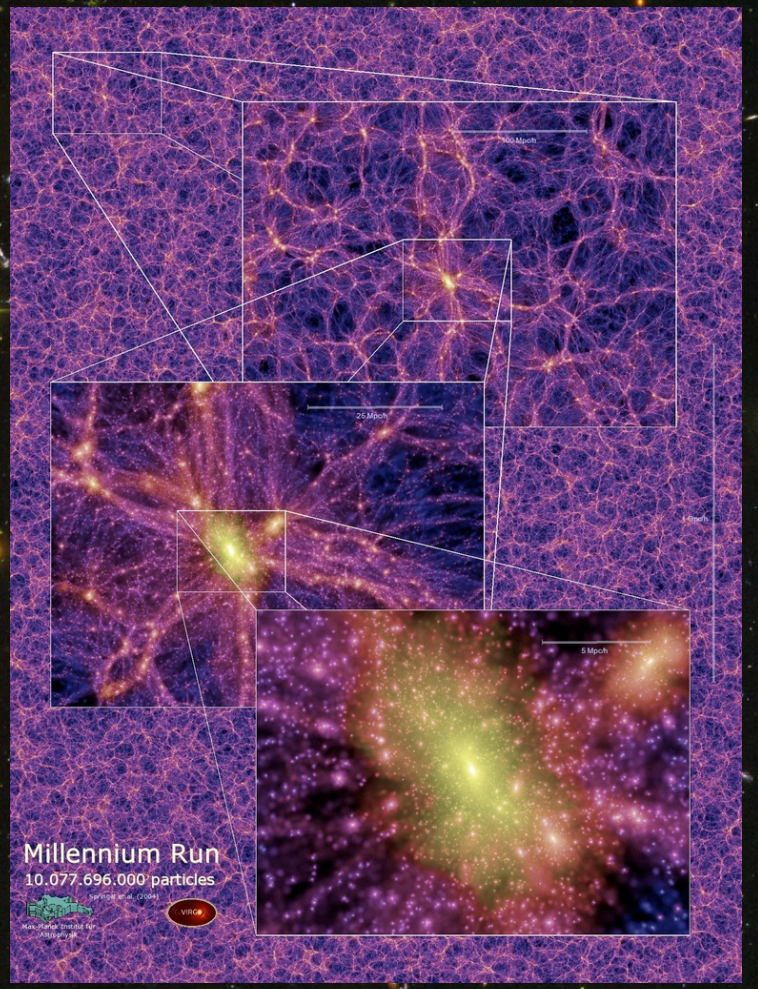
Galaxy Build-up from z~7 to z~4

Garth Illingworth

Rychard Bouwens



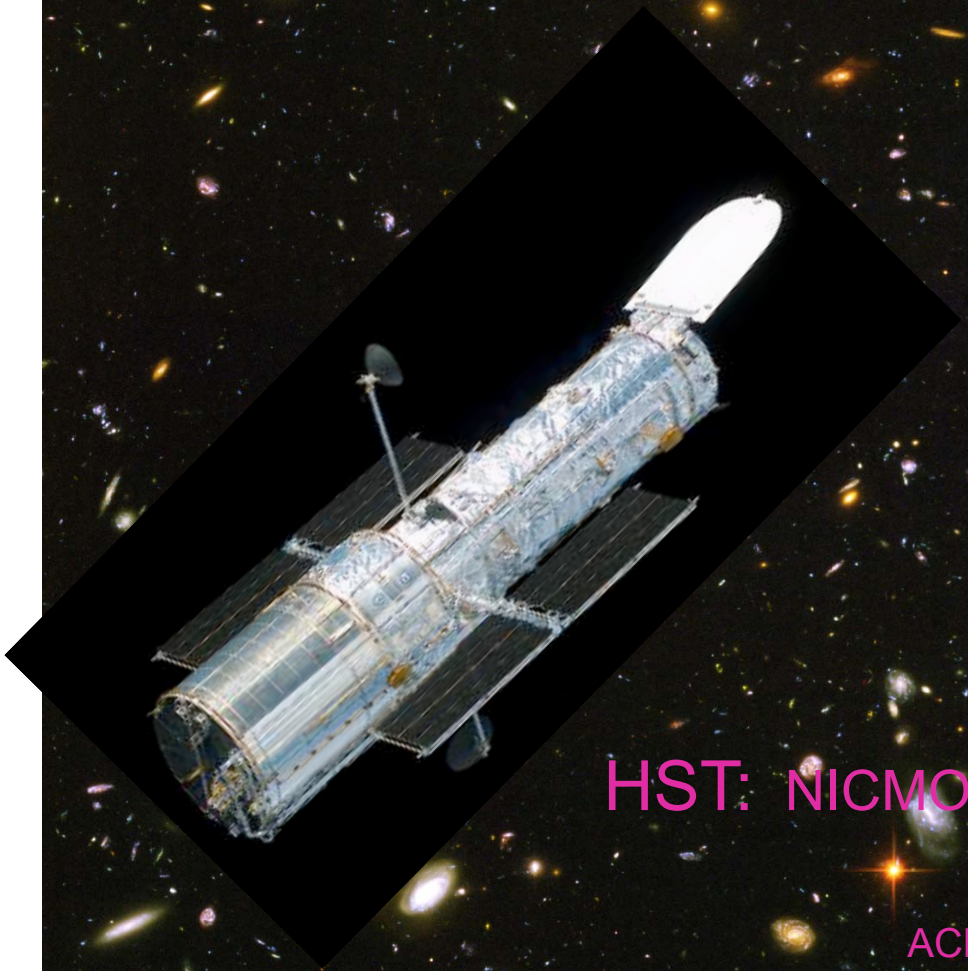
Aspen Center for Physics

Galaxy Build-up from z~7 to z~4

Special thanks:

Holland Ford, Marijn Franx, Ivo Labbe

And the ACS GTO team, the UDF IR team, the HUDF team (and Steve Beckwith for his support in doing the UDF), and the GOODS team



HST: NICMOS + ACS

Galaxy Build-up from z~7 to z~4

Topics

1) Large samples of z~6 galaxies
2) ***Faint*** luminosity functions at z~4, 5, 6
3) Luminosity density; SFR from z~4 to z~7-8
4) z~7-8-10 detections/limits (?)
5) z~6-7-8 masses

SUMMARY

Characterizing UV-bright galaxies at z~4-5-6

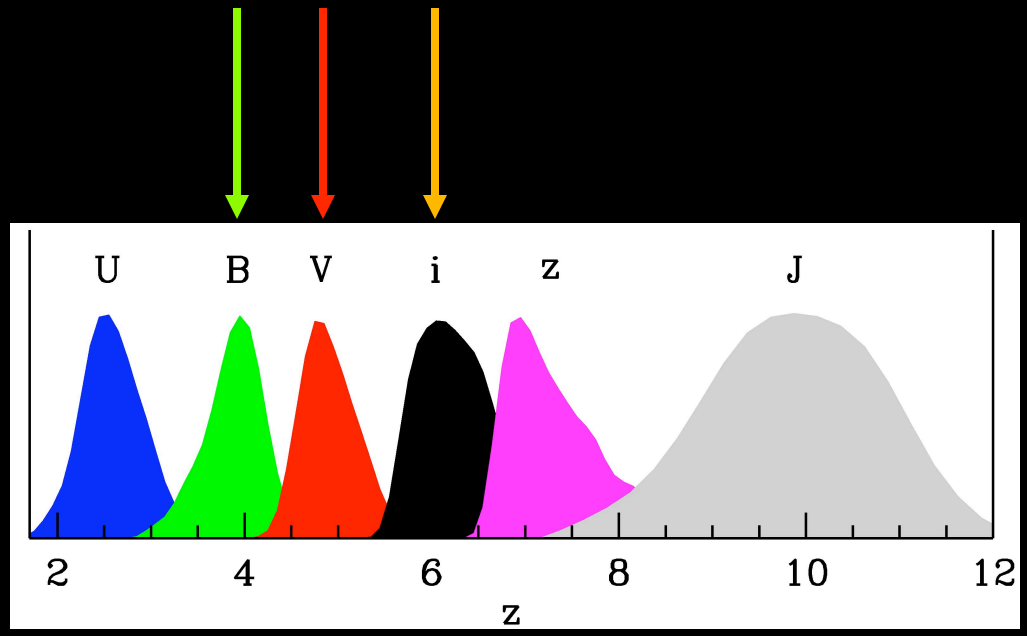
Robust detections and constraints at z~7

Mass estimates at z~7

Upper limits at z~9-10

Galaxies at *z*~4, 5 & 6

(B, V, i-dropouts)



Dropout Redshift Selection Functions

Galaxies at *z*~4, 5, 6

ACS data circa 2007 => SM4 recovery!

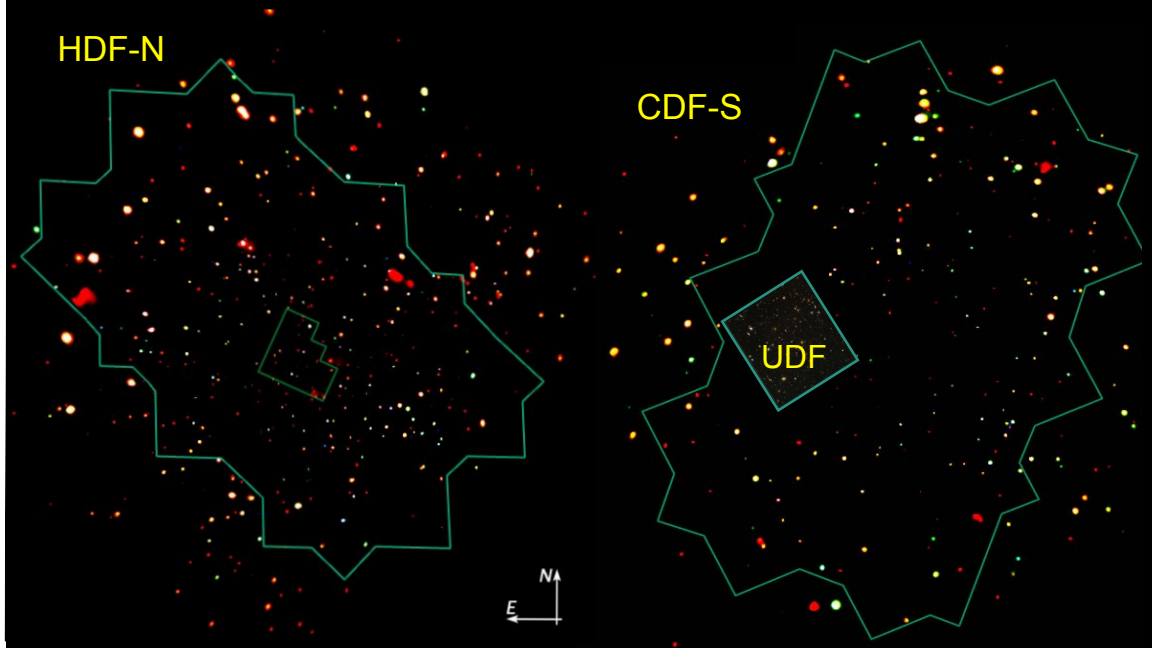
Wide ⟷ Deep

GOODS

HDF-N

CDF-S

UDF



$z_{850,AB}$~ 27.5 (10σ)

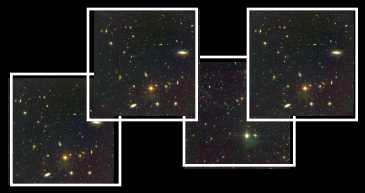
320 arcmin^2

UDF

$z_{850,AB}$~ 29.2 (10σ)

10 arcmin^2

UDF-Parallels



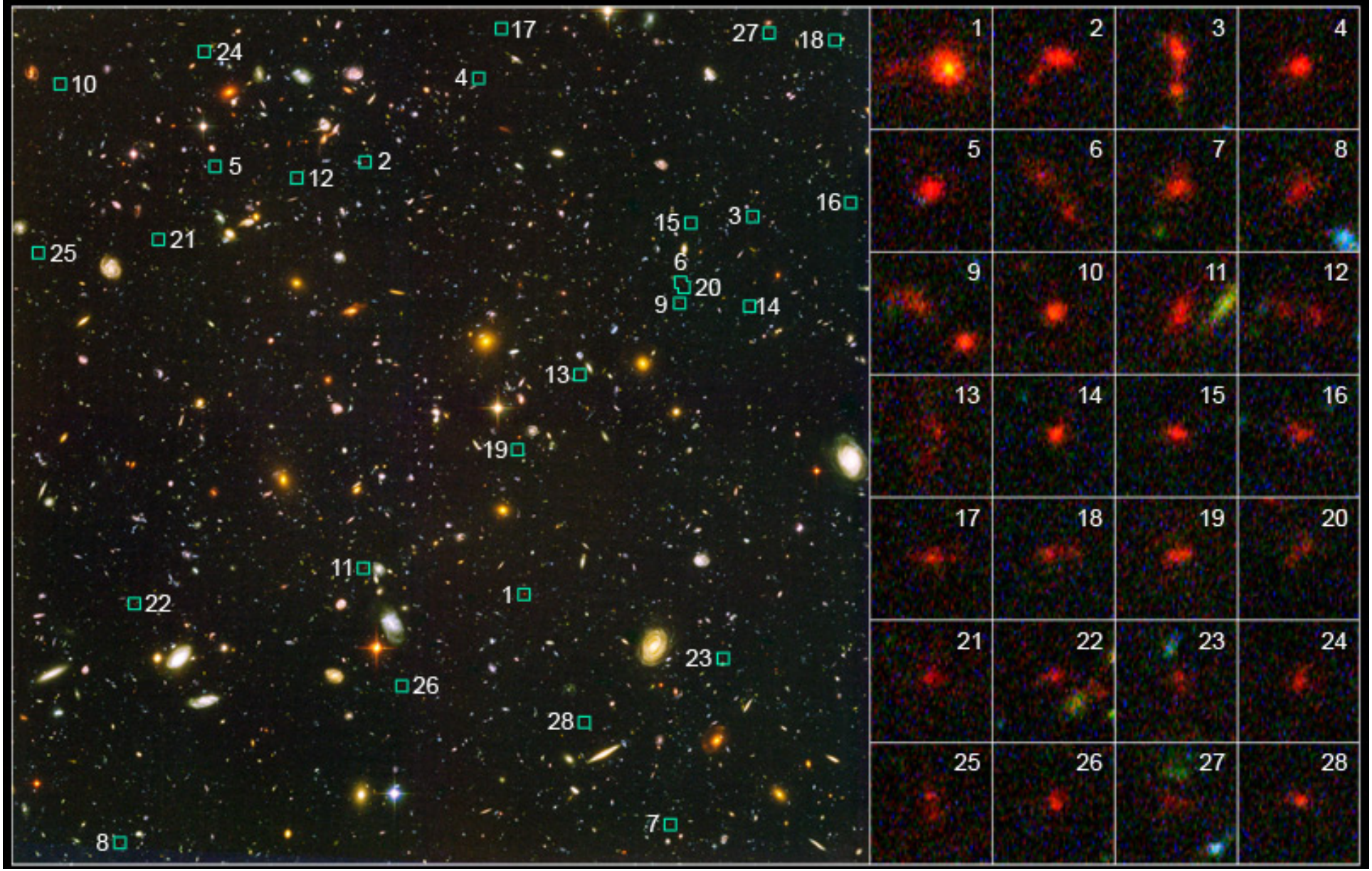
$z_{850,AB}$~ 28.4-28.7 (10σ)

40 arcmin^2

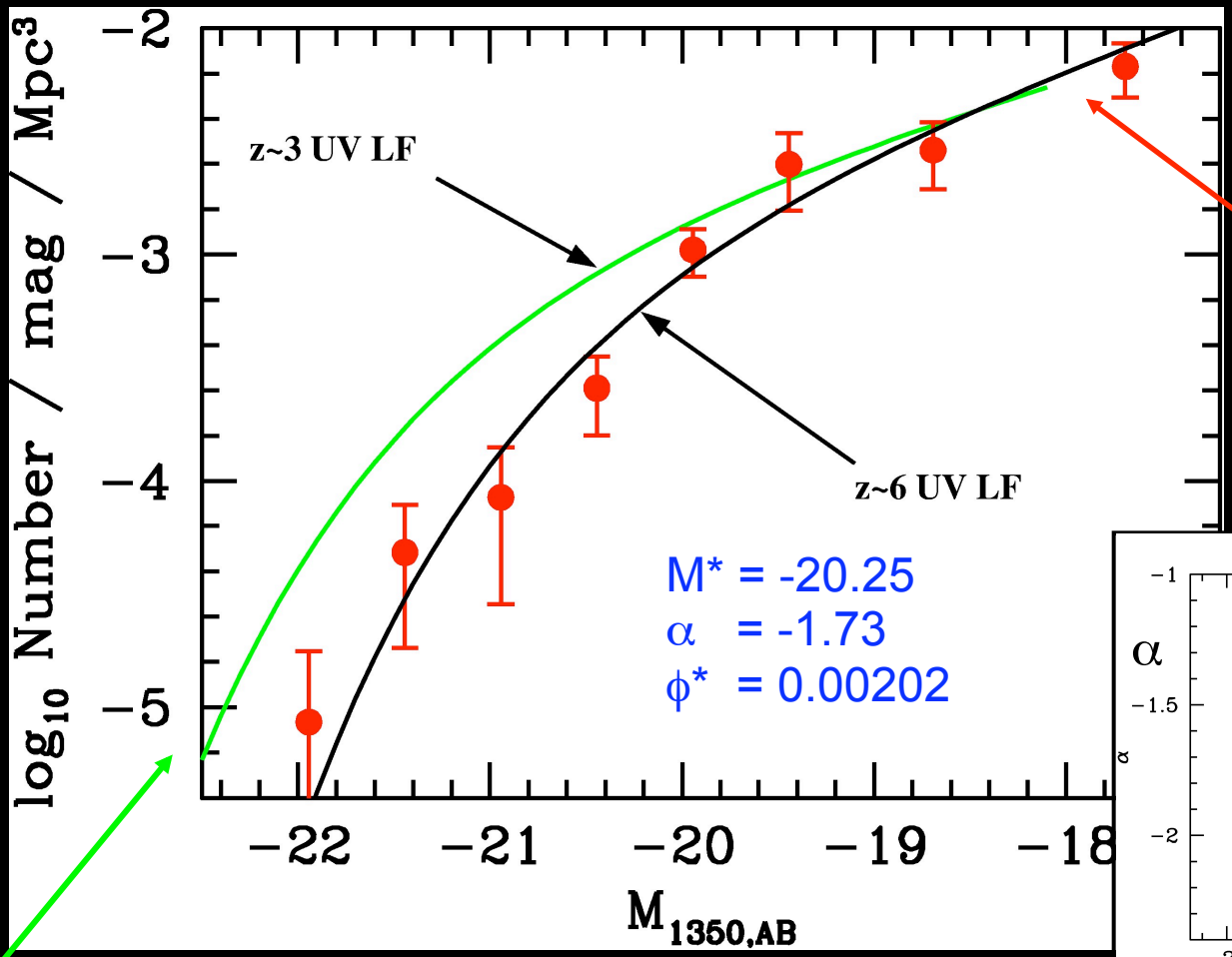
4671 *z*~4 B-dropouts
1416 *z*~5 V-dropouts
627 *z*~6 *i-dropouts*!

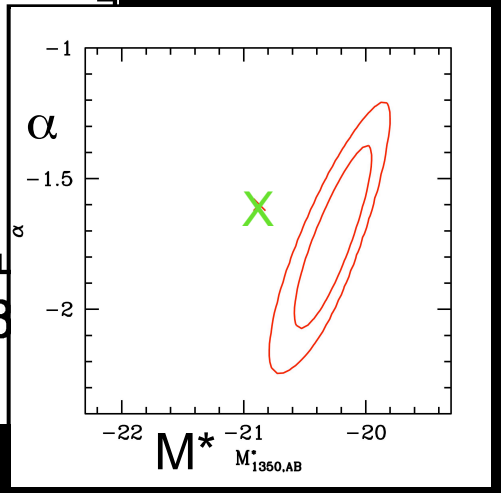
ACP W08 *GDI*

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



z~6 UV Luminosity Function





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

LF at z~6: goes ~3 mag below L*

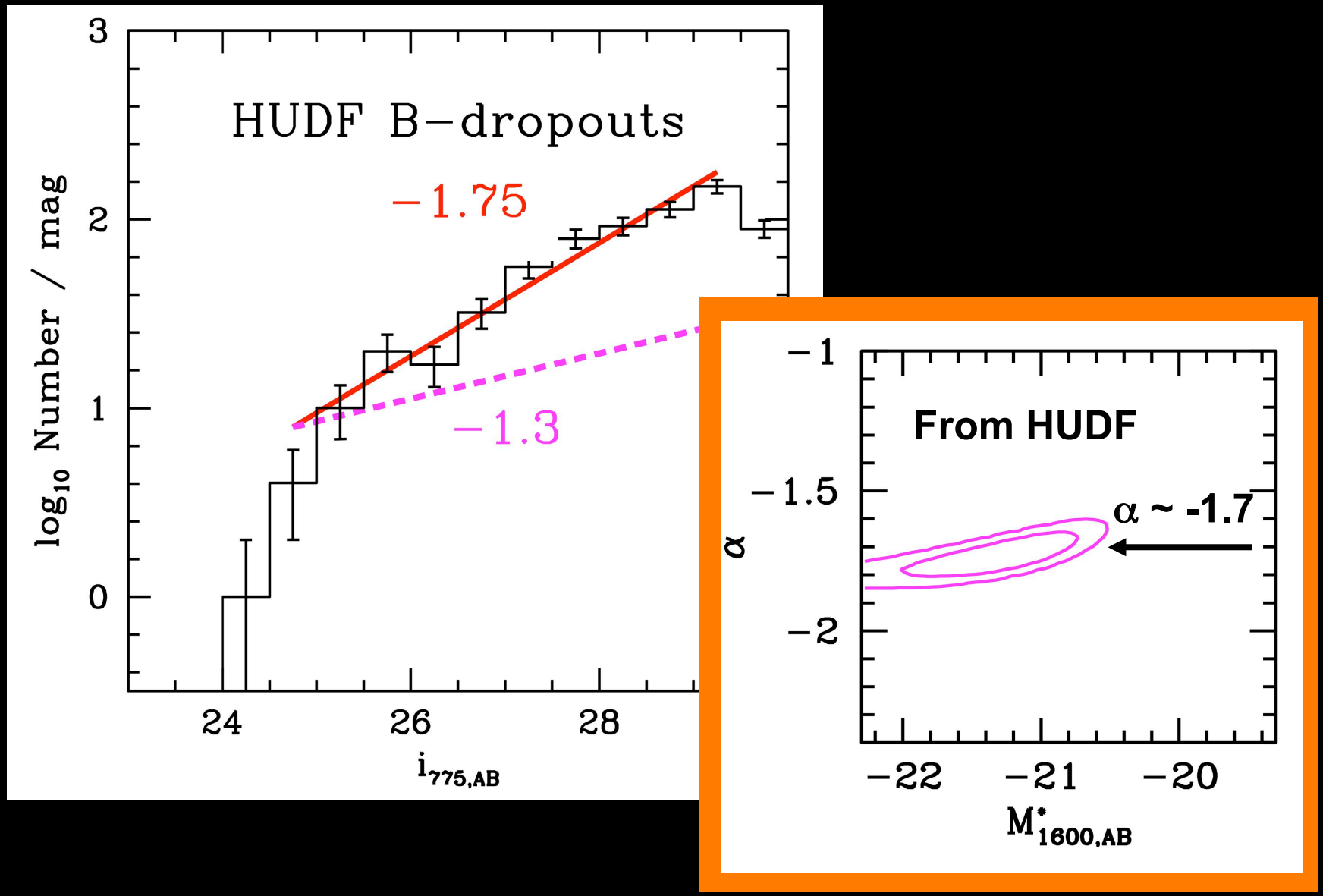
Steidel et al 1999

Bouwens et al 2006

ACP W08 *GDI*

Is the faint end of the LF steep?

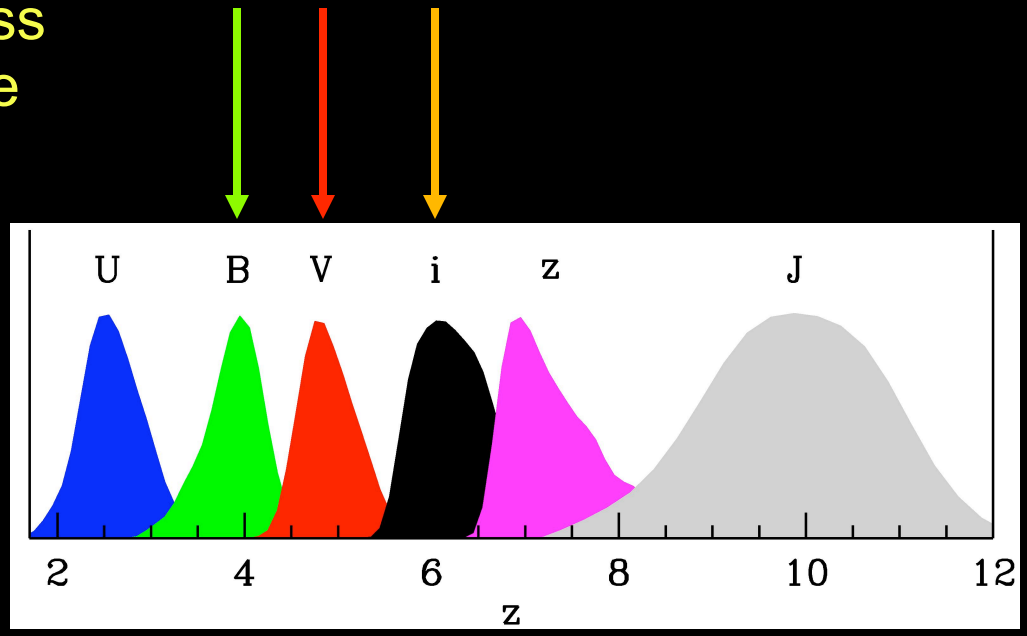
Faint end slope is not easy to determine – HUDF shows it is very steep



Galaxies at *z*~4, 5 & 6

Differences in literature in LF led us to try to do a consistent analysis using all data across GOODS fields, UDF and the parallel fields.

(B, V, i-dropouts)



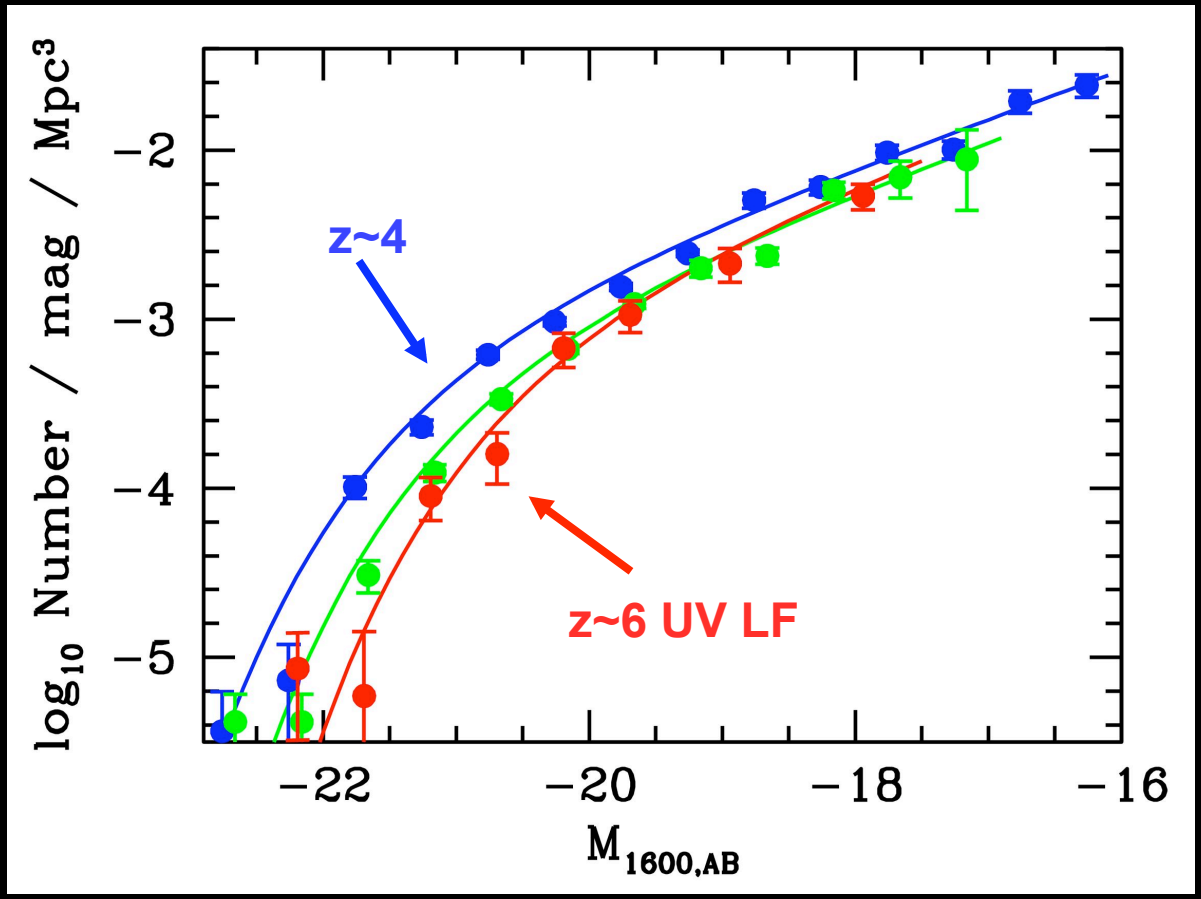
Dropout Redshift Selection Functions

Large Samples:

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

z~4, 5, 6 UV Luminosity Function

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



Measurements done over a very large range in M_{1600} From -16/18 to -22.5!

Faint-end slope steep & ~constant

M* is fainter at higher z

Rest frame UV 1600 Å

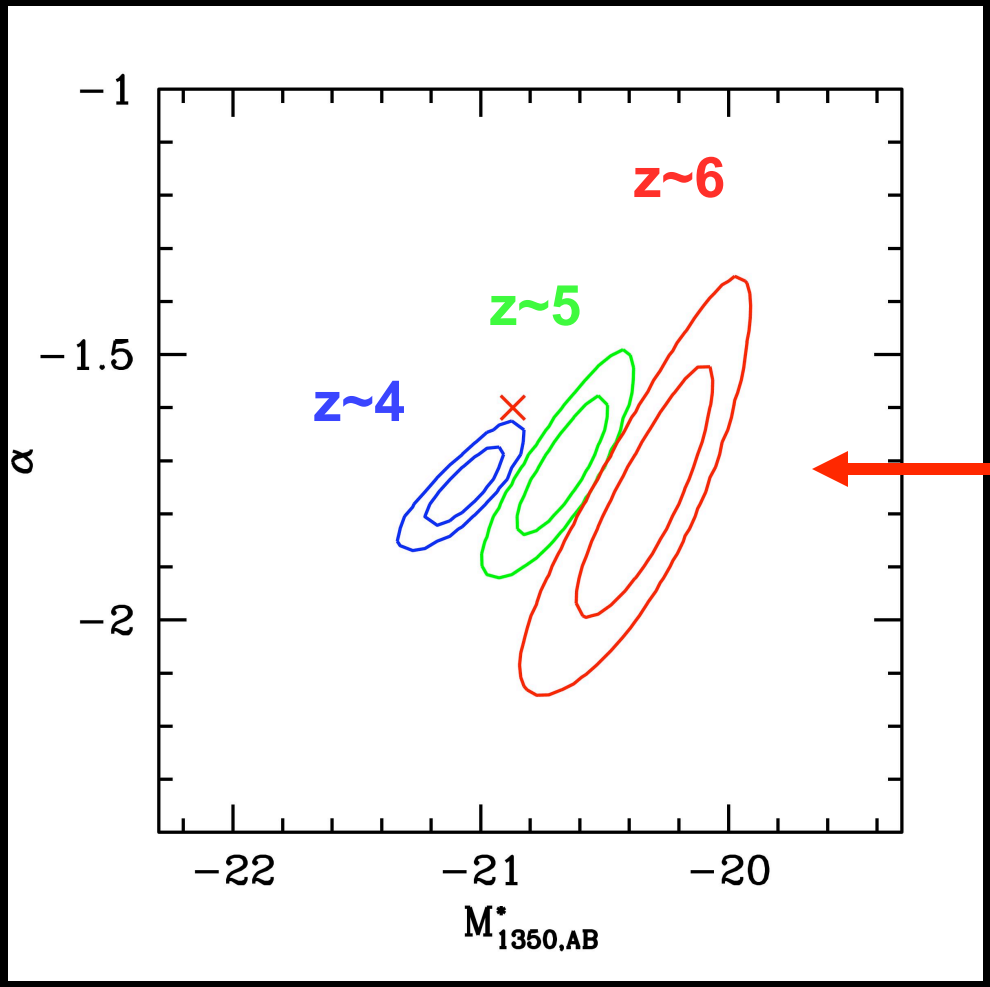
Bouwens, Illingworth, Franx and Ford ApJ 2007

Schechter Luminosity Function Parameters:
α vs M*

Shallow

Faint-end slope α

Steep



Bright M* Faint

Density ϕ* is ~constant

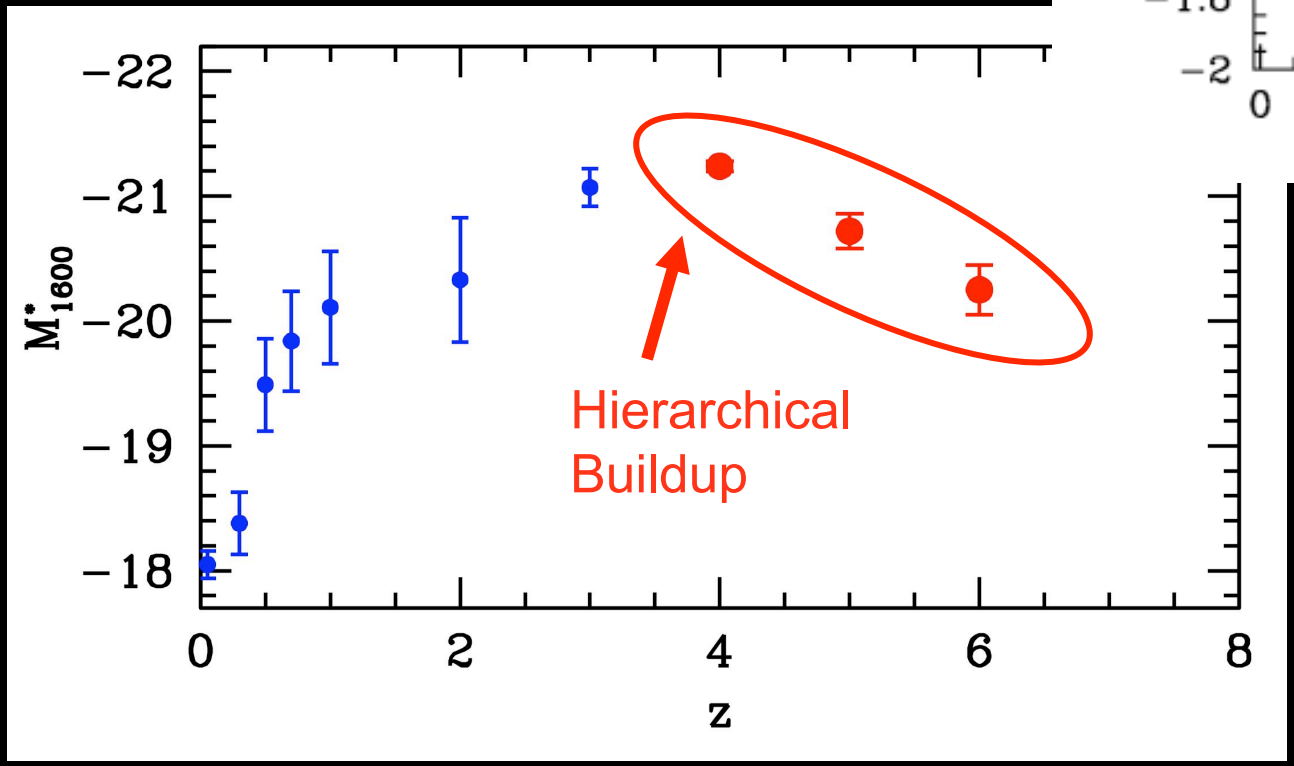
~constant faint end slope: α ~ -1.7

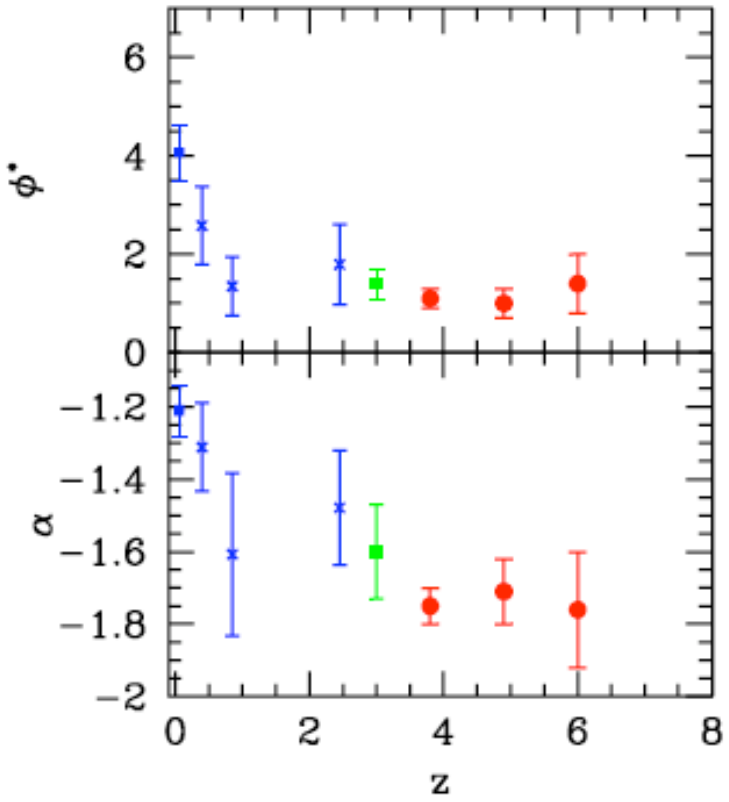
M* brightens by ~0.8 mag

ACP W08 *GDI*

Change of L* with Redshift

Progressive buildup of more luminous (massive) galaxies





see also
Rychard's talk

ACP W08 *GDI*

Luminosity Density & SFR since z ~ 6:

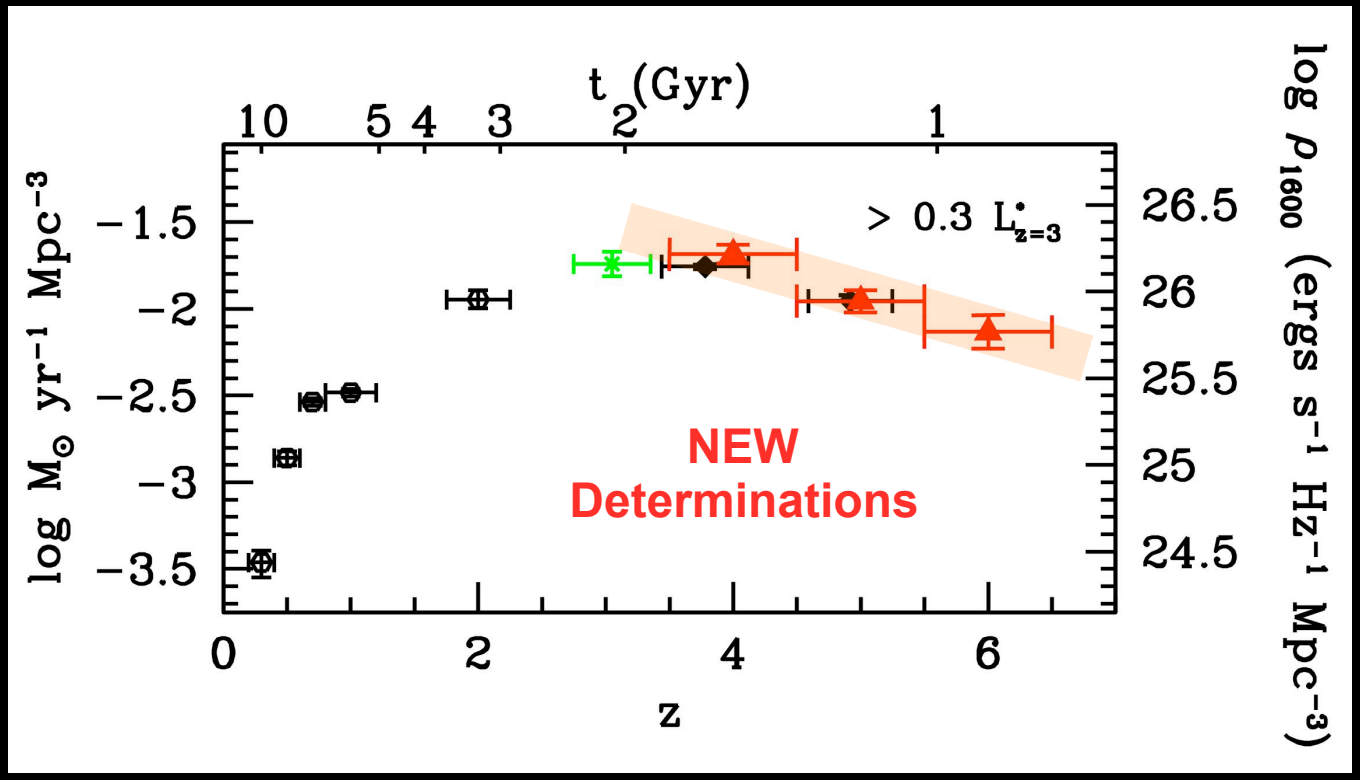
for >0.3L*

"Madau" plot

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

(Star Formation Rate Density - if no extinction)

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

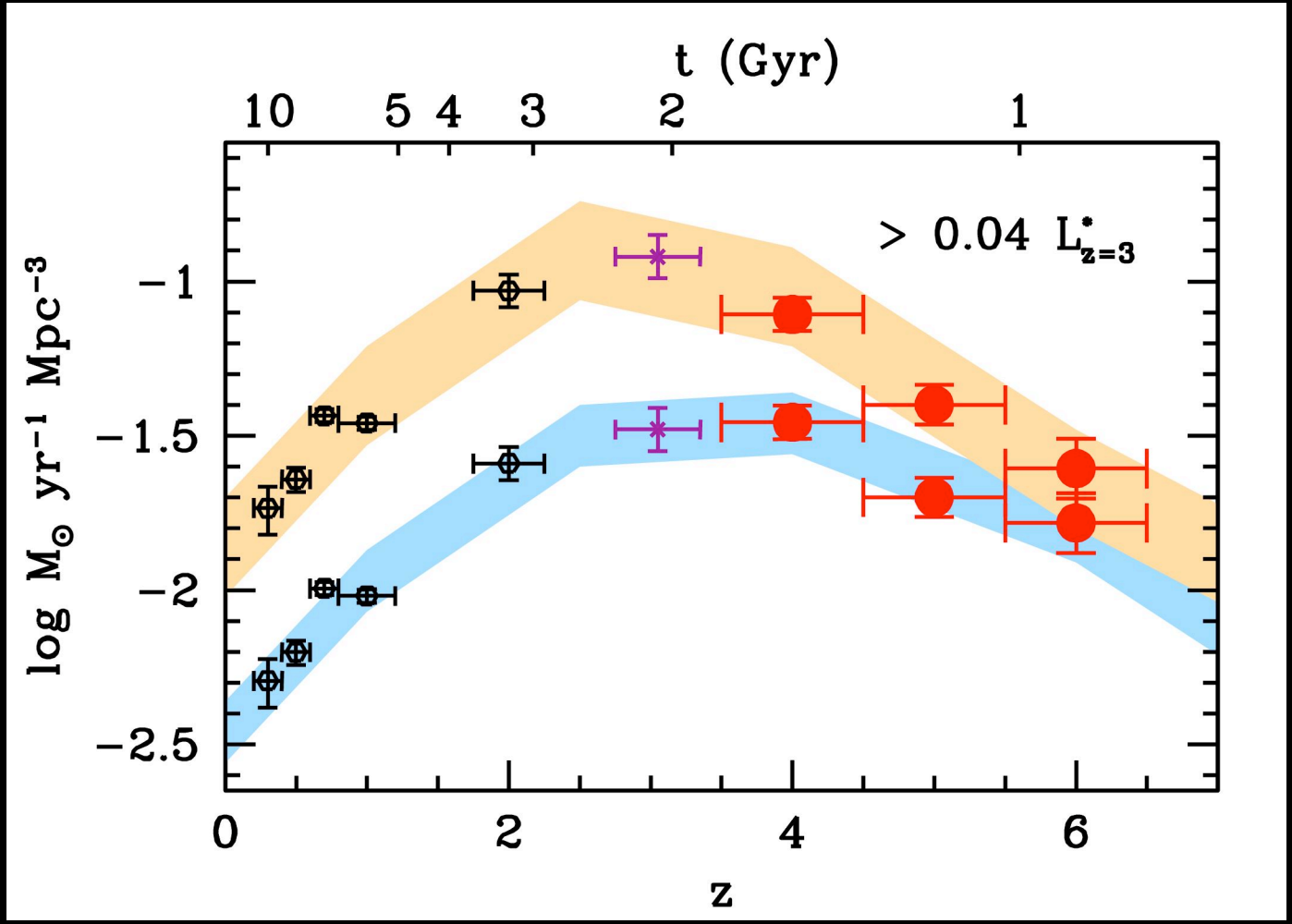


Bouwens, Illingworth, Franx and Ford ApJ 2007

Star Formation Rate (SFR) History from z~6

Star Formation History for >0.04L*

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



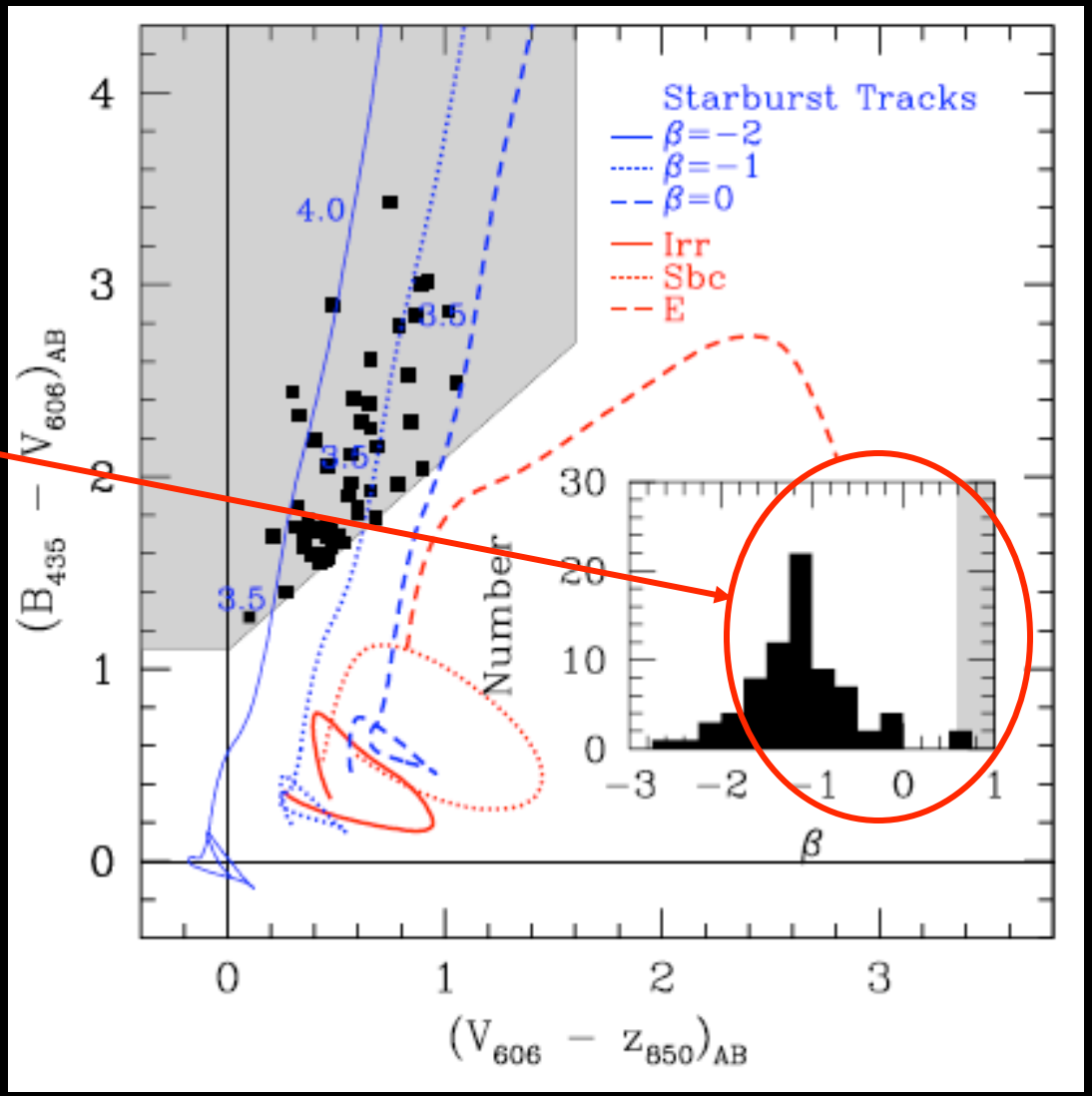
Dust-corrected SFR shows a more significant drop to high redshift than uncorrected (less extinction at high z).

ACP W08 *GDI*

Evolved Galaxies at $z \sim 4$?

Evolved galaxies at z~4?

There is NOT a continuum of UV slopes:
and so if there are evolved galaxies or dusty galaxies they must have *distinctly* different UV properties or are quite rare



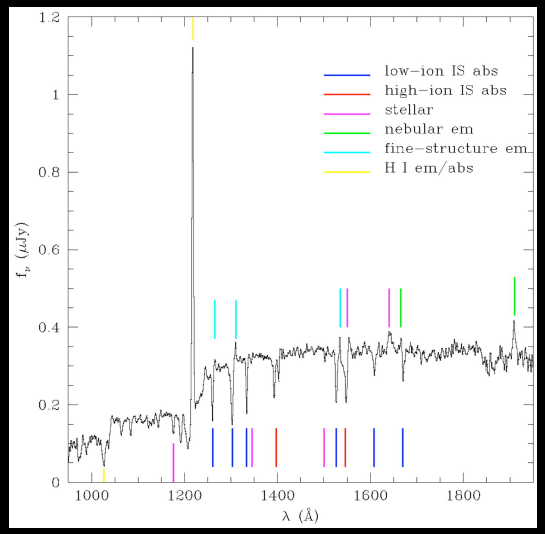
cf. Brammer talk

Bouwens Illingworth Franx and Ford 2007

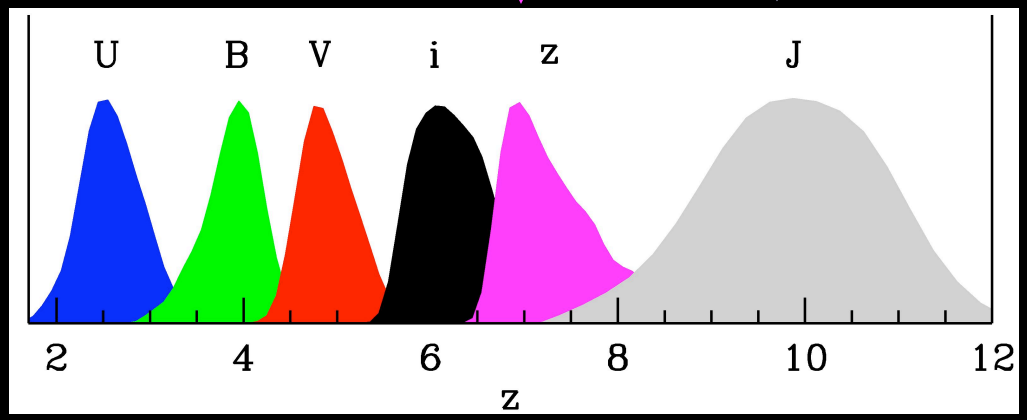
ACP W08 *GDI*

Galaxies at z~7-8+ & z~10

(z & J-dropouts)



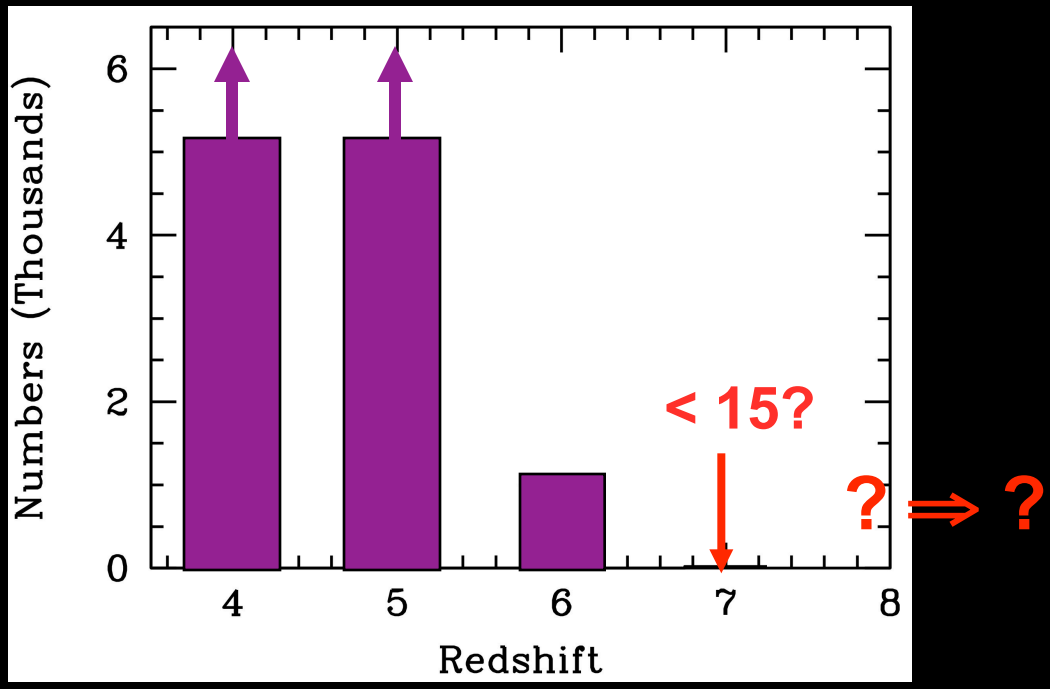
Lyα searches



Dropout Redshift Selection Functions

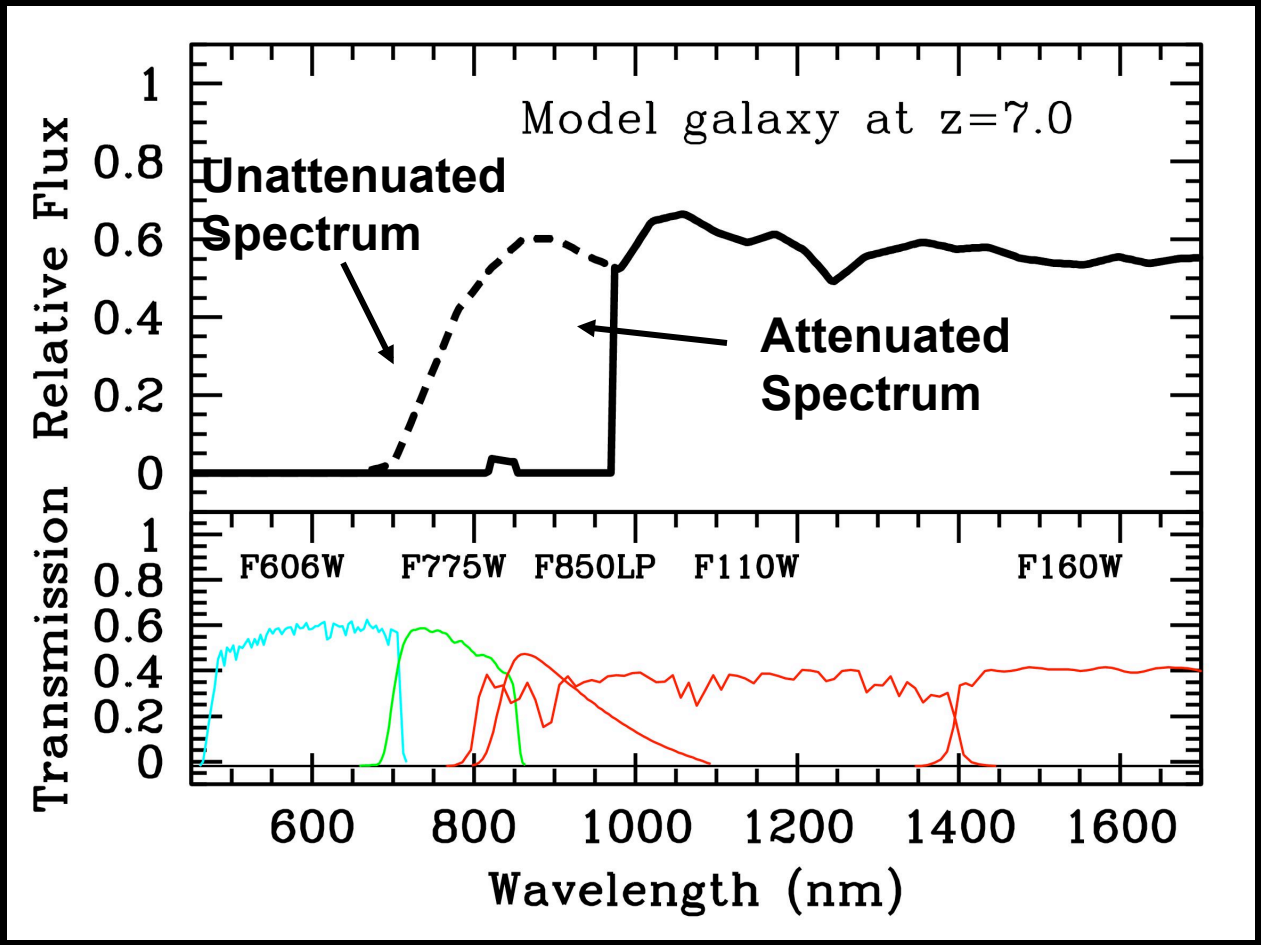
Finding galaxies at z>6 is hard!

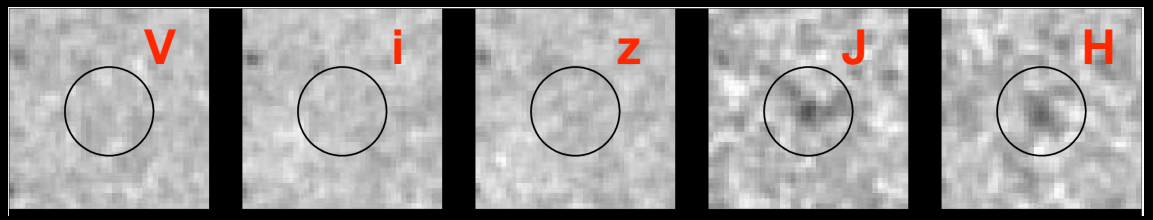
High Redshift Galaxies: HST, Subaru, VLT, Keck



The z>6 universe is “exploration” territory:
1) find and confirm sources
2) get number density

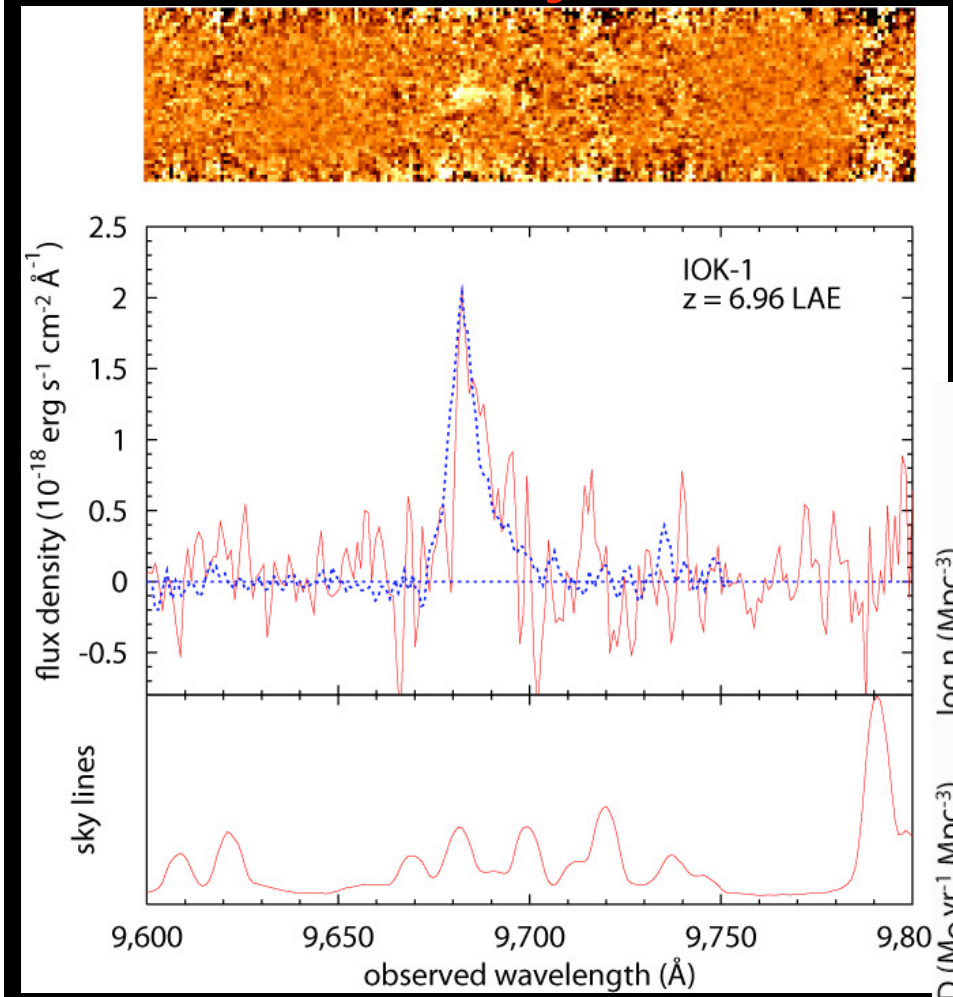
Dropouts - Lyman Break Galaxies at z~7





No Detection in optical filters Blue Continuum in IR filters

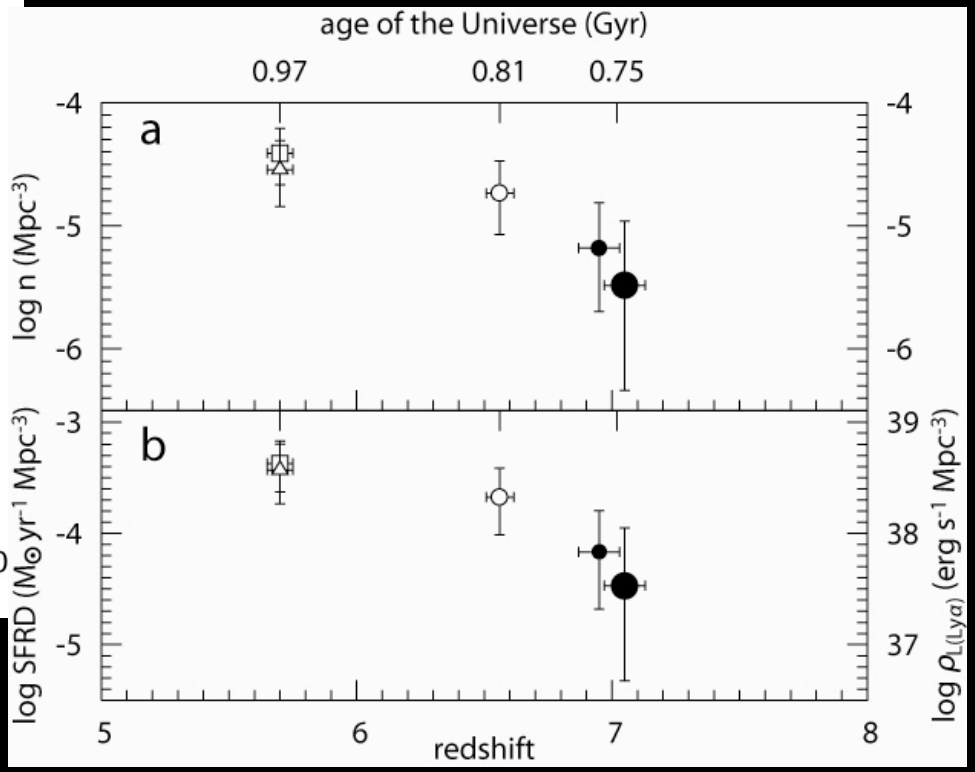
Lyα Detections at z~7



Iye et al 2006

Subaru Suprime Camera (narrow band) and FOCAS Spectroscopy

Lyα detection at z=6.96



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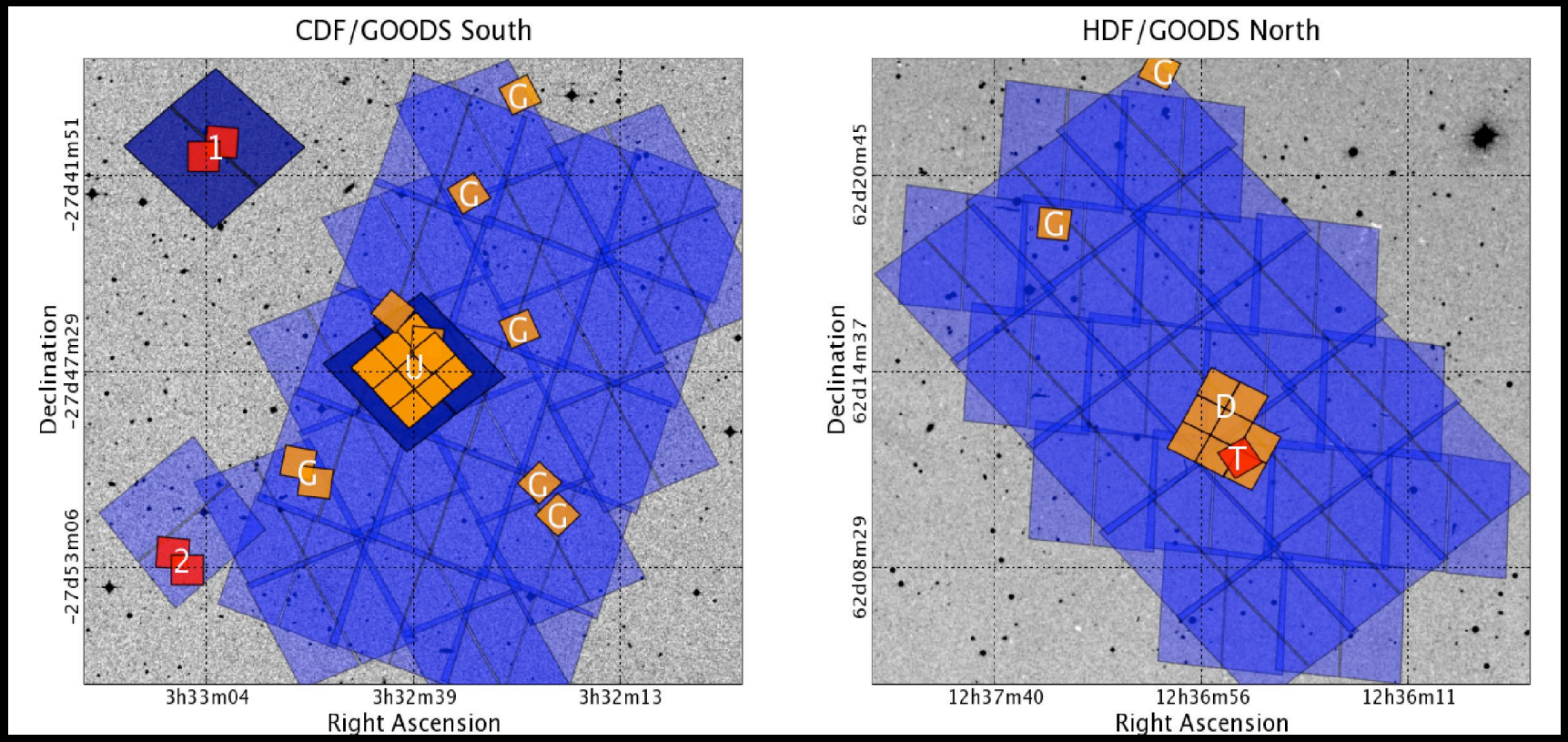
Searches for *z~7-8+* Galaxies - *z-dropouts*

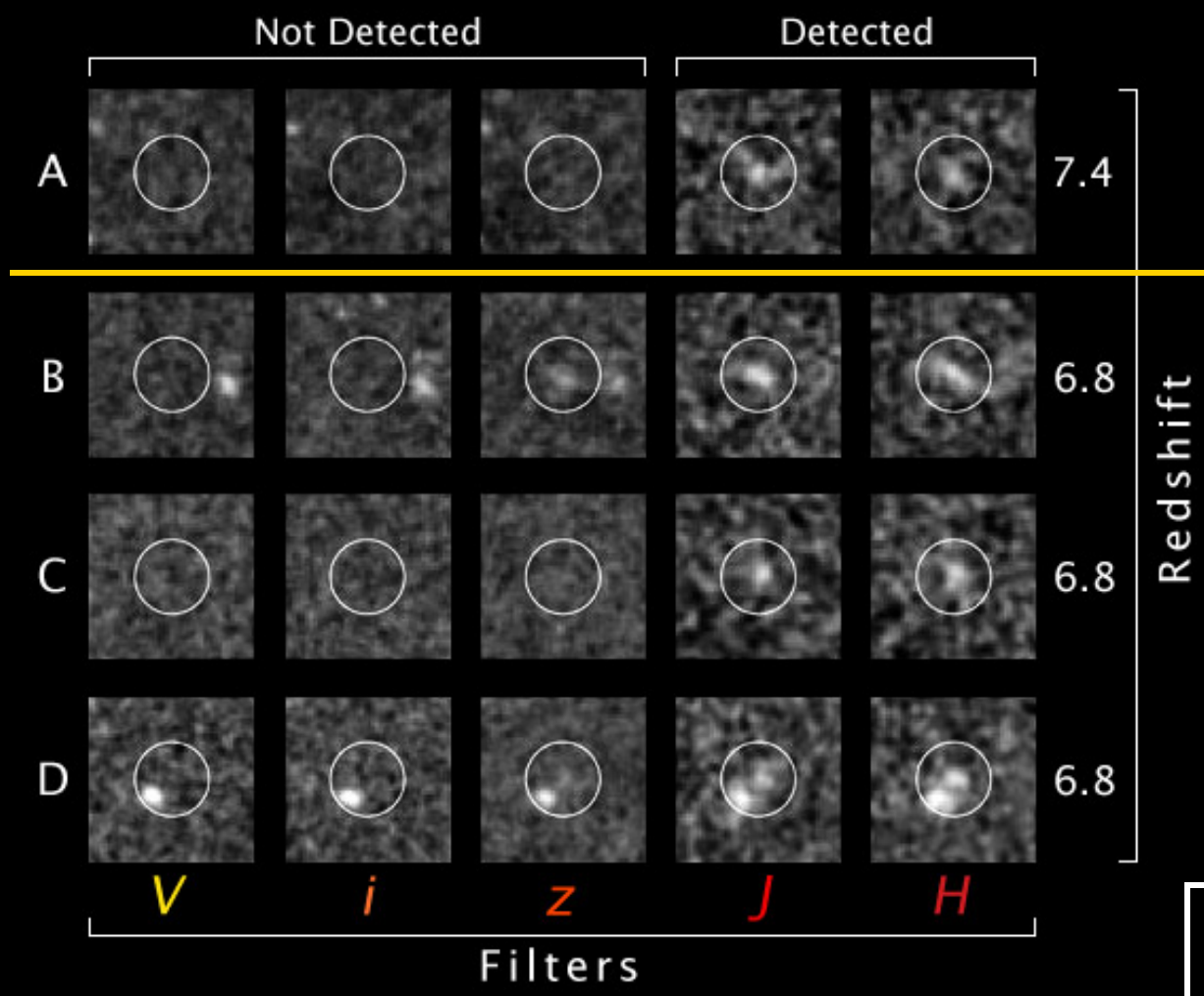
Fields with deep ACS and NICMOS data for dropout searches



ACS GOODS and UDF (blue)

NICMOS (orange and red) > ~20 arcmin^2

Evolution of z ~ 7-8 Galaxies *vs* z~6



Bouwens & Illingworth, *Nature*, 2006

Most conservative selection - get 1

Detect 1 but expect 10±4

Less conservative selection - get 3 more

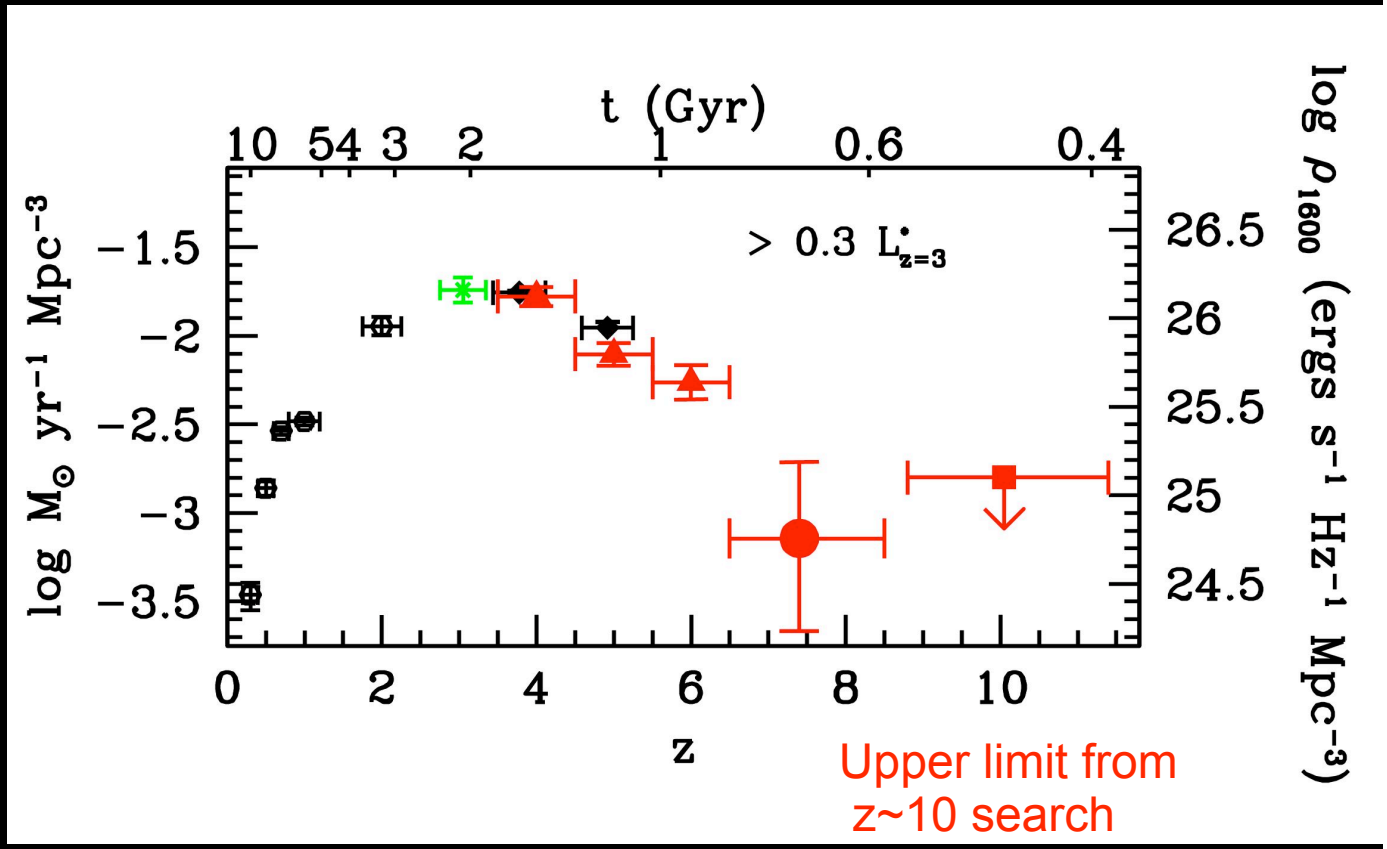
Detect 4, but expect 17±4

Inconsistent with no evolution from z~6 to z~7 at >99.5%

Luminosity Density & SFR History

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

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



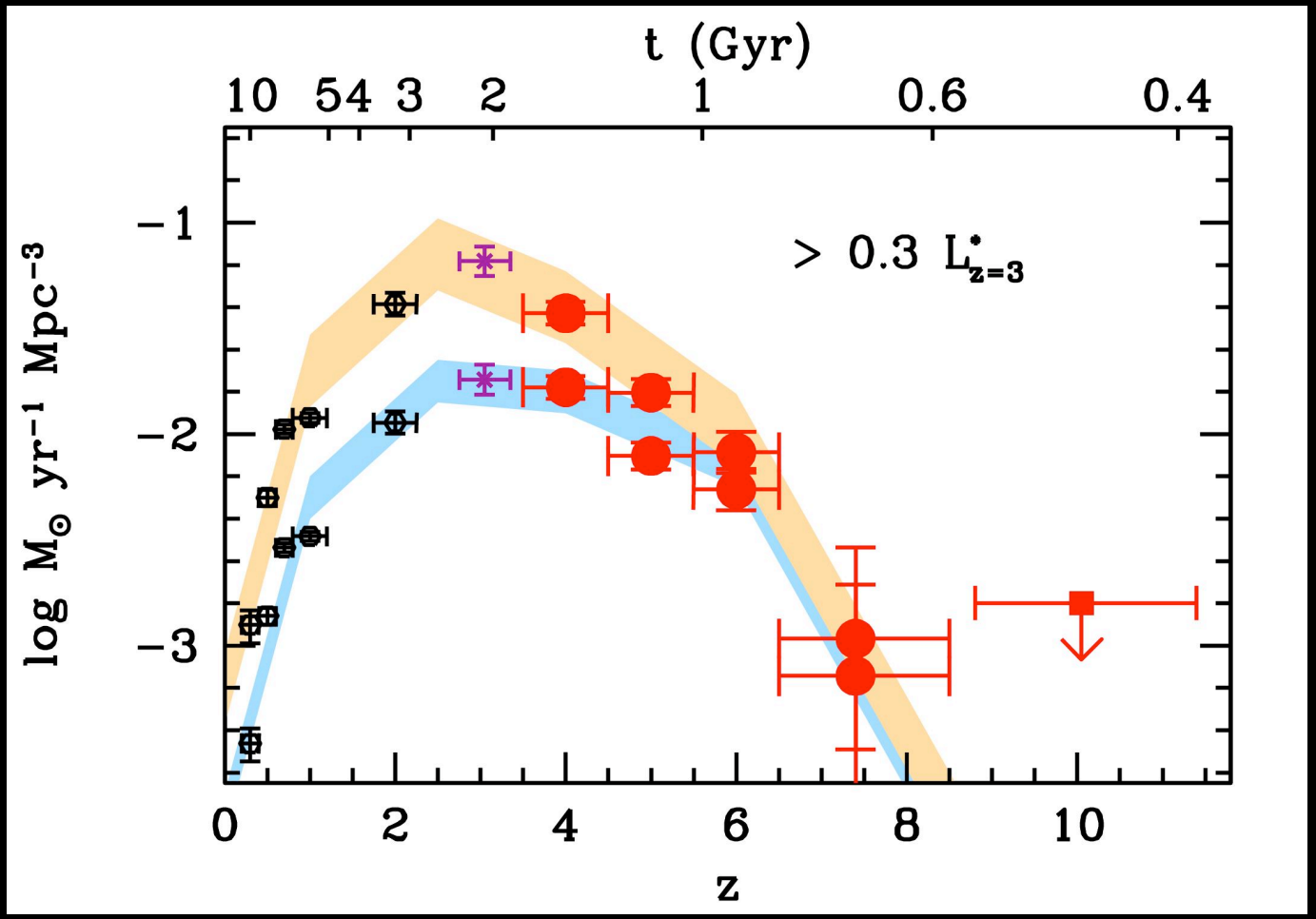
"Cosmic Variance" due to large scale structure:
at z~4-6 ~14% RMS
at z~7-8 ~30% RMS
at z~10 ~19% RMS

At z~7-8 *vs* z~6: very substantial drop at bright end (>0.3L*)

Star Formation Rate (SFR) History from z~10

Star Formation History for >0.3L*

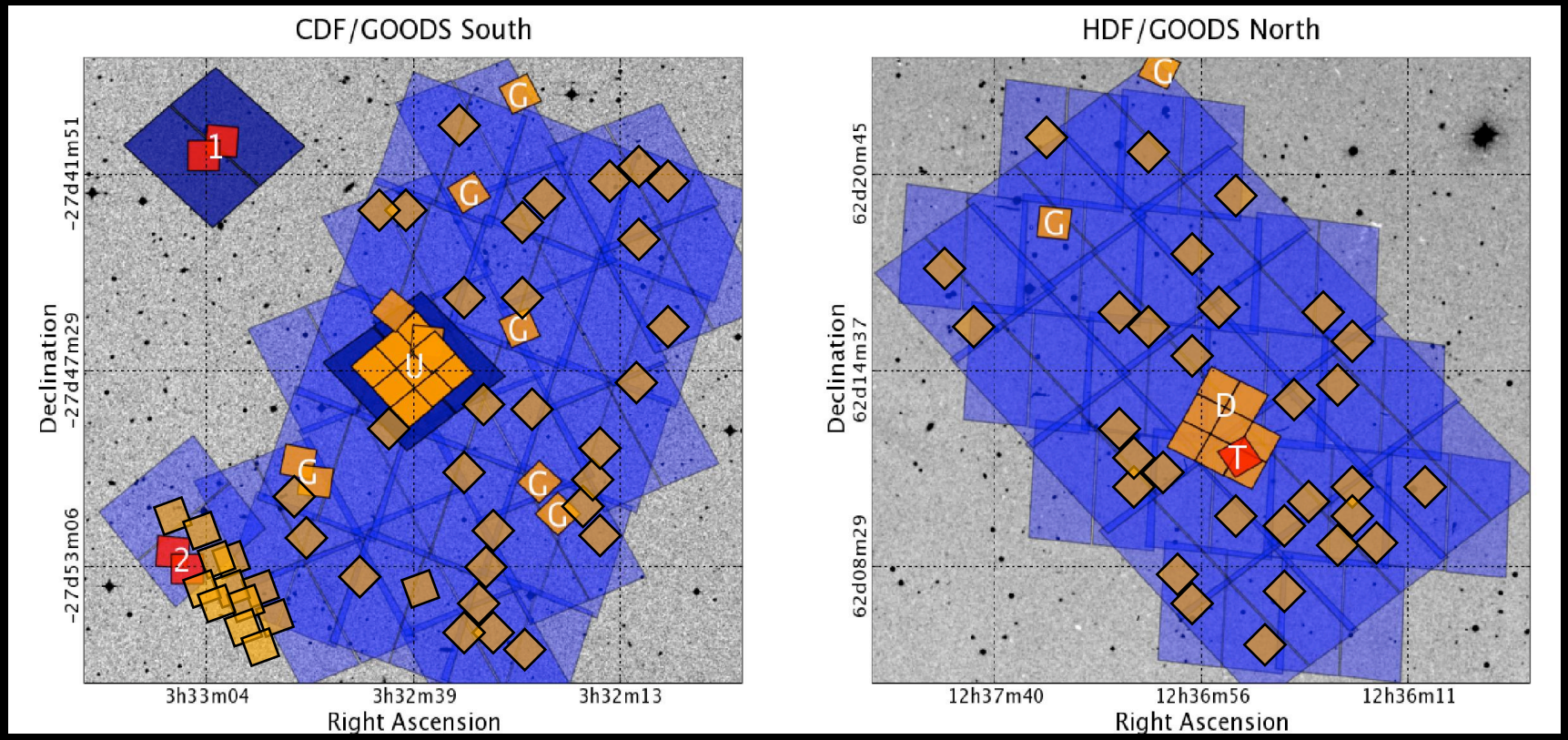
Log SFR:
$M_\odot$ $yr^{-1}Mpc^{-3}$



Large drop at z~7-8 for luminous (more massive…) galaxies
-- less if measurements extended fainter??

Searches for *z~7-8-10* Galaxies

Many more fields with deep NICMOS data for dropout searches



New Search =>

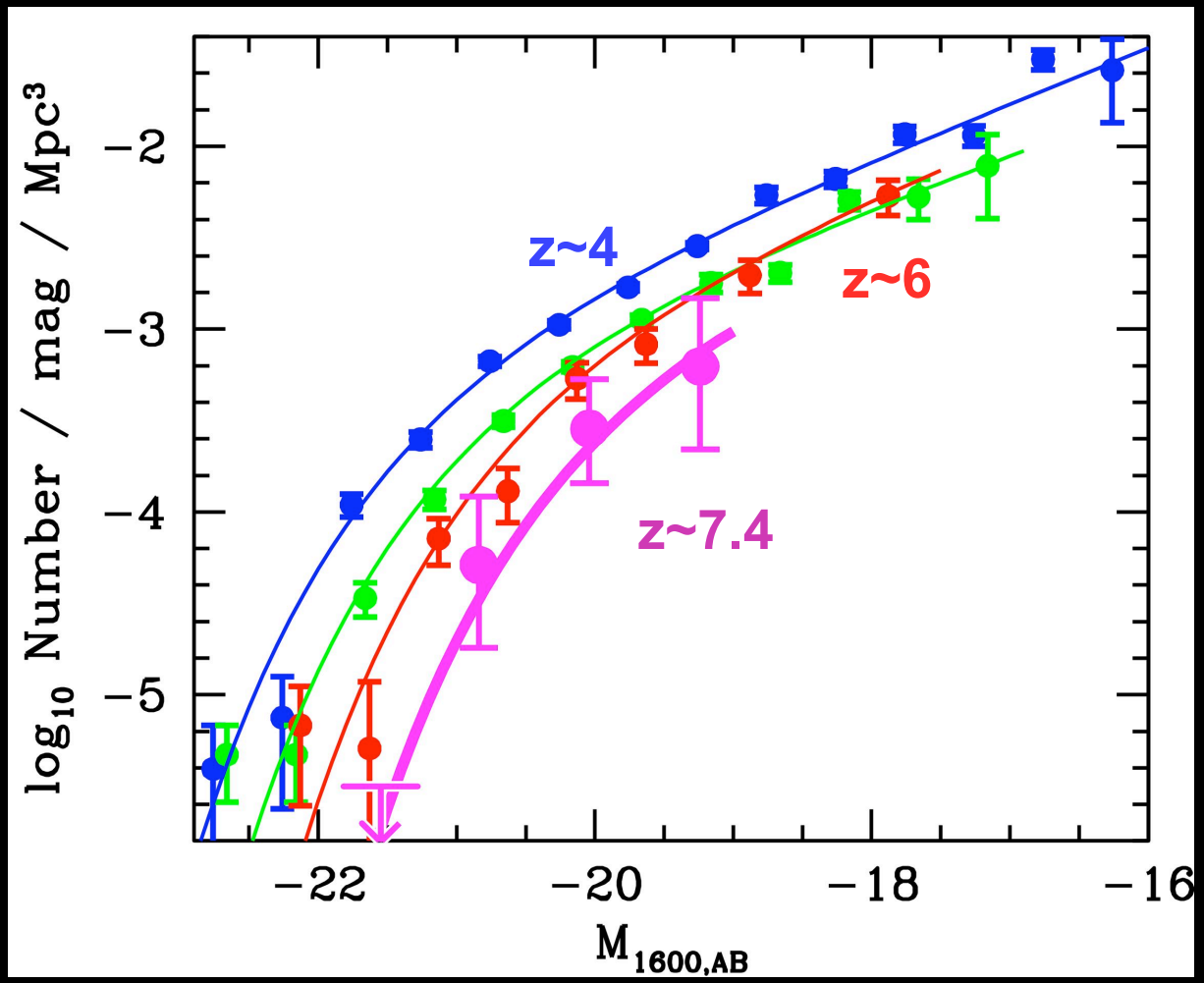
9 z~7 sources

No z~9-10 sources

ACP W08 *GDI*

z~4, 5, 6, 7.4 UV Luminosity Functions

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



Bright

Faint

Bouwens, Illingworth et al. 2007

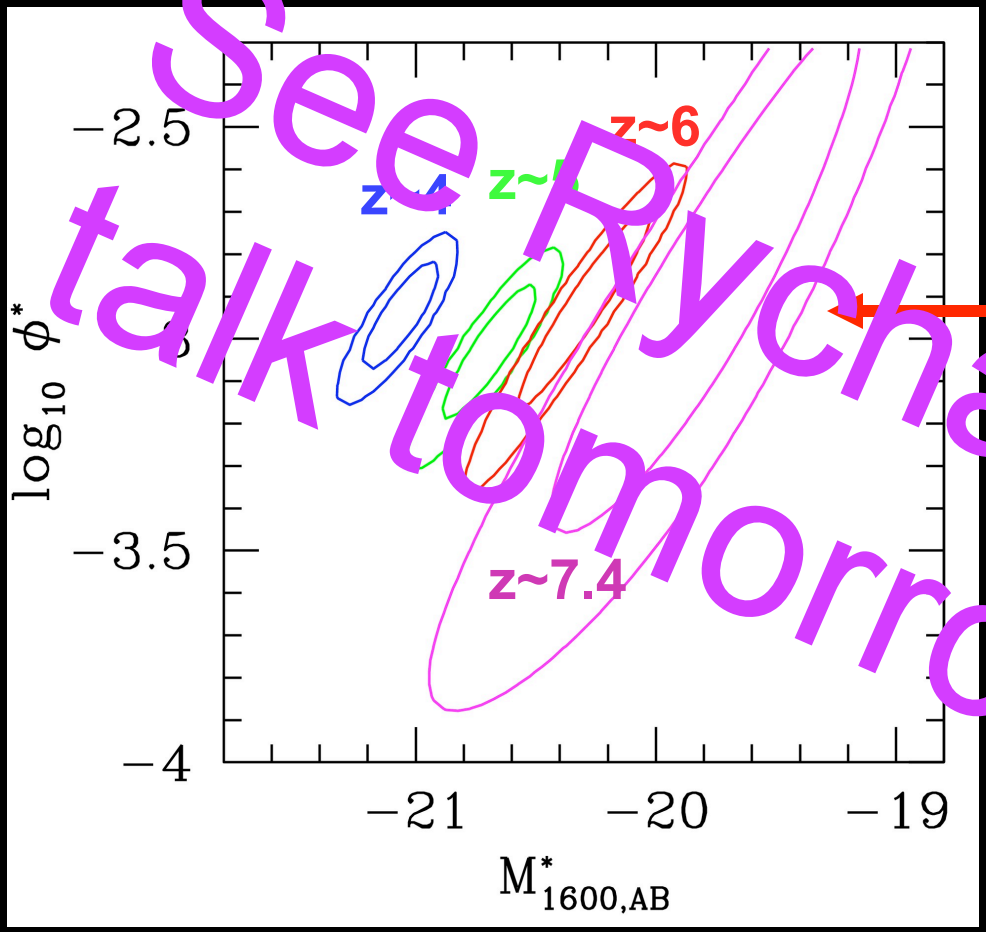
ACP W08 *GDI*

z~4, 5, 6, 7.4 UV Luminosity Functions

High

Volume Density ϕ^*

Low



See Rychard's talk tomorrow

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

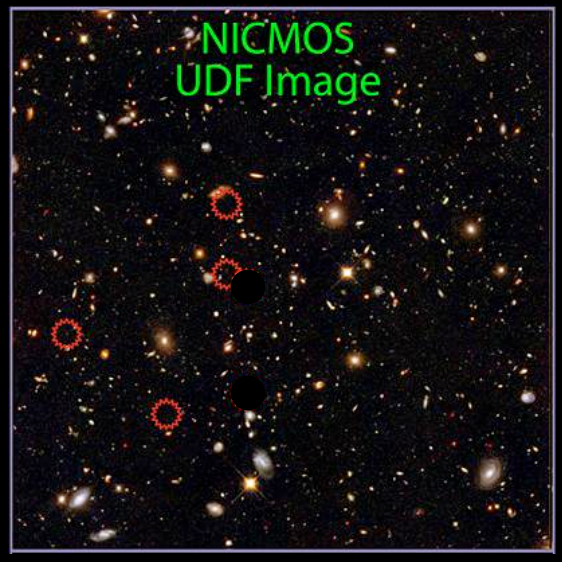
z~7-8 contours fit in nicely with z~4-6 trends!

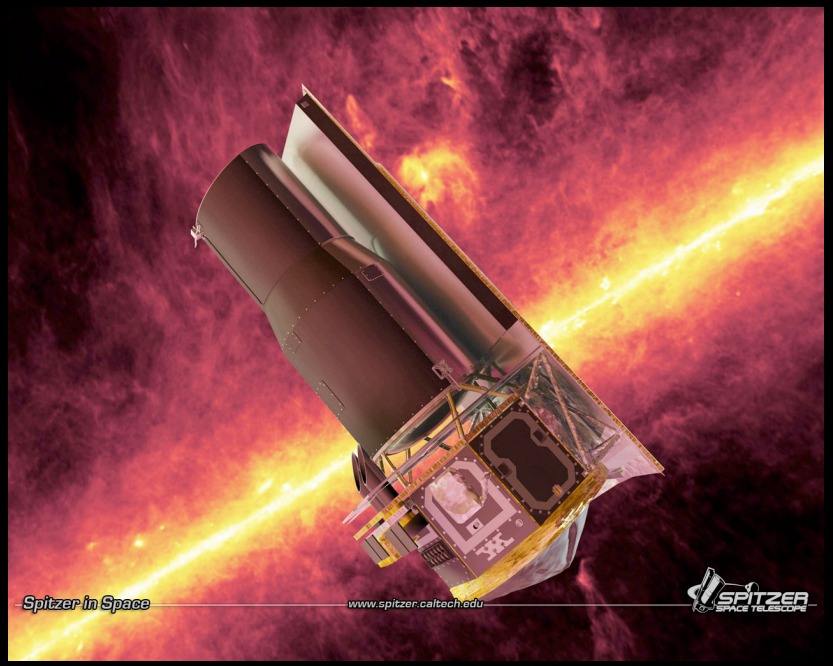
Suggests we are actually finding z~7-8 galaxies!

Bright M* Faint

Bouwens, Illingworth et al. 2007

Spitzer Observations of z~7 Galaxies





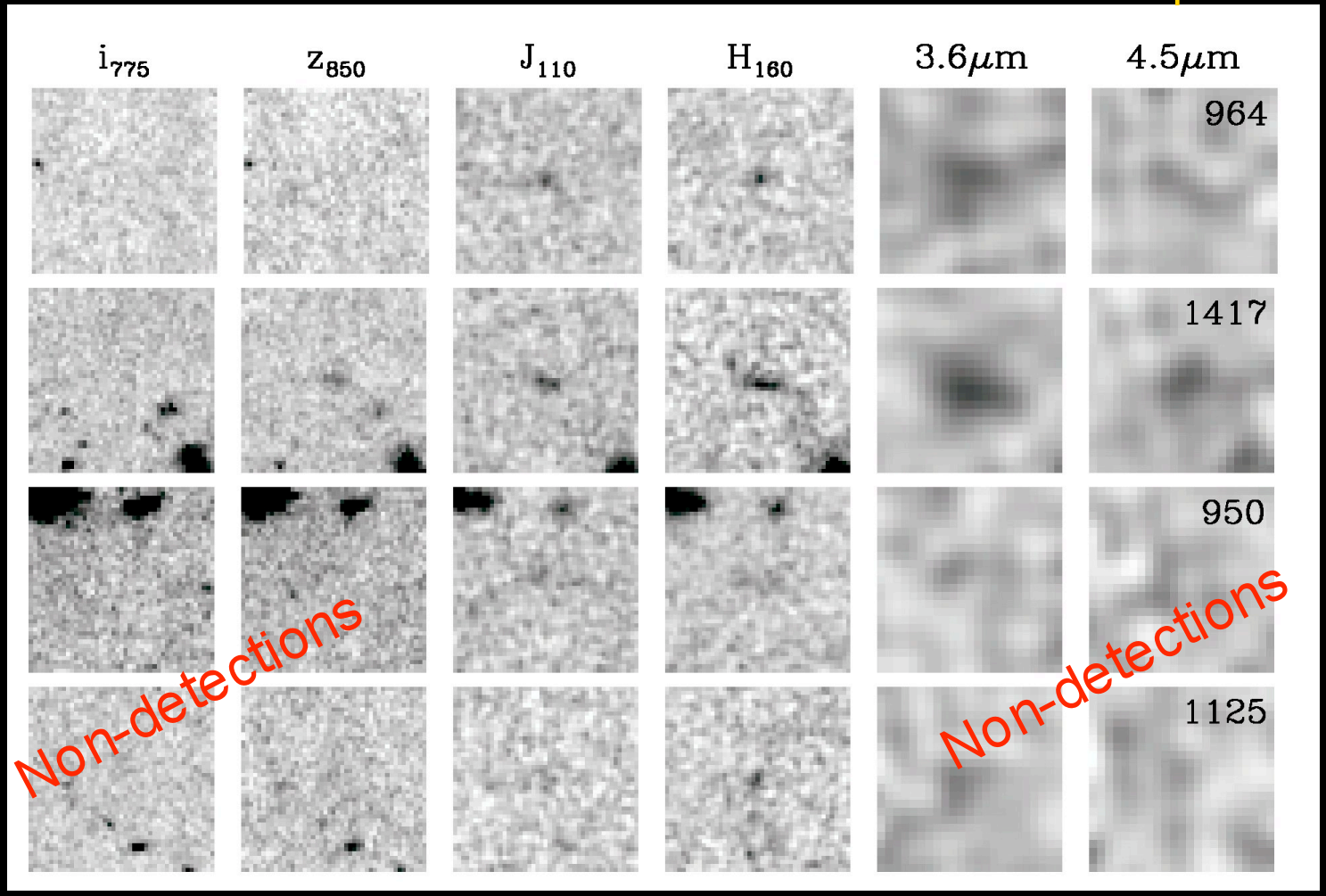
Spitzer IRAC Observations of z~7 Galaxies

Rest-frame UV and optical fluxes from HST & Spitzer

Rest-frame UV | Rest-frame Optical

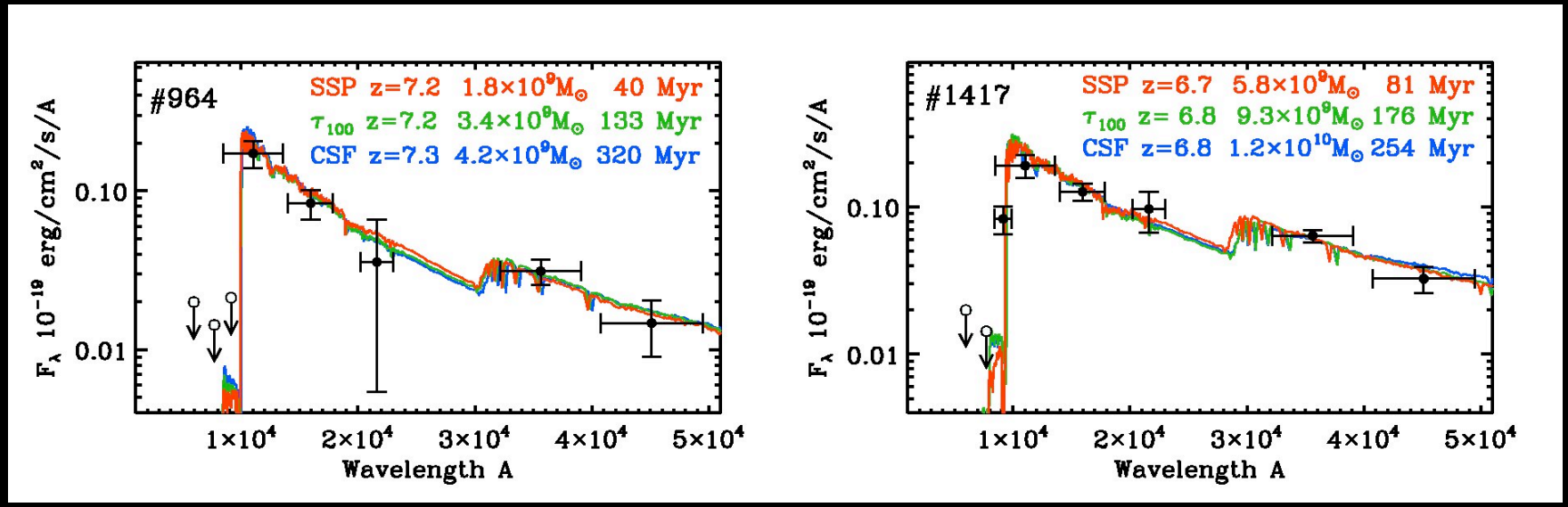
4 *z-dropout* candidates from the HUDF

From Bouwens, Thompson, Illingworth et al. 2004 and Bouwens & Illingworth 2006



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

SED Fits of z~7 Galaxies from HST and Spitzer



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

Ages of ~50-200 Myr - SFR ~ 5-10 $M_\odot$ yr^{-1}

Substantial star formation under way at z~8-10!

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

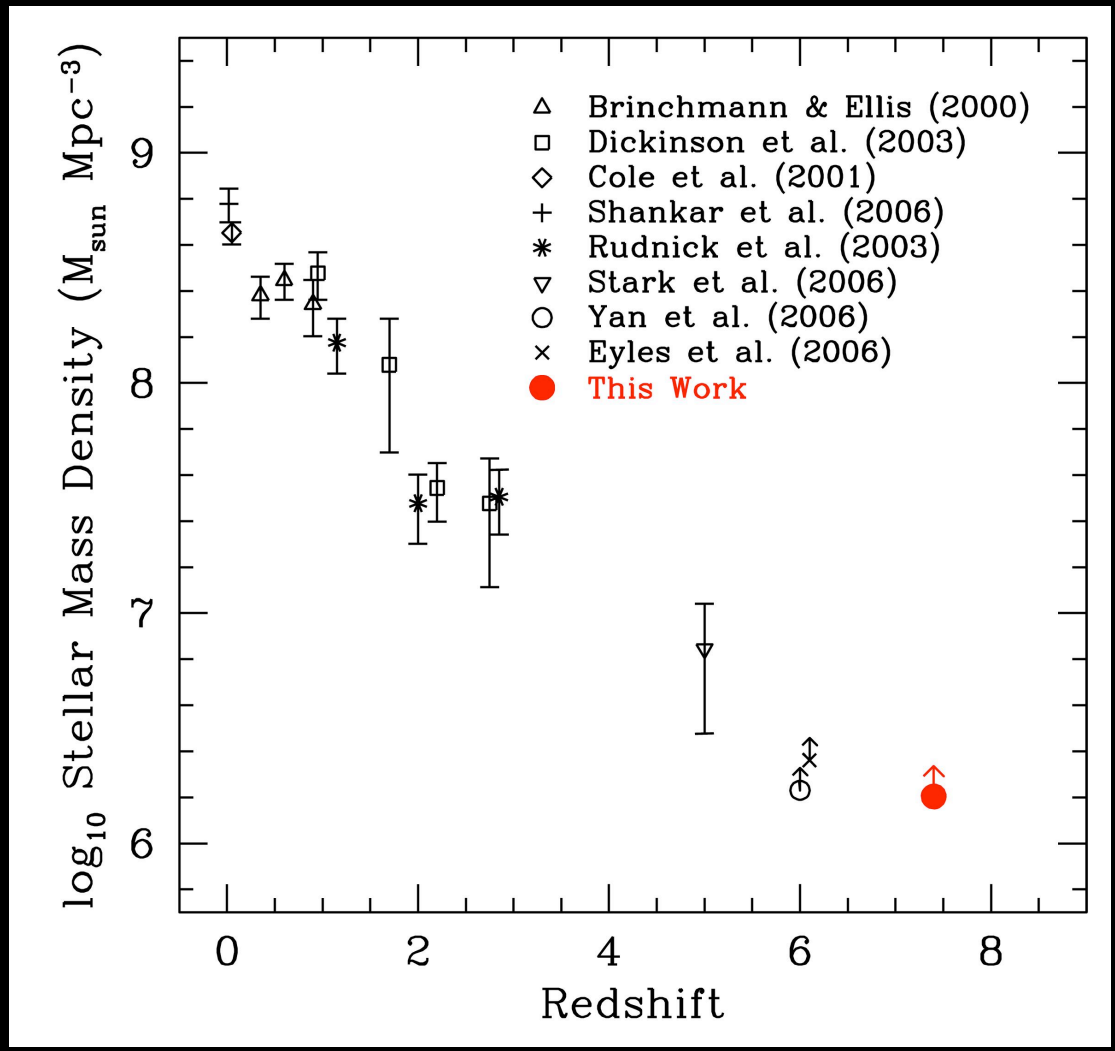
Buildup of Stellar Mass in Galaxies from z~7

Stellar Mass Density vs Redshift

From z~7 (0.7Gyr) to present day

Obviously much remains to be done but impressive to be adding constraints within the first Gyr!

Eyles et al 2006



Galaxy Build-up from z~7 to z~4 Conclusions

Reliable z~4, 5 and 6 UV Luminosity Function LF to ~3-4 mags below L*

Steep faint end slope: ~constant α ~ -1.7 for z~4, 5, 6 LF (reionization!)

Evolution of luminous galaxies => $L^*_{UV, z\sim6}$ is ~50% fainter than $L^*_{UV, z\sim3}$

Evolved/dusty galaxies rarer by z~4, unless distinctly different population

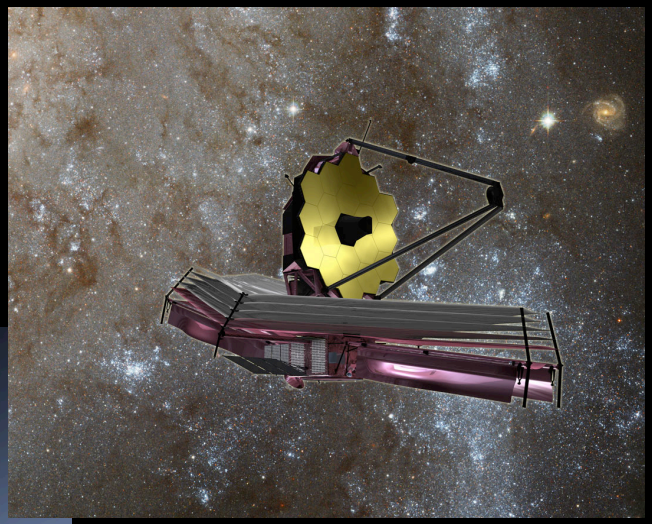
Detections at z~7-8, but upper limits at z~9-10: spurious sources or TBD

SED Masses for Spitzer z~7 objects ~0.3-1 x 10^{10} $M_\odot$ – ages ~50-200+ Myr

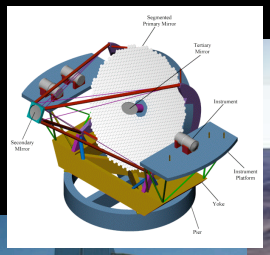
Future Capabilities for Exploring the z>6 Universe

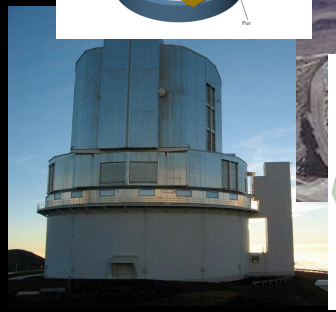
HST SM4 WFC3 IR and ACS

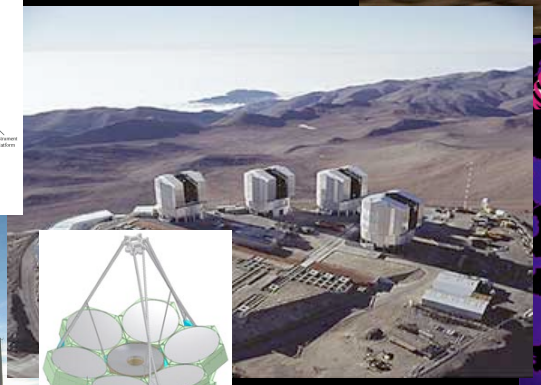
JWST



Numerous O/IR Telescopes

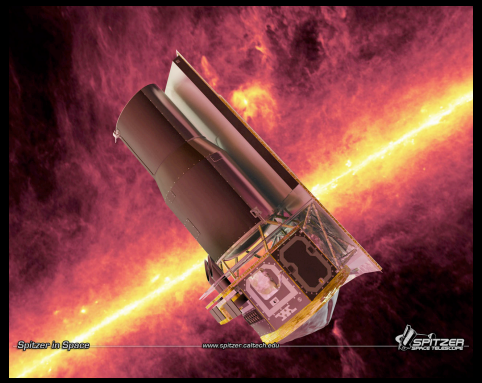






Radio Telescopes
EVLA/ALMA/LOFAR…

Spitzer IRAC (warm)
Herschel + …..

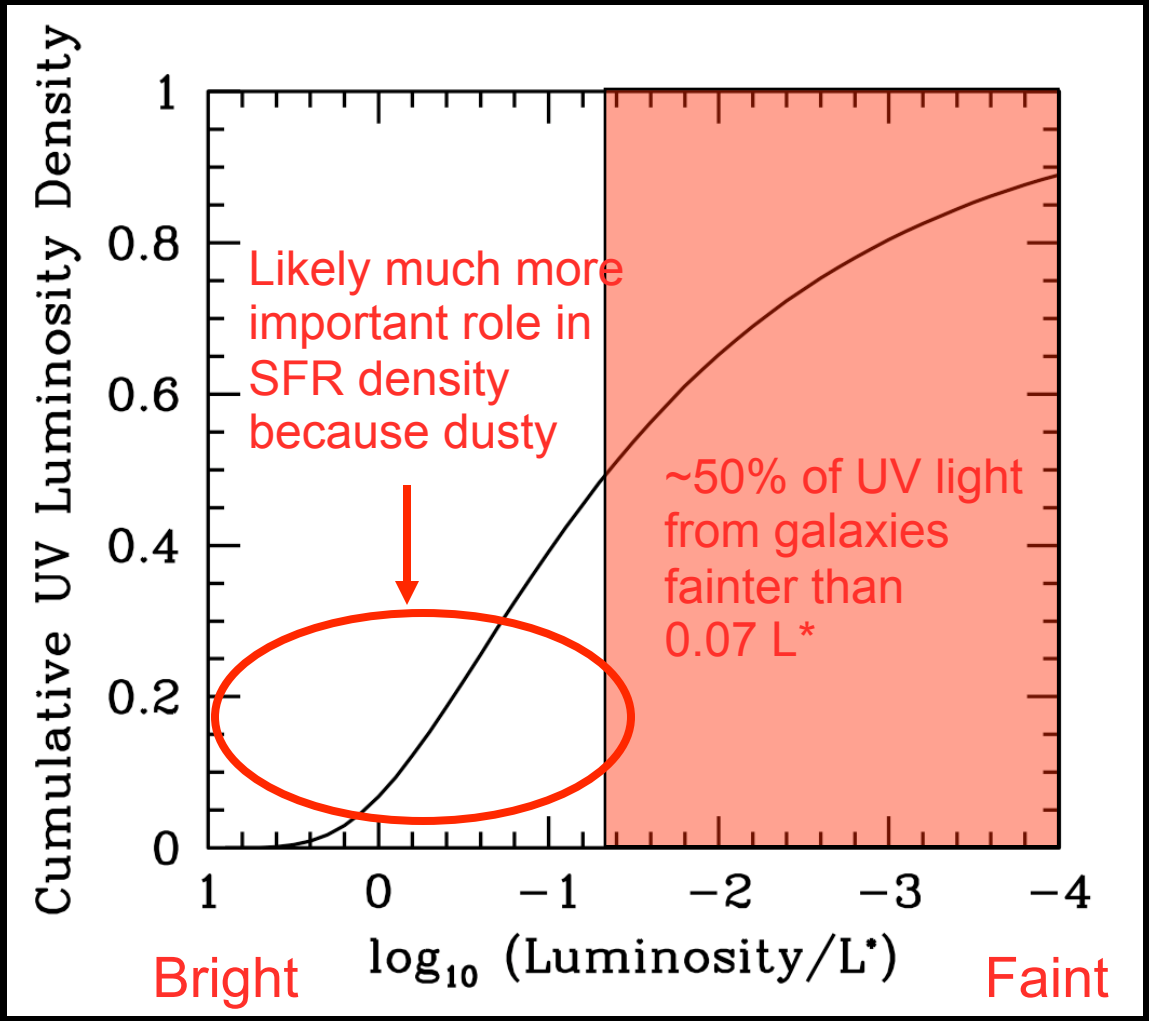


What are the implications of a steep faint-end slope?

Which galaxies output more UV light?

Fraction of UV light in sources brighter than some luminosity

Bouwens, Illingworth et al. 2007



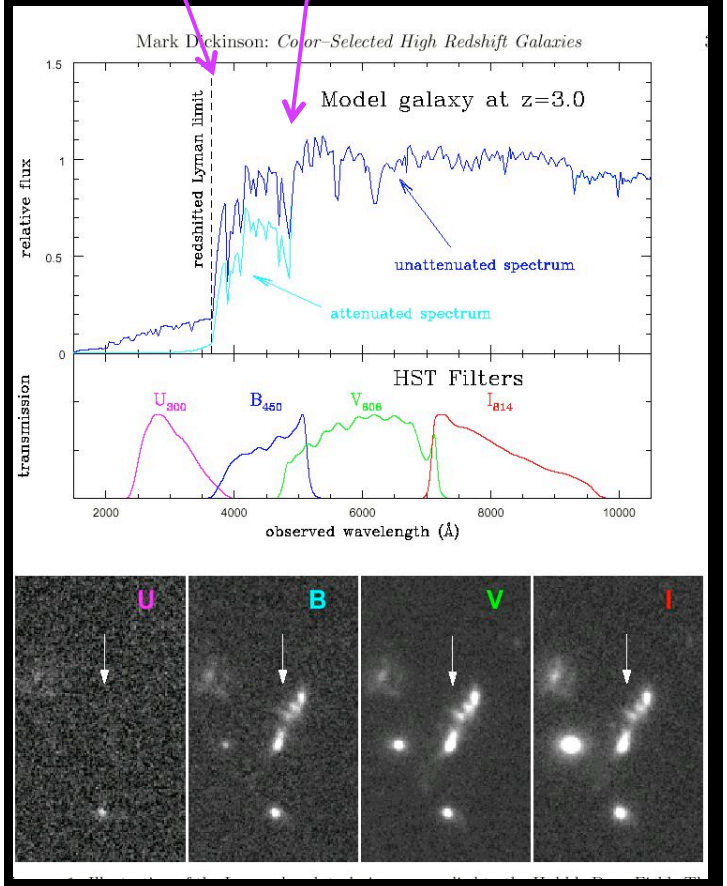
See also: Sawicki & Thompson 2006; Yan & Windhorst 2004; Beckwith et al. 2006

Galaxies at z~4-7

The "dropout" technique:
Pioneered in the 1980s for QSOs & the 1990s for galaxies

Lyman limit break

Lyα break at high z



z~3 '*U-dropout*' (Dickinson 1999)