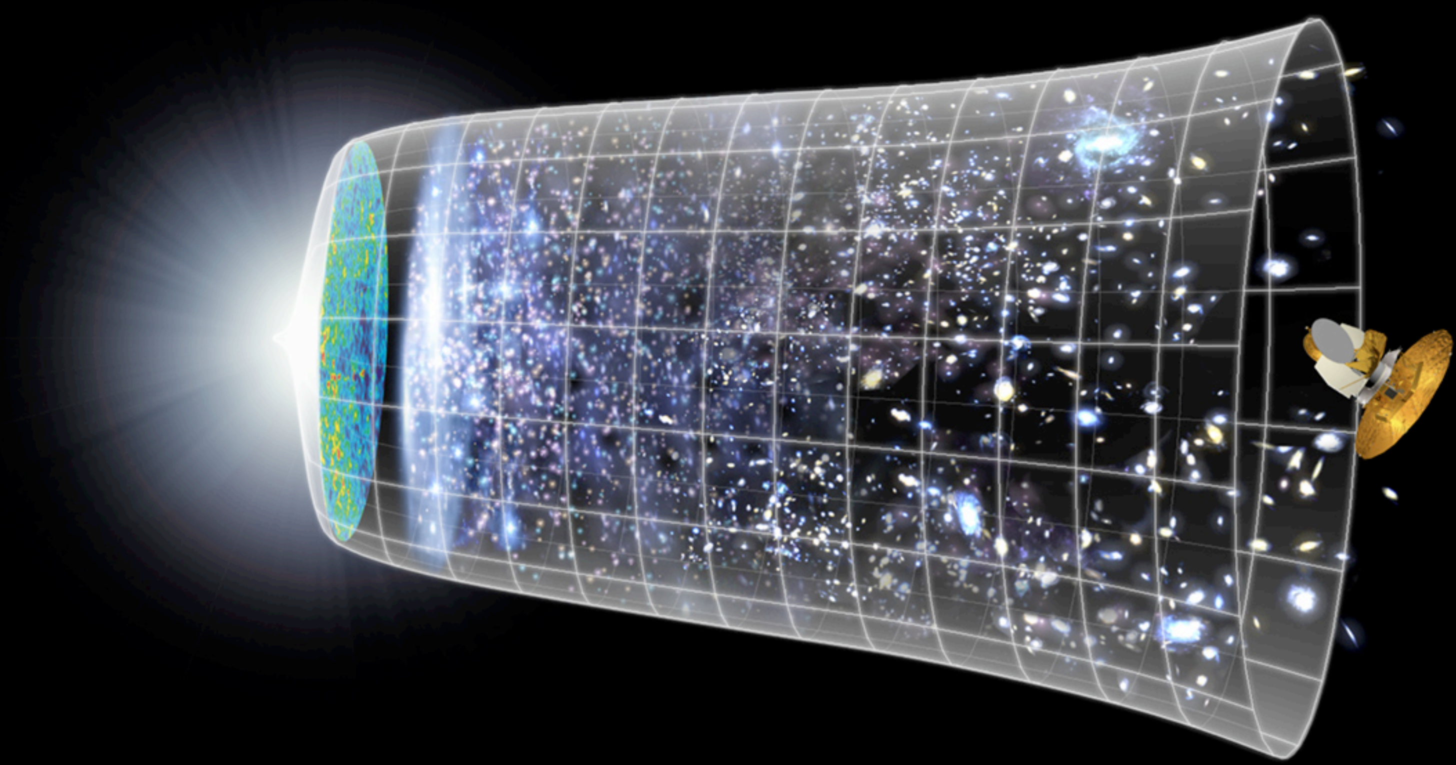
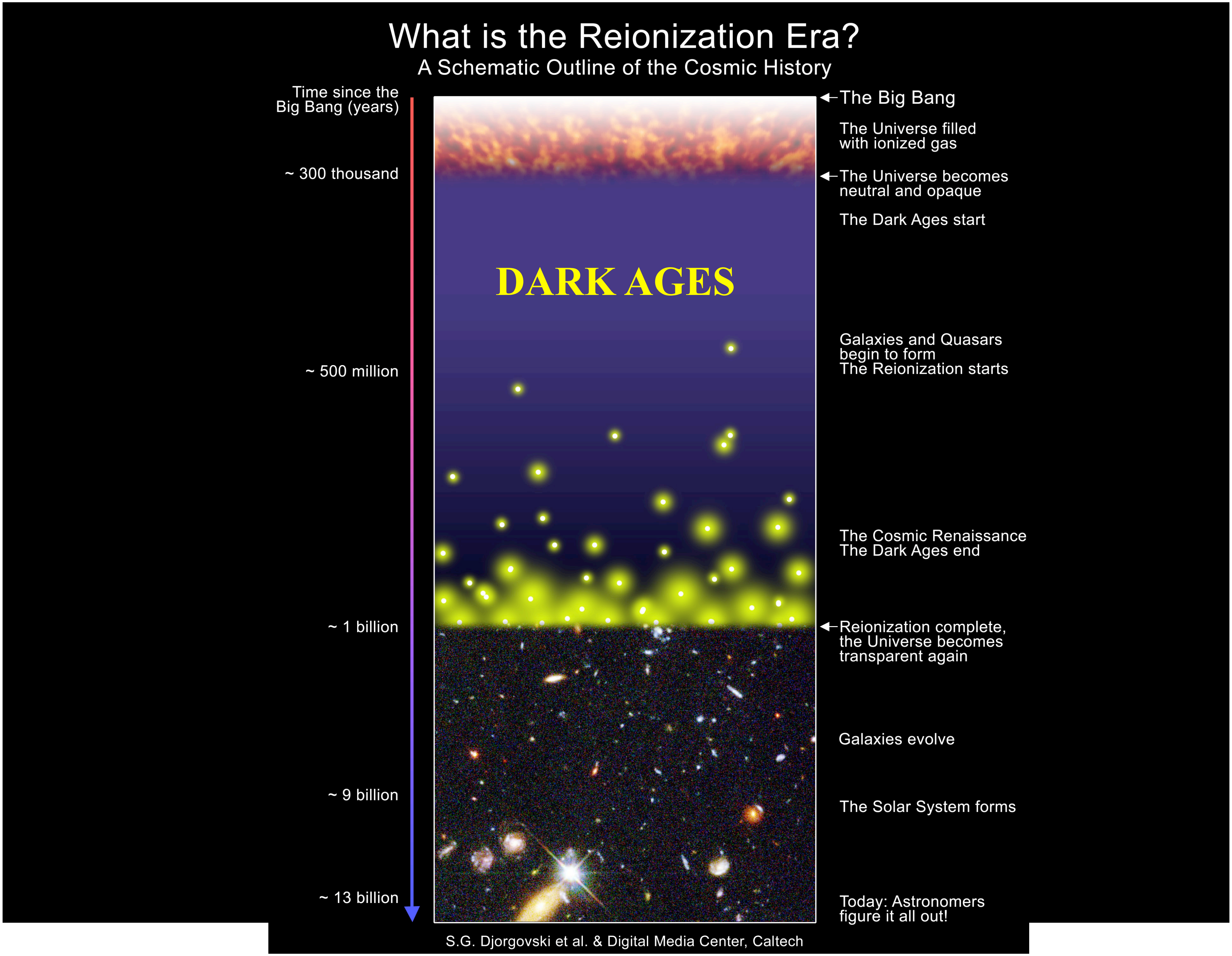
Witnessing the End of Cosmic Reionization

Ay211



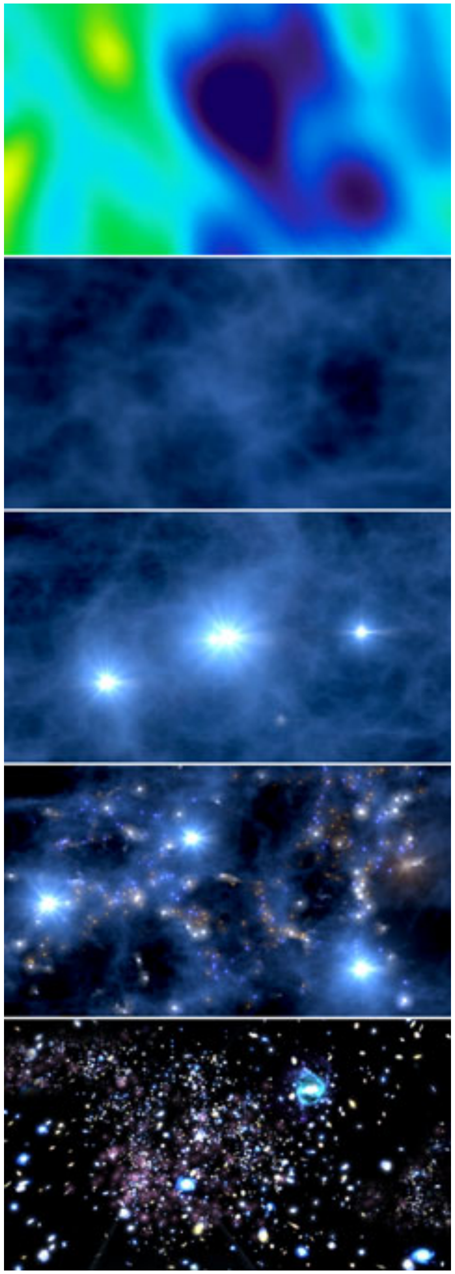
Lecture is on http://www.astro.caltech.edu/~rse/ay211_reioniz.ppt

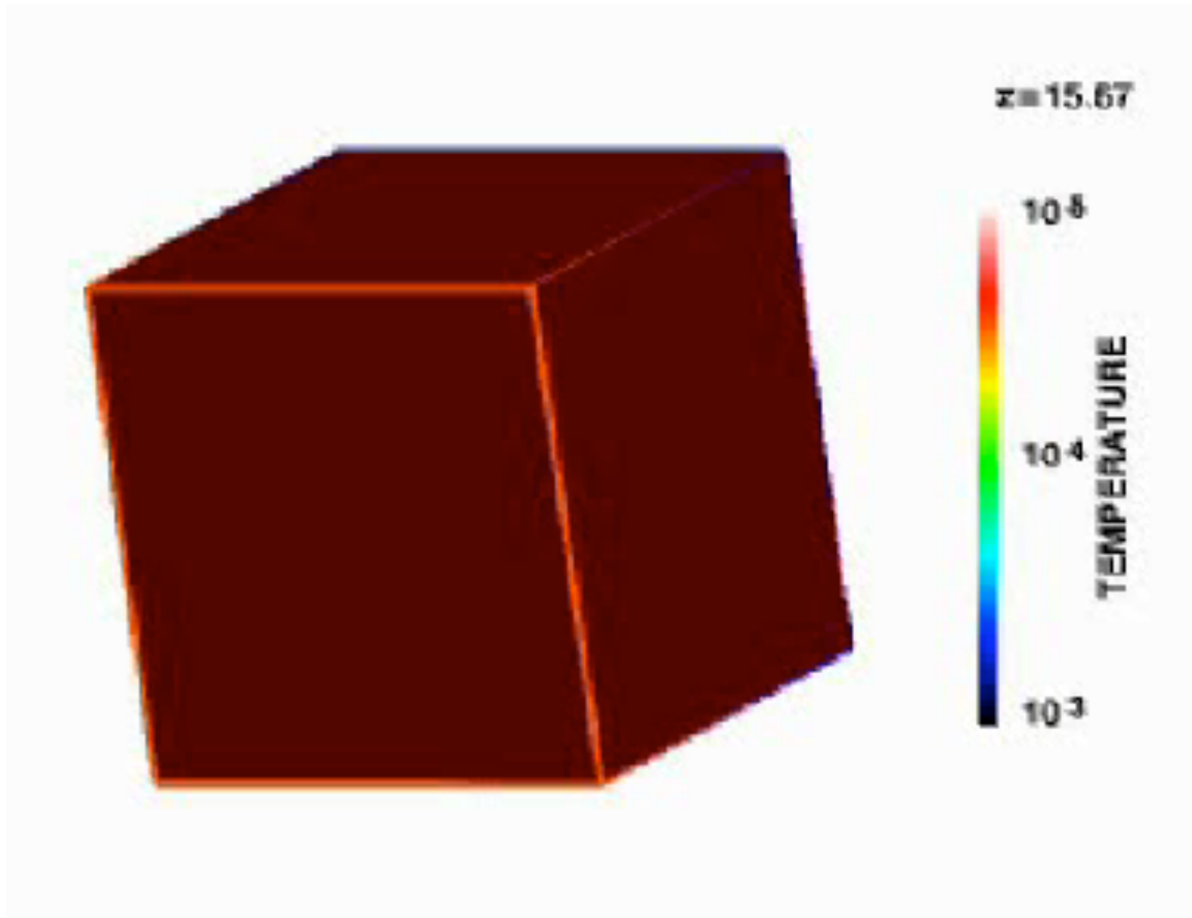
NASA/WMAP Science Team


What is the Reionization Era?
A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
DARK AGES
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

End of the Dark Ages:

Reionization of Hydrogen by First Star-forming Galaxies





time

Courtesy: Nick Gnedin

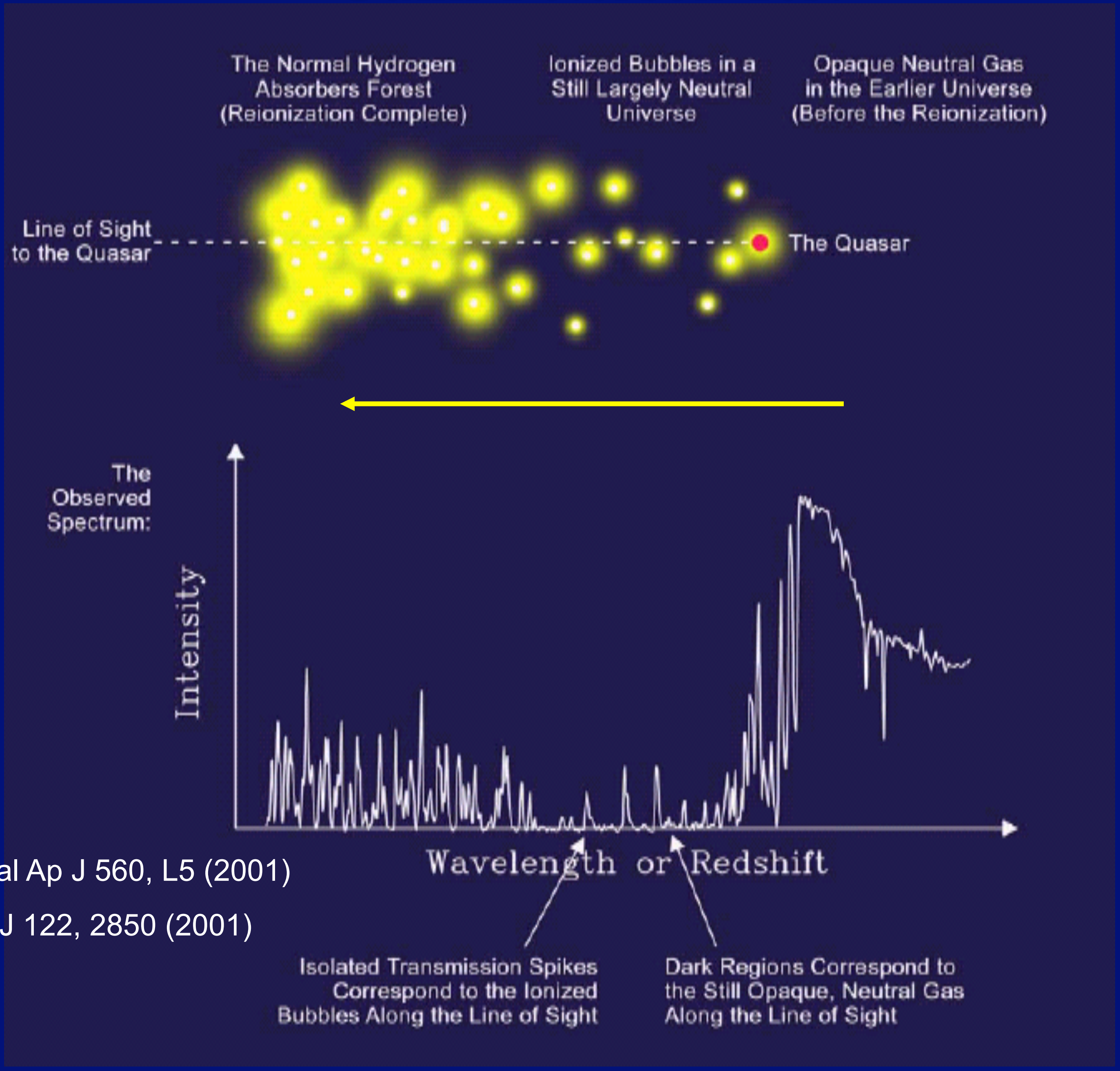
Clues to the End of Cosmic Reionization

- Evolution in the optical depth of Lyα absorption in high redshift QSOs (Fan et al AJ 131, 117, 2006; Fan et al ARAA 44, 415, 2006)
- Metals in the intergalactic medium (Songaila AJ 131, 24 2006; Ryan-Weber et al MN 395, 1476 2009)
- Large angular scale power in the temperature-polarization cross-correlation function in the CMB (Dunkley et al Ap J Suppl, 180, 306 2009)
- Assembled mass density at z~5-6 from HST/Spitzer probes of faint galaxies (Eyles et al MNRAS 374, 910, 2007; Stark et al Ap J 659, 84, 2007; Stark et al Ap J 697, 1493 2009)
- Rapid evolution in the Lyman alpha luminosity function $5.7 < z < 6.5$ (Kashikawa et al Ap J 64, 7, 2006, Ouchi et al 2009 in prep)

These motivate us to search the era $z > 7$ for star forming sources

First results from WFC3/IR on Hubble Space Telescope

Gunn-Peterson Test



Djorgovski et al Ap J 560, L5 (2001)

Becker et al AJ 122, 2850 (2001)

SDSS QSOs (2003)

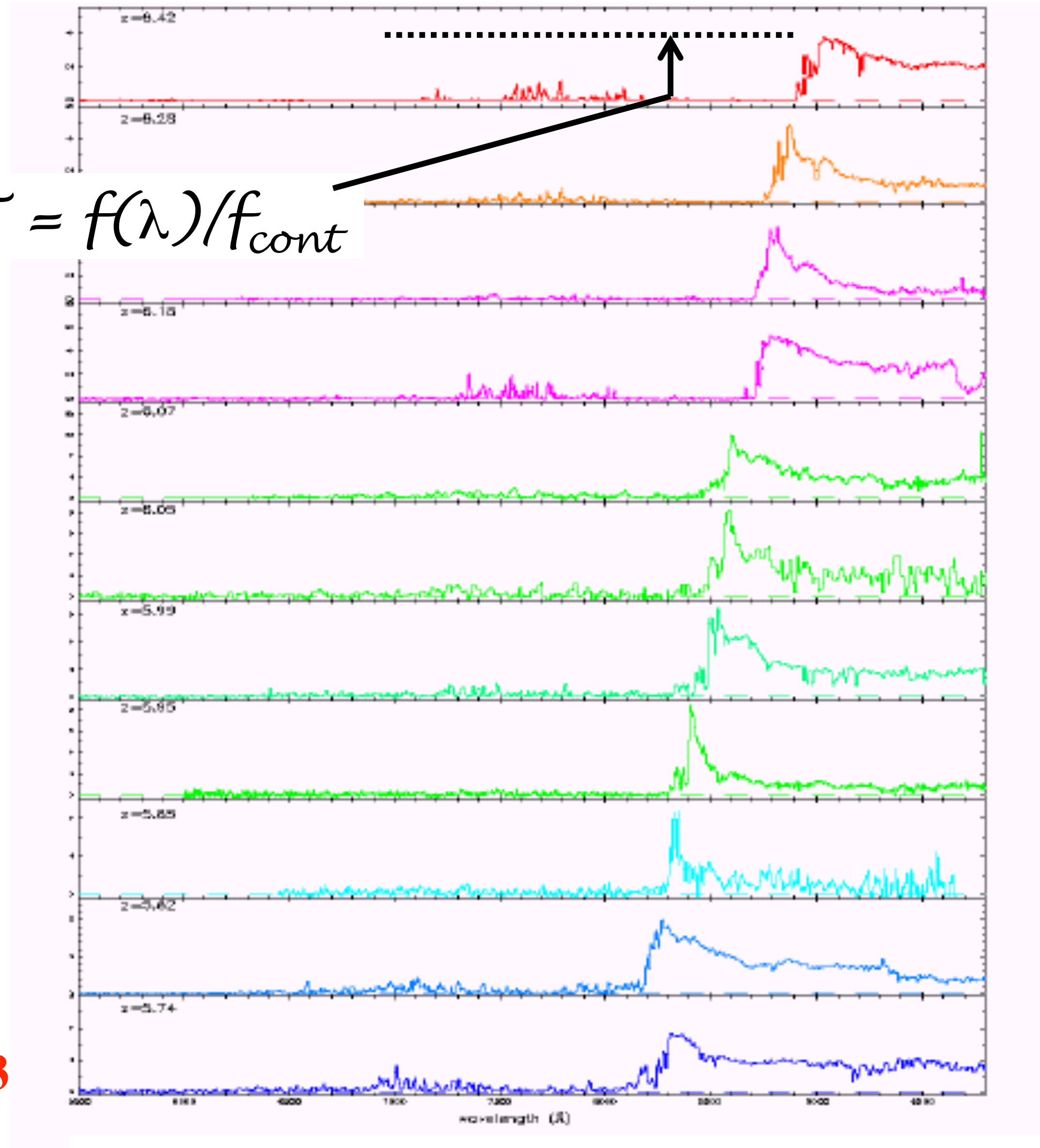
Cosmic variance along available sightlines

$\tau_{GP} = -\ln \mathcal{T}$

Do complete troughs mean reionization just ended at z=6.2?

Or is it just natural thickening of the forest as we move to higher z?

Clue: as we approach end of reionization we expect abrupt change in optical depth τ_{GP} with z



11 SDSS QSOs

Fan et al AJ 125, 1649 2003

SDSS QSOs (2006)

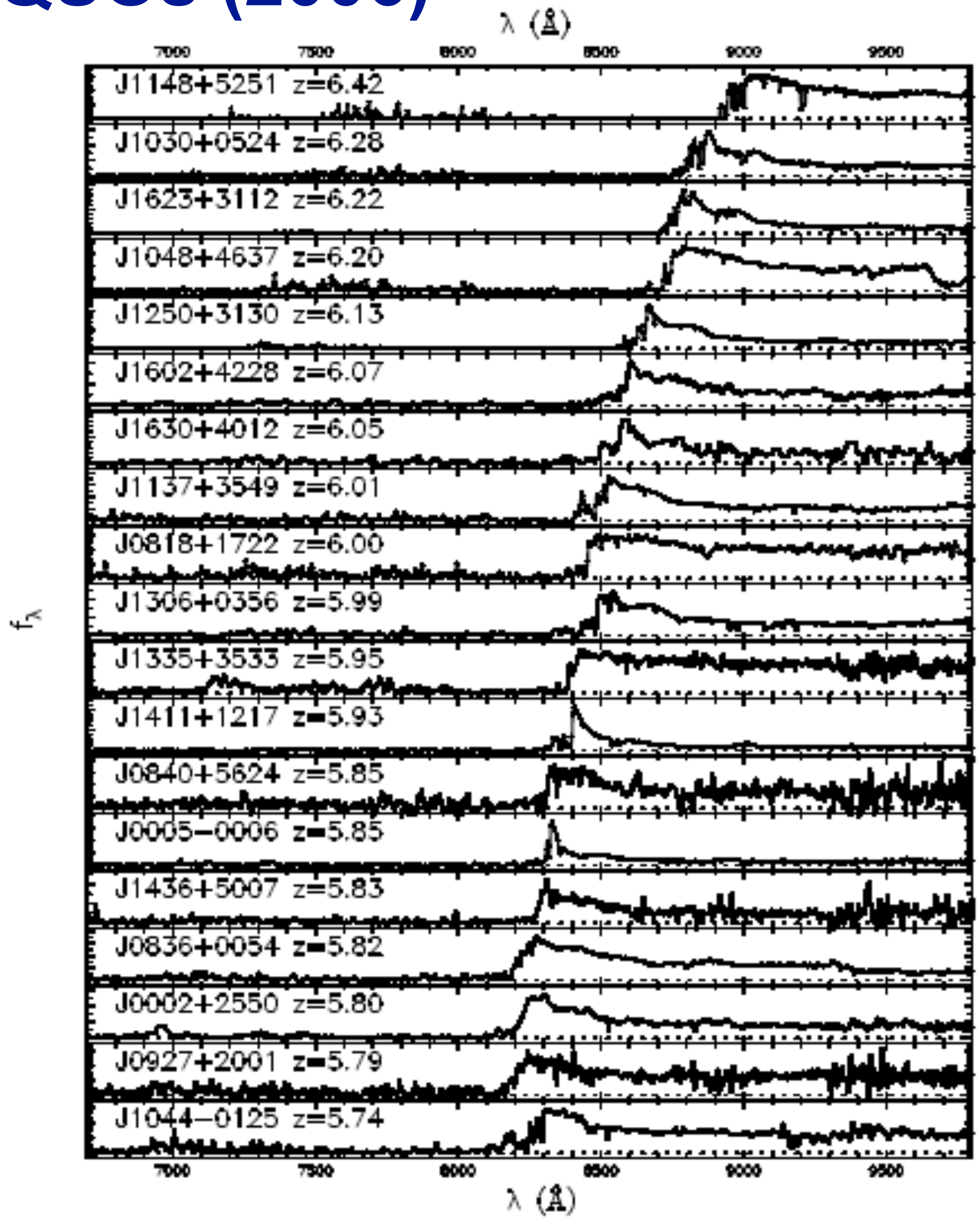
SDSS i-z colors in 6600 deg^2 used to locate 19 QSOs with 5.74<z<6.42

Combined analysis of Lyα,β,γ opacity used to verify $\tau_{GP}(z)$:

Wavelength ranges:

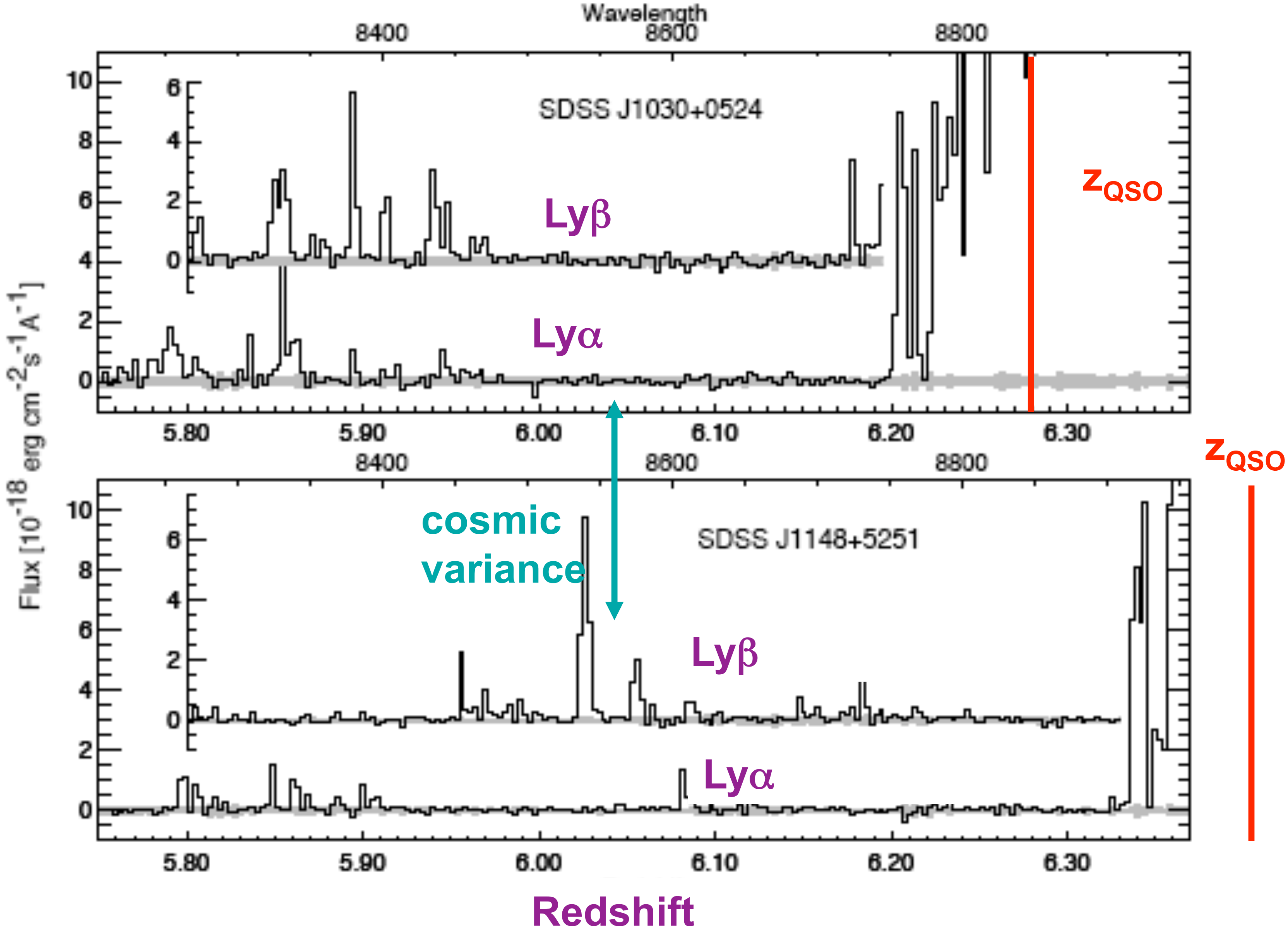
Lyα: 1040 < λ (Å) < (1216)
Lyβ: 970 < λ (Å) < (1040)
Lyγ: 949 < λ (Å) < (970)

( ) - region affected by QSO ionization (proximity effect) excluded



Fan et al AJ 132, 117, 2006

Using Ly α & Ly β together



How GP effect works

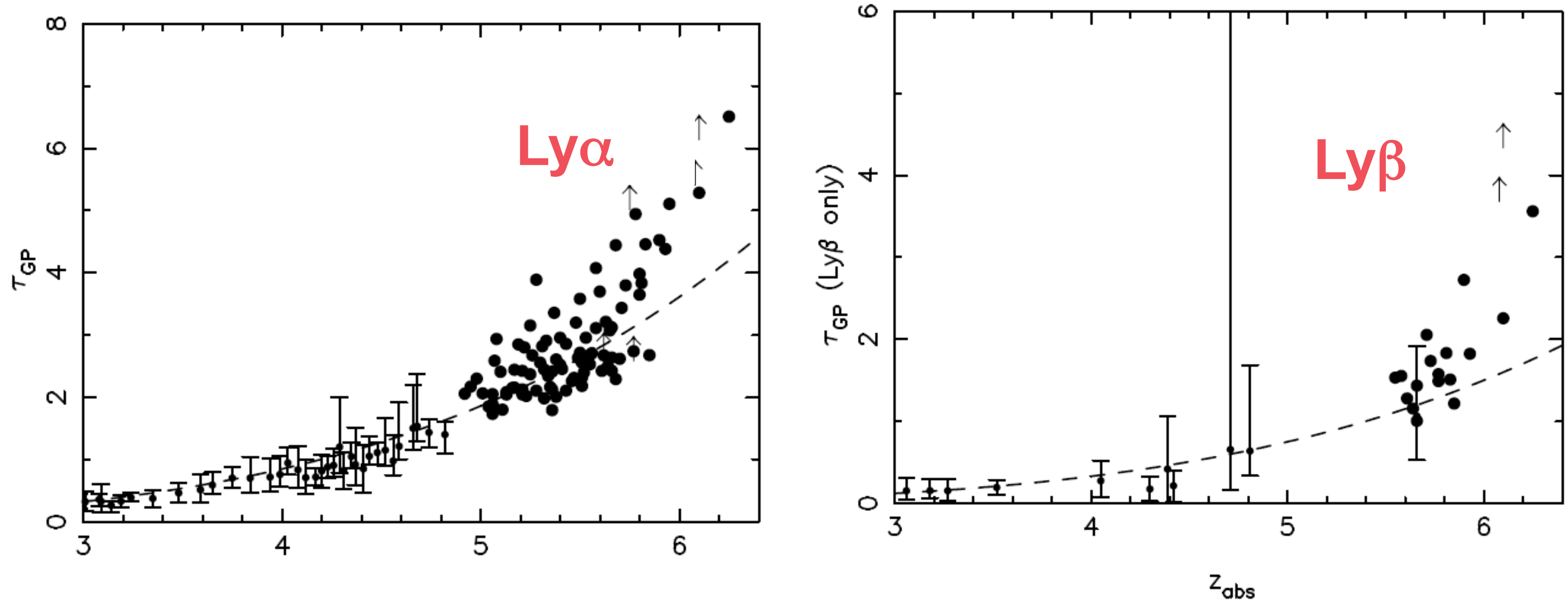
$$\tau_{\rm GP} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z) n_{\rm HI}$$

$$\tau_{\rm GP}(z) = 1.8 \times 10^5 h^{-1} \Omega_m^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{\rm HI}}{n_{\rm H}}\right)$$

neutral fraction $x_{\rm HI}$

- So even tiny neutral fraction $x_{\rm HI}$~10^{-4} gives a complete GP trough
- For reference $x_{\rm HI}$~10^{-5} at z~0
- But since $\tau_{\rm GP} \propto f\,\lambda$, for same $n_{\rm H}$, τ(Lyβ), τ(Lyγ) are <6.2,<17.9 smaller
- In practice, conversion from $\tau \rightarrow n_{\rm HI}$ depends on IGM clumpiness
- So absolute comparison of higher order Lyman lines more complicated than identifying relative trends in each

Comparing τ(Lyα) and τ(Lyβ)



Empirical argument; discontinuity seen in both samples:

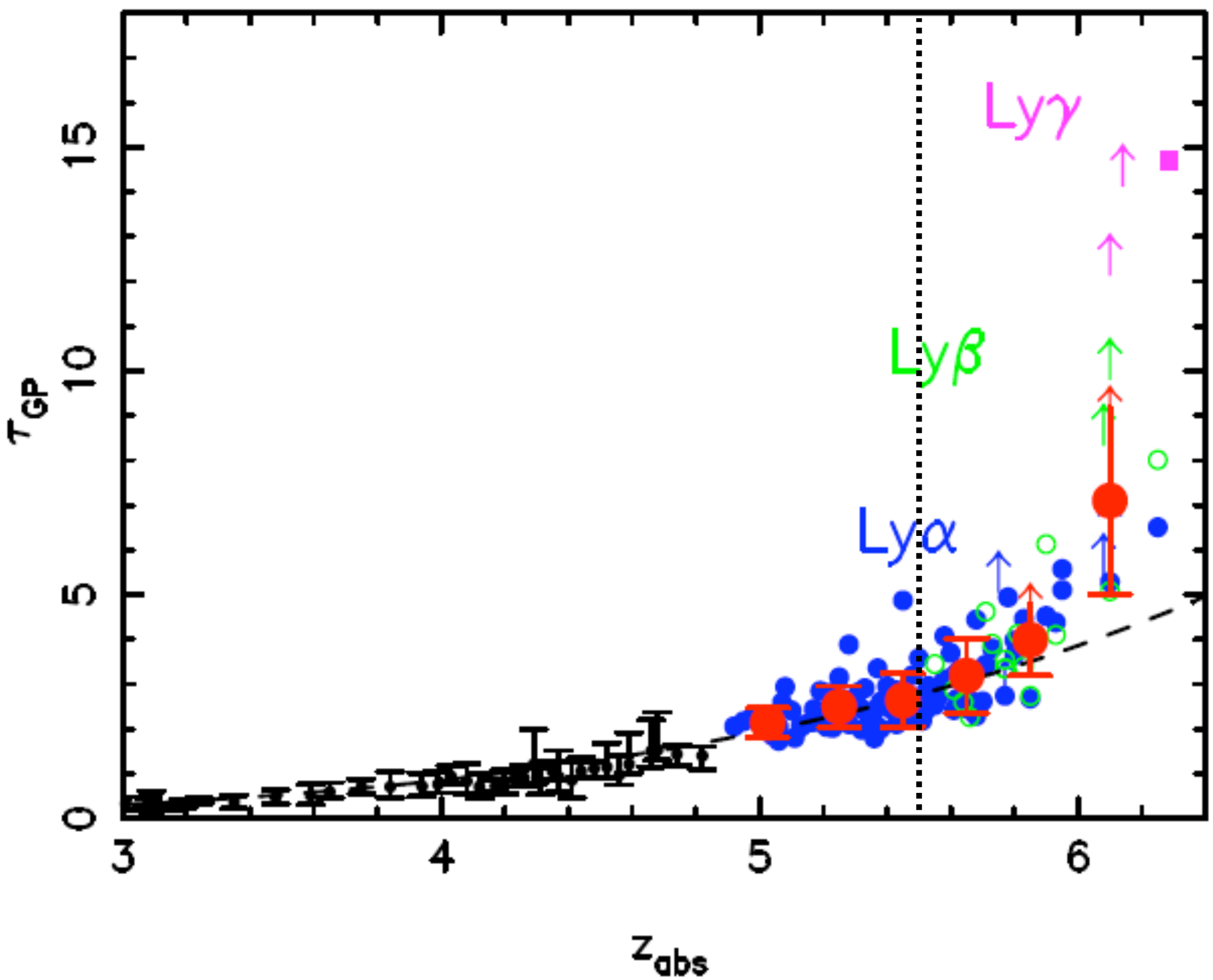
For z<5.5 $\tau(\alpha) = 0.85[(1+z)/5]^{4.3}$; $\tau(\beta) = 0.38[(1+z)/5]^{4.3}$

Data for z > 5.5 is inconsistent: $\propto (1+z)^{10.9+}$

Dispersion increases likewise: $\sigma(\tau)$ from 0.3→0.6

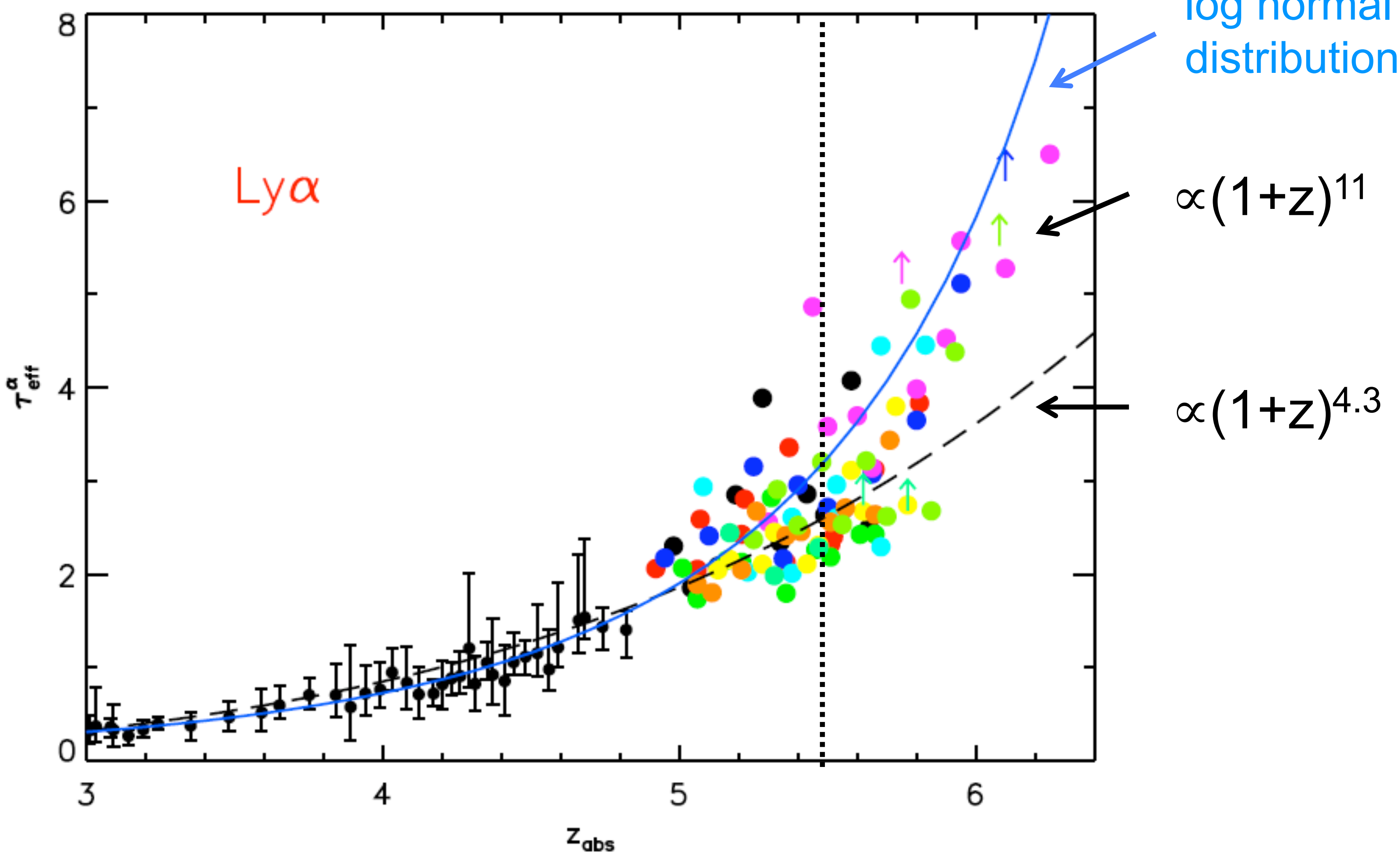
This is the fundamental justification for the end of reionization

Combined Trend in $\tau_{GP}(z)$



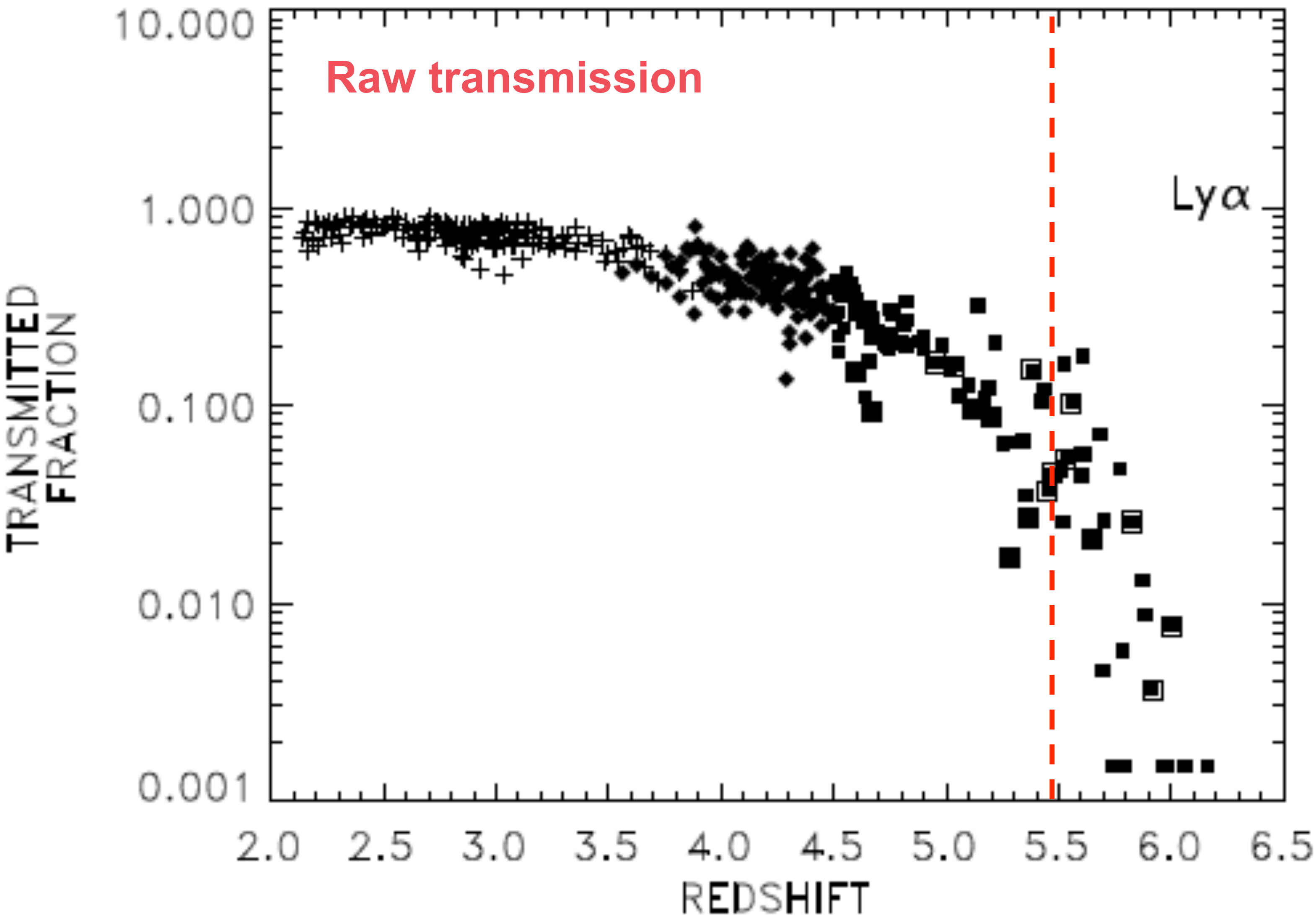
Fan et al (2006): Combining the higher order Lyman lines on an absolute scale is hard

Trend in $\tau_{GP}(z)$



Becker et al Ap J 662, 72 (2007) show the strength of any discontinuity depends on the (unknown) form of the distribution function $P(\tau)$
For a log-normal P there is no apparent discontinuity.

Is there really a break at z ~5.5?



Summary of the G-P Issues

Optical depth τ is not very sensitive to ionized fraction

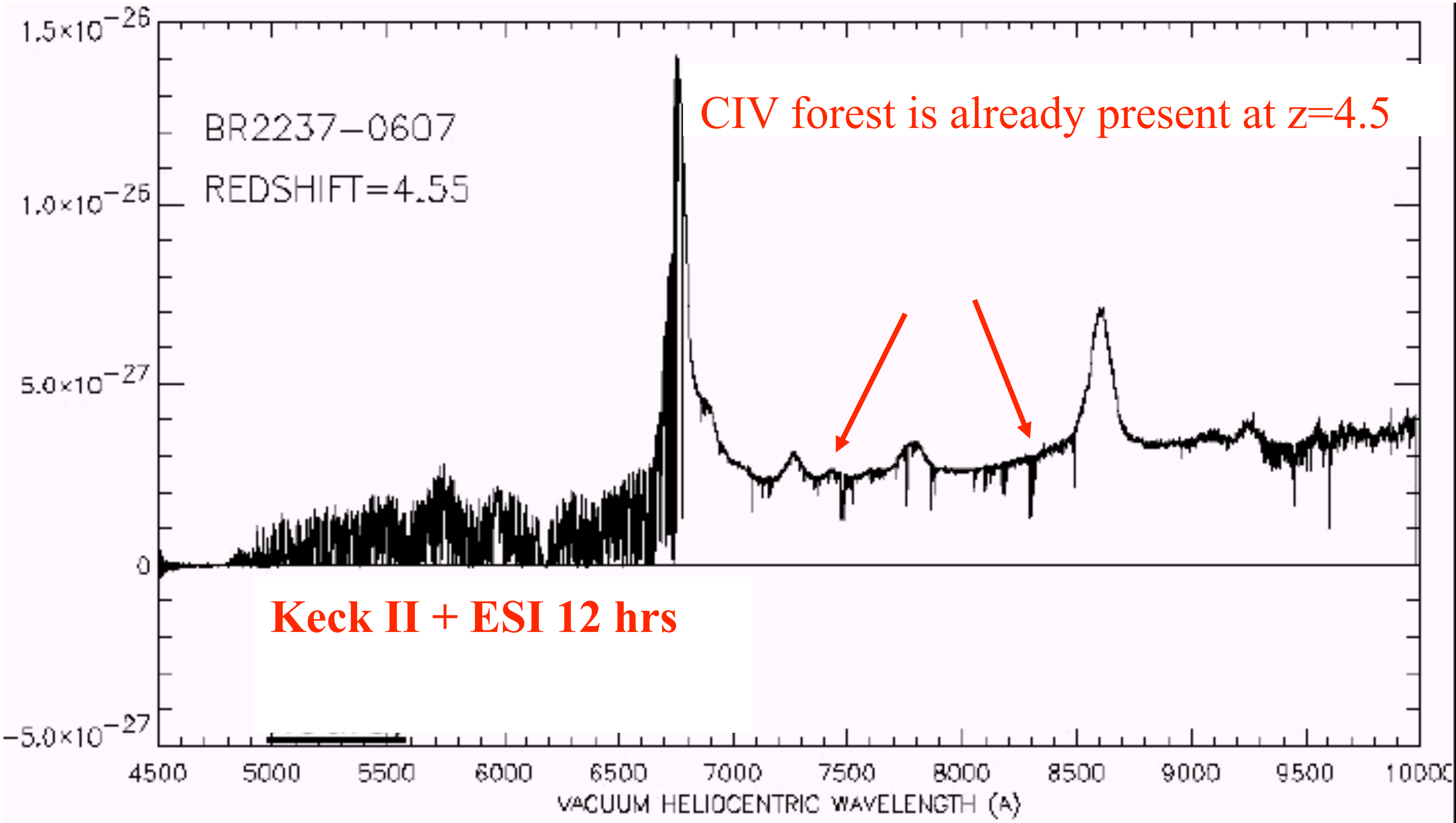
Key issue is <u>rate of change</u> in $\tau(z)$: this distinguishes reionization (overlapping HII regions) from thickening in forest: do we see a break in trends as we approach $z>6$?

Geometry important: knowing UV background can we directly infer sizes of Stromgren spheres at various z?

Line of sight fluctuations and statistics of `dark gaps' contains information on topology of late stages

Are some lines of sight at $z>6$ still consistent with large neutral fraction?

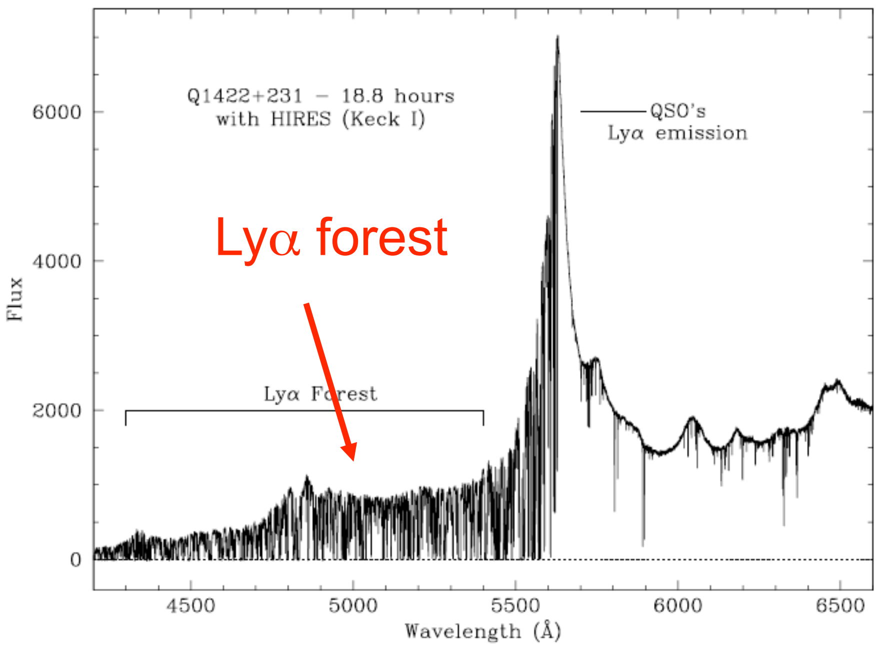
Metallicity of the Intergalactic Medium

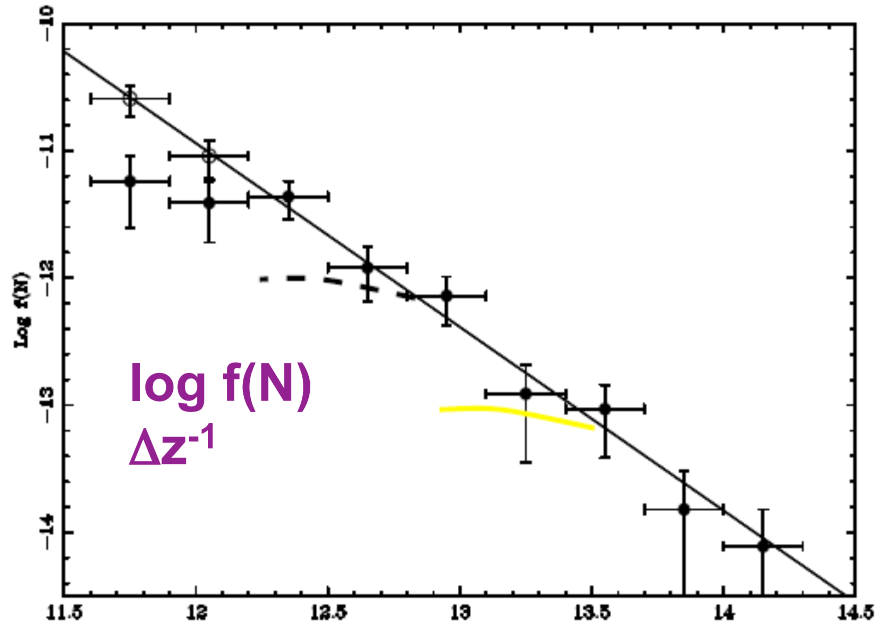


Ubiquity of CIV in many sight-lines to z~5 indicates earlier SF

Songaila & Cowie (AJ 123, 2183, 2002)

Carbon is also present in Ly α Forest





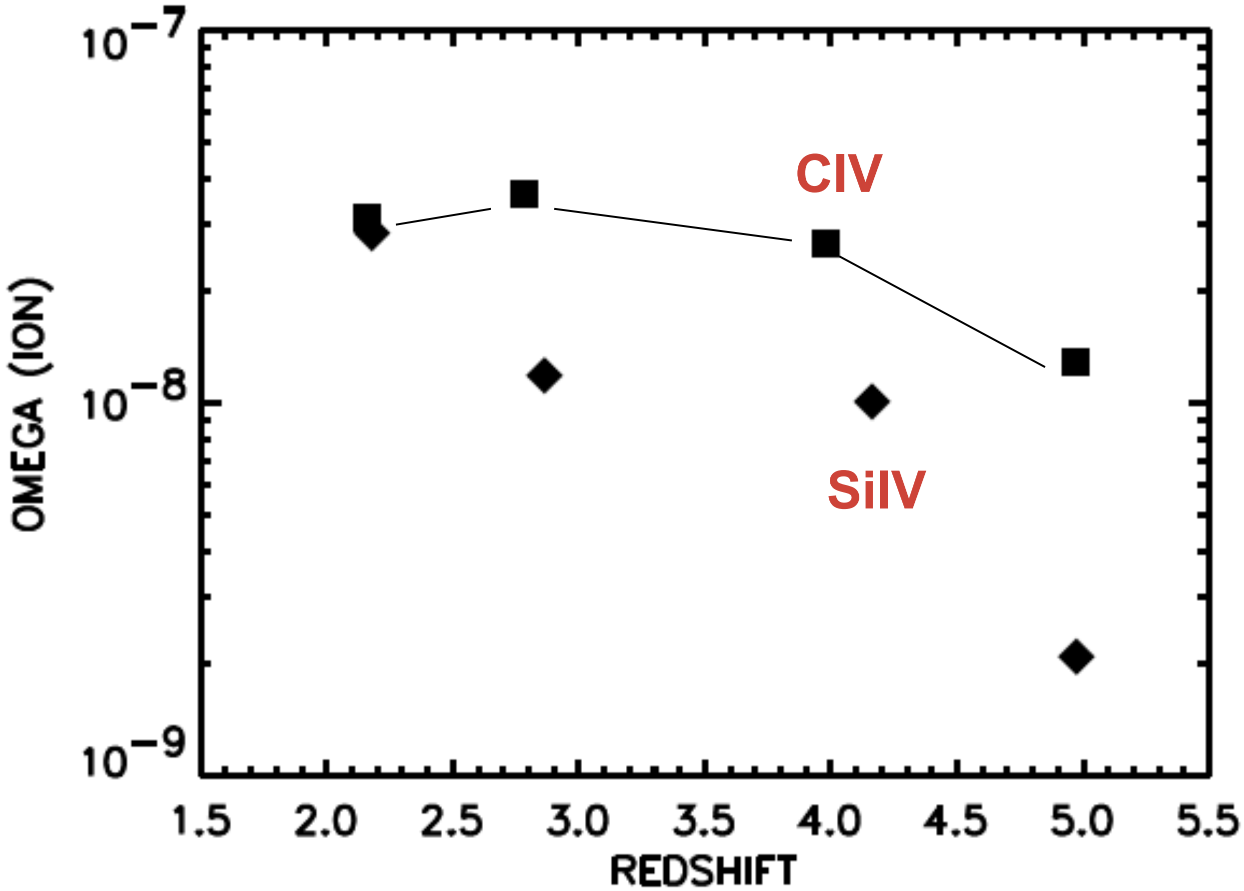
CIV was detected in the Lyα forest in 1995 with N(CIV)/N(HI)~10^{-2} -10^{-3}

CIV is seen in even the weakest Lyα systems (Ellison et al AJ 120, 1175, 2000)

How did it get there? These are low column density HI systems

Suggestive of ubiquitous enrichment from early times

Modest Evolution in Ω(CIV) 2 < z < 5



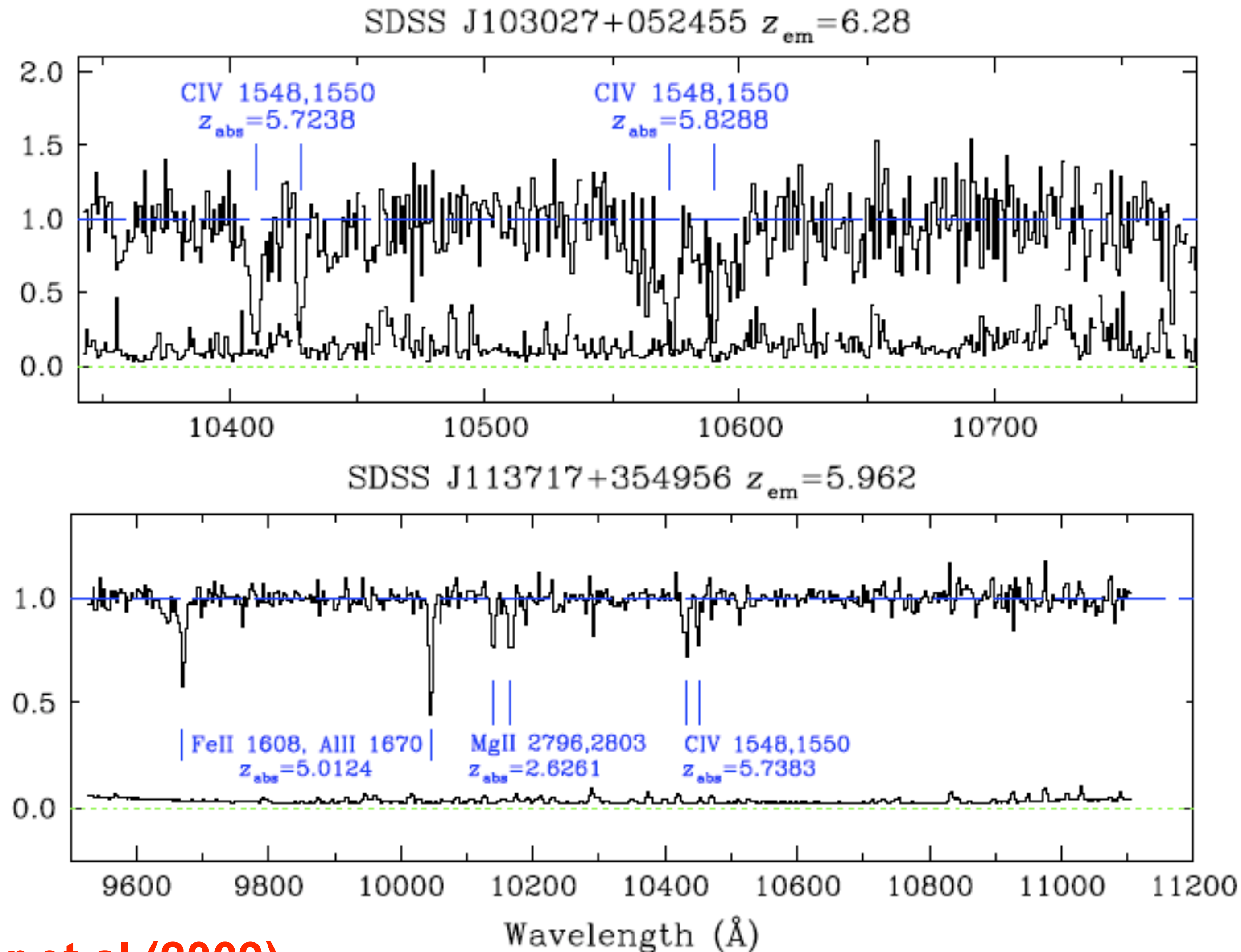
Puzzle: why does CIV abundance change so little during period of intense SF activity – presumably ionization changes?

Songaila AJ 131, 24 (2006)

CIV Absorbers in High z QSOs

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

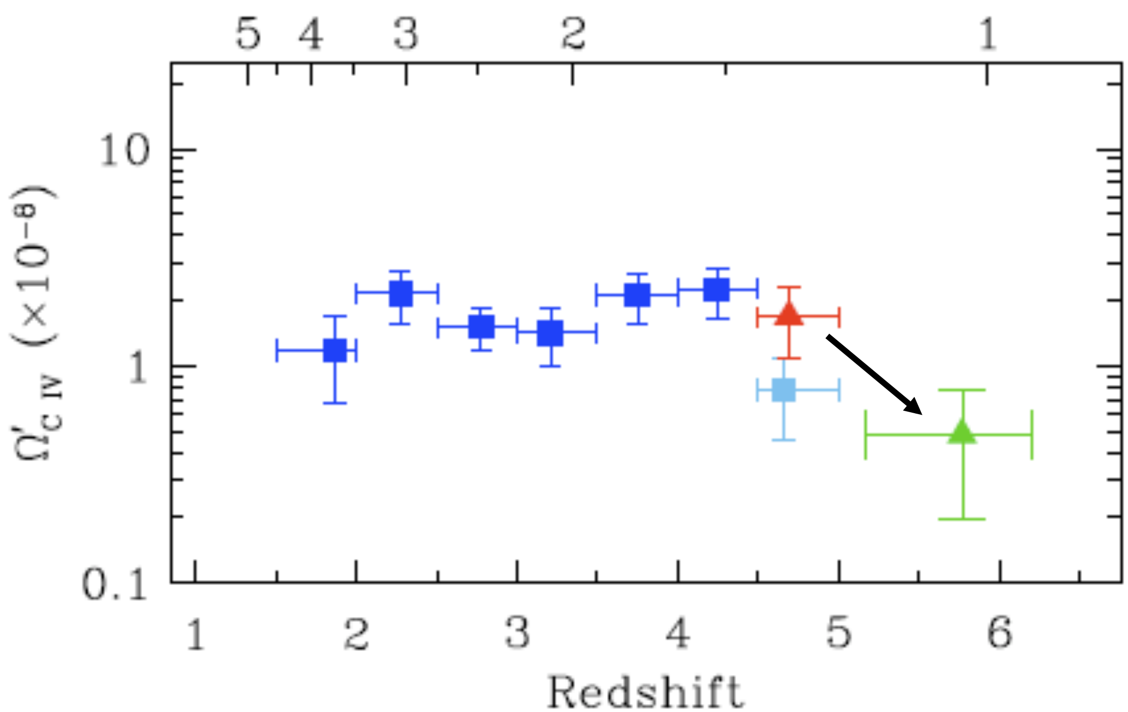
Complementary deeper search with X ~ 11 to log n_{CIV}~13.4 (Becker et al 2009)

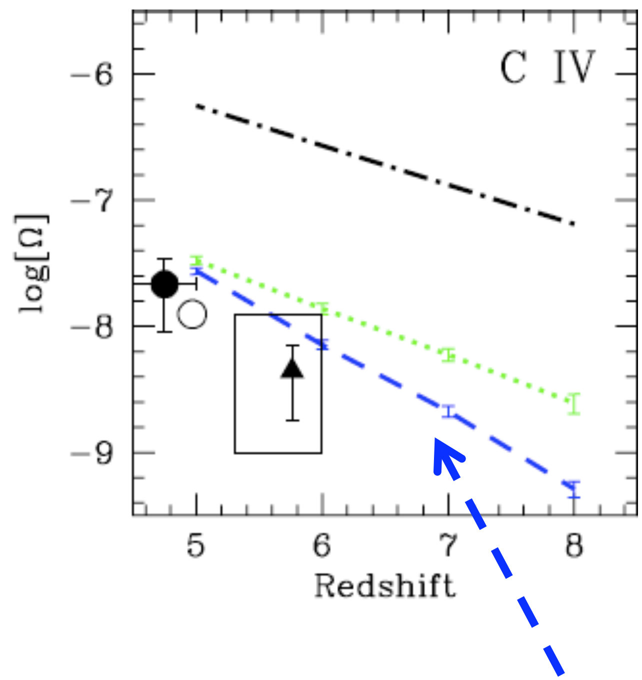


Ryan-Weber et al (2009)

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

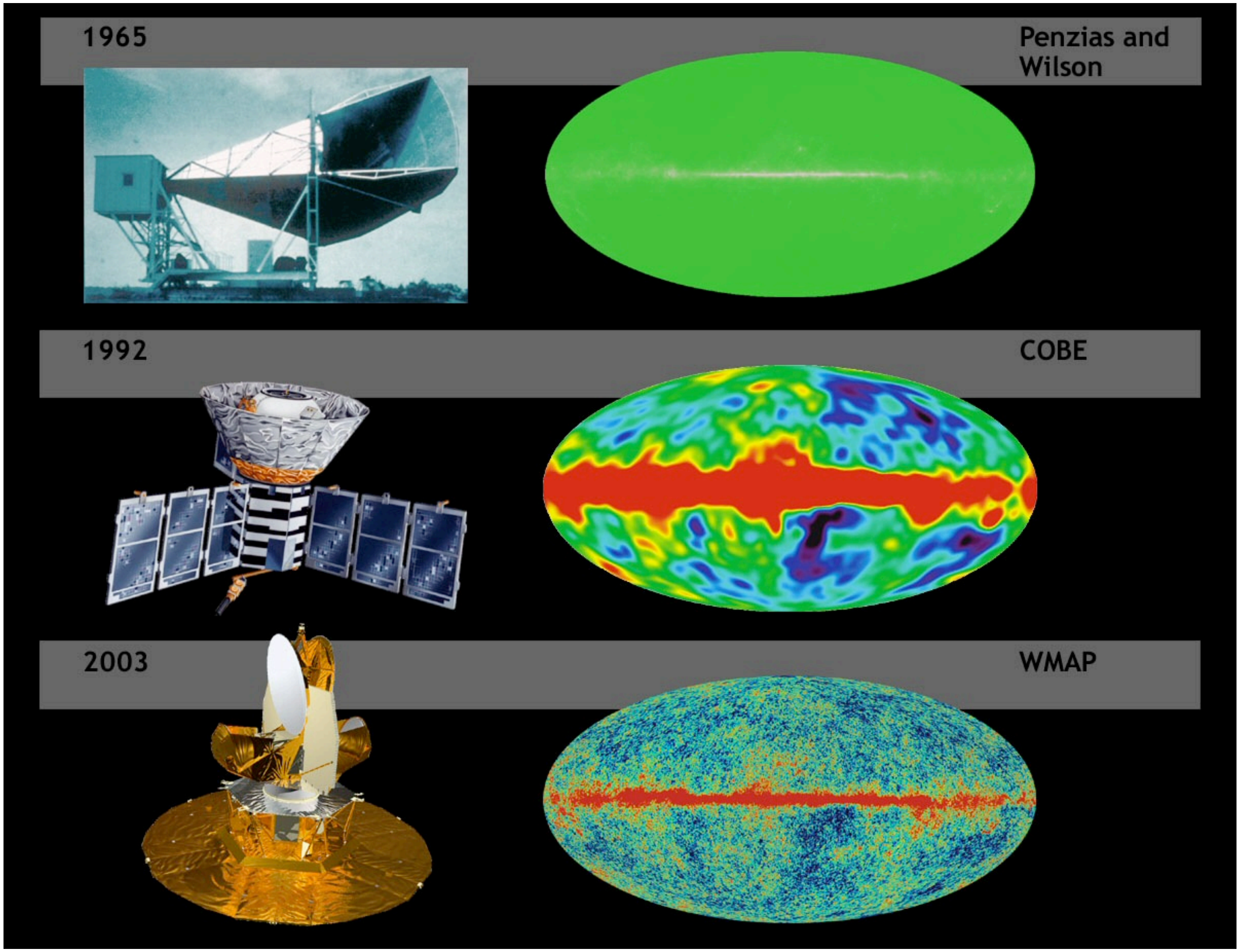
×3.5 drop in Ω_{CIV} (4σ) over 300 Myr (4.7 < z < 5.8)

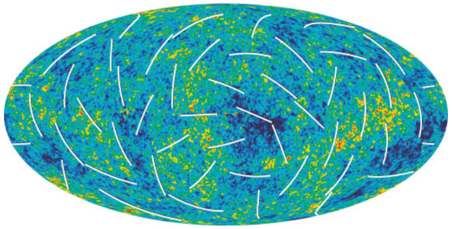




- Suggests rapid enrichment since z~9 (c.f. Oppenheimer et al vzw model)
- Caveats: ionization changes, blending (c.f Becker et al), cosmic variance
- If absorbers representative: $Z_{IGM}(z\sim6) \sim 10^{-4}\ Z_{\odot}$ (depends on ioniz^{n})
- Puzzle: implies too few escaping photons (6<z<9) to keep IGM ionized

Progress in Microwave Background Studies





Polarization in WMAP Data

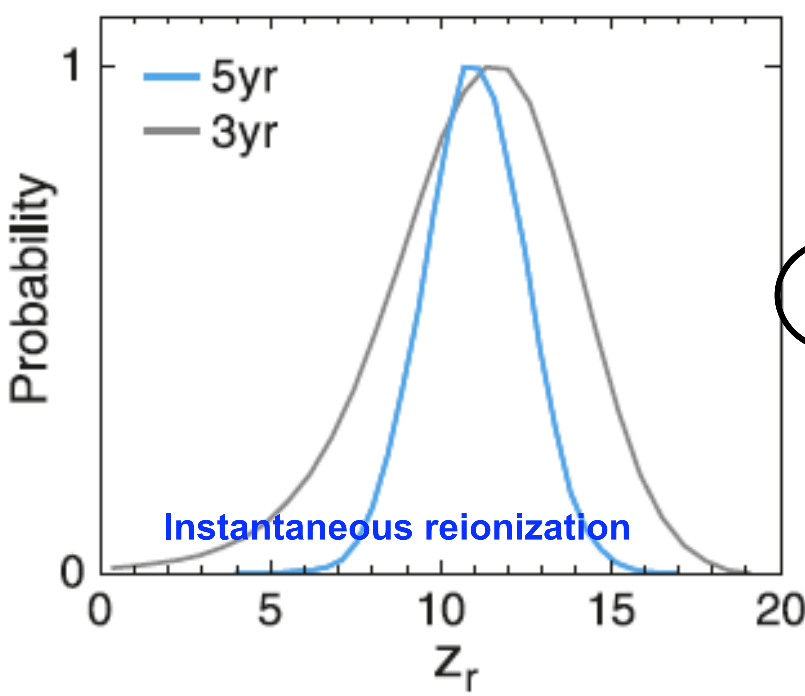
$$x_e = 0 \quad z > z_{reion}$$
$$= x_e^0 \quad z_{reion} > z > 7$$
$$= 1 \quad z < 7$$

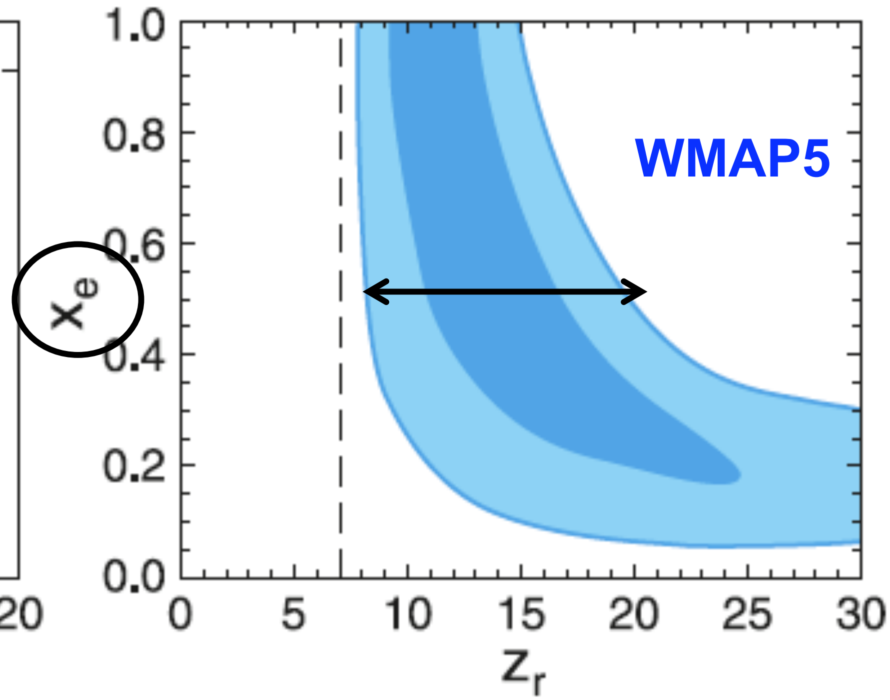
Power law ΛCDM

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

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

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



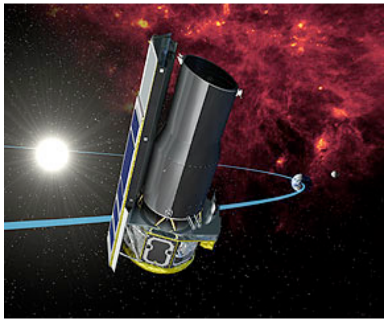


CMB polarization from scattering by foreground electrons at reionization

Data rejects instantaneous reionization at z~6-7, suggests process is extended 6<z<20

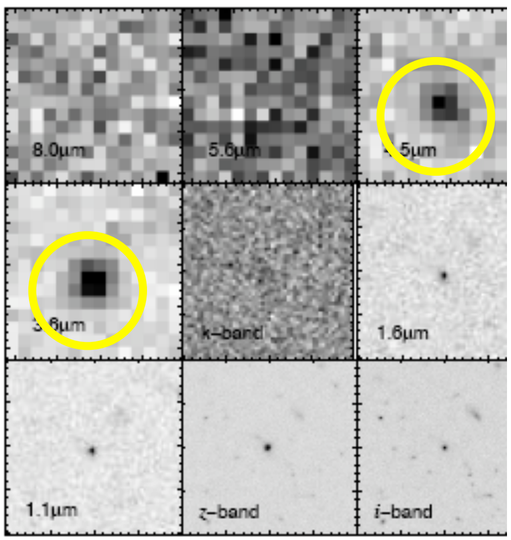
CMB studies do <u>not</u> pinpoint the responsible cosmic sources Dunkley et al (2009)

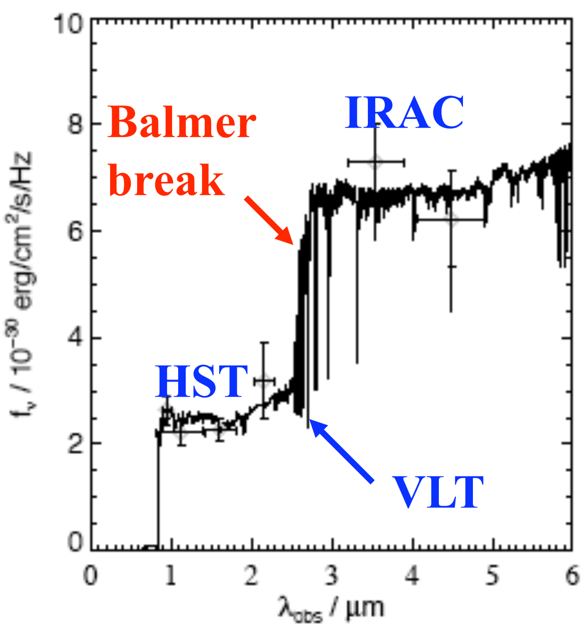
The Spitzer Revolution: Stellar Masses

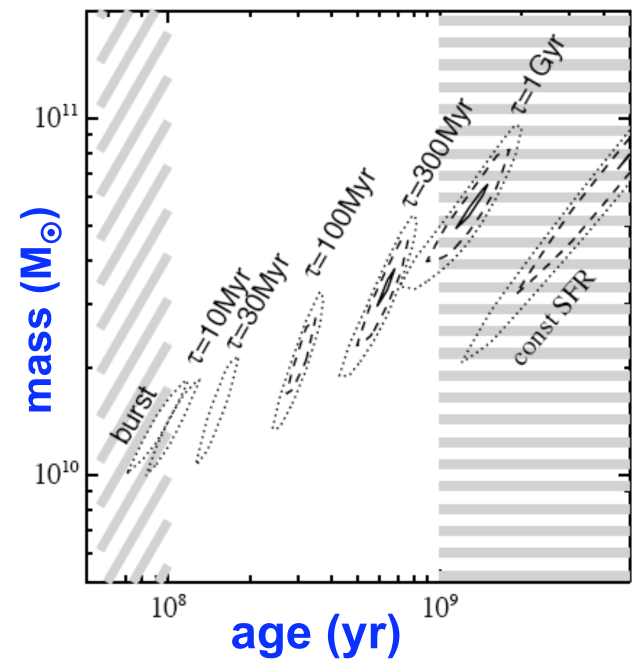


A modest 85cm cooled telescope can see the most distant known objects and provide crucial data on their **assembled stellar masses and ages**

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

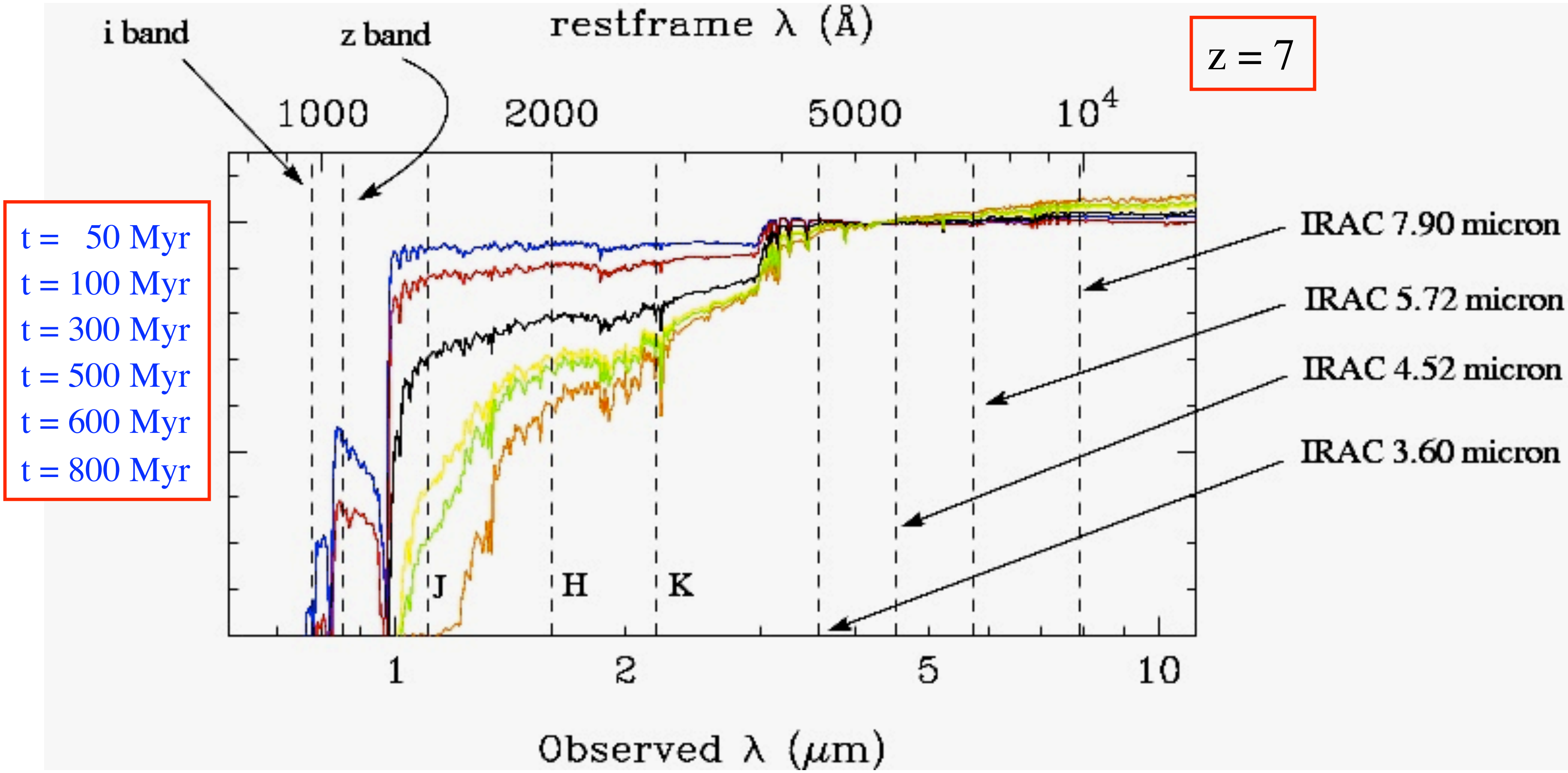






Eyles et al (2005): to produce this mass required 5-30 $M_\odot$ yr^{-1} since z~7-10 comparable to the ongoing SFR (6-20 $M_\odot$ yr^{-1}) so should see earlier examples if unobscured

Balmer Break Galaxies



Stellar Mass Densities @ z~5-6

Extend earlier work to attempt to conduct census of stellar mass in v- and i-drop samples. This is much harder because:

- relies largely on photometric redshifts; contamination by foreground sources will bias mass density upwards
- typically 50% of faint sources are confused in IRAC data; scale up mass densities proportionally using isolated IRAC sources
- stellar populations may be diverse & different to those at low z: opportunity for big errors by taking conventional approximations
- drop-out target selection focuses only on active SF sources, so mass estimates likely will be lower limits

Results: Yan et al (Ap J 651, 24, 2006): z~6 GOODS I-drops
Stark et al (Ap J 659, 84, 2007): z~5 GOODS v-drops
Dunlop et al (MN 376, 1054, 2007): K<23.5 GOODS-S massive gals
Eyles et al (MN 374, 91, 2007): z~6 GOODS I-drops

What does assembled mass imply for SF before z~6?

Assembled Stellar Mass at z~5-6

Integrated stellar mass density at z~5-6:

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

Now turn the argument around:

Instead of checking that mass is consistent with past SF we can ask:

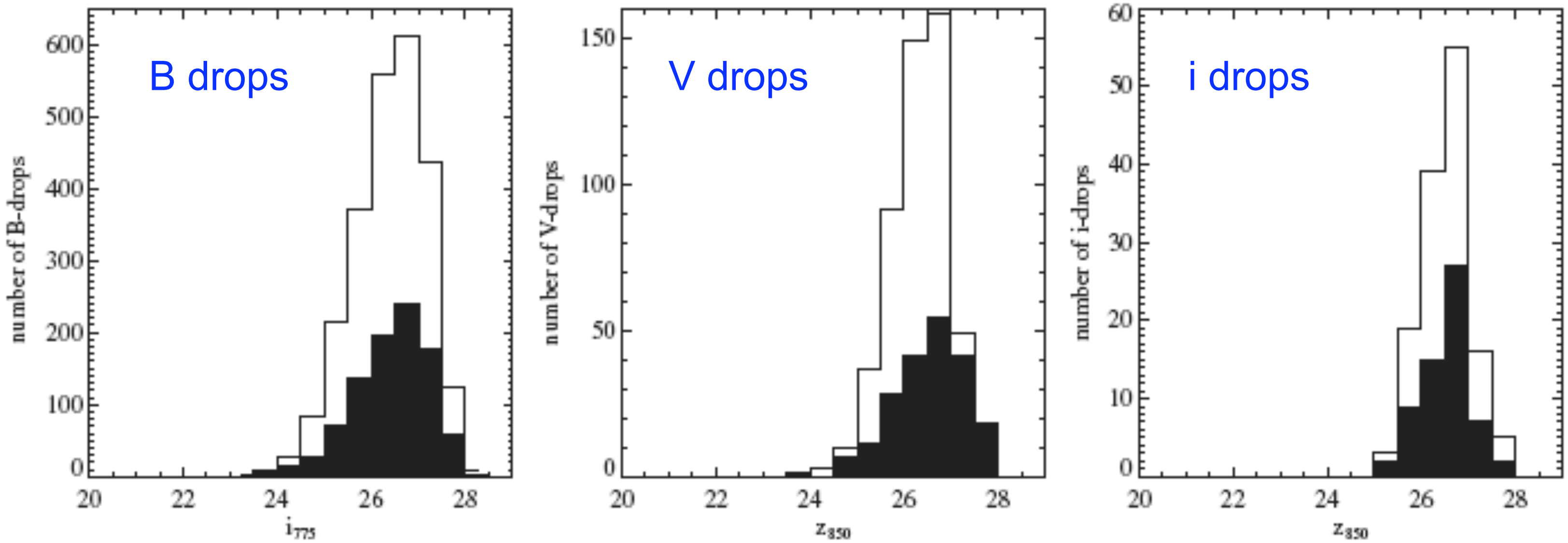
What does accumulated stellar mass imply for earlier SF & reionization?

If mass density at z~5-6 is ***greater*** than can be accounted for by previous SF history, options include:

- extinction: star formed but dust is present
- intrinsically faint contributors: lensing may find them
- upturn in SFH before z~10

Stark & Ellis New Astr. Rev. 50, 46 (2006)

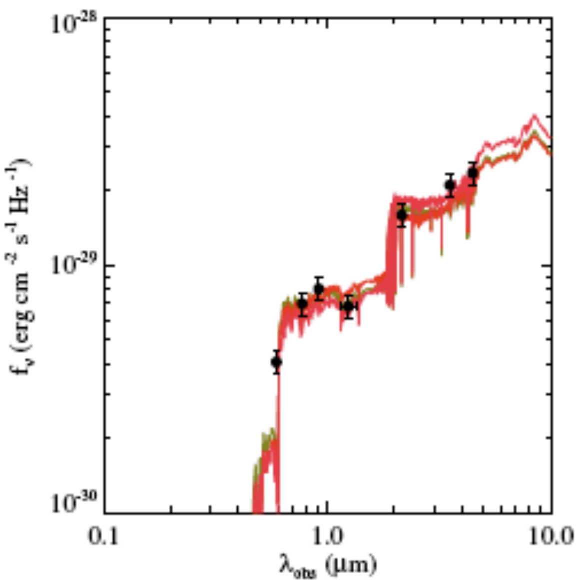
Stellar Mass Functions 4 < z < 6 (Stark et al 2009)



- 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 $M \sim 10^{9.5}\ M_{\odot}$; stacked properties for fainter sources

Examples across the full range of data

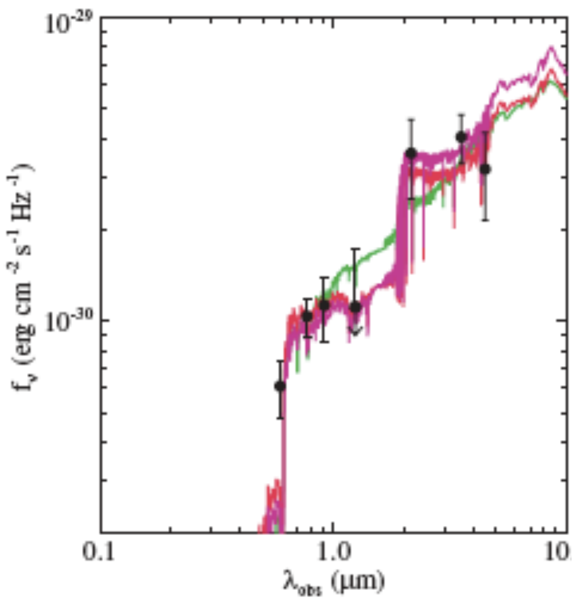
High mass/bright



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

age = 290 Myr

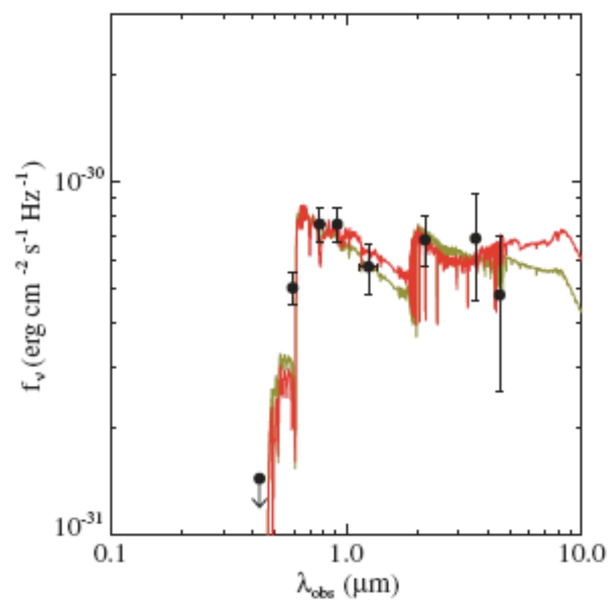
Low mass/faint



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

- **Factor ×5 growth in mass density over 4 < z < 6:**

$M_{UV} < -20$:

z~4: $\rho_* = 1.1\ 10^7\ M_\odot\ Mpc^{-3}$

z~5: $\rho_* = 4.0\ 10^6\ M_\odot\ Mpc^{-3}$

z~6: $\rho_* = 2.0\ 10^6\ M_\odot\ Mpc^{-3}$

- **Substantial mass in place at z~5 suggesting vigorous activity >300 Myr earlier (z > 7)**

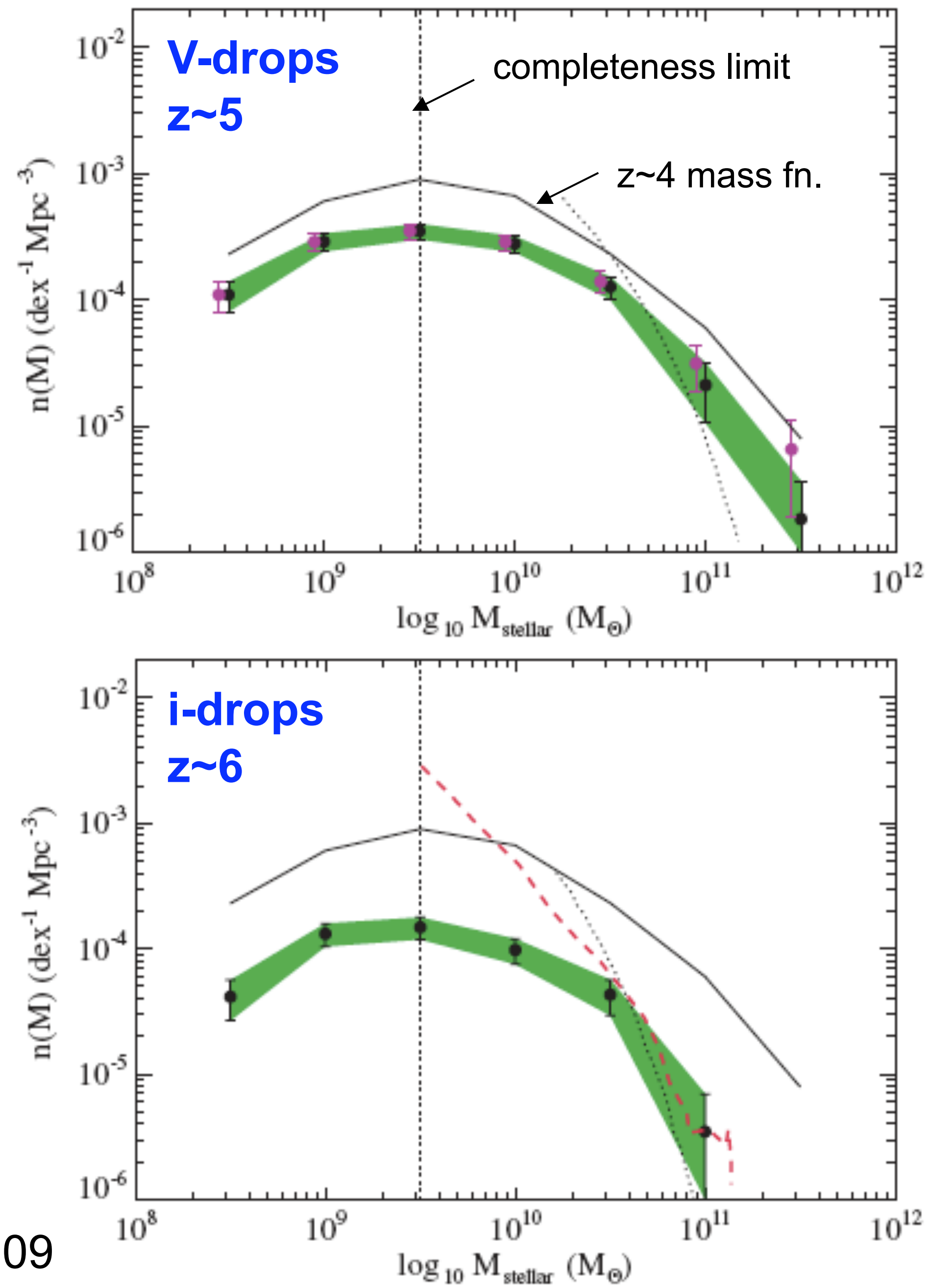
Extrapolation to $M_{UV}<-10$

z~5: $\rho_* = 10^7\ M_\odot\ Mpc^{-3}$

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

Hard to reconcile this mass with observed decline in luminous LBGs

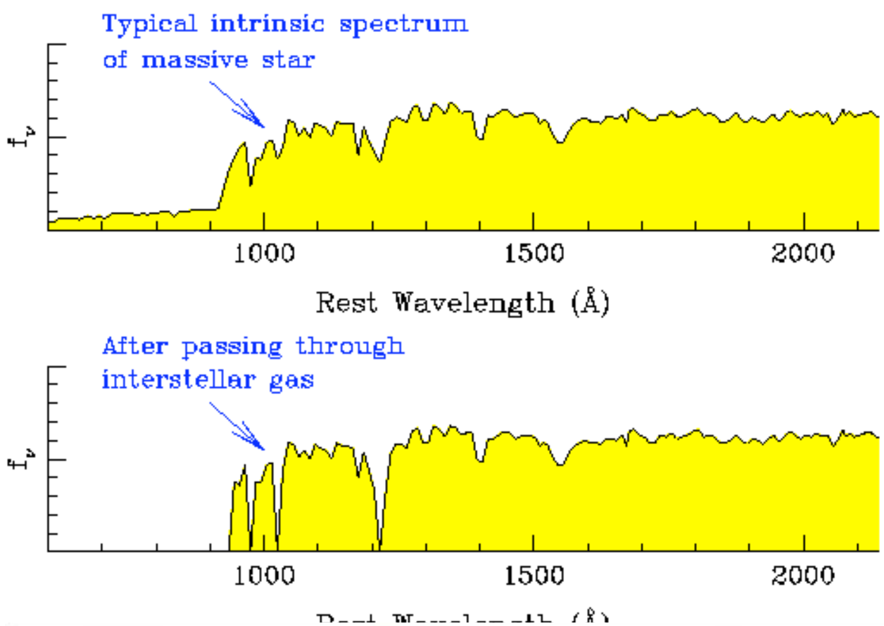
Stark & Ellis 2006, Stark et al 2007, 2009

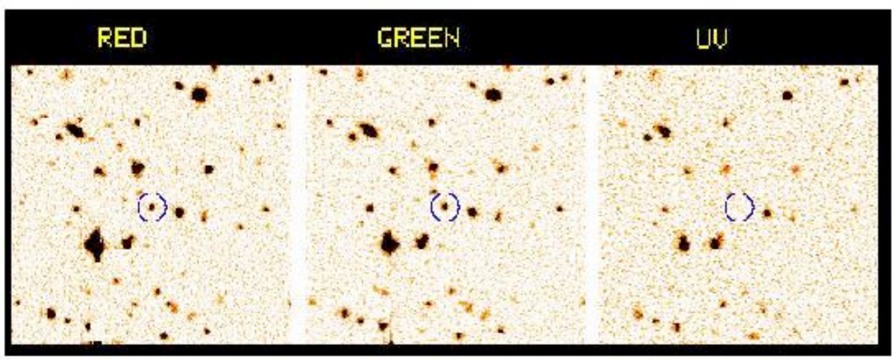


High Redshift Star Forming Galaxies

Lyman break galaxies:

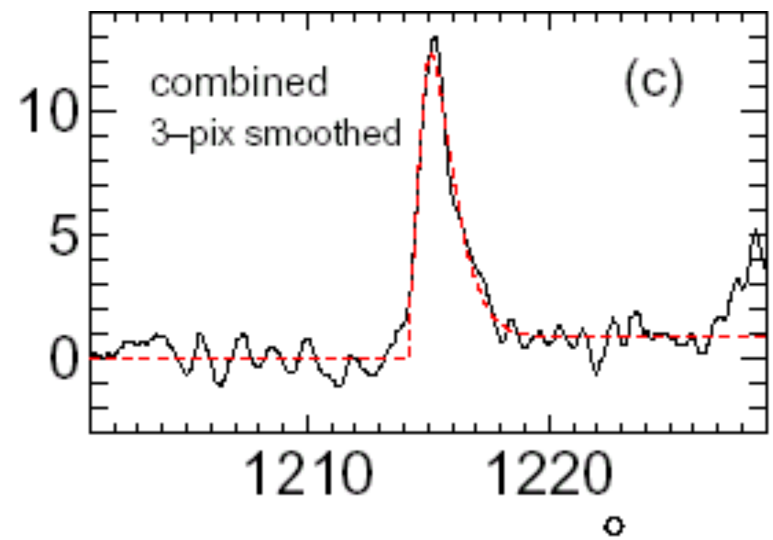
Rest-frame UV continuum discontinuity

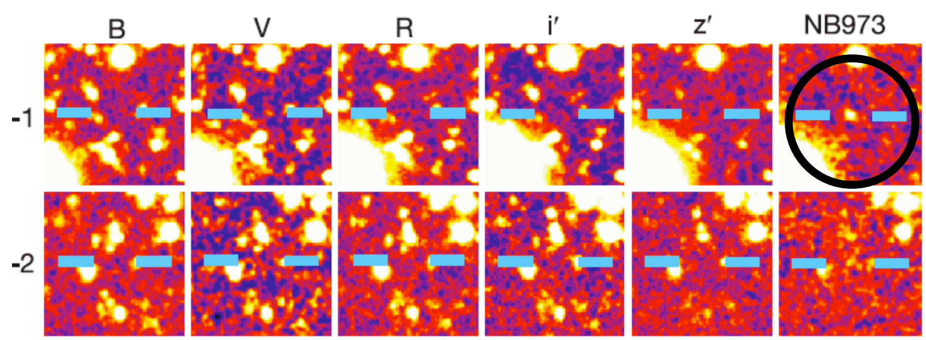




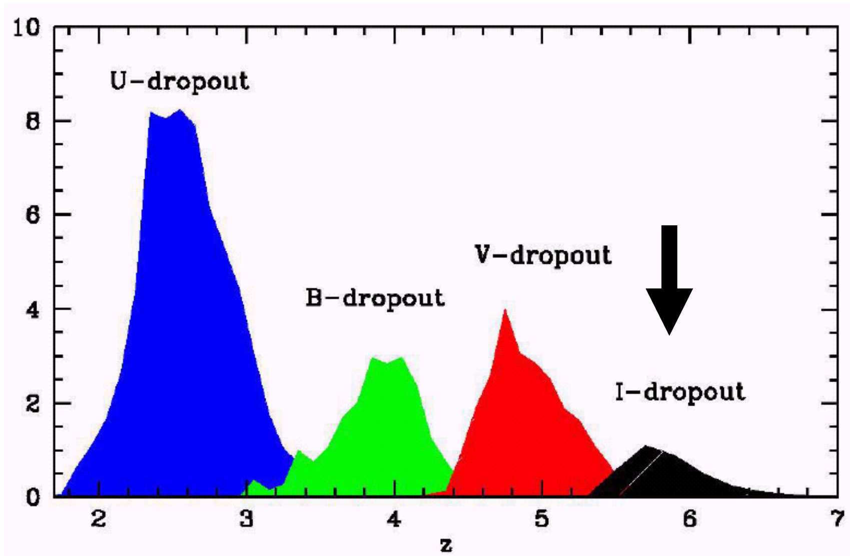
Lyman alpha emitters:

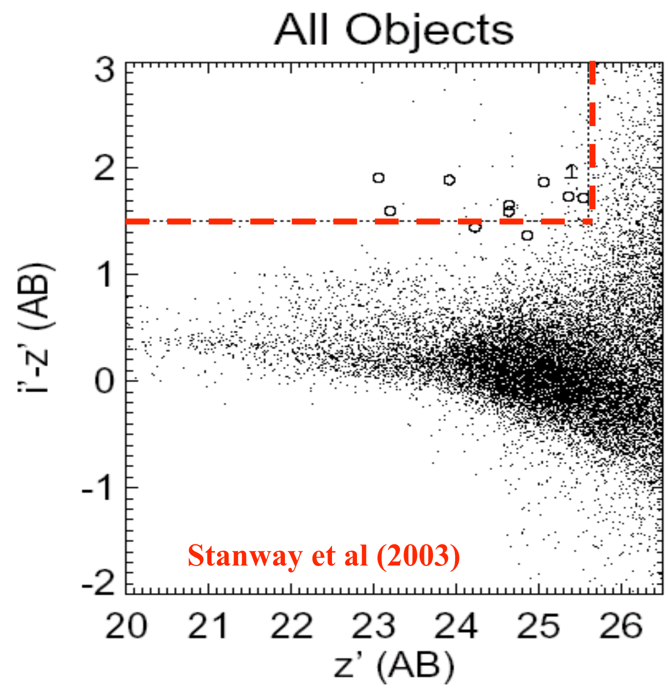
Located via narrow band imaging





Extending Lyman break technique to high z





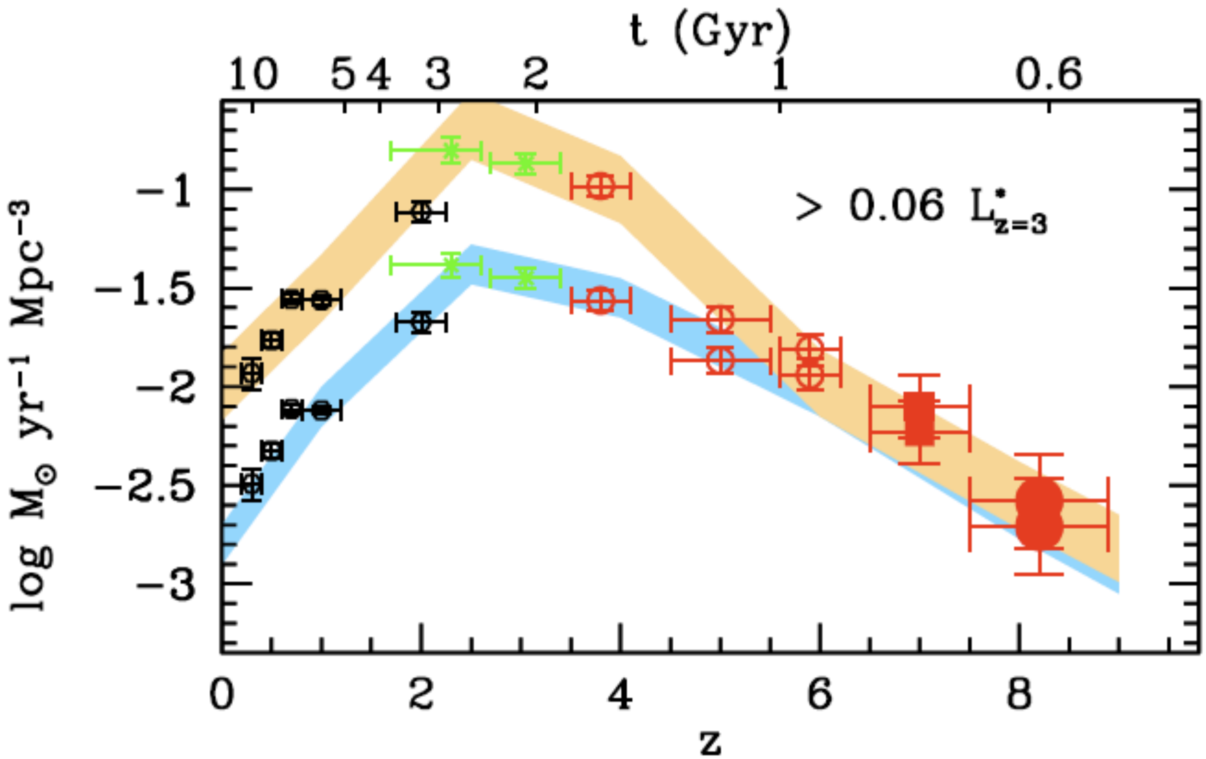
Traditional dropout technique poorly-suited for z~6 galaxies:

- significant contamination (cool stars, z~2 passive galaxies)
- spectroscopic verification impractical below ~few L*

i-drop volumes: UDF ($2.6\ 10^4$), GOODS-N/S (5.10^5), Subaru (10^6) Mpc^3

flux limits: UDF $z' < 28.5+$, GOODS $z' < 25.6$, Subaru $z' < 25.4$

Declining star formation density of LBGs



Monotonically declining population to z~6 and beyond

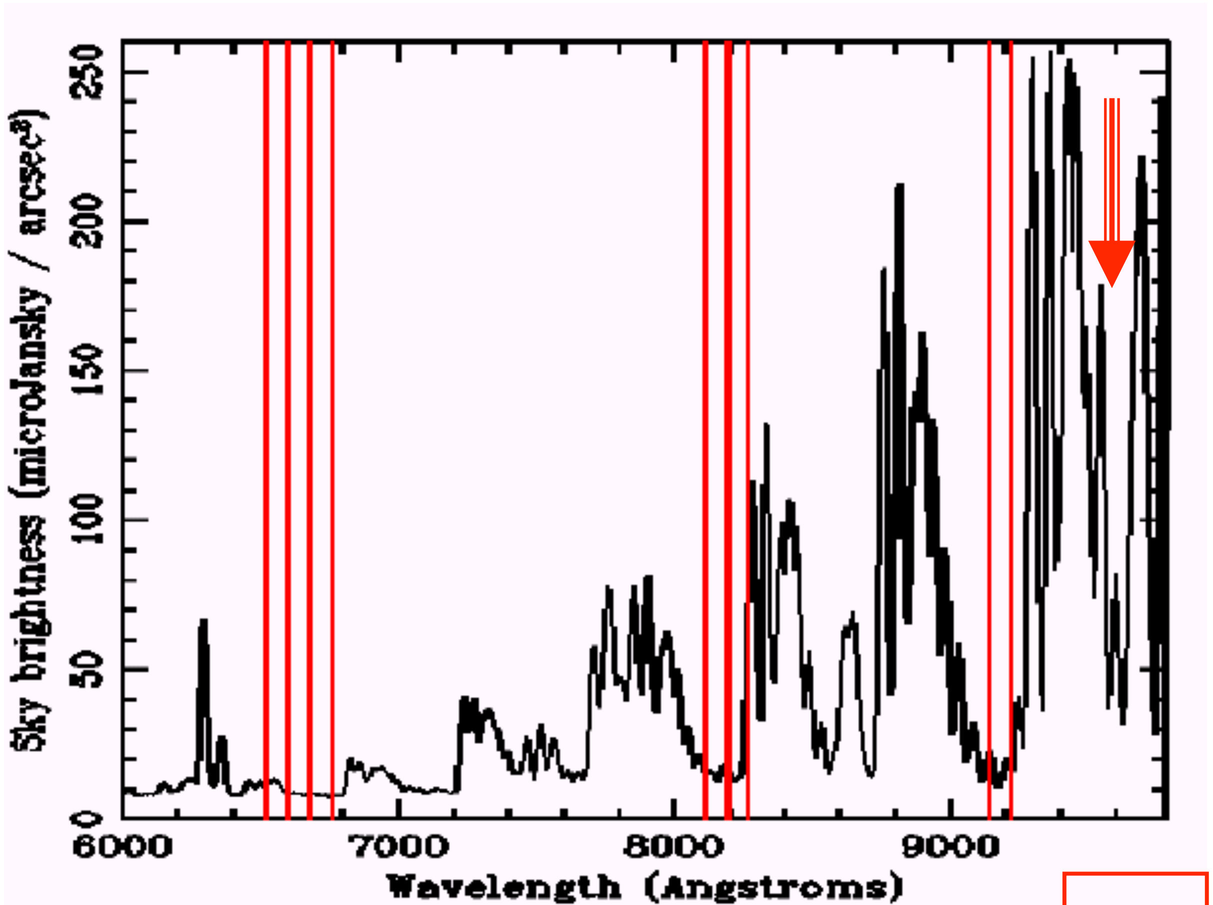
Drop of ×8 in UV luminosity density 2<z<6

1.2 mag dimming in characteristic luminosity L*

Reddy & Steidel (2009)

Bouwens et al (2009)

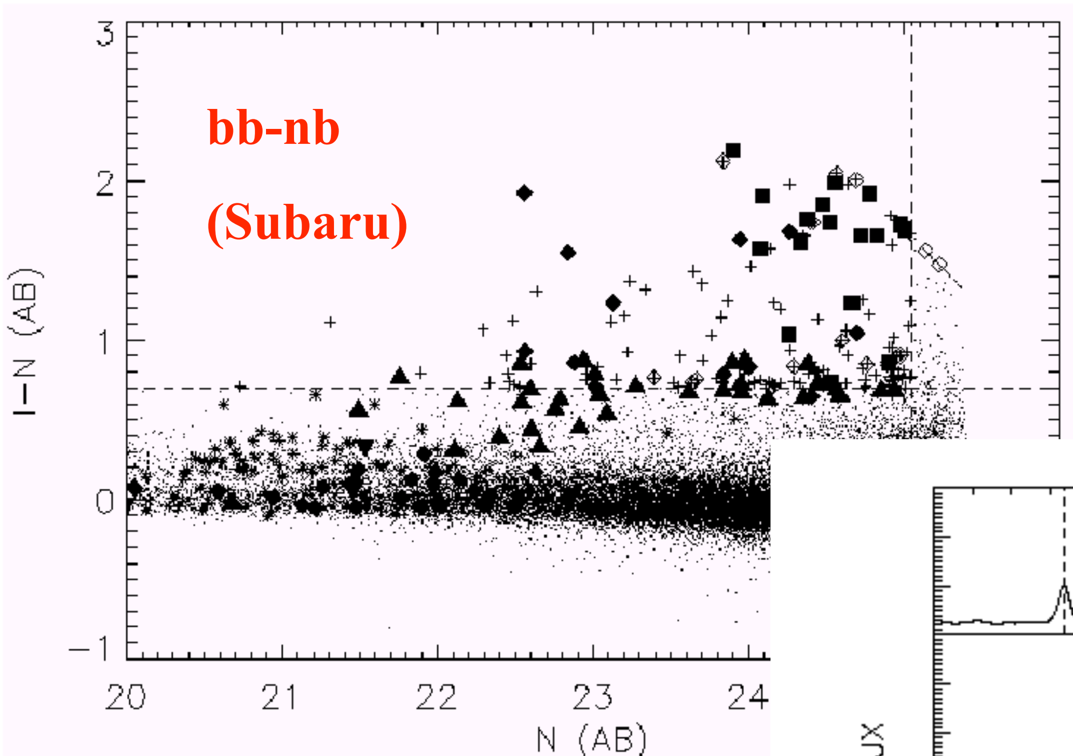
Narrow band filters & z=7 barrier



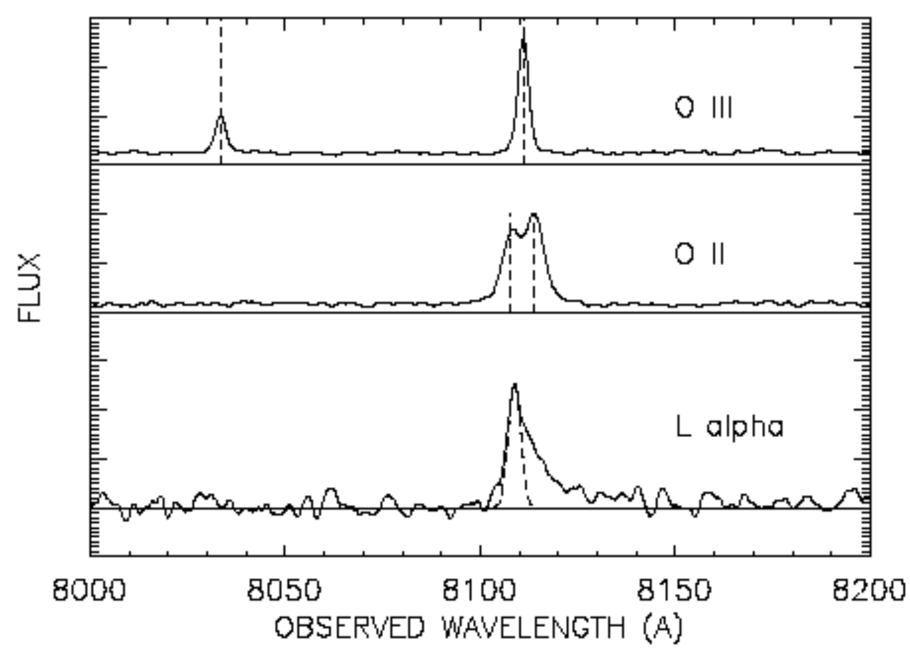
z(Lα) = 4.7 5.7 6.6 6.9

Requires panoramic imaging as Δz range is small: restricted to z<7

Candidate Selection & Removal of Interlopers



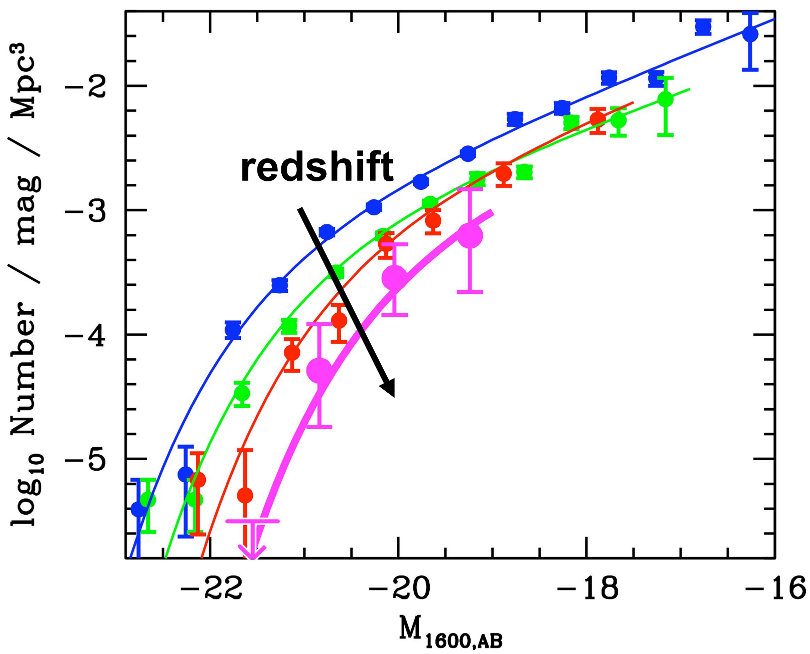
Keck spectra



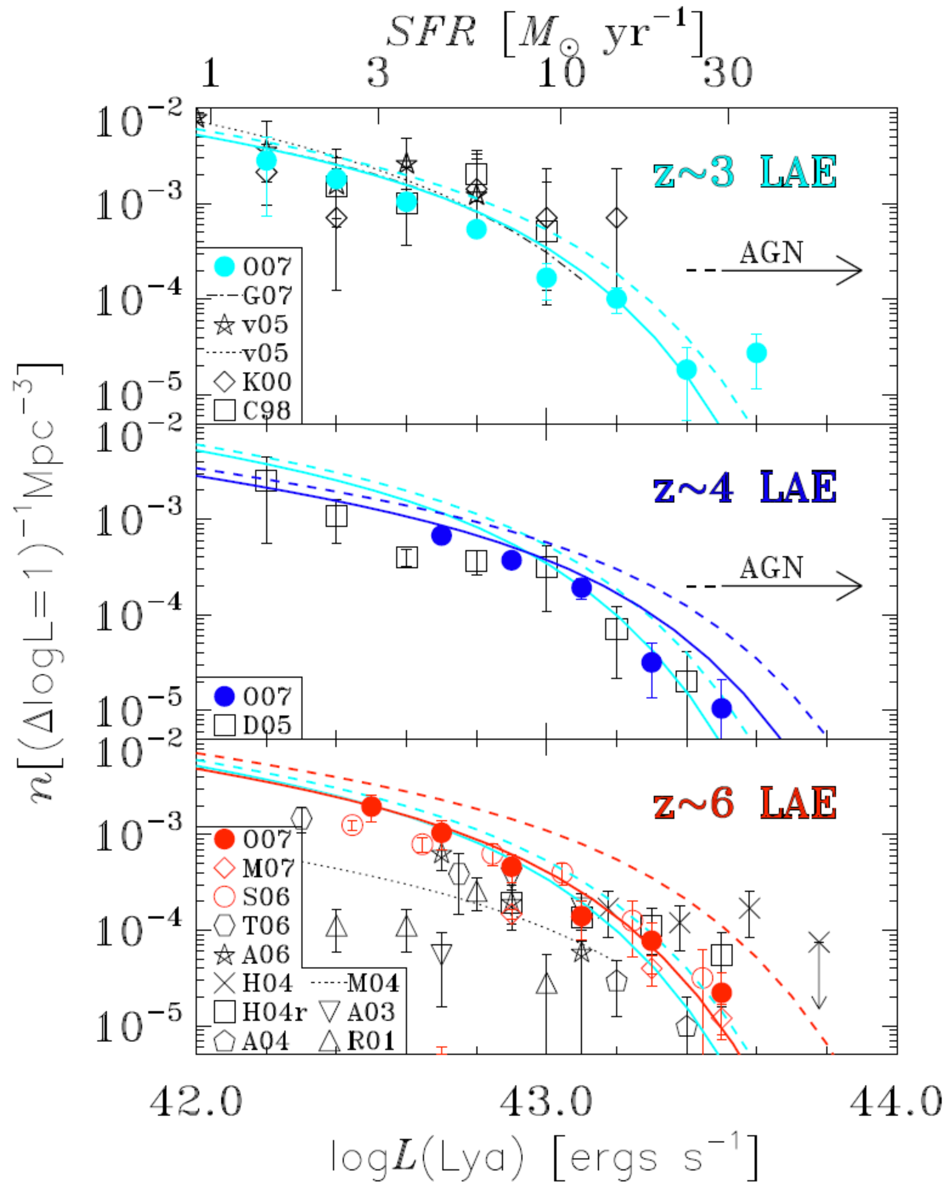
Hu et al (2003) z=5.7 survey

LBGs vs LAEs: Very Different Evolution

Bouwens (HST)



Ouchi (Subaru)



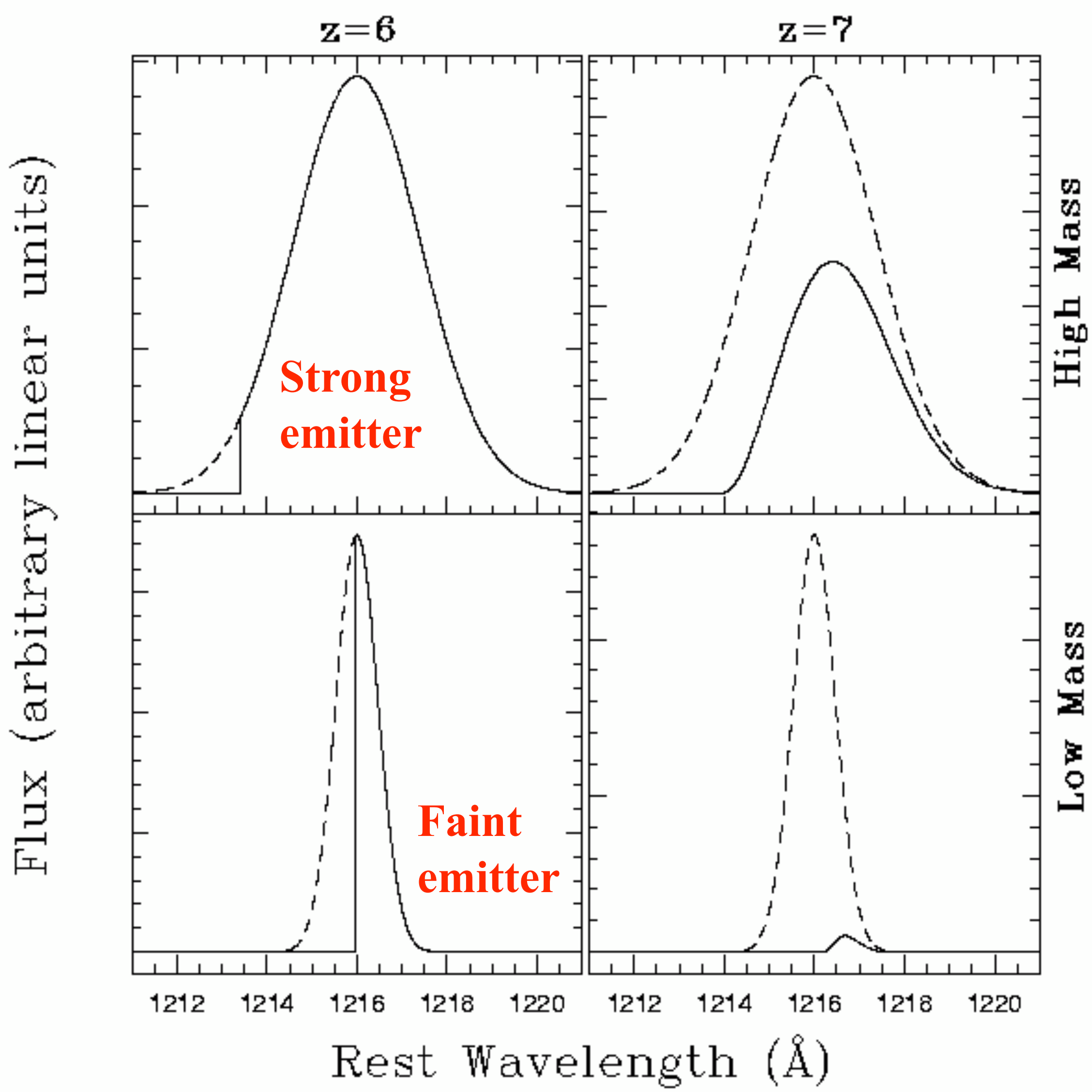
- Lyman break (continuum): clear decline in abundance over 3<z<6, especially for luminous examples
- Lyman alpha (line) emitters: no signifcant change
- Suggests early galaxies dominated by Lyman alpha emission

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.

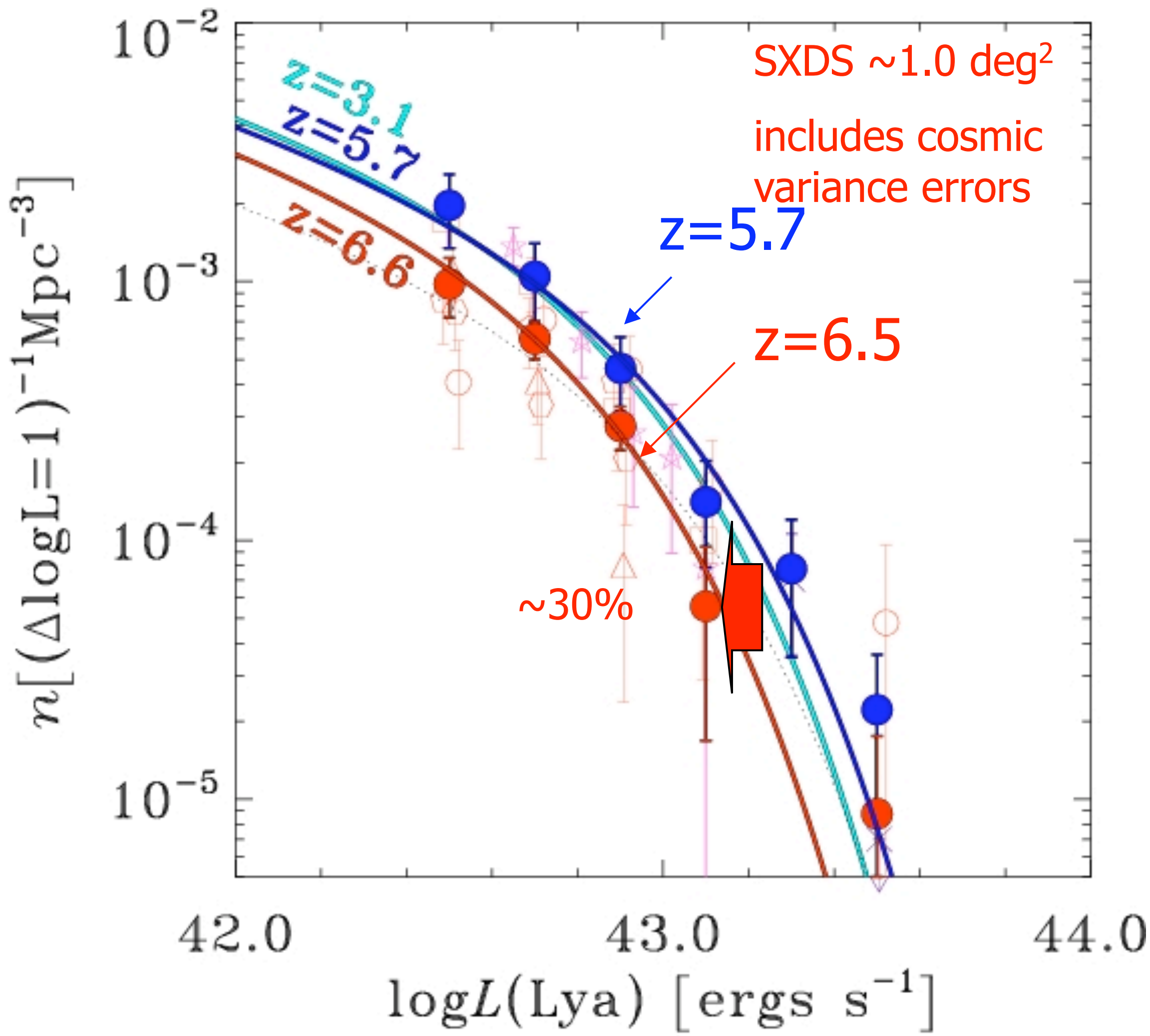
• In weaker systems, it may be a ***sensitive probe of reionisation***



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)

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)

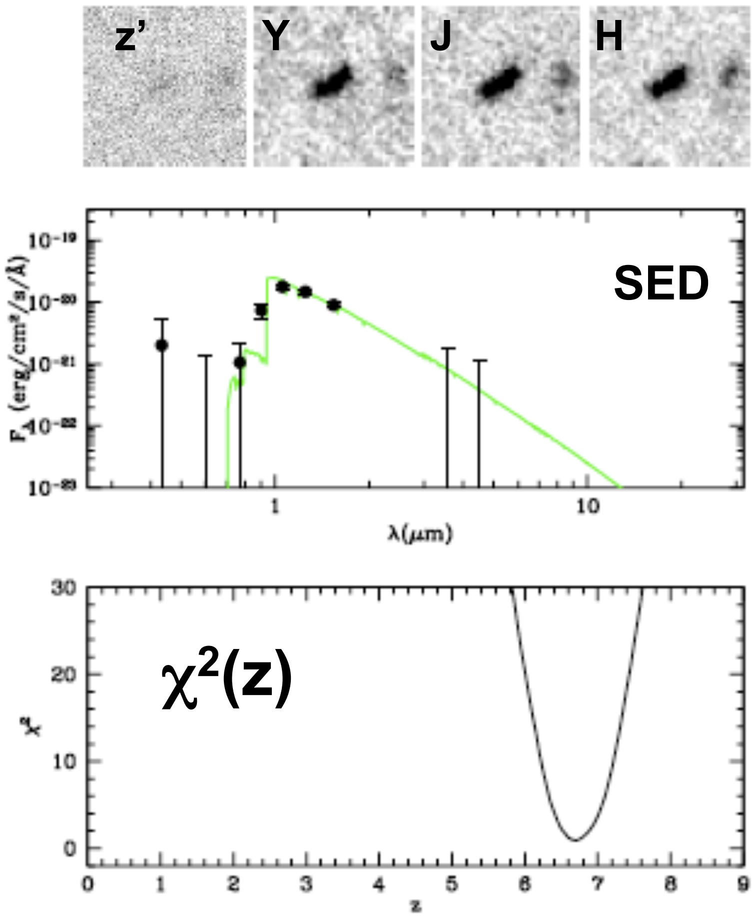
Hubble WFC3 High z Stampede

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

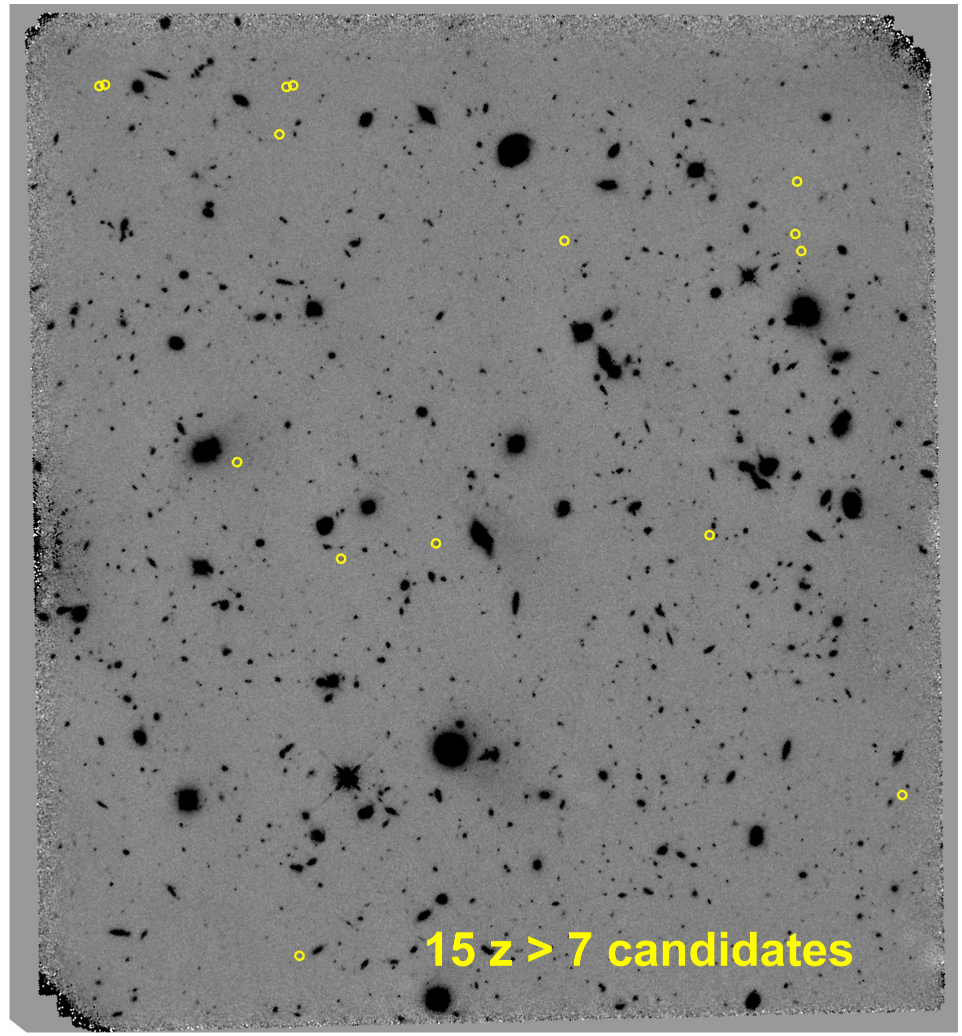
UDF 4.7 arcmin^2
60 orbits in YJH
Reaches m_{AB}~29 (5σ)

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



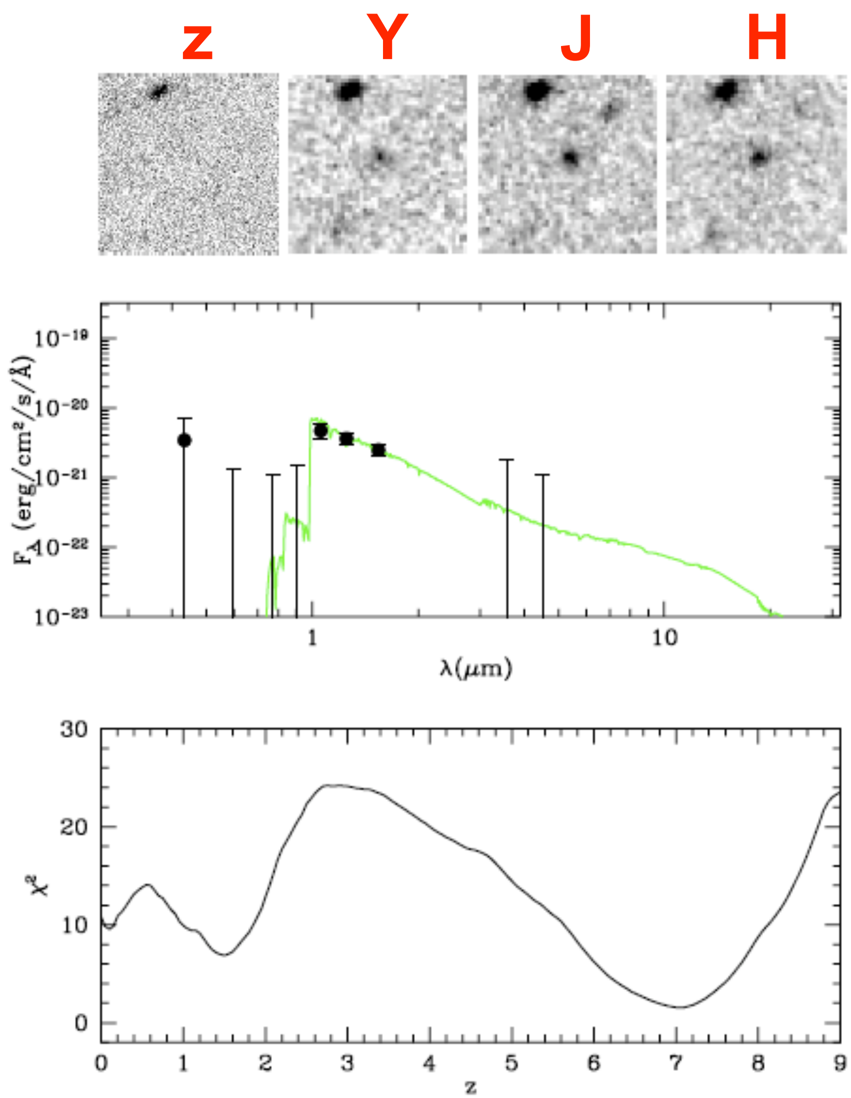
688: $z_{est} = 6.70\ (6.50 - 6.90)$



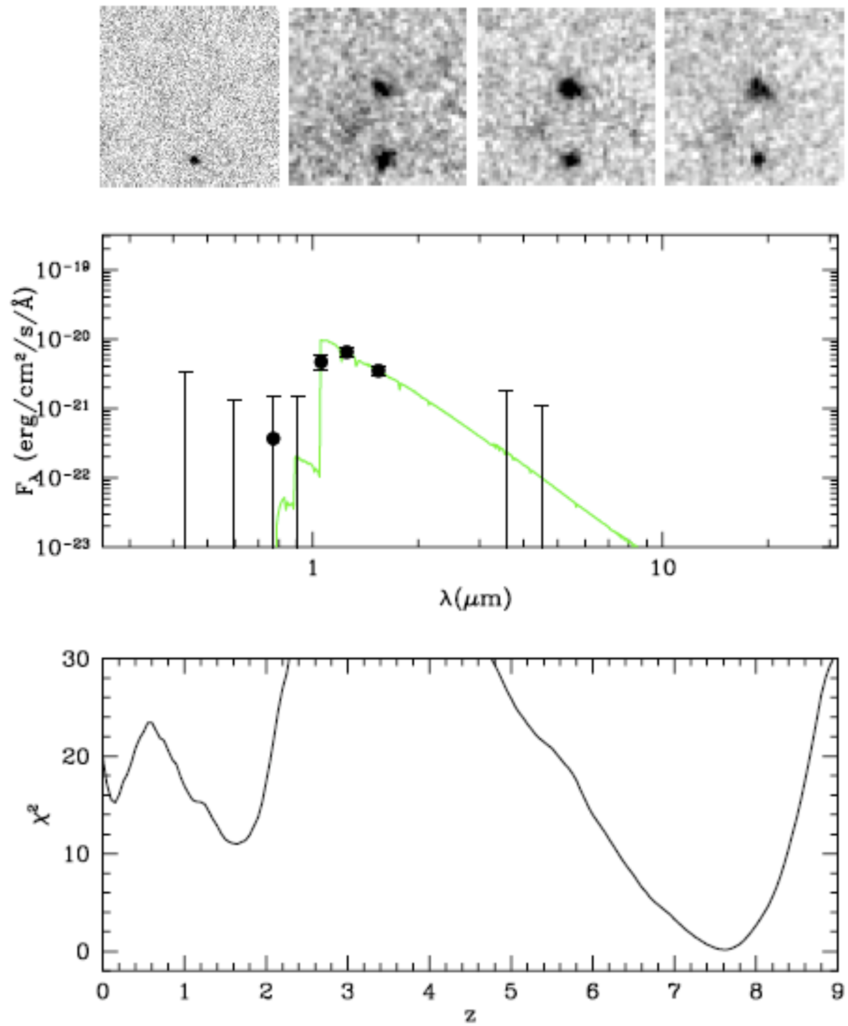
3 IR filters c.f. 2 leads to more secure photometric redshifts and reliable UV continuum slopes

McLure et al (2009)

But beware..uncertain redshifts still an issue..

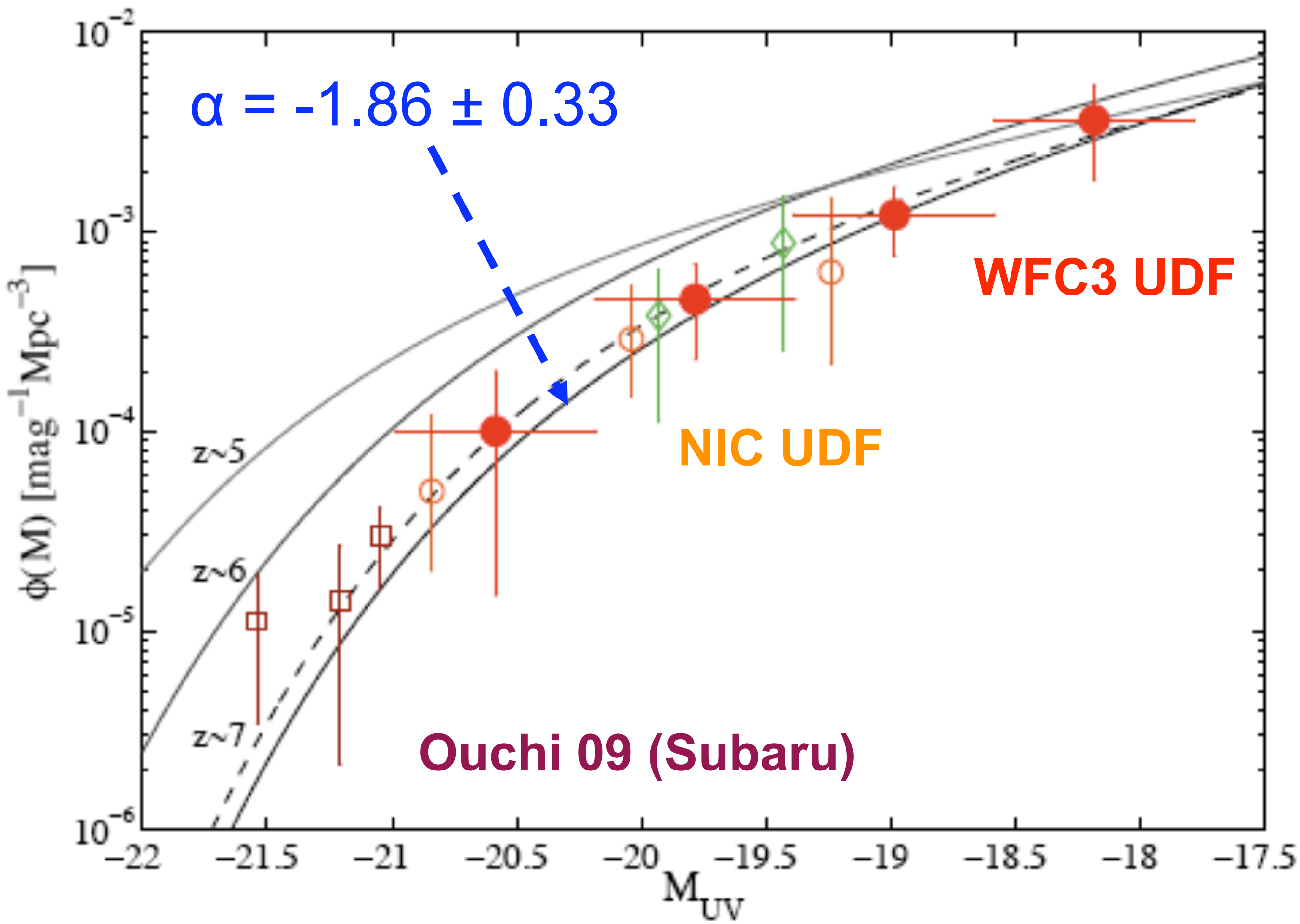


1678: $z_{\rm est} = 7.05\ (6.60 - 7.40)$



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

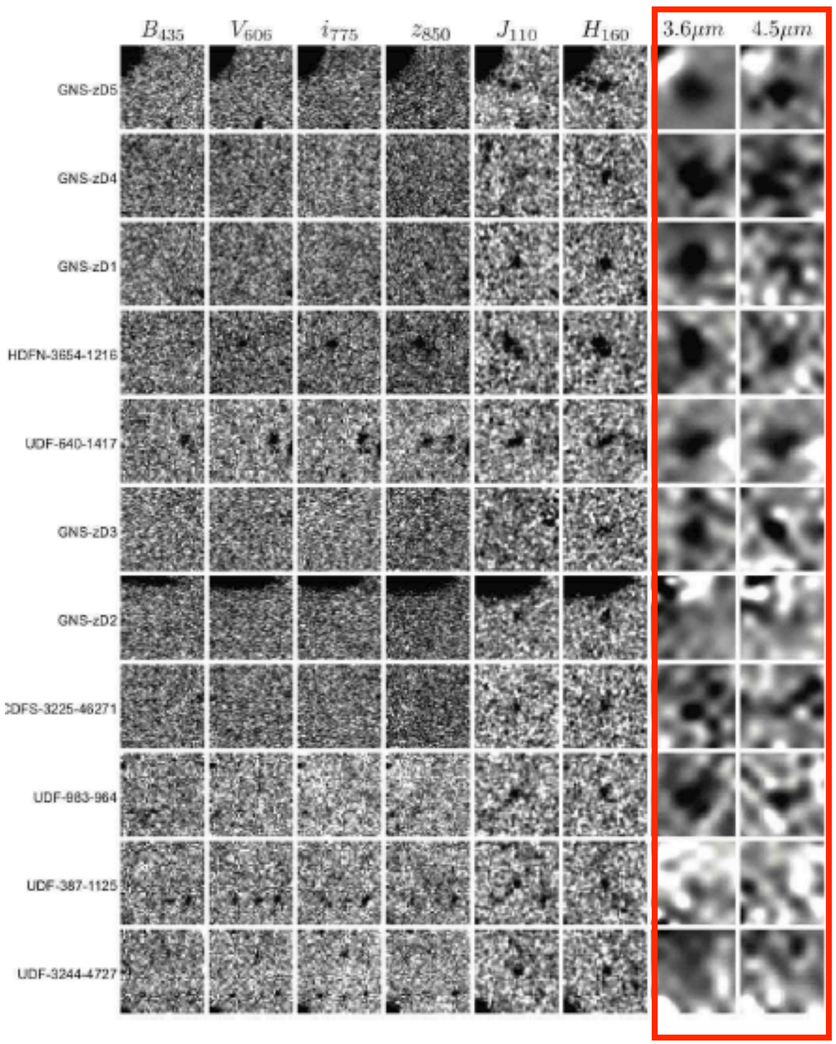
WFC3 Progress – I: z~7 Luminosity Function

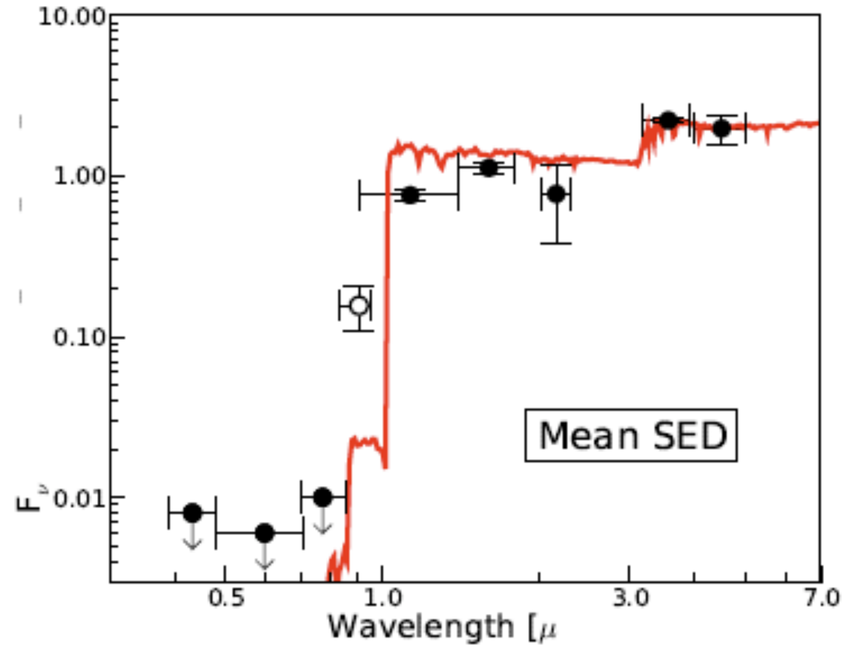


- 10-16 z-band dropouts to Y_{AB}~28.5 corresponding to 6.5<z<7.5
- Towards a reliable faint end slope: low star formers ~1 $M_\odot$ yr^{-1} dominant
- Abundance decline of ~×2 since z=6

Oesch et al, Bunker et al 2009

IRAC Detections of Luminous Galaxies @ z~7



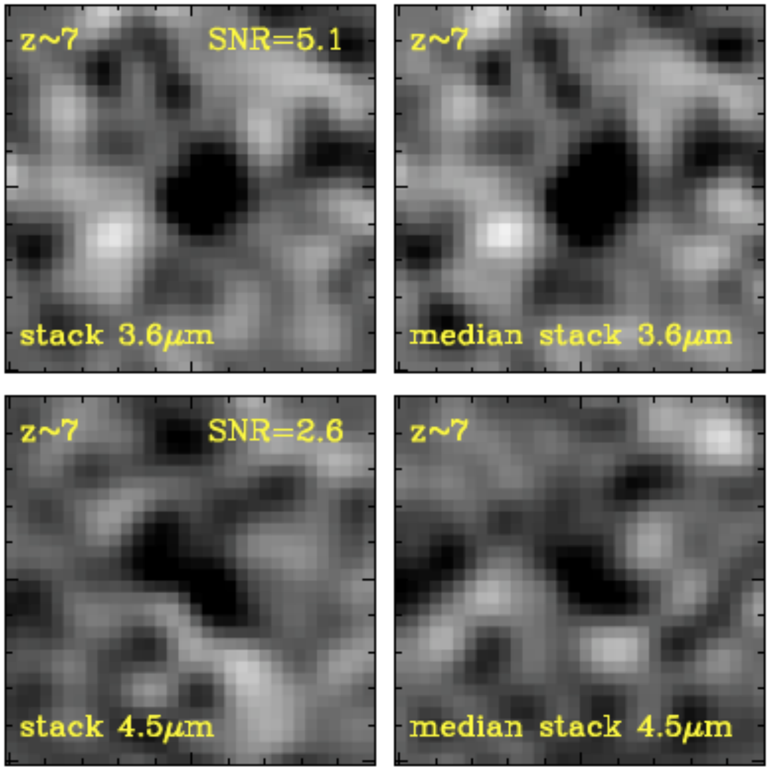


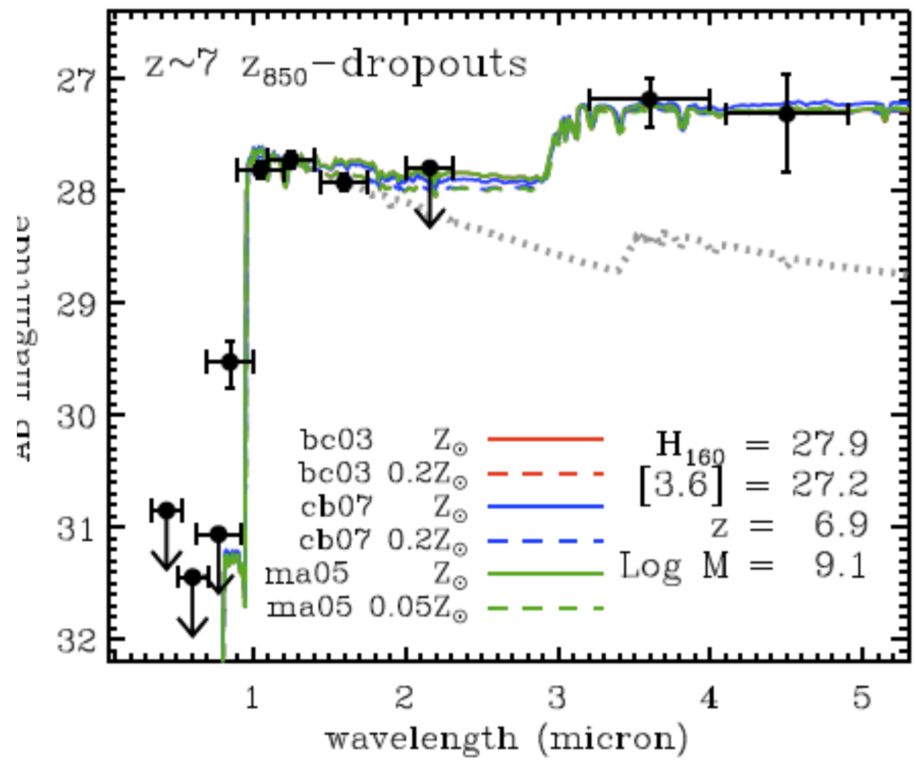
11 objects in GOODS/UDF
$M<10^{10}\ M_{\odot}$ ages <400 Myr

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

Gonzalez et al 2009

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

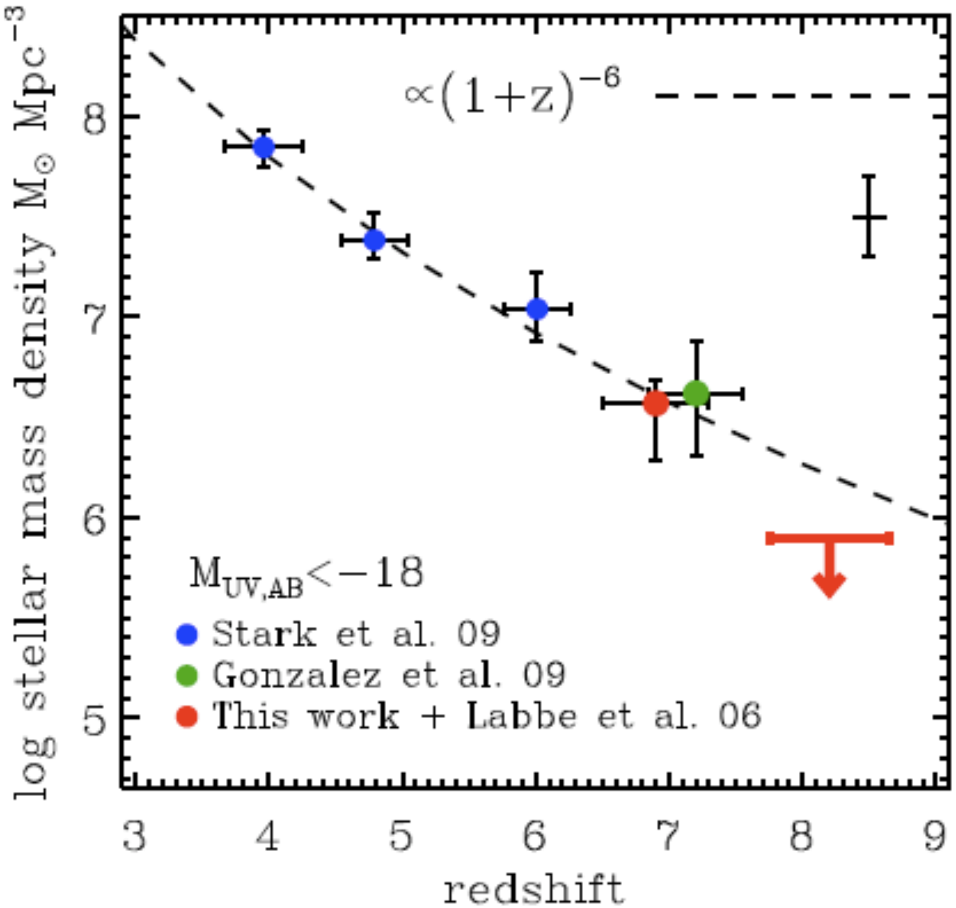




- To complete mass density at z~7 need to probe much fainter
- UDF z~7 candidates only detected in stacked IRAC data (N=12)
- Highly uncertain but estimate $M{\sim}10^9\ M_\odot$ and ages>100 Myr
- Warm mission should improve constraints significantly

Labbé et al 2009

Did Star Forming Galaxies Reionize the Universe?

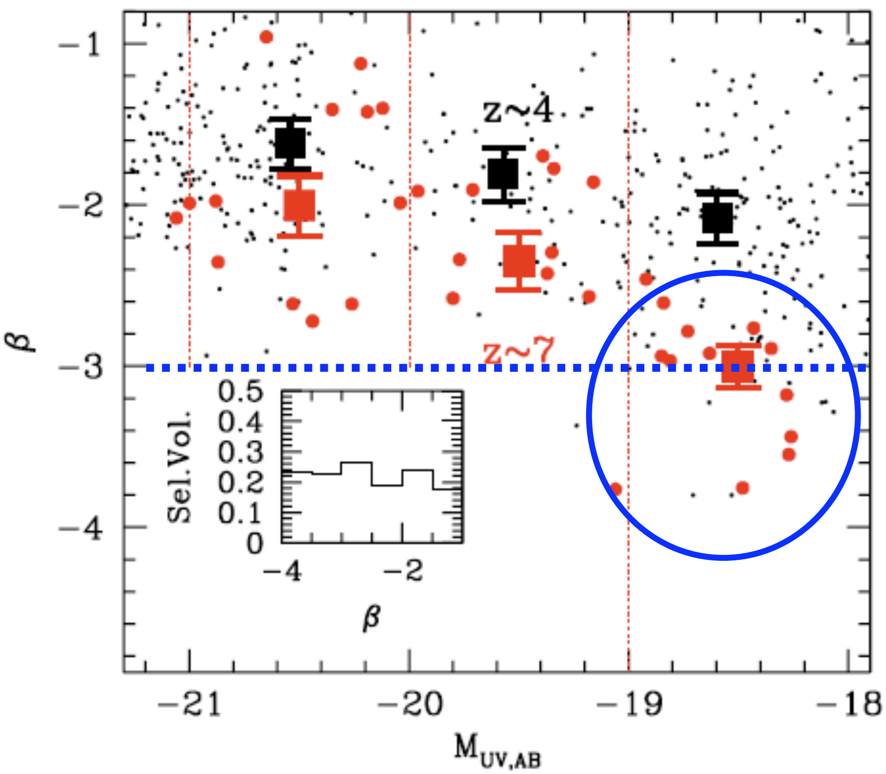


Stellar mass density at z~5-6 (and with greater uncertainty at z~7) implies past SF in low luminosity galaxies may be sufficient for reionization, especially if escape fraction of photons is >0.2

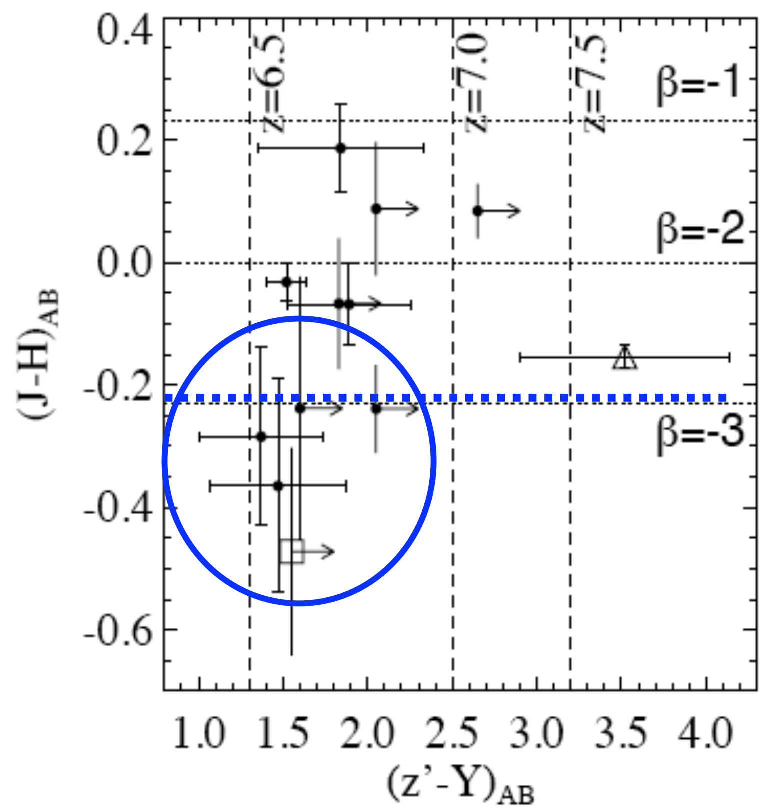
Stark et al 2007,2009; Labbé et al 2009

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 $\beta \rightarrow -3$!

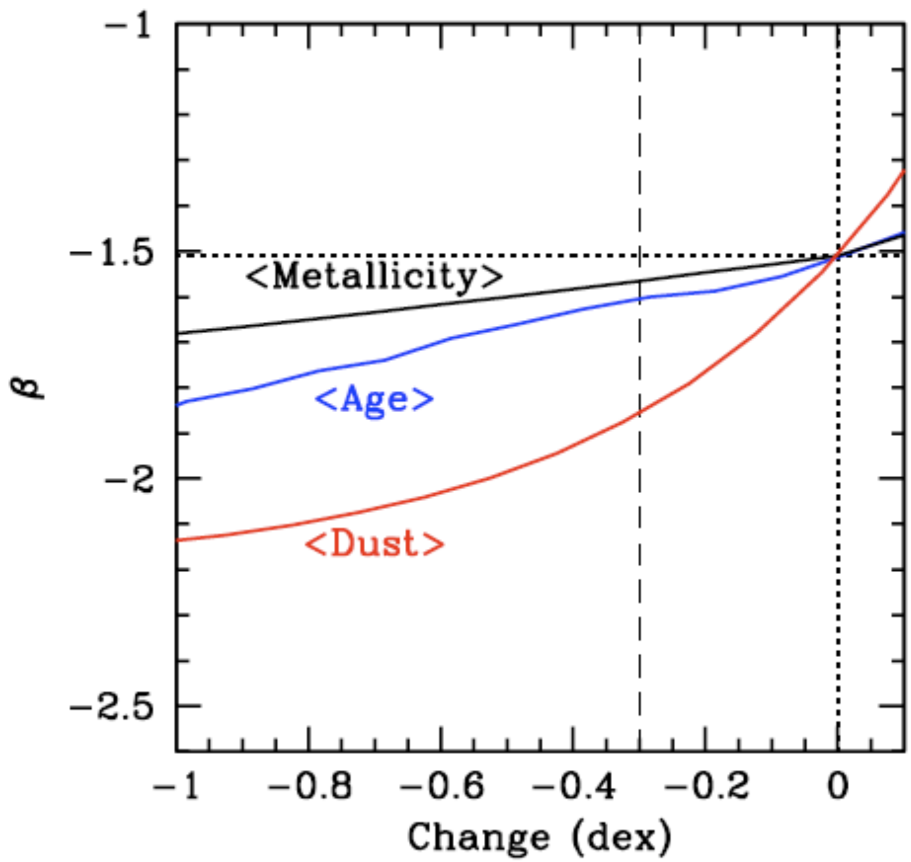


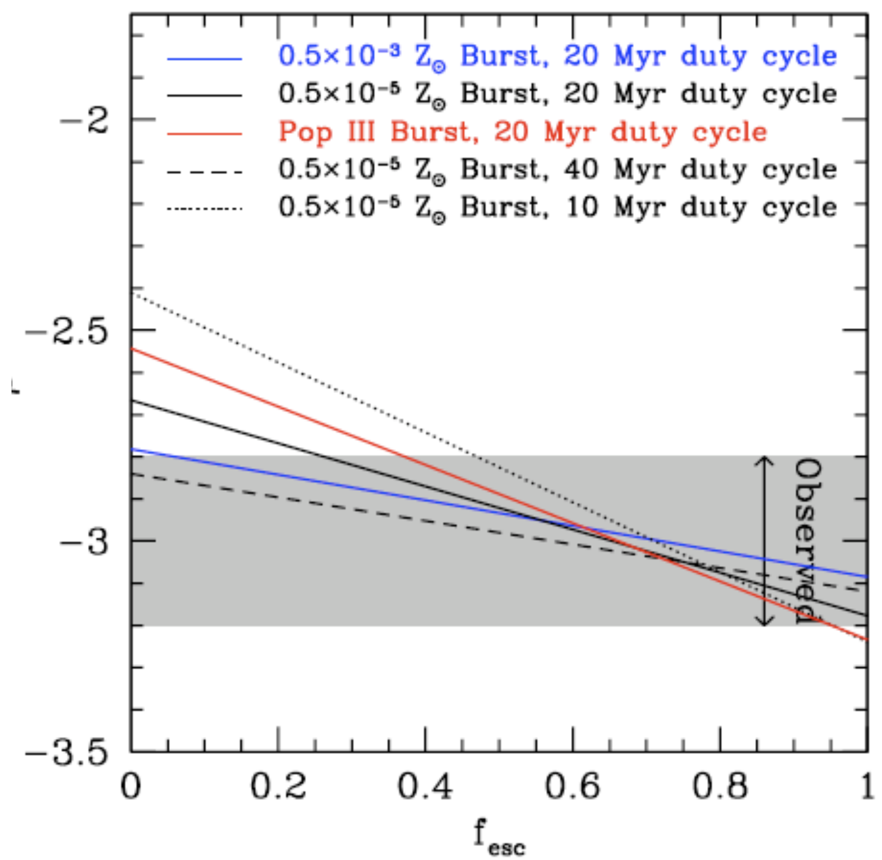
Bouwens et al 2009



Bunker et al 2009

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





- Can reproduce β > -2.5 with dust-free young stars with $Z \sim 0.1 Z_\odot$
- 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

Summary

- Discussed various independent & indirect probes of cosmic reionization suggestive of star formation in interval $6<z<12$
- The HI troughs in SDSS QSOs - the arguments rely on a subtle change in properties below and above $z\sim5.5$
- Decline of CIV to $z\sim6$ in deep intergalactic space - they can only have got there from a rapid early period of SF $z > 6$
- WMAP polarization from electron scattering - not as precise a pointer to the redshift of activity as reported
- The remarkable amount of assembled mass at $z\sim5$ - perhaps the best pointer to much SF $z > 5$
- Puzzling decline in abundance of Lyman alpha emitters $5.7<z<6.6$
- Initial results from WFC3/IR – much cosmic variance and other uncertainties but suggestive of steep UV slopes from Pop III stars

Discussion Topics

1. How reliable is claim that QSO spectra indicate the neutral era ended just before z~6?

Consider tests other than Gunn-Peterson: Fan et al ARAA 44, 415 (2006)

Consider the counter-arguments raised: Becker et al Ap J 662, 72 (2007)

2. Lyman alpha as a tracer of reionization

Classic papers: Miralda-Escude Ap J 501, 15 (1998)
Santos MNRAS 349, 1137 (2004)

Observational tests: Malhotra & Rhoads Ap J 617, L5 (2004)

Kashikawa et al Ap J 648, 7 (2006); Ouchi et al (in prep)

3. First results from WFC3/IR

Steep continuum slopes: Bunker et al 0909.2253; Bouwens et al 0910.0001

Models of Pop III spectra: Schaerer A&A 397, 527 2003& refs therein