Chapter 4: A Reverse Engineering approach to galaxy evolution

Part 1: What do I mean by “reverse engineering”

The reverse engineering approach

Basic idea:

- Identify the main, possibly surprising, features of the observed evolving galaxy *population*.
- Construct Ansätze, or possibly very simple toy models, that capture these features.
- Explore these *analytically* to see what they tell us, looking for explanations of other phenomena and/or unexpected connections with other parts of the puzzle.

Motivation:

- Highly likely to be observationally self-consistent
- Distils data to produce observational constraints that any more physical models must satisfy.
- By focusing on characterizing physical *outcomes* rather than identifying input physical *processes*, it provides (in principle) a common language for discussion.
- Gives increased clarity on problems of uniqueness and causality.

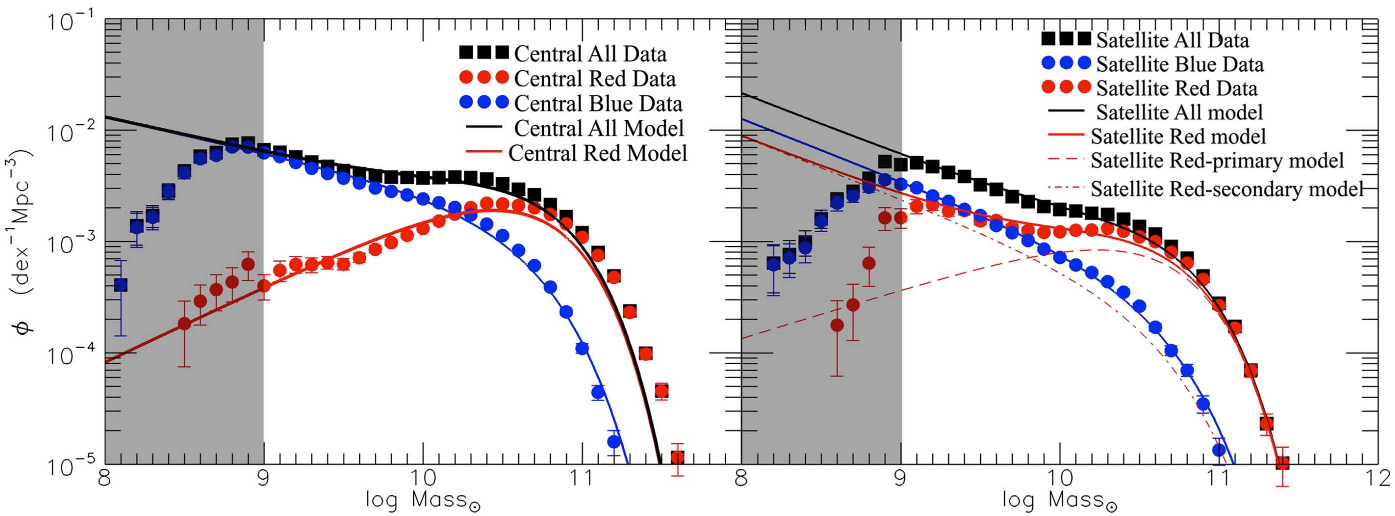
Example: Quenching of galaxies in Peng et al (2010)

Based on two interesting facts:

(a) What fraction of galaxies are quenched as f(mass,environment)?

(b) How does the mass function $\phi(m)$ of star-forming galaxies evolve?

This is all to do with the mass functions of star-forming and passive galaxies….



Fact 1: $f_{red}(m_{star},\rho)$ is separable in m_{star} and ρ

environment quenching (=satellites)

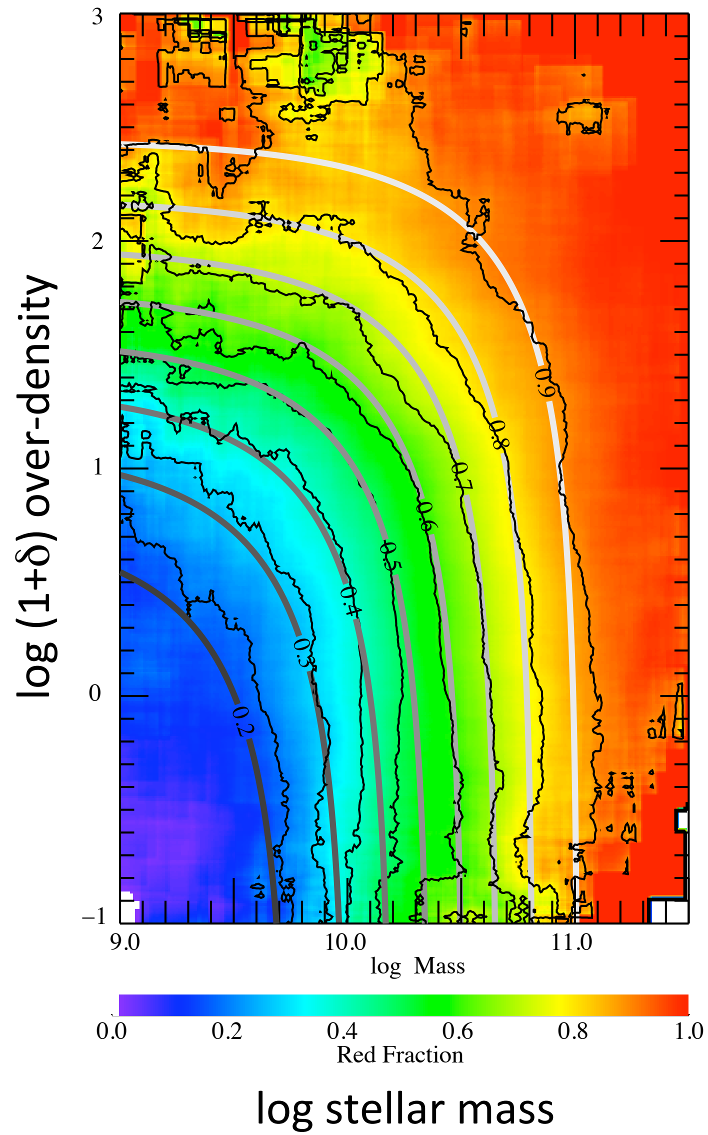
$$f_{blue}(m,\rho) = \left(1-\varepsilon_m(m)\right) \times \left(1-\varepsilon_\rho(\rho)\right)$$

mass quenching

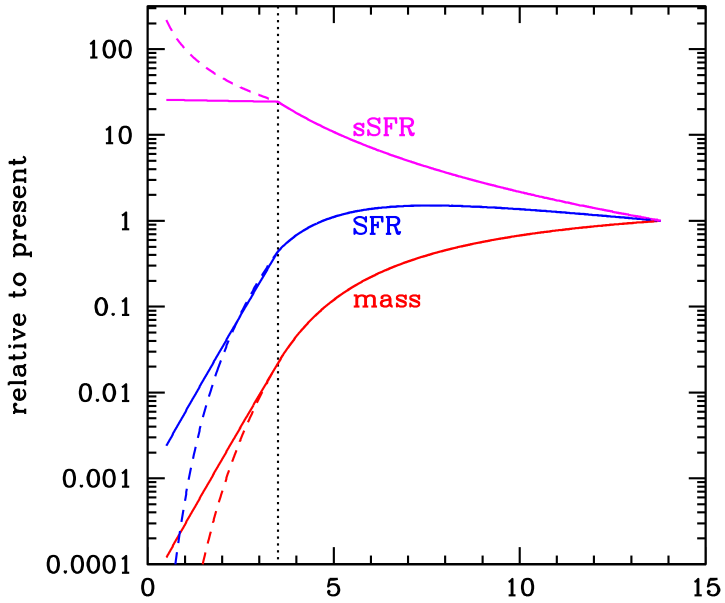
Only mass quenching depends on mass, and therefore it is that process that controls the mass function of the surviving star-forming galaxies

Environmental effects are dominated by satellite* population

* satellite galaxies are those orbiting within the dark matter halo of another more massive "central" galaxy



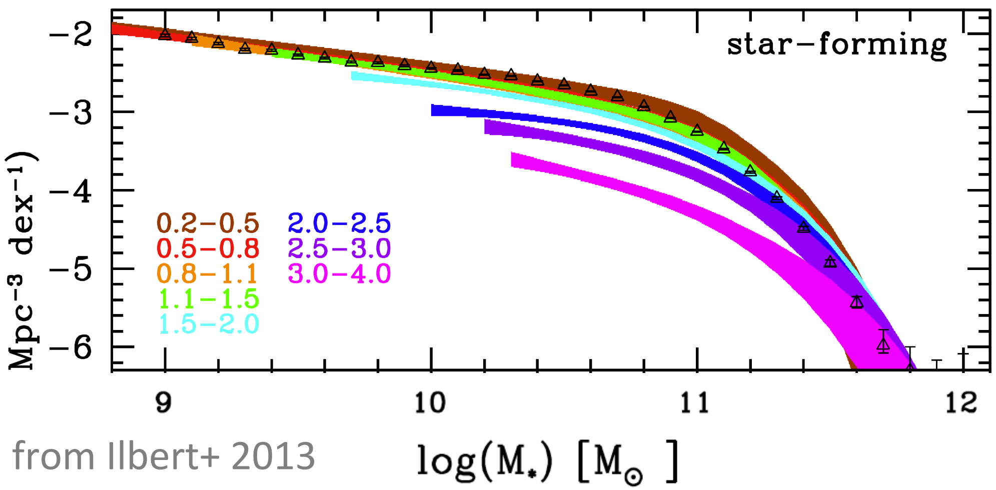
Fact 2: $\phi(m)$ of star-forming galaxies has constant M* and α



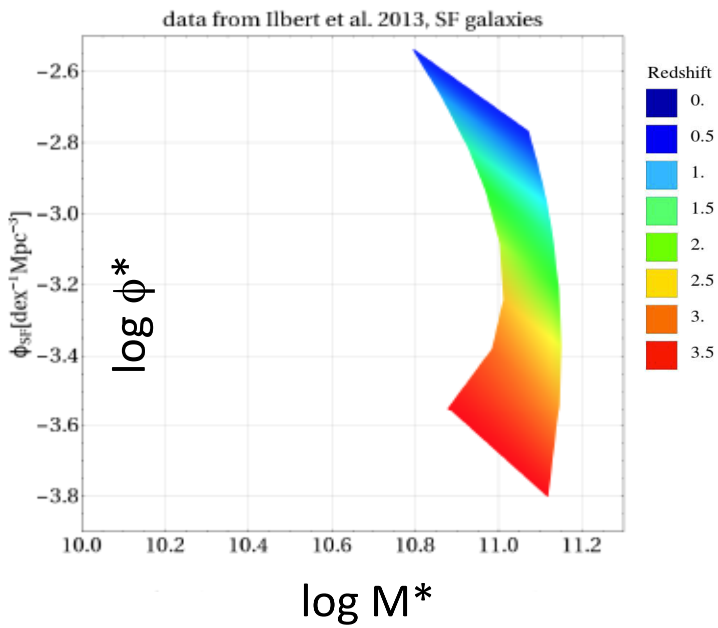
A galaxy that stays on the Main Sequence increases its mass ×20 since $z \sim 2$, and even more since z ~ 4. YET, the characteristic M^*_{star} nevertheless stays constant!

Schechter function

$$\phi(m)\,dm = \phi^* \left(\frac{m}{M^*}\right)^{\alpha} \exp\left(-\frac{m}{M^*}\right) dm$$

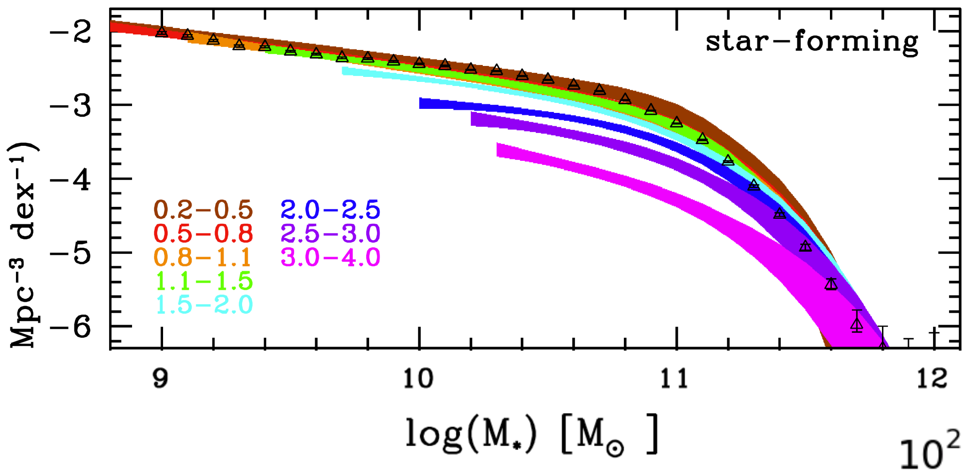


from Ilbert+ 2013

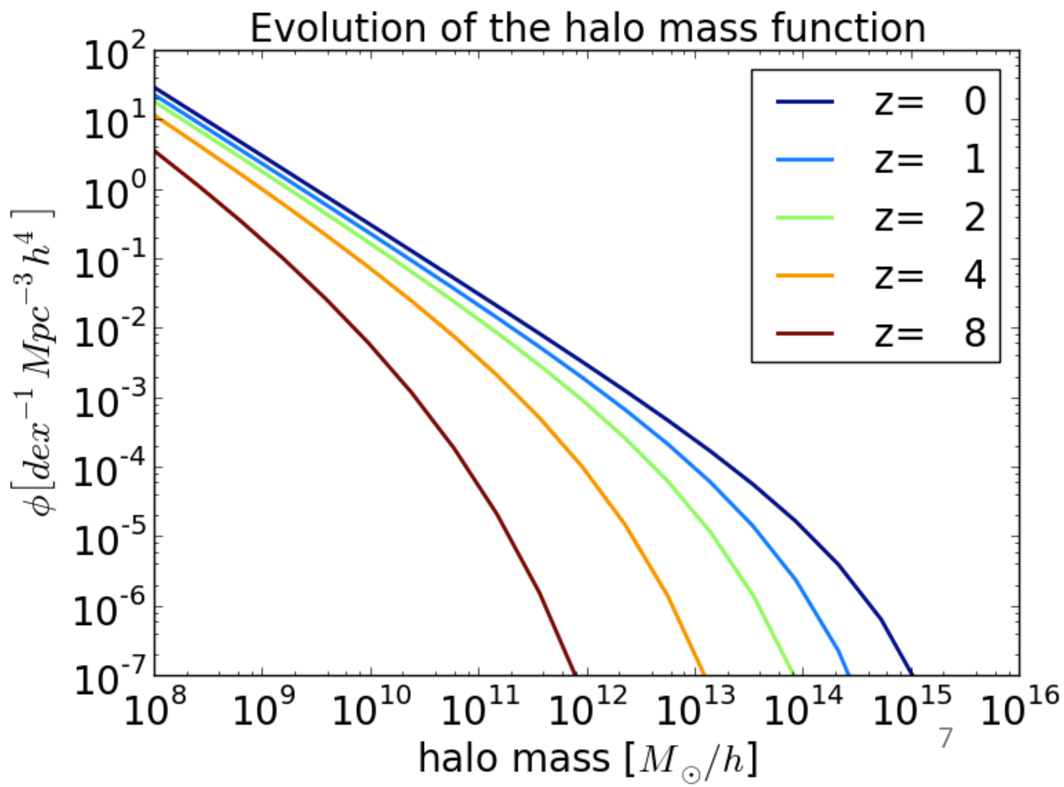


Comparison with evolving halo mass function

Ilbert+ (2013)



While galaxies may follow the halo mass function at very high redshifts, the evolving $\phi(m)$ of galaxies breaks away and follows vertical evolution after $z \sim 4$. This is due to cessation of mass growth of individual galaxies, i.e. quenching



The required form for quenching to preserve a Schechter function

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

Usual continuity equation for flow with source/sink term (sink due to a quenching rate η converting "blue" to "red", + possibly merging of galaxies)

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

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

$$\frac{\partial \ln \phi}{\partial t} = -sSFR\,(\alpha_s - \frac{m}{M^*} + \beta) - (\lambda_m + \kappa)$$

α is local logarithmic slope of mass-function, $\alpha = \alpha_s - m/M^*$.
Also, can write $\eta = \lambda_m(m,t) + \kappa(t)$

This must be independent of mass if M* and α_s are to be constant. So, the mass-dependent terms must cancel out, but the mass-independent terms need not.

Simplest case of β ~ 0, i.e. an sSFR independent of mass then gives

$$\lambda_m = SFR / M^*$$

NB: Does not mean that quenching mechanism must be star-formation, just that it's mass and time dependences must mimic the behaviour of SFR(m,t)

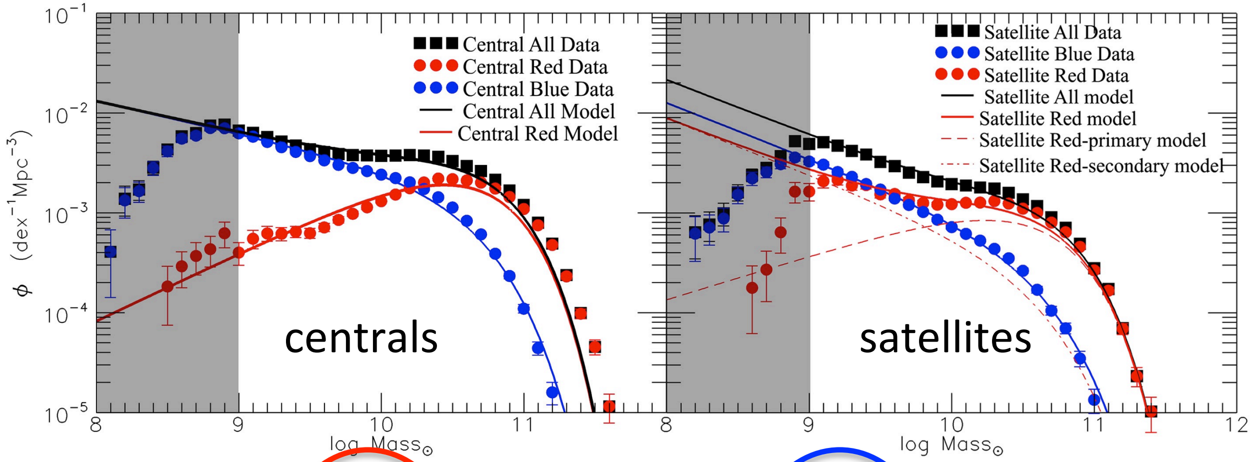
$$P_\lambda(m) = \exp(-m/M^*)$$

Can re-write our quenching law in terms of a survival probability to reach mass m, P(m)

Production of the mass functions of passive galaxies

Star-forming population with constant M* and $\alpha \sim -1.5$ (but evolving ϕ^*) produces a passive population via

- "mass-quenching" with same M* and $\alpha \sim \alpha_{SF} + 1$ and $\phi_Q^* \sim -\phi_{SF}^*/(1+\alpha_s)$
- "environment/satellite-quenching" with same M* and $\alpha \sim \alpha_{SF}$



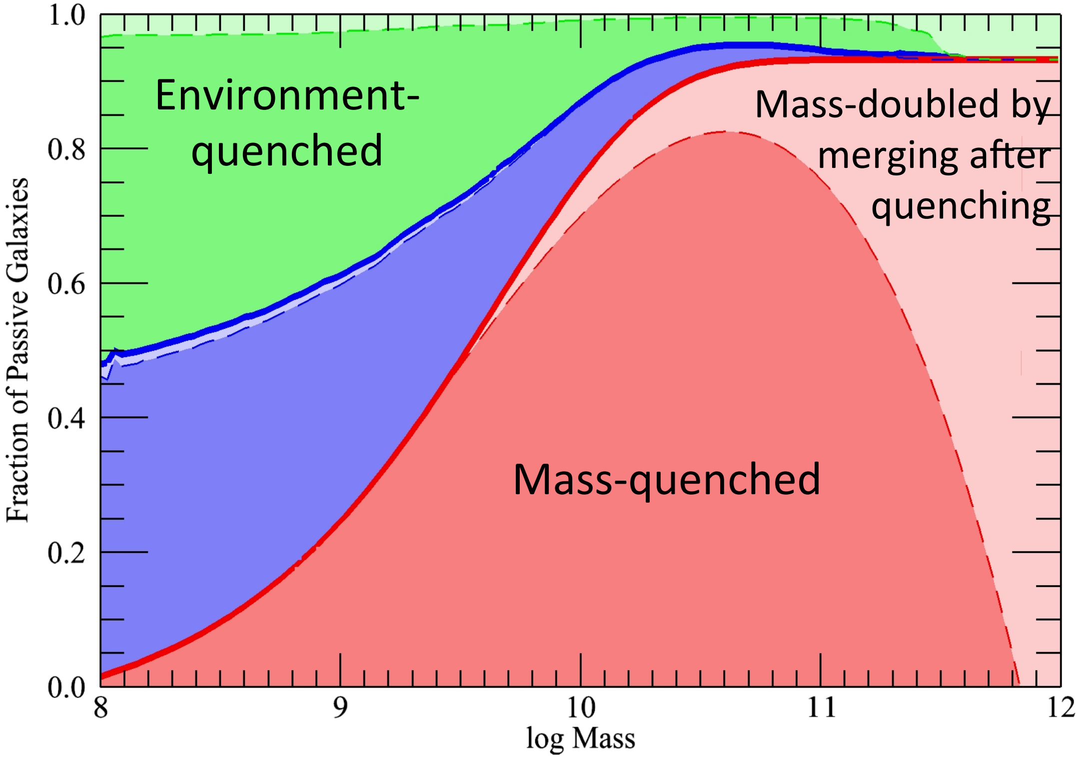
from Peng et al (2012)

Sample	log (M*/M$_\odot$)	$\phi_1^*/10^{-3}$Mpc^{-3}	α_1	$\phi_2^*/10^{-3}$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]

Note: pretty good agreement with expectations. These mass functions are the simple consequence of the quenching law derived from constant M*, α and a flat $sSFR_{MS}$.

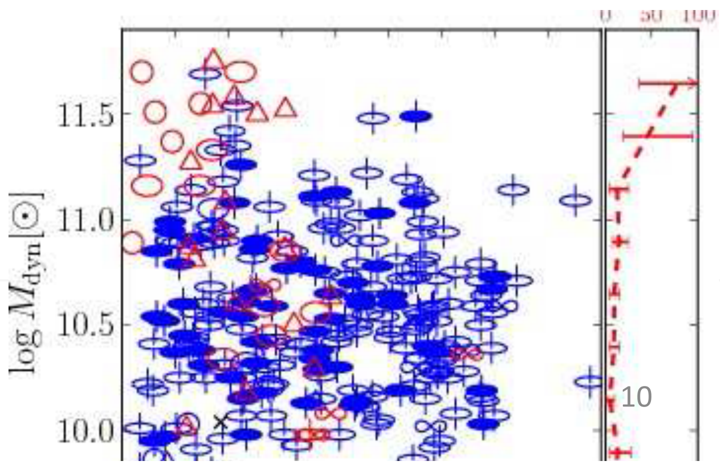
Final further details: Note how the M* for red centrals is a little too high (by of order 0.1 dex). Obvious possibility is that there is some modest amount of merging of passive galaxies after they have quenched.

- This sets quite a stringent new limit on how much merging could have taken place.
- If we simply add a second component to the the passive population (shifted down in density and up in mass), we can then produce the following prediction for the origin of the passive galaxies.



Very nice: we expect a transition between passive galaxies that have had mergers and those that have not, to occur at log $m \sim 11.3$.

Indeed, there is a transition in rotational dynamics in passive galaxies at this mass!



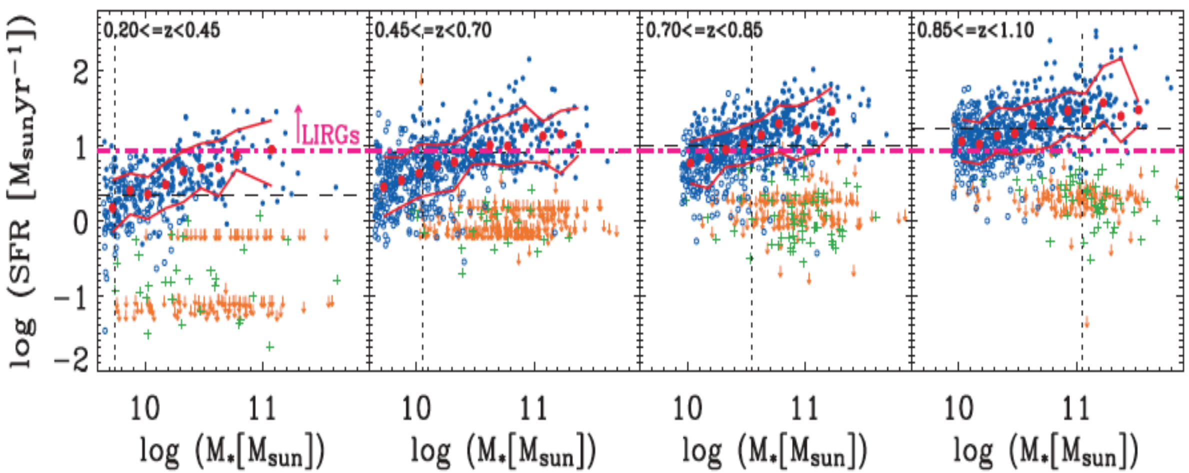
Notice how simple this is:

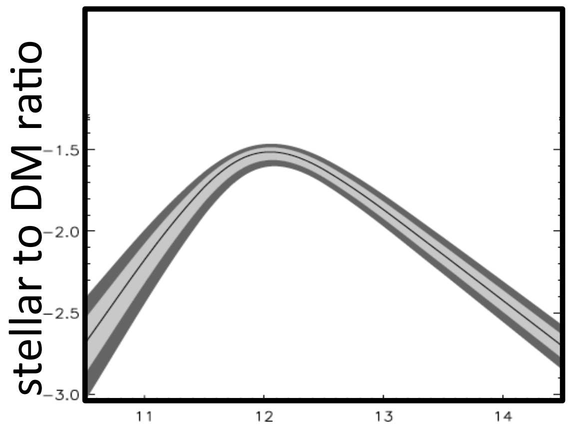
- Separability of f_{passive}(m,r) introduces ideas of mass and environmenyt quenching.
- Constant $M^*_{SF}(z)$ + flat sSFR enables us to derive a simple empirical “quenching law” from the basic continuity equation.
- That quenching law correctly explains the precise shape of the mass functions of passive galaxies and the total mass functions, i.e. the quantitative relations between the M*, α, ϕ^* of the different populations.
- We then can constrain the amount of post-quenching merging that occurred, and even naturally explain the transition in rotational dynamics of passive galaxies at around log $m \sim 11.3$.

Of course, we have not here determined what physically quenches galaxies, only the (precise) form of the quenching rate that any physical process must satisfy.

Part 2: What controls the characteristic star-formation rate of galaxies, and why do low mass haloes not convert baryons into stars very efficiently?

This will involve the $(1+z)^{2.5}$ evolution of the Main Sequence sSFR, and the form of the $m_{\rm star}$-$m_{\rm halo}$ relation…





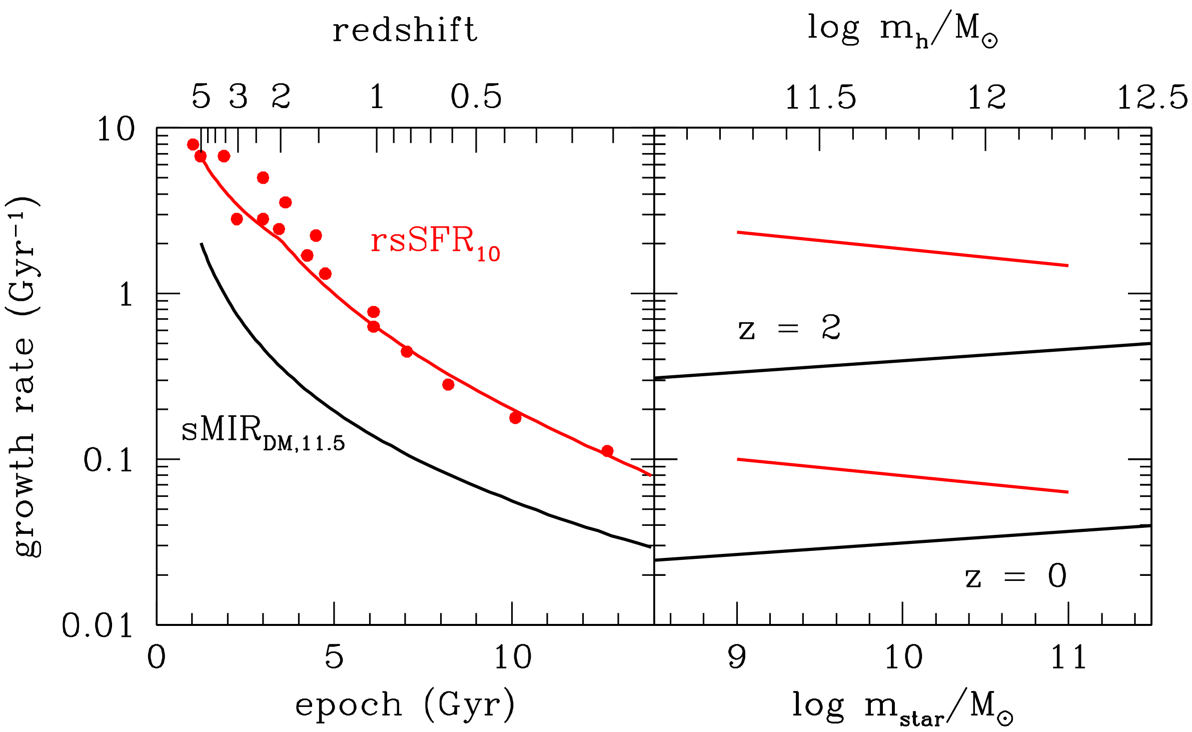
Moster+ (2010)

Starting point: There are clear similarities between the specific growth rates of DM haloes and the stellar mass of galaxies

Specific rate of increase in mass:

Dark matter haloes: $sMIR = \frac{\dot{M}_h}{M_h}$

Stellar mass: $sSFR = \frac{SFR}{m_{star}}$



sSFR from data compilation from Stark et al (2012)
sMIR from Neistein & Dekel

The observed sSFR(τ) closely follows the theoretical specific growth rate of dark matter haloes:

- similar weak dependence on mass, but with a reversed slope: $\beta_{star} \sim -0.1$, $\beta_{DM} \sim +0.1$, and
- similar strong dependence on redshift $(1+z)^{2.5}$, but with an offset sSFR > $sMIR_{DM}$

Hypothesis: A simple regulator system that is regulated (only) by the gas content

Star-formation	$SFR = \varepsilon m_{gas}$
Wind outflow	$\Psi = \lambda \cdot SFR$

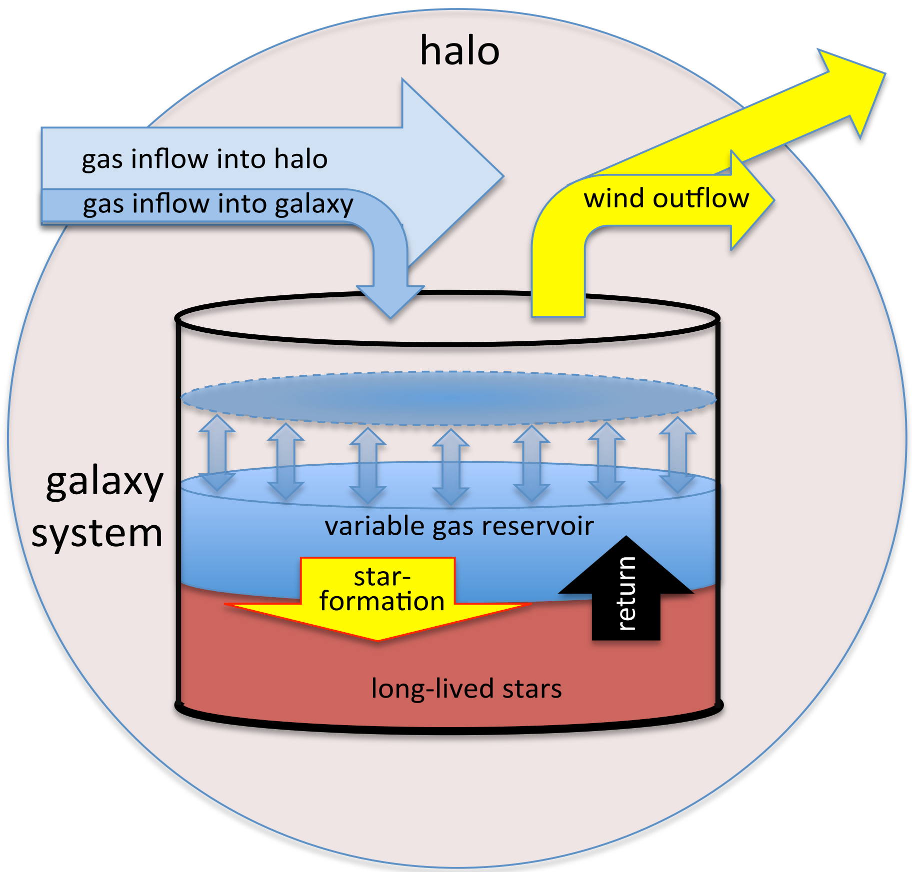
Introduce the gas depletion timescale τ_{gas}

$$\tau_{gas} = \frac{m_{gas}}{SFR} = \epsilon^{-1}$$

Also effective gas depletion timescale, or gas retention timescale, $\tau_{eff,gas} = \tau_{gas}/(1+\lambda)$

Note there is a mathematical identity concerning the gas content of the regulator, parameterized by the gas ratio μ

$$\mu = \frac{m_{gas}}{m_{star}} = \varepsilon^{-1} \cdot sSFR = \tau_{gas} \cdot sSFR$$



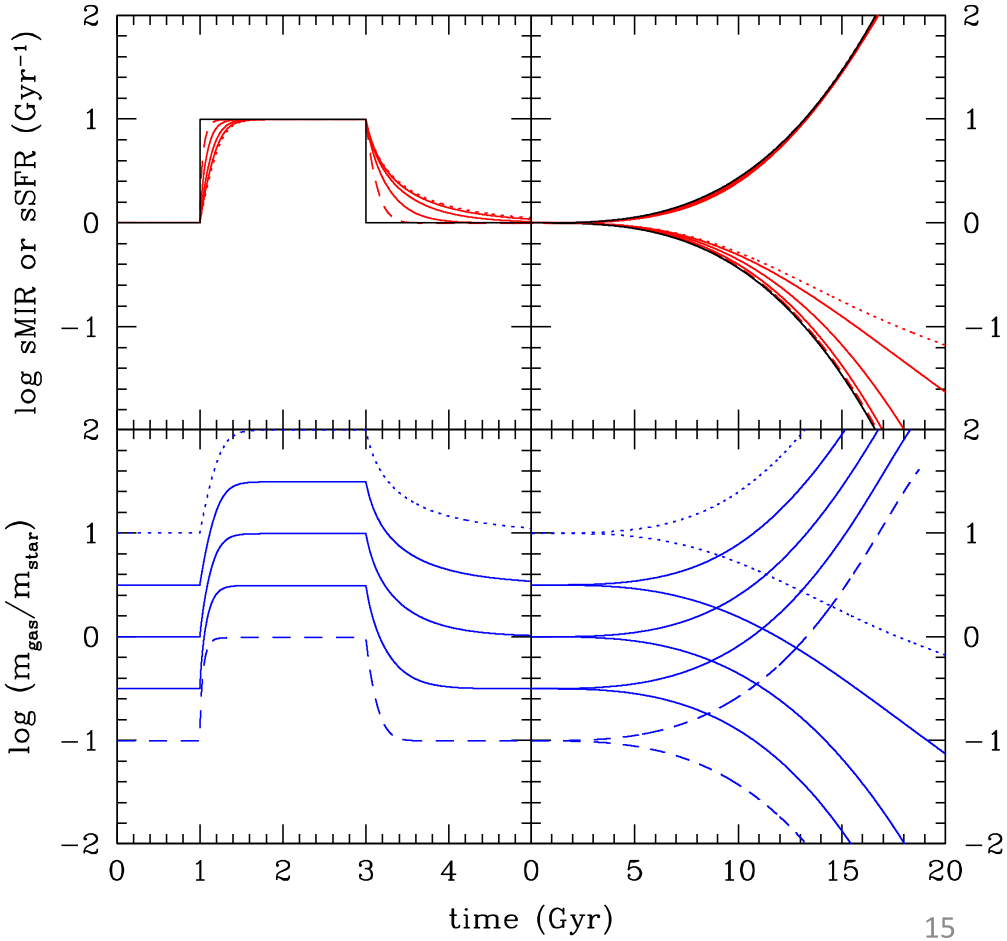
Lilly et al (2013), c.f.
Bouché et al (2010), Dave et al (2012)

What happens if you feed the regulator system with a certain specific inflow rate of baryons, $sMIR_B$, which we will imagine to be the same as the $sMIR_h$?

Key point: if ε and λ are constant ("ideal regulator"), then the regulator quickly sets the sSFR to be <u>exactly</u> the $sMIR_B$, <u>independent</u> of values of ε and λ

Why? The regulator sets f_{star}, the fraction of incoming gas that is formed into stars, to a particular value, set by ε and λ.
Constant f_{star} quickly sets sSFR = sMIR, independent of its value.

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



Will the regulator work in practice? Timescales in galaxy evolution

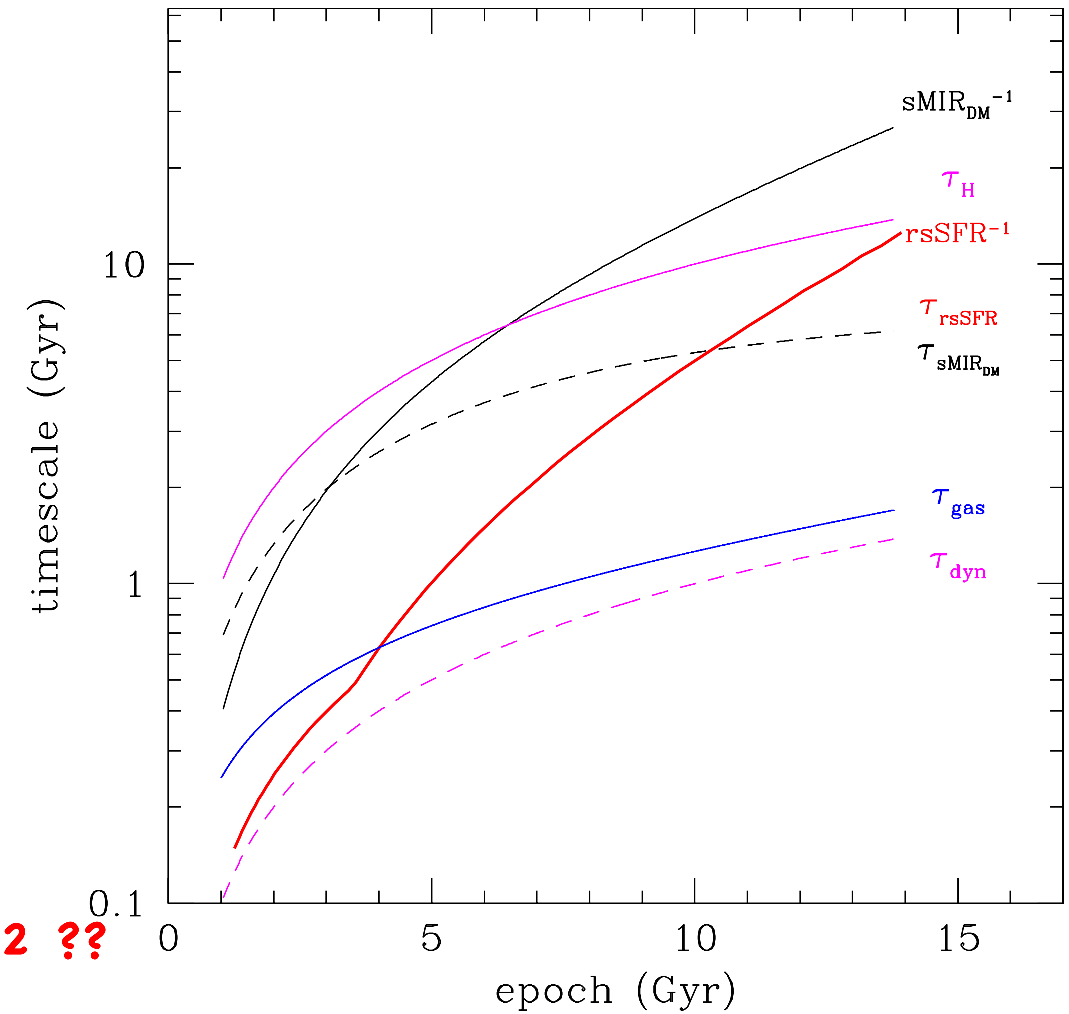
In order to regulate effectively, we need the gas retention time $\tau_{gas}/(1+\lambda)$ to be

- shorter than the timescale on which *external* conditions (i.e. $sMIR_B$) are changing

  OK!

- shorter than the timescale on which *internal* parameters ε and λ are changing: If ε and λ depend strongly on m_{star}, this will be ~ $sSFR^{-1}$, the timescale on which the mass is changing

  No longer OK at $z \geq 2$??
  Changes in sSFR(z)?
  Clumpy disks?



A simple regulator system regulated by the gas content

Incoming packet of gas stays in regulator for short period of time

$$t = \frac{m_{gas}}{(1+\lambda)SFR} = \frac{\tau_{gas}}{(1+\lambda)} << \tau_H$$

The flow rates can all be written in terms of the SFR

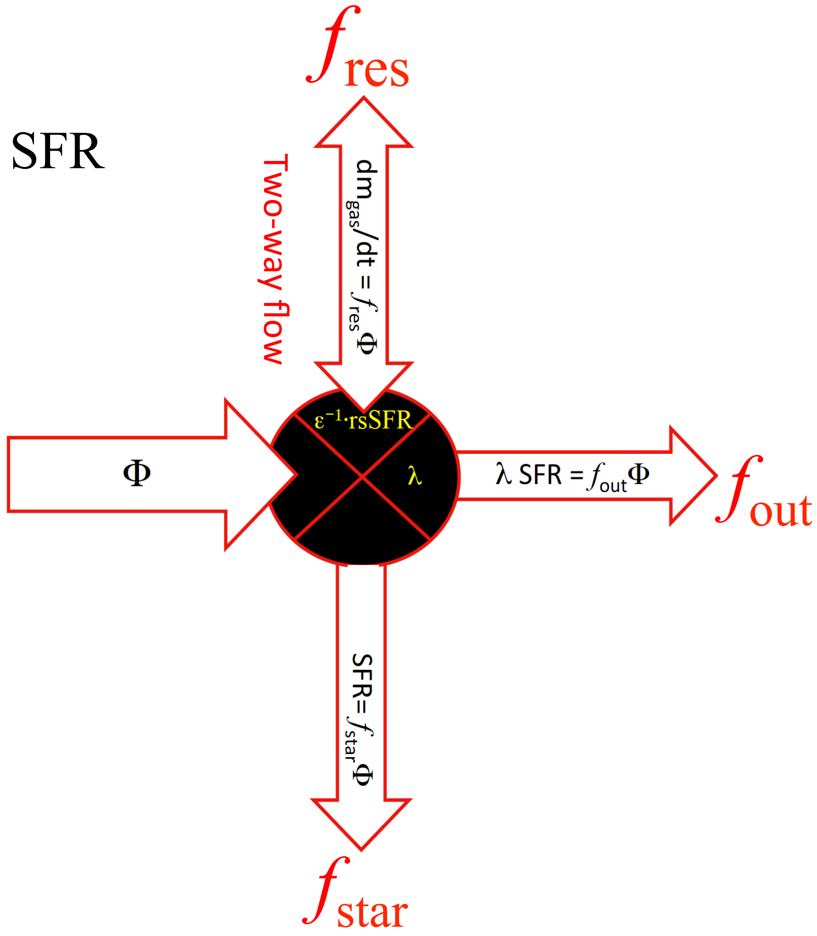
$$\Psi = \lambda \cdot SFR$$

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

$$\frac{dm_{gas}}{dt} = \left(\mu + \varepsilon^{-1} \frac{d \ln \mu}{dt} \right) \cdot SFR$$

The fraction of inflowing gas that is formed into stars is f_{star}

$$f_{star} = \frac{SFR}{\Phi} = \left(1 + \lambda + \mu + \varepsilon^{-1} \frac{d \ln \mu}{dt} \right)^{-1}$$



Notice how this changes one's perspectives

High z galaxies are gas rich <u>because</u> they *must* have a high sSFR <u>because</u> they have a high $sMIR_B$, <u>because</u> their haloes have a high $sMIR_{DM}$.

The gas content of galaxies tells us about ε and/or λ, and not about $SFR(z)$

Physics digression I: Energy injection from Supernovae

When some mass m_{star} of stars is formed, some fraction of these will have $M > 8\ M_{\odot}$, and will, after a short lifetime of ~ 10^7 yr, explode as a core-collapse supernova. Each supernova releases ~ 10^{51} erg (10^{44} J).

We can therefore define the energy released per unit mass of stars formed: $\varepsilon_{SN} \sim 4\times10^{48}$ erg $M_{\odot}^{-1}$.

If this energy drives a wind out of the galaxy, what can we learn about the velocity and mass outflow of the wind?

χ is a dimensionless efficiency of using the SN energy to drive a wind, while λ is the dimensionless "mass-loading" of the wind λ = outflow/SFR. Both are likely of order unity.

$$\frac{1}{2}\dot{M}_W v_W^2 \sim \chi \varepsilon_{SN} \dot{M}_{star}$$

$$v_W \sim \sqrt{2\chi\lambda^{-1}\,\varepsilon_{SN}}$$

Note that $\varepsilon_{SN}^{1/2}$ has the units of velocity and has a numerical value ~ 500 kms^{-1}.

Physics digression I: Energy injection from Supernovae

This characteristic velocity of order 500 kms^{-1} is very interesting:

It is very comparable to the escape speed from the Milky Way halo
At the Sun's location, which is estimated to be $v_{\rm esc} = 580 \pm 60$ kms^{-1} .

What about haloes of different mass? For lower mass haloes, it is easier to drive out a wind at $v > v_{\rm esc}$ (or to support higher λ winds at $v_{\rm esc}$)

$$v_{esc}^2 \propto \frac{M_h}{r_h} \quad \text{but} \quad \frac{M}{r^3} \propto \rho_H$$

$$v_{esc}^2 \propto M_h^{2/3}$$

Bottom-line conclusion: energy injection from supernovae is likely to be sufficient to drive significant winds of material out of galaxies, possibly even out of the halo, especially for low mass galaxies with $M_h < 10^{12}\ M_\odot$

Actually, it seems v_W is (somehow) set to $\sim v_{\rm esc}$, and extra available energy in low mass galaxies goes into driving a higher "mass-loading" λ of the wind.

Digression II: Chemical evolution

Heavy elements above [4]He (= "metals") are produced by (short-lived) massive stars and returned to the interstellar medium (ISM), along with some fraction *R* of the original gas mass. *In these lectures, I ignore R and set it to zero (actually ~ 0.4)*

$$\frac{dm_{star}}{dt} = (1 - R) \cdot SFR = SFR$$

We can make an "instantaneous recycling approximation: We assume that the return of metals and mass occurs immediately that the new stars are formed,

Define the chemical yield to be the mass of metals returned to the interstellar medium (ISM) per unit mass of stars made.

$$y = \frac{dm_Z}{dm_{star}}$$

Further, define the "metallicity" to be the ratio of the mass of metals to the total mass, e.g. for the ISM

$$Z = \frac{m_Z}{m_{gas}}$$

Digression II: Chemical evolution

Simplest case: So-called "closed box" evolution. Assume a galaxy is an isolated system with no exchange of gas into or out of the system.

Change of metal content of ISM given by new metals produced minus those locked into stars

$$\frac{dm_Z}{dt} = y\frac{dm_{star}}{dt} - Z\frac{dm_{star}}{dt}$$

Change of metal content of ISM

$$\frac{dZ}{dt} = -\frac{(y-Z)}{m_{gas}}\frac{dm_{gas}}{dt} - \frac{Z}{m_{gas}}\frac{dm_{gas}}{dt}$$

$$= -y\frac{dm_{gas}}{dt}$$

$$Z = -y\ln\frac{m_{gas}}{m_{gas,init}} = -y\ln\frac{m_{gas}}{m_{gas}+m_{star}}$$

In a closed box, the metallicity increases monotonically and depends only on how much of the closed system has been converted to stars

Metallicity of the gas in the regulator

The equation on the previous slide must be modified for the more general case with non-zero inflow Φ or outflow Ψ

$$\frac{dm_Z}{dt} = (y - Z) \cdot \frac{dm_{star}}{dt} + Z_{\text{inflow}}\Phi - Z\Psi$$

But we saw that for the gas-regulator that all of these terms can be written in terms of the SFR, allowing for a simple solution. Also for simplicity we can set the $Z_{\text{inflow}} = 0$

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

We can look for an an equilibrium Z_{eq} by setting $dZ/dt = 0$, convincing ourselves that Z will approach this equilibrium value on a (short) timescale (given by $f_{\text{star}}\tau_{\text{gas}}$)

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

Easy to see that the "equilibrium" Z_{eq} is given by

$$Z_{eq} = \frac{y}{1+\lambda+\mu+\varepsilon^{-1}\dfrac{d\ln\mu}{dt}}$$
$$= \frac{y}{1+\lambda+\varepsilon^{-1}\left(sSFR + \dfrac{d\ln\varepsilon^{-1}sSFR}{dt}\right)}$$

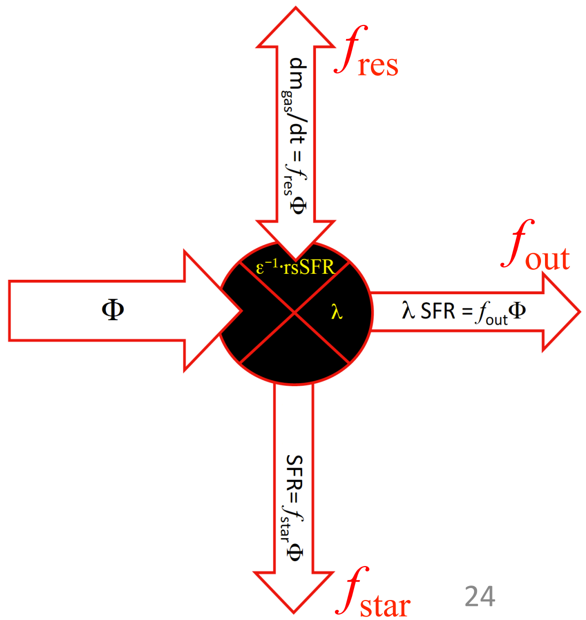
c.f. closed box

$$Z = Z_0 - y\ln\left(\frac{\mu}{1+\mu}\right)$$

Again, this gives us a new perspective:

Metallicity is set "instantaneously" by the parameters of the regulator, and not by the previous <u>history</u> of the galaxy, which enters only via the (small) dlnμ/dt term. This is ultimately because τ_{gas} is short.

Not surprisingly, we can also write $Z_{eq} = y \cdot f_{star}$



$$Z_{eq} = \frac{y}{1 + \lambda + \varepsilon^{-1}\left(sSFR + \frac{d\ln \varepsilon^{-1} sSFR}{dt}\right)} = y \cdot f_{star}$$

Note the following from the regulator:

- If ε(*m*) or λ(*m*), then we'd expect both $f_{star}(m)$ and $Z(m)$.

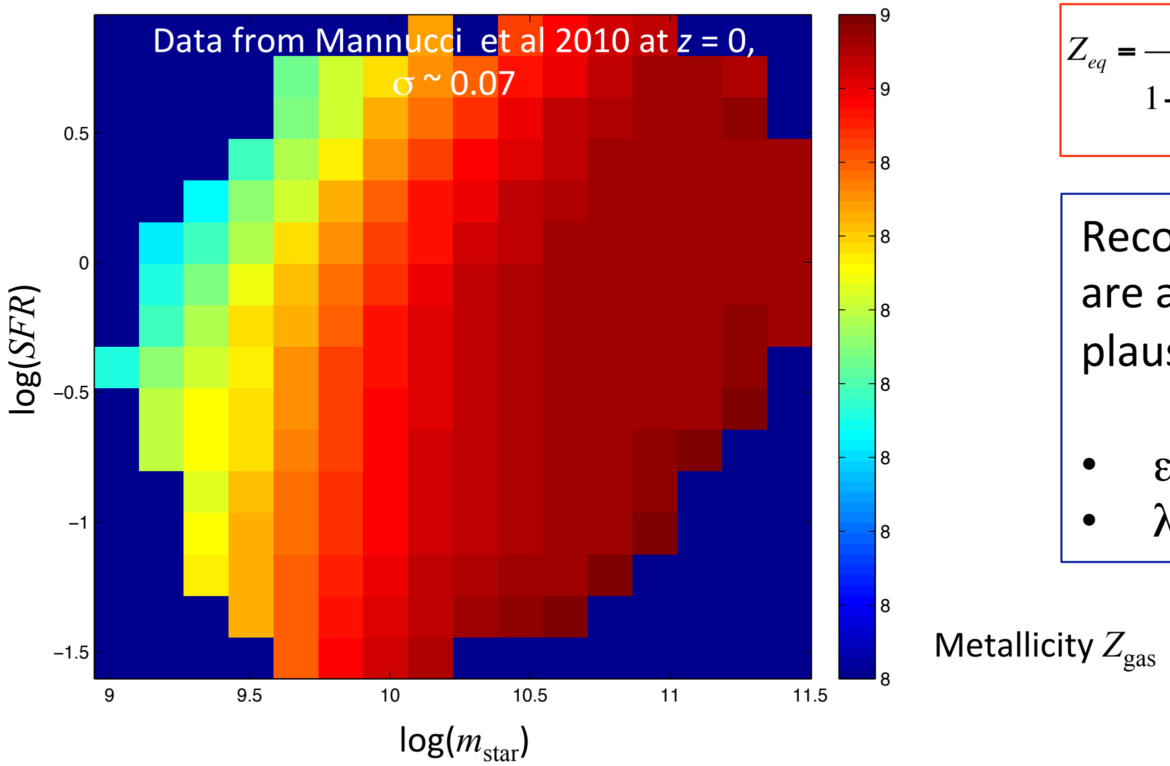
- In fact, we'd expect a straightforward link between $f_{\mathrm{star}}(m)$ (i.e. efficiency of a halo converting gas into stars) and $Z(m)$ – the "mass-metallicity relation" for galaxies – without in fact needing to know ε or λ.

- We would expect SFR to enter as a second parameter in the mass-metallicity relation $Z(m)$. In fact, there should be a $Z(m_{\mathrm{star}},SFR)$ relation, which will only change with time to *the extent that ε(m) and λ(m) do:* The gas-regulator naturally produces a constant $Z(m_{\mathrm{star}},SFR)$.

- Given that the sSFR of the Main Sequence changes with epoch, we'd expect changes in the metallicities even if ε(*m*) and λ(*m*) are independent of epoch. New perspective: galaxies at high redshift *z* have lower metallicity *Z* because they have higher sSFR, not because they are younger *per se*.

The "mass-metallicity relation" and claims for the "fundamental metallicity relation" (FMR)

- Correlation between Z and m_{star} well known since 1970's.
- Evidence for SFR as second parameter, i.e. $Z(m_{\mathrm{star}}, SFR)$ at low redshift. (Ellison+ 2008, Manucci+ 2010, Andrewes+, 2012, Yates+ 2012)
- Claim that $Z(m_{\mathrm{star}}, SFR)$ is <u>independent</u> of epoch, i.e. an "FMR", but this seemed mysetrious (Manucci+ 2010)



$$Z_{eq} = \frac{y}{1 + \lambda + \varepsilon^{-1}\left(sSFR + \frac{d\ln \varepsilon^{-1} sSFR}{dt}\right)} = y \cdot f_{star}$$

Recovered values of ε and λ are actually astrophysically plausible:

- $\varepsilon^{-1} = \tau_{\mathrm{gas}} \sim 2\, m_{10}^{-0.3}$ Gyr
- $\lambda \sim 0.5\, m_{10}^{-0.8}$

Interesting implications of $f_{star}(m_{star})$ from $Z(m_{star})$

In the gas-regulator model, the slope of $Z(m)$ gives $f_{star}(m)$

$$Z \propto m_{star}^{\eta} \Leftrightarrow f_{star} \propto m_{star}^{\eta} \quad \text{with } \eta \sim 0.4 \pm 0.1$$

Two interesting consequences:

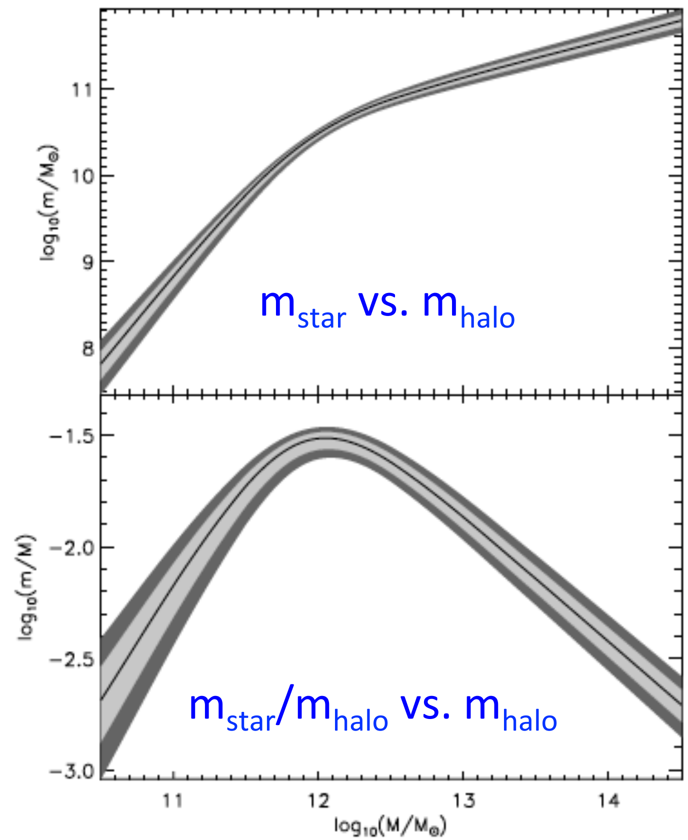
- Variation of f_{star} with mass suggests a m_{star}-m_{halo} relation given by (see also e.g. Peeples & Shankar 2011)

$$m_{star} \propto m_{halo}^{1/(1-\eta)} \sim m_{halo}^{1.7}$$ ✔

- Fact that f_{star} increases with mass boosts the sSFR relative to specific accretion rate. Flattening of f_{star} at high masses reverses the weak mass dependence.

$$sSFR \sim \frac{1}{1-\eta} sMIR \sim 2\, sMIR$$ ✔

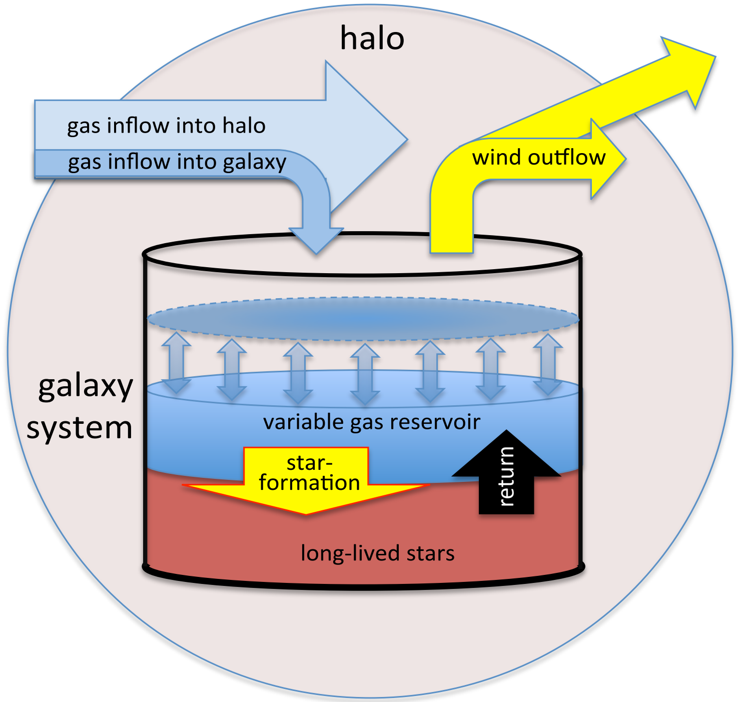
Abundance matching from Moster + 2010



Successes of this incredibly simple "toy model" for galaxies

It accounts for the close similarities between sSFR and sMIR of haloes, quite independent of the physics involved in ε and λ, but then also

- naturally explains*why the SFR appears as a second parameter in the $Z(m)$ mass-metallicity relation, and
- naturally explains* why the $Z(m,SFR)$ relation may not change with epoch
- analytically links
  - the mass-metallicity relation Z(m)
  - the m_{star}-m_{halo} relation
  - the offset* between the $sSFR_{MS}(z)$ and $sMIR(z)$ of the haloes



Plus, new "concepts": (a) metallicity as a probe of the "instantaneous" state of the regulator. (b) apparent reversal of causality: gas content as the "result" of matching required SFR.

Summary of Part 2:

We asked: What controls the characteristic specific star-formation rate of galaxies $(1+z)^{2.5}$, and why do low mass haloes not convert baryons into stars very efficiently?

The sSFR of galaxies will track the sMIR of the haloes (which goes as $(1+z)^{2.5}$ if the gas that enters the halo then enters a simple gas-regulator system, in which SFR = ε m_{gas}. The cosmic decline of the Main Sequence sSFR is thus simply a consequence of the slowing down of cosmological structure formation as described by the sMIR of haloes which declines in the same way.

Winds driven by energy injection from supernovae produce (self-consistently) the m_{star}-m_{halo} relation at $m < 10^{12} M_{\odot}$, the elevation of sSFR over the sMIR, and the mass-metallicity m_{star}-Z relation, and can even explain the existence of the "fundamental metallicity relation" (FMR). These winds are why lower mass haloes are less efficient at forming stars.

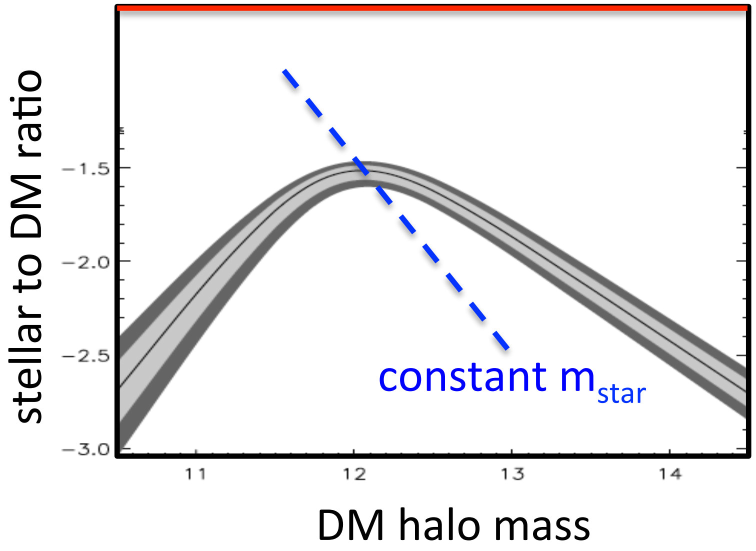
So, we now have a good feel for the evolution of the Main Sequence, and for the rising part of the m_{star}-m_{halo} relation.

We will talk more about quenching later: for the time being, we should realise that quenching produces the quite sharp peak in the m_{star}-m_{halo} relation, since the stellar mass m_{star} stops increasing even as m_{halo} continues to increase.

Key point for now: there is a "magic" halo mass, around 10^{12} $M_{\odot}$ where the Universe is most efficient at making stars.

(Note: we live in such a halo!).

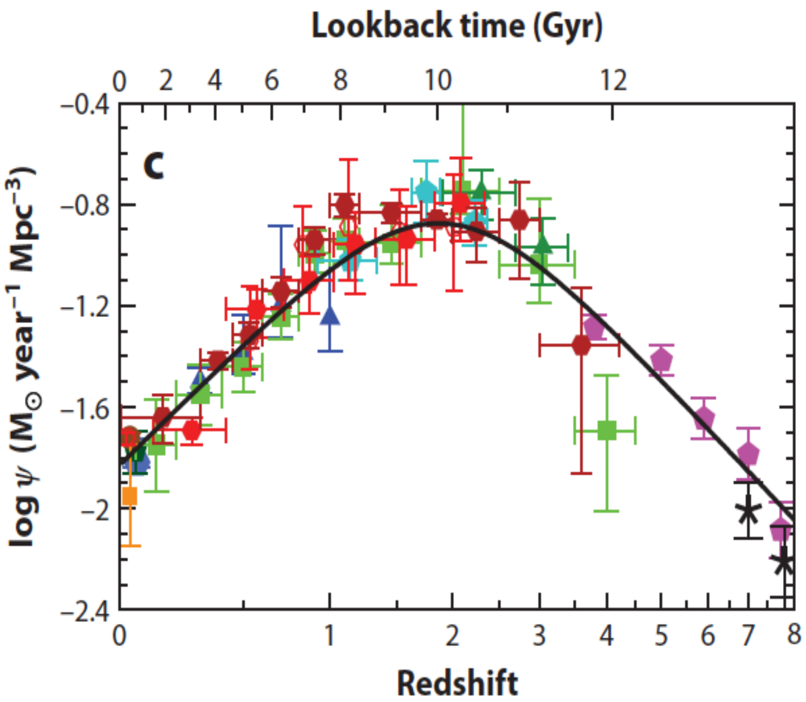
Stellar to halo mass relation



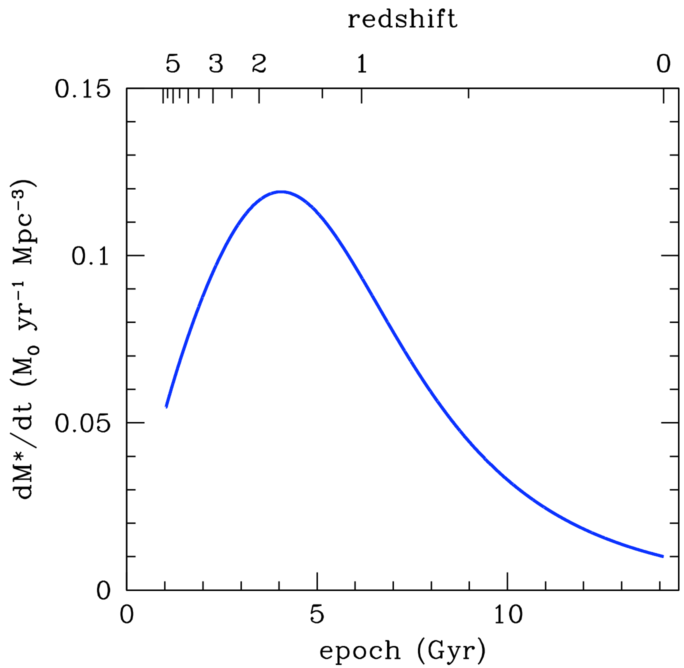
Moster+ (2010)

Part 3: What produces the overall star-formation history of the Universe, which initially rises up to a peak at "cosmic noon" at $z \sim 2$ and then declines again to the present epoch?

SFRD = star-formation rate density (SFR per unit comoving volume of the Universe)



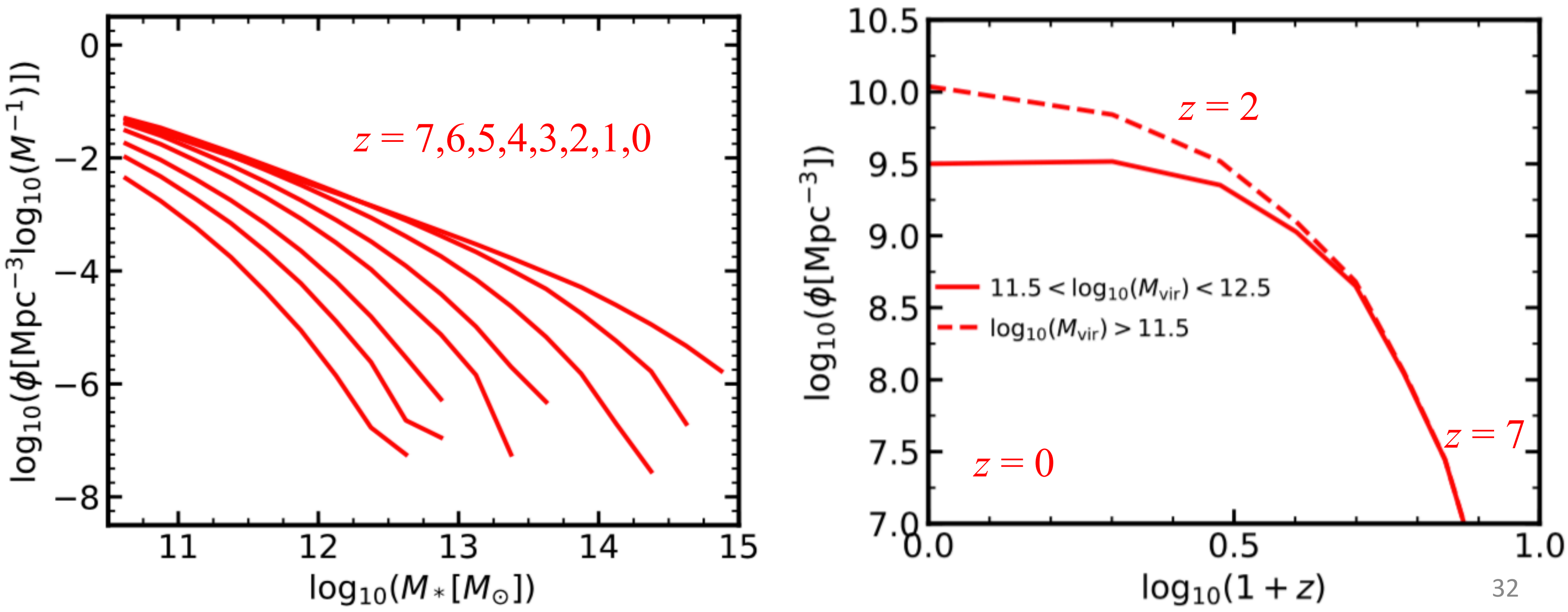
Madau & Dickinson
Review (2014)



If haloes around 10^{12} $M_\odot$ are particularly efficient at making stars, let's look at the number of such haloes in the Universe as a *f*(epoch)?

Press-Schechter gave us an analytic form for the evolution of the DM halo mass function, that is a quite good description of the $\phi(m, \tau)$ measured in N-body DM simulations. The following plots are from the "Millenium" DM simulation (courtesy B. Henriques from last year's course).

Notice how the number density (per comoving volume) of haloes around 10^{12} $M_\odot$ rapidly increases with time, but stops increasing at $z \sim 2$. This is the redshift at which the Schechter M* of the halo $\phi(m)$ has reached about 10^{12} $M_\odot$ (see earlier discussion of P-S analysis)



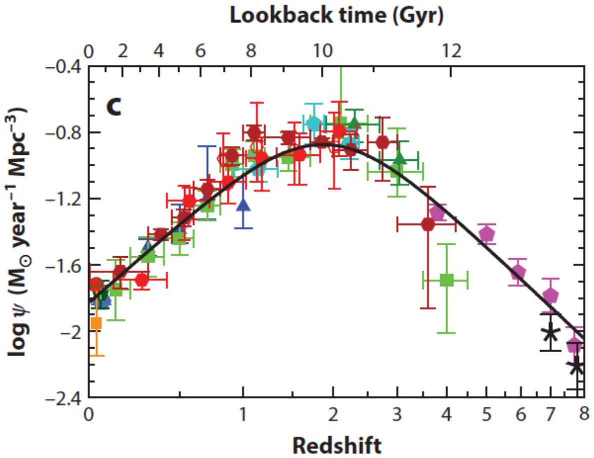
So, the rise in the overall SFRD from very high redshift up to "cosmic noon" at $z \sim 2$ is simply due to the rapid increase in the number of haloes of the optimum mass (around 10^{12} $M_\odot$).

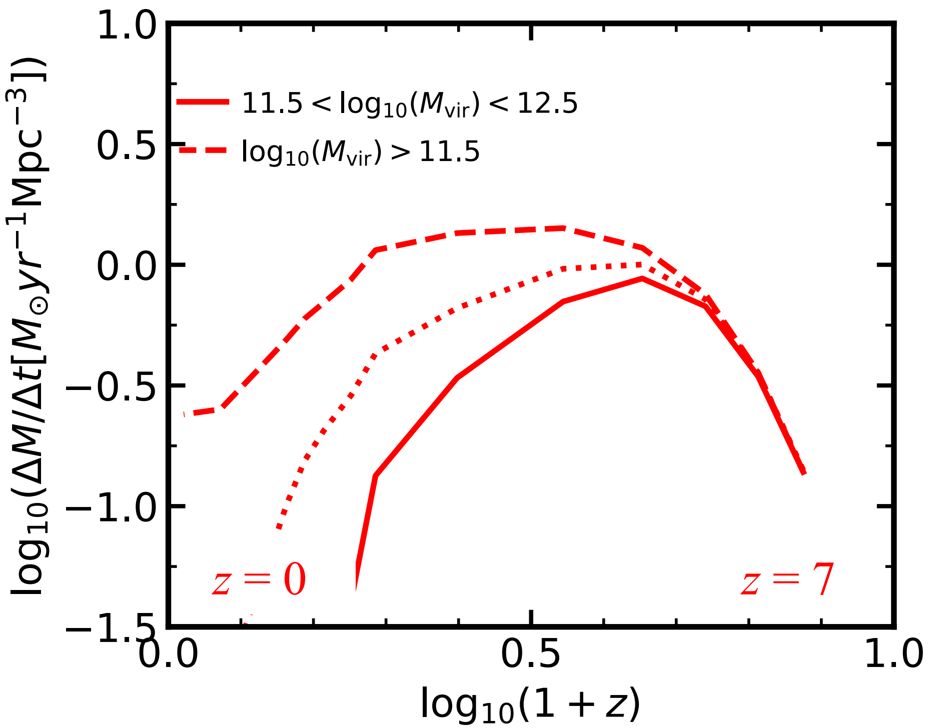
In summary, there are two competing effects:

a. the rapid increase with time in the number of suitable haloes (but plateauing at $z \sim 2$).
b. the rapid decline in the rate at which the masses of all haloes is increasing, since we have seen that this is what is fueling star-formation.

(a) dominates at $z > 2$, and then (b) dominates once the increase in density levels off.

Plot of the <u>total</u> rate of change of mass of (i) all haloes above $10^{11.5}$ $M_\odot$ and (ii) only those between $10^{11.5}$ and $10^{12.5}$ $M_\odot$. (dotted line includes sub-haloes within $10^{11.5}$–$10^{12.5}$ $M_\odot$ haloes) looks promising.





Qualitatively similar, given the limitations (e.g. we're ignoring other mass haloes) !

Can we explore this further with a toy semi-analytic model with essentially no adjustable parameters? (MSc thesis: Birrer et al 2014 ApJ, 793, 12)

Take our empirical prescriptions for (a) gas-regulators (i.e. ε and λ) and for (b) quenching from our previous work and insert them into a dark matter halo merger tree.

ε and λ of regulators from Lilly+13

M* and ε_{sat} of quenching from Peng+10, Peng+12

Cosmology for DM halo $\phi(m,z)$

Three other practical parameters on which output has little sensitivity in mass range of interest

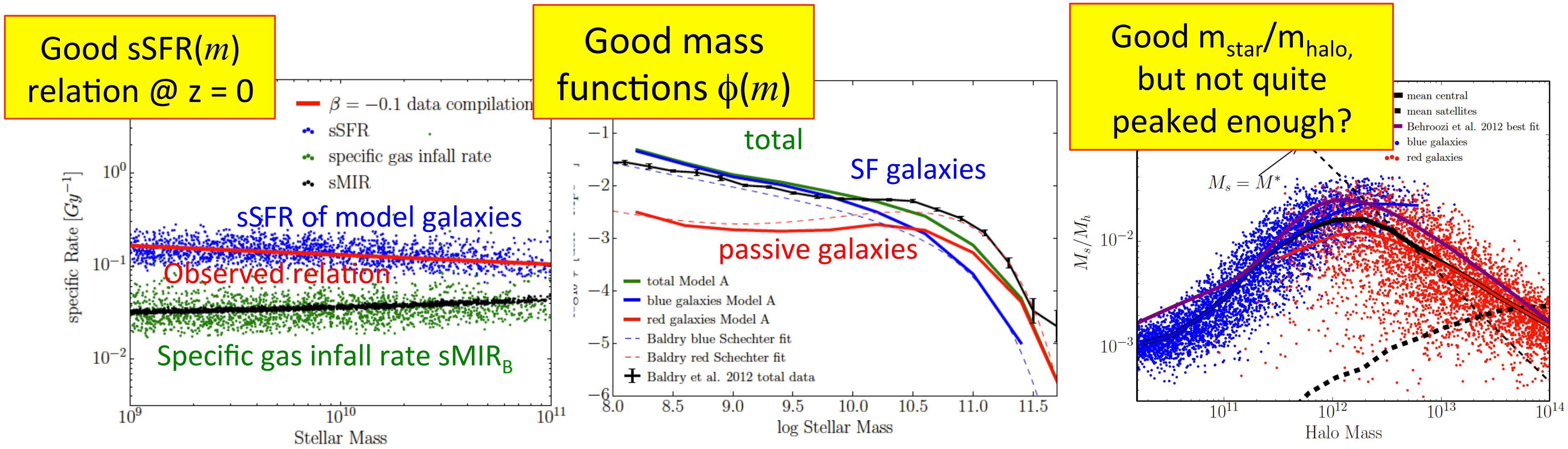
THIS TABLE LISTS ALL OUR MODEL PARAMETERS, ITS VALUES AND TO WHAT SET OF DATA THEY ARE TUNED TO.

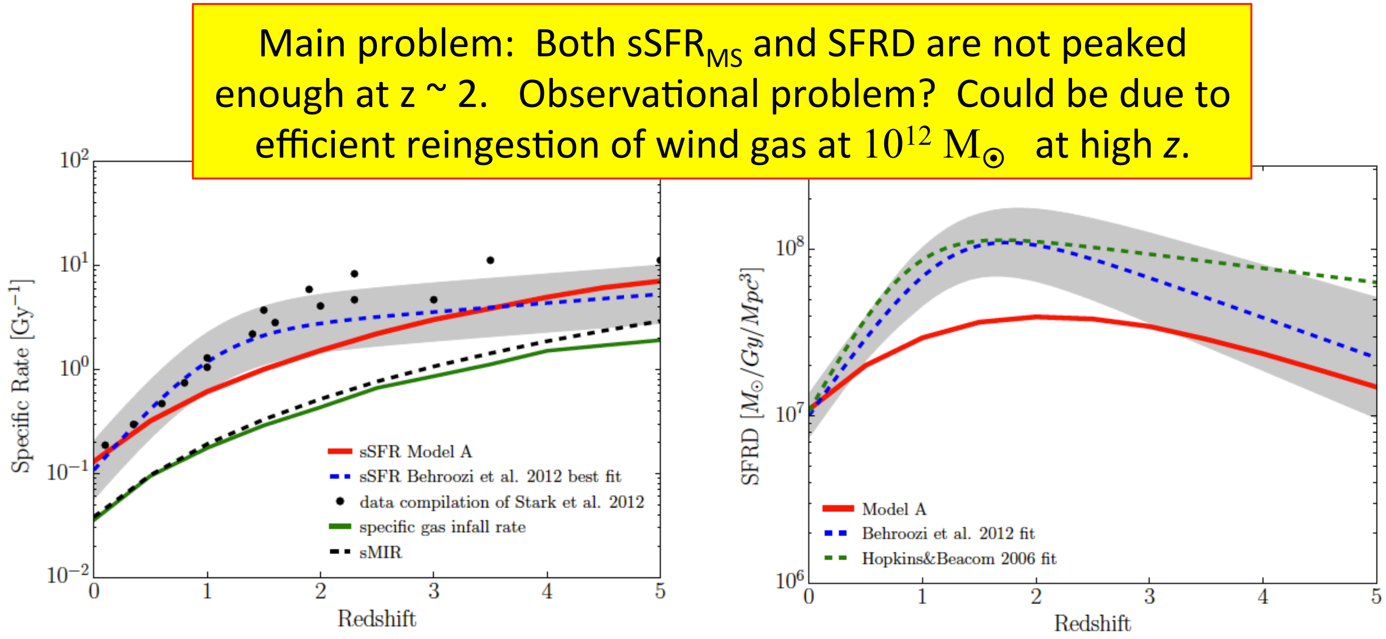
Symbol	Description	Fixed to:	Units	Value
		Regulator Parameters (externally derived)		
ϵ_{10}	Efficiency normalization to $10^{10} M_{\odot}$ stellar mass	Metallicity data [a]	Gy^{-1}	0.33
b	Power law of efficiency as a function of stellar mass	Metallicity data [a]	-	0.3
λ_{10}	Outflow load normalization to $10^{10} M_{\odot}$ stellar mass	Metallicity data [a]	-	0.3
a	Power law of outflow load as a function of stellar mass	Metallicity data [a]	-	-0.8
		Quenching parameters (externally derived)		
M^{*}	Critical mass of quenching	Exponential cutoff of main sequence [b]	$M_{\odot}$	$10^{10.6}$
$p_{\rm sat}$	satellite quenching probability	Elevated ref fraction in clusters [c]	-	0.5
		Cosmological Parameters (externally derived)		
h	dimensionless Hubble parameter	CMB [d]	-	0.7
Ω_b	Baryonic density	CMB [d]	-	0.45
Ω_m	Matter density	CMB [d]	-	0.3
Ω_λ	Dark Energy density	CMB [d]	-	0.7
σ_8	Power spectrum normalization	CMB [d]	-	0.8
n_s	spectral index	CMB [d]	-	1.0
		Choices of our combined model		
$f_{\rm merge}$	merging fraction of gas and stars of disrupted subhalos	Parameter with no significant effect on our conclusions [e]	-	0.5
$\lambda_{\rm max}$	Maximum outflow load of regulator	Upper bound provided by regulator action in tuning range [f]	-	100
$M_{\rm thresh}$	Threshold in halo mass for having a regulator	Photo-ionisation model [g]	$M_{\odot}/h$	10^9

Default initial assumptions:

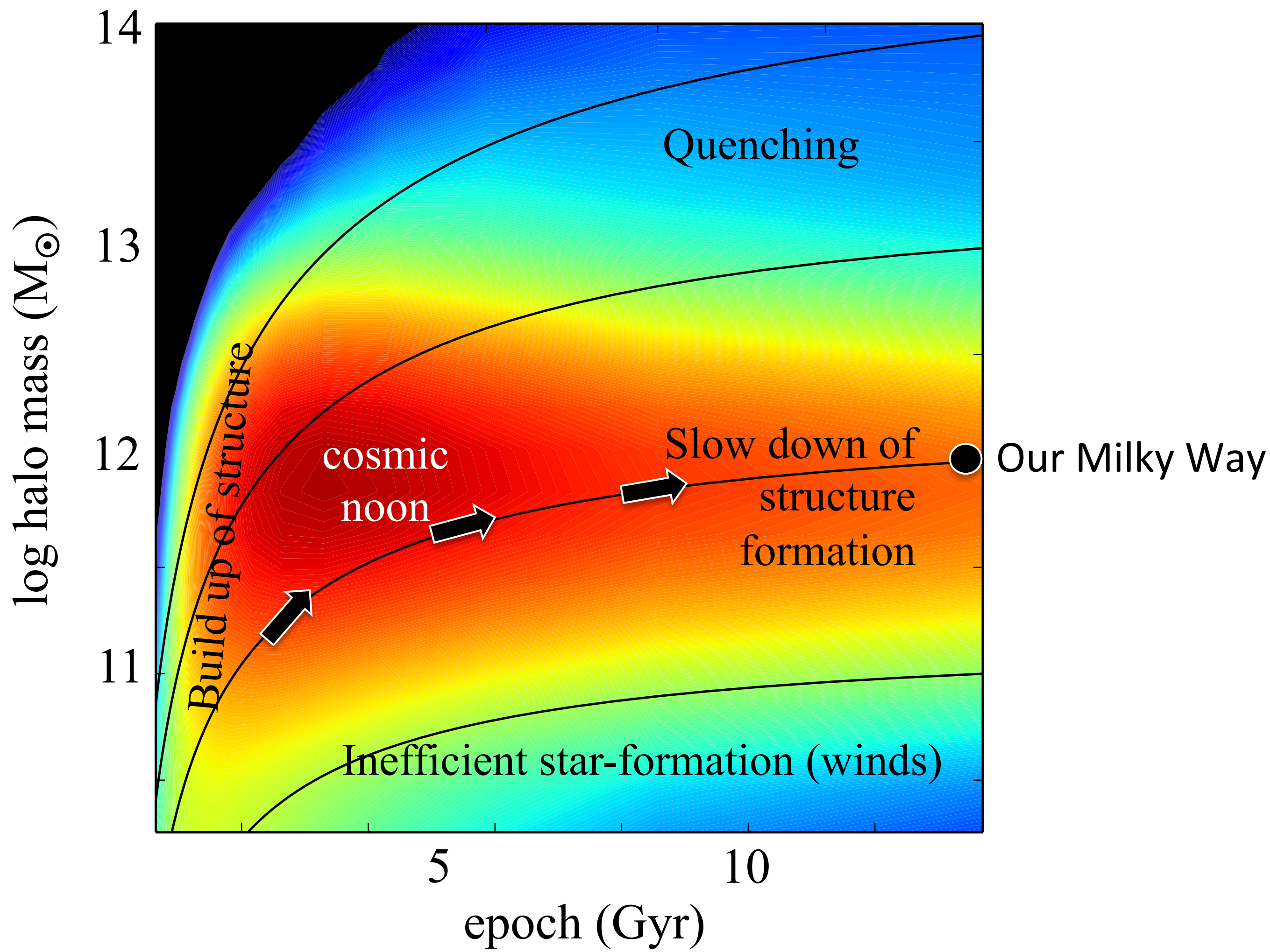
- all the incoming gas in a halo is immediately assigned to a regulator
- none of the ejected gas from galaxies is ever re-ingested

Overall this absurdly simple model works pretty well given its extreme simplicity





Summary: where and when did stars form in the Universe?

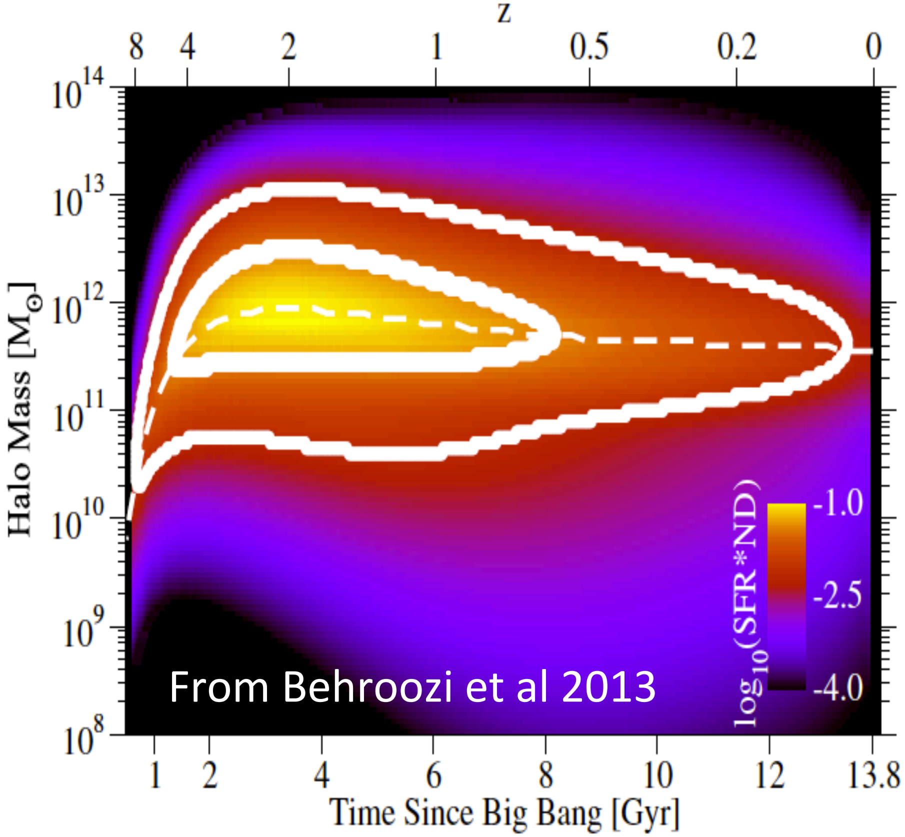


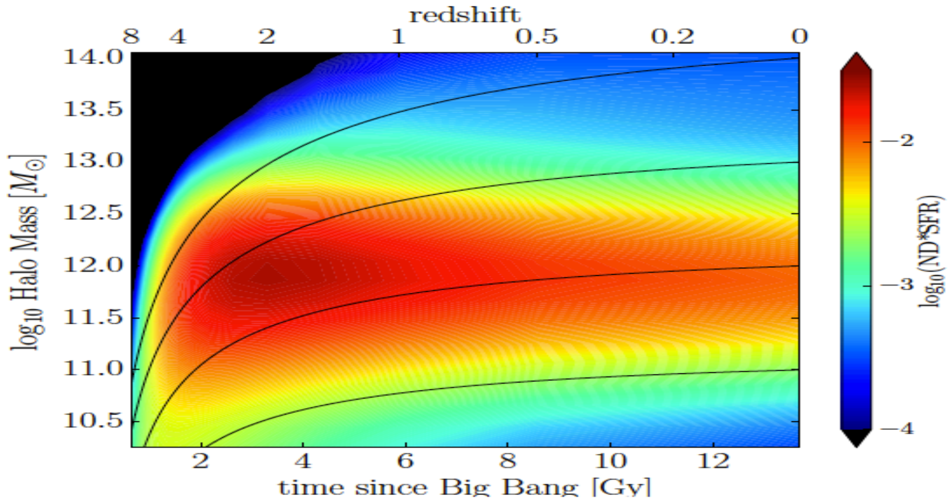
Colour scale indicates total SFR in all haloes of a given mass

Another phenomenological approach gives very similar answers

Behroozi et al (2012) analysis:

- Start with $\phi(m)$ for DM haloes (theory) and galaxies (observed):
- Abundance-match galaxies and haloes at all redshifts to fix $m_{star}(m_{halo},z)$
- Differentiate m_{star} to get the SFR(m_{halo},z).
- Global fit to observational data sSFR, SFRD etc.

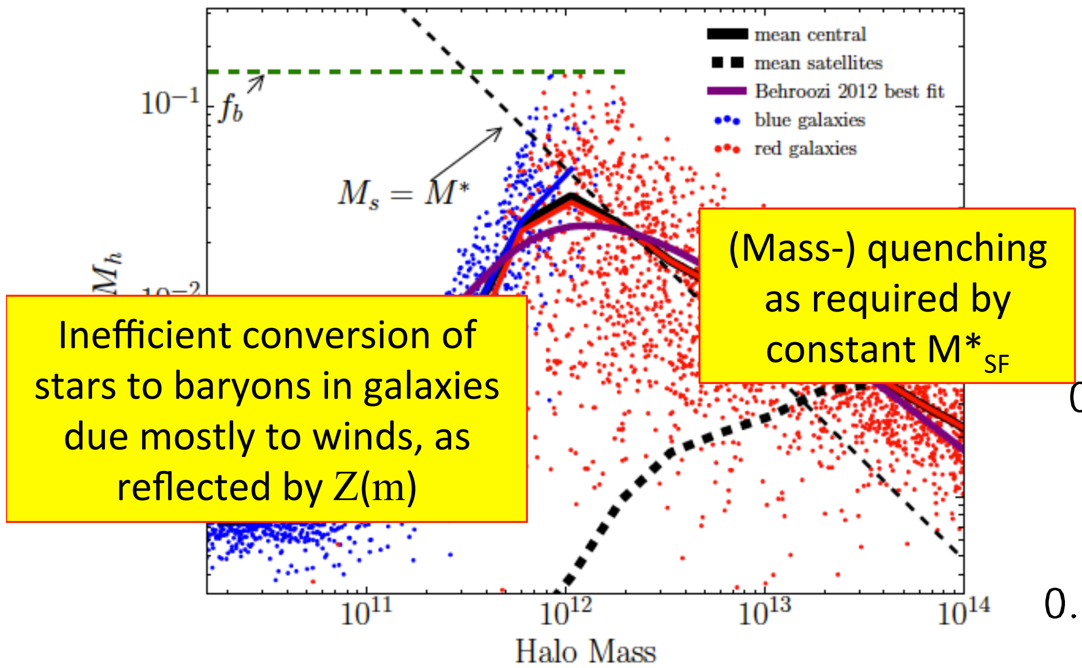


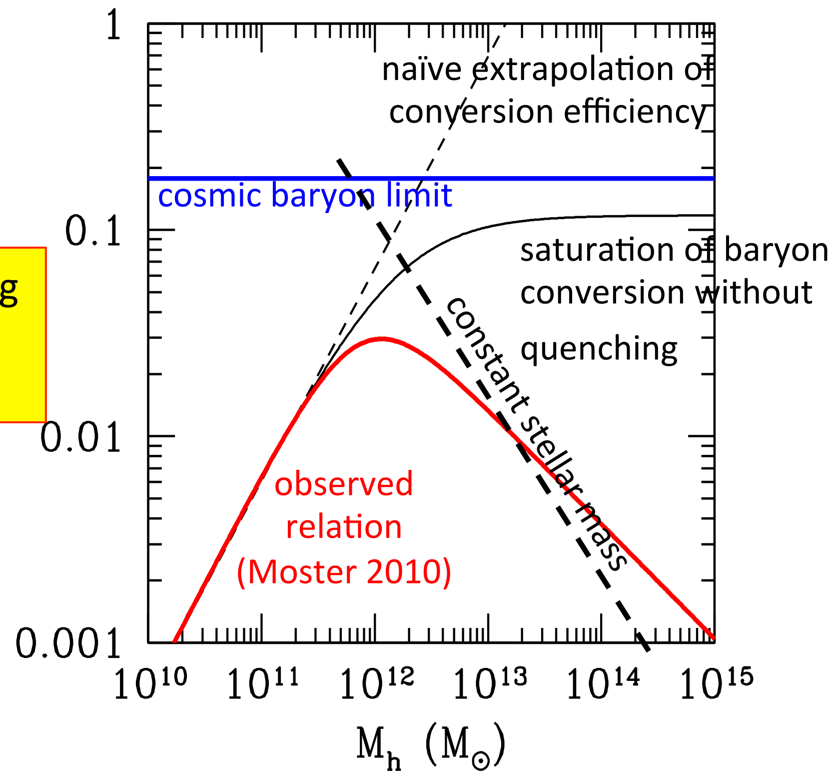


Our phenomenological SAM
Birrer et al (2014)

Last point: the curious "co-incidence" of the quenching mass Birrer et al 2014

The overall conversion of baryons into stars increases dramatically as the halo mass approaches $10^{12}M_\odot$, but then declines due to (mass)-quenching, producing a sharp peak in m_{star}/m_{halo} at $10^{12}M_\odot$





"Quenching" happens just as m_{star}/m_{halo} approaches to within a factor of a few of the cosmic baryon fraction (i.e. just when a halo approaches "maximum possible efficiency"). Not before, and not after. **What is this telling us? (see later)**

Summary of Part 3:

We asked: What produces the overall star-formation history of the Universe, which initially rises up to a peak at "cosmic noon" at $z \sim 2$ and then declines again to the present epoch?

It is a combination of three simple things:

The effect of SN-driven winds (at low halo masses) and "mass-quenching" (at higher halo masses) produces a sharp peak in the M_{star}/m_{halo} ratio at 10^{12} $M_{\odot}$. This is a "magic mass" for making stars in the Universe.

The number density of these magic haloes around 10^{12} $M_{\odot}$ increases rapidly with time at high redshifts, when $M^*_{DM} < 10^{12}$ $M_{\odot}$, but then levels off after $z \sim 2$ when $M^*_{DM} > 10^{12}$ $M_{\odot}$.

Throughout this time, the rate of structure growth, as parameterized by the specific growth rate of DM haloes, sMIR, is continuously declining with time, leading to lower sSFR of star-forming galaxies. This dominates at $z < 2$, since the number of magic haloes stays roughly constant.