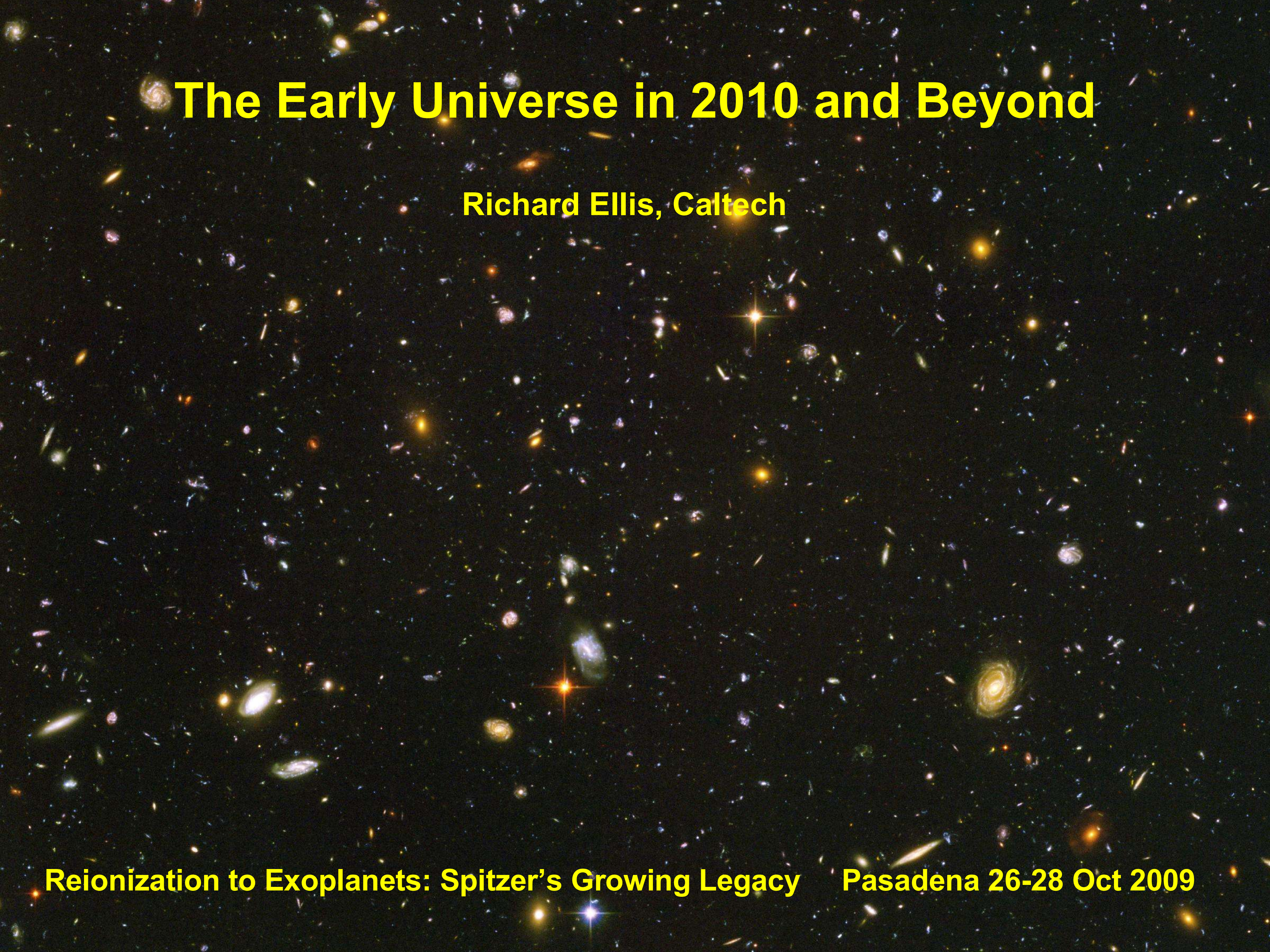


The Early Universe in 2010 and Beyond

Richard Ellis, Caltech

Reionization to Exoplanets: Spitzer’s Growing Legacy   Pasadena 26-28 Oct 2009

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

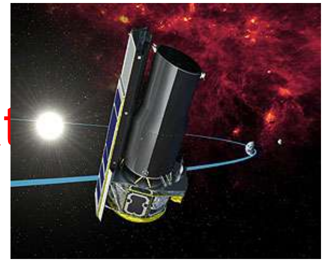
Mostly a review, but with some collaborative material from:

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

The Landscape - 2010

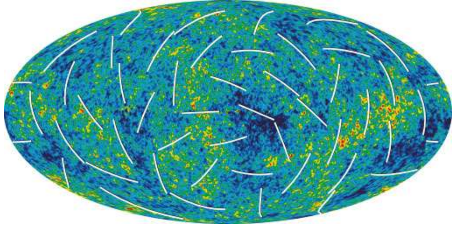
- Refined measures of optical depth to reionization, τ, from WMAP5
- First indications of downturn in IGM CIV abundance at $z > 5$
- Discontinuity in Lyman α luminosity function $5.7 < z < 6.5$
- Stellar masses and mass densities $4<z<6 \rightarrow$ measure of earlier SF
- Demographics and evolution of Lyman break population
- Studies of important diagnostic objects at z>6.5

  - Subaru Lyα emitter at z=6.96 - large Lyα emitter at z=6.60 - long duration GRB at



- Promising young galaxy candidates beyond z~7
- Limits from background light measures
- Challenges and prospects for the future

*Spitzer data



WMAP Polarization: Scattering by foreground electrons

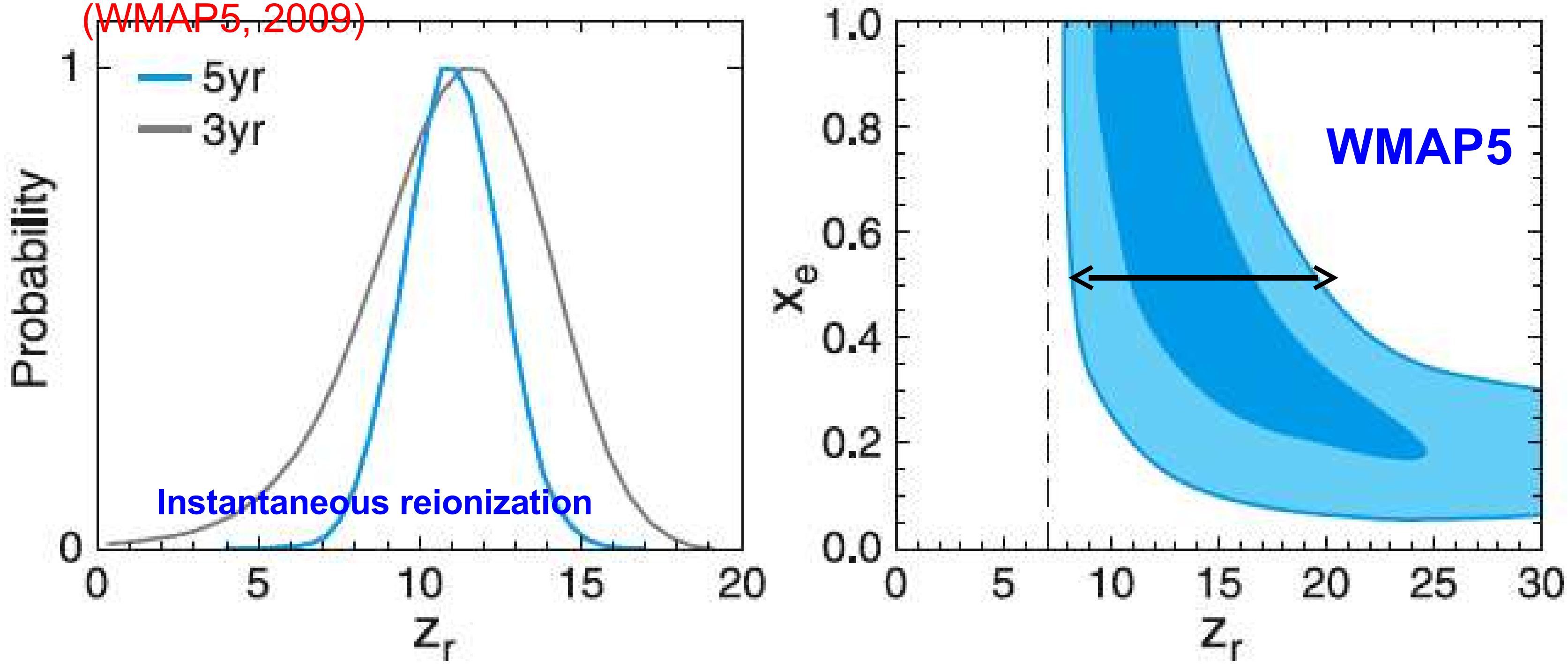
Optical depth to scattering:

$\tau = 0.17 \pm 0.08$ (WMAP1, 2003)

$\tau = 0.09 \pm 0.03$ (WMAP3, 2007)

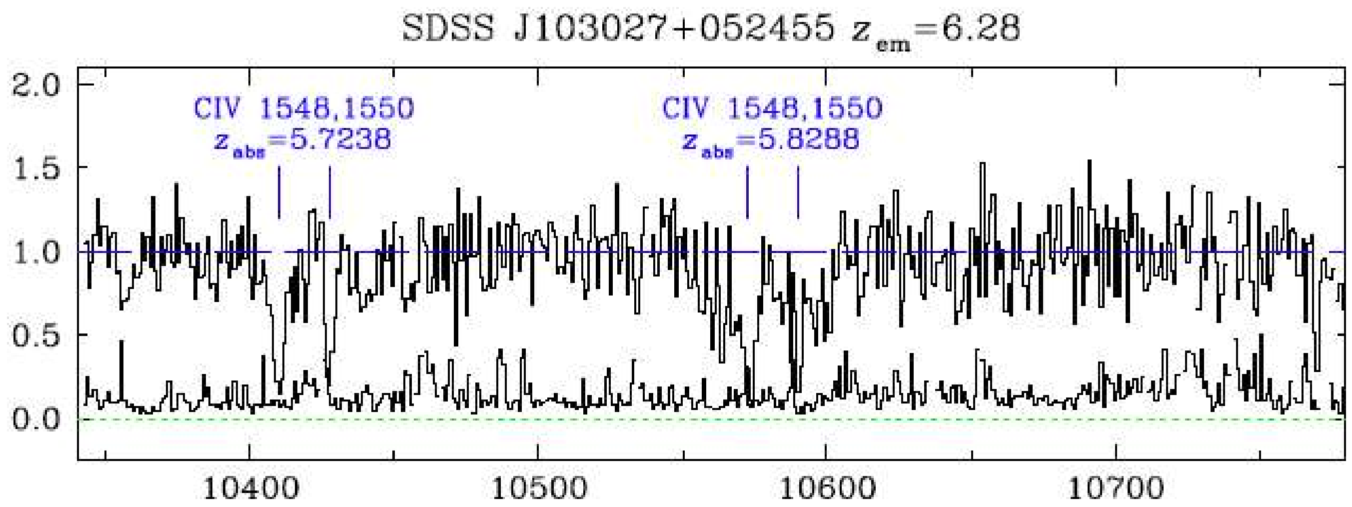
$\tau = 0.087 \pm 0.017$ (WMAP5, 2009)

Dunkley et al 2009

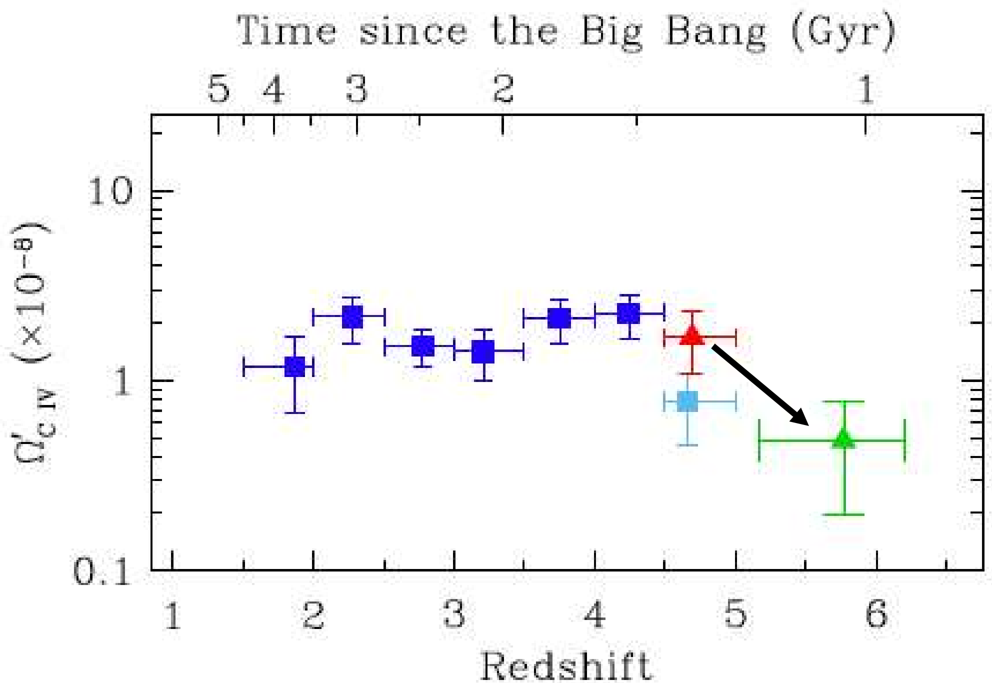


Data rejects instantaneous reionization at z~6-7. Process is likely extended over 6<z<20. CMB studies do <u>not</u> pinpoint the responsible cosmic sources

CIV Absorbers in High z QSOs



- Factor 3.5 drop in Ω_{CIV} over 4.5<z<6 (300 Myr)
- Caveats: ionization changes, cosmic variance
- Rapid enrichment since z~9?
- If absorbers representative: Z_{IGM} (z~6) ~ 10^{-4} Z implying too few escaping photons (6<z<9) to keep IGM ionized

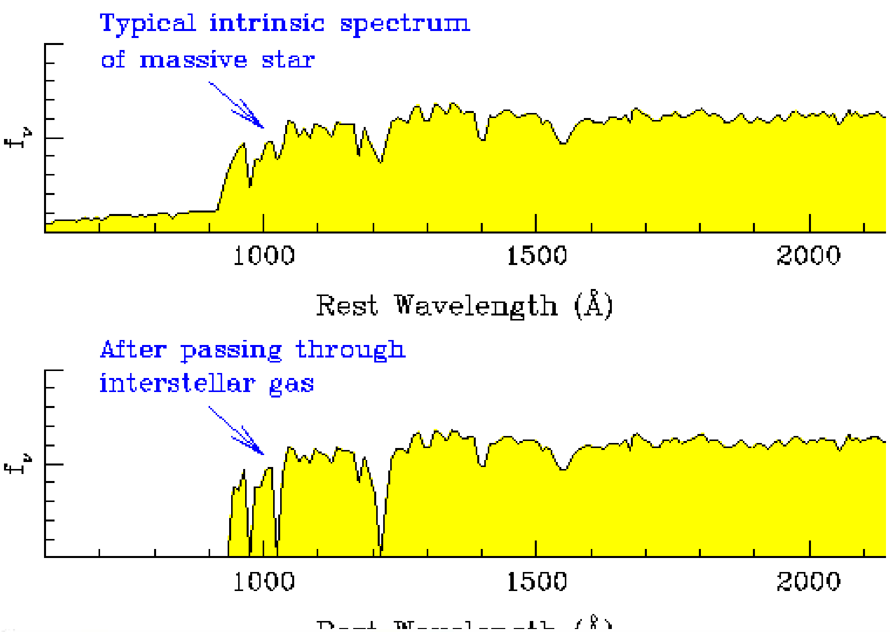


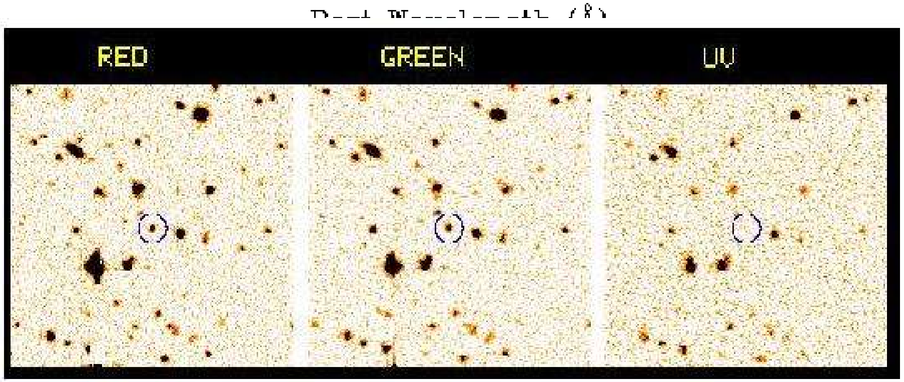
Ryan-Weber et al (2009)

High Redshift Star Forming Galaxies

Lyman break galaxies:

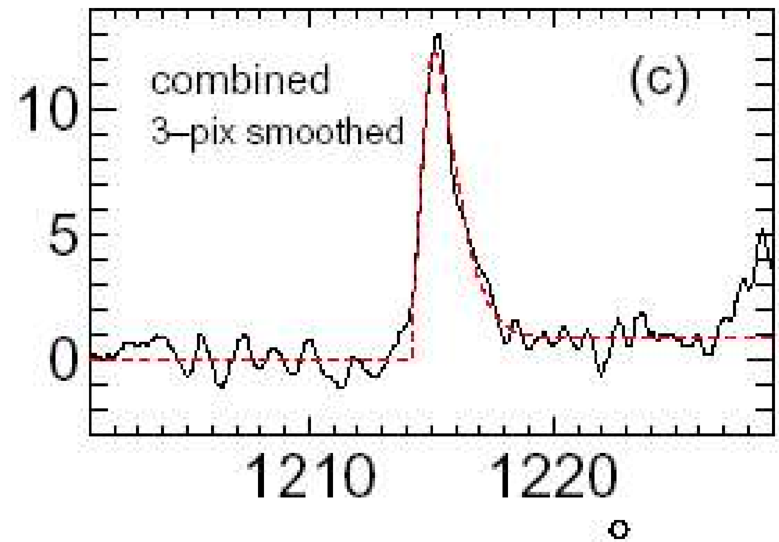
Rest-frame UV continuum discontinuity

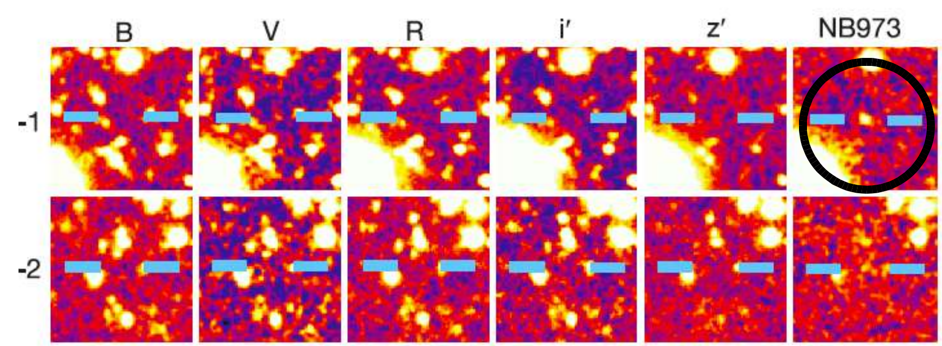




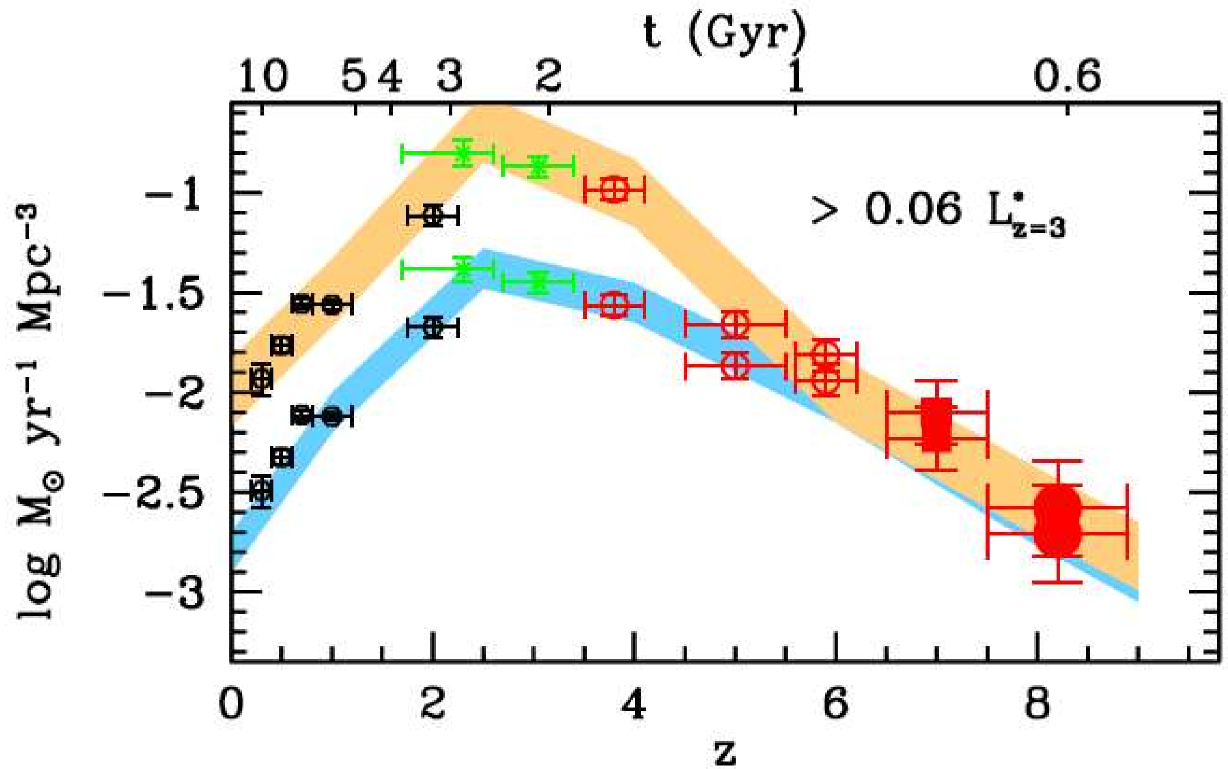
Lyman alpha emitters:

Located via narrow band imaging





Declining star formation density of LBGs



Monotonically declining population to z~6 and beyond

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

1.2 mag dimming in characteristic luminosity L*

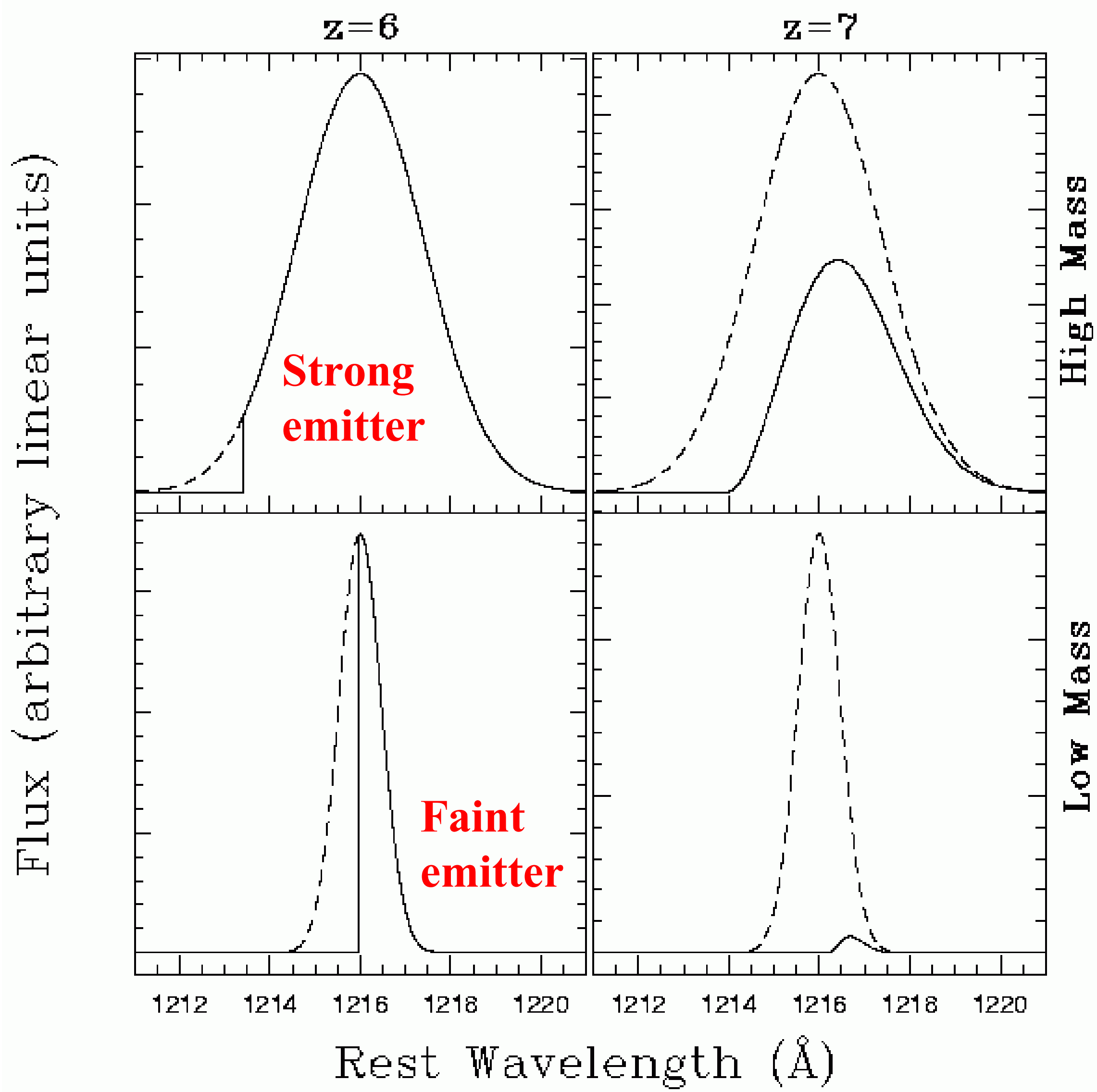
Reddy & Steidel (2009)

Bouwens et al (2009)

Lyman α emitters as probes of reionization

Efficient: < 6-7% of young galaxy light may emerge in Lyα depending on IMF, metallicity etc.

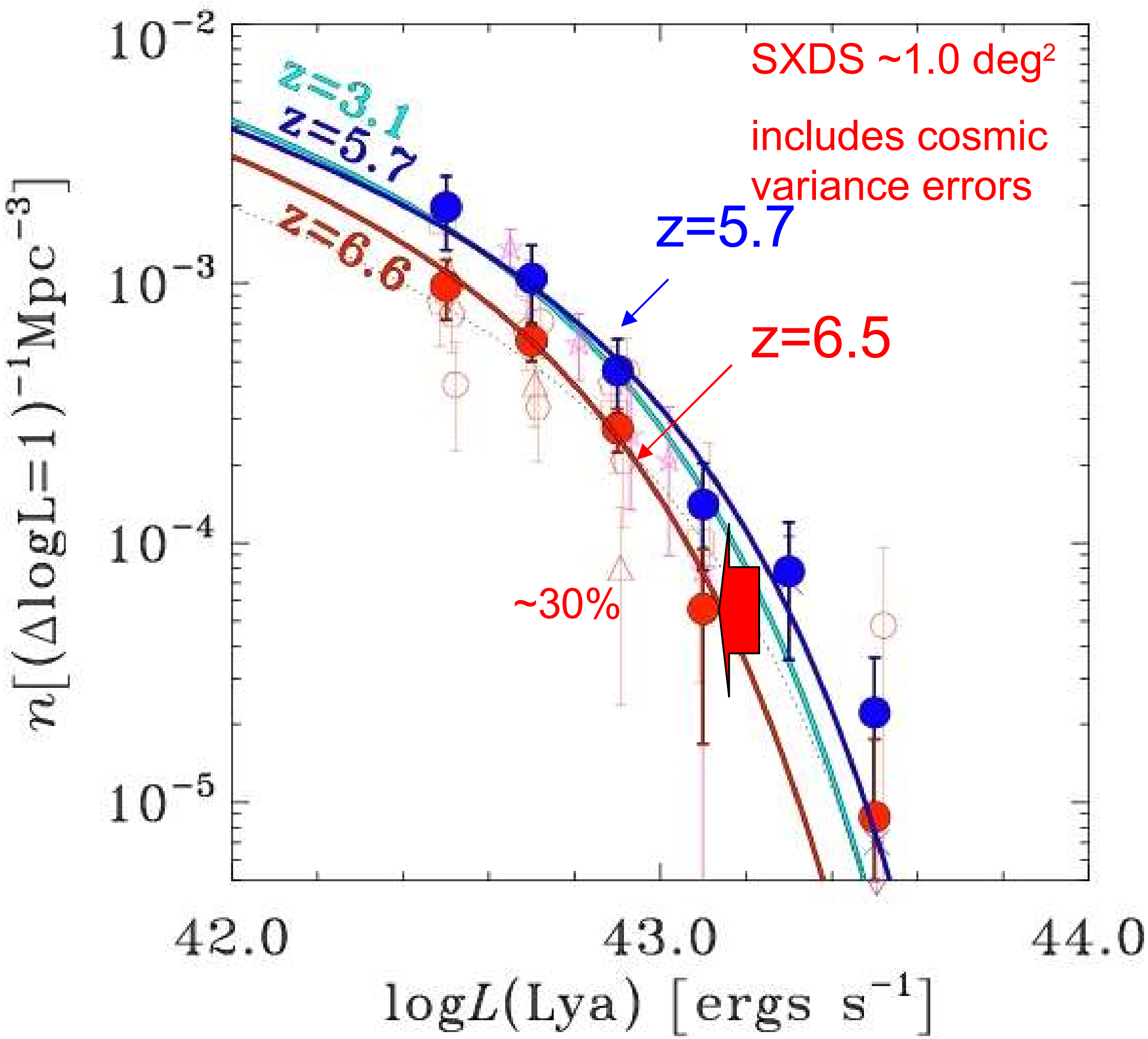
- **Lyα damping wing is absorbed by HI and thus valuable tracer of its presence.**
- **In weaker systems, it may be a** ***sensitive probe of reionisation***



Santos (2004)

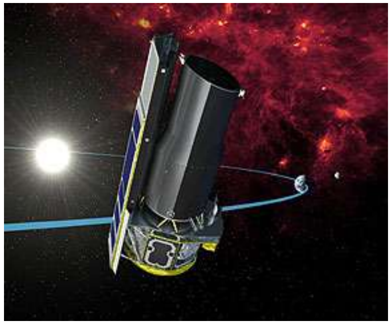
A Rapid Drop in Lyα Emitters from 5.7<z<6.6?

- 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} ?



Ouchi et al (2009)

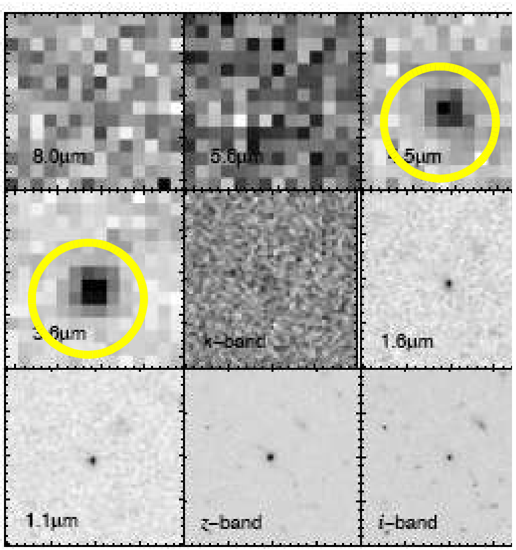
The Spitzer Revolution: Stellar Masses

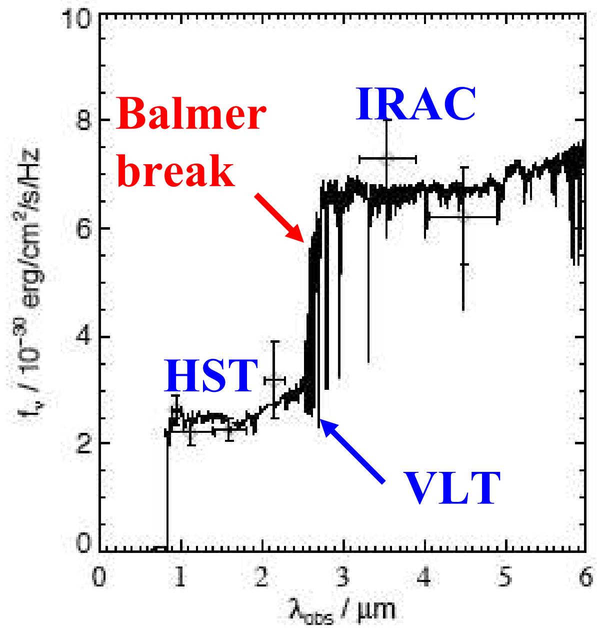


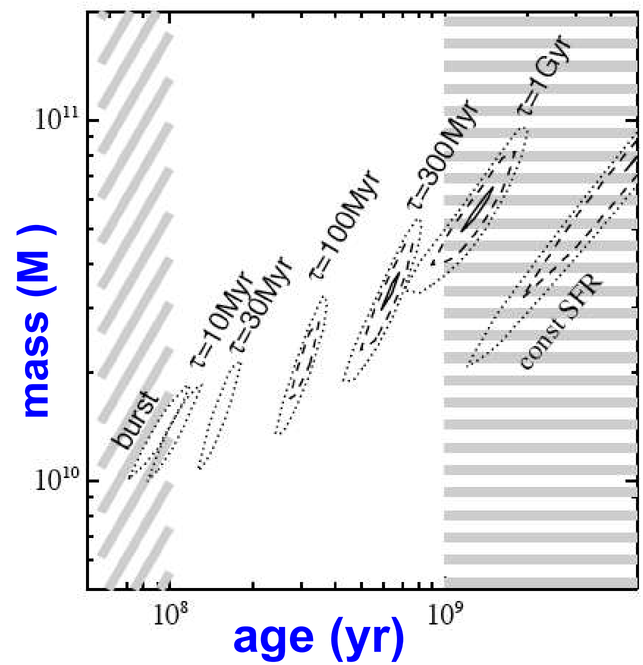
A modest 85cm cooled telescope can see the most distant known objects and provide crucial data on their **<u>assembled stellar masses and ages</u>**

SMB03-1: z_{spec}=5.83 IRAC(3.6μm)=24.2 (AB)

stellar mass = 3.4 10^{10} M   age > 100 Myr



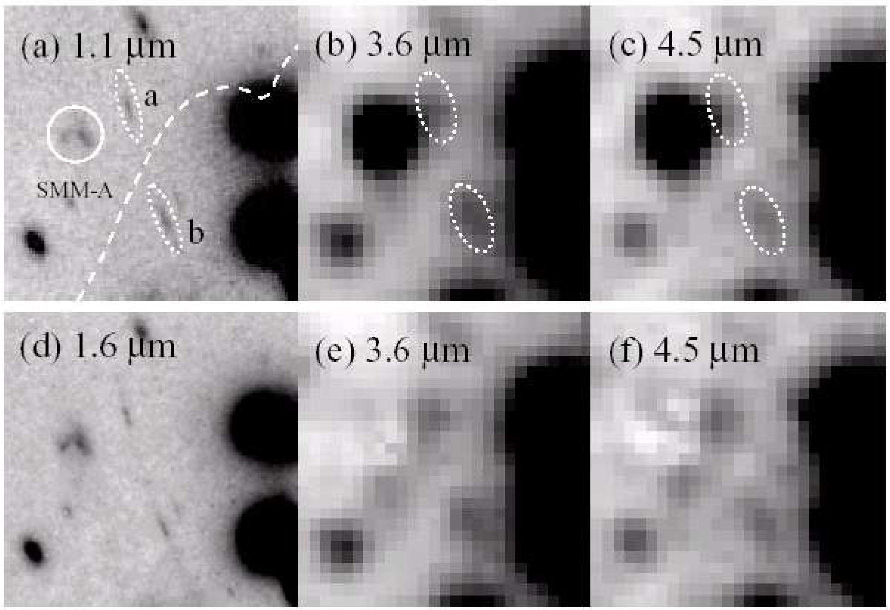




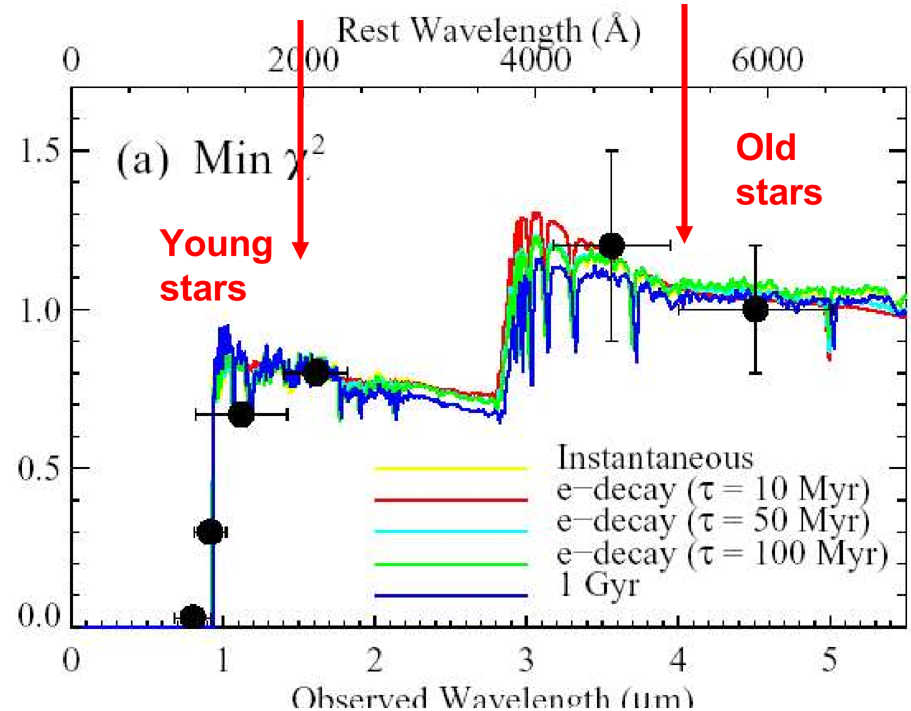
Eyles et al (2005): to produce this mass since z~10 required 5-30 M yr^{-1} comparable to the ongoing SFR (6-20 M yr^{-1}) so should see earlier examples if unobscured

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

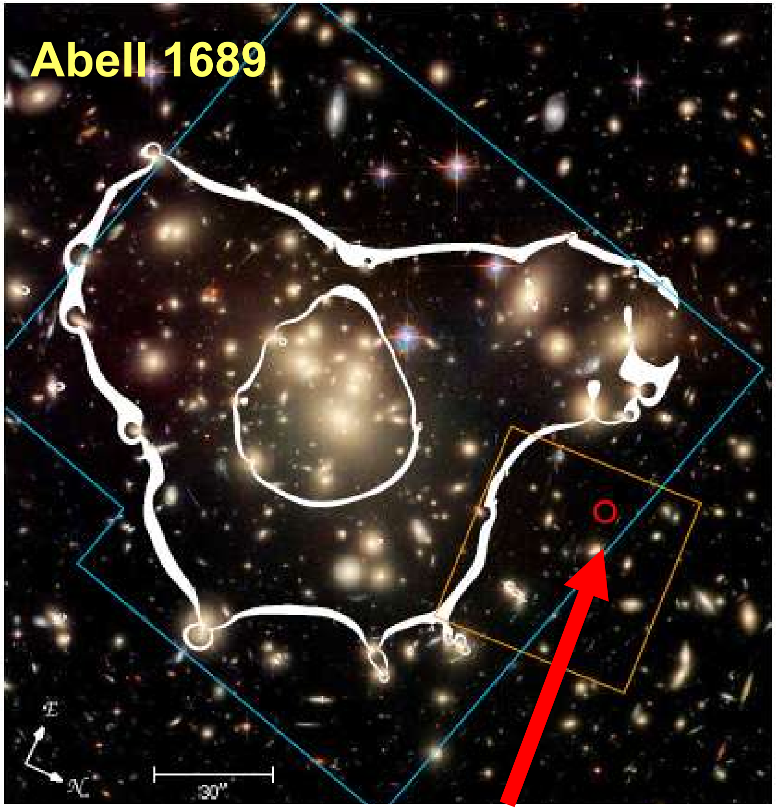
Star formation rate = 2.6 M yr^{-1} Stellar mass ~ 5-10 10^8 M

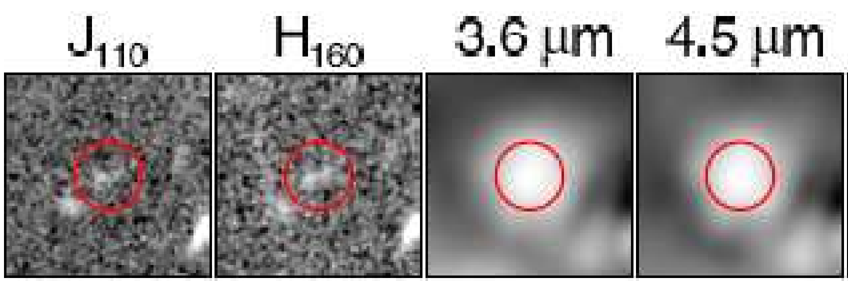
Balmer break gives age = 100 – 450 million yrs, so formed at 9 < z_F < 12

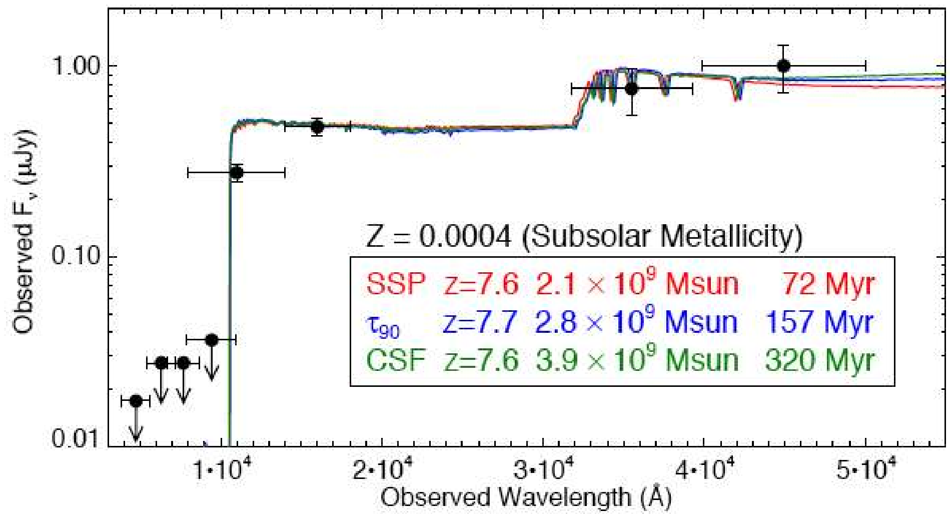
This is already a well-established system 800 Myrs after E

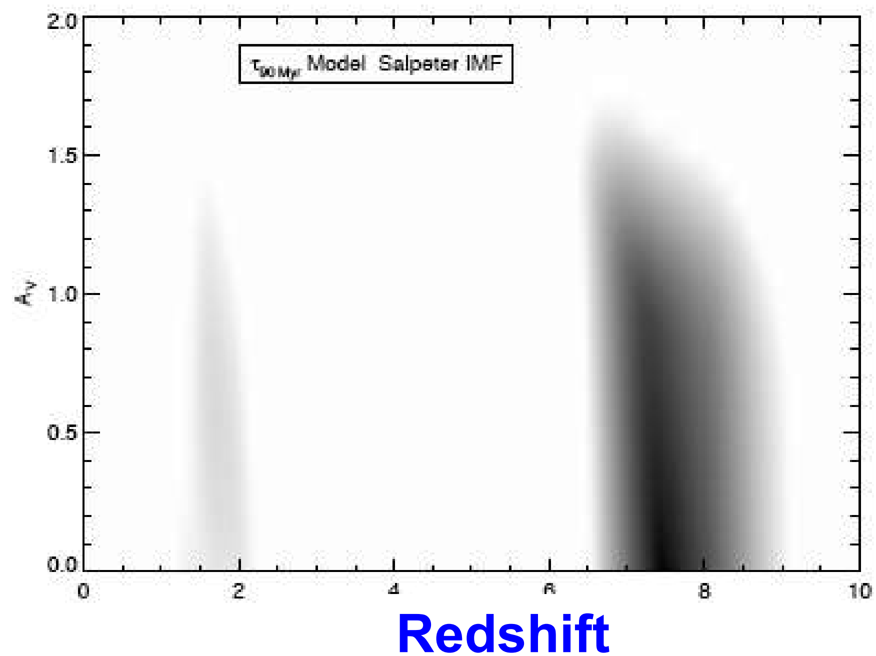
Egami et al (2005)

Lensed LBG at redshift 7.6?



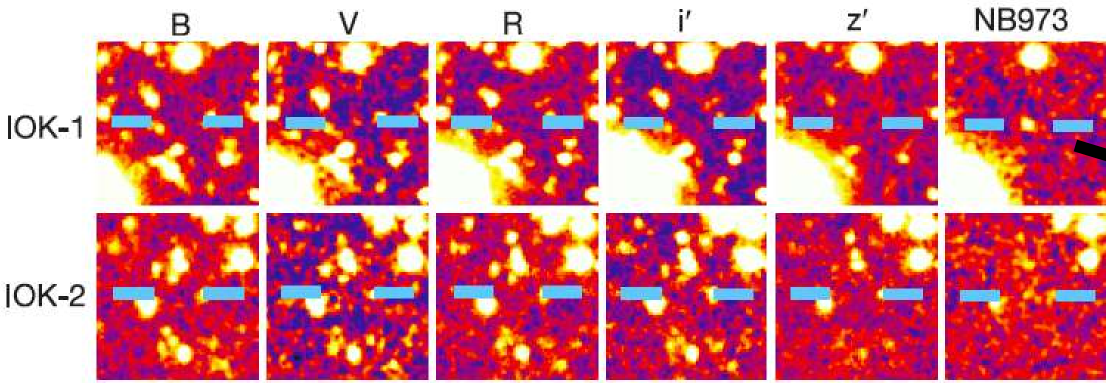


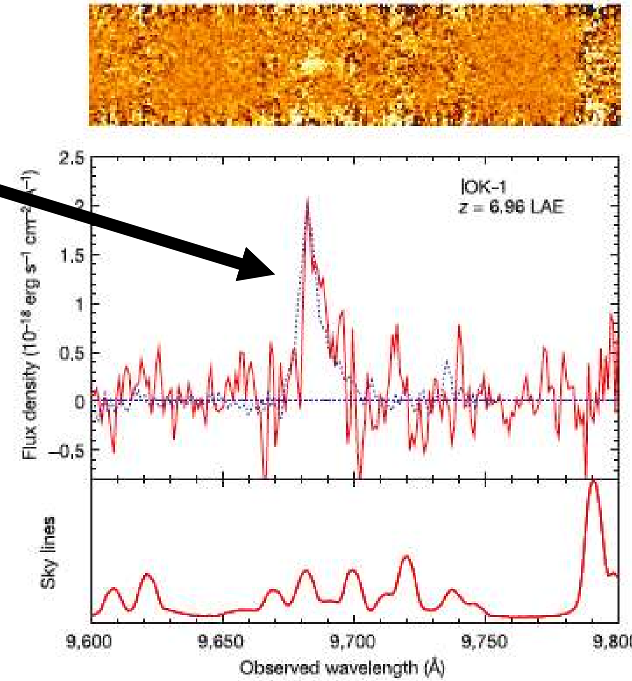




Bradley et al (2008)

Contrast with Subaru Lyα emitter at z=6.96





Iye et al (2006) FOCAS 8.5 hrs

SFR (Lyα) = 10 M yr^{-1}

Egami & Jiang (in prep):

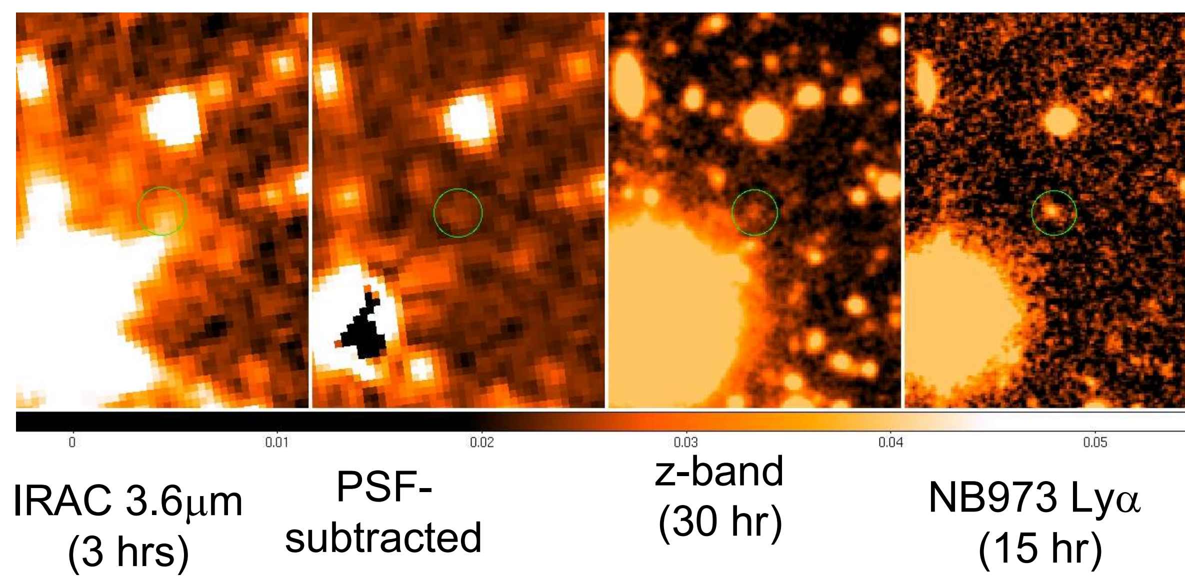
- **Poss IRAC detection (2-3σ due to nearby star)**
- **z-band flux affected by Lyα**

f(z-band) ~ f(3.6μm) ~ 0.1 μJy

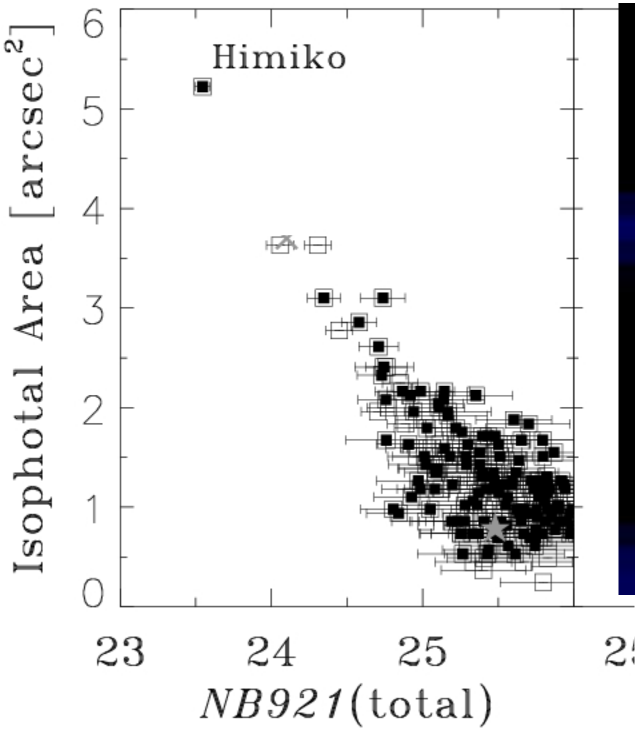
No Balmer break?

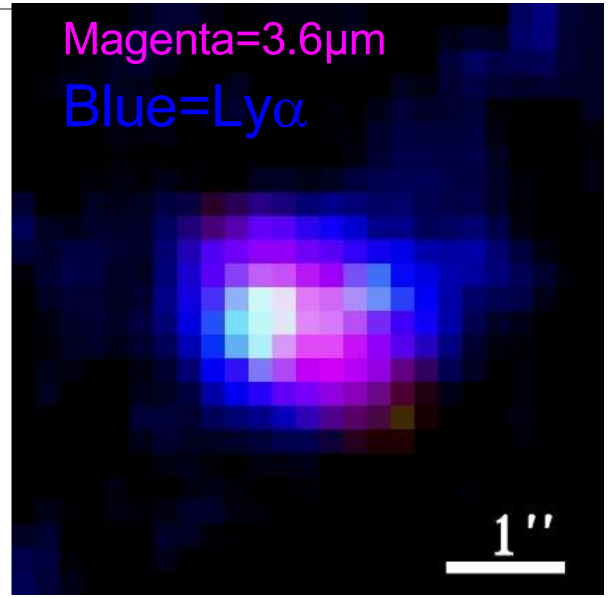
Mass ~ 5-8 10^8 M ?

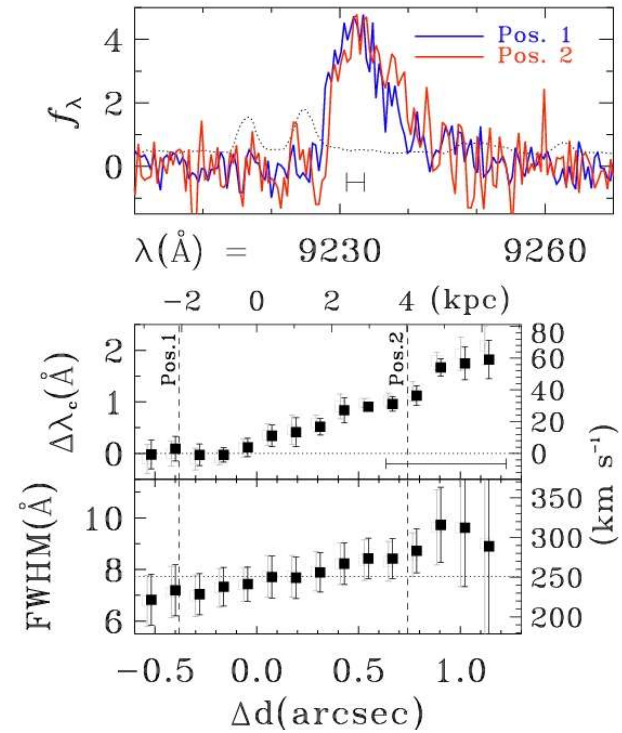
Age < 50 Myr?



`Himiko' - a Giant Lyα Emitter at z=6.6



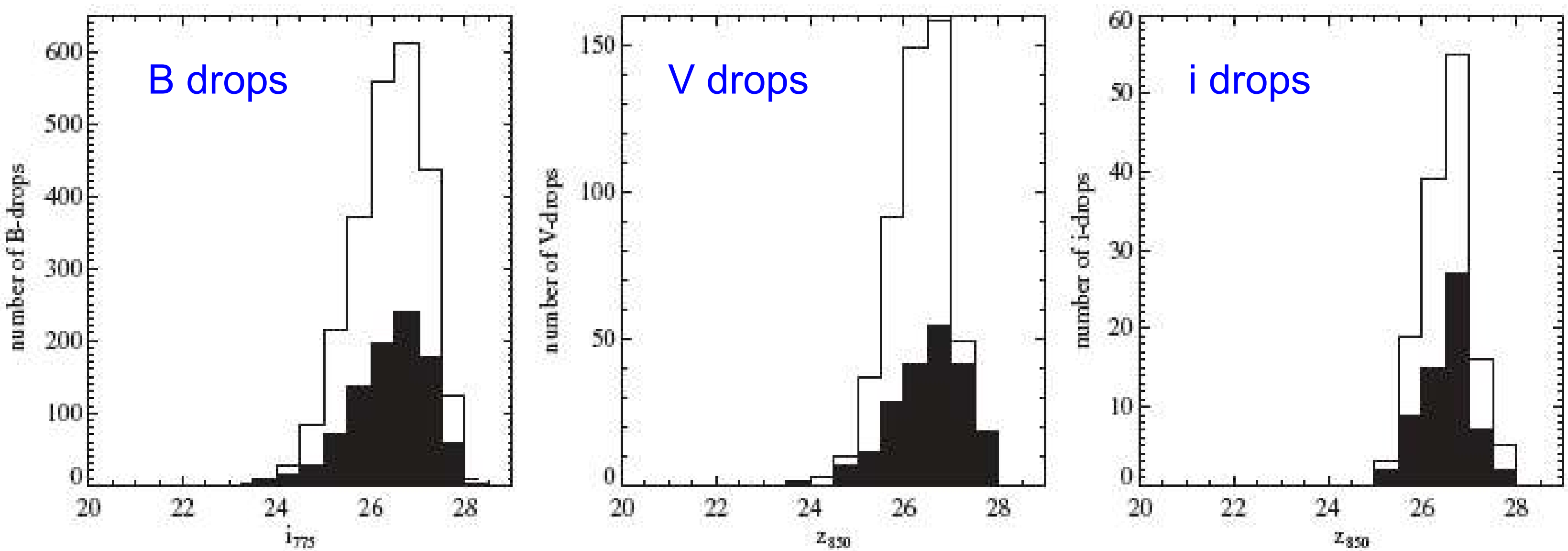




- From 207 LAEs in SXDS survey (volume 10^6 Mpc^3), find a **monster LAE**
  L=4x10^{43} erg s^{-1}; size~17kpc; Δv=± 60 km s-^{1}; σ = 100 km s^{-1}
- No AGN signatures, not lensed; IRAC detection, not yet in JHK (Keck Oct 31)
- M* = M_{dyn} ~ 1-5 10^{10} M
- Gas excited by shocks due to starburst or cooling gas accreting onto DM halo?
- Accurate SED will determine age & clarify whether Himiko is seen at formation

Ouchi et al. (2009)

GOODS Stellar Mass Functions 4 < z < 6

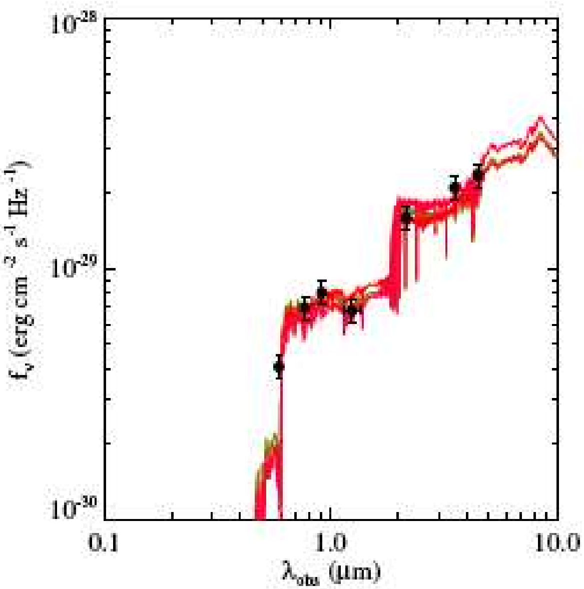


- 2443 B-drops, 506 V-drops, 137 i-drops in ACS GOODS N/S
- 35% sufficiently isolated with Spitzer/IRAC for robust photometry
- Deep K imaging from ISAAC (Cesarsky), MOIRCS (Bundy)
- Low z contaminants identified (morphology, MIPS)
- Masses and ages using CB07, testing effect of TP-AGB stars
- Individual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

Stark et al 2009

Examples across the full range of data

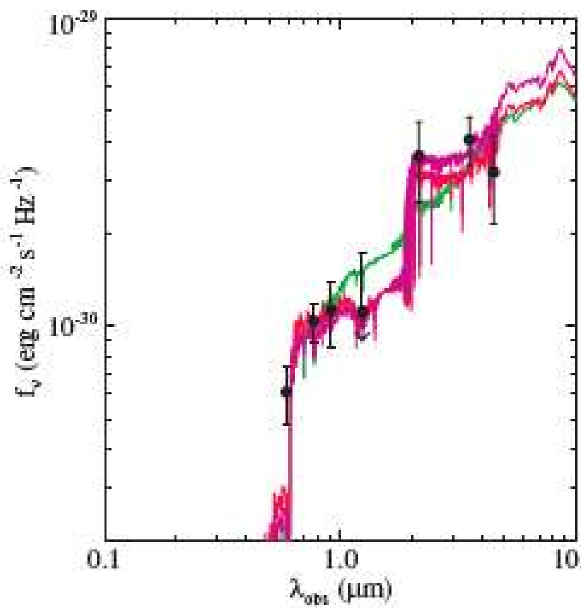
High mass/bright



mass = 2.3 10^{10} M

age = 290 Myr

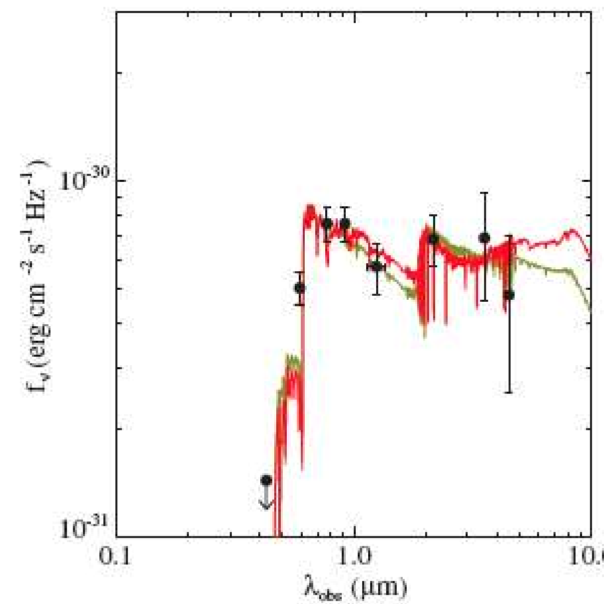
Low mass/faint



mass = 4.8 10^{9} M

age = 320 Myr

Stacked data



mass = 1.7 10^{8} M

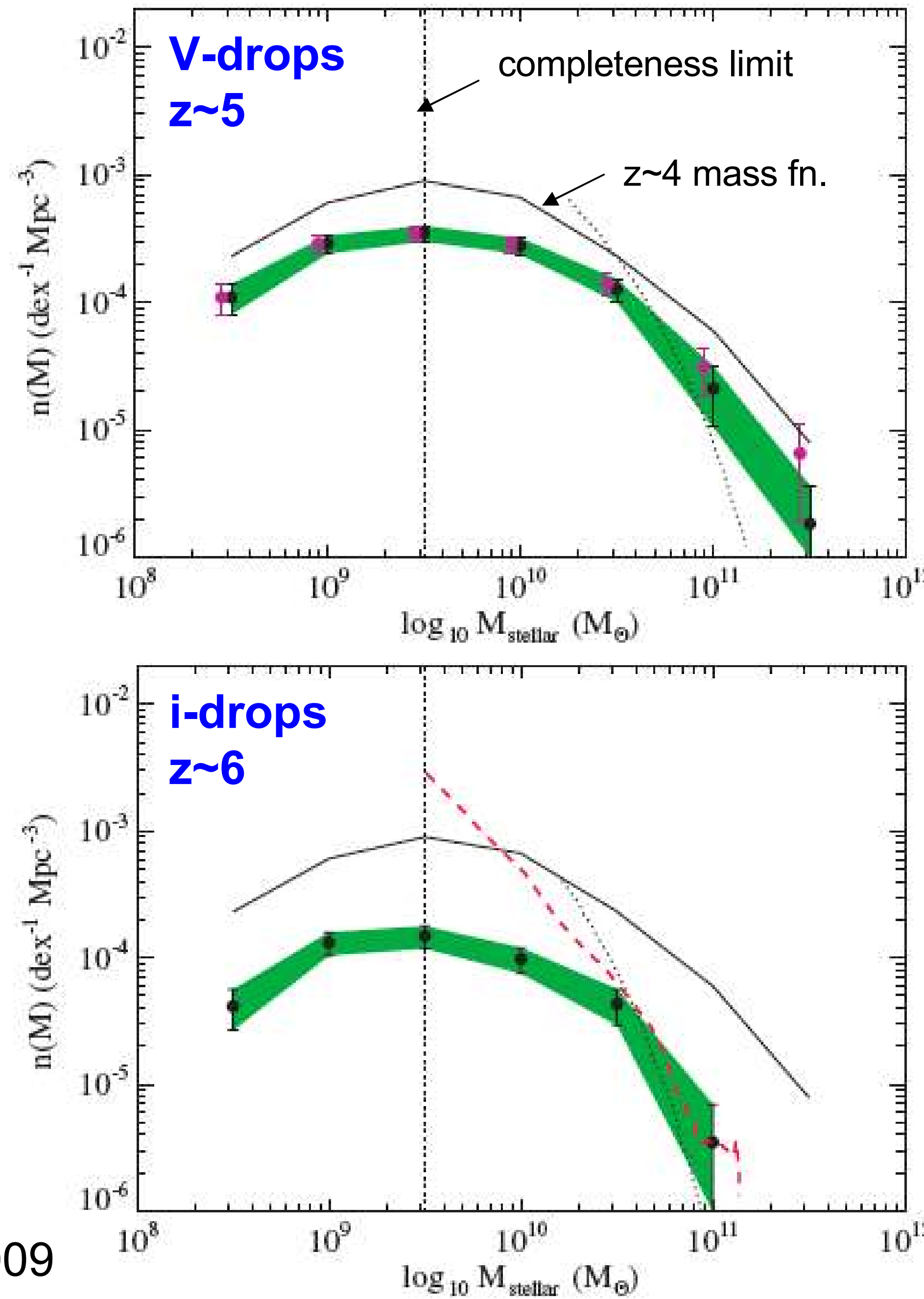
age ~ 50 Myr

Stellar Mass Density

- Factor ×5 growth in mass density over 4 < z < 6:
- Substantial mass density at z~5 suggesting much activity >300 Myr earlier (z > 7)
- Mass in place is integral of the past activity

$$M_*(z) \quad \int_{z\,5}^{z\,10} {}_*(z)\, dV(z)$$

- Hard to reconcile implied past SF with that observed for <u>luminous</u> dropouts but implied SF nonethless may be sufficient to maintain reionization
- Perhaps early SF is in sub-L* galaxies or is obscured



Stark & Ellis 2006, Stark et al 2007, 2009

Summary (z < 7)

- WMAP polarization data rules out instantaneous reionization at late times (z~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~9

- Drop in Ly α LF over 5.7<z<6.6 may indicate modest increase in neutral fraction to z~7 or perhaps other obscuration

- Assembled stellar mass at z~5 indicative of much earlier SF

- Detailed studies of individual z~7 sources present a diverse set:

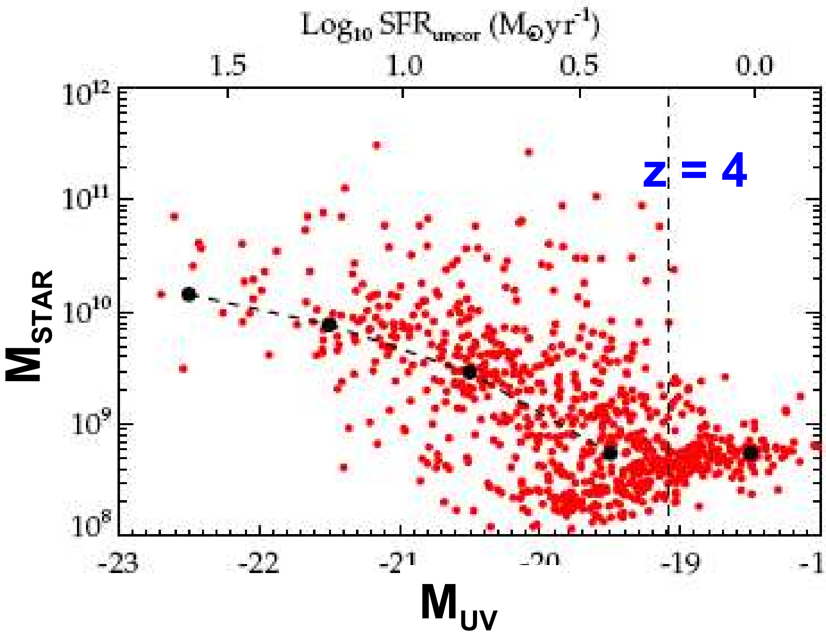
  - LBGs with Balmer breaks indicative of activity since z~10

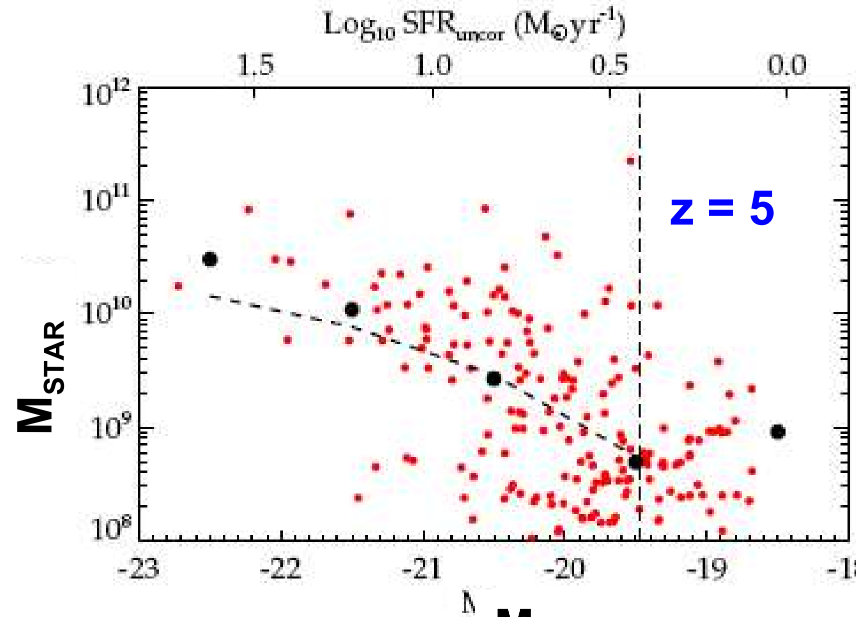
  - LAEs seen during active (perhaps primeval) phases

- No single epoch of formation but mix of continually-forming systems

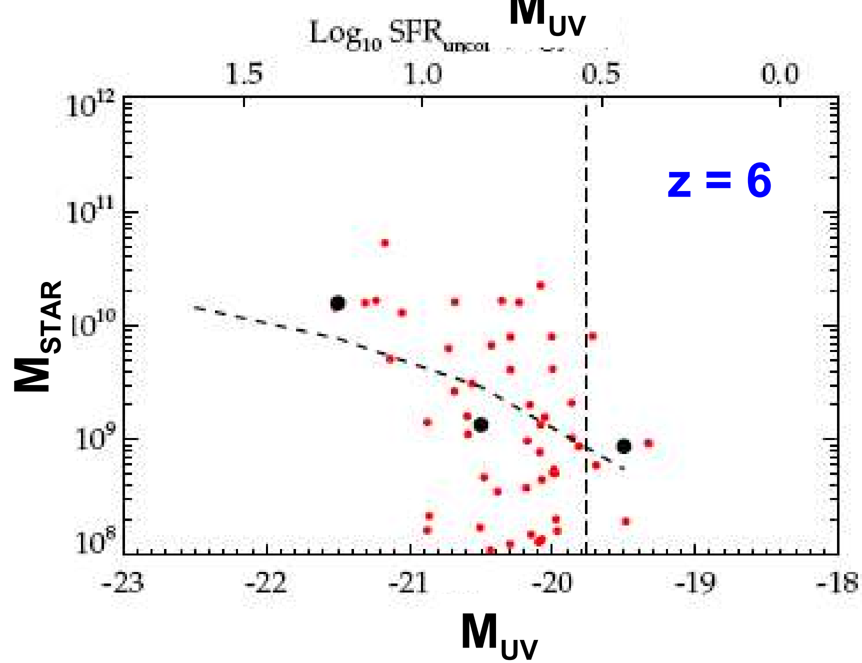
Upshot: expect abundant population of SF sources z>7 but they may be sub-luminous/obscured (and perhaps not emit Ly α)

Short duty cycle of SF at high z (Stark et al 2009)



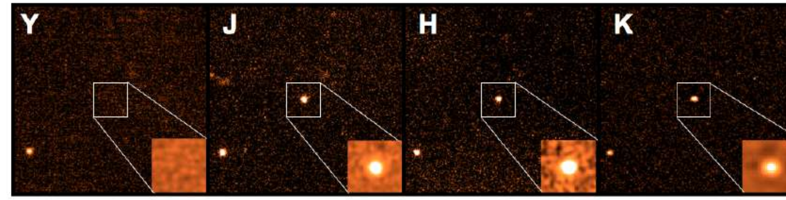


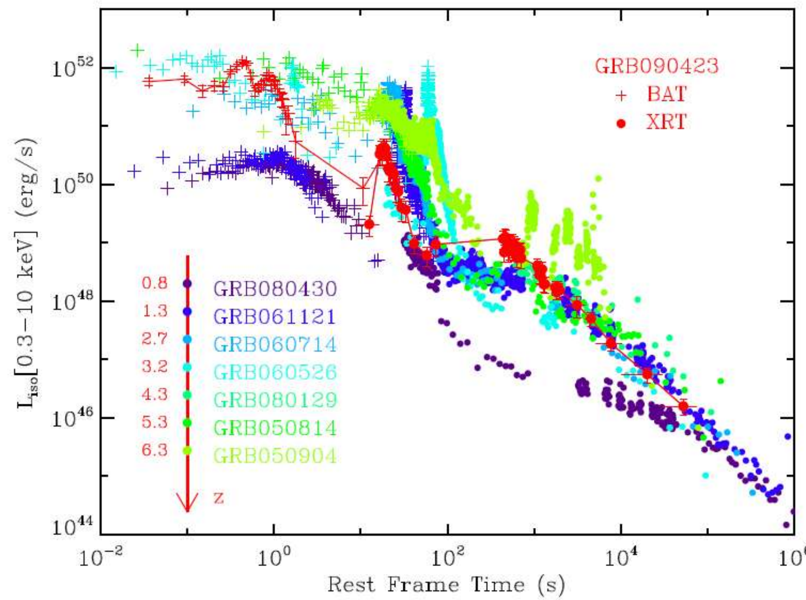
- Mass ÷ SFR gives an `effective age'
- Remarkably these ages are short (<300 Myr) and don't get longer as Universe ages!
- So LBGs at z~6 cannot all grow into more massive versions at z~5 and z~4
- Successive generations arriving consistent with faster cycles of SF

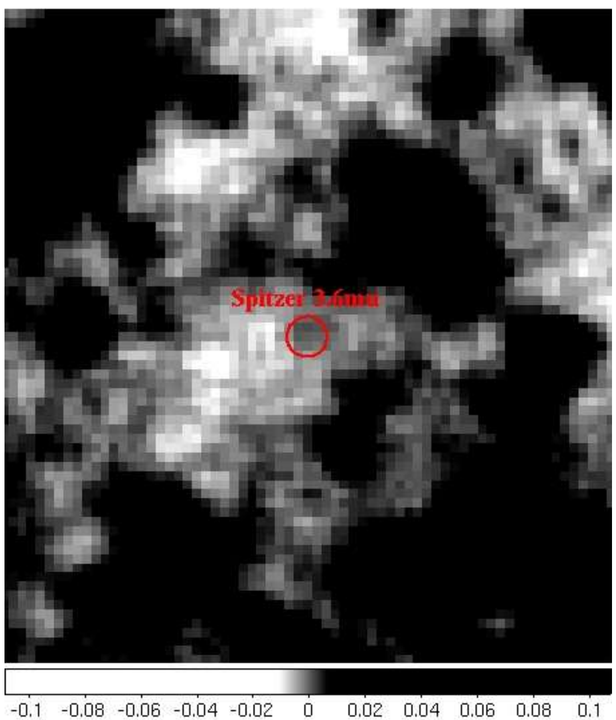


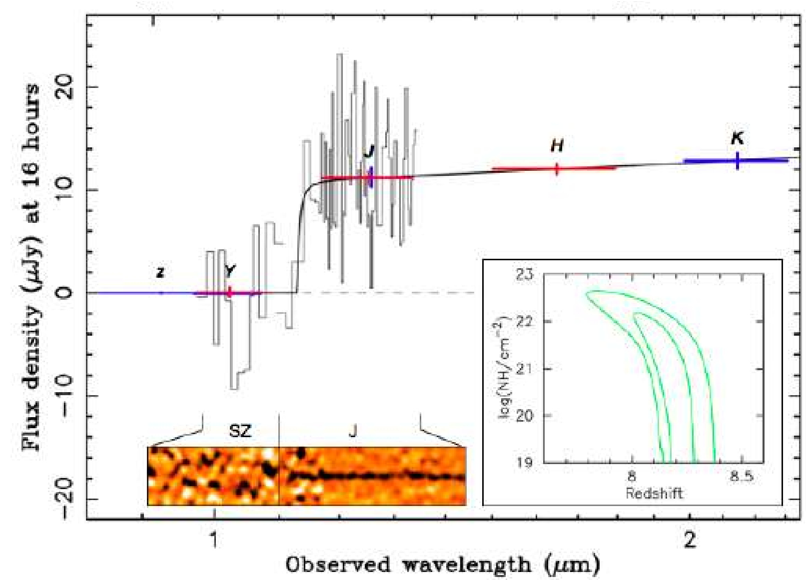
GRB090423 z=8.26

- Long burst typical of lower z examples similar massive star progenitor (Salvaterra et al)
- VLT spectrum t=16 hrs (Tanvir et al)
- 3σ IRAC detection (46 ± 17 nJy) at 3.6μm (5 days post-burst) (Chary et al. 2009; GCN9582)

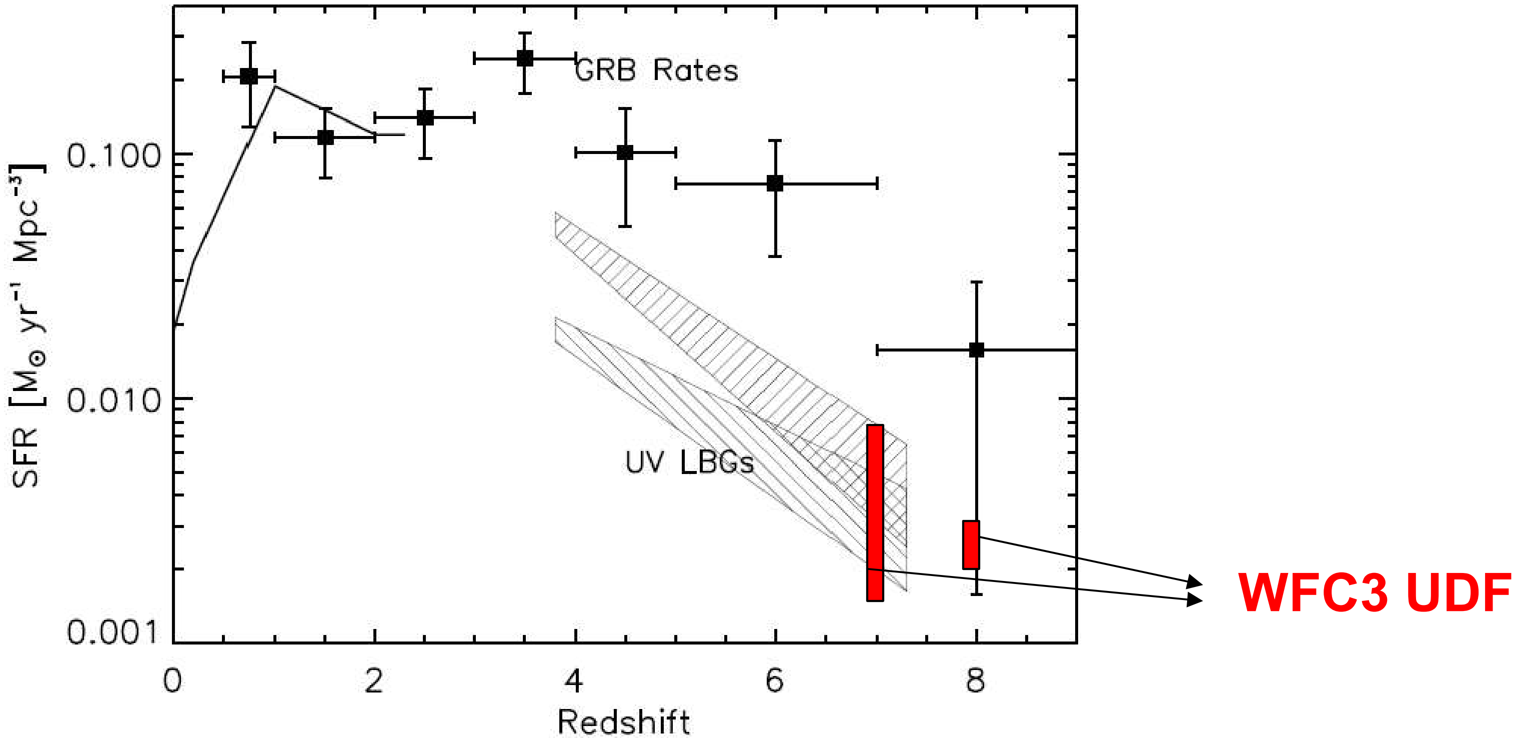








Testing for obscured SF at high z



Could there be a discrepancy between the SFR derived from the rate of GRBs and UV-emitting LBGs?

- Dust obscuration ?
- GRBs more efficiently produced because of lower metallicity ?
- Changes to a top-heavy initial Mass Function more top-heavy ?

Chary 2009

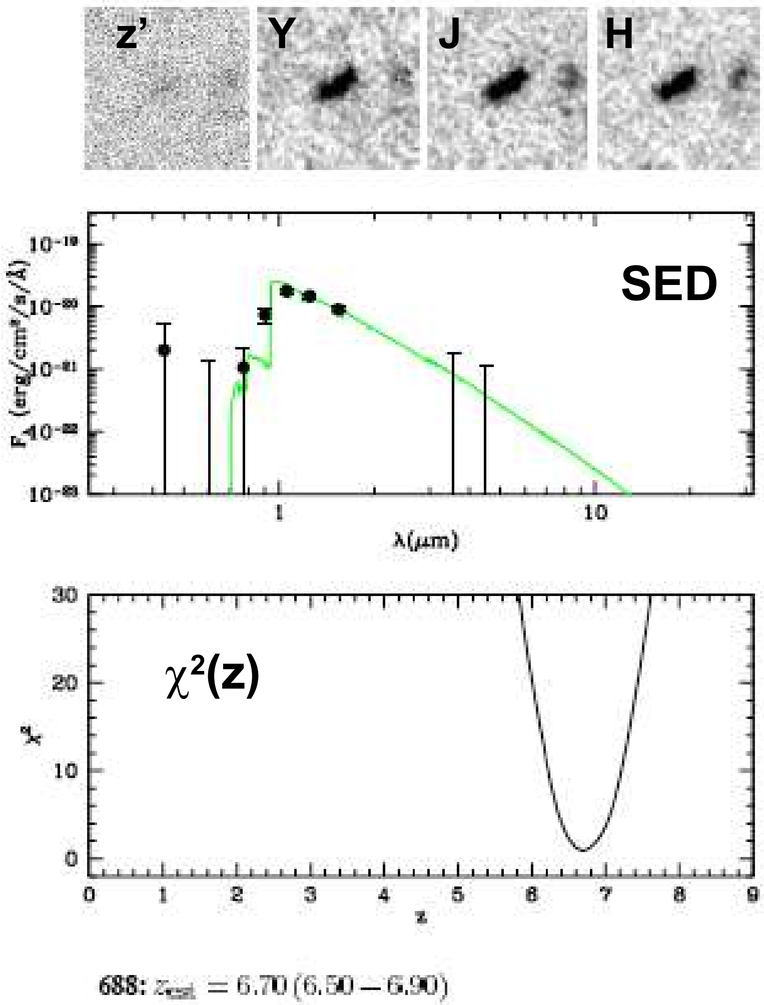
Hubble WFC3 High z Stampede

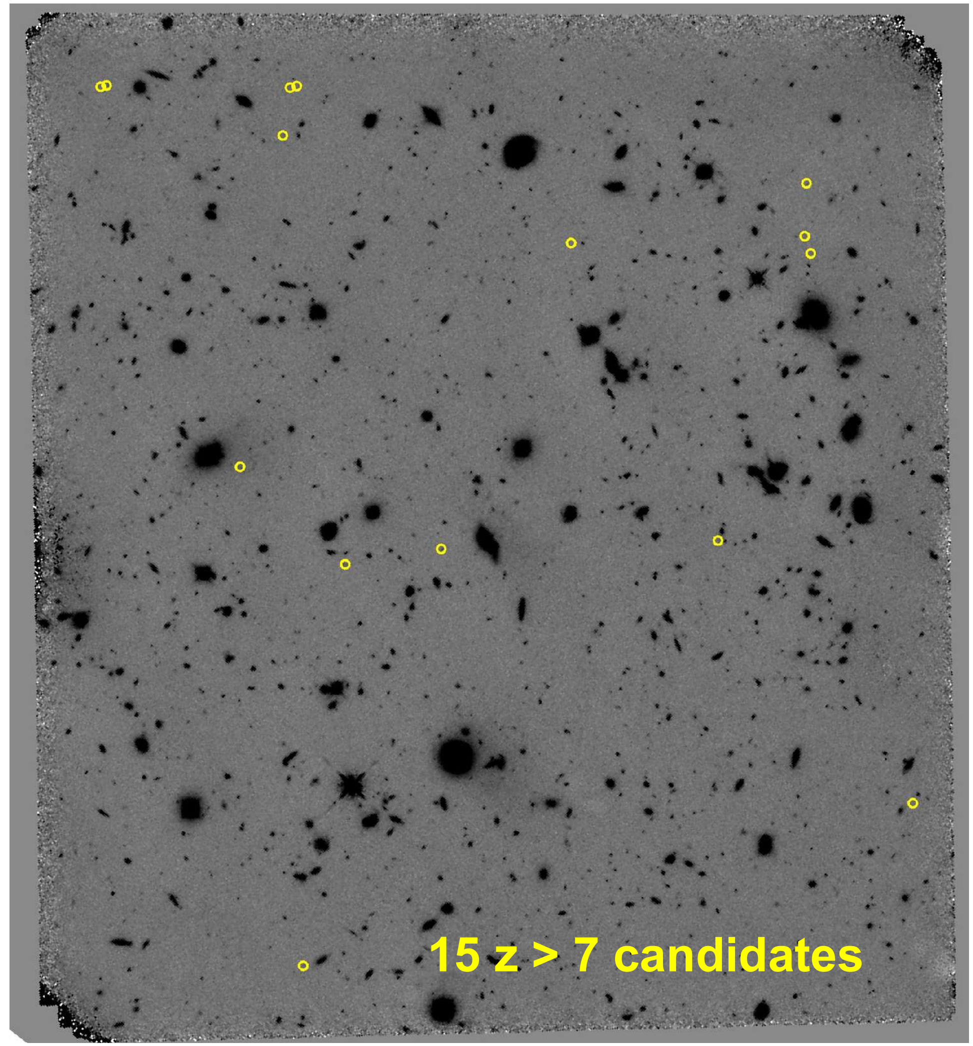
WFC3/IR: 850 - 1170nm
2.1 × 2.3 arcmin field of view
0.13 arcsec $pixel^{-1}$
10 times survey power of NIC3

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
Labbe et al 0910.0838
Bunker et al 0910.1098

z >7 candidates from WFC3 UDF campaign

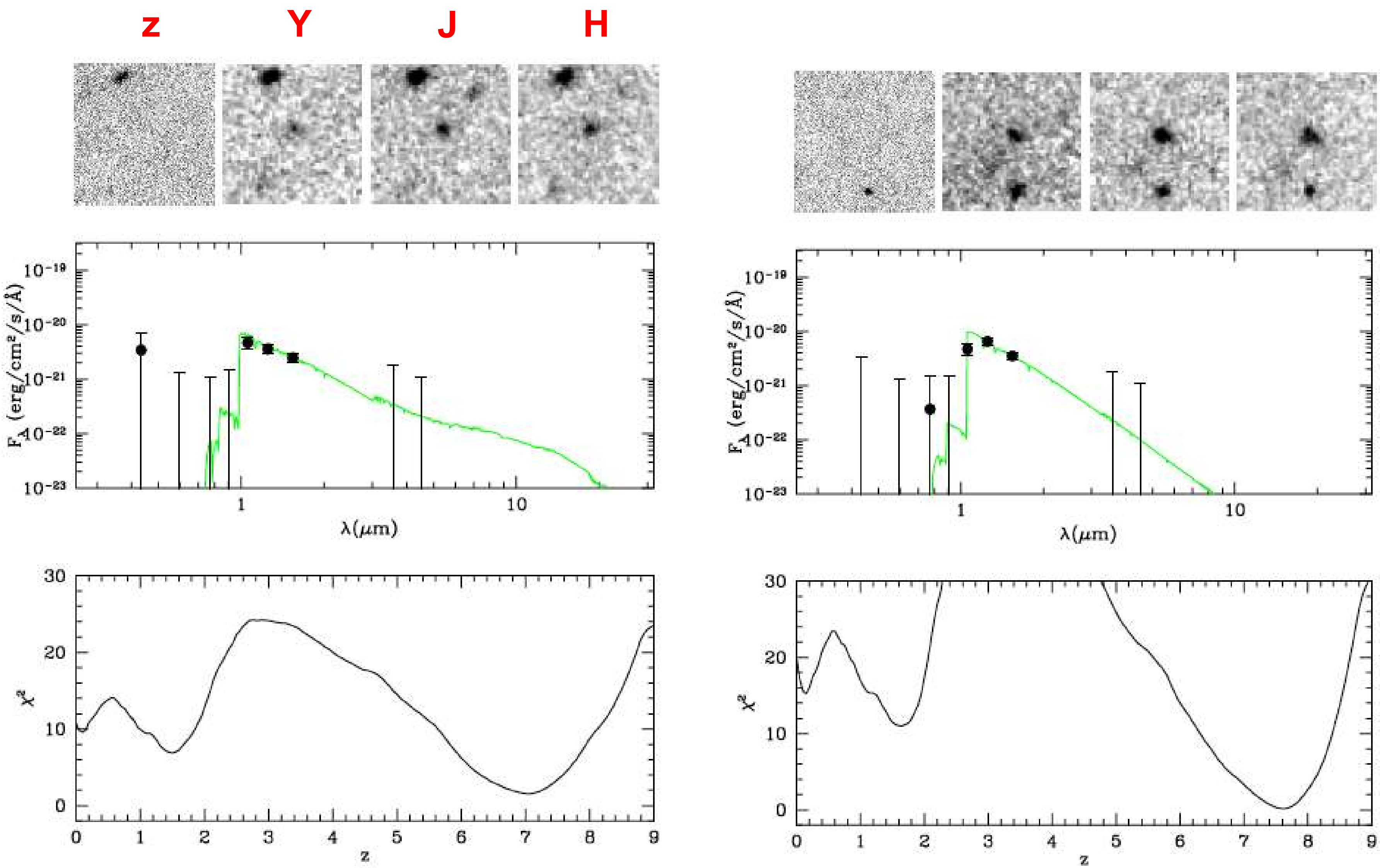




3 IR filters c.f. 2 leads to more secure photometric redshifts and reliable UV continuum slopes

McLure et al (2009)

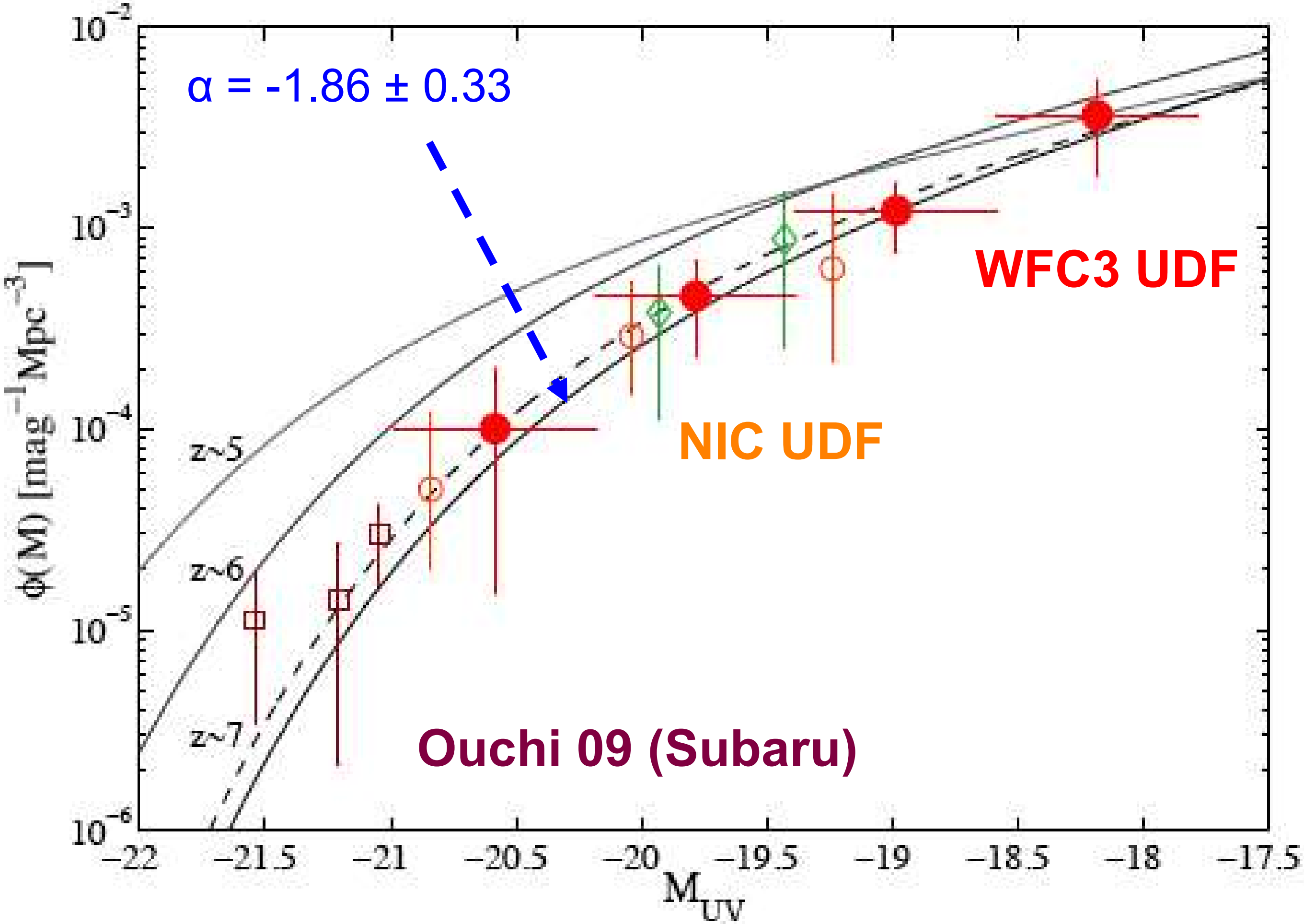
But beware..uncertain redshifts still an issue..



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

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

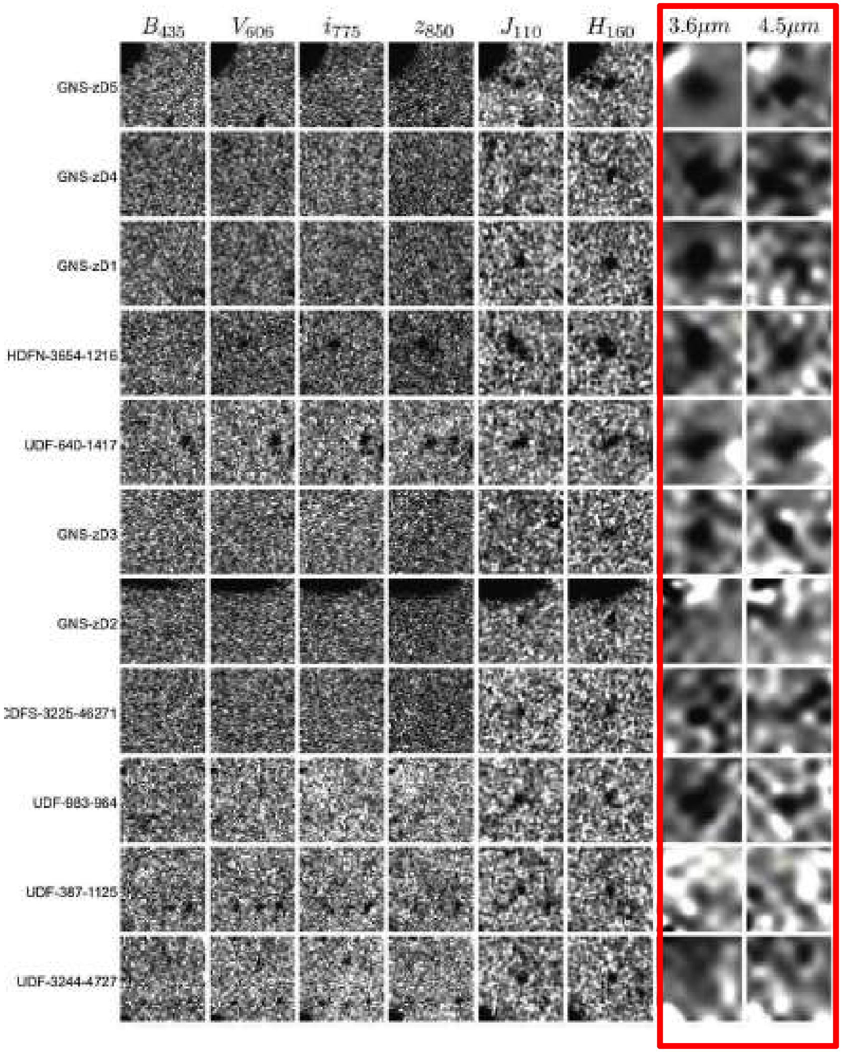
WFC3 Progress – I: z~7 Luminosity Function

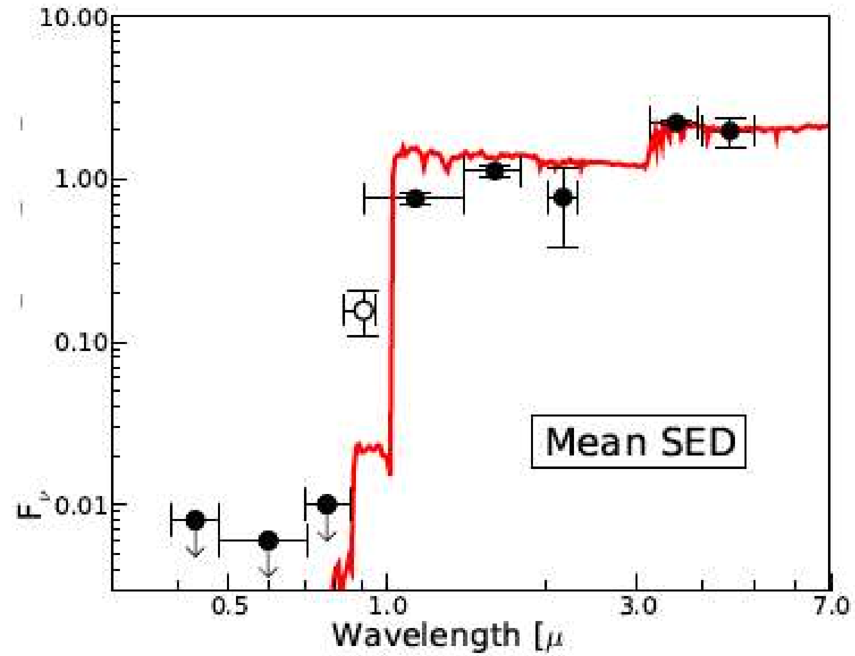


- 10-16 z-band dropouts to Y_{AB}~28.5 corresponding to 6.5<z<7.5
- Towards a reliable faint end slope: low star formers ~1 M yr^{-1} dominant
- Abundance decline of ~×2 since z=6

Oesch et al, Bunker et al 2009

IRAC Detections of Luminous Galaxies @ z~7



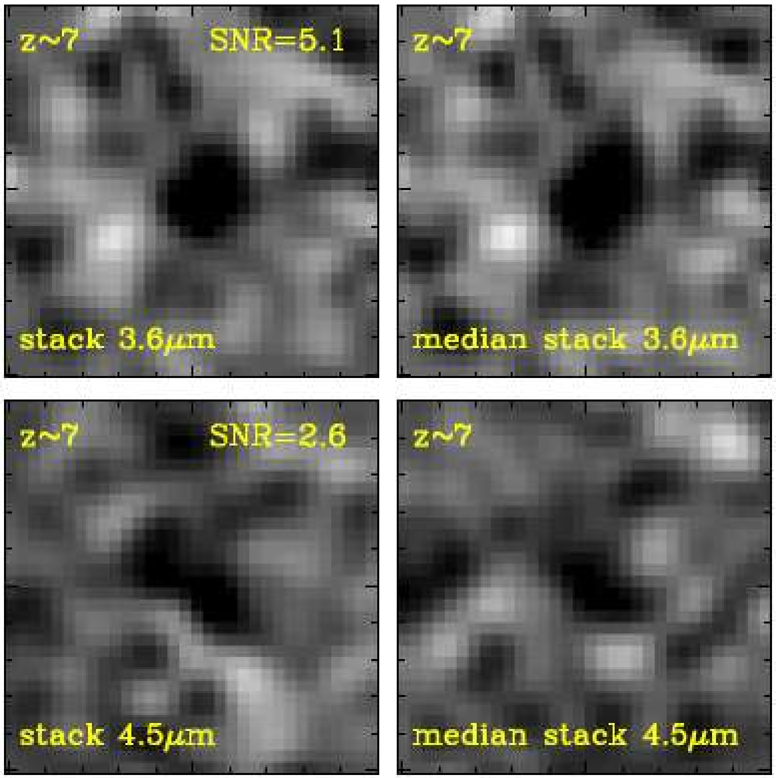


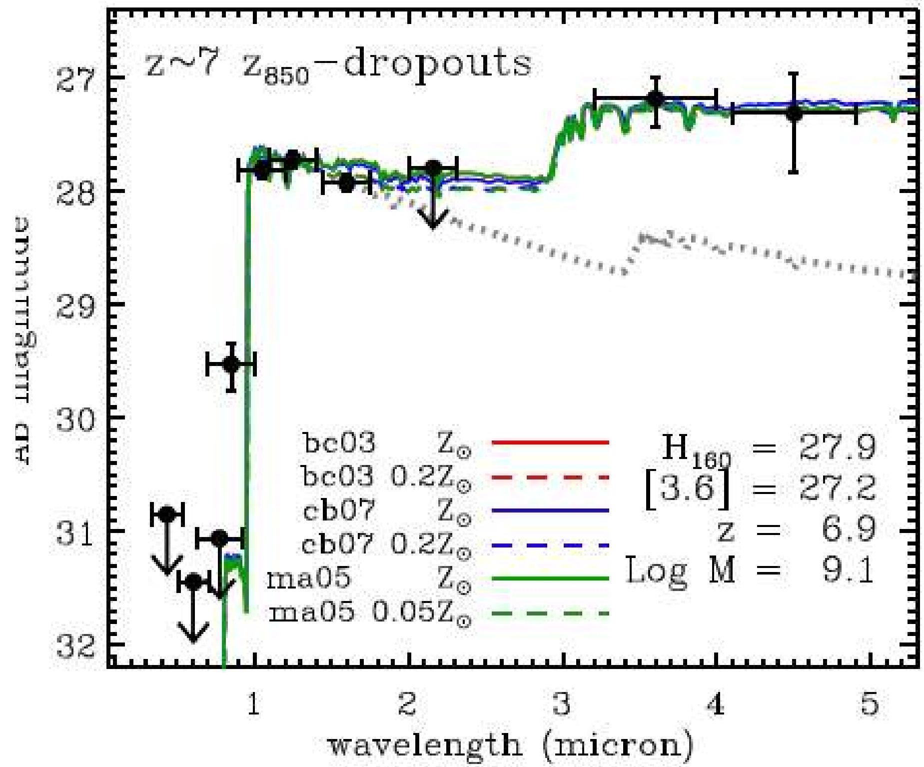
11 objects in GOODS/UDF M<10^{10}
M ages <400 Myr

SF that produced <u>these galaxies</u> likely insufficient for reionization

Gonzalez et al 2009

WFC3 Progress – II: Stellar Mass Density @ z~7

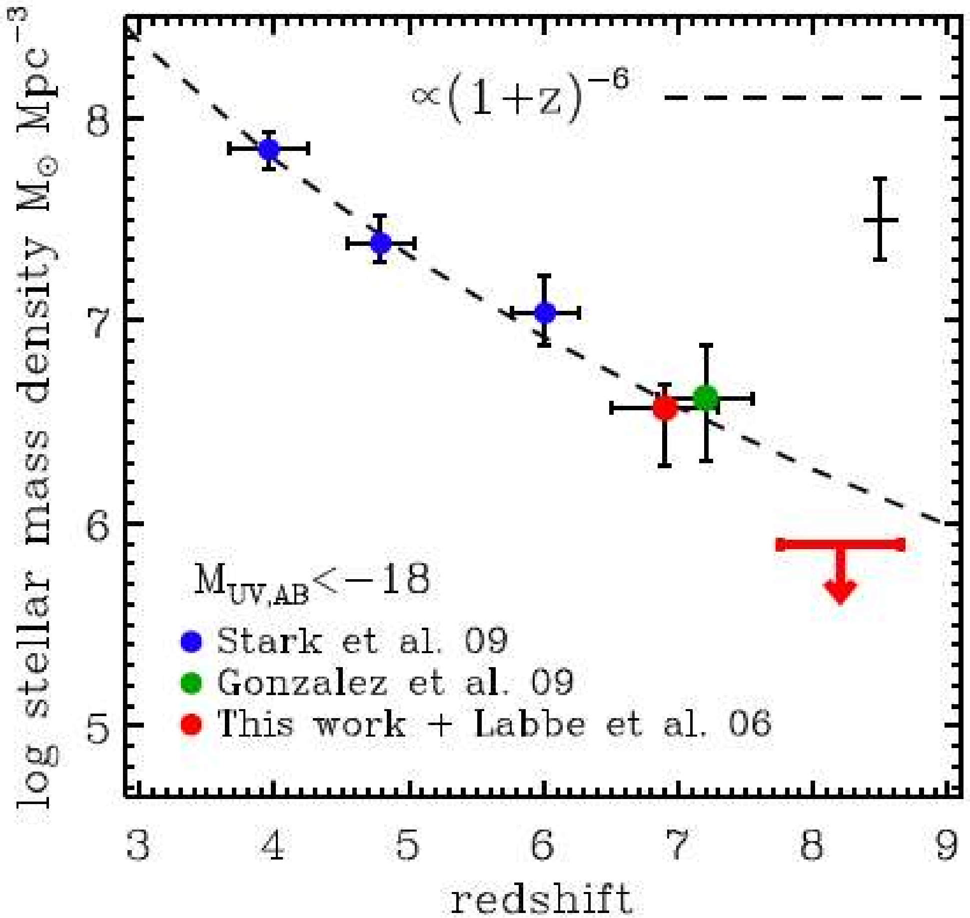




- To complete mass density at z~7 need to probe much fainter
- UDF z~7 candidates only detected in stacked IRAC data (N=12)
    - Highly uncertain but estimate M~10^9 M and ages>100 Myr
- Warm mission should improve constraints significantly

Labbé et al 2009

Did Star Forming Galaxies Reionize the Universe?

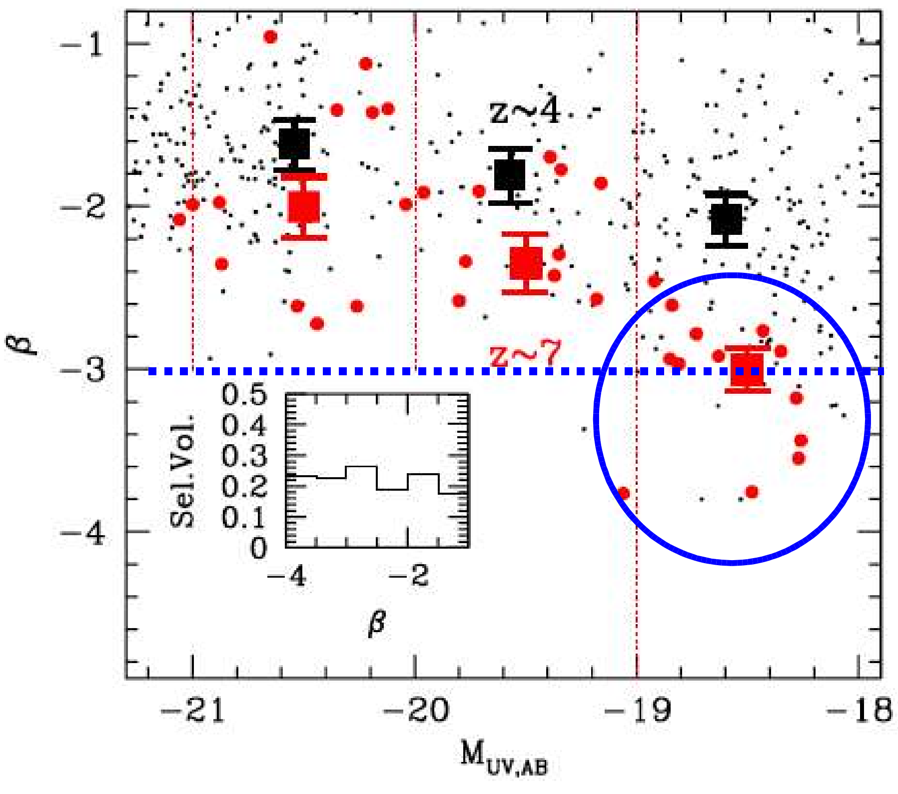


Stellar mass density at z~5-6 (and with greater uncertainty at z~7) implies past SF in low luminosity galaxies may be sufficient for reionization, especially if escape fraction of photons is >0.2

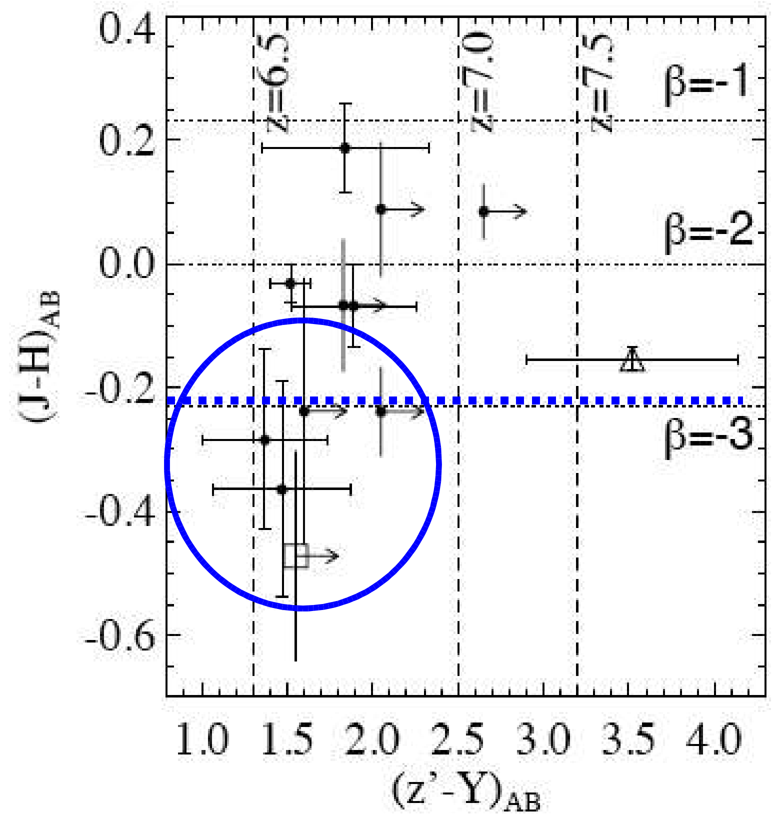
Stark et al 2007,2009; Labbé et al 2009

Unusually Blue UV Continua?

z~7 WFC3 data provides Y+J+H data and thus the first reasonable estimate of the slope β of the stellar continuum where $f(\lambda) \propto \lambda^{\beta}$: remarkably steep values $\beta \rightarrow -3$!

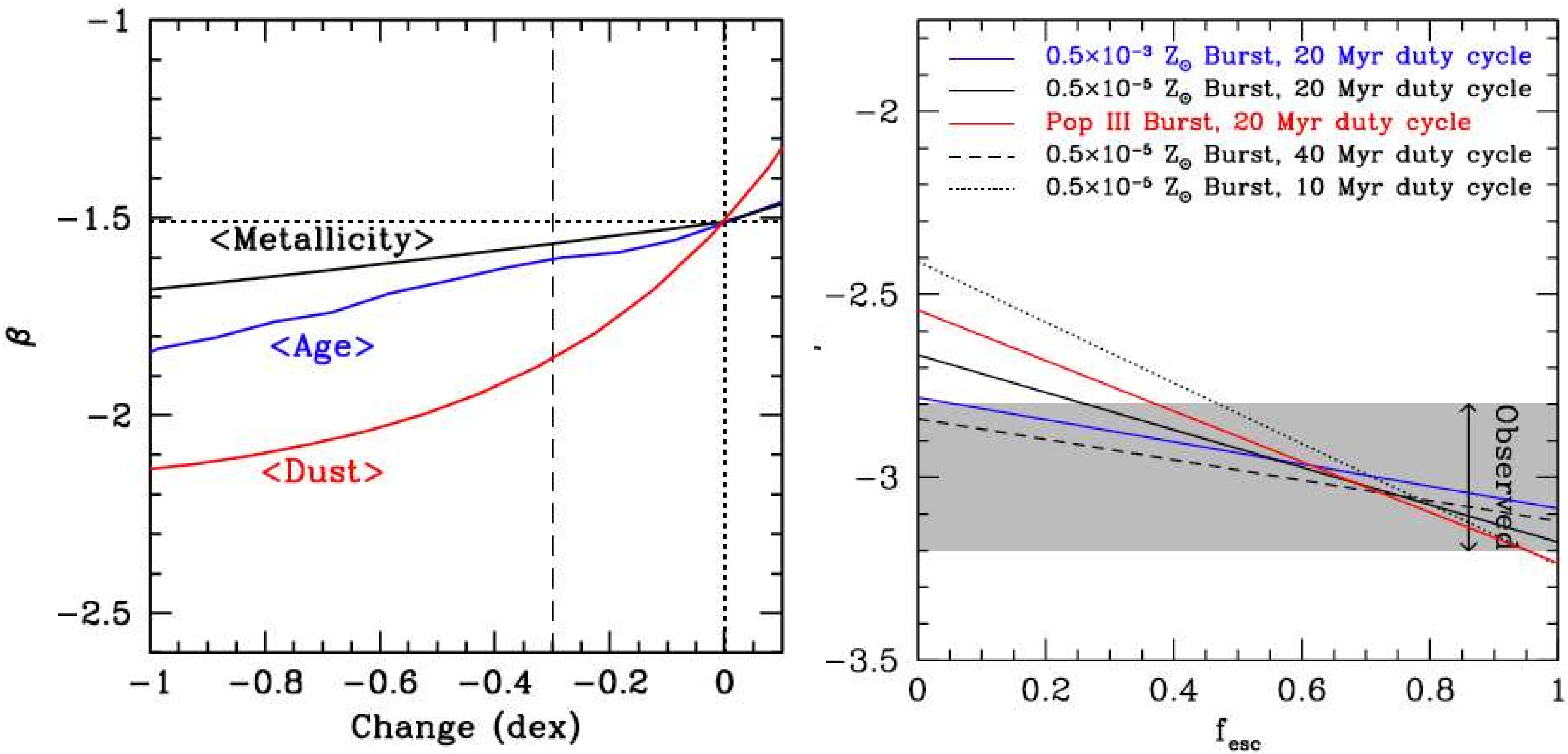


Bouwens et al 2009



Bunker et al 2009

What Might This Mean? (..if correct..)

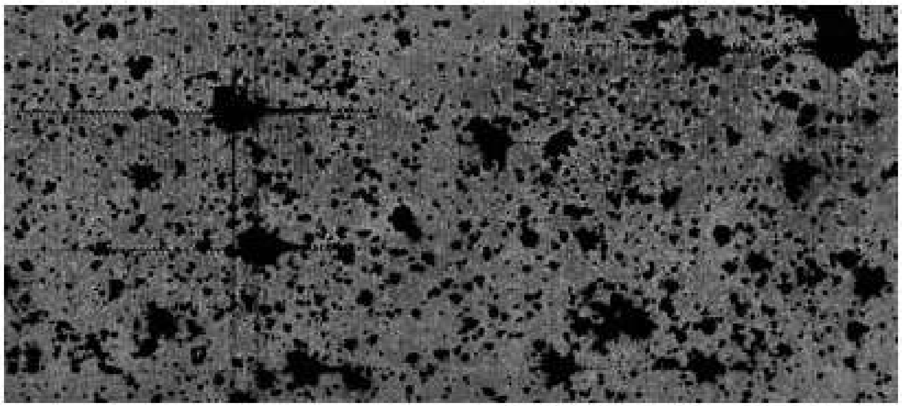


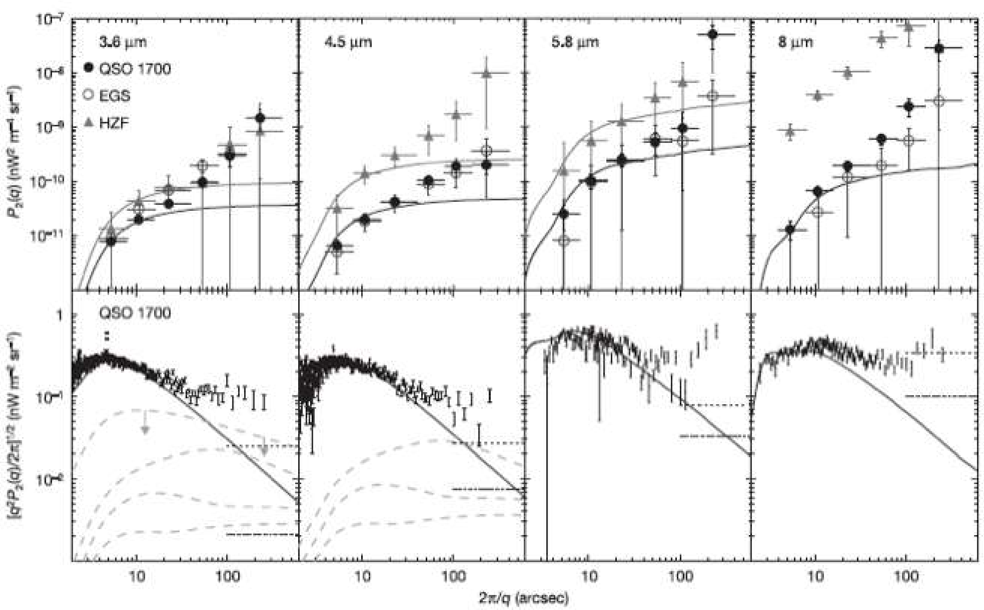
- Can reproduce β > -2.5 with dust-free young stars with Z~0.1Z

- To reproduce β ~ -3 need very low metallicities, extremely young bursts or top-heavy IMF with implied high escape fraction - If verified, strengthens case for reionization from low L galaxies

Status of excess IR Background Fluctuations

Is foregoing inconsistent with earlier claims for detected fluctuations in background light?





- **First detection reported by Kashlinksy *et al*. 2005**, with Spitzer at 3.5 and 4.5 μ m Interpreted as evidence for a z > 8 first-light component responsible for reionization
  (also **Kashlinsky *et al*. 2006** with GOODS)

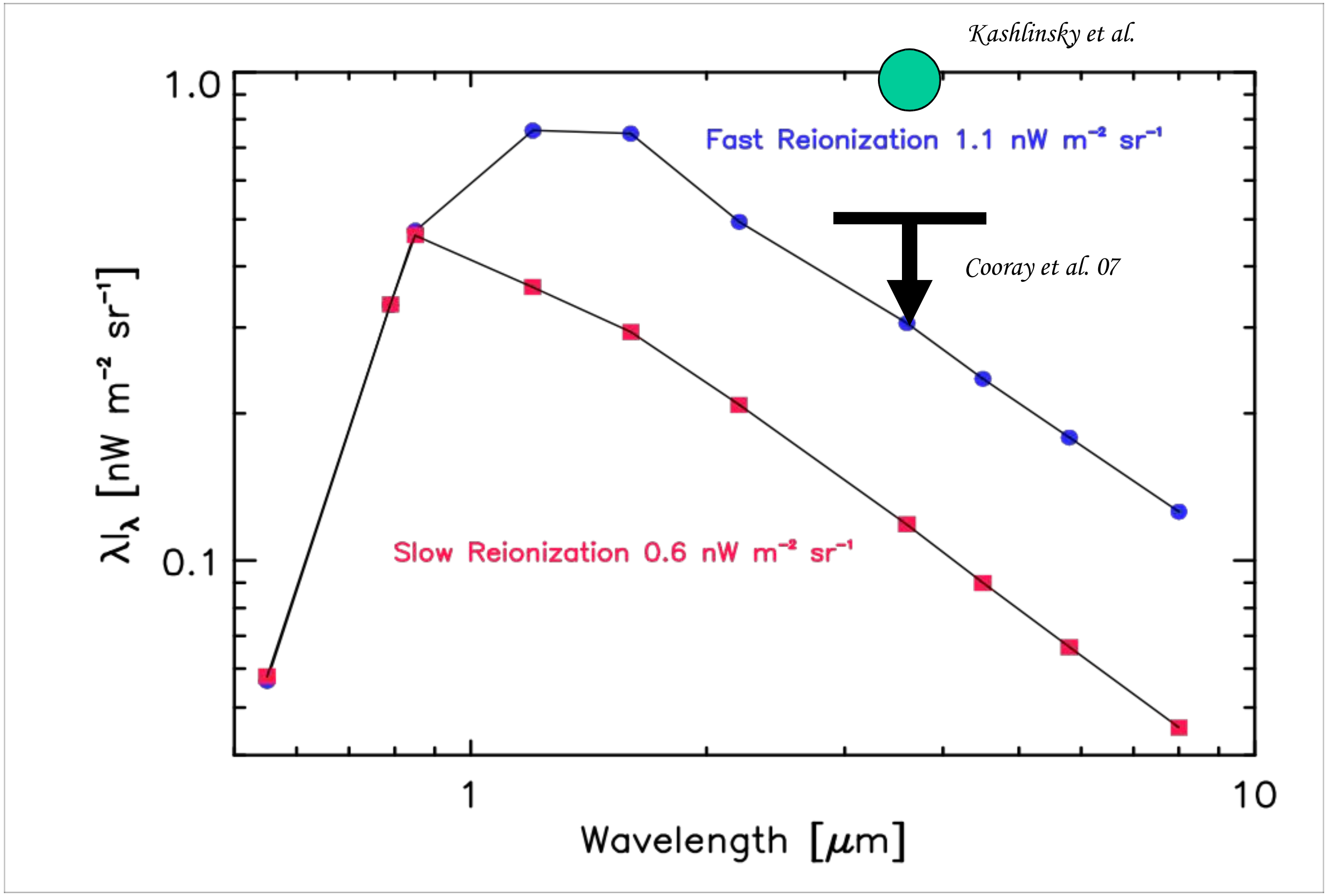
- **Could it be partly due to undetected dwarf galaxies at moderate redshifts of 1 to 3**
  Cooray *et al*. 2006; Chary et al. 2008 using fluctuations in GOODS and a stacking analysis on multi-wavelength ACS data;

- **Thompson *et al*. 2007 report upper limits** with HST/ NICMOS, which are argued to be inconsistent with Kashlinsky interpretation for z > 8 sources

Kashlinksy et al 2005

Expected near-IR EBL from reionization

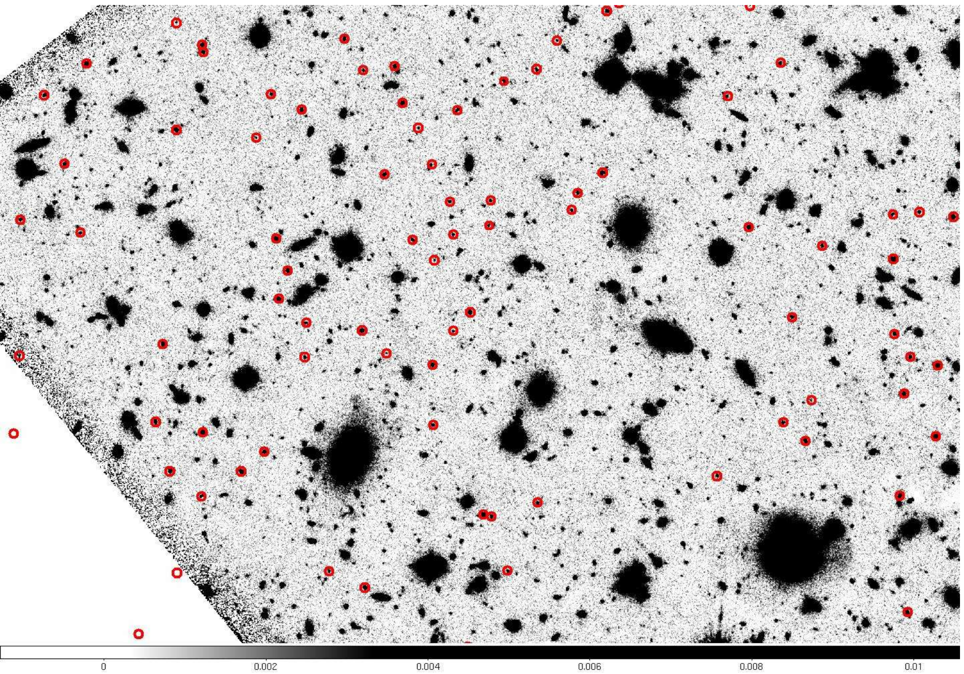
Reionization models matched to WMAP 5-year; two extreme histories with source counts matched to bright-end LBG LFs in UDF

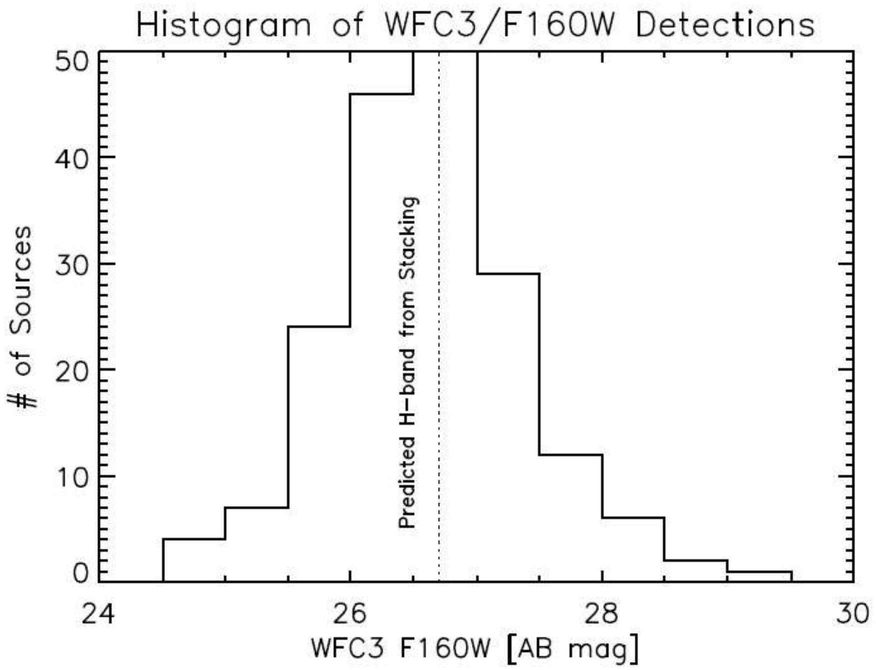


Cooray et al argue Kashlinky et al's fluctuations arise from low L z~2 sources

Check using new deep WFC3/UDF data

To explain contamination in Kashlinky et al signal: need a sizeable z~2 dwarf galaxy population with H~27





Scarlata, Chary & Koekemoer 2009

Conclusions & Future Prospects

- This is an exciting time in the study of z>5 galaxies with Spitzer 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
- With individual diagnostics objects, Spitzer continues to play a key role
- WFC3 has led to a flurry of recent conclusions (past 6 weeks!): galaxies may not maintain reionization over 7<z<10 as WMAP requires unless:
    - dominant fraction of sub-luminous galaxies
    - increased escape fraction
    - tantalizing evidence for both in early data!
- Crucial to fully exploit IRAC in warm mission in concert with WFC3 – legacy of JWST/ELT targets