A Simple Model for Galaxy Evolution

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in a statistical view

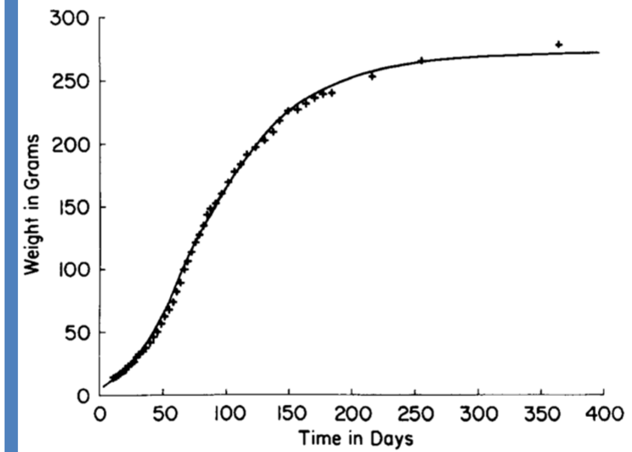


FIG. 2. Least-squares fit of generic curve to Donaldson's rat data.

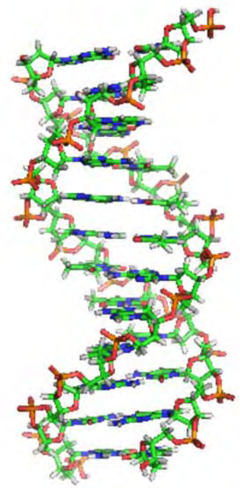
macroscopic

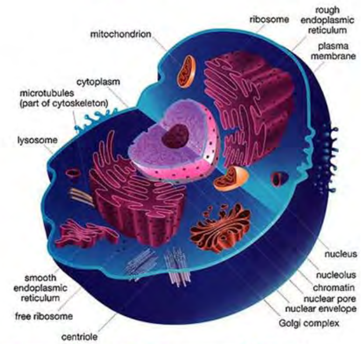
Population of Rats

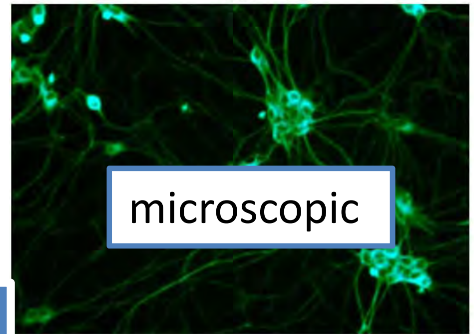
Statistical mechanics

the second law of thermodynamics

in a physical view

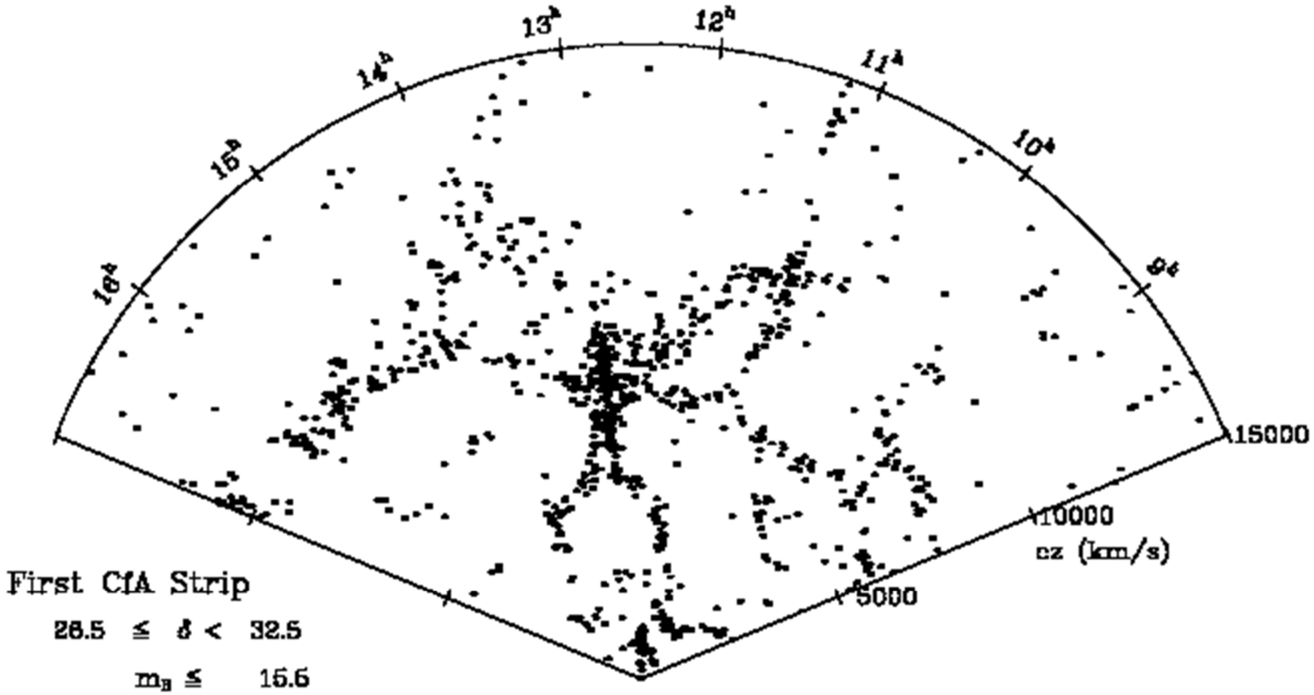




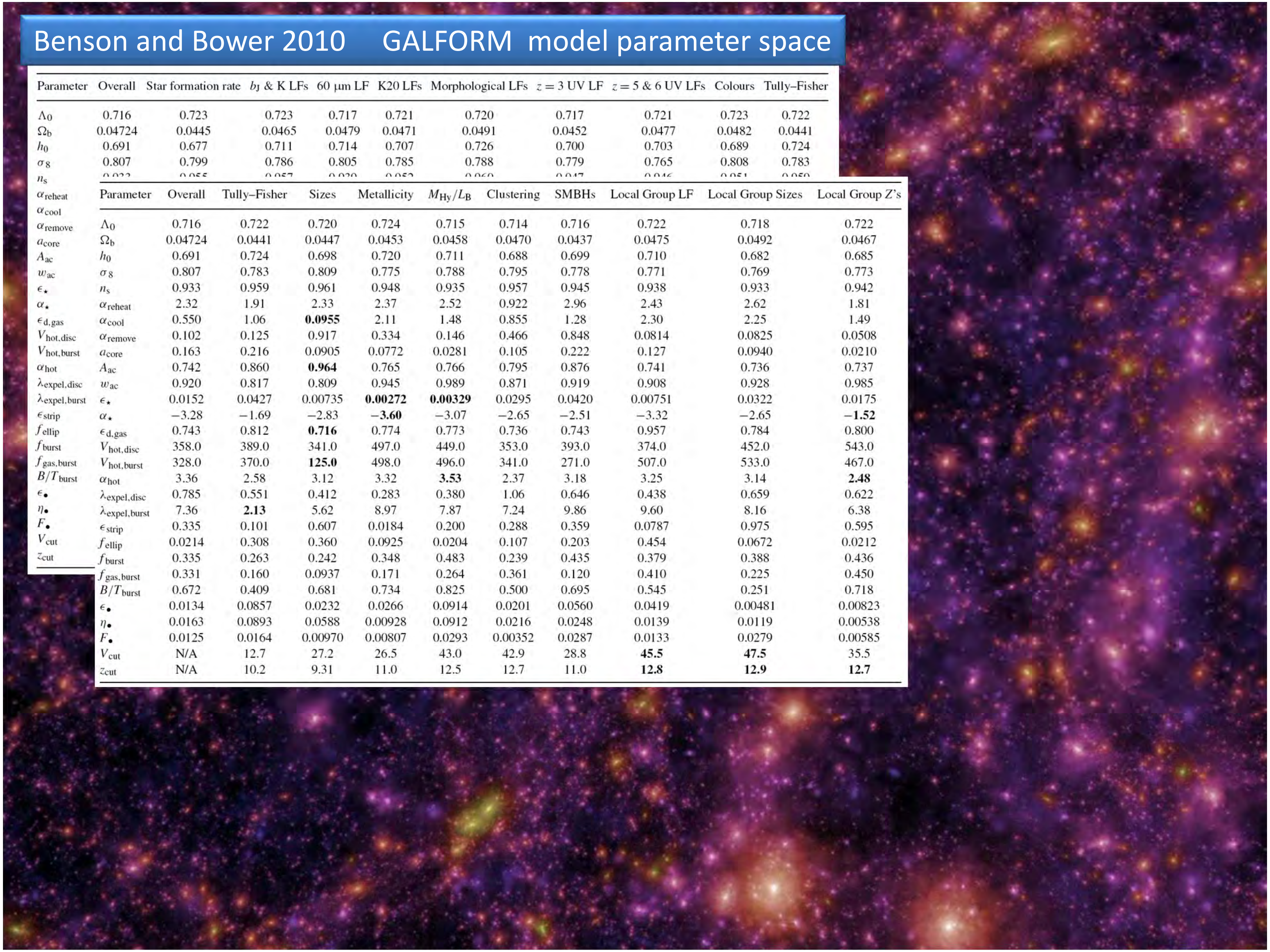


microscopic

The first slice of the CfA Survey 1985

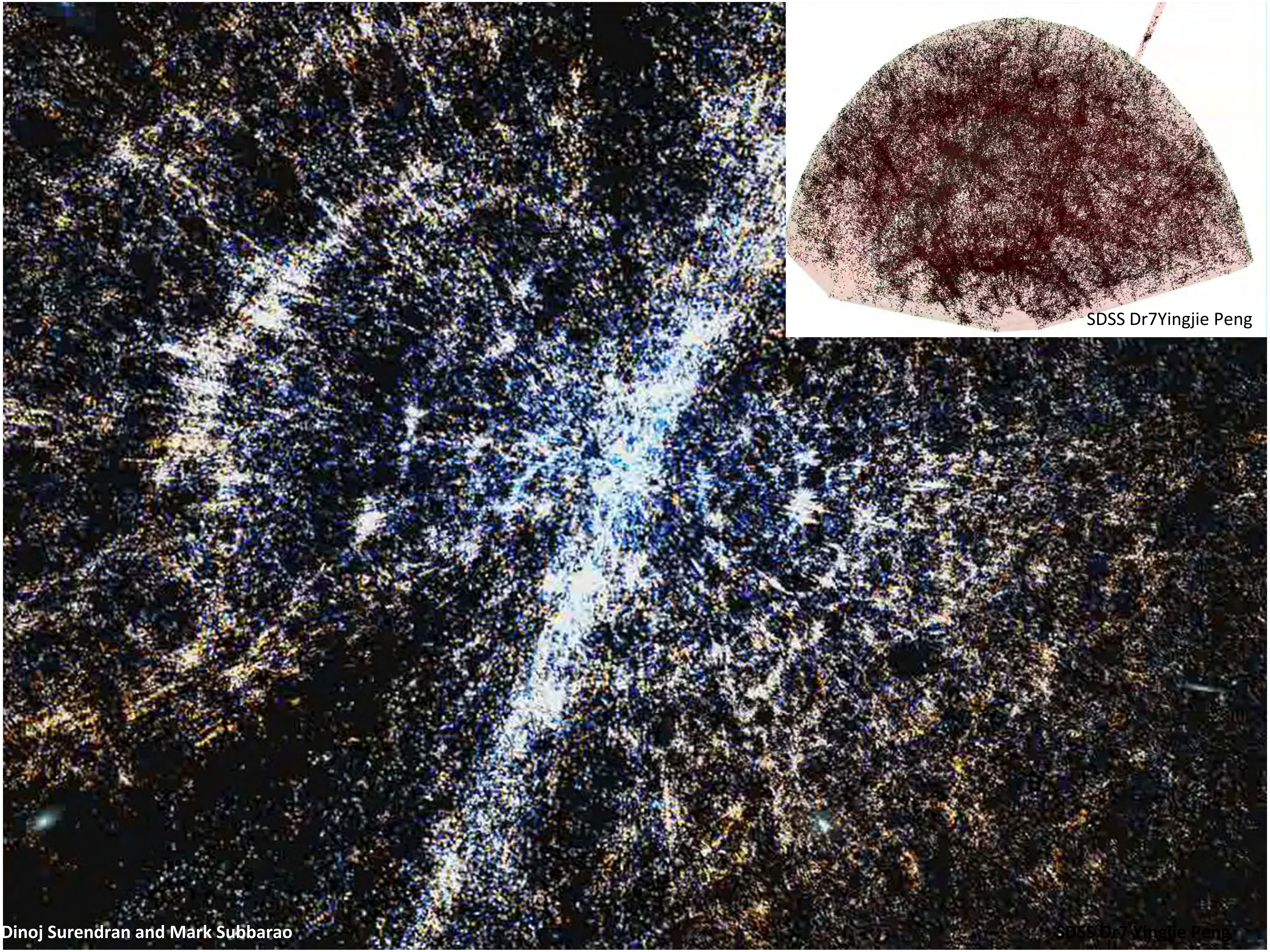


Benson and Bower 2010 GALFORM model parameter space



Parameter	Overall	Star formation rate	b_J & K LFs	60 μm LF	K20 LFs	Morphological LFs	$z=3$ UV LF	$z=5$ & 6 UV LFs	Colours	Tully–Fisher
Λ_0	0.716	0.723	0.723	0.717	0.721	0.720	0.717	0.721	0.723	0.722
Ω_b	0.04724	0.0445	0.0465	0.0479	0.0471	0.0491	0.0452	0.0477	0.0482	0.0441
h_0	0.691	0.677	0.711	0.714	0.707	0.726	0.700	0.703	0.689	0.724
σ_8	0.807	0.799	0.786	0.805	0.785	0.788	0.779	0.765	0.808	0.783
n_s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
α_{reheat}										
α_{cool}										
α_{remove}										
a_{core}										
A_{ac}										
w_{ac}										
$\epsilon_\star$										
$\alpha_\star$										
$\epsilon_{d,gas}$										
$V_{hot,disc}$										
$V_{hot,burst}$										
α_{hot}										
$\lambda_{expel,disc}$										
$\lambda_{expel,burst}$										
ϵ_{strip}										
f_{ellip}										
f_{burst}										
$f_{gas,burst}$										
B/T_{burst}										
$\epsilon_\bullet$										
$\eta_\bullet$										
$F_\bullet$										
V_{cut}										
z_{cut}										

Parameter	Overall	Tully–Fisher	Sizes	Metallicity	M_{HI}/L_B	Clustering	SMBHs	Local Group LF	Local Group Sizes	Local Group Z's
Λ_0	0.716	0.722	0.720	0.724	0.715	0.714	0.716	0.722	0.718	0.722
Ω_b	0.04724	0.0441	0.0447	0.0453	0.0458	0.0470	0.0437	0.0475	0.0492	0.0467
h_0	0.691	0.724	0.698	0.720	0.711	0.688	0.699	0.710	0.682	0.685
σ_8	0.807	0.783	0.809	0.775	0.788	0.795	0.778	0.771	0.769	0.773
n_s	0.933	0.959	0.961	0.948	0.935	0.957	0.945	0.938	0.933	0.942
α_{reheat}	2.32	1.91	2.33	2.37	2.52	0.922	2.96	2.43	2.62	1.81
α_{cool}	0.550	1.06	**0.0955**	2.11	1.48	0.855	1.28	2.30	2.25	1.49
α_{remove}	0.102	0.125	0.917	0.334	0.146	0.466	0.848	0.0814	0.0825	0.0508
a_{core}	0.163	0.216	0.0905	0.0772	0.0281	0.105	0.222	0.127	0.0940	0.0210
A_{ac}	0.742	0.860	**0.964**	0.765	0.766	0.795	0.876	0.741	0.736	0.737
w_{ac}	0.920	0.817	0.809	0.945	0.989	0.871	0.919	0.908	0.928	0.985
$\epsilon_\star$	0.0152	0.0427	0.00735	**0.00272**	**0.00329**	0.0295	0.0420	0.00751	0.0322	0.0175
$\alpha_\star$	−3.28	−1.69	−2.83	**−3.60**	−3.07	−2.65	−2.51	−3.32	−2.65	**−1.52**
$\epsilon_{d,gas}$	0.743	0.812	**0.716**	0.774	0.773	0.736	0.743	0.957	0.784	0.800
$V_{hot,disc}$	358.0	389.0	341.0	497.0	449.0	353.0	393.0	374.0	452.0	543.0
$V_{hot,burst}$	328.0	370.0	**125.0**	498.0	496.0	341.0	271.0	507.0	533.0	467.0
α_{hot}	3.36	2.58	3.12	3.32	**3.53**	2.37	3.18	3.25	3.14	**2.48**
$\lambda_{expel,disc}$	0.785	0.551	0.412	0.283	0.380	1.06	0.646	0.438	0.659	0.622
$\lambda_{expel,burst}$	7.36	**2.13**	5.62	8.97	7.87	7.24	9.86	9.60	8.16	6.38
ϵ_{strip}	0.335	0.101	0.607	0.0184	0.200	0.288	0.359	0.0787	0.975	0.595
f_{ellip}	0.0214	0.308	0.360	0.0925	0.0204	0.107	0.203	0.454	0.0672	0.0212
f_{burst}	0.335	0.263	0.242	0.348	0.483	0.239	0.435	0.379	0.388	0.436
$f_{gas,burst}$	0.331	0.160	0.0937	0.171	0.264	0.361	0.120	0.410	0.225	0.450
B/T_{burst}	0.672	0.409	0.681	0.734	0.825	0.500	0.695	0.545	0.251	0.718
$\epsilon_\bullet$	0.0134	0.0857	0.0232	0.0266	0.0914	0.0201	0.0560	0.0419	0.00481	0.00823
$\eta_\bullet$	0.0163	0.0893	0.0588	0.00928	0.0912	0.0216	0.0248	0.0139	0.0119	0.00538
$F_\bullet$	0.0125	0.0164	0.00970	0.00807	0.0293	0.00352	0.0287	0.0133	0.0279	0.00585
V_{cut}	N/A	12.7	27.2	26.5	43.0	42.9	28.8	**45.5**	**47.5**	35.5
z_{cut}	N/A	10.2	9.31	11.0	12.5	12.7	11.0	**12.8**	**12.9**	**12.7**


SDSS Dr7Yingjie Peng
Dinoj Surendran and Mark Subbarao
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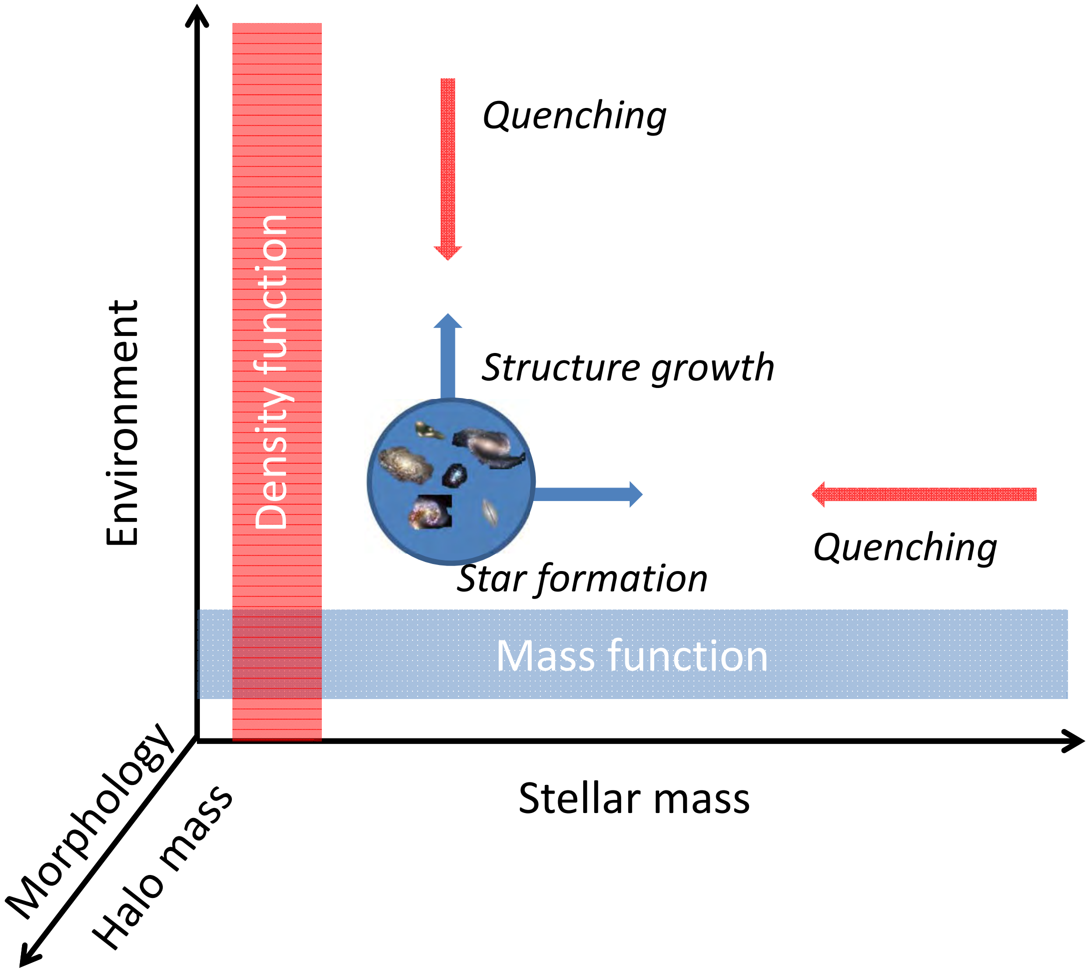
Galaxy Evolution as a Dynamic Process



All from the point of view of the *population*

- **Structure-formation**
- **Star-formation**
- **Merging**
- **Quenching**

Continuity Equation:

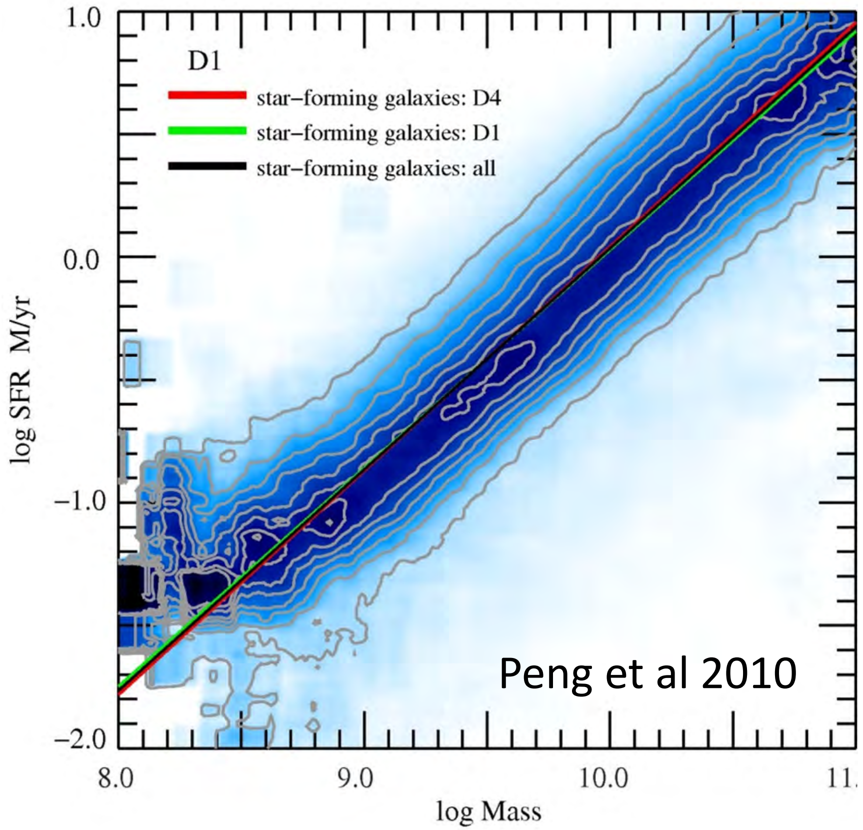
$$\frac{\partial \phi_b(m,\rho)}{\partial t} + \left(\frac{\partial}{\partial \log M}\hat{m} + \frac{\partial}{\partial \log \rho}\hat{\rho}\right) \bullet \left[\phi_b(m,\rho)\left(\frac{\partial}{\partial \log M}\hat{m} + \frac{\partial}{\partial \log \rho}\hat{\rho}\right)\right] = -(\eta_m + \eta_\rho)\phi_b(m,\rho)$$

Main-Sequence of star forming galaxies

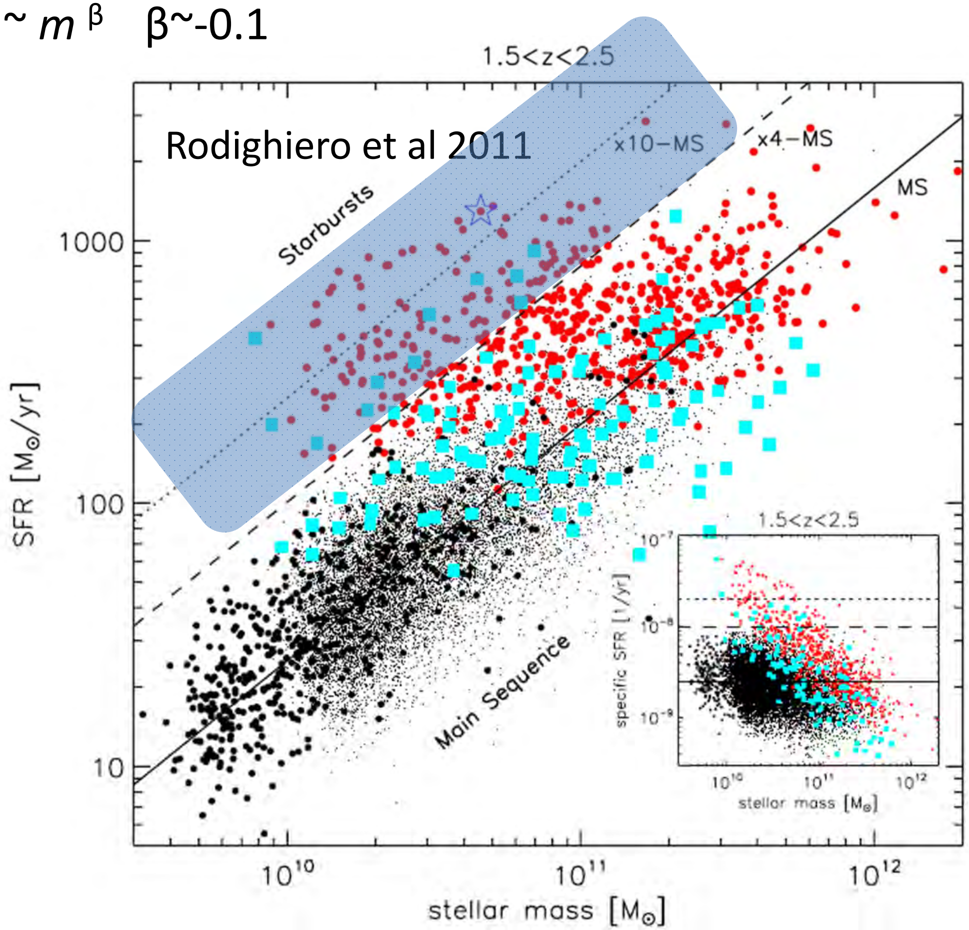
sSFR is a tight but weak function of mass at all epochs z≤2 for most star forming galaxies

e.g. Noeske et al (2007), Salim et al (2007), Elbaz et al (2007) Daddi et al (2007), Gonzalez et al (2009), Panella et al (2009), Peng et al (2010), Rodighiero et al 2011

$sSFR \sim m^{\beta}$ β~-0.1



Hα star formation rates in SDSS at z ~0

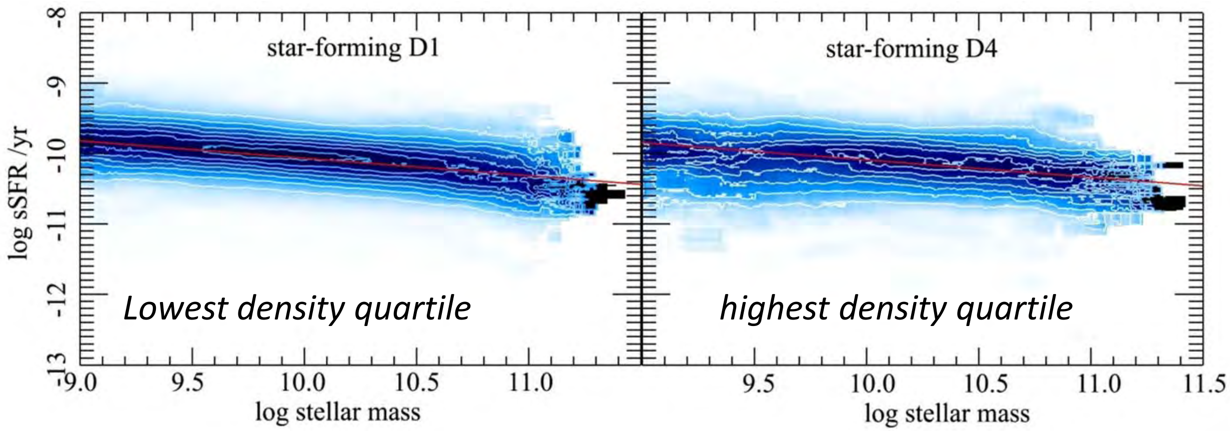


Starburst galaxies represent only 2% of star-forming galaxies and account for only 10% of the cosmic SFR density at $z \sim 2$.

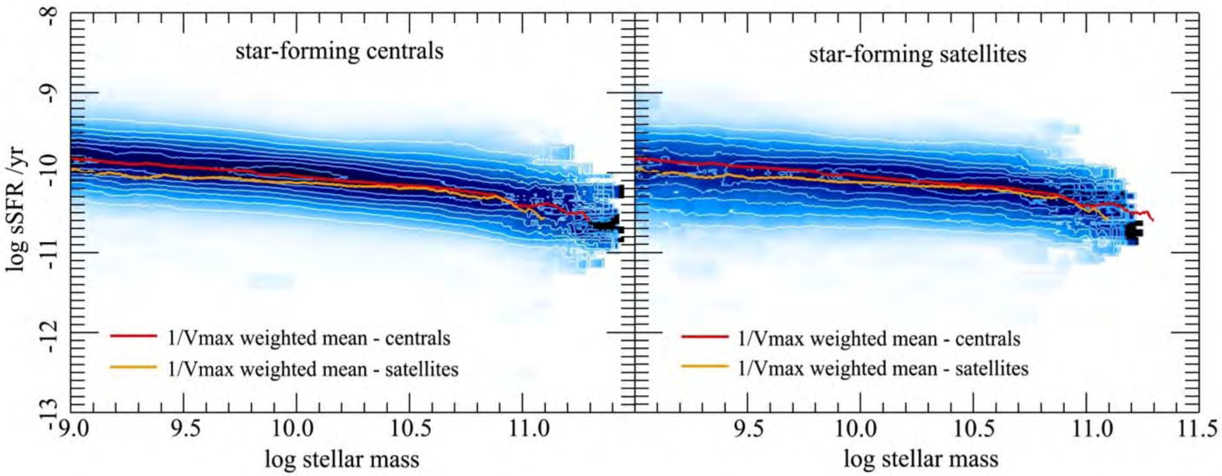
sSFR of star forming galaxies does not depend on environment (at least at z<1)

Peng et el (2010, 2011)

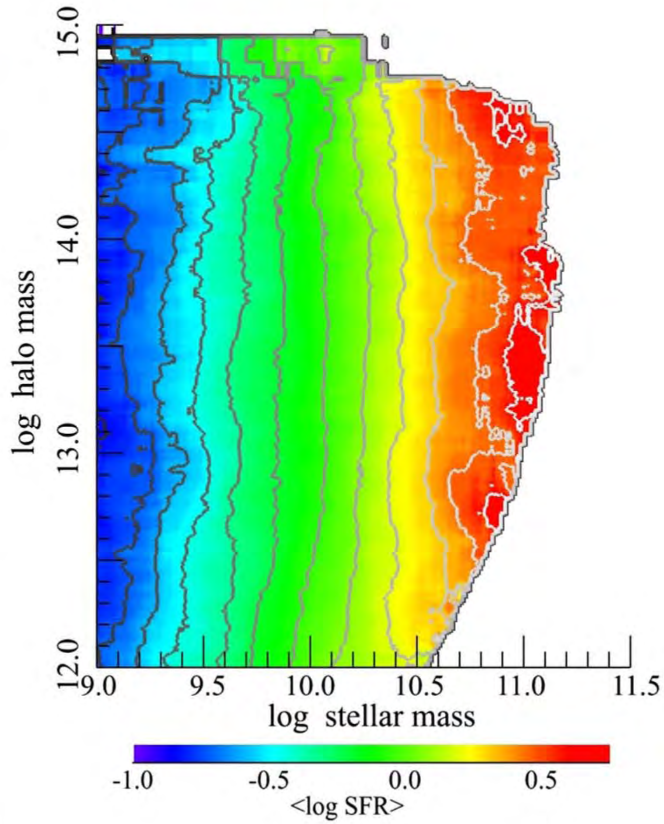
over-density



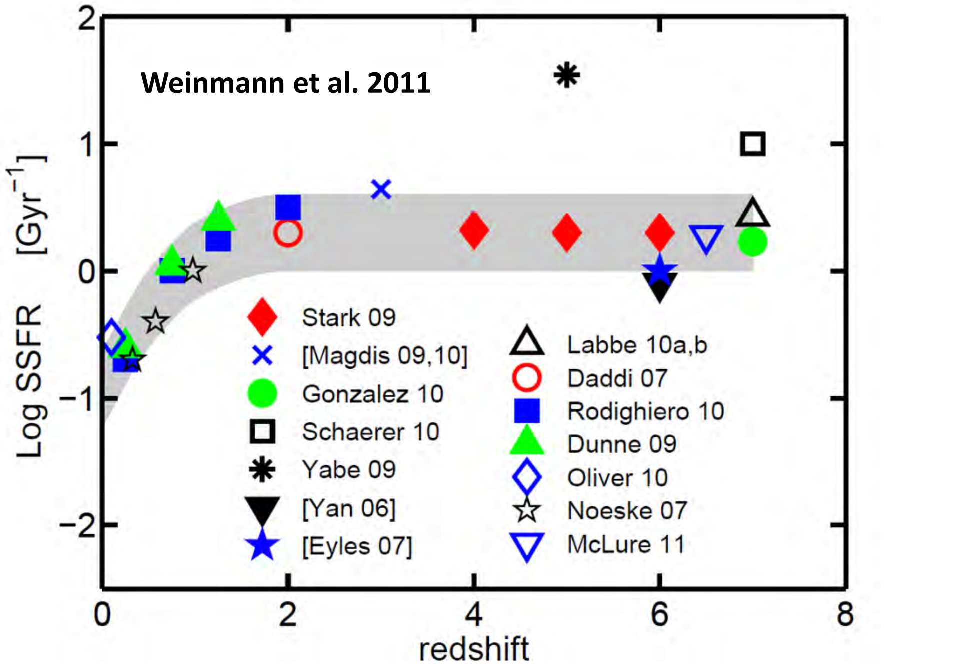
central/satellite



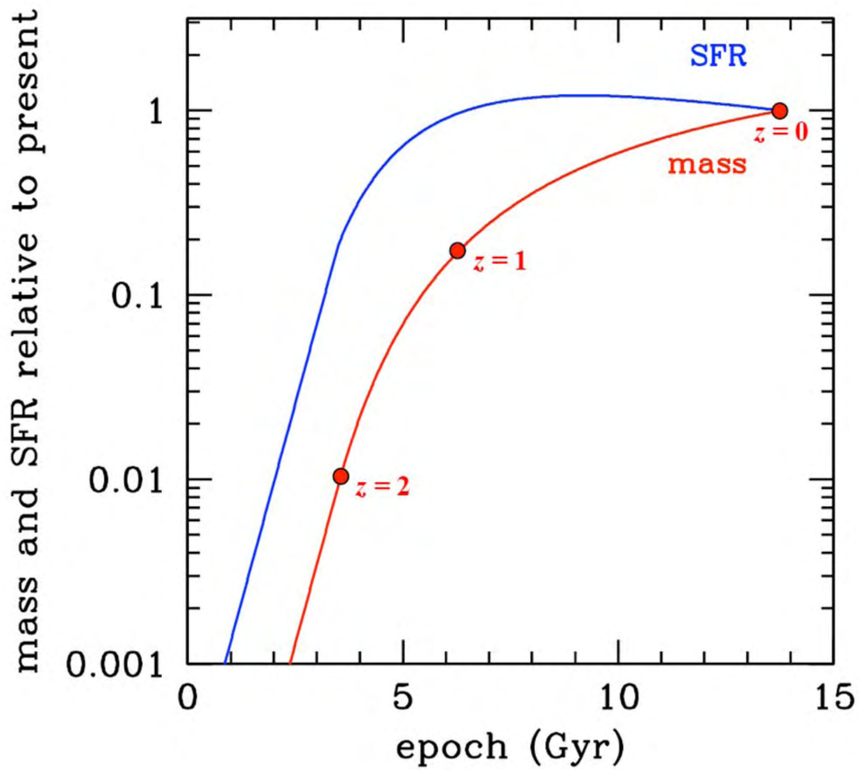
dark matter mass of halo



The growth of stellar mass through star formation



Renzini et al. 2009, Peng et al. 2010



$$\mathrm{sSFR}(m,t) = \frac{1}{\tau(m,t)}$$
$$= 2.5 \left(\frac{m}{10^{10}\ M_\odot}\right)^{\beta} \left(\frac{t}{3.5\ \mathrm{Gyr}}\right)^{-2.2}\ \mathrm{Gyr}^{-1}$$

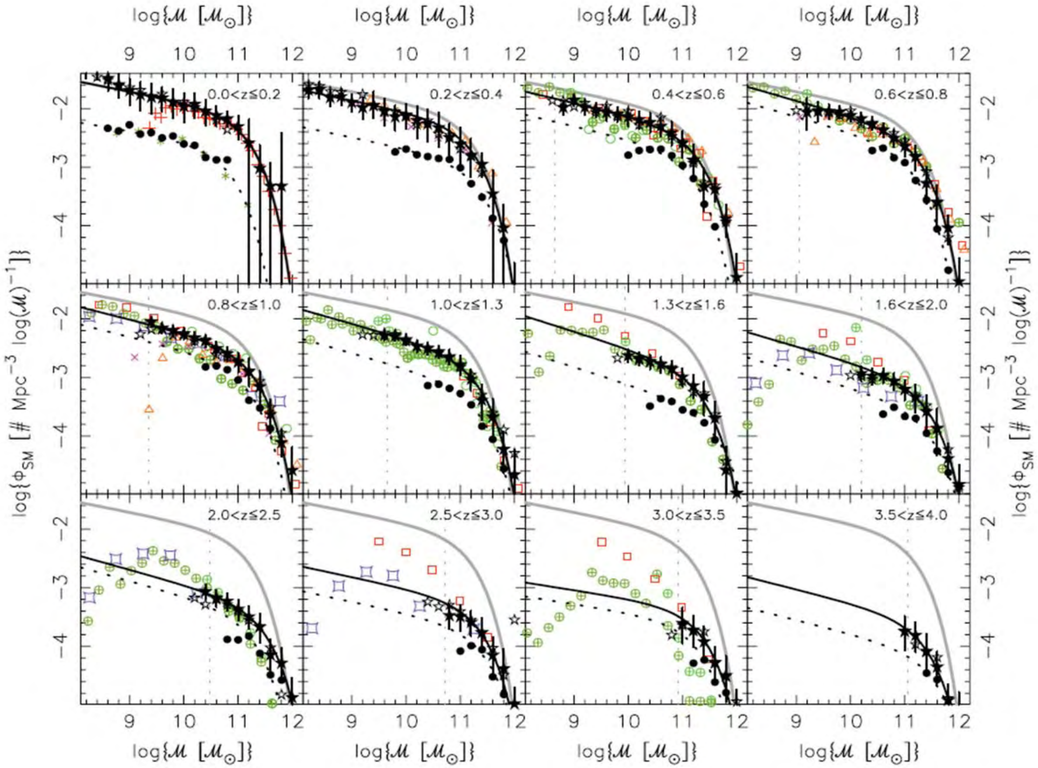
$$M(t) = \int_{t_0}^{t} SFR(t)\,dt$$
$$= M(t_0)e^{\int_{t_0}^{t} sSFR(t)\,dt}$$

If galaxies are not quenched, this implies
Δlog m_{star} ~ 0.8 since z = 1
Δlog m_{star} ~ 2.0 since z = 2

Remarkable observational fact: Schechter M^* and α are constant for *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)

Ilbert et al (2010): COSMOS photo-z

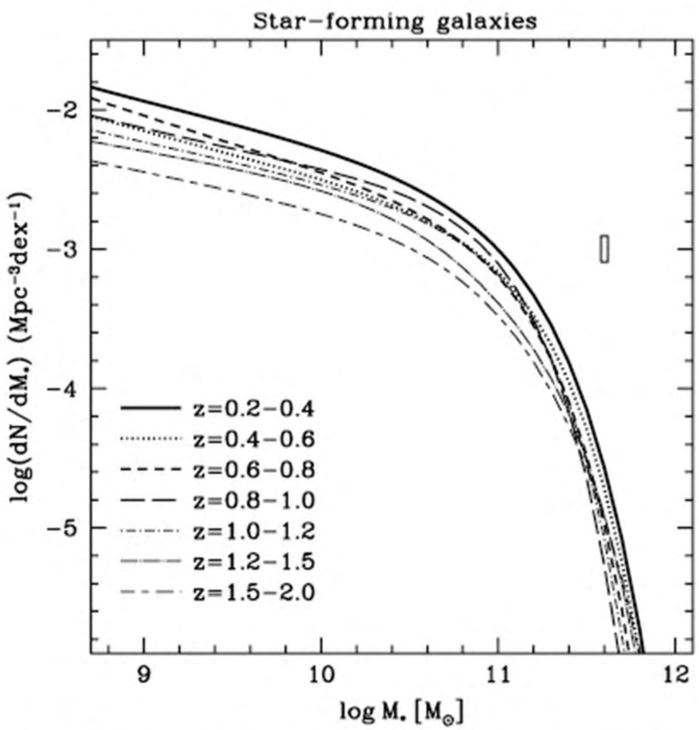


Figure 18. MF of "star-forming" galaxies (sum of intermediate and high activity galaxies) from $z = 2$ to $z = 0.2$. The vertical box quantifies the cosmic variance at $z = 0.2$–0.4 (Scoville et al. 2007).

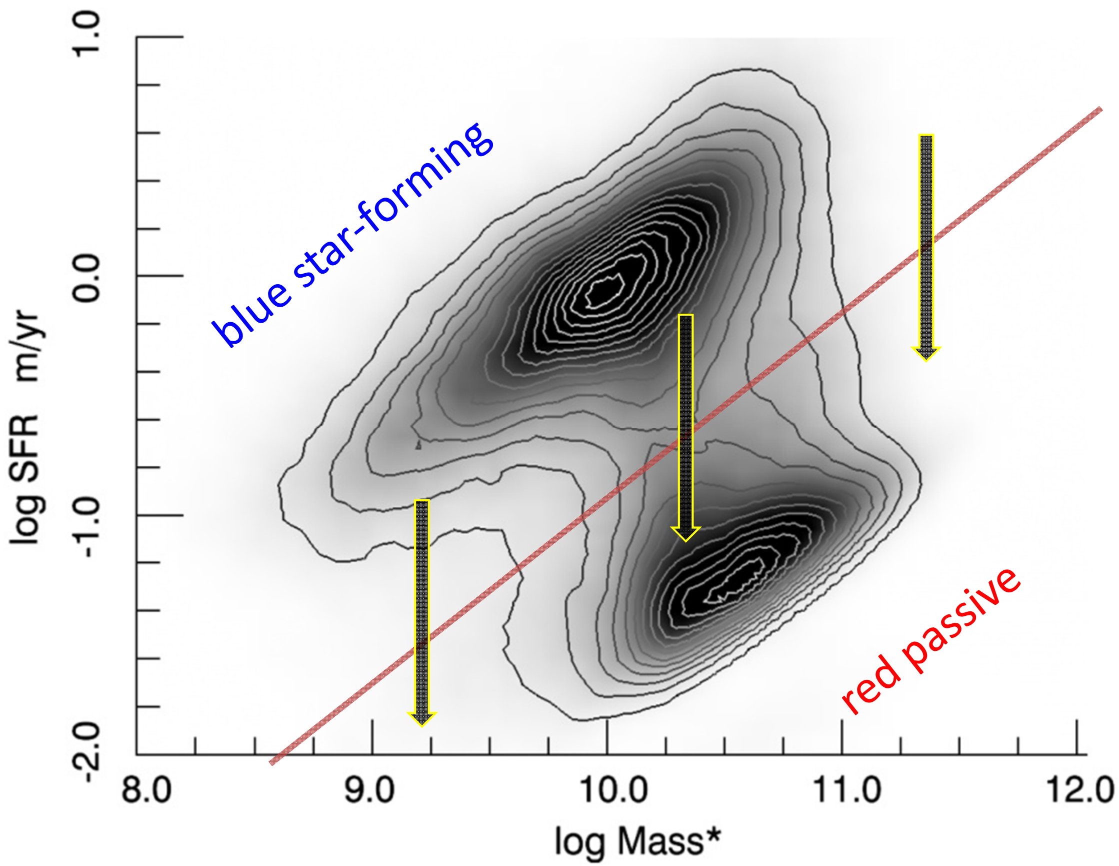
Constancy of shape of $\phi(m)$ of SF galaxies requires very careful quenching!

Quenching

Star-formation seems easy…

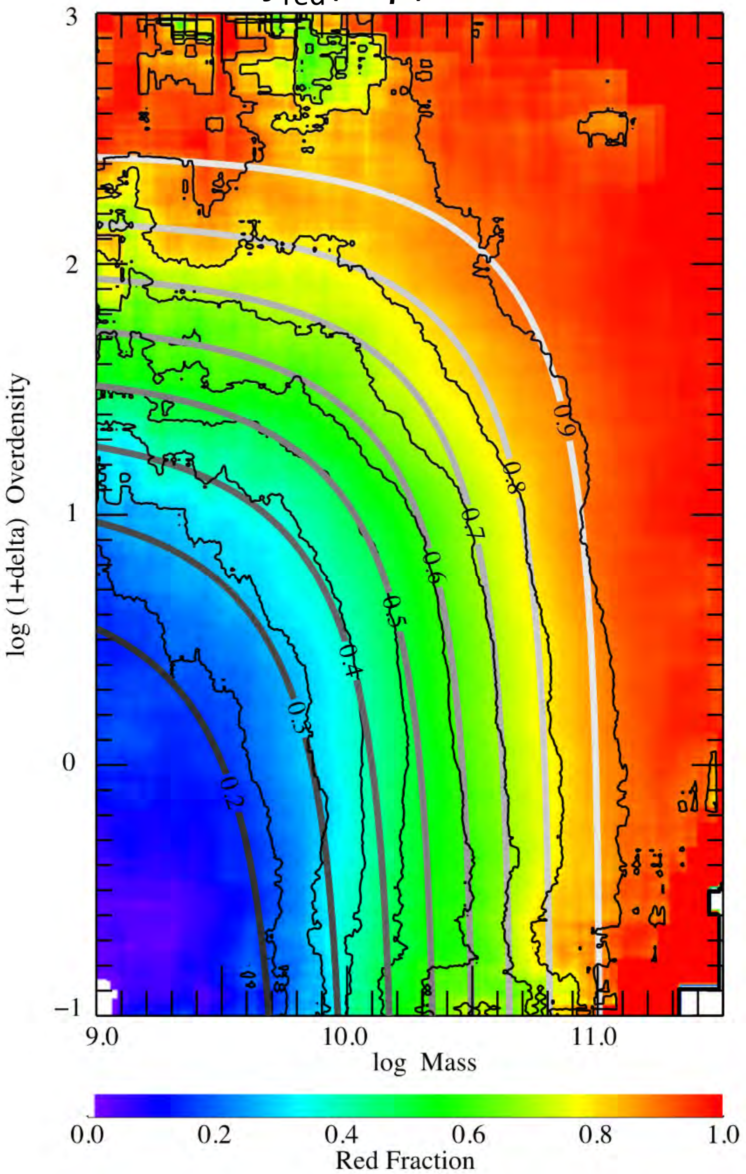
Key process in galaxy evolution is ***Quenching***

What process(es) take(s) galaxies off the Main Sequence, and keeps their star-formation low for long periods of time?



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

$f_{red}(m,\rho)$ in SDSS



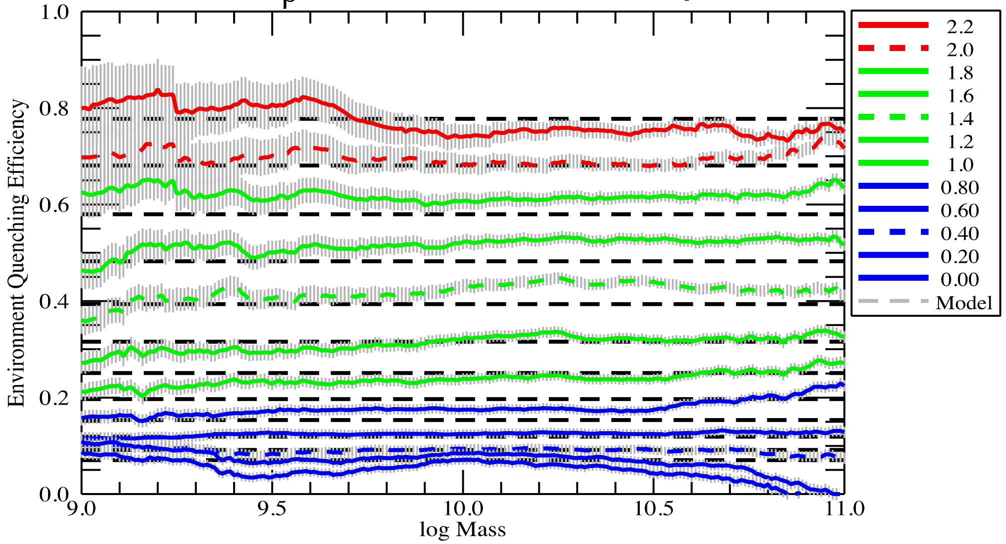
"Relative environment-quenching efficiency"

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

"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 $f(m)$ at different ρ



Environment-quenching is independent of mass, mass-quenching is independent of environment: two independent quenching processes

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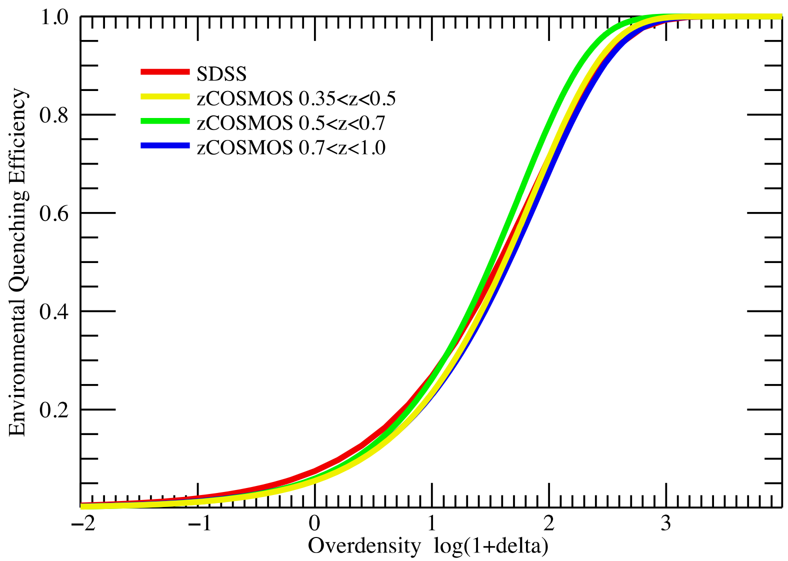
$$\varepsilon_\rho(\rho,\rho_0,m) = \frac{f_{red}(\rho,m) - f_{red}(\rho_0,m)}{f_{blue}(\rho_0,m)}$$

"Relative mass-quenching efficiency"

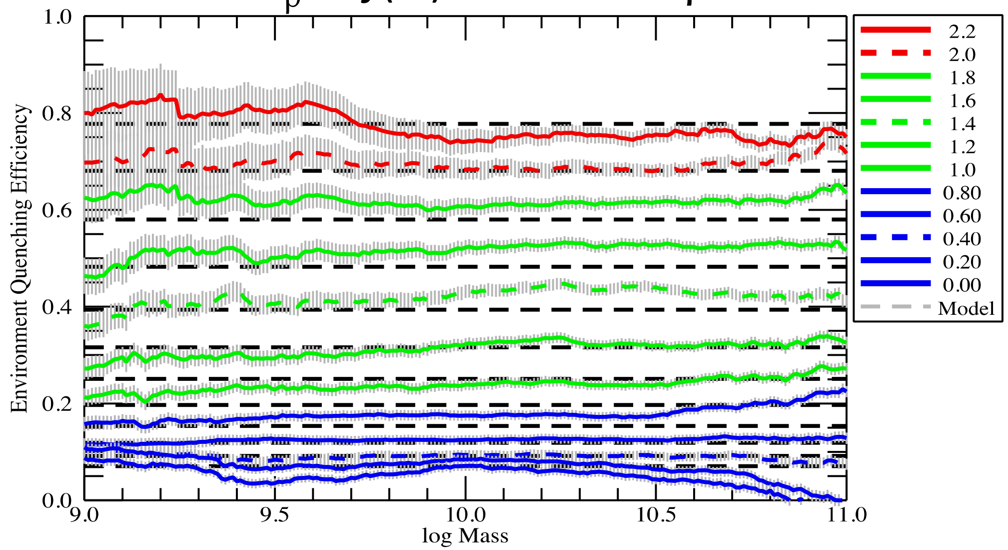
$$\varepsilon_m(m,m_0,\rho) = \frac{f_{red}(m,\rho) - f_{red}(m_0,\rho)}{f_{blue}(m_0,\rho)}$$

Environment-quenching is also independent of epoch in zCOSMOS, at least to z ~ 1



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

ε_ρ as $f(m)$ at different ρ



Environment-quenching is independent of mass, mass-quenching is independent of environment: two independent quenching processes

two distinct phenomena: $sSFR(m,\rho,t)$ 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
Uniformity of the star-forming galaxies	**Quenching**

Peng et al 2010 “Model”

3-4 key observations

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

require

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 the “clock” but do not affect final outcome

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

Continuity Equation

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

overall quenching rate (time^{-1})

mass quenching (independent of environment)

environment quenching effects (independent of mass)

establishes and controls precise Schechter mass functions of galaxies

establish and maintain all environment effects limited to satellites only (Peng et al 2011)

There are no non-observational parameters in the model

Model Implications and Predictions

- Schechter function of star-forming galaxies
- Double-Schechter function of passive galaxies and all galaxies
- f_{red} (mass, environment, time)
- evolutionary histories of today's passive galaxies
- the "anti-hierarchical" run of mean age with mass for passive galaxies
- satellites-quenching
- the role of halo mass
- mass- function evolution, star formation history and stellar mass assembly history
- the amount of "dry merging"
- galaxy major and minor merger rate
- Mass-function of the transient galaxies (e.g. AGN mass function)
- An inevitable evolution of the mass function

The origin of the Schechter function

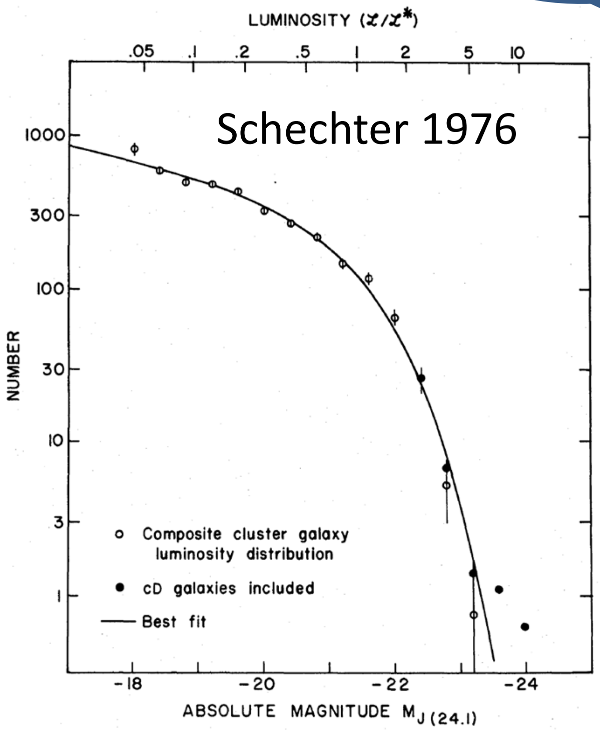
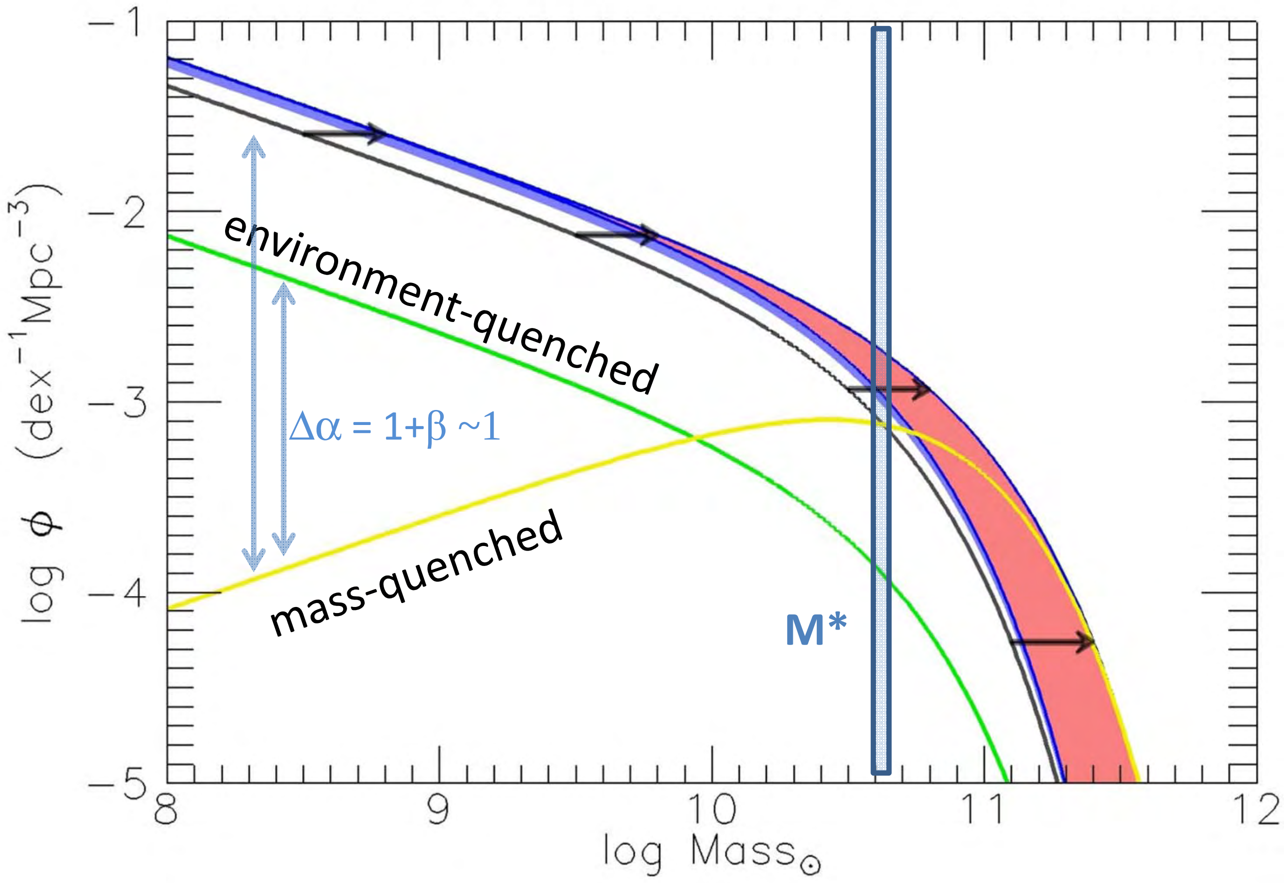


FIG. 2.—Best fit of analytic expression to observed composite cluster galaxy luminosity distribution. Filled circles show the effect of including cD galaxies in composite.

Binggeli's (1987) cartoon of Paul Schechter and his function. Quite why it has this form buries ***details*** under foot.

The origin of the Schechter function



Mass-quenching establishes a perfect Schechter function for Star-forming galaxies

Mass increase due to SF

Constant M* and α (z<~2)

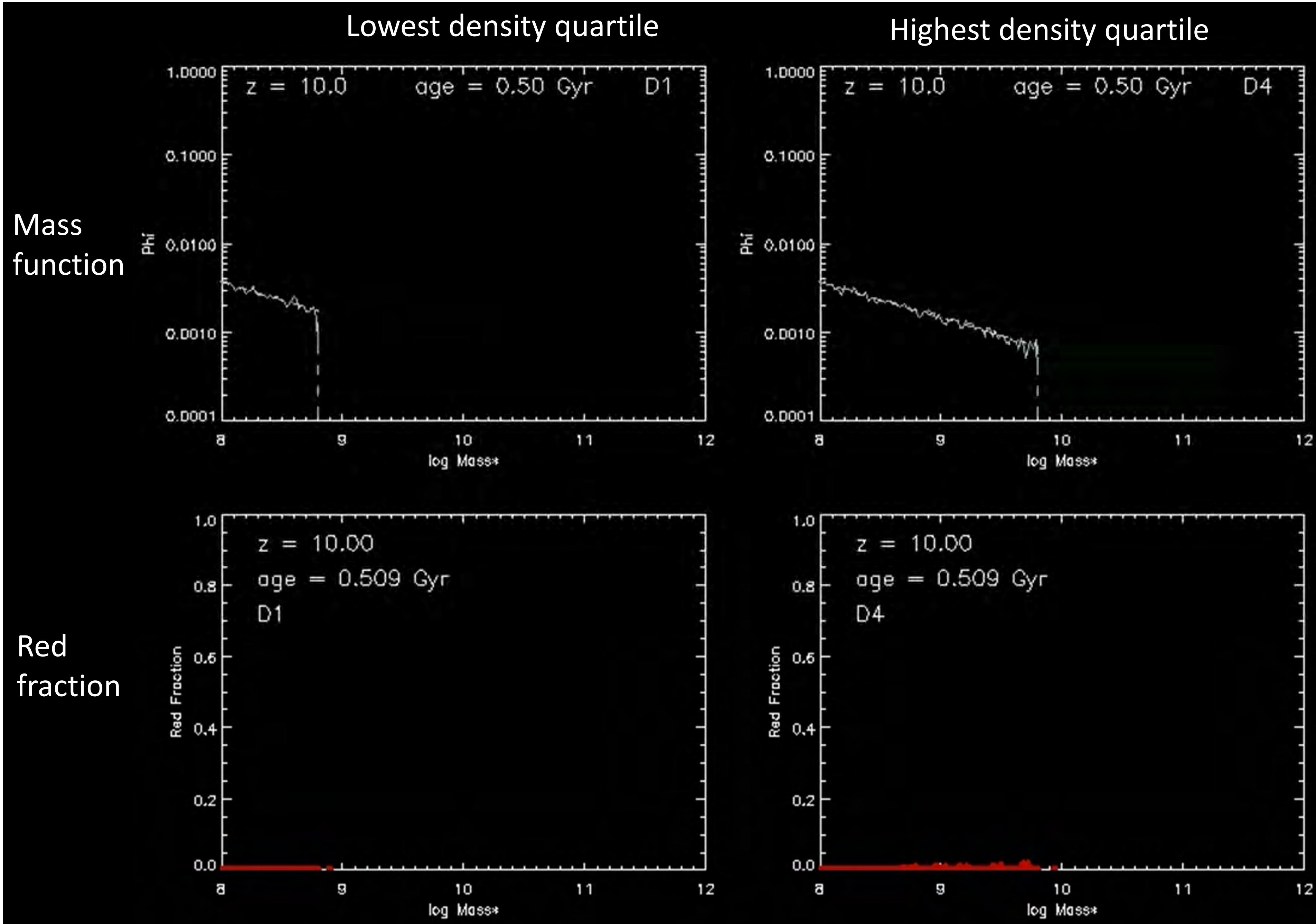
mass-quenching

environment-quenching

post-quenching merging

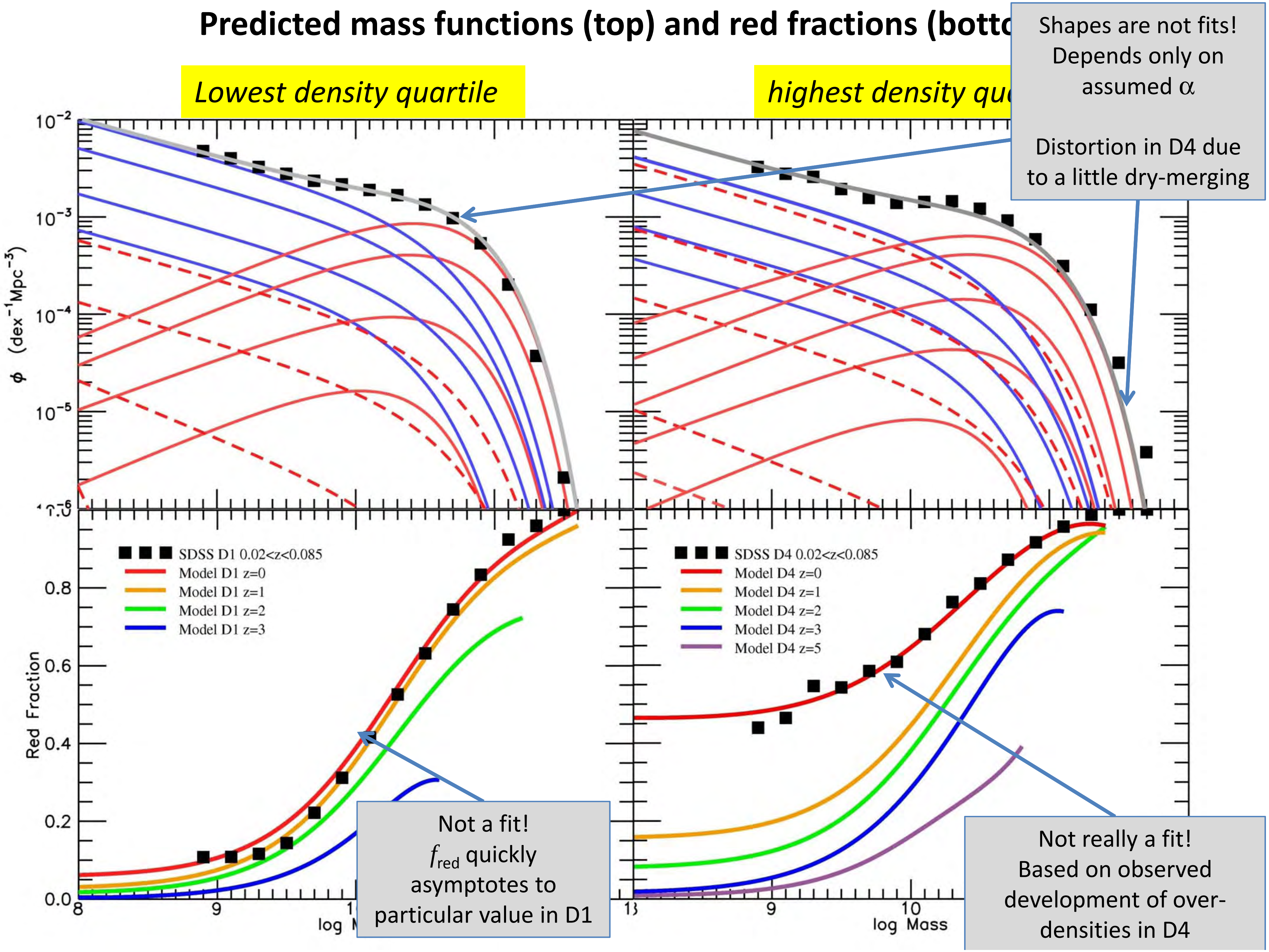
increases the M* of the

passive galaxies



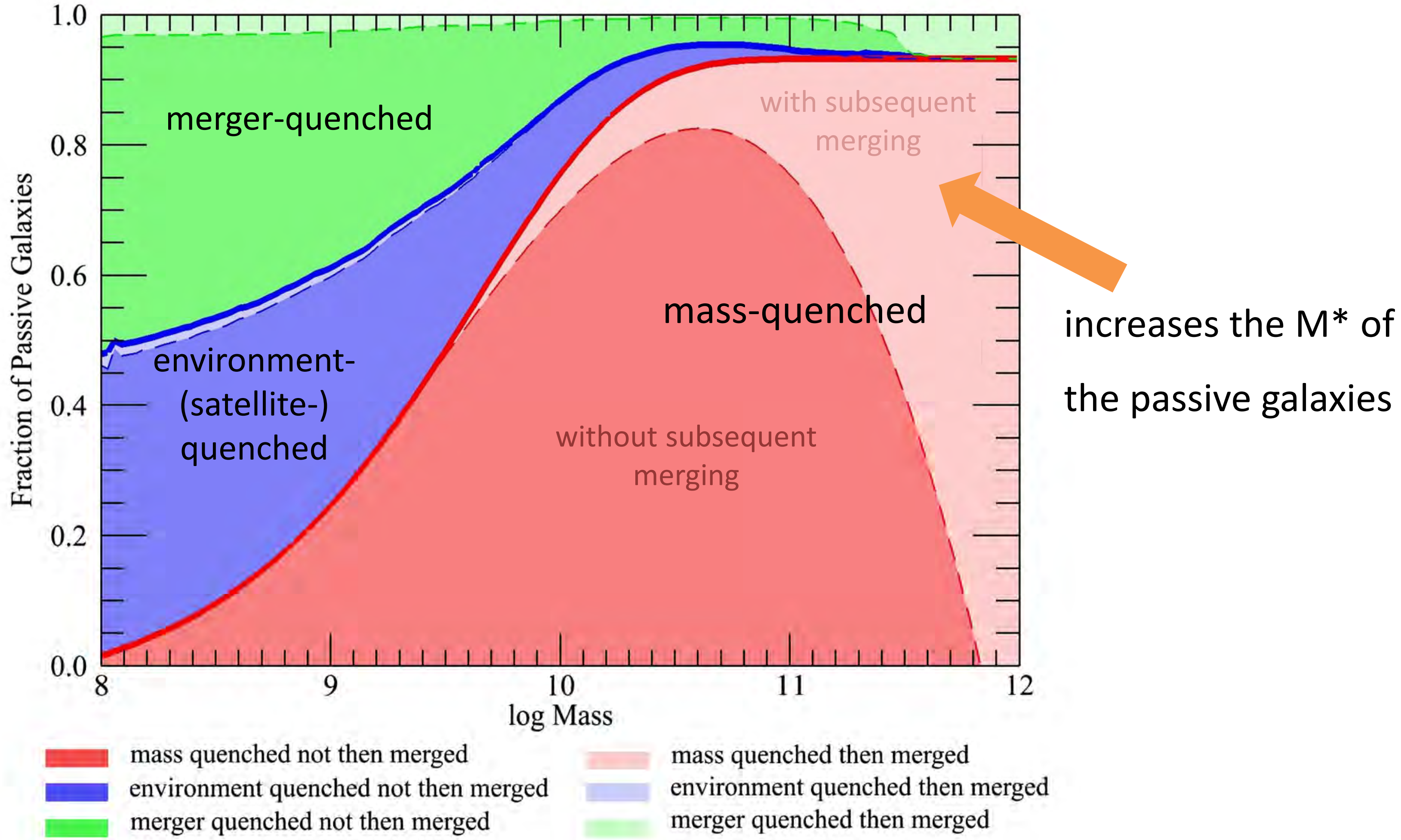
Movie from Peng et al (2010), $\alpha_s = -1.4$ and $\beta = 0$ assumed

Predicted mass functions (top) and red fractions (botto

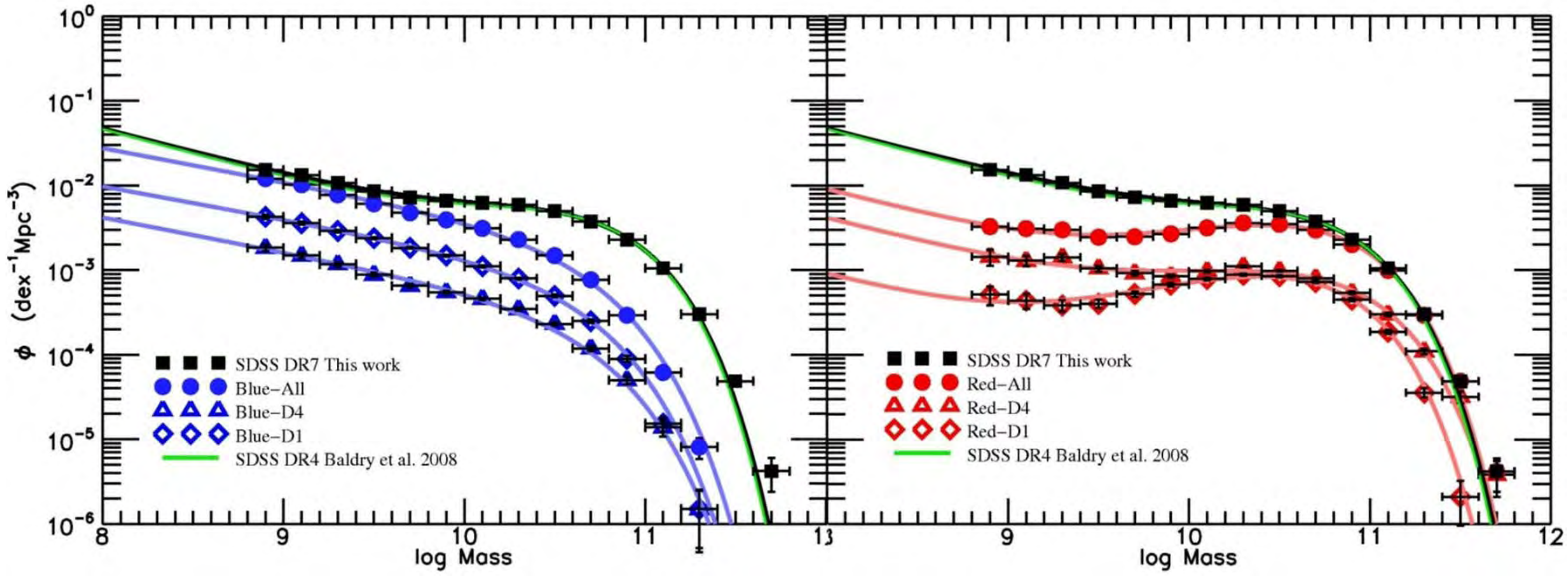


Merging Histories of today's passive galaxies

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



Observational Tests with SDSS



	Log($M^*/M_\odot$)	$\phi_1^*/10^{-3}$Mpc^{-3}	α_1	$\phi_2^*/10^{-3}$Mpc^{-3}	α_2
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)

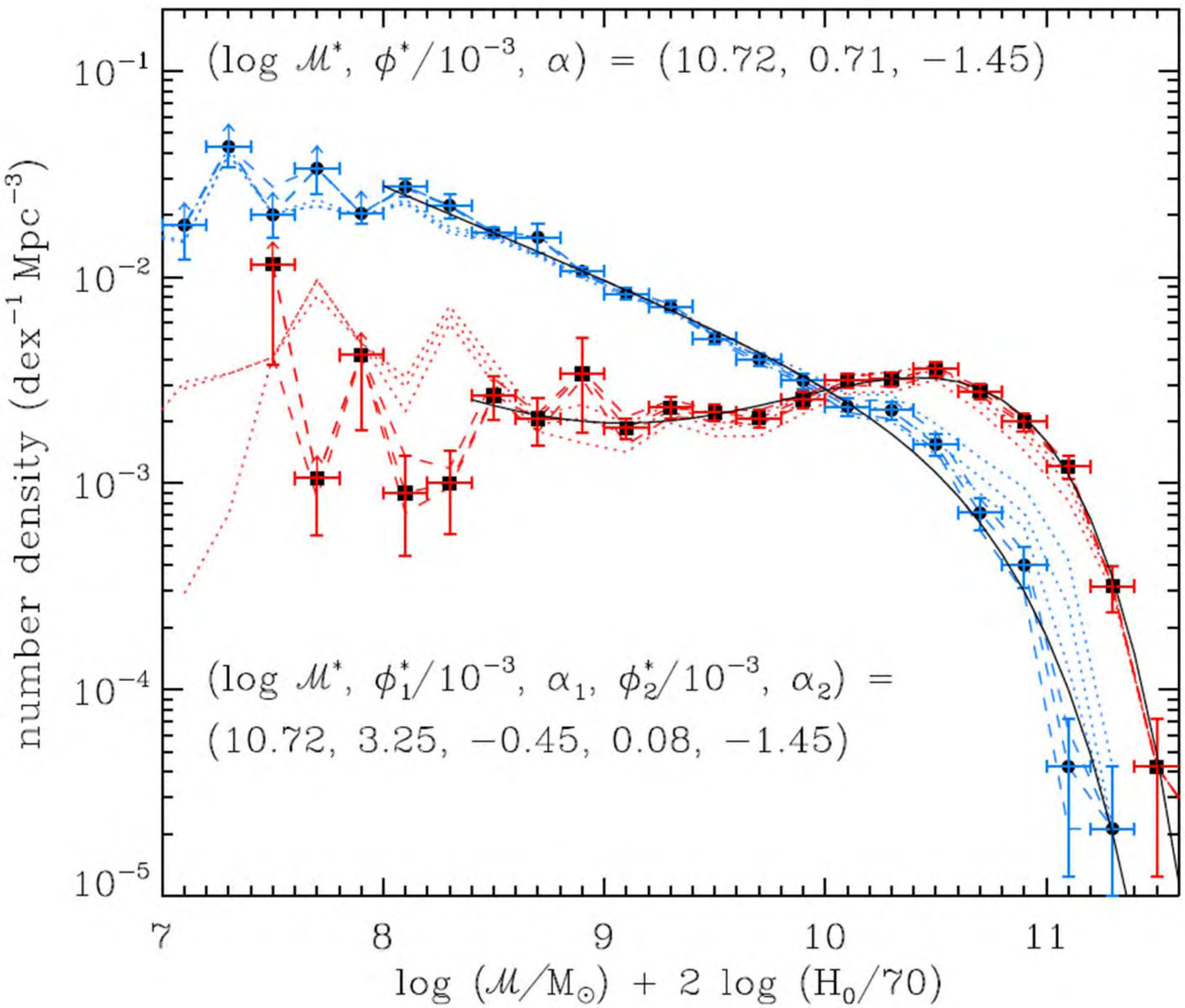
Single and Double Schechter functions for SF and passive? Double for total? ✔

M* and α the same for SF in D1 and D4? ✔

M* the same for SF and passive in D1, α differs by Δα = 1 (for β = 0)? ✔

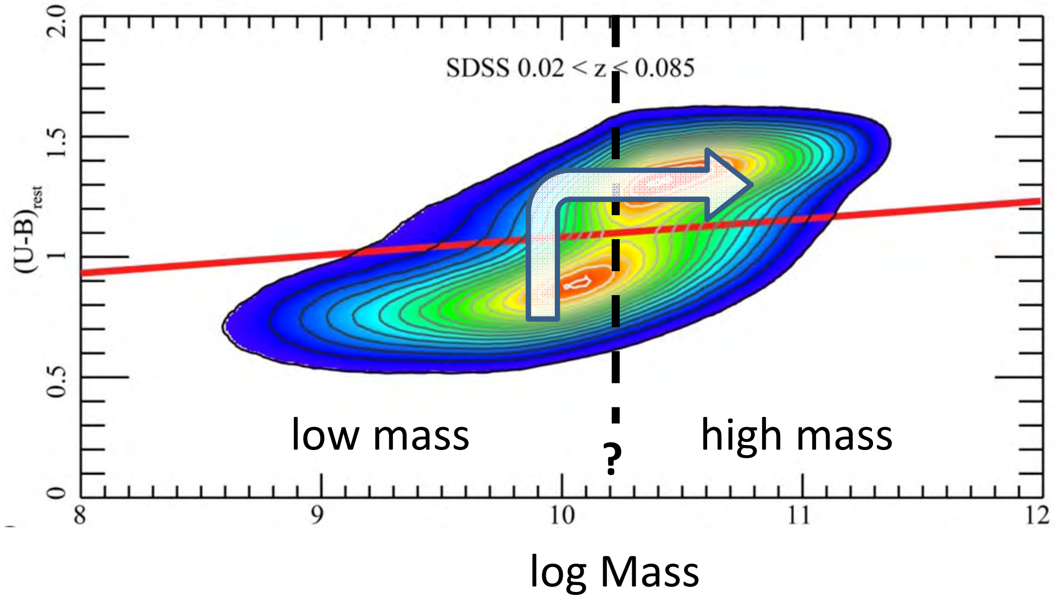
Post-quenching merging modifies M* and α for passives in D4? ✔

Baldry et al (2011) GAMA z < 0.06



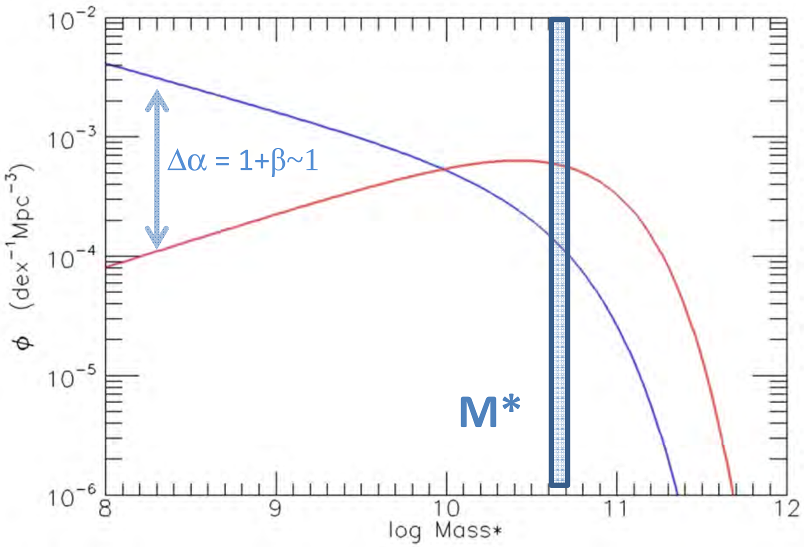
Baldry et al 2011:
This supports the empirical picture, quenching model, for the origin of the Schechter function by Peng et al. (2010)

Two common misconceptions



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

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

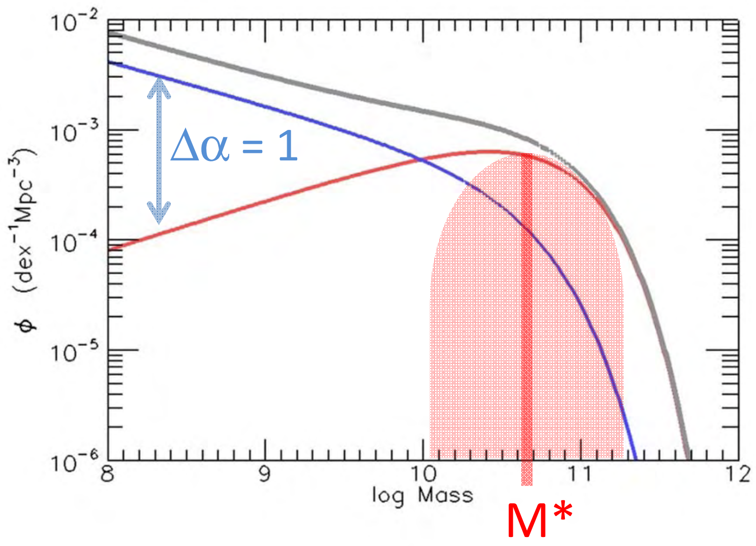


2. Do we require a lot of dry merging to populate red sequence given an absence of bright blue galaxies ?

No, the red passive population is populated by quenching of star forming galaxies at the ***same*** mass.

What's is "mass-quenching"? Is our "mass-quenching" simply rephrasing an underlying "mass-limiting" law?

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



$$\eta = \mu \bullet \mathrm{SFR} \quad \Longleftrightarrow \quad \frac{dP}{dt} = -\eta P = -\mu \frac{dm}{dt} P$$

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

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

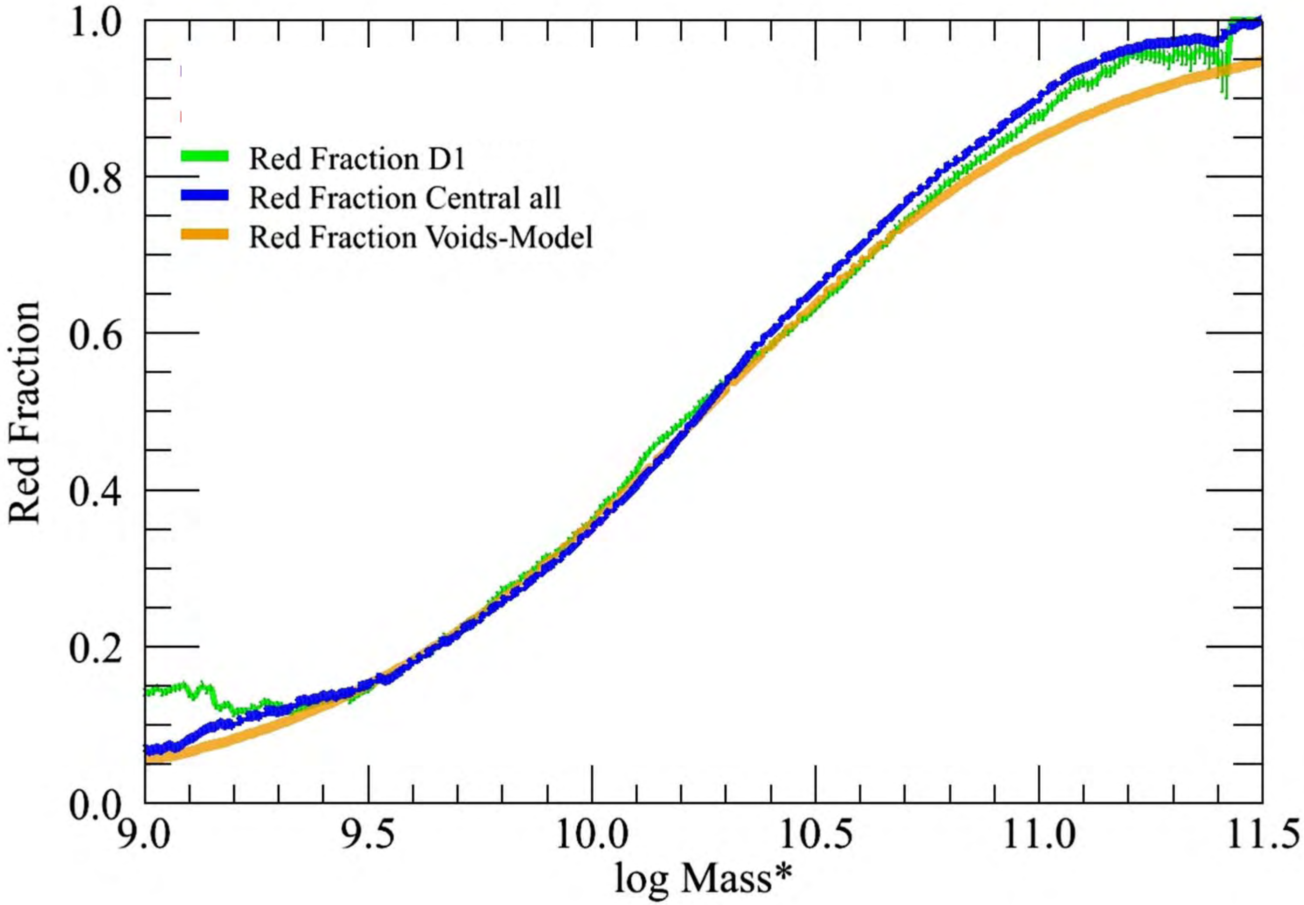
Survival probability is simple f (m), not of the detailed SFR history.

Is this just representing a limit to the (stellar) mass of a galaxy, or a limit to the halo mass able to support stars?

But why should a mass-limiting law so accurately reproduce the Schechter function with $\Delta\alpha$ = 1? i.e. why is P(m) exponential?

Any "second parameter" controlling m_{lim} must be <u>strictly</u> independent of environment

Environment-quenching as satellite quenching



Peng et al. 2011

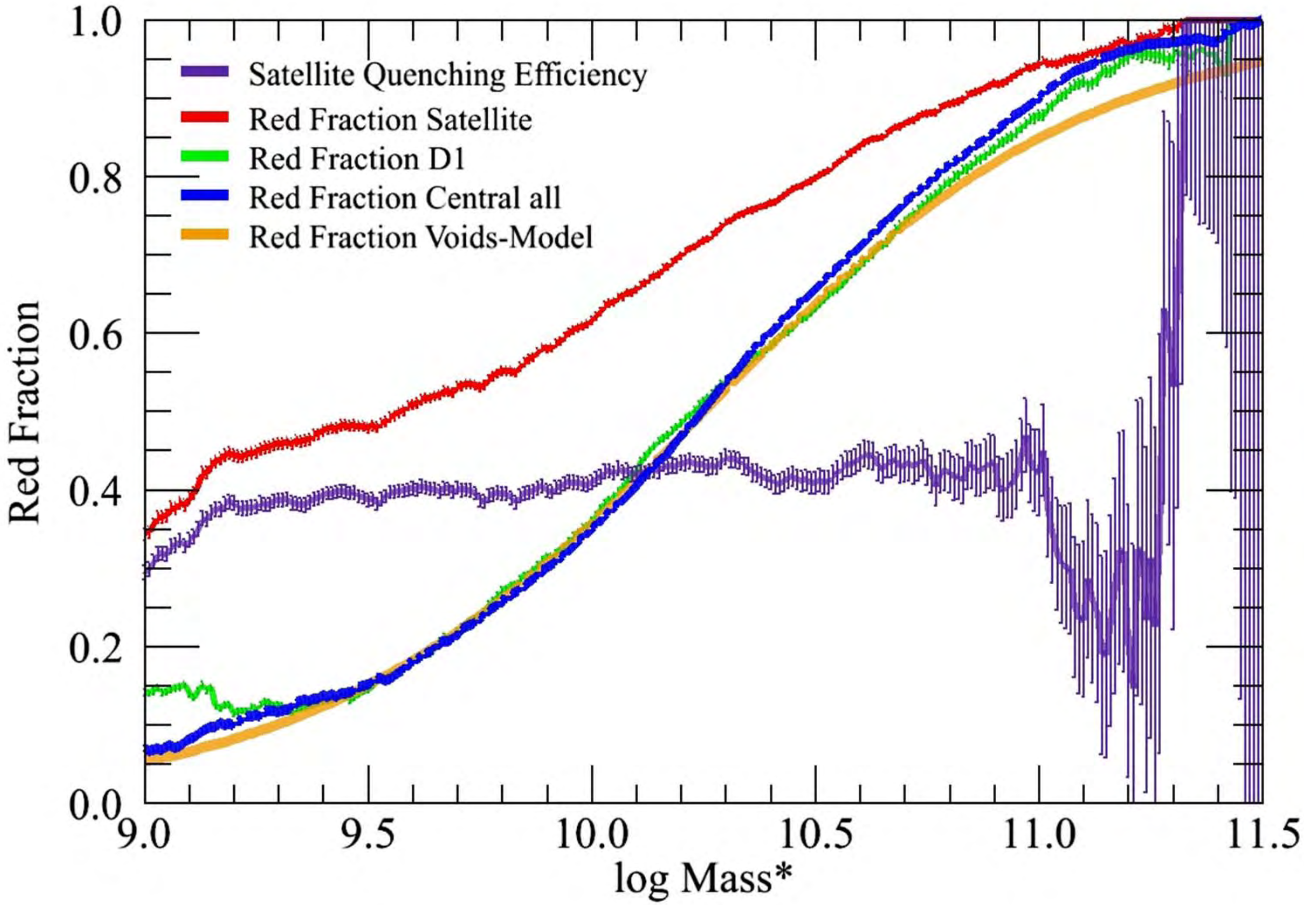
mass-quenching efficiency –
f_{red} in the most under dense regions

$$\varepsilon_m = f_{red}(m, \rho_0) = \frac{1}{1-(1+\alpha_s)\frac{M^*}{m}}$$

log M* ~ 10.6

α_s ~ -1.4

Environment-quenching as satellite quenching



Peng et al. 2011

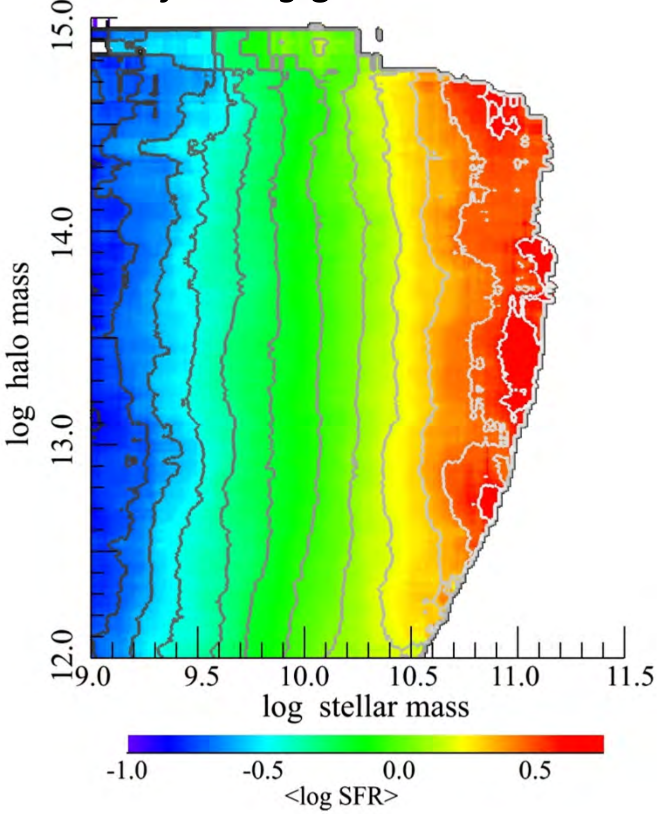
environment averaged satellite – quenching efficiency

$$\bar{\varepsilon}_{sat}(m) = \frac{\bar{f}_{sat,red}(m) - \bar{f}_{cen,red}(m)}{\bar{f}_{cen,blue}(m)}$$

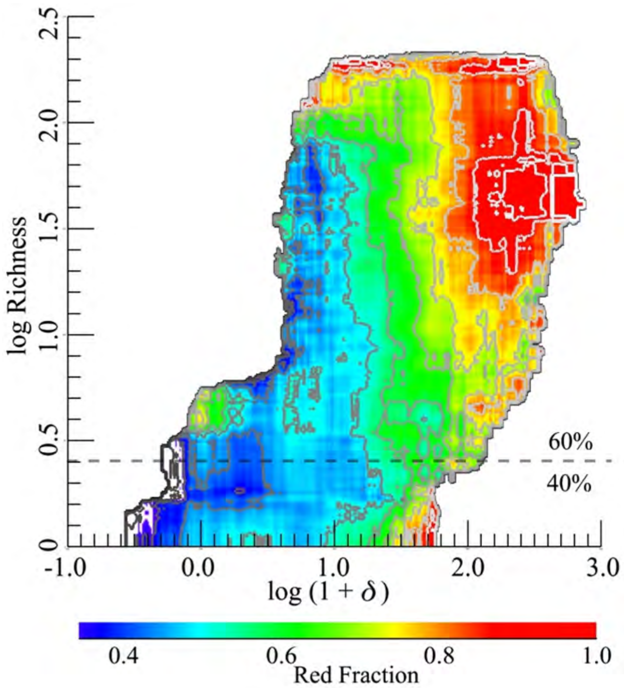
$$\bar{\varepsilon}_{sat} \sim 40\%$$

the role of the dark-matter haloes

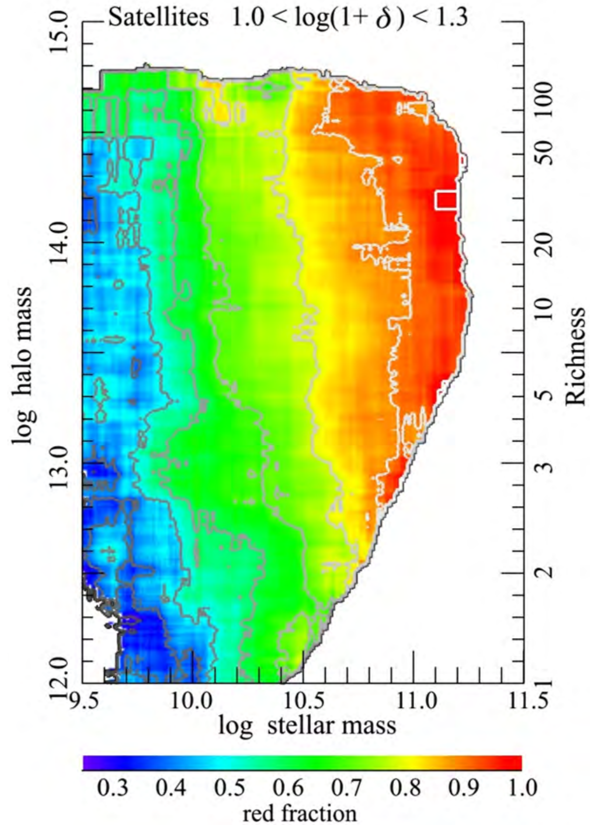
in control of the SFR of the *star-forming* galaxies



in control of the environment-quenching



in control of the mass-quenching

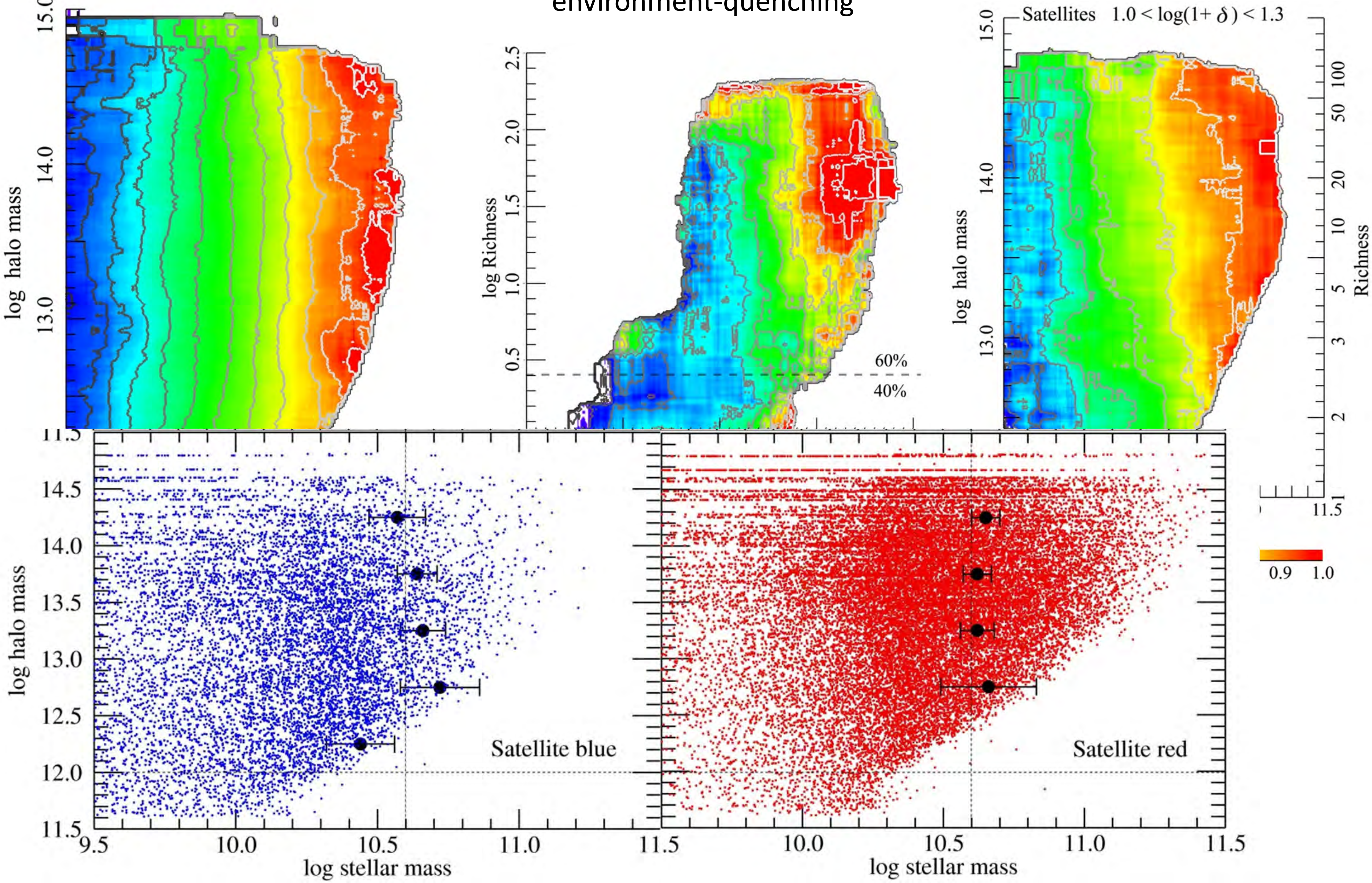


the role of the dark-matter haloes

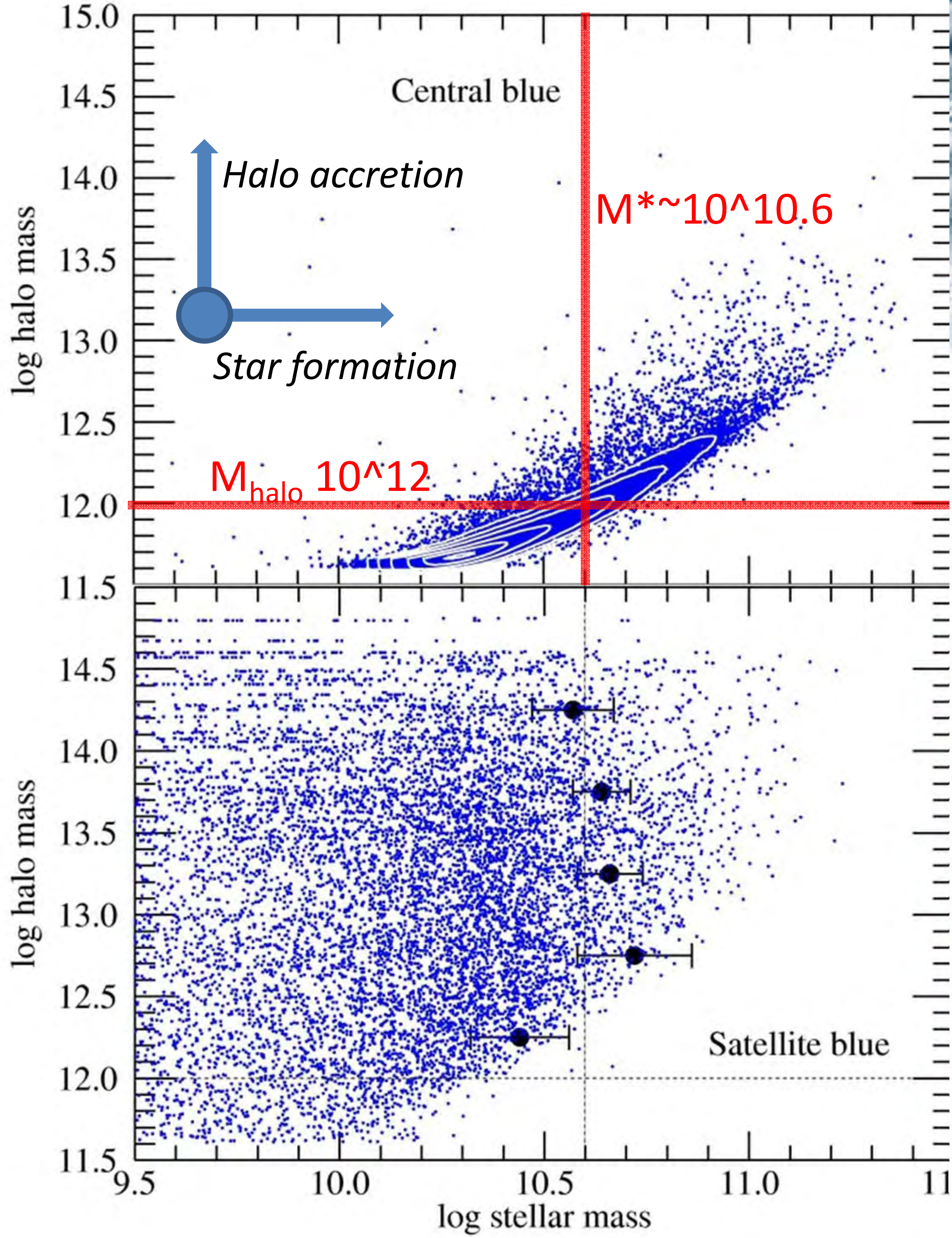
in control of the SFR of the *star-forming* galaxies

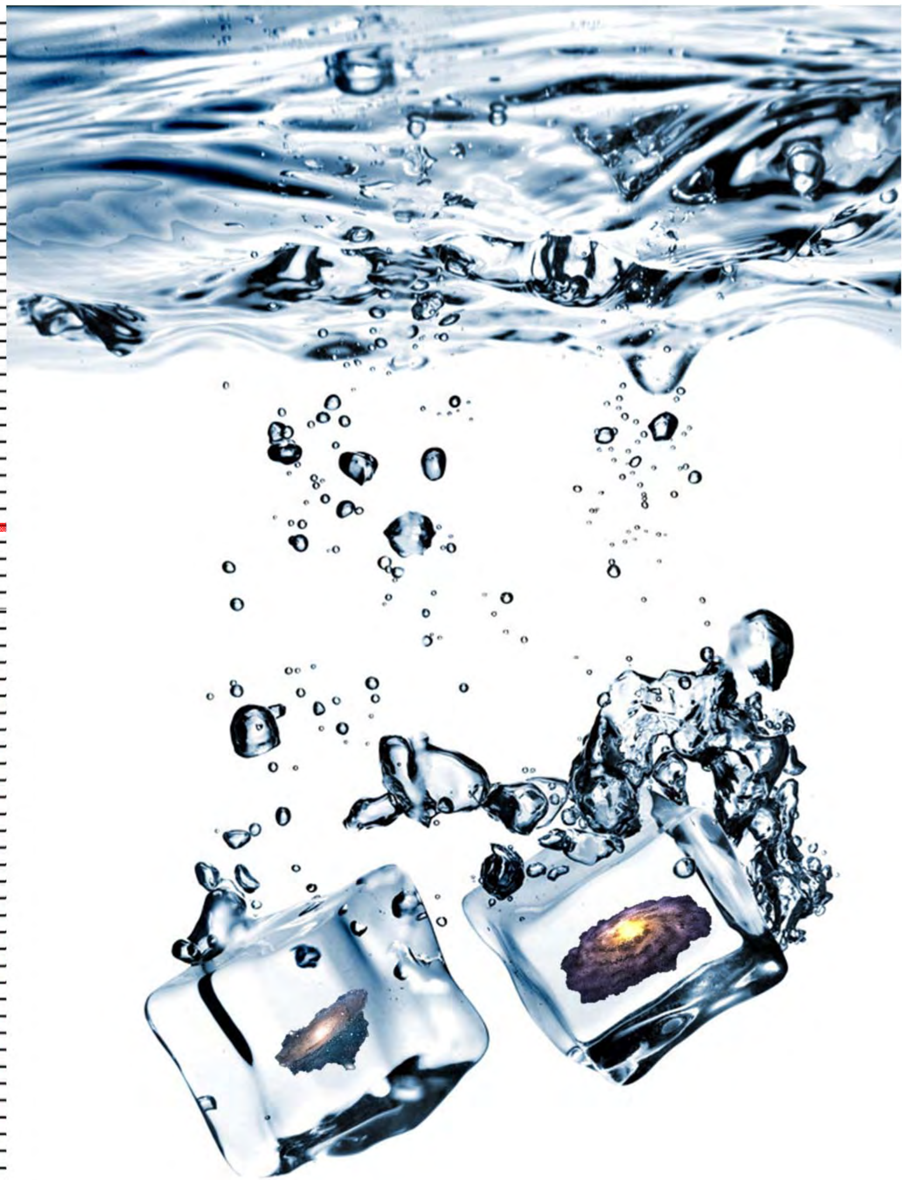
in control of the environment-quenching

in control of the mass-quenching



the role of the dark-matter haloes





Merging in this phenomenological approach

1. Limits on “post-quenching merging” (a.k.a. “dry merging”)

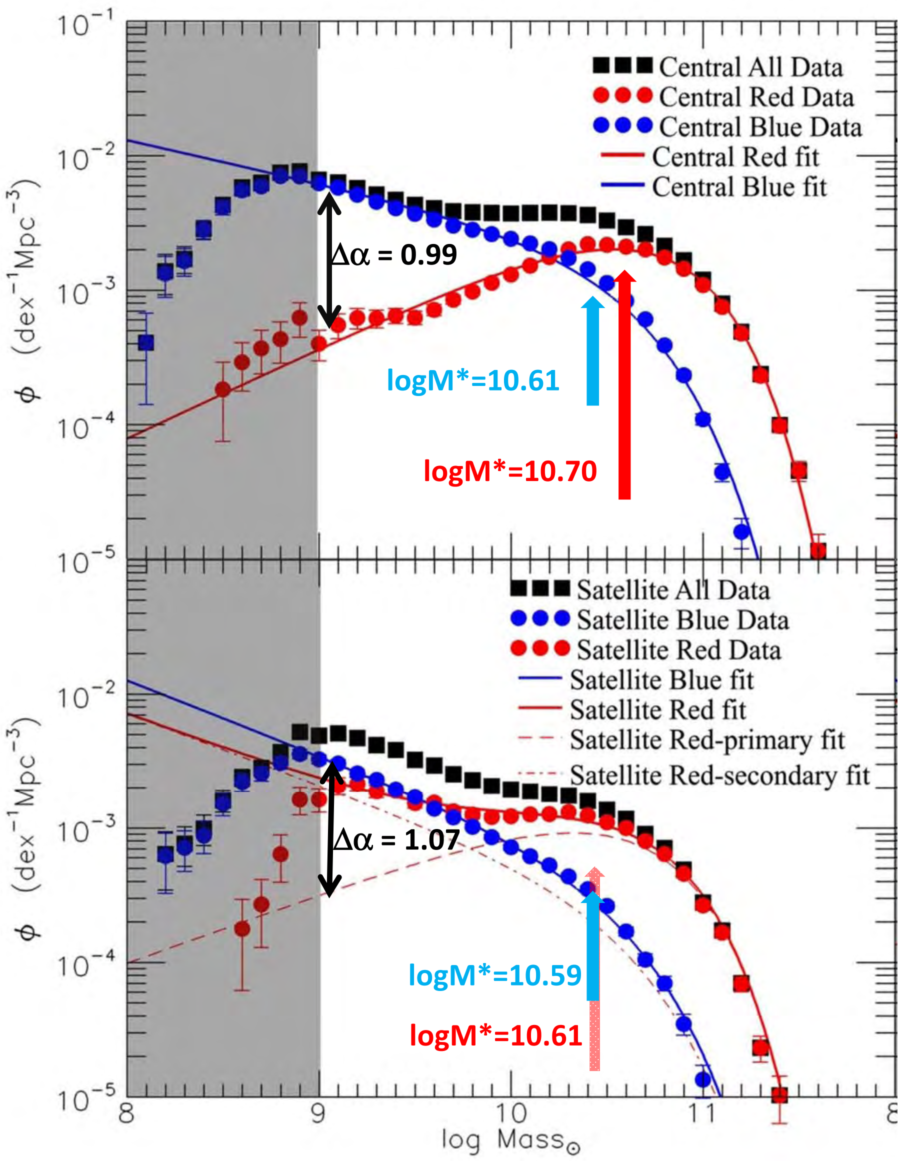
2. Merging as a source of quenching – the κ-term

3. Destruction of galaxies – the problem of α and β

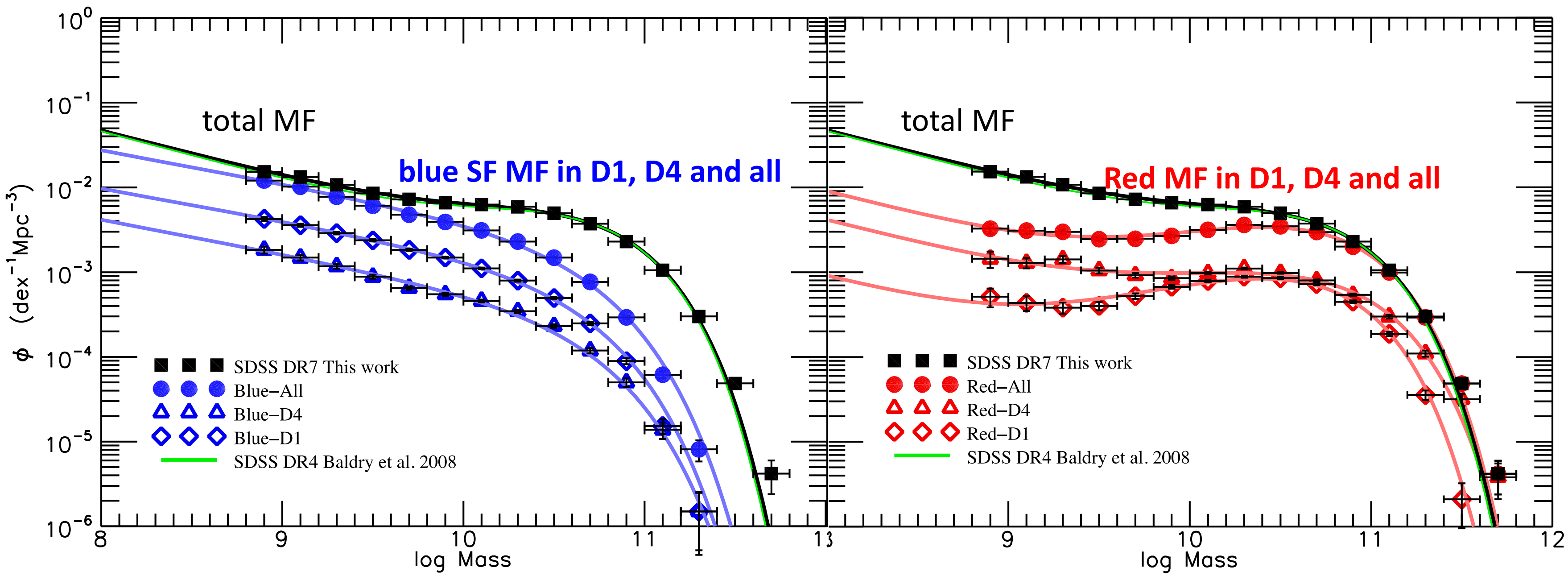
4. Early merging and the “inevitability” of today’s population

5. Merging Histories of today's passive galaxies

1. The post-quenching merging of passive galaxies



Average increase in the mass of passive central galaxies *after they have been quenched* is ~ 35%



	$\mathrm{Log}(M^*/M_\odot)^a$	$\phi_1^*/10^{-3}\mathrm{Mpc}^{-3}$	α_1	$\phi_2^*/10^{-3}\mathrm{Mpc}^{-3}$	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)

Average increase in the mass of typical passive galaxies (in highest density quartile D4) after they have been quenched is probably only about 25% (and 10% in D1)

2. The κ-quenching term

Peng et al (2010)

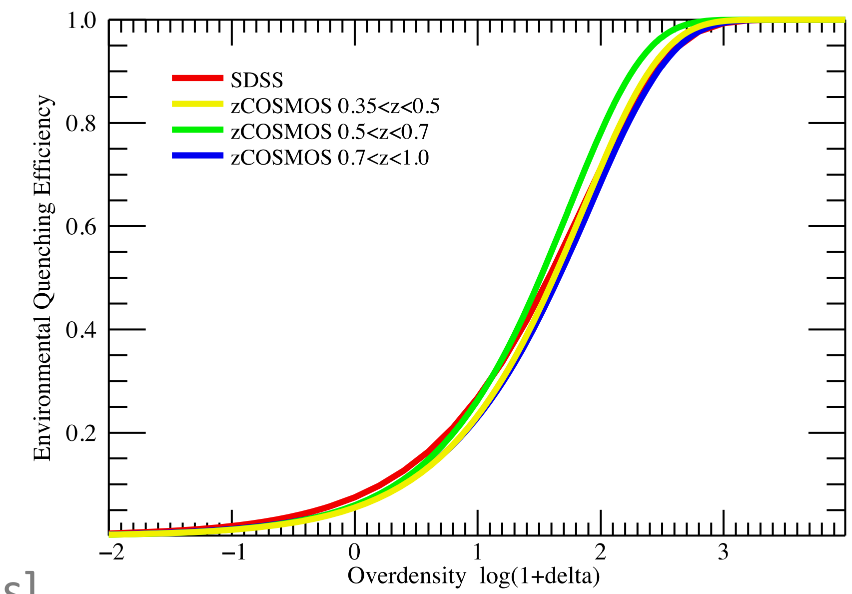
$$\eta = \mu\, SFR + \left(\frac{1}{1-\varepsilon_\rho} \frac{\partial \varepsilon_\rho}{\partial \log \rho} \frac{\partial \log \rho}{\partial t} \right) + \kappa(\rho, t)$$

κ-term was originally introduced because "we thought merging ought to be a quenching channel for galaxies". We took an observational estimate for the merger rate from the literature…

We now understand that, if environmental effects ε_ρ are to be constant with time (as observed) then $\kappa(\rho,t)$ must have a particular form, to prevent "dilution" of environmental differentiation with time due to SF

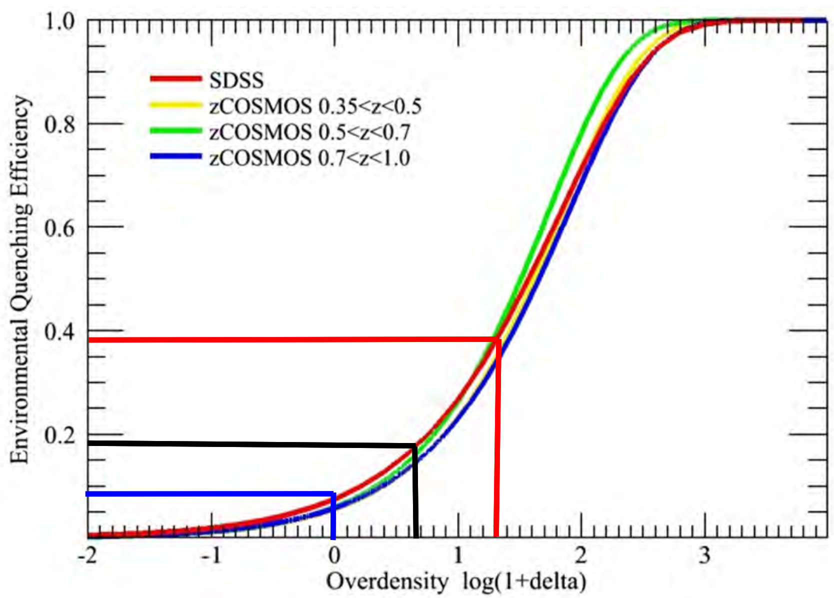
$$\kappa(\rho,t) = \varepsilon_\rho(\rho)\; sSFR(t)$$

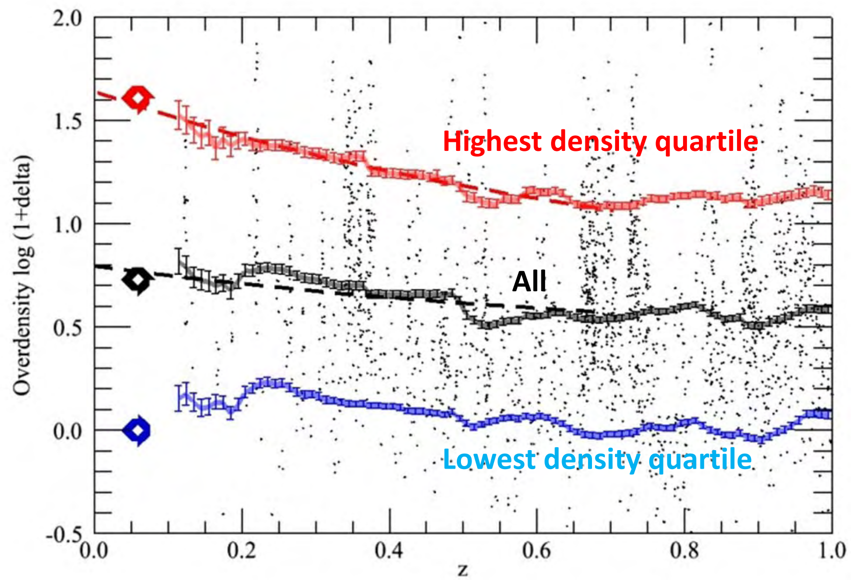
[NB: should be independent of stellar mass]



κ-quenching in the sky: merger-quenching?

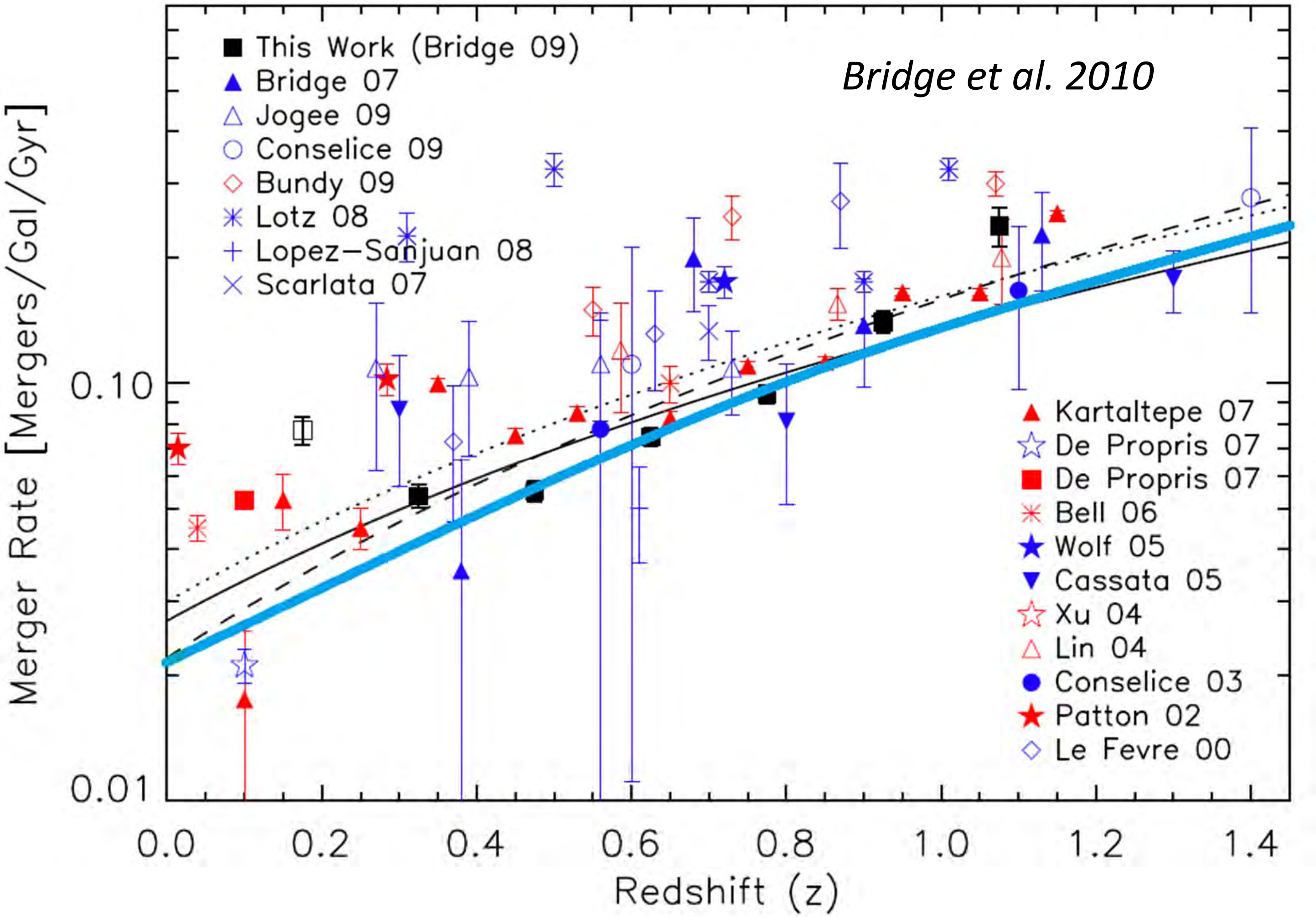
$$\kappa \sim \varepsilon_{\rho}\mathrm{sSFR}$$





- $\kappa \sim 0.2\, sSFR$ on average for $0 < z < 1$
- κ-quenching is about 4 times higher in highest-density D4 quartile as in lowest-density D1 quartile

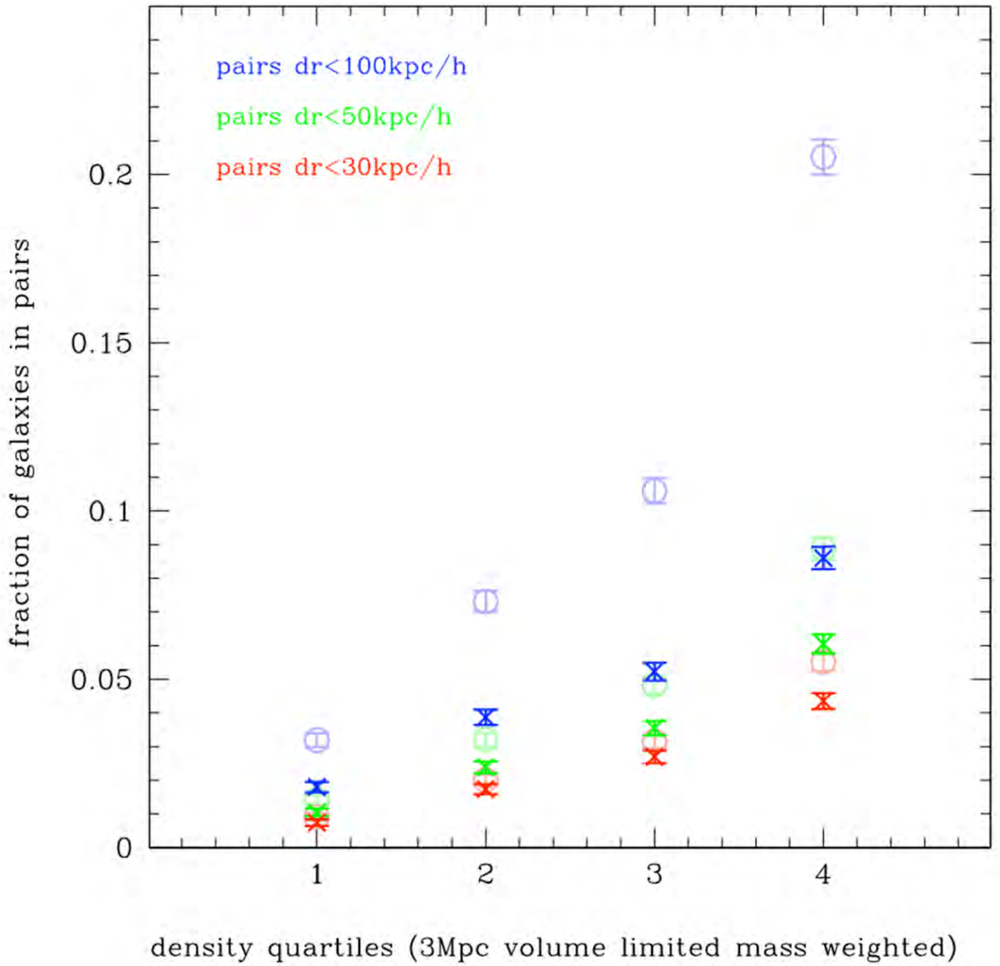
κ-quenching in the sky: merger-quenching?



$\kappa \sim 0.2$ sSFR 0<z<1

κ-quenching in the sky: merger-quenching?

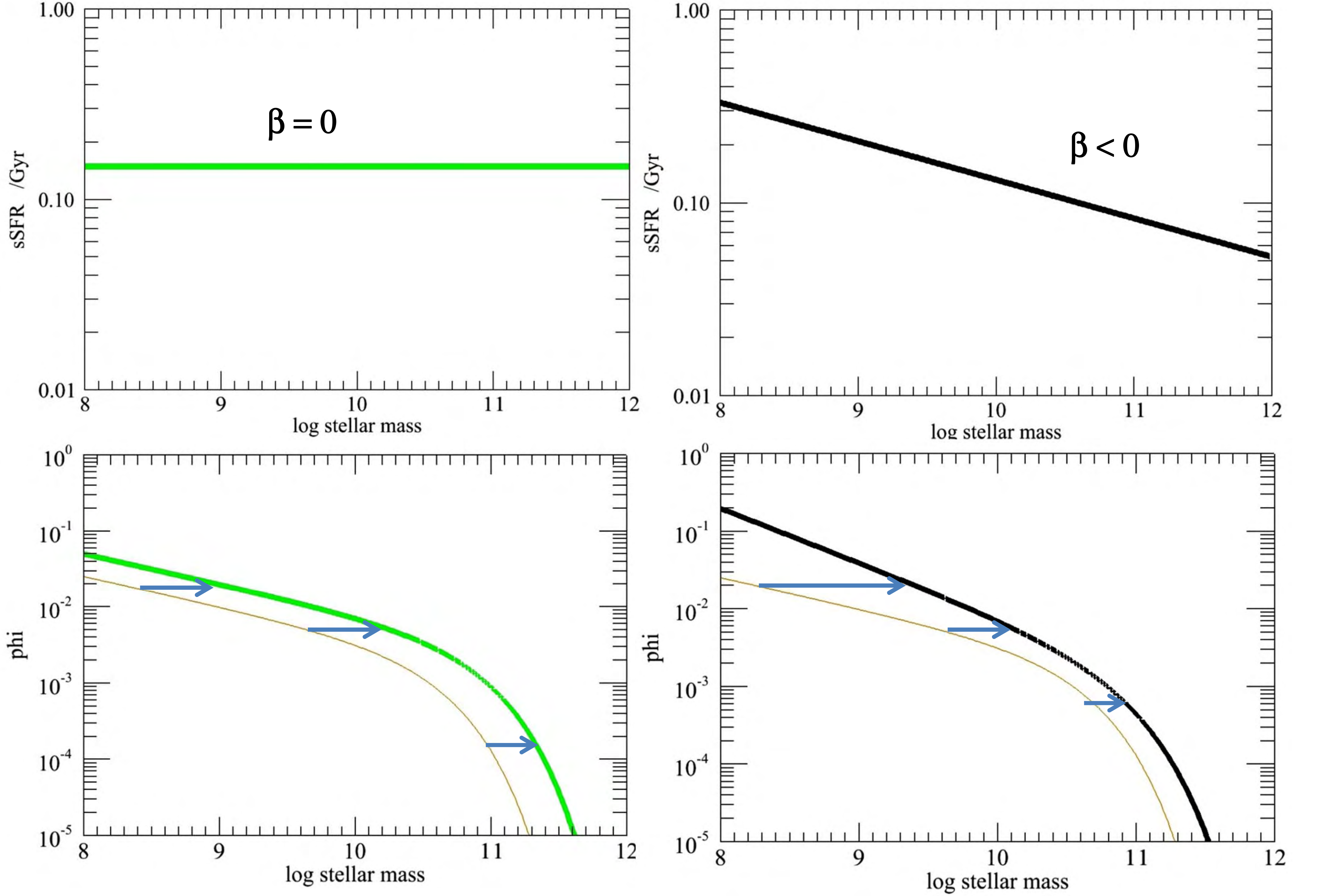
$$\kappa \sim \varepsilon_{\rho} \mathrm{sSFR}$$

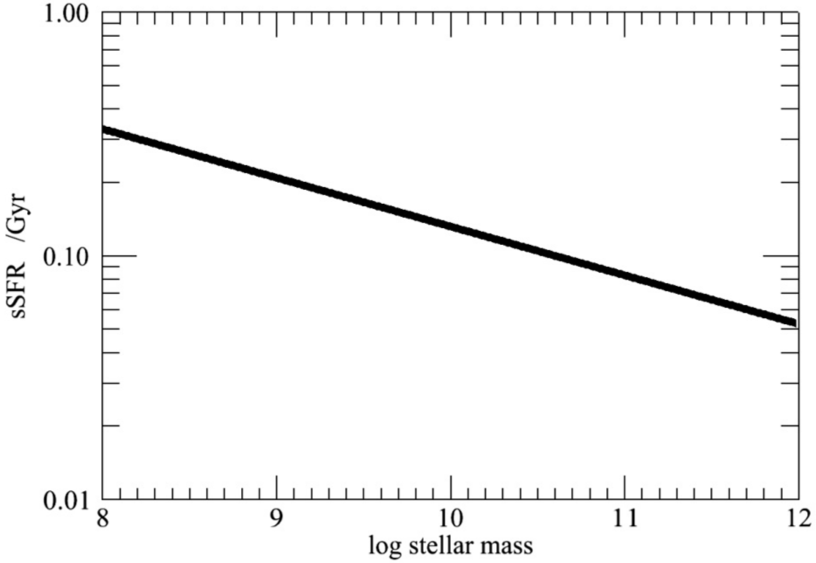


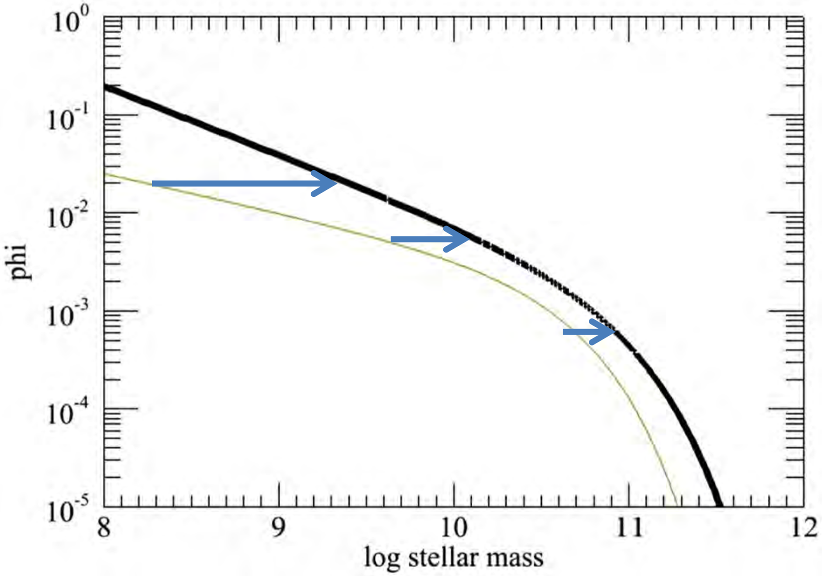
Environment dependence of close kinematic pairs in zCOSMOS (Kampczyk et al. 2011)

So, "κ-quenching" is quite likely to be merger-induced quenching, after all

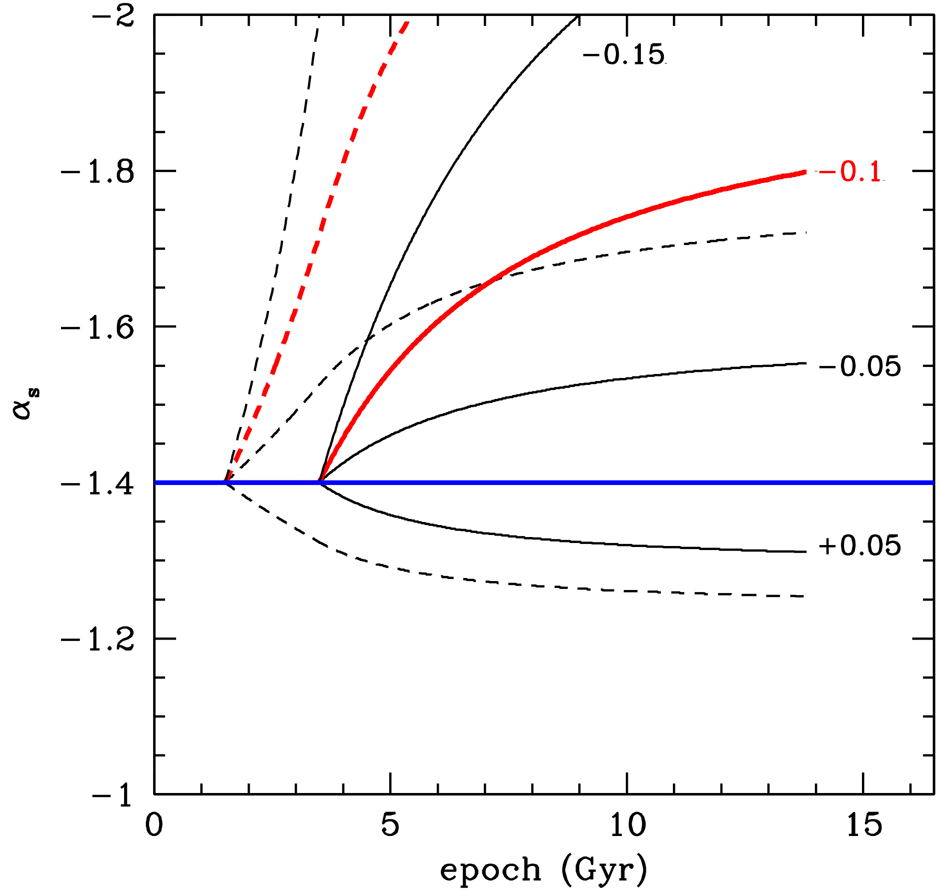
3. The destruction of galaxies and the problem of α and β







the steepening of α_s is rather efficient for a negative beta even faster at t<3.5 Gyr in the exponential growth phase



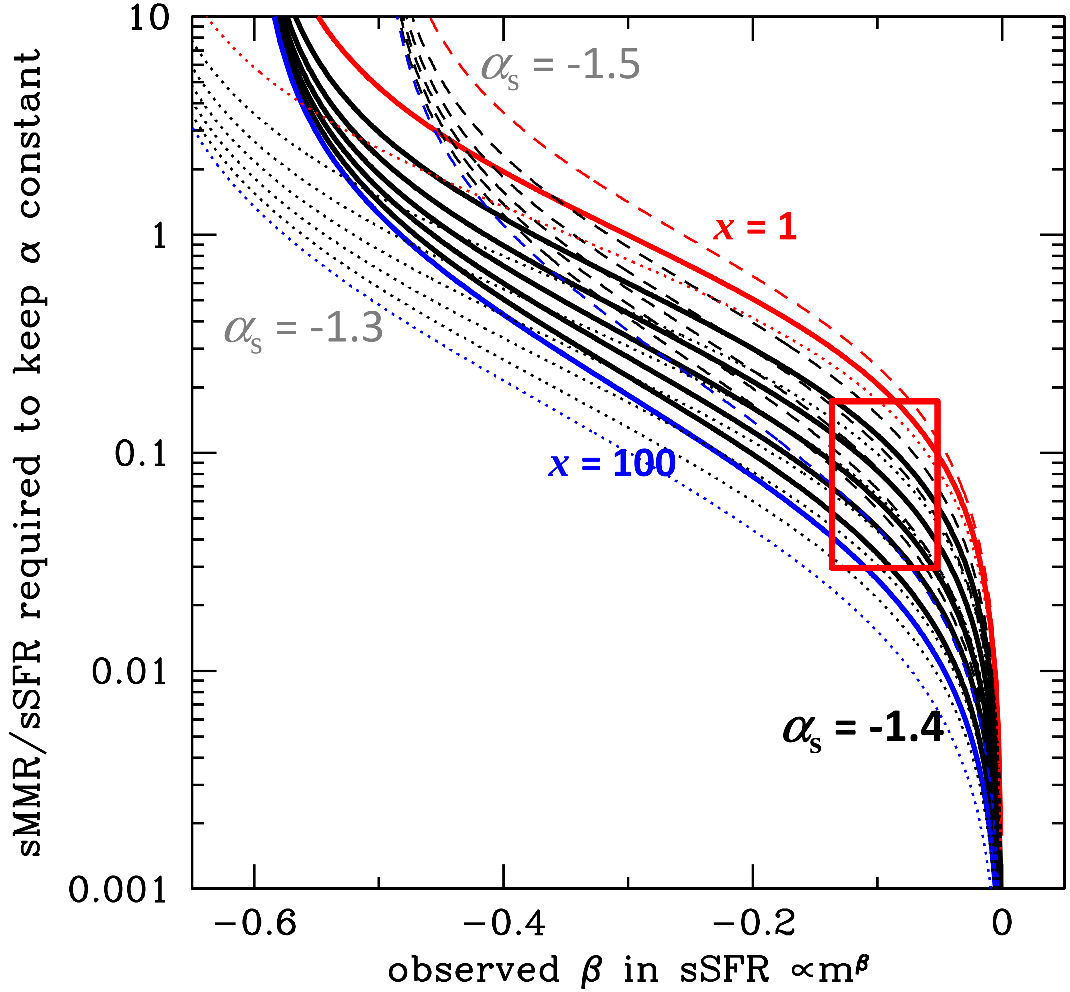
sMMR: specific mass increase rate due to mergers

$$sMMR = -\frac{(1+\alpha_s+\beta)}{(1+\alpha_s+\beta)+x^{(1+\alpha+\beta)}}\,sSFR + \frac{\alpha}{(1+\alpha_s)+x^{1+\alpha}}\,sSFR\Big|_{M^*}\frac{\Gamma(\alpha_s+\beta+2)}{\Gamma(\alpha_s+2)}$$

Easy for small β;
but impossible for $\beta \sim (1+\alpha_s)$

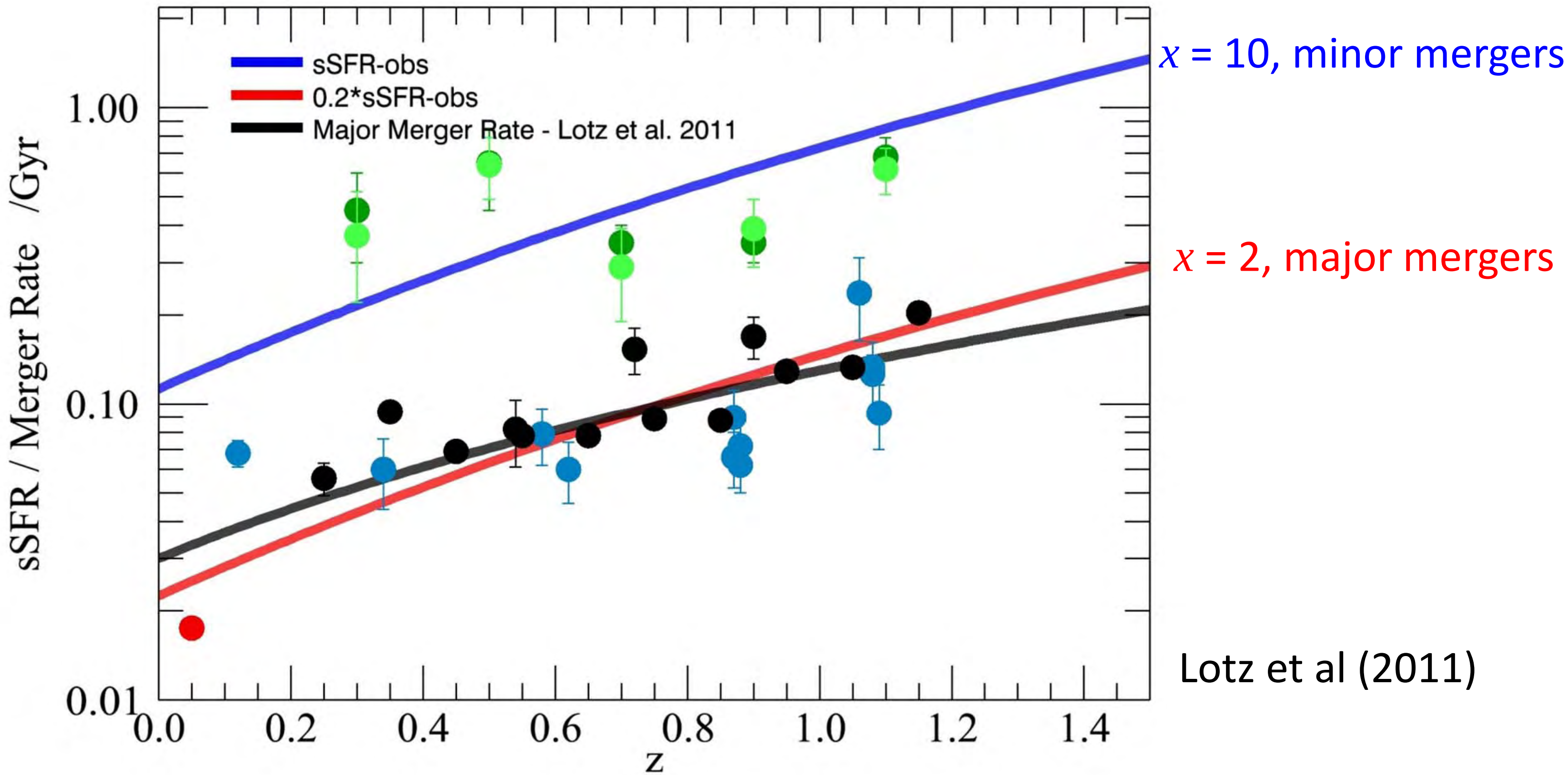
Suggests **sMMR ~ 0.1 sSFR**
for α_s = -1.4, β = -0.1

Mass assembly through merging is significant but not dominant relative to in situ SF



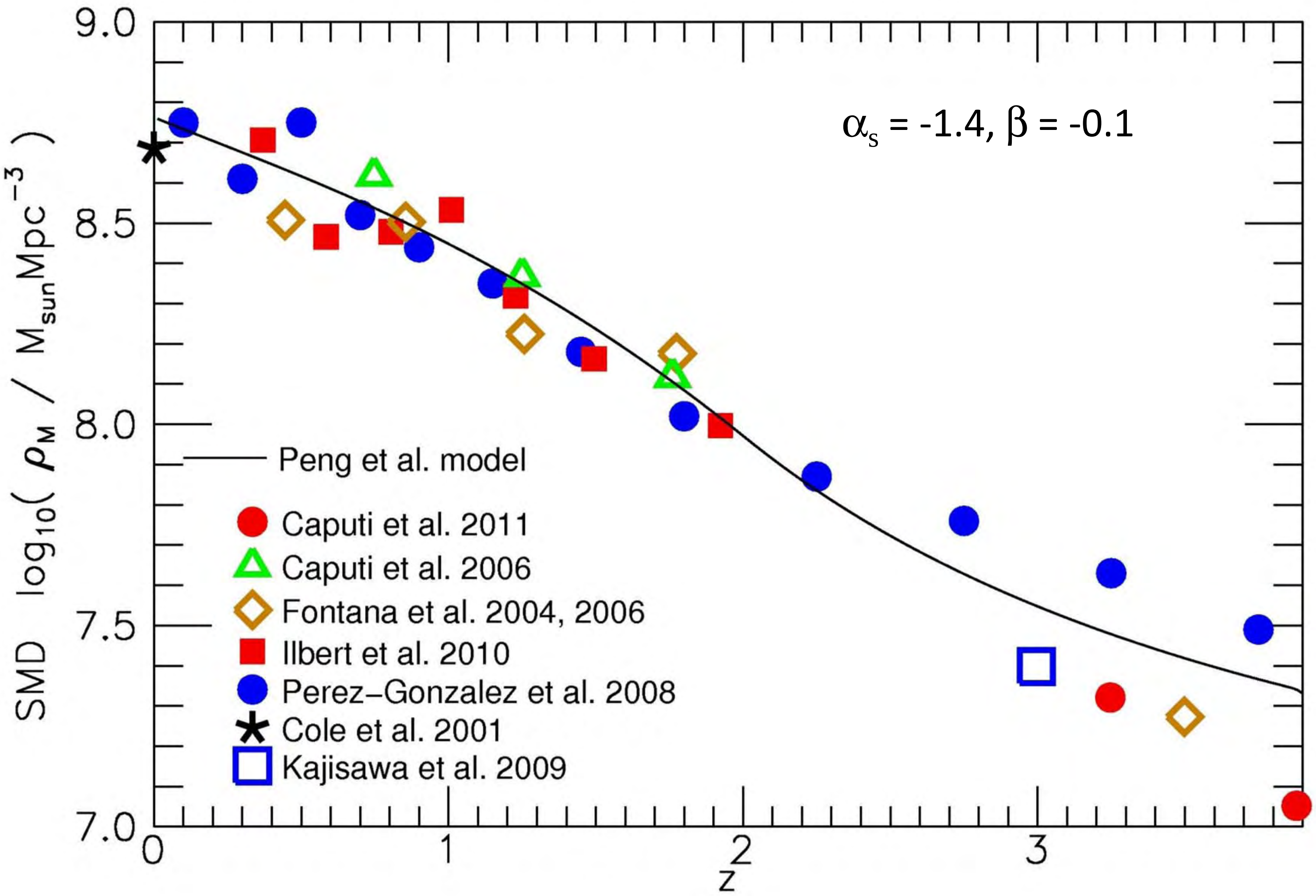
Is there evidence in the sky for these merger rates?

$$\text{merger rate} = x\ sMMR \sim 0.1x\ sSFR$$



Lotz et al (2011)

Predicted Stellar mass density (SMD) as a function of redshift with *sMMR*



Bottom line: Everything is consistent with α_s = -1.4, β = -0.1, implying ***sMMR ~ 0.1 sSFR***

Note the very nice connection between these two quite <u>independent</u> approaches

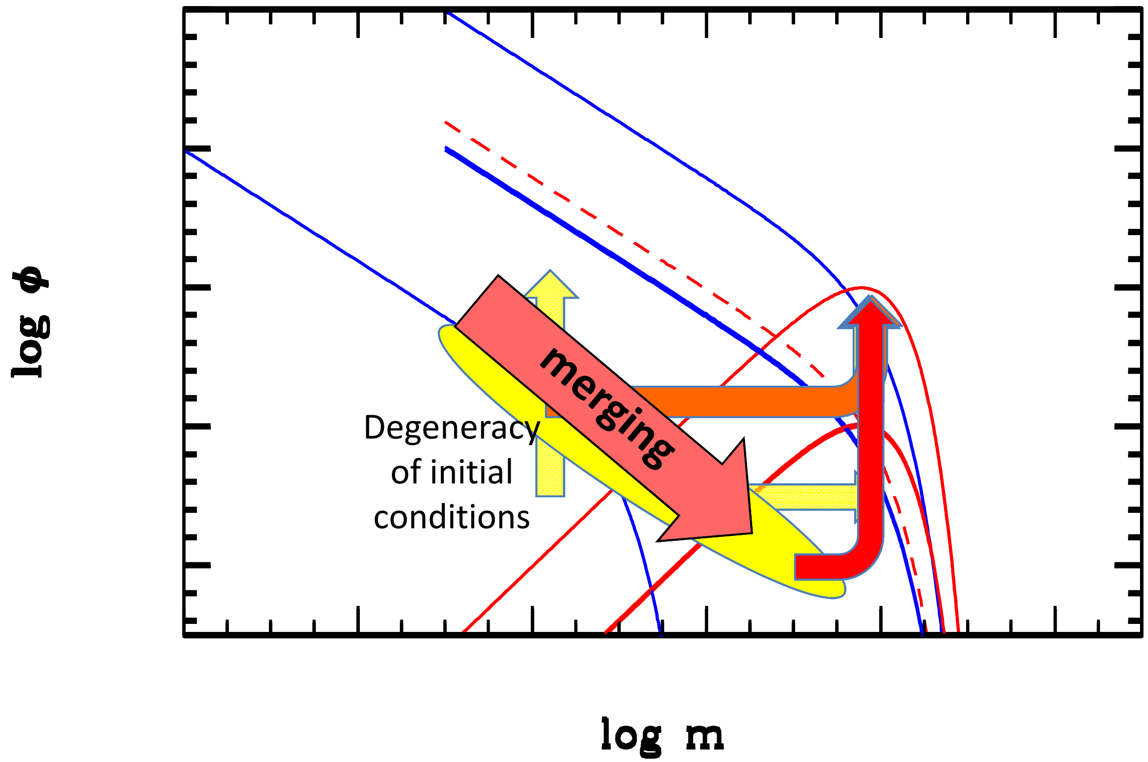
- Average mass <u>accumulation</u> through merging has been estimated to be ***sMMR* ~ 0.1 *sSFR***

  Implied ***merger rate* = *x* sMMR ~ 0.1*x* *sSFR***

- Rate of κ-<u>quenching</u> was **~ 0.2 *sSFR***

i.e. consistent with idea that all 1:2 mergers (*x* ~ 2) ultimately lead to quenching of the galaxies concerned

4. Degeneracies at high redshifts and the inevitability



Phase 1. Uniform increase in masses of SF galaxies...

...which stops when the passives appear, i.e. when $M^* = \mu^{-1}$

Phase 2. Increase in ϕ^* of both SF and passive galaxies

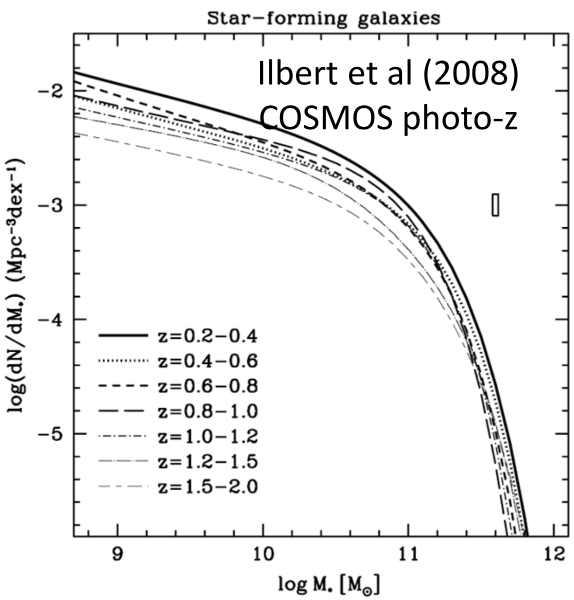
Phase 3. Late development of environmental effects at low masses

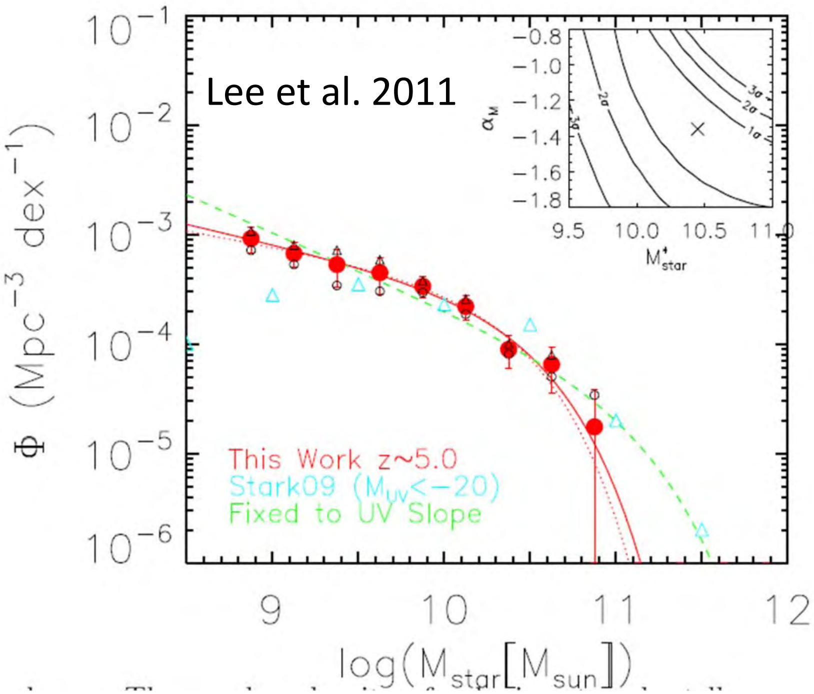
Double Schechter shape of today's overall mass function is "inevitable", with simple relationship between ϕ^* of two components

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

Today's mass-function is "inevitable", but there is a degeneracy in the initial conditions.
which is largely parallel to merging vector.
→ Can have a lot of merging at high z (in Phase 1)

When was Phase 1-2 transition and is there a progenitor problem?





We seem to have been in Phase 2 since z ~ 4, or even z ~ 5

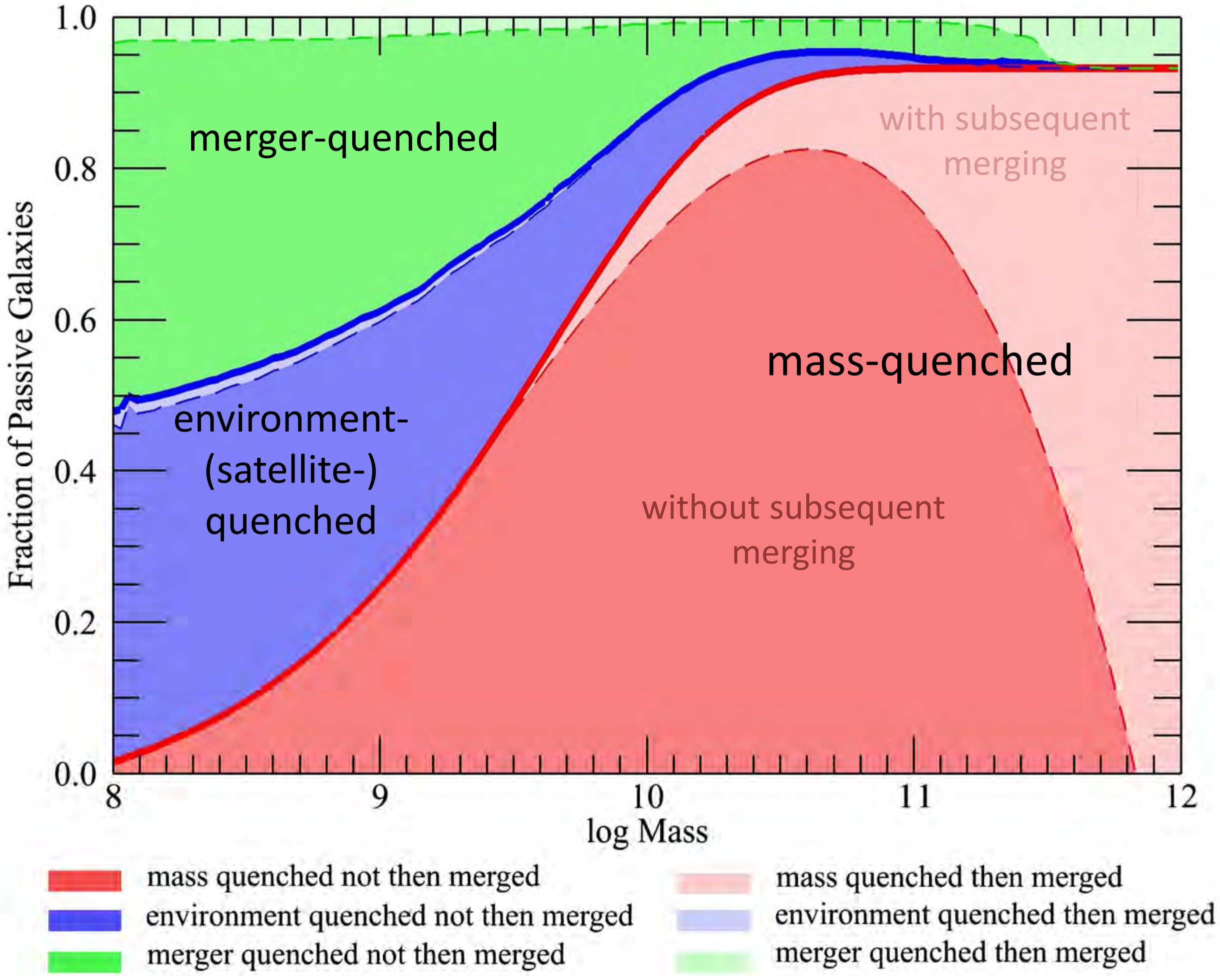
M* at z ~ 5 is still > ~ $10^{10.5}$ M_O

If sSFR = 2 Gyr^{-1}, this only gives three e-folds since the Big Bang, i.e. a factor of 20.

- **sSFR is not constant at z < 5?**
- **Merging sMMR >> sSFR?**

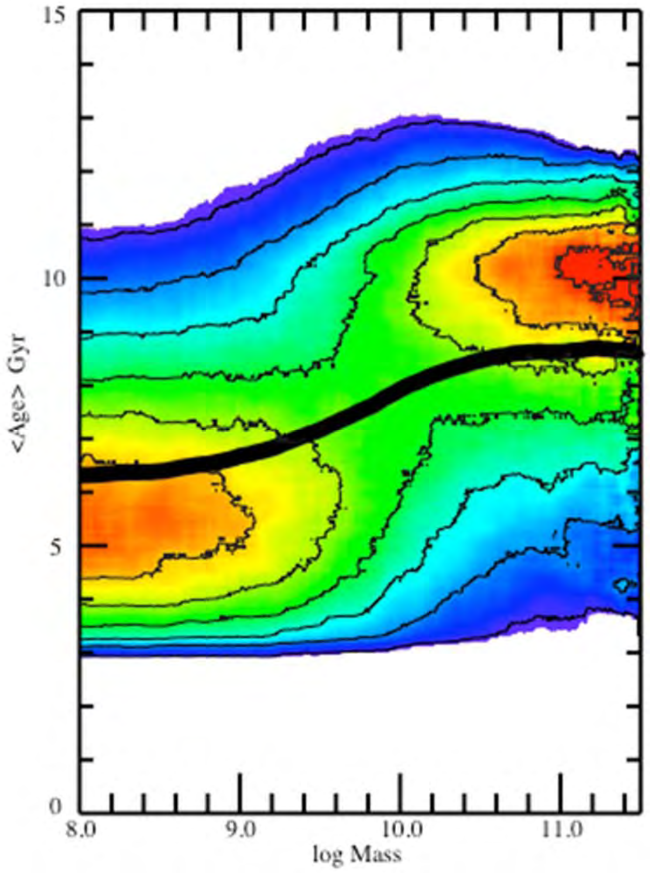
5. Merging Histories of today's passive galaxies

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

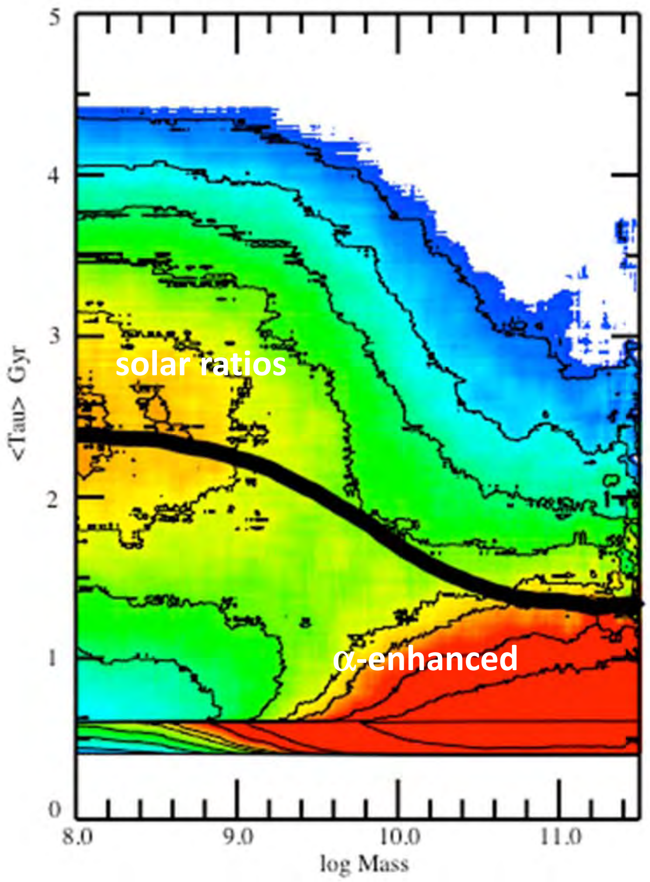


Ages and α-element abundances for passive galaxies as *f* (mass)

The simple empirical quenching laws naturally produces the "anti-hierarchical" run of light-weighted age and α-element abundances with mass.



light-weighted stellar age



light-weighted stellar sSFR^{-1}

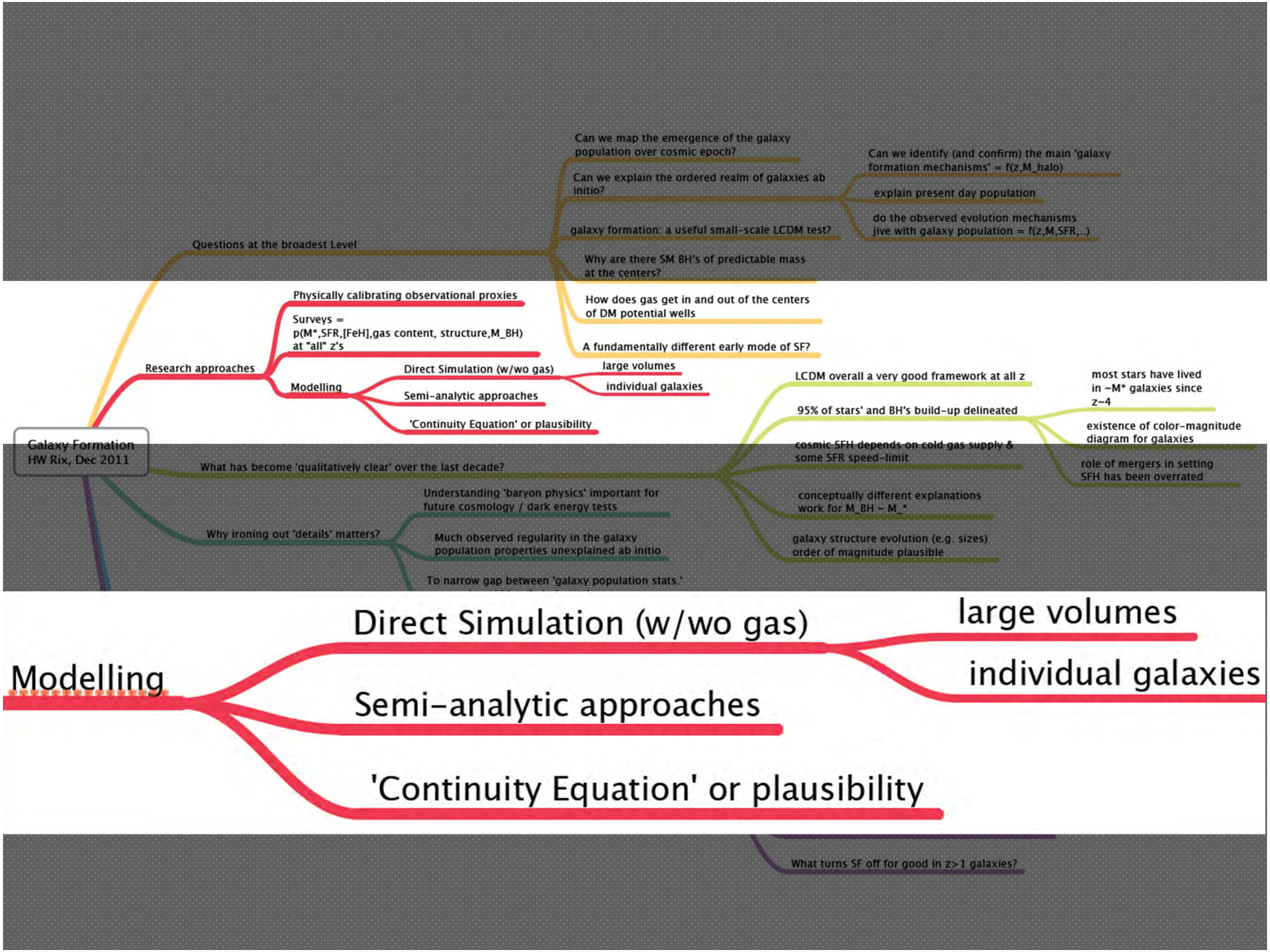
Predictions for transitory objects

Assume galaxies being mass-quenched which is visible for some period of time $\tau_{\rm trans}$. What is mass function of these transitory galaxies?

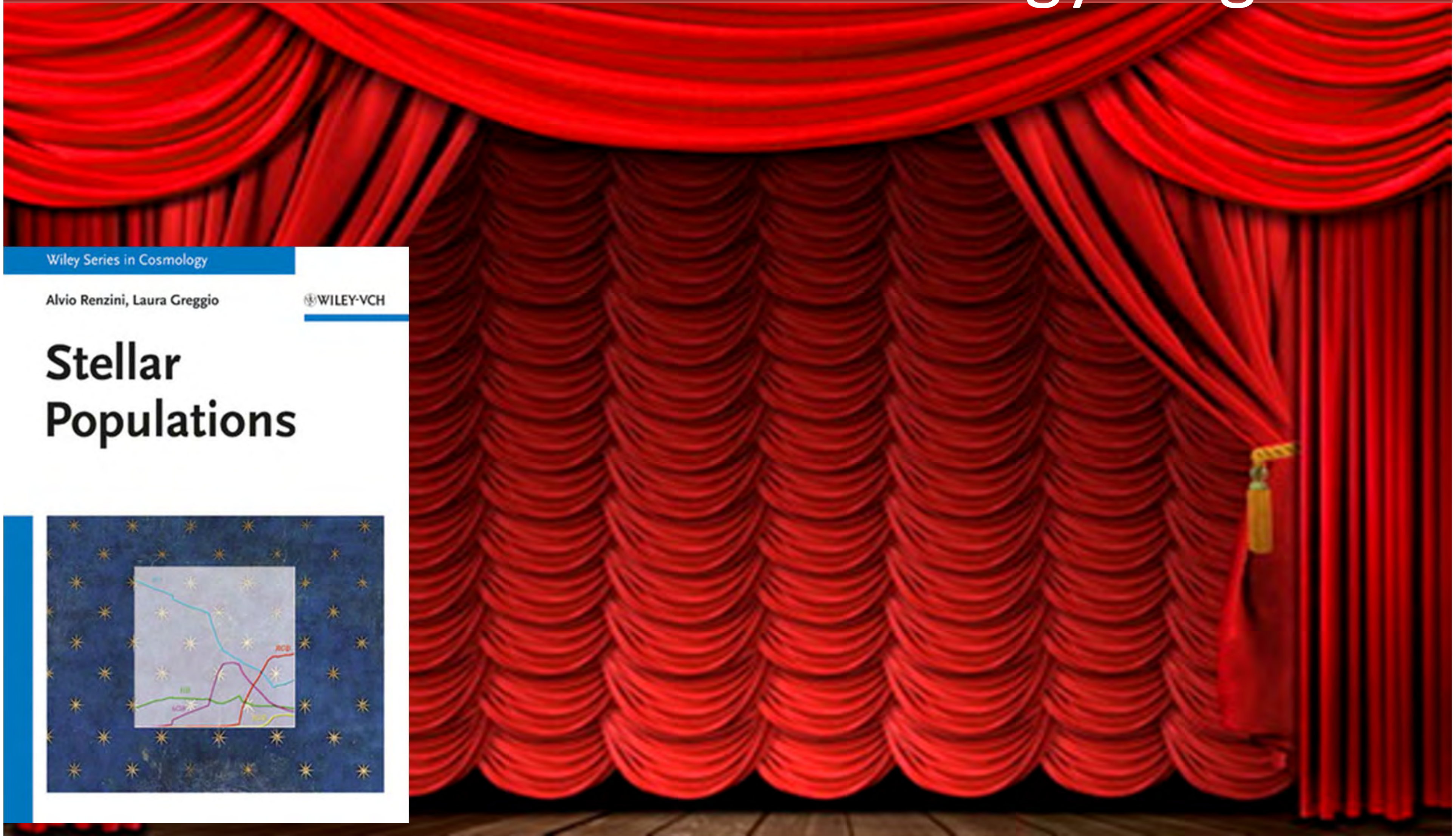
$$M^*_{\rm trans} = M^*_{\rm blue} = M^*_{\rm red}$$
$$\alpha_{s,\rm trans} = \alpha_{s,\rm blue} + (1+\beta) = \alpha_{s,\rm red}$$
$$\phi^*_{\rm trans} = \phi^*_{\rm blue}\ {\rm sSFR}(t)|_{M^*}\ \tau_{\rm trans} = \phi^*_{\rm blue}\frac{\tau_{\rm trans}}{\tau(t)|_{M^*}}$$

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

the number density normalization $\varphi*_{\rm trans}$ will be the product of the $\varphi*_{\rm blue}$ of the currently star-forming galaxies multiplied by the dimensionless ratio of the visibility timescale $\tau_{\rm trans}$ and the star formation timescale τ, which evolves strongly with epoch as $t^{-2.5}$


Galaxy Formation
HW Rix, Dec 2011
Questions at the broadest Level
Can we map the emergence of the galaxy population over cosmic epoch?
Can we explain the ordered realm of galaxies ab initio?
Can we identify (and confirm) the main 'galaxy formation mechanisms' = f(z,M_halo)
explain present day population
do the observed evolution mechanisms jive with galaxy population = f(z,M,SFR,..)
galaxy formation: a useful small-scale LCDM test?
Why are there SM BH's of predictable mass at the centers?
How does gas get in and out of the centers of DM potential wells
A fundamentally different early mode of SF?
Research approaches
Physically calibrating observational proxies
Surveys = p(M*,SFR,[FeH],gas content, structure,M_BH) at "all" z's
Modelling
Direct Simulation (w/wo gas)
large volumes
individual galaxies
Semi-analytic approaches
'Continuity Equation' or plausibility
What has become 'qualitatively clear' over the last decade?
LCDM overall a very good framework at all z
95% of stars' and BH's build-up delineated
most stars have lived in ~M* galaxies since z~4
existence of color-magnitude diagram for galaxies
role of mergers in setting SFH has been overrated
cosmic SFH depends on cold gas supply & some SFR speed-limit
conceptually different explanations work for M_BH ~ M_*
galaxy structure evolution (e.g. sizes) order of magnitude plausible
Why ironing out 'details' matters?
Understanding 'baryon physics' important for future cosmology / dark energy tests
Much observed regularity in the galaxy population properties unexplained ab initio
To narrow gap between 'galaxy population stats.'
What turns SF off for good in z>1 galaxies?
Modelling
Direct Simulation (w/wo gas)
large volumes
individual galaxies
Semi-analytic approaches
'Continuity Equation' or plausibility

The Concordance Cosmology Stage



Alvio Renzini: At the beginning of the era of Precision Cosmology Somebody said:
"Now that the stage has been set up, what we need is a good play"
I think this phenomenological model tells what the plot is and ought to be.

The Concordance Cosmology Stage

The Characters of the Play

- Cold Streams
- IMF
- AGN Feedback
- Winds
- Star Formation
- Clump Physics
- Strangulation
- Ram pressure
- SN Feedback
- Disk instability
- Chemistry
- Mergers
- Starbursts

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