Probing the Dawn of Galaxies at z~9-12:
New Insights from Deep HST and Spitzer Observations

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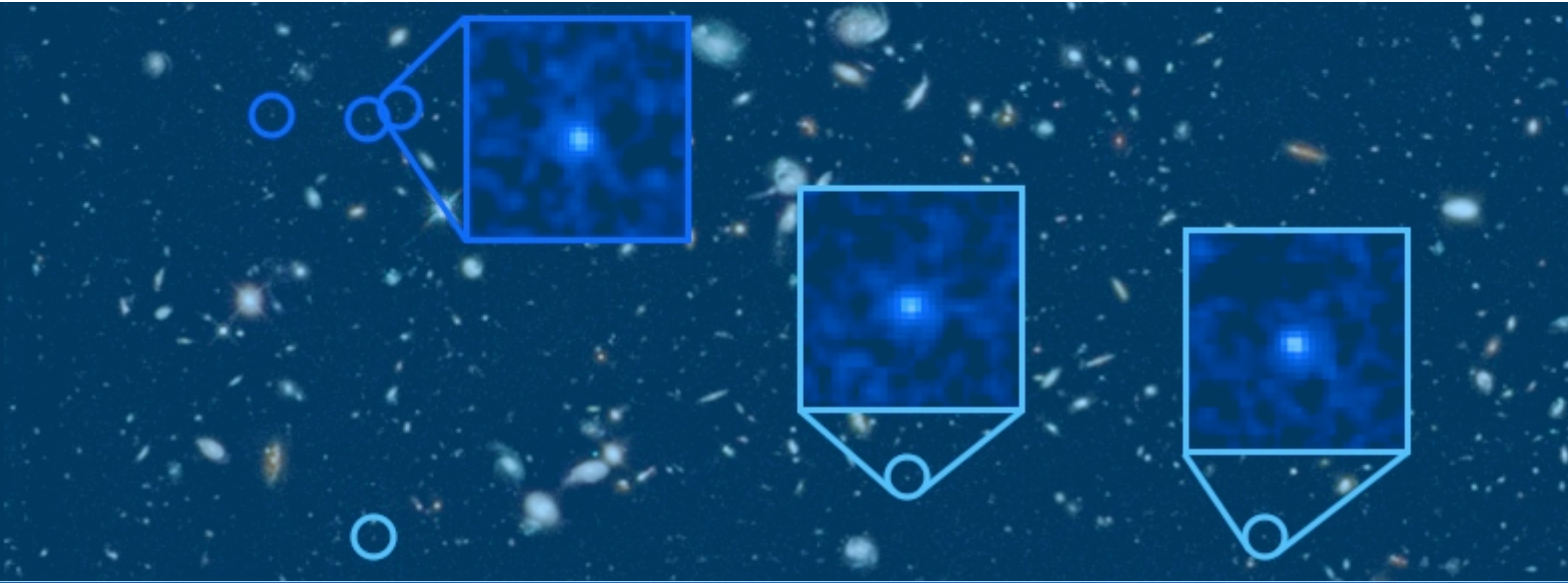


Loeb 2006

z~1100: CMB

After radiation-matter decoupling, the universe is dark for a 100-200 Myr, before the first stars (so-called PopIII) form in mini-halos (~10^6 $M_\odot$) thanks to H_2 cooling.

z~20-30: First Stars

Simulations show: a given mini-halo may only form one PopIII star (of mass ~50-100 $M_\odot$)

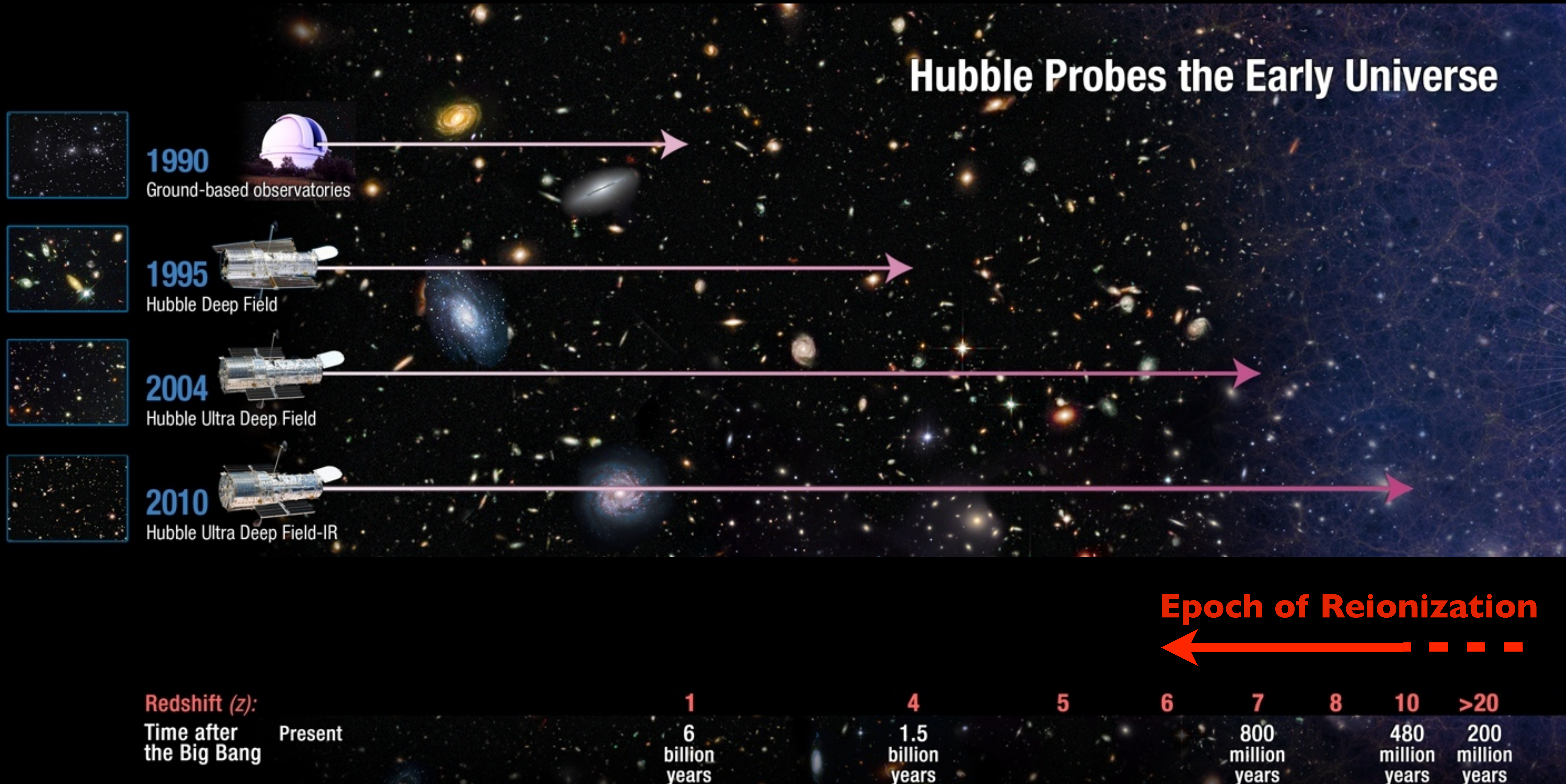
Their SNe enrich the IGM enabling more efficient cooling and making way for the formation of the first galaxies.

z~15-6: Reionization

These first galaxies are believed to drive cosmic reionization, which is likely a prolonged process, ending at z~6.

z<6: Build-up of today's galaxies

The Reionization Epoch with HST

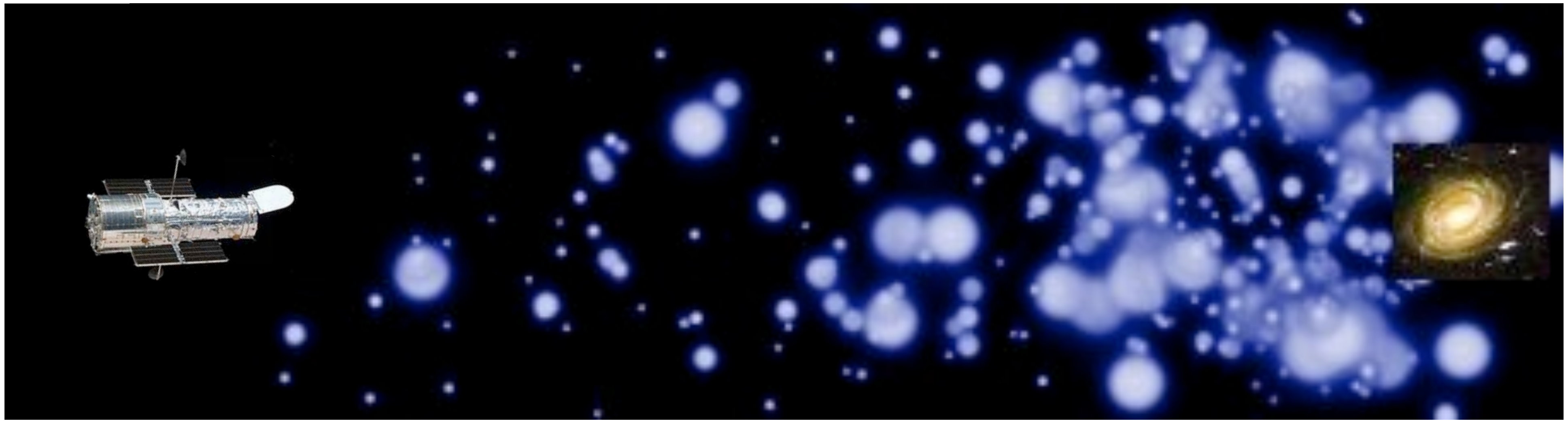


When did first galaxies form? How fast did they build up?
What regulates SF in early universe?
Were there enough galaxies to complete cosmic reionization?

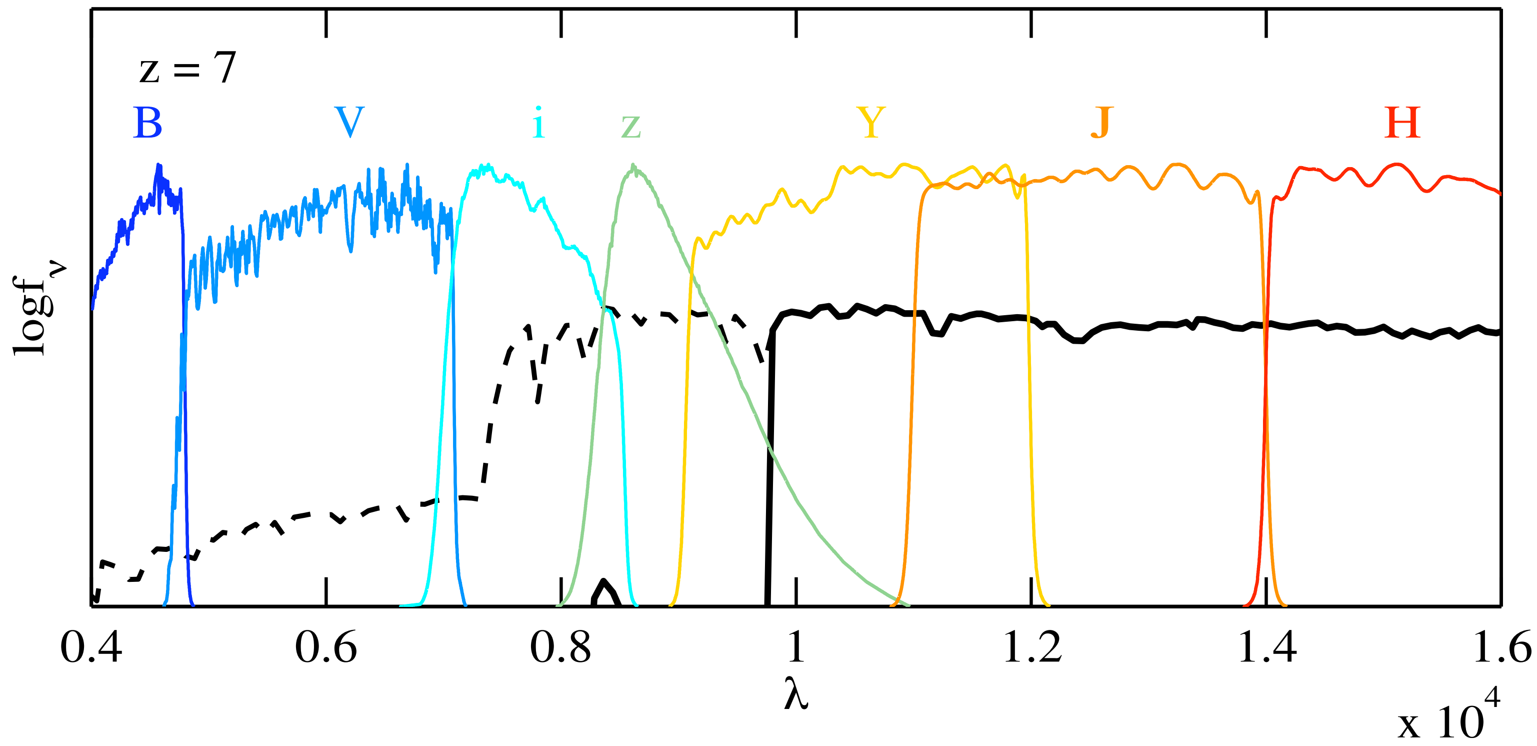
Outline

- **Introduction**
- **Galaxy Build-up Based on the Evolution of the UV LF**
- **Pushing the Frontier to z~9-12**
- **The Role of Galaxies in Cosmic Reionization**
- **Growing Galaxies: Evolution of Physical Parameters**

Selection of z>7 Galaxies: Need NIR Imaging

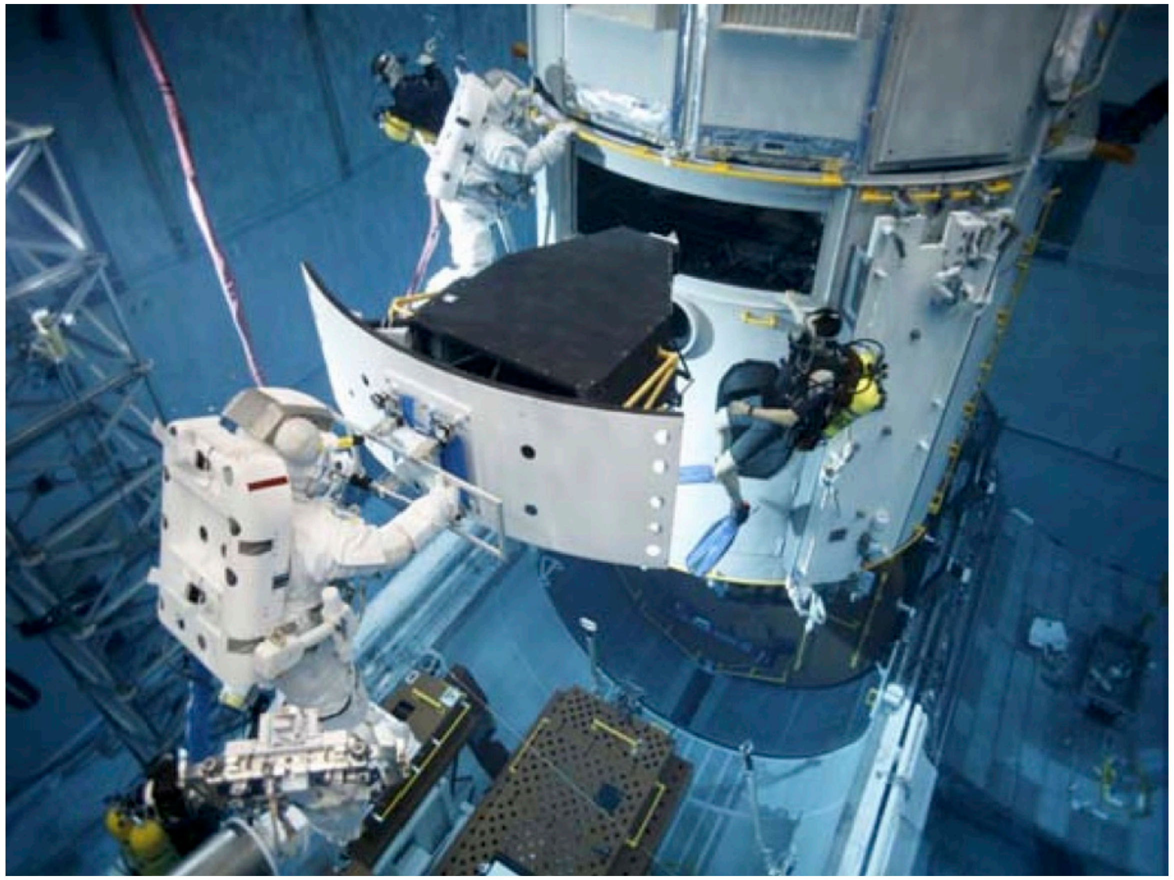


Lyman Break Galaxy Selection: based on IGM absorption



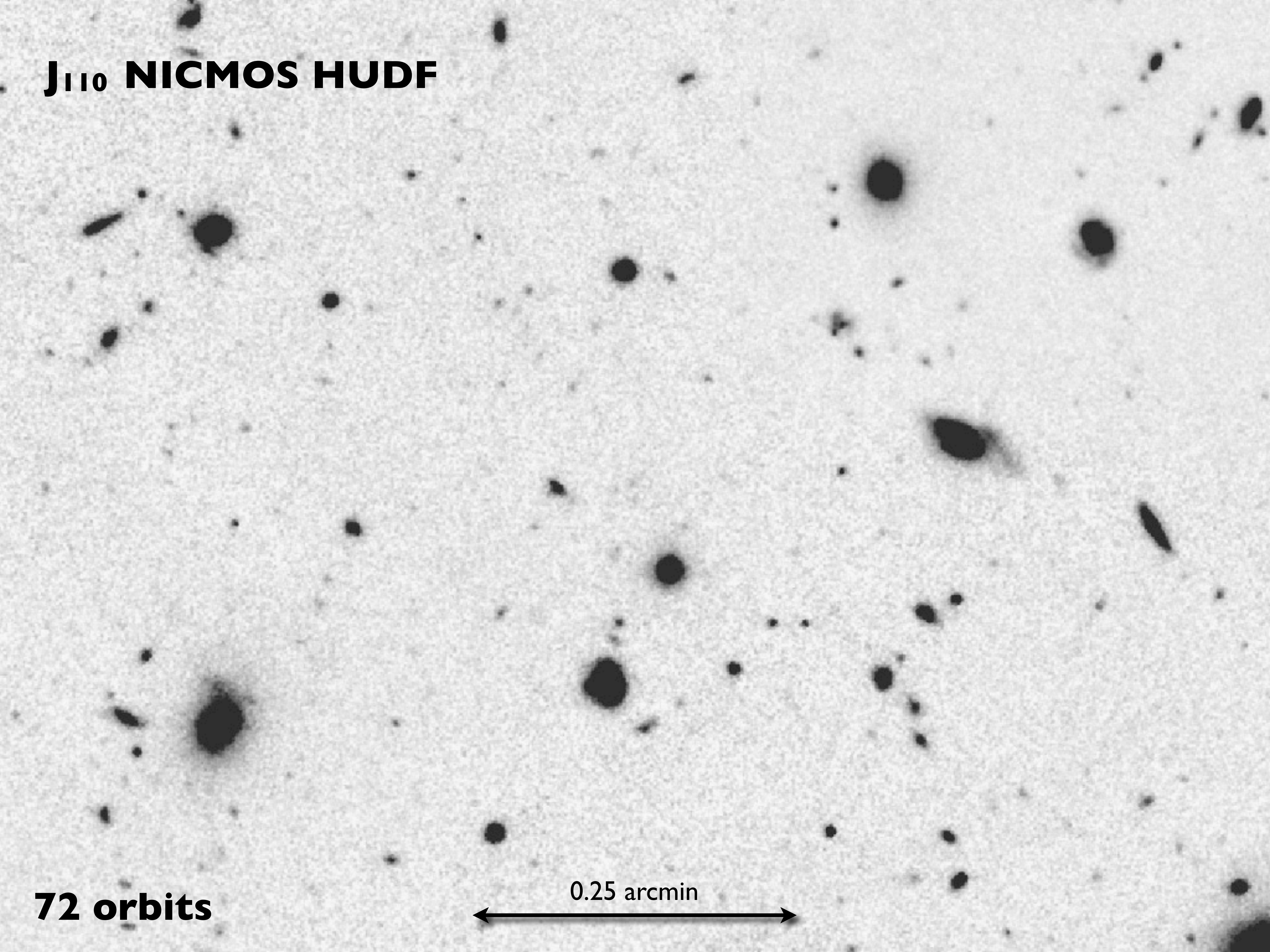
z>=7 galaxies can only be seen at NIR wavelengths

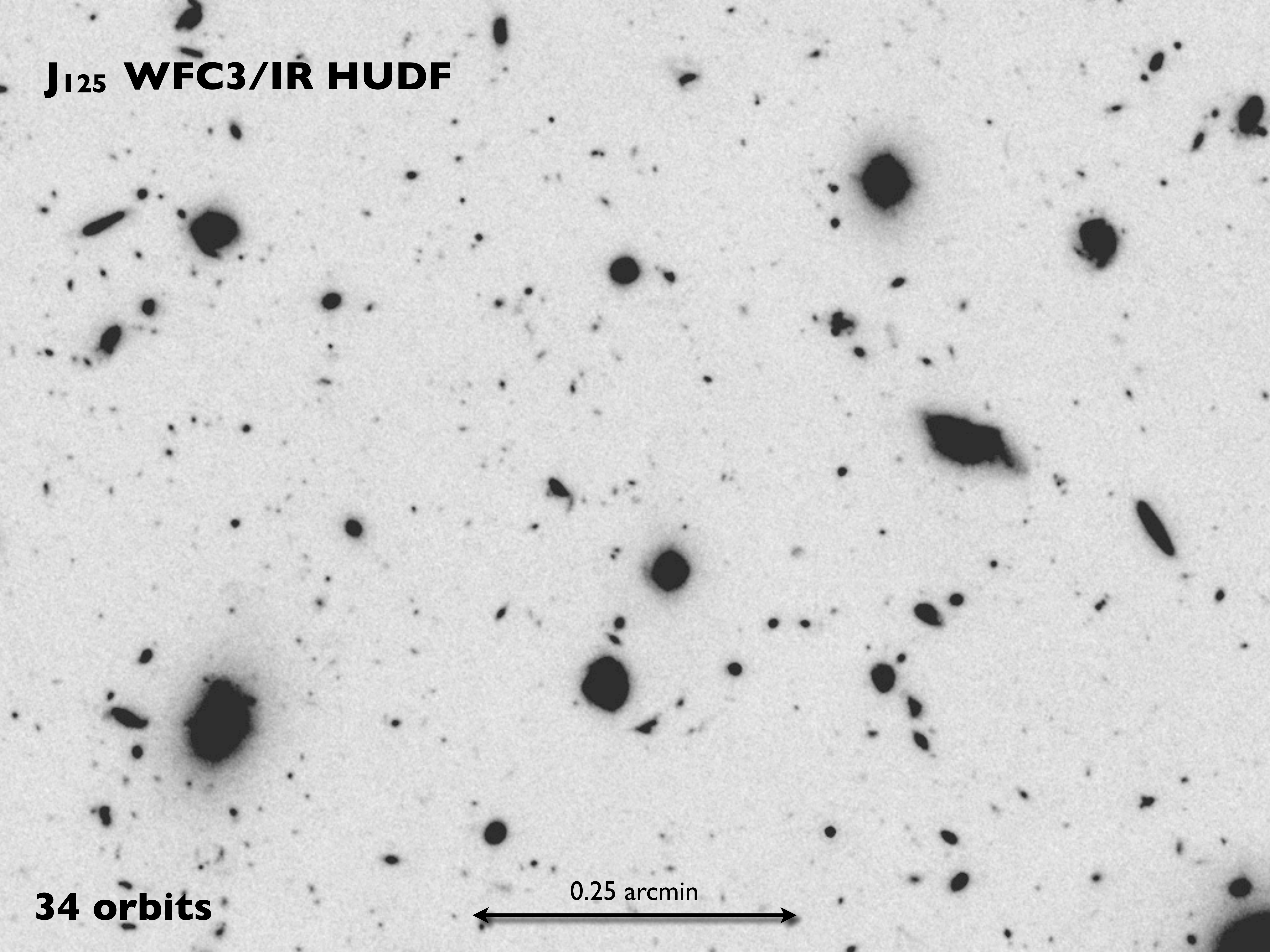
NIR with WFC3 on HST



- 6.5x larger field-of-view than previous NIR camera (NICMOS)
- 3-4x more sensitive than before
- 2x higher spatial resolution

➡ **~40x more efficient to explore the high-redshift universe**

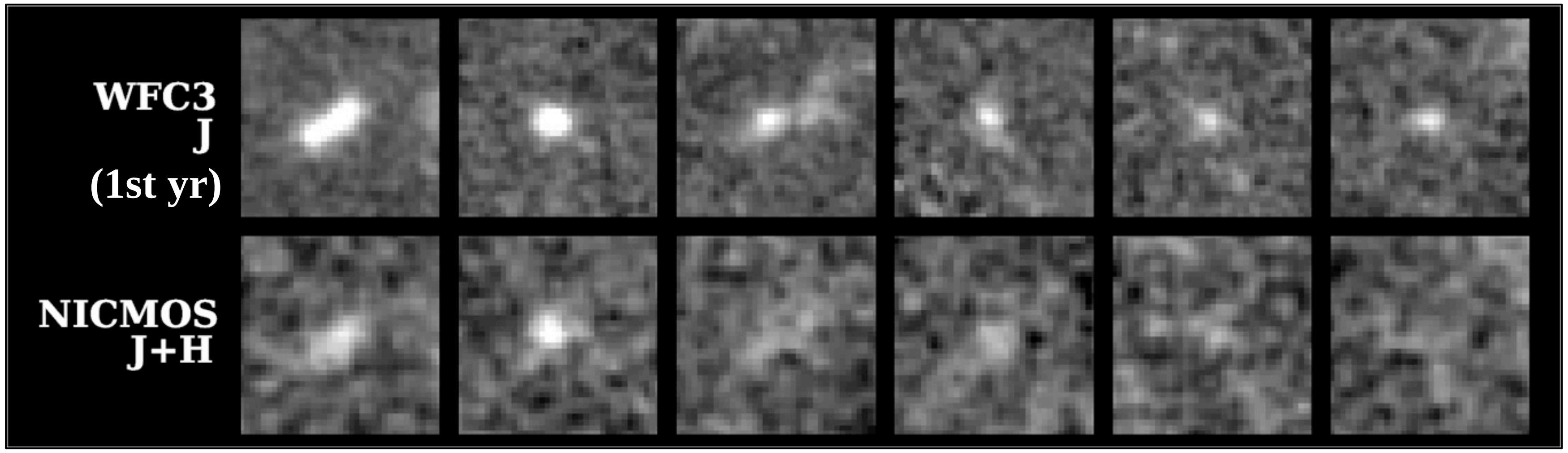

J110 NICMOS HUDF
72 orbits
0.25 arcmin


J125 WFC3/IR HUDF
34 orbits
0.25 arcmin

Progress on z>6.5 Samples with WFC3/IR

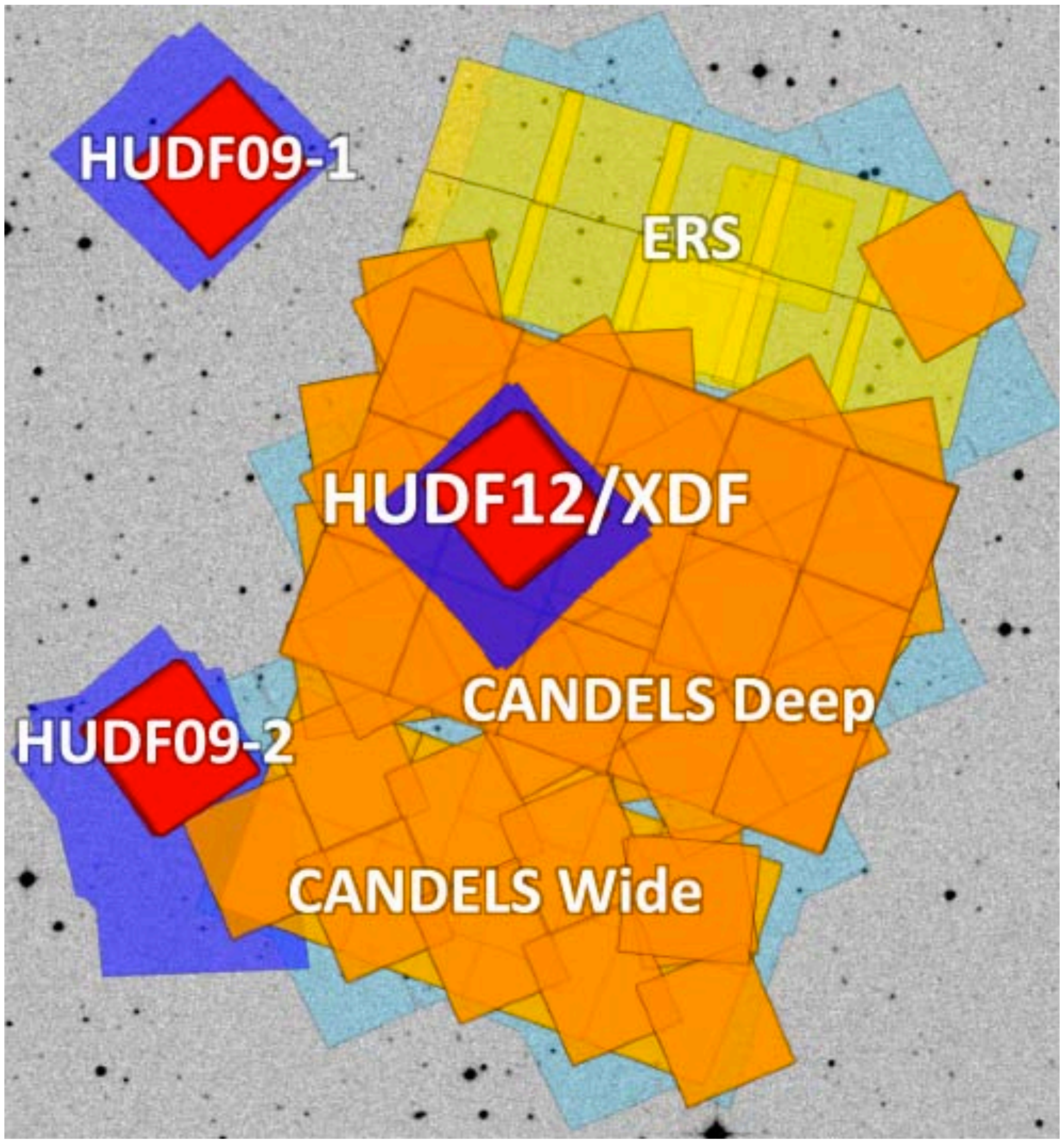
NICMOS: **12** galaxies (10 years of observations)

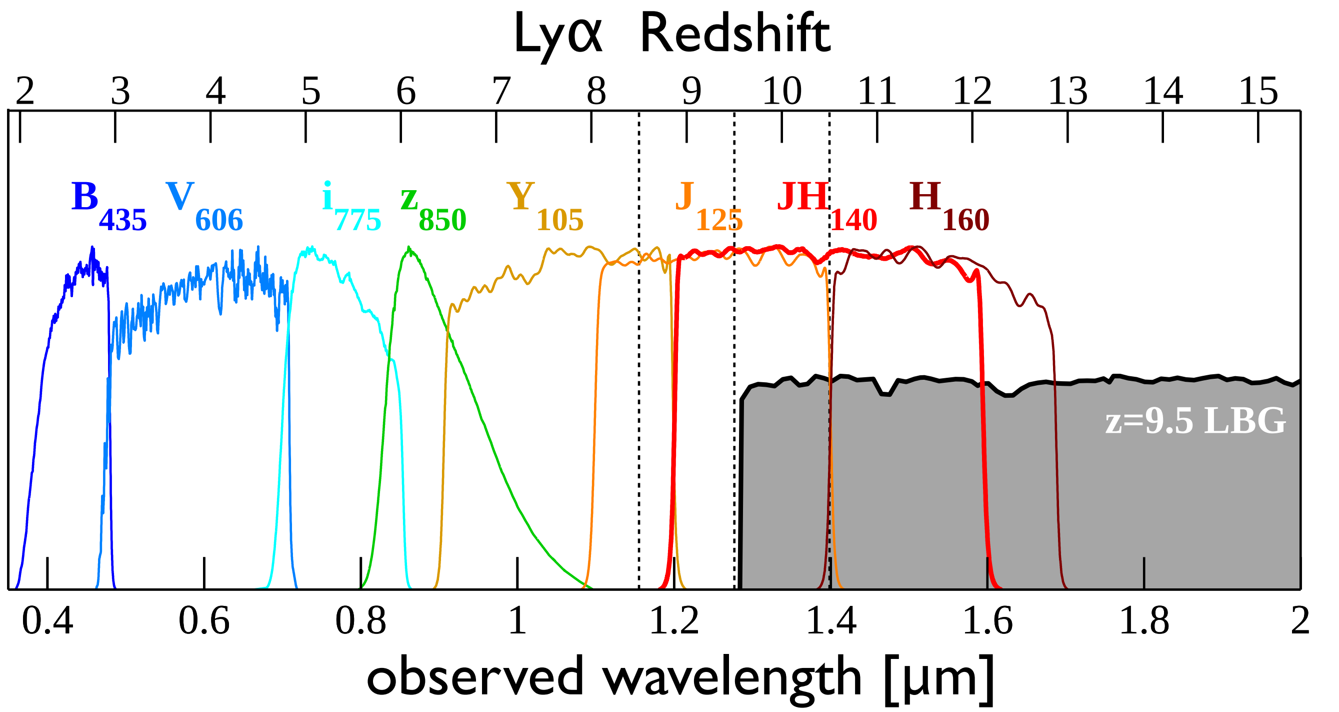
WFC3/IR: **20** galaxies (1st weeks of observations)



WFC3/IR: **>200** galaxies (3 years of data)

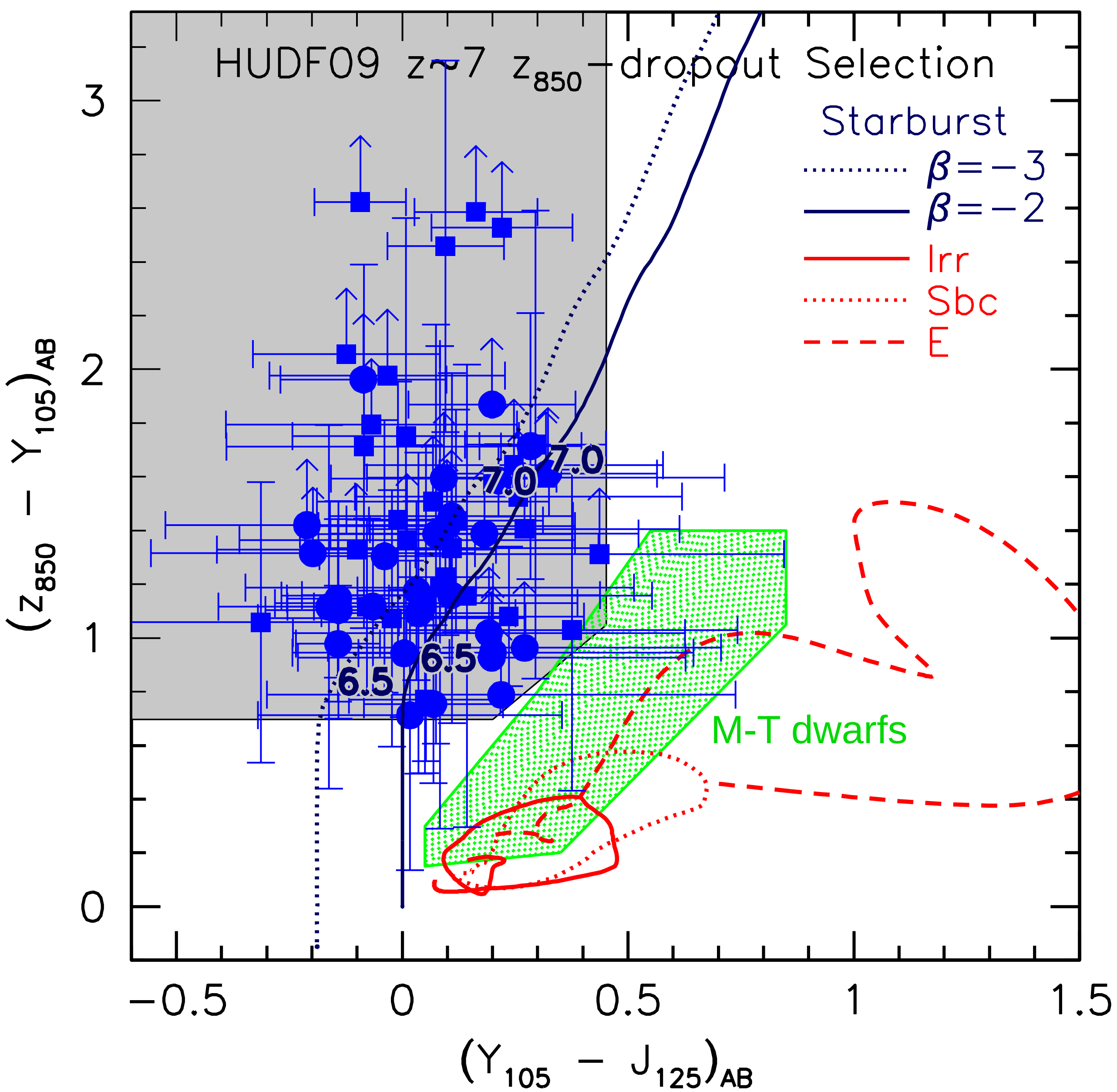
WFC3/IR Data around GOODS-South





- CDFS is perfect dataset for z>7 galaxy search
- 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 - 29.8 AB mag

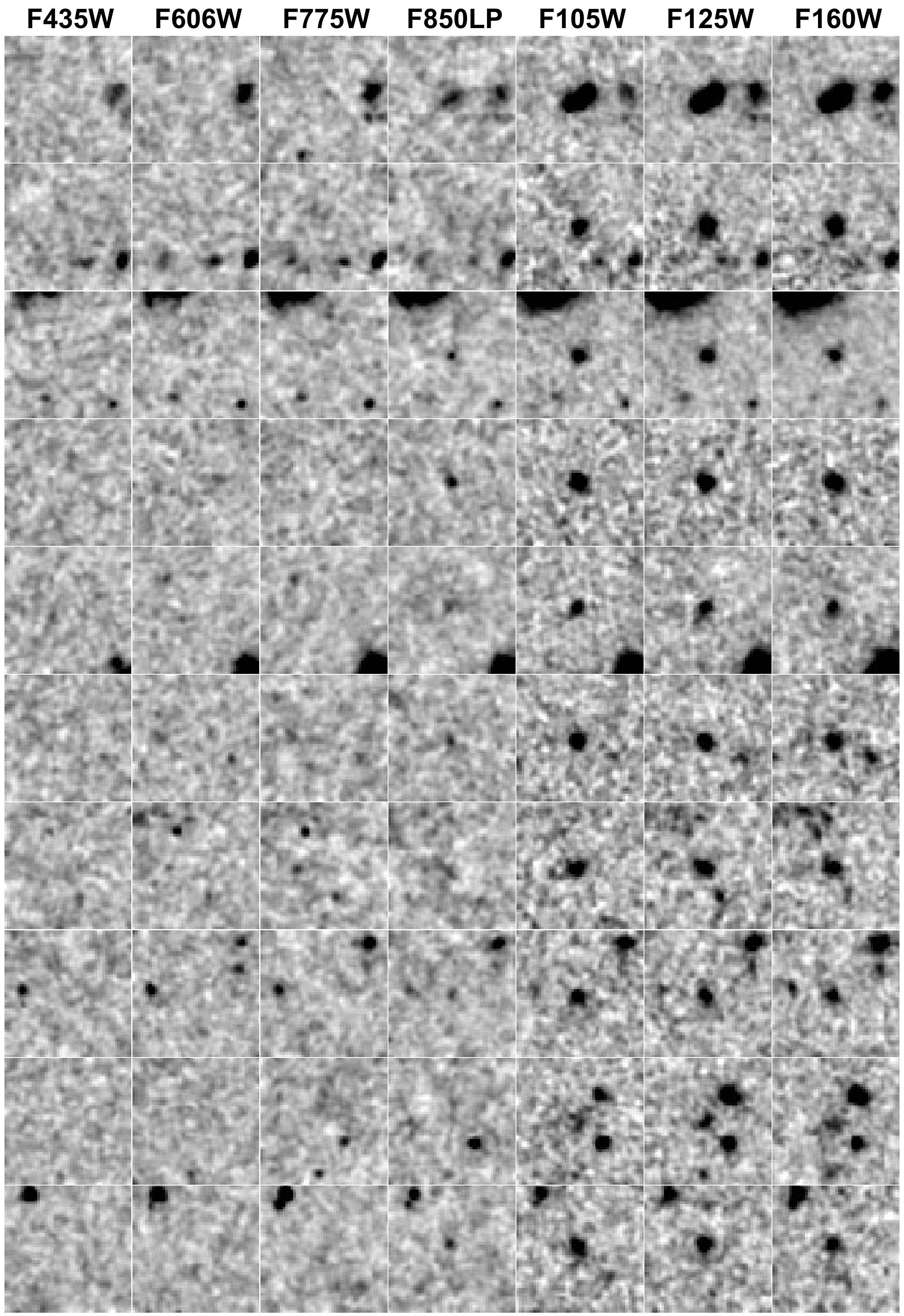
z~7 LBG Candidates in HUDF09+ERS Data



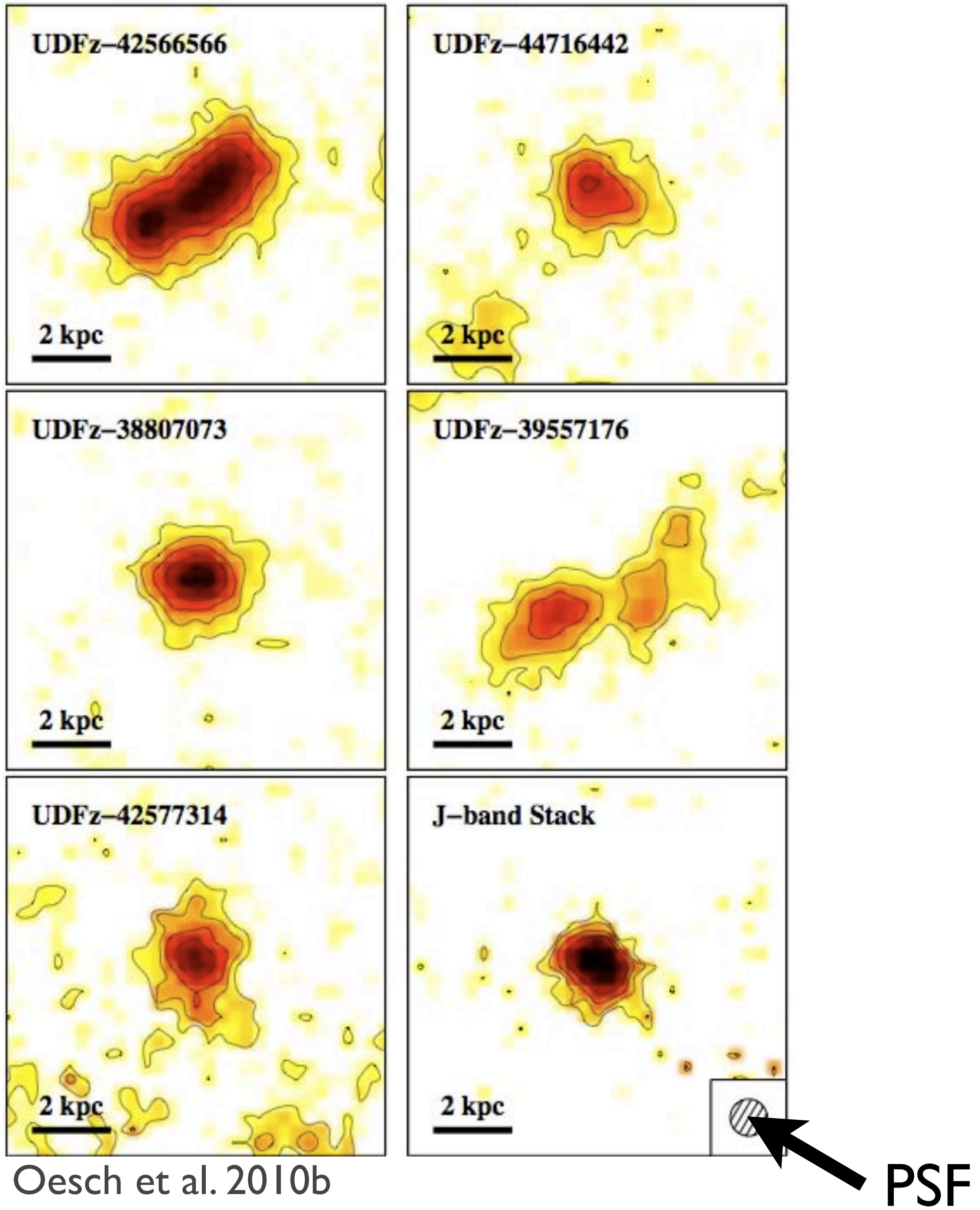
- Select galaxies in color-color diagram
- Require non-detection in any optical band
- over HUDF09+ERS fields: 73 candidates, z_{avg}=6.8 (Bouwens et al. 2011)

- Expect only small fractions of contamination
  - Supernovae
  - Cool Galactic stars
  - Photometric scatter

z~7 LBGs in HUDF



Galaxies at z~7 are extremely compact, but resolved with WFC3/IR



Oesch et al. 2010b

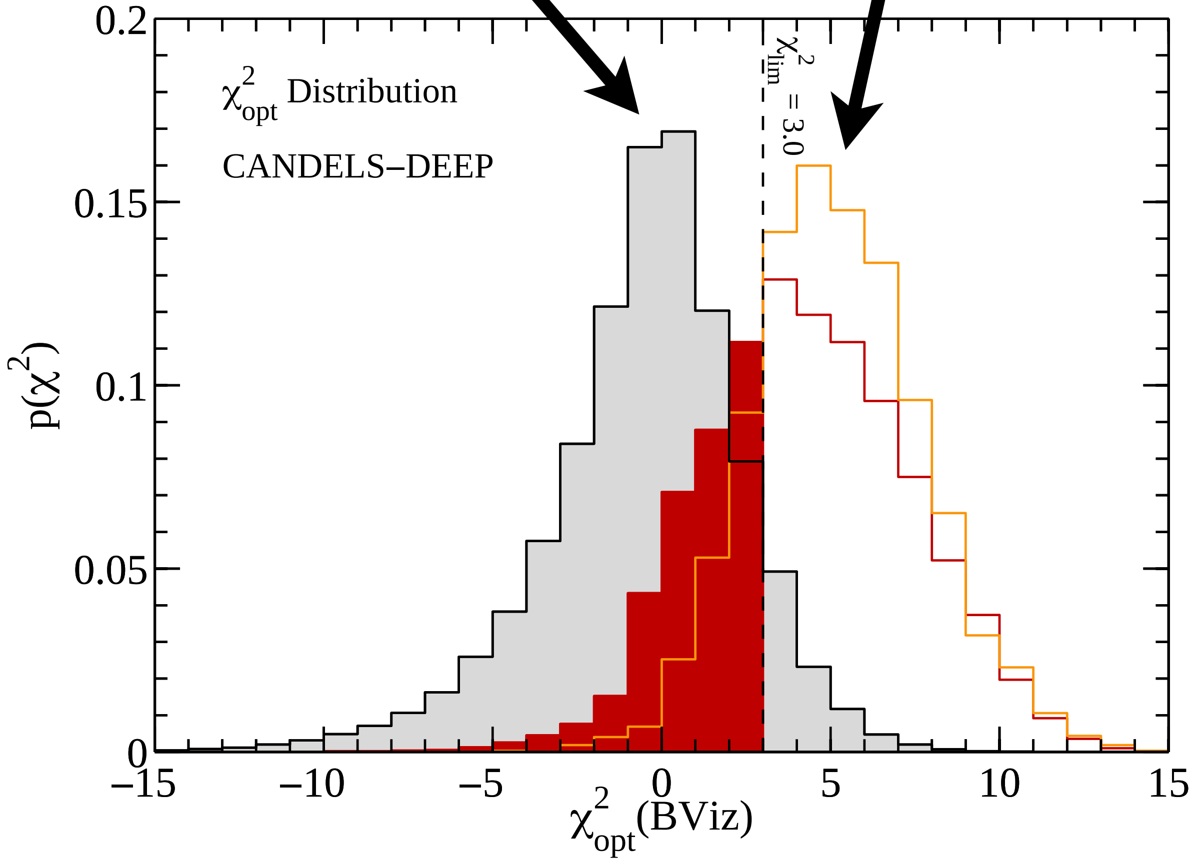
Minimizing Contamination: Extended LBG Selection

- Most problematic source of contamination: photometric scatter of faint, low-z galaxies
- These are expected to show flux in optical images: typically use <2σ criterion
- Make full use of all information in optical data to minimize contamination further:

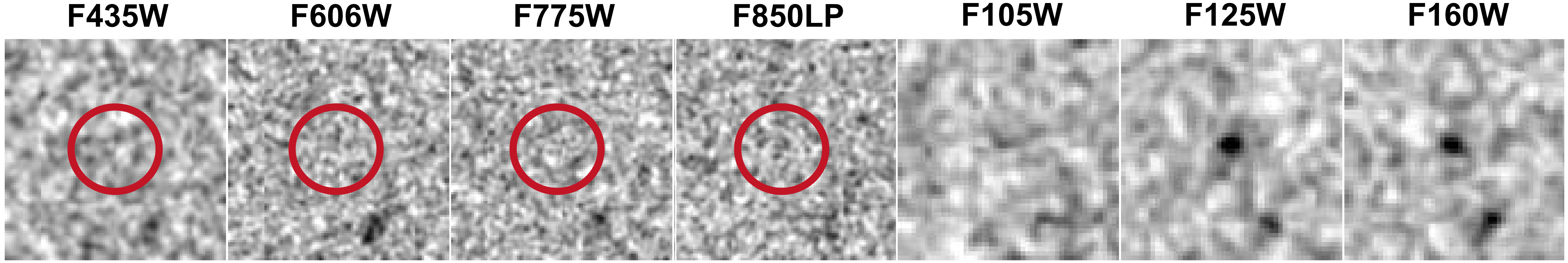
$$\chi^2_{opt} = \sum_i \mathrm{SGN}(f_i)(f_i/\sigma_i)^2$$

Empty sky, i.e. real high-z sources

Simulated contaminants with <2σ in all optical bands



Reduction of contamination by factor ~3-4x



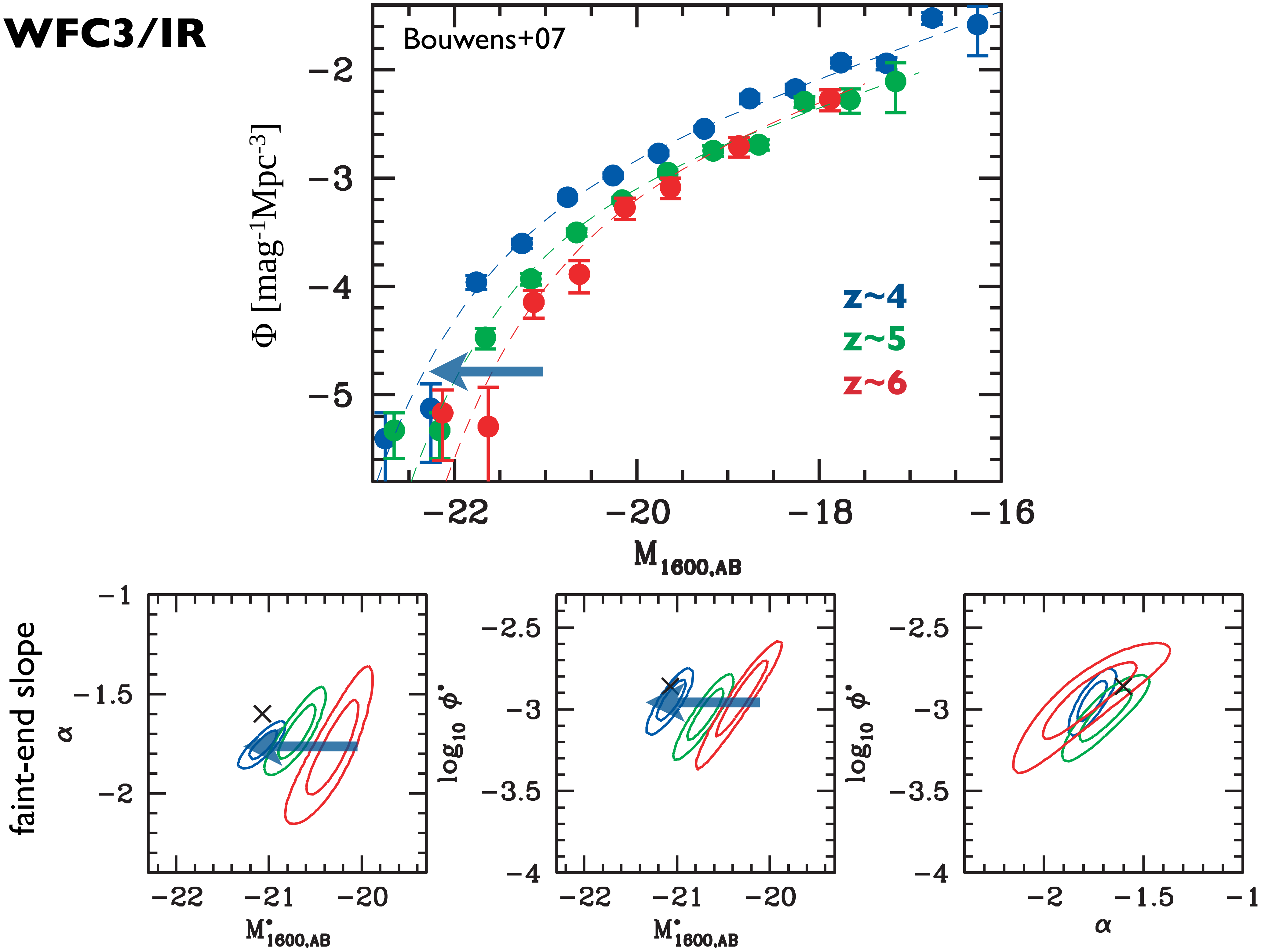
z~8 LBG

Galaxy Build-up in Epoch of Reionization Based on the UV Luminosity Function

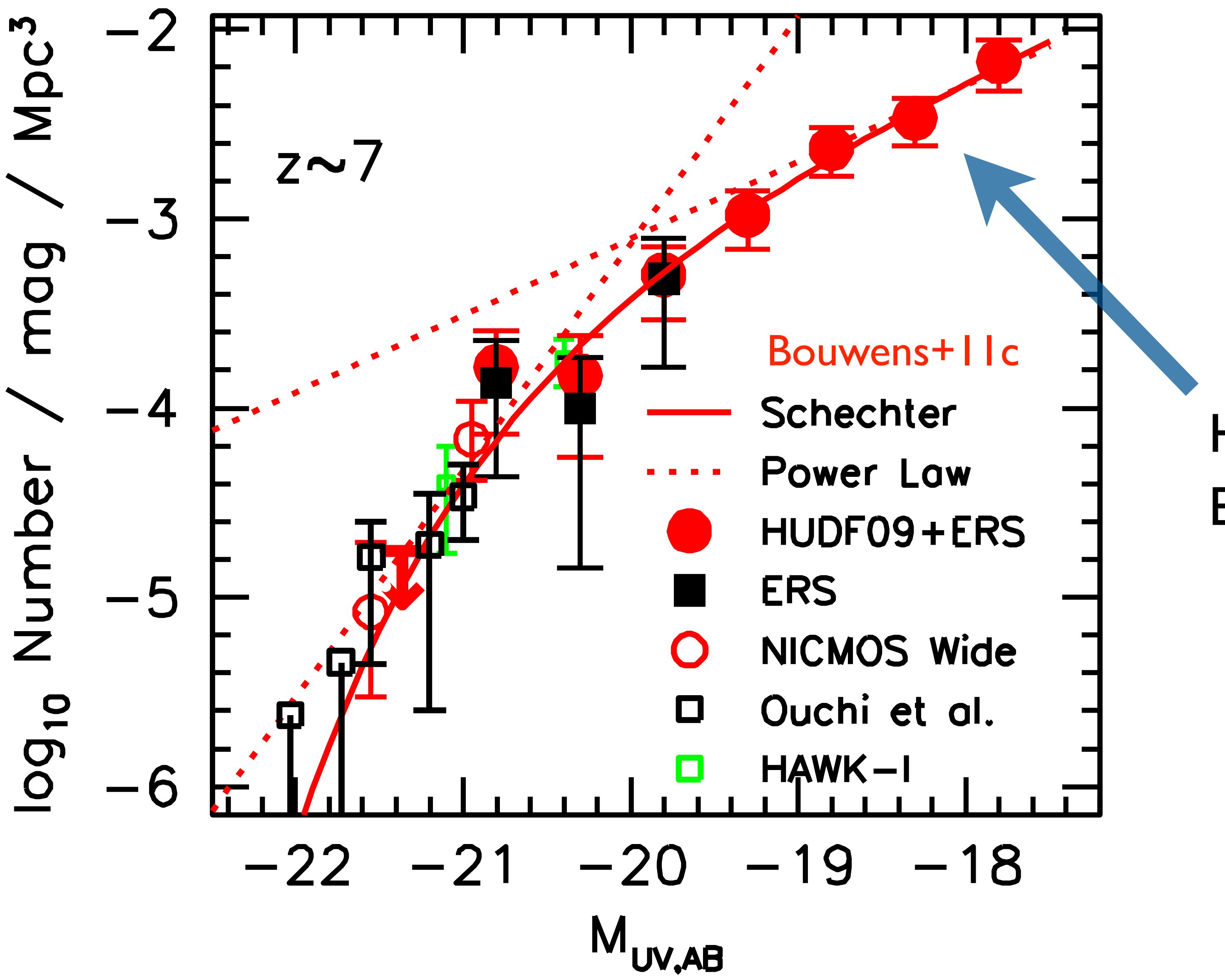
WFC3/IR probes rest-frame UV,
after dust-correction this is proportional to SFR

Evolution of the LBG LF at z~4-6

pre-WFC3/IR



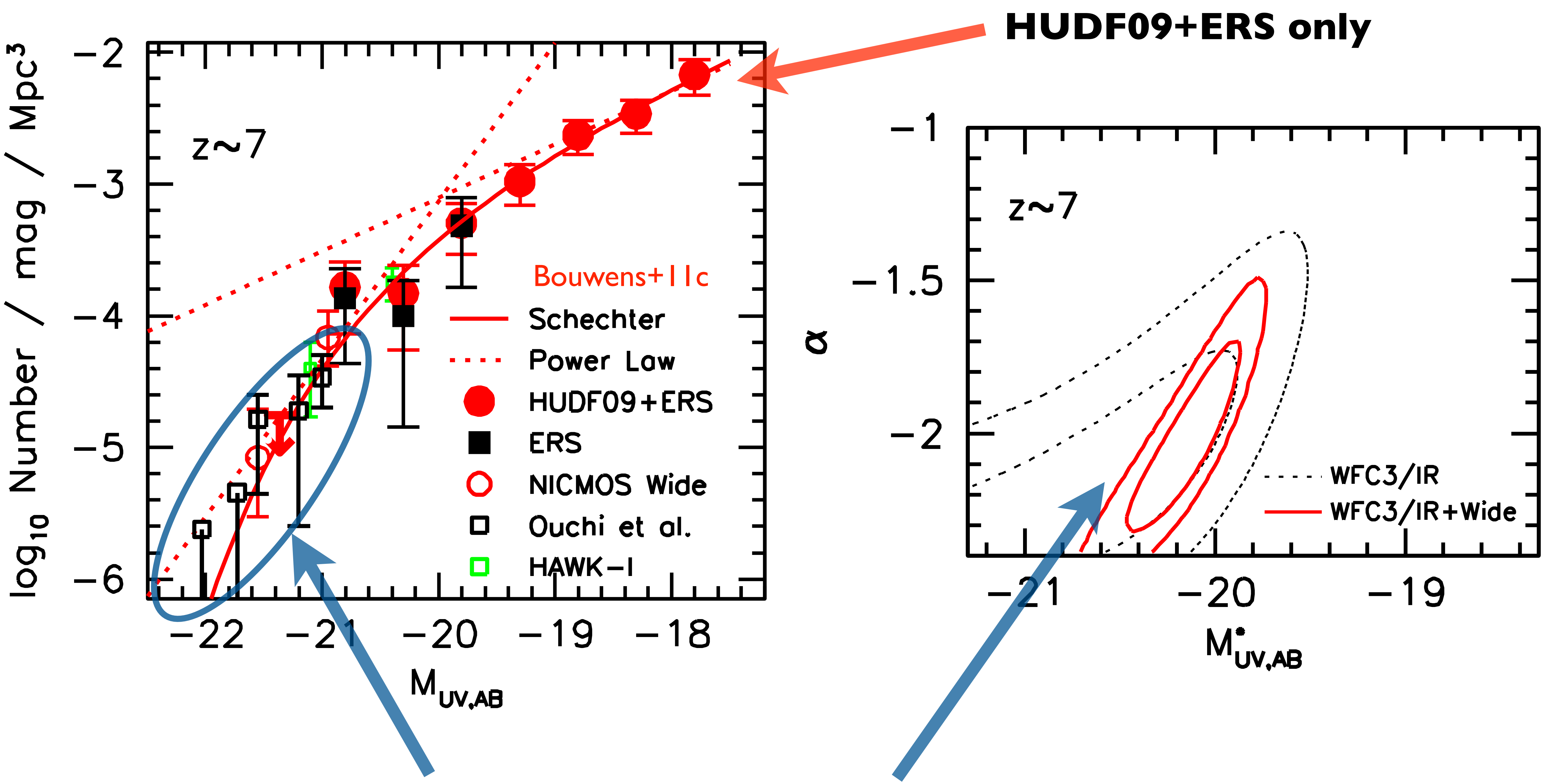
z~7 LF from HST and from Ground



HST (HUDF09+ERS): well-sampled faint end

Extremely steep slope: **α ~ -2**

z~7 LF from HST and from Ground

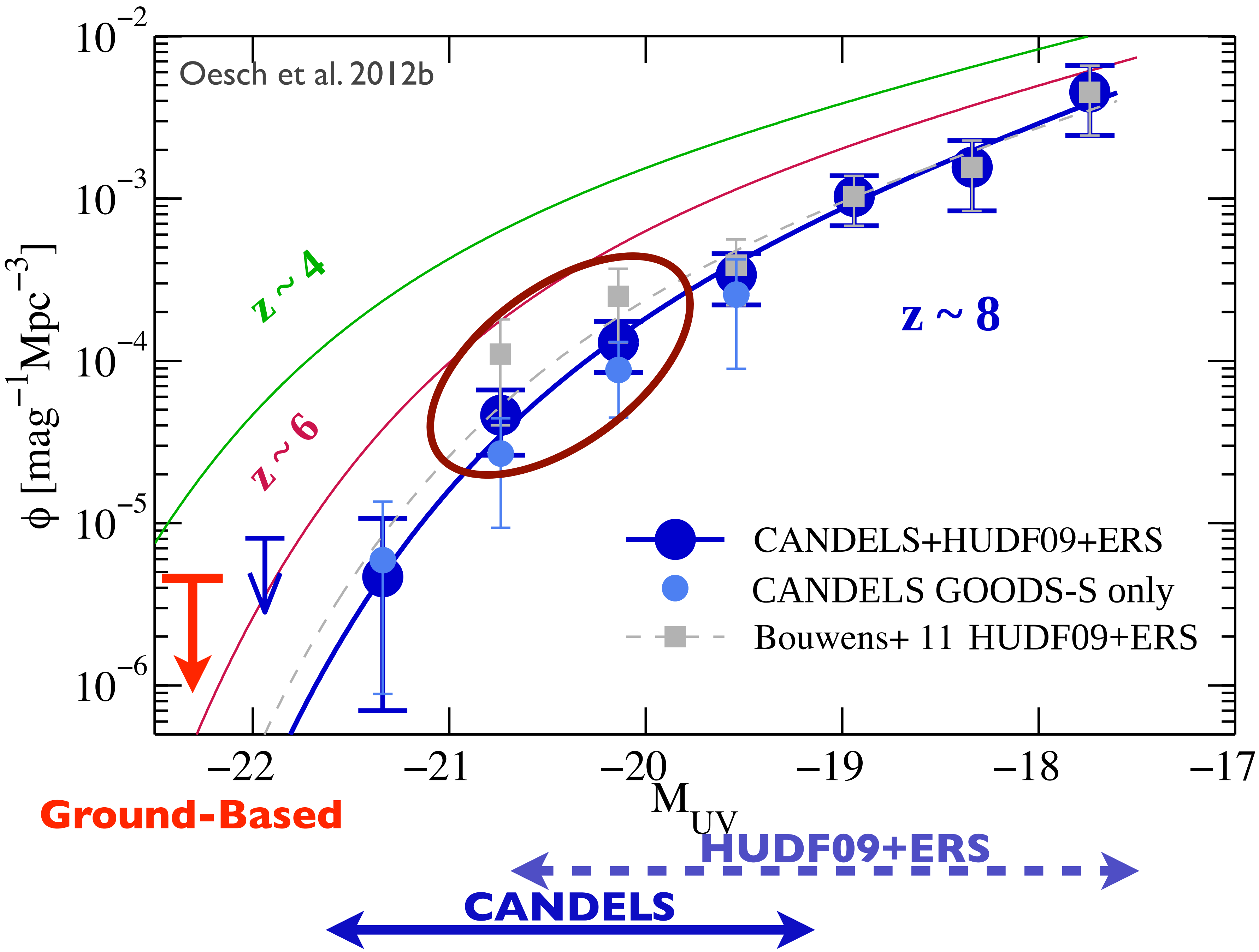


Subaru data (Ouchi+09) extremely useful for bright end constraints

See also: e.g. Oesch+10, Bunker+10, Finkelstein+10, Yan+10, Wilkins+10/11, McLure+10, Schenker+13

The UV Luminosity Function at z~8

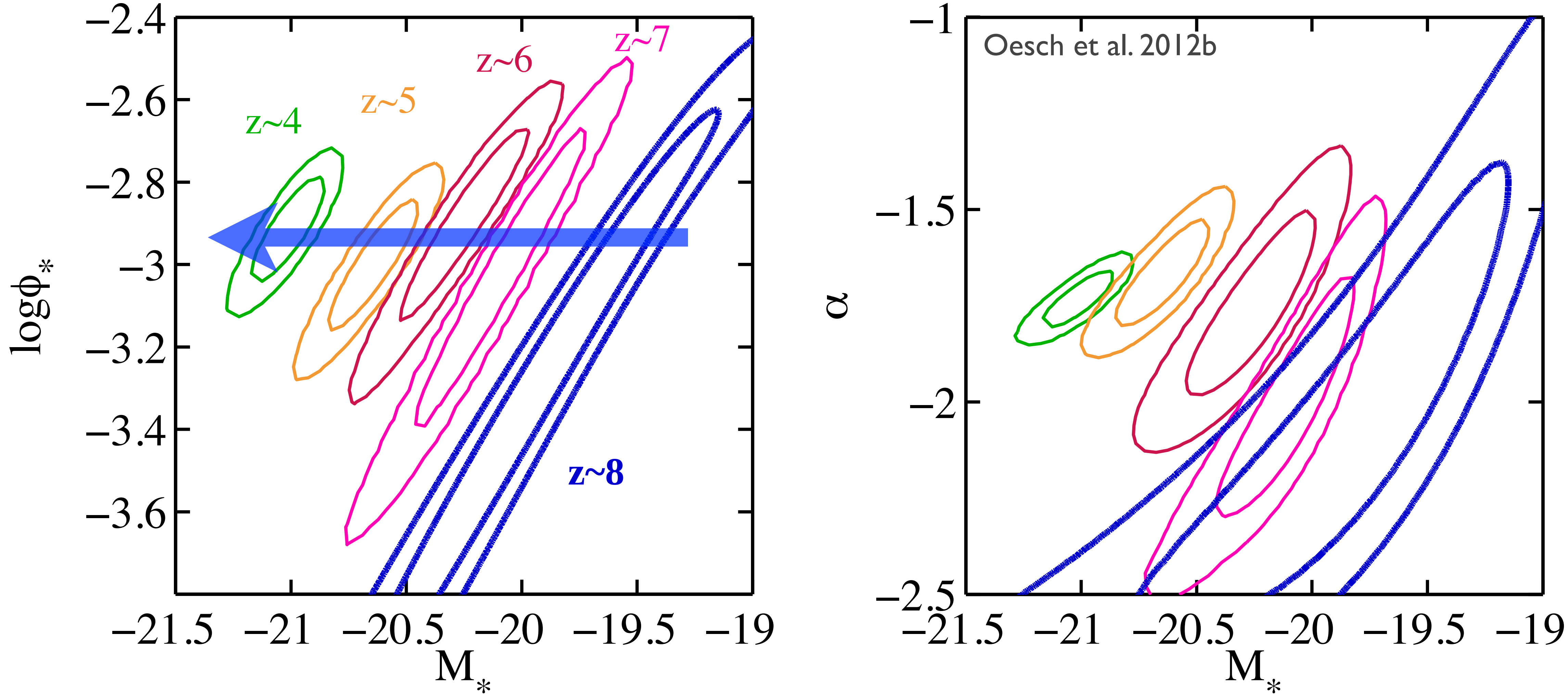
F105W data over GOODS-S allows for much improved constraints on bright end: combine data over all fields (75 candidates) to provide best possible LF measurement



See also: e.g. McLure+13, Schenker+13, Lorenzoni+12, Yan+12, Bradley+12

Build-up of UV LF from z~8 to z~4

UV luminosity increases uniformly to lower redshift

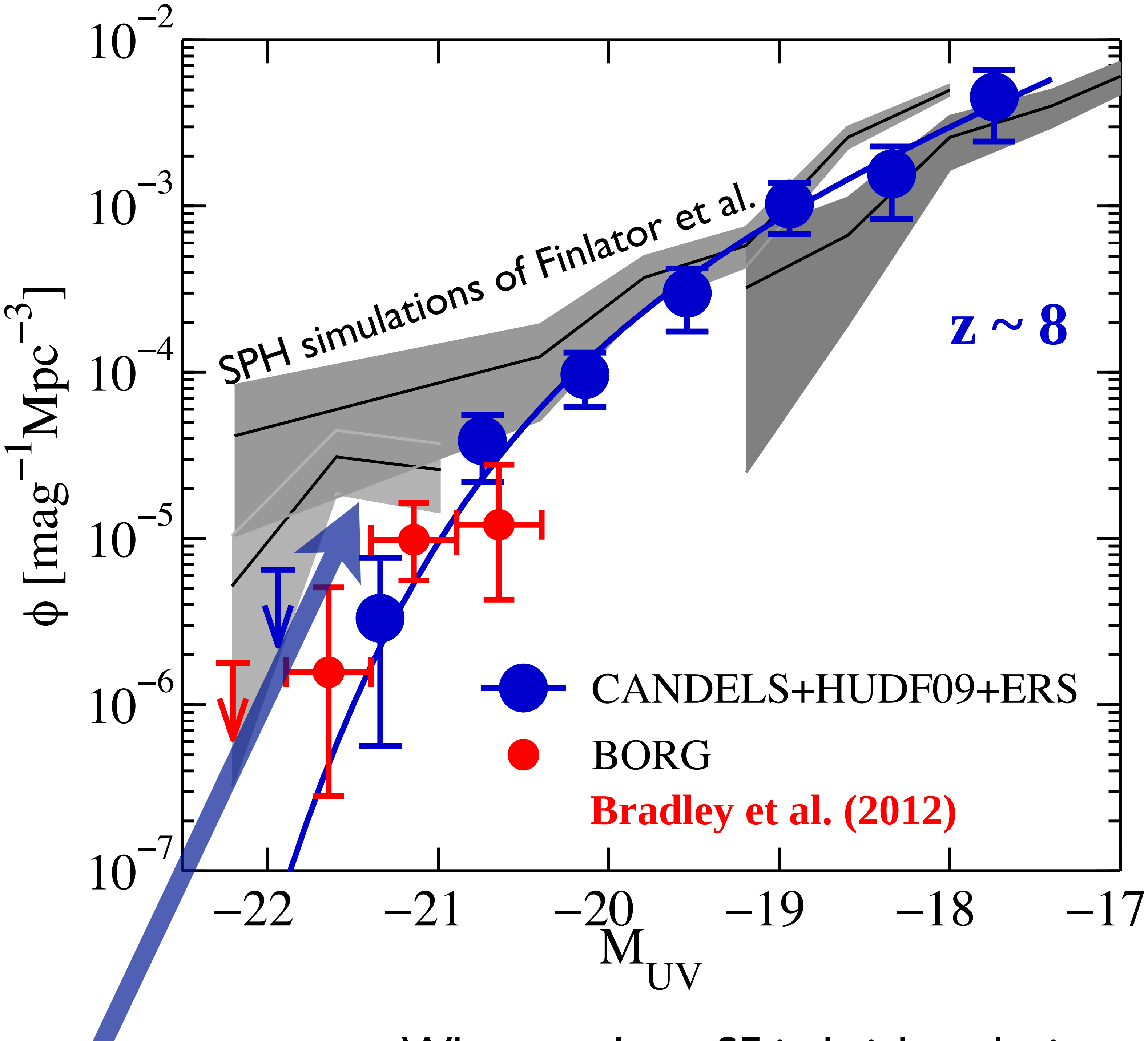


Main Evolution: only in M* (0.33 mag per unit z)

Very steep faint-end slope: -1.7 at z<7, with possible trend to steeper slopes at higher z

Combination with pure parallel data (e.g. BORG), CANDELS GOODS-N, CLASH, and HUDF12 will help reduce this (see Schenker+13, McLure+13).
But deep ground-based surveys are needed for bright end.

Exponential Cutoff at z~8?



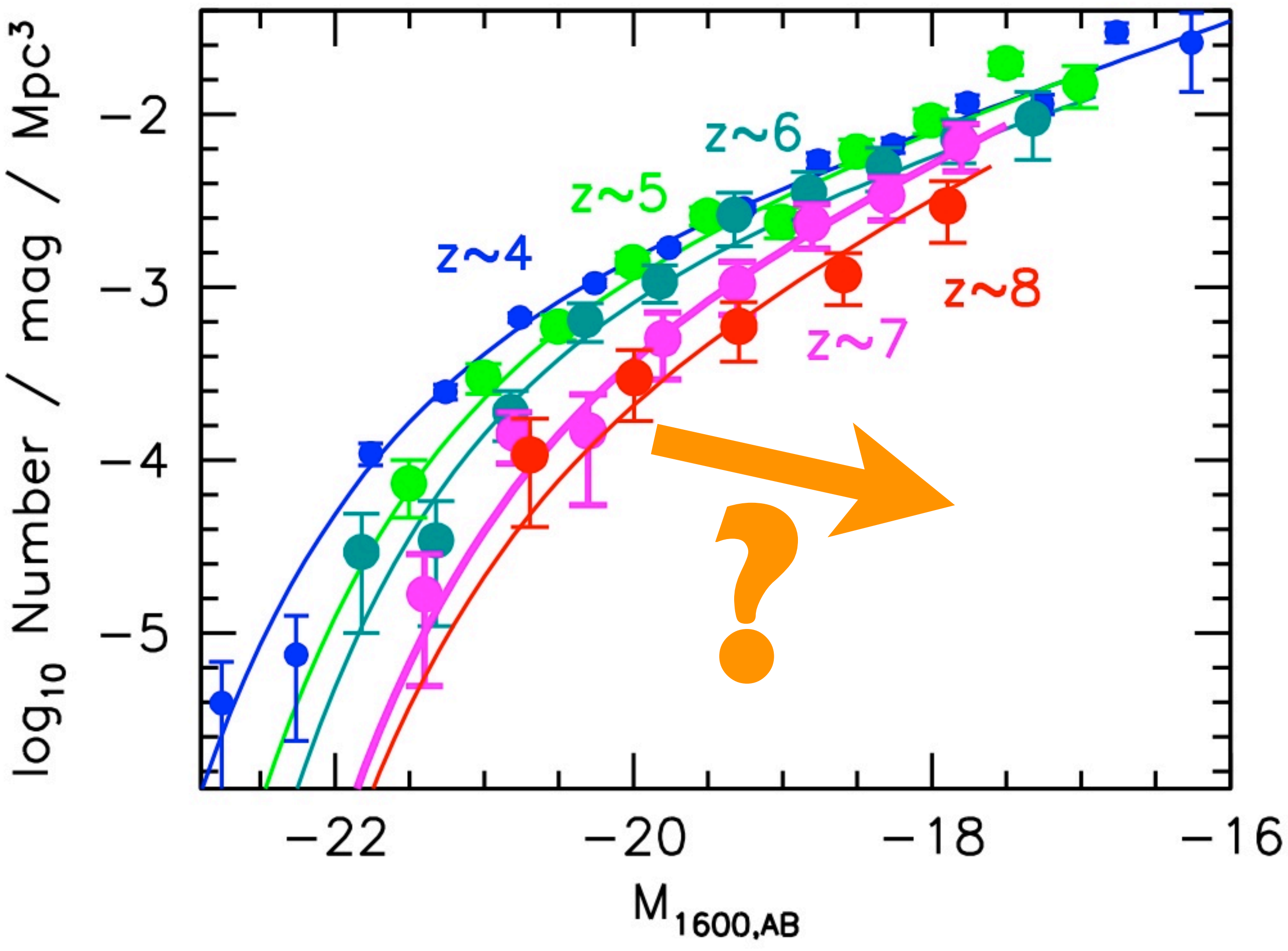
Excess relative to observations?

What regulates SF in bright galaxies at T_{univ} ~ 600 Myr?

➡ Test with wide area data

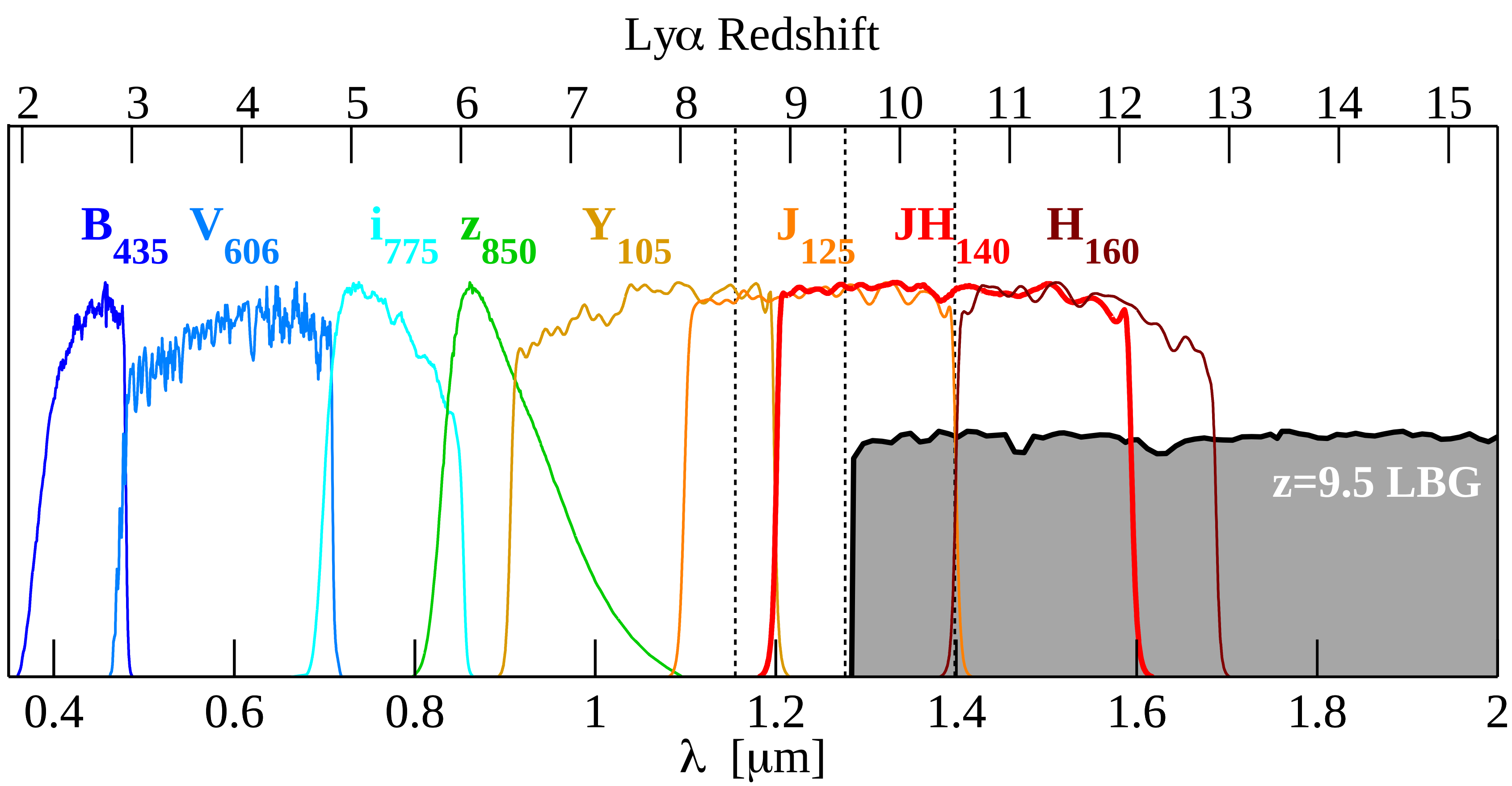
So Far:

Galaxy build-up is remarkably smooth from z~8 down to z~4



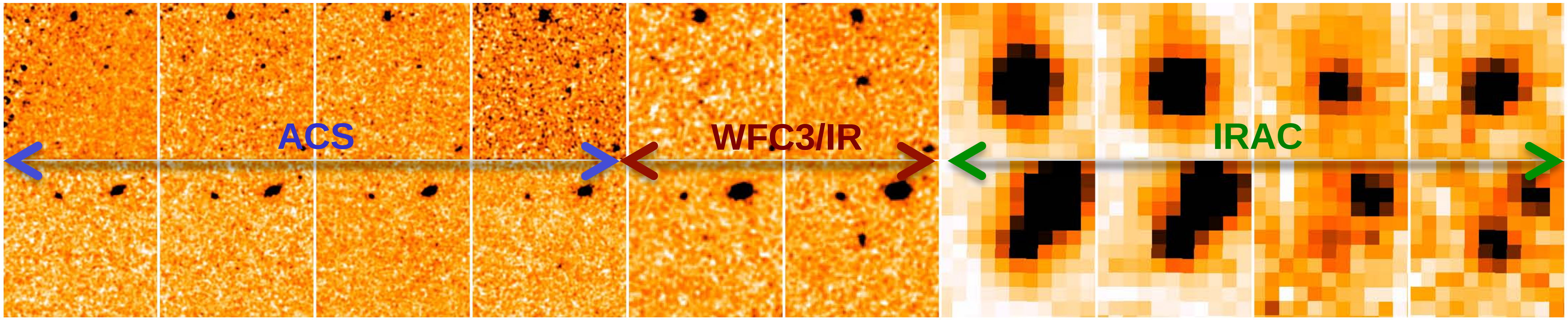
Pushing the High-Redshift Frontier with HST

- At z~8: neutral IGM starts affecting J_{125}
- Can select z>9.5 galaxies as J-dropouts based on red J_{125}-H_{160} colors
- Thanks to new F140W imaging from HUDF12: z~9 and z~11 selections

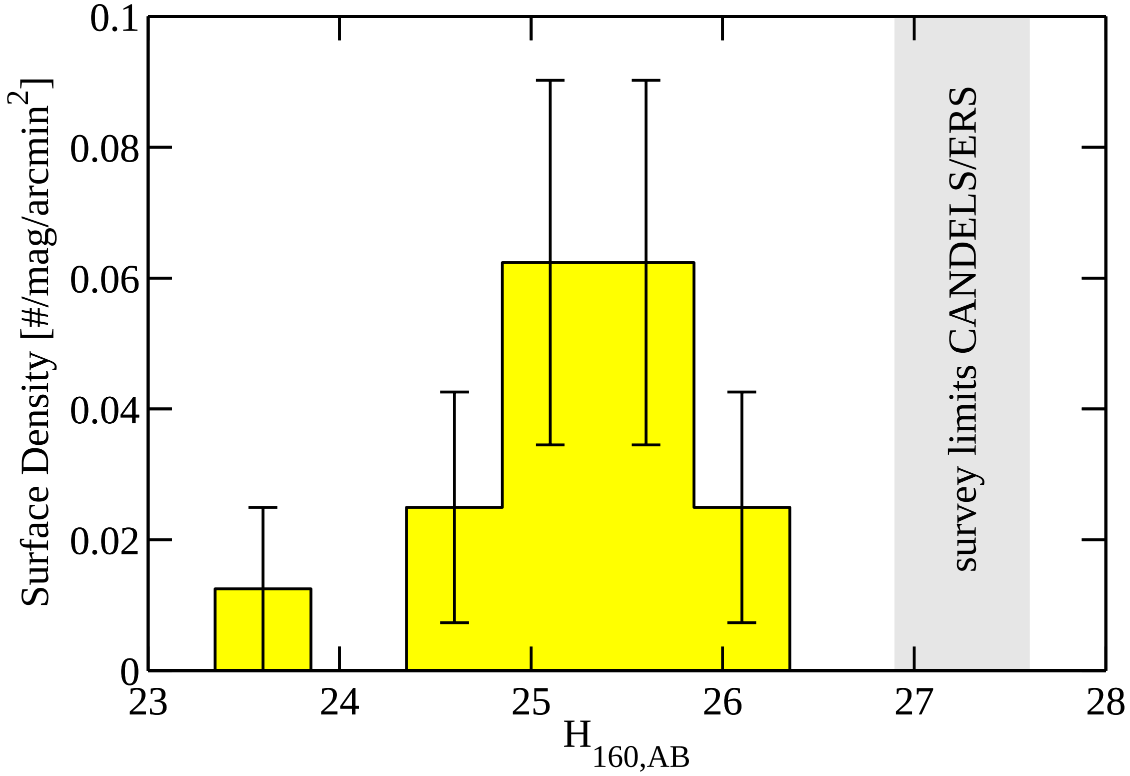


- Very challenging:
  - z>8 galaxies expected to be extremely faint
  - intermediate-z dusty galaxies can exhibit similar colors

Intermediate-Redshift Contaminants



- Over GOODS-South data, find 16 dusty/evolved sources at intermediate redshift (z~2-4), which all satisfy the z~10 HST selection criteria
- These are identified by strong Spitzer IRAC detections (H_{160}-[3.6]>2)

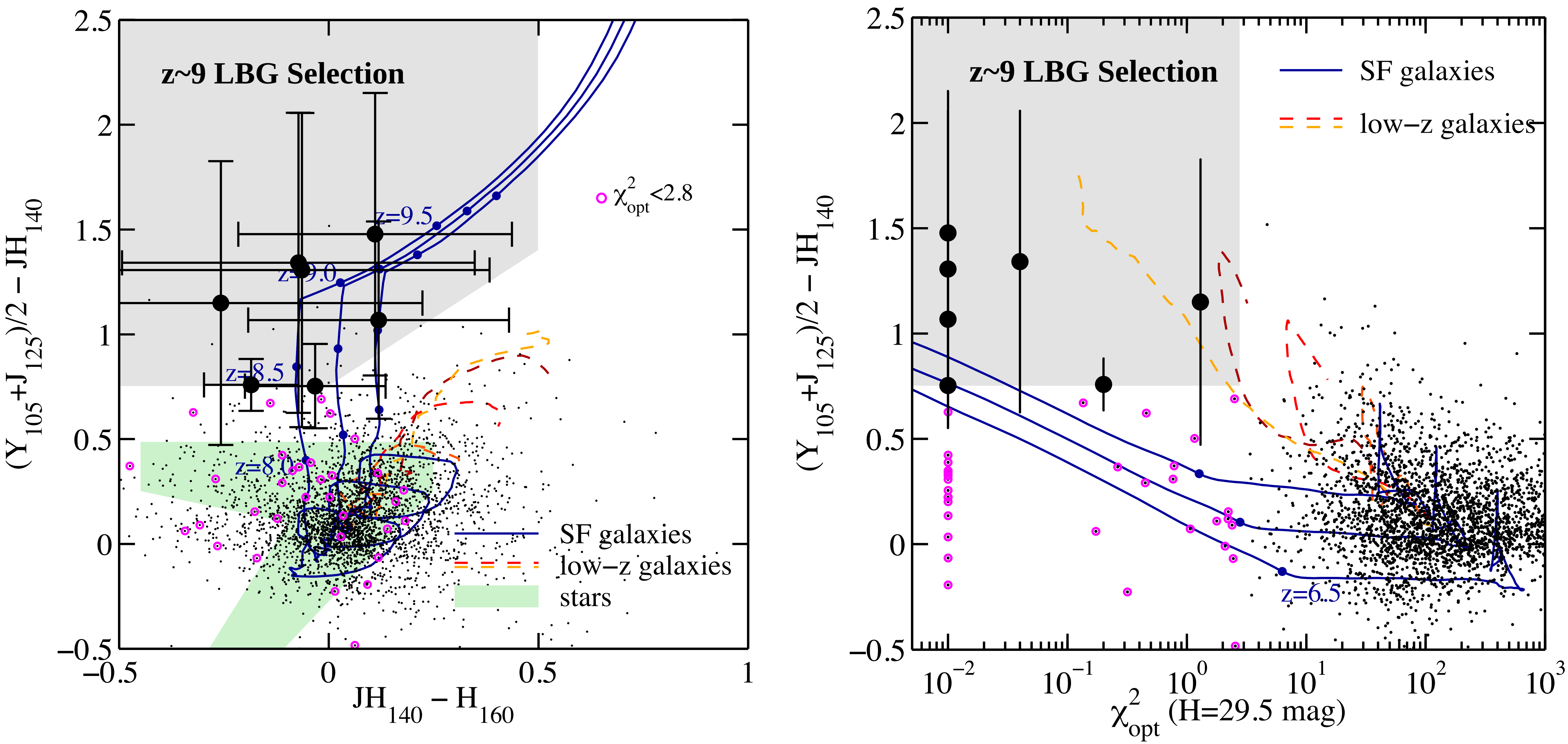


Such red intermediate redshift sources appear to have a peaked LF

However: Beware of z~10 selections without Spitzer coverage

z~9 LBG Selections with HUDF12 Data

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

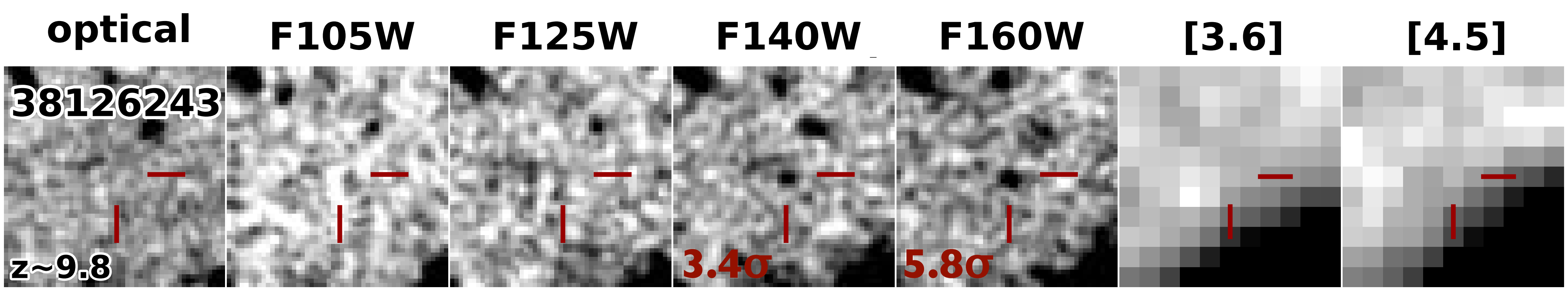


Our HUDF12 z~9 LBG sample contains seven sources (H = 28.0 - 29.9 mag, <z_{phot}> = 8.7)

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.

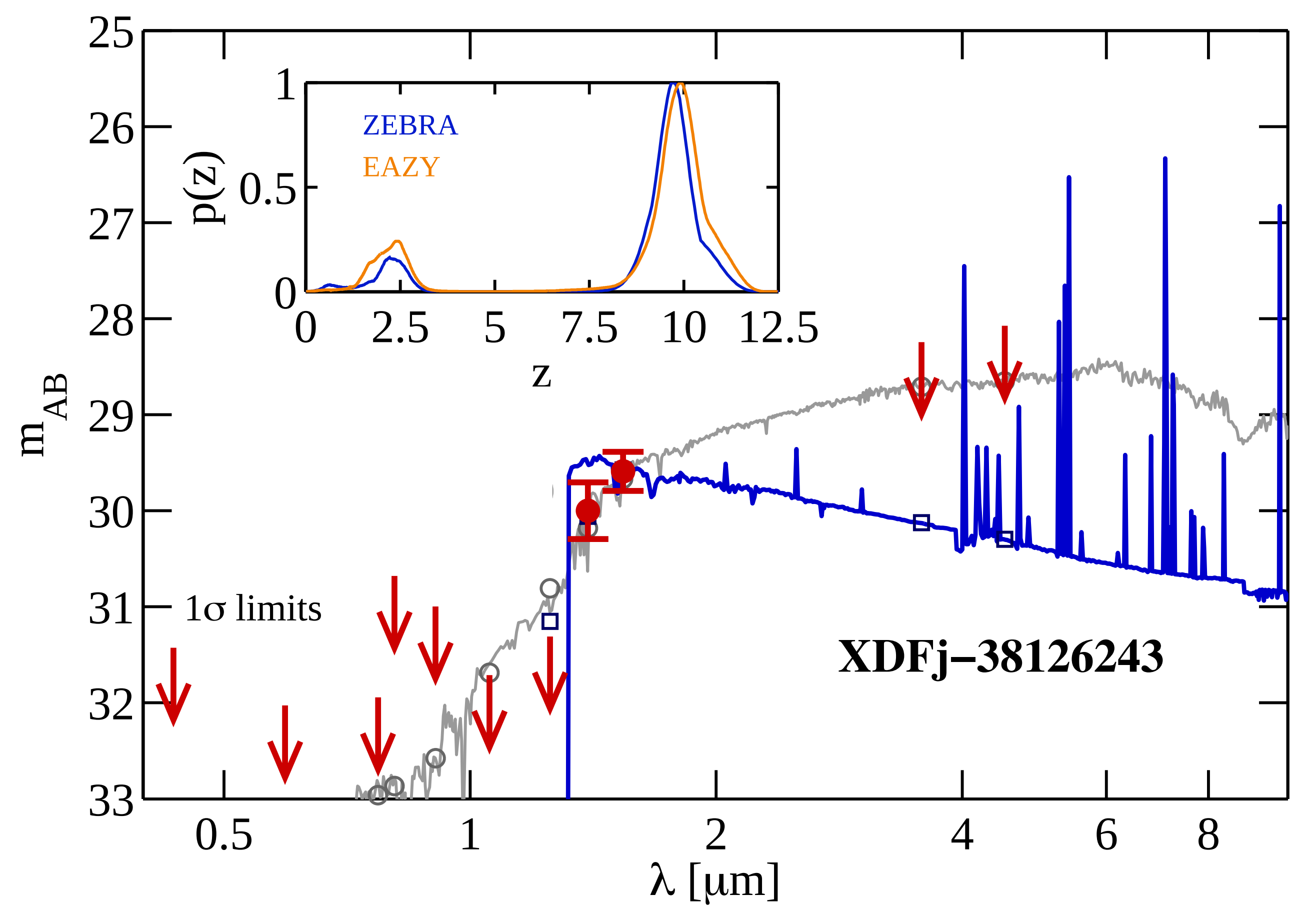
"New" z~10 source

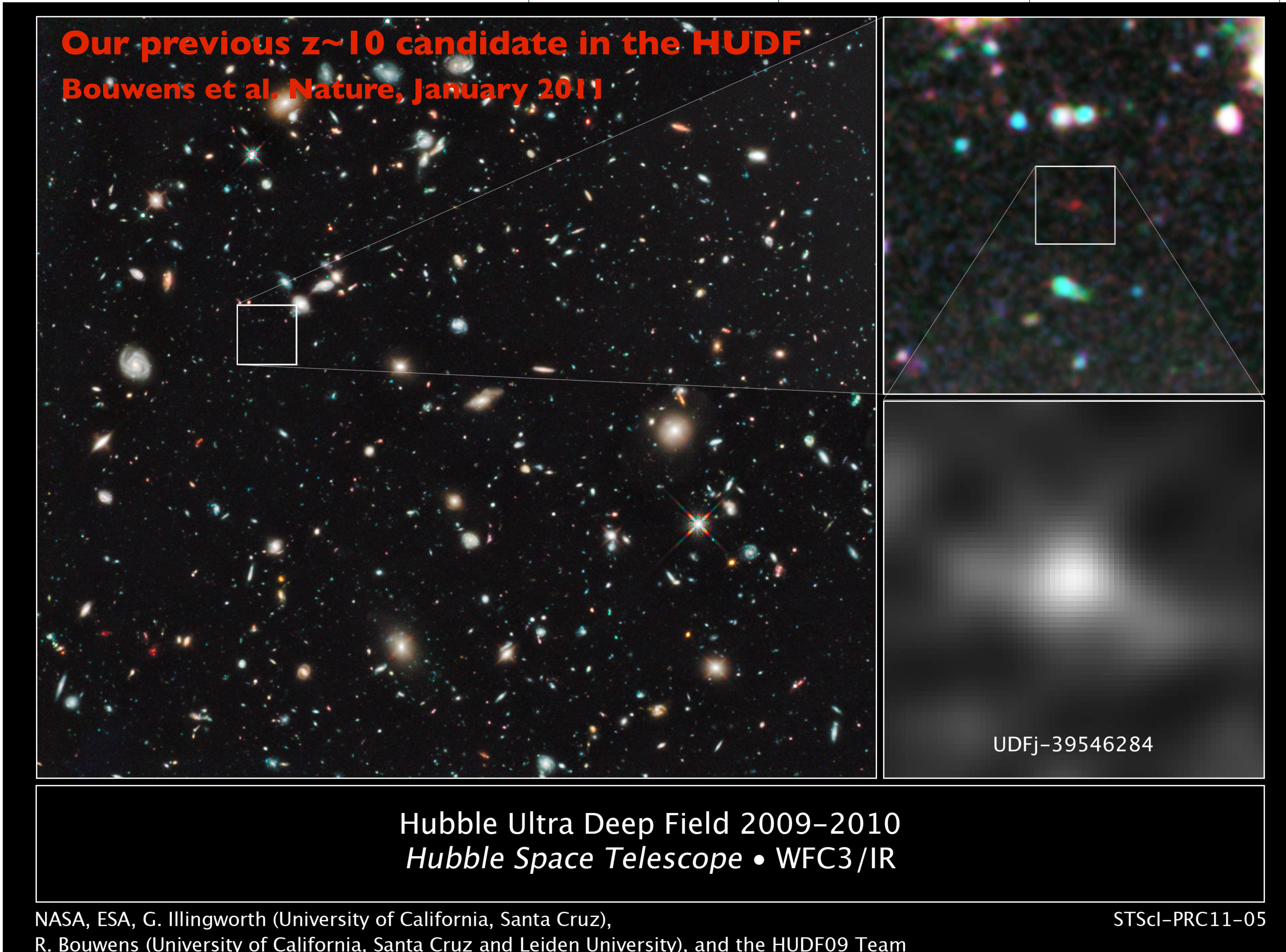


The source is definitely real. It is detected at >3σ in several independent subsets of the data (H-Epoch1, H-Epoch3, and JH)

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

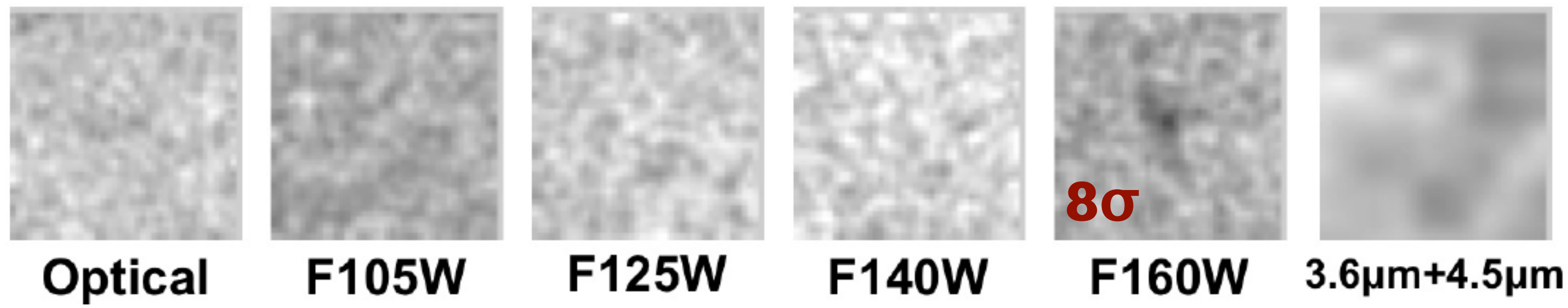
It has H_{AB}=29.6 mag and a photometric redshift of z_{phot} = 9.8±0.6

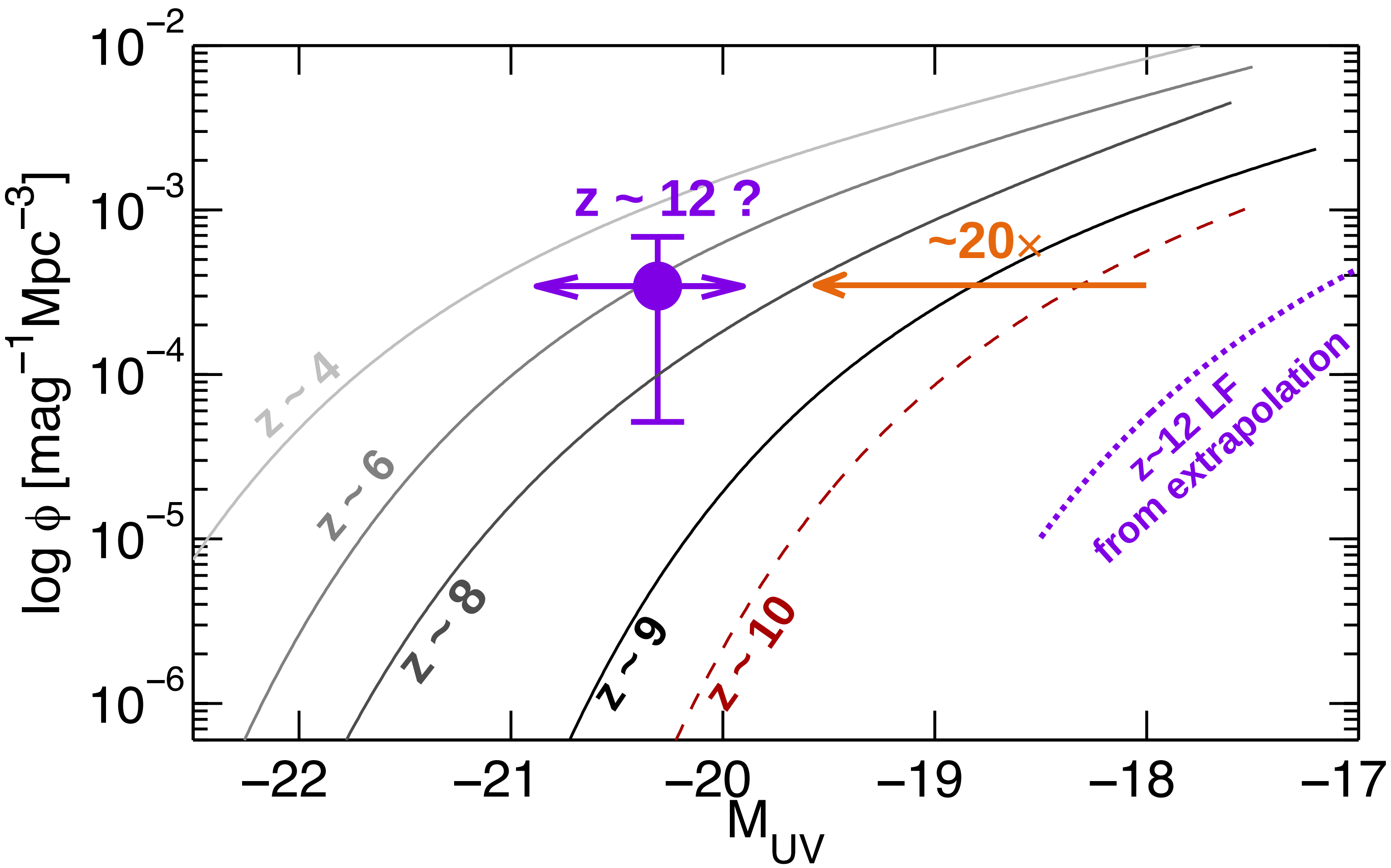


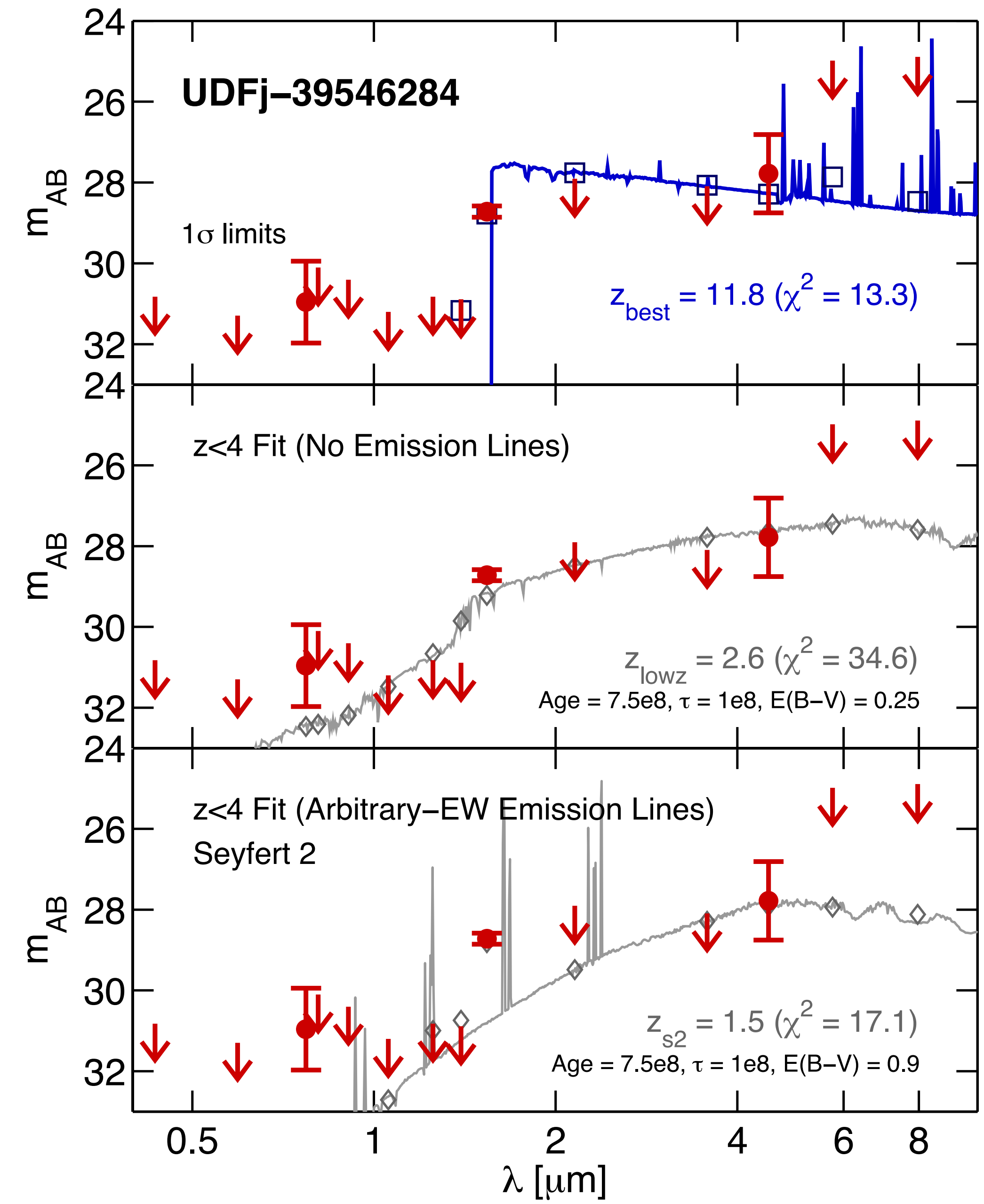

Our previous z~10 candidate in the HUDF
Bouwens et al. Nature, January 2011
UDFj-39546284
Hubble Ultra Deep Field 2009-2010
Hubble Space Telescope • WFC3/IR
NASA, ESA, G. Illingworth (University of California, Santa Cruz),
R. Bouwens (University of California, Santa Cruz and Leiden University), and the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

Nature of UDFj-39546284?

Our previous z~10 source



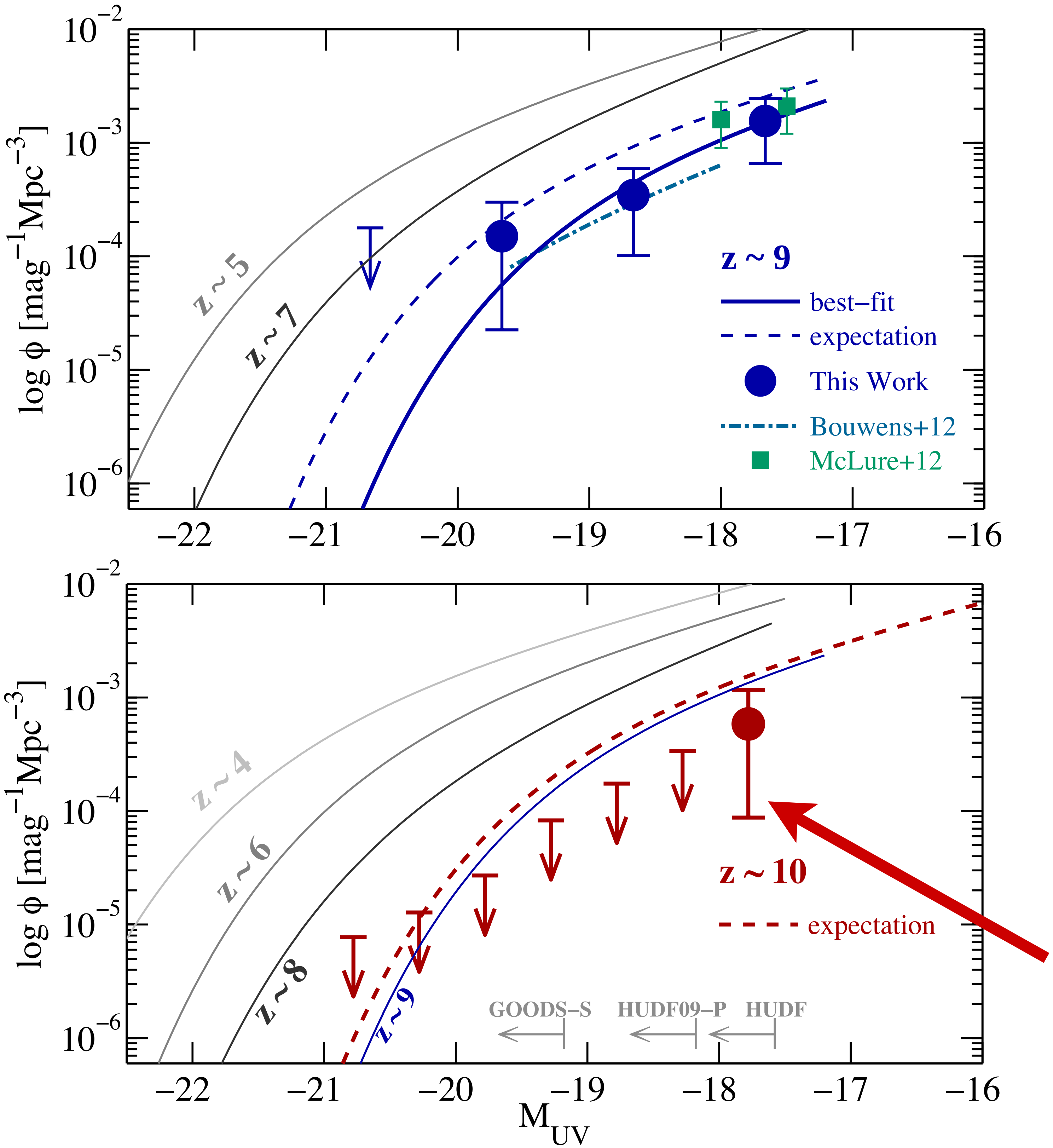




If this source was at z~11.8, its luminosity would be 10-20x brighter than expected.

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

The z~9 and z~10 UV LF Constraints



First Constraints at z~9:

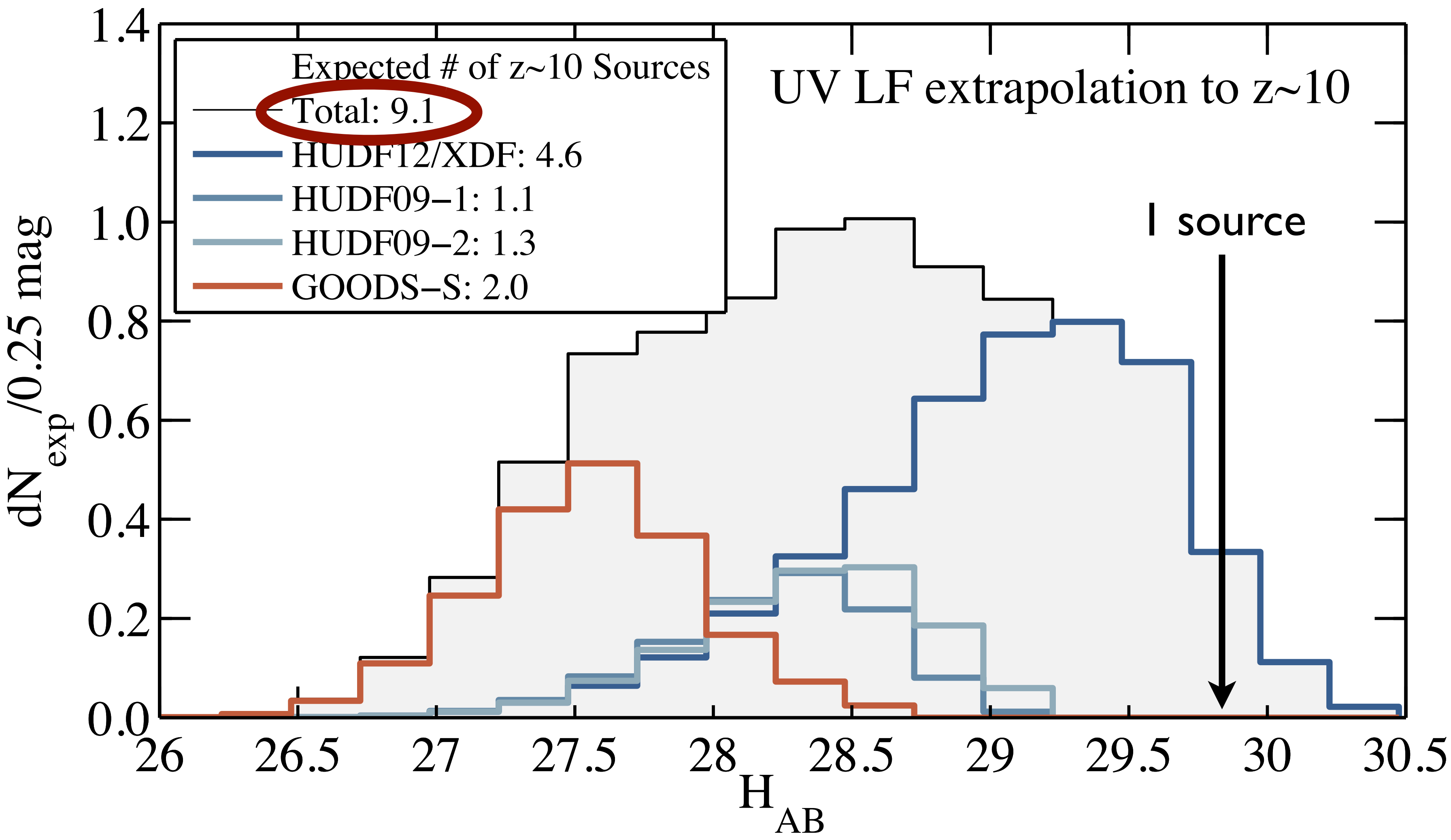
Number of sources is small in each bin, however, all determinations lie systematically below extrapolation of low-z trends.

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

Three HUDF09/12 Fields:

z~10 limits are below extrapolation

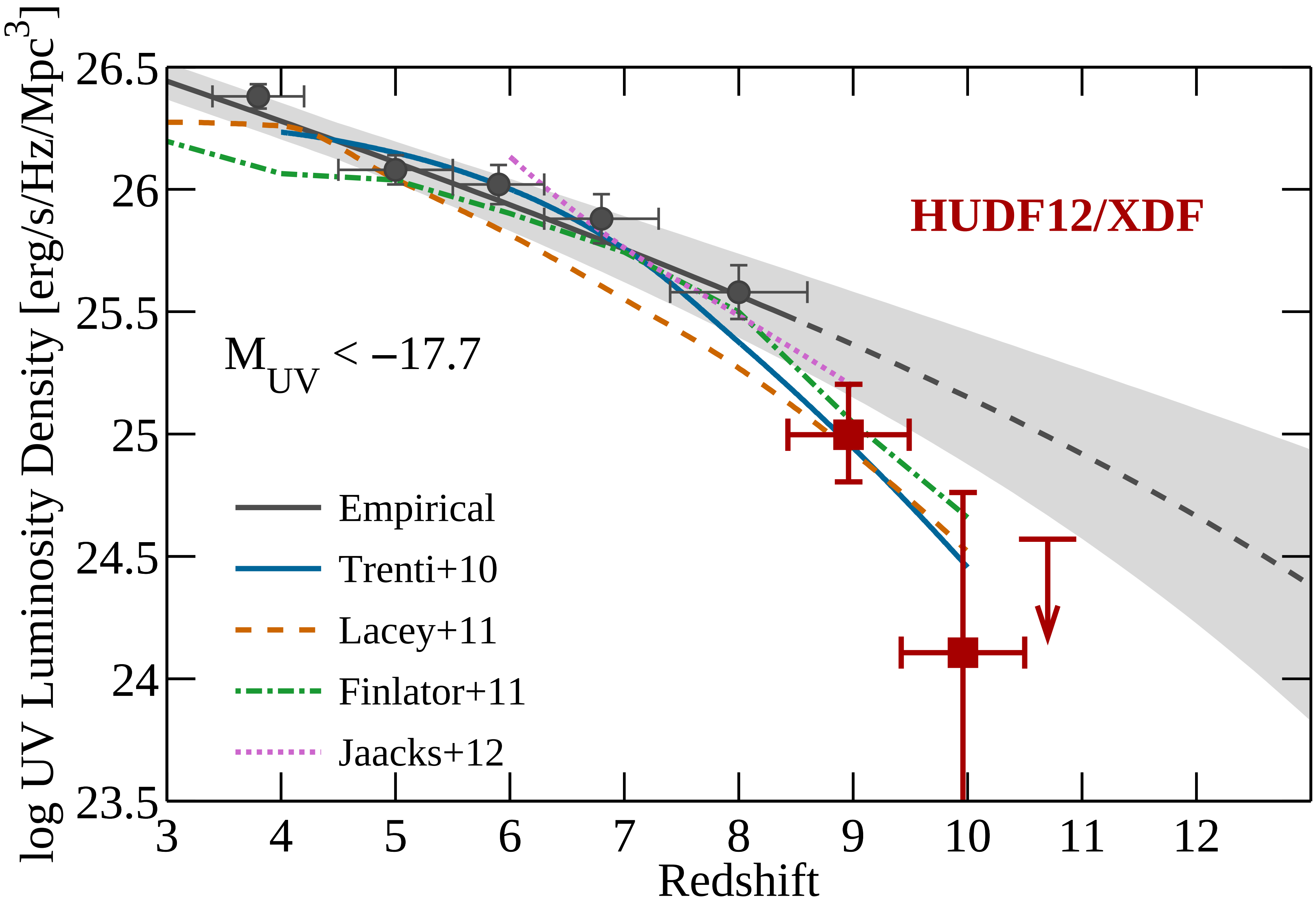
Expectation from Smoothly Evolving LF to z>8



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

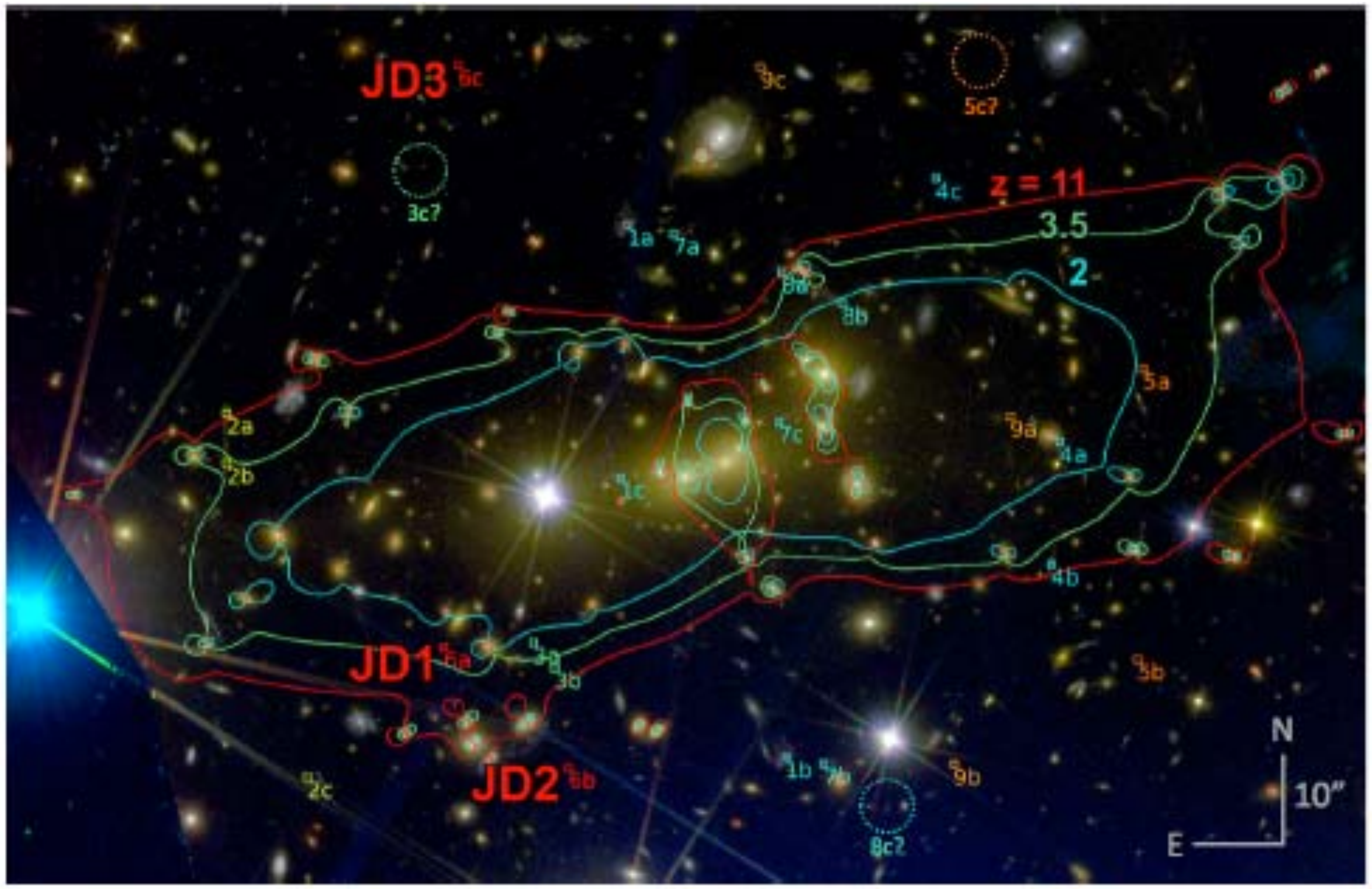
Therefore, galaxy evolution at z>8 is accelerated.

Accelerated Evolution is Expected from Models

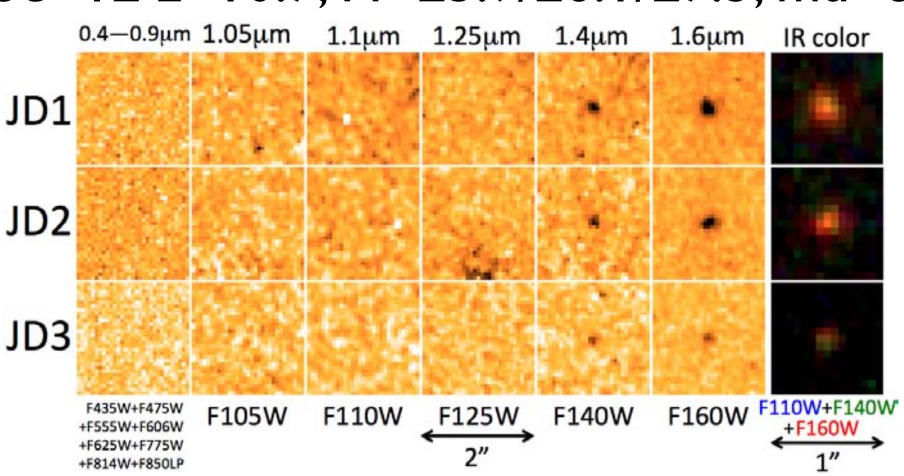


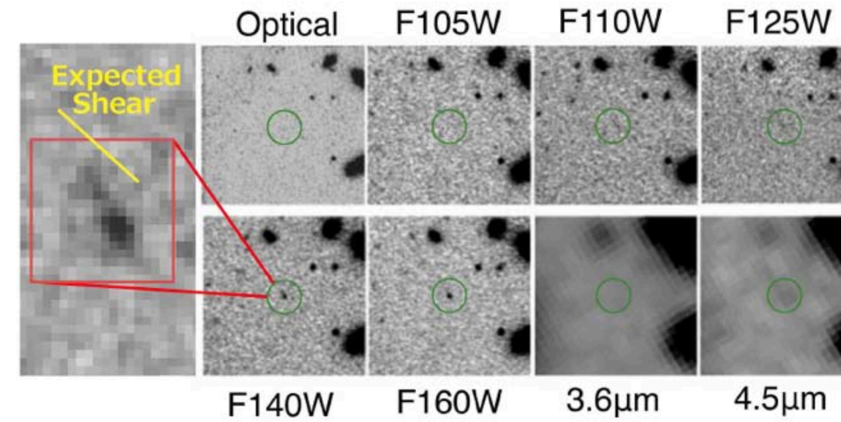
Accelerated evolution is in agreement with theoretical models.
Major driver is most likely the underlying DM halo MF.

Two Additional z~10 Candidates from CLASH

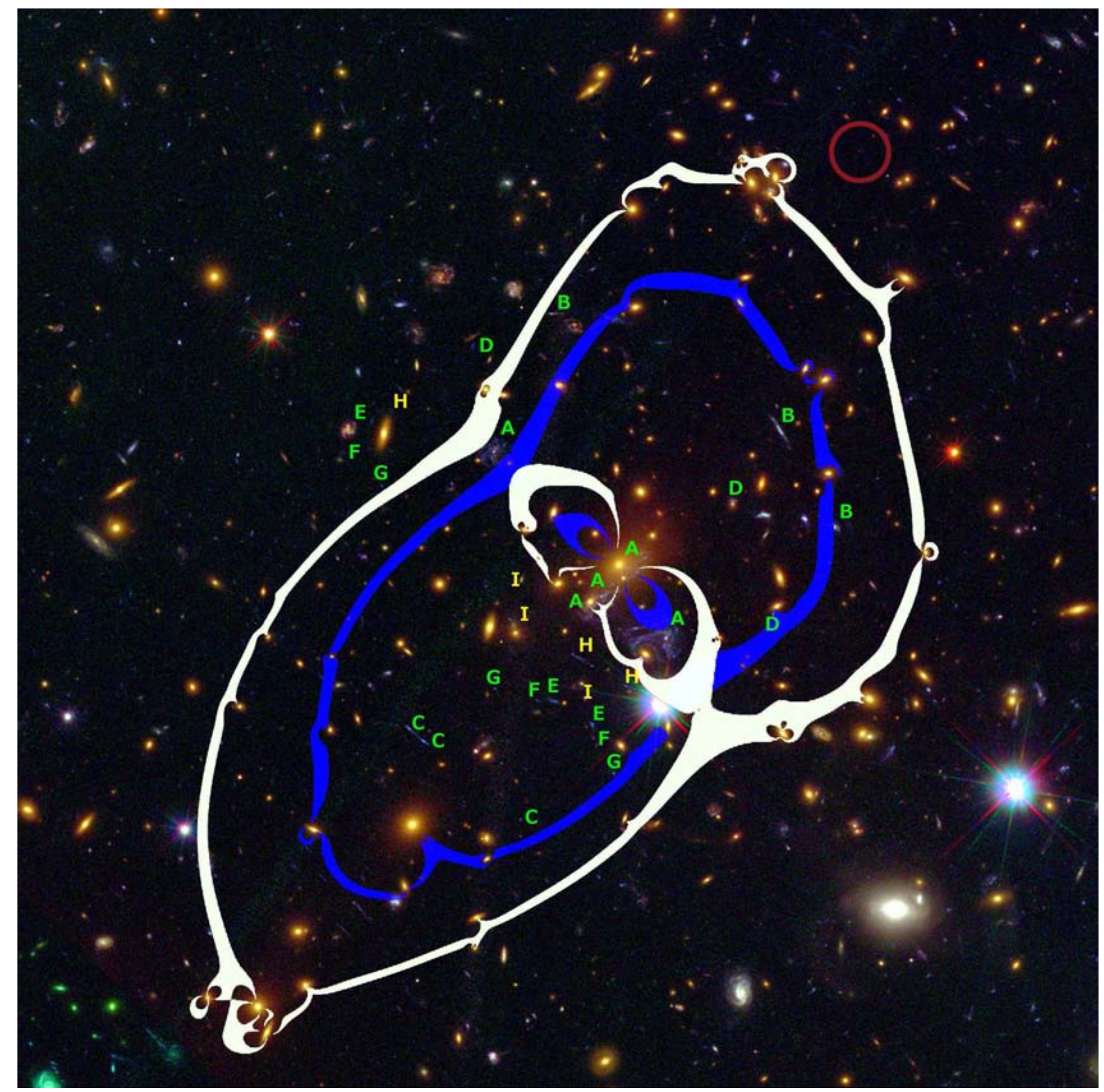


Coe+12 z=10.7, H=25.9/26.1/27.3, mu~8/7/2

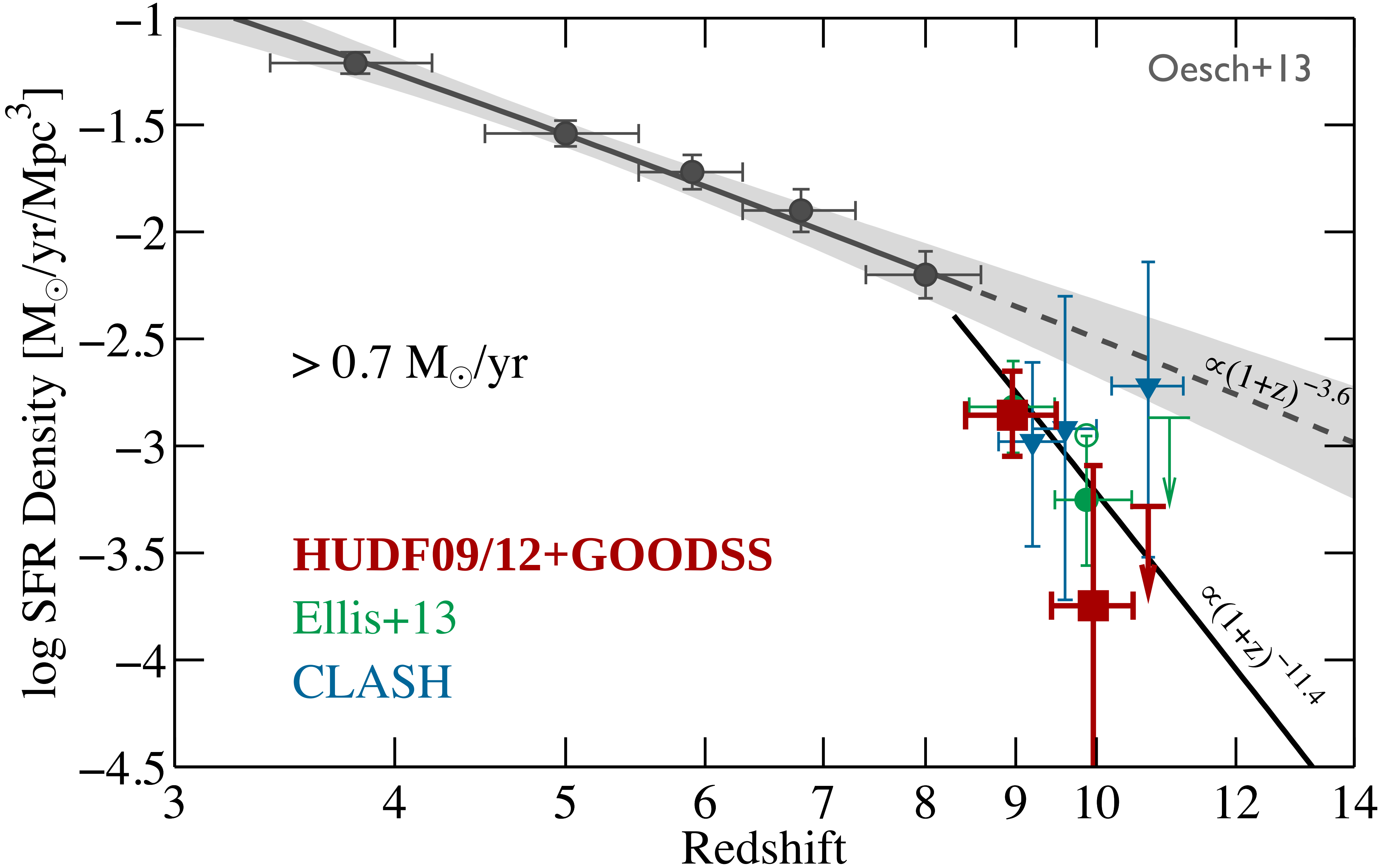




Zheng+12 z=9.6, H=25.7, mu=14-26



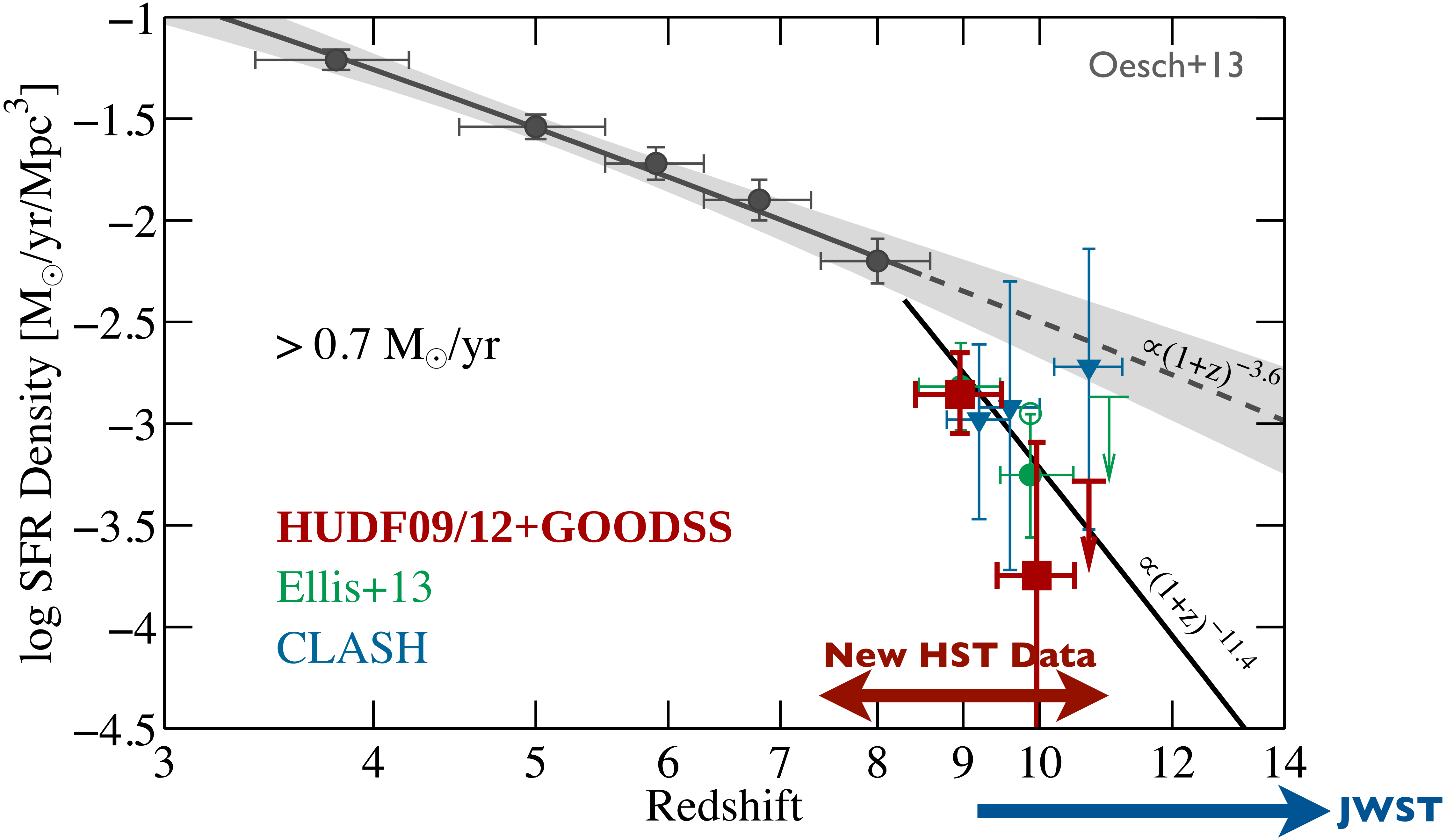
SFRD Evolution at z>8



Combining the constraints from CLASH and HUDF+GOODS-S data, we still find accelerated 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 UV luminosity in galaxies within only 170 Myr

But: observational result is still uncertain and needs confirmation with future deeper data, i.e. dedicated HST program or, at z>=10, JWST!

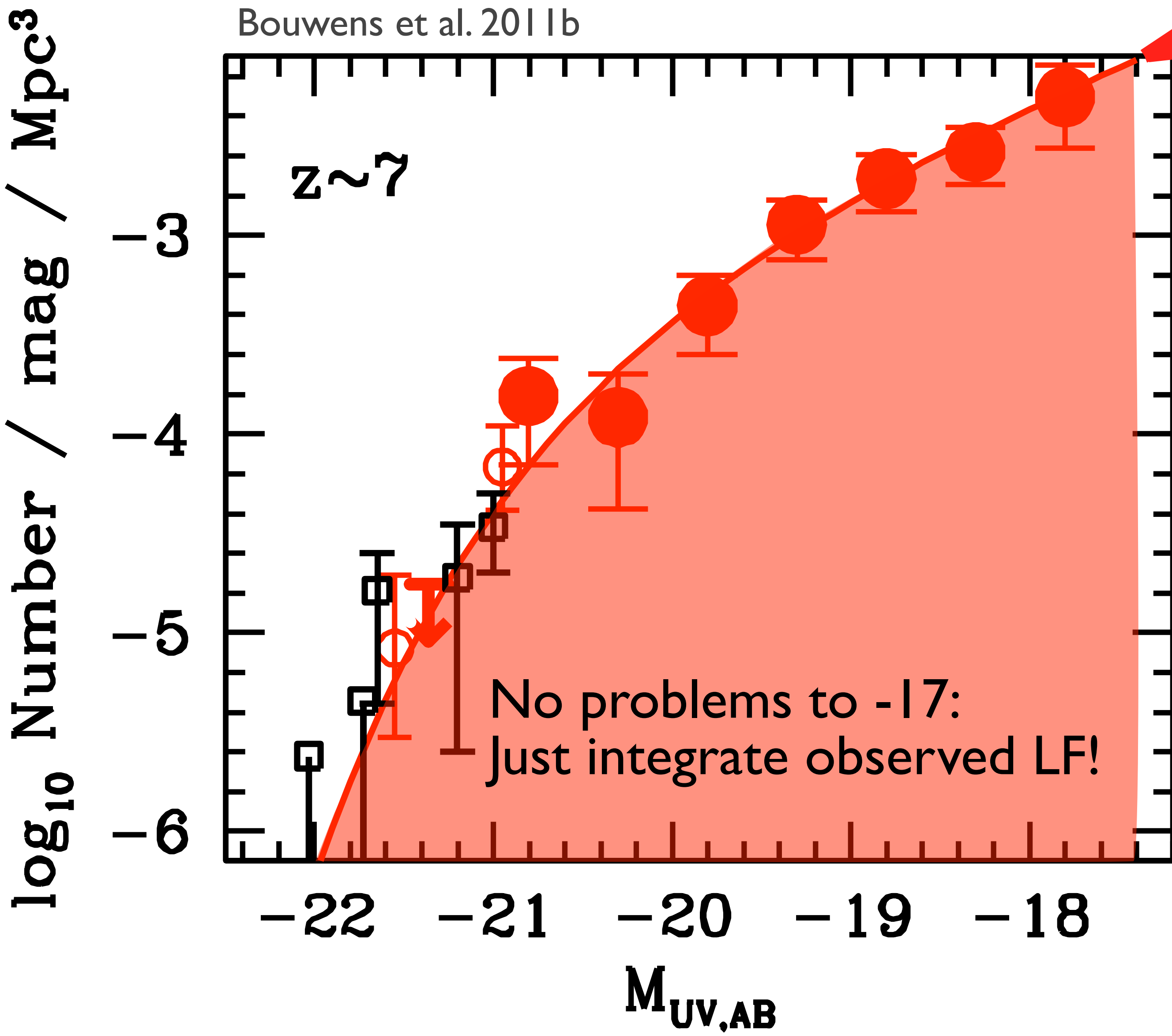
Are Galaxies Responsible for Cosmic Reionization?

WMAP implies mean redshift of reionization at 10.6
(τ = 0.088 ± 0.015; Komatsu+ 2011)

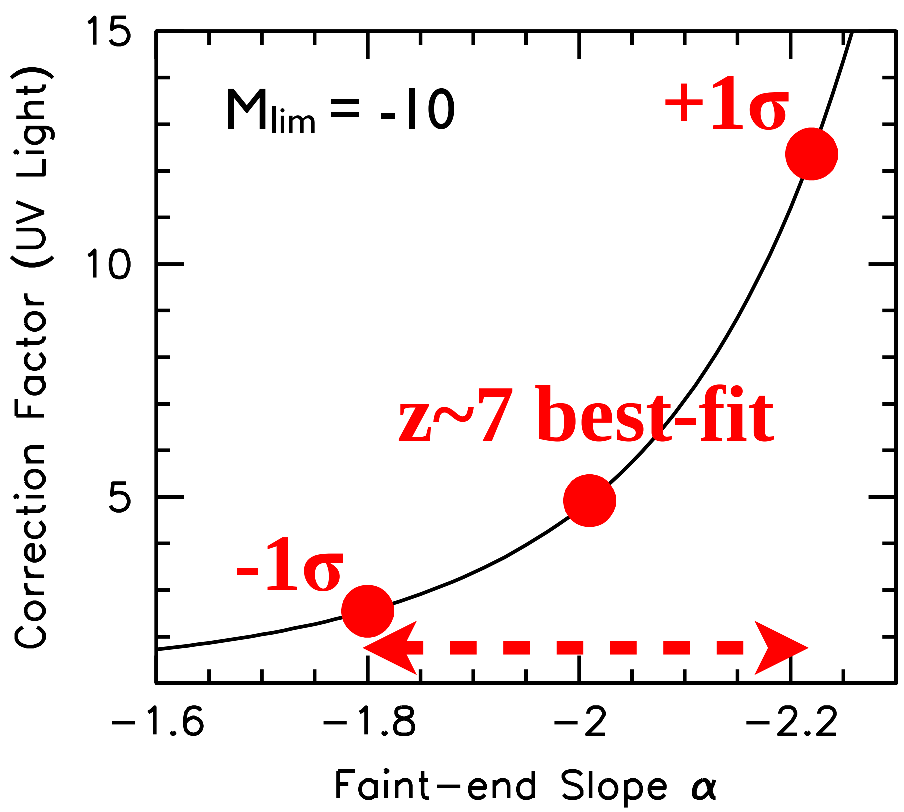
The Ionizing Flux Density from Galaxies

$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{lim}]{} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}^{int}_{ion} \xrightarrow[f_{esc,rel}]{} \dot{N}_{ion}$$

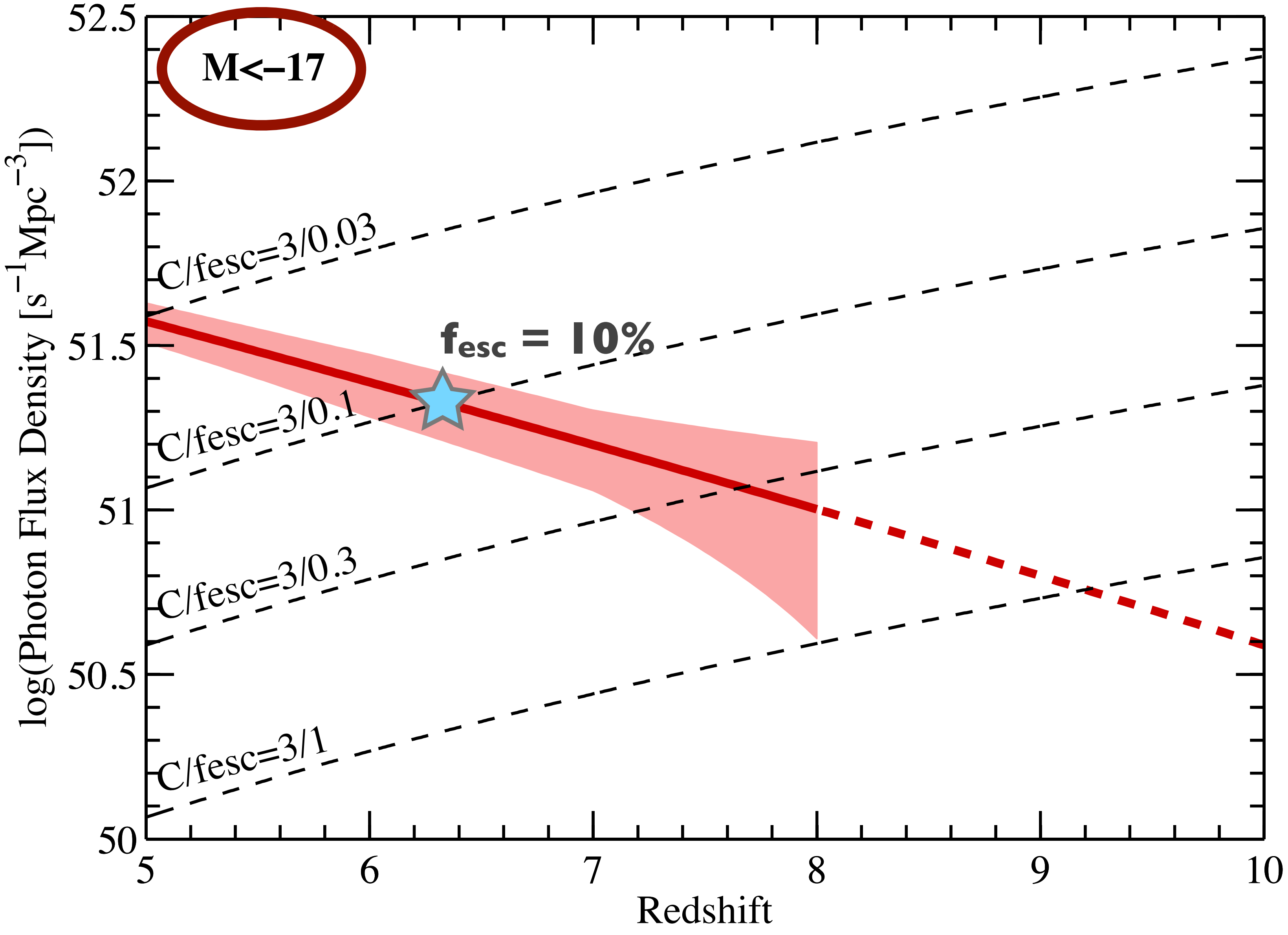
? Faint contribution: Have to extrapolate to below detection limits



With these steep faint-end slopes as observed: luminosity density completely dominated by faint galaxies



Keeping the Universe Ionized



The observed galaxy population (above our z~6 completeness limit) can keep the universe ionized already at z~6-7 with an average escape fraction of 10-30%

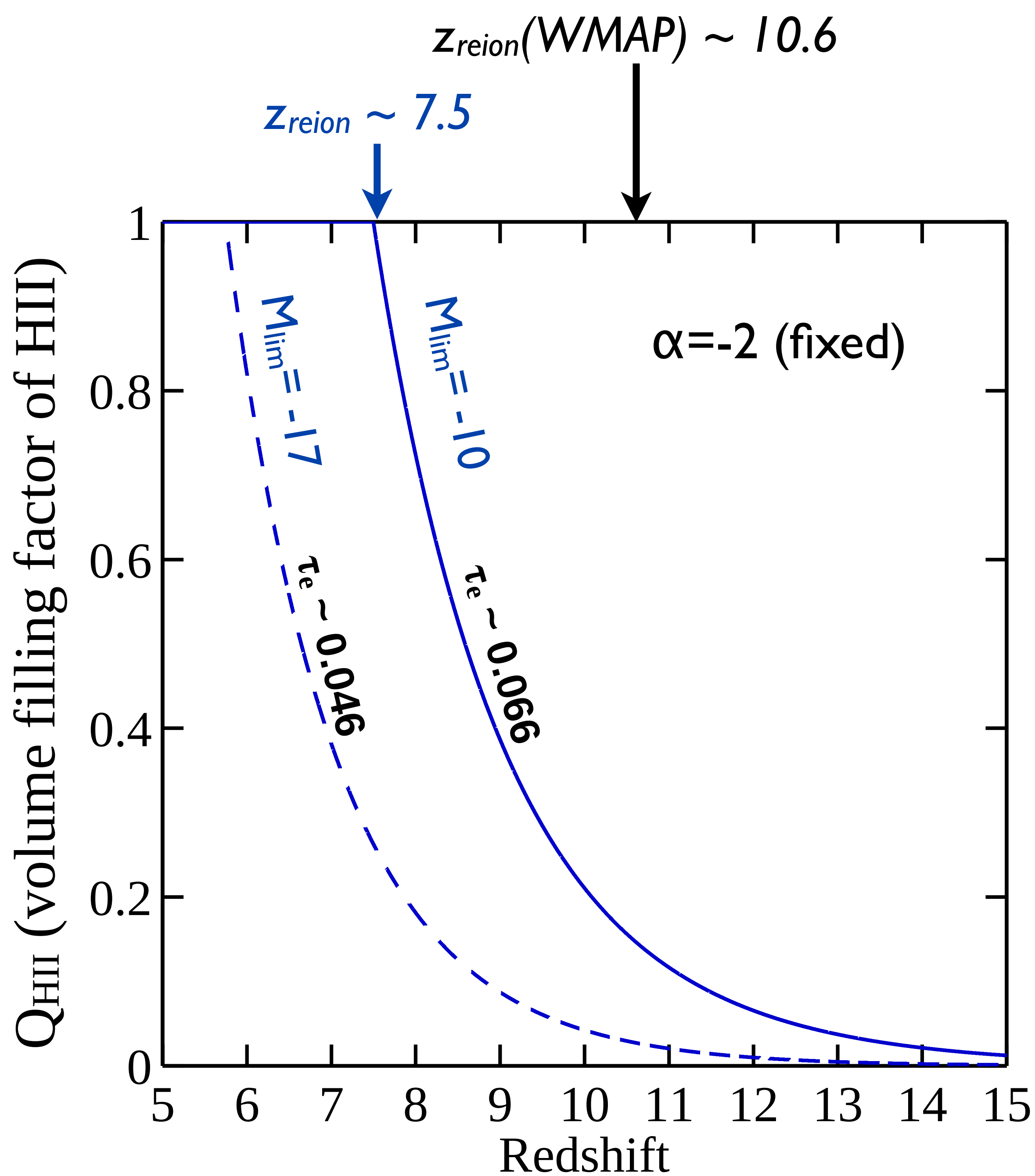
Inferred Reionization History

- A steep faint-end slope makes it easy for the faint (undetected) galaxy population to complete reionization above z>6
- **But:** optical depth to electron scattering is below measured values from WMAP by 1.5σ

Thomson optical depth of model: $\boldsymbol{\tau_e}$ **~ 0.066**

WMAP measurement: $\boldsymbol{\tau_e}$ **= 0.088 ± 0.015**

Note: Observed galaxies down to M_{lim} = -17: can complete reionization just below z~6, with $\boldsymbol{\tau_e}$ **~ 0.046**



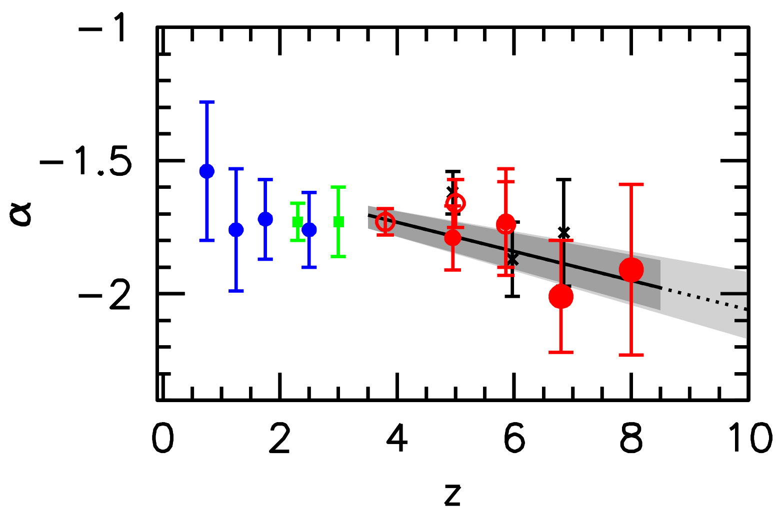
Additional assumptions:
clumping factor = 3
relative escape fraction = 20%

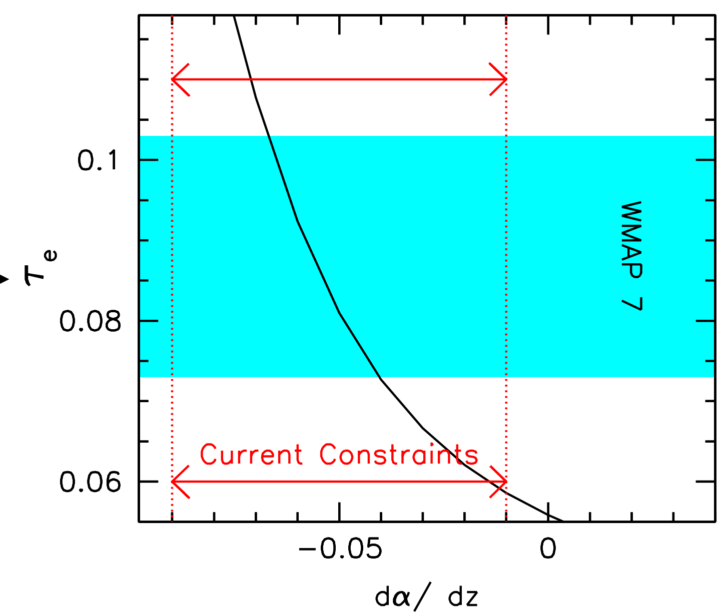
Matching WMAP Optical Depth

For galaxies alone to drive reionization, need more ionizing photons at z>8

Evolution in Faint-End Slope

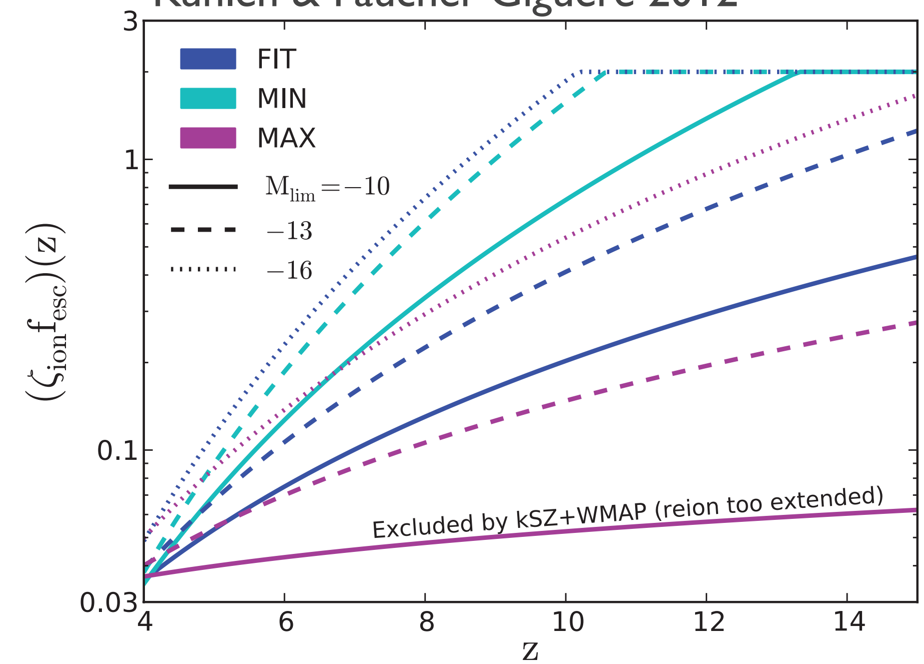
Bouwens et al. 2011c





Evolution in escape fraction and/or metallicity

Kuhlen & Faucher-Giguere 2012



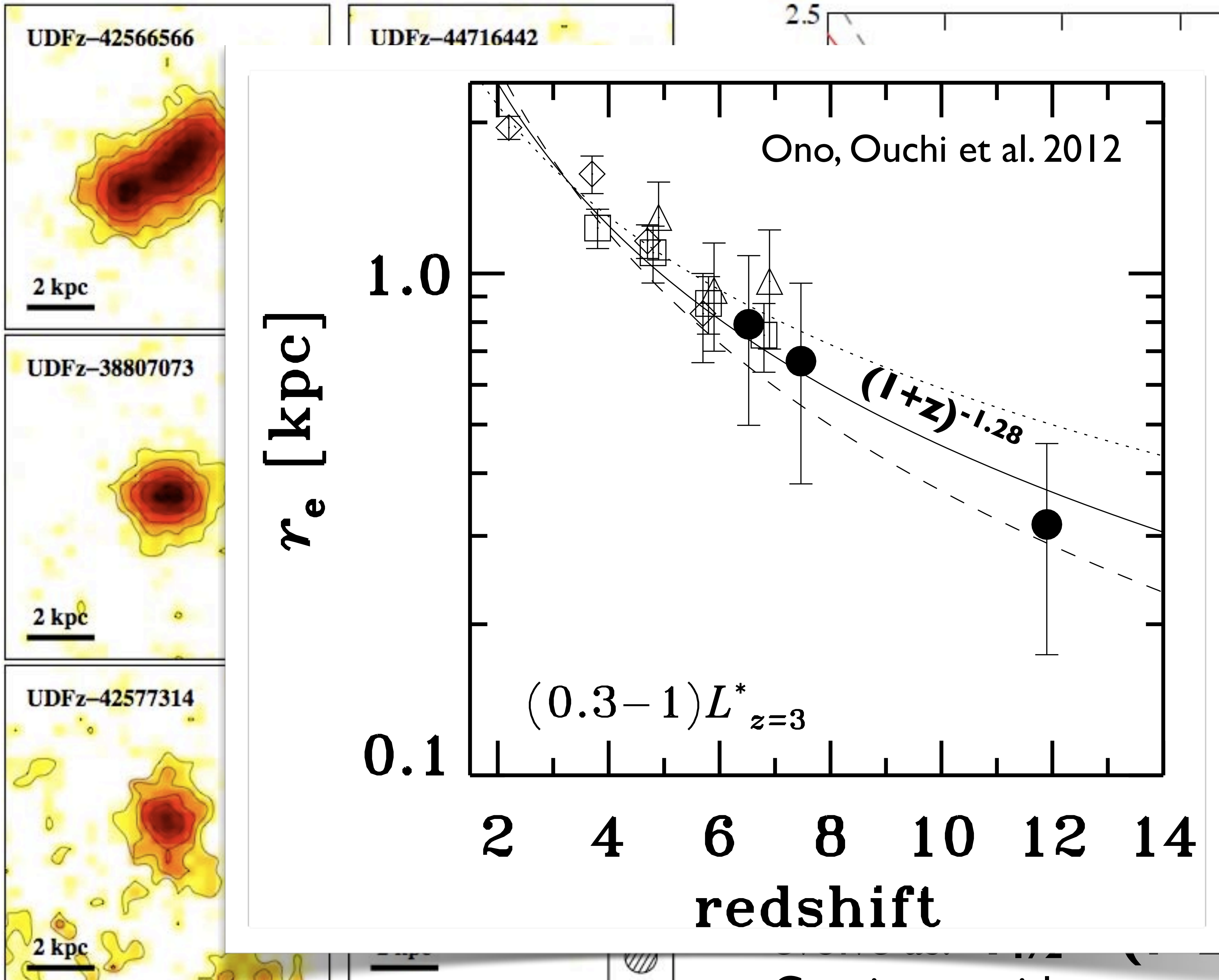
High-z contribution of PopIII stars may add a few percent in optical depth.

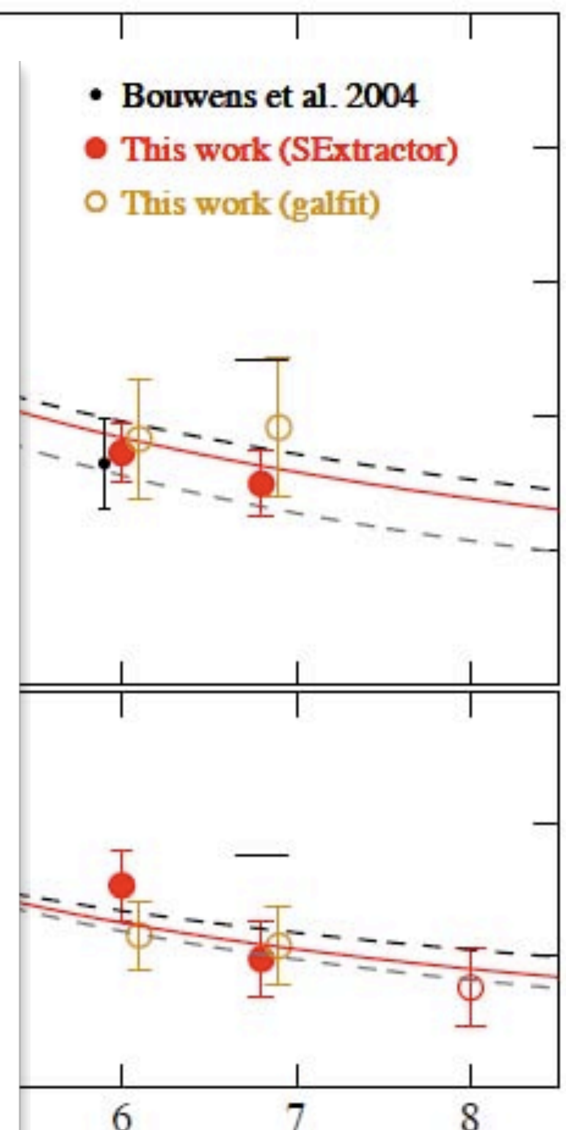
➡ Galaxies below detection threshold can reionize the universe consistent with WMAP: Need better constraints on evolution of faint end slope with redshift (as well as escape fractions)!

The Physical Properties of High-z LBGs

Sizes, Dust Content, SFRs, and Masses

The Resolution of WFC3/IR’s ➡ Structure/Sizes





Gyr of cosmic time

)$^{-1}$

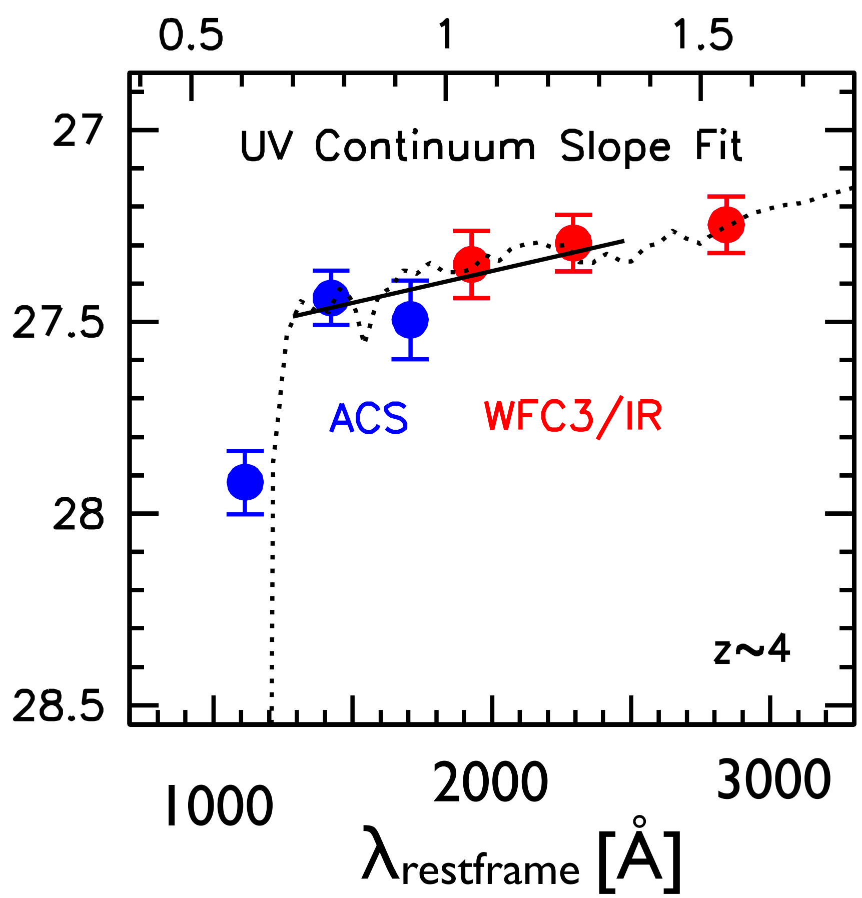
Consistent with constant L at fixed halo mass.

Oesch et al. 2010b

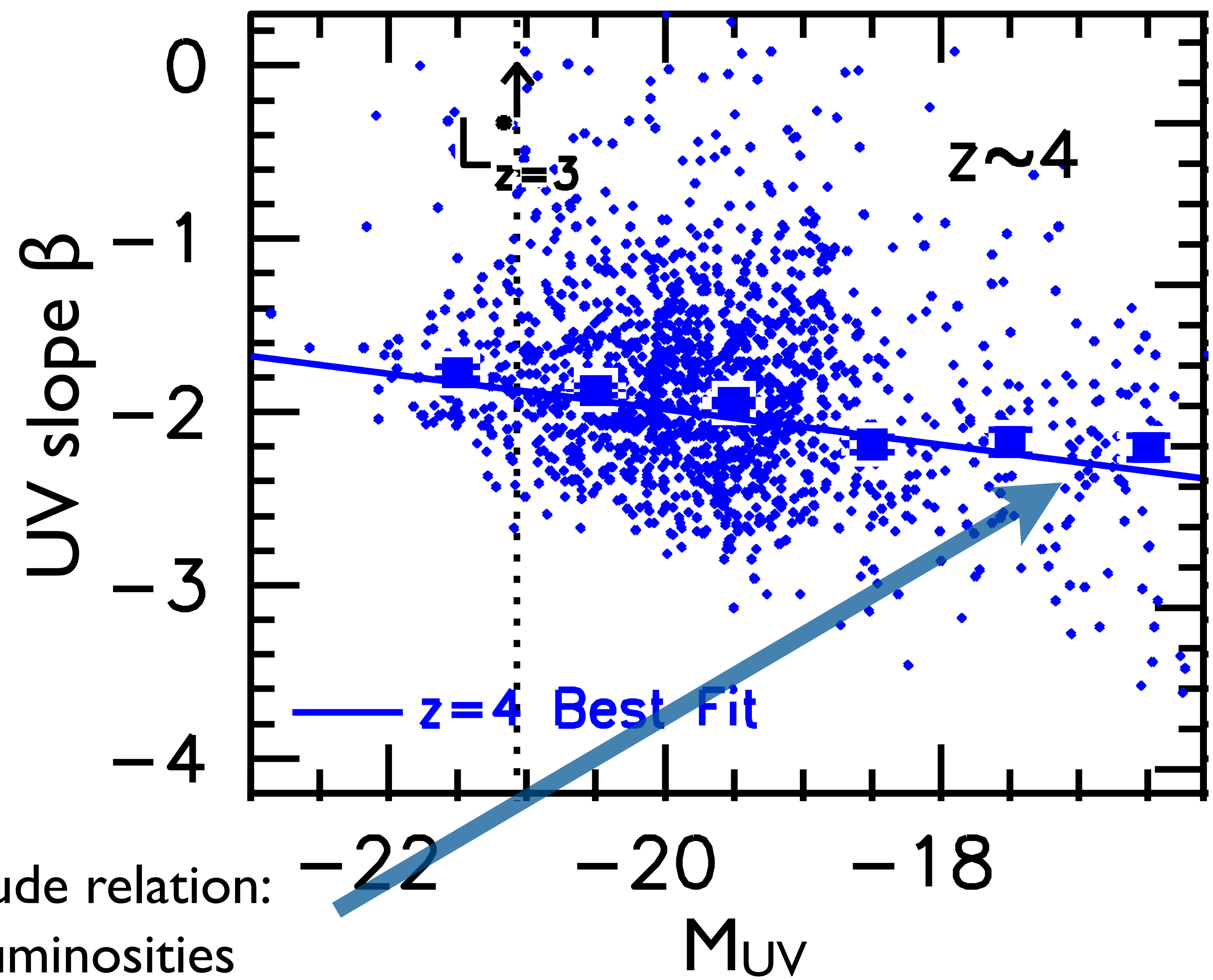
UV Continuum Slopes

Can obtain information on slope of UV continuum spectral slope based on a combination of ACS and WFC3/IR broad-band colors

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



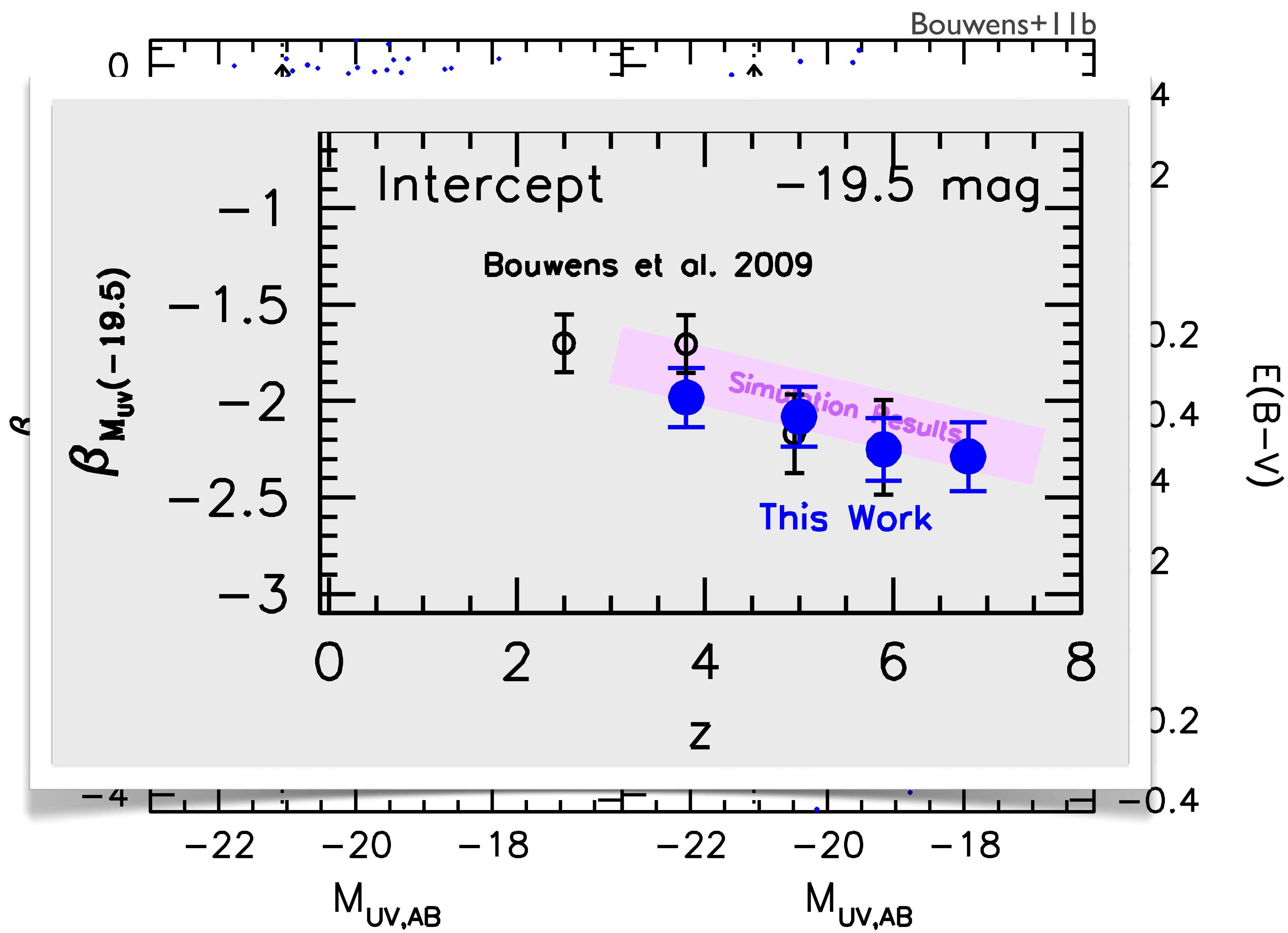
Bouwens+11b



Relatively well-defined color-magnitude relation:
Galaxies are very blue at faintest luminosities

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

UV Continuum Slopes

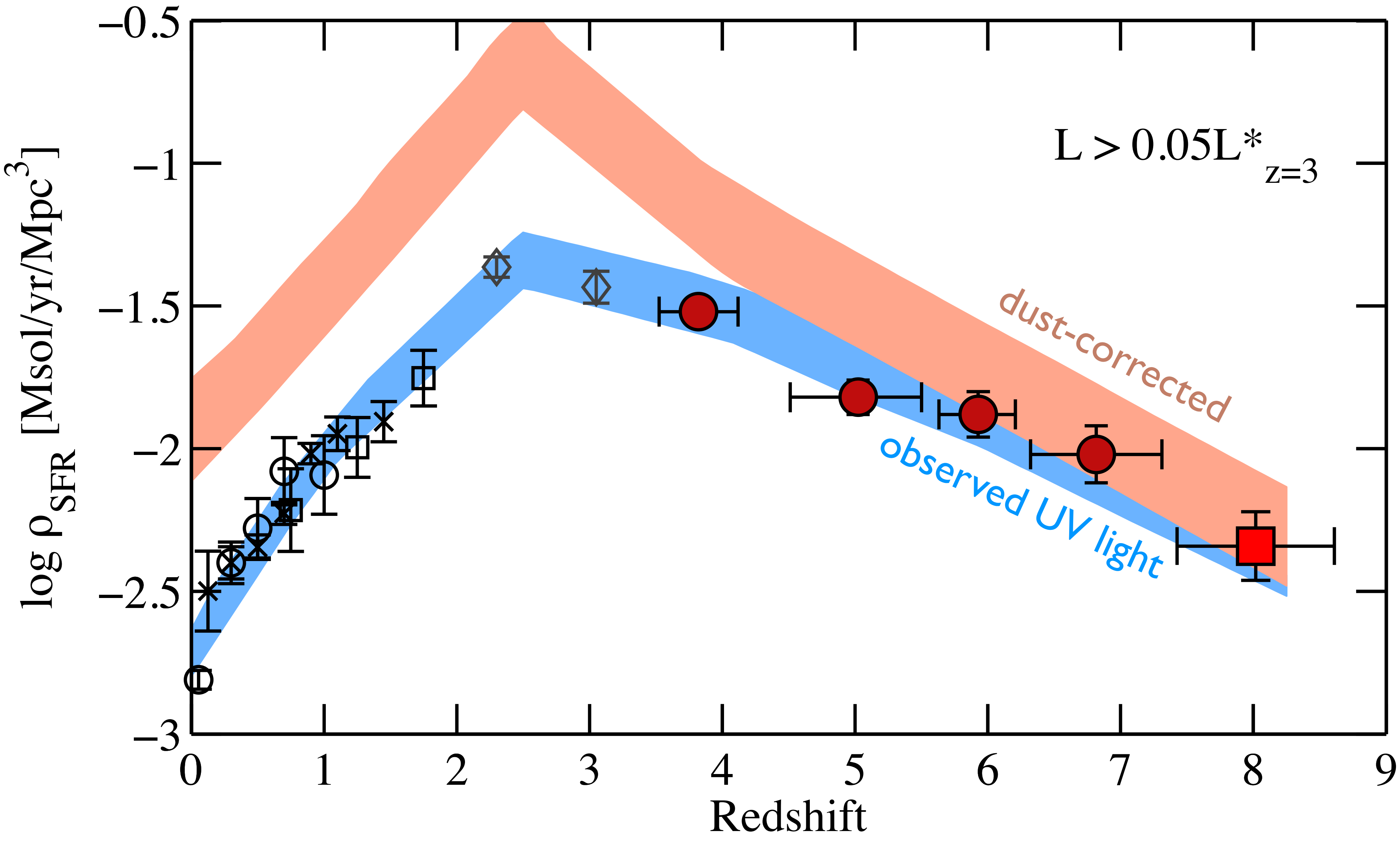


- Essentially constant slopes to color-mag relation at different redshifts
- Trend to redder UV continuum slopes with time: z~7 essentially dust free

Cosmic SFR Density

Combination of ACS and WFC3/IR observations allows us to measure UV continuum slopes of galaxies at z~4-7.

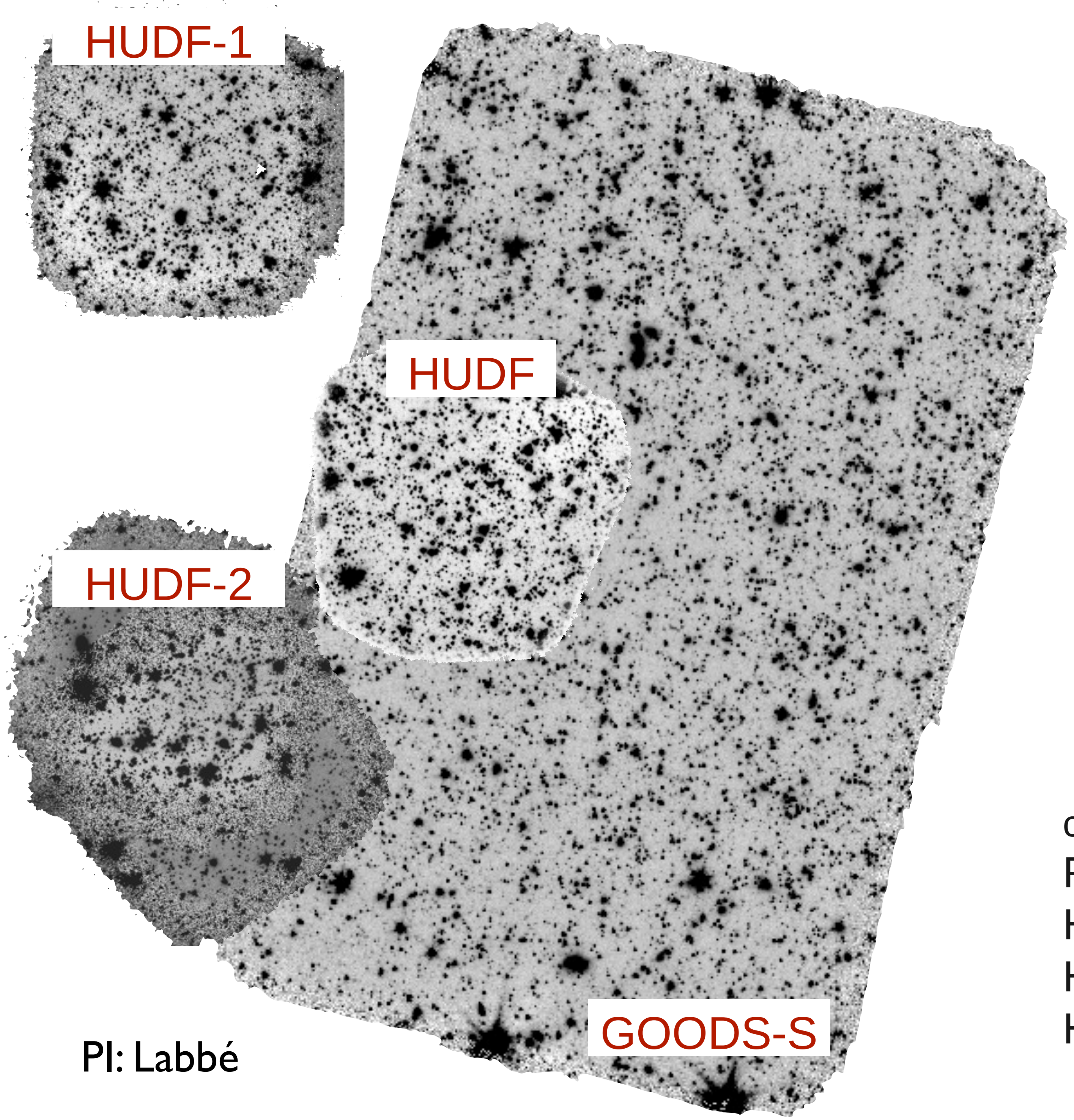
→ cosmic SFR density



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

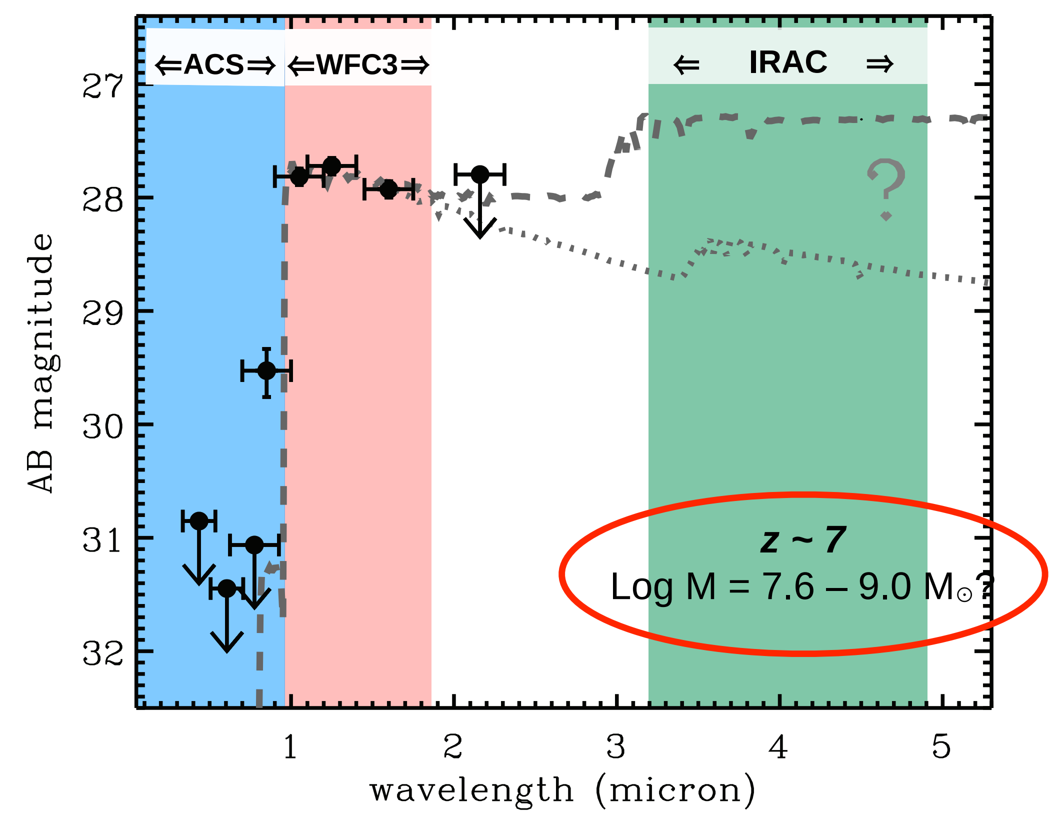
Spitzer IRAC probes rest-frame optical

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):

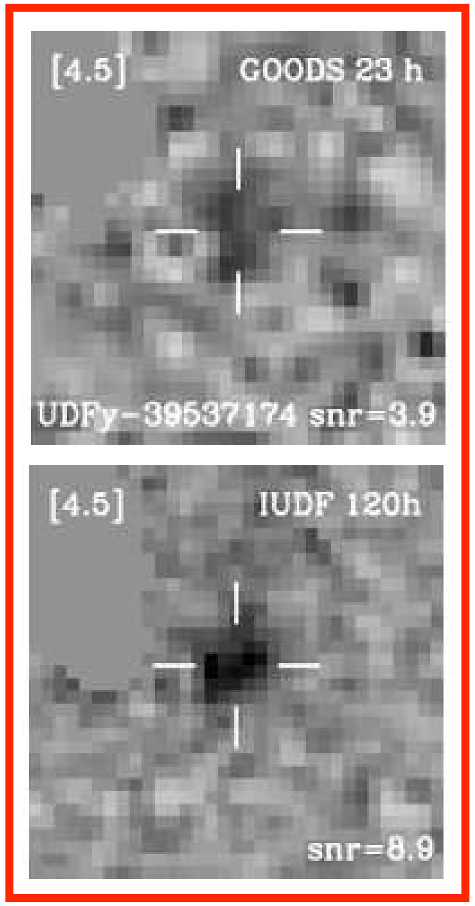
FIELD	[3.6]	[4.5]
HUDF	126	126
HUDF-1	52	52
HUDF-2	125	92

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).

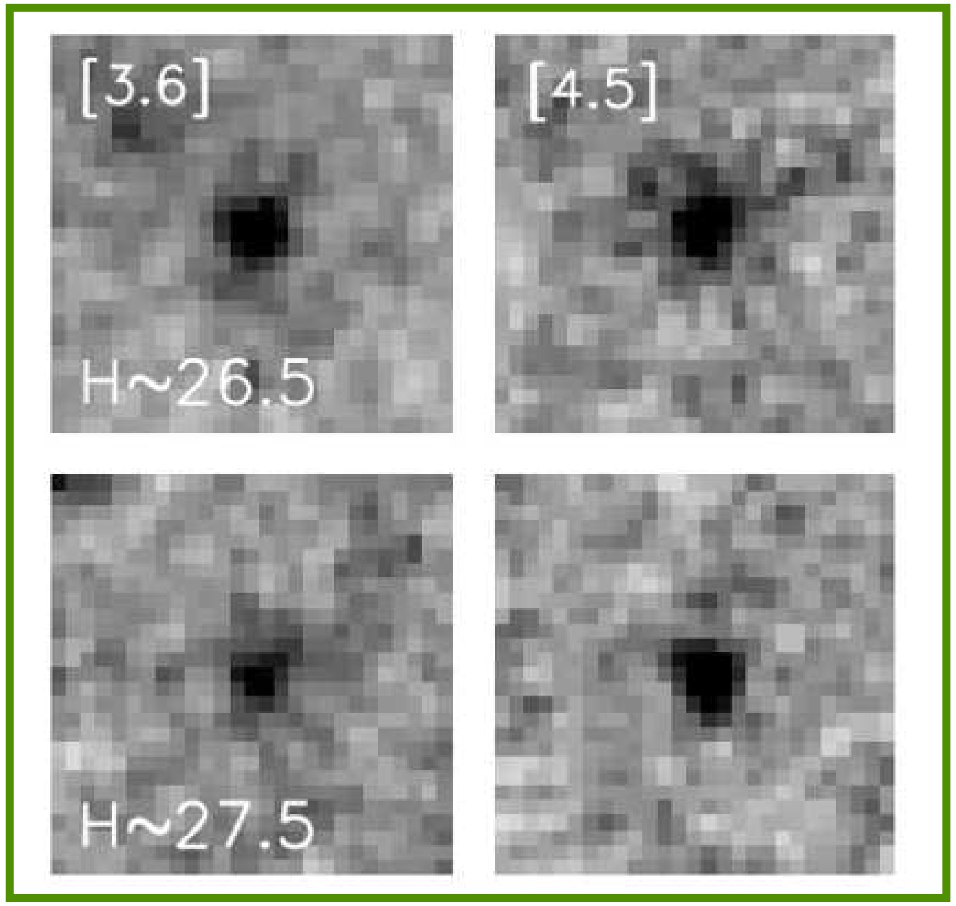
Median stacked images of 55 Y-dropouts in IUDF10 yield z~8 SED at >L*.

few robust individual detections

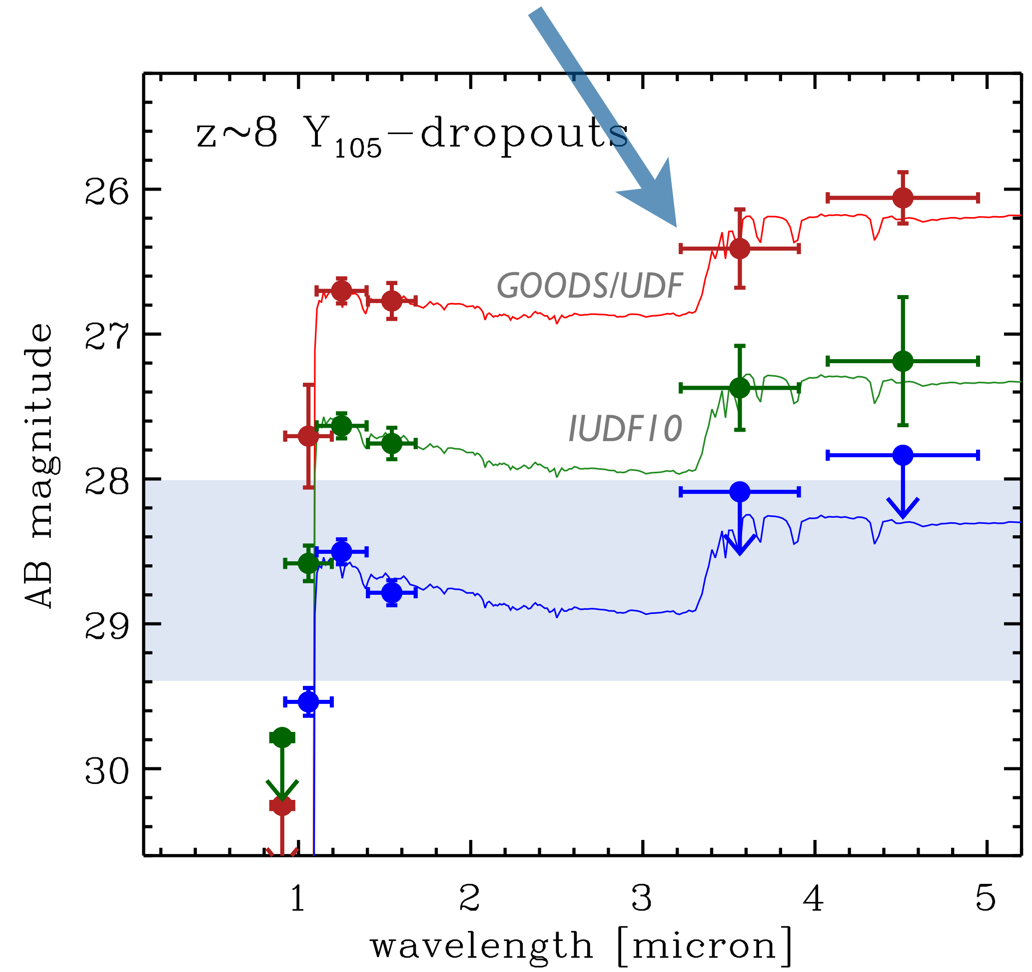


Labbé, Oesch et al. 2012

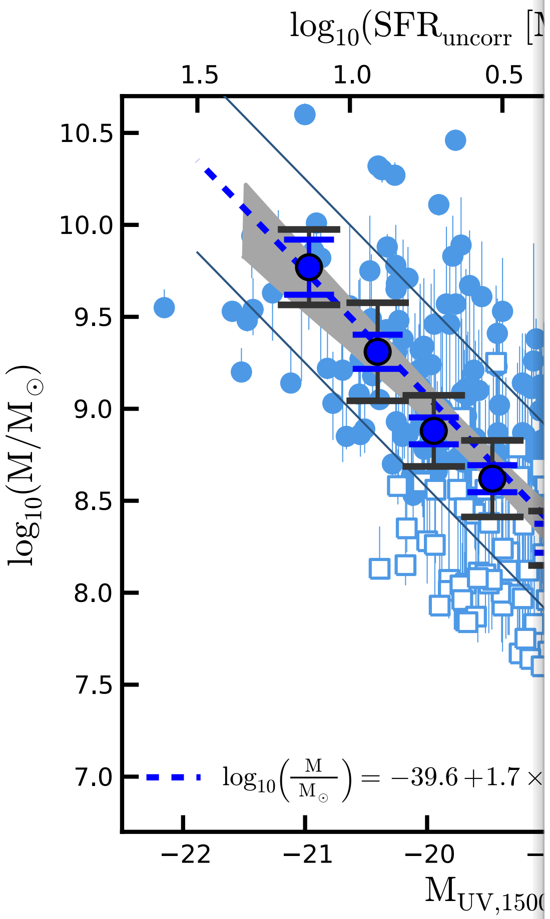
clear detections in stacks



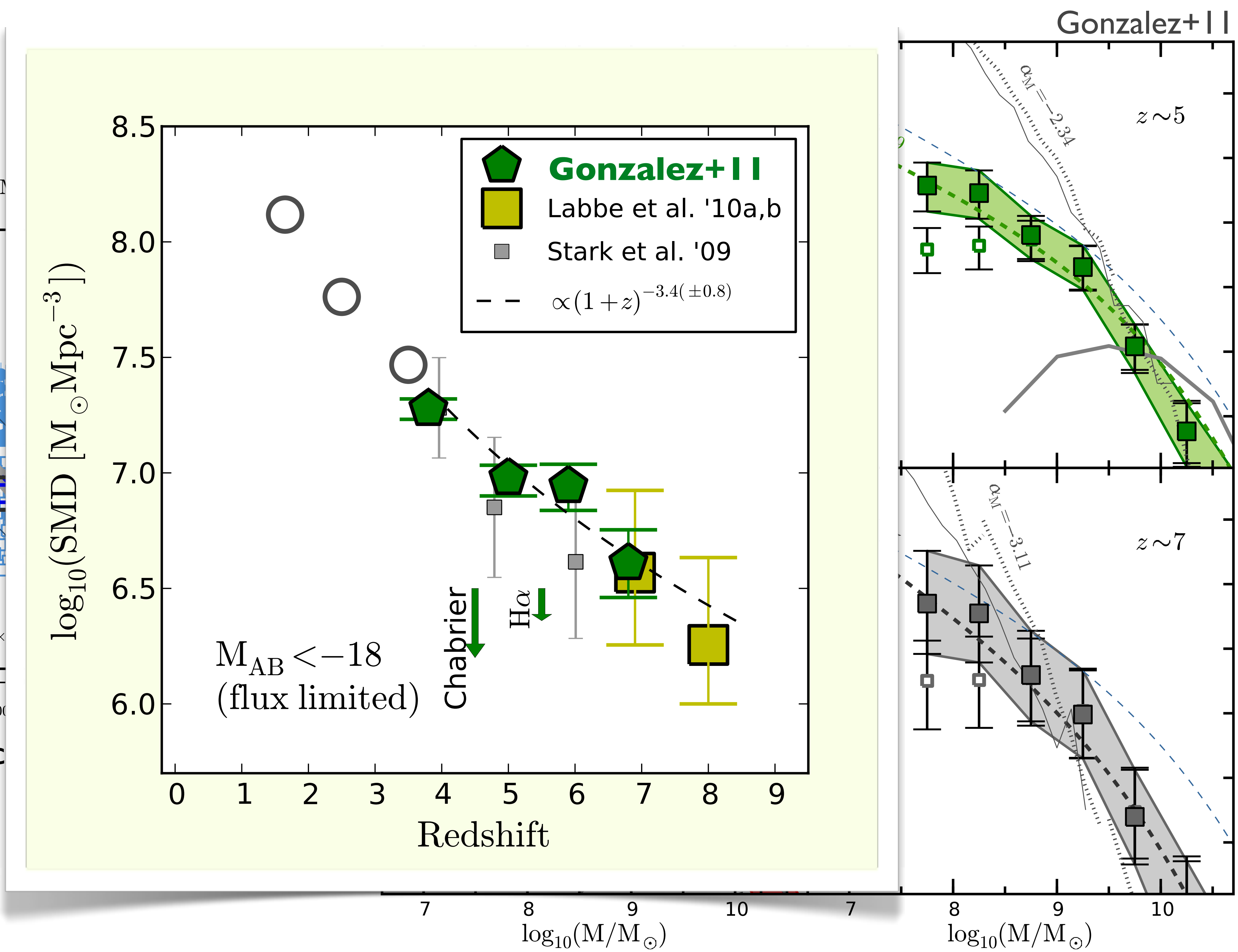
spectral break: indicates ages>~300 Myr, i.e. onset of SF at z>~12



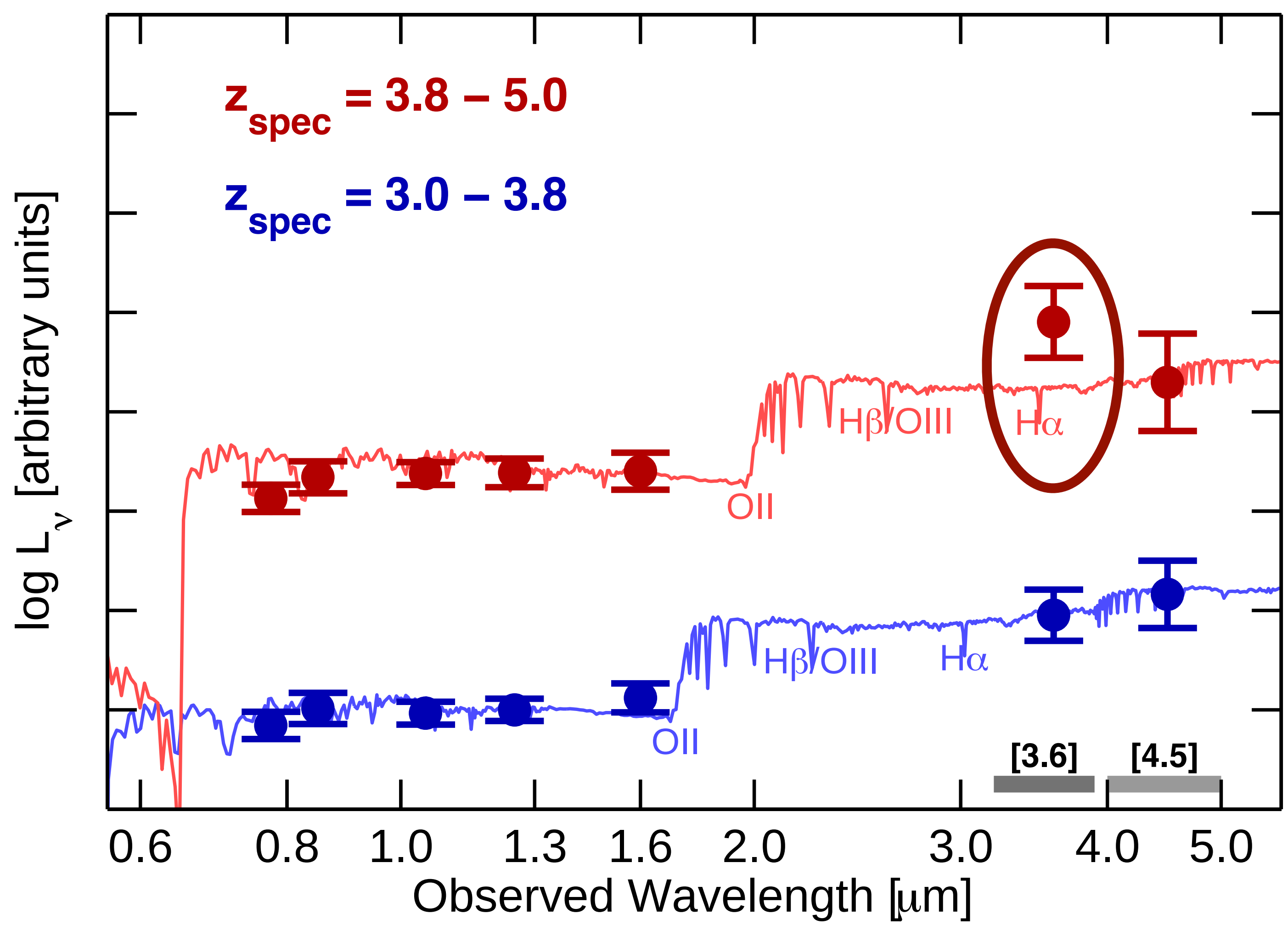
Evolution of the Mass Function



UV luminosity c
relatively well with



Caveat: Strong Emission Lines



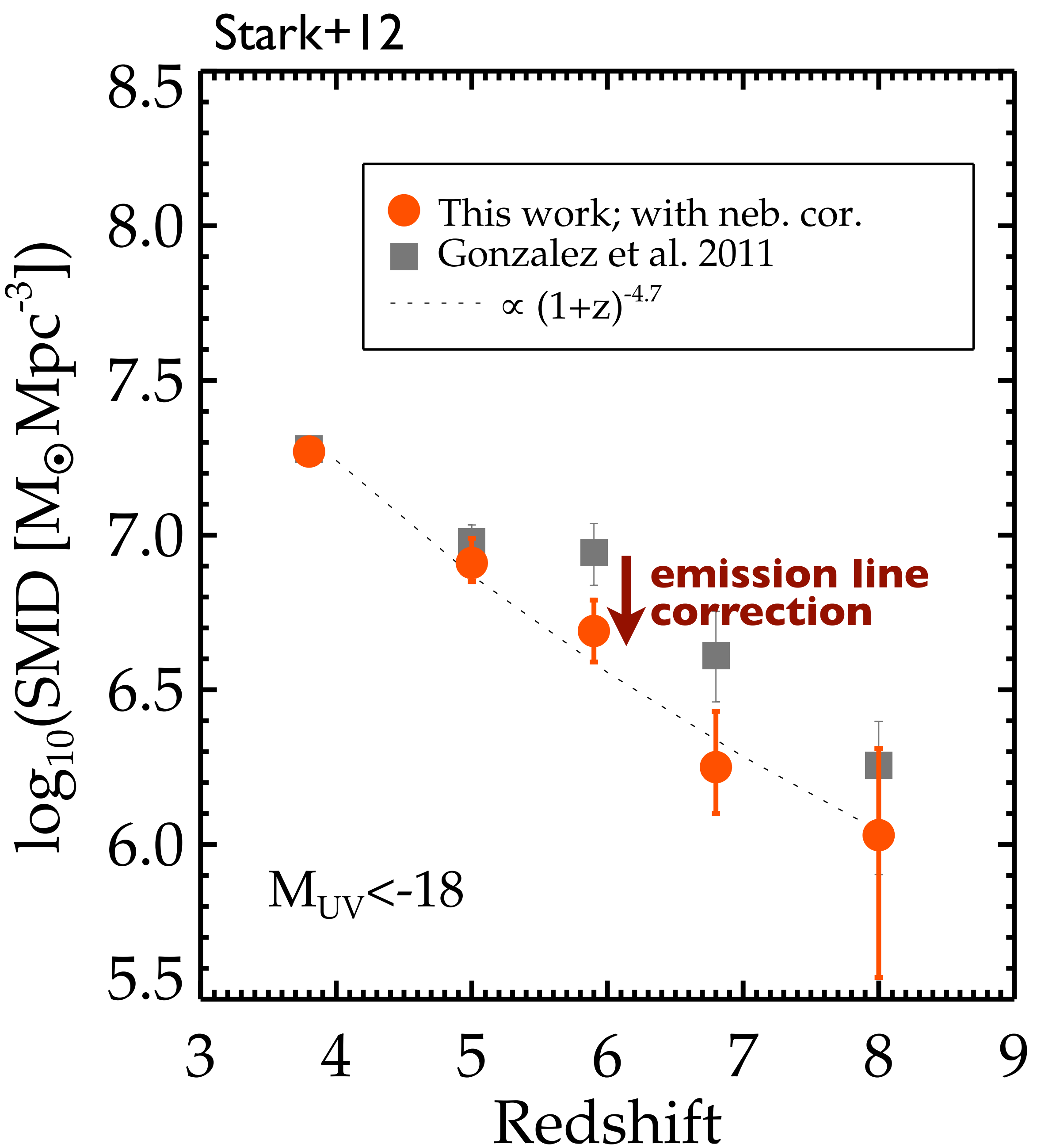
on average: 0.3 mag

EW(Hα) ≃ 300 Å

Strong rest-frame optical emission lines can significantly contribute to IRAC flux measurements. These will thus bias mass measurements.

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

Emission Line Contamination



Zero-th order empirical correction of Stark et al.:

➡ up to a factor 2-3x in stellar mass density

Correcting for emission lines:

➡ lower fluxes

➡ lower masses

➡ younger ages

➡ lower M/L ratios

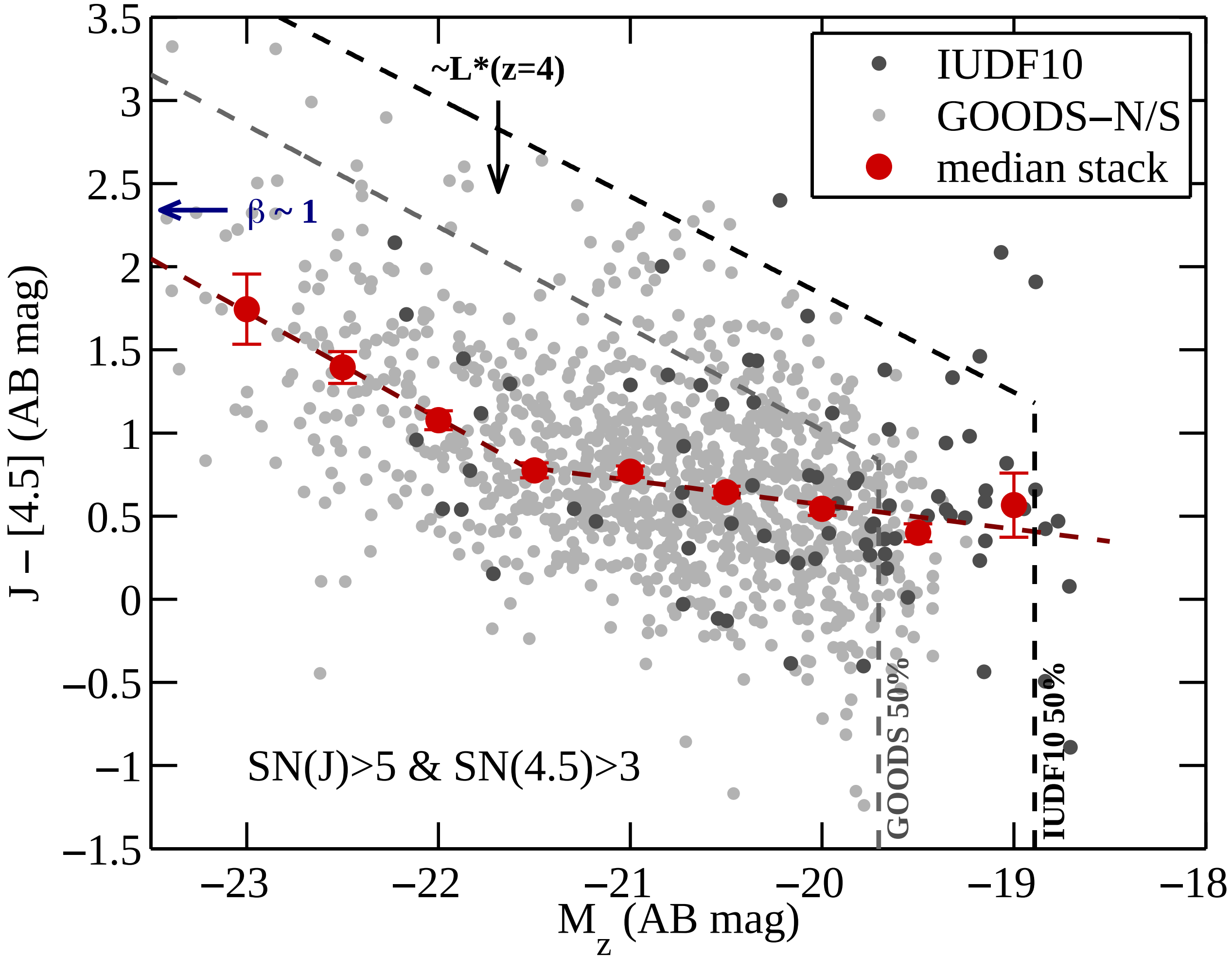
However, self-consistent fit of Gonzalez et al.:

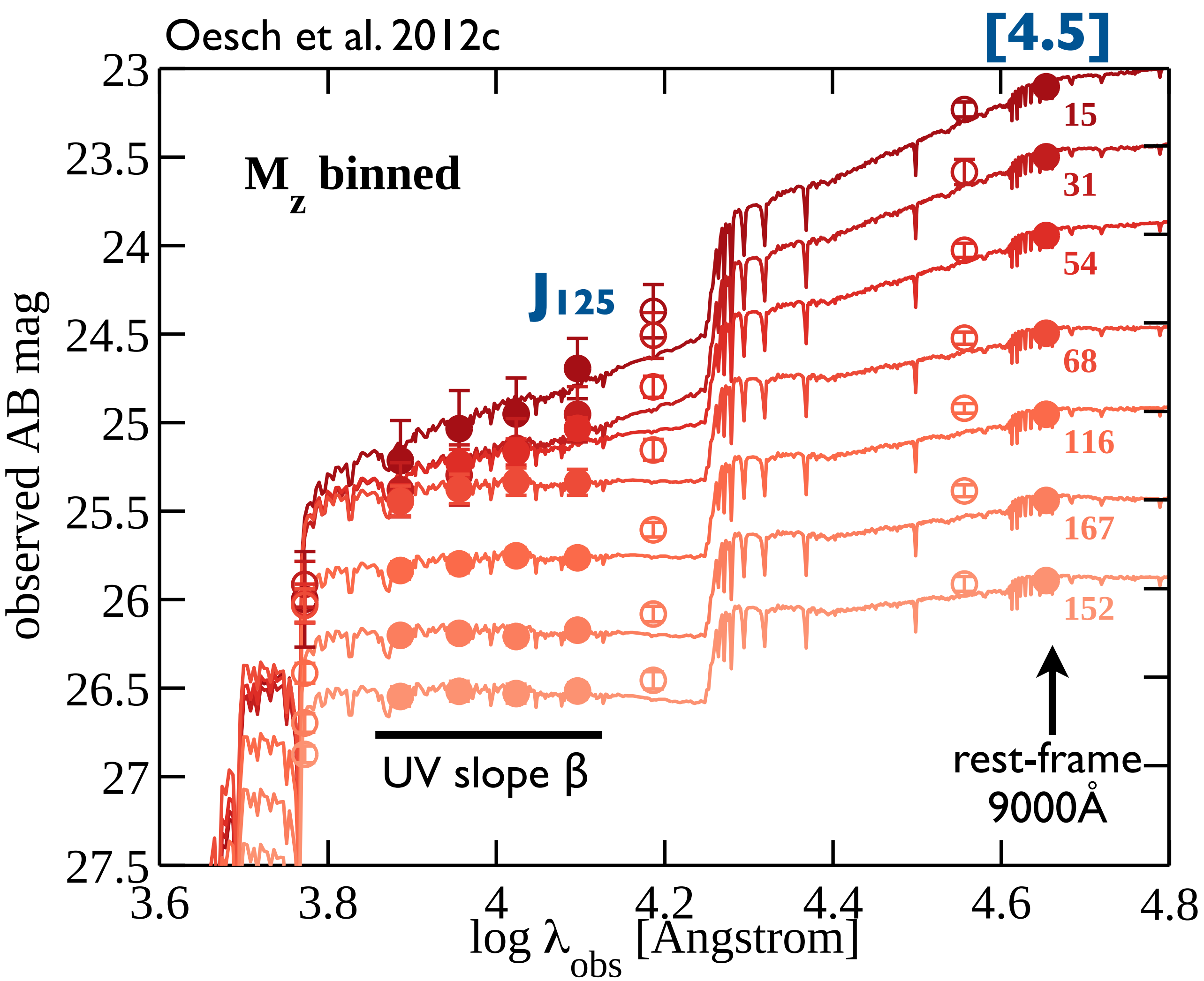
changes are possibly smaller, if using updated dust extinction measurements and rising SFHs

However, our samples with IRAC detections at higher redshifts are still small.
Recently acquired IRAC data over CANDELS will change this in near future!

The Rest-Frame Optical View of z~4 Galaxies

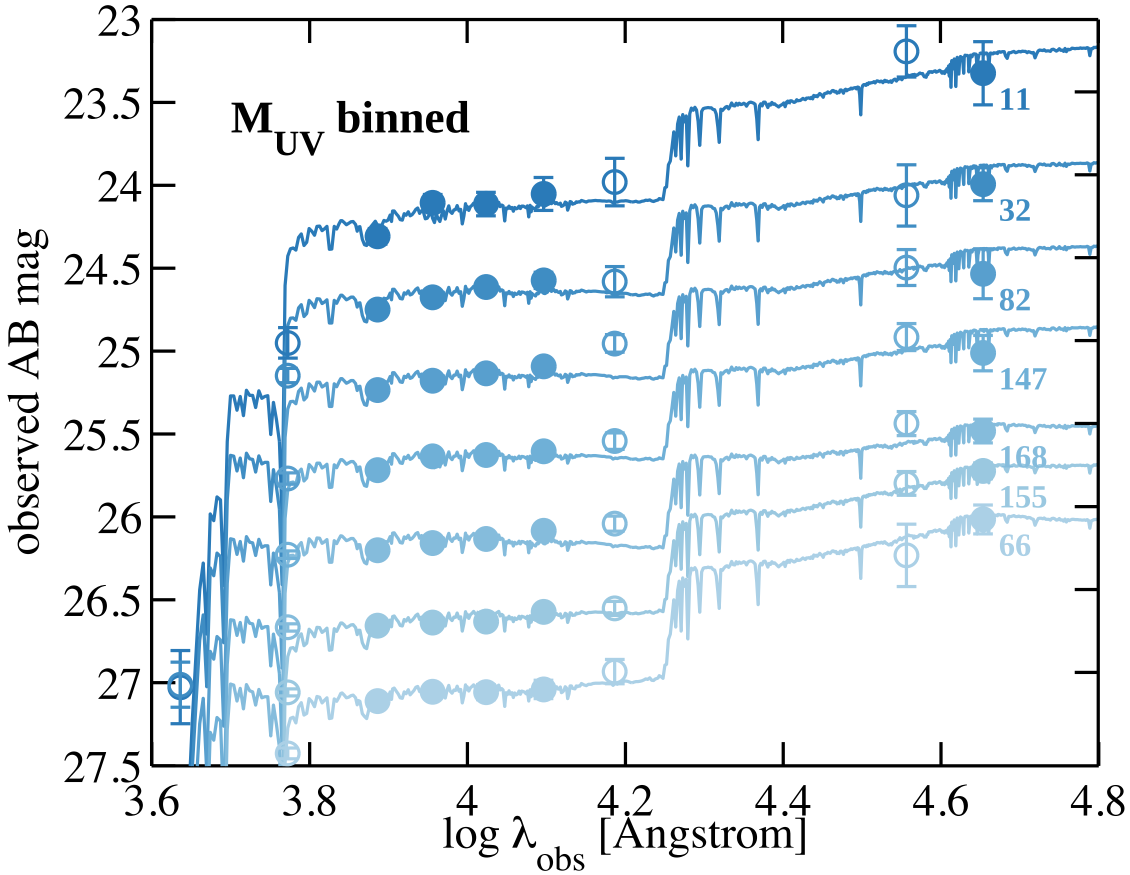
At z~4, we already now have samples of 2600 galaxies in GOODS-S/N and the IUDF10

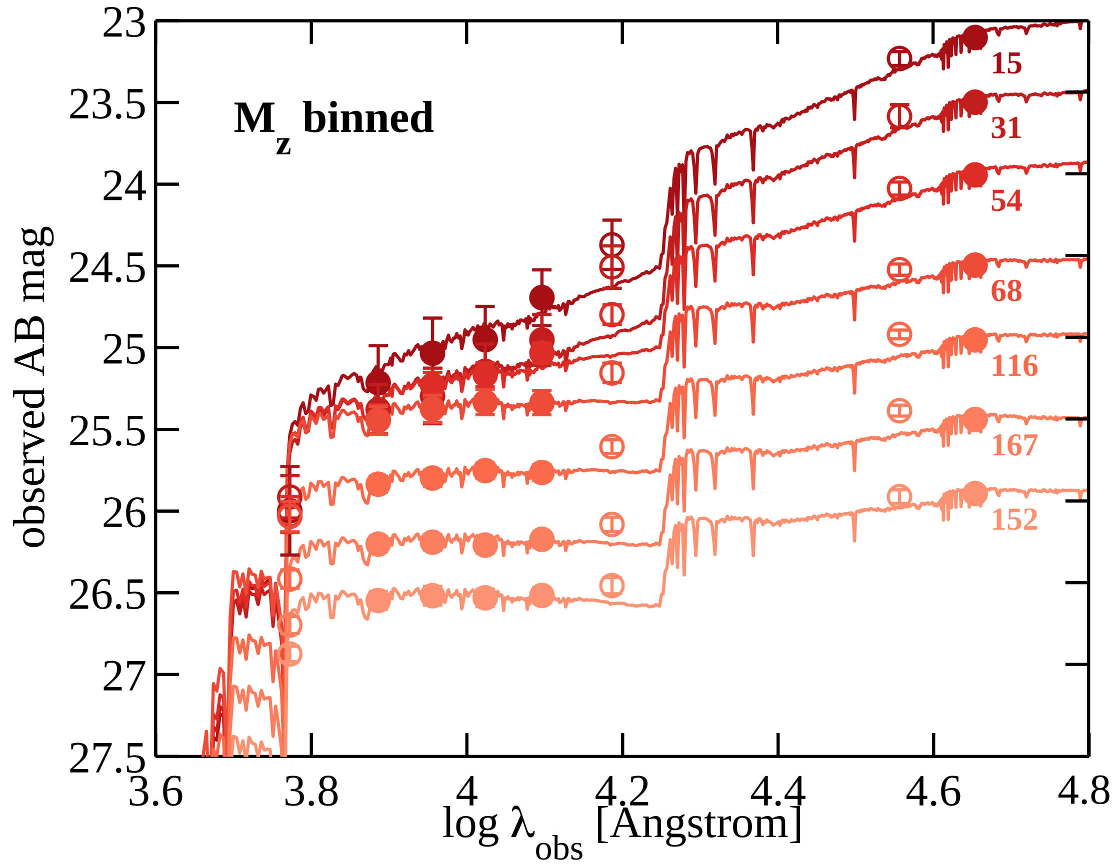




Brighter galaxies are significantly redder in their UV-to-optical colors wrt fainter sources. Bright galaxies also show redder UV continuum slopes.

Rest-Frame Optical vs Rest-Frame UV View



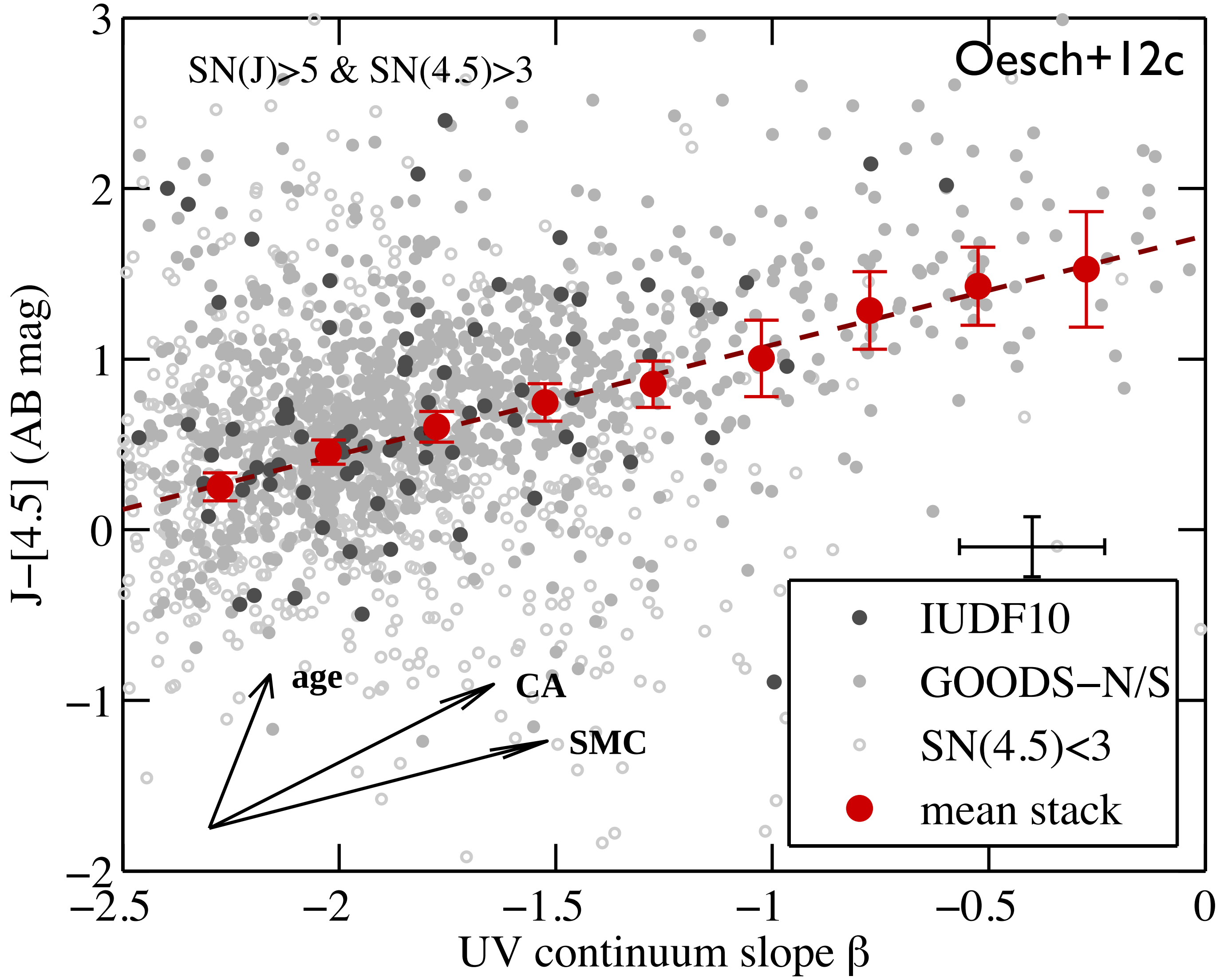


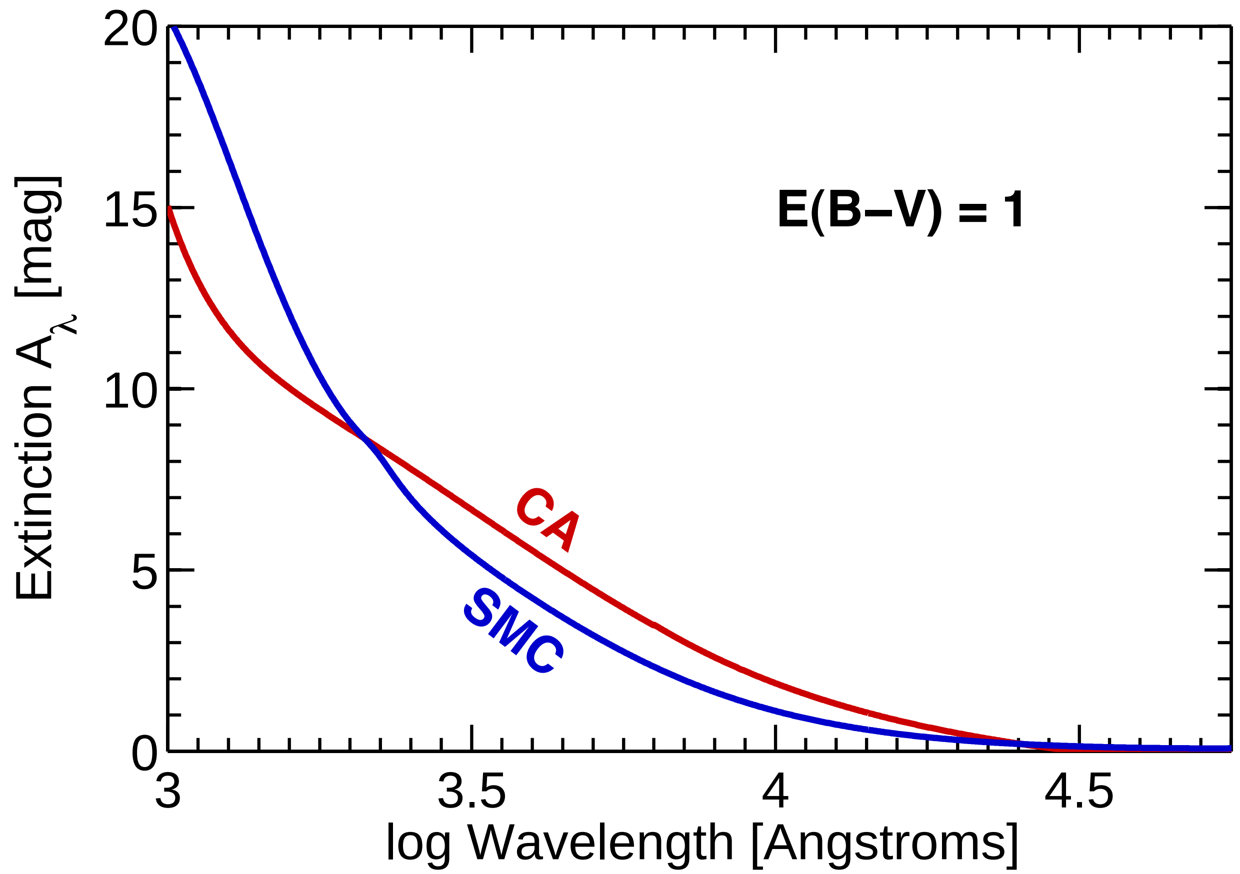
Rest-frame optical view reveals that z~4 galaxy population is more diverse than what is inferred from UV-based analyses.

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

Extinction Curve

UV-to-optical colors and UV continuum slope are correlated.

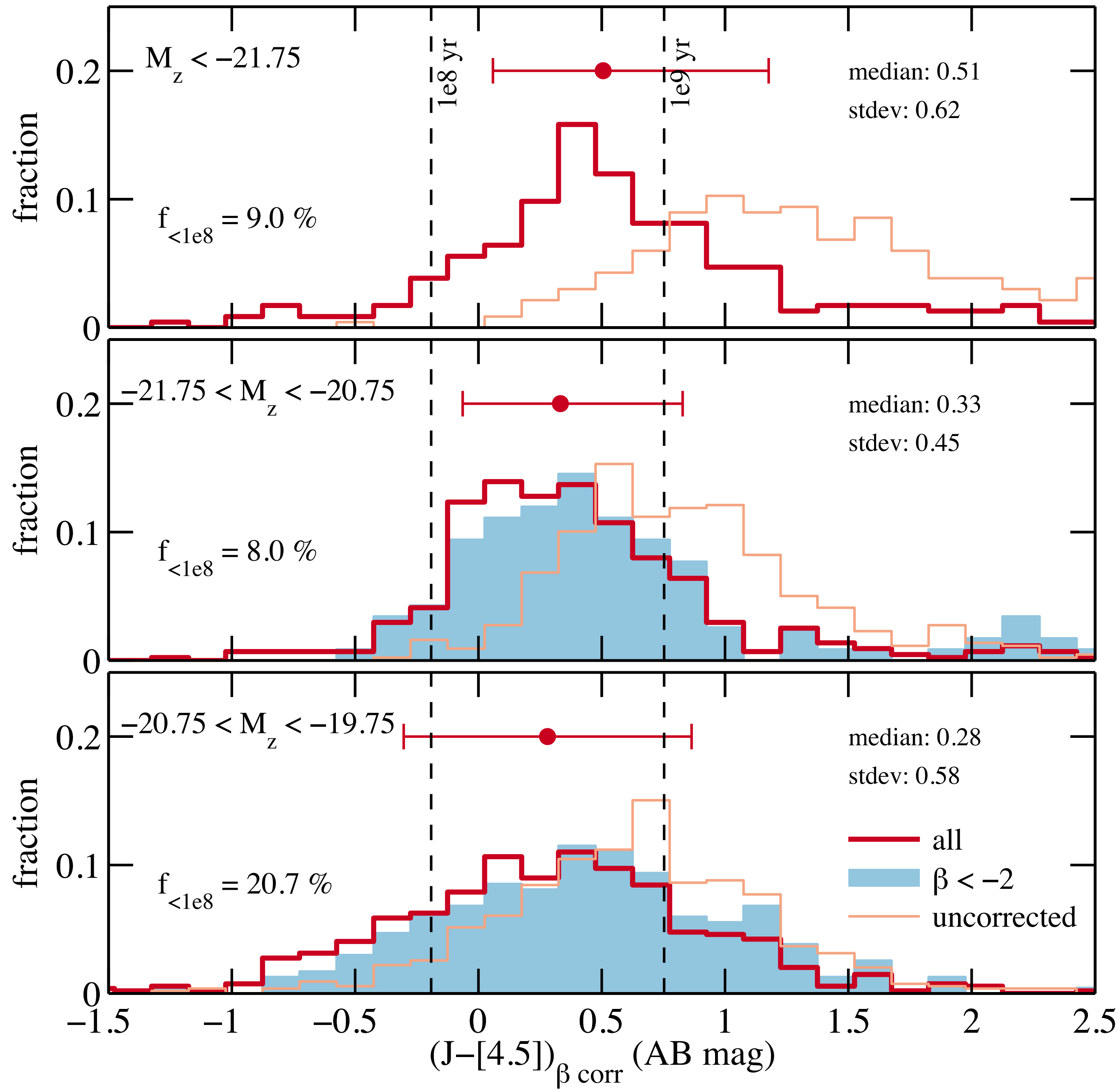


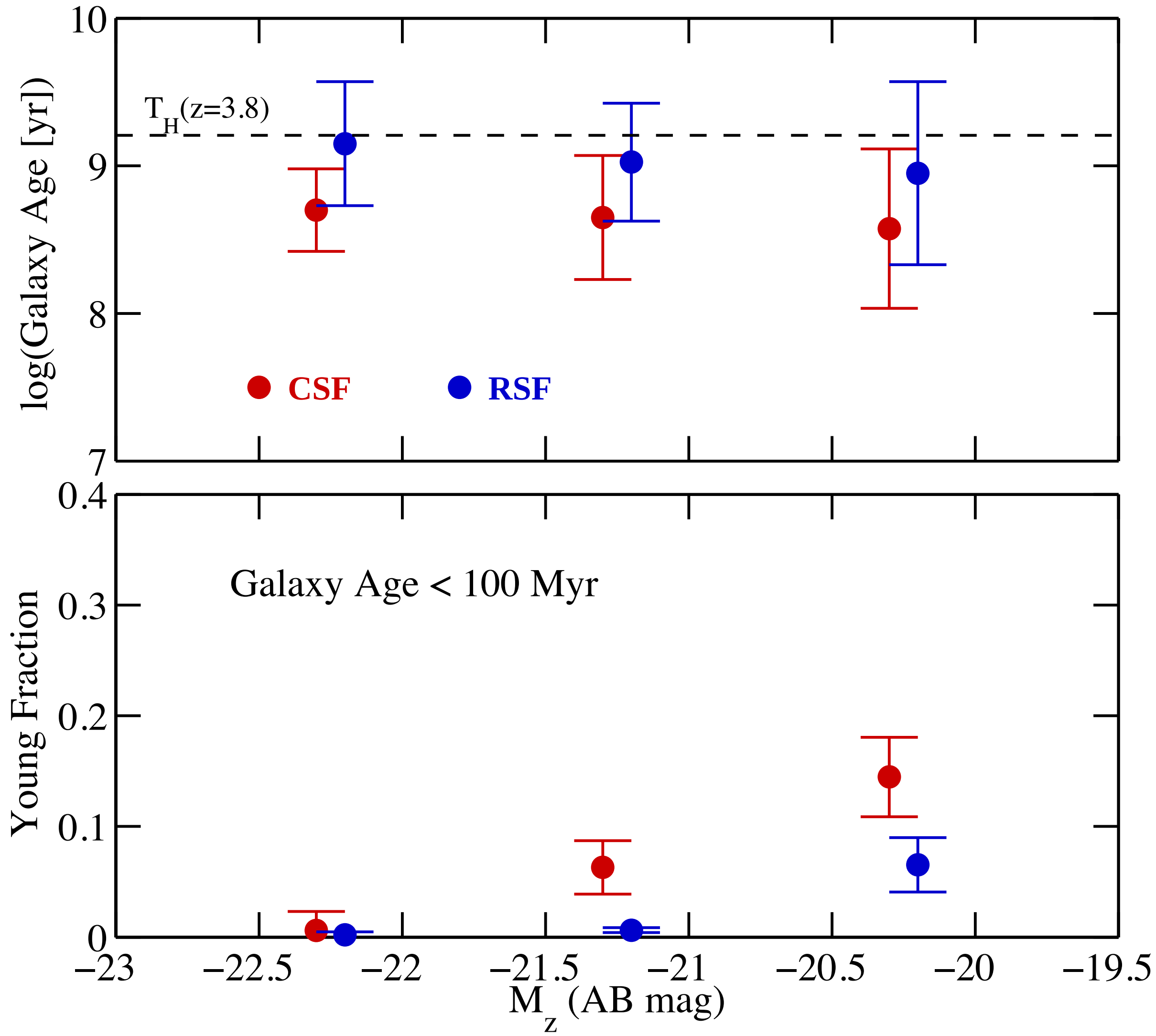


Easiest explanation for this slope: Colors are driven by SMC-like dust extinction

Consistent with recent results from Herschel for bright z~4 sources (Lee+12)

Age Distributions





Dust-corrected colors show that galaxies have ages between log(age) = 8.5 - 9.0 yr and are consistent with gradual build-up of their dust and stars with time

Summary

- WFC3/IR has opened up the window to very efficient studies of z>6.5 galaxies: by now, we have identified **>200 galaxy candidates** at these redshifts; 3 at z~10!
- The **UV LF evolves smoothly** from z~8 to z~4, mainly changing in M* only corresponding to a growth in UV luminosity by a factor ~4 (a factor ~10x increase in SFR after dust correction)
- The HUDF12 data allowed for searches of **z~9-11** LBGs, and resulted in smaller numbers than expected from gradual evolution across z=8 to z=4.
  ➡ **Accelerated evolution** is most likely explained by growing DM halo MF
- The faint-end slopes measured at z≥6 are **very steep** and show weak trends to steepen towards high redshift. If true, **ultra-faint galaxies** are consistent with being capable of **reionizing** the universe, with high enough τ_e.
- The large samples of galaxies at z=4-8 are used to measure build-up of masses, SFRs, sizes, stellar population properties, dust extinction in the first 2 Gyr.
- First **detections** of **z~8** galaxies with Spitzer **IRAC** show these galaxies are not primordial (onset of SF z~12), and galaxy mass density also builds up by a factor ~10x from z~8 to z~4, in agreement with SFR density.
- **Rest-frame optical** data from IRAC is crucial for self-consistent picture of star-formation and stellar mass build-up.