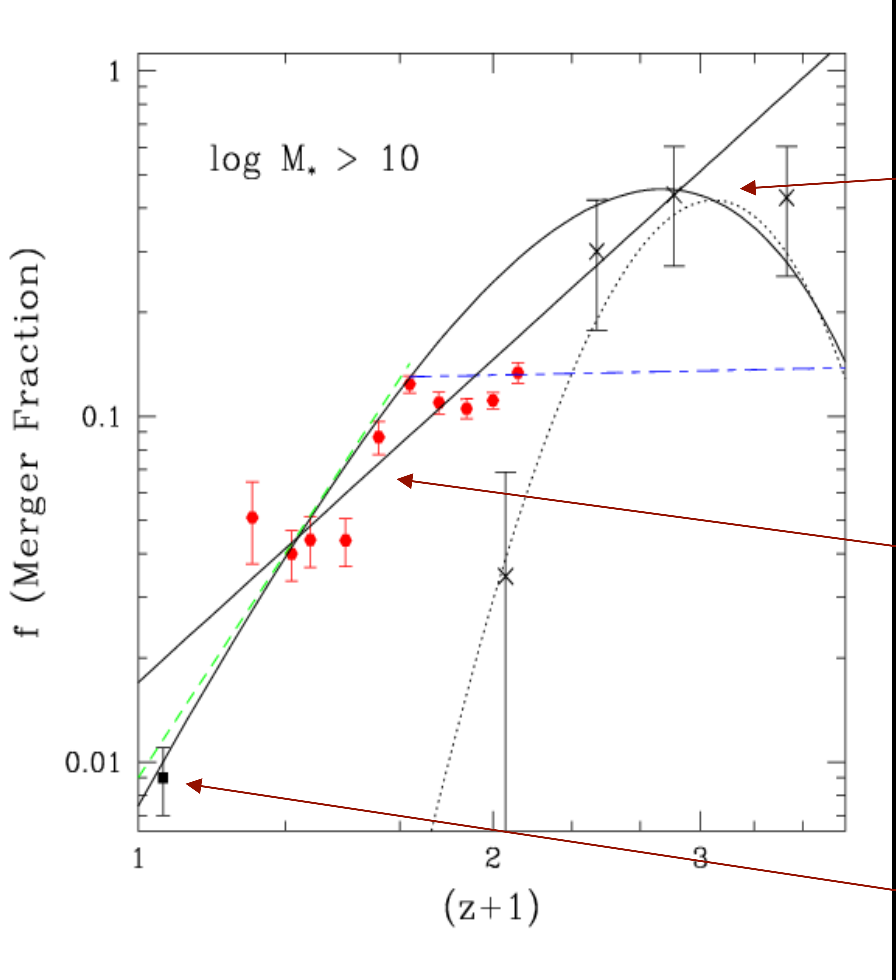
$Z_{trans} \sim 1.85$

Rate of change in the formation of Hubble types



Roughly constant formation rate for E/Spirals

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)

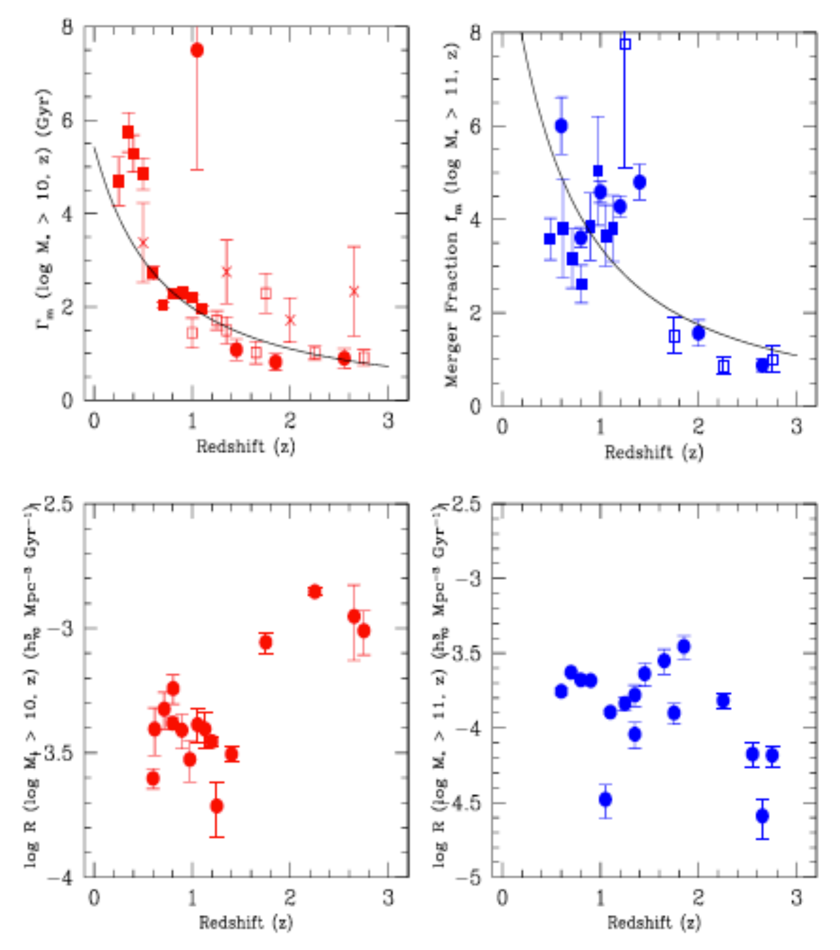
Number of Major Mergers

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

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

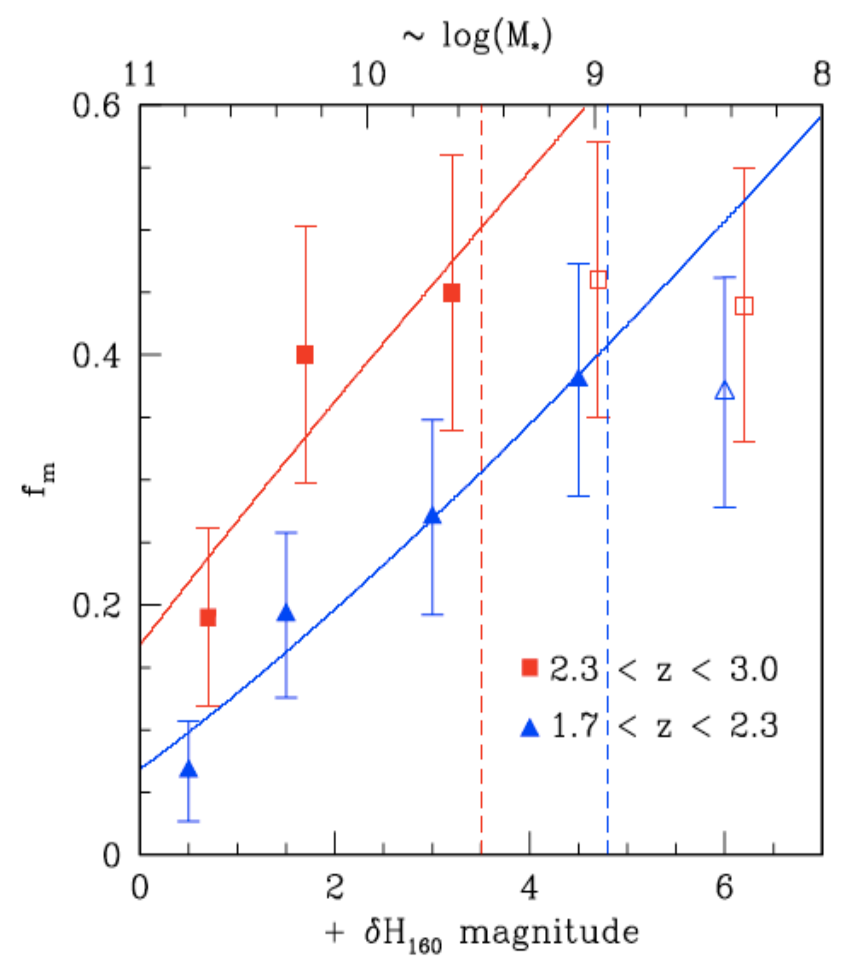
For our best fit for Γ(z), integrating over the redshift range of our galaxies we obtained:

N = 1.7 +/- 0.5
(Major mergers / Galaxy)



Roughly doubles the stellar masses of galaxies from z=0 to 3

Role of minor mergers



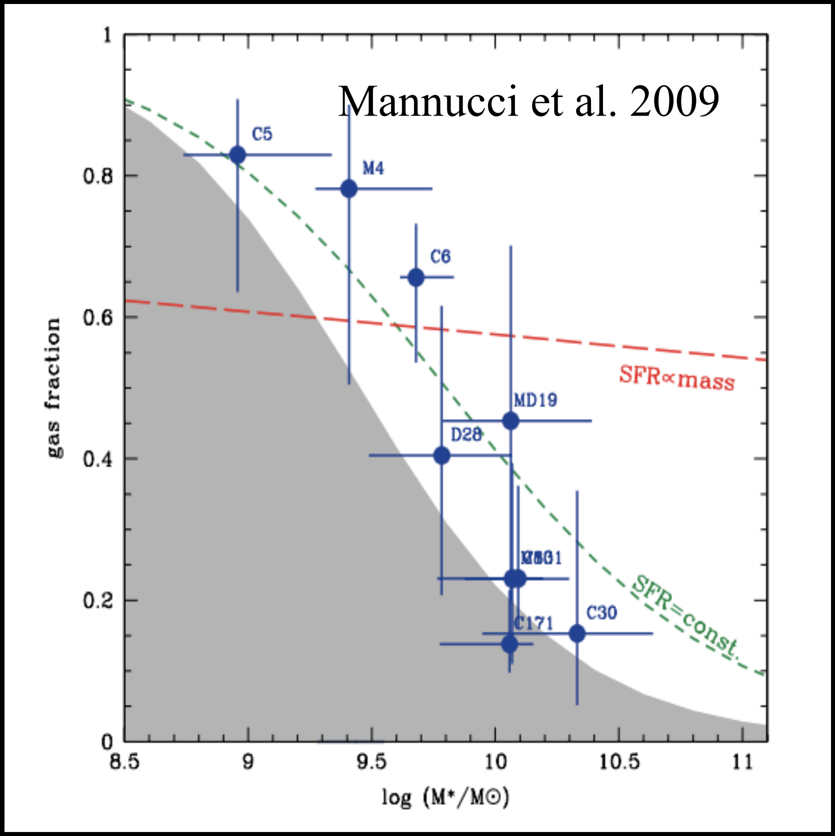
More minor mergers add about the same mass as major mergers

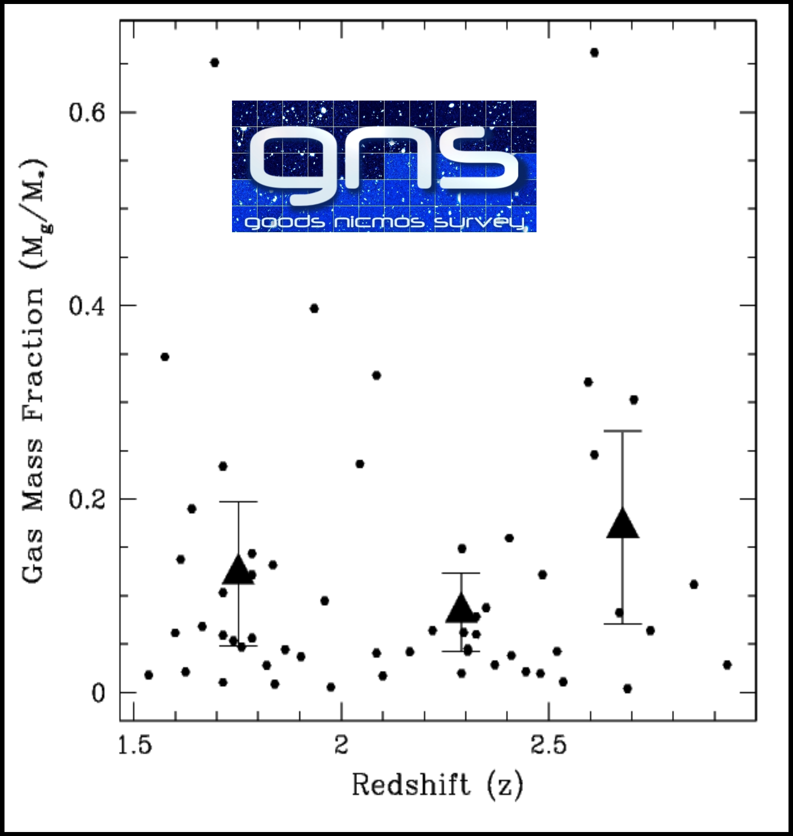
Total mass added from all mergers from 1<z<3

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

Bluck, Conselice et al. (2011)

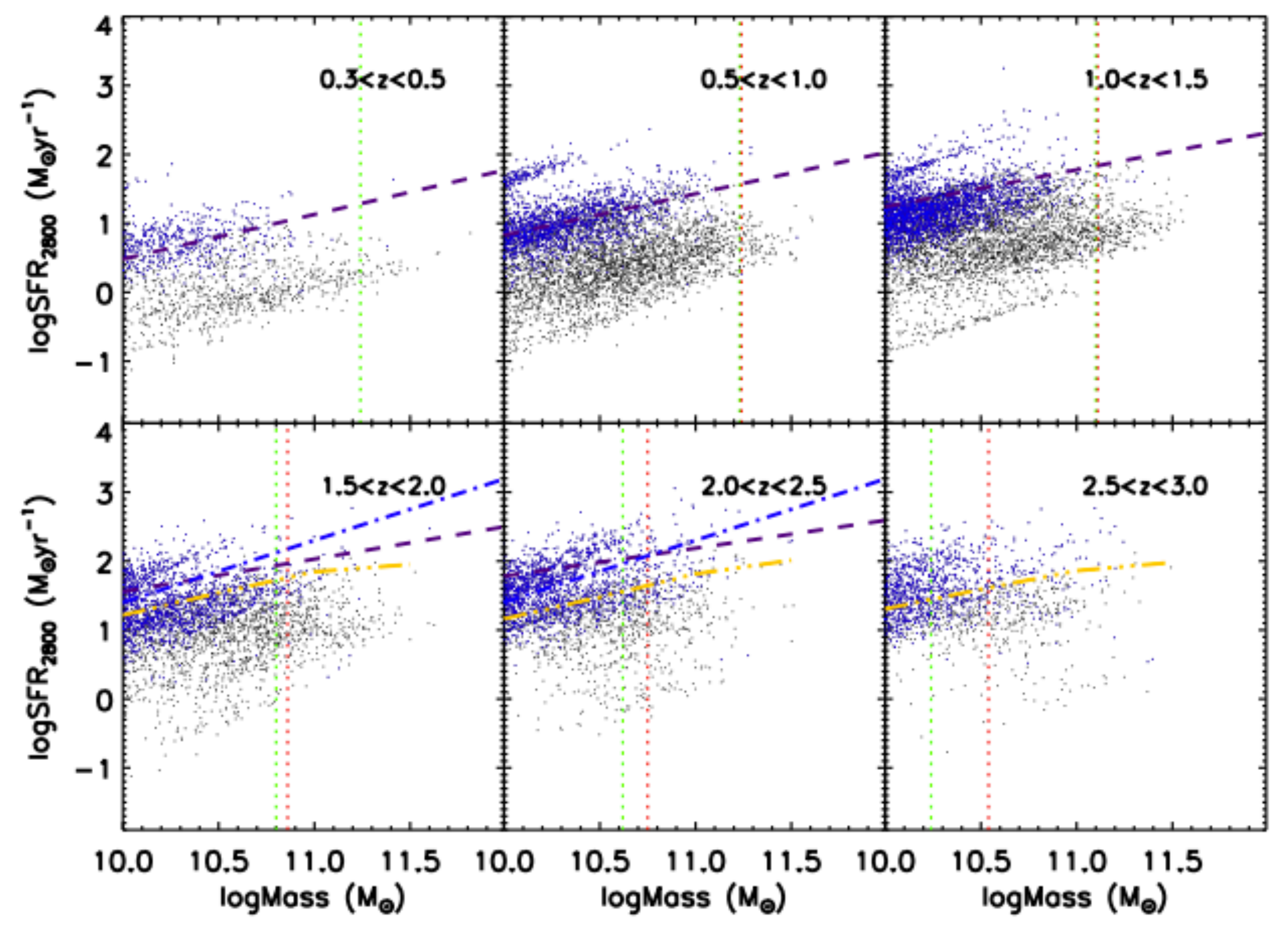
Gas mass fractions


Mannucci et al. 2009



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

The star formation rates as a function of stellar mass



Ownsworth et al. 2014

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

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

Stellar mass evolution

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

Gas mass evolution

$$\frac{\mathrm{M}_\mathrm{g}(t)}{\mathrm{M}_*(t)} \sim \frac{\mathrm{M}_\mathrm{g}(0)}{\mathrm{M}_*(0)}$$

Observed condition

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

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

→ *Evidence for cold gas accretion?*

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

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

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

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

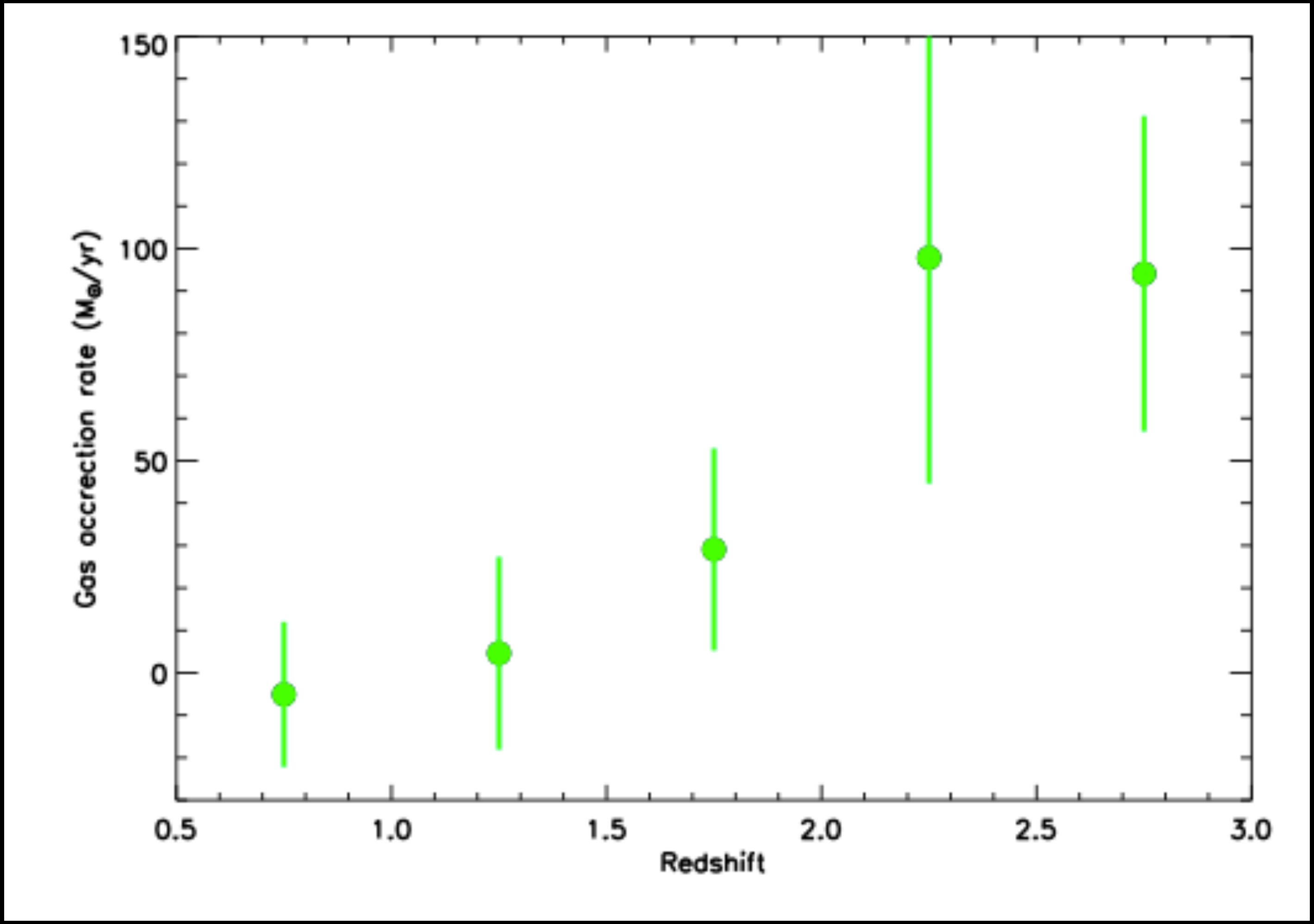
Over 1.5 < z < 3 (2.16 Gyr)

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

Average amount of gas accreted

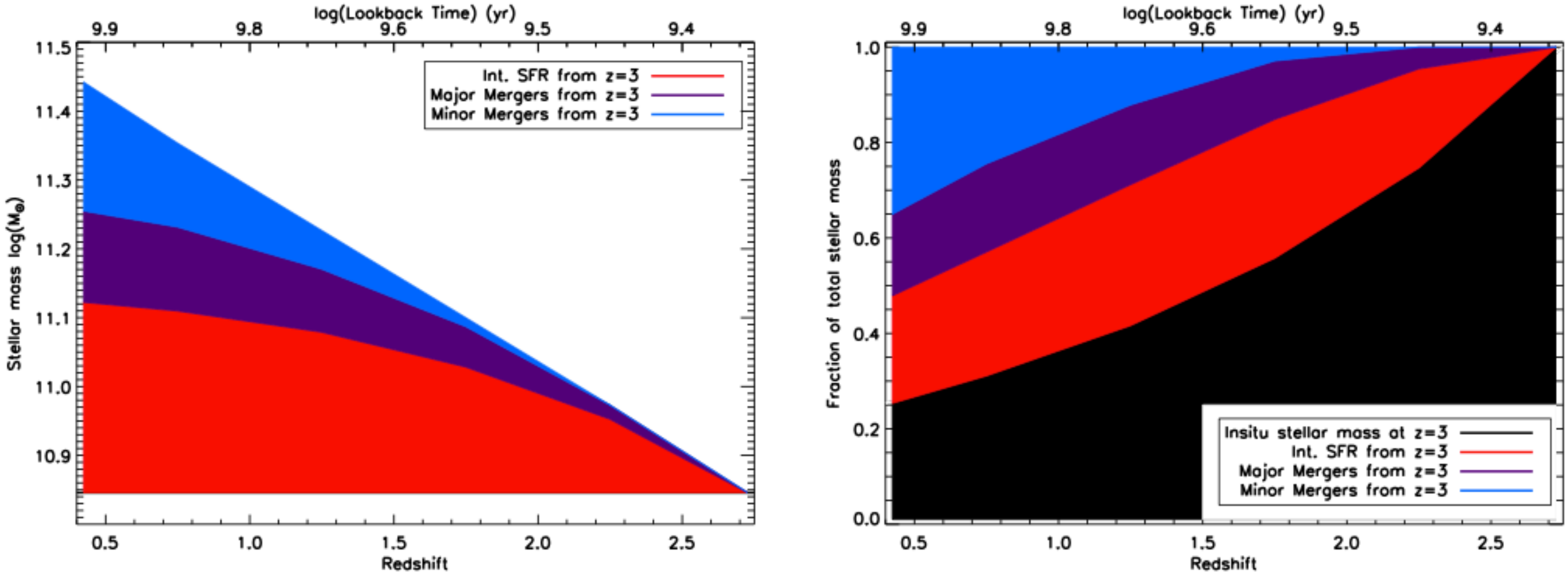
Results in accretion rate of $\frac{\mathrm{dM_{g,A}}(t)}{\mathrm{dt}} = \dot{\mathrm{M}}_{\mathrm{g,A}} = (83 \pm 36)\,\mathrm{M_\odot\ yr^{-1}}$

Gas accretion rate history for massive systems



Ownsworth et al. (2014)

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

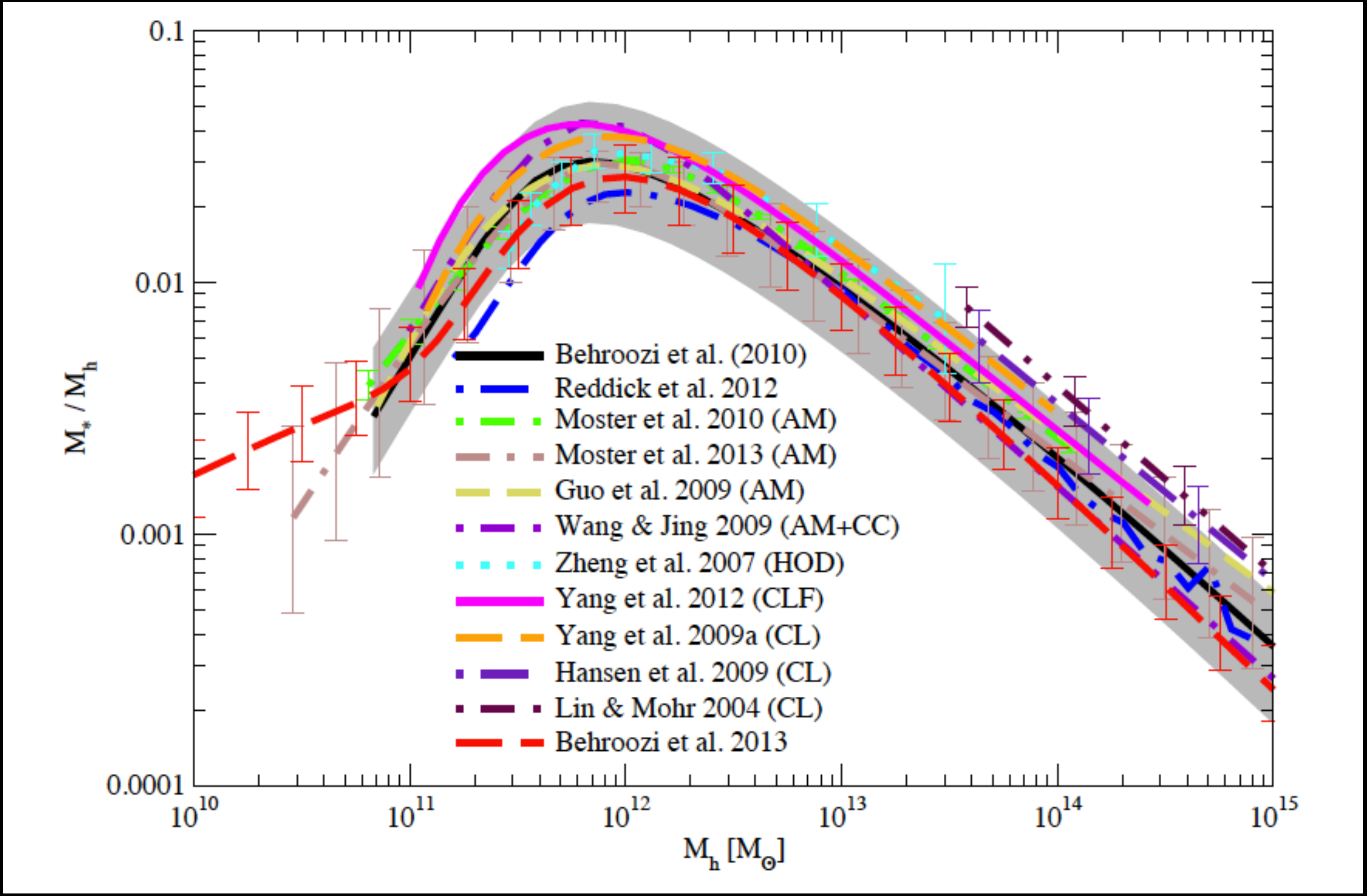


(a)

(b)

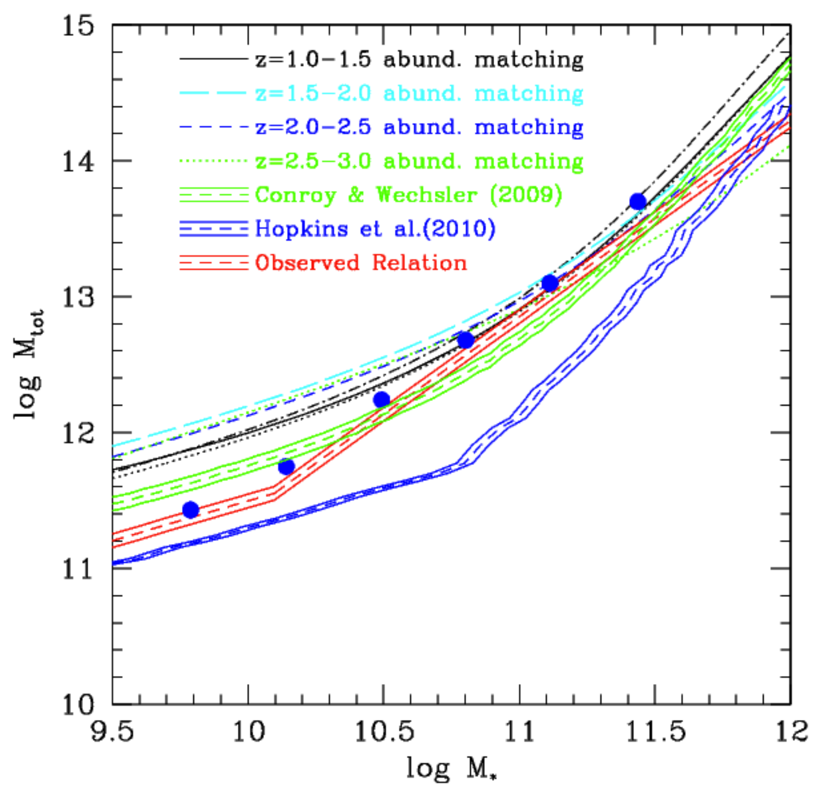
Ownsworth, CC et al. (2014)

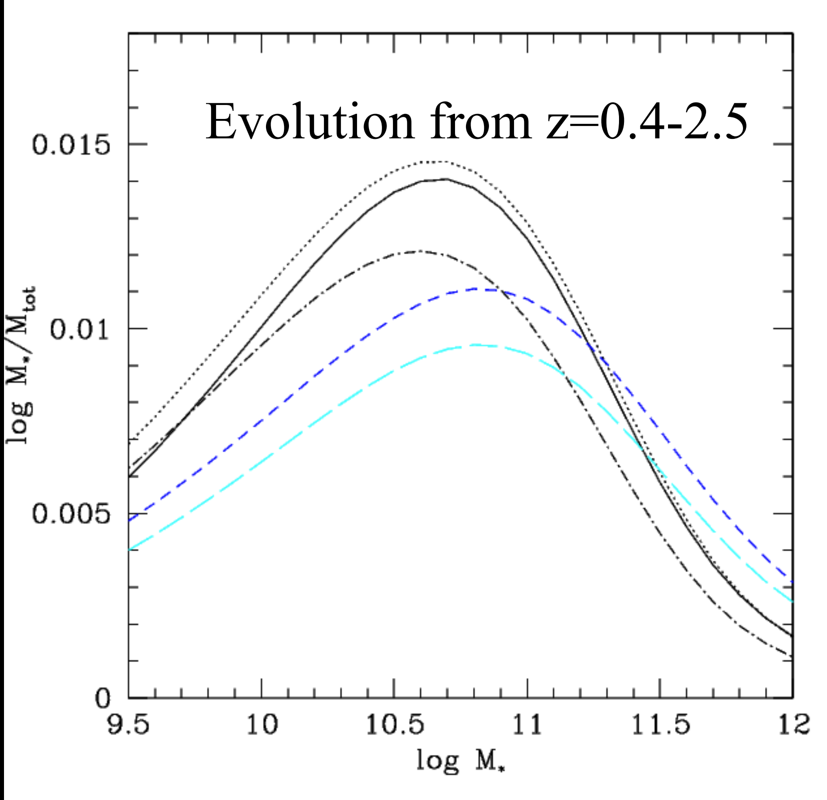
Abundance matching of galaxies and halos



Suggests a peak in the ‘efficiency’ of galaxy formation (Behroozi et al. 2013)

Observations suggest this peak does not evolve significantly

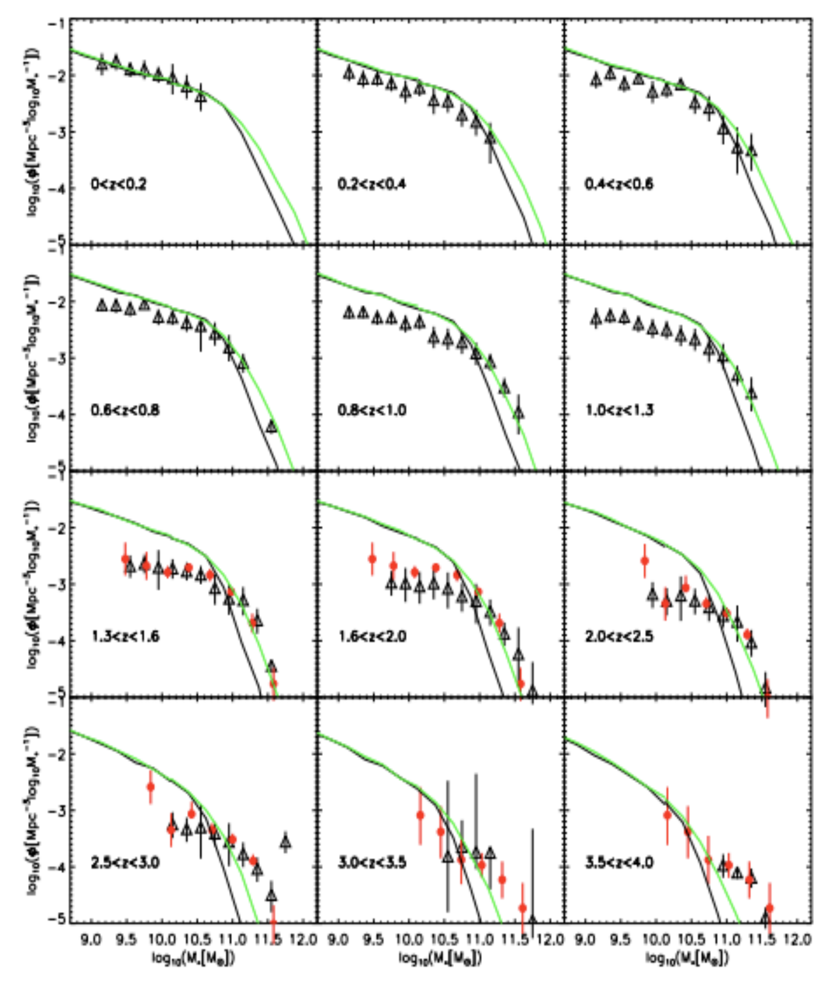




Find a similar peak in ‘efficiency’ up to z = 2.5 (Twite, CC, et al. 2014)

Galaxy formation models in Lambda CDM

Traditional method: Make a model to predict or match observations



Need a complementary approach for understanding galaxy formation

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

MORE problems than just satellites, DM profiles

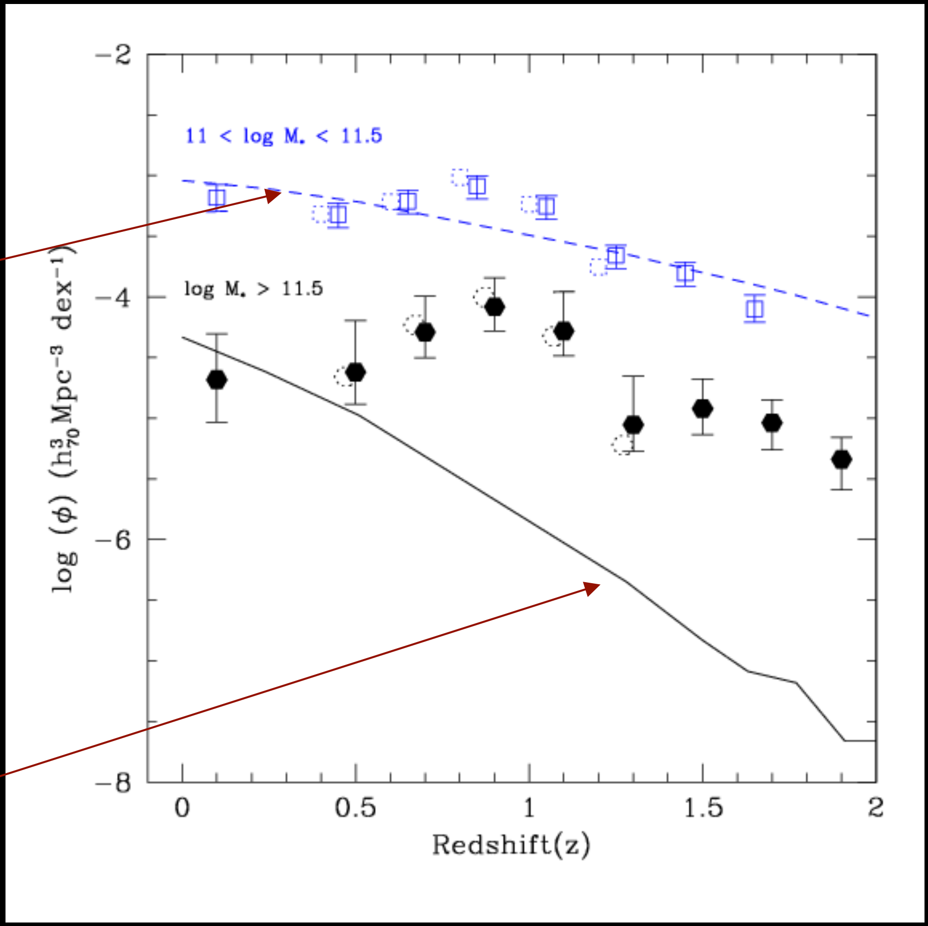
Problems at high-z: Guo et al. (2010)

There are too many distant massive galaxies in LCDM

Millennium simulation

Prediction for 11 < log M < 11.5

Prediction for log M > 11.5

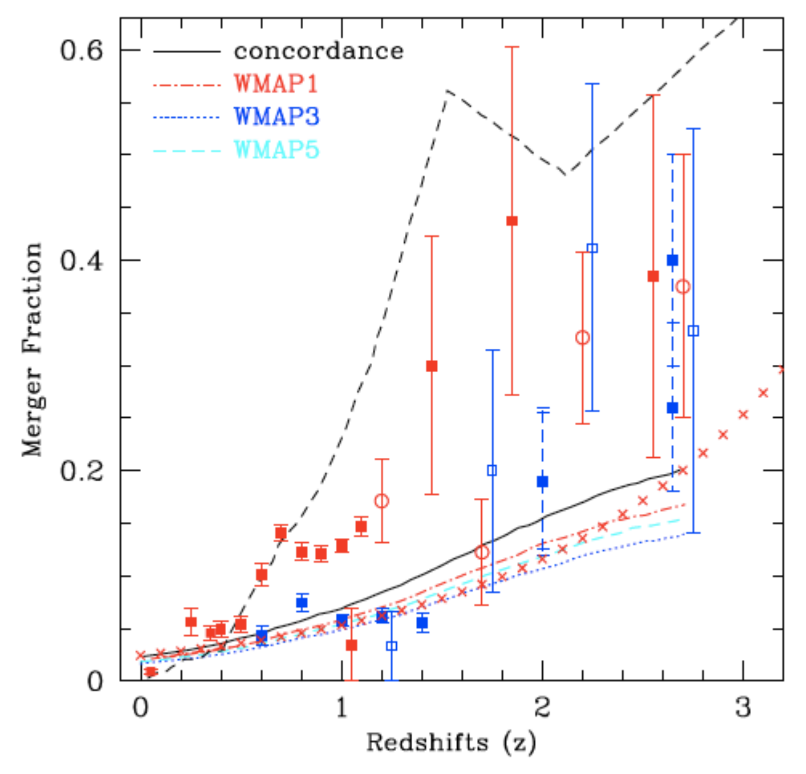


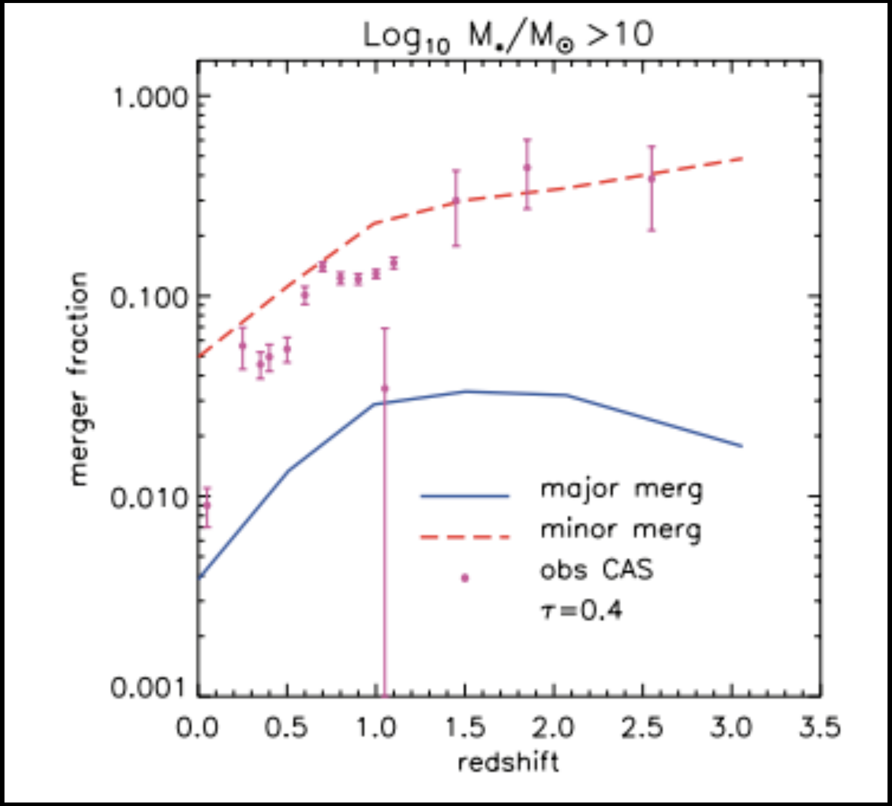
Vast under prediction in models compared to observations

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

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

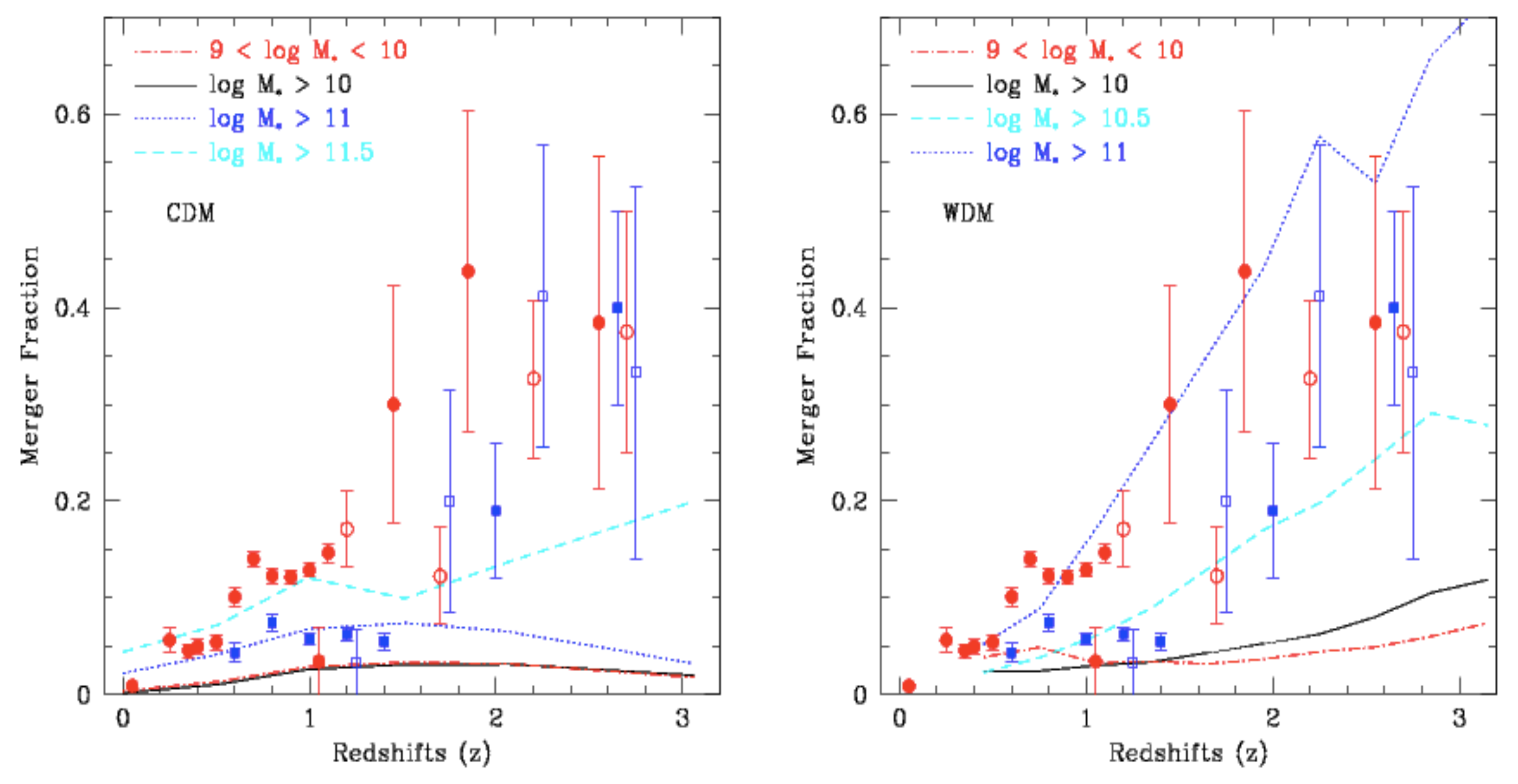
Different ΛCDM model predictions of the merger rate





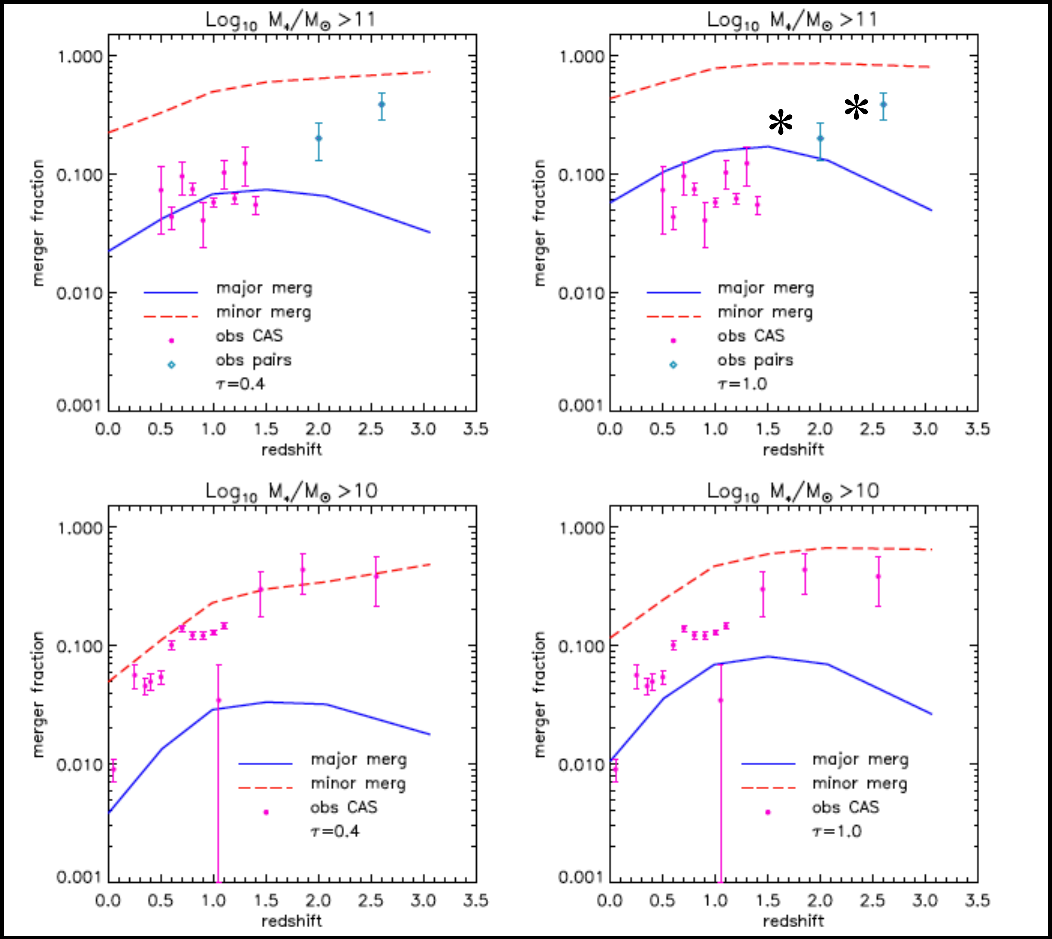
Maller et al. (2006); Bertone & Conselice (2009); Hopkins et al. (2010)

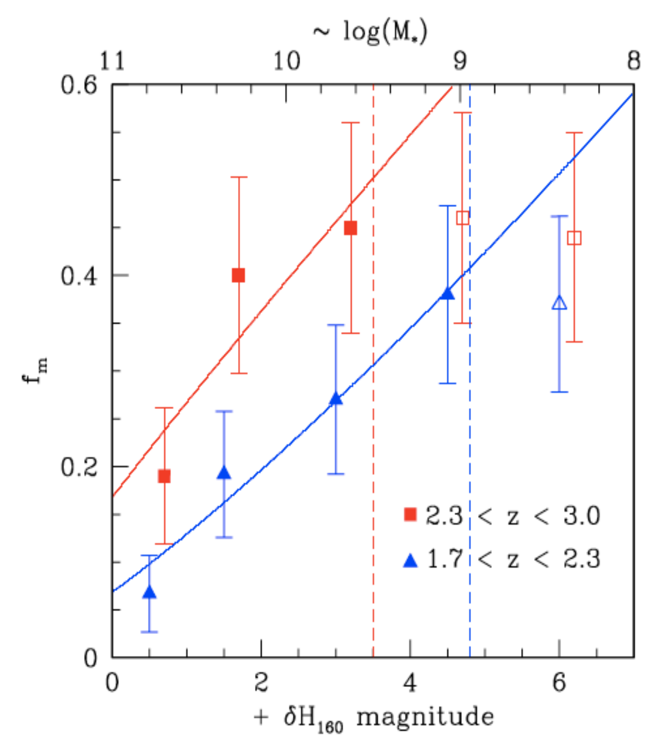
While merger history is not predicted well by CDM



Warm dark matter at ~1 keV fits much better

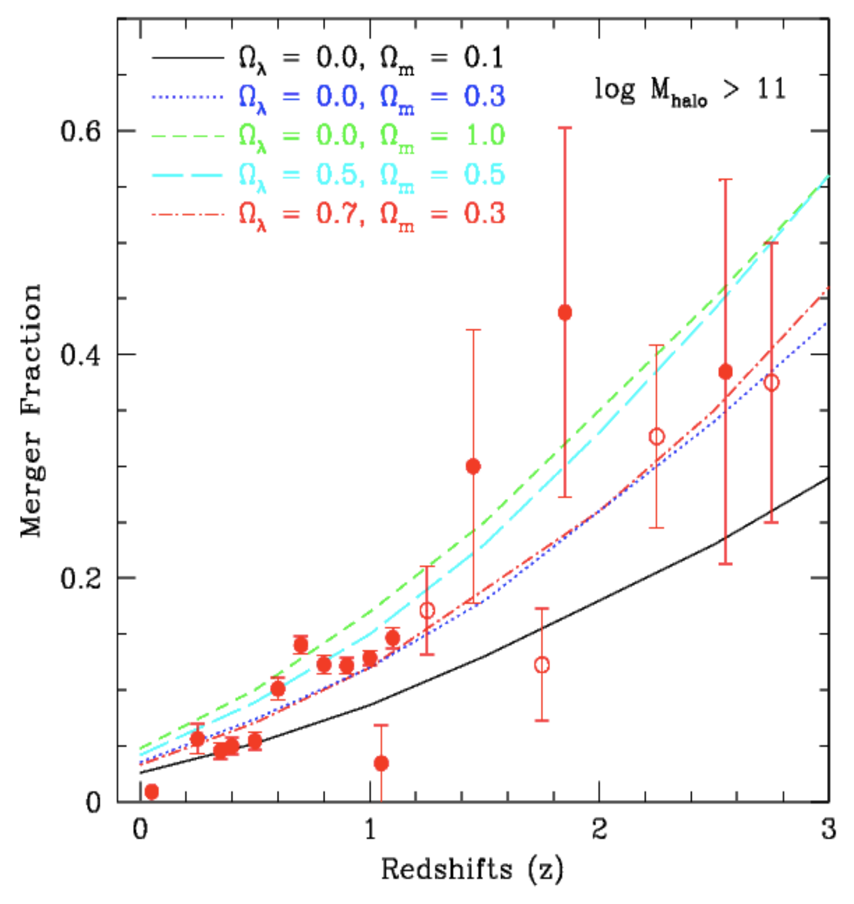
Also, too many minor mergers in LCDM





Bluck et al. 2012

Better agreement between dark matter halo mergers

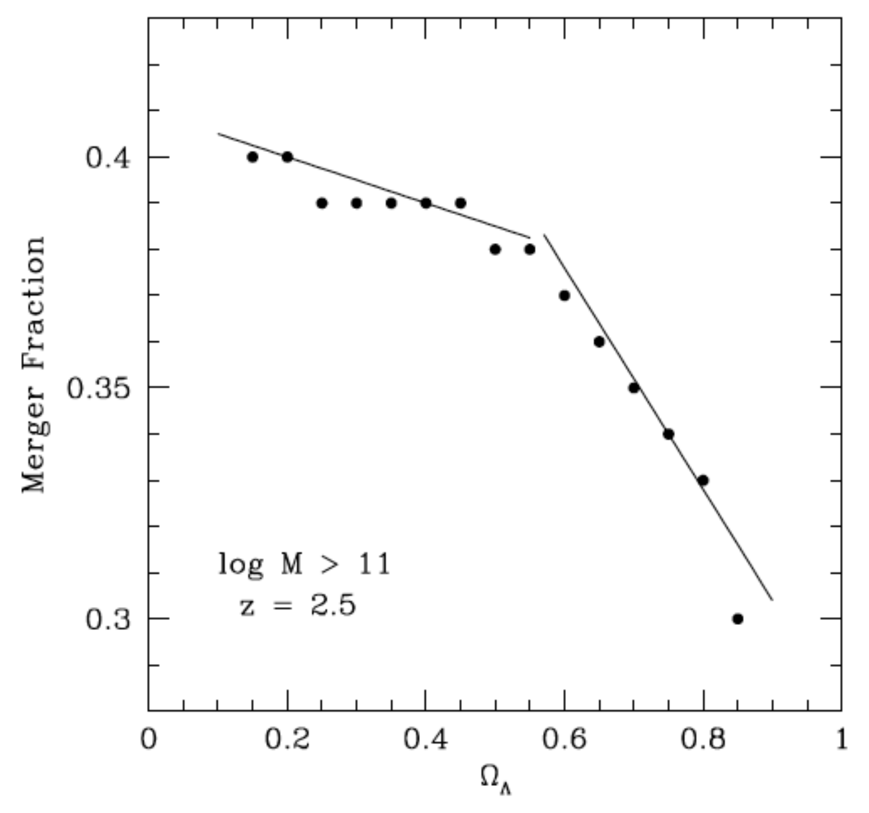


Best fitting
model is
standard
cosmology

Higher merger fractions
at higher matter densities

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

Can we use mergers to measure cosmological parameters?



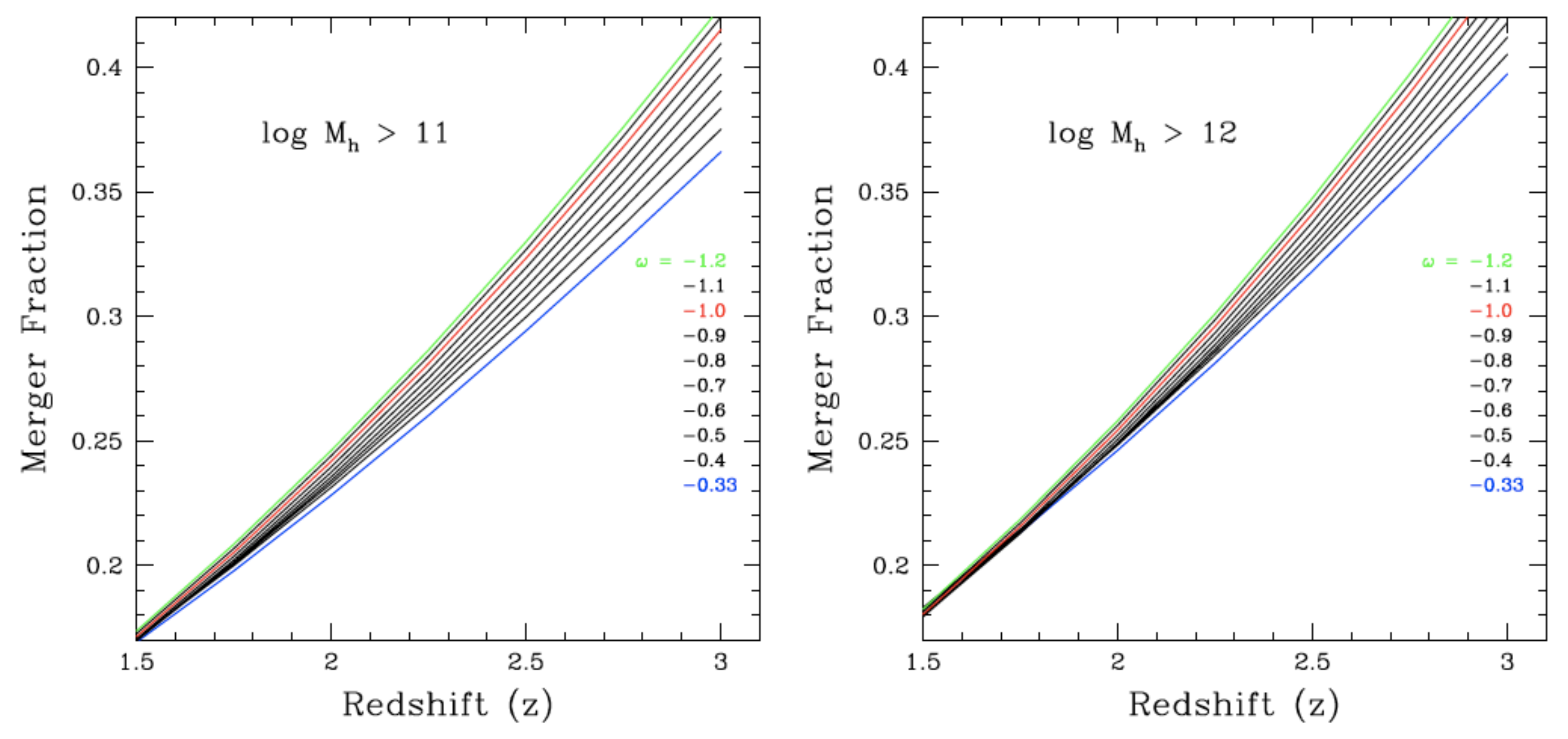
Best fit value currently gives $\Omega_\Lambda = 0.84^{+0.16}_{-0.17}$

With available data – not currently competitive with measurements from standard methods giving error 1/10th of these errors (e.g. Planck)

Partially due to limited area surveys that can currently be used for this type of analysis

Conselice et al. (2014), arXiv:1407.3811

Some variation with ω however, very small differences

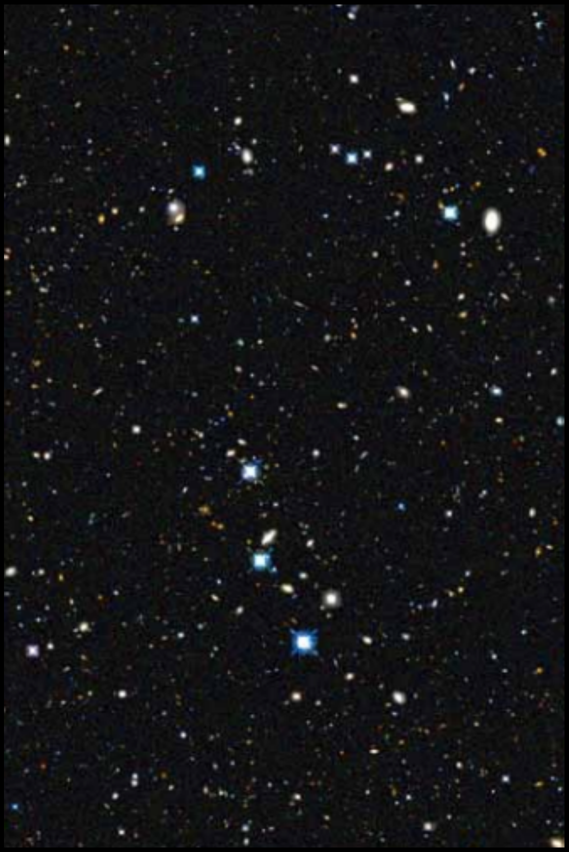


Need a survey of > 10 deg^2 with accurate mergers
to z=3 to use as a test of cosmology

Can probe in future with large and deep imaging/spectroscopic surveys such as Euclid and LSST in 2018-2020

Euclid Consortium

LSST



Simulated Euclid data

Survey of 15,000 deg^2 with 40 deg^2 in deep fields

Summary

1. 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 unique 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 $1 < z < 3$, but not as much as CDM predicts.

4. Gas accretion from the intergalactic medium can account for roughly half of the baryonic formation of massive galaxies. We are 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.