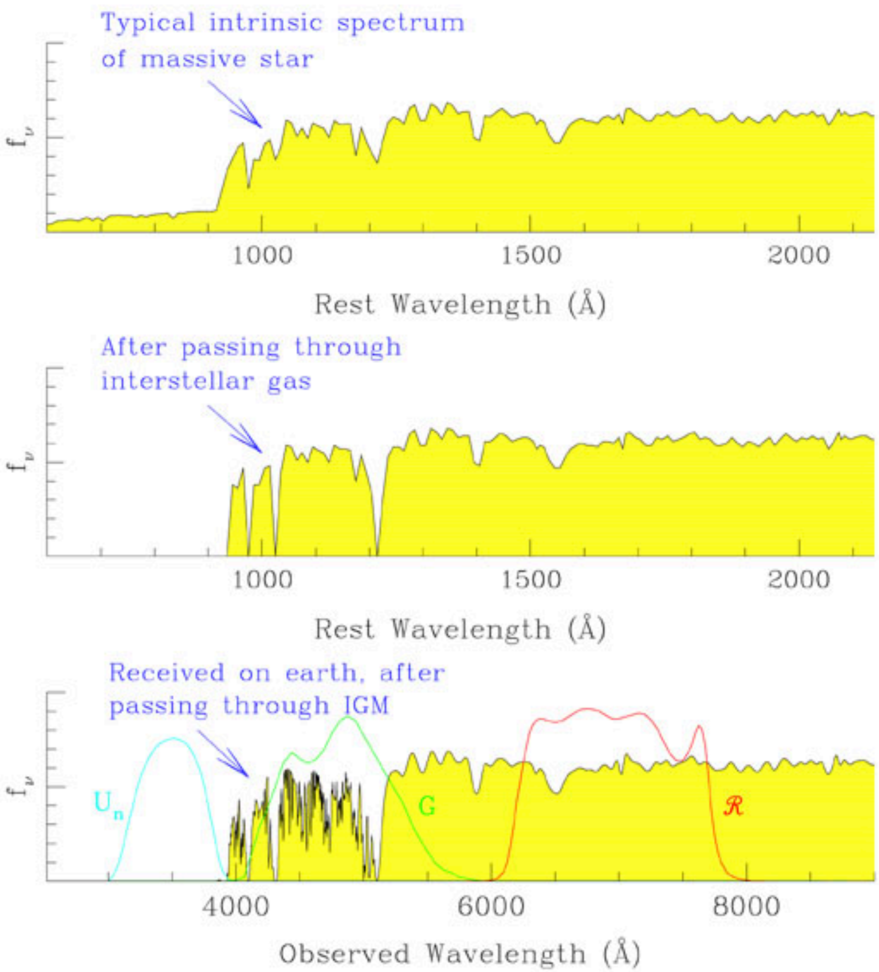
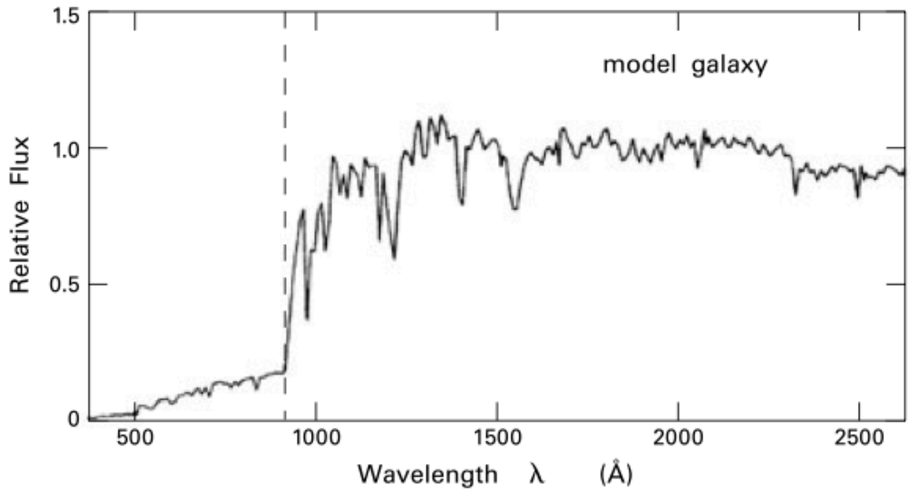
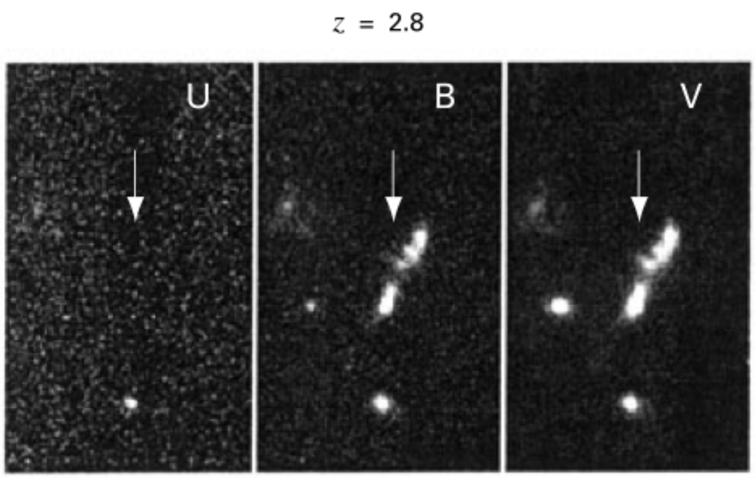
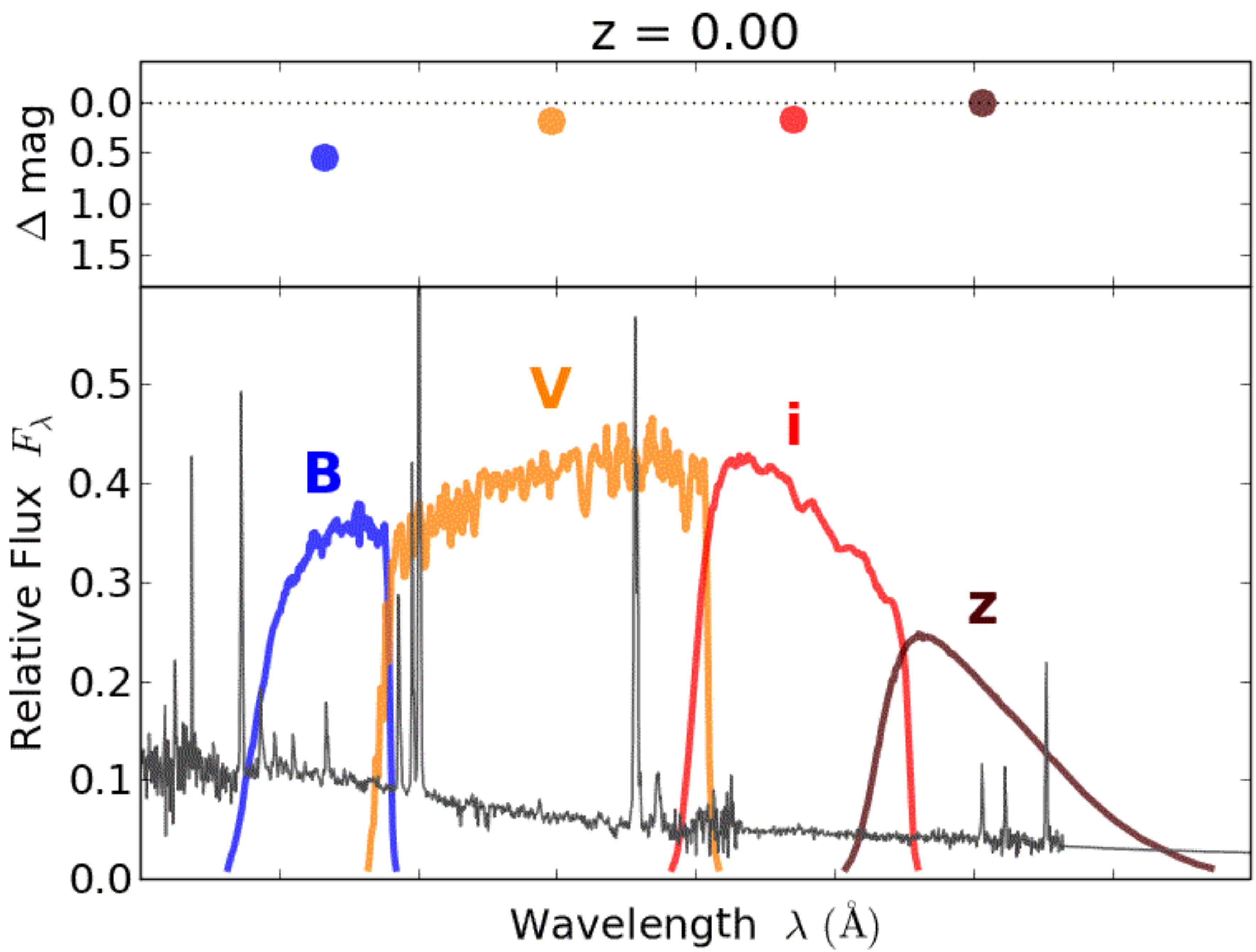
How to search for high-z Galaxies

- Lyman-break galaxies
  - Galaxy spectra have a discontinuity at the Lyman continuum edge (912 Å). Atomic hydrogen along the line of sight will absorb most of the flux at λ<912Å



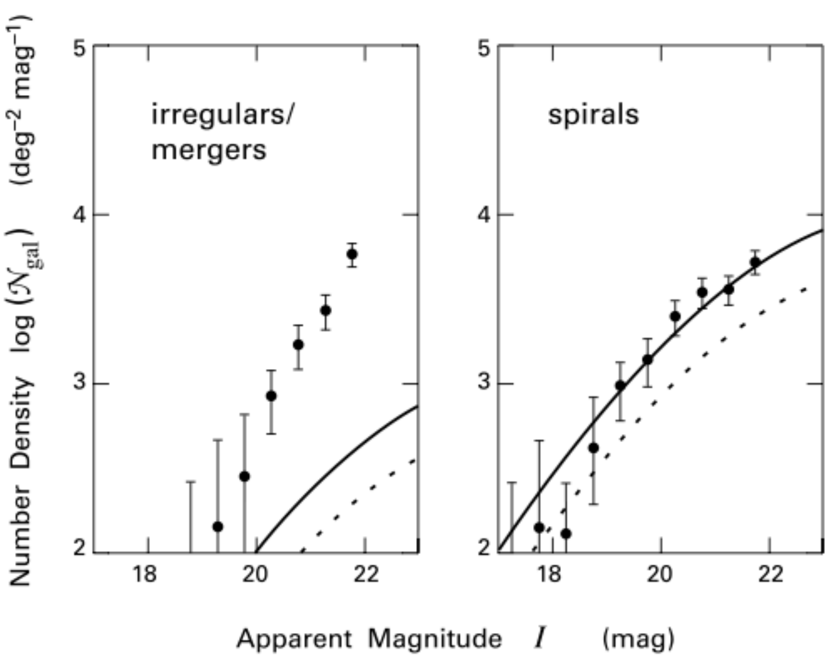


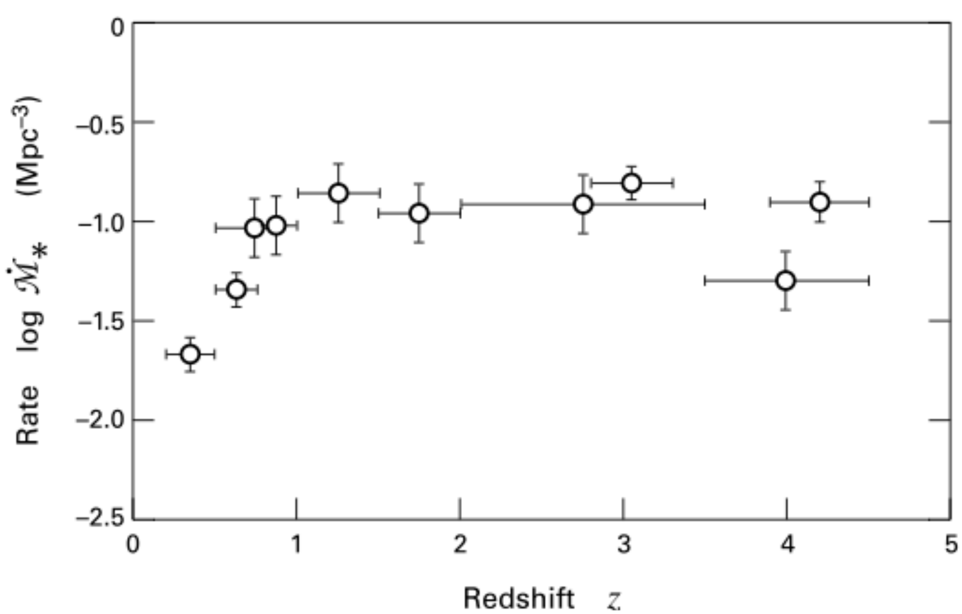



z = 0.00
Δ mag
0.0
0.5
1.0
1.5
Relative Flux F_λ
0.5
0.4
0.3
0.2
0.1
0.0
B
V
i
z
Wavelength λ (Å)

Dwarf Irregulars

- More active in the past
- Figure shows the activity of spirals at z~0.5 did not change much w.r.t the present times
- The irregulars were a lot more active
- Two solutions:
  - They faded in luminosity
  - They merged

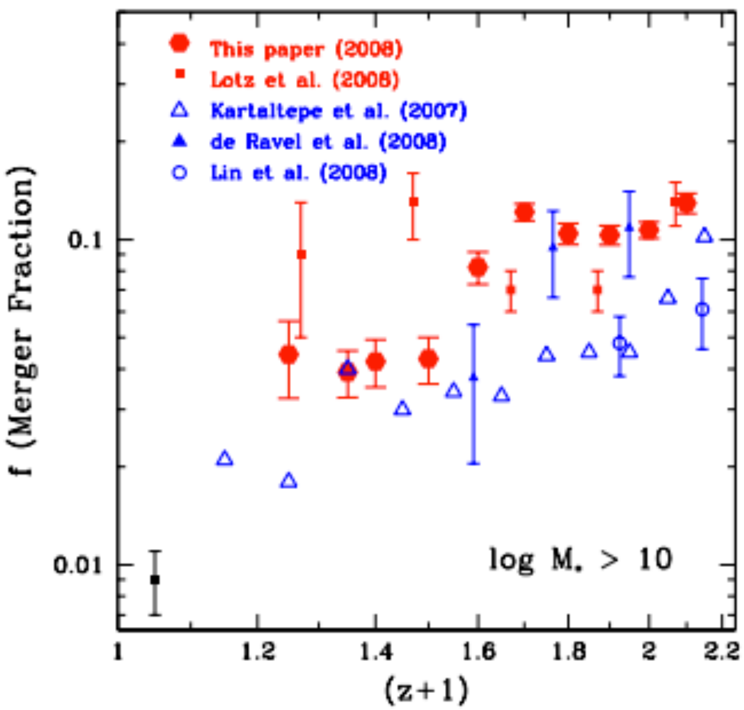




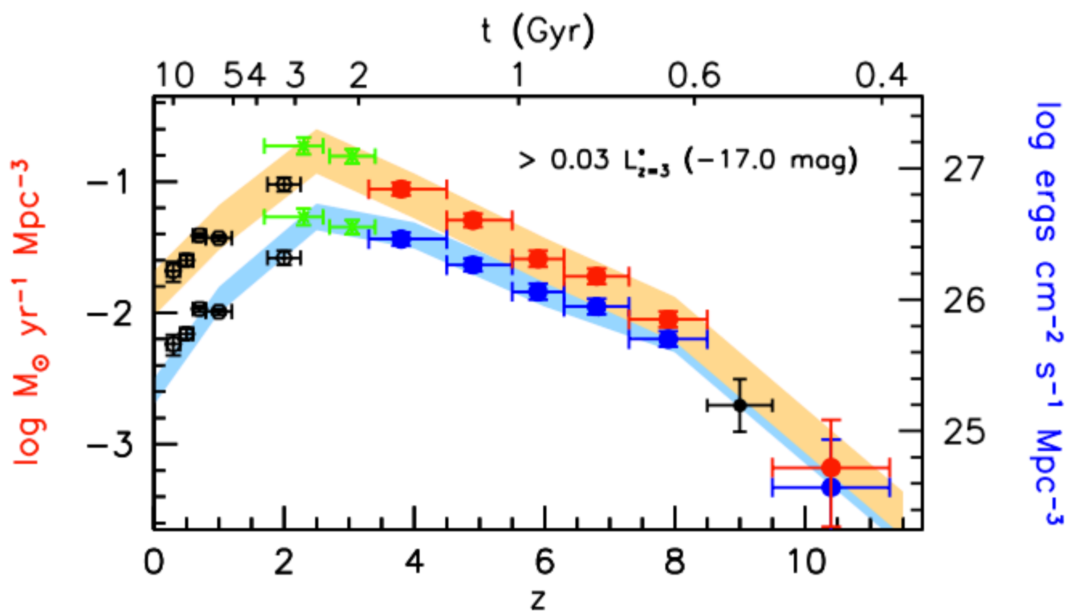
Merger Rates

- Mergers were more common in the past

Conselice et al. 2009



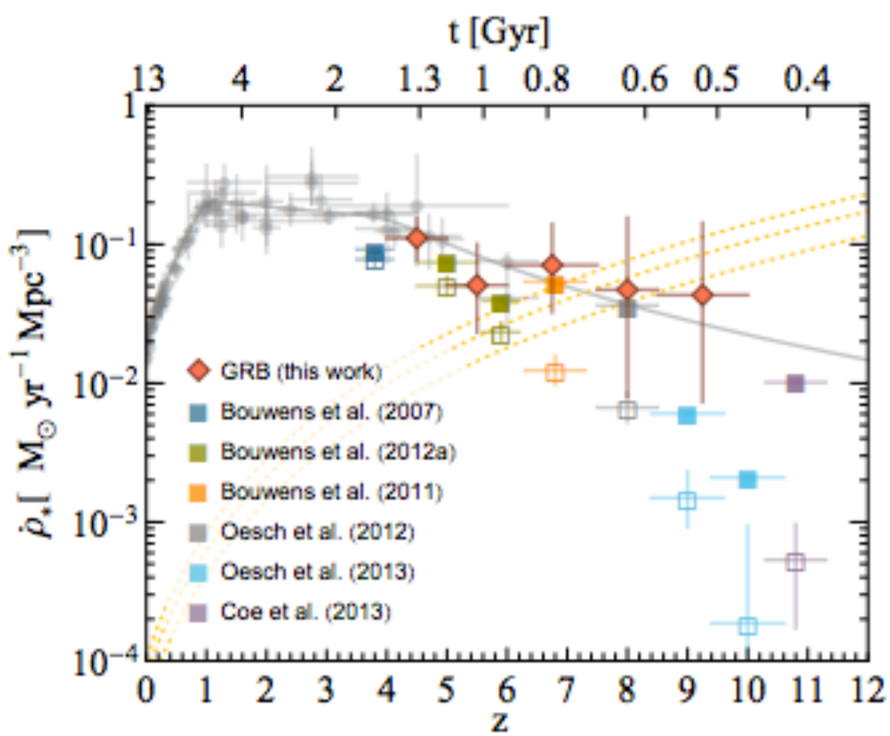
Bouwens+14



Star Formation History from GRBs

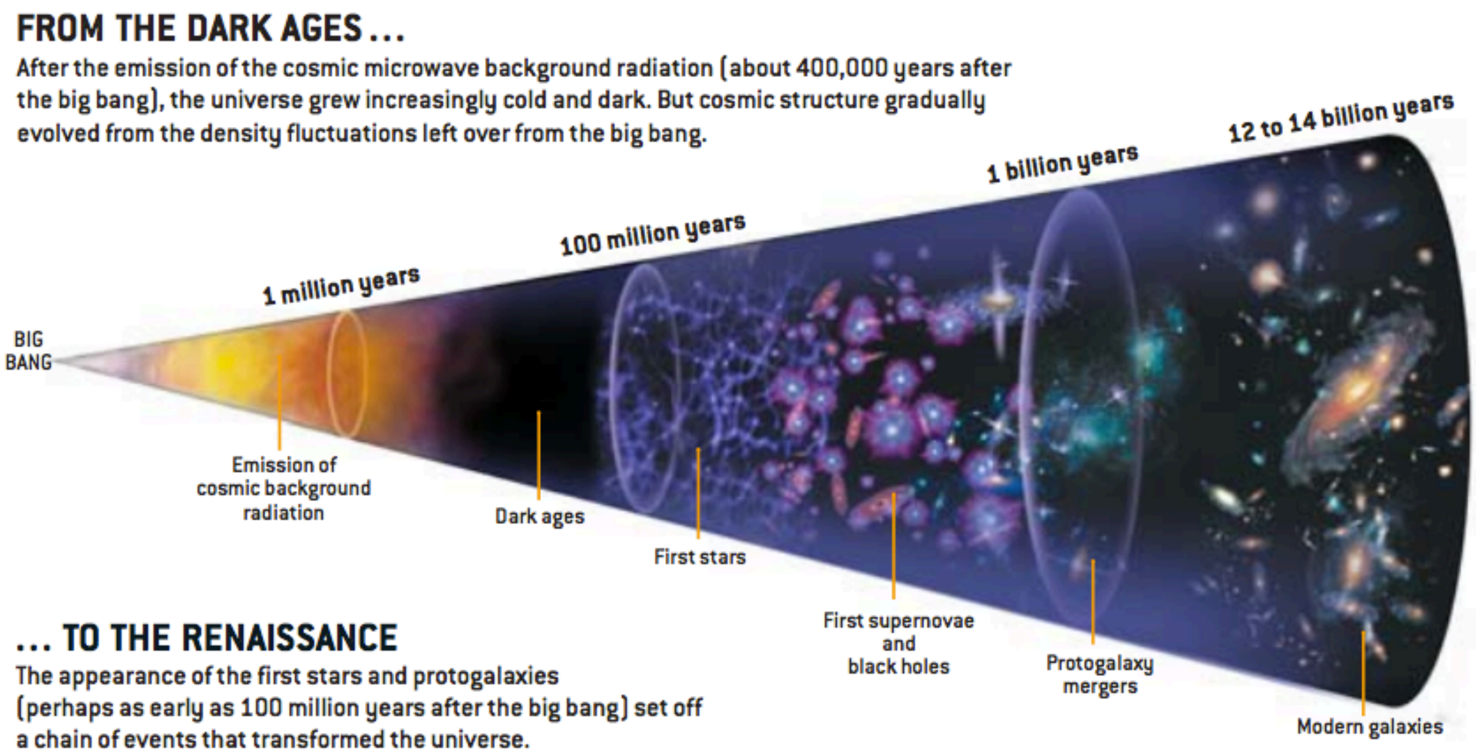
- GRBs yield a larger SFR at high-z
- There could be `many’ dwarf galaxies active in the early Universe

Kistler et al 2013



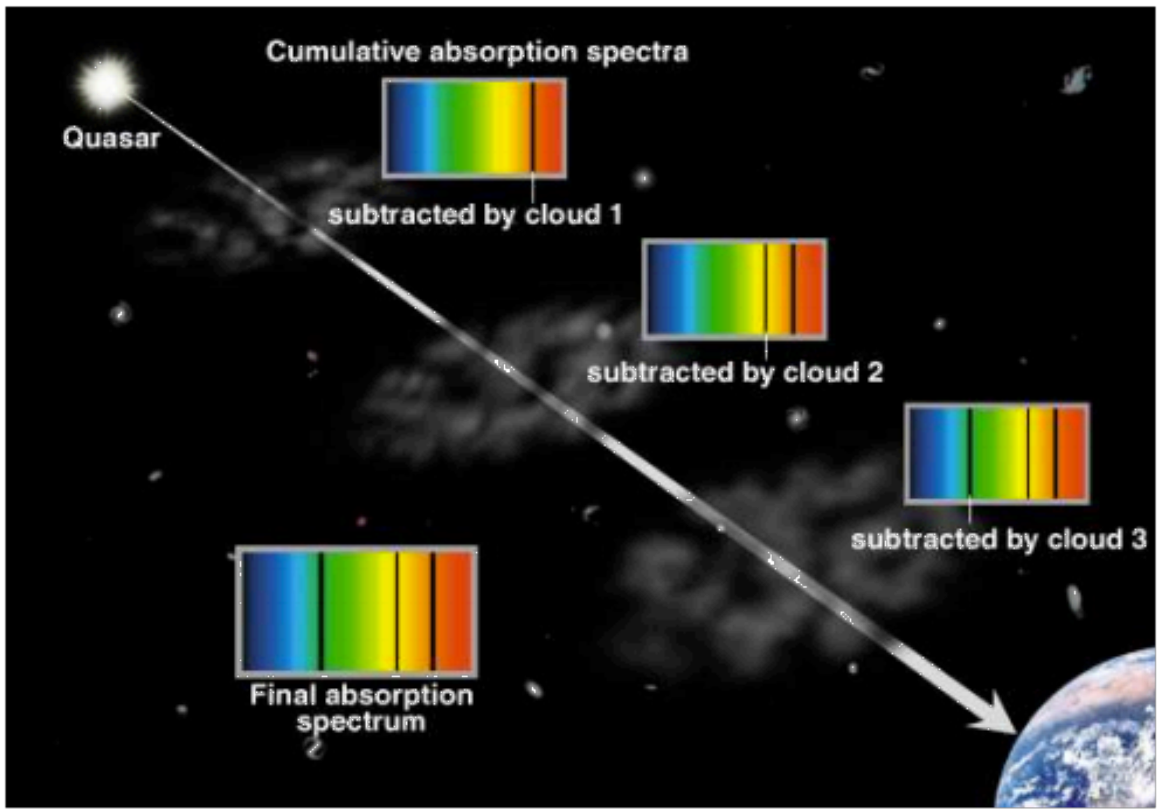
Cosmic History

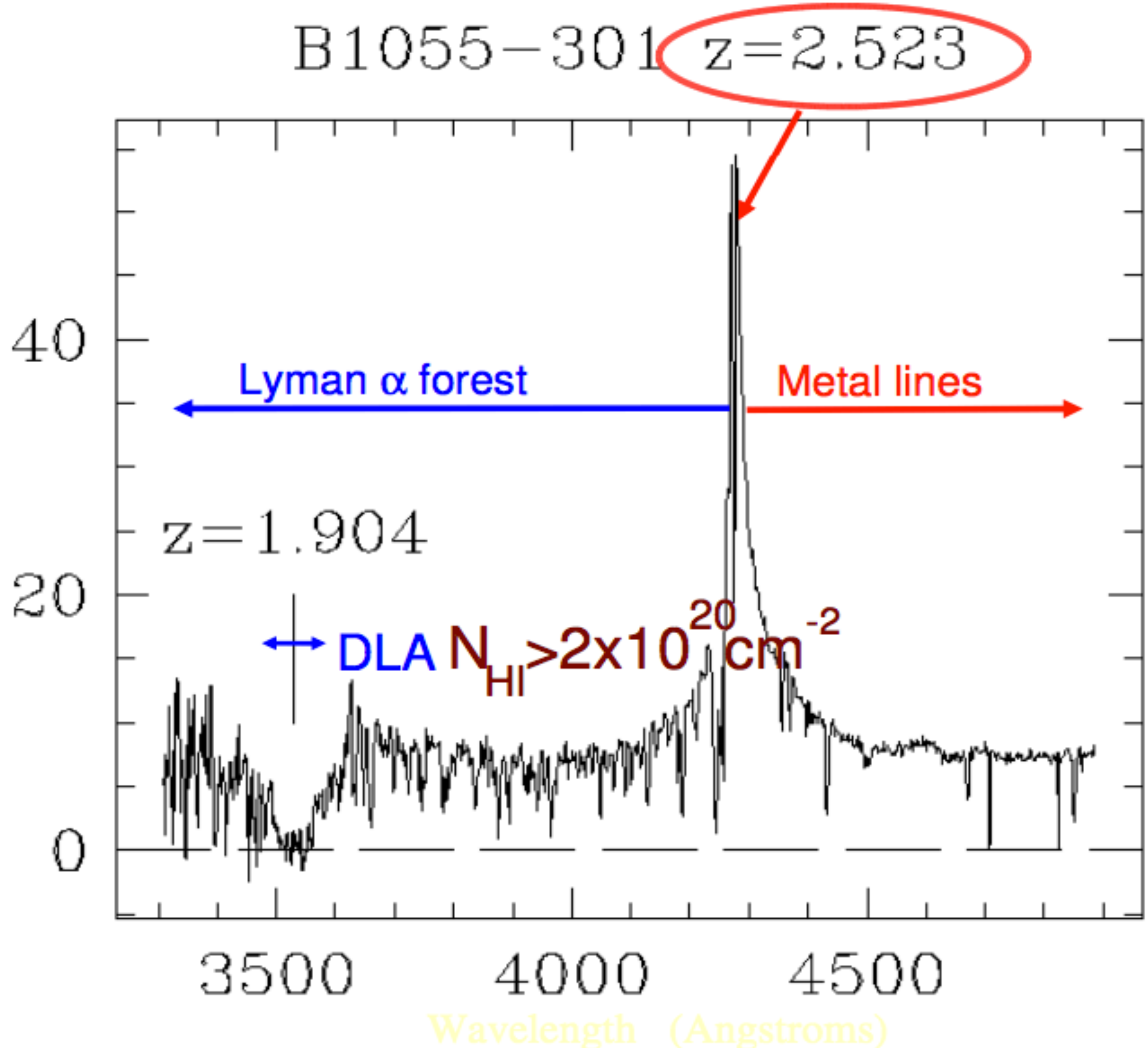
1. z>1100: all matter is hot, ionized, optically thick to Thomson scattering and strongly coupled to photons
2. z<1100: the plasma recombines, Universe becomes neutral. With matter and radiation decoupled, the CMB free to propagate
3. What happens next ?



A "Forest" of Absorption Lines

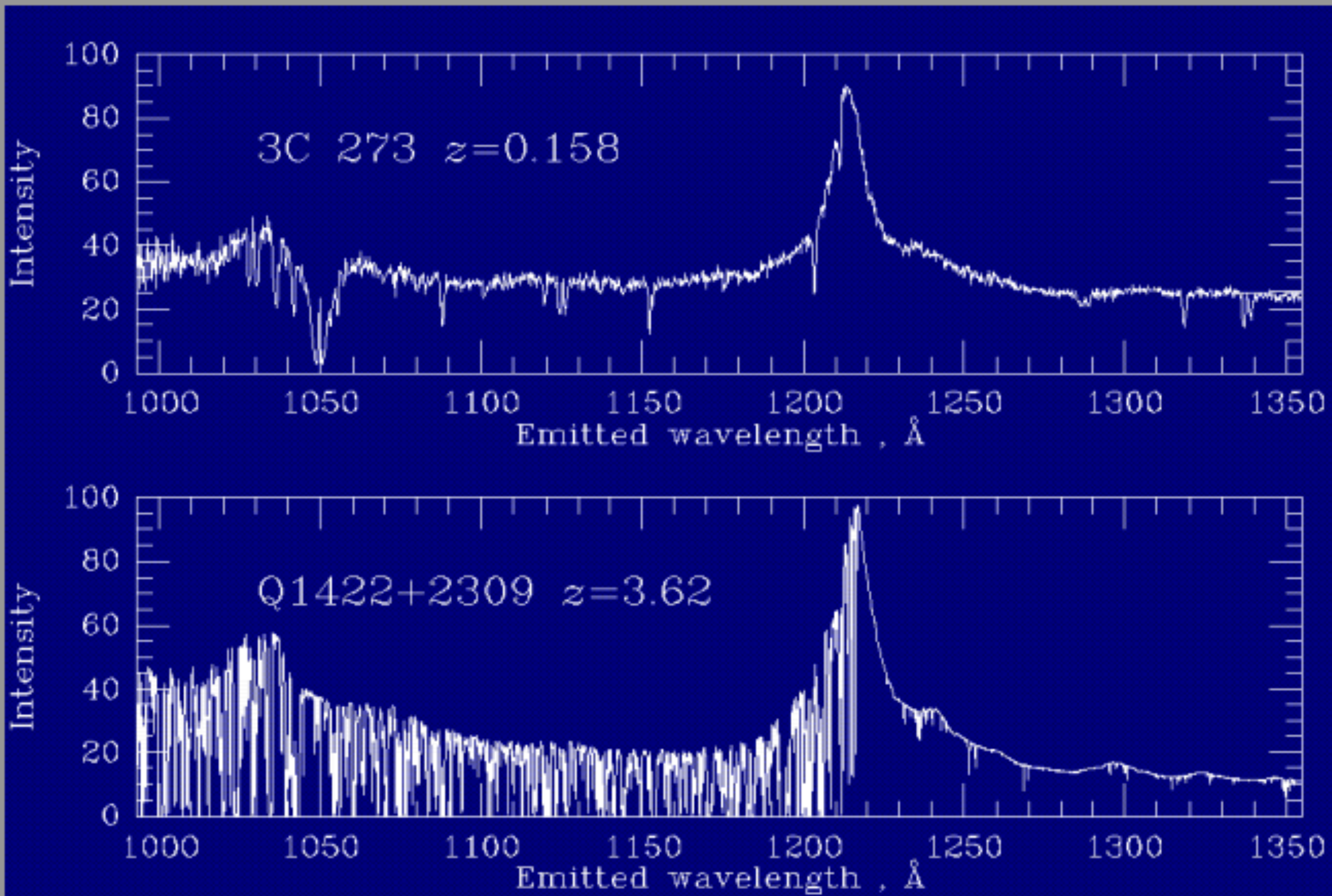
- As light from a quasar travels towards Earth…
  - it passes through intergalactic Hydrogen clouds and galaxies
  - each cloud leaves absorption lines at a *different* z on the quasar spectrum
  - this is the only way we can "observe" protogalactic clouds





B1055−301 z=2.523
Lyman α forest
Metal lines
z=1.904
DLA N_HI>2x10^20 cm^-2
40
20
0
3500
4000
4500
Wavelength (Angstroms)

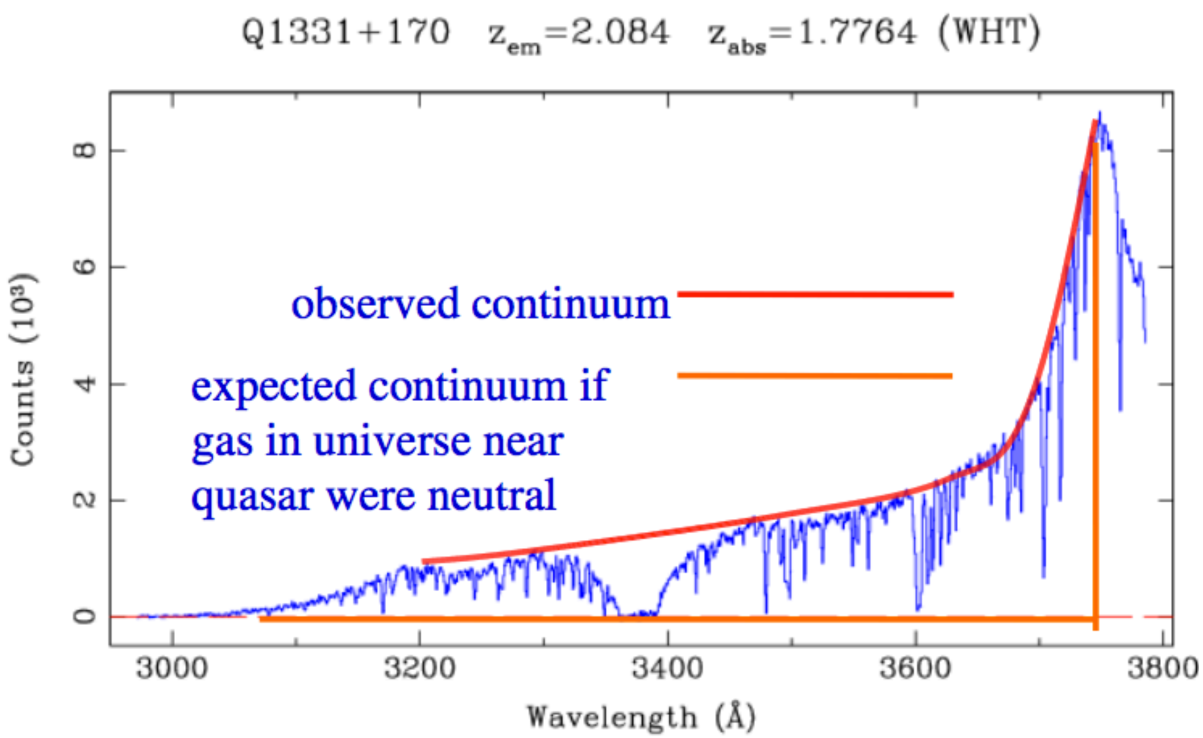
Lyα Absorbers Evolve Strongly!



Cosmological density evolution of the gas, $(1+z)^3$

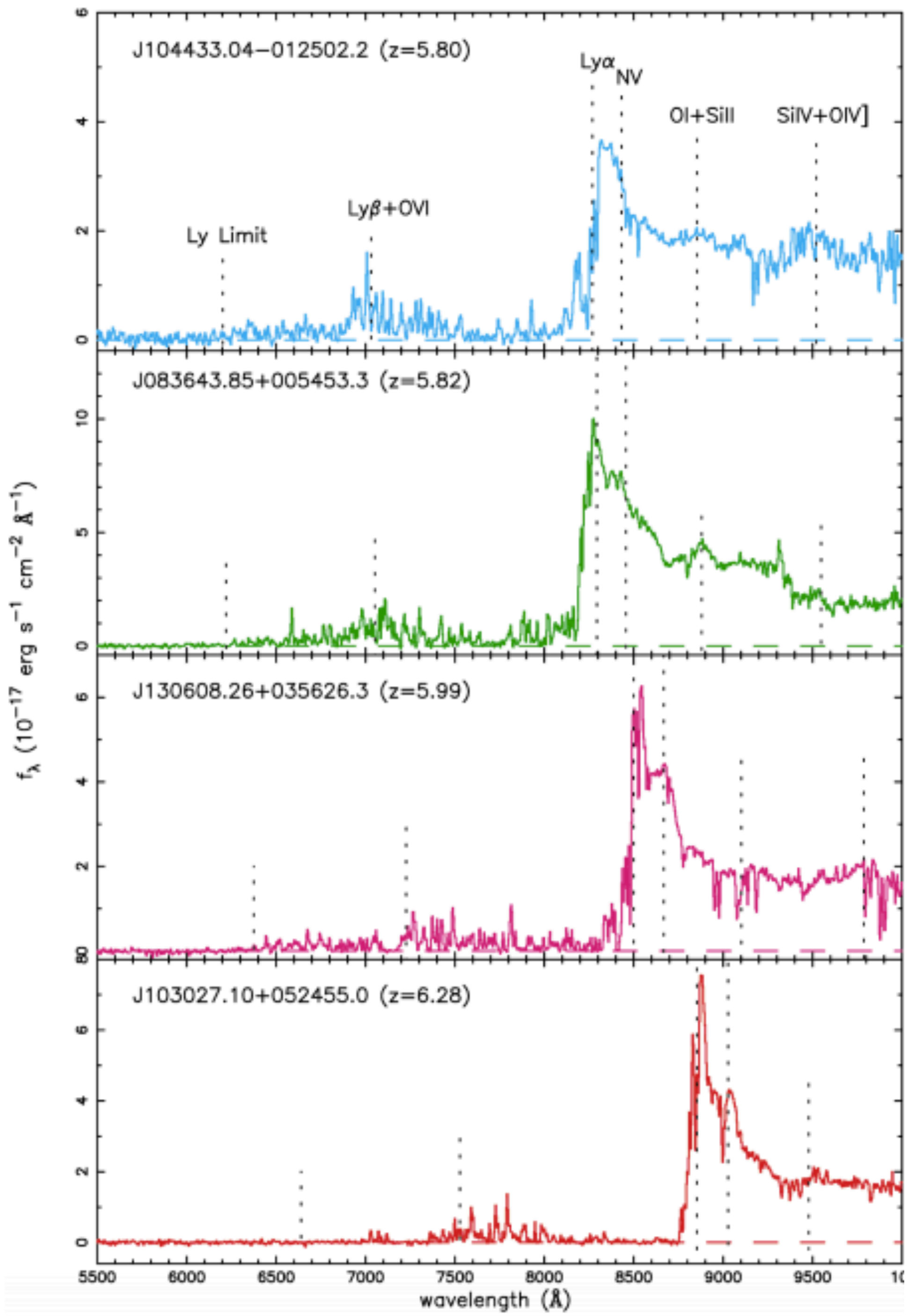
The Gunn Peterson Effect

- If there is a continuous distribution of neutral gas along the line of sight: the quasar spectra should show `no flux' bluewards of the Lyα
- In 1965 G&P computed the expected Lyα absorption along the l.o.s. of a quasar assuming the H was neutral
  - Even small values $n_{HI}=10^{-4}$ cm^{-3} would make the Universe opaque



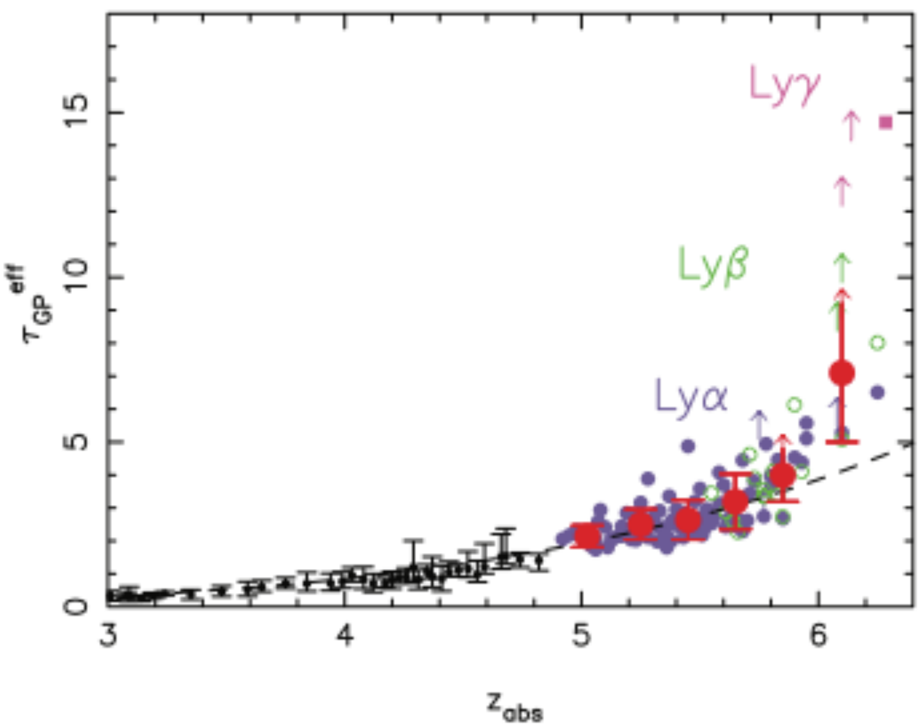
First GP Trough

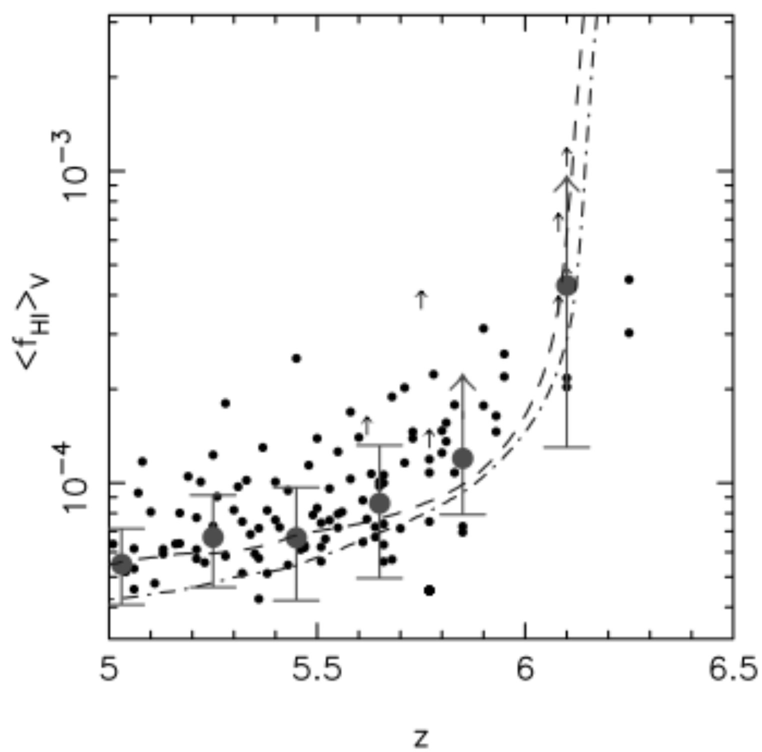
- Becker et al. 2011 reported the first discovery of the GP trough



Neutral Hydrogen fraction

- Quasars at z~5.8 do not have full GP troughs
- Quasars at z~6.2 have full GP troughs
- → H is ionized by z~6 and reach n~10^{-3} by z~6.3
  - Reionization is complete by z~6 !
  - This method saturates for small densities of neutral H, so we can't say when re-ionization started

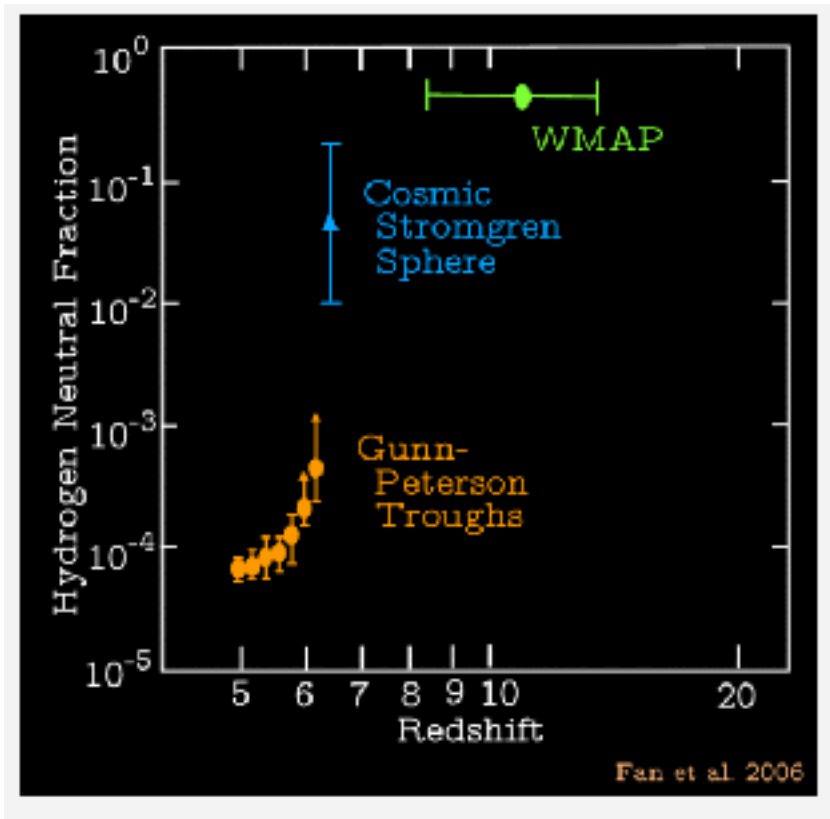




Polarization of the CMB

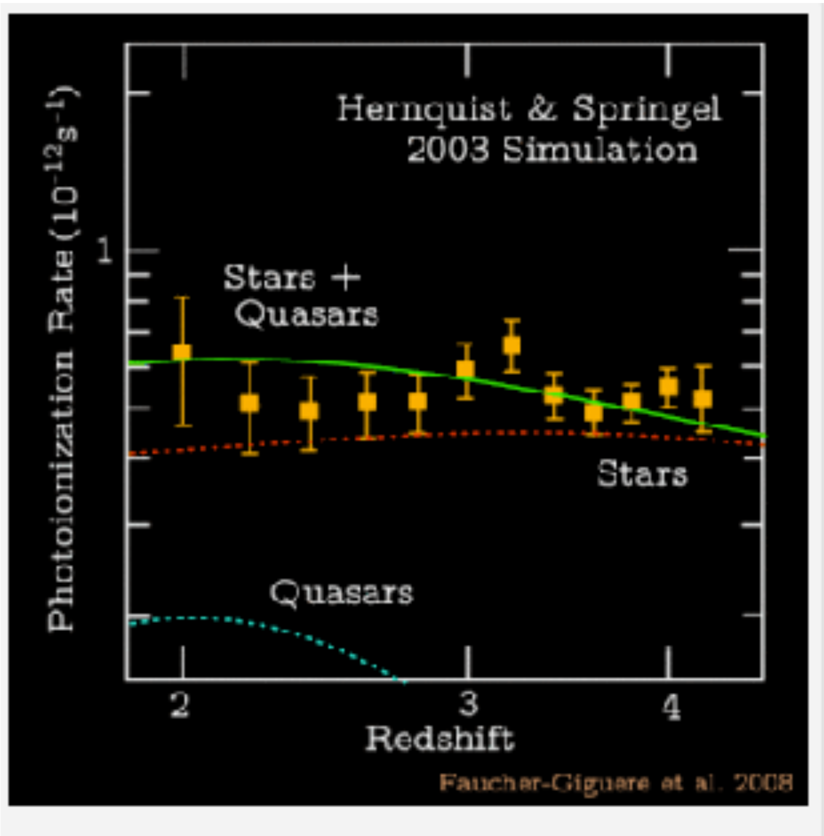
- Thompson scattering of light off electrons introduces polarization
  - This method is sensitive to the fraction of ionized-H

- Large scale polarization of the CMB can be used to understand when the re-ionization started: at around z~10

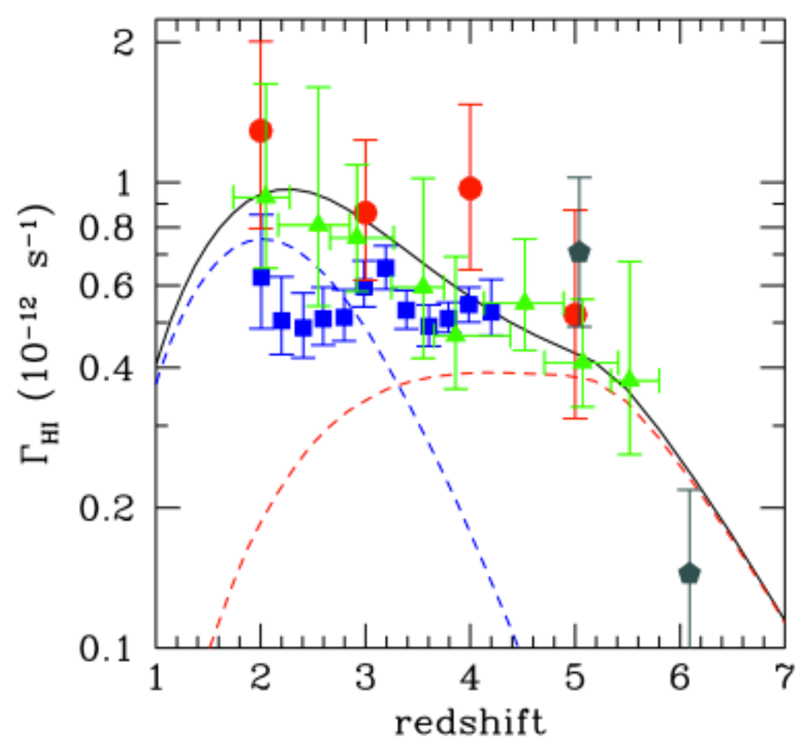


What Ionized the IGM ?

- By studying the Lya absorption one can determine the Ionization rate
  - It's flat over redshift
  - Becker & Bolton estimate is a larger than that reported below



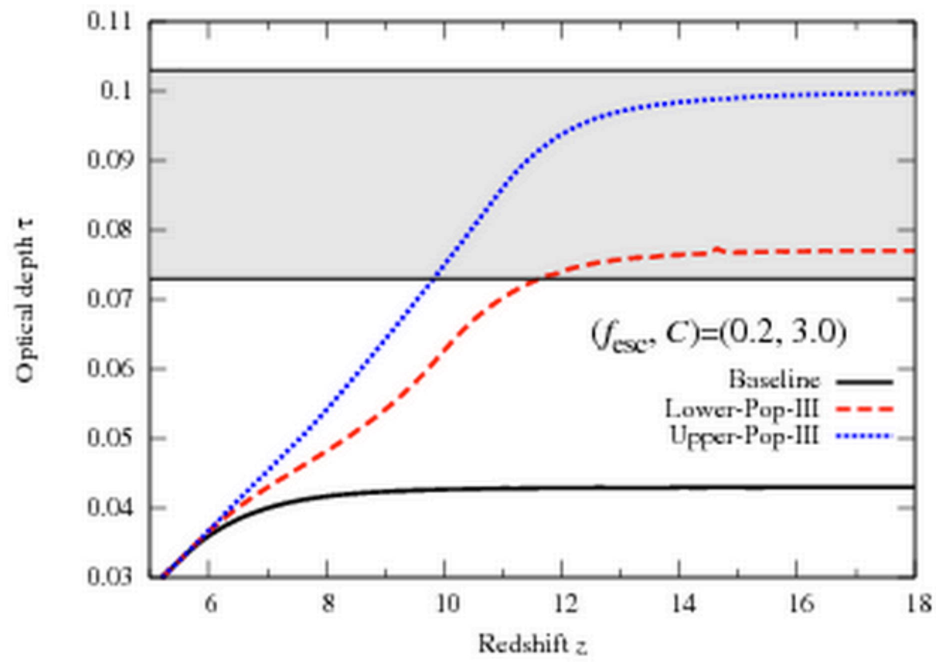
Hardt&Madau 2012



What ionized the IGM ?

- Star forming galaxies + quasars typically fail to reproduce the optical depth to Thompson scattering
- It requires a fact 50-100 more ionizing photons
- Who produces those photons ?
- Moreover:
  - Big bang metallicity $Z = 10^{-10} - 10^{-6}$
  - Pop-II metallicity $Z = 10^{-4} - 10^{-3}$

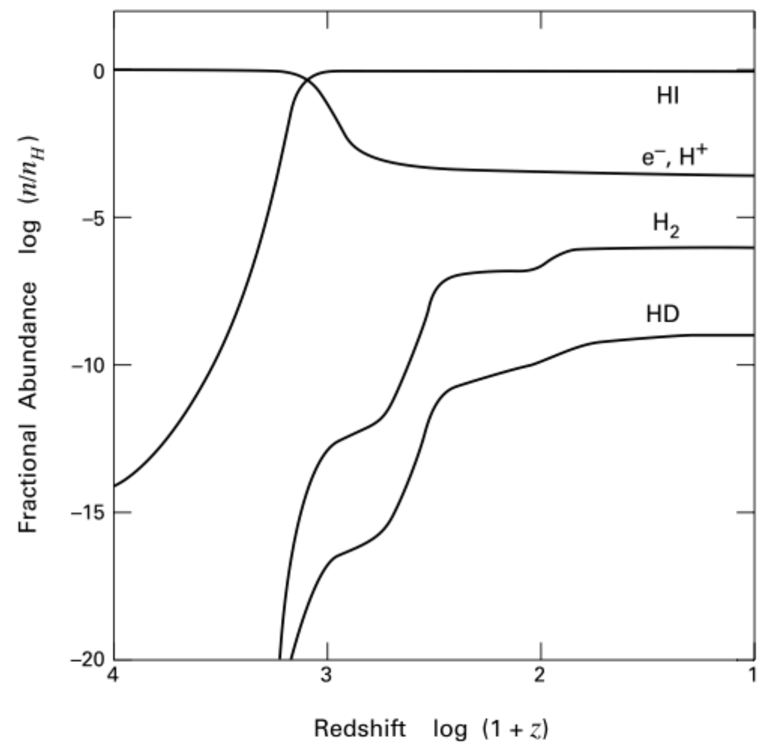
Inoue et al. 2013



First Stars

- Key point: gas must cool for collapse to happen
- HI gas does not cool very efficiently
  - Any collapse would quickly be reverted
- Free e^- and p lying around lead to the creation of some H_2 which can cool:
  - $$H + H^+ \rightarrow H_2^+ + h\nu$$ $$H_2^+ + H \rightarrow H_2 + H^+$$ ← this leads to H_2 abundance of 10^{-7} cm^{-3} by z~300
  - a $$H + e^- \rightarrow H^- + h\nu$$ $$H^- + H \rightarrow H_2 + e^-$$

$$D^+ + H_2 \rightarrow HD + H^+$$



First Stars

- Molecular clouds do not cool efficiently at high –z
  - Jean's mass depends on T
  - The larger the temperature, the larger the mass
  - T~1e4 K → M~10^5 $M_\odot$
  - However gas is able to cool (roto-vibrational) at the center of MC (T~300K) → M~500 $M_\odot$
  - Primordial stars where more luminous

$$M_J = \left(\frac{4\pi}{3}\right)\rho R_J^3 = \left(\frac{\pi}{6}\right)\frac{c_s^3}{G^{3/2}\rho^{1/2}}$$

- During collapse mass inflow rate
  - All the UV light is absorbed by the thick inflow

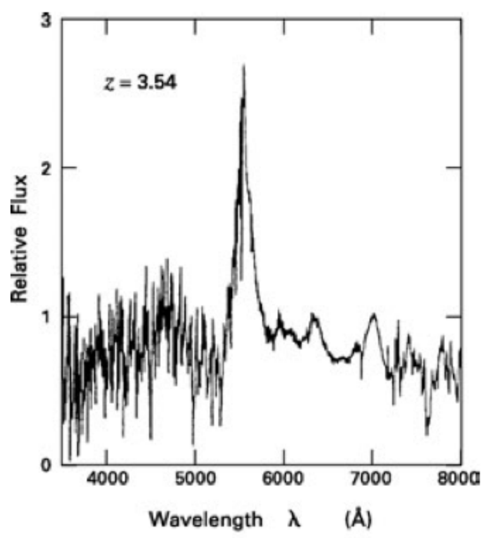
$$\dot{M} = m_\circ \frac{a_T^3}{G}$$

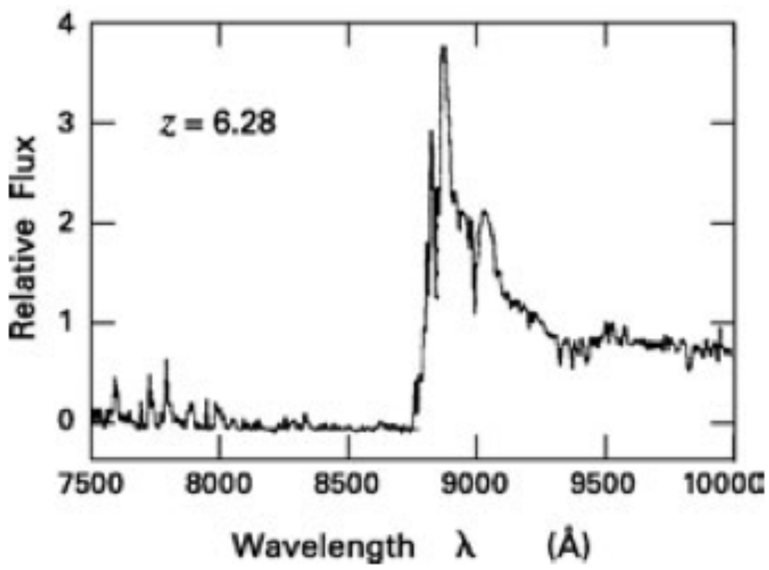
- Clouds do not fragment
  - Fragment mass found by imposing the transition between the isothermal regime e.g. the opacity limit
  - Further fragmentation is suppressed by the lack of cooling beside the roto-vibrational
- Simulations predict a Top-heavy IMF (Abel+96 etc)

Re-ionization

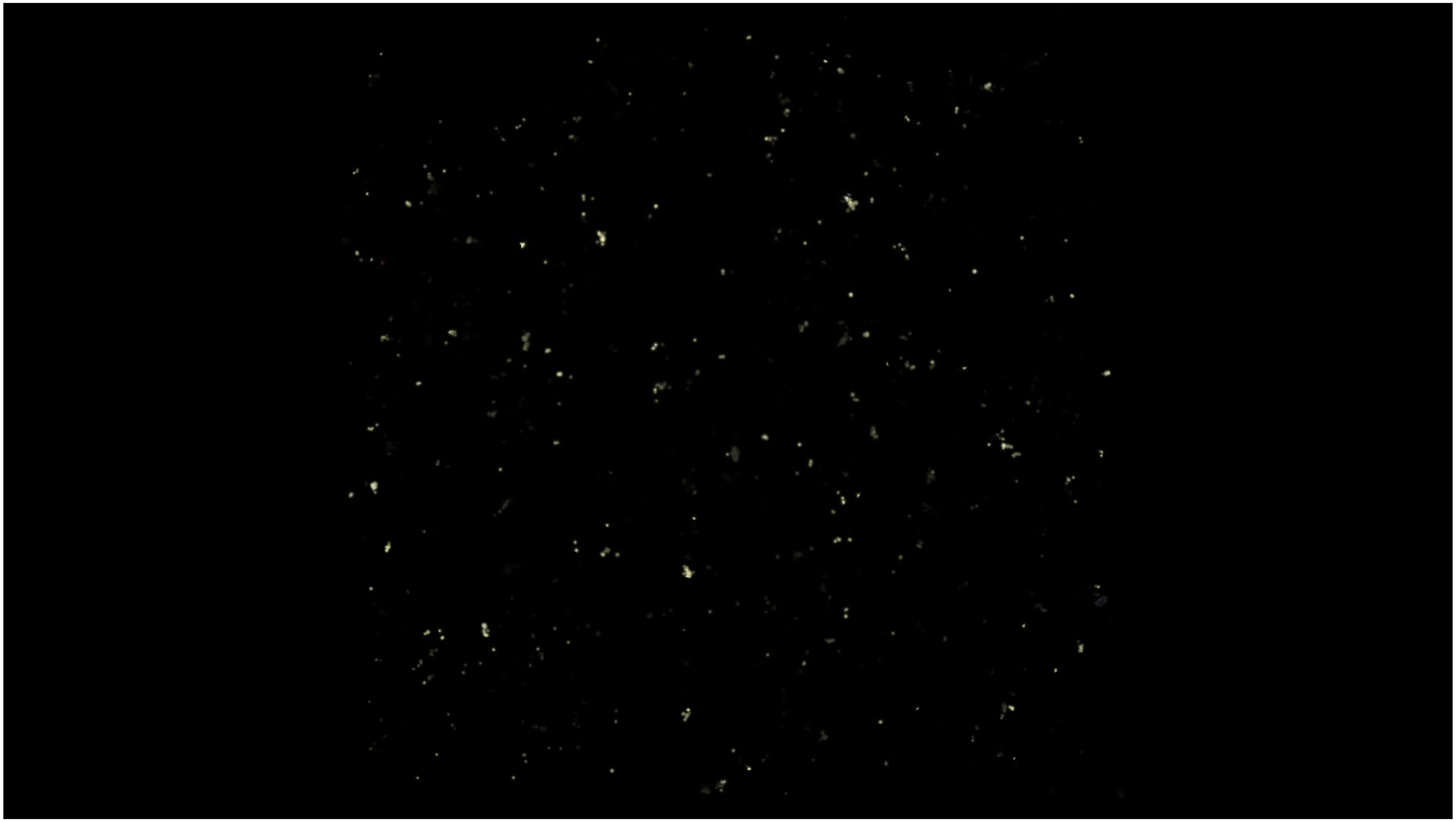
- Lacking metals all pop-III stars have a T~10^5 K ($M>M_{\odot}$)
  - This is caused by the lack of opacity from metal lines
  - Pop-III have copious UV emission and come before/during galaxies !
  - Pop-III stars may ionize the universe (mean E~30 eV) and also photo-dissociate H_2 e.g. preventing further star formation

- Is there evidence for sources of ionizing photons ?
  - The Gunn-Peterson effect shows that there was Neutral Hydrogen in the Universe at z~6.28 but the Universe is full ionized at z~3.5





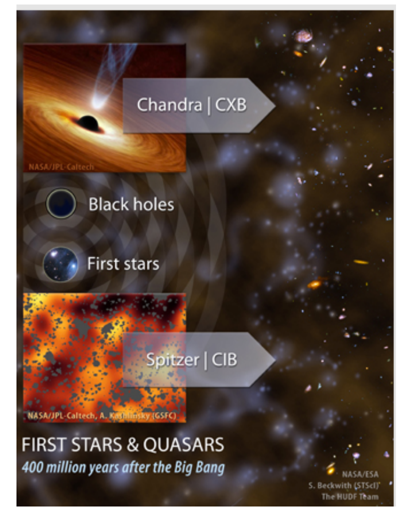
Re-ionization

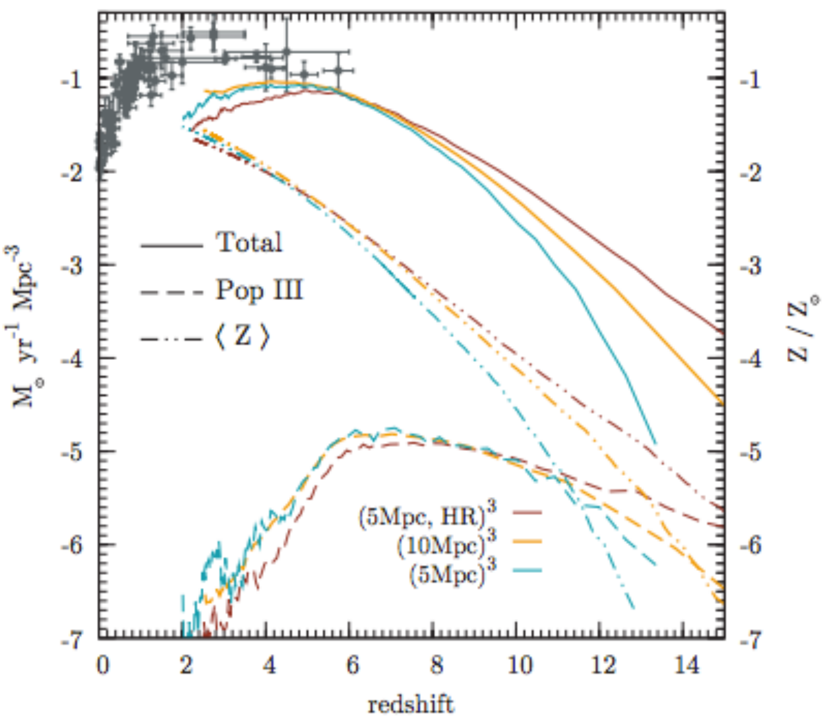


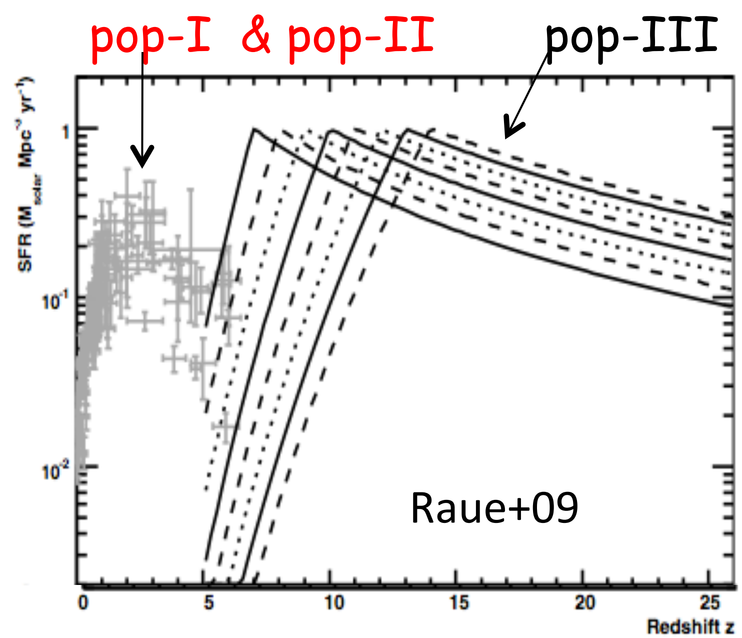
Current Estimates / Constraint

- The true level of SFR of pop-III stars is unknown
  - JWST should find them, or at least measure their integrated emission
- It could be black holes too

Cappelluti+12







Readings

- Gunn & Peterson 1965
- http://ay201b.wordpress.com/2013/04/20/on-the-density-of-neutral-hydrogen-in-intergalactic-space-2/
- Fantastic interacting tool on Quasar absorption
  - https://www.cfa.harvard.edu/~yuan-sen.ting/Lyman_Alpha_Module/HTML/lyman_alpha2.html