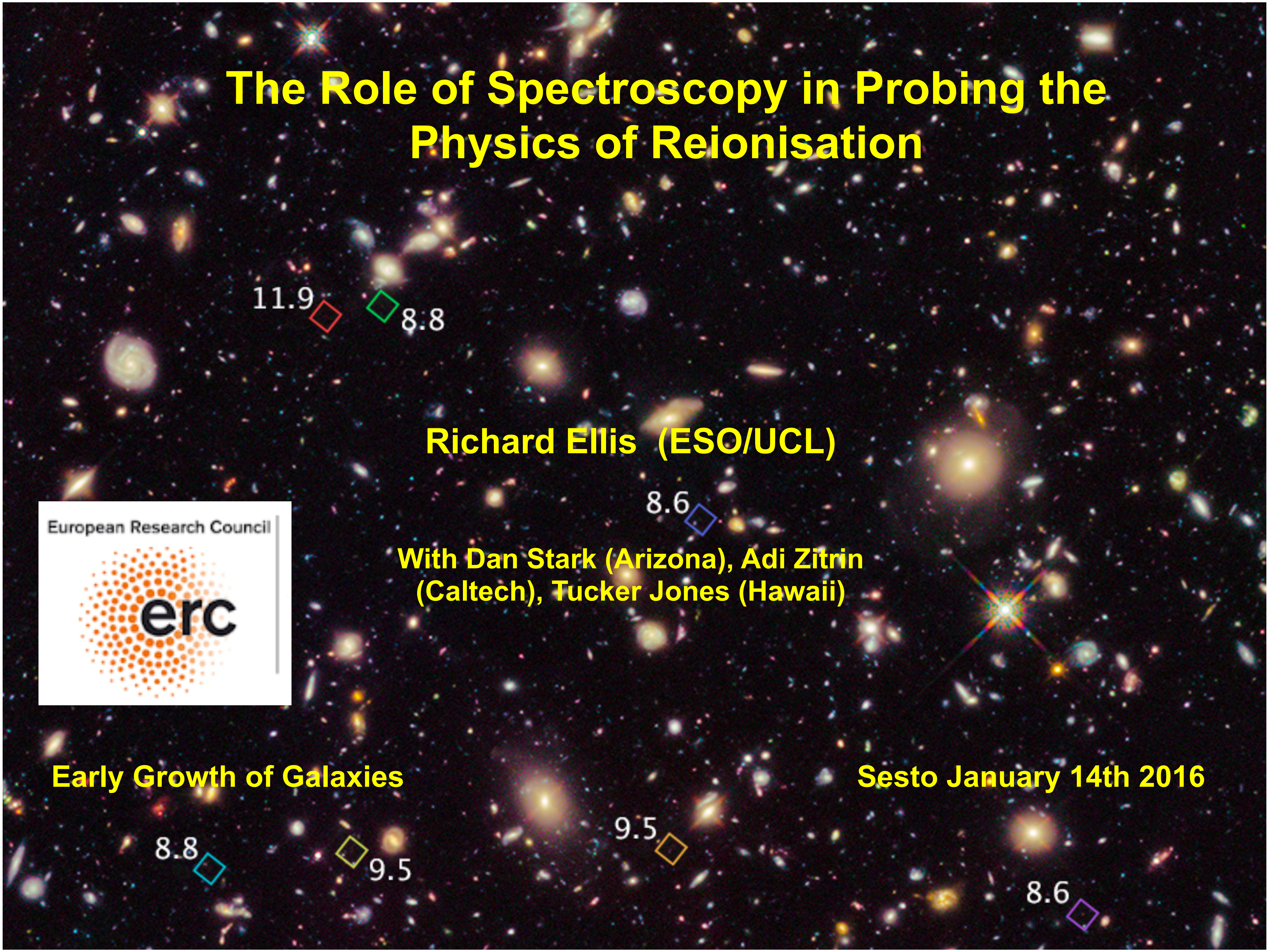
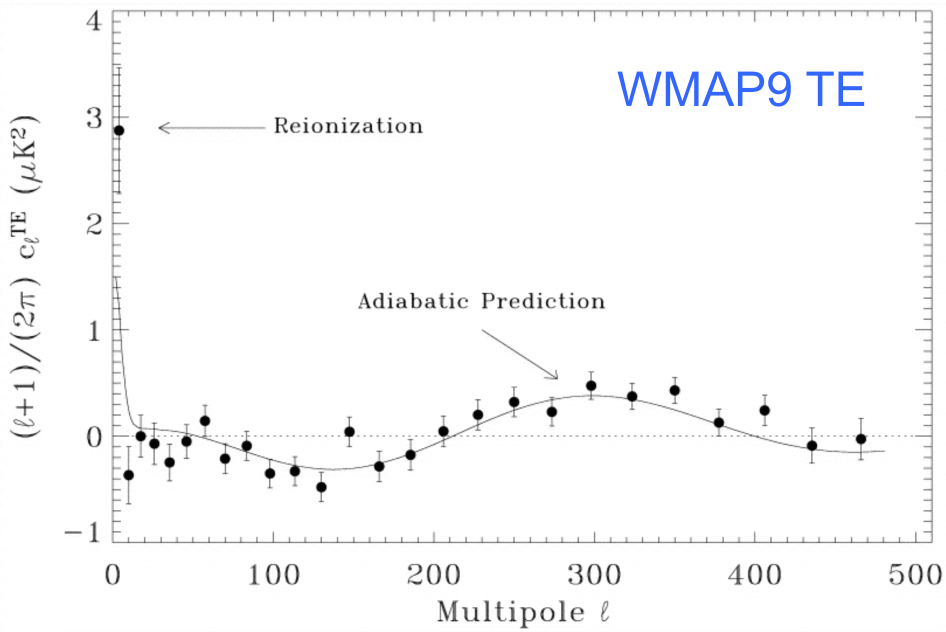
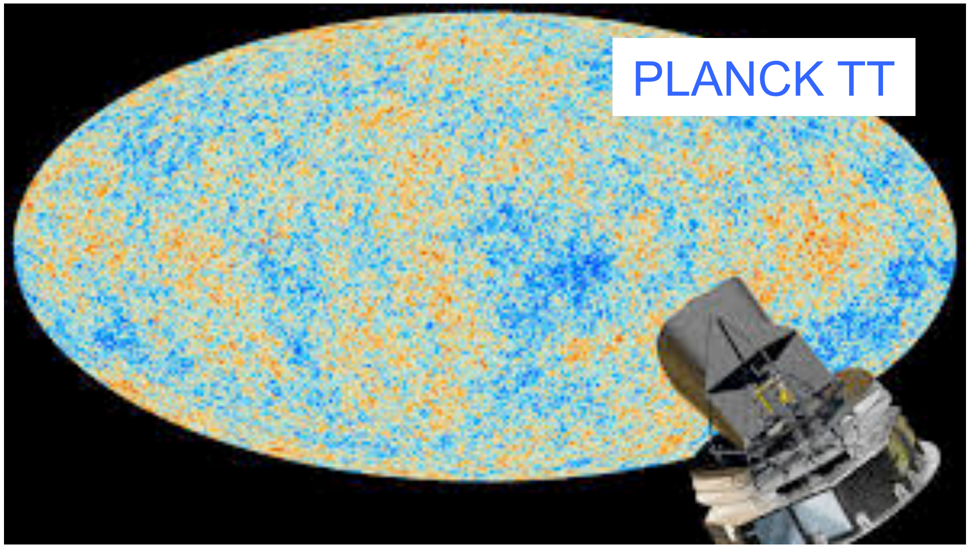

The Role of Spectroscopy in Probing the Physics of Reionisation
11.9
8.8
Richard Ellis (ESO/UCL)
8.6
European Research Council
erc
With Dan Stark (Arizona), Adi Zitrin (Caltech), Tucker Jones (Hawaii)
Early Growth of Galaxies
Sesto January 14th 2016
8.8
9.5
9.5
8.6

Planck CMB: Shorter & Later Reionization Era?





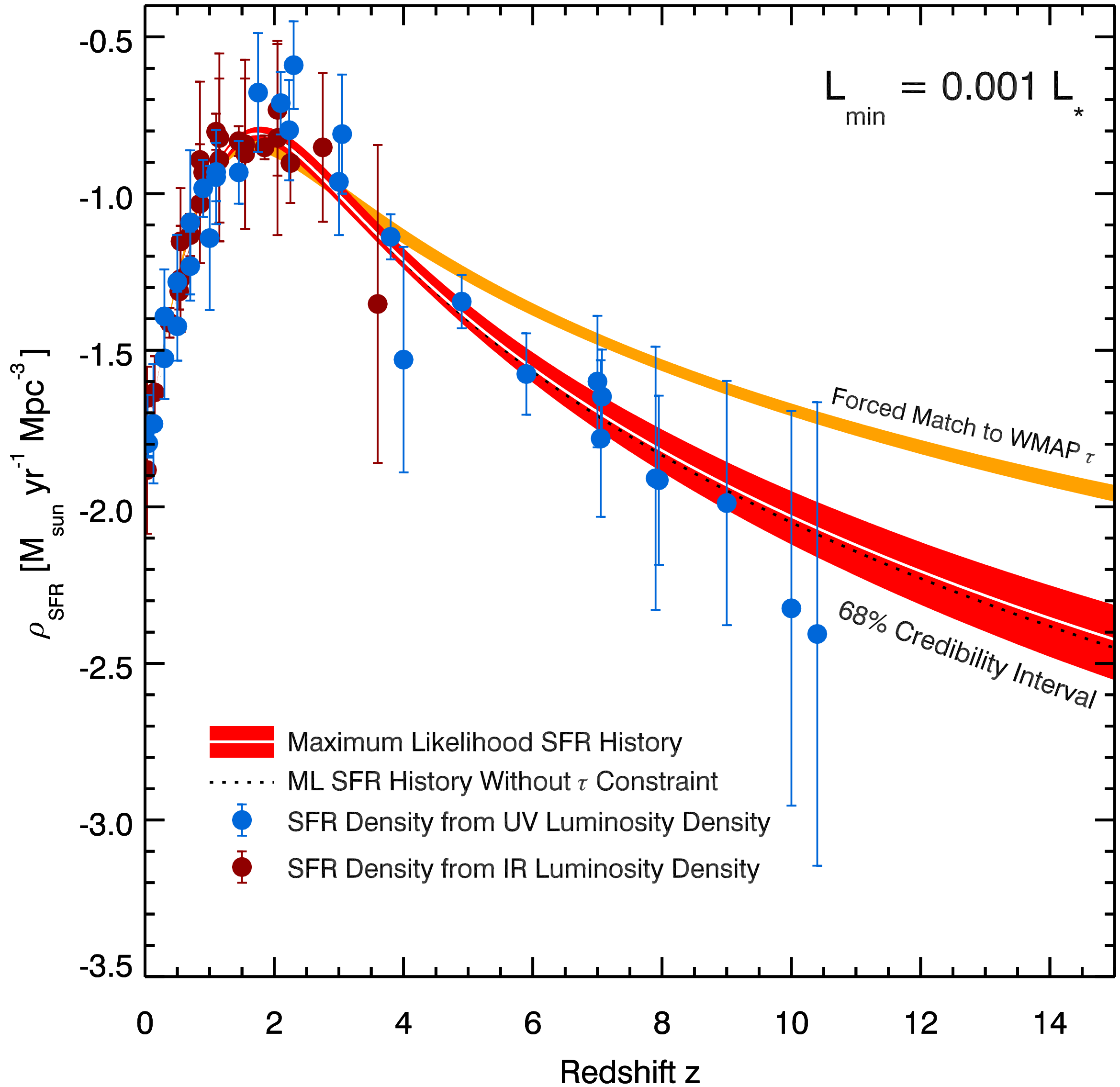
τ = 0.088 ± 0.013; z = 10.5 ± 1.1 **τ = 0.066 ± 0.013; z = 8.8 ± 1.2**

Planck Consortium argue the WMAP τ, derived largely from TE/EE (polarization) data, is less convincing than the superior TT data from Planck whose degeneracy with the amplitude A_s can now be broken via CMB lensing constraints.

Does it Matter? Star Formation History

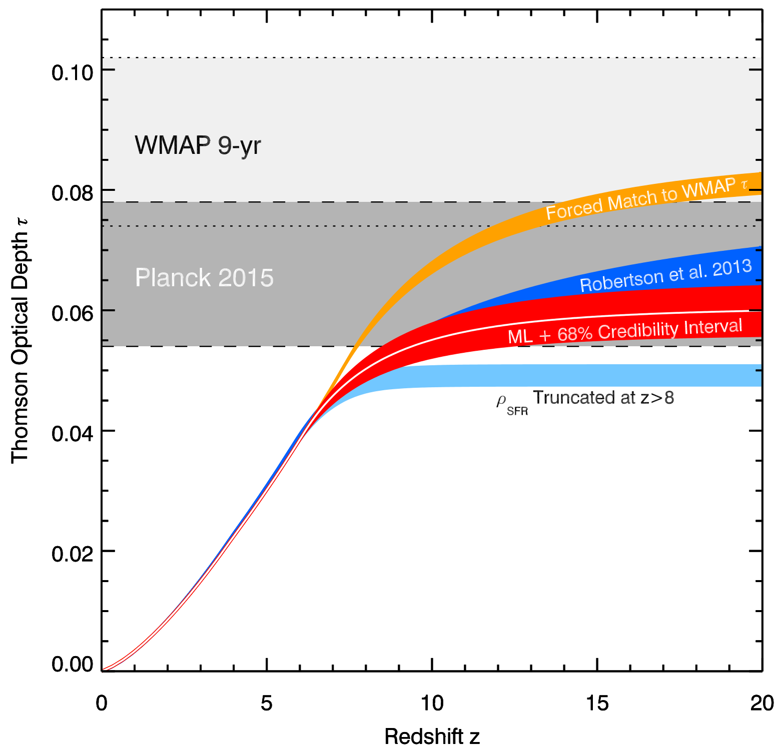
A change of Δz~1.7 in instantanous redshift of reionization makes a big difference to the role of galaxies since their numbers decline very rapidly for z > 6.

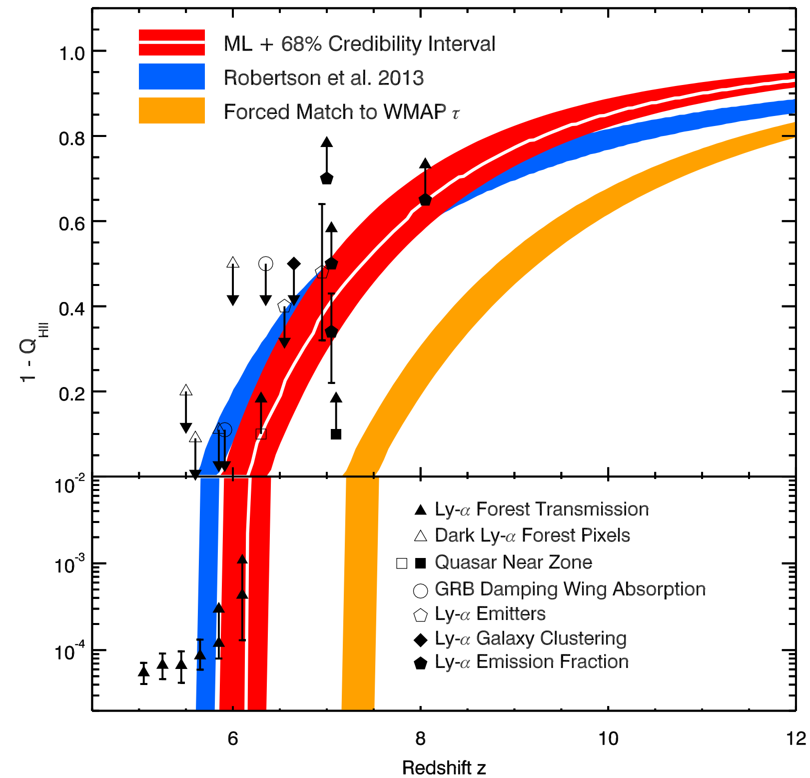
Census of galaxies now reaches to z~10 utilizing both blank fields and lensed surveys.



Robertson et al (2015)

Planck & HST: Reionization over 6 < z < 12





With various assumptions (f_{esc} = 0.2, ξ_{ion} consistent with UV slope β= -2, a LF extending to M_{UV}=-13) the HST-observed galaxy population can match Planck data with reionization largely contained with 10 < z < 6

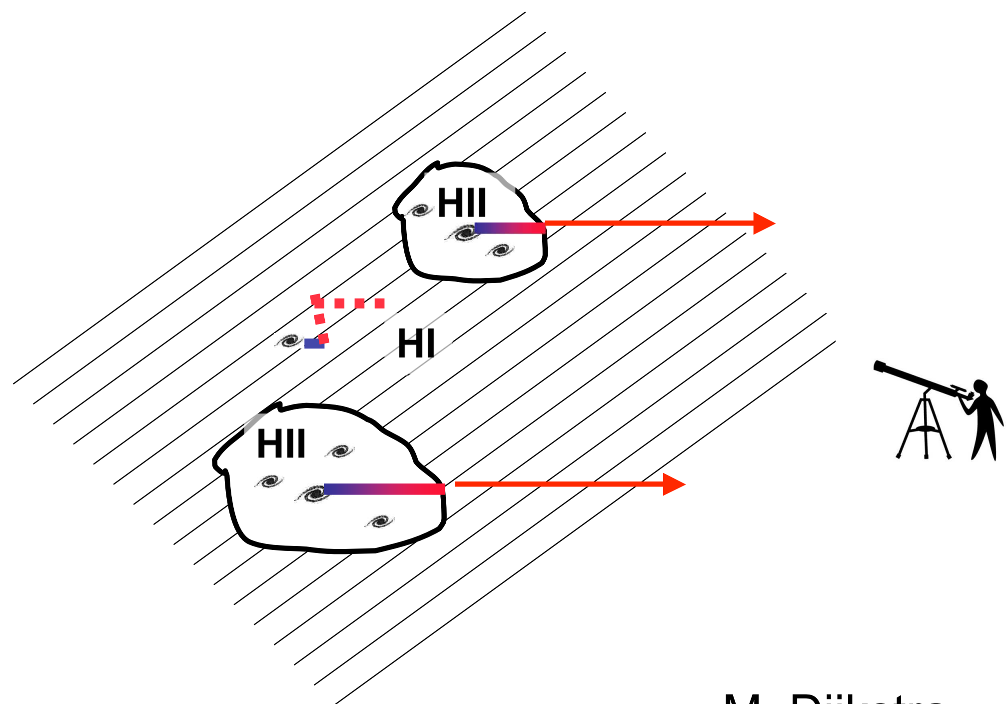
So how can we verify these assumptions? – SPECTROSCOPY!

Robertson et al (2015), see also Bouwens+(2015), Mitra+(2015)

Lyα Emission as a Probe of Reionization

Up to 6-7% of young galaxy light could emerge in Lyα:

- But resonant scattering by neutral gas reduces its visibility
- In a significantly neutral IGM, galaxy must lie in an ionized bubble in order for Lyα to escape
- Expect a sudden drop in the fraction of galaxies revealing line emission as enter the neutral era
- Caveats: dust, outflows etc



M. Dijkstra

Miralda-Escudé (1998), Santos (2004), Dijkstra+ (2007), McQuinn+ (2007)

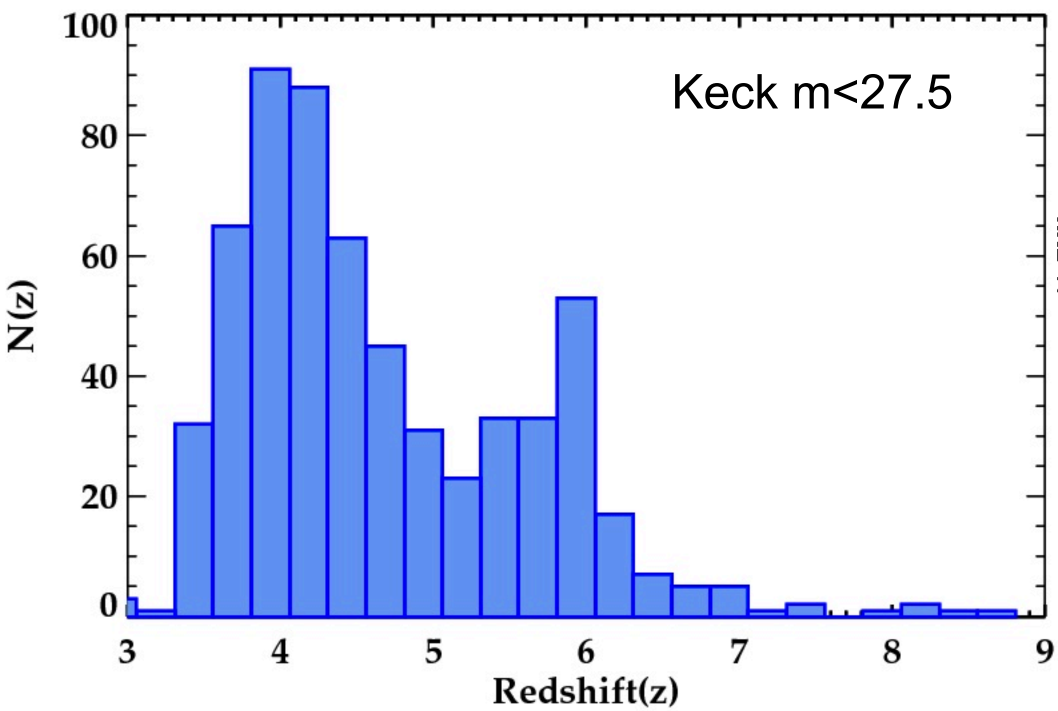
Keck Spectroscopic Survey 2009-2015

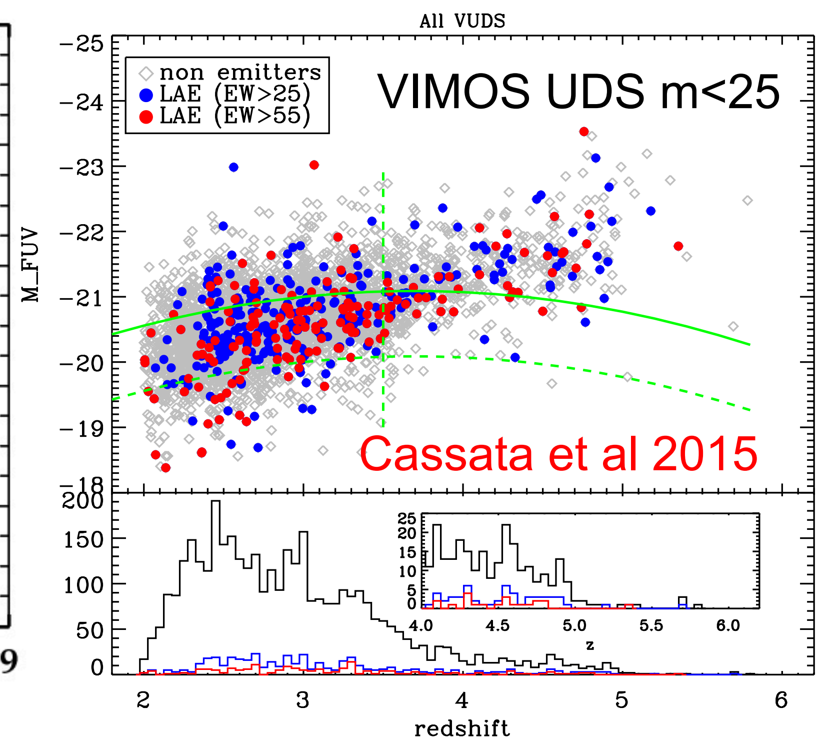
Targets: HST GOODS & CANDELS-UDS m_{AB}<27.5

DEIMOS 3<z<6; LRIS-R 6<z<7; MOSFIRE z>7

351 B + 201 V + 89 i + 40 z + 5 Y drops = 686 spectra

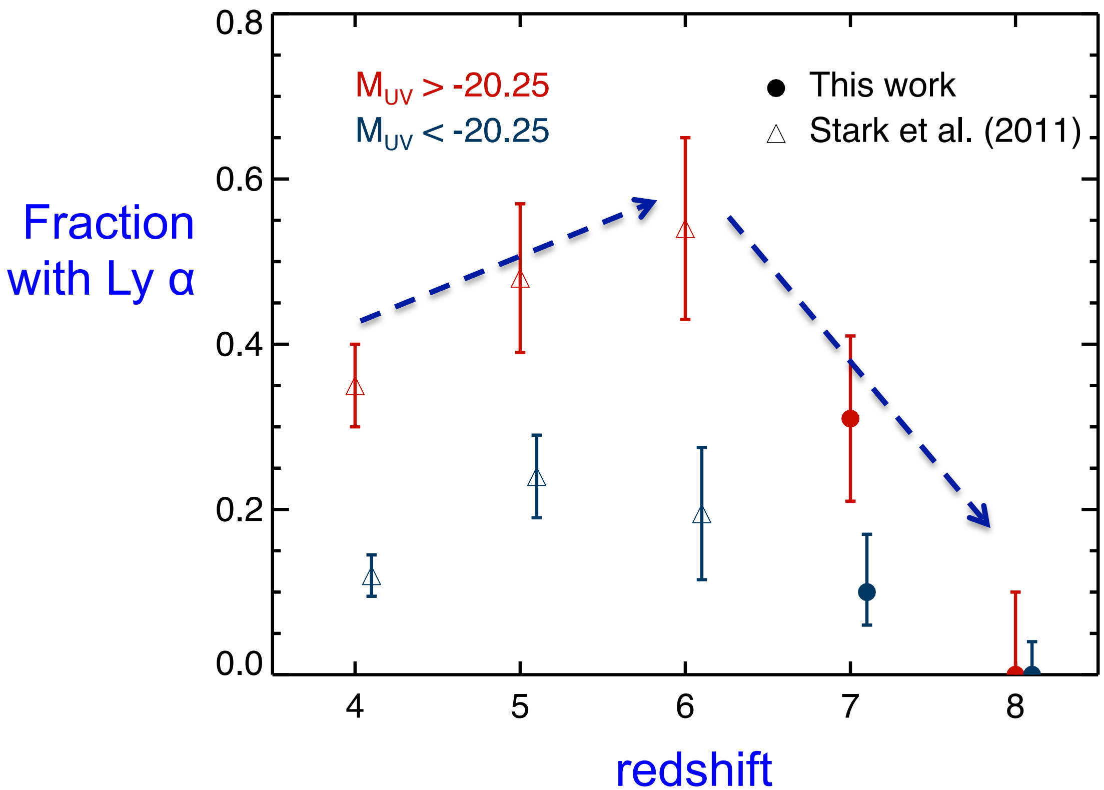
VLT/FORS2 retro-selected: 195 spectra (Vanzella et al)



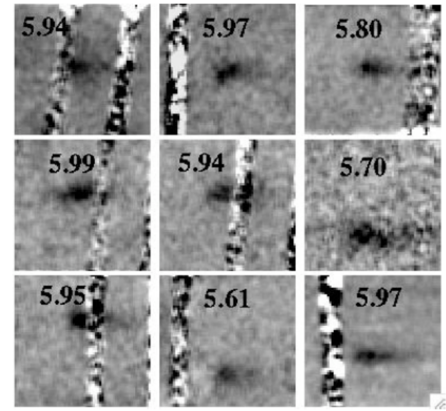


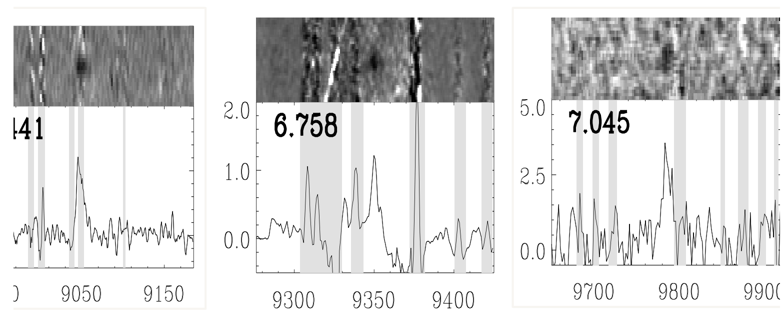
Stark et al (2009, 2010, 2011, 2013, 2015 in prep), Schenker et al (2012, 2014)

Confirmation: Lyα fraction declines sharply for z > 6



50% at z~6 are emitters





But <10% are emitters @ z > 7

Schenker et al (2014) – Keck MOSFIRE + UDF, CLASH 7<z<8.2

also Treu et al (2013) – Keck MOSFIRE + BoRG z~8

Finkelstein et al (2013) – Keck MOSFIRE + CANDELS z > 7

Tilvi et al (2014) – Keck MOSFIRE 7<z<8.2

Pentericci et al (2014) – VLT FORS 6<z<7.3

Schmidt et al (2015) – WFC3 grism z>7

Can this rapid decline in Lyα be understood?

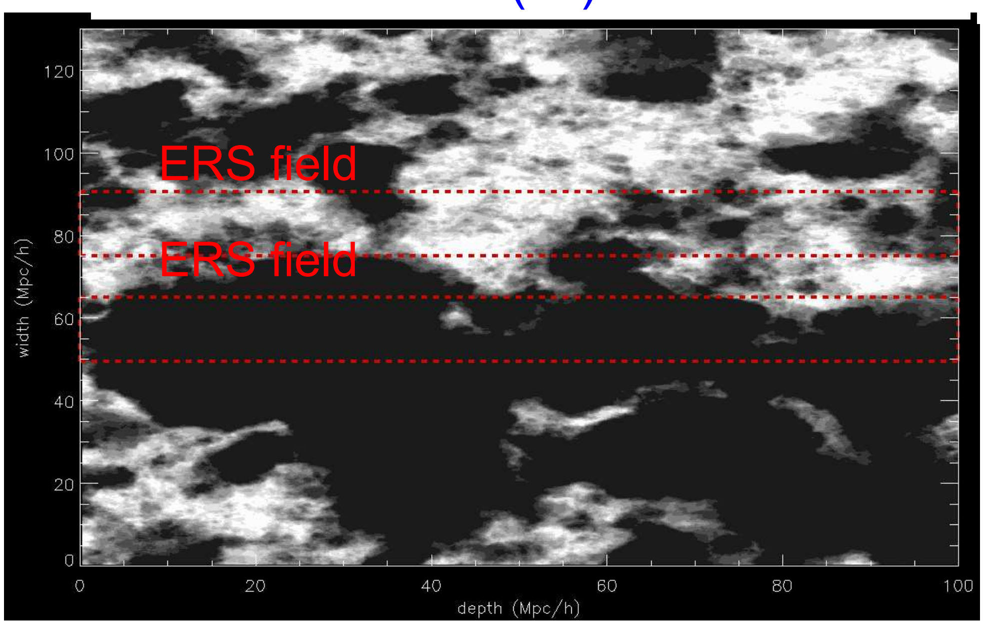
Δx(HI) ~ 0.3-0.5 in 200 Myr? Very rapid for WMAP, less so for Planck

Choudhury et al (2015), Mesinger et al (2015)

Other explanations:

- Low z contaminants: requires unreasonably high fraction (>50%)
- Cosmic variance: non-uniform X(Lyα, z) across fields
- Reduced Lyα velocity offset: reduces rapidity of reionization

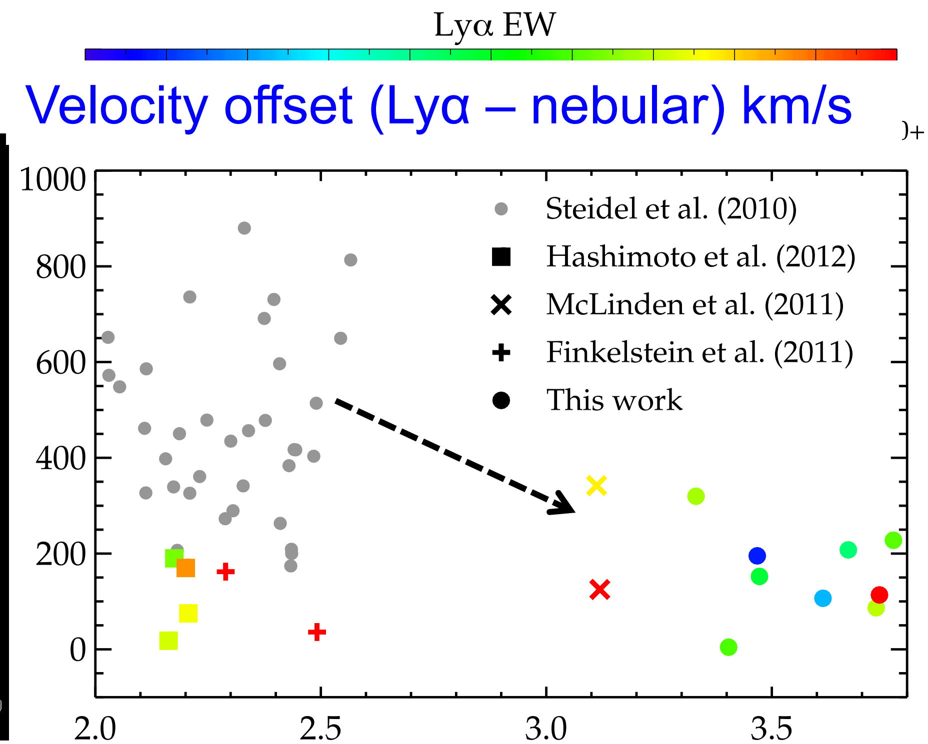
Simulation for <x(HI)>~0.2



depth (Mpc)➔

Taylor & Lidz (2014)

Velocity offset (Lyα – nebular) km/s



redshift

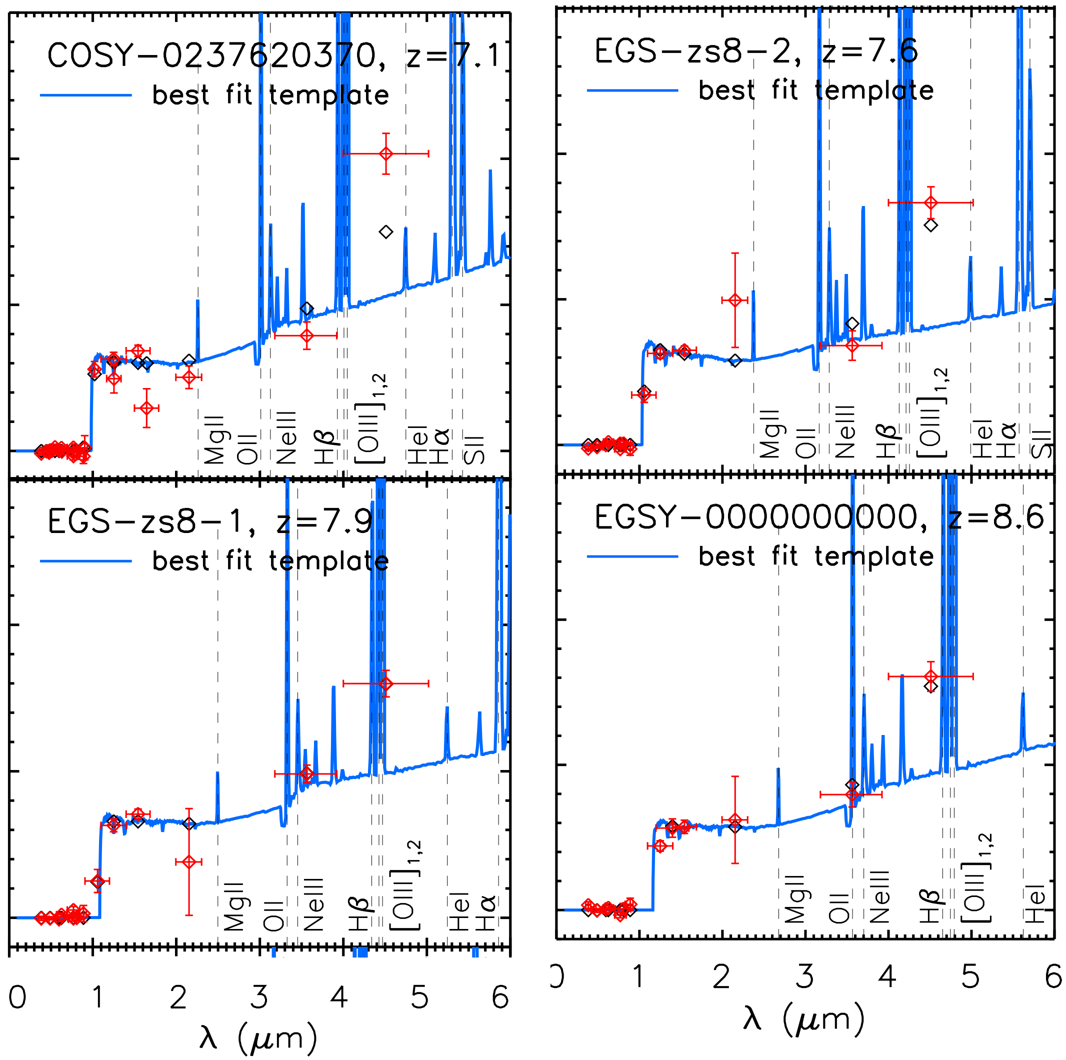
Schenker et al (2013)

A New Development !

Most z > 7 galaxies to date were selected primarily on the basis of a strong Lyman continuum drop and a blue rest-frame UV continuum. As we have seen, few show Lyα

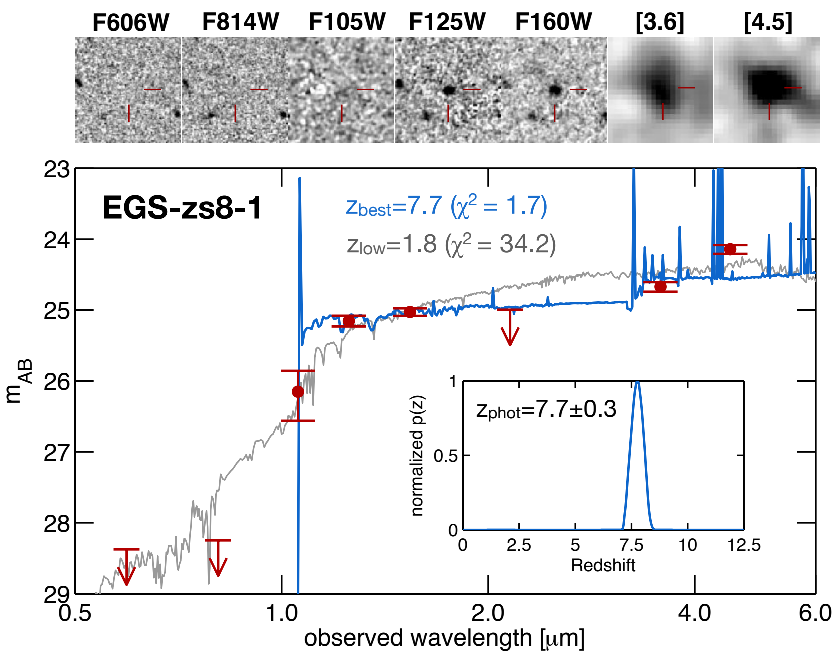
But for 7 < z < 9 [O III]/Hβ pollutes the 4.5μm IRAC band. Selecting sources with a strong 4.5μm excess targets intense line emitters

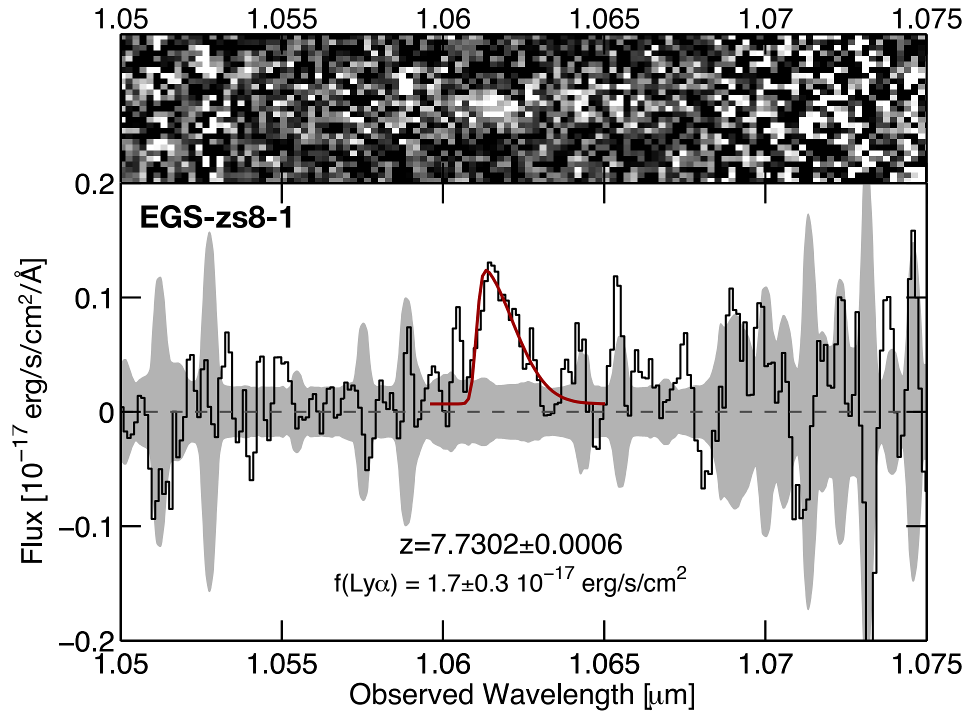
4 such luminous objects (H~25) located in CANDELS fields



Roberts-Borsani et al (2015)

Redshift Record May 2015: EGS-zs8-1 at z=7.73

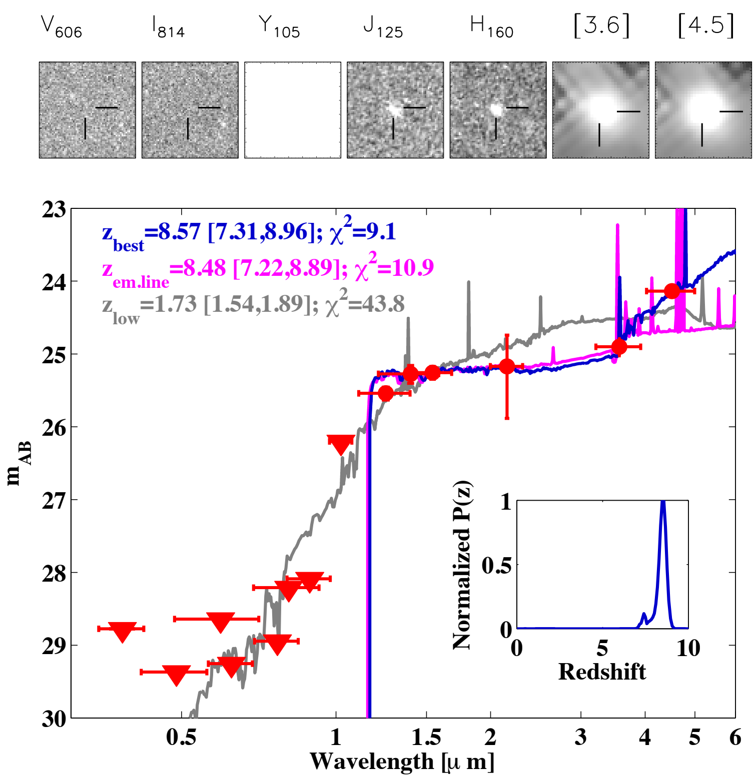


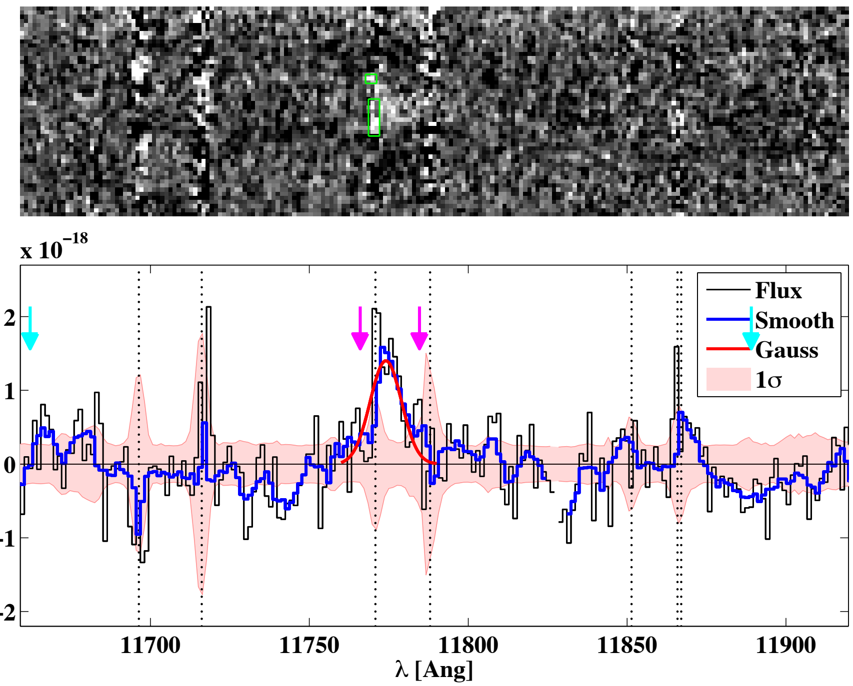


- Luminous LBG in CANDELS fields at H=25.0 with 4.5μm excess
- Robust spectrum in only 2 hours with MOSFIRE!
- z_{phot} = 7.92 ± 0.36; z_{spec}= 7.73; Lyα EW ≈ 21 Å

Oesch et al (2015)

Redshift Record July 2015: EGSY8p7 at z=8.68





- Luminous LBG in CANDELS fields at H=25.3 with 4.5μm excess
- Good spectrum in only 4.3 hours with MOSFIRE
- Z_{phot} = 8.57 ± 0.3; Z_{spec}= 8.68; Lyα EW ~ 30 Å

Now confirm EGS-z38-2 z(Lyα)=7.477, COSMOS z(Lyα)=7.15 (Stark et al (2016)!

Zitrin et al (2015)

Sources with extremely strong ionizing radiation?

TABLE 2
A COMPLETE LIST OF THE RESULTING Z≥7 SOURCES IDENTIFIED AFTER APPLYING OUR SELECTION

ID	R.A.	Dec	m_{AB} [a]	[3.6]-[4.5]	z_{phot} [b]	$Y_{105} - J_{125}$ [c]
COSY-0237620370	10:00:23.76	02:20:37.00	25.06±0.06	1.03±0.15	$7.14\pm^{0.12}_{0.12}$	−0.13±0.66
EGS-zs8-1	14:20:34.89	53:00:15.35	25.03±0.05	0.53±0.09	$7.92\pm^{0.36}_{0.36}$	1.00±0.60
EGS-zs8-2	14:20:12.09	53:00:26.97	25.12±0.05	0.96±0.17	$7.61\pm^{0.26}_{0.25}$	0.66±0.37
EGSY-2008532660	14:20:08.50	52:53:26.60	25.26±0.09	0.76±0.14	$8.57^{+0.22}_{-0.43}$	

4/4 sources with z_{phot} > 7.5 with 4.5μm excess show prominent Lyα !
EGSY8p7 at z=8.68 shows Lyα where IGM is expected to be ~60% neutral
At lower redshift such luminous galaxies are <u>less</u> likely to have strong Lyα

How can this be???

They could be a different class of galaxy with unusually strong radiation fields which have created early ionized bubbles. Conceivably such luminous early galaxies contain AGN or unusually hot stellar populations?

Did Galaxies Reionize Universe?

Ionization rate $\dot{n}_{\rm ion} = \boxed{f_{\rm esc}\xi_{\rm ion}\rho_{\rm UV}}$

Recombination time $t_{\rm rec} = [C_{\rm H\,II}\alpha_{\rm B}(T)(1+Y_{\rm p}/4X_{\rm p})\langle n_{\rm H}\rangle(1+z)^3]^{-1}$

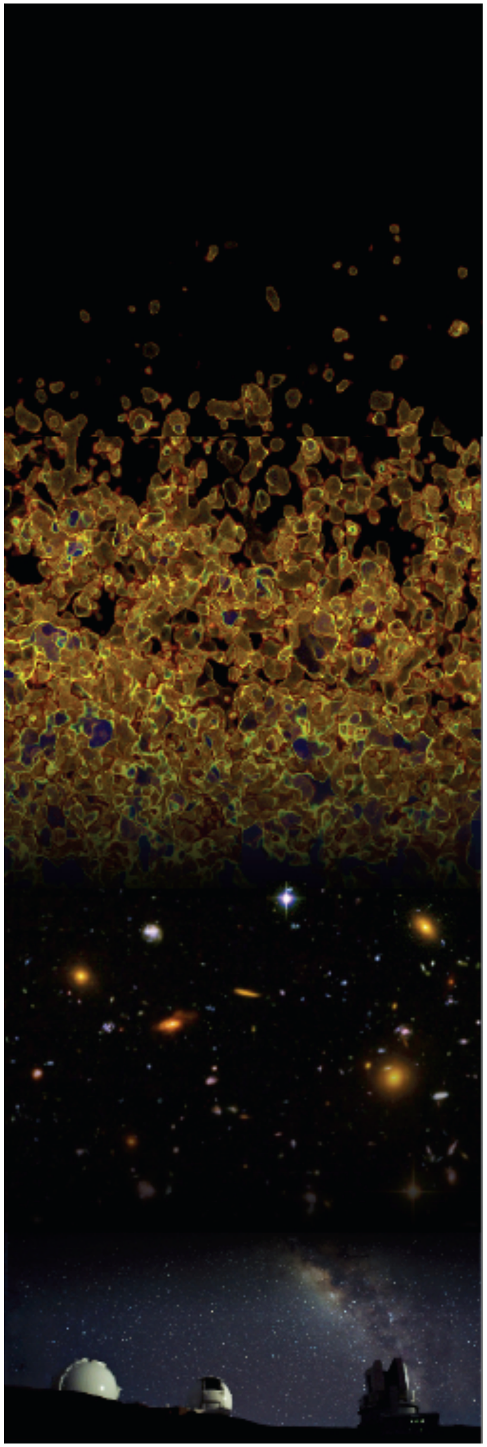
Key observables:

1. Integrated abundance of high z star-forming galaxies especially contribution of low luminosity sources : ρ_{UV}

2. Nature of the stellar populations in distant galaxies which determines the rate of ionizing photons: ξ_{ion}

3. Fraction of ionizing photons that escape: f_{esc}

4. Optical depth of electron scattering to CMB: τ

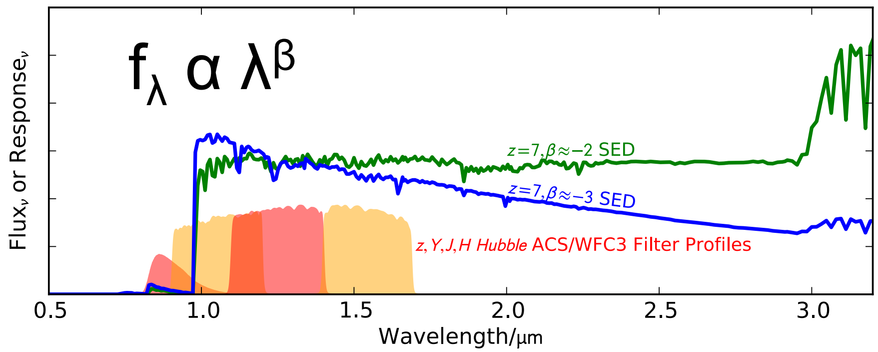


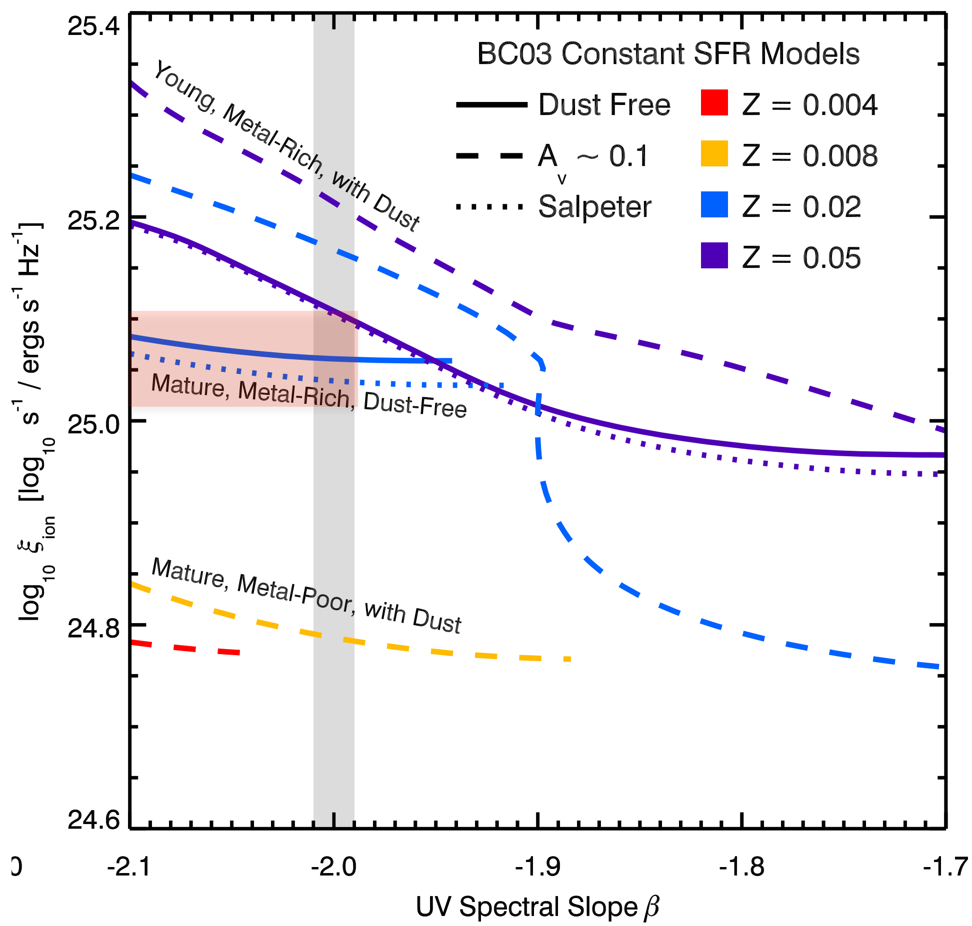
Ionising to UV Photon Ratio ξ_{ion}

UV continuum slope β measured using HST colours distinguishes between:

(i) metal-poor galaxies with steep UV continua, i.e. **large ξ_{ion}**

(ii) metal-enriched systems with flatter spectral slopes, i.e. **lower ξ_{ion}**





z~7-8 galaxies show a uniform slope **β=-2** consistent with mature (>100 Myr) enriched stars and

log ξ_{ion} ~25.1 (cgs)

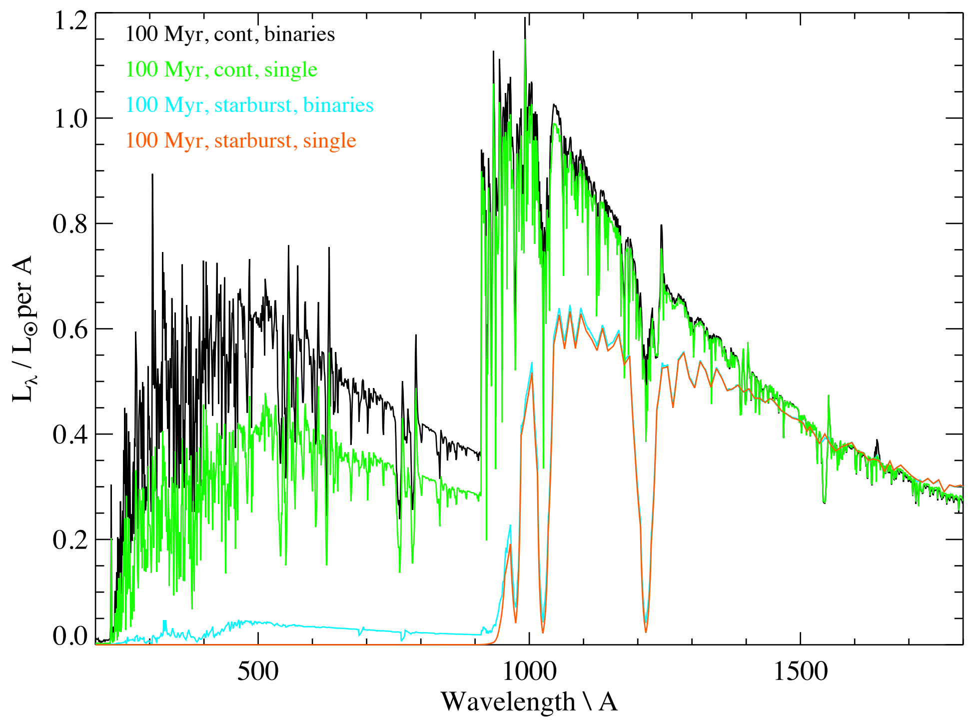
but ambiguities remain depending on composition, dust and IMF.

Dunlop et al (2013), Roberston et al (2013)

Do We Understand Stellar Evolution Well Enough?

Given the UV continuum slope @ 1500 A can we predict the Lyman continuum flux?

Degeneracy in spectral energy distributions

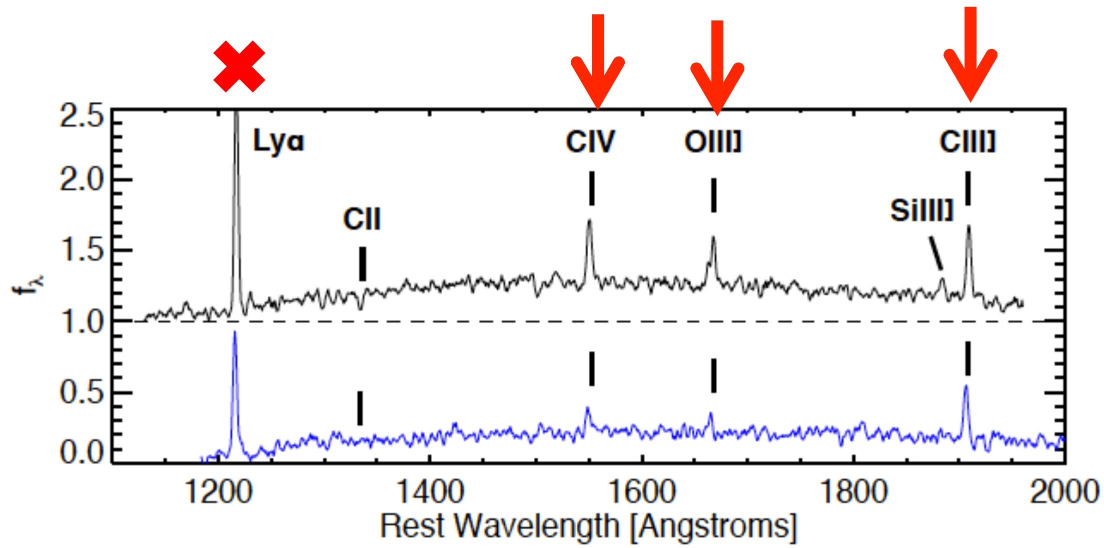


Imponderables include: stellar initial mass function, rotation in hot MS stars, effect of binaries etc…all have significant effect on ξ_{ion}

Stanway et al (2015)

More Robust Diagnostics with UV Metal Lines

Spectra of lensed $10^{6\text{-}9}$ $M_\odot$ z~2-3 galaxies similar to those at z~7



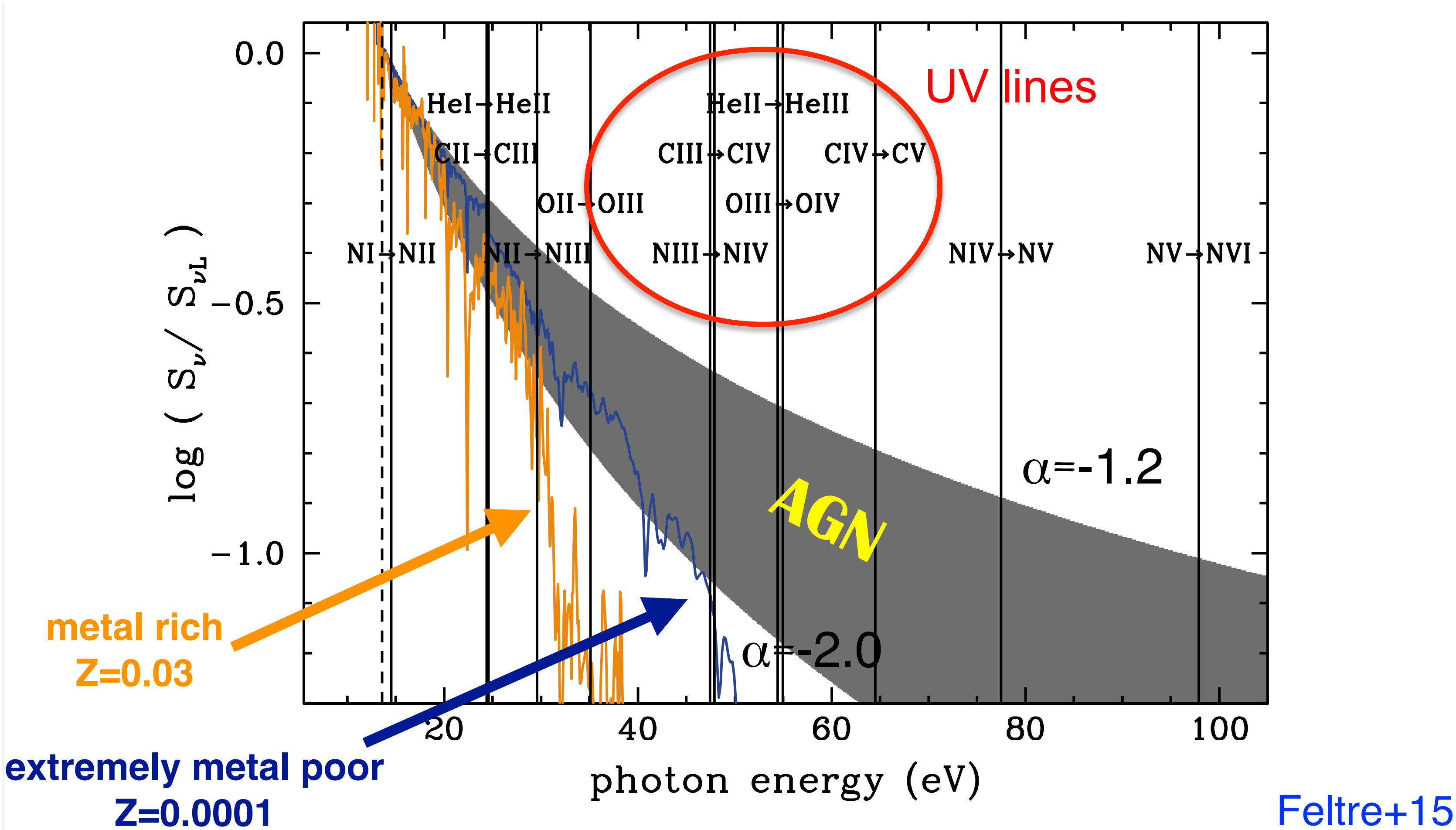
Key lines include:

- CIV 1548 Å   48 eV
- O III] 1664 Å 35 eV
- CIII] 1909 Å   29 eV

These are prominent in metal-poor systems reflecting harder ionizing spectra so valuable indicators of ξ_{ion} in early stellar populations

Stark et al (2014)

Important UV Emission Lines

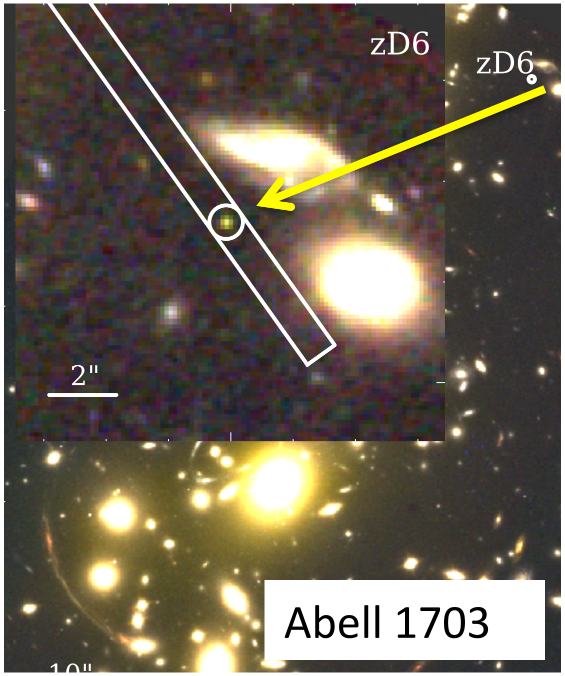


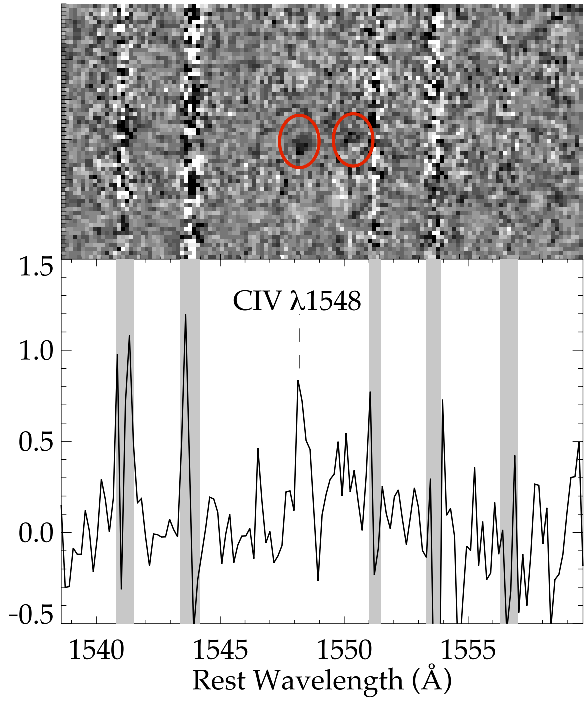
Two grids of photoionization models predicting nebular emission line ratios:

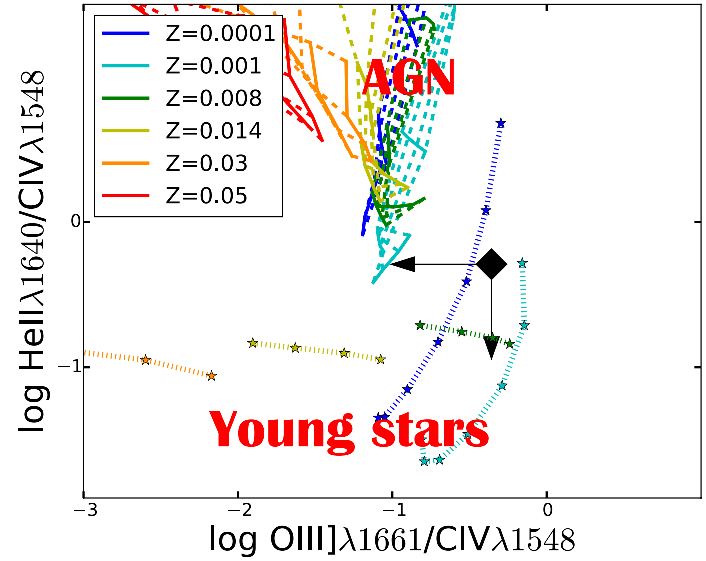
Young stars: CB15 (new tracks, WR stars) + CLOUDY (Gutkin et al 2015)

AGN-driven: Power law $F(\nu) \sim \nu^{\alpha}$ + CLOUDY (Feltre et al 2015)

Illustration: CIV Doublet in z ~ 7.045 Galaxy





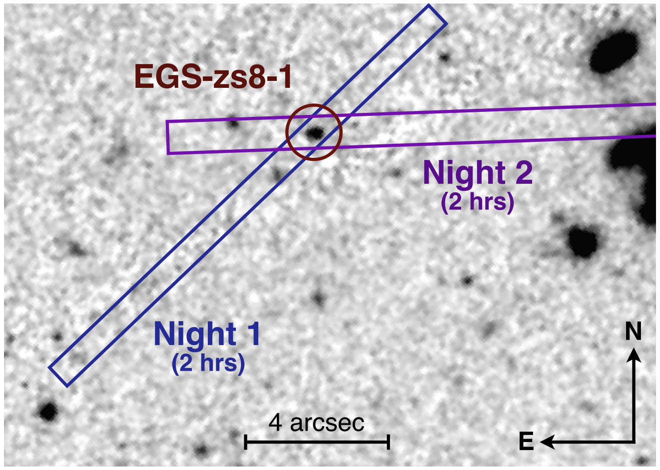


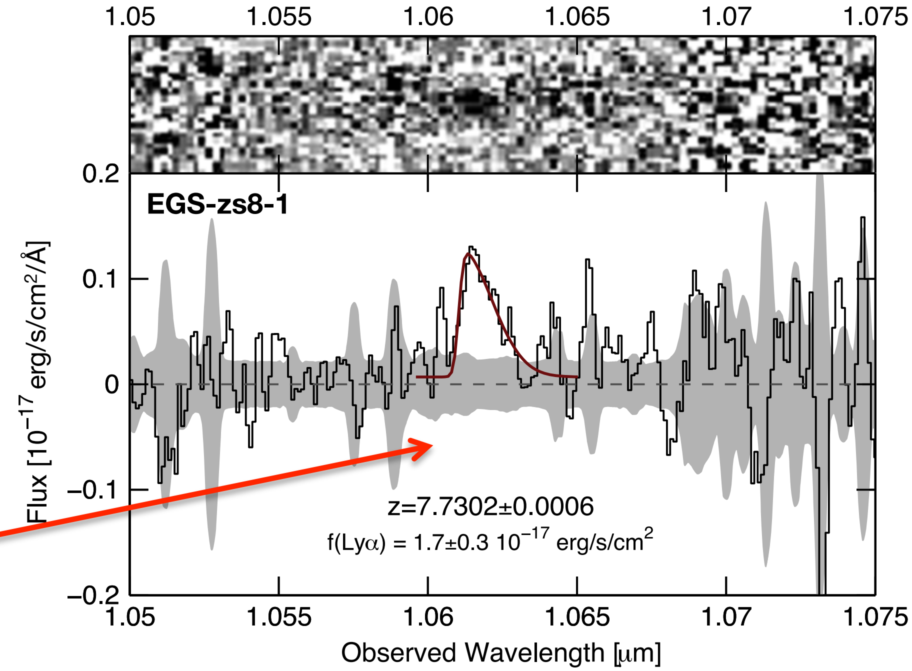
CIV / Lyα ratio much stronger than in z~2 sample – what does this mean?

- High ionisation parameter ξ_{ion} = 25.5 ± 0.16
- Low metallicity: ~0.01 solar

Stark et al (2015)

CIII] at z=7.73

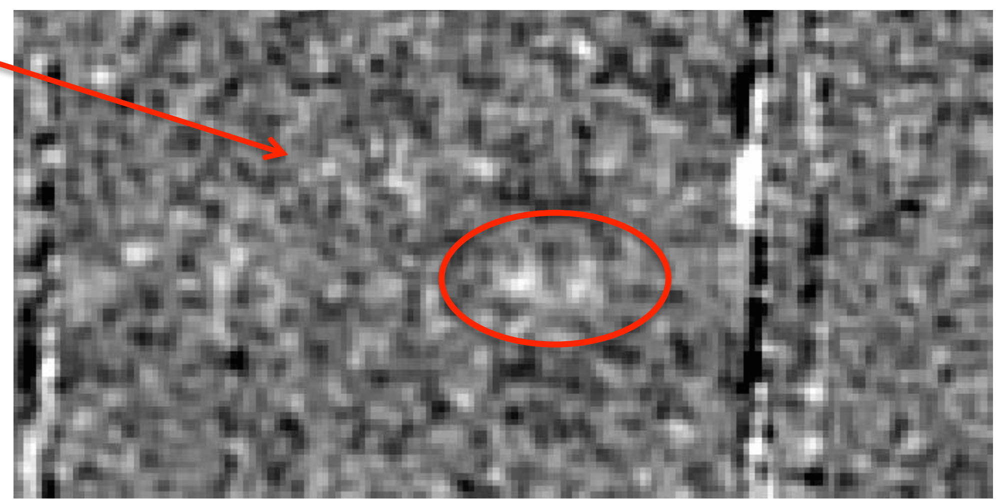




Lyα at z=7.73 Oesch et al (2015)

Detection of CIII] doublet – April/June 2015

CIII] 1909/1905 line ratio is a valuable indicator of the electron density and hence, together with UV luminosity can constrain the production rate of ionizing photons.

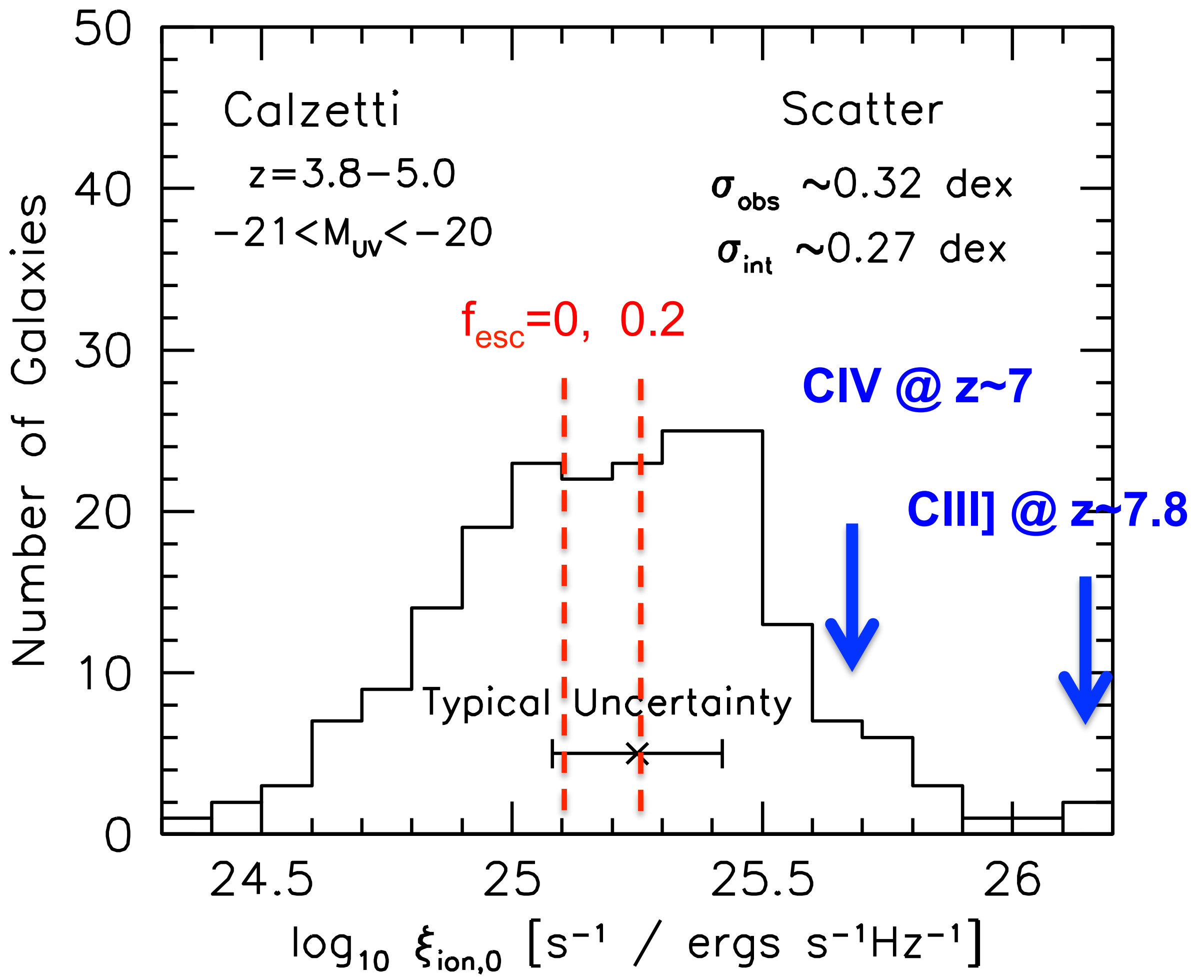


An Alternative Route to ξ_{ion}

Can also derive ξ_{ion} by estimating the strength of Hα from Spitzer photometry in SEDs of z~4-5 galaxies and thereby infer the production rate of Lyman continuum photons.

The calculation must assume f_{esc} (the other big unknown) although the dependence is not that sensitive

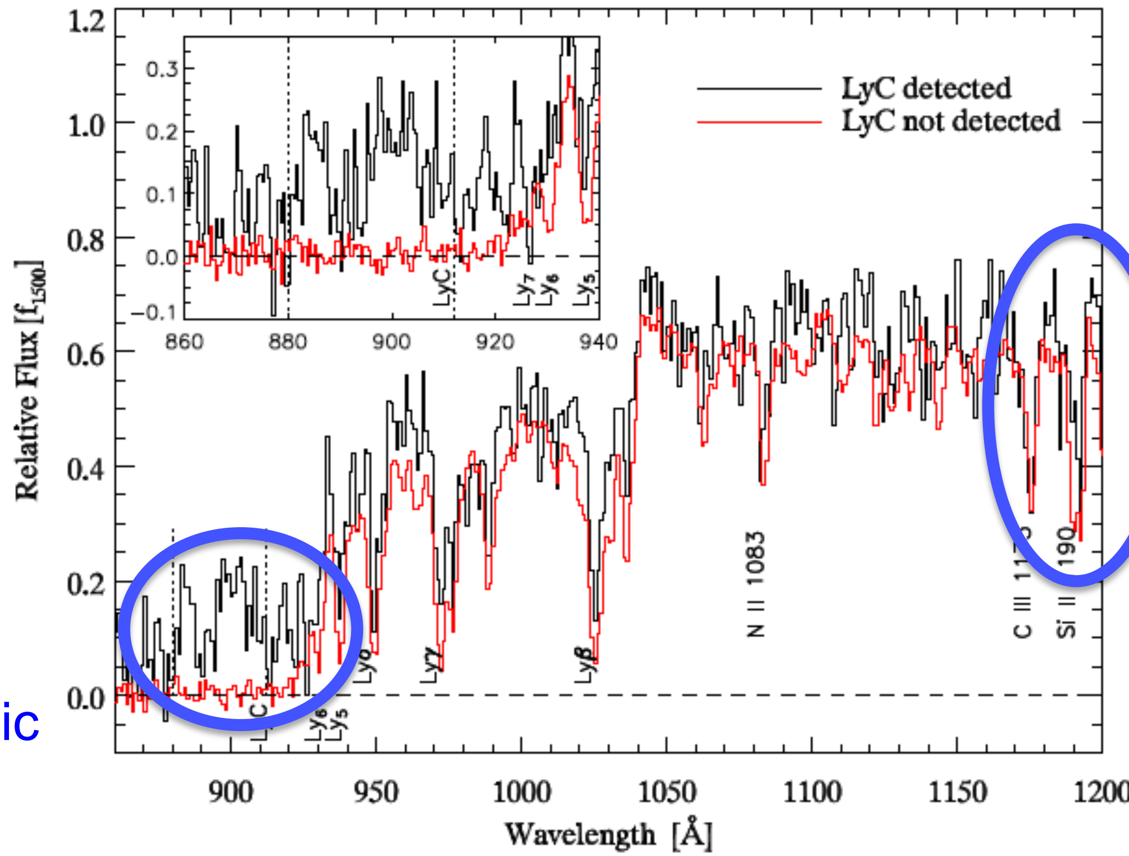
Result: <log ξ_{ion}> ~ 25.2



Bouwens et al (2015)

Escape Fraction of Ionising Photons f_{esc} @ z~2

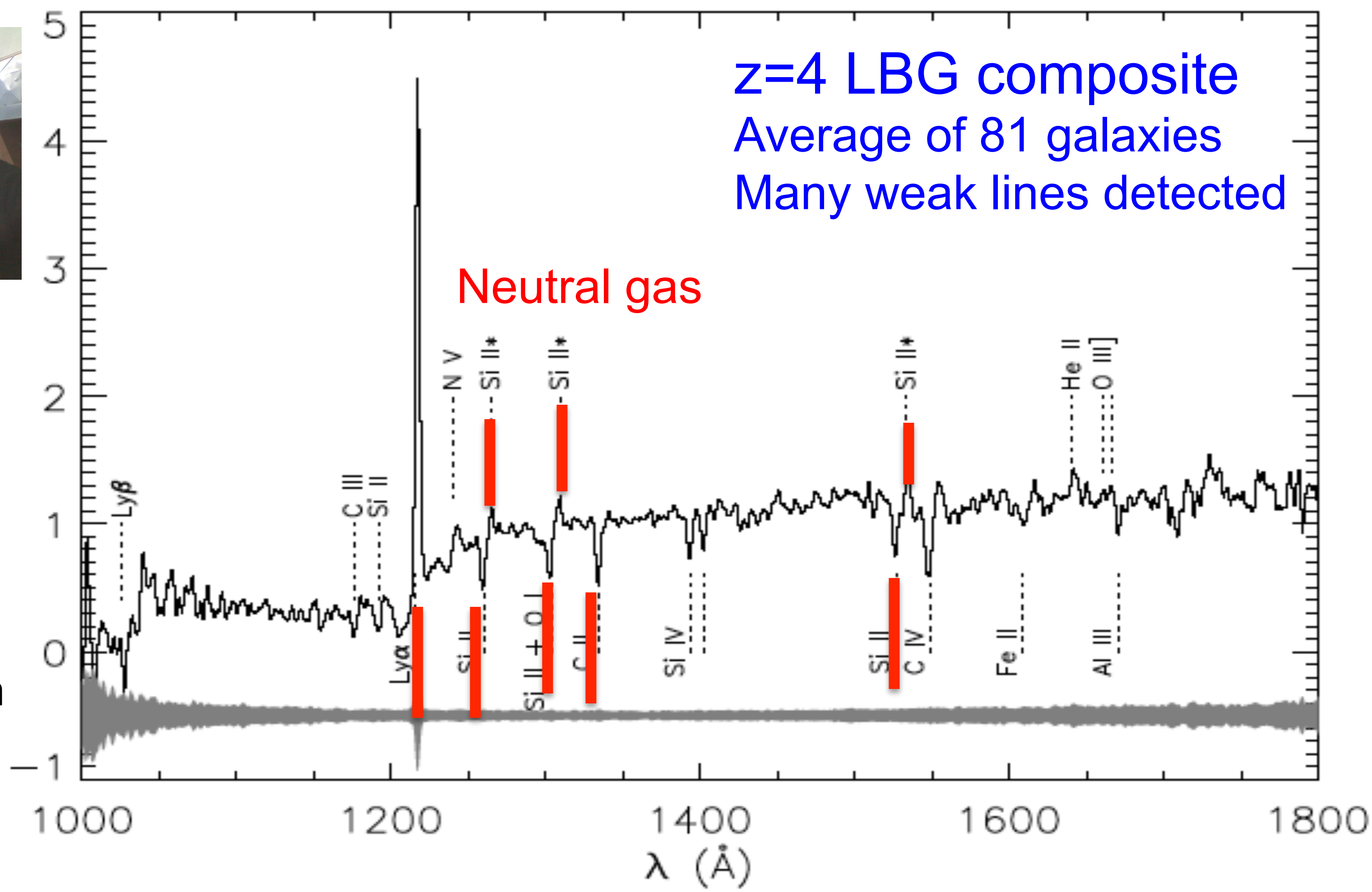
Escaping ionizing radiation at z=3 (Bogosavljevic thesis)



Weaker low-ionization absorption in sources with escaping ionizing flux

- f_{esc} estimated via spectroscopic or UV imaging below Lyman limit (e.g. Nestor et al 2013)
- Impractical for high z galaxies due to intervening absorption by Lyα forest
- Consider low-ionization absorption lines which trace the HI covering fraction whence $f_c = 1 - f_{esc}$

Outflowing Neutral Gas as probe of f_{esc}

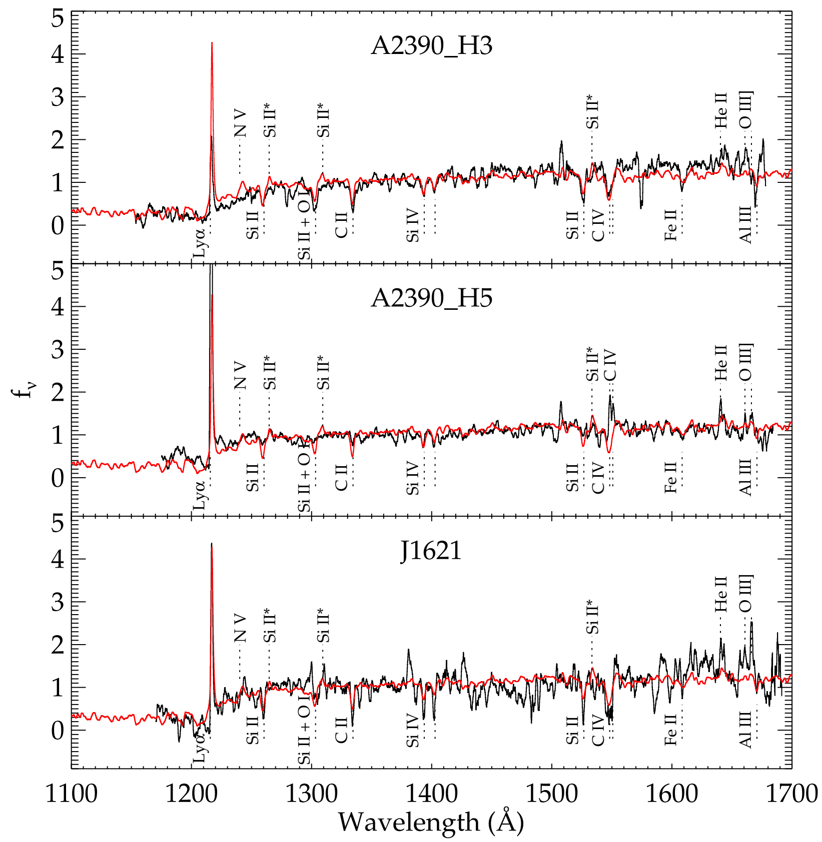


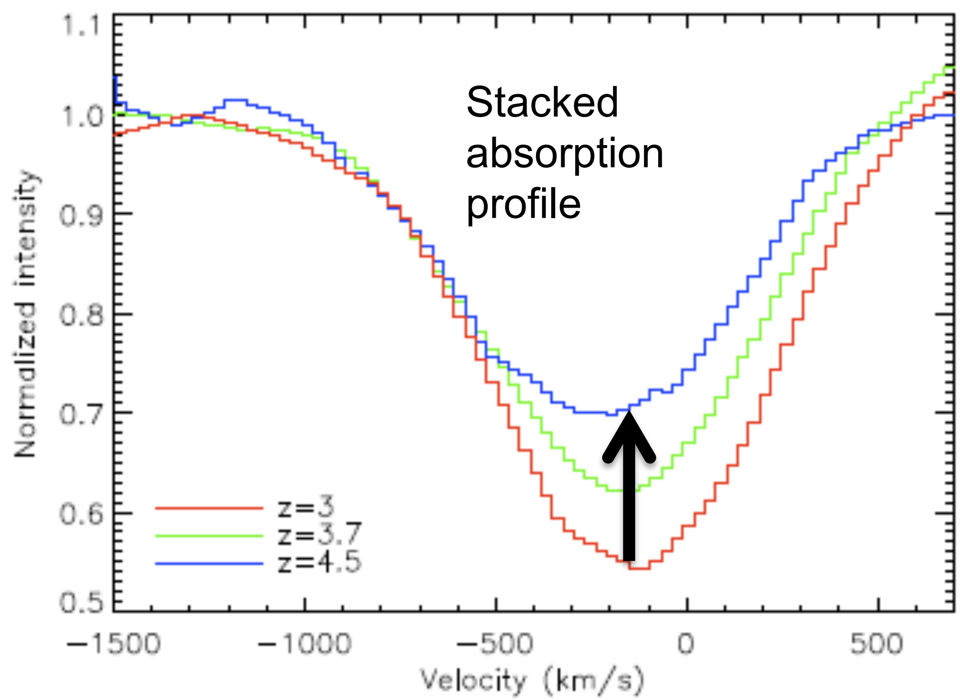
By stacking Keck spectra we can detect weak low ionisation absorption from neutral outflowing gas

EW of low ionisation line gives covering fraction of neutral gas $f_c = 1 - f_{esc}$

Jones et al (2012,2013)

Reduced Covering Fraction of HI at high z?



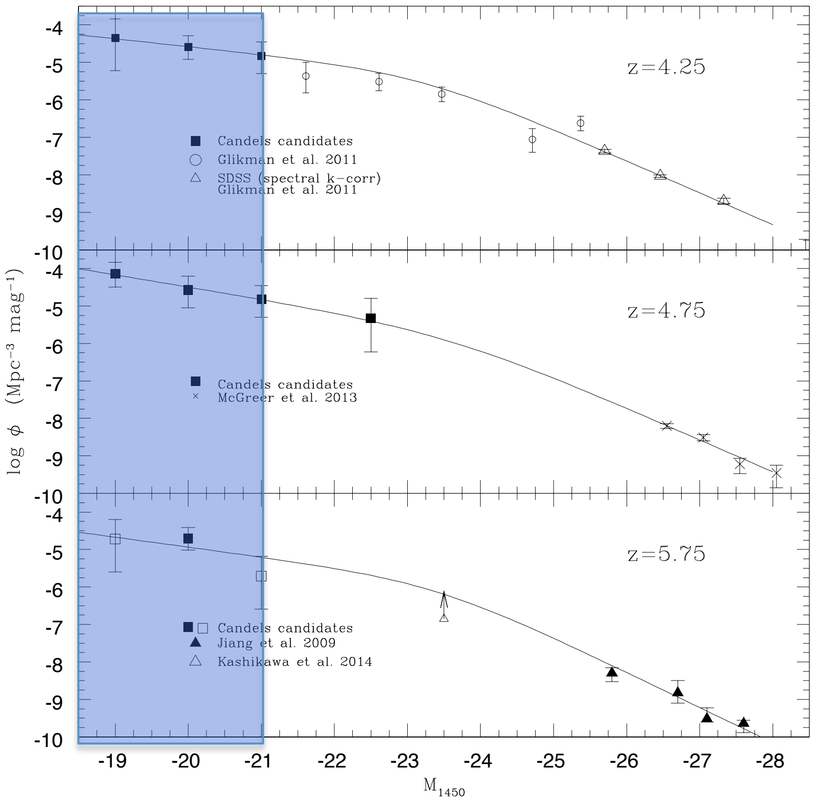


- Using 8 lensed LBGs with 2.5<z<4.5 observe EW of low ionisation lines decreases with increasing redshift
- Suggests escape fraction is slowly increasing with redshift (from 5 to 12%)
- Radiation pressure leads to `cometary like' structures in simulated high z galaxies implying favourable geometries for escaping photons)

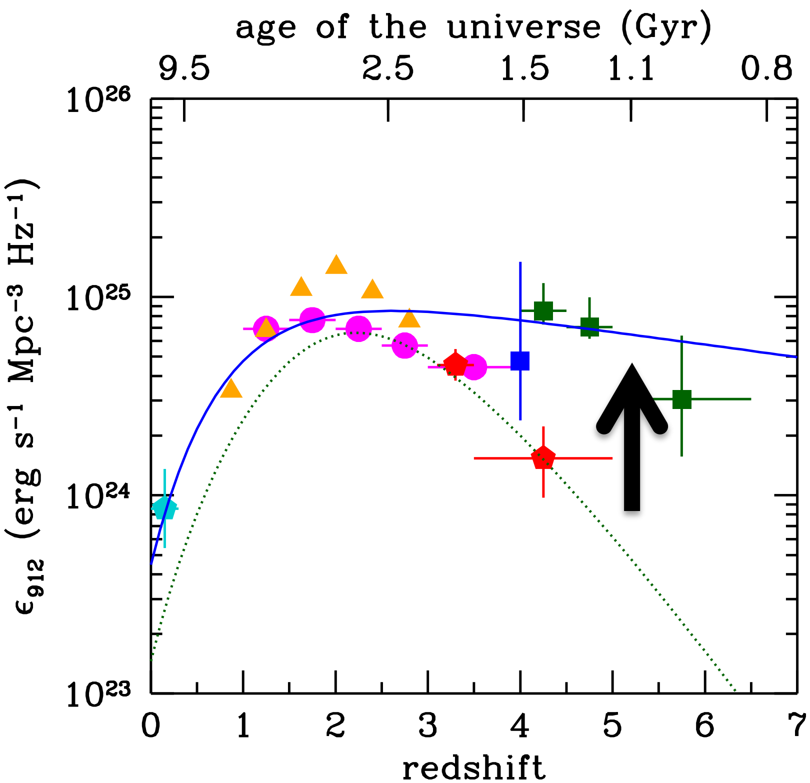
Jones et al (2012, 2013)

Other Sources of Ionising Photons: – An Italian Viewpoint

UV Luminosity Function of AGN



Integrated ionising emissivity



Recent estimates of number of faint AGN and, assuming f_{esc}=1, implies a significant contribution to reionizing photons from non-thermal sources.
Key issue is whether all UV light is non-thermal?

Giallongo et al (2015), Madau & Hardt(2015)

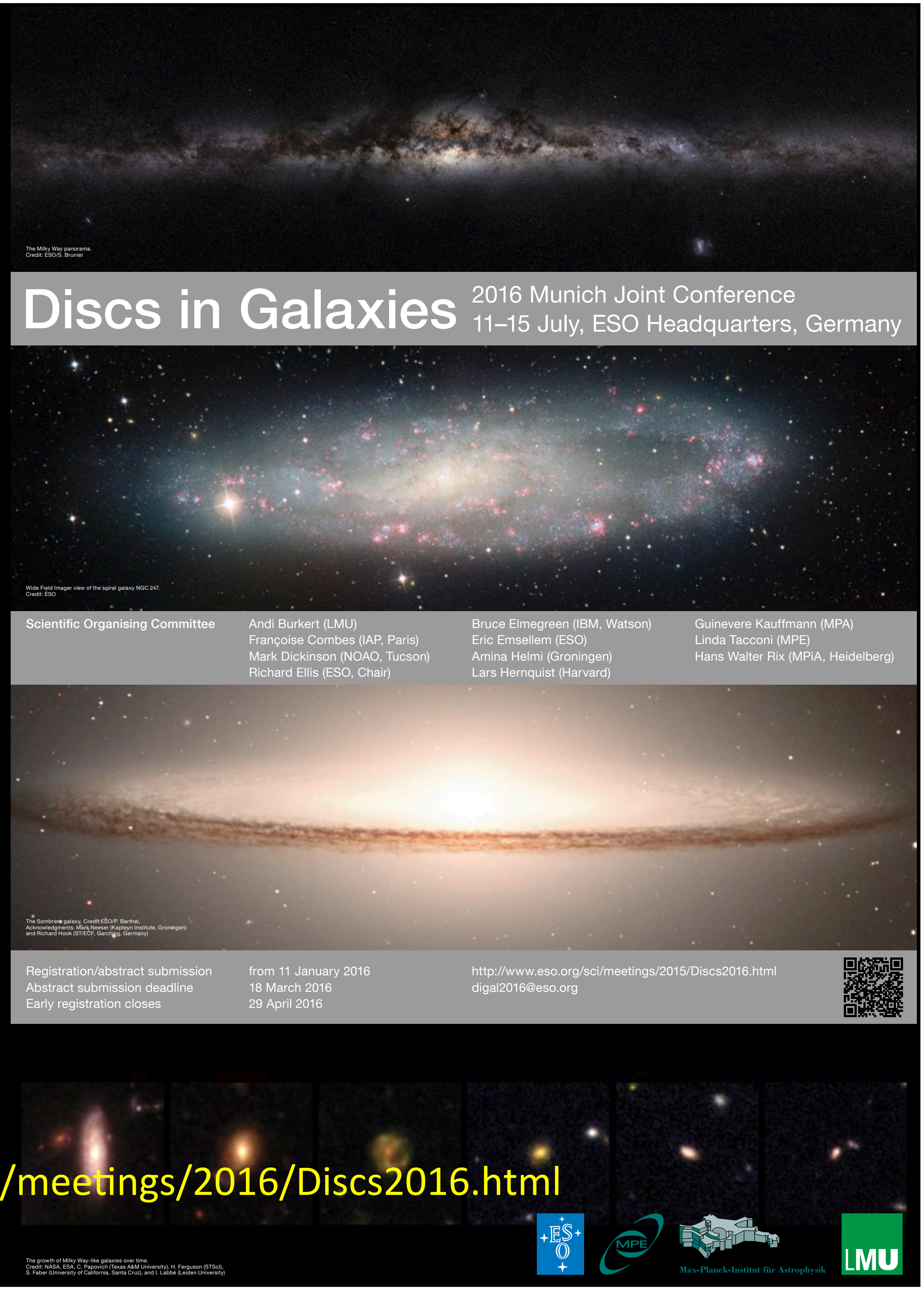
Summary

- Analysis of Planck CMB data has led to a significant revision of when reionisation occurred. Now imagine it began at z~10-12 and ended at z~6 increasing the likelihood that galaxies played a significant role in the process
- Until recently, the sharply-declining fraction of HST-selected galaxies with z > 7 showing the Lyman alpha emission line confirmed reionization ended at z~6 given it is hard to see in the neutral era.
- However, a new “population” (ok..4/4 sources) of luminous [O III] emitting galaxies at z>7.5 are now found with detectable Lyman alpha? Are these a distinct early population with more efficient and harder ionizing spectra?
- Tracking UV metal lines will help quantify the radiation field and see if it comes from unusually hot stars or AGN?
- Spectroscopy holds the key to resolving the two outstanding questions relating to the role of galaxies in cosmic reionization. All key lines are within reach of JWST and ground-based telescopes for most of the reionization era

Munich Joint Conference 2016
“Discs in Galaxies”
11 – 15 July 2016

Invited Speakers:

Maria Bergemann
Fréderic Bournaud
Jo Bovy
Richard Bower
Kevin Bundy
Bruce Elmegreen
Annette Ferguson
Shy Genel
Reinhard Genzel
Tucker Jones
Mark Krumholz
Drew Newman
Florent Renaud
Eva Schinnerer
Rowan Smith
Steffi Walch
Risa Wechsler



http://www.eso.org/sci/meetings/2016/Discs2016.html