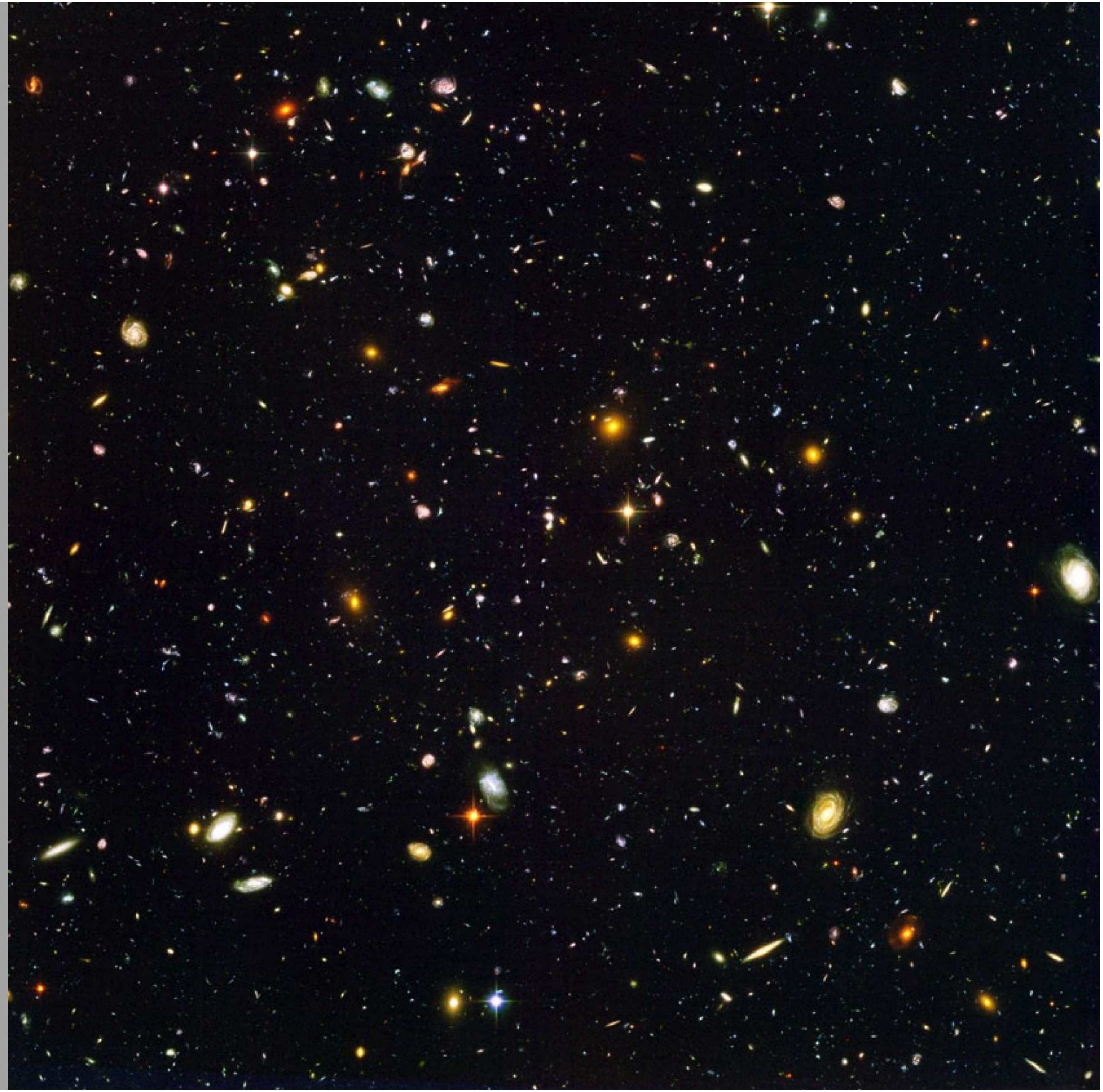
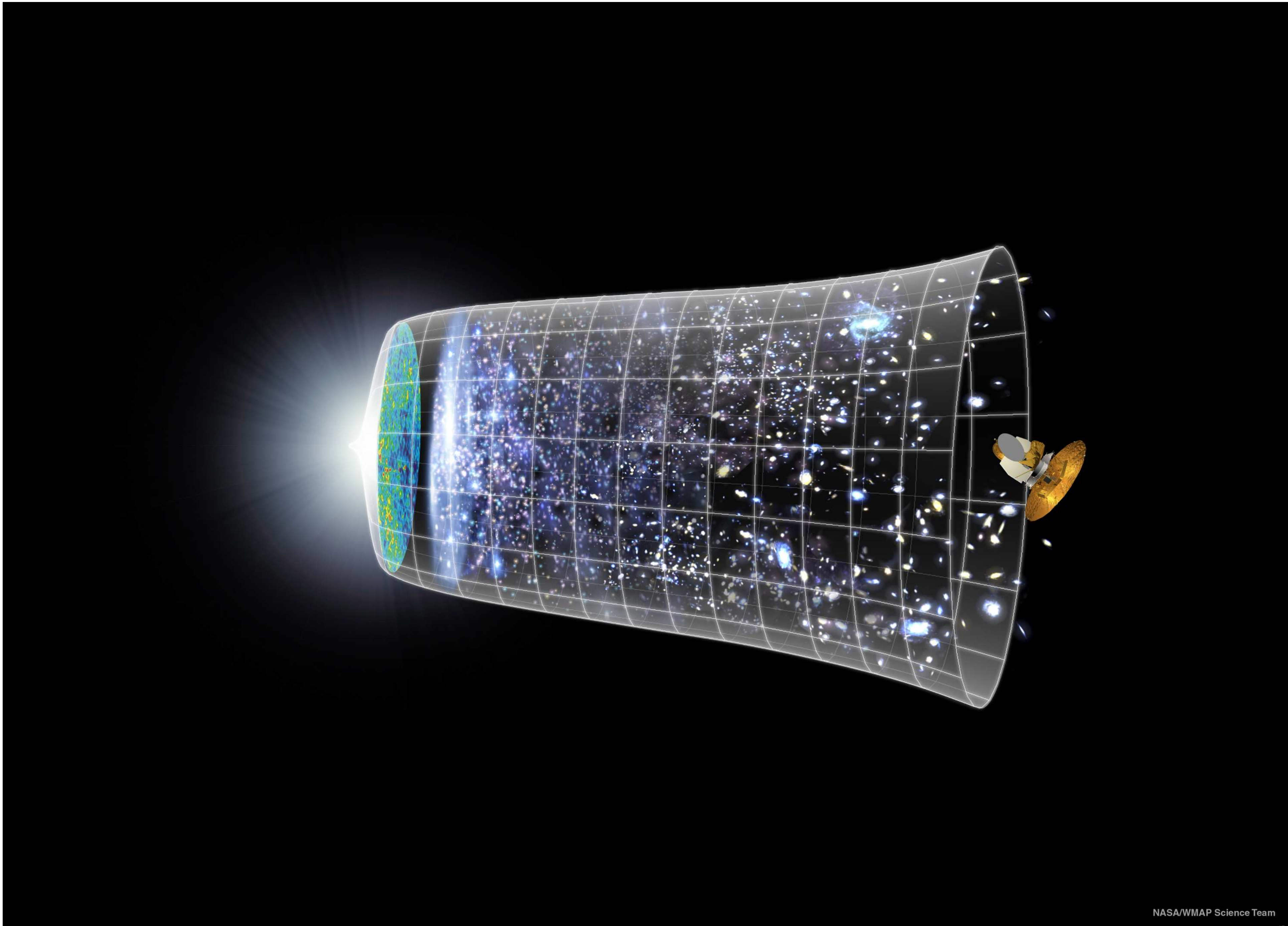
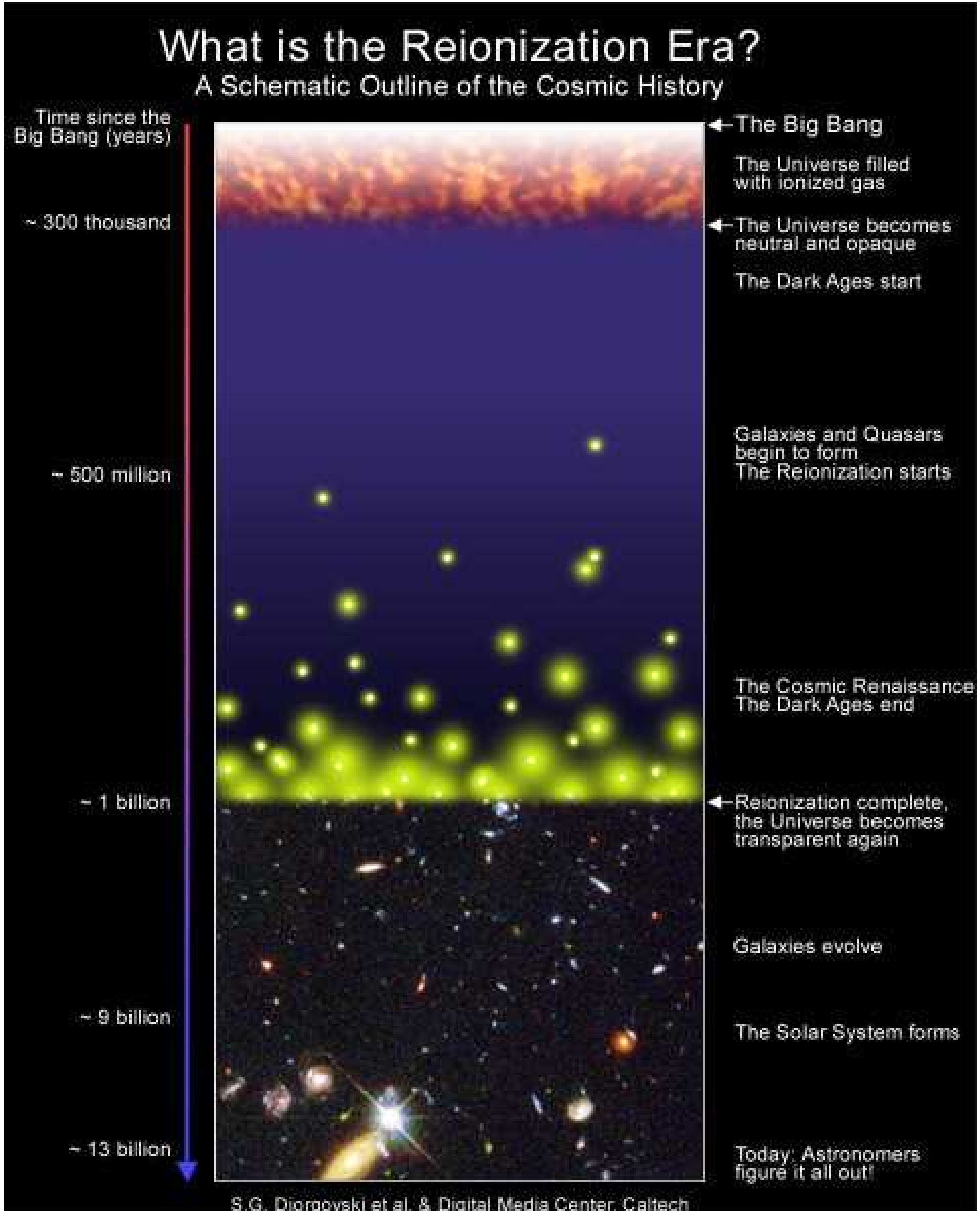
The First Stars: Clues from Lyman Break Galaxies and QSO Absorption Systems

Max Pettini
Institute of Astronomy



Current View of Cosmic History




What is the Reionization Era?
A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

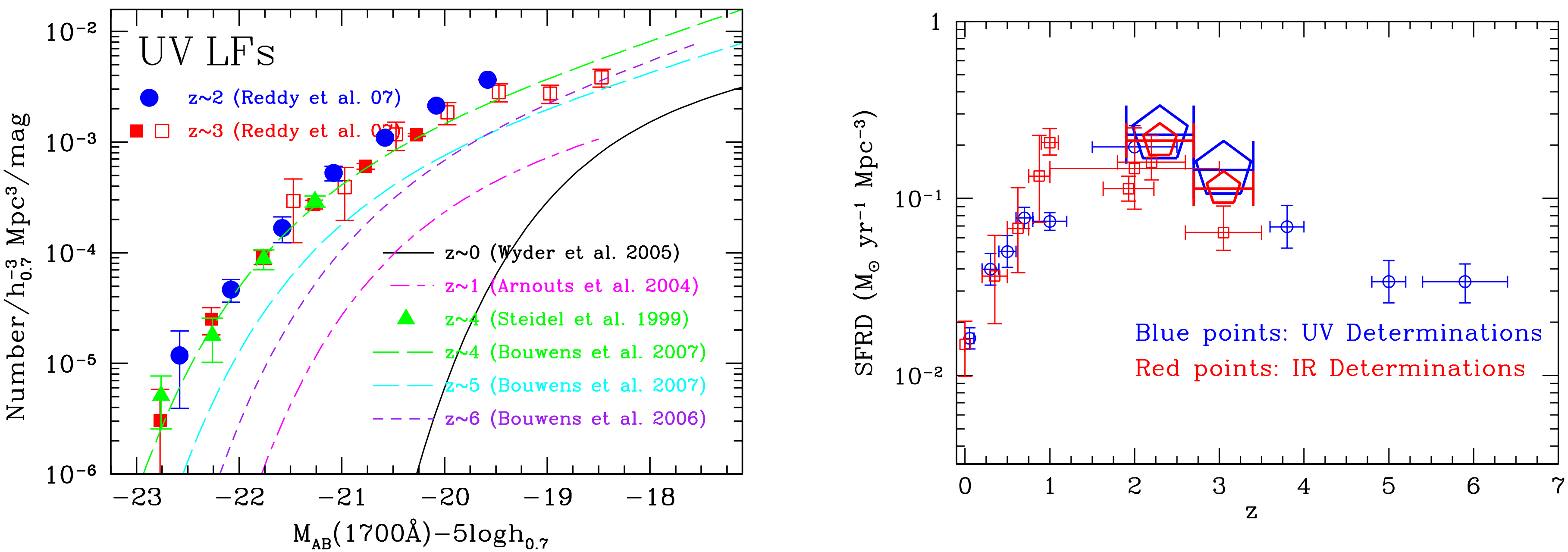
"The epoch of reionisation is the last directly observable phase of cosmic evolution which remains to be verified and explored"

(Fan, Carilli, & Keating 2006, ARAA, 44, 415).

It is acting as a catalyst, focusing the attention of astronomers studying:

- The Cosmic Microwave Background
- The Lyman α forest at $z \gtrsim 6$
- The highest redshift galaxies up to $z_{\rm max} \simeq 7$
- The chemical composition of the oldest stars in the Galactic halo

Galaxies detected up to $z \sim 7$



Reddy et al. 2007

Four Strands

- Metals in the Intergalactic Medium at $z \gtrsim 6$:
  Pop III Stars or ‘Normal’ Star-Forming Galaxies?

Four Strands

- Metals in the Intergalactic Medium at $z \gtrsim 6$:
  Pop III Stars or 'Normal' Star-Forming Galaxies?

- Ionising Radiation from Star-Forming Galaxies at $z \simeq 3$

Four Strands

- Metals in the Intergalactic Medium at $z \gtrsim 6$:
  Pop III Stars or 'Normal' Star-Forming Galaxies?

- Ionising Radiation from Star-Forming Galaxies at $z \simeq 3$

- The Most Metal-Poor Damped Lyα Systems: Clues to Nucleosynthesis at Low Metallicities

Four Strands

- Metals in the Intergalactic Medium at $z \gtrsim 6$:
  Pop III Stars or ‘Normal’ Star-Forming Galaxies?

- Ionising Radiation from Star-Forming Galaxies at $z \simeq 3$

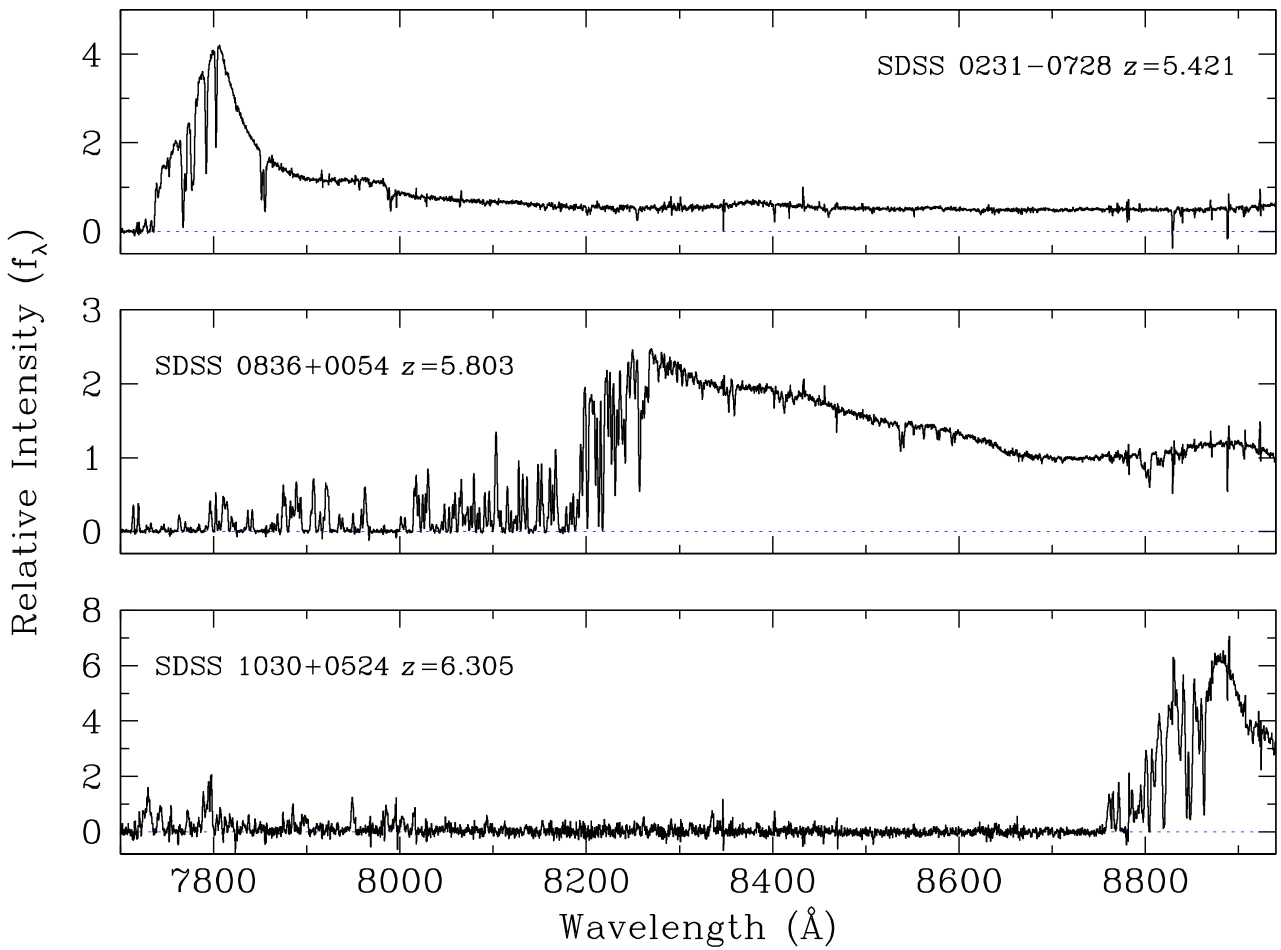
- The Most Metal-Poor Damped Lyα Systems: Clues to Nucleosynthesis at Low Metallicities

- ‘First Stars’ in Galaxies at $z \simeq 2$

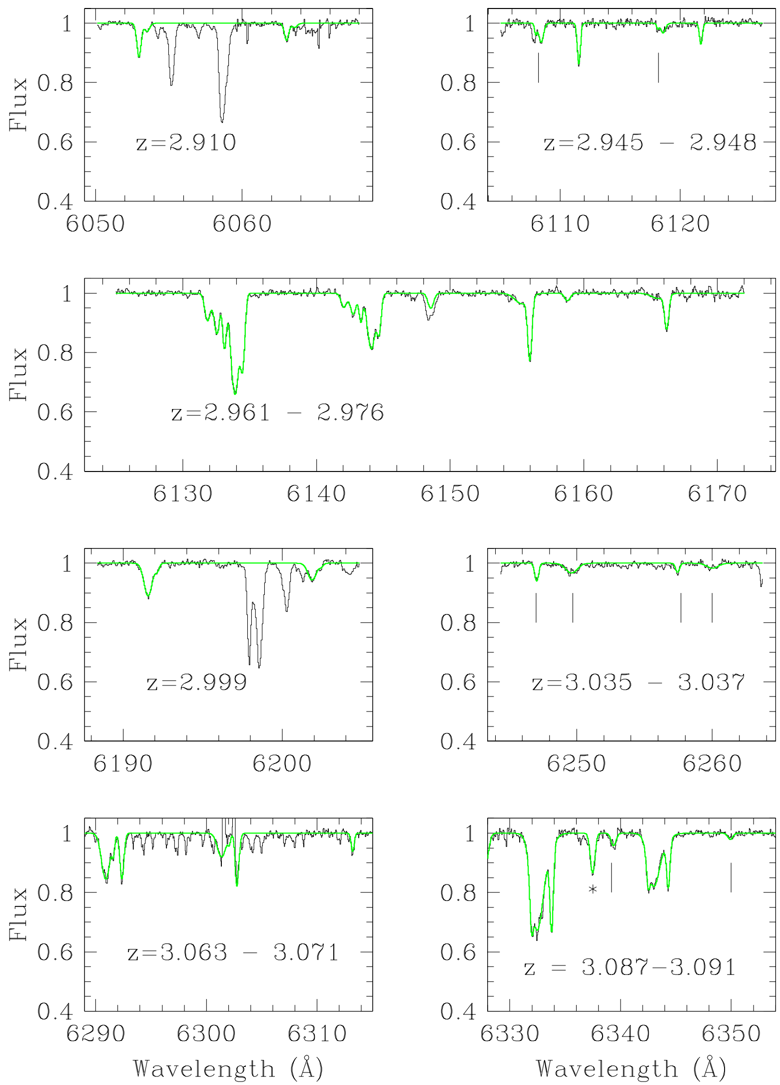
Metals in the Intergalactic Medium

- Can now probe the IGM to $z > 6$ using SDSS QSOs (and GRB afterglows)

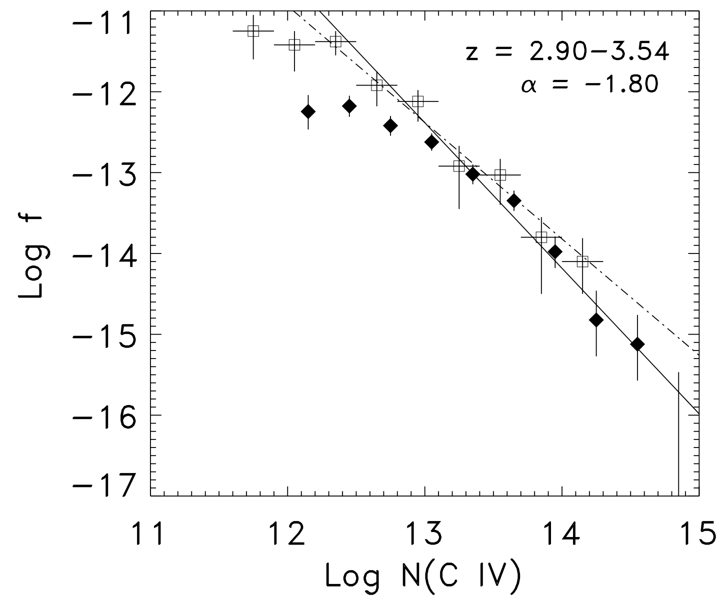
  Little information left in the Lyα forest itself, but still plenty of signal longwards of Lyα emission line, where metal absorption lines occur



Most common tracer of metals in the Lyα forest is C IV $\lambda\lambda 1548, 1550$



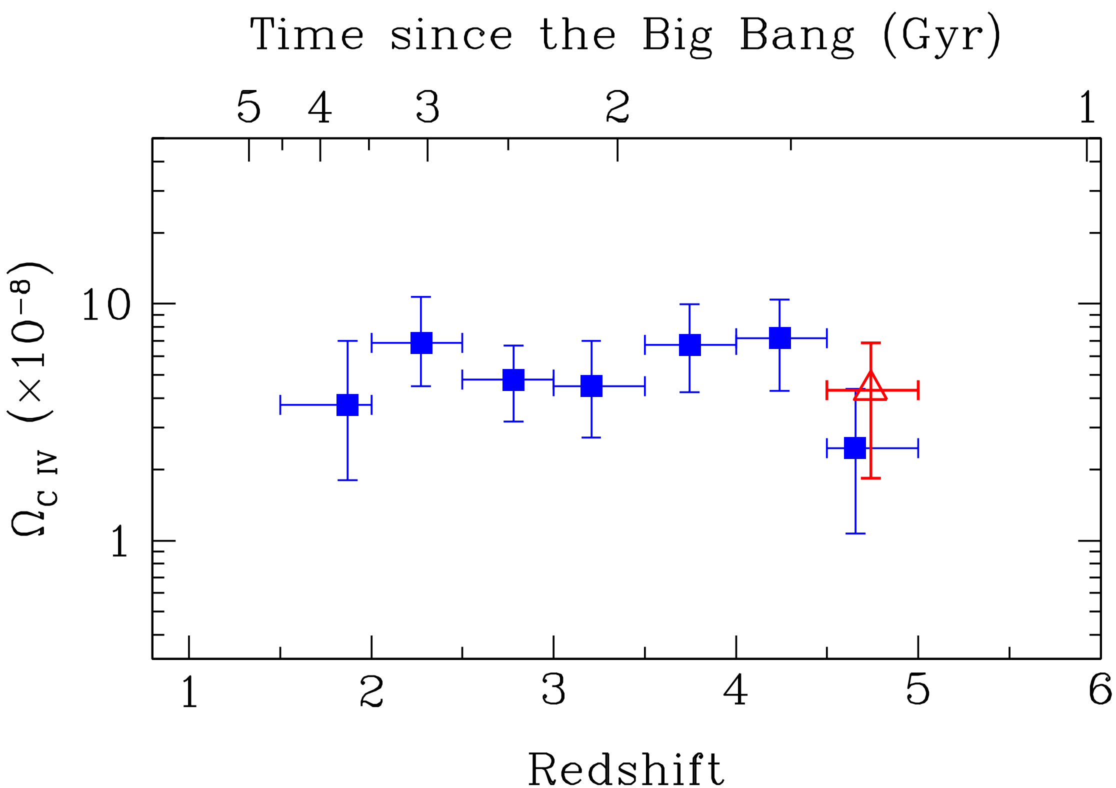
Ellison et al. 2000



Songaila 2001

Metals in the Intergalactic Medium

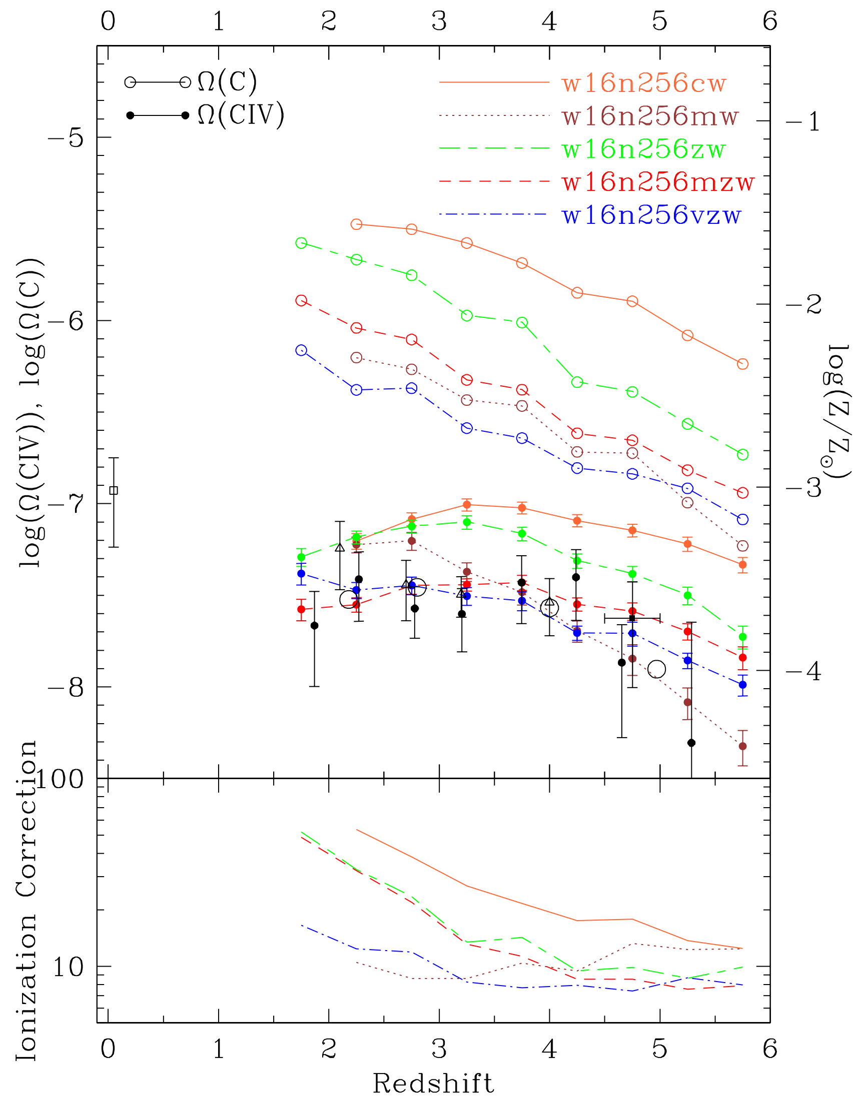
- Integration of $f(N)$ gives $\Omega_{\rm C\,IV}$
- Surprising result: $\Omega_{\rm C\,IV} \approx$ constant from $z = 1.5$ to 5



Songaila 2001; Pettini et al. 2003

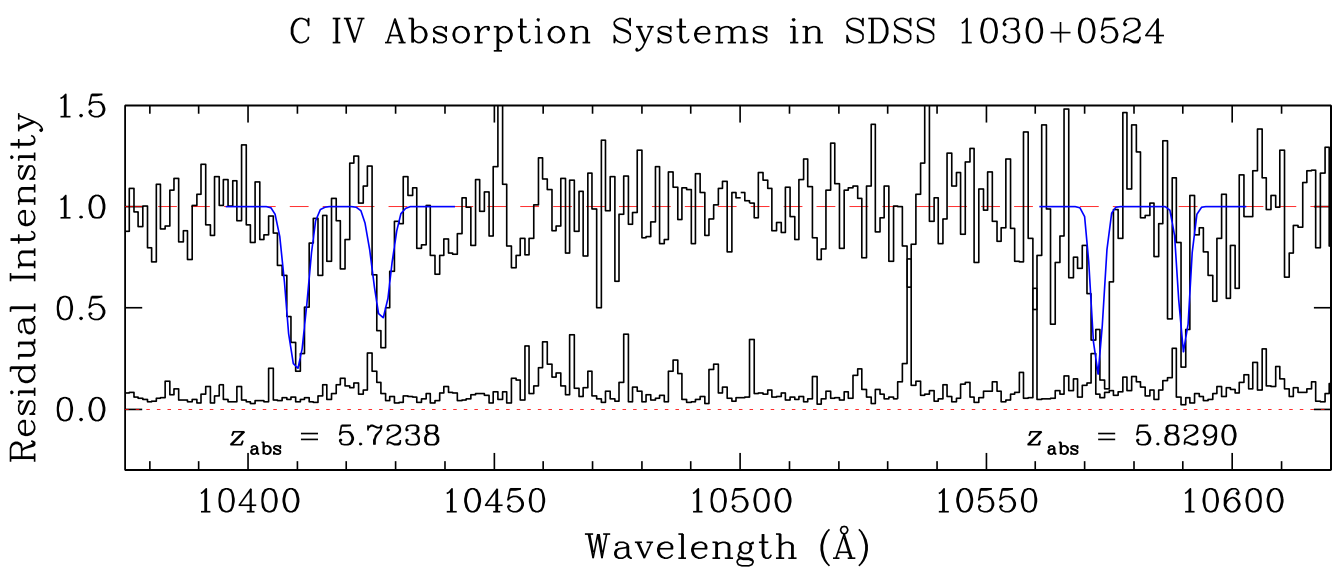
Are we seeing carbon produced by the 'first stars' at $z \gg 5$?

Not necessarily—Oppenheimer & Davé (2006) can reproduce the approx. constant behaviour of $\Omega_{\rm CIV}$ in models (with feed-back) in which $C_{\rm TOT}$ increases with time, but $C^{3+}/C_{\rm TOT}$ *de-creases* with time



Metals in the Intergalactic Medium

- Searches for C IV at $z > 6$ may provide clues to the origin of C in the IGM
  Require high resolution spectroscopy in the near-IR ($\sim 1\,\mu$)

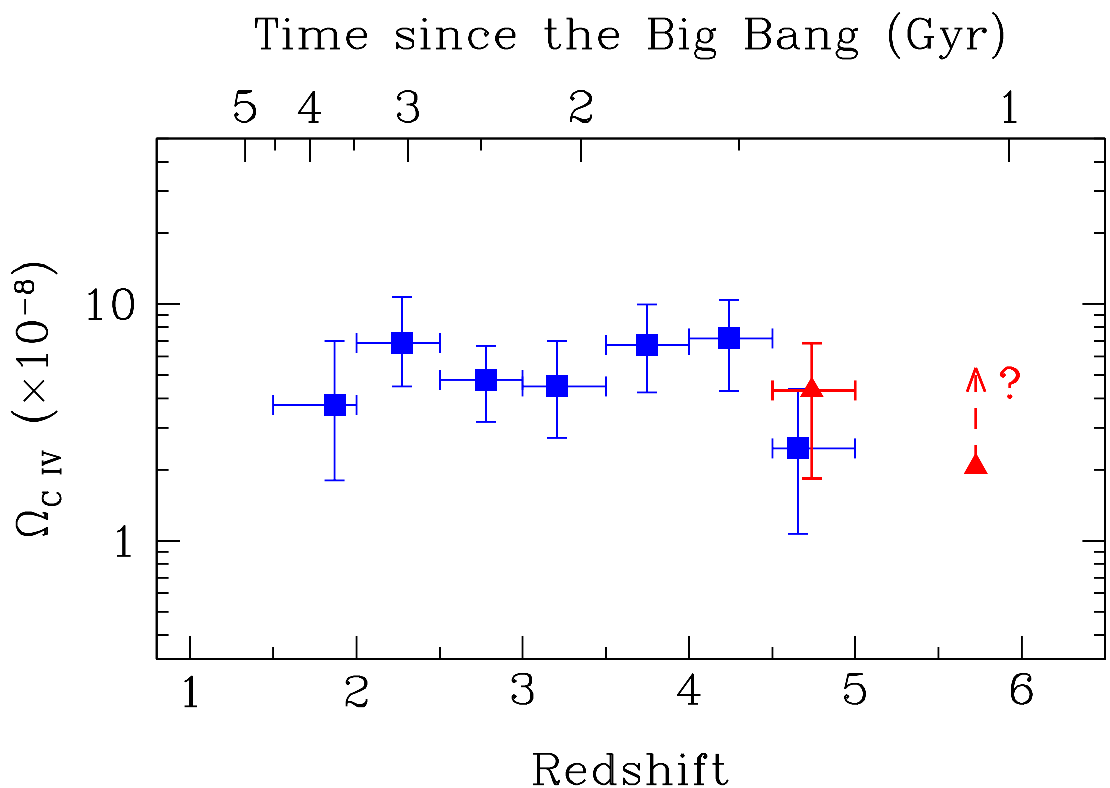


VLT-ISAAC (Ryan-Weber, Pettini, & Madau 2006)

- Similar results with Gemini-NIRS (Simcoe 2006)
- O I, C II up to $z = 6.26$ (Keck-HIRES; Becker et al. 2006)

Metals in the Intergalactic Medium at $z \sim 6$

- Strong hints that we are not yet seeing a fall in $\Omega_{\rm C\,IV}$
- How typical of the IGM is this particular sight-line?
  Excess of galaxies in the field, two within 100 kpc from QSO sight-line.



Lyman Continuum Radiation from LBGs

- Do (faint) galaxies at $z > 6$ provide sufficient photons to keep the IGM ionised?

Lyman Continuum Radiation from LBGs

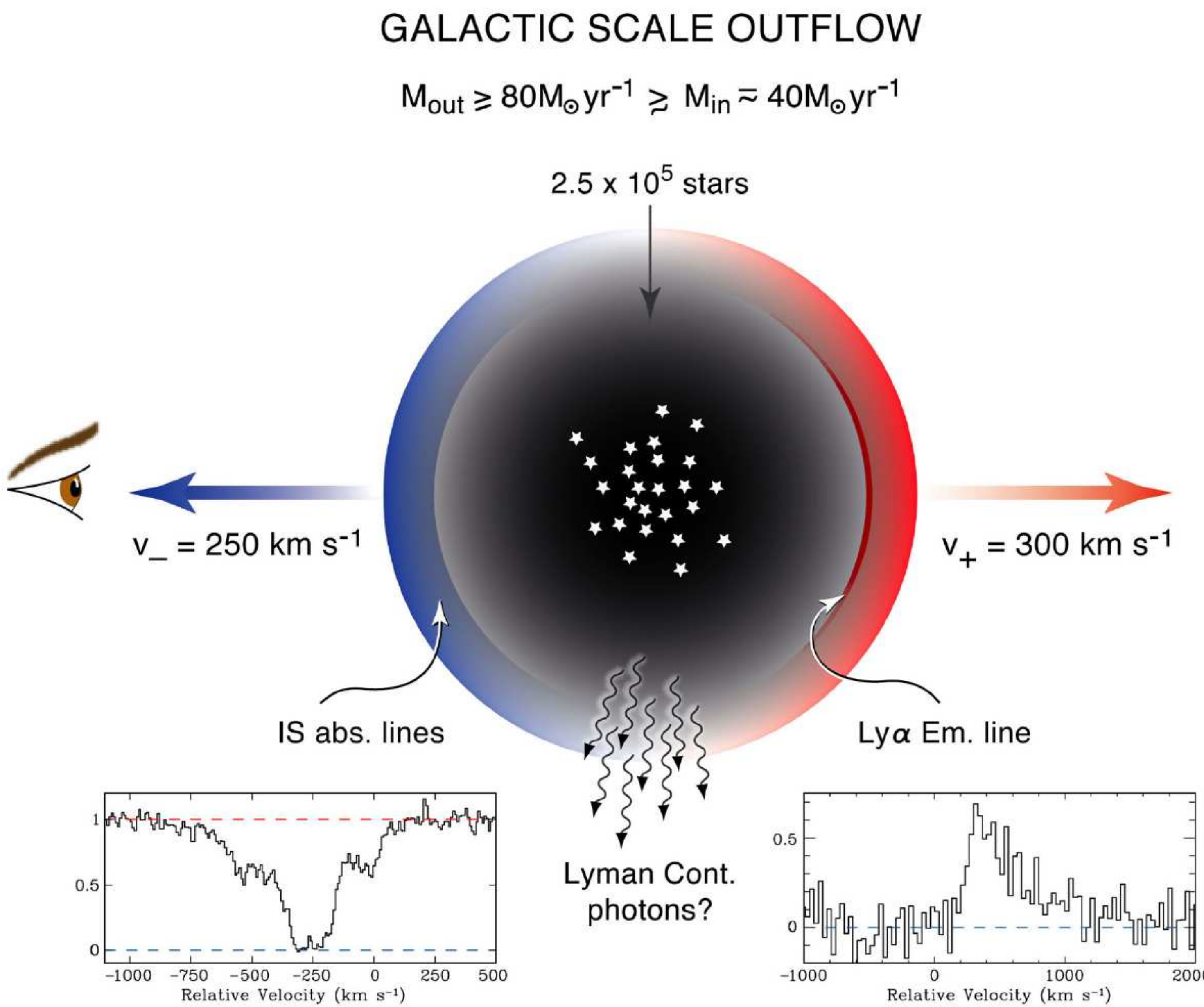
- Do (faint) galaxies at $z > 6$ provide sufficient photons to keep the IGM ionised?
- It all depends on the escape fraction of Lyman continuum photons

Lyman Continuum Radiation from LBGs

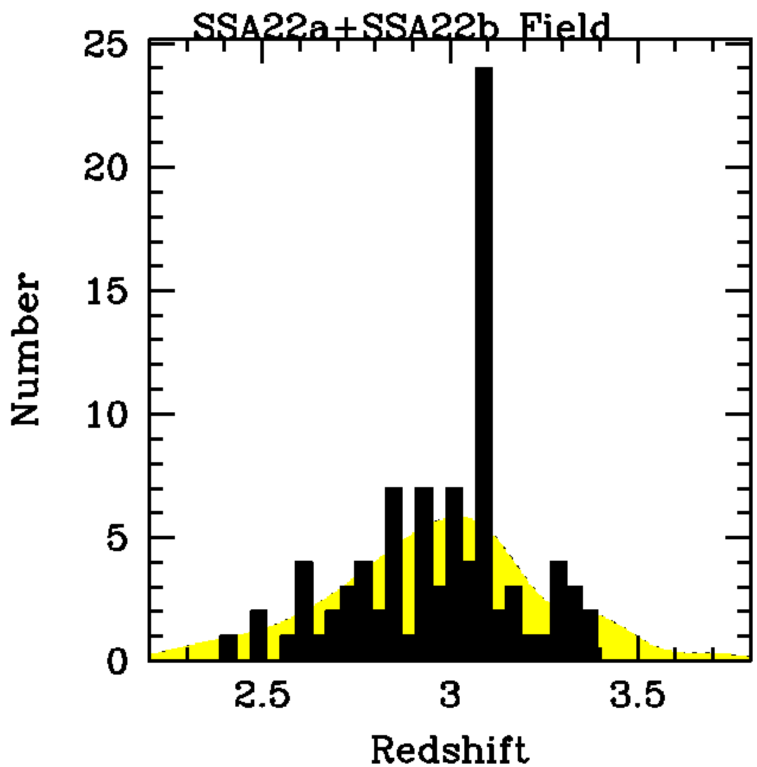
- Do (faint) galaxies at $z > 6$ provide sufficient photons to keep the IGM ionised?
- It all depends on the escape fraction of Lyman continuum photons
- In starburst galaxies at $z < 1$ (down to the present time) $f < 0.1$

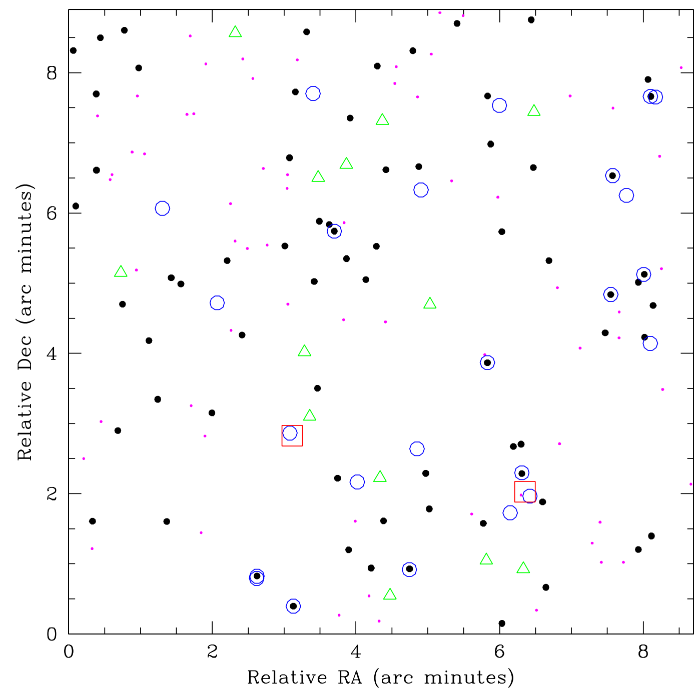
Lyman Continuum Radiation from LBGs

- Do (faint) galaxies at $z > 6$ provide sufficient photons to keep the IGM ionised?
- It all depends on the escape fraction of Lyman continuum photons
- In starburst galaxies at $z < 1$ (down to the present time) $f < 0.1$
- Is this also the case at higher redshifts?


GALACTIC SCALE OUTFLOW
$M_{out} \geq 80 M_\odot yr^{-1} \gtrsim M_{in} \approx 40 M_\odot yr^{-1}$
2.5×10^5 stars
$v_- = 250$ km s^{-1}
$v_+ = 300$ km s^{-1}
IS abs. lines
Lyα Em. line
Lyman Cont. photons?
Relative Velocity (km s^{-1})
Relative Velocity (km s^{-1})

Lyman Continuum Radiation from LBGs

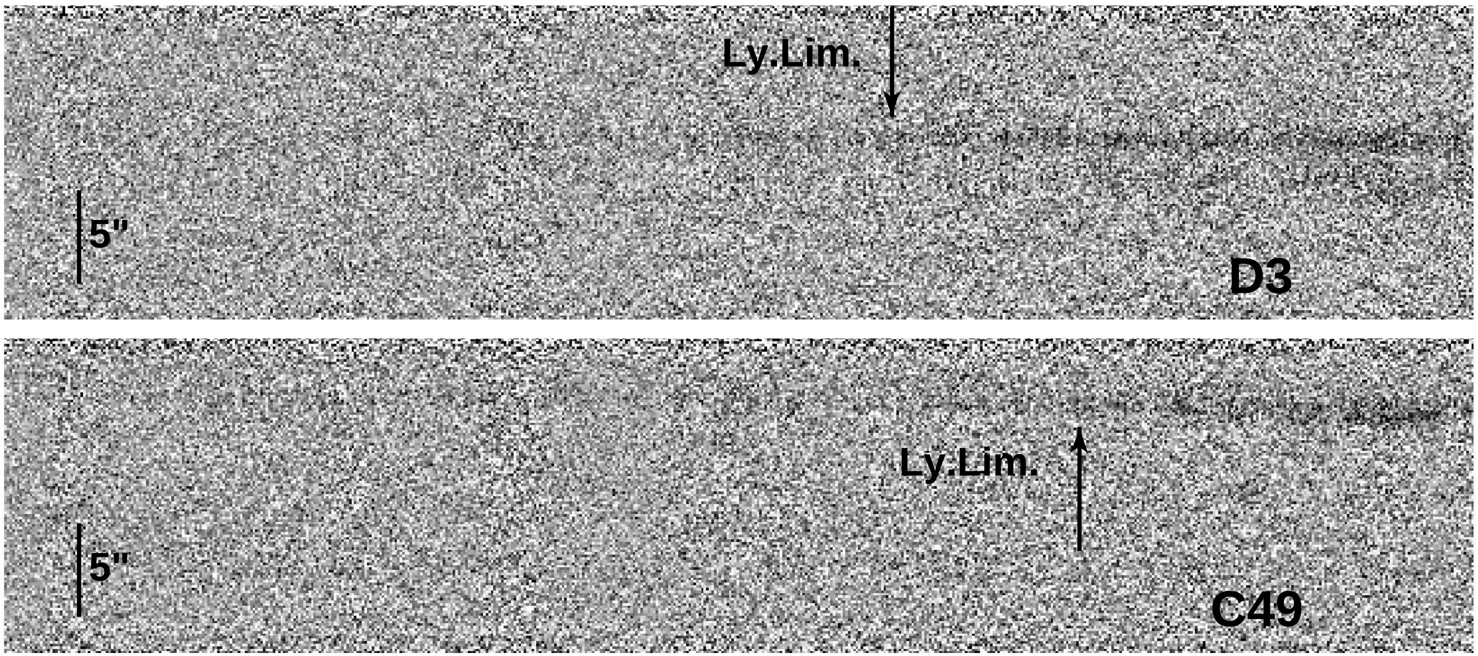




Overdensity of galaxies at $\langle z \rangle = 3.09$ in the H'ii SSA22 field

Lyman Continuum Radiation from LBGs

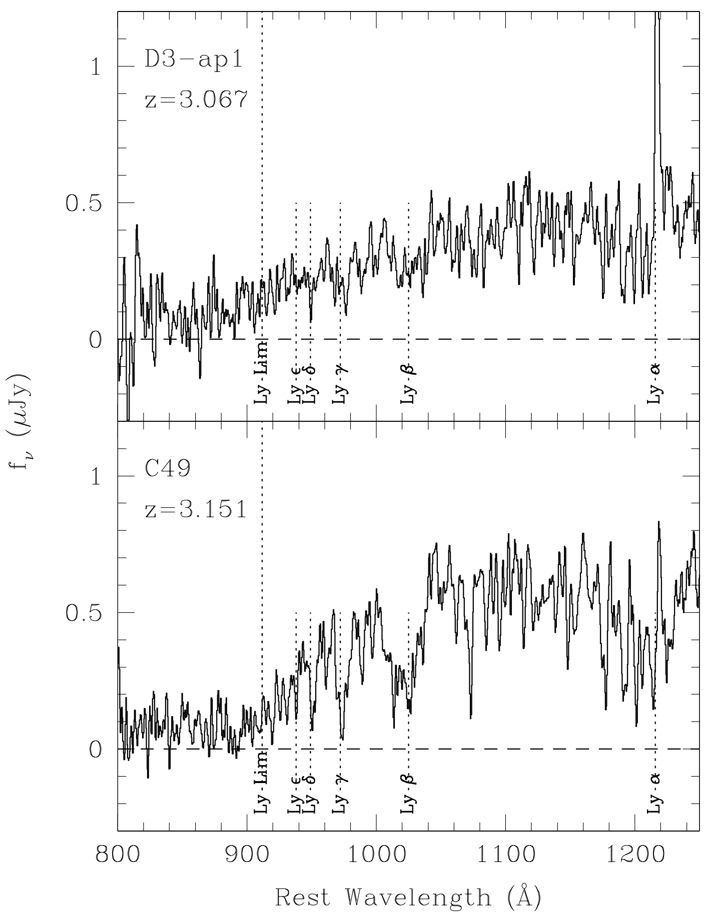
Shapley et al. 2006



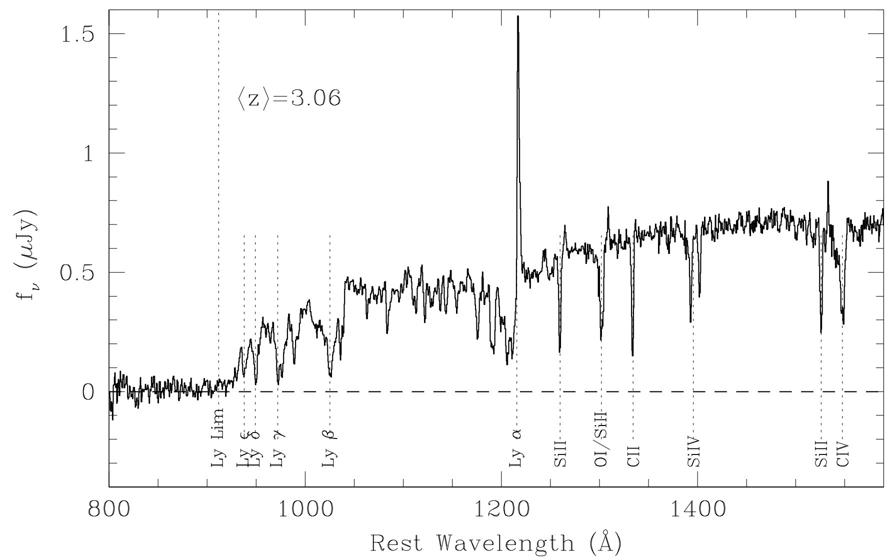
Deep (30 000 – 80 000 s) spectroscopy of 14 galaxies

With LRISB can now reach to $\lambda_{\rm obs} \simeq 3200\,$Å, $\lambda_0 \simeq 800\,$Å

Lyman Continuum Radiation from LBGs

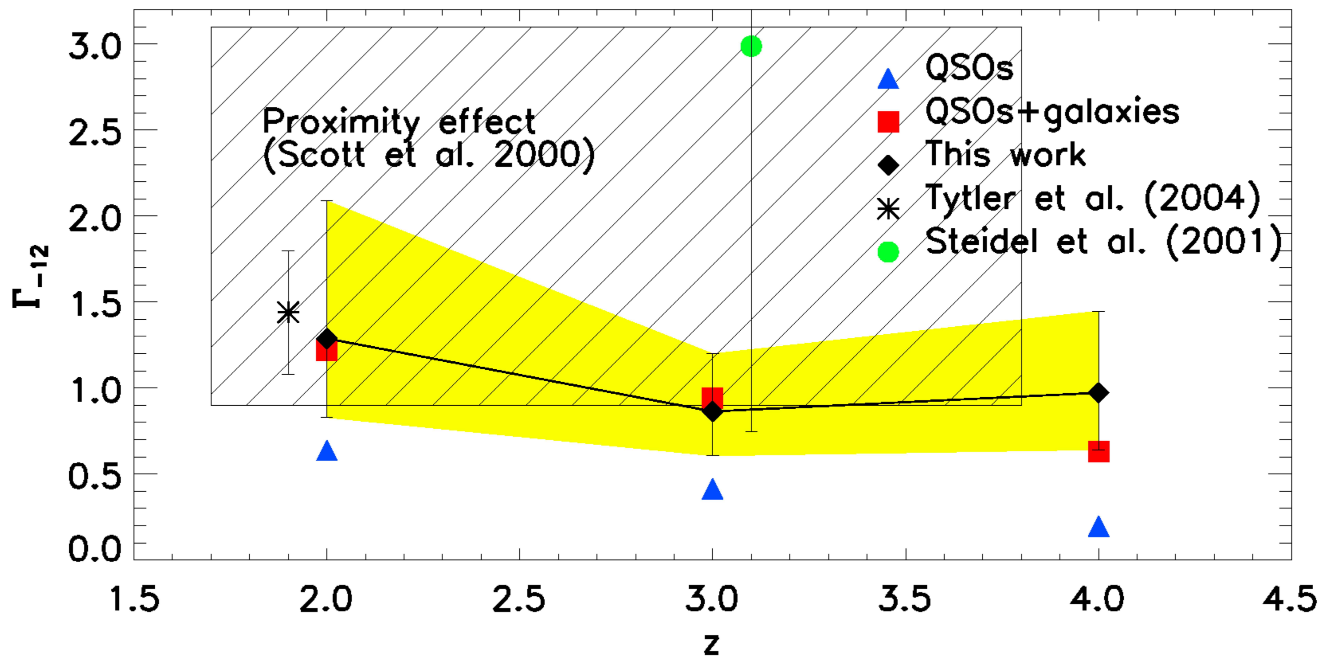


Composite of 14 spectra



Two out of 14 show signal below the Lyman edge

Metagalactic Ionising Background

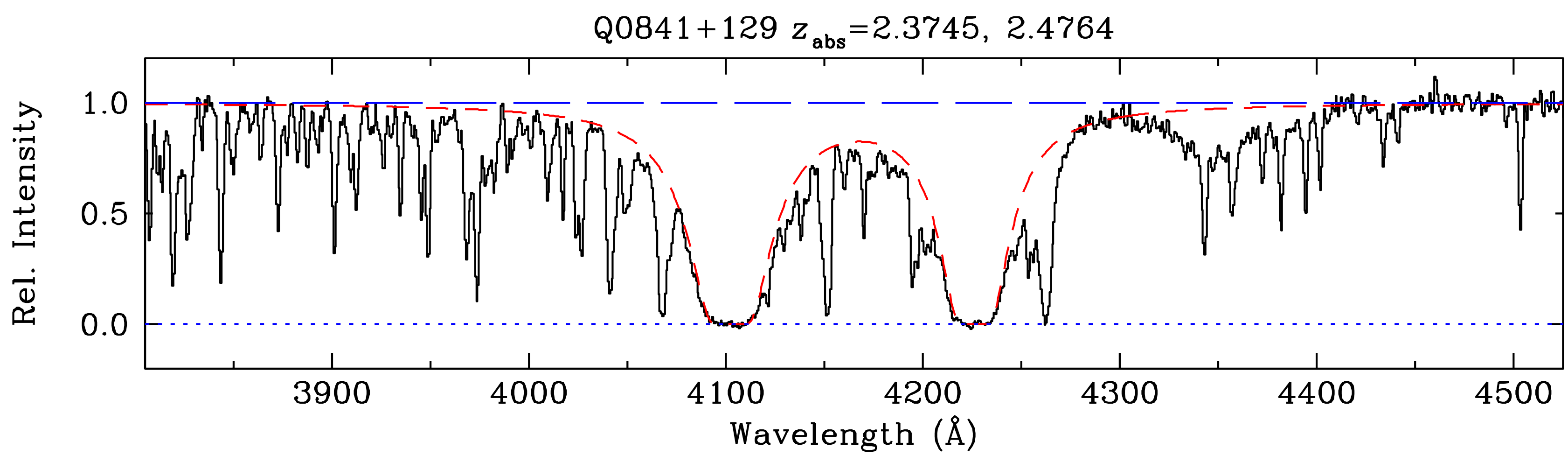


$\log J_\nu^{\rm gals} \simeq 2.6 \times 10^{-22}$; $\log J_\nu^{\rm QSOs} \simeq 2.4 \times 10^{-22}$ (Hunt et al. 2004)

Together $\Longrightarrow$ $\Gamma_{-12} \simeq 1.3$, in good agreement with Bolton et al. (2005).

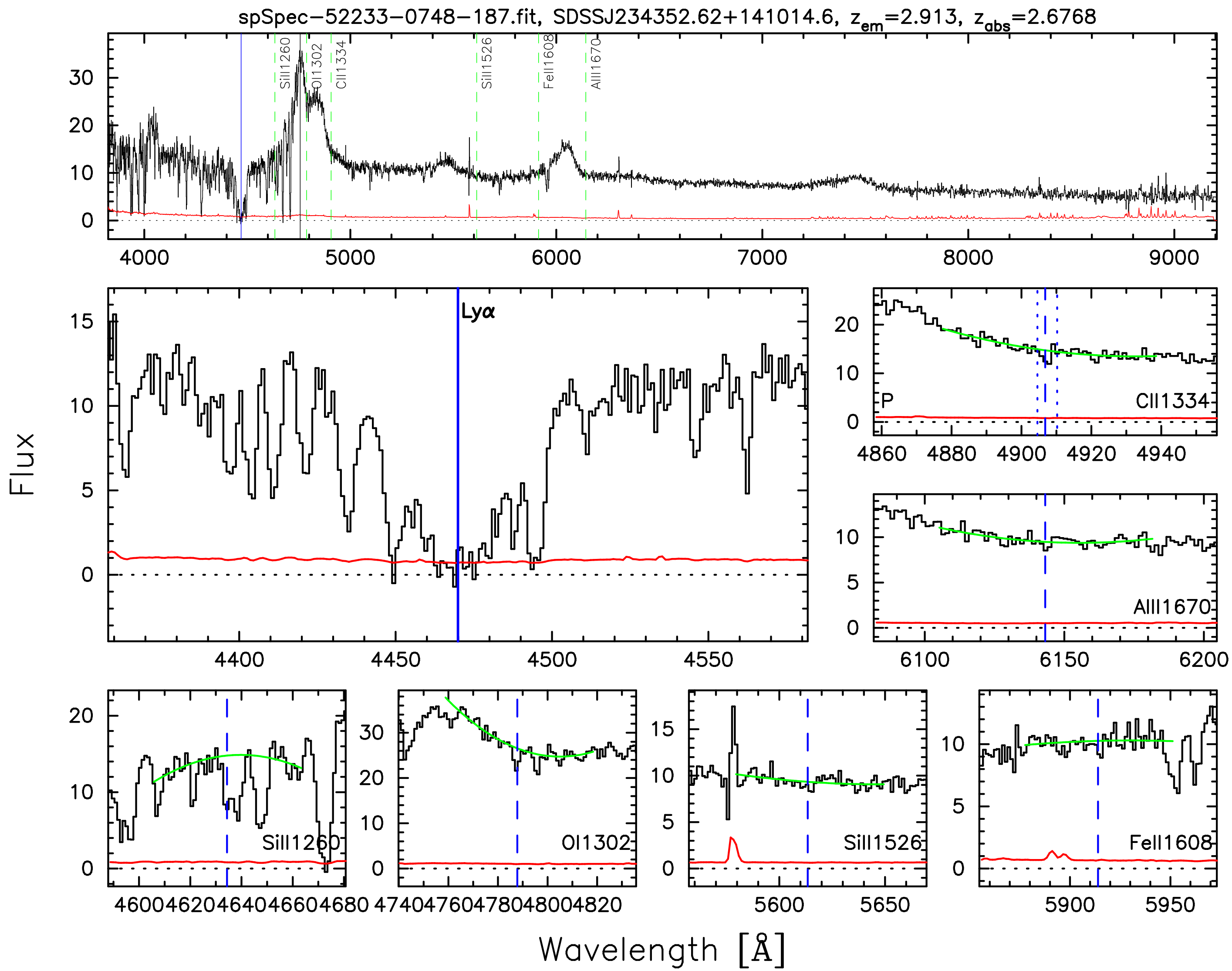
C, N, O in Damped Lyman α Systems

- DLAs are a valuable complement to Galactic studies of element abundances in metal-poor stars
- Abundance measurements are relatively straightforward, provided relevant absorption lines are not saturated
- Samples of DLAs increased by an order of magnitude by SDSS



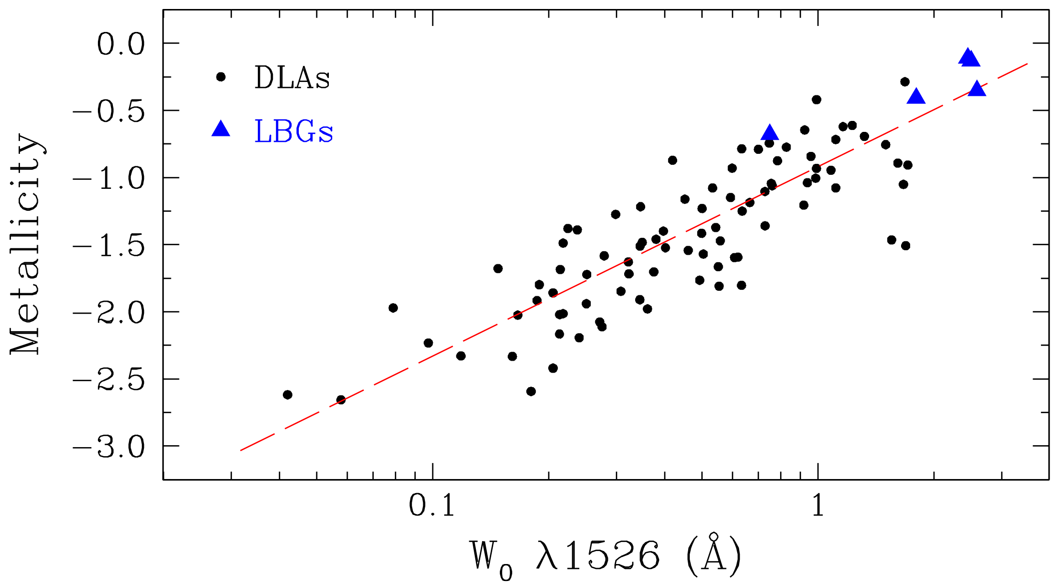
Search the database of SDSS QSOs with damped Lyα systems for DLAs (apparently) *without* associated metal lines...

Search the database of SDSS QSOs with damped Lyα systems for DLAs (apparently) *without* associated metal lines...



...because they are likely to have the *narrowest* metal absorption lines and therefore are likely to be the most metal-poor.

...because they are likely to have the *narrowest* metal absorption lines and therefore are likely to be the most metal-poor.

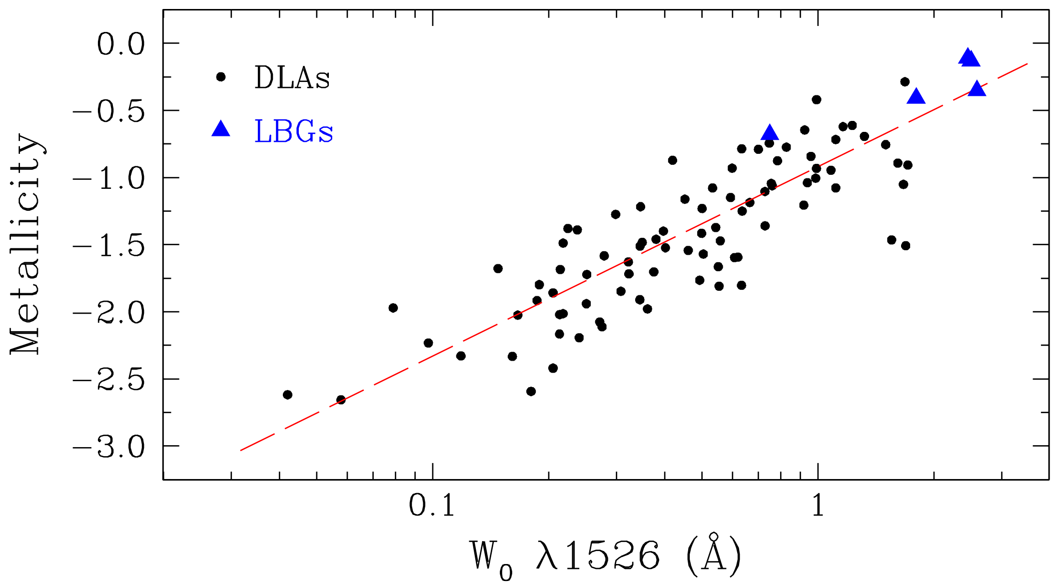


Prochaska et al. 2007

Murphy et al. 2007

Ledoux et al. 2006

...because they are likely to have the *narrowest* metal absorption lines and therefore are likely to be the most metal-poor.



Prochaska et al. 2007

Murphy et al. 2007

Ledoux et al. 2006

- These are the only DLAs where (C/O) may be measurable (the C II and O I absorption lines are normally too strong).

Most metal-poor DLAs have [Fe/H] $\simeq -2.5$

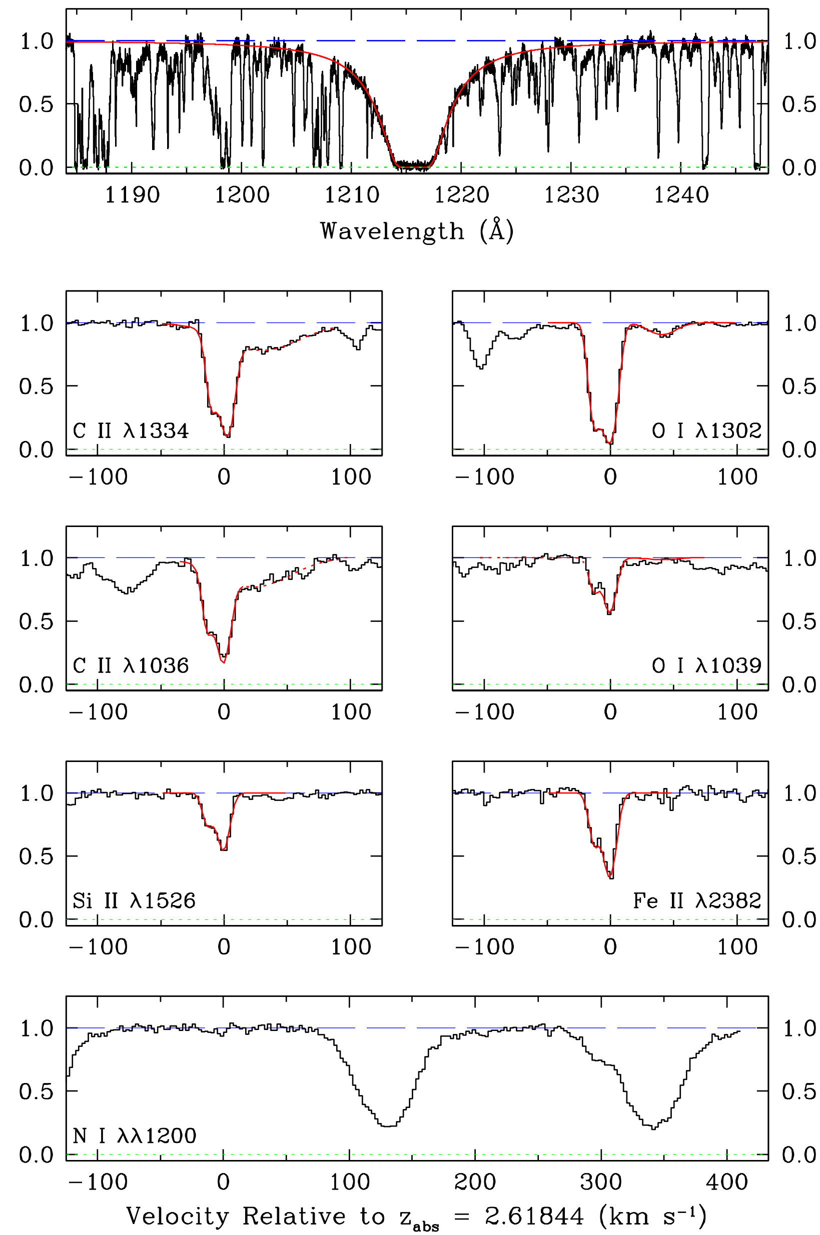
Q0913+072, $z_{\rm em} = 2.785$

DLA at $z_{\rm abs} = 2.61844$

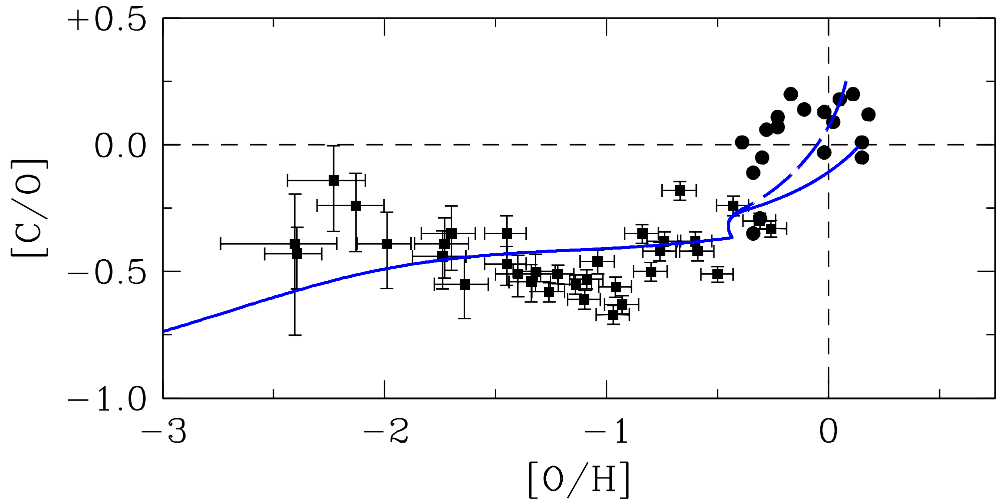
N(H I) $= 2.3 \times 10^{20}$

$({\rm O/H}) + 12 = 6.22$; [O/H] $= -2.44$

High S/N VLT-UVES spectrum

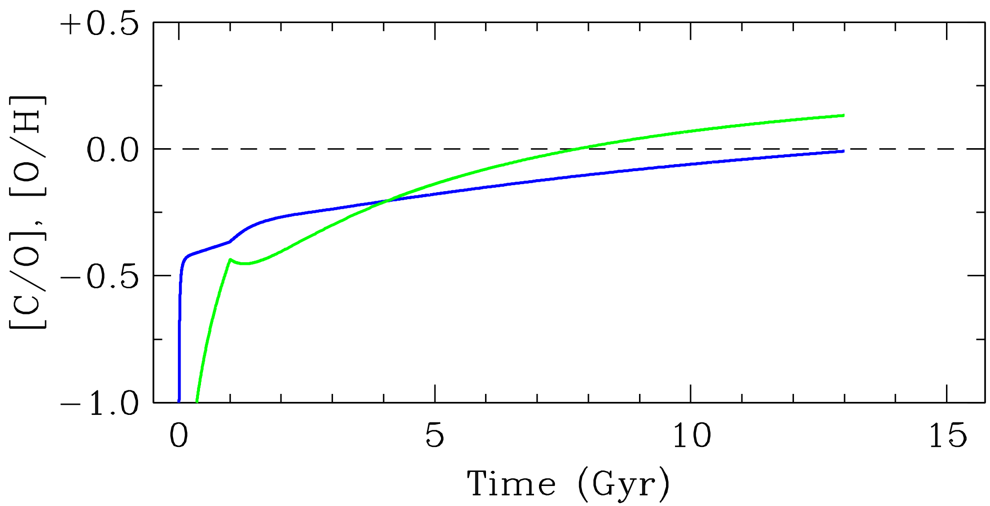


An Additional Source of C at low Metallicities?

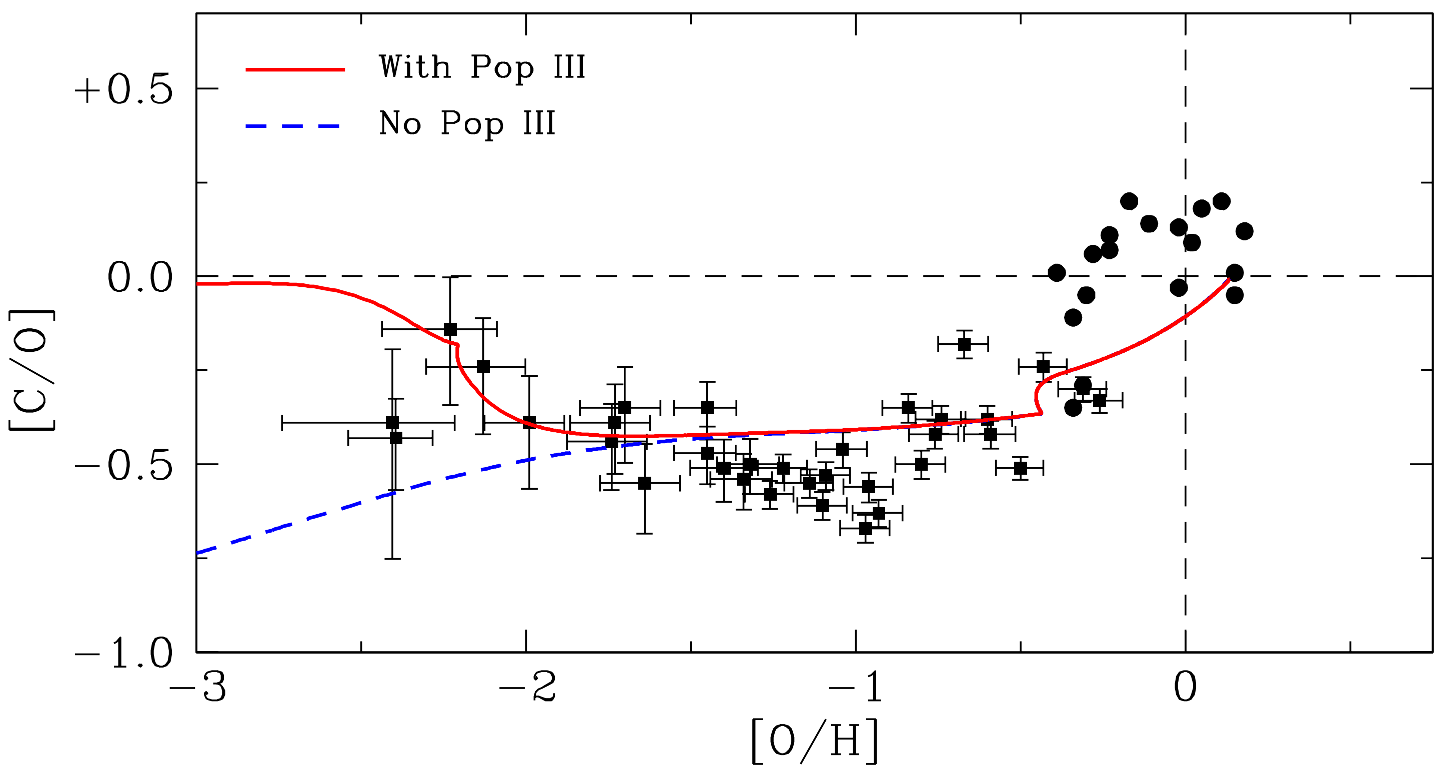


Akerman et al. 2004

(Meynet & Maeder 2002 yields)

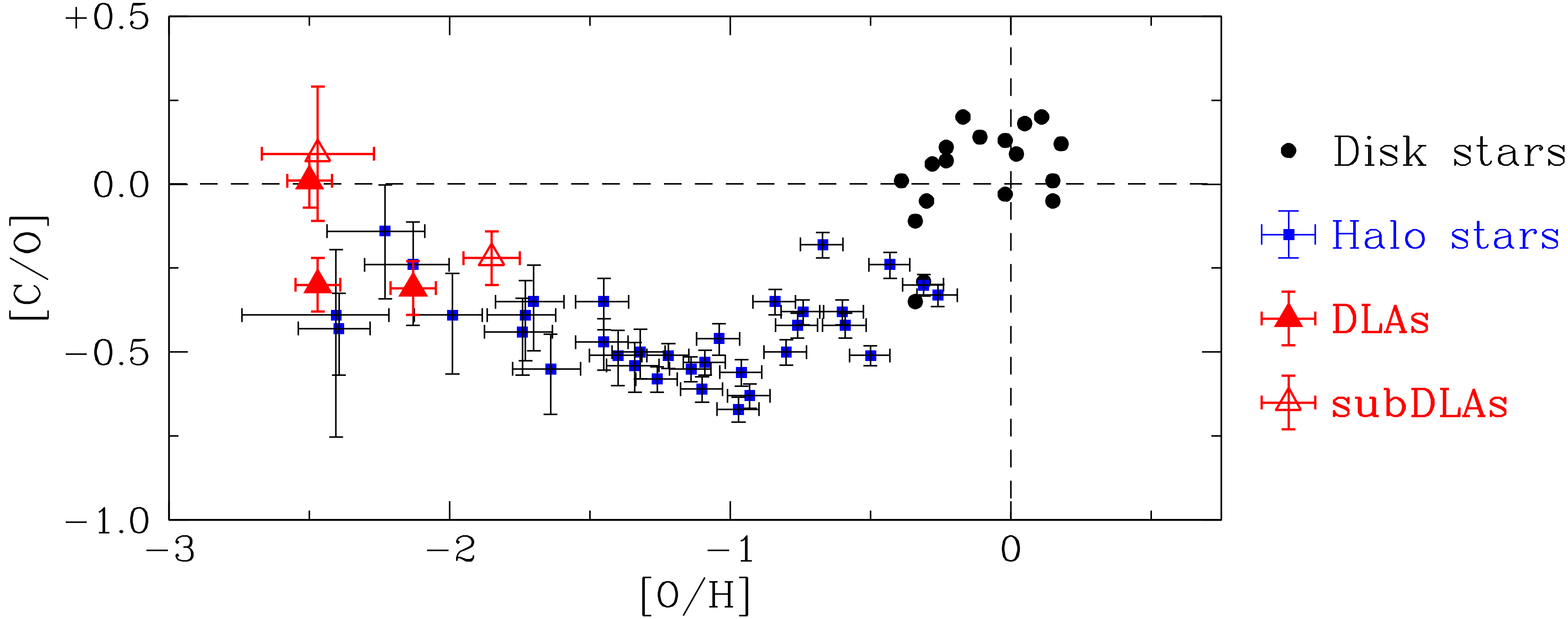


An Additional Source of C at low Metallicities?



(Chieffi & Limongi 2002 Pop III yields)

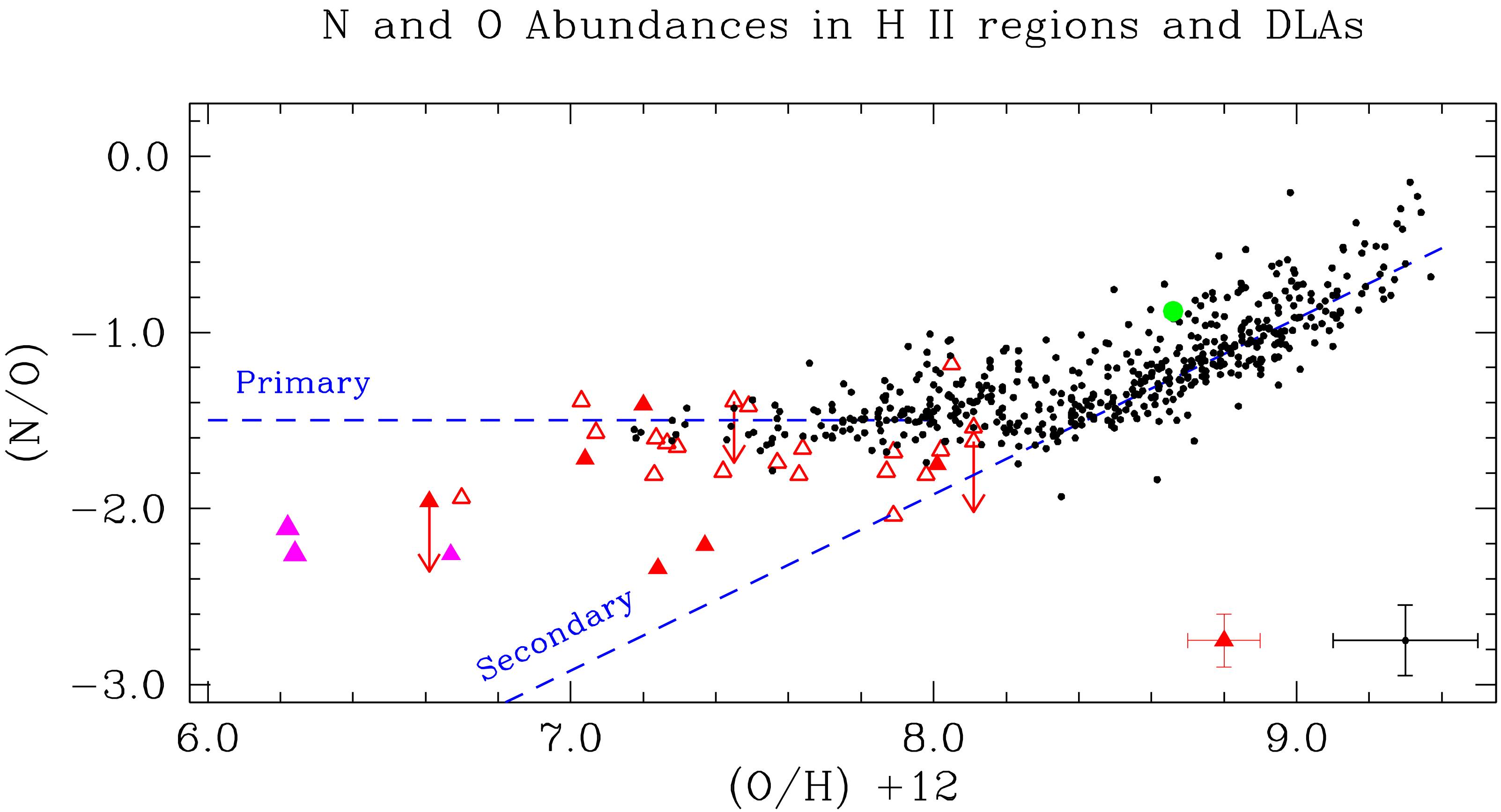
An Additional Source of C at low Metallicities?



(Pettini et al. 2007)

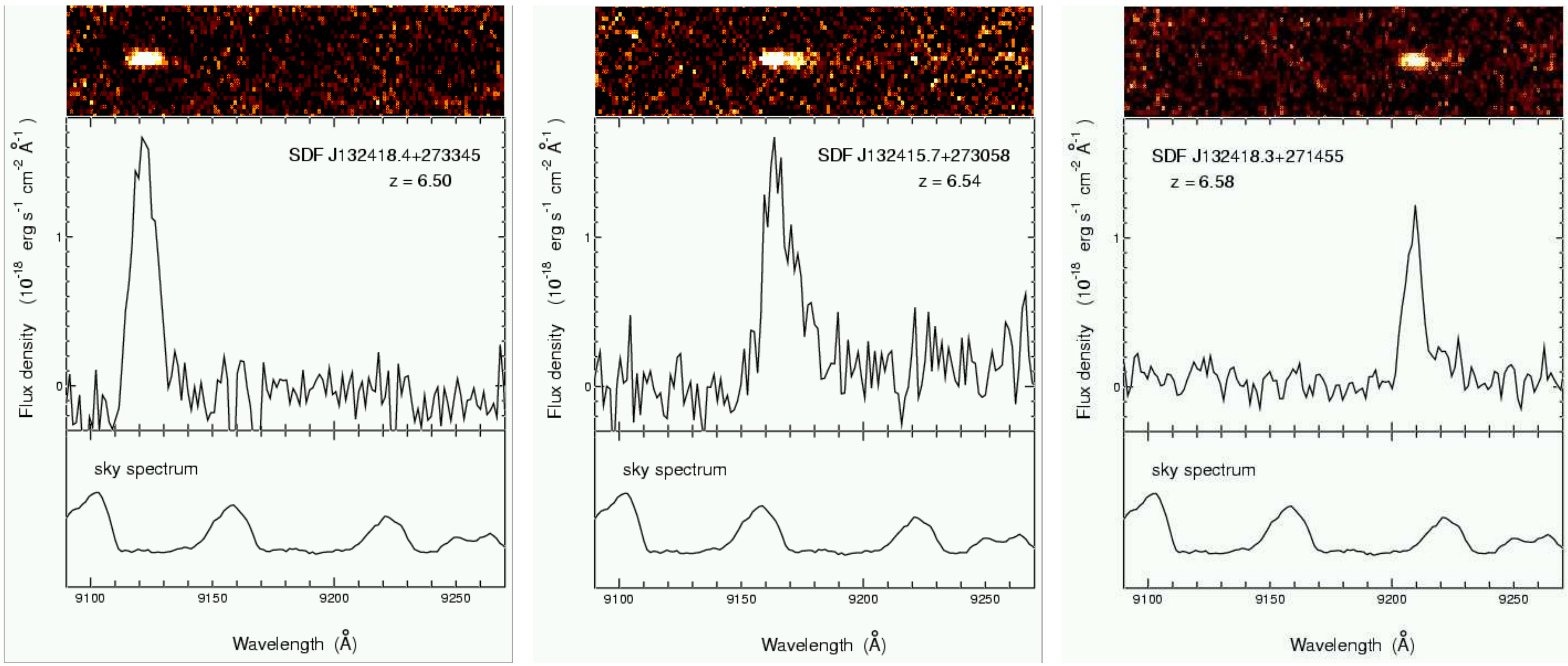
- The few DLA measurements available appear to confirm the rise in [C/O] at [O/H] $\lesssim -1$ seen in MW halo stars

Primary Nitrogen from Massive Stars?



- A floor at (N/O) $\simeq -2.3$?

The ‘First’ Galaxies?

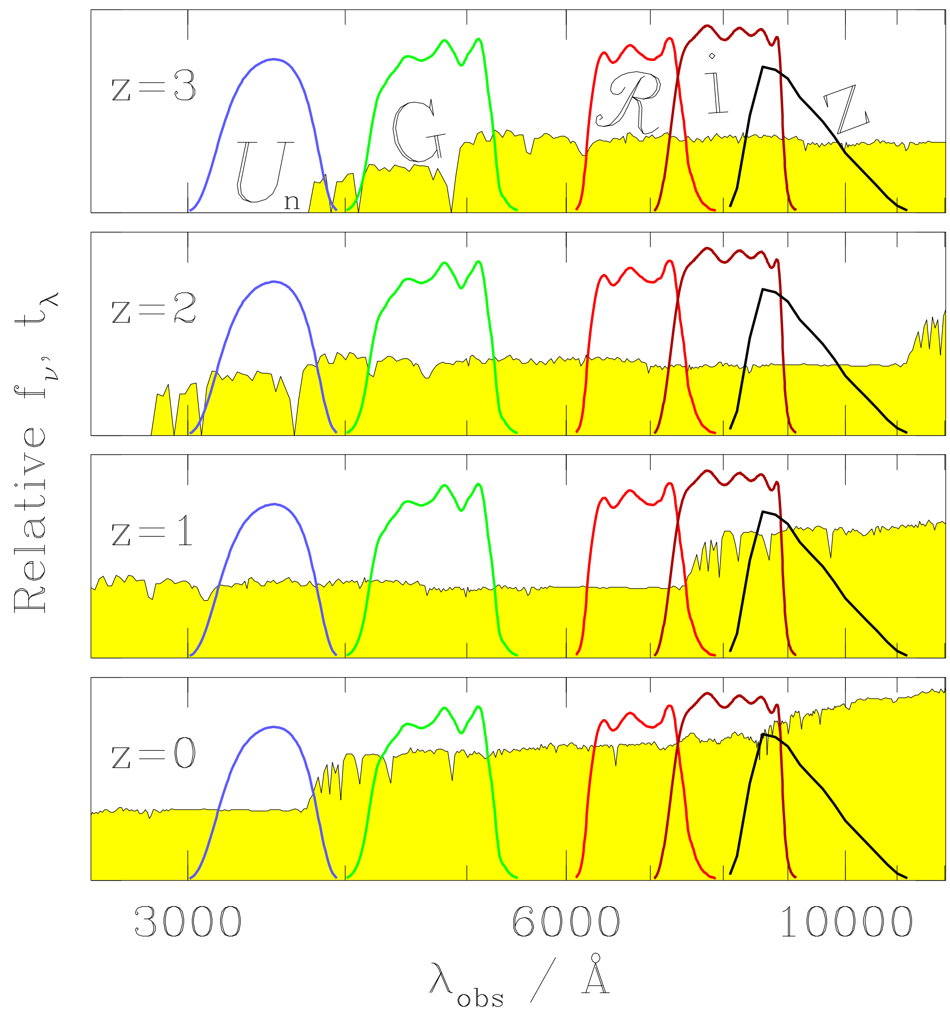


Taniguchi et al. 2005

High Redshift Galaxies: How Do We Find Them?

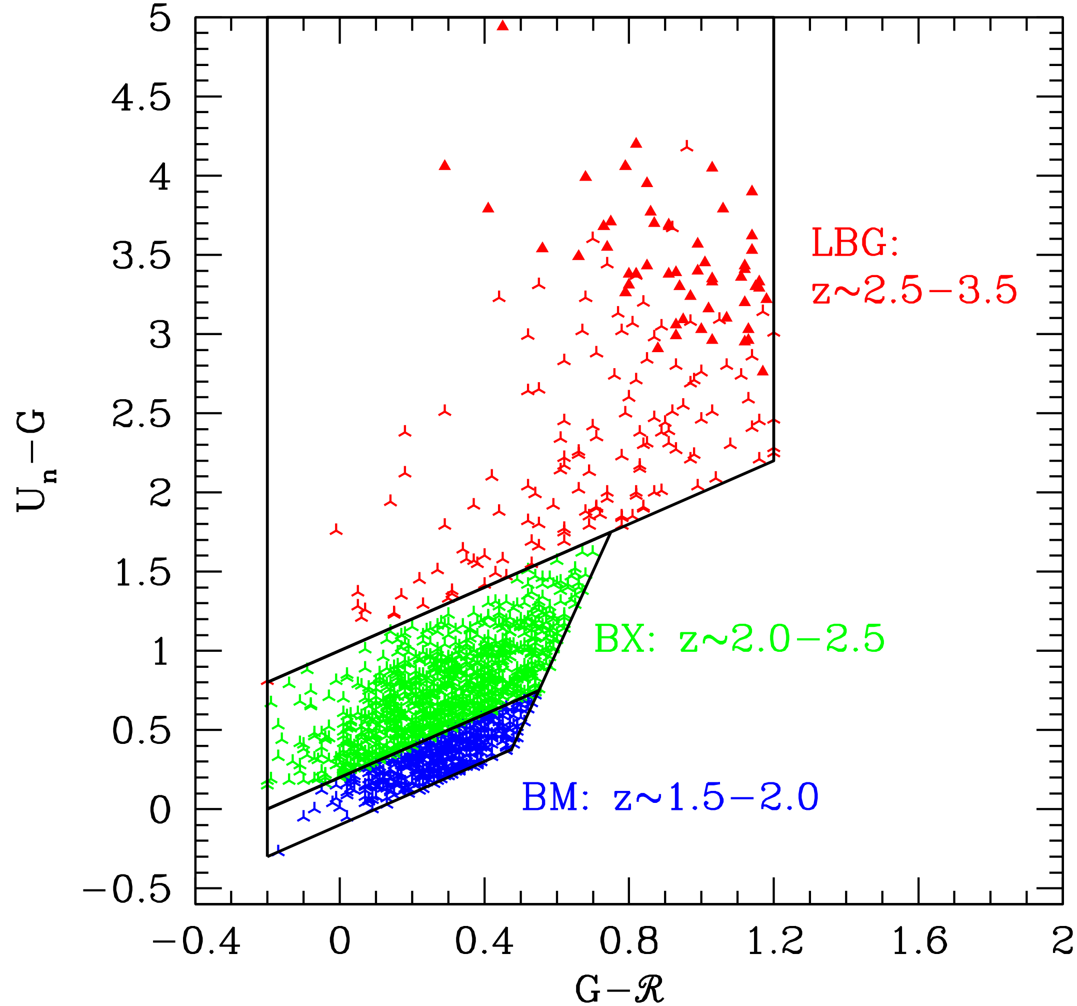
I. Efficient Photometric Preselection

Galaxies at redshifts spanning most of the Hubble time can now be found efficiently using photometric pre-selection tuned to well-defined redshift intervals. (Steidel et al. 2004)



LBG ($\langle z \rangle = 3.0$)*, BX* ($\langle z \rangle = 2.2$)*, BM* ($\langle z \rangle = 1.7$)

Photometric Selection



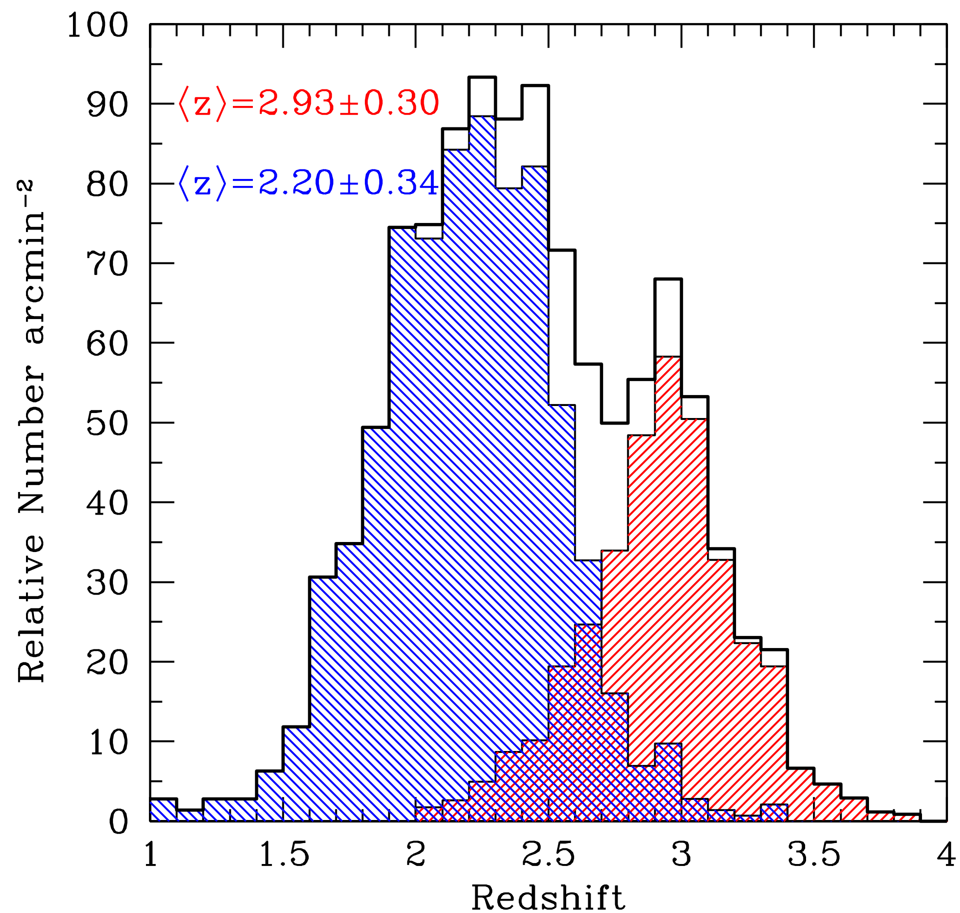
High Redshift Galaxies: How Do We Find Them?

II. Multi-object Follow-up Spectroscopy

Relatively easy to assemble samples of thousands of galaxies at $z \gtrsim 1.5$, e.g.

940 Lyman break galaxies
2050 'BX' galaxies

with $\mathcal{R} < 25.5$, i.e. $L \gtrsim 0.2L^*$ at $z = 2.2$

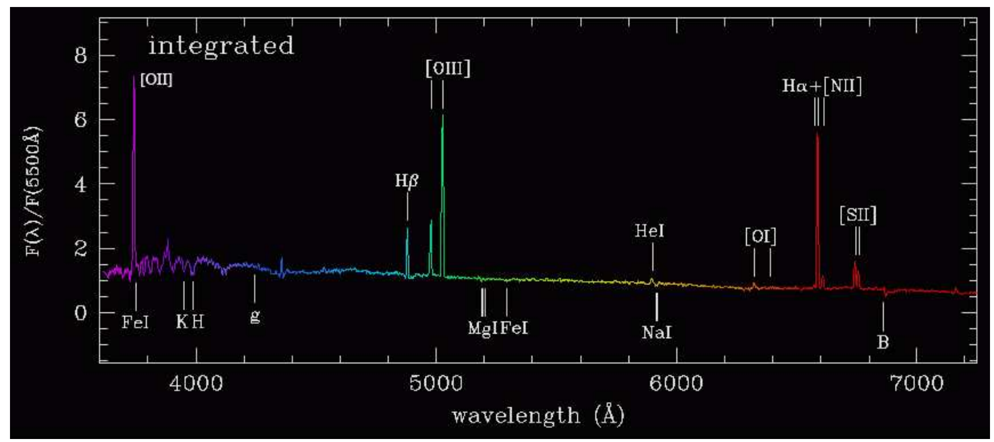


Infrared Observations of a sub-sample of 'BX' ($z \simeq 2$) Galaxies

114 with NIRSPEC K-band spectra ($R \simeq 1400$): Hα, [N II], [S II] emission lines.

90 with ground-based (WIRC) J- and K-band photometry to $J \simeq 24.0$, $K \simeq 22.3$ (3σ, Vega)

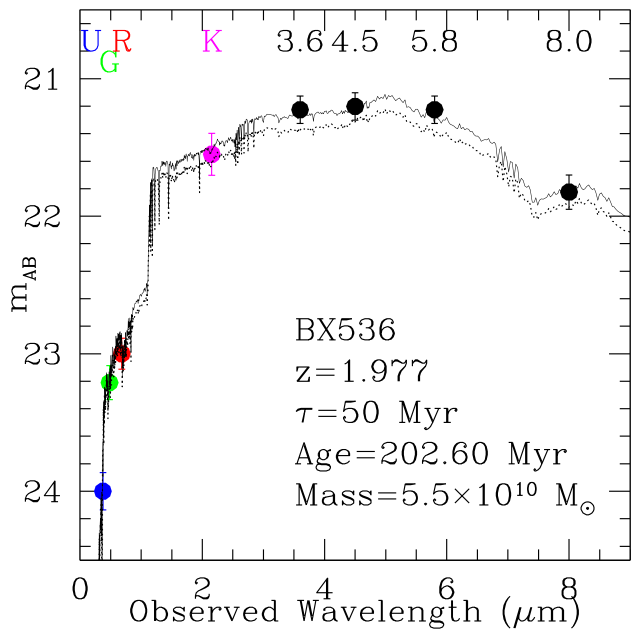
35 with *Spitzer* IRAC photometry (3.6, 4.5, 5.8, 8.0 μm)

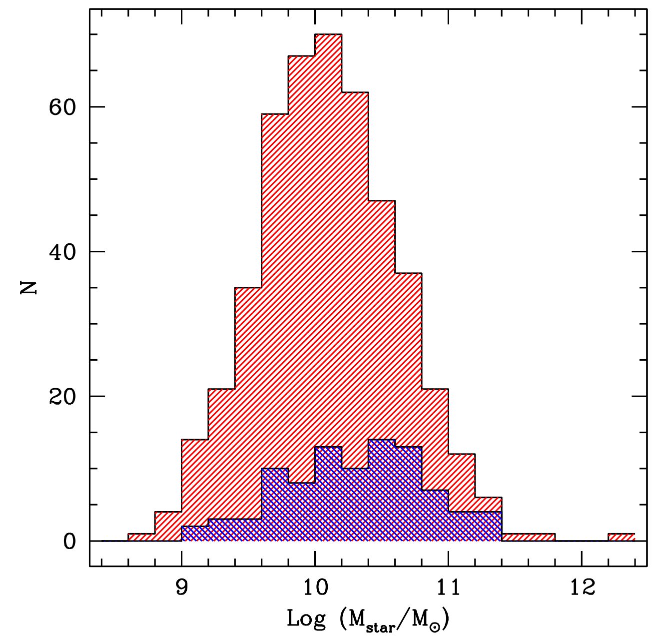


Assembled Stellar Masses

- Deduced from best fitting Bruzual & Charlot models to rest-frame UV-optical-(near-IR) SEDs.

  Relatively insensitive to exact details of star-formation history

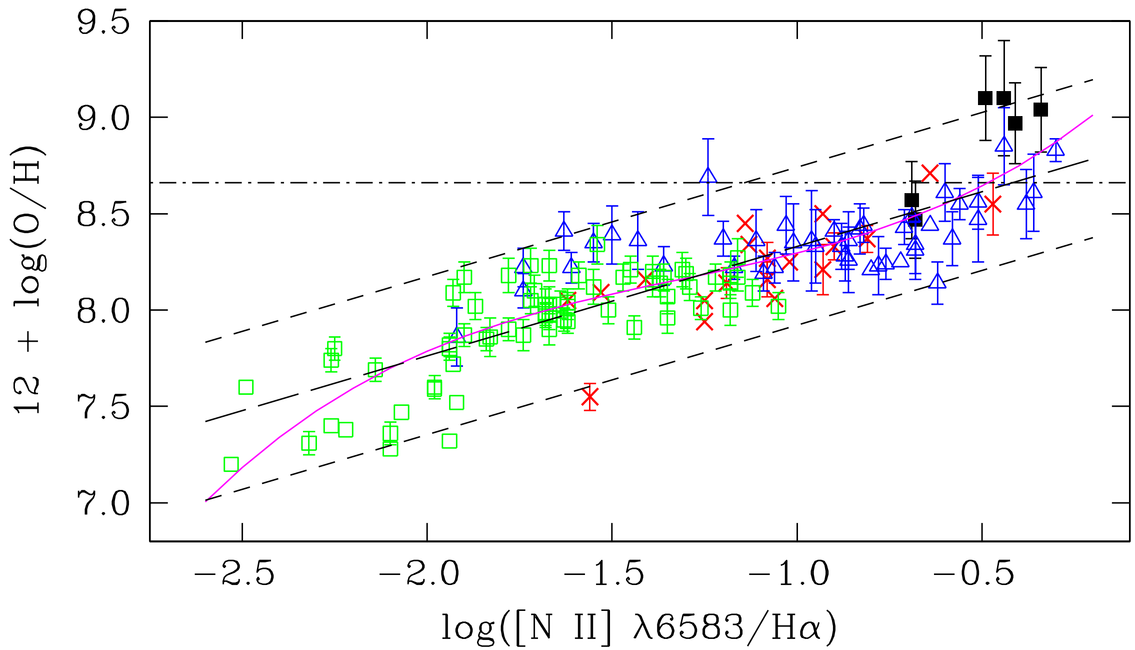




- Results: $M_{\rm stars} = 10^9 - 10^{11.5} M_\odot$, $\langle M_{\rm stars} \rangle = 3 - 4 \times 10^{10} M_\odot$

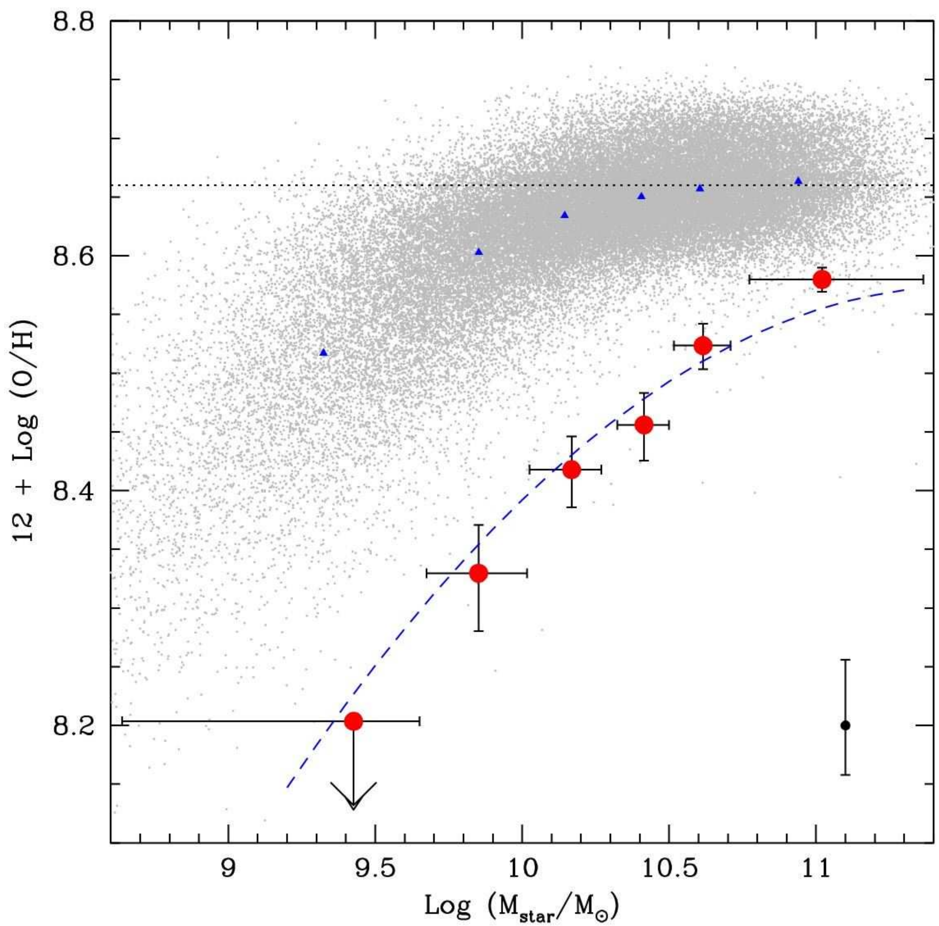
Metallicities

- The ratio of the intensities of [N II] and Hα measures the oxygen abundance (Pettini & Pagel 2004):



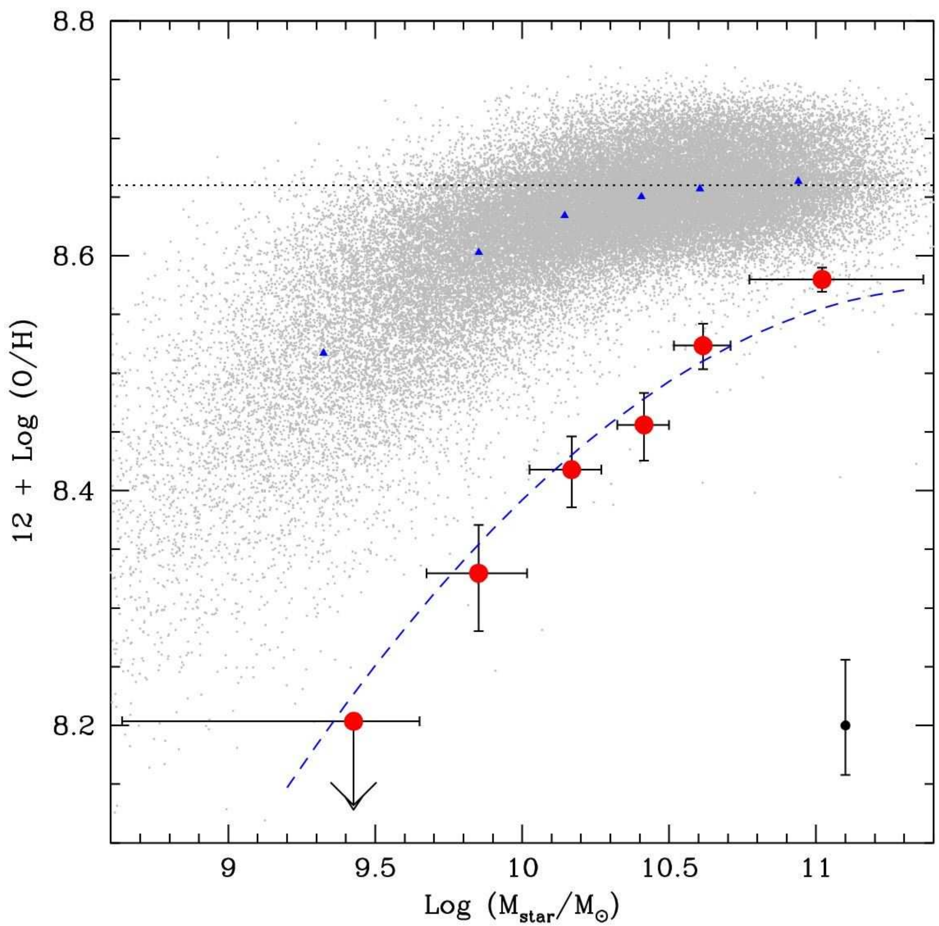
- Advantage: only two emission lines needed, close in wavelength
- Disadvantages: Saturates at near-solar metallicity
  Dependence on ionisation parameter

A Stellar Mass-Metallicity Relation at High Redshift



(Erb et al. 2006)

A Stellar Mass-Metallicity Relation at High Redshift

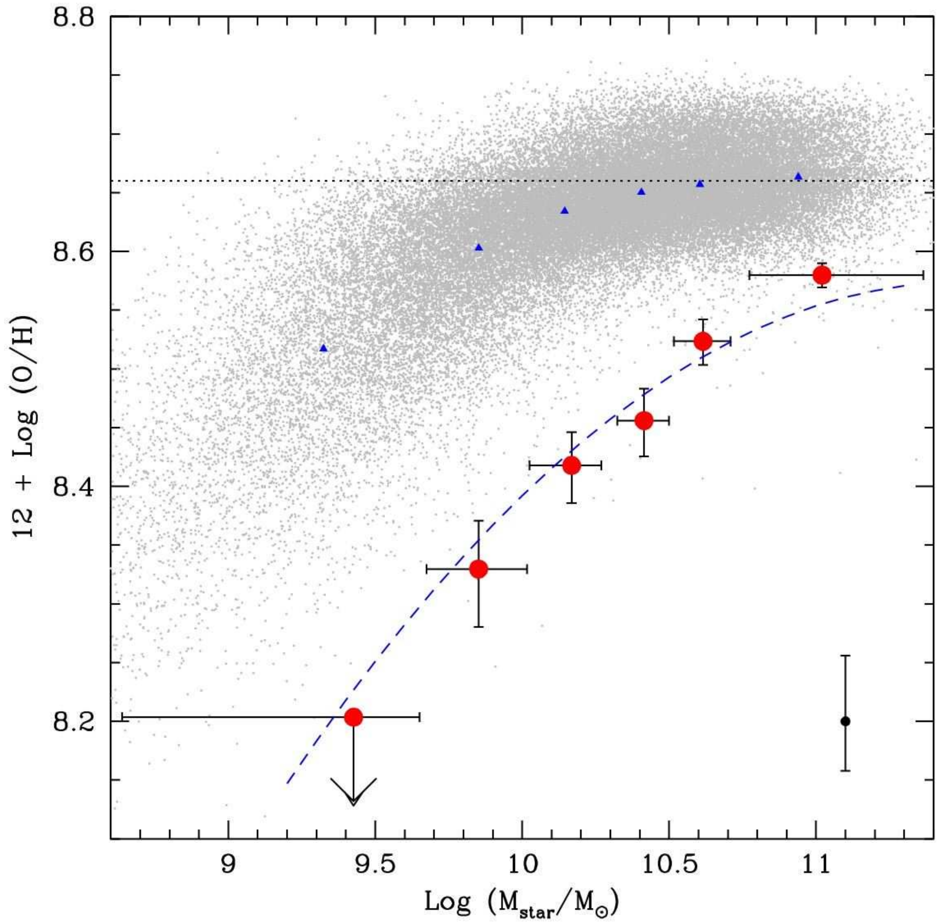


(Erb et al. 2006)

Note:

- Most galaxies have (O/H) $\gtrsim 1/3$ (O/H)$_{\odot}$

A Stellar Mass-Metallicity Relation at High Redshift



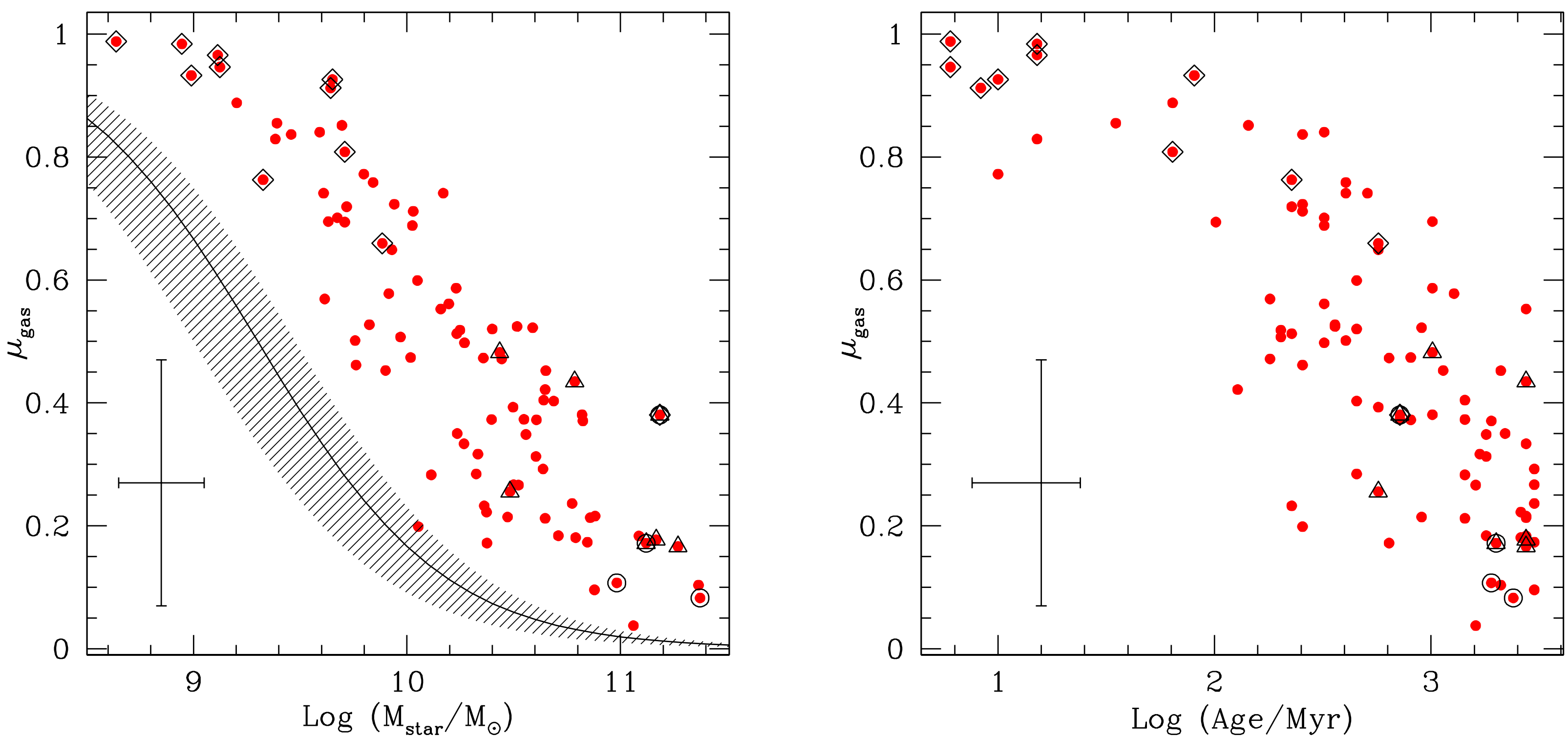
(Erb et al. 2006)

Note:

- Most galaxies have (O/H) $\gtrsim 1/3$ (O/H)$_{\odot}$
- Offset from present-day (SDSS) $M - Z$ relation

Star-Forming Galaxies at $z \sim 2$

Recent progress in determining their masses in (a) stars; (b) gas; (c) metals; and (d) dark matter (Erb et al. 2006a,b, and c)



Interpretation

- We are seeing galaxies over a range of evolutionary stages

Interpretation

- We are seeing galaxies over a range of evolutionary stages
- Some have apparently just ‘turned on’, with:
  (i) Low stellar masses: $M_{\rm star} \lesssim {\rm few} \times 10^9 \, M_\odot \ll M_{\rm dyn}$
  (ii) Young best-fitting ages: $t \sim t_{\rm dyn} \lesssim {\rm few} \times 10^7$ years
  (iii) High gas fractions: $\mu \sim 1$

Interpretation

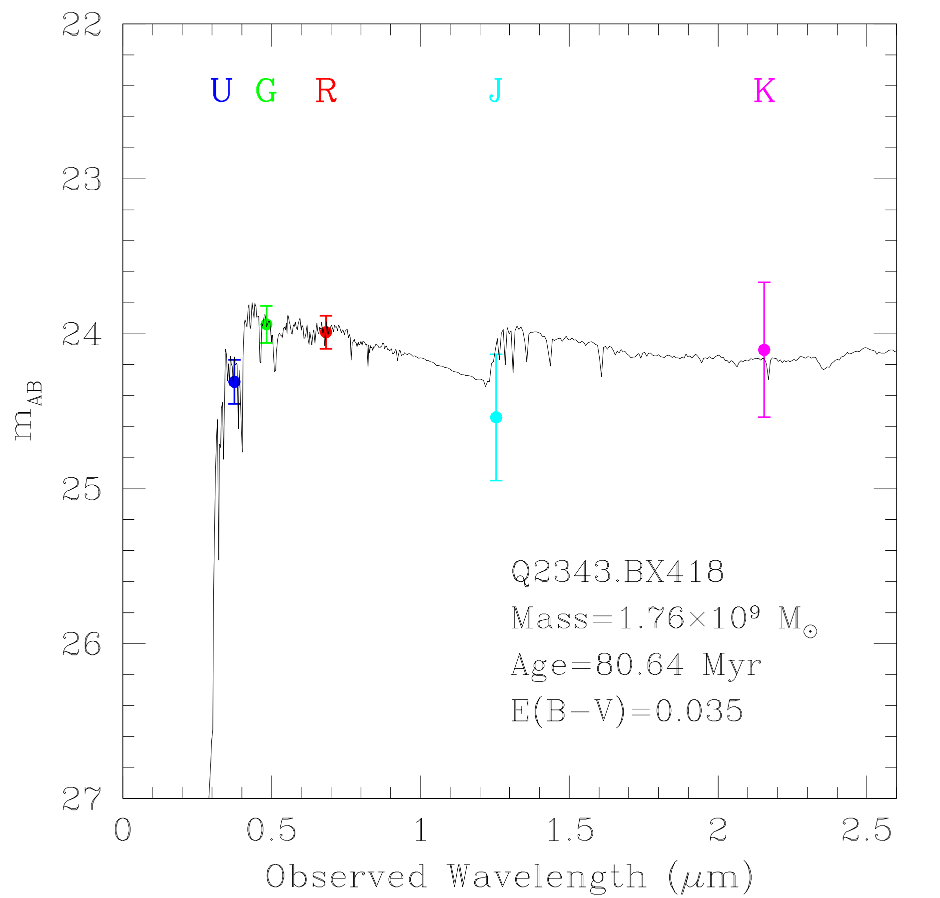
- We are seeing galaxies over a range of evolutionary stages
- Some have apparently just ‘turned on’, with:
  (i) Low stellar masses: $M_{\rm star} \lesssim {\rm few} \times 10^9\, M_\odot \ll M_{\rm dyn}$
  (ii) Young best-fitting ages: $t \sim t_{\rm dyn} \lesssim {\rm few} \times 10^7$ years
  (iii) High gas fractions: $\mu \sim 1$
- Others have nearly exhausted their fuel supply:
  (i) $\mu \lesssim 0.2$
  (ii) $M_{\rm stars} + M_{\rm gas} \gtrsim 10^{11}\, M_\odot$
  (iii) $z_{\rm form} > 4$ (15% of the sample has ages ≈ age of the universe)
  (Entirely consistent with number density of $z \simeq 5.5 - 6.5$ galaxies in GOODS fields — Yan et al. 2006)

Interpretation

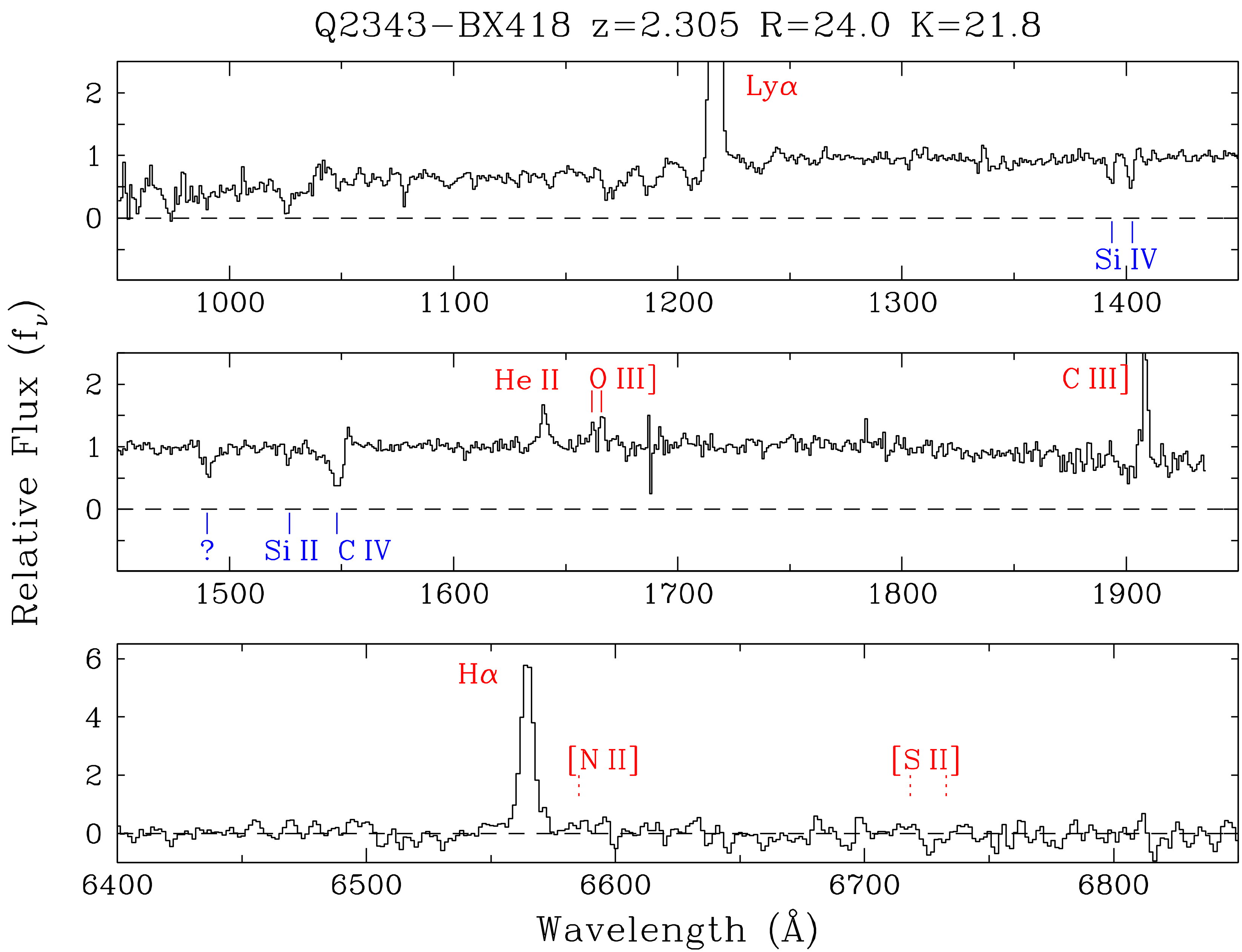
- We are seeing galaxies over a range of evolutionary stages
- Some have apparently just 'turned on', with:
  (i) Low stellar masses: $M_{\rm star} \lesssim {\rm few} \times 10^9\, M_\odot \ll M_{\rm dyn}$
  (ii) Young best-fitting ages: $t \sim t_{\rm dyn} \lesssim {\rm few} \times 10^7$ years
  (iii) High gas fractions: $\mu \sim 1$
- Others have nearly exhausted their fuel supply:
  (i) $\mu \lesssim 0.2$
  (ii) $M_{\rm stars} + M_{\rm gas} \gtrsim 10^{11}\, M_\odot$
  (iii) $z_{\rm form} > 4$ (15% of the sample has ages ≈ age of the universe)
  (Entirely consistent with number density of $z \simeq 5.5 - 6.5$ galaxies in GOODS fields — Yan et al. 2006)
- Galaxies of similar $M_{\rm tot}$ began forming stars at different times
- At a given redshift, galaxies with a wide variety of $M_{\rm tot}$ have just begun forming stars

Q2343-BX418 $z = 2.305$:

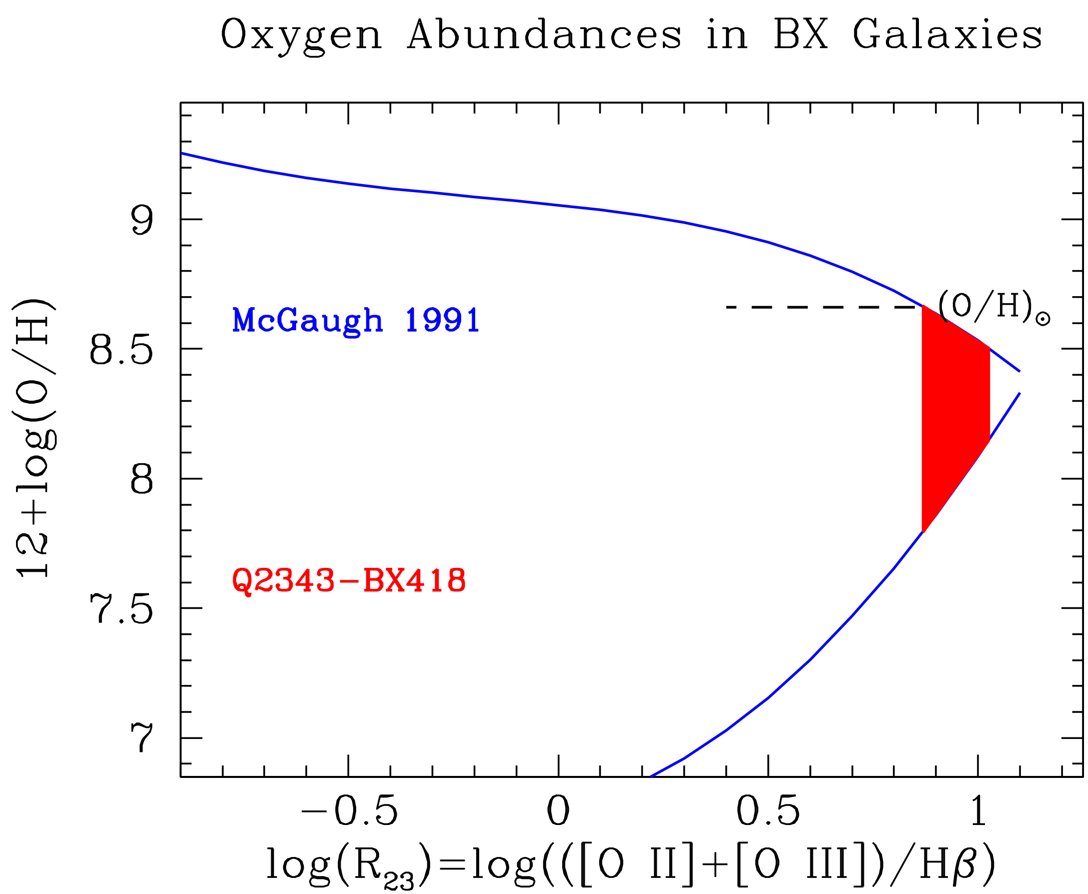
A Lower Redshift Analogue to $z = 6.5$ *Ly*α *Emitters?*



Pettini et al. 2007


Q2343−BX418 z=2.305 R=24.0 K=21.8
Lyα
Si IV
He II
O III]
C III]
?
Si II
C IV
Hα
[N II]
[S II]
Relative Flux (f_ν)
Wavelength (Å)
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
6400
6500
6600
6700
6800

Q2343-BX418 $z = 2.305$



- R_{23} gives (O/H) $\simeq 1/5$ (O/H)$_\odot$— i.e. already relatively metal-rich after less than 100 Myr from the onset of star formation

Conclusions

- There are metals in the IGM at $z \gtrsim 6$, although their distribution may be very patchy

Conclusions

- There are metals in the IGM at $z \gtrsim 6$, although their distribution may be very patchy

- Star-forming galaxies at $z > 6$ are:
  (a) numerous,
  (b) probably already metal-enriched, and
  (c) likely to leak ionising photons into the IGM (although typical escape fraction has yet to be determined)

Conclusions

- There are metals in the IGM at $z \gtrsim 6$, although their distribution may be very patchy

- Star-forming galaxies at $z > 6$ are:
(a) numerous,
(b) probably already metal-enriched, and
(c) likely to leak ionising photons into the IGM (although typical escape fraction has yet to be determined)

- Near-IR observations of DLAs at $z > 5$ (if they can be found) are more likely to take us close to uncovering the nucleosynthetic products of the ‘First Stars’