Galaxy Buildup in the First 2 Gyr: The Evolution of the UV LF from z~8 to z~4

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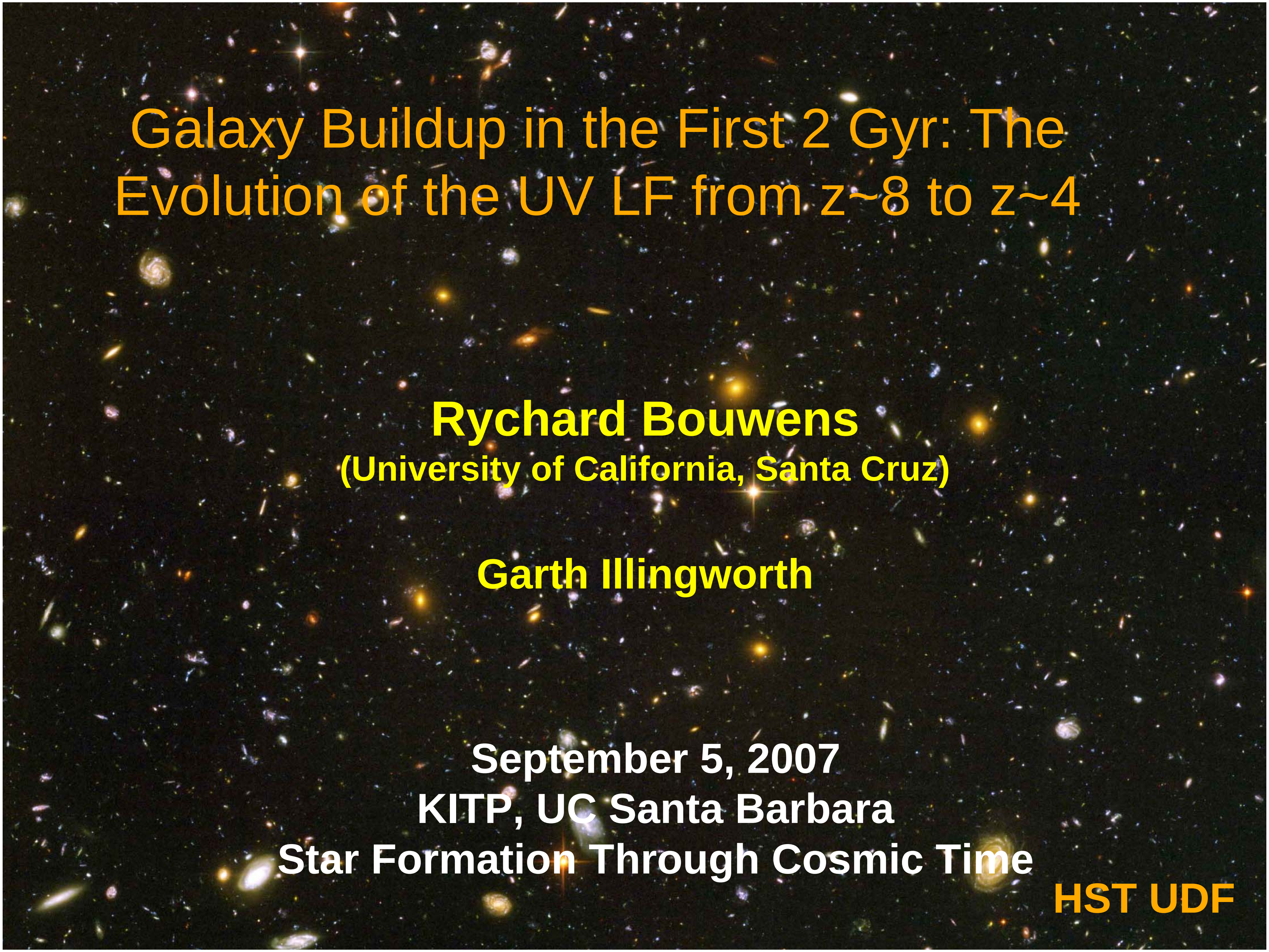
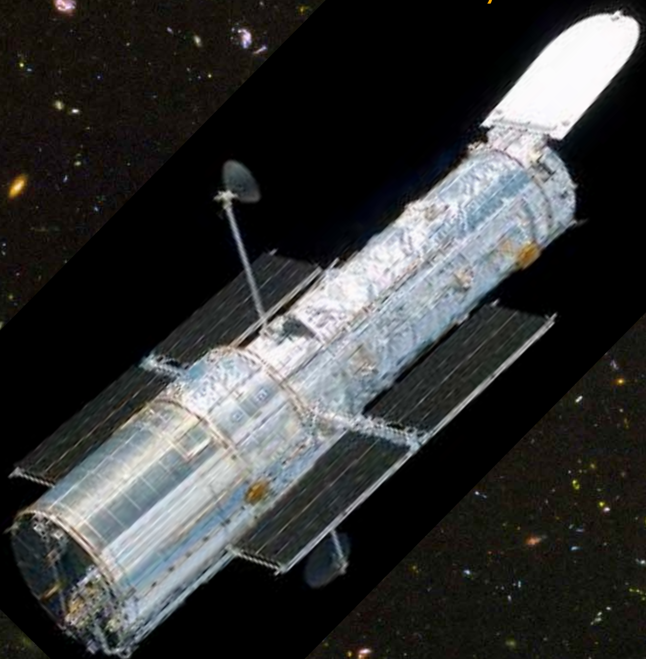
KITP, UC Santa Barbara
Star Formation Through Cosmic Time



Galaxy Buildup in the First 2 Gyr

With a Special Thanks to:

Marijn Franx, John Blakeslee, Holland Ford, Rodger Thompson, Louis E. Bergeron, Massimo Stiavelli, Dan Magee, Ivo Labbe, Pieter van Dokkum, Dan Coe, Larry Bradley



ACS GTO team: Holland Ford, Garth Illingworth, Mark Clampin, George Hartig, Txitxo Benitez, John Blakeslee, Rychard Bouwens, Marijn Franx, Gerhardt Meurer, Marc Postman, Piero Rosati, Rick White, Brad Holden, Dan Magee + many other team members

UDF-IR team: Rodger Thompson, Garth Illingworth, Rychard Bouwens, Mark Dickinson, Pieter van Dokkum, Dan Eisenstein, Xiaohui Fan, Marijn Franx, Marcia Rieke, Adam Riess

HST: NICMOS + ACS

Galaxies at Redshift z~4-10

Key Science Interests

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

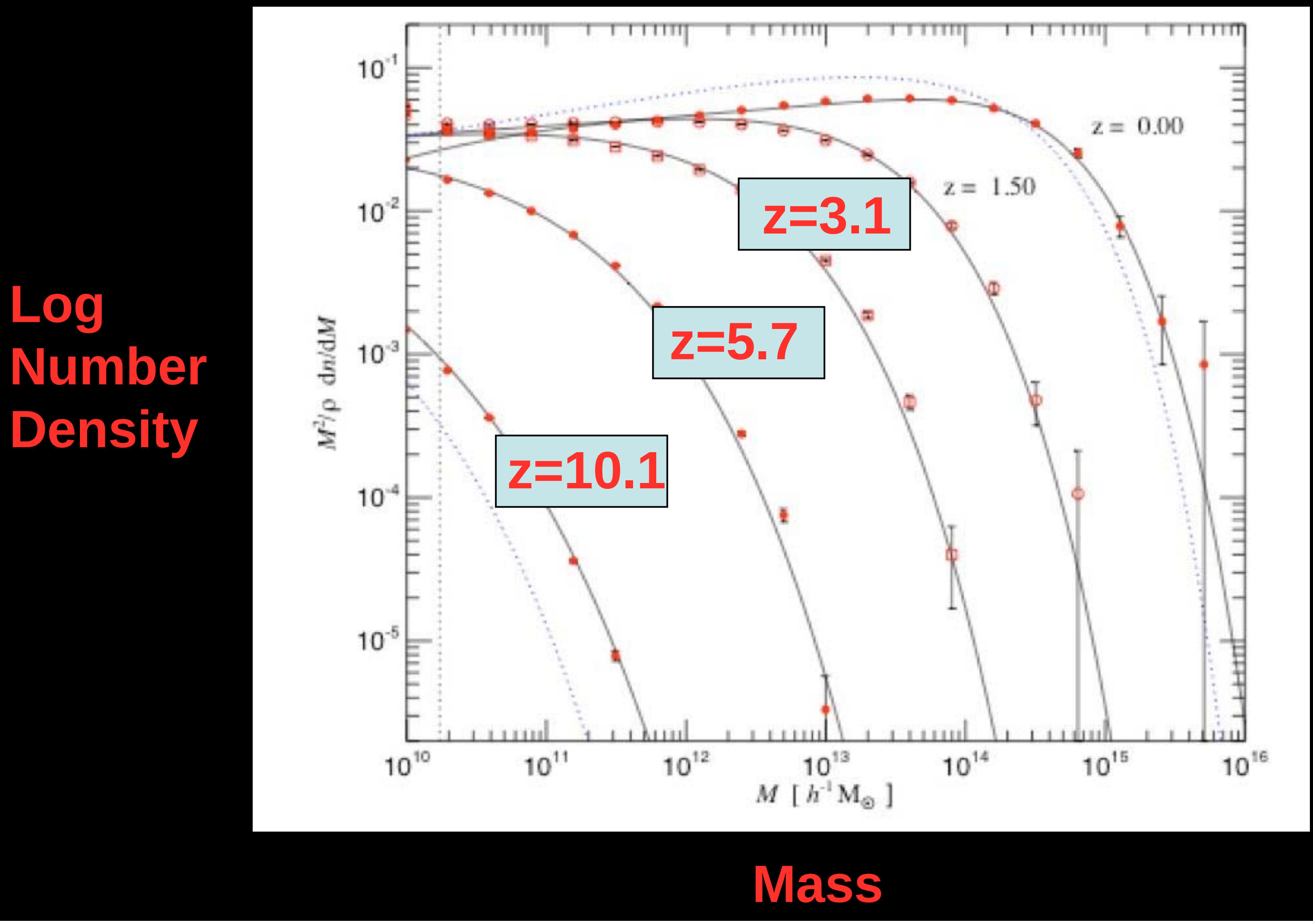
Near Uniform → Highly Structured

Post Inflation (t~0) → Now

Galaxies at Redshift z~4-10

Key Science Interests

1) The luminosity and masses of galaxies at these epoches are likely to build up very rapidly to z~6.

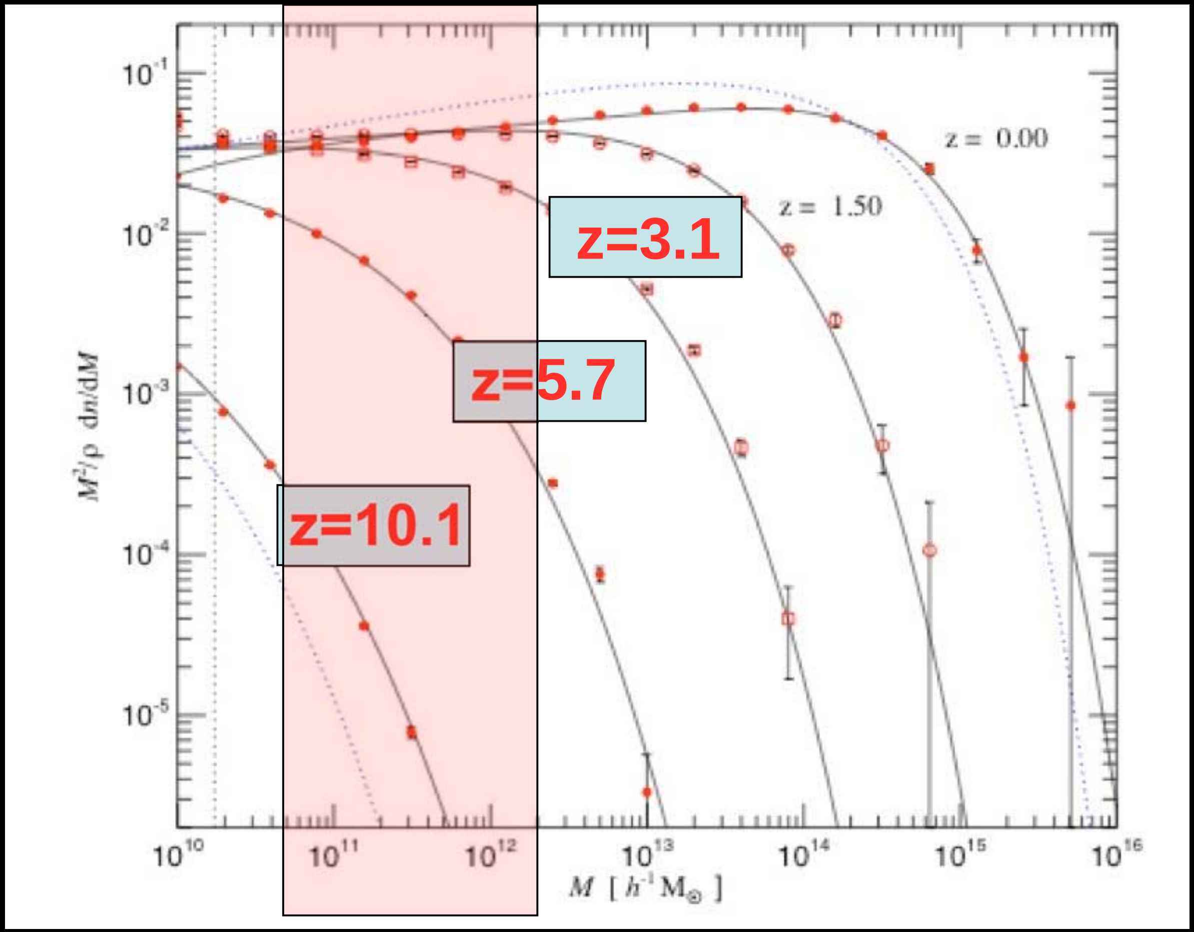


Galaxies at Redshift z~4-10

Key Science Interests

1) The luminosity and masses of galaxies at these epoches are likely to build up very rapidly to z~6.

Log Number Density



Mass of ~L* galaxies

Galaxies at Redshift z~4-10

Key Science Interests

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

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

Zero Metallicity → Metal Rich

Post BBN (t~0) → Now

Galaxies at Redshift z~4-10

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Galaxies at Redshift z~4-10

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

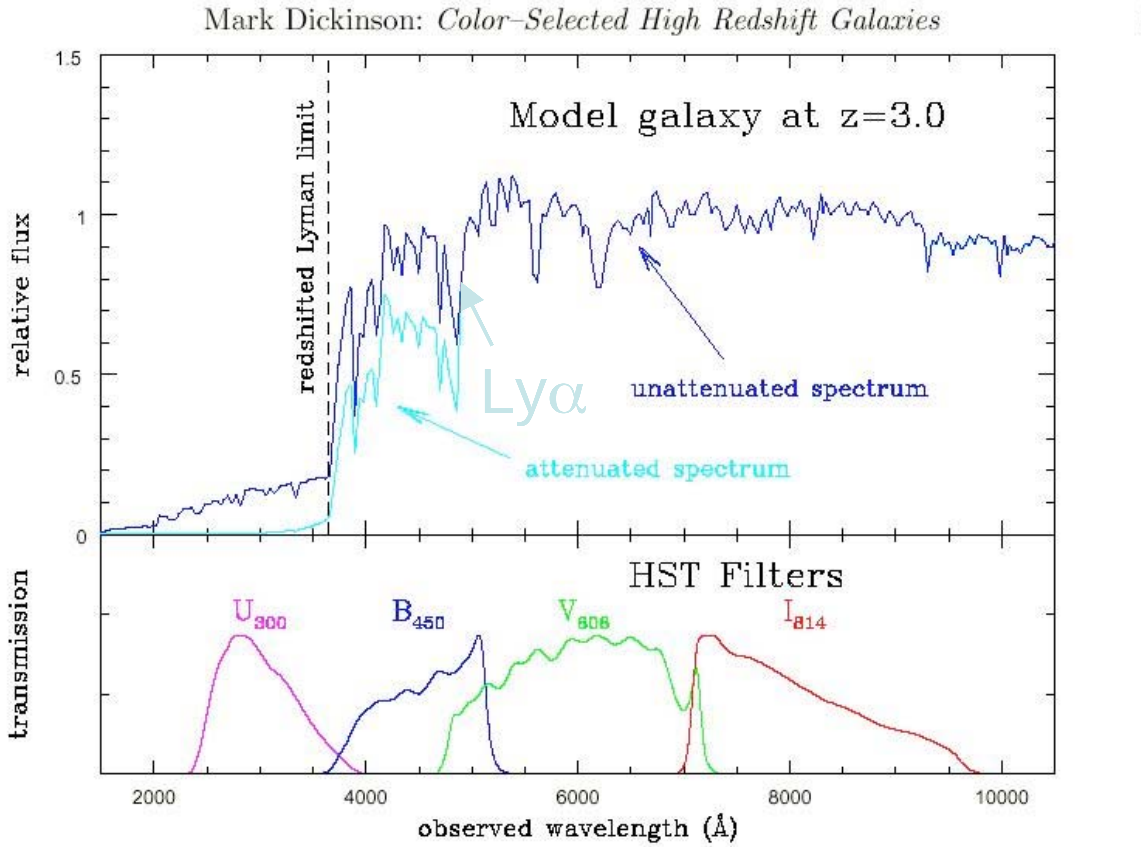
3) Galaxies as possible reionization sources
   -- This follows from evidence from z~6 SDSS quasars and 3-year WMAP optical depth measurements that the universe was likely reionized between z~6 and 11…

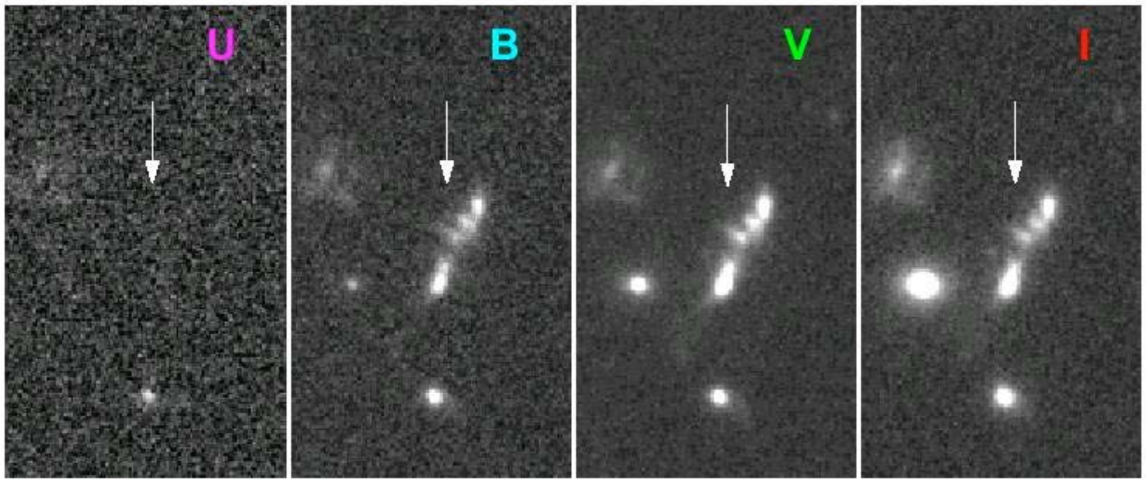
Identifying Star-forming Galaxies at z~2-10

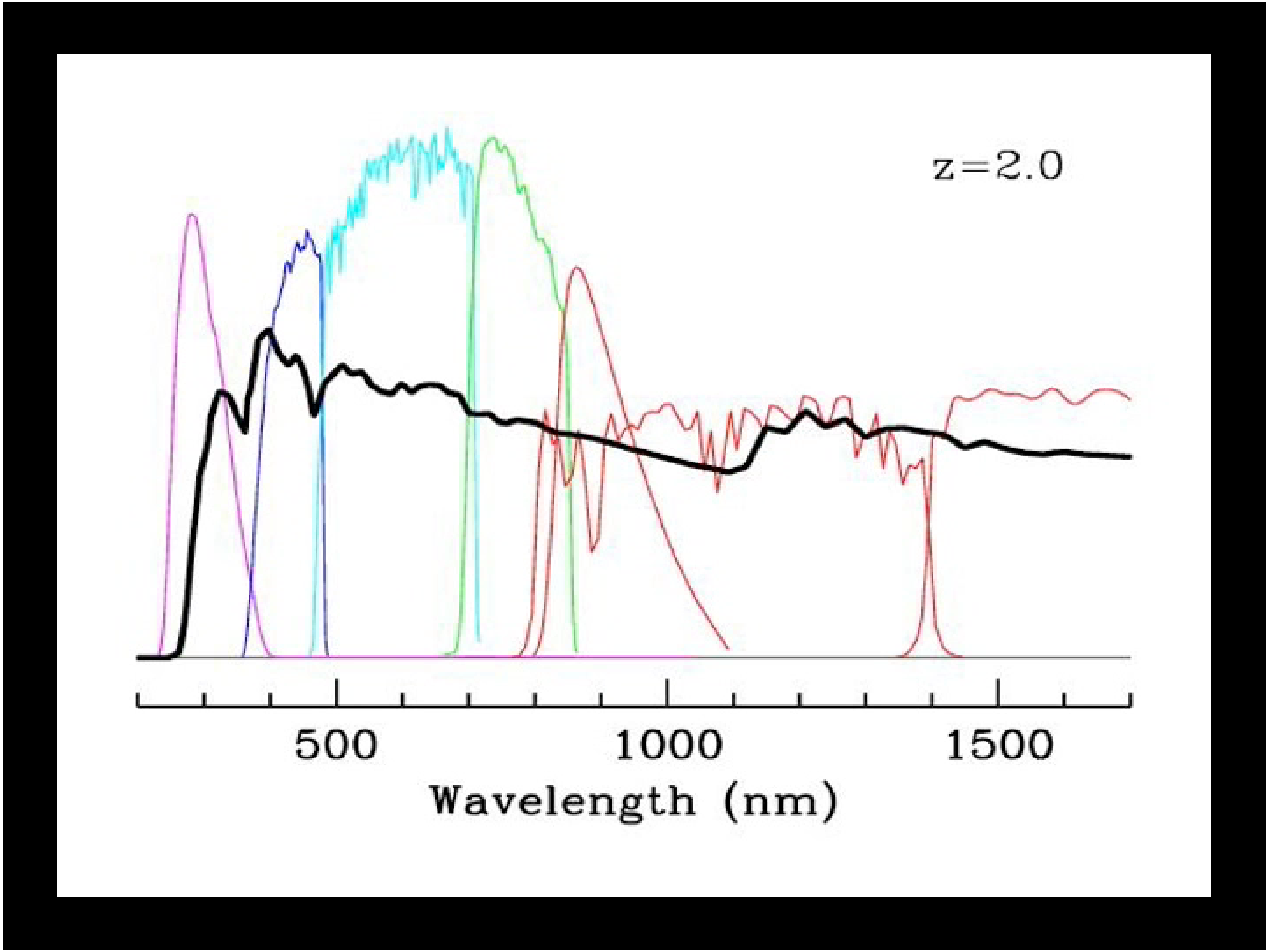
The “dropout” technique:

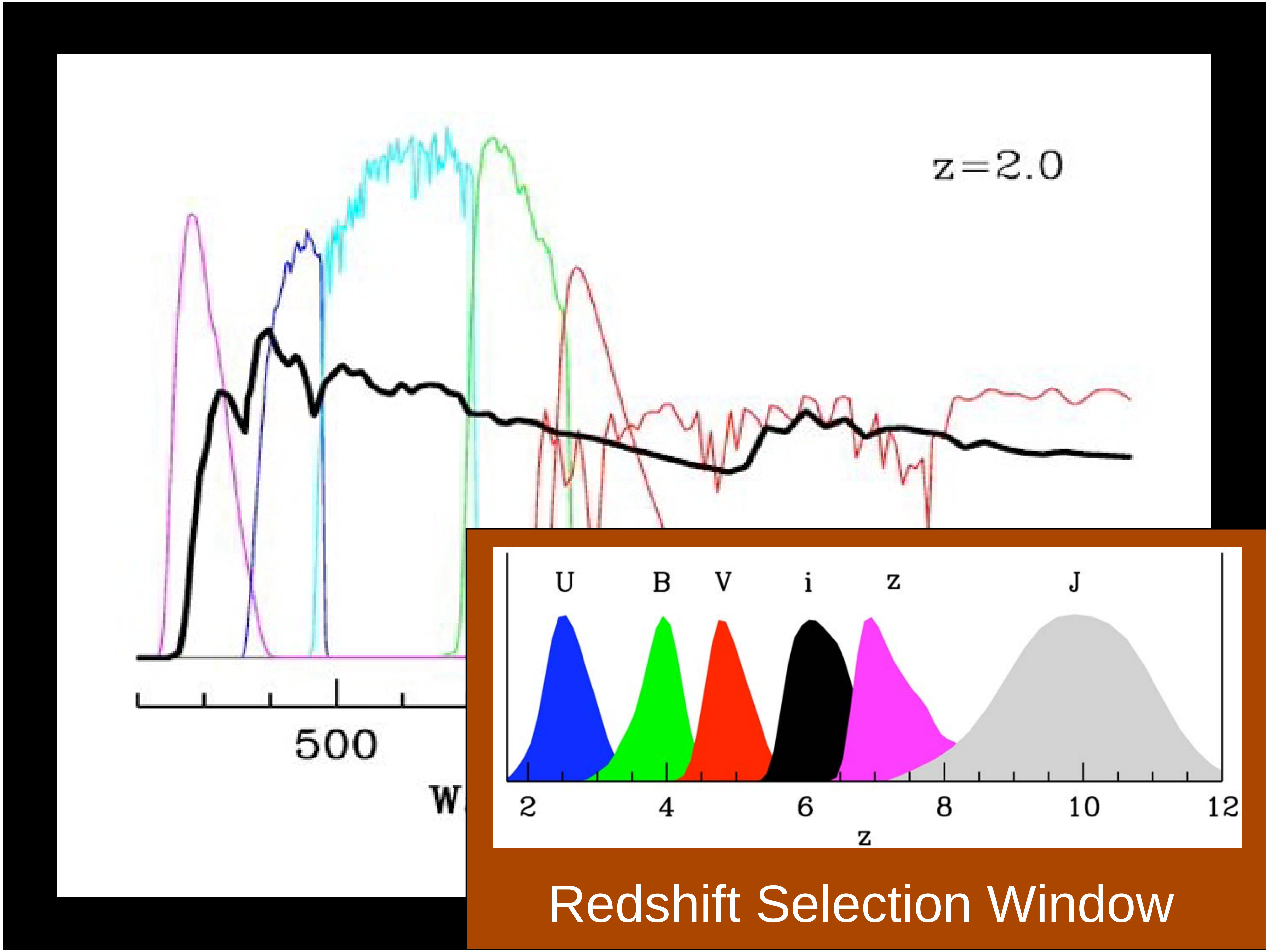
1) Lyman limit break
2) Lyα break at high z

Distant galaxy selection by the “drop-out” technique:
here a ‘*U-dropout*’
(Dickinson 1999)



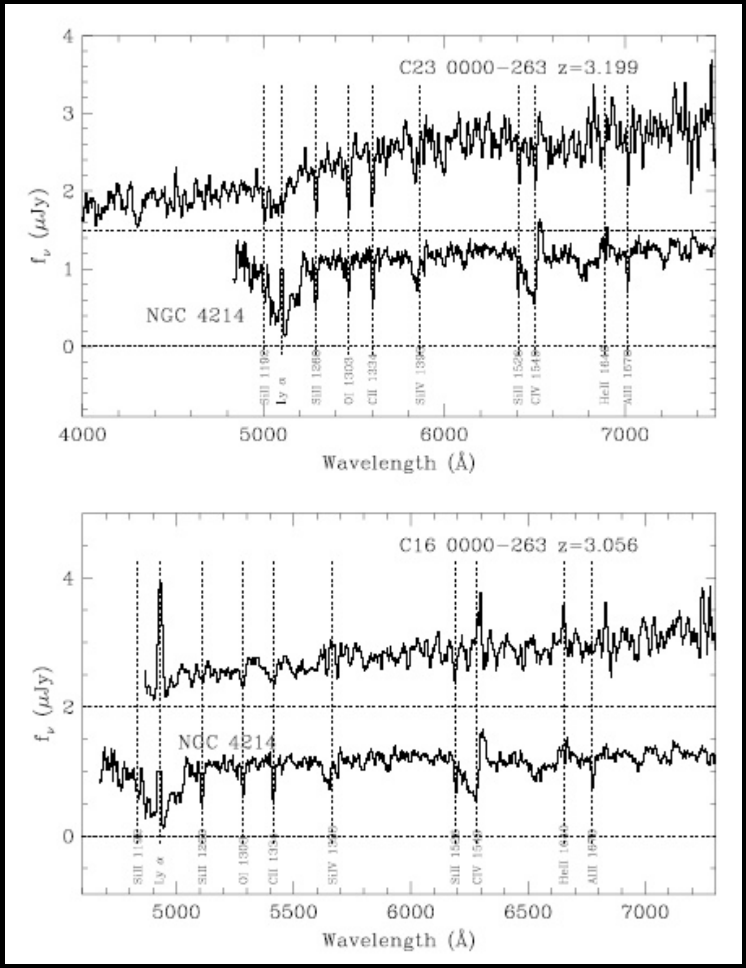



z=2.0
500
1000
1500
Wavelength (nm)


z=2.0
500
U
B
V
i
z
J
2
4
6
8
10
12
z
Redshift Selection Window

Original z~3-4 dropout work

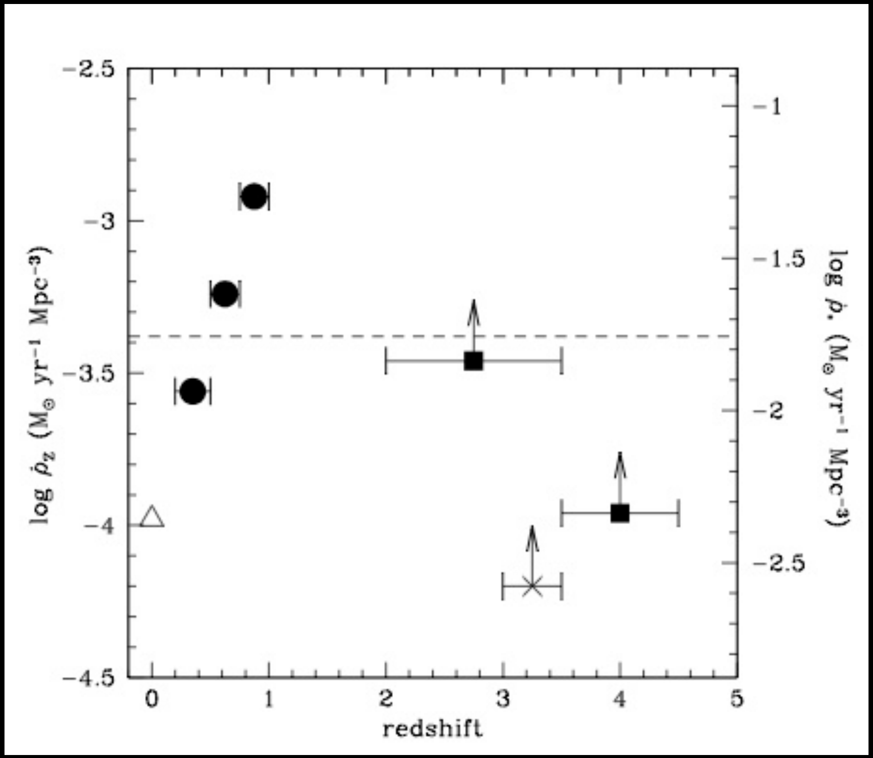
Steidel et al. 1995



Madau et al. 1996

70 z~2.5 U-dropouts

15 z~4 B-dropouts



Much bigger and higher redshift samples

==> ~30000 z~4-6

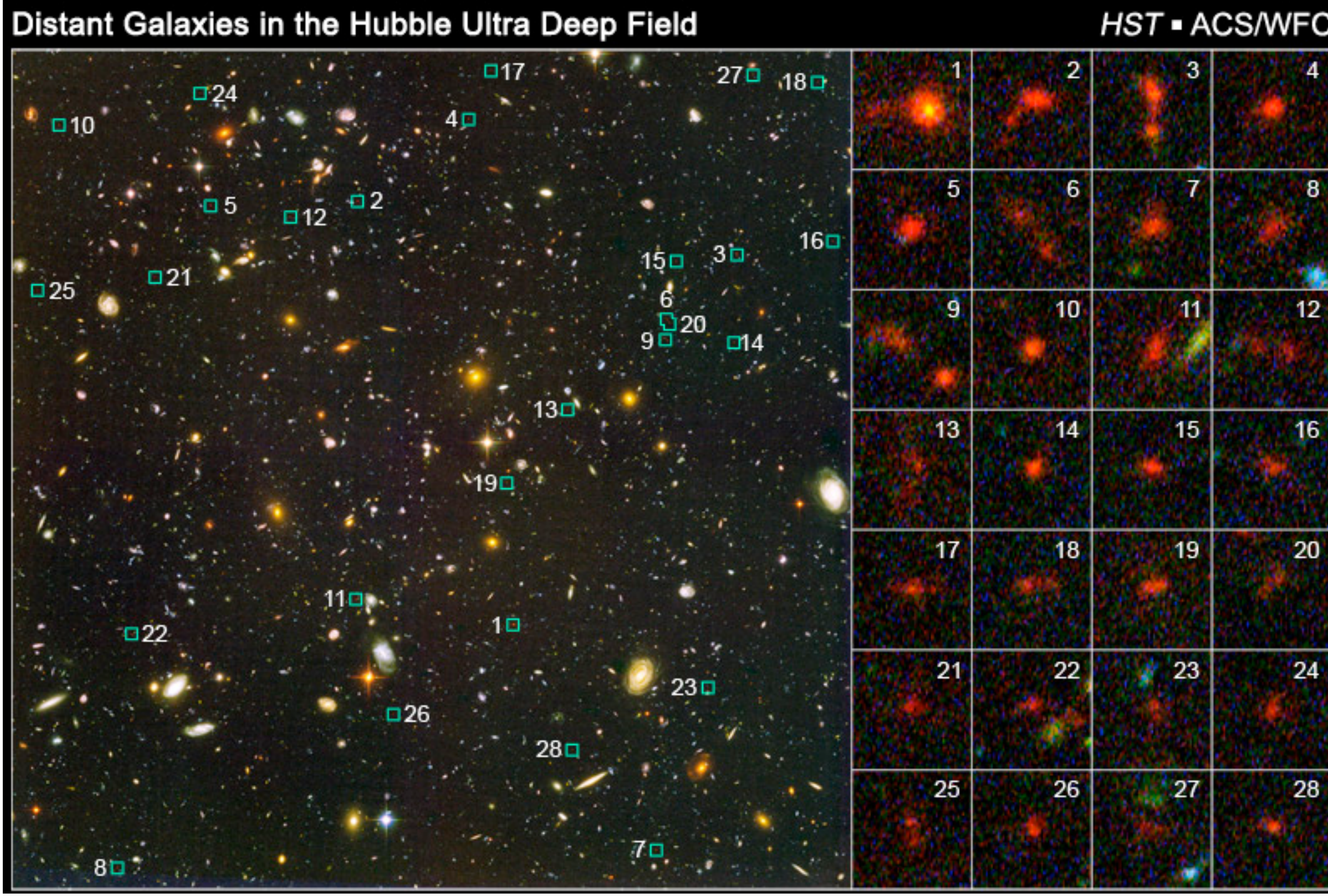
==> ~7000 z~4-6 from HST

HST Advanced Camera for Surveys

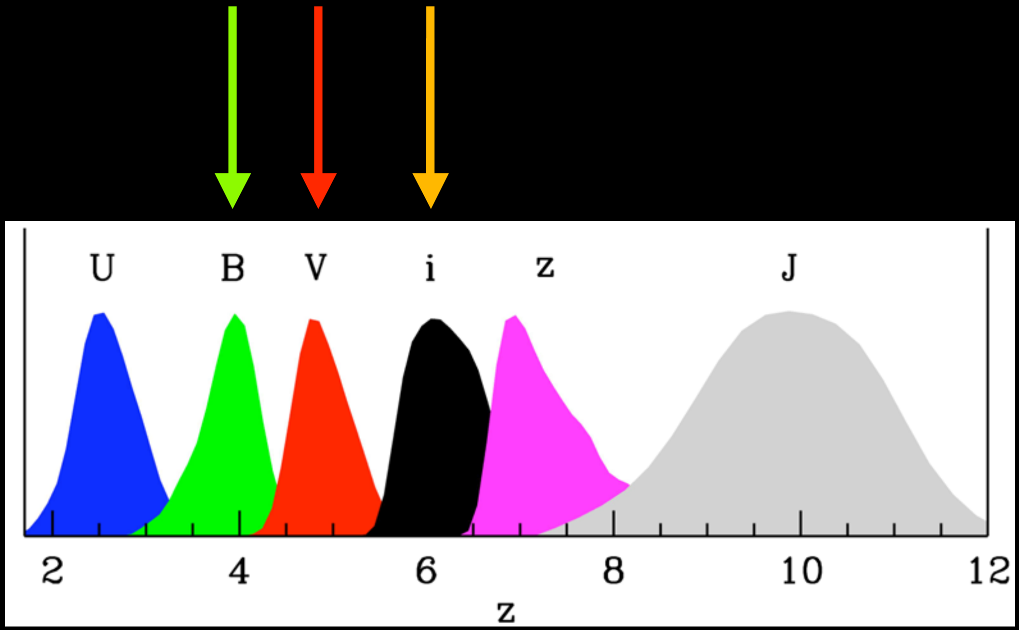
Subaru Suprime-Cam

VLT ISAAC

Galaxies at *z*~6 *(i-dropouts)*



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

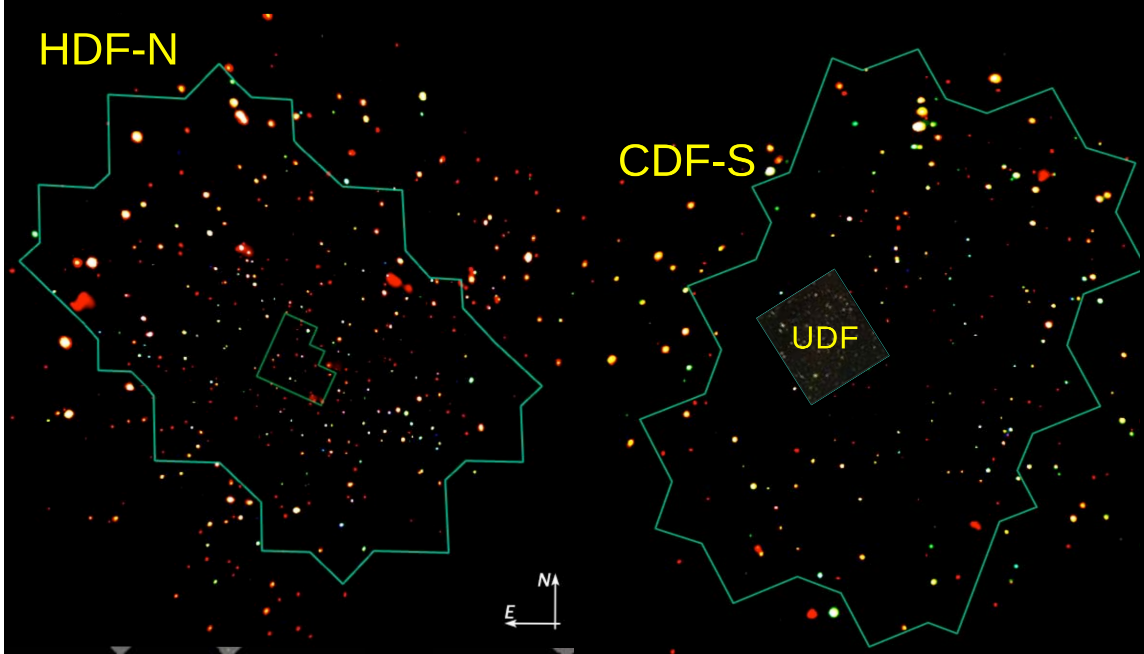


Dropout Redshift Selection Functions

Galaxies at z~4, 5, 6

Wide ⟷ Deep

GOODS "v2.0"



UDF

$z_{850,AB} \sim 29.3$ (5σ)

11 arcmin^2

UDF-Parallels

$z_{850,AB} \sim 28$ (5σ)
320
arcmin^2

$z_{850,AB} \sim 28.8$ (5σ)

40 arcmin^2

4671 z~4 B-dropouts,
1416 z~5 V-dropouts,
627 *z*~6 *i-dropouts*!

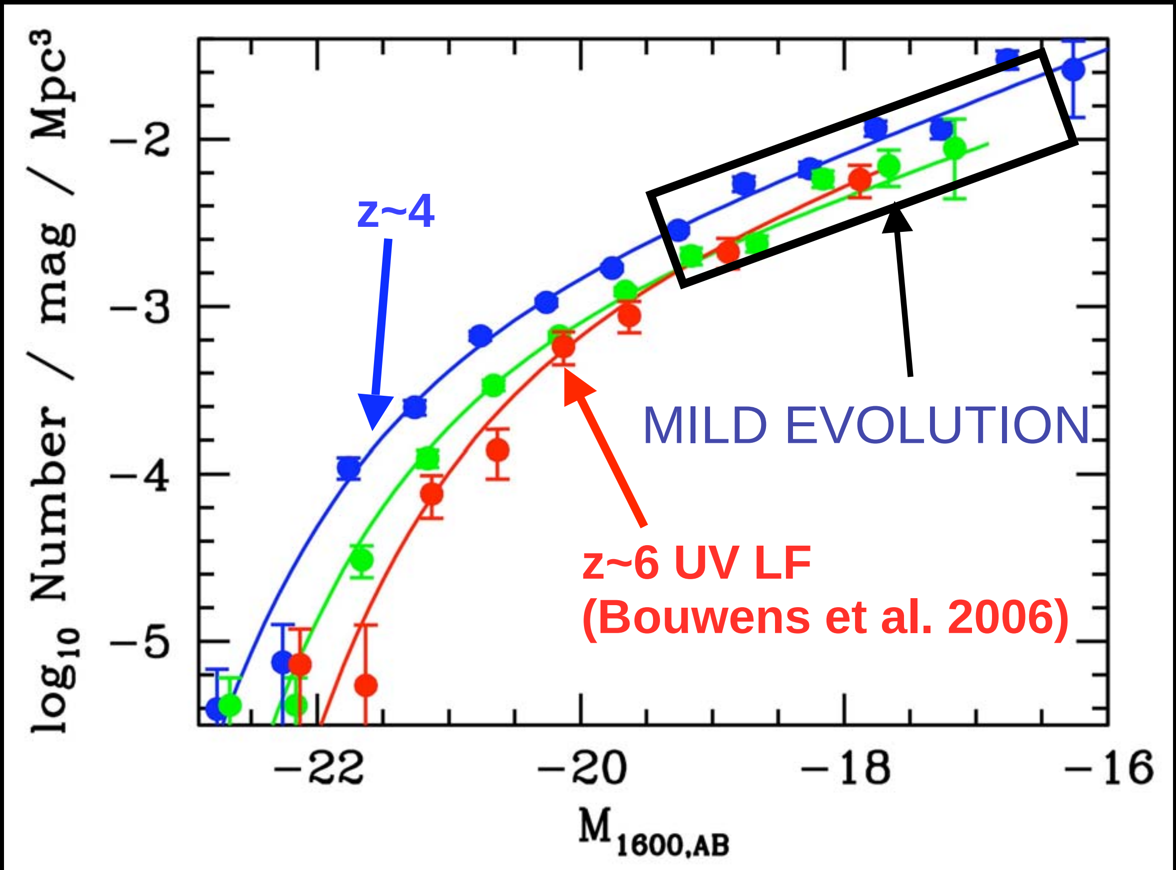
Bouwens, Illingworth, Blakeslee, Franx et al 2006
Bouwens, Illingworth et al. 2007

(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}



Rest frame UV 1600 Å

Large range in M_{1600}: -16 to -22.5!

Same faint-end slope α ~ -1.75

Bouwens, Illingworth, Franx, and Ford 2007

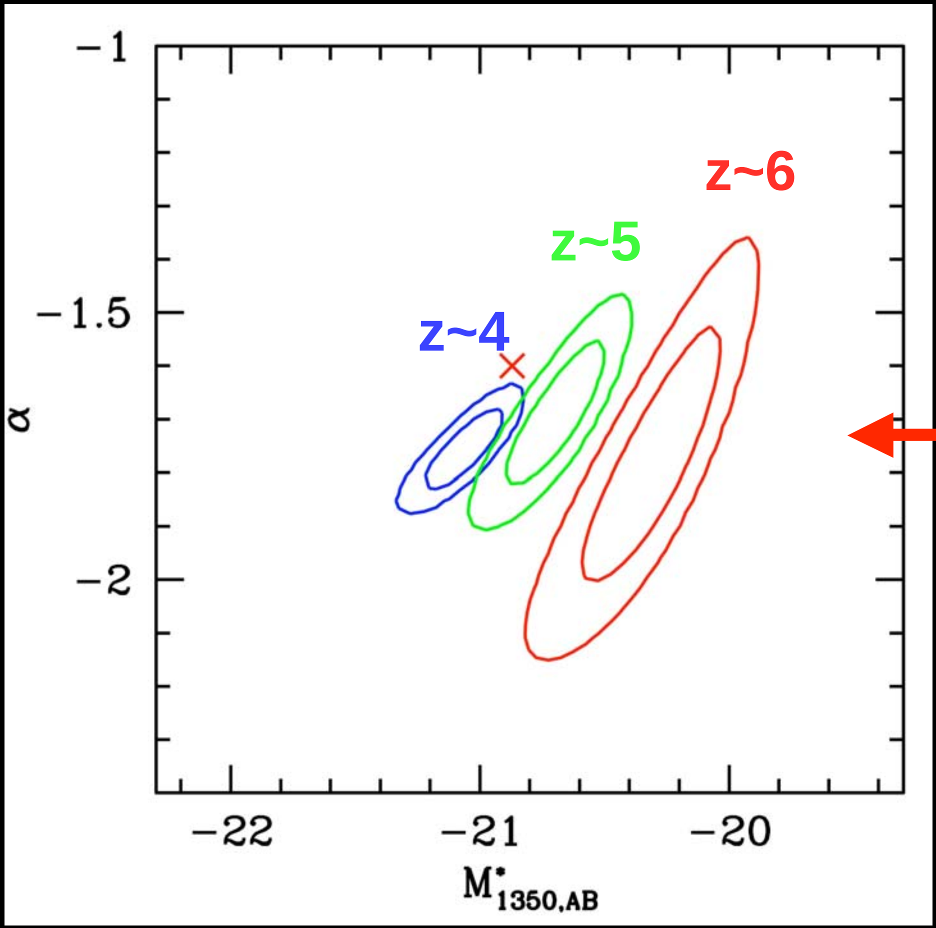
Galaxies at *z*~4, 5, 6 *(B, V, i-dropouts)*

UV Luminosity Functions

Shallow

Faint-end slope α

Steep

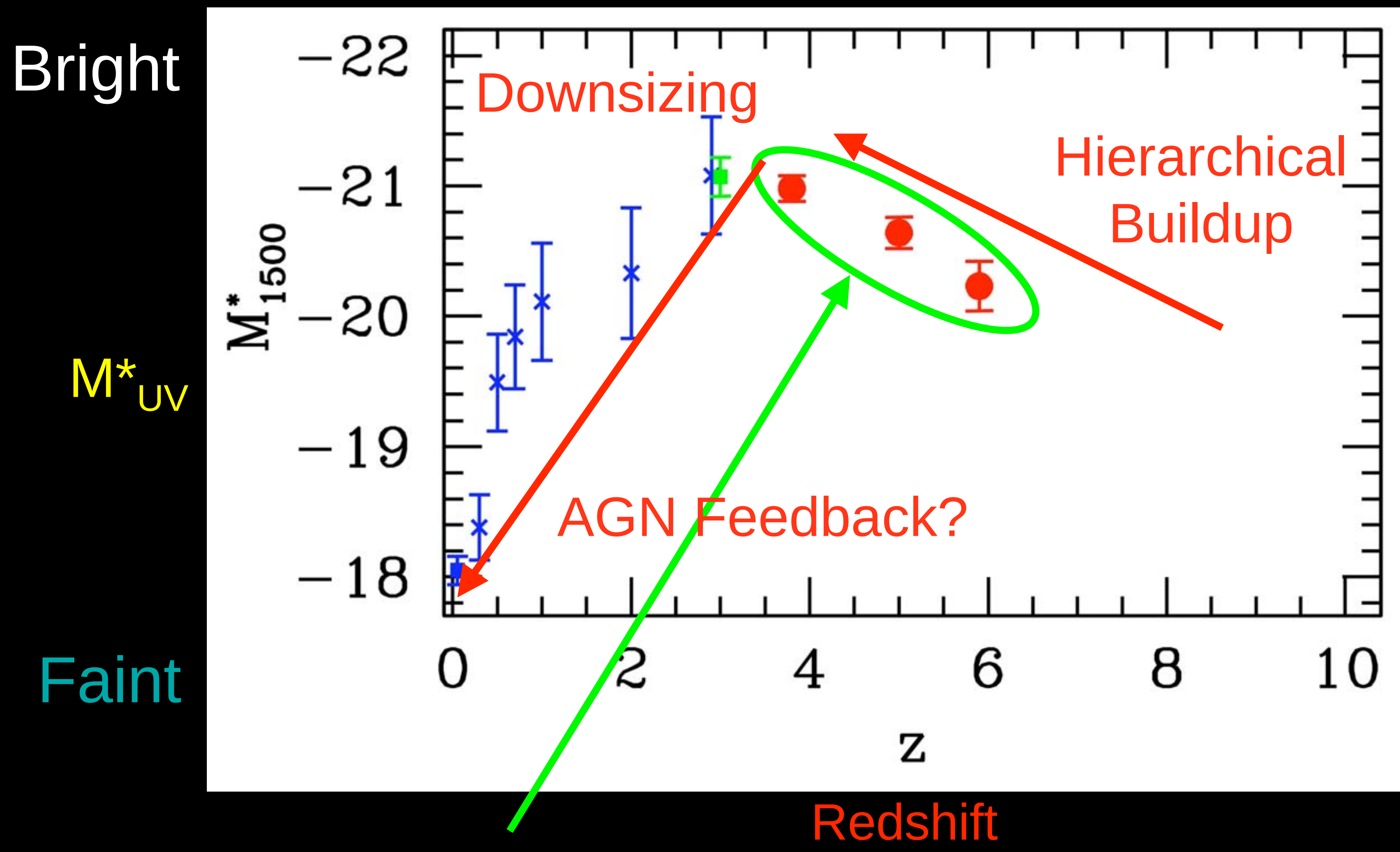


Faint end slope is constant α ~ –1.75

Bright M* Faint

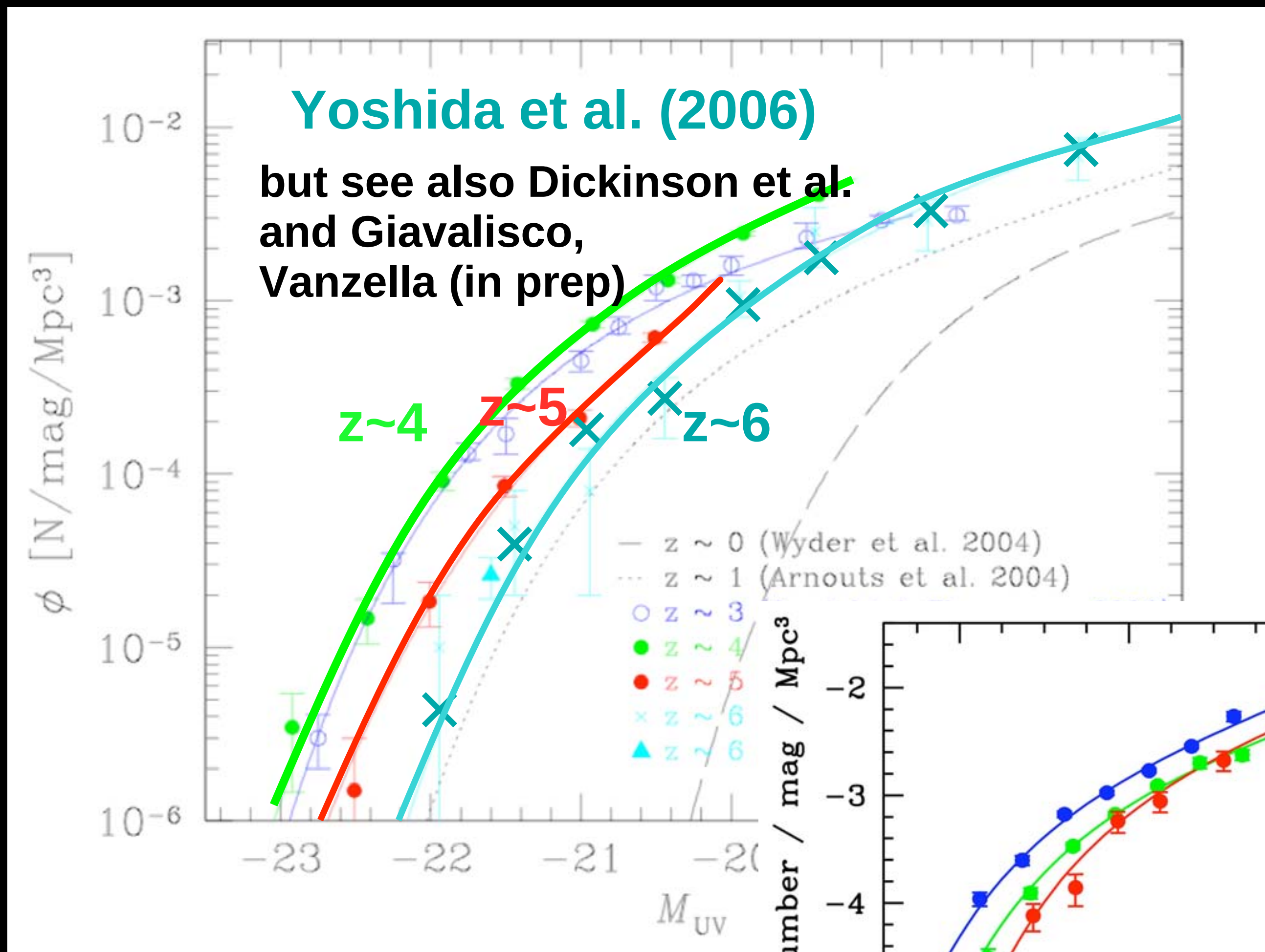
Bouwens, Illingworth, Franx, and Ford 2007

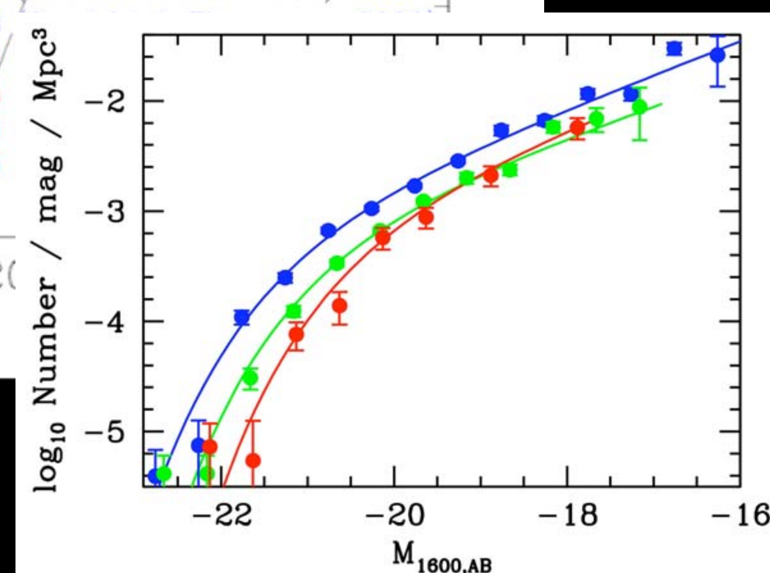
Evolution of the UV Luminosity Function



Bouwens, Illingworth, Franx, & Ford 2007

A few other groups find similar trends



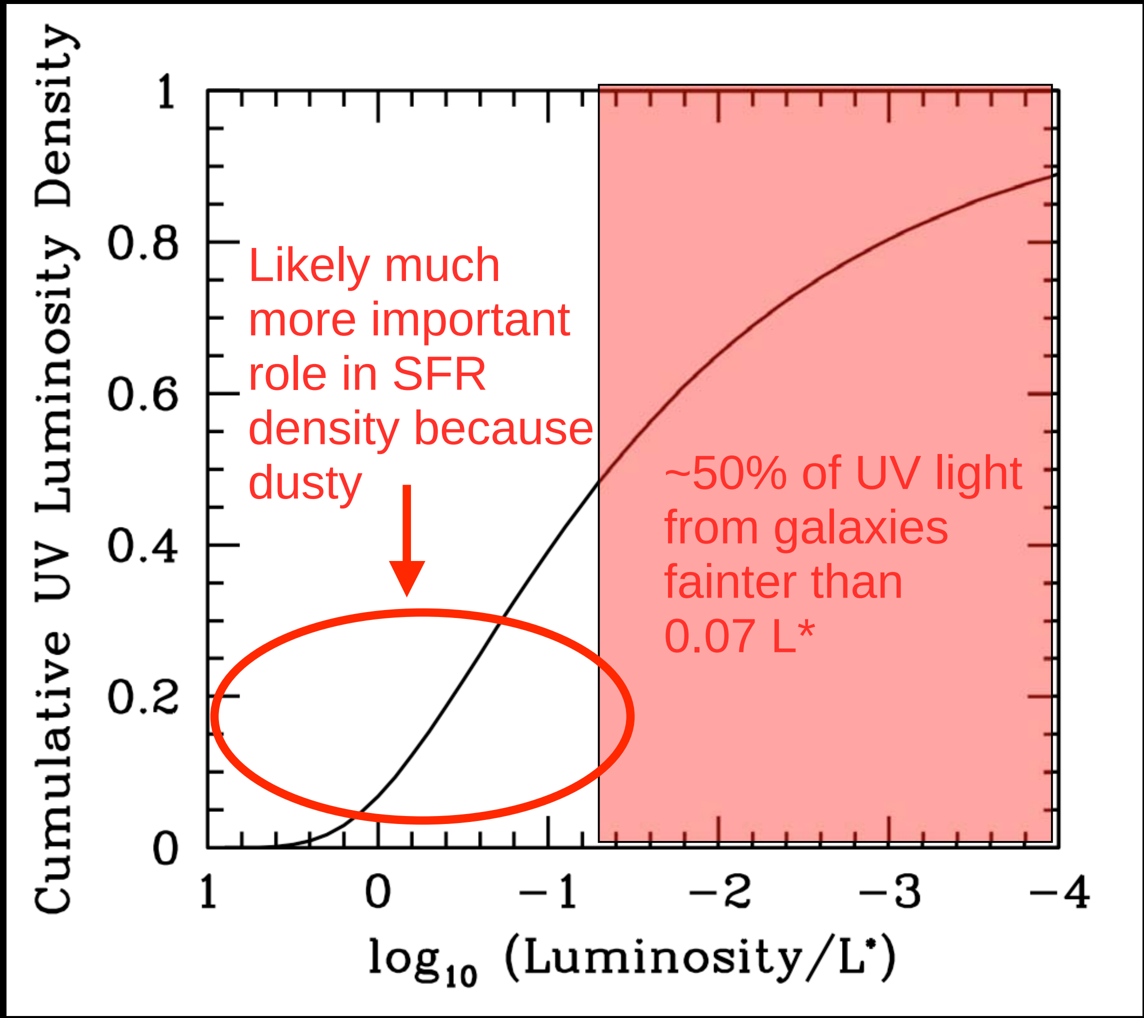


Disagree with the intepretation of Beckwith et al., Iwata et al., and Sawicki & Thompson

What are the implications of a steep faint-end slope?

Which galaxies output more UV light?

Fraction of UV light in sources brighter than some luminosity



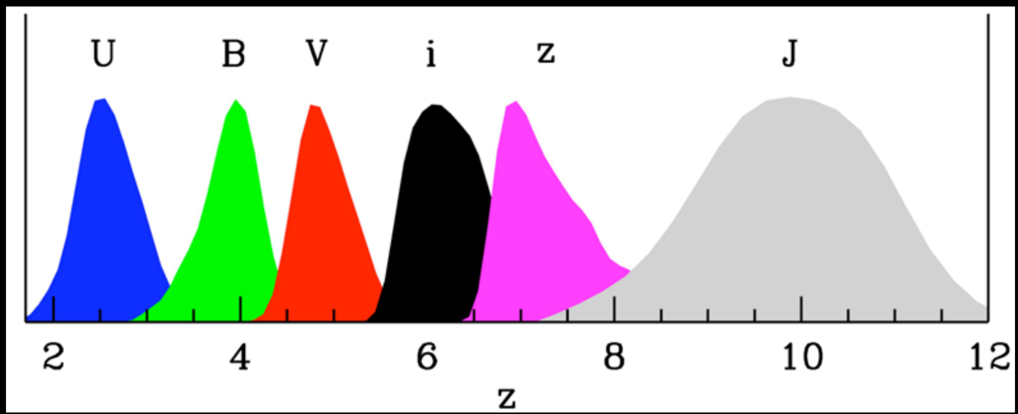
Bouwens, Illingworth et al. 2007

Bright — Luminosity — Faint

See also discussion in Sawicki & Thompson 2006; Yan & Windhorst 2004; Beckwith et al. 2006

Galaxies at *z*~7-8

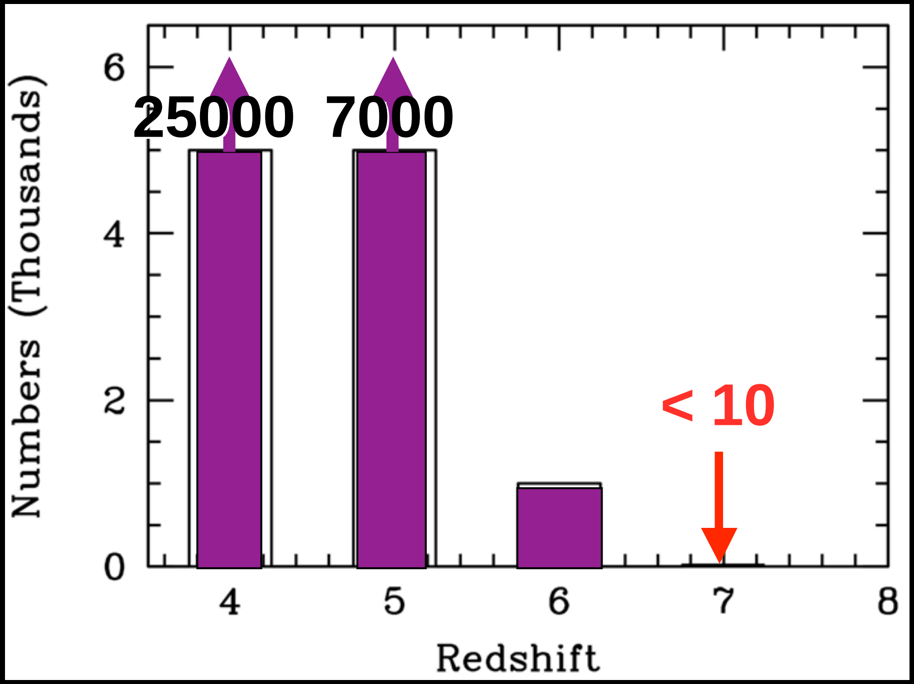
(z-dropouts)



Dropout Redshift Selection Functions

Galaxies at z>6 are the Frontier

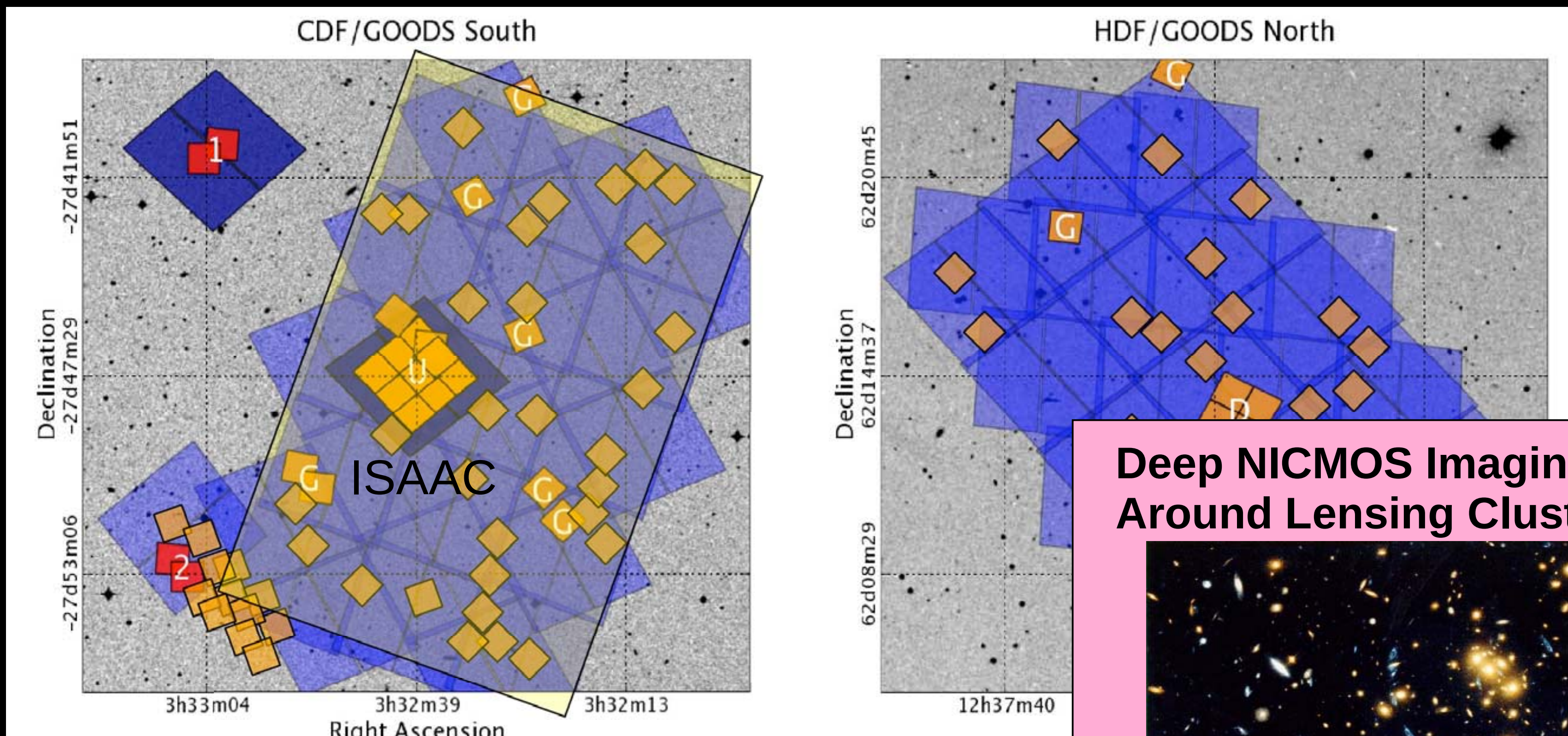
High Redshift Galaxy Candidates from HST, Subaru, VLT, Keck



The z>6 universe is still very much in the stage of early exploration, with most work simply trying to find and confirm these sources and determine their number density.

Galaxies at *z~7-8 (z-dropouts)*

Many fields with deep ACS and NICMOS data for dropout searches

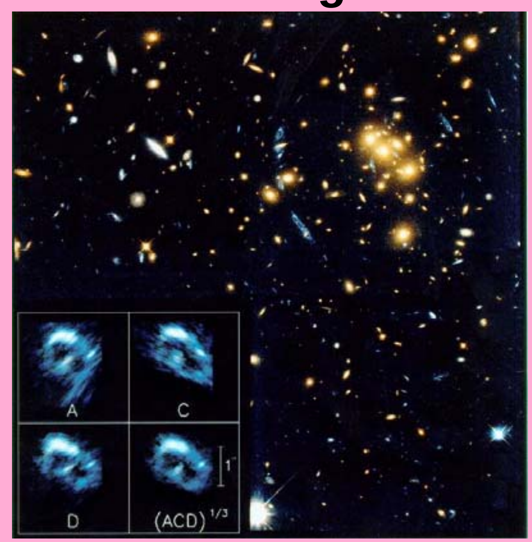


Deep NICMOS area (orange and red regions) will

ACS *NICMOS*

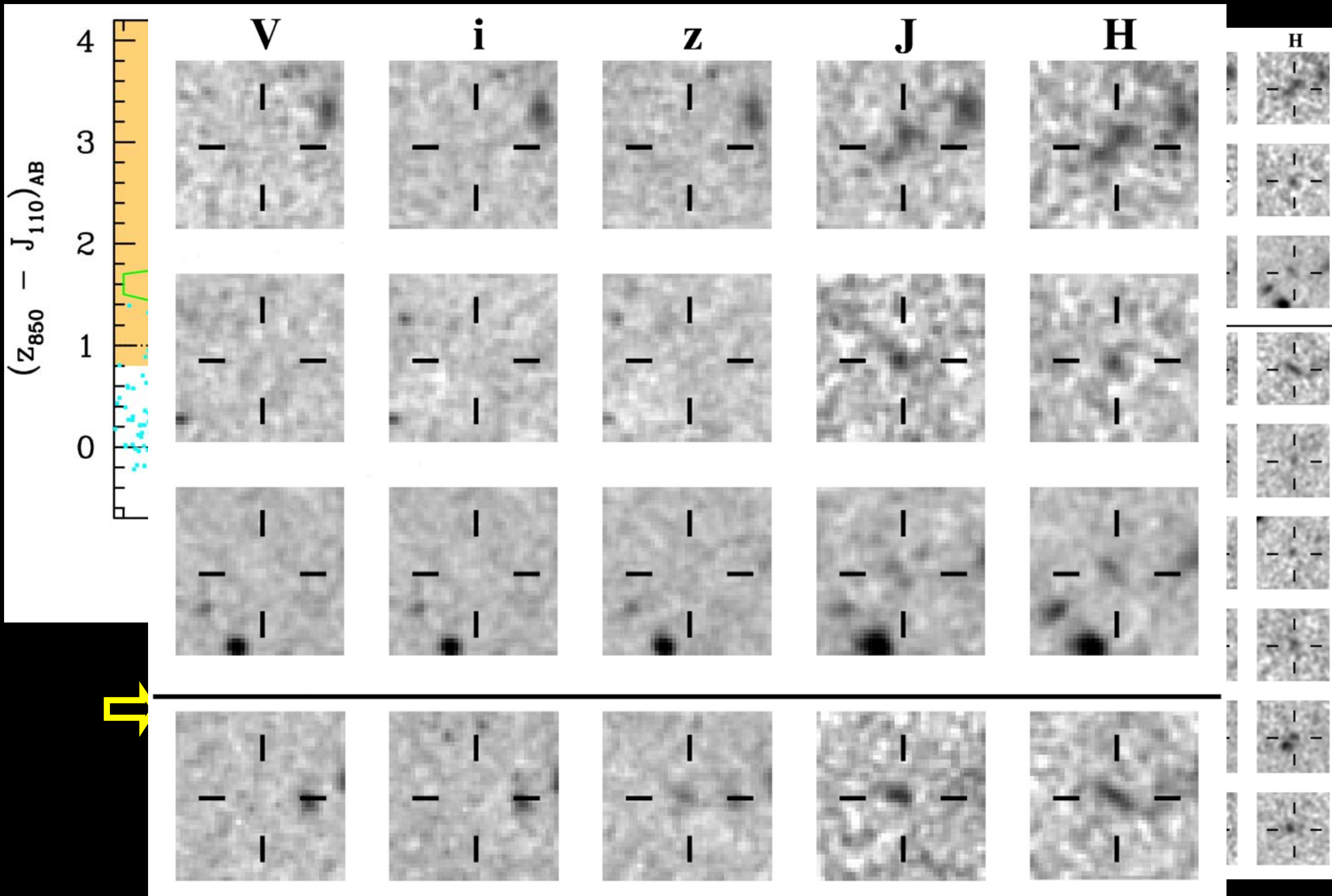
J_{AB} ~ H_{AB} >= 26.5 mag

Deep NICMOS Imaging Around Lensing Clusters

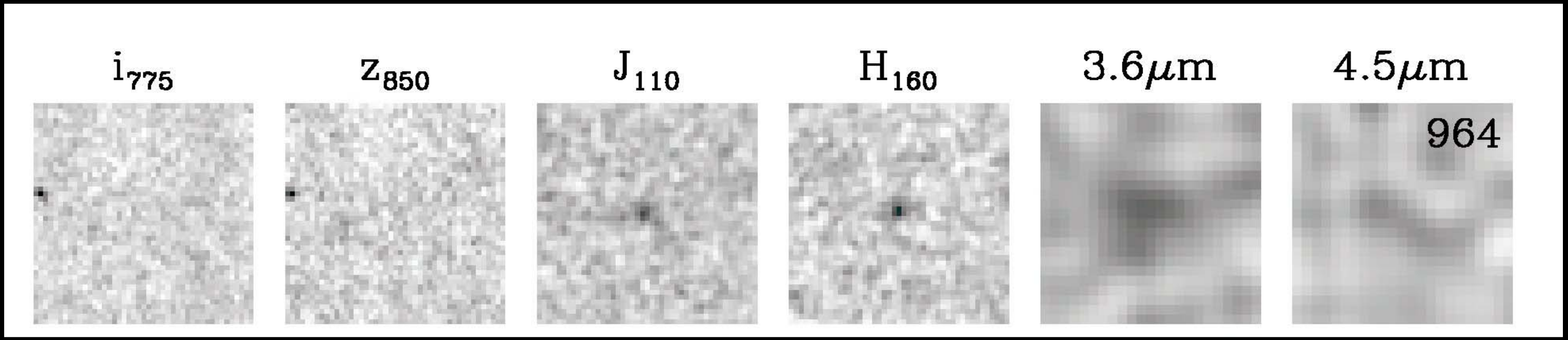


z ~ 7-8 Galaxies

Bouwens et al. 2007



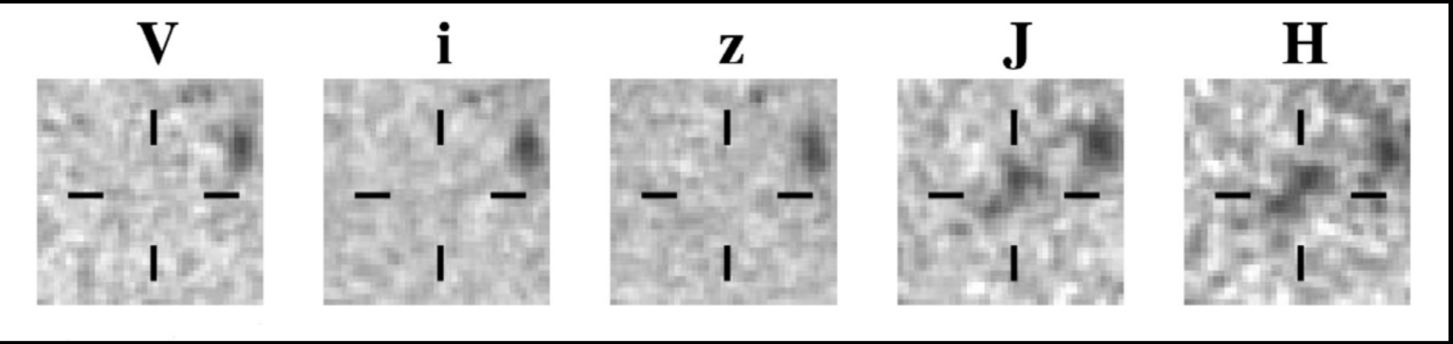
Are we really finding z>7 galaxies?



- 5σ detections in J, H, IRAC 3.6μ channel, and 2.5 σ in IRAC 4.5 μ 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 - 3.6μ) colors similar to z~6 objects

Labbe, Bouwens, Illingworth, Franx 2006

Are we really finding z>7 galaxies?

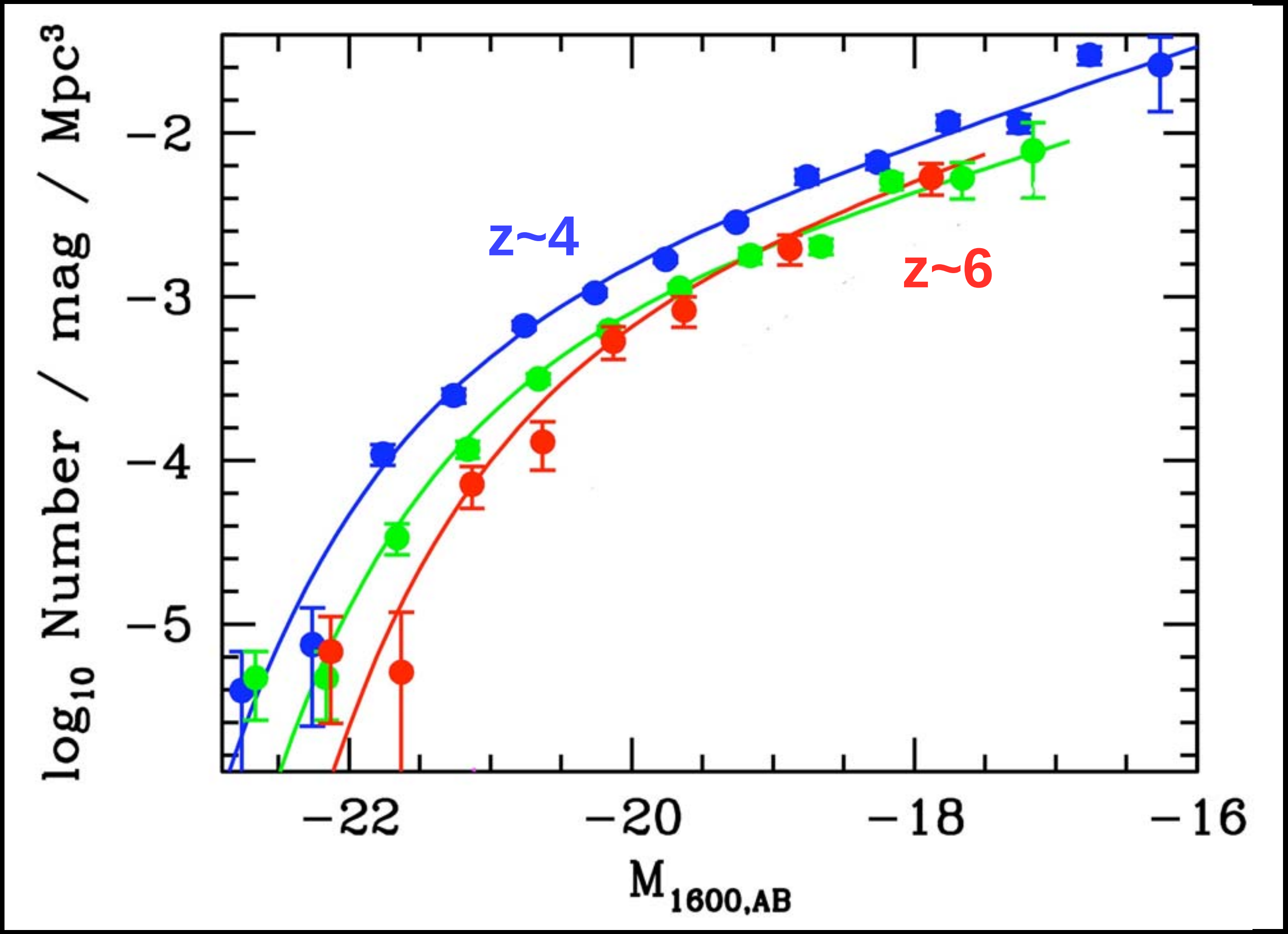


- 8σ detections in J, H, IRAC 3.6μ channel, and 2.5 σ in IRAC 4.5 μ channel
- Very Blue J - H colors
- Extremely red z-J > 2.5 colour
- Undetected in very deep V, i, z band imaging, even in stacked exposures
- Extended so cannot be a brown dwarf
- (H - 3.6μ) colors similar to z~6 objects

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

UV Luminosity Functions

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



Bright

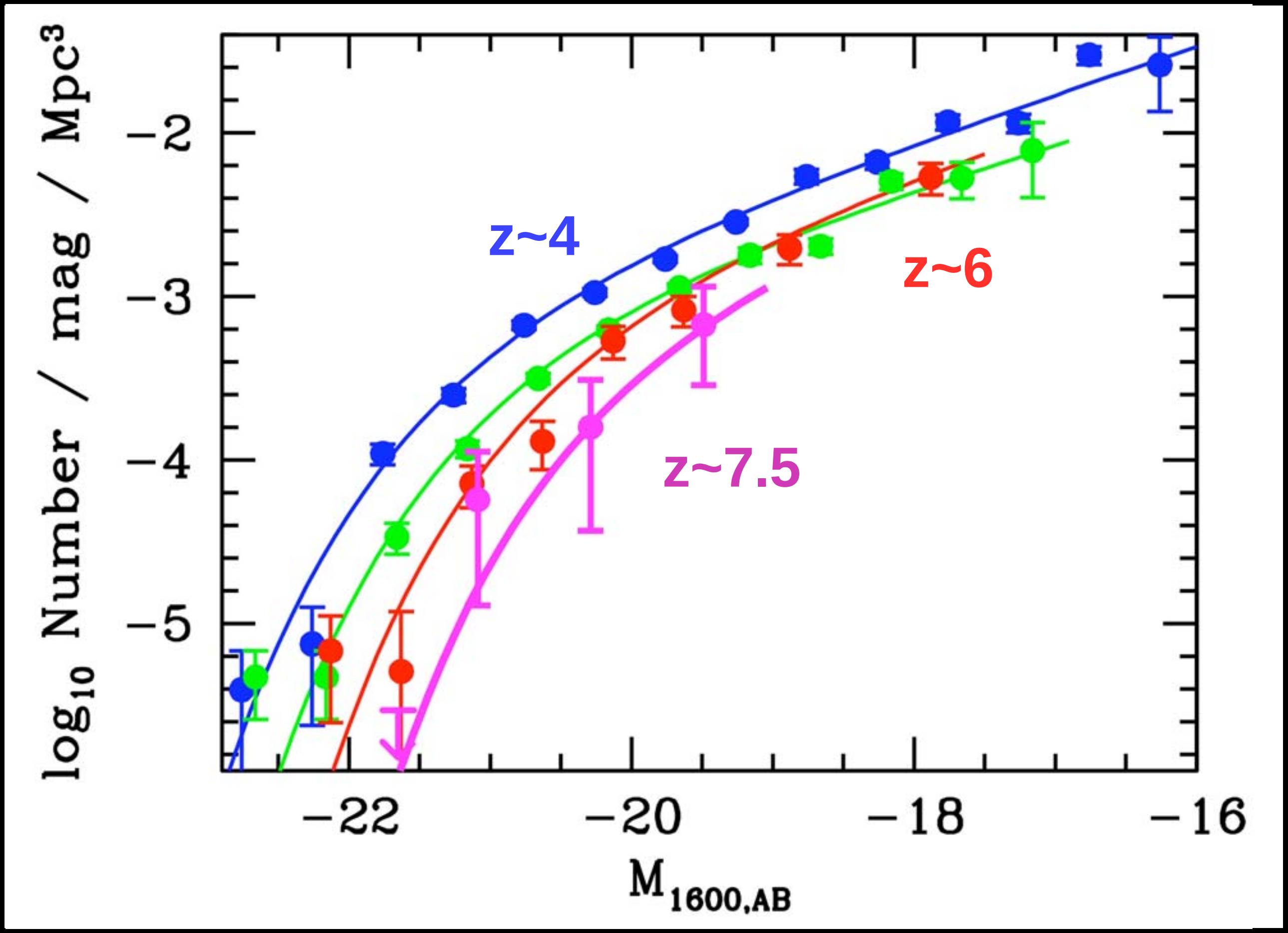
Faint

Bouwens et al. 2007

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

UV Luminosity Functions

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



Bright

Faint

Bouwens et al. 2007

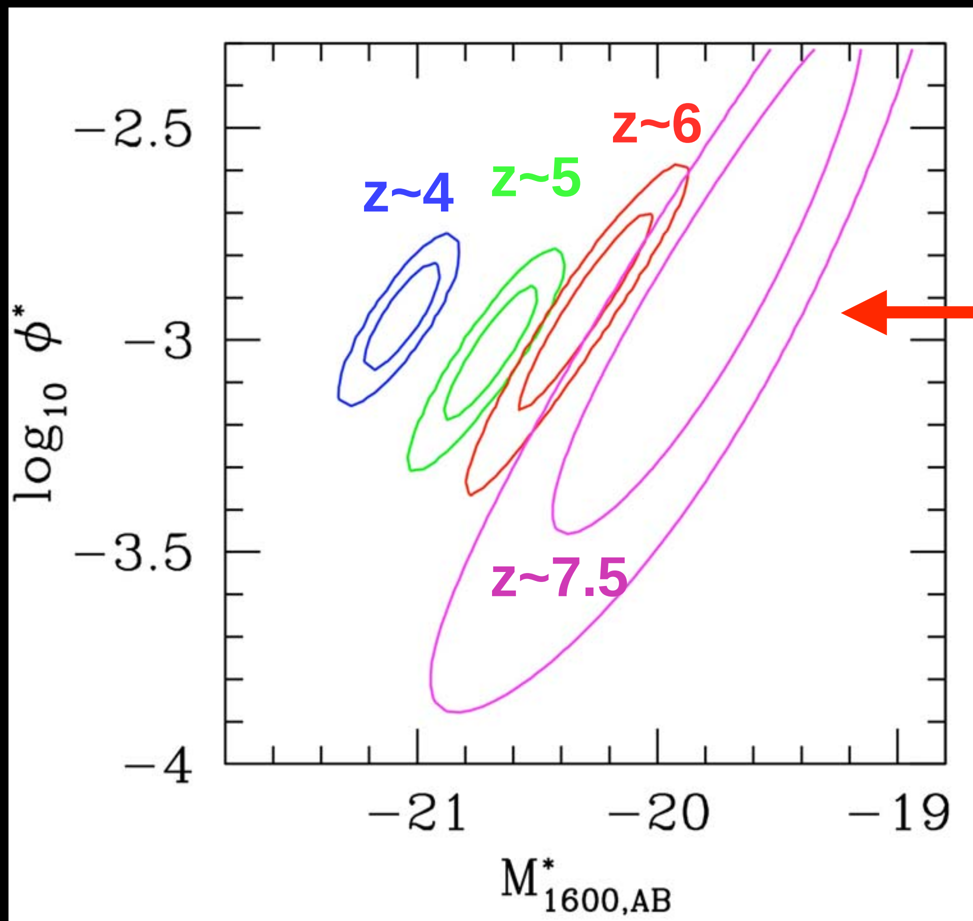
Galaxies at *z*~4, 5, 6, 7.5 *(B, V, i, z-dropouts)*

UV Luminosity Functions

High

Volume Density ϕ^*

Low



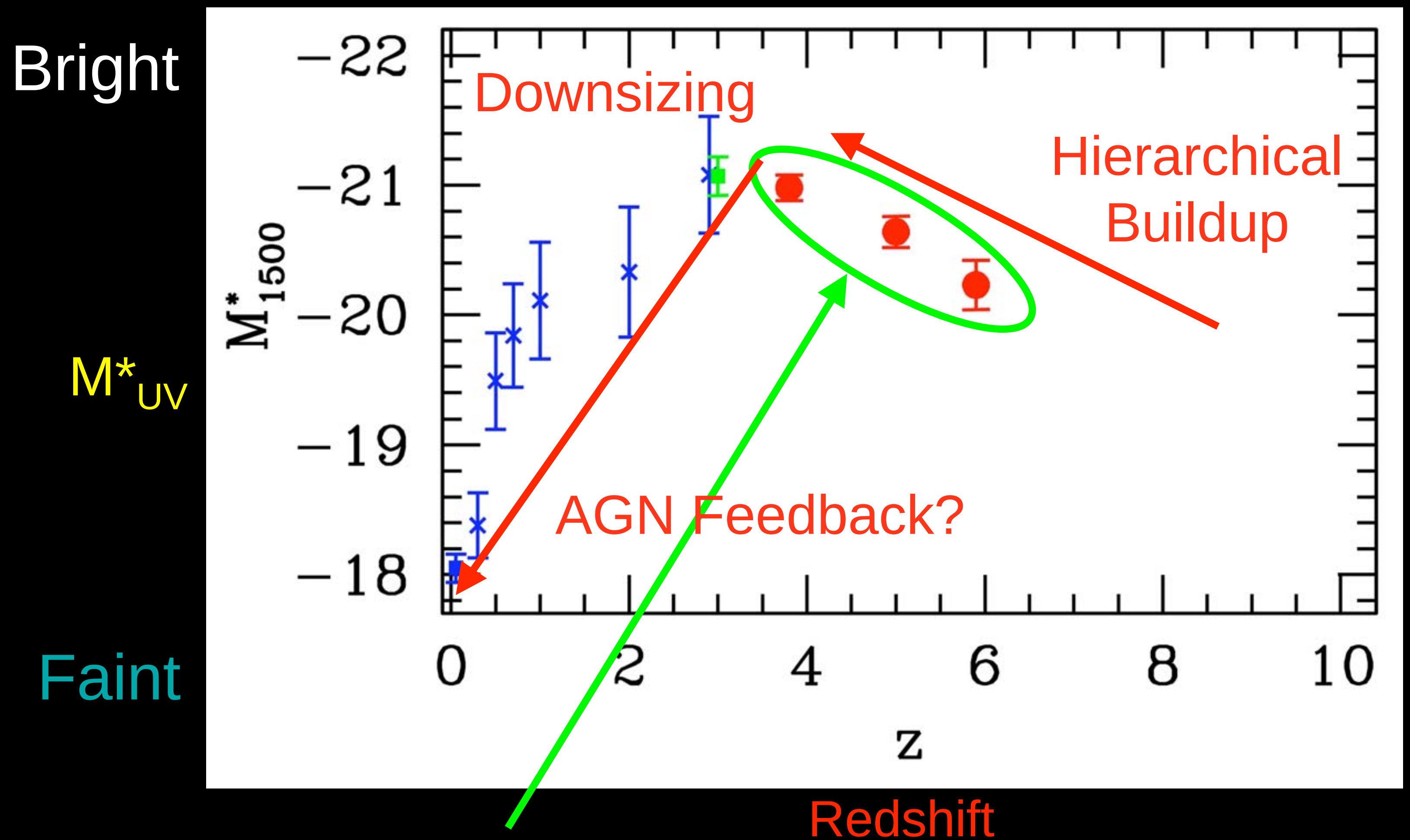
Bright M* Faint

$\phi^* \sim 0.0013$ Mpc^{-3} at z~4, 5, 6, 7.5

z~7-8 contours fit in nicely with z~4-6 trends! Suggests we are actually finding z~7-8 galaxies!

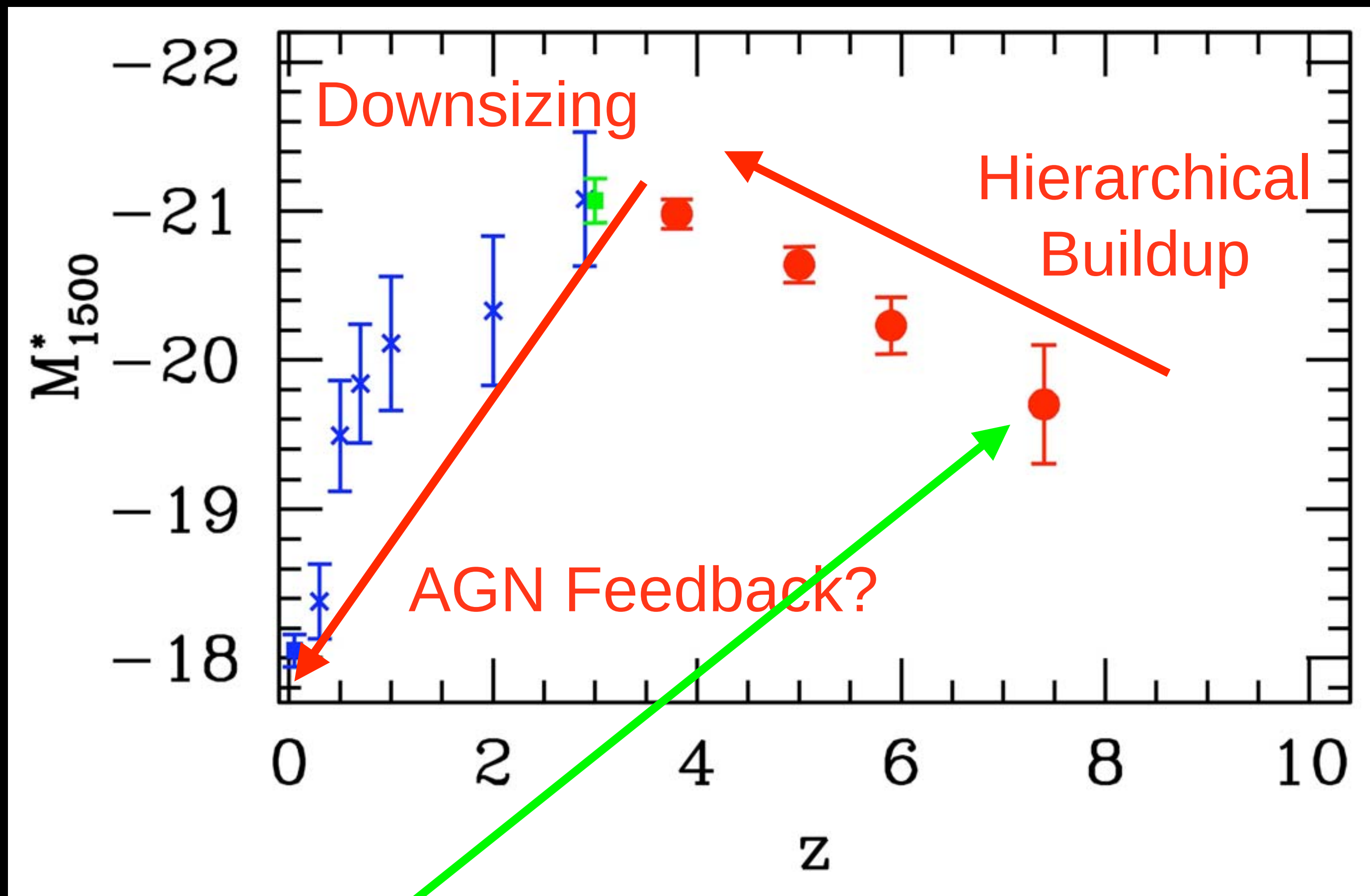
Bouwens et al. 2007

Evolution of the UV Luminosity Function



Bouwens, Illingworth, Franx, & Ford 2007

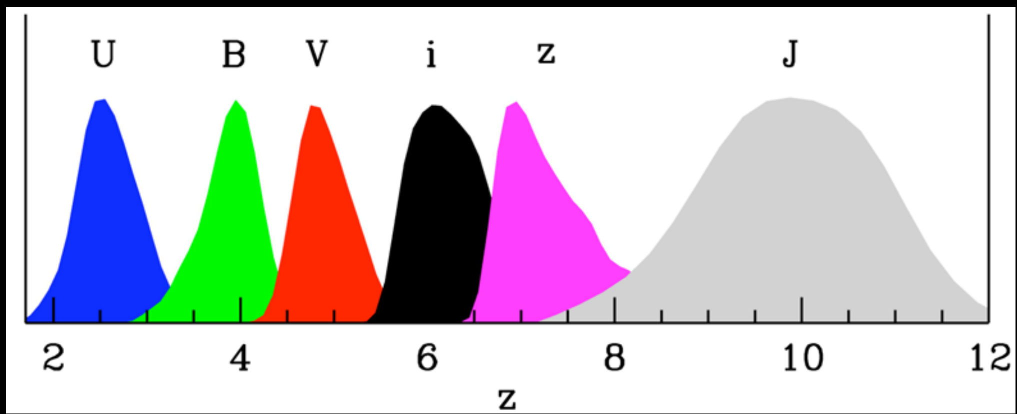
Evolution of the UV Luminosity Function



Bouwens, Illingworth et al. 2007

Galaxies at *z*~10

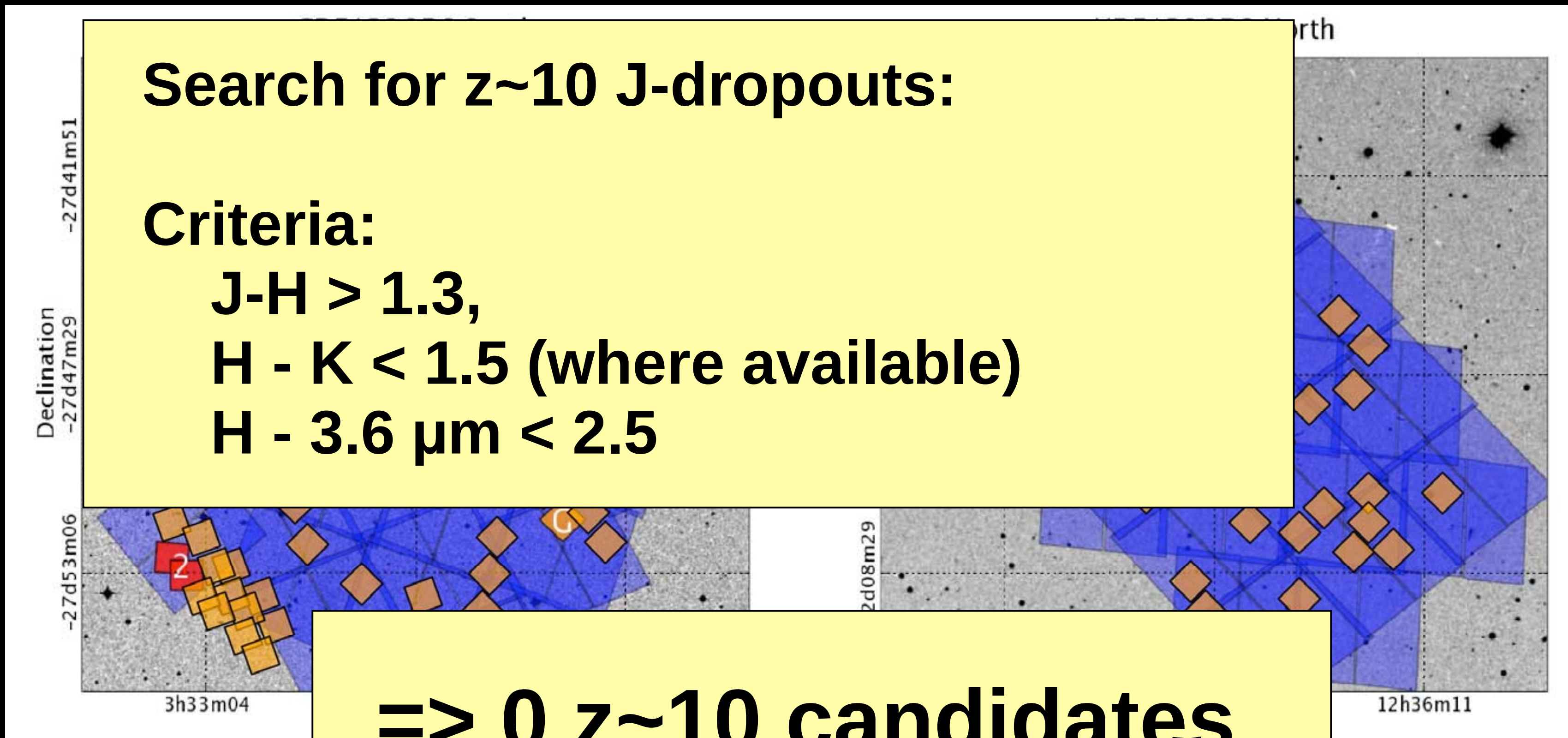
(J-dropouts)



Dropout Redshift Selection Functions

Galaxies at *z~10 (J-dropouts)*

Many fields with deep ACS and NICMOS data for dropout searches



Search for z~10 J-dropouts:

Criteria:

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

=> 0 z~10 candidates

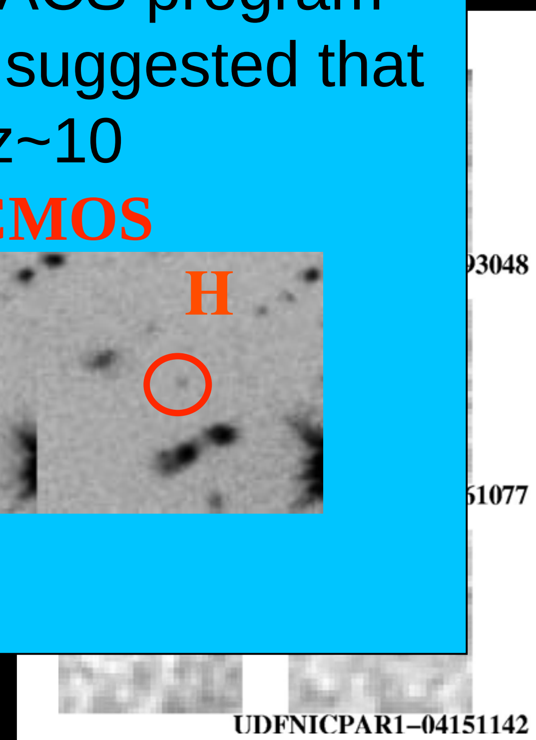
Deep NICMOS ... ~80 arcmin^2

ACS *NICMOS*
$J_{AB} \sim H_{AB}$ >= 26.5 mag

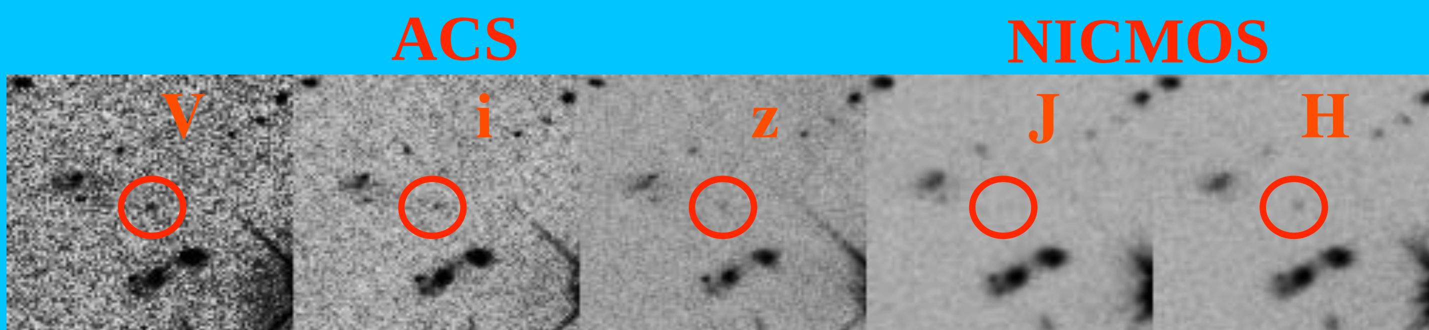
Previous J-dropout Search

- *J-H*>1.8 *“J-dropout”* criterion -- excluding sources with optical detections, very red H-K colours, or very H-3.6μm colours

Exa



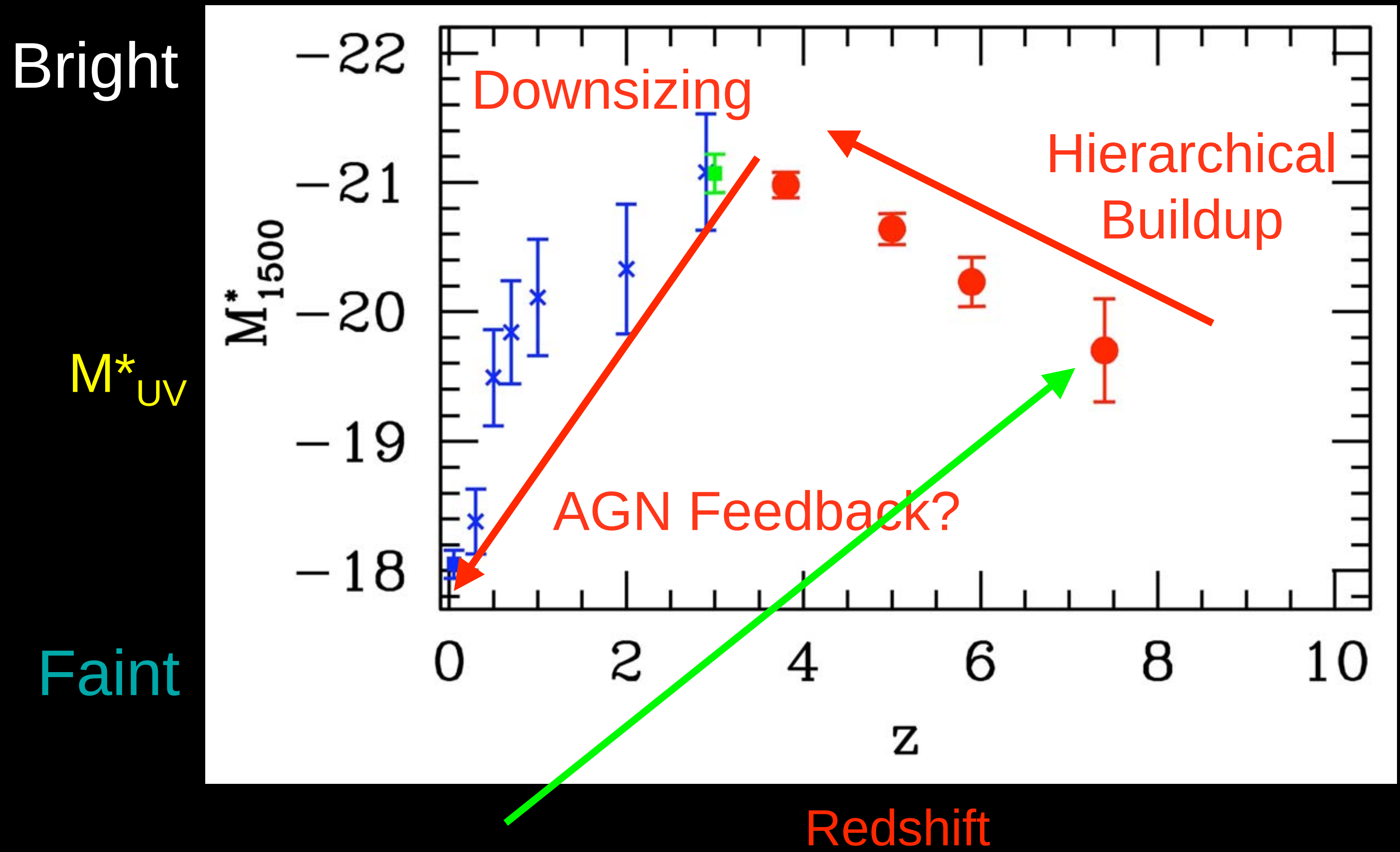
However, new data from a very deep ACS program and improved NICMOS reductions has suggested that none of the 3 candidates at z~10



Credit: Stiavelli

Bouwens, Illingworth, Thompson, Franx 2005a

Evolution of the UV Luminosity Function



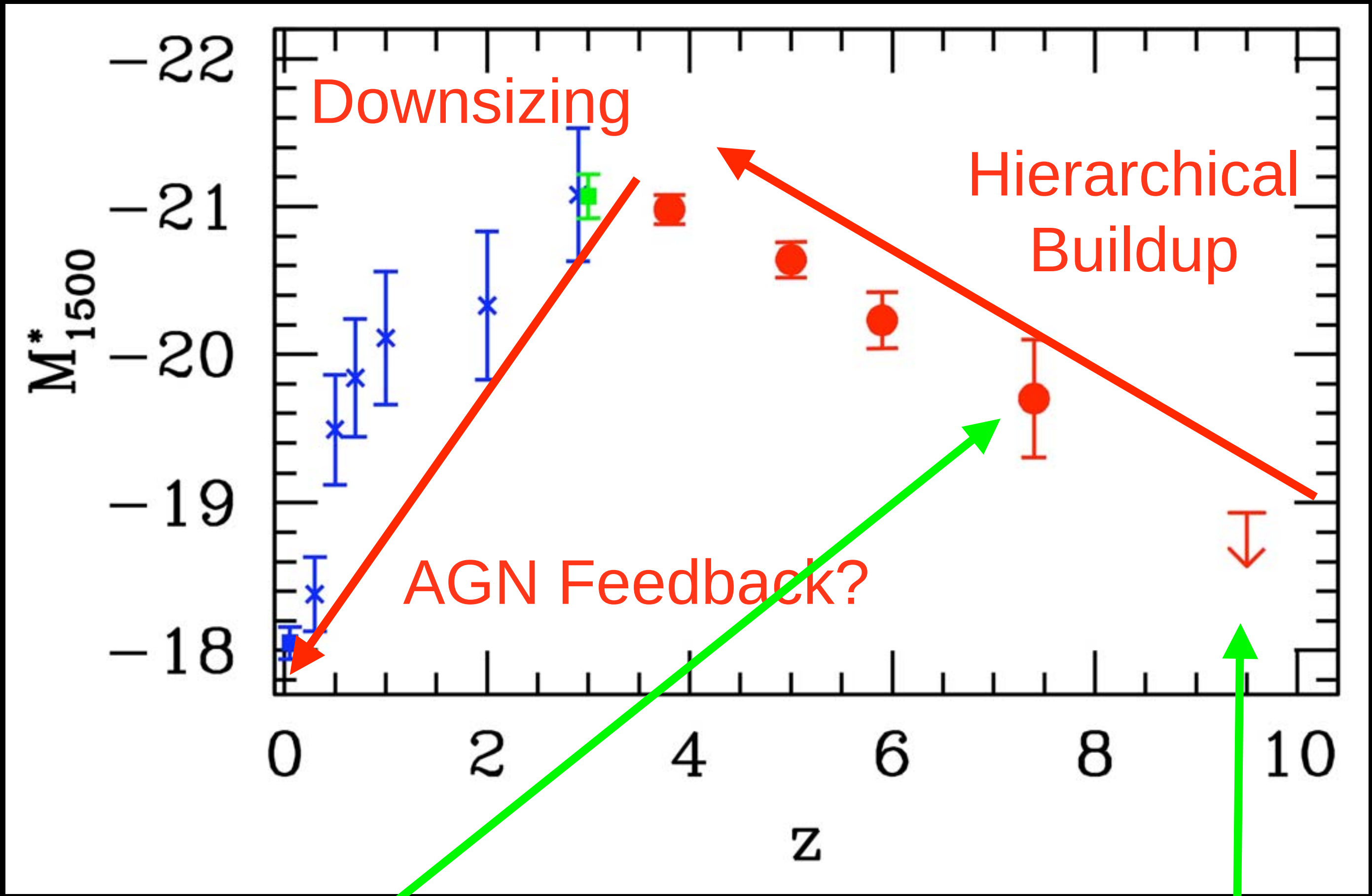
Bouwens, Illingworth et al. 2007

Evolution of the UV Luminosity Function

Bright

M^*_{UV}

Faint



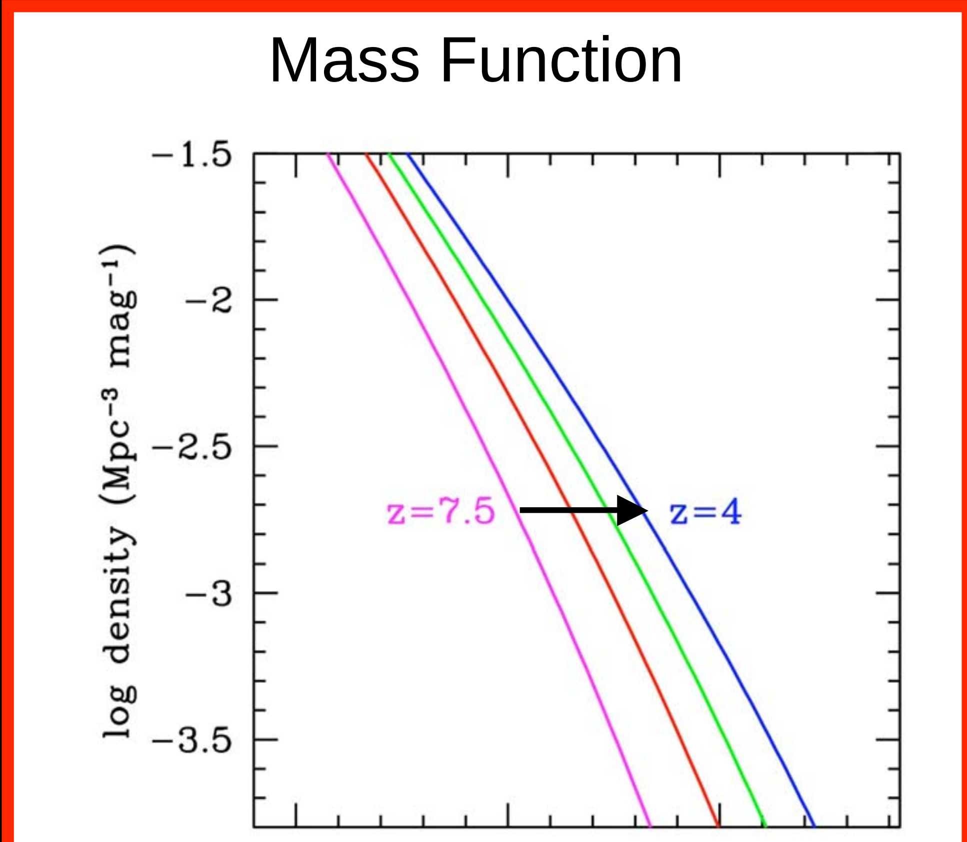
Redshift

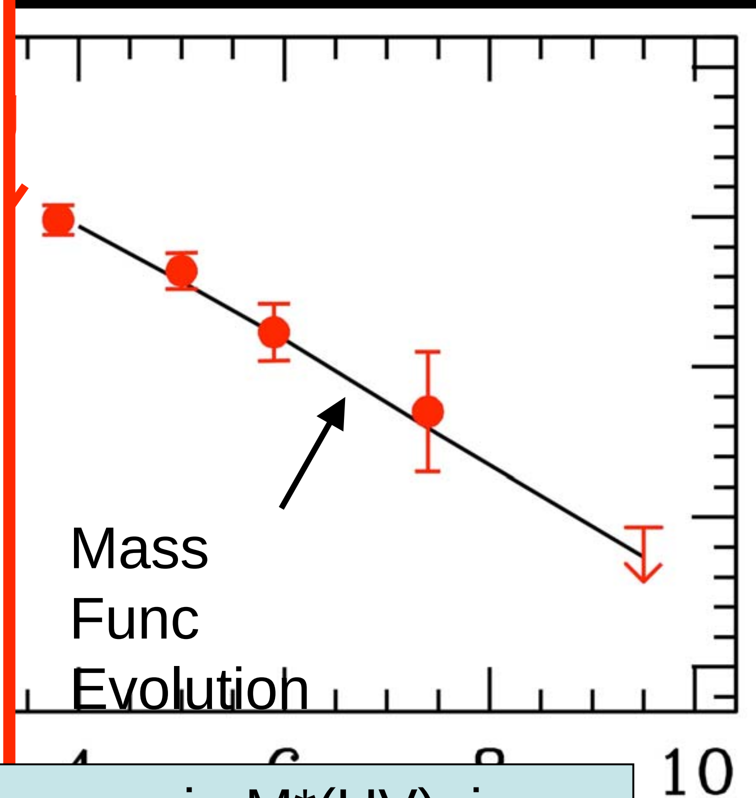
Bouwens, Illingworth et al. 2007

Assuming phi* ~ 0.0013 Mpc^{-3}
at z~10 (i.e., no evolution)

Venice 08/29/07 RJB

Evolution of the UV Luminosity Function

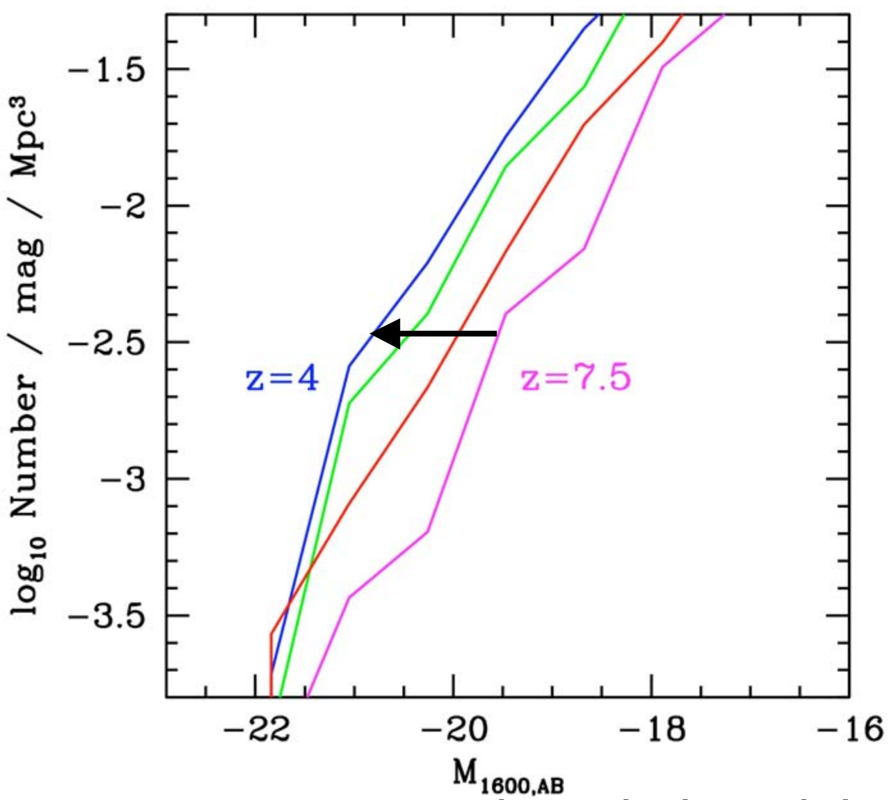




Surprisingly, the evolution we observe in M*(UV) is almost identical to what we would expect from the evolution of the halo mass function and assuming no evolution in the M/L ratio!

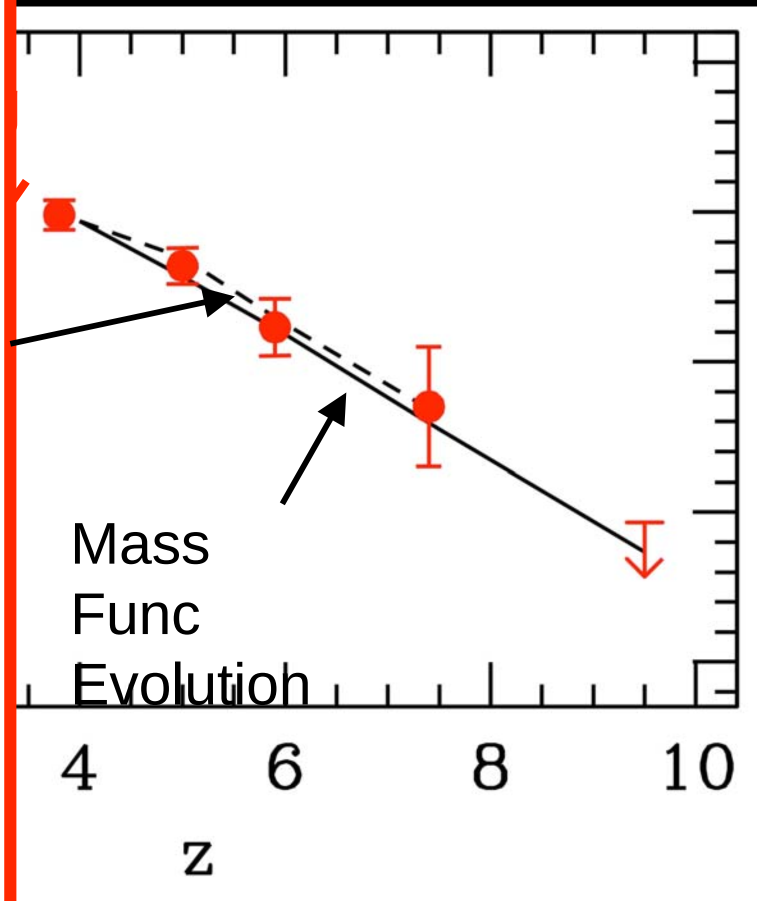
Evolution of the UV Luminosity Function

Gravity + Hydro Model Results



Momentum conserving wind model

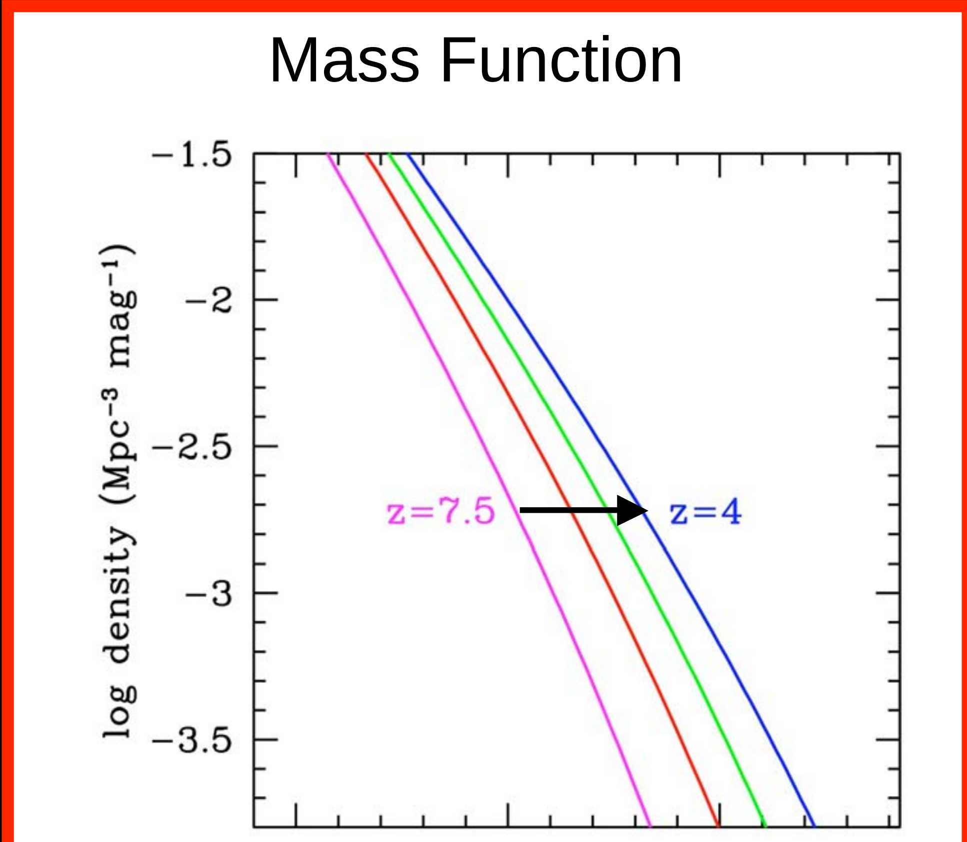
Oppenheimer & Dave 2006

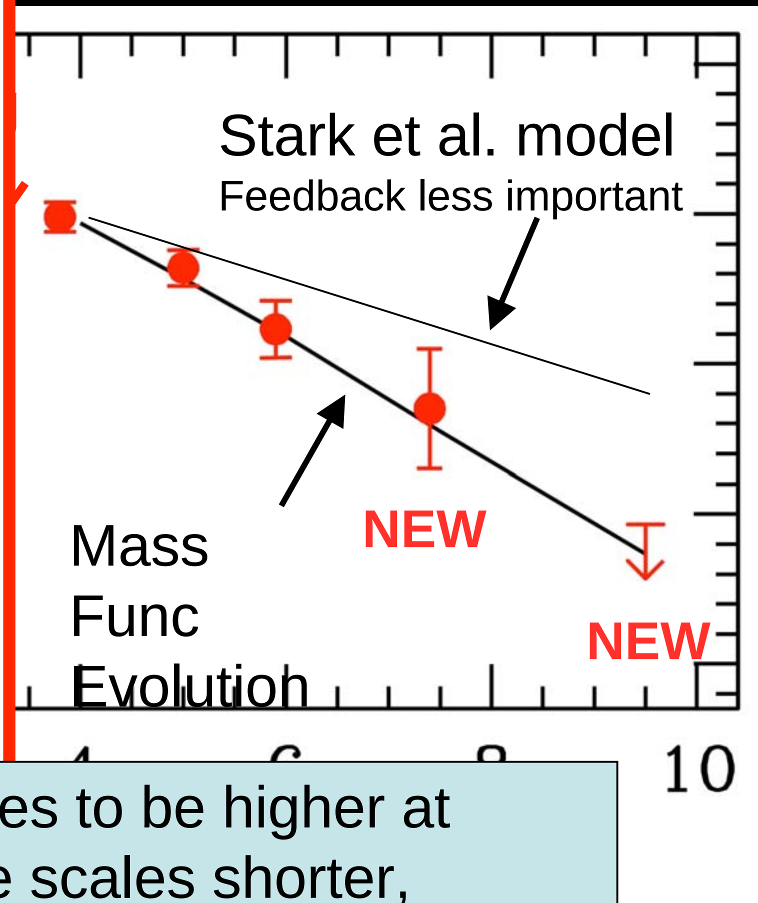


Redshift

Bouwens, Illingworth et al. 2007

Evolution of the UV Luminosity Function





Would expect M/L ratio of galaxies to be higher at early times because cooling time scales shorter, dynamical time scales less, etc., so might expect real evolution in M* to be less than predicted from the halo mass function, i.e., as in Stark et al. model

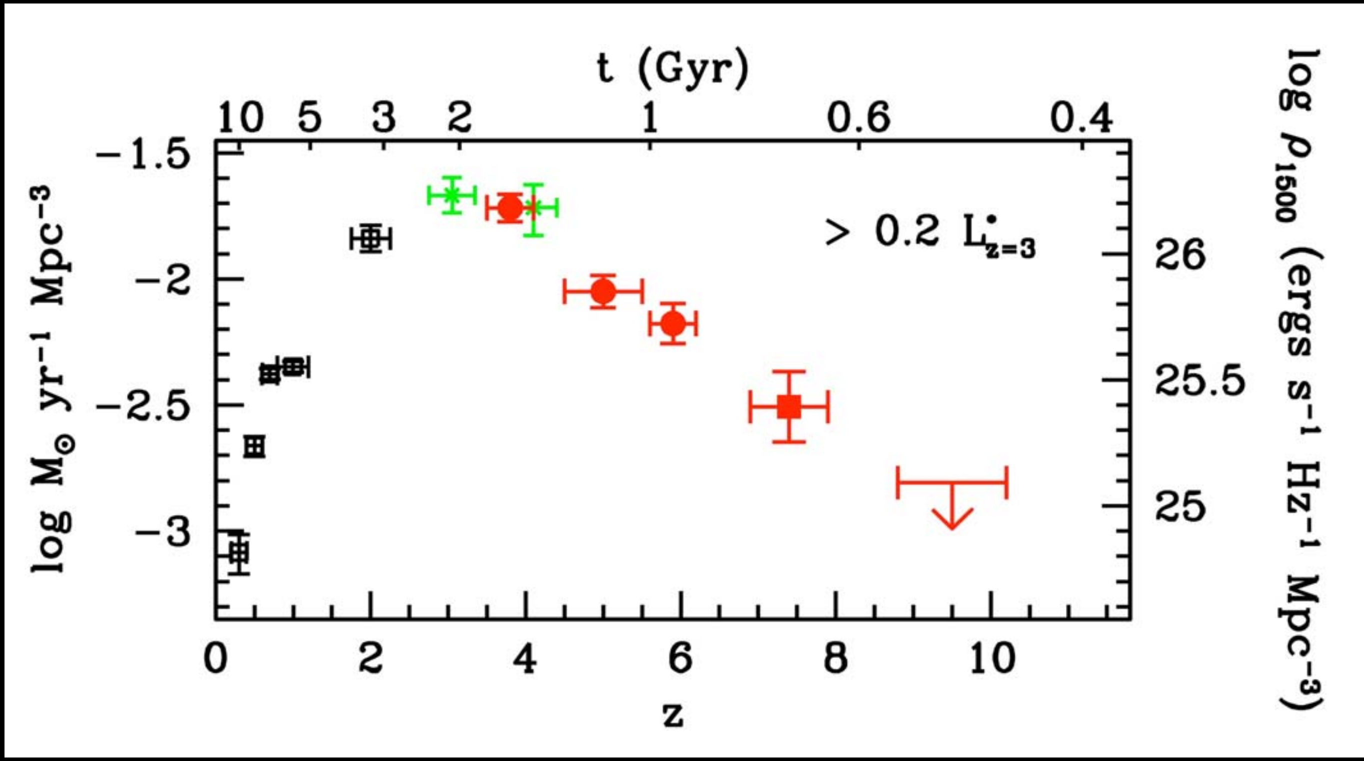
UV Luminosity Density & SFR History

Luminosity Density:
Log ergs s^{-1} Hz^{-1} Mpc^{-3}

SFR:
Log_{10} $M_{\odot}$ $yr^{-1}Mpc^{-3}$

"Cosmic Variance" due to large scale structure:

at z~4-6 ~14% RMS
at z~7-8 ~25% RMS
at z~10 ~19% RMS



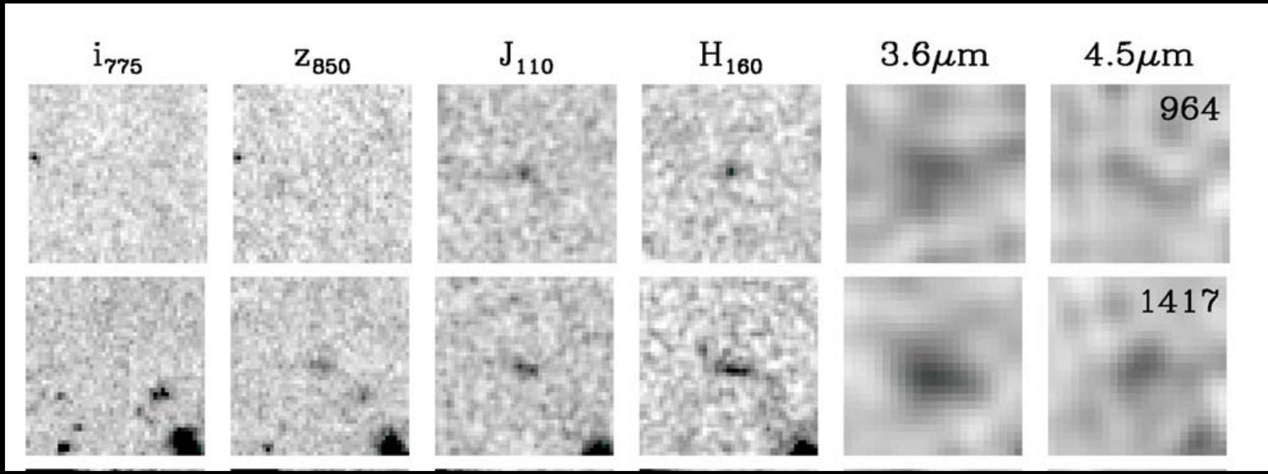
Upper limit from z~10 search

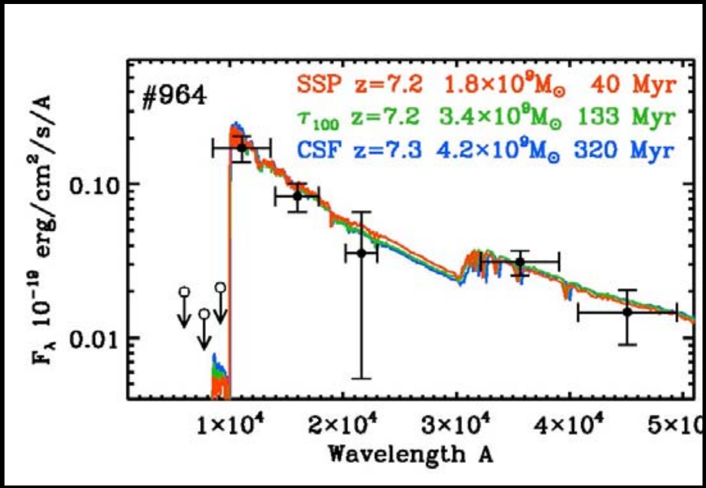
Bouwens et al. 2007

Spitzer Observations of z~7 Galaxies

Stellar Masses of z~7 Galaxies
Rest-frame optical fluxes from Spitzer IRAC

Rest-frame UV Rest-frame Optical





Stellar Masses of 0.3 - 1.0 x 10^{10} $M_\odot$

Ages of ~50-200 Myr

Stellar Mass Density at z~7.4 (> 0.3 L*) is

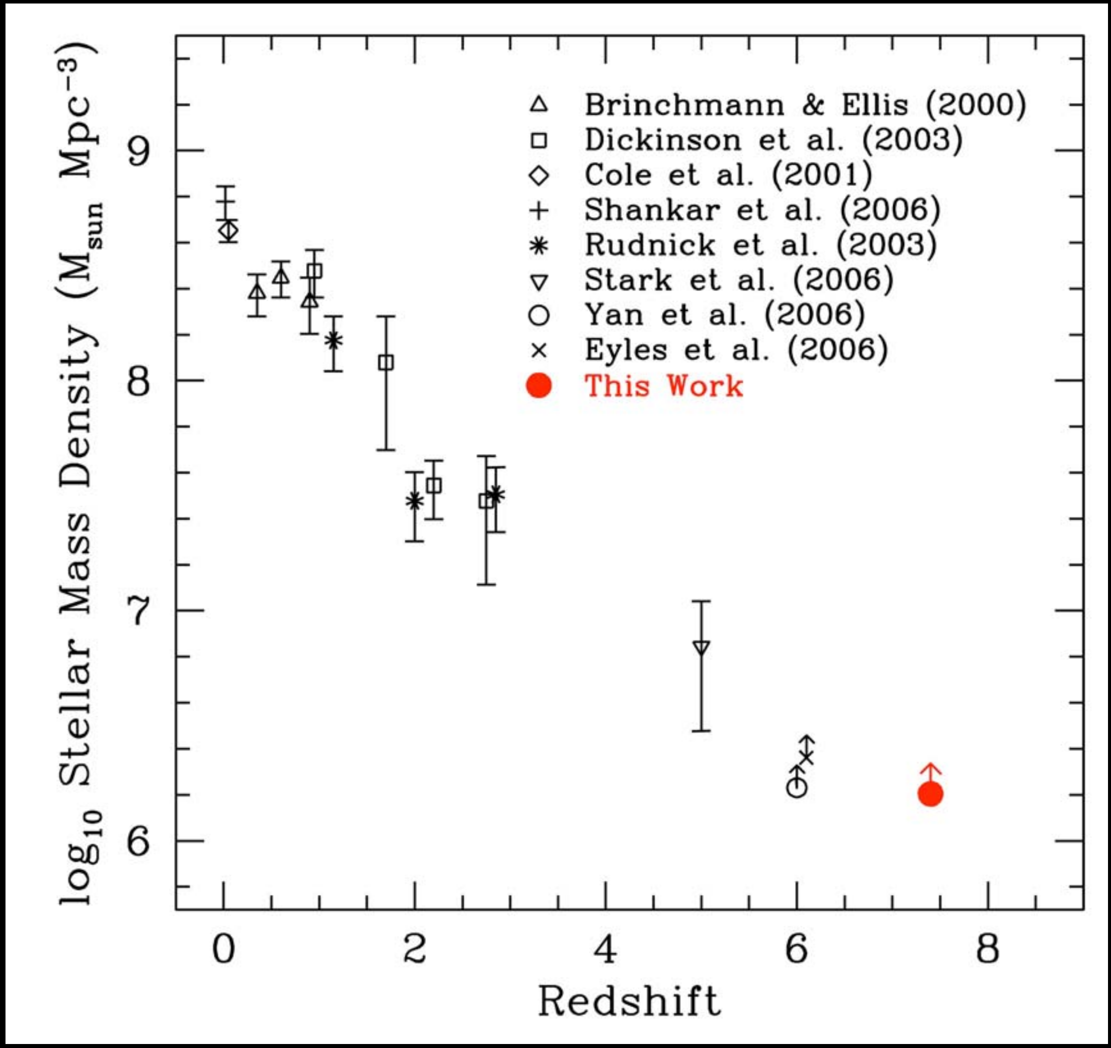
20-60% of z~5-6 values

Labbe, Bouwens, Illingworth, Franx, *Ap.J.,* 2006

Mass Buildup from z~7

- Stellar Mass Density
- vs Redshift

- From z~7 (0.7Gyr) to present day



Labbe, Bouwens, Illingworth, Franx, *Ap.J.*, 2006

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

- UDF and GOODS ACS and NICMOS data are superb for z~4 to z~7-10 dropout searches
- ~4700 B-dropouts (z~4), ~1400 V-dropouts (z~5) and ~600 i-dropouts (z~6) are found in deep HST ACS data
- z~4,5,6 UV Luminosity Function determined to 3-5 mags below L*
- Soon >=80 arcmin^2 of deep (>=26.5 AB mag) near-IR data will be available over areas with deep optical coverage
- Using these data, we have identified 9 z~7-8 z-dropout candidates, with luminosities ranging from 0.1 L*(z=3) to 1.0 L*(z=3)
- The characteristic luminosity of galaxies in the UV appears to brighten substantially (by ~1.2 mag) from z~7.5 to z~3.
- The increase in the characteristic luminosity M* is almost identical to that expected for the halo mass function -- suggesting that the observed evolution can be explained with hierarchical buildup
- We have detected likely z~7-8 galaxies with Spitzer IRAC in the rest-frame optical and estimated stellar masses of ~5 x 10^9 solar masses