"Overwhelming simplicity of galaxy evolution: answers and new questions for JWST"

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or

"Mass and environment as drivers of galaxy evolution in SDSS and zCOSMOS and the origin of the Schechter function"

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** many in audience

arXiv 1003.4747

Philosophy:

- Reduce the observations to a few very simple "statements" – parametric representations of the data over a range of redshift: in particular, star-formation rates, masses, and Mpc-scale environments

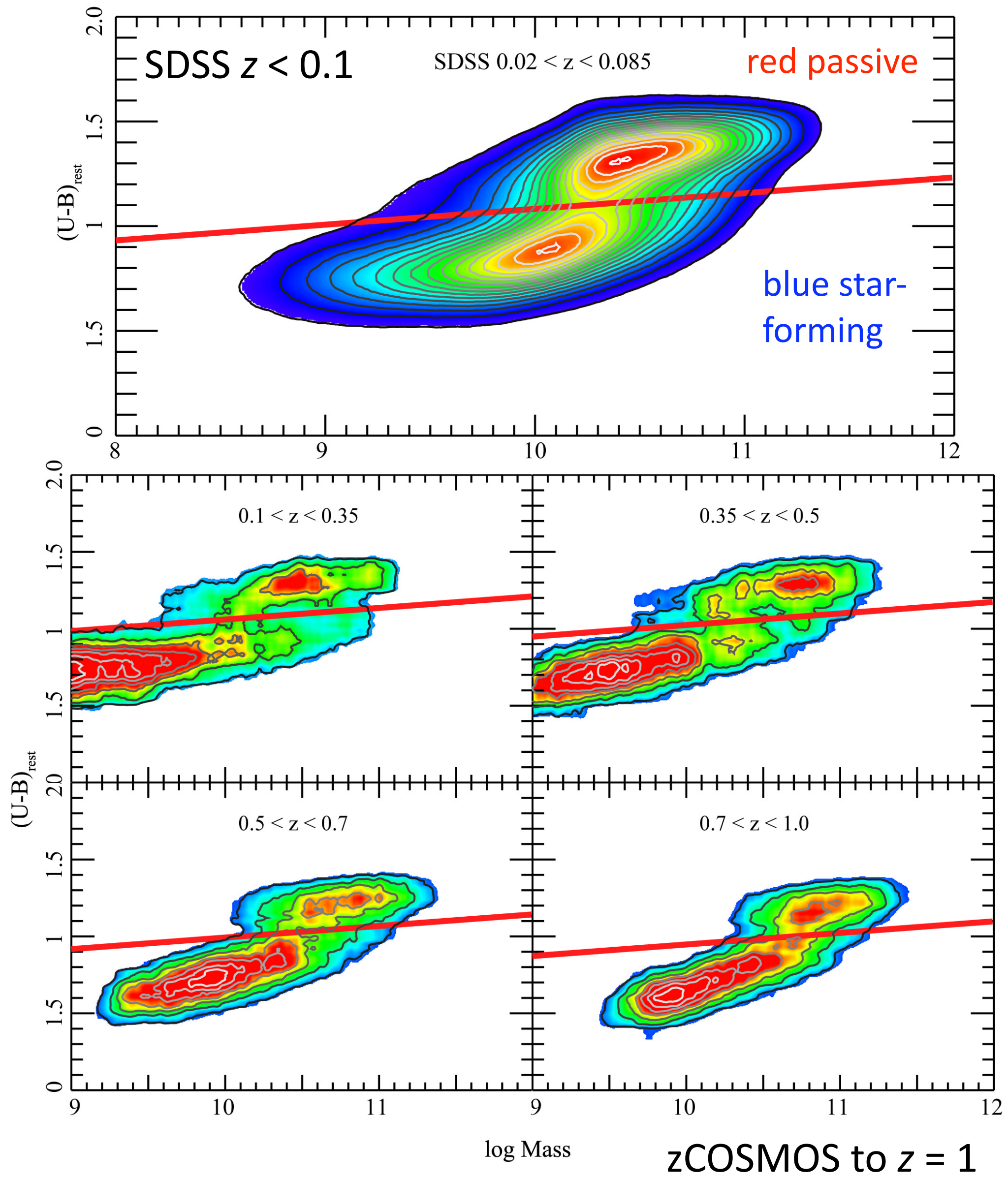
- Infer what the analytic consequences of these are for the most important evolutionary processes

- Test against other independent data (e.g. SDSS mass functions)

- Gain clues as to dominant characteristics of the underlying physical processes

- A kind of "empirical (semi-)analytic model" – providing a context for study of physical processes with JWST and ELTs.

Red and blue galaxies in SDSS and zCOSMOS



Assume: There is a bi-modal population of red "passive" (i.e. negligible SFR) + blue "star-forming" galaxies

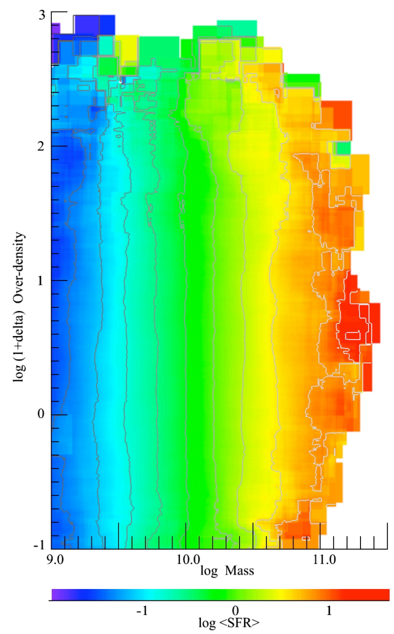
Assume: an instantaneous net transformation from blue to red, **"quenching"**, may depend on *mass*, *environment* and *time*

Assume: "major mergers" (1:3) will quench. Merger rate from observations (assumed mass-independent), and neglect "minor mergers".

Star-forming blue galaxies

Three observed "facts" about blue star-forming galaxies are also assumed to be true (but are not critical)

- sSFR is a weak function of mass at all epochs $z \leq 2$ ($\beta \sim -0.1$)
- sSFR does not depend on Mpc-scale environment (new)
- sSFR follows universal epoch dependence



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

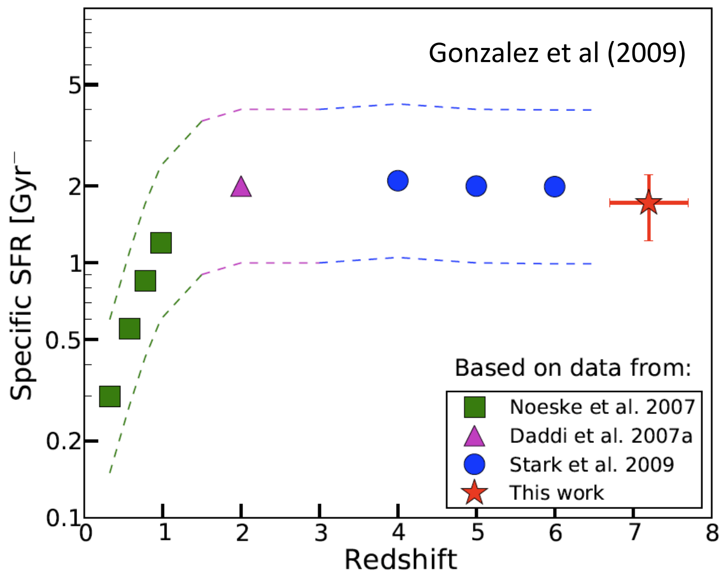
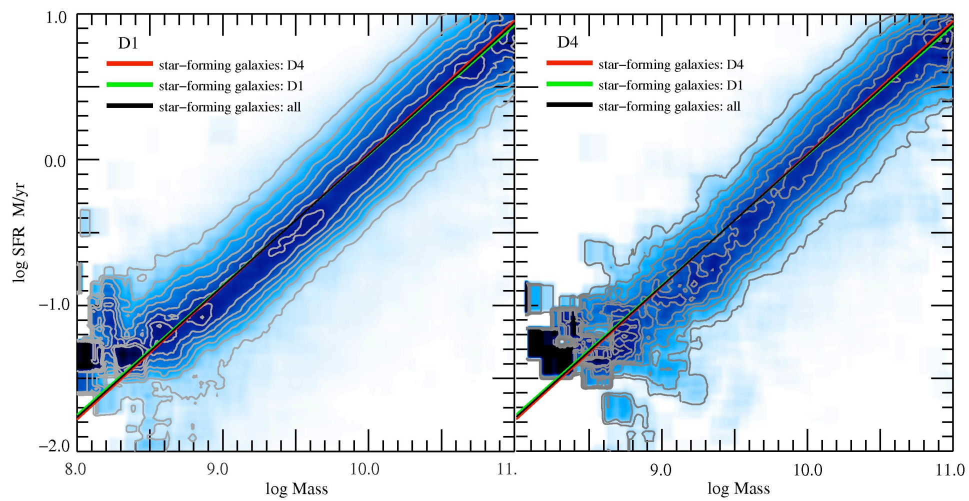


FIG. 5.— The SSFR measured from our data at $z \sim 7$ compared

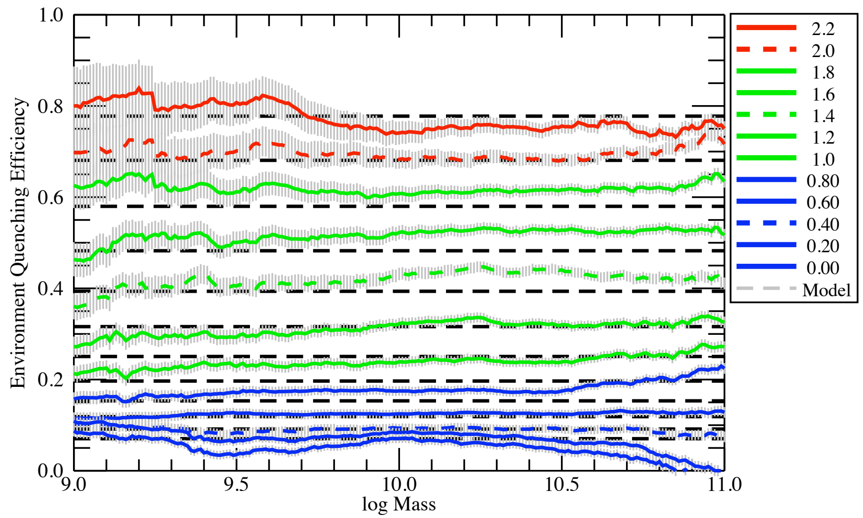


Differential effects of environment and mass are fully separable

"Relative environment-quenching efficiency"

Of those galaxies that are, at a certain mass, blue in the voids, what fraction are red in richer environments?

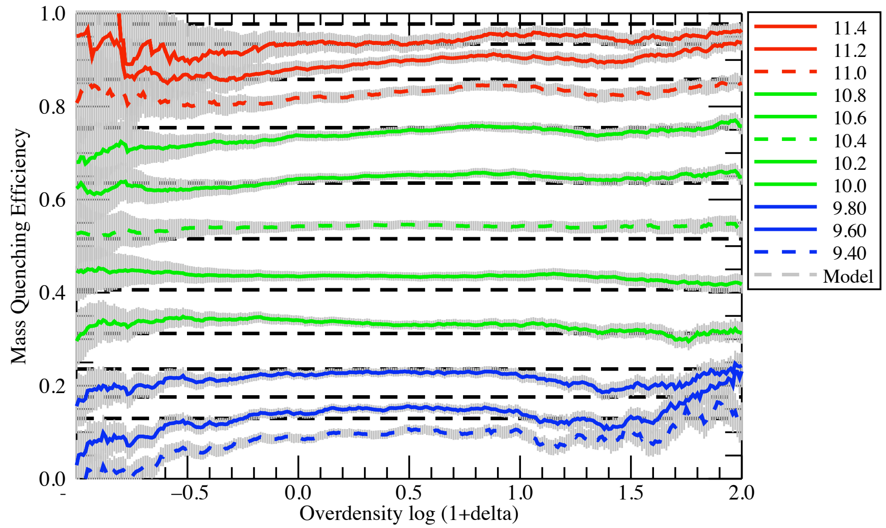
$$\varepsilon_\rho(\rho,\rho_0,m) = \frac{f_{red}(\rho,m) - f_{red}(\rho_0,m)}{f_{blue}(\rho_0,m)}$$



"Relative mass-quenching efficiency"

In a given environment, what fraction of the galaxies that are blue at very low masses, are red at higher masses?

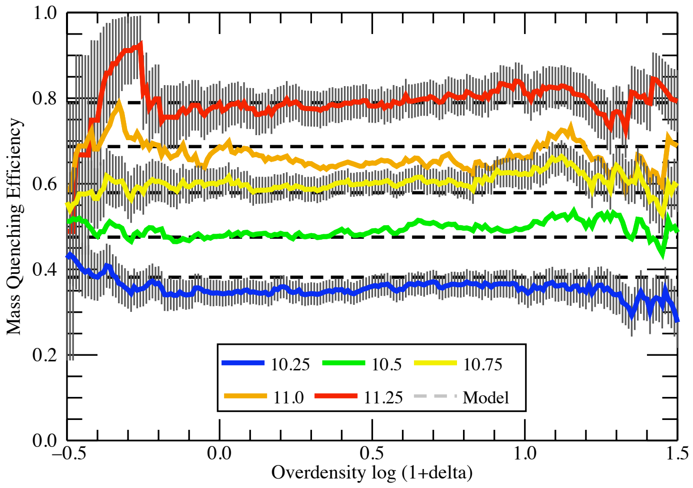
$$\varepsilon_m(m,m_0,\rho) = \frac{f_{red}(m,\rho) - f_{red}(m_0,\rho)}{f_{blue}(m_0,\rho)}$$

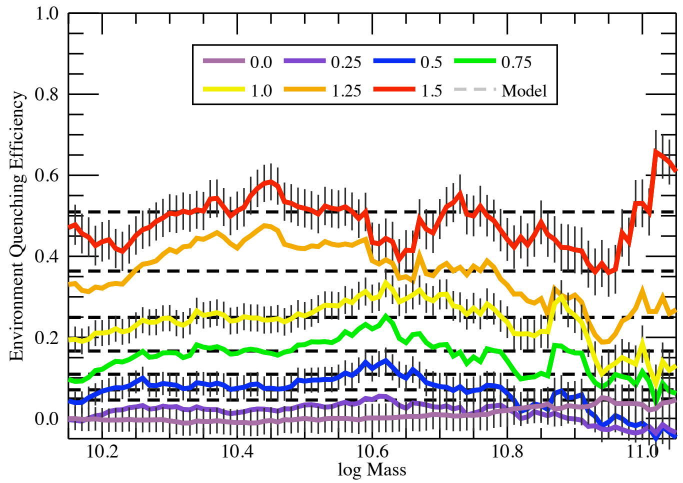


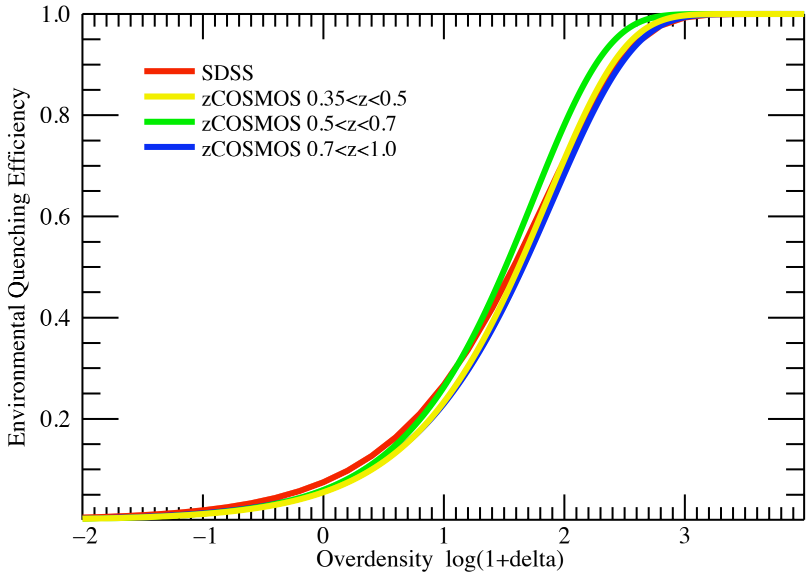
(A) Two distinct physical effects: (a) "environment-quenching", independent of mass

(b) "mass-quenching", independent of environment

Effects of mass and environment also separable in zCOSMOS to z ~ 1





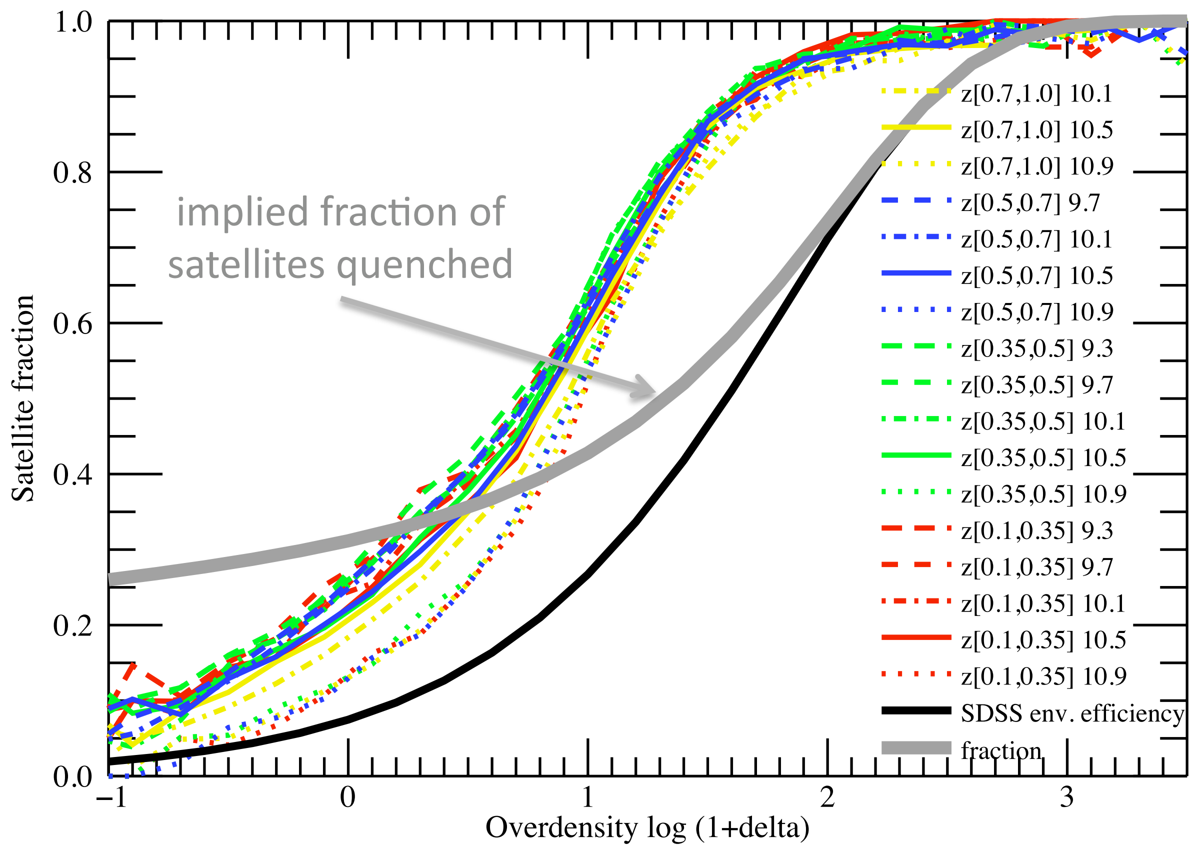


The effect of environment <u>at fixed over-density</u> does not change since z ~ 1

i.e. Environmental effects in the galaxy population appear as galaxies migrate to <u>higher</u> overdensities as LSS grows

Thus the environment quenching depends on environment but not on *mass* or *epoch*:
These are signatures of "satellite quenching"

Satellite fraction in Millennium Run mocks (Kitzbichler & White 2007) also depends on environment but not on mass ($M < 10^{10.9}\,M_\odot$) or epoch ($z < 1$)



(B) Therefore our "environment-quenching" is probably simply "satellite-quenching", with $30\% < f_{quench} < 75\%$ for $\log(1+\delta) < 2$, independent of mass

What about mass-quenching and the the evolution in ε_m?

The dominant effect in mass-quenching is not the change in the red fraction at fixed mass, (i.e. ε_m) but the effect of SFR bringing up new blue galaxies from lower masses:
i.e. most information on mass-quenching is in the evolving mass-function of star-forming galaxies rather than in the red fraction at fixed mass.

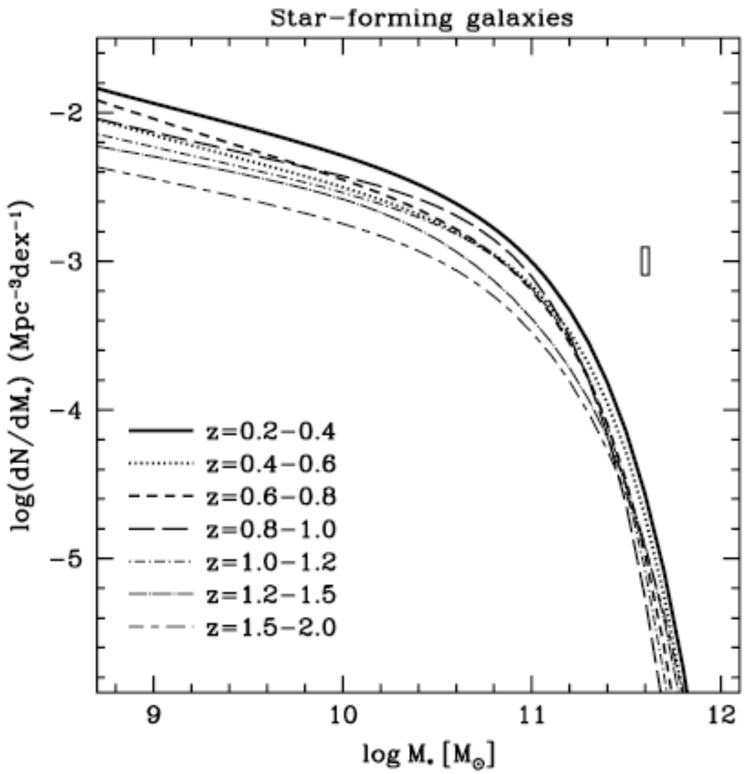


Figure 18. MF of "star-forming" galaxies (sum of intermediate and high activity galaxies) from $z = 2$ to $z = 0.2$. The vertical box quantifies the cosmic variance at $z = 0.2$–0.4 (Scoville et al. 2007).

Observed fact: M* for blue star-forming galaxies is remarkably constant since z ~ 2, despite the hundred-fold increase in masses of individual star-forming galaxies, e.g. Ilbert et al (2010), also Pozzetti et al (2010), Bell et al (2005)

z	M*	α_s	$\phi^*/10^{-3}$ Mpc^{-3}
(a) Free-fits			
0.3	10.99	-1.31	1.21
0.5	11.02	-1.30	0.75
0.7	10.96	-1.35	0.80
0.9	10.89	-1.22	1.22
1.1	10.94	-1.24	0.84
1.35	10.89	-1.26	0.74
1.75	10.94	-1.26	0.48
(b) Fits with α_s constrained			
0.3	10.97	(-1.30)	1.28
0.5	11.02	(-1.30)	0.75
0.7	10.90	(-1.30)	0.98
0.9	10.96	[illegible]	[illegible]
1.1	11.00	[illegible]	[illegible]
1.35	10.95	[illegible]	[illegible]
1.75	10.99	(-1.30)	0.41

ϕ^* drifts upwards?

α gradually steepens?

Constancy of M* of star-forming galaxies

It is "easy to see" (and to show analytically) that constancy of M* of star-forming galaxies requires a mass-quenching rate that is proportional to sSFR and to mass, i.e. to the SFR alone

$$\eta_m = \mu \times \mathrm{SFR} \quad \text{with } \mu = (M^*)^{-1}$$

This quenching law will maintain constant M*, but will cause a small increase in $\phi^*(t)$, as observed, plus a small upwards drift in faint end slope α (unless $\beta = 0.0$)

(C) Our "mass-quenching" rate must be proportional to the star-formation rate (or must mimic such a dependence) independent of environment, and of both epoch and mass (except in so far as they control the SFR).

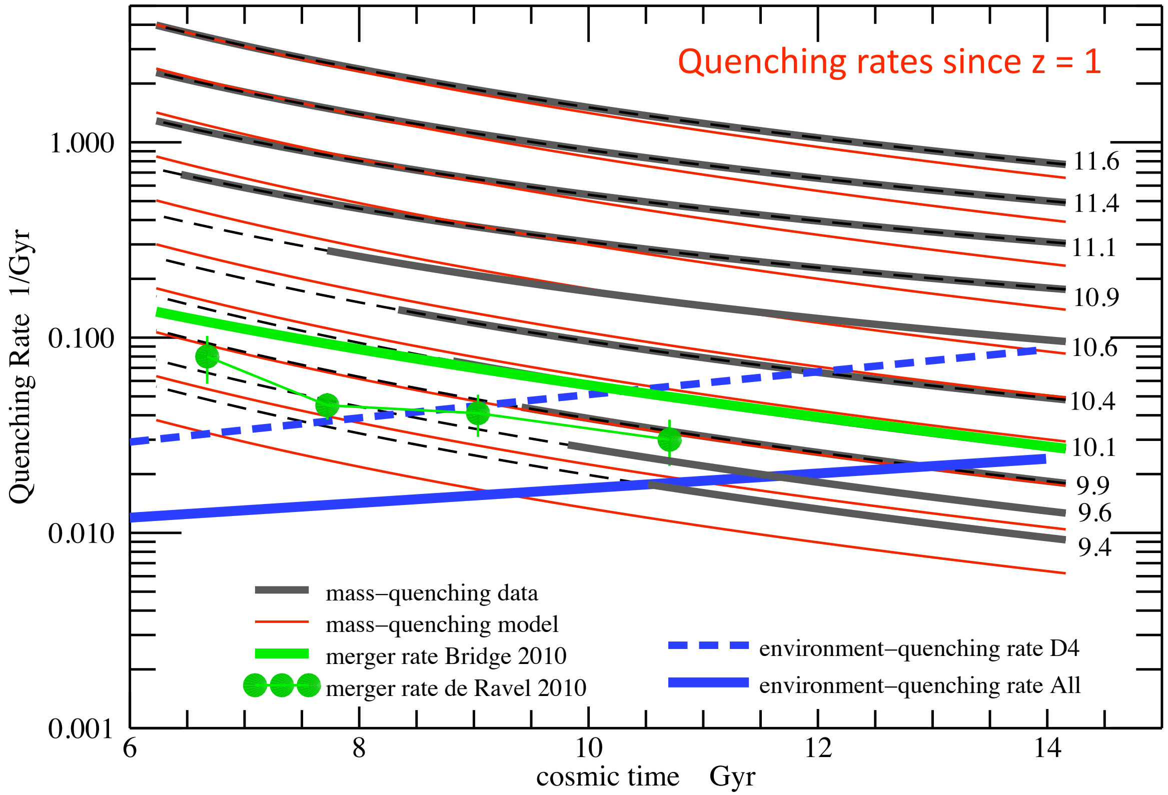
Some feedback mechanism, perhaps AGN?

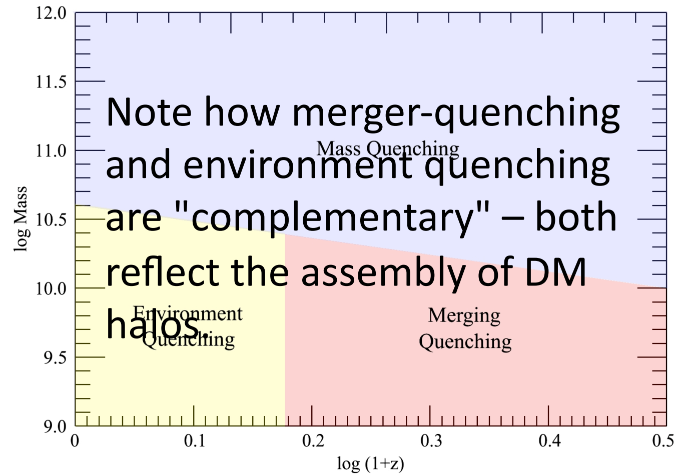
Combined quenching rates: mass-, environment- and merging-:

$$\eta = \lambda_m + \left(\lambda_\rho + \kappa_-\right)$$

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

mass quenching — environment quenching — merger quenching





Note how merger-quenching and environment quenching are "complementary" – both reflect the assembly of DM halos.

The origin of the Schechter function

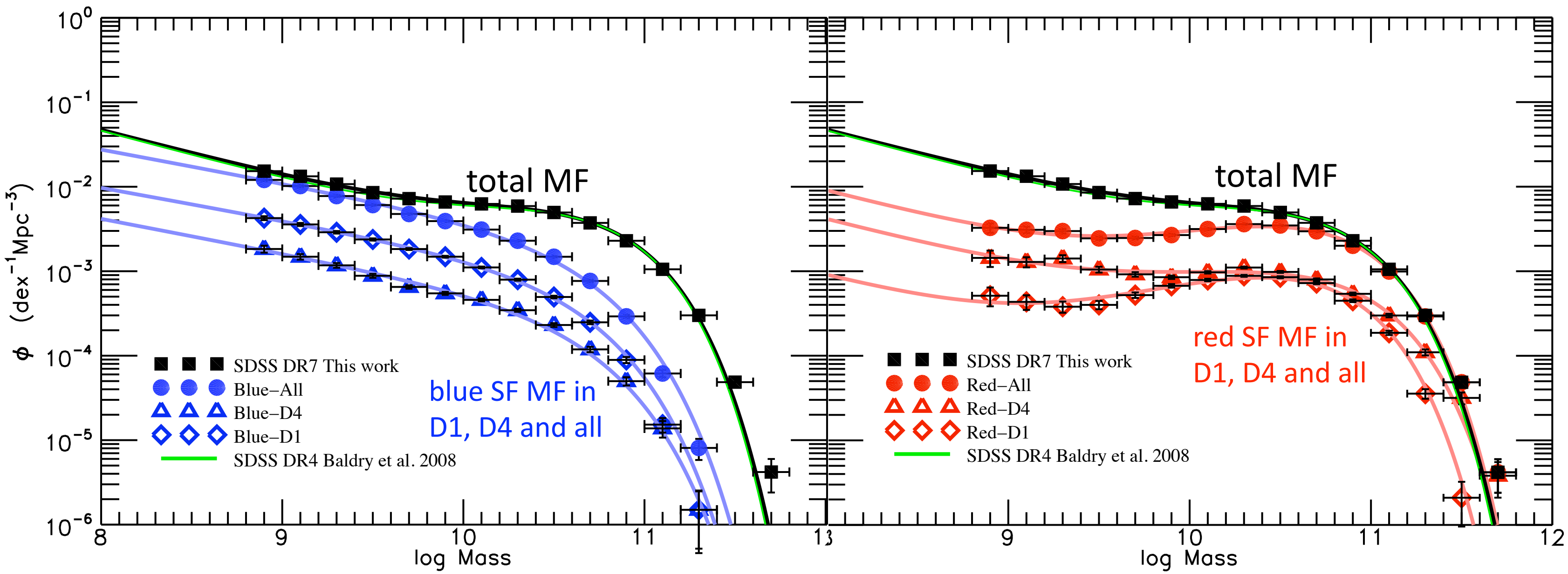
$$\eta = \lambda_m + \left(\lambda_\rho + \kappa_-\right)$$

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

observed proportional to mass$^{(1+\beta)}$ — observed independent of mass — assumed independent of mass

- Mass-quenching not only maintains but also <u>produces</u> (from more general mass functions) a single Schechter function of star-forming galaxies, with constant $M^*_{SF} = \mu^{-1}$, independent of environment
- Mass-quenching produces a primary Schechter function for passive galaxies with identical $M^* = M^*_{SF}$ but with a modified faint end slope that is less negative by $\Delta\alpha = (1+\beta) \sim 1$, again independent of environment. Added to the mass-function of SF galaxies, the overall population will have a "double" (two-component) Schechter function.
- Environment-quenching and merger-quenching produce a second Schechter function for passive galaxies with precisely the same M^* and α as the SF galaxies, but with a ϕ^* that is strongly dependent on environment (about x 4 from D1 to D4).
- Subsequent "dry-merging" of passive galaxies in high density environments increases M^* and makes α slightly more negative (e.g. $\Delta\log M^* \sim 0.09$ dex, $\Delta\alpha = -0.15$ for 7.5% equal mass merging).

SDSS $\phi(m)$ for blue and red in different environments



	$Log(M^*/M_\odot)^a$	$\phi_1^*/10^{-3}Mpc^{-3}$	α_1	$\phi_2^*/10^{-3}Mpc^{-3}$	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	-0.3[illegible] ± 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)

The era of precision galaxy evolution has apparently arrived!

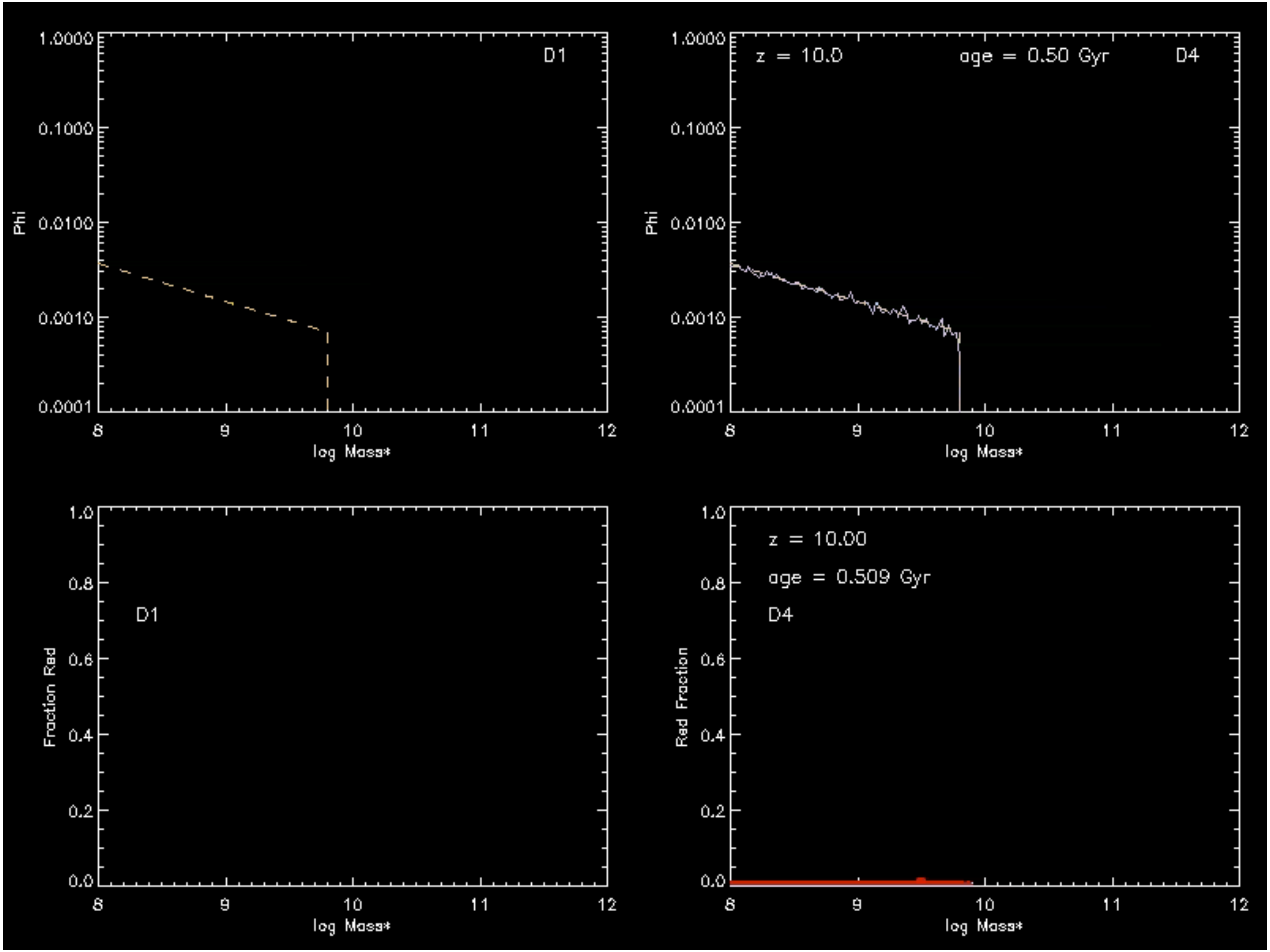
(a) single and double Schechter functions for SF and passive? Double for total? ✔

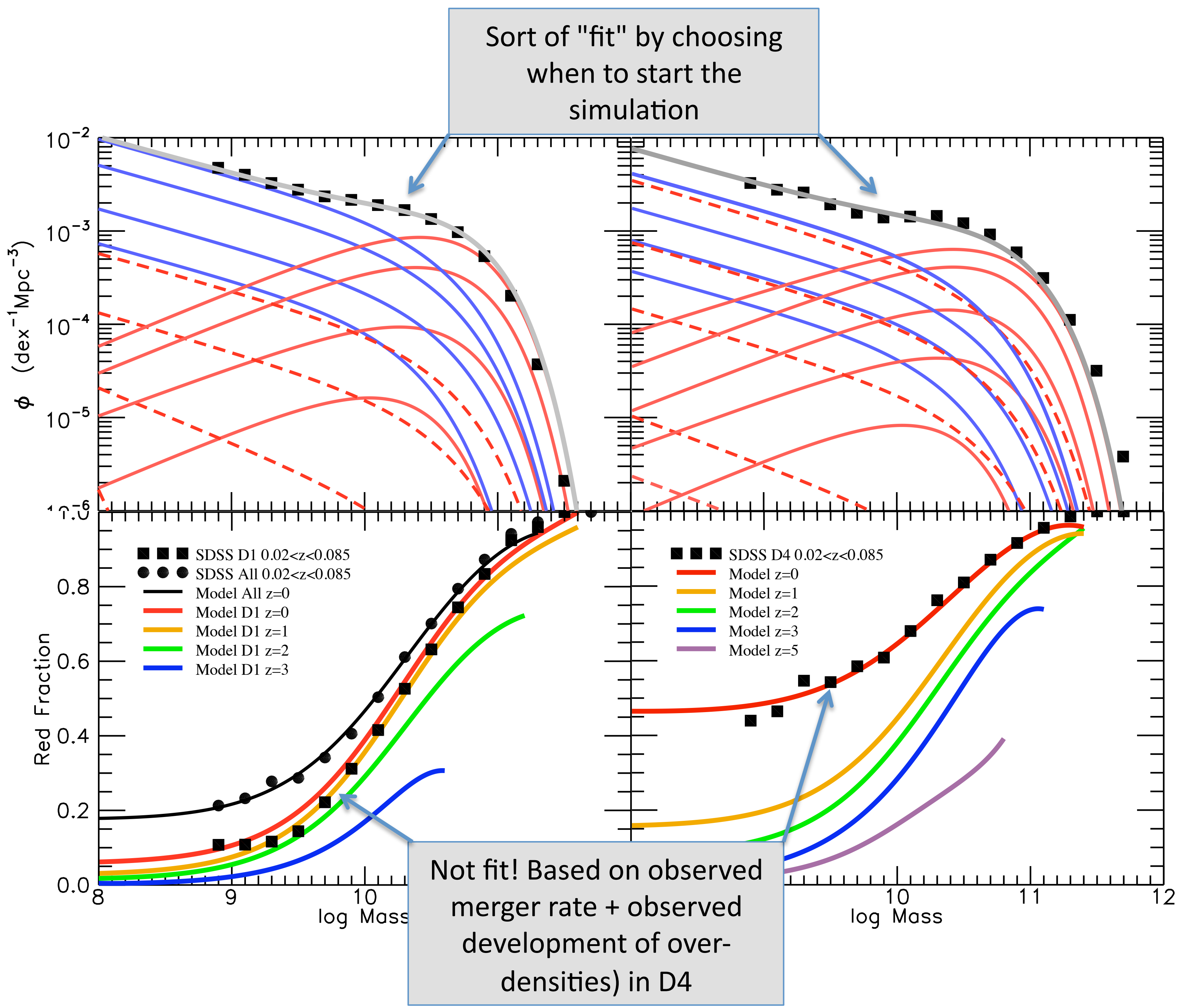
(b) M^* and α same for SF in D1 and D4? ✔

(c) M^* same for SF and passive in D1, α differ by $\Delta\alpha = 1$ (for $\beta = 0$)? ✔

(d) ϕ^* for secondary passive population about 4x higher in D4 as D1? ✔

(e) post-quenching merging modifies M^* and α for passives in D4? ✔


D1
Phi
log Mass*
z = 10.0
age = 0.50 Gyr
D4
Phi
log Mass*
D1
Fraction Red
log Mass*
z = 10.00
age = 0.509 Gyr
D4
Red Fraction
log Mass*



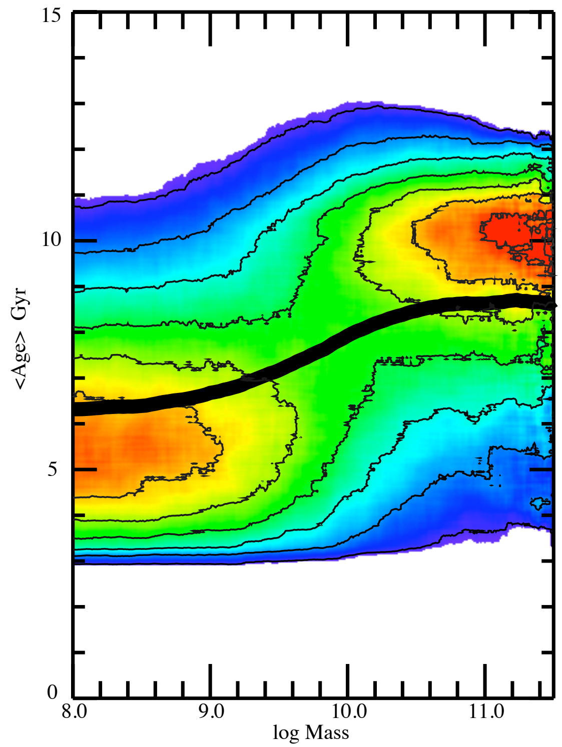
Sort of "fit" by choosing when to start the simulation
Not fit! Based on observed merger rate + observed development of over-densities) in D4
SDSS D1 0.02<z<0.085
SDSS All 0.02<z<0.085
Model All z=0
Model D1 z=0
Model D1 z=1
Model D1 z=2
Model D1 z=3
SDSS D4 0.02<z<0.085
Model z=0
Model z=1
Model z=2
Model z=3
Model z=5
Red Fraction
log Mass

Ages and α-element abundances for passive galaxies as f(mass)

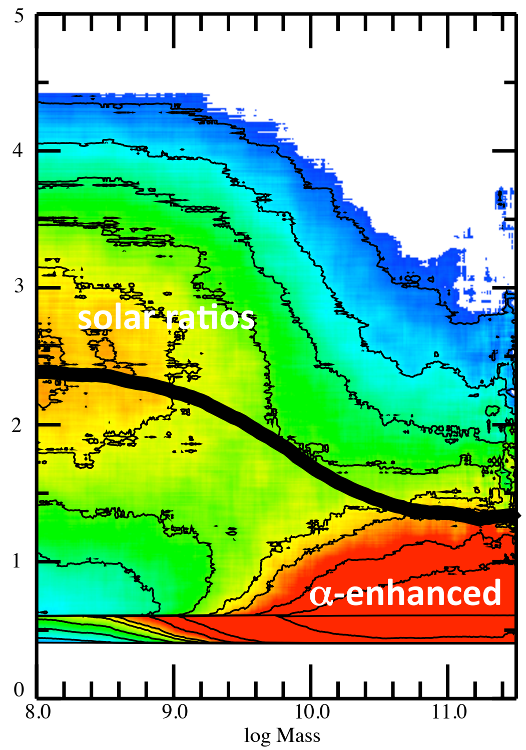
At a given mass:

- Rate of production of primary (i.e. mass-quenched) passive component is proportional to sSFR, and drops sharply since z ~ 2
- Rate of production of secondary (i.e. merger-quenched plus environment-quenched) component is more or less constant with epoch.

Combination naturally produces run of light-weighted age and α-element abundances with mass



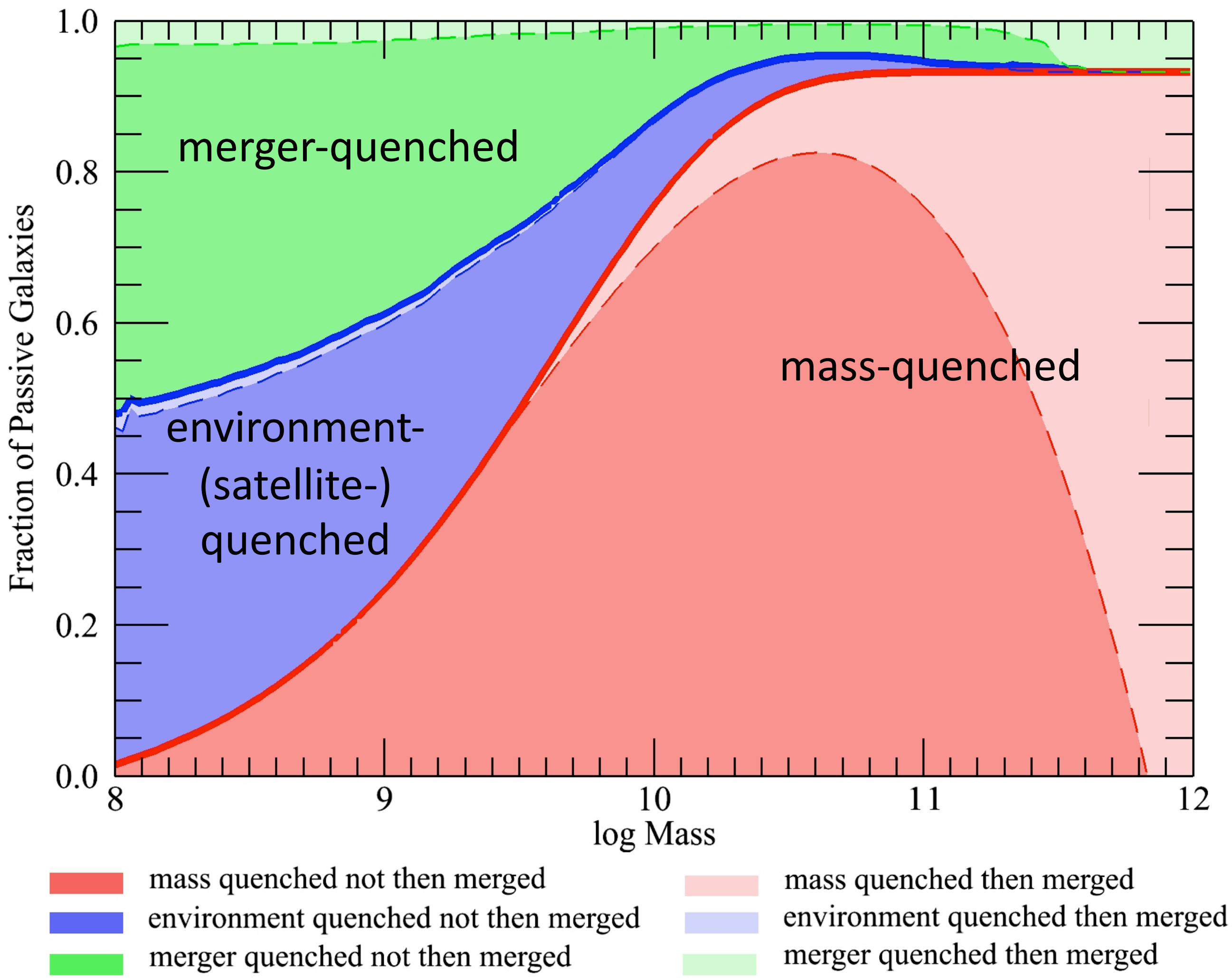
light-weighted stellar age



light-weighted stellar $sSFR^{-1}$

Histories of today's passive galaxies

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



There are, from an empirical stand-point, three main drivers of galaxy evolution with the following characteristics and outcomes:

(a) a process that sets a roughly uniform sSFR for all star-forming galaxies (independent of mass and environment) and also presumably controls its evolution with redshift; *this effectively sets the "cosmic clock" for the evolution of the galaxy population.* Modulation of accretion flow of gas?

(b) an unknown physical process, but probably involving feedback of some sort, that "mass-quenches" galaxies at a rate that is independent of environment and is (apparently) precisely proportional to galaxies' individual star-formation rates; *this produces the Schechter mass-function of star-forming galaxies, the shallower Schechter mass-function of the dominant passives, and sets the characteristic mass M* of both.* Feedback from SF, or AGN?

(c) the hierarchical assembly of dark matter haloes, which modifies the galaxy population, mainly at lower masses through, initially, the merging of galaxies and, subsequently, through the "environment-quenching" of those satellites that do not merge; *this produces the second Schechter function of passive galaxies, the appearance of environmental effects in the galaxy population, and also explains a number of other properties of passive galaxies (mass-age etc).* Merging and various "satellite-quenching" mechanisms

Some implications for JWST and E-ELT?

- **Search for physical processes:**

e.g. "SINFONI" $z = 2$ unstable star-forming disks (e.g. Natascha F-S talk) are statistically within few 10^8 years of death. What properties for healthy galaxies ten times lower mass (but same sSFR)?

- **Baryon accumulation:**

e.g. Model constrained at $z < 2$, but works very well at all $z < 10$. How does baryonic mass accumulate on galaxies (gas? stars?). Model has almost entirely gas accretion – but minor mergers and/or mergers with ongoing star-formation look like star-formation?

- **Passive galaxies**

The model has (can have) little post-quenching evolution of passive galaxies. What is happening with the size-mass relation?

- **Power of statistics**

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

Quenching occurs statistically when a galaxy has formed M* of stars. Is this a trivial statement?

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

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

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

Possibly: But why should a mass-limiting law so accurately produce a Schechter function with $\Delta\alpha = 1$?