The galaxy population over cosmic time: An observational perspective from large scale surveys

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Lecture 3: Phenomenological interpretation

Based on new *phenomenological* approach based on:

- reduction of the large survey data to a few key (simple) observational "axioms" describing the evolving galaxy population, plus
- application of simple continuity equations to explore the consequences

Aims:

- a clear (simple) phenomeological description of what is happening in the sky, so we can talk the same language and ask the right questions plus
- a set of empirical constraints that more physically based models must satisfy, and
- identification of connections between seemingly unrelated aspects of galaxy evolution

Today: 2.5 topics (if possible)

- **How are galaxies quenched?**
  see Peng et al (2010, ApJ 721, 923, 2012, ApJ 757,4)
  Knobel et al (2012, arXiv 12115607), Kovac et al (2012, arXiv soon)
- **How important is merging** (as above + Peng et al in preparation)
- **What controls the star-formation rate of galaxies?**
  see Lilly et al (2012, arXiv soon)

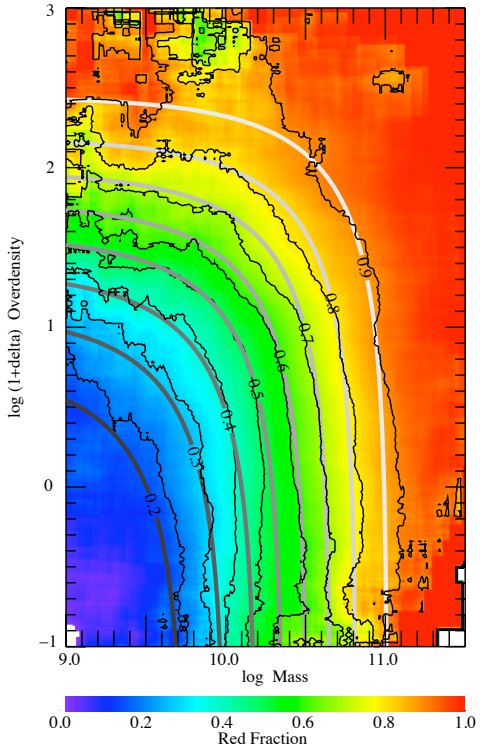
Observational axioms

1. The red fraction of galaxies gives the population of quenched and star-forming galaxies and is separable in mass and environment

$$f_{blue} = \left(1 - \varepsilon_m(m)\right) \times \left(1 - \varepsilon_\rho(\rho)\right)$$

Suggests two ("probabilistic") quenching processes:

- Mass-quenching independent of environment
- Environment-quenching, independent of mass



2. The mass function of star-forming galaxies has constant M* and constant α back to $z \sim 4$

3. Will also take from observations following simplicities (not essential)
   - β on the MS is small ($\beta \sim 0$ etc.)
   - scatter on MS is small
   - $\varepsilon_\rho(\rho)$ is more or less constant with time
   - Quenching is instantaneous

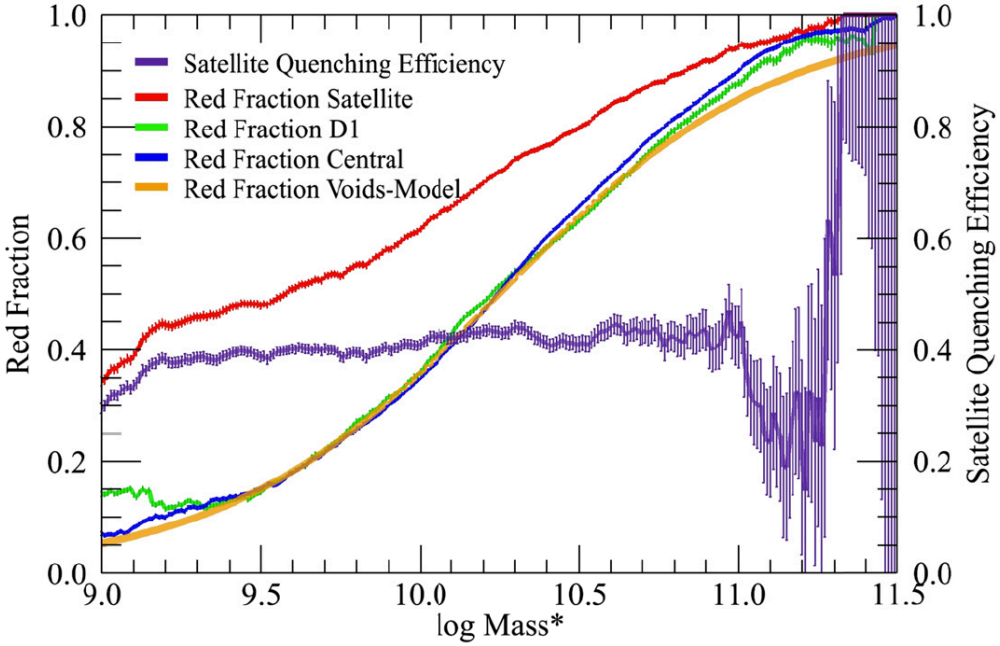
Environment-quenching is *satellite*-quenching

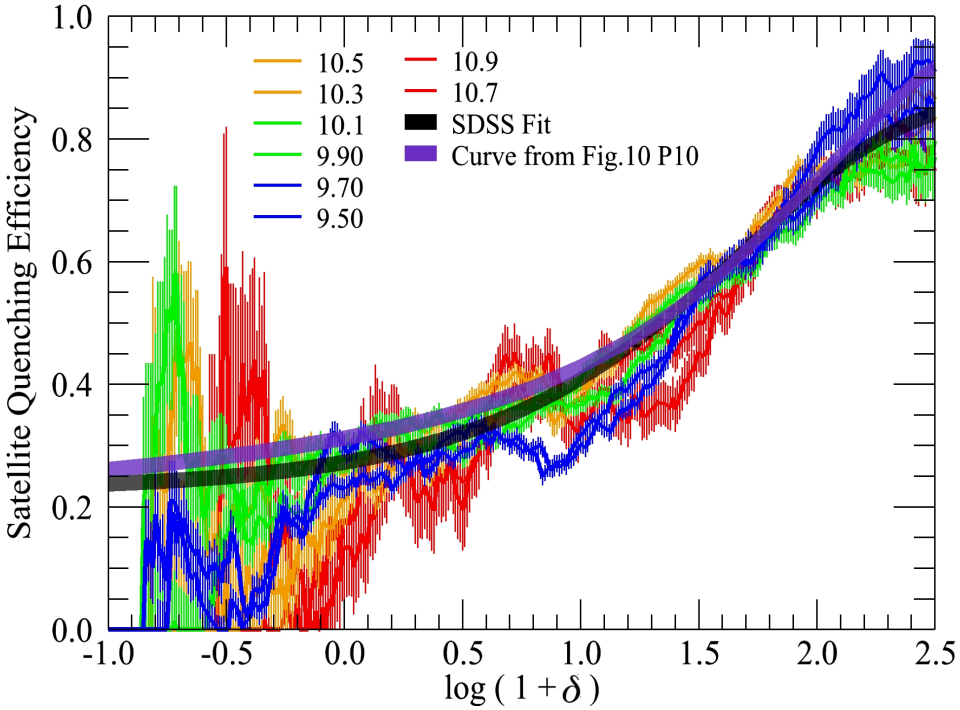
Why?

- f_{red} for *centrals* in SDSS is not a $f(\rho)$ and is exactly as predicted from mass-quenching alone

- For *satellites*,
  $\varepsilon_{sat} = (f_{red,sat} - f_{red,cen})/f_{red,cen}$
  is not a $f(m)$ but is $f(\rho)$

  Also, the observed $e_{sat}(\rho)$ is as predicted from $\varepsilon_{\rho}(\rho)$ and $f_{sat}(\rho)$

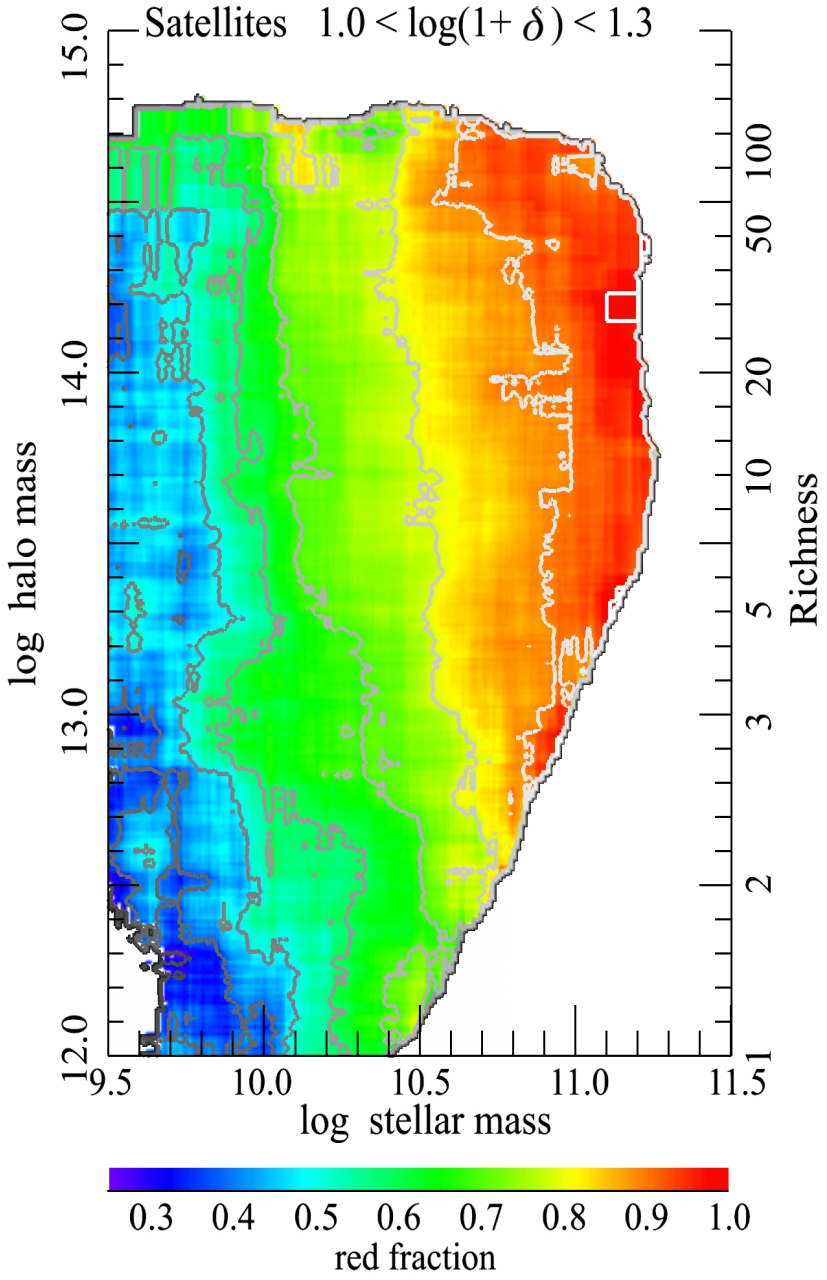




Satellite quenching does not depend in SDSS on parent halo mass, above 10^{12} M

Why?

- ε_{sat} in SDSS depends on local density, a proxy for groupcentric position, rather than on parent halo mass (Peng et al 2012)



The required form for the rate of mass quenching

$$\frac{\partial N}{\partial t} + \nabla \bullet (N v) = \sigma$$

$$\frac{\partial N_{blue}}{\partial t} + \frac{\partial}{\partial \log m} \bullet [N_{blue} \frac{\partial \log m}{\partial t}] = -\eta N_{blue}$$

η is a total quenching rate (+ possible sink due to merging)

$$\frac{\partial N_{blue}}{\partial t} = N_{blue}[-sSFR(\alpha + \beta) - \eta]$$

α is local logarithmic slope of mass-function. Set η to be mass-dependent λ_m + another term κ-

$$\frac{1}{\phi_{blue}(t)} \frac{\partial \phi_{blue}(t)}{\partial t} = -sSFR(t)(\alpha + \beta) - \lambda_m(t) - \kappa_(t)$$

Must be independent of mass if M* and α_s are to be constant

$$= -sSFR(t)(1 + \alpha_s + \beta) + \frac{SFR(t)}{M^*} - \lambda_m(t) - \kappa_(t)$$

For Schechter function, $\alpha = \alpha_s - m/M^*$

At fixed observed mass and environment

$$\left. \frac{dN_{blue}}{dt} \right|_{m,\rho} = N_{blue}\{-(\alpha + \beta)\, sSFR - \lambda_m - \kappa_\}$$

Again, must be independent of mass. Assume κ- is independent of mass (or negligible).

Equating mass-dependent terms

$$\lambda_m(t) = SFR(t)/M^* + C(t)$$

Low mass galaxies in low density environments are still all blue, so C ~ 0

$$\lambda_m(t) = SFR(t)/M^* = \mu\, SFR(t)$$

Production of the Schechter functions

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

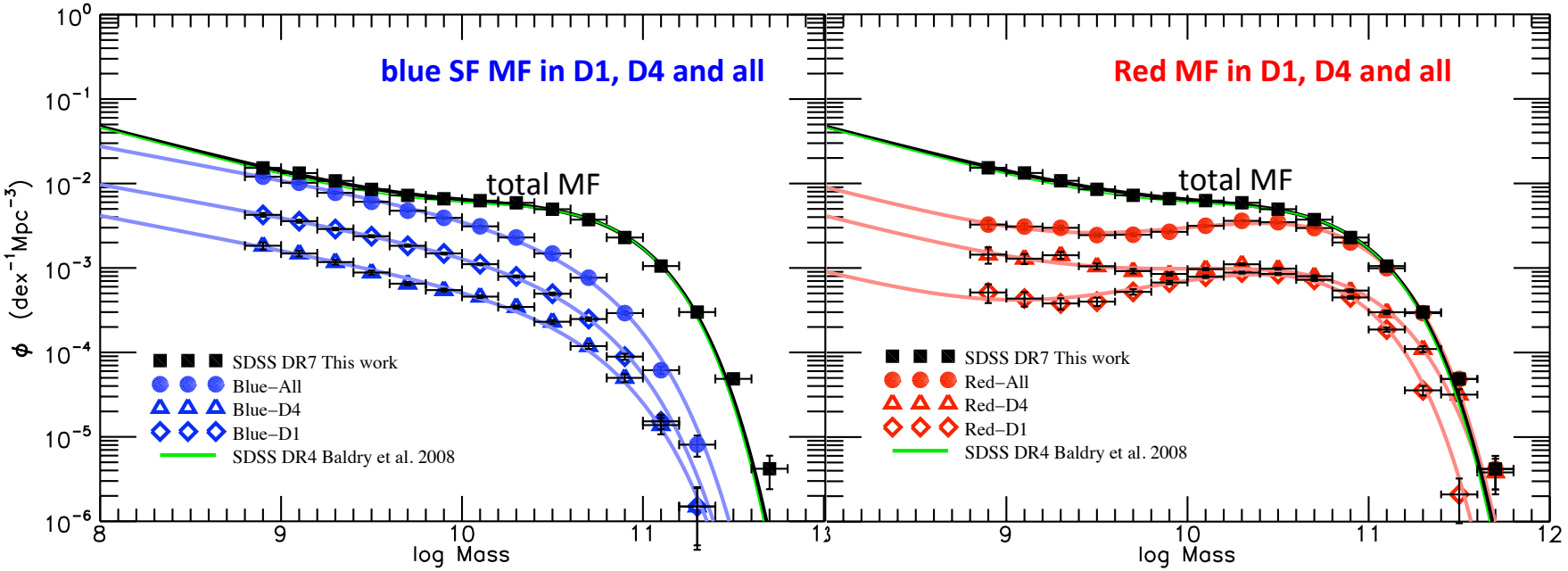
$$= \mu\, SFR + \left(\frac{1}{1-\varepsilon_\rho} \frac{\partial \varepsilon_\rho}{\partial \log \rho} \frac{\partial \log \rho}{\partial t} + \kappa_- \right)$$

observed proportional to mass$^{(1+\beta)}$

Environment terms, independent of mass

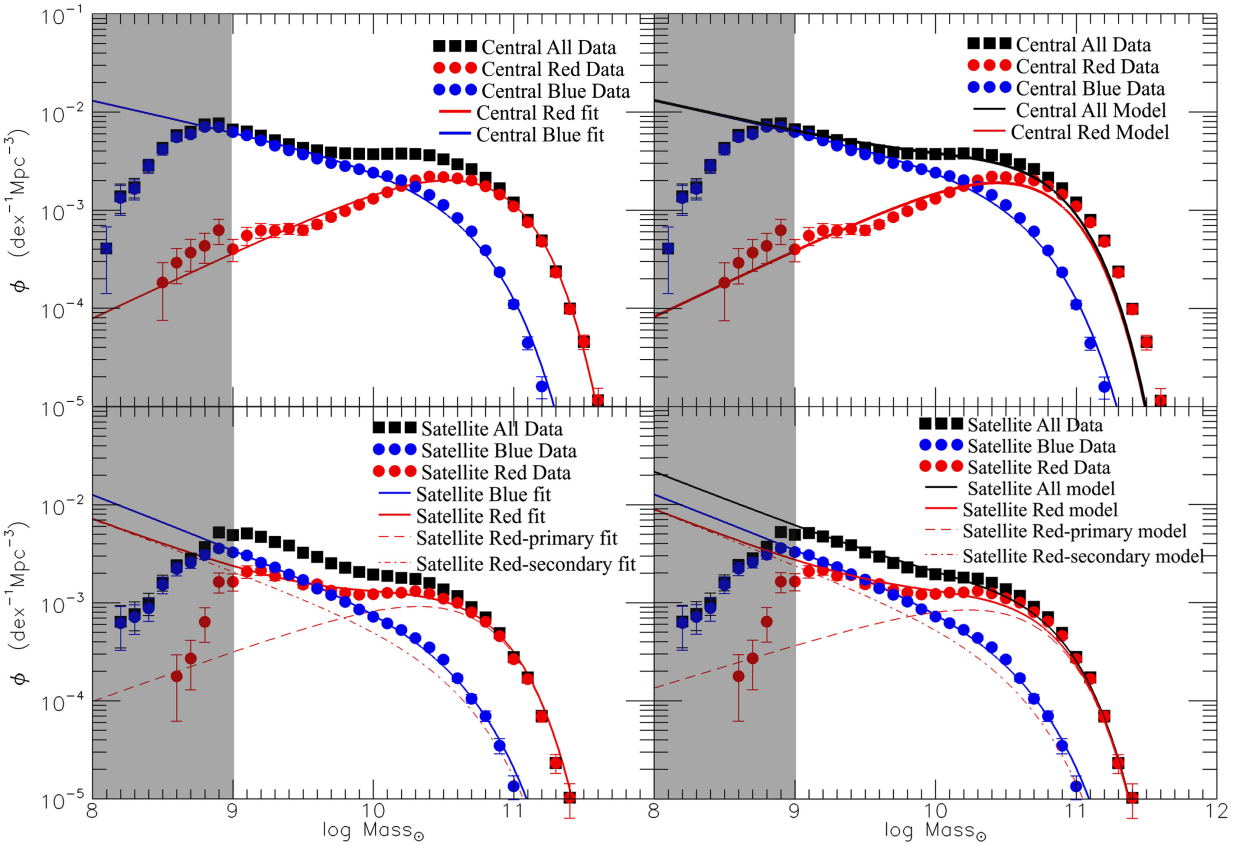
- Mass-quenching not only maintains, but also *produces* from more general mass functions, a single Schechter function of star-forming galaxies, with constant $M^*_{SF} = \mu^{-1}$, independent of environment
- Mass-quenching produces a primary Schechter function for passive galaxies with identical $M^* = M^*_{SF}$ 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.
- (Mass-independent) environment-quenching and merger-quenching produce a second Schechter function for passive galaxies with precisely the same M^* and α_s 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_s slightly more negative (e.g. $\Delta \log M^* \sim 0.09$ dex, $\Delta\alpha_s = -0.15$ for 7.5% equal mass merging).

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

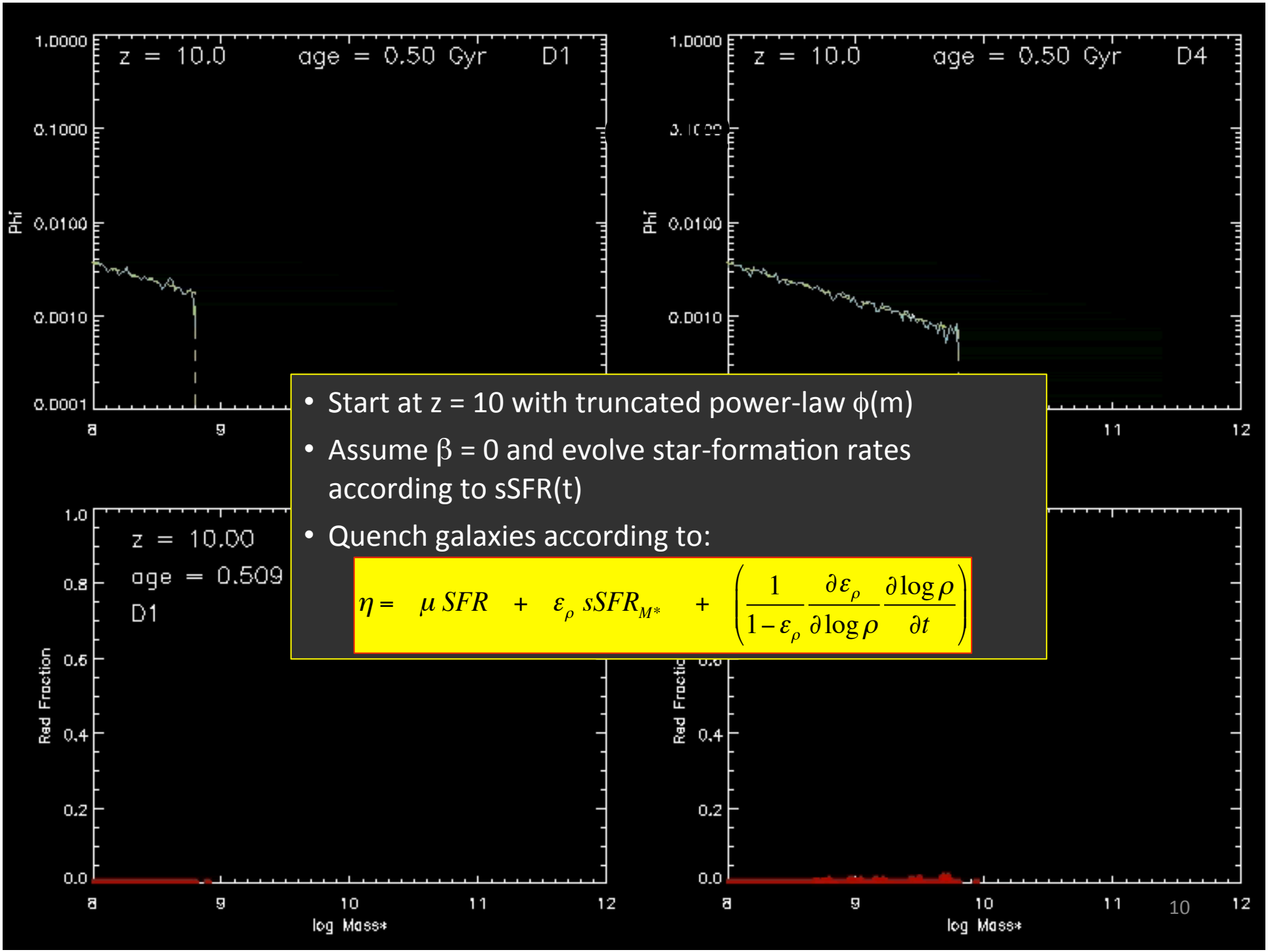


	Log(M*/M$_\odot$)[a]	ϕ_1*/10^{-3}Mpc^{-3}	α_1	ϕ_2*/10^{-3}Mpc^{-3}	α_2
(a) Free fitting parameters					
Global	10.67 ± 0.01	4.032 ± 0.12	-0.52 ± 0.04	0.655 ± 0.09	-1.56 ± 0.12
Blue-all	10.63 ± 0.01	...	...	1.068 ± 0.03	-1.40 ± 0.01
Blue-D1	10.60 ± 0.01	...	...	0.417 ± 0.02	-1.39 ± 0.02
Blue-D4	10.64 ± 0.02	...	...	0.151 ± 0.01	-1.41 ± 0.04
Red-all	10.68 ± 0.01	3.410 ± 0.07	-0.39 ± 0.03	0.126 ± 0.02	(-1.56)
Red-D1	10.61 ± 0.0	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)

SDSS ϕ(m) for blue and red centrals and satellites



Sample	log (M*/M$_\odot$)	ϕ_1*/10^{-3}Mpc^{-3}	α_1	ϕ_2*/10^{-3}Mpc^{-3}	α_2
Blue central	10.61±0.01	...	...	0.827±0.030	-1.32±0.02
Red central	10.70±0.02	2.23±0.08	-0.33±0.04	...	...
Blue satellite	10.59±0.02	...	...	0.196±0.013	-1.56±0.03
Red satellite	10.61±0.02[a]	0.935±0.07	-0.49±0.08	0.130±0.042	[-1.5][a]

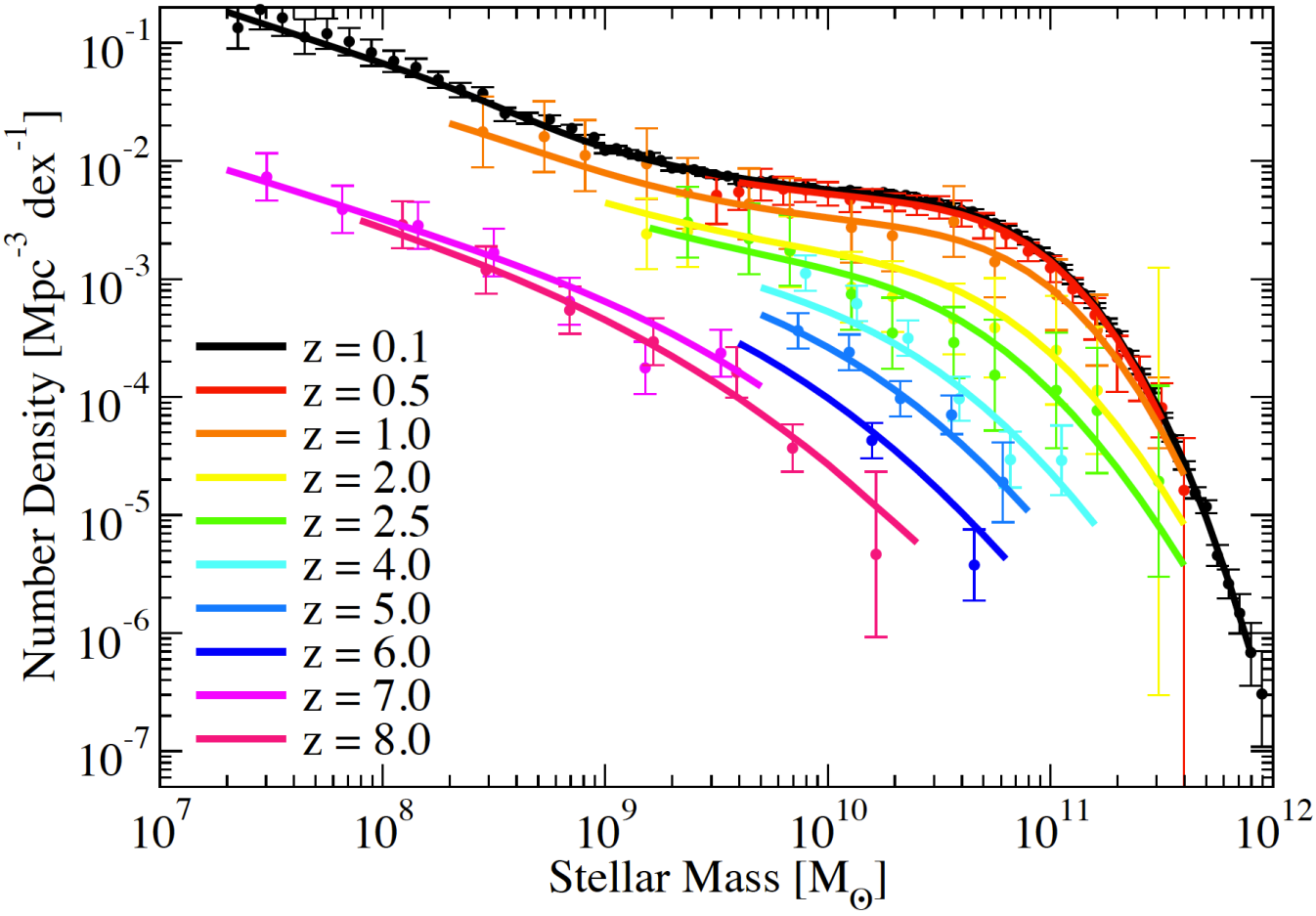


- Start at z = 10 with truncated power-law $\phi(m)$
- Assume $\beta = 0$ and evolve star-formation rates according to sSFR(t)
- Quench galaxies according to:

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

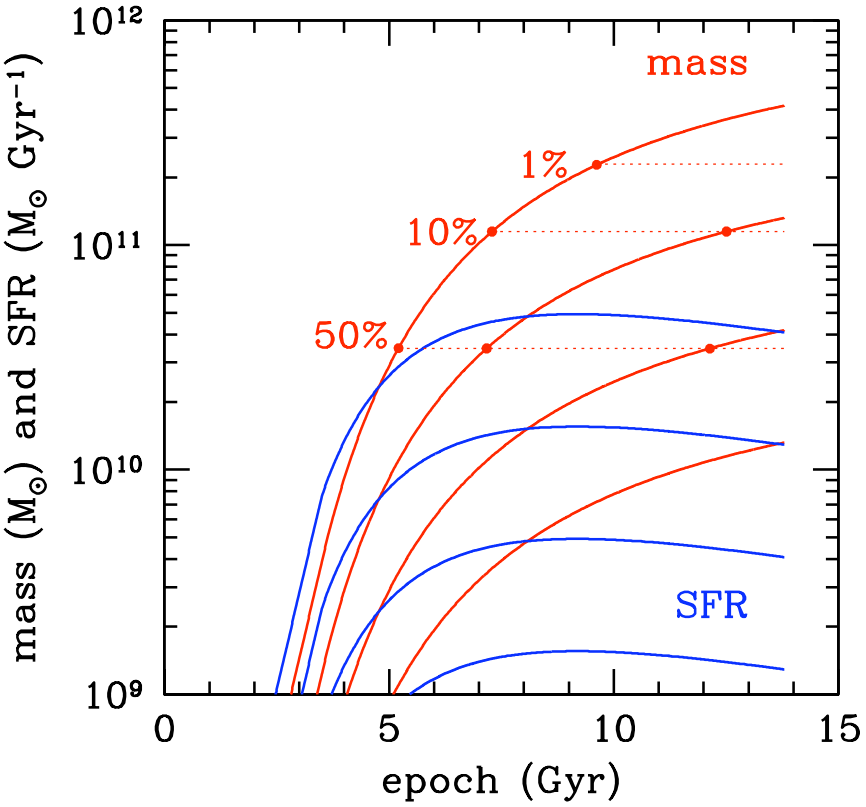
Evolving mass function: summary

Data compilation from
Behroozi et al 2012
arXiv 1207.6105



η = SFR/M* is equivalent to survival probability P = exp-(m/M*)

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



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

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

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

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

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

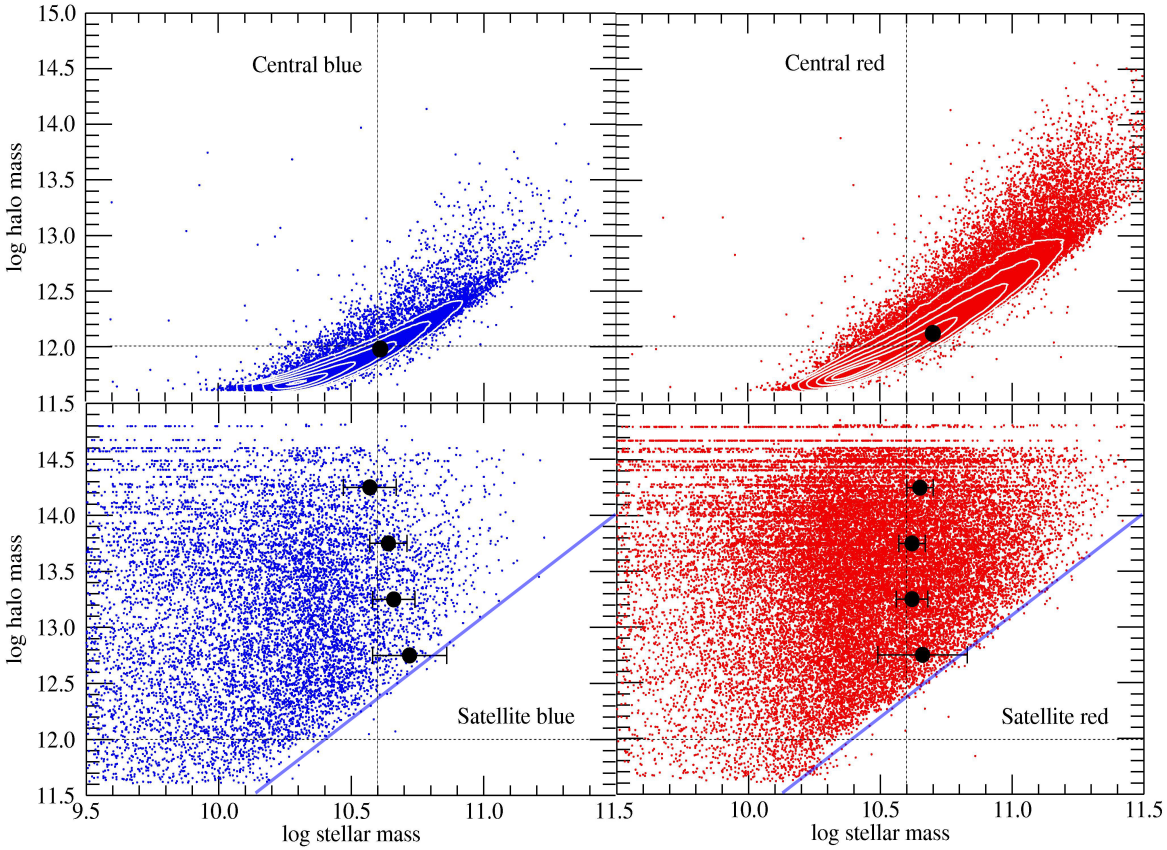
One consequence: Model does not depend on individual SFR(t) histories (why we could ignore ULIRGs)

Is our "mass quenching" just halo-quenching?

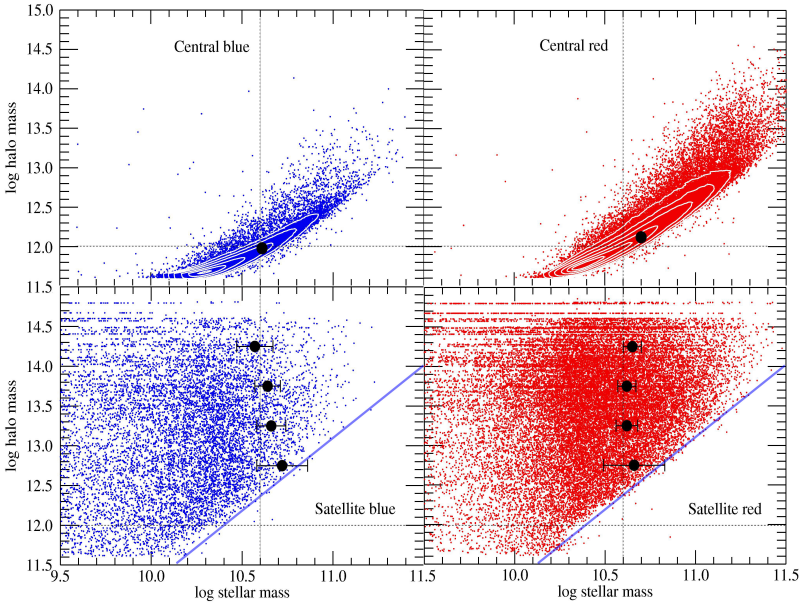
Since m_{star} correlates well with m_{halo} for centrals, does $P(m_{star})$ reflect the probability of a DM halo shutting down star-formation?

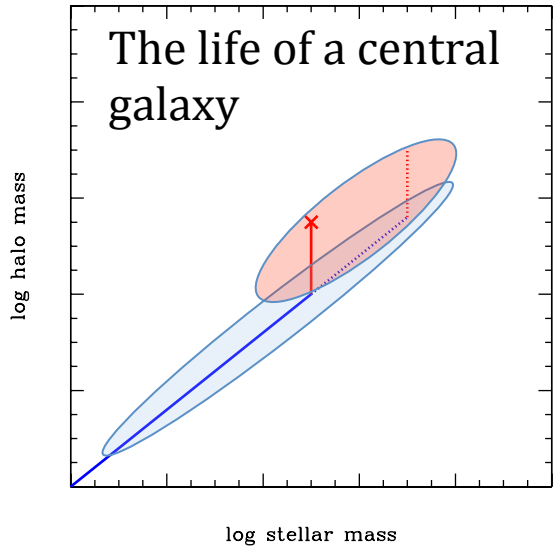
Note
(i) M* for satellites does not change with parent halo mass
(ii) satellites have exactly the same M* as centrals

Action of mass-quenching on satellites is evidently <u>independent</u> of the parent halo mass and is the <u>same</u> as on centrals

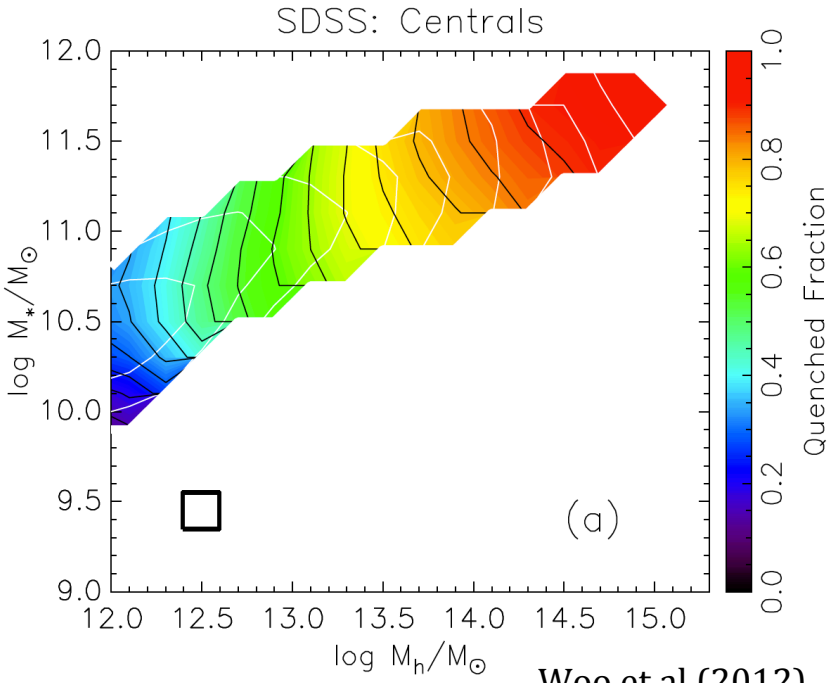


Is our "mass quenching" just halo-quenching? (Part II)





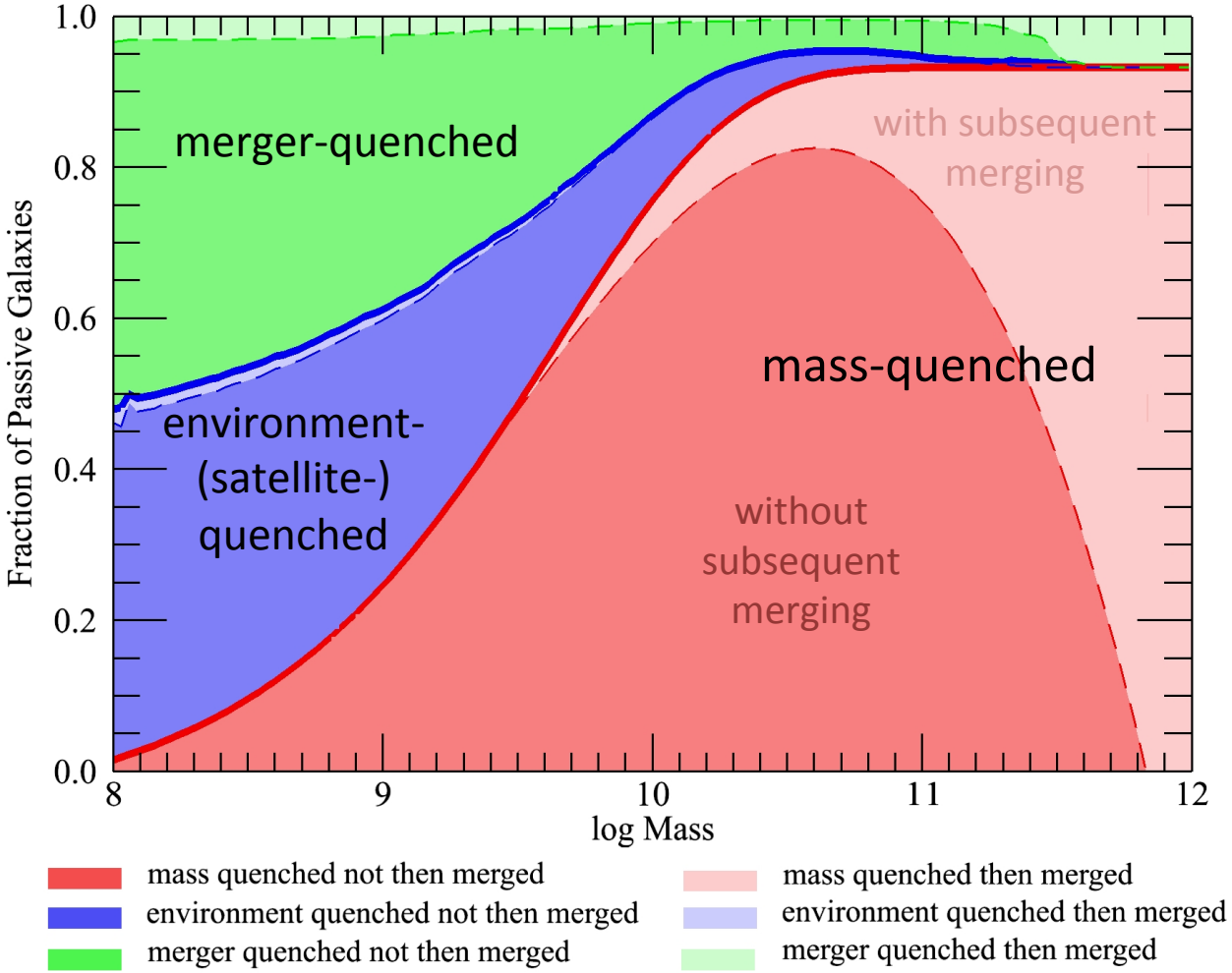
At a fixed stellar mass, centrals are redder in more massive haloes: clear evidence for halo quenching?



Woo et al (2012)

Histories of today's passive galaxies

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

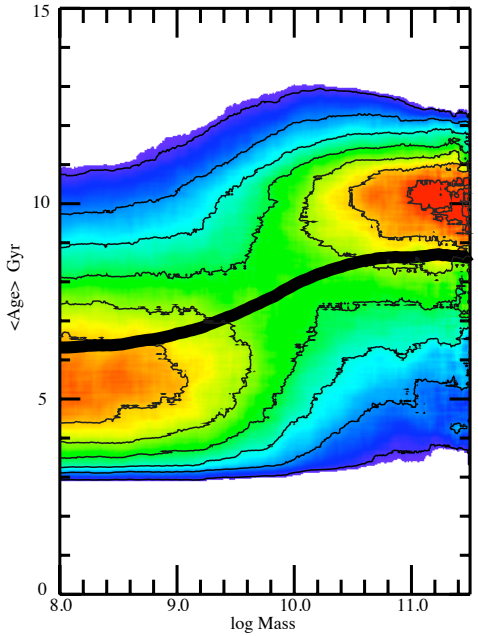


Ages and α-element abundances for passive galaxies as *f* (mass)

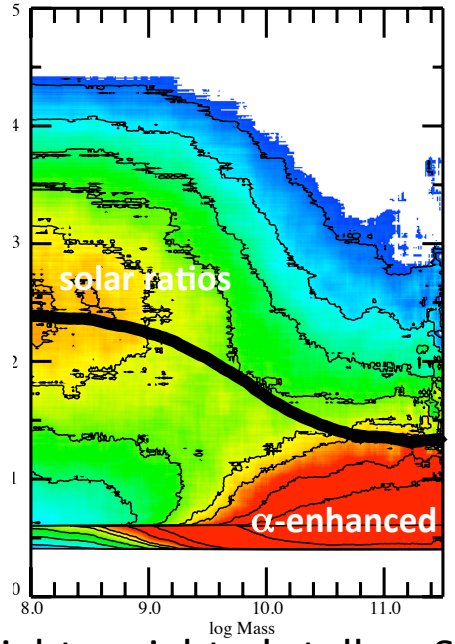
At a given mass:

- 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

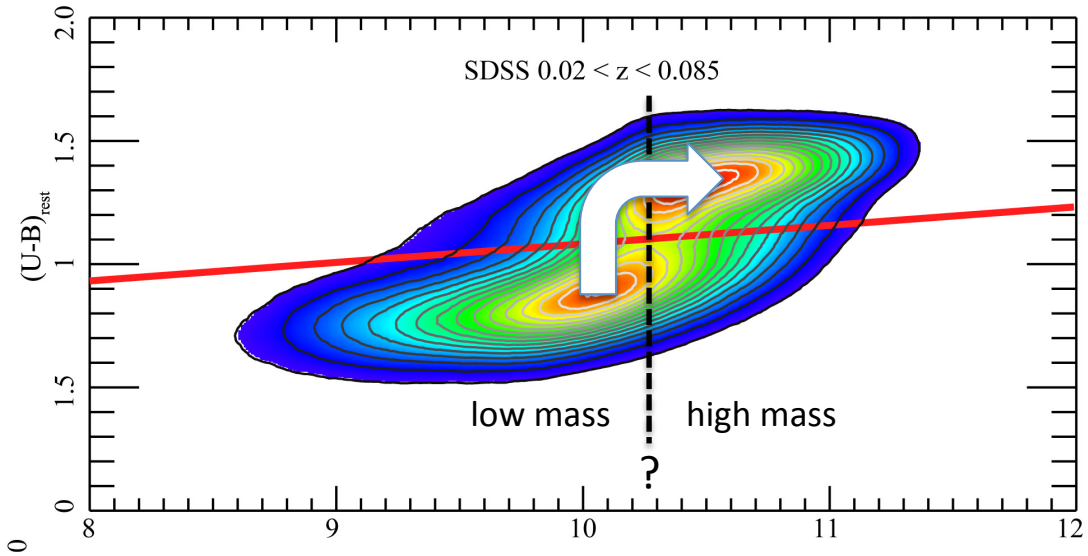


light-weighted stellar age



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

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 same mass.

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 ?

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

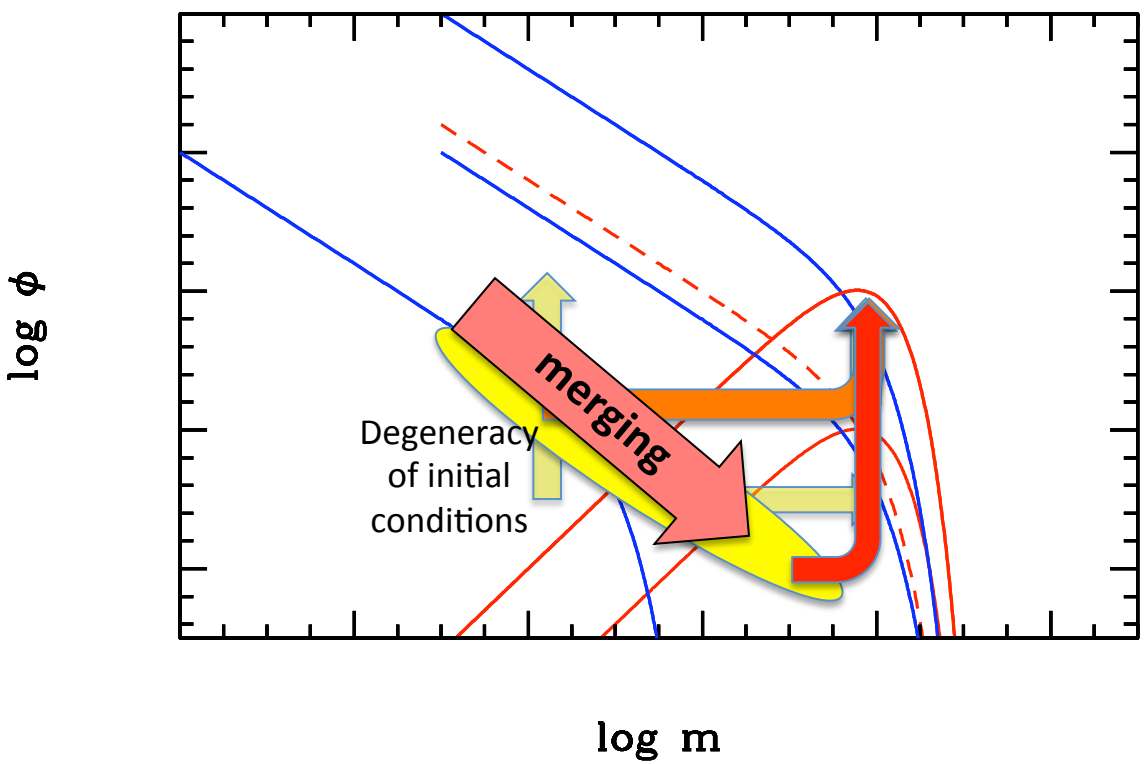
$$\alpha_{s,trans} = \alpha_{s,blue} + (1+\beta) = \alpha_{s,red}$$

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

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

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

4: Degeneracies at high redshifts



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 <u>both</u> 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 <u>initial</u> conditions.

which is largely parallel to merging vector.

→ Can have a lot of merging at high z (in Phase 1)

Merging in this phenomenological approach

1. Limits on “post-quenching merging” (a.k.a. “dry merging”)
2. Destruction of galaxies – the problem of α and β

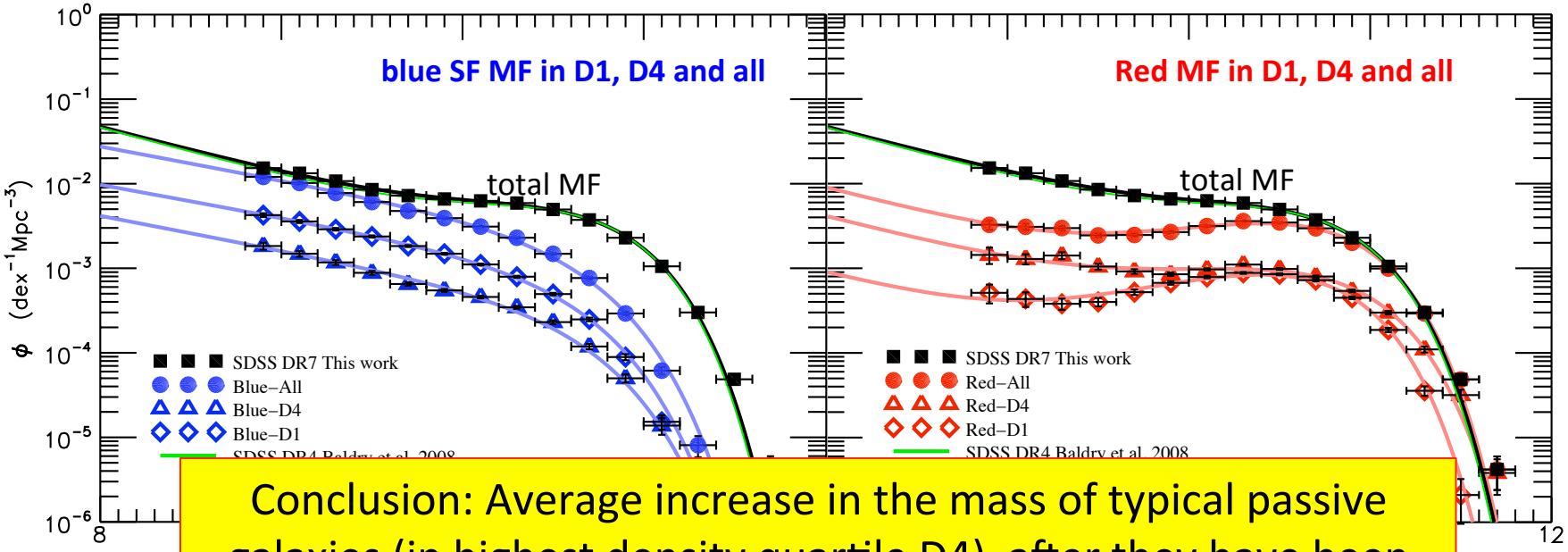
1. The post-quenching merging of passive galaxies

The (observed) constant shape of the Schechter function of star-forming galaxies since z >> 2 severely constrains the form of the mass-function of the passive galaxies that result from quenching (e.g. same M*)

Why? A Schechter function multiplied by a power-law m^{γ} gives another Schechter function with same M^* and different faint-end slope $\Delta\alpha_s = \gamma$

Merging of passive galaxies after mass-function established by quenching will change Schechter M^*

- Without change in numbers (centrals consume satellites) $\Delta \log M^* = \Delta \log < m >$
- With change in numbers $\Delta \log M^* \sim 0.6\, \Delta \log \alpha \sim 3\, \Delta \log < m >$



Conclusion: Average increase in the mass of typical passive galaxies (in highest density quartile D4) after they have been quenched is probably only about 35% (and 15% in D1)

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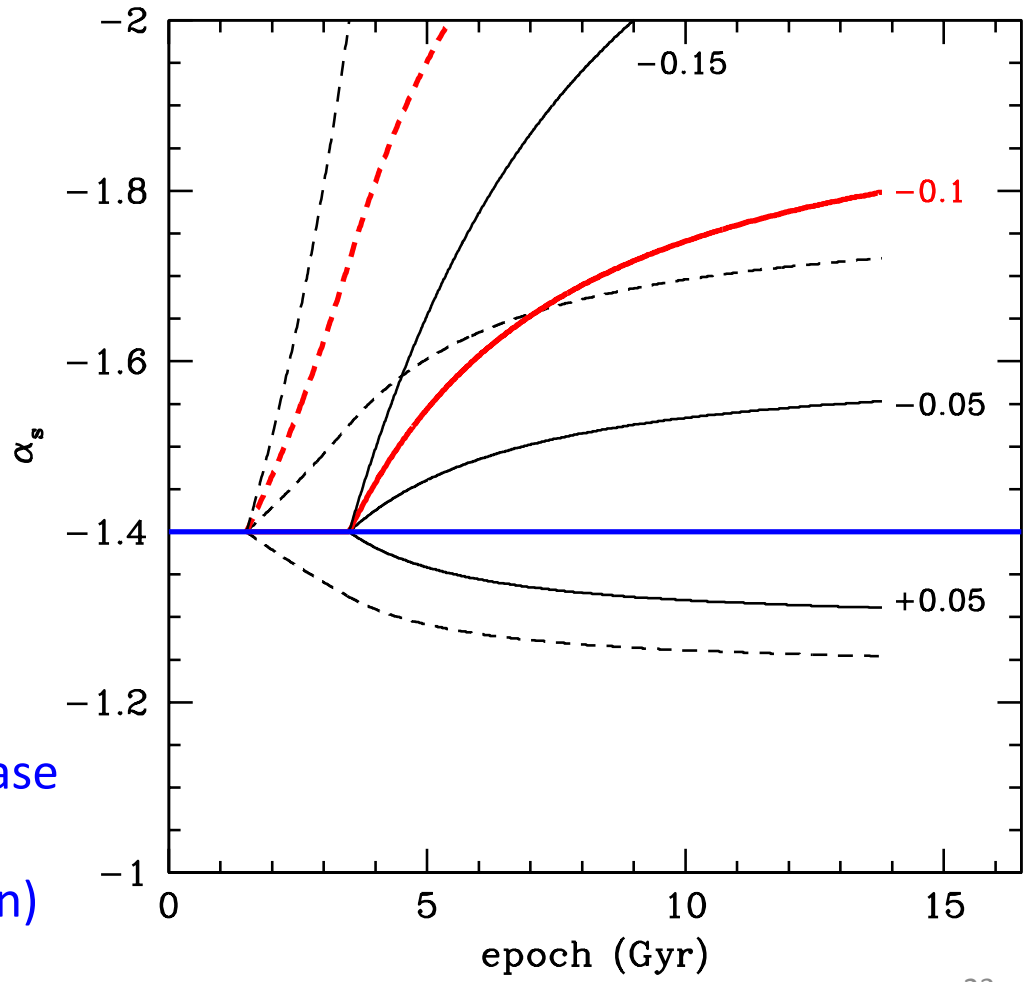
2. The destruction of galaxies and the problem of α and β

Unless $\beta = 0$, the faint end slope, of Schechter function α_s rapidly diverges

Can this be controlled through destruction of galaxies through merging, whilst preserving global mass conservation?

- Define merging mass ratio x with $1 < x < 100$
- Define *sMMR* as specific increase in mass due to merging (*c.f. sSFR* due to star-formation)



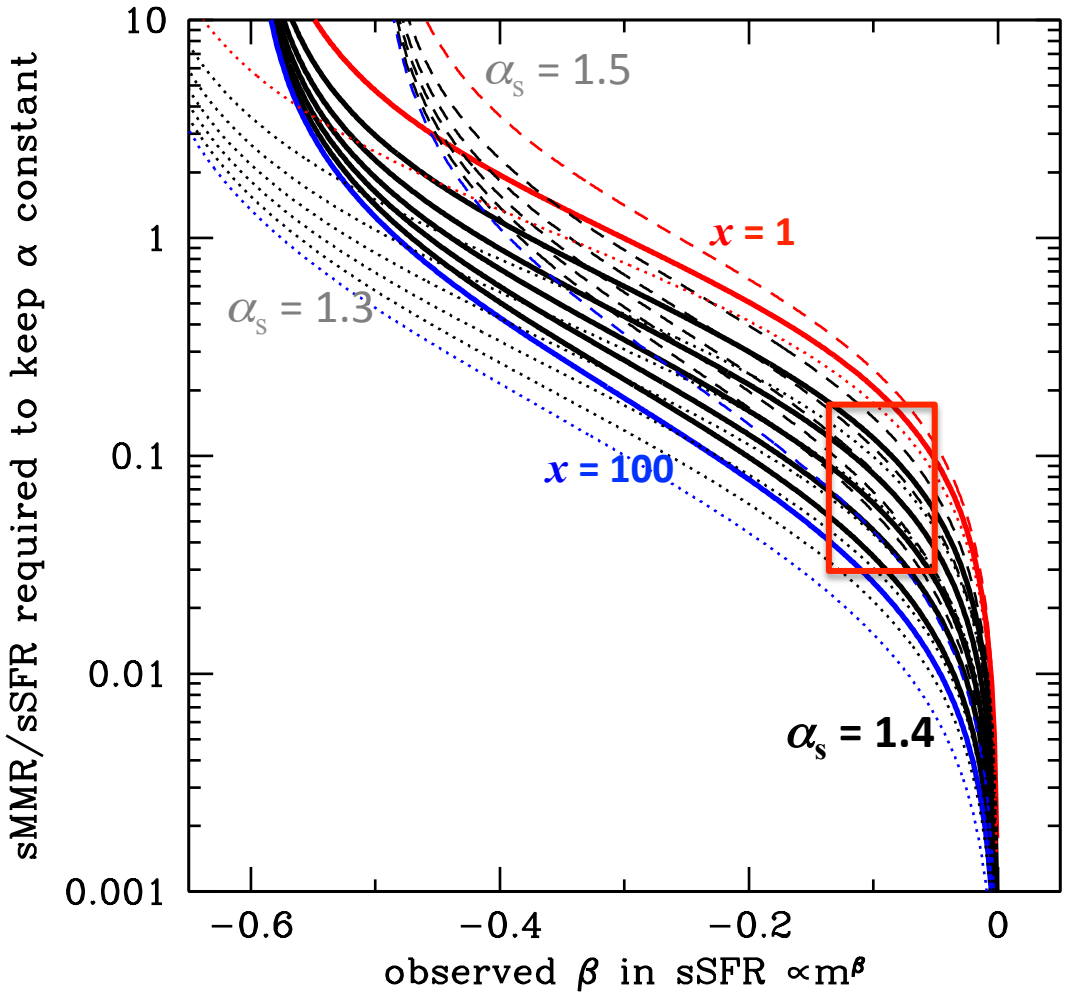
$$sMMR = -\frac{(1+\alpha_s+\beta)}{(1+\alpha_s+\beta)+x^{(1+\alpha+\beta)}}\,sSFR + \frac{\alpha}{(1+\alpha_s)+x^{1+\alpha}}\,sSFR\big|_{M*}\,\frac{\Gamma(\alpha_s+\beta+2)}{\Gamma(\alpha_s+2)}$$

Easy for small β;
but impossible for β ~ (1+α_s)

Suggests **sMMR ~ 0.1 sSFR**
for α_s = -1.4, β = -1

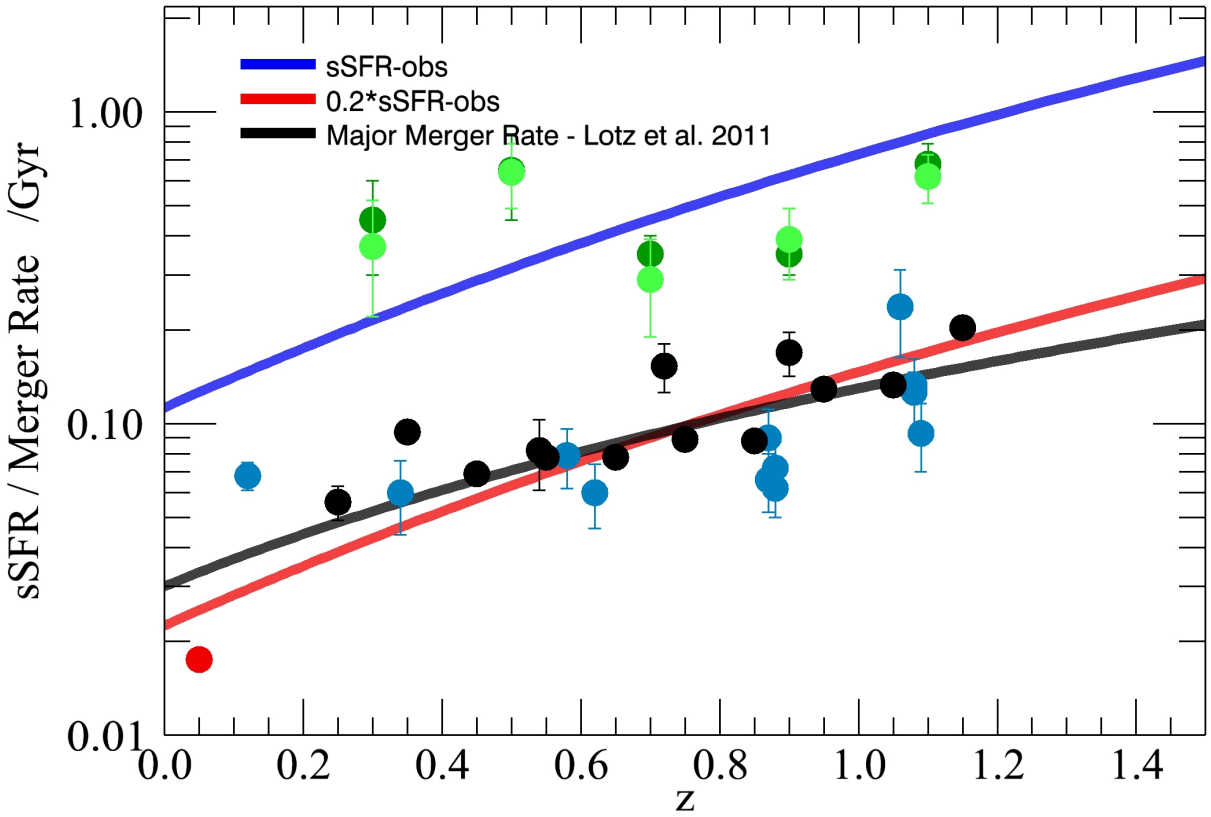
Mass assembly through merging is significant but not dominant relative to in situ SF

Note (unexpected?) link between time evolution of merging rate and sSFR. Not surprising, since sSFR is known to track specific mass increase of haloes.



Is there evidence in the sky for these merger rates?

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



x = 10, minor mergers

x = 2, major mergers

Lotz et al (2011)

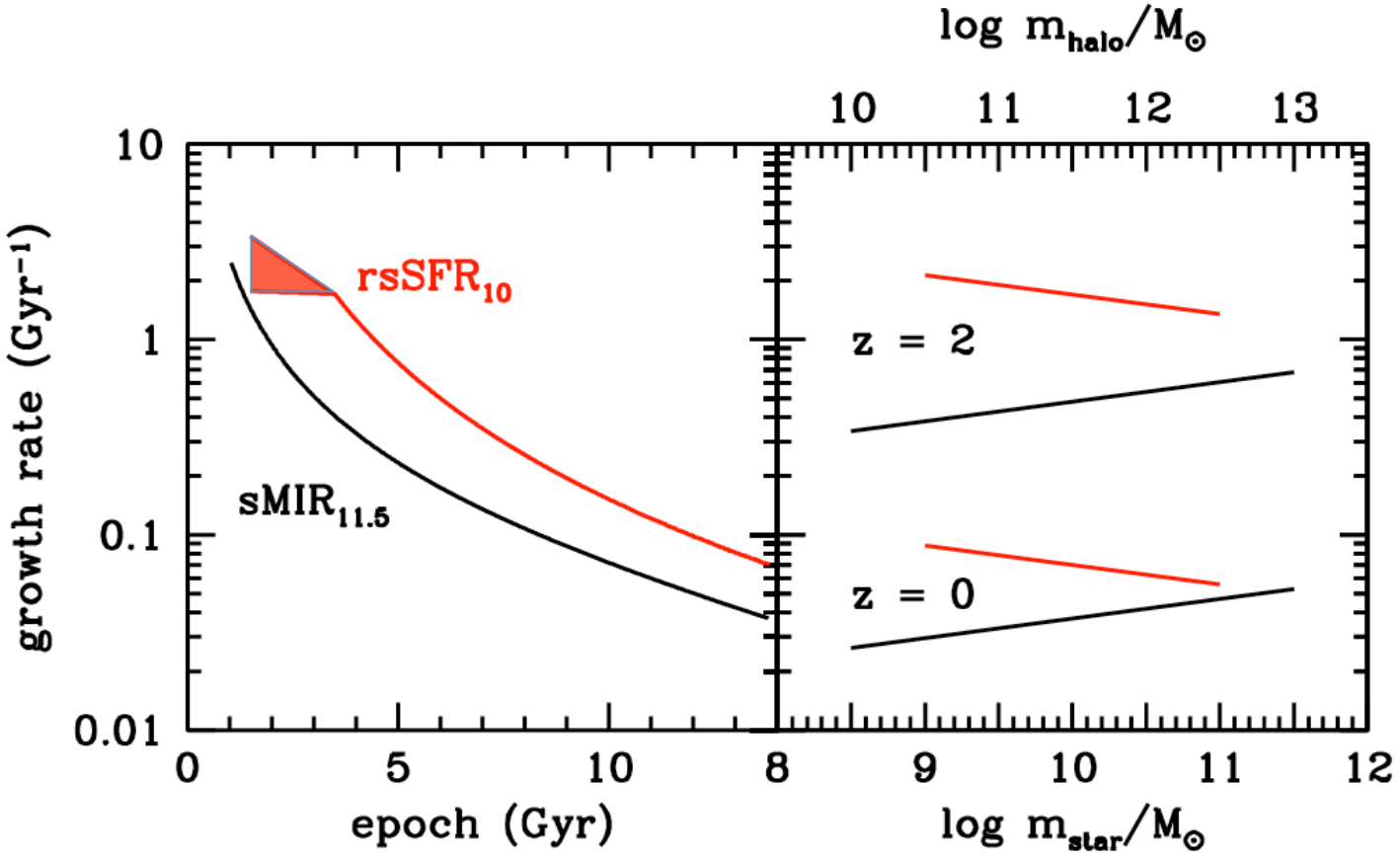
Gas-regulated evolution of galaxies: the evolution of the cosmic sSFR, the metallicity-mass-SFR relation and the M/L ratio of galaxies

Simon Lilly, Marcella Carollo, Antonio Pipino,
Alvio Renzini & Yingjie Peng

Submitted to ApJ

Starting point: There are striking similarities between the cosmic evolution of the rsSFR and the specific growth rate of dark matter

This agreement motivates the adoption of the gas-regulator model



However, there are differences:

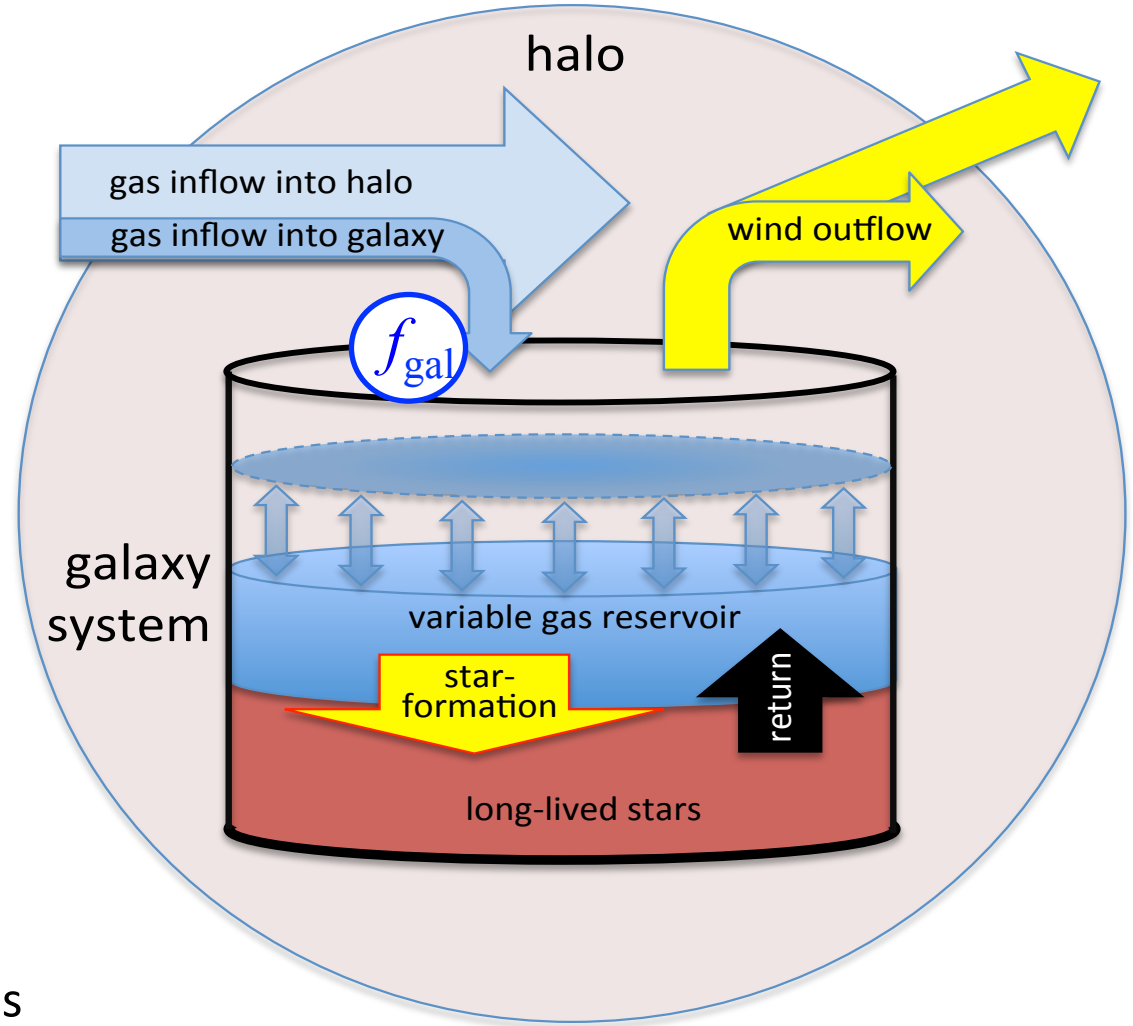
- the rsSFR is systematically higher (by a factor of 2) and
- the mass dependence of rsSFR and the $sMIR_{DM}$ is reversed: $\beta_{sSFR} \sim -0.1$, $\beta_{DM} \sim +0.1$

Inflow $\Phi = f_{gal} \cdot \left(\frac{\Omega_B}{\Omega_{DM}} \cdot \frac{dm_{DM,halo}}{dt} \right)$

$SFR = \varepsilon m_{gas}$

Gas ratio $\mu = \frac{m_{gas}}{m_{star}}$

Outflow $\Psi = \lambda \cdot SFR$



From these follow:

$\tau_{gas} = \varepsilon^{-1}$

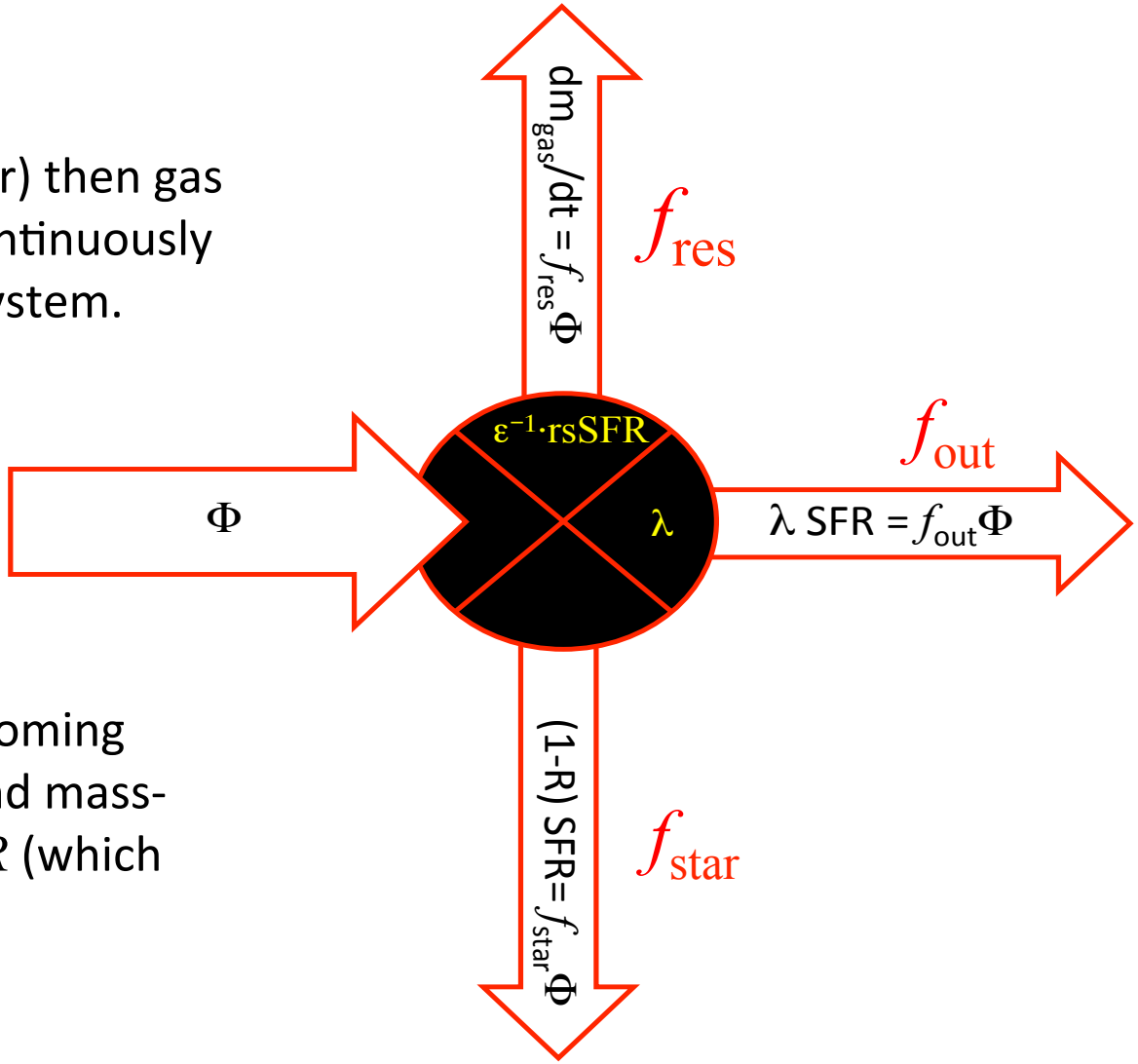
$\mu = \varepsilon^{-1} \cdot sSFR$

and mass continuity gives

$\Phi = (1 - R + \lambda) \cdot SFR + \frac{dm_{gas}}{dt}$

$\frac{dm_{gas}}{dt} = \left(\mu(1 - R) + \epsilon^{-1} \frac{dln\mu}{dt} \right) \cdot SFR$

If τ_{gas} is short (see later) then gas can be regarded as continuously flowing through the system.



The division of the incoming stream is set by λ (wind mass-loading) and $\varepsilon^{-1} \bullet rsSFR$ (which sets the gas ratio μ).

Specific quantities

$$rsSFR = (1 - R) \cdot sSFR$$

$$sMIR_{DM} = \frac{1}{m_{halo}} \frac{dm_{halo}}{dt}$$

$$sMIR_B = \frac{\Phi(\mathrm{t})}{\int_0^t \Phi(\mathrm{t}')dt'}$$

Recall: f_{gal} = fraction of baryons flowing into the halo that penetrate down to enter the galaxy system)

If f_{gal} is constant, then $sMIR_{\mathrm{B}} = sMIR_{\mathrm{DM}}$

Why focus on specific quantities?

- sSFR and sMIR are both easy "observables". Inflow Φ is unfortunately not.
- sSFR and sMIR vary only weakly with mass

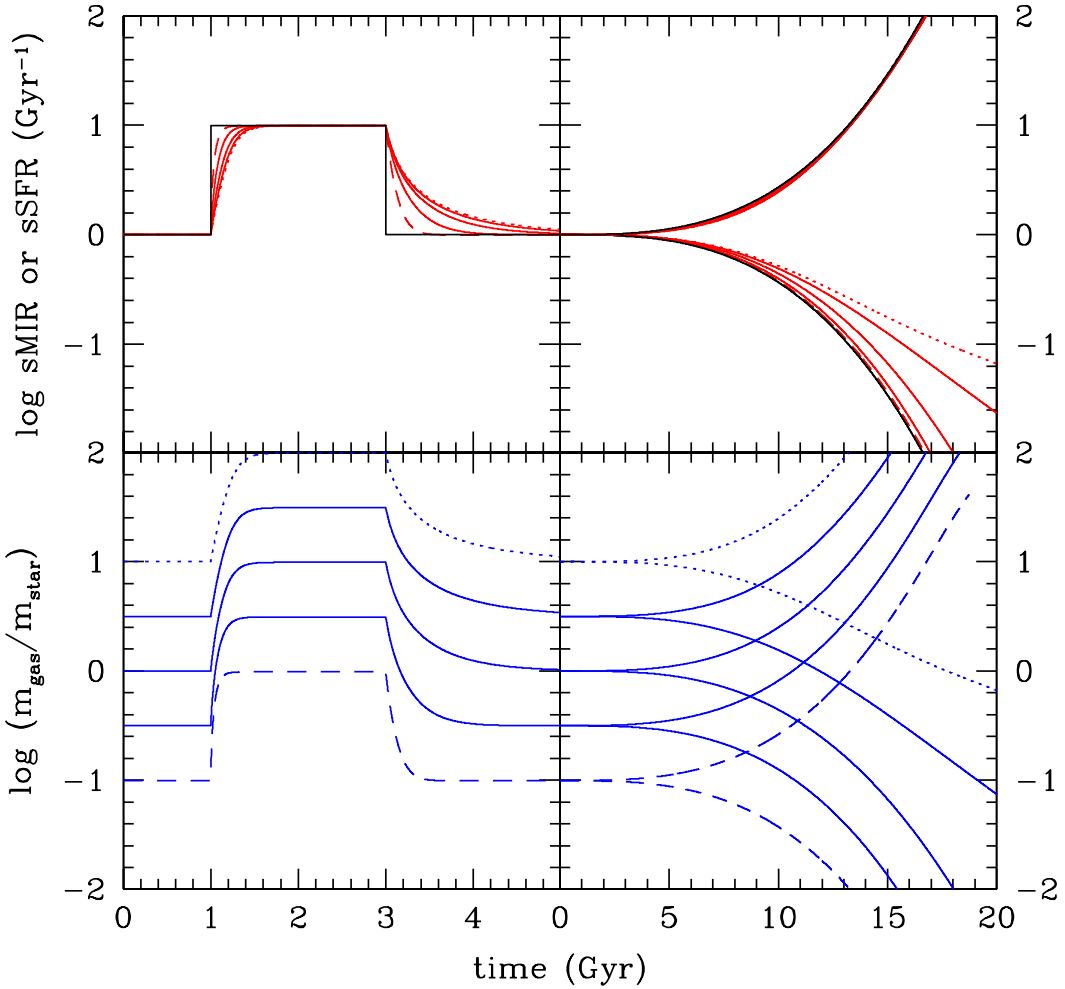
The regulator with constant ε and λ and varying $sMIR_B$ quickly sets the rsSFR to the $sMIR_B$

Why? The regulator works by establishing f_{star} ~ constant.

Changes to the sMIR change equilibrium gas ratio μ, which changes value of f_{star}

Constant f_{star} quickly sets rsSFR = sMIR

Toy model: constant λ, five constant values of $\varepsilon = \tau_{gas}^{-1}$ and varying sMIR



Timescales in galaxy evolution

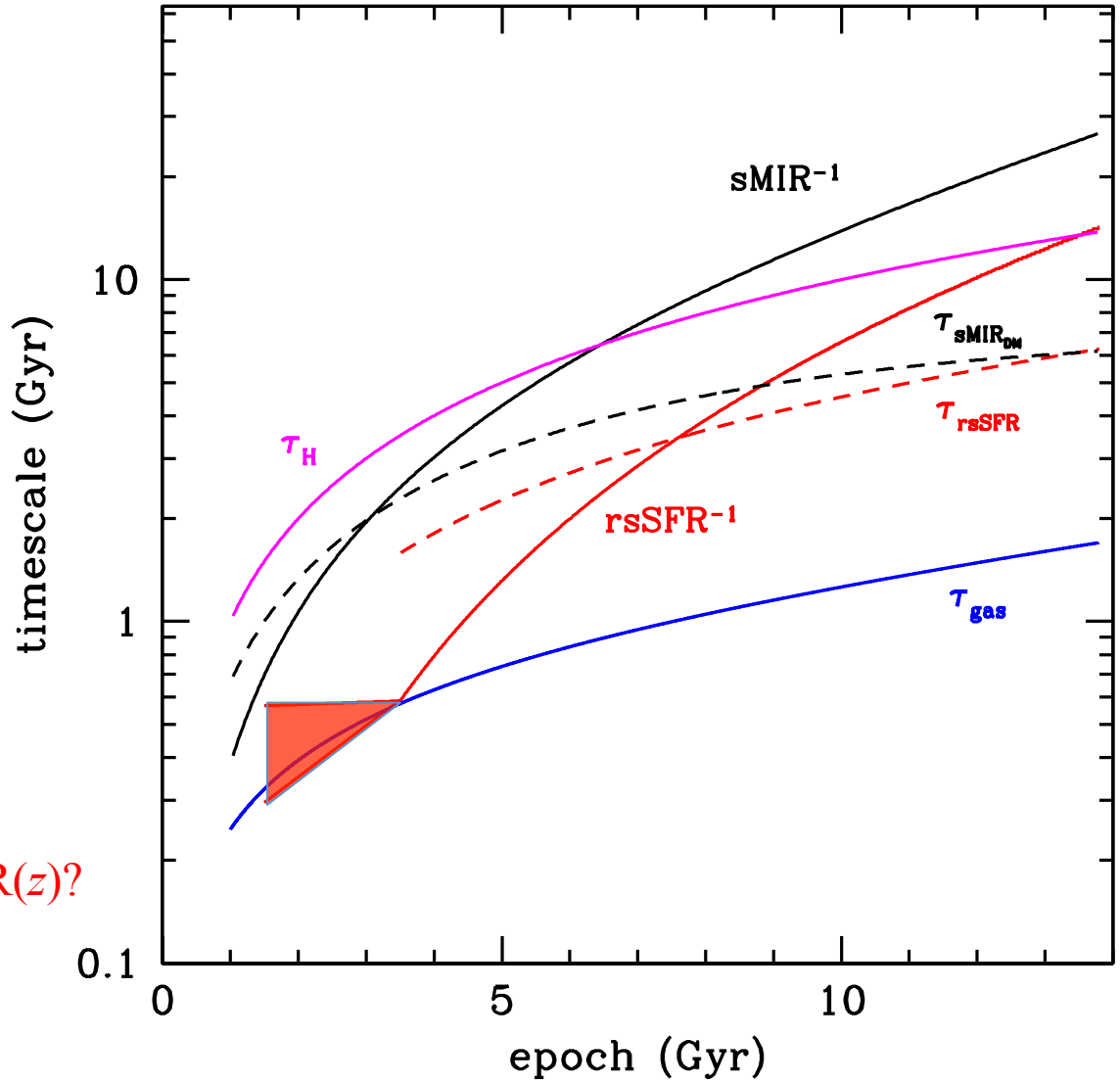
The gas regulator requires

- τ_{gas} < timescale on which *external* conditions ($sMIR_B$) are changing

  OK!

- τ_{gas} < timescale on which internal parameters ε and λ are changing, i.e. $rsSFR^{-1}$ if ε and λ depend strongly on m_{star}

  Not OK at $z \geq 2$?
  Changes in $rsSFR(z)$?
  Clumpy disks



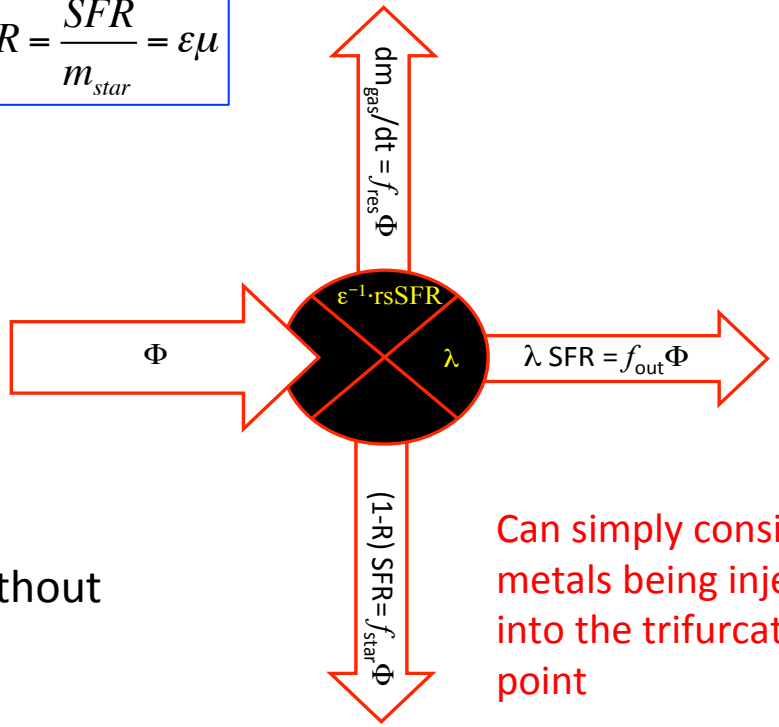
$$\frac{dZ}{dt} = \frac{1}{m_{gas}}\left[\left(y - (Z - Z_0)(1 - R + \lambda)\right) \cdot SFR - (Z - Z_0)\frac{dm_{gas}}{dt}\right]$$

$$Z_{eq} = Z_0 + \frac{y_R}{1 + \lambda(1 - R)^{-1} + \varepsilon^{-1} \cdot \left(sSFR + (1 - R)^{-1}\frac{dln\mu}{dt}\right)}$$

$$sSFR = \frac{SFR}{m_{star}} = \varepsilon\mu$$

Metallicity is set instantaneously and not by the previous history of the galaxy, which enters only via the (small) dlnμ/dt term.

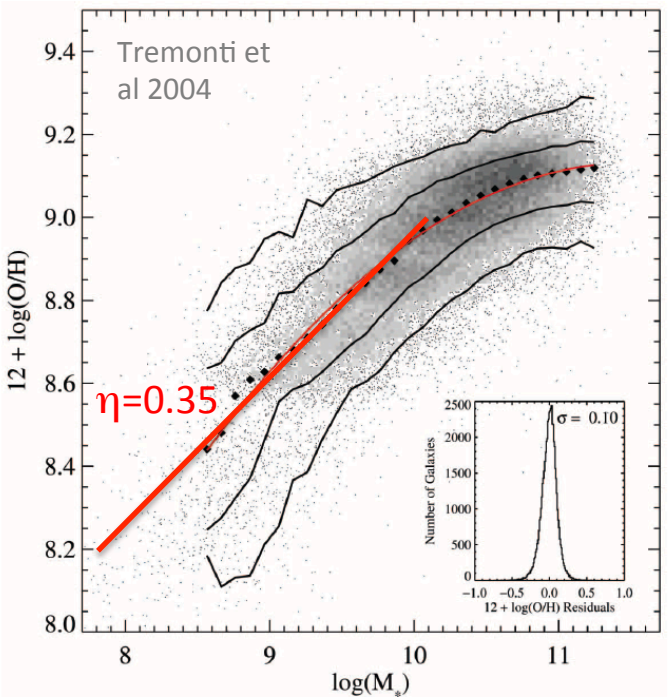
This is because τ_{gas} is short

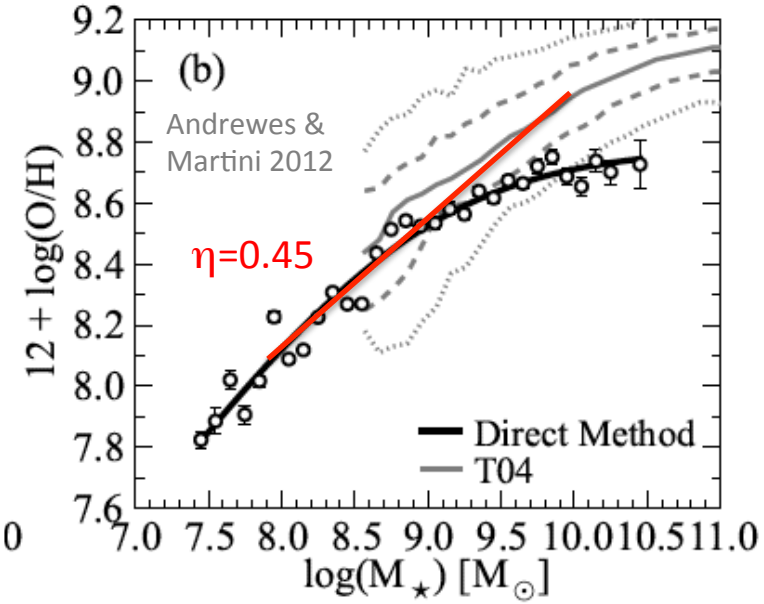


Can simply consider metals being injected into the trifurcation point

- Natural $Z(m_{\rm star}, SFR)$ relation
- $f_{\rm star}(m_{\rm star})$ comes directly from $Z(m_{\rm star})$ (without knowing ε or λ)

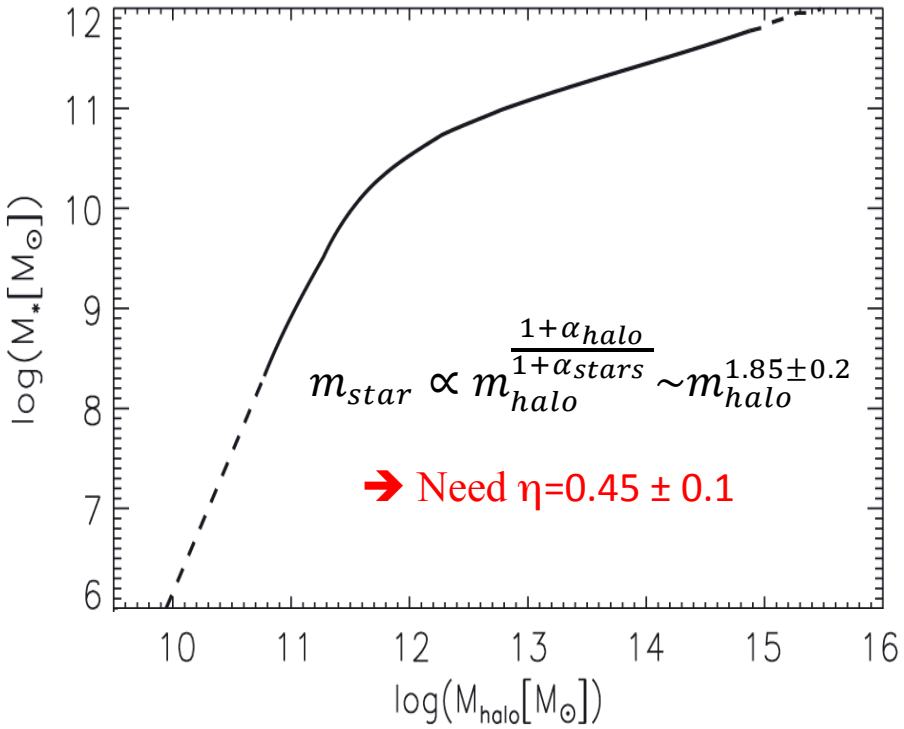
$$Z_{eq} = Z_0 + y_R\frac{(1 - R)SFR}{\Phi} = Z_0 + f_{star}y_R$$





$$Z_{eq} = Z_0 + f_{star} y_R$$

$$F = \frac{m_{star}}{m_{halo}} = \frac{\int_0^t f_{gal} f_{star} \frac{dm_{halo}}{dt'} dt'}{\int_0^t \frac{dm_{halo}}{dt'} dt'} \propto m_{star}^{\eta}$$



SDSS $Z(m_{\rm star})$ relation predicts correct $f_{\rm star}(m_{\rm star})$ relation to solve abundance matching, without changing $f_{\rm gal}$

Catch-up effects

$$F = \frac{m_{star}}{m_{halo}} = \frac{\int_0^t f_{gal} f_{star} \frac{dm_{halo}}{dt'} dt'}{\int_0^t \frac{dm_{halo}}{dt'} dt'} \propto m_{star}^{\eta}$$

If $f_{\rm star} f_{\rm gal}$ is constant, then $rsSFR = sMIR_{\rm B} = sMIR_{\rm DM}$.

If $f_{\rm star} f_{\rm gal}$ is actually increasing as the mass grows, then $rsSFR > sMIR_{\rm DM}$

$$rsSFR = sMIR_{DM} + \frac{1}{F}\frac{\partial F}{\partial m_{star}}\frac{\partial m_{star}}{\partial t} + \frac{1}{F}\frac{\partial F}{\partial t}$$

small

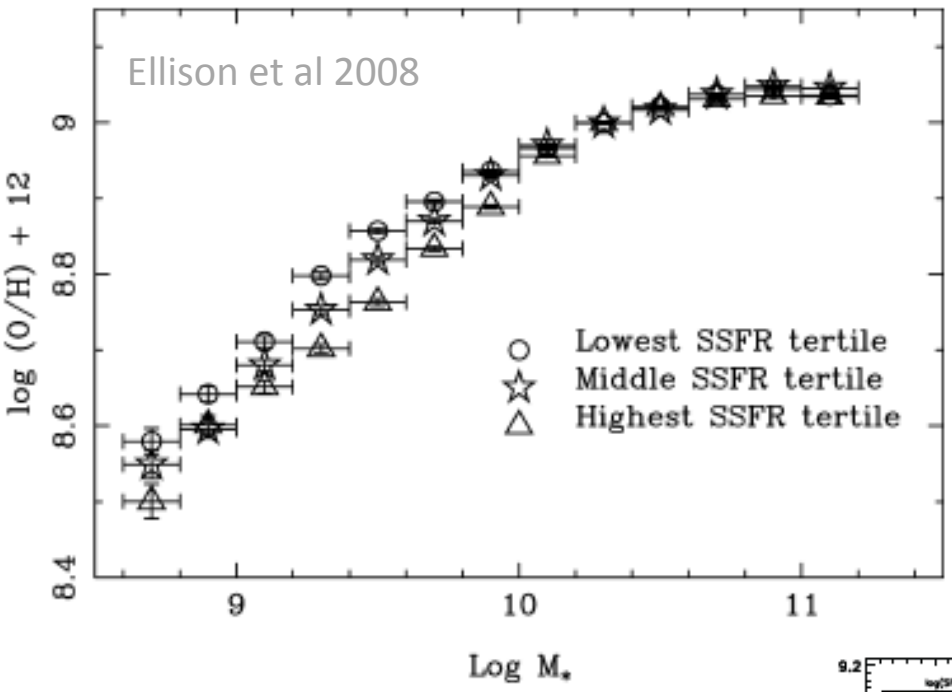
$$rsSFR \sim \frac{1}{1-\eta} sMIR_{DM}$$

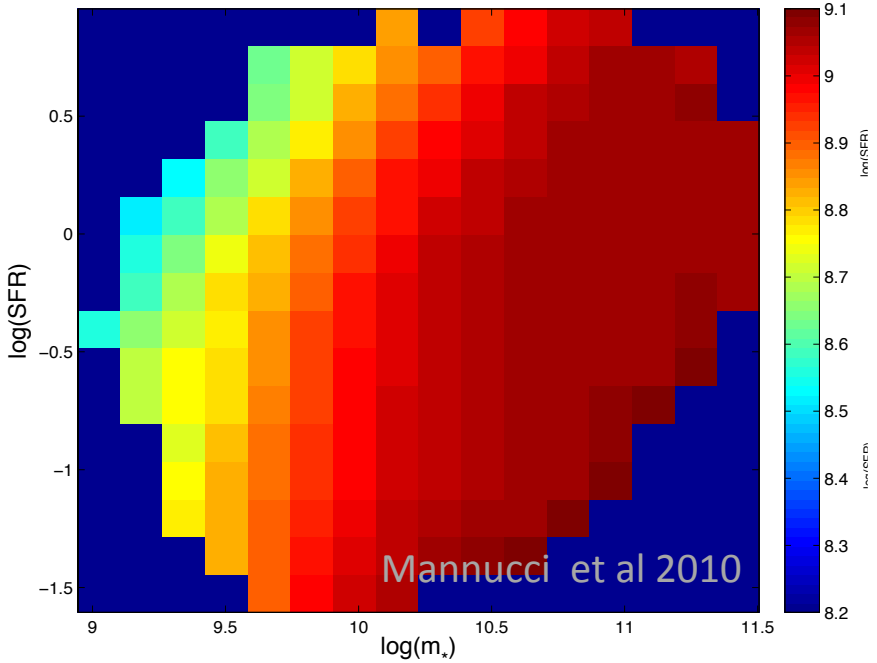
η ~ 0.5 from observed m-Z relation would indicate $rsSFR \sim 2 \times sMIR_{\rm DM}$ if $f_{\rm gal}$ is constant

Curvature of relation would predict larger offset at low masses, i.e. reversal of β

$Z(m_{star},SFR)$ is a mess

$$Z_{eq} = Z_0 + \frac{y_R}{1 + \lambda(1-R)^{-1} + \varepsilon^{-1} m_{star}^{-1} \cdot SFR}$$





Yates et al 2012

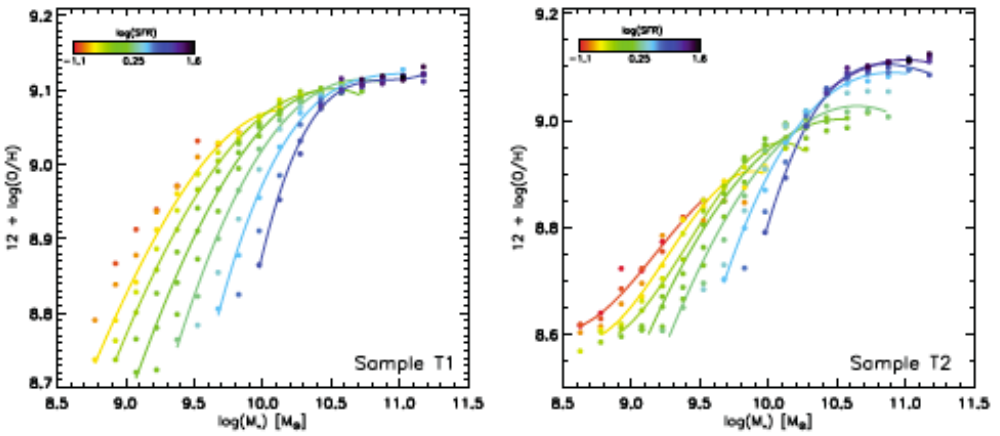


Figure 1. The M_*–Z relation for Sample T1 (left-hand panel) and Sample T2 (right-hand panel). Filled circles show the median metallicities of galaxies binned by M_* and SFR, for bins containing ≥50 galaxies. Binned data are coloured by SFR, as are the fits at fixed SFRs (solid lines), plotted for log(SFR) = (−0.975, Sample T2 only), −0.675, −0.375, −0.075, 0.225, 0.525, 0.825 (1.125 Sample T2 only). The dependence of Z on SFR for the two samples is clearly different. For example, Sample T2 exhibits a clear dependence at high mass.

$$Z_{eq} = Z_0 + \frac{y_R}{1 + \lambda(1-R)^{-1} + \varepsilon^{-1}\left(m_{star}^{-1} \cdot SFR + (1-R)^{-1}\frac{dln\mu}{dt}\right)}$$

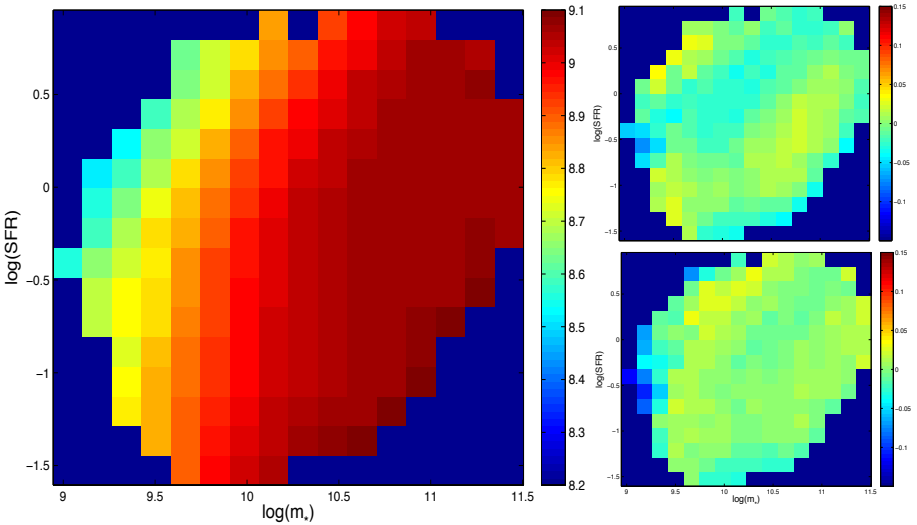


Table 1: Fits of Equation (40) to observational data[a]

Z_0/y_R	$\log y_R$[b]	λ_{10}	a	ε_{10}^{-1} Gyr	b
Fits to Mannucci et al (2010) SDSS $Z(m_{star},SFR)$ data					
[0.00]	9.02	0.25±0.02	−0.81±0.03	2.4±0.2	0.28±0.03
[0.03]	9.00	0.29±0.03	−0.79±0.03	2.8±0.2	0.32±0.03
[0.10]	8.98	0.40±0.04	−0.77±0.03	3.8±0.3	0.41±0.04
Fits to Tremonti et al (2004) SDSS $Z(m_{star})$ relation[c]					
[0.00]	9.19	0.57±0.03	−0.48±0.02	[2.7]	[0.3]
[0.03]	9.16	0.55±0.04	−0.52±0.02	[2.7]	[0.3]
[0.10]	9.10	0.51±0.03	−0.62±0.02	[2.7]	[0.3]

$\varepsilon^{-1}(@10^{10}M_\odot) \sim$ 2-3 Gyr and $\varepsilon \propto m_{\rm star}^{-1/3}$

Bit high? But this includes all gas!

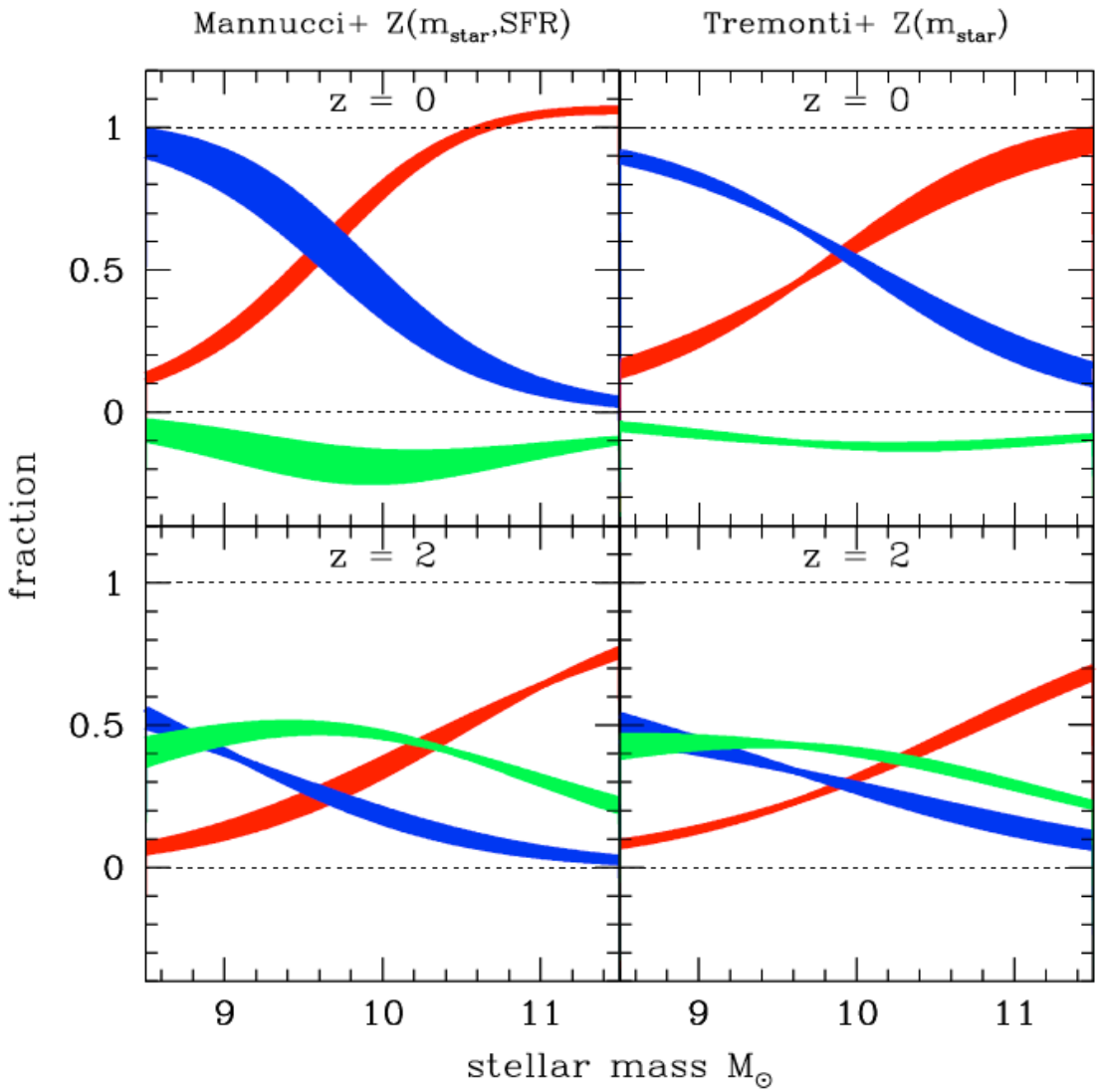
$\lambda(@10^{10}M_\odot) \sim$ 0.25-0.4 and $\lambda \propto m_{\rm star}^{-0.8}$

Bit low and steep? But this increases if I fit Tremonti et al m-z relation

Will take these "determinations" of ε and λ at face value, and assume ε varies as $(1+z)$

Three-way split into stars, outflow and in or out of the reservoir

- Most baryons entering the galaxy system end up in stars at high masses. Most are re-ejected at low masses
- Change in the reservoir size is significant at high redshift (marginally dominant at some masses)i.e.
- Reservoir is depleting at present epoch (i.e. negative $f_{\rm res}$), but at rate that is still small compared with the flow through the system

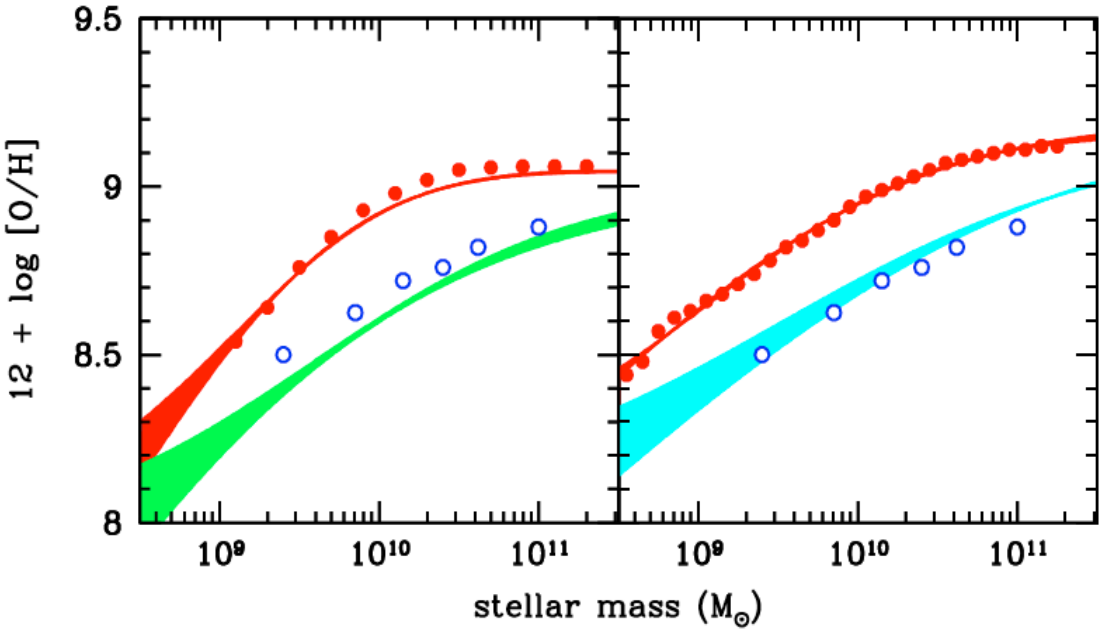


Chemical evolution

$$Z_{eq} = Z_0 + \frac{y_R}{1 + \lambda(1-R)^{-1} + \varepsilon^{-1}\left(m_{star}^{-1} \cdot SFR + (1-R)^{-1}\frac{dln\mu}{dt}\right)}$$

- Metallicity Z is set "instantaneously". Only knowledge of past history is contained in the (small) $d\ln\mu/dt$ term
- The $Z(m_{\rm star}, SFR)$ "fundamental metallicity relation" (so-called) will evolve only to the extent that λ and ε evolve. I will assume ε varies as $(1+z)$.
- The evolution of the $Z(m_{\rm star})$ mass-metallicity relation will be driven by the evolving cosmic sSFR(z) (slightly reduced by likely evolution in ε)

Qualitatively works!

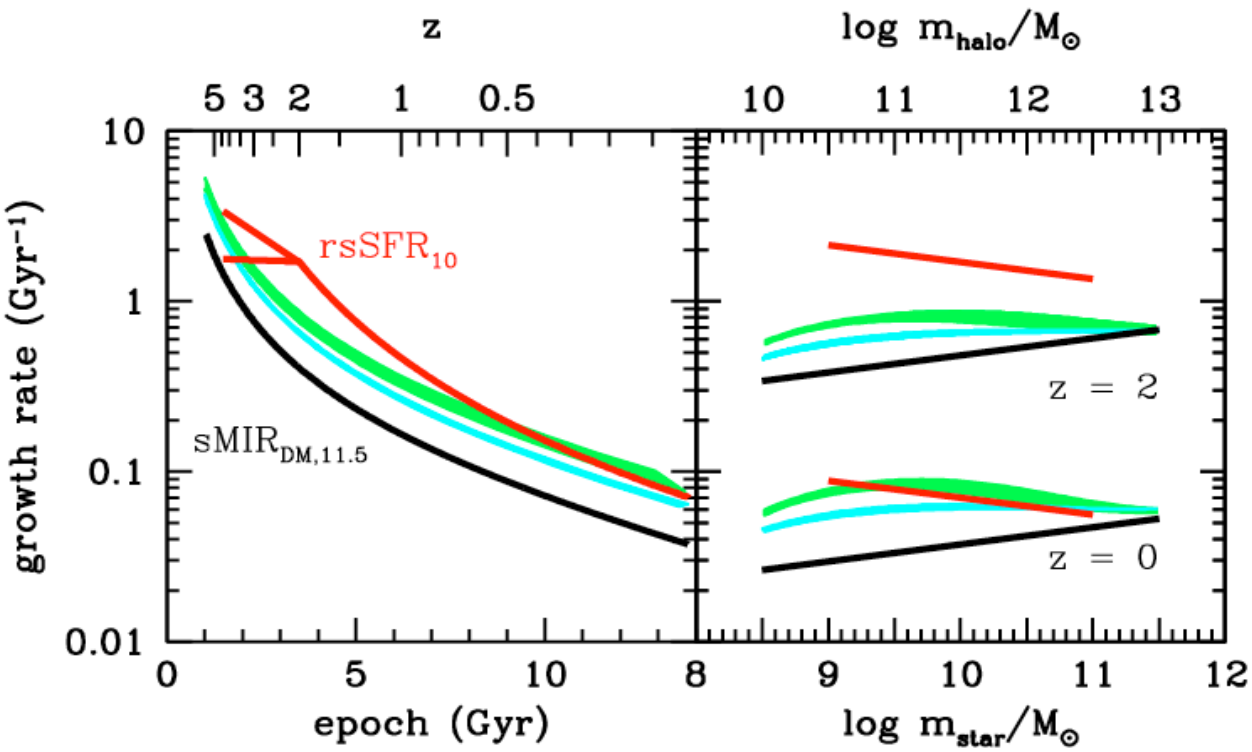


Simple numerical model

$$Z_{eq} = Z_0 + f_{star} y_R$$

Numerical model:

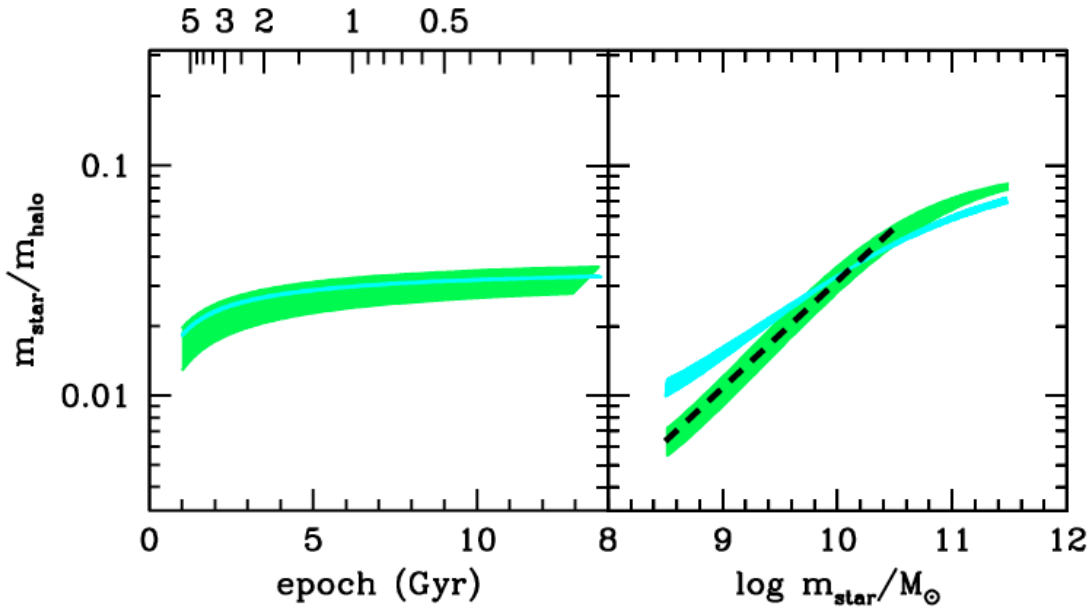
- Haloes grow as per "observed" $sMIR_{DM} = 0.04 \left(\frac{m_{halo}}{10^{12} M_\odot}\right)^{0.1} (1+z)^{2.2}$
- Baryons fed in with constant $f_{\rm gal}$
- Stars form and mass is lost according to "fitted" ε and λ, with ε increasing as (1+z)



Simple numerical model (2)

$$Z_{eq} = Z_0 + f_{star} y_R$$

Value of f_{gal} required to get m_{star} ~ 0.03 m_{halo} in massive galaxies is high: f_{gal} ~ 0.6



Taken at face value, would suggest that variation in m_{star}-m_{halo}, boost of rsSFR relative to sMIRDM and inefficiency of galaxy formation are due to baryonic processes operating within galaxies, rather than within the haloes, because f_{gal} is high and independent of mass.

What's the point?

Conclude that the simple gas-regulator model

- naturally sets rsSFR = $\mathrm{sMIR_B} \sim \mathrm{sMIR_{DM}}$ (if $f_{\mathrm{gal}} \sim$ constant)

- works, but may break-down at $z > 2$ when $\tau_{\mathrm{gas}} \sim$ ssSFR (i.e. when mass-dependent internal parameters are changing fast compared with τ_{gas}

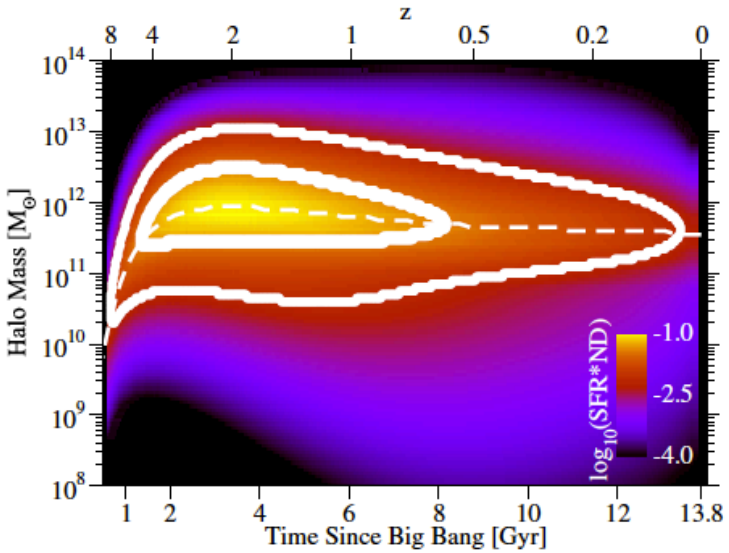
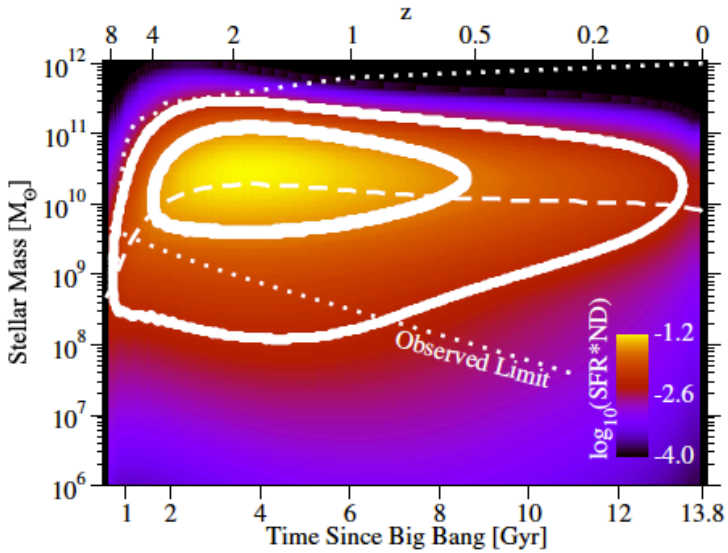
- gives $f_{\mathrm{star}}(m)$ directly from $Z(m)$ and this:
  - naturally accounts for abundance matching
  - naturally accounts for sSFR > $\mathrm{sMIR_{DM}}$ and different slopes β

  Both of these through baryonic processes *internal* to galaxies

- produces a $Z(m,SFR)$ relation that can reproduce Mannucci et al $Z(m,SFR)$ SDSS data with sensible parameters ε and λ (especially ε) and explains the claimed redshift-independent "fundamental" metal relation.

- fitted parameters then correctly predict f_{gas} and $Z(m)$ etc. at $z = 2$.

Final comment from three lectures

Increasingly good convergence between observations and phenomenological theory (abundance matching etc.). Phenomena in individual objects also seems very consistent.

Are these phenomena being driven by halo physics or by internal physics?