Galaxy evolution since z = 2

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(Simple) phenomenology of an evolving population

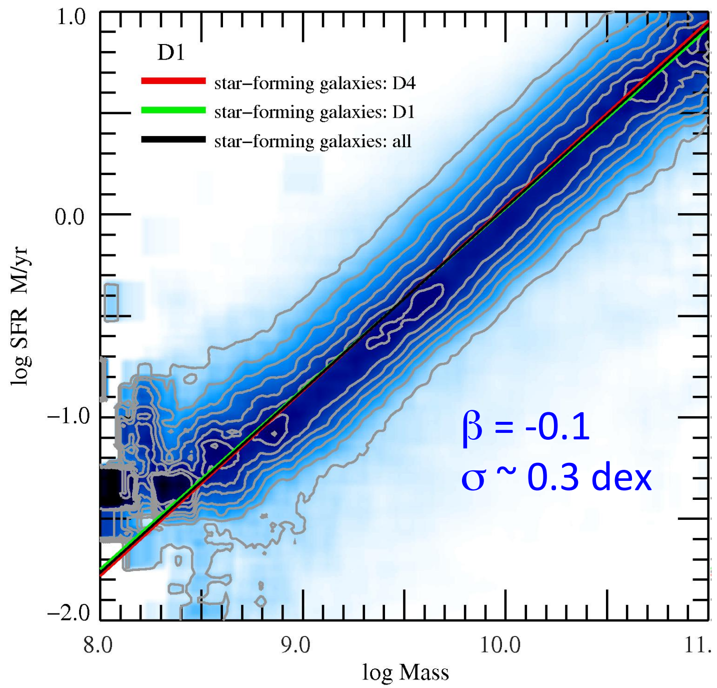
Star-formation rates and the evolution of the sSFR
Gas inflow, outflow and the steady state
(The apparent size evolution)
Environmental effects on star-formation and quenching
Quenching
A simple phenomenological model
Some clarifications

Star-formation rates in “main-sequence” SF galaxies

sSFR is a tight but weak function of mass at all epochs z ≤ 2 for <u>most star-forming</u> galaxies (β ~ -0.1)

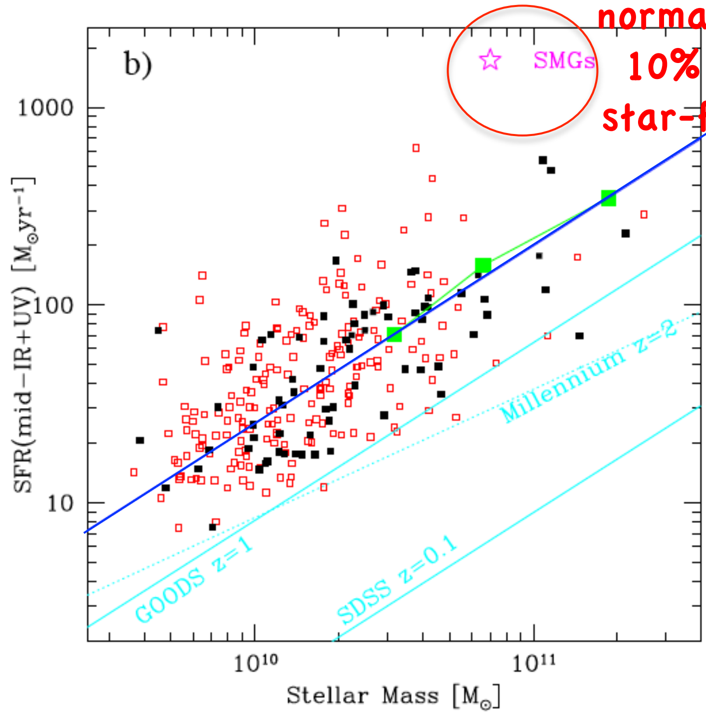
e.g. Salim et al (2007), Elbaz et al (2007) Daddi et al (2007)

$$sSFR \propto m^{\beta}$$



Hα star-formation rates in SDSS at low z, based on Brinchmann et al (2004) SDSS data

Note "ULIRGs/ SMGs" lie above normal relation: 10% of total star-formation?



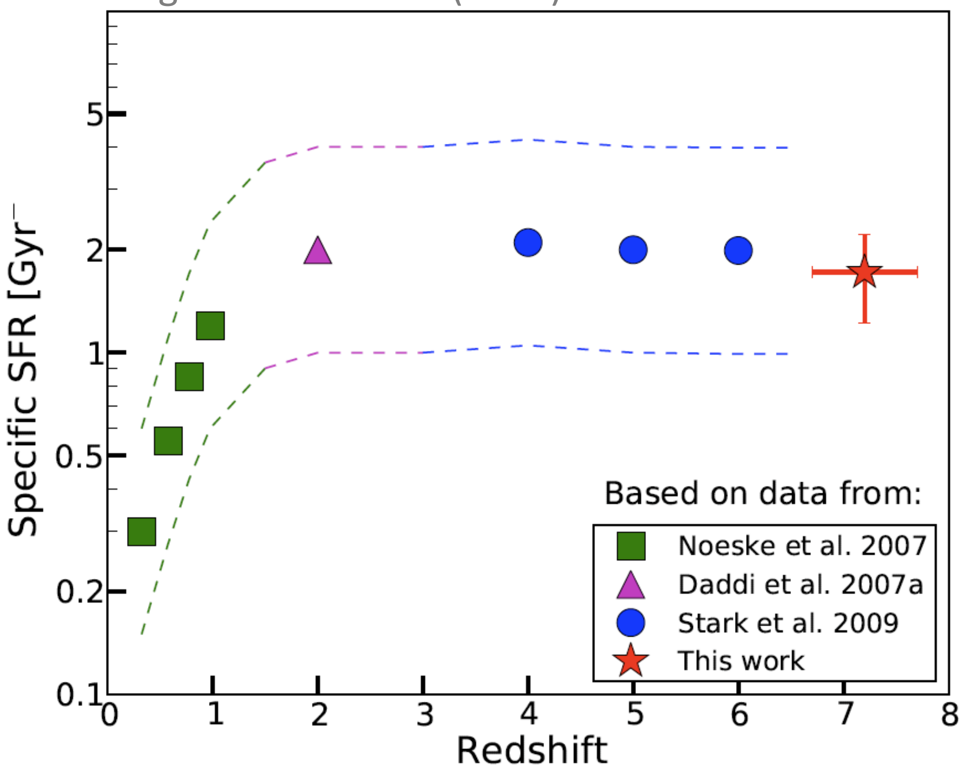
β = -0.05

z ~ 2 from Daddi et al (2007)

sSFR evolves strongly with epoch – factor of 20 to z ~ 2

e.g. Noeske et al 2007, Elbaz et al 2007, Daddi et al 2007, Damen et al 2009, Gonzalez et al 2009, Panella et al 2009

e.g. Gonzalez et al (2009)



$$sSFR(m,t) = 2.0 \left(\frac{t}{3.5\,\mathrm{Gyr}}\right)^{-2.2} \left(\frac{m}{10^{10}\,\mathrm{M_O}}\right)^{\beta} \mathrm{Gyr}^{-1}$$

$$= \text{constant} \quad \text{at } z \geq 2$$

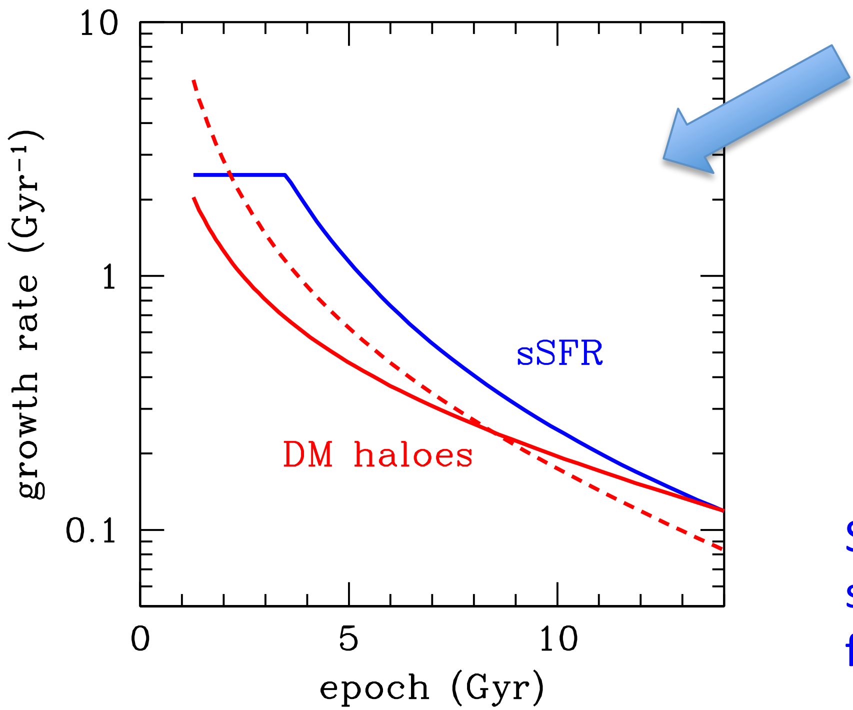
If not quenched, this implies 0.8 dex mass growth since z =1 , 2 dex since z = 2

What causes the evolution in the sSFR ?

Similarities in specific mass increase rate of DM haloes and specific star-formation rate

- Similar $m^{-1}dm/dt$ as $f(t)$
- Both very weak dependence on mass

$\beta_{DM} \sim +0.05\text{-}0.1$ c.f. $\beta_{SFR} \sim -0.1$



e.g. Faucher-Giguere, Keres, Ma (2011)
Tillson, Miller, Devriendt (2011)

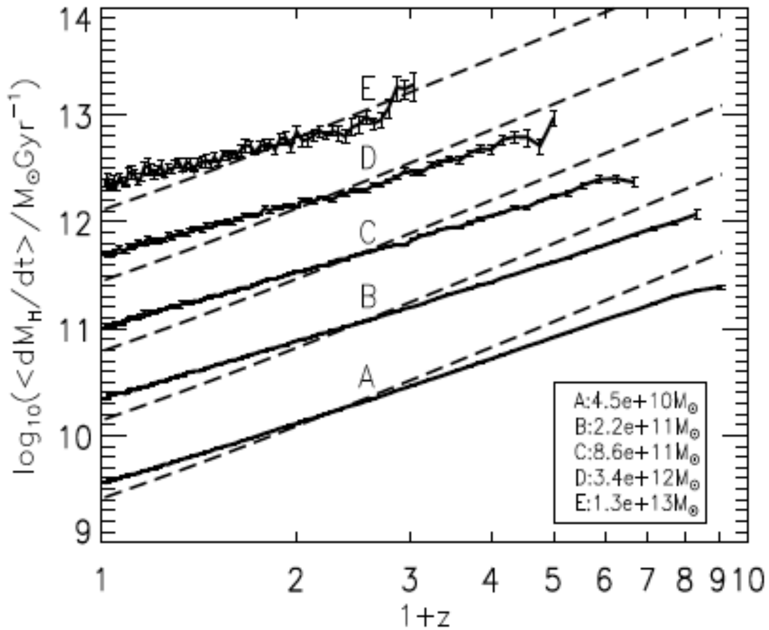
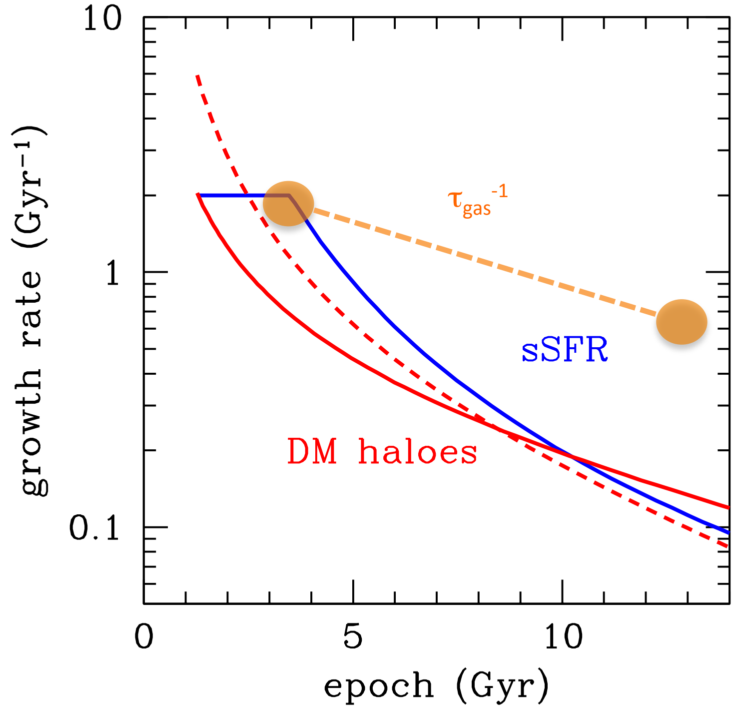


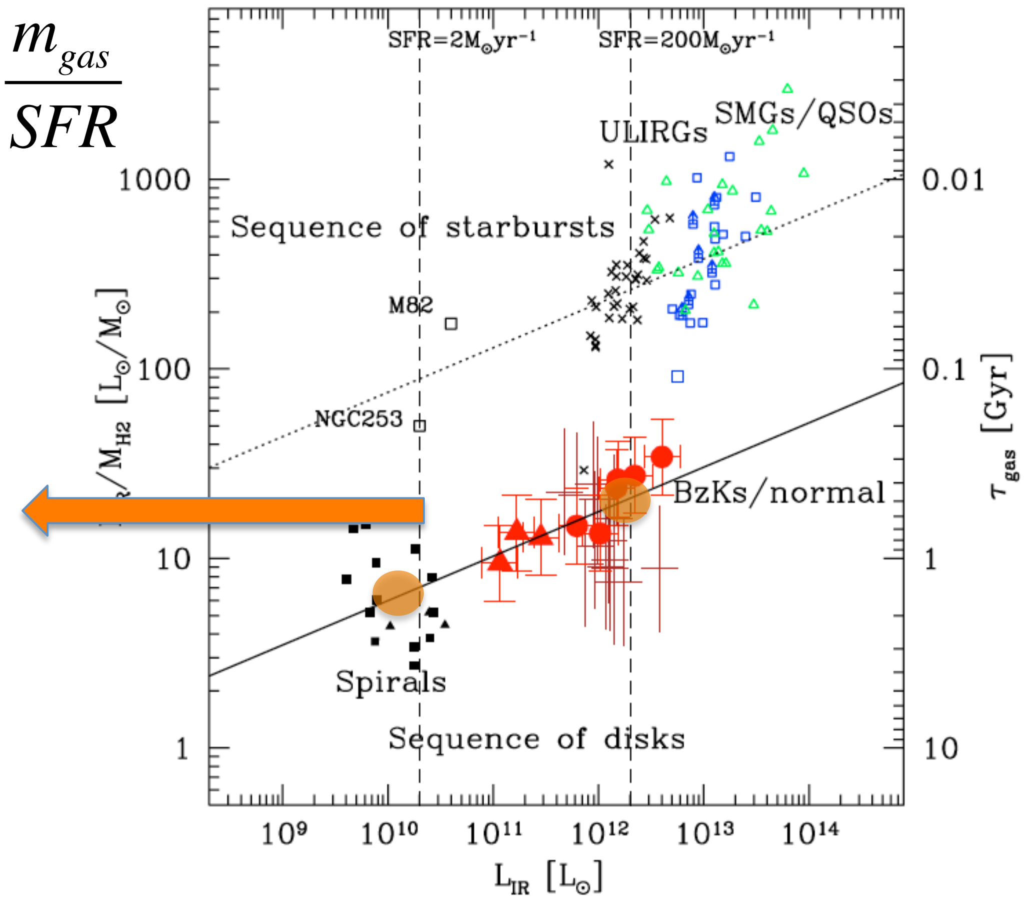
Figure 3. The average halo accretion rate as a function of redshift and halo mass. The accretion values onto the AHOP halos are shown as the solid lines for each of the five $\langle M_H \rangle$ bins, with the errors corresponding to the 1σ errors on the mean accretion rate. The EPS curves using equation (1) are shown as the dashed lines for each mass bin.

SFR evolution in star-forming galaxies is simply driven by accretion of ~ constant fraction of incoming baryonic material ?

Why high redshift galaxies must be gas rich

$$R_{gas} = \frac{m_{gas}}{m_{star}} = sSFR \times \tau_{gas} \qquad \tau_{gas} = \frac{m_{gas}}{SFR}$$





Daddi et al (2010), Genzel et al (2010)

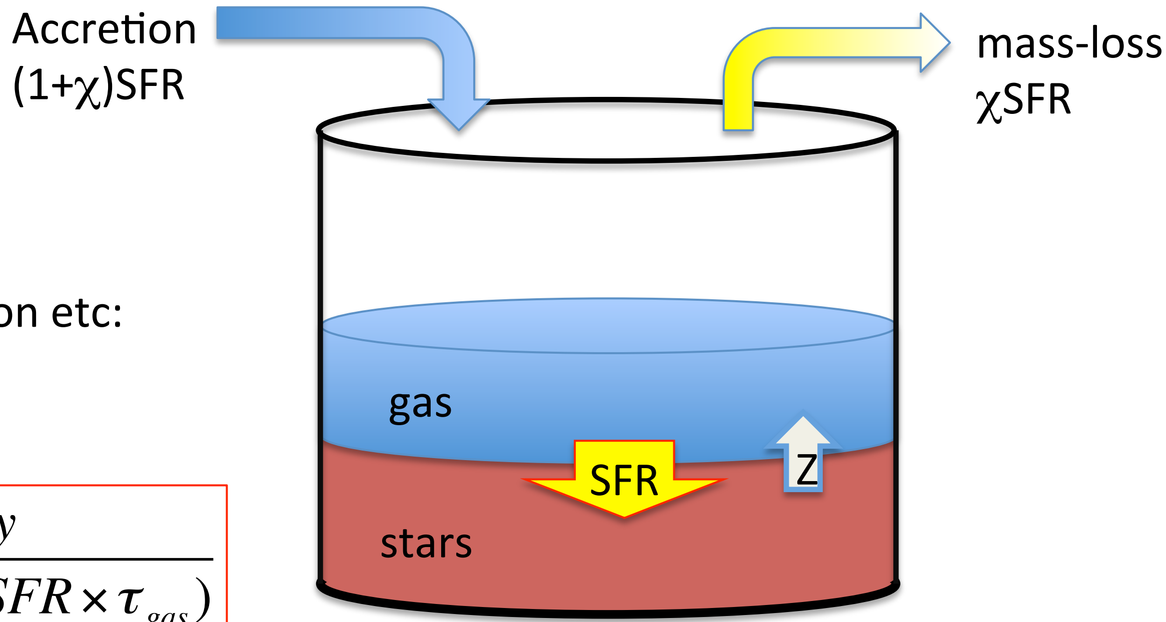
Timescale for depletion of gas < the mass increase timescales at all epochs, so there will be quasi-steady-state evolution

Quasi-steady state evolution ("bath tub model")

Bouche et al (2010), Dave et al (2011)

Steady-state balance between inflow, SFR and outflow sets gas content

$$R_{gas} = \frac{m_{gas}}{m_{star}} = sSFR \times \tau_{gas}$$



Implications for chemical evolution etc:
Pippino et al (in prep.)

$$Z_{gas} = \frac{y}{(1 + \chi + R_{gas})} = \frac{y}{(1 + \chi + sSFR \times \tau_{gas})}$$

Ubiquitous winds: mass loss ~ SFR

- Blue-shifted MgII absorption in spectra "down the barrel"

  e.g. Weiner et al (2009)… Rubin et al (2010).

Weiner et al (2009) – stacked DEEP spectra

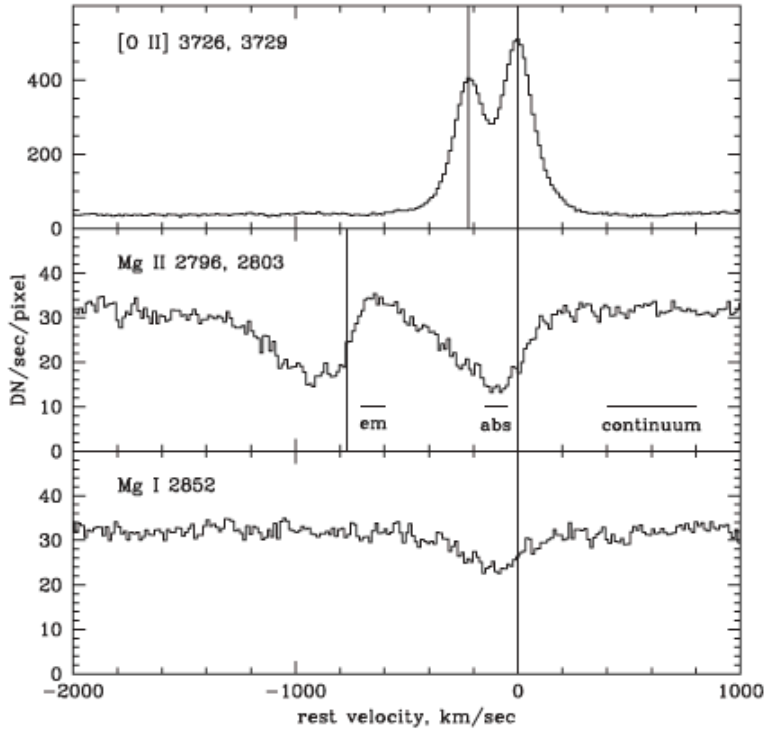


Figure 3. [O II] 3726.0, 3728.8, Mg II 2795.5, 2802.7, and Mg I 2852.1 Å lines in the co-added spectrum of 1406 galaxies, relative to zero velocity as defined by the redshift derived from [O II]. The [O II] doublet lines are at their nominal systemic velocities, but the Mg I and both Mg II lines show blueshifted and asymmetric absorption profiles. The horizontal bars in the middle panel show the extent of the windows used in Section 3.4 to measure absorption and excess emission in individual spectra.

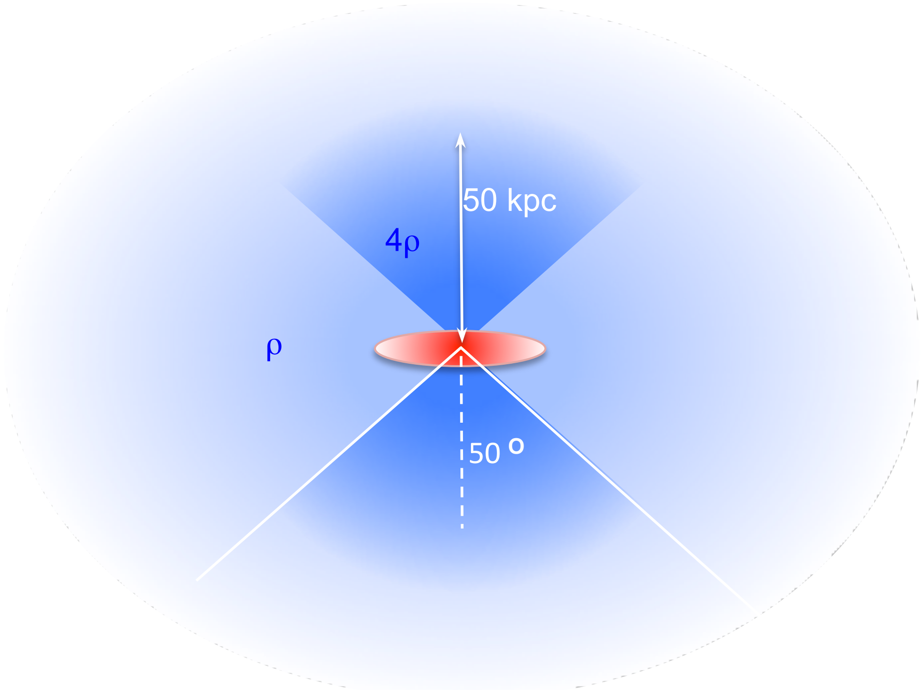
Ubiquitous winds: mass loss ~ SFR

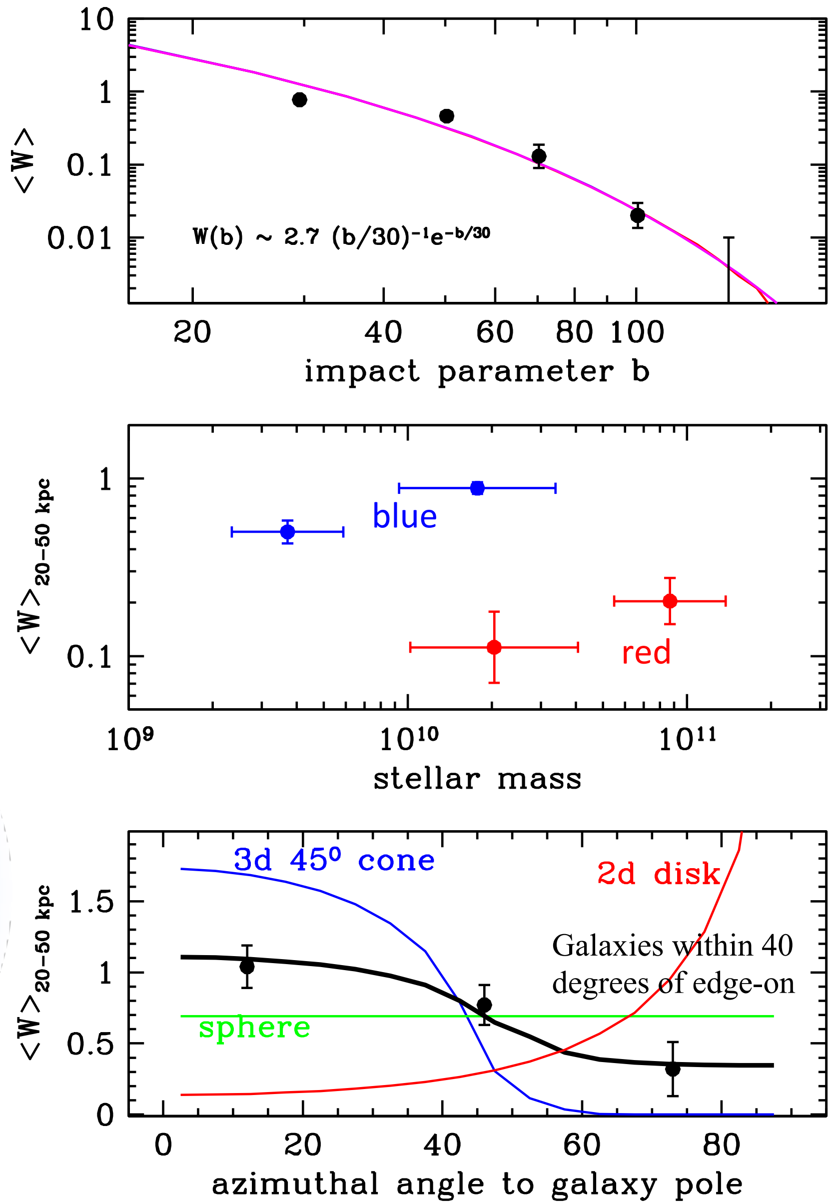
- Cause of extended MgII absorption haloes at b < 50 kpc ?

  Bordoloi et al (2011)

  (but see also Kacprzak et al 2010)

Stacked spectra of ~ 5200 zCOSMOS z > 1.2 galaxies lying behind 4000 0.5 < z < 0.9 galaxies with b < 200 kpc

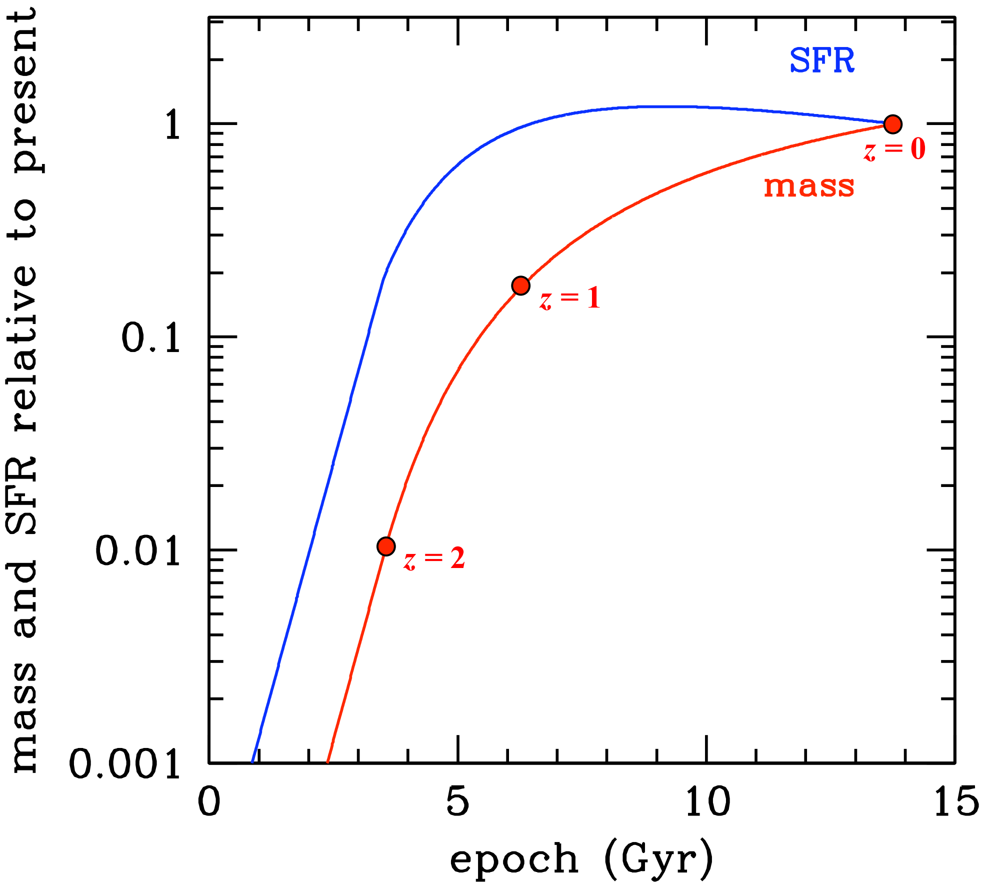




The growth of stellar mass through star-formation

$$sSFR(m,t) = 2.0 \left(\frac{t}{3.5\,\mathrm{Gyr}}\right)^{-2.2} \left(\frac{m}{10^{10}\,\mathrm{M_O}}\right)^{\beta} \mathrm{Gyr}^{-1}$$

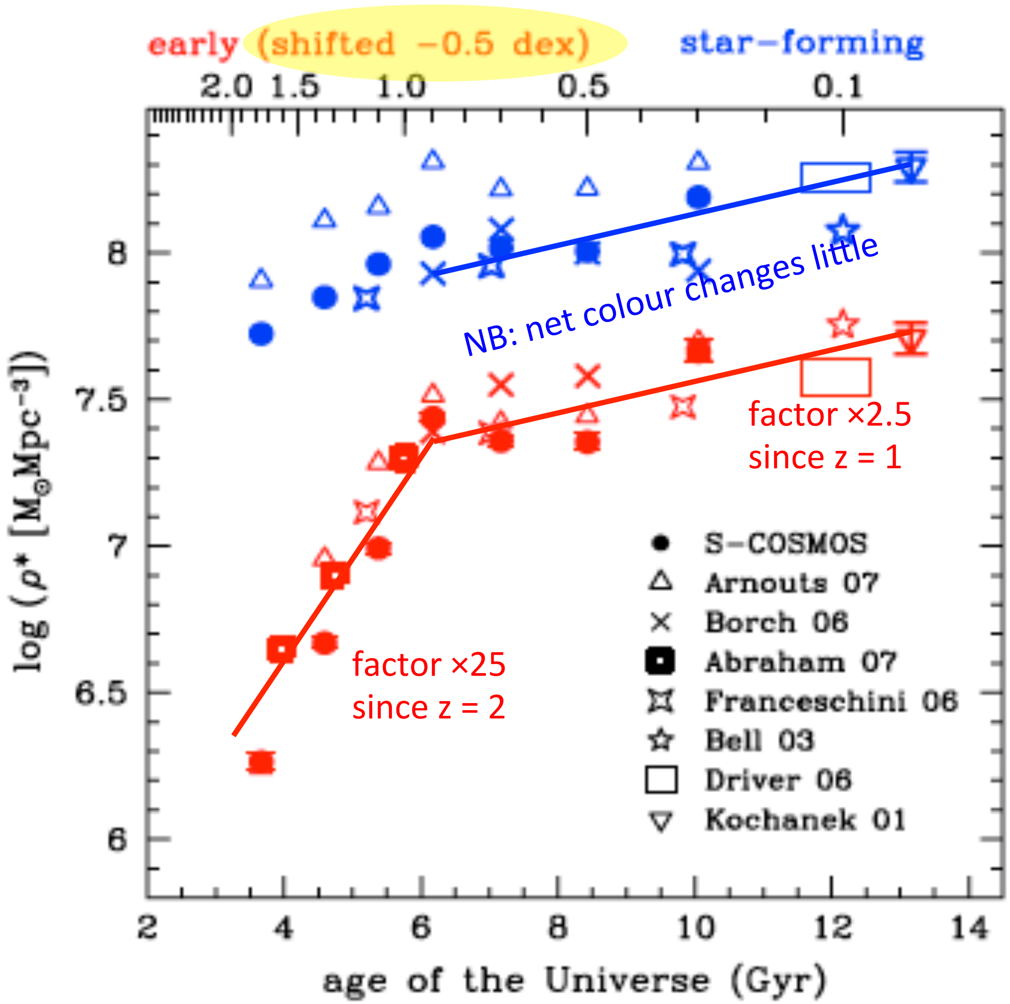
$$= \text{constant at } z \geq 2$$



Integrating the *sSFR(t)* relation gives the growth in stellar mass of a given star-forming galaxy.

- 0.8 dex since z ~ 1
- 2.0 dex since z ~ 2

Large creation of stellar mass since z ~ 2

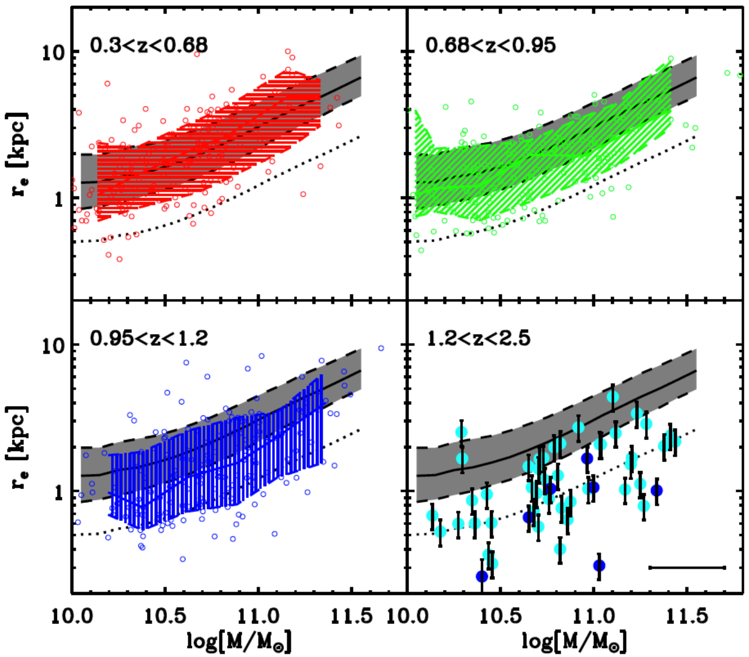


Coupled with absence in change of M* (see later) implies galaxies at given stellar mass at one epoch are not the same as at another epoch.

The galaxy population is a dynamically evolving one tracked with continuity equation(s)

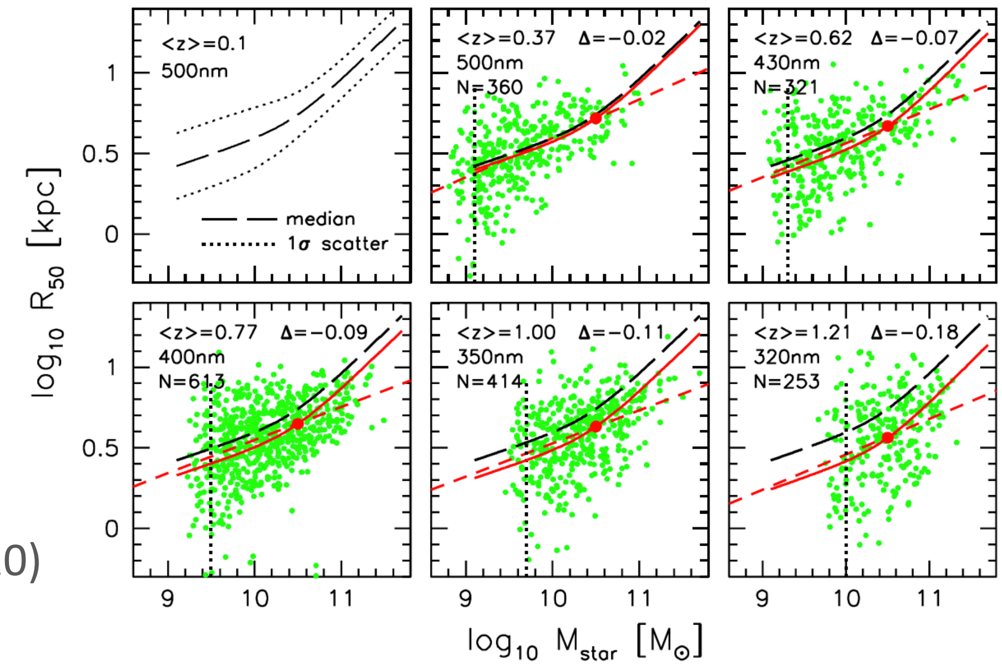
The size evolution of ellipticals and disks

Daddi et al. 2005; Trujillo et al. 2007; Toft et al. 2007; Zirm et al. 2007; van Dokkum et al. 2008; Buitrago et al. 2008; Cimatti et al. 2008



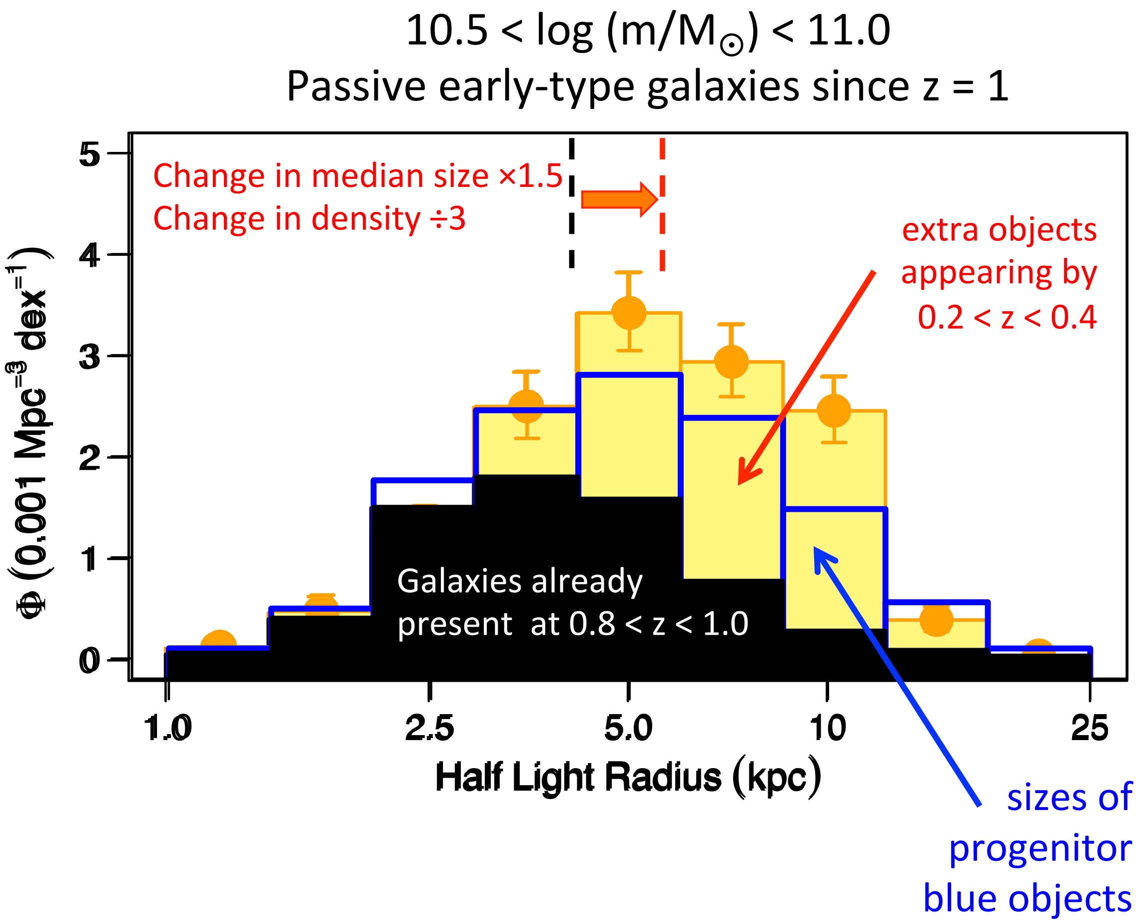
Passive early-type galaxies are smaller at high redshifts (from Cassata et al 2011)

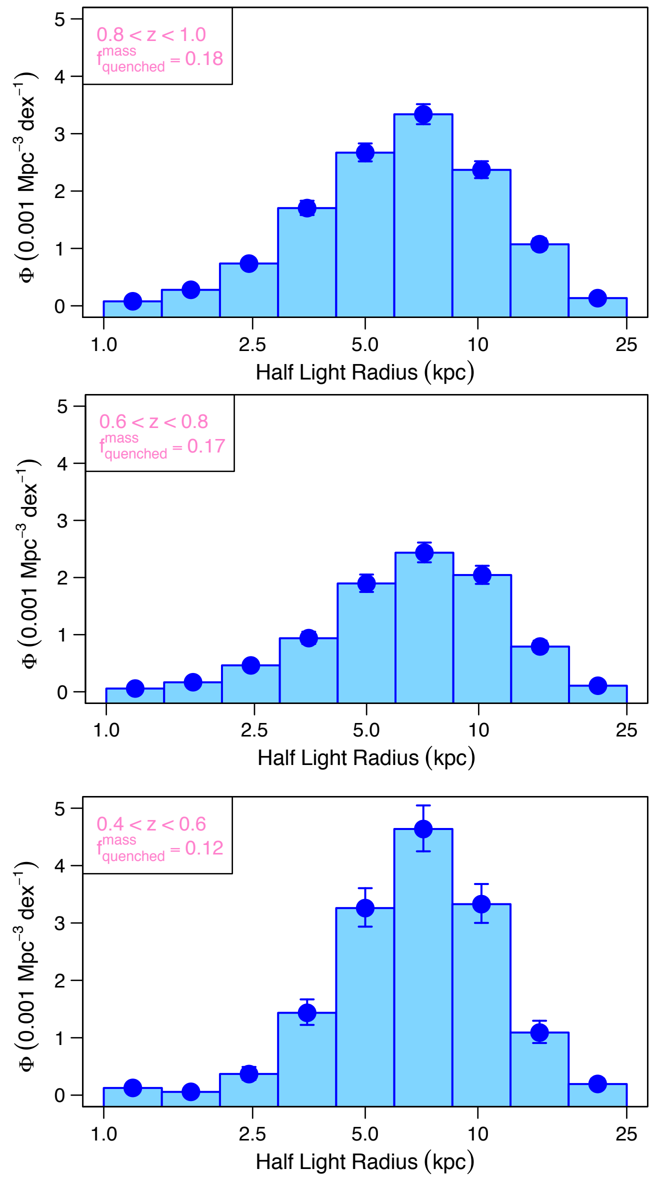
Also for disks (from Dutton 2010)



The size evolution of ellipticals

Carollo et al (2011)

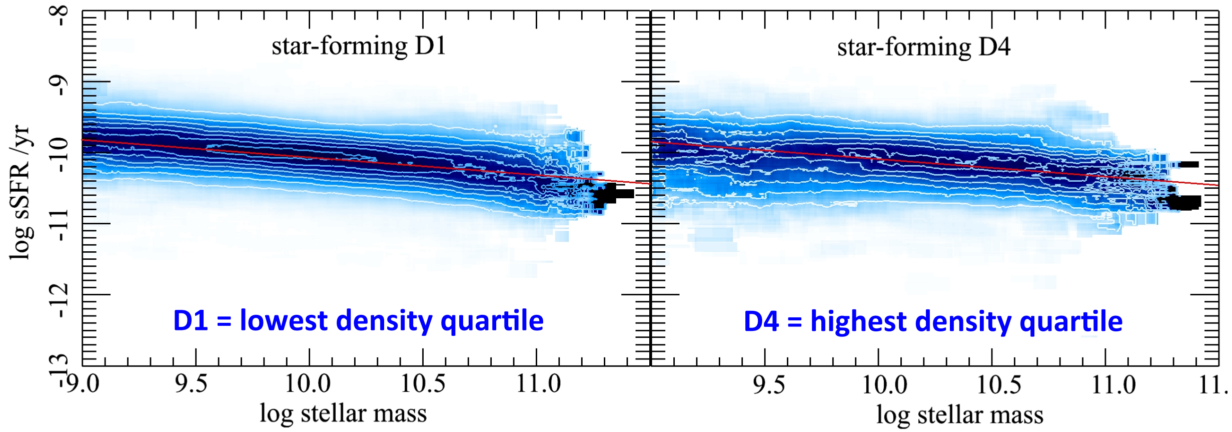


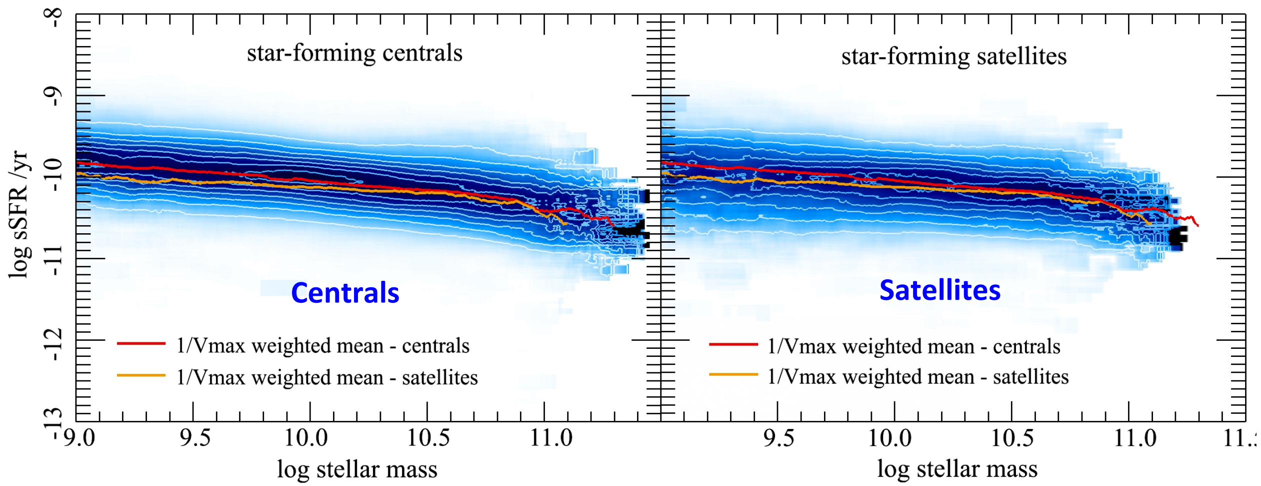


sSFR of <u>star-forming</u> galaxies does not depend on environment** at z ~ 0

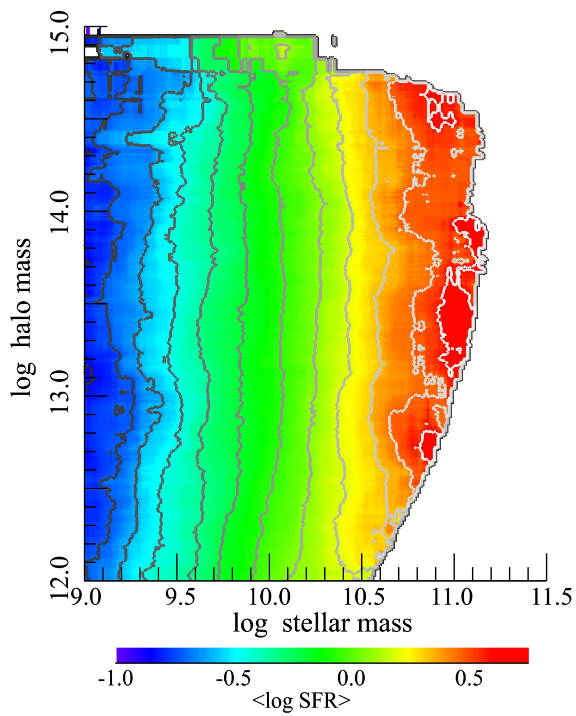
Peng et al (2010, 2011)

** either overdensity, central/satellite, or dark matter mass of halo



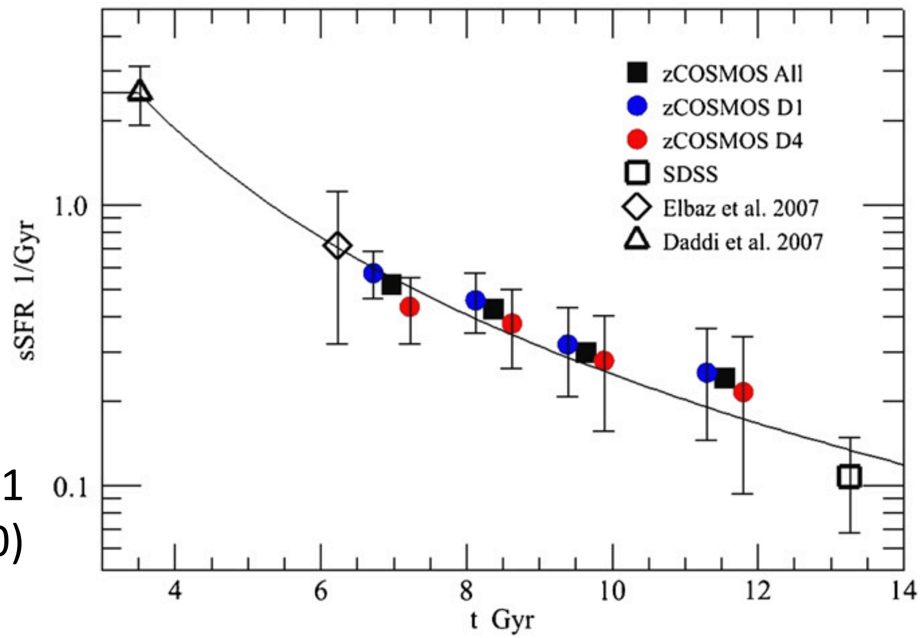


Mean <log SFR> of satellites as f(DM halo mass)



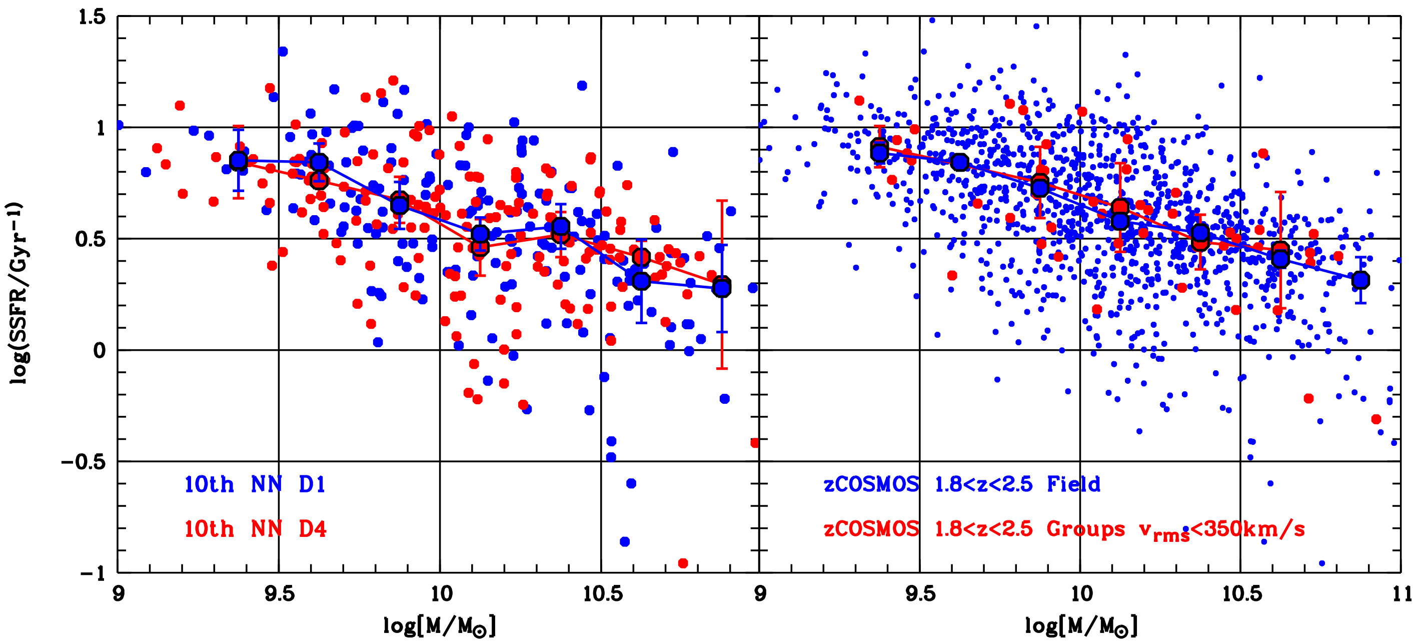
At higher z?

Jury still out:
no compelling evidence for sSFR-density relation

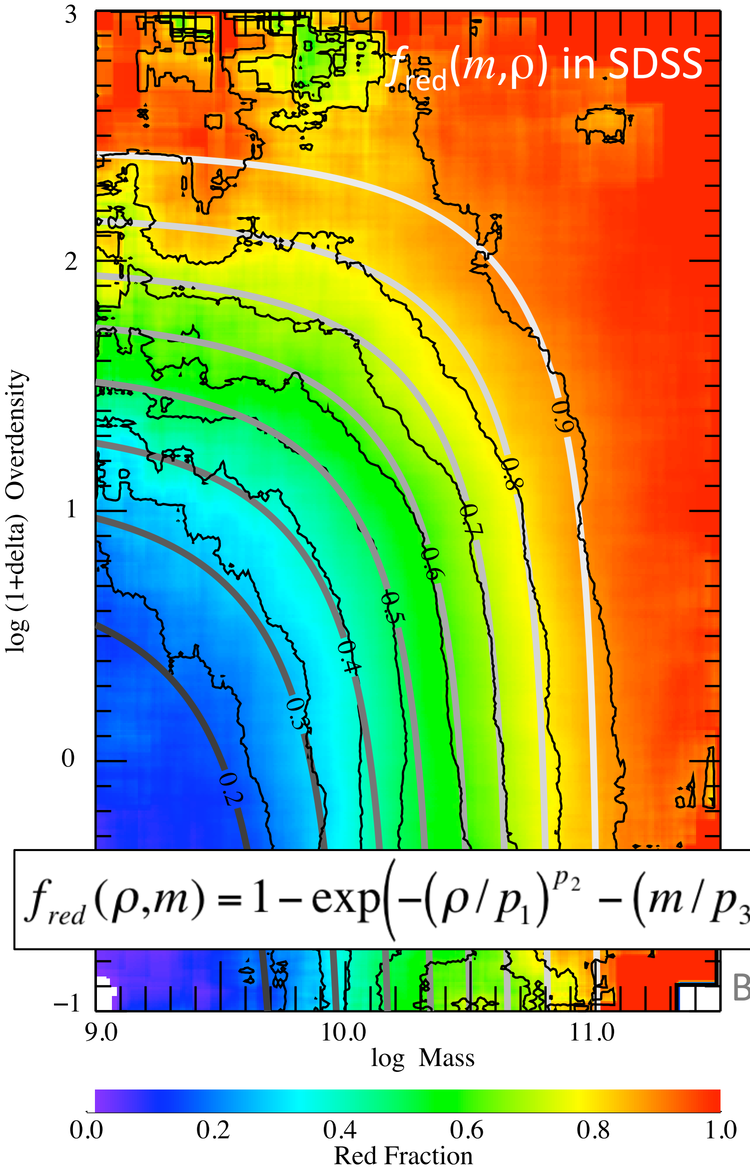


zCOSMOS-bright to z ~ 1
(Peng et al 2010)

zCOSMOS-deep ~ 4000 galaxies 1.4 < z < 3.0 (Maier et al 2011, in prep see poster)



The fraction of (red) passive galaxies depends strongly on stellar mass and environment in SDSS <u>but are separable</u> (Peng et al 2010)



$$f_{red}(\rho,m) = 1 - \exp\left(-(\rho/p_1)^{p_2} - (m/p_3)^{p_4}\right)$$

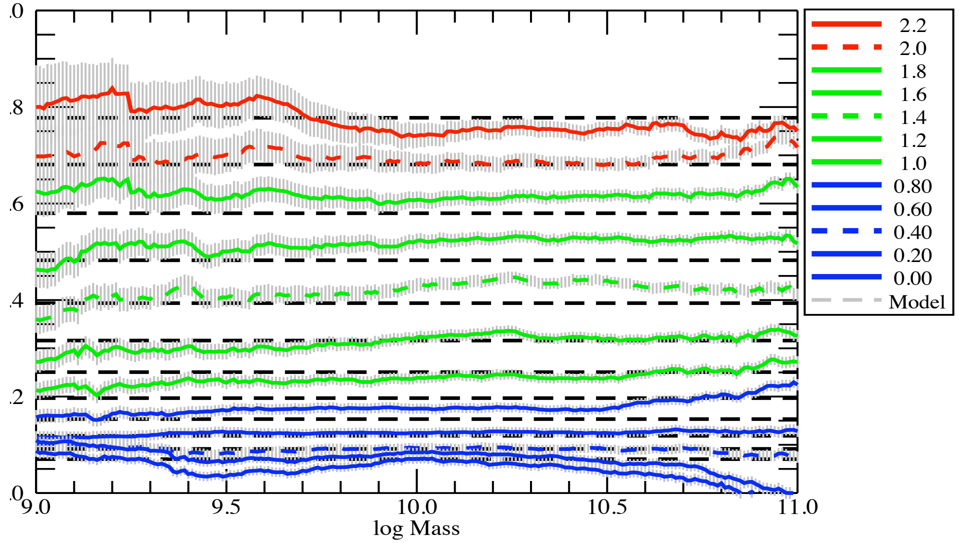
Baldry et al 2006

"Relative environment-quenching efficiency"

$$\varepsilon_\rho(\rho,\rho_0,m) = \frac{f_{red}(\rho,m) - f_{red}(\rho_0,m)}{f_{blue}(\rho_0,m)}$$

"Relative mass-quenching efficiency"

$$\varepsilon_m(m,m_0,\rho) = \frac{f_{red}(m,\rho) - f_{red}(m_0,\rho)}{f_{blue}(m_0,\rho)}$$



ε_ρ as $f(m)$

The fraction of (red) passive galaxies depends strongly on stellar mass and environment in SDSS but are separable (Peng et al 2010)

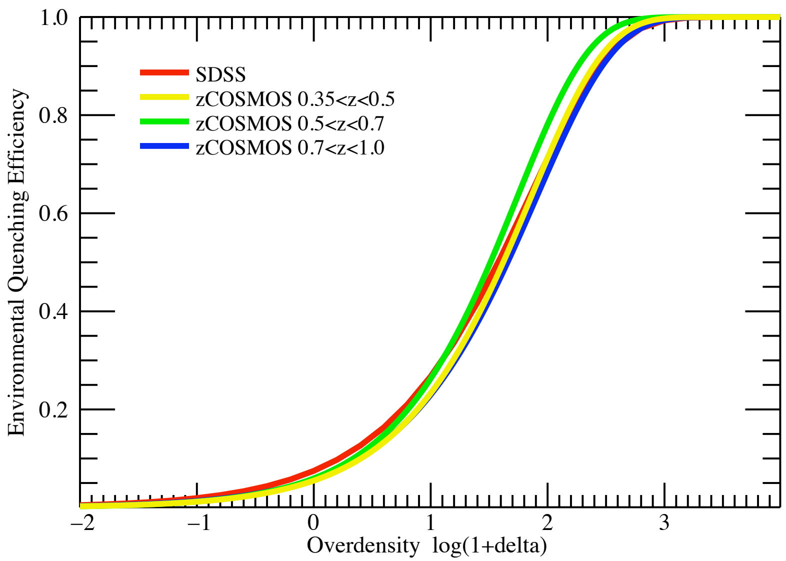
This differential effect of the environment is unchanged to z ~ 1. Environmental differentiation with time is caused by sampling wider range of densities

"Relative environment-quenching efficiency"

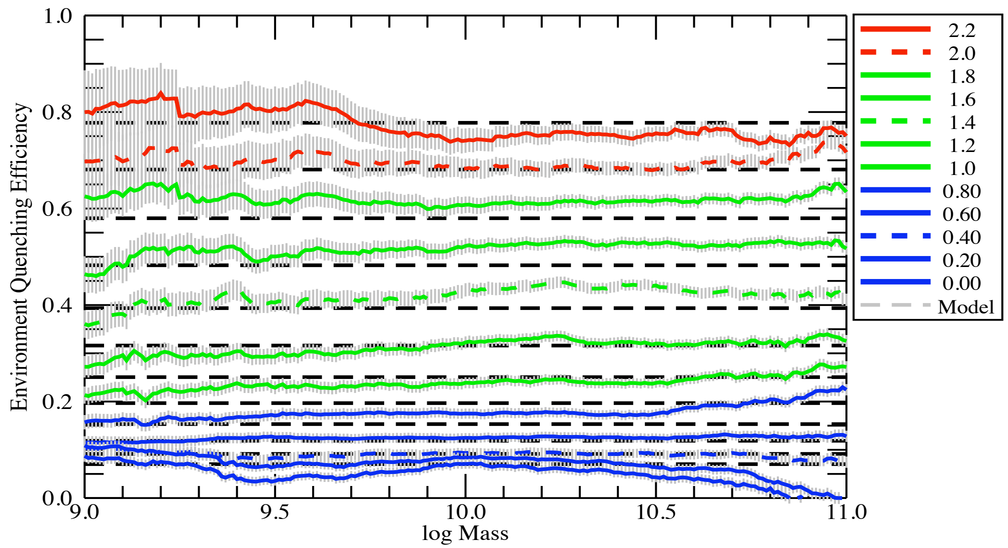
$$\varepsilon_\rho(\rho,\rho_0,m) = \frac{f_{red}(\rho,m) - f_{red}(\rho_0,m)}{f_{blue}(\rho_0,m)}$$

"Relative mass-quenching efficiency"

$$\varepsilon_m(m,m_0,\rho) = \frac{f_{red}(m,\rho) - f_{red}(m_0,\rho)}{f_{blue}(m_0,\rho)}$$



$\varepsilon_\rho(\rho)$ as $f(z)$



ε_ρ as $f(m)$

Contrasts between
$sSFR(m,\rho,t)$ and $f_{red}(m,\rho,t)$
back to z ~ 1 to 2

$sSFR$	f_{red}
Weakly dependent on stellar mass	Strongly dependent on stellar mass
Largely independent of environment	Strongly dependent on environment, especially at low stellar masses
Strongly evolves with redshift, uniformly for all masses and environments	Weakly evolves with redshift (except for lowest stellar masses in high density environments)

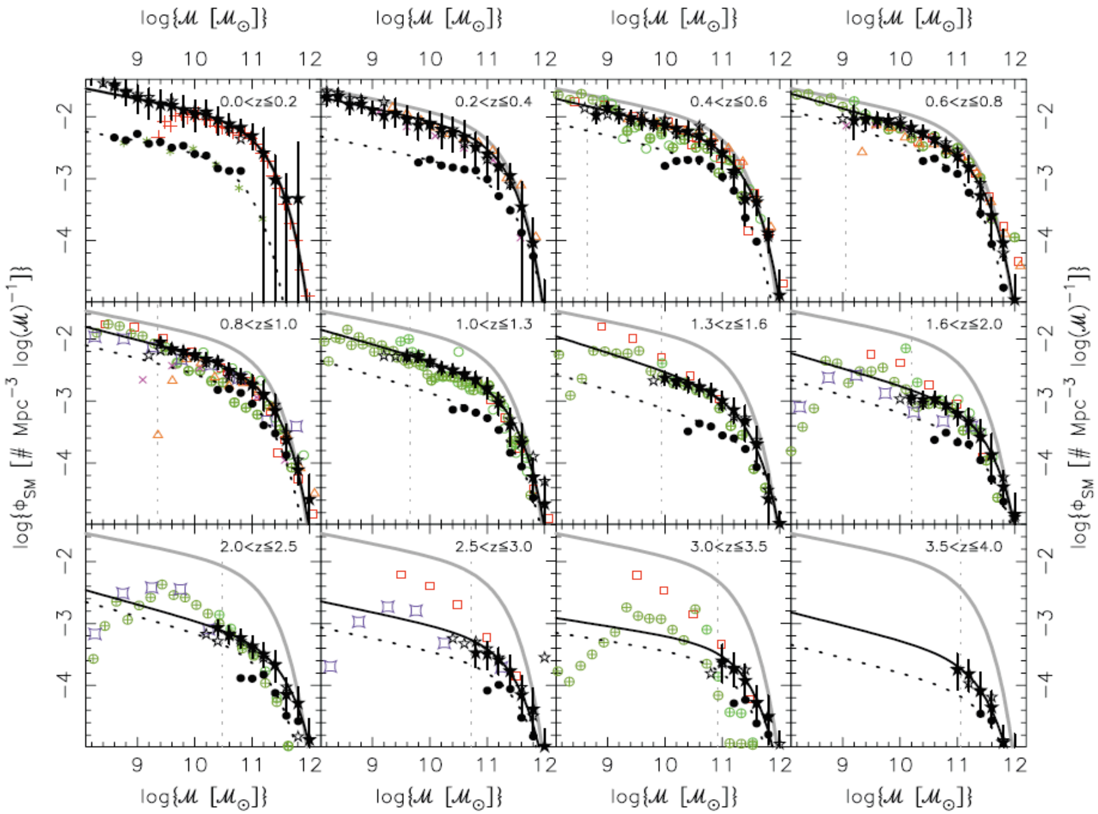
Need to distinguish between two distinct phenomena

- Evolution of sSFR of star-forming galaxies
- "Quenching"

The constancy of M* (and α) of star-forming galaxies to z ~ 2+

(despite 0.8 dex increase in *m* since z = 1, and 2 dex since z = 2)

e.g. Bell et al (2005), Perez-Gonzalez et al (2008), Pozzetti et al (2010), Ilbert et al (2010)



Perez-Gonzalez et al (2008)

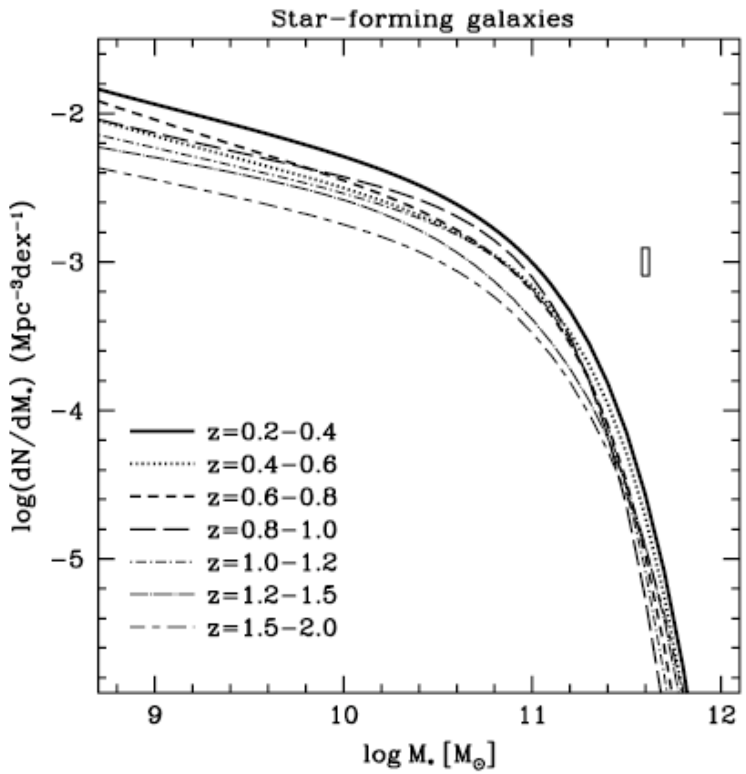


Figure 18. MF of "star-forming" galaxies (sum of intermediate and high activity galaxies) from $z = 2$ to $z = 0.2$. The vertical box quantifies the cosmic variance at $z = 0.2$–0.4 (Scoville et al. 2007).

Ilbert et al (2008): COSMOS photo-z

See Peng et al 2010, ApJ, 721, 193, Peng et al 2011 arXiv:1106:2546 and talk this afternoon by Yingjie Peng

3-4 key observations

- Separability of $f_{red}(m,\rho)$ to z ~ 1
- Constancy of M* of star-forming galaxies since *z* = 2
- Constancy of α of star-forming galaxies ⇔ $\beta \sim 0$
- Constancy of $\varepsilon_\rho(\rho)$ since z ~ 1

3 parameters determined from observations

- μ, from $\mu = M*^{-1}$
- α, Schechter faint end slope
- the $\varepsilon_\rho(\rho)$ curve

Other observational inputs that set "clock" but do not affect final outcome

- sSFR(m,r,t) – star-formation rates
- N(ρ,t) – growth of structure

$$\eta = \quad \mu\, SFR \quad + \quad \left(\frac{1}{1-\varepsilon_\rho} \frac{\partial \varepsilon_\rho}{\partial \log \rho} \frac{\partial \log \rho}{\partial t} \right) \quad + \quad \kappa$$

overall quenching rate (time^{-1})

mass quenching (independent of environment)

environment quenching (independent of mass)

originally introduced as merging, now understand that it must have specific form

equivalent to $P(m) = e^{-\mu m}$

limited to satellites only

$\kappa = -(1+\alpha)\, \varepsilon_\rho\, \text{sSFR}$

establishes and controls precise Schechter mass functions of galaxies

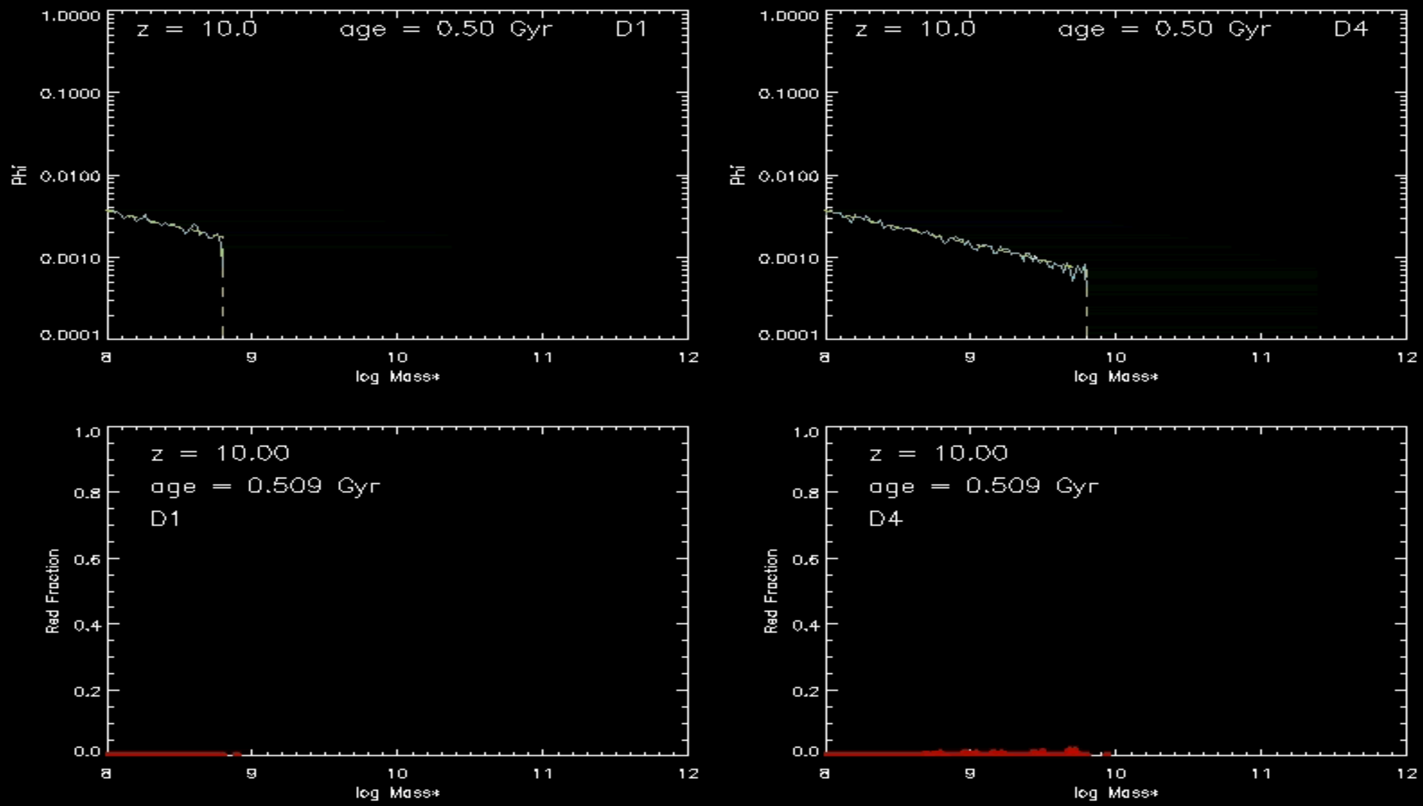
establish and maintain all environment effects

Lowest density quartile

highest density quartile

Mass function

Red fraction



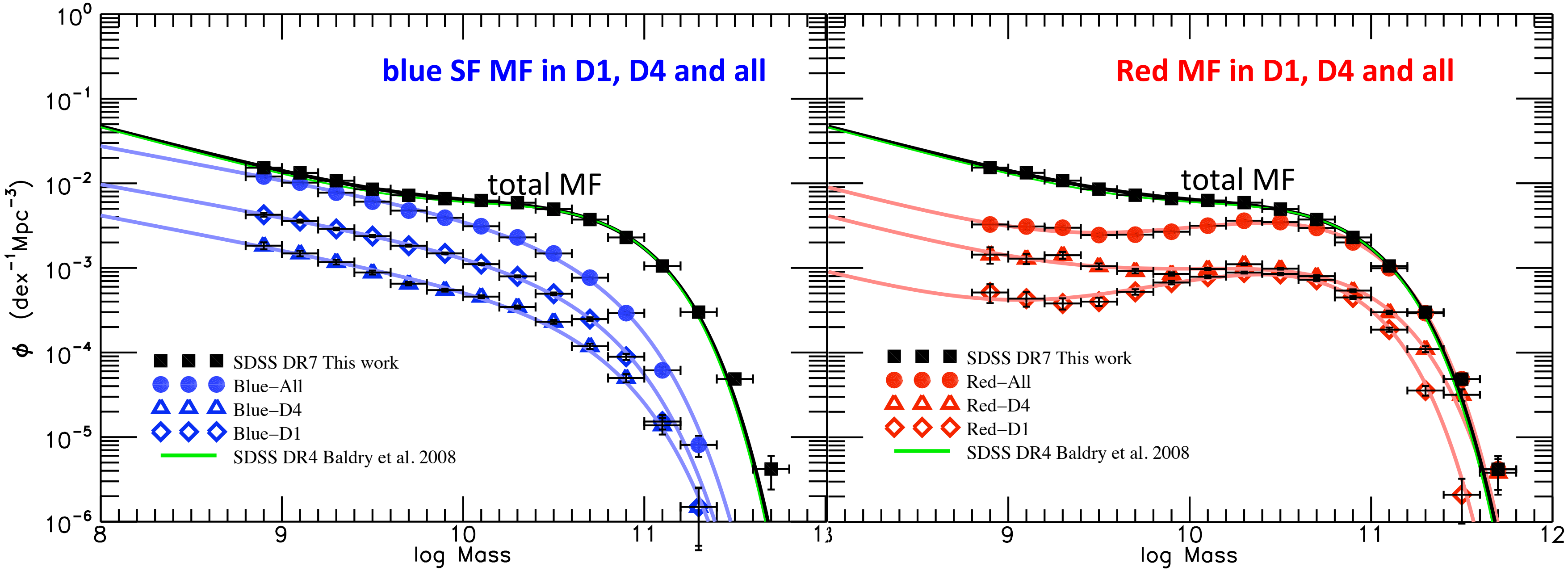
- Precise relationships between M*, α and ϕ* for different components.
- SDSS mass functions at z ~ 0 are "inevitable" and do not strongly depend on what happens at z >> 2

$$\alpha_{s,red} = \alpha_{s,blue} + (1+\beta)$$

$$M^{*}_{-0.4,red} = M^{*}_{-1.4,blue} = M^{*}_{-1.4,red}$$

$$\frac{\phi^{*}_{-0.4}}{\phi^{*}_{-1.4}} = \frac{1}{(-\alpha_s - 1)} \sim 2.5$$

SDSS ϕ(m) for blue and red in different environments

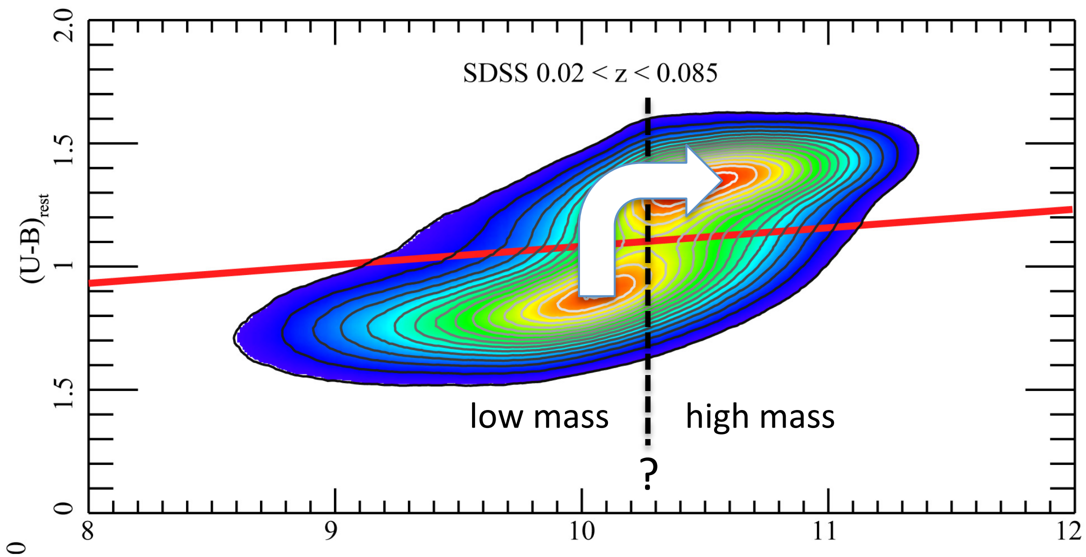


	$\text{Log}(M^*/M_\odot)^a$	$\phi_1^*/10^{-3}\text{Mpc}^{-3}$	α_1	$\phi_2^*/10^{-3}\text{Mpc}^{-3}$	α_2
(a) Free fitting parameters					
Global	10.67 ± 0.01	4.032 ± 0.12	-0.52 ± 0.04	0.655 ± 0.09	-1.56 ± 0.12
Blue-all	10.63 ± 0.01	...	...	1.068 ± 0.03	-1.40 ± 0.01
Blue-D1	10.60 ± 0.01	...	...	0.417 ± 0.02	-1.39 ± 0.02
Blue-D4	10.64 ± 0.02	...		0.151 ± 0.01	-1.41 ± 0.04
Red-all	10.68 ± 0.01	3.410 ± 0.07	-0.39 ± 0.03	0.126 ± 0.02	(-1.56)
Red-D1	10.61 ± 0.01	0.893 ± 0.03	-0.36 ± 0.05	0.014 ± 0.01	(-1.56)
Red-D4	10.76 ± 0.02	0.814 ± 0.03	-0.55 ± 0.06	0.052 ± 0.01	(-1.56)

Two common misconceptions

Are there two populations of galaxies divided by an evolving threshold mass ?

Do we require a lot of dry-merging to populate red sequence given an absence of bright blue galaxies ?



No, there isn't a bifurcation in mass, since M* is the same for both

No, the red passive population is populated by quenching of star-forming galaxies at <u>same</u> mass.

Three approaches to the importance of merging

- Conventional direct estimates of the merging rate
  - recognition of "mergers"
  - (extended) timescales for merging
  - Biasses due to e.g. enhanced SF

- Constraints from continuity analysis M* of passives is ~ M* of SF galaxies means that the average Δm for post-quenching increase of stellar mass
  - Around 15% for all passive galaxies
  - 25% for centrals, zero for satellites

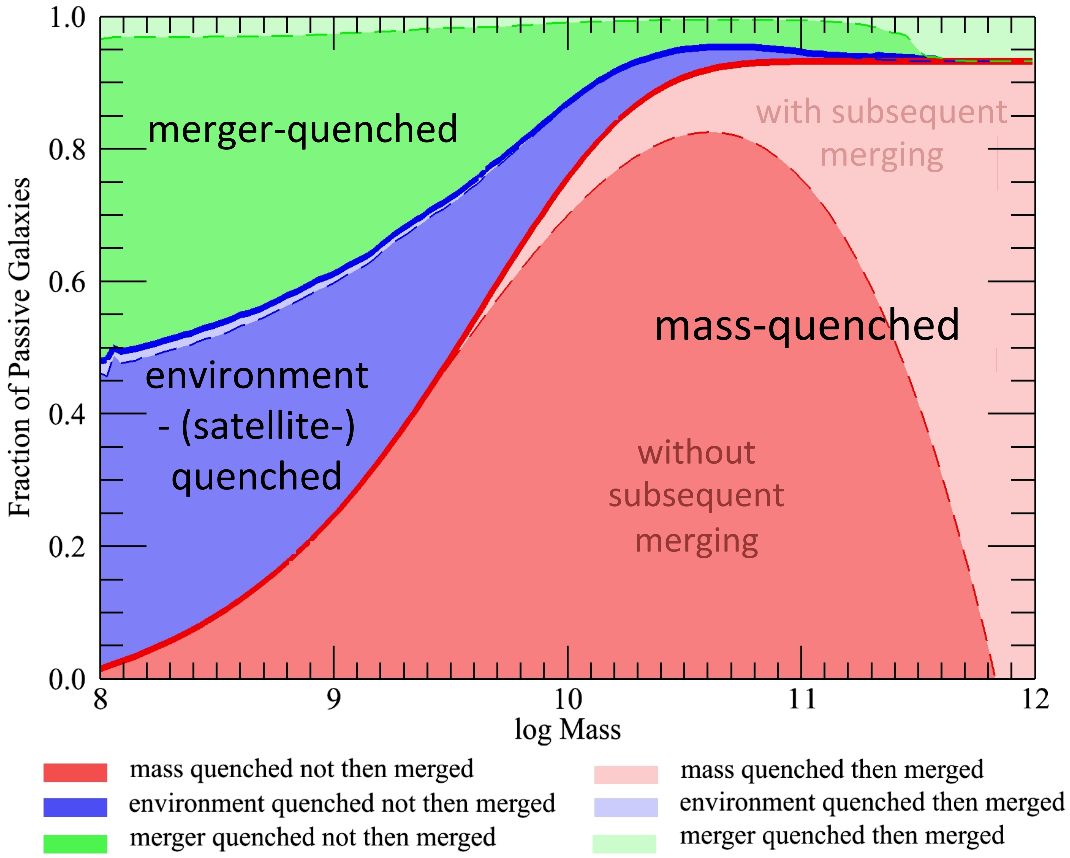
- Analysis of "merger-quenching" of star-forming objects $\kappa = -(1+\alpha)\,\varepsilon_\rho$ sSFR

$$\left.\frac{\dot{m}}{m}\right|_{merge} = \left\{\frac{\Delta m}{m}(1+\alpha_s)\,\varepsilon_\rho\right\}\left.\frac{\dot{m}}{m}\right|_{SFR}$$

$$\leq 0.1\left.\frac{\dot{m}}{m}\right|_{SFR}$$

Histories of today's passive galaxies

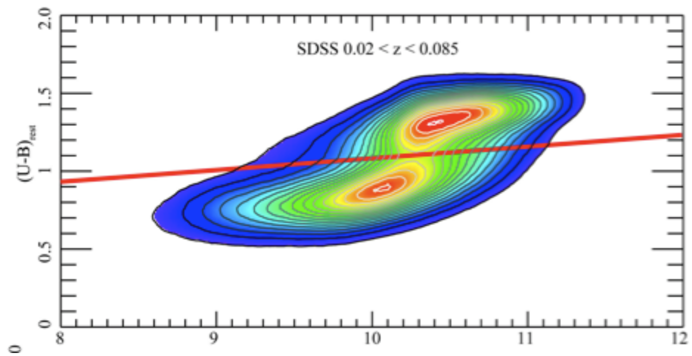
- What quenched today's passive galaxies?
- Did they subsequently (post-quenching) merge?



Where's the "down-sizing" ?

There is no explicit down-sizing in the <u>inputs</u> to the model (e.g. uniform increase in sSFR(t) across all masses).

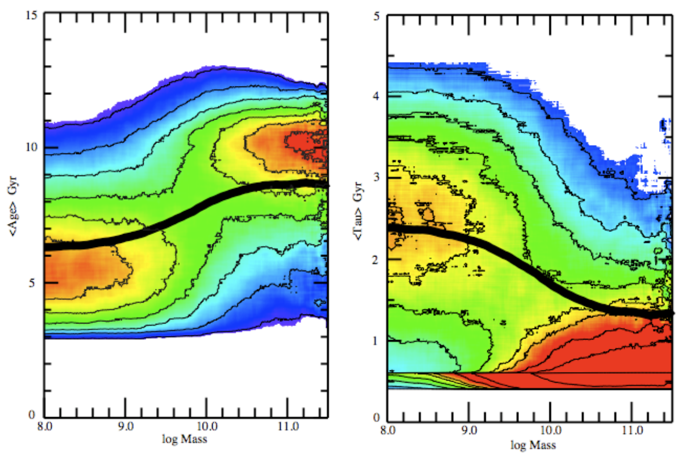
But what actually is down-sizing?



- "Activity-mass dichotomy" for <u>overall population</u> comes from the mass-dependence of quenching $m^{(1+\beta)}$ (at a given epoch)

- "Anti-hierarchical age-mass relation" for <u>passives</u> appears naturally due to early mass-quenching at high masses and later environment quenching at lower masses.

- If $\beta < 0$, the threshold for $sSFR^{-1} <$ Hubble time will migrate to higher z (as per Cowie et al's 1996 original definition of down-sizing)



Predictions for transitory objects "caught in the act"

Assume objects being mass-quenched exhibit some transitory "signature" for some time τ_{trans}. What is mass-function of these transitory galaxies ?

$$M^*_{trans} = M^*_{blue} = M^*_{red}$$

$$\alpha_{s,trans} = \alpha_{s,blue} + (1+\beta) = \alpha_{s,red}$$

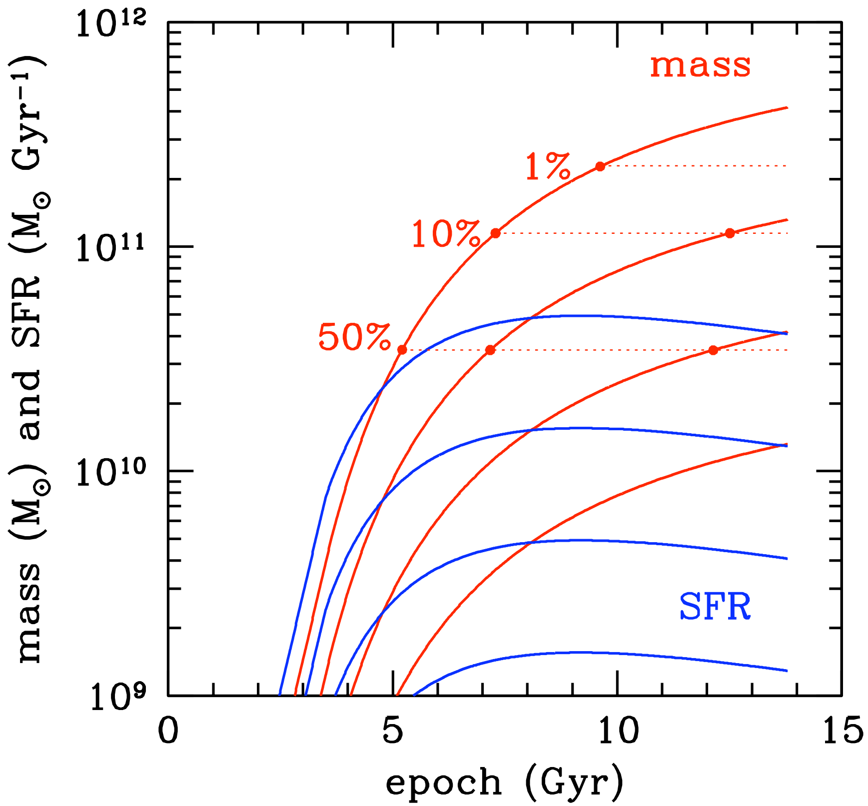
$$\phi^*_{trans} = \phi^*_{blue} \; sSFR(t)\big|_{M*} \; \tau_{trans} = \phi^*_{blue} \frac{\tau_{trans}}{\tau(t)\big|_{M*}}$$

- The shape (M^*_{trans} and $\alpha_{s,trans}$) of $\phi_{\mathrm{trans}}(m)$ should be the same as that of the red passive galaxies (in low density environments) and be *independent* of environment.

- But, the normalisation ϕ^*_{trans} is given by the density of the blue active star-forming galaxies, multiplied by the ratio of τ_{trans} and the star-formation time-scale, which evolves strongly with epoch as $t^{-2.5}$

Is "mass-quenching" simply rephrasing an underlying "mass-limiting" law?

Quenching occurs, statistically, when a galaxy has formed M* of stars.



Survival probability is simple *f*(m), not of the detailed SFR history.

$$\frac{dP}{dt} = -\eta\, P = -\mu \frac{dm}{dt} P$$

$$\frac{dP}{P} = -\mu\ dm$$

$$P \propto \exp(-\mu m) = \exp(-m/M^*)$$

But why should a mass-limiting law so accurately reproduce the Schechter function with $\Delta\alpha = 1$ over two dex of mass?

Any "second parameter" controlling m_{lim} must be strictly independent of environment

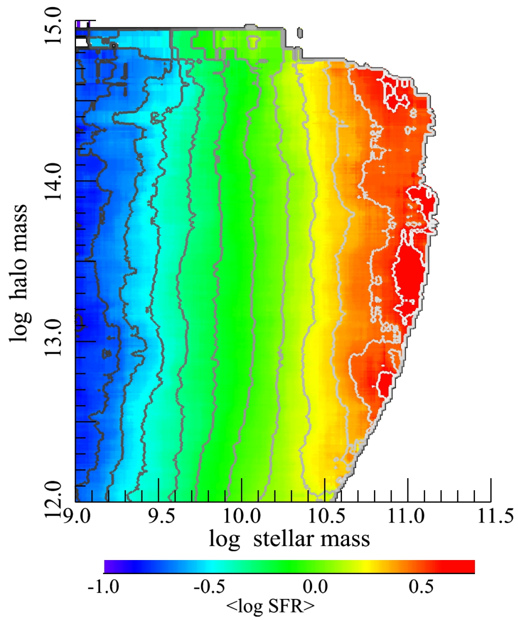
So, how important really are the dark-matter haloes?

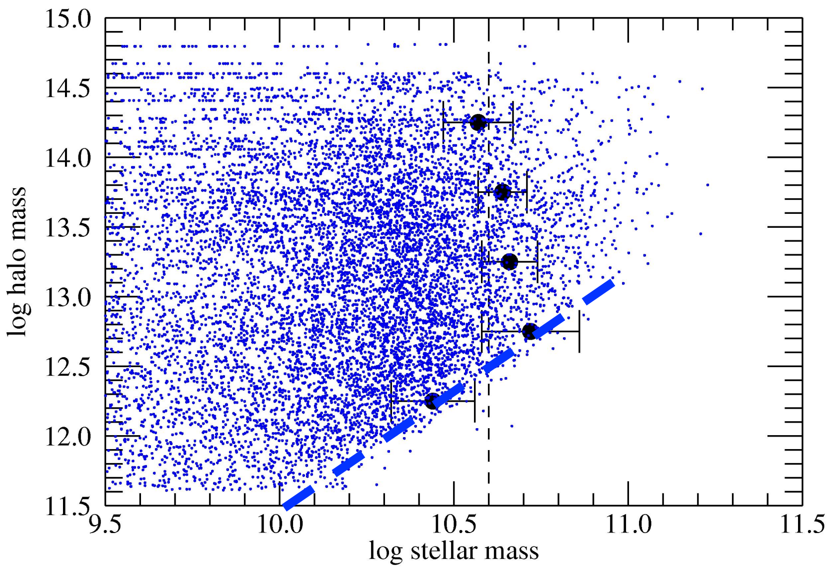
Most things of interest seem to be strikingly <u>independent</u> of the mass of the dark haloes (above 10^{12} $M_\odot$) in SDSS from Peng et al 2011 using Yang et al SDSS DR7 catalogue)

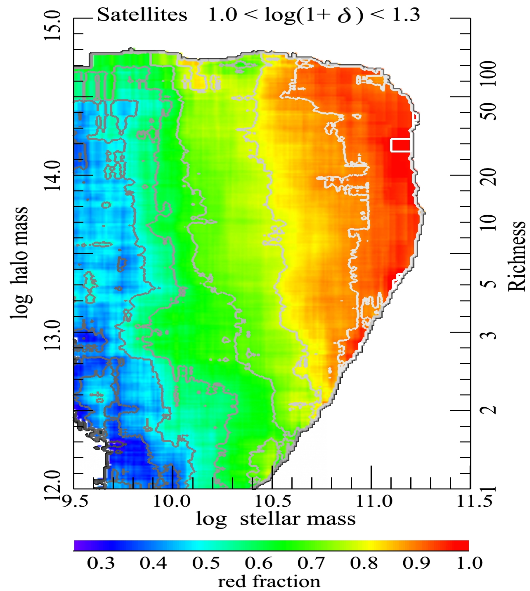
(1) star-formation rates: sSFR

(2) satellite-quenching: red fraction of satellites at fixed m and ρ

(3) mass-quenching: mass function $\phi(m)$ of satellites







Summary:

- The galaxy population exhibits certain clear "simplicities" in its evolution
  - sSFR – DM growth link
  - sSFR largely independent of mass and environment
  - separability of mass and environment effects in quenching
  - constant M* and α of star-forming mass function

- These in term demand that the dominant evolutionary processes take particular, simple forms.

- Simple models using these reproduce basic properties, e.g. $\phi(m)$, with impressive accuracy

Questions: Why does it look so simple with all we know about complex astrophysics ?

- Why does the sSFR so simply follow the DM accretion history ?
- Why does sSFR on the main sequence not depend on environment ?
- Why does the Peng et al phenomenological model work so well ?
  - what is the mass-quenching (independent of environment) ?
  - how does the environment quench (independent of stellar mass and acting only on satellites) ?