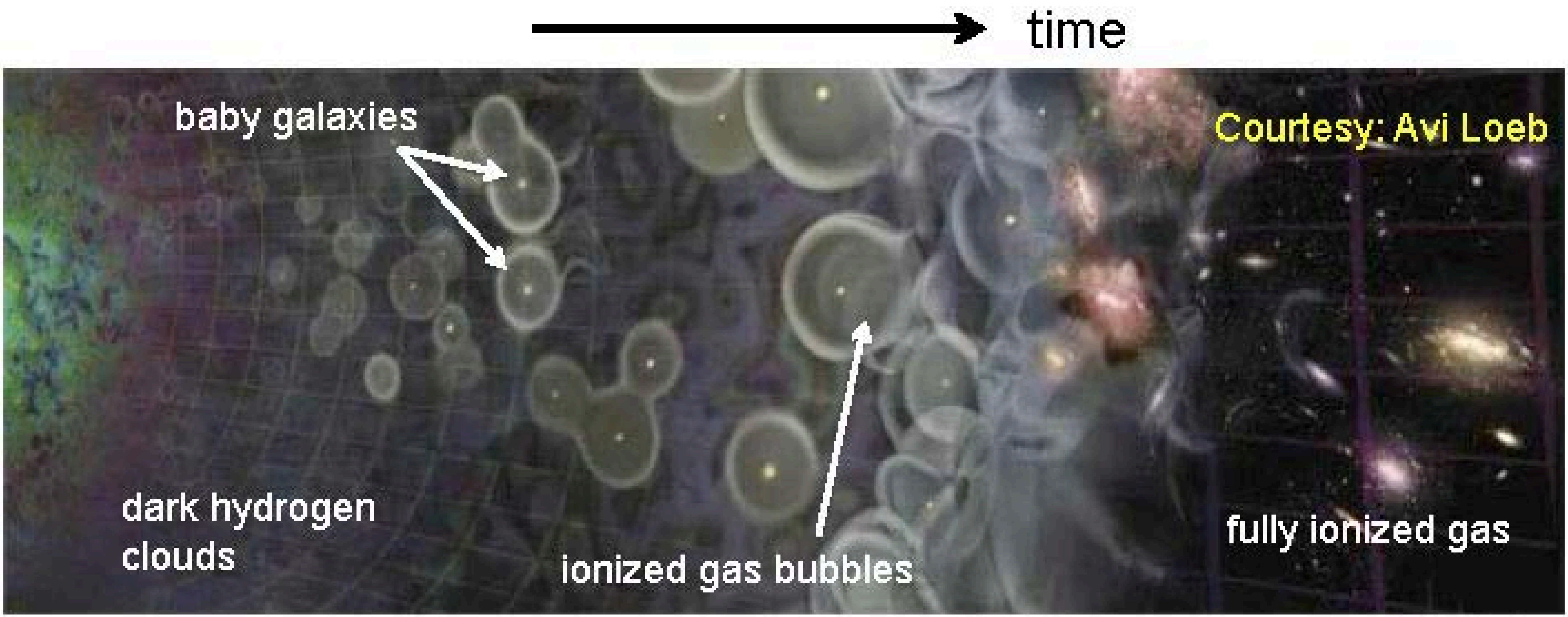

Observations of Star Forming Galaxies in
the Heart of the Reionization Era
11.9
8.8
Richard Ellis, Caltech
8.6
NAOJ
January 24th 2014
8.8
9.5
9.5
8.6

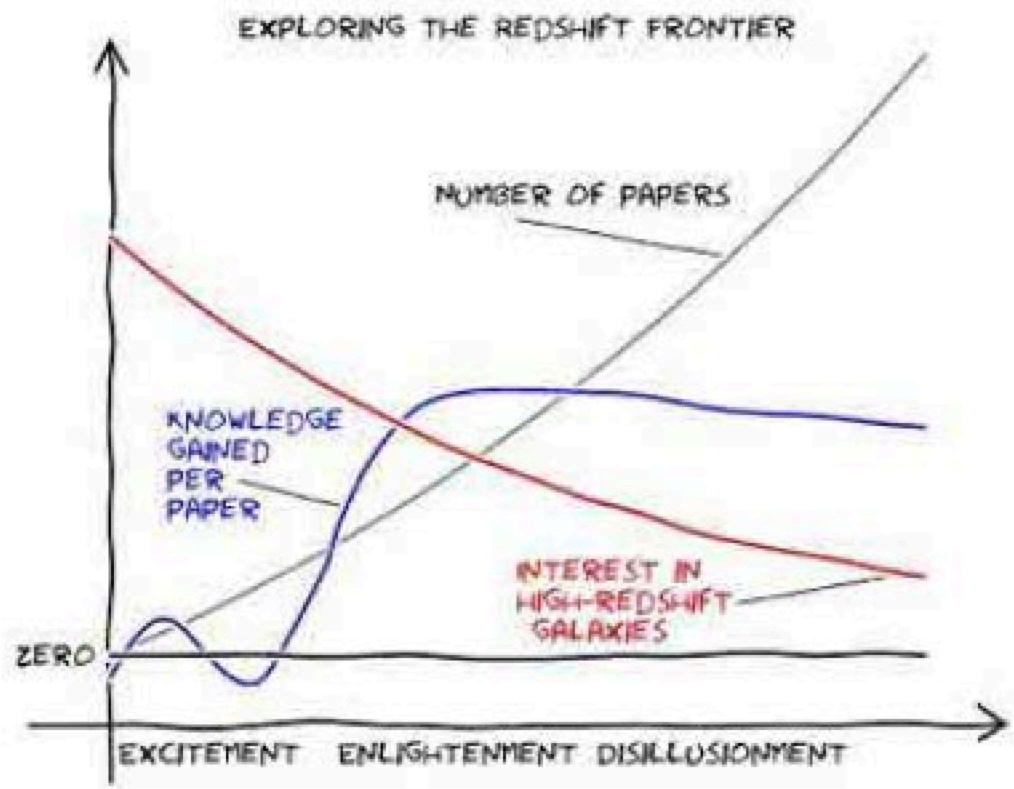
Cosmic Dawn and Reionization



When the first galaxies emerged (**cosmic dawn**), the Universe was bathed in ultraviolet light from young stars which produced ionized spheres of electrons and protons inbetween the galaxies (**reionization**).

This landmark probably occurred 200-800 million years after the Big Bang when the Universe was <5% of its present age (redshifts z~6-20).

Cosmic Reionization: the latest frontier



- Cosmic reionization is one of the very few remaining unobserved periods of cosmic history
- Promises insight into the first generation of stars/galaxies, development of black holes, feedback processes governing fate of low mass halos and dwarf galaxies
- Significant investment being made to make relevant observations (ALMA, JWST, E-ELT/TMT, SKA..); any insight we can gain now will be highly valuable

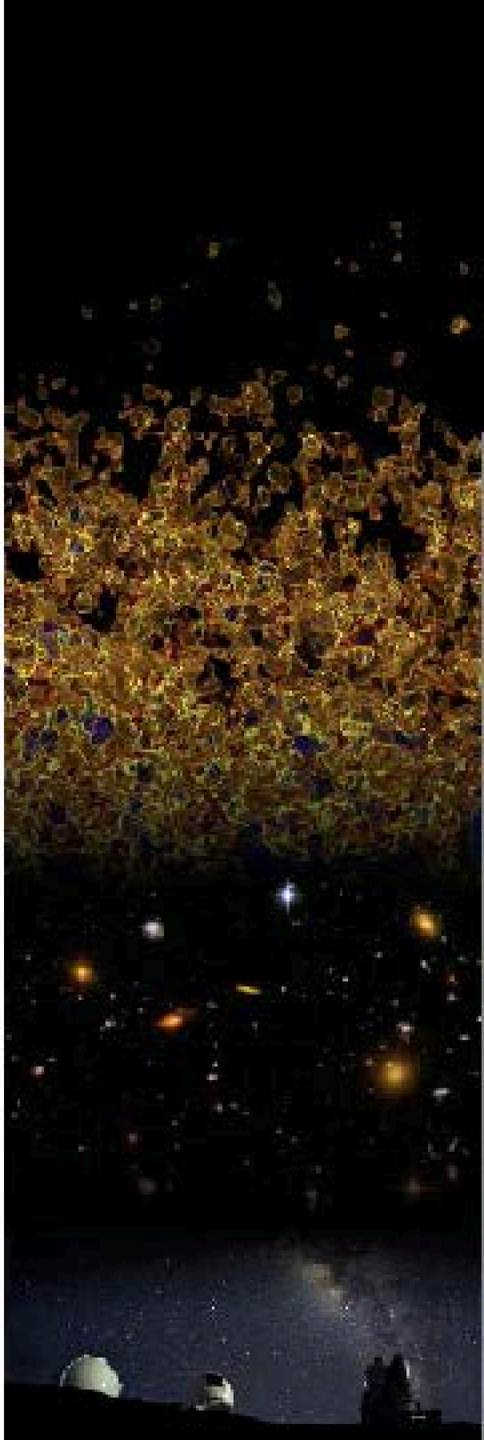
The Big Questions

- When did reionization occur?
  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)

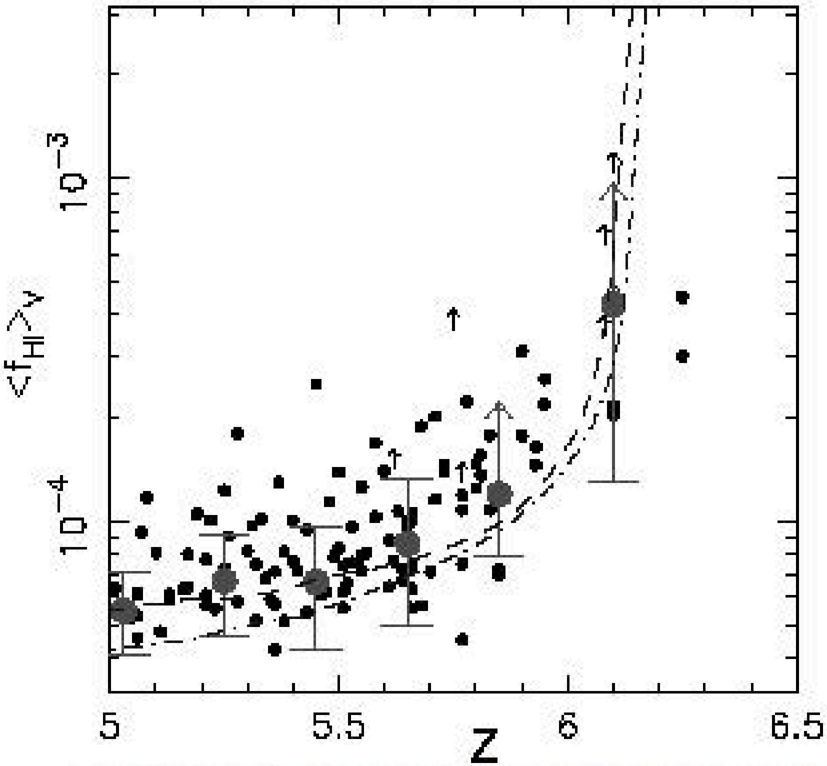
- Issues and challenges:
  - Nebular contamination of broad-band photometry
  - Escape fraction of ionizing photons
  - Future opportunities

Collaborators: Matt Schenker (Caltech), Tucker Jones (UCSB), Brant Robertson, Dan Stark, (Arizona), Steve Furlanetto (UCLA), Jim Dunlop, Ross McLure (Edinburgh), Stephane Charlot (IAP), Yoshiaki Ono, Masami Ouchi (Tokyo), Anton Koekemoer(STScI)

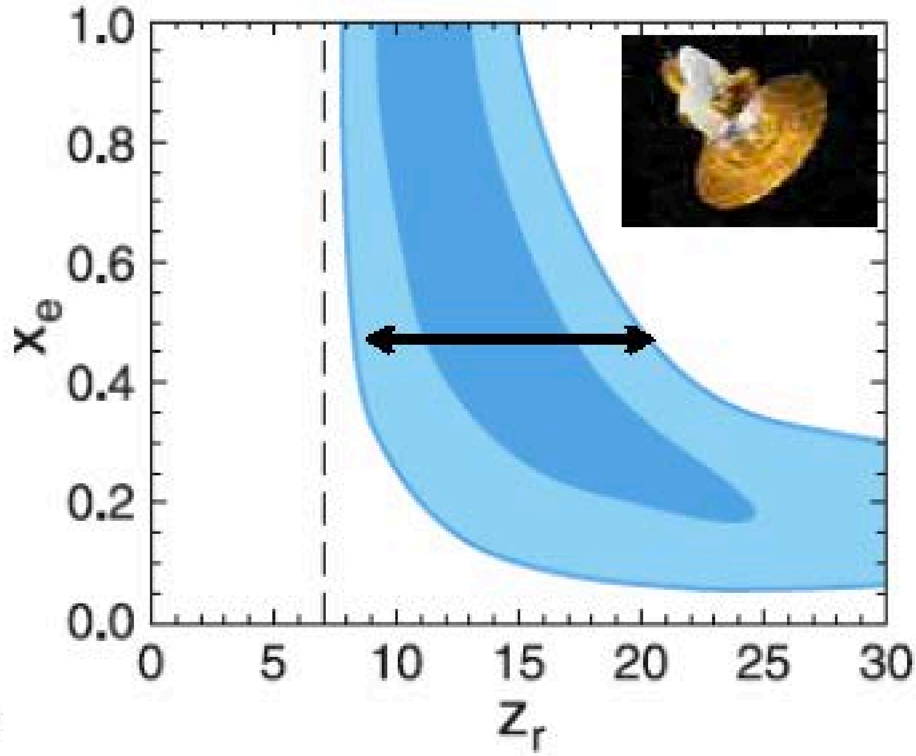


When Did Reionization Occur?

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



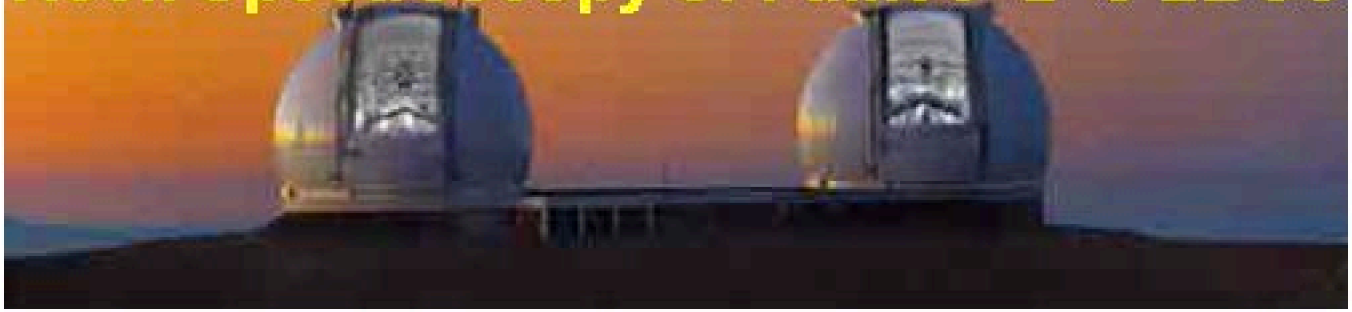
WMAP+eCMB, Hinshaw et al (2012): $\tau = 0.084 \pm 0.013$ consistent with instantaneous reionization z=10.3 ± 1.1



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)

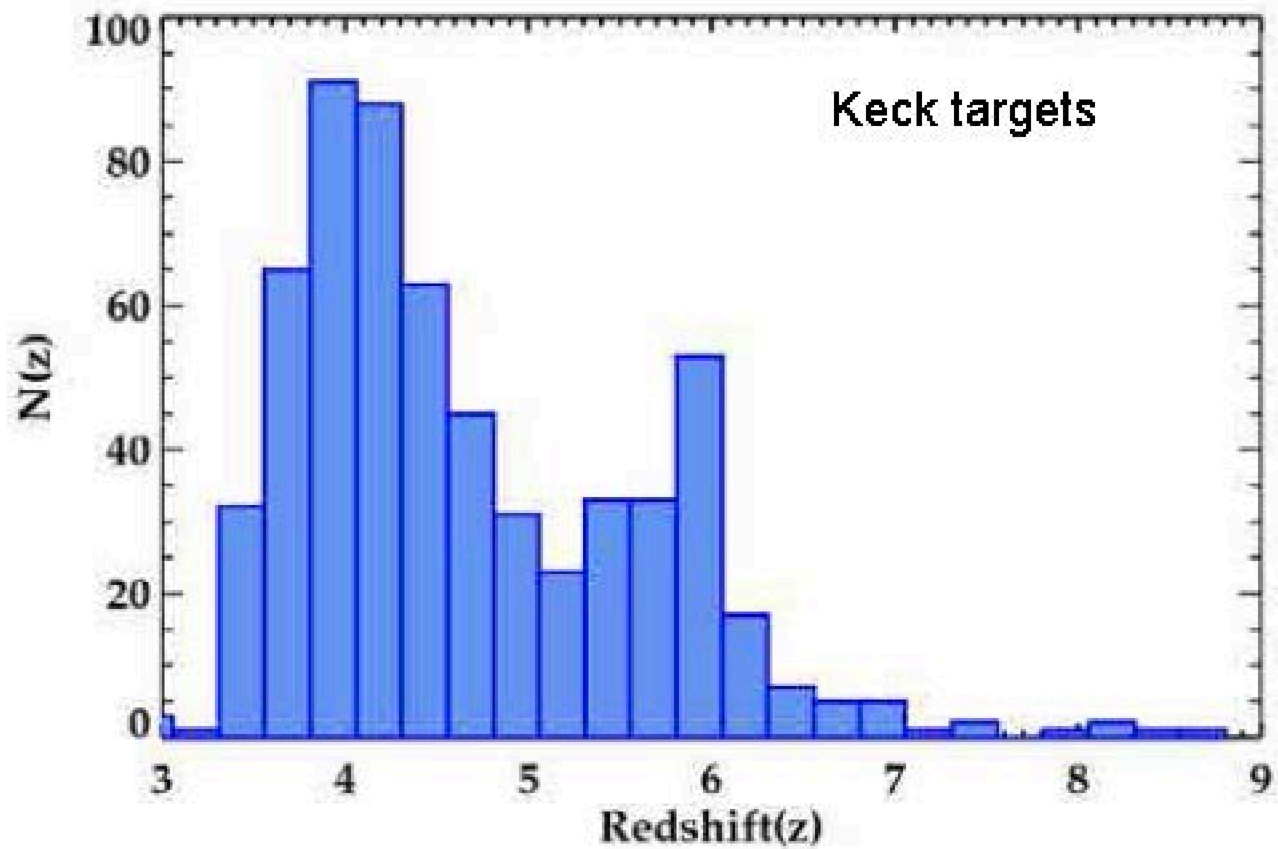
Target catalog:	Stark et al (2009) Ap J 697, 1493
Spectroscopy 3<z<5	Stark et al (2010) MNRAS 408, 1628
Spectroscopy z~6	Stark, Ellis & Ouchi (2011) Ap J 728, L2
Spectroscopy z~7	Schenker et al (2012) Ap J 744, 179
Stacked z~4-5 spectra	Jones et al (2012) Ap J 751, 51
Nebular emission	Stark et al (2013) Ap J 763, 129
Nebular emission	Schenker et al (2013) Ap J 777, 67

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

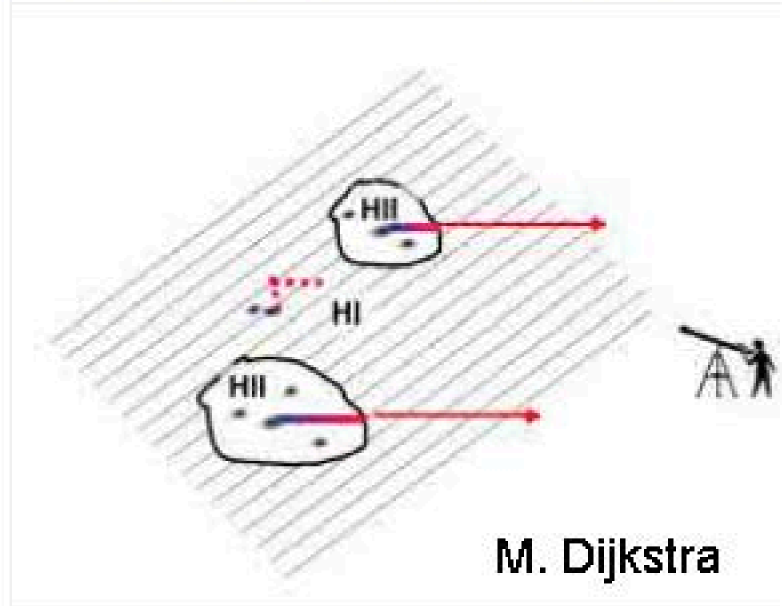
- Keck: 351 B + 151 V + 89 i + 21 z + 5 Y drops = 617 spectra
- VLT/FORS2 retro-selected + same criteria: 195 spectra (Vanzella et al)

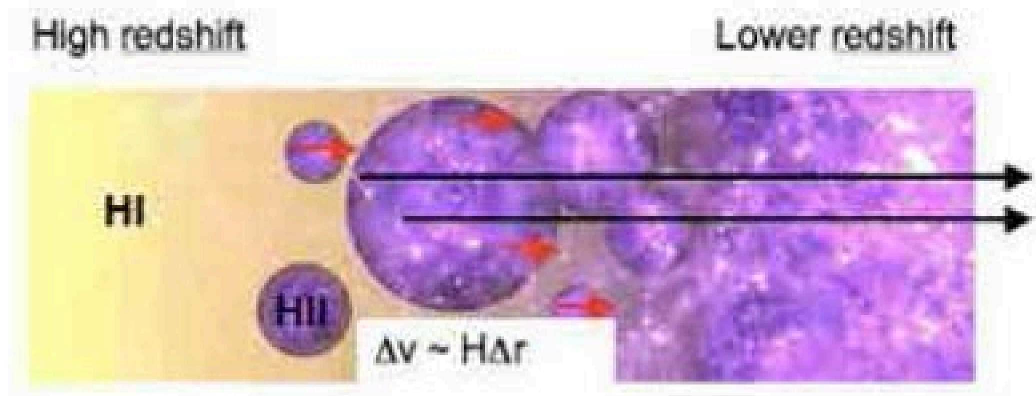


Lyα Emission as a Probe of Reionization

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

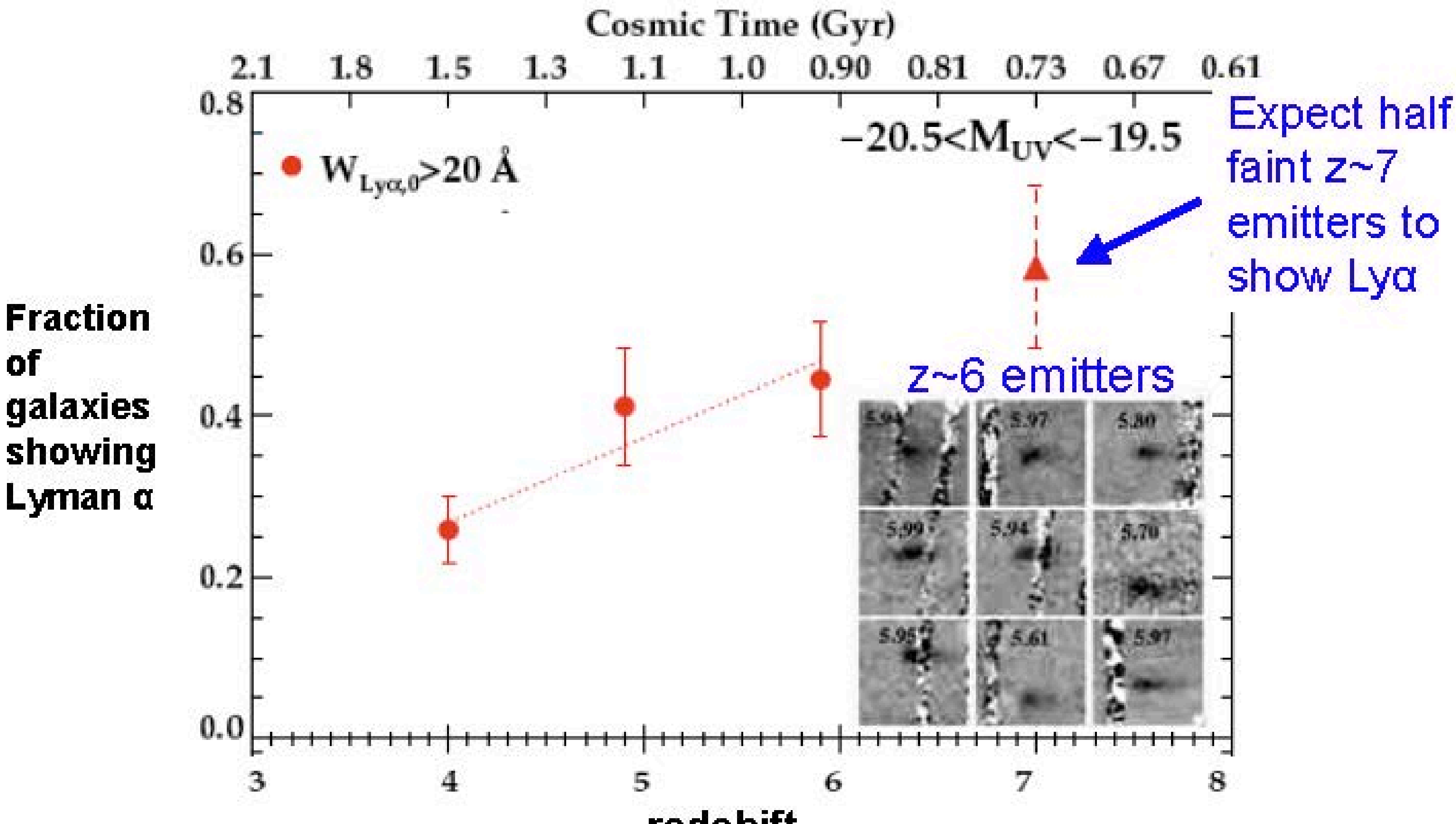
- But resonant scattering by neutral gas reduces visibility of Lyα
- So, in a significantly neutral IGM, galaxy must lie in an ionized bubble in order for Lyα to escape
- Expect a sudden drop in the fraction of galaxies revealing line emission as we enter the neutral era
- **Caveats: dust, outflows etc**





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

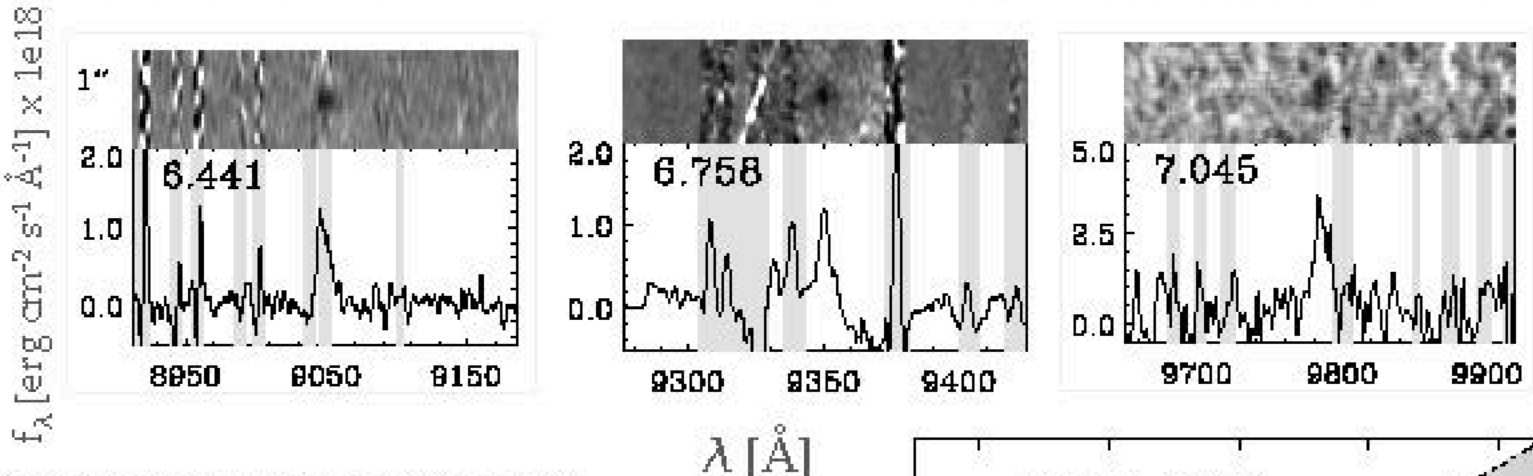
`Lyman α Visibility' versus Redshift



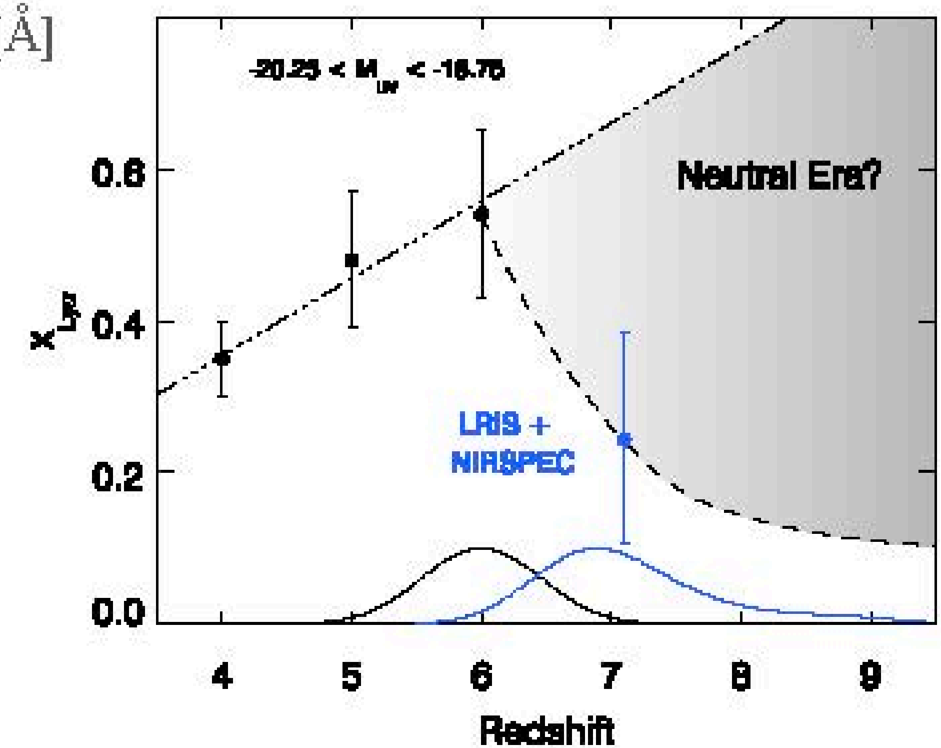
High visibility at z~6 implies should readily detect emission at z > 7

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

Sudden Decline in Lyα Fraction z > 6.3 ?

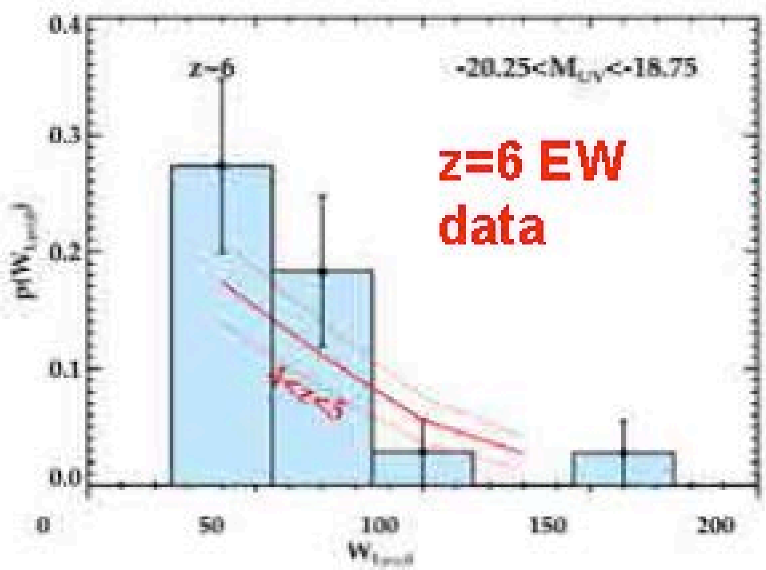


- 24 galaxies with 6.3<z<8 surveyed, Lyα detected in only 3 sources to same EW limit
- Implies decline in fraction (although still marginal result)
- Adopting McQuinn et al. (2007) ➔ X_{HI} ~ 0.44 at z ~ 7
- Explanations other than a neutral IGM (contamination from low z, dust) unlikely



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

Assessment with Monte Carlo Simulations



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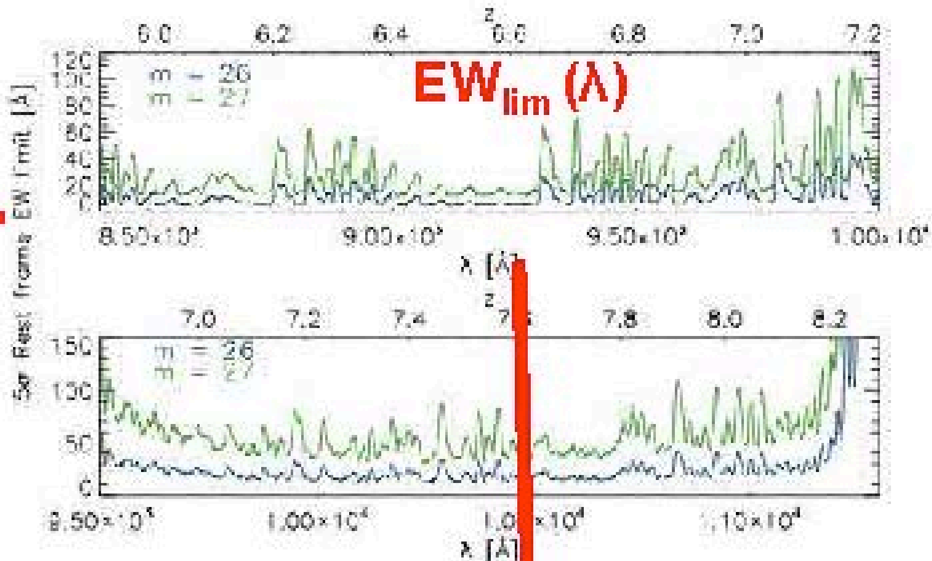
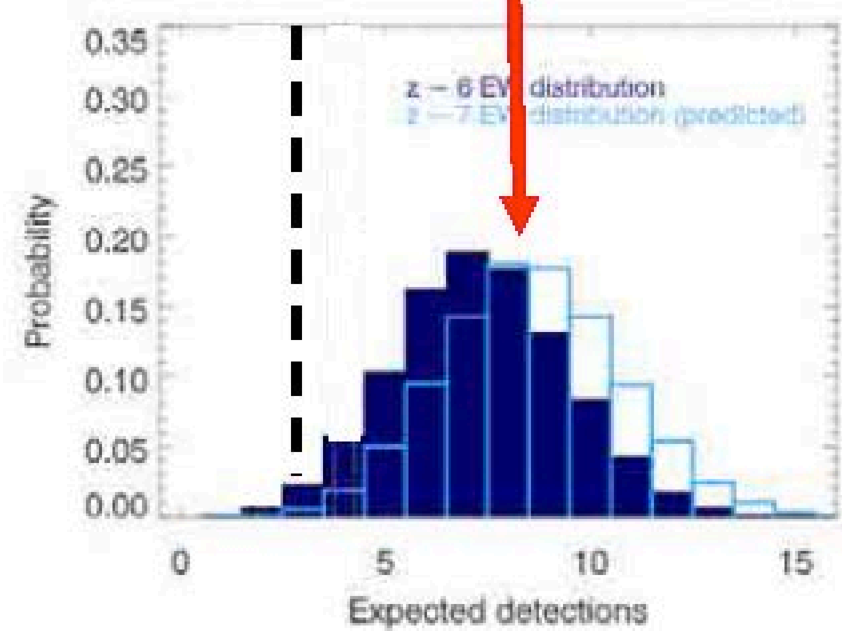




Since we cannot conduct a perfectly uniform search for line emission in the near-IR, we take the expected EW distribution of Lyα at z~6 and predict, given the observations, OH sky and photometric p(z) of our targets how many lines we should have seen.

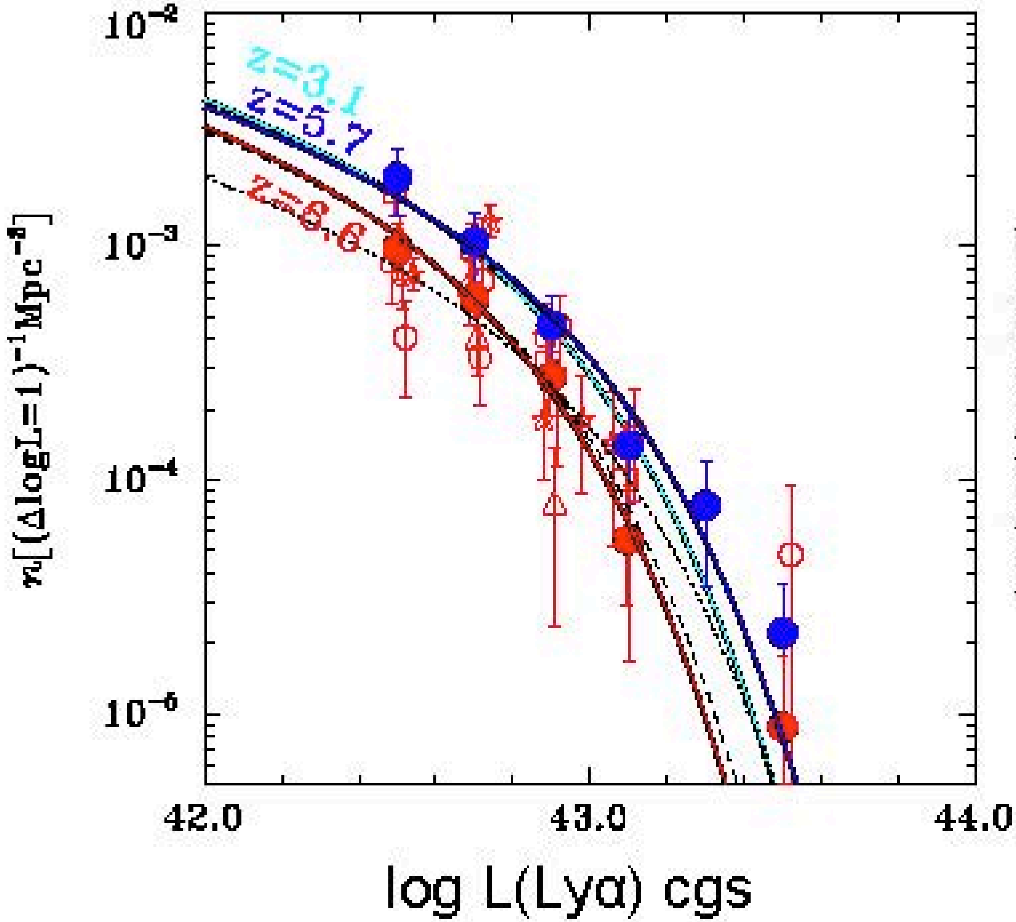
Observe 3 (8) and expect 8-9 (24) detections [reject at >99.5%]

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

Further Evidence for Late Reionization

Rapid decline in Lyα emitters from 5.7<z<6.6 (Kashikawa et al 2006, Ouchi et al 2010, Kashikawa et al 2011)

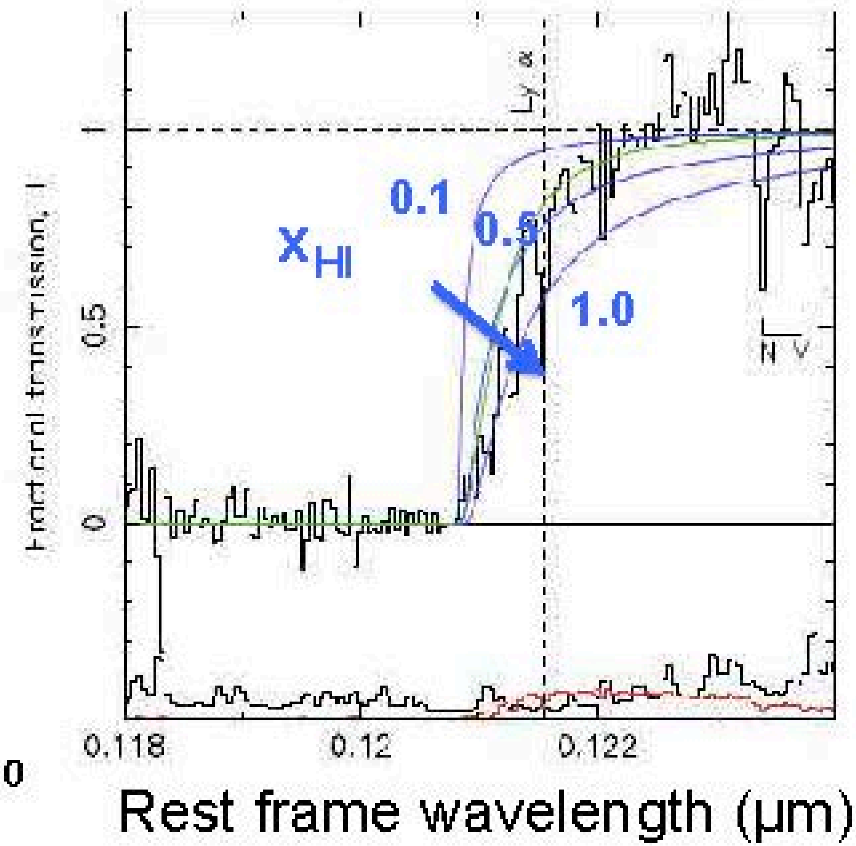
$x_{HI} \sim 0.1$ at z=6.6?



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)



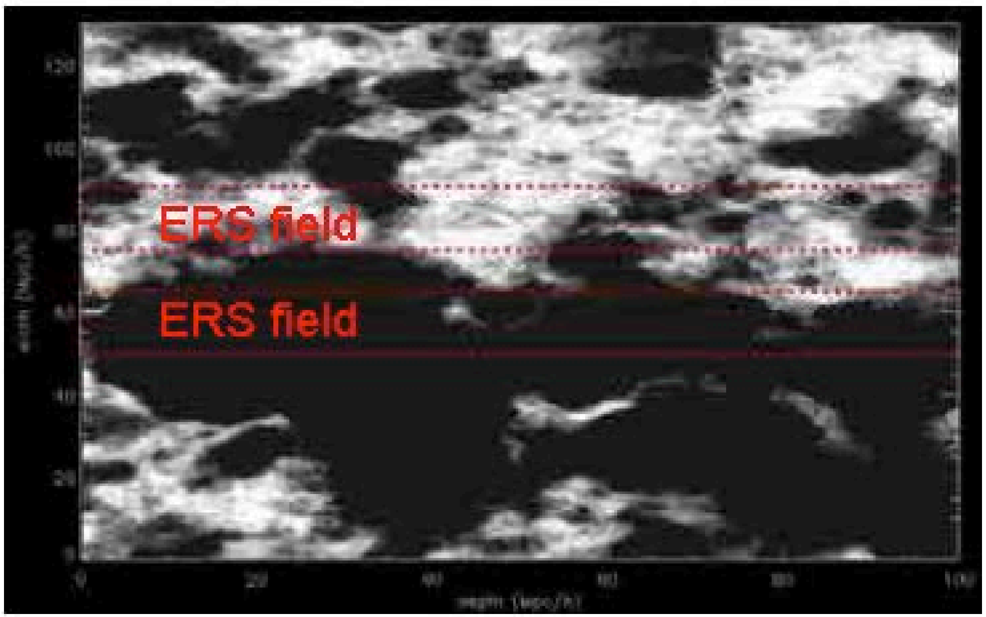
Is this rapid decline in x(Lyα) due to the IGM?

According to some models, data imply x(HI)~0.5 by z~7 (change in 200 Myr)
Some caveats:

- Cosmic variance: do not expect uniform X(Lyα, z) over all fields
- Inferred x(HI) depends on velocity offset of emerging Lyα which may decrease at high z

Simulation for <x(HI)>~0.2

Velocity offset (Lyα – nebular) km/s



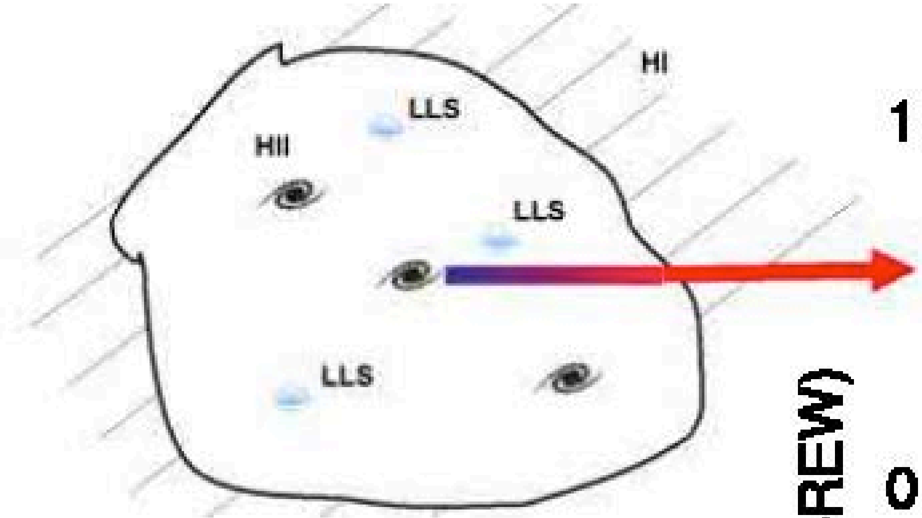
depth (Mpc)➔

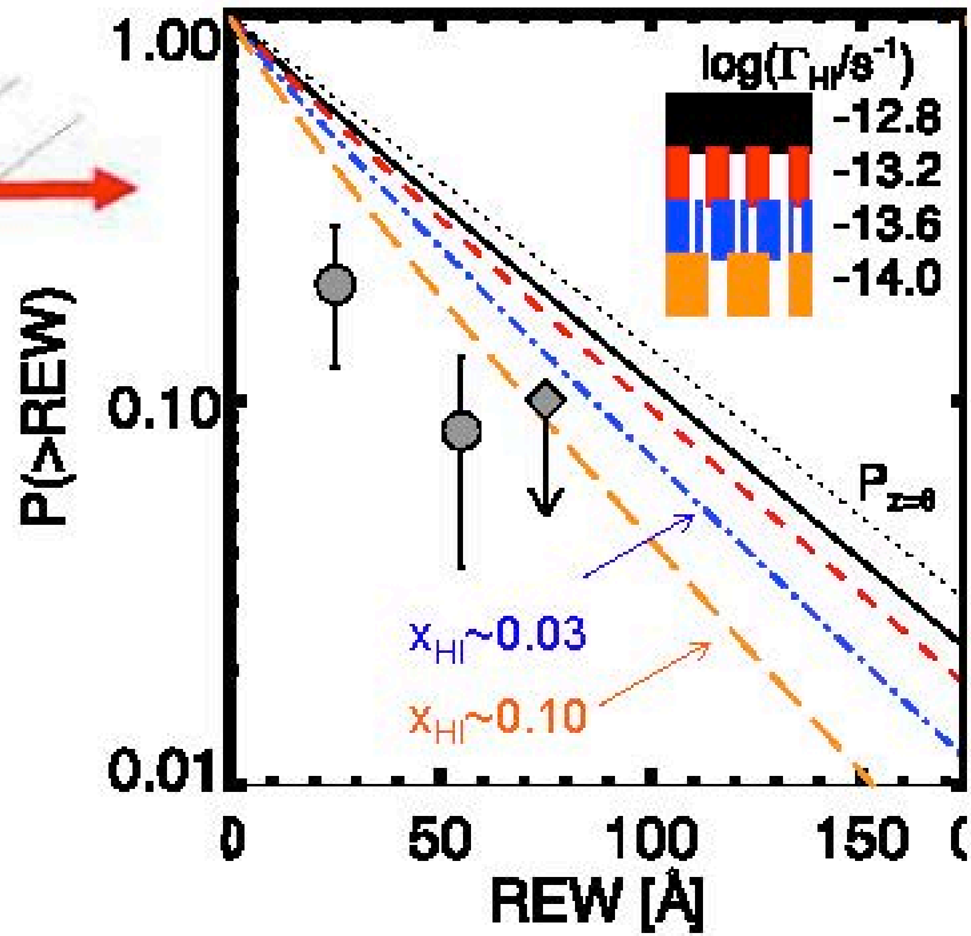
redshift

Taylor & Lidz arXiv:1308.6322

Schenker et al Ap J 777, 67 (2013)

Effect of Optically-thick Clouds



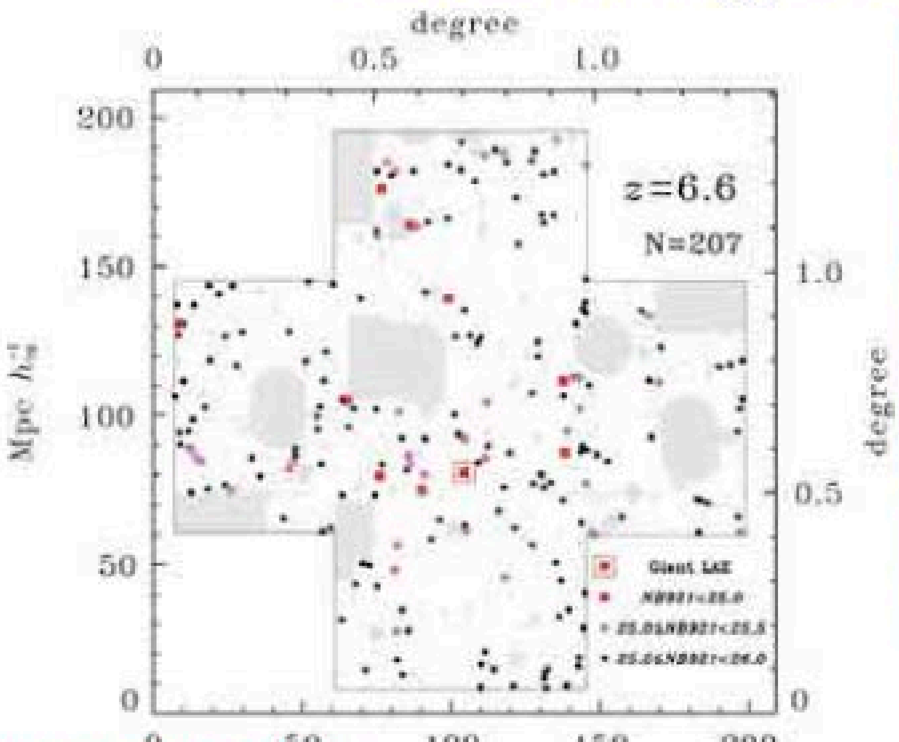


Optically-thick (LLS) clouds may obscure the line of sight and give misleading impression of the volume-averaged opacity of the IGM, reducing x_{HI} from 0.7-0.9 to 0.03-0.10

How to test?

Bolton & Haehnelt MNRAS 429, 1695 (2013)

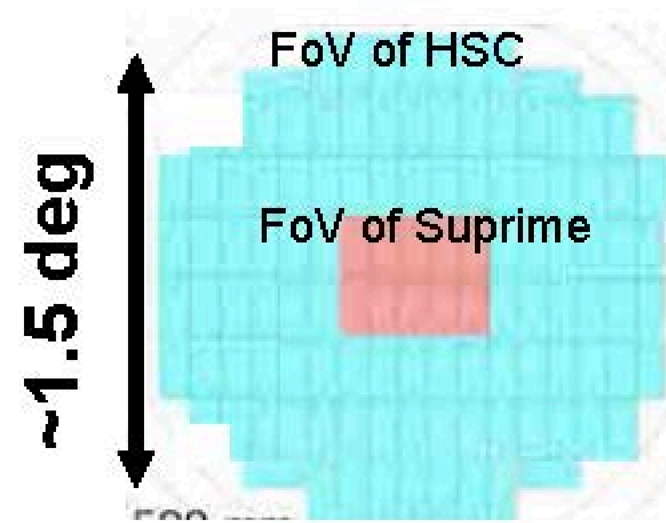
Clustering of Lyman α Emitters



Ouchi et al (2010)

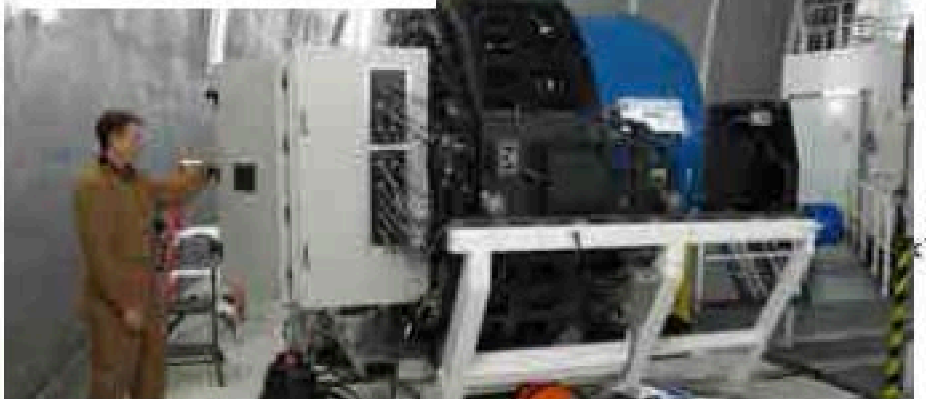
The spatial distribution of Ly emitters over key redshift ranges 5.7, 6.6 and 7.0 may contain information on the emerging distribution of ionized bubbles ; expect boosting in bias at higher z.

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

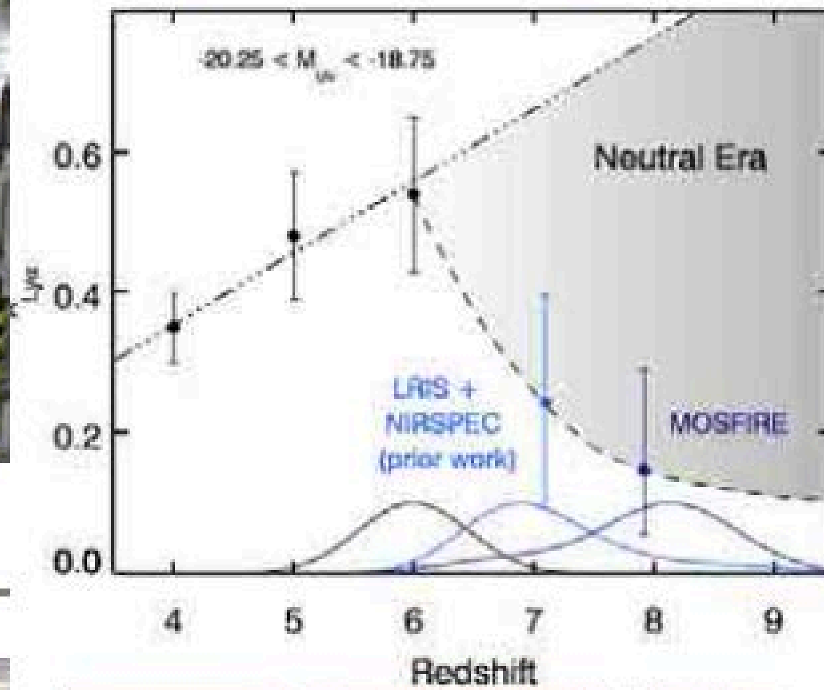


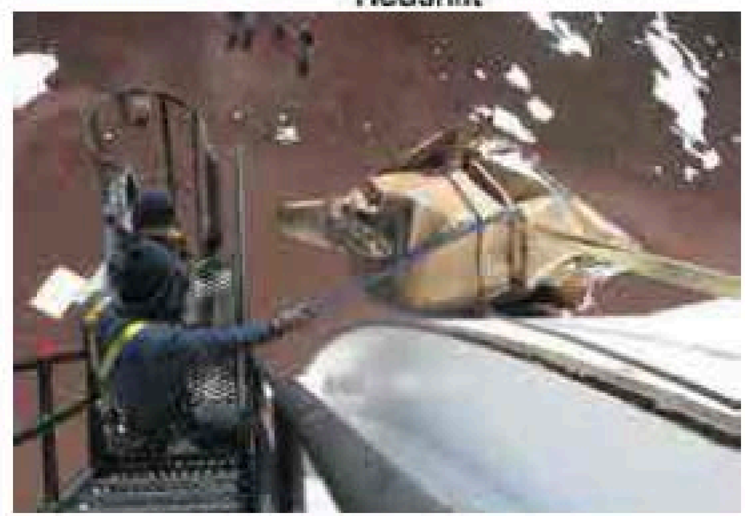
MOSFIRE: Can Confirm Lyα visibility decline

MOSFIRE@K1



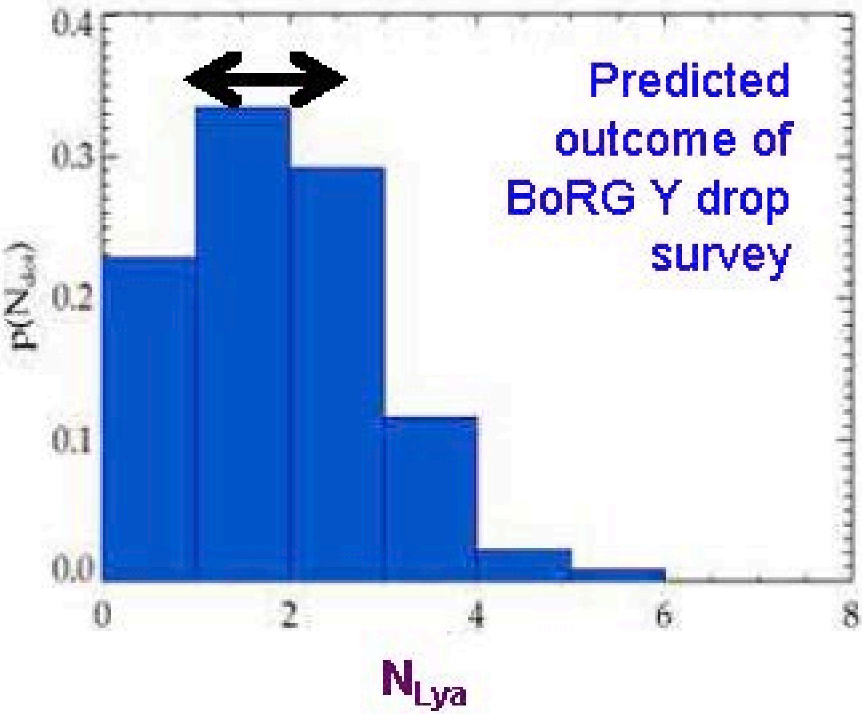
6.1 x 3.1 arcmin field λλ0.97 - 2.45 μm
R ~3300 for 45 configurable slits

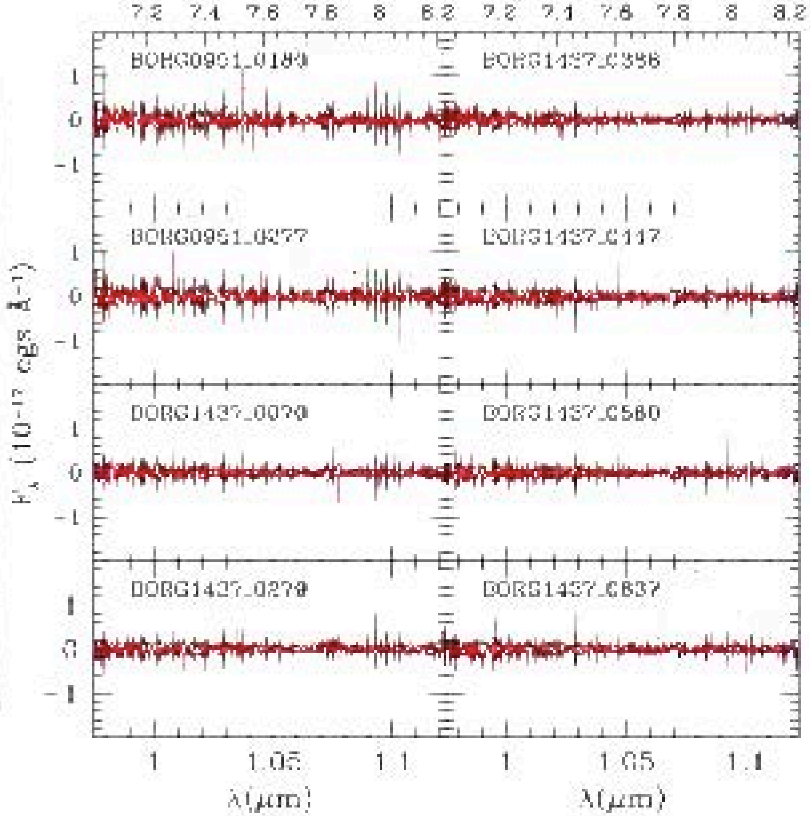




No luck yet...12 cloudy MOSFIRE nights out of 15!

First z~8 Results from MOSFIRE

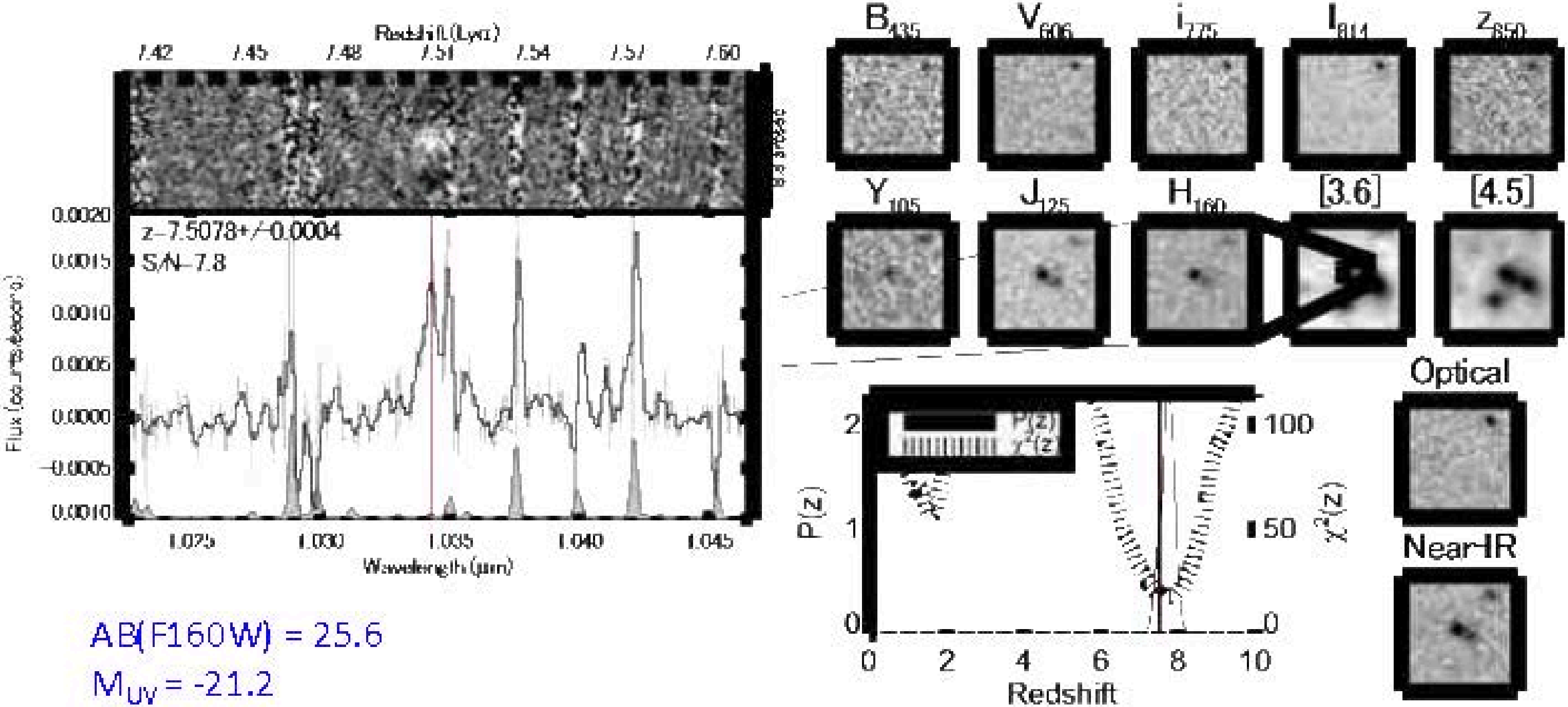




For sample of robust BoRG Y-drops, Lyα is not seen (EW<25Å 1σ). However, BoRG targets are quite luminous and Stark et al z~6 EW distribution predicts only < 1-2 should have detectable Lyα. Improved leverage would come from fainter Y-drops which MOSFIRE can reach

Treu et al Ap J 775, L29 (2013)

Spectroscopic Redshift Record – April 2013: z=7.51



AB(F160W) = 25.6

M_{UV} = -21.2

Photometry 7.5 < z < 8.1

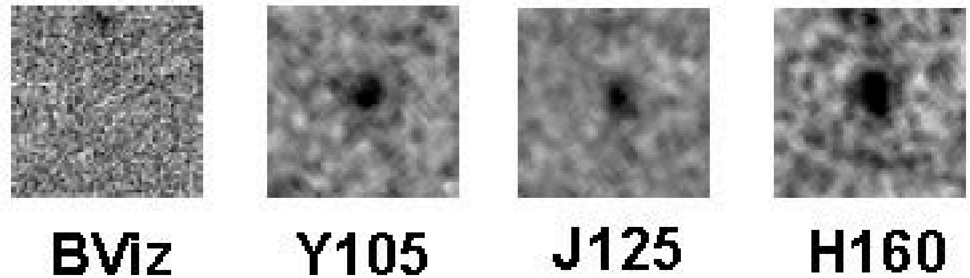
S/N (line) = 7.8

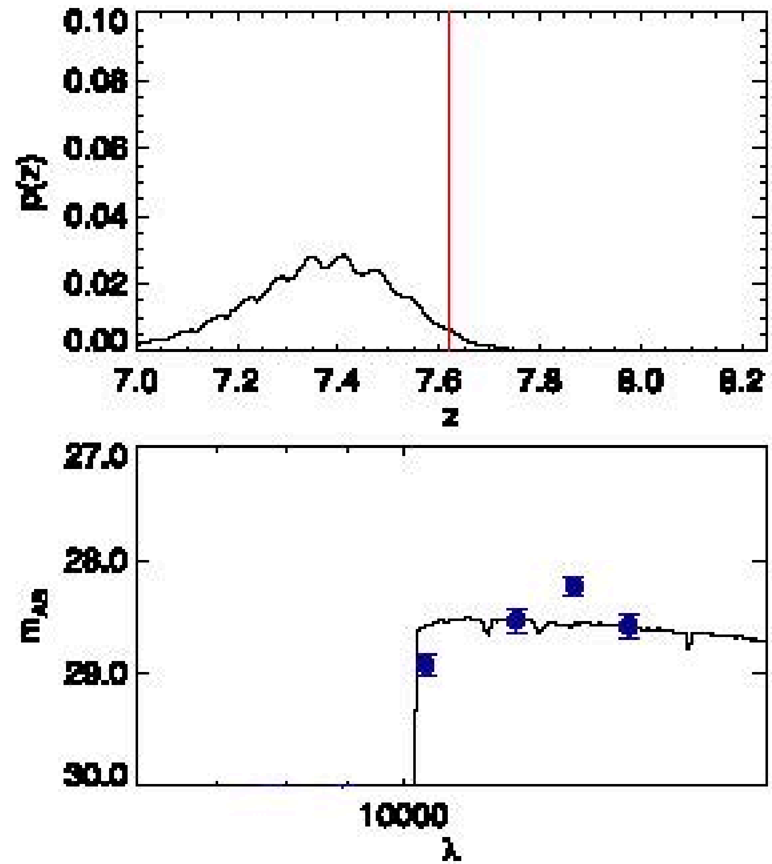
EW (Lyα) = 8

β (UV)= -1.5

Finkelstein et al Nature 502, 524 (2013)

Spectroscopic Redshift Record – Nov 2013: z=7.62



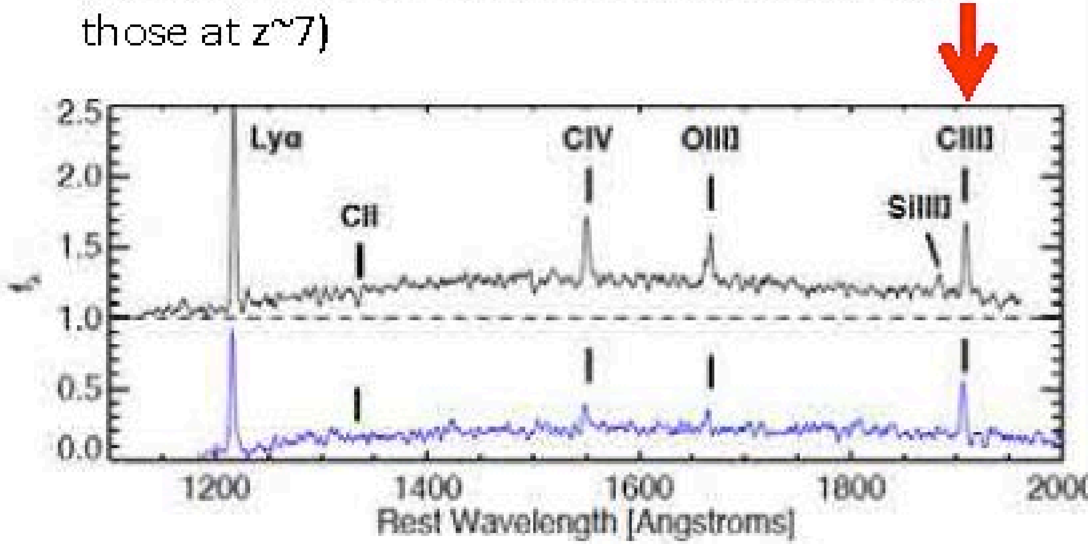


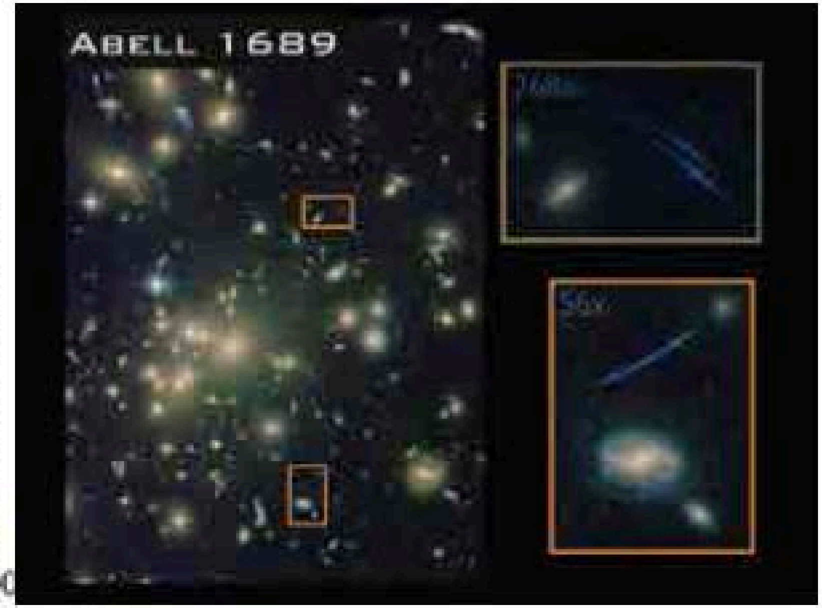
AB(F160W) = 28.6
M_{UV} = -18.5
Photometry 7.1 < z < 7.6
S/N (line) = 4.2
EW (Lyα) ~ 110 (± 30)
β (UV)= -2.3

Schenker et al 2014 (in prep)

High Redshift Measurements without Lyα?

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

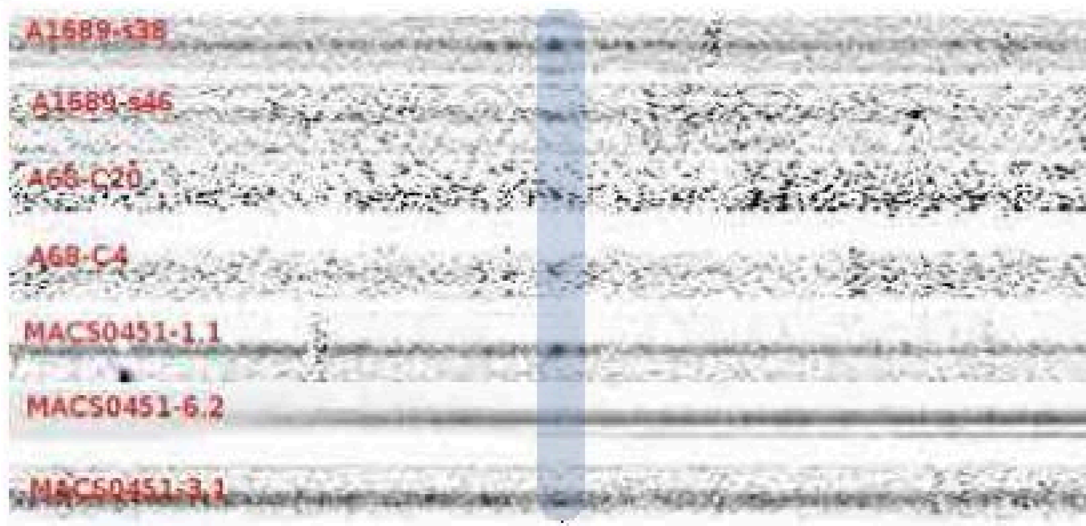




CIII] 1909 Å emission common

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}

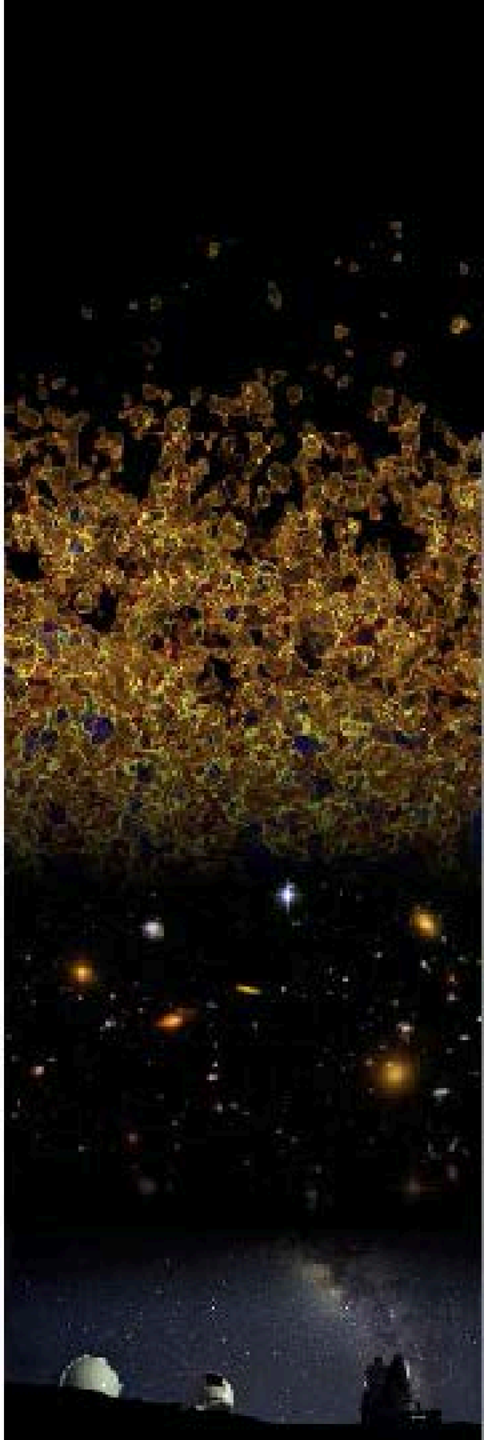
2. Nature of the stellar populations in distant galaxies which determines the rate of ionizing photons: ξ_{ion}

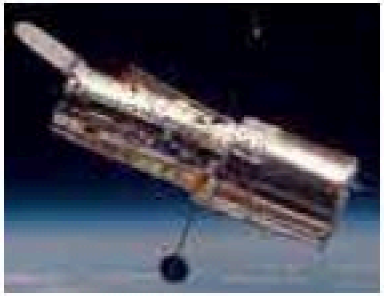
3. Fraction of ionizing photons that escape: f_{esc}

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

5. Optical depth of electron scattering to CMB: τ

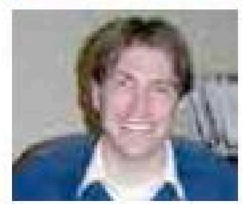
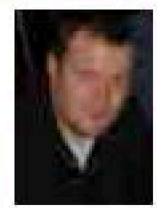
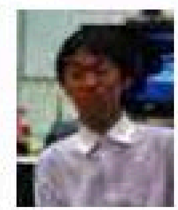
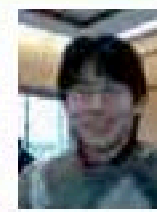
Improved data on [1] and [2] provided by new Hubble UDF 2012 campaign with additional constraints on [3, 4] from Keck spectroscopic survey





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

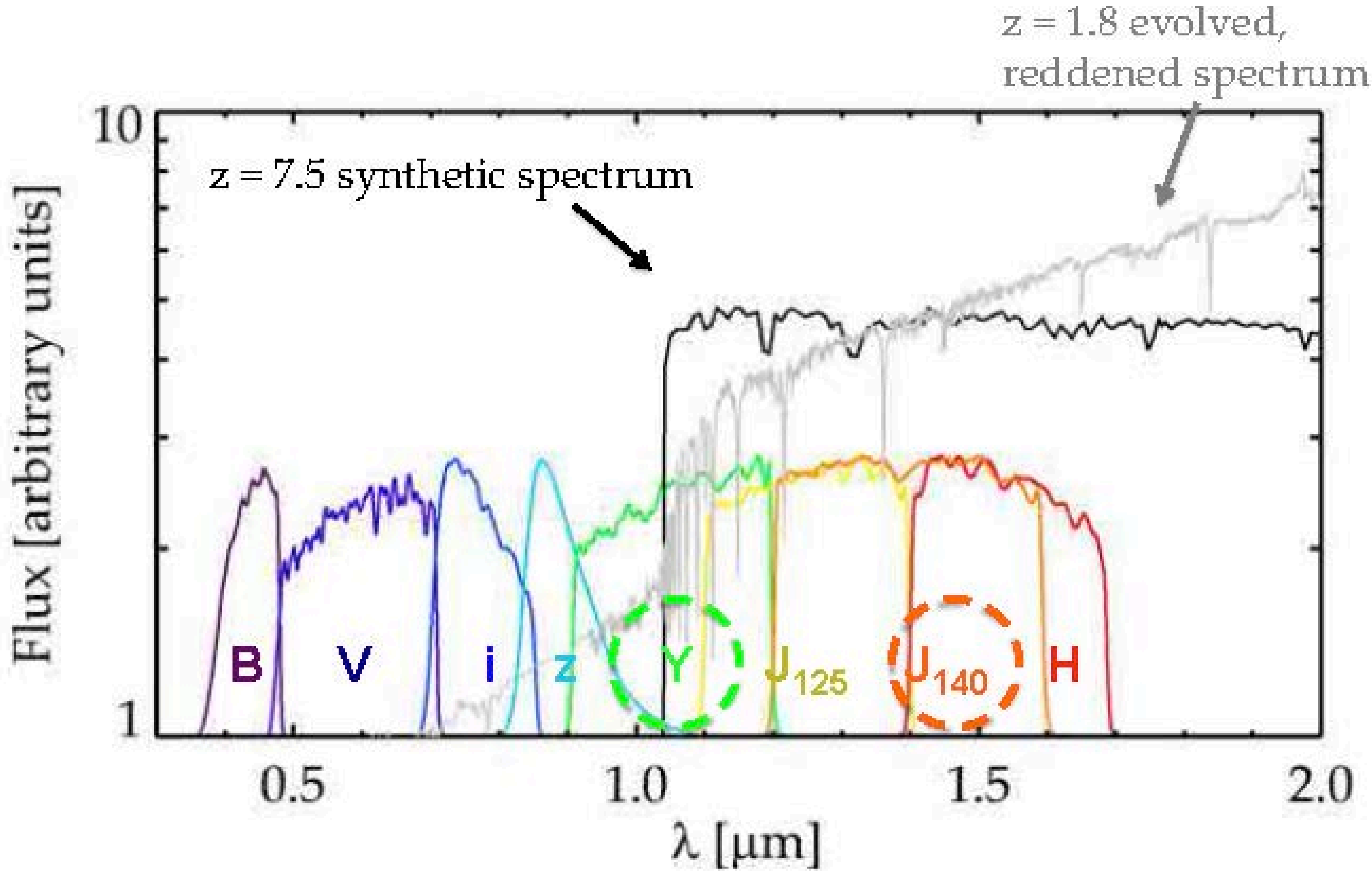
128 orbit Cycle 20 campaign designed to improve depth and fidelity of z>7 candidates

- 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

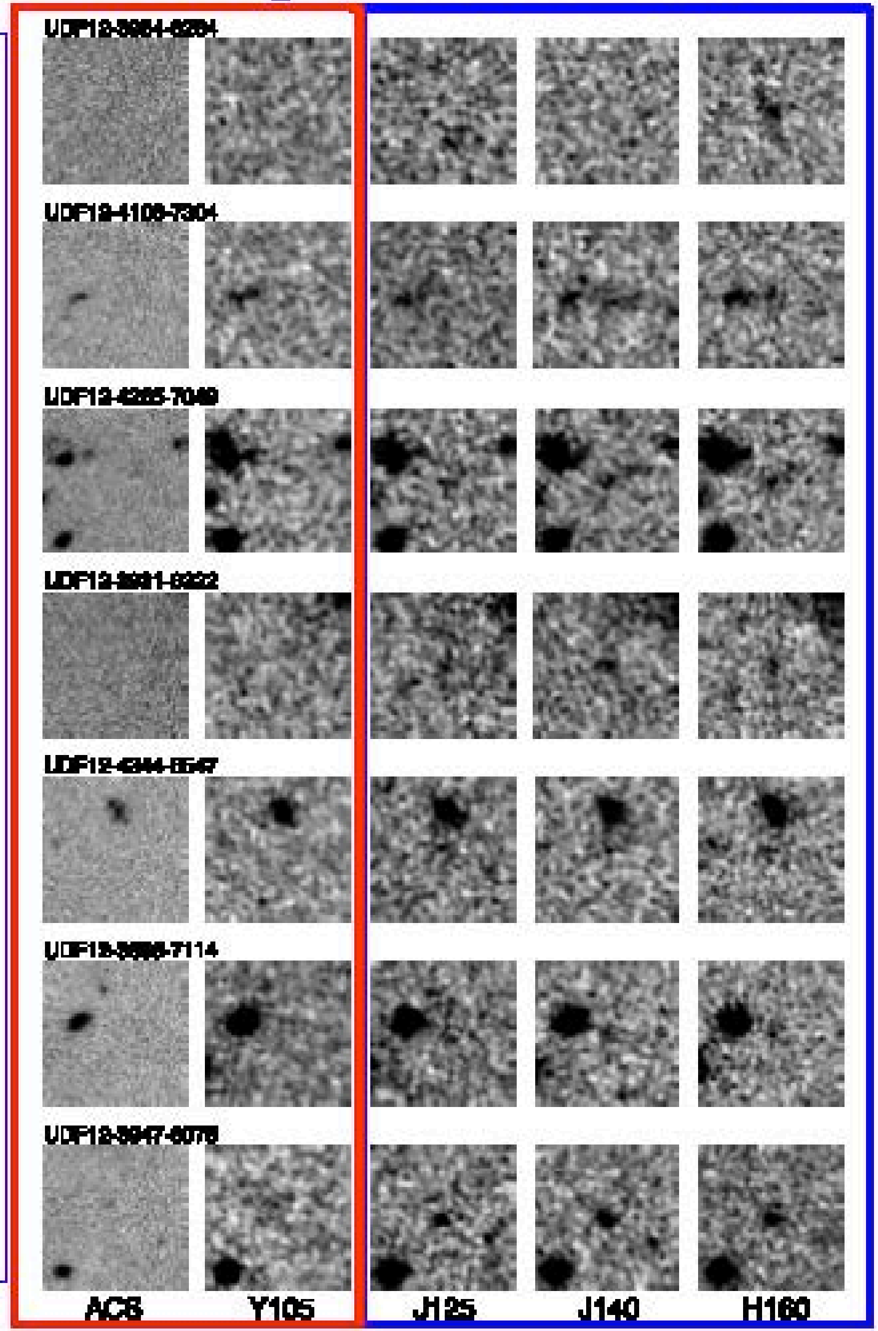
7 star-forming galaxies located $8.5<z<12$

5σ detections in (160W+140W+125 W) 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) Ap J Lett 763, L7



z=11.9? 380 Myr

z=9.5 520 Myr

z=9.5 520 Myr

z=8.8 570 Myr

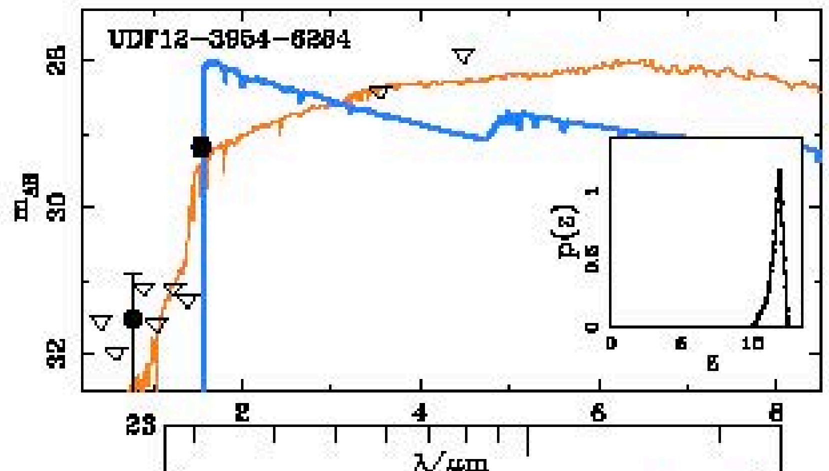
z=8.8 570 Myr

z=8.6 590 Myr

z=8.6 590 Myr

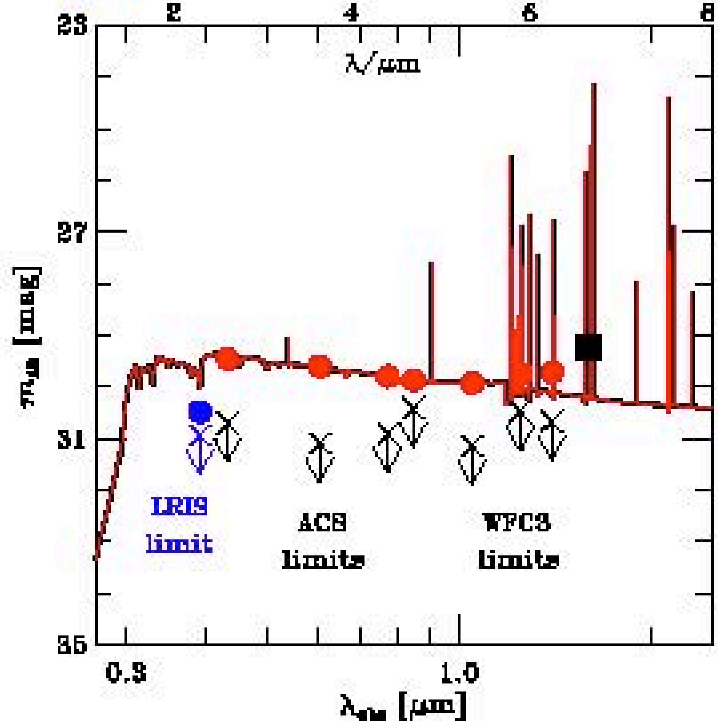
The Enigmatic z=11.9 Candidate

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



Y105 J140 H160

- 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



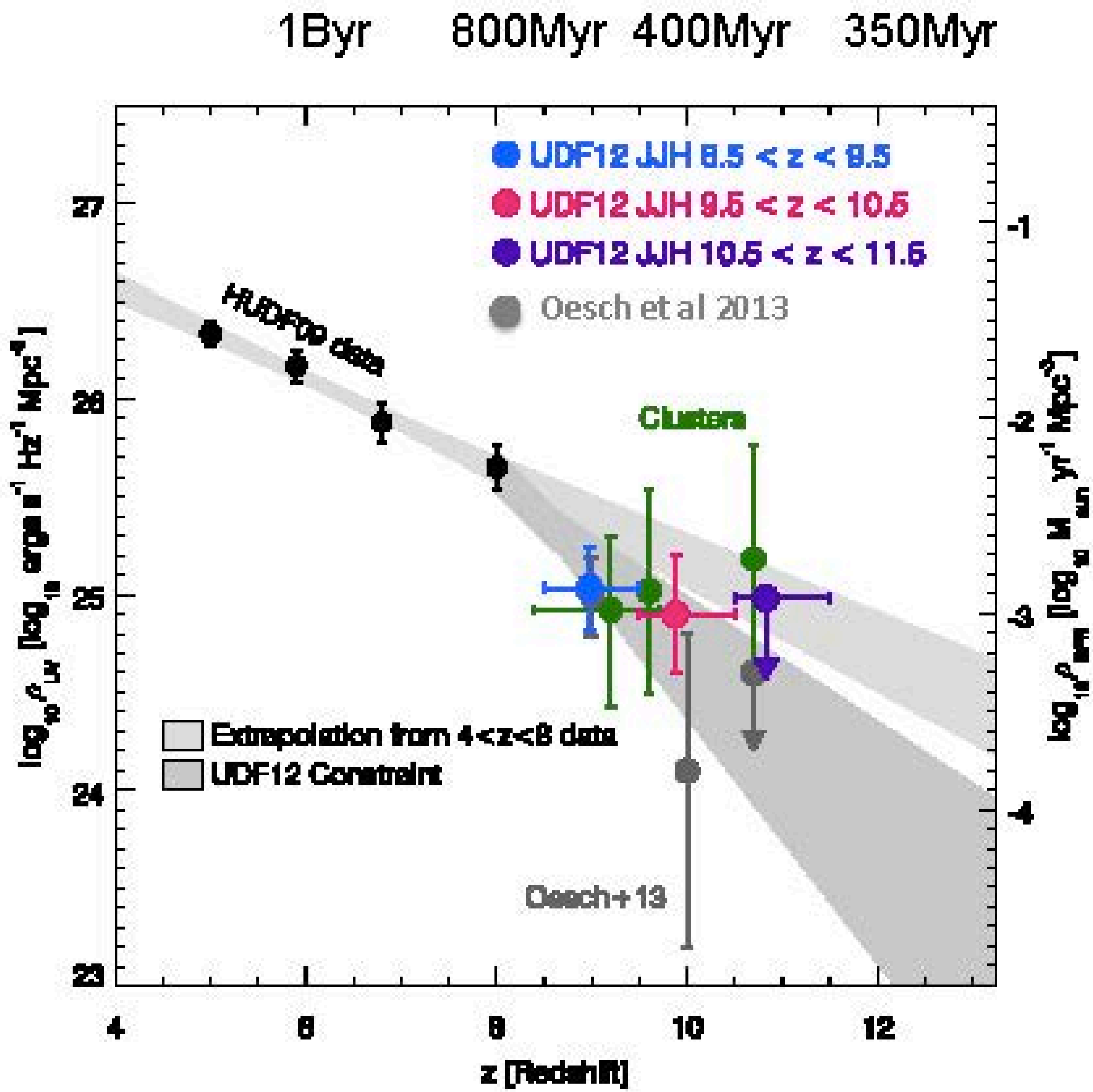
Star Formation History

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

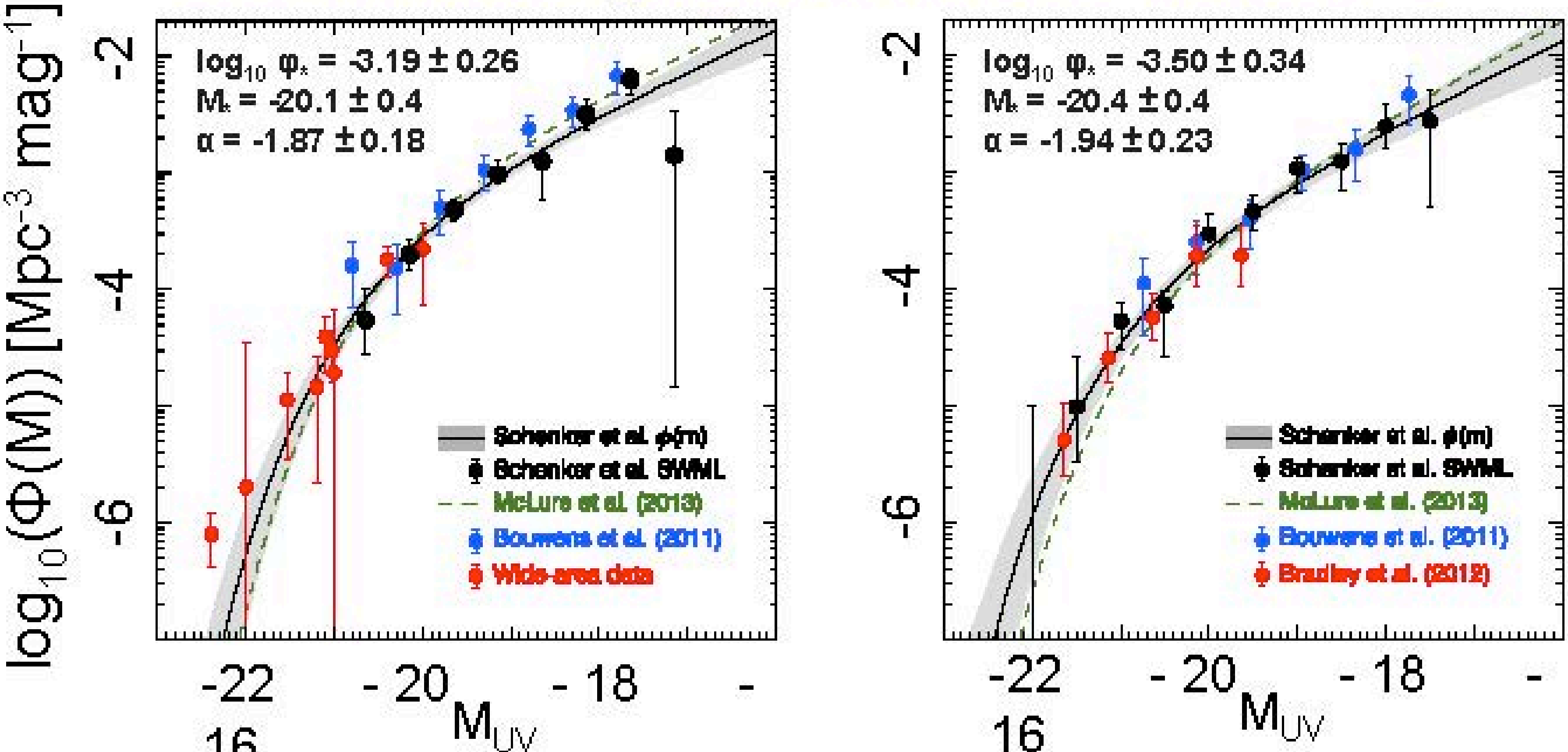


http://udf12.arizona.edu

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



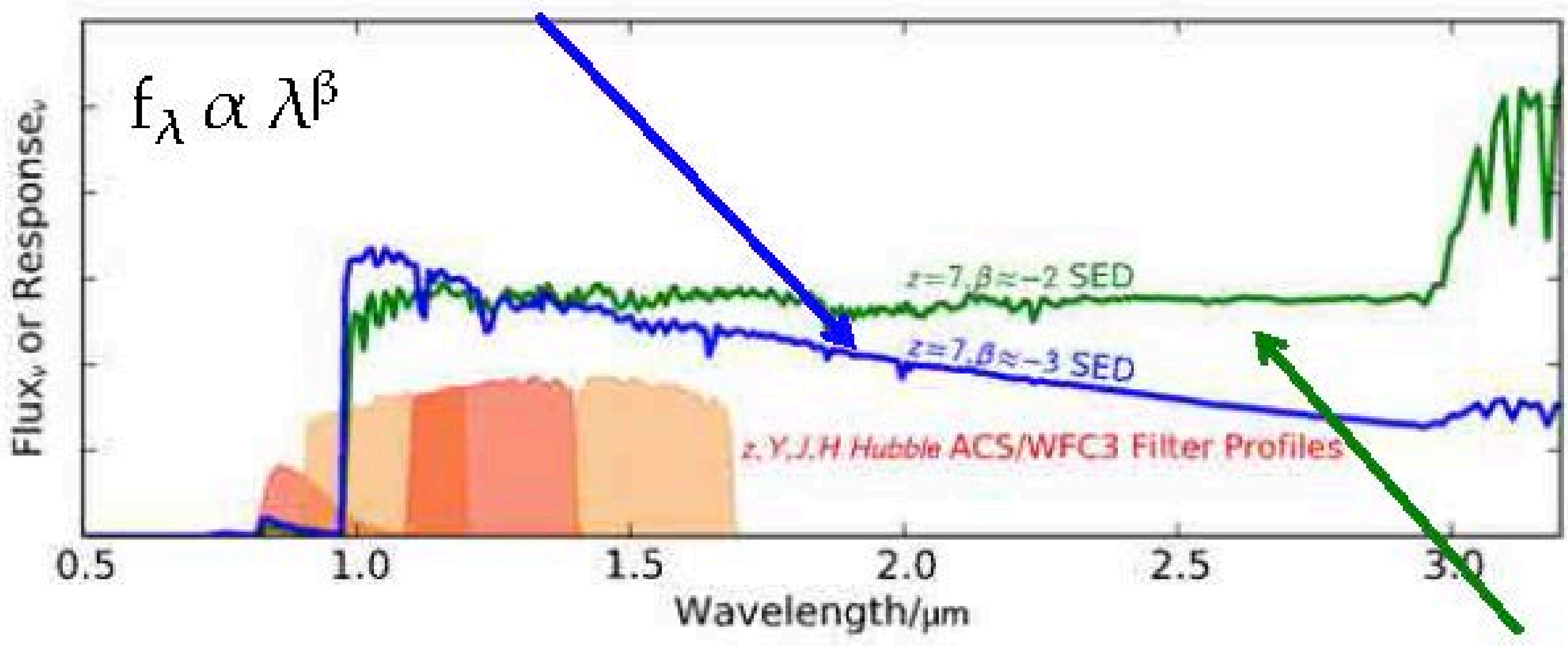
- UDF12 enables us to reach lower luminosity galaxies at z~7 and 8
- At z~7 N=47 (20 new); at z~8 N=27 (9 new)
- Confirm steep faint end slopes indicating dominant contribution from feeble galaxies, at least to M_{UV}~-17
- Two independent selection techniques are in excellent agreement

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}

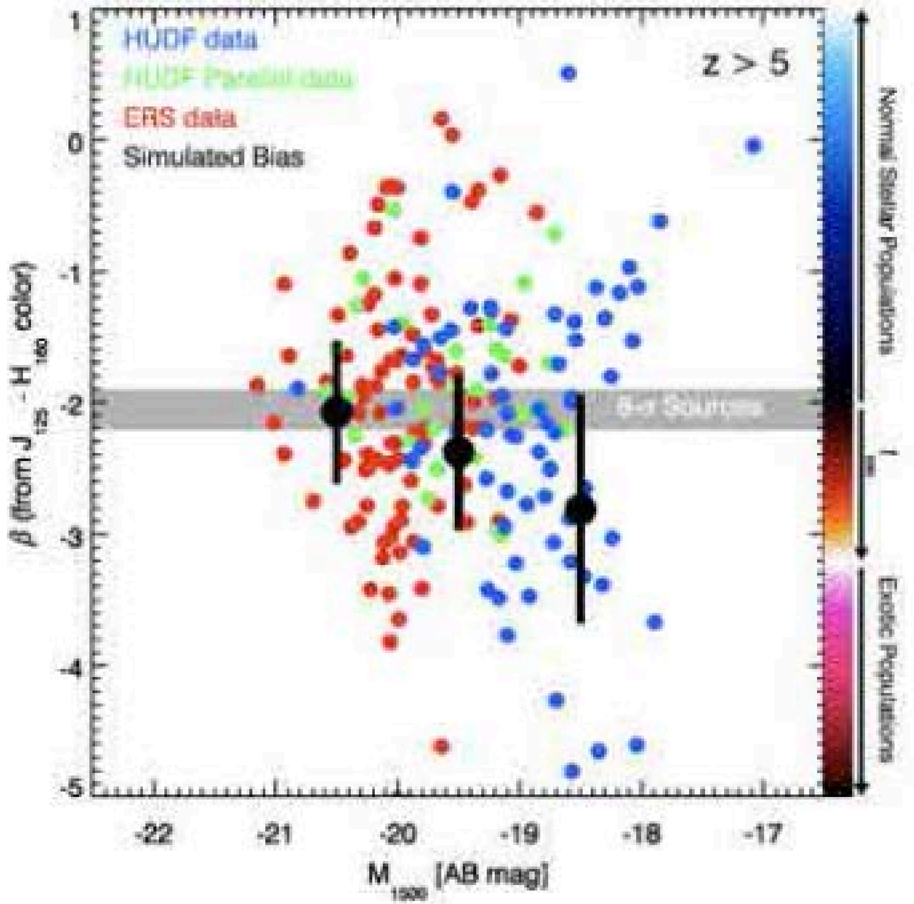
Disentangling which of these stellar population types are being observed involves measuring the UV spectral slope β

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)

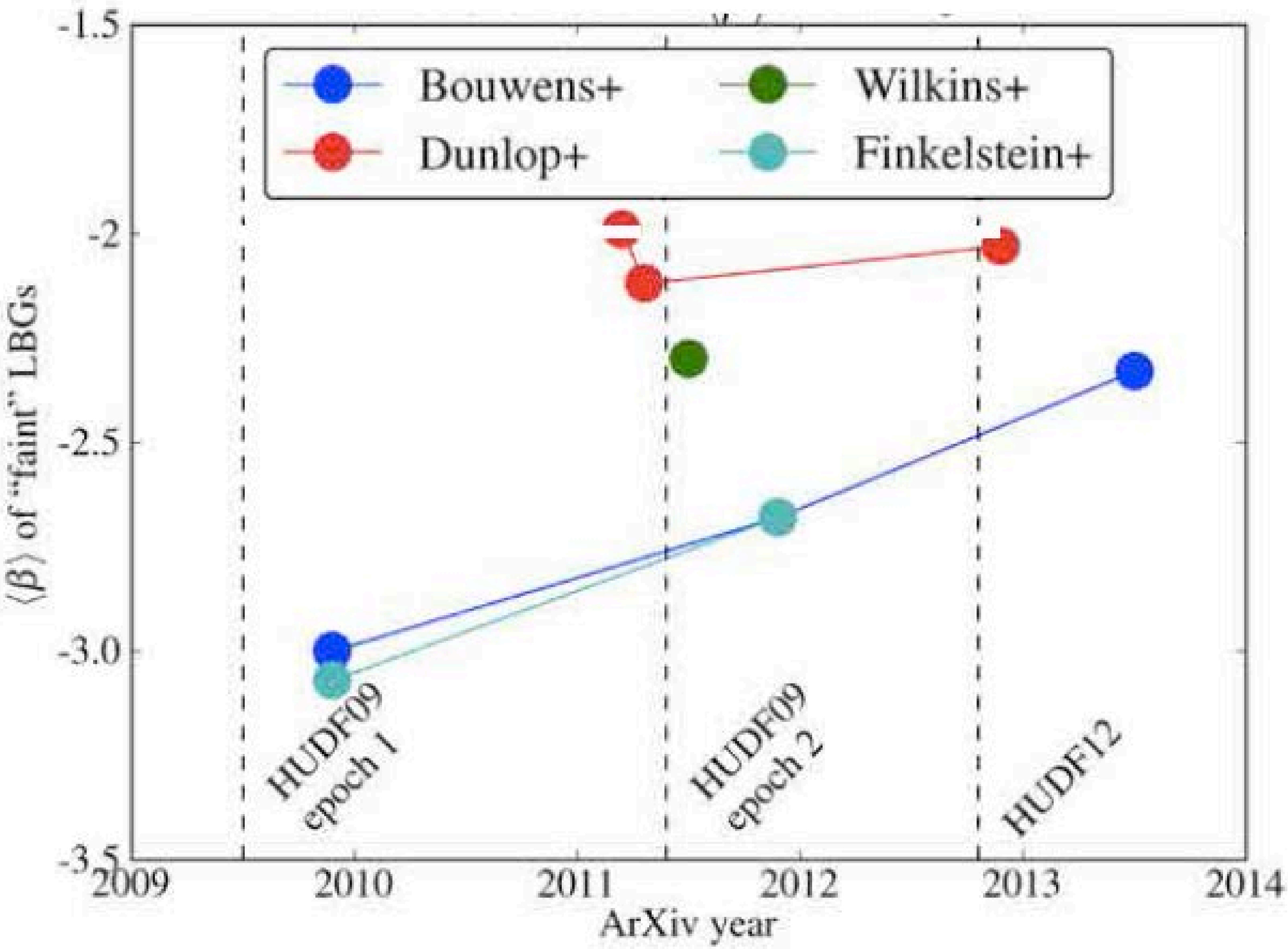
- Boosting in J biases β to bluer, more extreme values
- Boosting in H affects photo-z solution, placing object at z~2
- Simulations can reproduce trends for a fixed input β

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



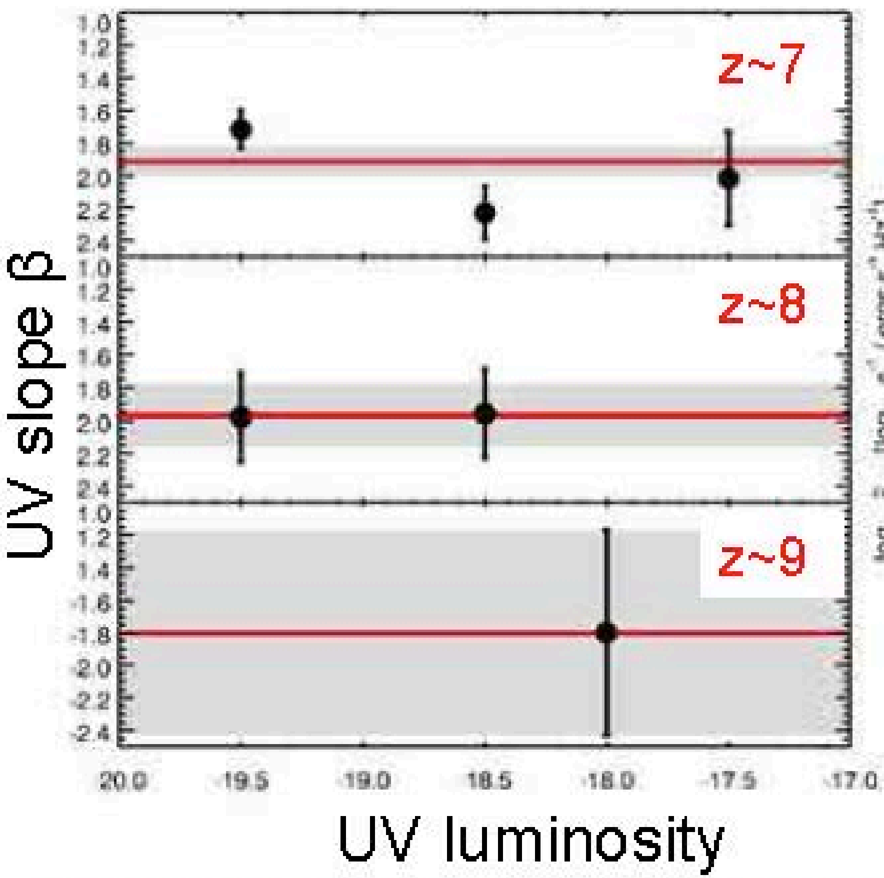
Dunlop et al (2012) MNRAS 420, 901

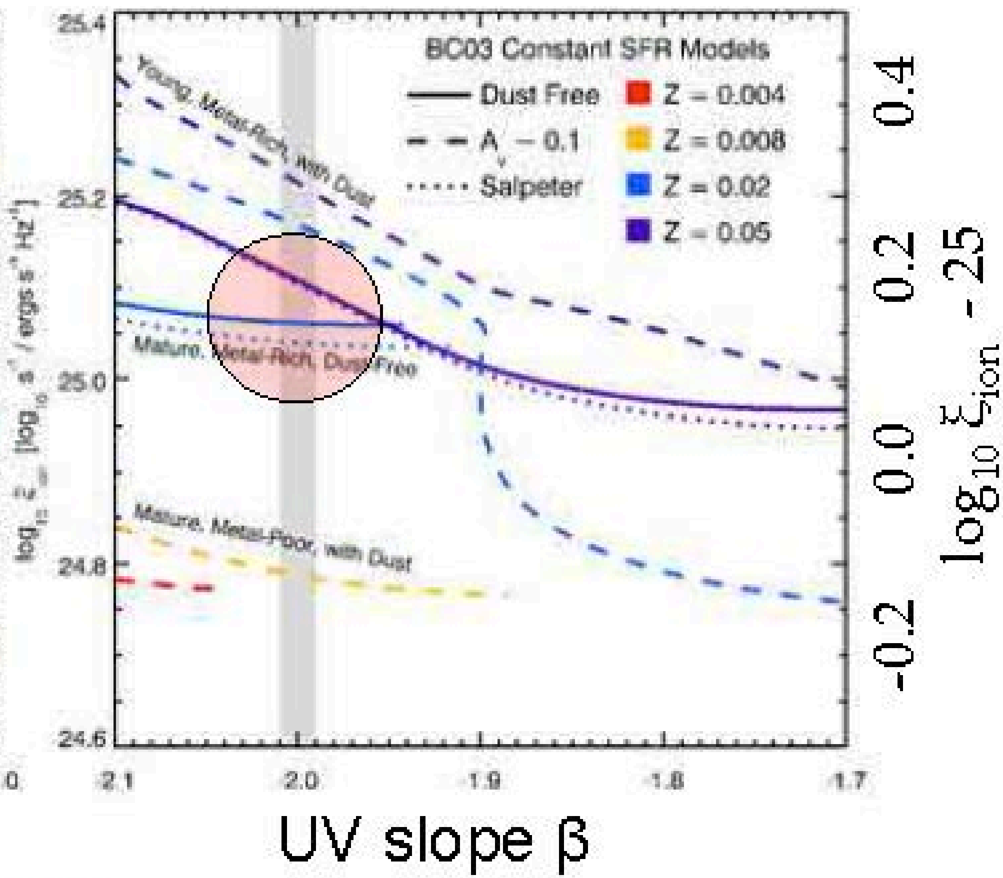
Gradual Reconcilation of β (2010-2014)?



Constraining Ionizing to UV Photon Ratio ξ_{ion}

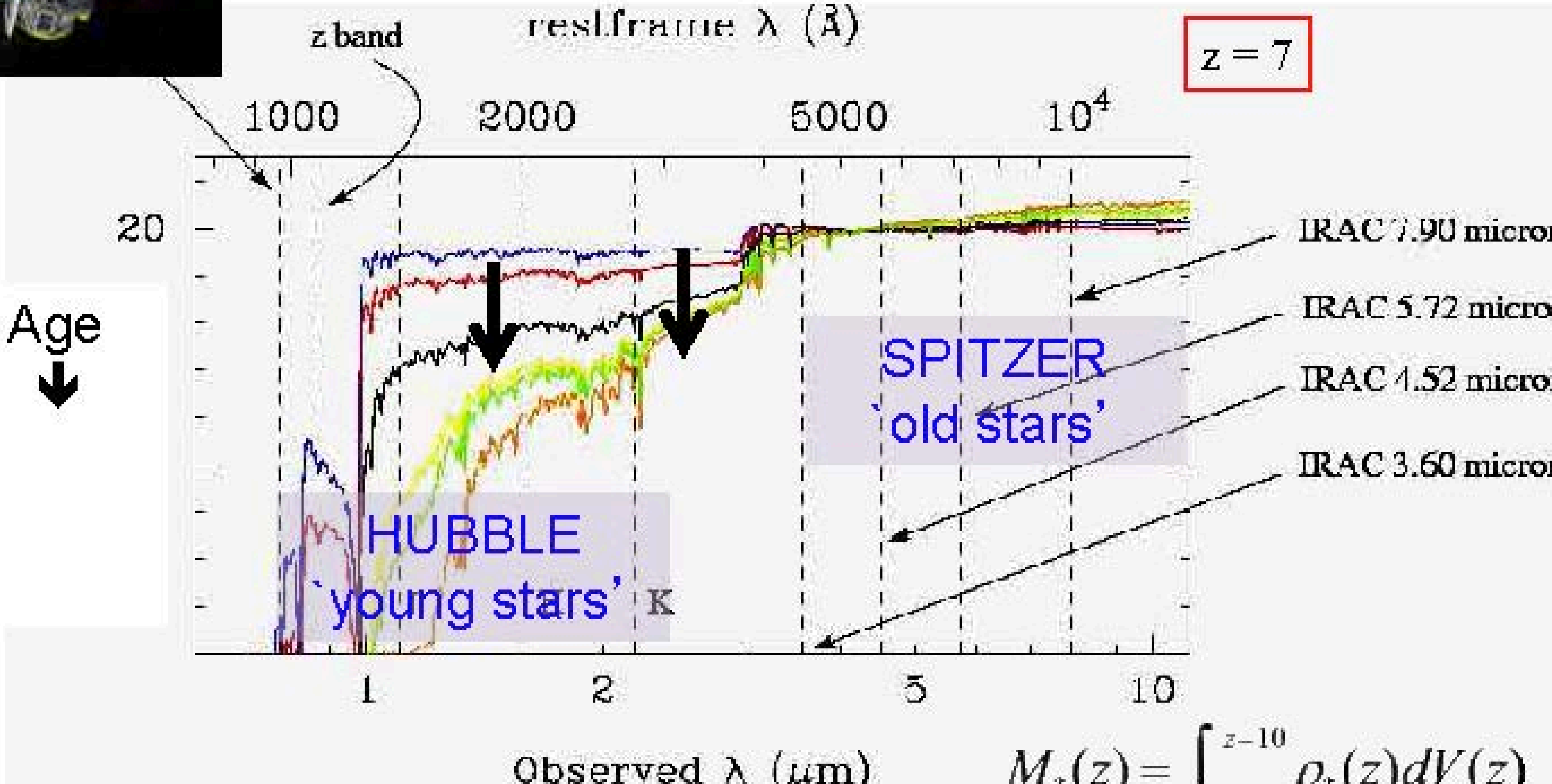
Contrary to earlier claims, z~7-8 galaxies have **normal UV colors** at all probed luminosities consistent with **mature > 100Myr stellar populations** (supporting SF beyond z~10) and narrow range in ionizing supply factor ξ_{ion}





Dunlop et al MNRAS 432, 3520 (2013)

Key Role of Spitzer: Masses and Ages

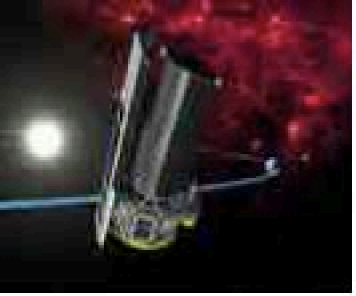


$$M_*(z) = \int_{z-5}^{z-10} \rho_*(z) dV(z)$$

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>

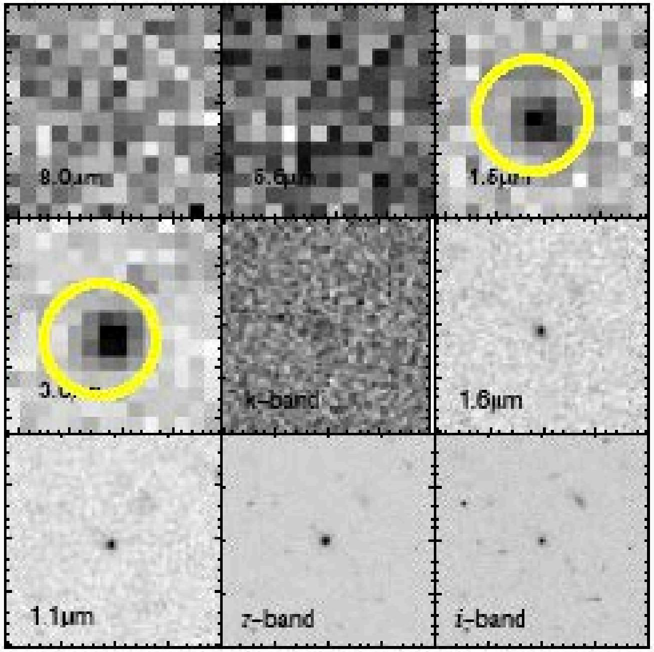
Eyles+ 2005, Stark+ 2007, 2009, Labbé+ 2010, 2012, Gonzalez+2010, 2011

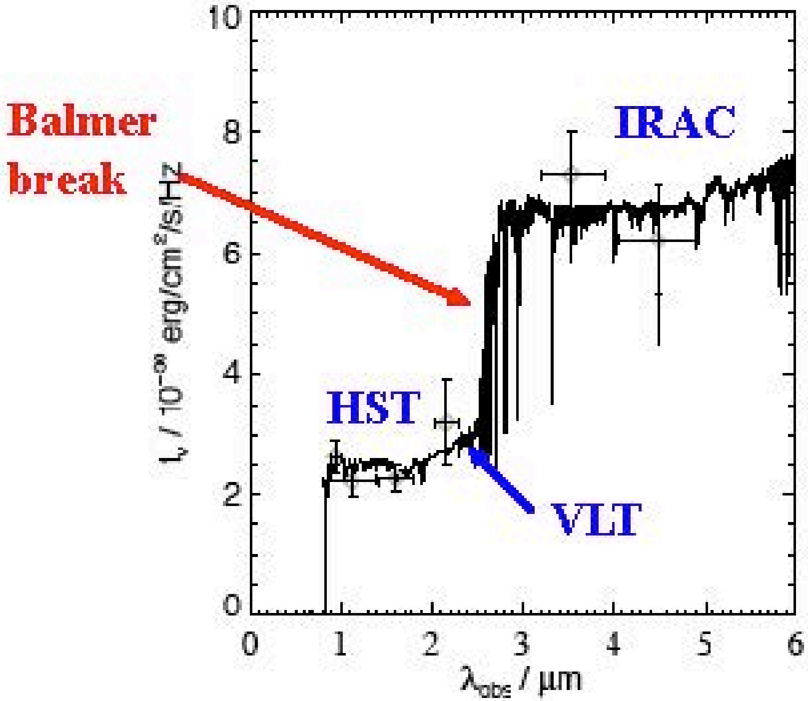


Early Example

A 85cm cooled telescope can see very distant objects & provide crucial data on **stellar masses and ages**

SMB03-1: z_{spec}=5.83   stellar mass = 3.4 10^{10} $M_\odot$ age > 100 Myr





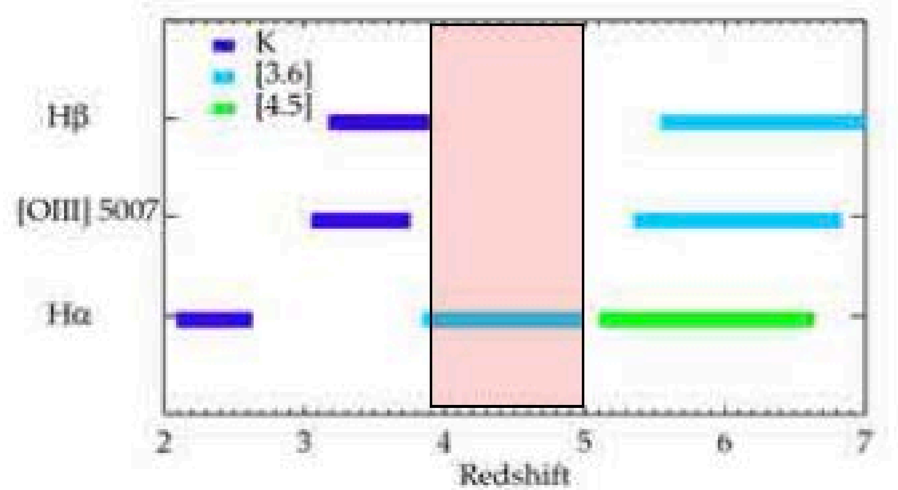
Eyles et al (2005): to produce M~3 10^{10} $M_\odot$ since z~10 required 5-30 $M_\odot$ yr^{-1} comparable to the ongoing SFR (6-20 $M_\odot$ yr^{-1}) so acts as probe of earlier activity

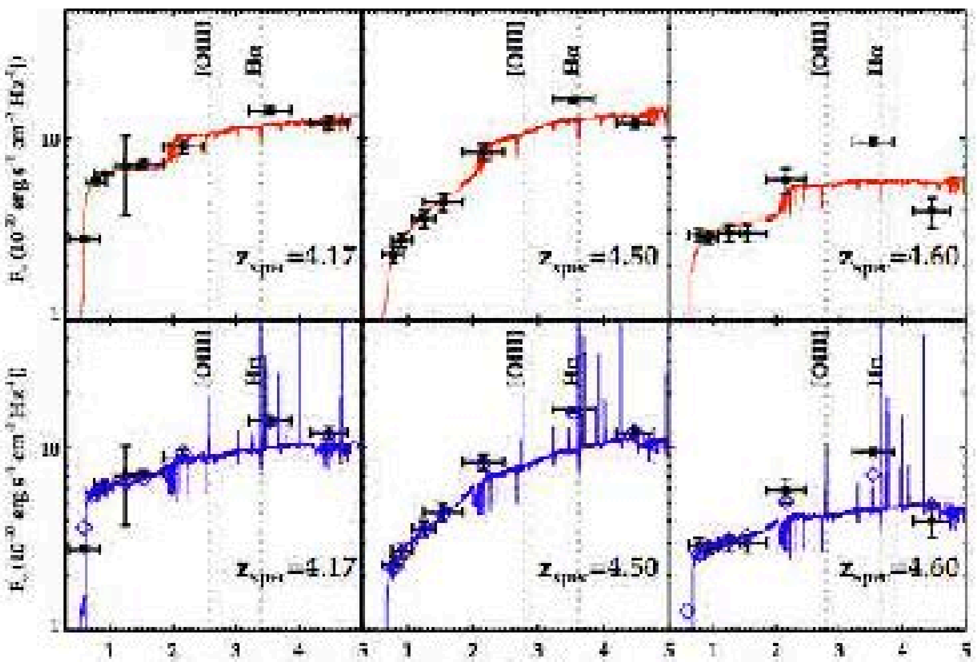
One Wrinkle…Nebular Emission

- 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

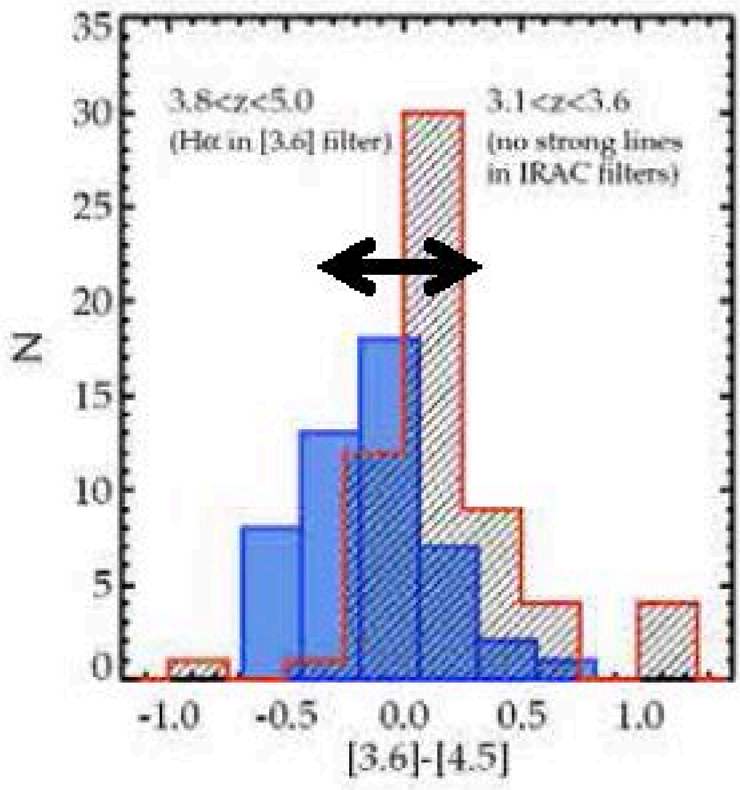
- Examining N=45 galaxies with spectroscopic 3.8<z<5.0 for IRAC excess c.f. stellar only model fits reveals serious contamination

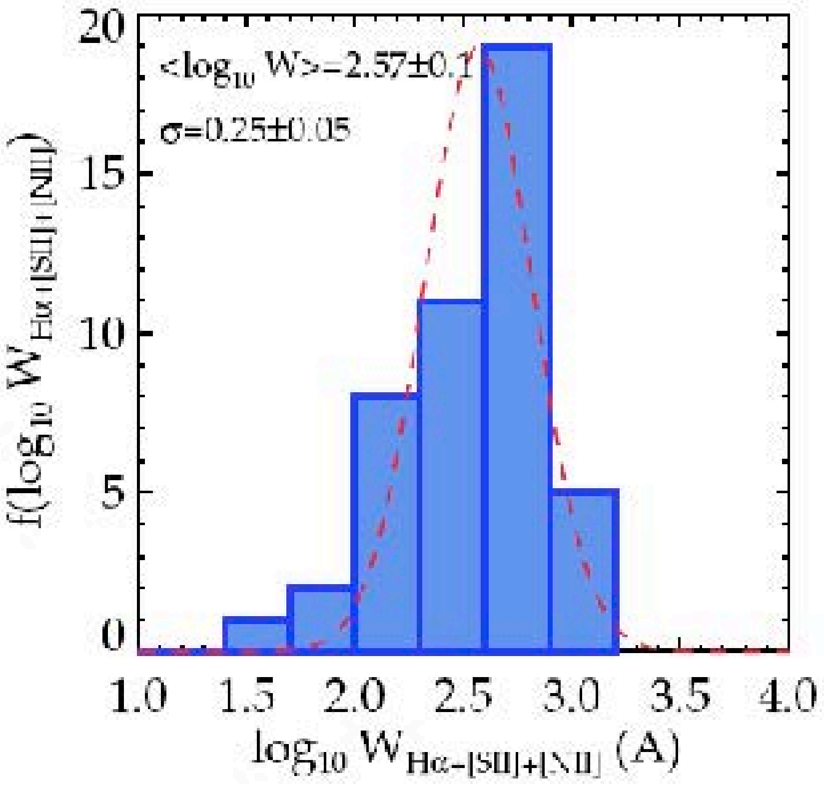




Stark et al (2012) (also Schaerer+09,10, Ono+10, Shim+11, Atek+11)

Nebular Emission in Keck Spectroscopic Sample



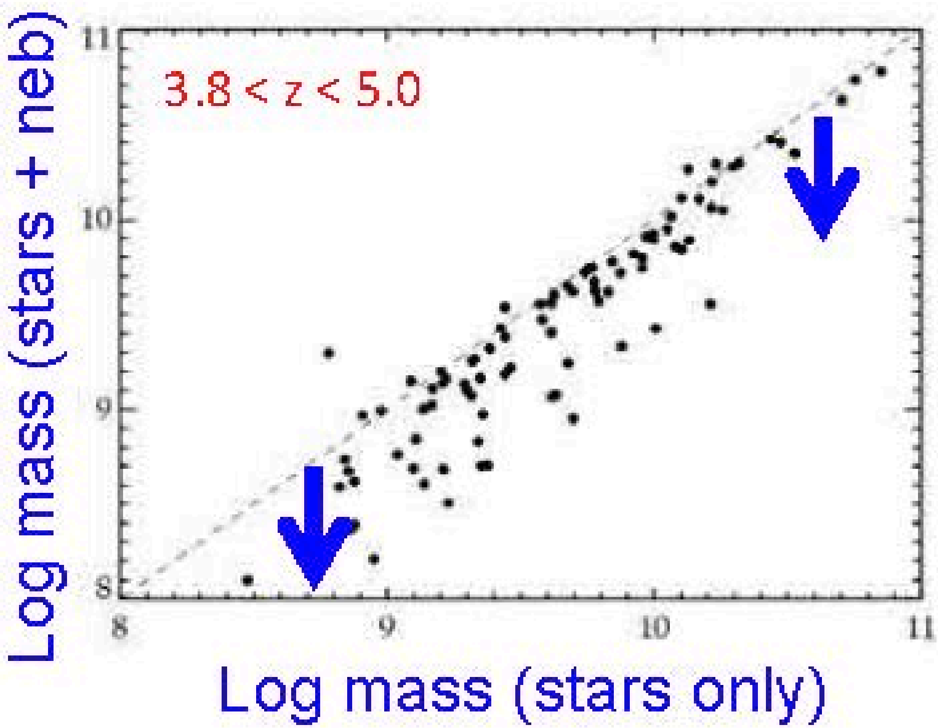


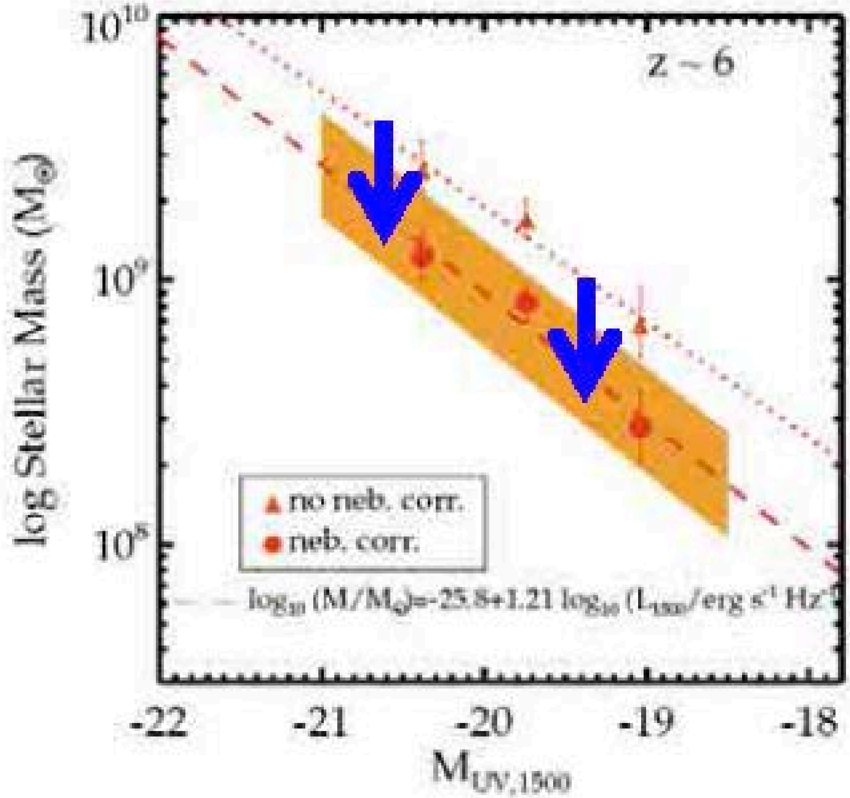
- When Hα is redshifted into the 3.6μm band, the effect is clearly seen in the IRAC colors c.f. control sample with 3.1<z<3.6
- 86% of 3.8<z<5.0 sample shows 3.6μm excess
- Median EW=270 Å (30% of light in 3.6μm)

Stark et al (2012) see also Shim et al (2011)

Effect of Nebular Emission on Stellar Masses

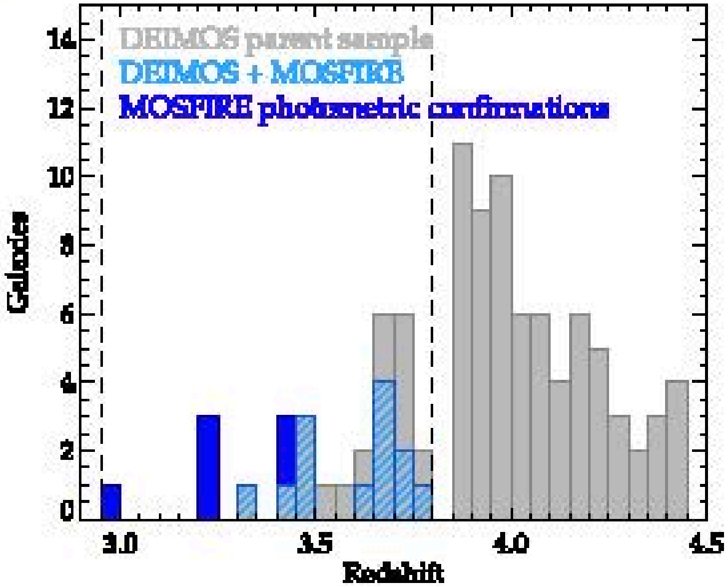
- Modest reduction (0.3 dex) of stellar masses for 3.8<z<5.0
- But nebular contamination will be greater at z~6-7 (Hβ, [O III], Hα)
- Can estimate contribution from EW(Hα) distribution at 3.8<z<5.0
- Reduces stellar masses by ~2-4x depending on evolution of EW(z)

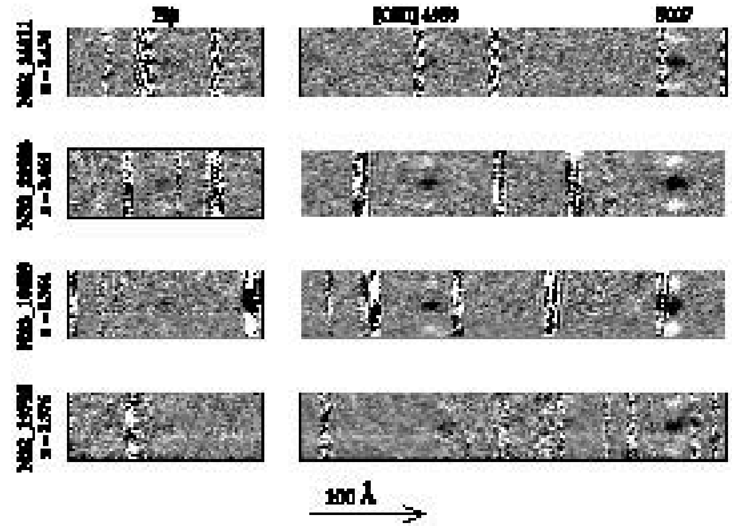




Stark et al (2013) see also Curtis-Lake et al (2012)

Spectroscopic Verification of Nebular Emission





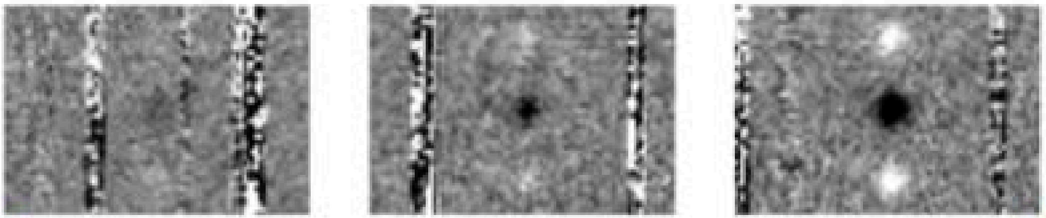
- We cannot spectroscopically confirm inferred EW(Hα) 3.8<z<5.0 before launch of JWST
- But we can test strength of [O III] using a Keck sample of 20 3.0<z<3.8 galaxies using MOSFIRE
- Assuming [O III]/Hα ~2.2 (for $0.2Z_{\odot}$), agreement with Stark et al is reasonably good (Δz~1 but MOSFIRE probes 1^{m} fainter in M_{UV})

Inferred from Hα study of Stark et al 2013

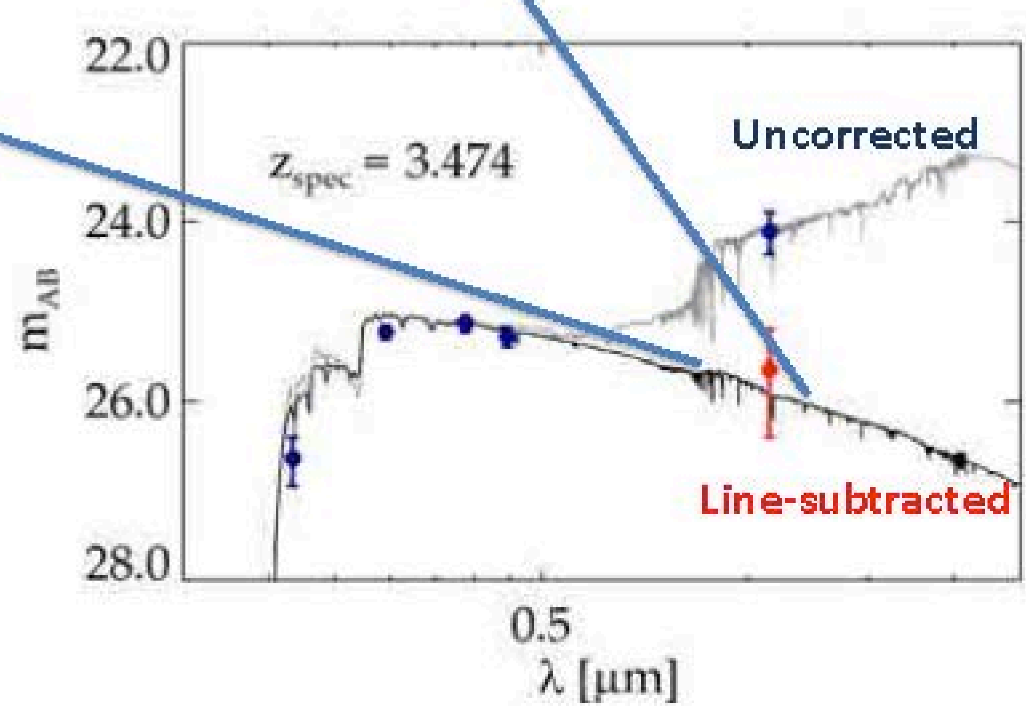
Schenker et al Ap J 777, 67 (2013)

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



Did Galaxies Reionize the Universe?

UDF2012 Data
Theoretical models
External observations

UV Luminosity function

+

UV slope

Population synthesis models

+

Escape fraction

Largely unconstrained (see later)

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

WMAP optical depth to surface of last scattering

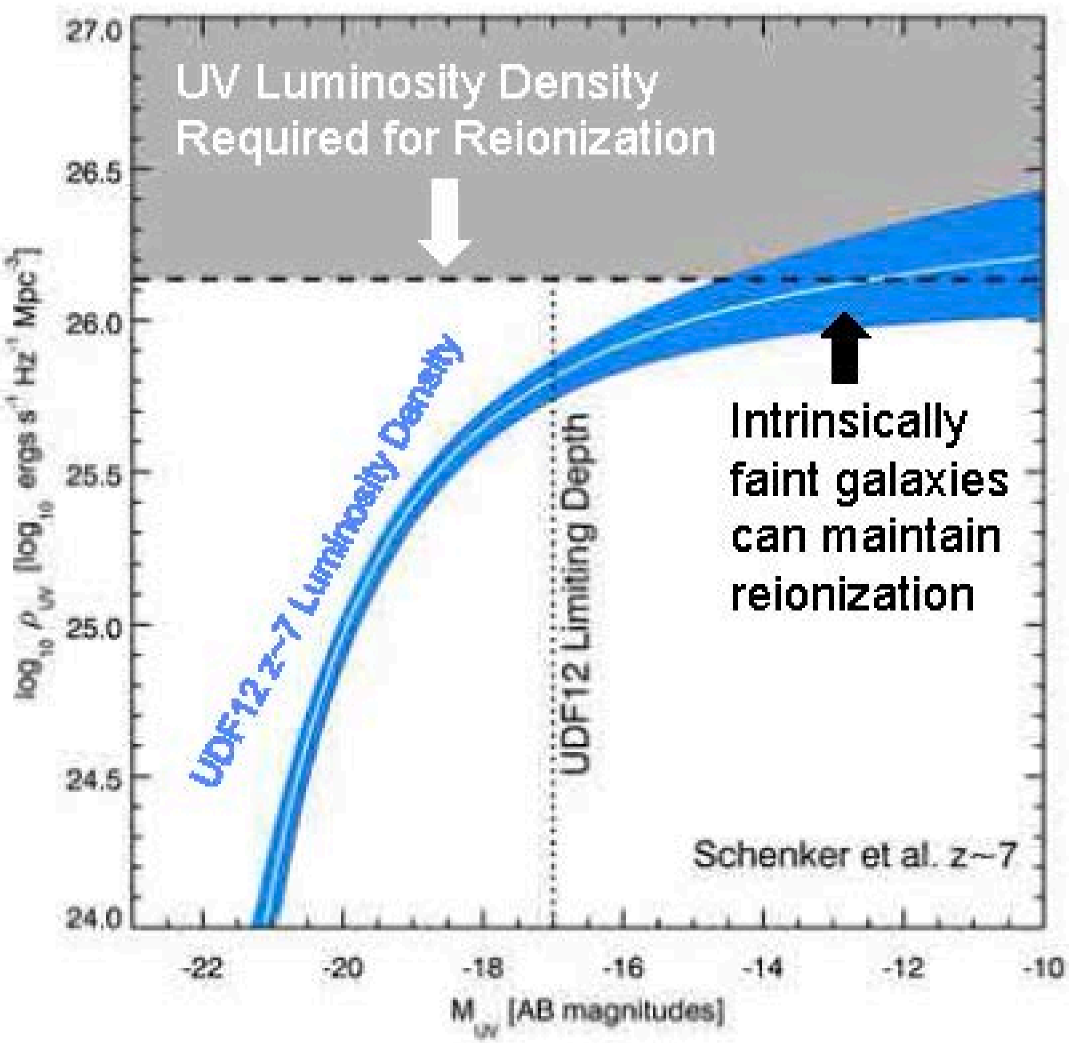
+

Stellar mass density

Evolution of volume-filling fraction of HII, $Q_{\rm HII}$

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

UDF12 Reionization Constraints: A Simple Illustration



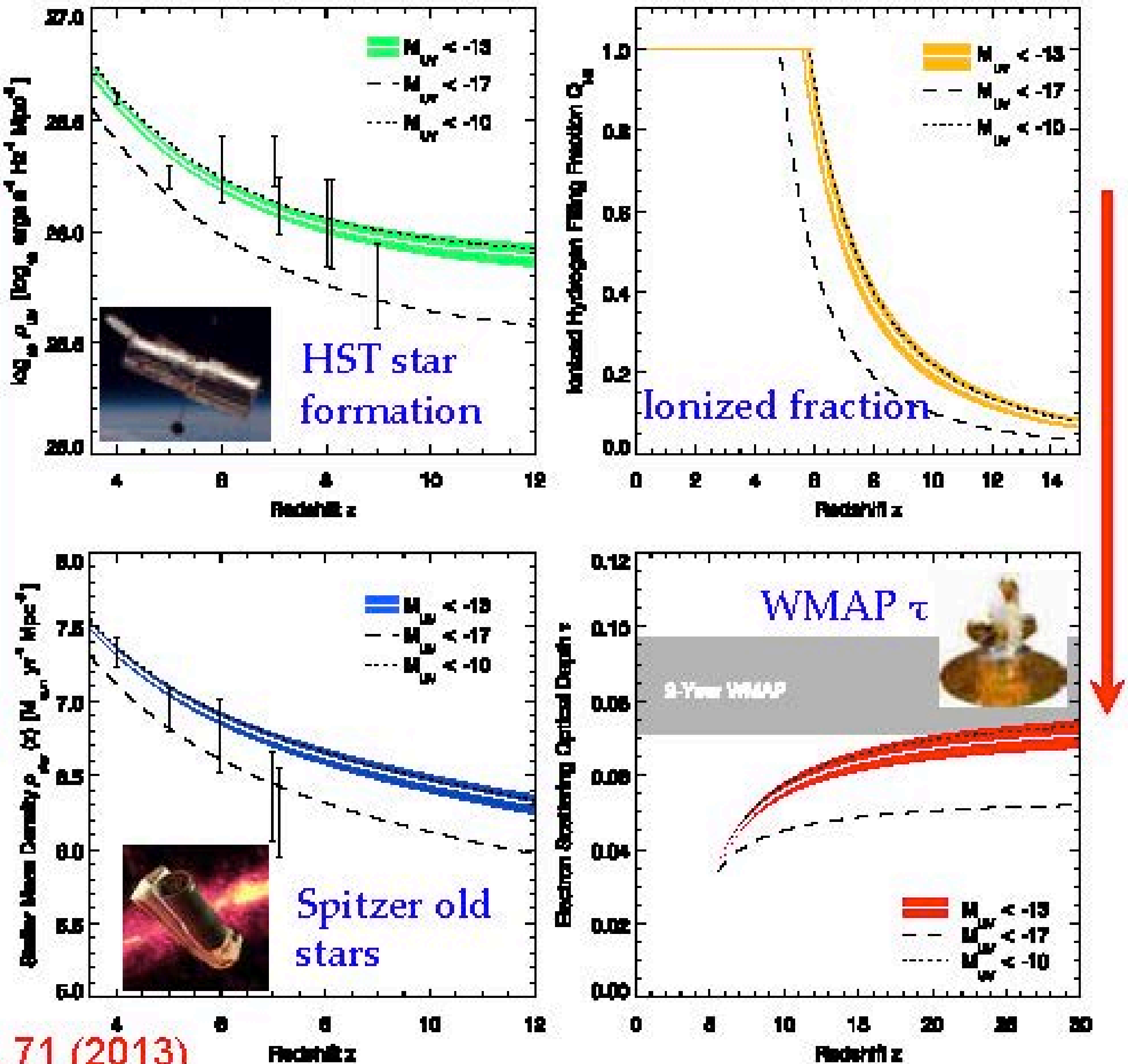
- The constrained faint end slope of the luminosity function allows us to conclude that **fainter, yet unseen galaxies (extrapolating to M_{UV}~-13)** would be sufficient to maintain reionization

Robertson et al Ap J 768, 71 (2013)

The Full Monty: Galaxies Ended the Dark Ages

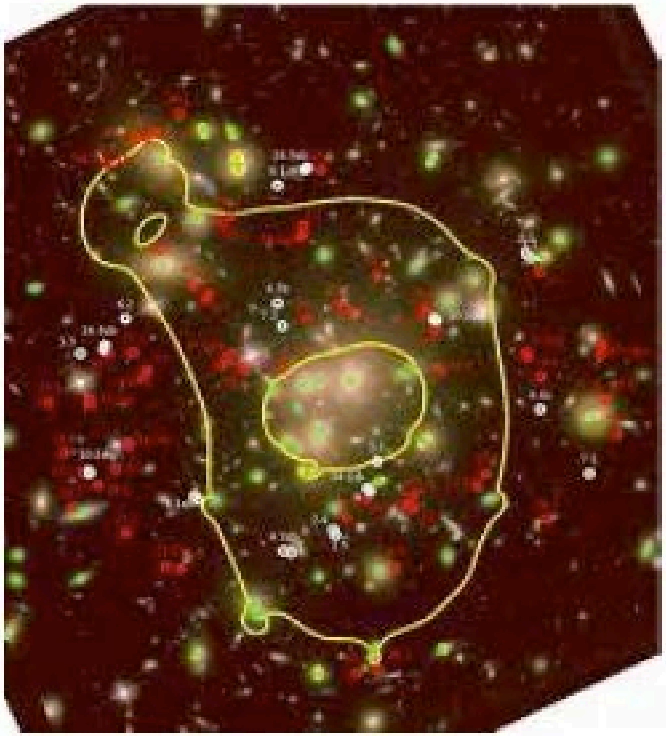
The UDF2012 star formation rate density (N(z) and faint end LF slope) integrates to match the stellar mass density and given ξ_{ion} (β) matches the CMB optical depth τ provided

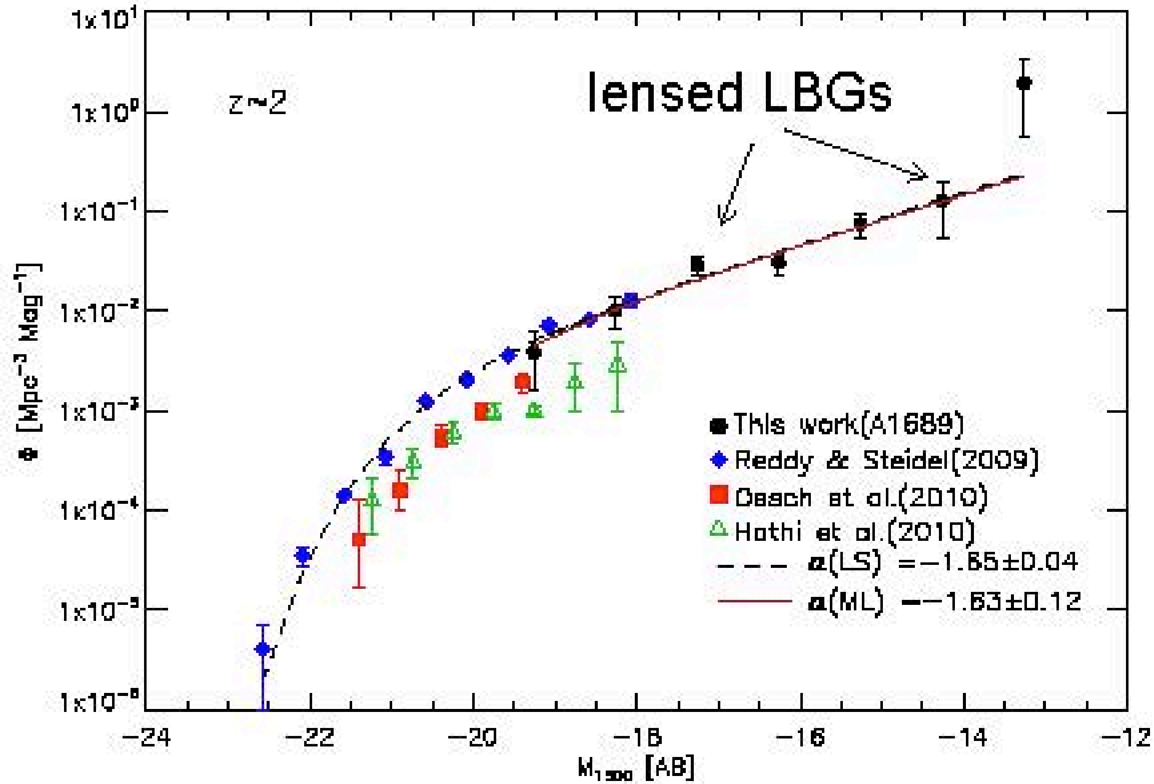
- LF extrapolated to M_{UV}~-13
- f_{esc}~0.2
- SFR extends beyond z~10



Robertson et al Ap J 768, 71 (2013)

Faint End of the LBG LF at z~2



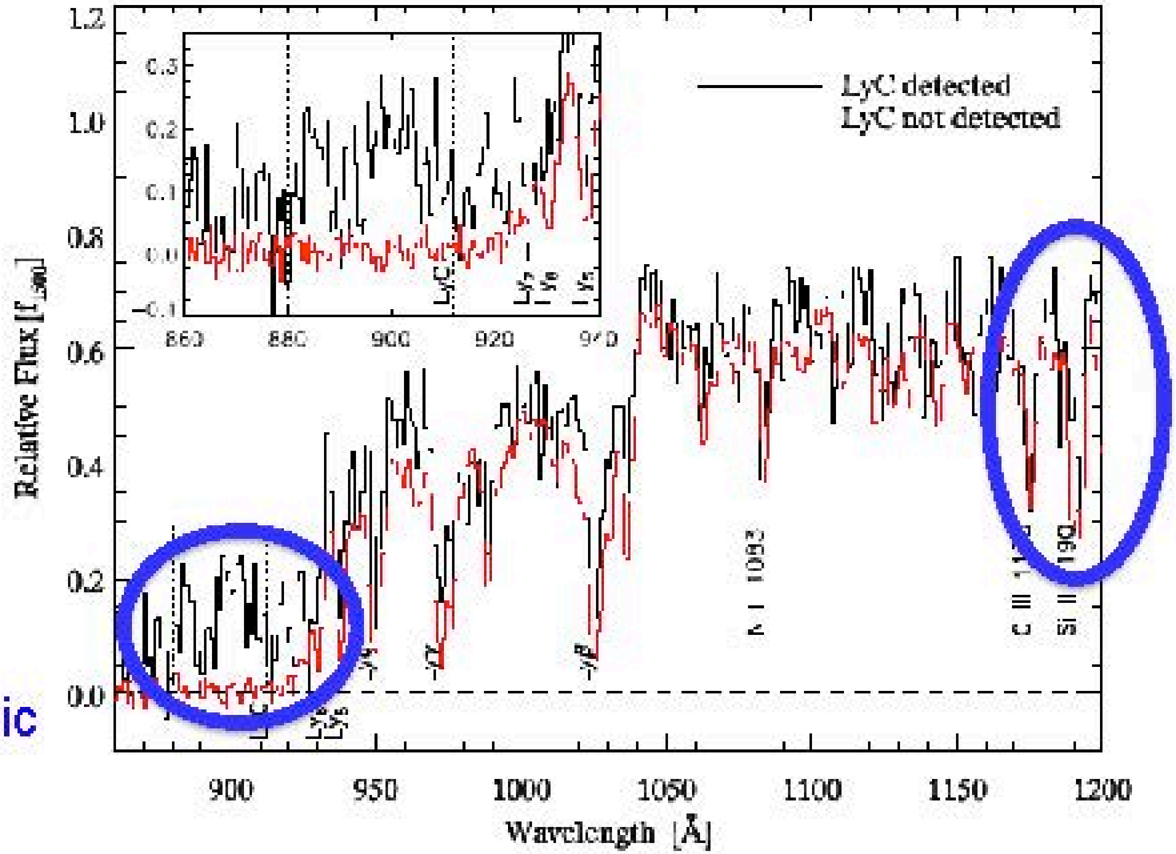


72 strongly-lensed z~2 LBGs locating using WFC3/UVIS in Abell 1689 offer first glimpse at the faint end of the LF down to M_{UV}~-13 providing a proof of concept for possible existence of galaxies to this faintness at z~7-8

Alavi et al arXiv 1305.2413

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

Escaping ionizing radiation at z=3 (Bogosavljevic thesis)

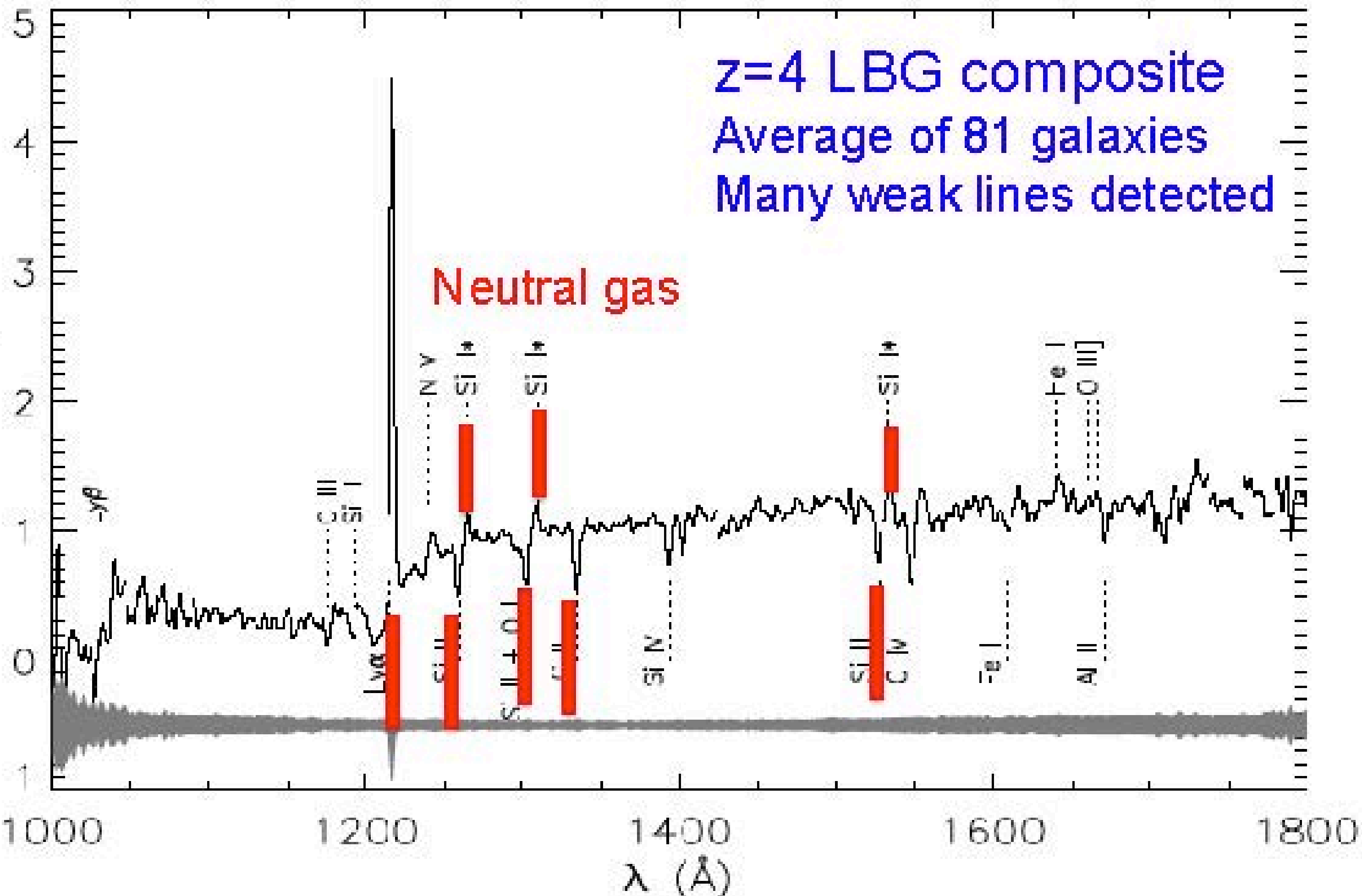


Weaker low-ionization absorption in sources with escaping ionizing flux

- f_{esc} estimated via spectroscopic or UV imaging below Lyman limit (e.g. Nestor et al Ap J 765, 47)
- 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}

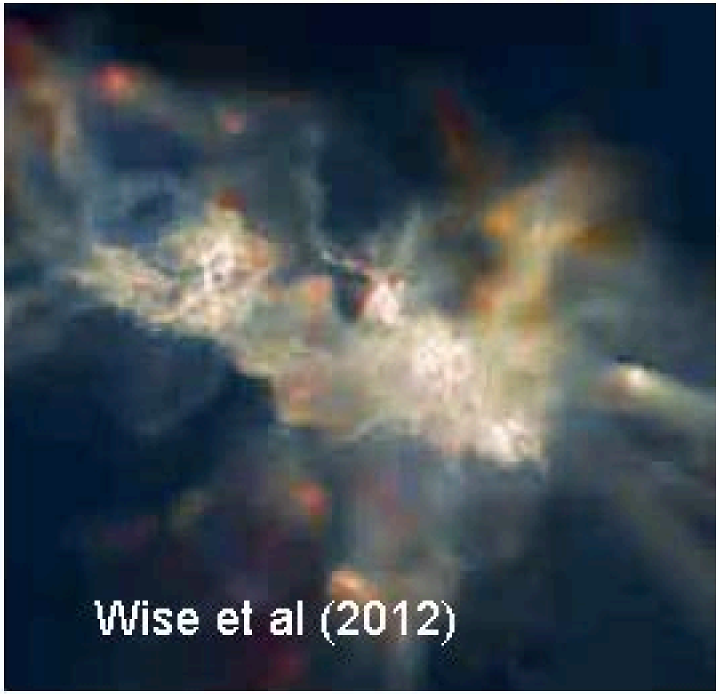
By stacking Keck spectra we can detect weak low ionization absorption from neutral outflowing gas

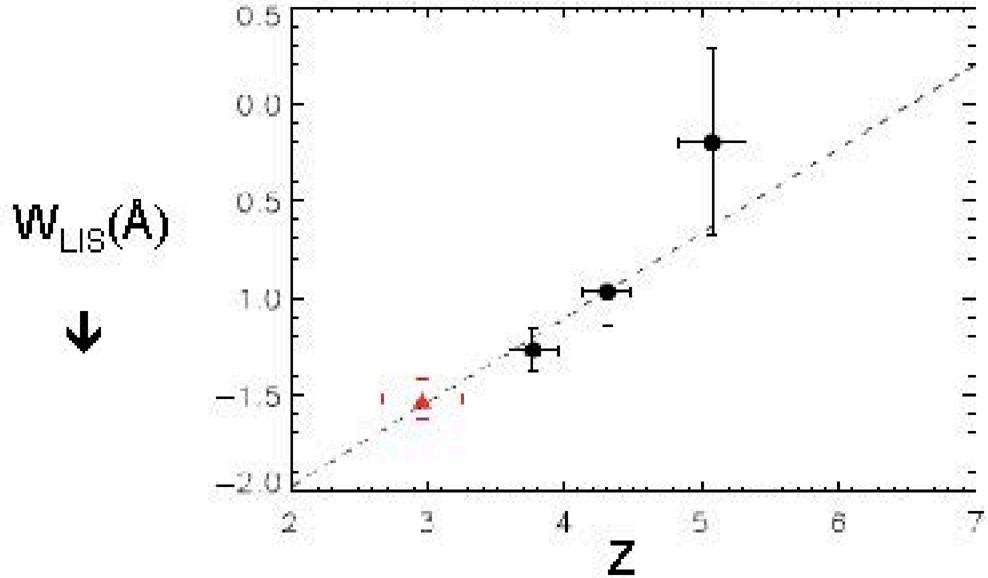


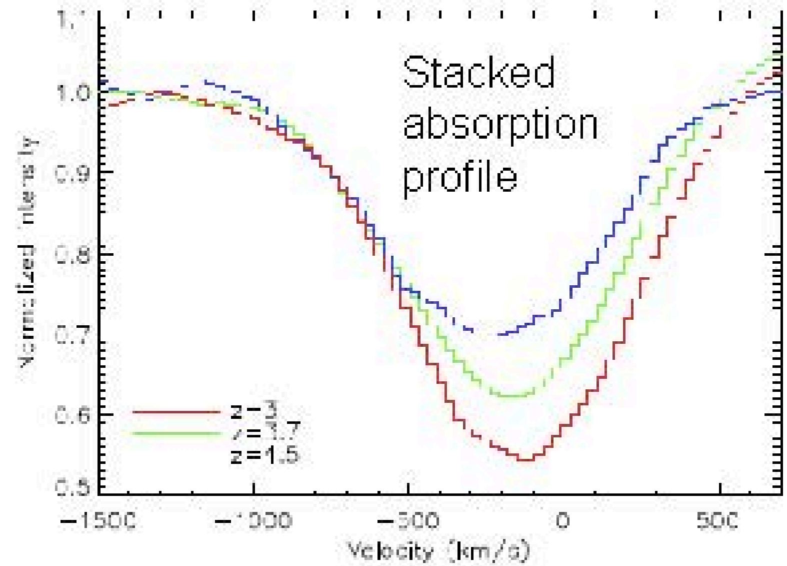
EW of low ionization lines estimates covering fraction of neutral gas $f_c = (1 - f_{esc})$

Jones et al (2012) Ap J 751, 51

Reduced Covering Fraction of HI at high z?





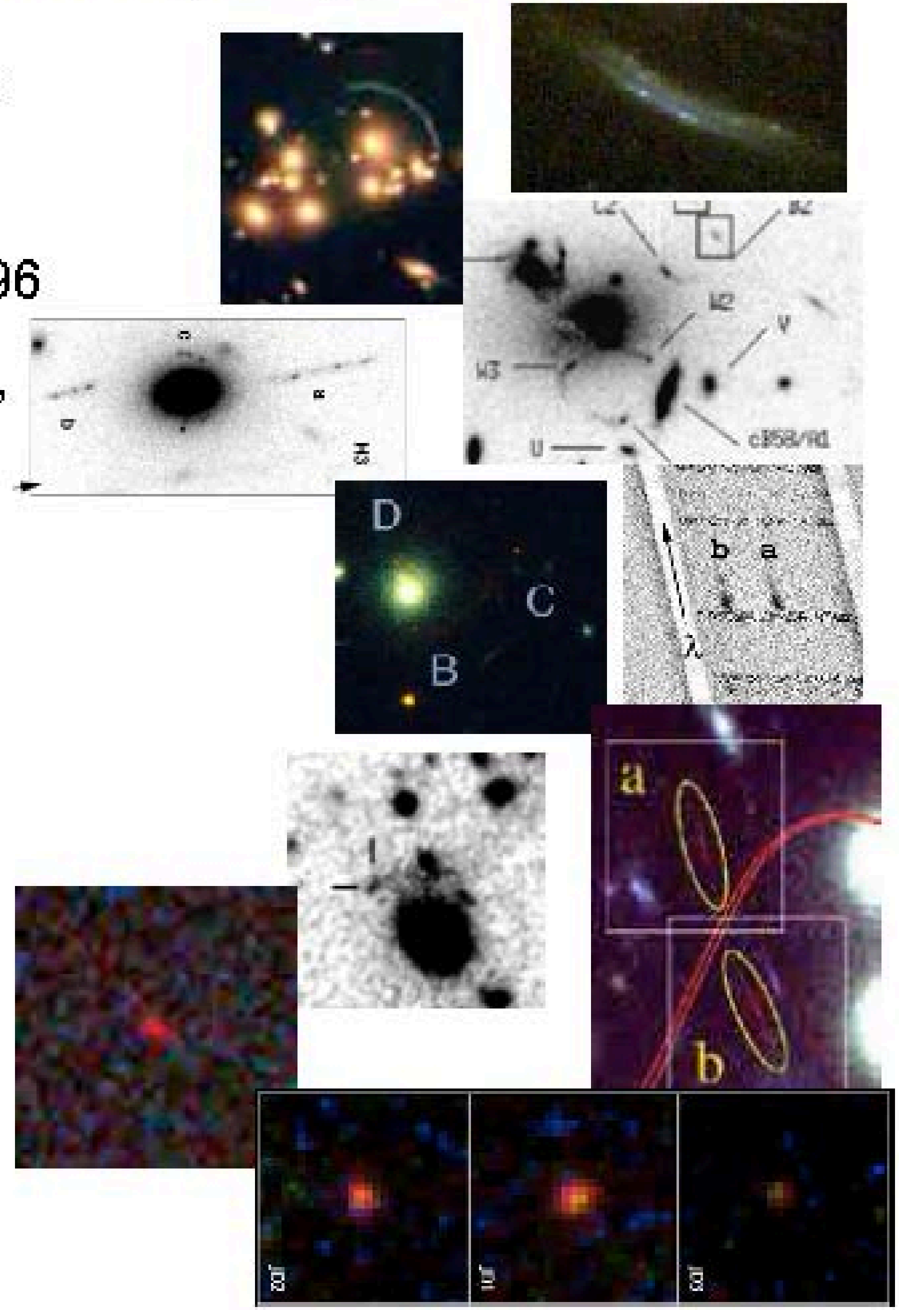


Jones et al (2012) Ap J 751, 51

- 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)

What About Gravitational Lensing? High z Records

- Abell 370 (z=0.724); Soucail et al 1988
- Cl2244-02 (z=2.237); Mellier et al 1991
- A2218 #384 (z=2.515); Ebbels et al 1996
- MS1512 cB58 (z=2.72); *Yee et al 1996*, Seitz et al 1998
- A2390 (z=4.05); Frye et al 1998
- MS1358+62 (z=4.92); Franx et al 1997
- A2218 (z=5.7); Ellis et al 2001
- A370 (z=6.56); Hu et al 2002
- *A2218 (z~6.8); Kneib et al 2004*
- A1689 (z~7.35); Bradley et al 2008
- *1149+2223 (z~9.6); Zheng et al 2012*
- *J0647+7015 (z~10.7); Coe et al 2013*



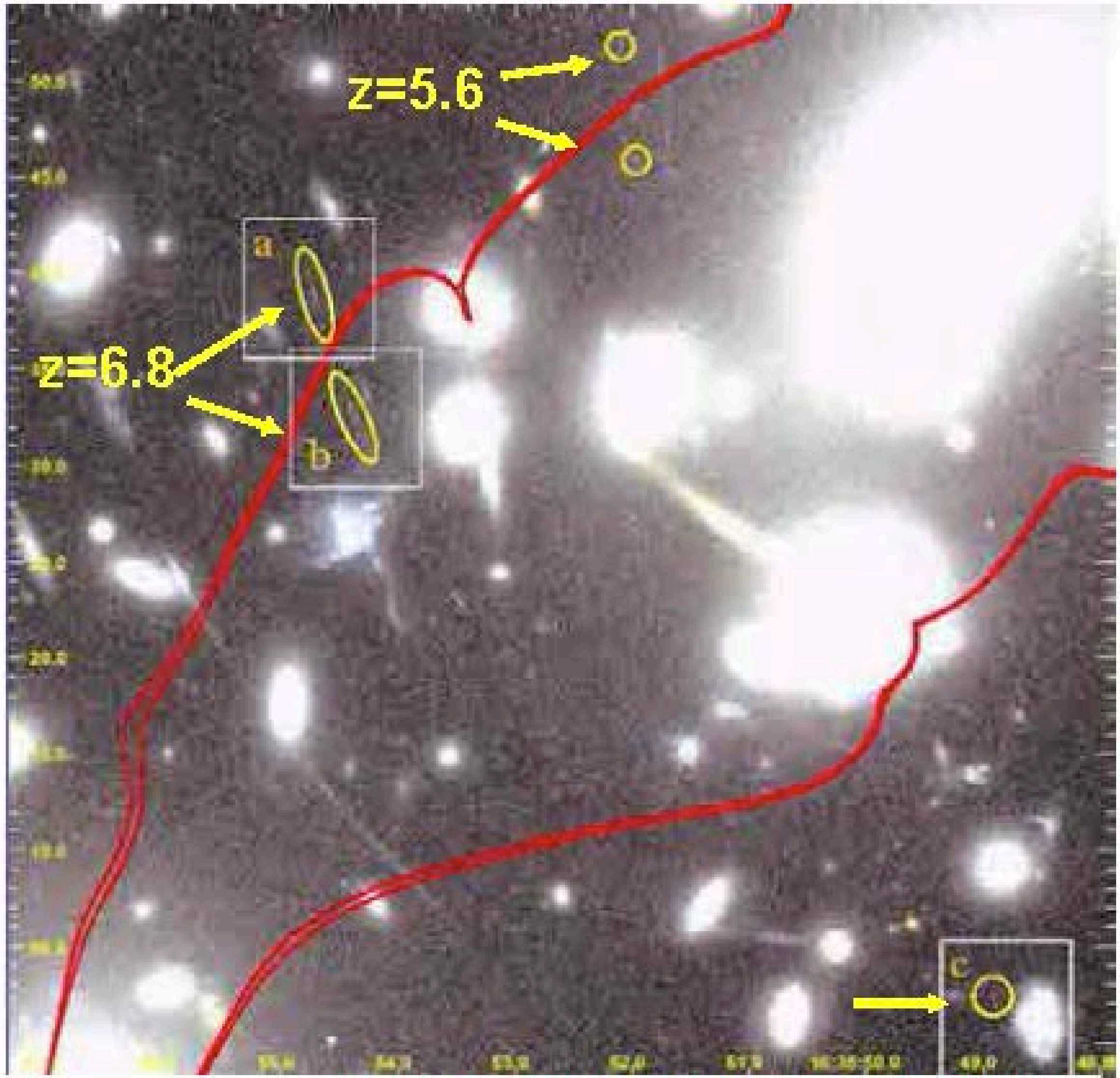
What Use is Lensing? Two Regimes - I

Multiply-imaged sources close to the `**critical line**' of maximum magnification offer a number of unique advantages:

- Geometrically constrained high magnifications (e.g. $\times 33$ and $\times 25$ here)
- Consequent good photometry and spectroscopic possibilities
- Resolved morphologies

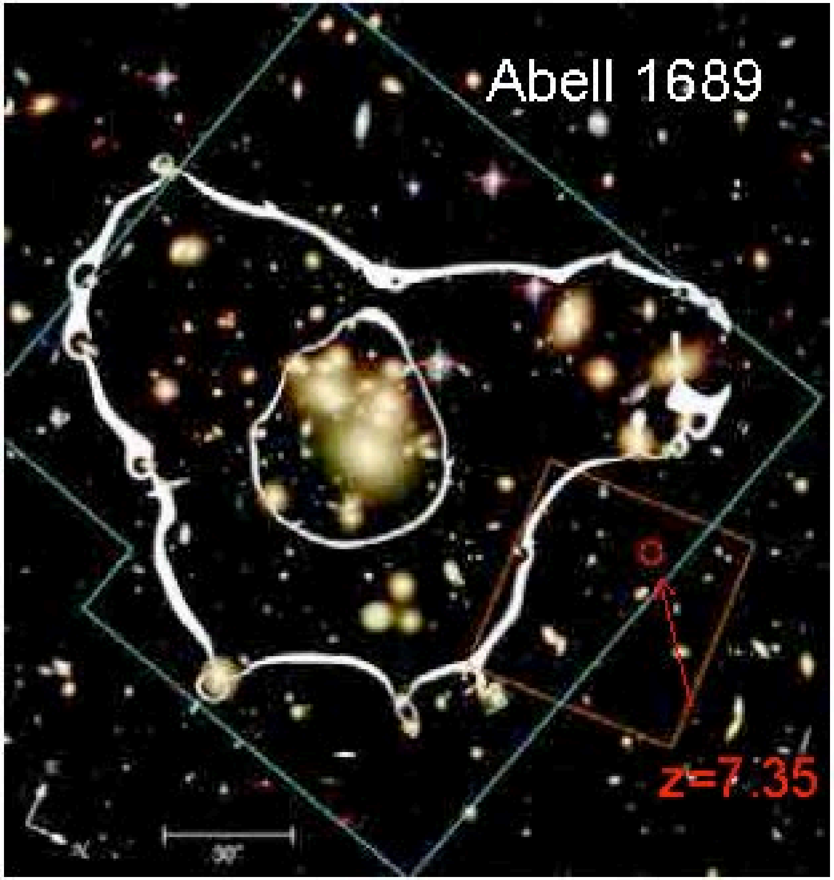
But they are RARE because the relevant survey volume is tiny!

Abell 2218

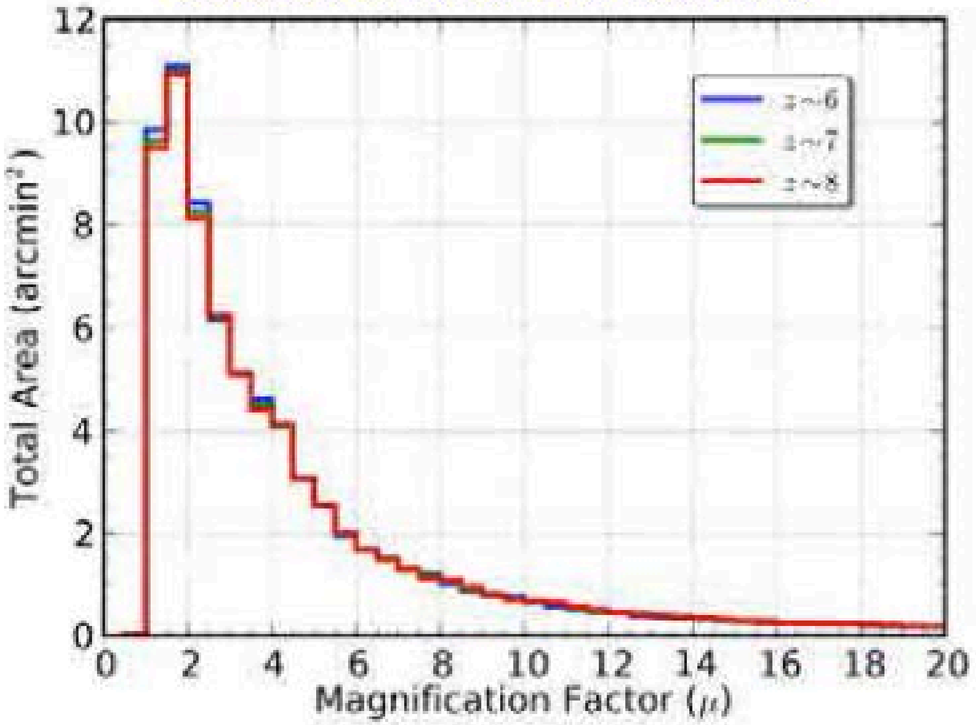


Ellis et al (2001), Kneib et al (2005)

What Use is Lensing? Two Regimes - II



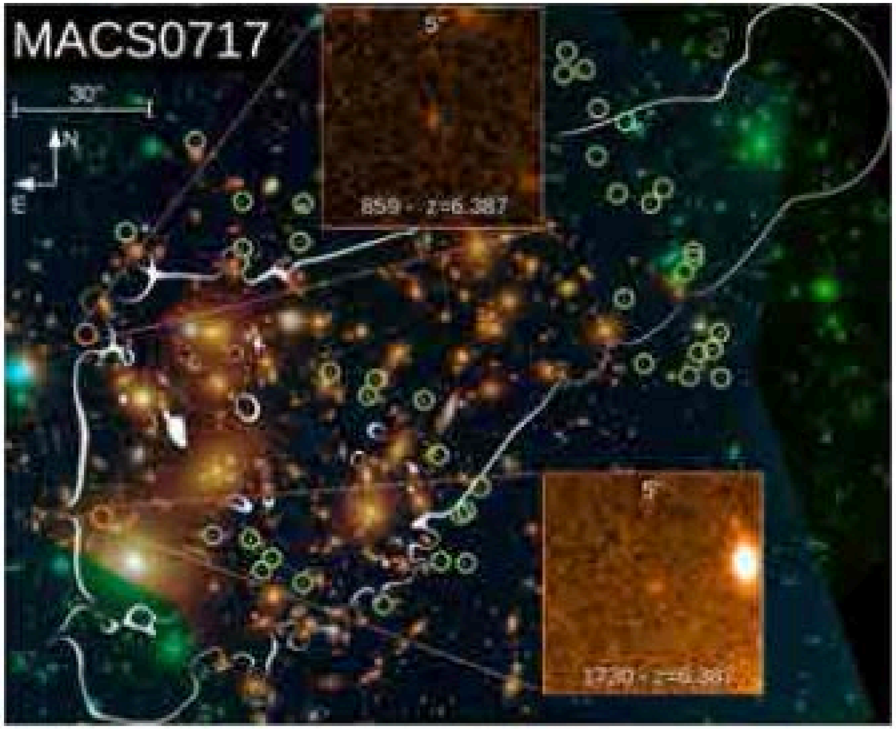
Area vs magnification for ~250 lensed sources in 18 CLASH clusters



More commonly a singly-imaged source is located in the vicinity of a cluster but far from the critical line. It offers no geometric information. The magnification is less (× ~9 here) and more uncertain. Such sources are much more common, but can they be used for representative surveying (other than a modest boosting in flux)?

Bradley et al arXiv 1308.1692

Improved Spectroscopic Prospects?



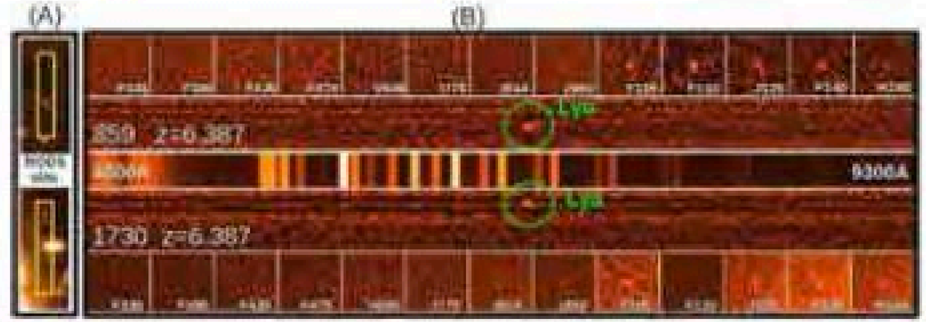
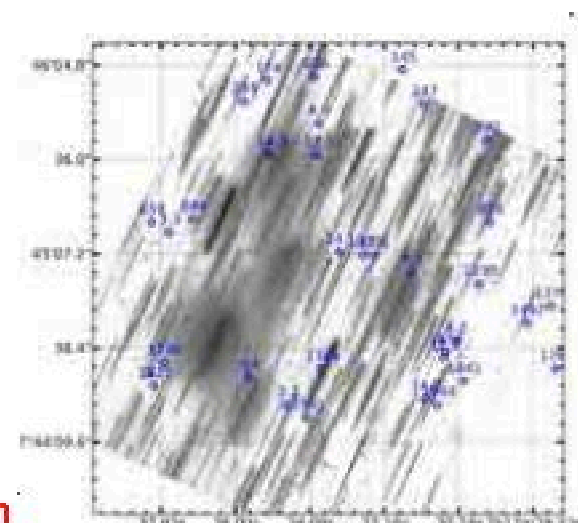


Table 1. Observed and physical parameters for 859 and 1730.

Quantity	macs0717_0859	macs0717_1730
R.A. (J2000)	07:17:38.18	+ 37:45:16.9
Decl. (J2000)	07:17:37.85	+ 37:44:33.7
Redshift	6.387(±0.002)	6.387(±0.003)
Y105(observed)	26.42(±0.11)	26.34(±0.16)
H160(observed)	26.88(±0.15)	26.78(±0.18)
H160(unlensed)	28.53+ 2.5 log$_{10}$(μ$_5$)	28.53+ 2.5 log$_{10}$(μ$_5$)



Spectroscopic follow up has begun of lensed z>6 sources found in the CLASH and early Frontier Field clusters.

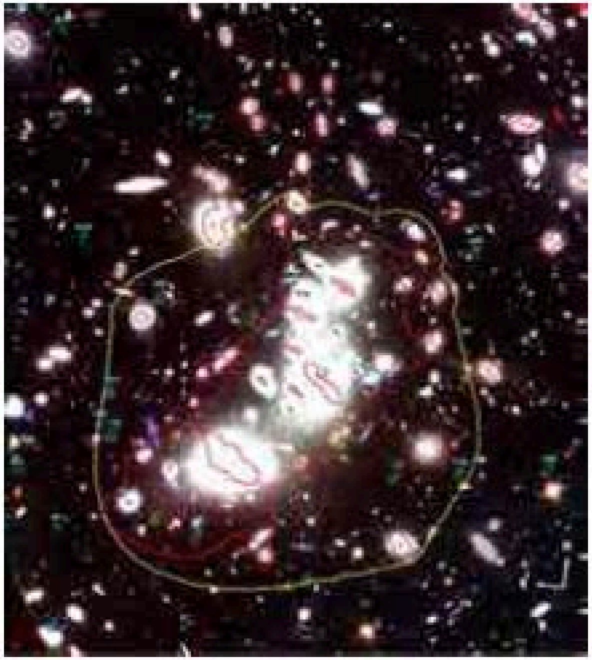
To date, no convincing z > 7 verifications...

Vanzella et al arXiv: 1312.6299 (LBT spectroscopy)
Schmidt et al arXiv: 1401.0532 (GLASS, WFC3 grism

Statistical Analyses of High z Galaxies?

TABLE 2
Photometric and color measurements for the z ~ 6−7 dropouts

Target	R.A. (J2000)	Dec (J2000)	$I_{814} - Y_{105}$	$Y_{105} - J_{125}$	J_{125}	Magnification[a]	Photo-z
93	3.593807	−30.415442	> 1.34	−0.03 ± 0.02	26.49 ± 0.01	3.42 ± 0.19	6.8
171	3.570648	−30.414602	1.89 ± 0.31	0.08 ± 0.02	26.59 ± 0.02	1.57 ± 0.03	6.3
561	3.603225	−30.410330	> 0.8	−0.10 ± 0.03	27.37 ± 0.03	3.75 ± 0.19	7.5
632	3.593541	−30.409719	1.46 ± 0.16	−0.06 ± 0.02	26.71 ± 0.02	6.28 ± 0.56	5.9
041	3.608378	−30.407279	2.10 ± 0.31	−0.01 ± 0.03	26.96 ± 0.02	2.27 ± 0.07	6.4
1127	3.580447	−30.405039	1.89 ± 0.36	0.09 ± 0.03	27.07 ± 0.02	4.71 ± 0.36	6.4
1180	3.600068	30.404382	1.47 ± 0.26	0.23 ± 0.04	27.69 ± 0.03	4.81 ± 0.40	6.2
1192	3.578128	30.404494	1.23 ± 0.10	0.08 ± 0.01	26.33 ± 0.01	2.92 ± 0.14	6.1
1205	3.570087	−30.403720	> 0.8	0.15 ± 0.02	26.85 ± 0.02	1.95 ± 0.05	7.0
1266	3.601099	−30.403956	2.09 ± 0.47	0.19 ± 0.03	26.99 ± 0.02	3.51 ± 0.22	6.5
1521	3.600541	−30.401804	1.12 ± 0.22	−0.03 ± 0.04	27.48 ± 0.03	3.04 ± 0.16	5.9
2276	3.608503	−30.390974	> 0.8	0.79 ± 0.07	26.47 ± 0.02	1.38 ± 0.02	7.4
2715	3.596100	−30.385832	> 0.8	0.74 ± 0.05	26.97 ± 0.02	2.06 ± 0.07	5.9
2770	3.606230	30.386646	1.32 ± 0.15	0.16 ± 0.02	26.51 ± 0.02	1.52 ± 0.03	5.5
3204	3.578655	−30.391364	2.58 ± 0.07	0.22 ± 0.00	24.18 ± 0.00	5.87 ± 0.55	6.5
3458	3.603540	30.393106	0.91 ± 0.10	0.03 ± 0.02	26.75 ± 0.02	1.77 ± 0.05	6.0
3761	3.597850	30.395970	> 0.77	0.38 ± 0.03	27.21 ± 0.03	2.79 ± 0.13	6.7
Target	R.A. (J2000)	Dec (J2000)	$Y_{105} - J_{125}$	$J_{125} - H_{140}$	H_{140}		
2070	3.604522	−30.380403	1.07 ± 0.03	0.30 ± 0.02	26.23 ± 0.01	1.47 ± 0.02	8.35

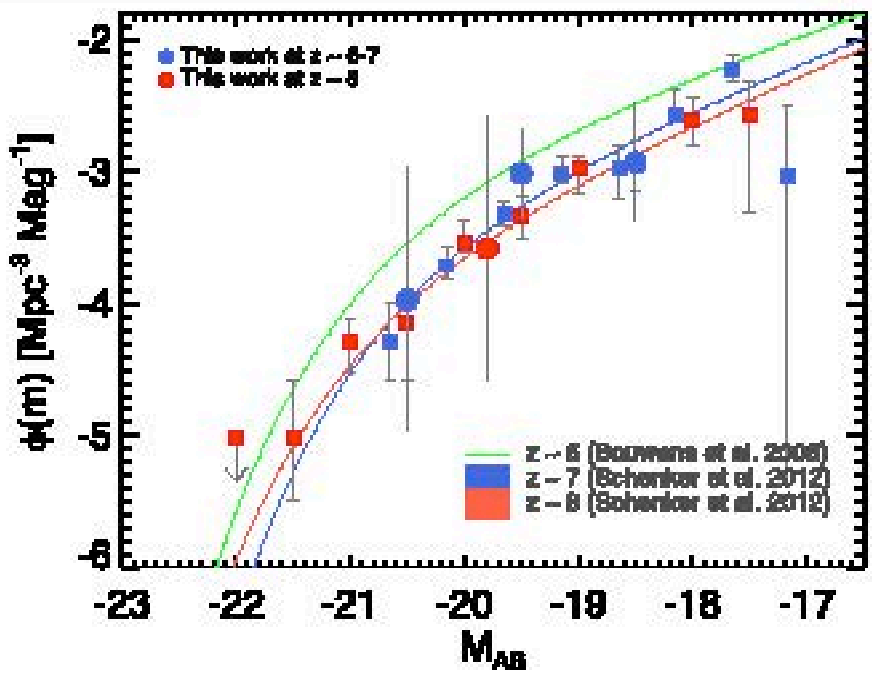


First results from the Frontier Fields disappointing

Only 1 z > 8 candidate in the first cluster

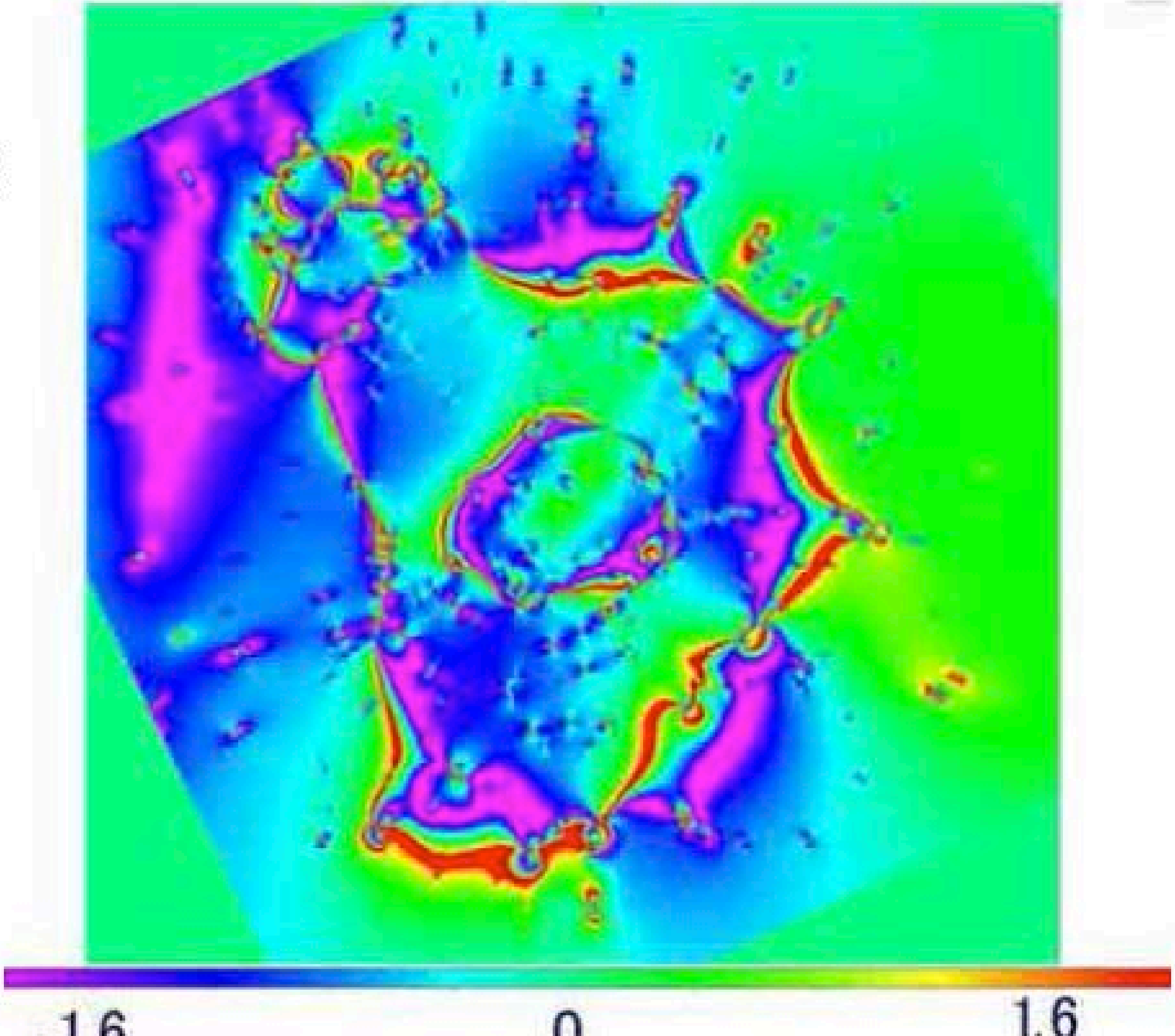
z~7 Luminosity Function consistent with UDF12 but no deeper

Atek et al arXiv: 1311.7670



Magnification Uncertainties Across Abell 1689

Tom
Broadhurst
vs
Johan
Richard

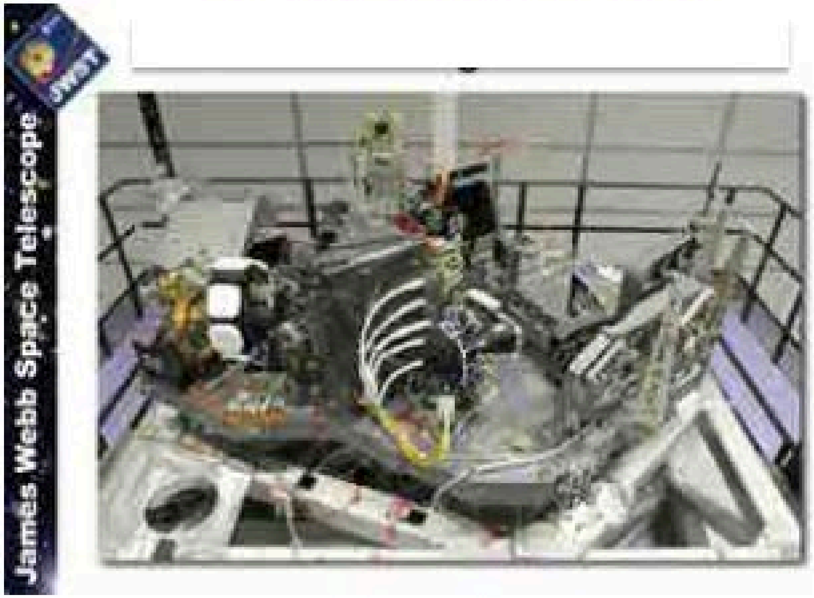


$$\Delta = 2.5 log_{10}\frac{\mu_1}{\mu_2}$$

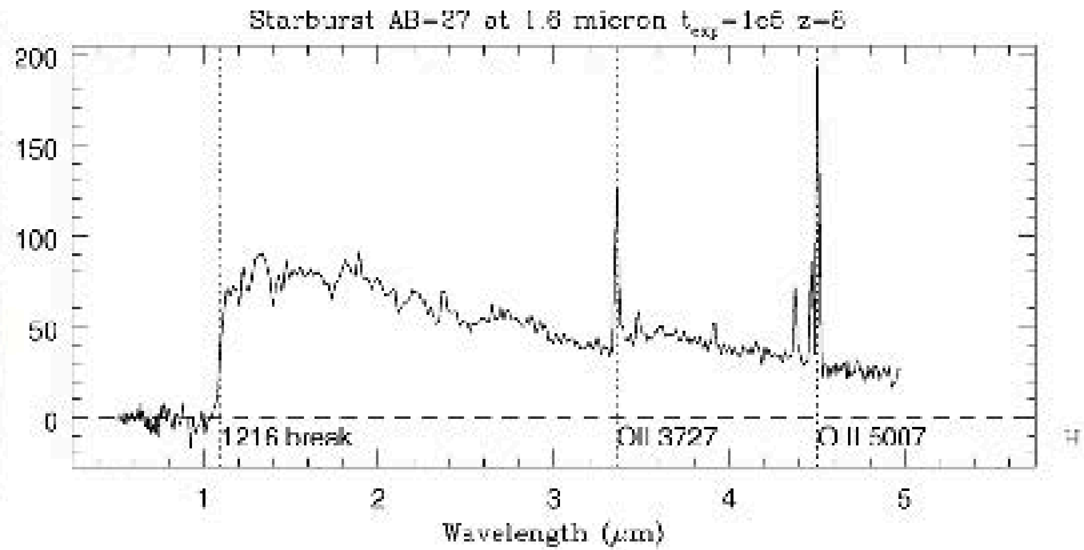
Maruša Bradač (STScI
Conference April 2013)

Spectroscopy with James Webb

NIRSpec Instrument



z=8 galaxy; 25 hour exposure



JWST provides access beyond 2 microns enabling us to

- Confirm faint end of z~7-8 LF extends to M_{UV}~-13
- Confirm presence of earlier galaxies with z>12 as predicted from UDF2012 analyses
- Search for pristene stellar populations via measures of metallicity

AO impacts JWST-TMT Synergy

TMT with AO will have <u>better resolution</u> than JWST – together with large aperture significantly changes space-ground synergy

- TMT optimal for studies of more abundant, fainter, smaller sources (AO gives ×10-100 gain over JWST depending on size).
- JWST optimal for λ > 2 μm spectroscopy

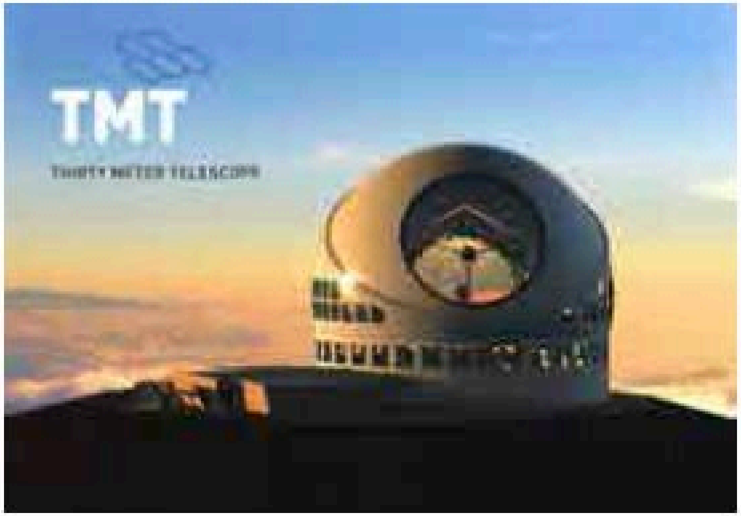
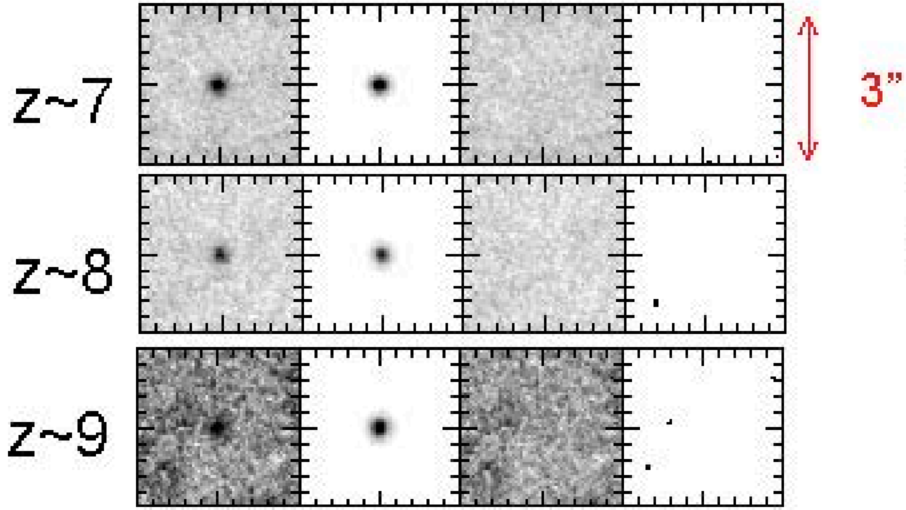
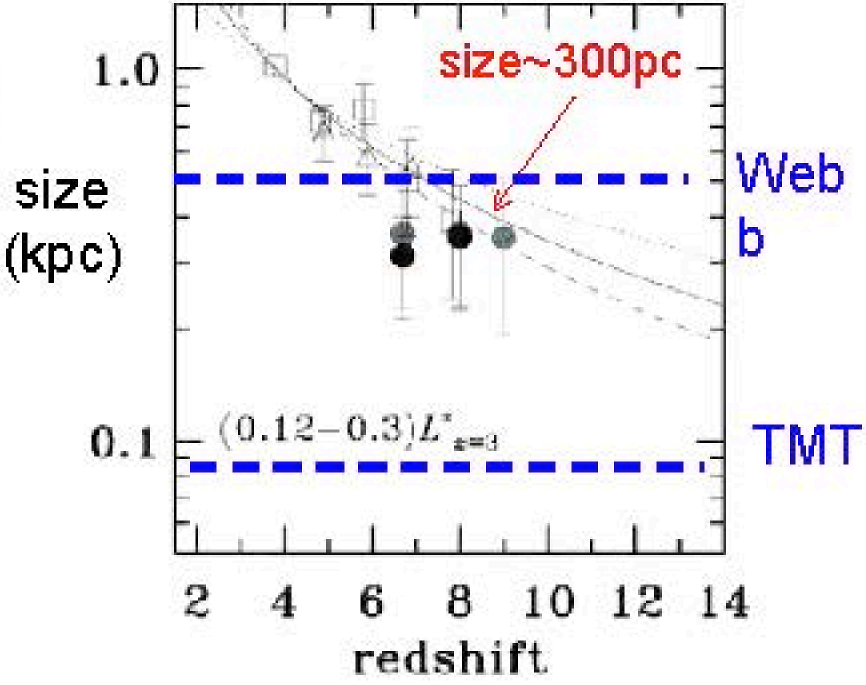


Image stacks for sub-L* galaxies



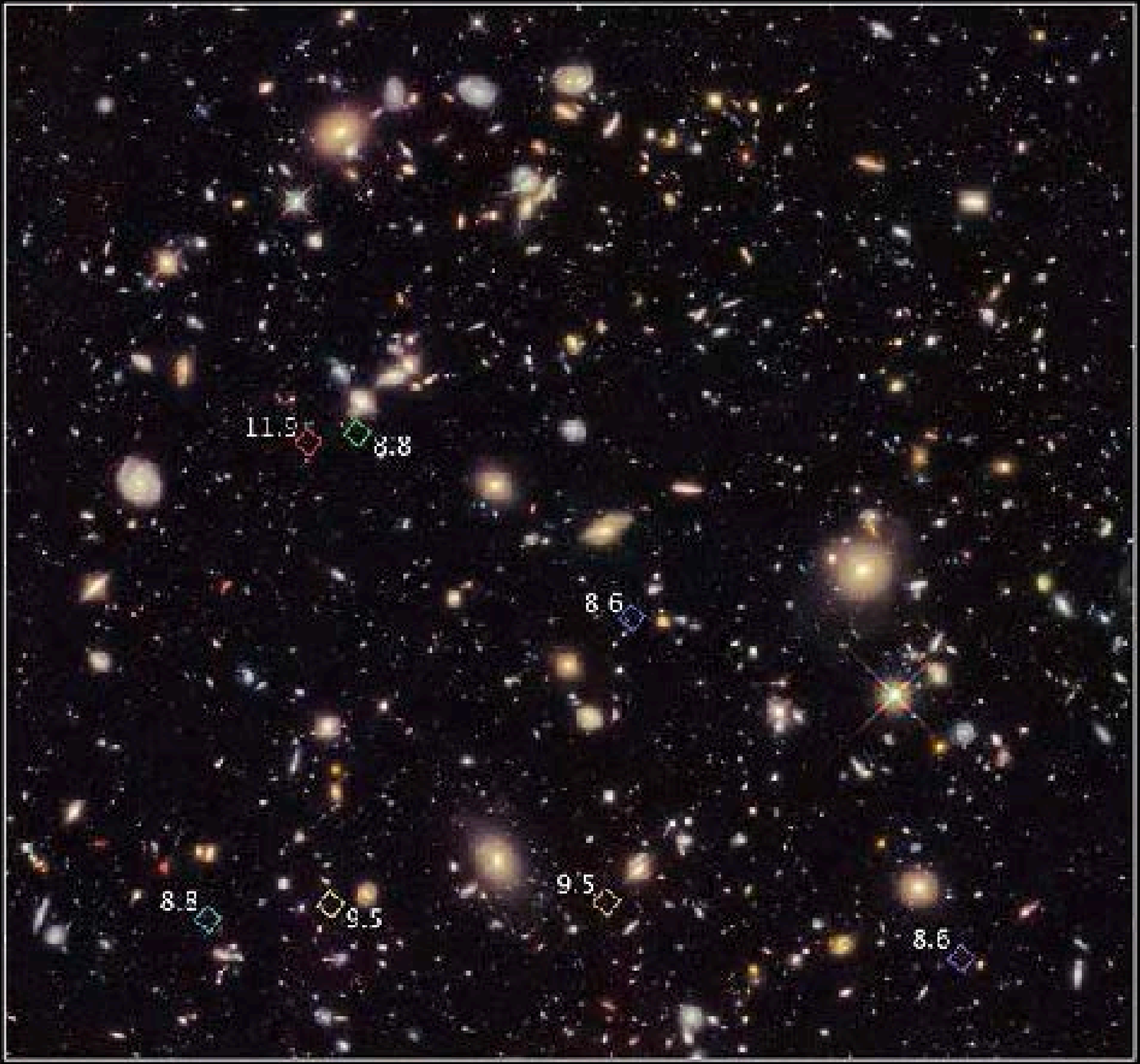


Ono et al Ap J 777,155 (2013)

Conclusions

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

1. Decline in visibility of Lyman α over $6.5<z<8$ suggests neutral era begins in this redshift range: working to extend this test with larger samples using MOSFIRE
2. UDF2012 data has provided first census of galaxies beyond z~8.5, continued decline in SFH to z~10 in agreement with lensed studies
3. Deeper higher fidelity data provides improved z~7-8 LFs
4. No evidence for unusually blue stellar populations; z~7-8 galaxies are >100 Myr old
5. Providing SF extends beyond z~10 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~4-5 LBGs offers a route forward
7. Implication: expect z>10 galaxies will be found by JWST/TMT



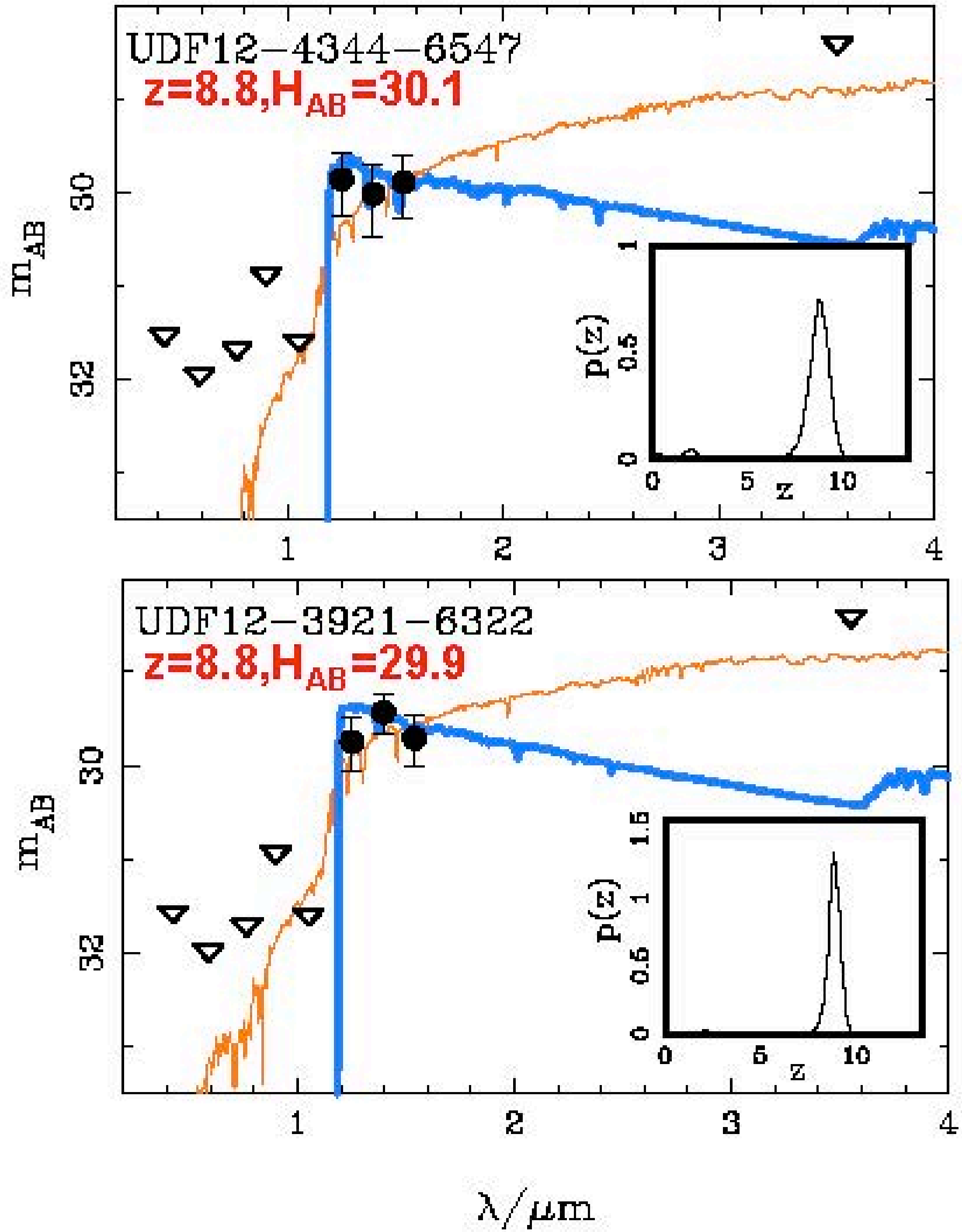
Hubble Ultra Deep Field 2012
Hubble Space Telescope WFC3/IR

NASA and ESA STScI PRC12 48a

Photometric Redshifts

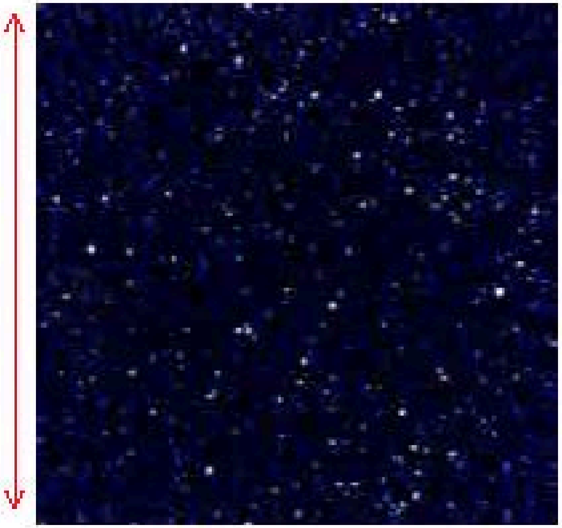
Using the combination of 4 optical and 4 infrared filters, the redshifts of individual galaxies can be estimated for systems well beyond current spectroscopic reach.

Prior to UDF 2012, foreground contamination was a big issue.



ALMA Cycle 1 UDF program

4 arcmin

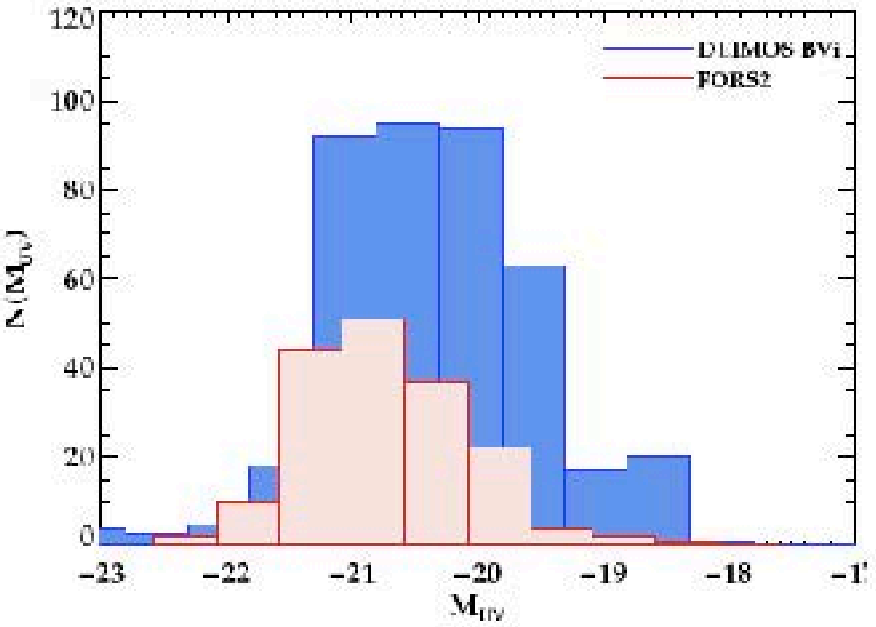


Approved Cycle 1 UDF program (PI: Dunlop; 20 hrs, Band 6)

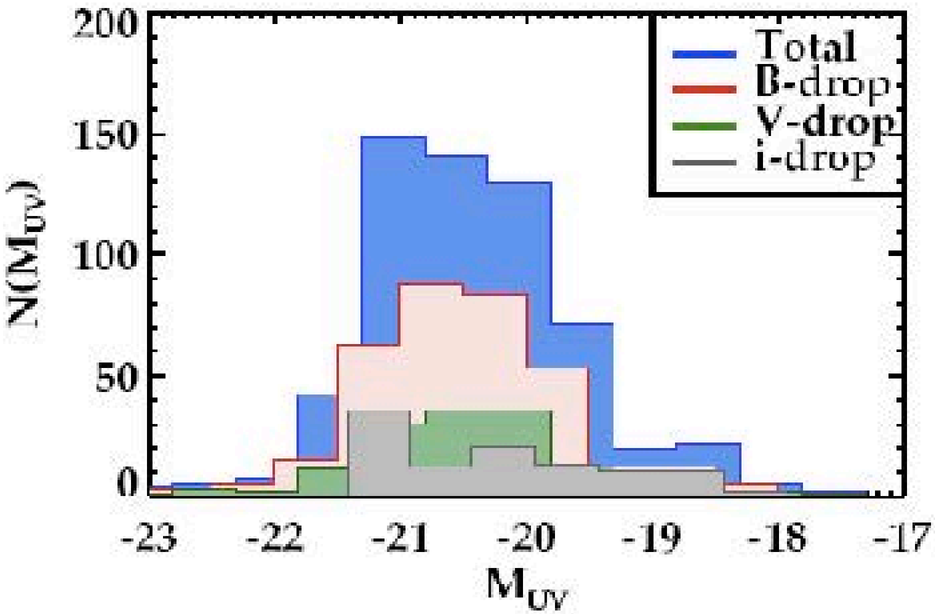
- 1.3mm depth: 0.12 mJy
  (20x fainter than AzTEC)
- ~50-100 sources over 2<z<8 for sources with HST-based photo-z's
- N(z) depends critically on UV vs far-IR SFR

Extending the Luminosity Range for z > 4

Keck c.f. VLT



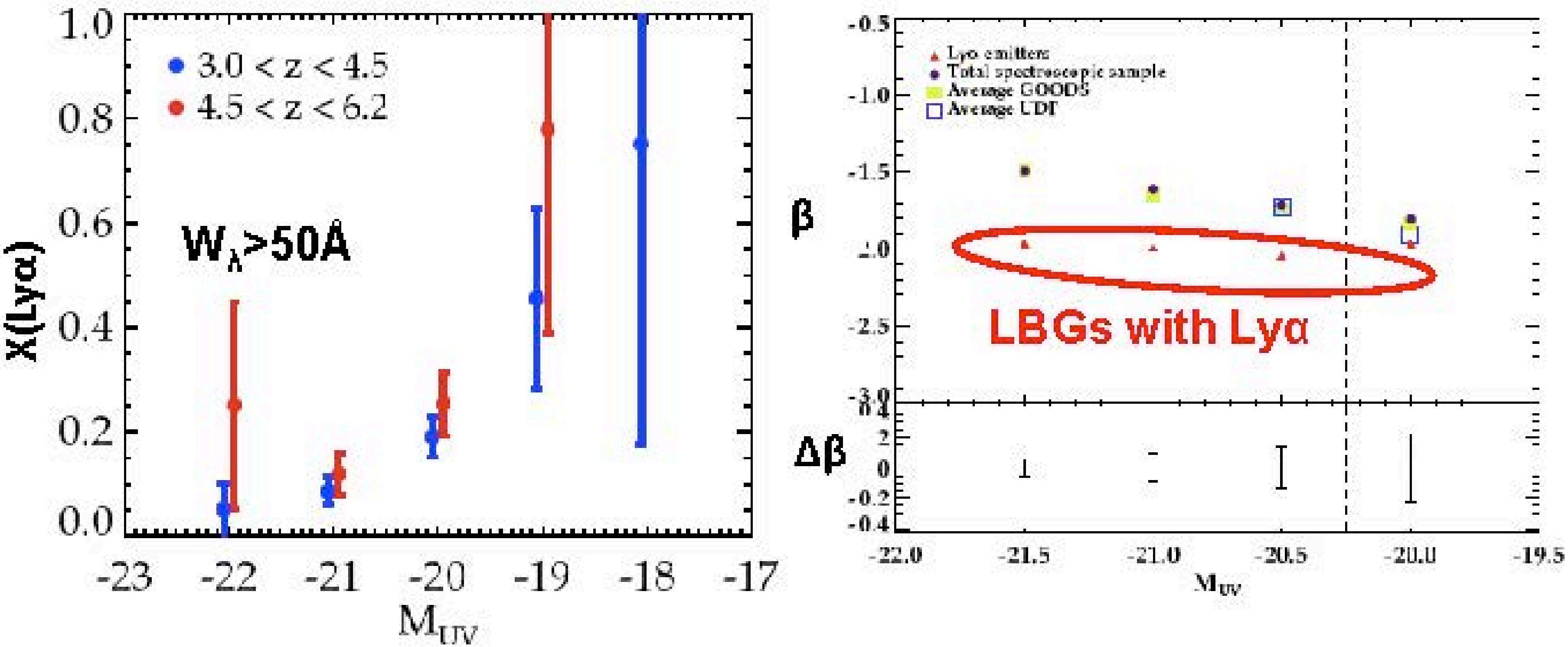
Luminosity distributions 4<z<7



Important to extend the luminosity range to probe sources more typical of those contributing to reionization at z>6

Via larger Keck aperture & longer exposures we have pushed ~1½ mags fainter than VLT and maintained a reasonably unifom luminosity range over 3<z<7 so we can reliably examine evolutionary changes

Lyα fraction with UV luminosity and color



- Lyα stronger in lower luminosity galaxies (as found in z~3 samples, Shapley et al 2003, Reddy et al 2009)

- Lyα also stronger in LBGs with bluer UV continua (as quantified via β parameter where $f_{UV} \sim \lambda^{\beta}$) suggesting the trends relate to presence/absence of dust.

LRIS/NIRSPEC Spectroscopy of 19 z>6.3 Candidates

ID	R.A.	Dec	z_{850}	J_{125}	H_{160}	μ[a]	z_{phot}	t_{exp} [hr]	z	EW [Å]
LRIS										
ERS 5847[dh]	03:32:16.0	-27:43:01.4	26.6(0.1)[b]	26.6(0.1)	26.7(0.1)	-	6.48	7		
ERS 7376[dh]	03:32:29.5	-27:42:04.5	27.2(0.1)[b]	27.0(0.1)	27.0(0.1)	-	6.79	7		
ERS 7412	03:32:10.0	-27:43:24.0	26.9(0.1)[b]	27.0(0.1)	26.7(0.1)	-	6.38	7		
ERS 8119	03:32:29.5	-27:41:32.7	27.7(0.2)[b]	27.1(0.1)	27.5(0.1)	-	6.78	7		
ERS 8290	03:32:13.4	-27:42:30.9	27.3(0.1)[b]	27.1(0.1)	26.8(0.1)	-	6.52	7		
ERS 8496[d]	03:32:29.7	-27:40:49.9	27.2(0.1)[b]	27.3(0.1)	27.5(0.1)	-	6.52	7	6.441	39 ± 10
ERS 10270	03:32:29.5	-27:42:54.0	28.1(0.1)[b]	27.4(0.1)	28.0(0.2)	-	7.02	7		
ERS 10373	03:32:27.0	-27:41:42.9	27.5(0.1)[b]	27.4(0.1)	27.8(0.2)	-	6.44	7		
NIRSPEC										
A1703_zD1[e]	13:14:59.4	51:50:00.8	25.8(0.2)	24.1(0.1)	24.0(0.1)	9.0	6.75	2,		
A1703_zD3[e]	13:15:06.5	51:49:18.0	26.8(0.5)	25.5(0.1)	25.1(0.2)	7.3	6.89	2, –		
A1703_zD6[e]	13:15:01.0	51:50:04.3	27.9(0.5)	25.8(0.1)	25.9(0.1)	5.2	7.02	5, 3	7.045	65 ± 12
A1703_zD7[e]	13:15:01.3	51:50:06.1	> 28.5	26.8(0.2)	26.4(0.2)	5.0	8.80	5, 3		
A2261_1	17:22:28.7	32:08:30.9	> 28.6	26.9(0.1)	27.3(0.1)	3.5	7.81	5.7, –		
BoRG_58_1787_1420[f]	14:36:50.6	50:43:33.6	> 27.9[c]	25.8(0.1)	25.9(0.2)	-	8.27	2, 3		
EGS_K1	14:19:24.2	52:48:36.2	> 27.8[c]	25.3(0.1)	25.4(0.1)	-	8.27	2.5,		
HUDF09_799[g]	03:33:09.1	-27:51:55.4	> 29.1	27.7(0.1)	27.6(0.2)	-	6.88	4.5, –		
HUDF09_1584[g]	03:33:03.8	-27:51:20.4	27.2(0.1)	26.7(0.1)	26.6(0.1)	-	7.17	5.5, –		
HUDF09_1596	03:33:03.8	-27:51:19.6	27.3(0.1)	26.8(0.1)	26.8(0.1)	-	7.46	5.5,	6.905?	30 ± 15
MS0451-03_10	04:54:08.8	-3:00:29.1	> 28.5	26.7(0.1)	26.9(0.1)	50	7.50	2.5, –		

Drawn from several WFC3 campaigns:

Early Release Science (ERS) in GOODS-S (Hathi et al)

BoRG Pure Parallel Survey (Trenti et al 2010)

UDF survey (Illingworth, Bouwens et al 2010, 2011)

CLASH lensing survey (Bradley et al 2011, Postman et al 2011)

plus 7 objects studied with FORS2 by Fontana et al (2010)

First Robust Census 8.5<z<12

z > 8.5 Candidates

ID	R.A.	Decl.	$z_{\rm SED}(\pm 1\sigma)$	Y_{105W}	J_{125W}	J_{140W}	H_{160W}	Notes
2012 Analysis								
UDF12-3954-6284	3:32:39.54	−27:46:28.4	$11.9^{+0.3}_{-0.5}$	>31.2	>30.7	>30.5	29.3 ± 0.2	UDFj-39546284 B11[b]
UDF12-4106-7304	3:32:41.06	−27:47:30.4	$9.5^{+0.4}_{-0.8}$	>30.8	>30.0	29.8 ± 0.3	29.7 ± 0.3	
UDF12-4265-7049	3:32:42.65	−27:47:04.9	$9.5^{+0.4}_{-0.7}$	>31.2	30.4 ± 0.6	29.9 ± 0.4	29.7 ± 0.4	
UDF12-3921-6322	3:32:39.21	−27:46:32.2	$8.8^{+0.4}_{-0.2}$	>31.2	29.9 ± 0.3	29.6 ± 0.3	29.9 ± 0.3	
UDF12-4344-6547	3:32:43.44	−27:46:54.7	$8.8^{+0.5}_{-0.5}$	>31.2	30.0 ± 0.3	30.1 ± 0.4	30.1 ± 0.3	
UDF12-3895-7114	3:32:38.95	−27:47:11.4	$8.6^{+0.8}_{-0.6}$	>30.9	30.4 ± 0.5	30.1 ± 0.3	30.1 ± 0.4	
UDF12-3947-8076	3:32:39.47	−27:48:07.6	$8.6^{+0.2}_{-0.2}$	31.0 ± 0.5	29.5 ± 0.2	29.0 ± 0.1	29.0 ± 0.1	UDFy-39468075 B11[b]
2009 Analysis								
UDFj-39546284	3:32:39.54	−27:46:28.4	$11.9^{+0.3}_{-0.5}$	>31.2	>30.7	>30.5	29.3 ± 0.2	B11[b] $z \simeq 10.3$
~~UDFj-38116243~~	~~3:32:38.11~~	~~−27:46:24.3~~	~~...~~	~~>31.2~~	~~>30.1~~	~~30.3 ± 0.5~~	~~30.0 ± 0.5~~	~~B UDF09[c] #1, B11[b] #2~~
UDFj-43696407	3:32:43.69	−27:46:40.7	$7.6^{+0.4}_{-0.6}$	31.0 ± 0.6	>30.1	29.9 ± 0.3	29.5 ± 0.2	B UDF09[c] #2
UDFj-35427336	3:32:35.42	−27:47:33.6	$7.9^{+0.5}_{-0.8}$	>30.8	30.3 ± 0.4	30.2 ± 0.4	29.6 ± 0.2	B UDF09[c] #3
UDFy-38135539	3:32:38.13	−27:45:53.9	$8.3^{+0.2}_{-0.1}$	30.1 ± 0.2	28.6 ± 0.1	28.5 ± 0.1	28.4 ± 0.1	B11[b] $8.5 < z < 9.5$
UDFy-37796000	3:32:37.79	−27:46:00.0	$8.1^{+0.1}_{-0.2}$	29.8 ± 0.1	28.6 ± 0.1	28.7 ± 0.1	28.7 ± 0.1	B11[b] $8.5 < z < 9.5$
UDFy-33436598	3:32:33.43	−27:46:59.8	$7.9^{+0.2}_{-0.3}$	30.3 ± 0.4	29.3 ± 0.2	29.4 ± 0.2	29.4 ± 0.1	B11[b] $8.5 < z < 9.5$

Only 1 of the 7 z>8.5 galaxies was claimed z>8.5 in shallower 2009 studies

Other z>8.5 galaxies claimed in 2009 lie at lower redshift (or are not confirmed)

Changing Views on the z=11.9 Candidate…

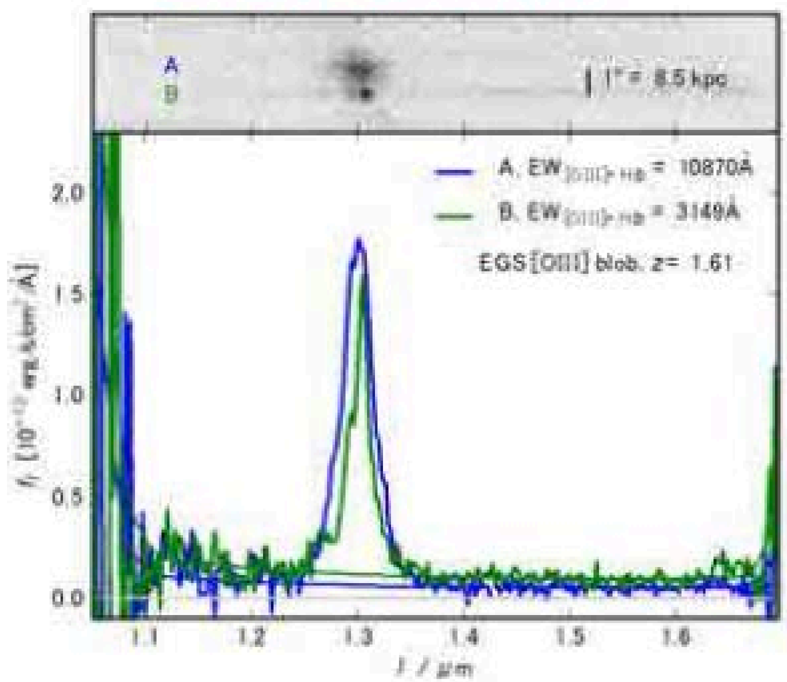
A TENTATIVE DETECTION OF AN EMISSION LINE AT 1.6 μm FOR THE Z ~ 12 CANDIDATE UDFJ-39546284*

Gabriel B. Brammer[1], Pieter G. van Dokkum[2], Garth D. Illingworth[4], Rychard J. Bouwens[3], Ivo Labbé[3], Mariju
Franx[3], Ivelina Momcheva[2], Pascal A. Oesch[4]

Submitted to ApJL

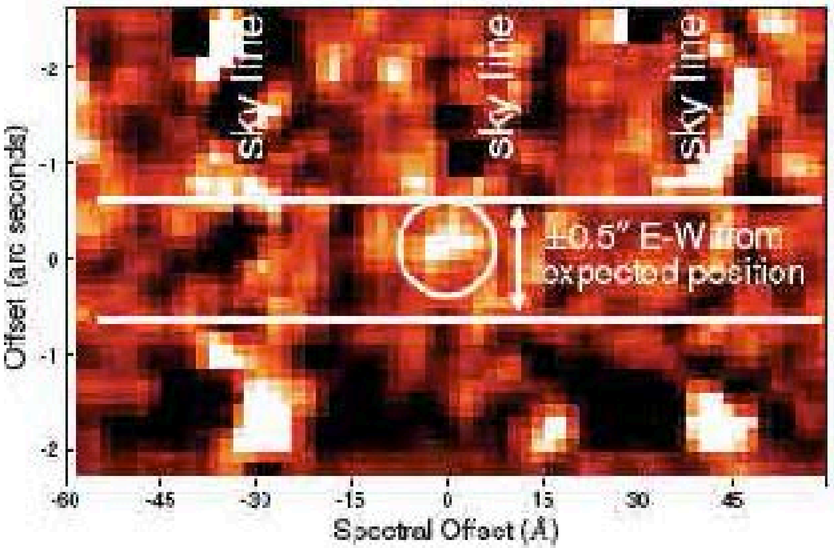
UDFj-39546284 z=2.19?

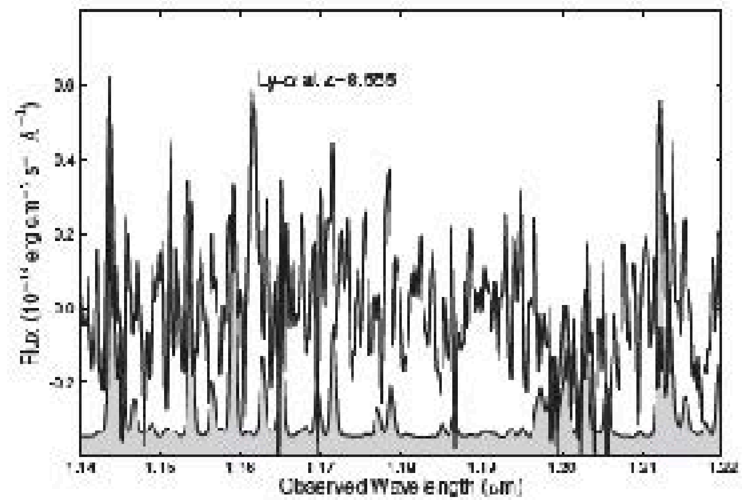
EGS-XEW-1 z=1.61



Query on z=8.55 LBG?

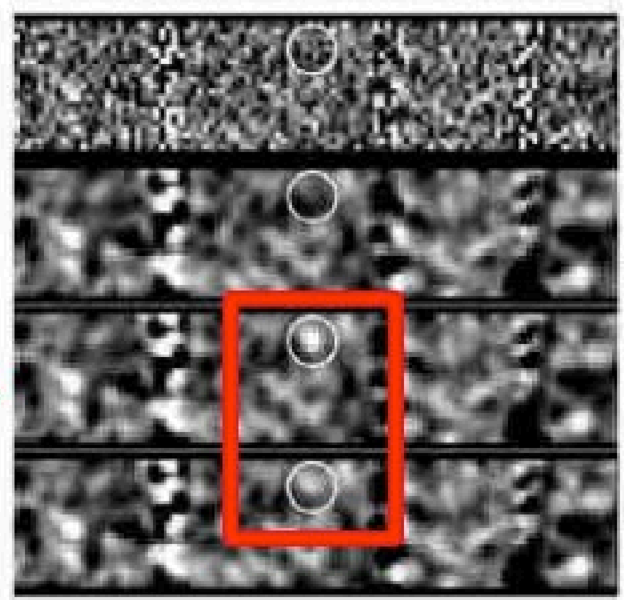
UDFy-38135539 = HUDF-YD3





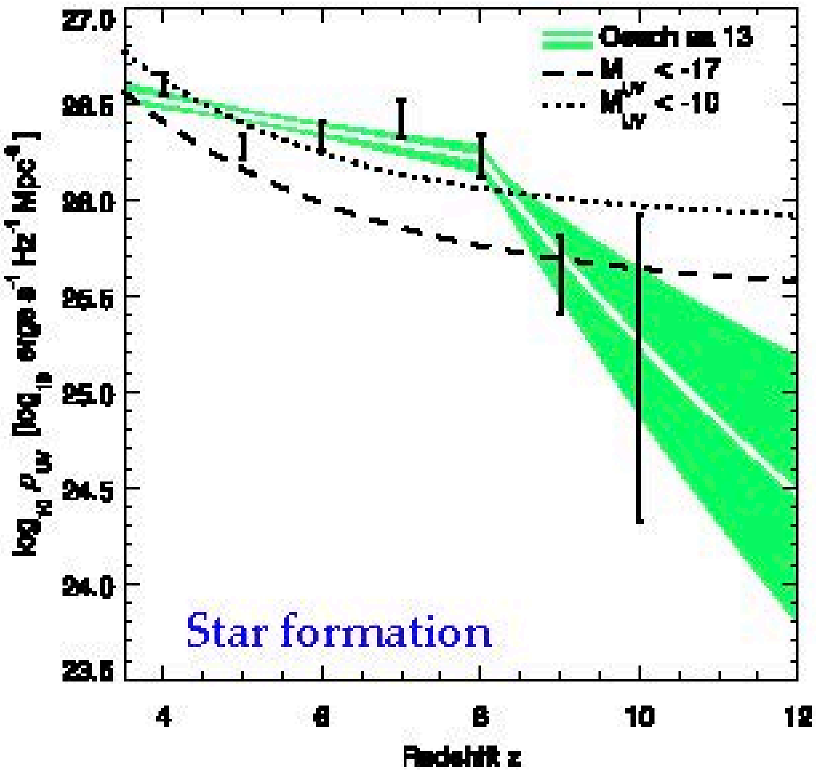
Lehnert et al (2010) VLT
SINFONI 14.8 hours R~2000
Claimed 6.0σ detection

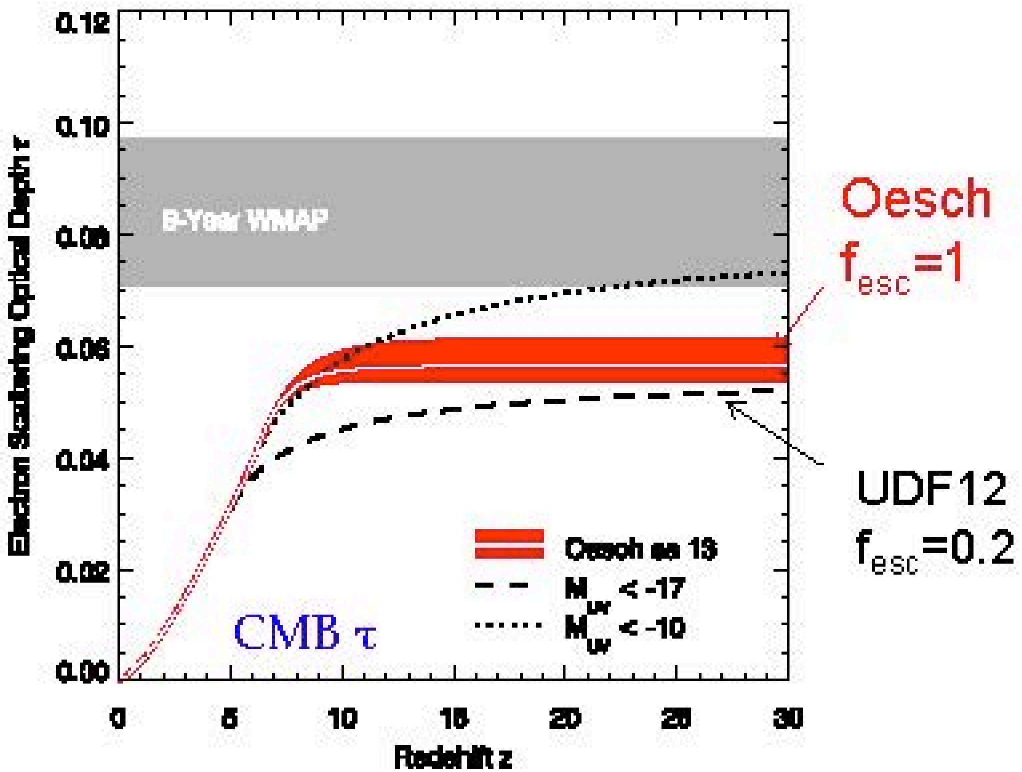
Bunker et al (2011) VLT X-Shooter
5 hours R~5100
Expected 3.5-4.5σ detection



Importance of SF beyond z~10

- Bouwens et al (2011, 2012), Oesch et al (2013) propose a sharp downturn in SF beyond z~8
- This produces a very rapid transition in x_{HI} at late epochs and fails to reproduce WMAP τ even with very high f_{esc}





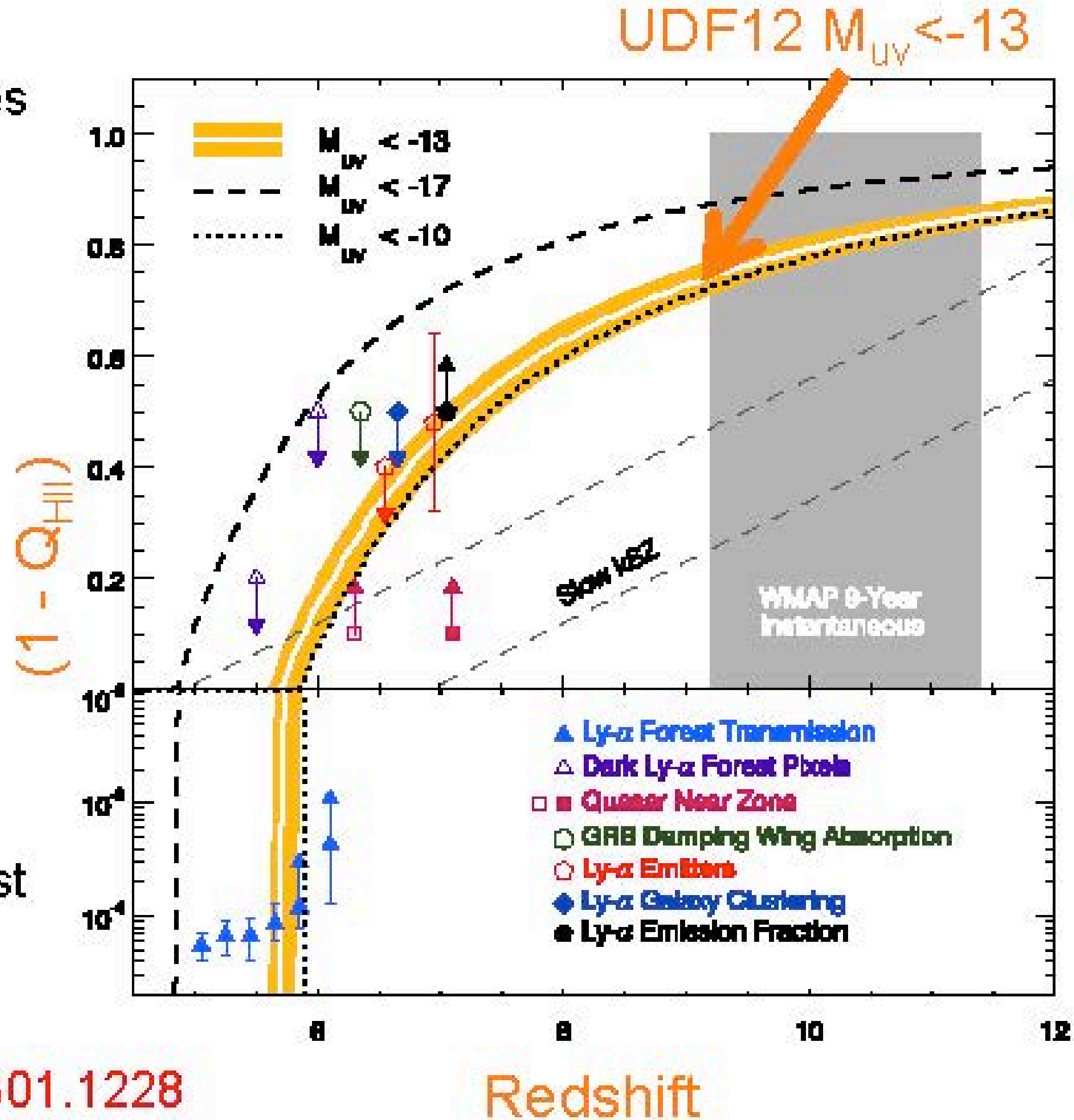
Comparison with Other Reionization Constraints

Empirical model matches various independent constraints for evolution of the neutral fraction:

$x_{HI} = (1 - Q_{HII})$

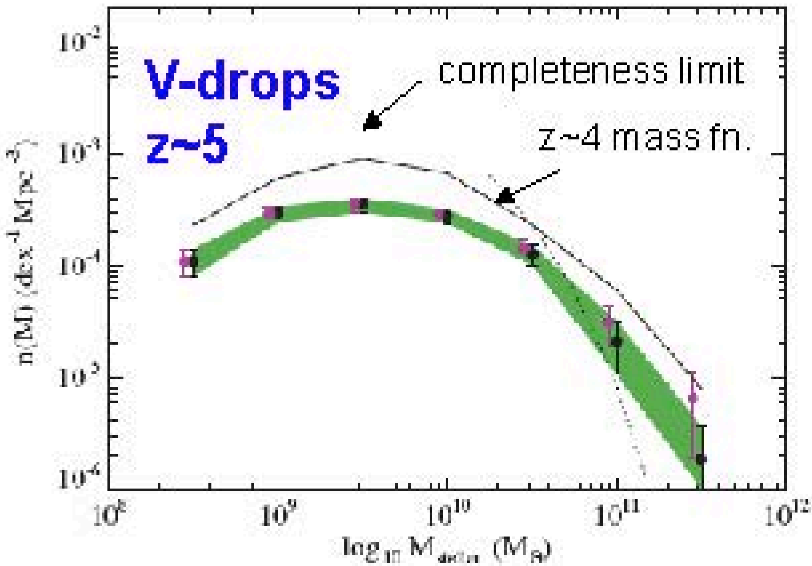
in interval of rapid evolution 6 < z < 8

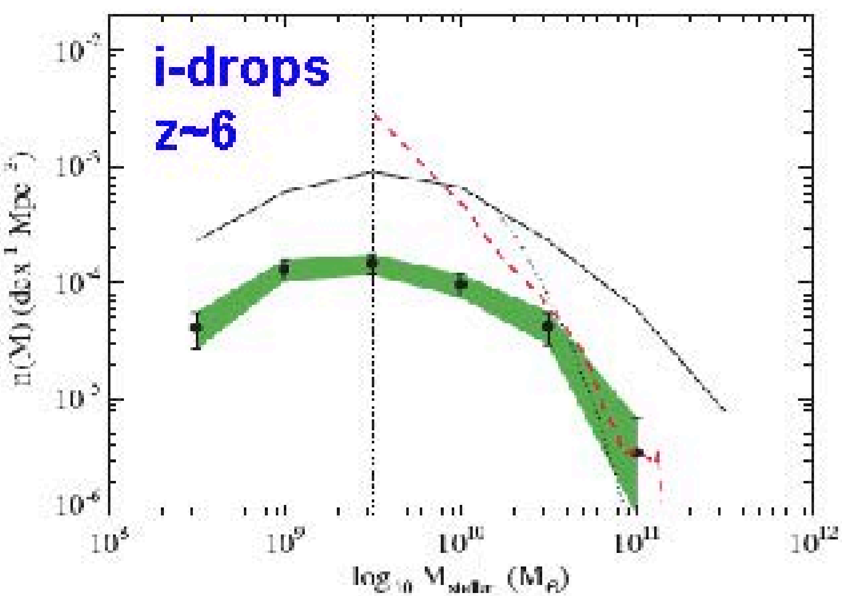
e.g. Lyα statistics in LBGs and LAEs, near zone in QSOs, Lyα forest in QSOs etc



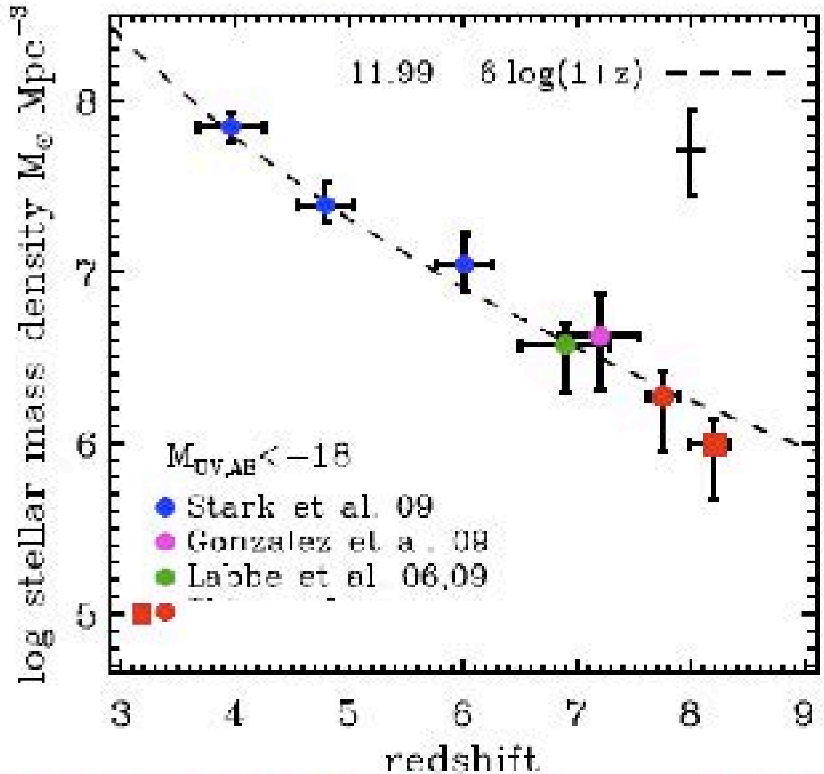
Robertson et al arXiv 1301.1228

Stellar Mass Density





Stark et al 2007,2009



Labbé et al 2009, Gonzalez et al 2010

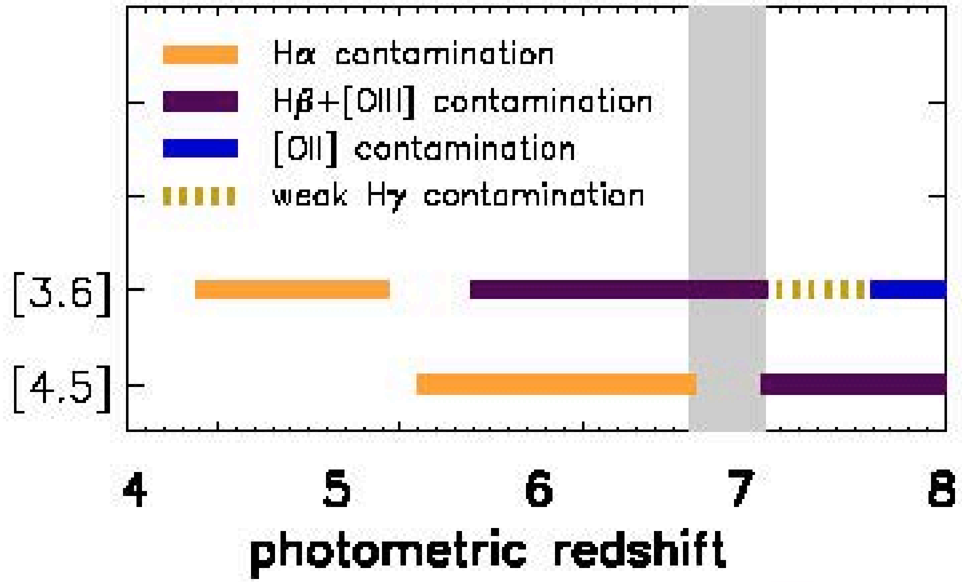
$$M_*(z) = \int_{z=5}^{z=10} \rho_*(z)\,dV(z)$$

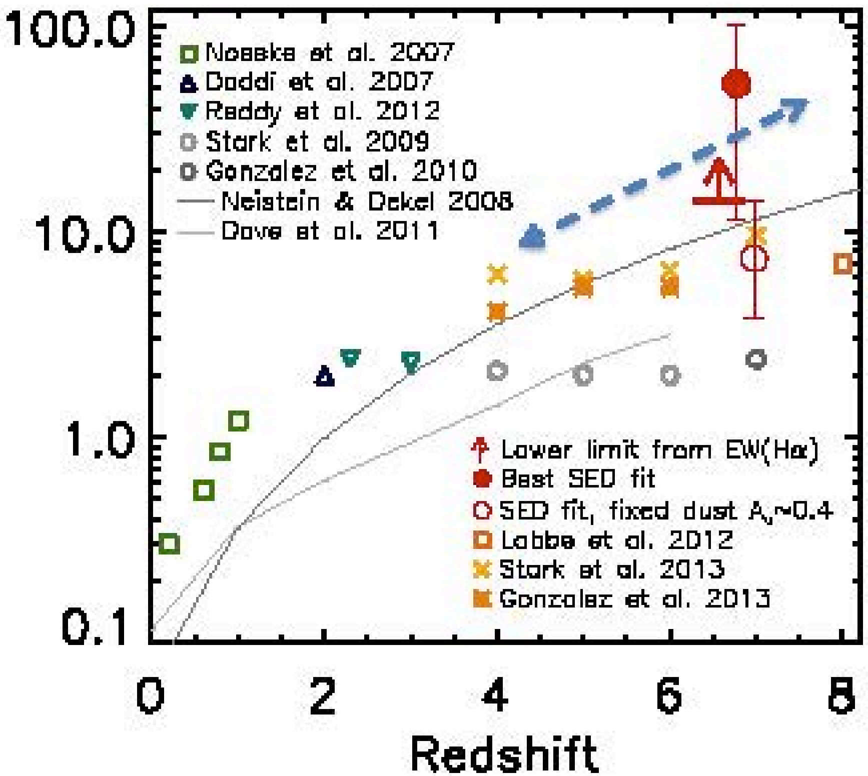
Stellar mass density at z~5-6 implies <u>significant past SF</u>

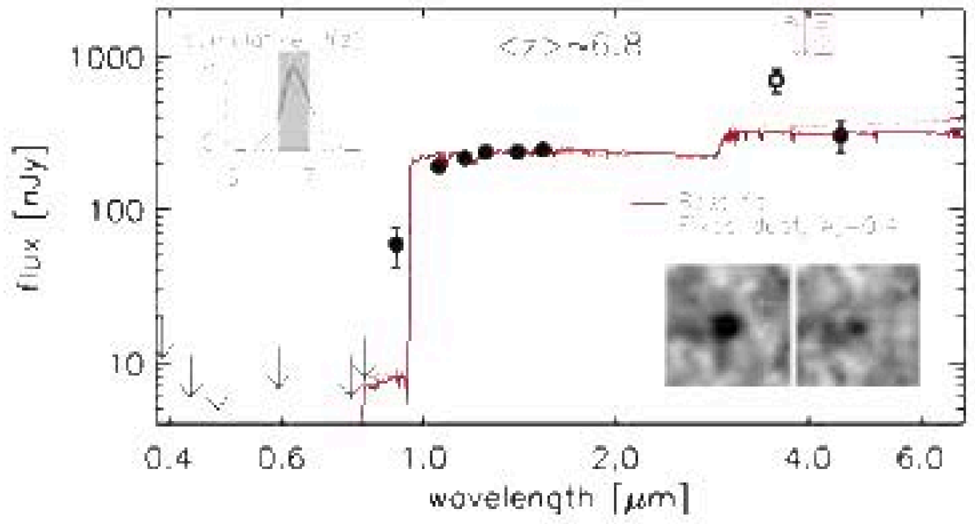
Nebular Emission at z~6.8

Same idea:

- SEDs of 7 lensed 6.6<z<7.0 galaxies from CLASH survey where [O III] pollutes IRAC 3.6μm band
- EWs ~1000Å produce a rising specific star formation rate with redshift consistent with theory



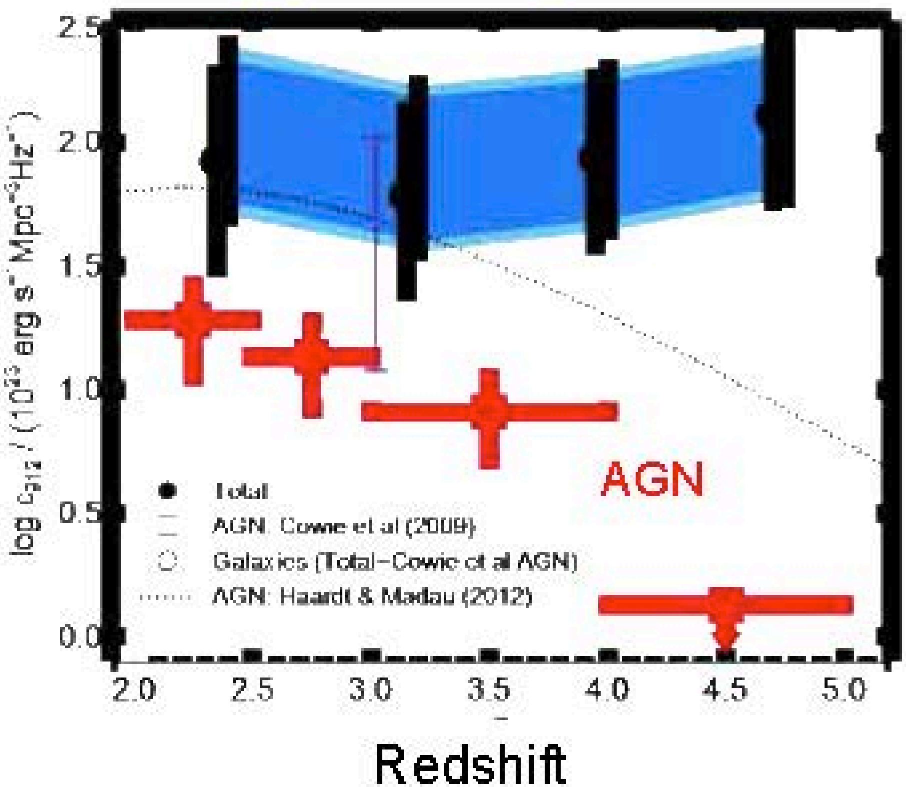




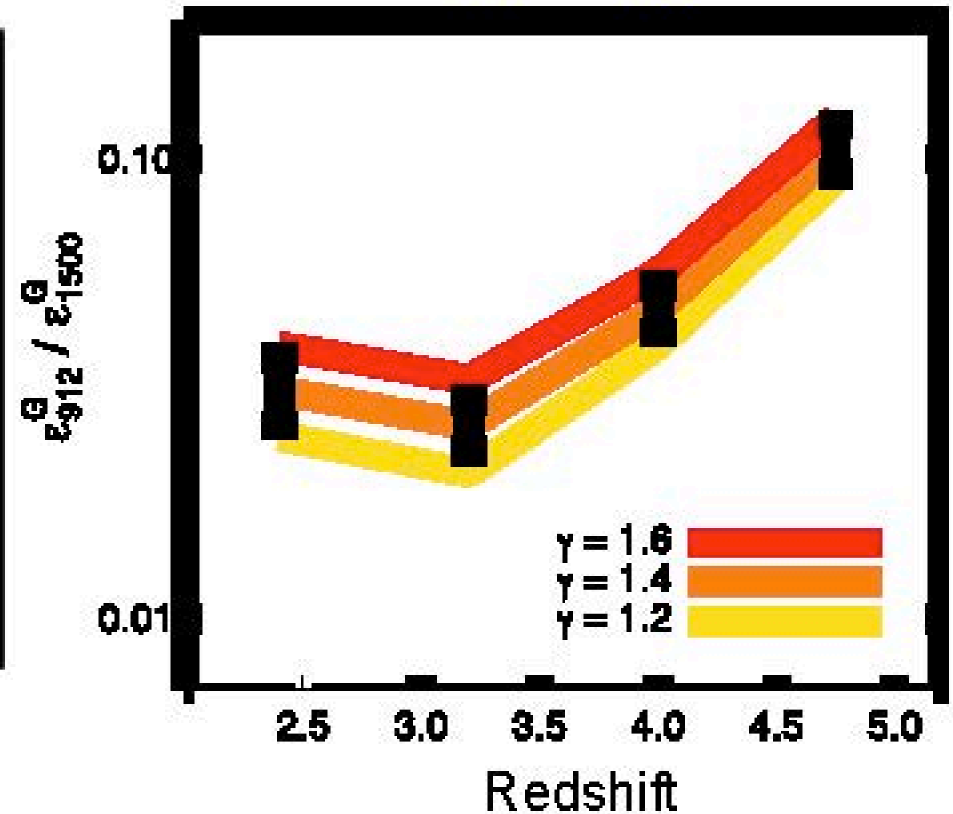
Smit et al arXiv: 1307.5847

Evolving Emissivity of Galaxies from QSO Spectra

ε_{912}: emissivity at 912 Å



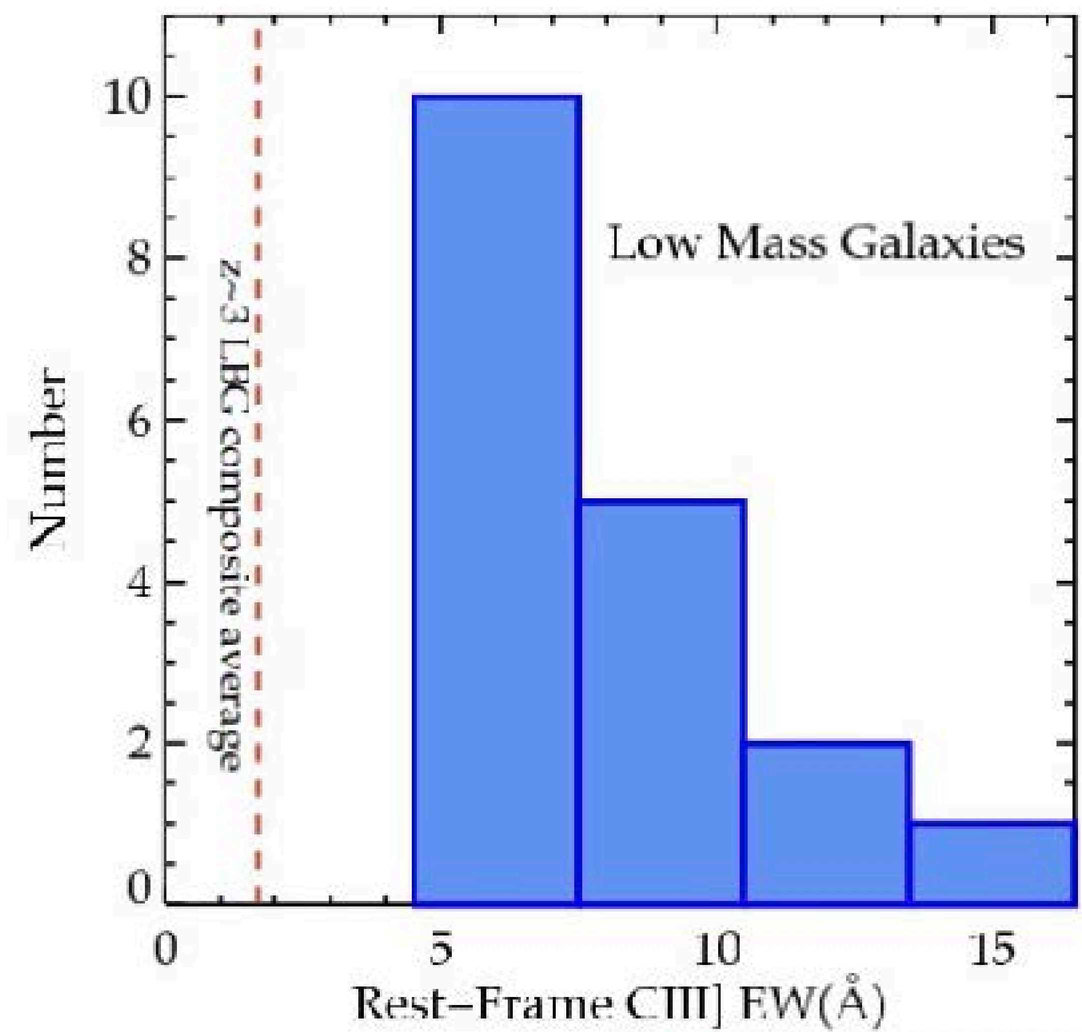
$\varepsilon_{912} / \varepsilon_{1500}$



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}

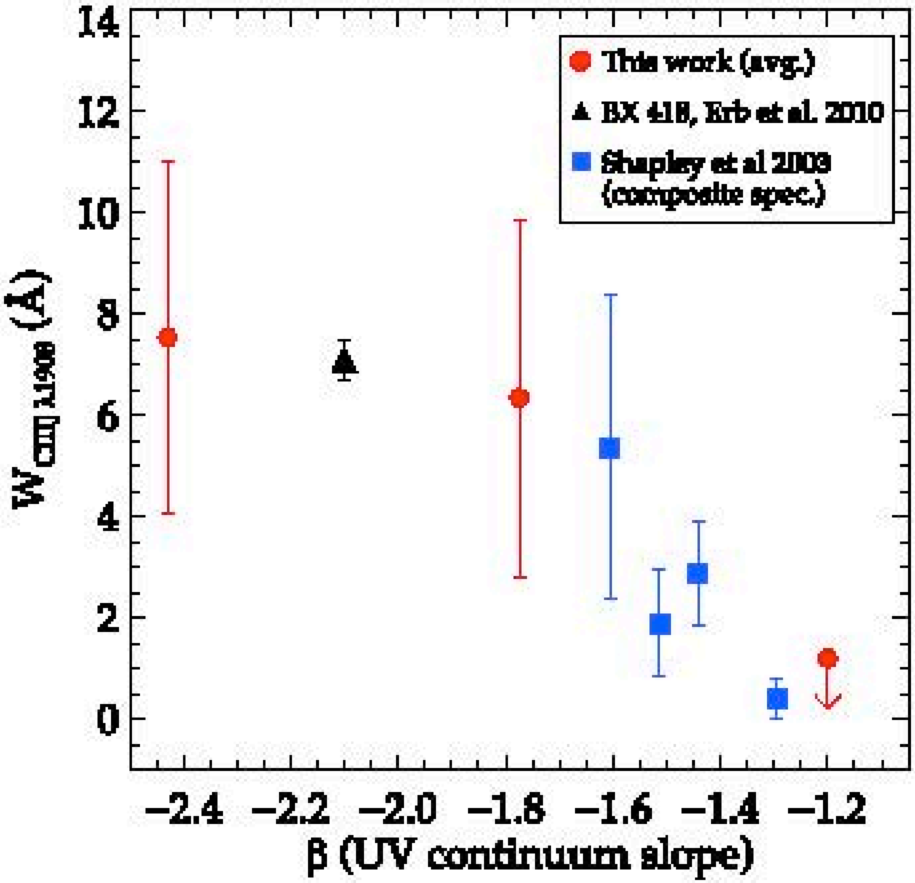
Becker & Bolton arXiv 1307.2259

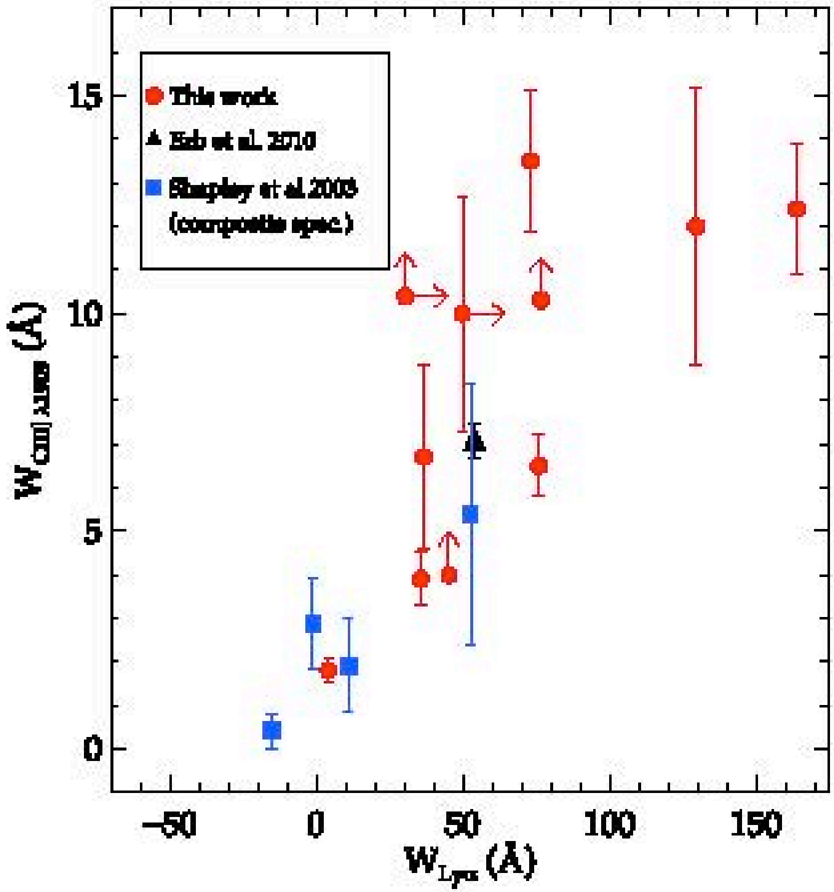
CIII] Lensed Galaxy EW Distribution



Stark, Richard, Siana et al (in prep)

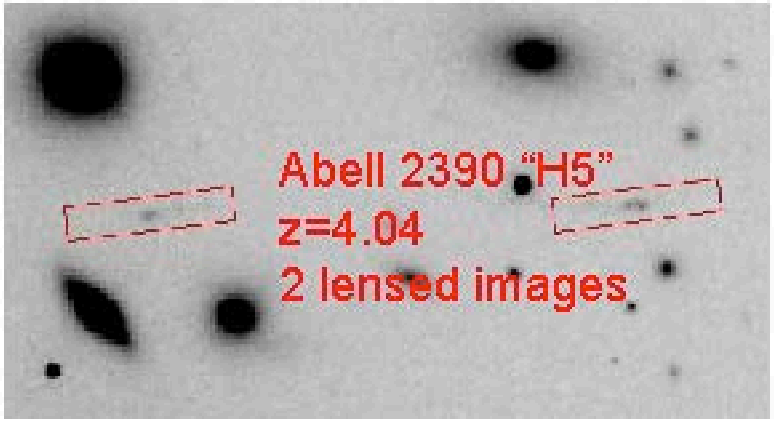
CIII] EW vs UV Slope and Lyα

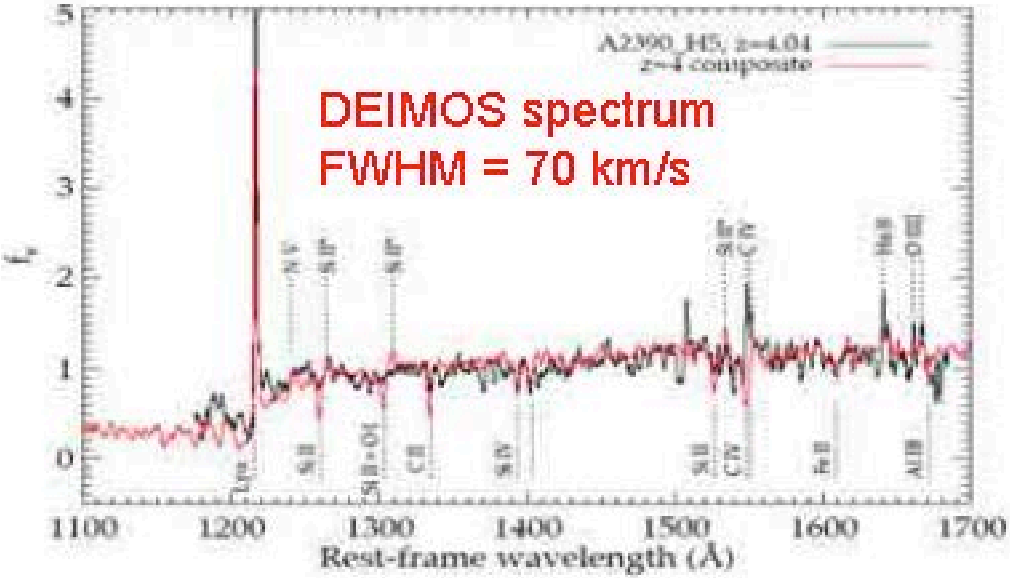




Stark, Richard, Siana et al (in prep)

Higher Resolution Spectra of z~4 arcs



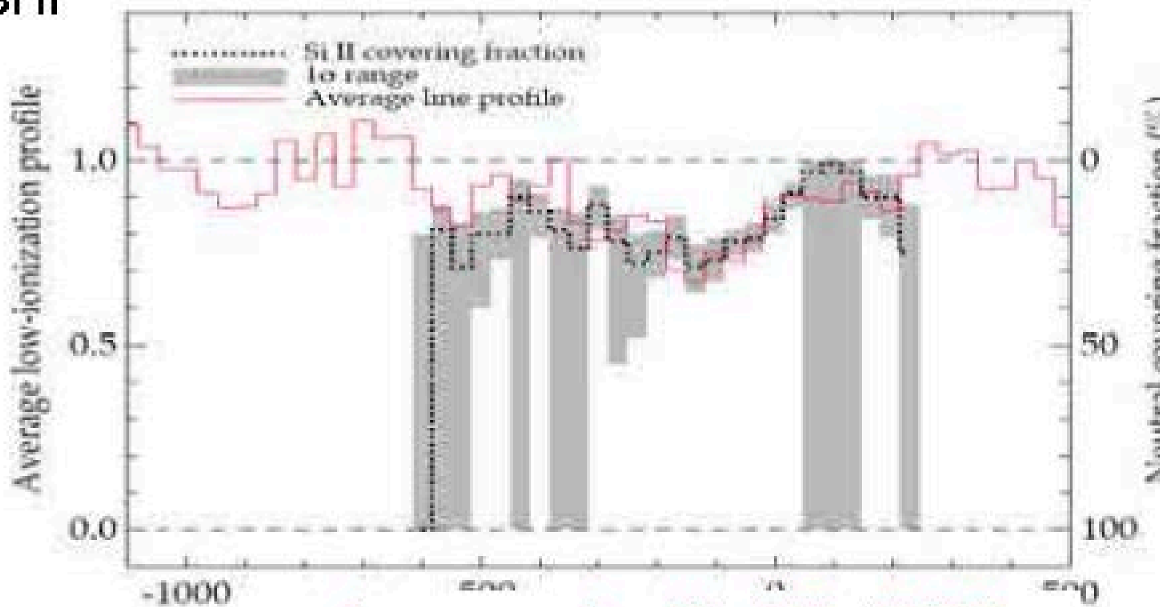


Covering fraction f_c derived from average profile for all low ionization lines *and* a pair of ground state Si II lines with different f values

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

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

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