Observing Star Forming Galaxies in the Heart of the Reionization Era

Richard Ellis, Caltech

CAASTRO 2013 `Reionization in the Red Center'

July 16th 2013

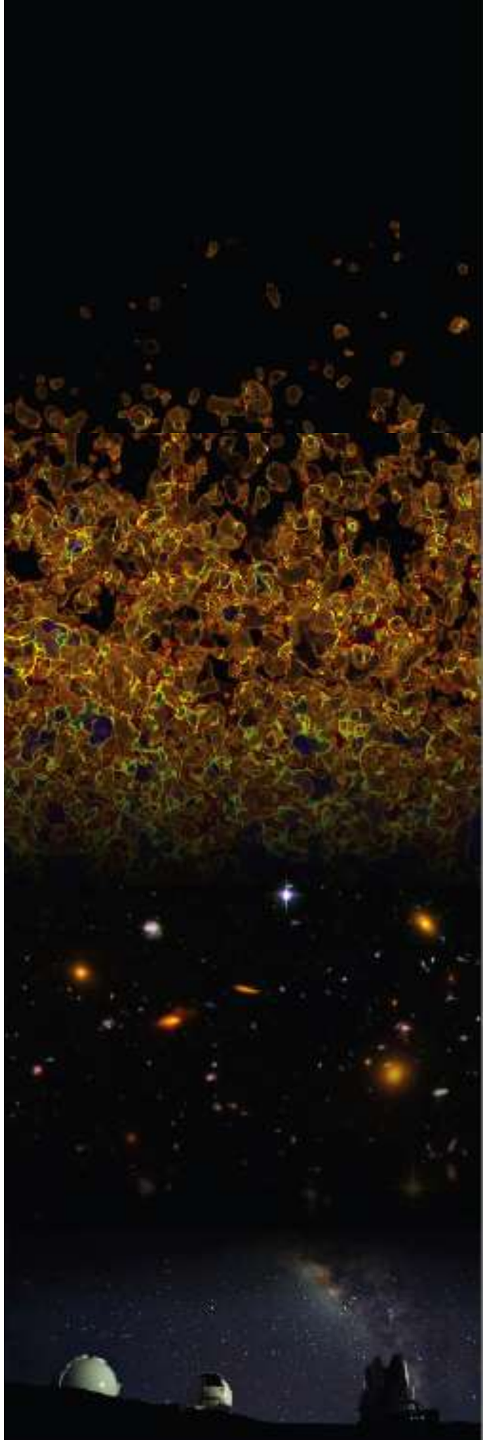
The Big Questions

- When did reionization occur?
  Weak constraints from the microwave background; results from Keck spectroscopy and other probes

- Were star forming galaxies responsible? Need to study galaxies in the reionization era
  - Abundance of star-forming galaxies
  - Nature of their stellar populations
  - Density of assembled stellar mass at lower z (integral constraint of earlier activity)

- Issues and challenges:
  - Nebular contamination of broad-band photometry (Schenker’s talk)
  - Escape fraction of ionizing photons
  - Future opportunities

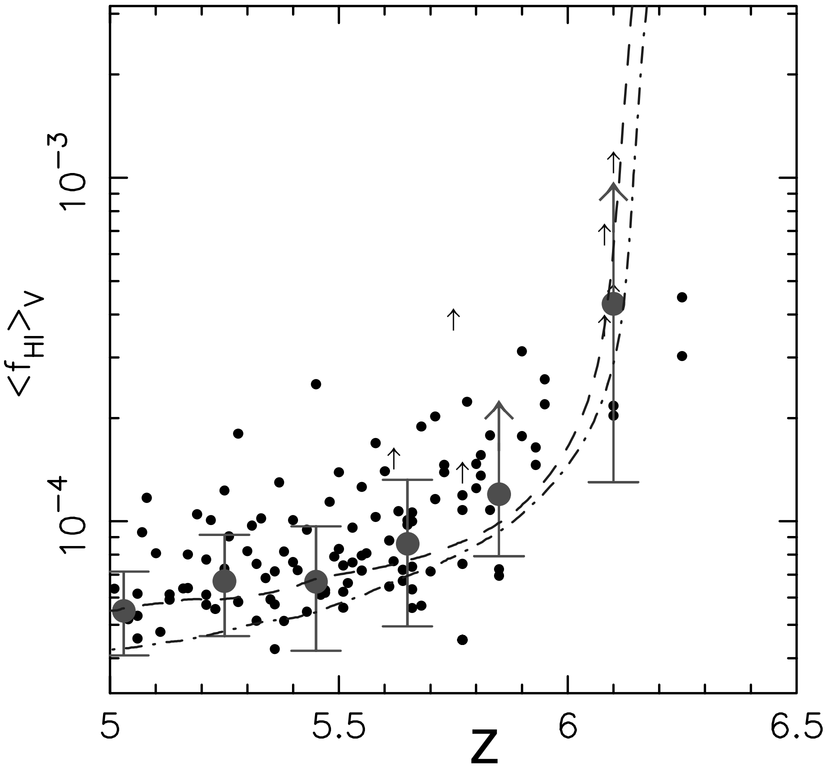
Collaborators: Matt Schenker (Caltech), Tucker Jones (UCSB), Brant Robertson, Dan Stark, Evan Schneider (Arizona), Steve Furlanetto (UCLA), Jim Dunlop, Ross McLure, Emma Curtis-Lake, Sandy Rogers, Rebecca Bowler (Edinburgh), Anton Koekemoer (STScI), Stephane Charlot (IAP), Yoshiaki Ono, Masami Ouchi (Tokyo),

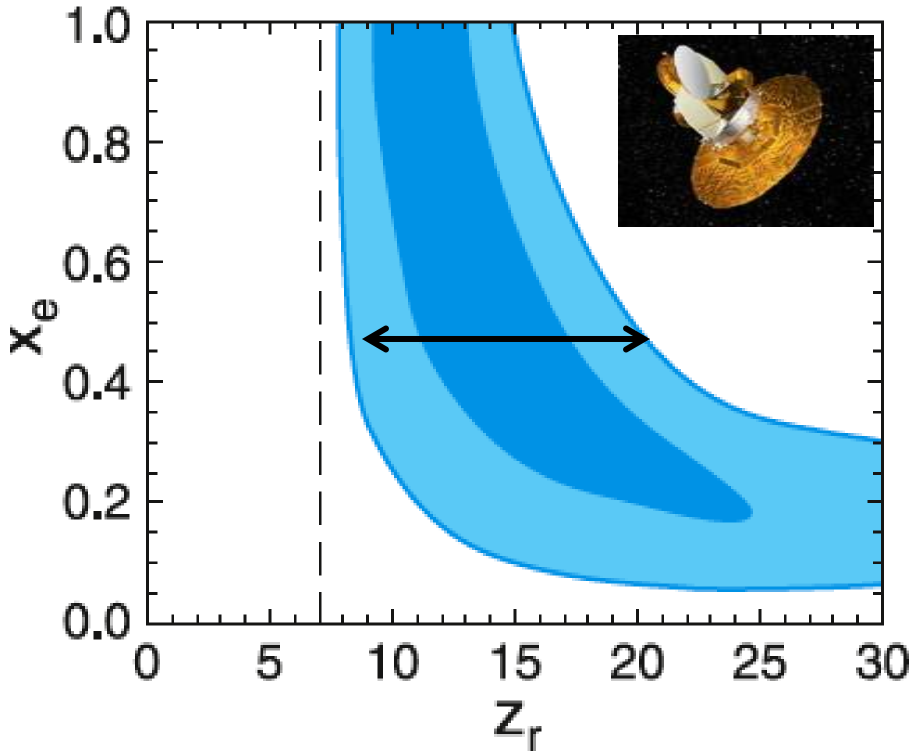


When Did Reionization Occur?

Gunn-Peterson trough in z>6 QSOs, Fan et al (2006): insensitive: only small amount of HI required (X_{HI} ~> 10^{-3})

WMAP+eCMB, Hinshaw et al (2012): τ = 0.084 $\pm$ 0.013 consistent with instantaneous reionization z=10.3 $\pm$ 1.1

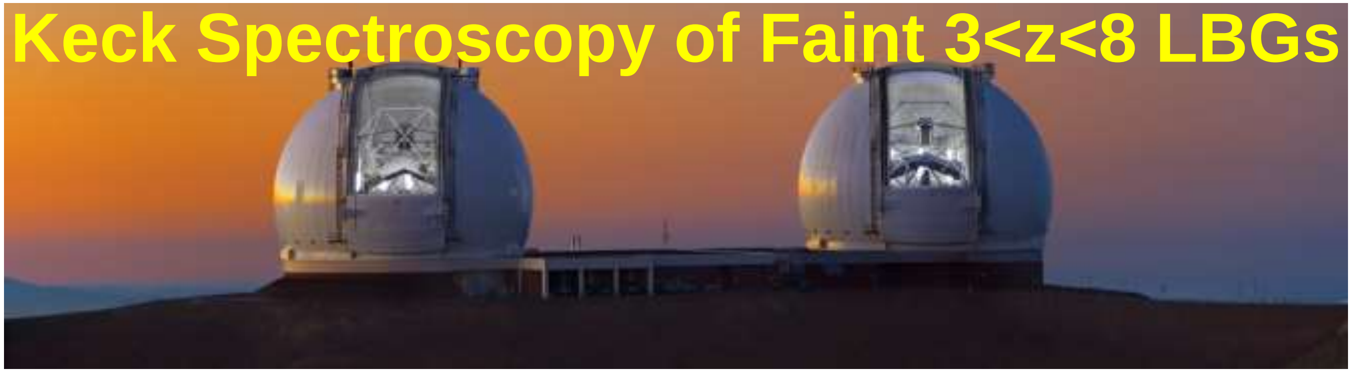




Data rejects instantaneous reionization at z~6-7; most likely gradual over 6<z<20? Await results from Planck

NB: CMB polarization will not pinpoint sources of reionization

Keck Spectroscopy of Faint $3<z<8$ LBGs



Motivation: improved understanding of high z SF galaxies

- verify photometrically-derived properties (redshifts, masses, SFRs)
- **visibility of Lyman α emission as probe of neutral gas in IGM**
- **investigate nebular emission as contaminant in bb photometry**
- **investigate demographic changes in SF population**

Targets: $m_{AB}<27.5$ 5-12hr exposures in GOODS & CANDELS-UDS fields

DEIMOS multi-slit $3<z<6$ - B,V,i drops

LRIS-R multi-slit $6<z<7$ - i, z’ drops

NIRSPEC long-slit $z>7$ - z’, Y drops (now MOSFIRE – Schenker’s talk)

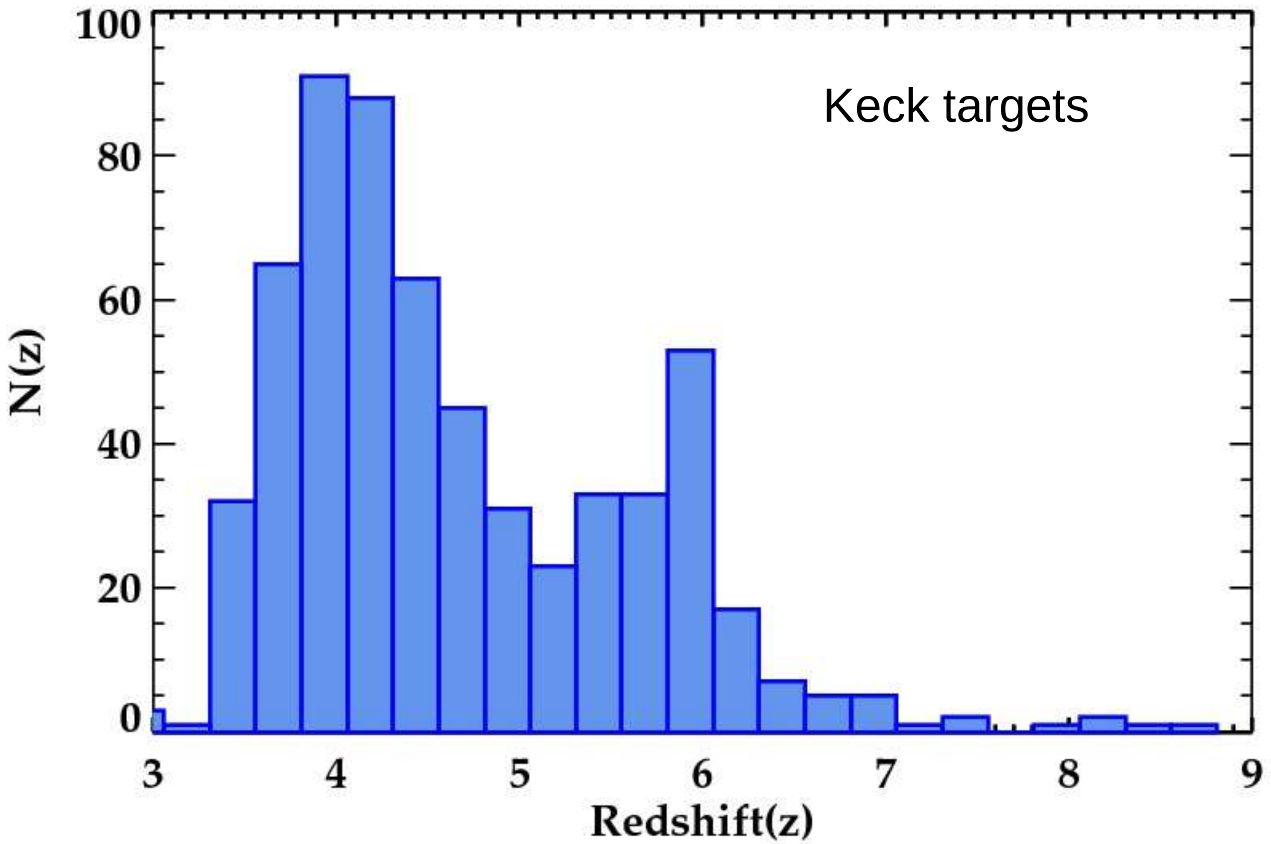
Target catalog:	Stark et al (2009) Ap J 697, 1493
Spectroscopy $3<z<5$	Stark et al (2010) MNRAS 408, 1628
Spectroscopy z~6	Stark, Ellis & Ouchi (2011) Ap J 728, L2
Spectroscopy z~7	Schenker et al (2012) Ap J 744, 179
Stacked z~4-5 spectra	Jones et al (2012) Ap J 751, 51
Nebular emission	Stark et al (2013) Ap J 763, 129
Nebular emission	Schenker et al arXiv 1306.1518

Keck Spectroscopic Survey of 3 < z < 8 LBGs

- Utilize Stark et al (2009) ACS/IRAC GOODS-N/S photometric catalog:

  2443 B-drops, 506 V-drops, 137 i-drops = 3086 sources

- Keck: 351 B + 151 V + 89 i + 21 z + 5 Y drops = 617 spectra
- VLT/FORS2 retro-selected + same criteria: 195 spectra (Vanzella et al)



Lyα Emission as a Probe of Reionization

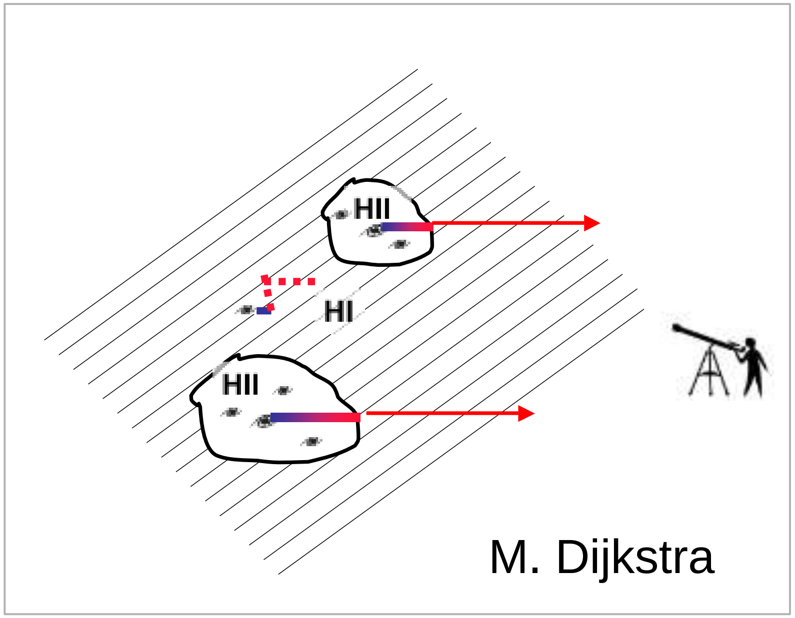
Up to 6-7% of young galaxy light could emerge in Lyα: prominent in early systems

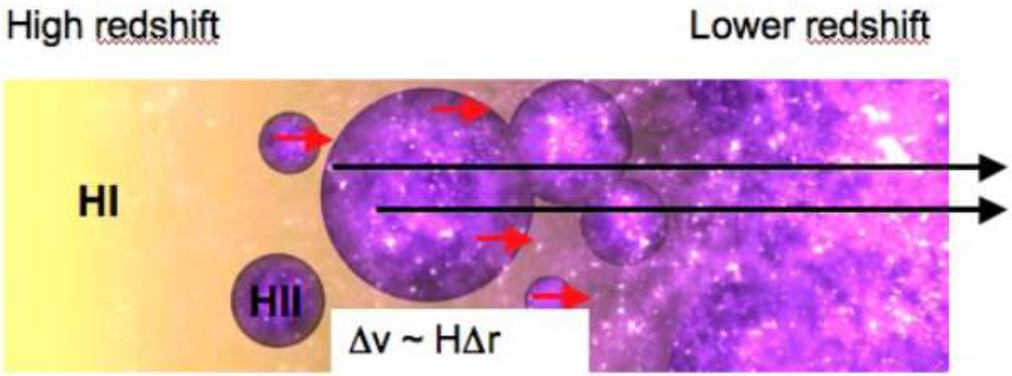
- But resonant scattering by neutral gas reduces visibility of Lyα

- So, 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 we enter the neutral era

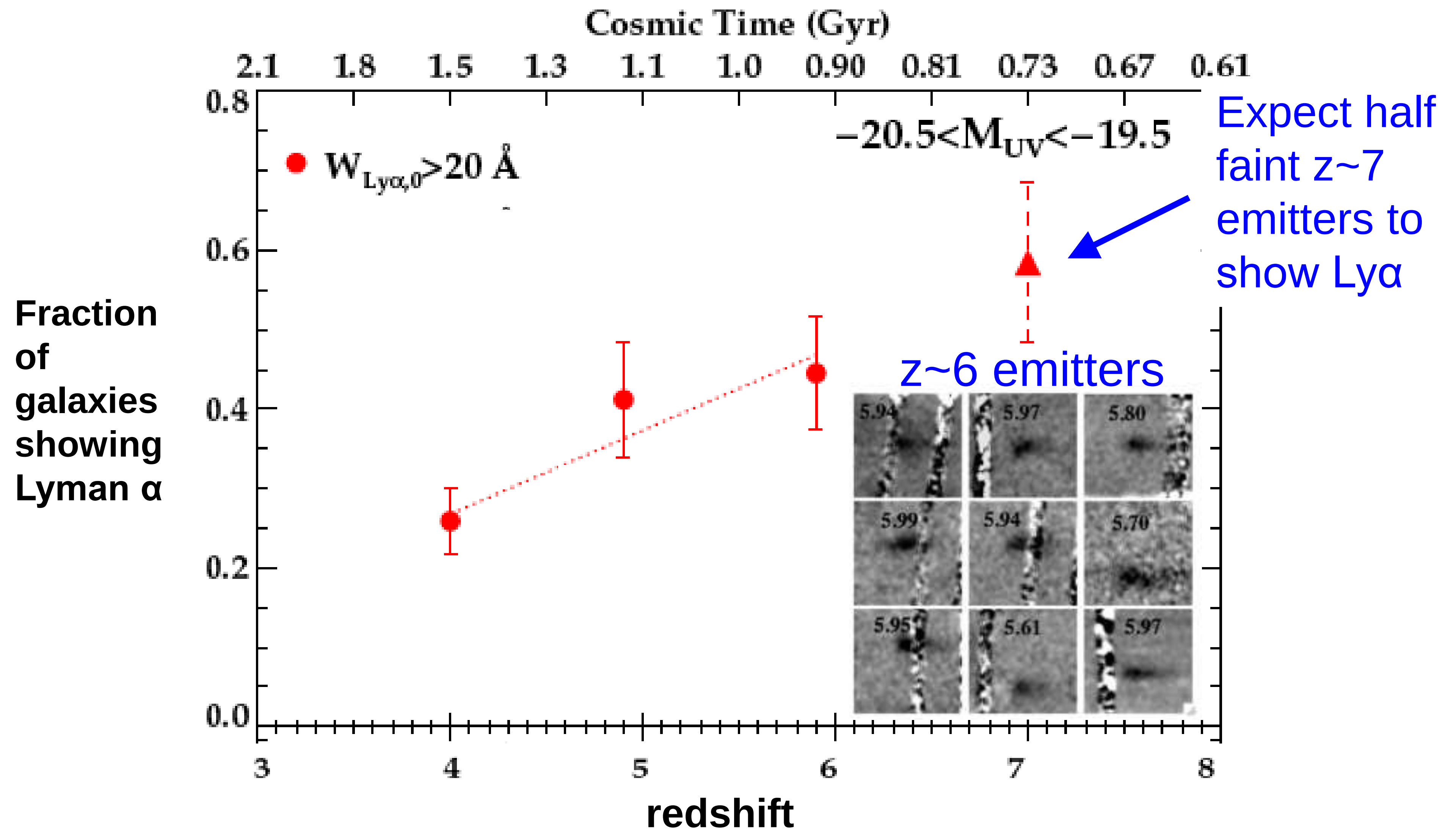
- **Caveats: dust, outflows etc**





Santos (2004), Dijkstra et al (2007), McQuinn et al (2007)

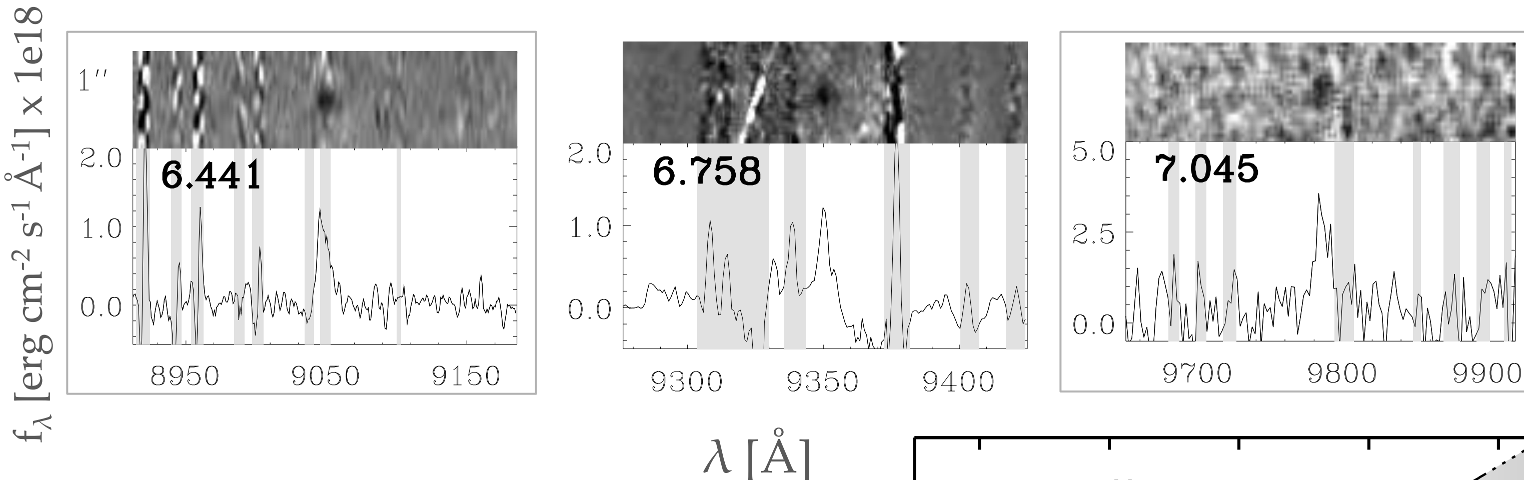
`Lyman α Visibility' versus Redshift



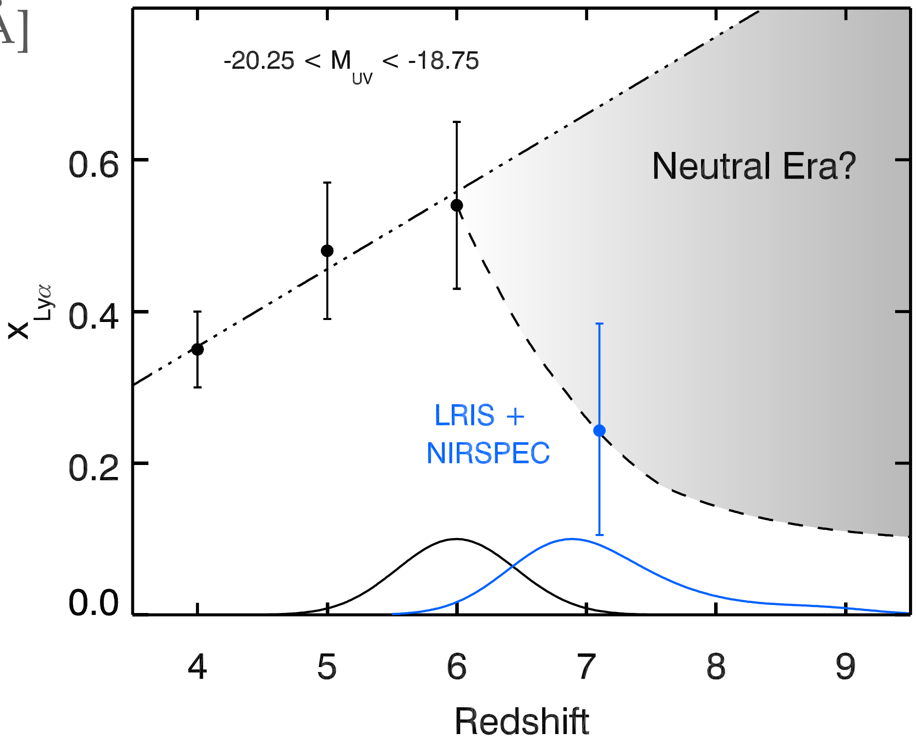
High visibility at z~6 implies should readily detect emission at z > 7

Stark, Ellis & Ouchi (2011) Ap J 728, L2

Sudden Decline in Lyα Fraction z > 6.3 ?

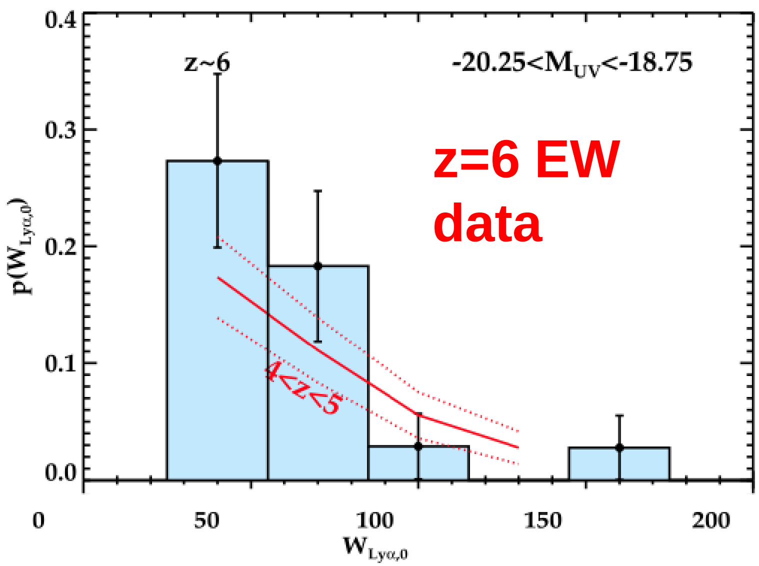


- 24 galaxies with 6.3<z<8 surveyed, Lyα detected in only 3 sources to same EW limit
- Implies decline in fraction (although still marginal result)
- Adopting McQuinn et al. (2007) ➔ X_{HI} ~ 0.44 at z ~ 7
- Explanations other than a neutral IGM (contamination from low z, dust) unlikely



Schenker et al (2012) see also Pentericci et al (2011), Ono et al (2012)

Assessment with Monte Carlo Simulations



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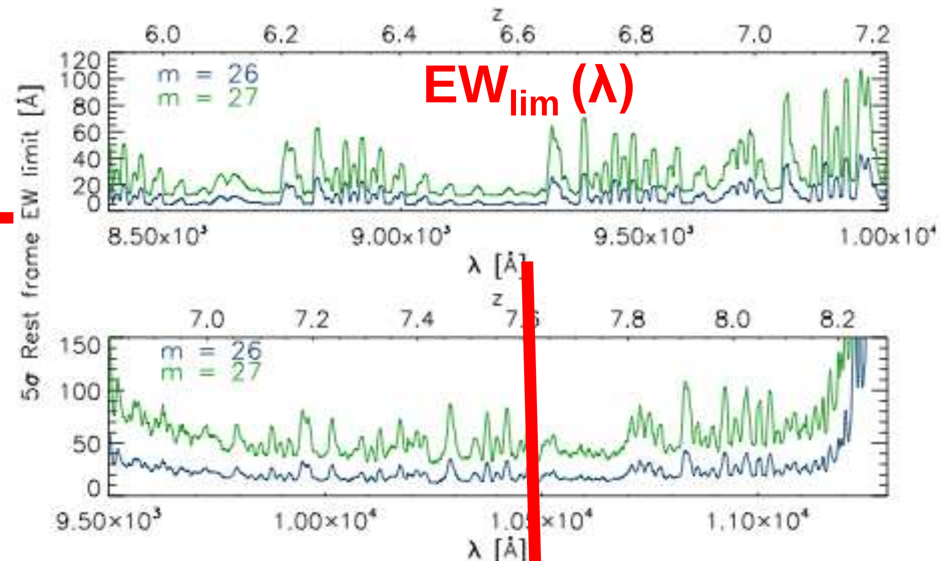
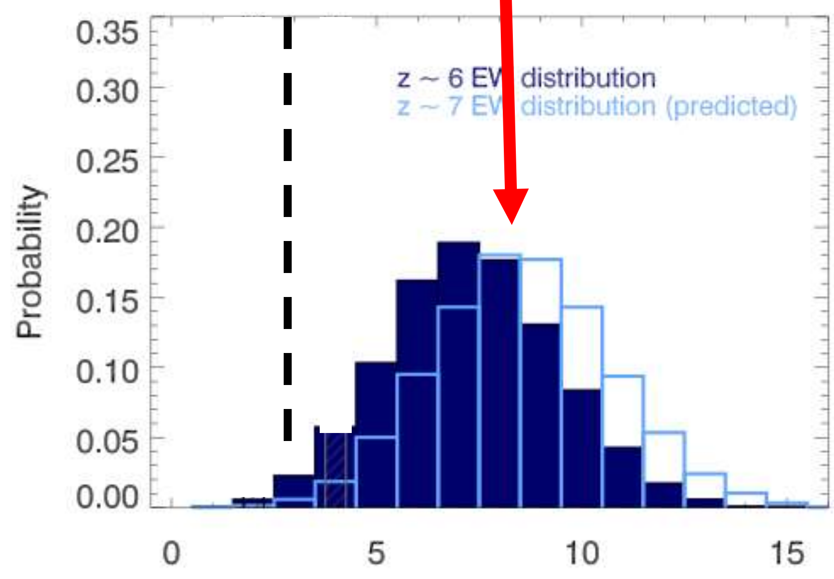


Since we cannot conduct a perfectly uniform search for line emission in the near-IR, we take the expected EW distribution of Lyα at z~6 and predict, given the observations, OH sky and photometric p(z) of our targets how many lines we should have seen.



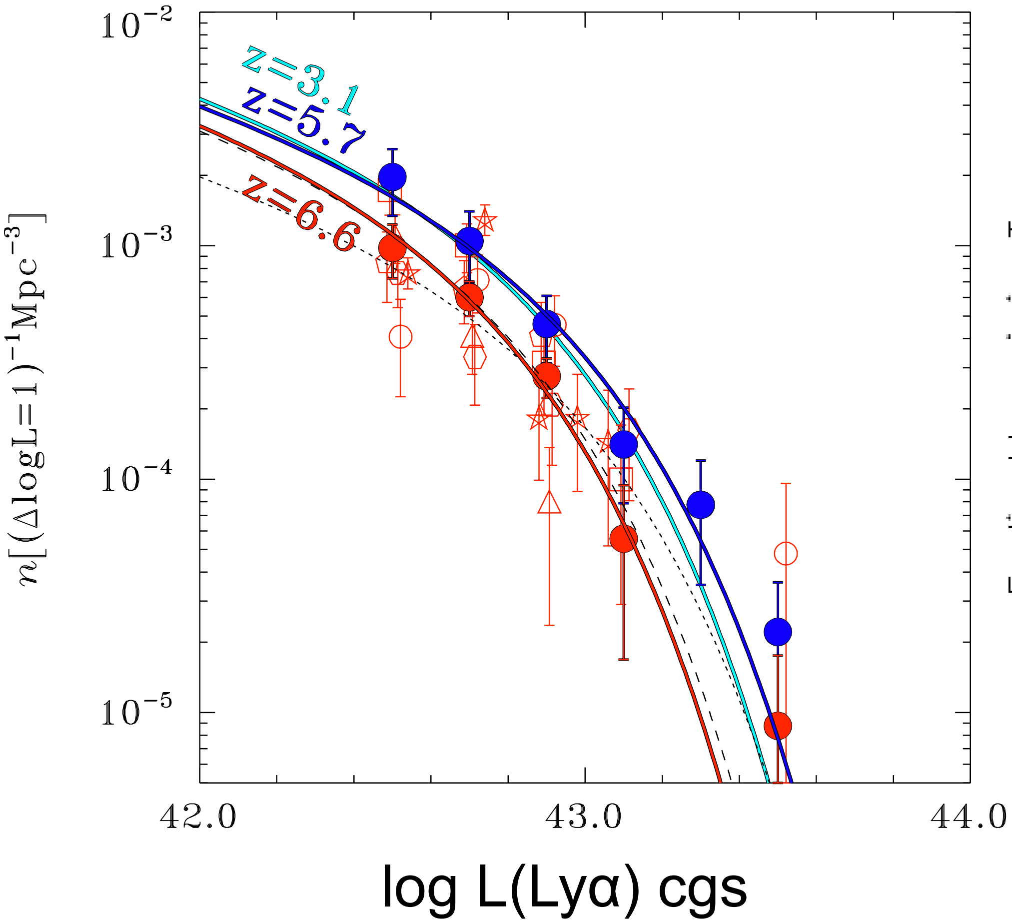
Observe 3 (8) and expect 8-9 (24) detections [reject at >99.5%]

Schenker et al (2012) Ap J 744, 179 (confirmatory update soon from Pentericci et al)

Further Evidence for Late Reionization

Rapid decline in abundance of Lyα emitters from 5.7<z<6.6 (Ouchi et al 2010)

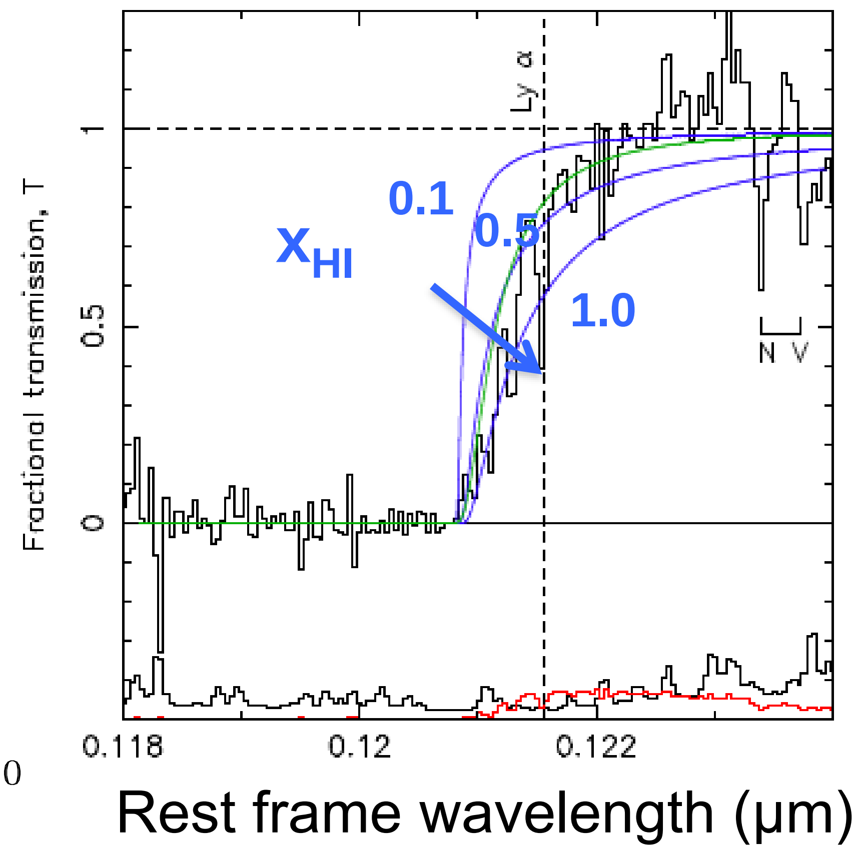
$x_{HI} \sim 0.1$ at z=6.6?



Damping wing of Lyα in z=7.085 QSO: Sharper decline c.f. lower z QSOs

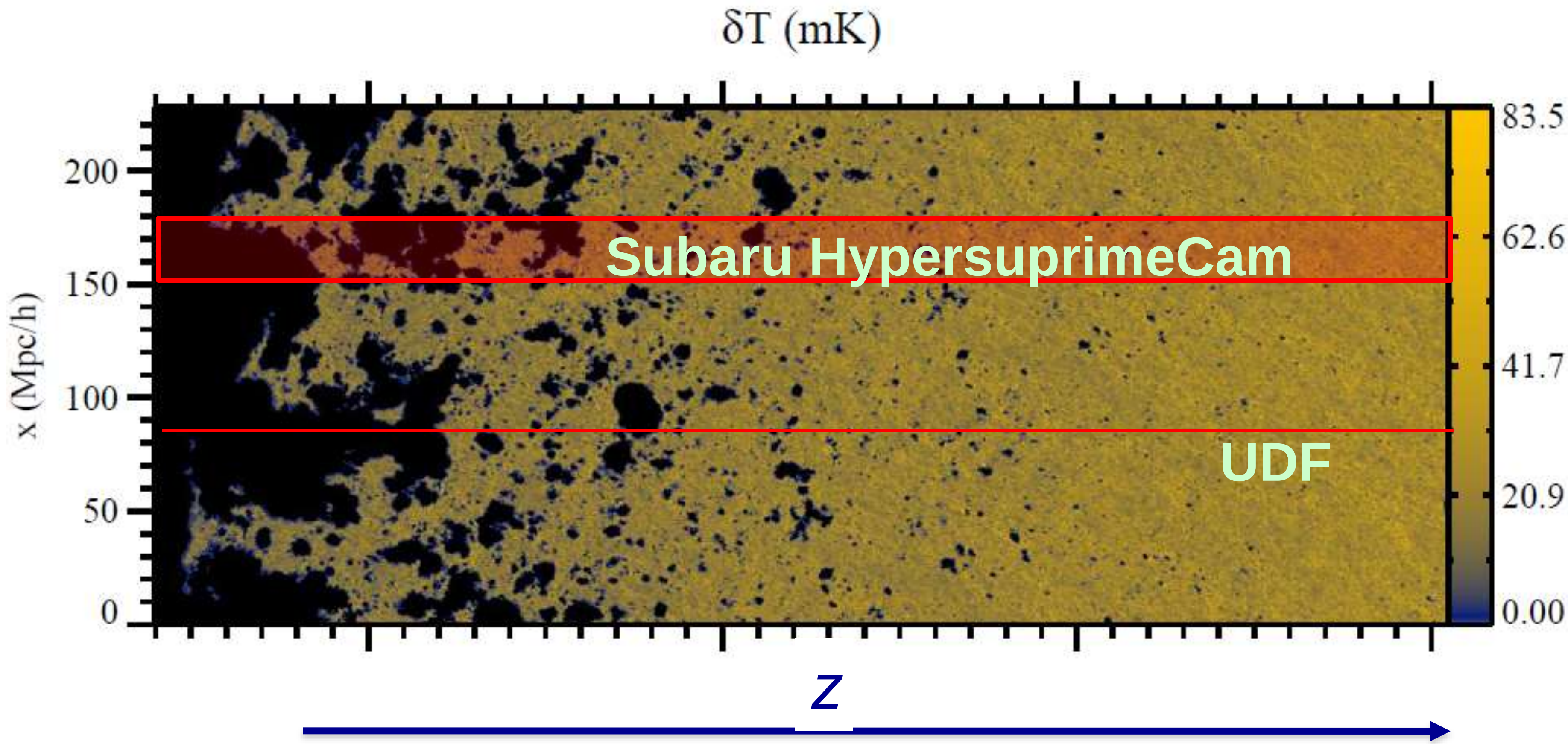
$x_{HI} > 0.1$ at z~7?

(Mortlock+ 2011, Bolton+ 2011)



Is this rapid change in x(Lyα) due to the IGM?

Some caveats (later talks):
-Cosmic variance: do not expect uniform X(Lyα, z) over all fields
-Inferred x(HI) depends critically on velocity offset of emerging Lyα
-Can significantly reduce inferred x(HI) by including small, optically-thick clouds (Bolton & Haehnelt 2013)

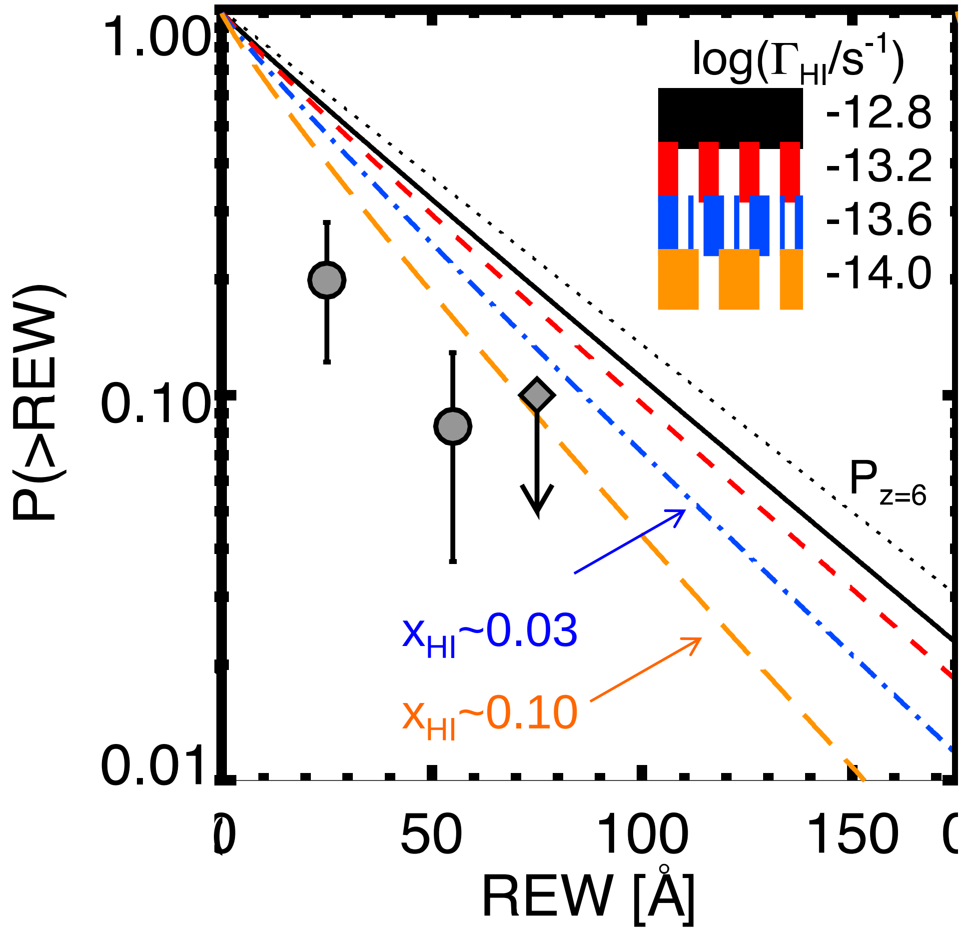


Iliev et al (2012) MNRAS 423, 2222

Effect of Optically-thick Clouds

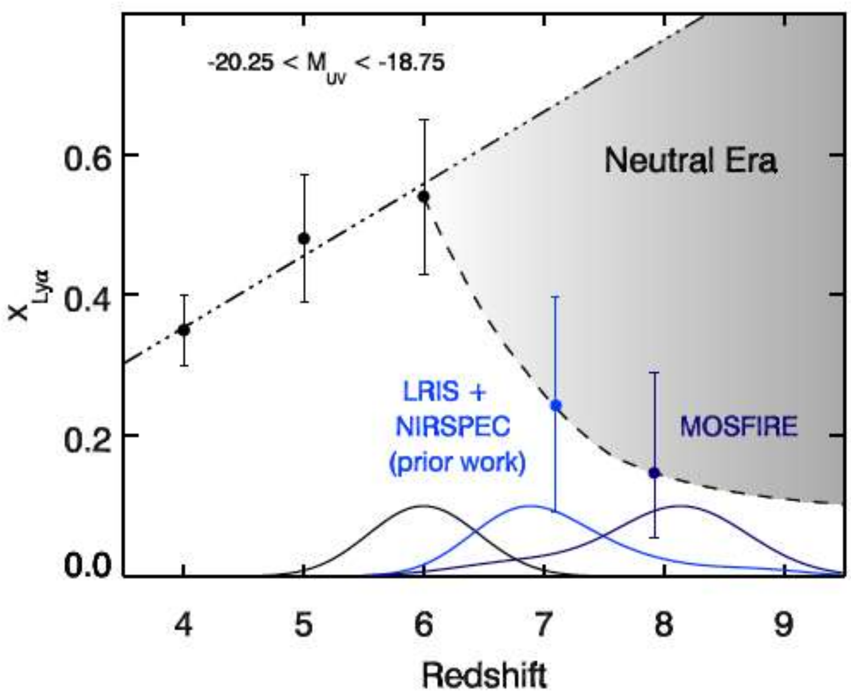
Optically-thick clouds may obscure the line of sight and give misleading impression of the volume-averaged opacity of the IGM, reducing x_{HI} from 0.7-0.9 to 0.03-0.10

How to test?



Bolton & Haehnelt arXiv 1208.4417

MOSFIRE: Aim to confirm Lyα visibility decline



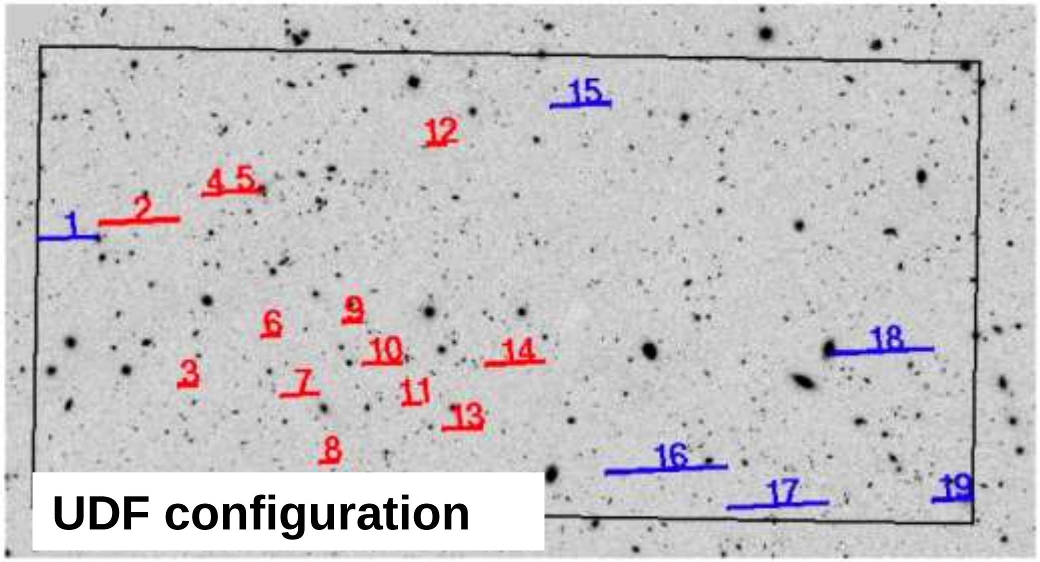
Multi-slit IR spectrograph

6.1 x 3.1 arcmin field

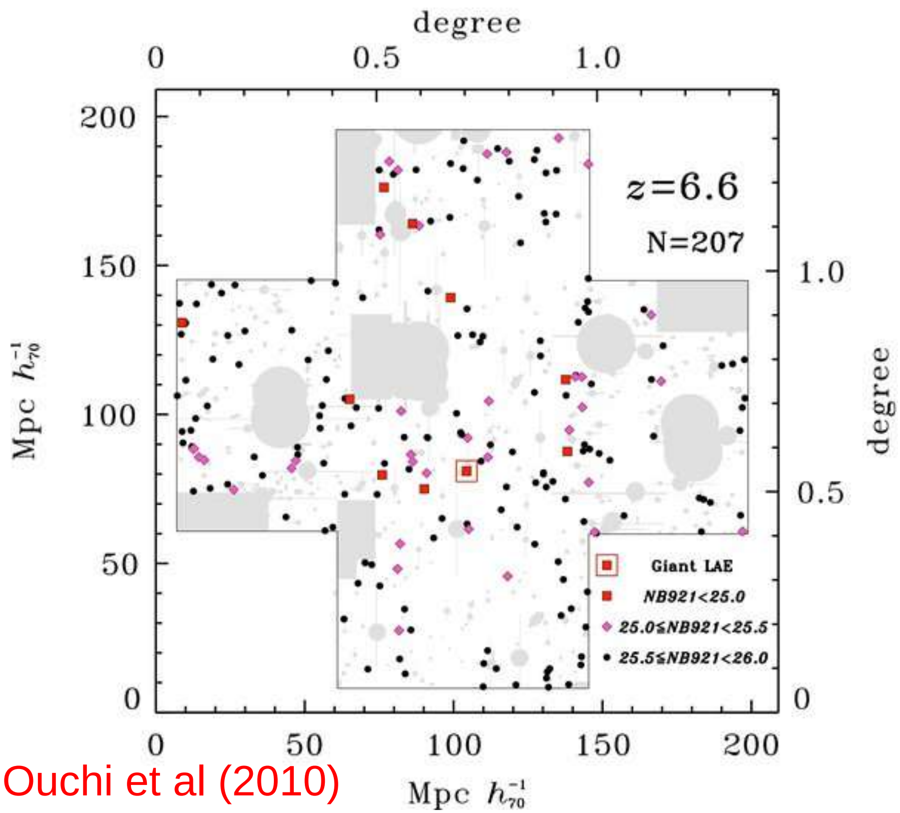
λλ0.97 - 2.45 microns

R ~3300 for 0.7 arcsec slit

45 slits via configurable slit unit

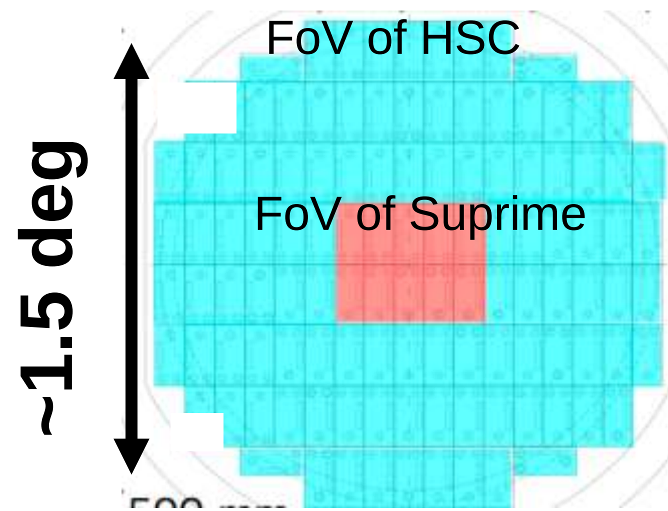


Clustering of Lyman α Emitters



Ouchi et al (2010)

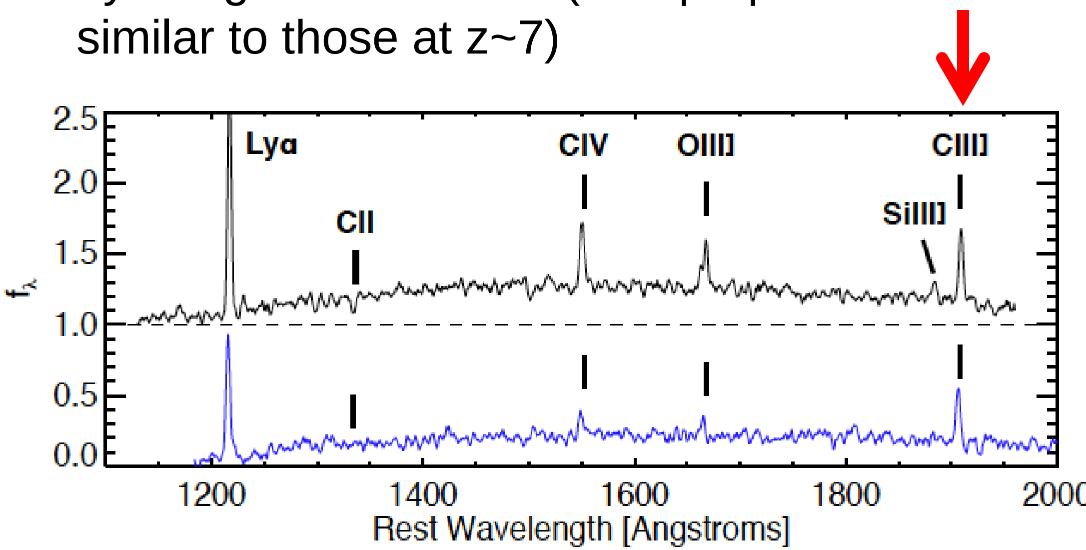
The spatial distribution of Ly emitters over key redshift ranges 5.7, 6.6 and 7.0 may contain information on the emerging distribution of ionized bubbles ; expect boosting in bias at higher z.

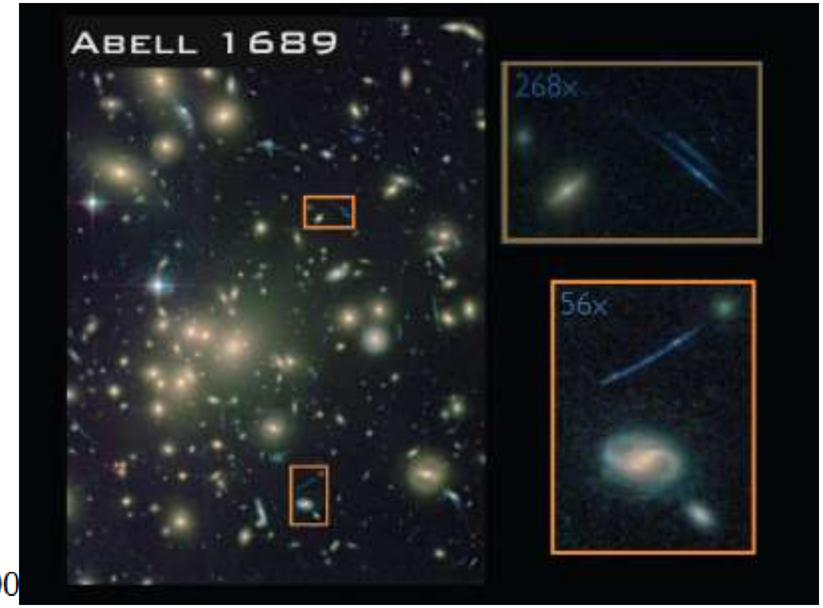


A challenging observation that may be possible with Subaru's HSC

High Redshift Measurements without Lyα?

Spectra of $10^{6\text{-}9}$ $M_\odot$ z~2-3 galaxies lensed by foreground clusters (with properties similar to those at z~7)

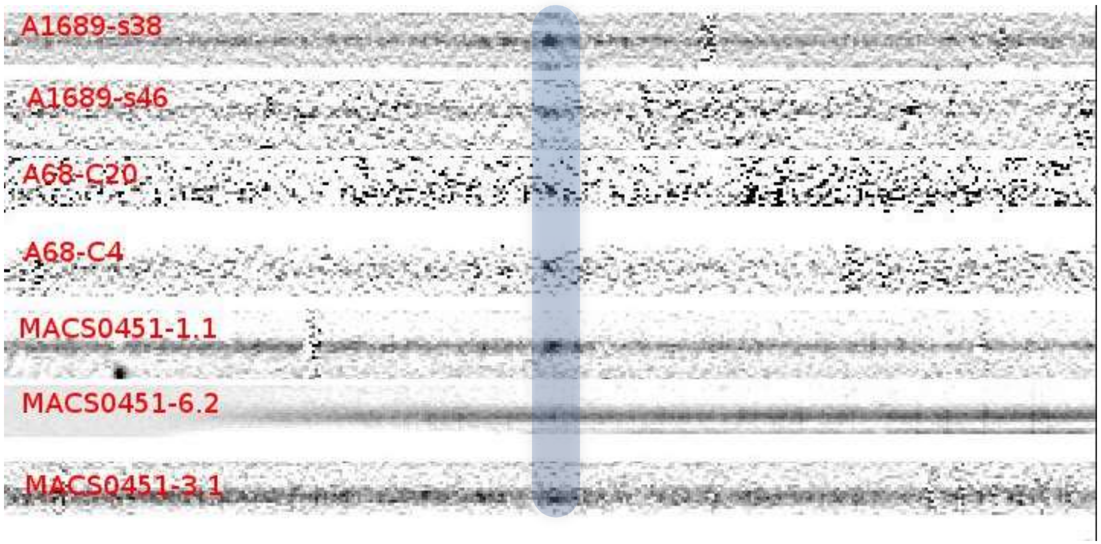




CIII] 1909 Å emission common

EW~5-10x that in massive gals (~10-30 Å)

Reflects larger T_e and harder ionizing spectrum expected at low (10% solar) metallicities.



Stark, Richard, Siana et al (2013)

Did Galaxies Reionize Universe?

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

Key observables:

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

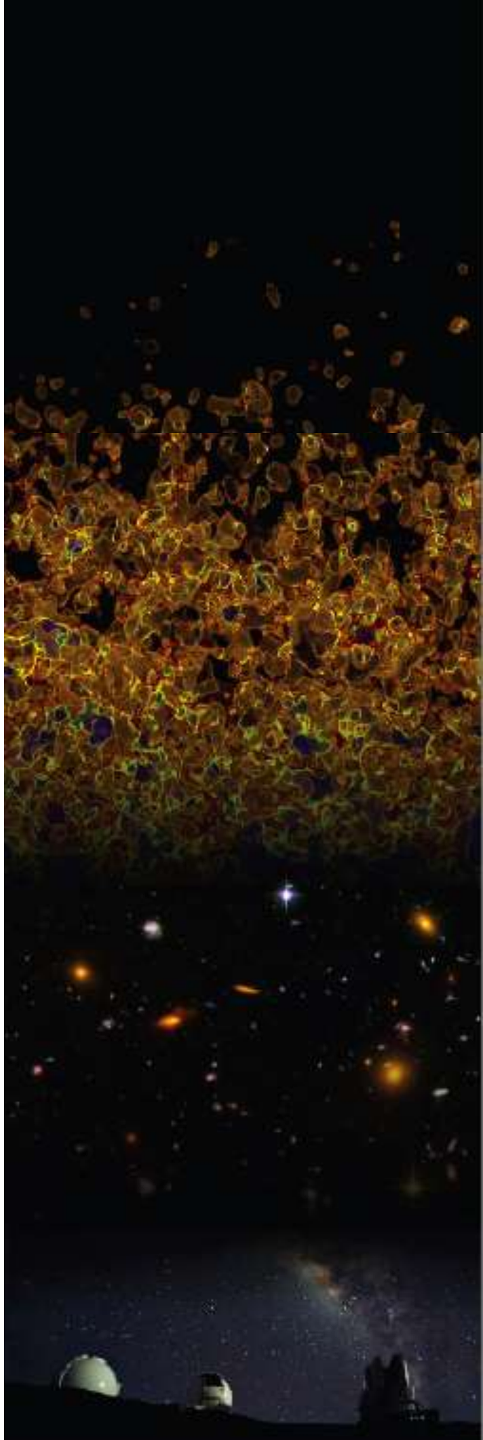
2. Nature of the stellar populations in distant galaxies which determines the rate of ionizing photons: ξ_{ion}

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

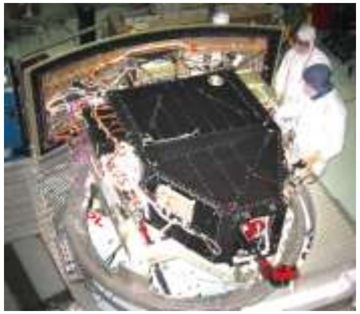
4. Stellar mass density at later times (z~4-5): $\rho_\star$

5. Optical depth of electron scattering to CMB: τ

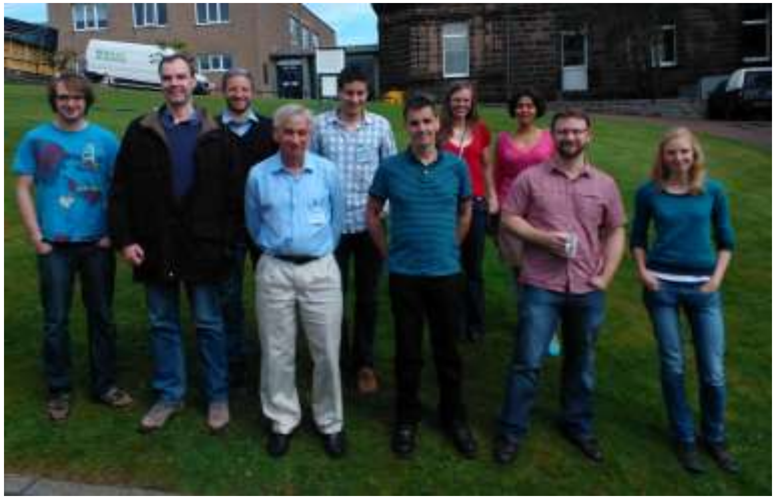
Improved data on [1] and [2] provided by new Hubble UDF 2012 campaign with additional constraints on [3, 4] from Keck spectroscopic survey



UDF 2012 Campaign



WFC3/IR: 850 - 1600nm
2.1 × 2.3 arcmin field of view
0.13 arcsec pixel^{-1}
40 times survey efficiency of NICMOS



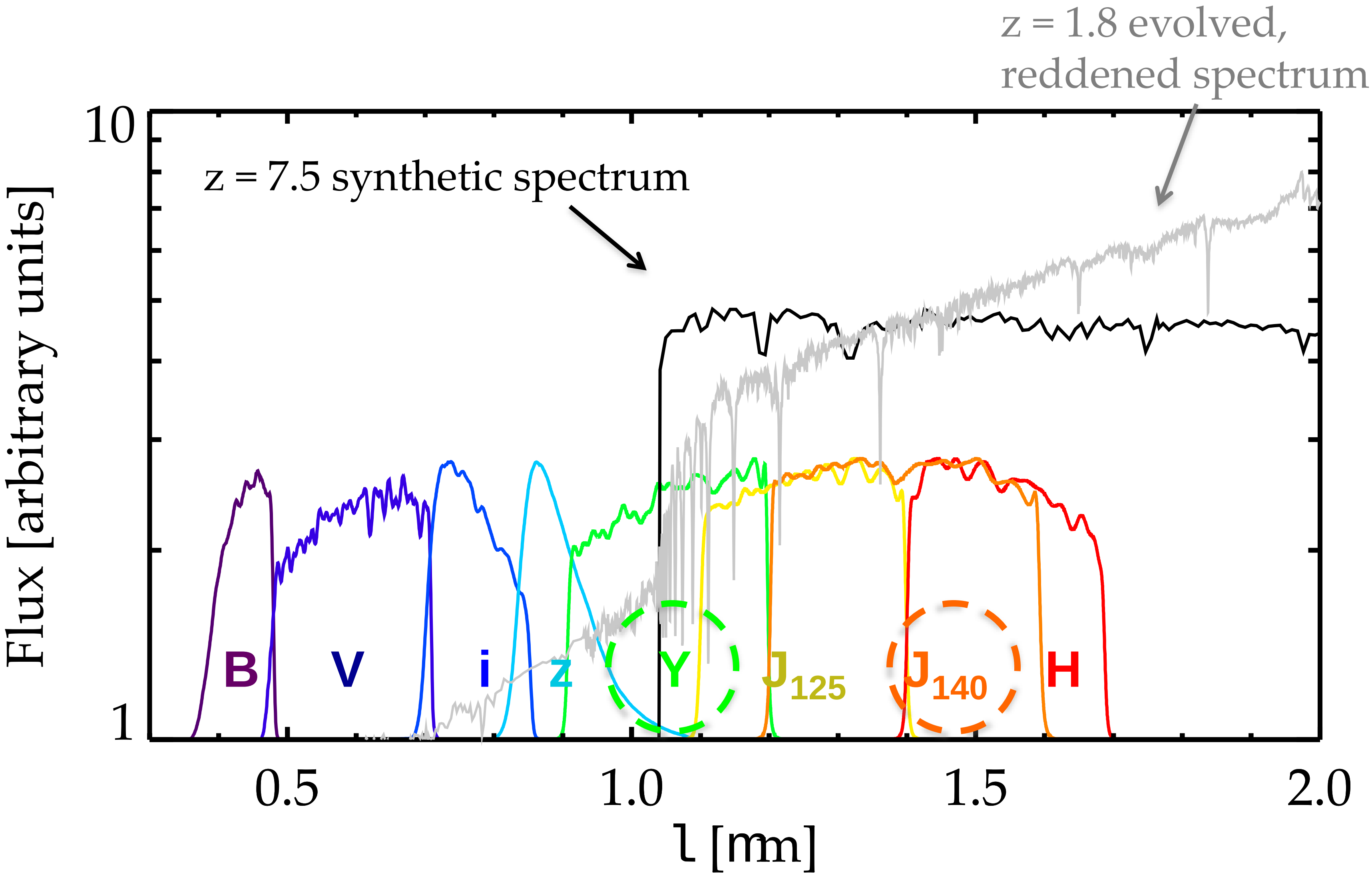
128 orbit Cycle 20 campaign designed to improve depth and fidelity of z>7 candidates

- 1.5x exposure in detection F160W
- 4x exposure in F105W reject
- additional filter F140W

Public versions of final reduced images incorporating earlier UDF and new parallel ACS data
http://udf12.arizona.edu

arXiV 1211.6804 Ellis et al: Abundances of SF Galaxies 7<z<12
arXiV 1212.0860 Dunlop et al: UV Continua & Stellar Populations
arXiV 1212.1448 Koekemoer et al: Observational Overview & Dataset
arXiV 1212.3869 Ono et al: Size Evolution 7<z<10
arXiV 1212.4819 Schenker et al: z~7-8 Luminosity Function I
arXiV 1212.5222 McLure et al: z~7-8 Luminosity Function II
arXiV 1301.1228 Robertson et al: Constraints on Reionization

UDF 2012 Filter Deployment



Star Forming Galaxies with z > 8.5

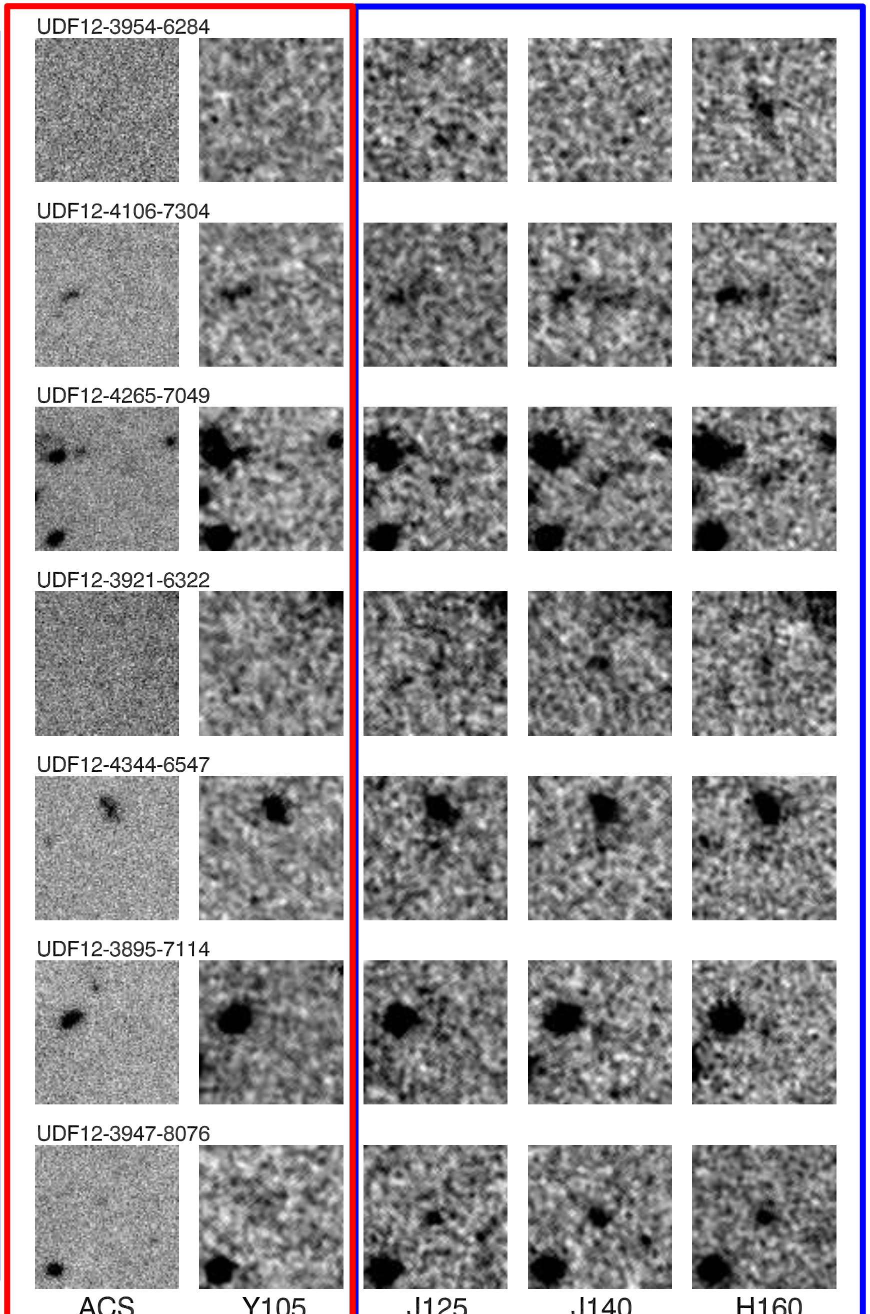
7 star-forming galaxies located 8.5<z<12

5σ detections in (160W+140W+125W) stack (m_{AB} < 30.1)

2σ rejection in ultradeep F105W (m_{AB} > 31.0)

2σ rejection in ACS BViz (m_{AB} > 31.3)

Ellis et al (2013) ApJ Lett 763, L7



z=11.9? 380 Myr

z=9.5 520 Myr

z=9.5 520 Myr

z=8.8 570 Myr

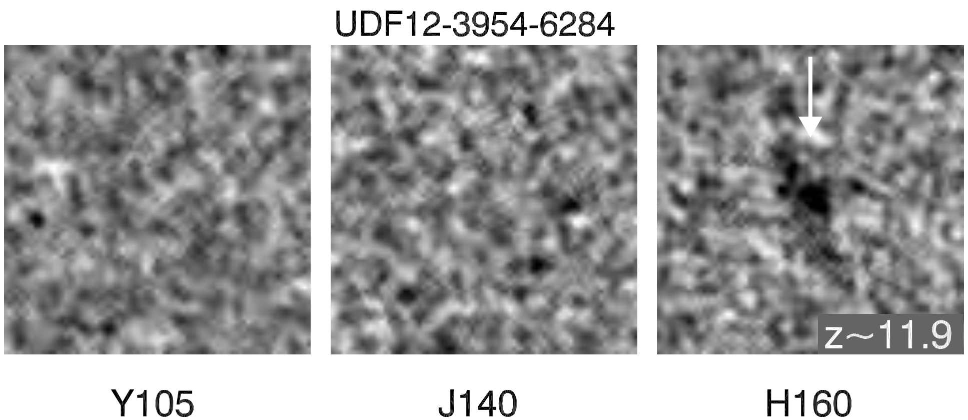
z=8.8 570 Myr

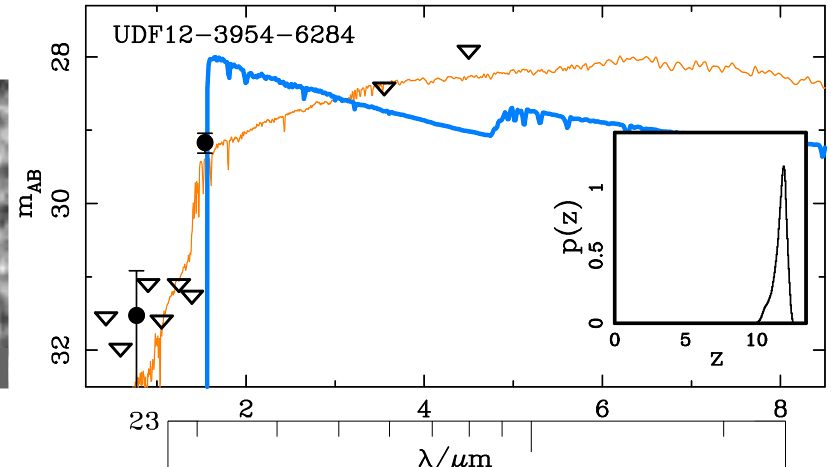
z=8.6 590 Myr

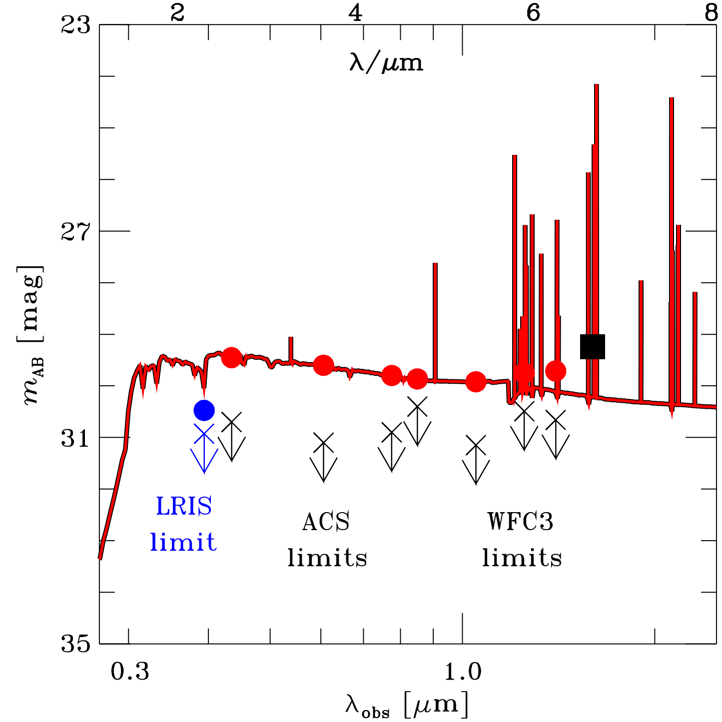
z=8.6 590 Myr

The Enigmatic z=11.9 Candidate

The only earlier z>8.5 candidate recovered is that claimed at z=10.3 by Bouwens et al (2011). It is now a single filter detection in F160W suggesting it could be at z=11.9







- Definitely a real source (7.5σ)
- Could be [O III] emitter at z=2.4. To explain non-detections in other bands would require an EW~4500 Å.
- Brammer et al (arXiv 1301.0317) have low s/n WFC3 grism spectrum supporting z=2.4
- No [O II] or Lyα from LRIS spectrum present a puzzle
- Capak et al have MOSFIRE spectrum

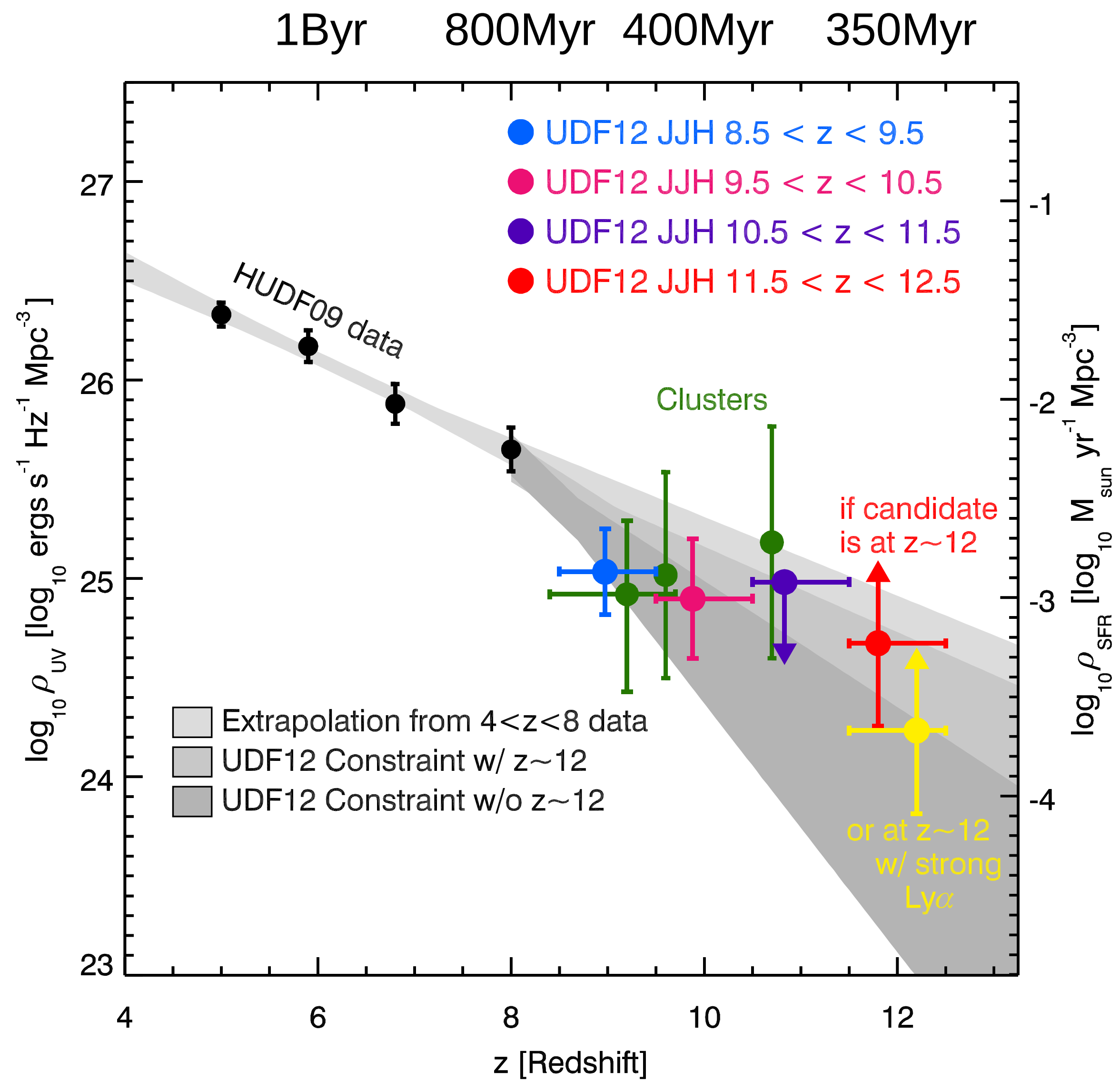
Star Formation History

Regardless of z~11.9 candidate, main advance is improvement in census of galaxies 8.5<z<10

6 robust objects (c.f. none confirmed from earlier UDF data)

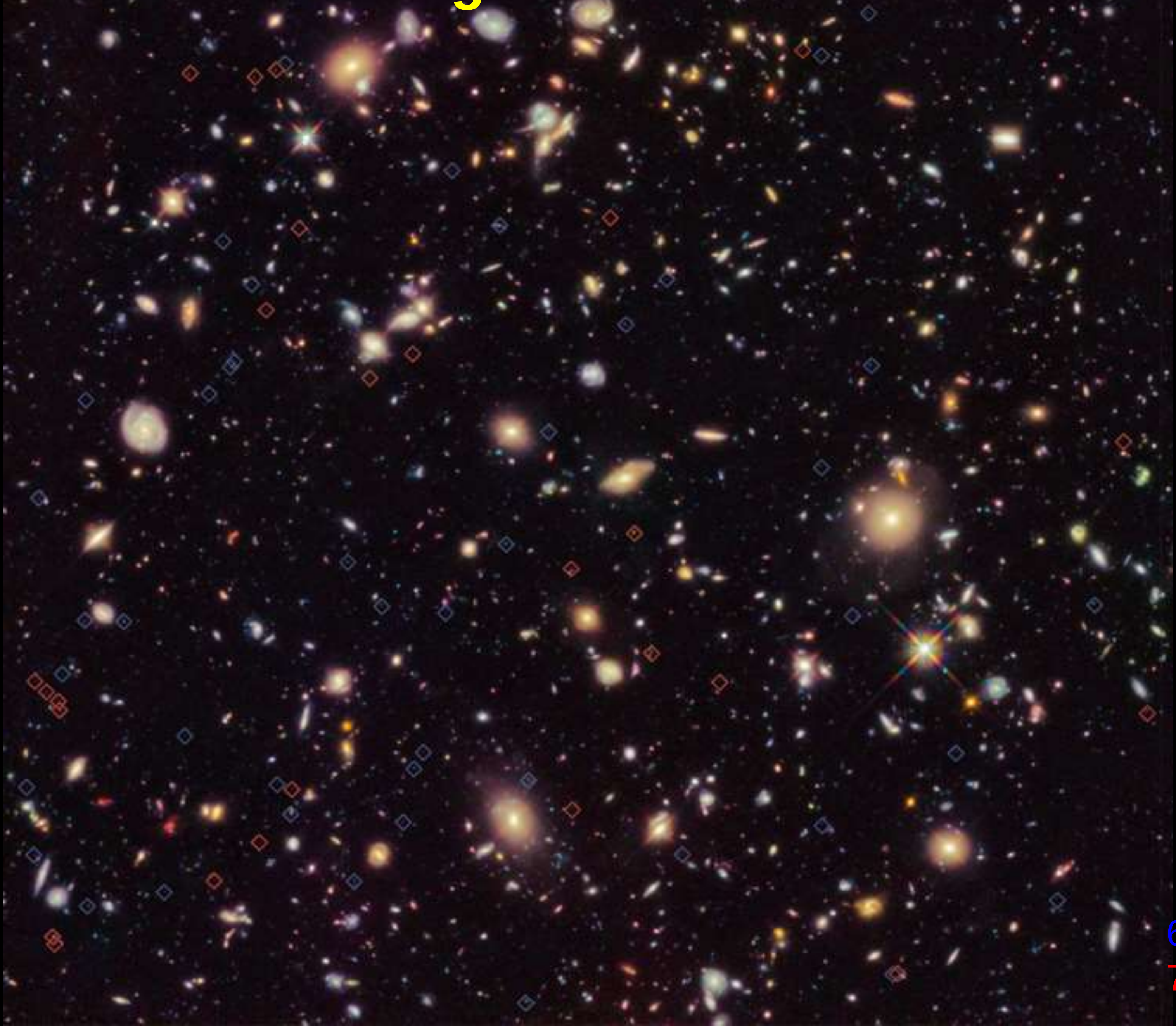
In agreement with CLASH, see smooth decline in SF history to z~10, possibly z~12

Continuity has important implications for z>10 studies with JWST and models of reionization



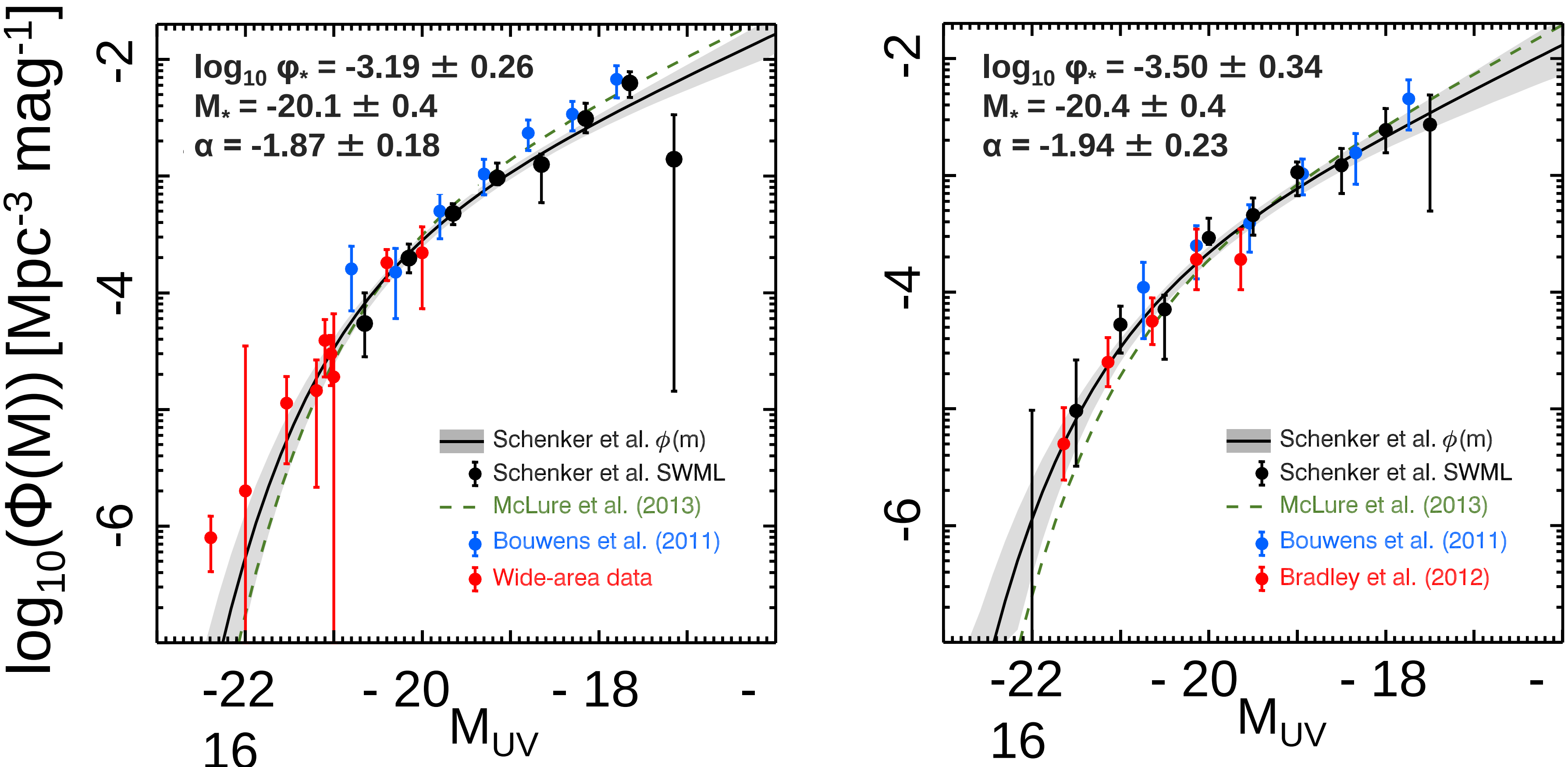
http://udf12.arizona.edu

74 Star Forming Galaxies with 6.3<z<8.6



6.3<z<7.2
7.4<z<8.6

UV Luminosity Functions at z~7 and z~8

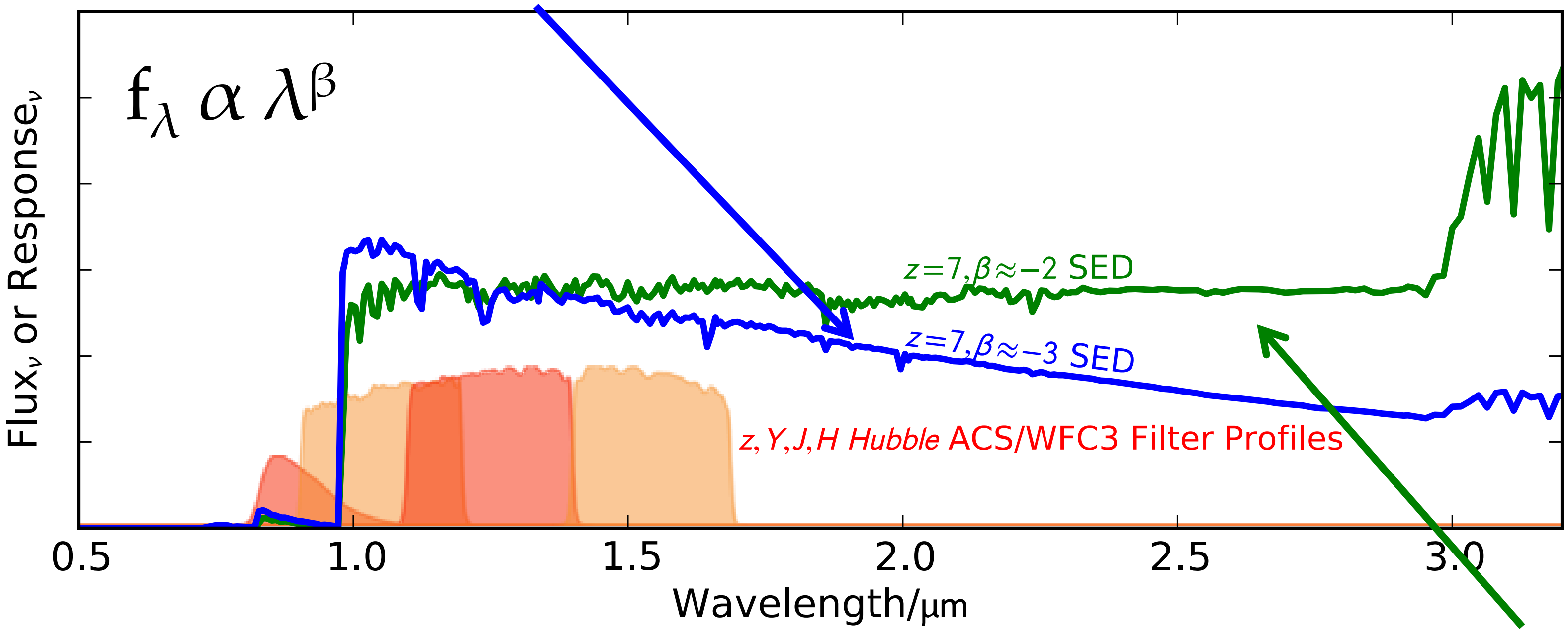


- UDF12 enables us to reach lower luminosity galaxies at z~7 and 8
- At z~7 N=47 (20 new); at z~8 N=27 (9 new)
- Confirm steep faint end slopes indicating dominant contribution from feeble galaxies, at least to M_{UV}~-17
- Two independent selection techniques are in excellent agreement

Schenker et al Ap J 768,196 (2013)
McLure et al MNRAS 432, 2696 (2013)

Stellar Populations at z~7-8 and ξ_{ion}

Early galaxies may be extremely metal-poor. Formed of "pristine" gas, galaxies harboring these stellar populations would have very blue colors with a steep UV spectral shape and emit prodigious amounts of ionizing photons, i.e. large ξ_{ion}



More mature stellar populations, formed from remnants of the first generation supernovae, will contain heavier elements,have less-blue colors (flat spectral slopes) and emit less ionizing photons, lower ξ_{ion}

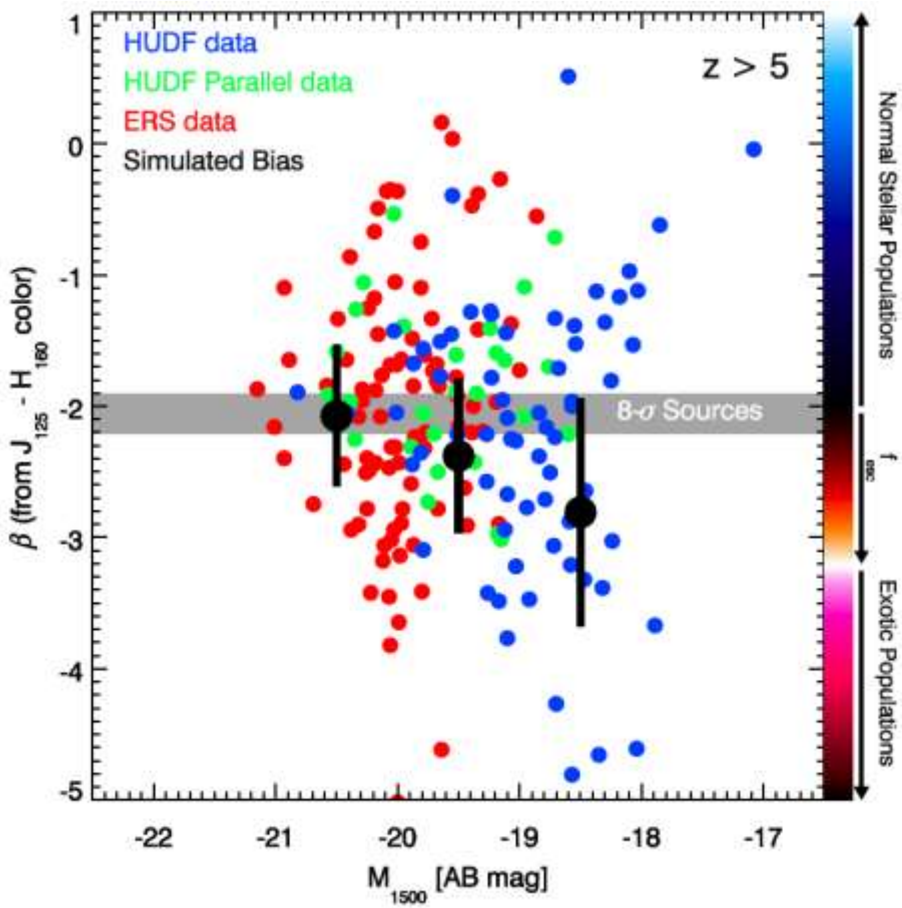
Disentangling which of these stellar population types are being observed involves measuring the UV spectral slope β

Nature of Stellar Populations: Earlier Work

β estimated from (J-H) colors in UDF 2009 suggested extremely blue populations for faintest galaxies (Bouwens et al 2010)

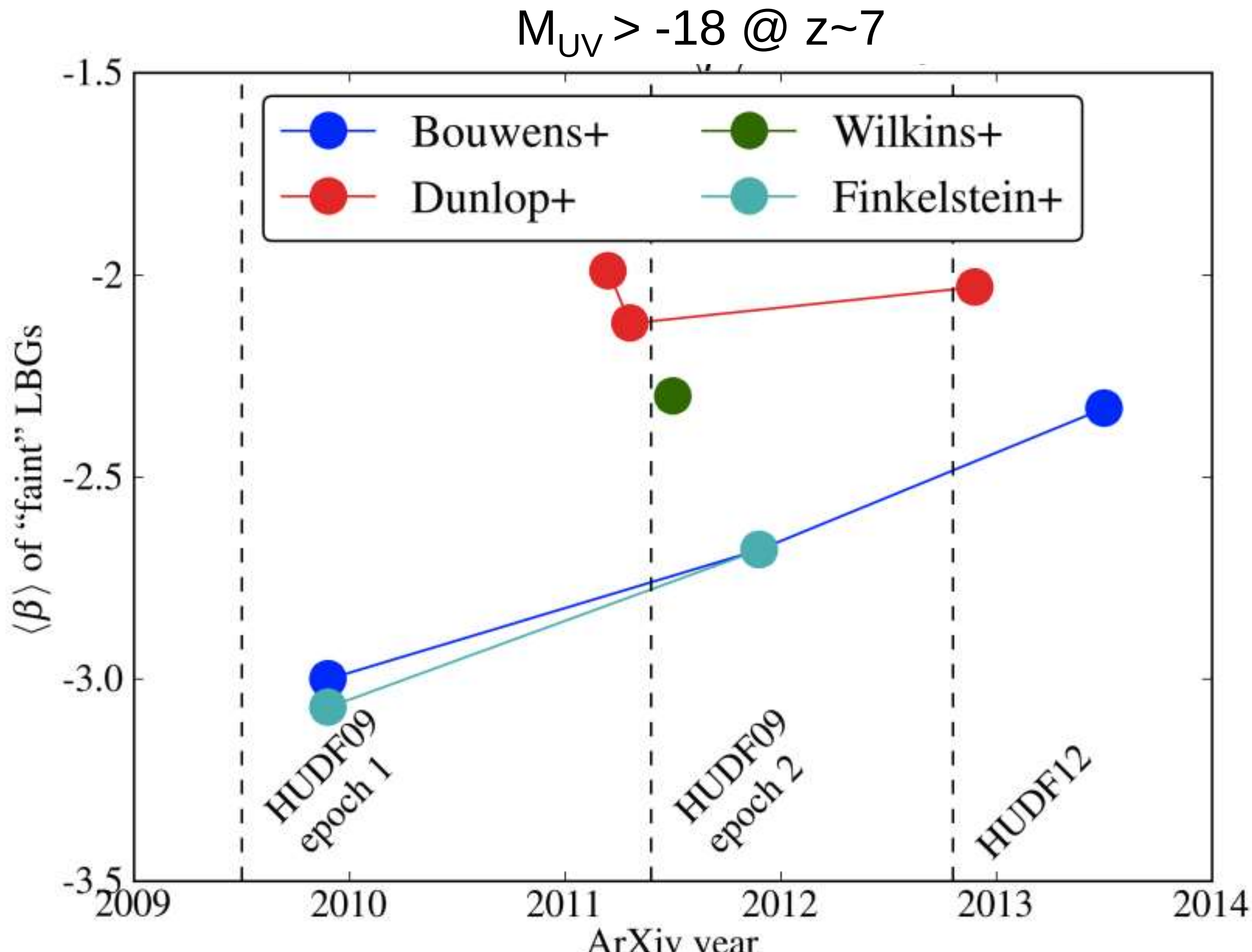
- Boosting in J biases β to bluer, more extreme values
- Boosting in H affects photo-z solution, placing object at z~2
- Simulations can reproduce trends for a fixed input β

Deeper HST data with additional J140W filter can clarify trends. We can select sources in a band independent of those used to estimate the UV color



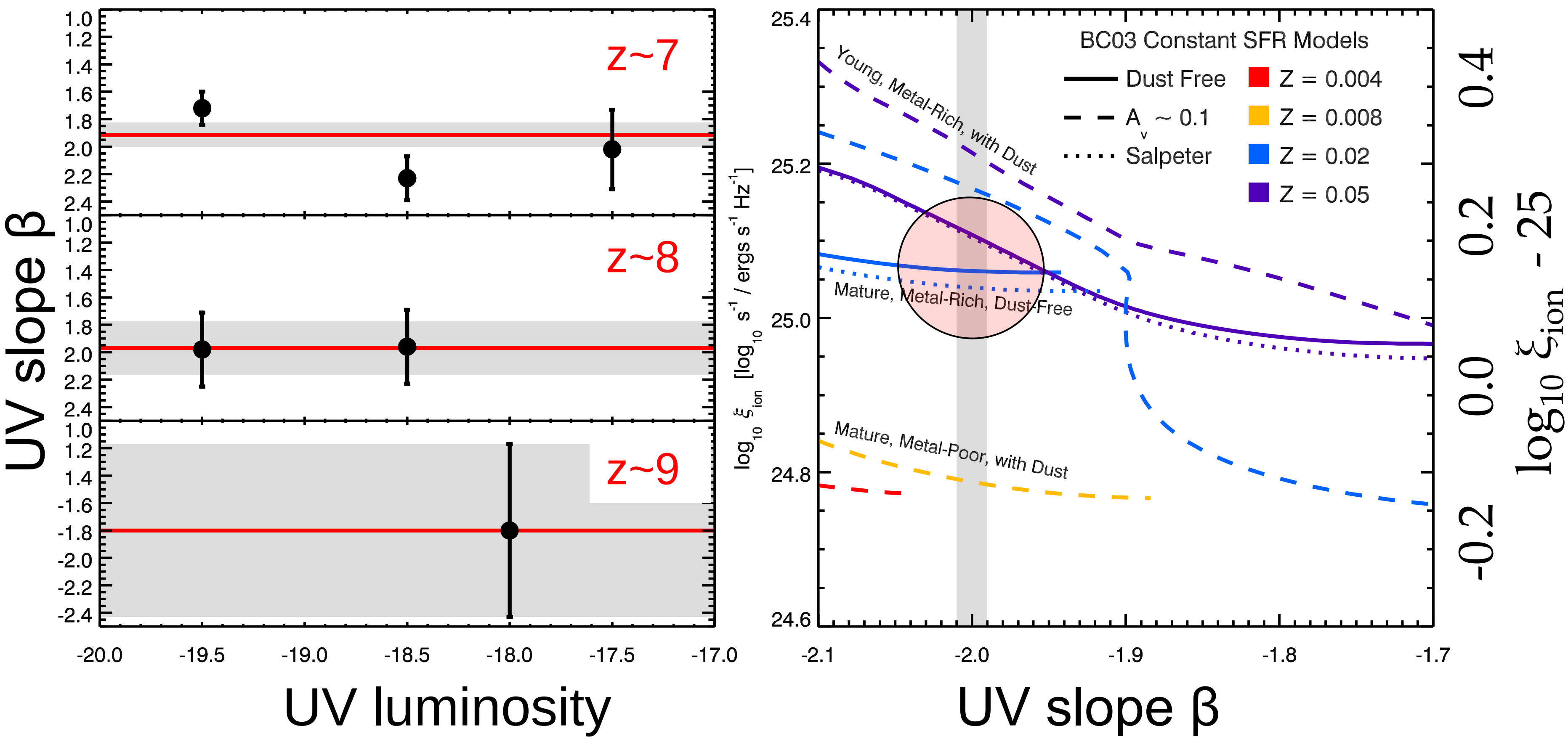
Dunlop et al (2012) MNRAS 420, 901

Gradual Reconcilation of β (2010-2014)

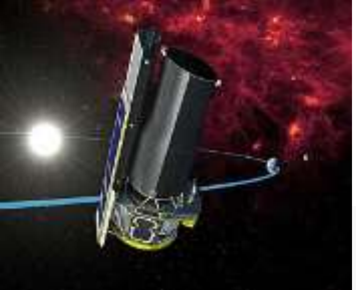


Constraining Ionizing to UV Photon Ratio ξ_{ion}

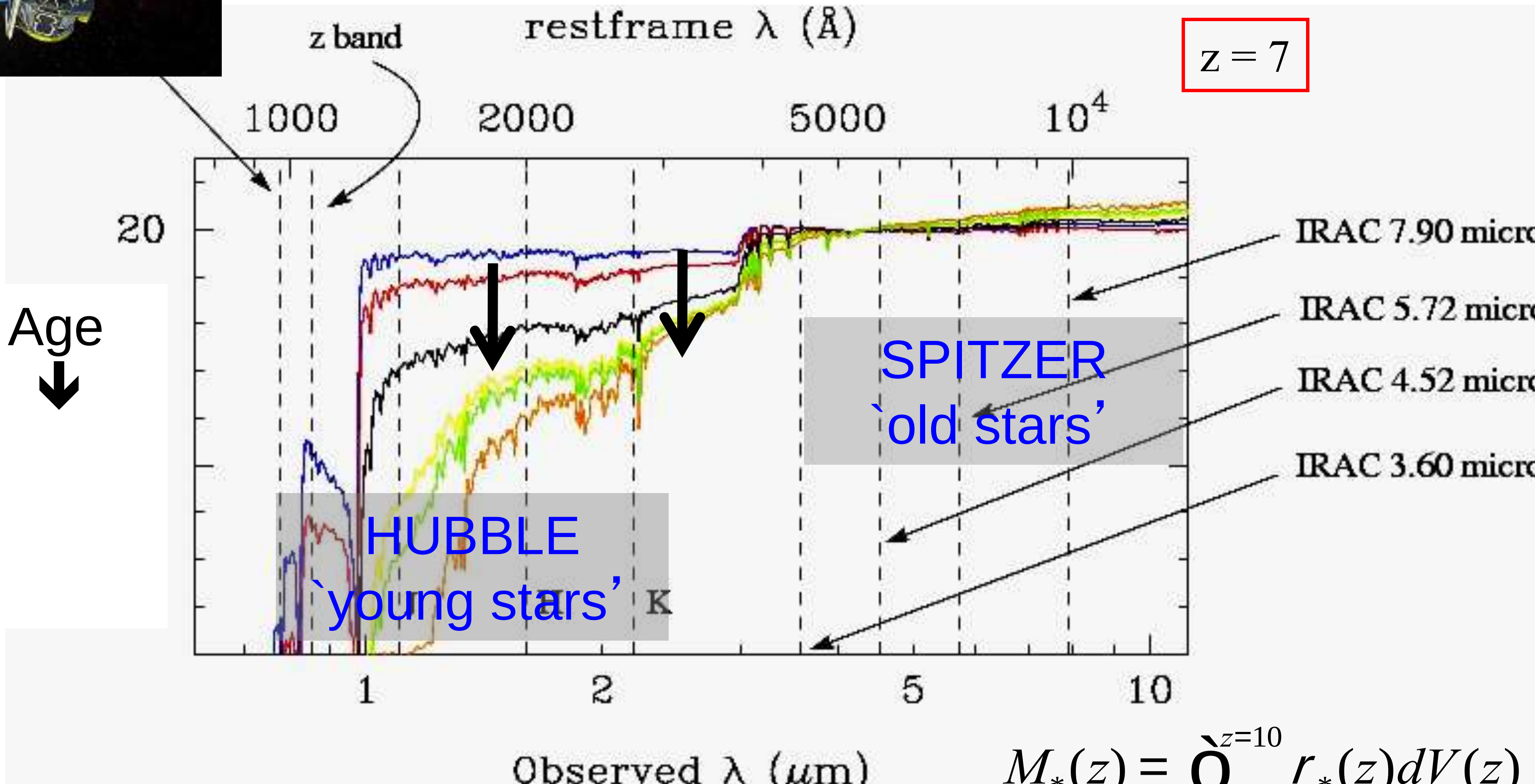
Contrary to earlier claims, z~7-8 galaxies have **normal UV colors** at all probed luminosities consistent with **mature > 100Myr stellar populations** (supporting SF beyond z~10) and narrow range in ionizing supply factor ξ_{ion}



Dunlop et al MNRAS 432, 3520 (2013)



Key Role of Spitzer: Masses and Ages



$$M_*(z) = \int_{z=5}^{z=10} \rho_*(z)dV(z)$$

Hubble measures current SFR
Spitzer measures mass in older stars
Combination gives mean age

Stellar mass density at z~5-6 implies <u>significant past SF</u>

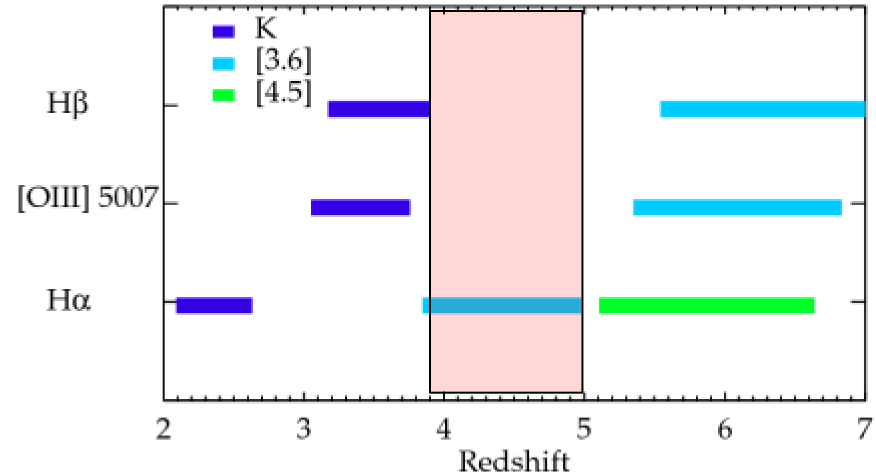
Eyles+ 2005,Stark+ 2007,2009, Labbé+ 2010, 2012, Gonzalez+2010, 2011

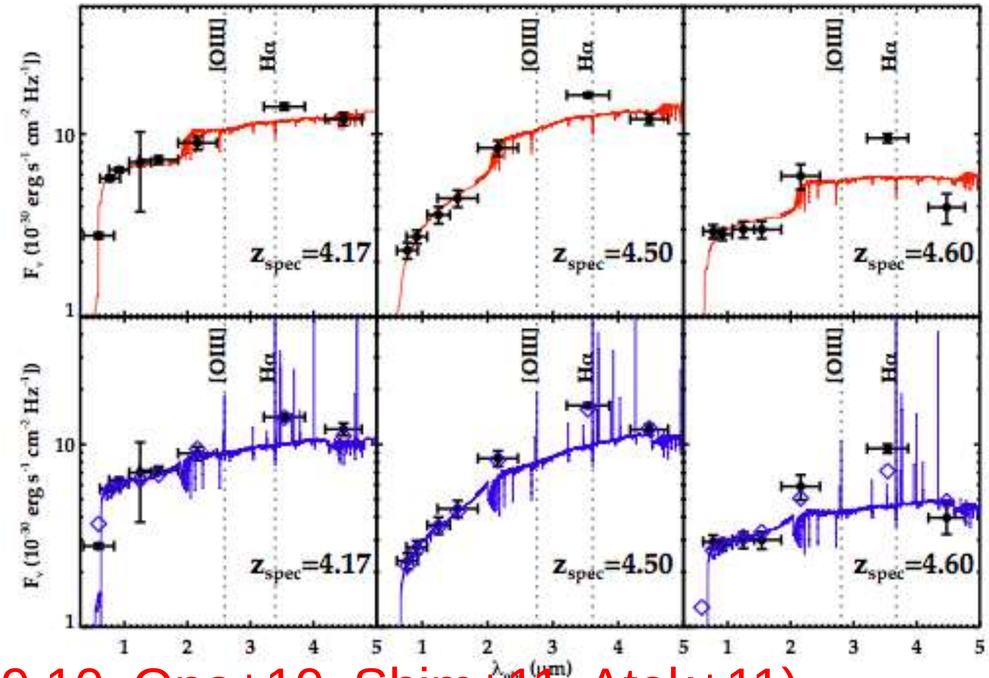
One Wrinkle…Nebular Emission

• HST/IRAC photometry permits stellar-only & stellar+nebular solutions; but ambiguous solutions without additional constraint

• Keck spectra provide unique opportunity to evaluate the effect of Hα in 3.6μm band as precise location of line is known

• Examining N=45 galaxies with spectroscopic 3.8<z<5.0 for IRAC excess c.f. stellar only model fits reveals serious contamination

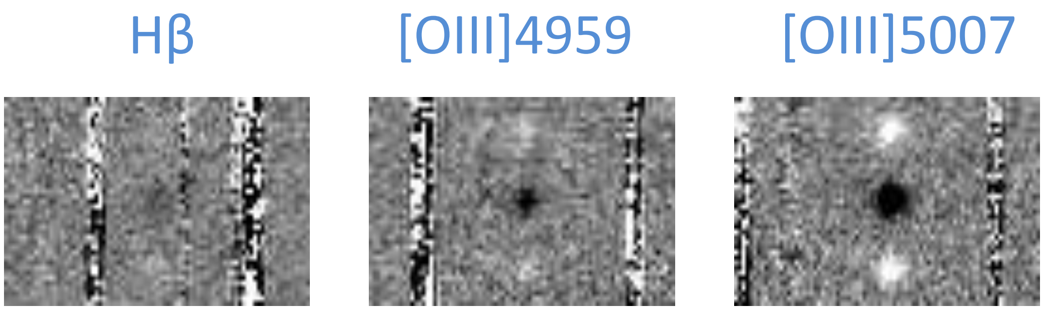




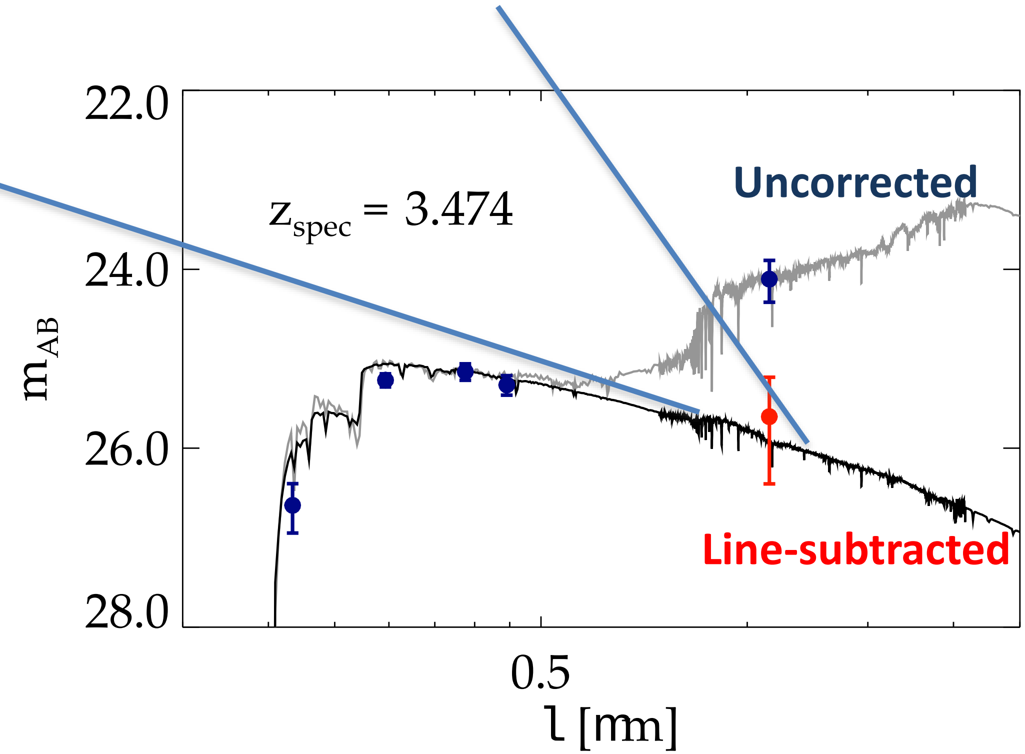
Stark et al (2012) (also Schaerer+09,10, Ono+10, Shim+11, Atek+11)

How bad could it get…?

Keck MOSFIRE spectrum of z~3.6 galaxy with [O III] in K-band



- Emission lines account for large fractions of broadband flux – 75% in this object!
- Line flux must be accurately measured and subtracted to derive unbiased ages and stellar masses



Matt Schenker’s talk…

Did Galaxies Reionize the Universe?

UDF2012 Data
Theoretical models
External observations

UV Luminosity function ρ_{UV}

+

UV slope

Population synthesis models ξ_{ion}

+

Escape fraction f_{esc}

Largely unconstrained (see later)

$$\dot{n}_{ion} = f_{esc}\,\xi_{ion}\,\rho_{UV}$$

WMAP optical depth to surface of last scattering

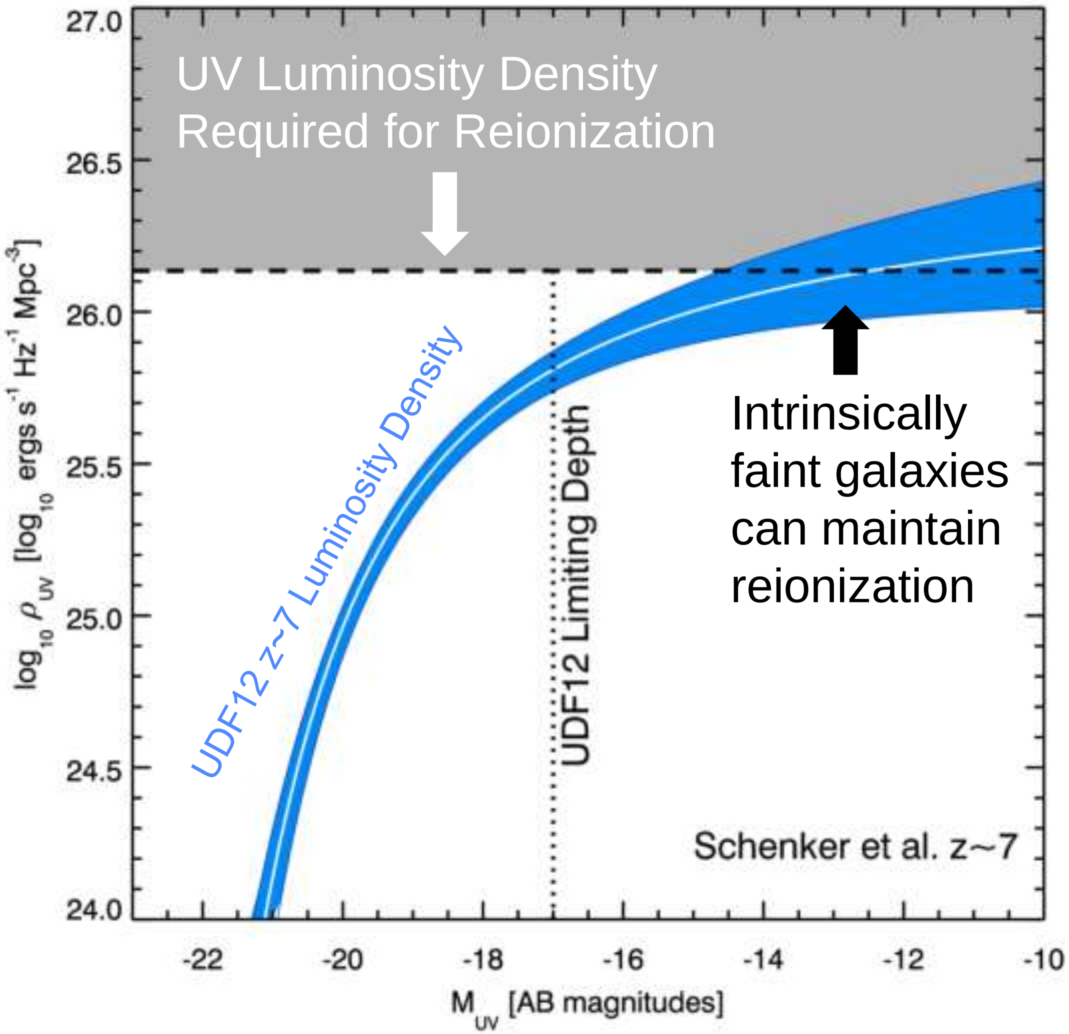
+

Stellar mass density

Evolution of volume-filling fraction of HII, Q_{HII}

$$\dot{Q}_{HII} = \frac{\dot{n}_{ion}}{\langle n_H \rangle} - \frac{Q_{HII}}{t_{rec}}$$

UDF12 Reionization Constraints: A Simple Illustration



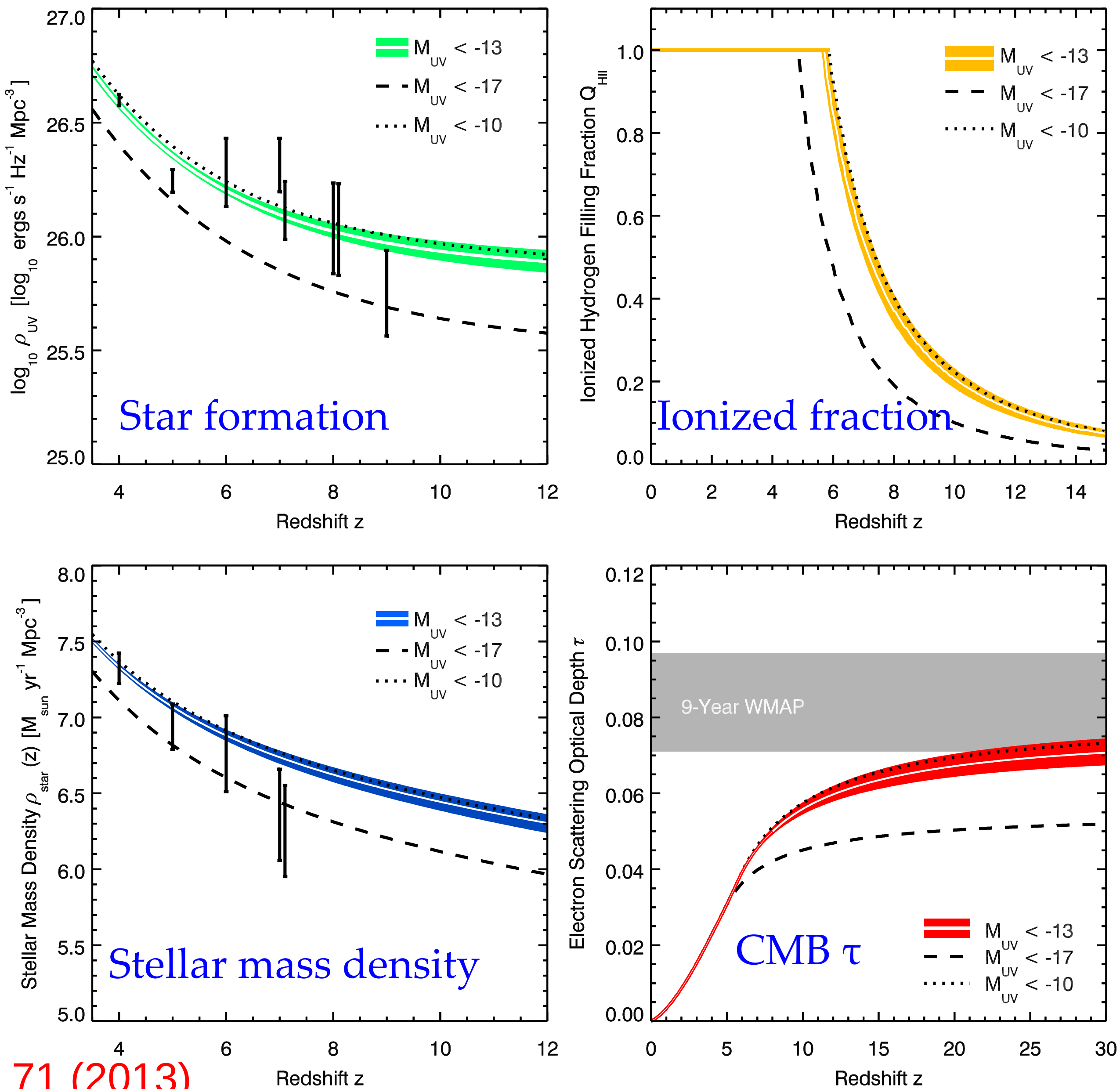
- The constrained faint end slope of the luminosity function allows us to conclude that **fainter, yet unseen galaxies (extrapolating to M_{UV}~-13)** would be sufficient to maintain reionization

Robertson et al Ap J 768, 71 (2013)

The Full Monty and Caveats

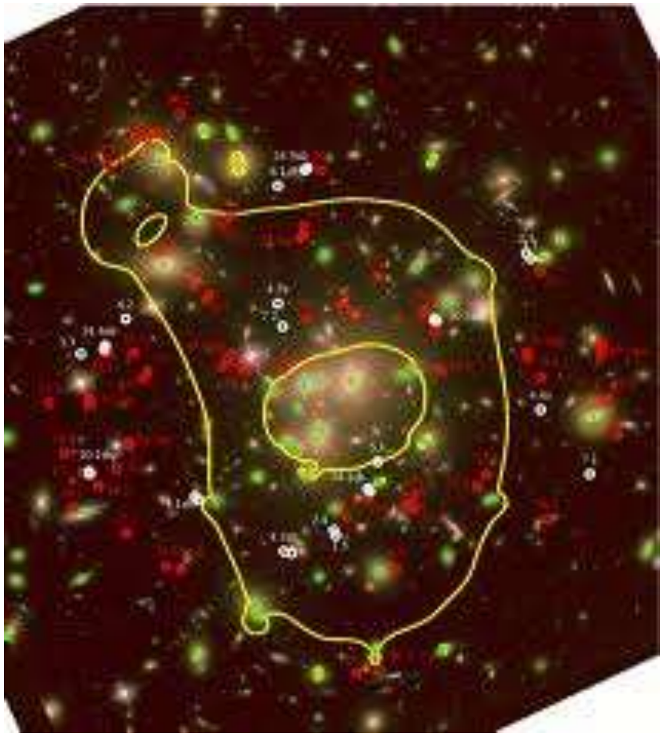
The UDF2012 star formation rate density (N(z) and faint end LF slope) integrates to match the stellar mass density and given ξ_{ion} (β) matches the CMB optical depth τ <u>provided</u>

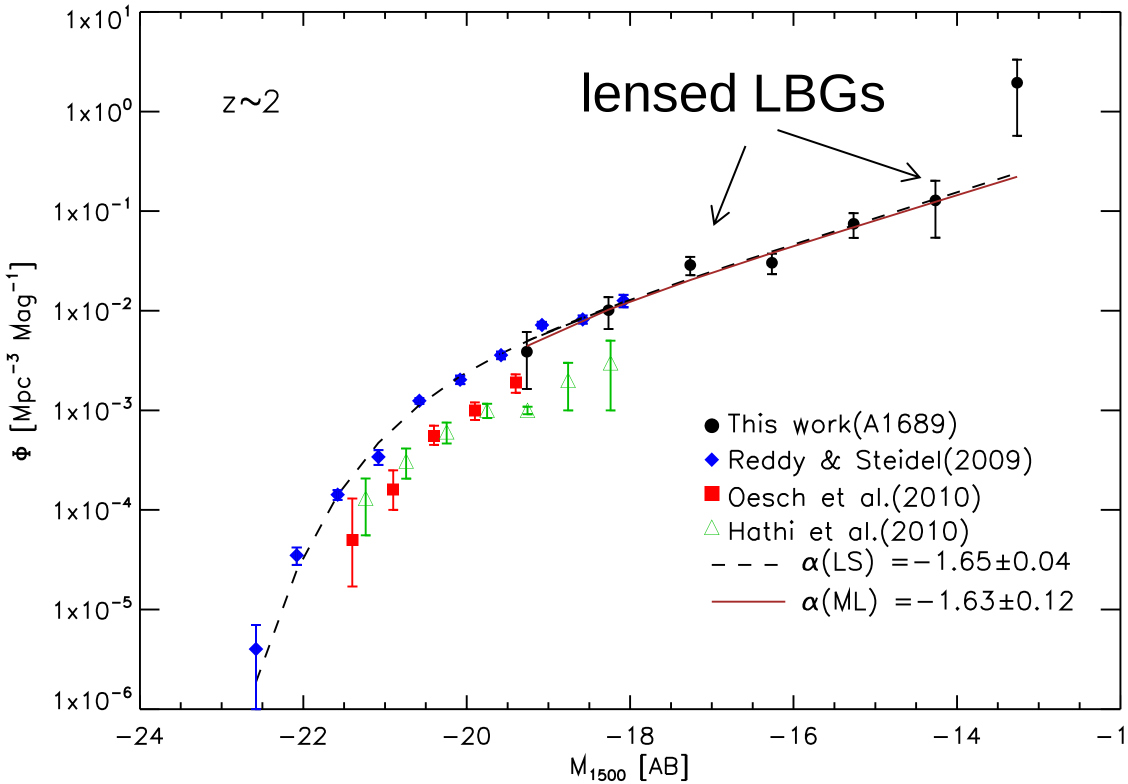
- **LF extrapolated to M_{UV}~-13**
- **f_{esc}~0.2**
- **SFR extends beyond z~10**



Robertson et al Ap J 768, 71 (2013)

Faint End of the LBG LF at z~2



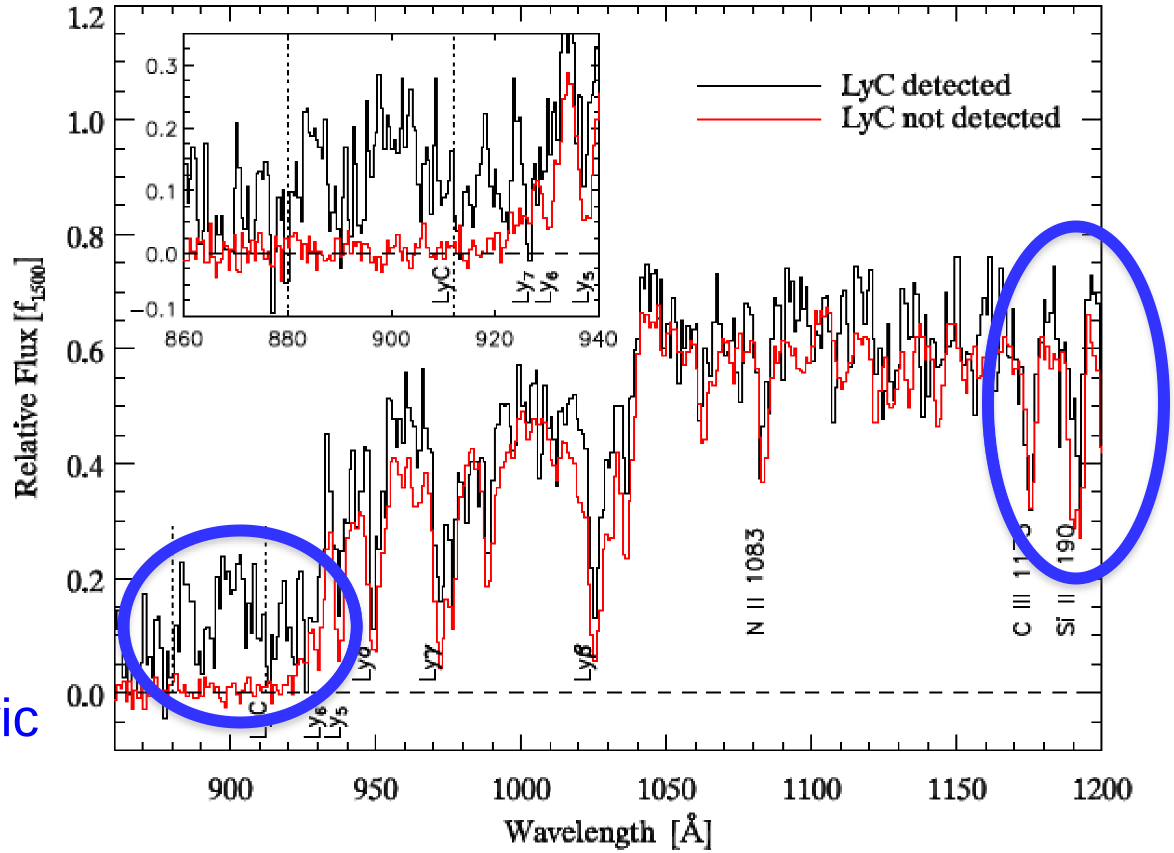


72 strongly-lensed z~2 LBGs locating using WFC3/UVIS in Abell 1689 offer first glimpse at the faint end of the LF down to M_{UV}~-13 providing a proof of concept for possible existence of galaxies to this faintness at z~7-8

Alavi et al arXiv 1305.2413

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

Escaping ionizing radiation at z=3 (Bogosavljevic thesis)

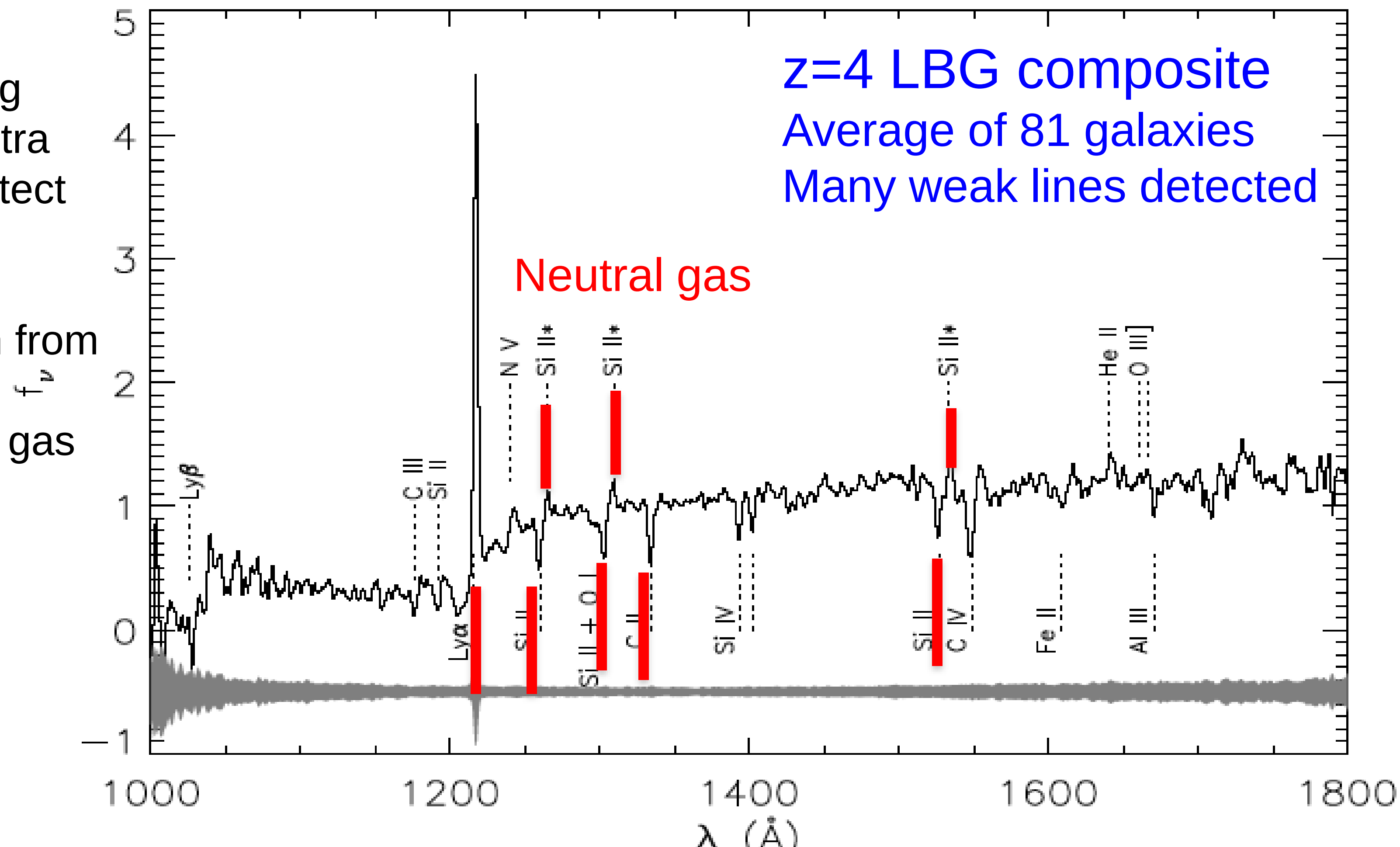


Weaker low-ionization absorption in sources with escaping ionizing flux

- f_{esc} estimated via spectroscopic or UV imaging below Lyman limit (e.g. Nestor et al arXiv 1212.2939)
- 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}

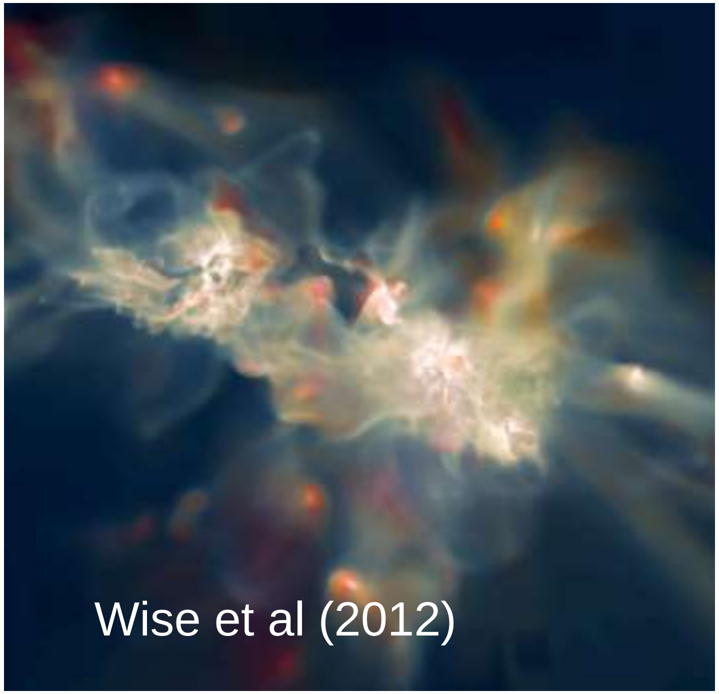
By stacking Keck spectra we can detect weak low ionization absorption from neutral outflowing gas

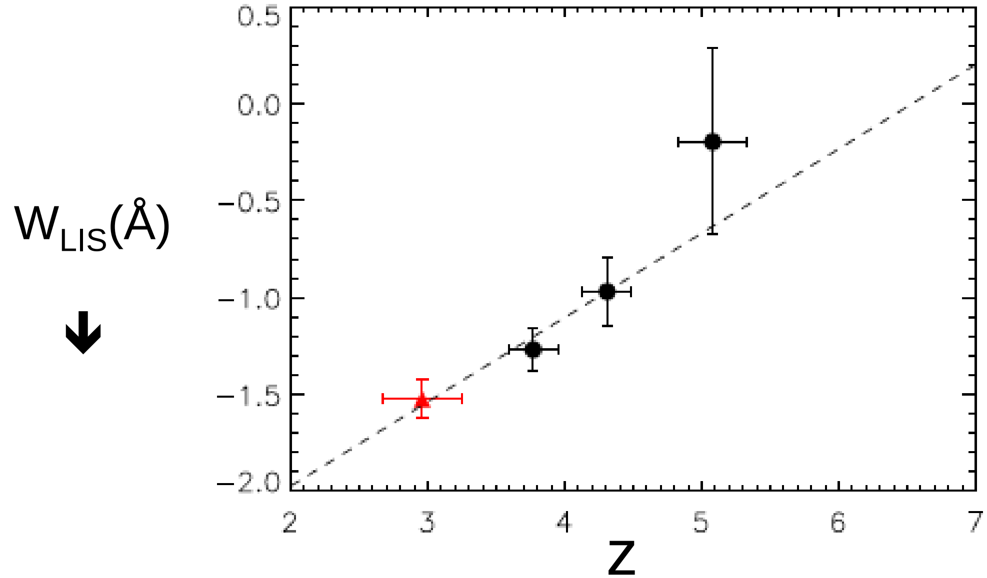


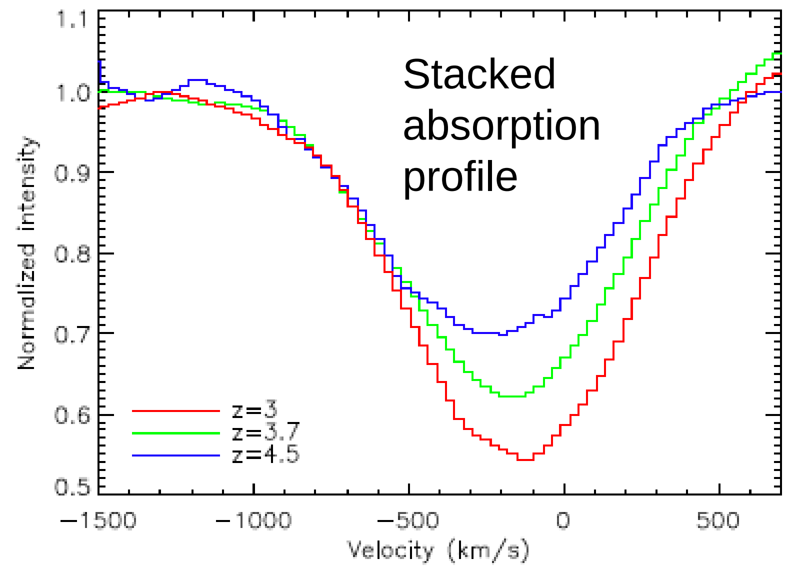
EW of low ionization lines estimates covering fraction of neutral gas $f_c = (1 - f_{esc})$

Jones et al (2012) Ap J 751, 51

Reduced Covering Fraction of HI at high z?



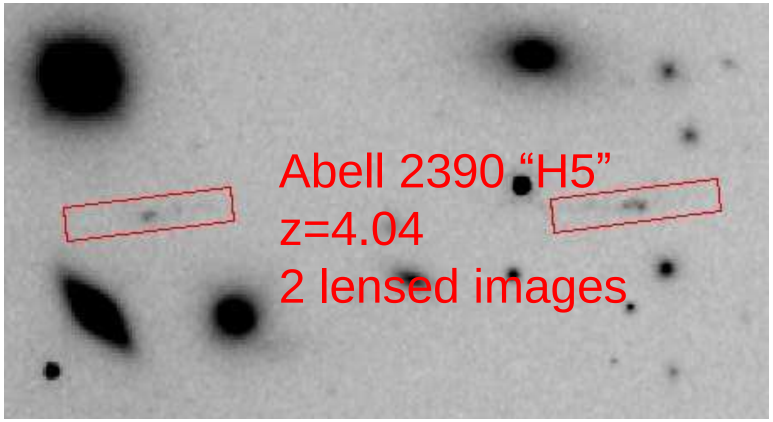


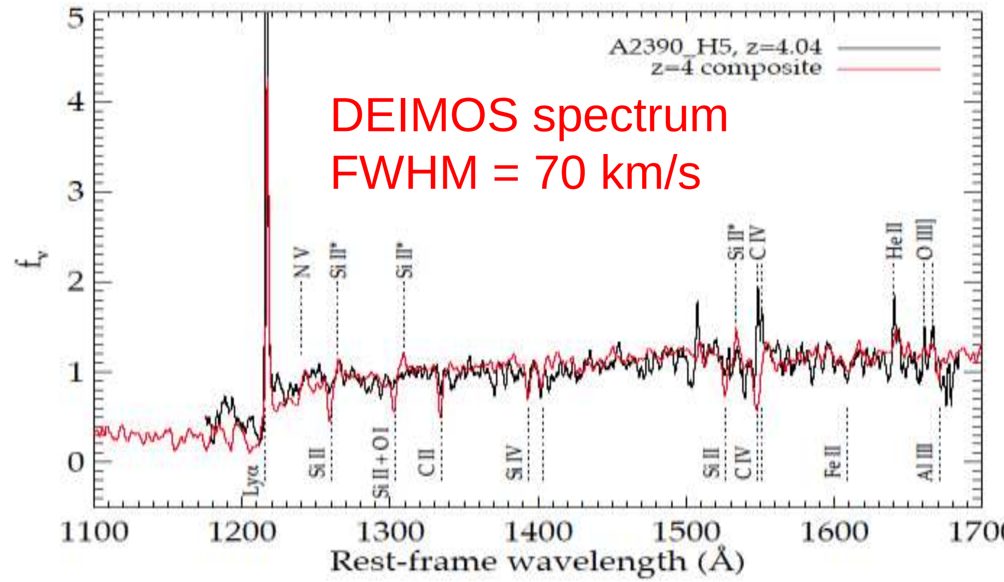


- Does f_c decrease with increasing redshift?
- Radiation pressure leads to `cometary like' structures in simulated high z galaxies implying favorable geometries for escaping photons
- We do observe EW of low ionization lines decreases with increasing redshift but this could be due to a variety of outflow parameters (need higher resolution data)

Jones et al (2012) Ap J 751, 51

Higher Resolution Spectra of z~4 arcs



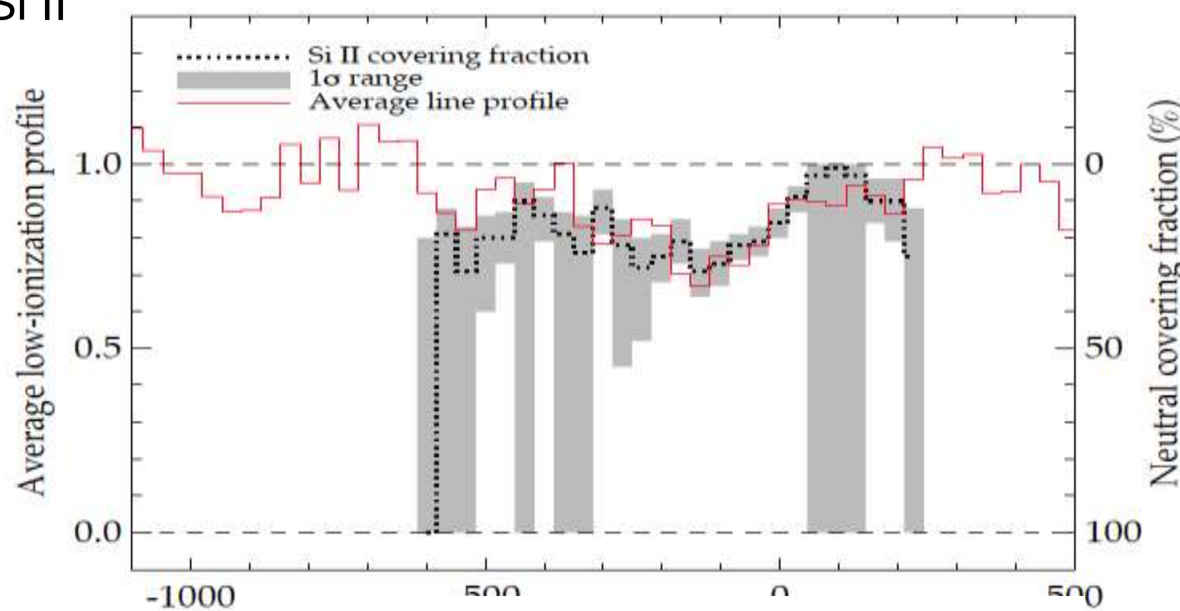


Covering fraction f_c derived from average profile for all low ionization lines *and* a pair of ground state Si II lines with different f values

$$\tau = -\ln\left[\frac{I - I_0(1 - f_c)}{I_0 f_c}\right]$$

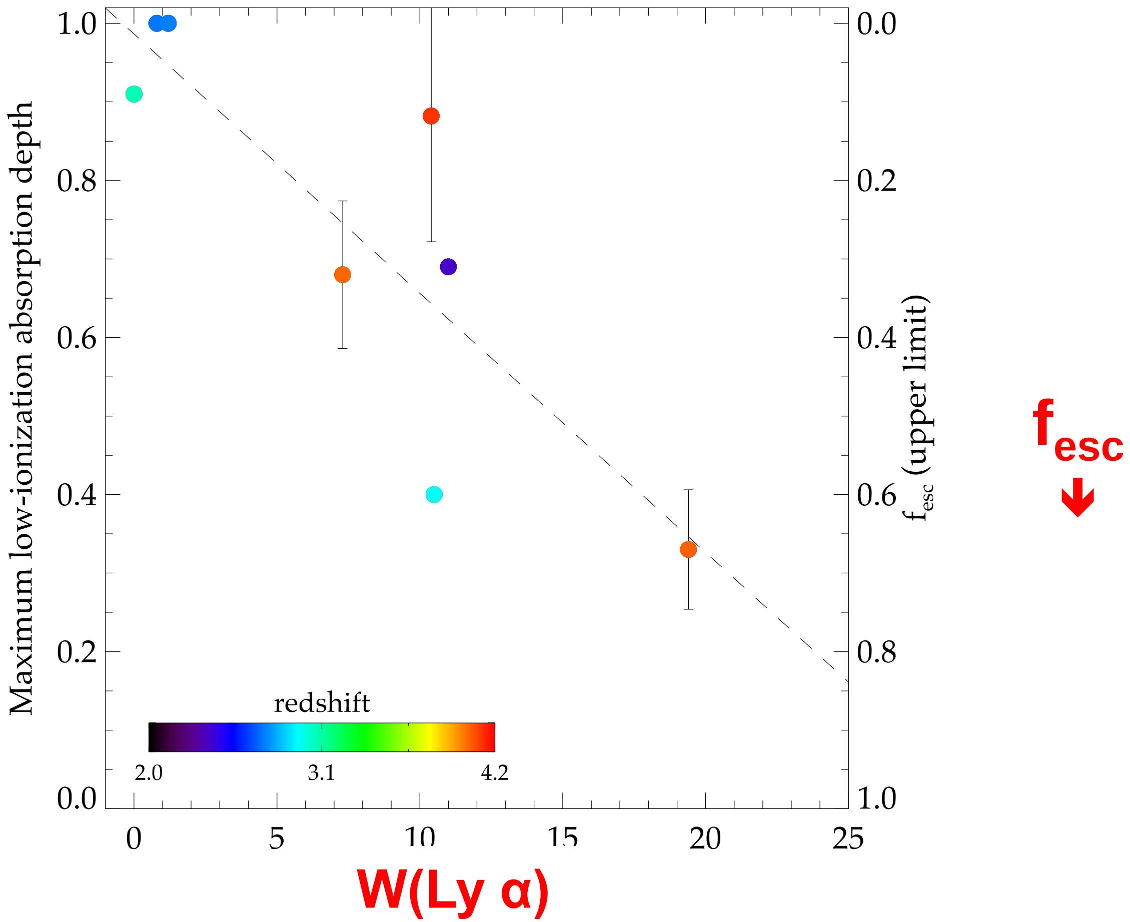
$$\tau = f\lambda\frac{\pi e^2}{m_e c} \times N$$

Covering fraction f_c~30%
Column density N>2×10^{15} cm^{-2}
Outflow velocity up to ~600 km/s



Jones et al, arXiv 1304.7015

Evidence for Increasing Escape Fraction at High z?

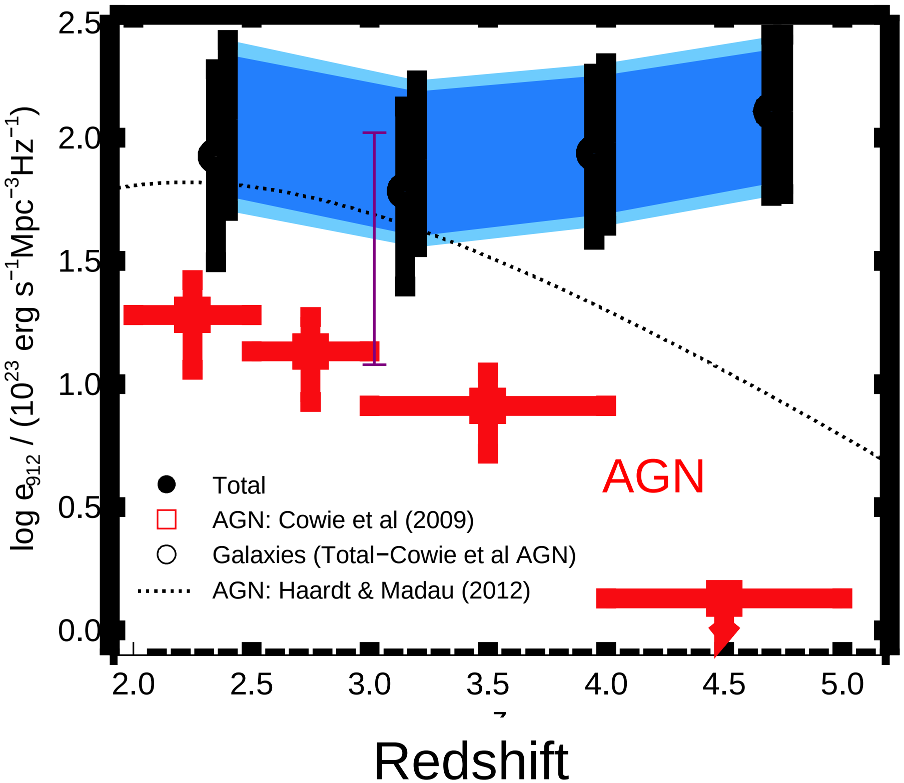


With earlier work (Pettini et al, Quider et al) now have 8 lensed LBGs with high dispersion spectra. Data are consistent with increased escape fraction for sources with strong Ly α which become more numerous at high z

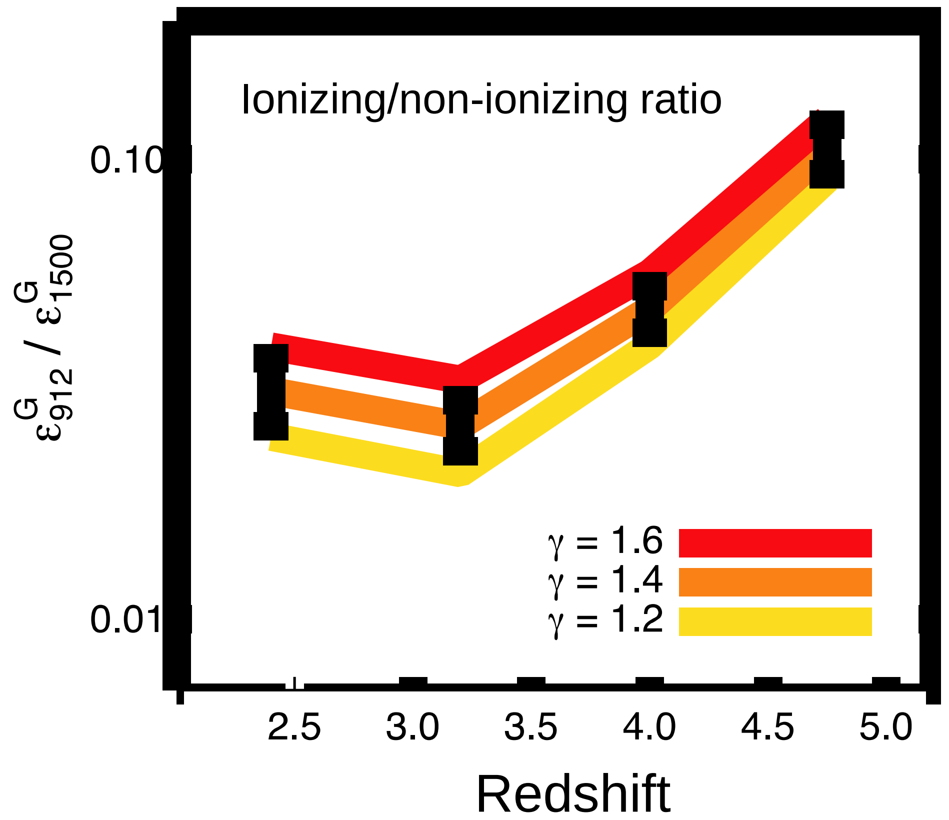
Jones et al, arXiv 1304.7015

Evolving Emissivity of Galaxies from QSO Spectra

ε_{912}: emissivity at 912 Å



$\varepsilon_{912} / \varepsilon_{1500}$



Ionizing emissivity ε_{912} (inferred from H ionizing rate Γ & T_{IGM} deduced from QSO spectra) increases with redshift when compared with UV emissivity of galaxies ε_{1500}

Becker & Bolton arXiv 1307.2259

Conclusions

Exciting time for $z>7$ studies: HST, Spitzer & Keck/VLT in vanguard!

1. Decline in visibility of Lyman α over $6.5<z<8$ suggests neutral era begins in this redshift range: feasible to extend this test with larger samples using MOSFIRE
2. UDF2012 data has provided first census of galaxies beyond $z\sim8.5$, continued decline in SFH to $z\sim10$ in agreement with lensed studies
3. Deeper higher fidelity data provides improved $z\sim7$-8 LFs
4. No evidence for unusually blue stellar populations; $z\sim7$-8 galaxies are >100 Myr old
5. Providing SF extends beyond $z\sim10$ and in low L systems with moderate f_{esc}, galaxies can be main agent of reionization
6. Quantifying f_{esc} remains a challenge but detailed studies of outflowing low ionization gas in $z\sim4$-5 LBGs offers a route forward
7. Implication: expect $z>10$ galaxies will be found by JWST/TMT