What can we learn about galaxies at z>=4 from the observations?

Rychard Bouwens
(University of California, Santa Cruz)

Special Thanks to Garth Illingworth, Marijn Franx, Ivo Labbe, Larry Bradley, Louis Bergeron, Rodger Thompson, Dan Magee, John Blakeslee

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Far Away: Light in the Young Universe at Redshifts beyond Three

Key Science Interests

1) Galaxies as possible reionization sources
   - -- This follows from evidence from z~6 SDSS quasars and WMAP optical depth measurements that the universe was likely reionized between z~6 and 17…

2) The luminosity and masses of galaxies at these epoches are likely to build up very rapidly.

3) Galaxies at these epochs are likely to show unique and very interesting stellar populations (new IMFs, zero metallicities, and no dust)

Observations of z>=4 Galaxies in the Distant Universe

1. Distant --> Need very deep observations (typical mags >= 24 AB mag)
2. Significantly redshifted --> Need to observe these sources in the redder optical bands, infrared

Because of their faint flux levels, deep imaging data have been our principal tool (spectroscopy only works for the brightest high-redshift sources):

Measurable Properties:

Luminosities (rest-frame UV and optical),
colors (UV-continuum slope & UV-optical),
sizes and surface brightnesses,
clustering properties,
Luminosity functions...

Inferrable Properties:

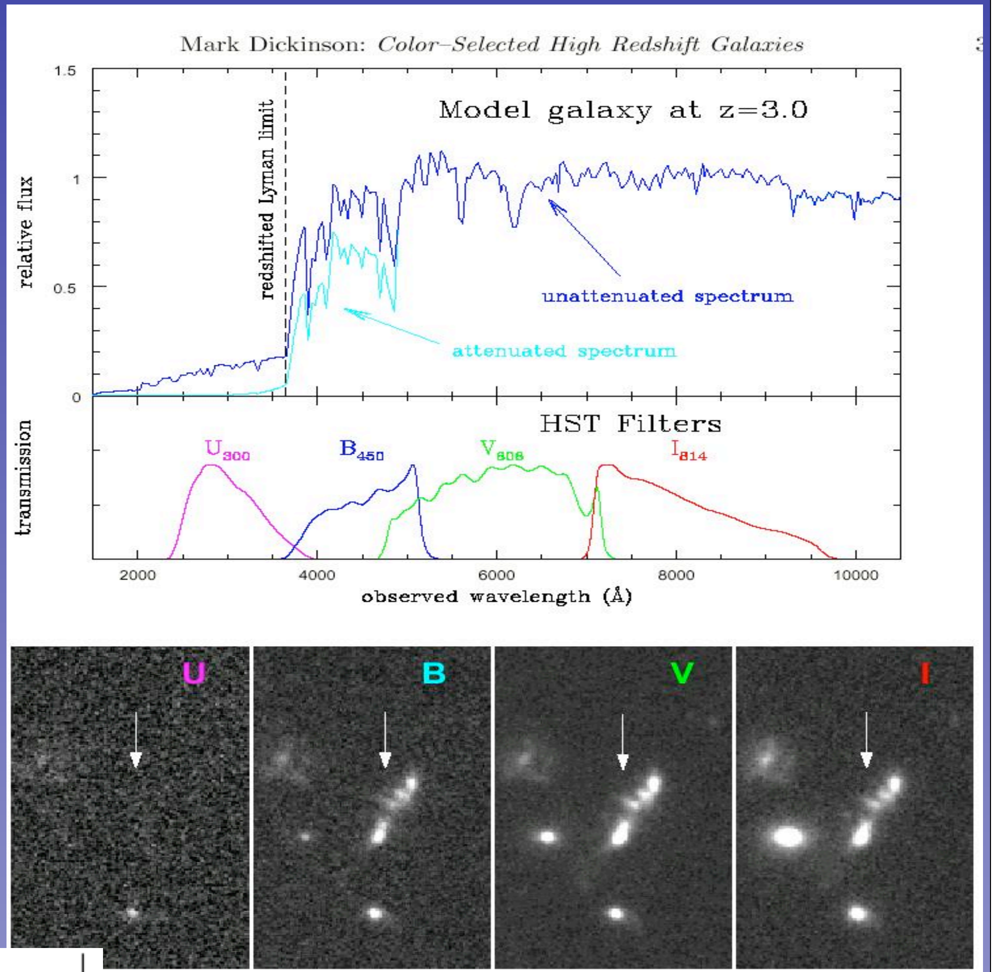
Star-Formation Rates,
Stellar Masses,
Ages,
Dust Extinctions,
Halo Masses,
Star Formation Rate Densities

Selection Techniques:

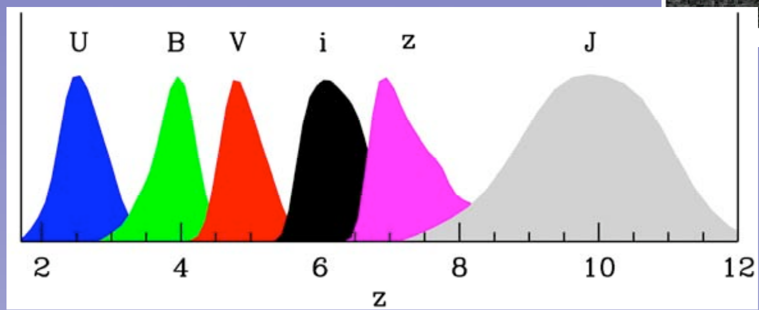
Lyman Break Galaxy ('dropout') Selection:

UV continuum slope of star-forming galaxies + sharp break in spectrum due to neutral hydrogen absorption produces unique spectral feature.

Because of the age of the universe at z>4, most galaxies are still actively forming stars.



Selection Window



Redshift

Luminosity Function of Galaxies at z~4, 5, 6

What kind of data do we want to robustly identify z>=4 galaxies?

1. **Deep optical imaging data to identify dropouts in data**
2. **High-resolution HST data to distinguish stars / quasars from extended sources (galaxies)**
3. **Remarkable photometric stability / precision with which to determine the colors/nature of distant sources**
4. **Longer wavelength mid-IR, far-IR data such as with Spitzer IRAC/MIPS and deep x-ray data**

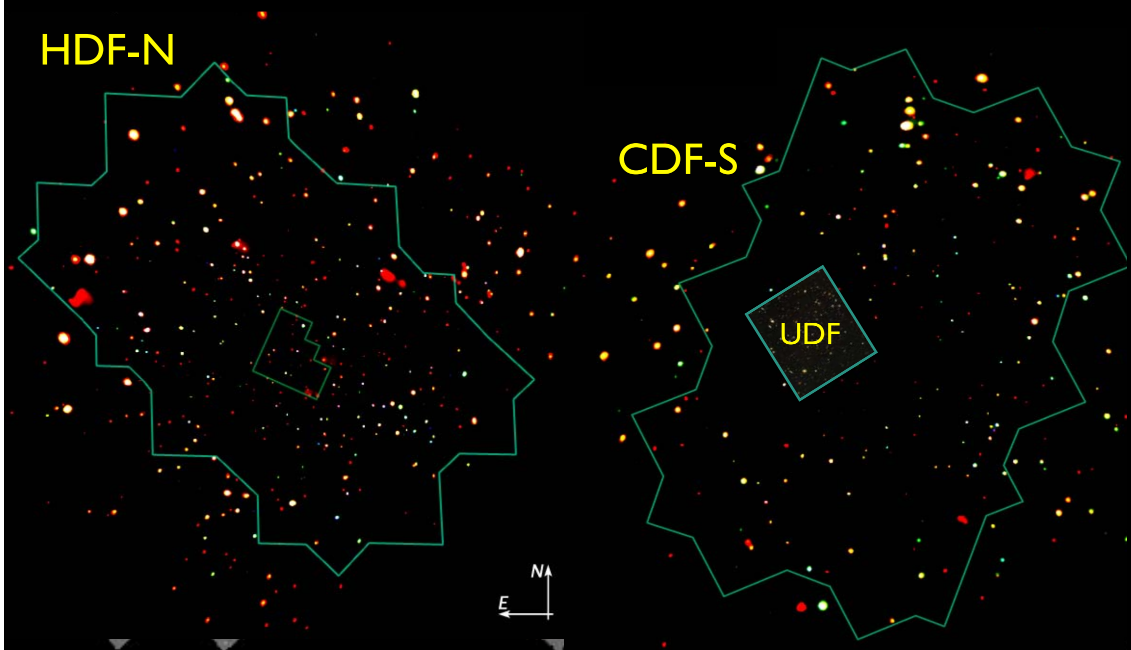
Notable Contributions:

Elizabeth Stanway, Andy Bunker, Haojing Yan, Mauro Giavalisco, Mark Dickinson, Masami Ouchi, Makiko Yoshida, Kazuhiro Shimasaku, Steve Beckwith, Massimo Stiavelli, Naveen Reddy, Chuck Steidel, Malcolm Bremer, Marcin Sawicki, Ikiru Iwata, Pascal Oesch, Laurence Tresse, Filippo Mannucci

Luminosity Function of Galaxies at z~4, 5, 6

Wide ⟷ Deep

GOODS "v2.0"



$z_{850,AB}$~ 28 (5σ)

320 arcmin^2

UDF

$z_{850,AB}$~ 29.5 (5σ)

11 arcmin^2

UDF-Parallels

$z_{850,AB}$~ 28.6-29.0 (5σ)

40 arcmin^2

4721 z~4 B-dropouts,
1415 z~5 V-dropouts,
630 *z*~6 *i-dropouts*!

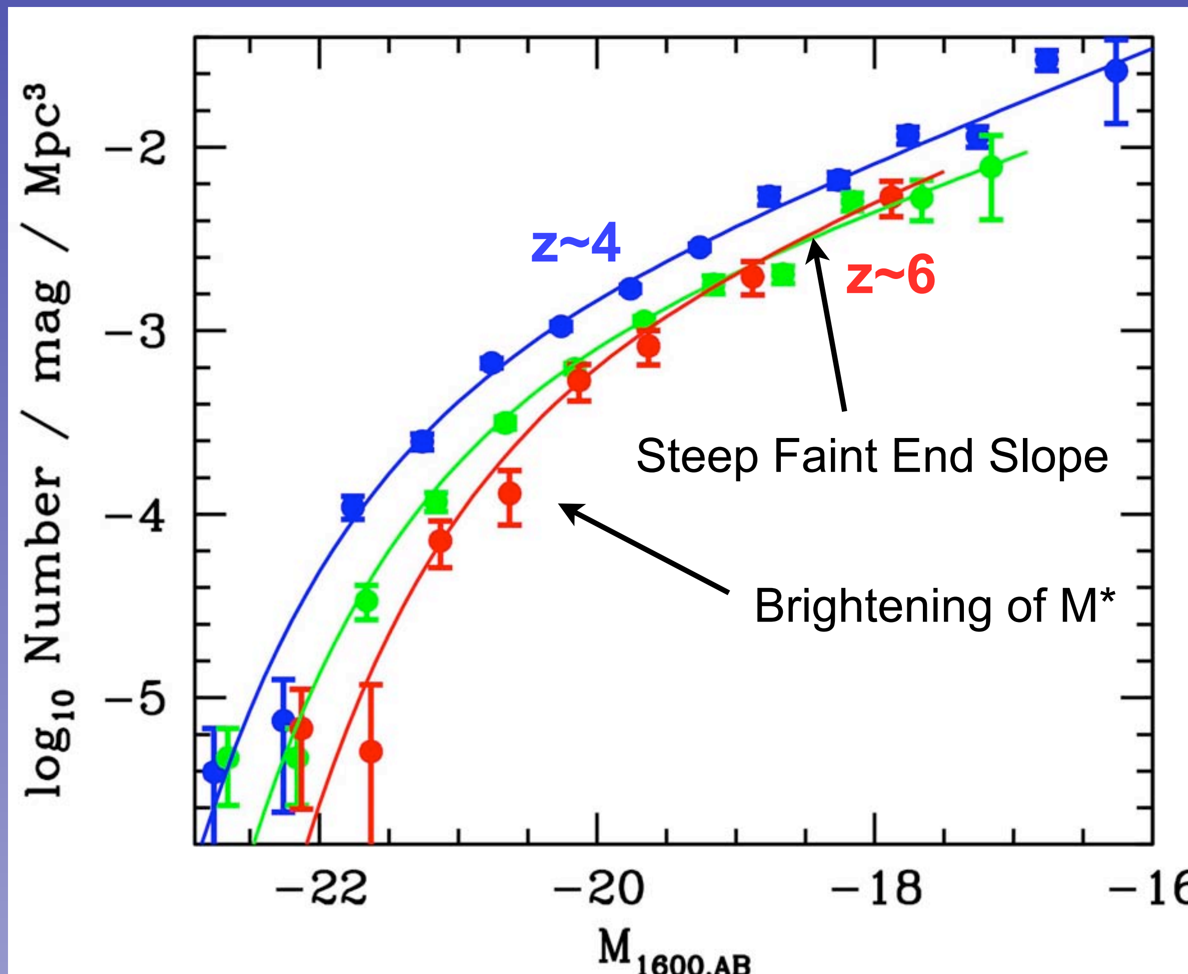
Bouwens, Illingworth, Blakeslee, Franx et al 2006
Bouwens, Illingworth et al. 2007

(see also work by Beckwith et al. 2006; Giavalisco et al.)

Galaxies at z~4, 5, 6 *(B, V, i -dropouts)*

UV Luminosity Functions

Log # mag^{-1} Mpc^{-3}



Bright Faint

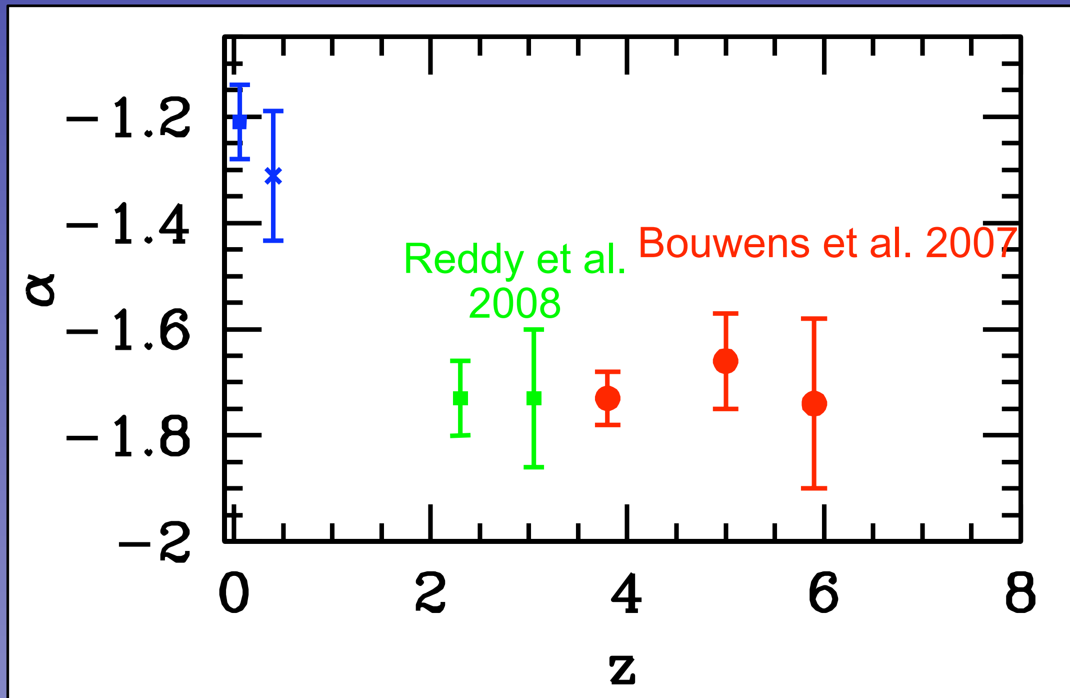
Bouwens et al. 2007

Faint-end Slope of the UV Luminosity Function

Shallow

Faint-end Slope

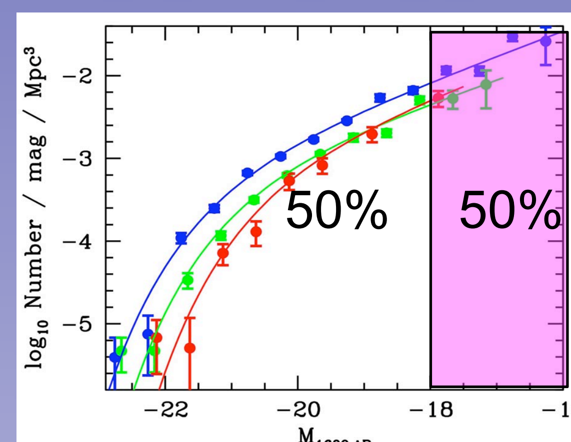
Steep



Need the deepest data to do this well, so use fields like HUDF!

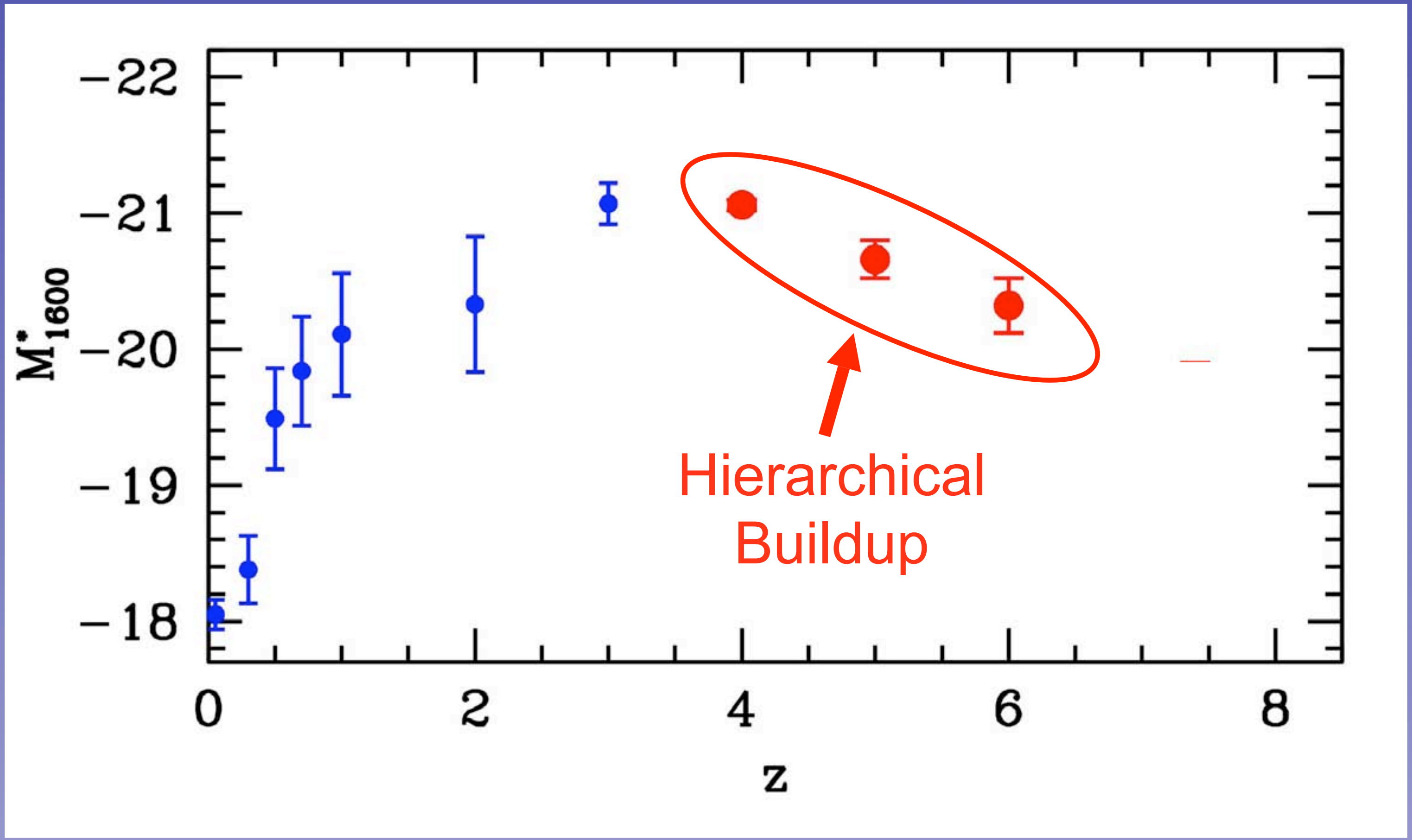
For such steep faint end slopes, the volume density of lower luminosity galaxies is substantial:

50% of the UV luminosity density is below 0.06 L*



Bouwens et al. 2007 (see also Beckwith et al. 2006 and Oesch et al. 2007)

Brightening of the M* (UV) -- maximum typical star formation rate -- with cosmic time

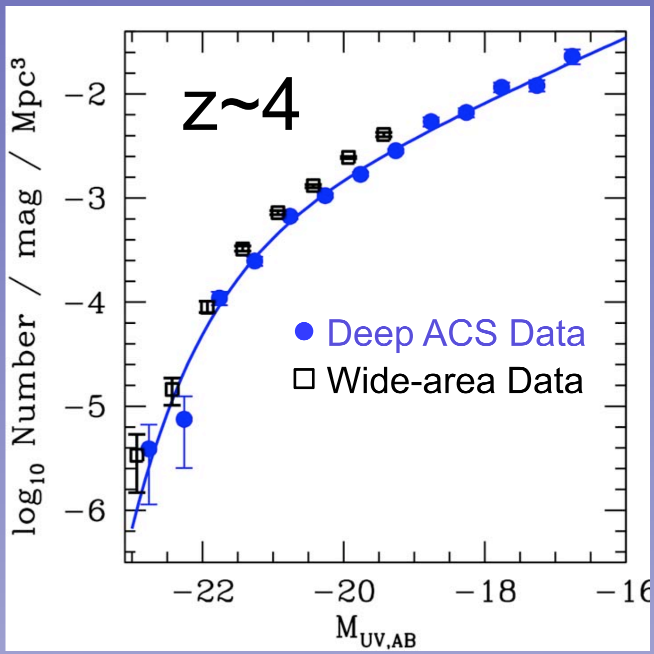


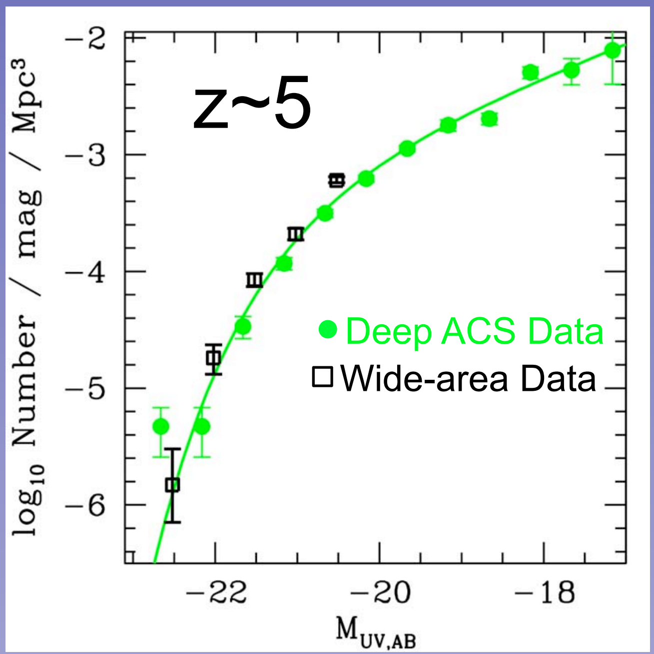
Bouwens et al. 2007

One weakness of the z~4-6 UV LF determinations from GOODS + HUDF + + ... is the limited search area to find rare, bright sources

But progress is being made using ground-based surveys:

e.g., from the Subaru Deep Field (Yoshida et al. 2006)



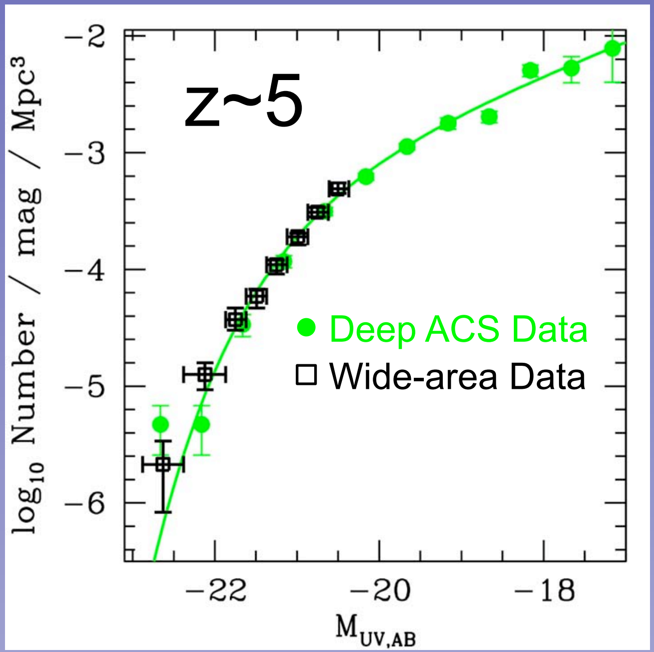


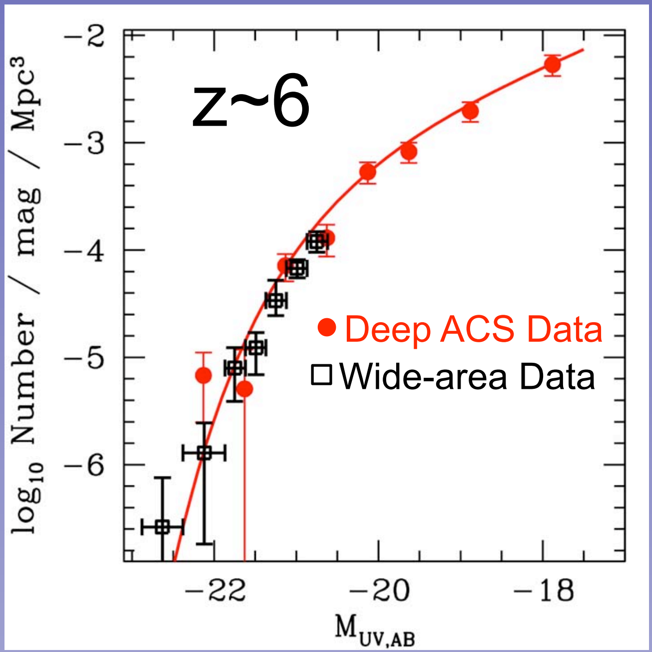
ACS LF results shown above are from Bouwens et al. 2007

One weakness of the z~4-6 UV LF determinations from GOODS + HUDF + + ... is the limited search area to find rare, bright sources

But progress is being made using ground-based surveys:

e.g., from the Subaru/XMM Deep Field + UKIDSS (McLure et al. 2008)





ACS LF results shown above are from Bouwens et al. 2007

One weakness of the z~4-6 UV LF determinations from GOODS + HUDF + + ... is the limited search area to find rare, bright sources

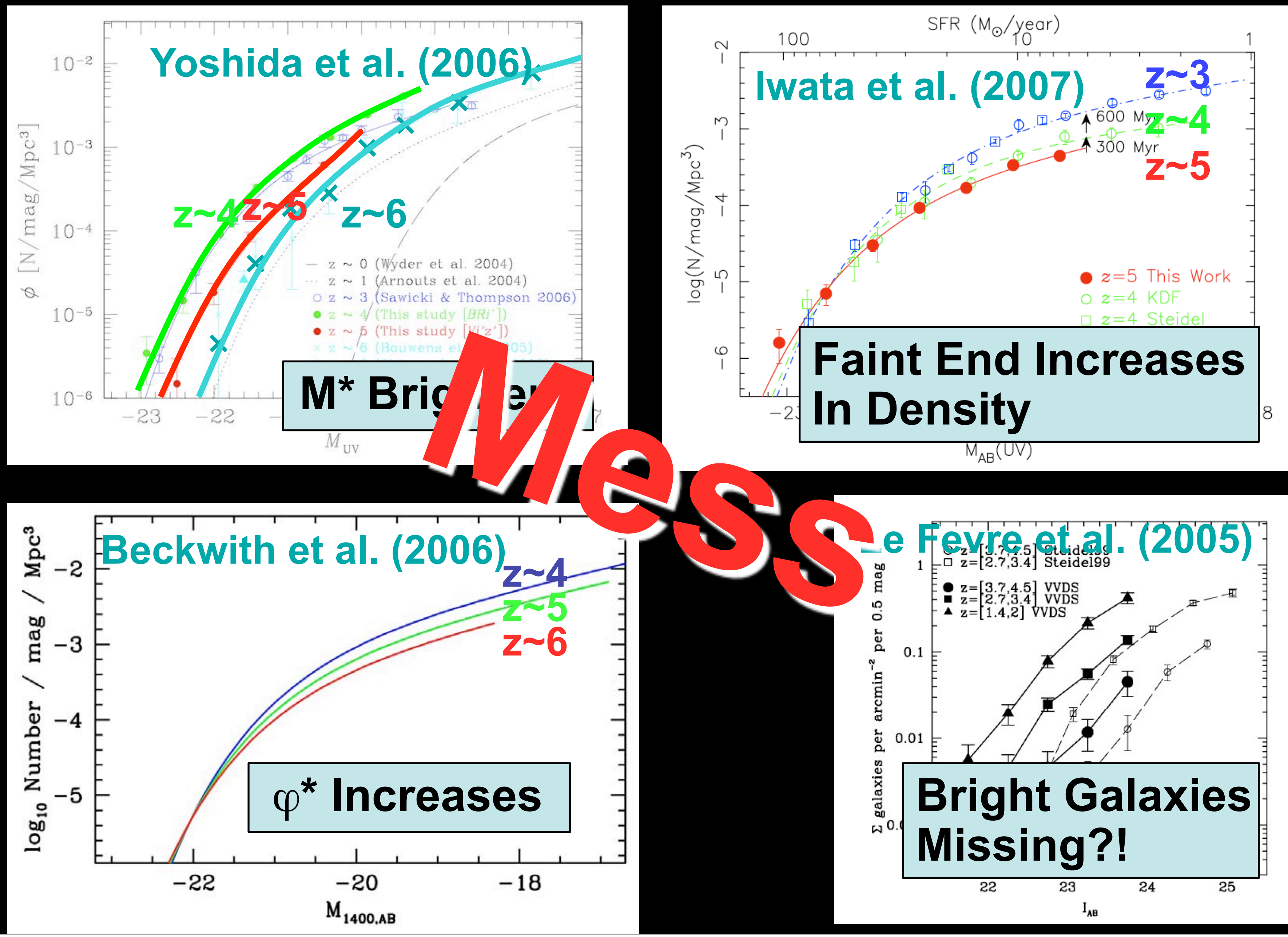
But progress is being made using ground-based surveys:

e.g., reasonable agreement is also found at z~5 from the EDICS fields + CDF-South GOODS (preliminary determinations by Bremer & Stanway)

Differences are found relative to Iwata et al. 2007 (contamination??? -- spectroscopic follow-up on-going)

Determining the bright end of the LF from ground-based data is challenging (see talks by Bremer & Stanway)

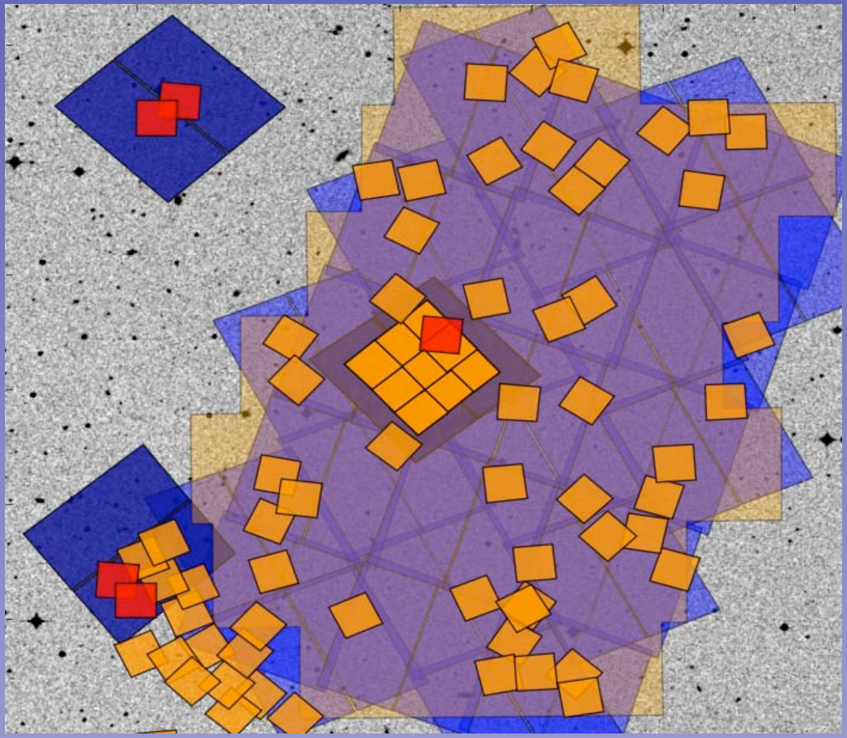
Many divergent evolutionary findings at z>=3



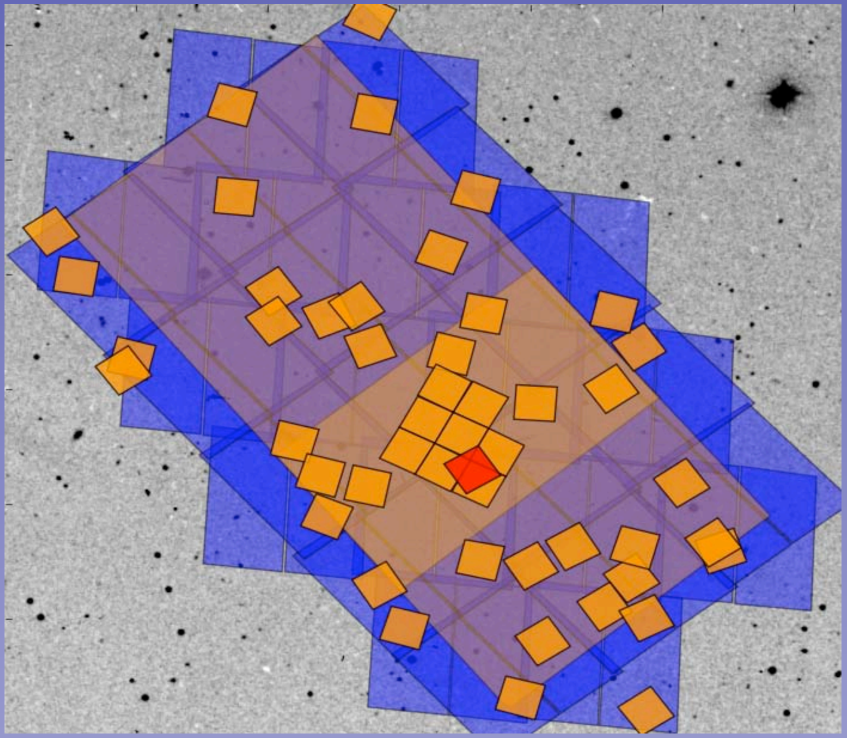
Higher-redshift (z>=7) dropout selections possible with deep near-IR/optical data

Many fields with deep ACS and NICMOS data for dropout searches

~76 arcmin^2 of Deep (J_{110} ~ H_{160} >= 26.5 AB mag) NICMOS coverage



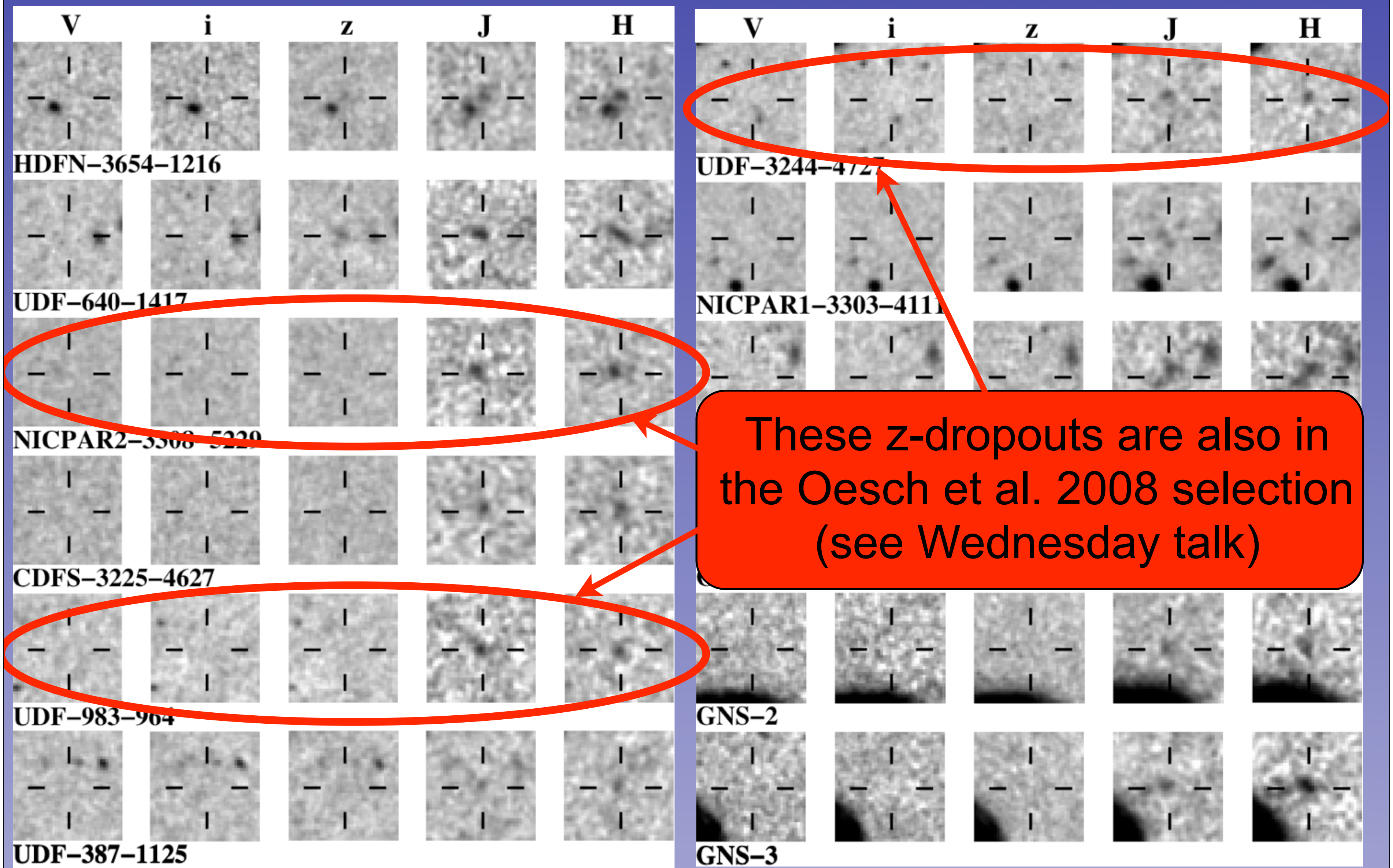
CDF-S GOODS



HDF-N GOODS

~163 arcmin^2 of Deep (J >= 25.3 AB mag) ground-based coverage

12 candidate z~7 z-dropouts



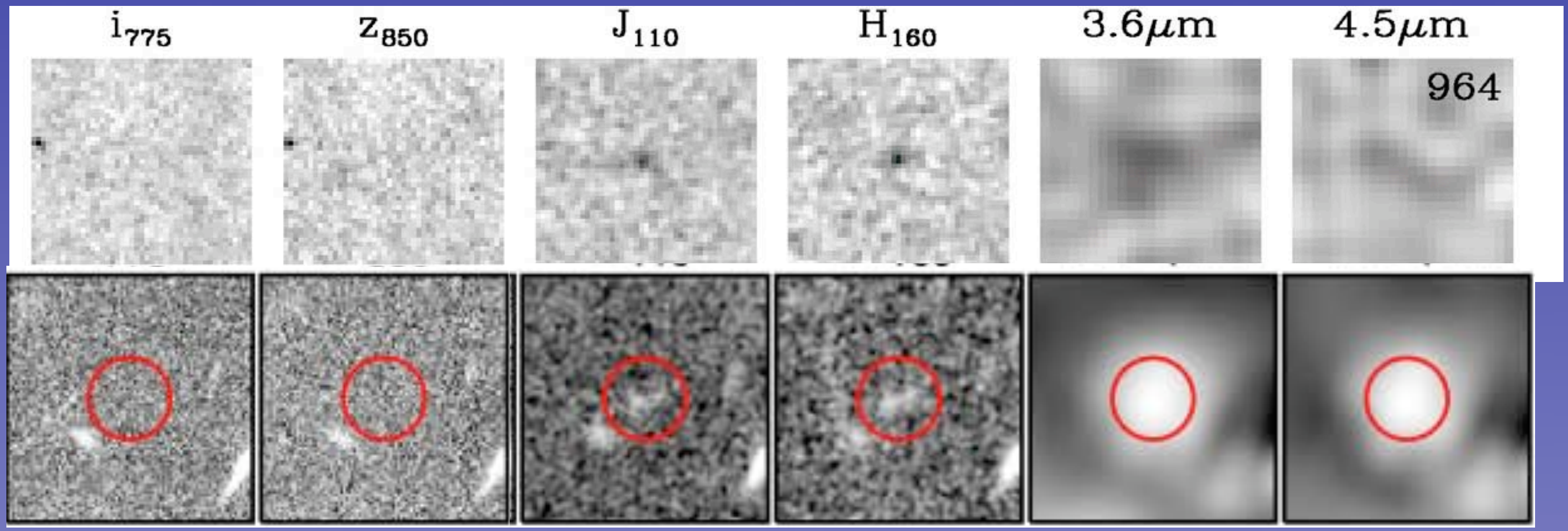
but

no z~9 J-dropout candidates

J-dropout Criteria:

J-H > 1.3,
H - K < 1.5 (where available)
H - 3.6 μm < 2.5

Are we really finding z>7 galaxies?

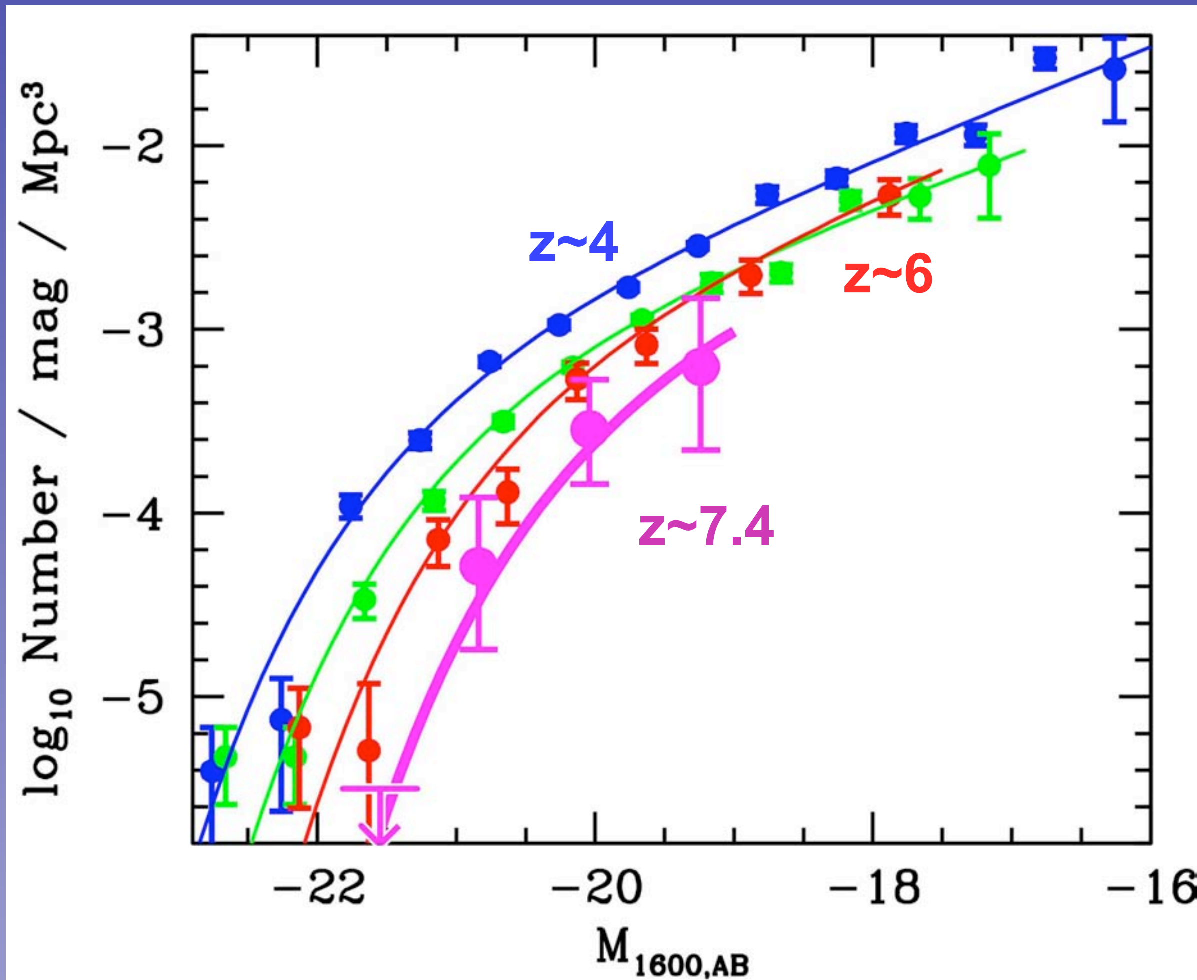


- 5 sigma detections in J, H, IRAC 3.6m channel, and 2.5 s in IRAC 4.5 m channel
- Very Blue J - H colors
- Undetected in the HUDF B, V, i, and z band imaging
- (z-J) > 3 -- too red to be a brown dwarf
- (H - 3.6m) colors similar to z~6 objects

Labbe, Bouwens, Illingworth, Franx 2006; Bradley et al. 2008

Galaxies at *z~4, 5, 6, 7.4 (B, V, i, z-dropouts)*

Log # mag^{-1} Mpc^{-3}



Bright

Faint

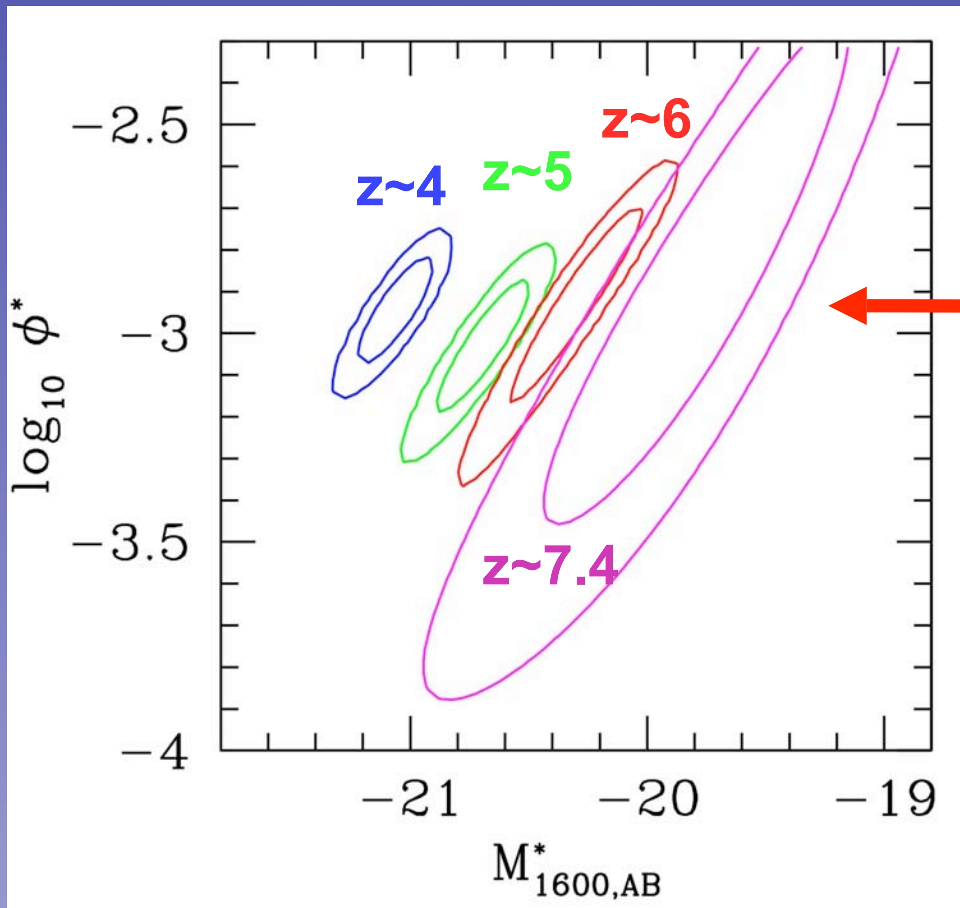
Bouwens, Illingworth et al. 2008

Galaxies at z~4, 5, 6, 7.5 *(B, V, i, z-dropouts)*

High

Volume Density ϕ^*

Low



Bright M* Faint

ϕ^* ~ 0.001 Mpc^{-3} at z~4, 5, 6, 7.4

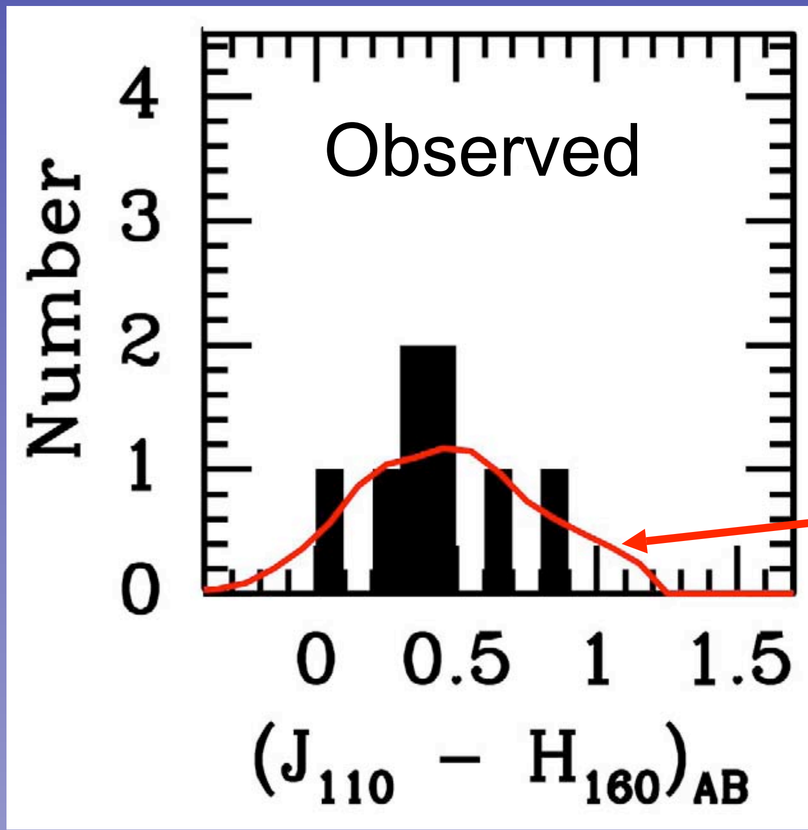
z~7-8 contours fit in nicely with z~4-6 trends!

Suggests we are actually finding z~7-8 galaxies!

Bouwens, Illingworth et al. 2008

Colours of the discovered z-dropout population agree with model expectations!

Number



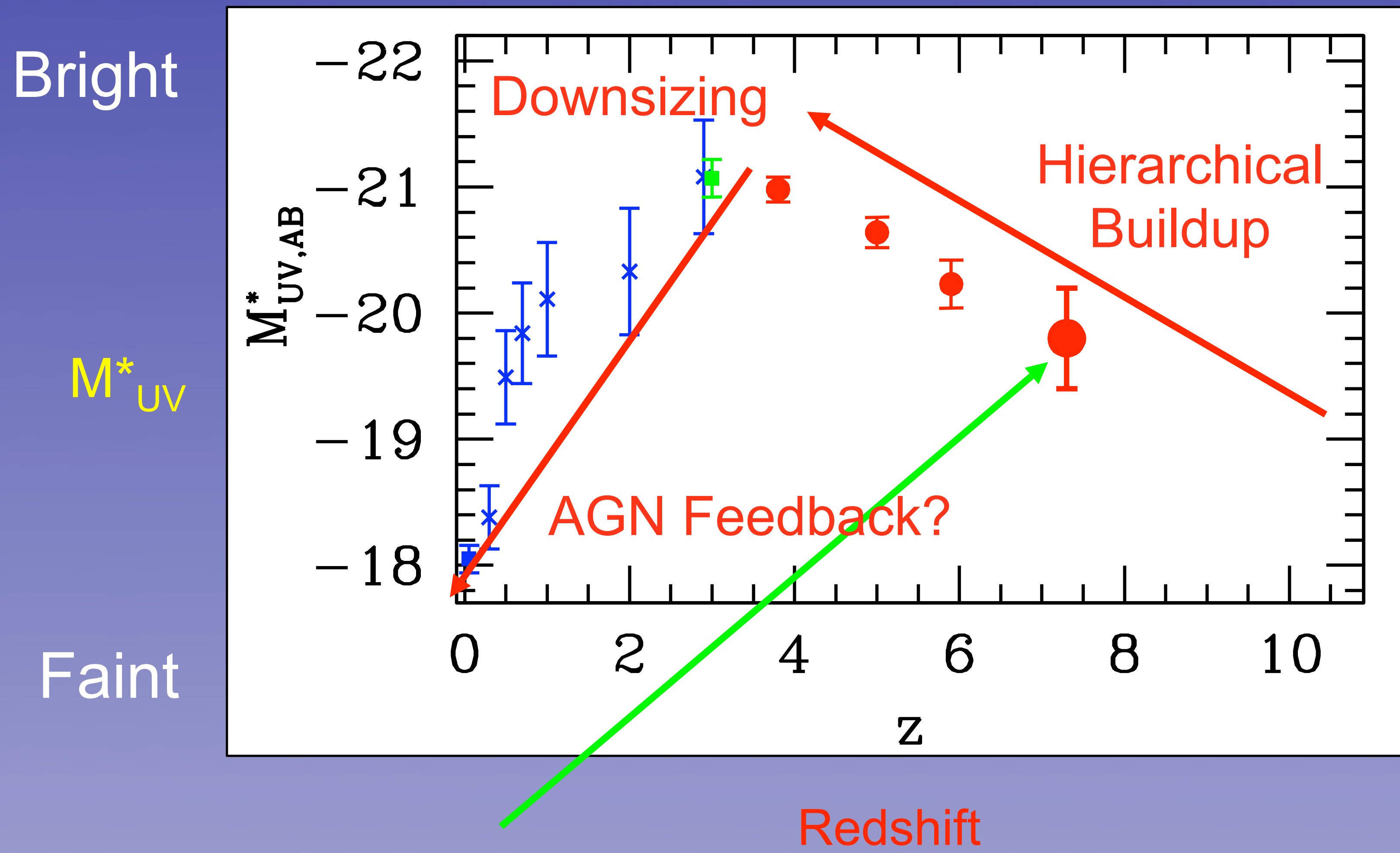
Expected for young star-forming objects at z~7-8

Near-IR J-H Colour

Suggests we are actually finding z~7-8 galaxies!

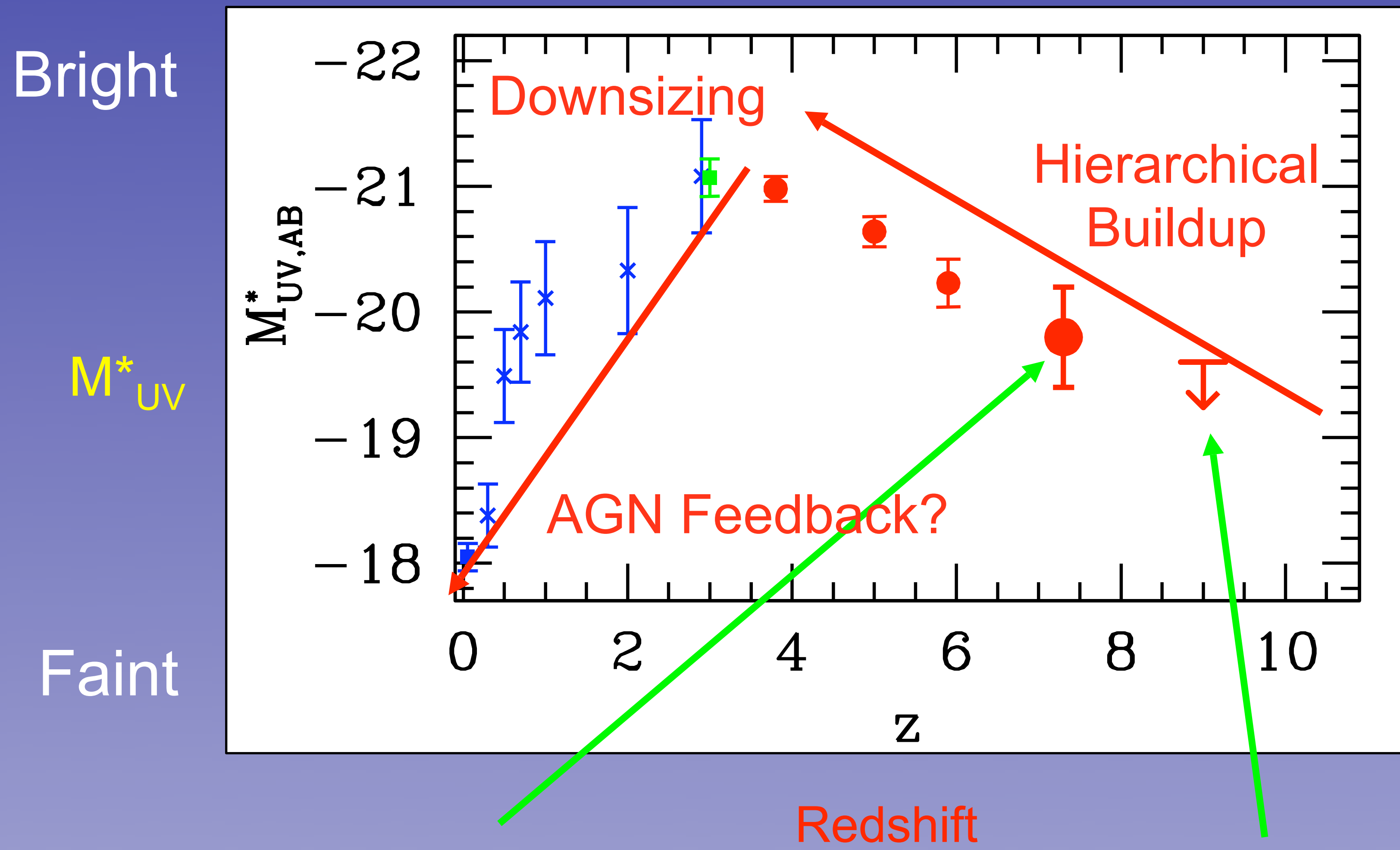
Bouwens, Illingworth et al. 2008

Evolution of the UV Luminosity Function



Bouwens, Illingworth et al. 2008

Evolution of the UV Luminosity Function

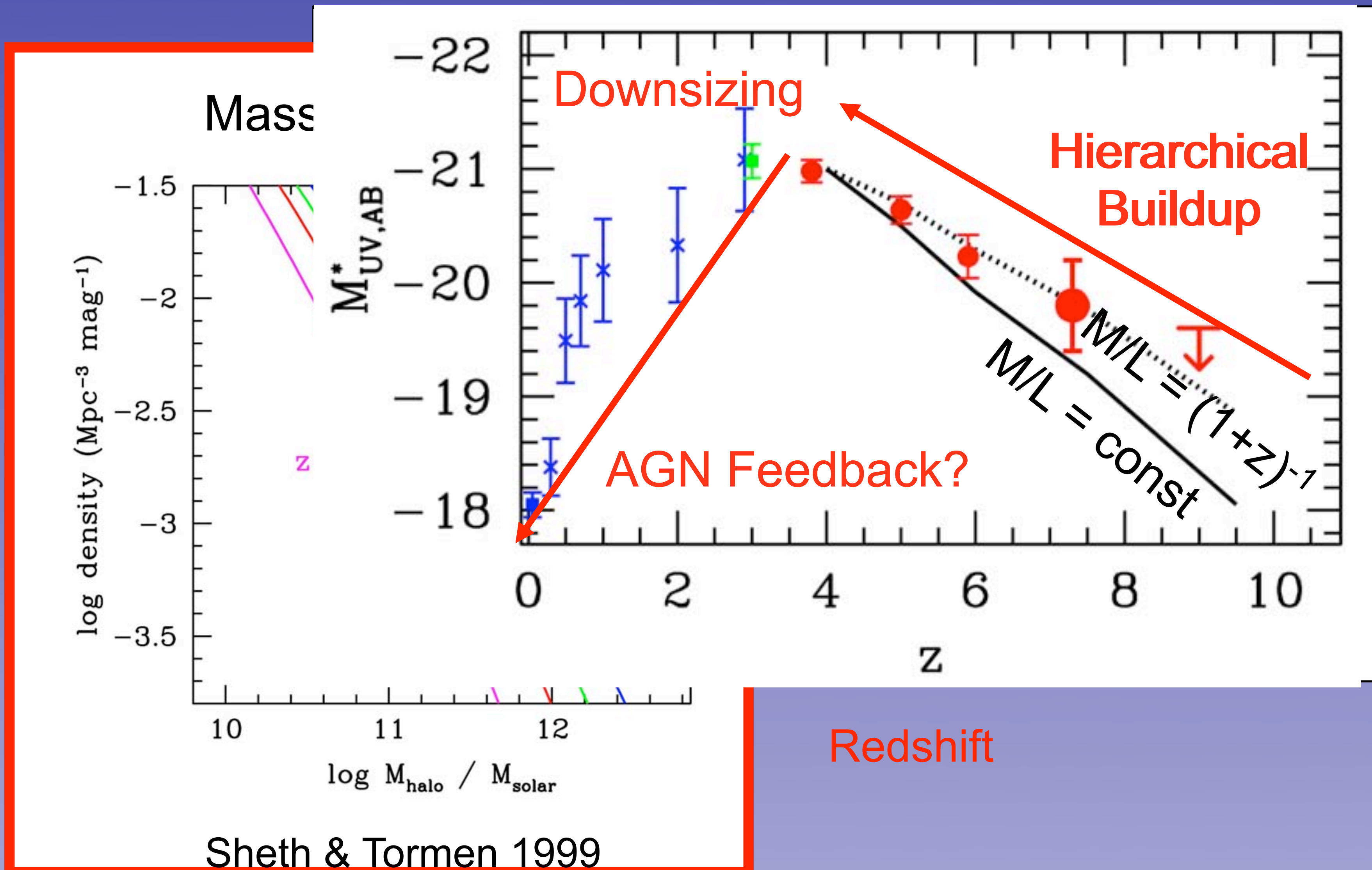


Bouwens, Illingworth et al. 2008

Assuming phi* ~ 0.001 Mpc^{-3} at z~9 (i.e., no evolution)

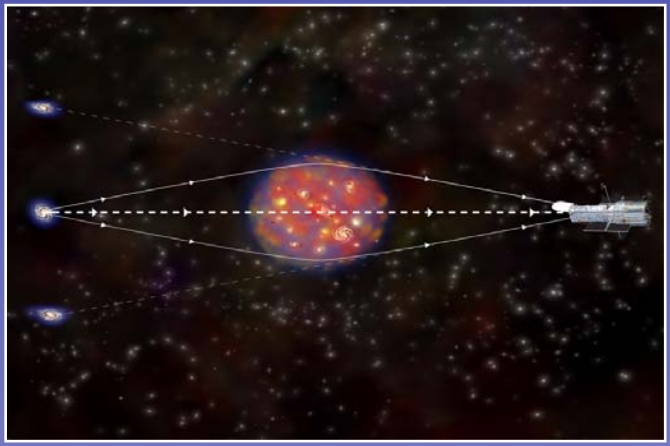
Paris 07/08/08 RJB

Evolution of the UV Luminosity Function



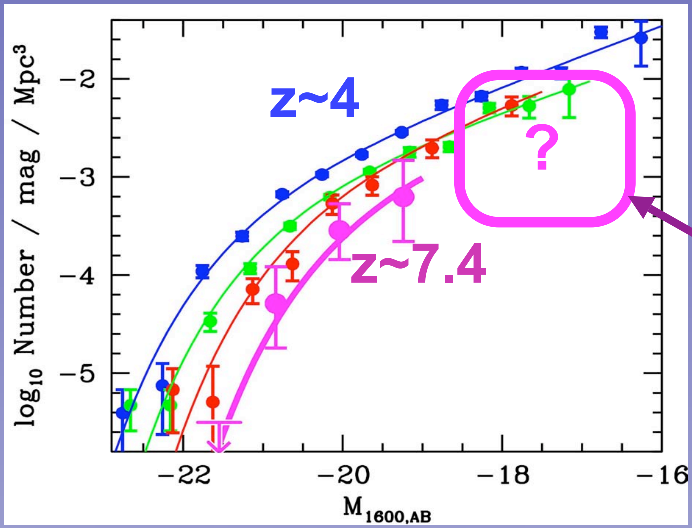
Redshift

Constraining Faint End of LF by taking advantage of gravitational lensing by clusters?



Take advantage of the substantial area around cluster with sizeable magnification factors to probe luminosities much fainter than otherwise

Log # mag^{-1} Mpc^{-3}



Bright Faint

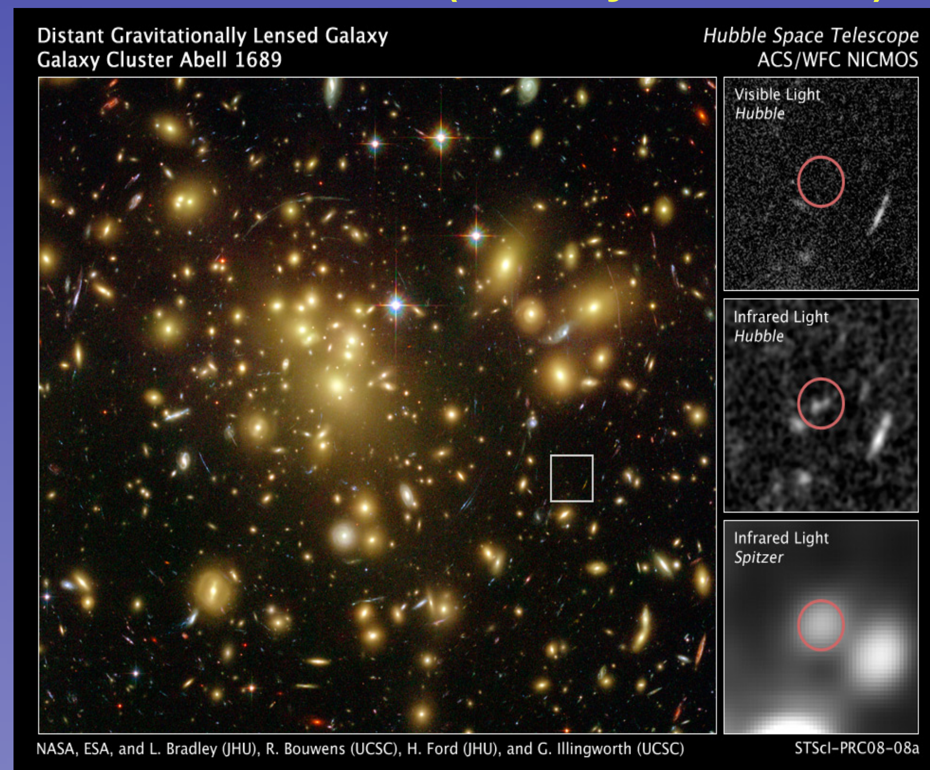
Determine by searches behind lensing clusters?

07/08/08 RJB

Massive galaxy clusters certainly useful for greatly magnifying faint sources that would otherwise be too faint for detailed studies, e.g., cB58

z~6.5 candidate (Kneib et al. 2004)

z~7.6 candidate (Bradley et al. 2008)



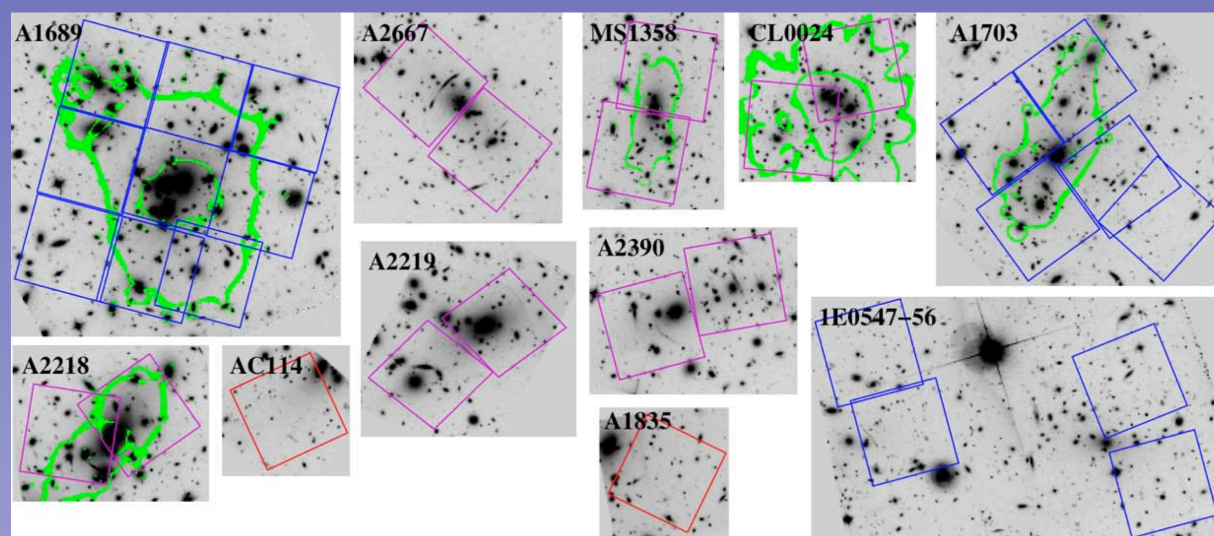
However, using these clusters to determine LF at lower luminosities is very uncertain.

1. Modelling the magnification by the cluster is very uncertain and model dependent (perhaps by factors of ~1.6-2.0)
2. Incompleteness difficult to model because of very different shear environments

→ In fact, our group has been unable to reproduce field LF results with z~4-6 dropouts found behind clusters and available lensing models

3. Currently the number of robust z>=7 candidates behind clusters is small, maybe 1 or 2

Cluster Search Fields:
-- 23 arcmin^2 search area (11 clusters)



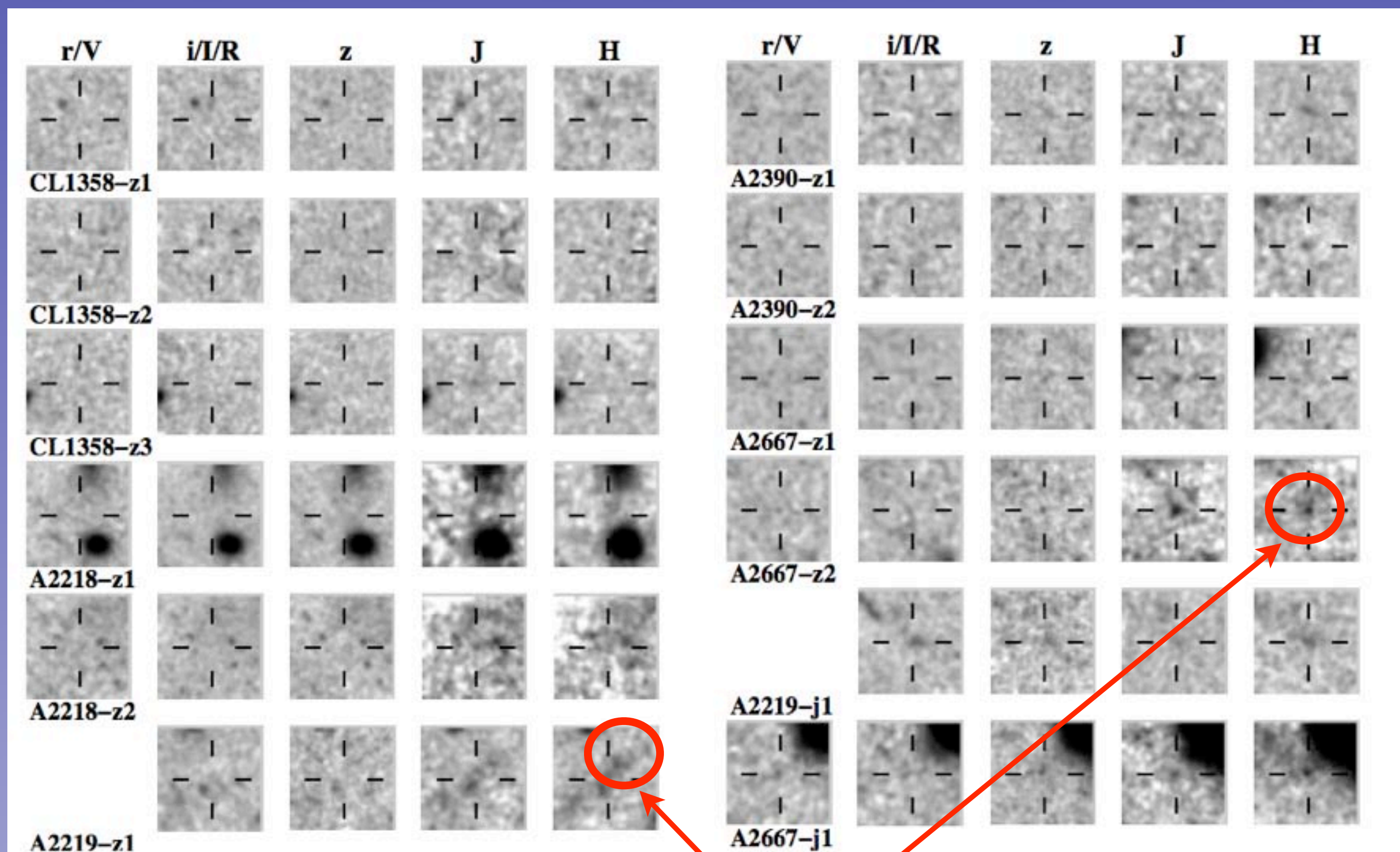
4 other z>=7 candidates (but which do not have deep enough optical data to be sure)

Bouwens et al. 2008; see also Richard et al. 2008

By contrast, Richard et al. (2008) claim to find 12 z>=7 candidates

However, 9 of the 12 seem very unlikely to be at z>=7 given our photometry

Gallery of 12 candidates from the
Richard et al. 2008 sample



Maybe a plausible candidate here, but
most seem doubtful based on our
photometry/ reductions

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Some Open Questions

1. - It appears difficult using the observed UV LFs and standard assumptions about escape fraction / clumping factors to significantly reionize the universe at z>=7. Why does the universe therefore seem to be significantly reionized out to redshifts beyond ~11?

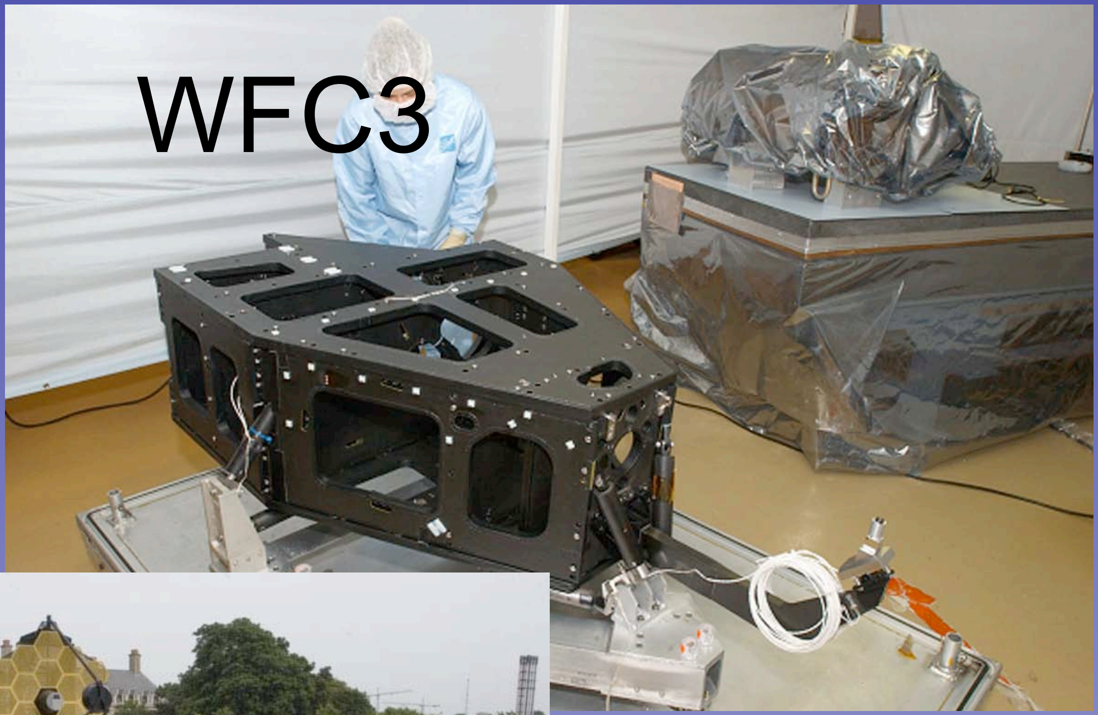
1. - Will this continue to be a problem as we push current LF determinations
2. fainter and to higher redshifts?

1. - What physical processes govern star-formation in galaxies forming at
2. early times? I showed that one can roughly reproduce the evolution assuming a M/L ratio that scales as 1/(1+z) and the expected halo mass function. Why might this be?

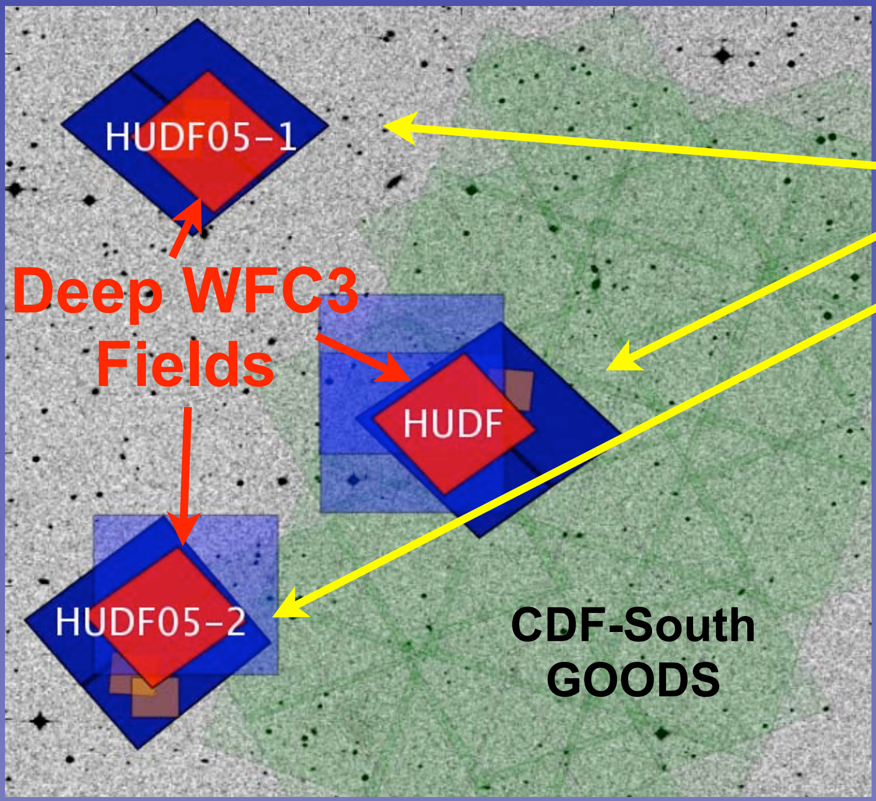
1. - The observed UV LFs seem to show an abrupt cut off at the bright end. This is very different from halo mass functions. However, one may not expect such cut-offs at very high redshifts given the masses involved (cooling criteria would not seem to work, AGN feedback not important, dust extinction not important???)

1. - We are making a number of assumptions in selecting z>=7 galaxies. How good are current LF determinations? Are the selections robust? They seem reasonable, but we still do not *know* for certain.

The Future



HUDF09 WFC3/IR program



Deepest optical data

192 WFC3/IR orbits:

96 orbits / 1 field

48 orbits / 2 fields

Will reach ~29 AB mag in near-IR (1.05,1.25,1.60 microns)

Should find 50-100 z>=7 galaxies

New Measurements of the UV LFs at z>6: Conclusions

- Great progress is being made in understanding the properties of galaxies at z~4-8 from current observational data
- The deep+wide area ACS data over the GOODS+HUDF+other deep fields allow for a reasonably reliable determination of the UV LF at z~4-6
- UV LFs determined from deep ACS data are able to reach -16 AB mag (0.01 L*)
- The faint-end slope of the UV LF appears to be very steep, i.e., -1.73
- There is an encouraging agreement b/w some wide-area LFs and our ACS LFs
- Large areas (~80 $arcmin^2$) of deep (>26.5 AB mag) near-IR+optical data are available to select z~7-10 galaxies
- >=12 good z~7-8 candidates have been identified from NICMOS data
- The characteristic luminosity of galaxies in the UV appears to brighten substantially (by ~1.2 mag) from z~7.4 to z~4. This increase is similar to what one expects from the mass function, if the M/L ratio varies as $(1+z)^{-1}$
- Using standard assumptions and the observed UV LFs at z>6, we are not able to reionize a large fraction of the neutral hydrogen in the IGM
- Current determinations of the faint-end of the high-z LF using searches behind lensing clusters is extremely uncertain.