Spectroscopic Studies of Galaxies in the Reionization Era

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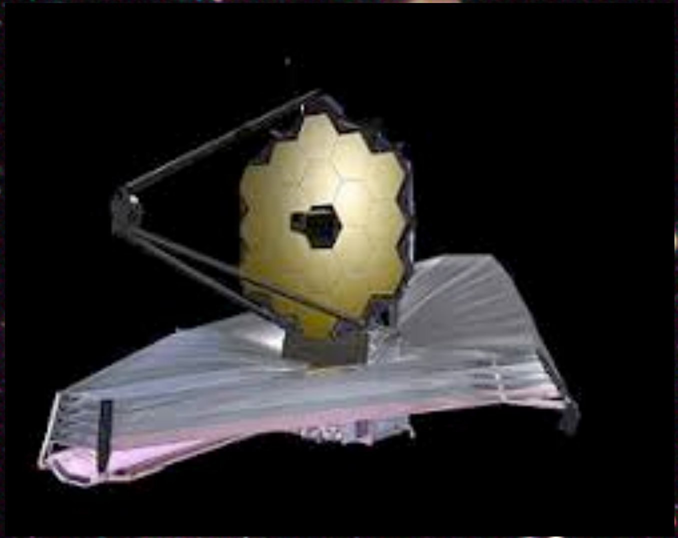


JWST@ESTEC

October 12th 2015

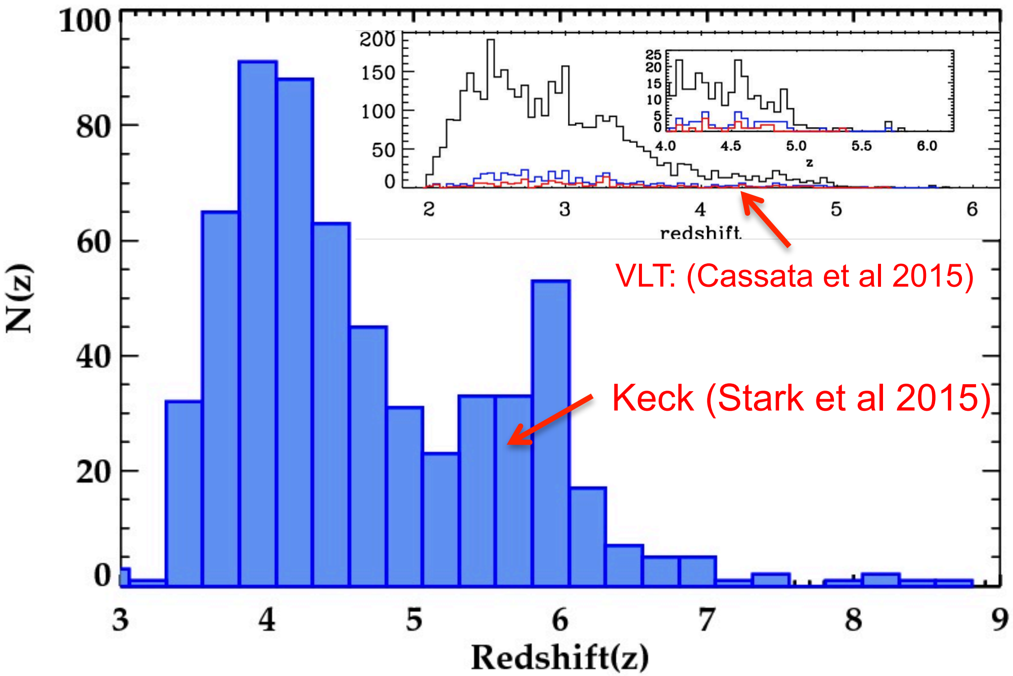
Ground-Space Synergy 1993-2015

Hubble Space Telescope

Ground-based 8-10m telescopes

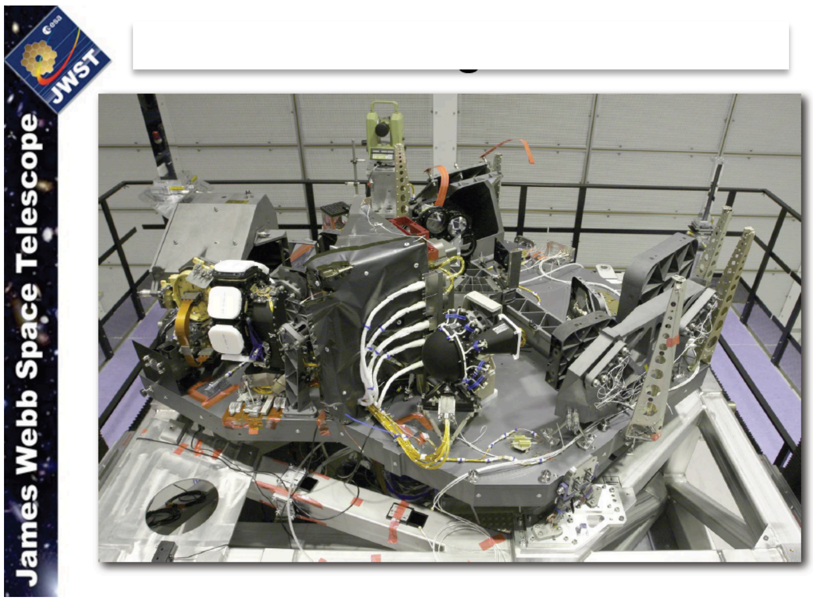
Precision/resolved optical/NIR imaging

Spectroscopy (redshifts, physical properties)

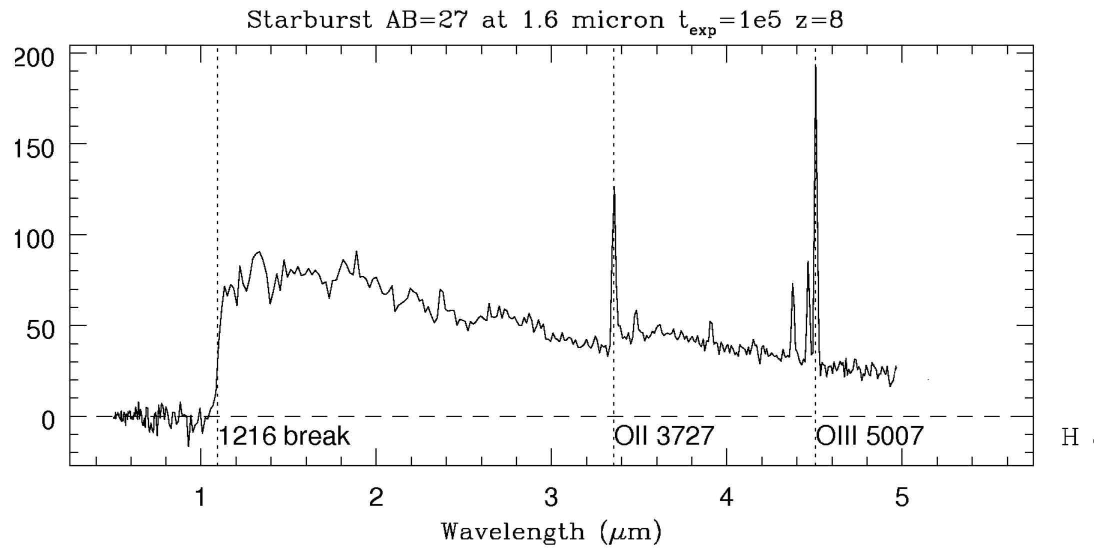


Ground-Space Synergy 2020s: JWST Spectra

NIRSpec



z=8 galaxy; 25 hour exposure



JWST spectroscopy will measure stellar continuum & composition of gas in z ~ 8+ galaxies using UV and optical lines longward of 2 microns beyond reach of current & future ground-based telescopes

Ground-Space Synergy 2020s: ELT AO Imaging

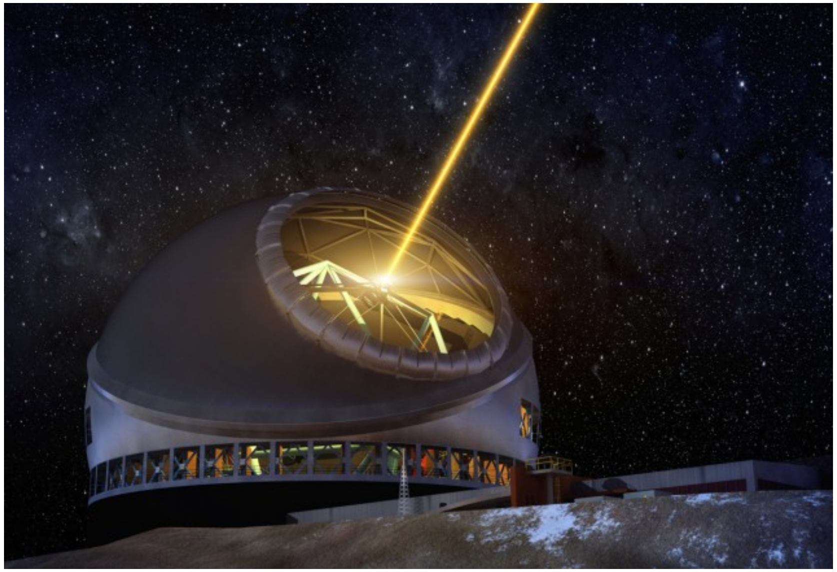
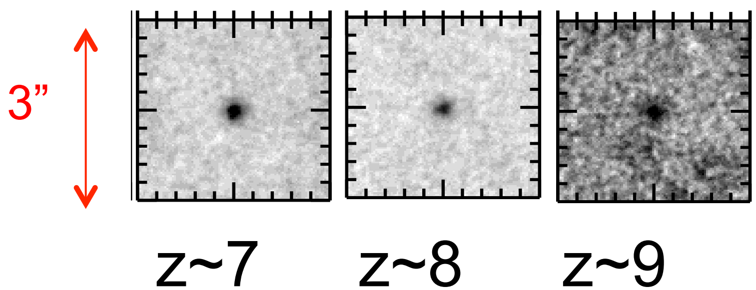
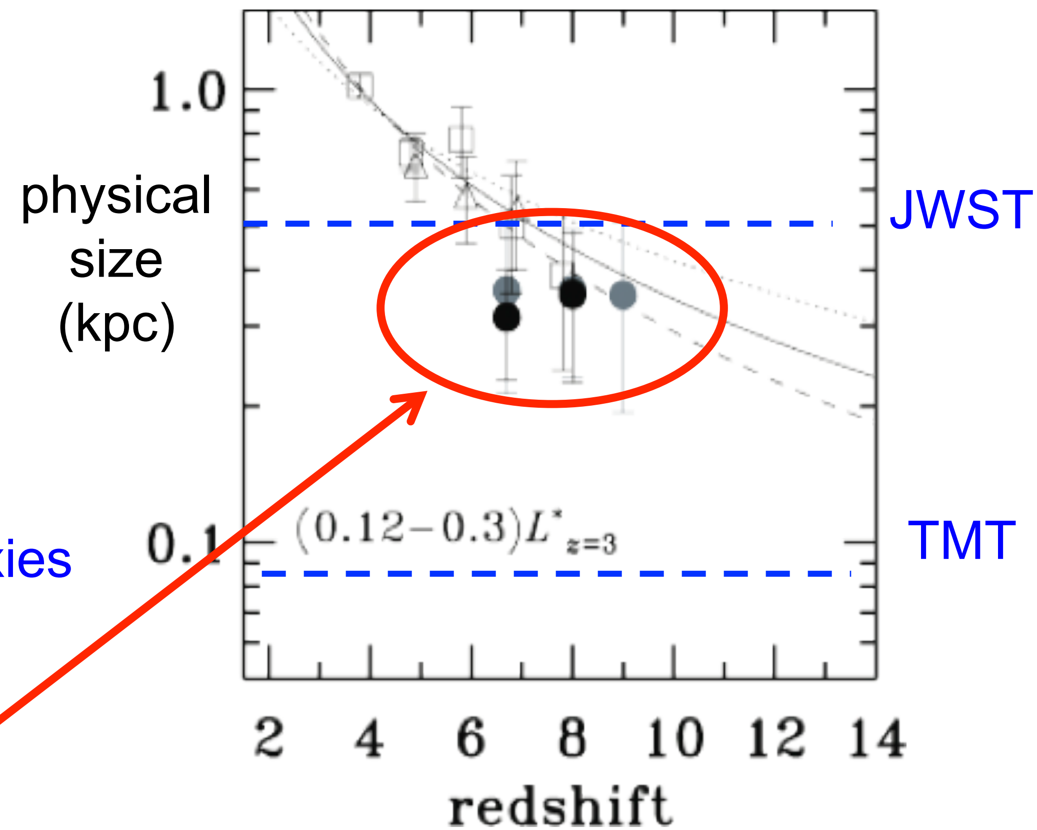


Image stacks for faint Hubble galaxies

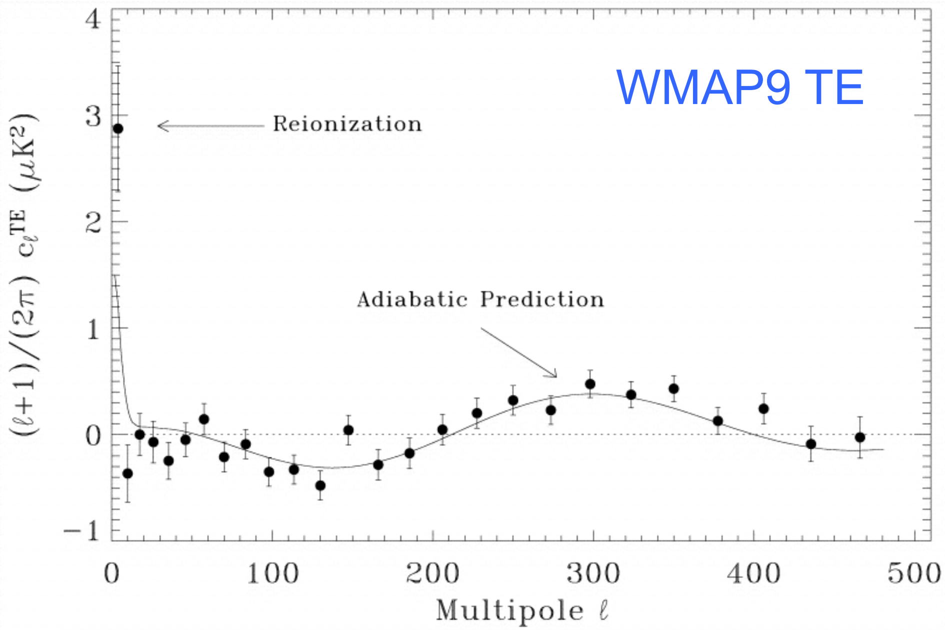


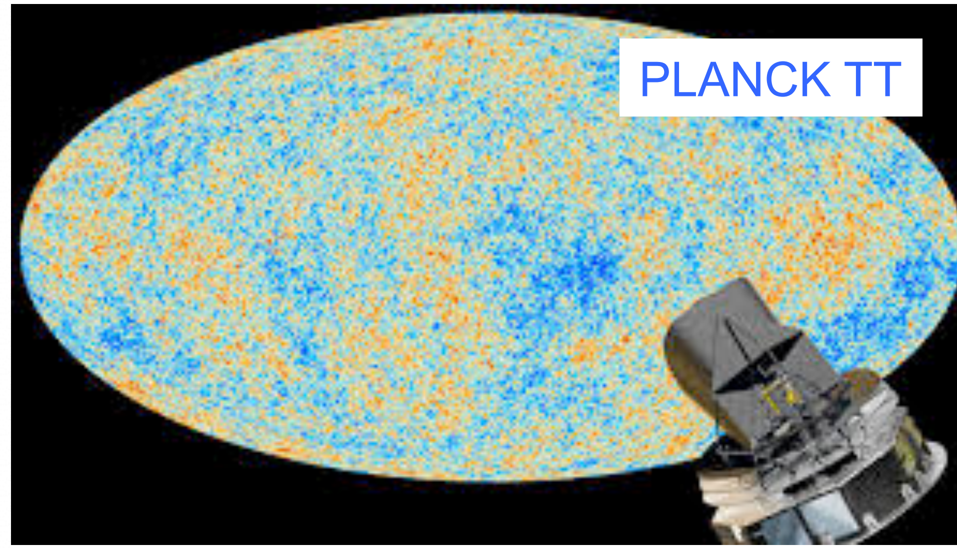


AO will enable TMT/E-ELT to outperform JWST in image quality

Unique advantage in imaging rest UV in physically-small distant galaxies

Planck CMB: Shorter Reionization Era?

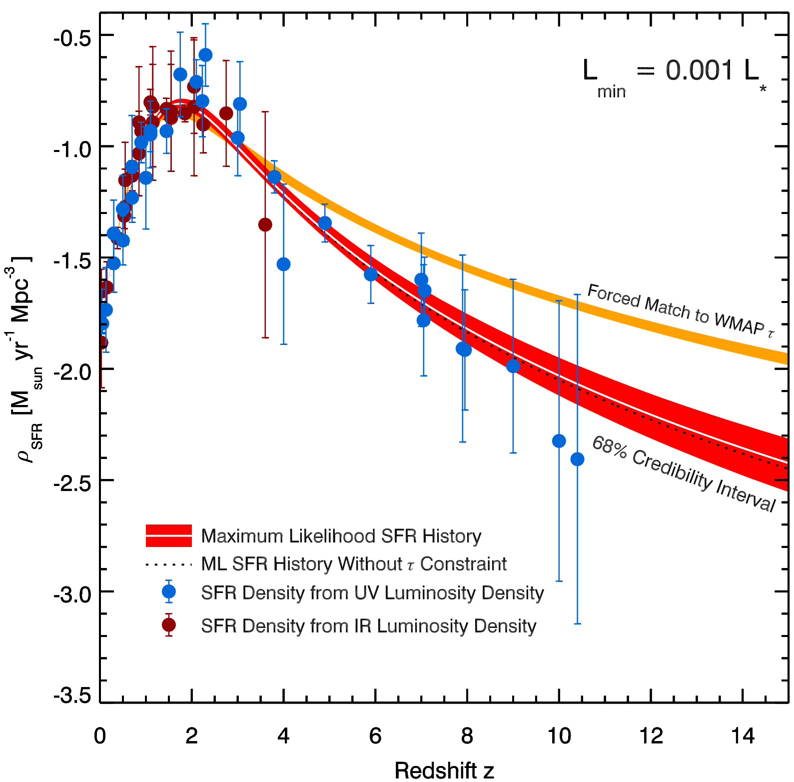


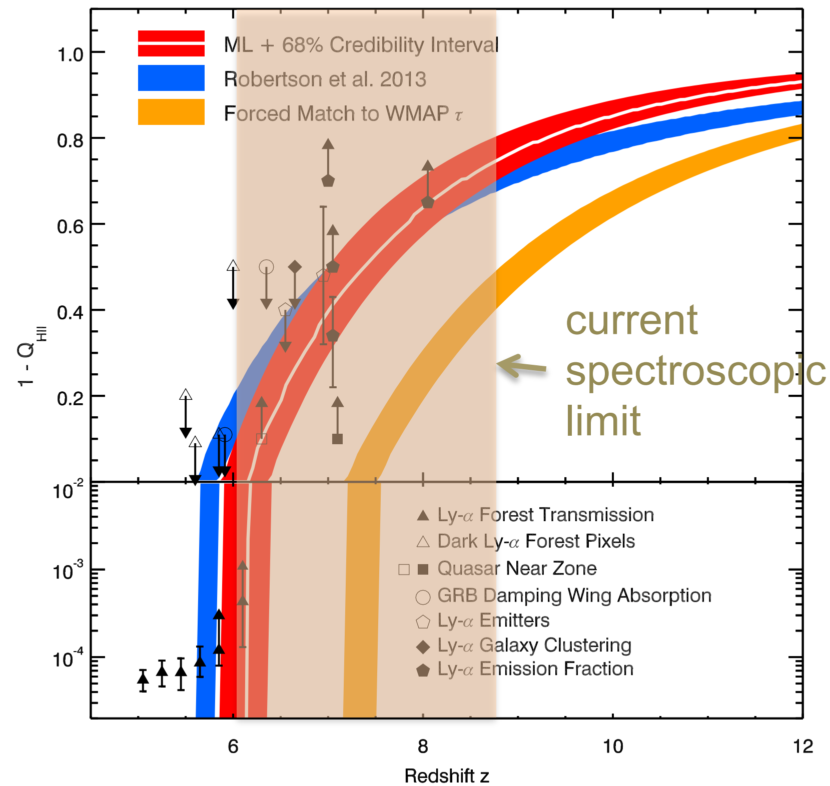


τ = 0.088 ± 0.013; z = 10.5 ± 1.1 **τ = 0.066 ± 0.013; z = 8.8 ± 1.2**

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.

Reionization Era is Already Being Probed..





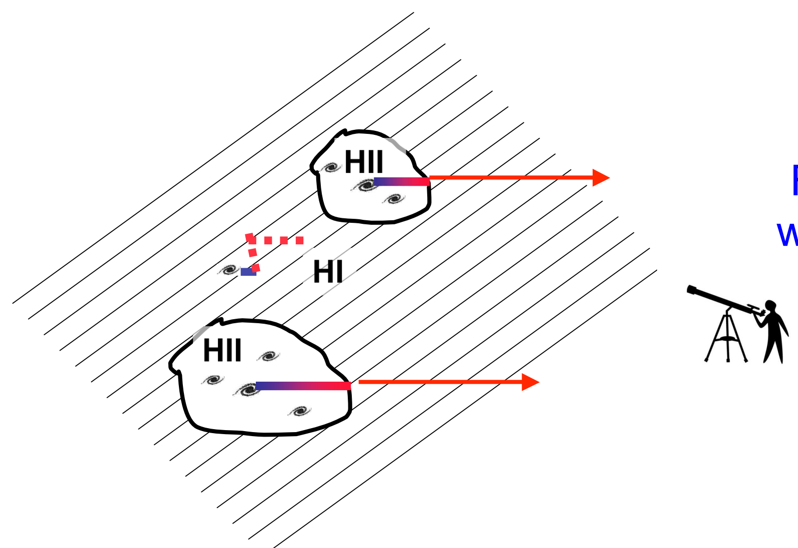
A change of $\Delta z\sim1.7$ in instantaneous redshift of reionization makes a big difference to the role of galaxies since their numbers decline very rapidly for $z > 6$

Adopting $f_{esc} = 0.2$, ξ_{ion} consistent with $\beta= -2$, a LF extending to $M_{UV}=-13$ galaxies can account for Planck τ with reionization largely contained with $10 < z < 6$

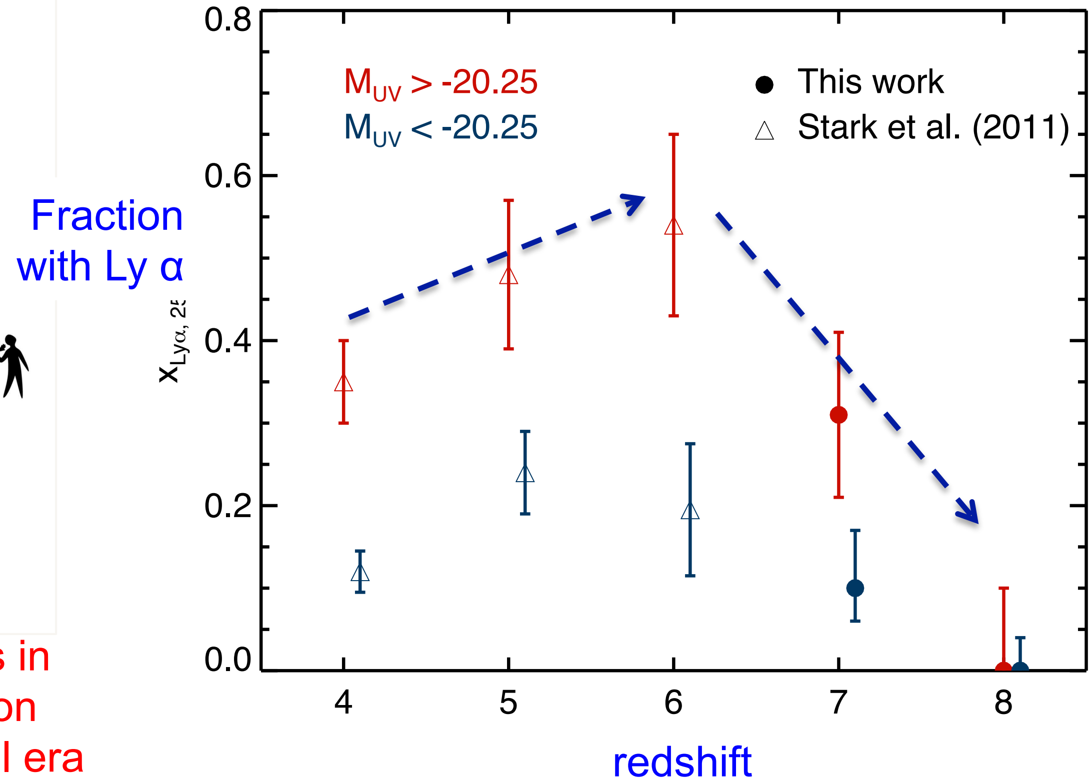
Robertson et al (2015)

also Choudhury et al (2015), Bouwens et al (2015)

Confirmation: Lyα fraction declines sharply for z > 6



Resonant scattering by neutral IGM reduces Lyα visibility unless galaxy is in ionized bubble. Expect drop in fraction with line emission as we enter neutral era



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, 2015) – VLT FORS 6<z<7.3

Challenges for JWST/ELTs

- Through deep and lensed fields, HST has primarily contributed to the demographics of the early galaxy population (#s, LFs, colors..)
- The next step is detailed astrophysics:
  - nature of star formation: regular or burst-like? ➔ feedback
  - ionizing spectrum (stellar populations, role of AGN) ➔ ξ_{ion}
  - escape fraction of Lyman limit photons ➔ f_{esc}
  - chemical composition: O/H, C/O ratios ➔ earlier nucleosynthesis
  - is there any dust?

  most of these issues can only be resolved via spectra
- Diagnostic features include both UV and optical lines:

  Combination of UV + Hα ➔ SF timescales $z < 6.5$

  [O II], [O III], Hβ ➔ O/H ratio and dust content $z < 9$

  UV metals ➔ C/O ratio, ionizing spectrum $z < 20$

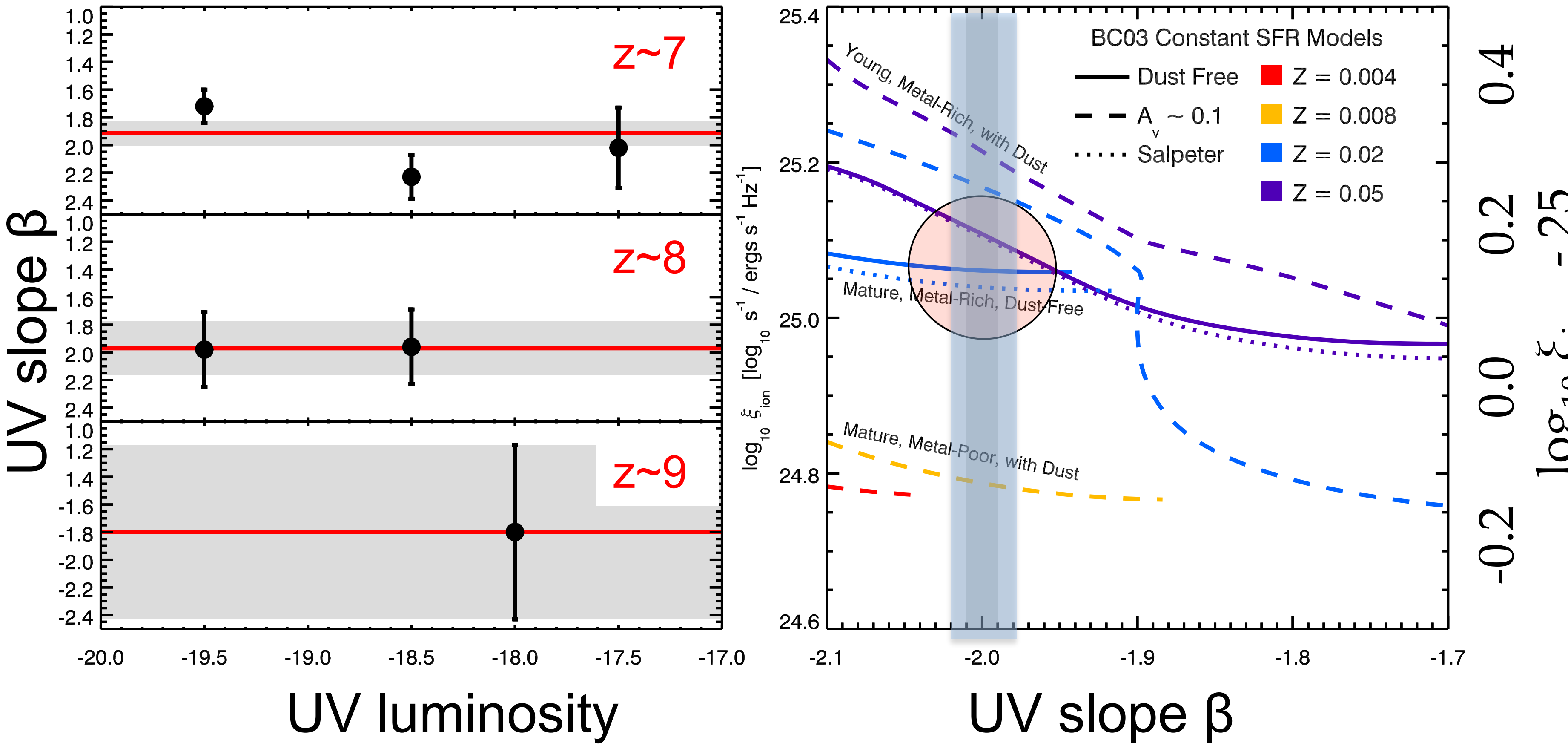
  Lyα detections & profiles ➔ velocity offsets, neutral fraction $z < 20$

To interpret such new observations requires population synthesis codes incorporating realistic models of line emission from hot stars and AGN e.g. Gutkin et al, Feltre et al 2015

Constraining Ionizing to UV Photon Ratio ξ_{ion}

Contrary to early claims, z~7-8 galaxies have **normal UV colors** but colors alone are insufficient in constraining the ionizing supply factor ξ_{ion}

Degeneracies from unknown age, metallicity and dust content!

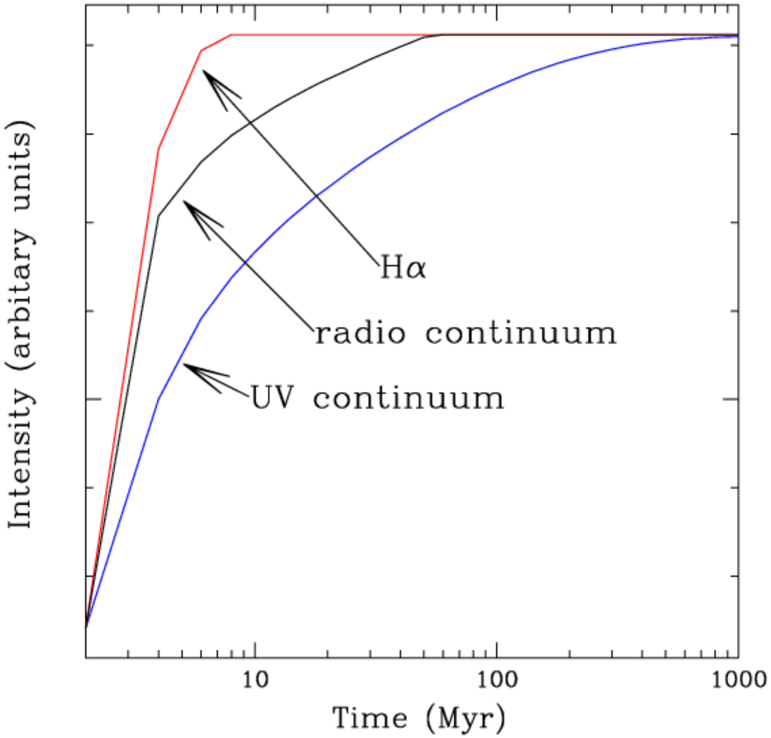


Dunlop et al (2013)

Line Diagnostics

Low redshift:

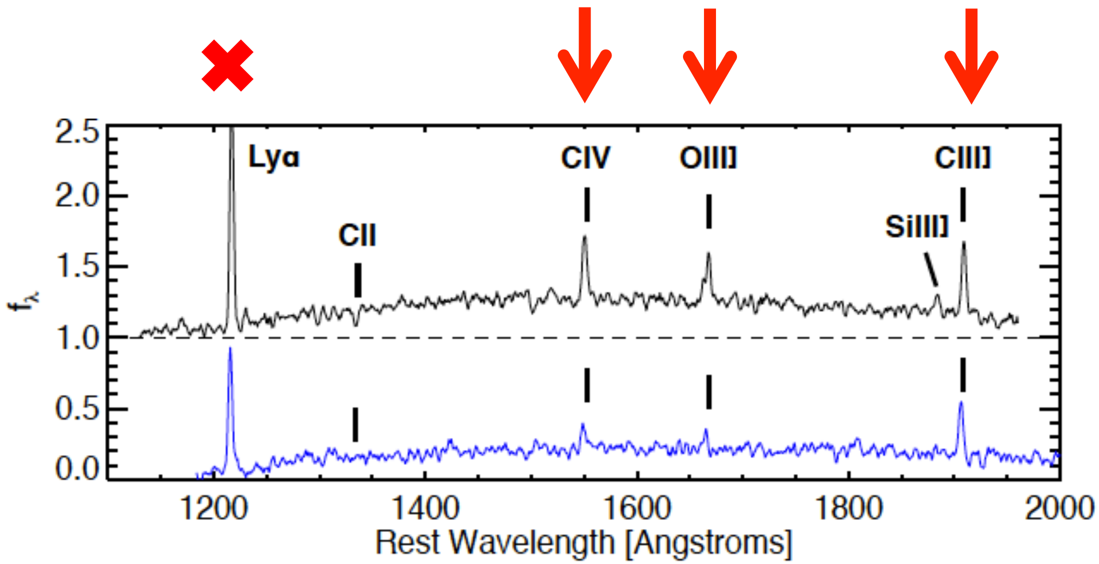
SF histories probed via different time sensitivities of UV and Hα luminosities



High redshift: UV metal lines, e.g.

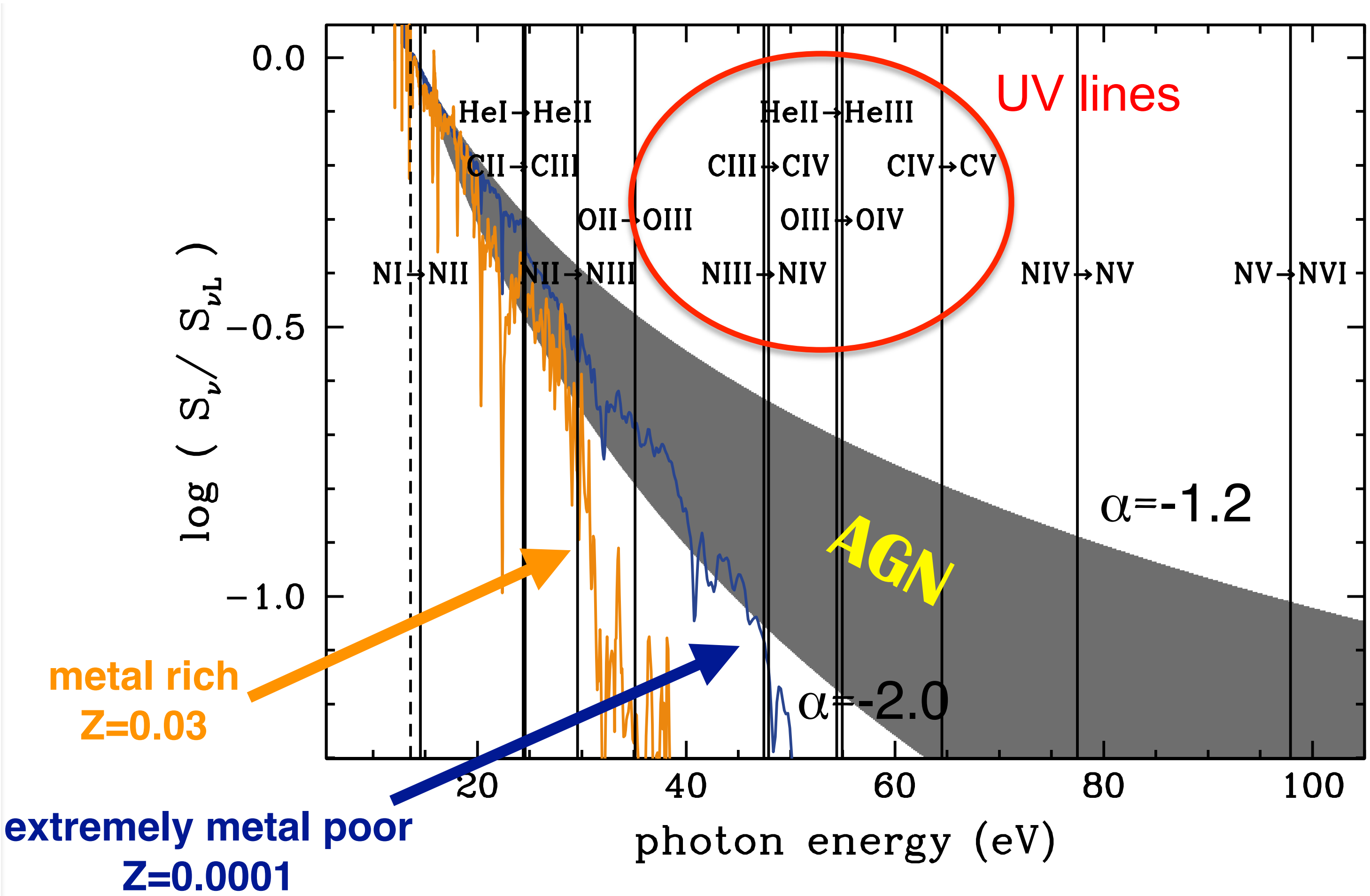
- CIV 1548 Å 48 eV
- O III] 1664 Å 35 eV
- CIII] 1909 Å 24 eV

probe ionizing spectrum and gas phase metallicity beyond z~8



Stark et al (2014)

Important UV Emission Lines



Feltre+15

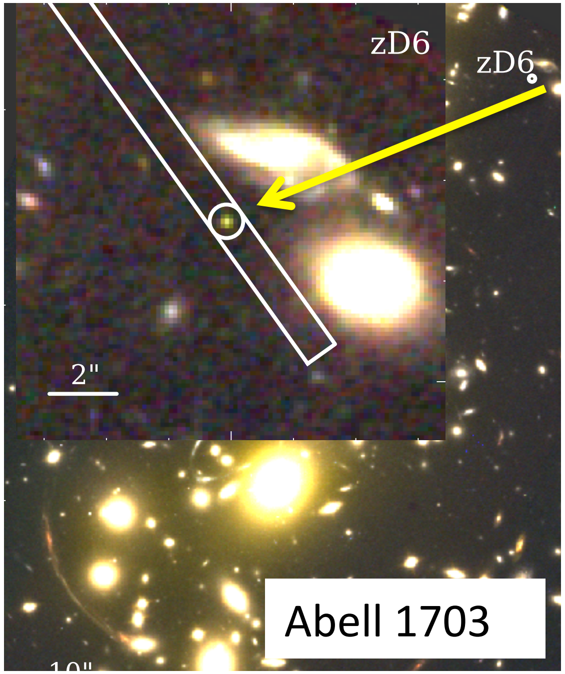
Two grids of photoionization models predicting nebular emission line ratios:

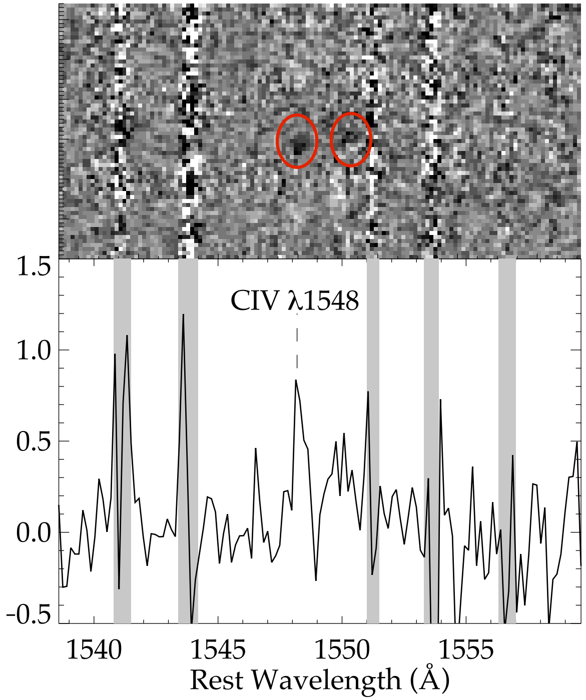
Young stars: CB15 (new tracks, WR stars) + CLOUDY (Gutkin+15)

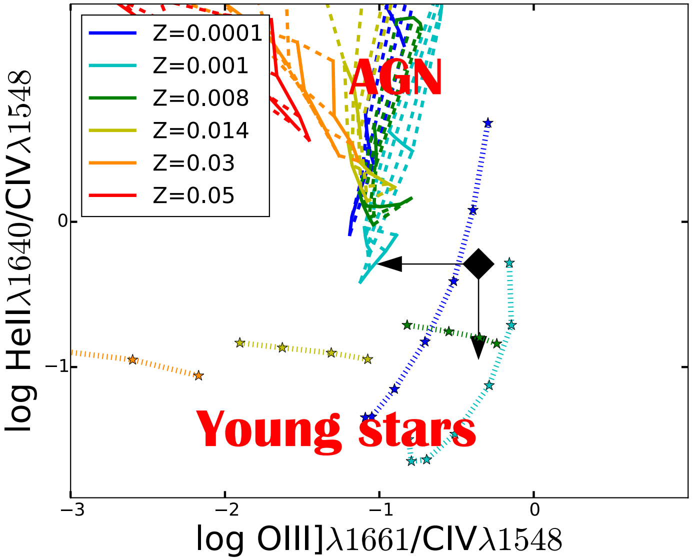
AGN-driven: Power law $F(\nu) \sim \nu^{\alpha}$ + CLOUDY

Utility of rest-UV line ratios CIII]/HeII/CIV as discriminants (see Feltre poster)

Illustration: CIV Doublet in z ~ 7.045 Galaxy







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

- High ionization parameter ($U_S = \rho_\gamma/\rho_{gas}$): log U_S ~ -1.35
- Low metallicity: ~0.01 solar

Conceivably the rarer z > 7 galaxies which reveal Lyα emission are atypical and extreme ionizing sources?

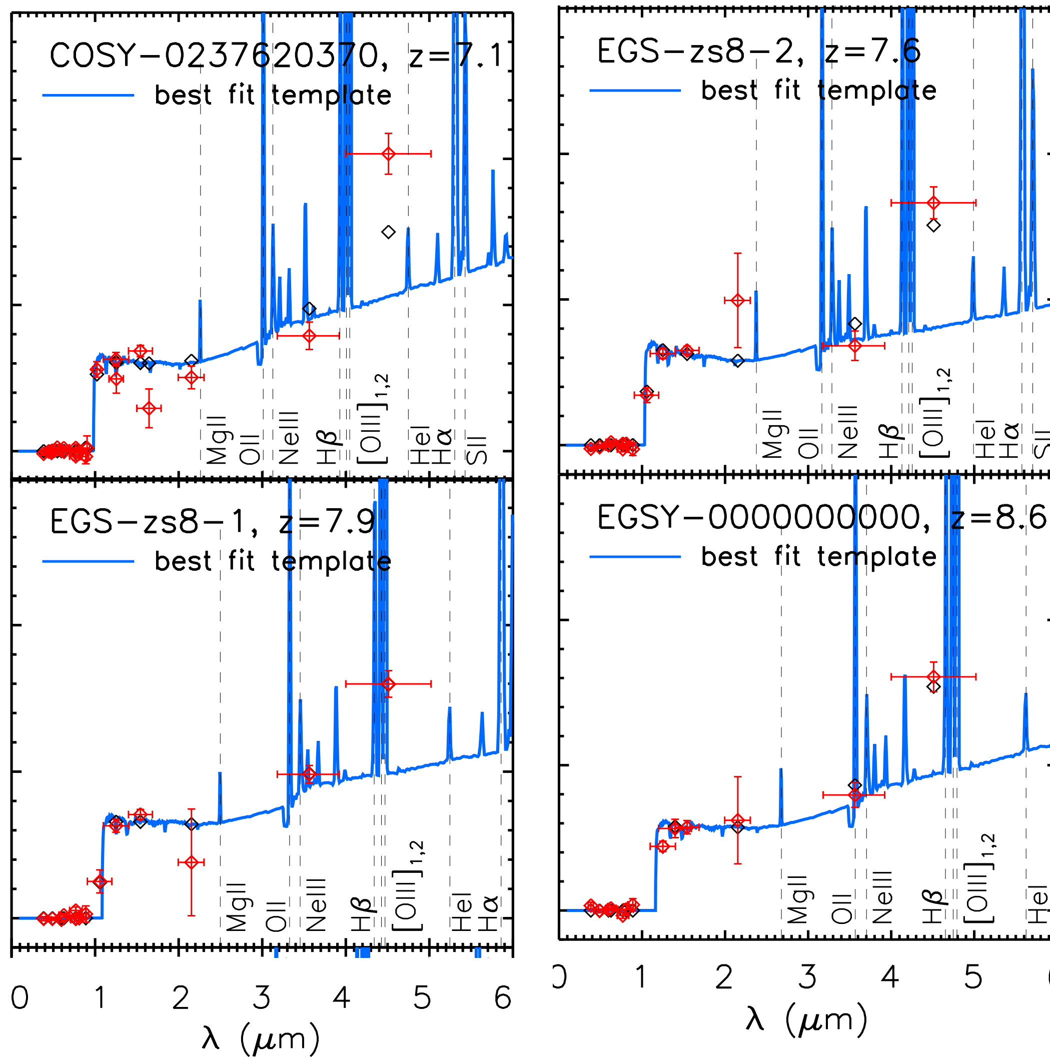
Stark et al (2015)

A New Class of Early Star-Forming Galaxies?

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.

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

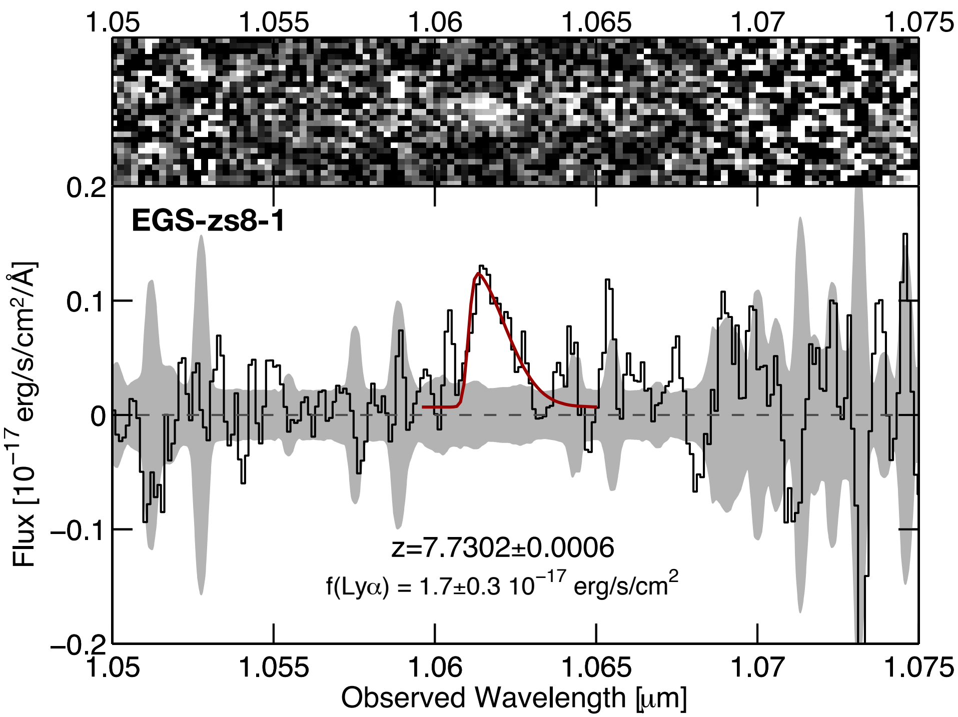
4 such luminous objects (H~25) located in CANDELS fields



Roberts-Borsani et al (2015)

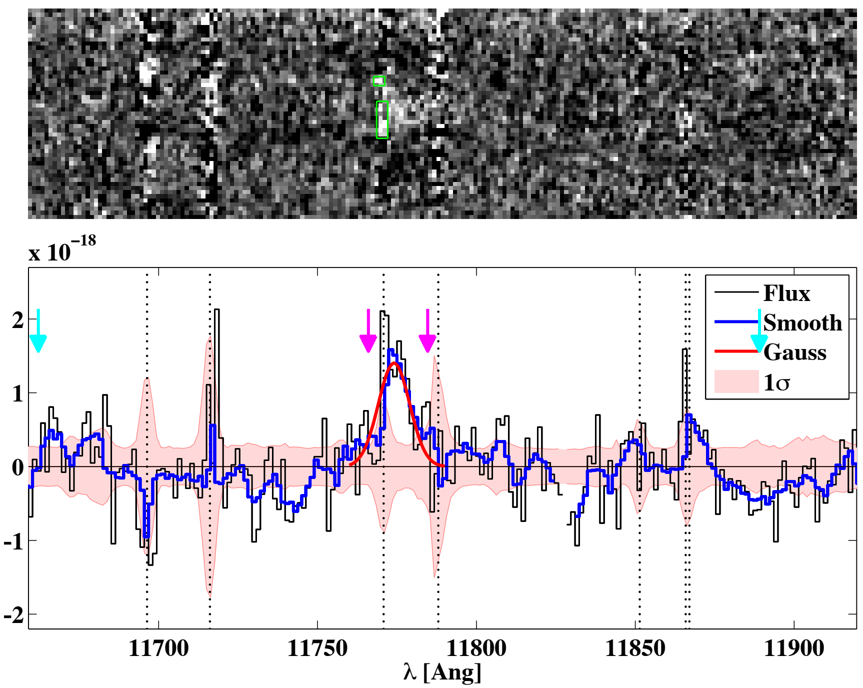
Redshift Records 2015

February: z_{spec}= 7.73; Oesch et al



z_{phot} = 7.92 ± 0.36; Lyα EW ≈ 21 Å

July: z_{spec}= 8.68; Zitrin et al



z_{phot} = 8.57 ± 0.3; Lyα EW ~ 30 Å

Also confirmed a third IRAC excess object EGS-z38-2 with Lyα at z=7.477

Sources with extremely strong ionizing radiation?

TABLE 2

A COMPLETE LIST OF THE RESULTING $z \geq 7$ SOURCES IDENTIFIED AFTER APPLYING OUR SELECTION

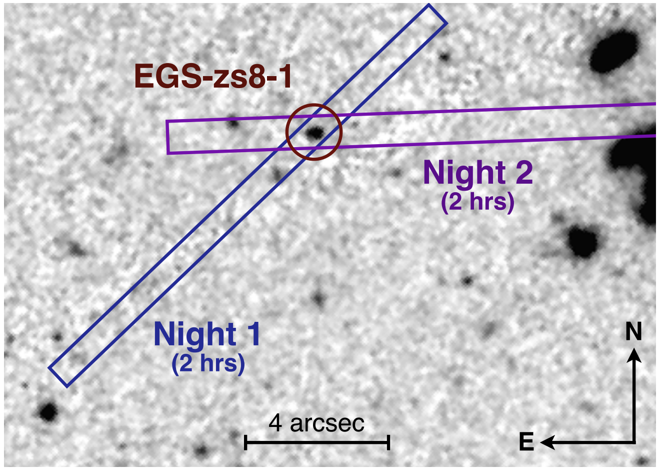
ID	R.A.	Dec	m_{AB}[a]	[3.6]-[4.5]	z_{phot}[b]	$Y_{105} - J_{125}$[c]
COSY-0237620370	10:00:23.76	02:20:37.00	25.06±0.06	1.03±0.15	$7.14\pm^{0.12}_{0.12}$	−0.13±0.66
EGS-zs8-1	14:20:34.89	53:00:15.35	25.03±0.05	0.53±0.09	$7.92\pm^{0.36}_{0.36}$	1.00±0.60
EGS-zs8-2	14:20:12.09	53:00:26.97	25.12±0.05	0.96±0.17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

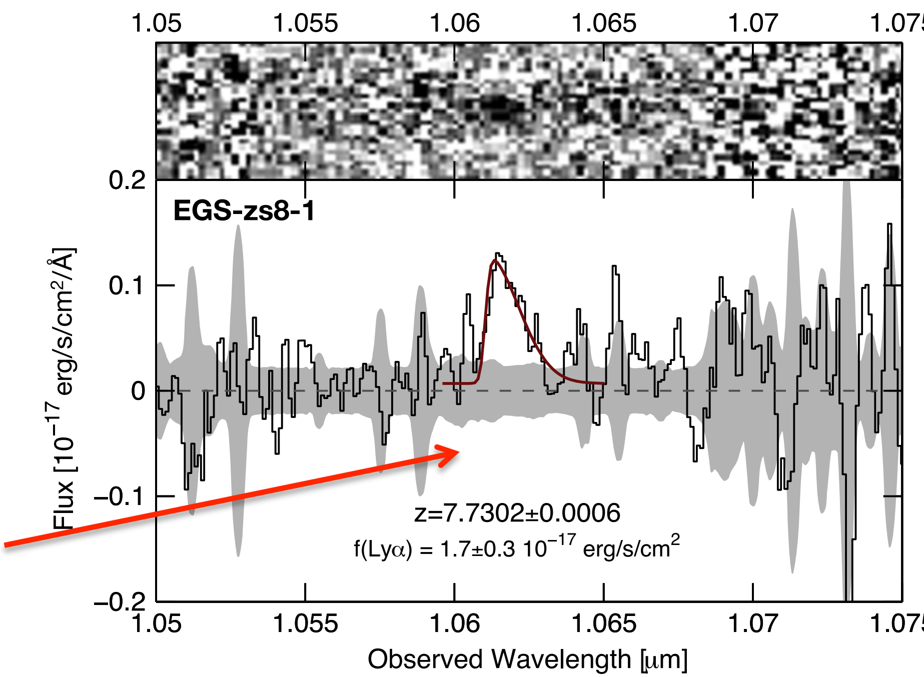
3/3 sources with z_{phot} > 7.5 with 4.5μm excess show prominent Lyα !
EGSY8p7 at z=8.68 shows Lyα where IGM is expected to be ~60% neutral

How can this be?

Further evidence z > 7 emitters are a different class of early galaxy with unusually strong radiation fields which have created early ionized bubbles

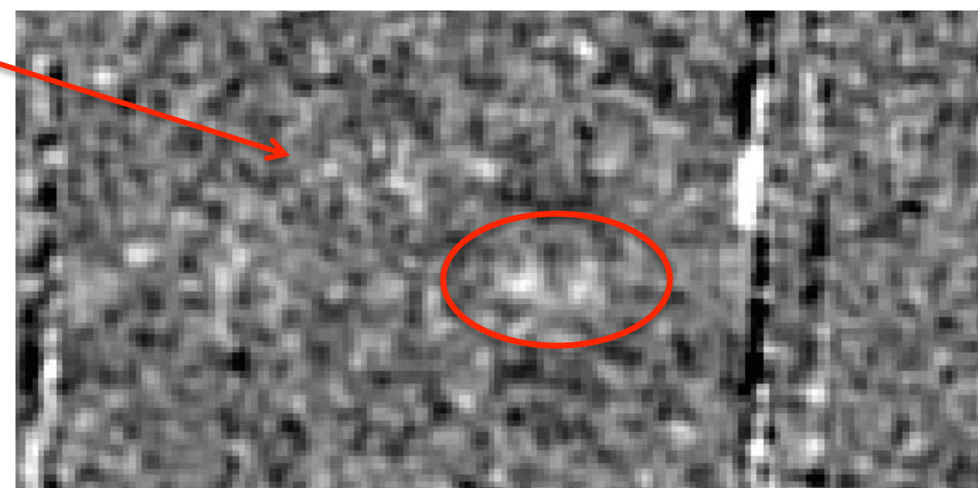
CIII] at z=7.73





Lyα at z=7.73 Oesch et al (2015)

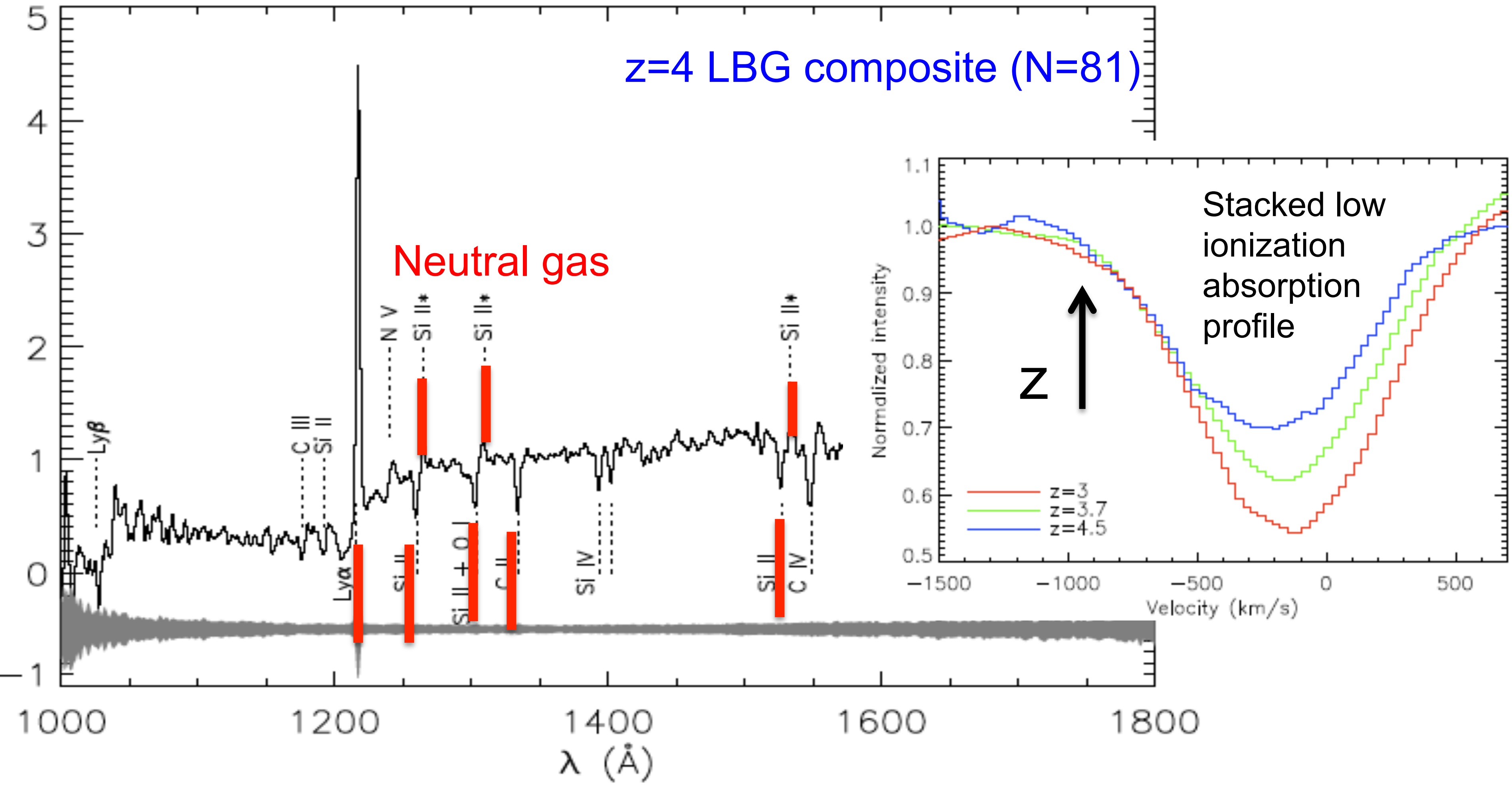
Detection of CIII] doublet – April/June 2015



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.

Stark et al (2015)

Rising Escape Fraction with Redshift?



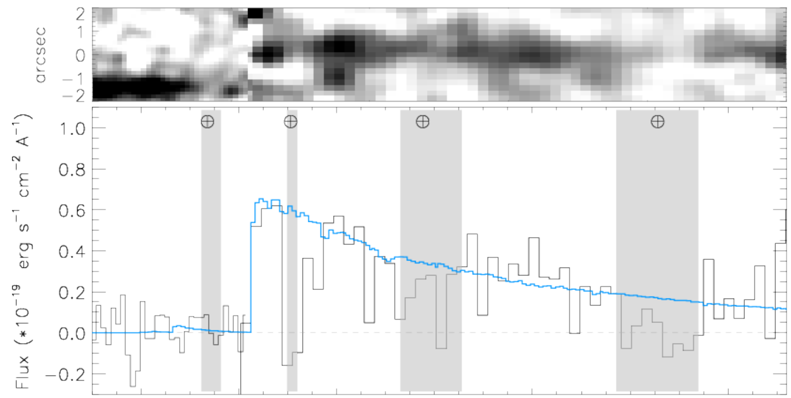
Reduced covering fraction of low ionization gas consistent with smaller galaxies, more energetic SF and higher escape fraction: $f_{esc} < 1 - f_{cov}$

Requires R~2700 stacks or individual lensed sources

Jones et al (2012, 2013)

Dust at High z?

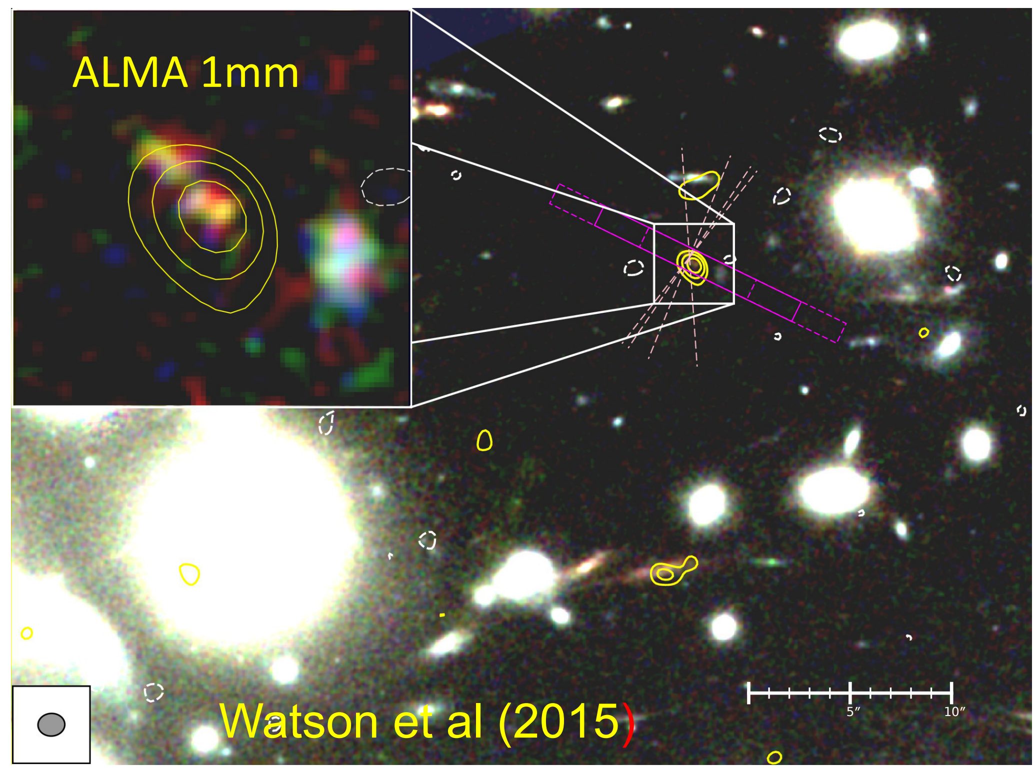
VLT X-shooter spectrum



- Lensed z~7.5 galaxy A1689_zD1 in Abell 1689 (Bradley et al 2008); magnification ~×9

- Low mass (log M*~9.2) with blue UV slope

- ALMA band 6 (1mm) detection confirmed via 3 independent exposures (log M_{dust} ~8)

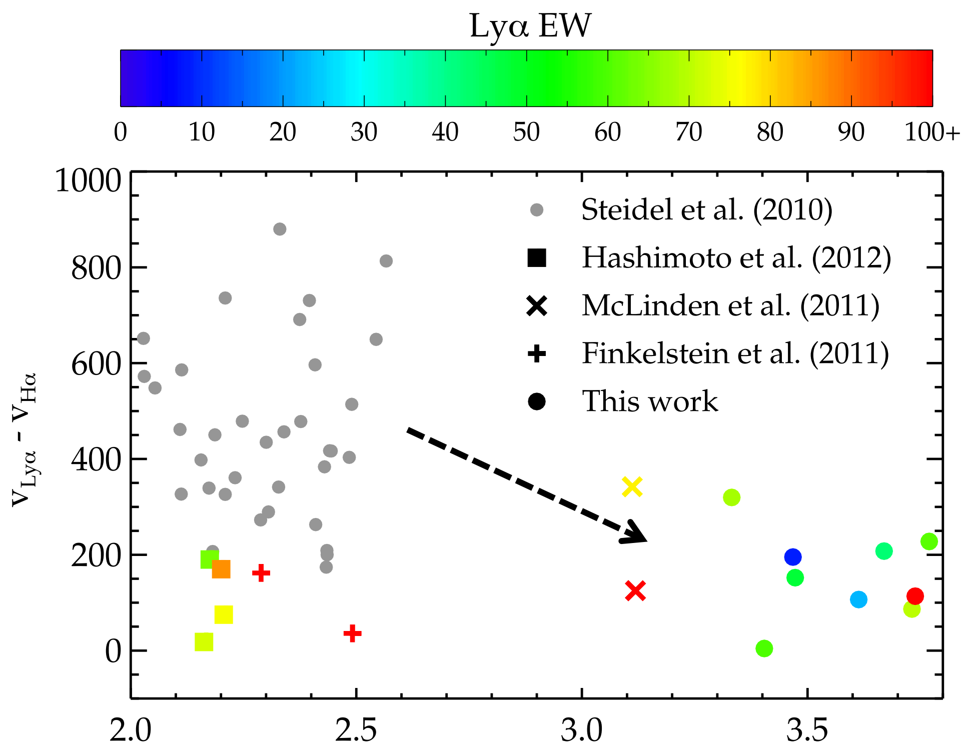


ALMA data on z > 7 LBGs!

Lyα still important to detect – even if suppressed

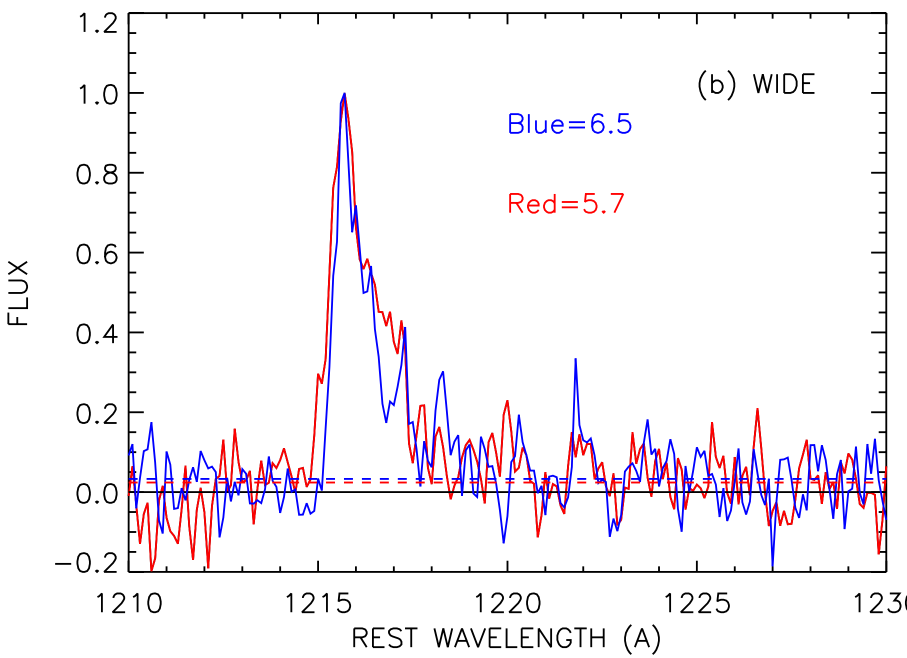
Inferred x(HI) depends on velocity offset of emerging Lyα which may decrease at high z according to MOSFIRE data. Line profiles also valuable probes

Velocity offset (Lyα – nebular) km/s



Schenker et al (2013)

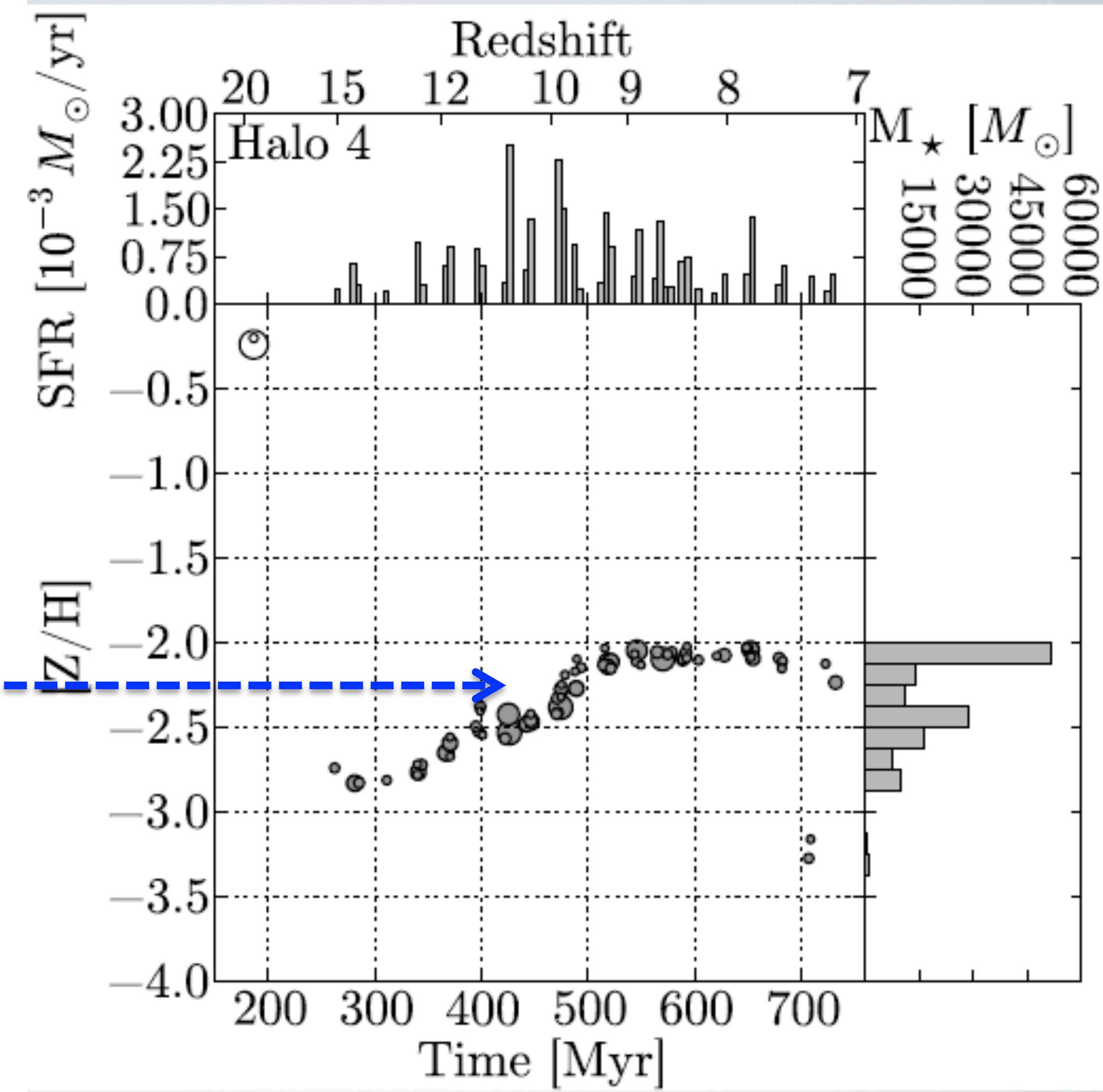
Stacked profiles



Hu et al (2010)

The Holy Grail: Detecting a Pristene Pop III Galaxy?

- Consider halo mass ~ $8\ 10^7\ M_\odot$
- Metallicity evolution governed by competition between enriched outflow vs pristene inflow
- Simulations suggest rapid enrichment (< 200Myr) to [Z/H] ~ -3; no low metallicity tail



UNLIKELY

Wise et al (2012)

Summary

- Recent progress supports the conjecture that reionization occurred rapidly and at later epochs than envisaged when JWST was planned, corresponding to $10<z<6$

- This increases the likelihood that galaxies were the dominant source of ionizing photons and that the earliest sources are within reach of JWST

- Spectroscopy is the only route to addressing several outstanding challenges in confirming this picture:

    - the nature of the ionizing radiation field
    - the fraction of ionizing photons that escape
    - the nature of early metal enrichment

- Traditional rest-frame optical diagnostics are only available for $z < 9$ but tools are now available to exploit the rich potential of rest-frame UV lines

- Application of these tools already suggests some $z>7$ sources displaying Lyα are efficient ionizing sources perhaps indicative of unusual populations of hot stars; thus reionization may be more complex than we imagined