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

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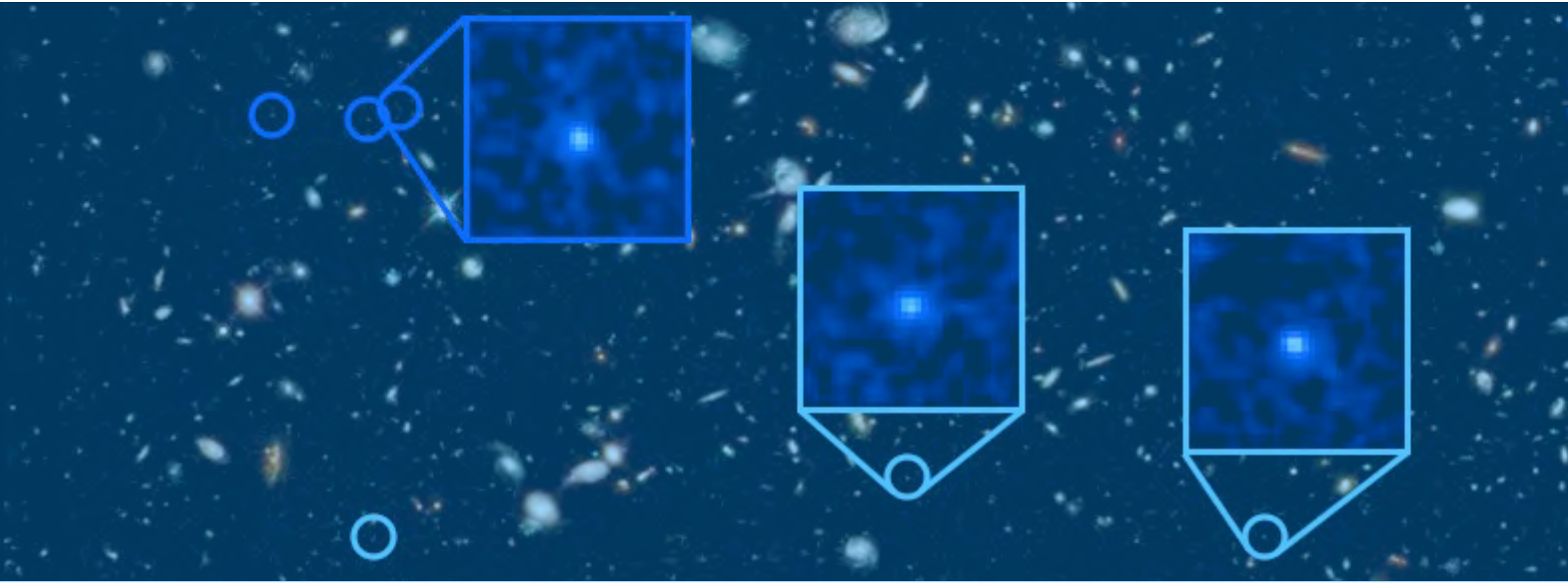
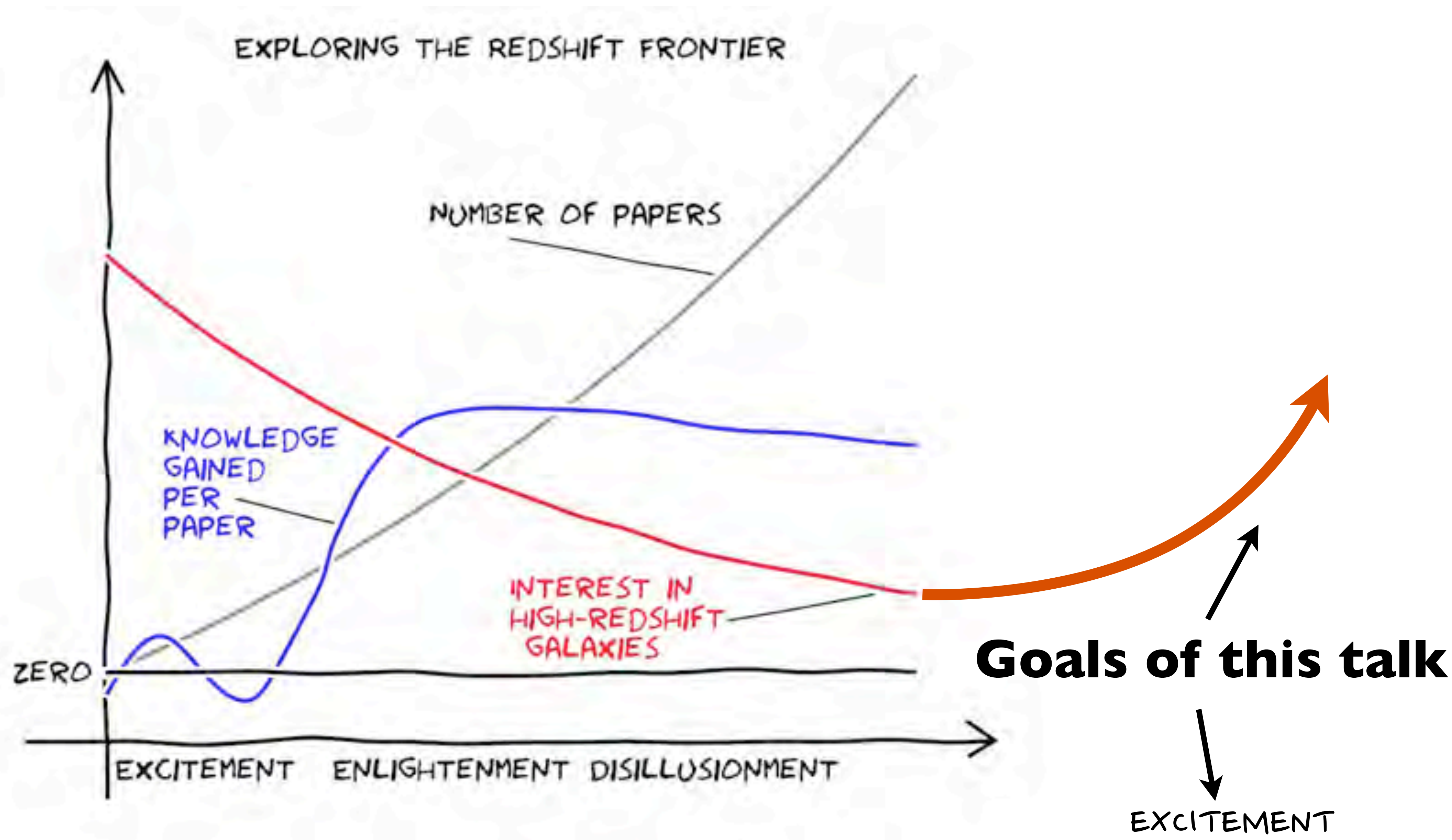
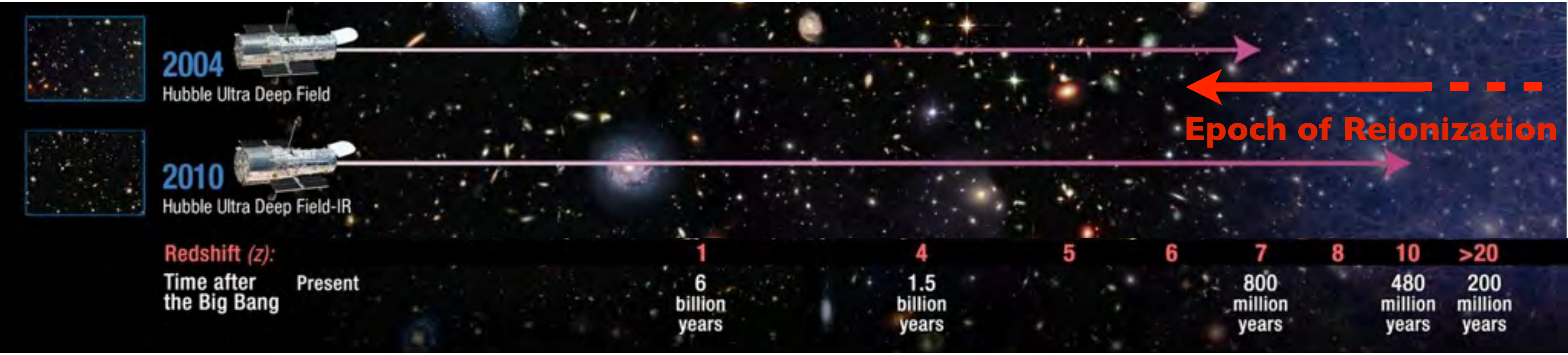


What Social Media say about Exploring the High-Redshift Frontier:

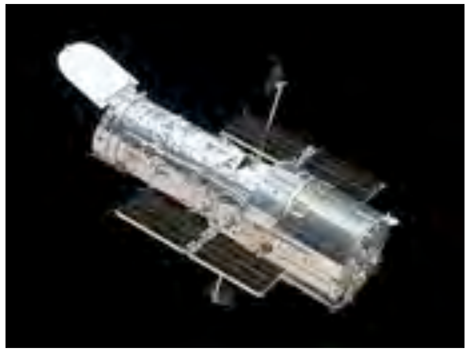
facebook
(author unknown)



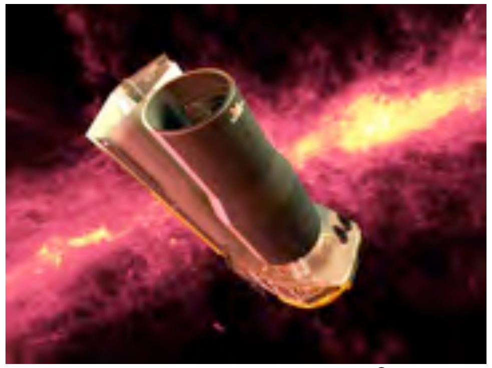
When and how did the first galaxies form? How fast did they grow and build-up?



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

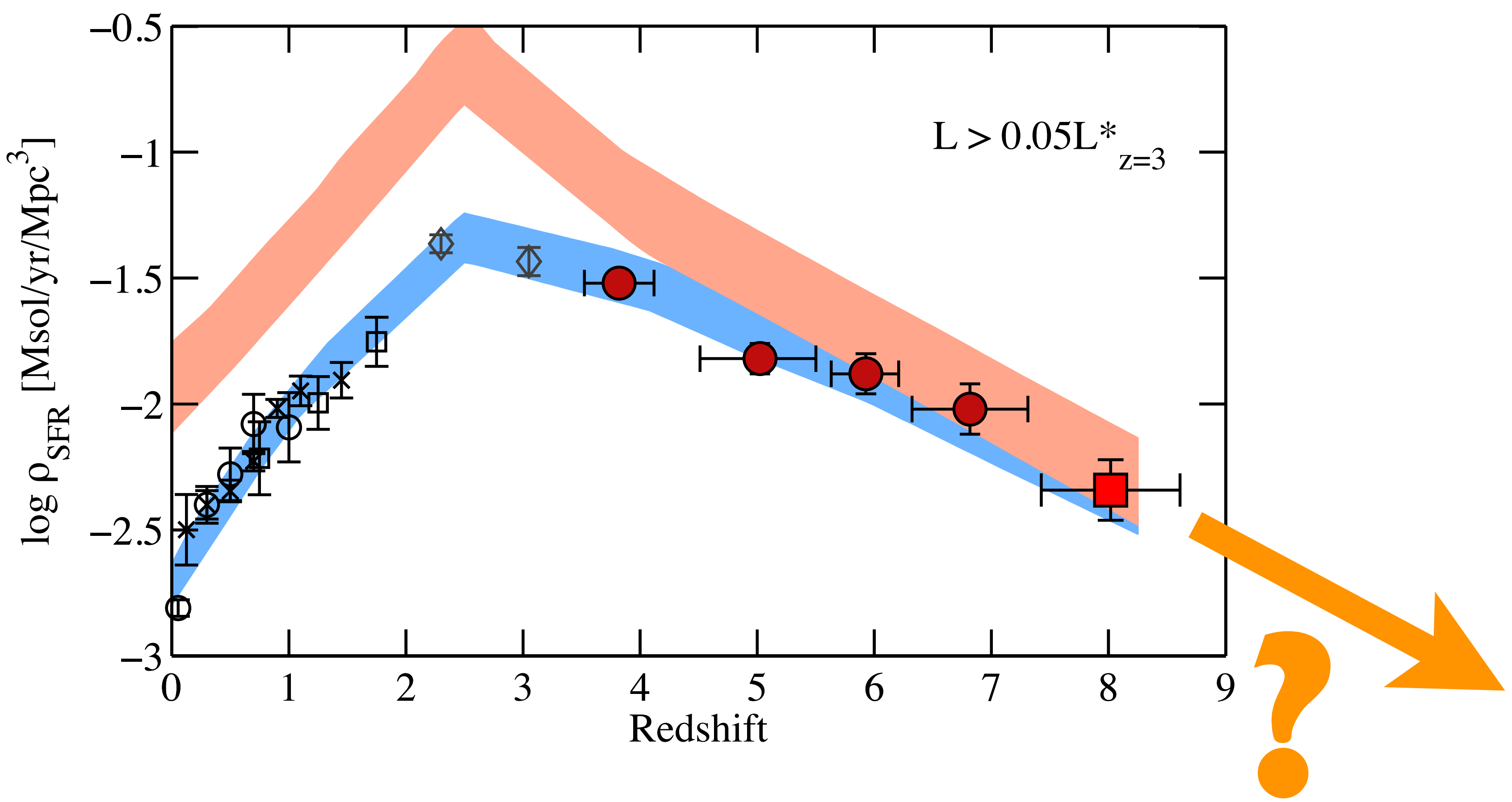


+



rest-UV SFRs + **rest-optical Masses**

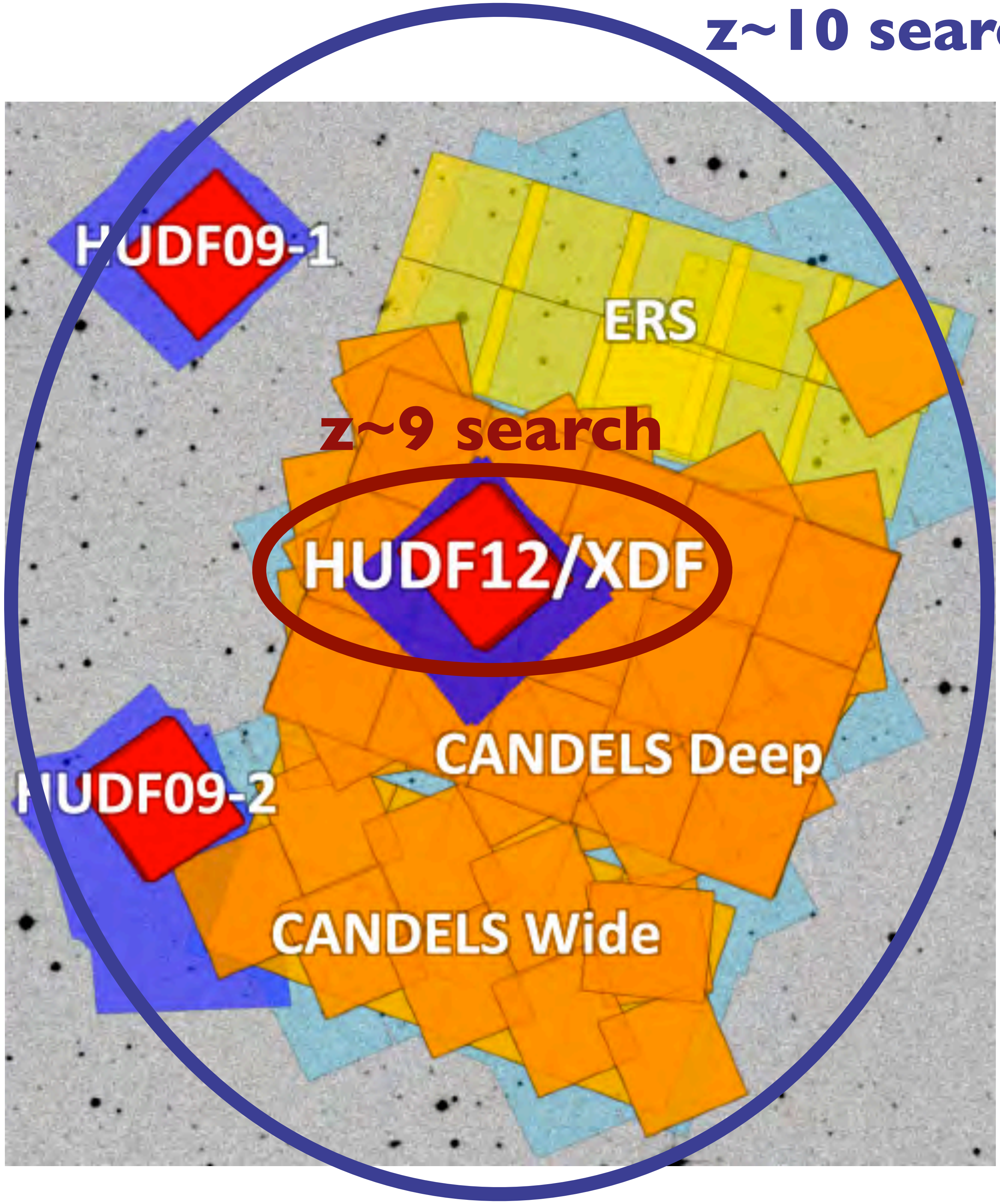
Do we see Evidence for Emergence of the First Galaxies?

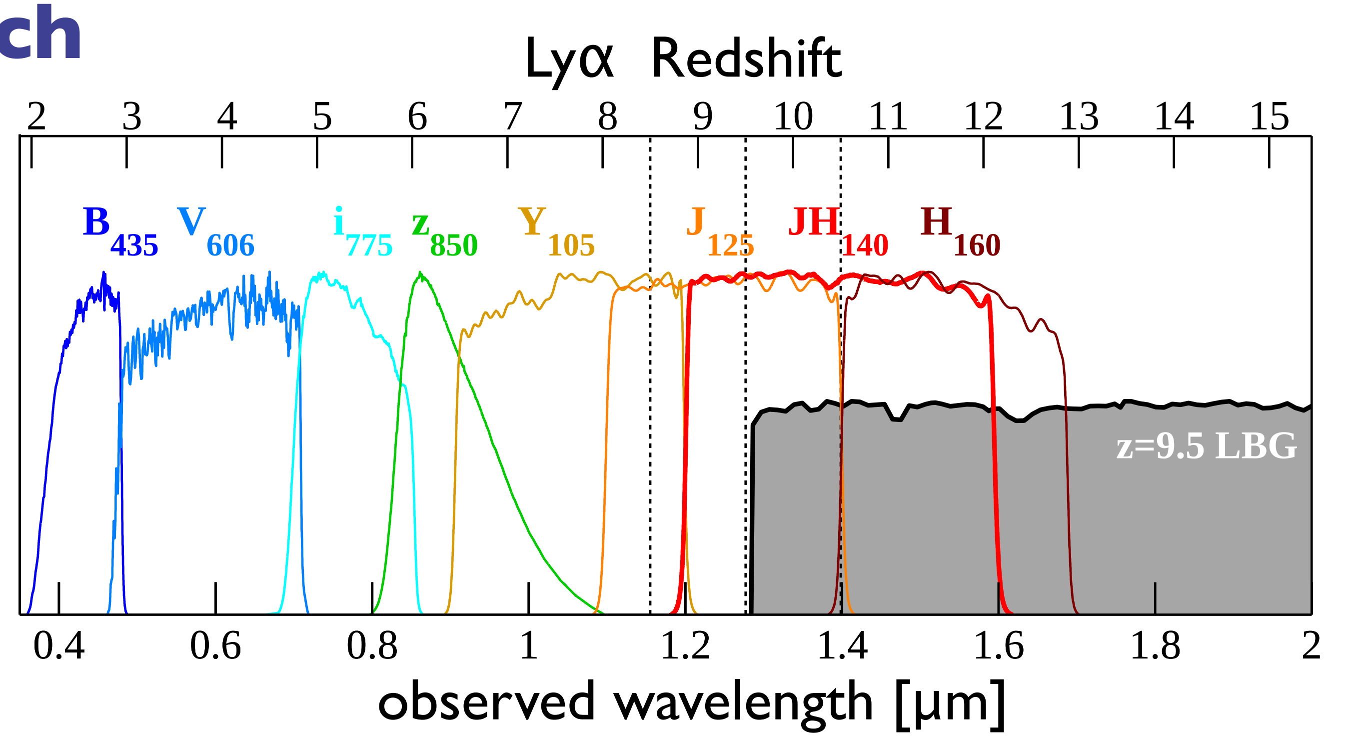


Galaxy Build-up at z<8 progresses monotonically.

What about at z>8?

WFC3/IR Data around GOODS-South

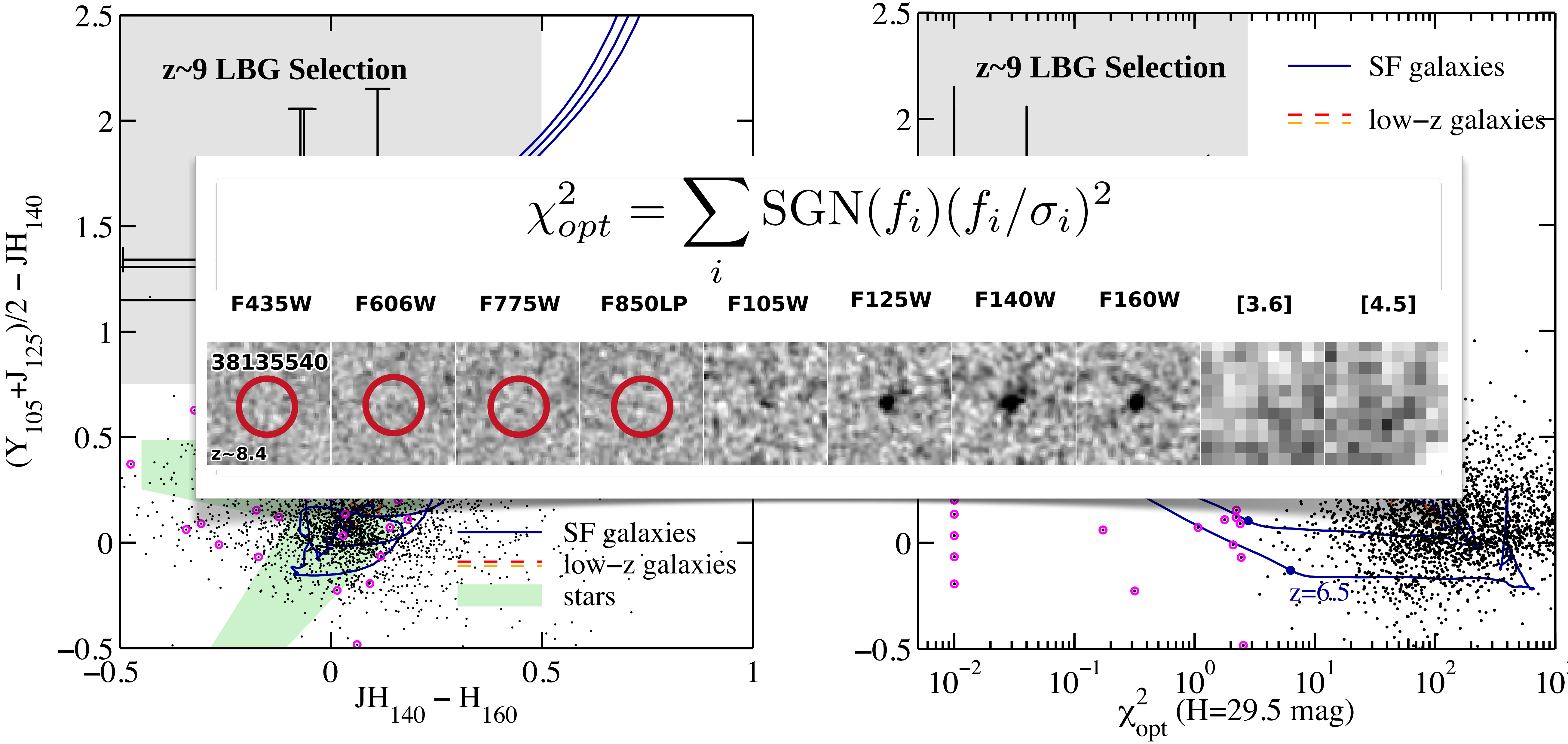




- Large amount of public optical (ACS) and NIR (WFC3) data
  - *HUDF12 & XDF*
  - ERS
  - CANDELS (Deep & Wide)
- Total of ~160 arcmin^2
- Reach to 27.5 - 30 AB mag
- Full data: can select z~10 galaxies
- HUDF12/XDF: can select z~9 galaxies

z~9 LBG Selections with HUDF12 Data

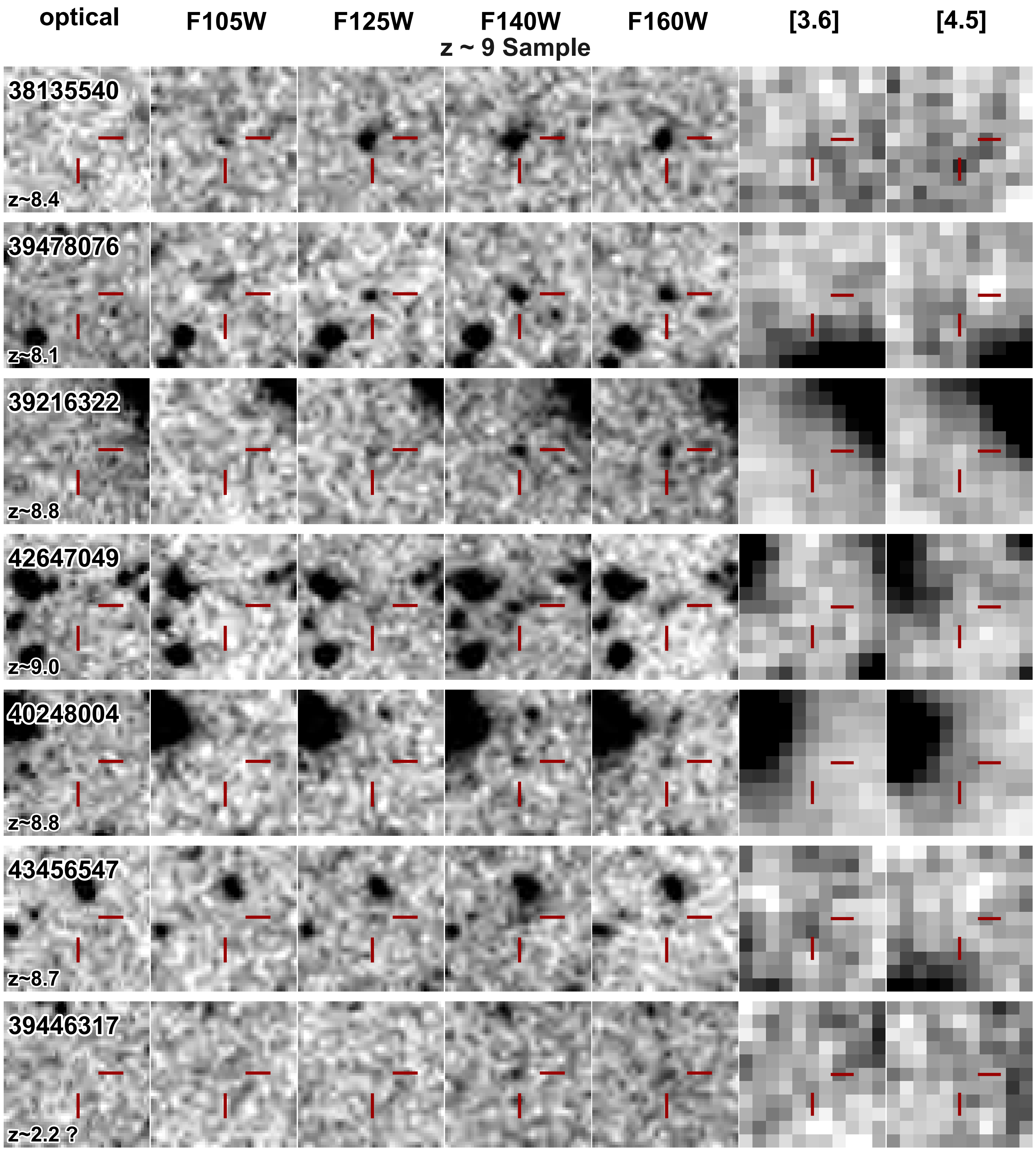
z~9 Selection is based on a red color in (YJ)-JH and optical non-detection.



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

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
z ~ 9 Sample
F160W
[3.6]
[4.5]
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

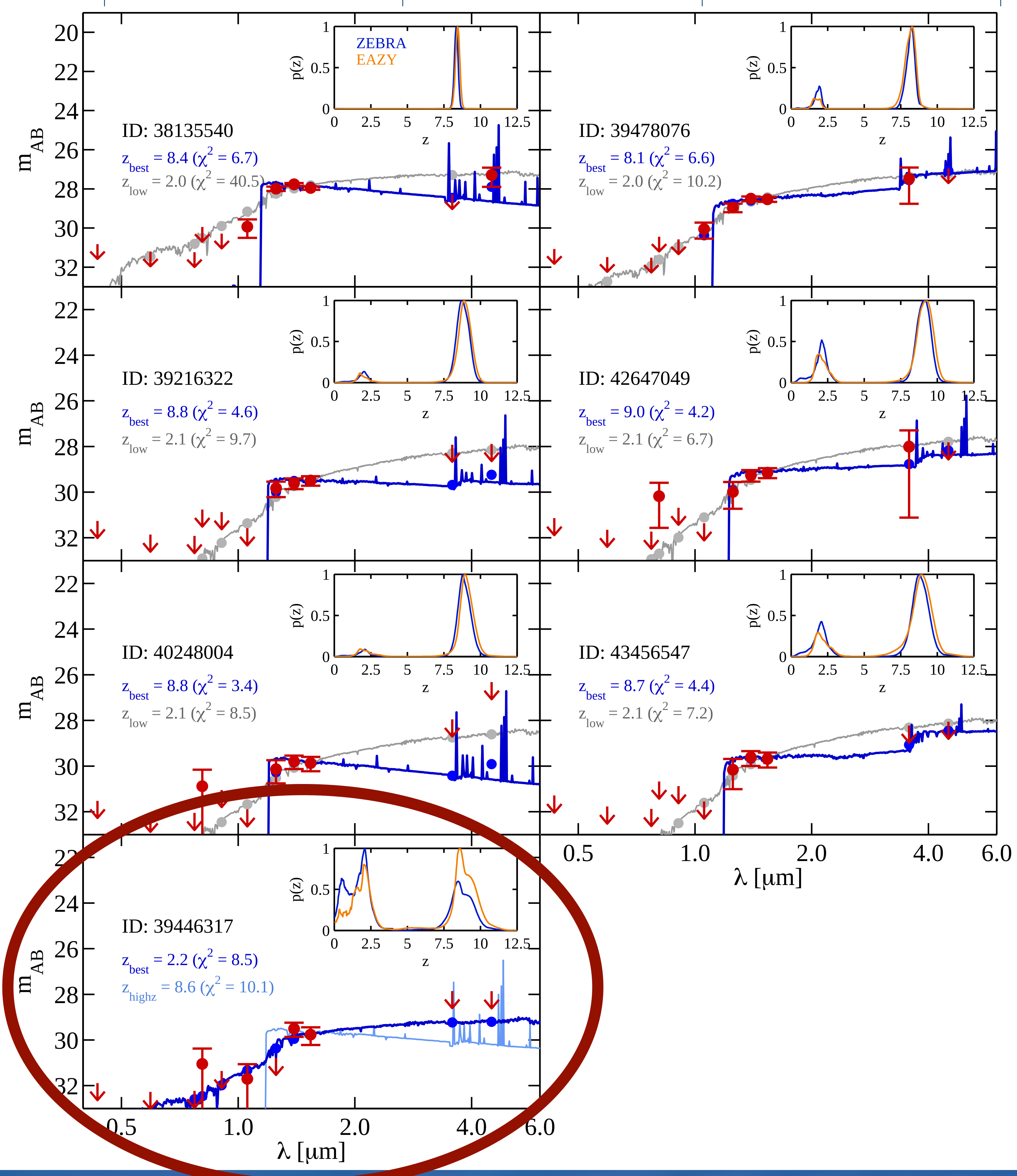
2 photo-z codes: EAZY + ZEBRA

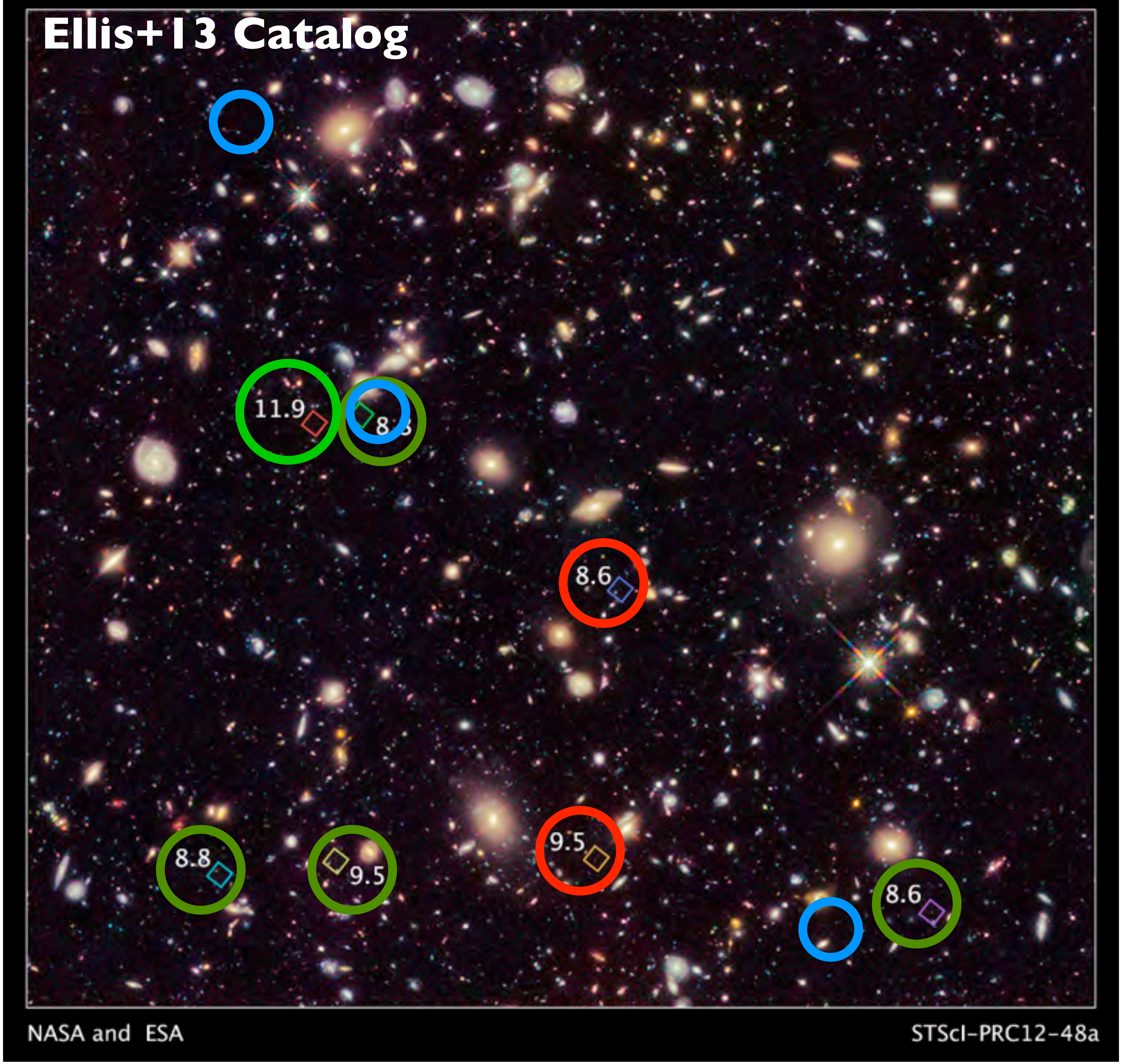
Photometric Redshifts: z~8.1-9.0

All sources have secondary peak in their p(z)

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

i.e. contamination fraction <15%

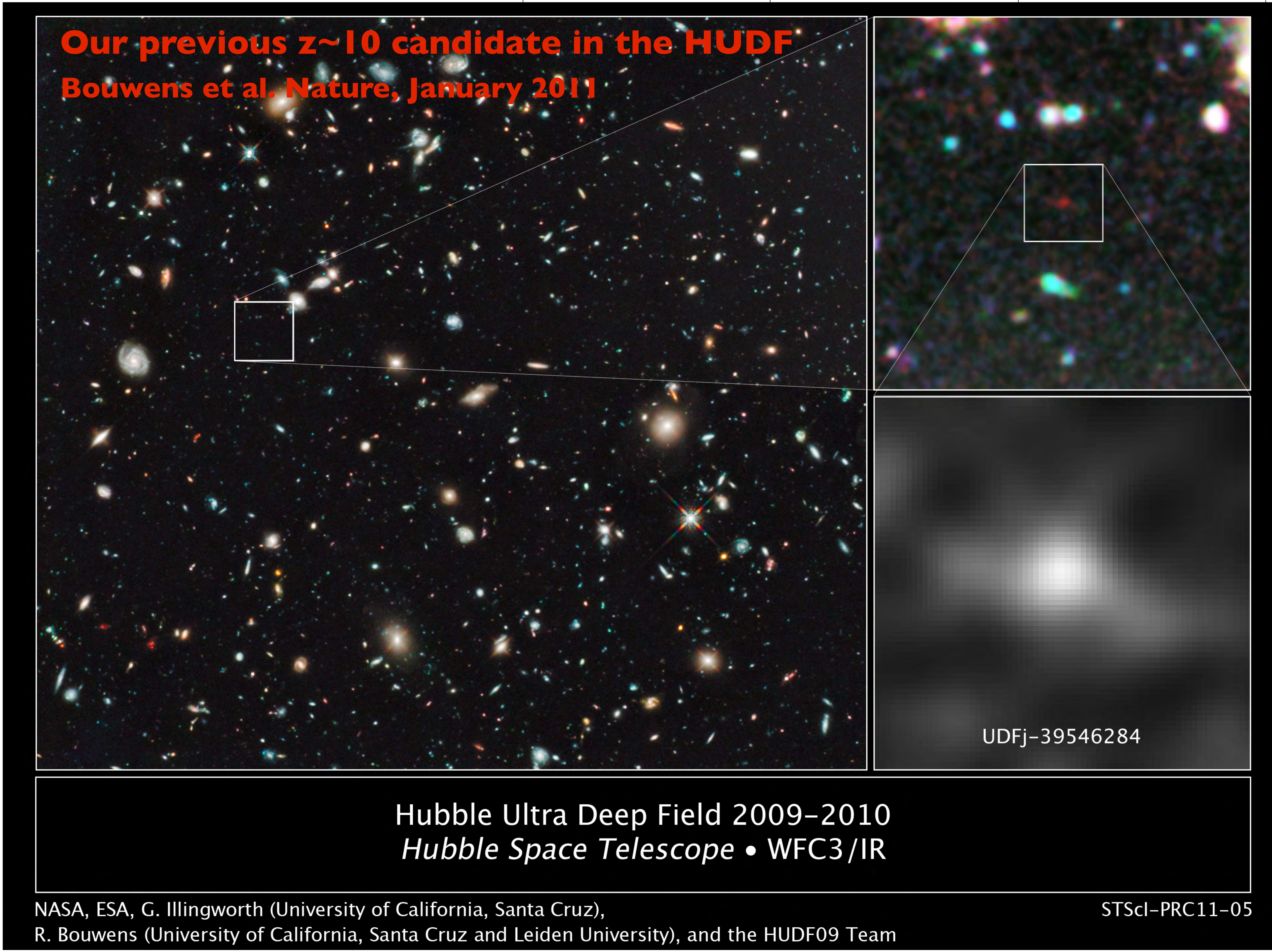




In both samples

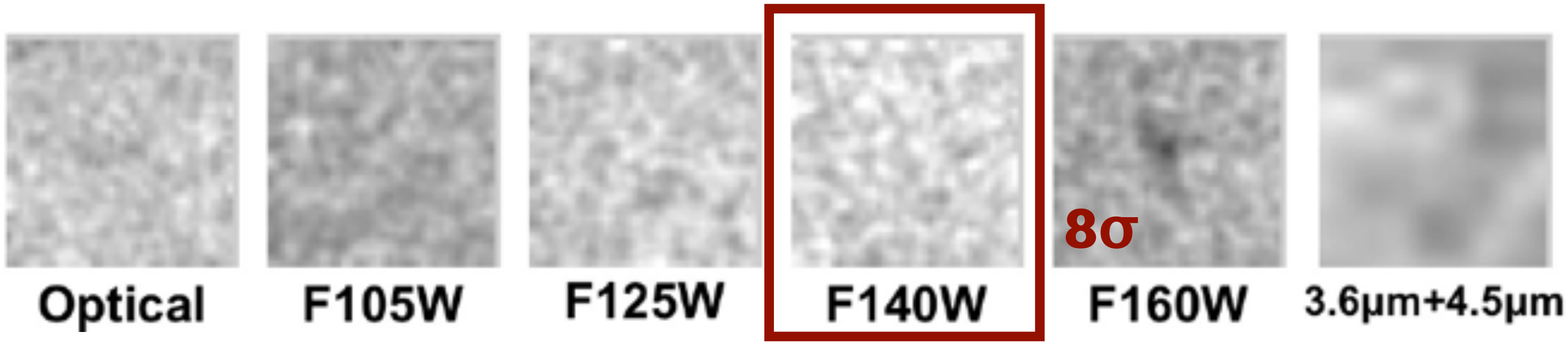
Only in our sample

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

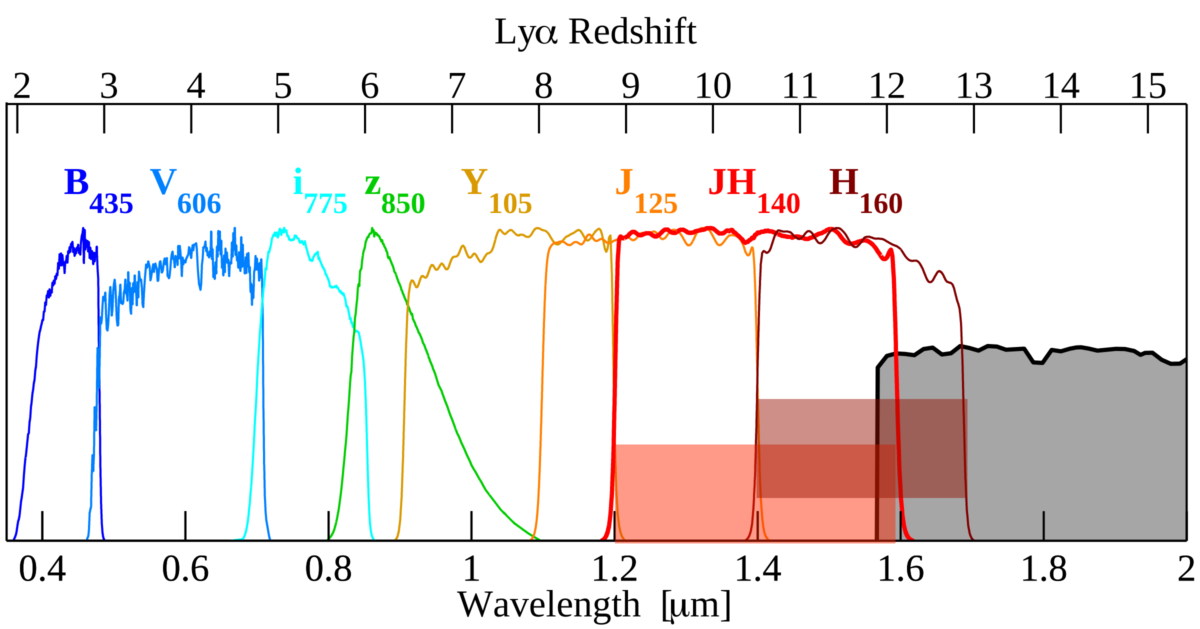
Nature of UDFj-39546284?

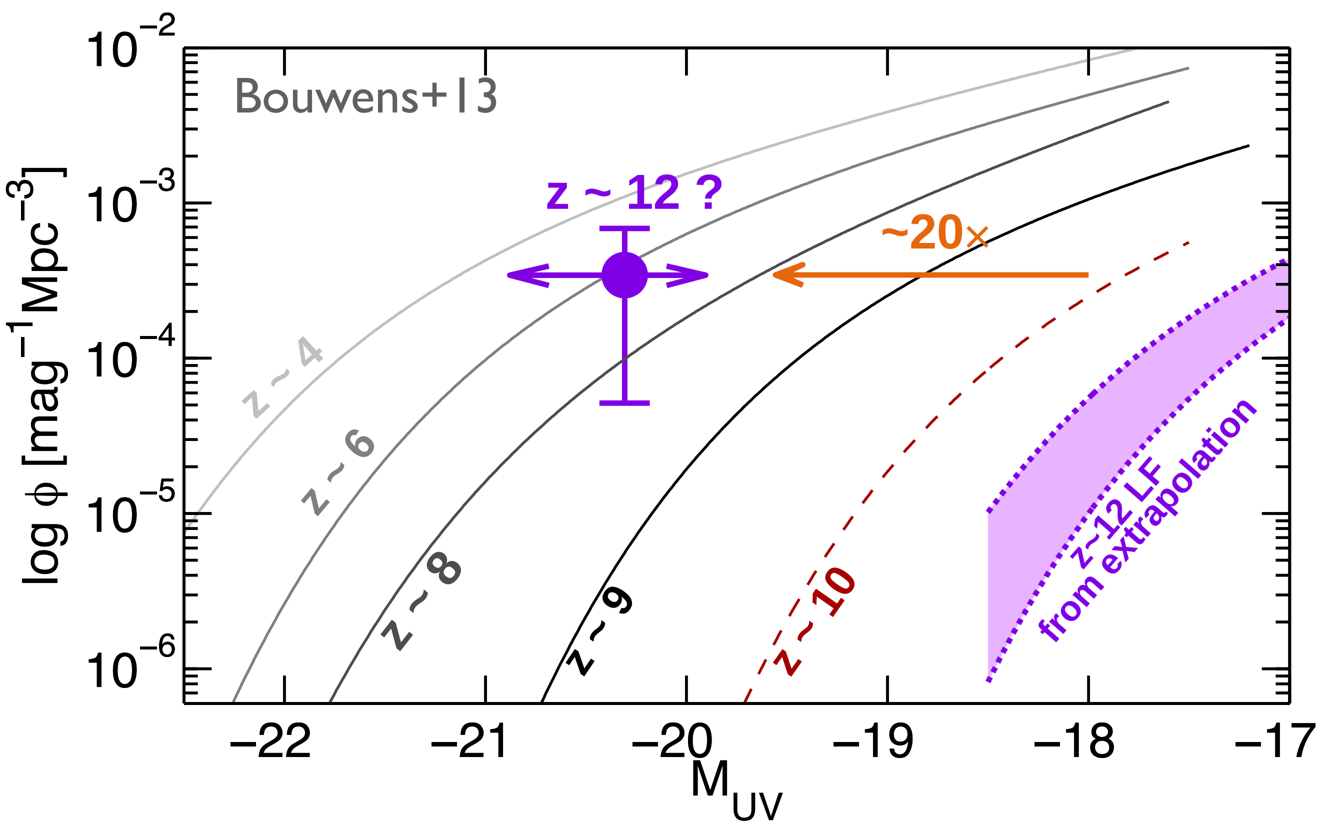
Our previous z~10 source



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.

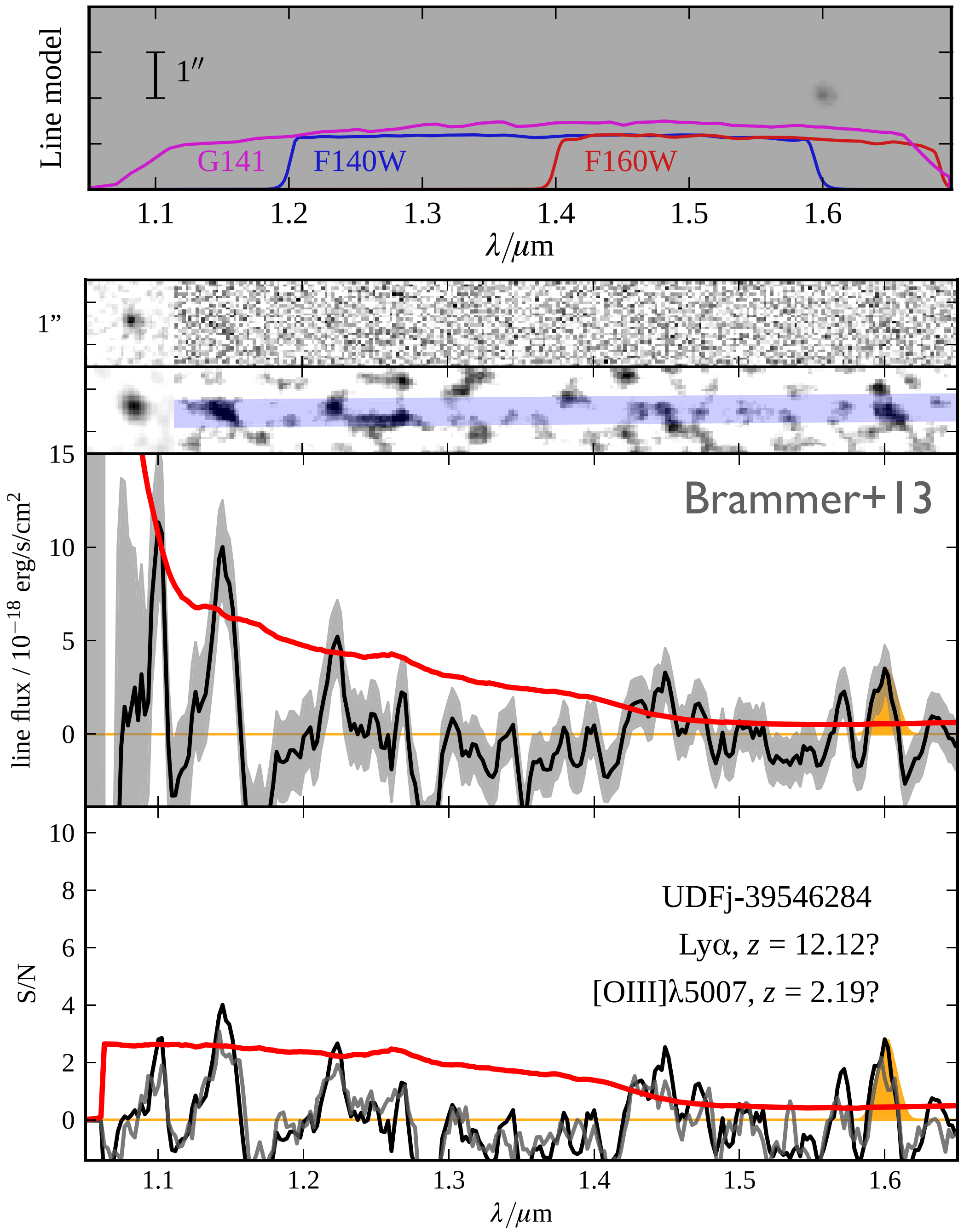


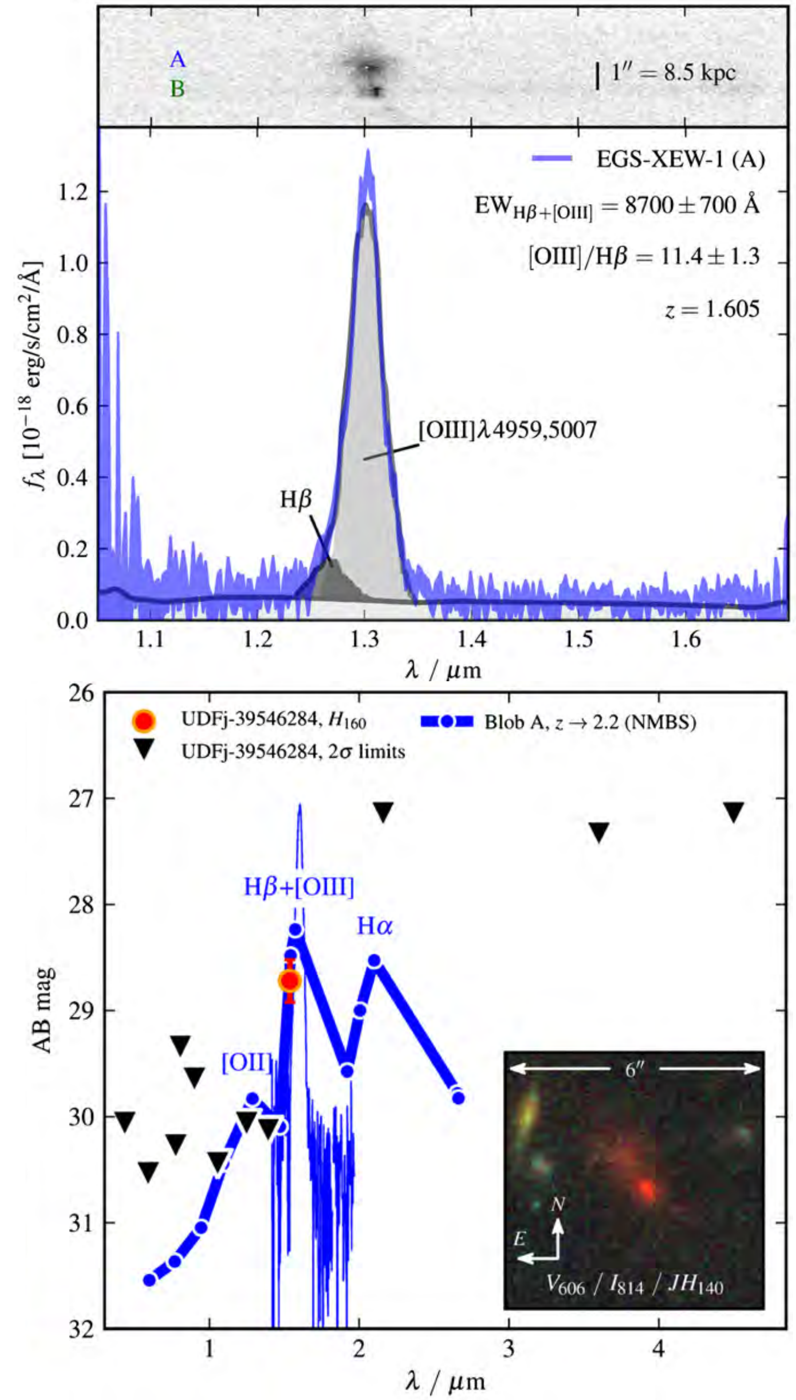


If this source was at z~11.8, its luminosity would be 10-20x brighter than expected.

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





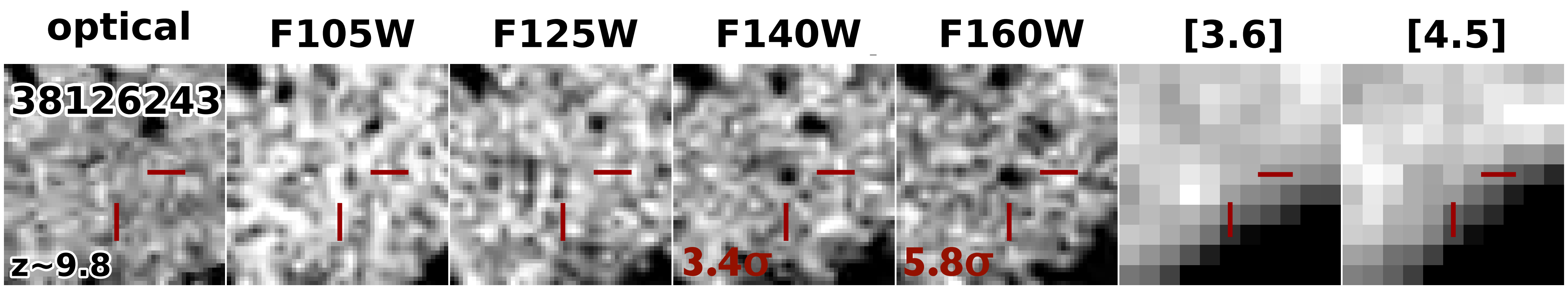
Potential line detected in Grism spectroscopy. However, also such strong line emitters are extremely rare.

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.

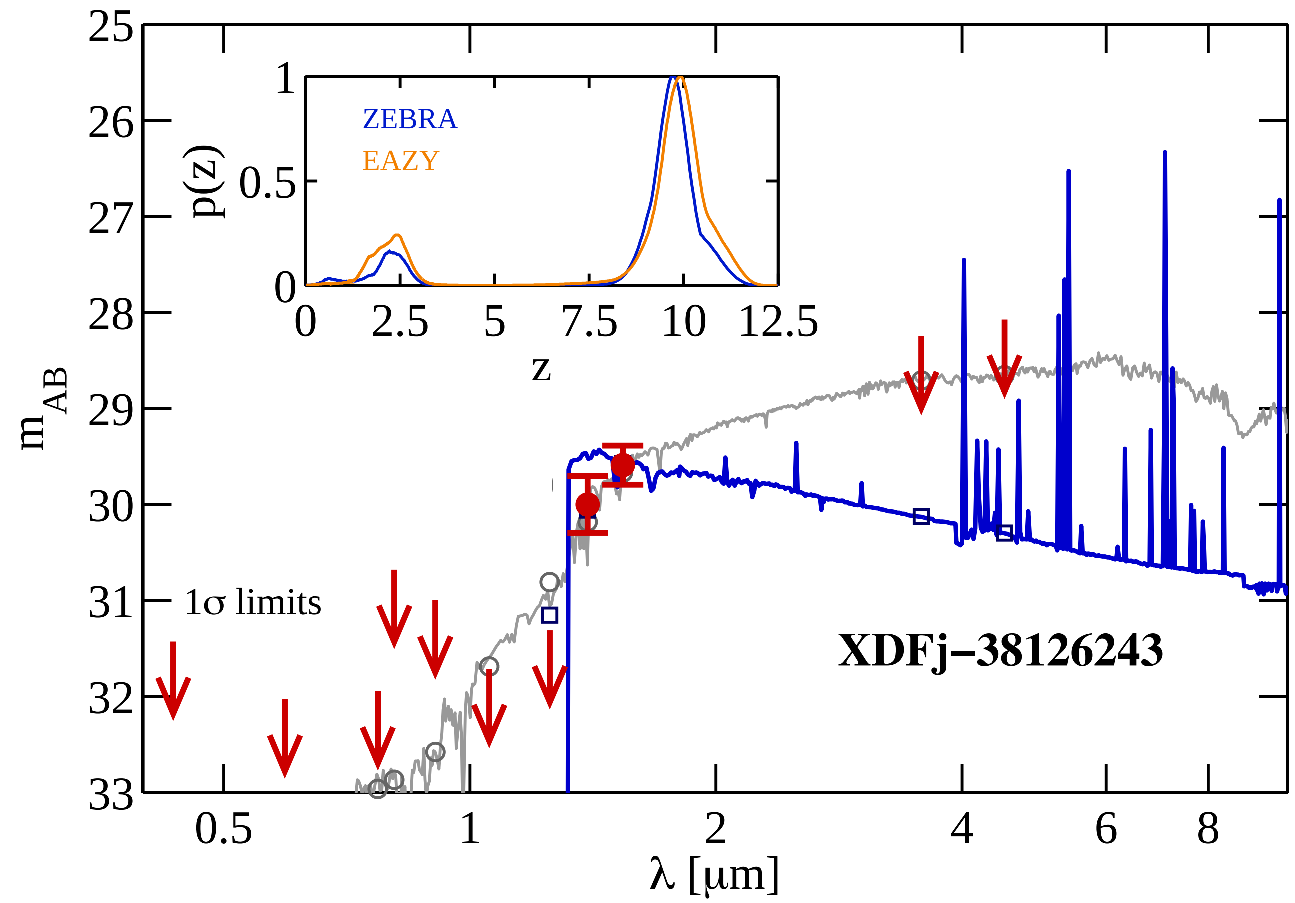
The only z~10 source



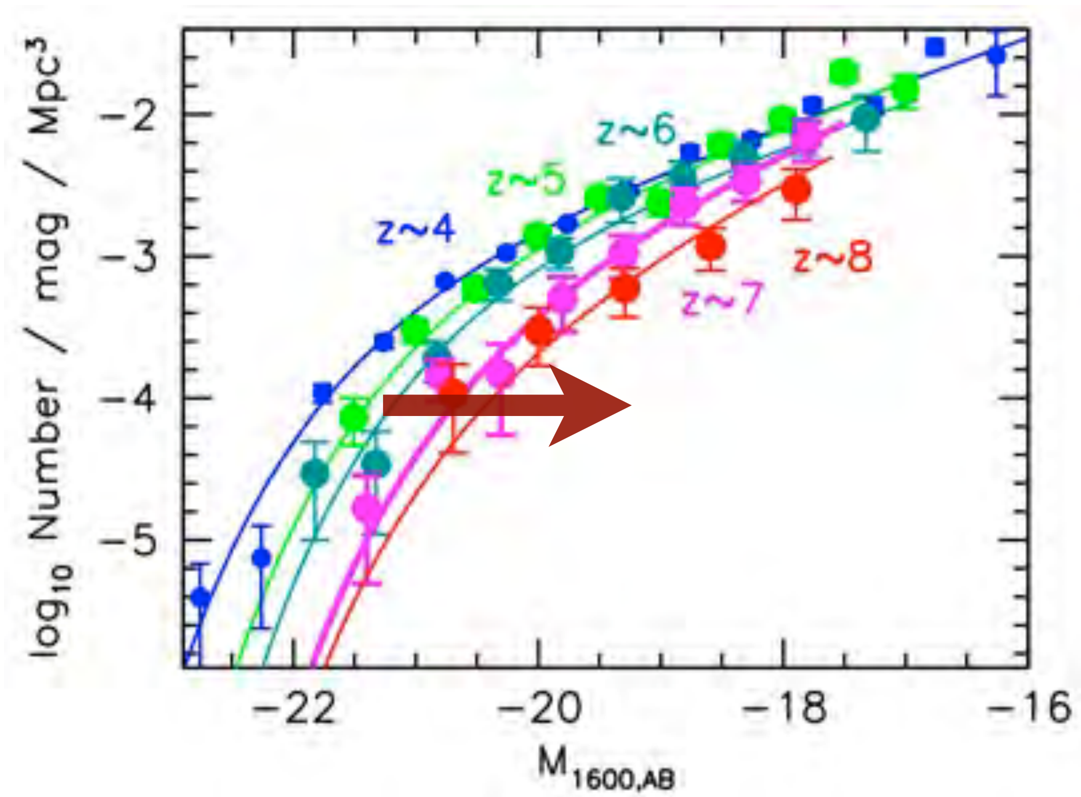
The source is definitely real. It is detected at >3σ in several independent subsets of the data (H-Epoch1, H-Epoch3, and JH)

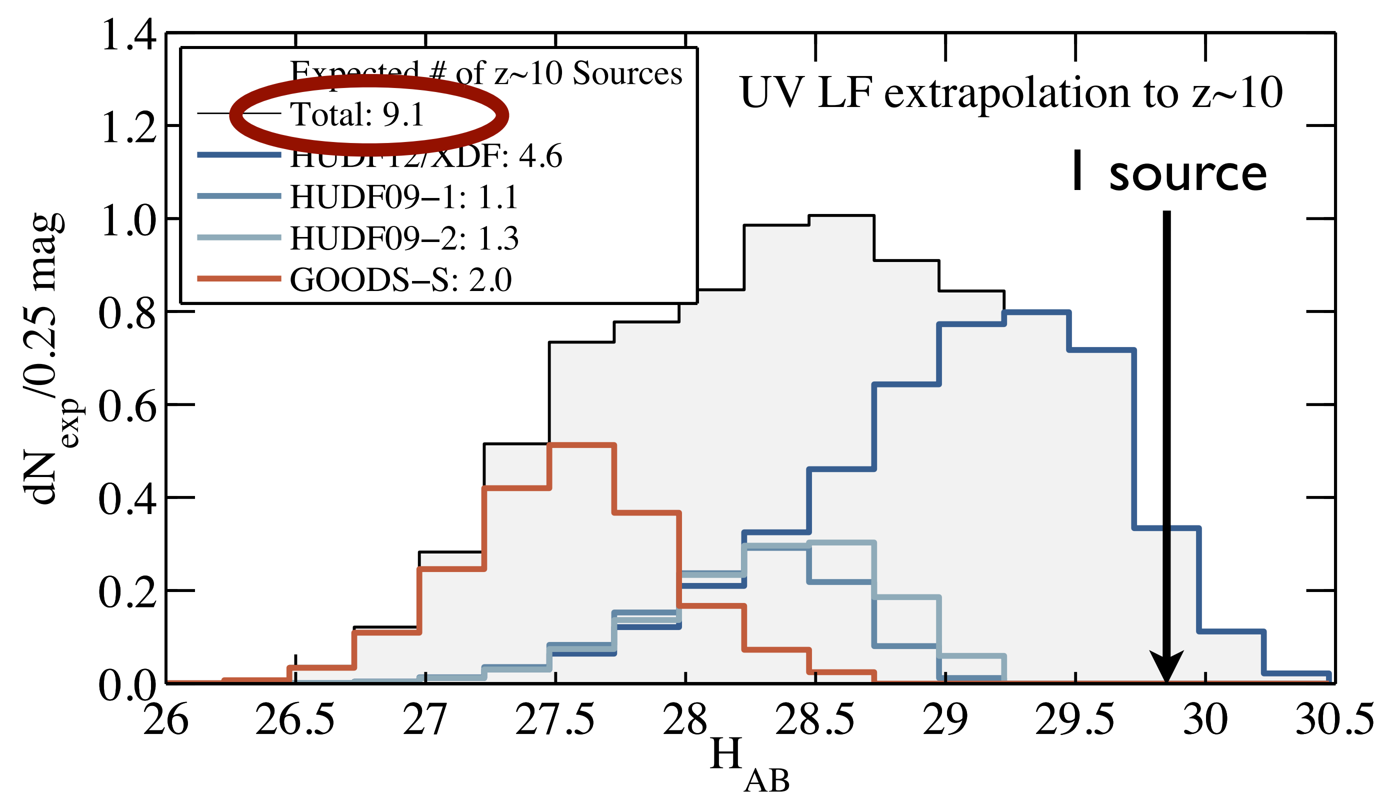
It is has S/H = 3.4 and 5.8 in JH_{140} and H_{160}.

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

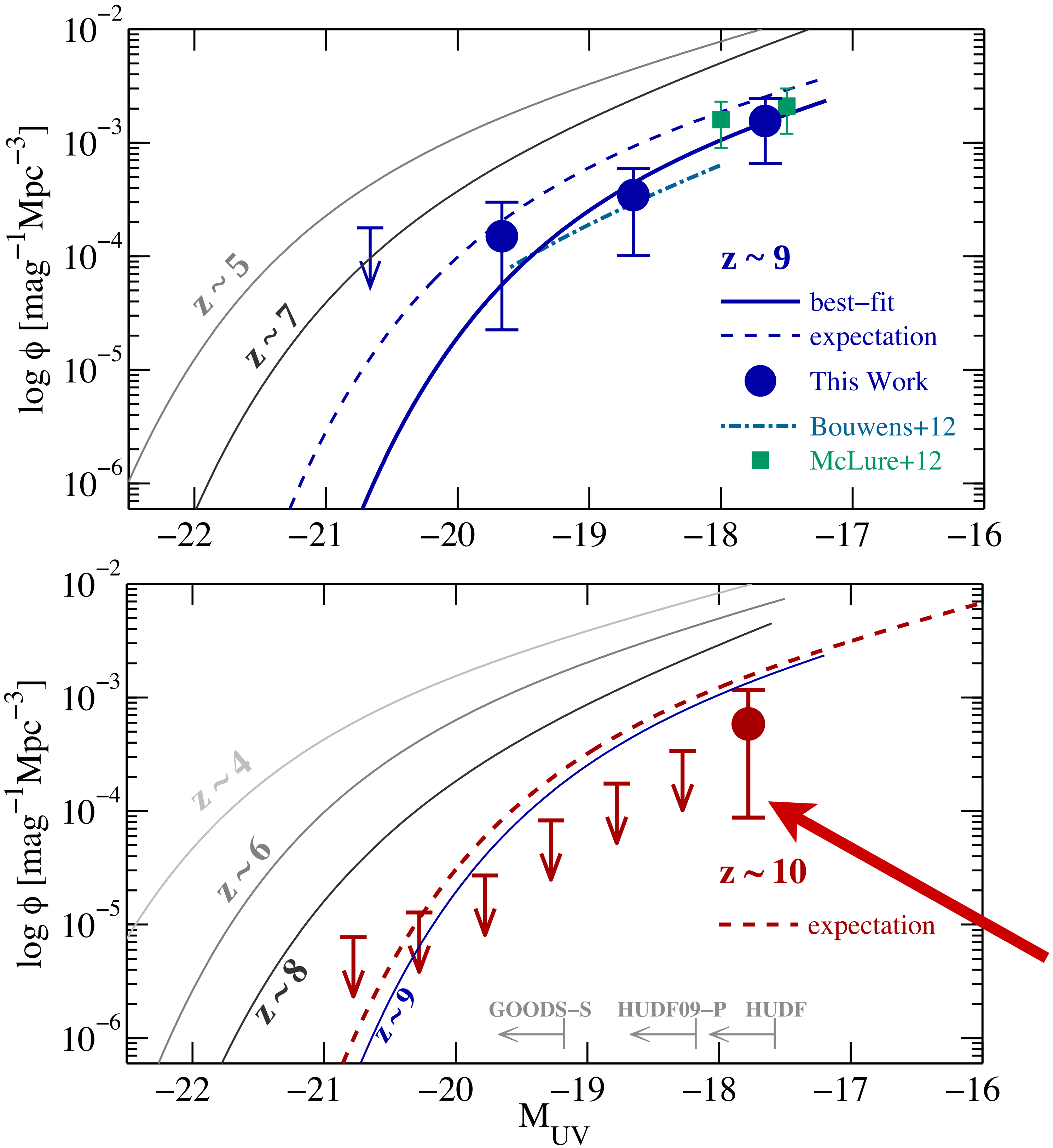




If LF evolution was constant across z~4 to z~10, we should have seen **9 z~10 sources** in our data. But, we find only 1. The chance of that happening is only 0.5%.

Therefore, galaxy evolution at z>8 is accelerated.

The z~9 and z~10 UV LF Constraints



First Constraints at z~9:

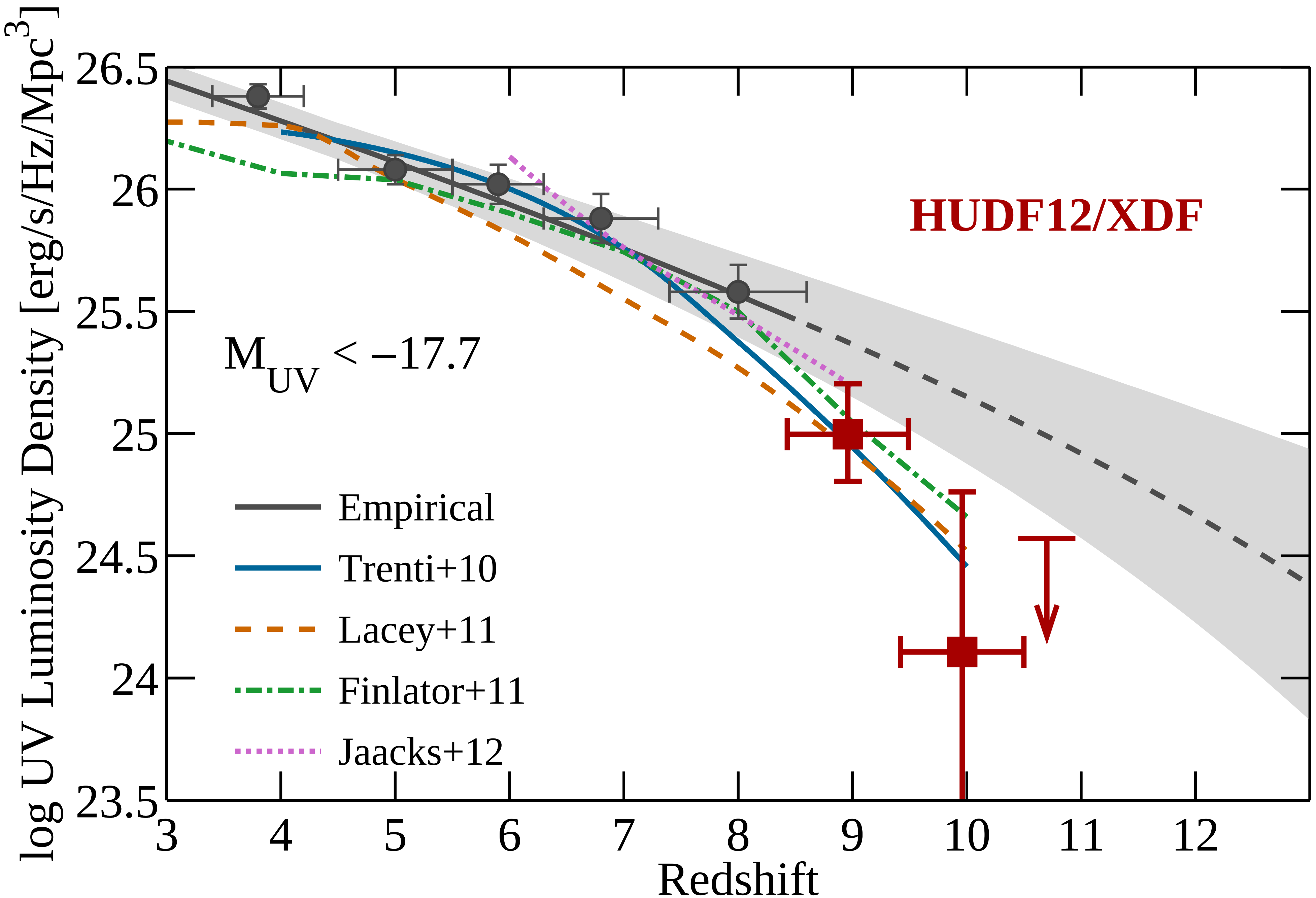
Number of sources is small in each bin, however, all determinations lie systematically below extrapolation of low-z trends.

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.

z~9 Samples from CLASH

Bouwens et al. 2013:

analyzed 19 CLASH clusters

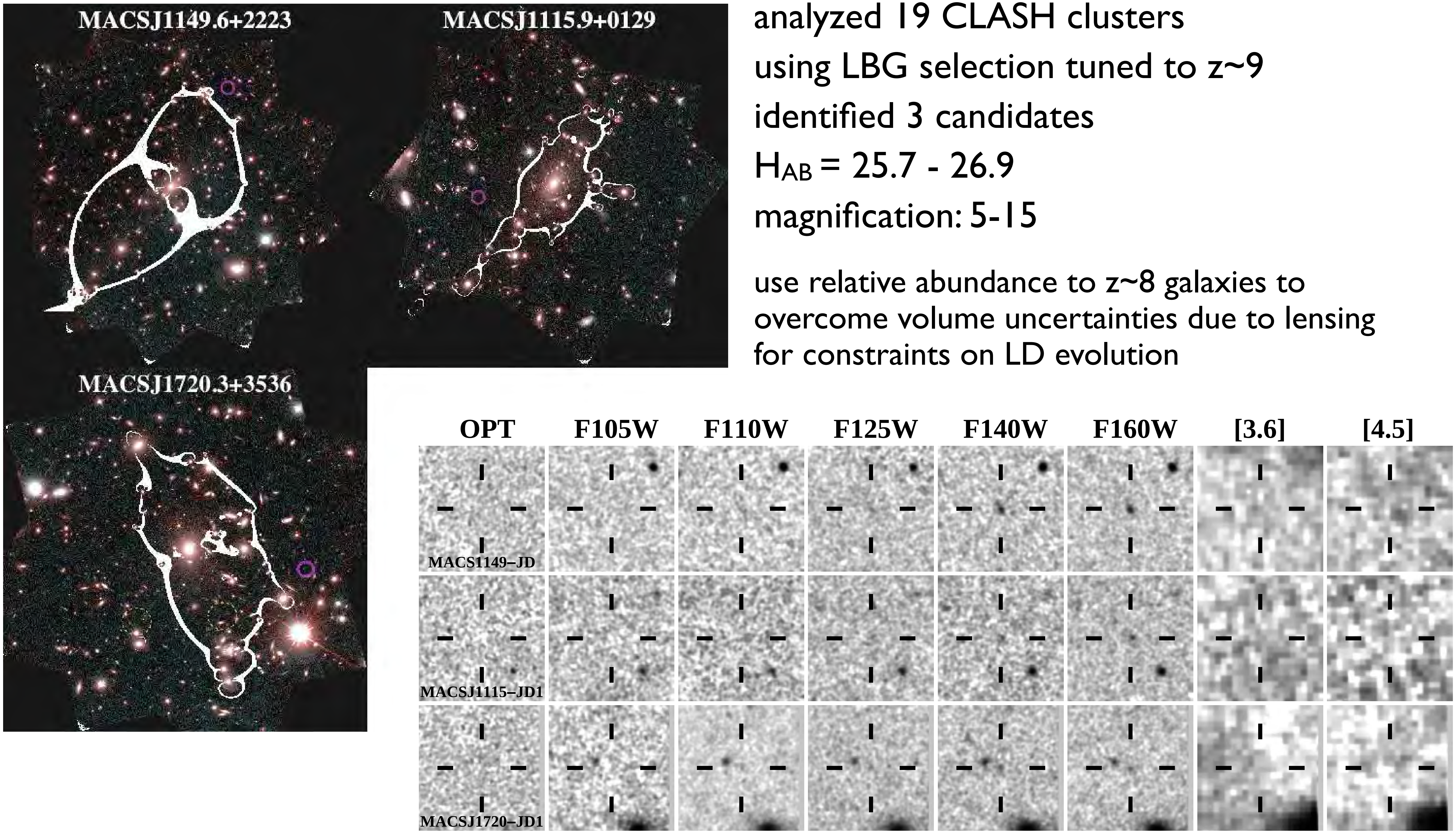
using LBG selection tuned to z~9

identified 3 candidates

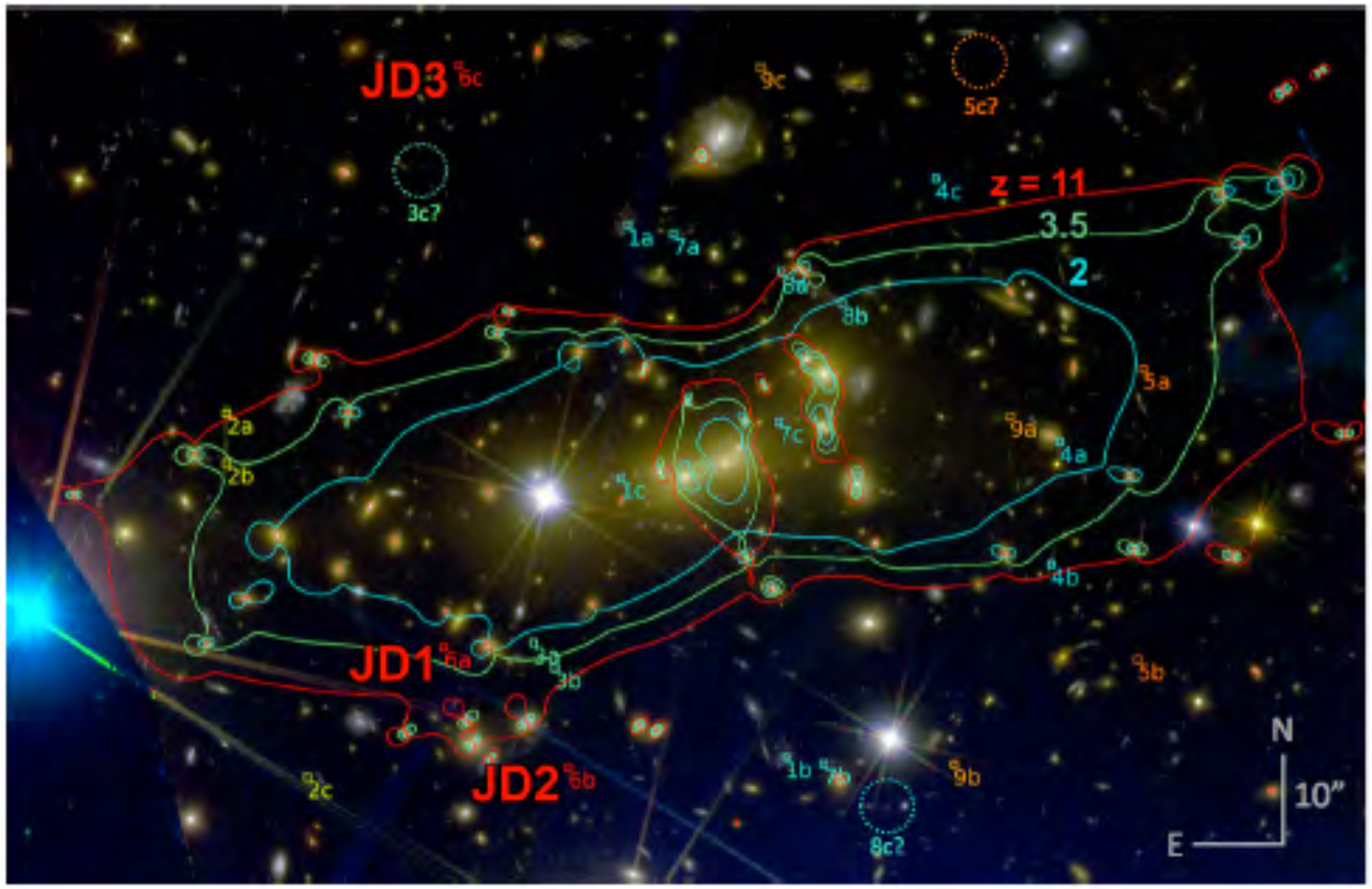
H_{AB} = 25.7 - 26.9

magnification: 5-15

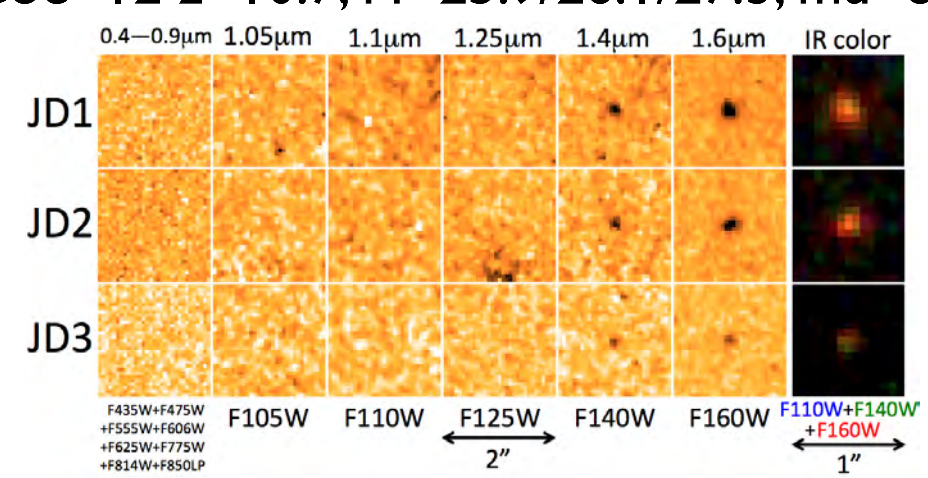
use relative abundance to z~8 galaxies to overcome volume uncertainties due to lensing for constraints on LD evolution

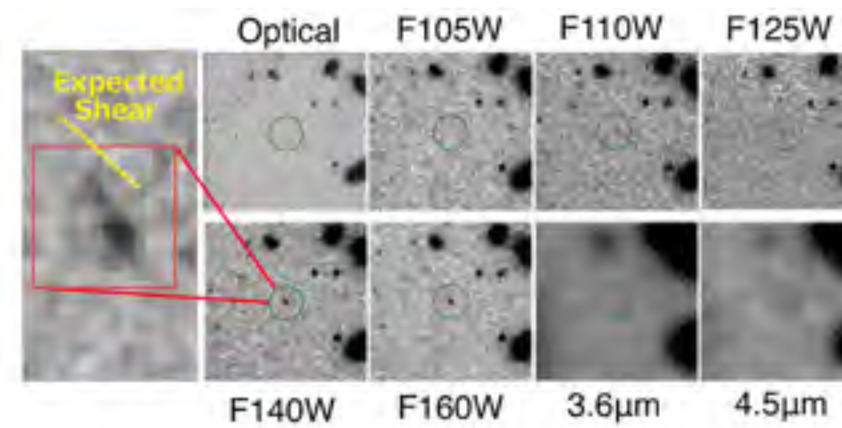


Two Additional z~10 Candidates from CLASH

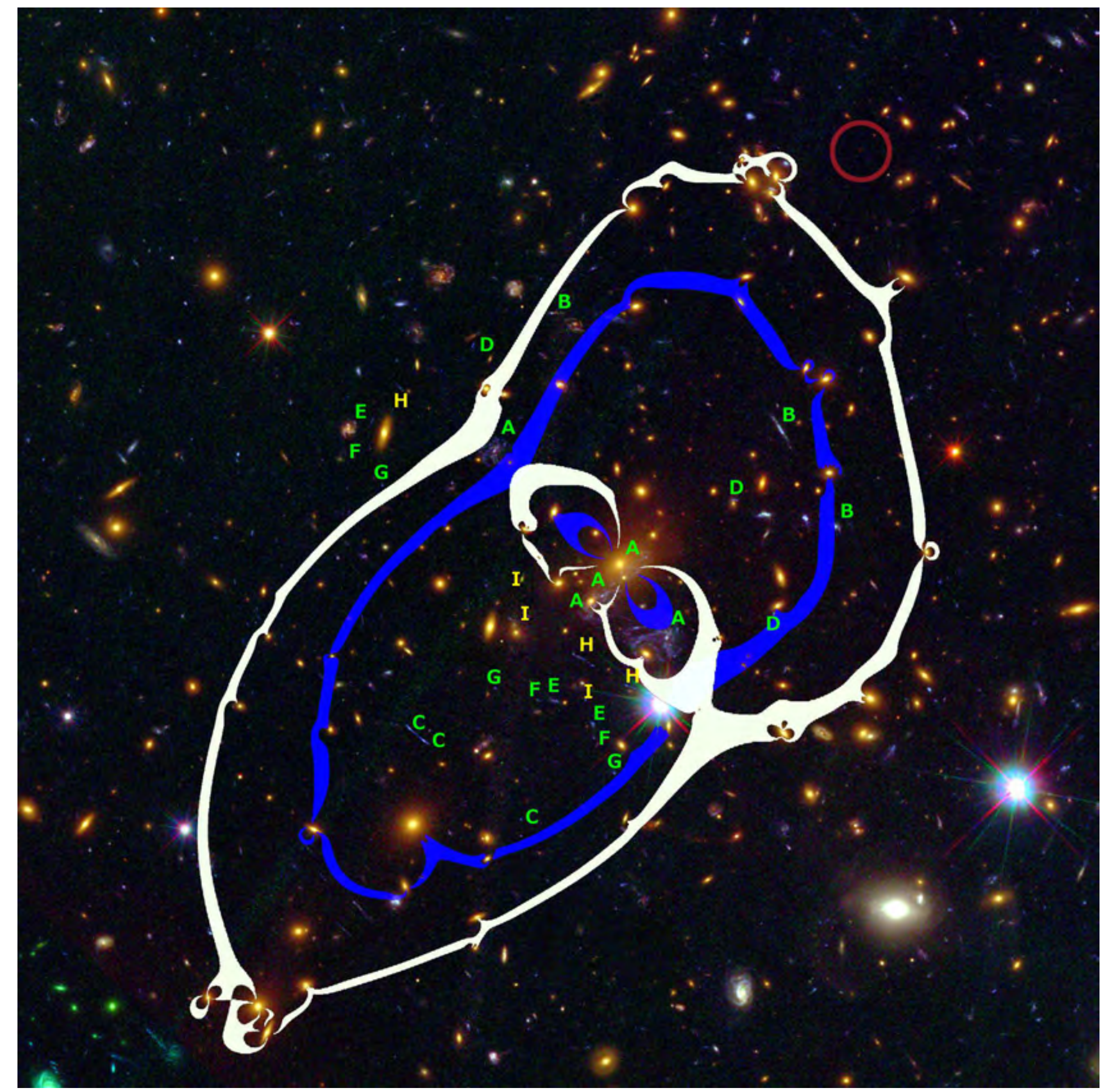


Coe+12 z=10.7, H=25.9/26.1/27.3, mu~8/7/2

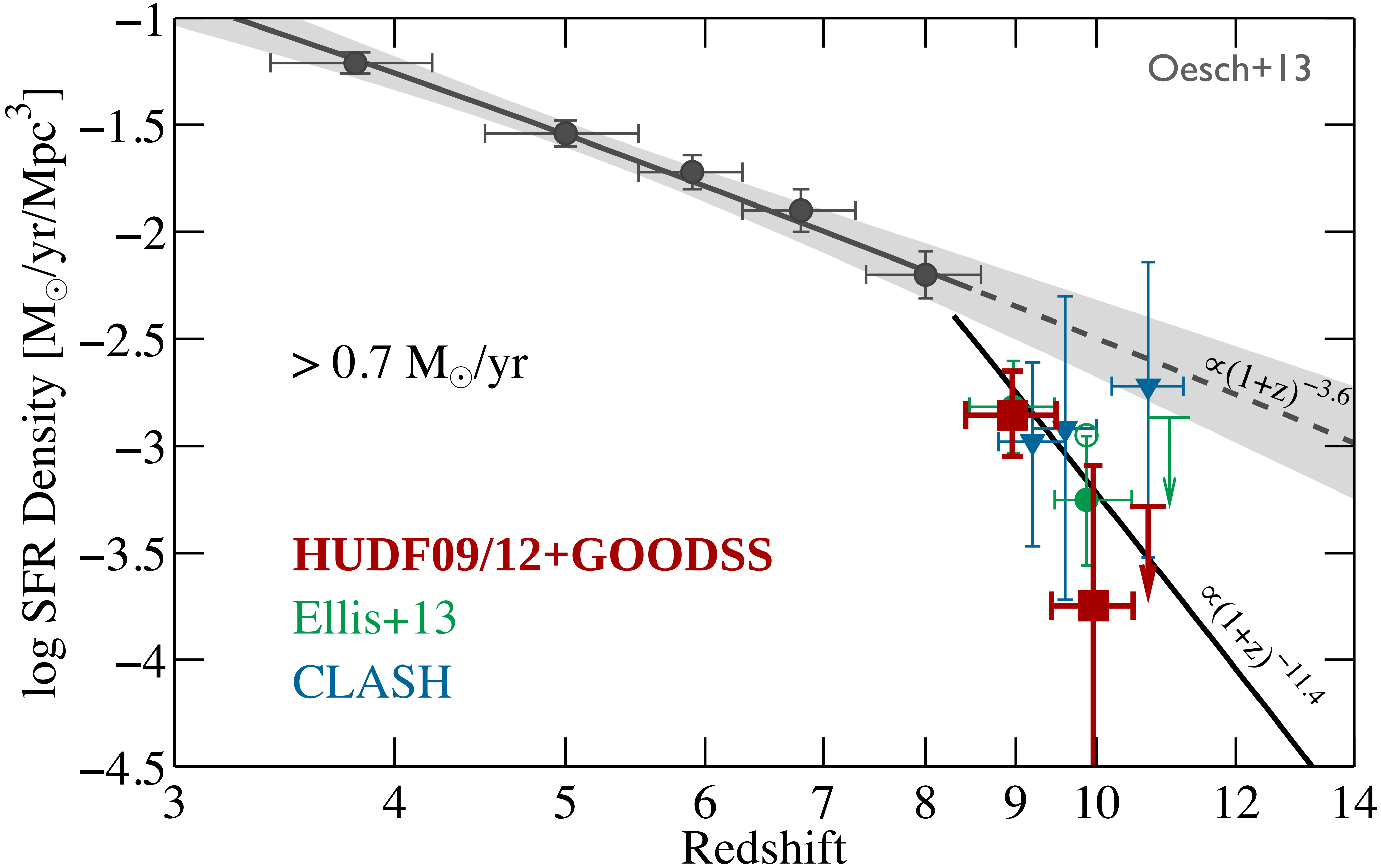




Zheng+12 z=9.6, H=25.7, mu=14-26



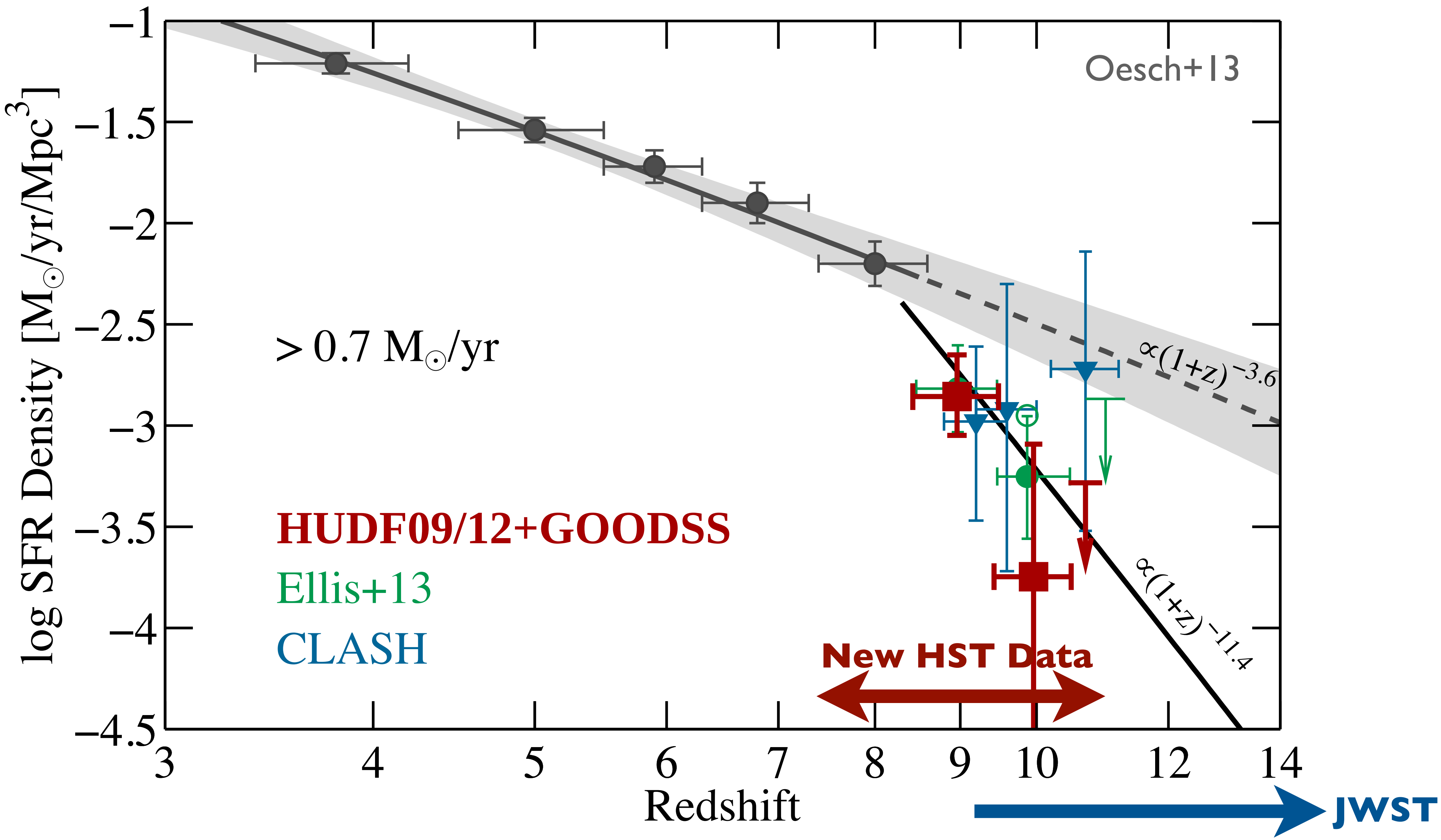
SFRD Evolution at z>8



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

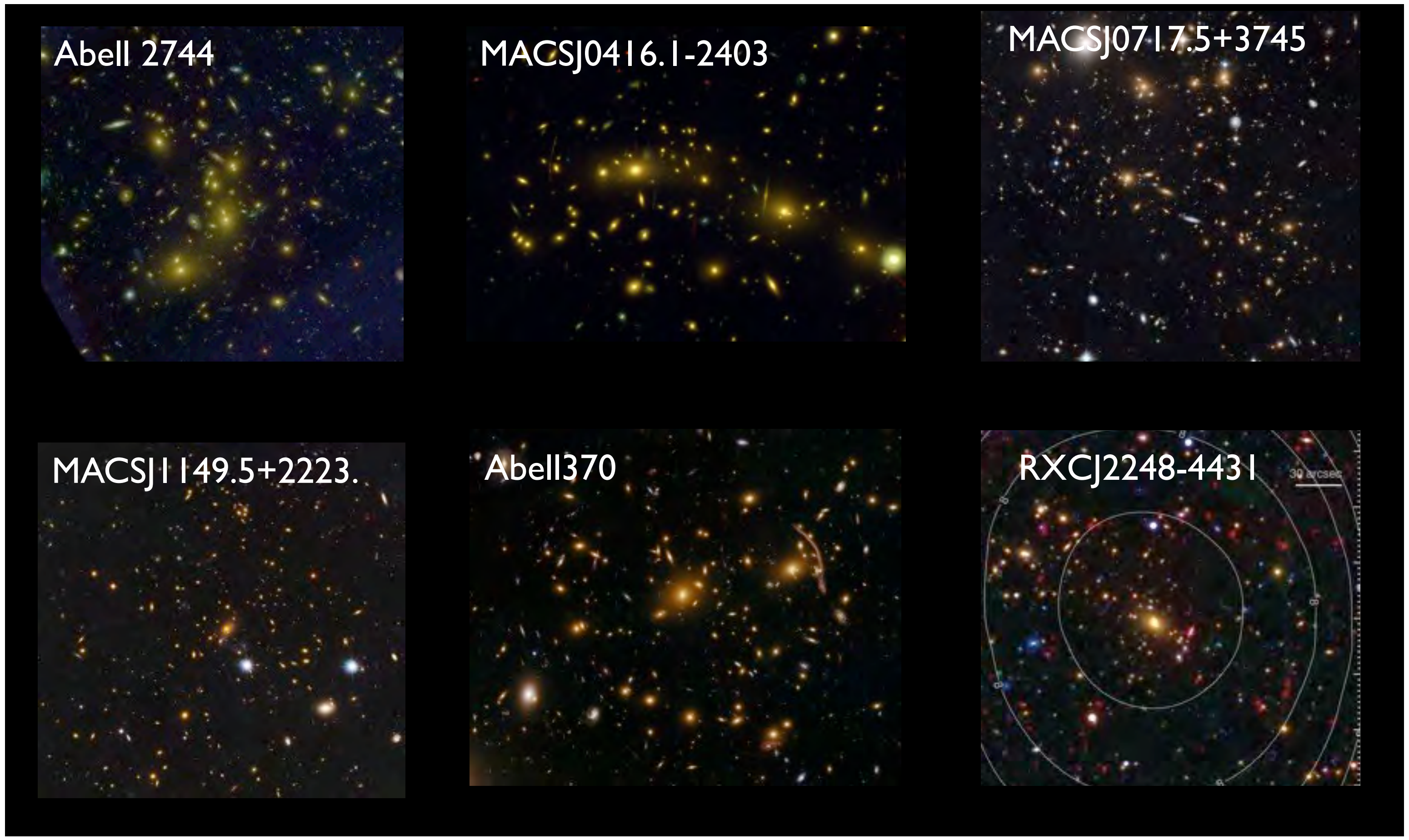
SFRD Evolution at z>8



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!

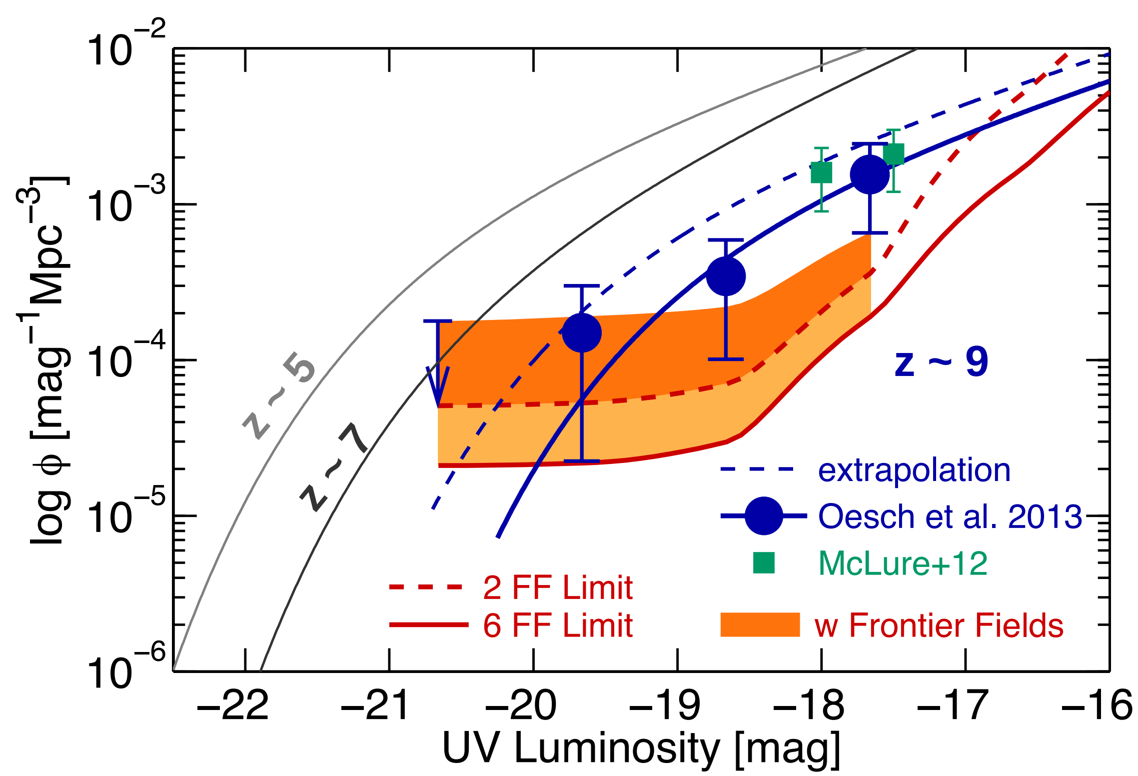
The Cosmic Dawn in the Near Future: The HST Frontier Fields



- ***HST Frontier Fields*** will vastly improve constraints on SFRD evolution at z>8 with 4-6 clusters and parallel blank field data with IRAC coverage

- If SFRD decline was **steady** as at z=4-8: expect **~30 z~10** galaxies in all 12 HFFs

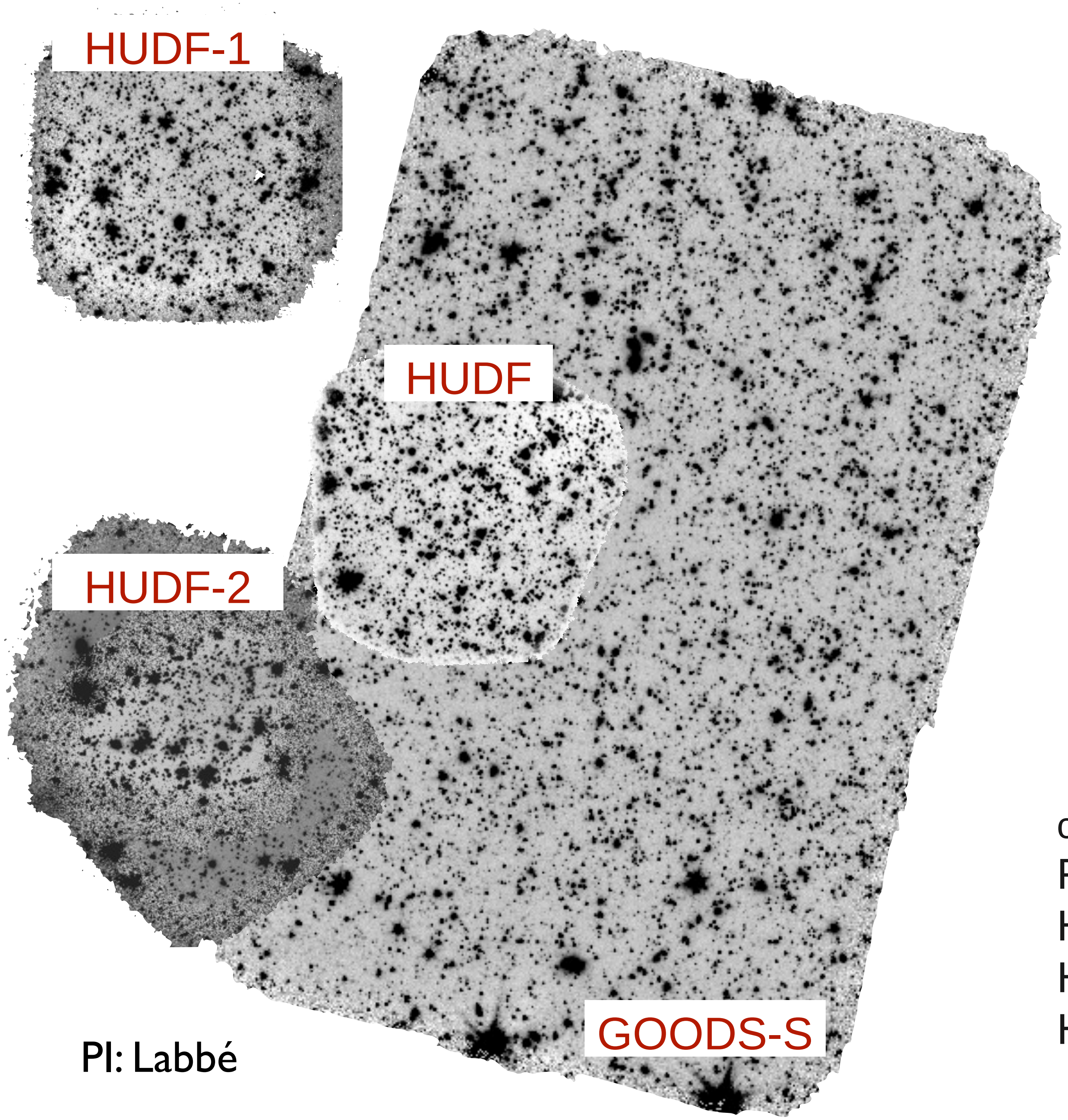
- If SFRD decline is as **rapid** as currently indicated: only **~3 z~10** galaxies expected



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

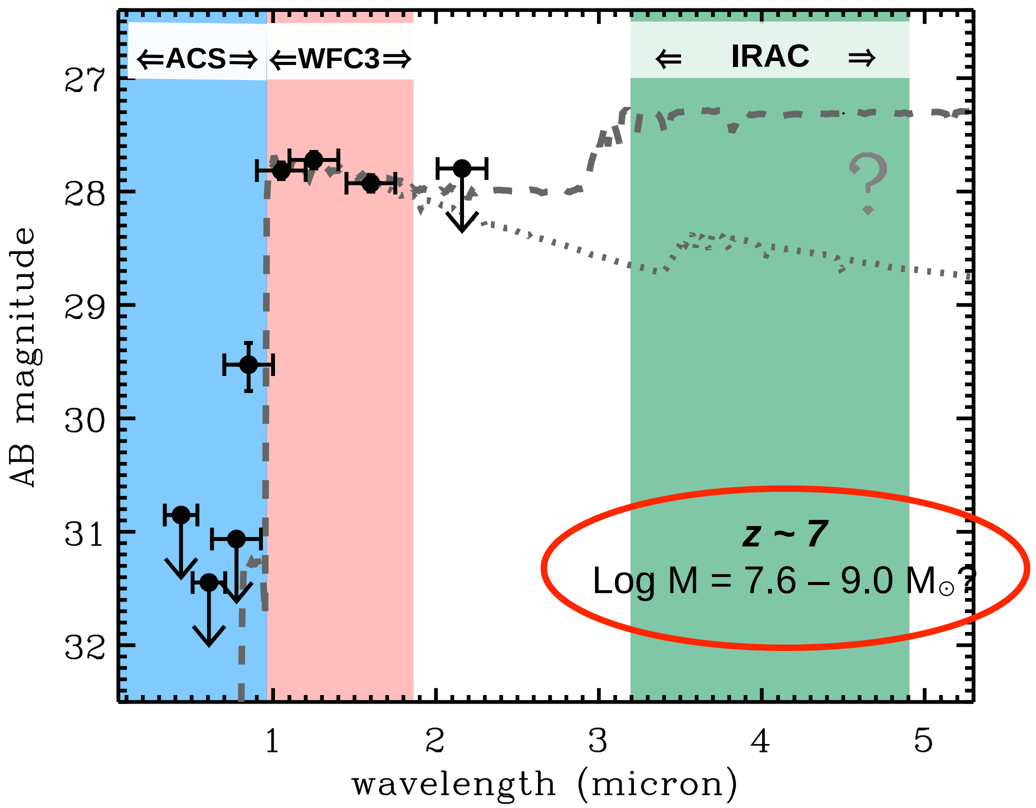
Spitzer IRAC probes rest-frame optical

Ultra-Deep IRAC Data over the HUDF09



PI: Labbé

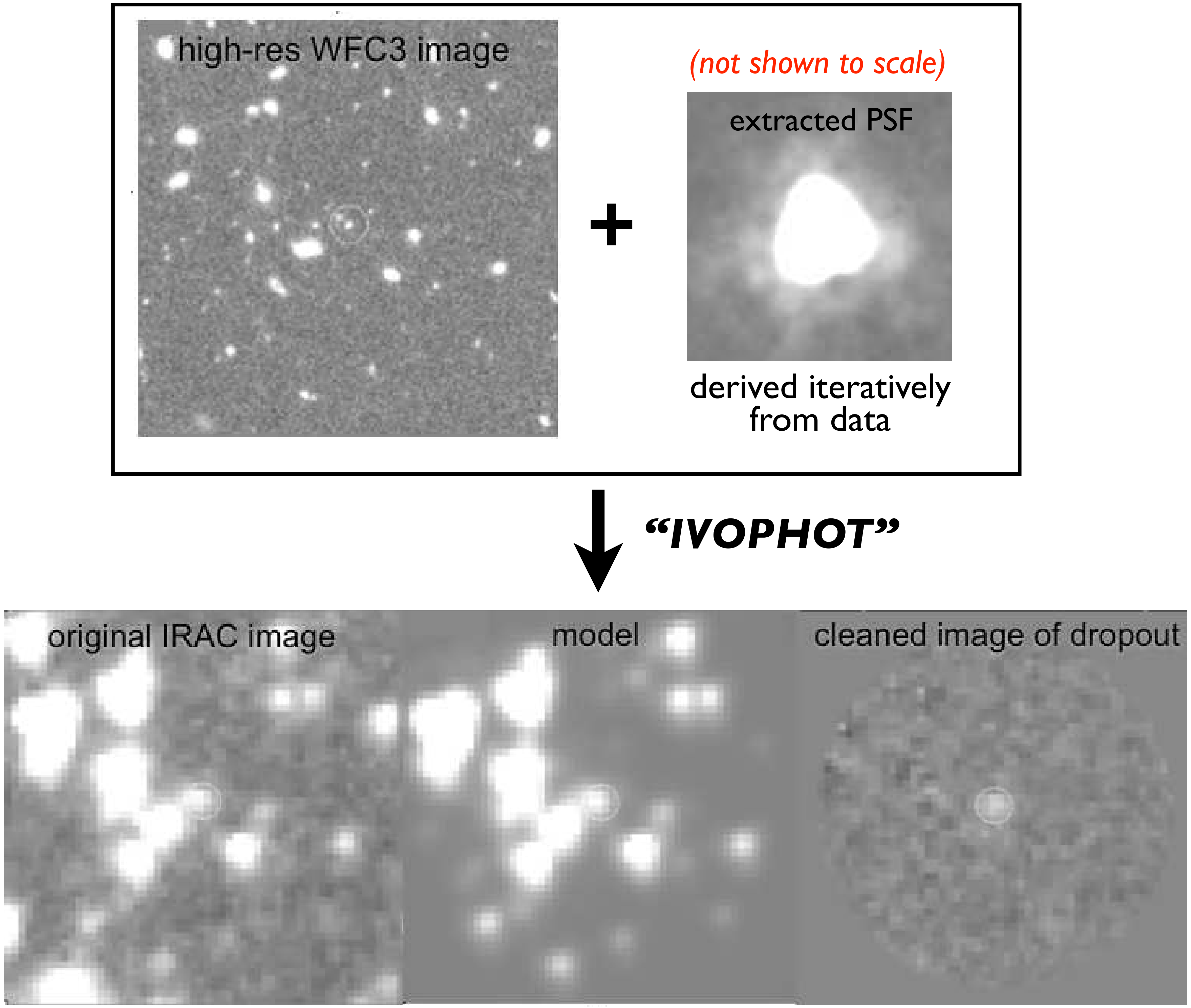
IRAC is crucial for rest-frame optical SEDs and constrains on stellar masses/ages at z>4



coverage (hours):

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

Extracting Rest-Frame Optical Photometry



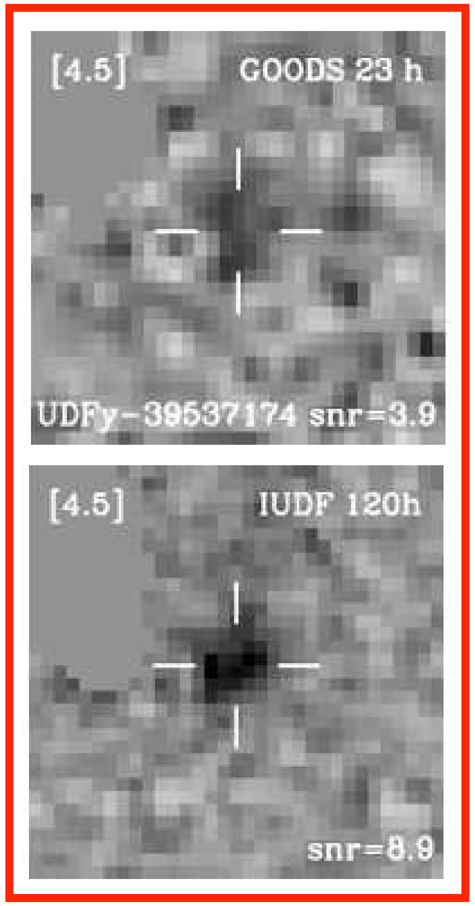
Need to model neighboring sources in a crowded field to extract accurate photometry

Mass Estimates are now possible out to z~8

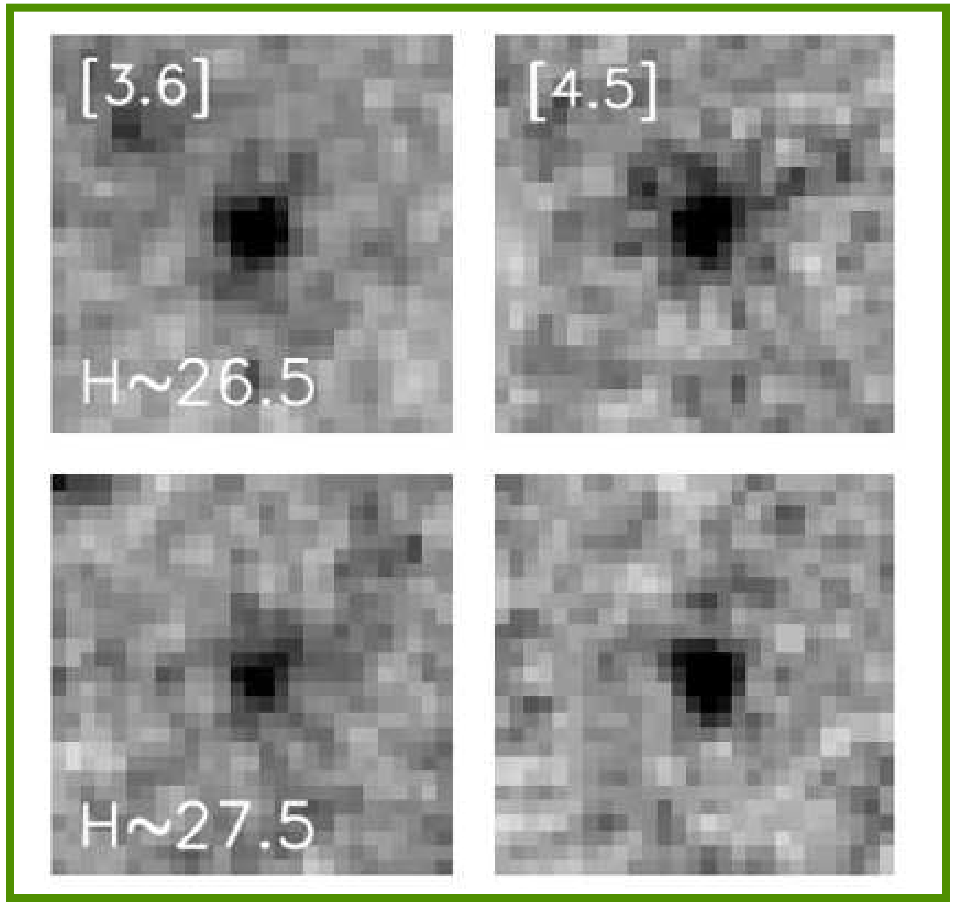
The IUDF10 led to the first robust (>5σ) detections of 9 z~8 candidates (~32% are detected at >3σ).

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

few robust individual detections

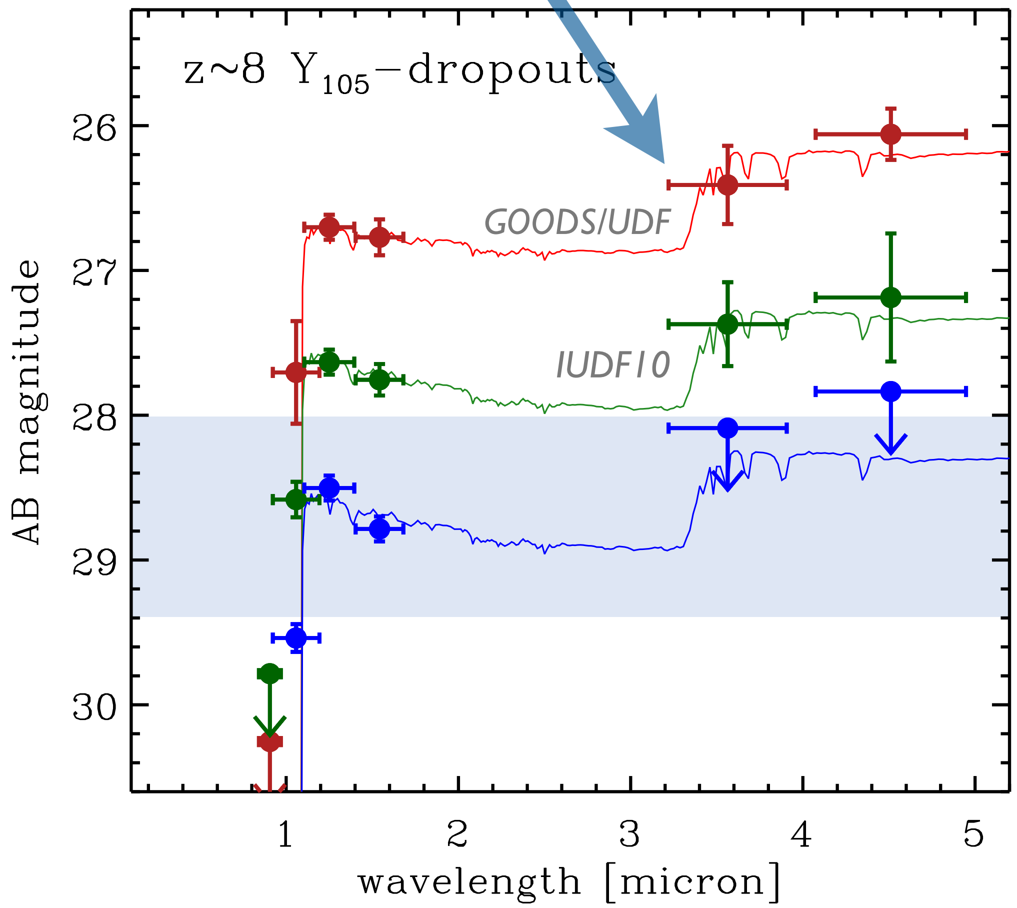


clear detections in stacks



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

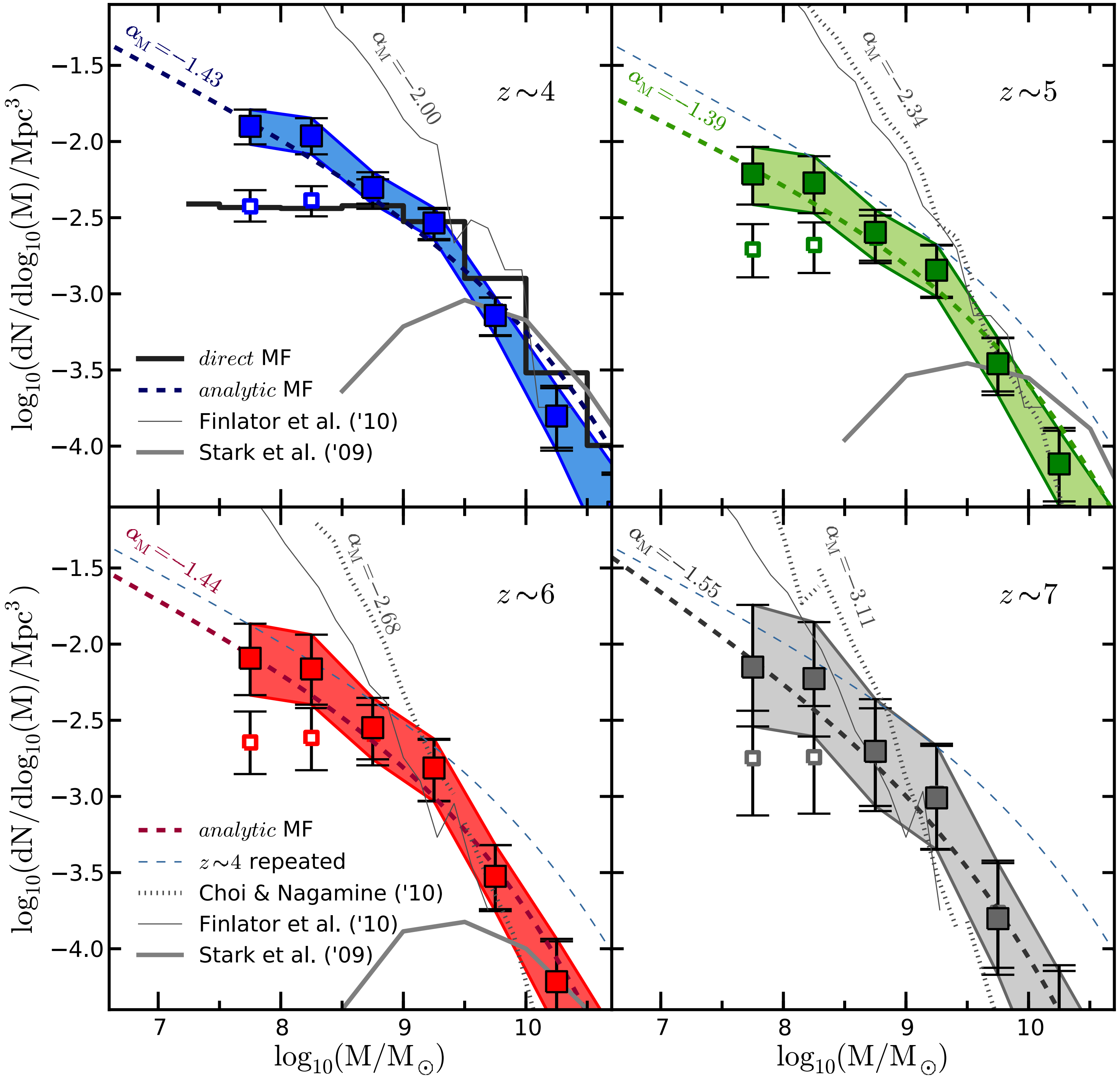
typical galaxy has mass of 1e9 Msol



Labbé, Oesch et al. 2012

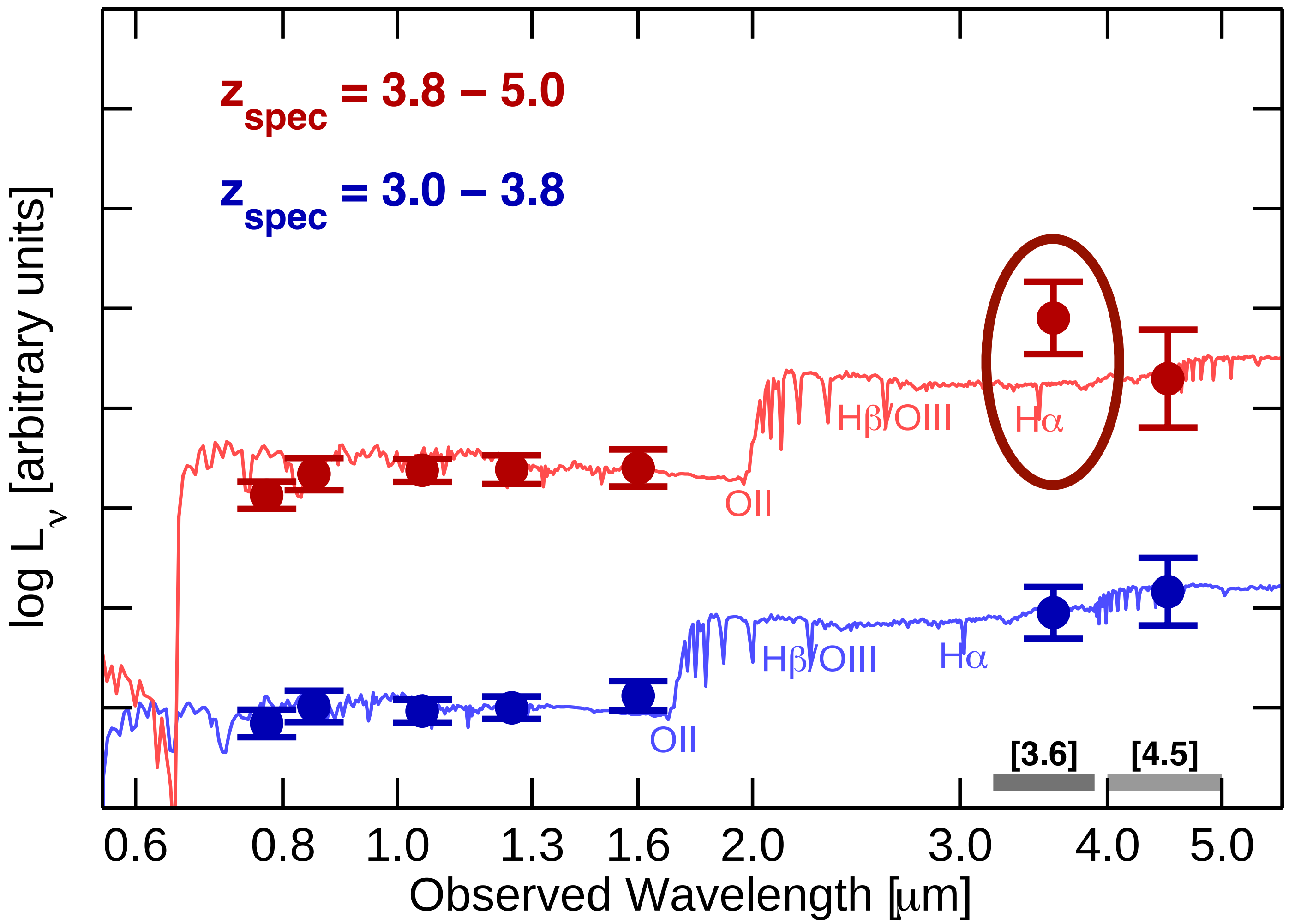
Evolution of the Mass Function

Gonzalez+11



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

Caveat: Strong Emission Lines



on average: 0.3 mag

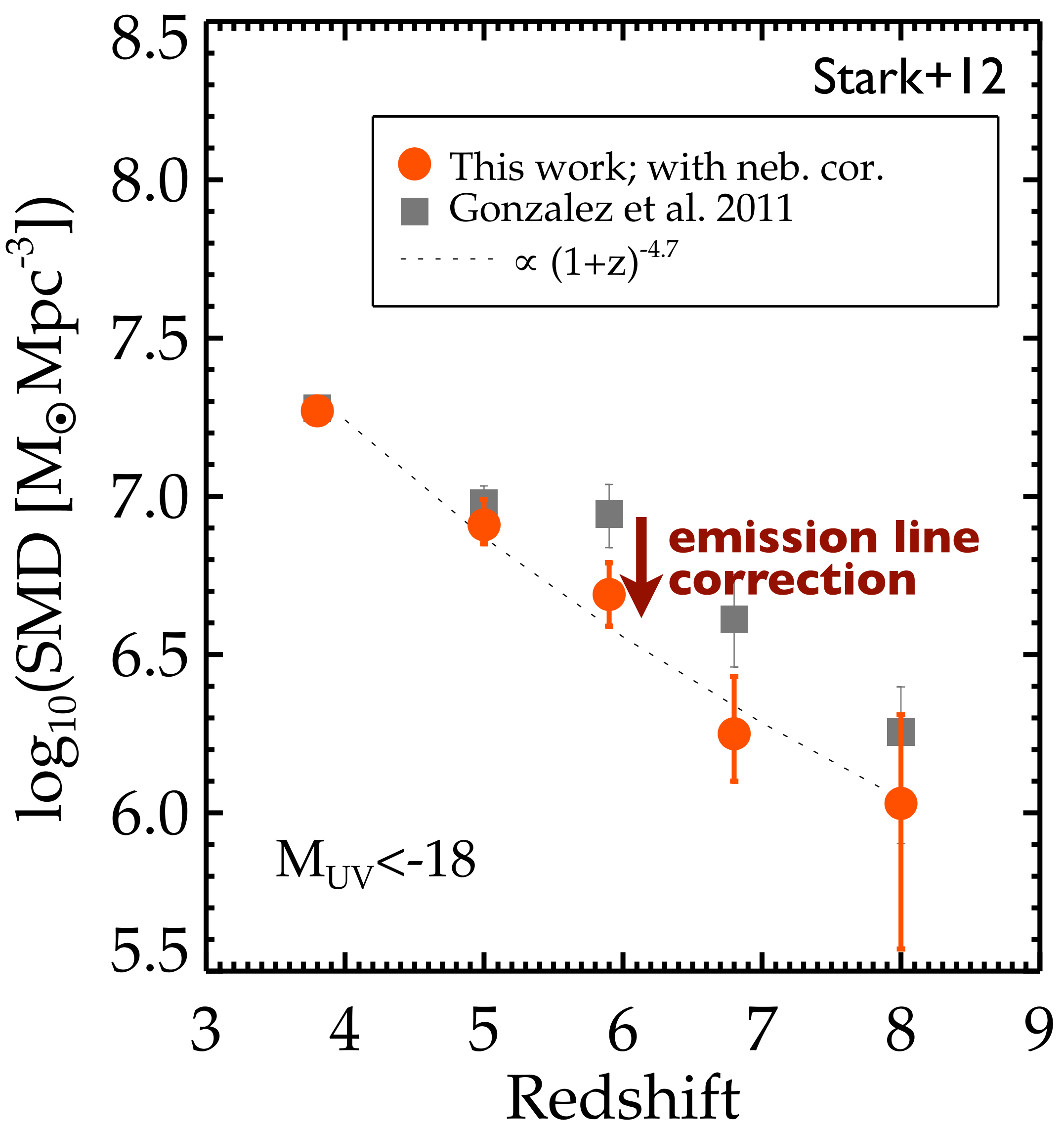
EW(Hα) ≃ 300 Å

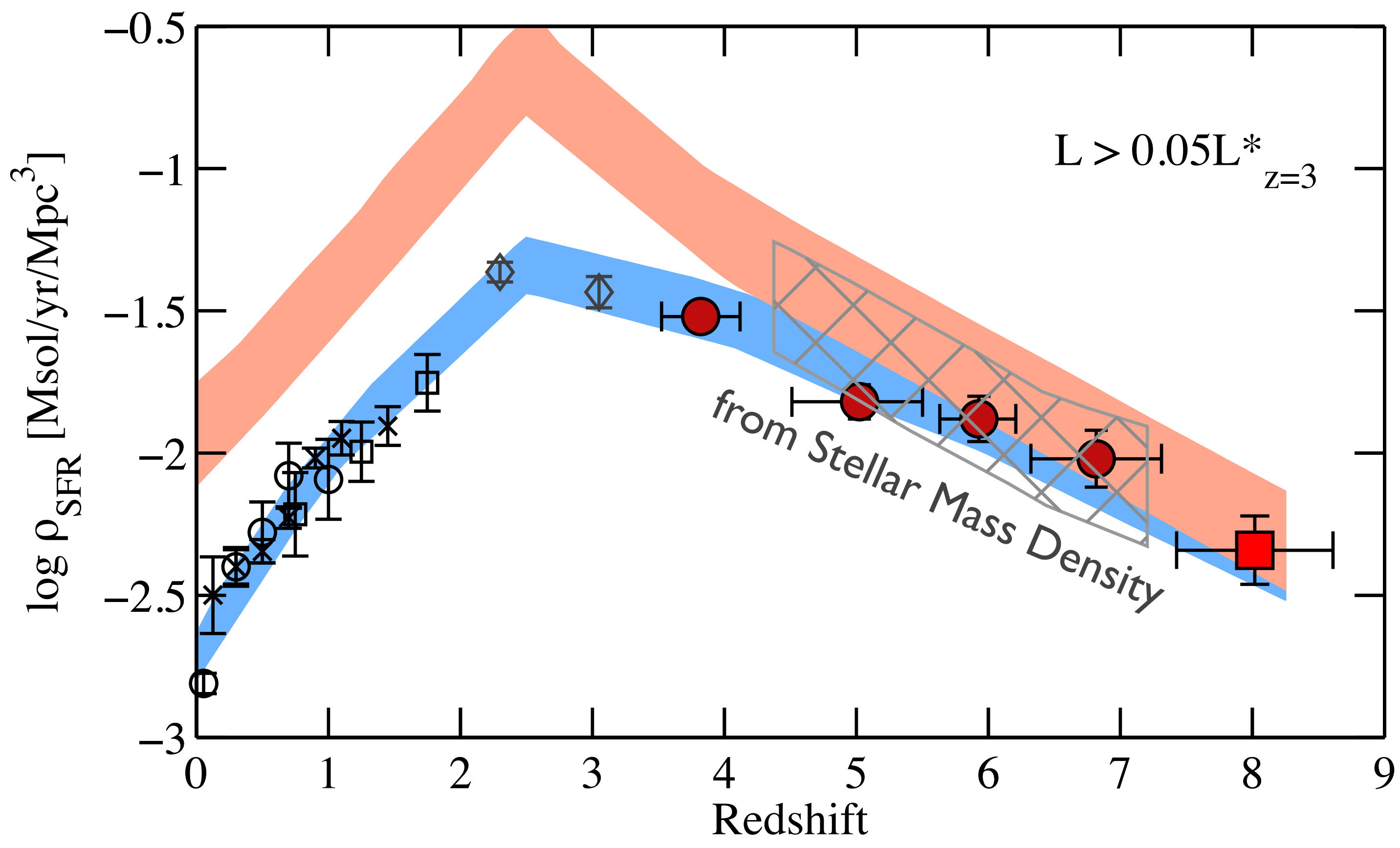
Strong rest-frame optical emission lines can significantly contribute to IRAC flux measurements. These will thus bias mass measurements. Important to estimate the magnitude of this effect.

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

Stellar Mass Density

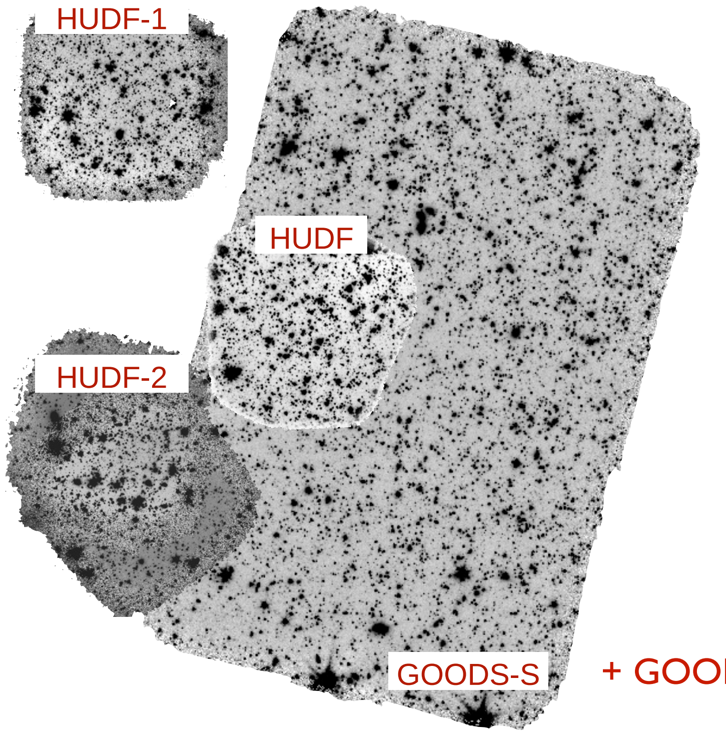
Zero-th order empirical correction for ELs: ➡ up to a factor 2-3x in stellar mass density





SFRD and SMD are in very good agreement!

A Rest-Frame Optical View on z~4 Galaxies



+ GOODS-N

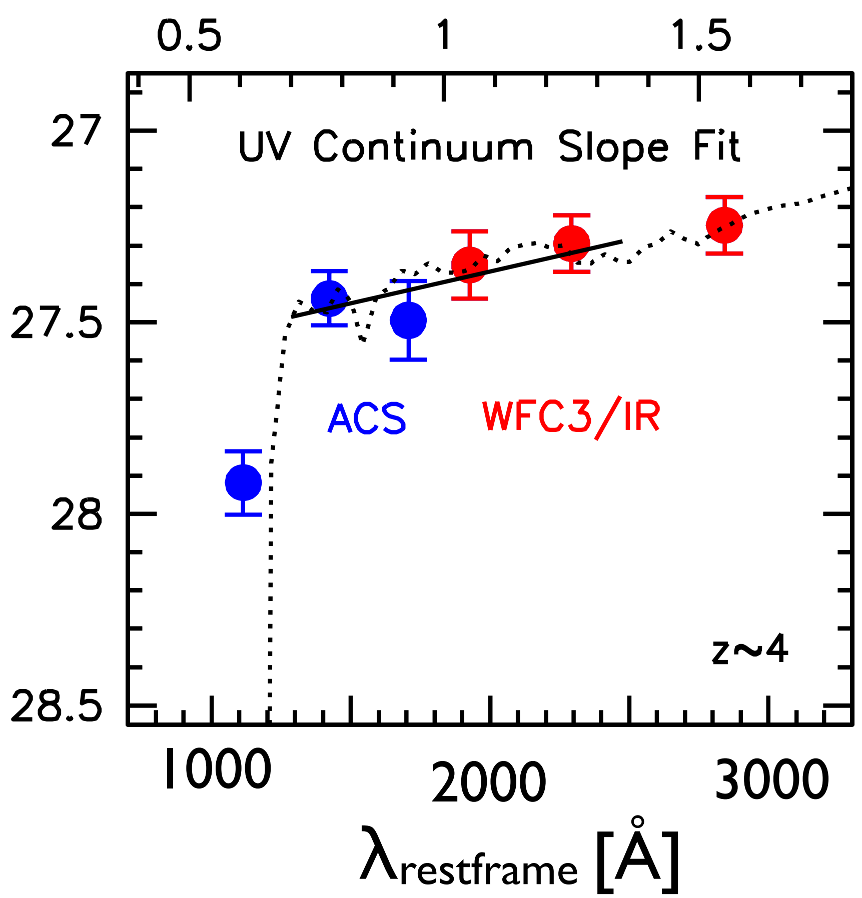
Large samples of galaxies available with deep IRAC coverage:

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

HST only probes UV: UV Continuum Slopes

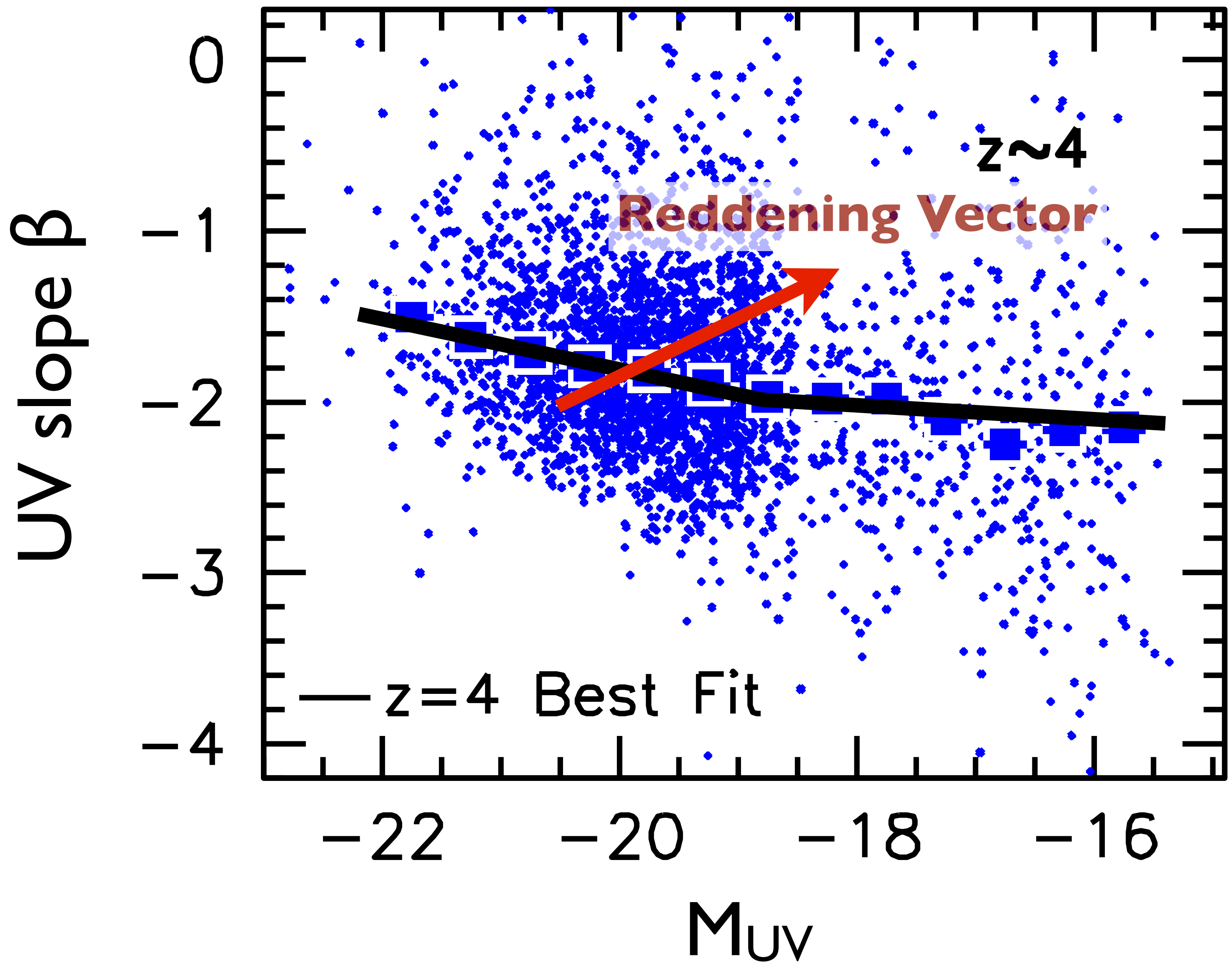
Large body of literature on inferring physical properties of high-z galaxies based on UV continuum slopes.

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



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

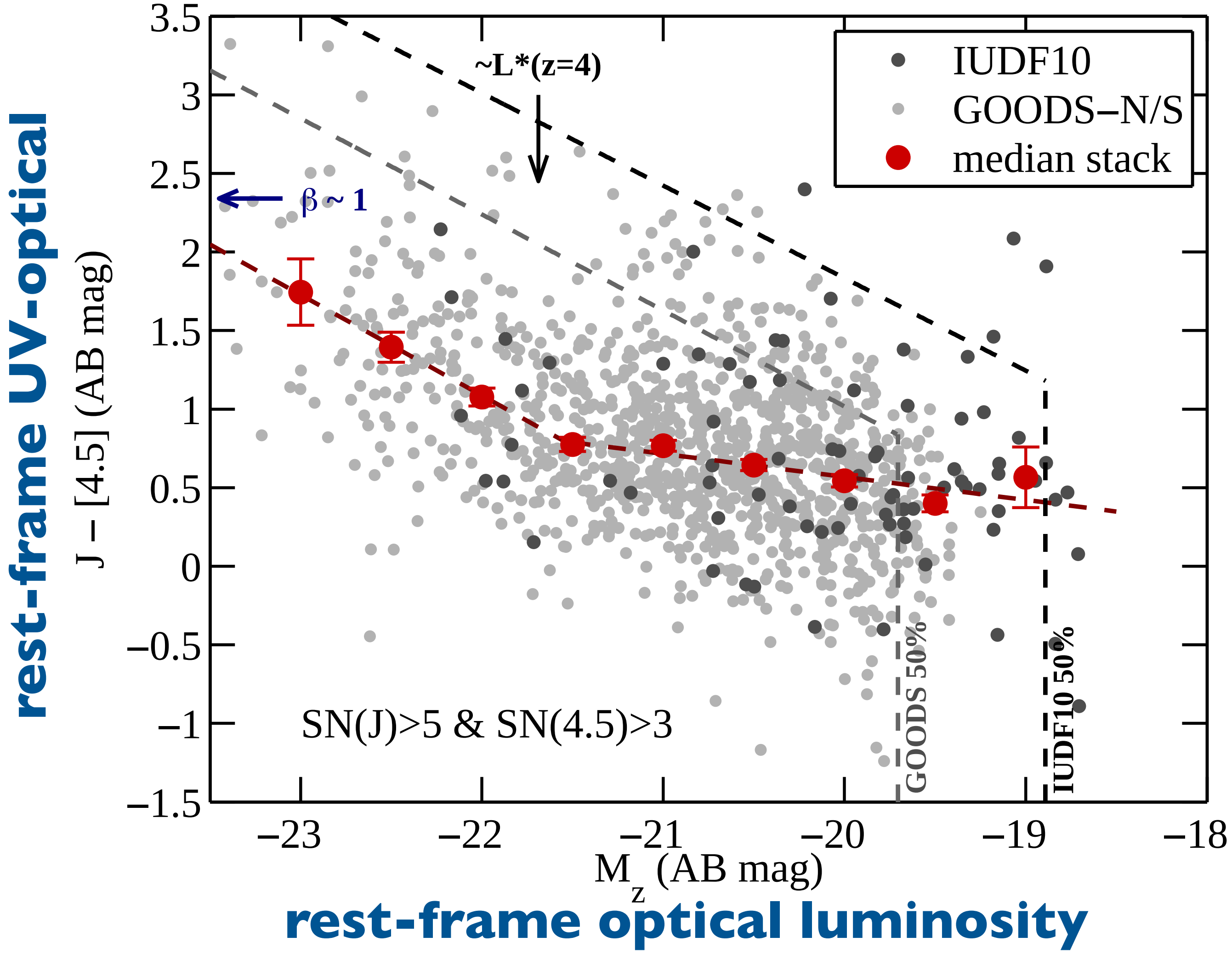
Bouwens+13

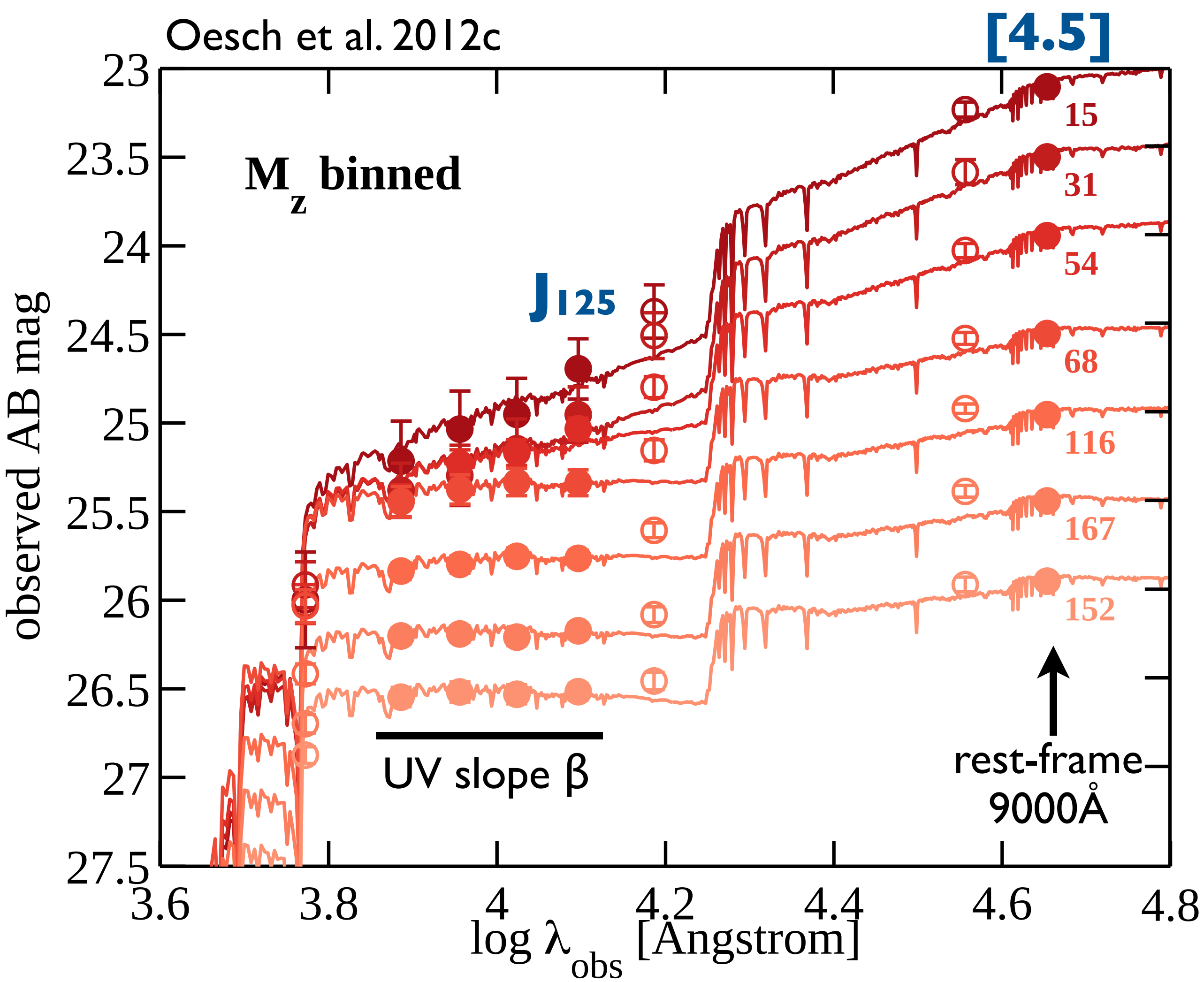


See also: Wilkins+11, Dunlop+11, Castellano+11, Bouwens+09/10, Finkelstein+10/11, Rogers+13

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

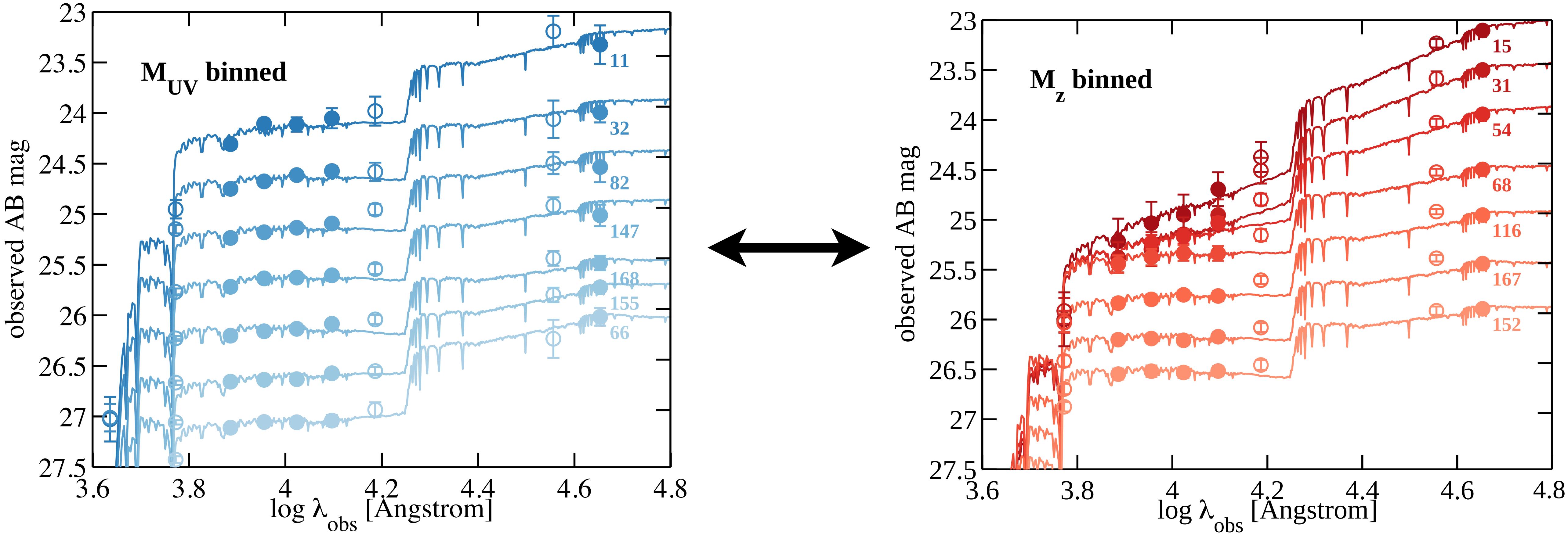




Brighter galaxies are significantly redder in their UV-to-optical colors wrt fainter sources.

Bright galaxies also show redder UV continuum slopes.

Rest-Frame Optical vs Rest-Frame UV View



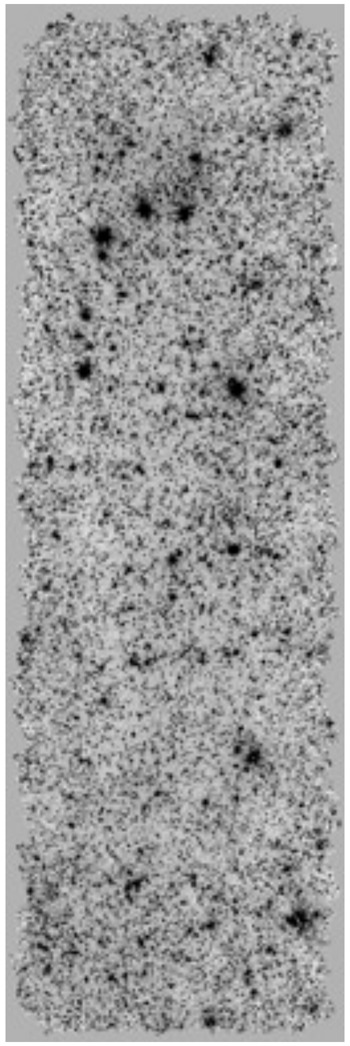
Rest-frame optical view reveals that z~4 galaxy population is more diverse than what is inferred from UV-based analyses.

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

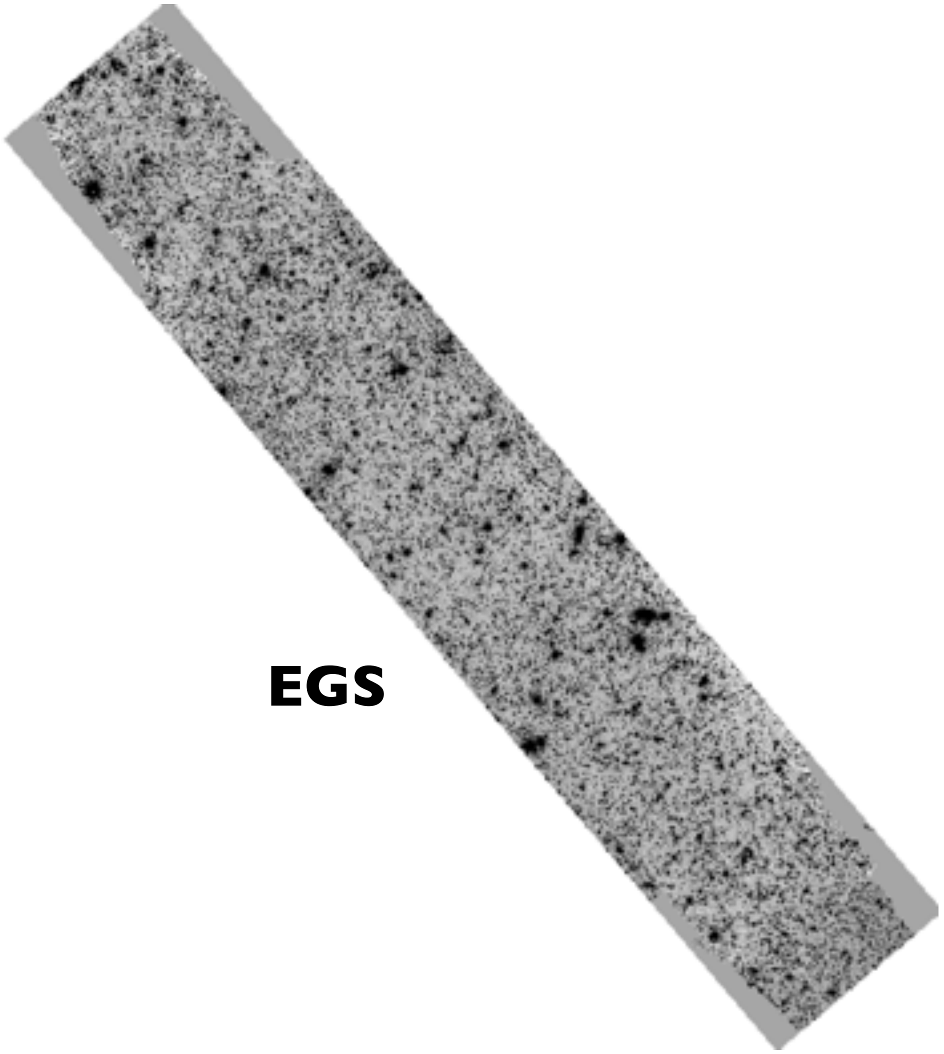
The (IR) Future is Bright: SEDS + S-CANDELS

- 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)

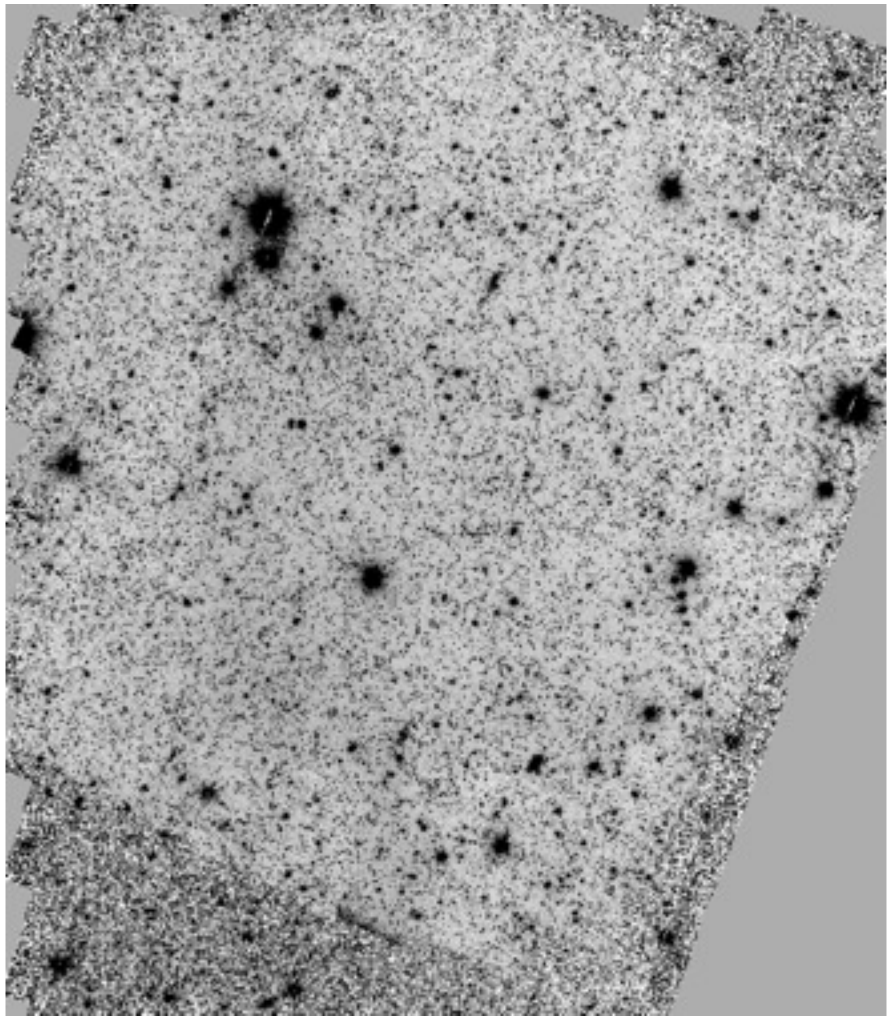
➡ MFs, duty cycles, etc..



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..)