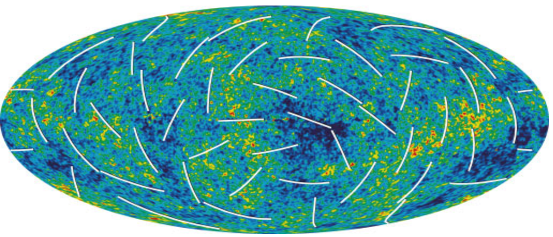
High Redshift Galaxies and Cosmic Reionization: Where Next?

Richard Ellis (UCL & ESO)

Dark Ages Heidelberg 2016

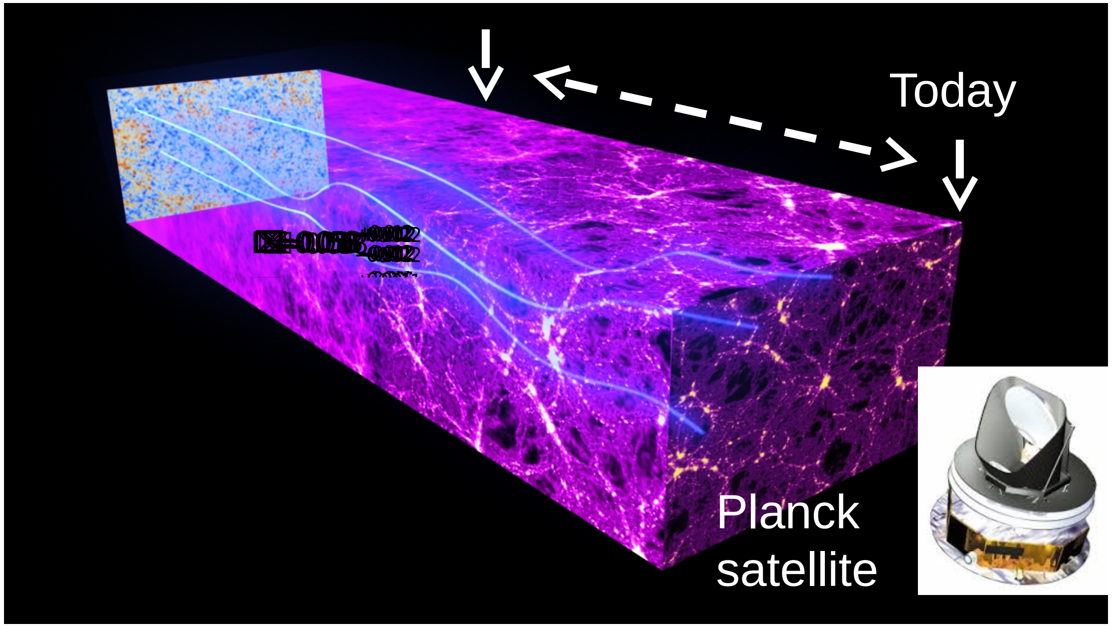
July 1st 2016

Planck Indicates Late and Fast Reionization

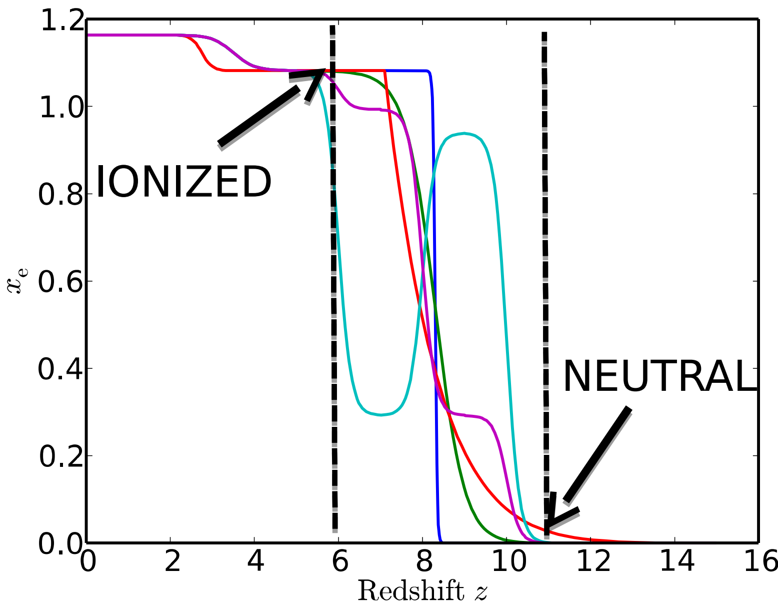


CMB polarisation probes foreground Thomson scattering from the start of reionization to the present epoch.
Optical depth of scattering τ constrains the mean redshift <z> and (model dependent) duration of reionization

Reionization begins



Models consistent with Planck τ

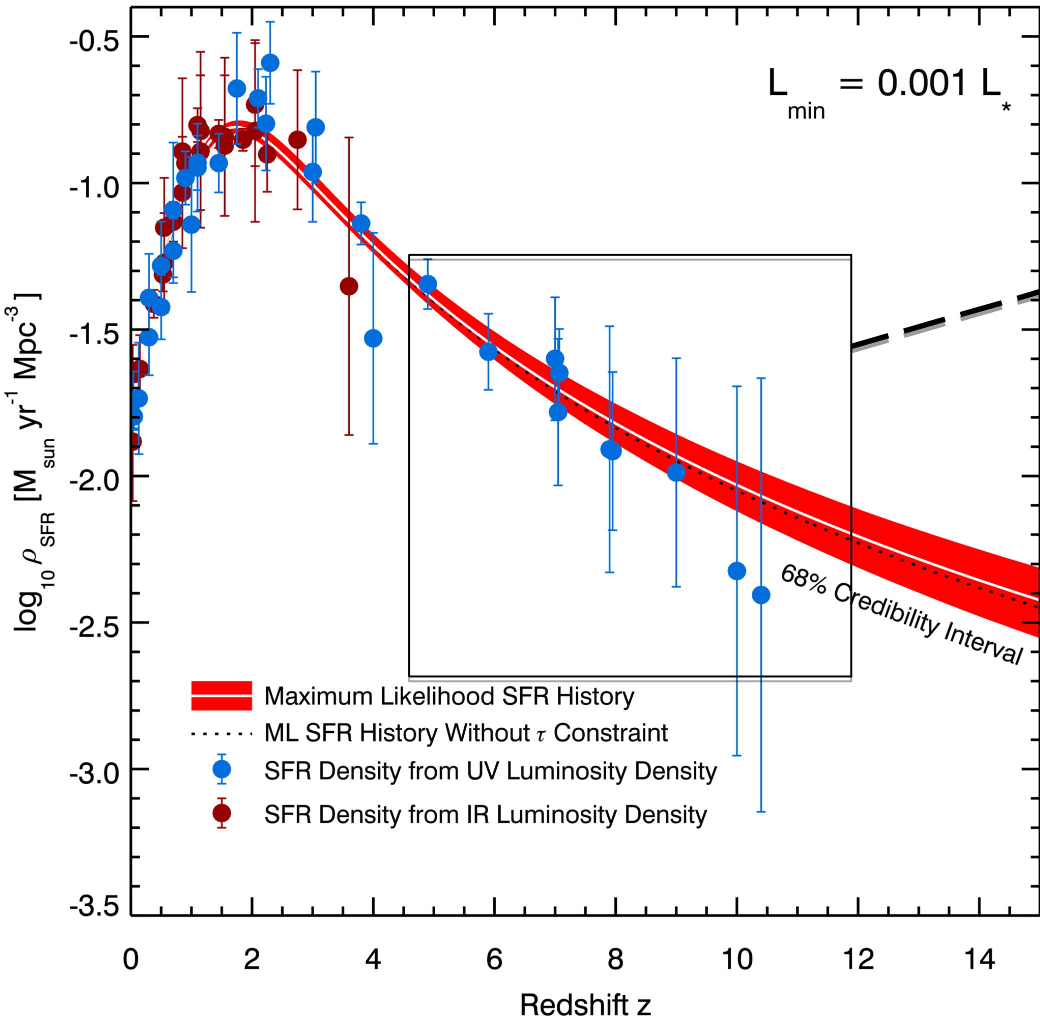


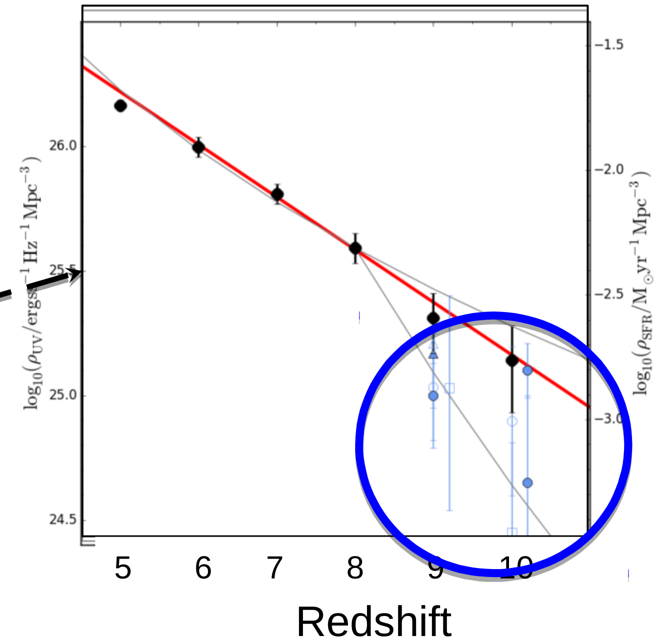
Planck consortium (2016) find τ = 0.058 ± 0.012 corresponding to <z> ~8.3 ± 0.5

Models indicate reionization began at z~10-12 and ended at 6

Census of Star Forming Galaxies

Reasonable agreement between blank & lensed surveys

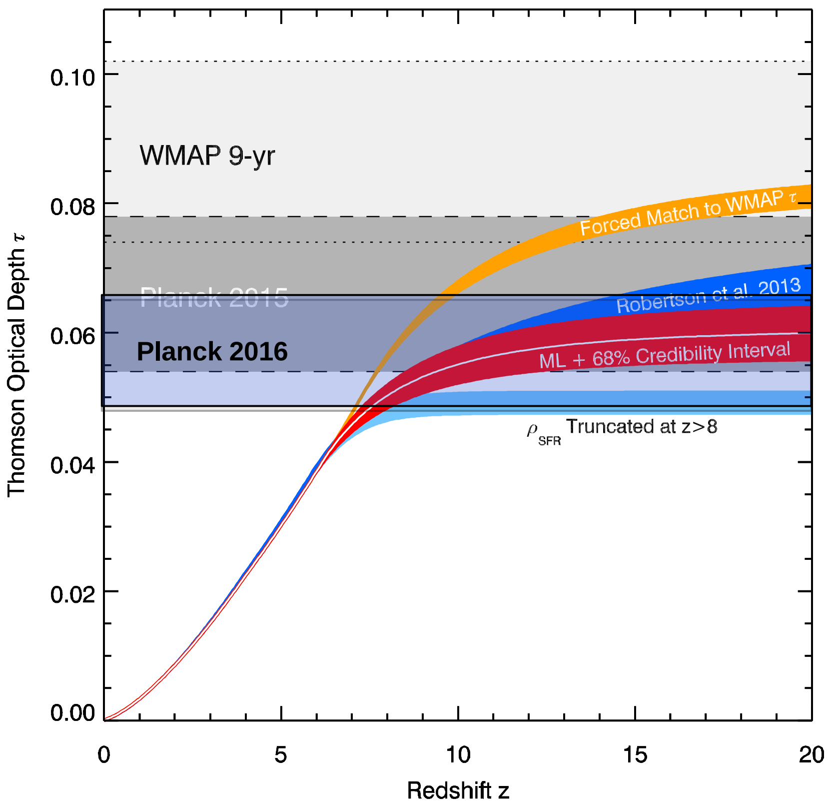


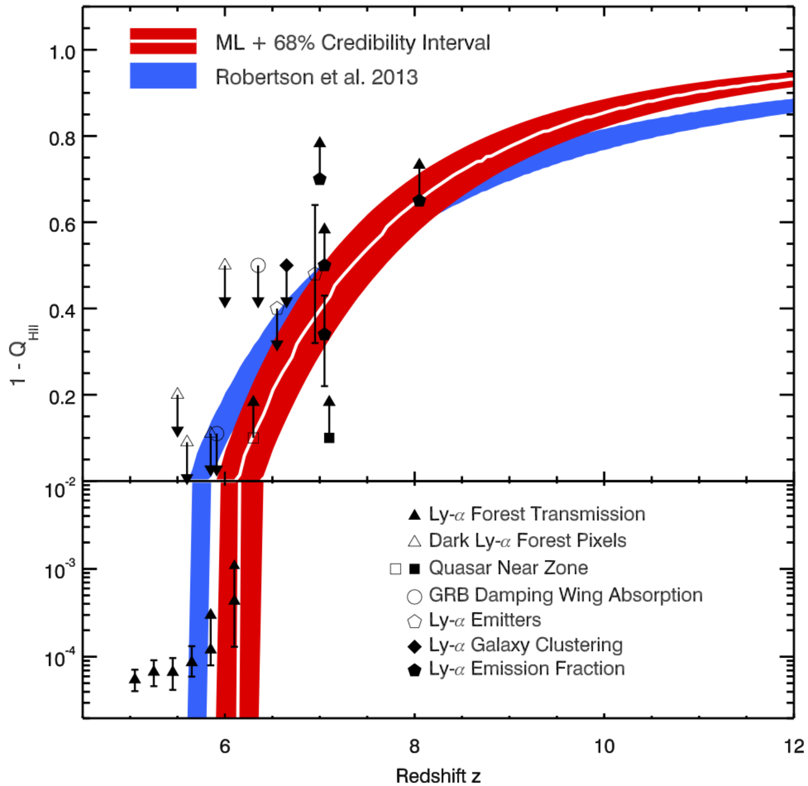


Claimed steeper decline in numbers beyond a redshift z > 8 now seems unlikely

Robertson et al (2015), McLeod et al (2016)

Reconciling Star-Forming Galaxies with Planck





Making (questionable) assumptions about their ionizing output, the demographics of early galaxies from HST data can match the Planck τ with reionization also contained with 12 < z < 6

Focus thus turns to demonstrating the validity of these assumptions about the ionizing output of early galaxies

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

So Did Galaxies Reionize Universe?

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

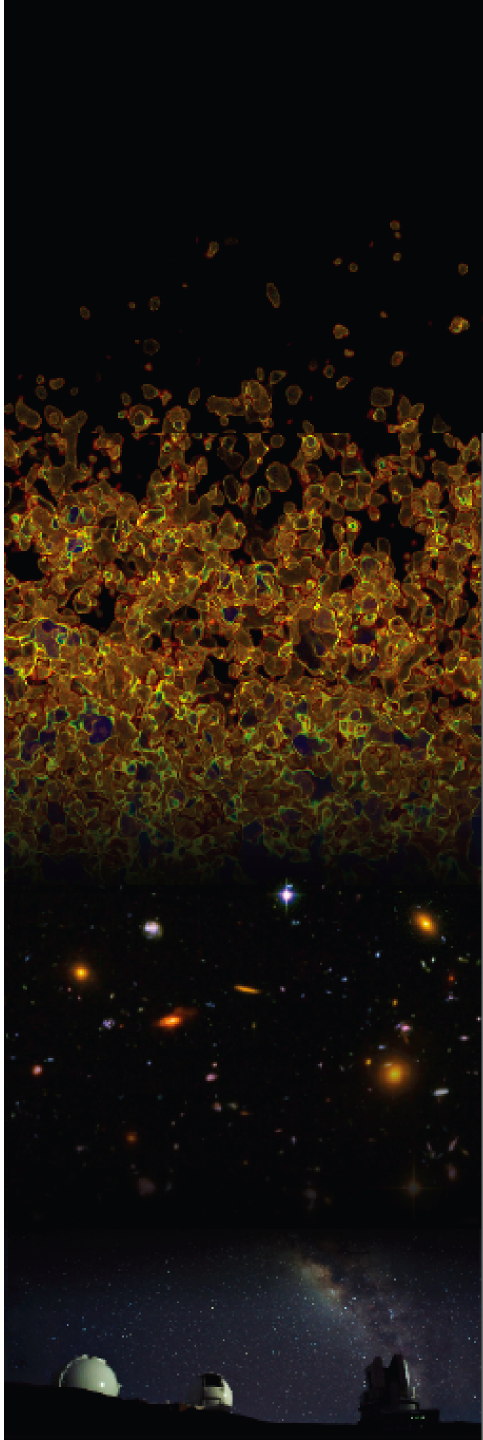
Recombination time $t_{\rm rec} = [C_{\rm H\,II}\alpha_{\rm B}(T)(1 + Y_{\rm p}/4X_{\rm p})\langle n_{\rm H}\rangle(1 + z)^3]^{-1}$

Key observables:

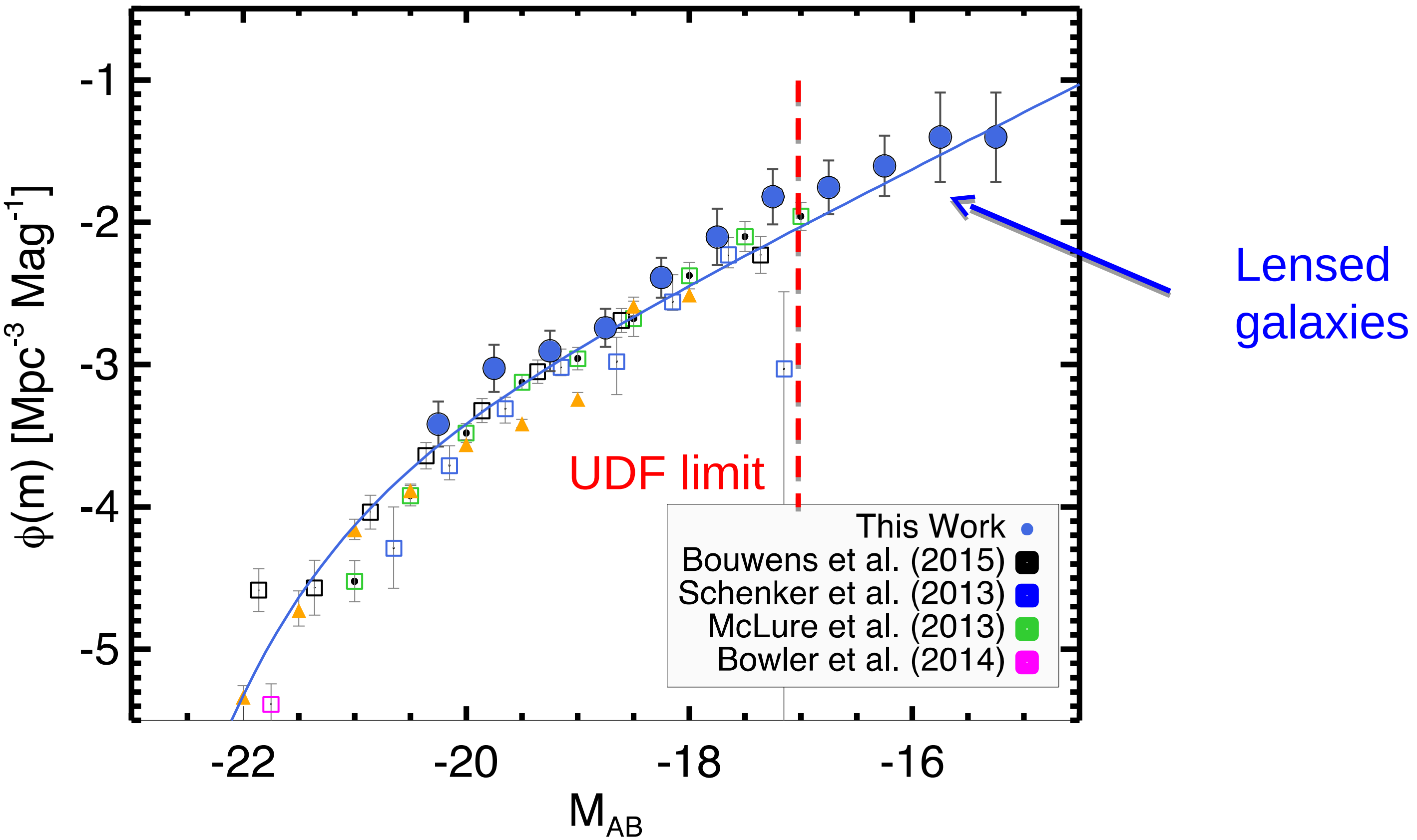
1. Integrated abundance of high z star-forming galaxies especially contribution of low luminosity sources : $\rho_{\rm UV}$

2. Nature of the stellar populations in distant galaxies which determines the rate of ionising photons: $\xi_{\rm ion}$

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



Improved Measures of Luminosity Density ρ_{UV}



Faint end slope of the LF α is critical!

UDF12 indicated α = -1.87 ± 0.18 @ z~7 to M_{UV}=-17

Frontier Field lensing data (3 clusters) gives α = -2.04 ± 0.13 to M_{UV}=-15.5

Including cosmic variance, 6 FF clusters should Δα to ± 0.05

This would reduce uncertainty on integrated **ρ (< M_{UV}=-13) to 30%**

Schenker et al (2013), Robertson et al (2014), Atek et al (2015)

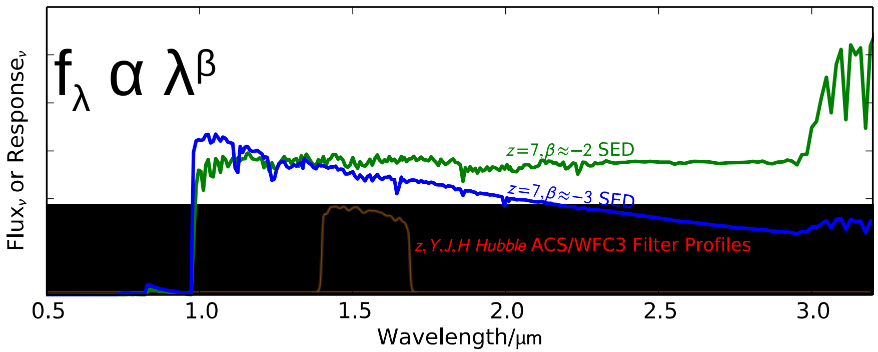
Progress in Estimating Ionization Parameter ξ_{ion}

Define ionization output ξ_{ion} via no. of LyC photons per UV (1500Å) luminosity

Traditionally estimated using HST colors and stellar models:

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

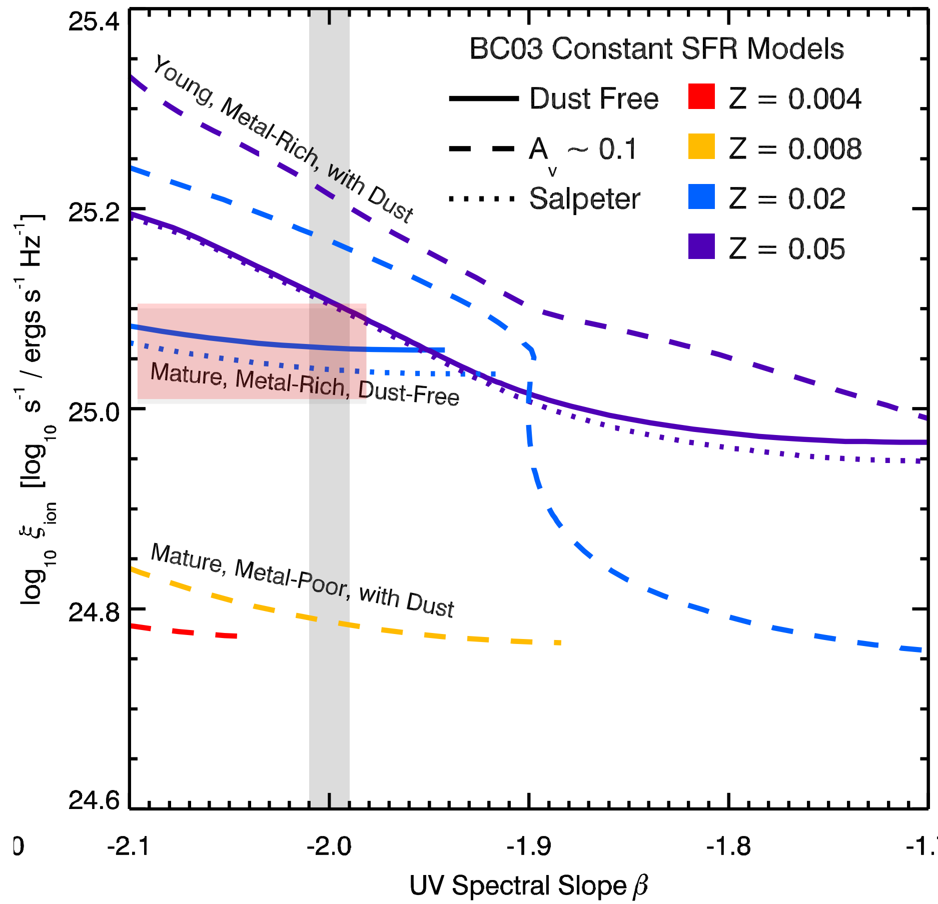
(ii) metal-enriched systems with flatter spectral slopes, i.e. **lower ξ_{ion}**



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

log ξ_{ion} ~25.1 (cgs)

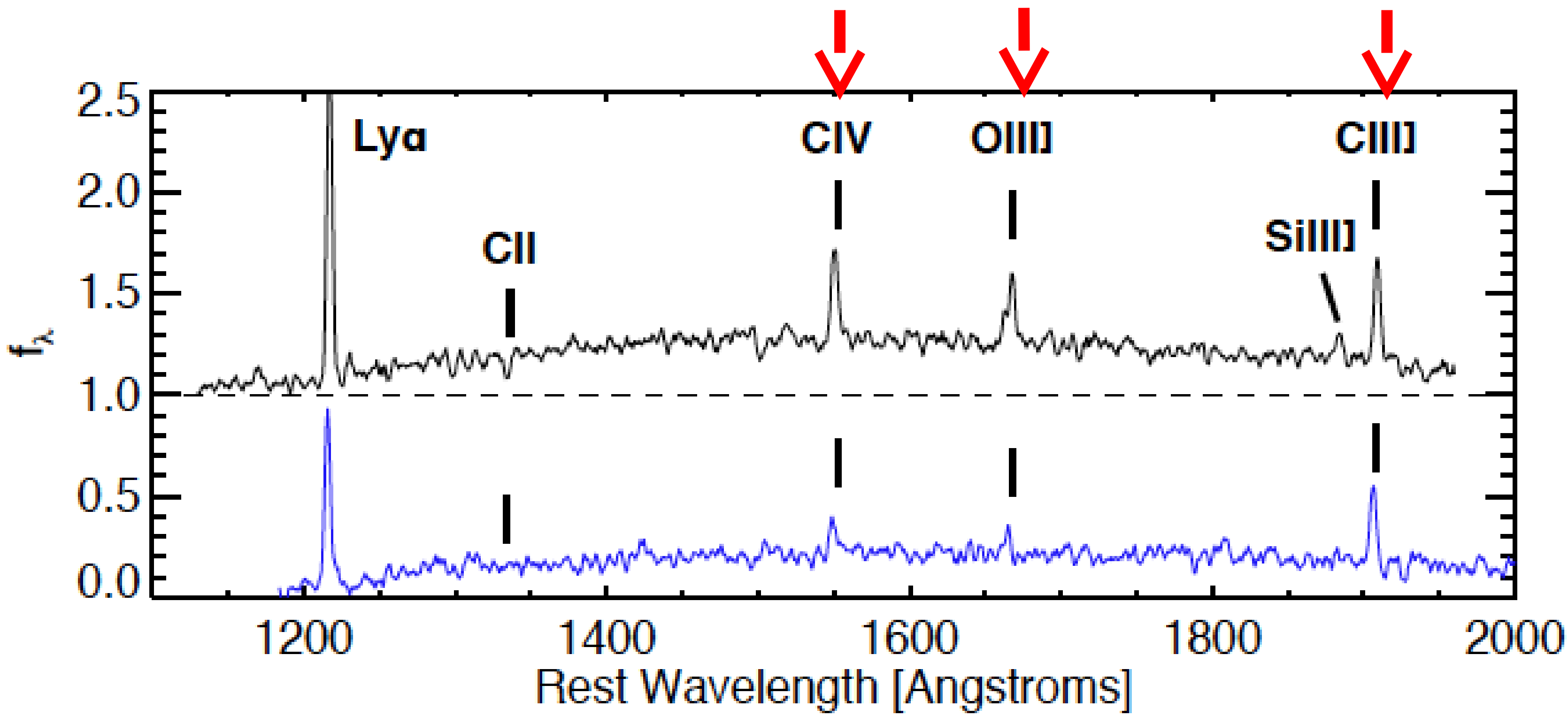
but ambiguities remain depending on composition, dust and IMF.



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

Better Diagnostics of ξ_{ion} using UV Metal Lines

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



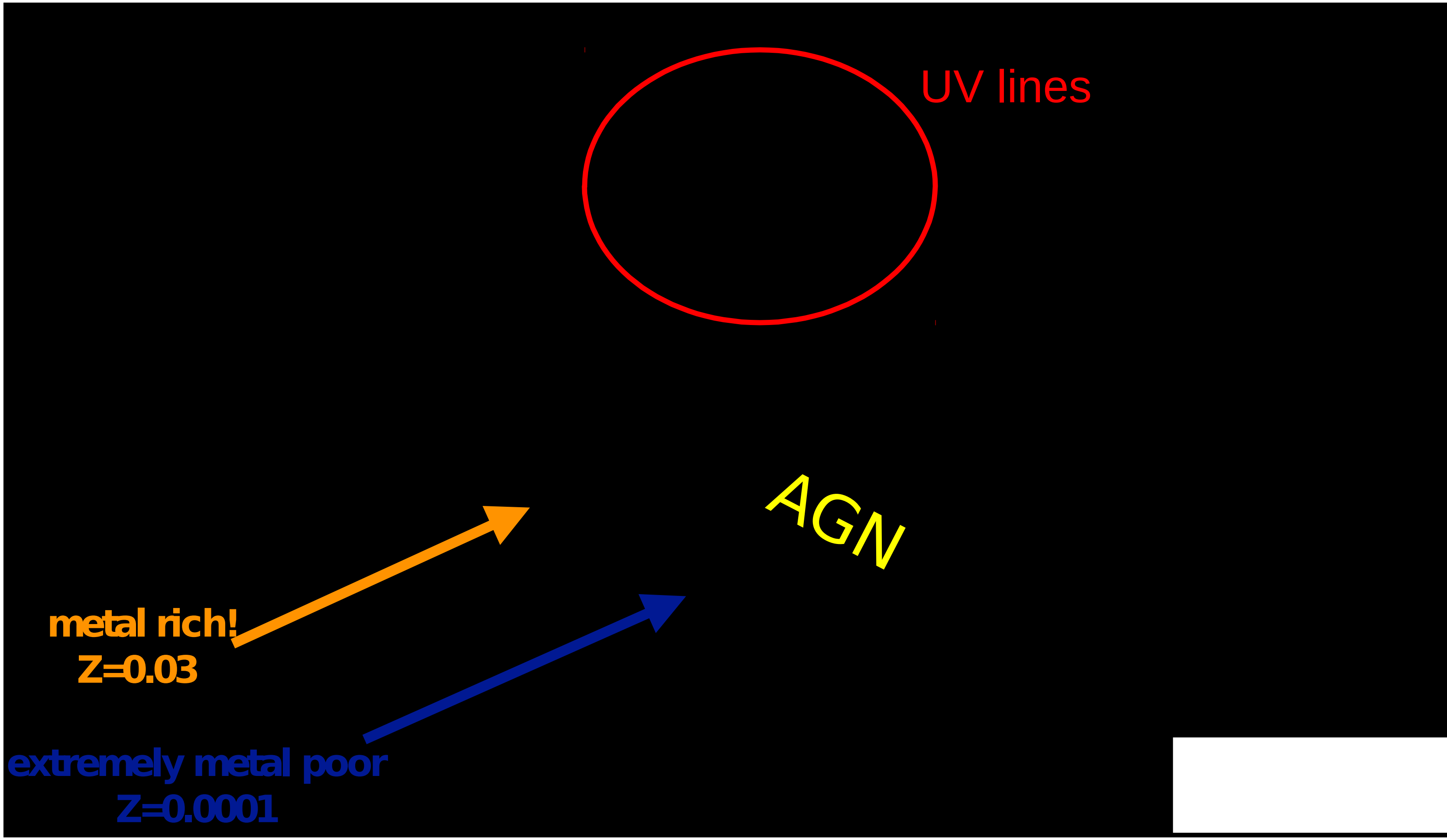
Prominent rest-frame UV emission lines with high ionization potentials

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

valuable indicators of ionizing radiation field

Stark et al (2014)

Interpreting UV Emission Lines for ξ_{ion}

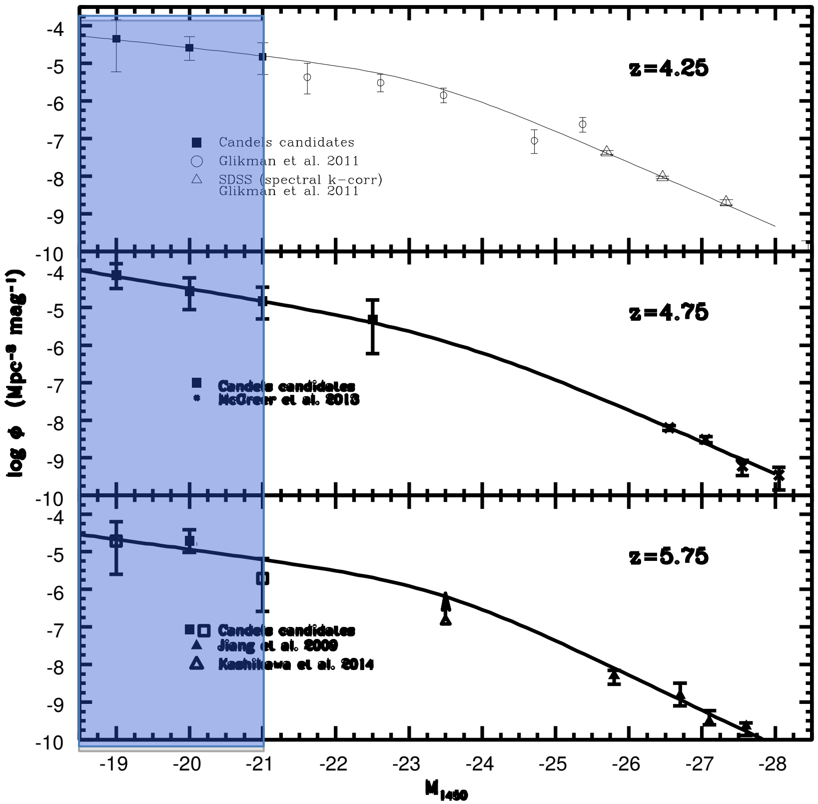


Grids of photoionisation models predict **nebular emission line ratios**:
Young stars: Charlot-Bruzual15 (new tracks, WR stars) + CLOUDY
AGN-driven: Power law $F(\nu) \sim \nu^{\alpha}$ + CLOUDY

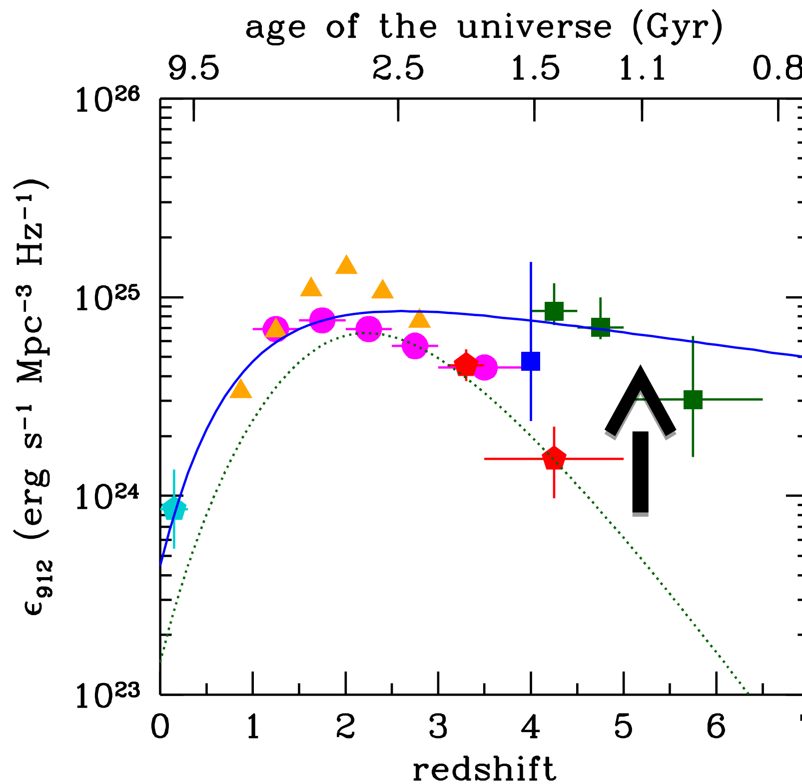
Feltre et al 2016

Other Sources of Ionizing 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?

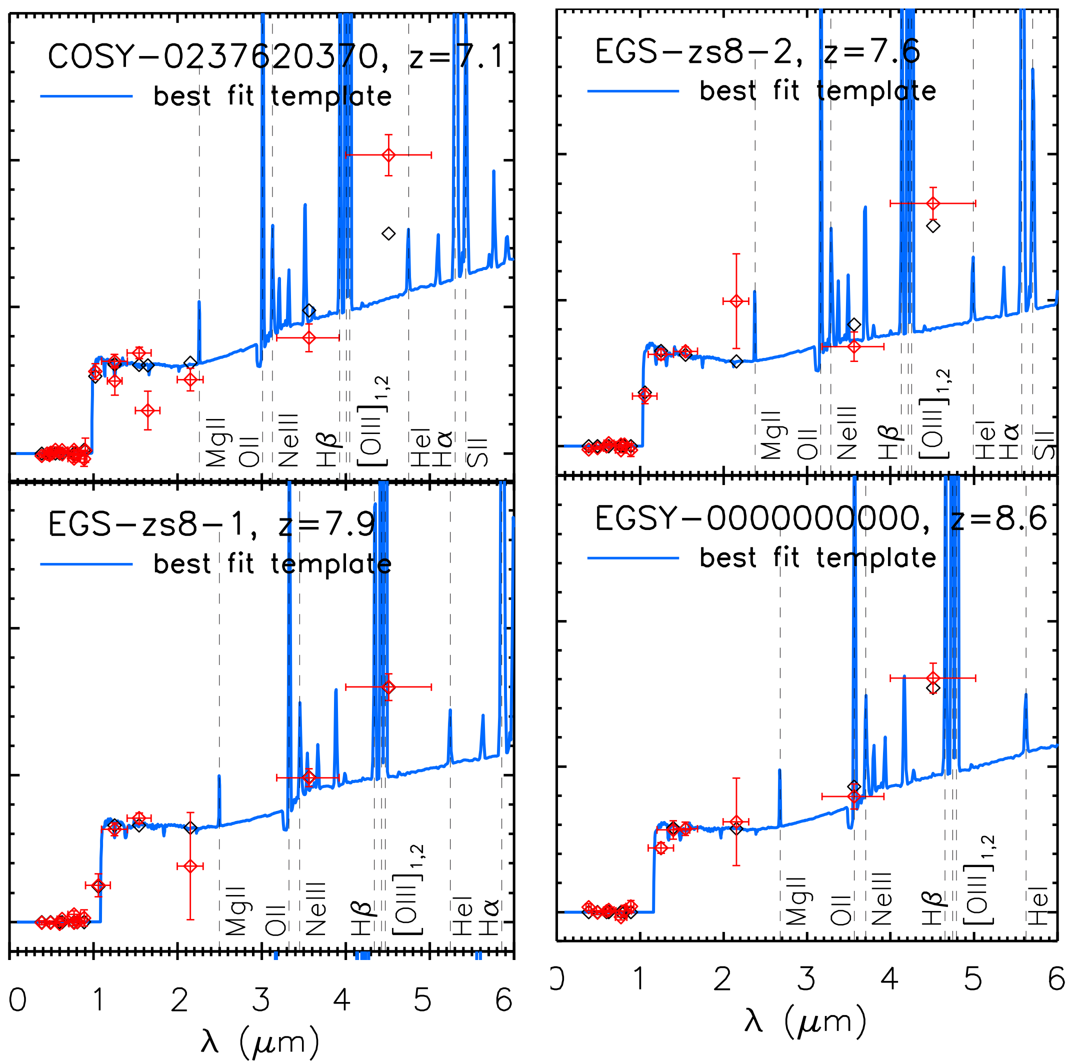
Giallongo et al (2015), Madau & Hardt(2015)

Strong [O III] Emitting Early 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. As we have seen, few show Lyα

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

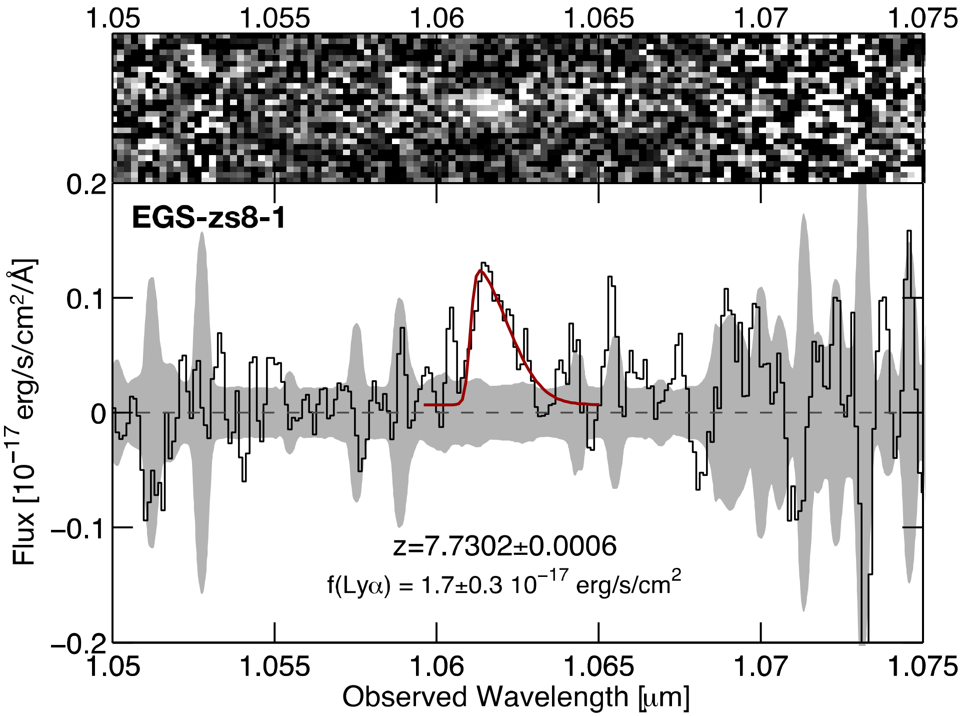
4 such luminous objects (H~25) located in CANDELS fields



Roberts-Borsani et al (2015)

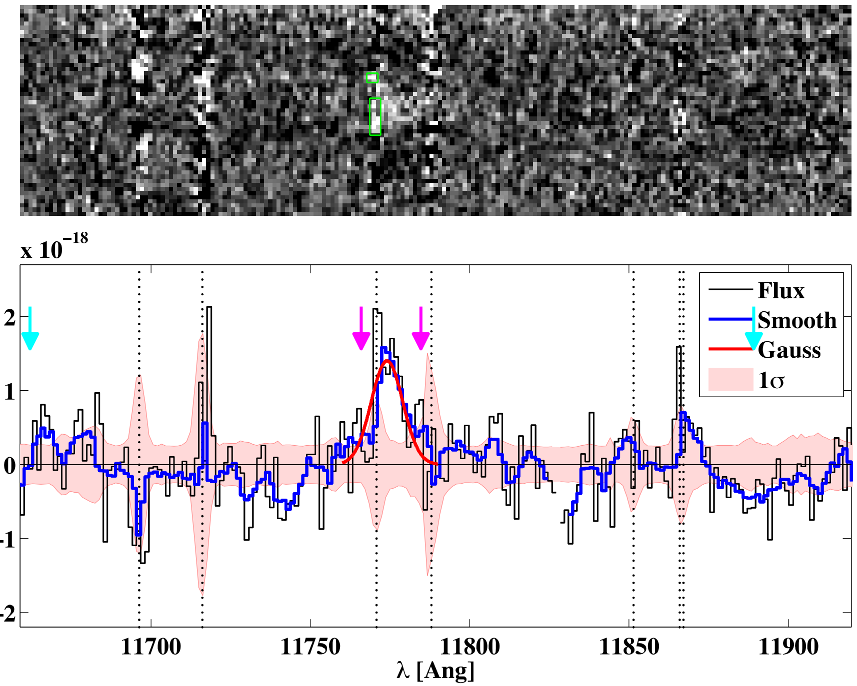
Luminous z >7.5 Galaxies Reveal Lyα Emission!

EGS-zs8-1 at z=7.73



- H=25.0; 2 hrs with MOSFIRE
- Z_{phot} = 7.92 ± 0.36; Z_{spec} = 7.73;
- Lyα EW ≈ 21 Å

EGSY8p7 at z=8.68



- H=25.3; 4.3 hrs with MOSFIRE
- Z_{phot} = 8.57 ± 0.3; Z_{spec} = 8.68;
- Lyα EW ~ 30 Å

Also confirmed EGS-z38-2 z(Lyα)=7.477, COSMOS source z(Lyα)=7.15!

Oesch et al (2015), Zitrin et al (2016)

Luminous sources have 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

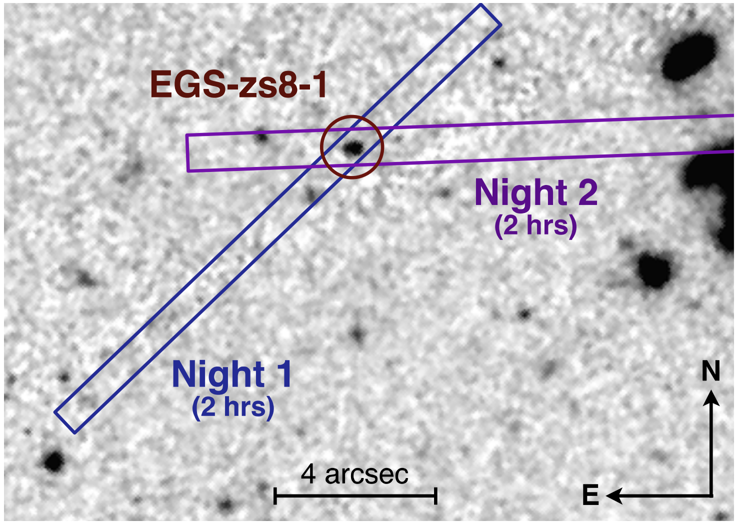
How can this be?

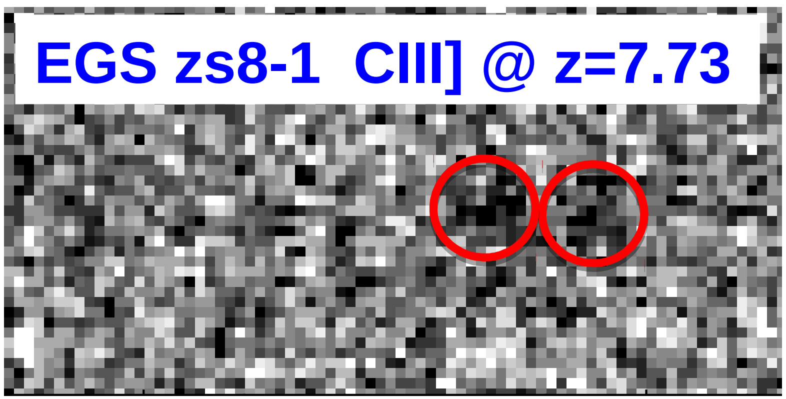
Patchy reionisation – certainly possible..OR

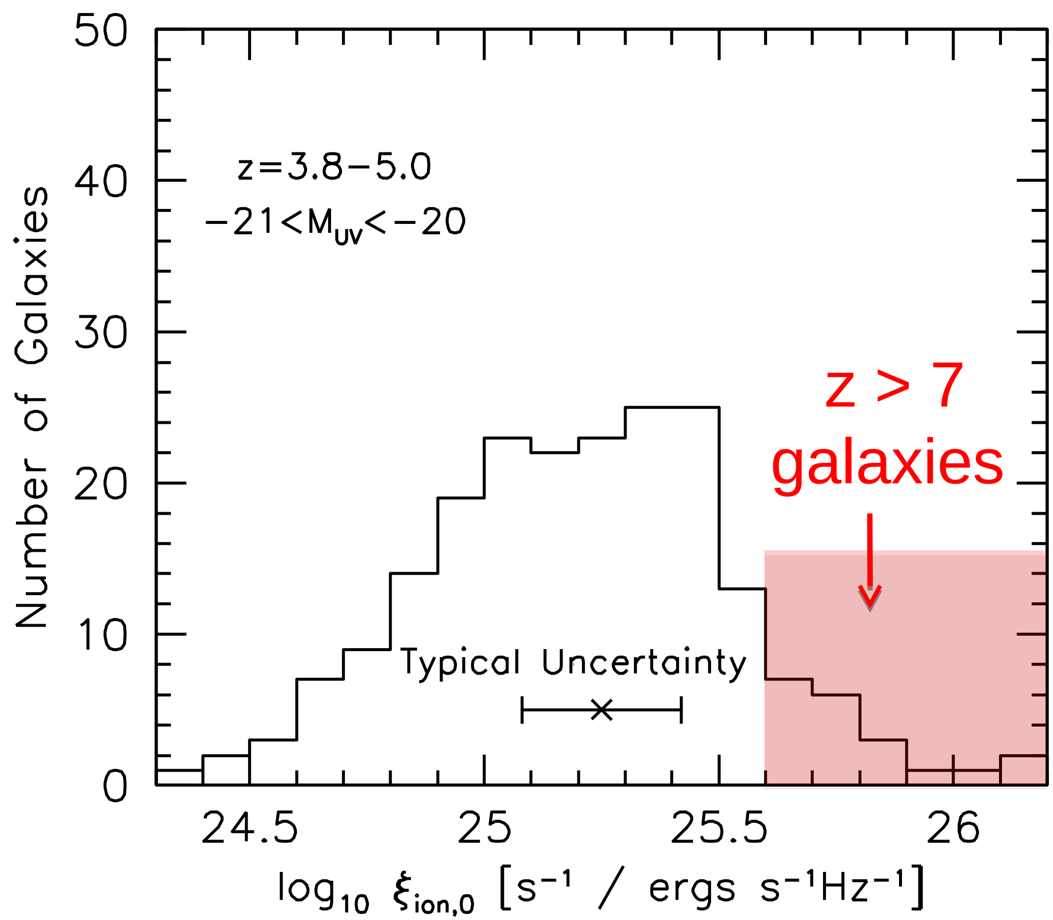
Luminous galaxies have stronger radiation fields which created early ionized bubbles. Conceivably AGN or unusually hot stellar populations?

[O III] strong sources also @ z~6 with Lyα emission (Smit et al, Pentericci)

Evidence for Strong Ionizing Radiation



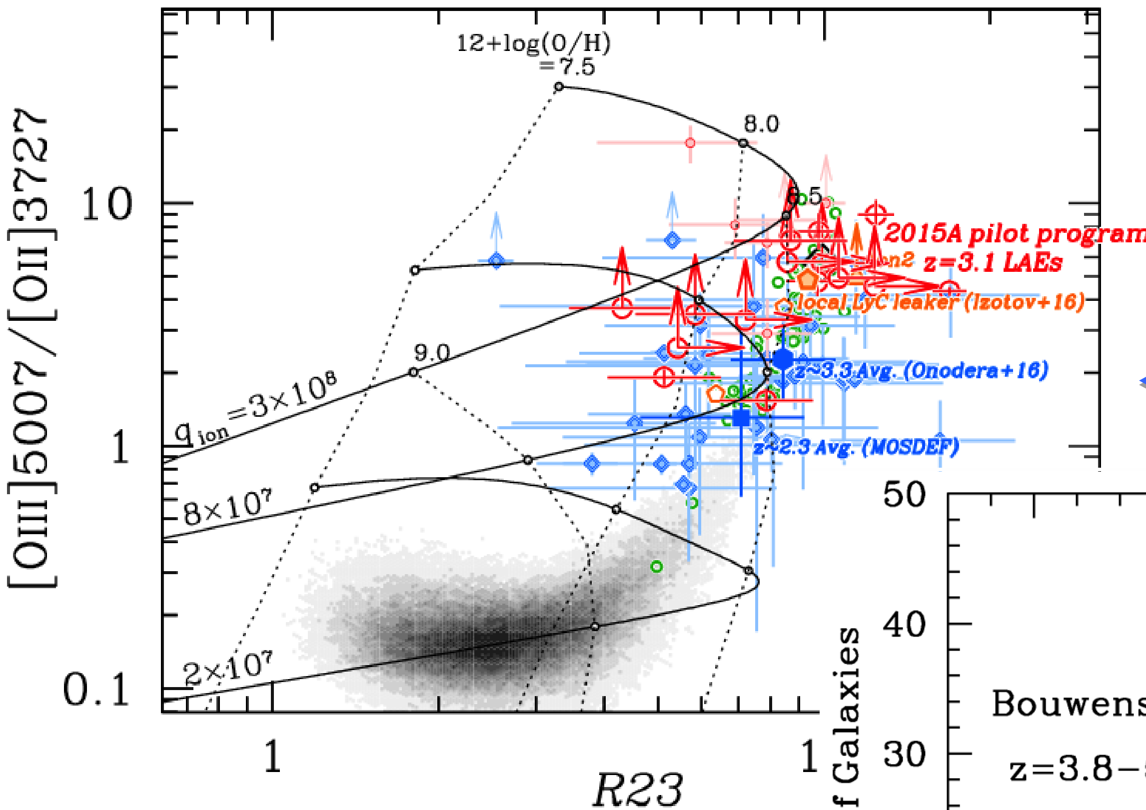




High ionization emission lines in luminous z > 7 galaxies indicates harder radiation fields (**larger ξ_{ion}**) possibly due (in part) to active nuclei (stay tuned!)

Stark et al (2015, 2016); Bouwens et al (2015)

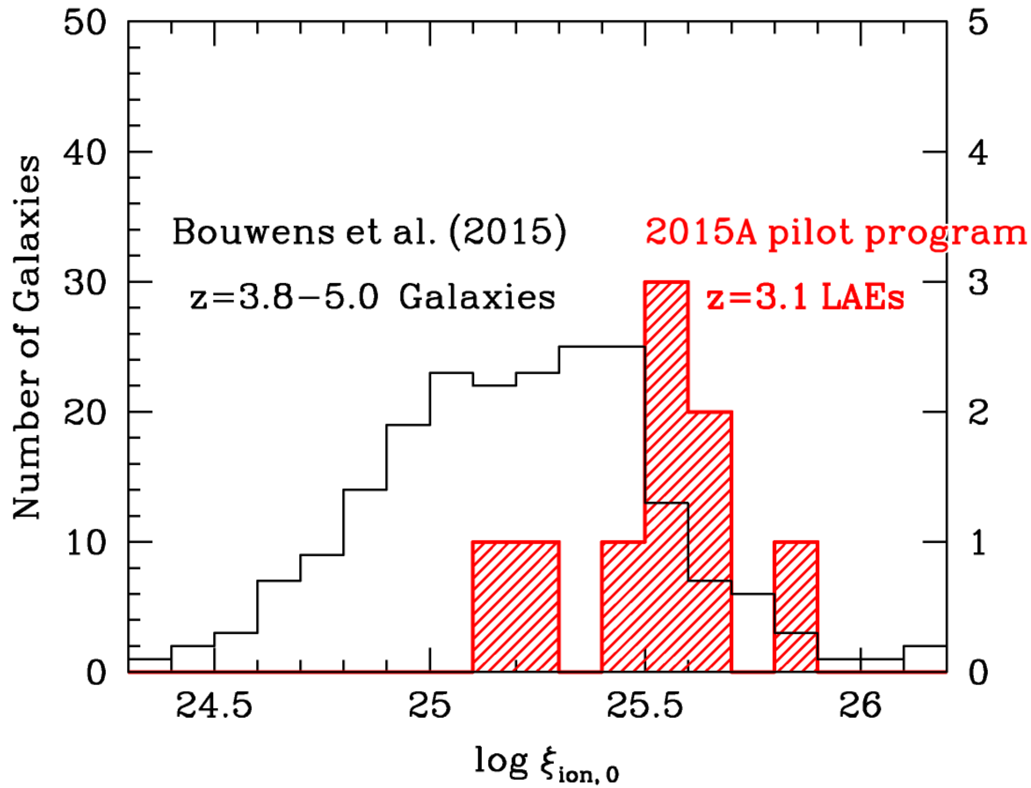
z~3 LAEs with intense [O III] as analogs: harder ξ_{ion}



Nakajima & Ouchi (2014)
Nakajima et al (2016)

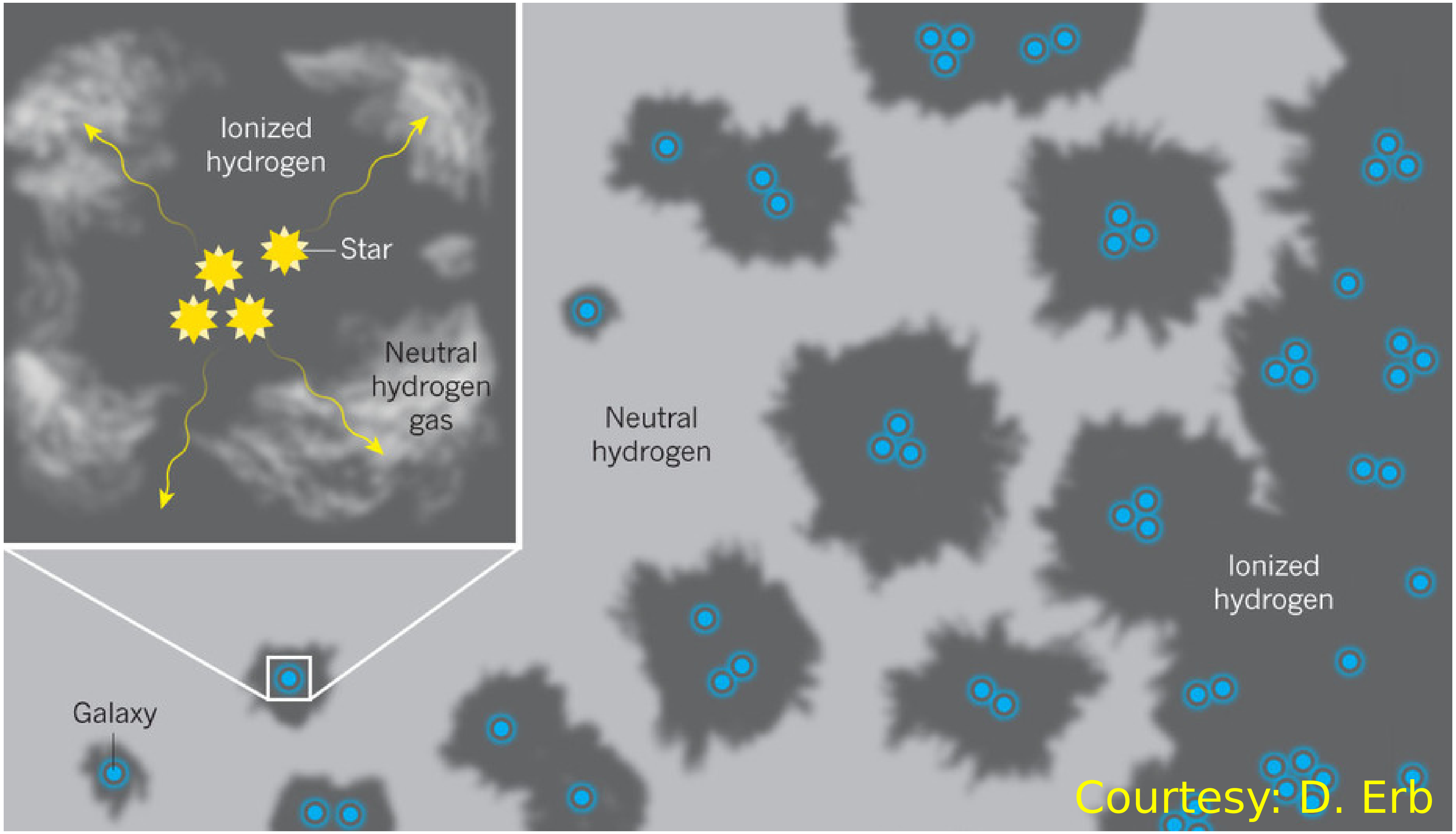
z~3 Lyα emitters

z~3 Lyman break galaxies



MOSFIRE spectra of 15 [O III] strong z=3.1 LAEs reveals Balmer Hβ that implies a much harder ionizing spectrum than equivalent redshift LBGs.

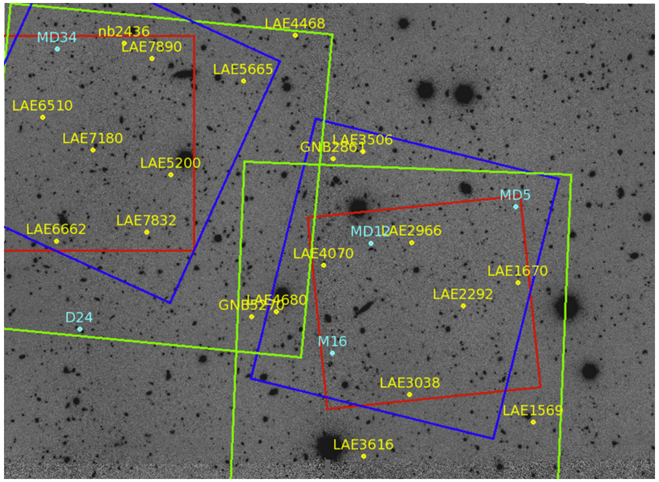
How Much Ionizing Radiation Escapes into the IGM?



Need f_{esc} > 10% to maintain reionization!

Simulations suggest young galaxies are porous with high escape fractions but hard to verify observationally

Foreground Contamination and low f_{esc} at z~2



At z~2 direct imaging below Lyman limit is practical, but for promising candidates selected from ground-based images, subsequent Hubble imaging and spectroscopy reveals contamination from lower redshift galaxies.

Implies f_{esc} < 2-5%

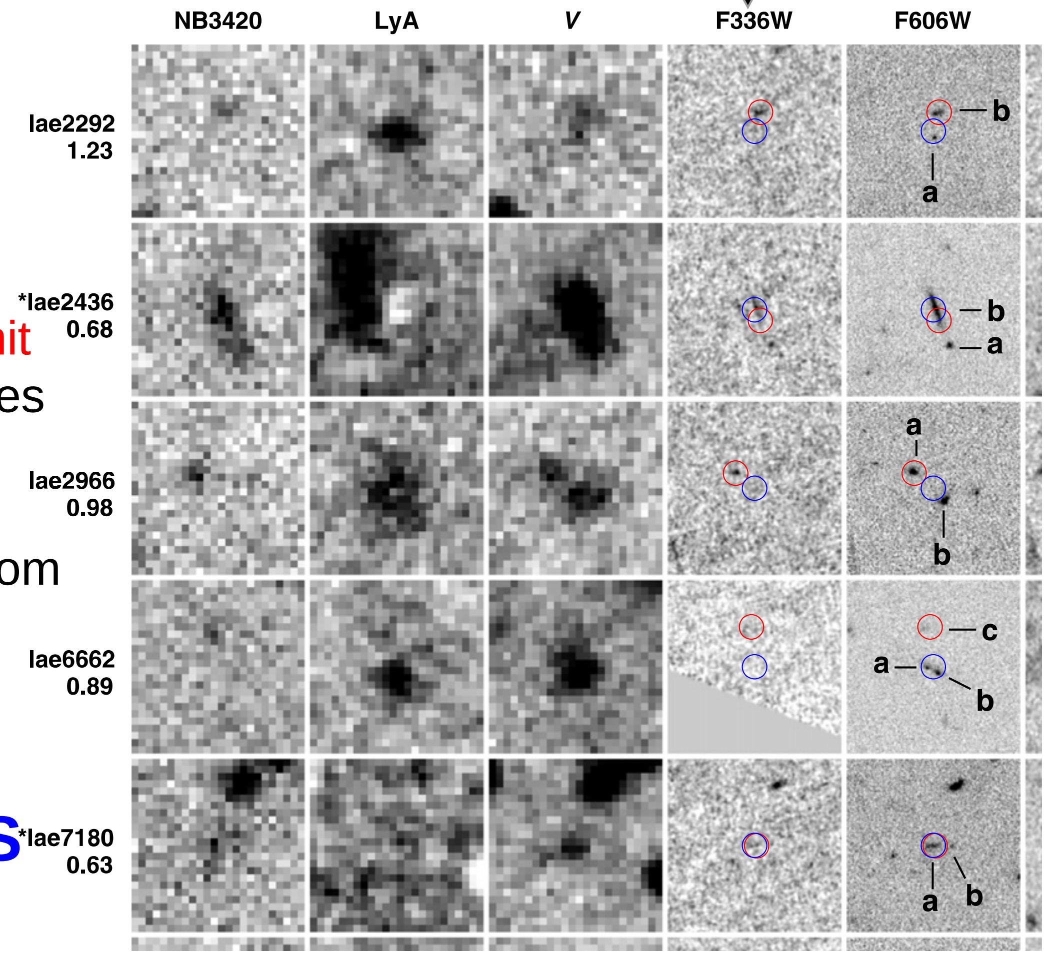
AT z > 6 DIRECT METHODS CAN'T BE APPLIED!

Ground-based LyC detection

HST LyC image

LyC centroid

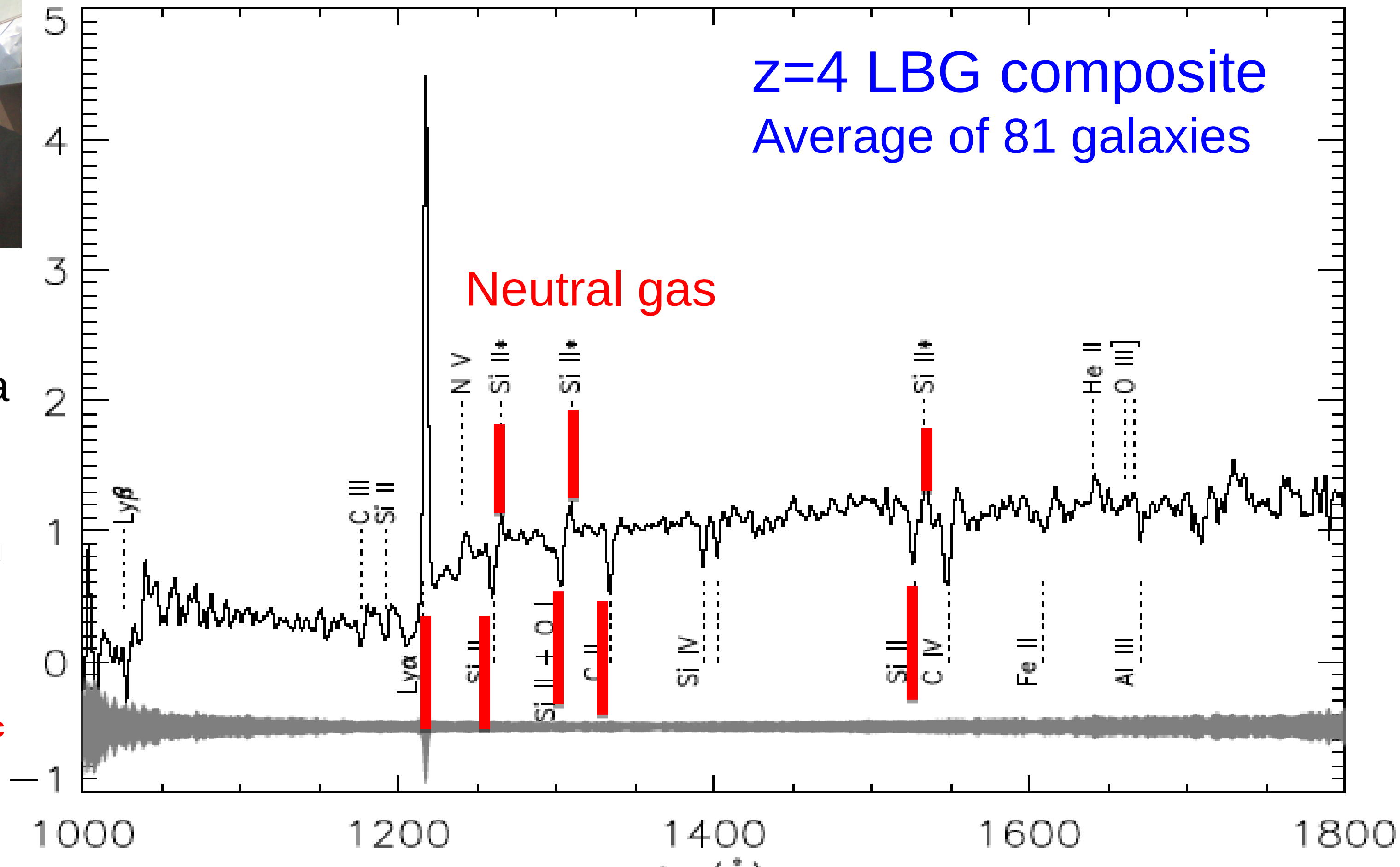
Lyα centroid



Mostardi et al (2015)

Outflowing Neutral Gas as probe of f_{esc}

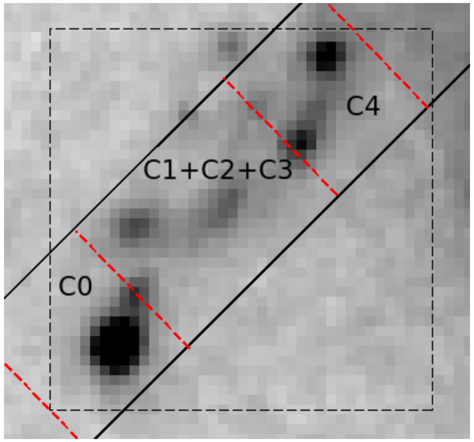
Keck DEIMOS R~3500 spectra probe low ionization absorption from neutral outflowing gas: i.e. **$f_c \sim 1 - f_{esc}$**

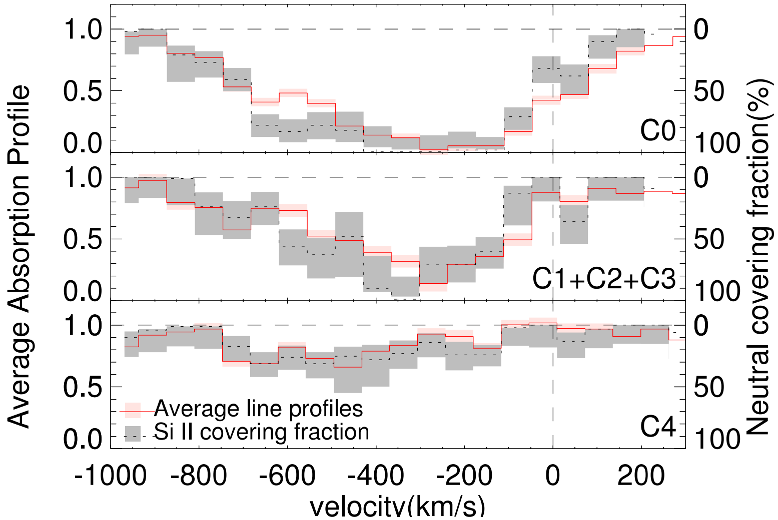


Stacked spectra have pros and cons – absorption also probes kinematics
Recent survey of seven 4 < z < 5 lensed galaxies demonstrates inhomogeneous covering of neutral gas with average f_{esc} ~ 10%

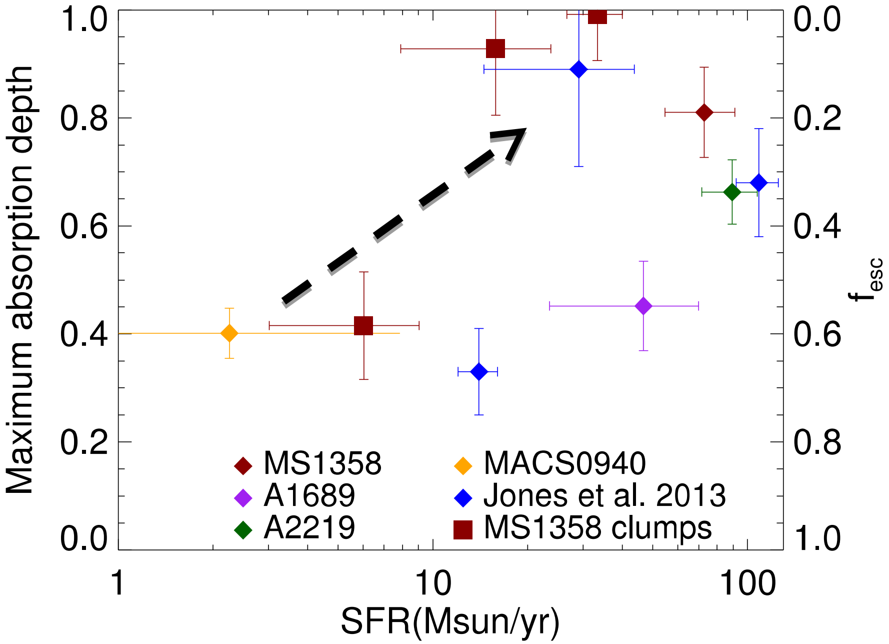
Jones et al (2012,2013); Leethochawalit et al arXiv 1606.05309

Resolved Covering Fractions in z~5 Lensed Galaxy





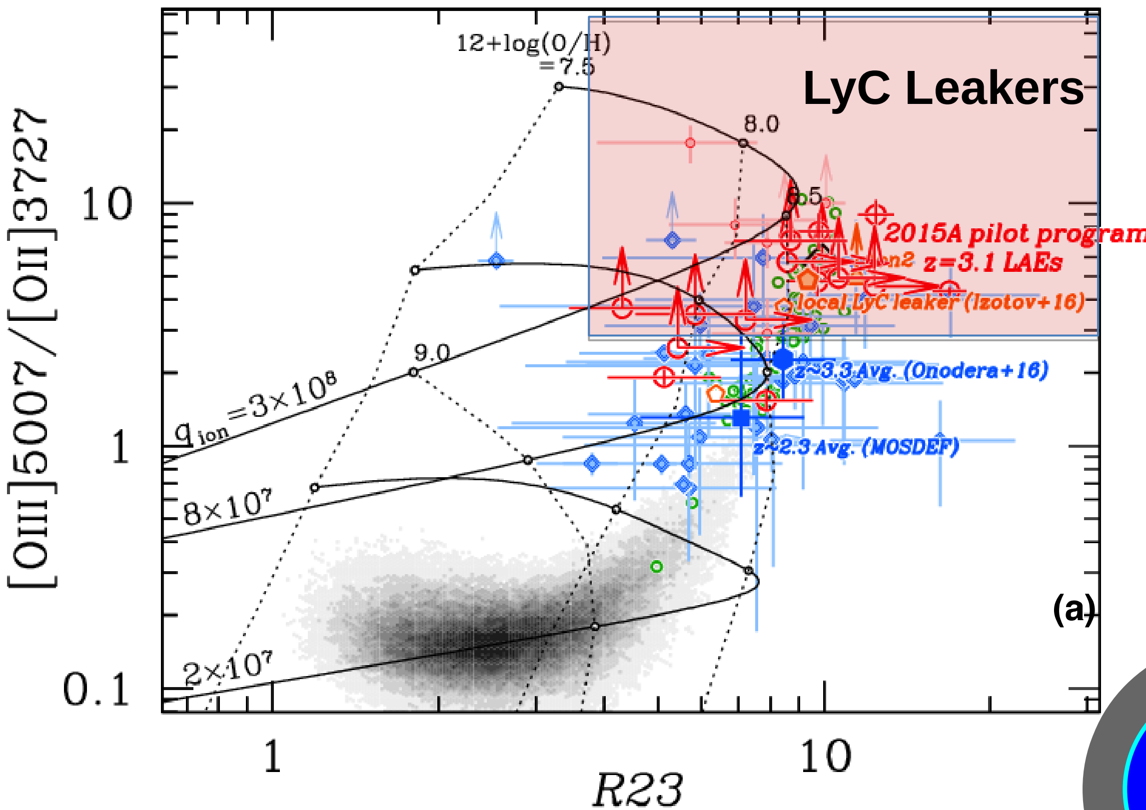
7.5 hour DEIMOS exposure on MS1358 (z=4.92) allows us to explore the covering fraction of low ionization gas **internally as a function of local SFR.**



Inferred escape fraction is **lower** in intensely SF regions consistent with time delay between burst-like activity and leaking LyC photons

Leethochawalit arXiv 1606.05309

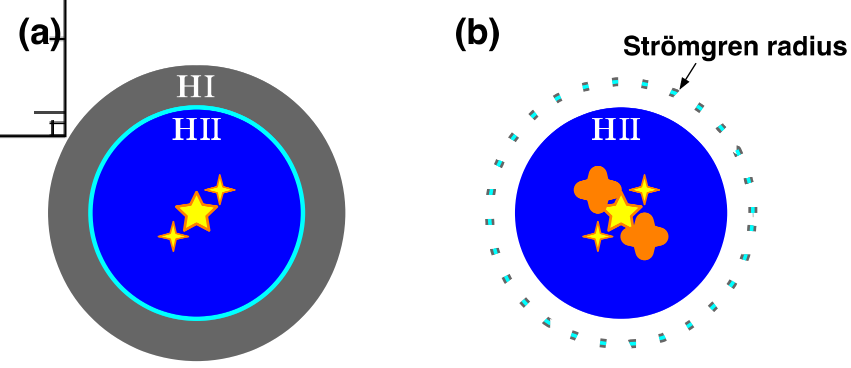
z~3 LAEs with intense [O III] as analogs: high f_{esc}?



Nakajima & Ouchi (2014)
Nakajima et al (2016)

z~3 Lyα emitters

z~3 Lyman break galaxies



Ionization-bounded nebula ***Density-bounded nebula***

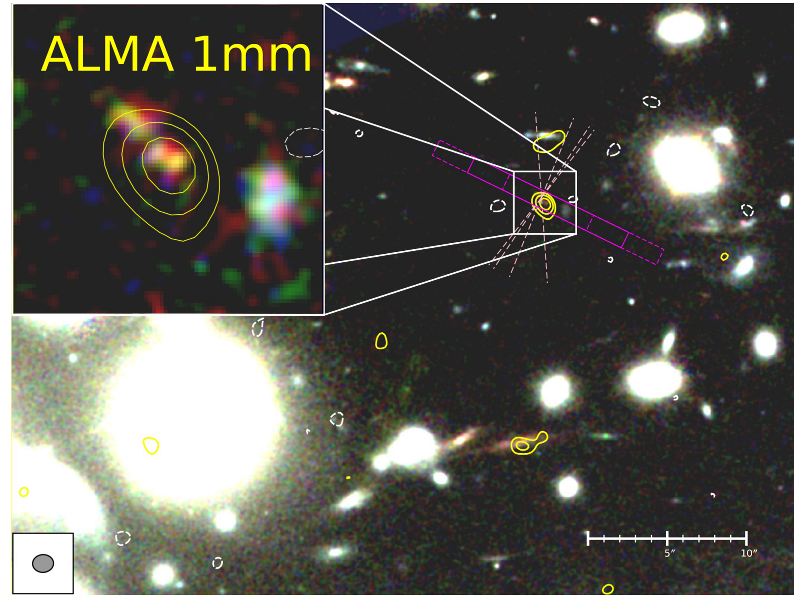
Photoionization models suggest high [O IIII]/[O II] ratios seen in z~3 Lyα emitters may have high escape fractions reflecting density-bound H II regions (c.f. Izotov et al 2016, Vanzella et al 2016)

STOP PRESS! HST PROGRAM TO TEST THIS IDEA (PI: ROBERTSON)

ALMA's Important Role

ALMA has key role in two respects:

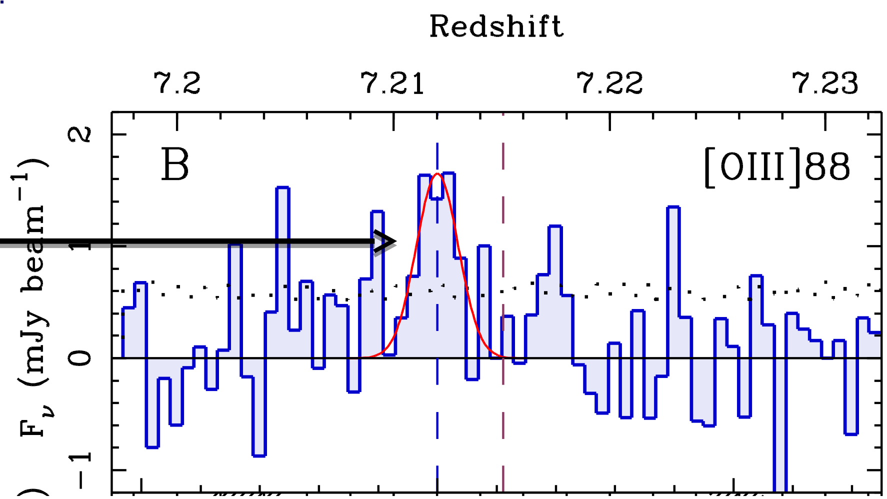
1. Tracing the emergence of early dust (affects interpretation of HST/Spitzer photometry and constrains chemical enrichment)



Band 6 dust continuum @ z=7.5 (log M_{dust} ~8)

2. Exploring ionization state & composition via emission lines complementary to those in UV

e.g. [O III]/[CII]>12 at z >7 could indicate ionized & low metallicity ISM and high f_{esc}

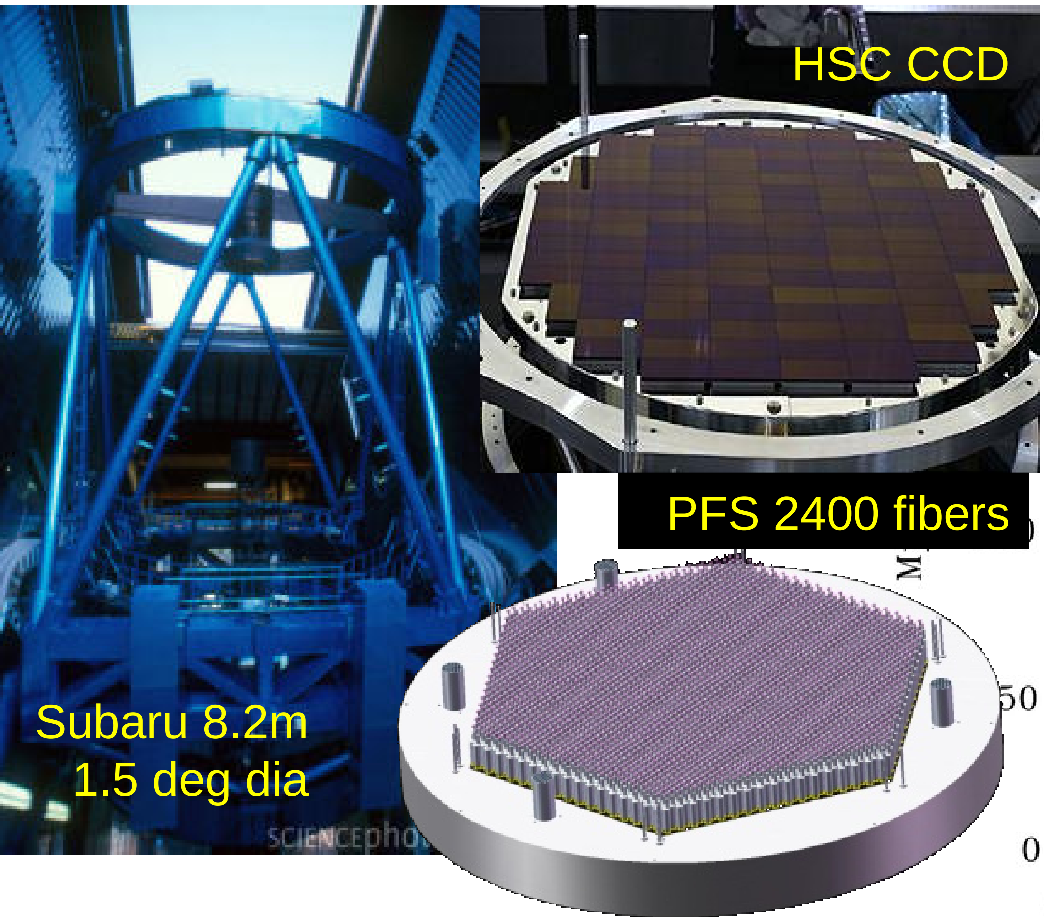


Watson et al (2015), Inoue et al (2016)

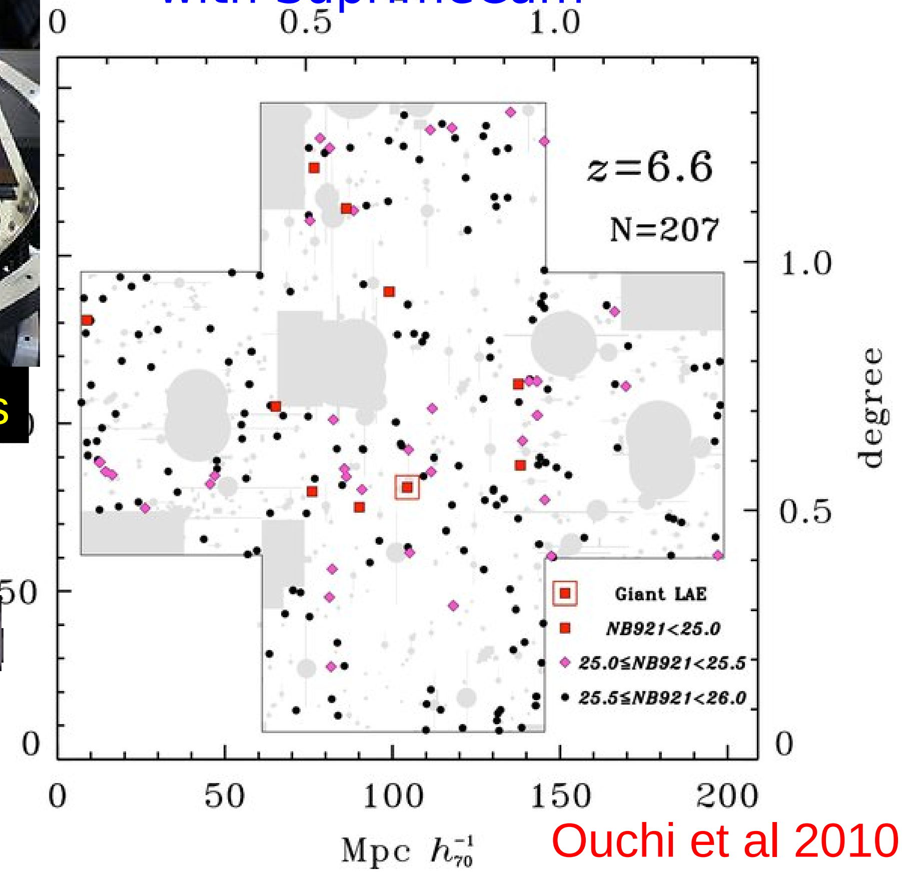
The Future

Coming Soon: Distribution of Lyα Emitters

Subaru HSC/PFS will chart distribution of Lyα emitters at end of reionization ($5.7<z<7.1$) over 25 deg^2 in possible coordination with LOFAR
Constrains evolving sizes of ionized bubbles & longevity of ionizing sources.



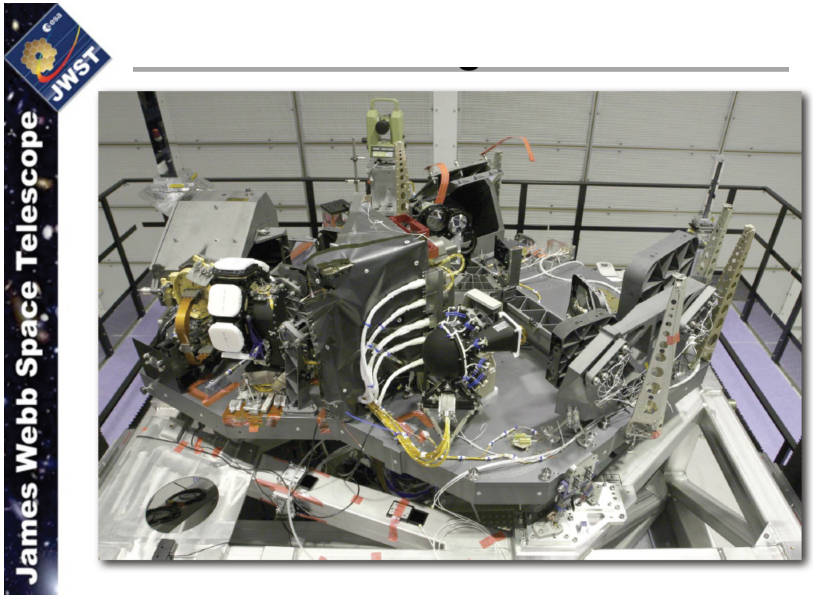
Angular distribution of z~6.6 LAEs via nb imaging with SuprimeCam



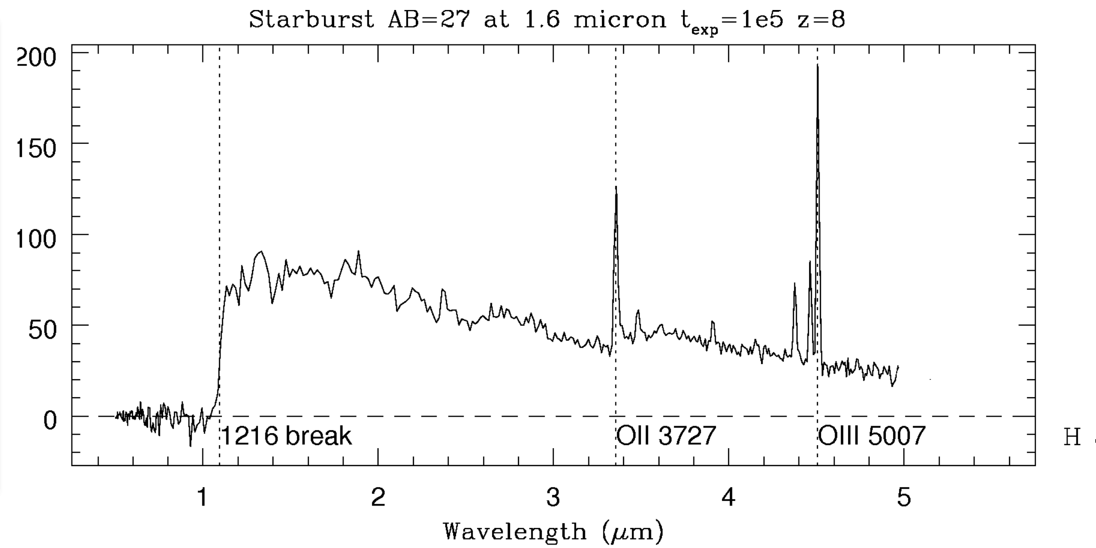
Ouchi et al 2010

Not Long to Wait: Spectroscopy with JWST

NIRSpec Instrument



z=8 galaxy; 25 hour exposure



JWST spectroscopy will detect the stellar continuum and measure composition of gas and the nature of ionizing radiation in redshift 8-12 galaxies using rest UV and optical lines ([O II], [O III], Hα) beyond reach of ground-based telescopes

Ground-Space Synergy 2020s: ELT AO Imaging

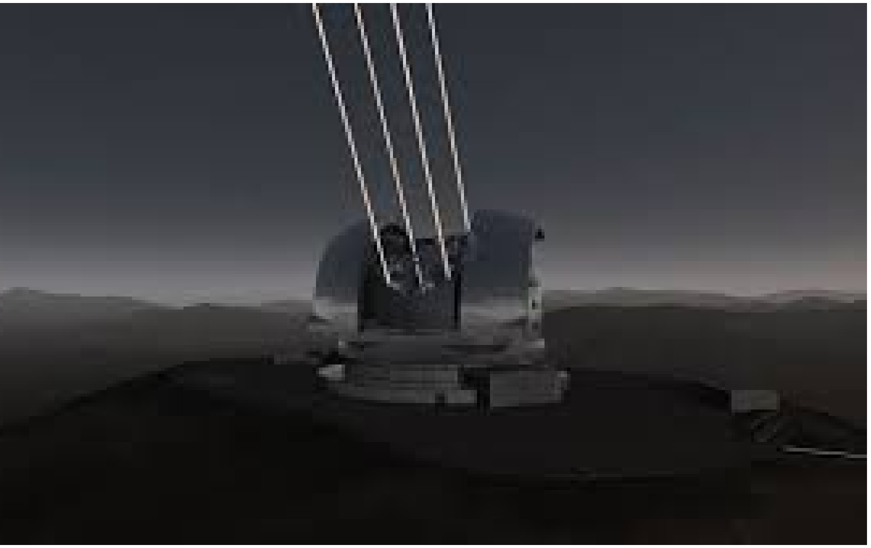
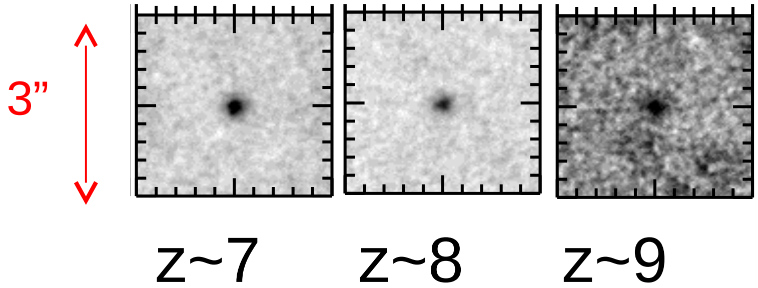
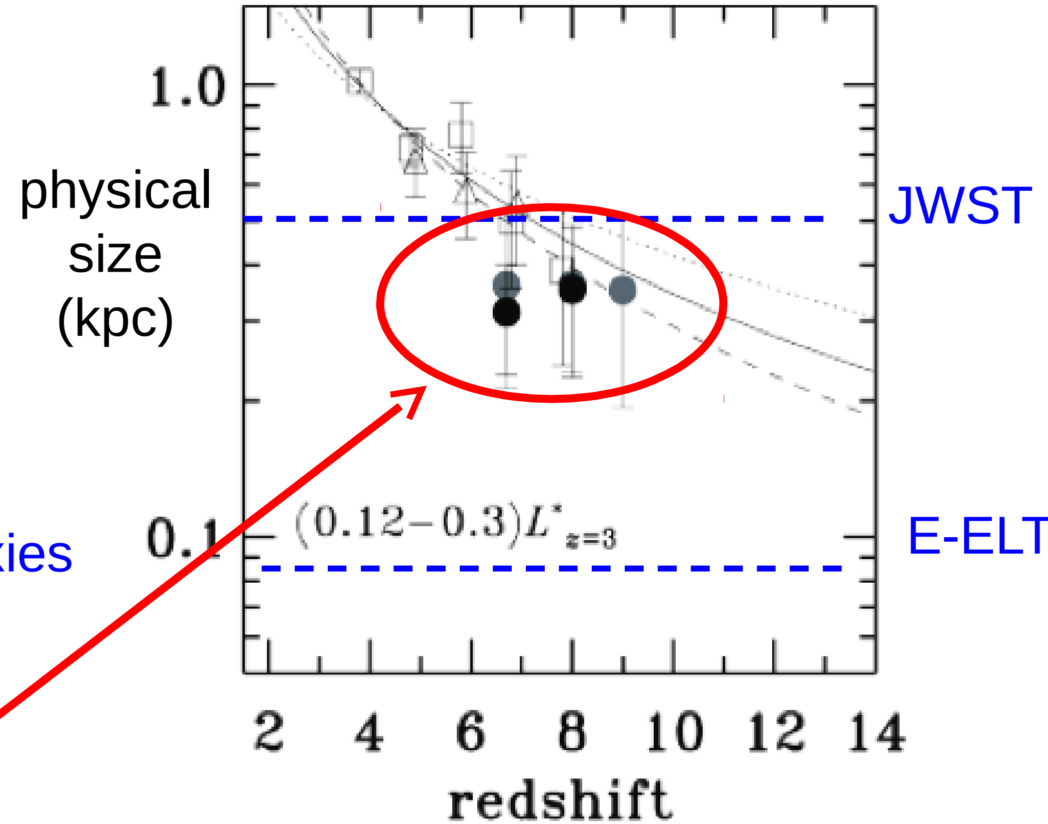


Image stacks for faint Hubble galaxies

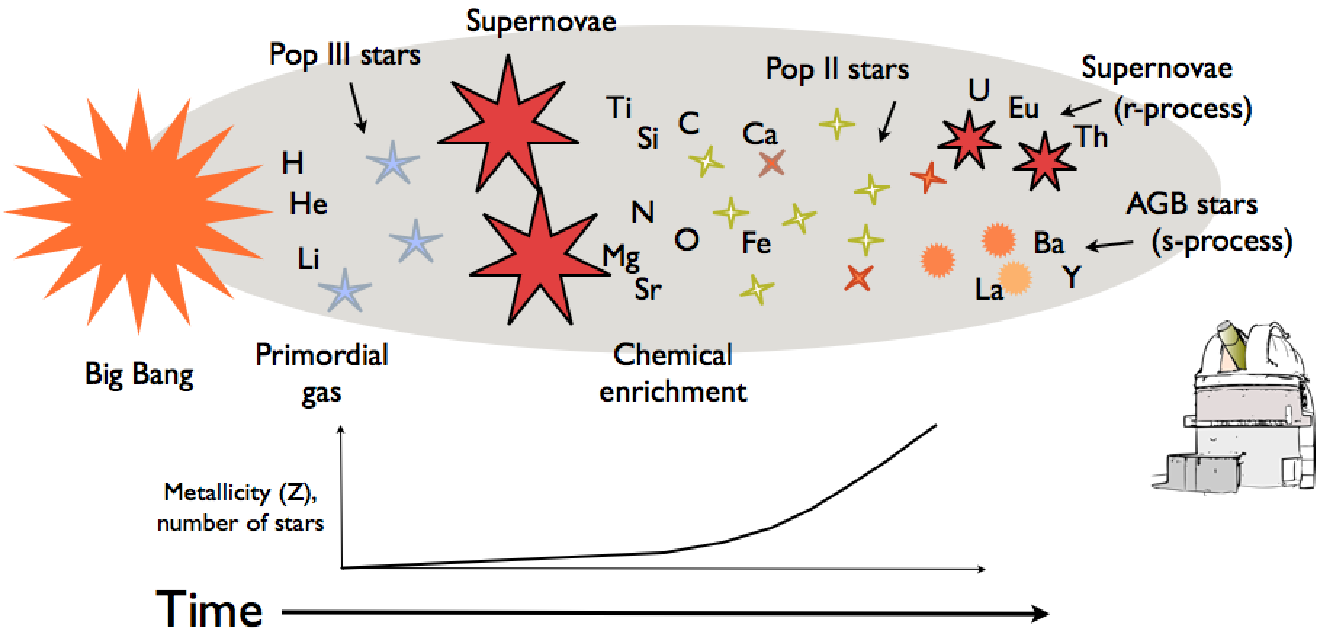




AO will enable ELTs to outperform JWST in image quality

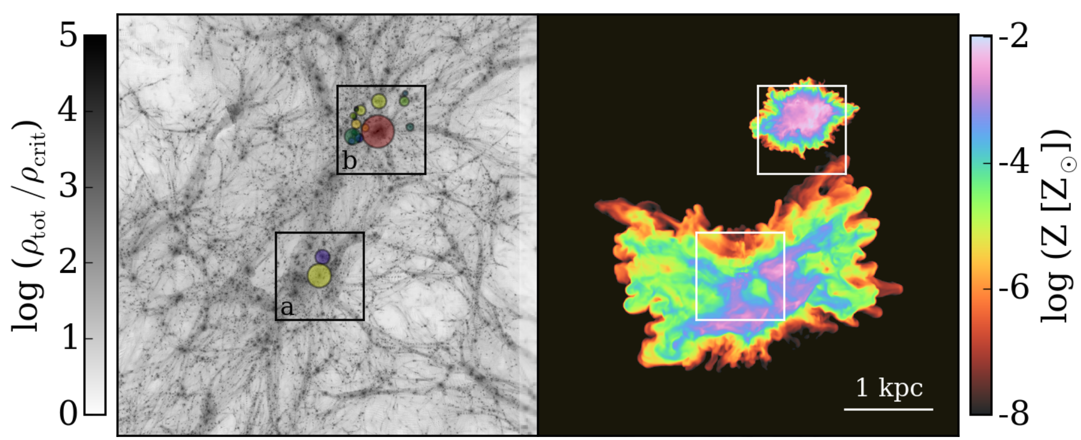
Unique advantage in rest UV studies of physically-small distant galaxies

Locating the First Generation?



A commonly promoted idea for isolating first generation systems has been to search for chemically pristene examples

Simulations suggest surprisingly prompt metal enrichment in early halos on timescale of 50-80 Myr; so pristene galaxies may be very rare



Smith, B. et al (2015)

Outstanding Challenges

- Is the low Planck τ correct? Main evidence for `late reionisation' since Lyα fraction test is hard to interpret quantitatively

- Soon will see new constraints on late reionization from Subaru HSC distribution of LAEs and 21cm pathfinders (e.g. LOFAR)

- Escape fraction of ionising photons f_{esc}
  - to maintain ionization at z~7-8 needs f_{esc}>10%
    - direct measures not possible in reionization era even with JWST
    - need to study nebulae with lower z analogs (z~3 LAEs?) or have better faith in covering fraction tests

- Production rate of ionizing photons per unit SFR ξ_{ion}
  - diagnostic spectroscopy of Balmer & high ionization lines
  - evolution of hot main sequence stars also critical

- Contribution of AGN? They must be there beyond z>7 with high f_{esc}

- Dust at high redshift? Crucial to secure more ALMA continuum measures