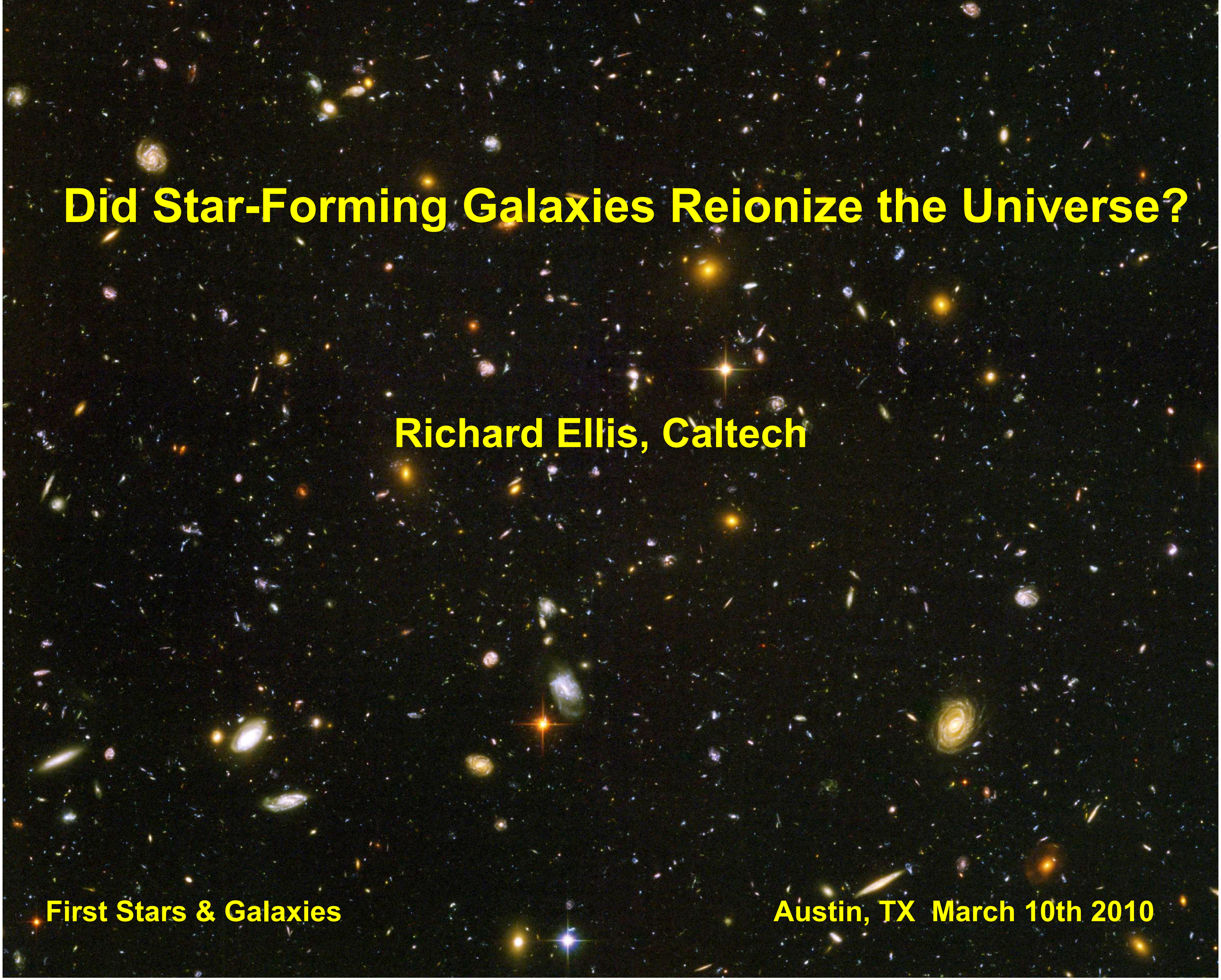


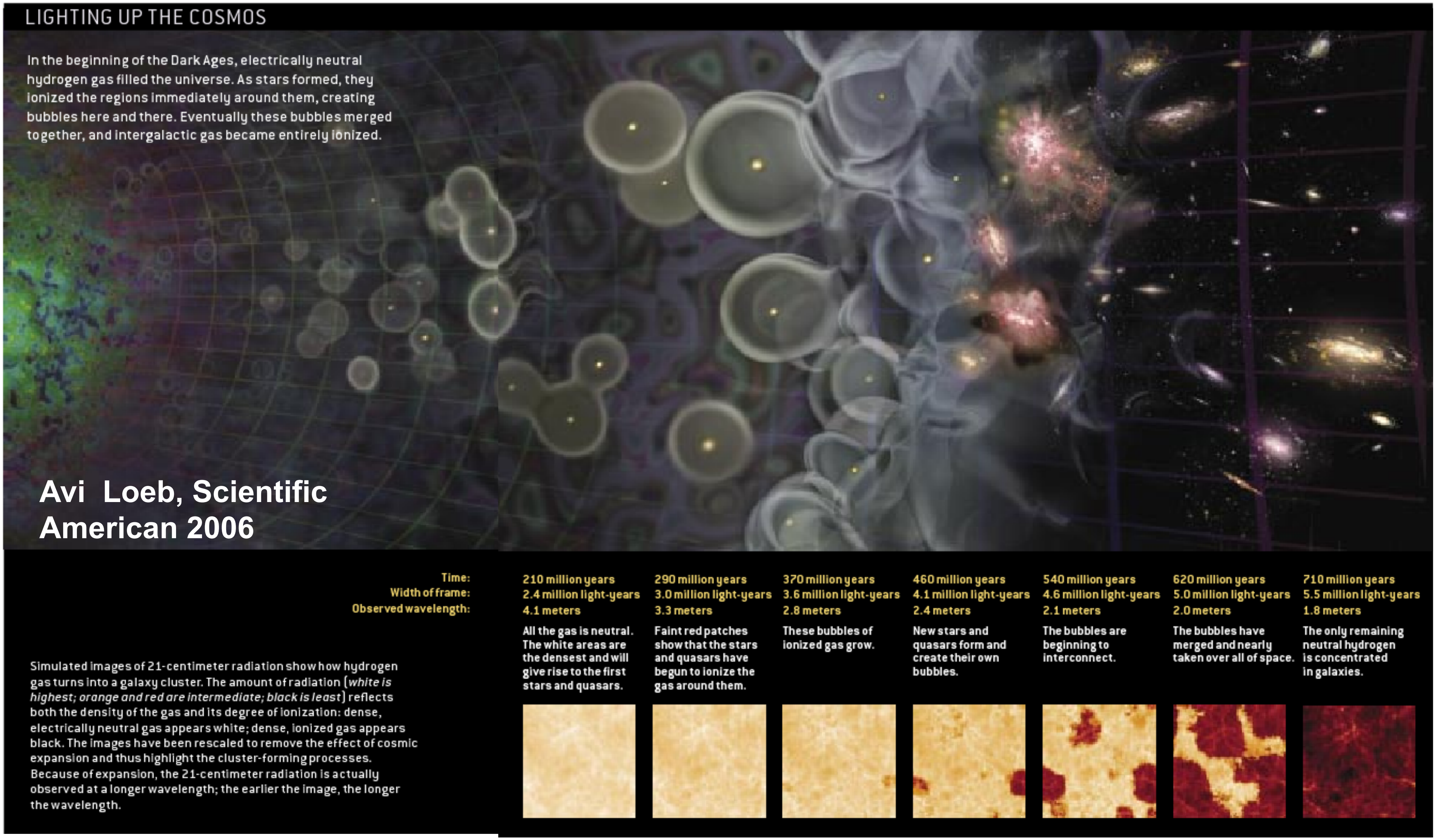
Did Star-Forming Galaxies Reionize the Universe?

Richard Ellis, Caltech

First Stars & Galaxies

Austin, TX March 10th 2010

Theorists' View of Cosmic Reionization



Avi Loeb, Scientific American 2006

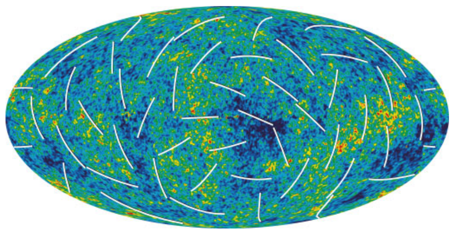
Wonderful..but did it really happen like this..?

Why the Early Universe? Grand Questions

- **What** - reionized the universe and were star-forming galaxies the primary agents?
- **When** - did reionization occur? Was it a sudden, protracted or even two-stage process?
- **How** - did it proceed? What processes defined the emerging mass function of galaxies
- **Then What?** - Implications for the subsequent development of galaxies and the IGM

Mostly a review, but with some collaborative material from:

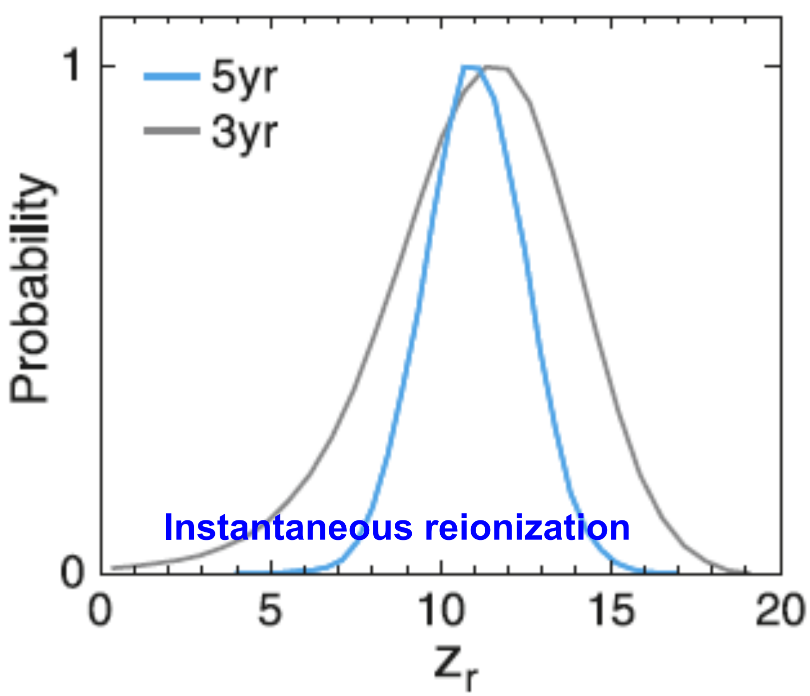
Brant Robertson (CIT), Dan Stark (IoA), Masami Ouchi (OCIW), Eiichi Egami (Arizona), Andy Bunker (Oxford), Jim Dunlop & Ross McLure (Edinburgh), Jean-Paul Kneib (Marseilles), Johan Richard (Durham),

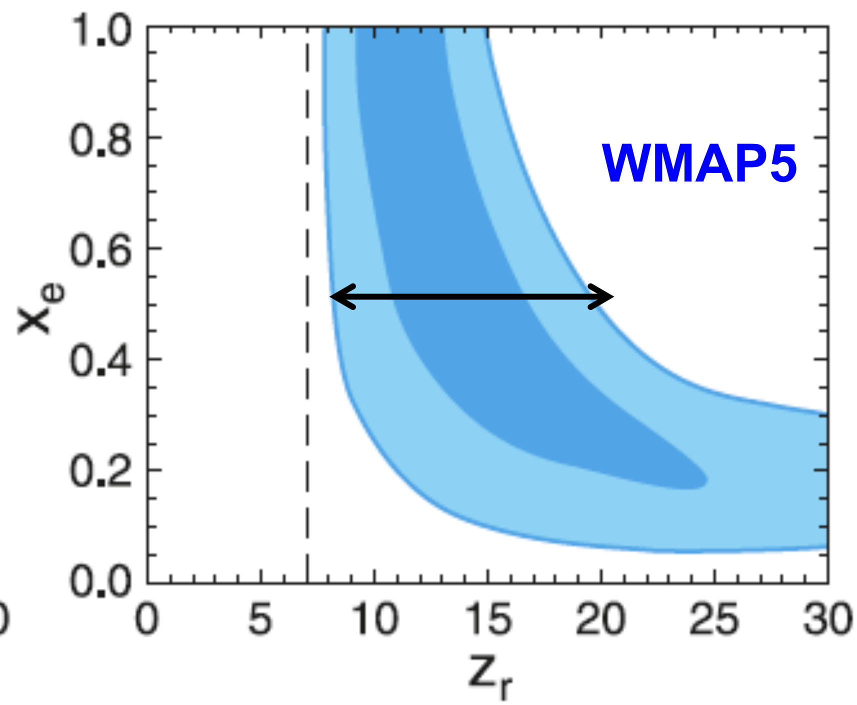


When? WMAP Polarization

$\tau = 0.17 \pm 0.08$ (WMAP1, 2003)
$\tau = 0.09 \pm 0.03$ (WMAP3, 2007)
$\tau = 0.087 \pm 0.017$ (WMAP5, 2009)
$\tau = 0.088 \pm 0.015$ (WMAP7, 2010)

Dunkley et al 2009
Jarosik et al 2010



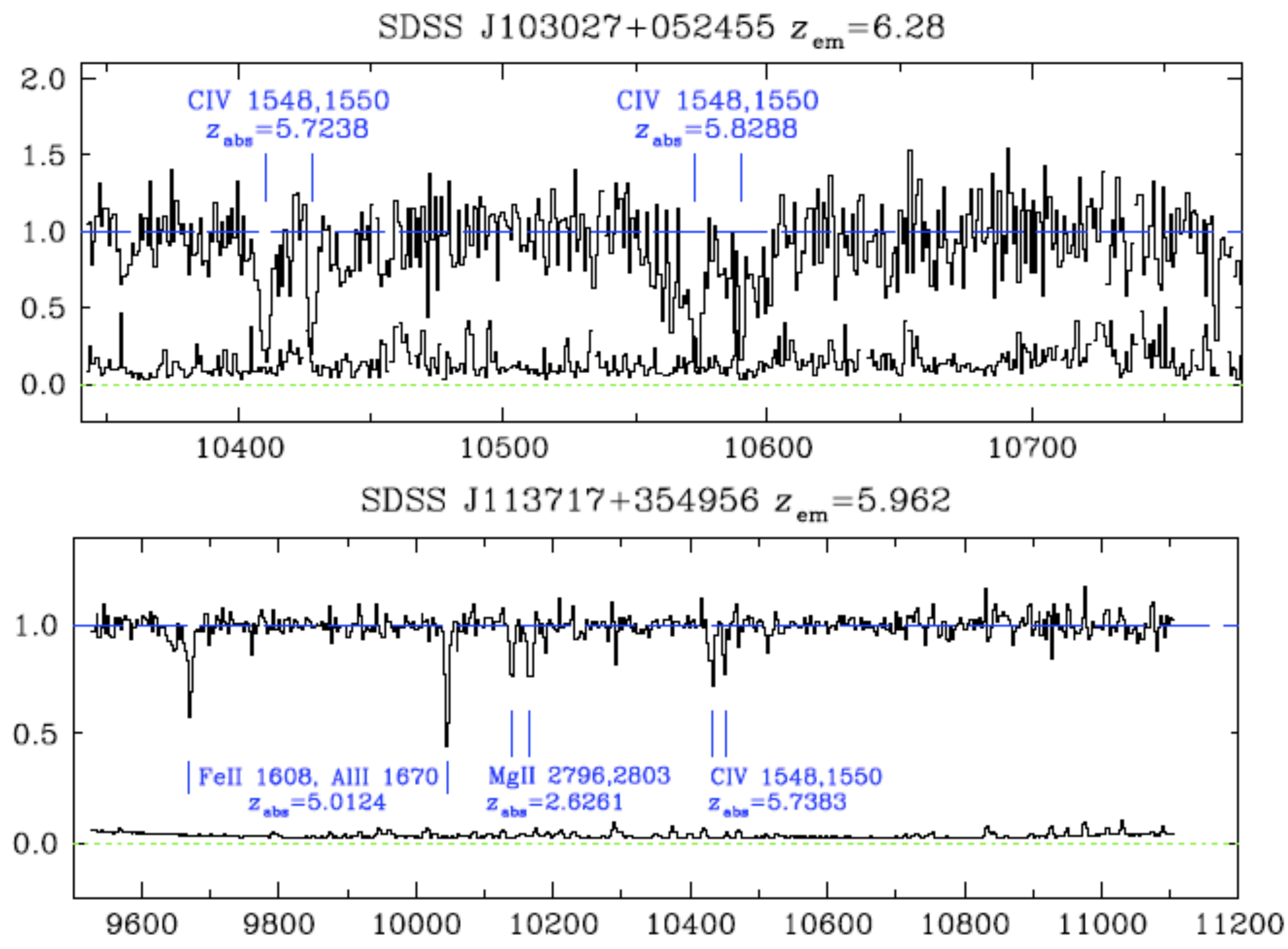


Data rejects instantaneous reionization at z~6-7
Process is likely extended over 6<z<20
CMB studies do <u>not</u> pinpoint the responsible cosmic sources

Ionized Carbon Absorbers in High z QSOs

IR spectra of 10 QSOs with "absorption distance" X(z>5)~25 to log n_{CIV}~14.2

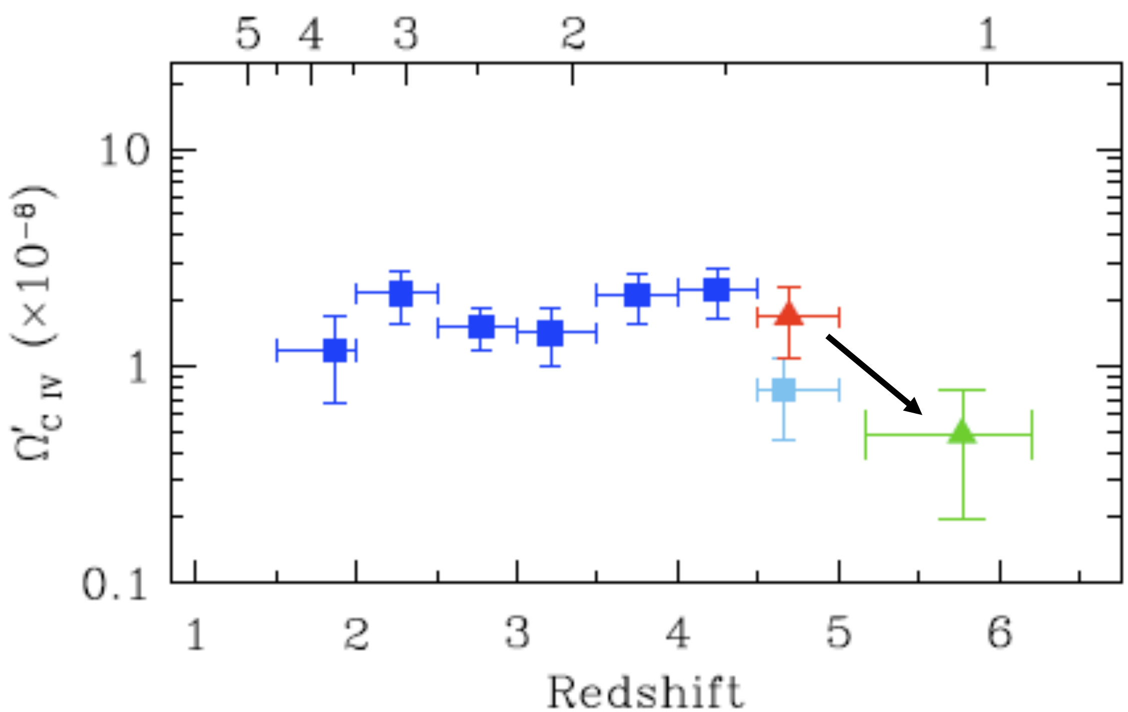
Complementary deeper search with X ~ 11 to log n_{CIV}~13.4 (Becker et al 2009)

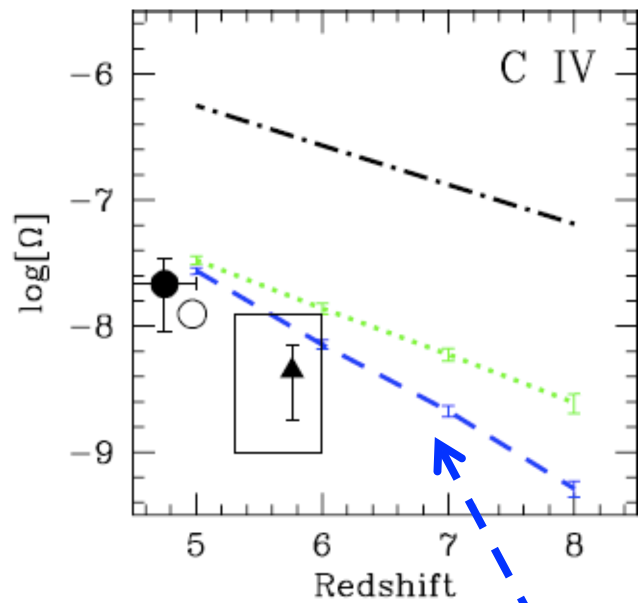


Ryan-Weber et al (2009)

Rapid drop in Ω_{CIV} from z=4.5 to z=6

$\times$3.5 drop in Ω_{CIV} (4σ) over 300 Myr (4.7 < z < 5.8)



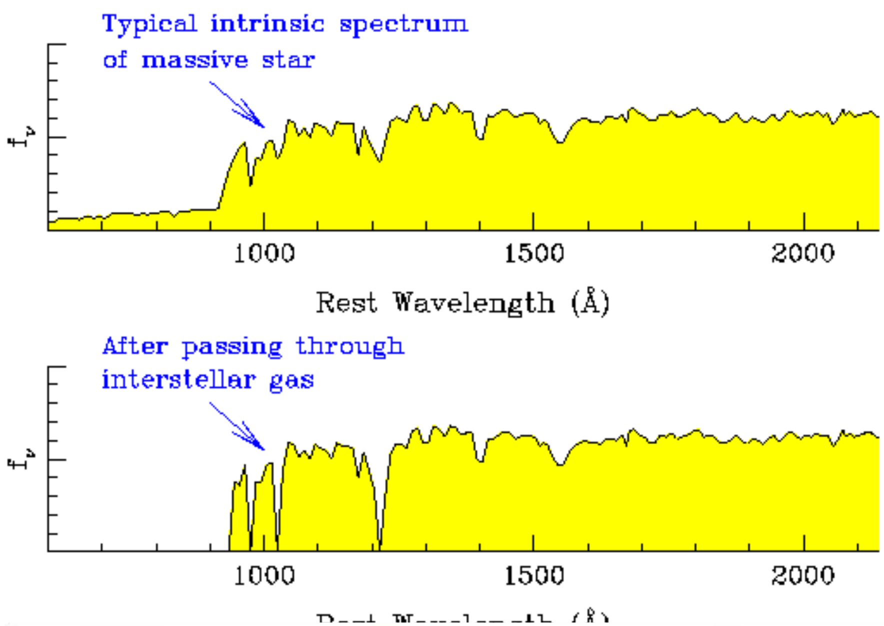


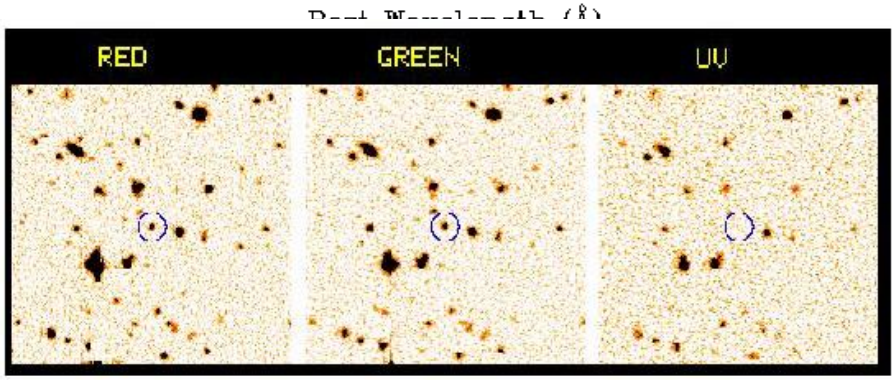
- Suggests rapid enrichment since z~9 (c.f. Oppenheimer et al vzw model)
- Caveats: ionization changes, blending (c.f Becker et al), cosmic variance
- If absorbers representative: Z_{IGM}(z~6) ~ 10^{-4} $Z_{\odot}$ (depends on ioniz^{n})
- Puzzle: implies too few escaping photons (6<z<9) to keep IGM ionized

High Redshift Star Forming Galaxies

Lyman break galaxies (LBGs):

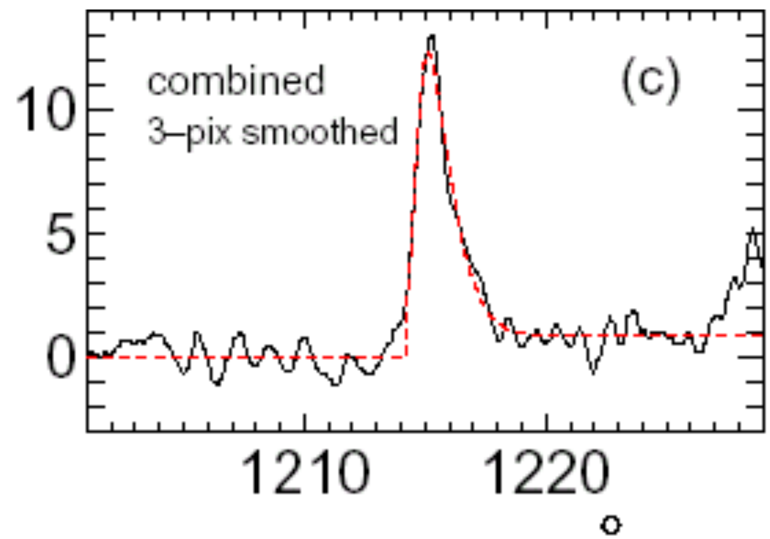
Rest-frame UV continuum discontinuity

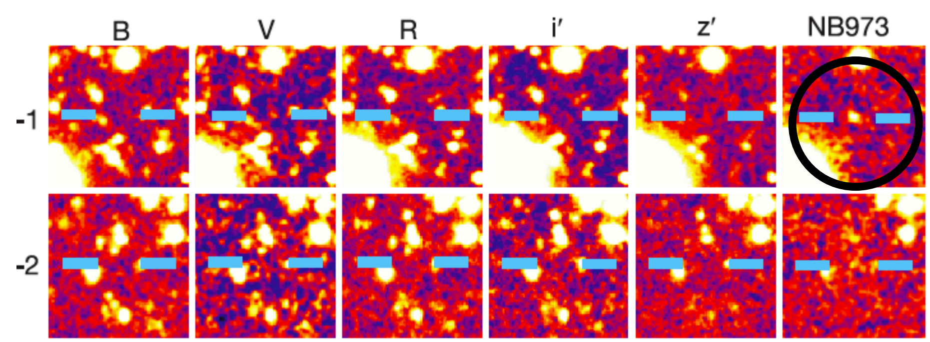




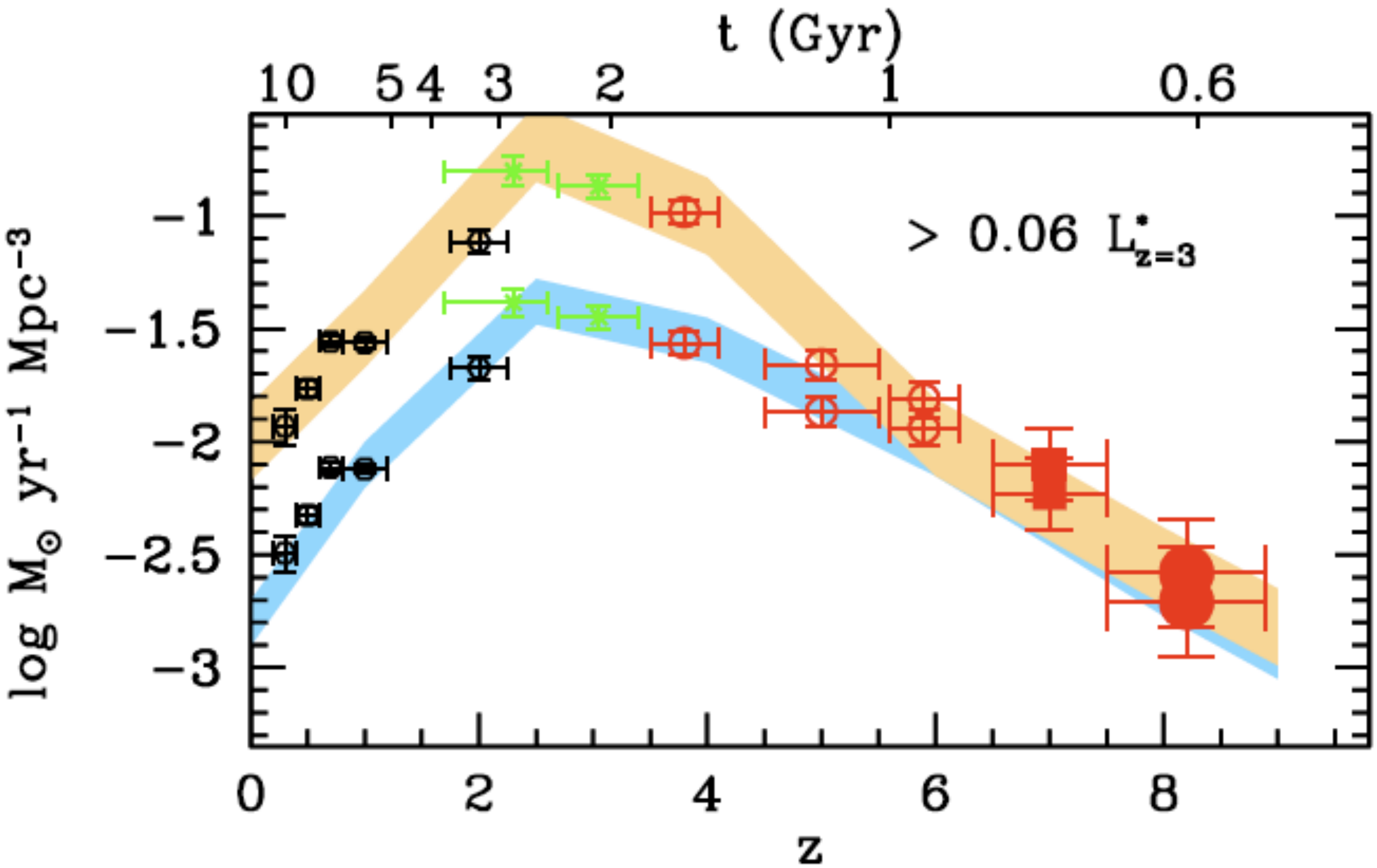
Lyman alpha emitters (LAEs):

Located via narrow band imaging





Star formation density of LBGs



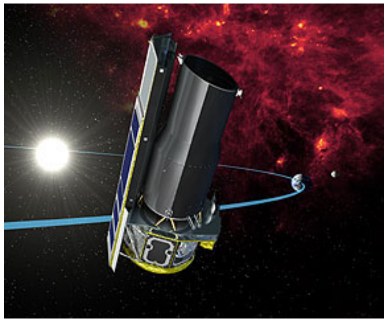
Monotonically declining population to z ~ 6 and beyond

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

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

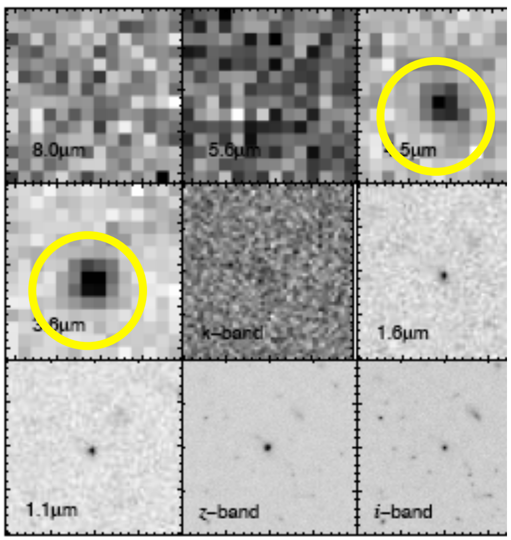
Reddy & Steidel (2009); Bouwens et al (2009)

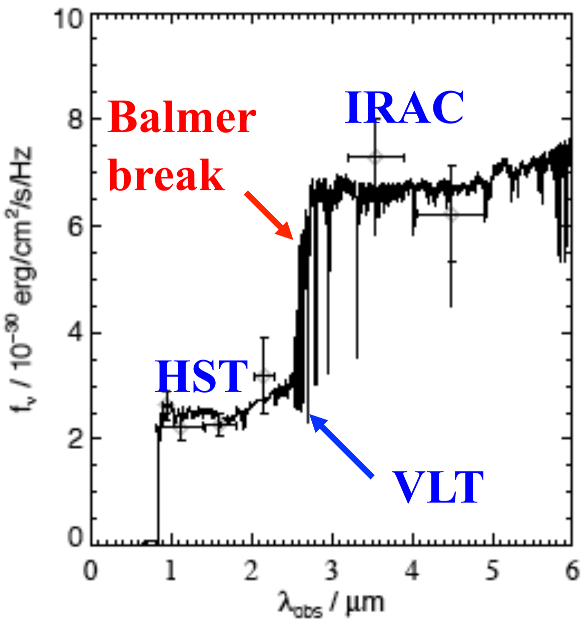
Spitzer Revolution: Stellar Masses & Ages

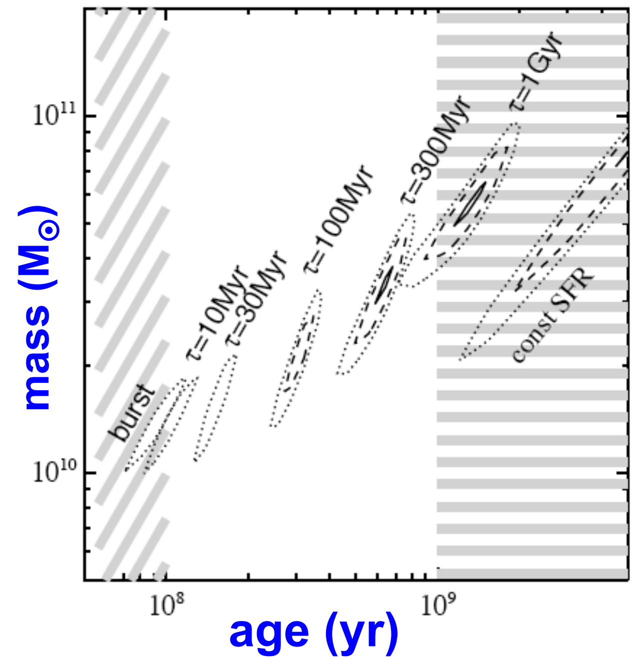


A modest 85cm cooled telescope can see the most distant known objects and provide crucial data on their **assembled stellar masses and ages**

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

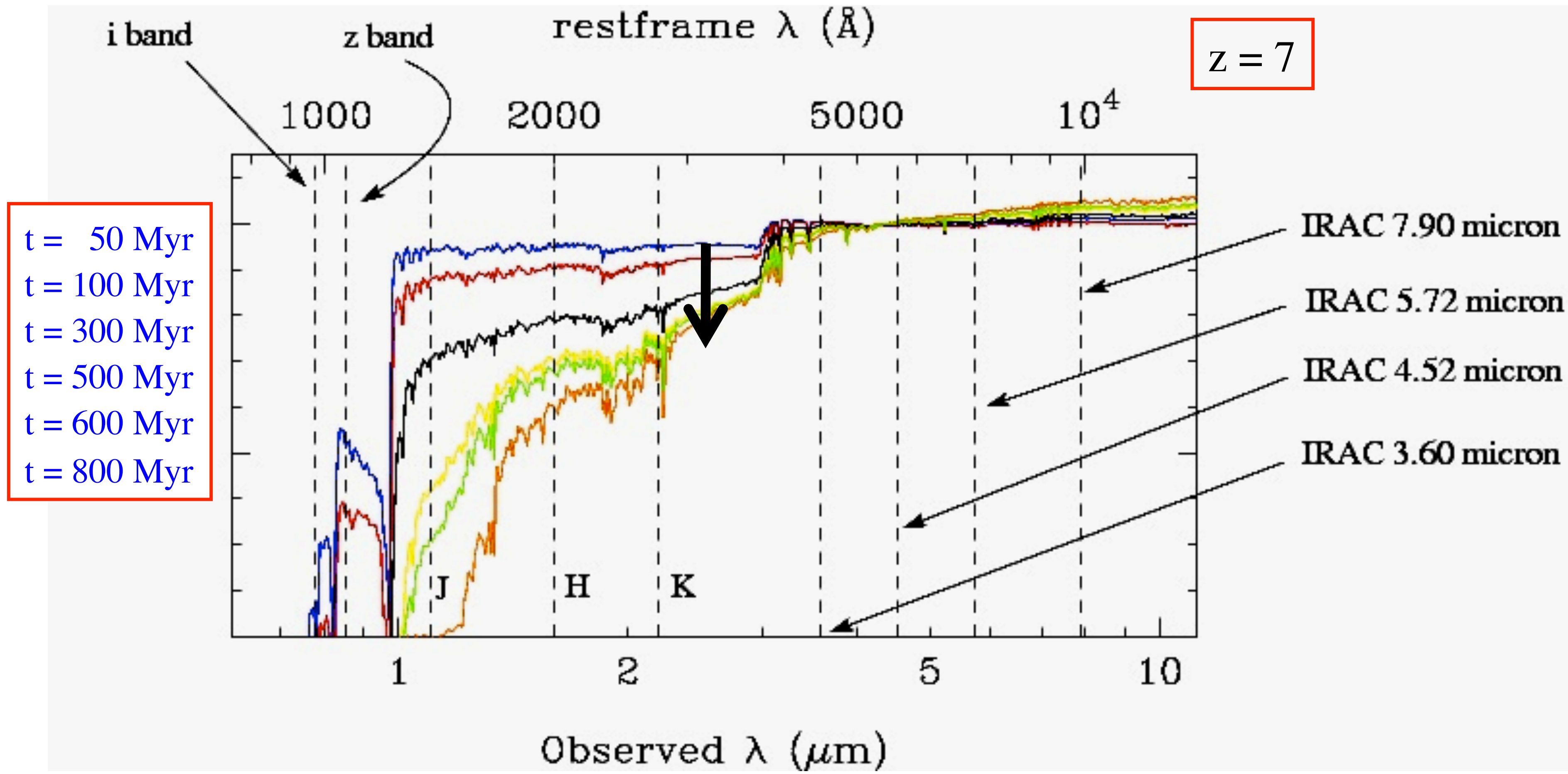






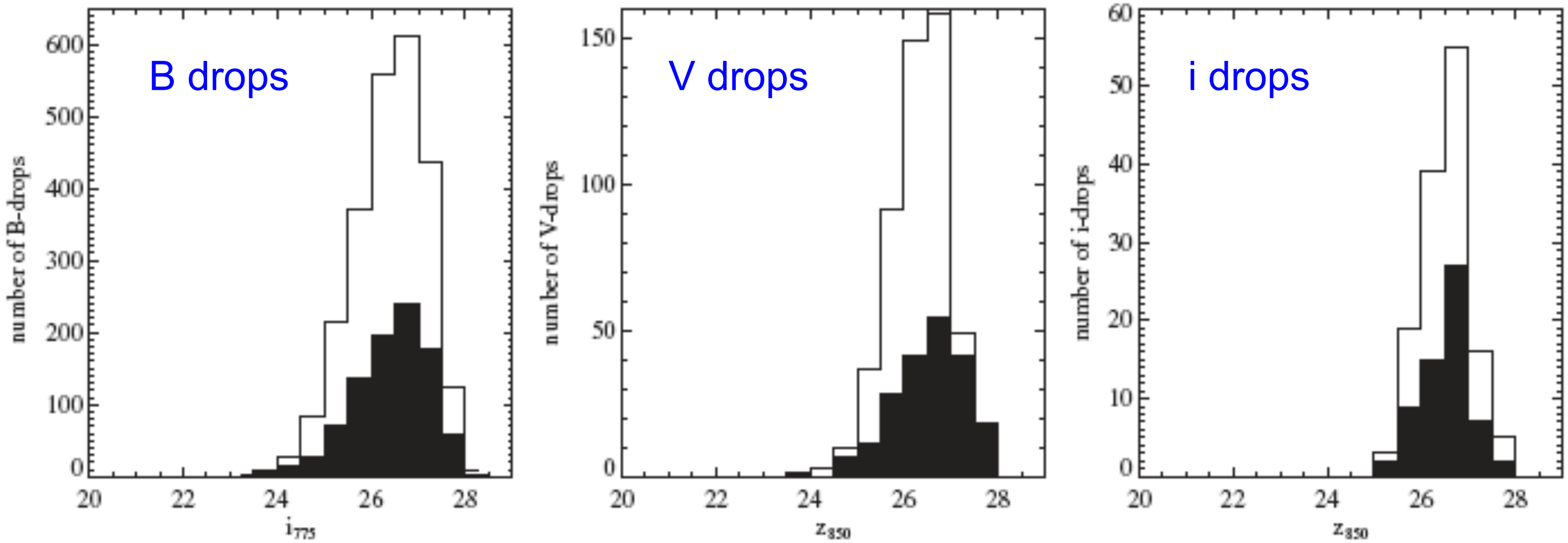
Eyles et al (2005): to produce this mass since z~10 required 5-30 $M_\odot$ yr^{-1}
comparable to the ongoing SFR (6-20 $M_\odot$ yr^{-1})
so should see earlier examples if unobscured

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

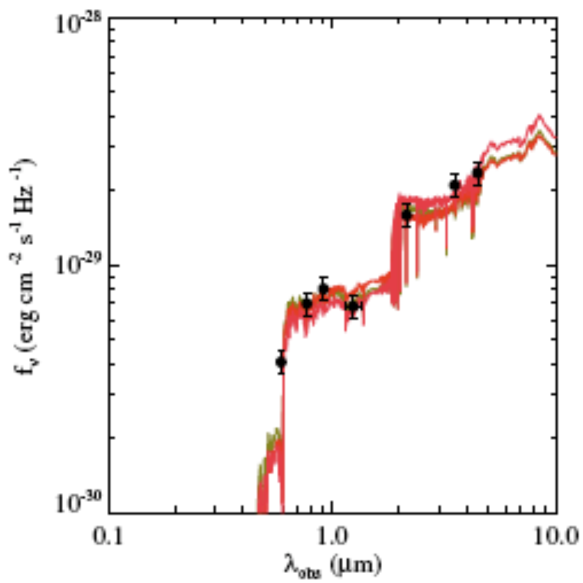
Stellar Mass Functions 4 < z < 6 (Stark et al 2009)



- 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 ISAAC (Cesarsky), MOIRCS (Bundy)
- Low z contaminants identified (morphology, MIPS)
- Masses and ages using CB07, testing effect of TP-AGB stars
- Individual measures to M~$10^{9.5}$ $M_{\odot}$; stacked properties for fainter sources

Examples across the full range of data

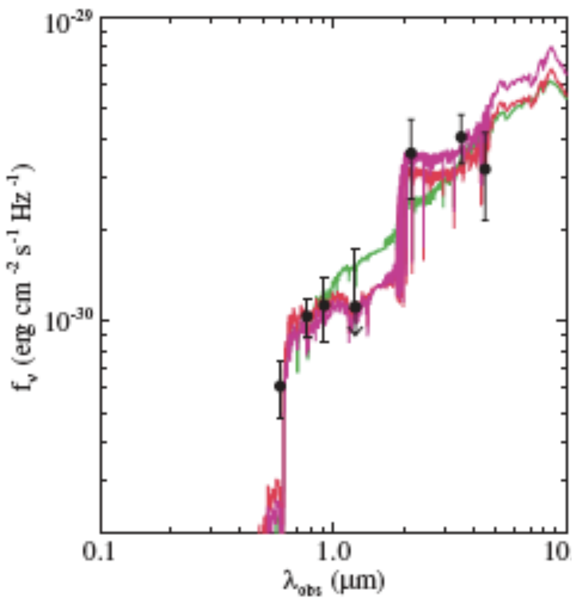
High mass/bright



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

age = 290 Myr

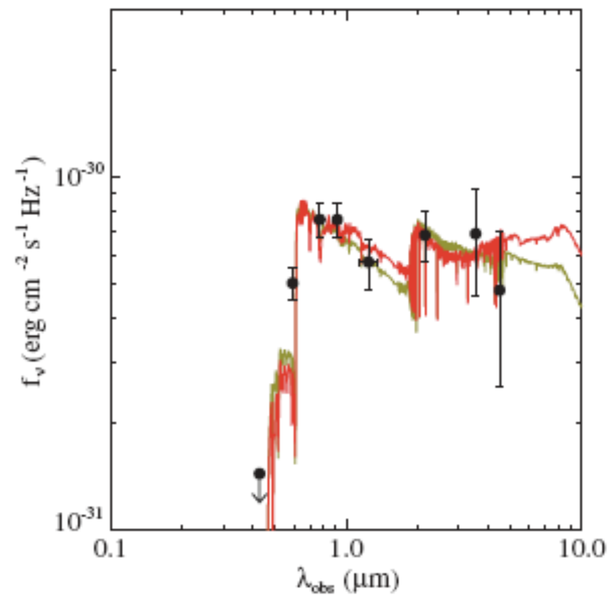
Low mass/faint



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

age = 320 Myr

Stacked data

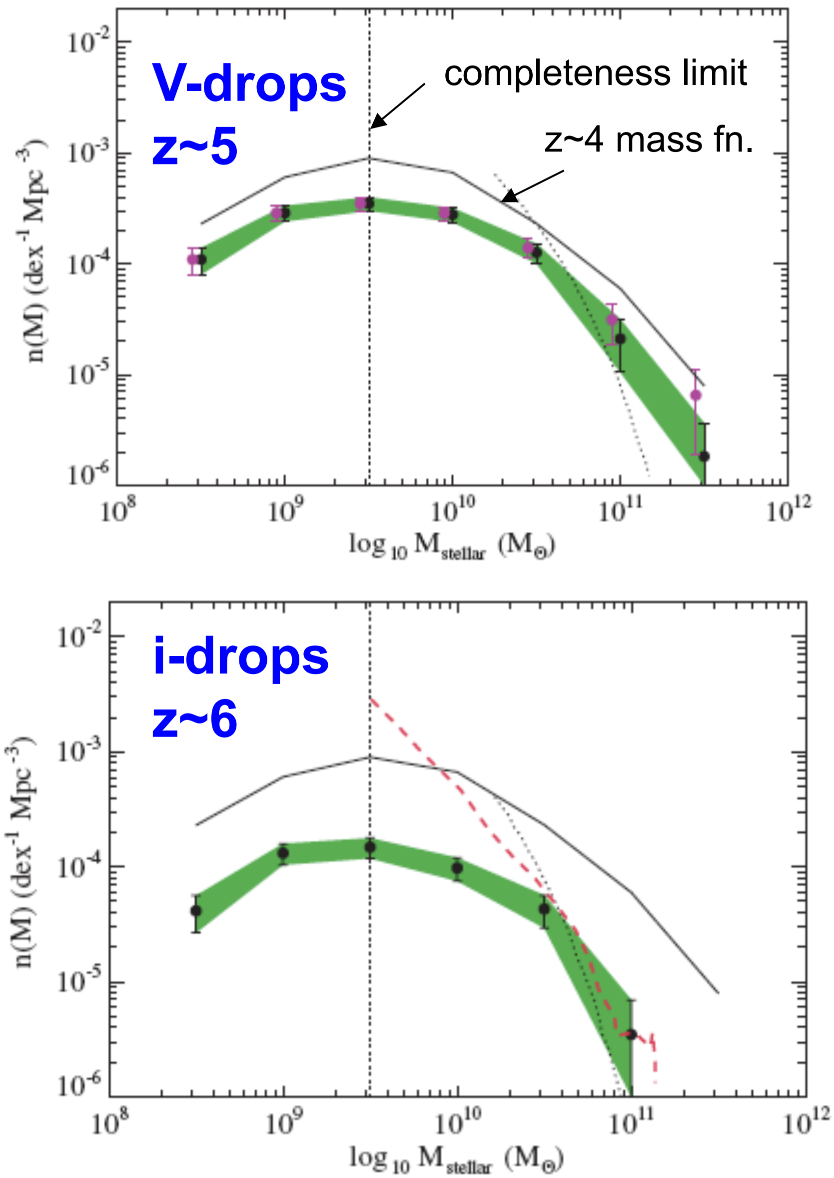


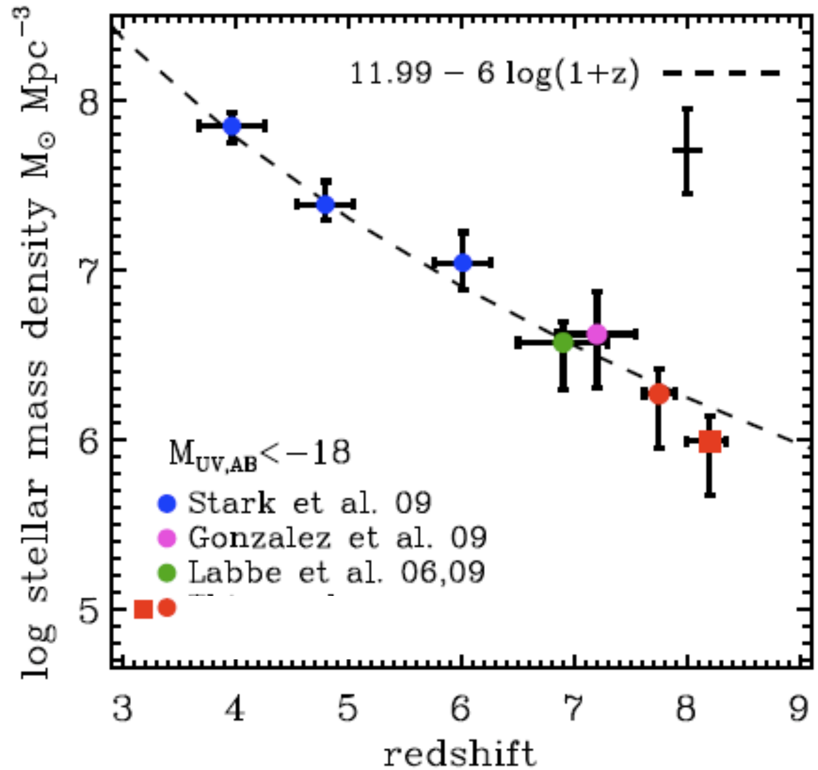
mass = 1.7 10^{8} $M_\odot$

age ~ 50 Myr

Stellar Mass Density

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

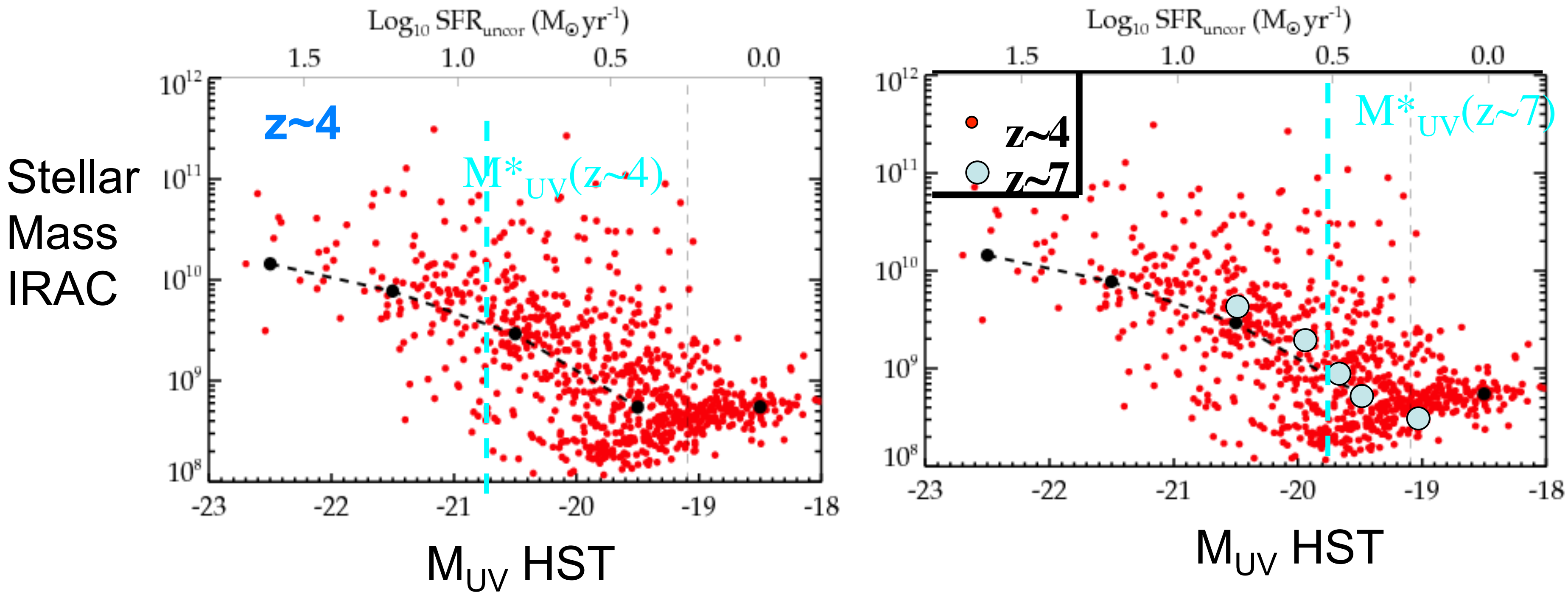




Stellar mass density at z~5-6 implies past SF in low luminosity galaxies may be sufficient for reionization, especially if escape fraction is high

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

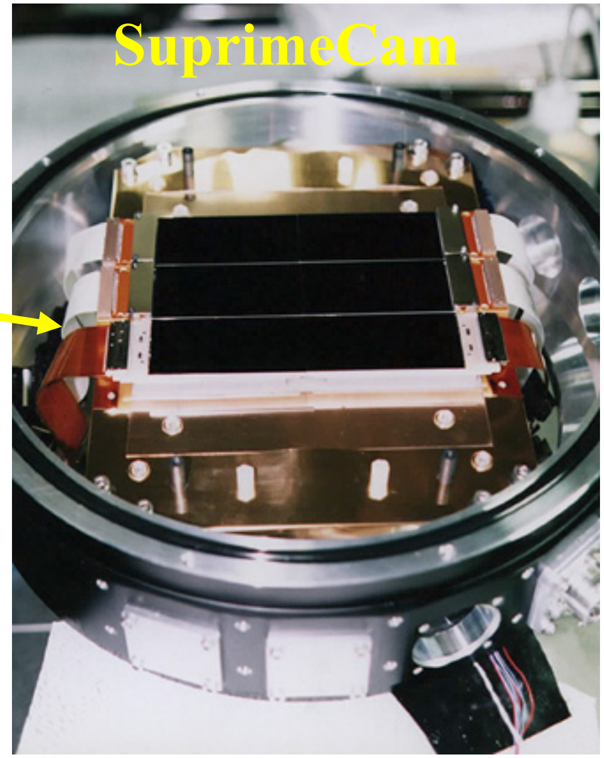
Ages of z~4-7 galaxies from Spitzer data



- Mass ÷ SFR gives `effective age'; low mass/UV faint galaxies younger
- Ages are short (<300 Myr) and don't lengthen as Universe ages!
- Successive generations arriving, consistent with faster cycles of SF at high z

Stark et al Ap J 697, 1493 (2009)

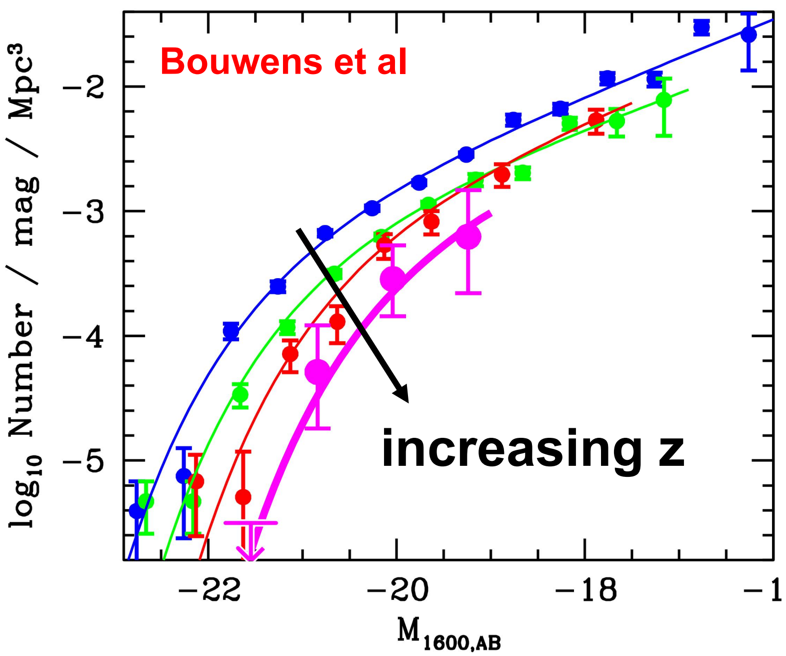
Wide Field Imaging of LAEs from Subaru

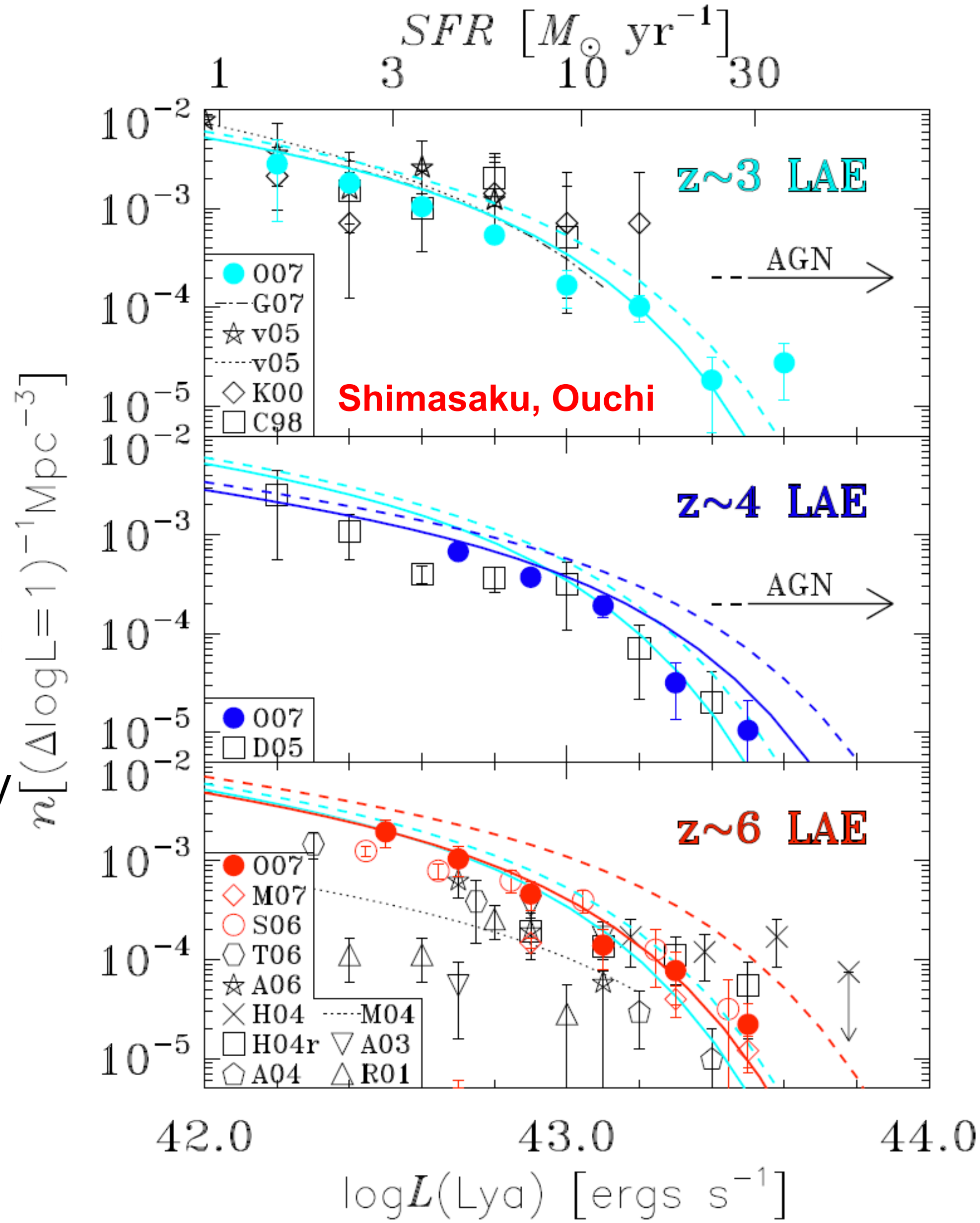


Panoramic imaging with Subaru using narrow-band filters has been used to locate high redshift Lyα emitters (LAEs)

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)

LBGs vs LAEs: Very Different Evolution





LBGs: Marked decline in UV luminosity density with redshift over 3<z<6

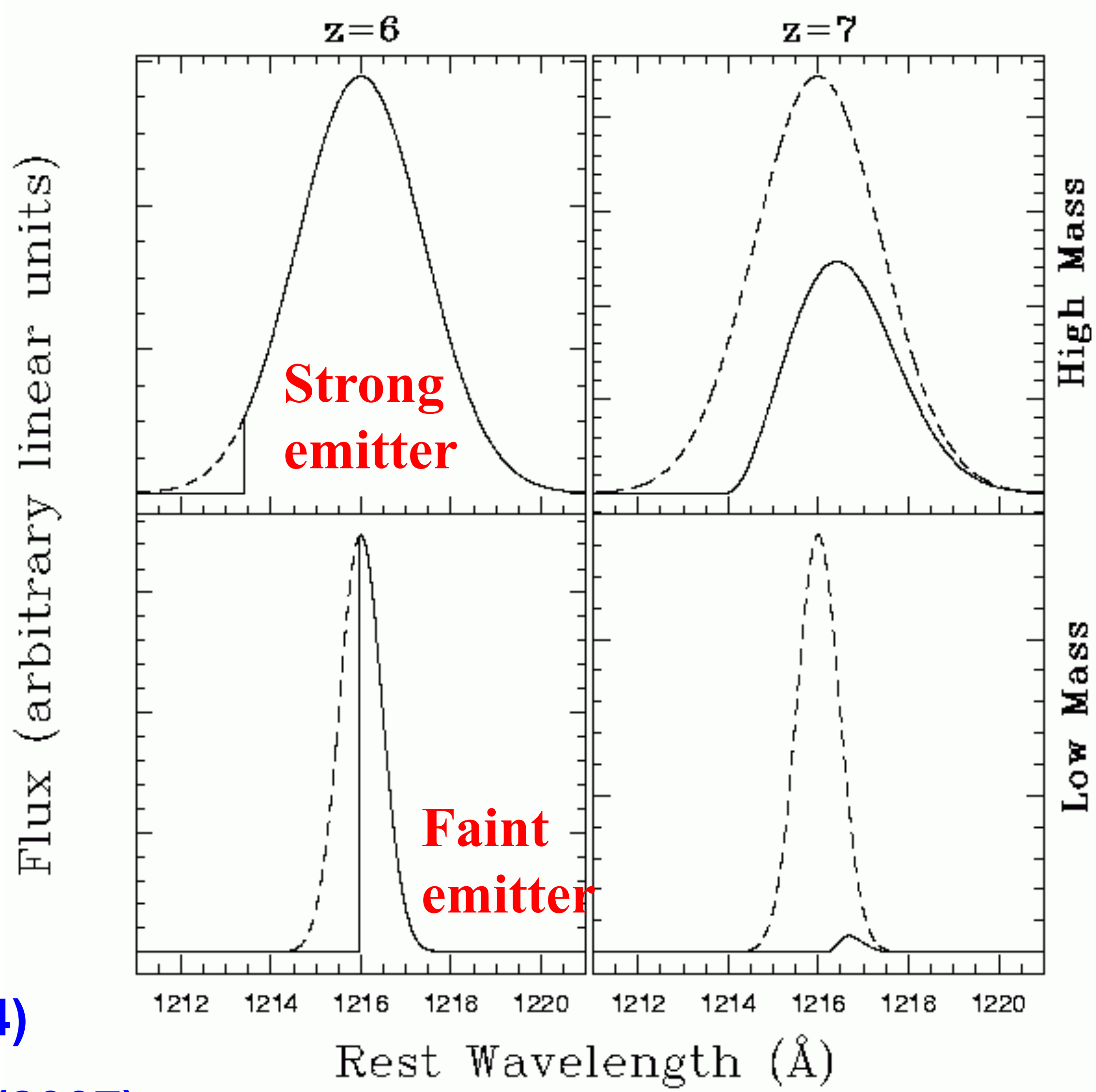
LAE: no evolution to z~5.7

Increasing dominance of Lyα emission at high z

Reduced dust; HI covering fraction, faster duty-cycle of SF?

Probes of Reionization: - Lyman α emitters

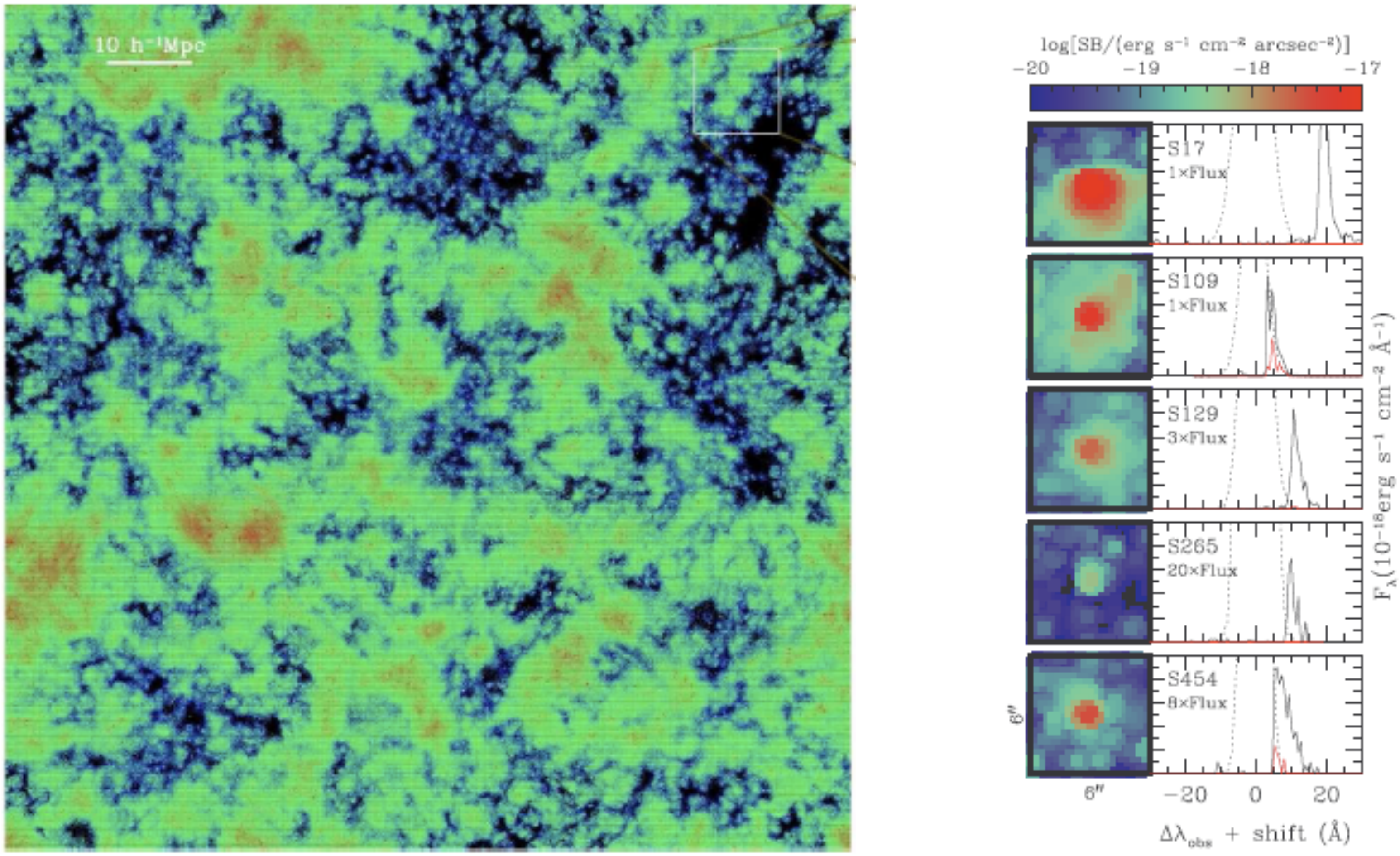
- **Lyα damping wing is absorbed by HI and thus valuable tracer of its presence.**
- **In weaker systems, it may be a *sensitive probe of reionisation***
- **Complicated by clumping of dust? (Dayal et al 1002.0839)**
- **Require detailed modeling of radiative transfer? (Zheng et al 0910.2712)**



Santos MN 349, 1137 (2004)

McQuinn et al MN 381, 75 (2007)

Radiative Transfer Modeling of Lyα Emission

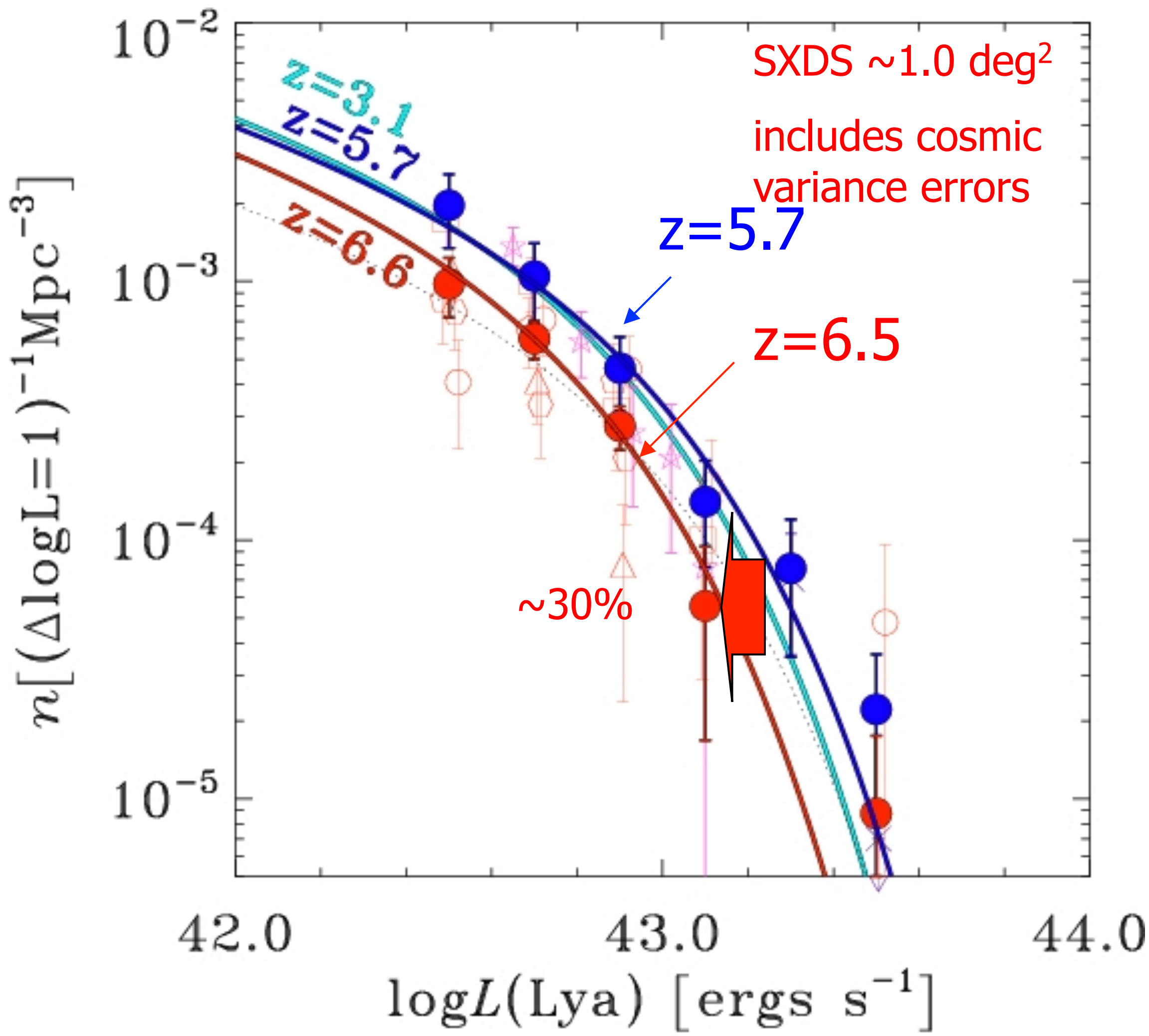


Spatial diffusion of Lyα photons leads to numerous complications: surface brightness biases, viewing angle & velocity structure dependencies

Zheng et al (0910.2712)

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
- Contrast with LBGs: no evolution 3<z<5.7!
- 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)?

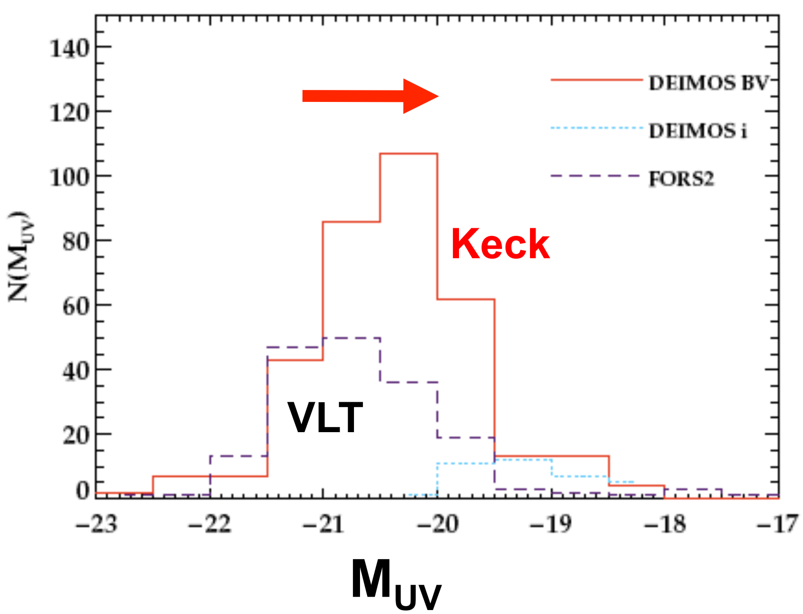


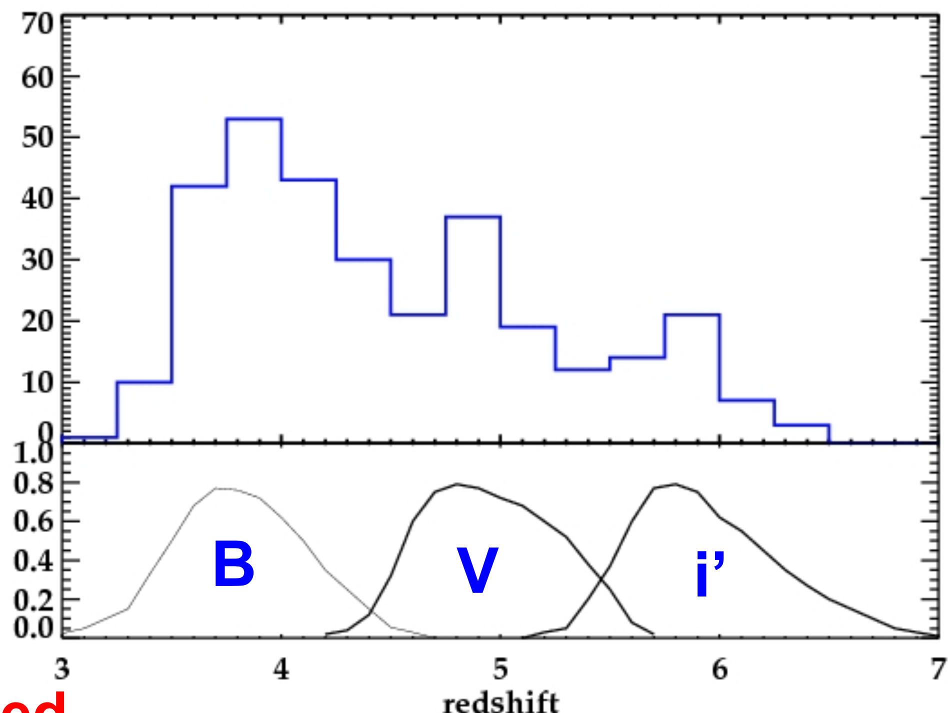
Ouchi et al (2010)

Keck Spectroscopic Survey of 4 < z < 7 LBGs

- B, V, I, z drops in GOODS/UDF from Stark et al (09) 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 targets
- VLT/FORS2 retro-selected + same criteria: 195 targets (Vanzella et al)

Probing sub-L* B,V drops

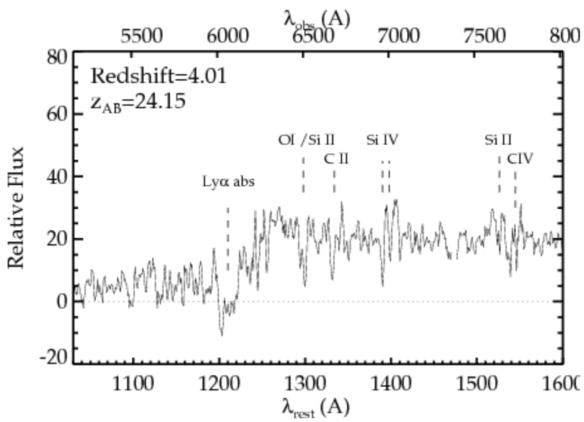




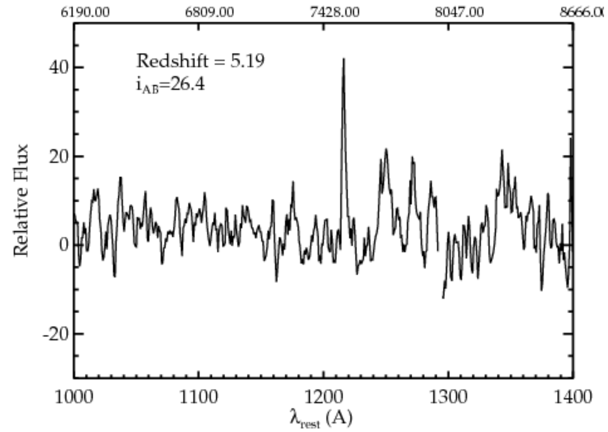
Stark et al (2010) MN submitted

Sample Keck Spectra (R~2500)

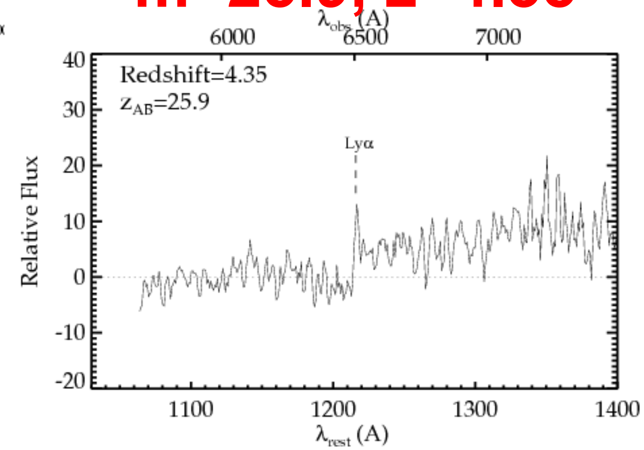
m=24.15, z=4.01



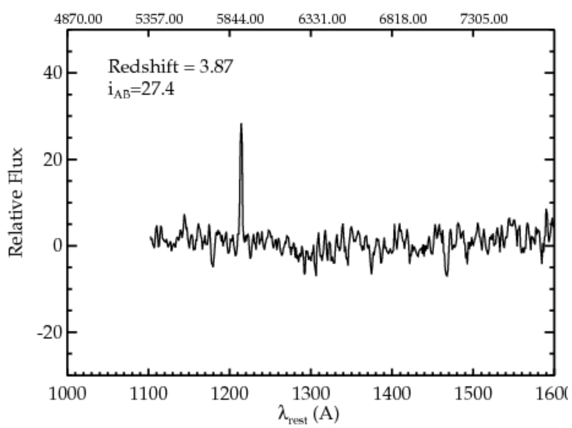
m=26.4, z=5.19



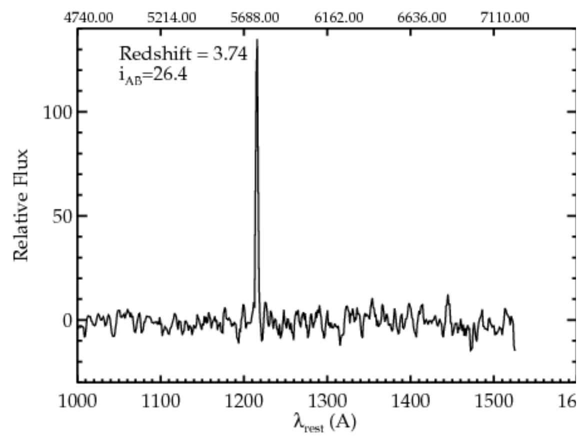
m=25.9, z=4.35



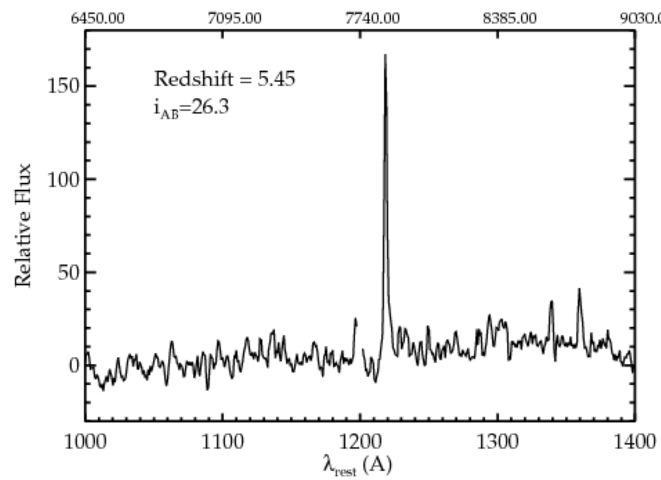
m=27.4, z=3.87



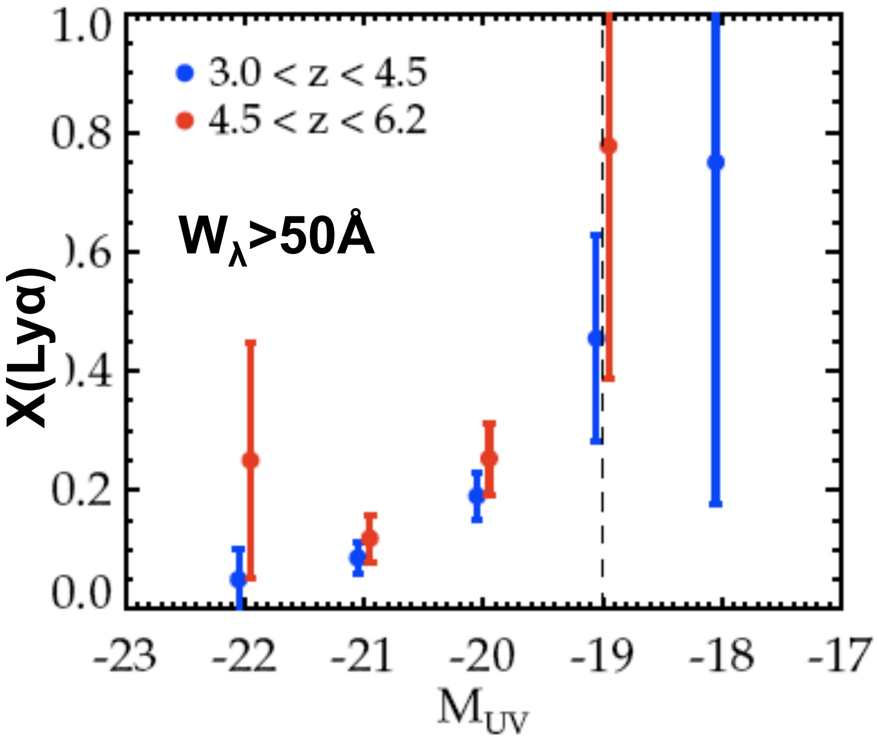
m=26.4, z=3.74

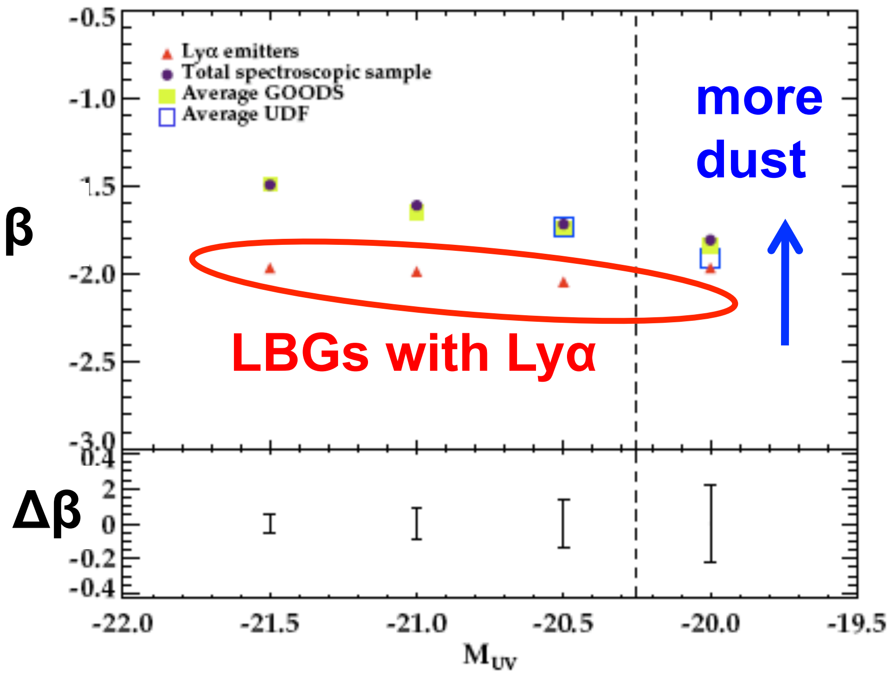


m=26.3,z=5.45



Lyα fraction vs UV luminosity and extinction





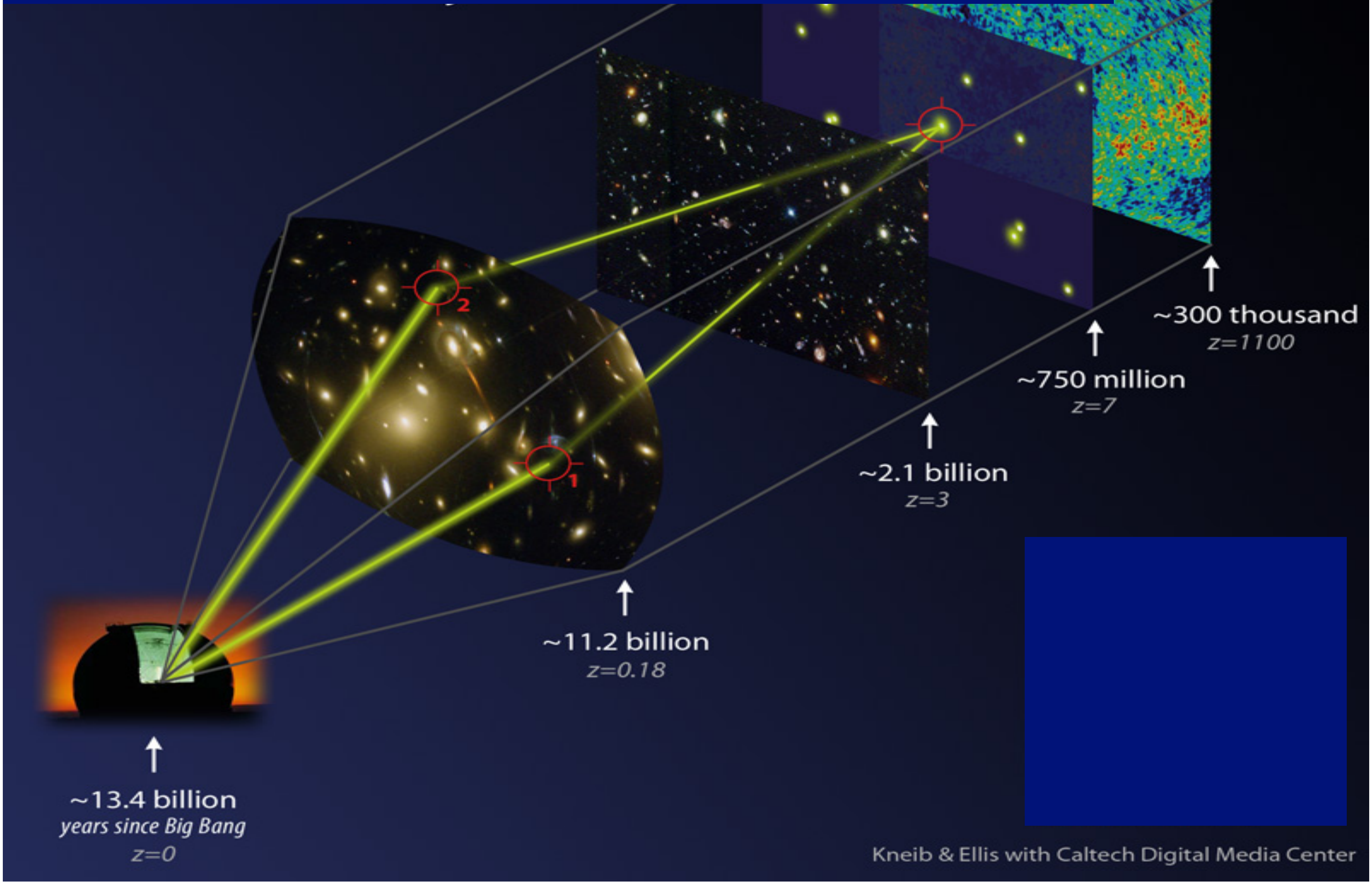
Strong correlation between extinction- inferred from UV slope β (flux ~ λ^β) and presence/absence of Lyα

Strongly suggests low luminosity galaxies are relatively dust-free

So their Lyα fraction might be valuable probe of reionization

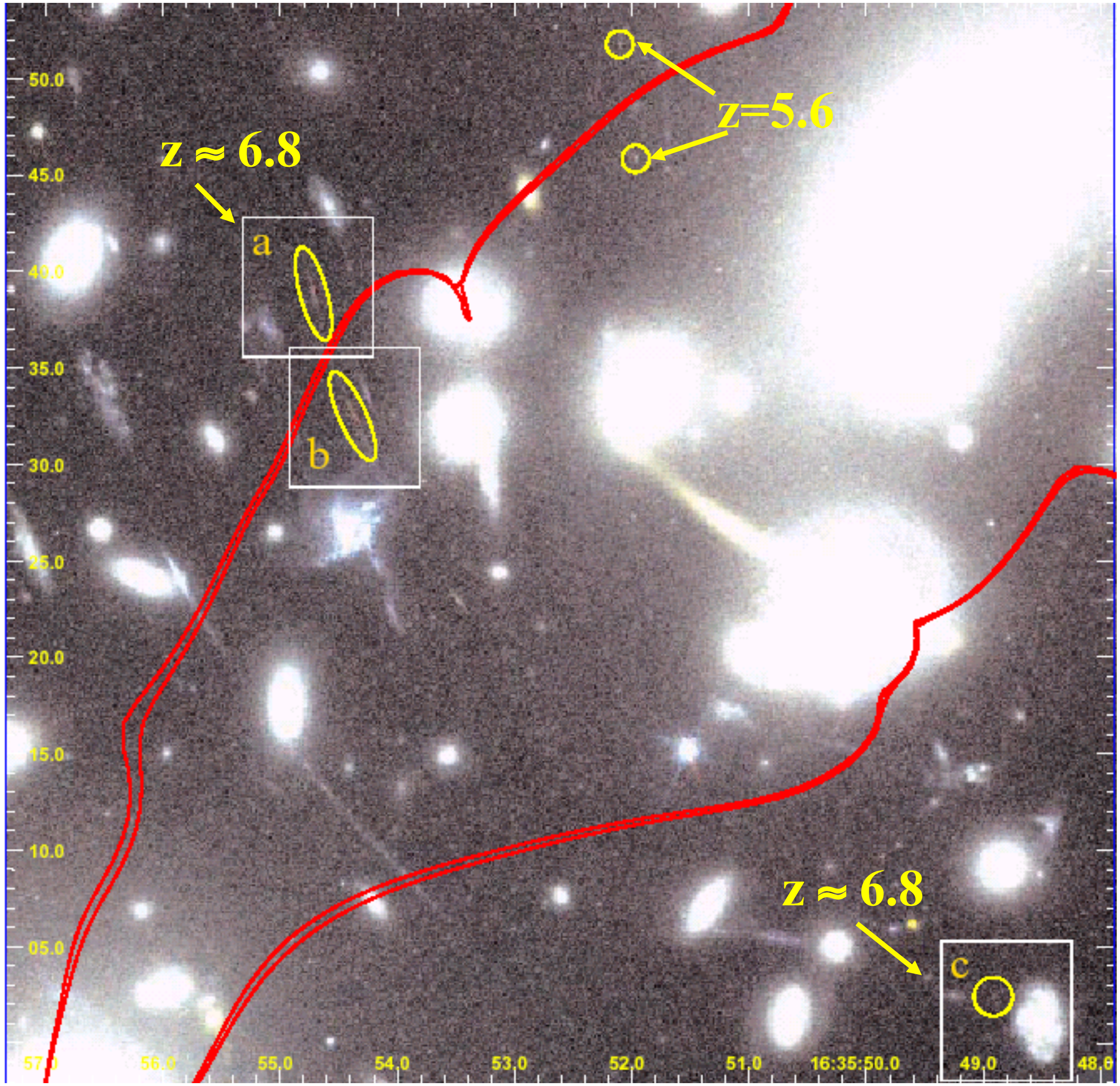
Stark et al (2010) MN submitted

Boosting the signal with gravitational lenses

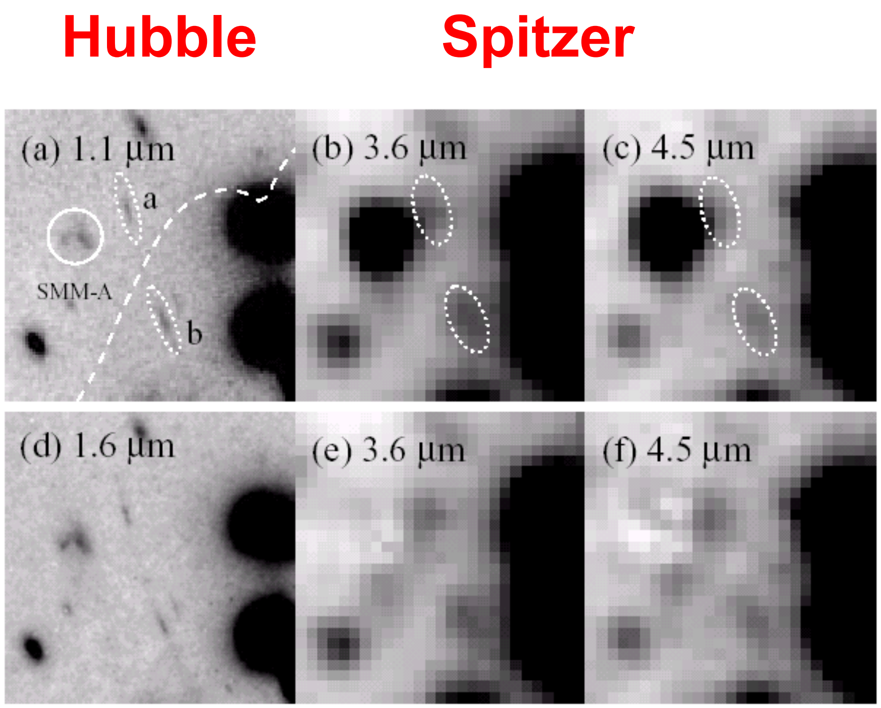


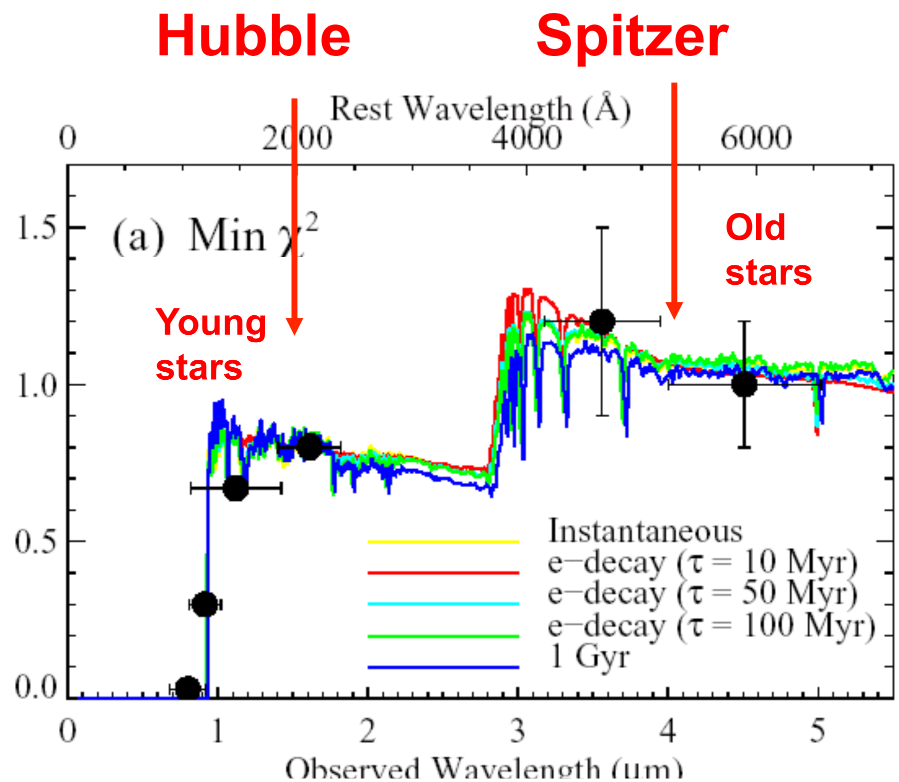
Critical line discoveries in Abell 2218

RSE et al 2001, Kneib et al 2004



Deciphering past history of z~6.8 lensed LBG





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

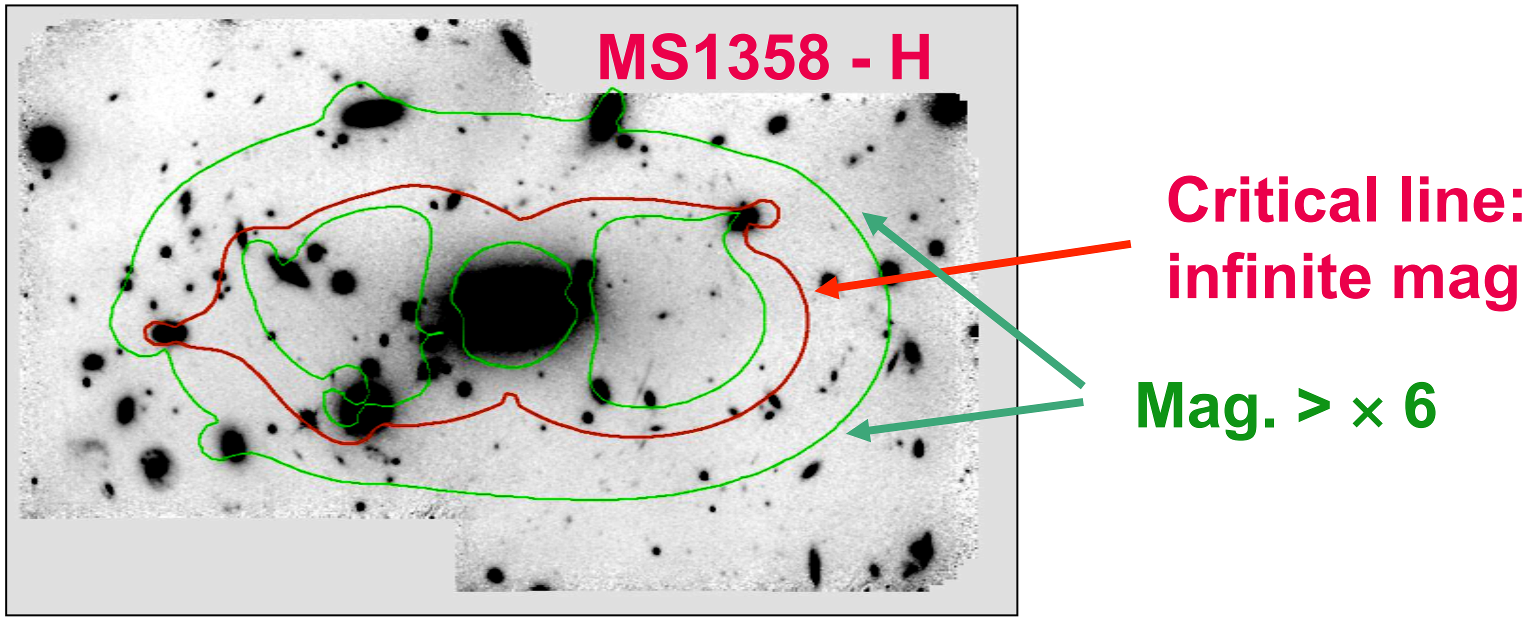
Star formation rate = 2.6 $M_\odot yr^{-1}$ Stellar mass ~ 5-10 10^8 $M_\odot$

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)

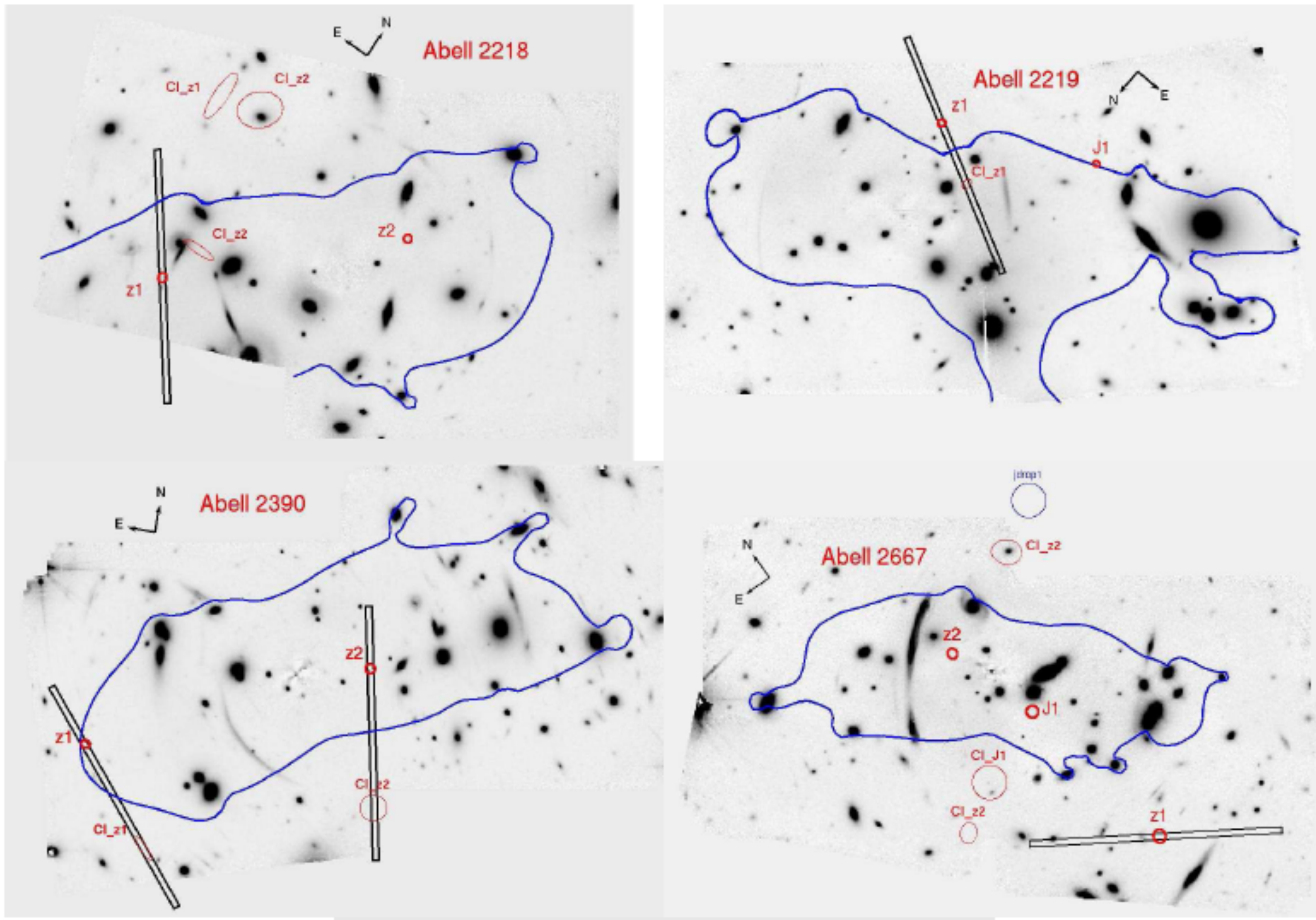
Lensed Dropouts with HST/Spitzer



- 6 well-constrained clusters with deep IRAC imaging
- 4 orbits J/F110W; 5 orbits H/F160W, ACS/F850LP imaging
- K-band from Keck/NIRC + Subaru/MOIRCS
- 8 candidates z~7.5 of which expect 2 (statistically) to be spurious/foreground
- <u>Statistically conclude there are 6 credible candidates</u>

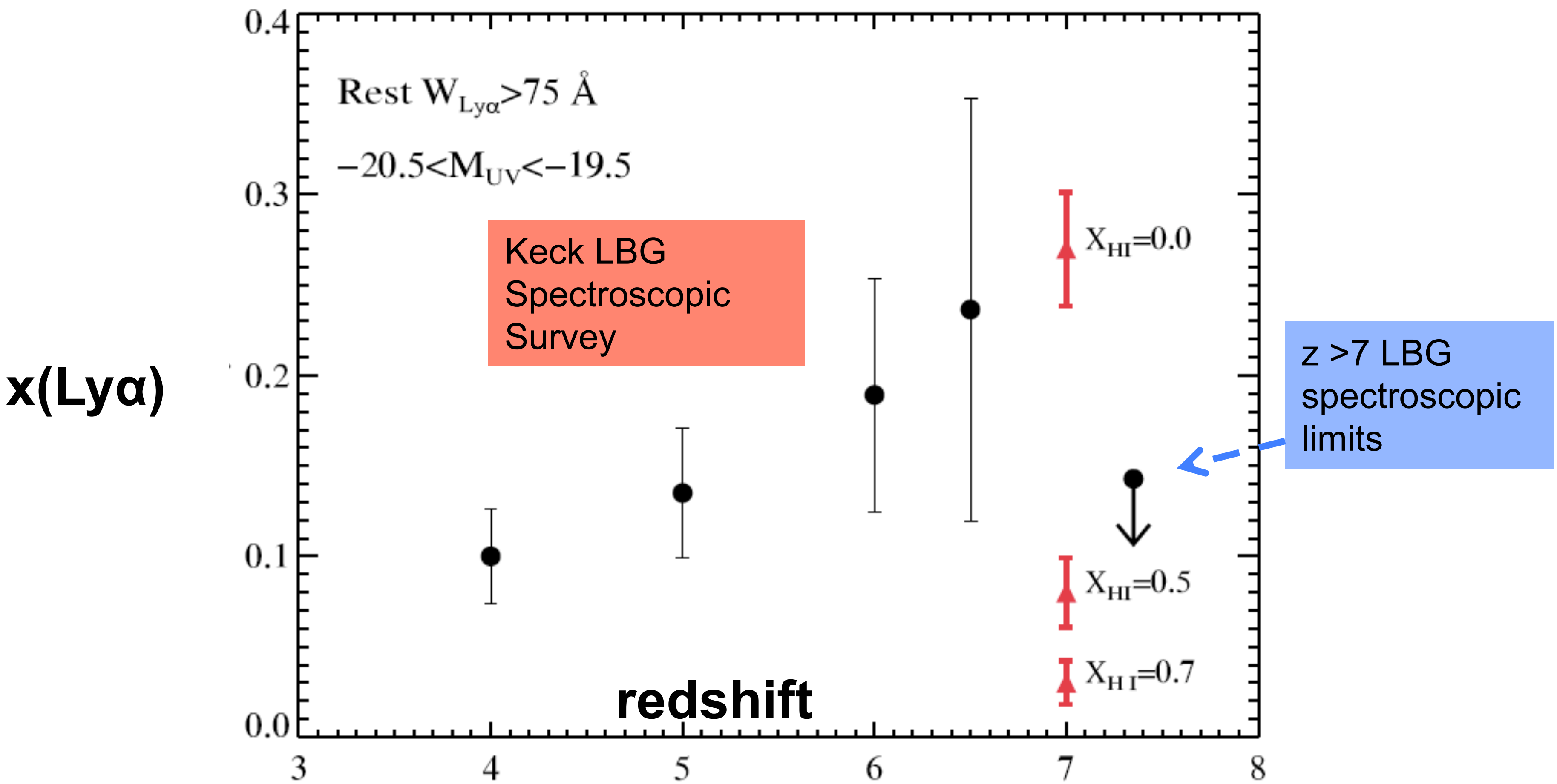
Richard et al (2008) Ap J 685, 705

Spectroscopic Followup (Keck NIRSPEC)



Angular distribution c.f. critical lines further supports a low foreground contamination but 4 hour exposures of 7/8 candidates with NIRSPEC failed to detect Ly α emission (as in A2218 z~6.8 source)

Lyα Emission Statistics versus Redshift



- Keck survey avoids confusion with dust as can also measure β
- Do not confirm 5.7<z<6.6 drop seen in the Subaru LAE LF
- **But rising fraction with z puzzle: why no z > 7 candidates with Lyα?!!**

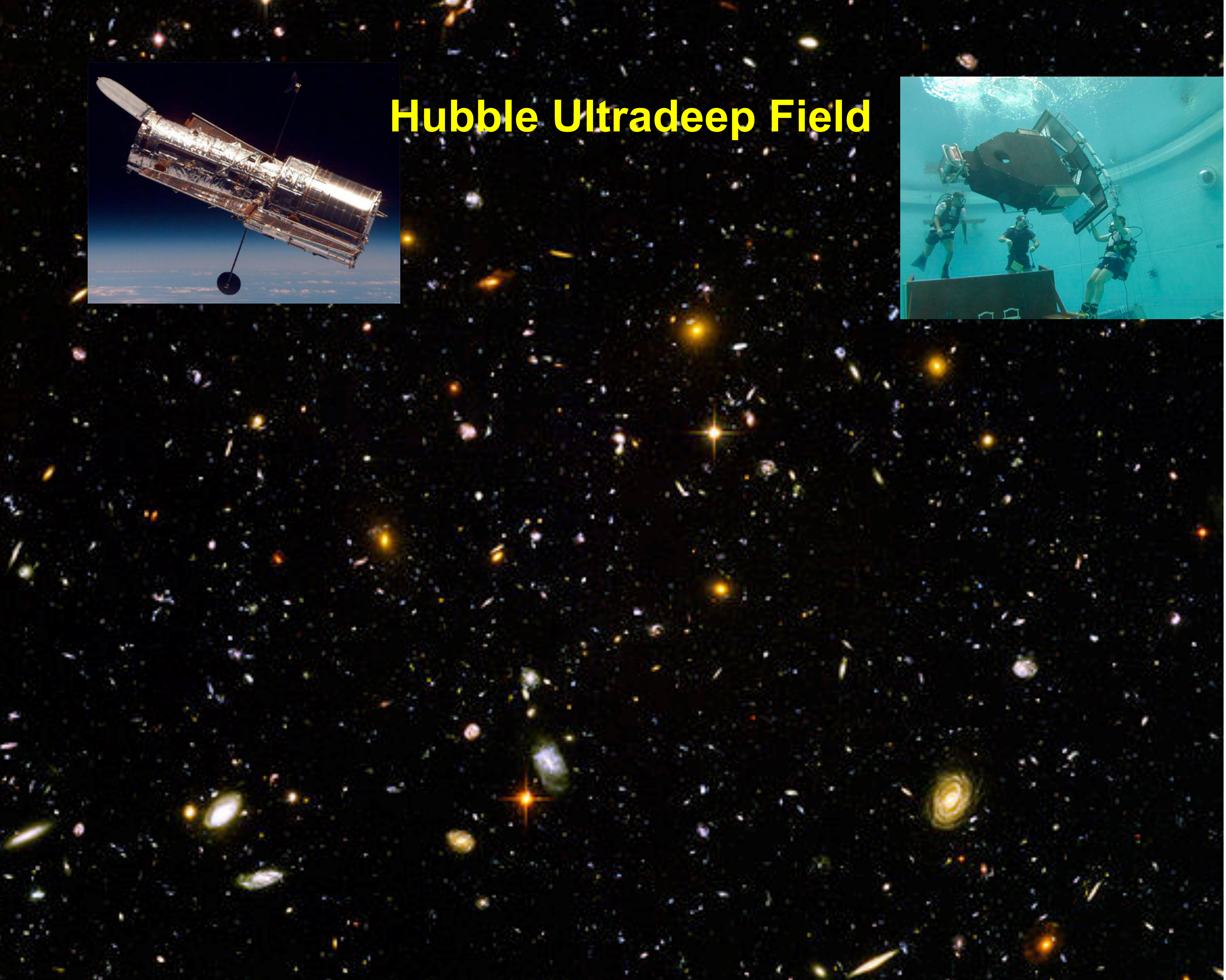
Stark et al (2010) MN submitted

Summary ($z < 7$)

- WMAP polarization data rules out instantaneous reionization at late times ($z \sim 6$-7); expect extended phase with sources distributed over $7<z<20$
- Rapid rise in CIV abundance over $4.5<z<6$ supports prompt enrichment since $z \sim 9$
- Assembled stellar mass at $z \sim 5$-6 indicative of much earlier SF
- Drop in Ly α LF over $5.7<z<6.6$ may indicate modest increase in neutral fraction to $z \sim 7$ or perhaps cosmic variance/other obscuration – implications unclear
- Rising Lyα fraction over $4<z<6.5$ in equivalent LBG population makes dearth of emission in many $z>7$ candidates puzzling

Upshot: Expect abundant population of SF sources $z>7$
Possibly sub-luminous/obscured (and not emitting Ly α)
making spectroscopic verification very tough

Hubble Ultradeep Field



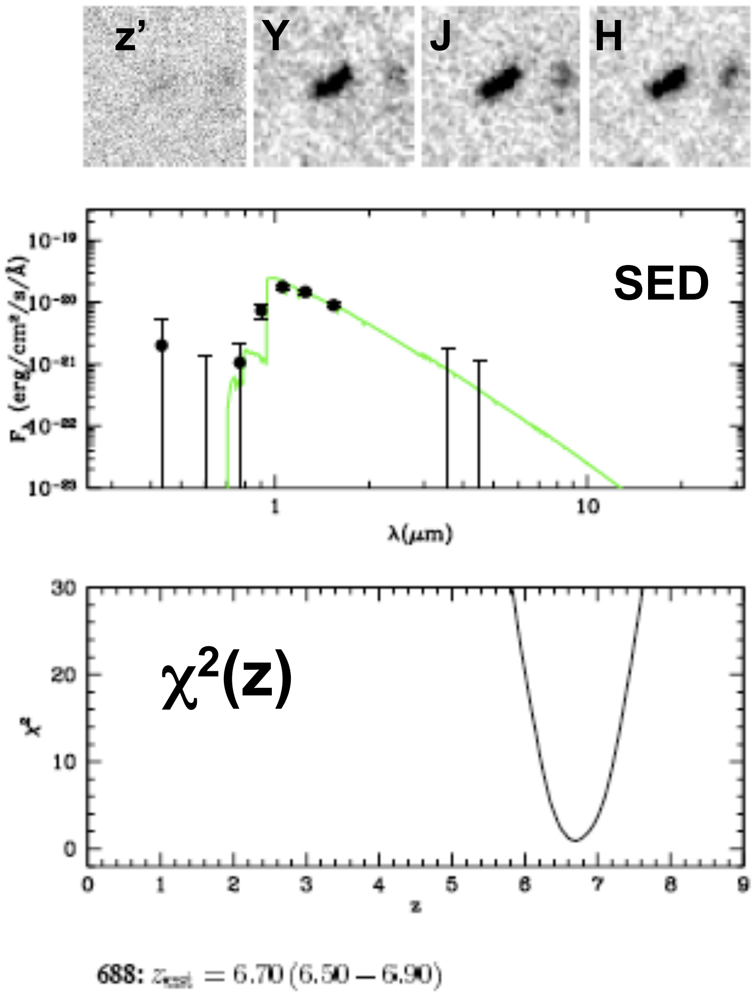
Hubble WFC3 High z Stampede

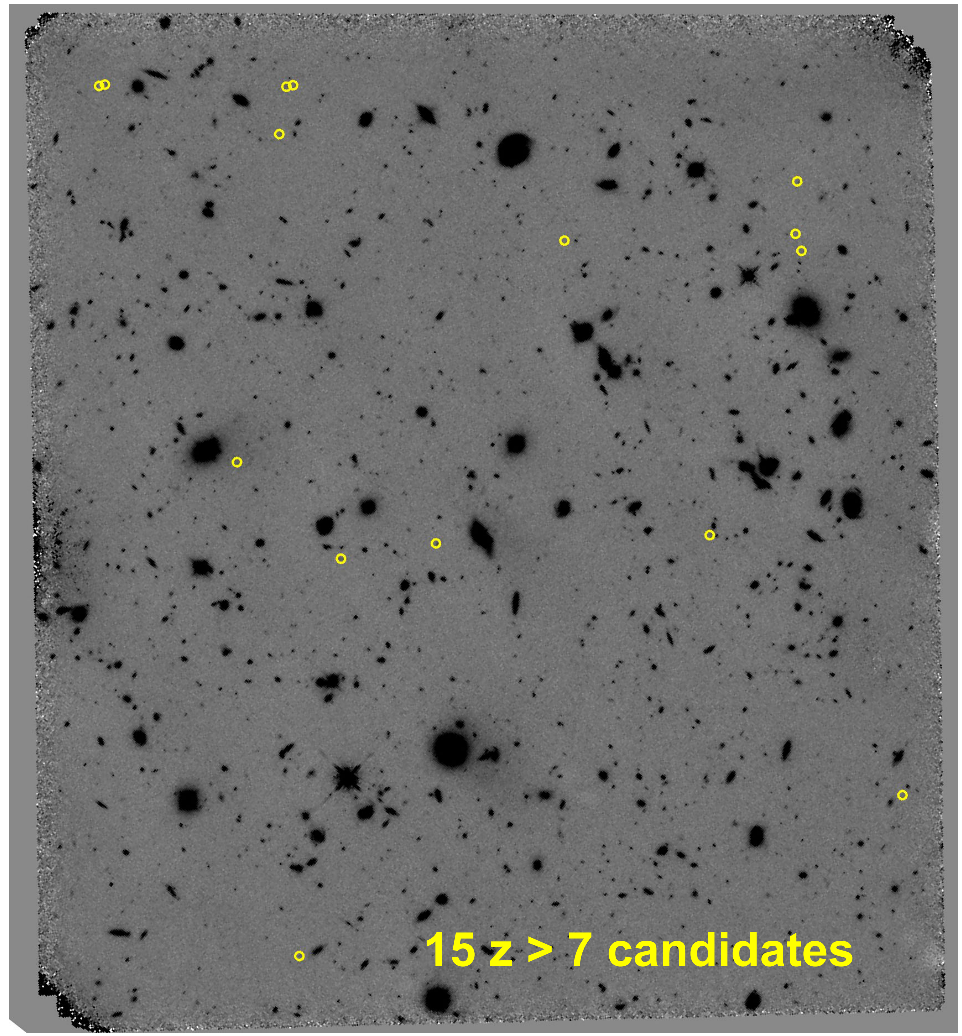
WFC3/IR: 850 - 1170nm
2.1 × 2.3 arcmin field of view
0.13 arcsec pixel^{-1}
10 times survey power of NIC3

UDF 4.7 arcmin^2
60 orbits in YJH
Reaches m_{AB}~29 (5σ)

Bouwens et al 0909.1803
Oesch et al 0909.1806
Bunker et al 0909.2255
McLure et al 0909.2437
Bouwens et al 0910.0001
Yan et al 0910.0077
Labbé et al 0910.0838
Wilkins et al 0910.1098
Labbé et al 0911.1365
Finkelstein et al 0912.1338
Bunker & Wilkins 0912.1351
Wilkins et al 1002.4866

z >7 candidates from WFC3 UDF campaign

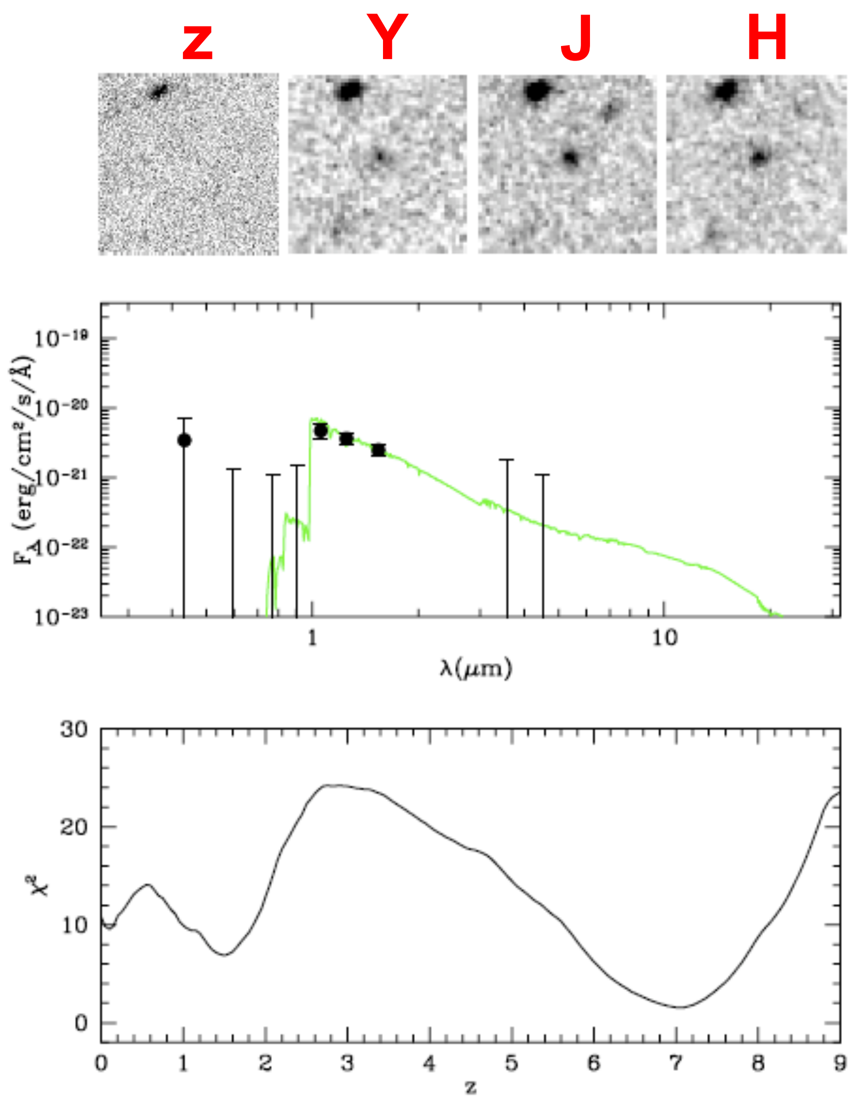




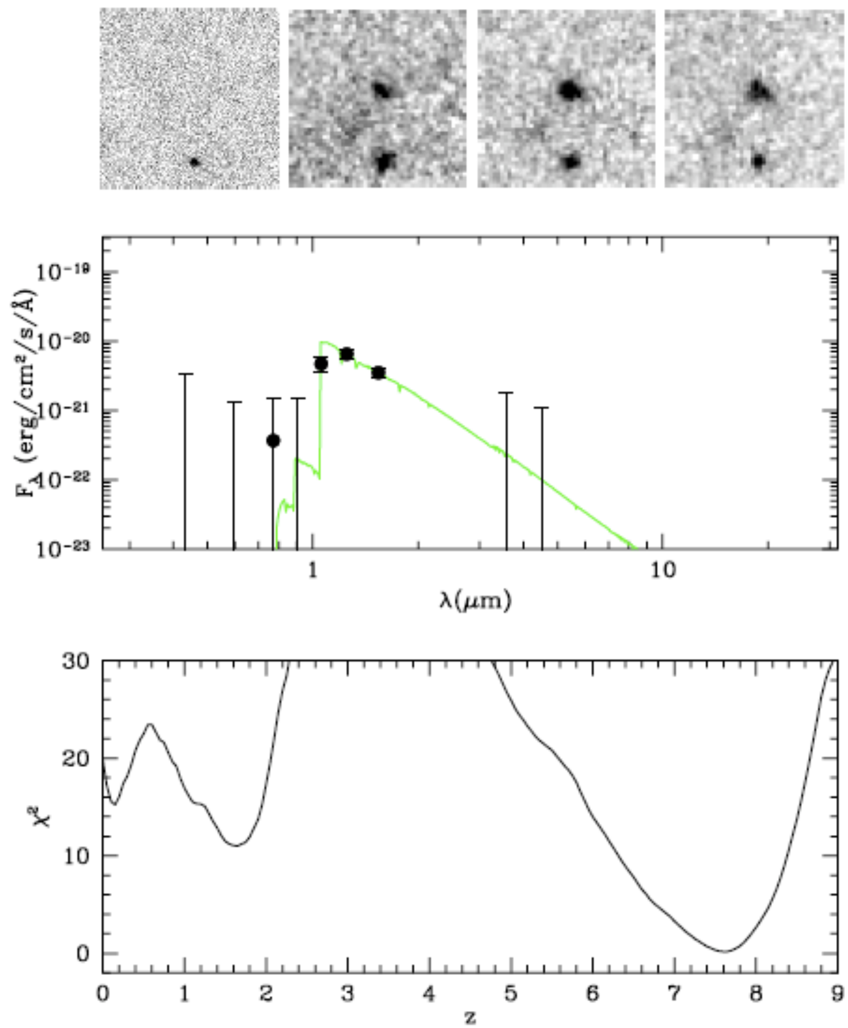
3 IR filters c.f. 2 leads to more secure photometric redshifts and reliable UV continuum slopes

McLure et al (2009)

But beware..uncertain redshifts still an issue..



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



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

Requirements for Reionization by Galaxies

Several workers have suggested the abundance and properties of SF galaxies over $7<z<10$ may drive cosmic reionization

Variously accounted for in terms of C_{HII}, n_γ, f_{esc}, Δt, ρ_{SFR}, IMF..

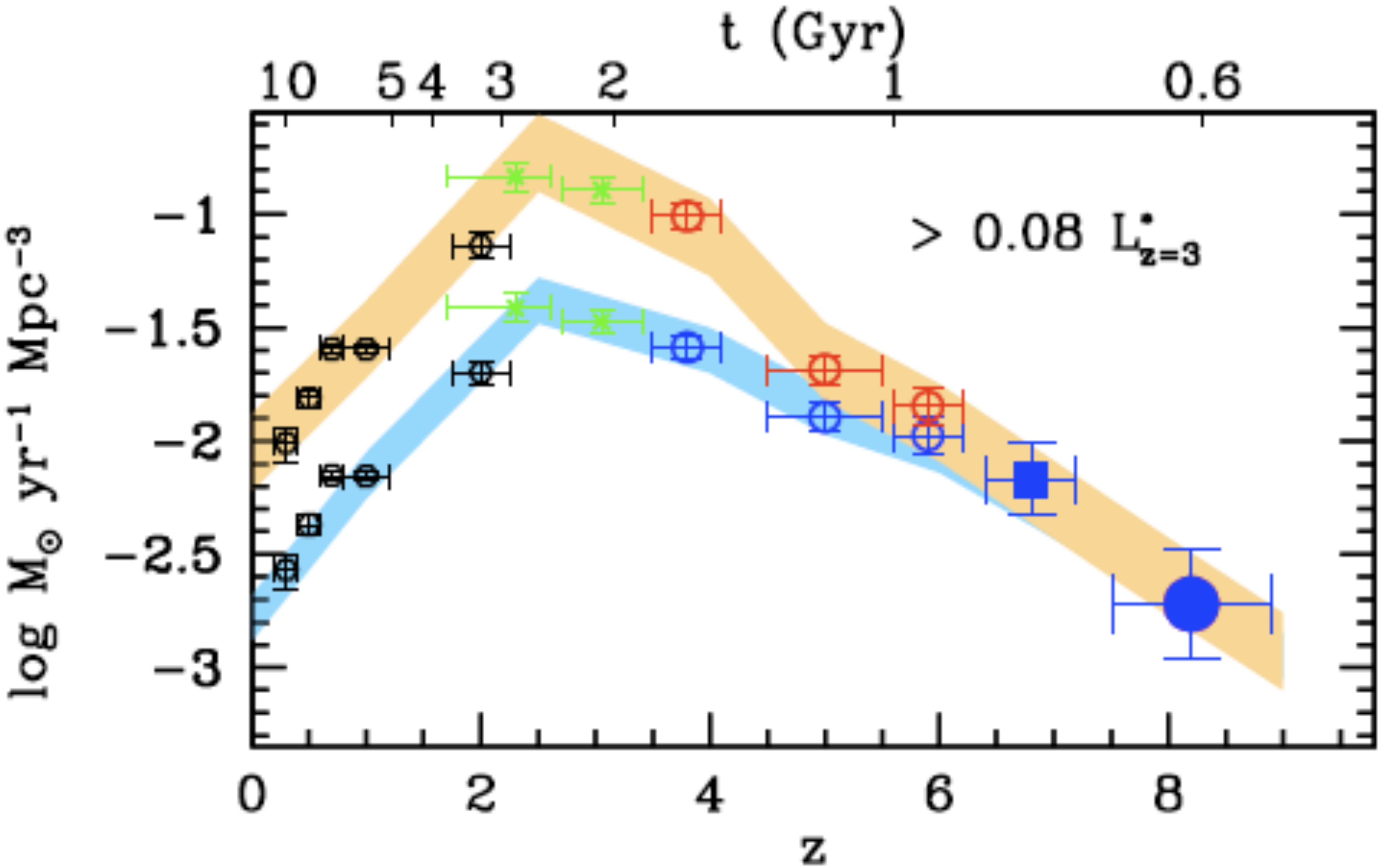
In fact, there are only 3 basic requirements:

- A sustained output from star-forming galaxies over $7<z<10$ (continuity in trends over $\Delta t \sim 300$ Myr)
- A steep faint end slope ensuring high fraction of UV photons arises from abundant sub-luminous sources ($\alpha < -1.8$), i.e. ρ_{SFR}
- A high escape fraction of ionizing photons ($f_{esc}>0.2$) via improved understanding of UV slope β

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

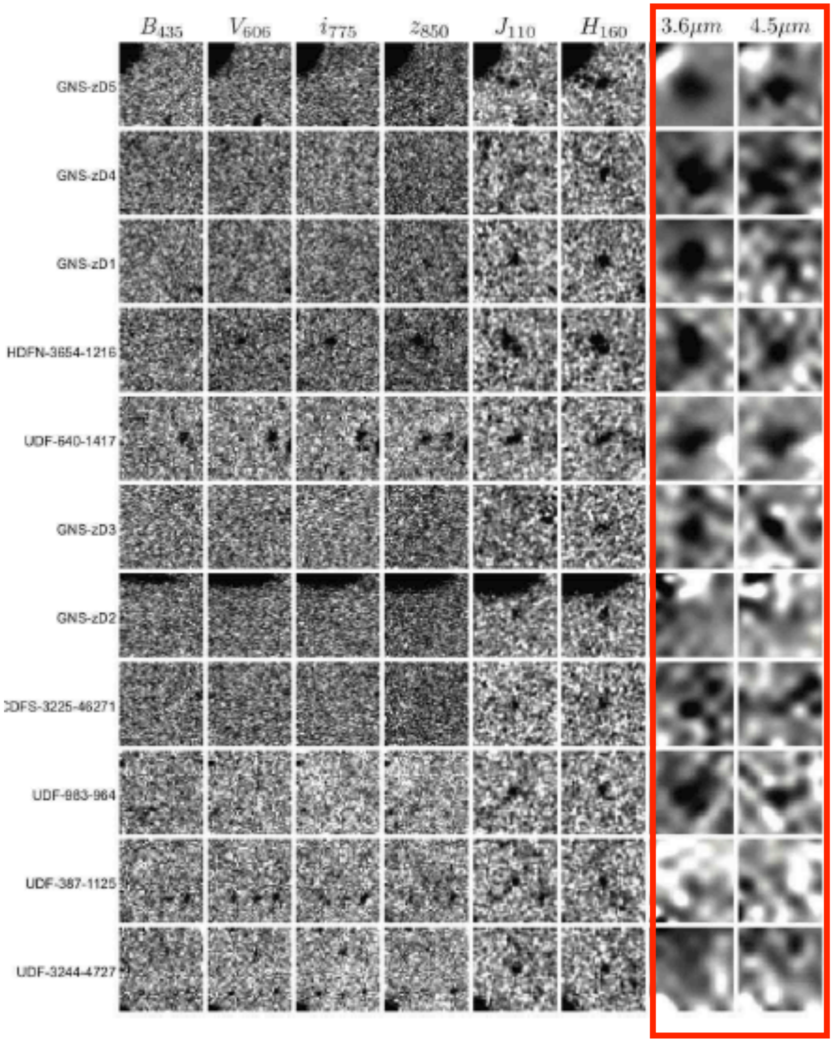
- current UDF campaign (Illingworth 105W, 125W, 160W)
- shallower GOODS MCT campaign (Faber/Ferguson)
- proposed deeper targeted UDF campaign (105W, 140W, 160W

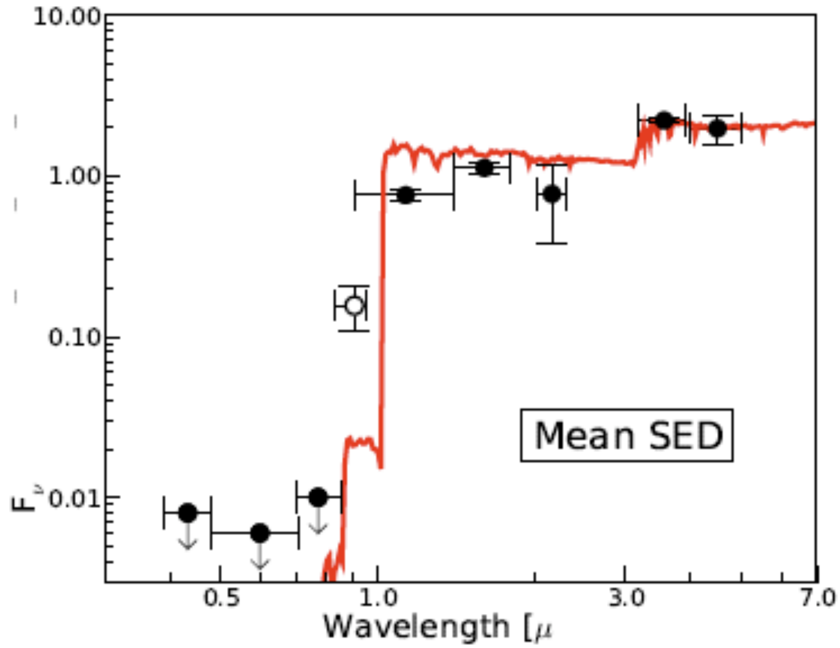
WFC3 Progress – I: Continued SF decline 3 < z < 8



Bouwens et al astro-ph/0909.1803

IRAC Detections of Luminous Galaxies @ z~7: Evidence of Star Formation at Earlier Epochs

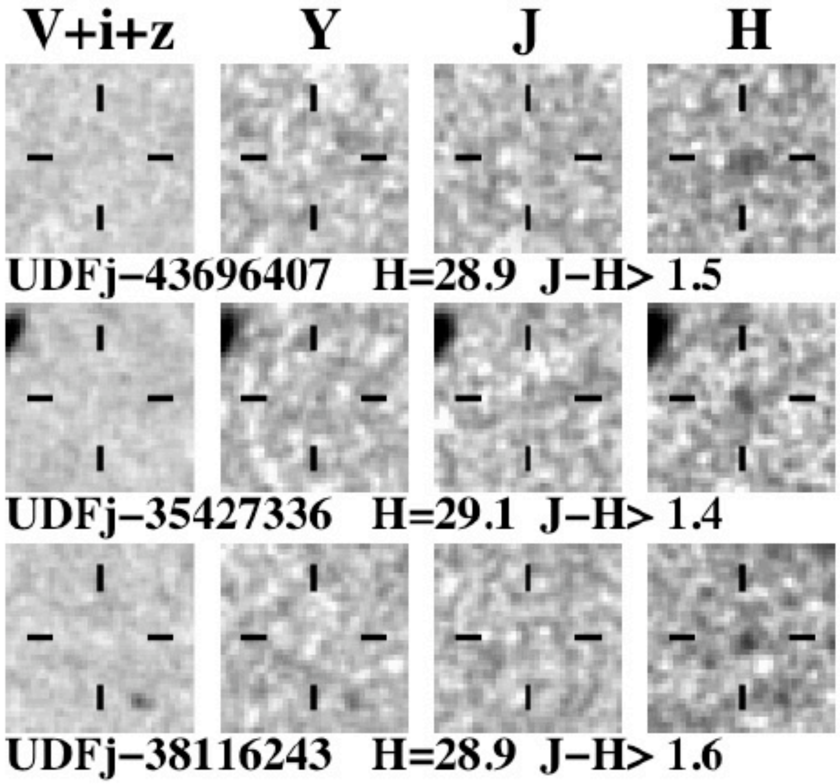




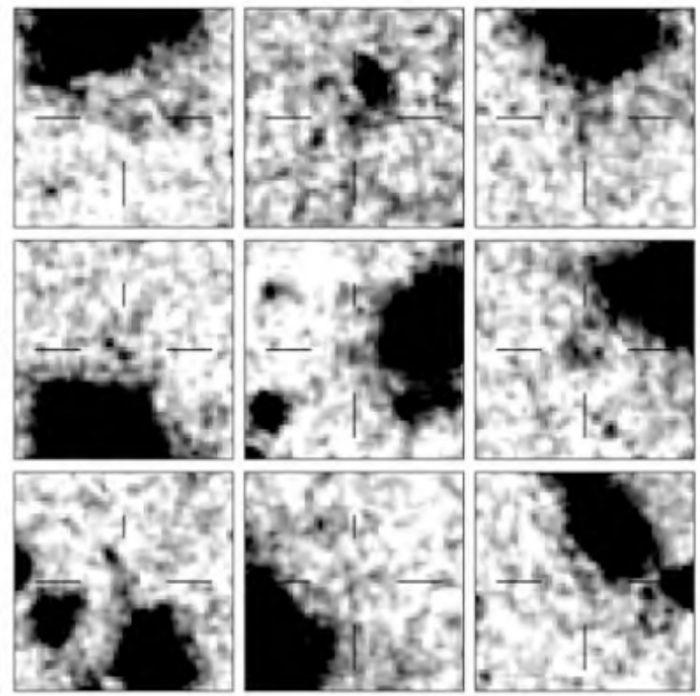
11 objects in GOODS/UDF
M<10^{10} $M_\odot$ ages <400 Myr

Gonzalez et al 2009

z~10? Bouwens et al vs Yan et al



Bouwens et al 0912.4263

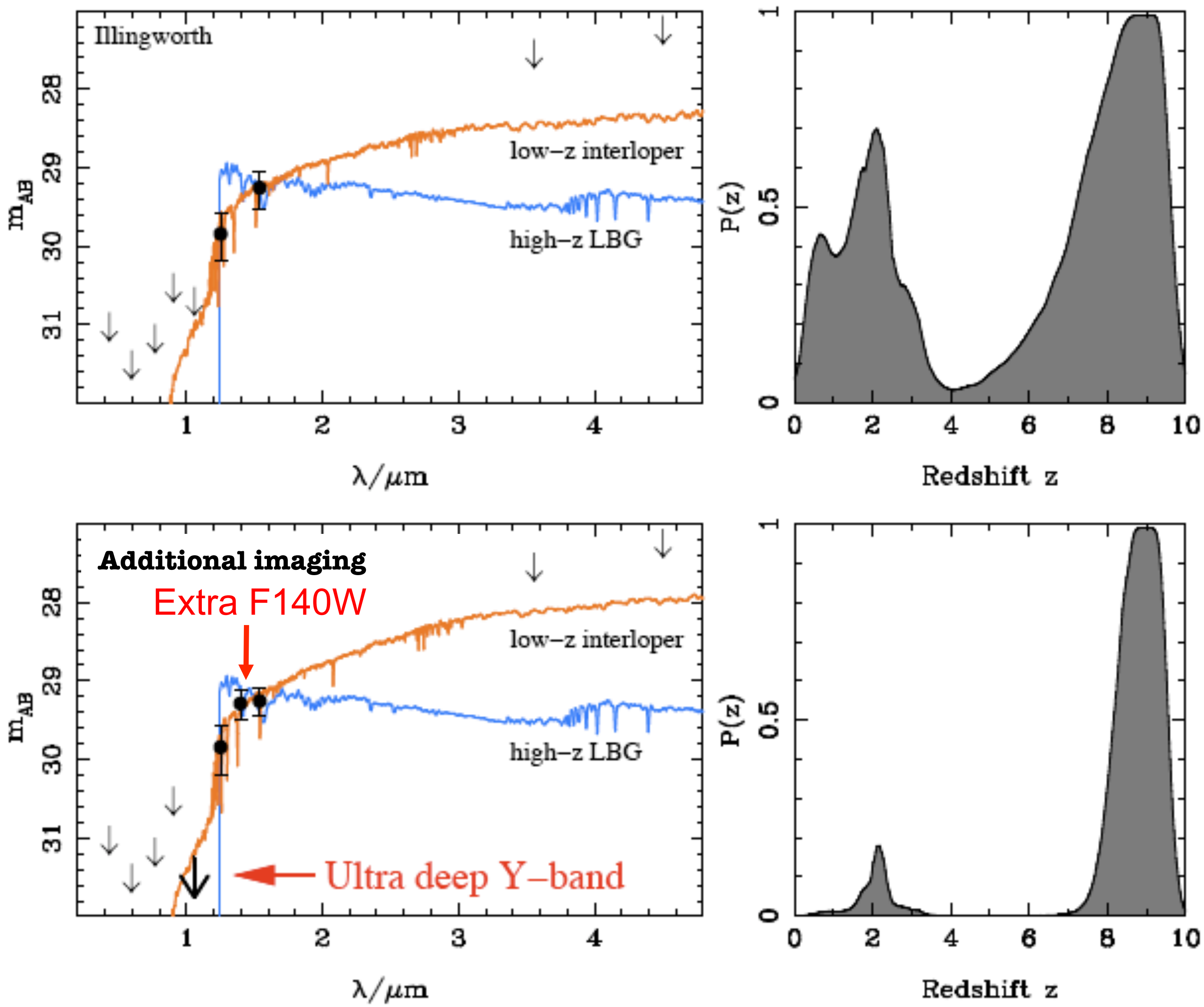


Yan et al 0910.0027

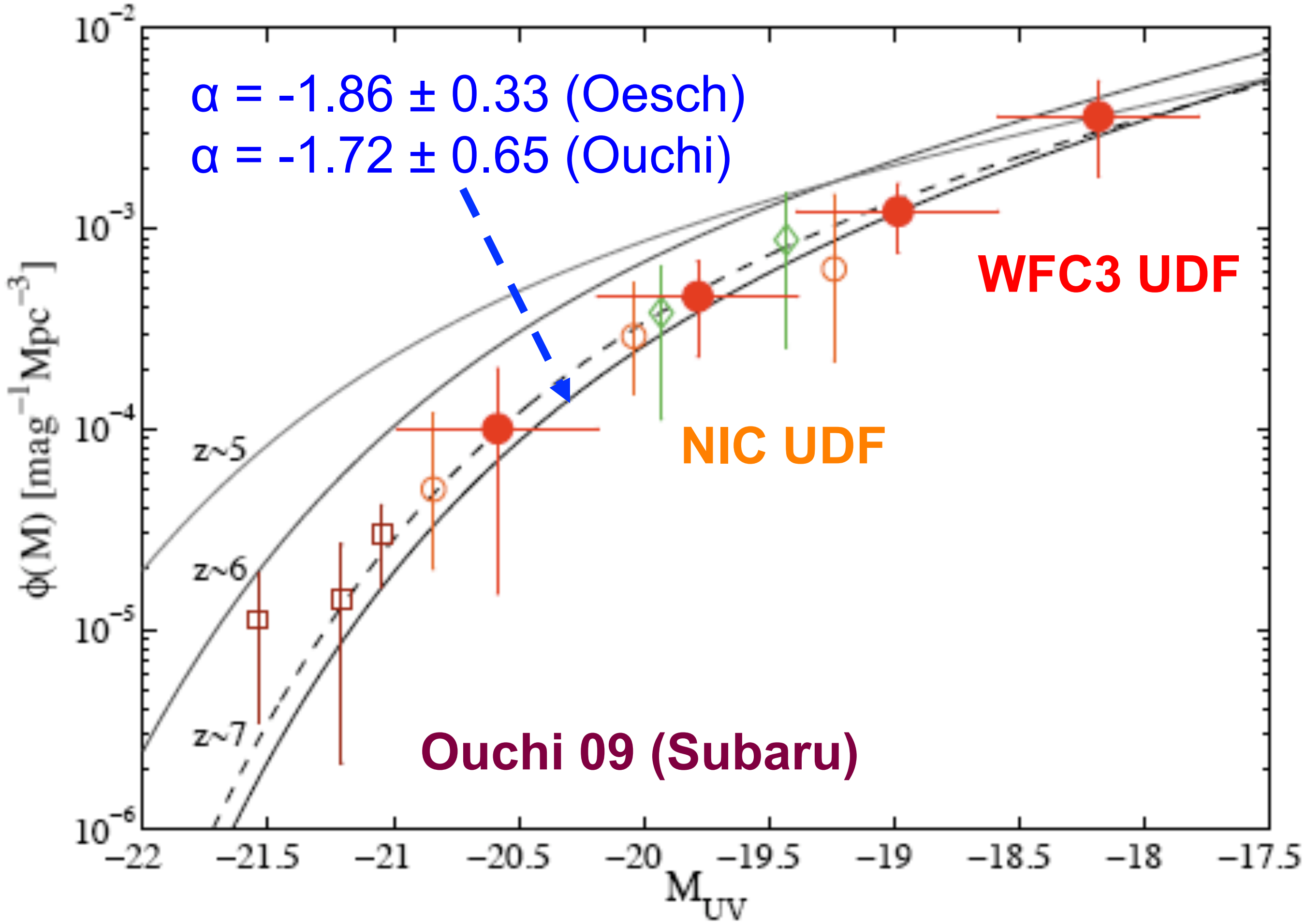
Bunker et al: no convincing J-drop candidates to H~28.5
Yan et al: 20 J-drops to H~29
Bouwens et al: 3 J-drops to H~29
One band detections and no candidate in common…..

Improved Identification of z~9 Sources

Ultra-deep F105W and additional F140W



WFC3 Progress – II: z~7 Luminosity Function



- ~25 z-band dropouts to Y_{AB}~28.5 corresponding to 6.5<z<7.5
- Steep faint end slope: low star formers ~1 $M_{\odot}$ yr^{-1} dominant as predicted from lensed surveys

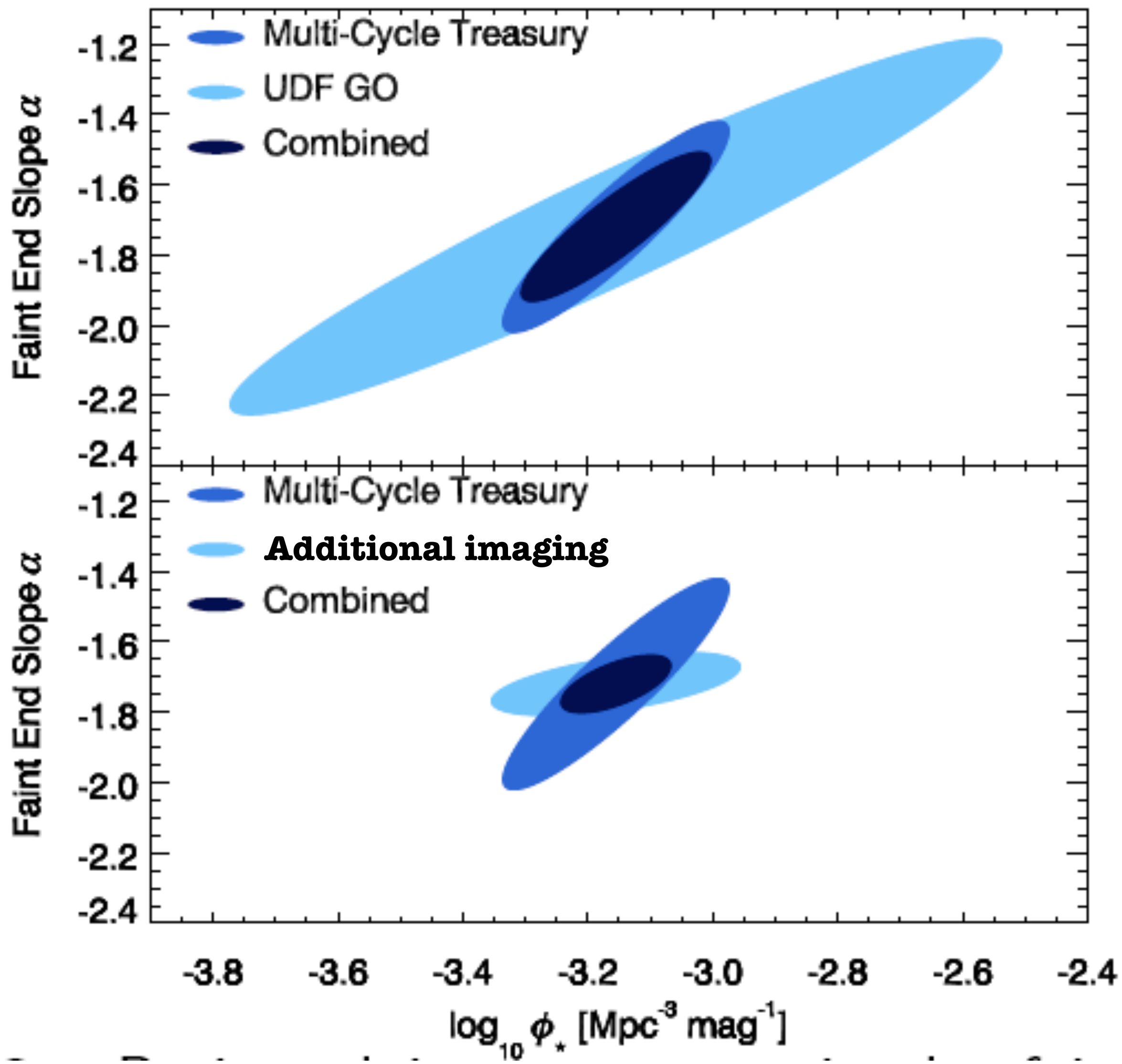
Oesch et al, Bunker et al 2009, 2010

Improved Measures of Faint End of LF

Increased depth in F105W and combined F140W+F160W

Brighter MCT proposal with larger area will improve LF at z~7 but still leave major uncertainties

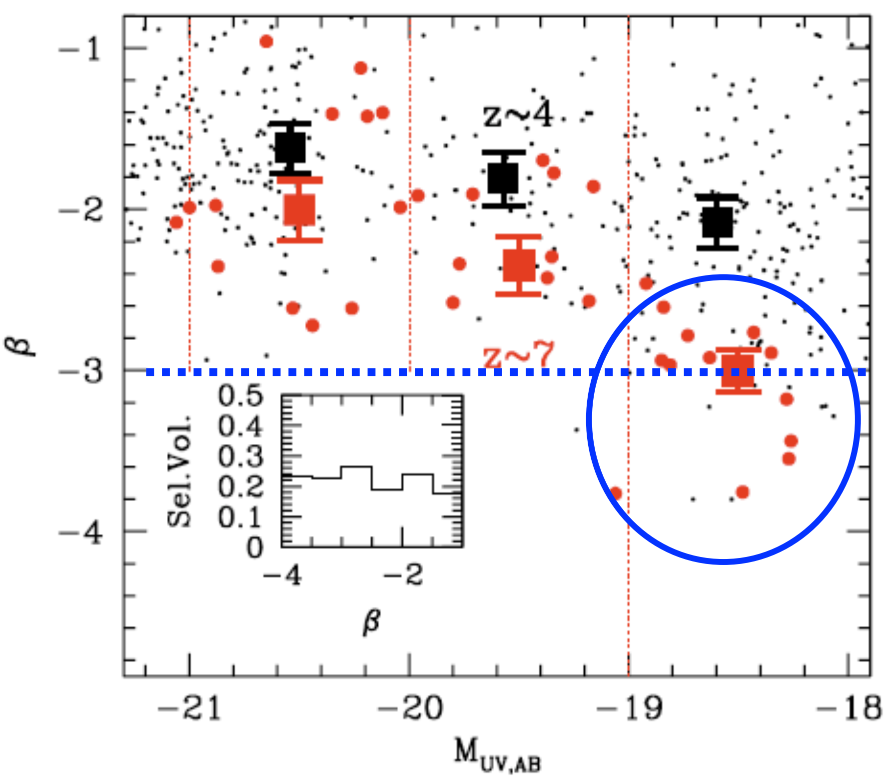
Additional depth would reduce these uncertainties



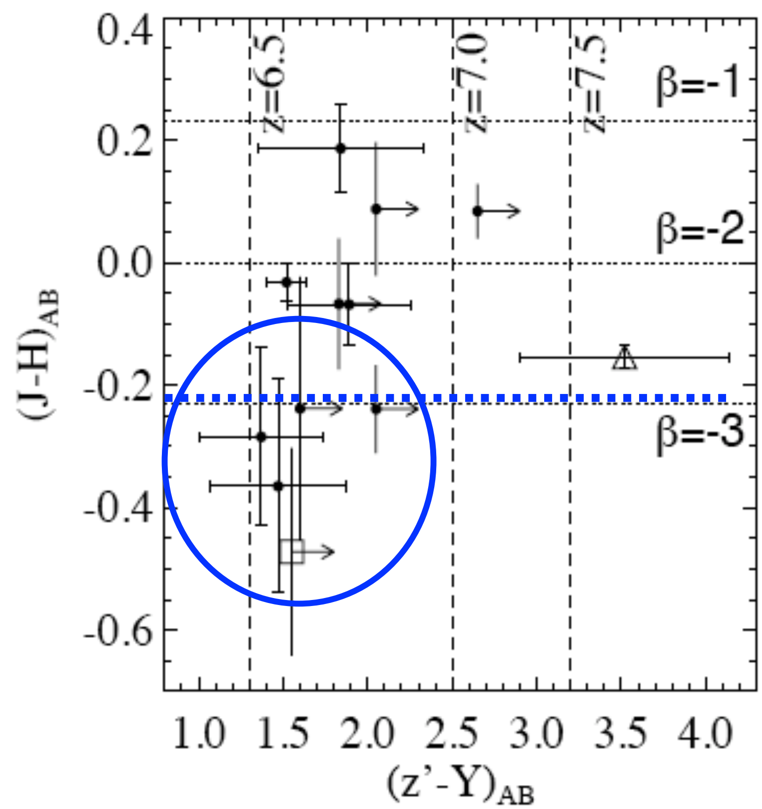
WFC3 Progress – III: Strong UV Continua?

WFC3 data provides Y+J+H data and first reasonable estimate of the slope β of the stellar continuum where $f(\lambda) \propto \lambda^{\beta}$: remarkably steep values $\beta \rightarrow -3$!

Strong trend of increasingly steep UV continua for high z, low L sources



Bouwens et al 2009



Bunker et al 2009

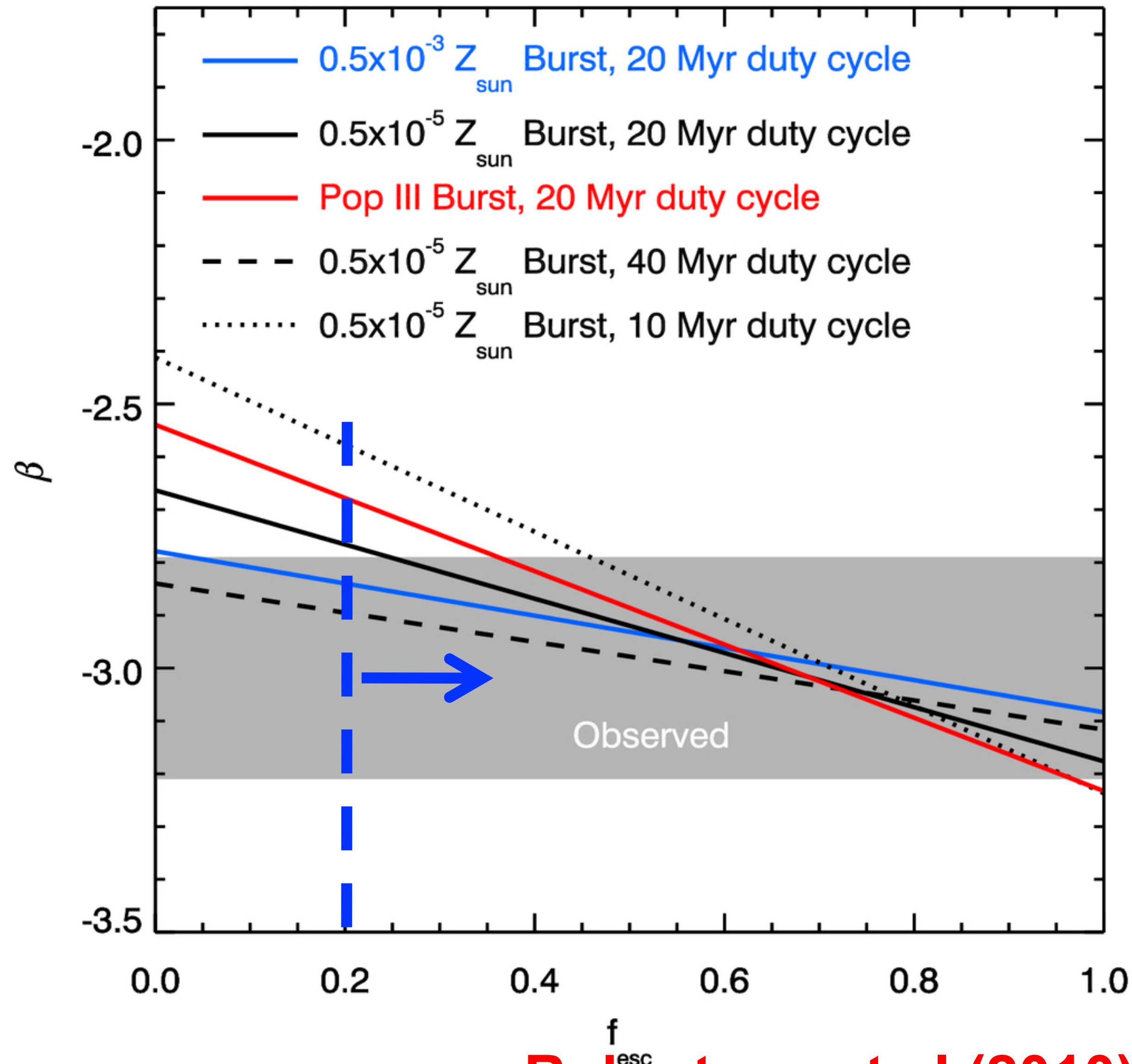
Can One Link β to the Escape Fraction f_{esc}?

3 questionable assumptions:

• Including nebular continuum corresponds to f_{esc}~0; pure stellar continuum to f_{esc}~1.

• Intermediate mixtures can be linearly interpolated

• In burst models, can simply `average' over a duty cycle to get representative relationship

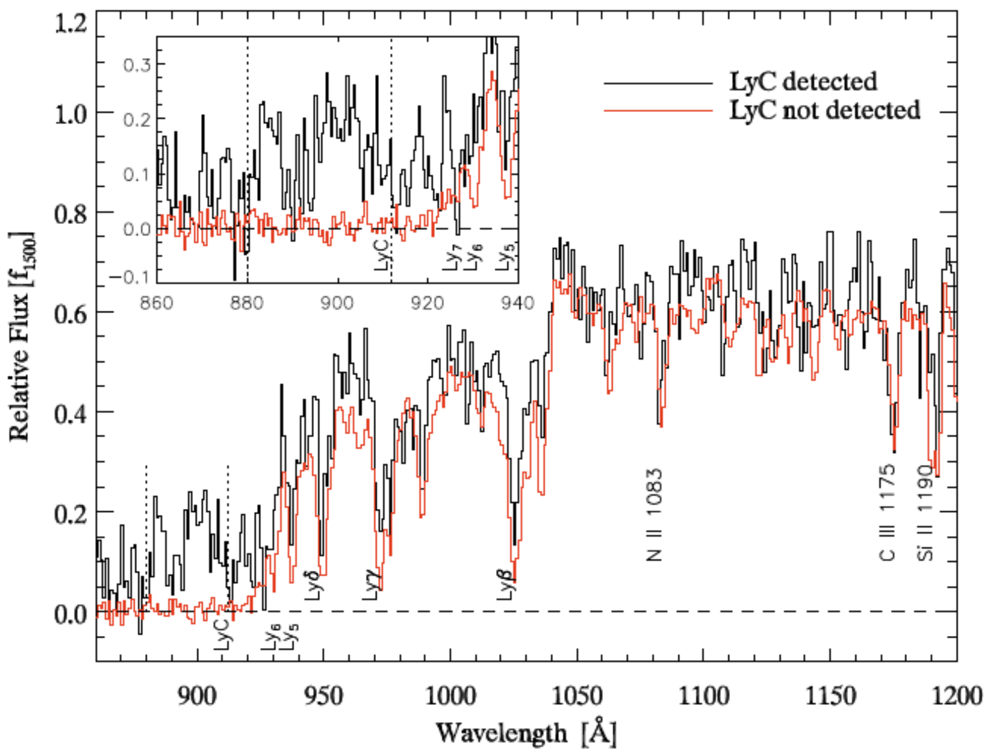


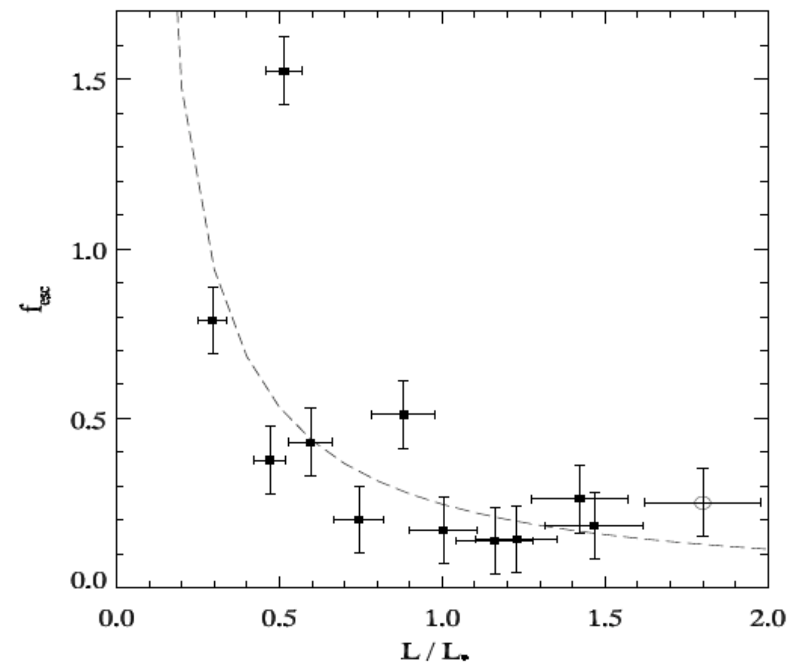
Robertson et al (2010)

Escape fractions in z~3 LBG spectra

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

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





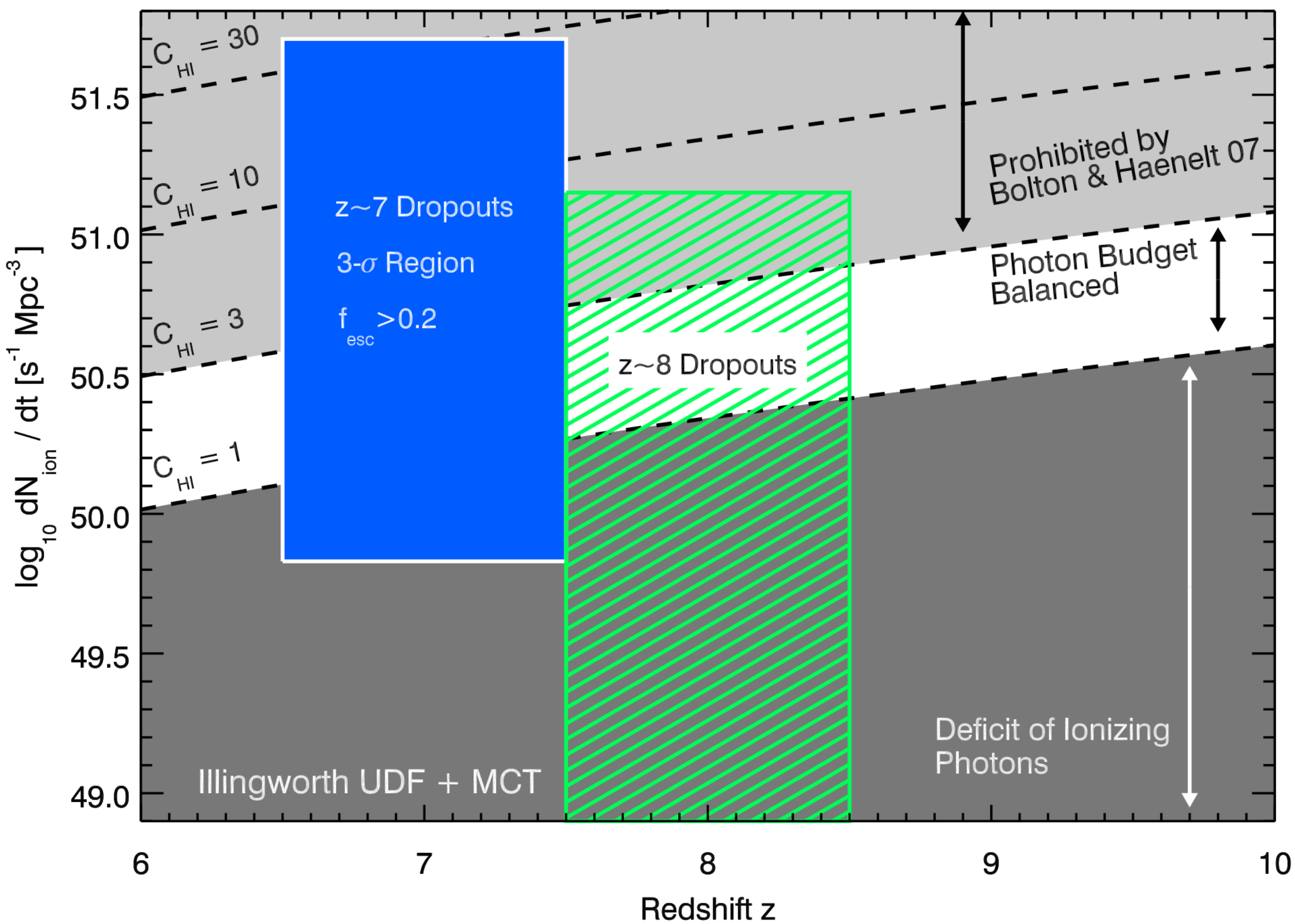
11/110 LBG spectra show positive Ly continuum flux

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

Bogosavljevic (2009)

Upshot: Did galaxies reionize the Universe?

Emission rate of ionizing photons Mpc^{-3} vs C_{HII} and f_{esc} compared to abundance of star-forming galaxies



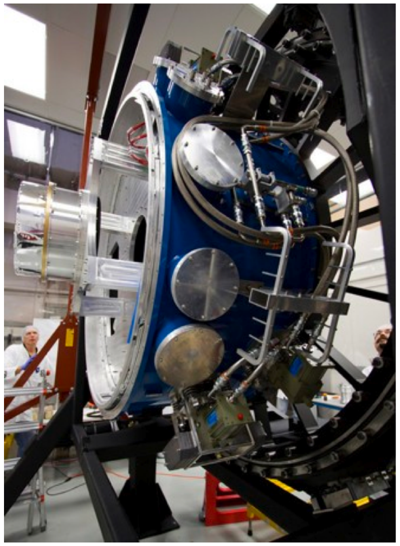
After Bolton & Haehnelt (2007), Ouchi et al (2009), Robertson et al (2010)

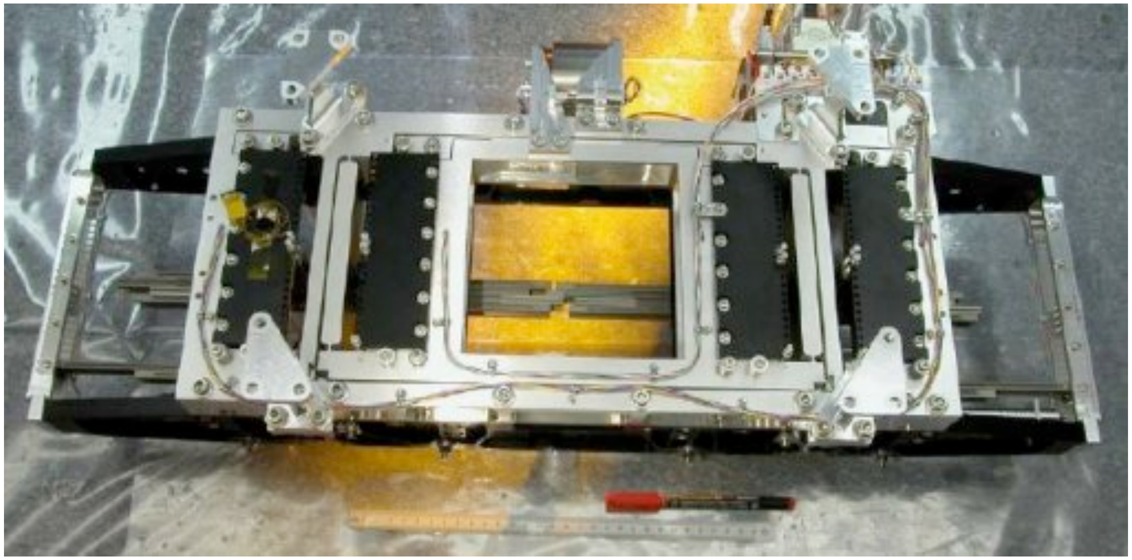
Future Prospects

- Continued improvement in 4<z<7 spectroscopic surveys:
  much to learn about demographics of LBGs/LAEs including spatial mapping of populations
- Multi-slit IR spectrographs for following existing and other z>7 candidates
  - MOSFIRE on Keck (2011A)
  - KMOS on VLT (2011B)
- HST + WFC3:
  - Multi-cycle Treasury program (improved z~7 LF)
  - Deeper UDF and other campaigns to probe fainter sources
- Adaptive optics imaging: all z>6 sources will benefit, lensed sources are only 30 milliarcsec across!
- JWST (2014) and..not too far off..(2018)..TMT/E-ELT

LOTS TO LOOK FORWARD TO!

MOSFIRE (Keck I) - 2010B





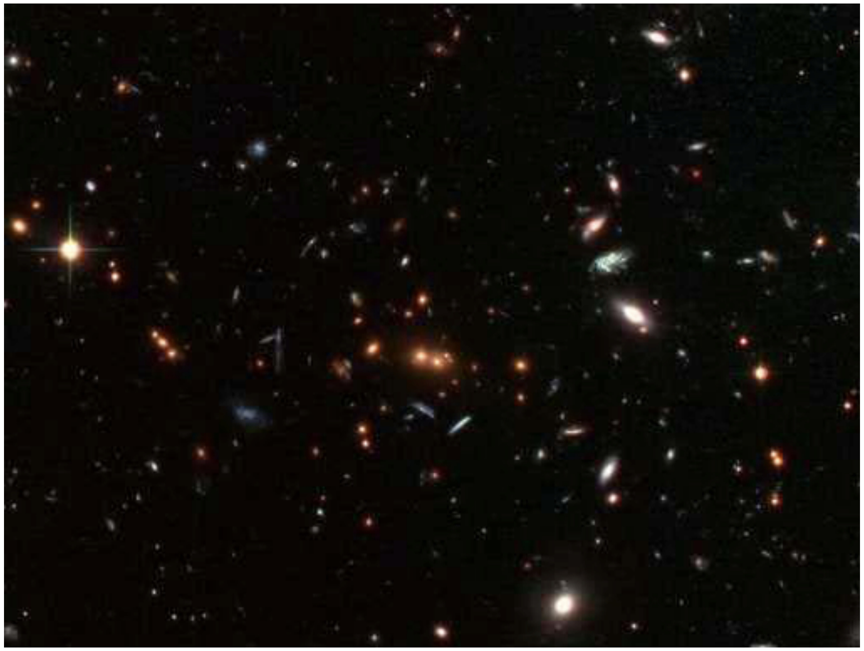
Cryogenic Multi-slit IR spectrograph

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)



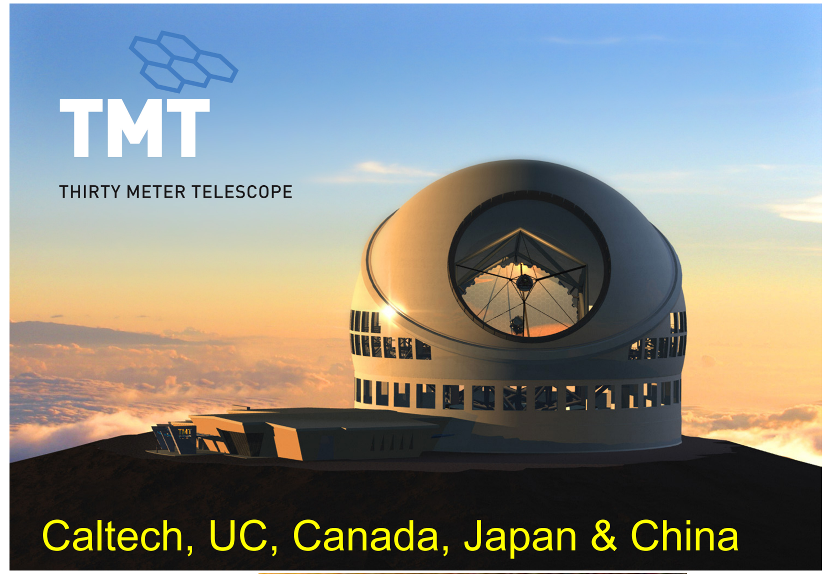
AO impacts JWST-TMT Synergy

TMT with AO will have <u>better resolution</u> than JWST (*not a dream: Keck AO has better resolution than HST*)

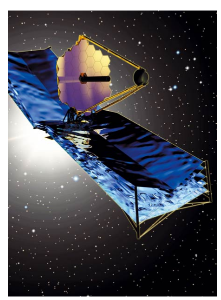
– together with large aperture significantly changes space-ground synergy

First sources & cosmic reionization:

- TMT is key to locating more abundant, fainter, smaller sources (AO gives ×10-100 gain over JWST depending on angular size).
- JWST probes to higher z in mid-IR



Lensed galaxies at z ~6
Unlensed sizes ~ 150pc or < 30mas!



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 $z\sim6$ detections in 2005 to comprehensive measures of the stellar mass density over $4<z<7$

- WFC3/IR has led to a flurry of new results:
  galaxies may maintain reionization over $7<z<10$ if:
    - continuity of SF trends over 300 Myr
    - dominant fraction of sub-luminous galaxies
    - increased escape fraction

- Many uncertainties but good prospects for better data from HST

- Key role of future ELTs exploiting adaptive optics with JWST