Probing the Dawn of Galaxies:
New Insights from Ultra-Deep HST and Spitzer Observations

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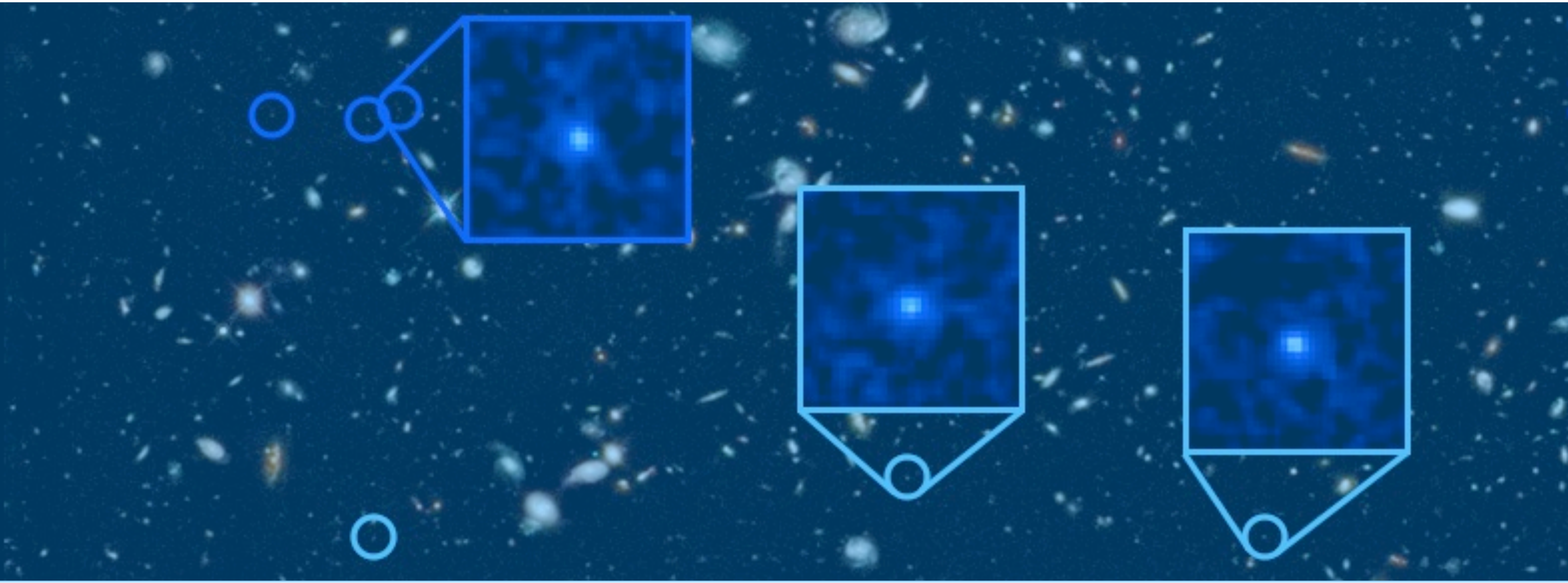
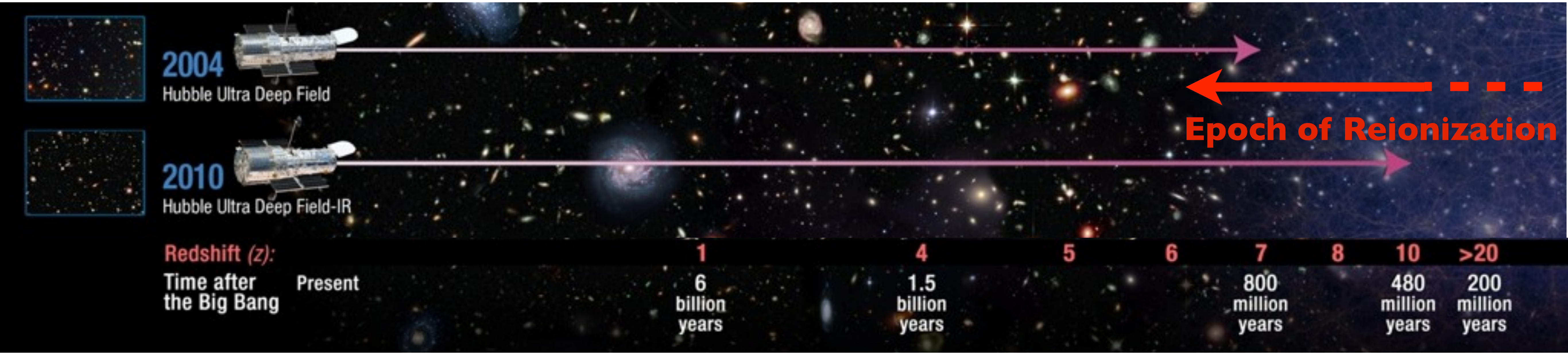


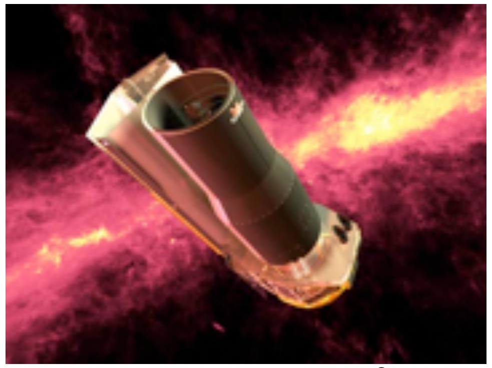
When and how did the first galaxies form? How fast did they grow and build-up?



Thanks to WFC3/IR: now able to overcome z~6-7 “barrier”

Now have large samples (>300) of galaxies in heart of reionization at z>6

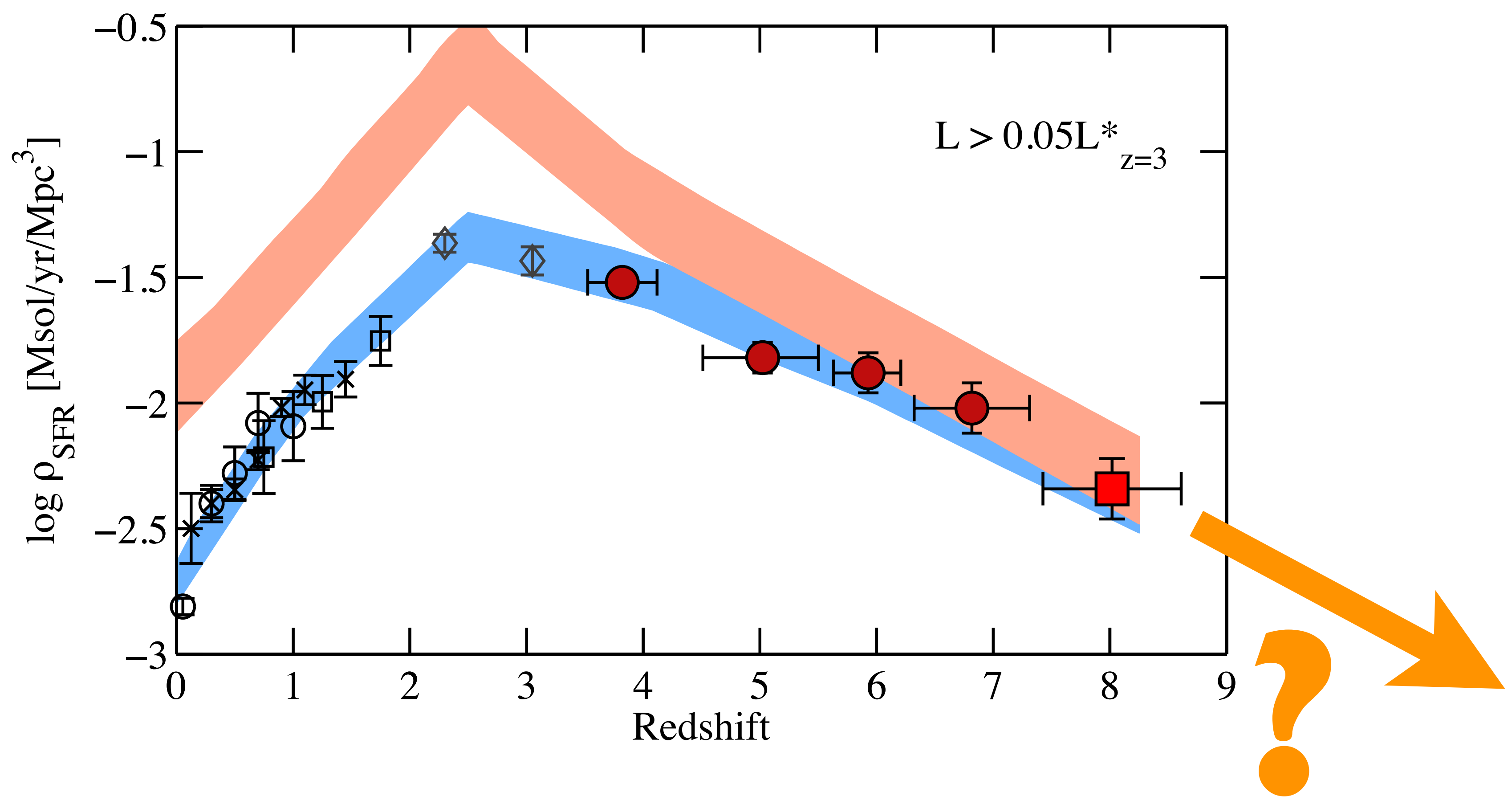
+



rest-UV SFRs

rest-optical Masses

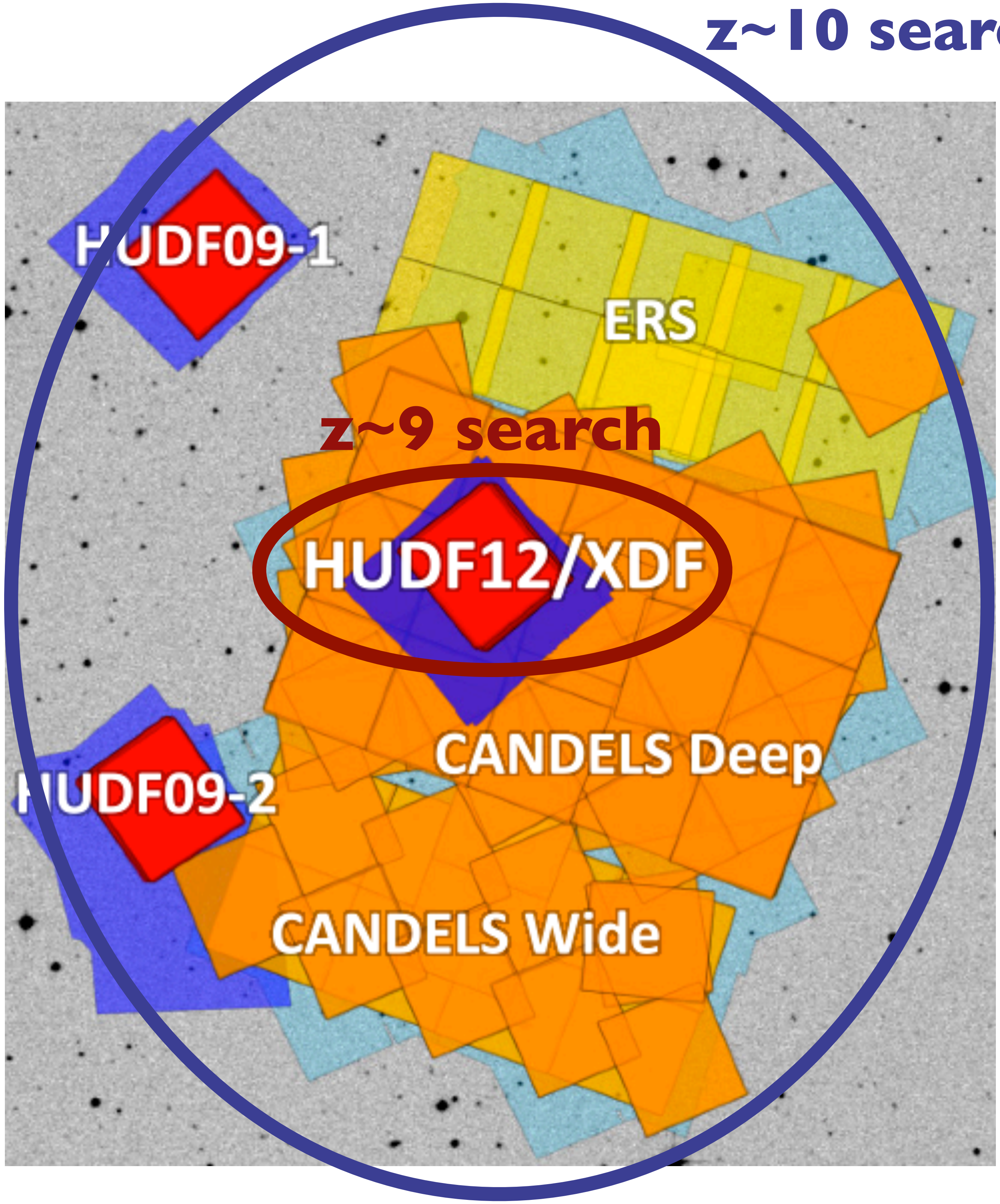
Do we see Evidence for Emergence of the First Galaxies?

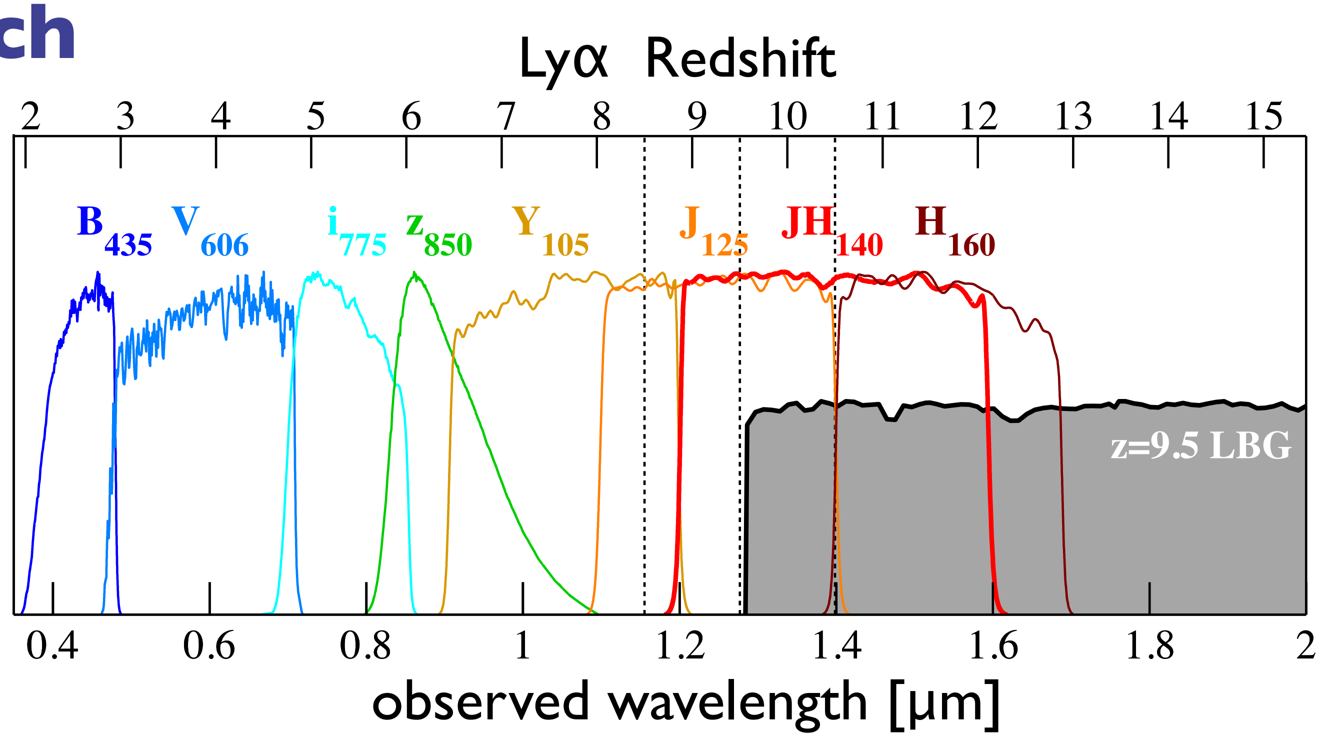


Galaxy Build-up at z<8 progresses monotonically.

What about at z>8?

WFC3/IR Data around GOODS-South





- Large amount of public optical (ACS) and NIR (WFC3) data
  - *HUDF12 & XDF*
  - ERS
  - CANDELS (Deep & Wide)
- Total of ~160 arcmin^2
- Reach to 27.5 - 30 AB mag
- Full data: can select z~10 galaxies
- HUDF12/XDF: can select z~9 galaxies

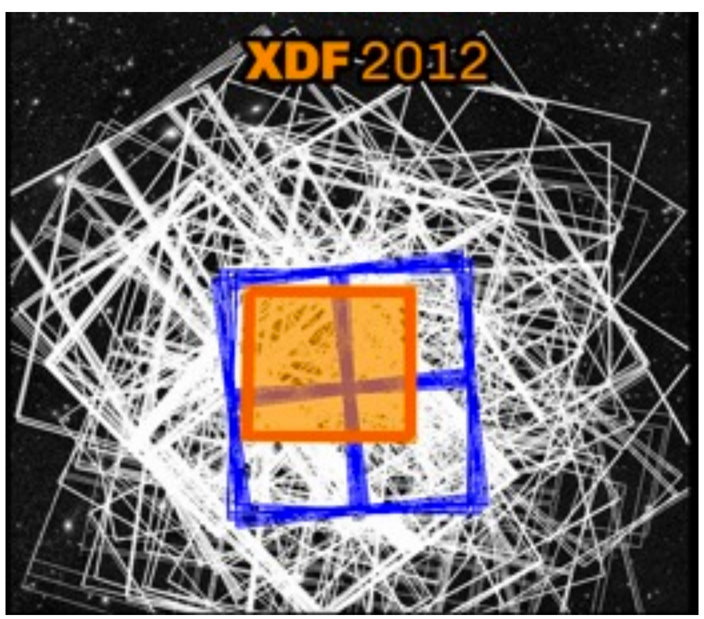
HUBBLE SPACE TELESCOPE

XDF ▪ eXTREME DEEP FIELD

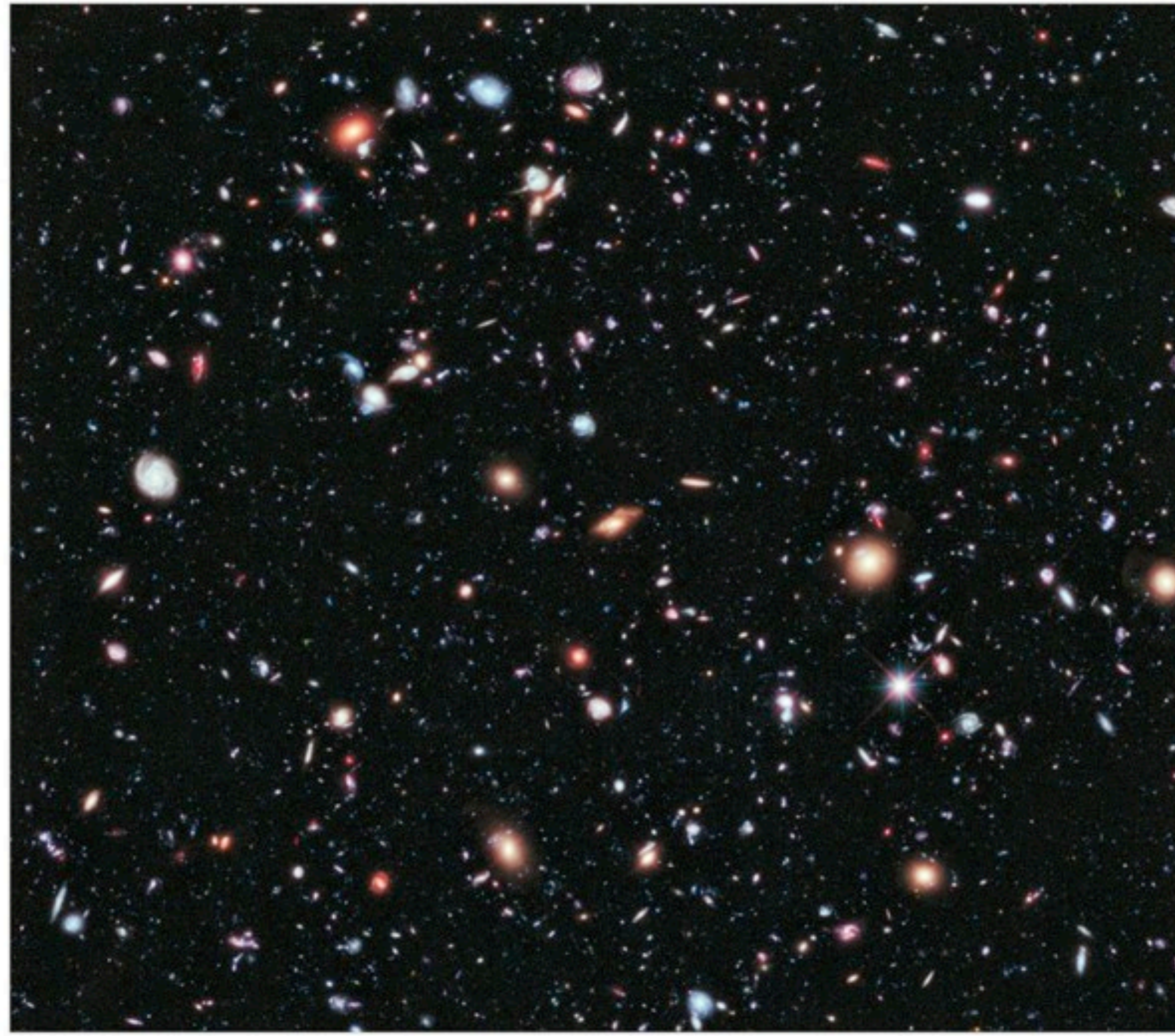
All optical ACS and WFC3/IR data over HUDF from 2003 to 2013 combined into eXtreme Deep Field (XDF)

Total of ~2Ms of HST data

Adds ~130 ACS orbits to the HUDF



Reaches about 31mag at 5σ: deepest multi-color image ever taken



xdf.ucolick.org

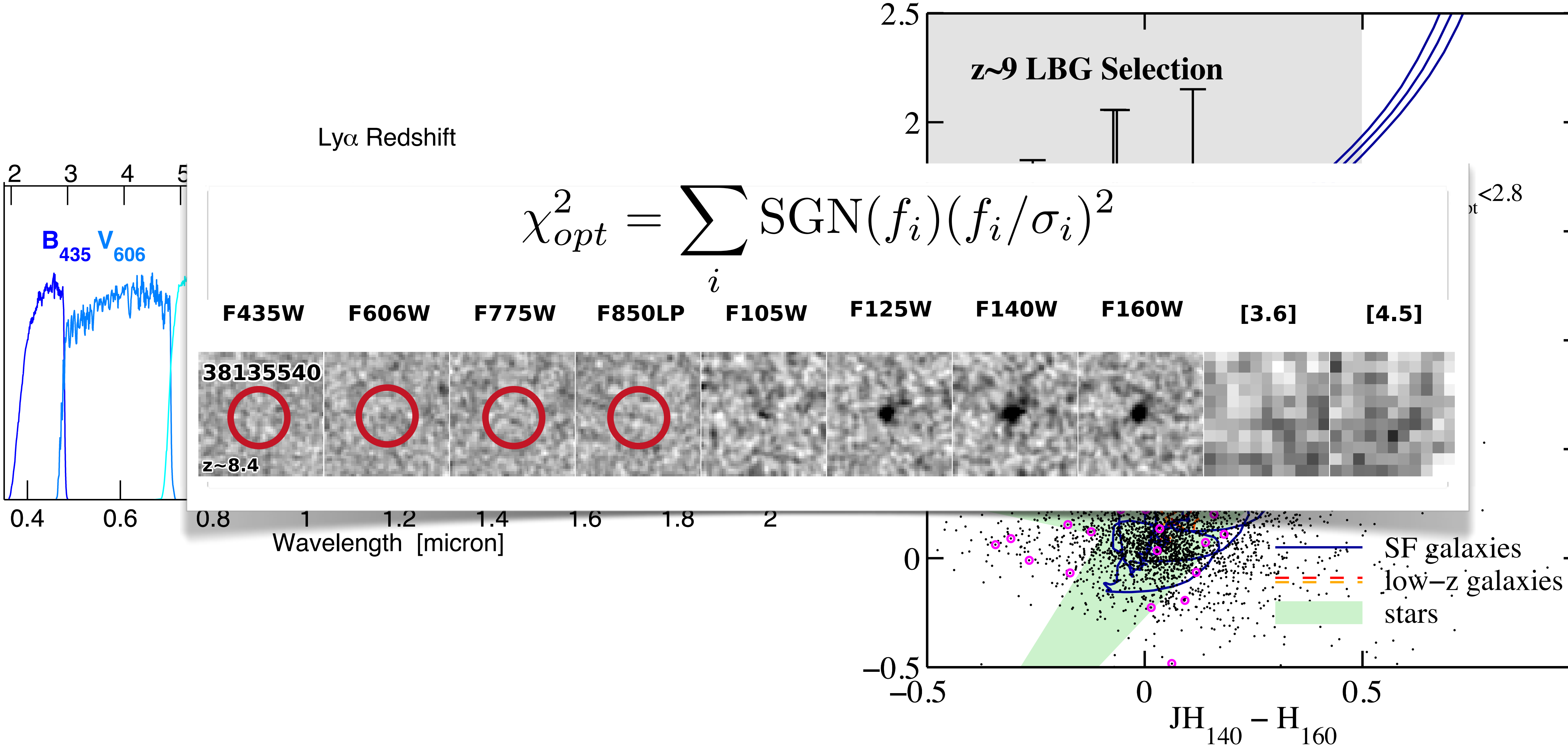
available from MAST!

(see Illingworth, Magee, Oesch et al. 2013)

2012
NASA, ESA,
G. Illingworth, D. Magee, and P. Oesch (University of California, Santa Cruz),
R. Bouwens (Leiden University), and the XDF Team

z~9 LBG Selections with HUDF12 Data

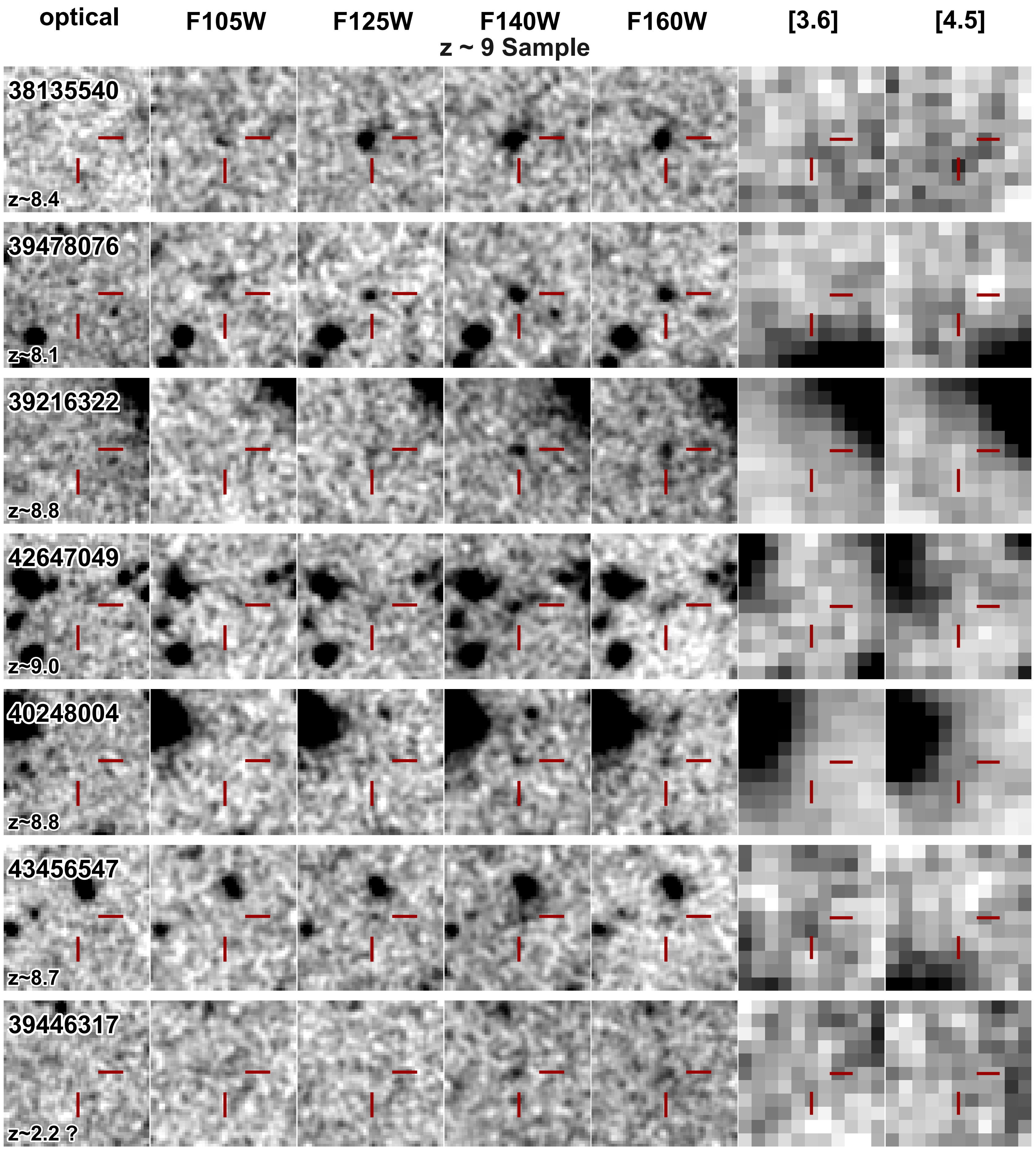
z~9 Selection is based on a red color in (YJ)-JH and optical non-detection.



$$\chi^2_{opt} = \sum_i \mathrm{SGN}(f_i)(f_i/\sigma_i)^2$$

Our HUDF12 z~9 LBG sample contains seven sources (H = 28.0 - 29.9 mag, <z_{phot}> = 8.7)

z~9 Sample



optical
F105W
F125W
F140W
F160W
[3.6]
[4.5]
z ~ 9 Sample
38135540
z~8.4
39478076
z~8.1
39216322
z~8.8
42647049
z~9.0
40248004
z~8.8
43456547
z~8.7
39446317
z~2.2 ?

z~9 Sample

SED fits using all HST and IRAC 1&2 bands

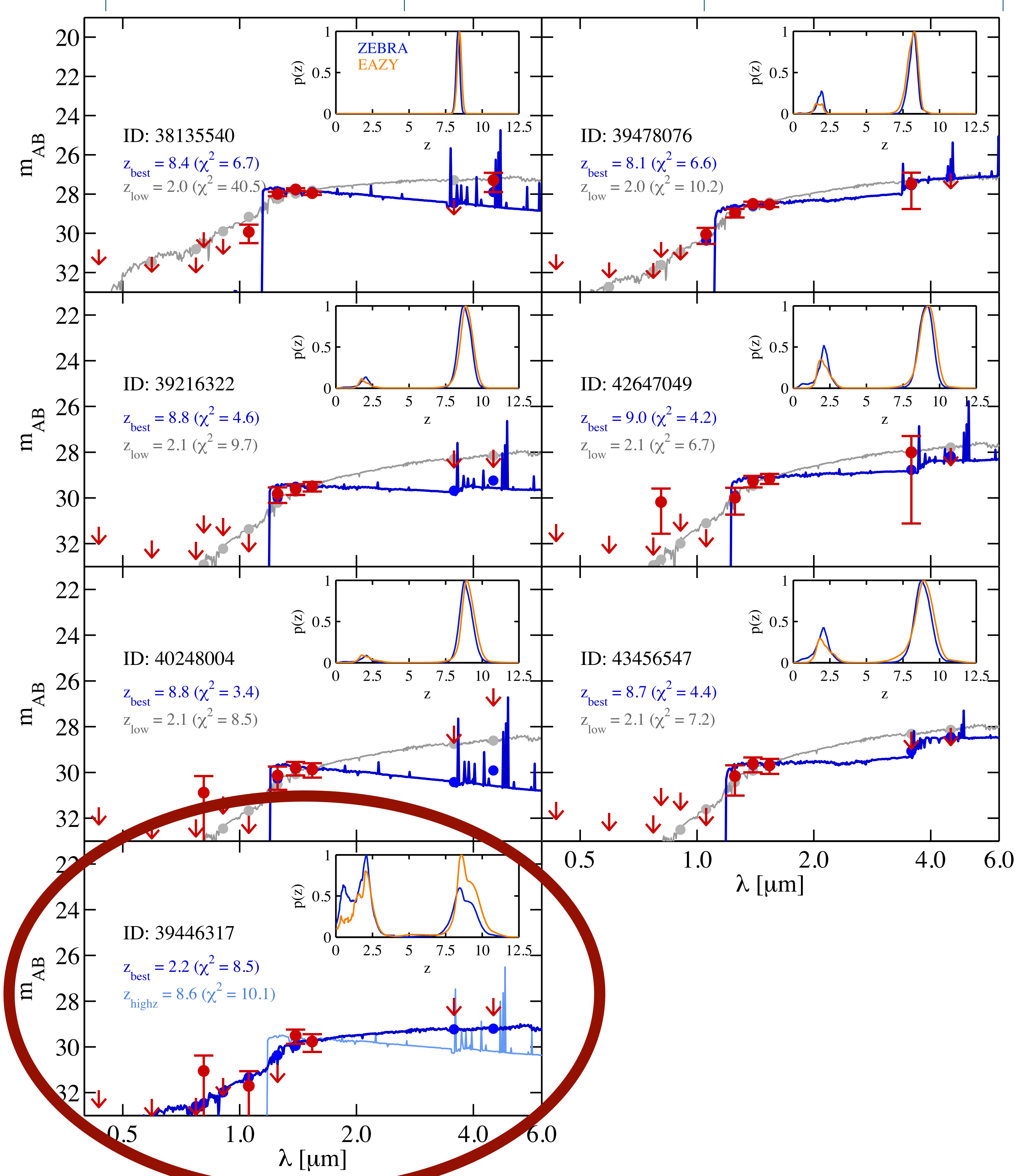
2 photo-z codes: EAZY + ZEBRA

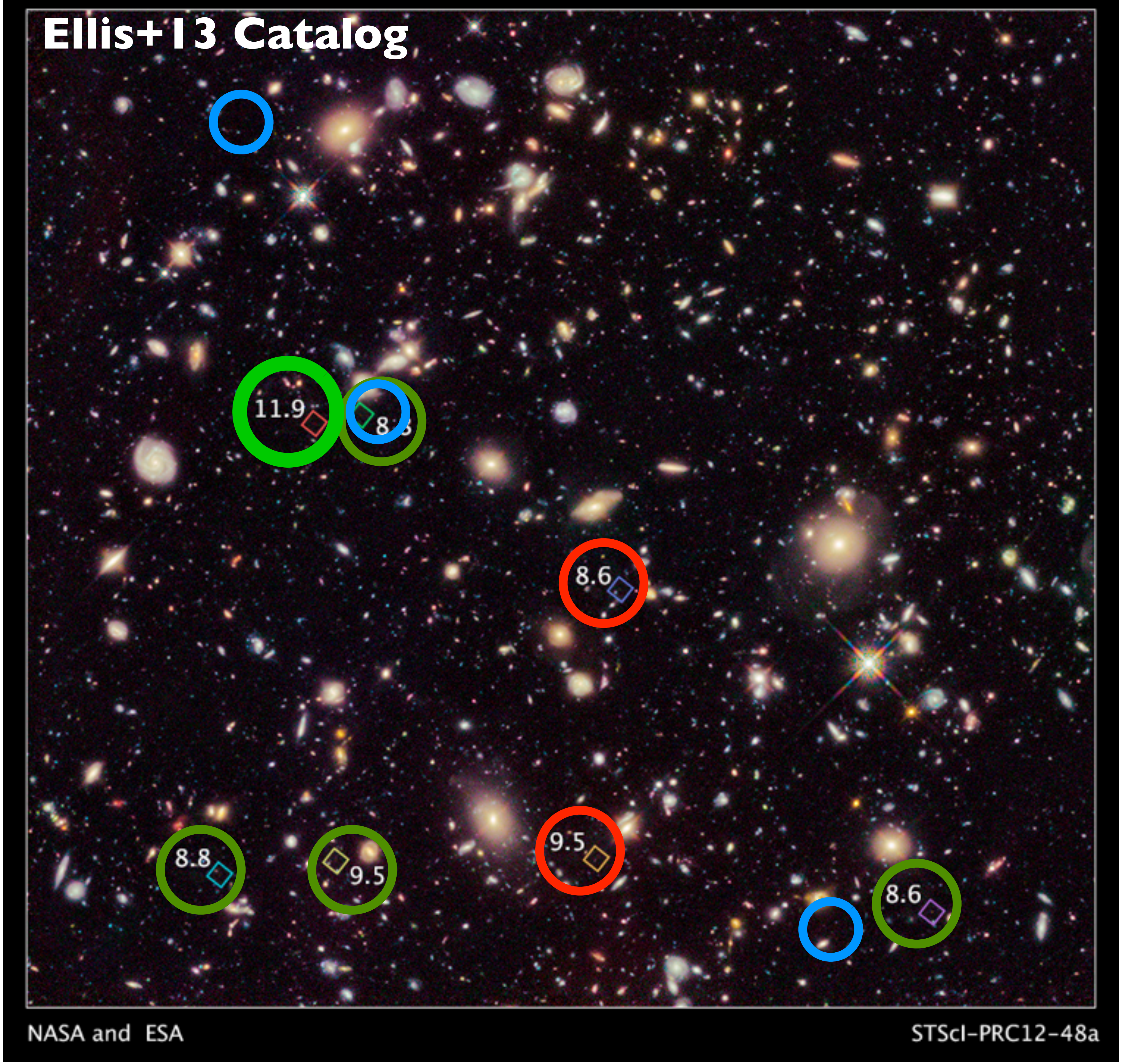
Photometric Redshifts: z~8.1-9.0

All sources have secondary peak in their p(z)

Statistically expect one source to be a low-redshift contaminant.

i.e. contamination fraction <15%

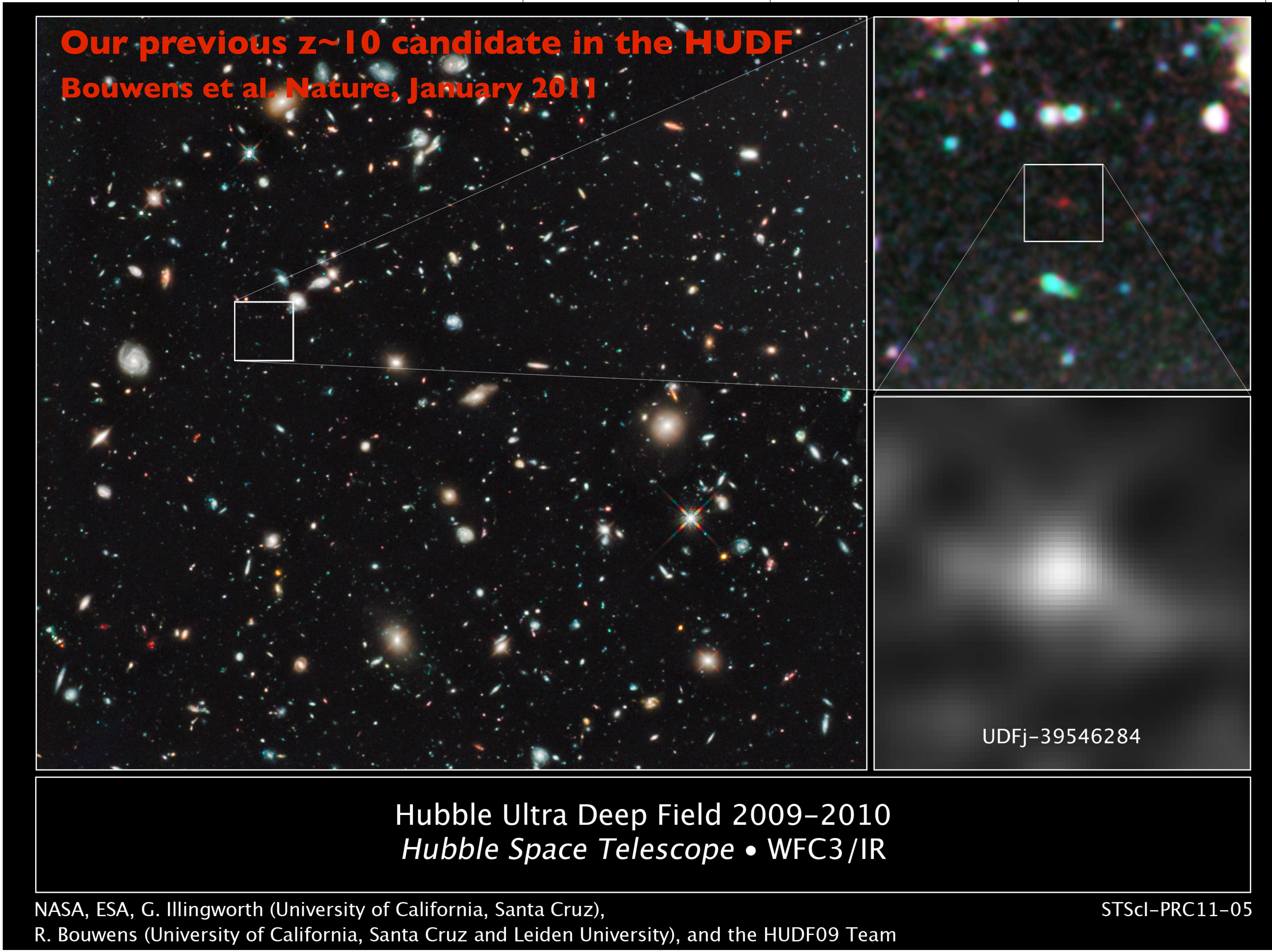




In both samples

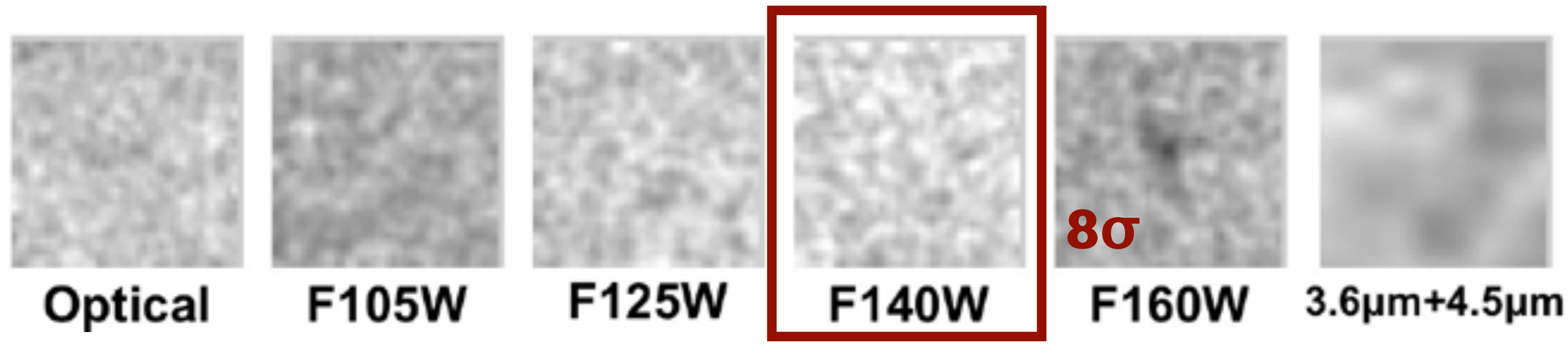
Only in our sample

Not in our sample


Our previous z~10 candidate in the HUDF
Bouwens et al. Nature, January 2011
UDFj-39546284
Hubble Ultra Deep Field 2009-2010
Hubble Space Telescope • WFC3/IR
NASA, ESA, G. Illingworth (University of California, Santa Cruz),
R. Bouwens (University of California, Santa Cruz and Leiden University), and the HUDF09 Team
STScI-PRC11-05

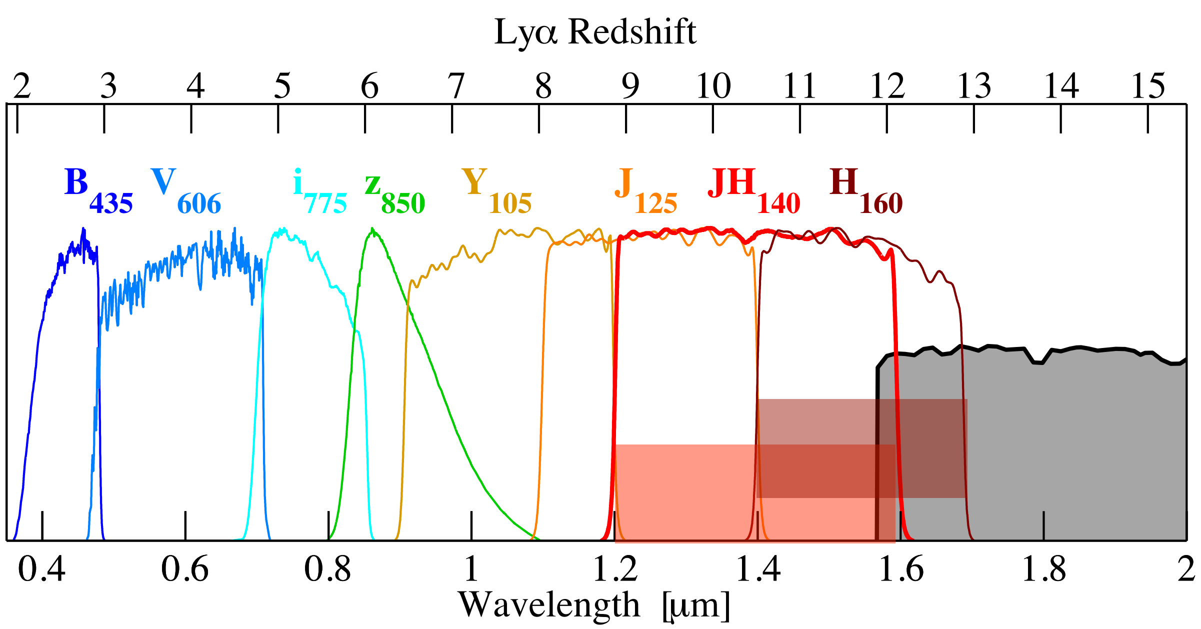
Nature of UDFj-39546284?

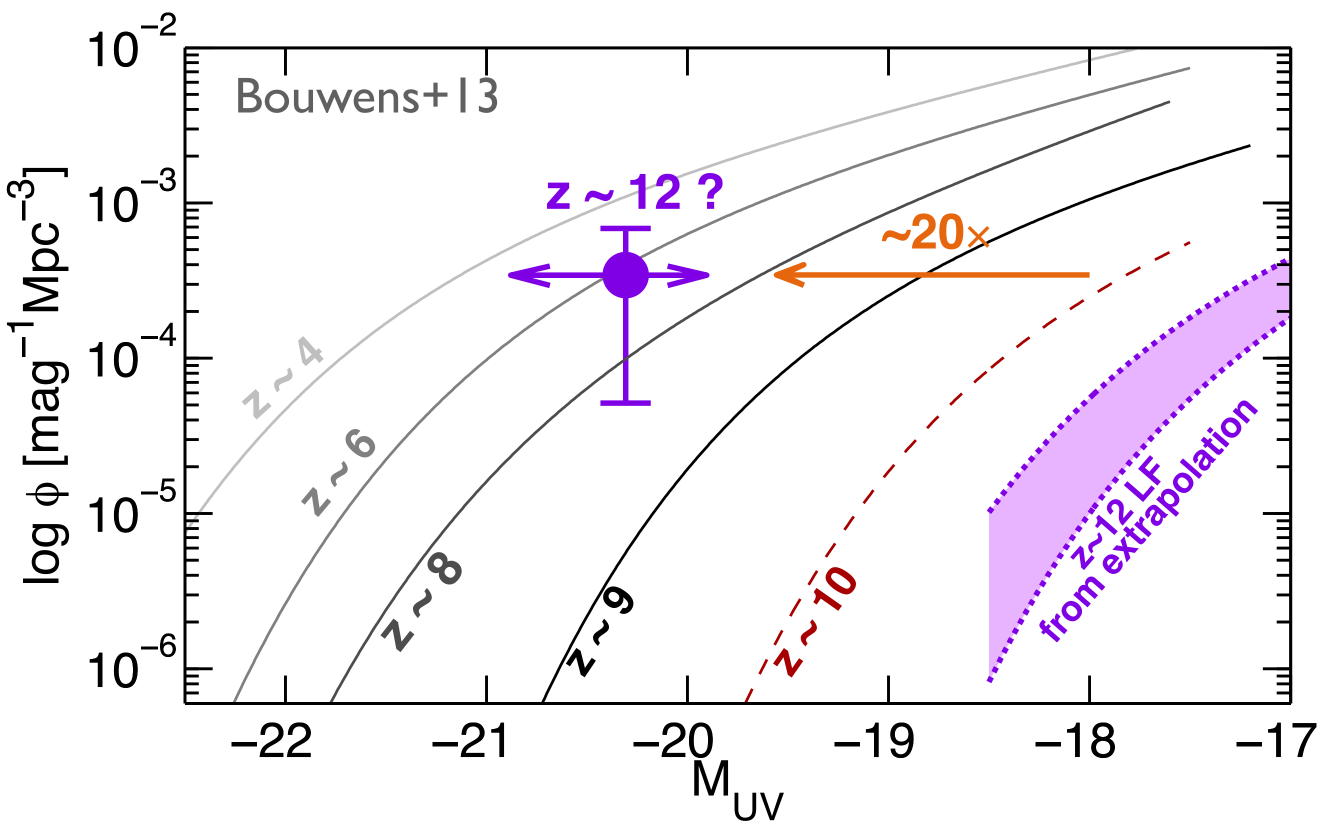
Our previous z~10 source



The source can not be at z~10!

It must have a strong break **or** a strong emission line at 1.6 micron, i.e. either at z~12 or z~2.

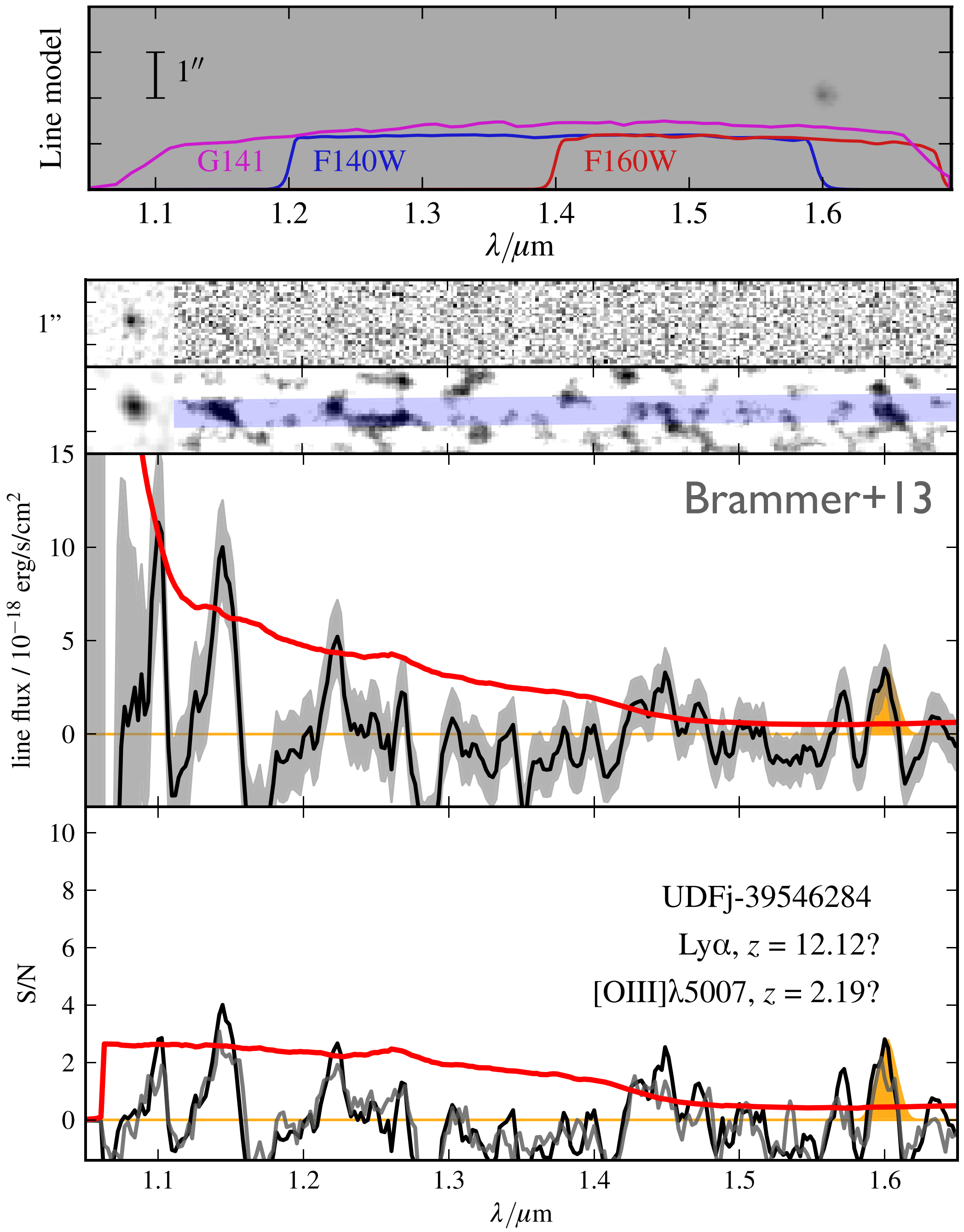


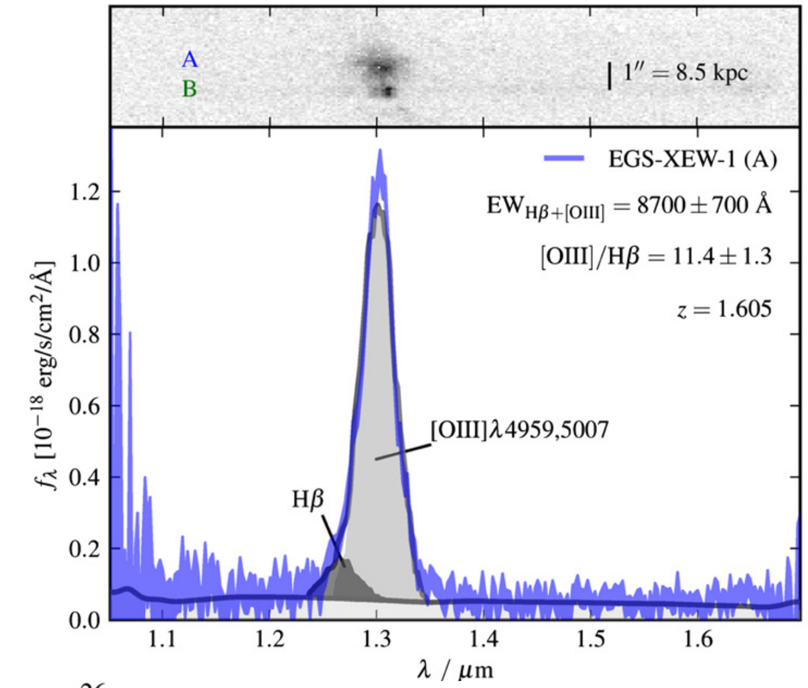


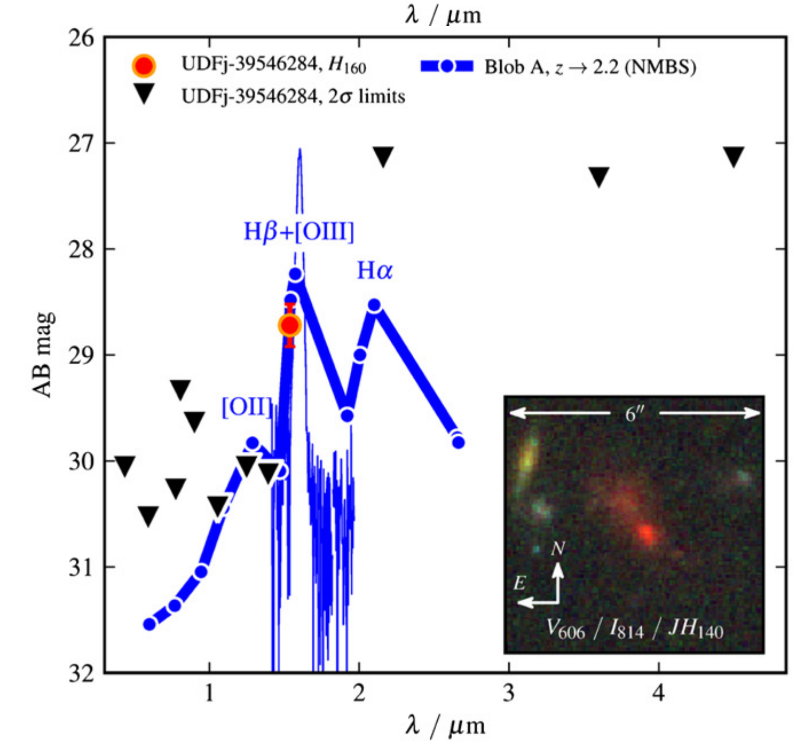
If this source was at z~11.8, its luminosity would be 10-20x brighter than expected.

But: need extreme emission lines to explain a low-z solution (see possible example in Brammer+13)

Nature of UDFj-39546284 - Clues from 3D-HST







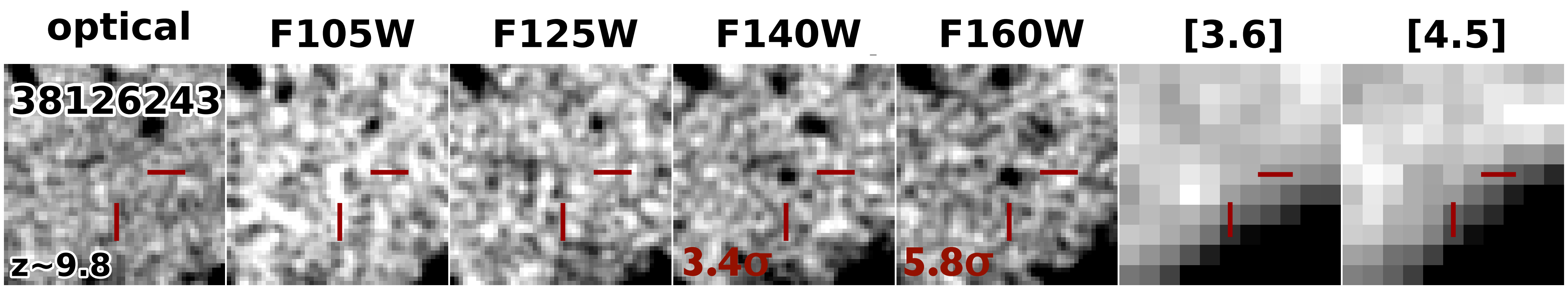
Tentative line detected in grism spectroscopy + MOSFIRE (Capak+13).
However, also such strong line emitters are extremely rare.

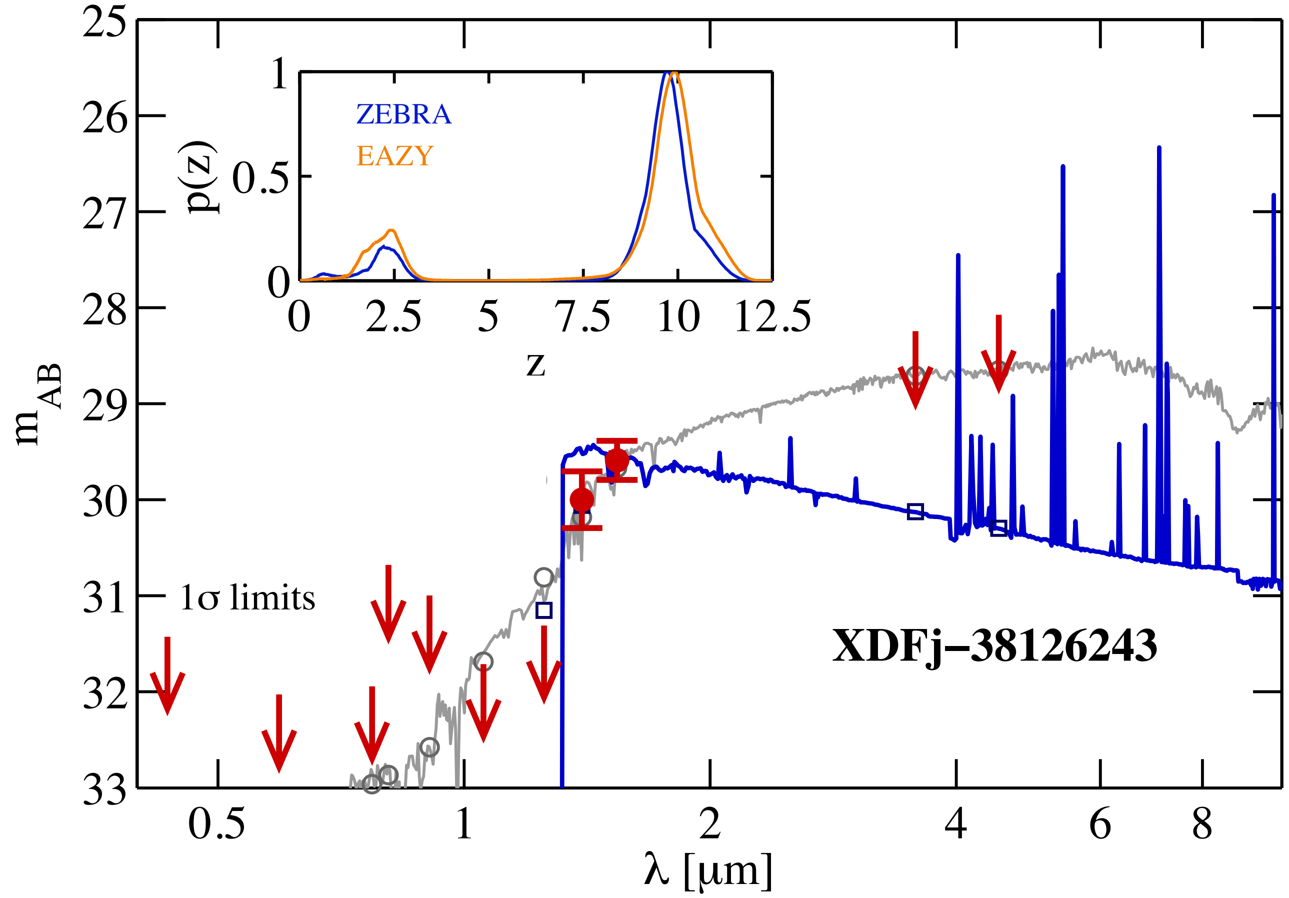
We will treat this source as an upper limit in the SFRD at z~11-12.

HUDF12+HUDF09+GOODS-S z~10 Sample

The z~10 selection can be applied to all the data around GOODS-S (J-H>1.2). We confirm one of our initial sources to be a high-quality z~10 candidate.

The only z~10 source



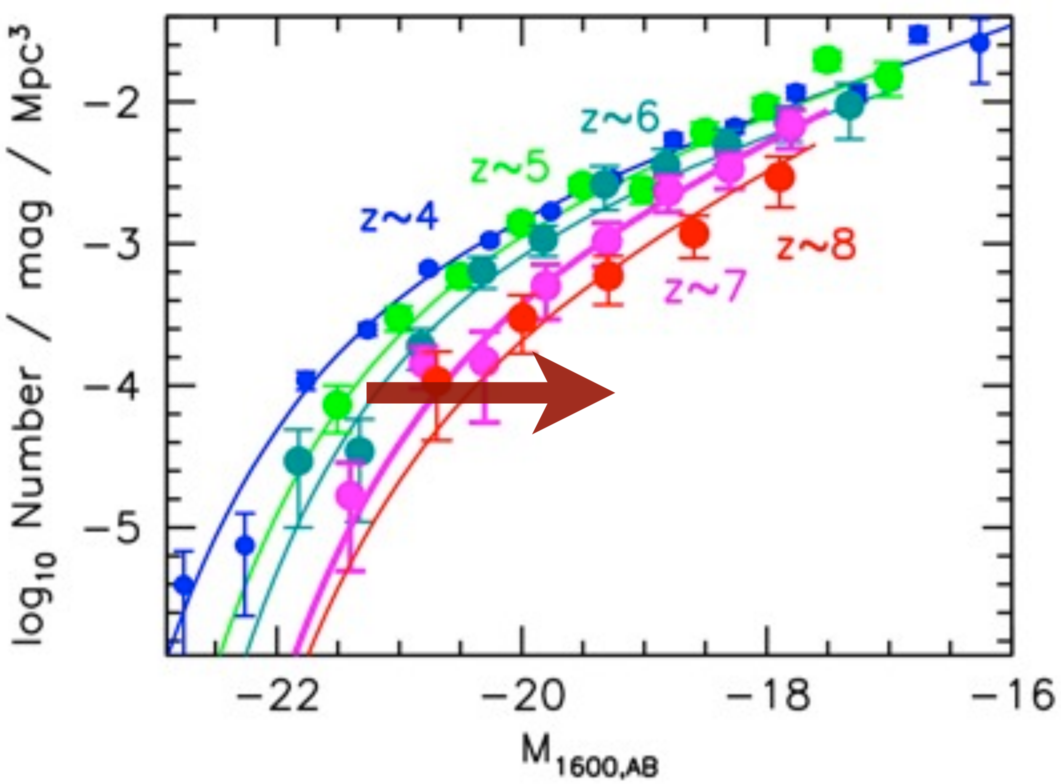


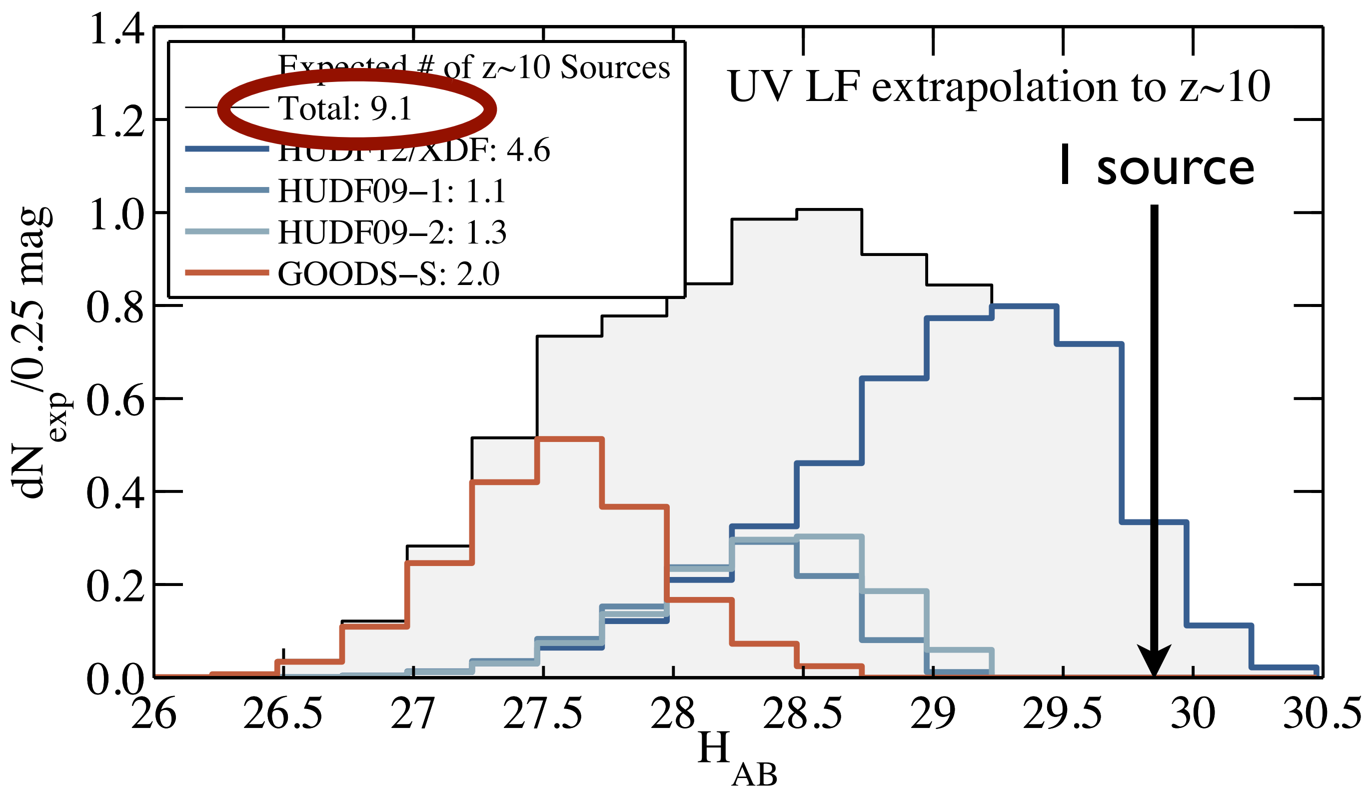
The source is definitely real. It is detected at >3σ in several independent subsets of the data (H-Epoch1, H-Epoch3, and JH)

It is has S/H = 3.4 and 5.8 in JH_{140} and H_{160}.

It has H_{AB}=29.8 mag and a photometric redshift of z_{phot} = 9.8±0.6

Expectation from Smoothly Evolving LF to z>8

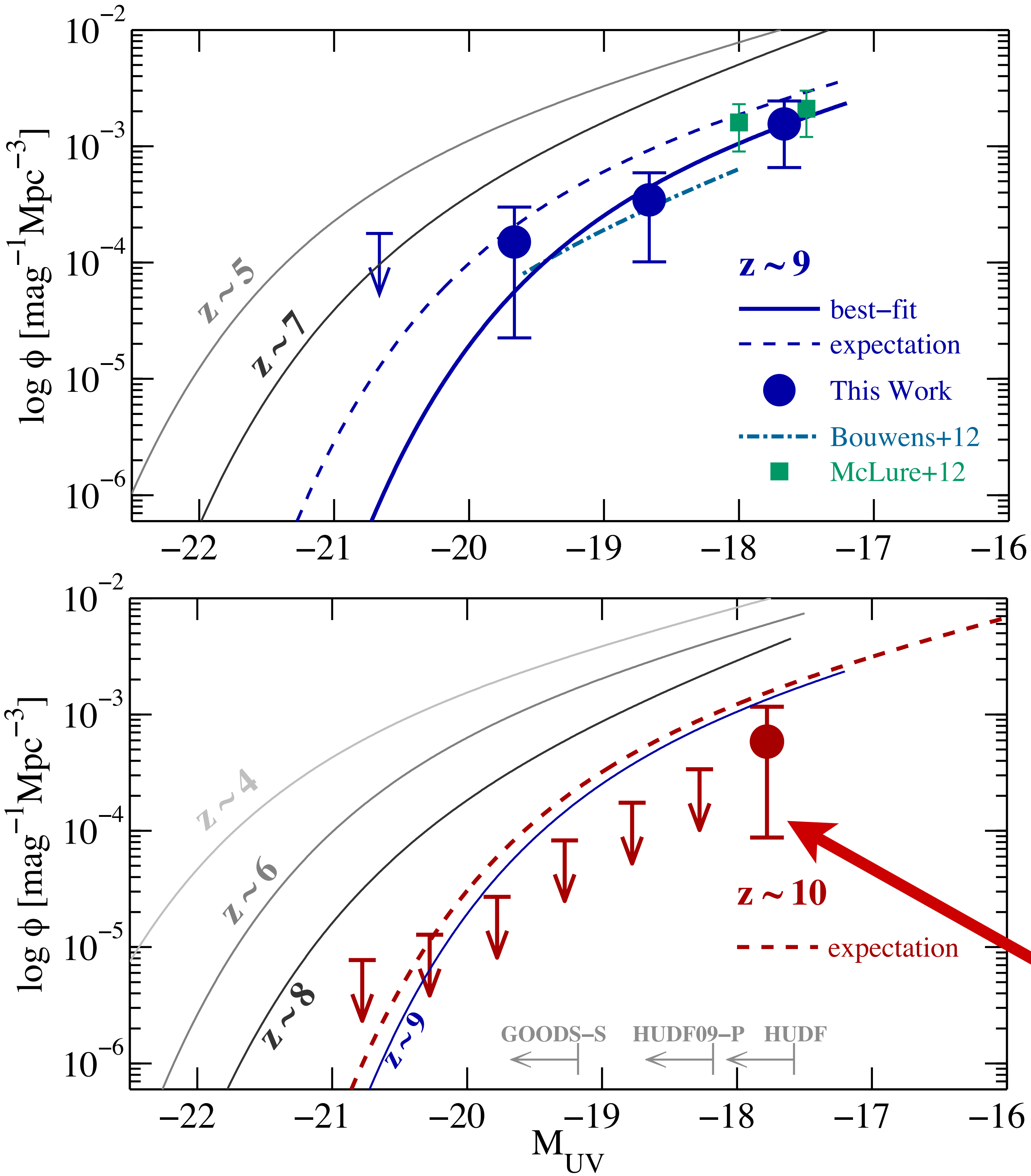




If LF evolution was constant across z~4 to z~10, we should have seen **9 z~10 sources** in our data. But, we find only 1. The chance of that happening is only 0.5%.

Therefore, galaxy evolution at z>8 is accelerated.

The z~9 and z~10 UV LF Constraints



First Constraints at z~9:

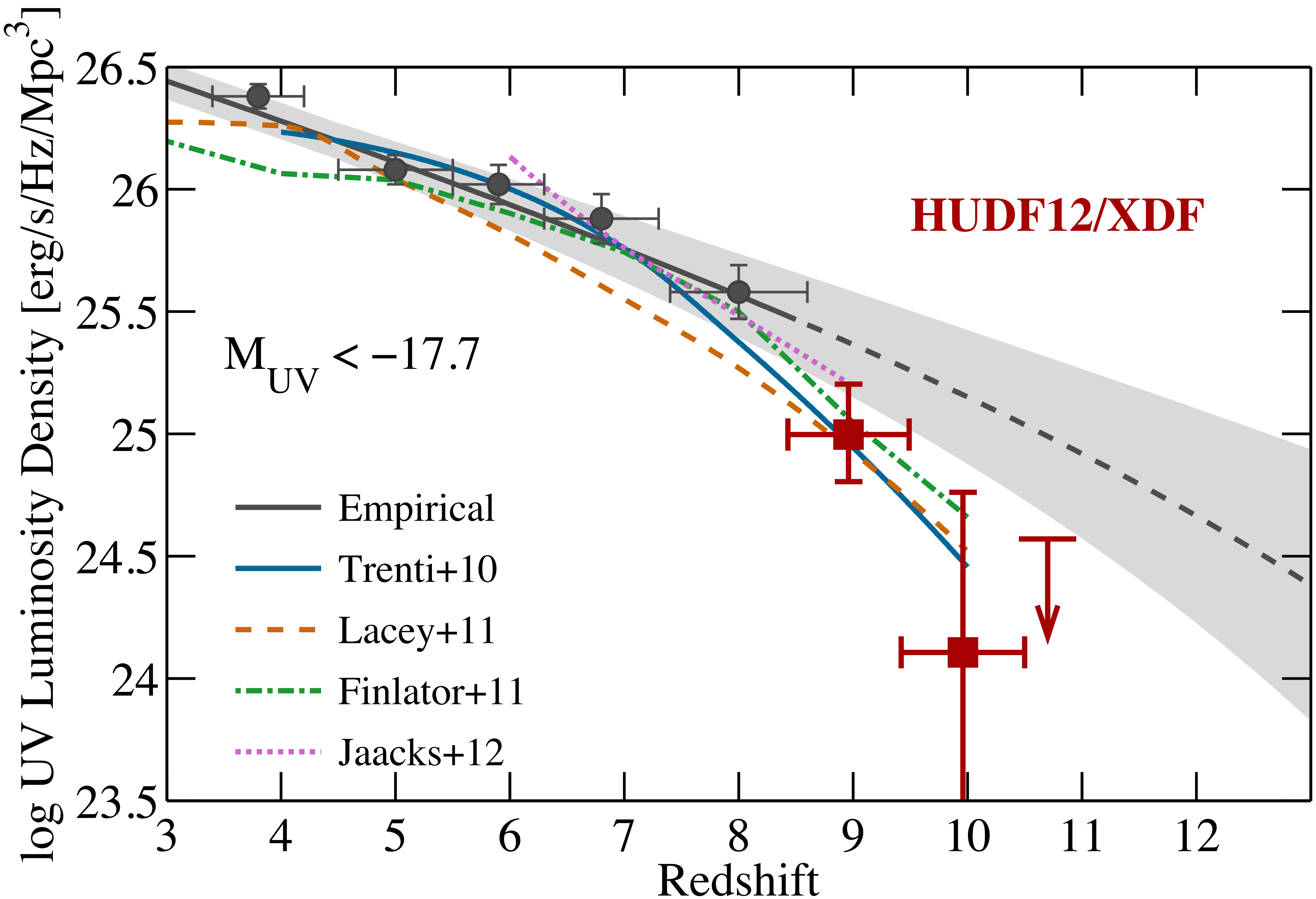
Number of sources is small in each bin, however, all determinations lie systematically below extrapolation of low-z trends.

z~10 Sample only contains one source: mostly only upper limits.

Three HUDF09/12 Fields:

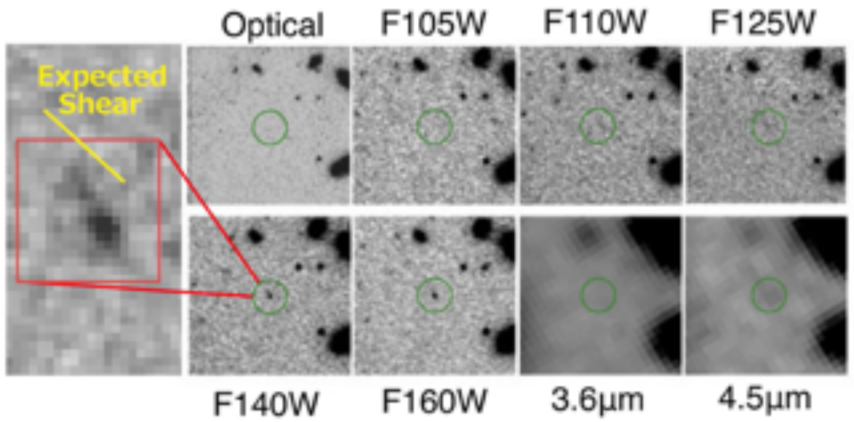
z~10 limits are below extrapolation

Accelerated Evolution is Expected from Models

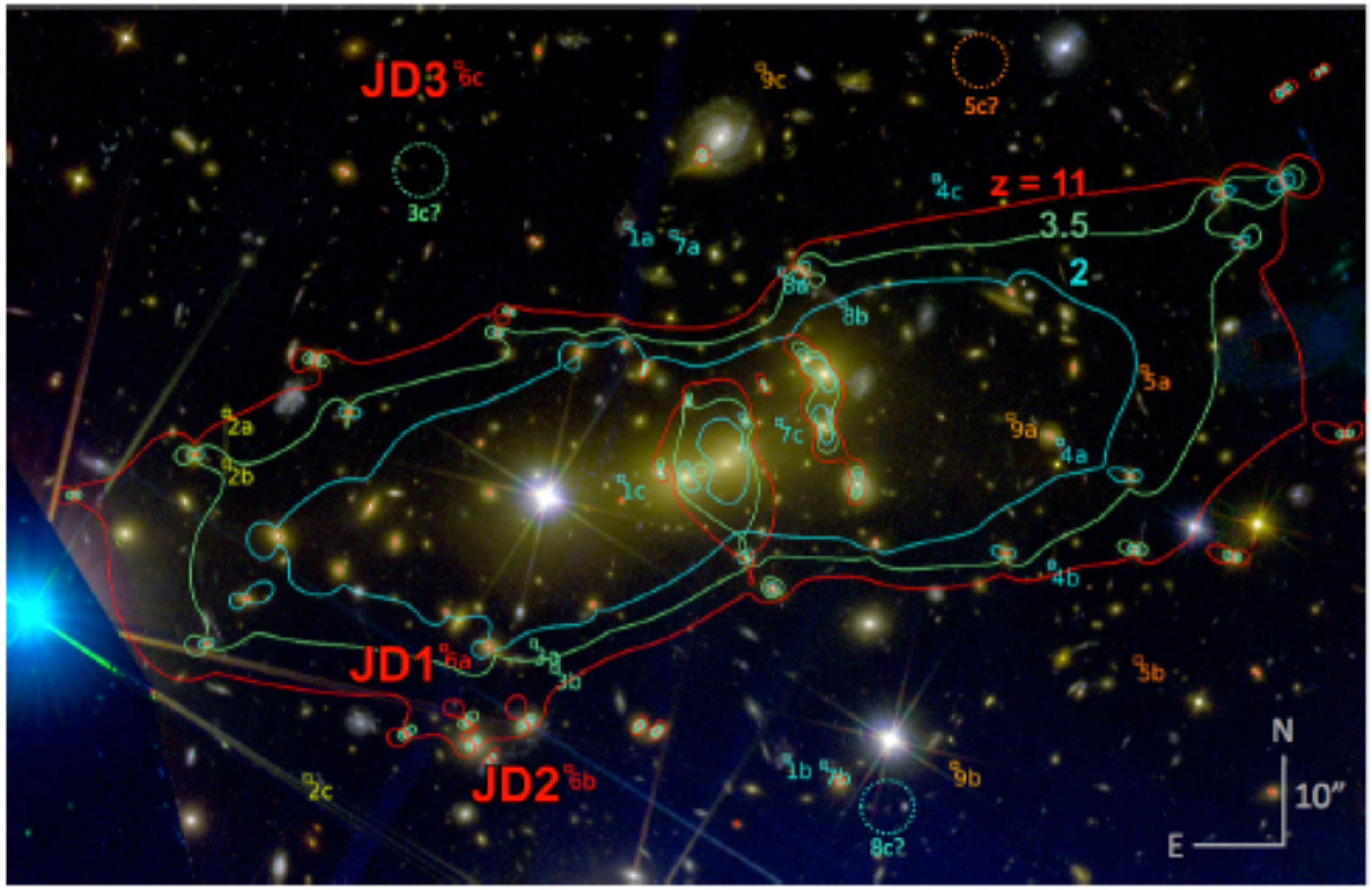


Accelerated evolution is in agreement with theoretical models.
Major driver is most likely the underlying DM halo MF.

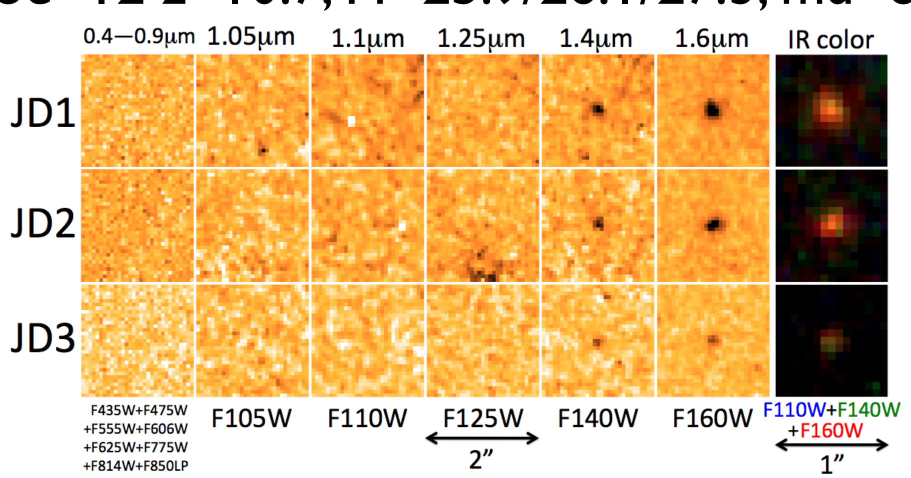
Two Additional z~10 Candidates from CLASH

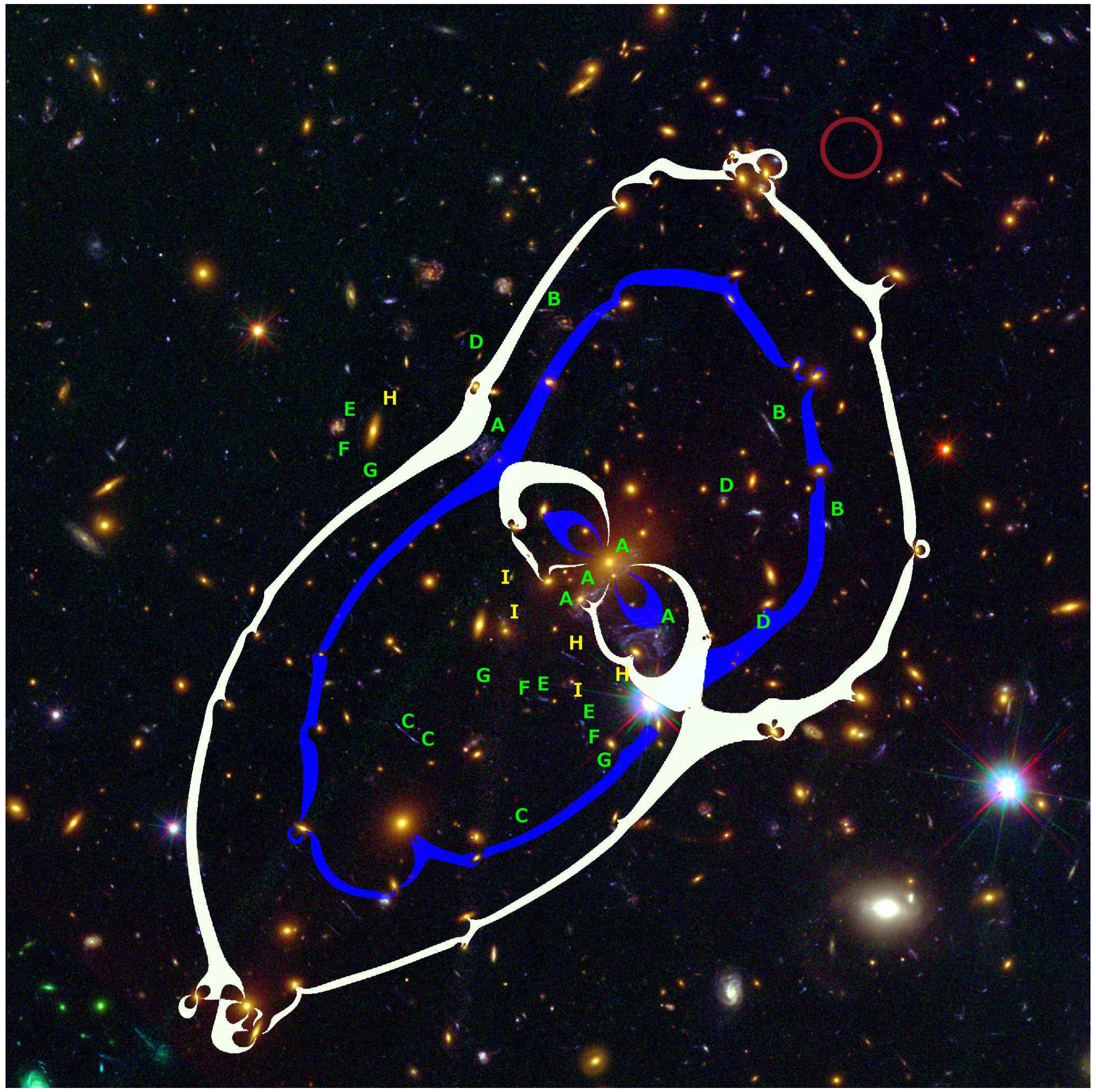


Zheng+12 z=9.6, H=25.7, mu=14-26

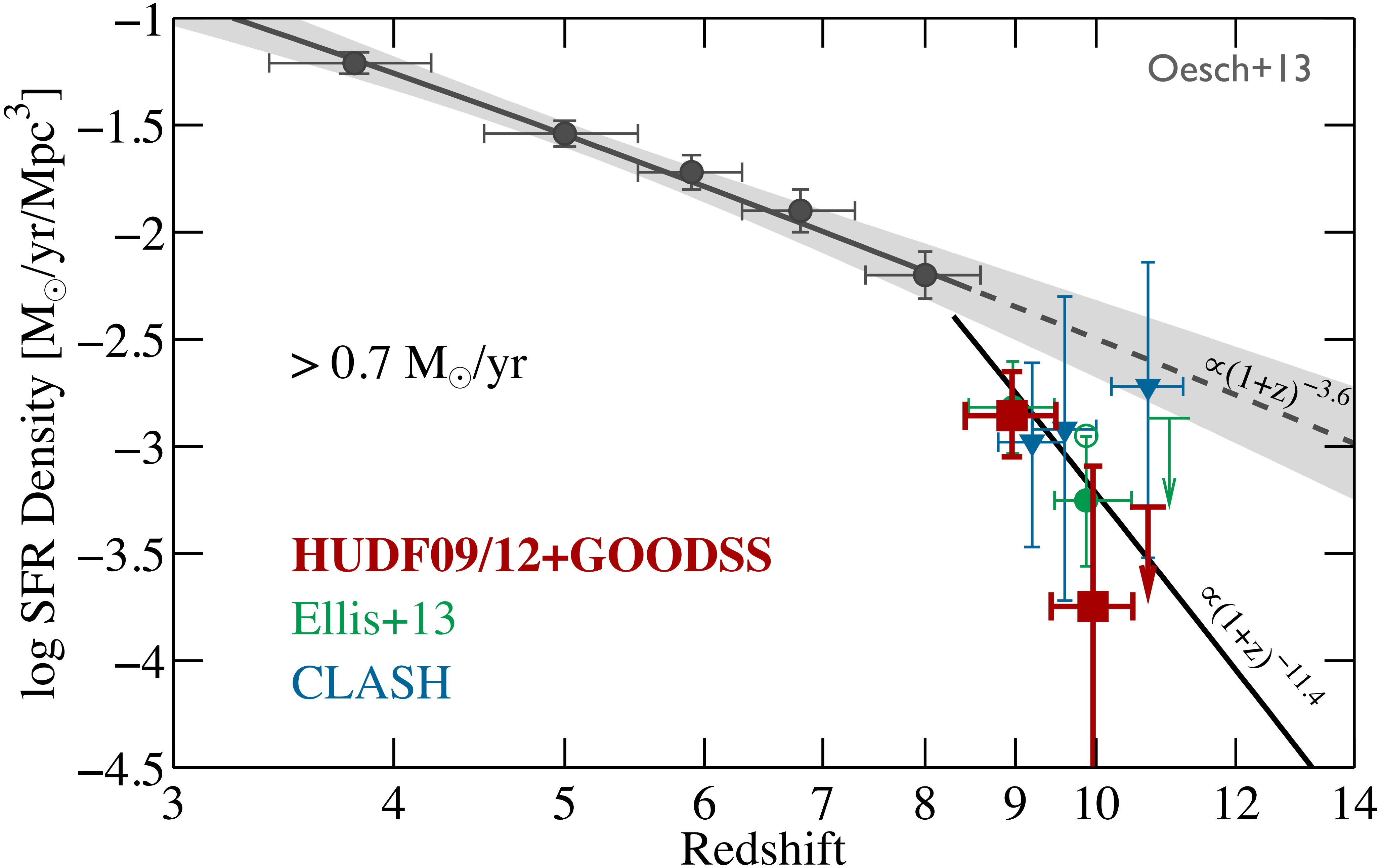


Coe+12 z=10.7, H=25.9/26.1/27.3, mu~8/7/2





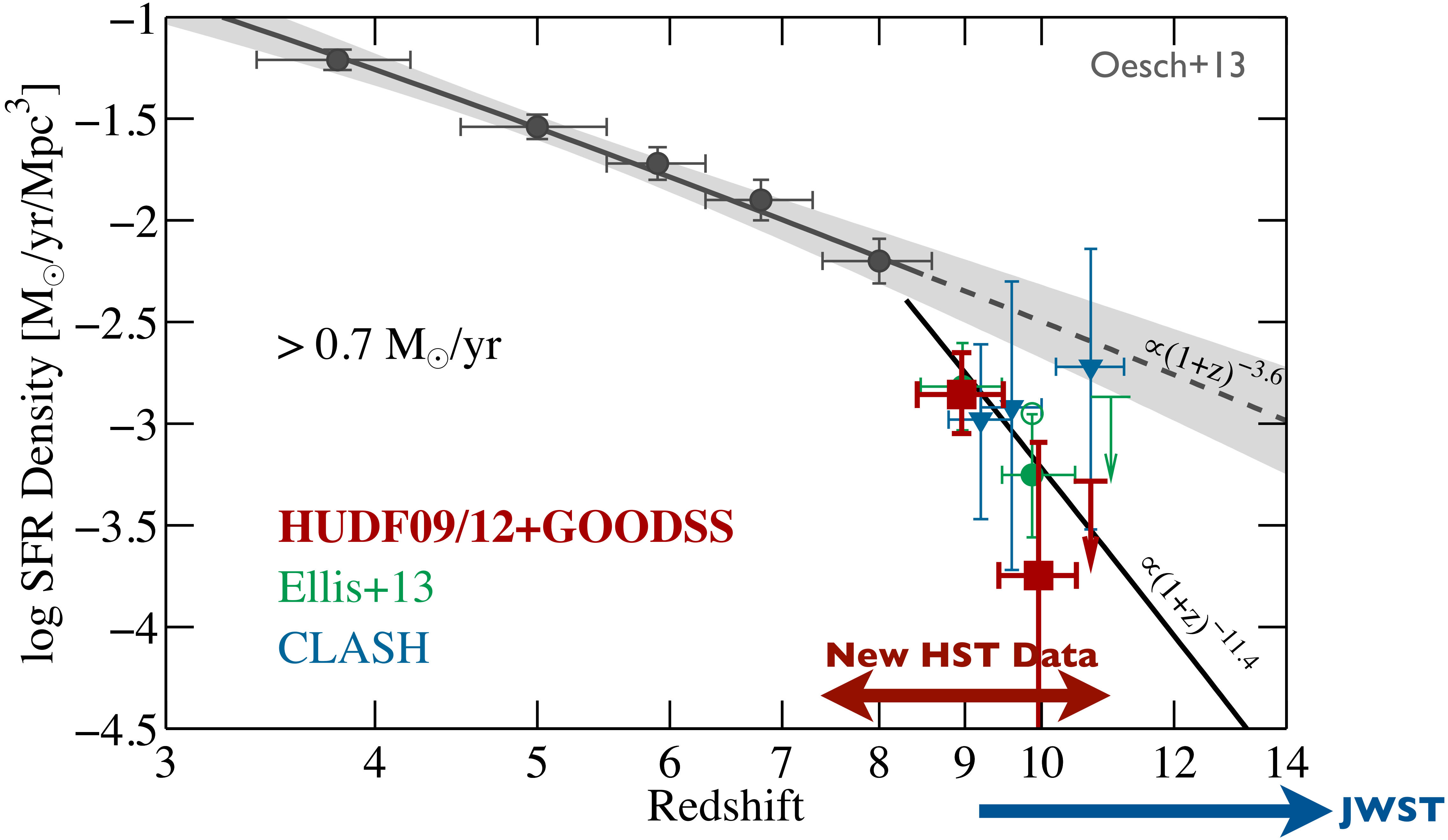
SFRD Evolution at z>8



Combining the constraints from CLASH and HUDF+GOODS-S data, we still find extremely rapid evolution in the cosmic SFRD.

Compare with conclusions from: Zheng+12, Coe+13, Bouwens+13, Ellis+13, McLure+13

SFRD Evolution at z>8



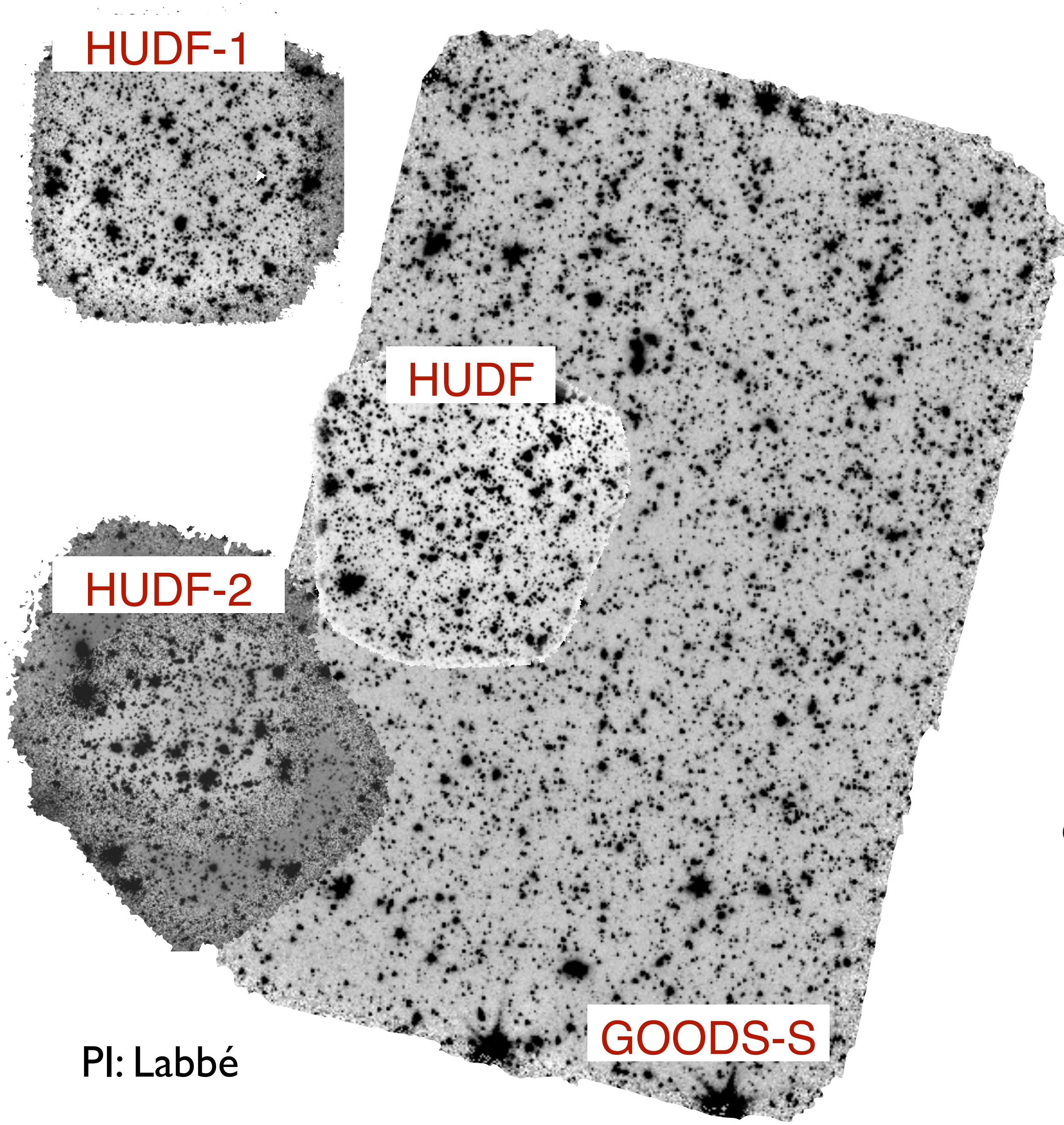
Rapid build-up of SFRD in galaxies within only 170 Myr

But: observational result is still uncertain and needs confirmation with future, deep data, e.g. Frontier Fields, and, at z>=10, JWST!

Using Spitzer IRAC to Constrain Mass-Build up to z~8

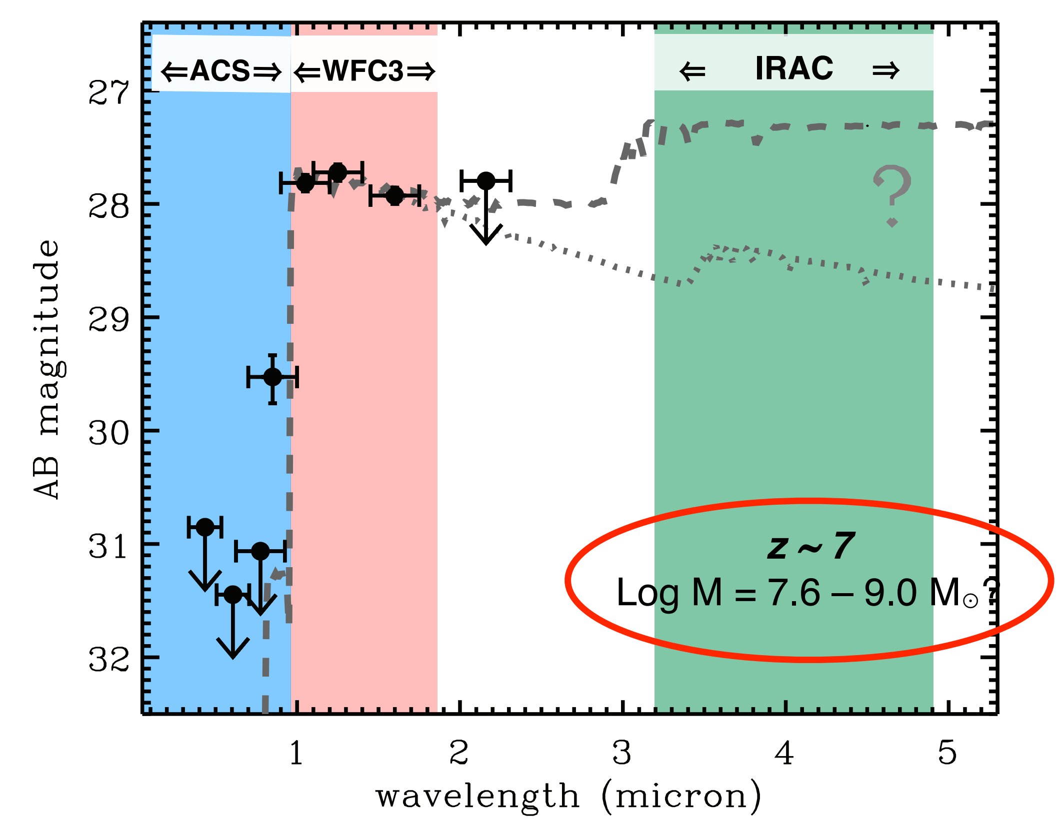
Spitzer IRAC probes rest-frame optical

Ultra-Deep IRAC Data over the HUDF09



PI: Labbé

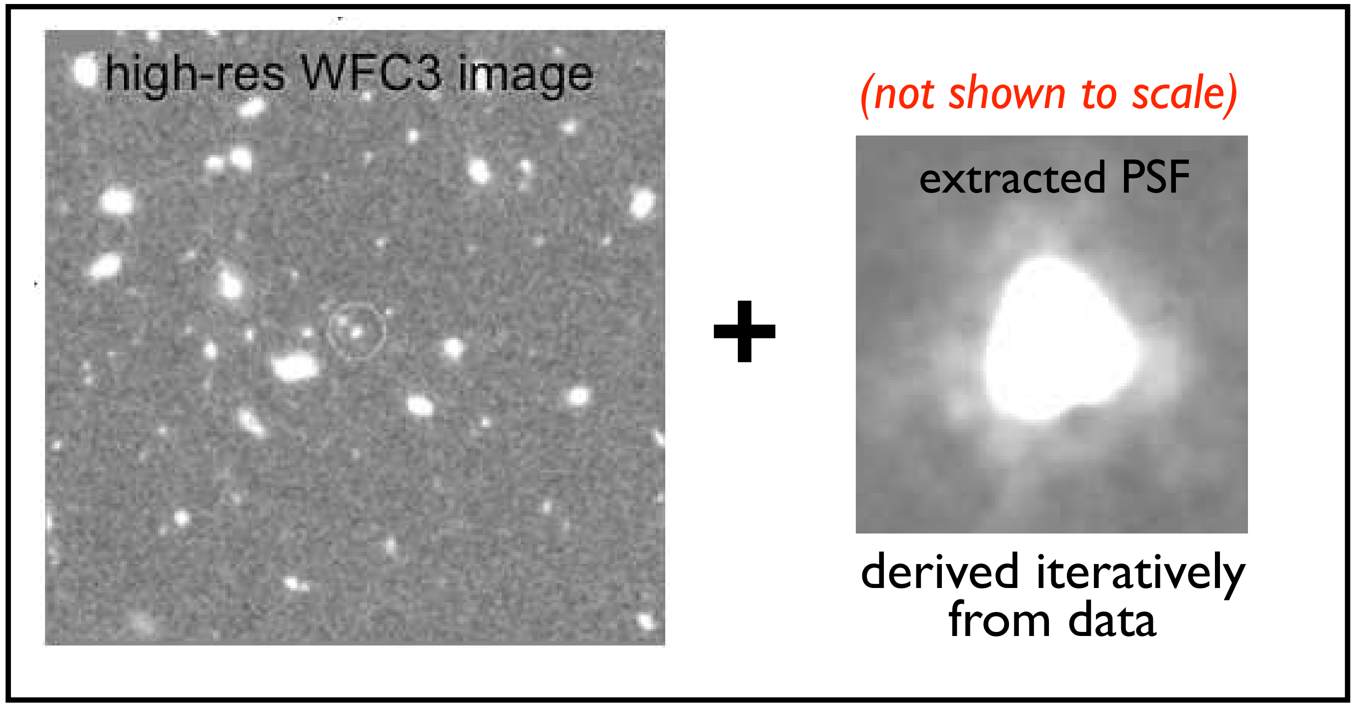
IRAC is crucial for rest-frame optical SEDs and constrains on stellar masses/ages at z>4



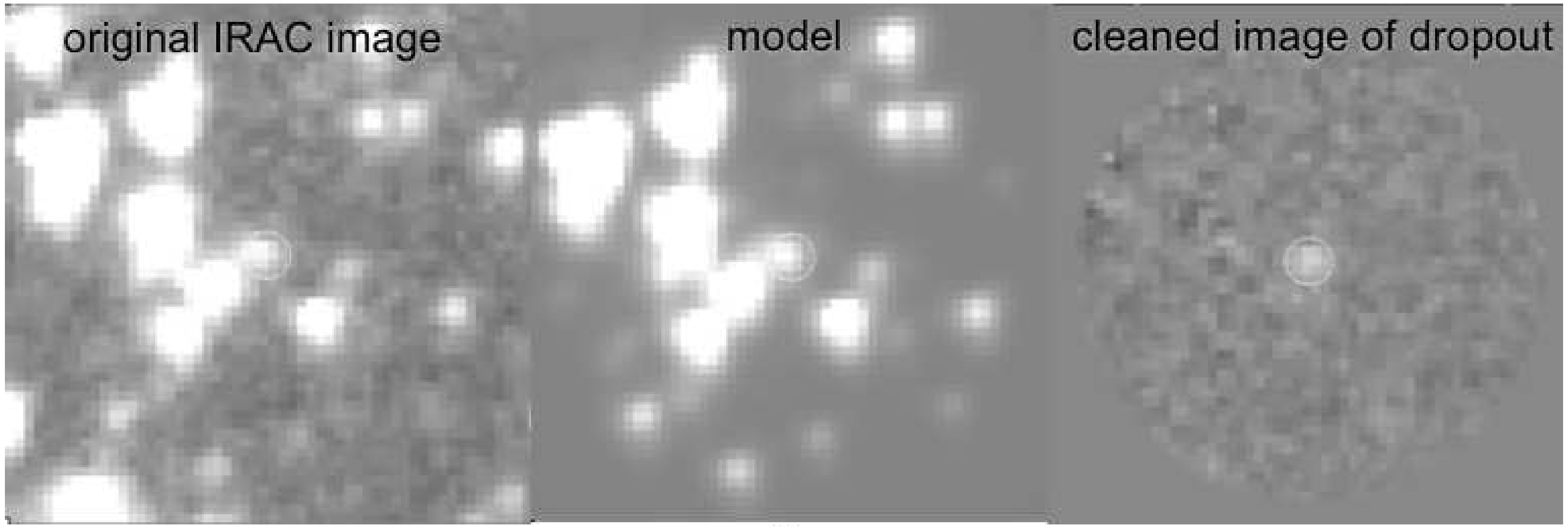
coverage (hours):

FIELD	[3.6]	[4.5]
HUDF	126	126
HUDF-1	52	52
HUDF-2	125	92

Extracting Rest-Frame Optical Photometry



"IVOPHOT"



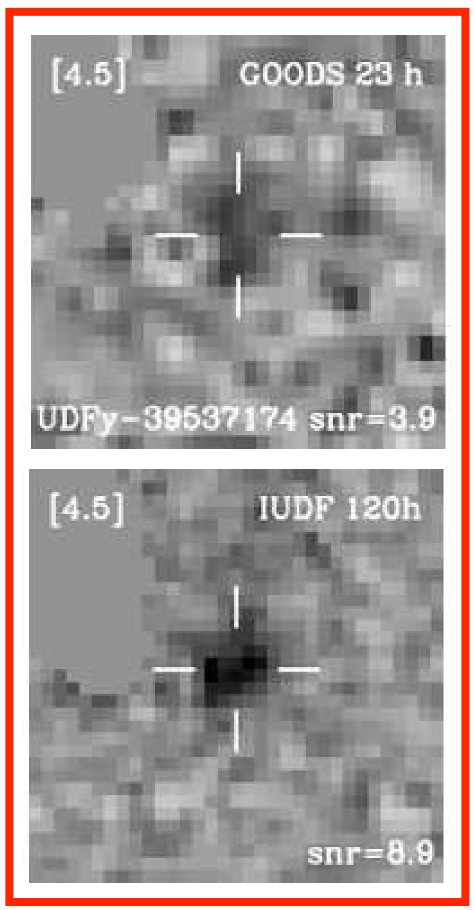
Need to model neighboring sources in a crowded field to extract accurate photometry

Mass Estimates are now possible out to z~8

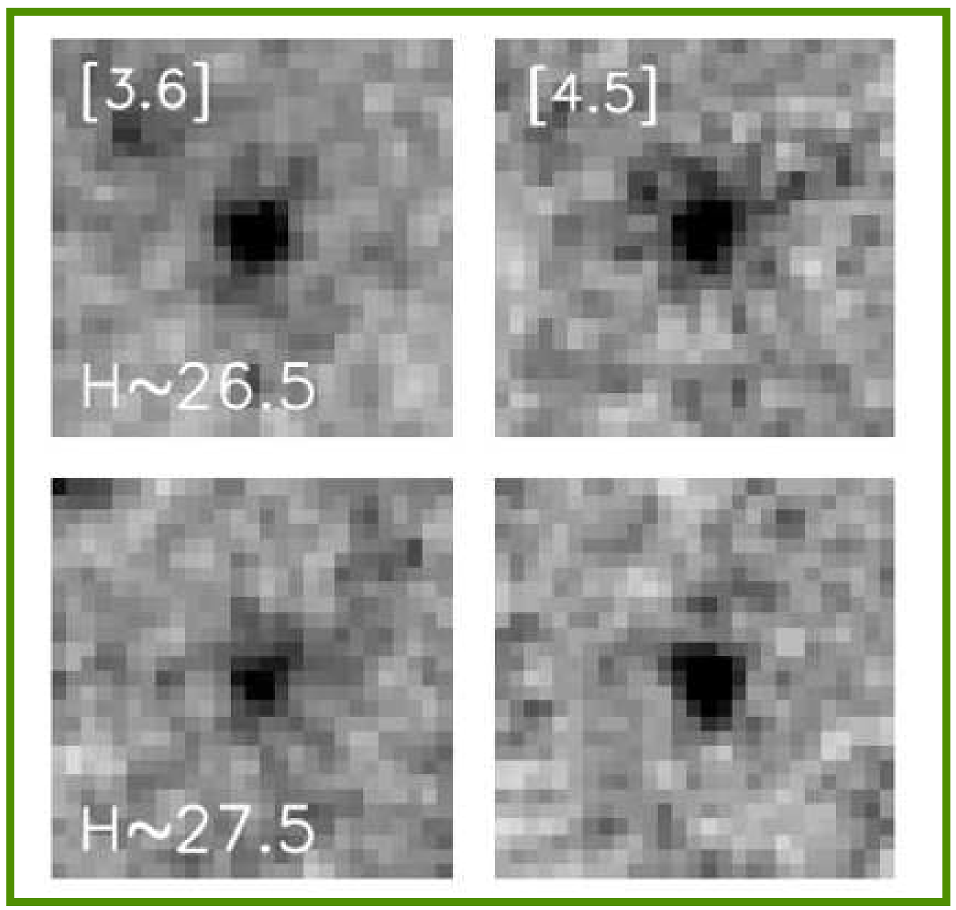
The IUDF10 led to the first robust (>5σ) detections of 9 z~8 candidates (~32% are detected at >3σ).

Median stacked images of 55 Y-dropouts in IUDF10 yield z~8 SED at >L*.

few robust individual detections

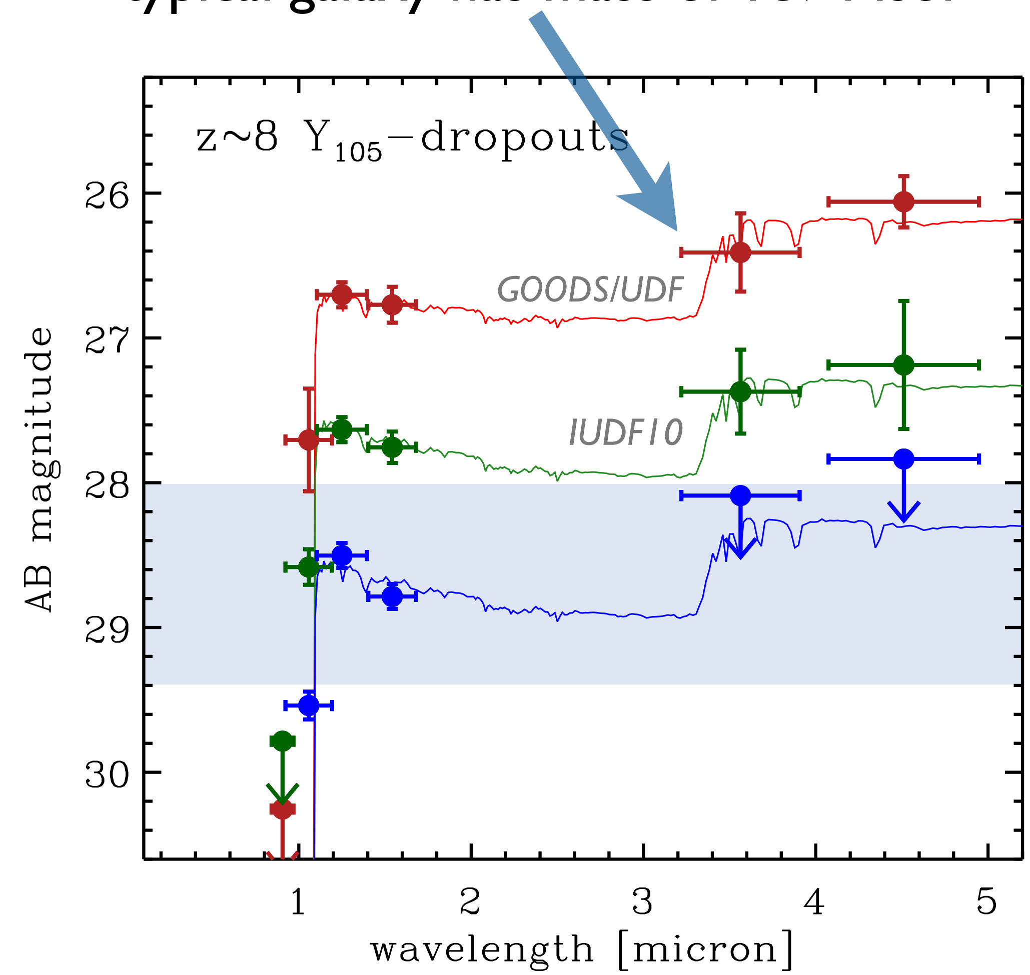


clear detections in stacks



spectral break: indicates ages>~200 Myr, i.e. onset of SF at z>~11

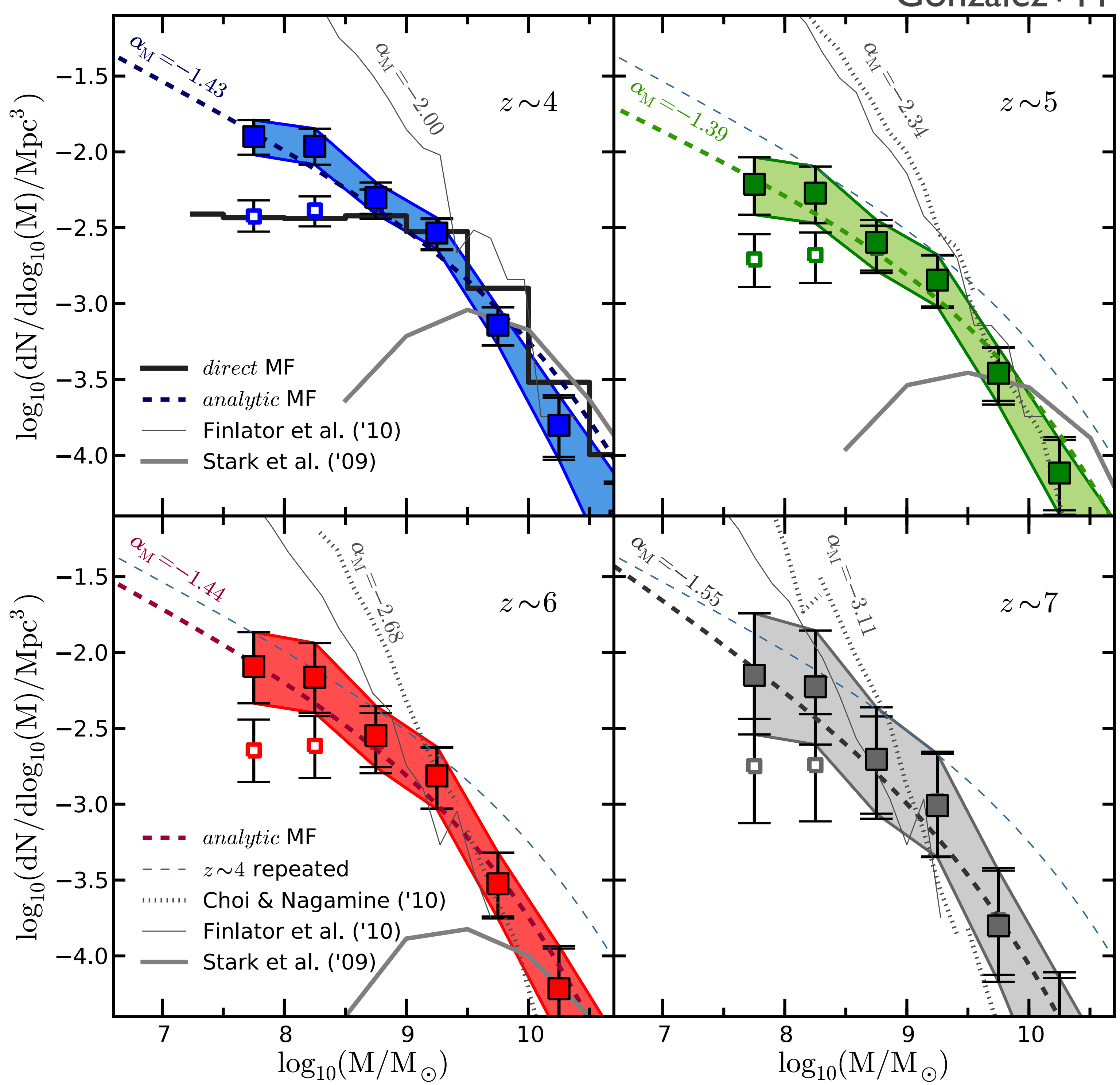
typical galaxy has mass of 1e9 Msol



Labbé, Oesch et al. 2012

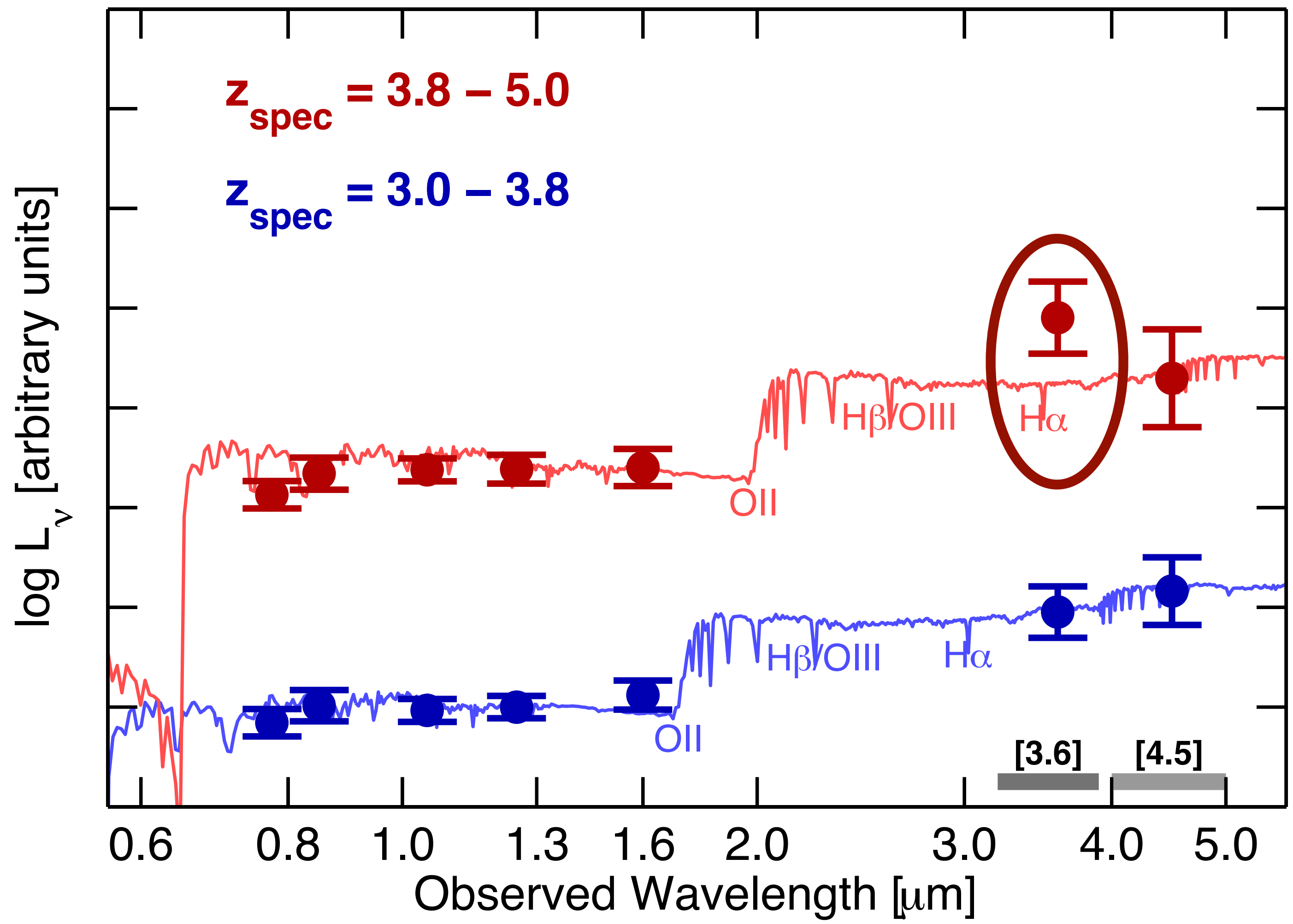
Evolution of the Mass Function

Gonzalez+11



See also: Stark et al. 2009, Lee et al. 2012

Caveat: Strong Emission Lines



on average: 0.3 mag

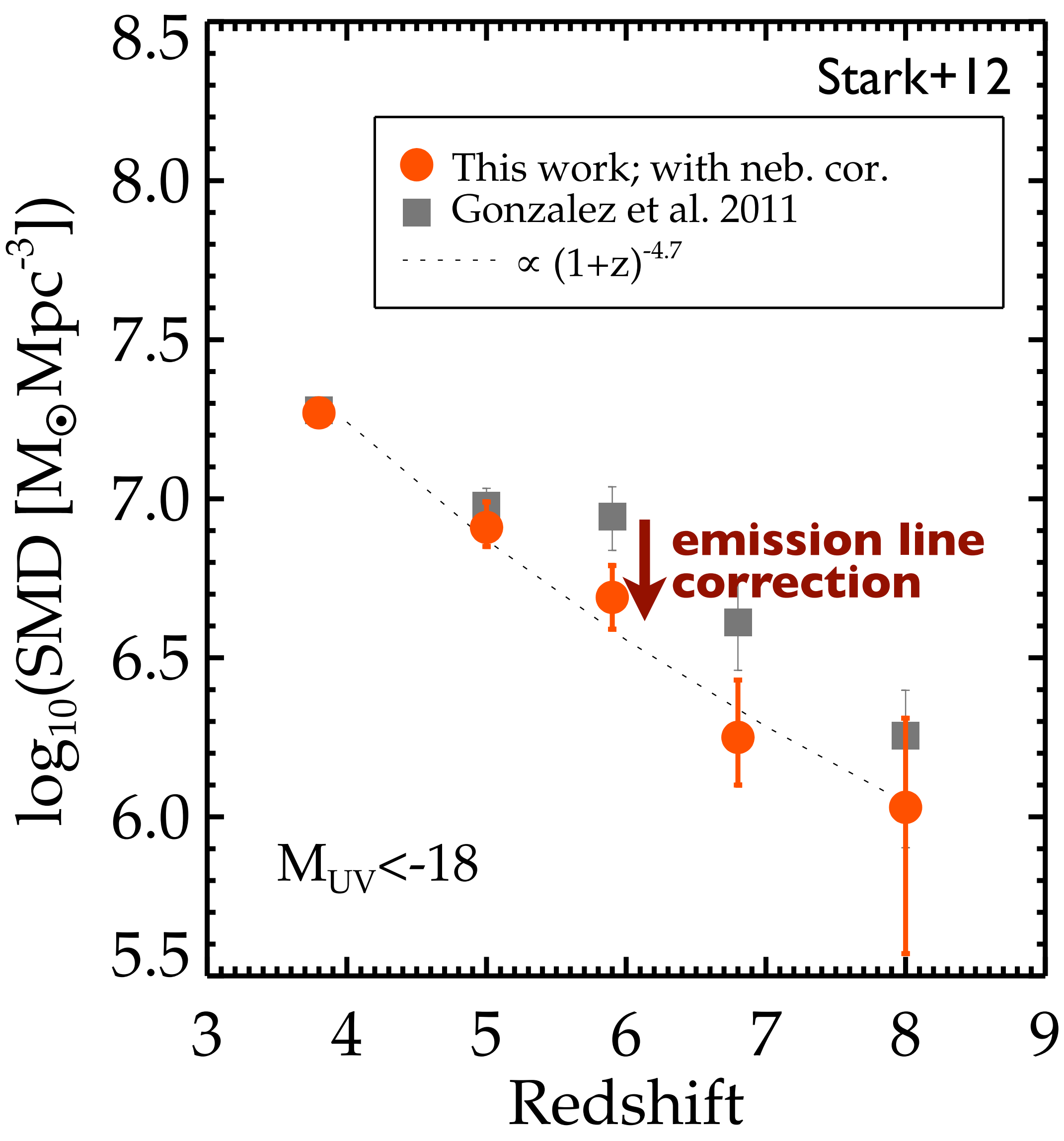
EW(Hα) ≃ 300 Å

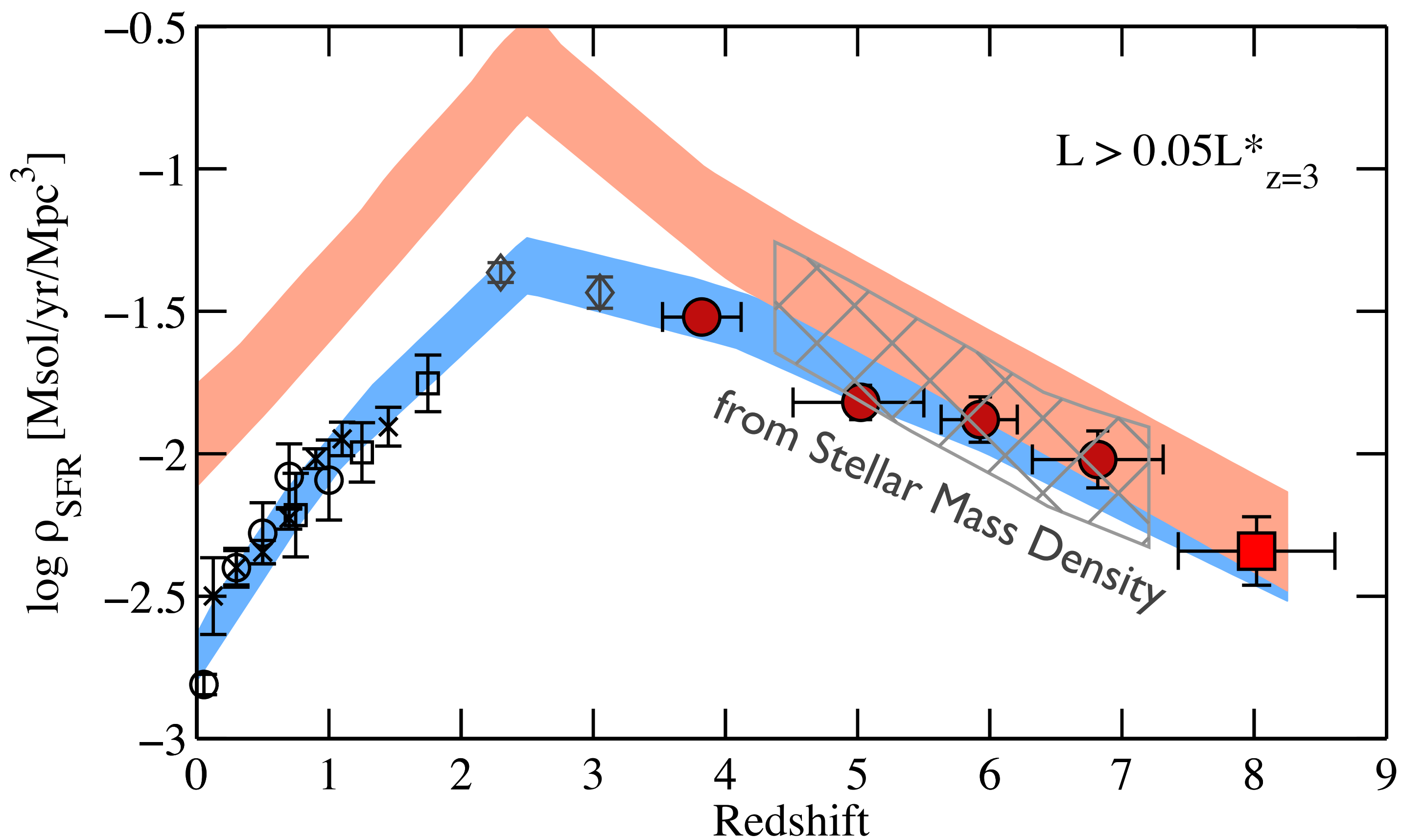
Strong rest-frame optical emission lines can significantly contribute to IRAC flux measurements. These will thus bias mass measurements. Important to estimate the magnitude of this effect.

See e.g. Shim+11, Stark+12, Gonzalez+12

Stellar Mass Density

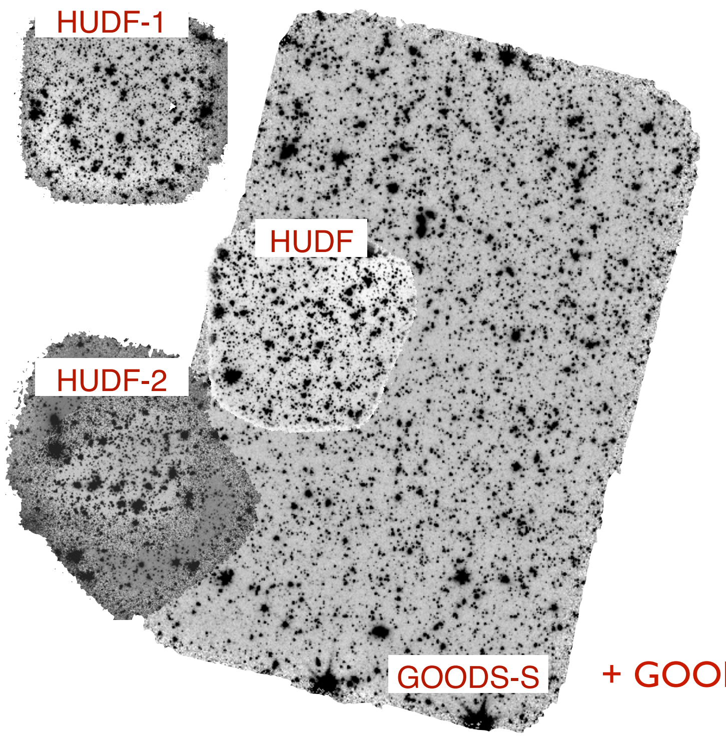
Zero-th order empirical correction for ELs: ➡ up to a factor 2-3x in stellar mass density





SFRD and SMD are in very good agreement (after correcting for line emission)

A Rest-Frame Optical View on z~4 Galaxies



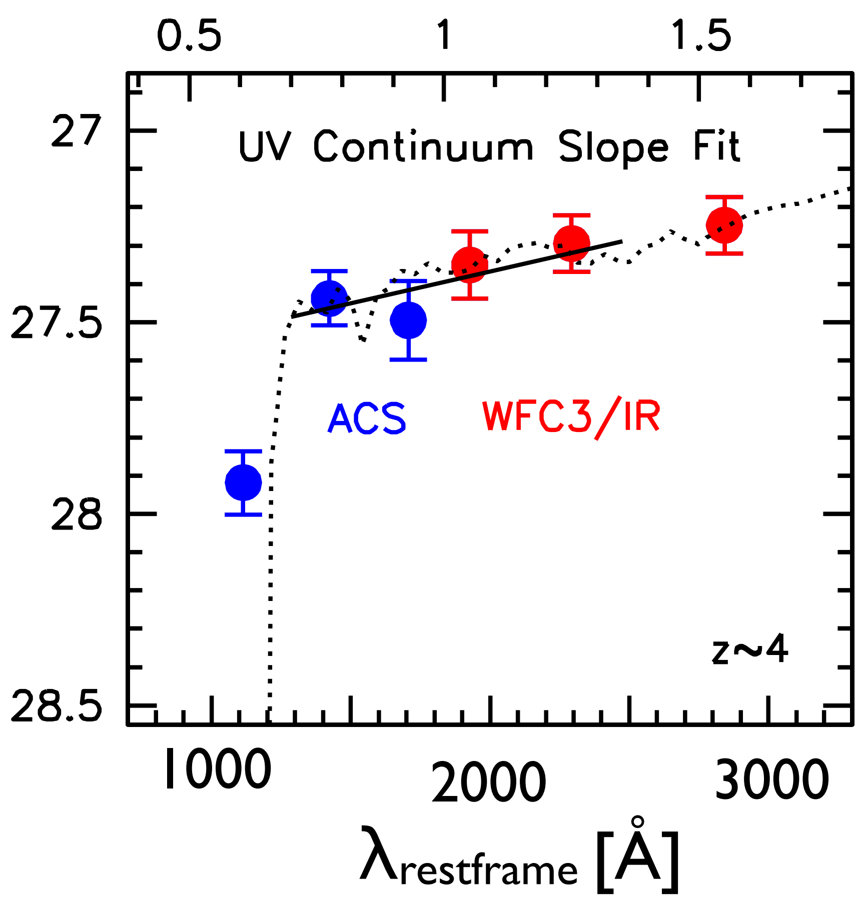
Large samples of galaxies available with deep IRAC coverage:

IUDF program (PI: Labbe) 125 h, S-CANDELS 50h exposures

HST only probes UV: UV Continuum Slopes

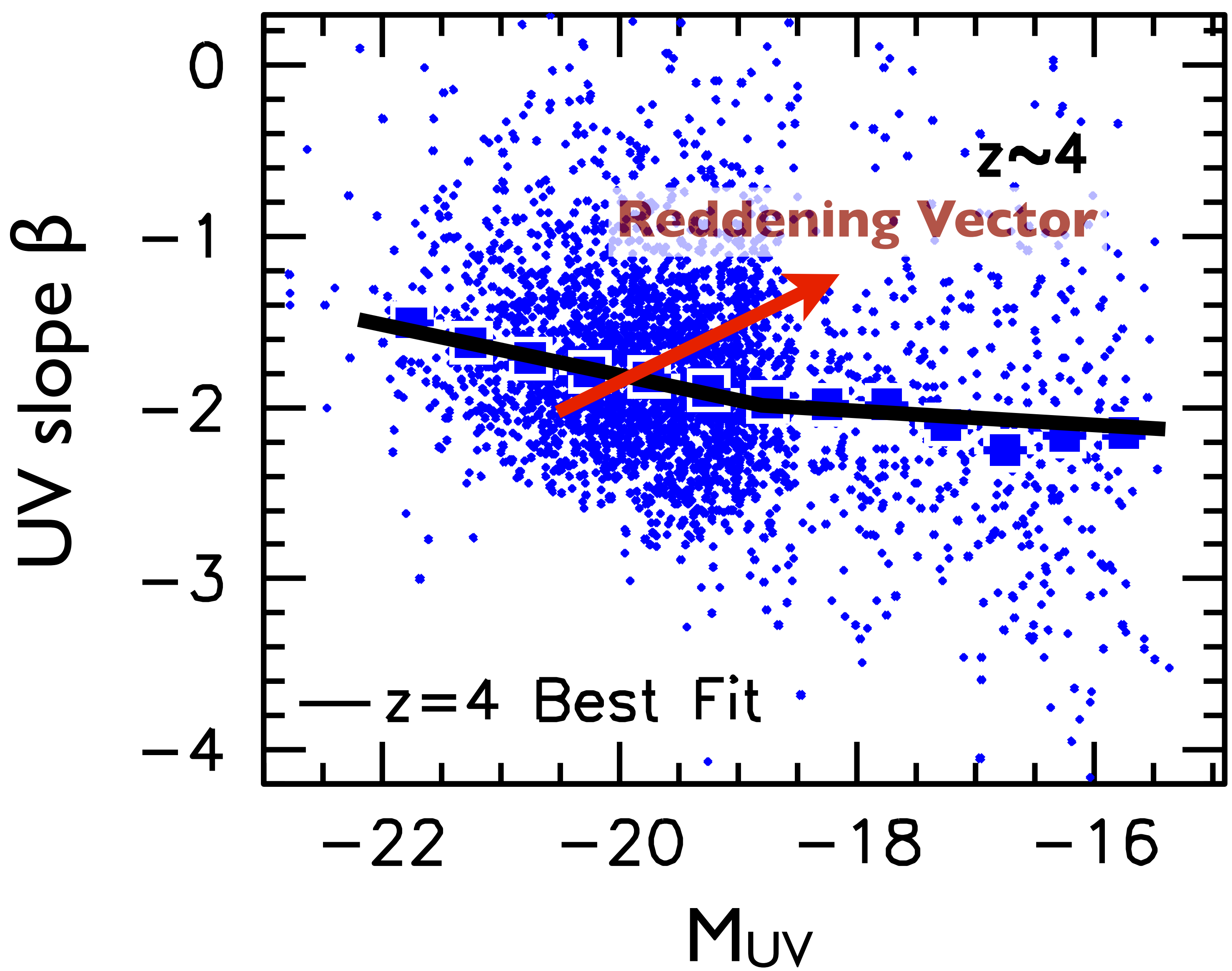
Large body of literature on inferring physical properties of high-z galaxies based on UV continuum slopes.

$f_\lambda \sim \lambda^\beta$



Slope is sensitive to:
dust, metallicity, age, IMF

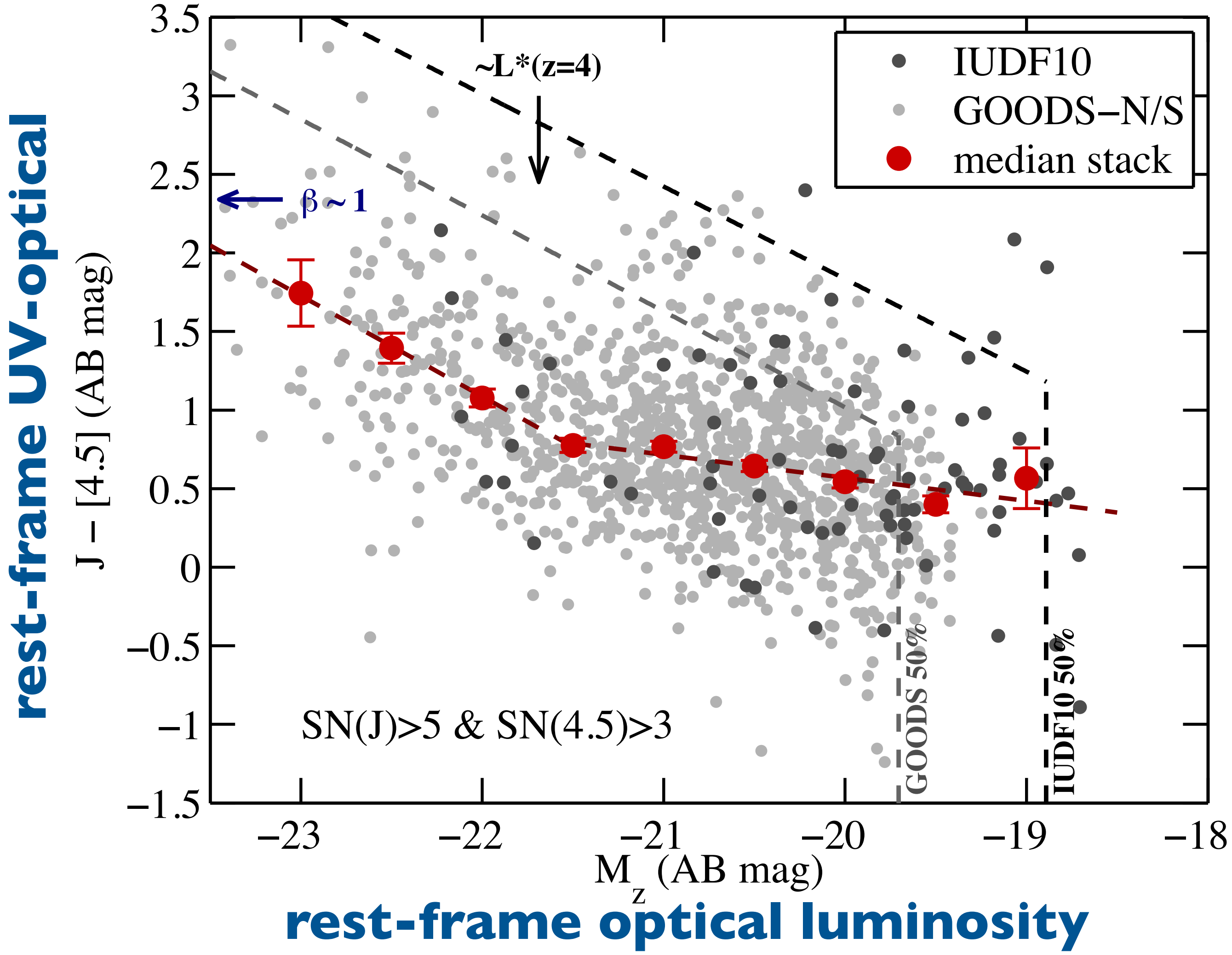
Bouwens+13

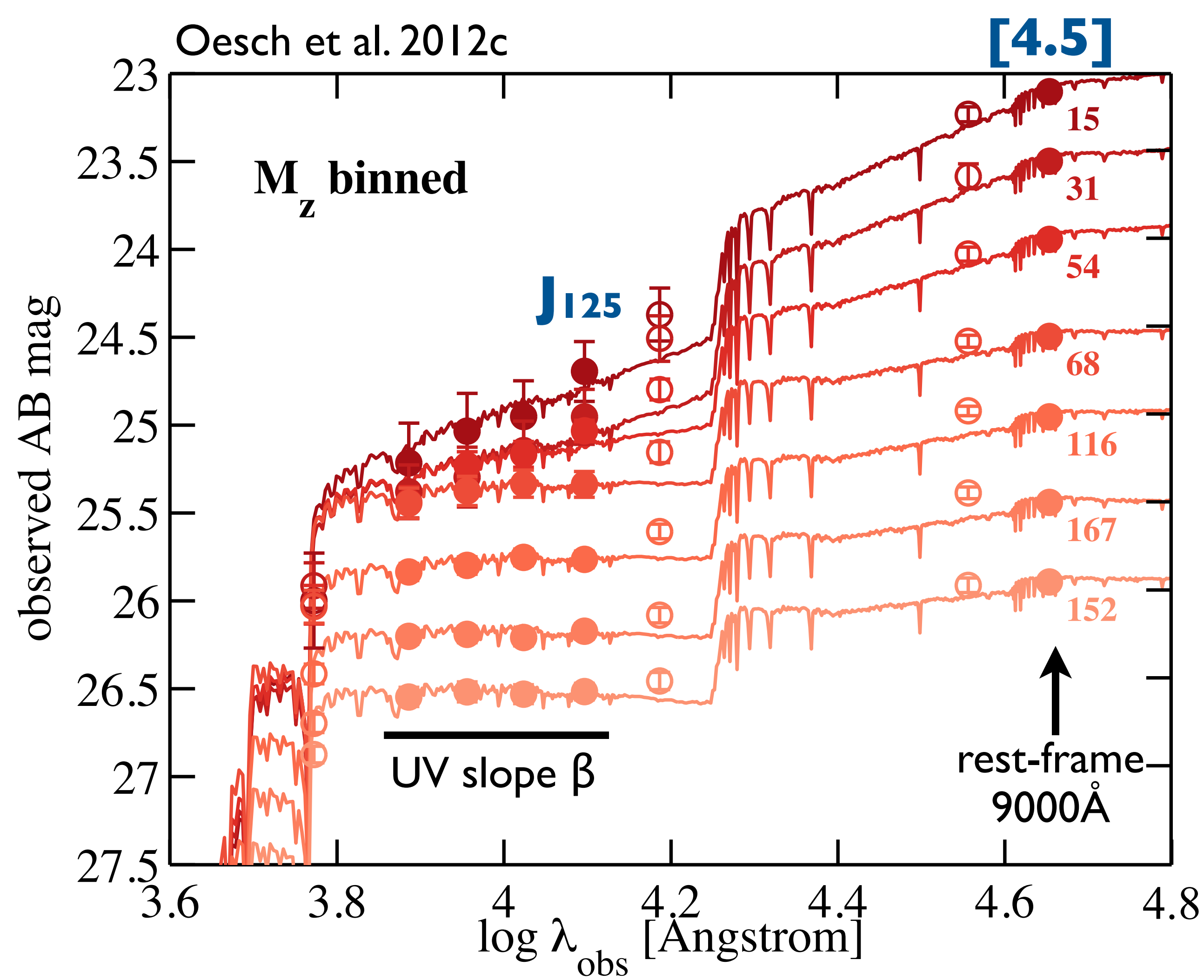


See also: Wilkins+11, Dunlop+11, Castellano+11, Bouwens+09/10, Finkelstein+10/11, Rogers+13

The Rest-Frame Optical View of z~4 Galaxies

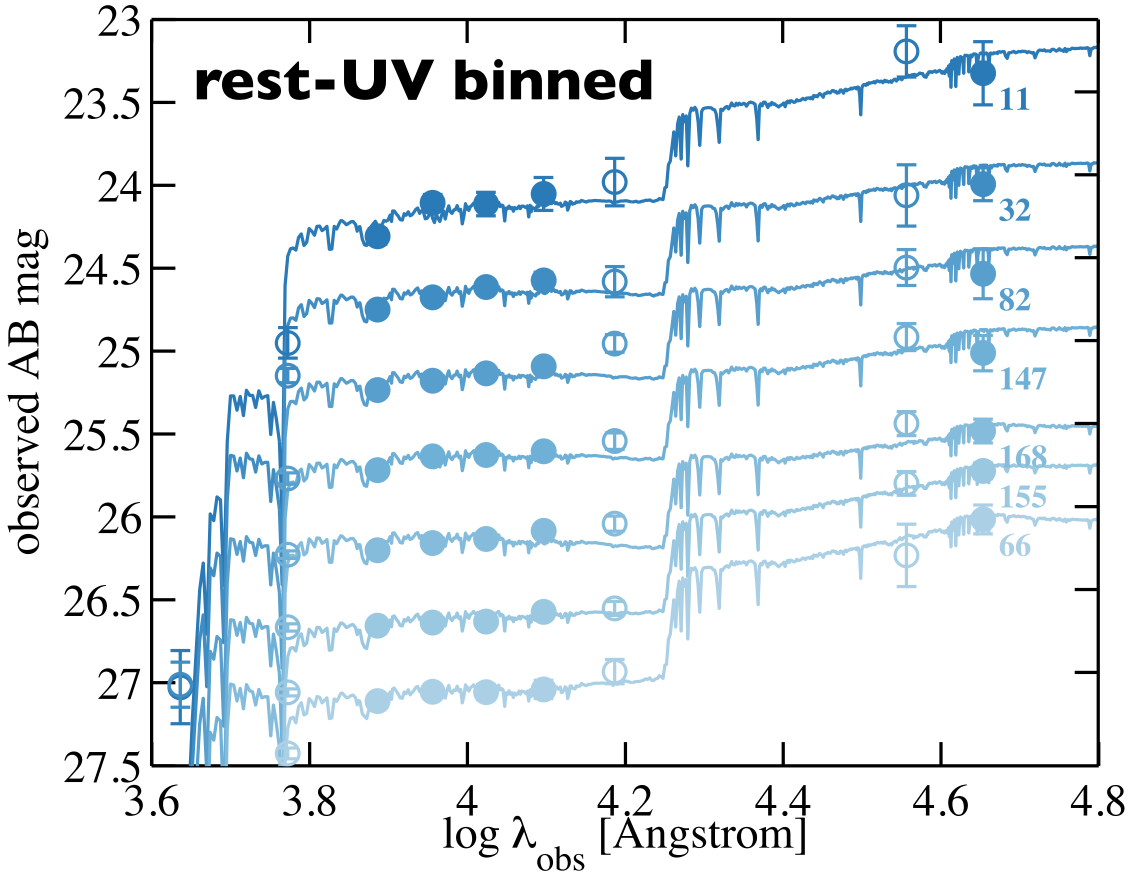
At z~4, we now have samples of 2600 galaxies in GOODS-S/N and the IUDF10

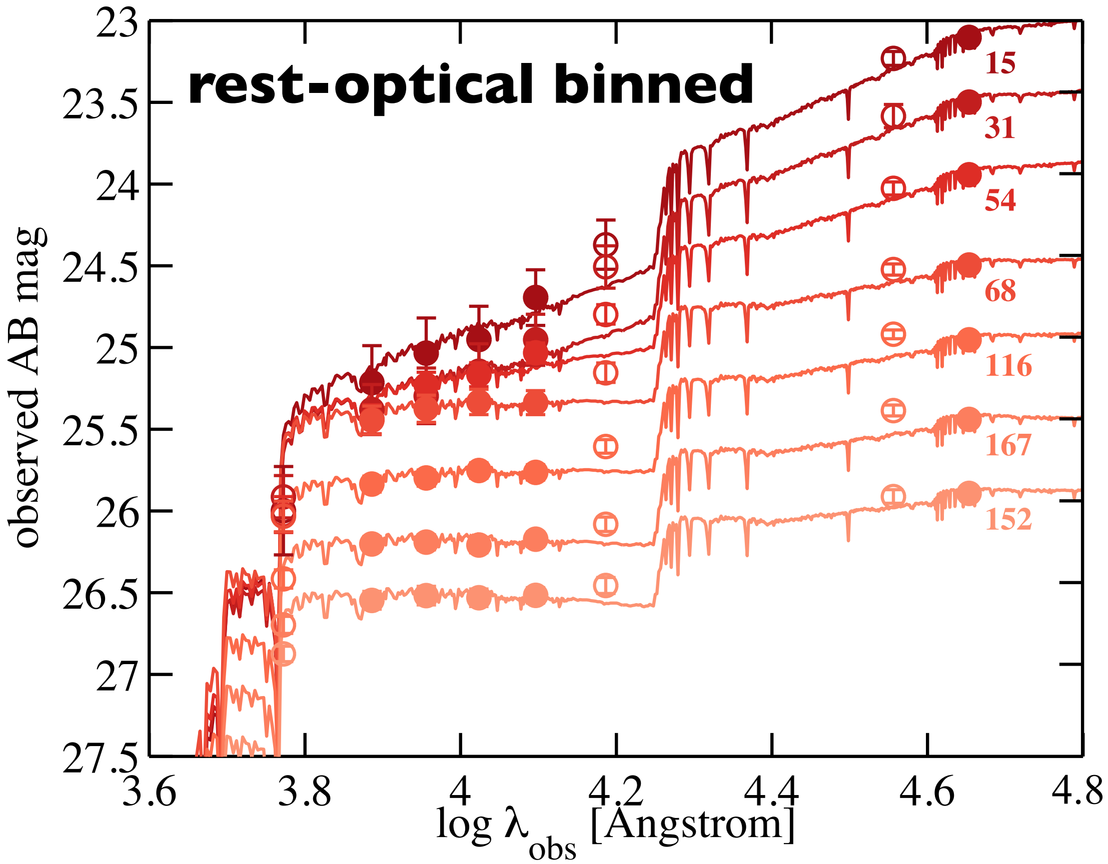




Brighter galaxies are significantly redder in their UV-to-optical colors wrt fainter sources.
Bright galaxies also show redder UV continuum slopes.

Rest-Frame Optical vs Rest-Frame UV View





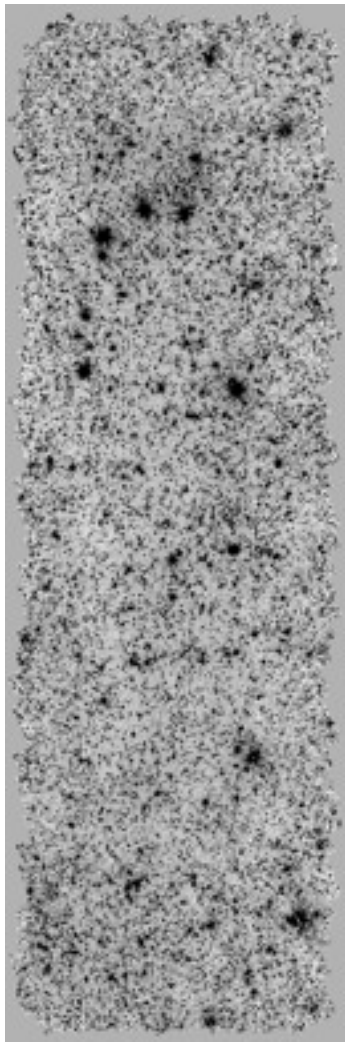
Rest-frame optical view reveals that z~4 galaxy population is more diverse than what is inferred from UV-based analyses.

IRAC data is crucial for working toward a self-consistent picture of star-formation and stellar mass build-up in high redshift galaxies!

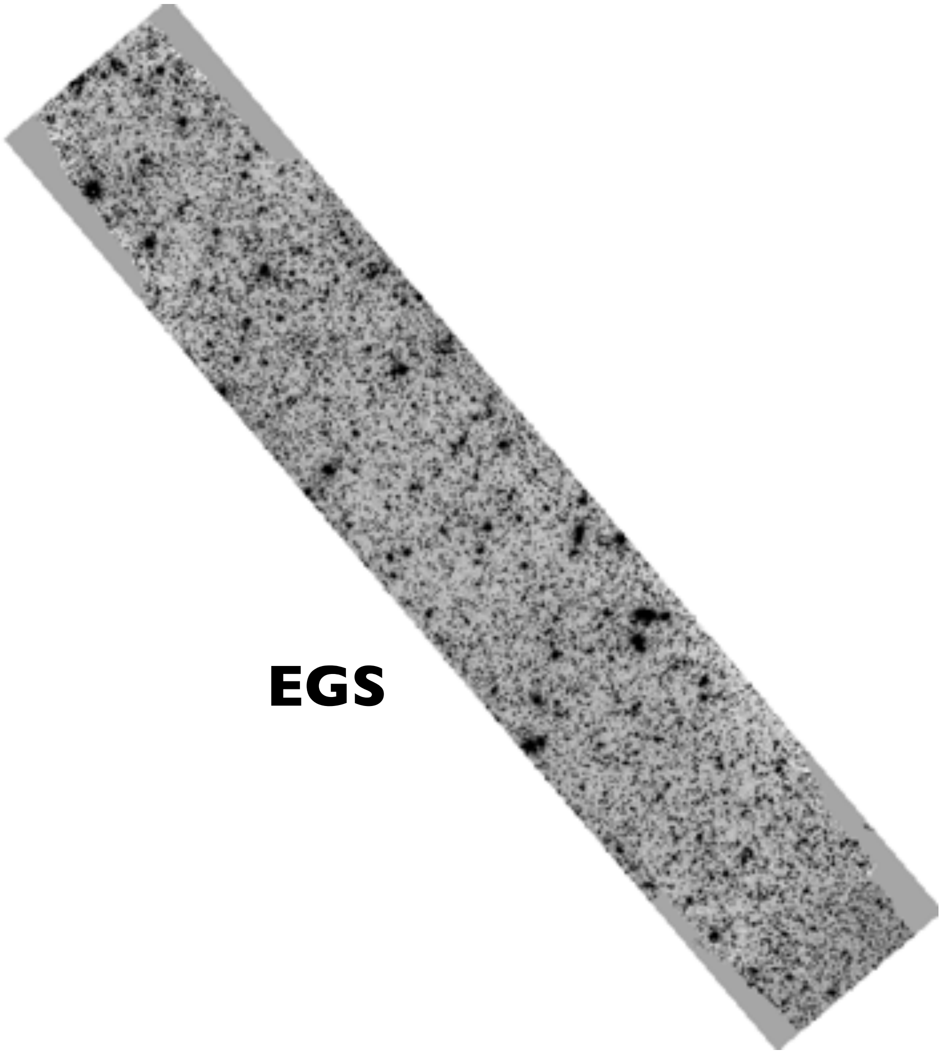
The (IR) Future is Bright: SEDS + S-CANDELS

- All HST CANDELS fields are now covered with 50h IRAC data (~26.8 mag)
- very large samples of LBGs from HST: ~10'000 z>=4 sources
- individually detect L* galaxies in rest-optical out to z~8 (~1e9 Msol)

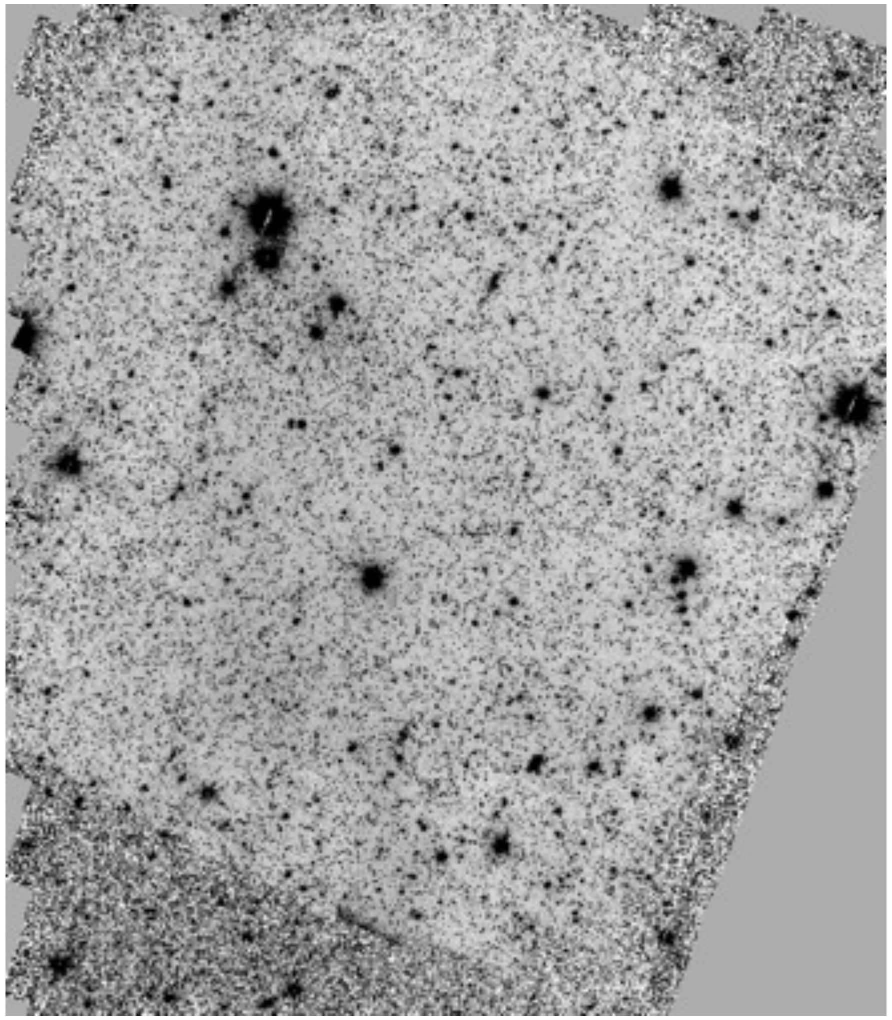
➡ MFs, duty cycles, etc..



COSMOS



EGS



UDS

Summary

- WFC3/IR has opened up the window to very efficient studies of z>6.5 galaxies: by now, we have identified >300 galaxy candidates at these redshifts; **3 at z~10**.
- The XDF/HUDF12 data allowed for searches of **z~9-11** LBGs, resulting in smaller numbers of candidates than expected from monotonic evolution of the UV LF across z=8 to z=4. Galaxy SFRD increases by ~1 order of mag in 170 Myr from z~10 to z~8.
  ➡ **Accelerated evolution** is most likely explained by growing DM halo MF.
- Combination of very deep **HST and IRAC** data allows for rest-frame optical detection of individual galaxies out to z~8, and MF determinations starting from only 750 Myr after the Big Bang.
- **Rest-frame optical** data from IRAC is crucial for self-consistent picture of star-formation and stellar mass build-up (z~4 UV binned SEDs are very different from 9000 Å binned ones: increase in dust extinction in high mass galaxies).
- **Great prospects** for high-z frontier **before JWST** based on deep IRAC S-CANDELS data (MFs, SF duty cycle, etc..) + Hubble Frontier Fields (SFRD evolution to z~10, UV continuum slopes, etc..)