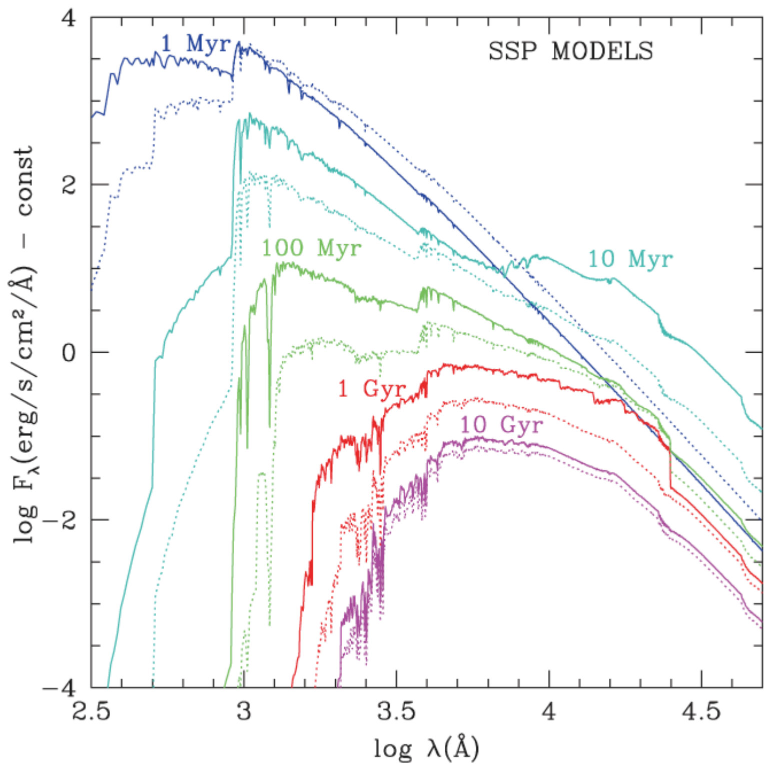
Week 4:
The star-formation rate of the Universe, Part 1:
Low redshift z < 2

Introduction by S. Lilly

How do we measure star-formation rates (SFR)?

The only absolute measurement of the SFR is to count stars In a star-forming region, but this is impossible outside of our own Galaxy. Everything else is an estimate, often simply empirically calibrated

Massive stars are very hot and luminous but have short lifetimes ($<10^7$ yr). So the best estimate of the number of young stars is simply the ultraviolet luminosity.



Note: In a young stellar population most of the light is from most massive (surviving stars) but most of the mass is in the lowest mass stars. dN/dm is the "initial mass function" (i.m.f.) which seems to be more or less "universal".

$$L \propto m^{3.5}$$

Luminosity of star as *f*(m)

$$\left(\frac{dN}{dm}\right) \propto m^{-(1+x)} \text{ with } x \sim 1.35$$

Number of stars as *f*(m)

This "Salpeter" i.m.f. is OK or our purposes: there are a number of other detailed forms (e.g. Chabrier)

How do we measure star-formation rates (SFR)?

But, the effects of dust obscuration are particularly severe at short wavelengths, so…

$$\mathrm{SFR}\,(M_\odot\,\mathrm{yr}^{-1}) \simeq 1.13 \times 10^{-28}\, L^\circ_{1500}\,(\mathrm{erg\,s^{-1}\,Hz^{-1}})$$

(a) Use Hα (656 nm) emission that us photoionized by <91 nm emission in SF regions.

$$\mathrm{SFR}\,(M_\odot\,\mathrm{yr}^{-1}) \simeq 5 \times 10^{-42}\, L^\circ_{\mathrm{H}\alpha}\,(\mathrm{erg\,s^{-1}})$$

(b) Estimate absorption by dust from either ultraviolet continuum slope, or from the Hα/Hβ ratio and correct uv luminosity

(c) Measure re-radiated emission from dust (at 30-50 K) in mid- and far-infrared (50μm-1mm)

$$\mathrm{SFR}\,(M_\odot\,\mathrm{yr}^{-1}) \simeq 4.5 \times 10^{-44}\, L_{\mathrm{FIR}}\,(\mathrm{erg\,s^{-1}})$$

(d) Use other proxies for young stars: radio emission from Cosmic rays from supernovae, or soft X-rays from X-ray binaries involving massive stars

$$\mathrm{SFR}\,(M_\odot\,\mathrm{yr}^{-1}) \simeq 5.9 \times 10^{-22}\, L_{1.4\,\mathrm{GHz}}\,(\mathrm{erg\,s^{-1}\,Hz^{-1}})$$

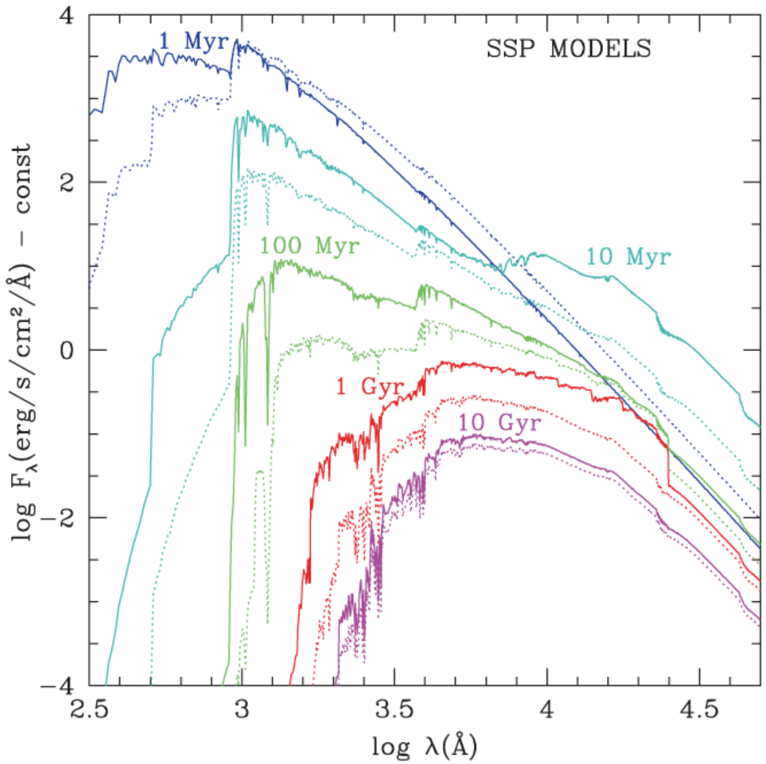
$$\mathrm{SFR}\,(M_\odot\,\mathrm{yr}^{-1}) \simeq 2.2 \times 10^{-40}\, L_{0.5-2\,\mathrm{keV}}\,(\mathrm{erg\,s^{-1}})$$

How do we measure stellar masses of galaxies?

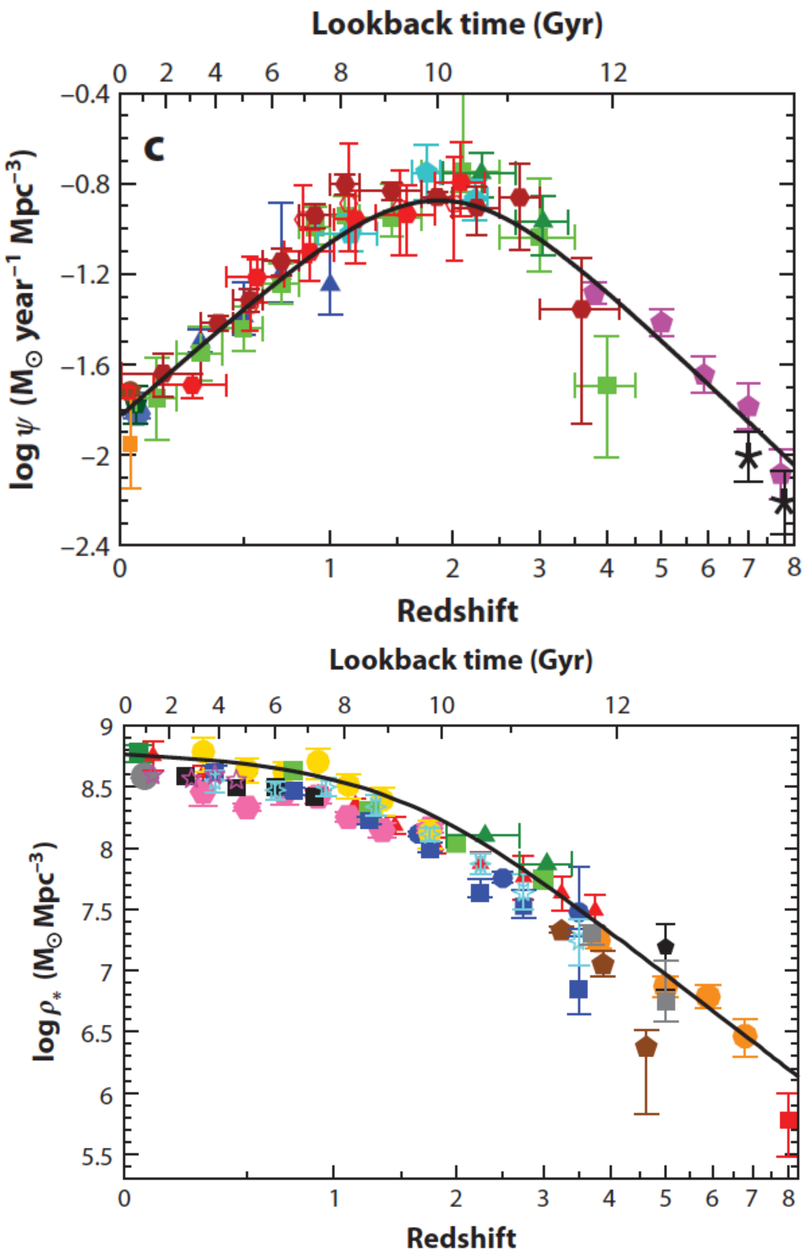
We know how a single population of stars will evolve in brightness as a function of time after it is formed.

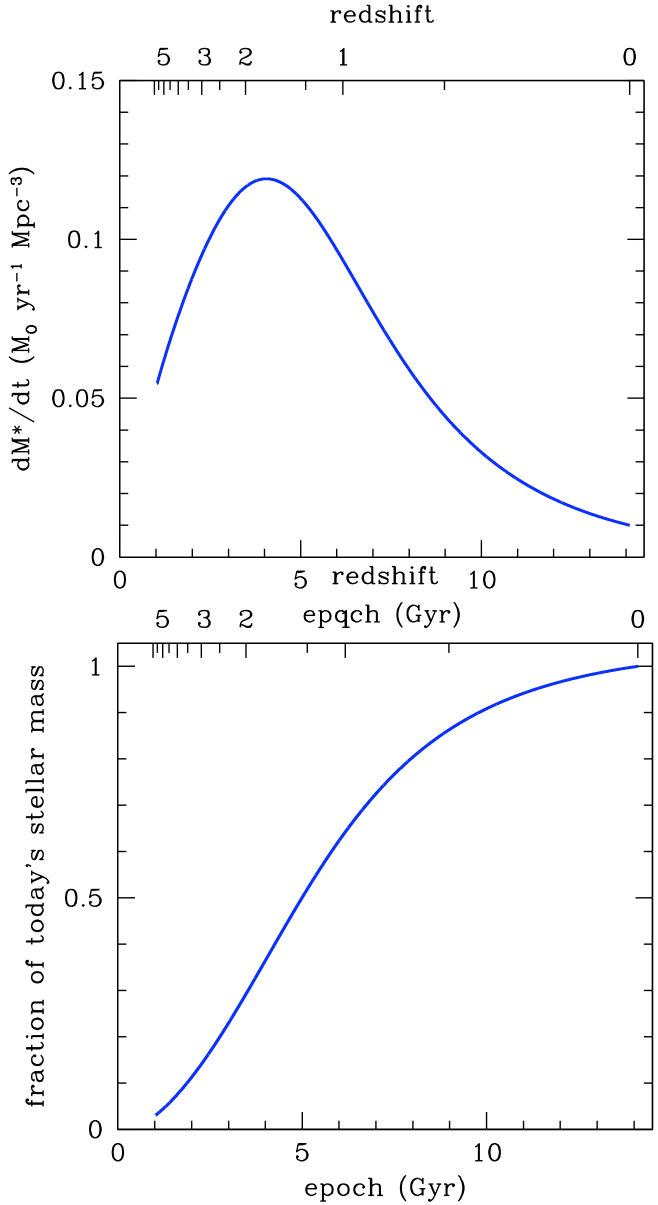
We can therefore model what any more complicated star-formation history will look like (simply a convolution with the age distribution).

Fit the overall spectra energy distribution of a galaxy including effects of reddening and parameters describing SFR history.



The star-formation rate density of the Universe





The specific star-formation rate of galaxies

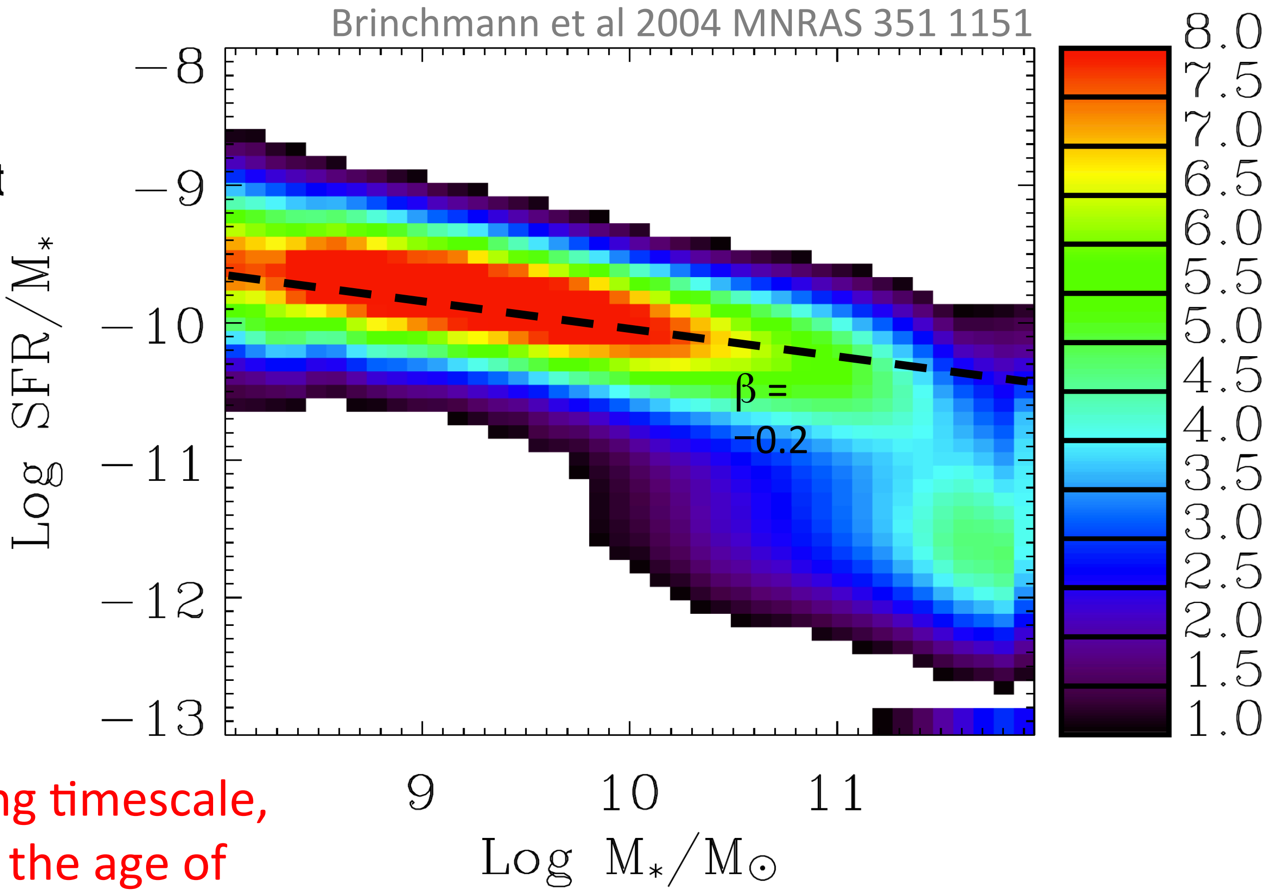
Most *actively star-forming* galaxies at present epoch have similar specific SFR. Plus there is a population of "passive" galaxies (generally but not always quite massive) in which the star-formation has been "quenched" by factors of 10-100.

This tight relation (σ ~ 0.3 dex) is called the *"Main Sequence"* of galaxies, not to be confused with Main Sequence of stars

$$SFR \propto m_{star}^{1+\beta}$$

$$sSFR \propto m_{star}^{\beta}$$

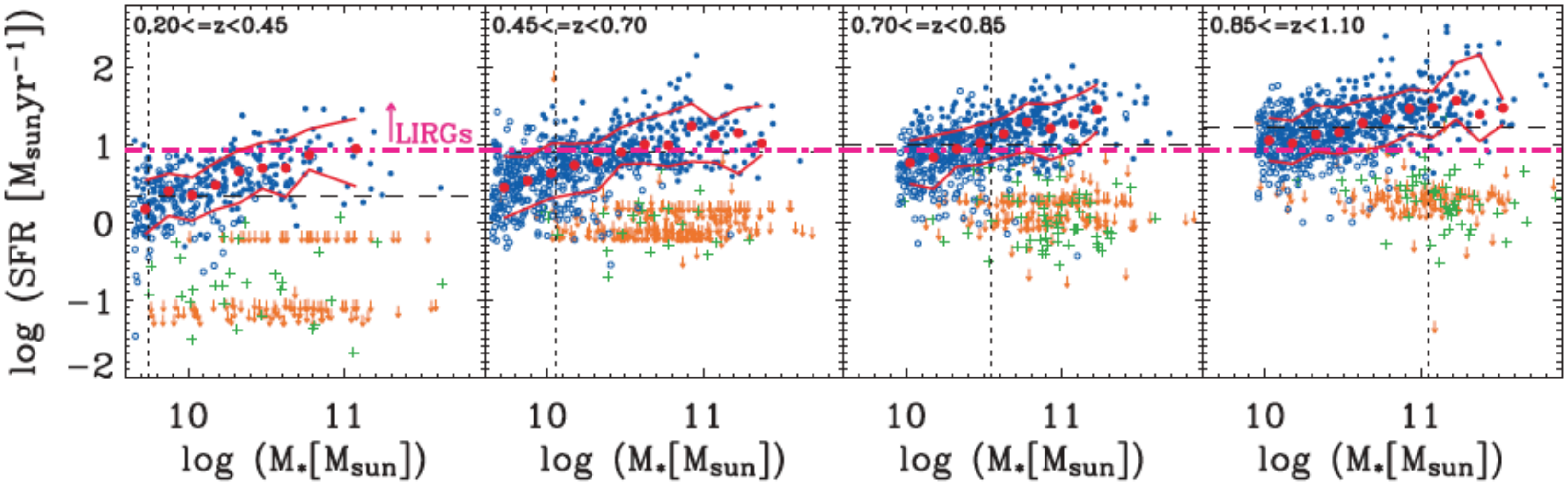
$$-0.1 < \beta \sim -0.2$$



Note that the mass-doubling timescale, $sSFR_{MS}^{-1}$ is ~ 10^{10} yr, about the age of Universe

The evolving Main Sequence

Noeske et al 2007 ApJ 660 L43



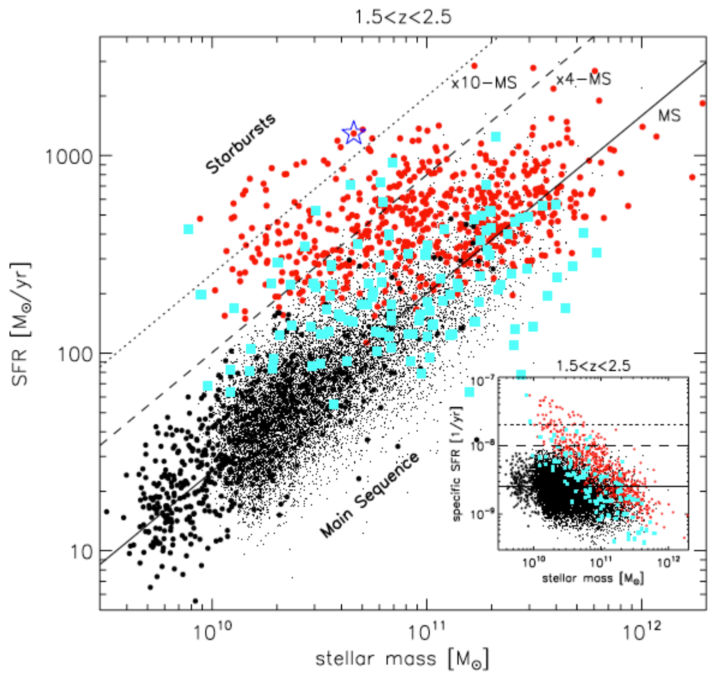
This characteristic sSFR of the Main Sequence population increases with redshift as something like $(1+z)^{2.5}$ and the mass doubling timescale has reduced to $sSFR_{MS}^{-1}$ ~ 0.5 Gyr at z ~ 2, which isconsiderably less that the age of Universe at that redshift.

Aside: galaxies above the Main Sequence

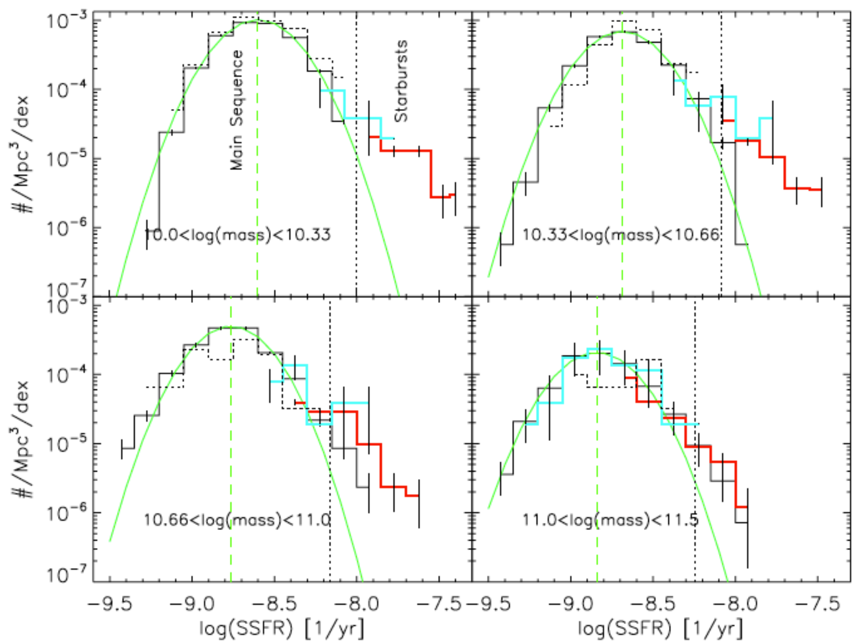
About 2% of galaxies at z ~ 2 lie significantly above MS, with sSFR > 4 $\langle \mathrm{sSFR} \rangle_{\mathrm{MS.}}$

These should be regarded as “star-bursts” (on duty-cycle arguments)

These are generally more highly dust-obscured. They are probably merger induced, producing short-lived enhancement in star-formation “efficiency” (*SFR*/ m_{gas}). They represent about 10% of the total SFR at this epoch.

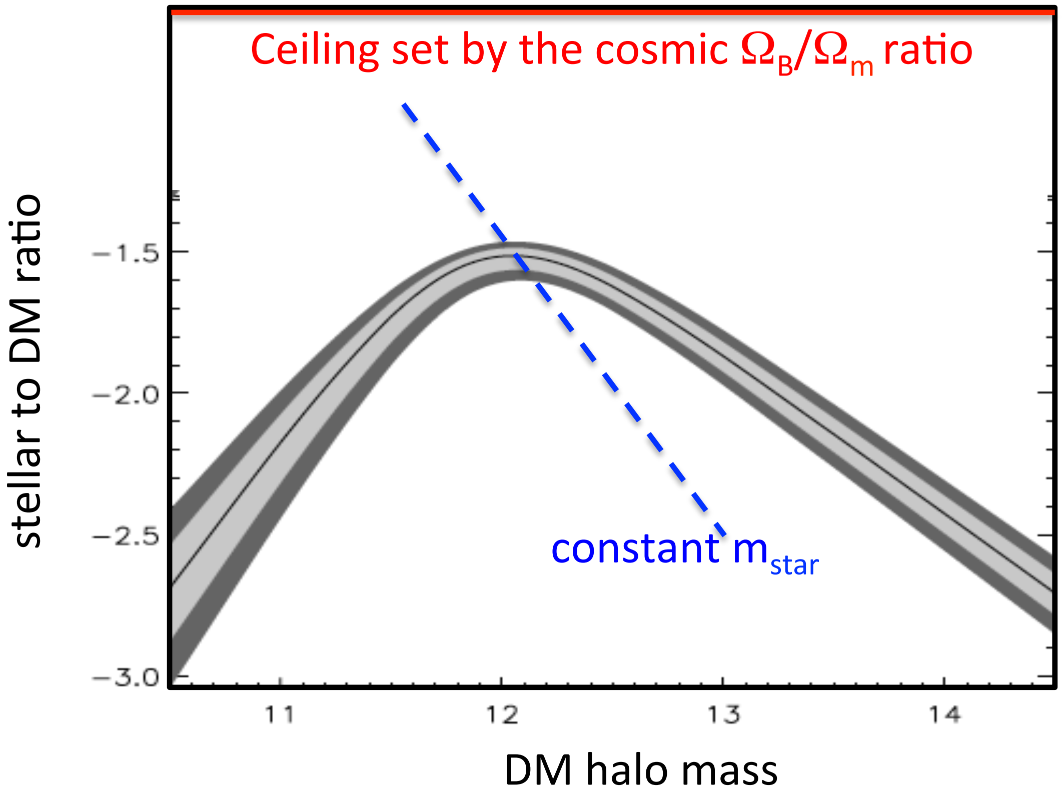


from Rodighiero et al 2012 ApJL 739, L40



The relation between stellar mass and halo mass

Stellar to halo mass relation

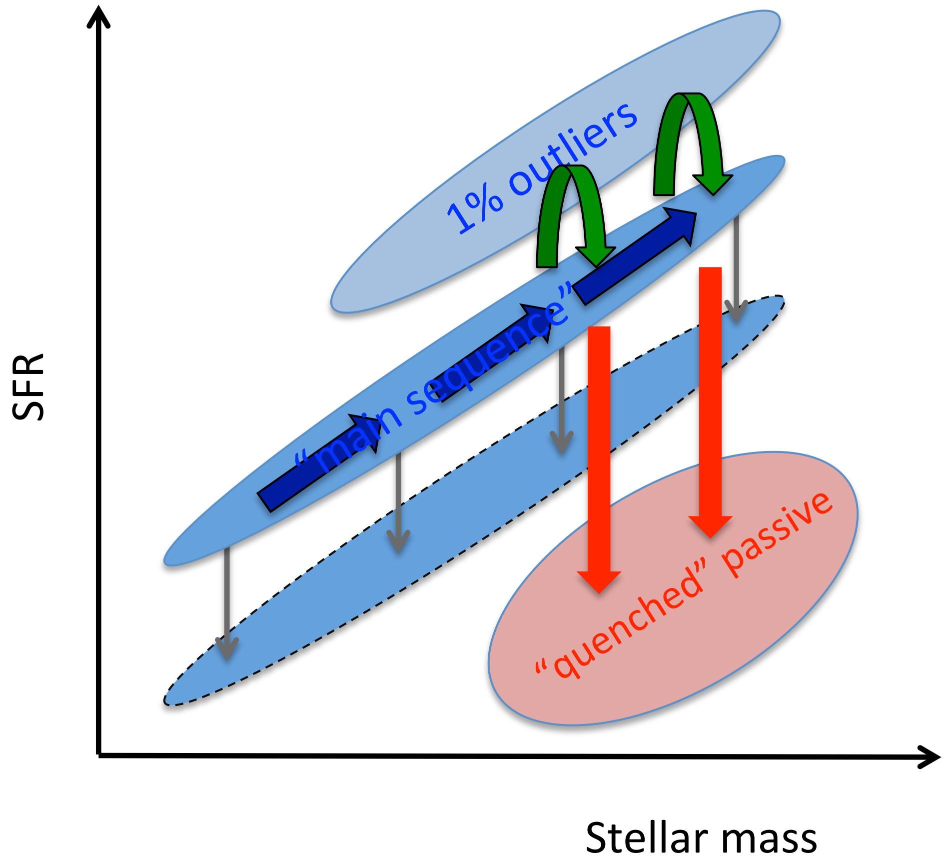


Moster+ (2010)

Estimated via extensive statistical analysis based on assumption of a simple monotonic relationship between the two, plus input of data on number density, spatial clustering, etc.

Then, checked with observational estimates of DM halo masses from weak lensing, X-ray gas data and dynamical mass estimates.

A cartoon of galaxy evolution (at least since z ~ 2)



Questions:

- What sets the value and rather small dispersion of the sSFR of typical "Main Sequence" star-forming galaxies?

- Why does this characteristic Main Sequence sSFR change with time/ redshift, increasing roughly as $(1+z)^{2.5}$?

- Why do lower mass haloes have a lower m_{star}/m_{halo} ratio than those at $10^{12}M_{\odot}$, i.e. why are they less effective at forming stars?

- Why is the characteristic star-formation timescale for most star-forming galaxies $\tau_{dep} \sim m_{gas}/SFR \sim 10^9$ yr so much longer than the free-fall time in gas clouds $\sim 10^7$ yr (see Lecture 1), but so much less than the mass-doubling timescale m_{star}/SFR?

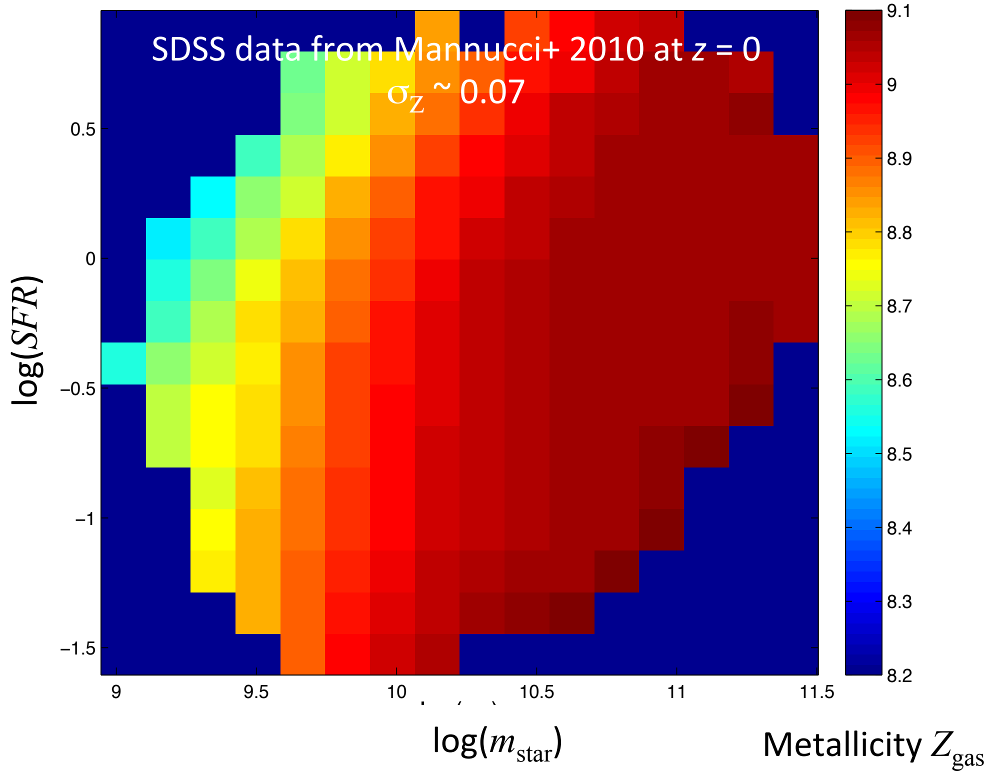
- Not for today: what causes some galaxies to stop forming stars altogether?

[redacted]

Reproducing the Mannucci et al Z(m,SFR) data

Analyzing local SDSS data, Mannucci et al (2010) (and others) had made two claims:

- The SFR of a galaxy is a "second parameter" in the well-known Z(m_{star}) relation
- The form of the Z(m,SFR) relation is the same at high redshift as locally: "Fundamental Metallicity Relation" = FMR



Aside: Metallicity as a diagnostic of the gas-regulator idea

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

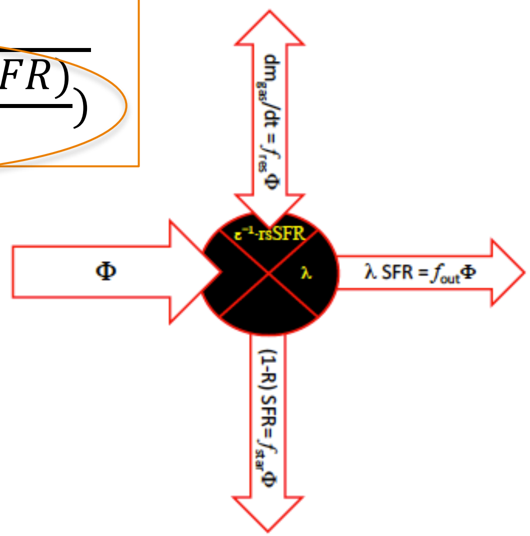
$$Z_{eq} = Z_0 + \frac{y}{1 + \lambda(1-R)^{-1} + \mu + (1-R)^{-1}\varepsilon^{-1}\frac{d\ln\mu}{dt}}$$

c.f. closed box

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

Generally small, only term that depends on history of system

$$Z_{eq} = Z_0 + \frac{y}{1 + \lambda(1-R)^{-1} + \varepsilon^{-1}\left(sSFR + (1-R)^{-1}\frac{d\ln(\varepsilon^{-1}sSFR)}{dt}\right)}$$



Key idea: Metallicity is set "instantaneously" by the parameters of the regulator, and not by the previous history of the galaxy, which enters only via the (small) $d\ln\mu/dt$ term.

This is because time gas spends in regulator is short

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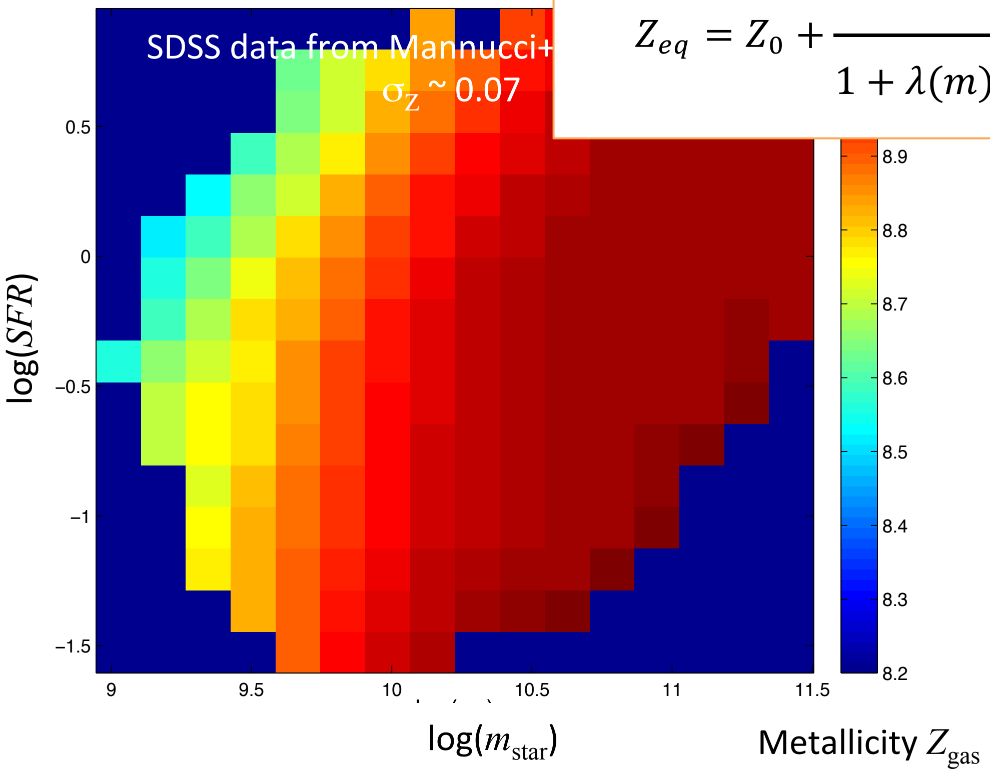


$$Z_{eq} = Z_0 + \frac{y}{1 + \lambda(m)(1-R)^{-1} + \varepsilon(m)^{-1}\left(sSFR + (1-R)^{-1}\frac{dln\mu}{dt}\right)}$$

The "recovered" values of ε and λ are astrophysically "plausible":

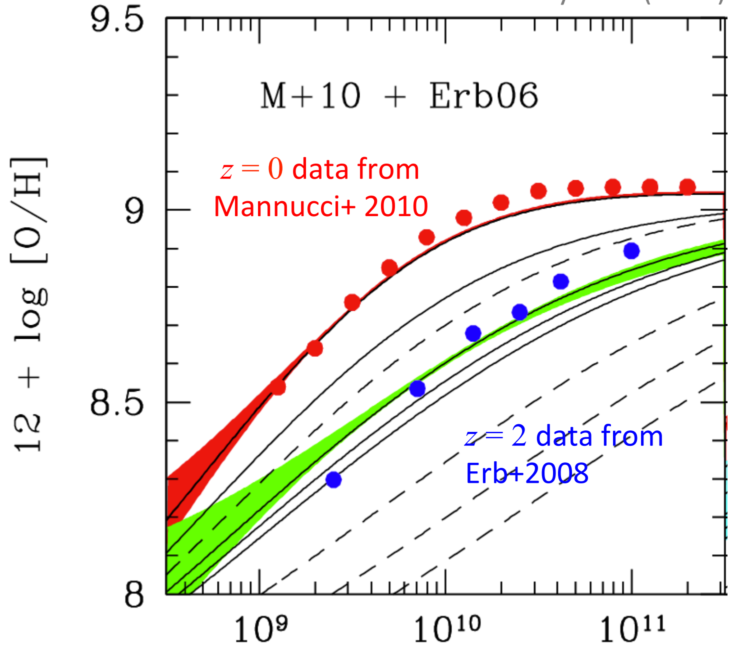
- $\varepsilon^{-1} = \tau_{gas} \sim 2.5\, m_{10}^{-0.3}$ Gyr
- $\lambda \sim 0.4\, m_{10}^{-0.8}$

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

Note four interesting things:

- Chemical "evolution" reflects the changing state of regulator over cosmic time, not a monotonic increase in metallicity in a pseudo-closed box.
- There is however a direct link between the "cosmic" evolution of $sSFR(z)$ and $Z(z)$
- A natural $Z(m_{star}, SFR)$ relation emerges. Furthermore, this will only change with time <u>to the extent that ε and λ do</u>*:*
  -> we would expect a so-called "fundamental metallicity relation" (FMR)

Lilly et al (2013)



- $f_{star}(m_{star})$ comes directly from $Z(m_{star})$ without needing to know ε or λ (assuming y is known and Z_0 is ~ negligible)

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