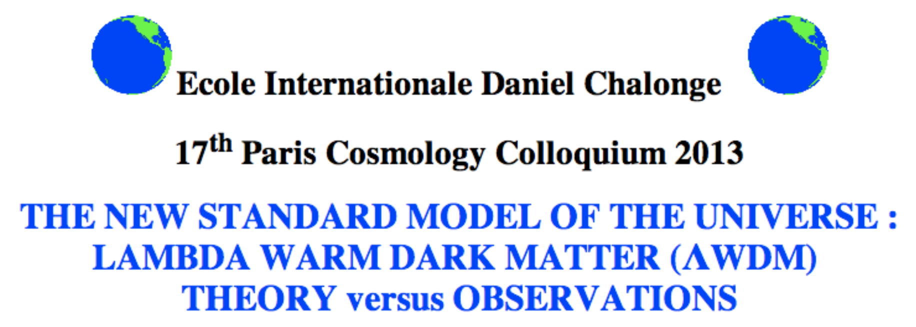
Observational Overview of Galaxy Formation and Evolution in a Cosmological Context

Christopher J. Conselice

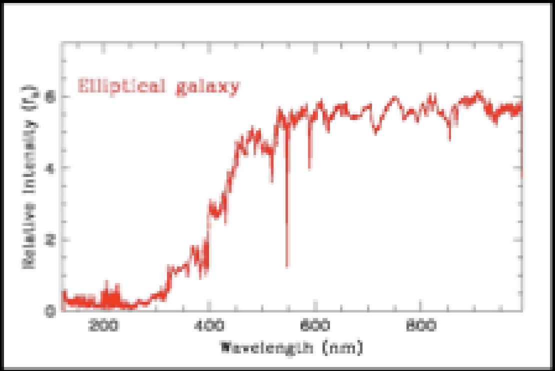
(University of Nottingham)

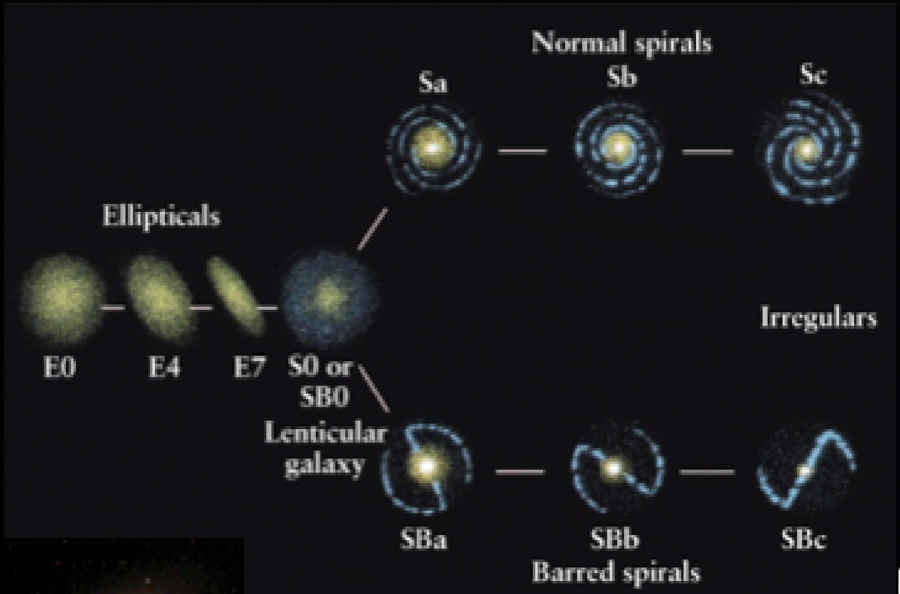


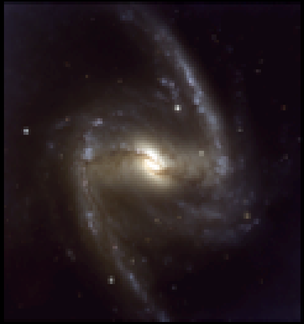
Ecole Internationale Daniel Chalonge

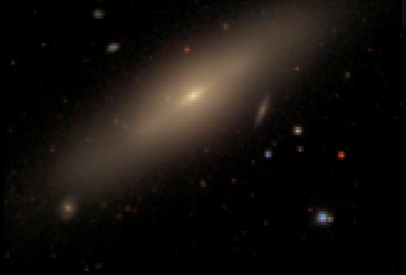
17th Paris Cosmology Colloquium 2013

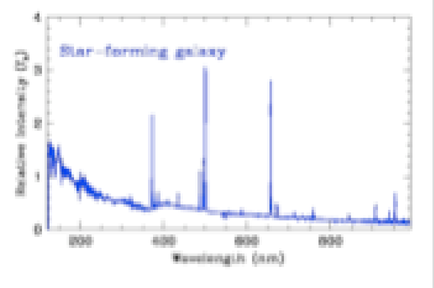
THE NEW STANDARD MODEL OF THE UNIVERSE :
LAMBDA WARM DARK MATTER (ΛWDM)
THEORY versus OBSERVATIONS


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

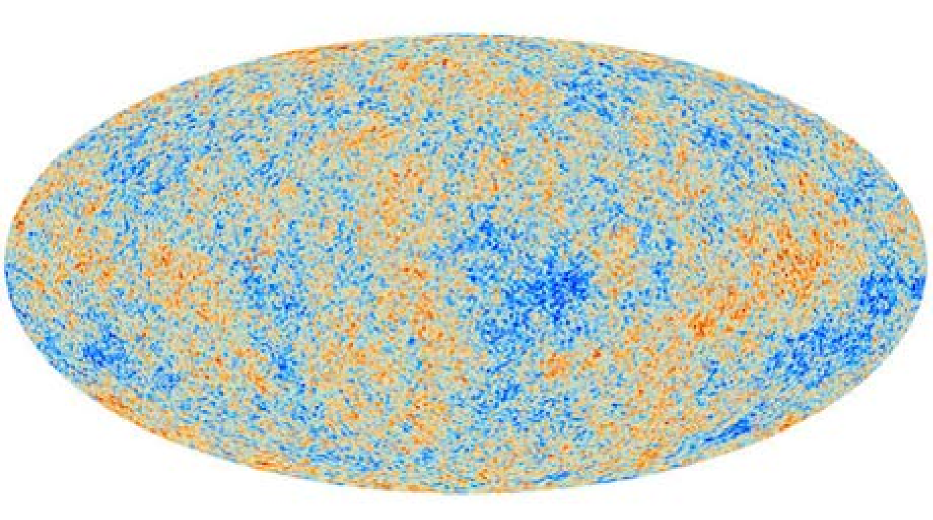

Normal spirals
Sa
Sb
Sc
Ellipticals
E0
E4
E7
S0 or SB0
Lenticular galaxy
Irregulars
SBa
SBb
SBc
Barred spirals

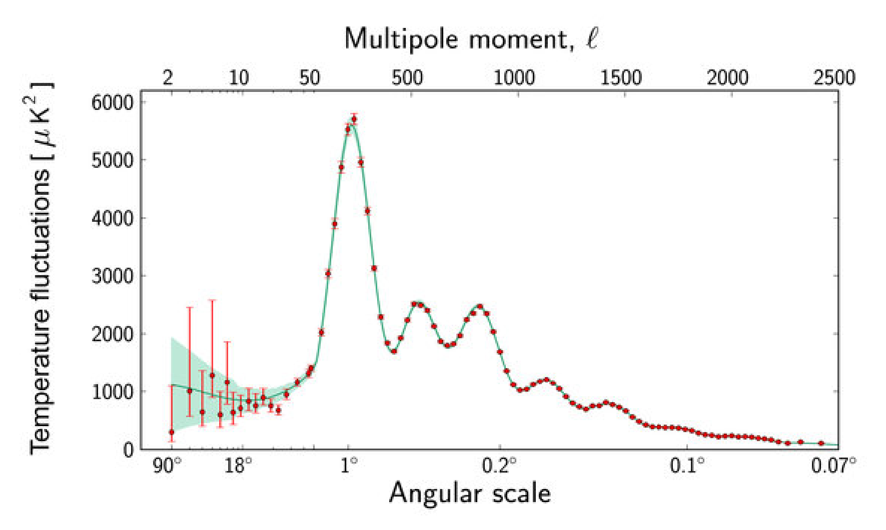





Star-forming galaxy
Relative Intensity (F_λ)
0
1
2
3
4
200
400
600
800
Wavelength (nm)

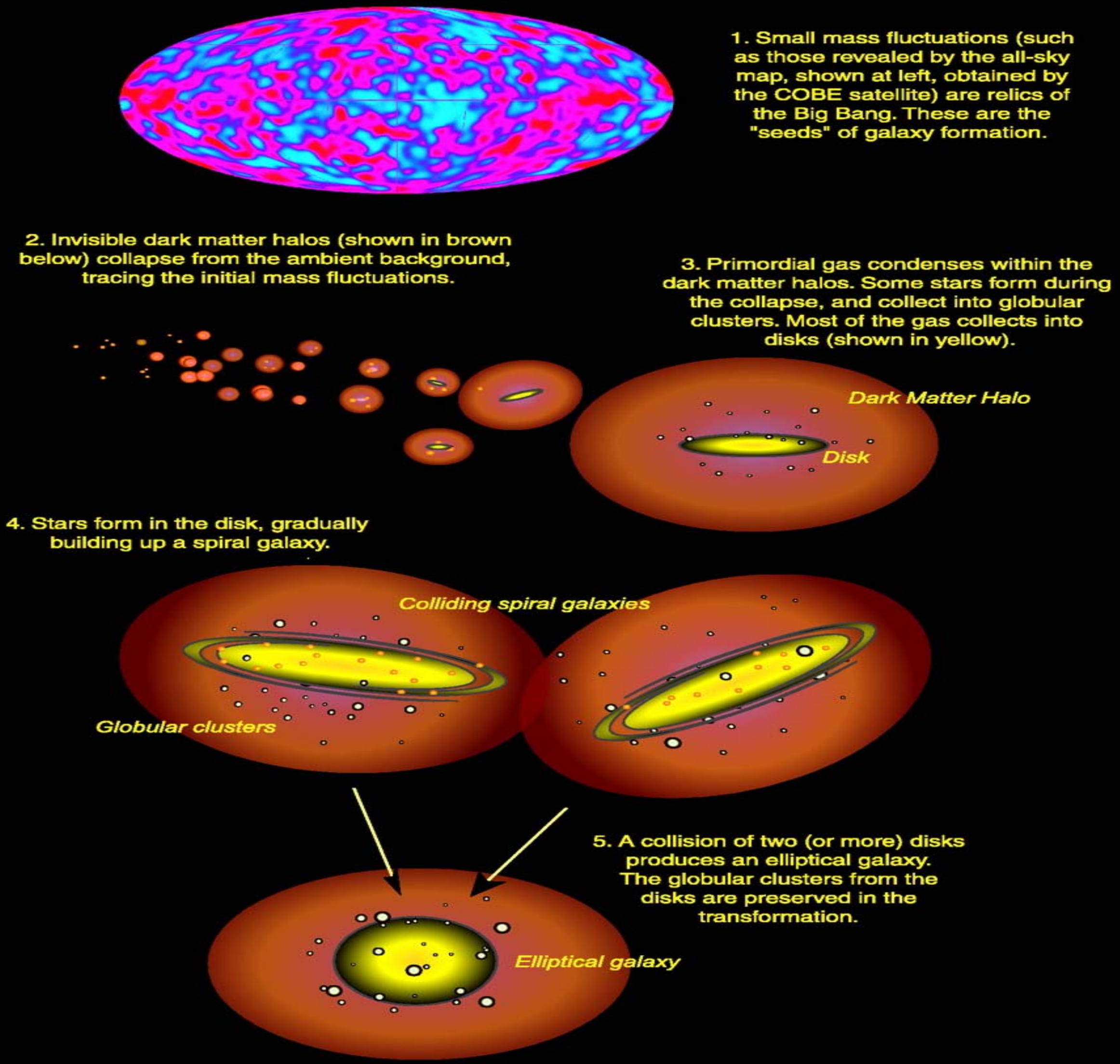
Cosmic Background Radiation – cosmological parameters





Planck collaboration results 2013

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.

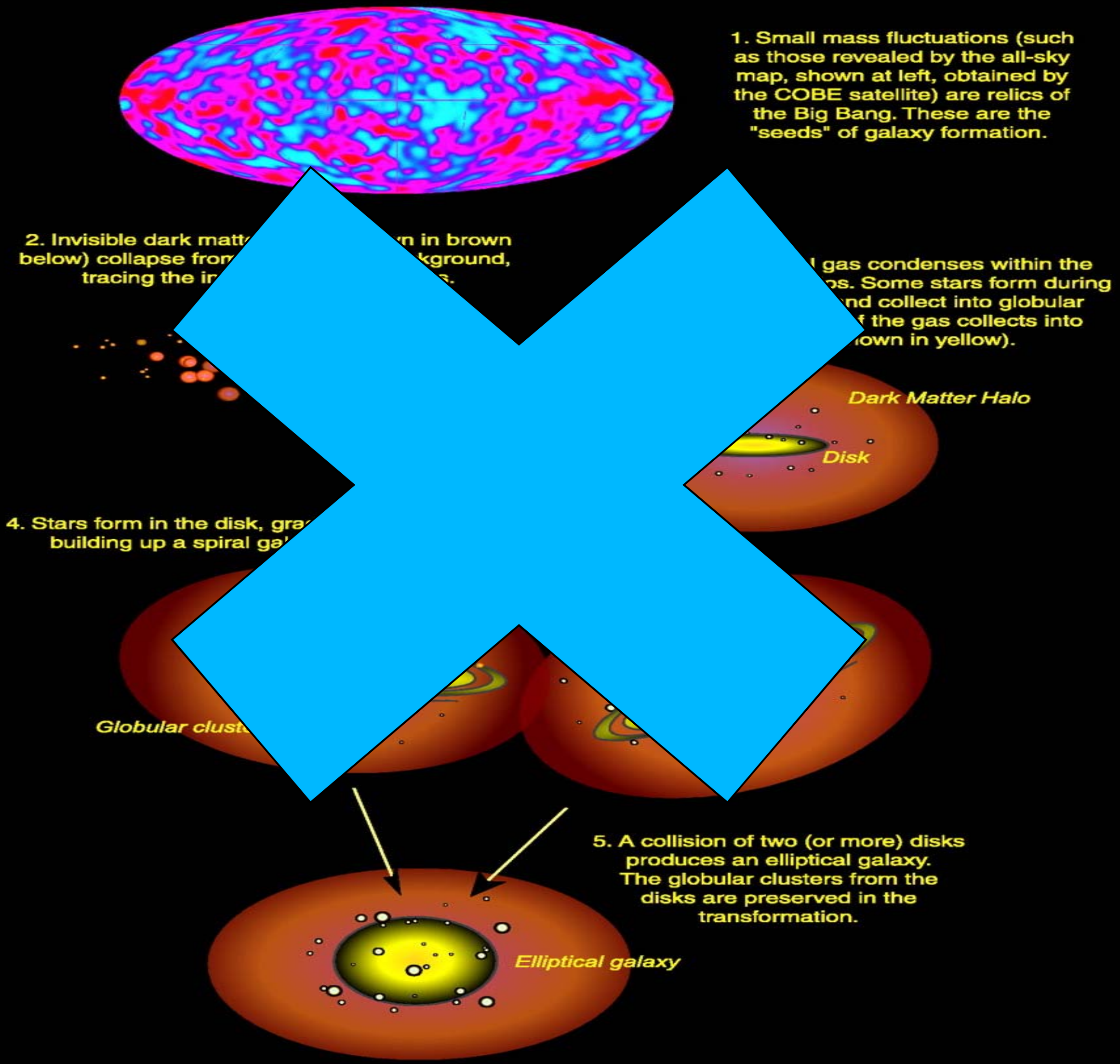
2. Invisible dark matter halos (shown in brown below) collapse from the ambient background, tracing the initial mass fluctuations.

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



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.

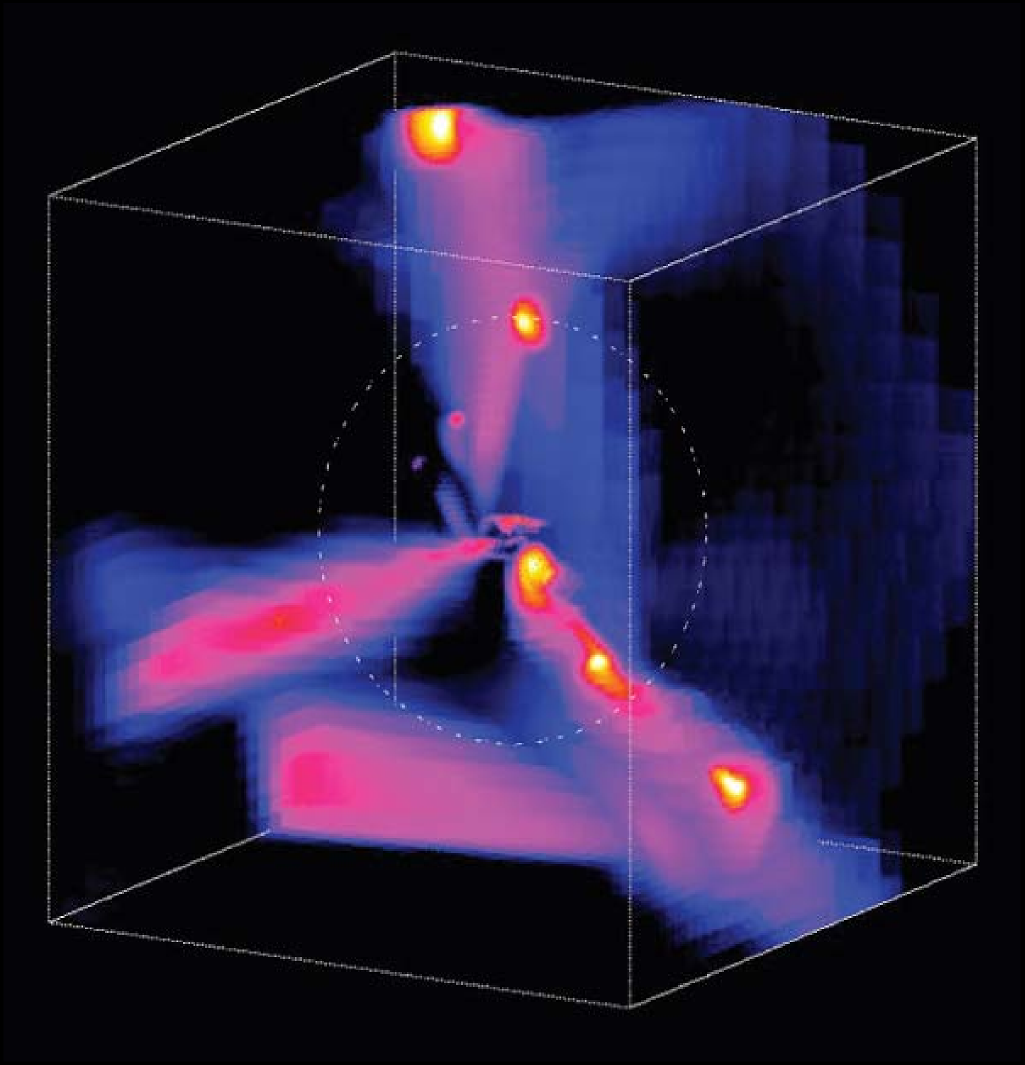
2. Invisible dark matt n in brown
below) collapse from kground,
tracing the in s.

l gas condenses within the
ps. Some stars form during
nd collect into globular
f the gas collects into
own in yellow).

4. Stars form in the disk, gra
building up a spiral ga

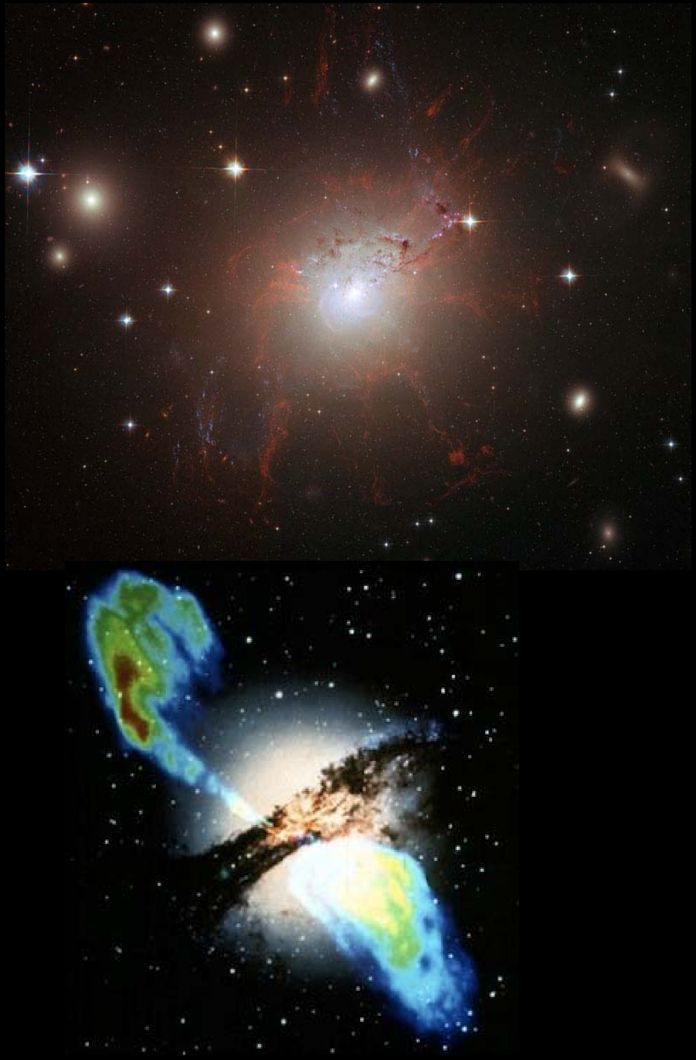
5. A collision of two (or more) disks
produces an elliptical galaxy.
The globular clusters from the
disks are preserved in the
transformation.

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 still being sorted out
(Gilmore & Walker talks on low mass galaxies)

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 (history not physics)

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 (history not physics)

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

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 (history not physics)

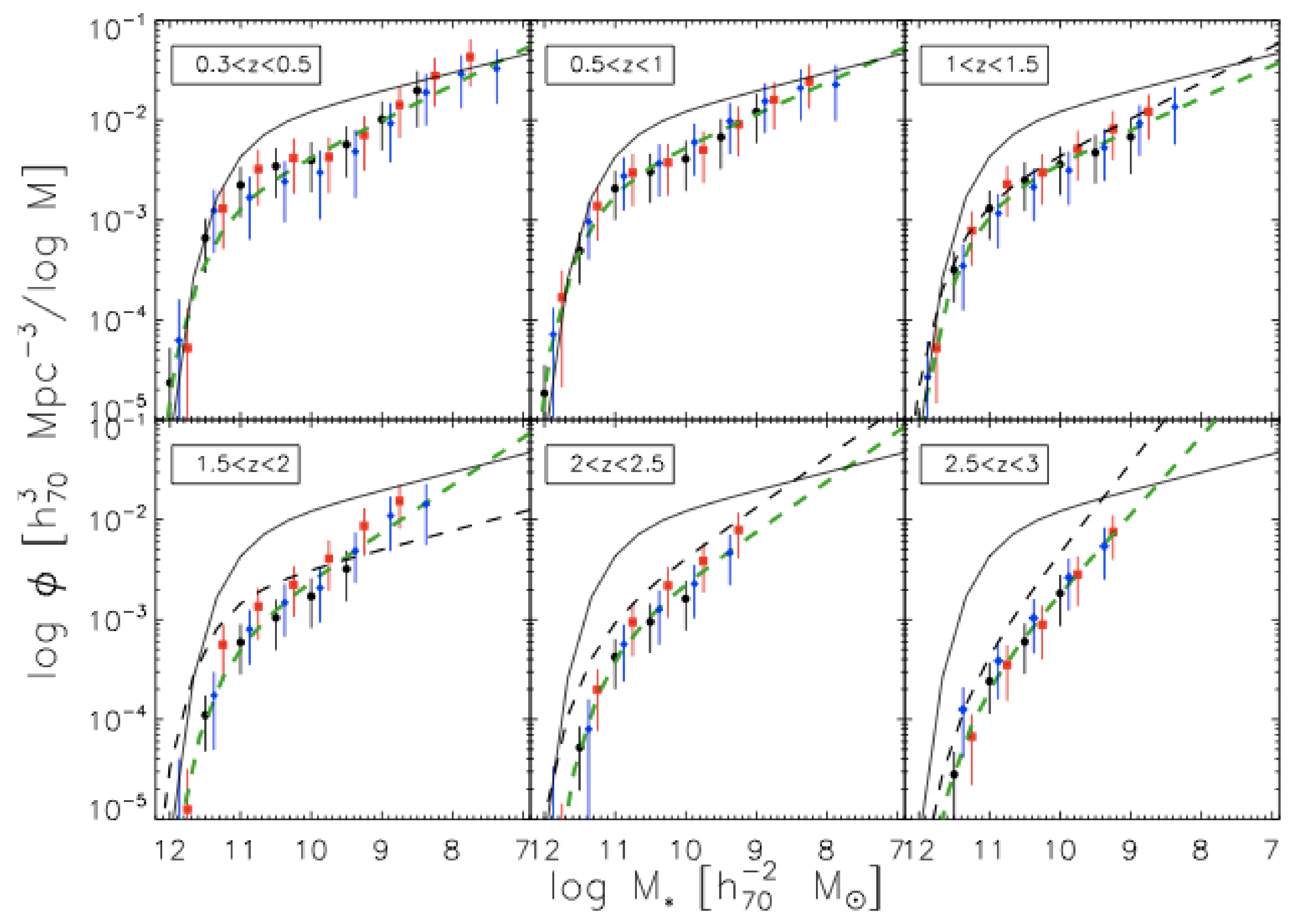
2. Theory - simulations of galaxy formation i.e., numerical, SPH, semi-analytical, etc. Try to match the observations with 'physics' – cosmological model with gas physics included

3. Direct probes - 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?

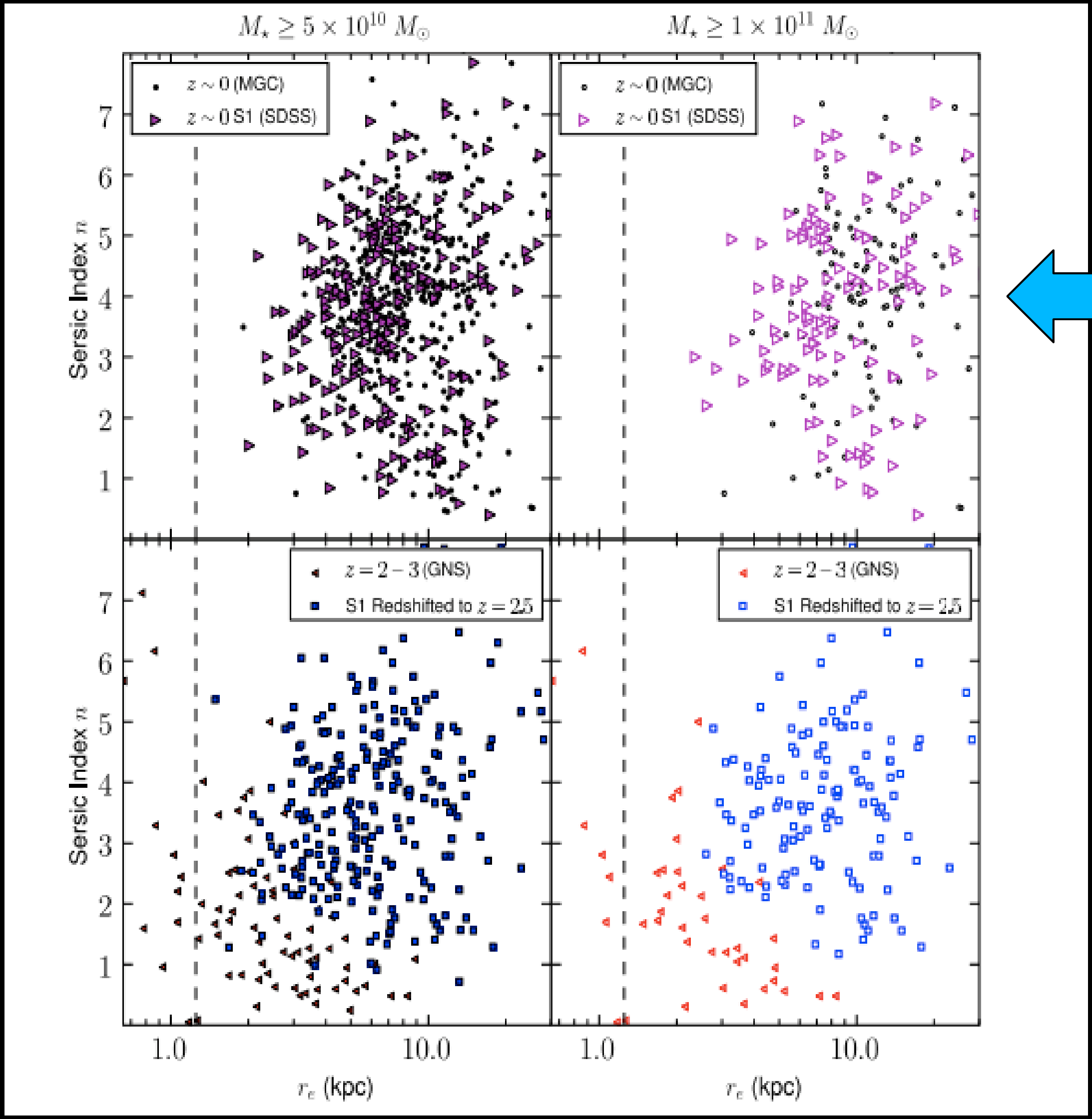
A first attempt to solve this problem is with massive galaxies



Mortlock, CJC, et al. (2013)

Most massive galaxies are formed by z = 1

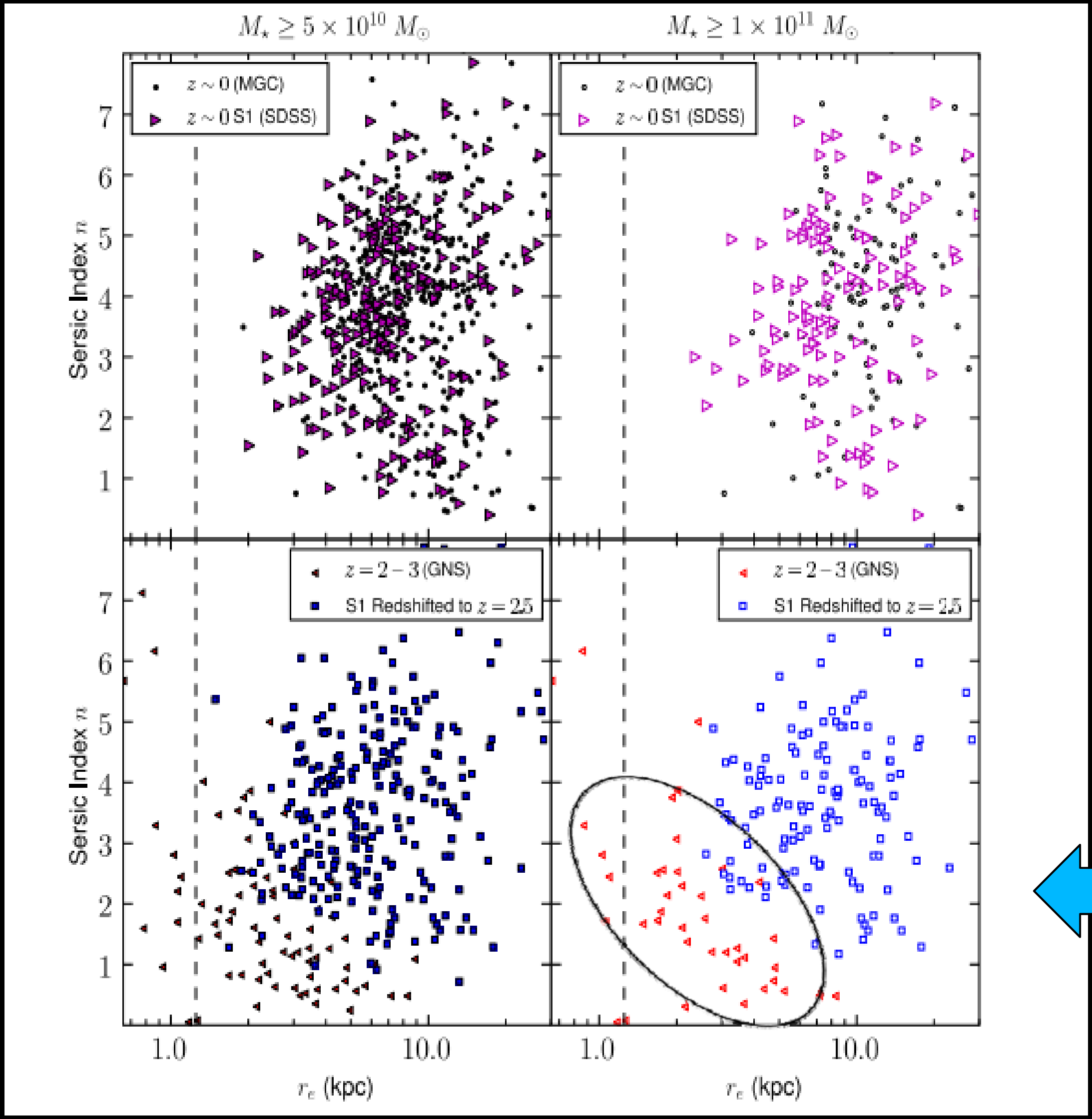
Galaxies at z = 2.5 --- different from nearby massive galaxies



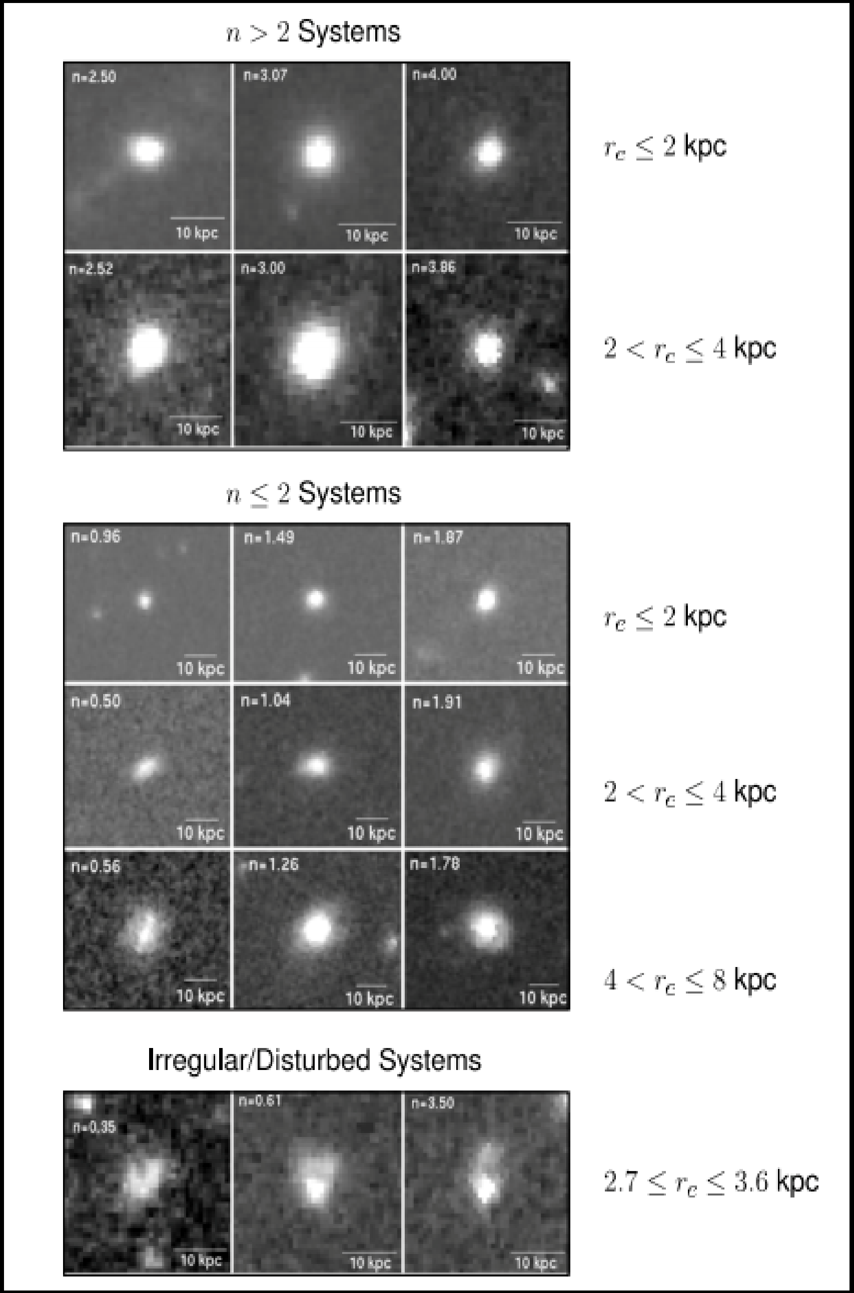
Nearby massive galaxies

Weinzirl et al. (2011)

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



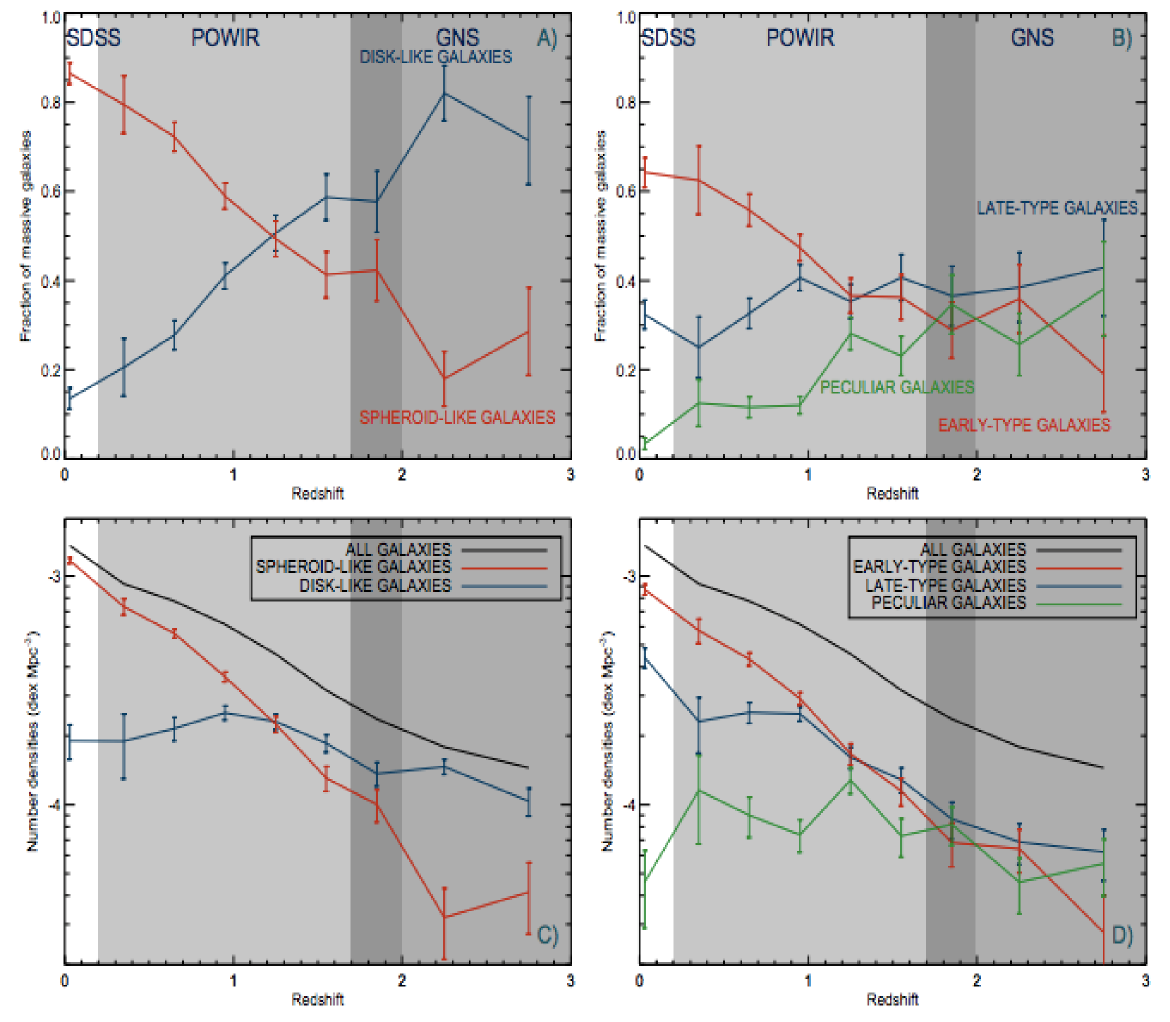
Same mass
but at z > 1



Massive Galaxies at $z > 1.5$

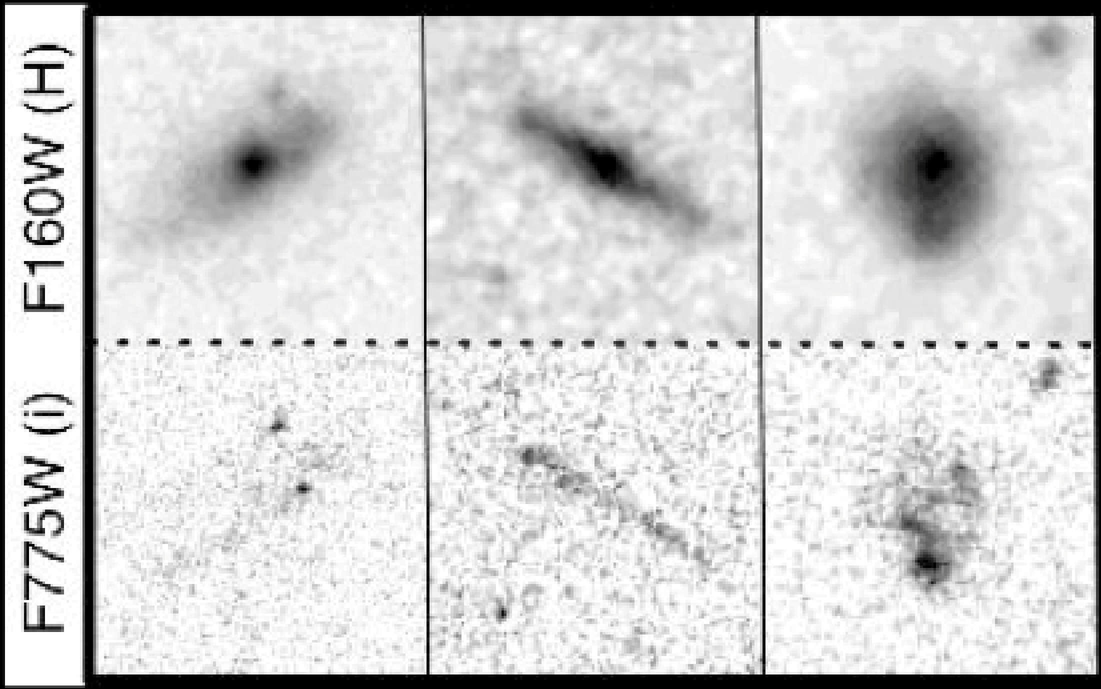
Mixture of morphologies

Massive galaxies become more disk like at higher redshifts



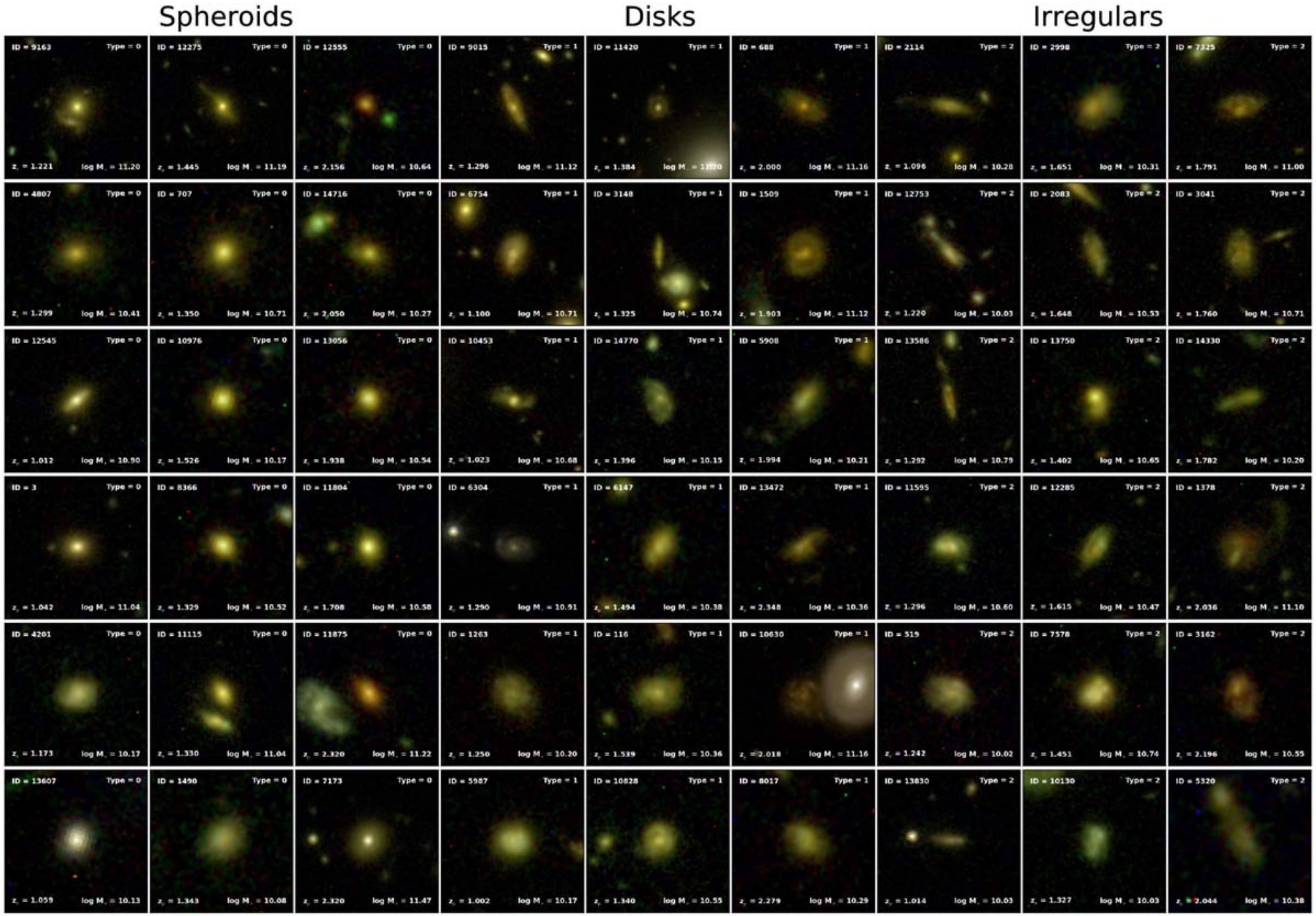
Buitrago et al. (2013)

CANDELS survey imaging – Hubble Sequence at z > 1



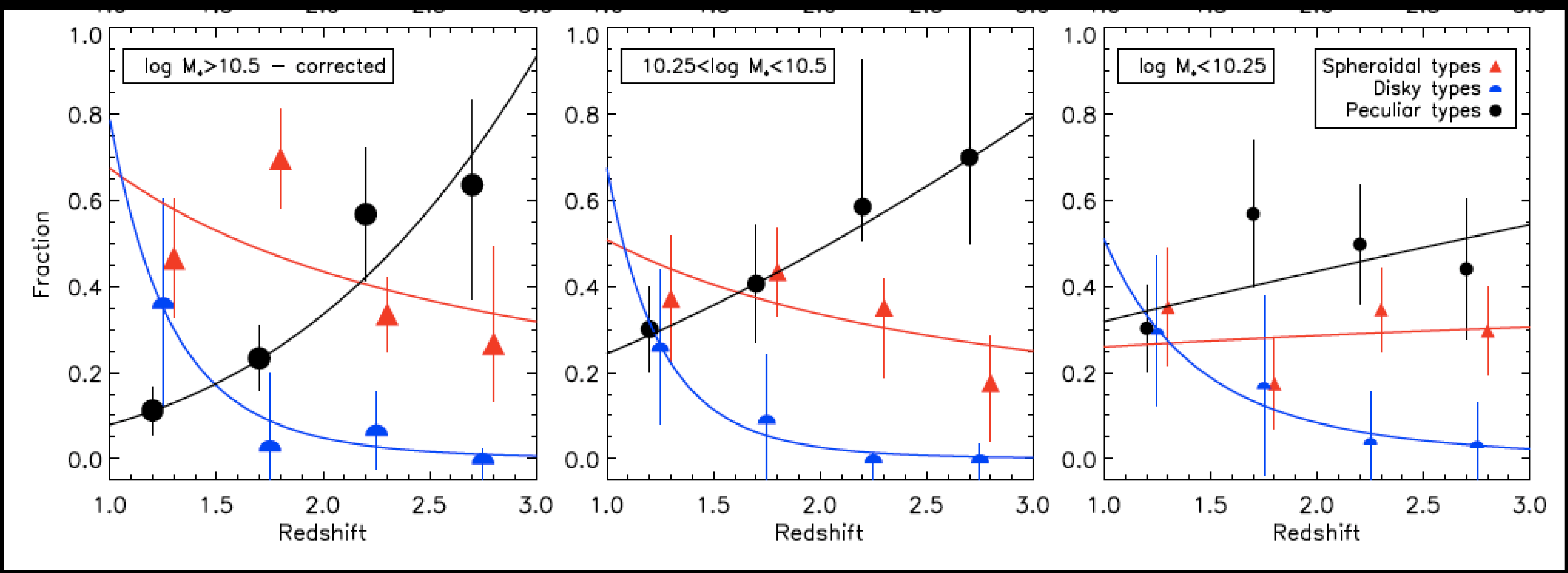
The CANDELS Survey – 900+ Hubble orbits to study high the resolution NIR Universe in five fields. Gives rest-frame optical structures for galaxies at z=1-3

Galaxy morphologies in CANDELS



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

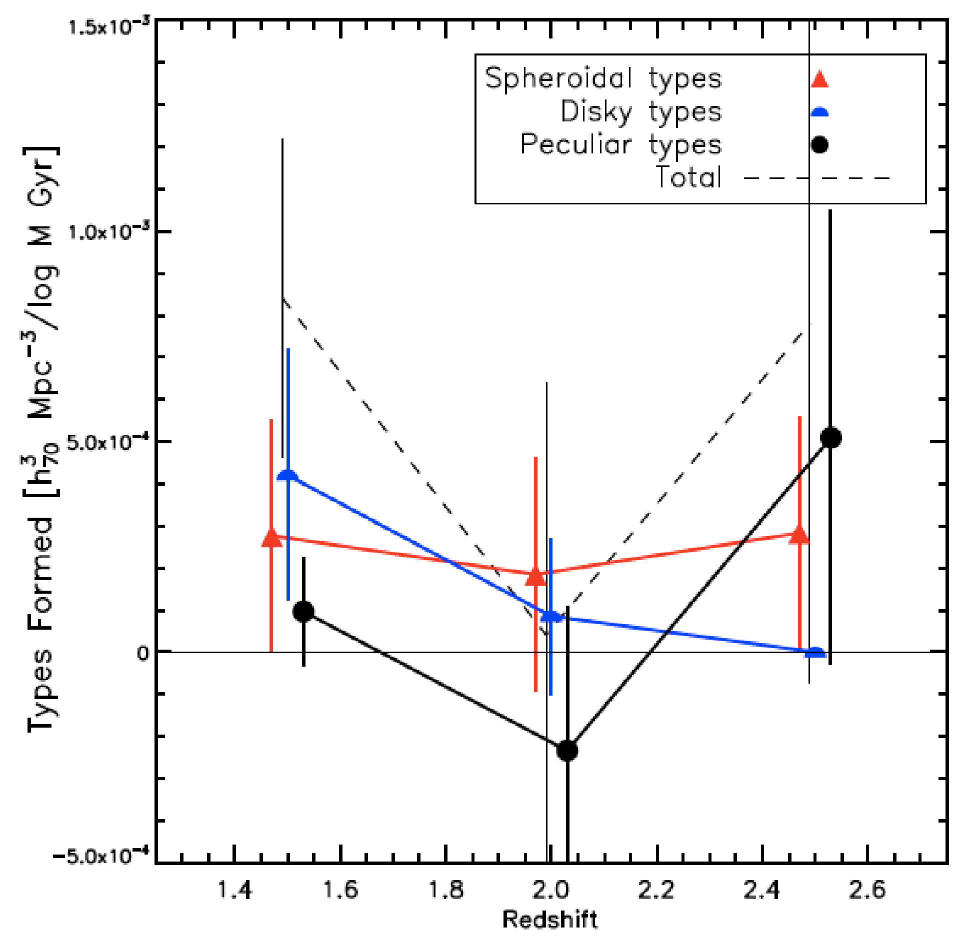
There is a dependence on stellar mass on morphological evolution



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

$Z_{trans} \sim 1.85$

Rate of change in the formation of Hubble types

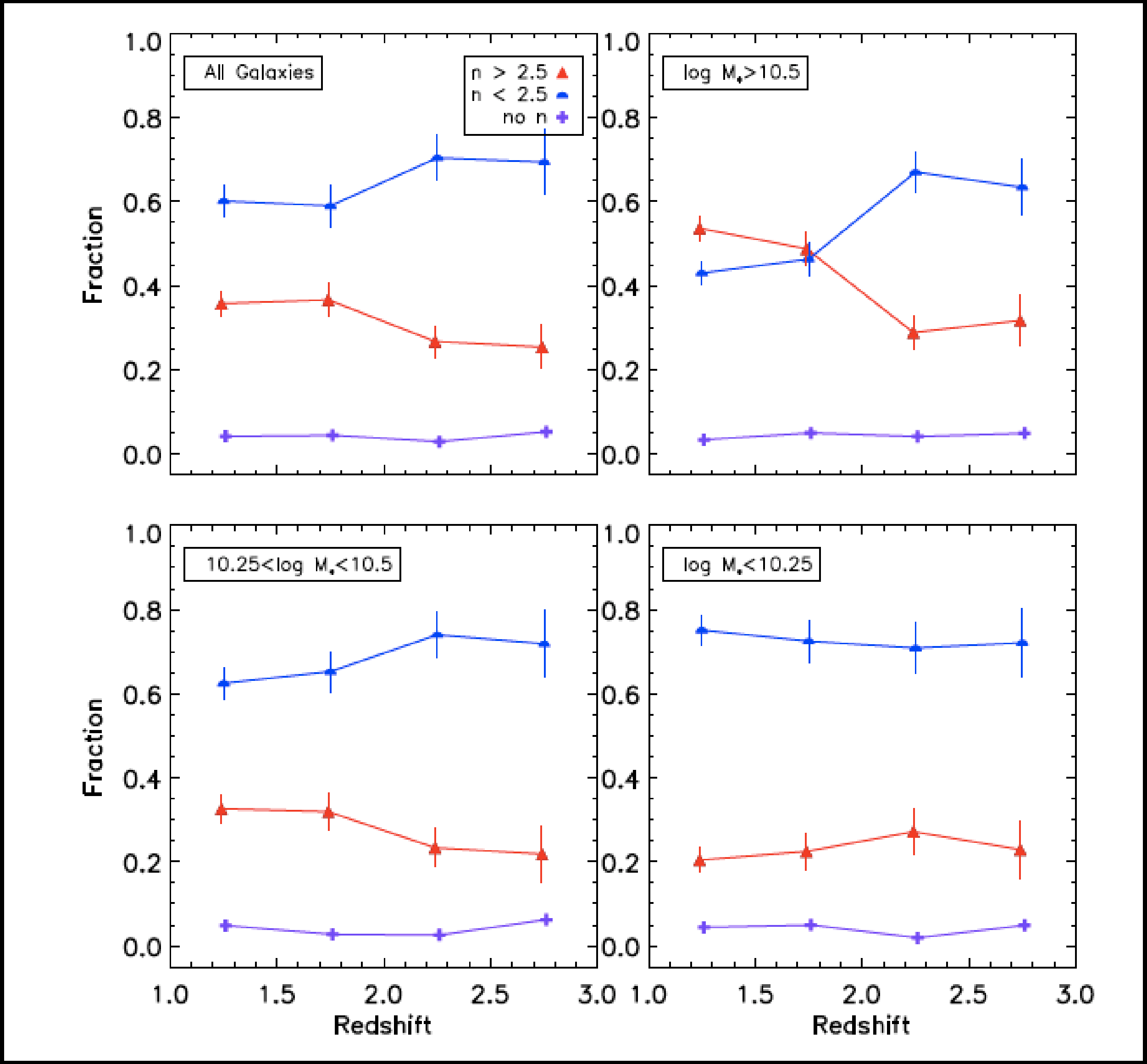


Roughly constant formation rate for E/Spirals

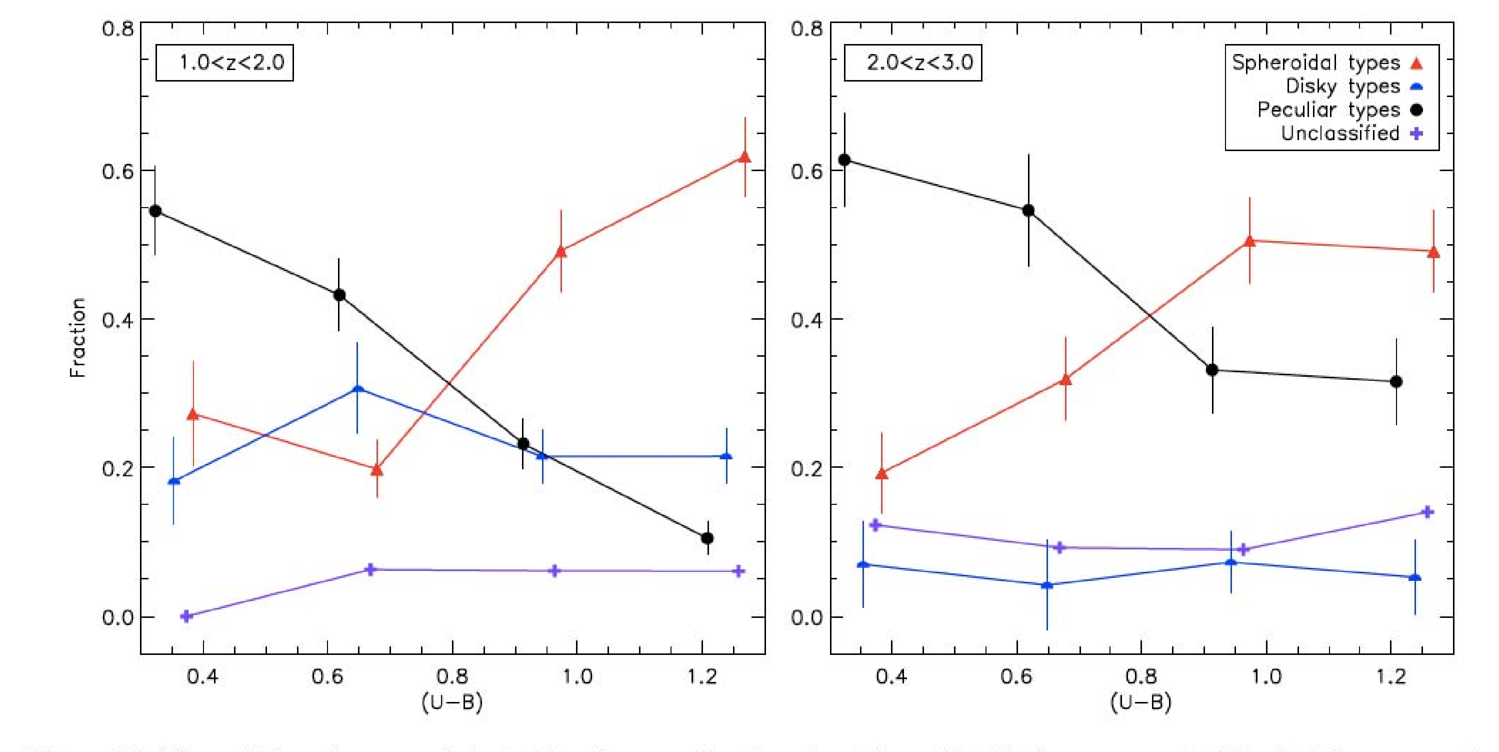
Are there disk galaxies at z > 2?

We find a large population of n < 2.5 galaxies at these redshifts

Inconsistent(?) with visual morphologies



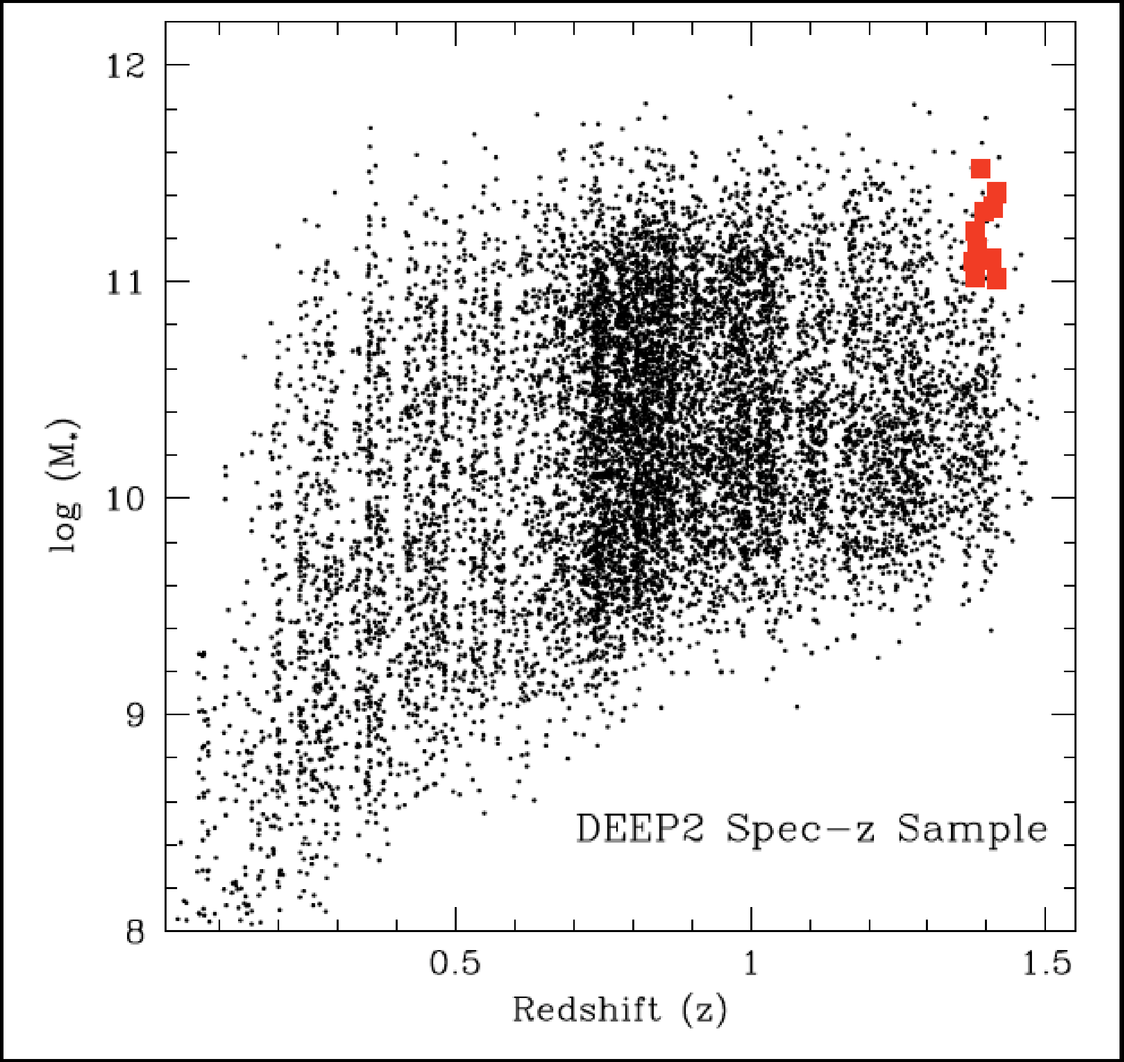
However, see a significant evolution in colour at a given morphology



Most modern disks must be ‘peculiar’ at z > 1

IFU spectra can help sort out nature of these systems

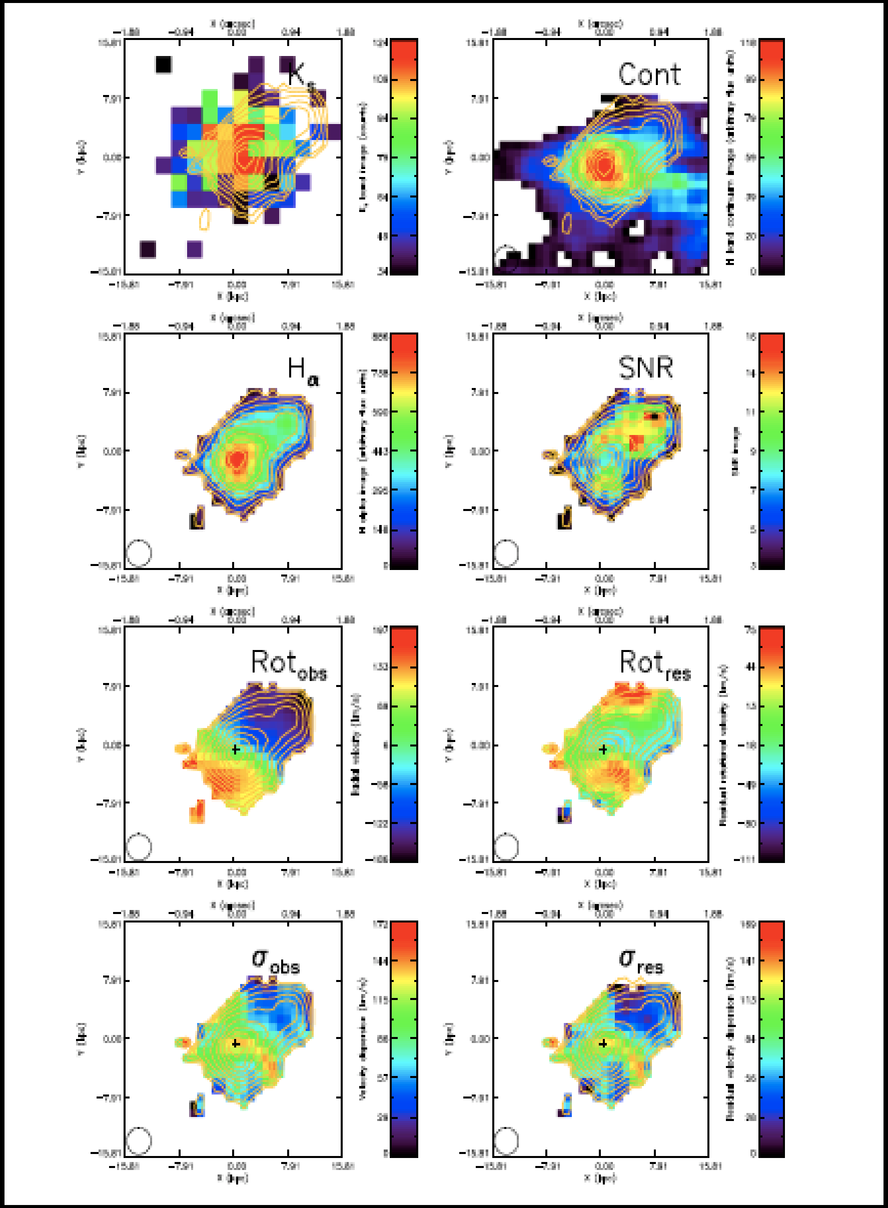
SINFONI spectra of
the highest mass
galaxies at z~1.4
in DEEP2 with
log Mstar > 11



Buitrago et al. (2013); arXiv: 1305.0268

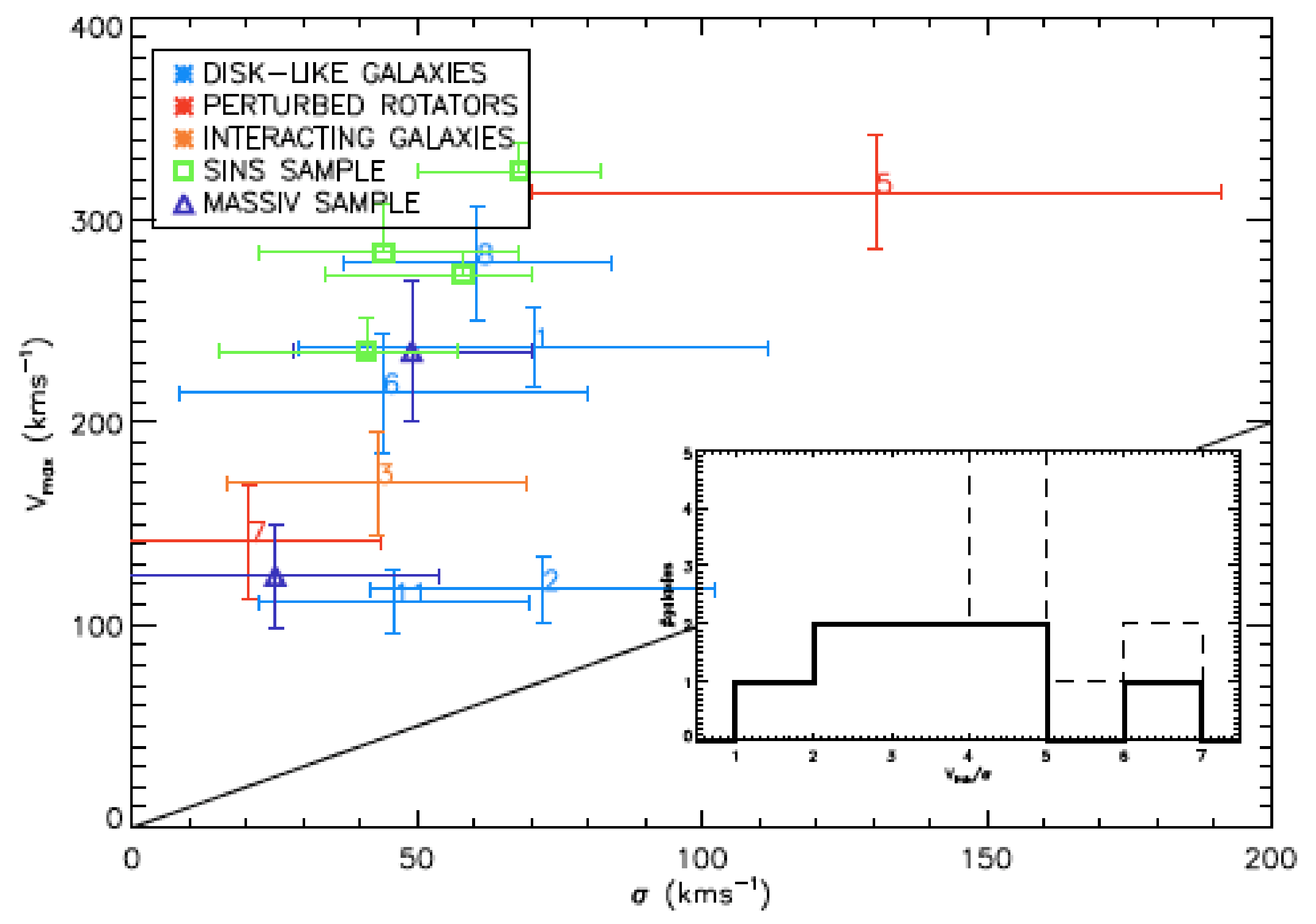
Example of a rotating galaxy from the POWIR Sample

Caveat – Hα kinematics, not of the underlying stars

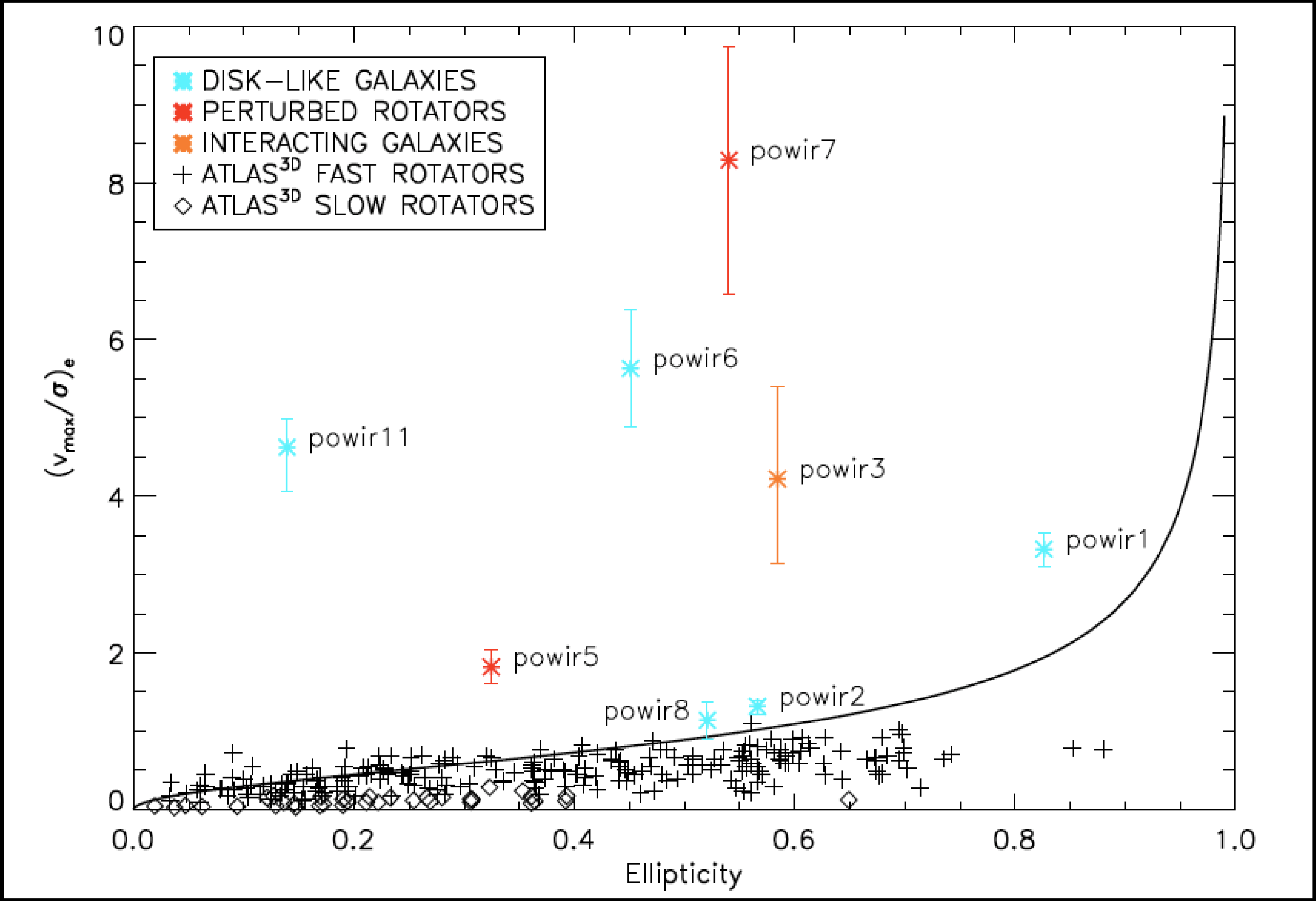


Buitrago, CJC, et al. (2013)

Compared to other, lower-mass samples, the massive sample has a lower V_{rot} at a given sigma – mass selection vs. SF selection

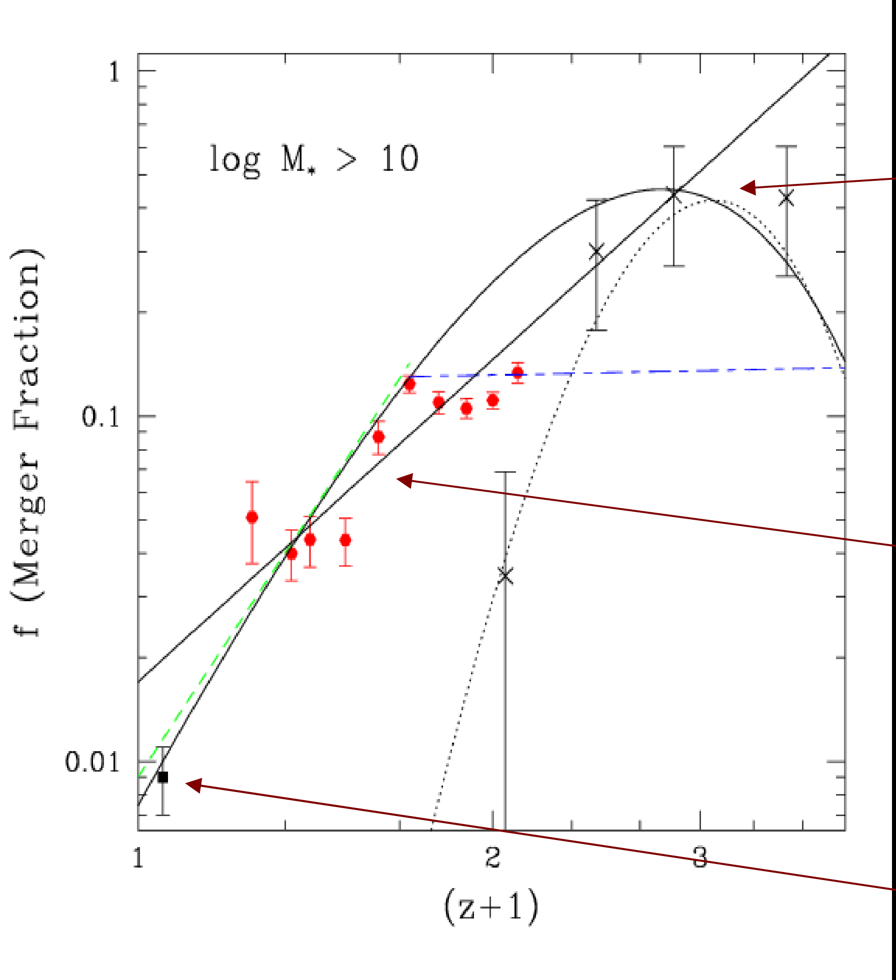


All have ‘disk-like’ kinematics – different from z=0 systems



Buitrago et al. (2013)

Do mergers form galaxies?



UDF+HDF
(z = 1 - 3)

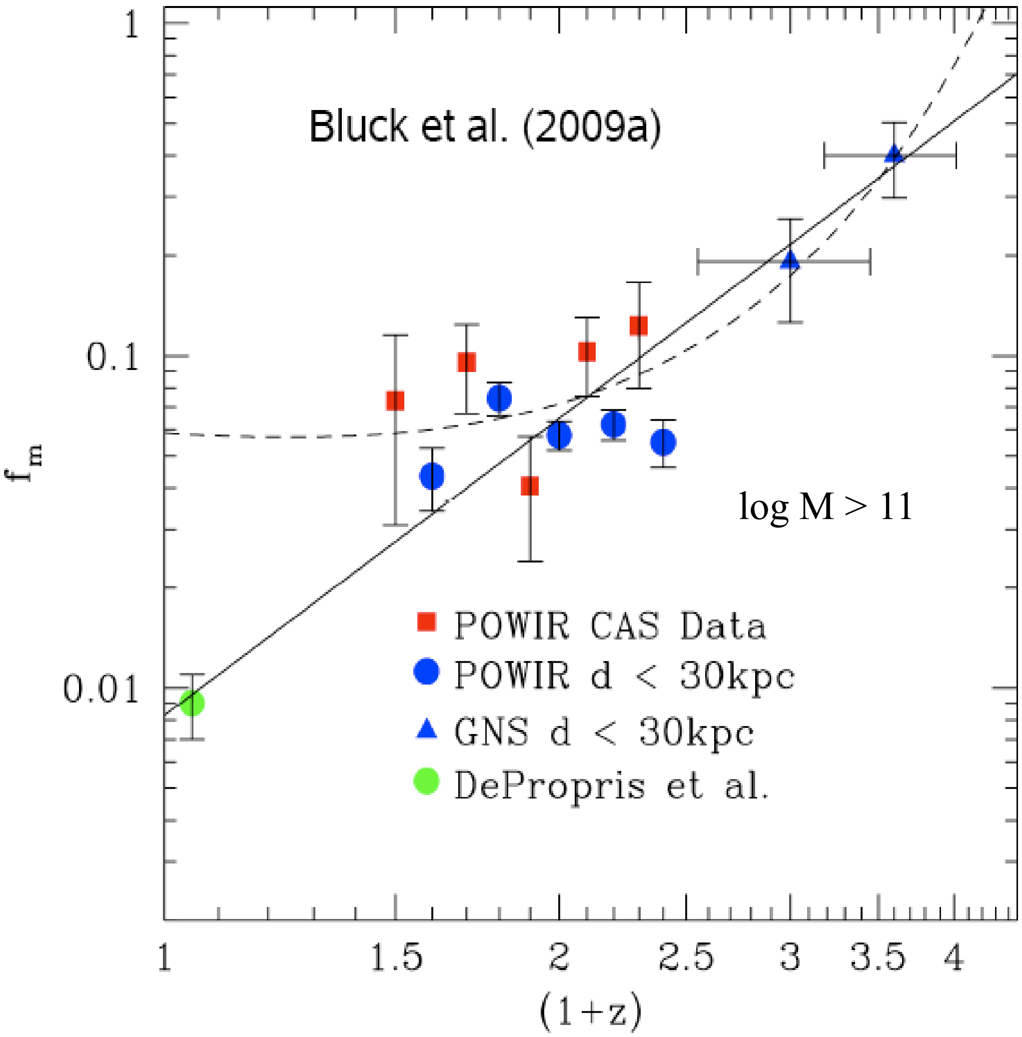
EGS+COSMOS
(z = 0.2 - 1.2)

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:

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

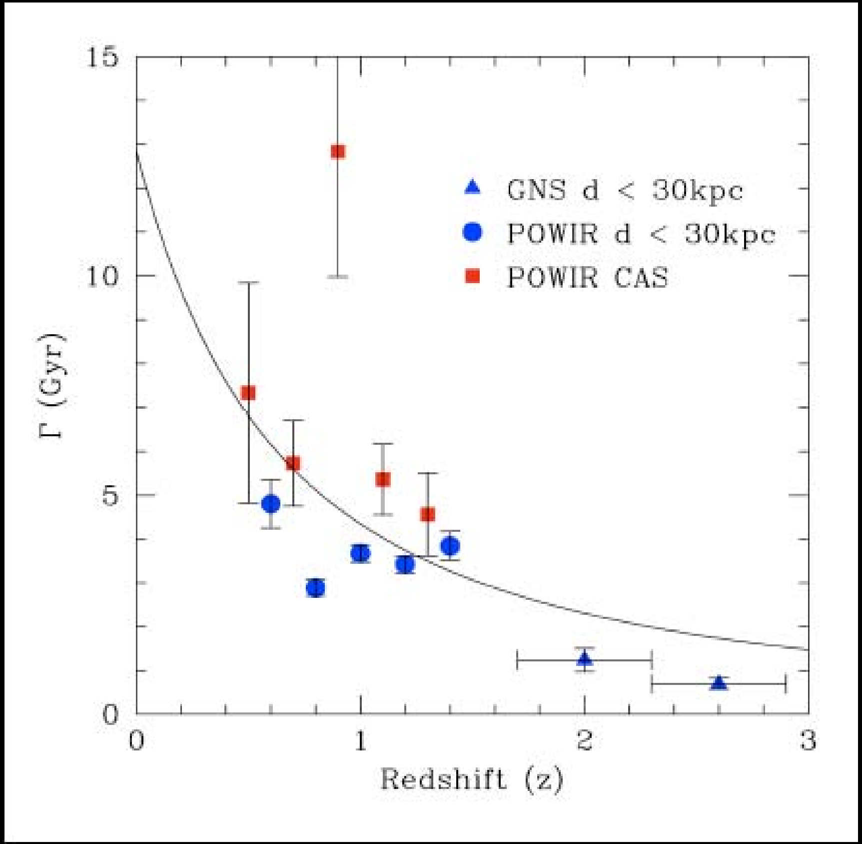
Dotted line is Press-Schetchter power low exp:

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

Number of Major Mergers

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

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

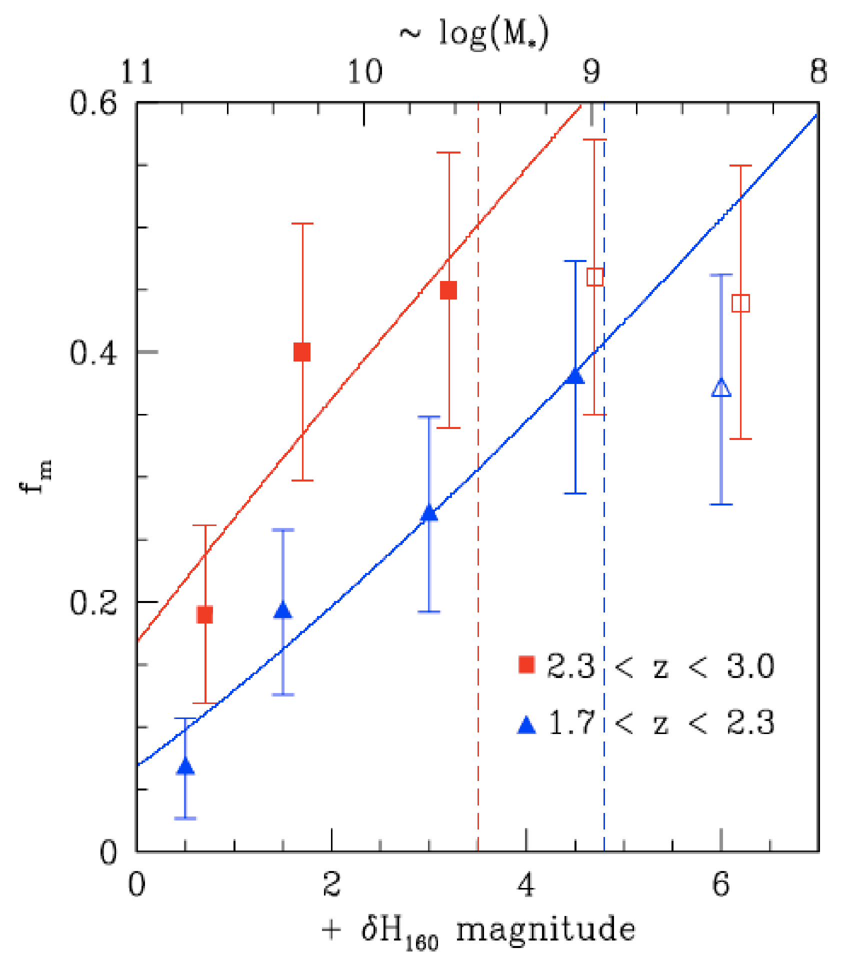


For our best fit for Γ(z), integrating over the redshift range of our galaxies we obtained:

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

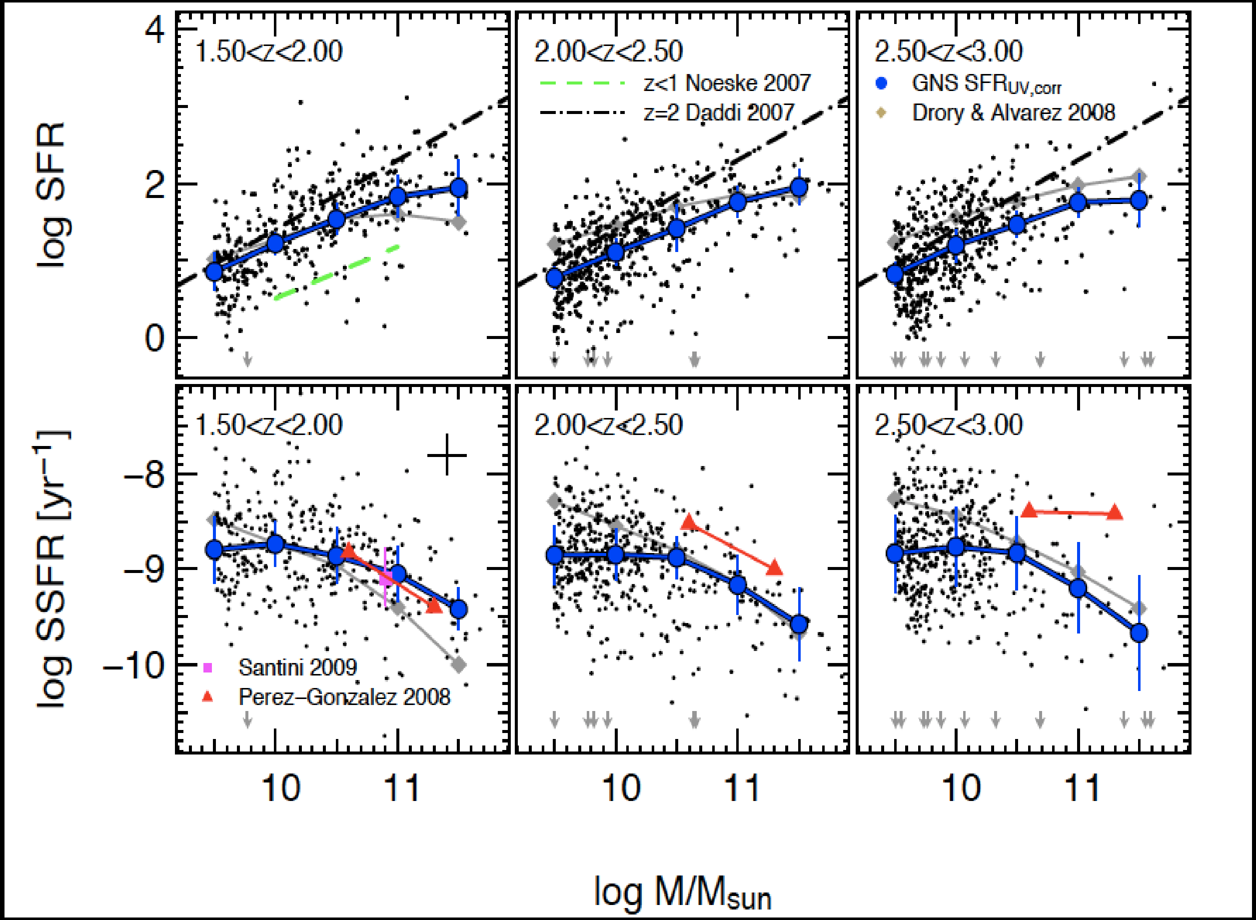
Total mass added from all mergers from 1<z<3

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

Bluck, Conselice et al. (2011)

goods nicmos survey

The star formation rates as a function of stellar mass



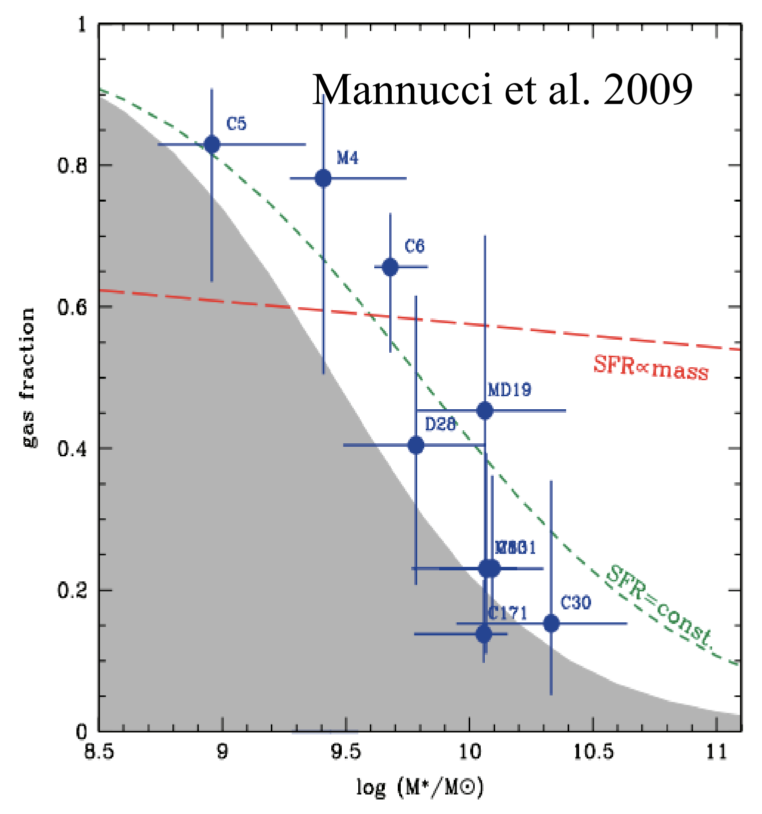
More massive galaxies have higher star formation rates at z > 1

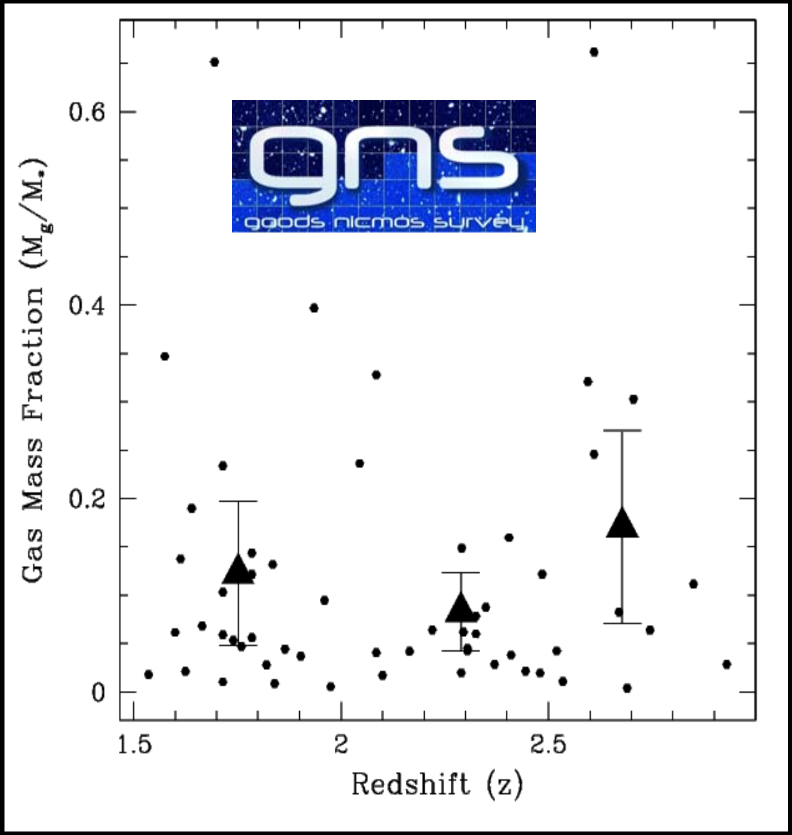
Stellar mass added by star formation

$$\int \psi \times \delta\, t / M_*(0) \;=\; 1.12 \pm 0.42$$

Bauer, CJC, et al. (2011)

Gas mass fractions


Mannucci et al. 2009



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

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

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

Gas mass evolution

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

Observed condition

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

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)

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

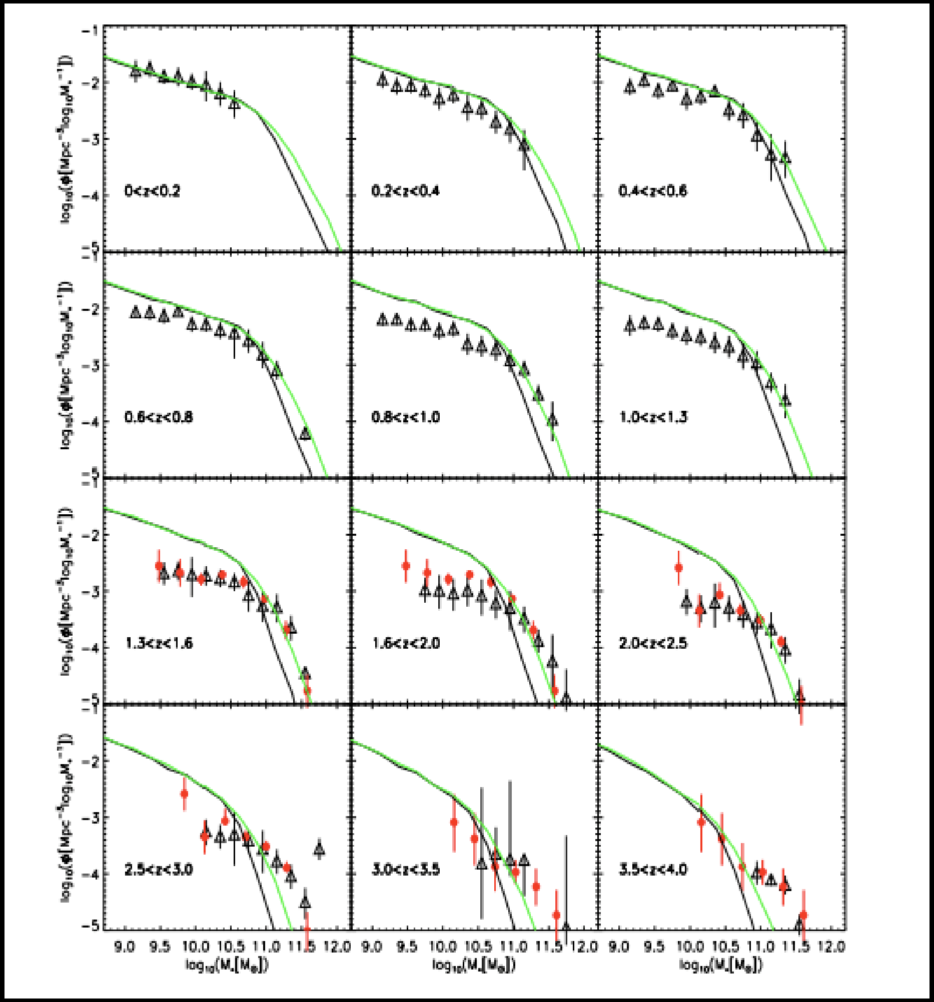
Average amount of gas accreted

Results in accretion rate of

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

Galaxy formation models in Lambda CDM

Traditional method: Make a model to predict or match observations



Need a complementary approach for understanding galaxy formation

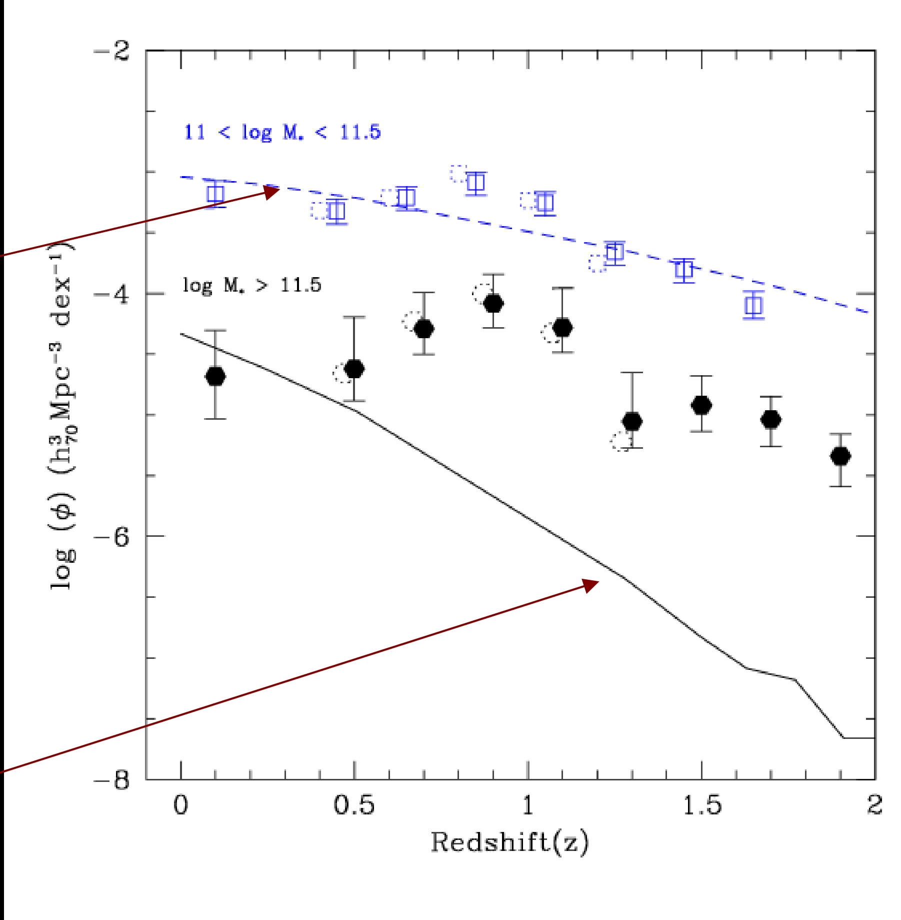
CDM does a very poor job at predicting galaxy evolution and properties of distant galaxies

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



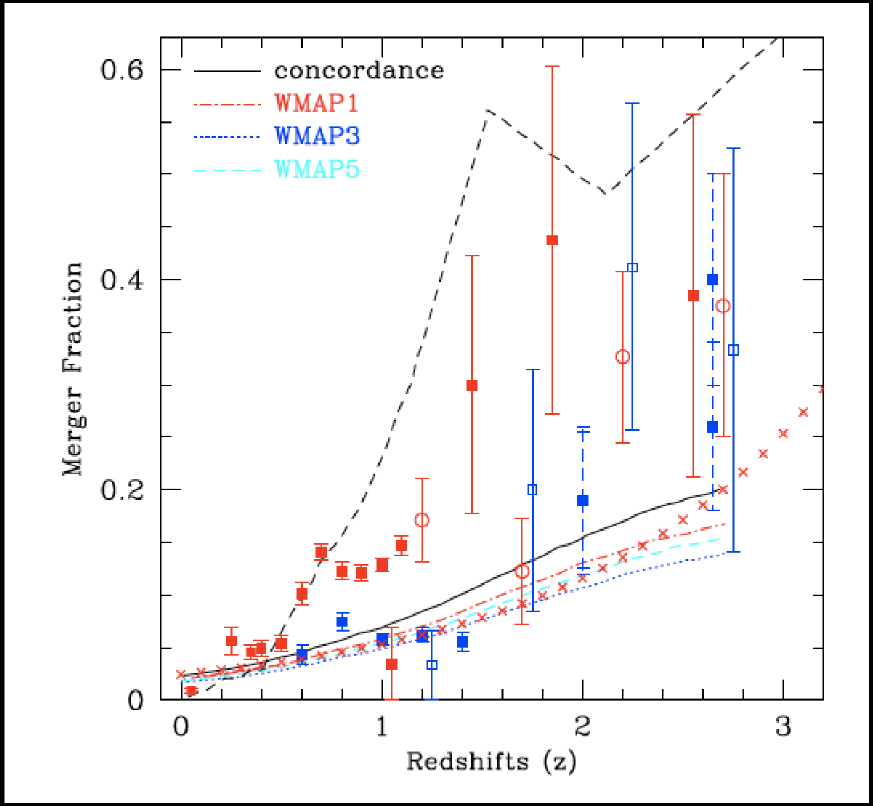
Prediction for log M > 11.5

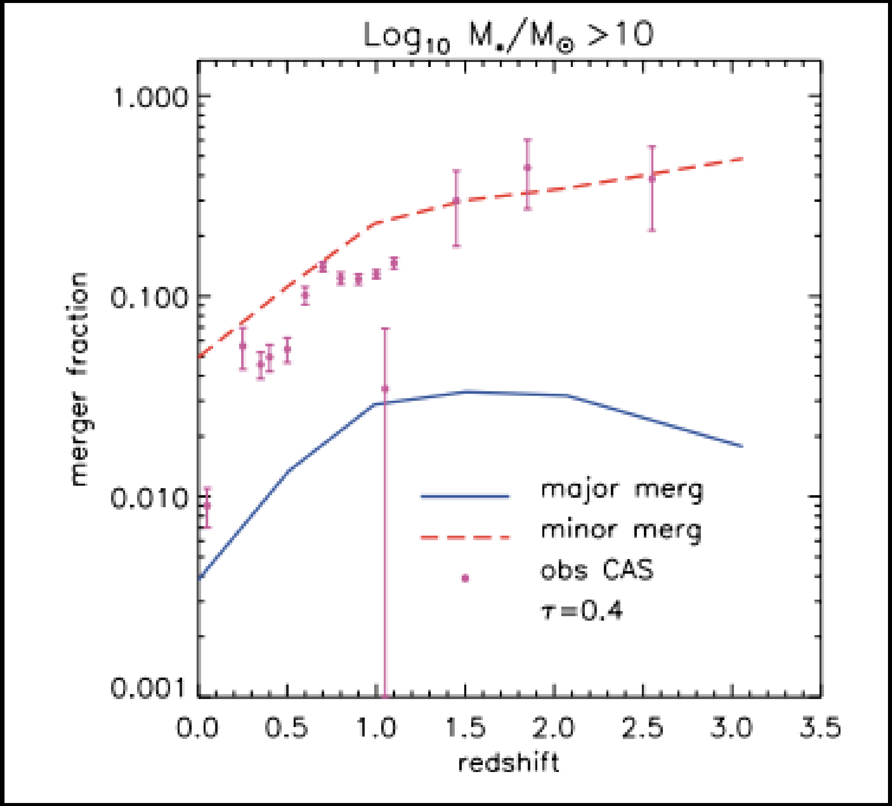
Vast under prediction in models compared to observations

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

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

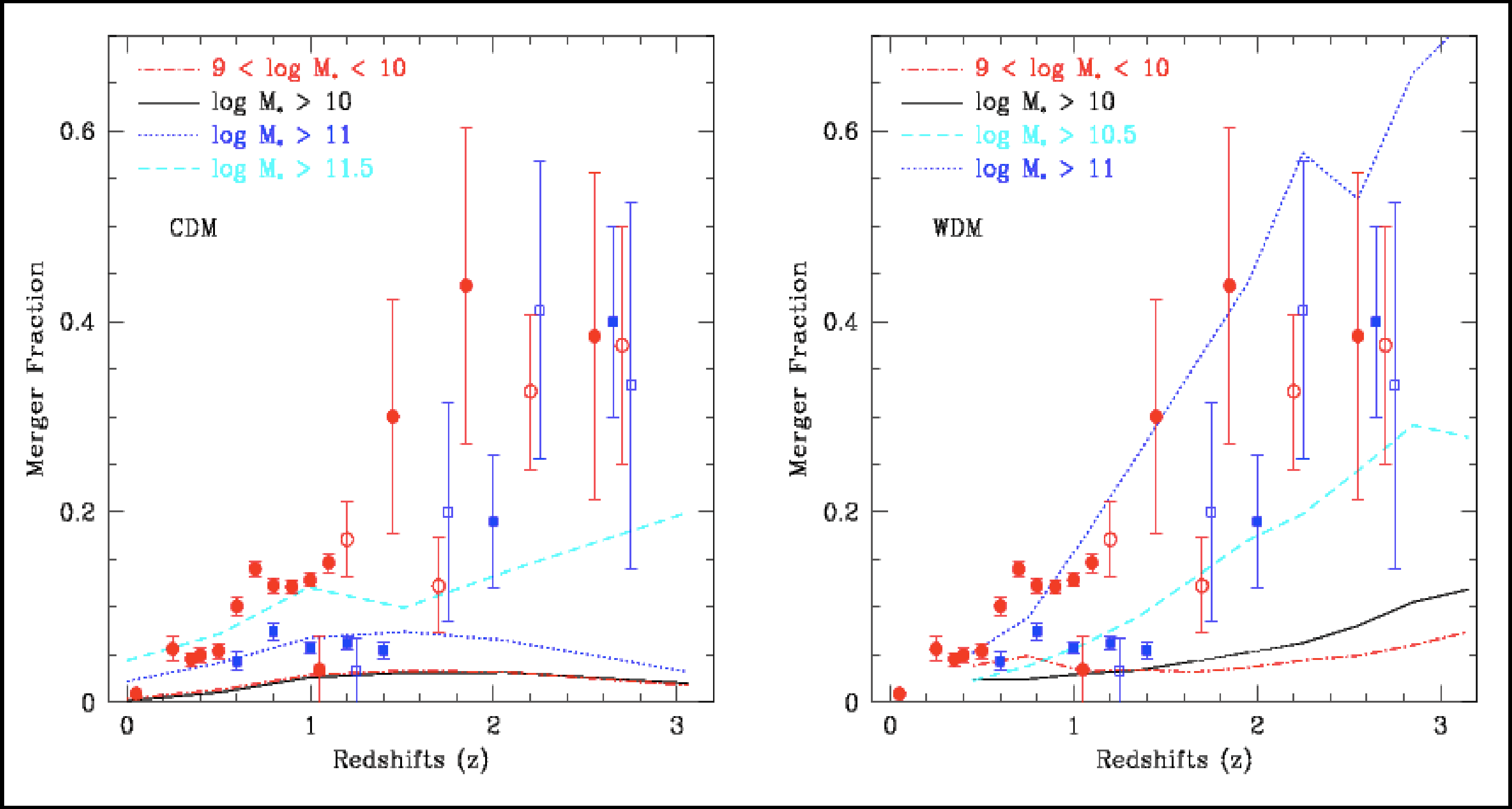
Different ΛCDM model predictions of the merger rate





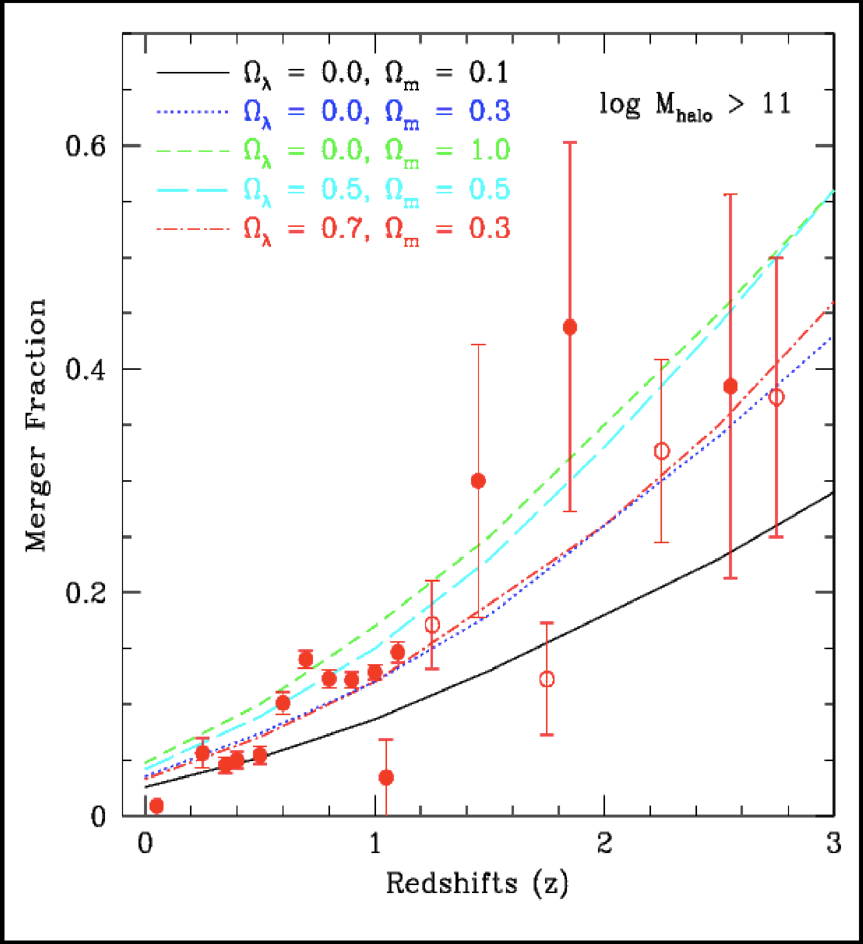
Maller et al. (2006); Bertone & Conselice (2009); Hopkins et al. (2010)

While merger history is not predicted well by CDM



Warm dark matter fits much better (e.g., Menci et al. 2012)

Better agreement between dark matter halo mergers

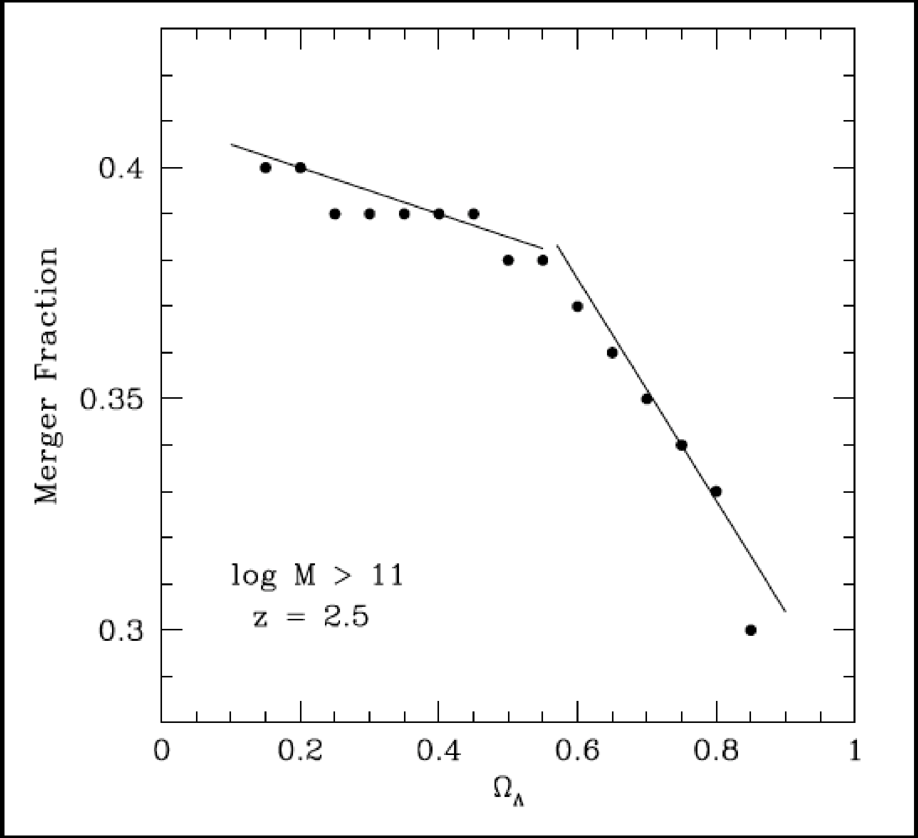


Best fitting model is standard cosmology

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?

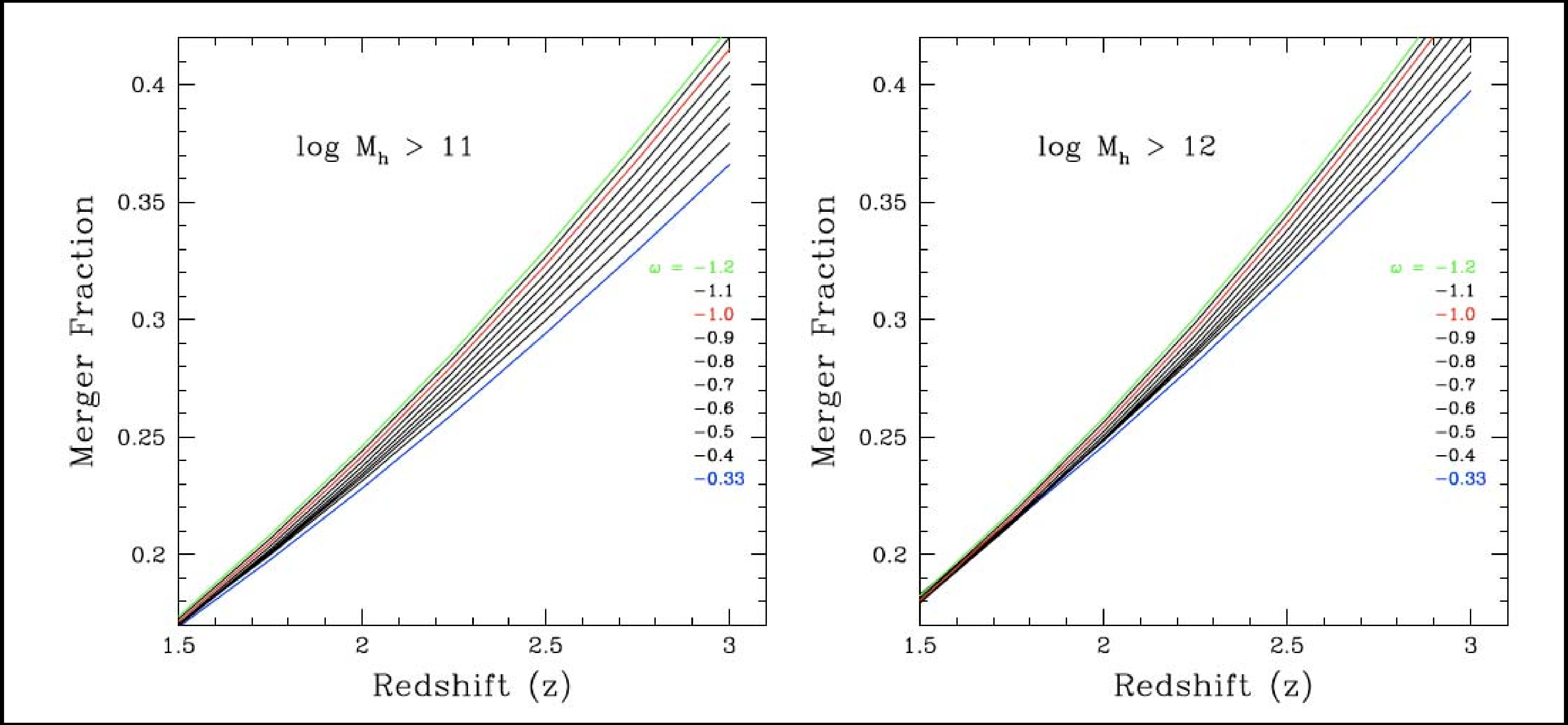


Best fit value currently gives $\Omega_\Lambda = 0.84^{+0.16}_{-0.17}$

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

Some variation with ω however, very small differences

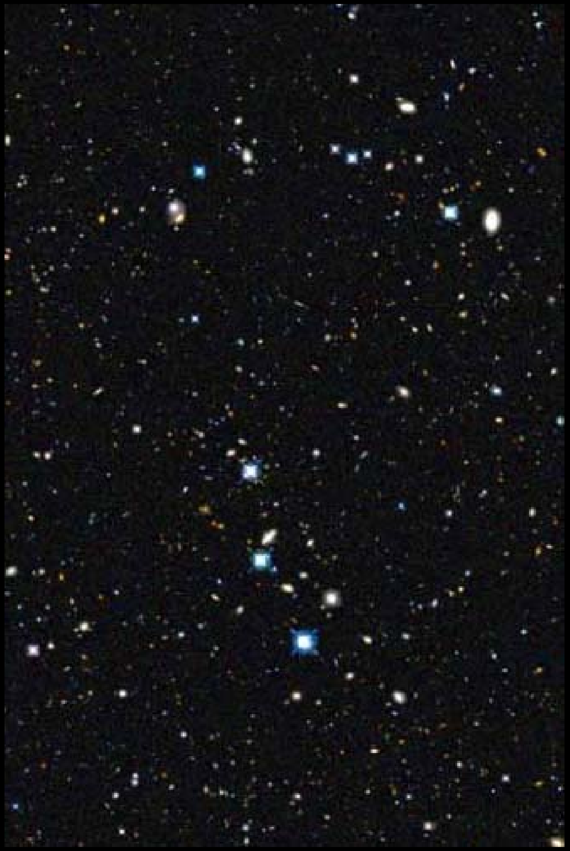


Need a survey of > 10 deg^2 with accurate mergers
to z=3 to use as a test of cosmology

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. 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.