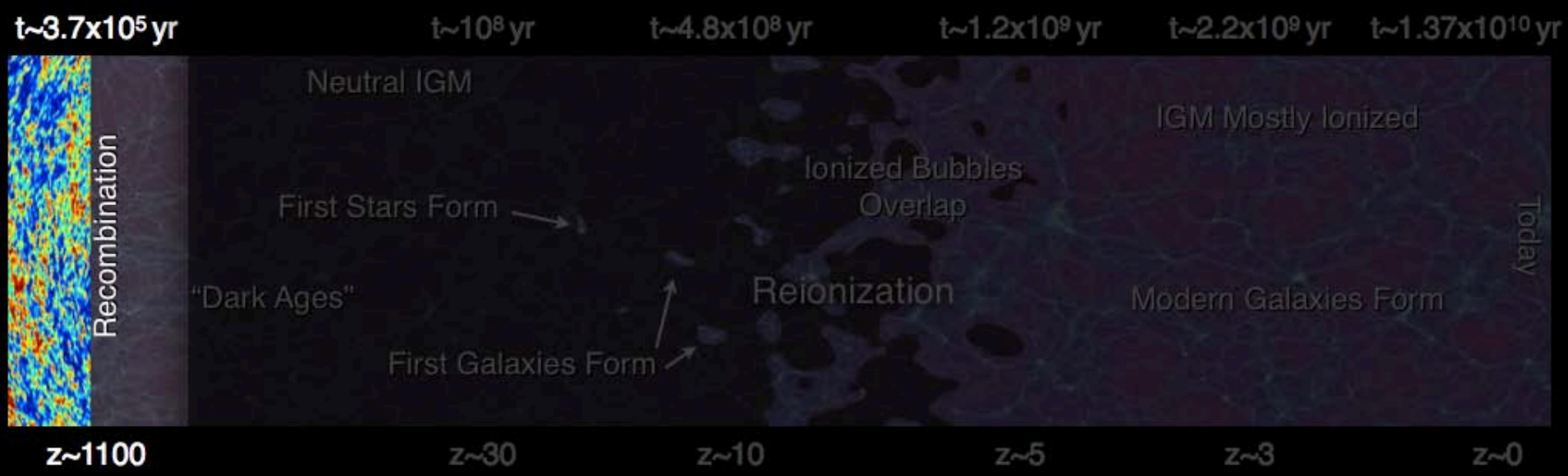
Did Galaxies Reionize the Universe? Progress and Challenges

Richard Ellis, Caltech

IPMU

October 3rd 2011

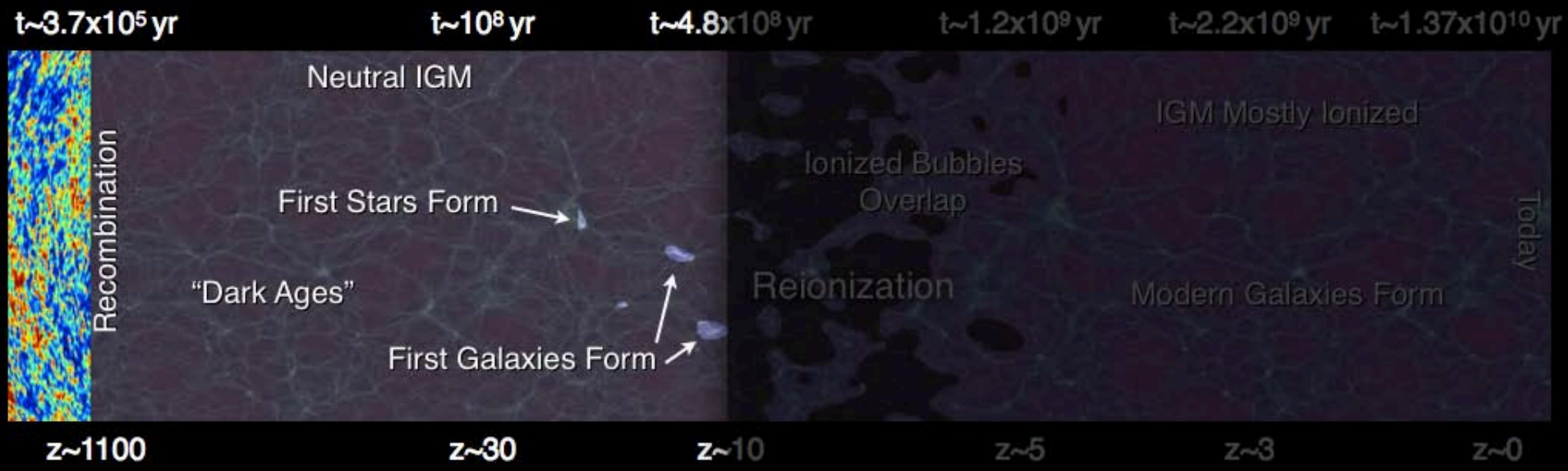
Observable Cosmological History



1) Recombination

Robertson et al., *Nature*, **468**, 49 (2010)

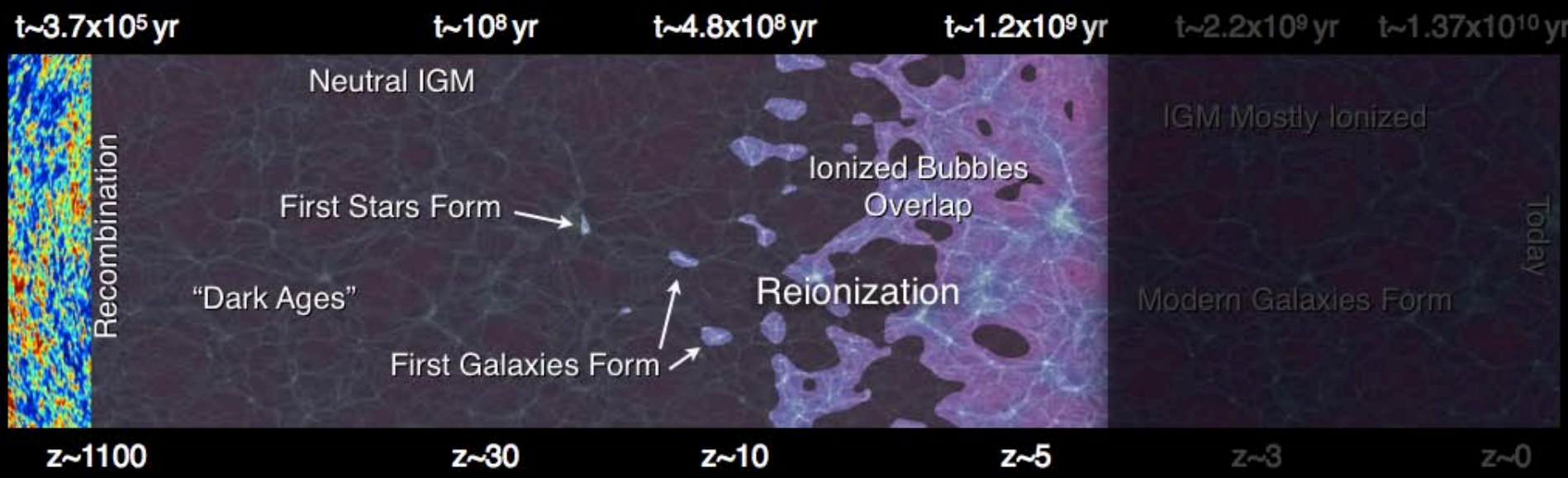
Observable Cosmological History



2) "Cosmic Dawn"

Robertson et al., *Nature*, **468**, 49 (2010)

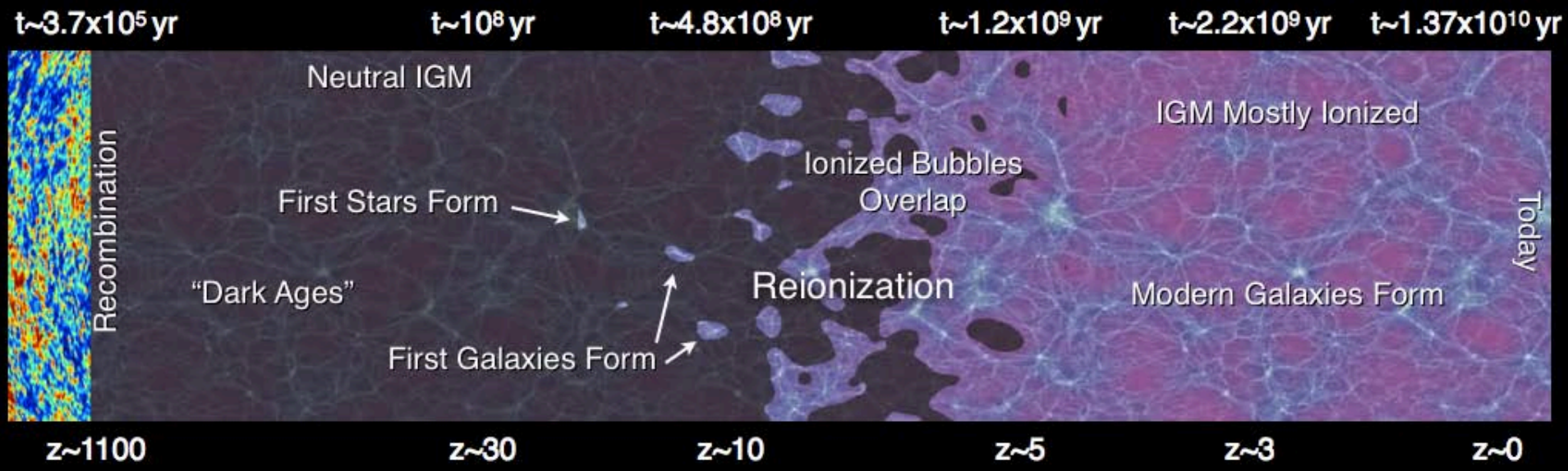
Observable Cosmological History



3) Reionization

Robertson et al., *Nature*, **468**, 49 (2010)

Observable Cosmological History



4) Modern Cosmological History

Robertson et al., *Nature*, **468**, 49 (2010)

Outline

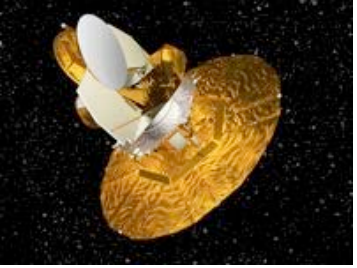
Indirect constraints on when reionization occurred:

- Optical depth to reionization, τ, from the WMAP satellite
- Downturn in ionized carbon abundance at $z > 5$
- Stellar mass density of $4<z<6$ galaxies: a gauge of earlier star formation

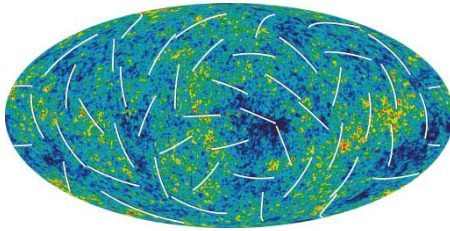
Early Galaxies & Reionization

- Lyman alpha emitters vs Lyman break galaxies
- The HST WFC3 revolution: new galaxy candidates beyond $z\sim7$
- Lyman α emission as a probe of reionization
- The biggest unknown: escape fraction of ionizing photons

Challenges and prospects for the future

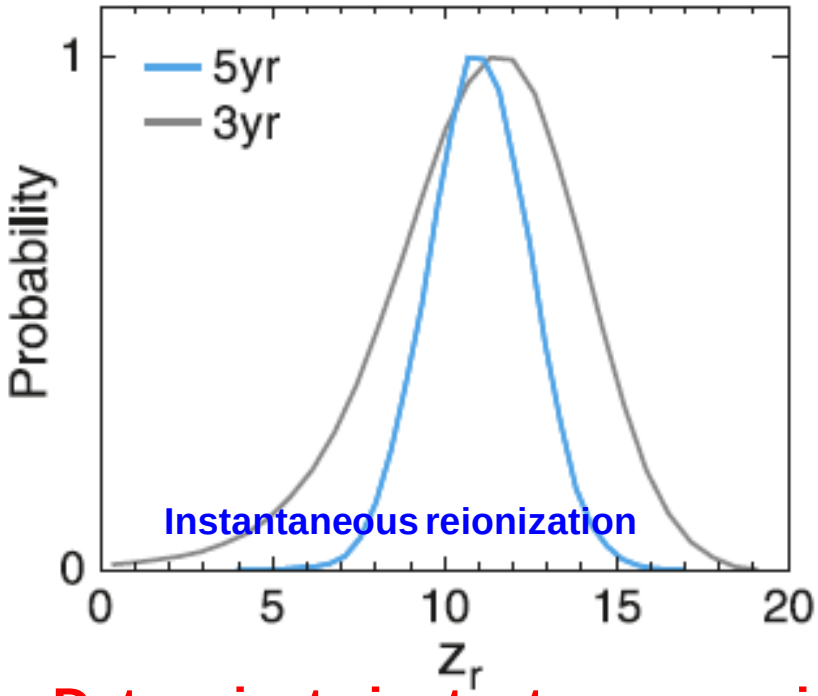


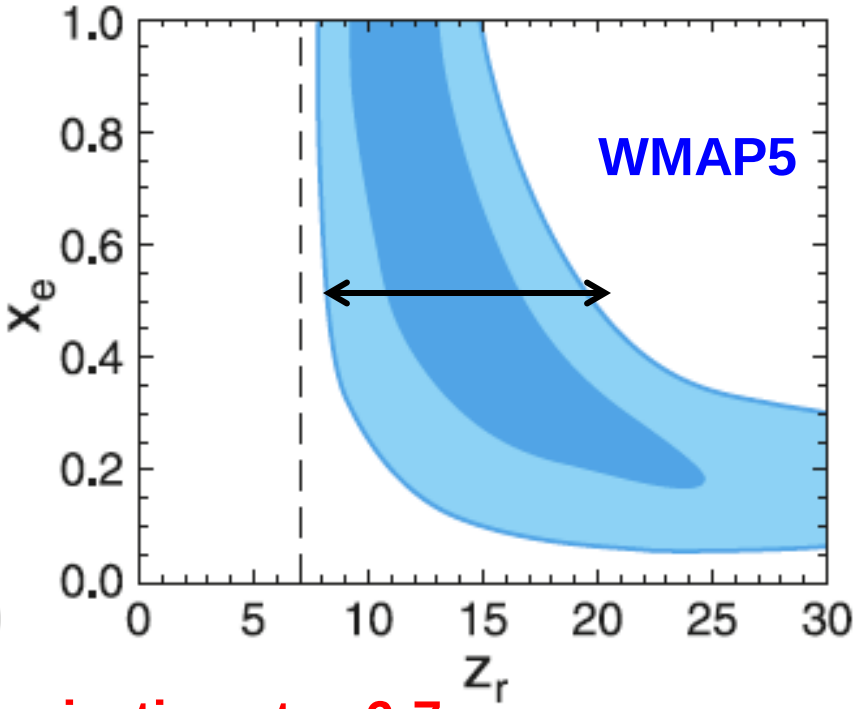
WMAP Polarization



$\tau = 0.088 \pm 0.015$
(WMAP7, 2010)

Larson et al 2011
Jarosik et al 2010





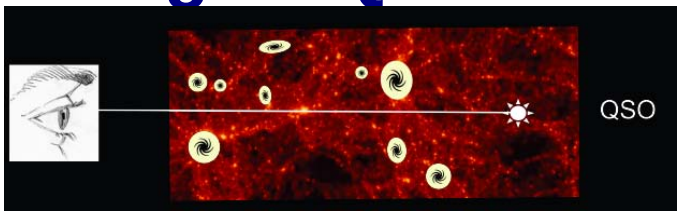
Data rejects instantaneous reionization at z~6-7

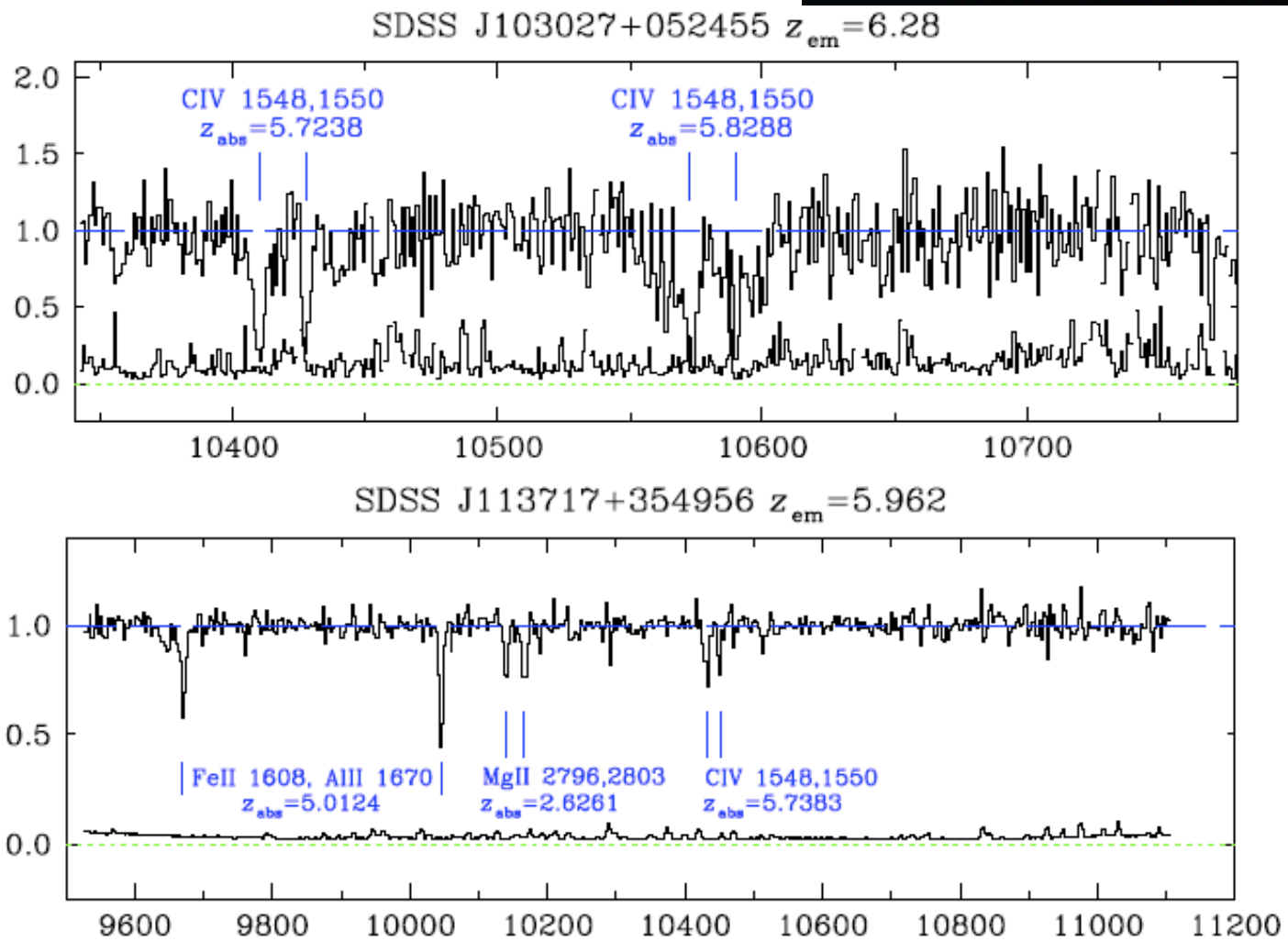
Planck may give more information on reionization history

CMB does <u>not</u> pinpoint the responsible cosmic sources

Ionized Carbon Absorbers in High z QSOs

Use QSOs as background beacons to highlight absorbing clouds in the high z intergalactic medium

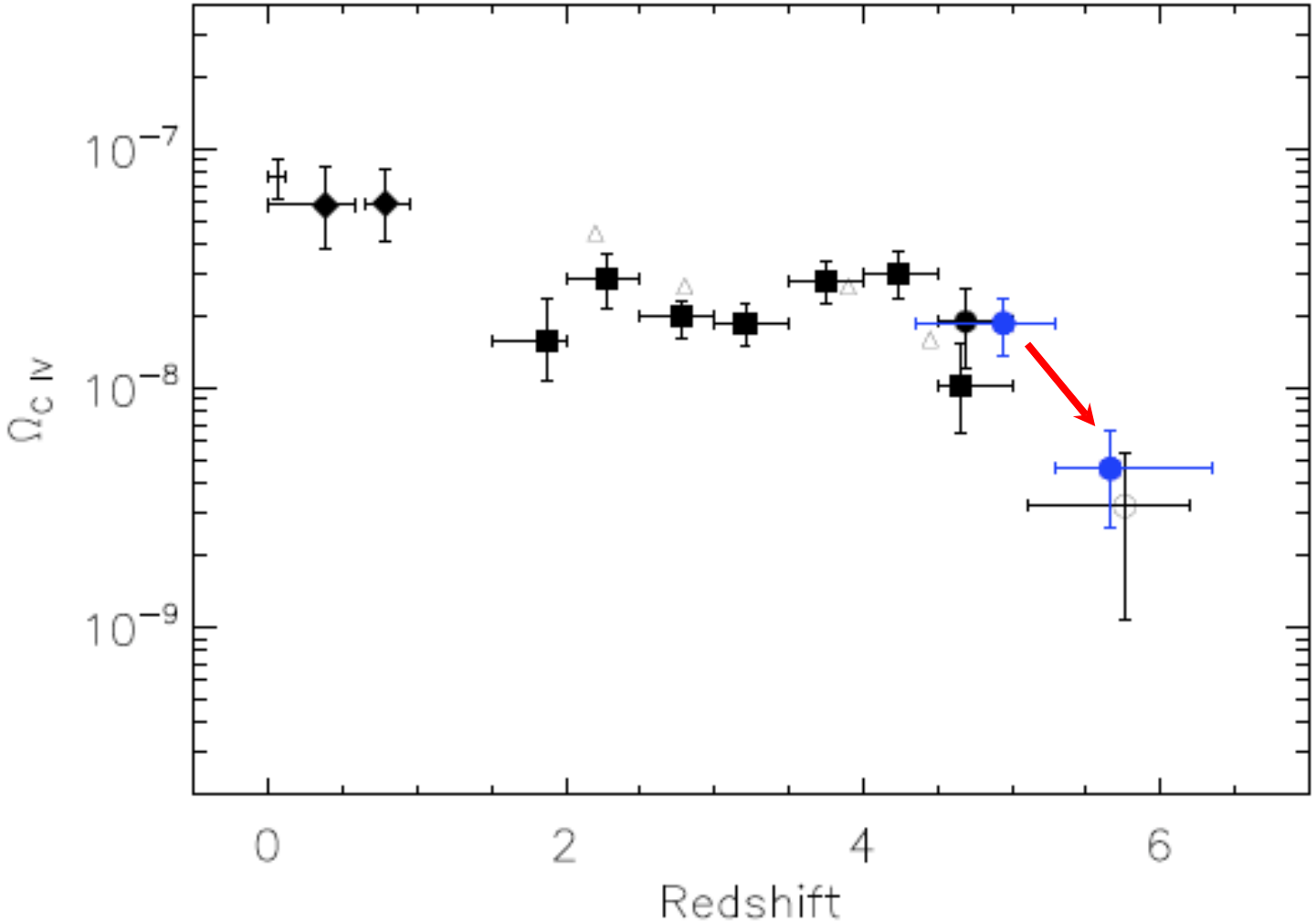




Ryan-Weber et al (2009)

Rapid Drop in Carbon Abundance beyond z~5?

- Near-IR spectra of z > 6 QSOs reveal CIV abundance (Ryan-Weber et al, Simcoe et al)
- Sudden decline over 300 Myr in $\Omega_{CIV}(z)$

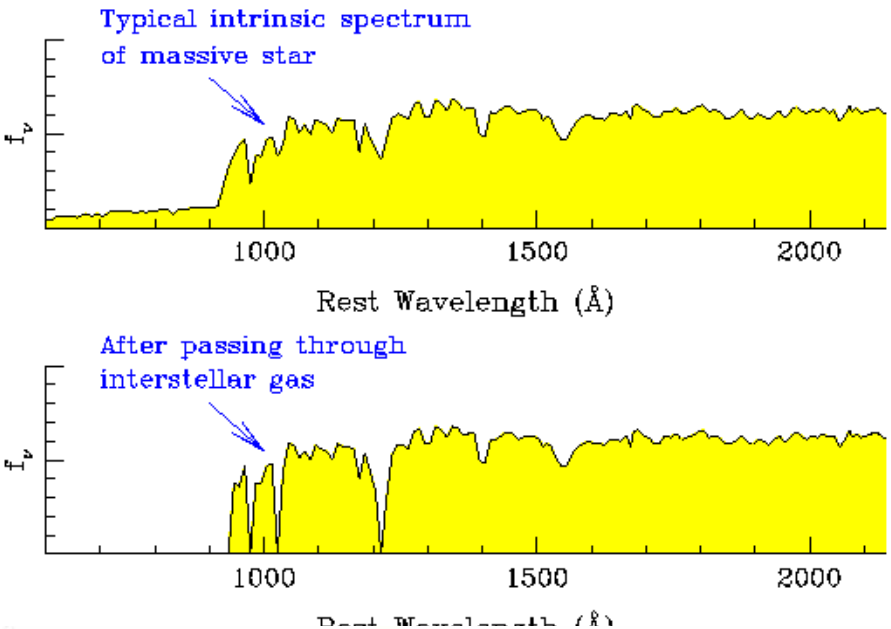


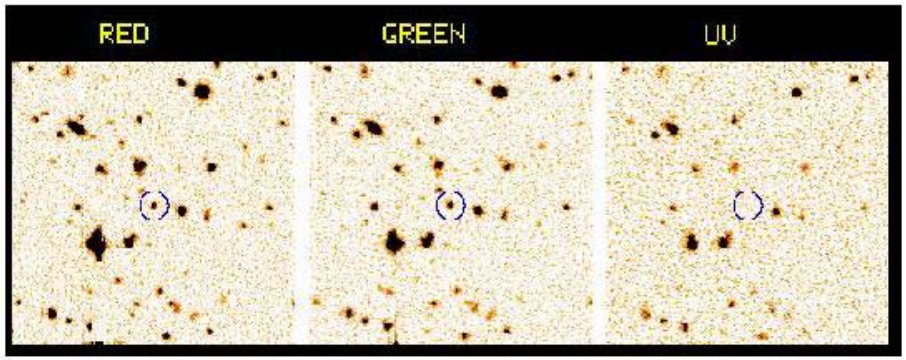
Sudden drop could arise from rapid abundance rise due to early enrichment of galaxy halos <u>or ionization changes?</u>

High Redshift Star Forming Galaxies

Lyman break galaxies (LBGs):

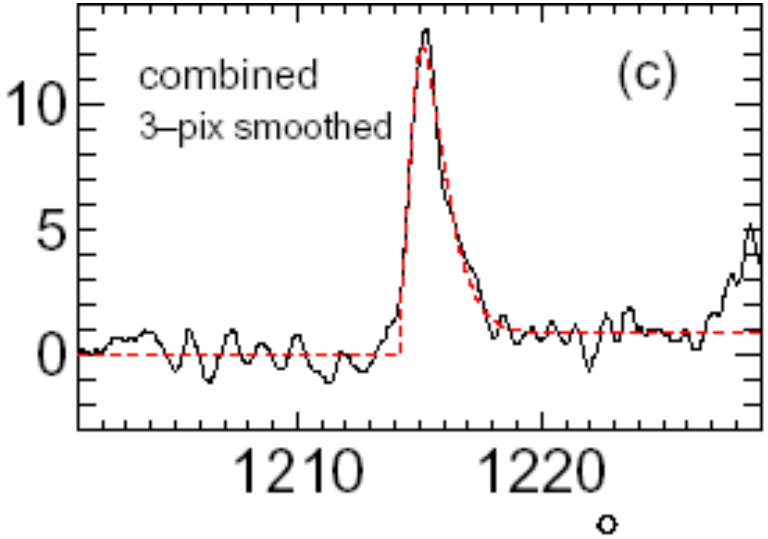
Rest-frame UV continuum discontinuity

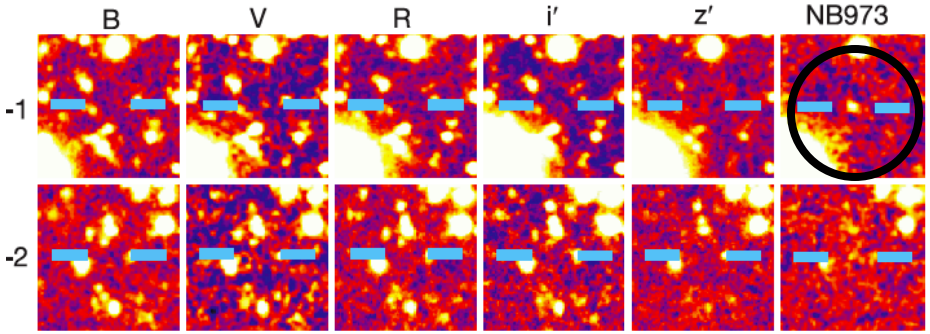




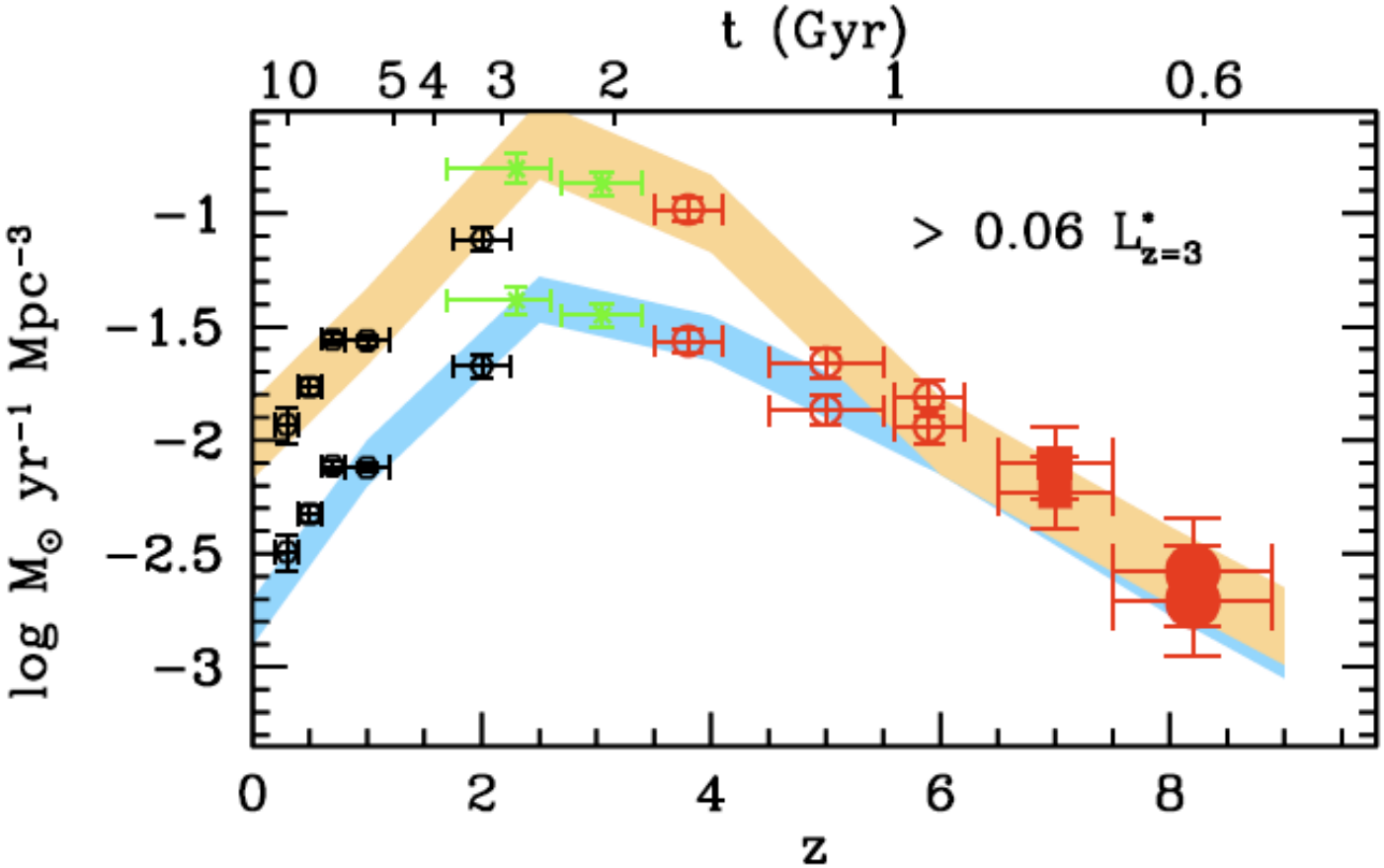
Lyman alpha emitters (LAEs):

Located via narrow band imaging





Star formation density of LBGs



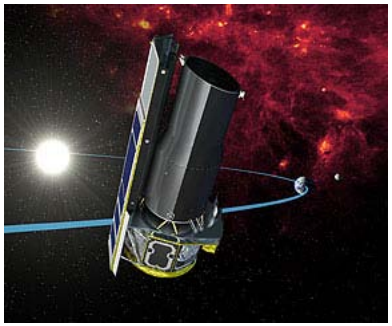
Monotonically declining population to z ~ 6 and beyond

Drop of ×8 in UV luminosity density 2 < z < 6

Appealing indicator: but `observed SF' may be misleading guide

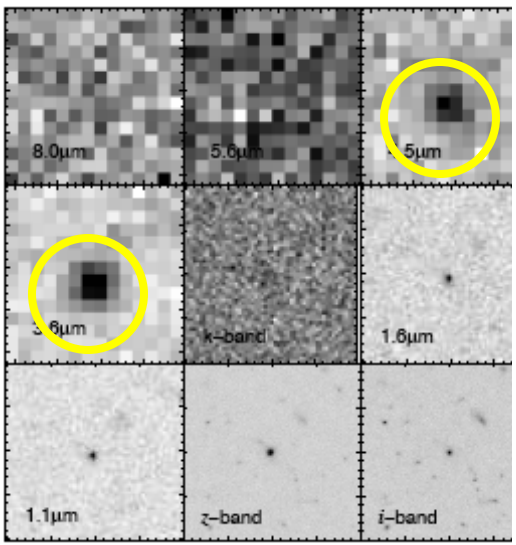
Reddy & Steidel (2009); Bouwens et al (2009, 2011)

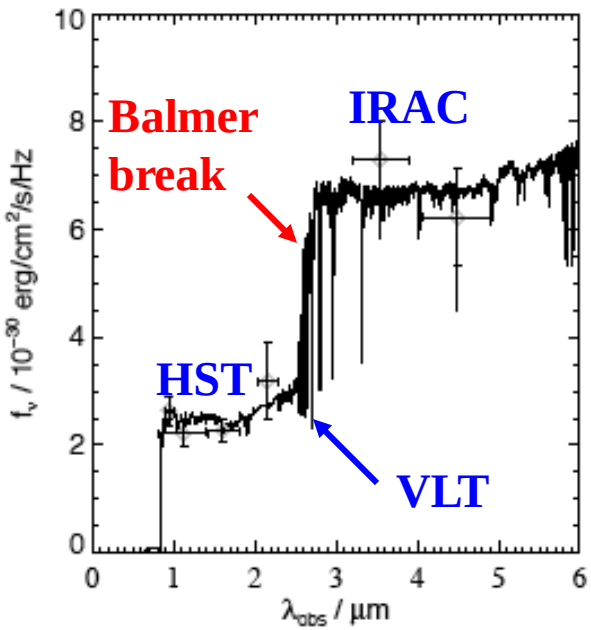
Spitzer Revolution: Stellar Masses & Ages

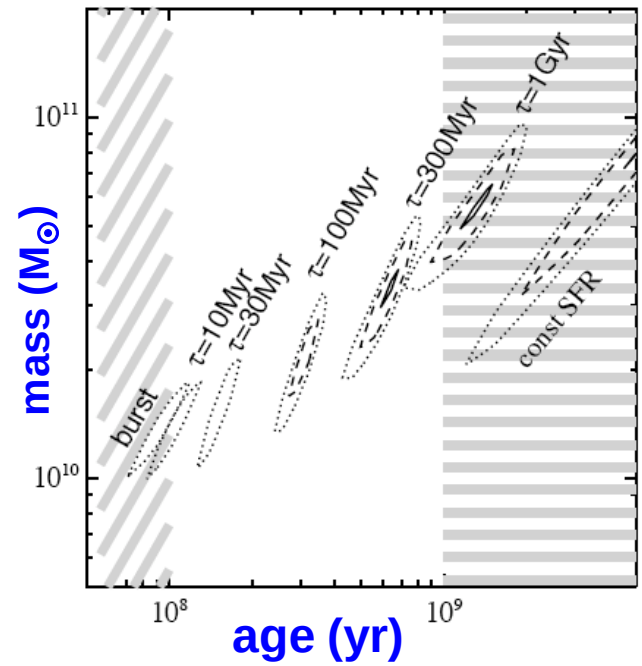


A modest 85cm cooled telescope can see the most distant known objects and provide crucial data on their **assembled stellar masses and ages**

SMB03-1: z_{spec}=5.83 IRAC(3.6μm)=24.2 (AB)
stellar mass = 3.4 10^{10} $M_\odot$ age > 100 Myr

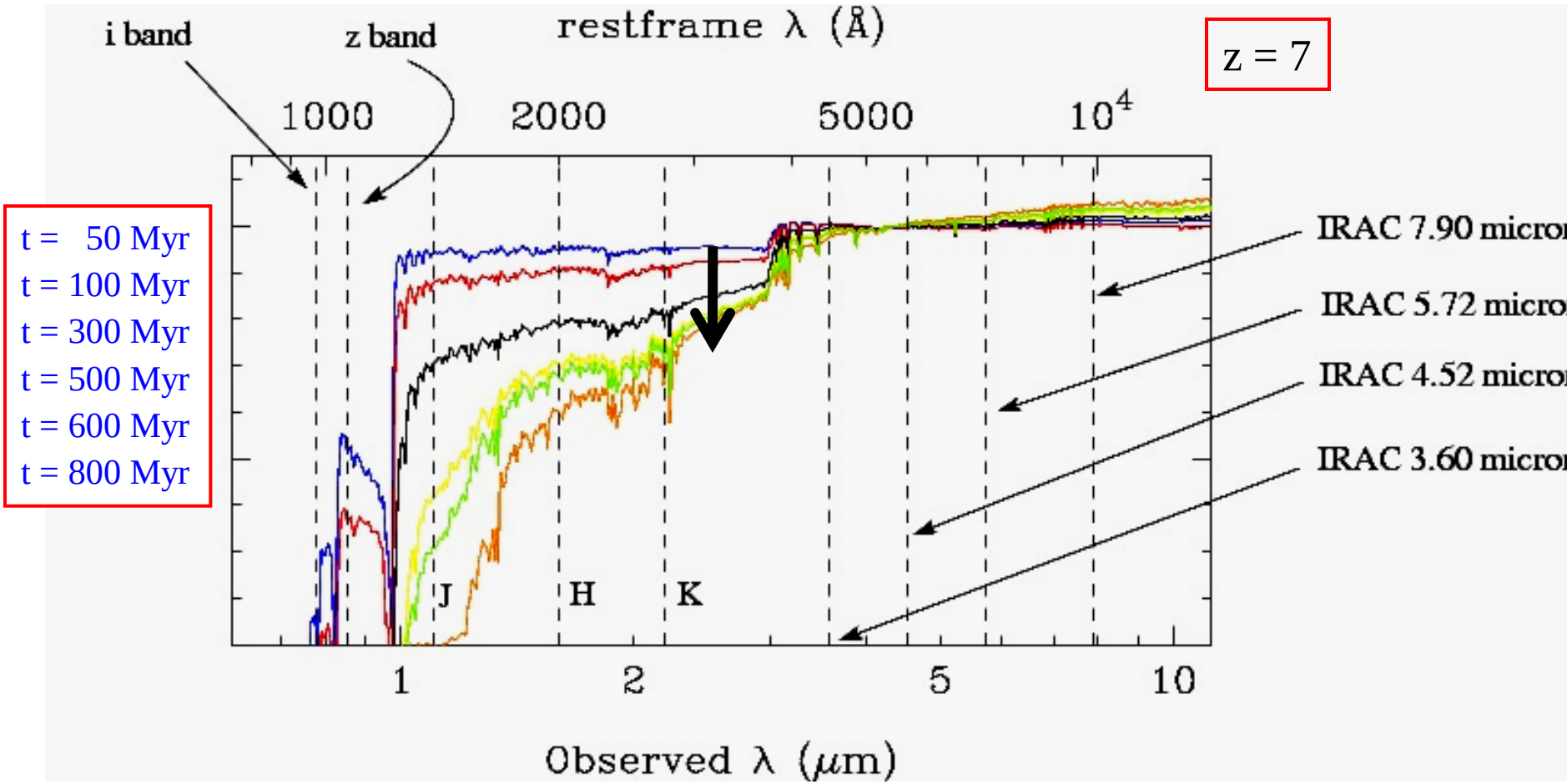






Eyles et al (2005): to produce this mass since z~10 required 5-30 $M_\odot$ yr^{-1} comparable to the ongoing SFR (6-20 $M_\odot$ yr^{-1}) so should see earlier examples if unobscured

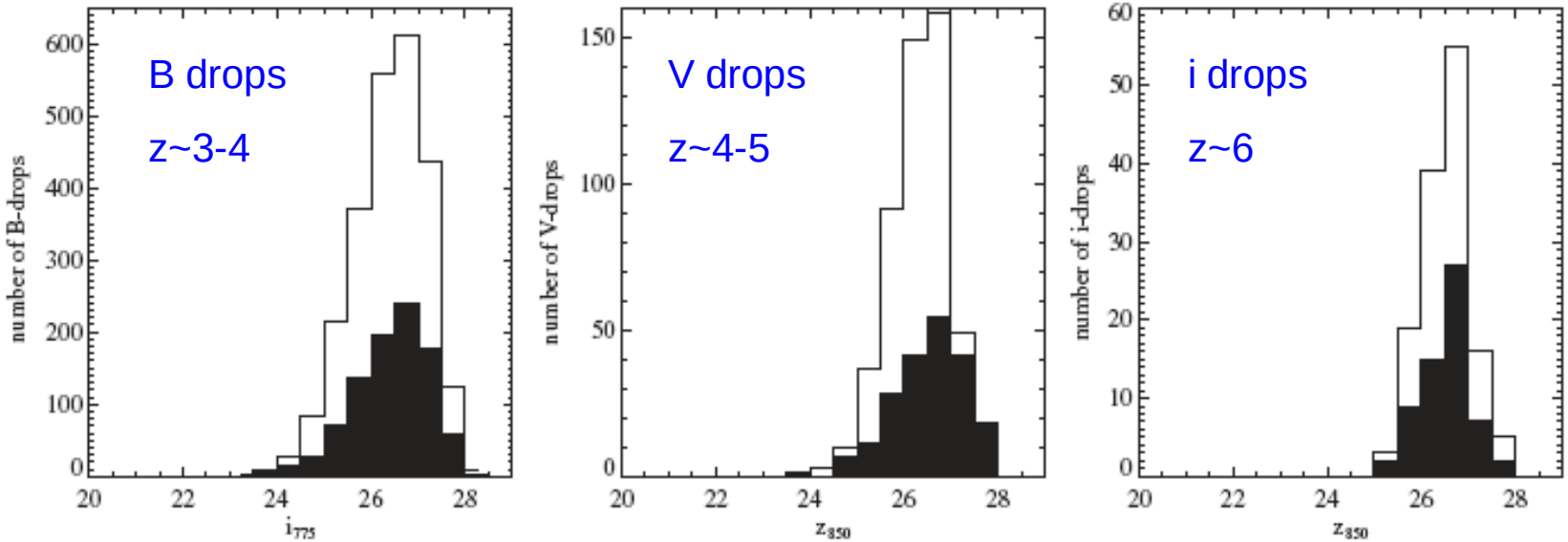
Balmer Break as Age Indicator



Age is degenerate with star formation history but can infer time-averaged star formation rate and compare this with actual on-going star formation rate

Key concern: do nebular emission lines contaminate the IRAC bands?

Stellar Mass Functions 4 < z < 6

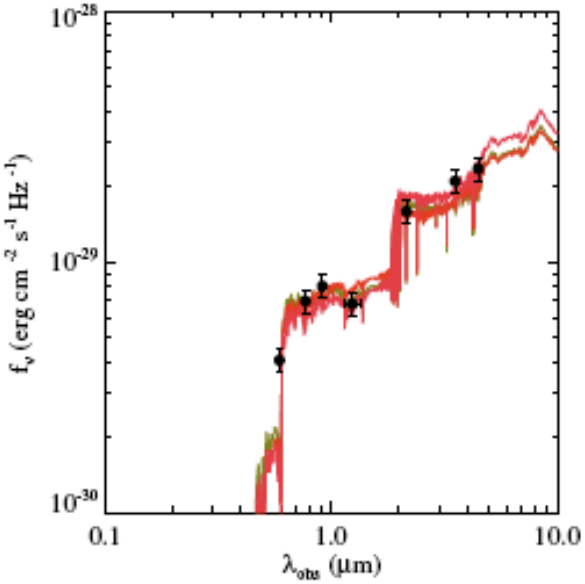


- 2443 B-drops, 506 V-drops, 137 i-drops in ACS GOODS N/S
- 35% sufficiently isolated with Spitzer/IRAC for robust photometry
- Deep K imaging from VLT (Cesarsky), Subaru (Bundy)
- Low z contaminants identified (morphology, MIPS)
- Masses and ages using CB07, testing effect of TP-AGB stars
- Individual measures to $M \sim 10^{9.5}\ M_{\odot}$; stacked properties for fainter sources

Stark et al (2009) Ap J 697, 1493

Examples across the full range of data

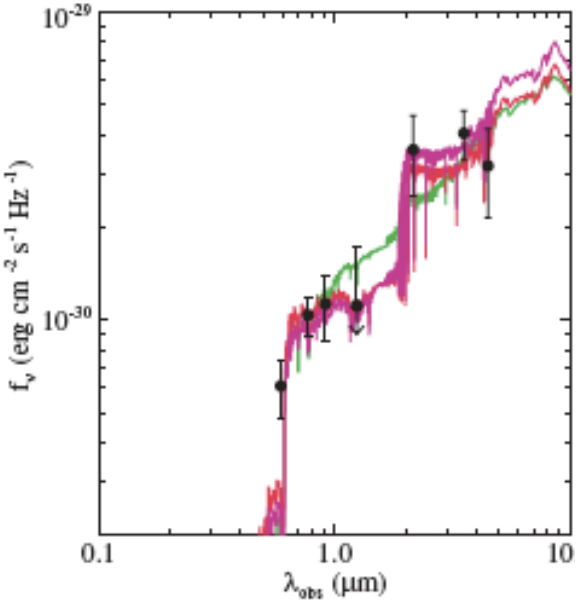
High mass/bright



mass = 2.3 10^{10} $M_\odot$

age = 290 Myr

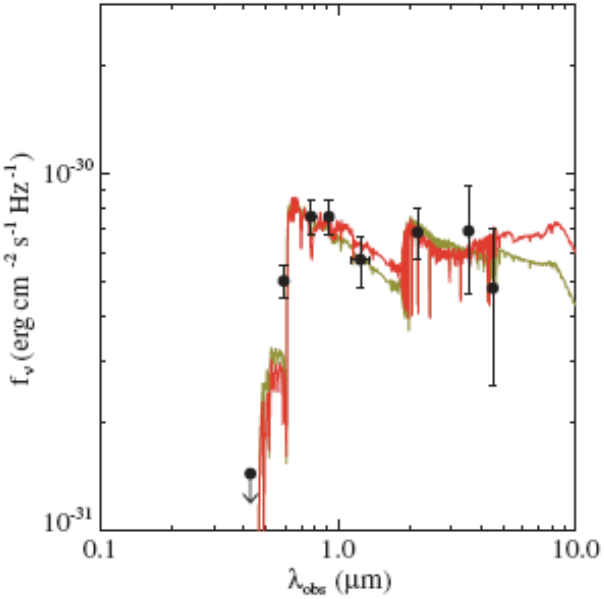
Low mass/faint



mass = 4.8 10^{9} $M_\odot$

age = 320 Myr

Stacked data



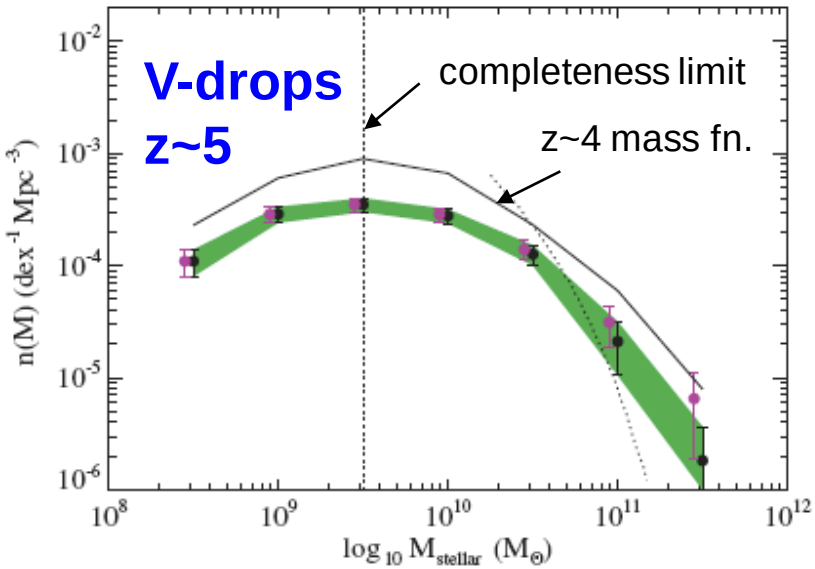
mass = 1.7 10^{8} $M_\odot$

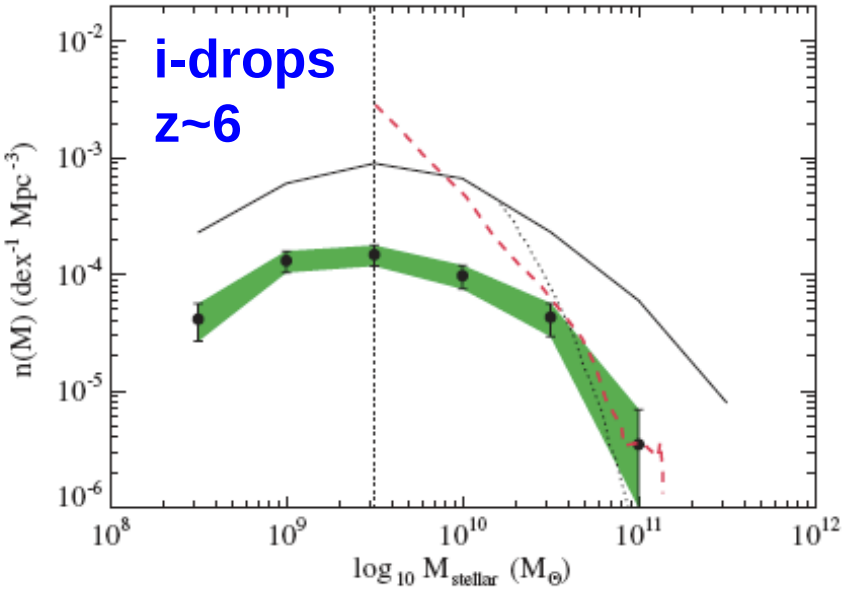
age ~ 50 Myr

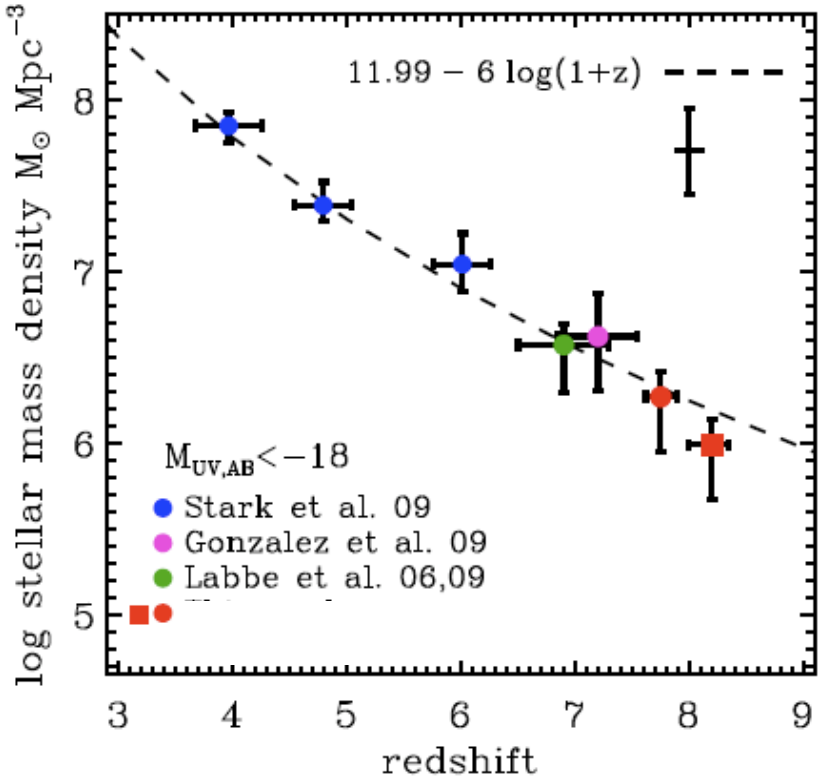
Stark et al Ap J 697, 1493 (2009)

Stellar Mass Density

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



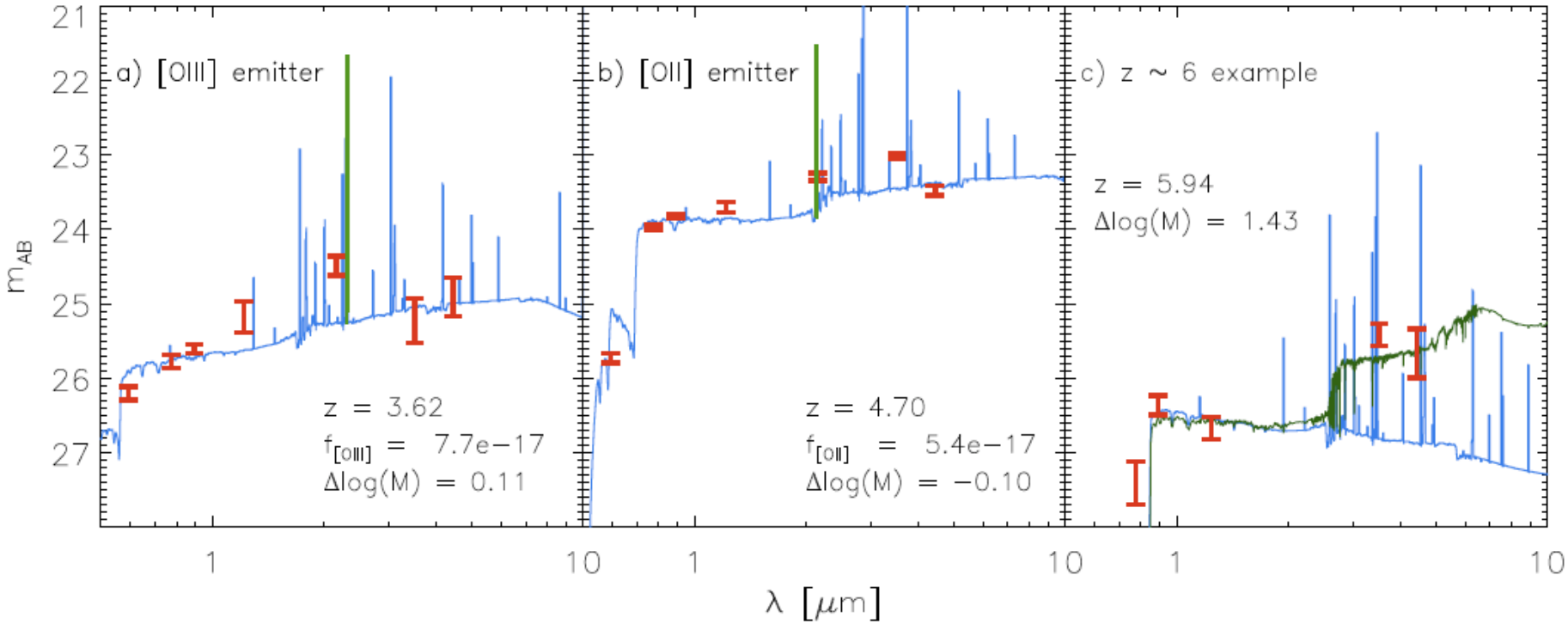




Stellar mass density at z~5-6 implies significant past SF in low luminosity galaxies: perhaps sufficient for reionization?

Stark et al 2007,2009; Labbé et al 2009ab, Gonzalez et al 2010

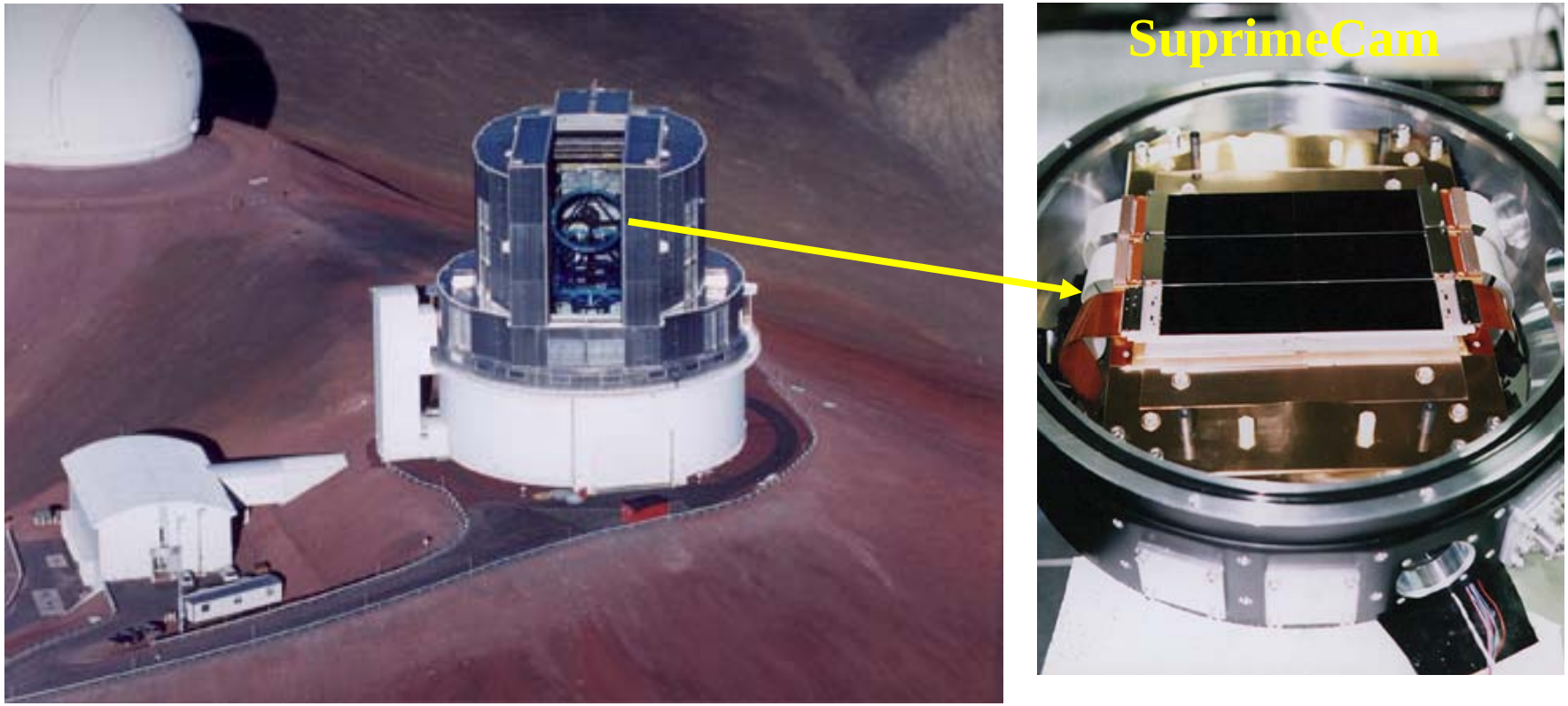
Contamination from Nebular Emission?



- Broad-band HST/Spitzer photometry permits stellar-only & stellar+nebular solutions
- Inclusion of nebular emission can significantly reduce stellar masses, esp. @ z~6
- Spectroscopy of z < 5.7 LBGs is currently the only route to testing this possibility

Shim et al (2011), Atek et al (2011), Stark et al (2011)

Wide Field Imaging of Lyα Emitters from Subaru

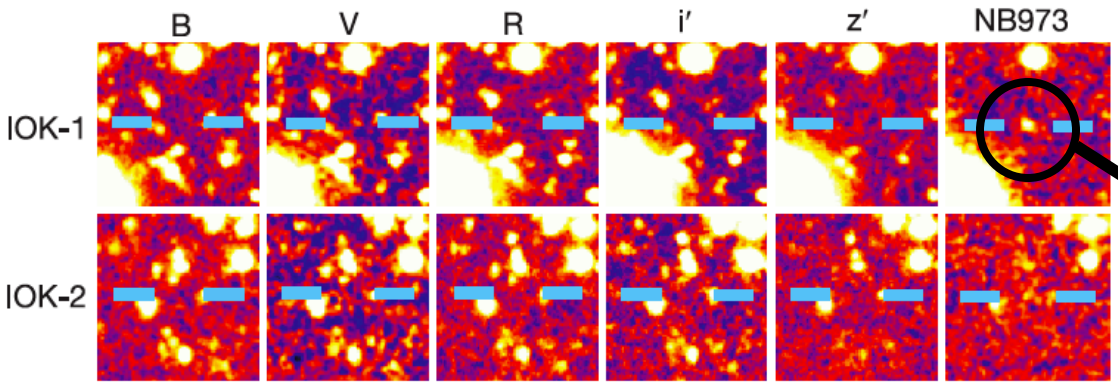


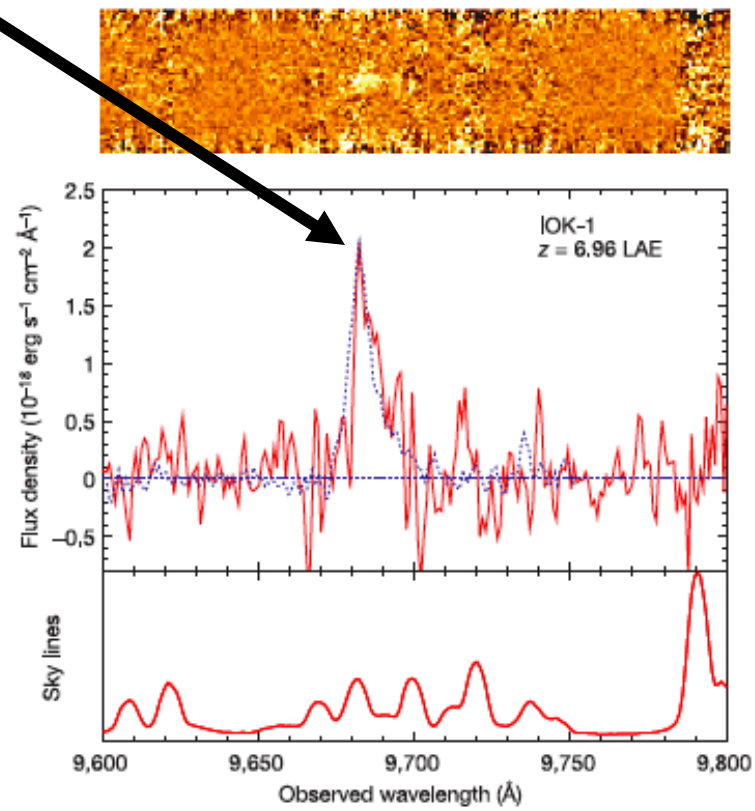
Panoramic imaging with Subaru using narrow-band filters has been used to locate high redshift Lyα emitters (LAEs)

As much as 7% of the total output of a young galaxy can be in this single emission line (so v. efficient for survey work)

A galaxy at a redshift $z = 6.96$

Masanori Iye[1,2,3], Kazuaki Ota[2], Nobunari Kashikawa[1], Hisanori Furusawa[4], Tetsuya Hashimoto[2], Takashi Hattori[4], Yuichi Matsuda[5], Tomoki Morokuma[6], Masami Ouchi[7] & Kazuhiro Shimasaku[2]



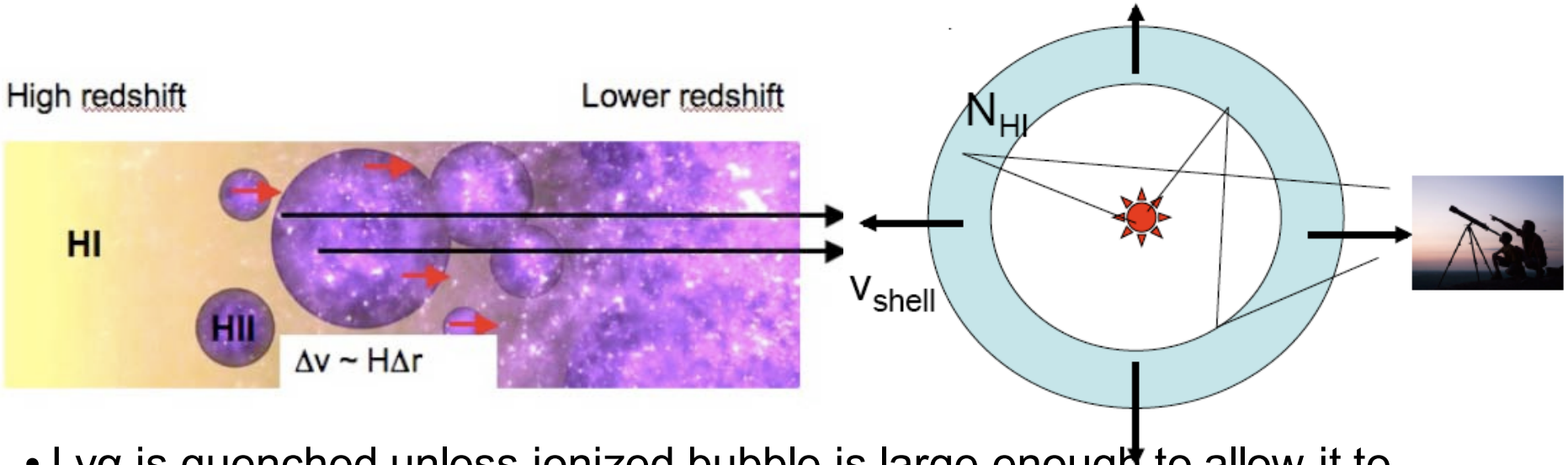


Direct imaging through a narrow band filter with Subaru found 2 candidate z~7 galaxies

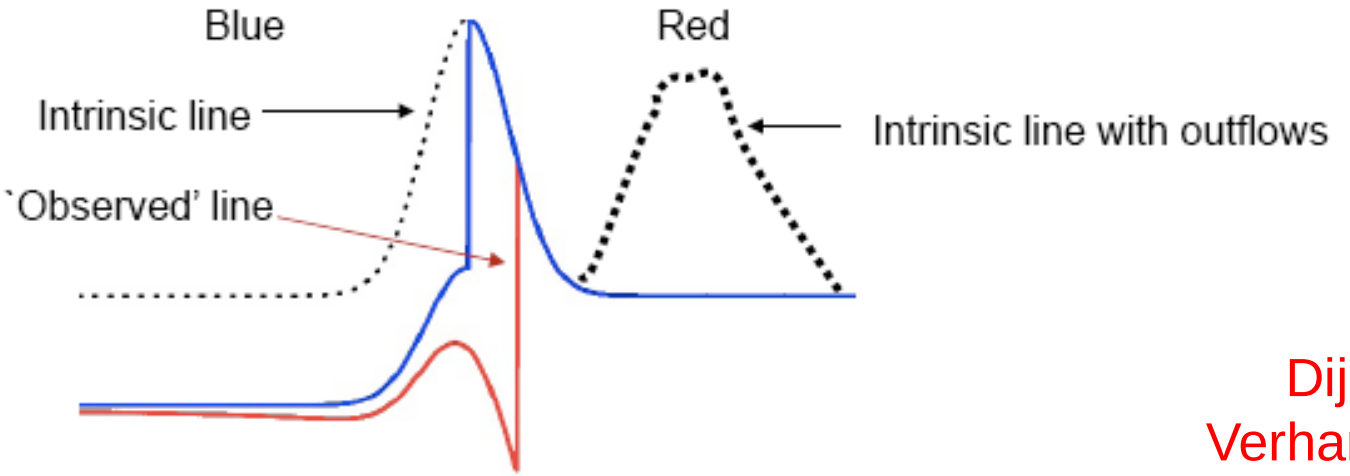
One was spectroscopically confirmed at z=6.96

Iye et al Nature 443, 186 (2006)

Effect of Outflows on Visibility of Lyα



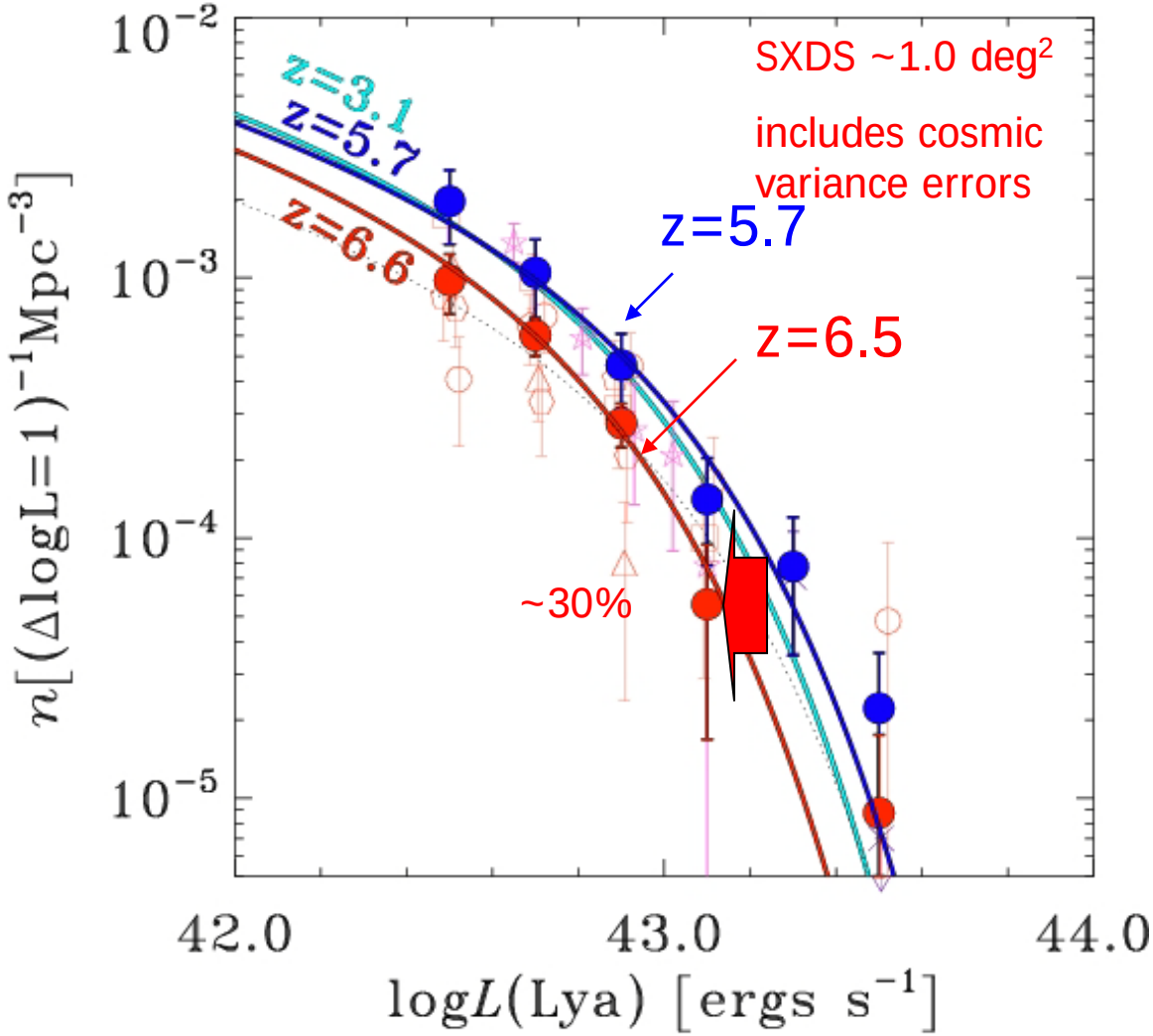
- Lyα is quenched unless ionized bubble is large enough to allow it to redshift out of resonance
- Can model line shape using spherical shells of outflowing HI gas with column density N_{HI} and velocity v_{shell}



Dijkstra et al (2007)
Verhamme et al (2008)

A Rapid Drop in Lyα Emitters from 5.7<z<6.6?

- 1 deg^2 SXDS field with 608 photometric and 121 spectroscopic Lyα emitters
- Tantalizing fading ($0.^m3$) seen in the LF of Ly α emitters over a small redshift interval 5.7< z< 6.6 (150 Myr)
- Does this mark the end of reionization corresponding to an increase in x_{HI} (e.g. x_{HI} ~0.6 at z~7)?

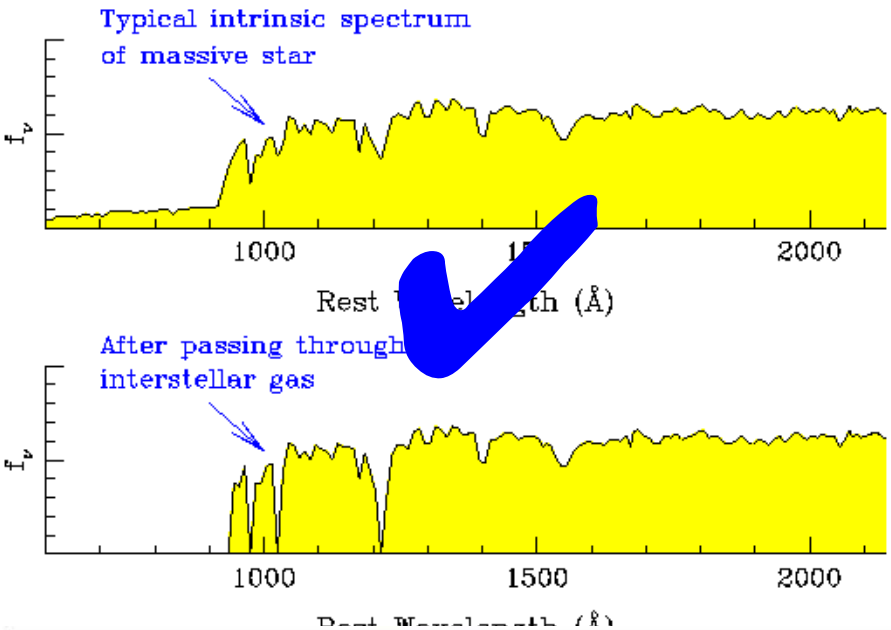


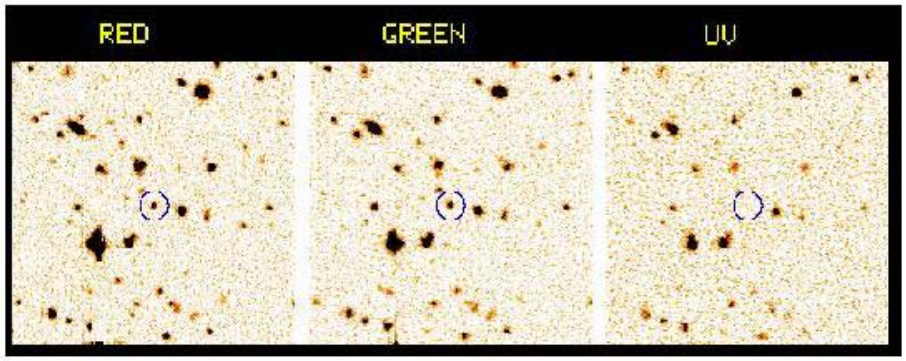
Ouchi et al (2010) Ap J 723, 869

High Redshift Star Forming Galaxies

Lyman break galaxies (LBGs):

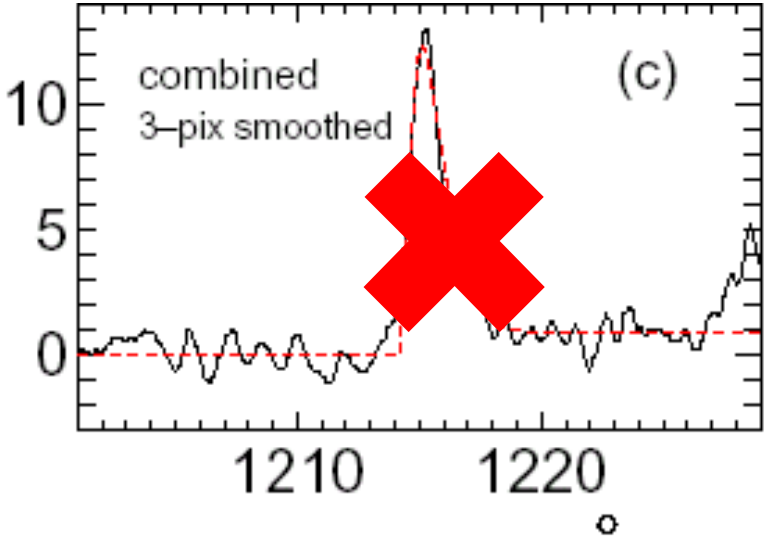
Rest-frame UV continuum discontinuity

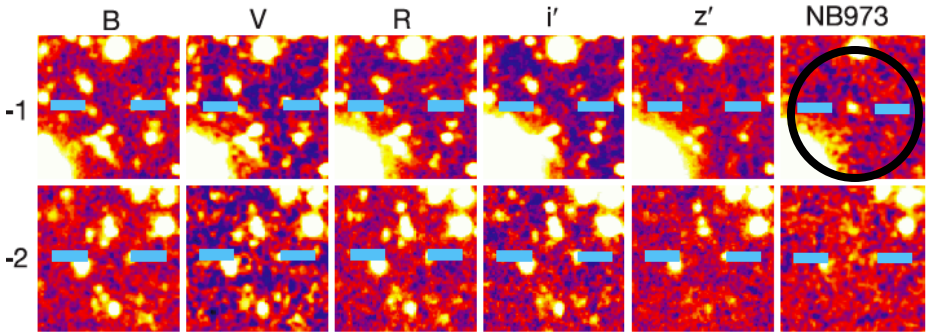




Lyman alpha emitters (LAEs):

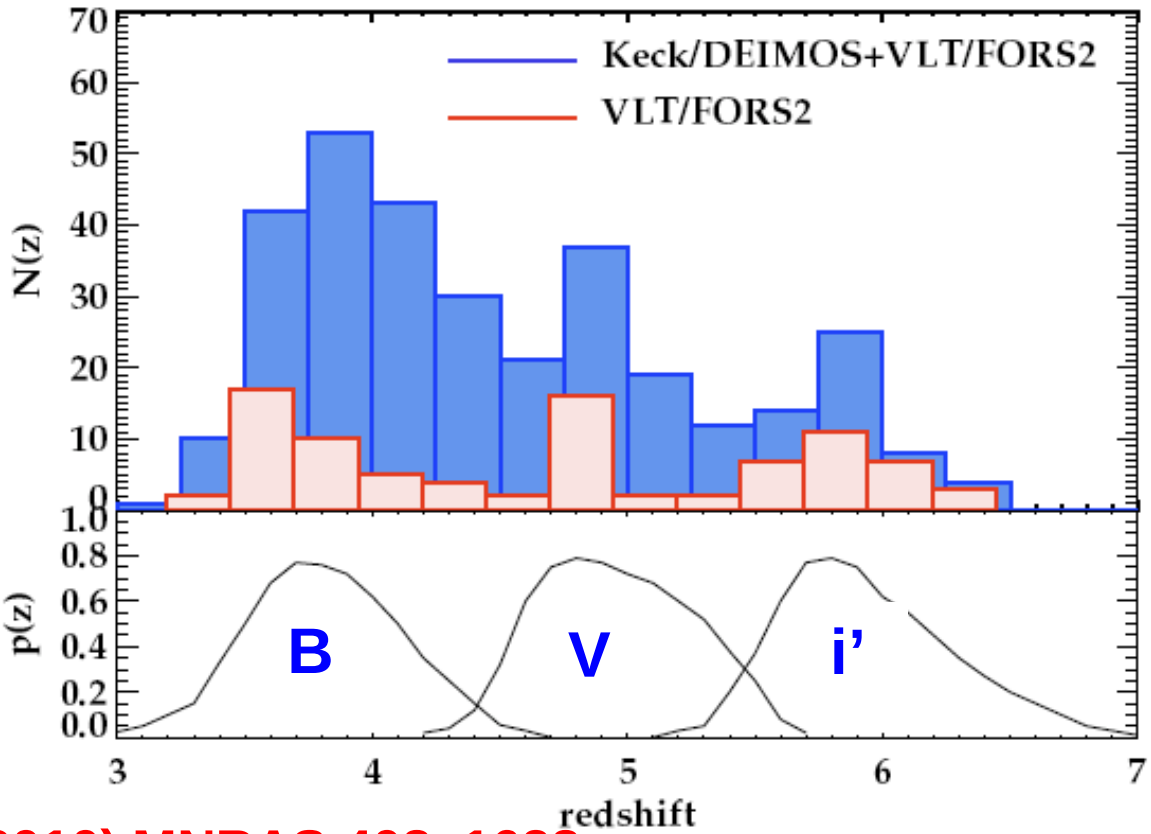
Located via narrow band imaging





Keck Spectroscopic Survey of 4 < z < 7 LBGs

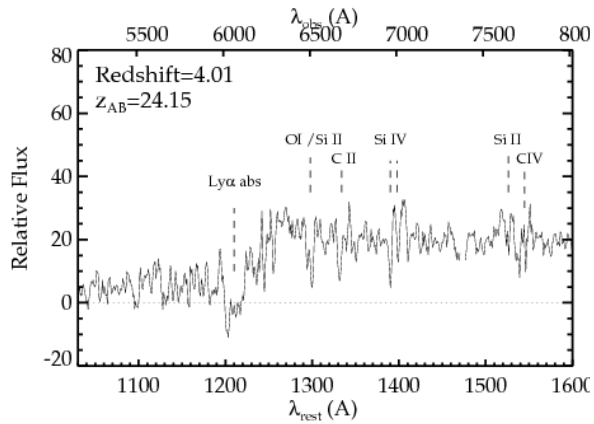
- B, V, i', z drops in GOODS from Stark et al (2009) ACS/IRAC catalog
- 8-16 hr exposures with DEIMOS to m_{AB}=26.5 (emission lines to m_{AB}~27.5)
- Keck/DEIMOS: 361 B + 141 V + 45 I + 17 z-drops = 564 spectra
- VLT/FORS2 retro-selected + same criteria: 195 spectra (Vanzella et al)



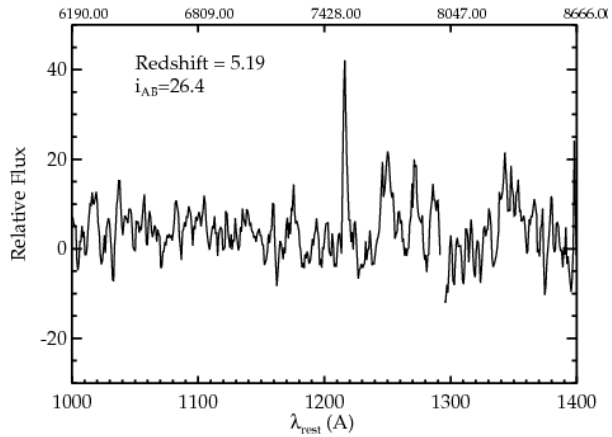
Stark et al (2010) MNRAS 408, 1628

Sample Keck Spectra (R~2500)

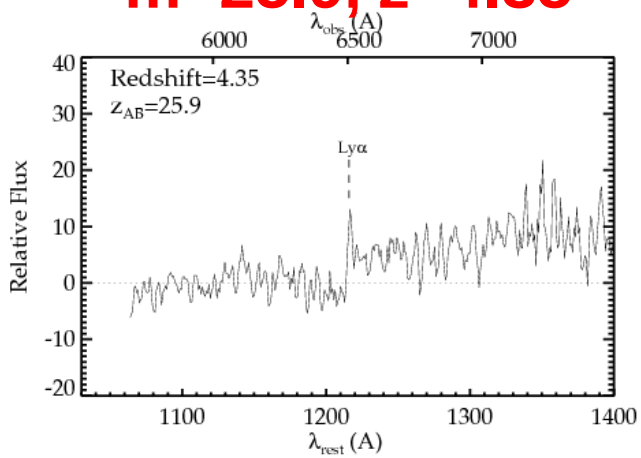
m=24.15, z=4.01



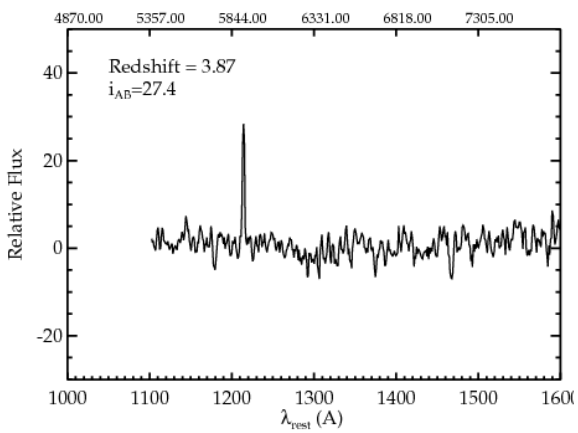
m=26.4, z=5.19



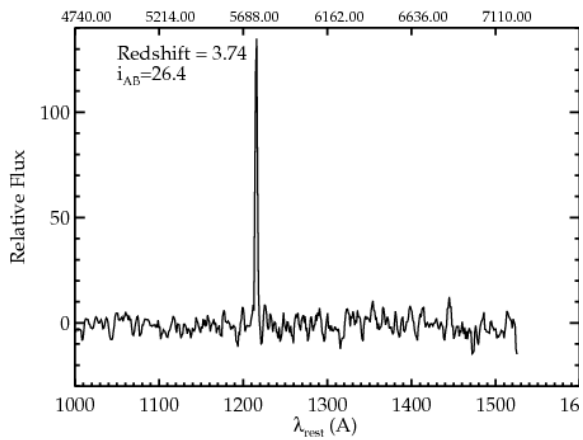
m=25.9, z=4.35



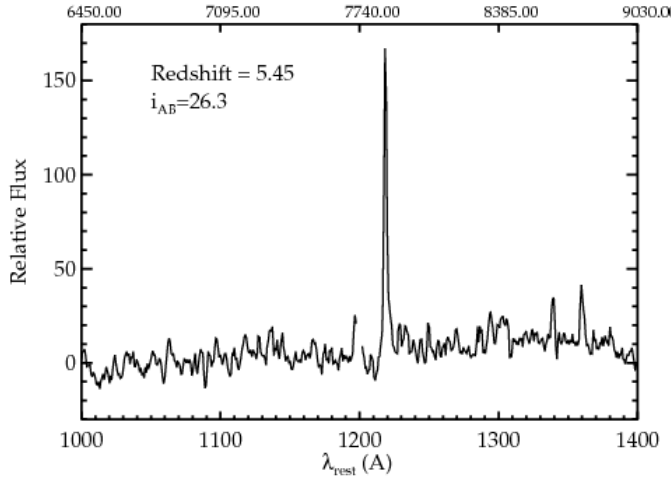
m=27.4, z=3.87



m=26.4, z=3.74

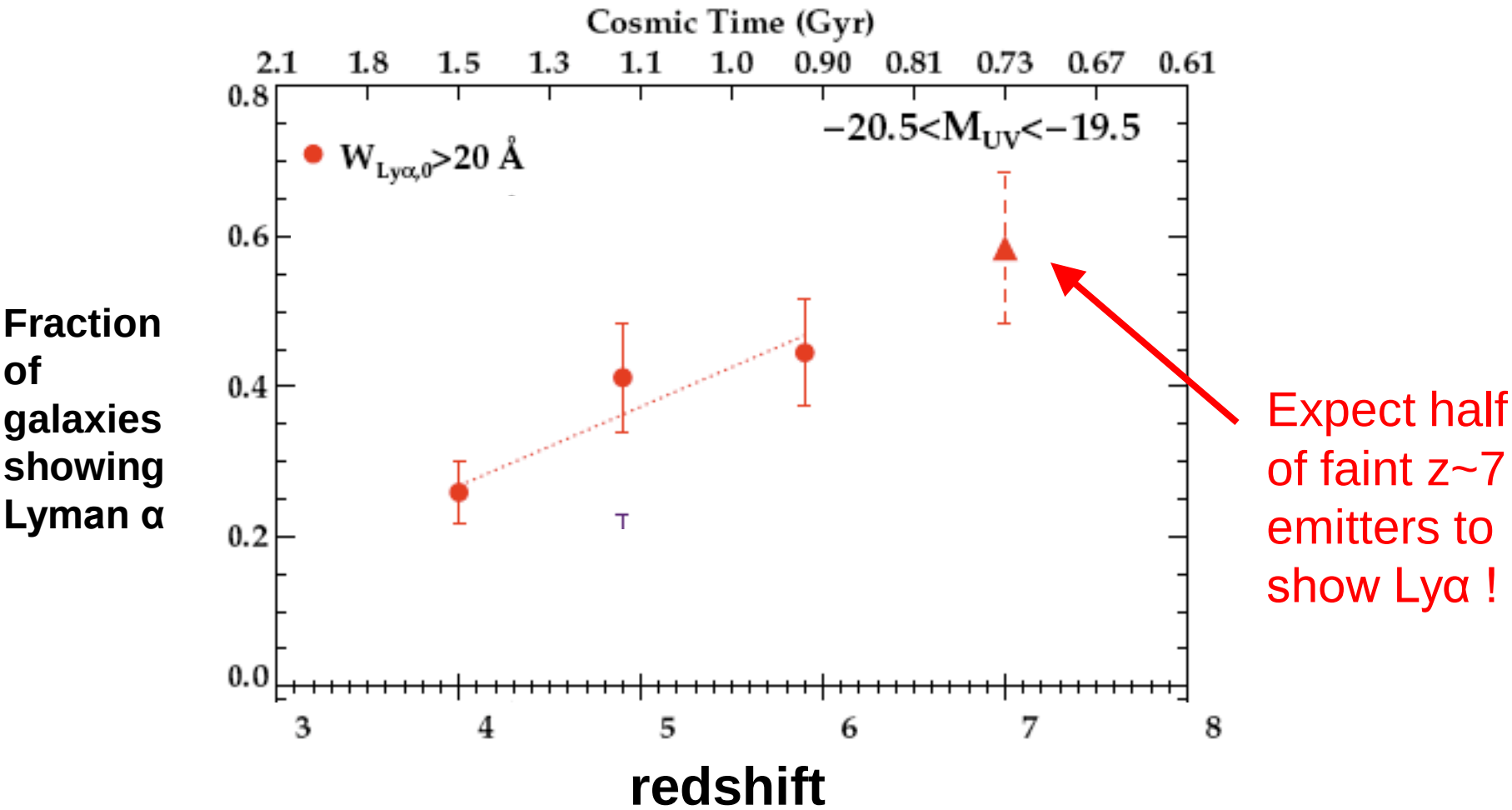


m=26.3,z=5.45



Stark et al (2010) MN 408, 1628

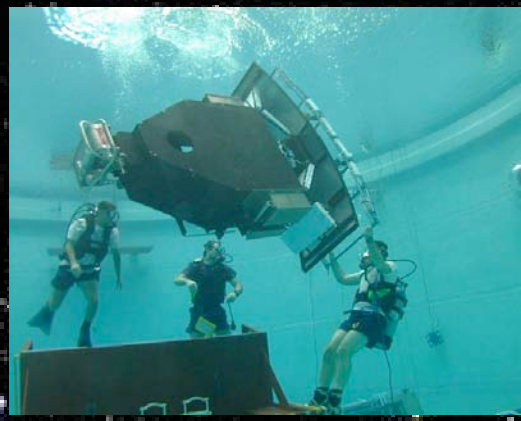
`Lyman α Visibility' versus Redshift



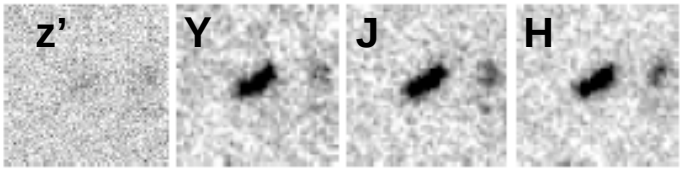
- We see a rising visibility with redshift to z~6
- Suggests should be straightforward to detect emission in z > 7 sources

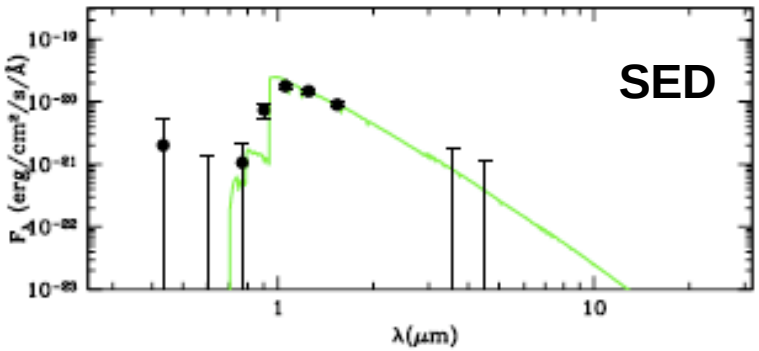
Stark, Ellis & Ouchi (2011) Ap J 728, L2

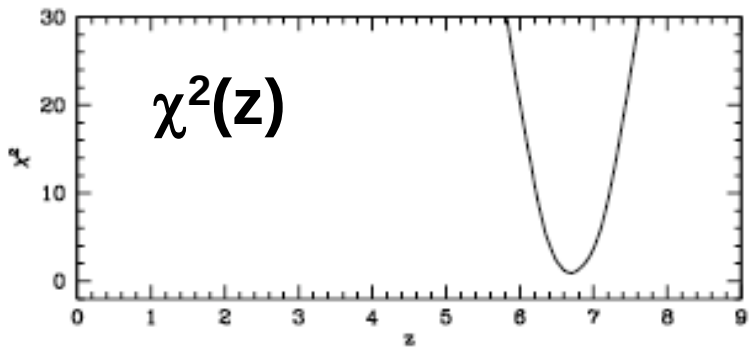
Hubble Ultradeep Field



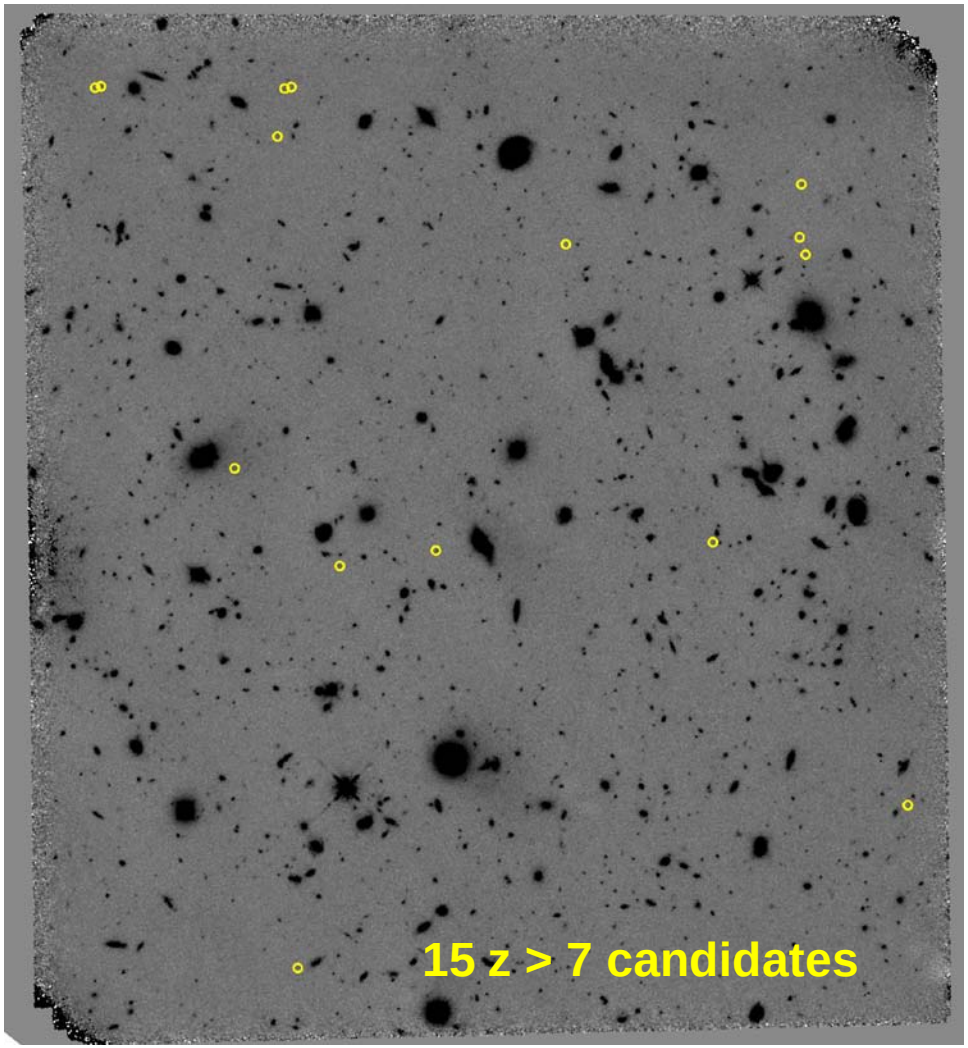
z >7 candidates from WFC3 UDF campaign







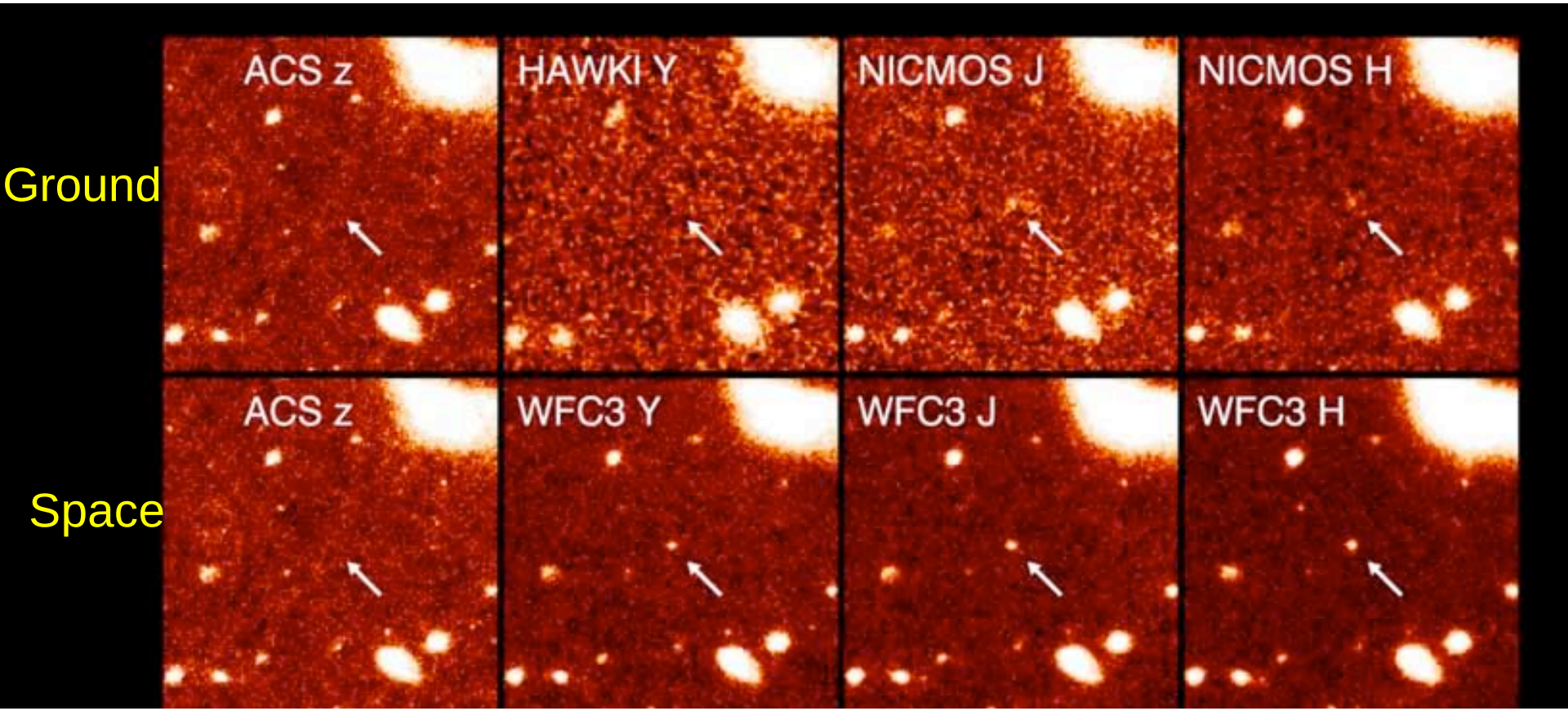
688: $z_{est} = 6.70\,(6.50 - 6.90)$



3 IR filters c.f. 2 leads to more secure photometric redshifts and reliable UV continuum slopes

McLure et al (2009, 2010)

The Space Advantage



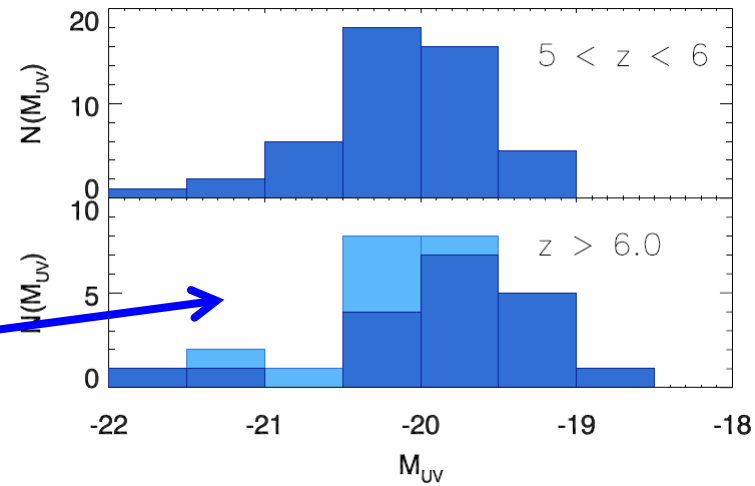
We now have over 100 z>7 candidates from the various Hubble campaigns using WFC3/IR!

Spectra of 26 WFC3 selected LBGs $6.3<z_{photo}<8$

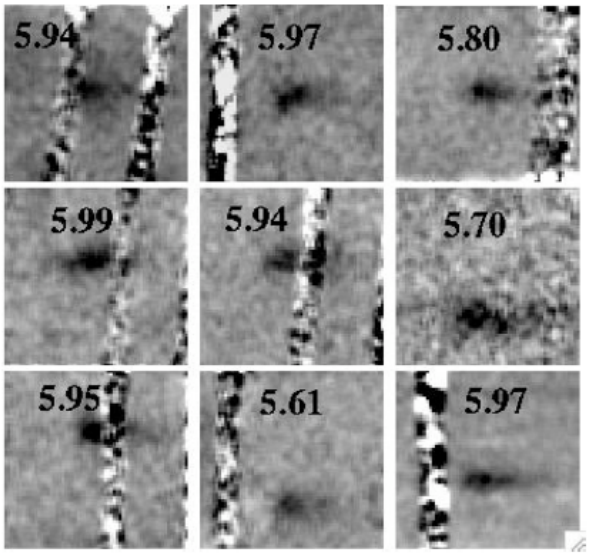
Keck NIRSPEC/LRIS-R spectra of 19 z>6.3 WFC3-IR LBGs from UDF, ERS, lensing clusters

Plus 7 Hawk-I/WFC3-IR FORS-2 spectra from Fontana et al (2010)

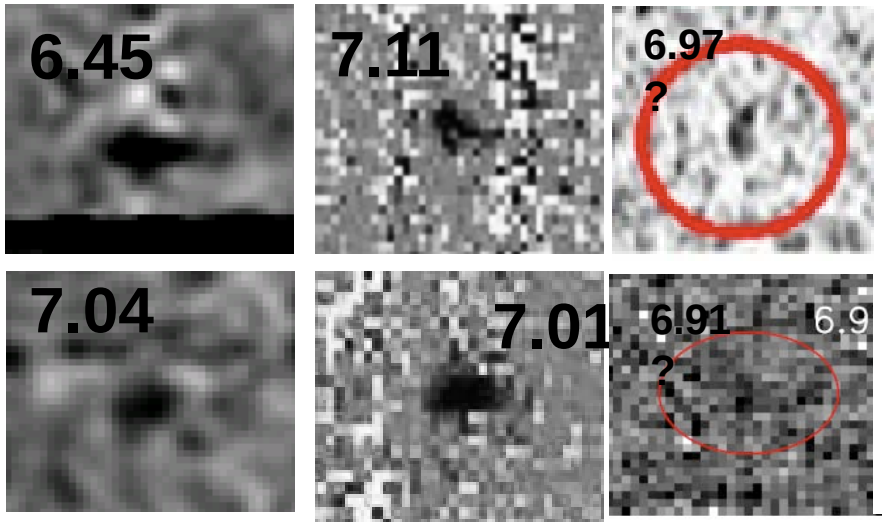
Luminosity distribution c.f. 5<z<6 sample



z~6 emitters

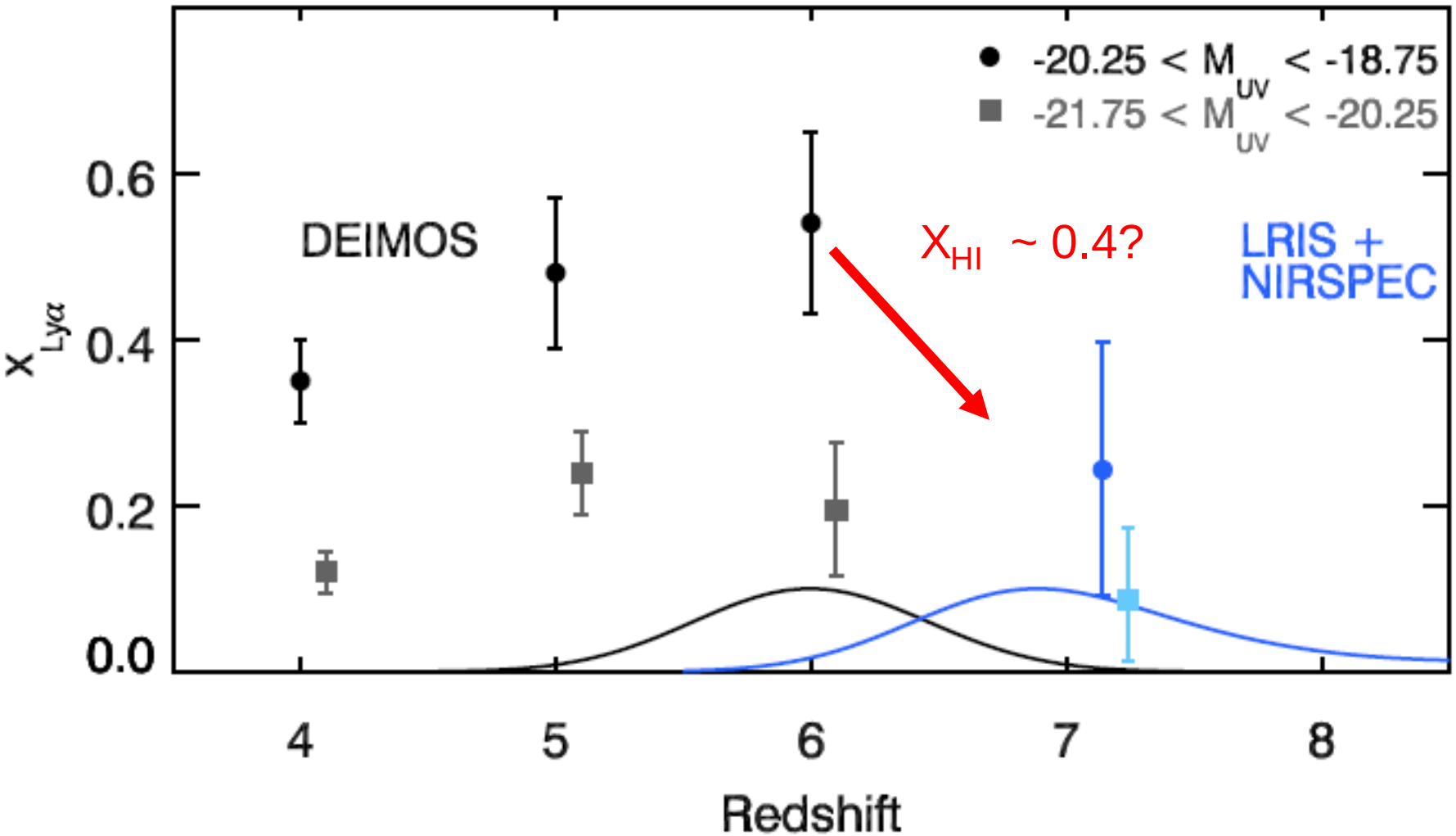


New z > 6.3 emitters



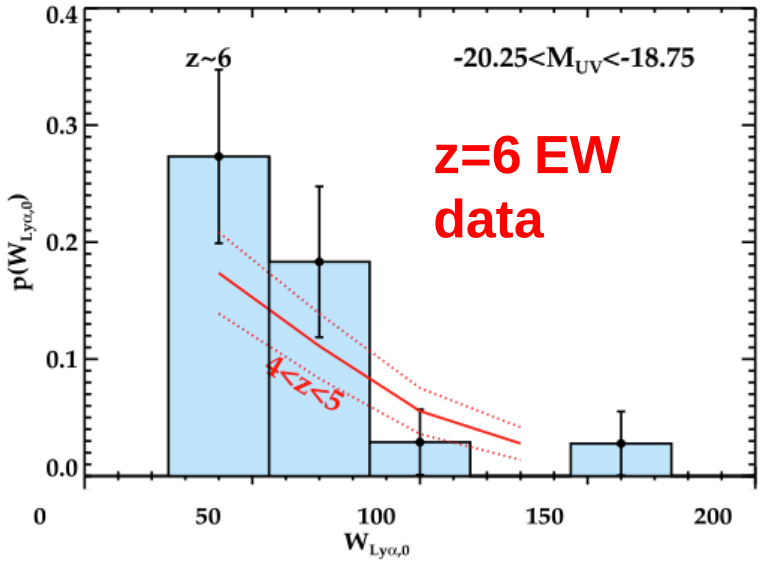
Schenker et al (2011) astro-ph/1107.1261

Sudden Decline in Lyα Fraction in LBGs

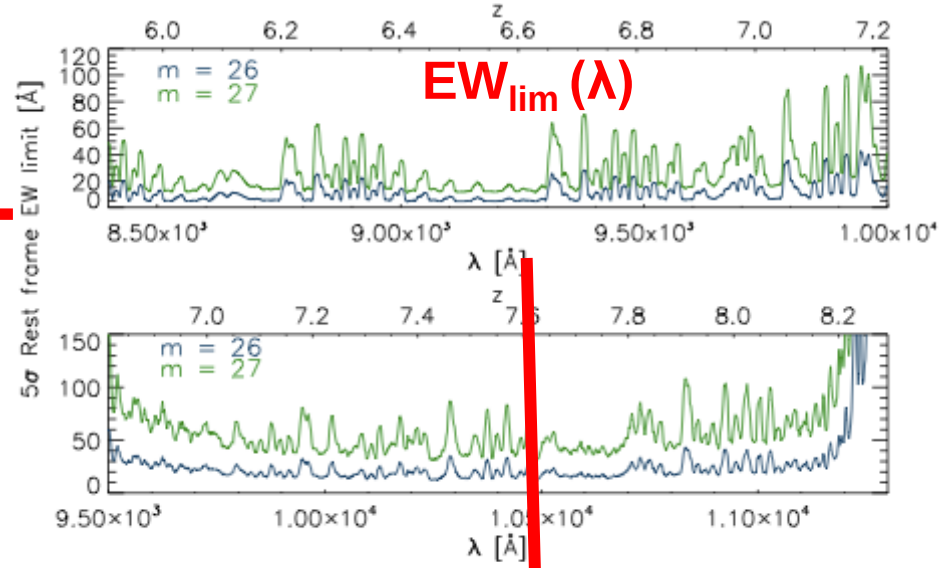


Schenker et al (astro-ph/1107.1261)
also Pentericci et al (astro-ph/1107.1376), Ono et al (astro-ph/1107.3159)

Monte Carlo Simulations

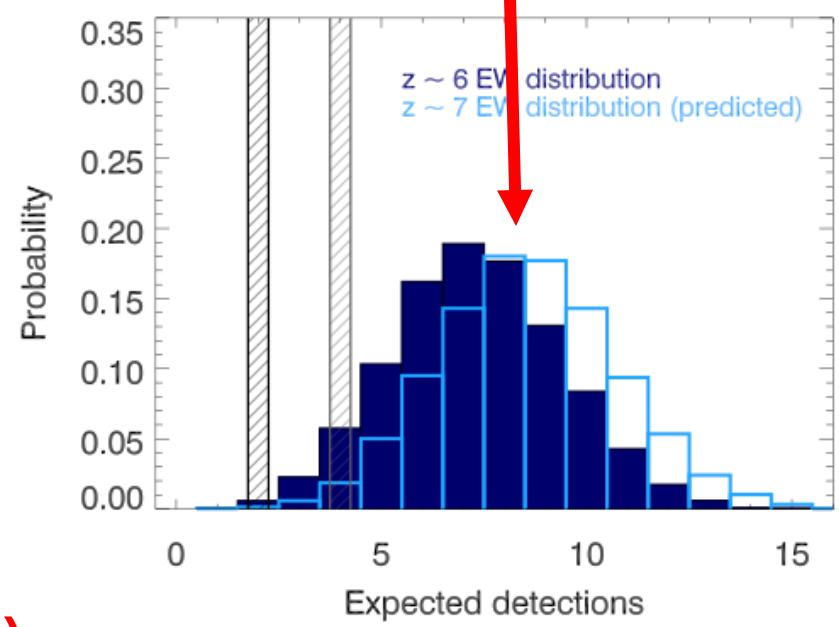


+



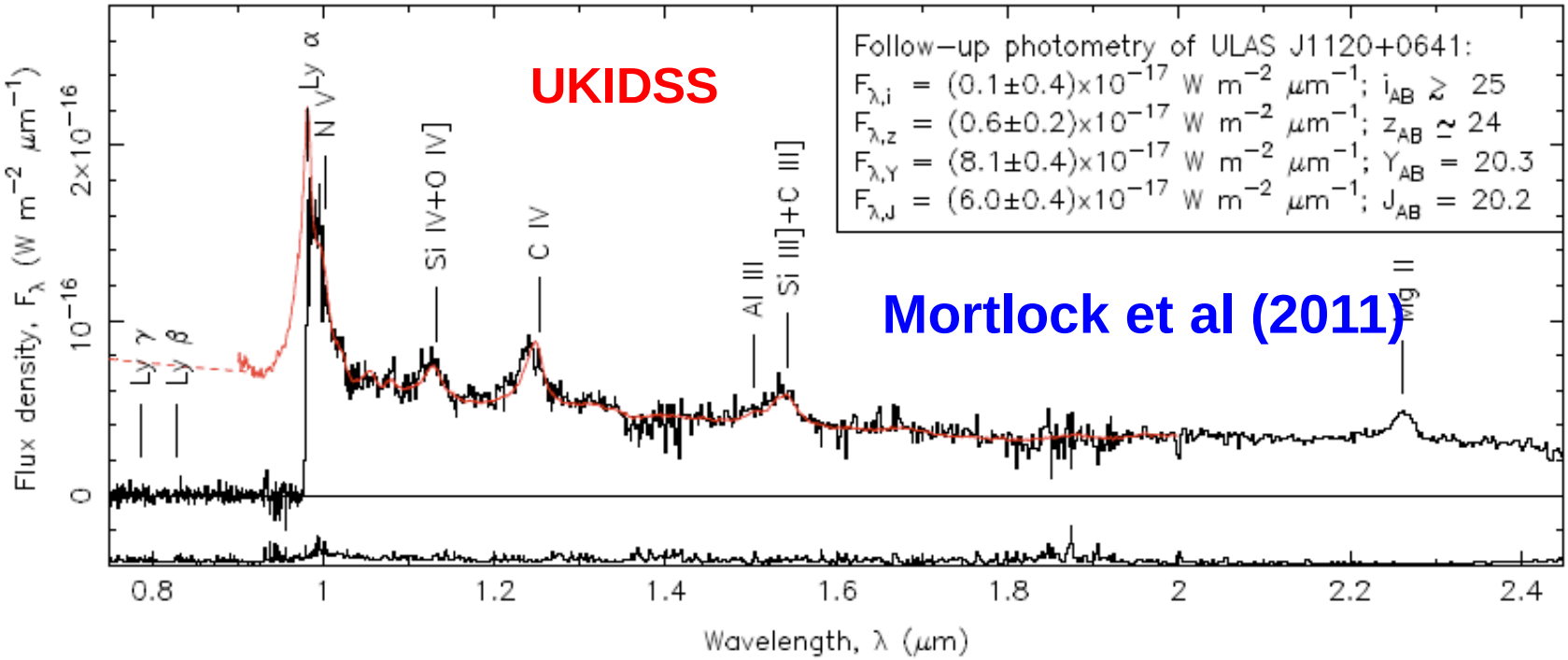
Since we cannot conduct a perfectly uniform search for line emission in the near-IR, we take the expected EW distribution of Lyα at z~7 and predict, given the observations and photometric p(z) of our targets how many lines we should have seen.

Observe 2(4) and expect 8-9 detections.

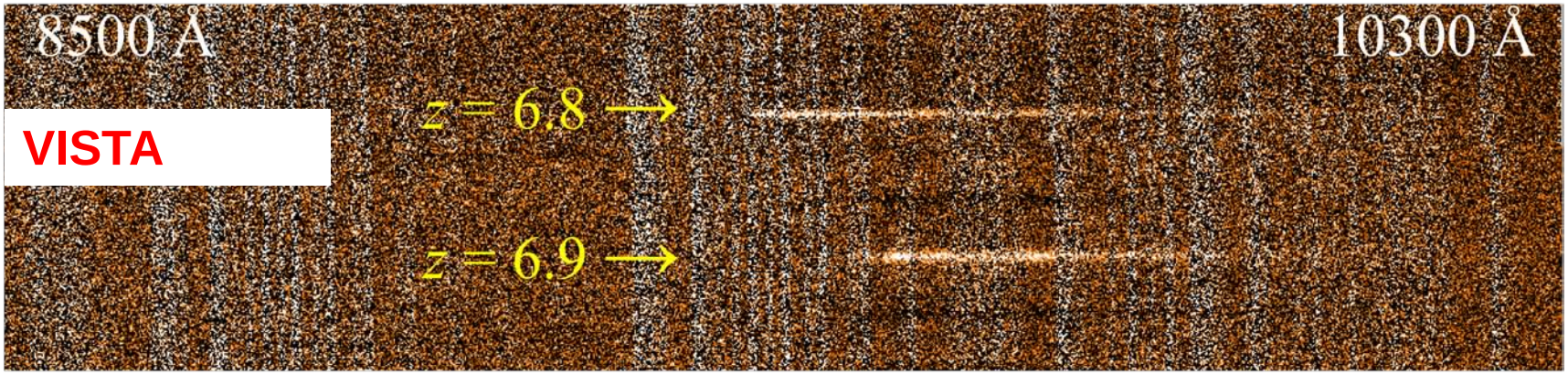


Schenker et al (astro-ph/1107.1261)

z~7 QSOs!



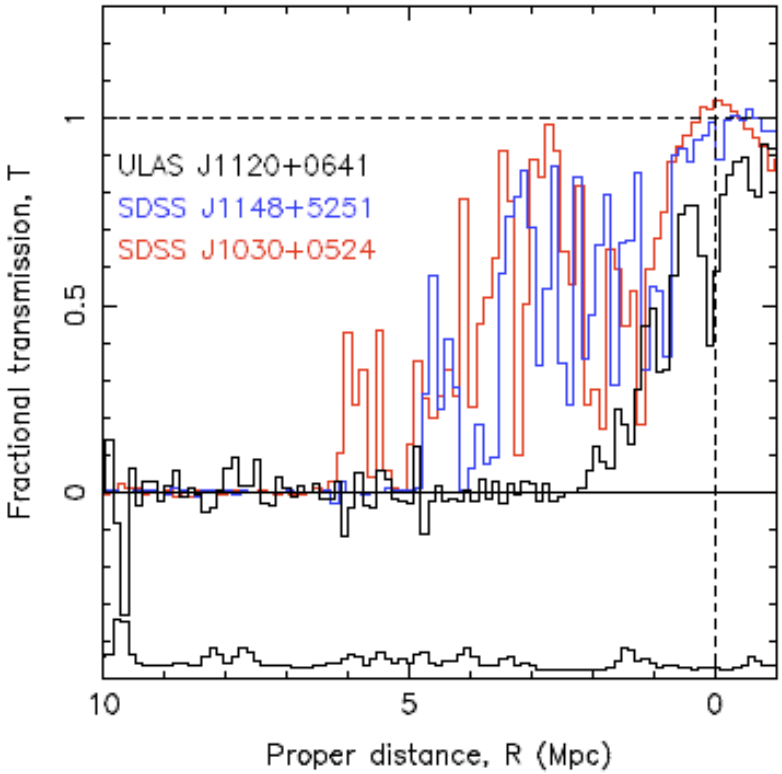
Mortlock et al (2011)

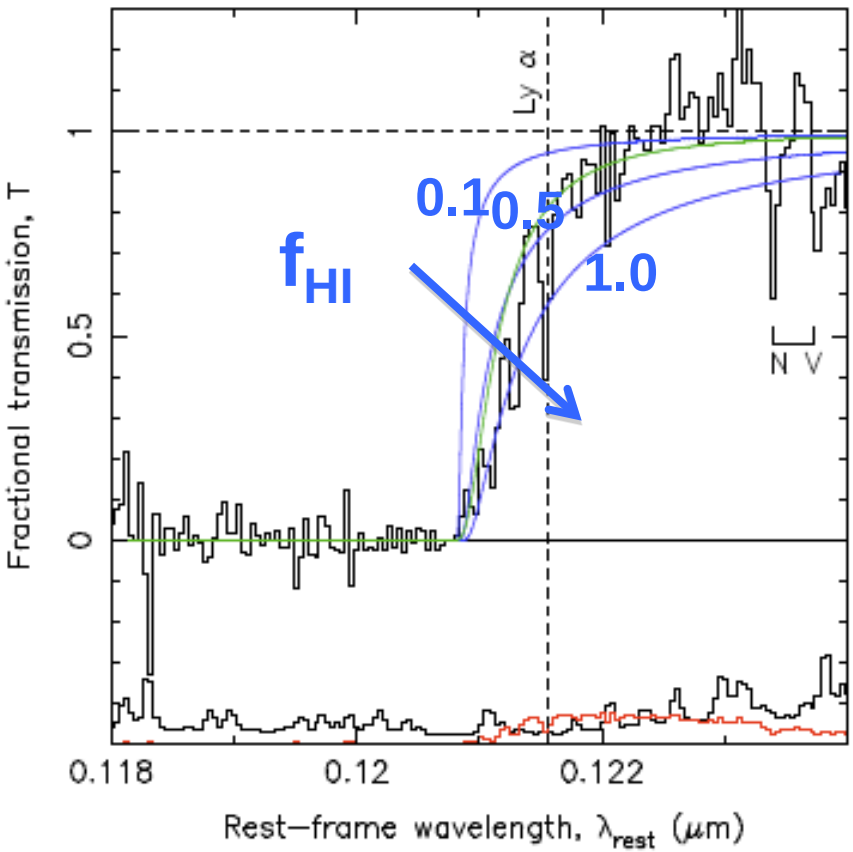


Venemans et al (in prep)

Further Evidence: Damping Wing in z=7.085 QSO?

Fit both near-zone radius & damping wing to red side of Lyα
Suggests $x_{HI} > 0.1$ at z~7
A proximate DLA is an alternative explanation but unlikely

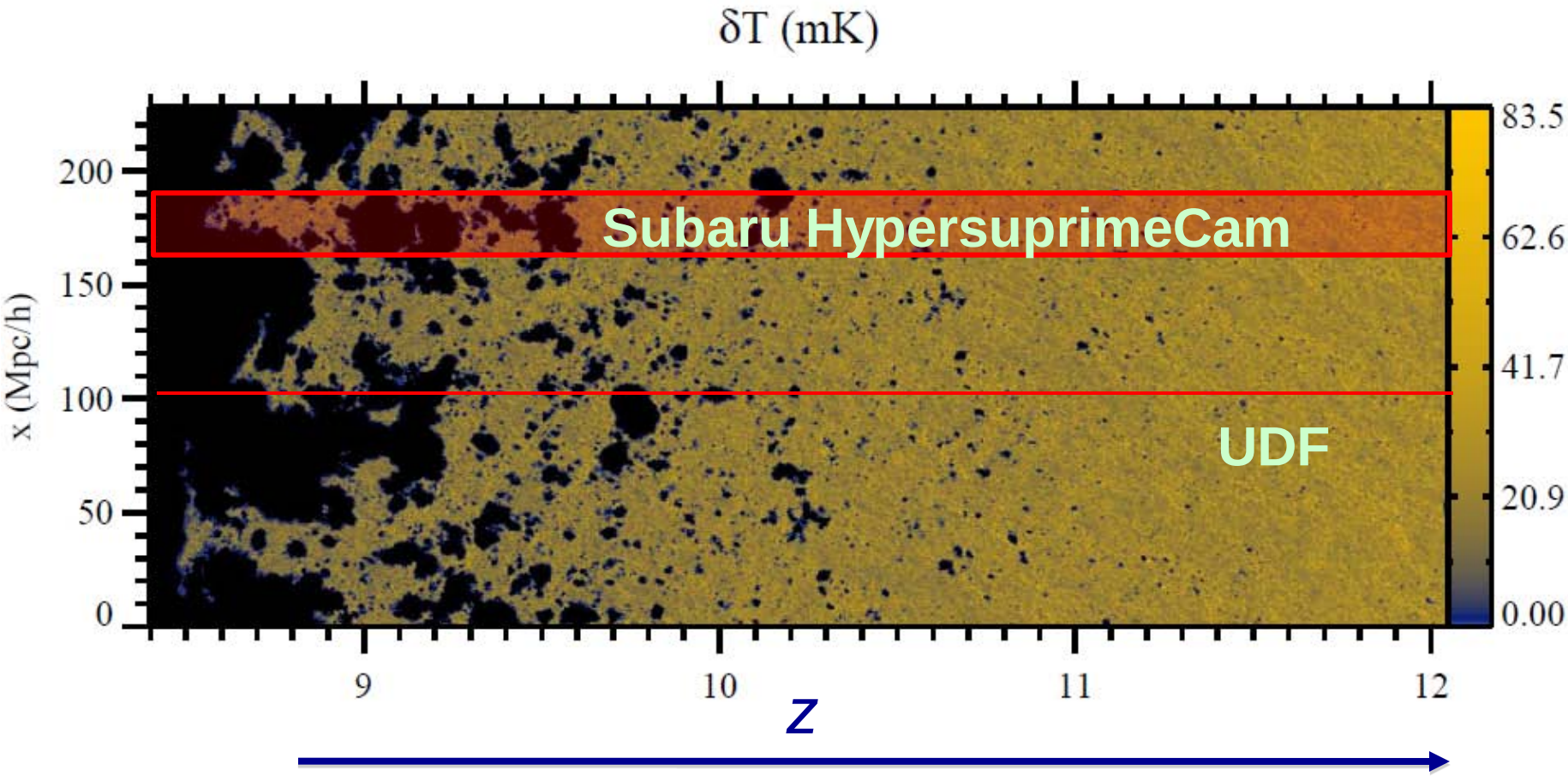




Bolton et al (2011)

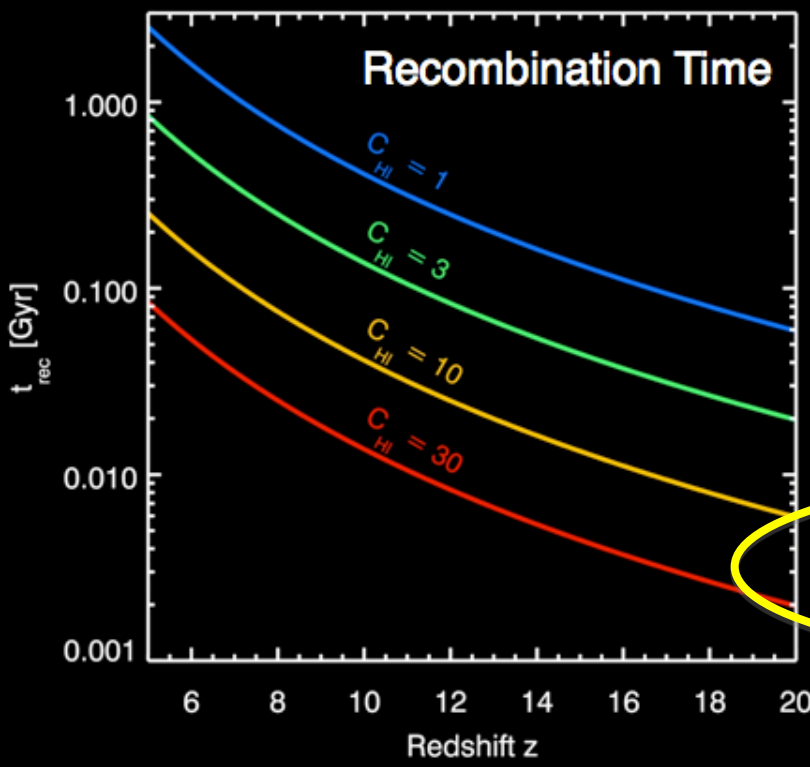
Is such a rapid change in x_{HI} feasible?

Beware of Cosmic Variance!



Iliev, et al 2011 arXiv:1107.4772

How Does Cosmic Reionizaton Occur?



Ionization Fraction Evolution

$$\frac{\mathrm{d}Q_{\mathrm{HII}}}{\mathrm{d}t} = \frac{1}{\langle n_{\mathrm{HII}} \rangle} \frac{\mathrm{d}n_{\mathrm{ion}}}{\mathrm{d}t} - Q_{\mathrm{HII}} C_{\mathrm{HII}} \frac{\langle n_{\mathrm{HII}} \rangle}{a^3} \alpha_{\mathrm{B}}(T)$$

Comoving H density

Scale factor

Case B recombination coefficient

Ionizing Photon Density

$$\frac{\mathrm{d}n_{\mathrm{ion}}}{\mathrm{d}t} = f_{\mathrm{esc}} \zeta_Q \rho_{\mathrm{SFR}}$$

Escape fraction

Ionizing photon production rate

Comoving star formation rate density

$$t_{\mathrm{rec}} = [(1 + 2\chi_{\mathrm{He}}) \langle n_{\mathrm{HII}} \rangle \alpha_{\mathrm{B}}(T) C_{\mathrm{HII}}]^{-1}$$

Helium fraction

Clumping Factor $C_{\mathrm{HII}} \equiv \frac{\langle n_{\mathrm{HII}}^2 \rangle}{\langle n_{\mathrm{HII}} \rangle^2}$

~1-6 (Pawlik et al. 2009)

Robertson et al (2010)

Madau et al. 1998, Bolton & Haehnelt 2007

Requirements for Reionization by Galaxies

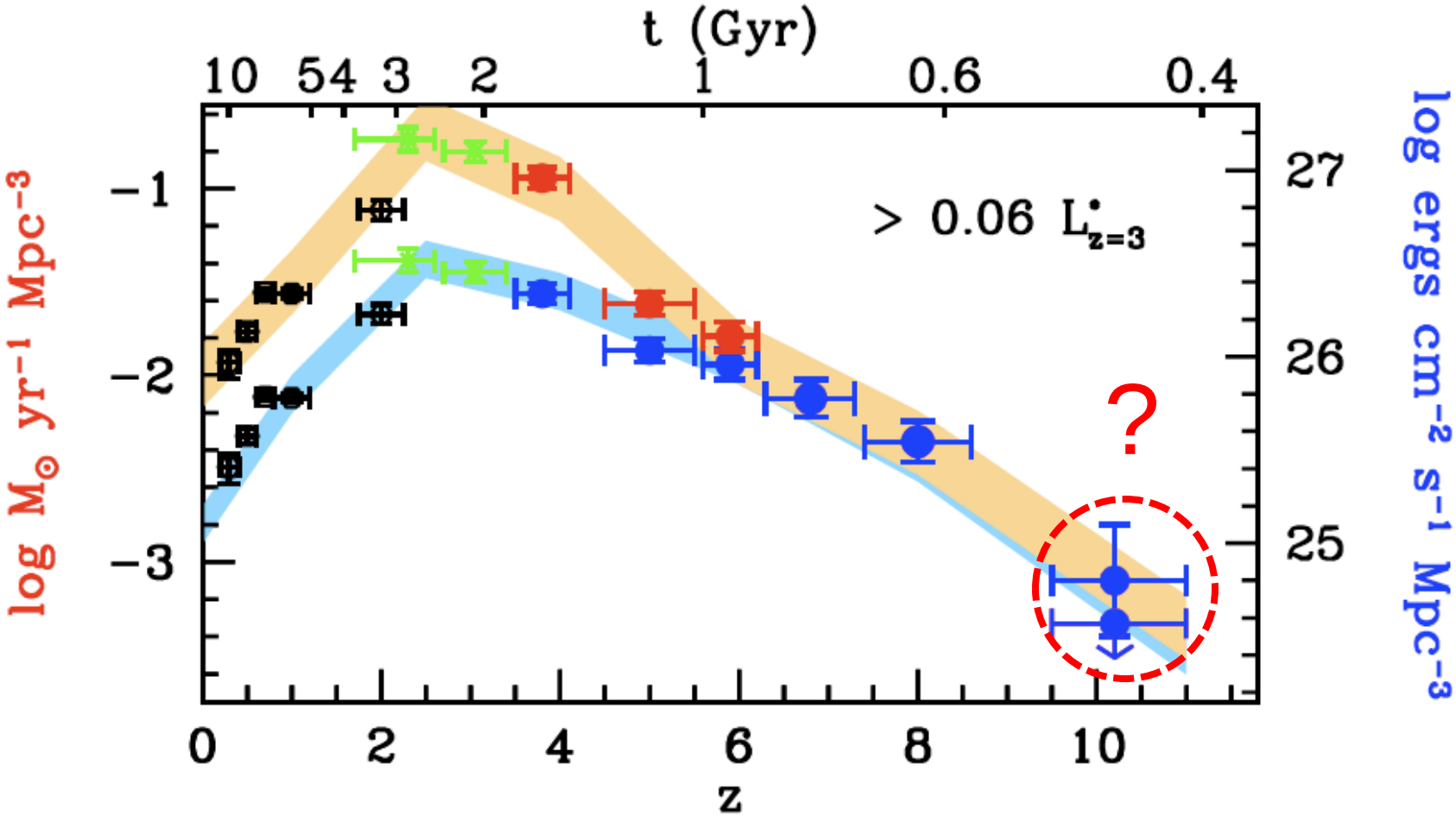
3 basic requirements to test hypothesis:

- A sustained output from star-forming galaxies over 7<z<10 (continuity in SF trends over Δt~300 Myr)
- A steep faint end slope ensuring high fraction of UV photons arises from abundant sub-luminous sources (α < -1.8), i.e. ρ_{SFR}
- A good understanding of the stellar populations, for example: is there a increased number of massive stars at high z such as might be expected in very metal poor young systems? i.e. ζ_Q
- A high escape fraction of ionizing photons f_{esc}

Prospects for resolving ambiguities in next 2-3 years is promising via

- first UDF campaign (Cy 18, Illingworth 105W, 125W, 160W)
- shallower CANDELS MCT campaign (Faber/Ferguson)
- deeper targeted UDF campaign (Cy 19, Ellis, 105W, 140W, 160W)

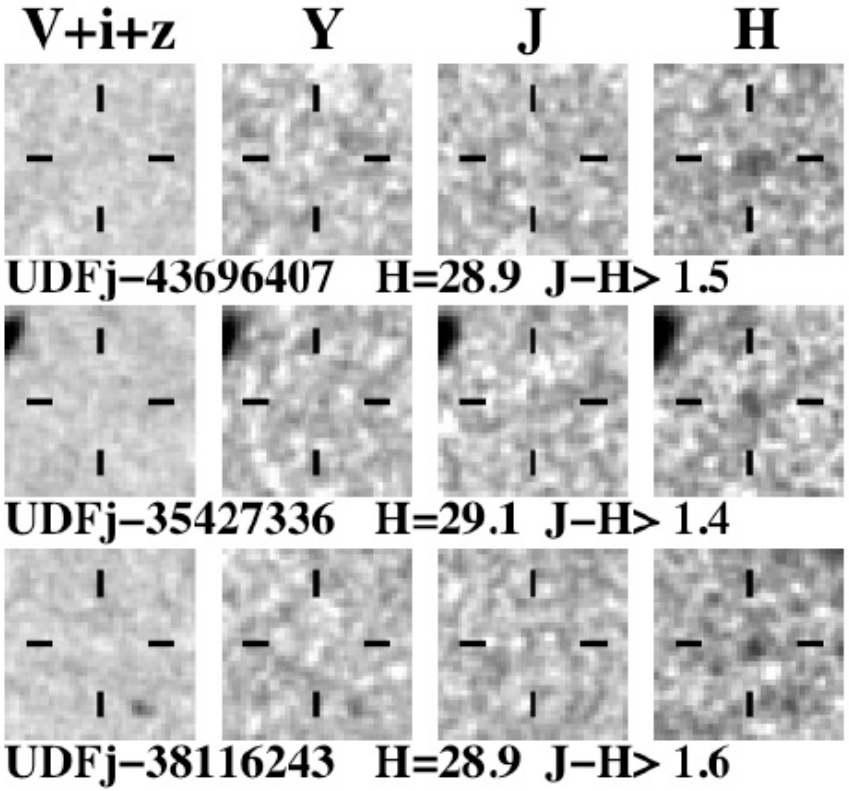
Sustained Output from SF Galaxies 3 < z < 10



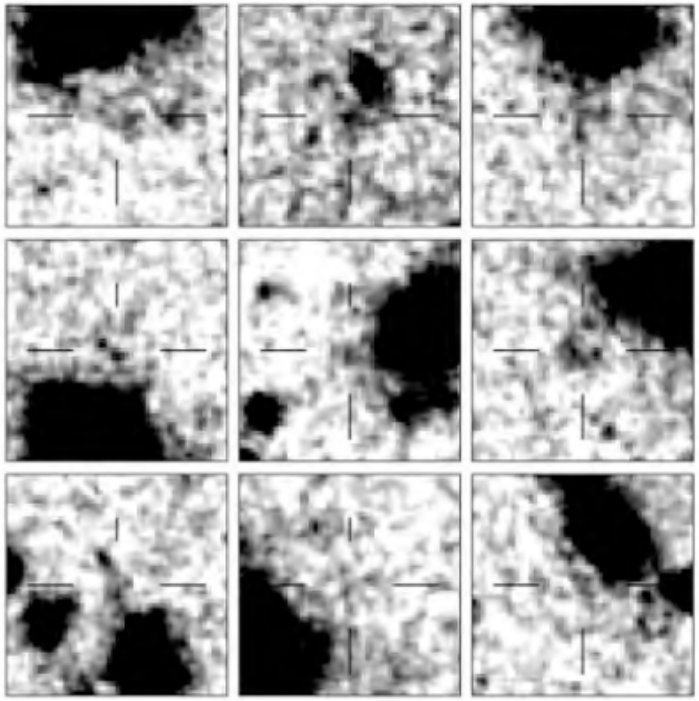
66 z~7 and 47 z~8 candidates in deep HUDF + parallel fields (AB~29, 4 arcmin^2) & shallower ERS area (AB~27.5, 40 arcmin^2)

Bouwens et al astro-ph/1006.4360

An aside: z~10? Bouwens et al vs Yan et al



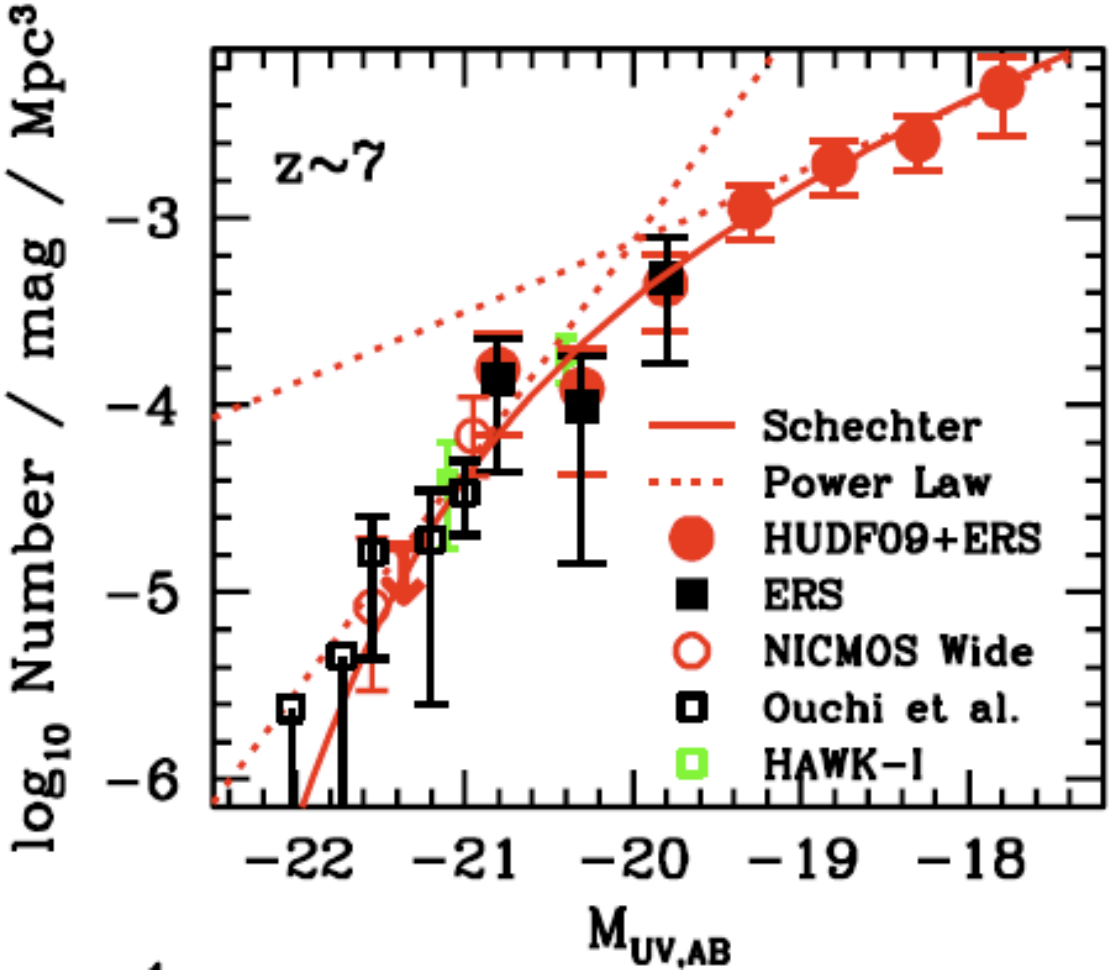
Bouwens et al 0912.4263



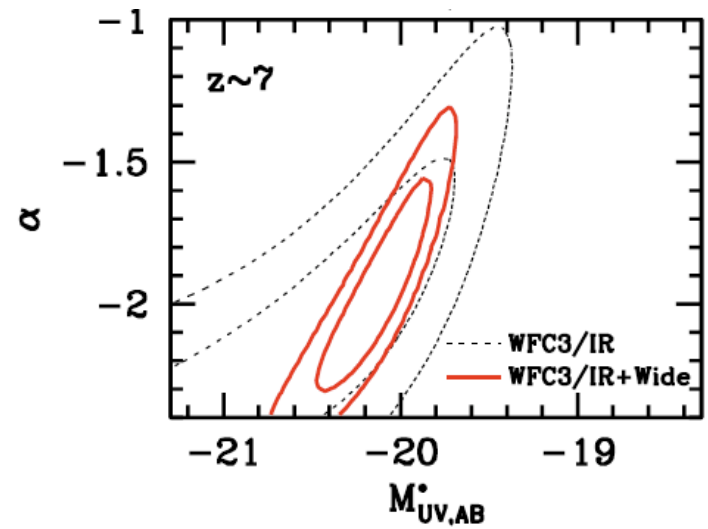
Yan et al 0910.0027

Bunker et al: no convincing J-drop candidates to H~28.5
Yan et al: 20 J-drops to H~29
Bouwens et al: 3 J-drops to H~29
One band detections and not a single candidate in common!

Steep Luminosity Functions @ z~7



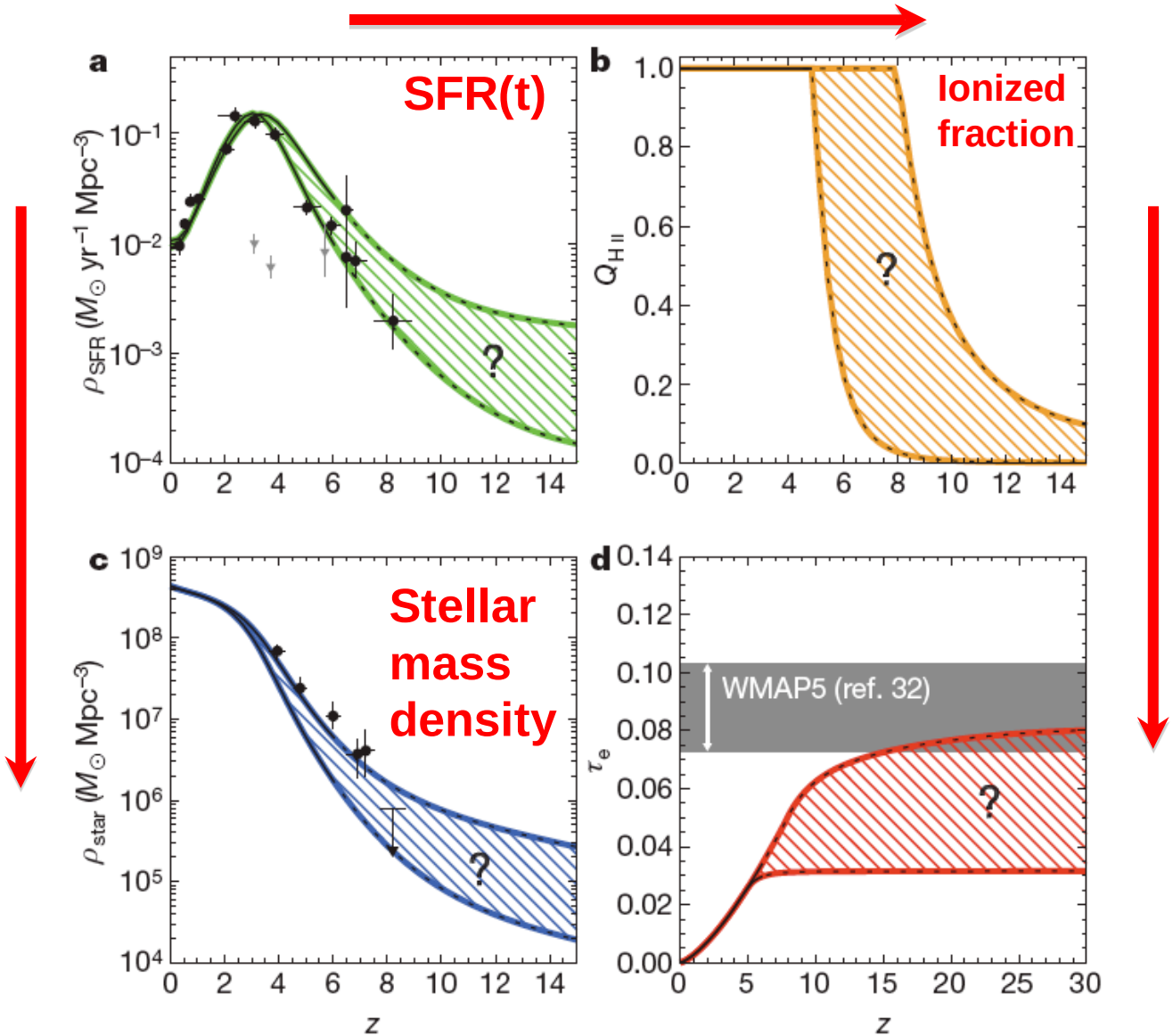
Utilizing deep + shallow WFC3/IR plus Subaru



Steep faint end slope: low star formers <1 $M_\odot$ yr^{-1} dominant

Ouchi et al 2009 Ap J 706, 1136; Bouwens et al astro-ph/1006.4360
plus many earlier papers (Oesch, Bunker, McLure…)

Did Galaxies Reionize the Universe?

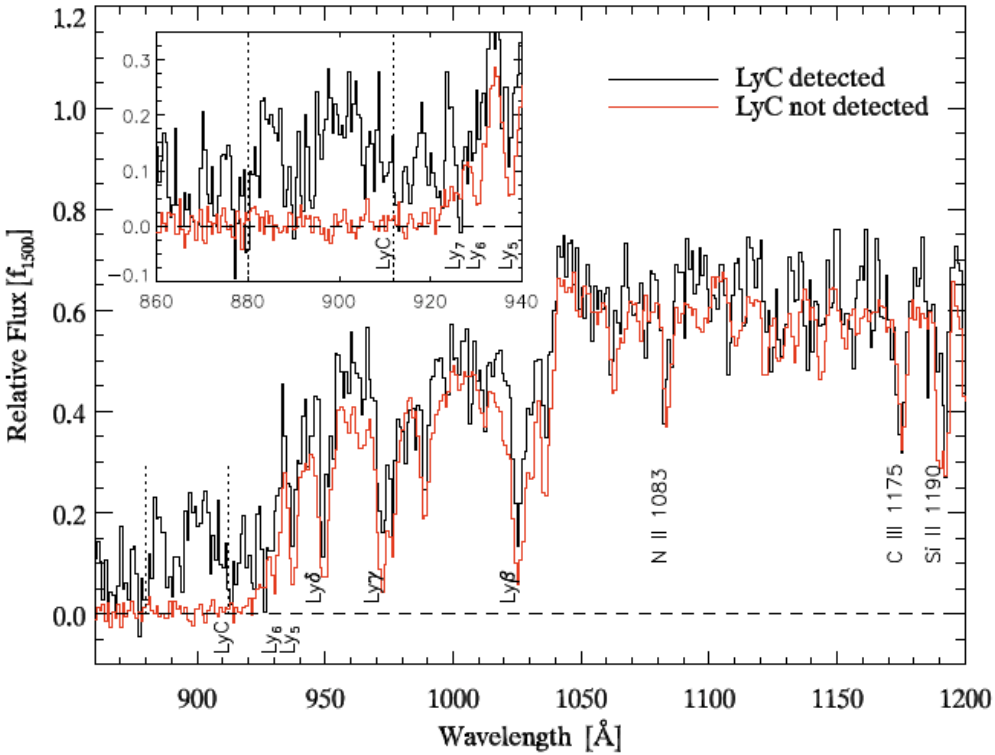


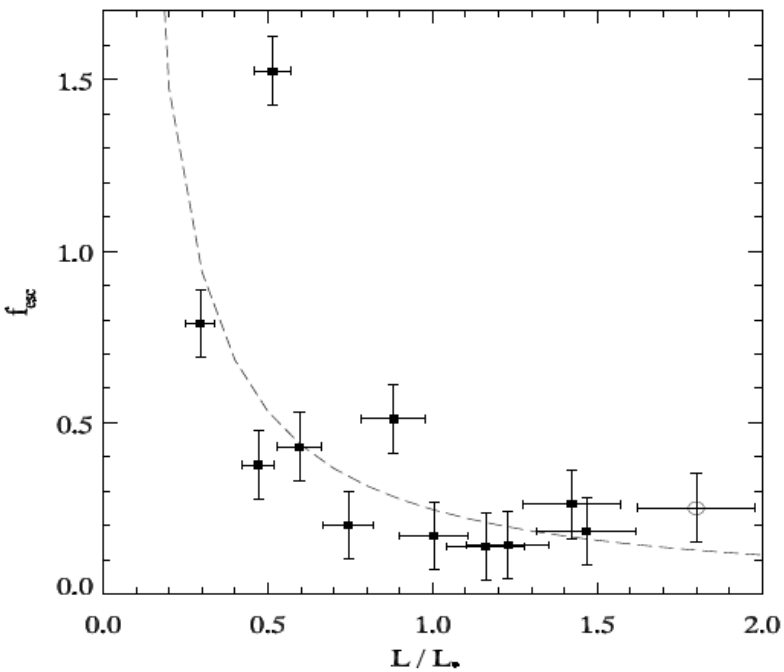
Robertson et al (2010) : some tensions even assuming f_{esc}=0.2, C_{HII} = 2

Escape fractions in z~3 LBG spectra

$$f_{esc,rel} = \frac{(L_{1500}/L_{900})_{int}}{(f_{1500}/f_{900})_{corr}}$$

$$f_{esc} = 10^{-0.4\times 10.33 E(B-V)} f_{esc,rel}$$



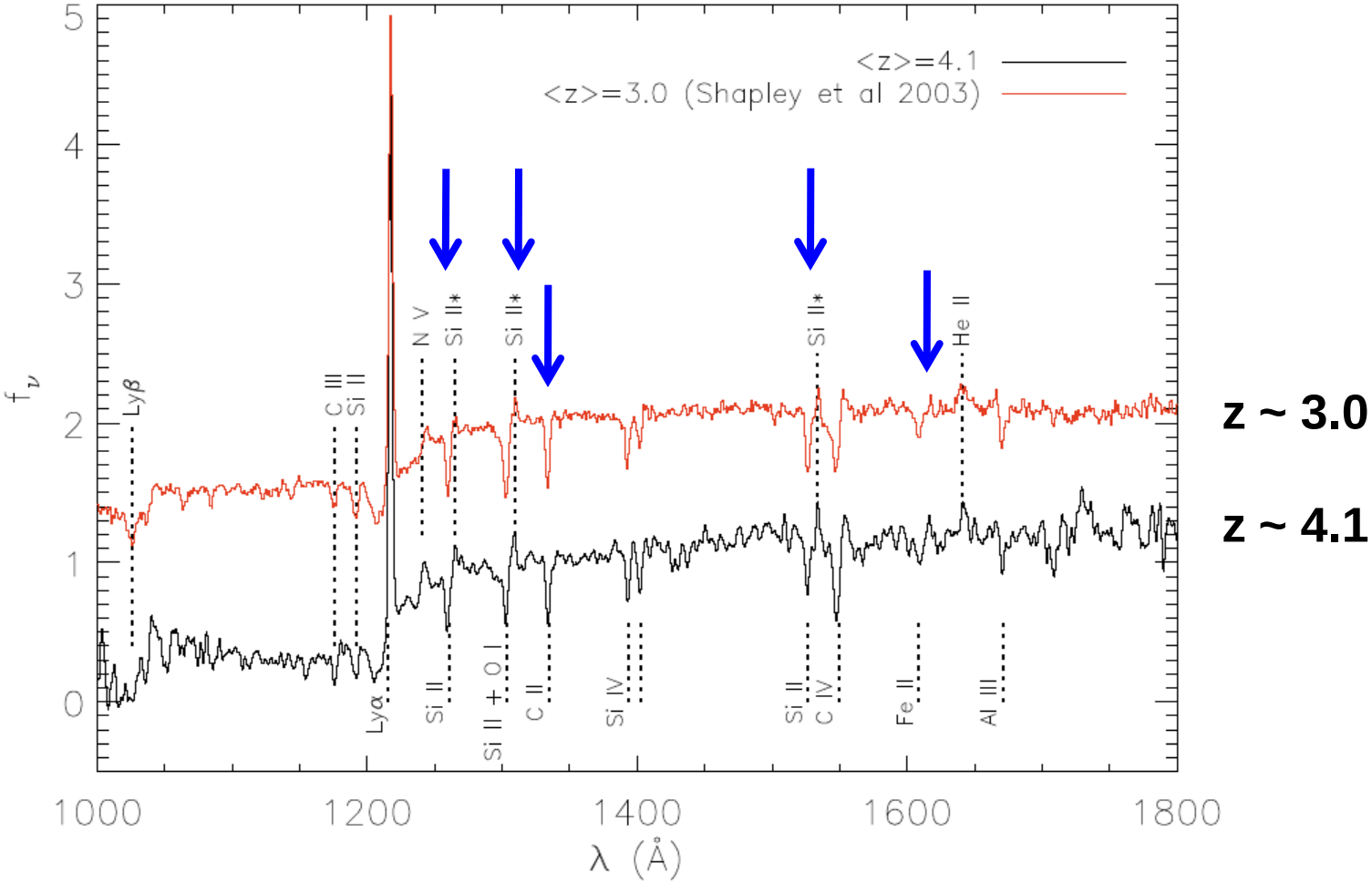


11/110 LBG spectra show positive Ly continuum flux

For that small subset, intringuingly, f_{esc} correlates as L^{-1}

Bogosavljevic (2009, Ph.D. Thesis)

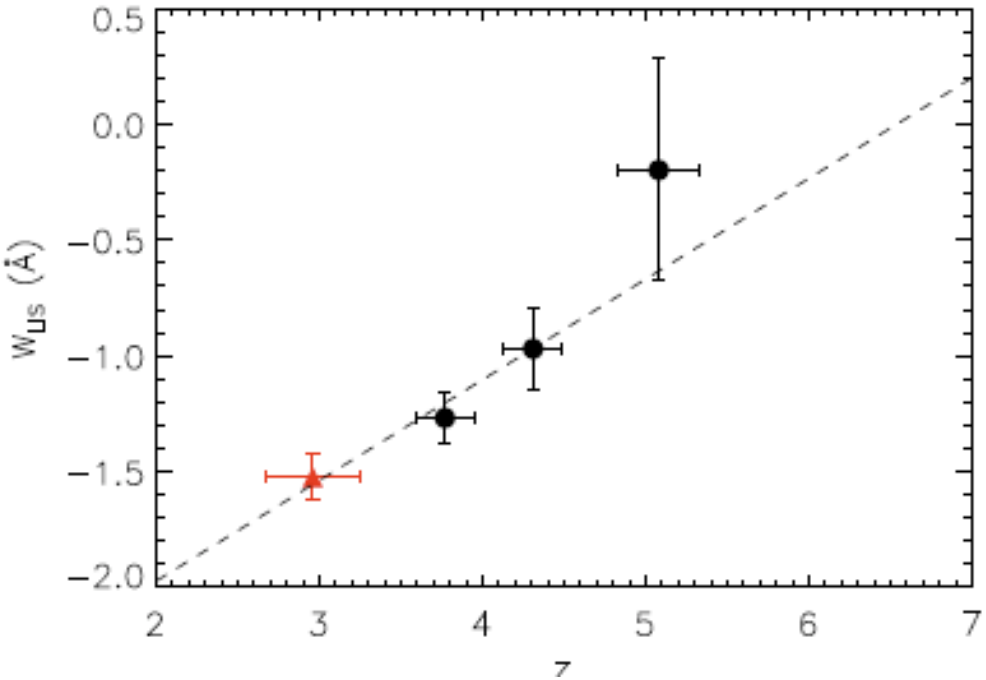
Covering Fraction of Low Ionization Absorption Lines

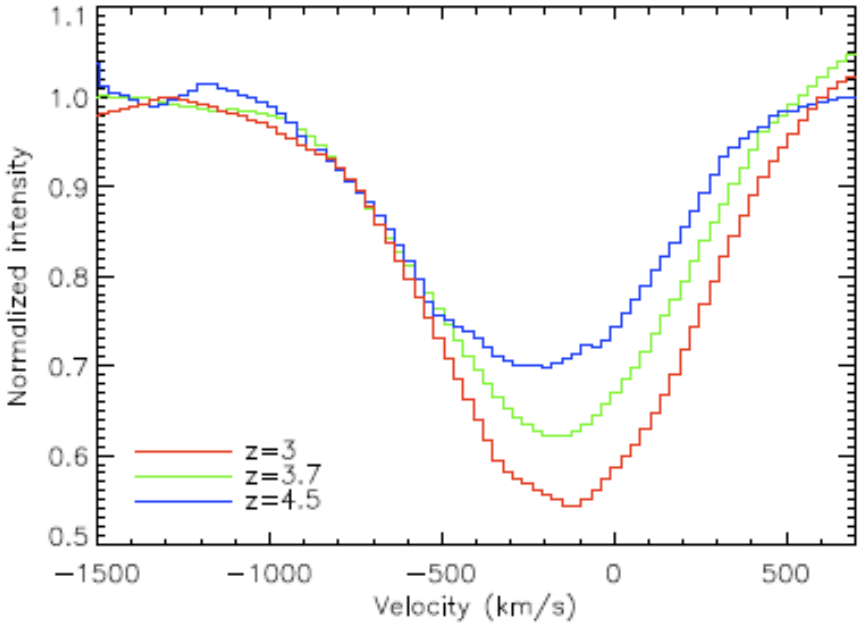


- Low ionization absorption lines of Si II, CII Fe II should be saturated
- Their depth measures covering fraction of neutral gas & outflow velocity
- Covering fraction of neutral gas is a direct proxy for the escape fraction

Jones et al (2011)

Reduced Low Ionization Absorption Lines vs Redshift





- Equivalent width of low ionization absorption lines W_{LIS} decreases with increasing redshift over $3<z<6$
- Can see effect directly in stacked absorption line profiles
- Could be due to reduced HI covering fraction or less outflow velocity
- Higher dispersion DEIMOS spectra needed to resolve this ambiguity

Jones et al (2011)

Supposing there is a photon shortfall..?

Possible solutions:

- Some component of WMAP τ (~0.02?) may come from first generation of massive stars; not all has to arise in $7<z<10$ galaxies

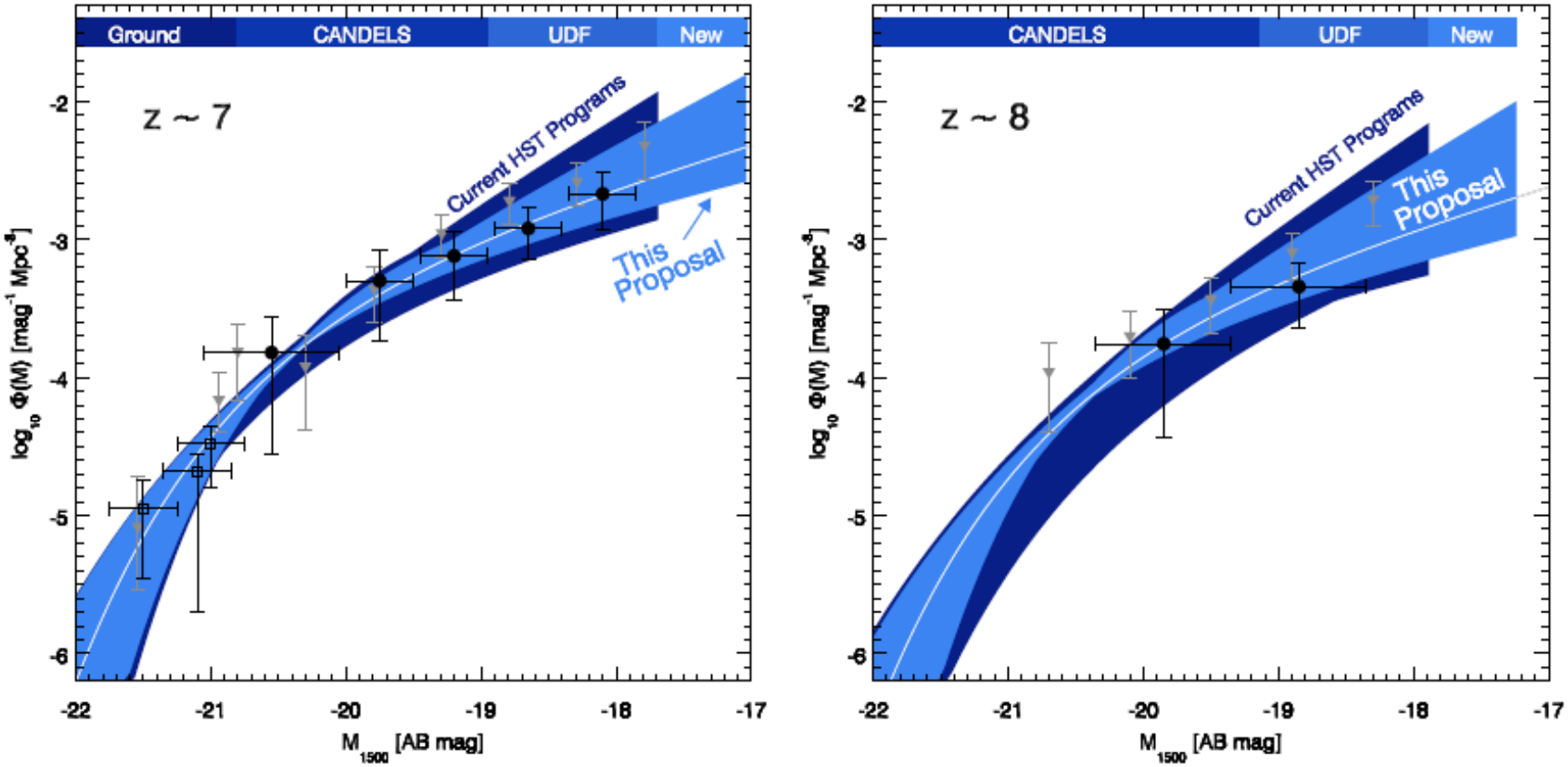
- Steeper than expected faint end slope of LF? Deeper HST survey in Cycle 19 will help

- Exotic stellar populations (e.g. top heavy IMF)? Interest in UV continuum slope

- Very high escape fraction of ionizing photons?

Otherwise we must consider another source of reionizing photons

Projected LFs @ z~7-8 with New HST campaign



- Very steep LFs (α ~ -2) necessary to close reionization budget
- Statement is highly dependent on assumed f_{esc}
- Current uncertainty in faint end slope Δα ~ 0.2-0.3 (Bouwens, McLure)
- New UDF program (128 orbits) will provide improved faint end constraints

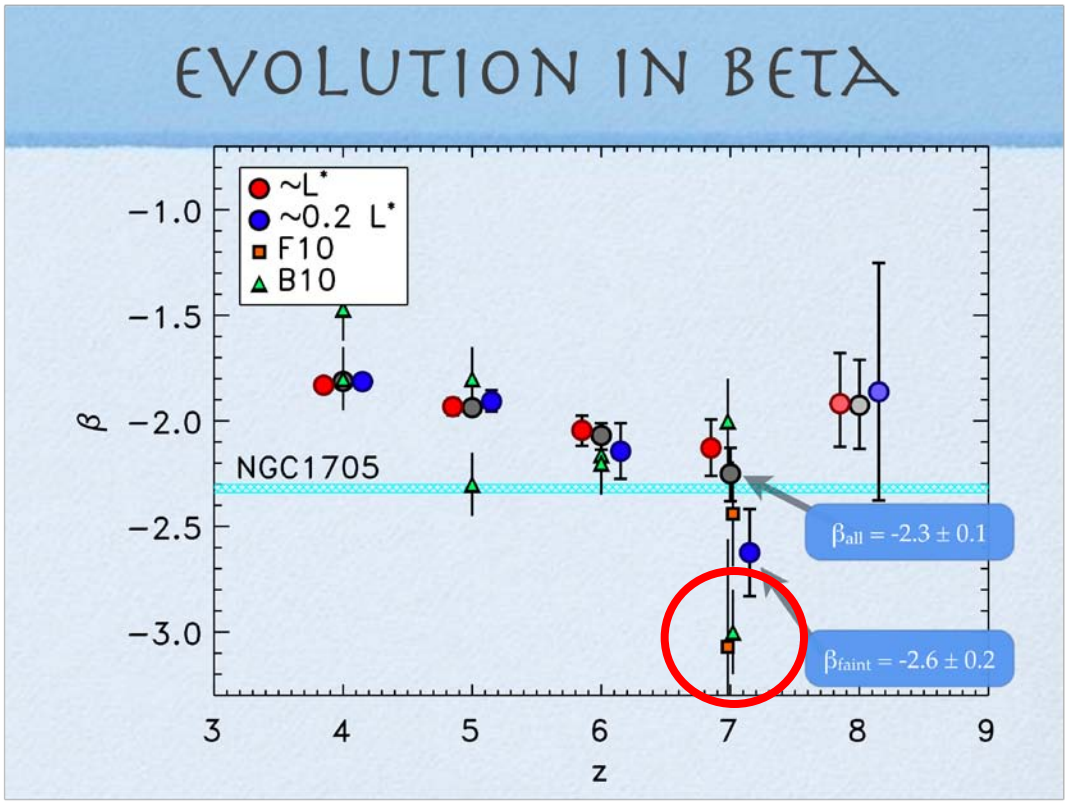
Steep UV Continua?

WFC3 data measure slope β of the stellar continuum:

$f(\lambda) \propto \lambda^{\beta}$: $\beta \rightarrow$ -3 !

Could imply very young, metal poor or even Pop III contributions

Early claim by Stanway et al (2004); see also Wilkins et al (2011)

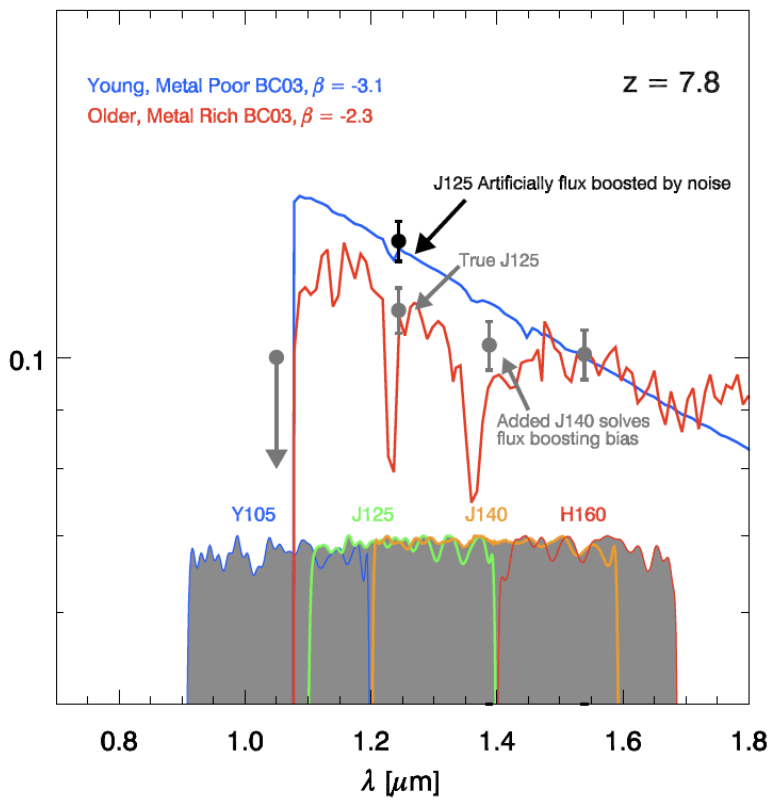


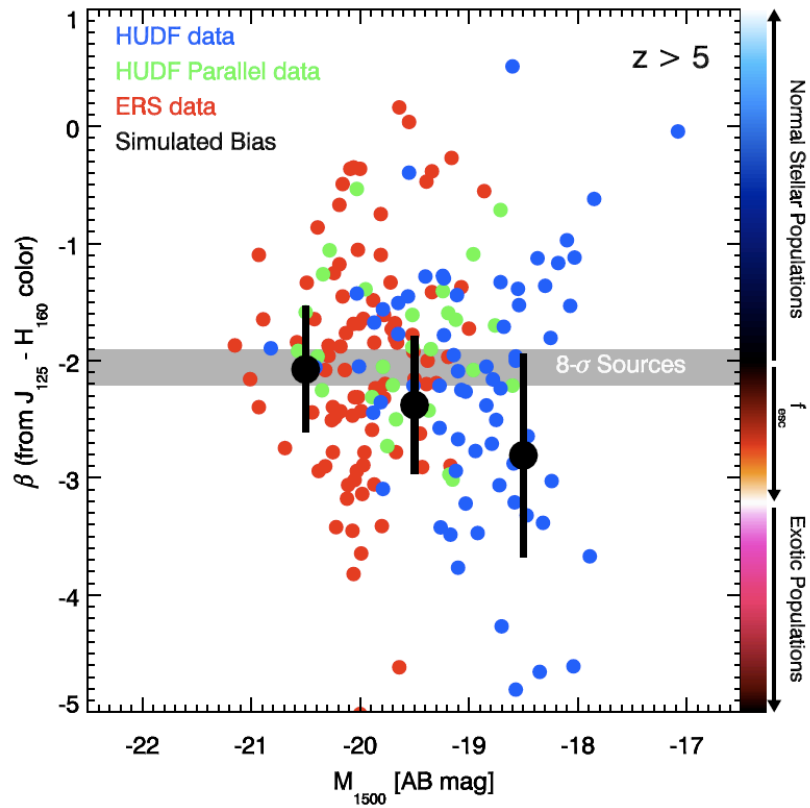
Higher z and low L galaxies are slightly bluer (less dusty)
But evidence for uncomfortably steep slopes limited to faint z~7 LBGs

Validity of UV slopes in Faintest Data?

β estimated from (J-H) using noisy photometric data

- Boosting in J due to noise biases β to bluer, more extreme values
- Boosting in H affects photo-z solution, placing object at z~2
- **Deeper HST data with additional J140W filter will clarify**



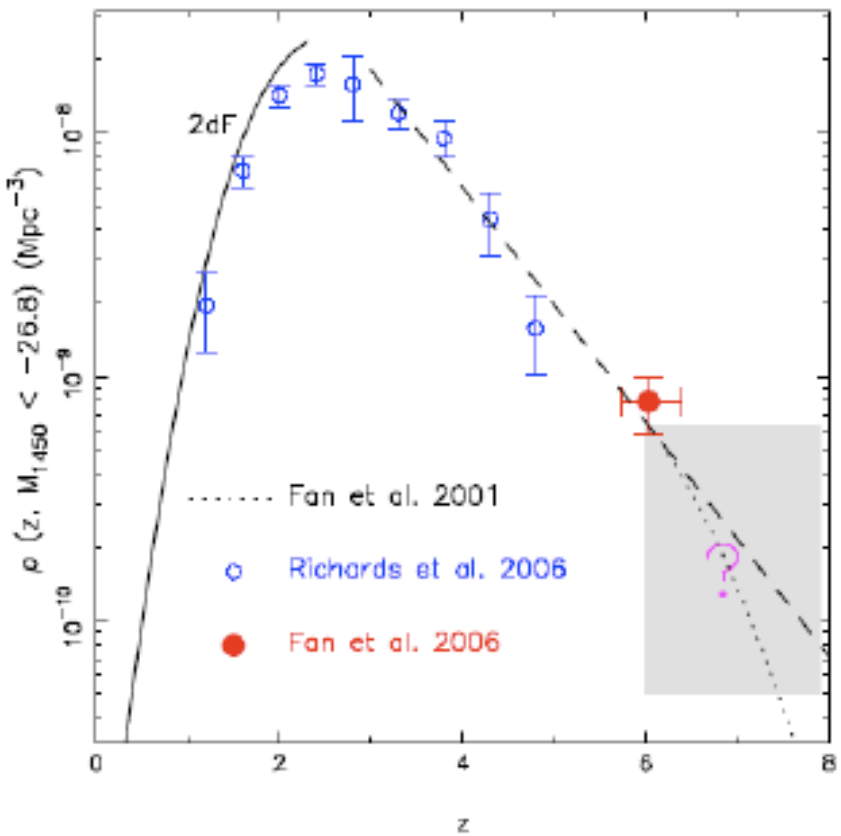


Dunlop et al astro-ph/1102.5005

Early Contribution from AGN?

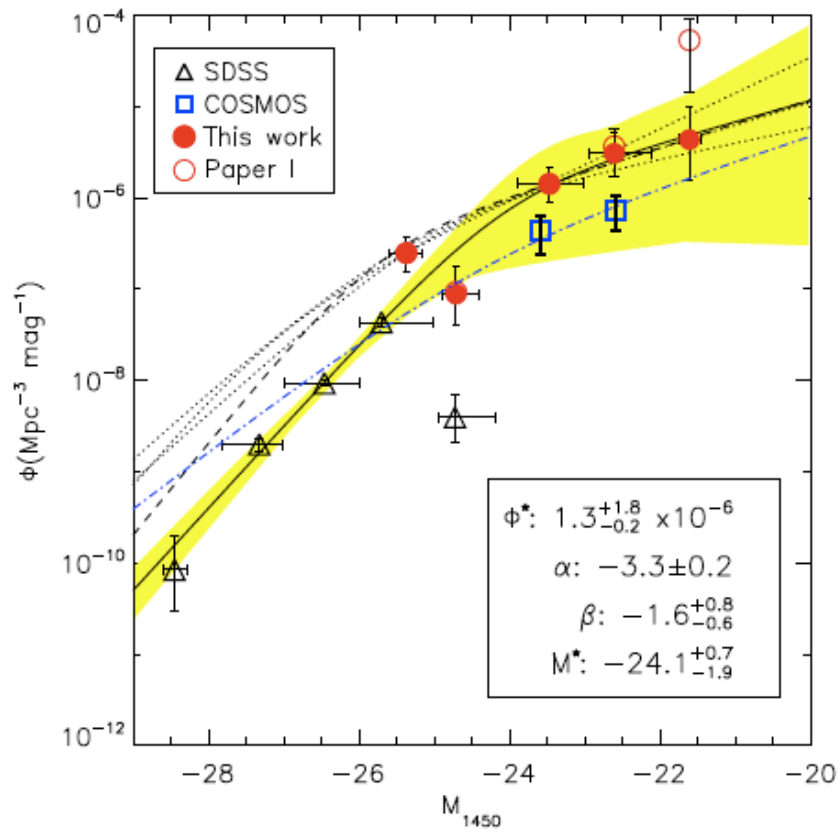
Unlikely unless LF steepens dramatically beyond z~4
Stacked X-ray images of z~6 UDF LBGs provides additional limits
Soft X-ray background provides further limits on early BH accretion

Density of QSOs



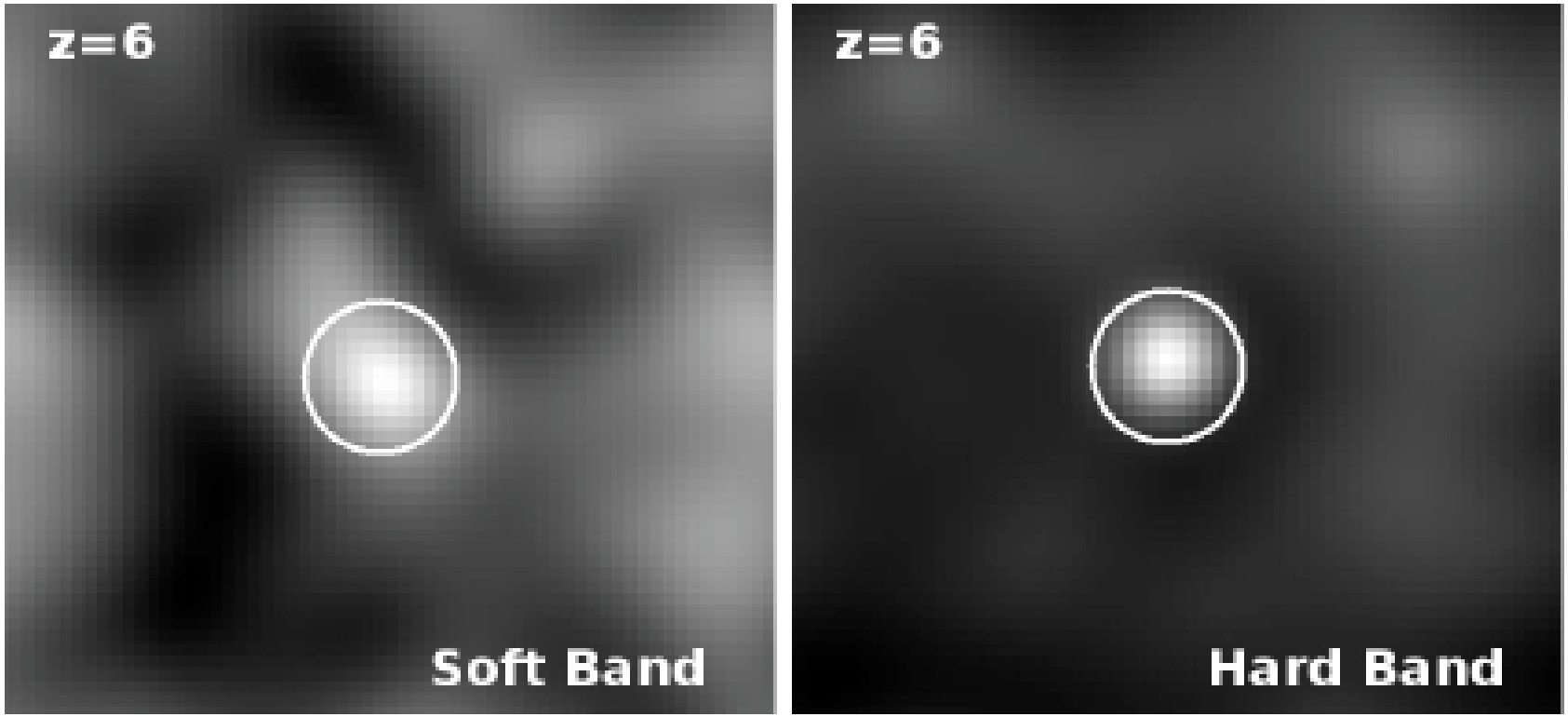
Fan (2007) NewAR 50, 665

Faint QSO LF at z~4



Glikman et al astro-ph/1101.0537

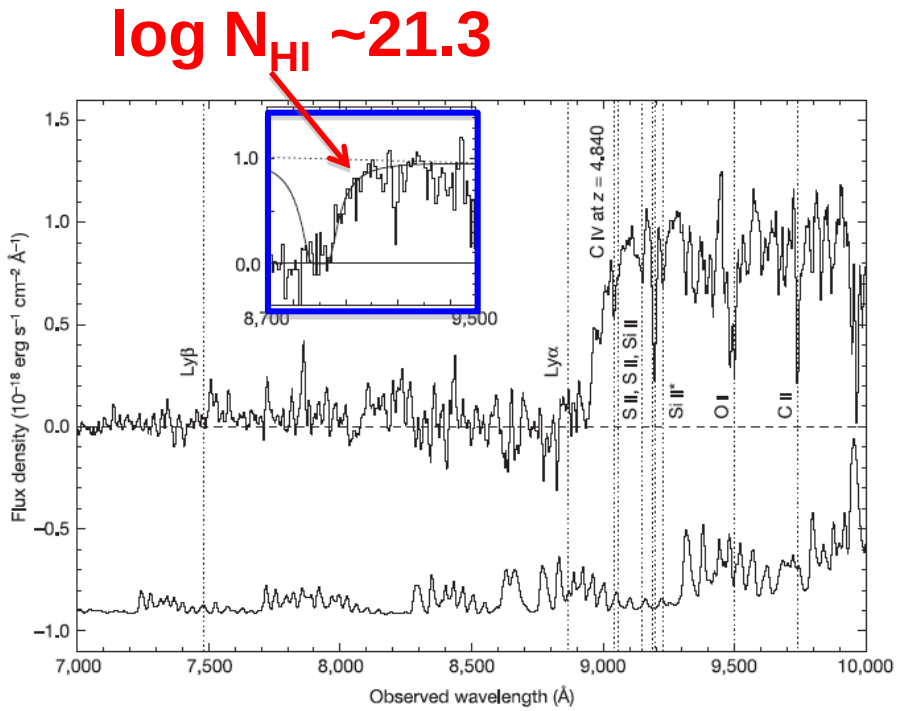
Obscured AGN in z~6-7 LBGs



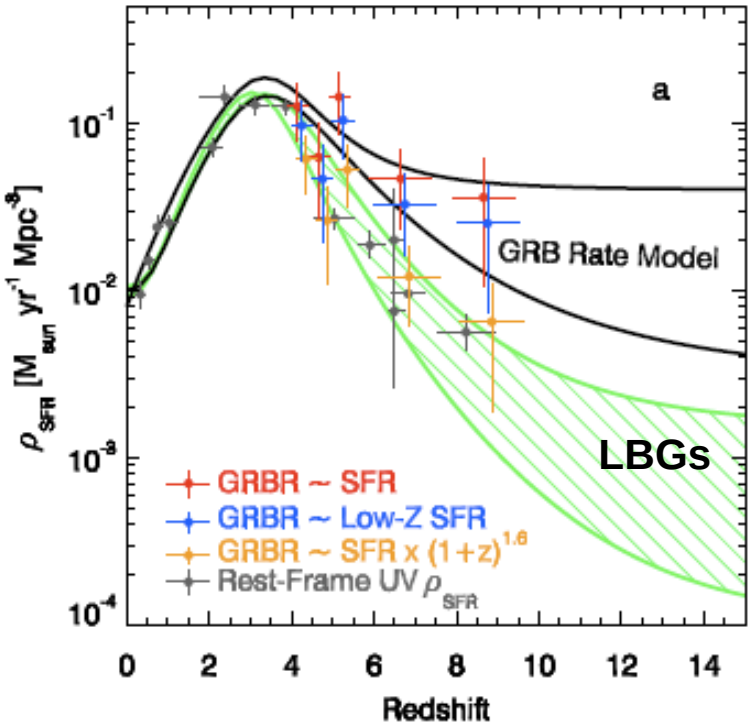
- Stacked 197 z~6 dropouts in CDF-S (4Msec) and CDF-N(2Msec)
- Hard/soft detection ratio implies high column density $N_{HI} > 10^{24}$ cm^{-2}
- Implies self-regulated formation tied to host galaxy assembly and little contribution of AGN to reionization photon budget

Triester et al (2011)

High Redshift GRBs: a puzzle



Kawai et al (2006) Nature 440, 184



Robertson & Ellis (astro-ph/1109.0990)

- Great potential for probing neutrality of IGM (fast response, high dispersion)

- Puzzling inconsistency between high z GRB rate and SF seen in deep HST surveys

Future Prospects

- HST + WFC3:

  Deeper UDF campaign will probe fainter sources and clarify faint end of z~7-8 luminosity function and test UV slope

- Continued improvement in 4<z<7 spectroscopic surveys:
  much to learn about demographics of LBGs/LAEs including spatial mapping of populations (Subaru/Keck)

- Multi-slit IR spectrographs for following existing and other z>7 candidates

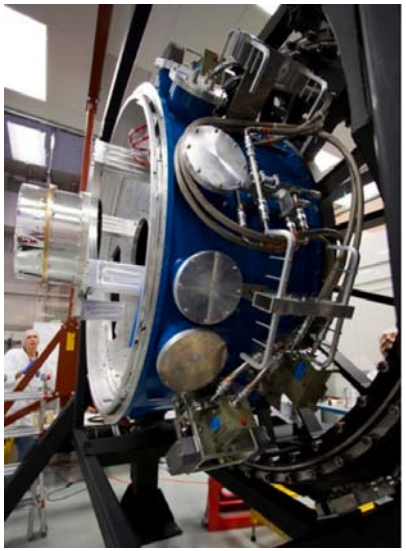
  - MOSFIRE on Keck (2012A)

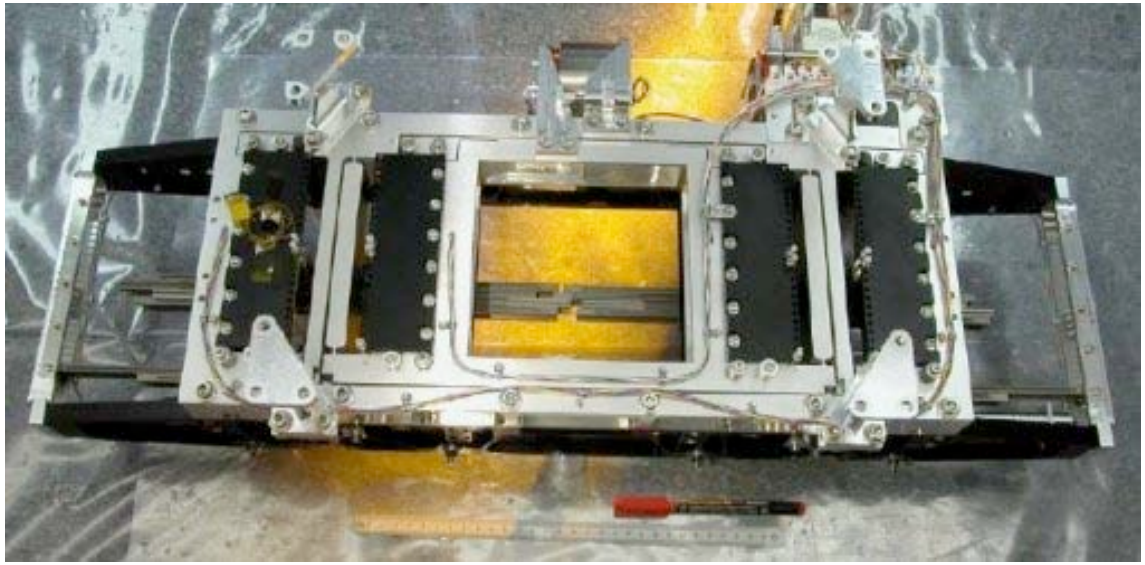
  - KMOS on VLT (2012B)

- JWST (2018?) and..not too far off..(2020)..TMT

LOTS TO LOOK FORWARD TO!

MOSFIRE (Keck I) – Jan 2012





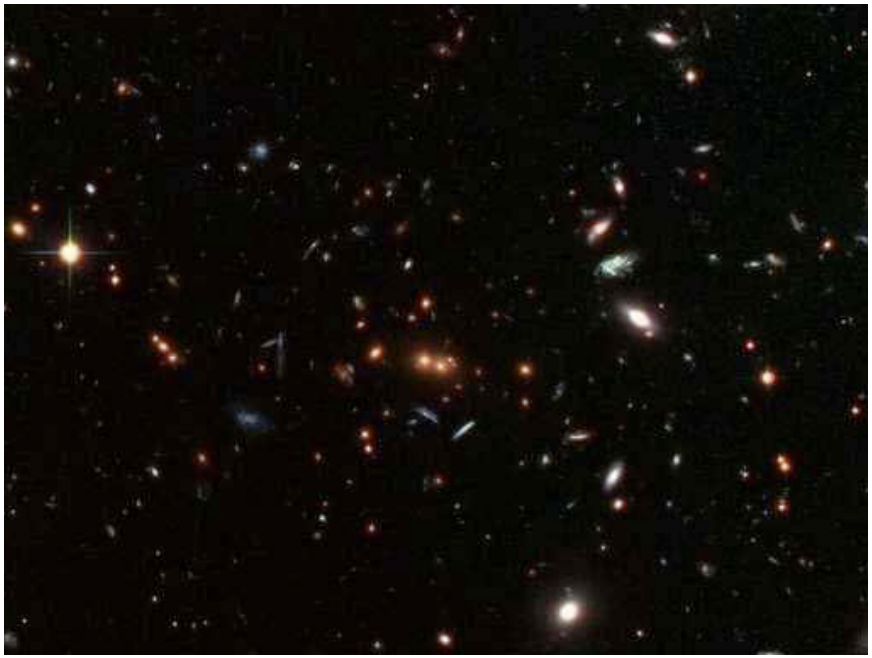
Cryogenic Multi-slit IR spectrograph

6.1 x 3.1 arcmin spectroscopic field

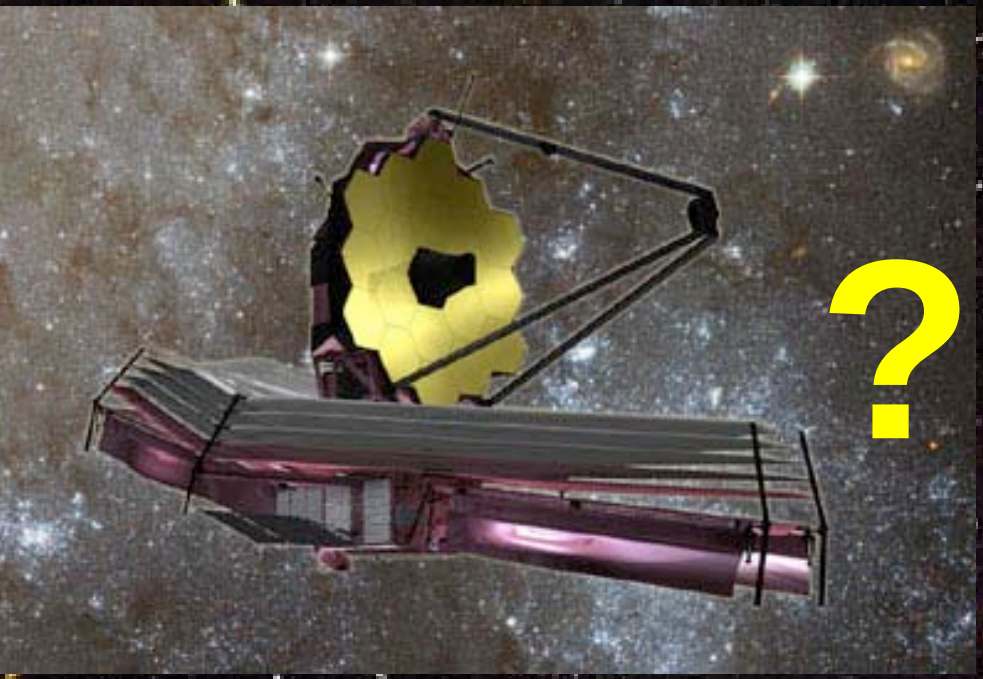
$\lambda\lambda$0.97 - 2.45 microns

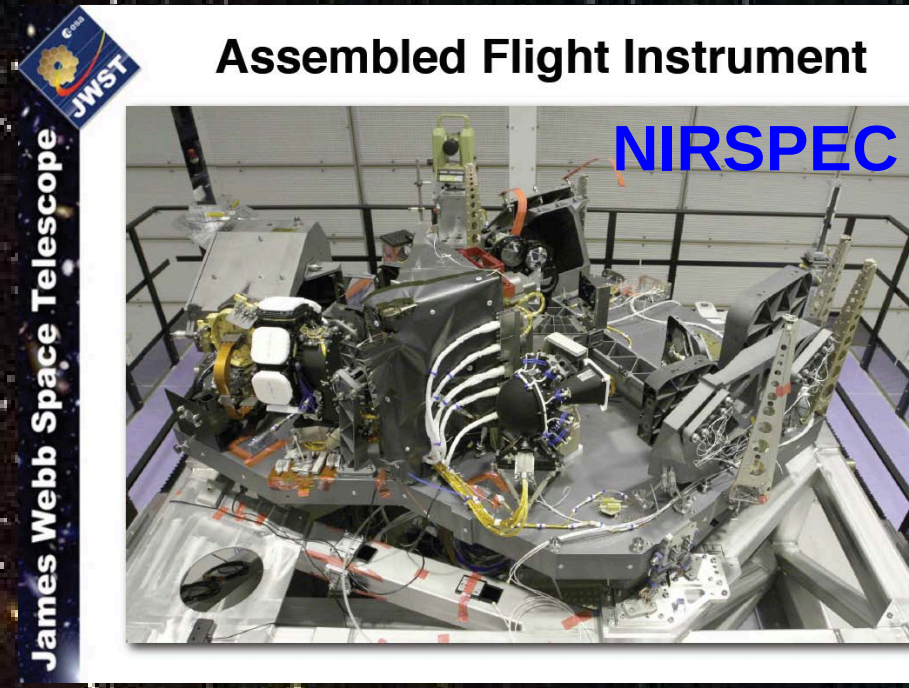
R ~3300 for 0.7 arcsec slit

45 slits via configurable slit unit (<5mins)



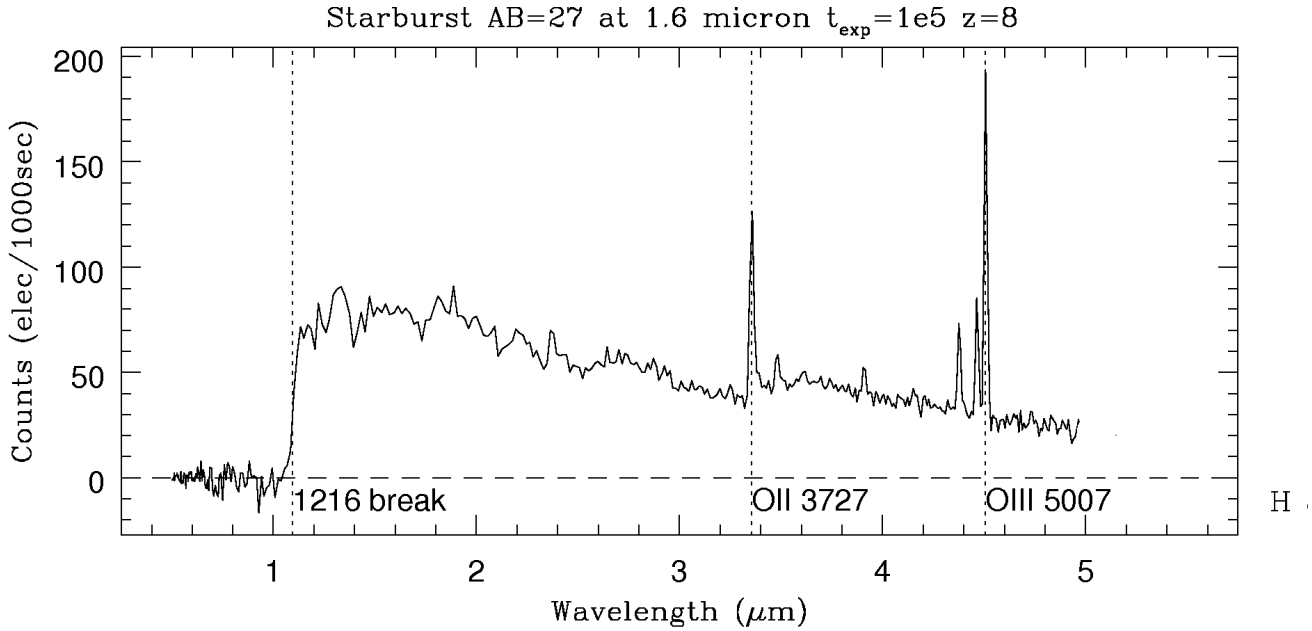
James Webb Space Telescope



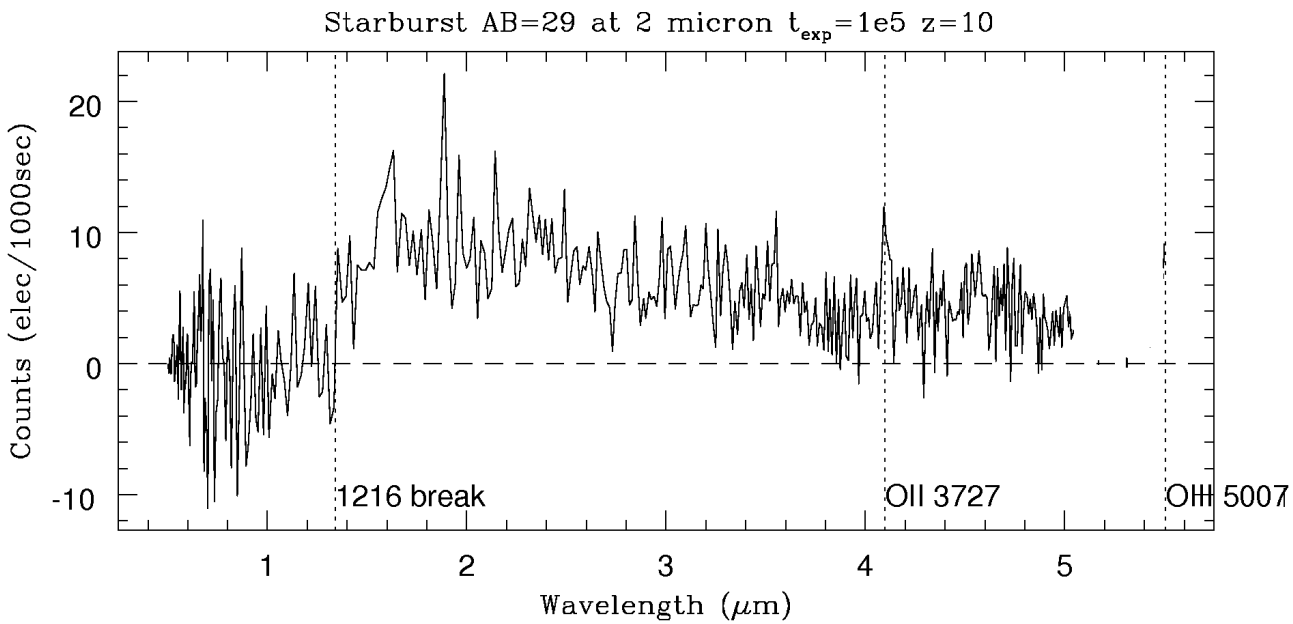


Simulated NIRSPEC spectra

AB=27 z=8 enabling full nebular/stellar decontaminati on and gas phase metallicities



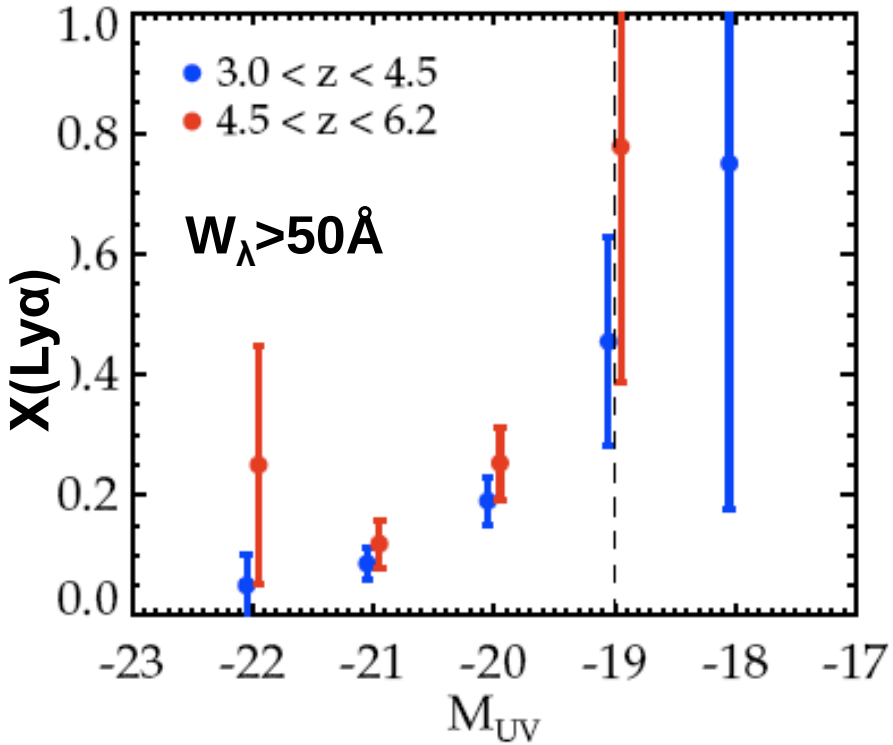
AB=29 z=10 (current UDF limit)

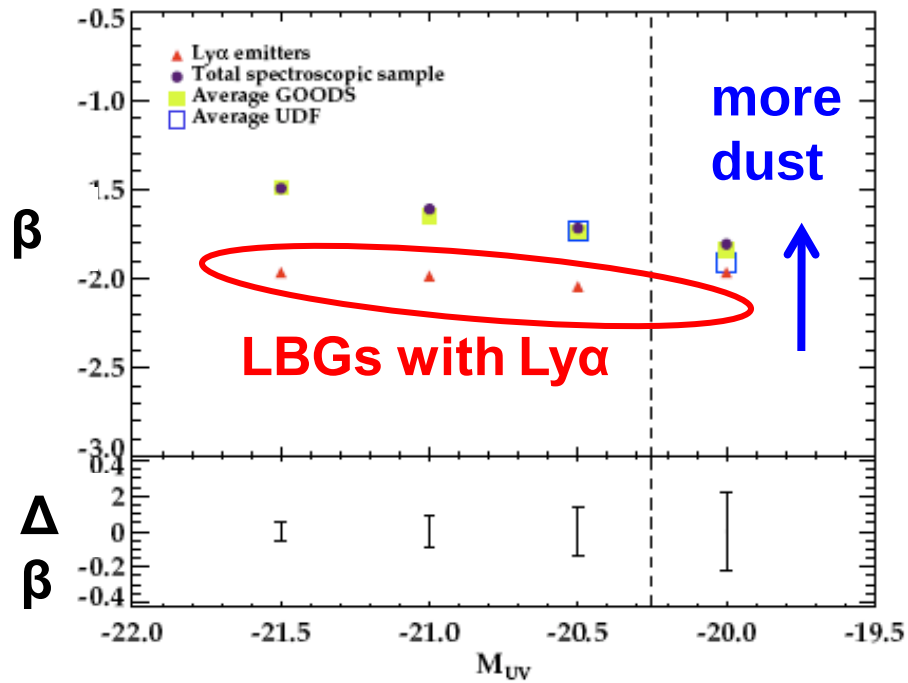


Conclusions & Future Prospects

- Exciting time in the study of z>7 galaxies with HST, Spitzer and large telescopes still in the vanguard
- Dramatic progress with deep IRAC observations: from a couple of z~6 detections in 2005 now to comprehensive measures of the stellar mass density over 4<z<7
- WFC3 has led to rapid progress:
  - continuity of SF trends over 300 Myr
  - dominant fraction of sub-luminous galaxies
- Rapid decline in visibility of Lyman α over 6.5<z<8 suggests neutral era begins in this redshift range
- Many uncertainties but good prospects for improved data which will address possible deficiency of galaxies as source of reionizing photons
- Key role of future large telescopes in exploiting adaptive optics and efficient multi-object spectrographs in concert with JWST and large samples of 7<z<10 which can still be delivered by HST

Lyα fraction vs UV luminosity and extinction





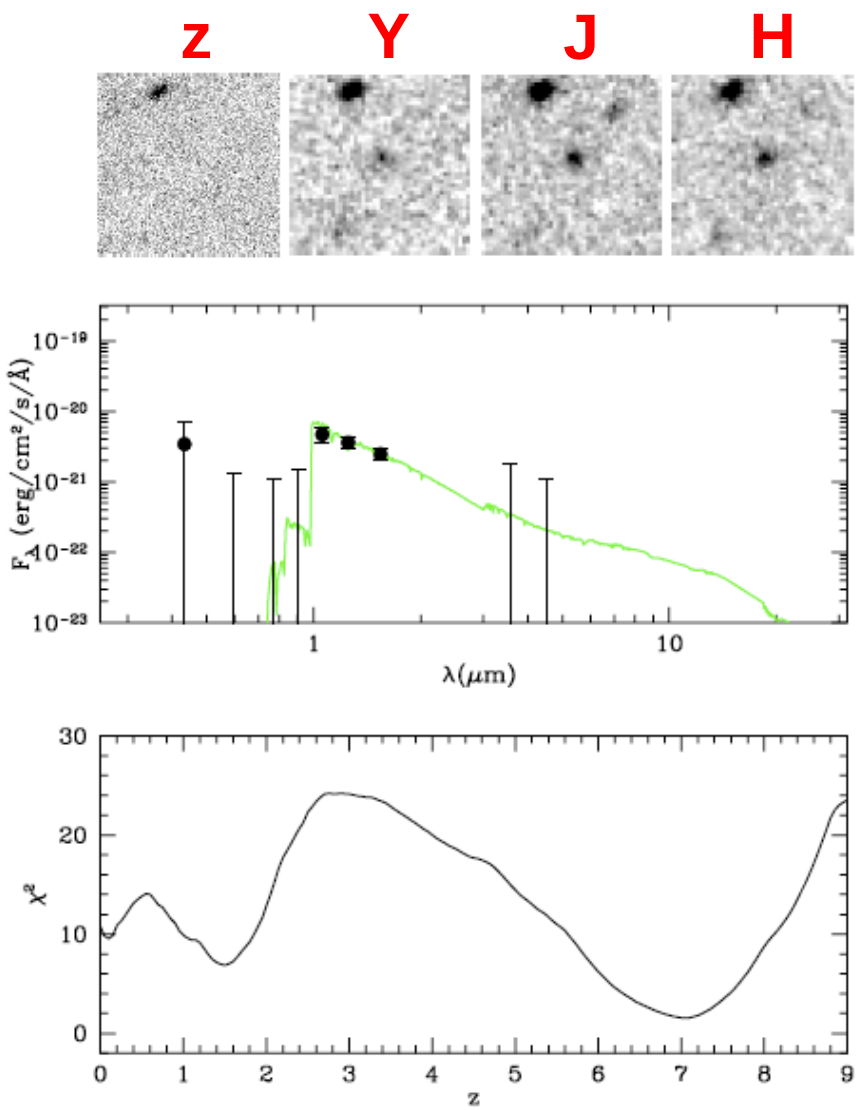
Strong correlation between extinction- inferred from UV slope β (flux ~ λ^β) and presence/absence of Lyα

Strongly suggests low luminosity galaxies are relatively dust-free

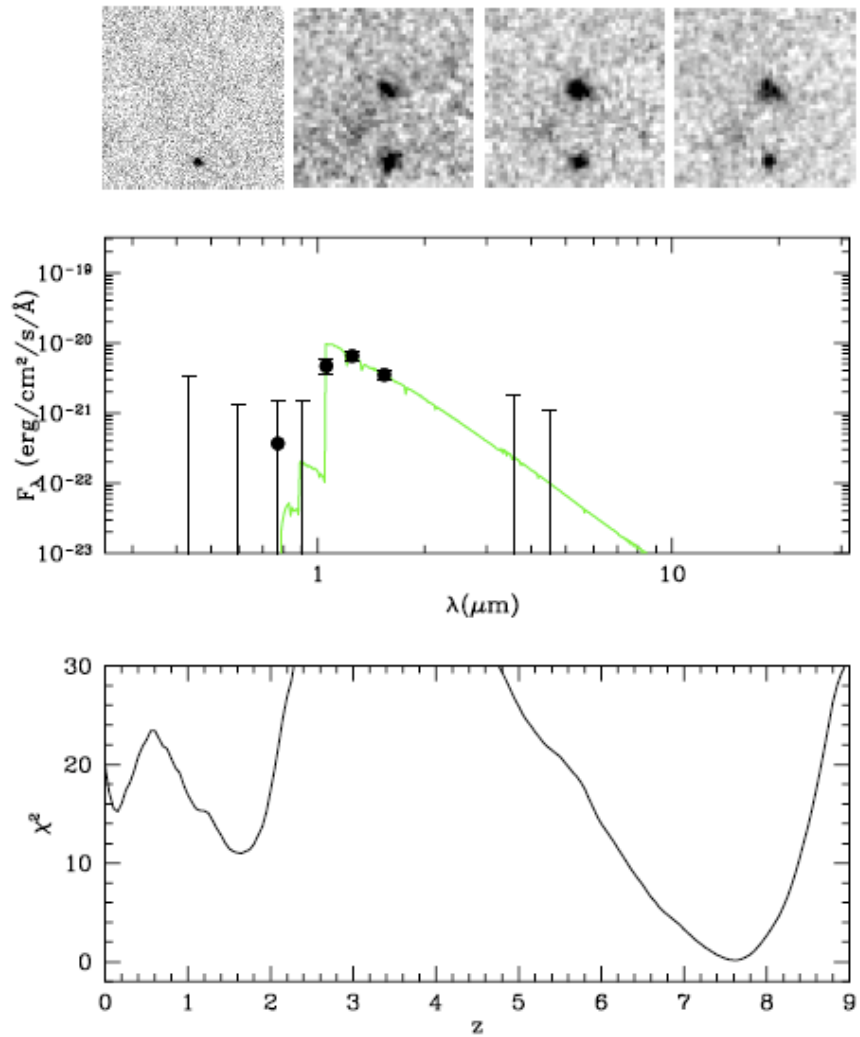
So their Lyα fraction might be valuable probe of reionization

Stark et al (2010) MN 408, 1628

Beware..uncertain photo-z's still an issue..



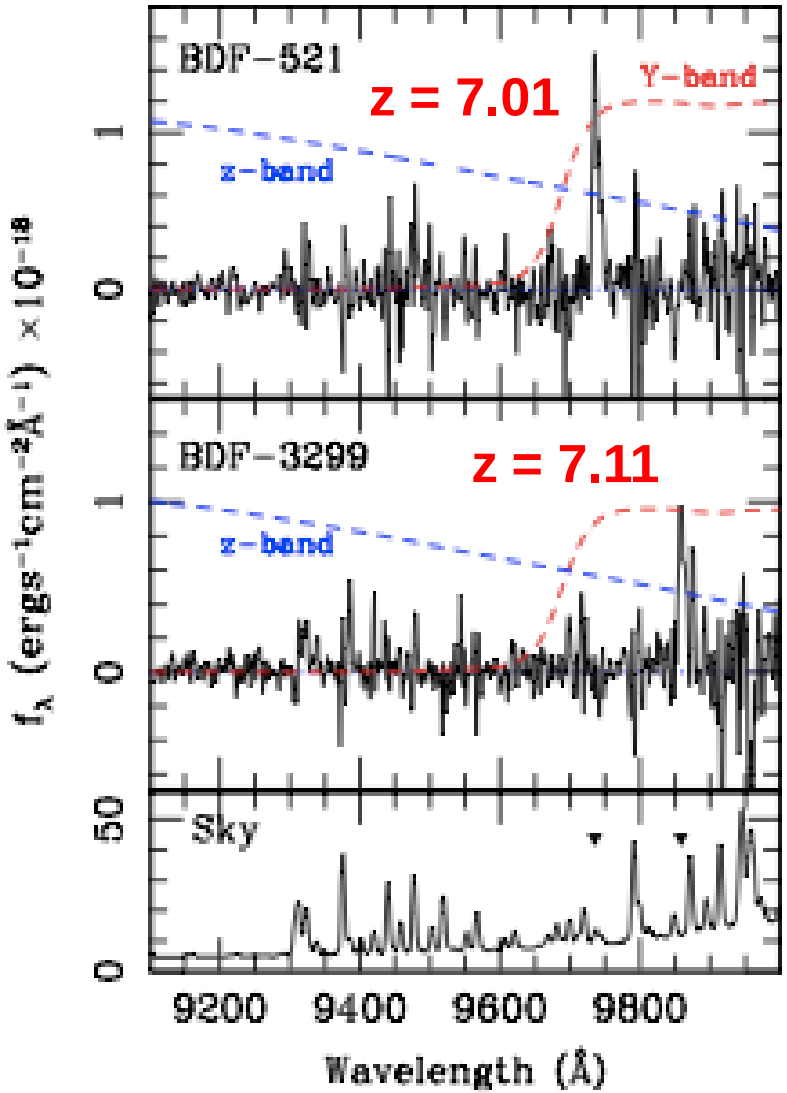
1678: $z_{\rm est} = 7.05\ (6.60 - 7.40)$



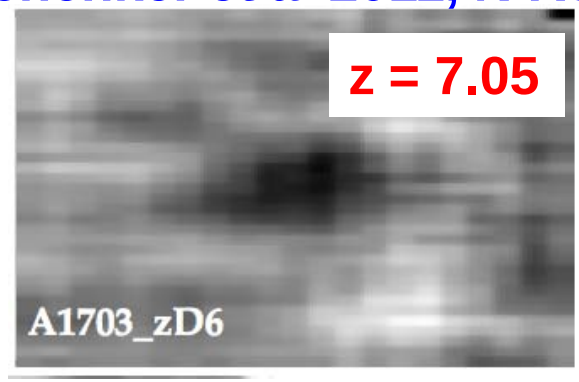
1107: $z_{\rm est} = 7.60\ (7.30 - 7.90)$

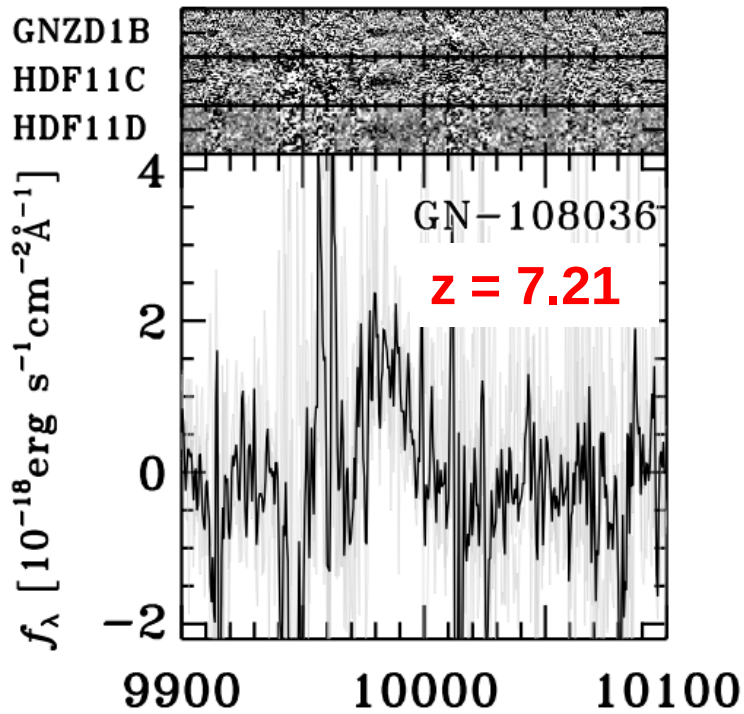
Convincing z > 7 Galaxy Spectra

Vanzella et al 2011, FORS2)



Schenker et al 2011, NIRSPEC)

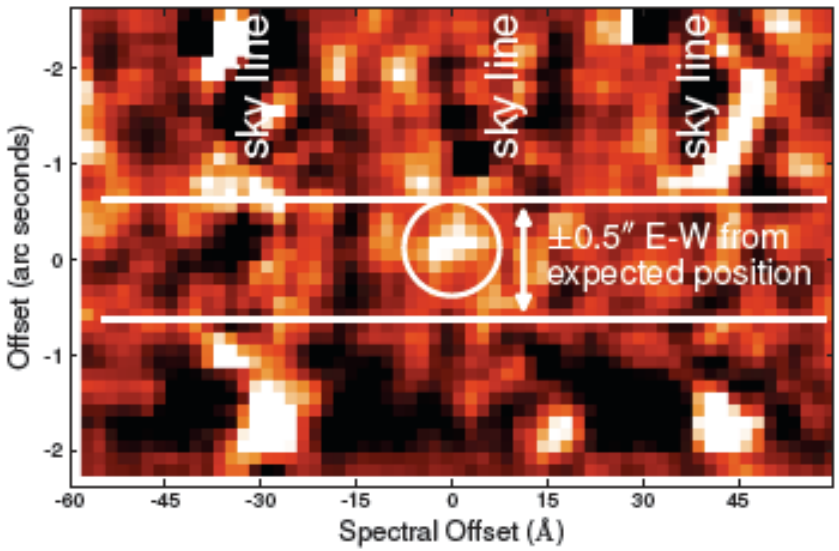


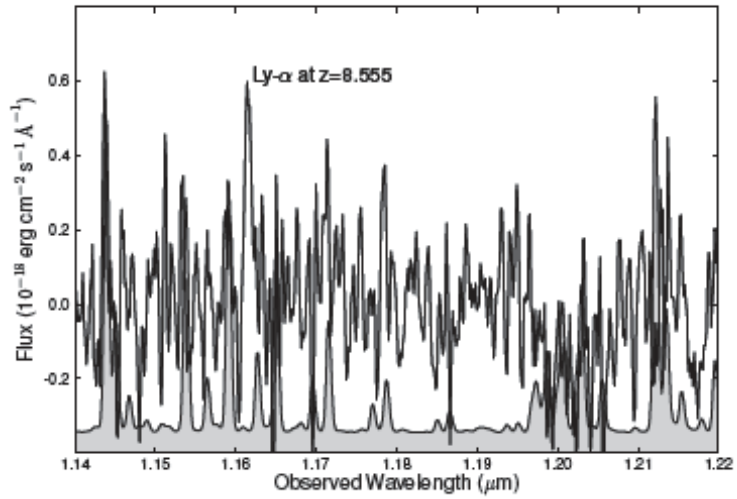


Ono et al 2011 (DEIMOS)

Query on z=8.55 LBG?

UDFy-38135539 = HUDF-YD3





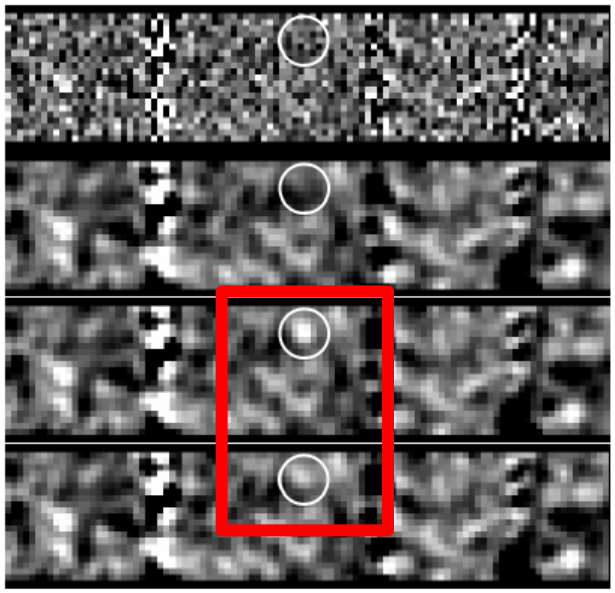
Lehnert et al (2010) VLT SINFONI 14.8 hours R~2000

Claims 6.0σ detection

Bunker et al (2011) VLT X-Shooter

5 hours R~5100

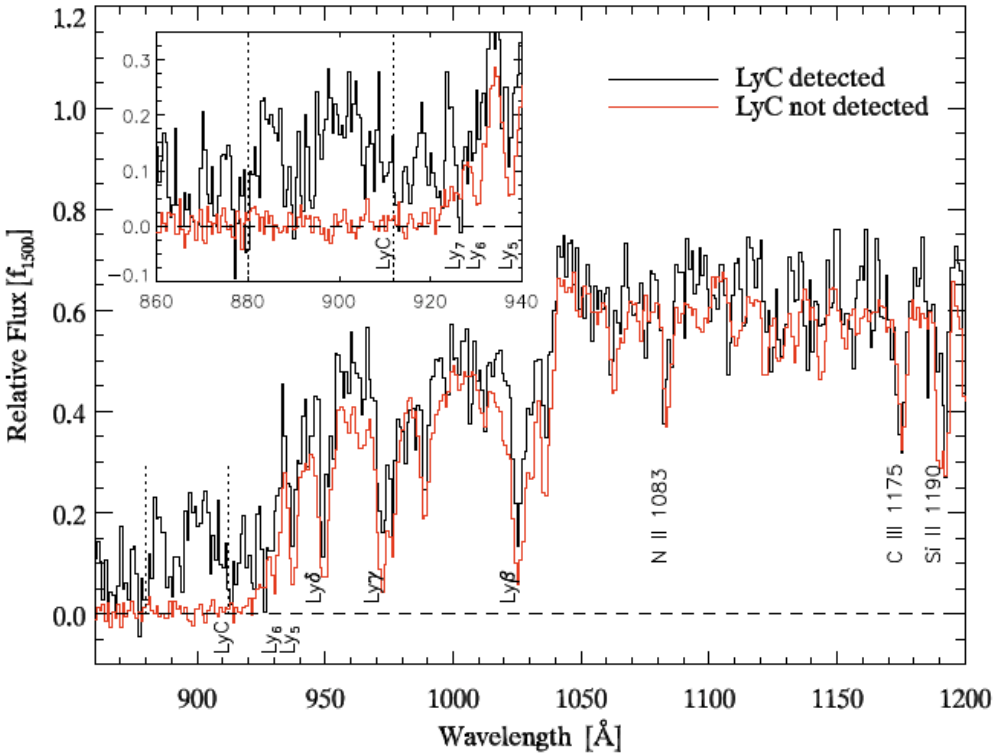
Expected 3.5-4.5σ detection

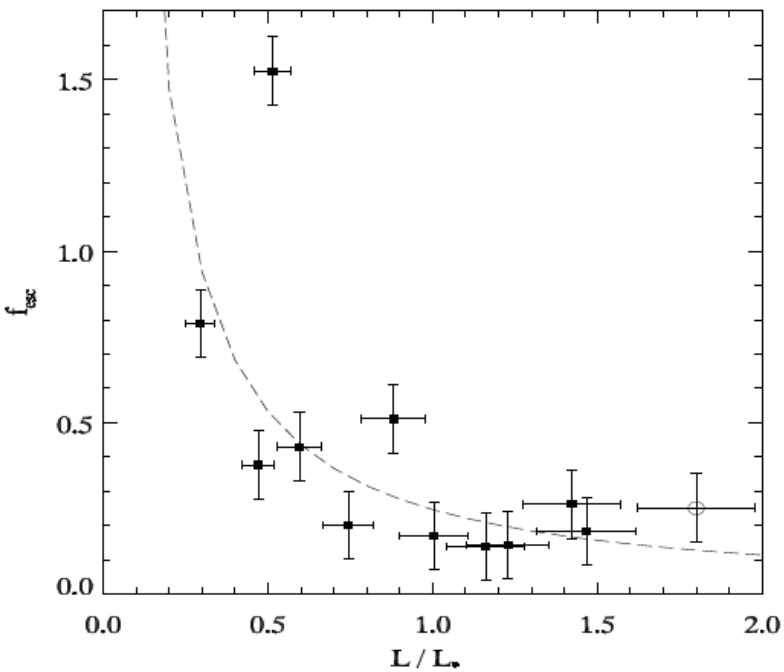


Escape fractions in z~3 LBG spectra

$$f_{esc,rel} = \frac{(L_{1500}/L_{900})_{int}}{(f_{1500}/f_{900})_{corr}}$$

$$f_{esc} = 10^{-0.4\times 10.33 E(B-V)} f_{esc,rel}$$





11/110 LBG spectra show positive Ly continuum flux

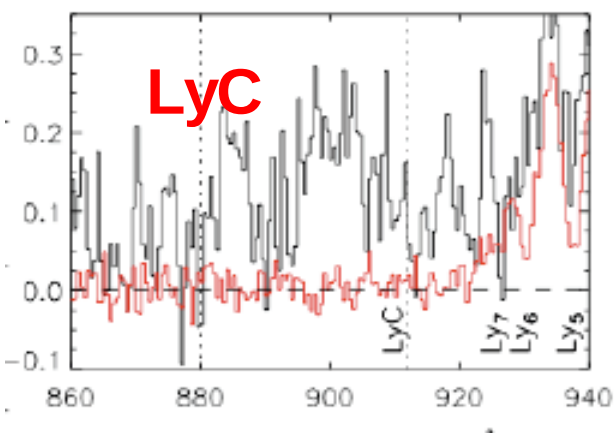
For that small subset, intringuingly, f_{esc} correlates as L^{-1}

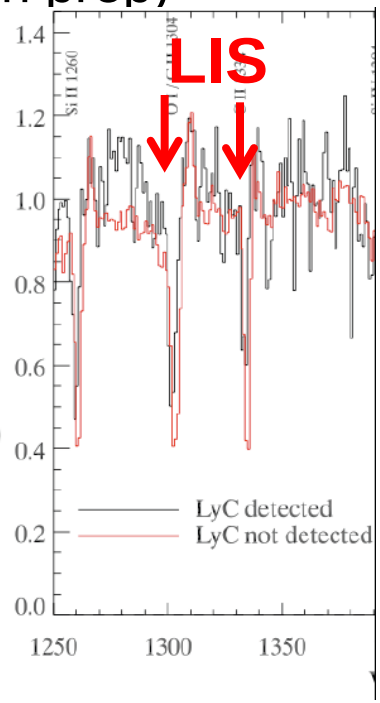
Not practical to consider this test at z~7

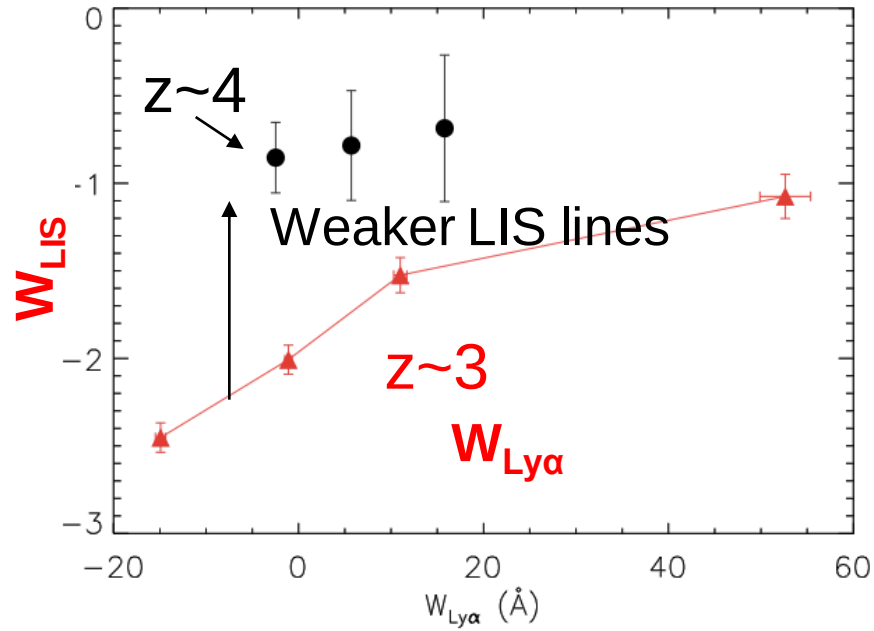
Steidel et al (2011)

Does f_{esc} increase with z?

Keck spectra reveal LyC is seen in faint blue LBGs where low ionization lines are shallower implying reduced covering fraction (Steidel et al 2011, in prep)





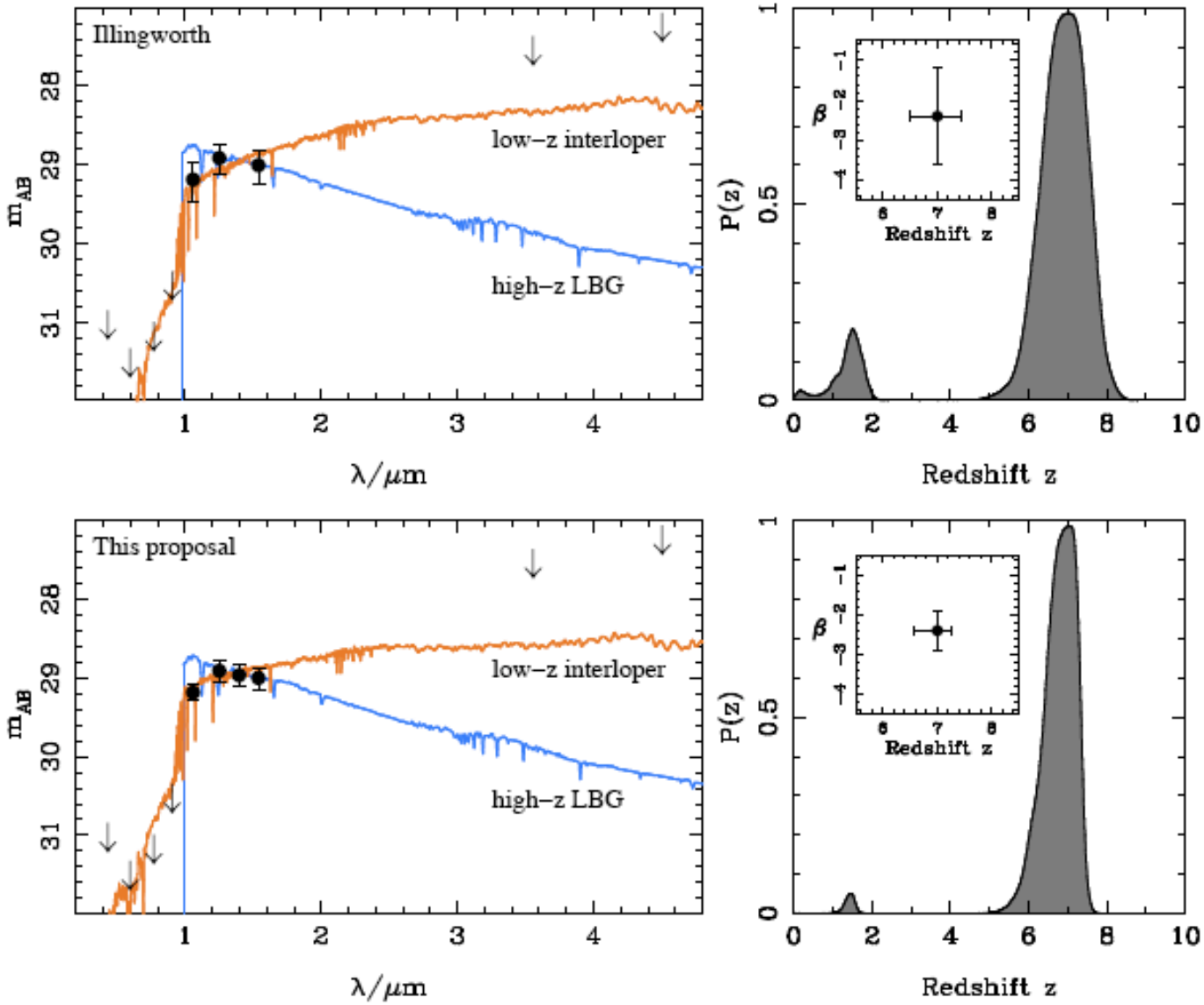


Stack of ~120 z~4 Keck DEIMOS spectra shows weaker low ionization lines which may imply increased f_{esc} (although other interpretations are possible).

Further DEIMOS spectra over 4<z<6 will clarify

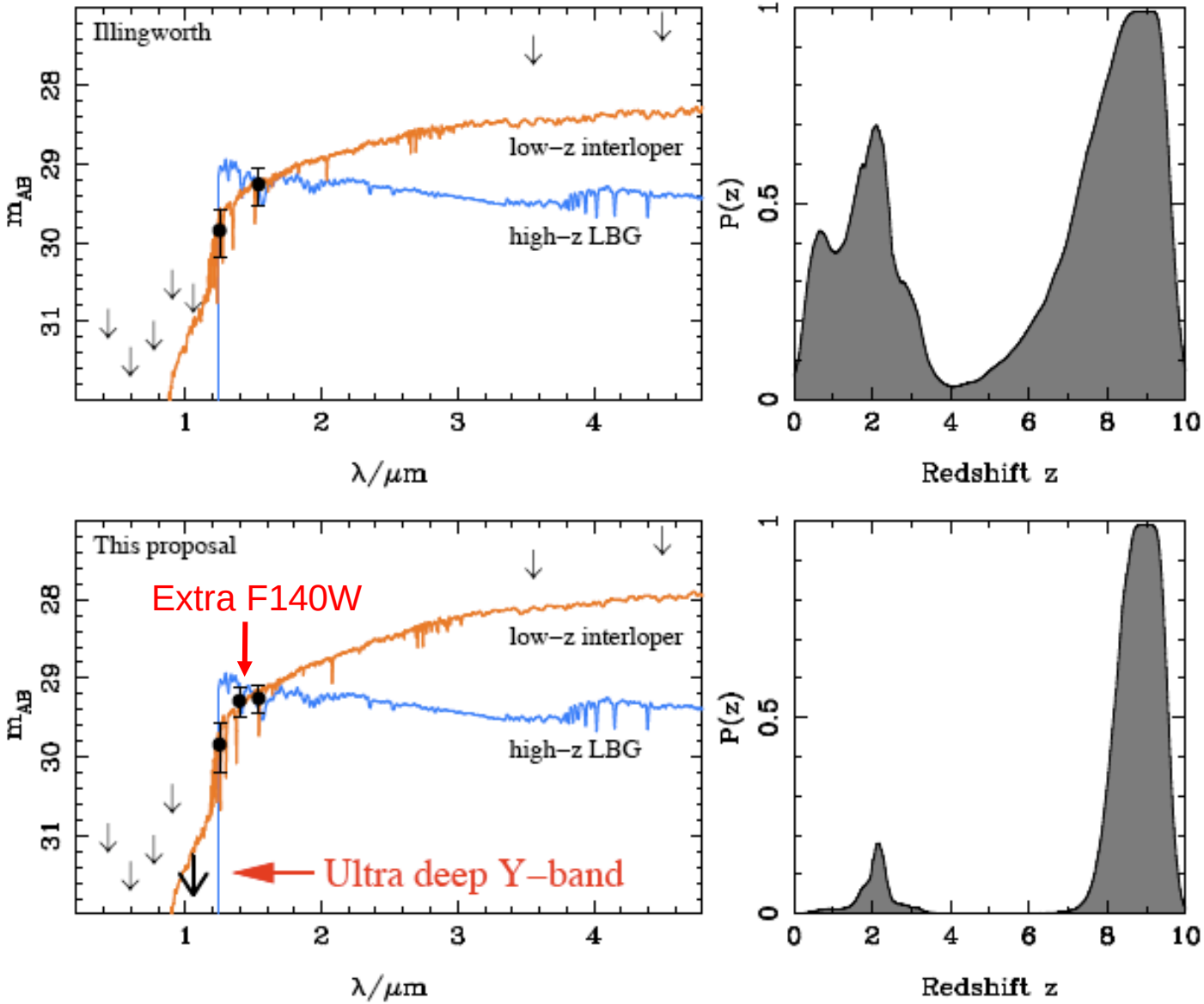
Improved Measures of UV slope β

Increased depth and additional filter

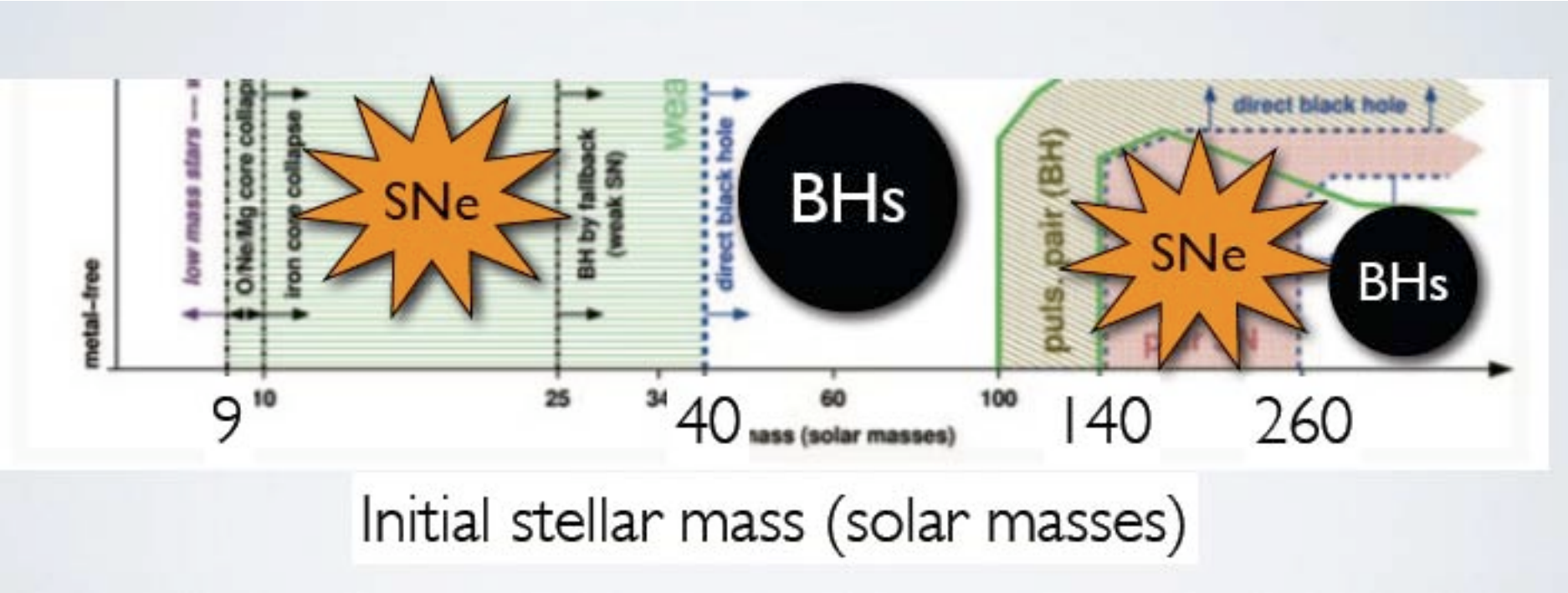


Improved Identification of z~10 Sources

Ultra-deep F105W and additional F140W



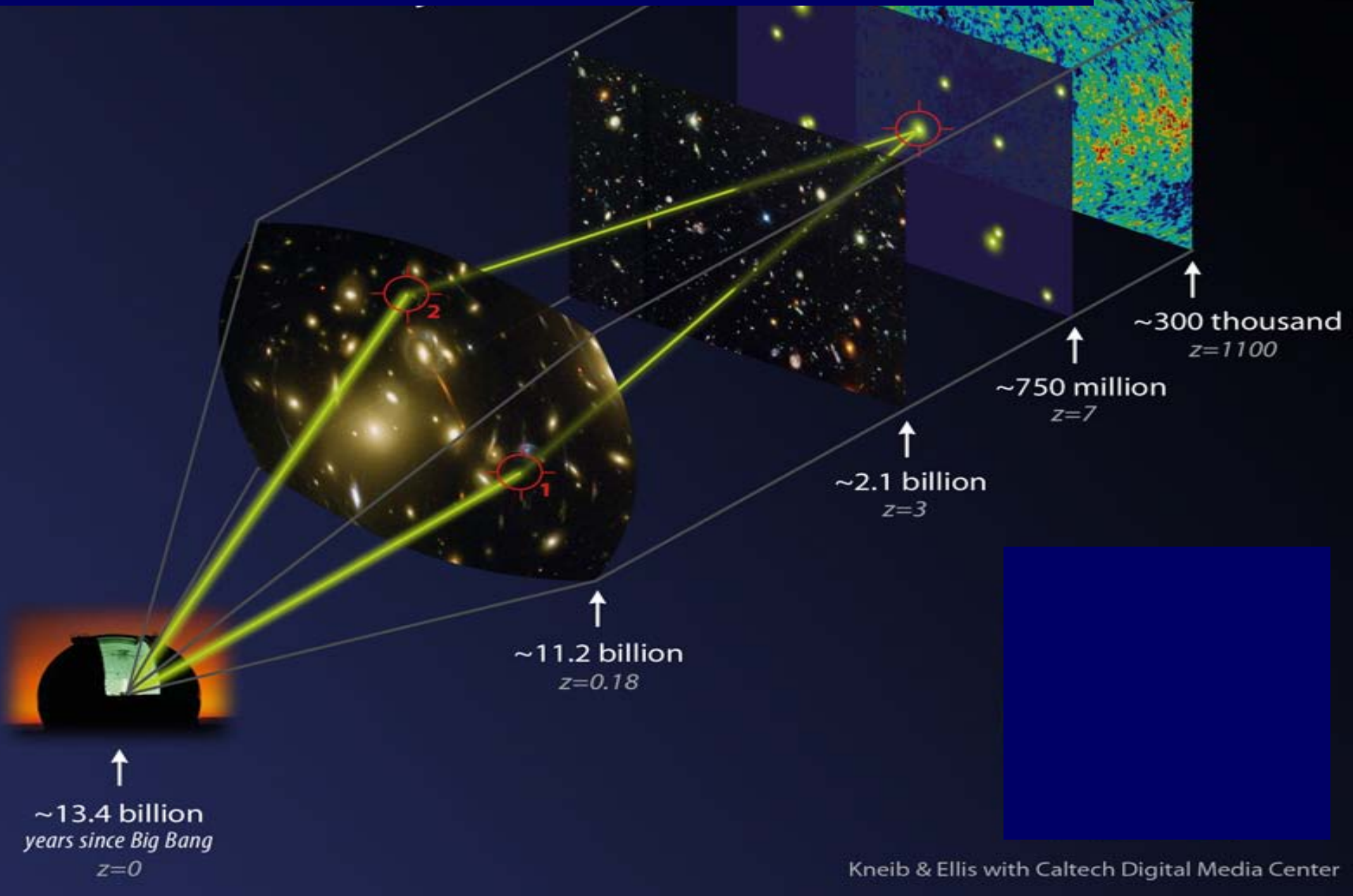
Important by-products of Population III



Low or zero metallicity stars leads to top-heavy IMF
Leads to large increase in SN IIp and GRBs
Beyond ~140 $M_\odot$ considerable increase in pair instability SNe (PISN)
Beyond 260 $M_\odot$ PISN leave massive BHs as remnants
Expect these BHs to seed AGN activity over 7<z<15

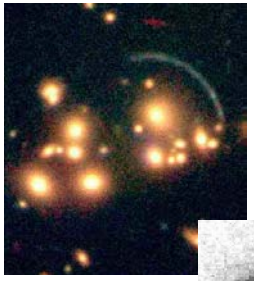
Heger et al (2002)

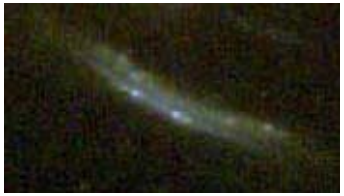
Boosting the signal with gravitational lenses

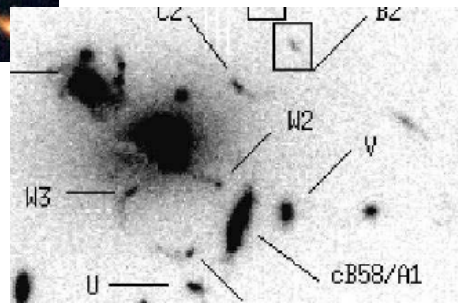


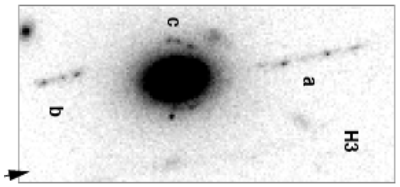
Gravitationally Lensed Galaxies: Record Breakers (1991-2008)

- 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, Pellò et al 1999

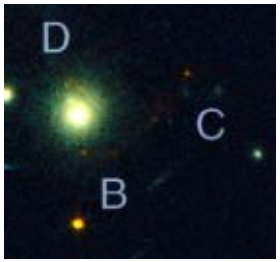


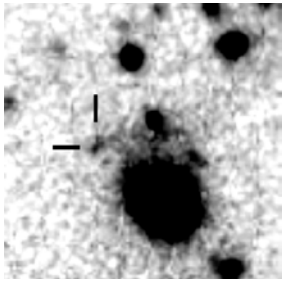


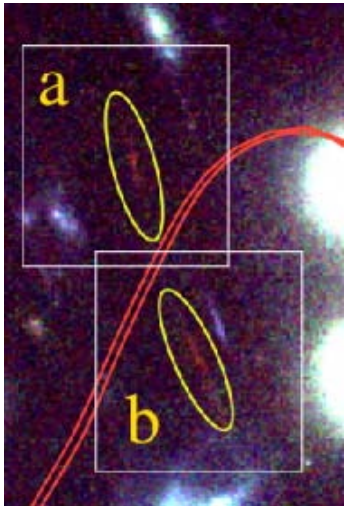




- MS1358+62 (z=4.92); Franx et al 1997
- A2218 (z=5.7); Ellis et al 2001
- A370 (z=6.56); Hu et al 2002
- ***A2218 (z~6.8); Kneib et al 2005***
- ***A1689 (z~7.6); Bradley et al 2008***

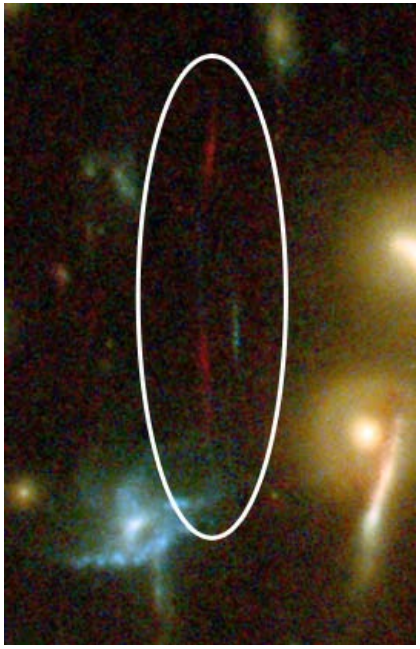


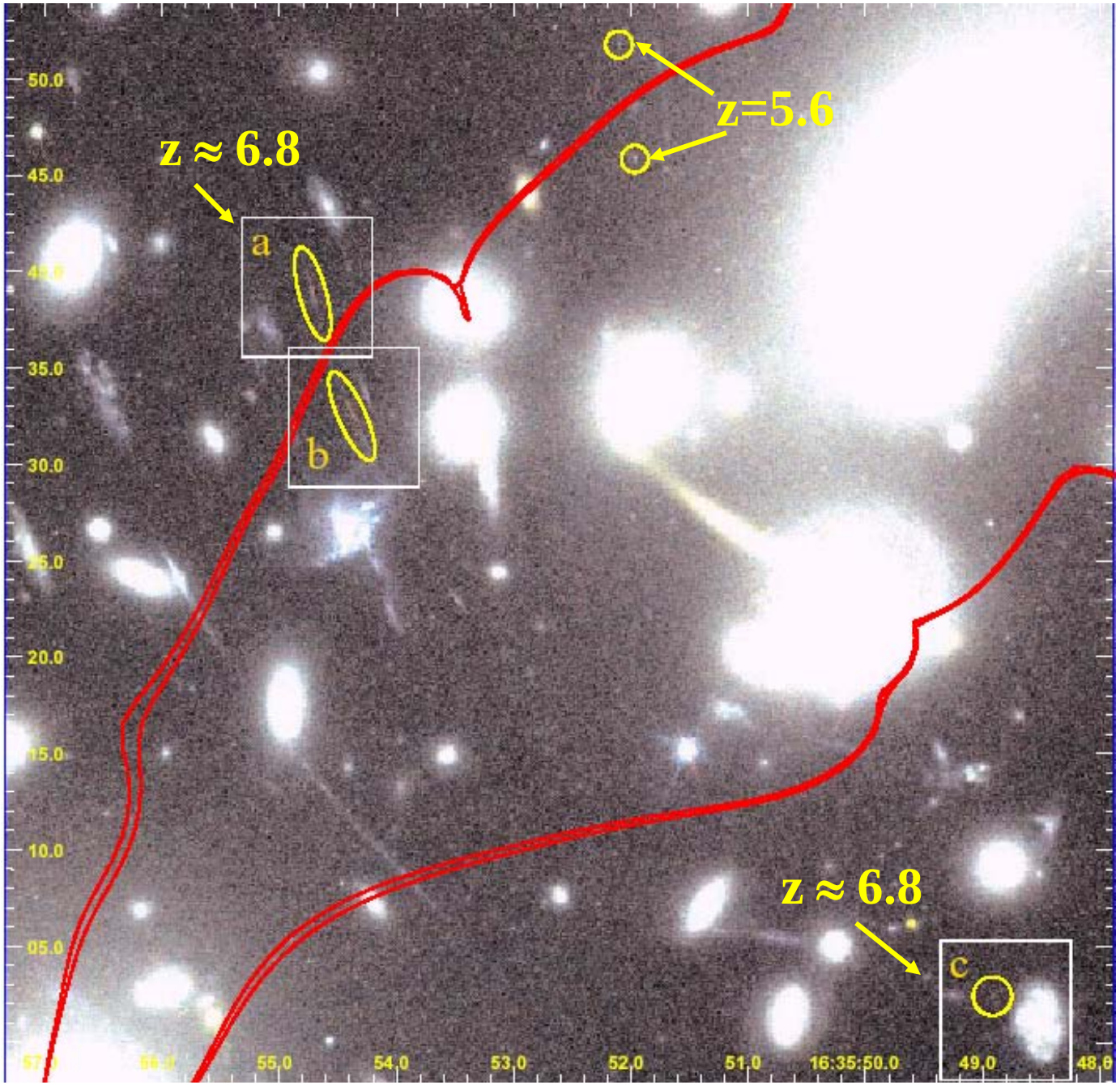




Critical line discoveries in Abell 2218

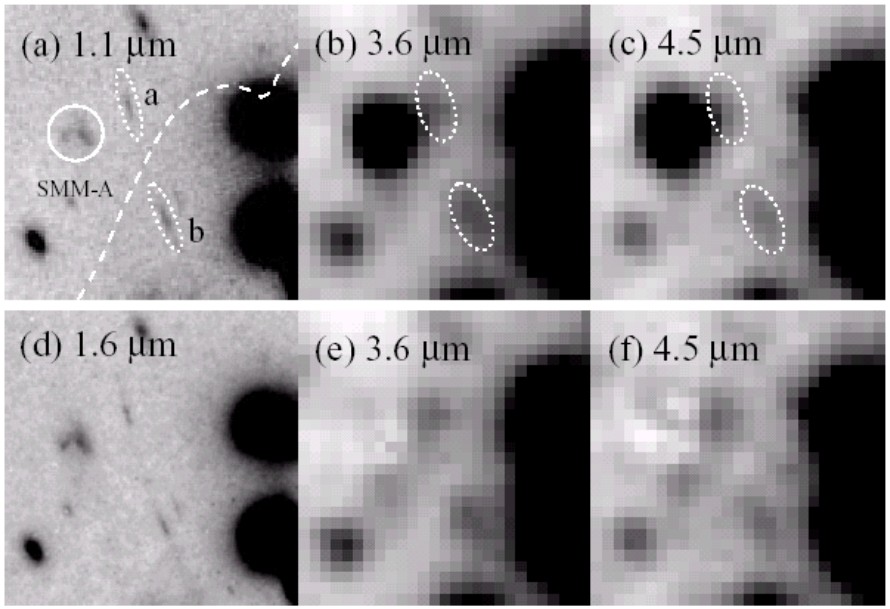
RSE et al 2001, Kneib et al 2004



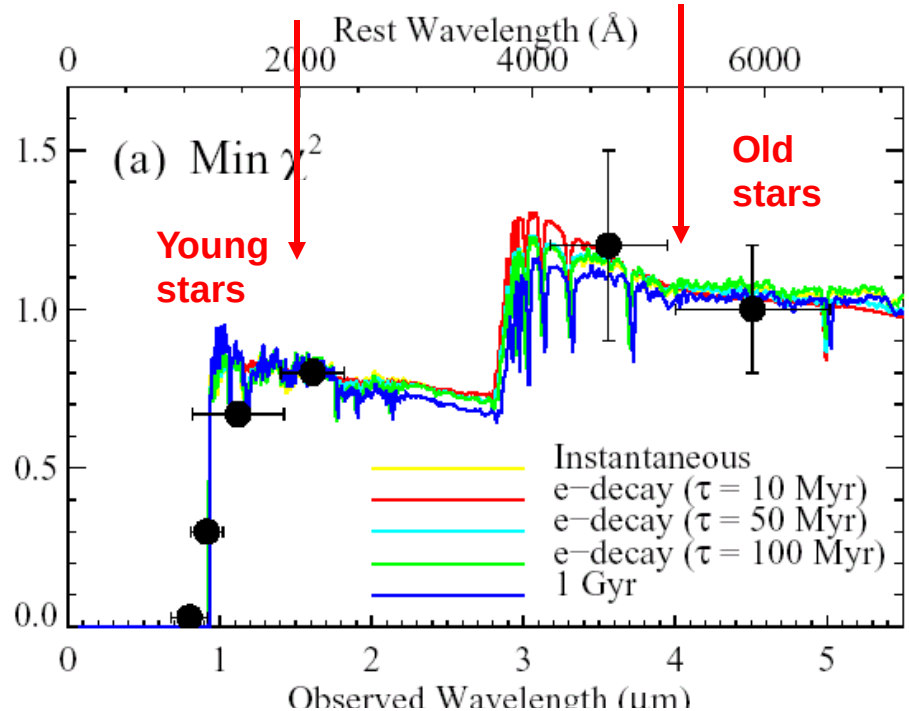


Deciphering past history of z~6.8 lensed LBG

Hubble **Spitzer**



Hubble **Spitzer**



Multiply-imaged z=6.8 galaxy in cluster Abell 2218; magnification ×25

Star formation rate = 2.6 $M_\odot yr^{-1}$ Stellar mass ~ 5-10 $10^8 M_\odot$

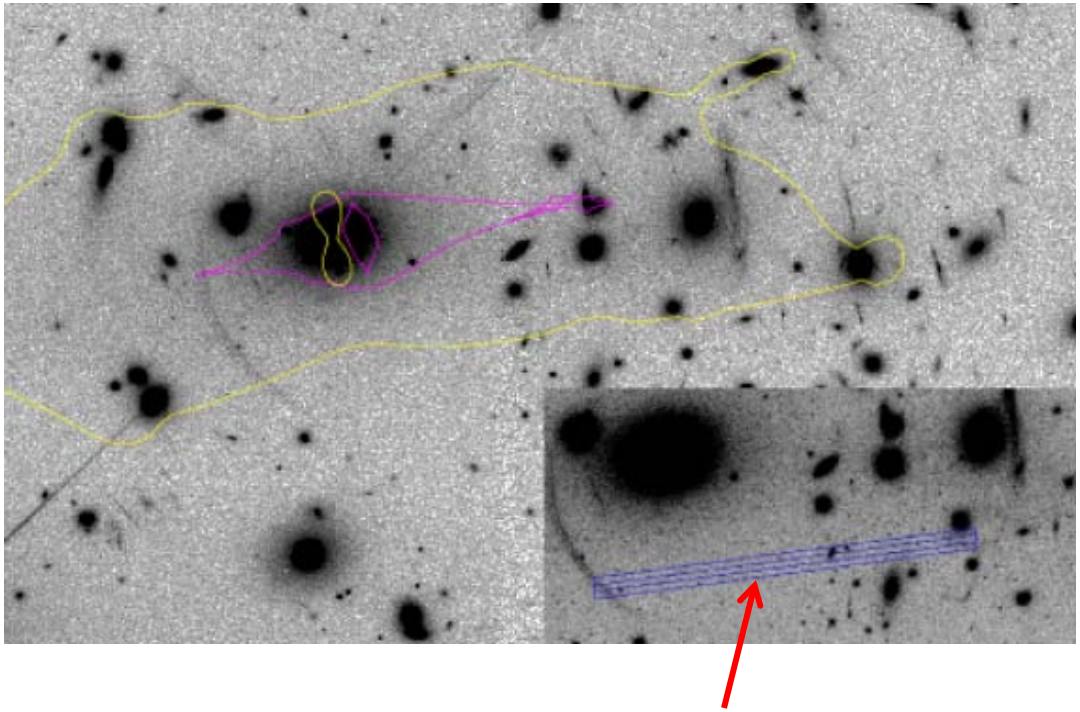
Balmer break gives age = 100 – 450 million yrs, so formed at $9 < z_F < 12$

This is already a well-established system 800 Myrs after Big Bang

Egami et al (2005)

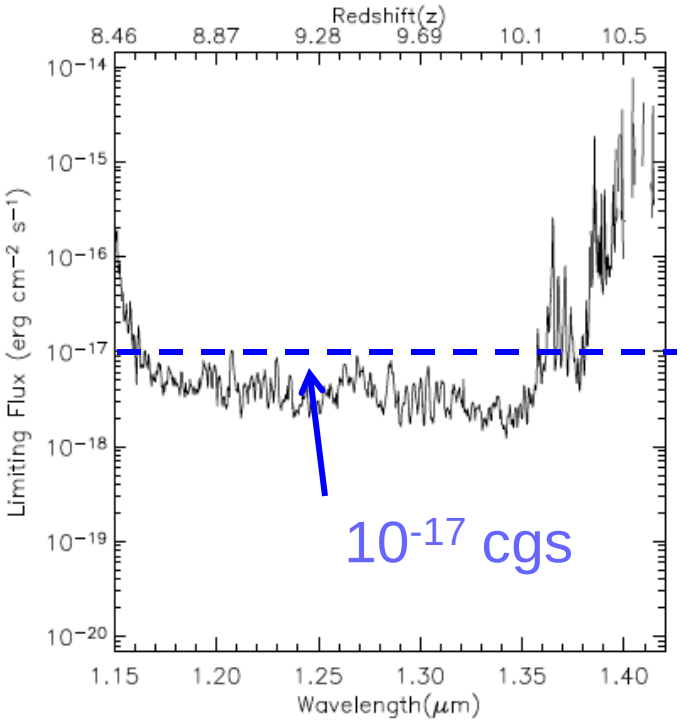
Low Luminosity z~8-10 Lyα Candidates

Cluster critical line for $z_S > 7$



NIRSPEC slit positions

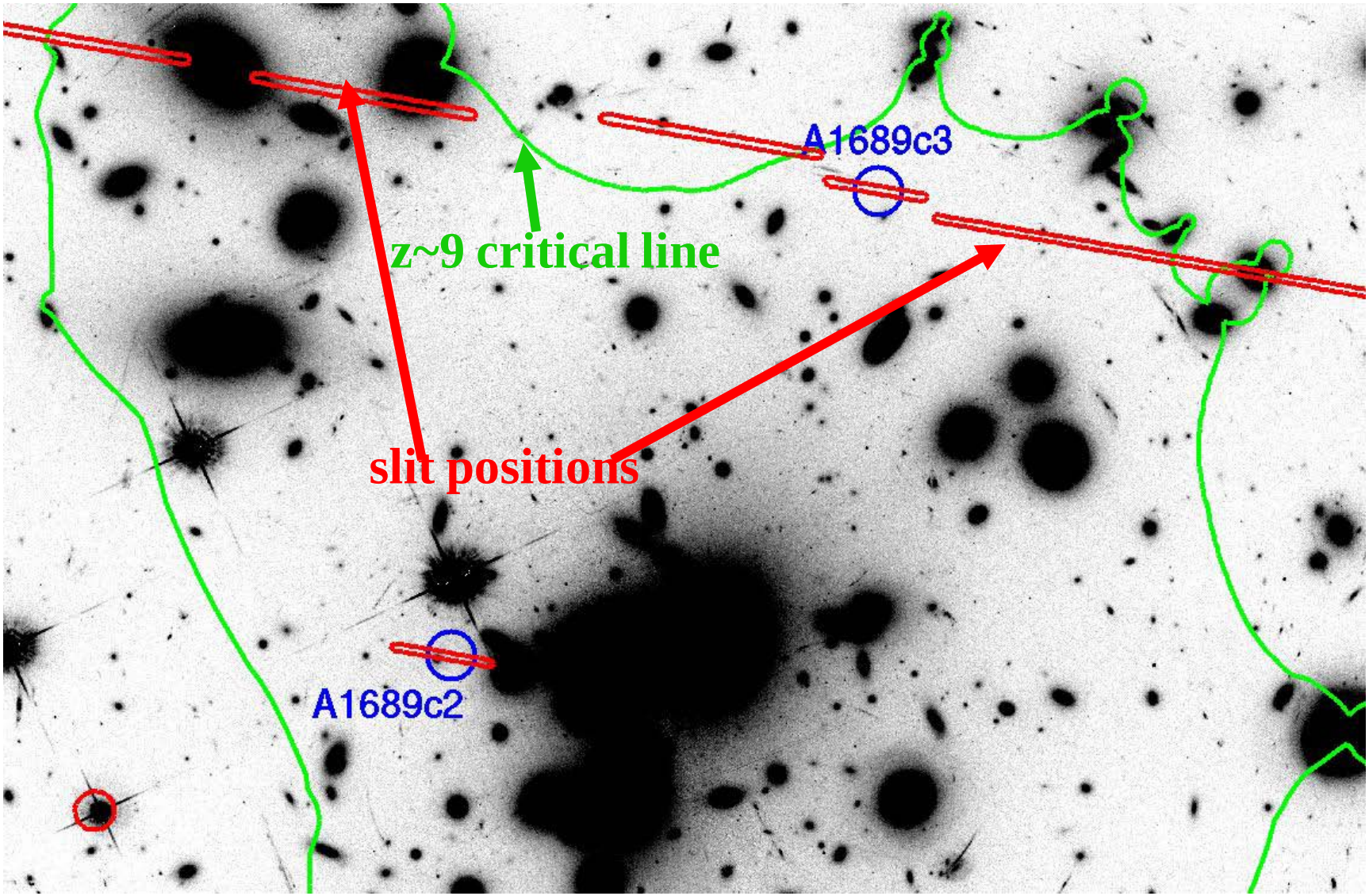
Wavelength sensitivity (1.5hr)



- 9 clusters with well-defined mass models & deep ACS imaging
- Obs. sensitivity ~ 3-9.10^{-18} cgs; magn. > $\times$15-20 throughout
- Sky area observed: 0.3 arcmin^2; V(comoving)~50 Mpc^3
- <u>6 promising lensed emitter candidates</u>
- 8.6 < z < 10.1; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 -1 $M_\odot$ yr^{-1}

Stark et al 2007

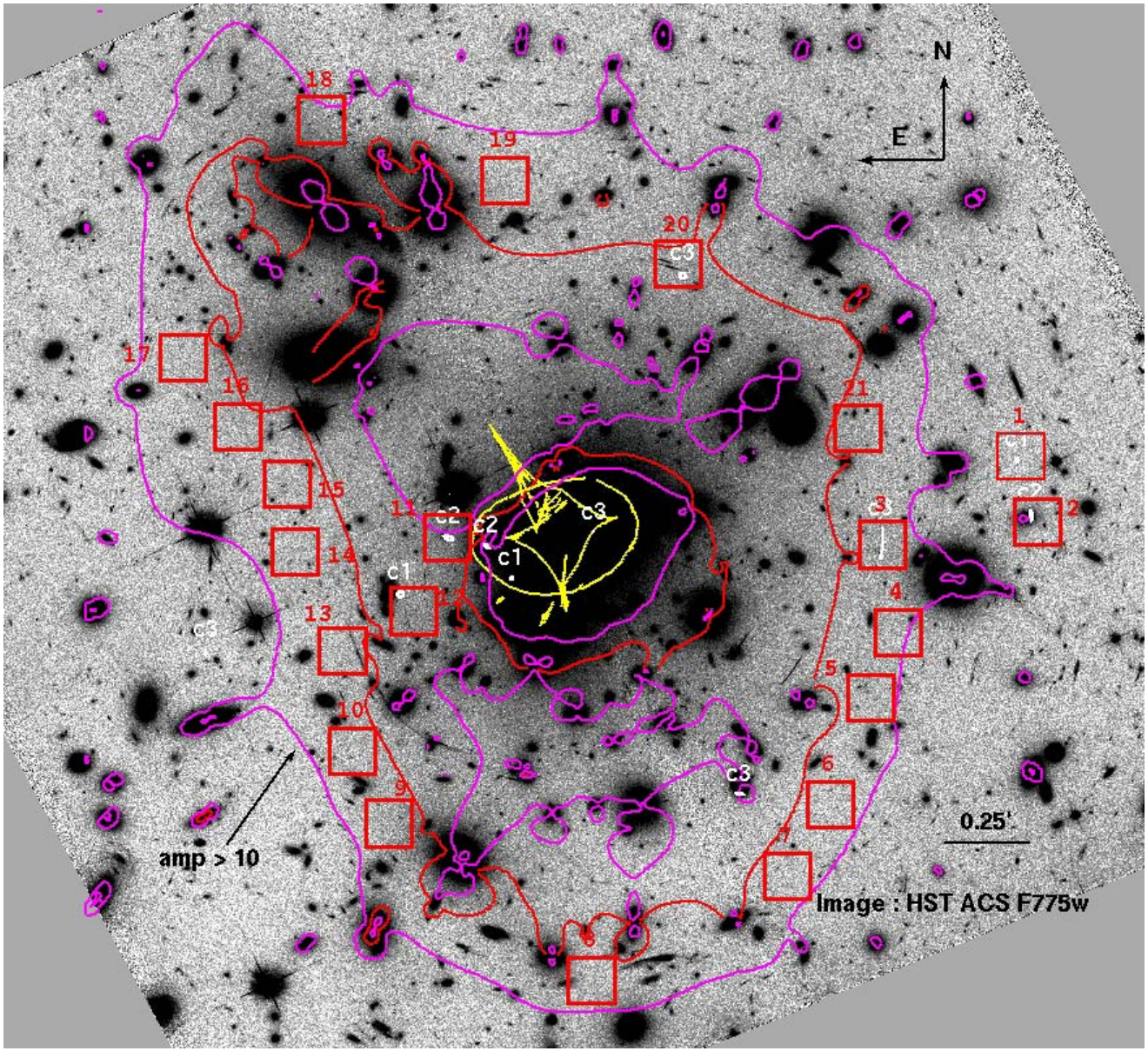
Revisited 4/6 Candidates with MOIRCS (PI: Egami)



4hrs with VPH grism (1.14 -1.34 micron), R~1900; seeing ~0.3-0.4”

VLT SINFONI critical line mapping (PI: Kneib)

- Sensitive 5”×6.5” IFU spectrograph with R~1400
- 21 distributed pointings totalling 680 sq.arcsec in image plane
- Equivalent to ~50 arcsec^2 in the source plane, or a covolume of ~50 Mpc^3
- Probe to L(α)~10^{41}



Line Sensitivity Comparison (preliminary)

SINFONI (prelim): ~5hr

Keck/NIRSPEC: 1.5hr

(Stark et al 2007)

Subaru/MOIRCS (uncertain): 4hr

Upshot so far:

A1689 c2, c3 candidates likely not confirmed with Sinfoni (TBC)

A 2219 c1, c2 maybe not confirmed with MOIRCS?

A1689 c1 too faint for SINFONI, not in λλ range for MOIRCS.

2 candidates remain untested (including A68 c1, the most promising example)