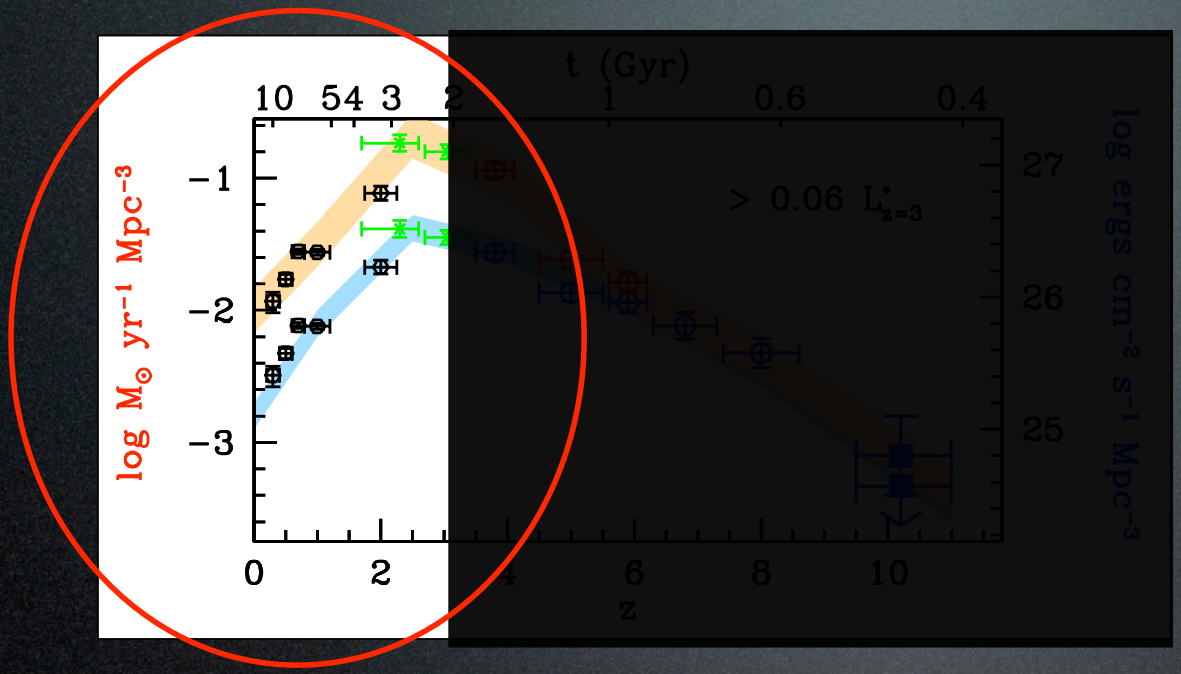
Observational Studies of Galaxy Formation: Reaching back to ~500 Myr after the Big Bang

Rychard Bouwens
(UC Santa Cruz / Leiden)

2010 Santa Cruz Galaxy Formation Workshop
August 19, 2010

Much of the discussion at this workshop has been on galaxy formation / evolution at late times...

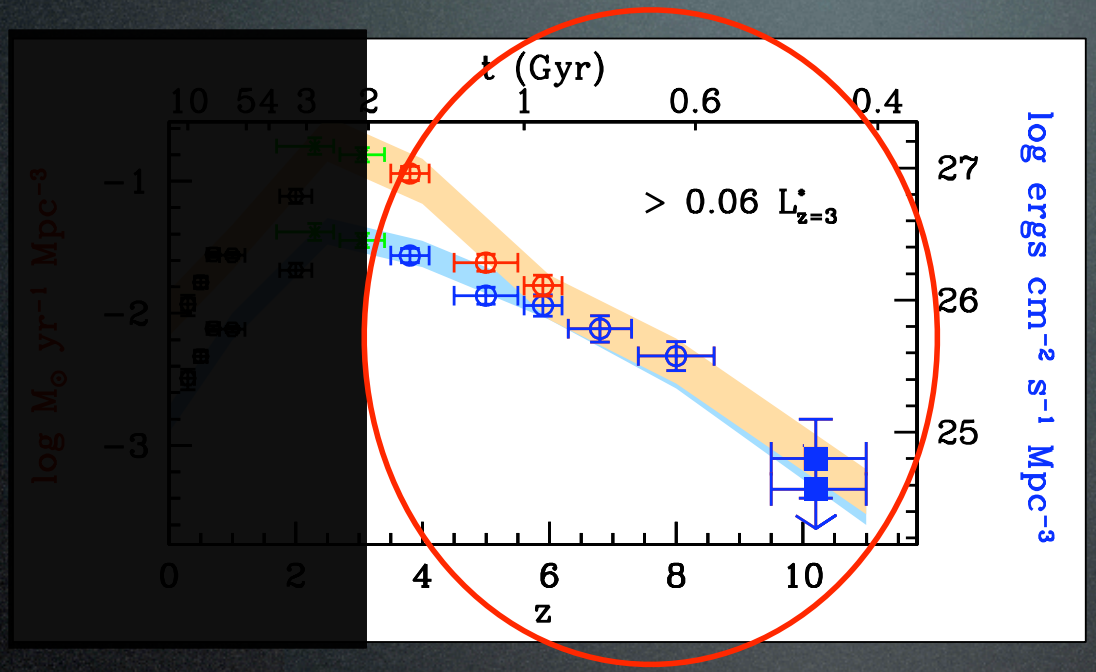


quenching, early-type galaxy evolution, size evolution, spiral, bulges, substructure,

SFRs in galaxies are decreasing with cosmic time...

Quenching / AGN feedback seems to become important

Galaxy Formation / Evolution is very different at z>=3



SFRs in galaxies are increasing rapidly with time

Galaxies appear to be growing exponentially...

Feedback processes seem to be less important...

Galaxy Formation / Evolution is very different at z>=3

Halos of L* / sub-L* galaxies form from z~15 to z~3...

Fundamental Questions for Galaxies at z>=3

1) How quickly do galaxies grow with cosmic time?

-- measure in a number of different ways....

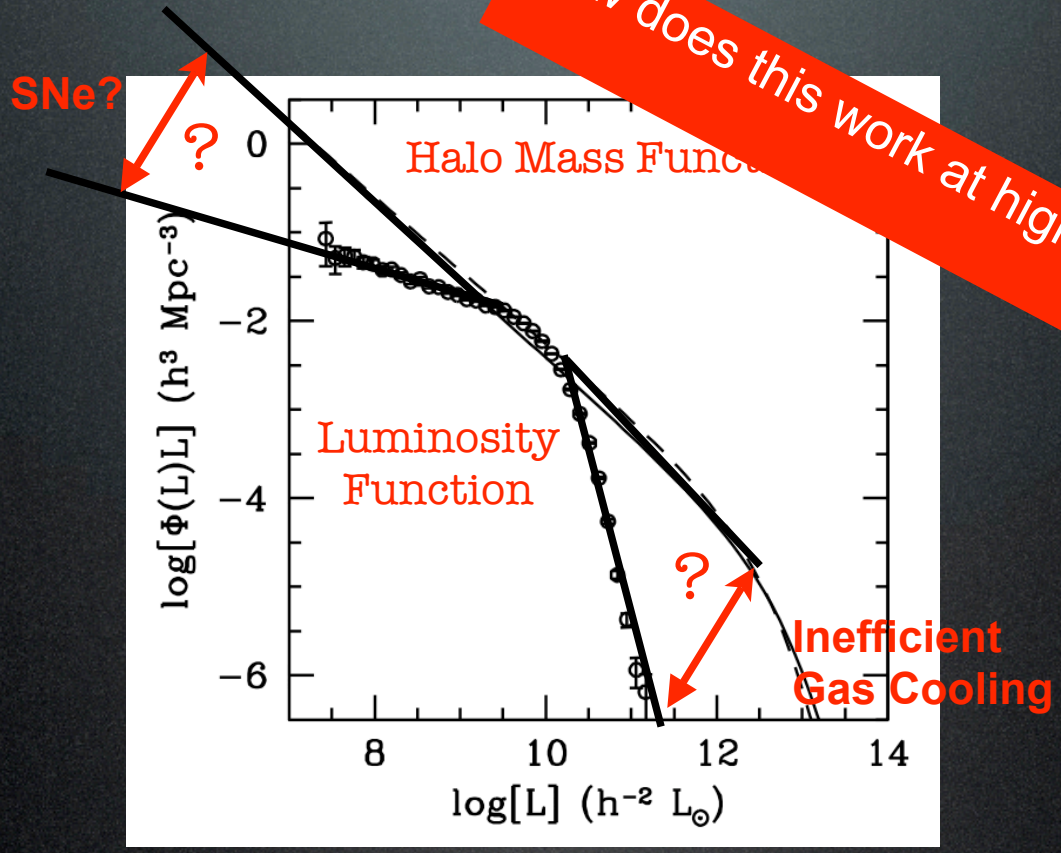
UV Light -- or UV Luminosity functions
(discussed in my presentation)

Stellar Mass -- or Mass Functions
(discussed in Valentino's presentation)

Fundamental Questions for Galaxies at z>=3

2) How does the Visible Matter in growing Galaxies Relate to Dark Matter?

How does this work at high redshift?



Yang et al. 2003

Fundamental Questions for Galaxies at z>=3

MORE APPLIED QUESTIONS

3) How rapidly does the SFR density of the universe increase with cosmic time? (can derive by integrating the UV LFs)

** Important for the build-up of metals, dust in universe...

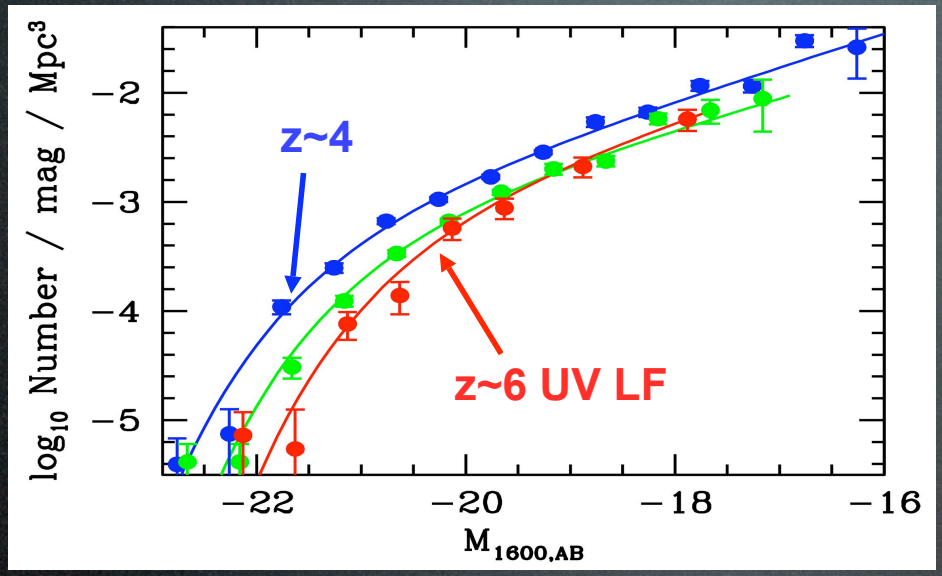
4) What role does the growth of galaxies have in the reionization of the universe?

Glimpse of Galaxy Growth at $z<6$...

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

UV Luminosity Functions

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



Bright Rest frame UV Faint

1. LFs have a Schechter-like shapes... with cut-off at bright end

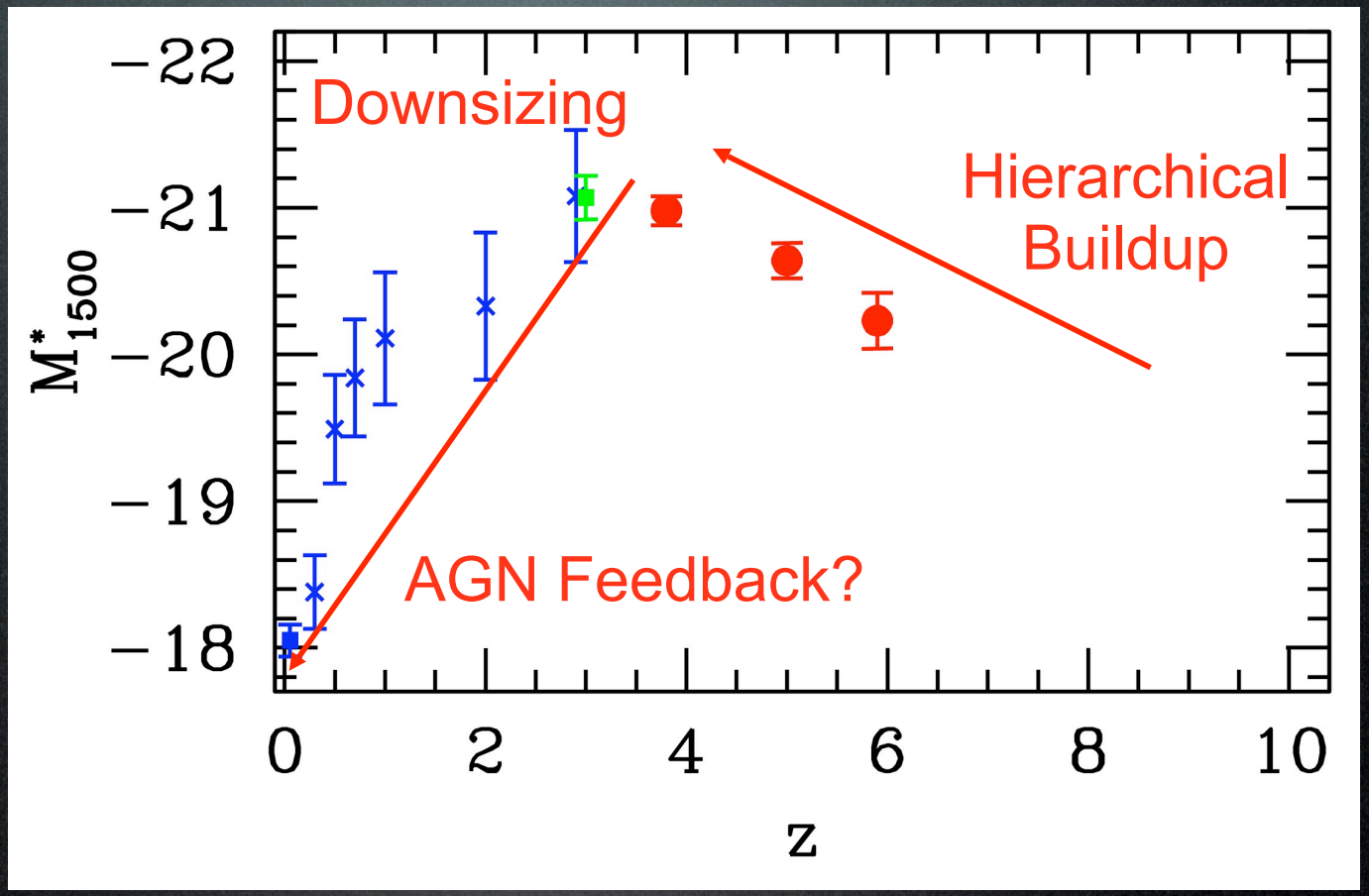
2. Galaxies become more luminous as a function of cosmic time

Brightening and Fading of LF with time

Bright

M^*_{UV}

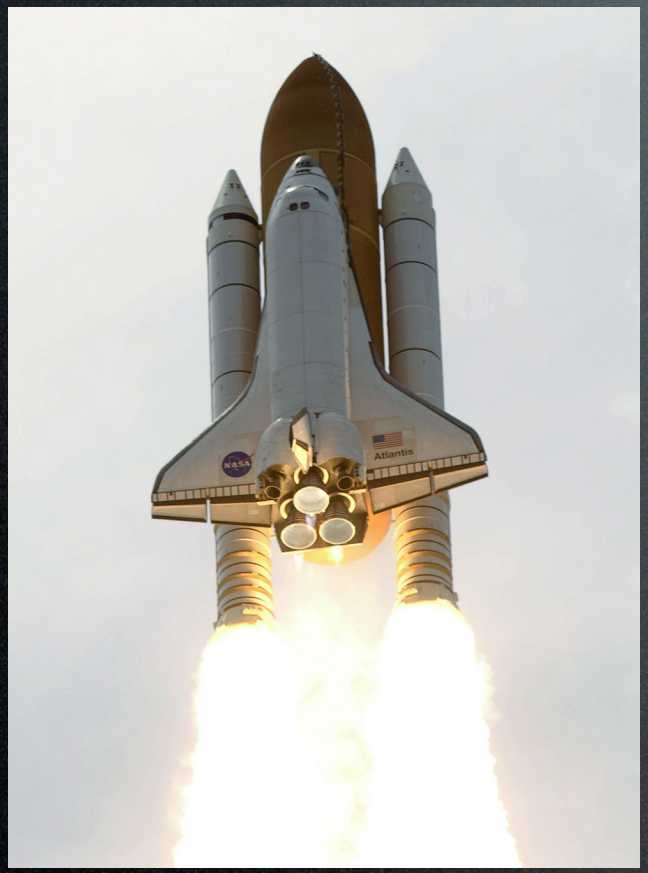
Faint

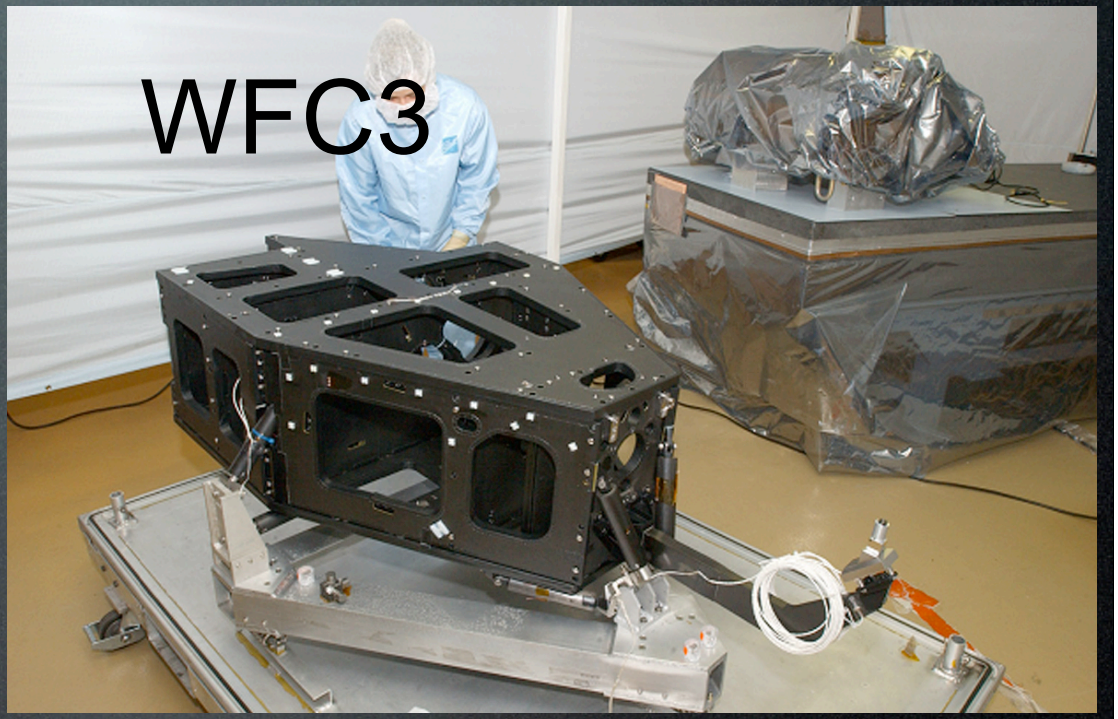


Redshift

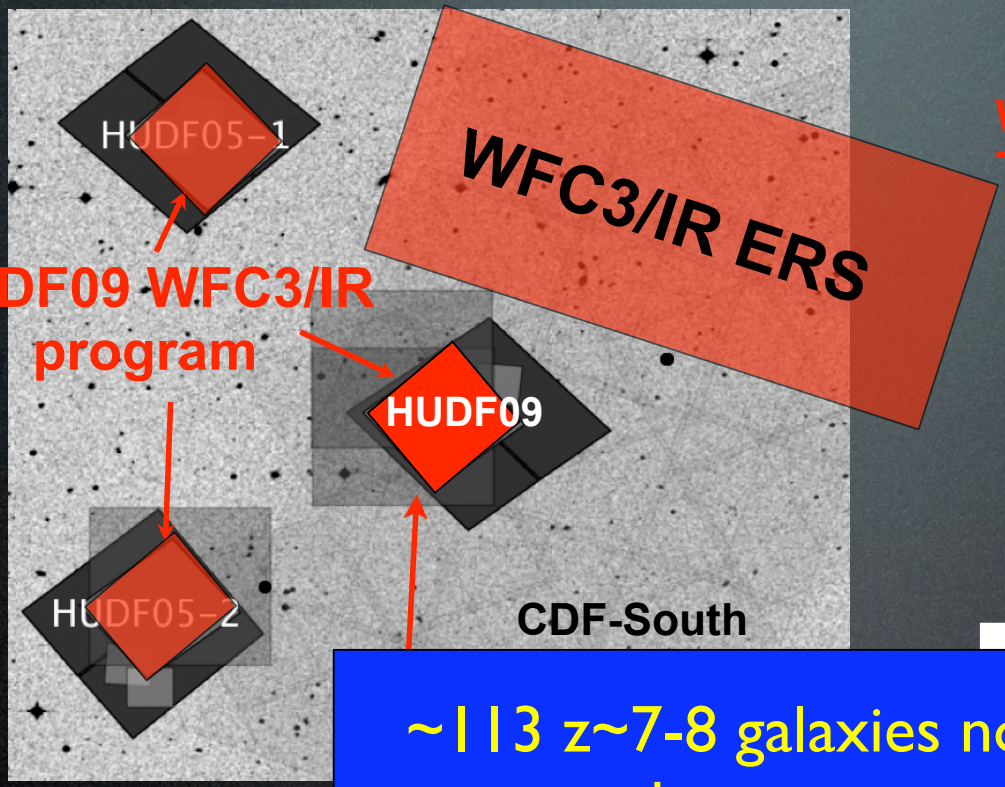
Glimpse of Galaxy Growth at z>=7...

Shuttle Servicing Mission SM4





Current WFC3/IR Samples



Wide-Area Observations +
Two Ultra-Deep HUDF09 Fields

Total z>=7 WFC3/IR sample

~66 z~7 z-dropouts
~47 z~8 Y-dropouts

~113 z~7-8 galaxies now known

Firs
data

Took us ~1-2 months to devise technique for selecting robust samples

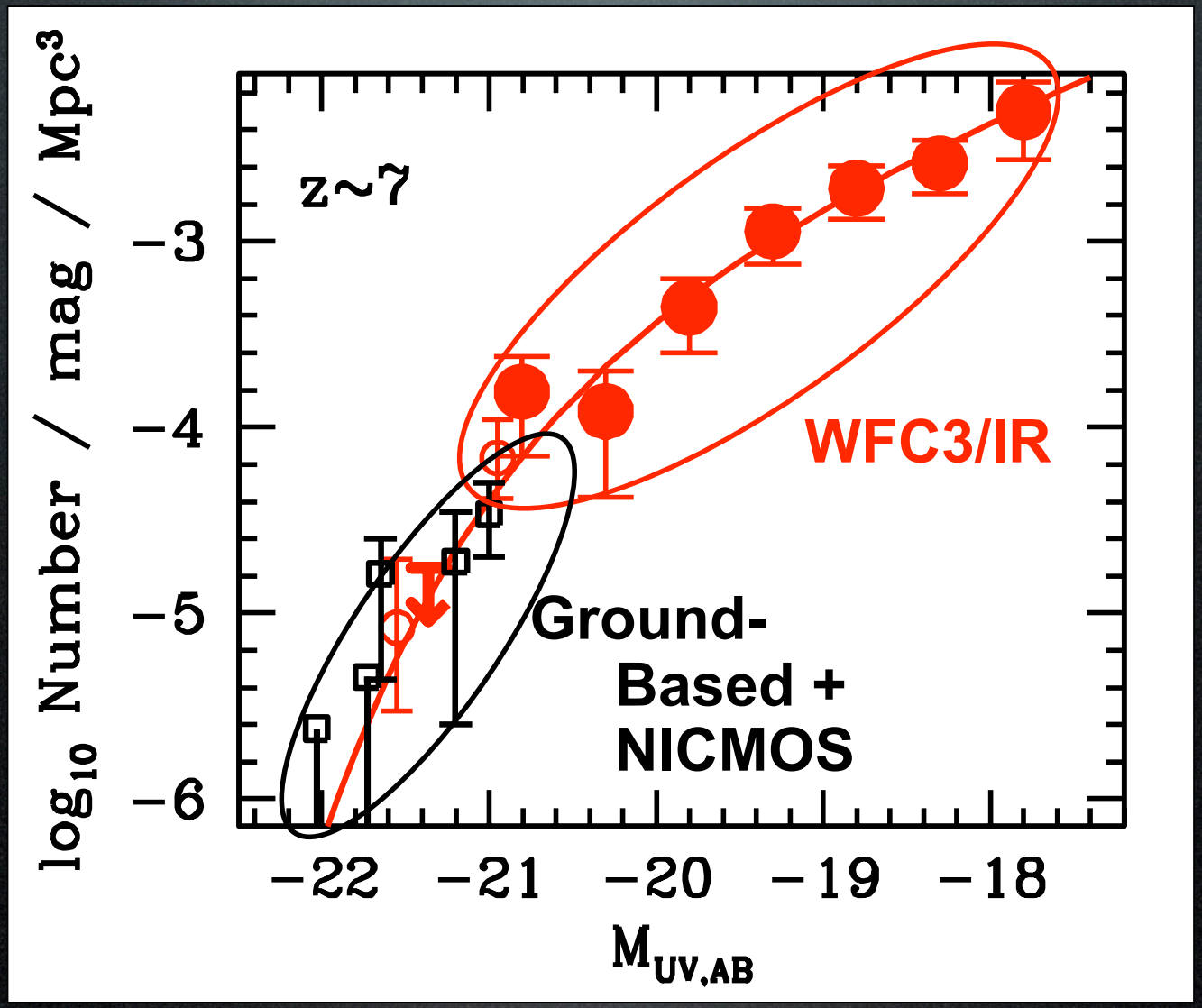
Special Thanks to My Collaborators

With a Special Thanks to:

The HUDF09 WFC3 IR team: Garth Illingworth, **Rychard Bouwens**, Marijn Franx, Pieter van Dokkum, Massimo Stiavelli, Ivo Labbe, **Michele Trenti**, Marcella Carollo, Pascal Oesch, Dan Magee

Galaxy Growth at High Redshift...

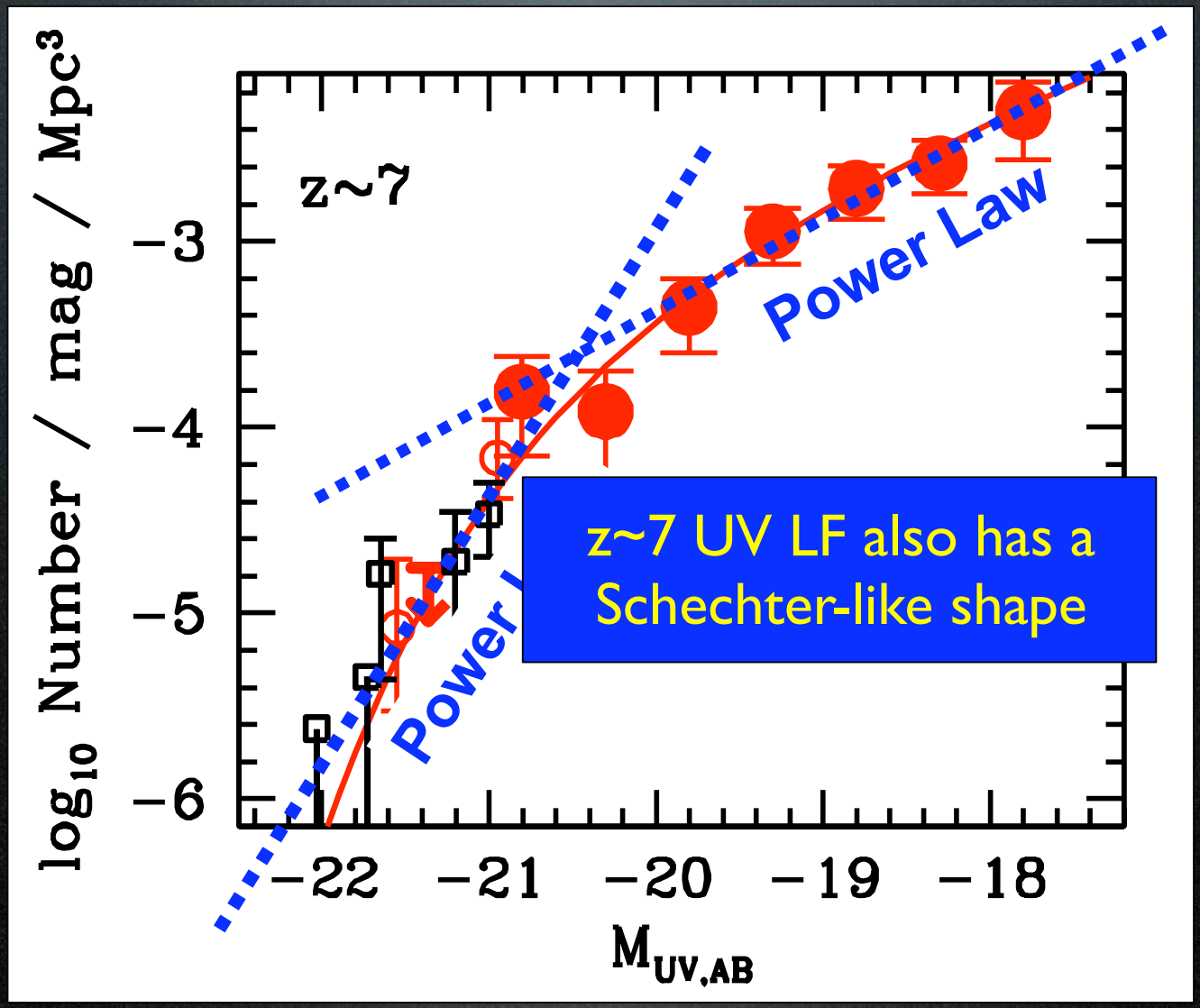
How do z>6 LFs look? What is the shape?



Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010

Galaxy Growth at High Redshift...

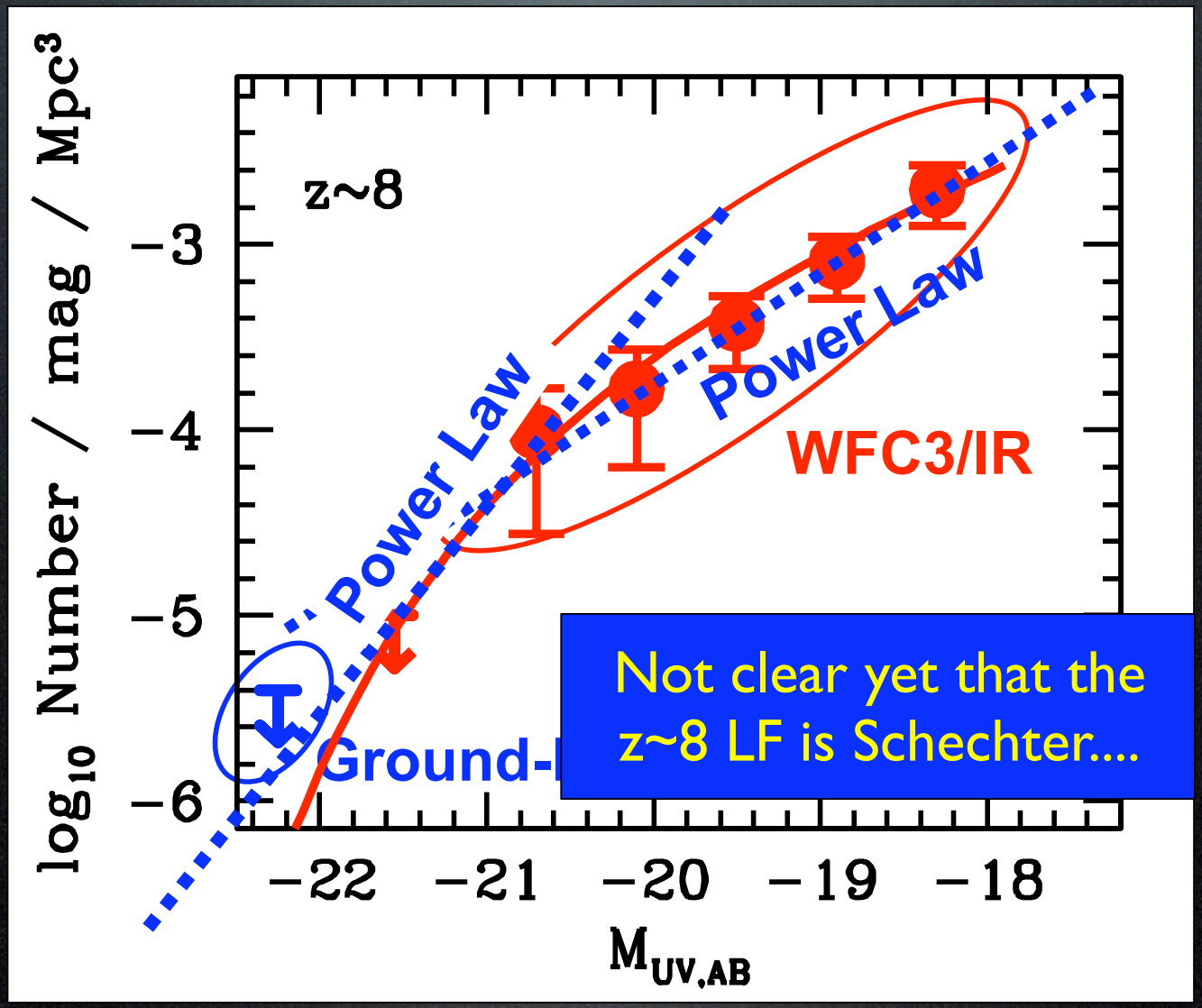
How do z>6 LFs look? What is the shape?



Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010

Galaxy Growth at High Redshift...

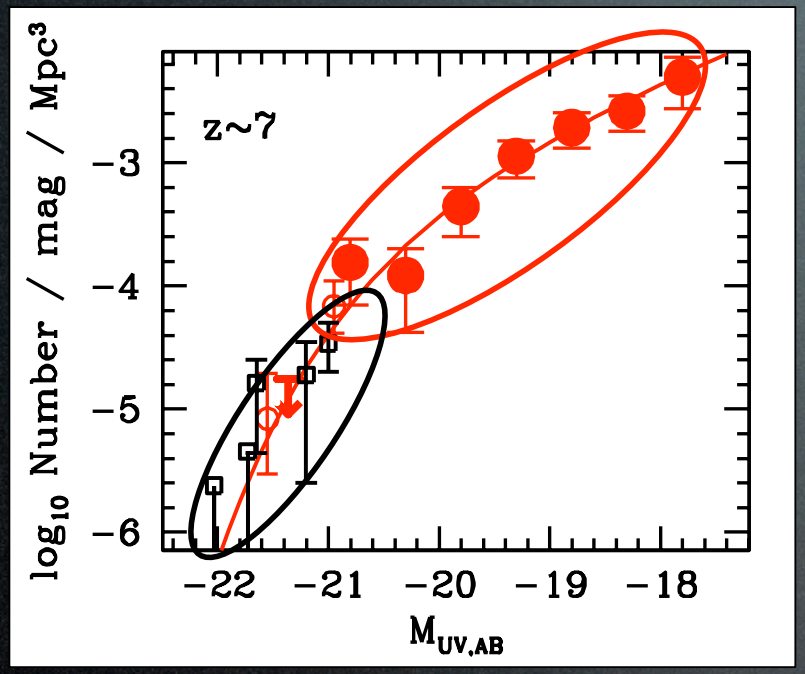
How do z>6 LFs look? What is the shape?



Bouwens et al. 2010; Castellano et al. 2010

Galaxy Growth at High Redshift...

What do we learn from the shape of the UV LFs at z>=7



Why does the UV LF cut-off at bright magnitudes?

STANDARD EXPLANATIONS AT z~0:

1. Inefficient cooling of gas.... (hot flows)
2. AGN feedback...

Halo masses are so low that neither explanation may be very effective...

Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010

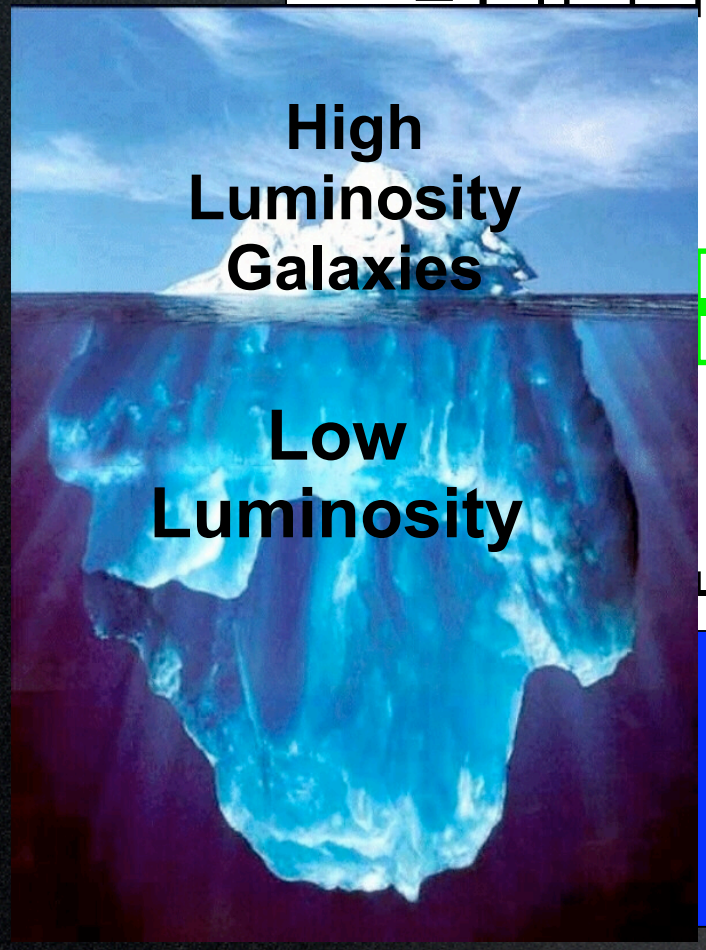
Summary

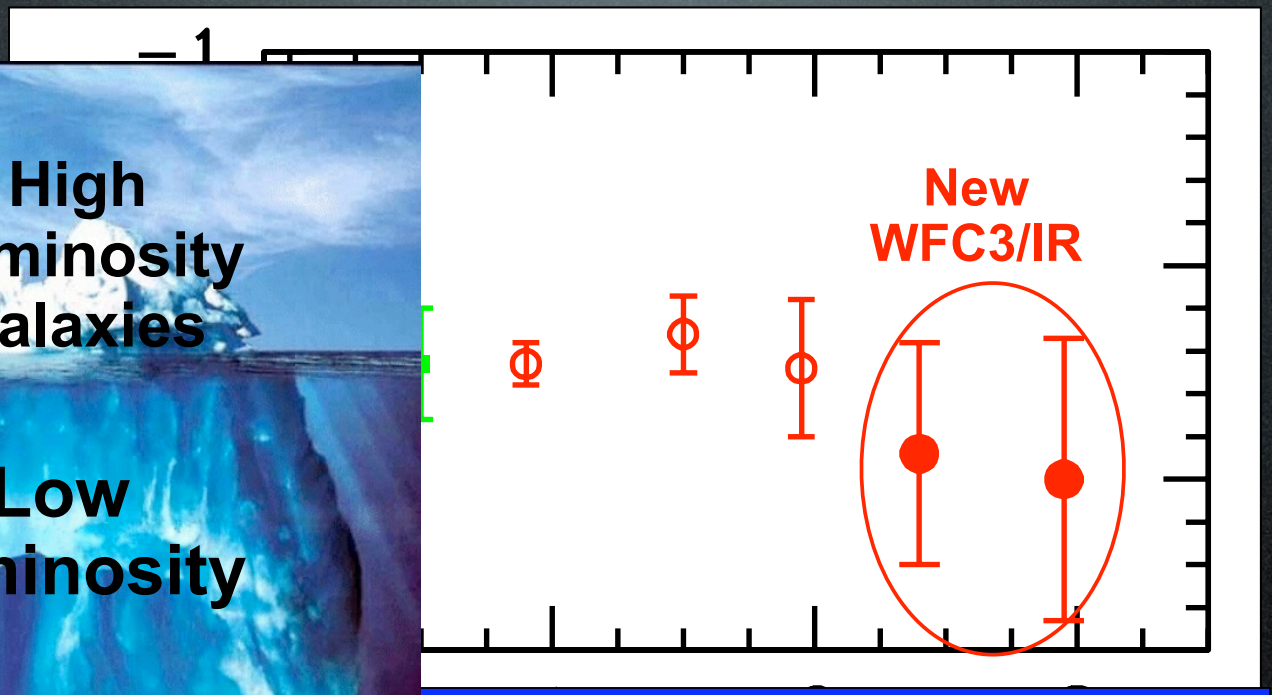
1. One distinct feature in the observed LF is an abrupt cut-off at the bright end of the LF
2. At [illegible] thought to result from inefficient cooling at large [illegible] feedback, or dust extinction.
3. The above mechanisms [illegible] at large masses, i.e., > 10[illegible]
4. Since most dark matter halos at z>5 [illegible] smaller masses than $10^{11.5}$ $M_{\odot}$, we would not expect this [illegible] to impart a sharp cut-off in the UV LF
5. But the UV LFs at z~5-6 do seem to have a sharp cut-off at the bright end. Why?
6. What will we find for LFs at z~7-9? Soon to be available HST WFC3 data will allow us to explore this issue.

2008 PRESENTATION

Galaxy Growth at High Redshift...

What is the faint-end slope?
(How numerous are very low luminosity galaxies?)





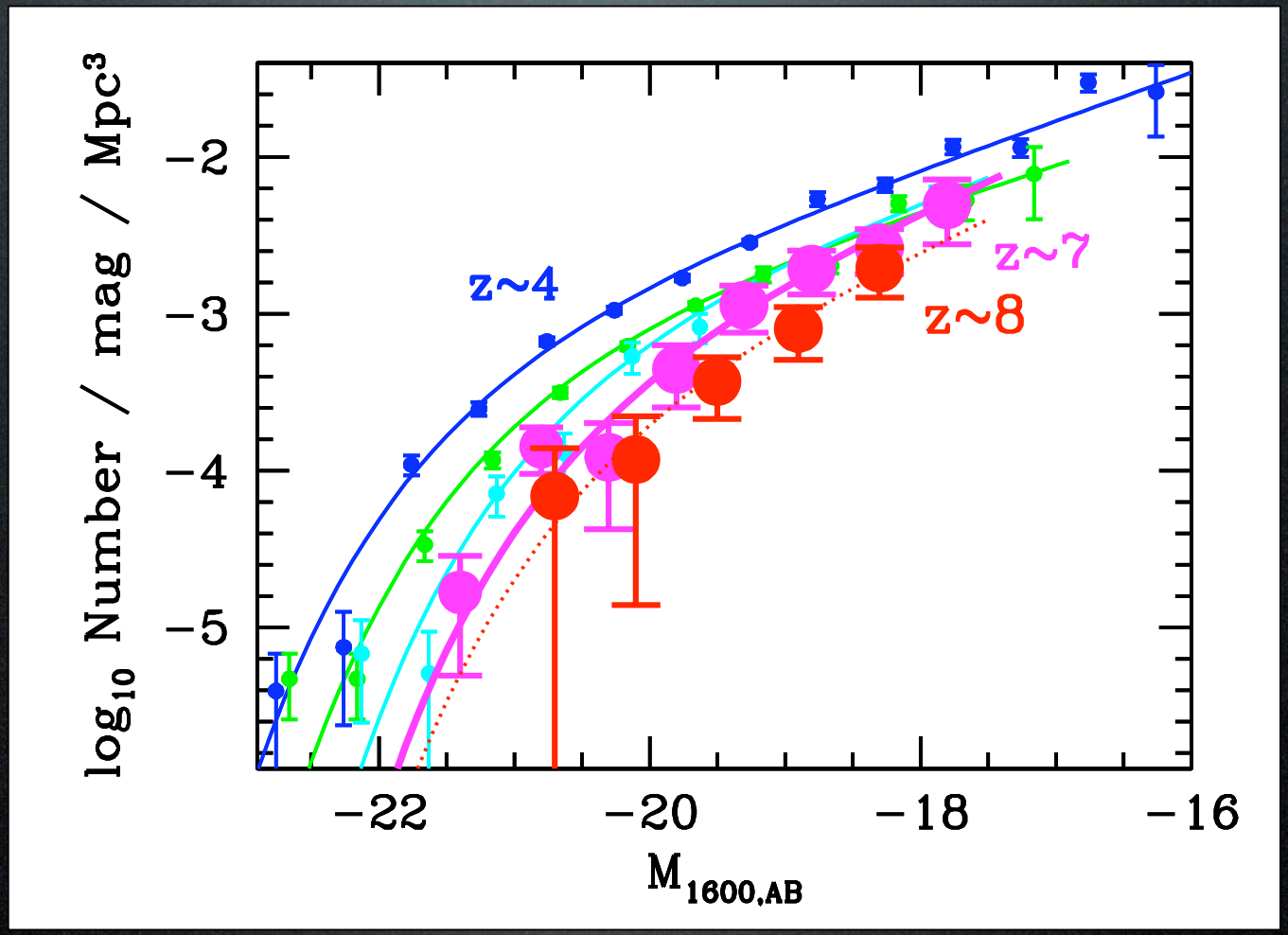
Lower luminosity galaxies provide the dominant contribution to SFR / luminosity densities

Bouwens et al. 2007, 2010; Reddy al. 2009
(see also Ouchi et al. 2009; Oesch et al. 2010; Yoshida et al. 2006)

Galaxy Growth at High Redshift...

How rapidly does the UV LF evolve from z~10+ to z~3?
(Are there many UV bright galaxies at z~10?)

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



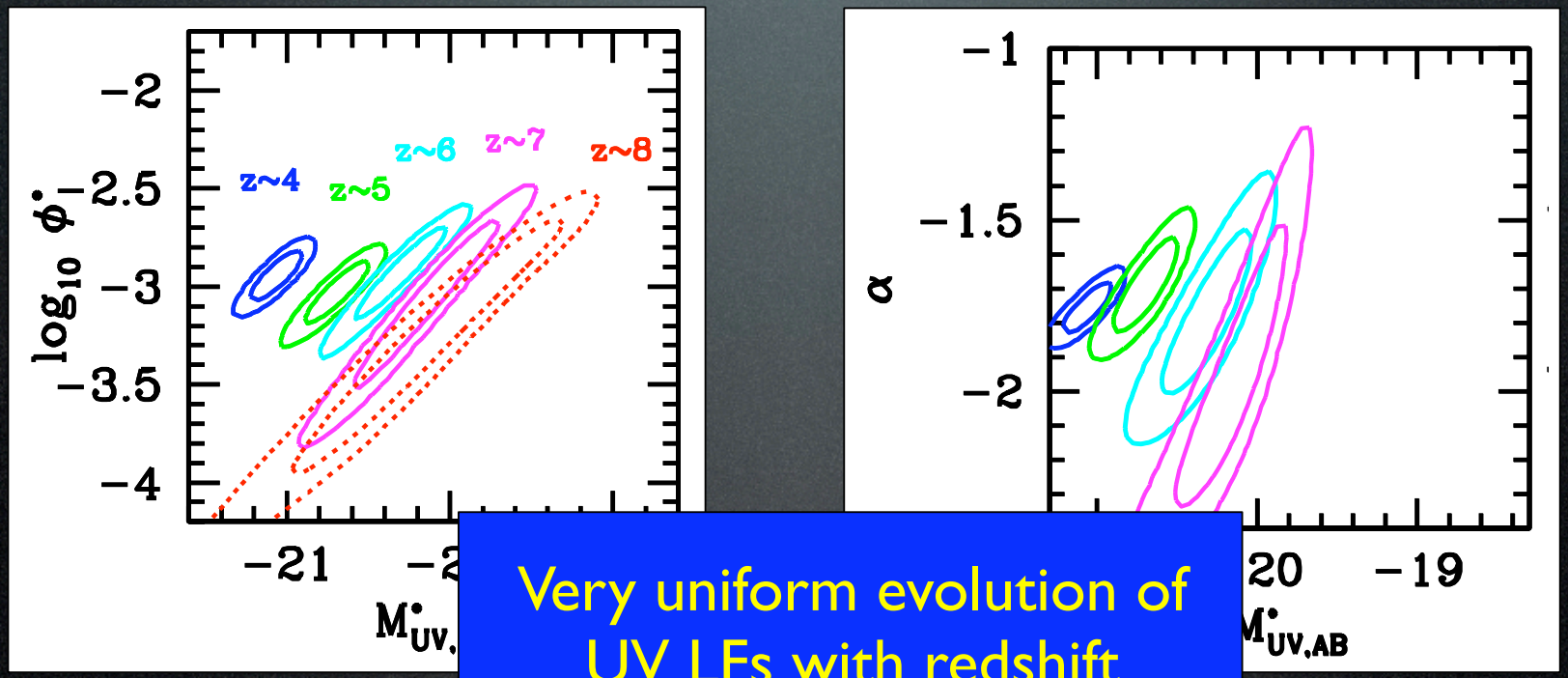
Bright

Faint

Bouwens et al. 2010

Galaxy Growth at High Redshift...

How rapidly does the UV LF evolve from z~10+ to z~3?
(Are there many UV bright galaxies at z~10?)



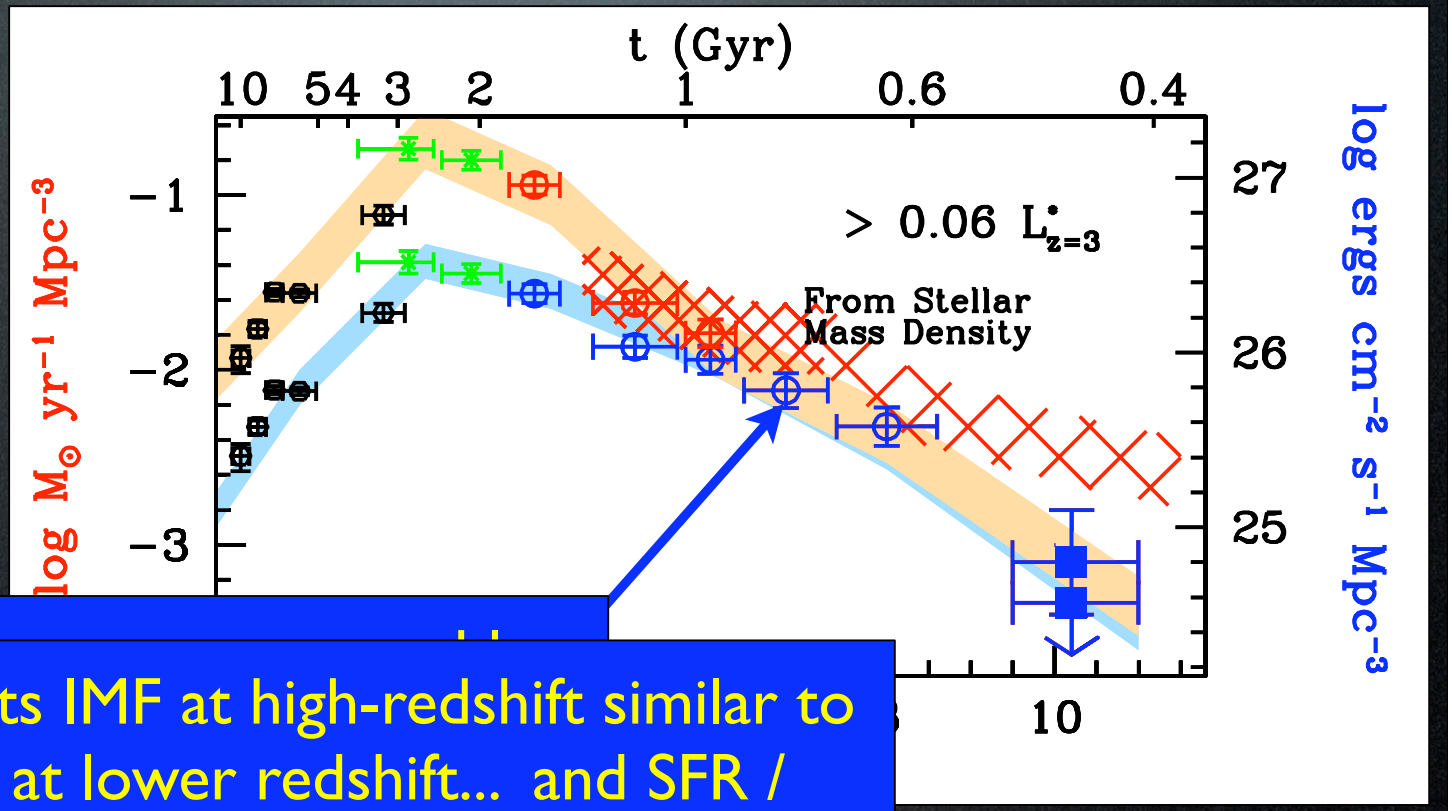
Very uniform evolution of UV LFs with redshift

68% and 95% confidence intervals

Bouwens et al. 2010

Integrate the UV LFs at z~7 and z~8, one derives the SFR density

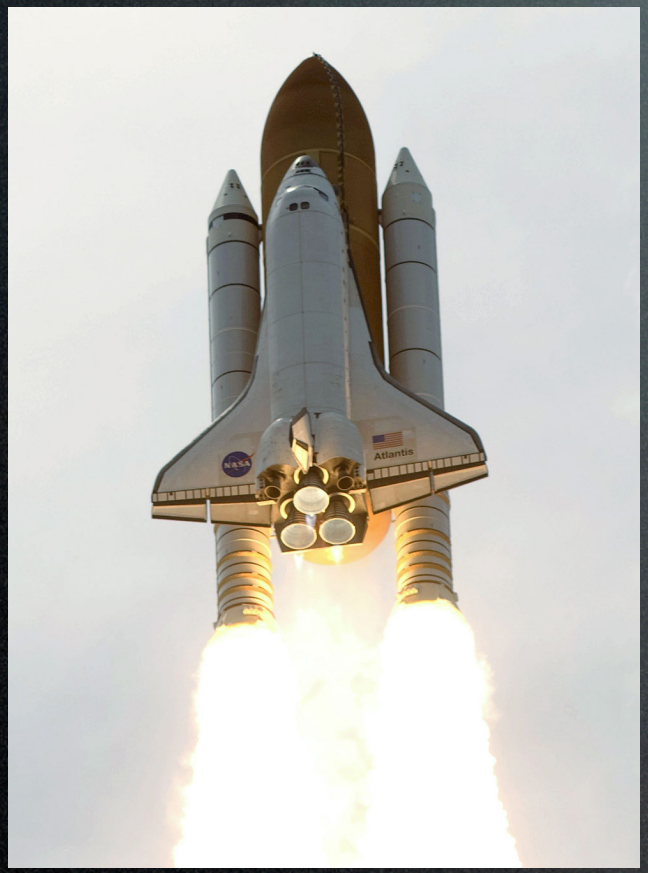
Star Formation Rate density

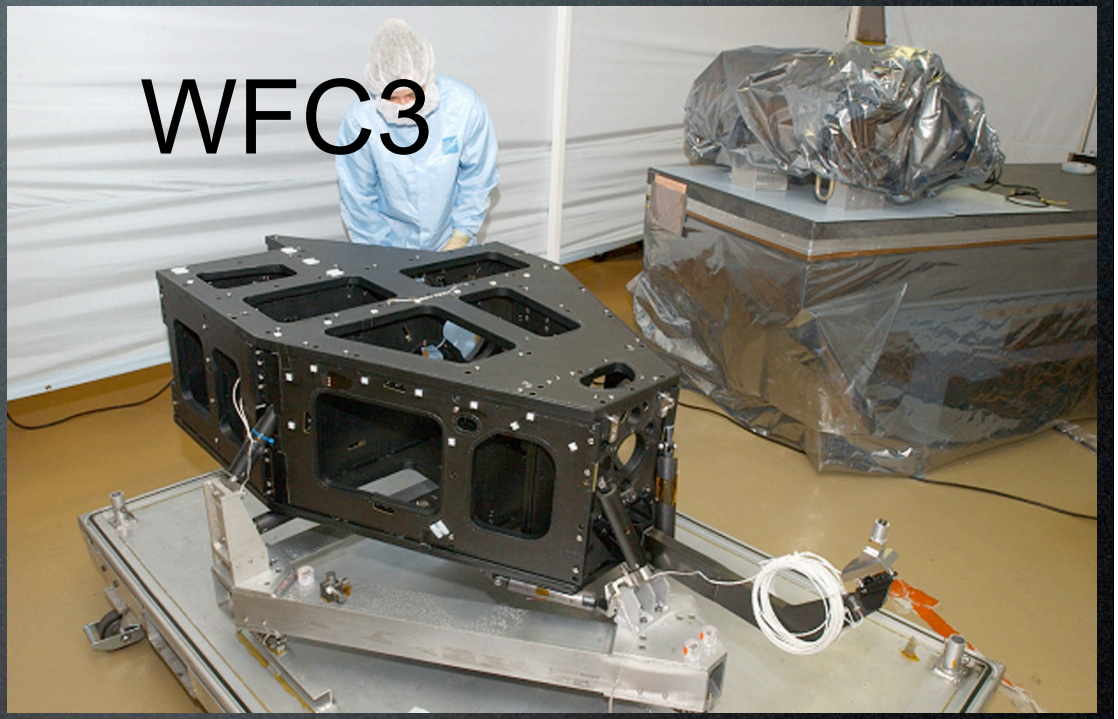


Suggests IMF at high-redshift similar to that at lower redshift... and SFR / stellar mass estimates reasonable

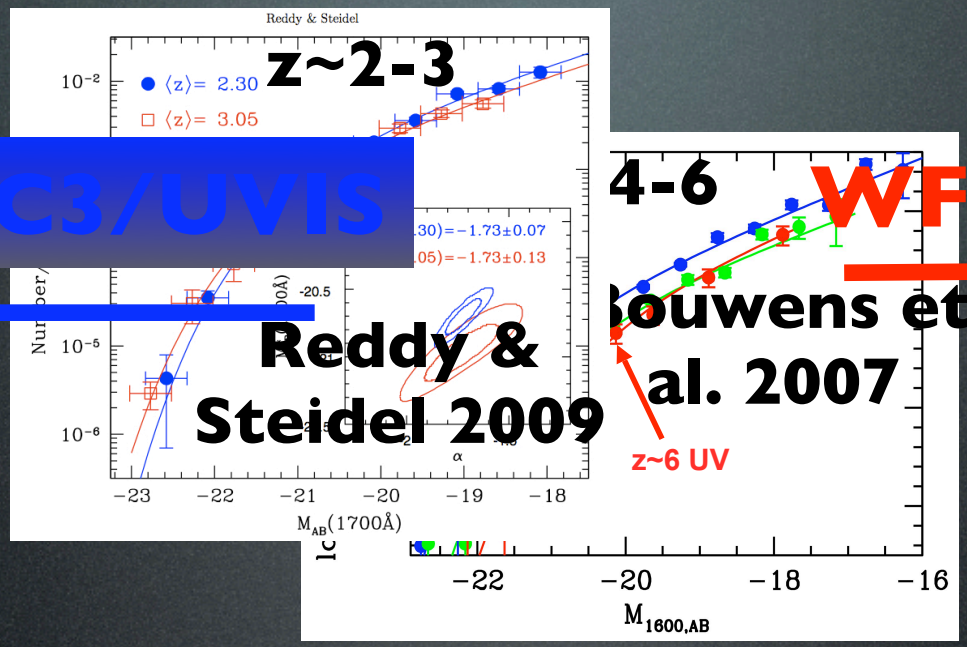
Bouwens et al. (2010); Gonzalez et al. (2010)

Shuttle Servicing Mission SM4





Previous State of Art: LFs at z~4-6, z~2-3



Redshift

0 1 2 3 4 5 6 7 8 9 10

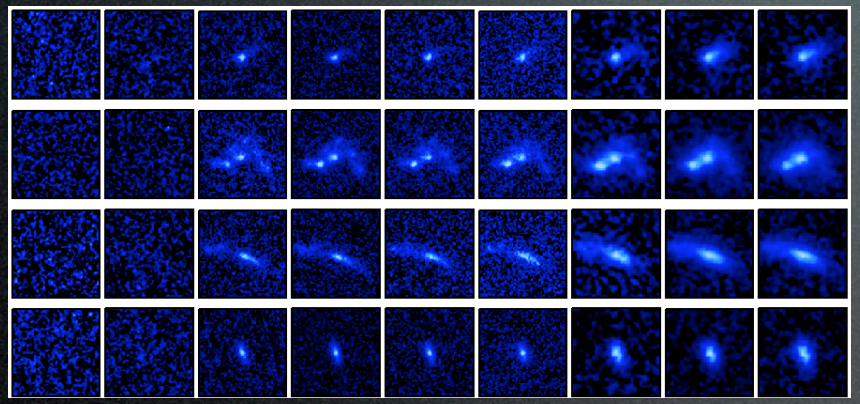
Bouwens et al. 2007; Reddy al. 2009

(see also Giavalisco 2005; Ouchi et al. 2004; Yoshida et al. 2006; Beckwith et al. 2006)

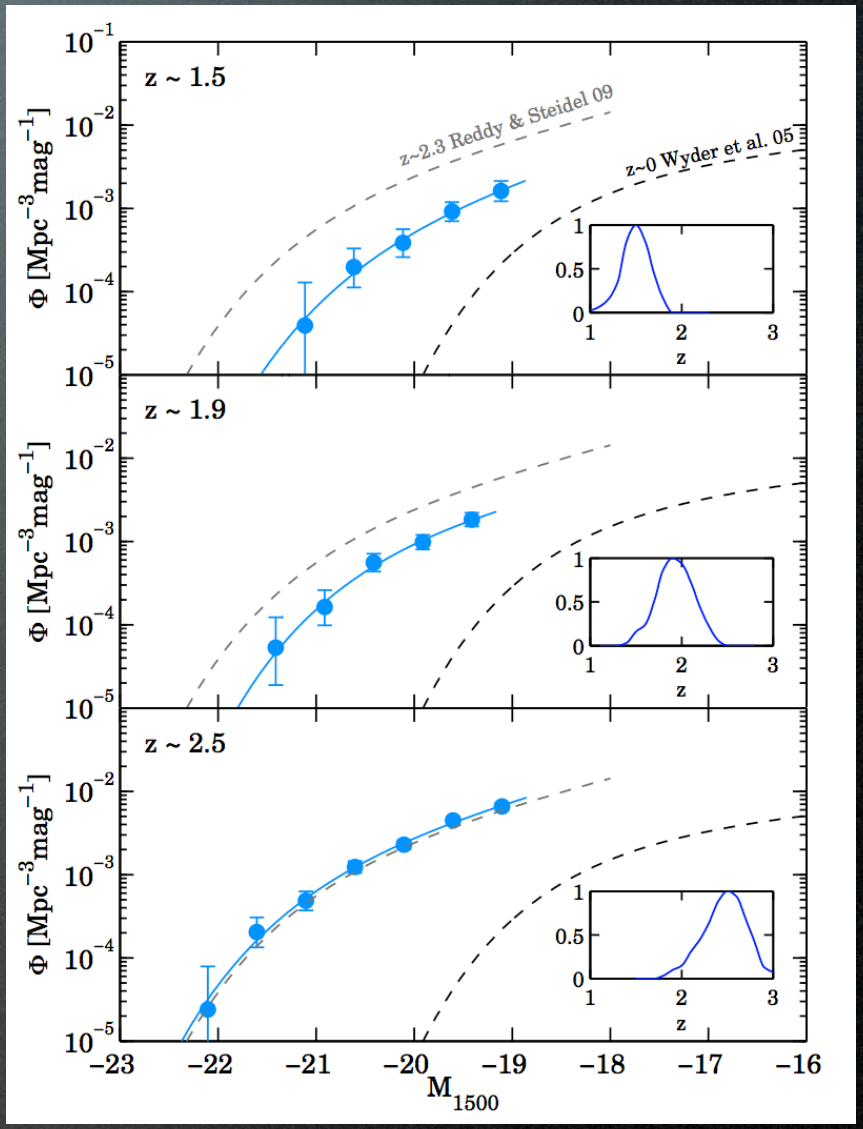
WFC3/UVIS results in the ERS field

ERS observations in UV let us search for star-forming galaxies at z~1 => z~2.5

WFC3/UVIS dropouts



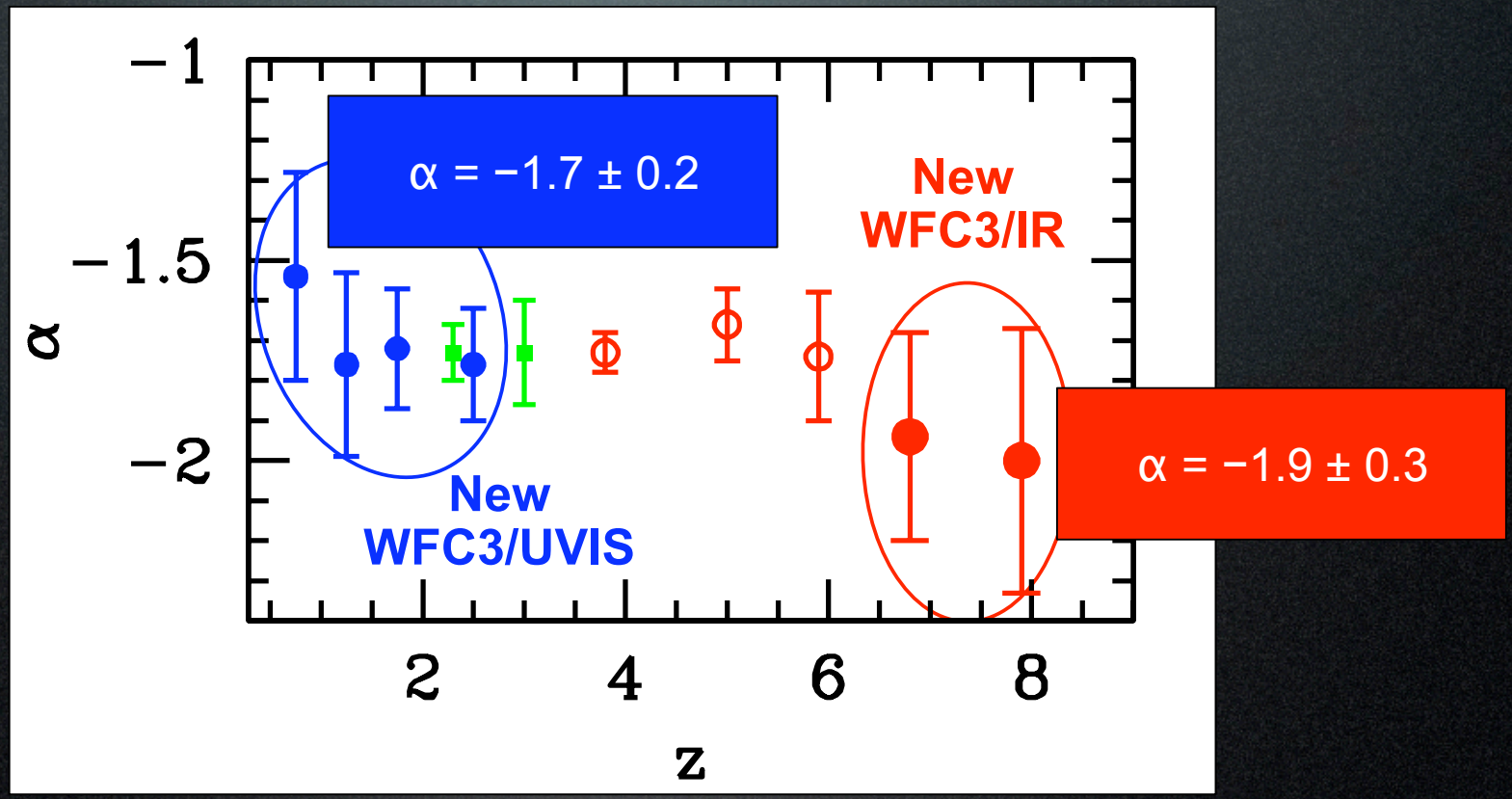
WFC3/UVIS ACS WFC3/IR



Oesch et al 2010c; see also Hathi et al. 2010

The Evolution of the UV LF from z~7-8+ to z~1

What is the faint-end slope in FUV at z<3?

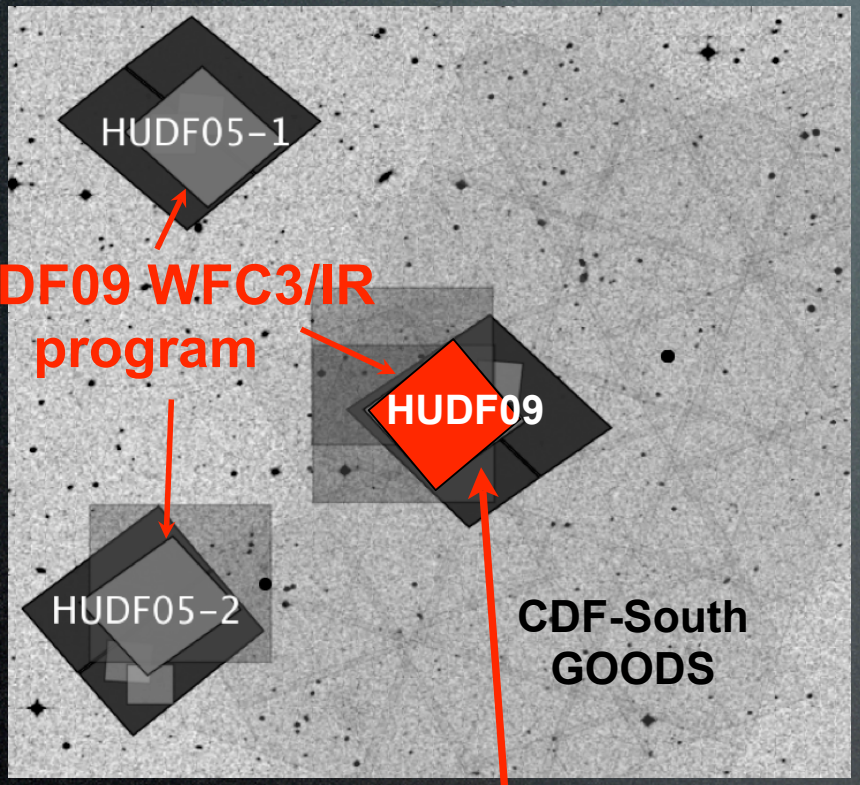


Oesch et al 2010; Reddy & Steidel 1999; Bouwens et al. 2010

Results are improving rapidly!

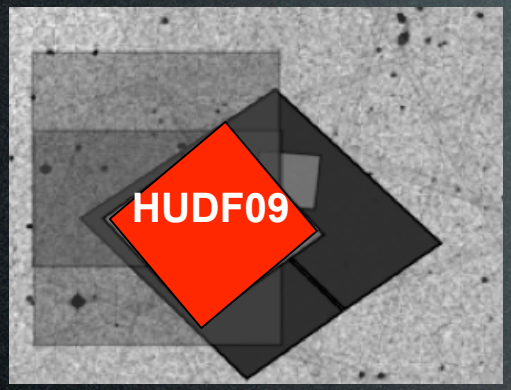
Deeper data already upon us!

More ultra-deep WFC3/IR observations coming!



Integration time over the HUDF is increasing by a factor of 2!

More ultra-deep WFC3/IR observations coming!



111 orbit integration

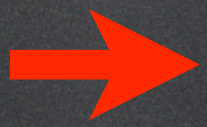
Reaches 29.5 mag

(within factor of ~4 of the depths planned for JWST deep field)

First Year Data

15 z~7 galaxies

16 z~8 galaxies

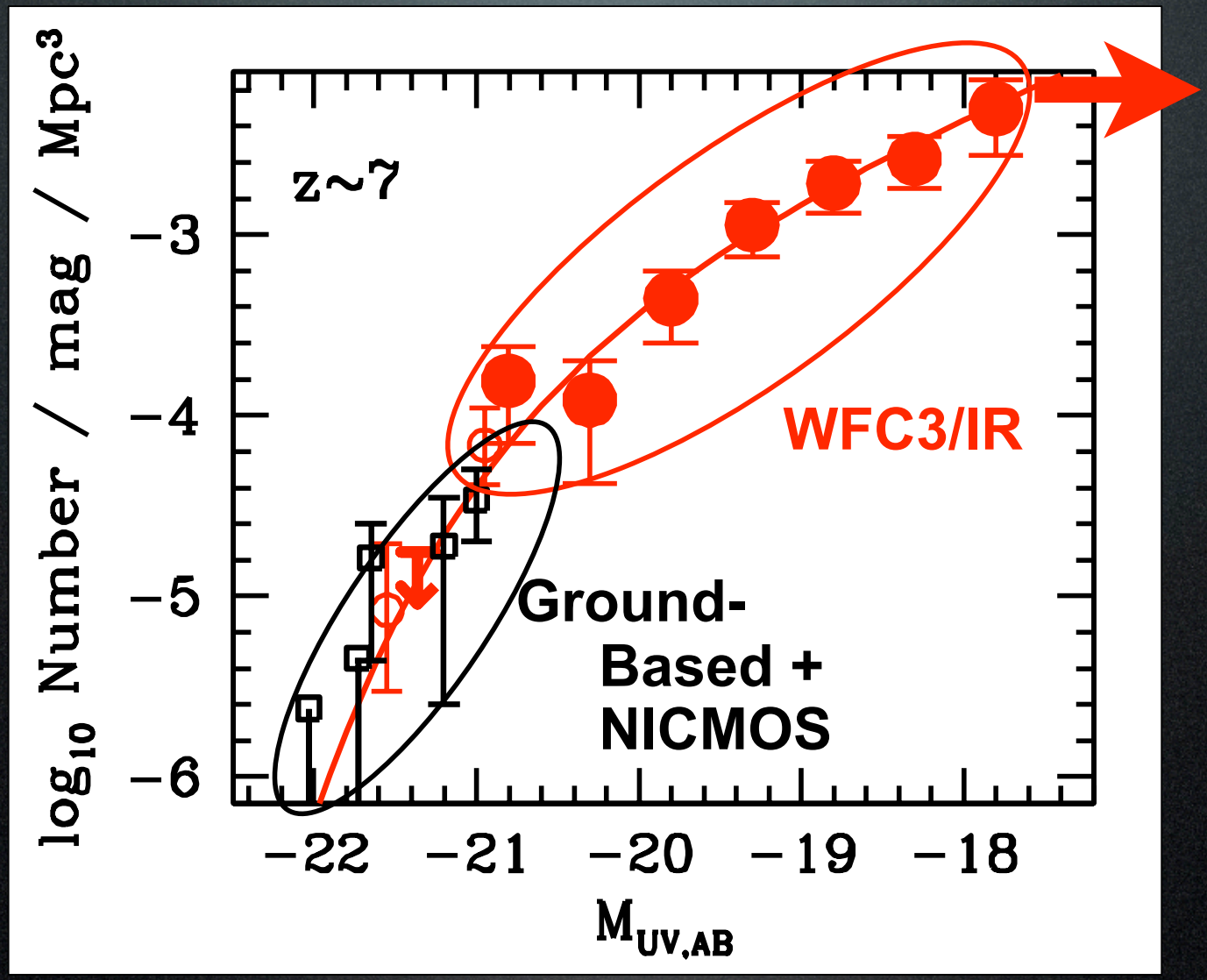


Second Year Data

28 z~7 galaxies

25 z~8 galaxies

The Evolution of the UV LF from z~7-8+ to z~1



Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010

Stay tuned for a variety of exciting results!

Galaxy Growth at High Redshift...

Galaxy formation in the z>=4 universe is very different in behavior from later times

WFC3/IR allows us to very efficiently identify galaxies at high redshift. We identify 67 z~7 z-dropouts and ~48 z~8 Y-dropout galaxies in the new observations

The UV LF of galaxies appears to have a Schechter-like shape at z~7 and also plausibly at z~8

The faint-end slope of the UV LF at z~7 and z~8 is ~ −1.9 ± 0.3.

The evolution of the UV LF continues very smoothly from z~8 to z~4, with an essentially linear rate of evolution with redshift.

Comparing the SFR density with that expected from the published stellar mass density, we find reasonable agreement -- suggesting that the IMF at z>4 may not be that different from what it is at later times.

WFC3/UVIS allows us to efficiently select star-forming galaxies at z<3 and measure their FUV flux. We identify >1000 galaxies to ~0.1 L* in the ~50 arcmin^2 WFC3/UVIS observations.

The faint-end slope of the UV LF at z~1-3 is ~ −1.7 ± 0.2.

Much exciting data coming!