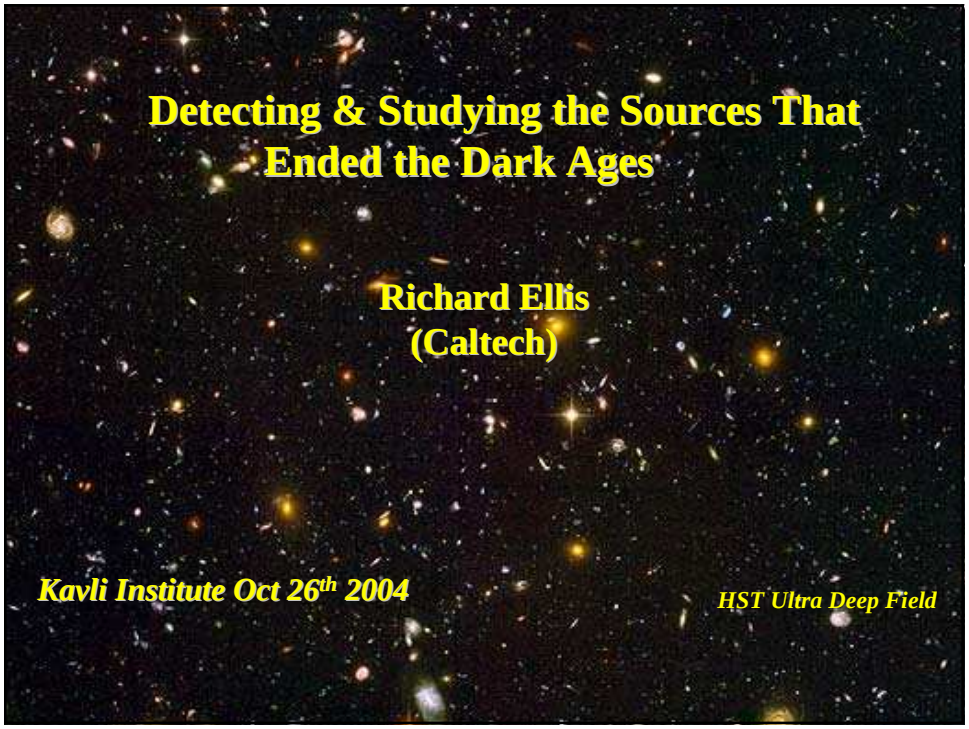


Motivation

• Significant evidence (theory, IGM metals, G-P trough and WMAP TE) that reionization occurred earlier than z~6

• Star forming systems appear the most promising candidate

• Can we trace this star formation and find the relevant epoch when the bulk of hydrogen was reionized?

• Early systems will be very faint (not just distance but also modest stellar masses)

• z ~ 7 and beyond is technically very hard; motivating JWST & TMT

• Any information on the surface density/luminosity of sources would be useful in designing future surveys

Strategy

Goal is to constrain surface density/luminosity of typical sources and characterize a few in detail

Two-pronged approach:

(i) Survey for abundance of star-forming sources in deep datasets (GOODS, UDF)

(ii) Detailed examination of highly magnified examples viewed through well-constrained cluster lenses

Collaborators:

Stark, Smith, Kneib (Caltech)

Bunker, Stanway, Santos (IoA, Cambridge, UK)

Egami, G. Rieke (U Arizona)

Reionization Photon Budget

e.g. Madau, Haardt & Rees (1999):

$$\dot{\rho}_{\rm SFR} \approx 0.013\, f_{\rm esc}^{-1} \left(\frac{1+z}{6}\right)^3 \left(\frac{\Omega_b\, h_{50}^2}{0.08}\right)^2 C_{30}\, M_\odot\, {\rm yr}^{-1}\, {\rm Mpc}^{-3}$$

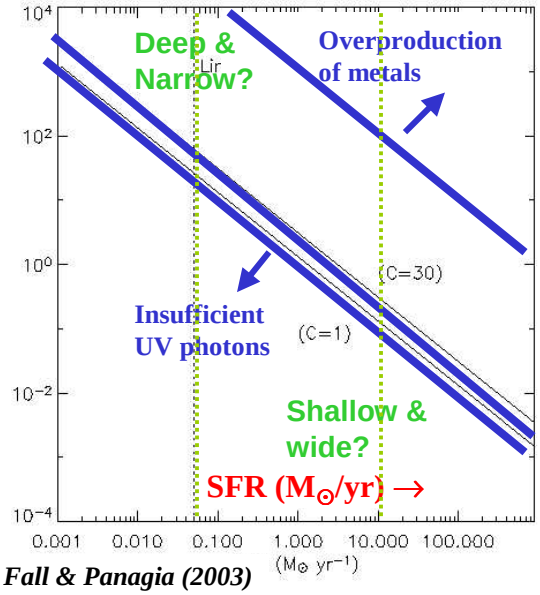
Input details depend on imponderables:

- $T_{IGM} \approx 10{,}000 - 20{,}000$ K ?
- T_{eff} & Z of stellar population (IMF) ?
- $C = \langle \rho_{HI}^2 \rangle / \langle \rho_{HI} \rangle^2$ simulations suggest $C \approx 30$?
- f_{esc} (=1 implies no HI absorption) ?

Observational issues include redshift range of activity
faint end slope of luminosity function

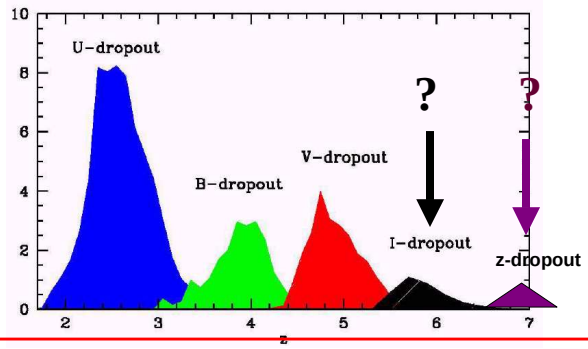
Counting Star Forming Sources

↑
Surface density of 7 < z< 10 sources (arcmin^{-2})



After Stiavelli, Fall & Panagia (2003)

Continuum sources probed via dropout technique

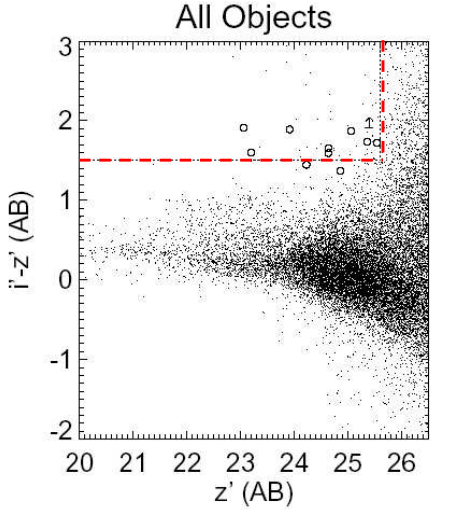


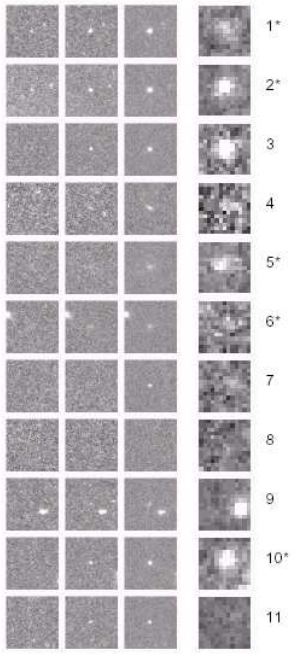
Stanway/Bunker et al: GOODS N+S (400 arcmin^2, z_{AB}<25.6, full IR, many spectra)
UDF (11.3 arcmin^2, z_{AB}<28.5, some IR, no spectra)

Yan & Windhorst: ACS: (10 arcmin^2, z_{AB}<28.3, no IR)
UDF (11.3 arcmin^2, z_{AB}<29.2, no IR, no spectra)

Bouwens et al: ACS GTO (46 arcmin^2, z_{AB}<27.3, limited IR, no spectra)
UDF NICMOS (5.7 arcmin^2, H_{AB}<28.0, no spectra) probes to z~7

Stanway et al (2004) Ap J 607, 704



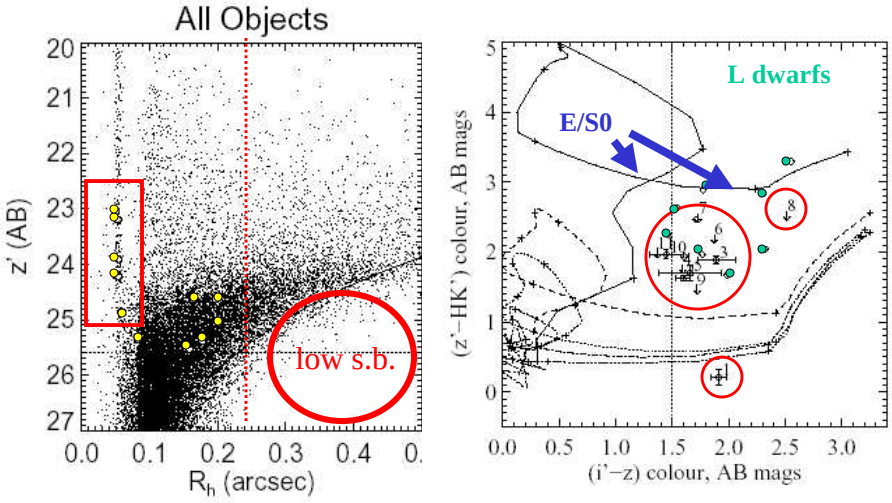


GOODS-N catalog within reach of Keck

Selection based on v,i,z, HK(Cowie)

z(AB) < 25.6 i-z > 1.5: 11 candidates

Foreground contamination serious in i-band drops

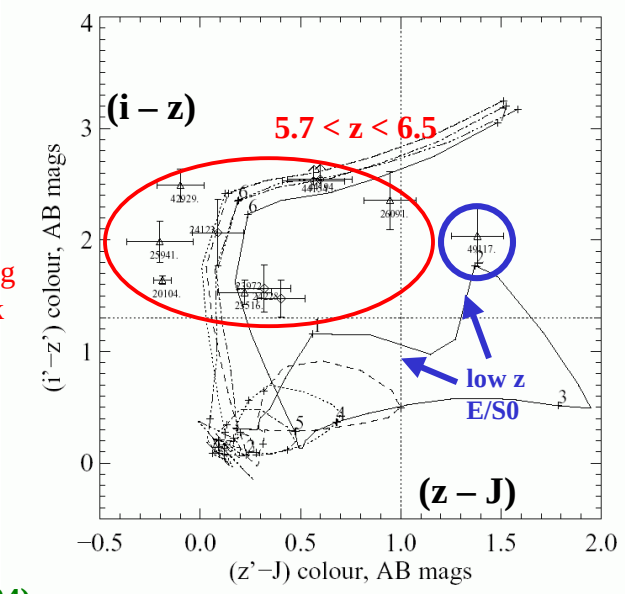


- Use HST half-light radius R_h and (*z-IR*) color to aid selection -

Note surface brightness biases – may miss low s.b. contributors

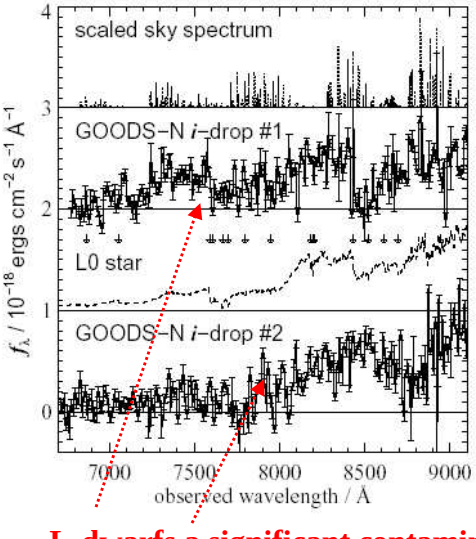
Improved Discrimination with NICMOS UDF data

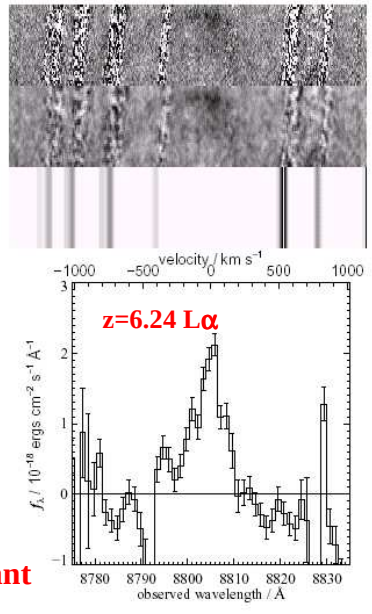
NICMOS coverage of center of UDF permits a more precise examination of 27 i-drop candidates supporting the idea that the bulk of the candidates are at z ≈ 6



Stanway et al (2004)

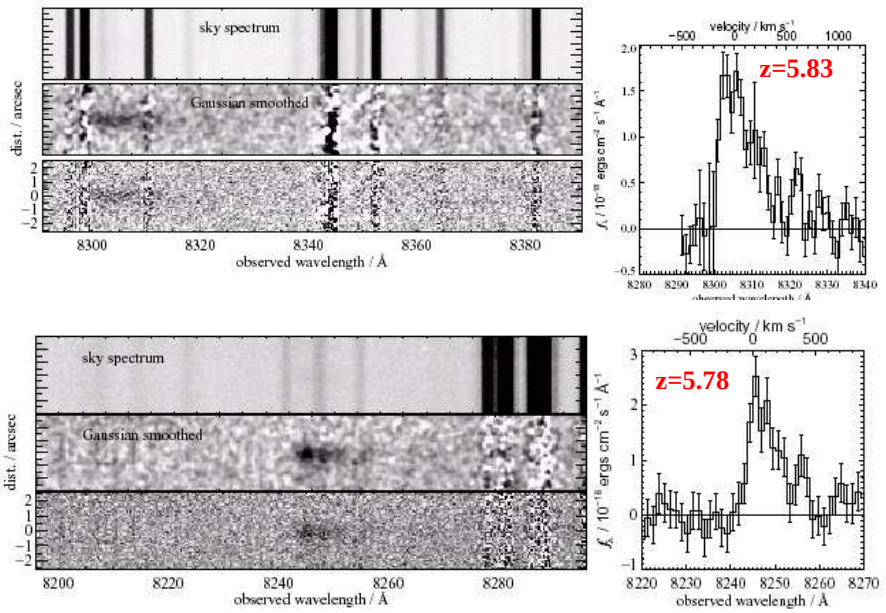
Keck II DEIMOS spectroscopy: April 2003 10.5 hrs integration



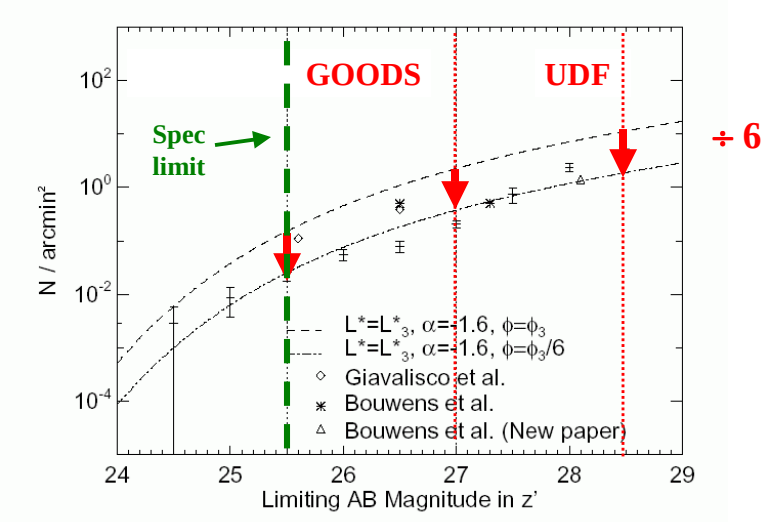


L-dwarfs a significant contaminant

More convincing Lα emitters (GOODS-S)



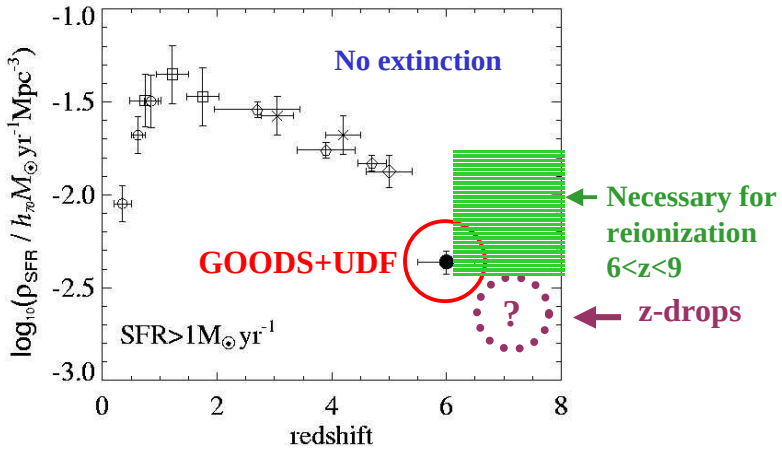
Number counts for i-band dropouts (GOODS+UDF)



GOODS/UDF data to z_{AB}=28.5 consistent with z=3 LBG LF but ÷ 6

Bunker et al (astro-ph/0403223)

Combining UDF + GOODS reduces LF uncertainty & provides interesting limit on UV emission at z ~ 6



Significant decline in UV emissivity (L > 0.1L*) to z=6:

Bunker, Stanway, Ellis & McMahon (astro-ph/0403223)

Possible Deductions from Low Abundance of i-drops

Reionization did end at z~6

- Theoretical uncertainty: data matches lower bound of expectations e.g. low metallicity, non-standard IMF (Stiavelli et al 2004)
- Cosmic variance: UDF (40%), GOODS (10%): observations underestimate true abundance of z~6 SF sources
- Steeper faint end slope for SF LF (Yan & Windhorst 2004)

Reionization ended at higher redshift:

- Significant abundance of objects at earlier times? Find them!

Reionization was not caused by star-forming systems

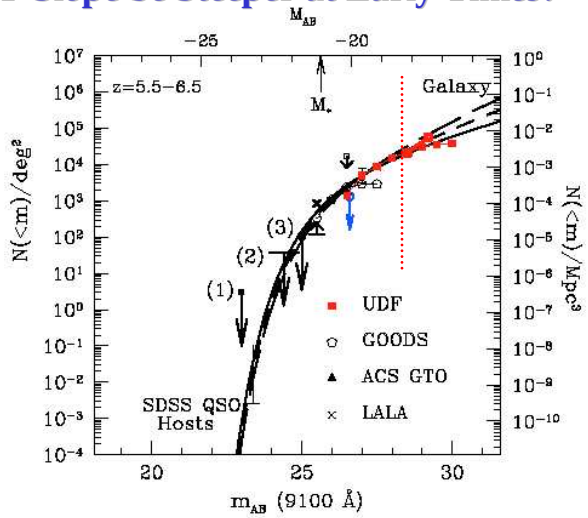
- Cannot exclude until we probe deeper in redshift space

Could LF Slope be Steeper at Early Times?

i-drop counts

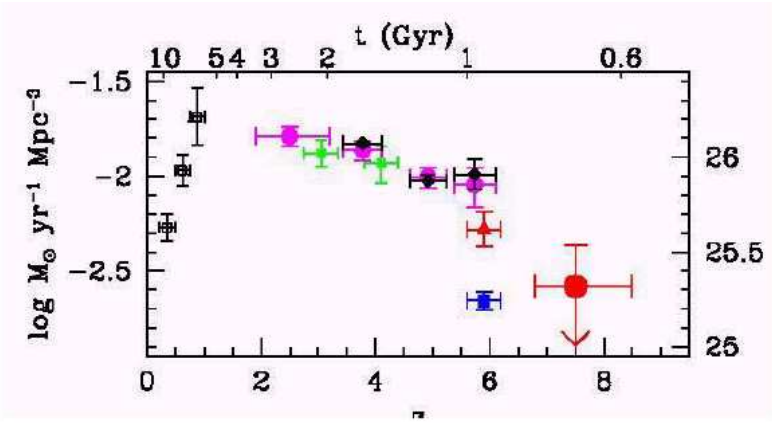
N(28.5) = 54

N(30.0) = 108



Yan & Windhorst (2004) extend UDF i-drop search to z(AB)=30.0 (c.f. Bunker et al z(AB)=28.5) and claim $\alpha \approx -1.9$ after correcting for incompleteness implying a significant increase in integrated density at z~6

Extending Technique to z-drops using NICMOS

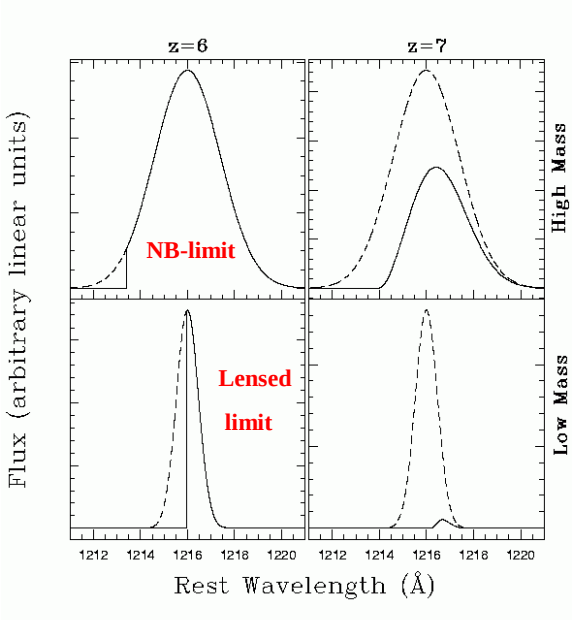


Bouwens et al (2004) extend search with NICMOS to find z-drops:

- 3σ limit of H(AB)=28.0; JH photometry only
- 4 candidates in 144 × 144 arcsec UDF NICMOS field (no spectra)

Lyα: Better Indicator of Reionisation?

- **Effficient tracer of SF in young galaxies (<8% of integrated output)**
- **Lyα damping wing is absorbed by HI and thus valuable tracer of its presence.**
- **In weaker systems, such as those found via strong lensing, it may be a *sensitive probe of reionisation***



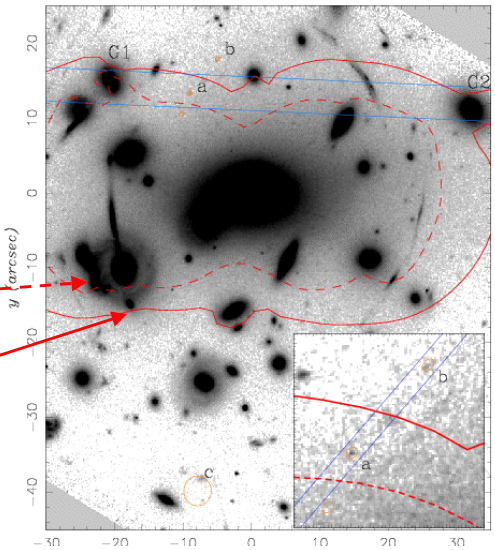
Critical Line Mapping with Keck

From arclet spectroscopy the location of the "critical lines" is known precisely for

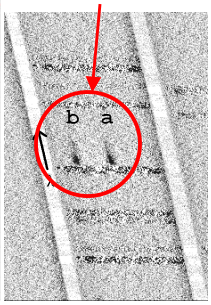
z=1

and for

z=5

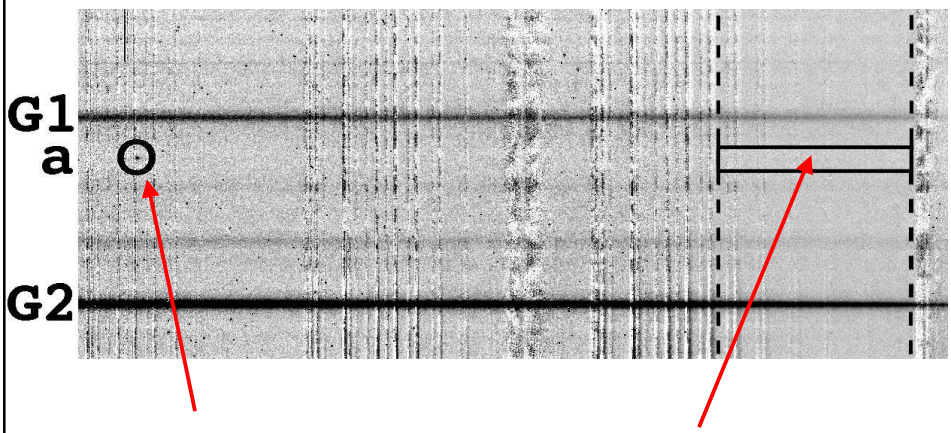


Blind Lyα search with LRIS: hi-res follow-up with ESI



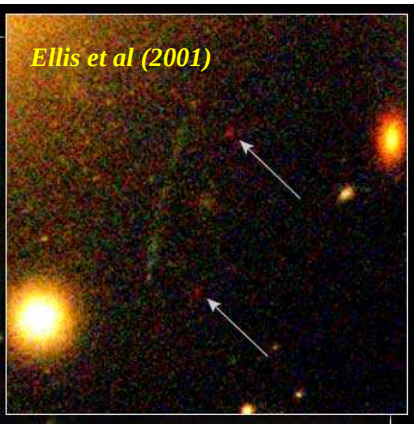
Utilizing strong magnification (×10-30) of clusters, probe much fainter than other methods in small areas (<0.1 arcmin^2 cluster^{-1})

Longslit search with LRIS



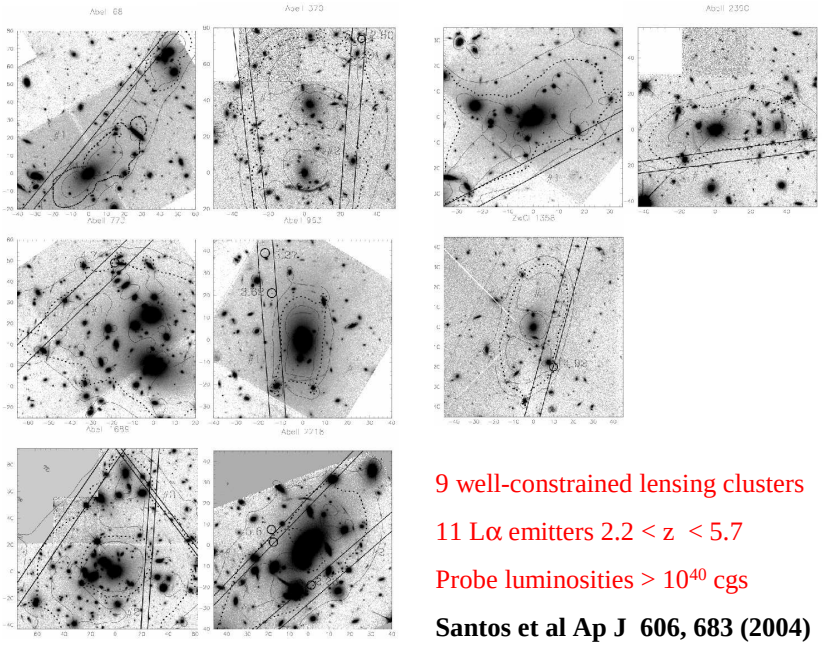
Candidate Lyman alpha (z=5.7) with no detectable stellar continuum

Low mass system at z=5.7



- **Magnification of x30 in Abell 2218 → unlensed Lα flux is 2. 10^{-18} cgs; 20 × fainter than limit for unlensed searches**
- **Unlensed Lα luminosity (10^{42} cgs) implies SFR ≈ 0.5 $M_\odot$ yr^{-1}**
- **Faint stellar continuum (<6. 10^{-21} cgs $Å^{-1}$) implies age < 1-2 Myr; forming globular cluster?**

Mass Production



9 well-constrained lensing clusters

11 Lα emitters 2.2 < z < 5.7

Probe luminosities > 10^{40} cgs

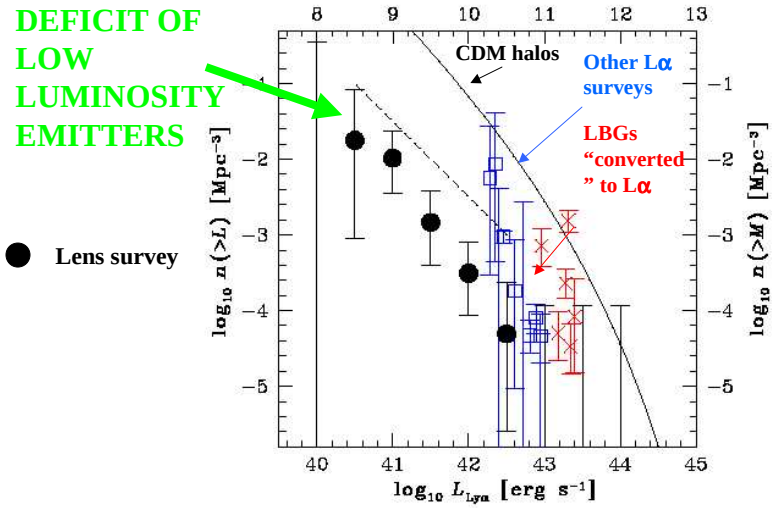
Santos et al Ap J 606, 683 (2004)

Cumulative Lyα LF: 4.7<z<5.7

Santos, Ellis, Kneib & Kuijken Ap J 606, 683 (2004)

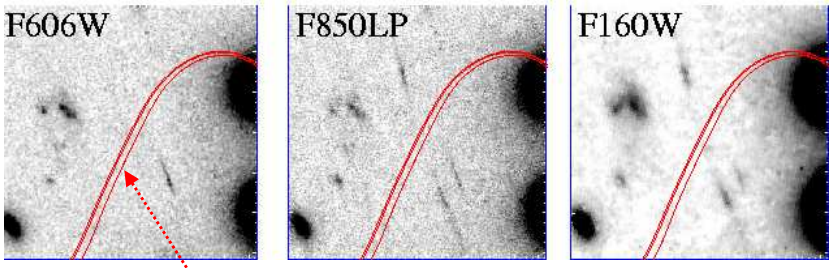
log M(halo)

DEFICIT OF LOW LUMINOSITY EMITTERS



Suppression of intrinsically faint Lα emitters may indicate HI at z~5-6

Lensed z-band drop-out in Abell 2218



Critical lines refer to z_s = 5, 6, 7 & indicate z_s > 6

Lens magnification = ×25

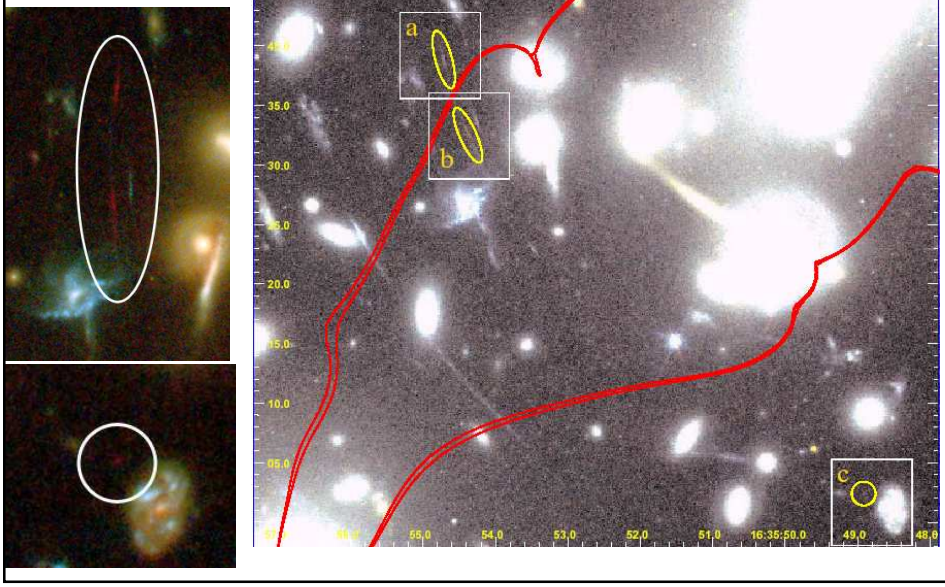
Intrinsic flux (unlensed) z =28.5; H=26.5 (~UDF limit)

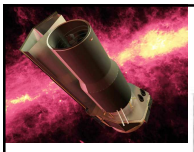
UV-inferred SFR ≈ 2.6 $M_\odot$ yr^{-1}

Physical Size: 1.2 × <0.5 kpc

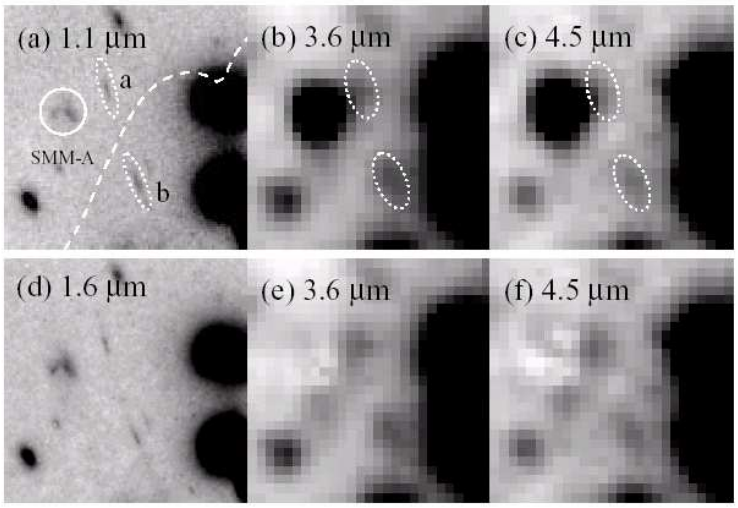
Kneib et al Ap J, 607, 697 (2004)

Multiple images provide crucial lower z limit





Spitzer Detection of Lensed z~7 Pair



IRAC flux densities: $f_\nu(3.6\mu m) = 1.2 \pm 0.3$ μJy

$f_\nu(4.5\mu m) = 1.0 \pm 0.2$ μJy

SED Implies Established Stellar Population @ z~7

Key parameters:

SFR = 2.6 $M_\odot$ yr^{-1}

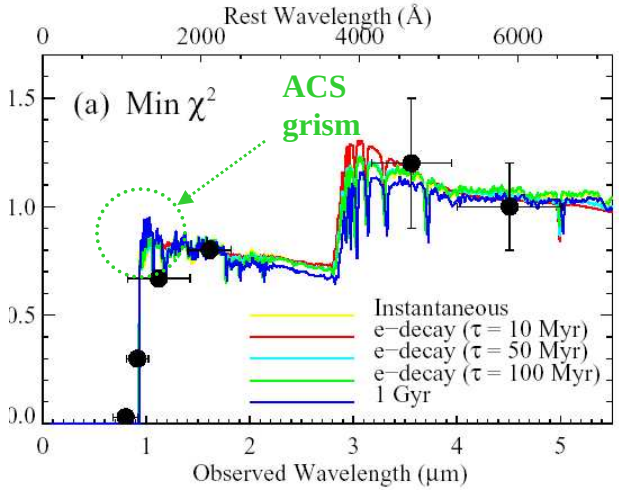
M_{star} ~ 5-10 10^8 $M_\odot$

z ~ 6.8 ± 0.1

age 40 – 450 Myr
($7 < z_F < 12$)

Age > e-folding SF time ⇒ **more luminous during active phase?**

(Egami et al 2004, Ap J in press)



Given small search area, such sources may be very common

Piecing It Altogether..

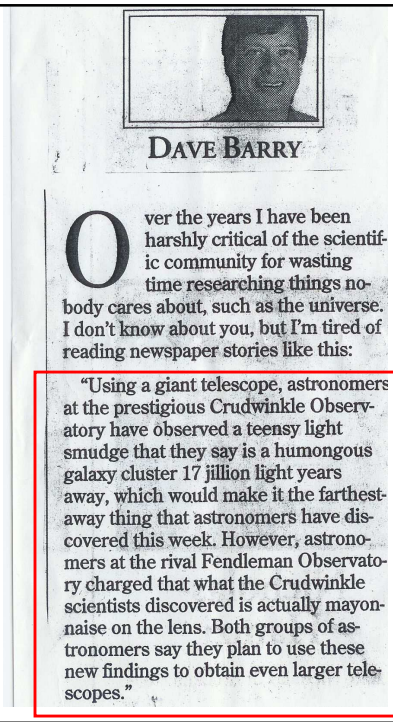
• Low abundance of i- and z-band dropouts suggests extended SF history prior to z~6 if SF galaxies are responsible for reionization

• Spitzer/HST photometry of lensed source in Abell 2218 identifies a clear example; given tiny survey area, such sources are likely to be very common

• If such sources are responsible for ending reionization, their low abundance either means the LF is steep (Windhorst & Yan) or they have steep UV continua (Stiavelli et al)..or the theoretical predictions are in error.

• If these sources are not responsible (& regardless), surveying for more z > 7 sources is a valuable test and likely to deliver data

Onward into the Dark Ages – warning from an independent commentator…

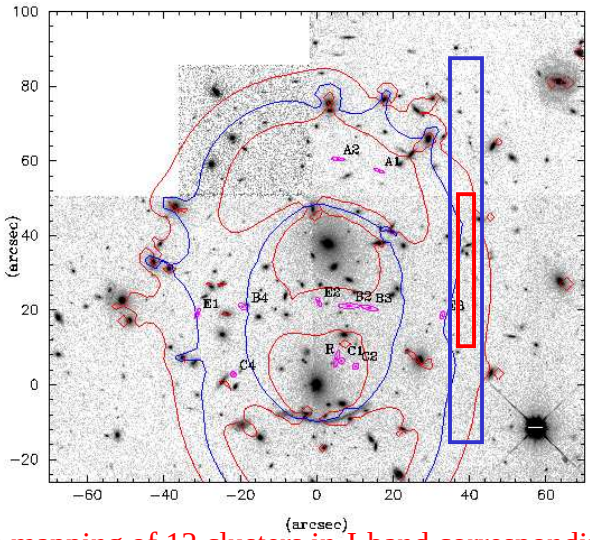


DAVE BARRY

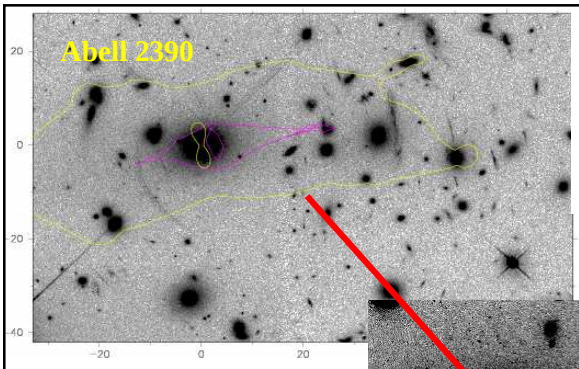
Over the years I have been harshly critical of the scientific community for wasting time researching things nobody cares about, such as the universe. I don't know about you, but I'm tired of reading newspaper stories like this:

"Using a giant telescope, astronomers at the prestigious Crudwinkle Observatory have observed a teensy light smudge that they say is a humongous galaxy cluster 17 jillion light years away, which would make it the farthest-away thing that astronomers have discovered this week. However, astronomers at the rival Fendleman Observatory charged that what the Crudwinkle scientists discovered is actually mayonnaise on the lens. Both groups of astronomers say they plan to use these new findings to obtain even larger telescopes."

Where Next?

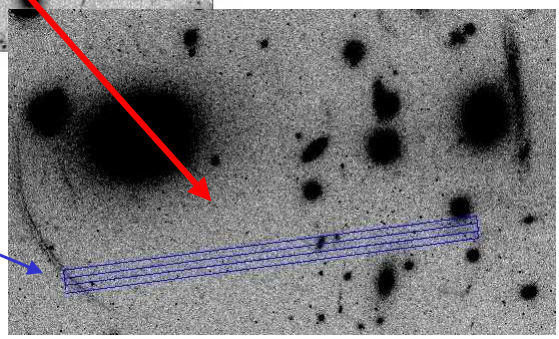


Critical line mapping of 12 clusters in J-band corresponding to Lyα in $8 < z < 10$ with sensitivity down to $< 0.1\ M_\odot\ yr^{-1}$ where surface densities of > 100 arcmin^{-2} can be tested



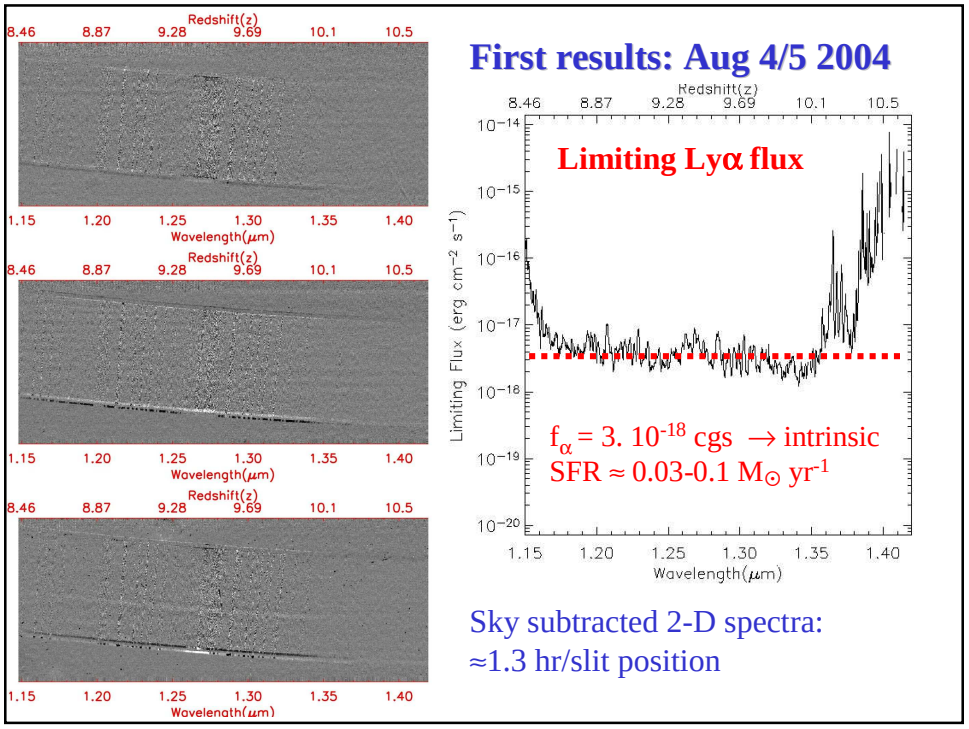
New NIRSPEC search for lensed Lα emitters with 8 < z < 10

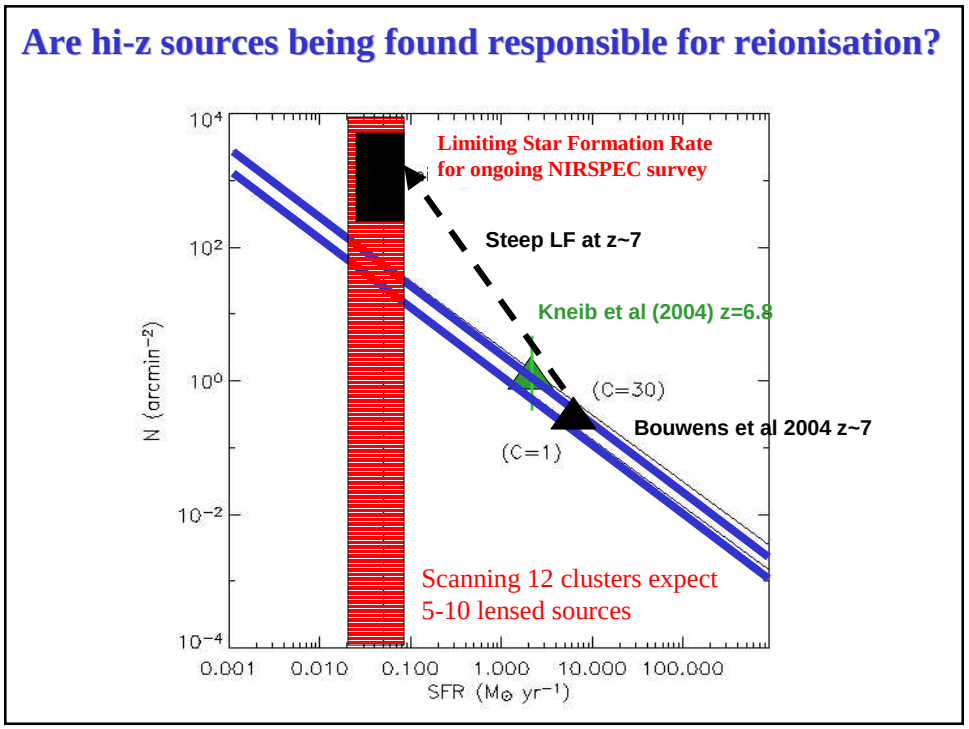
(Stark, Smith +RSE)



NIRSPEC J-band
42 ×0.75 arcsec slit
magn. > × 10 (all)
> × 30 50%
up to × 100

Critical line mapping of 12 clusters in J-band corresponding to Lyα in $8 < z < 10$ with sensitivity down to $< 0.1\ M_\odot\ yr^{-1}$


First results: Aug 4/5 2004
Redshift(z)
8.46 8.87 9.28 9.69 10.1 10.5
1.15 1.20 1.25 1.30 1.35 1.40
Wavelength(μm)
Limiting Lyα flux
Limiting Flux (erg cm⁻² s⁻¹)
10⁻¹⁴ 10⁻¹⁵ 10⁻¹⁶ 10⁻¹⁷ 10⁻¹⁸ 10⁻¹⁹ 10⁻²⁰
f_α = 3. 10⁻¹⁸ cgs → intrinsic
SFR ≈ 0.03-0.1 M⊙ yr⁻¹
Sky subtracted 2-D spectra:
≈1.3 hr/slit position


Are hi-z sources being found responsible for reionisation?
Limiting Star Formation Rate
for ongoing NIRSPEC survey
Steep LF at z~7
Kneib et al (2004) z=6.8
(C=30)
Bouwens et al 2004 z~7
(C=1)
N (arcmin⁻²)
10⁴ 10² 10⁰ 10⁻² 10⁻⁴
0.001 0.010 0.100 1.000 10.000 100.000
SFR (M⊙ yr⁻¹)
Scanning 12 clusters expect
5-10 lensed sources