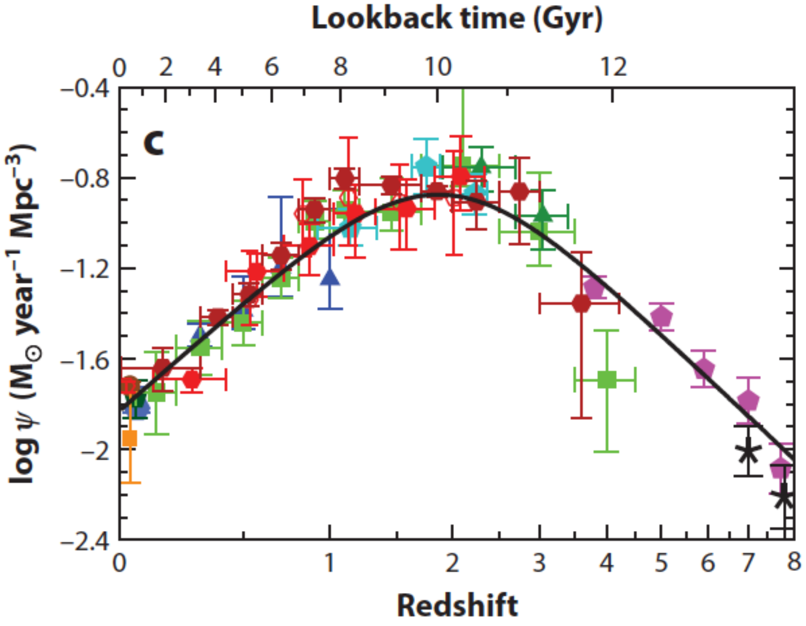
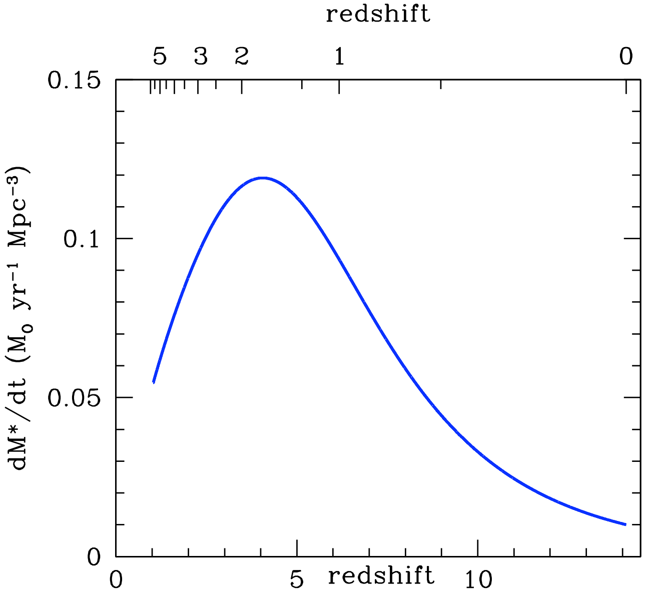
Week 5:
The star-formation rate of the Universe, Part 2:
High redshift z > 2

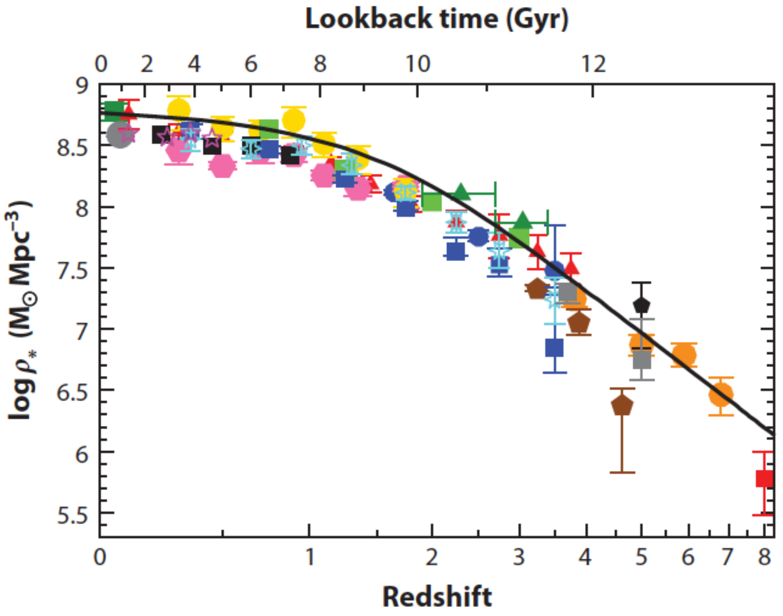
Introduction by S. Lilly

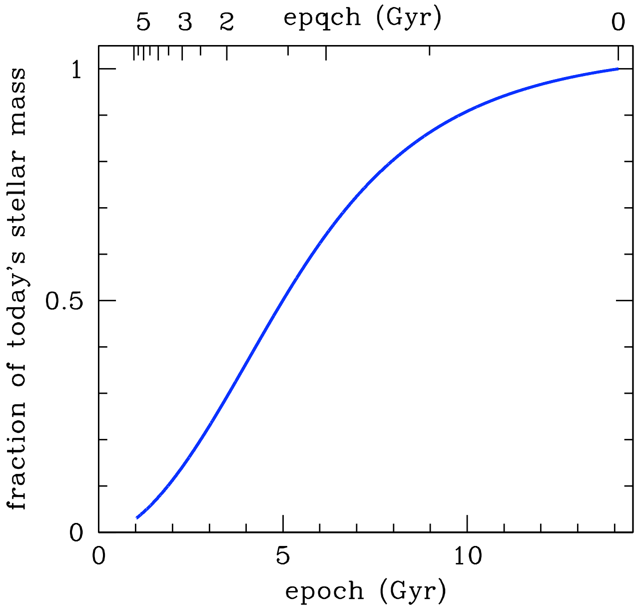
The star-formation rate density of the Universe



Madau & Dickinson Review (2014)







Recap from last week

Last week we focussed on two different elements of the rate of star-formation in galaxies.

(1) Energy injection from supernovae from young massive stars (Type II supernovae) has two effects:

- It quickly disrupts star-forming clouds, dispersing gas into non-starforming state in galaxies. This is why the gas depletion timescale in galaxies is long (of order 10^9 years).

- In low mass haloes, it can drive a galactic scale "wind" that carries material out of the galaxy and halo, especially for lower mass haloes with low escape velocities. This explains why m_{star}/m_{halo} increases rapidly as m_{halo}^2 up to 10^{12} $M_\odot$.

(2) Looking at why the overall star-formation rate density declined by a factor of ten between z ~ 2 and the present, we focused on the evolution of the sSFR of the majority of star-forming galaxies.

The sSFR fllows closely the behaviour of the sMIR of the DM haloes

A simple “bath-tub” gas-regulator model:

- sets sSFR = sMIR, independent of the parameters ε and λ.
- ε and λ will determine f_{star}, the fraction of incoming gas being turned into stars
- If f_{star} increases (e.g. as the mass increases), as it should to match the m_{star}-m_{halo} relation, then we will have sSFR > sMIR, as observed.
- Also, the metallicity of the gas also depends on ε, λ and sSFR, explaining the SFR as a second parameter in the mass-metallicity Z(m) relation.
- Thereby unifies the value of sSFR, the similar redshift evolution of the sSFR and sMIR (and their relative offset), the slope of m_{star}-m_{halo} relation, and the Z(m,SFR) relation by means of a very simple concept for how a galaxy works.

Questions:

- What sets the value and rather small dispersion of the sSFR of typical "Main Sequence" star-forming galaxies? The specific infall rate of material onto the galaxies (equivalent to specvific accretion rate of the haloes). The simple gas-regulator model sets sSFR=sMIR. If fstar increases with mass (and thus time), sSFR ~ 2 sMIR, as observed.

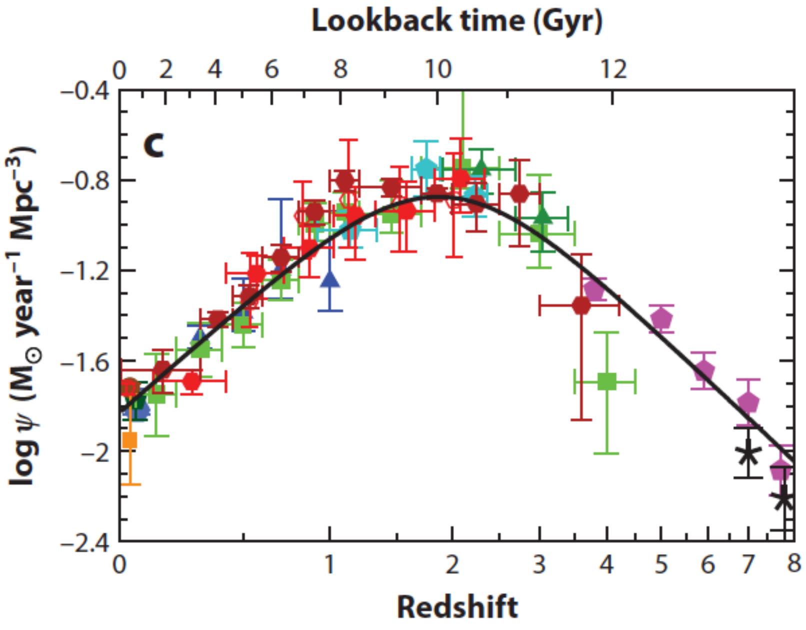
- Why does this characteristic Main Sequence sSFR change with time/redshift, increasing roughly as $(1+z)^{2.5}$? The specific growth rate of haloes follows this relation.

- Why do lower mass haloes have a lower m_{star}/m_{halo} ratio than those like the Milky Way , at $10^{12}M_{\odot}$, i.e. why are they less effective at forming stars? Energy injection (a.k.a. feedback) from supernovae drives galaxy scale winds, conveniently assumed to be λ.SFR which limit the ability of low mass haloes to form stars.

- Why is the characteristic star-formation timescale for most star-forming galaxies τ_{dep} ~ m_{gas}/SFR ~ 10^9 yr, so much longer than the free-fall time in gas clouds ~ 10^7 yr. This again is due to feedback quickly disrupting the dense regions in galaxies in which stars form.

- What does the fact that the mass doubling timescale $sSFR^{-1} = m_{star}/SFR$ is much longer than τ_{dep} tell us? It tells us that the gas in galaxies is continuously being replenished by infall from outside. This in term motivates the gas-regulator, "flow-through" picture.

This week: Two topics



A. The evolution of the star-formation rate density at early times z > 2.

What causes the rise in the SFRD up to cosmic noon" at z ~ 2?
Need to understand the number of haloes in the Universe, i.e. Press-Schechter

B. The re-ionization of the Universe at z > 6

The Universe was fully ionized at z > 1000 but then became a neutral gas. At some later point, ultraviolet light from the first stars/galaxies and also possibly from BH accretion re-ionized the Universe.

When did this occur, and what of any effect might it have on the formation of galaxies?

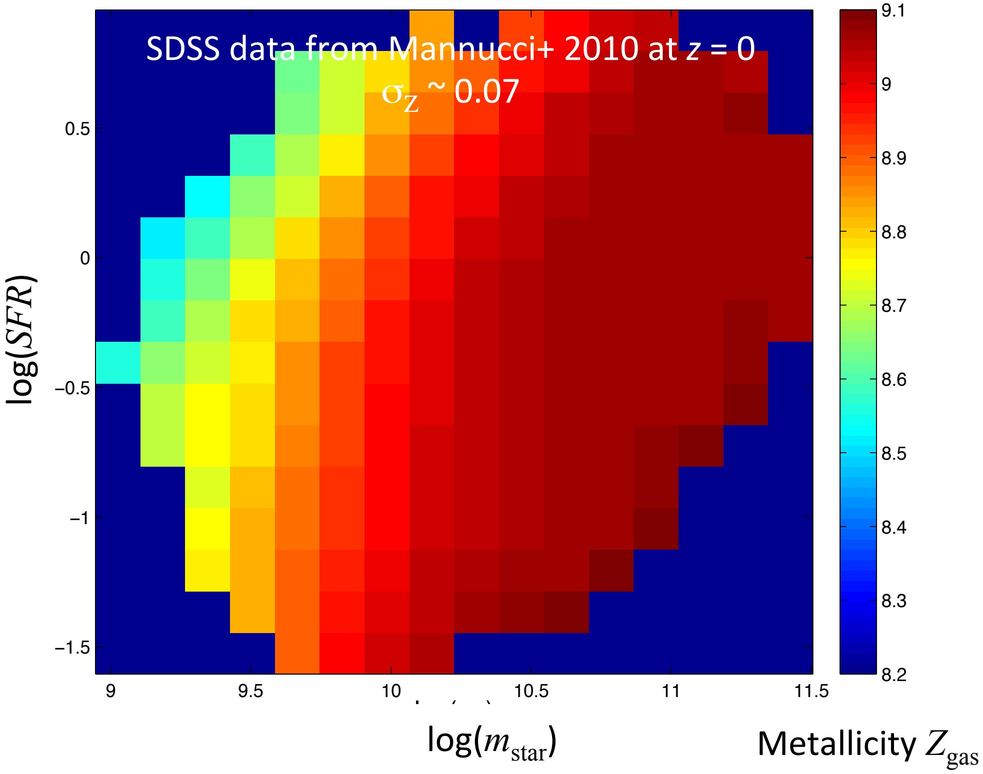
Questions:

- What causes the SFRD to rapidly rise up to the peak at z ~ 2?
- What is the observational evidence for reionization, and when did it occur?
- What sources caused the reionization, and can we identify them?
- What might reionization of the Universe have as an affect on the development of galaxies?

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

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

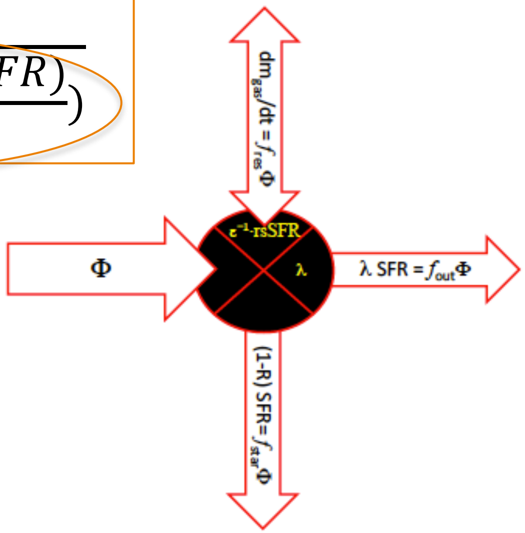
c.f. closed box

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

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

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) dlnμ/dt term.

This is because time gas spends in regulator is short

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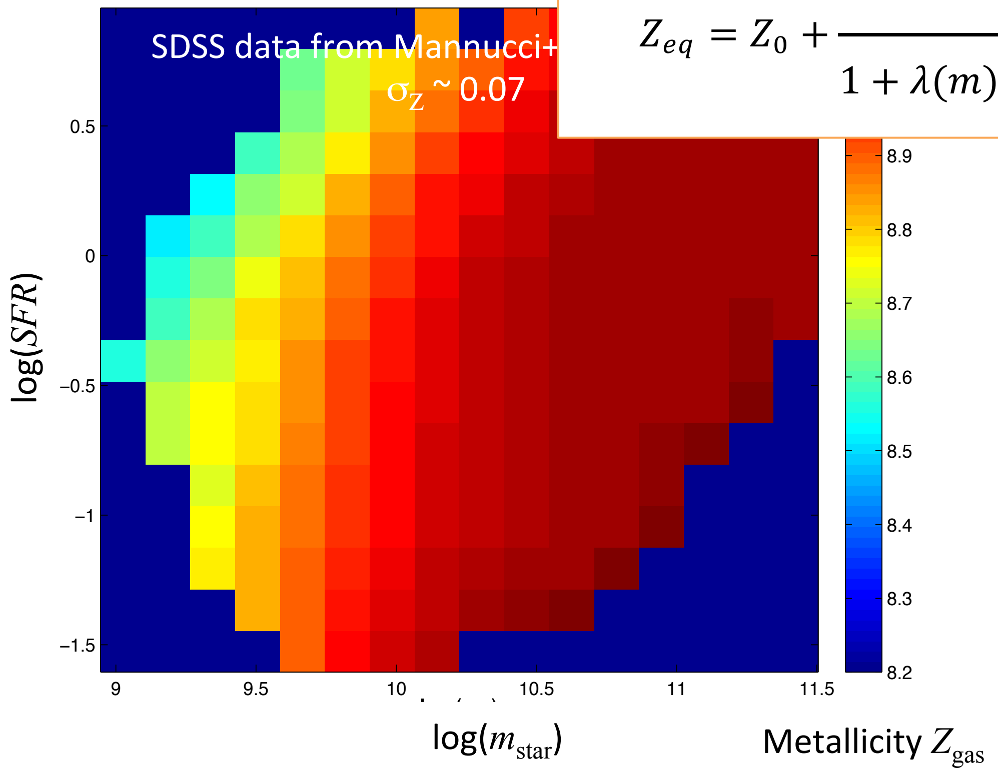
$$Z_{eq} = Z_0 + \frac{y}{1 + \lambda(m)(1-R)^{-1} + \varepsilon(m)^{-1}\left(sSFR + (1-R)^{-1}\frac{dln\mu}{dt}\right)}$$



The ”recovered” values of ε and λ are astrophysically “plausible”:

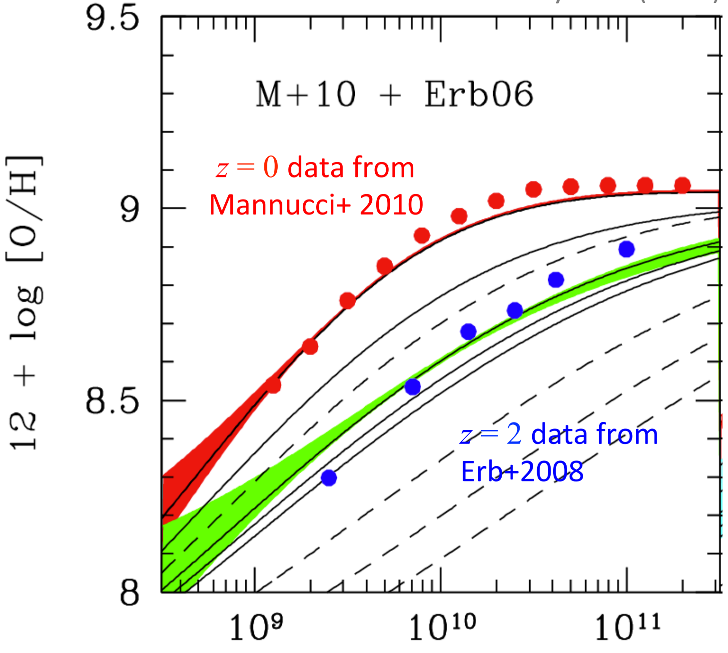
- $\varepsilon^{-1} = \tau_{gas} \sim 2.5\, m_{10}^{-0.3}$ Gyr
- $\lambda \sim 0.4\, m_{10}^{-0.8}$

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

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

Lilly et al (2013)



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