Uncovering the First Galaxies with HST:
New Insights from Deep WFC3/IR Fields

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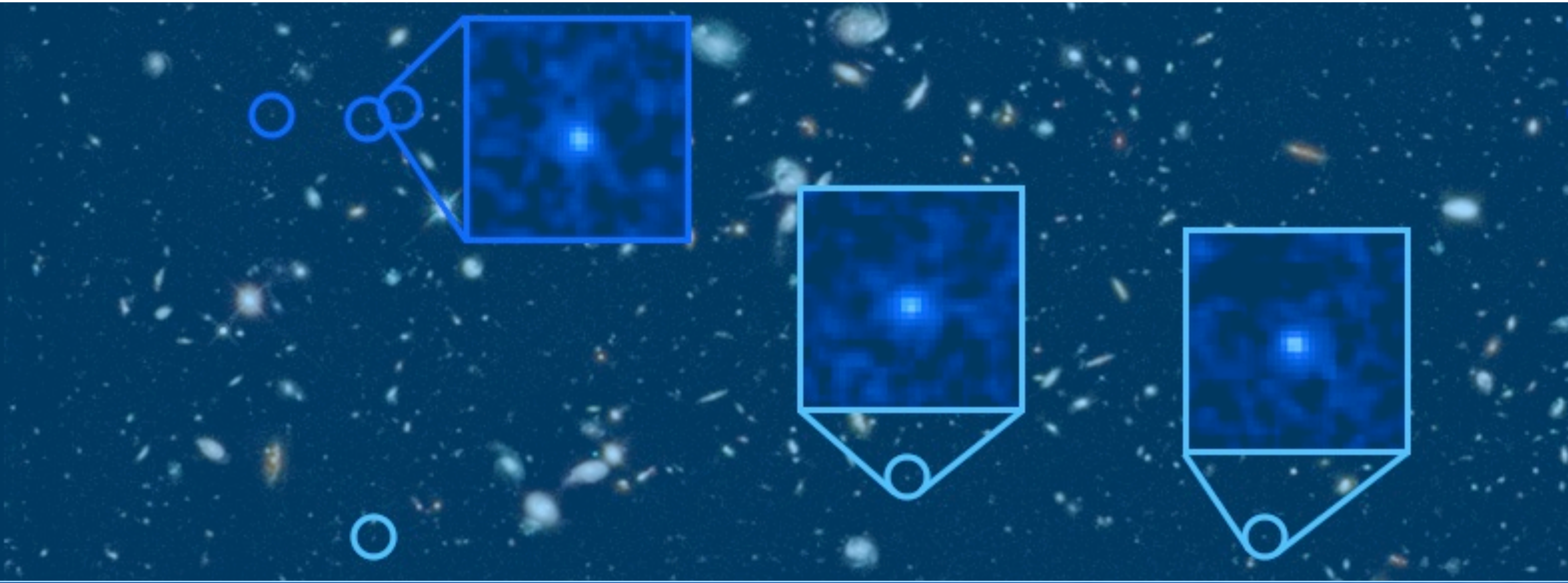
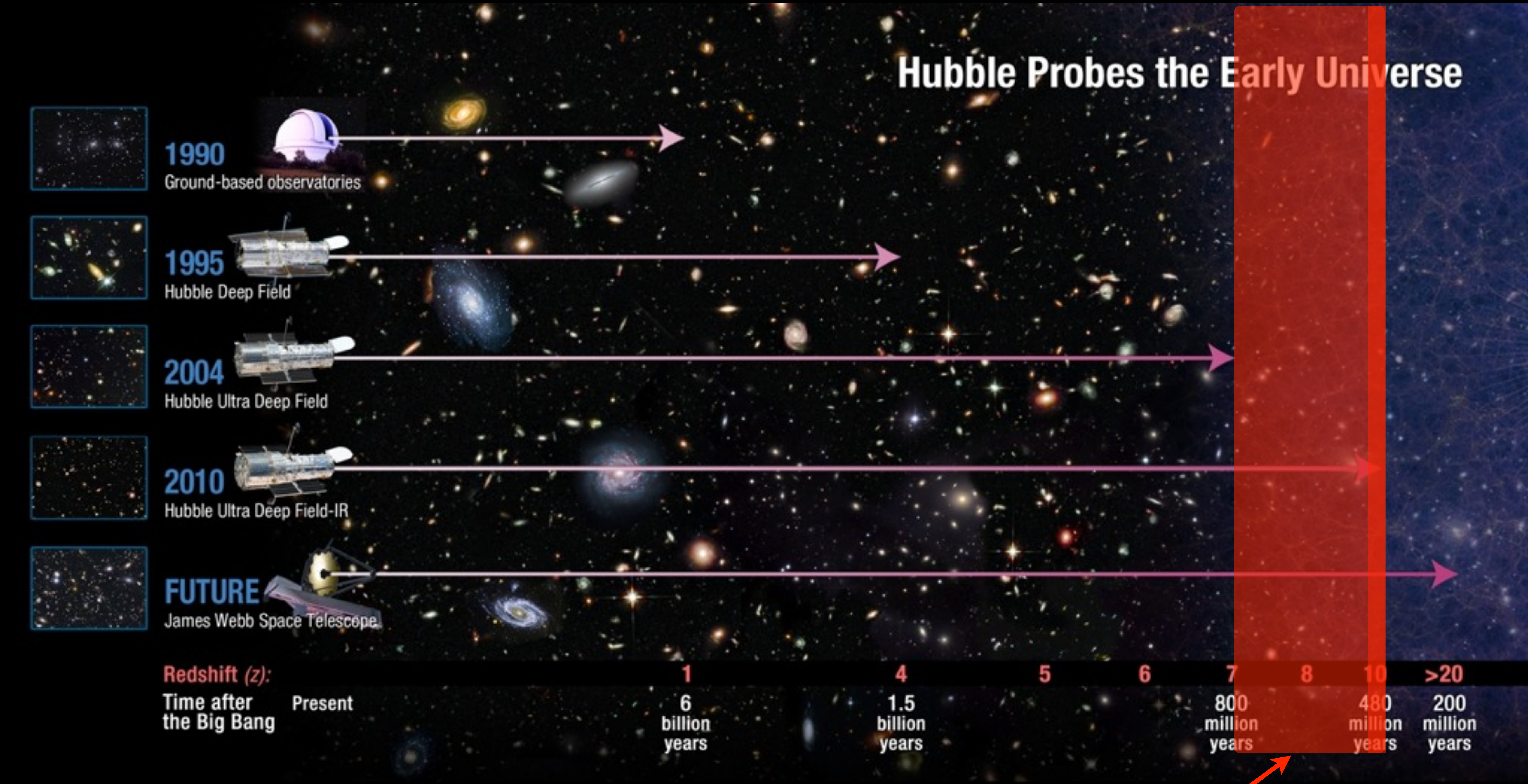
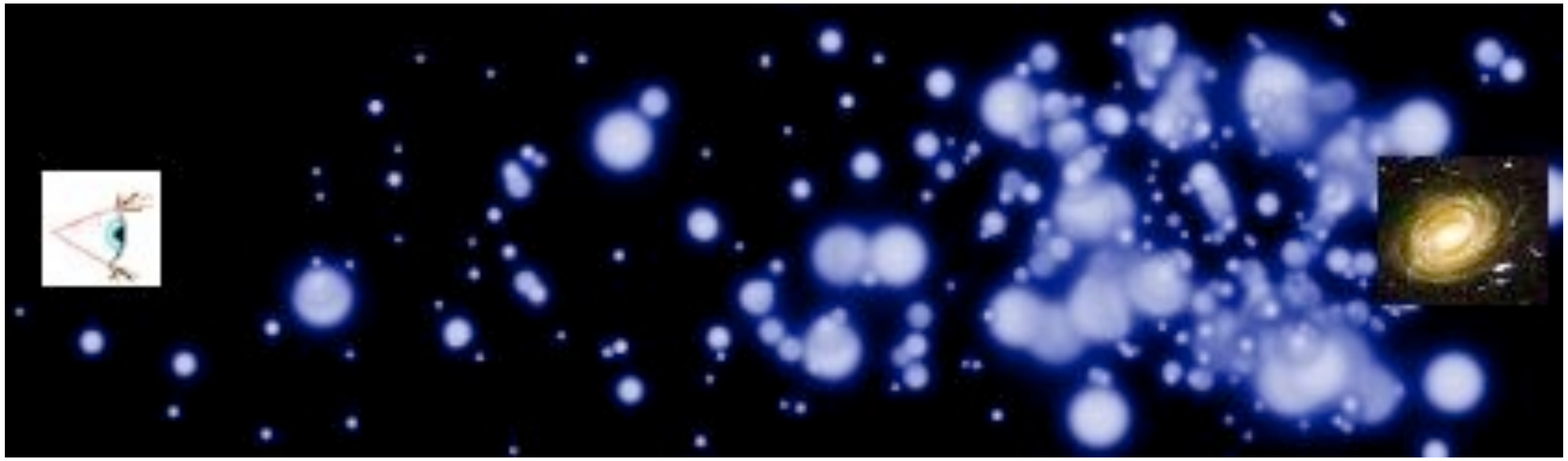


The Reionization Epoch with HST

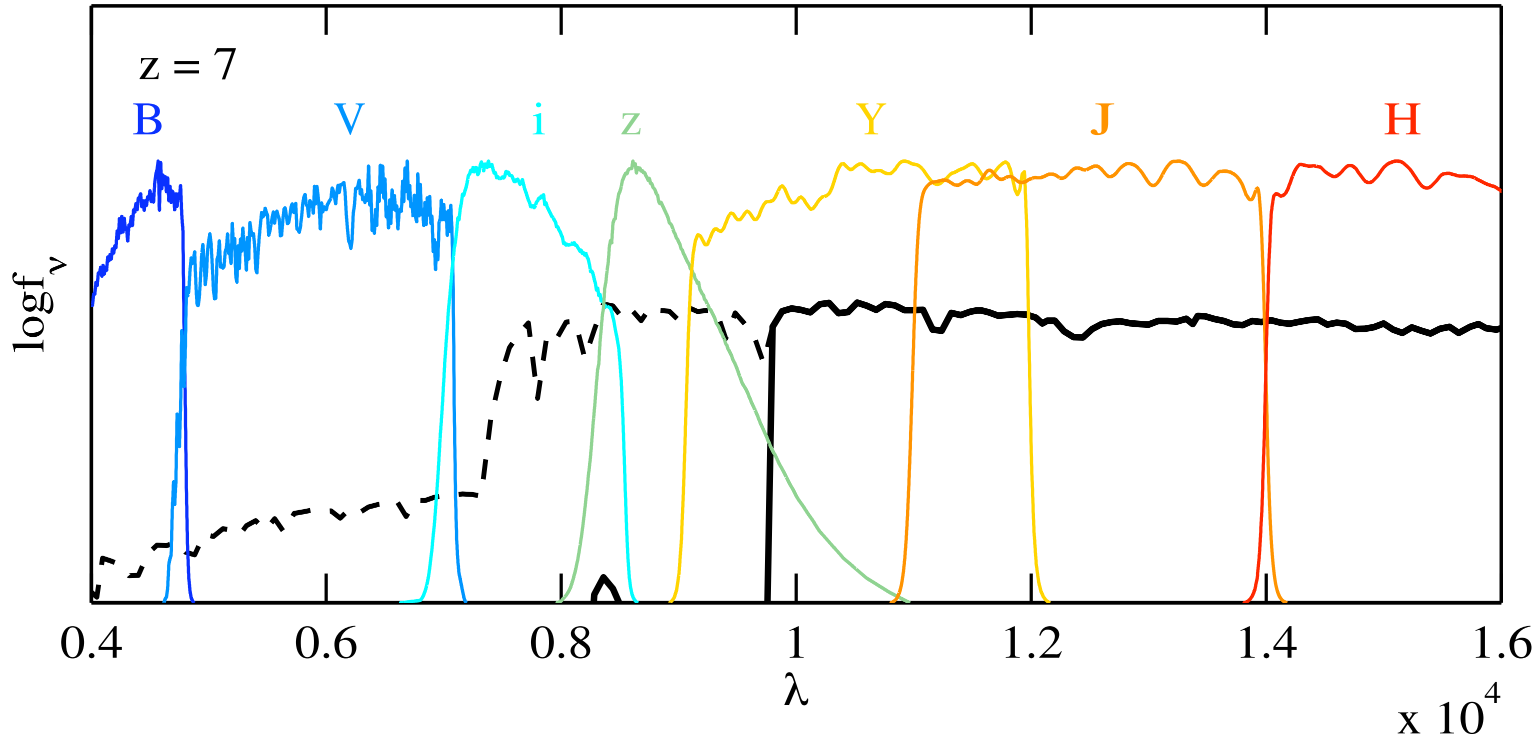


This talk: Galaxy Build-up in the First 800 Myr

Selection of z>7 Galaxies: Need NIR Imaging

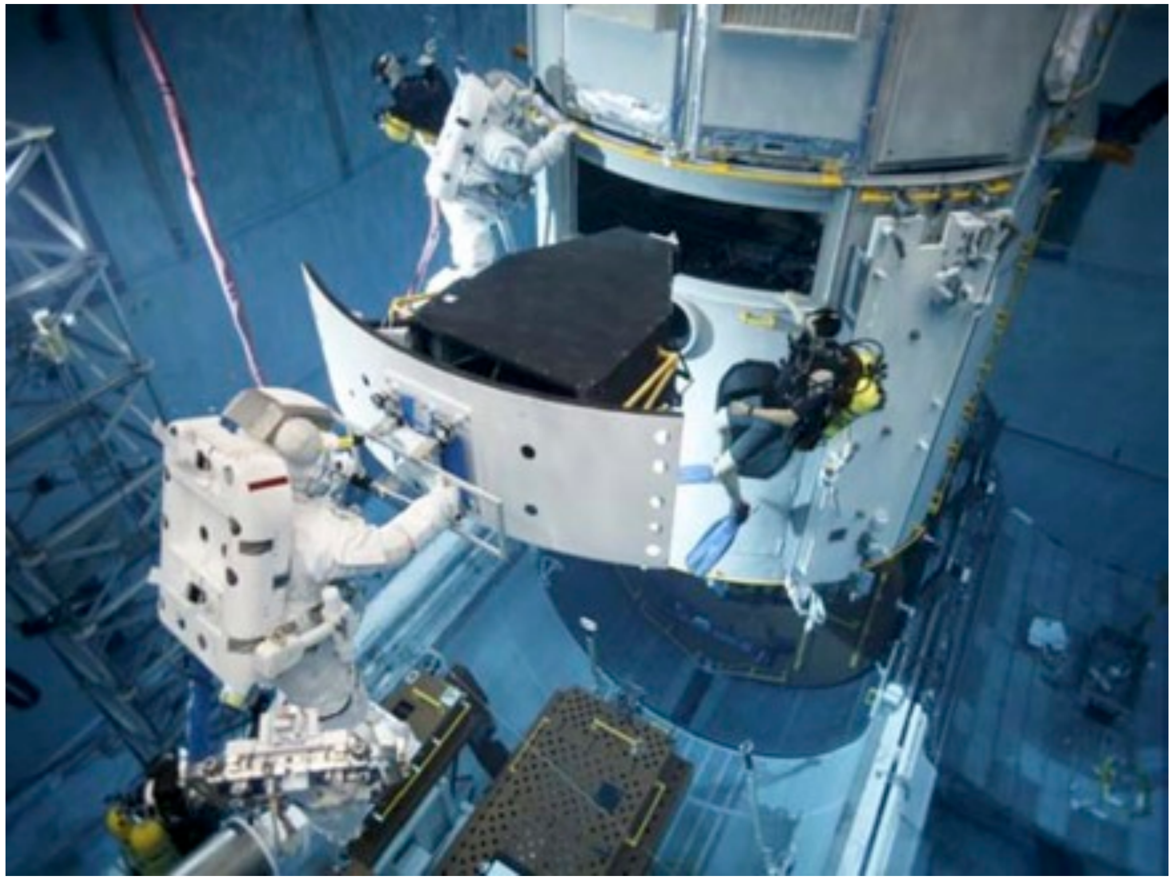


Lyman Break Galaxy Selection: based on IGM absorption



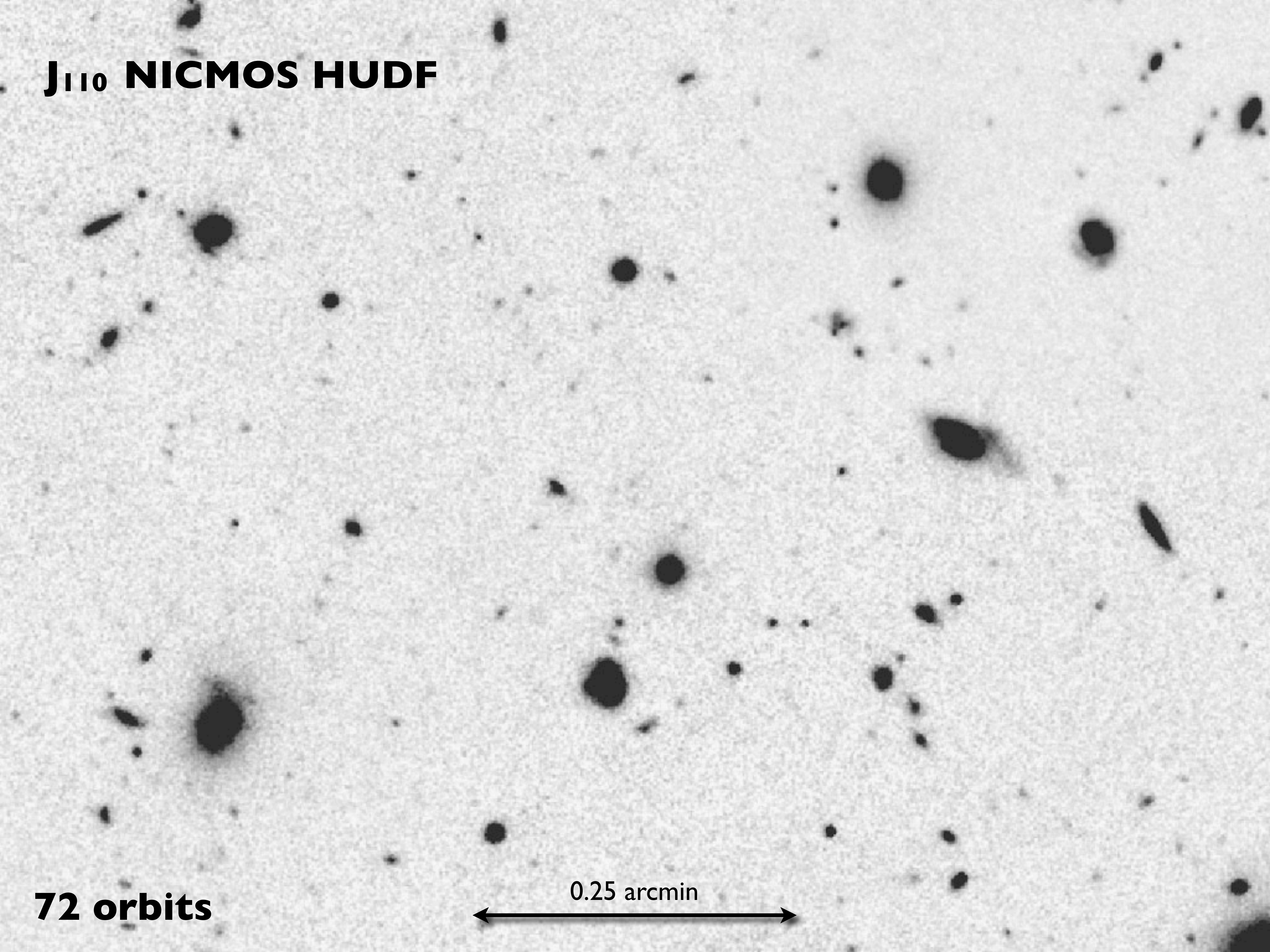
z>=7 galaxies can only be seen at NIR wavelengths

NIR with WFC3 on HST

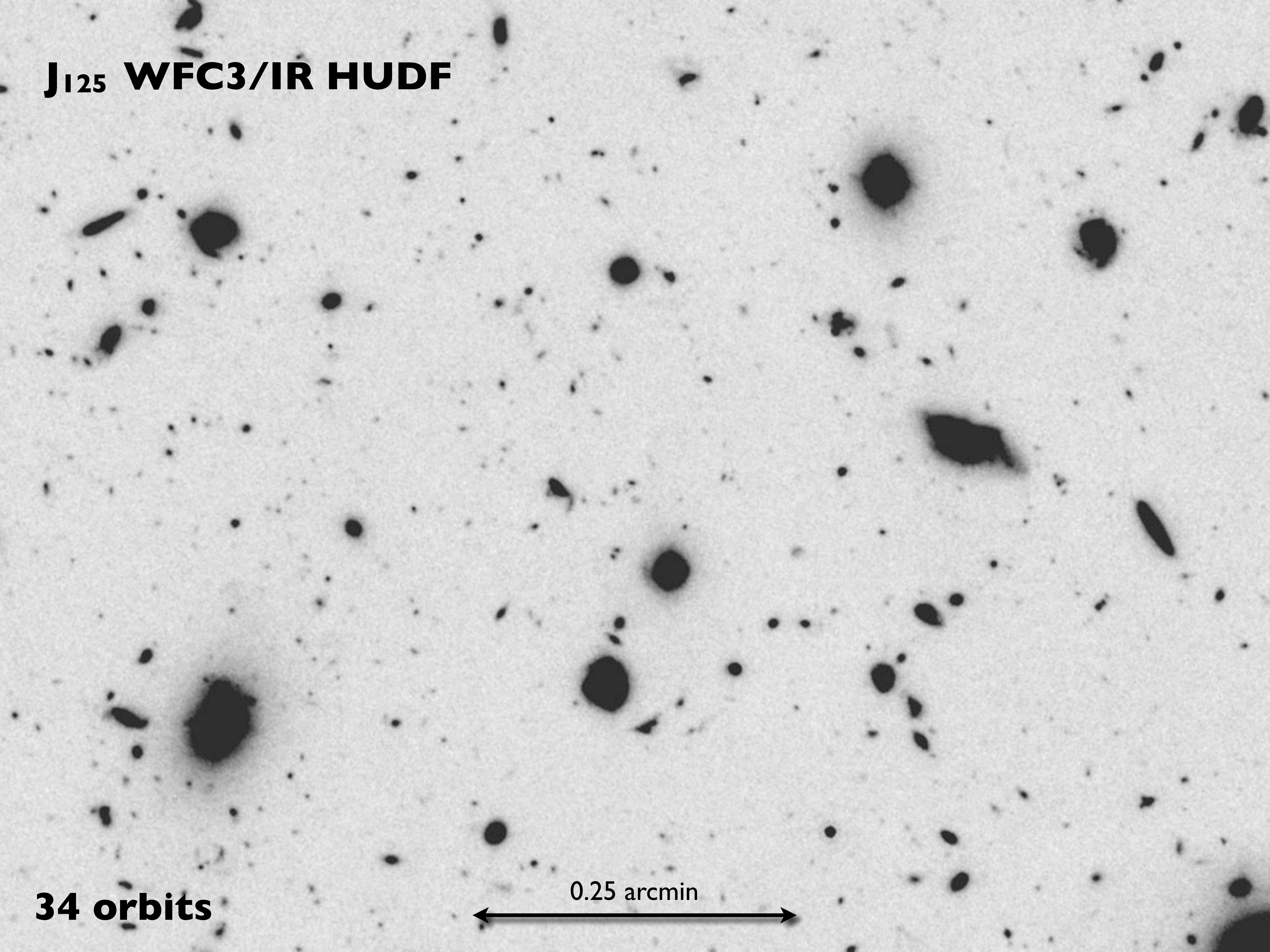


- 6.5x larger field-of-view than previous NIR camera (NICMOS)
- 3-4x more sensitive than before
- 2x higher spatial resolution

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



J_{110} NICMOS HUDF
72 orbits
0.25 arcmin

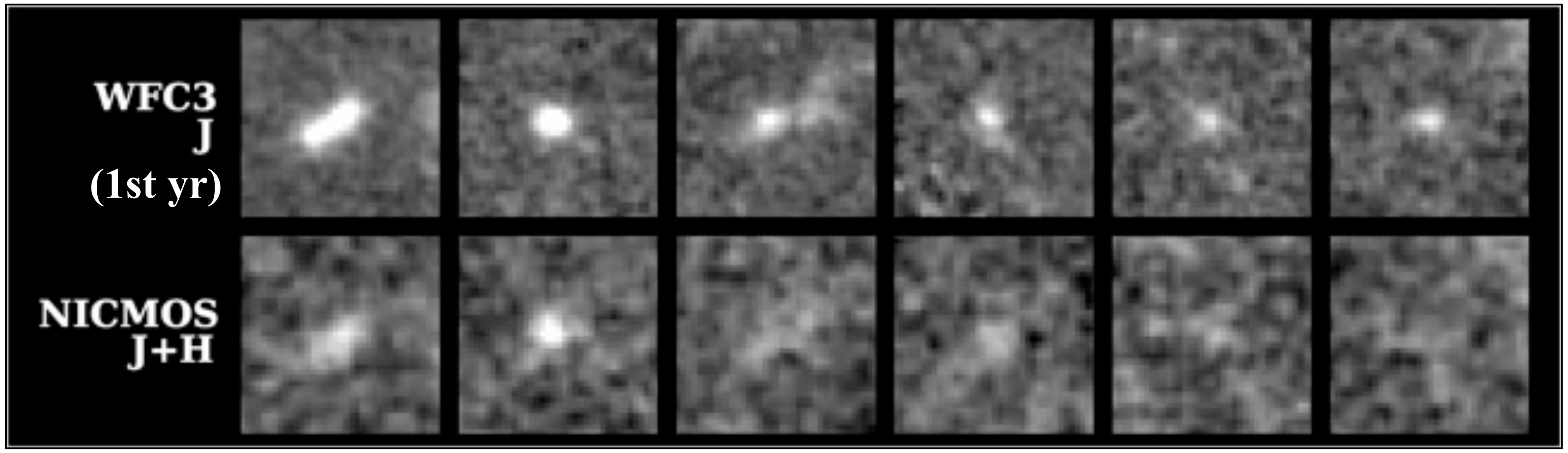

J125 WFC3/IR HUDF
34 orbits
0.25 arcmin

Progress on z>6.5 Samples with WFC3/IR

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

↓

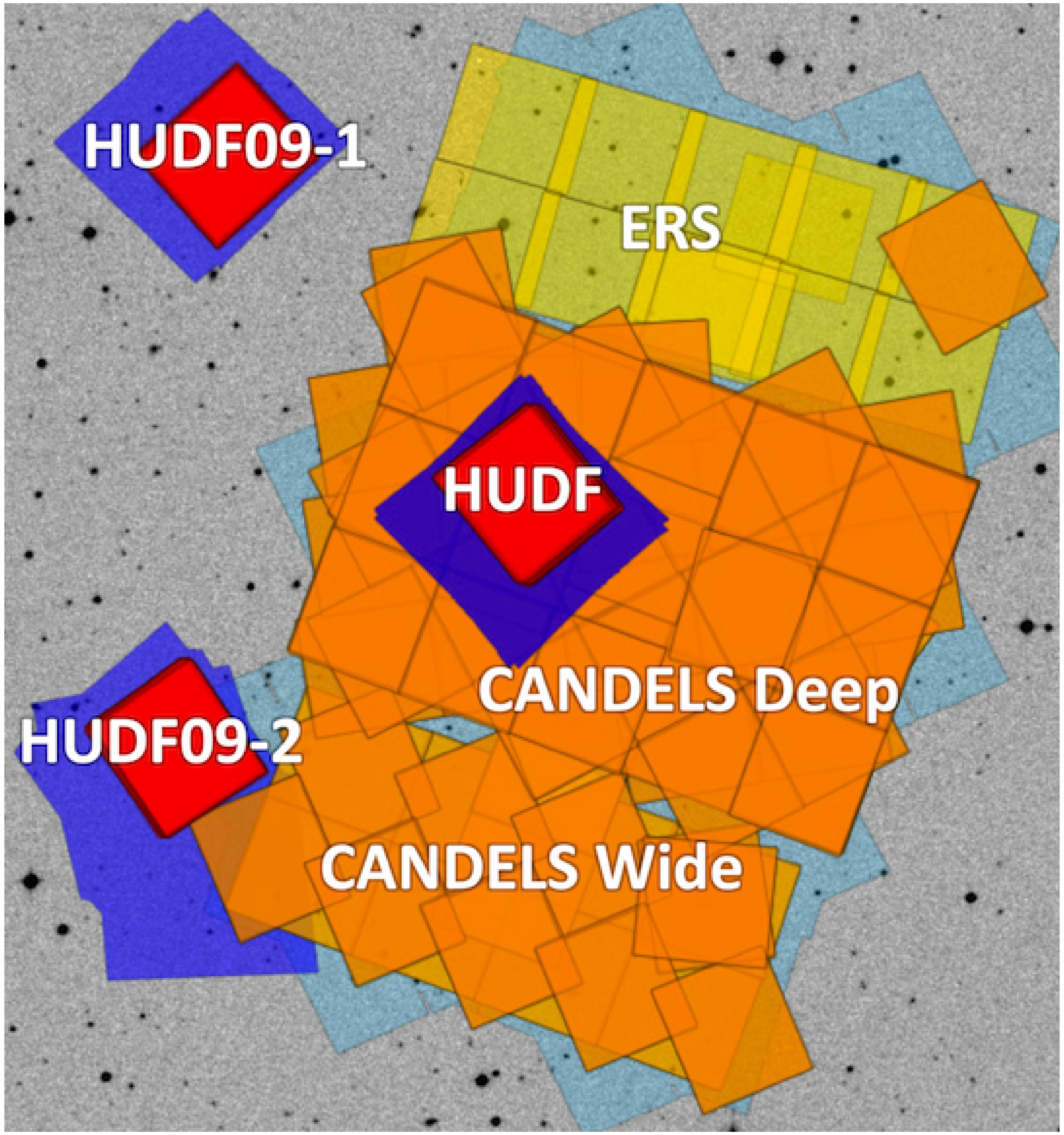
WFC3/IR: **20** galaxies (1st weeks of observations)



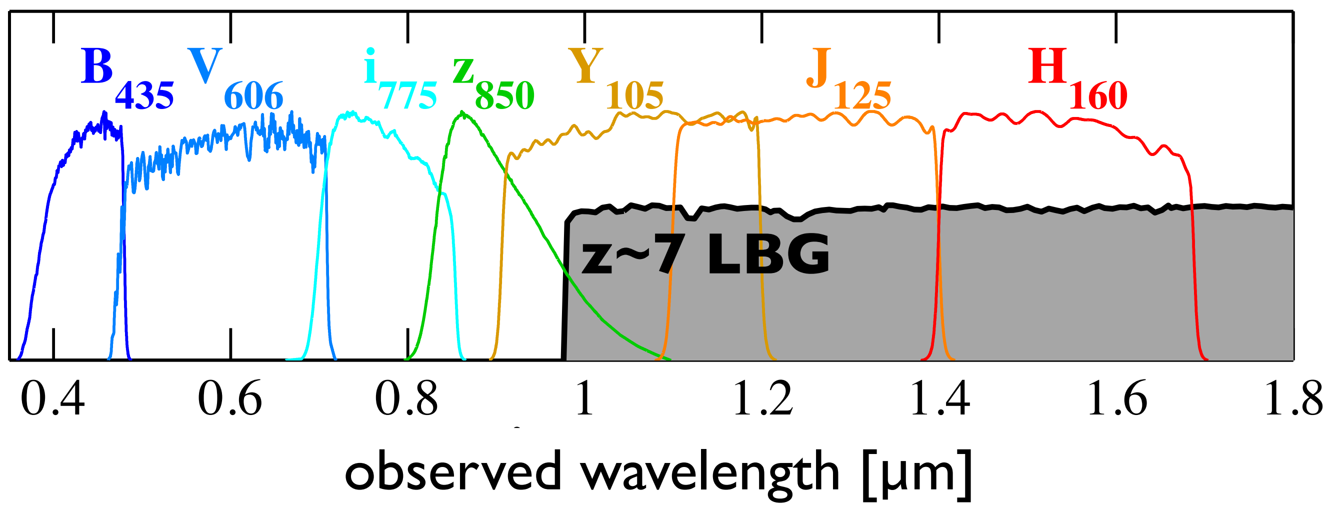
↓

WFC3/IR: **>100** galaxies (2 years of data)

WFC3/IR Data



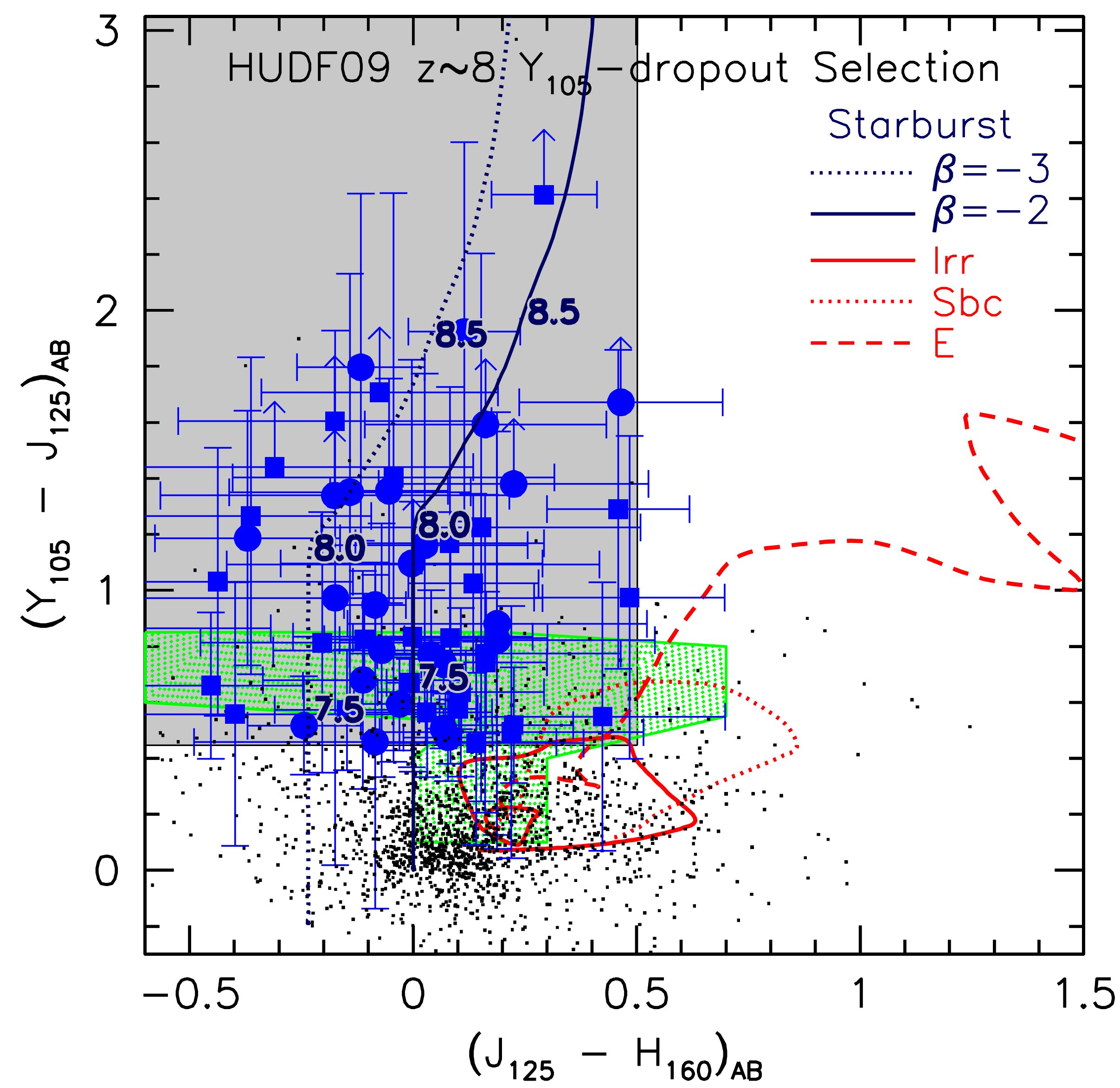
- CDFS offers perfect data for z>7 galaxy search
- Large amount of public optical (ACS) and NIR (WFC3) data
  - HUDF09
  - ERS
  - CANDELS (Deep & Wide)
- Total of 160 arcmin^2
- Reach to 26.9 - 29.4 AB mag

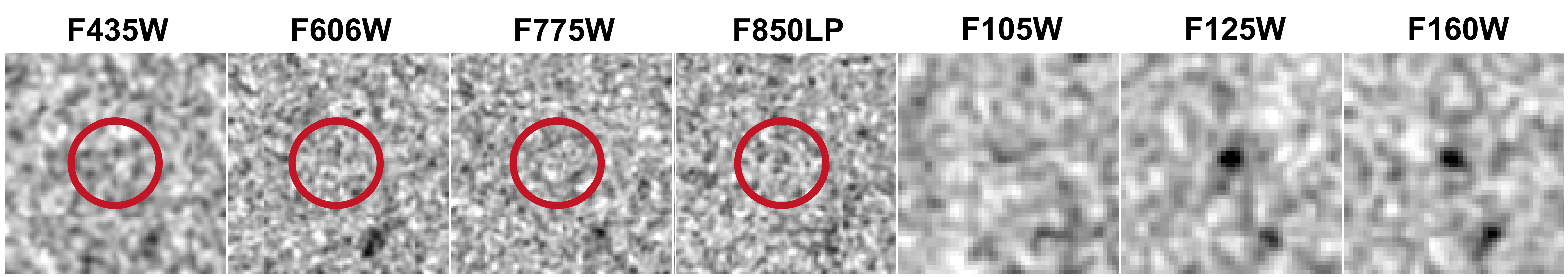


Extended LBG Selection

- Most problematic source of contamination: photometric scatter of 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:

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





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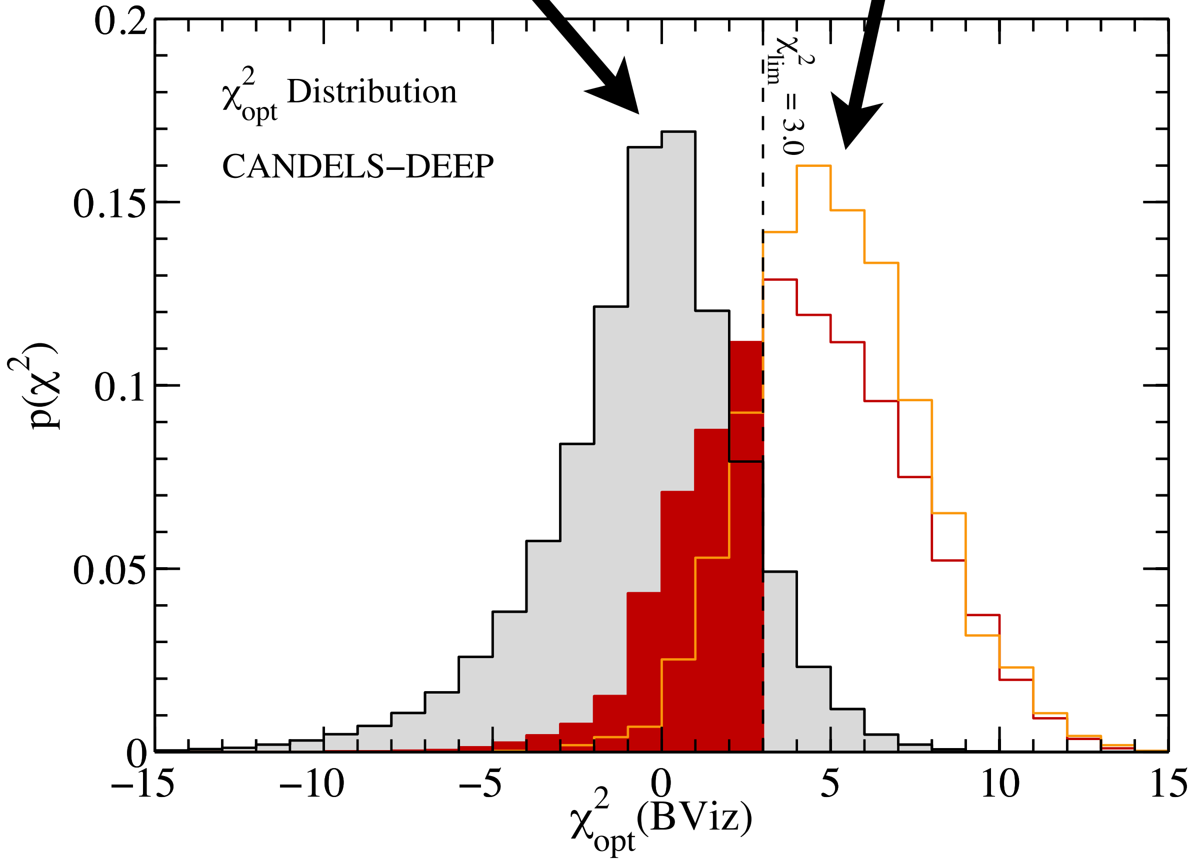
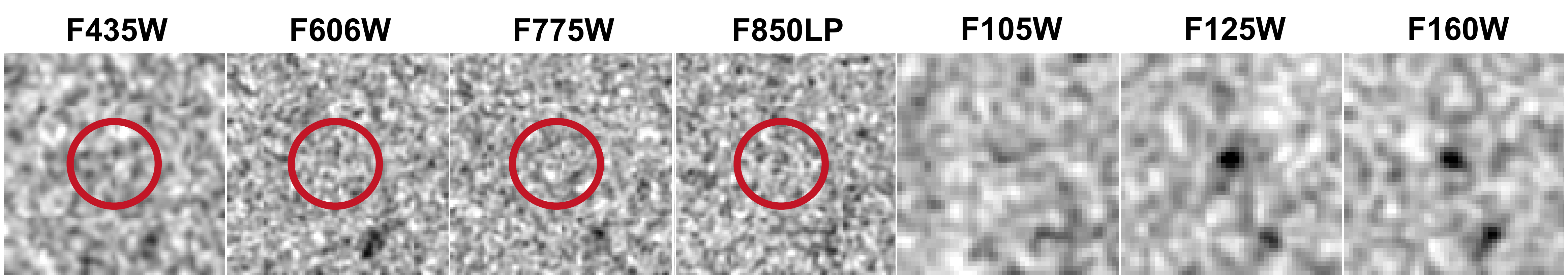
Empty sky, i.e. real high-z sources

Simulated contaminants with <2σ in all optical bands



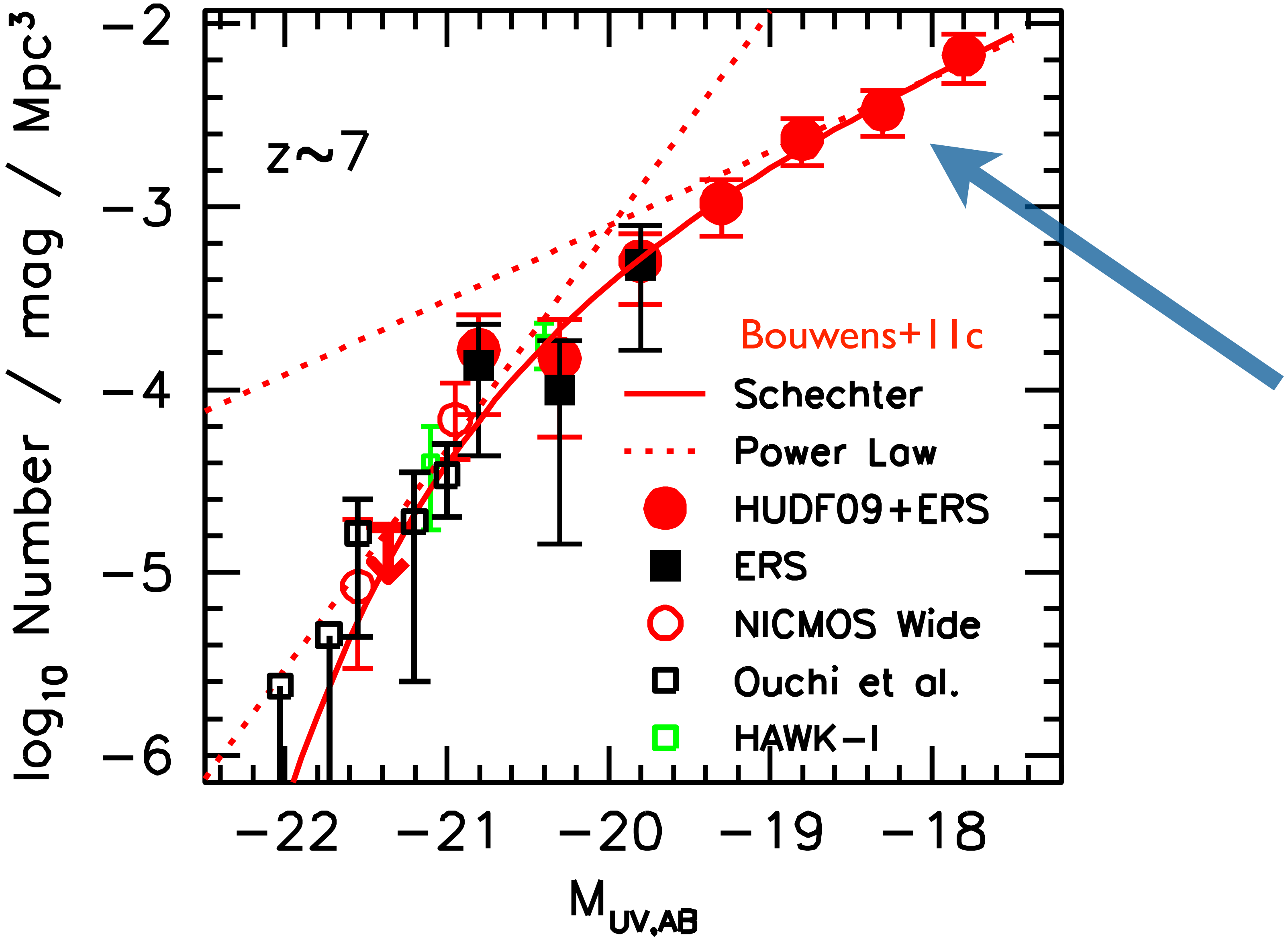
➡ Reduction of contamination by factor ~3-4x



Galaxy Build-up Based on the UV Luminosity Function

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

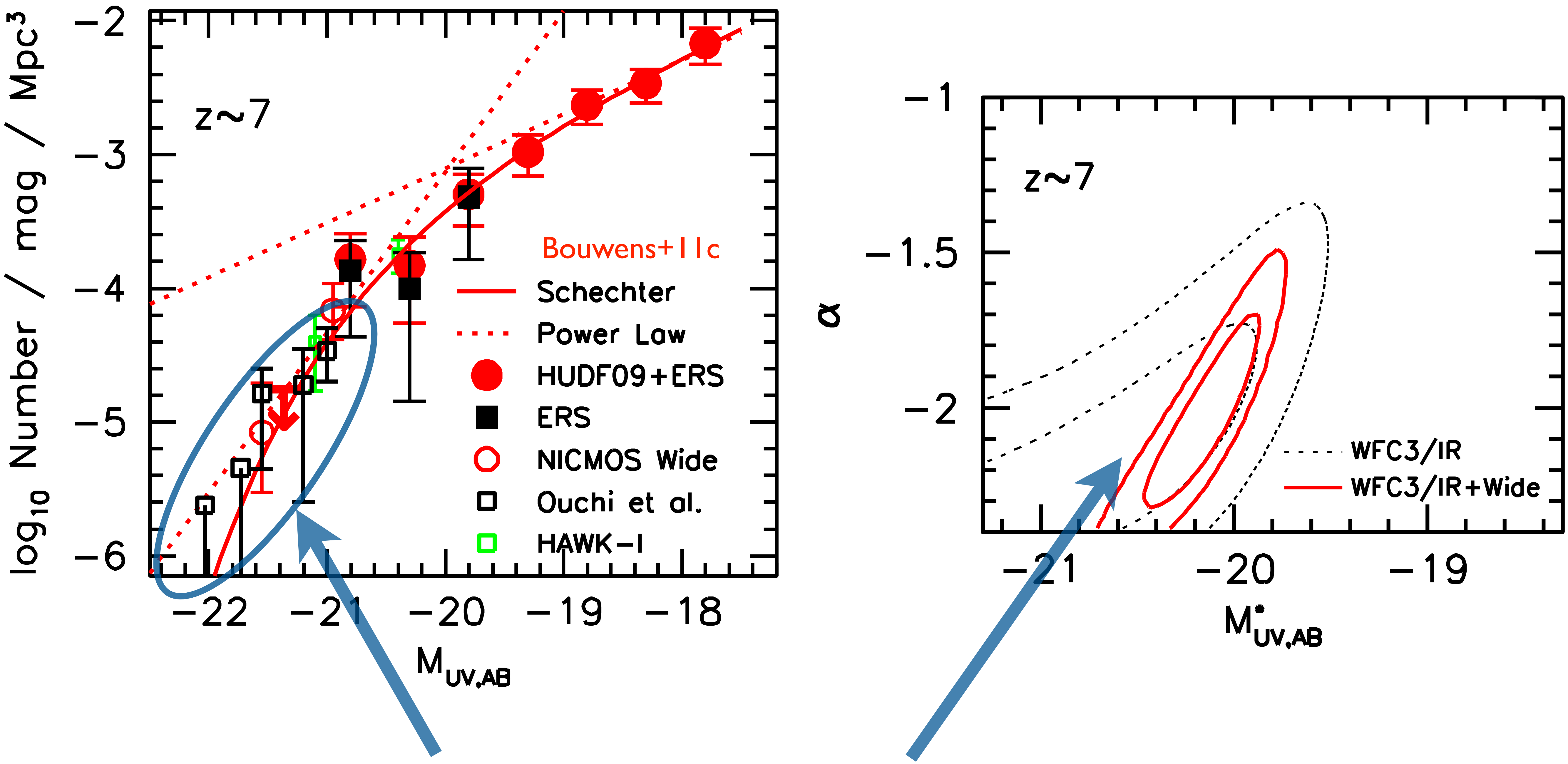
z~7 LF from HST and from Ground



HST: well-sampled faint end

Extremely steep slope: **α ~ -2**

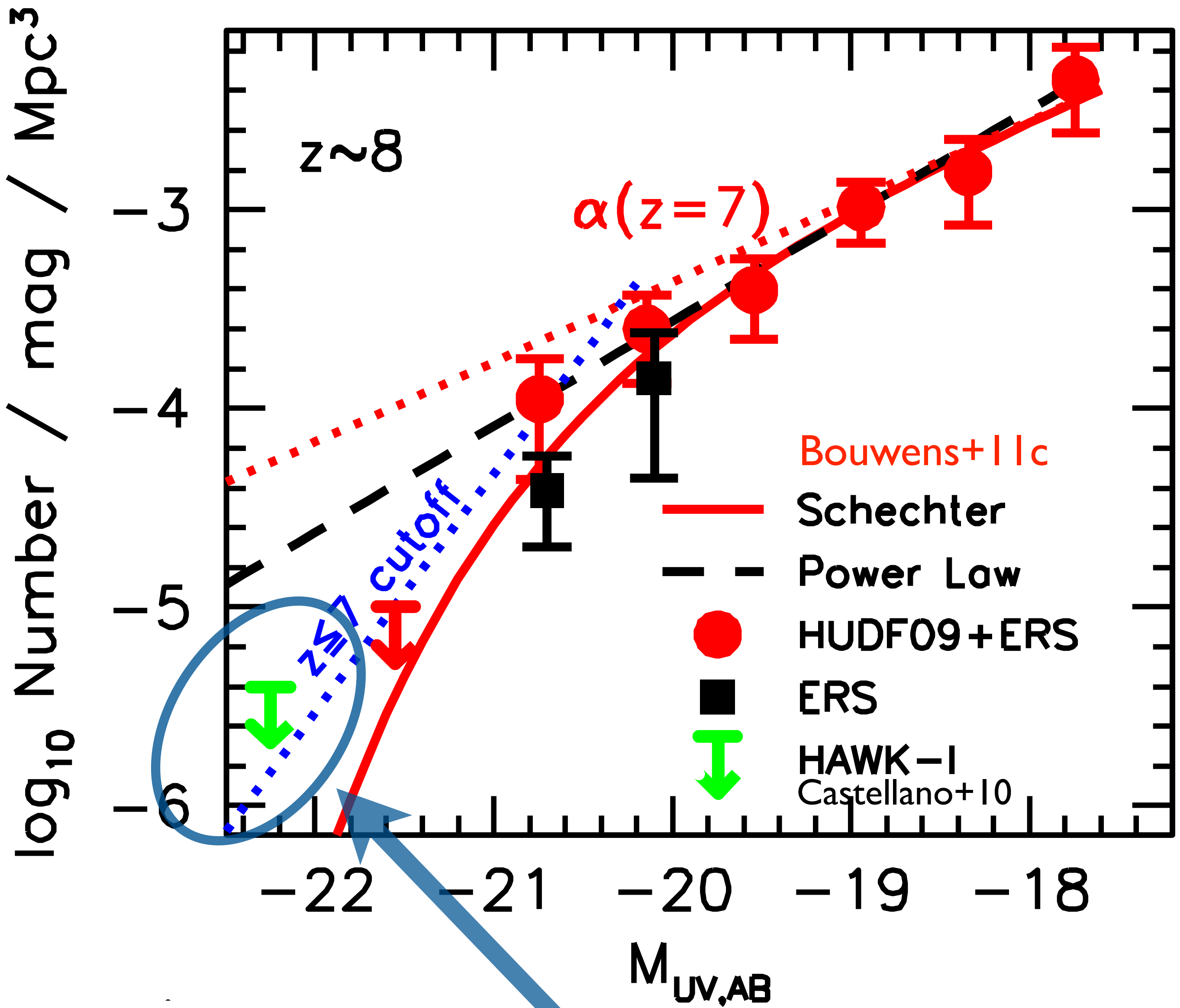
z~7 LF from HST and from Ground

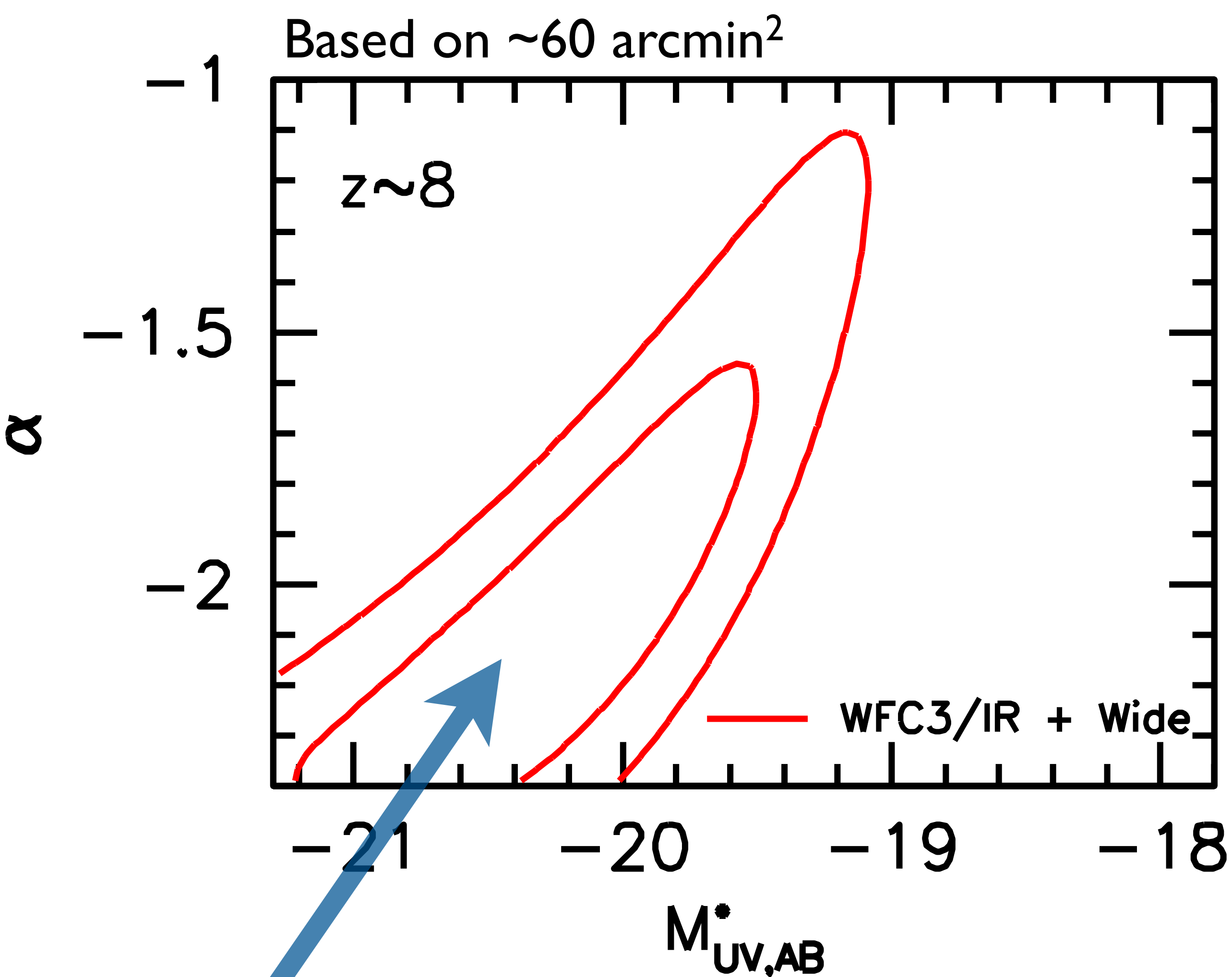


Ground-based data extremely useful for bright end constraints

See also: Oesch+10, Bunker+10, Finkelstein+10, Yan+10, Wilkins+10/11, McLure+10

z~8 LF from HST only



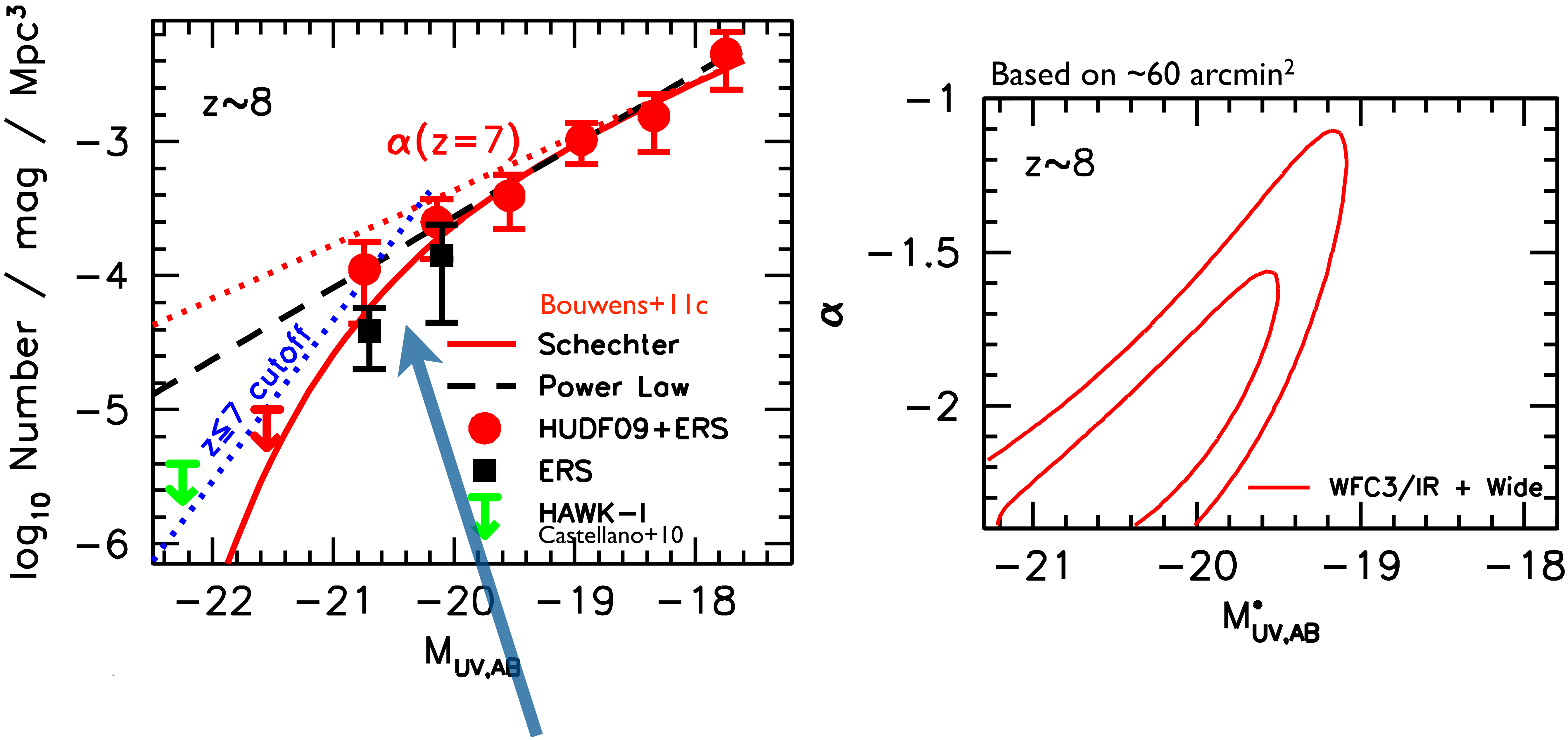


At z~8: Ground-based data only achieved upper limits at very bright M_{UV}

Correspondingly, errorbars are quite large

See also: Bouwens+10, Bunker+10, Finkelstein+10, Yan+10, McLure+10/11, Lorenzoni+11

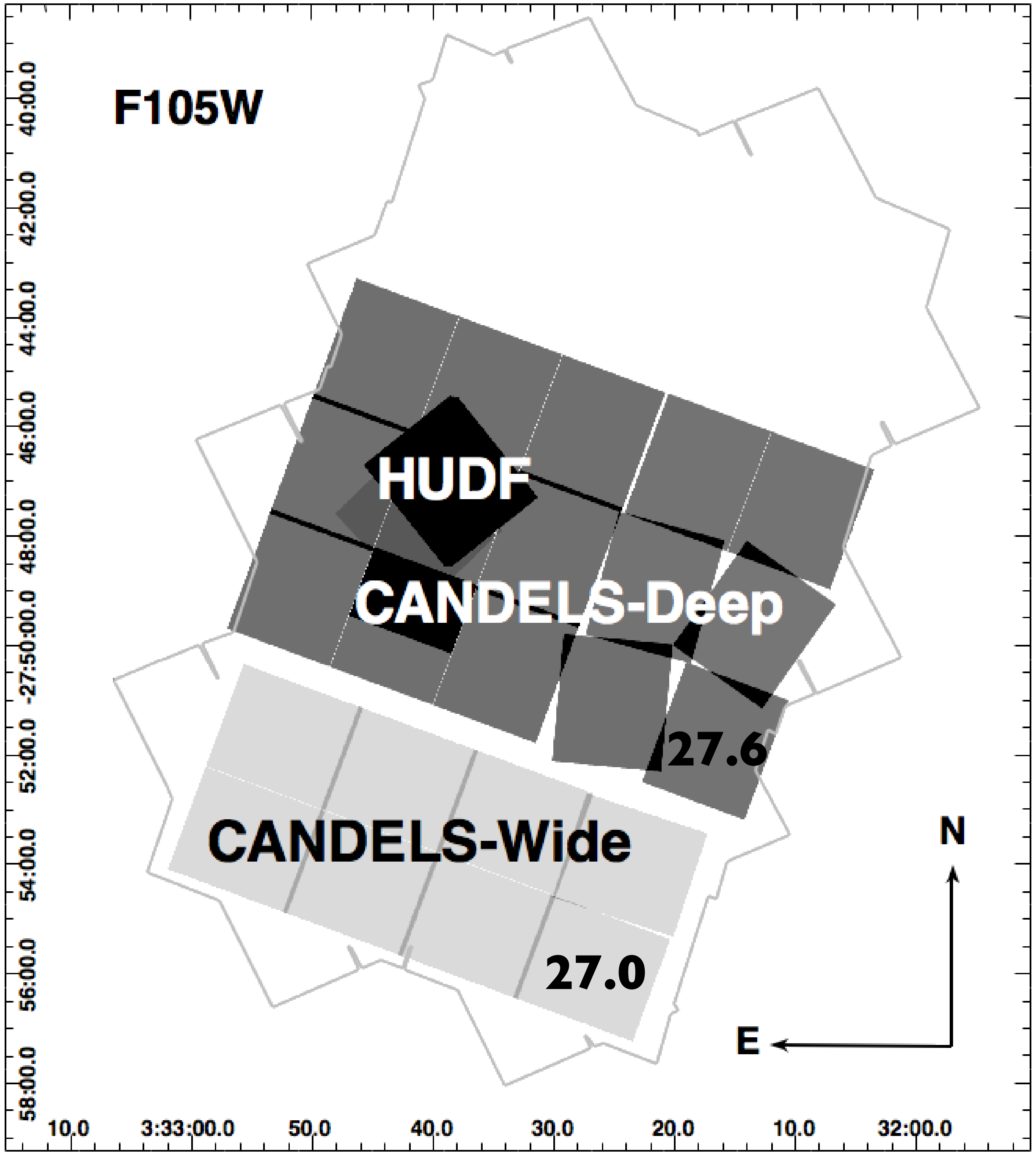
z~8 LF from HST only



A few very bright sources detected in the HUDF09 fields.

Are these representative for z~8 galaxies? Cosmic variance is large: ~30%

CANDELS z~8 Galaxies



CANDELS F105W Y-band data acquisition completed Dec 2011

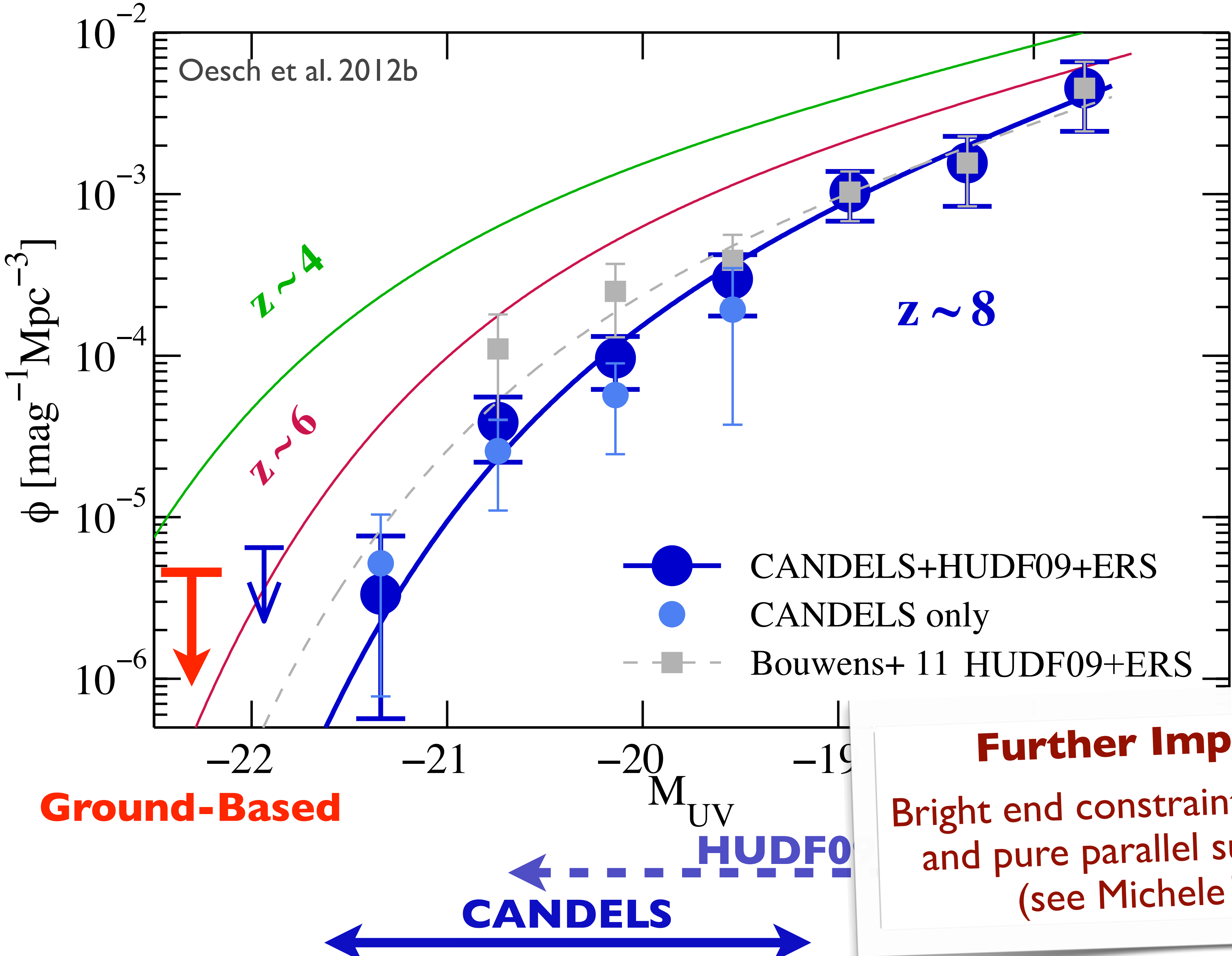
Allows for z~8 galaxy selections over additional 95 arcmin^2

If bright end of UDF z~8 LF correct: would expect 22 sources in this data

➡ Identified only **eleven** new candidates, with magnitudes: 25.8-27.5 in H_{160}

The UV Luminosity Function at z~8

New F105W data over GOODS-S allows for much improved constraints on bright end: combine data over all fields (70 candidates) to provide best possible LF measurement to date

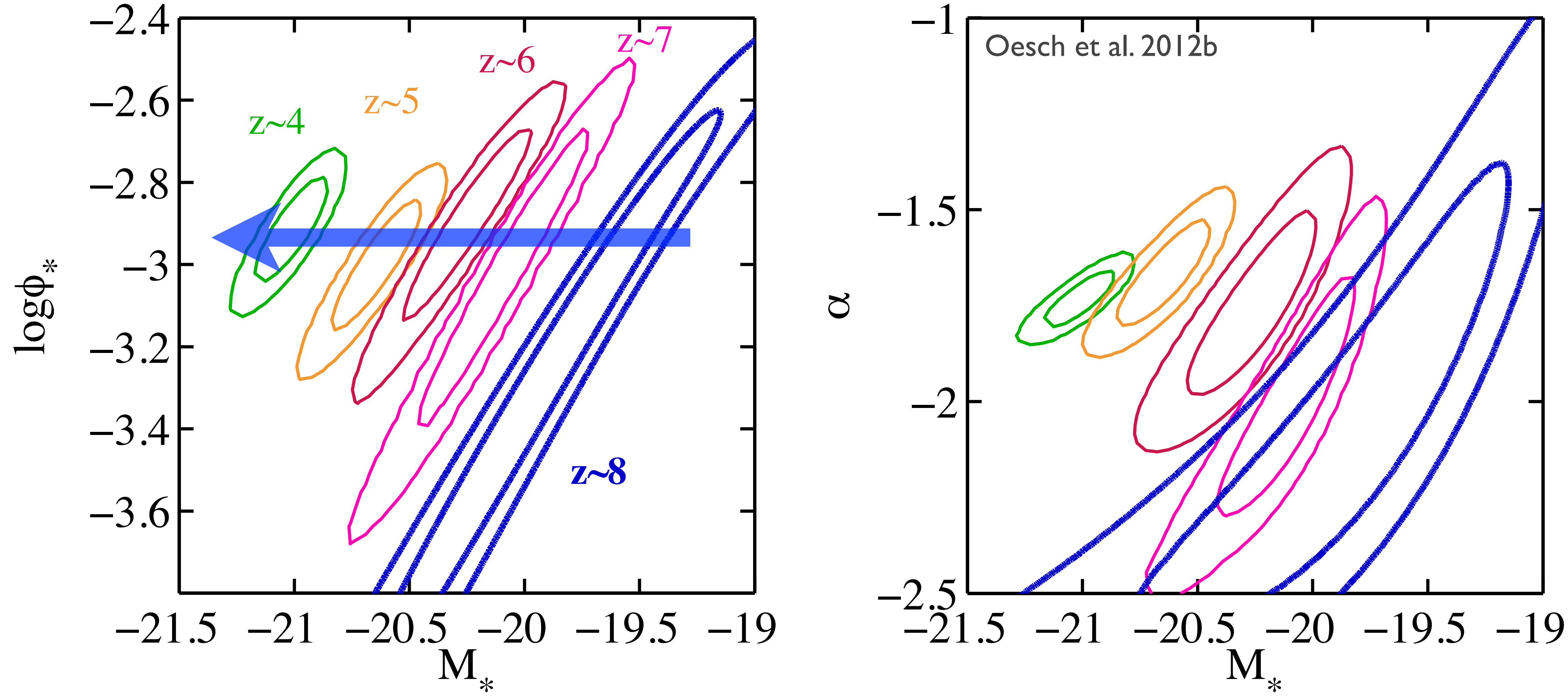


Further Improvements:

Bright end constraints from GOODS-N and pure parallel surveys, e.g. BORG (see Michele Trenti's talk)

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

UV luminosity builds up uniformly with redshift



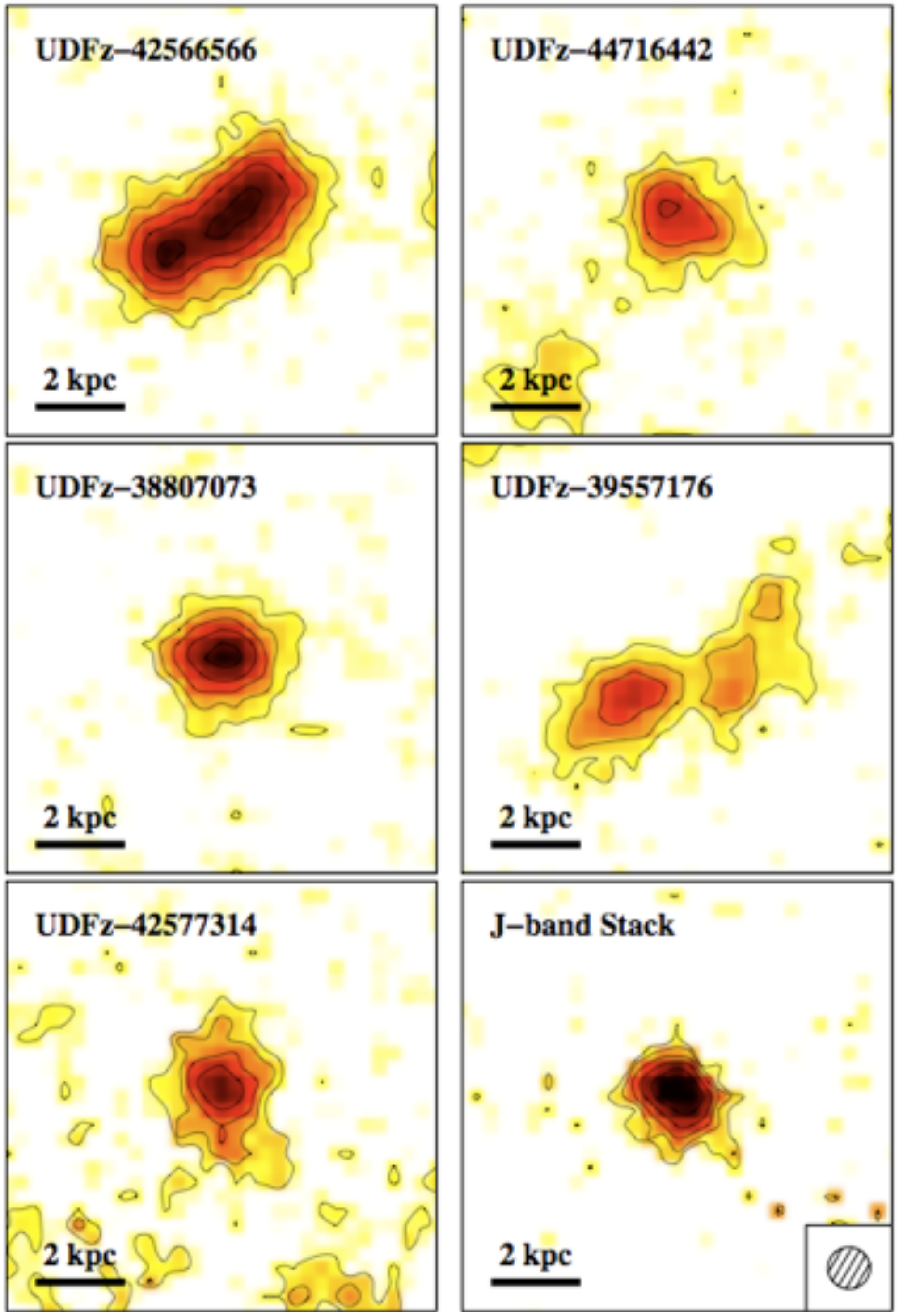
Main Evolution: only in M* (0.33 mag per unit z)

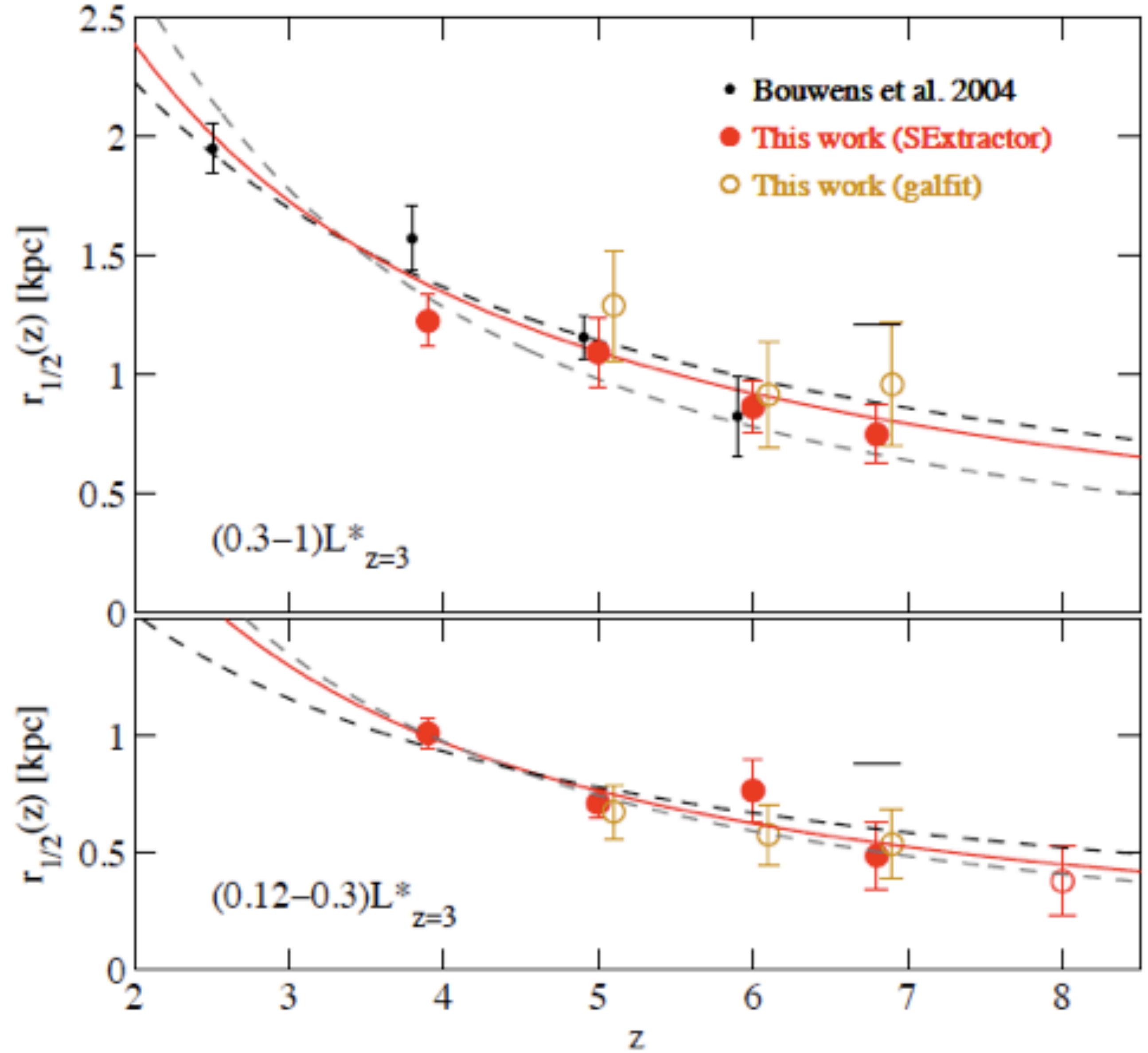
Very steep faint-end slope: -1.7 at z<7, with possible trend to steeper slopes at higher z

The Physical Properties of z>7 Galaxies

Sizes, Dust Content, SFRs, and Masses

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





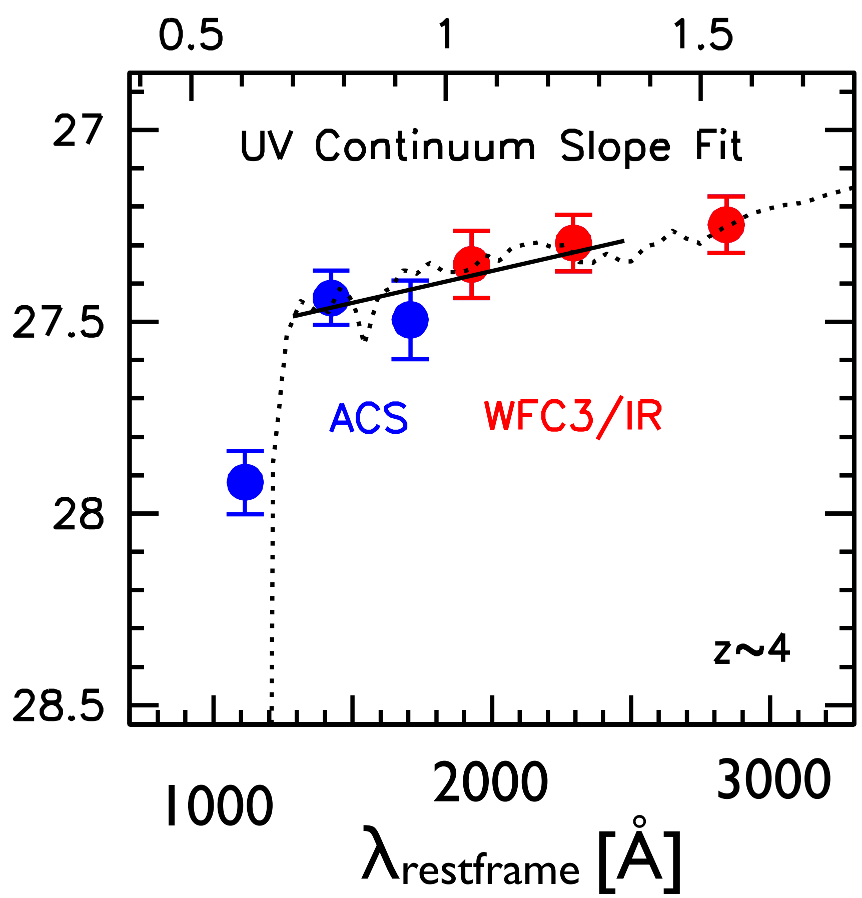
Sizes of LBGs in first 2 Gyr of cosmic time evolve as: $\mathbf{r_{1/2} \sim (1+z)^{-1}}$

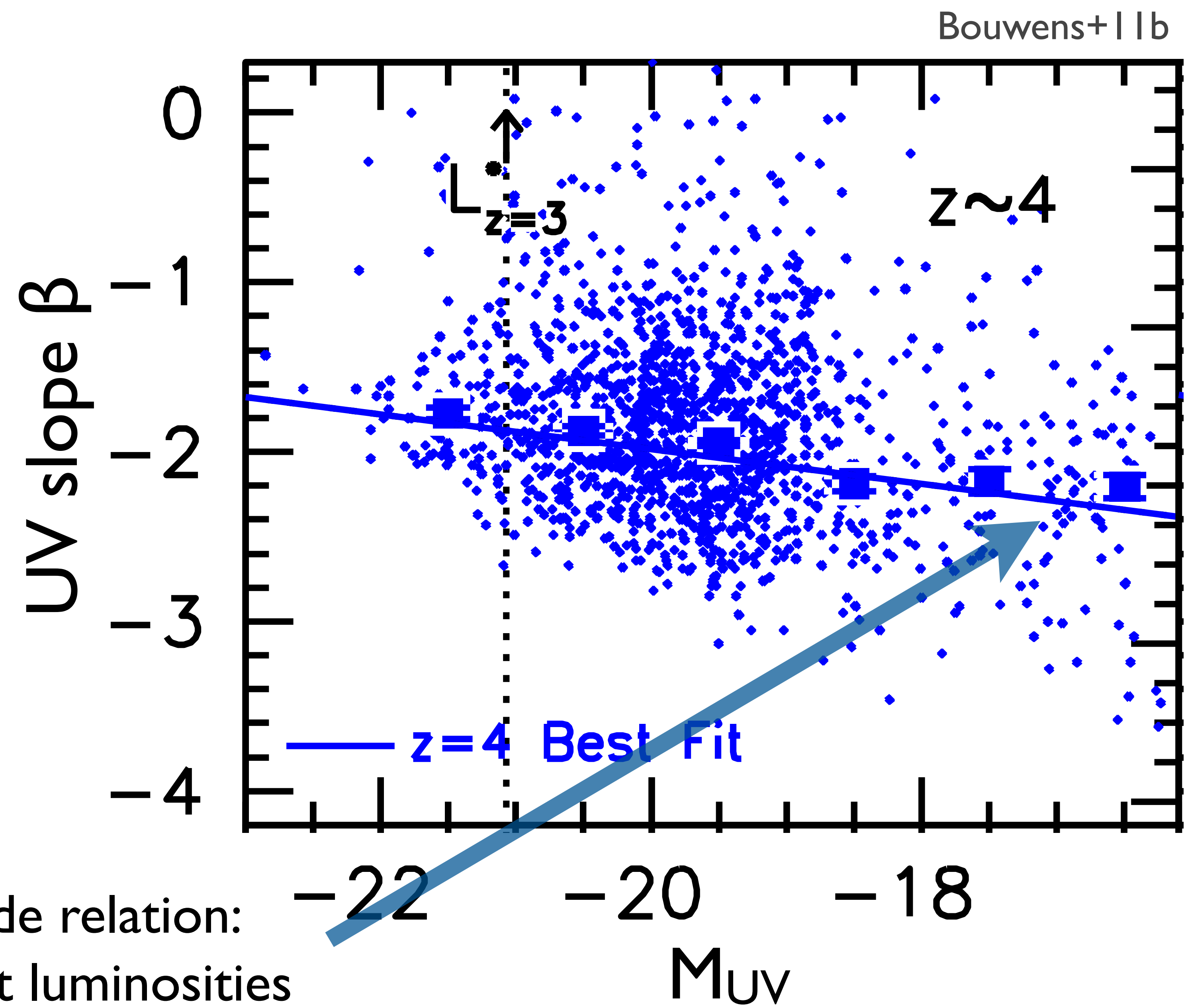
Oesch et al. 2010b

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

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



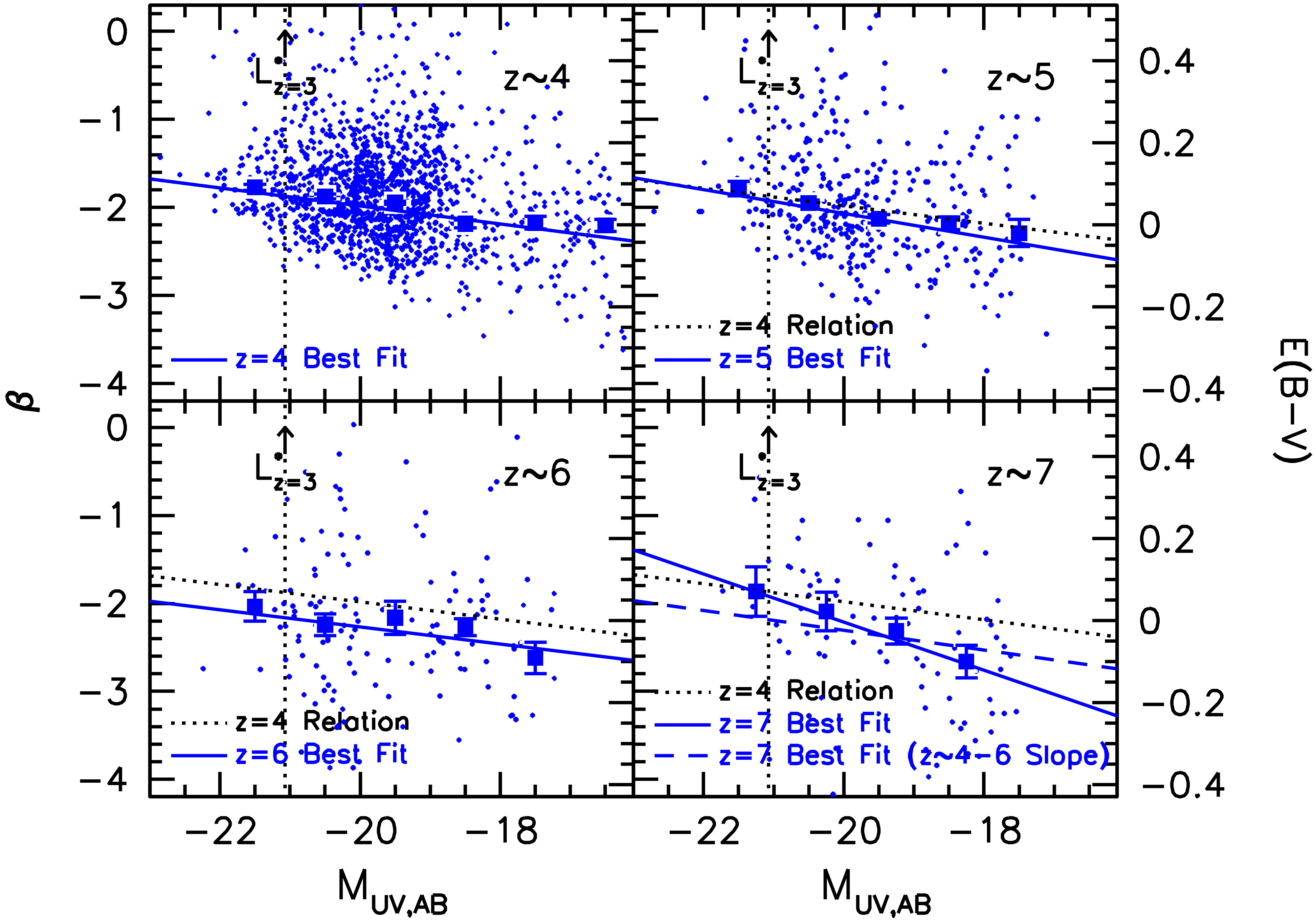


Relatively tight color-magnitude relation:
Galaxies are very blue at faintest luminosities

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

UV Continuum Slopes

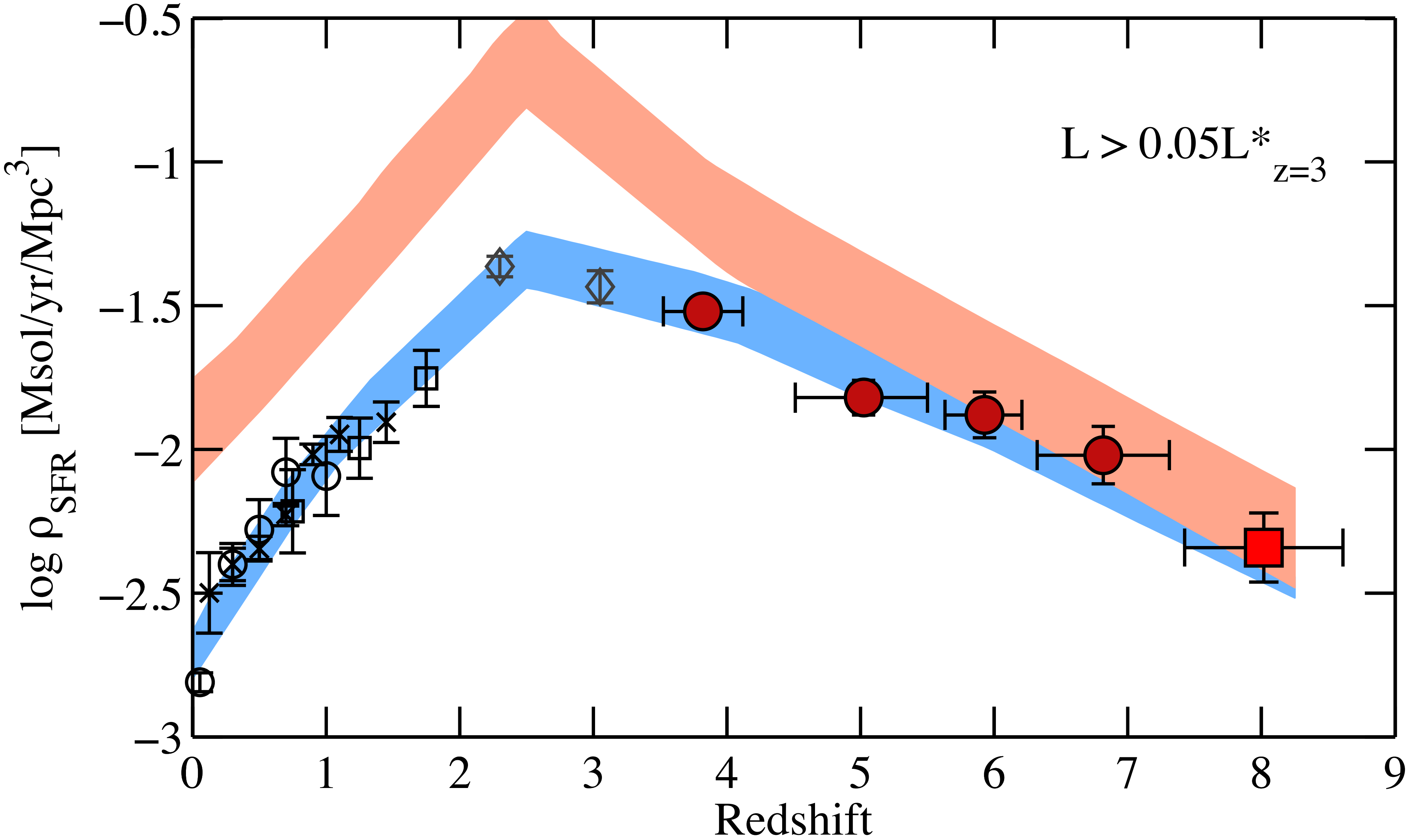
Bouwens+11b



- Essentially constant slopes to color-mag relation at different redshifts
- Trend to bluer UV continuum slopes to higher redshift: z~7 essentially dust free

Cosmic SFR Density

Use IRX-β relation to convert UV luminosity density to dust-corrected SFR density

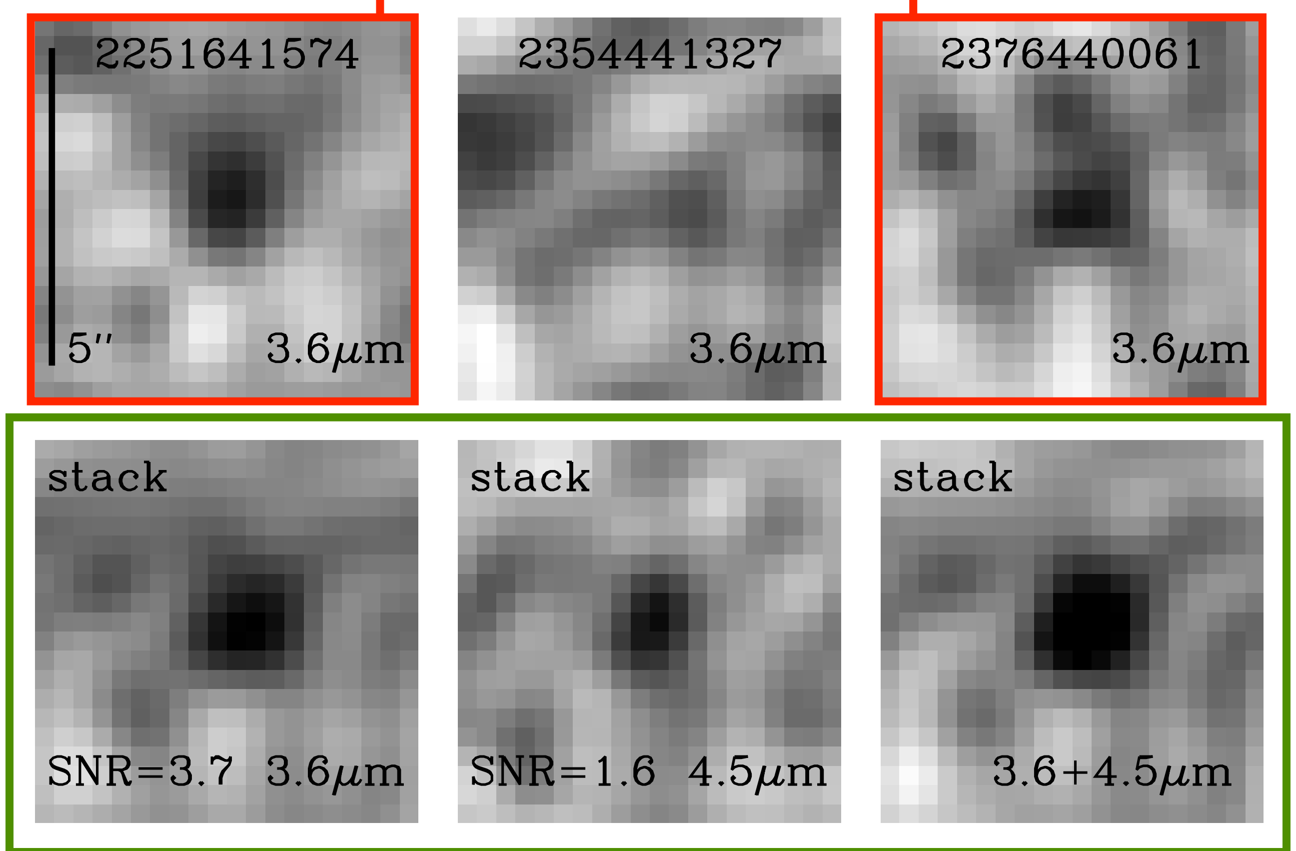


The High-z Universe with IRAC: Mass Estimates

Spitzer IRAC can detect rest-frame optical wavelengths of brightest z>7 galaxies

Two of bright z~8 galaxy candidates are individually detected in IRAC

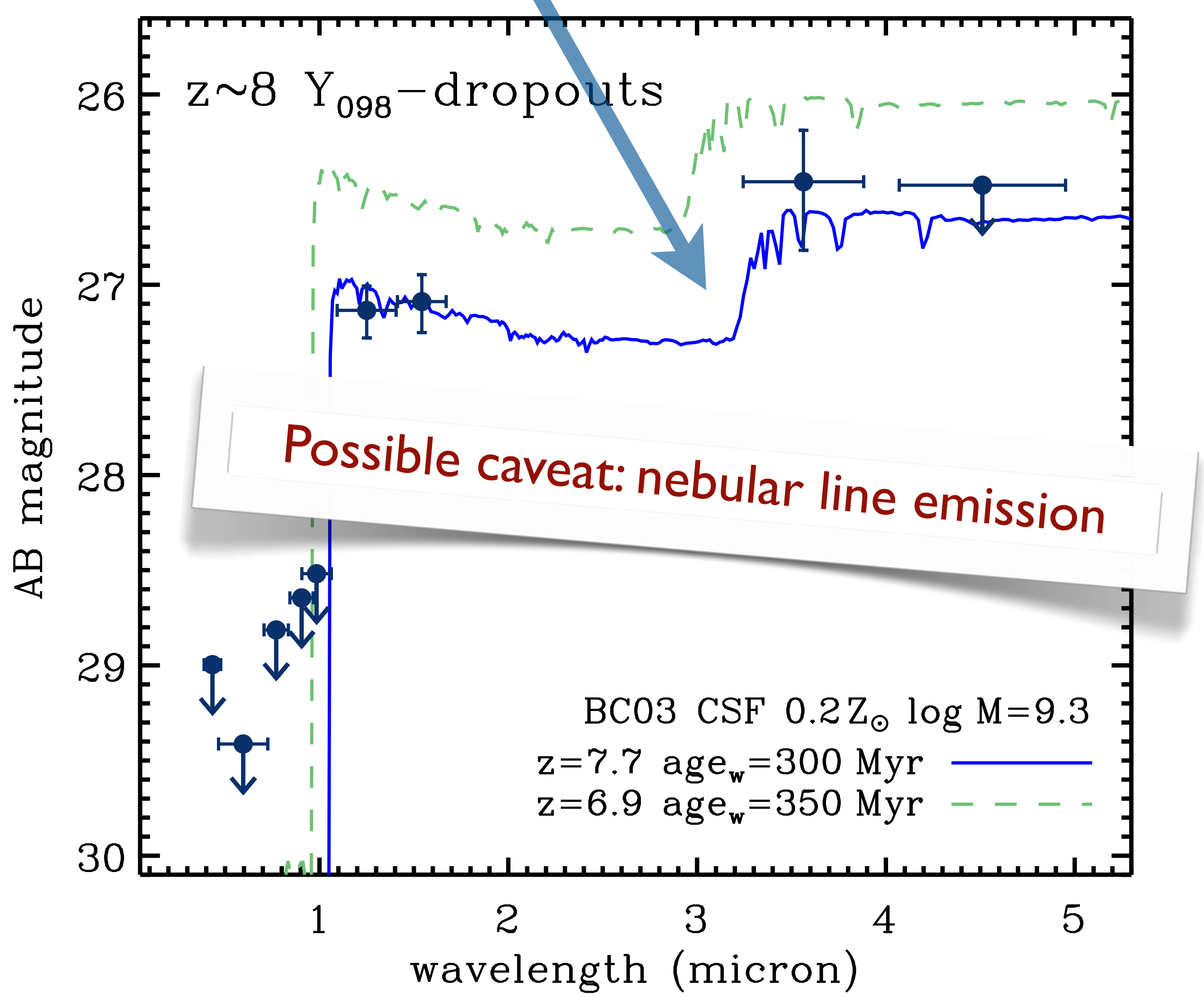
individual detections (~2.5σ)



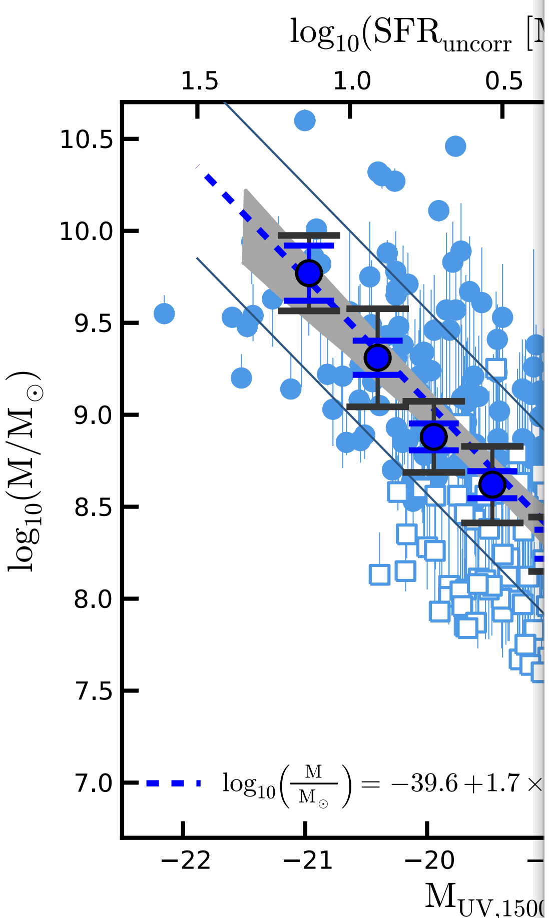
Labbé+2010a,2010b

stack

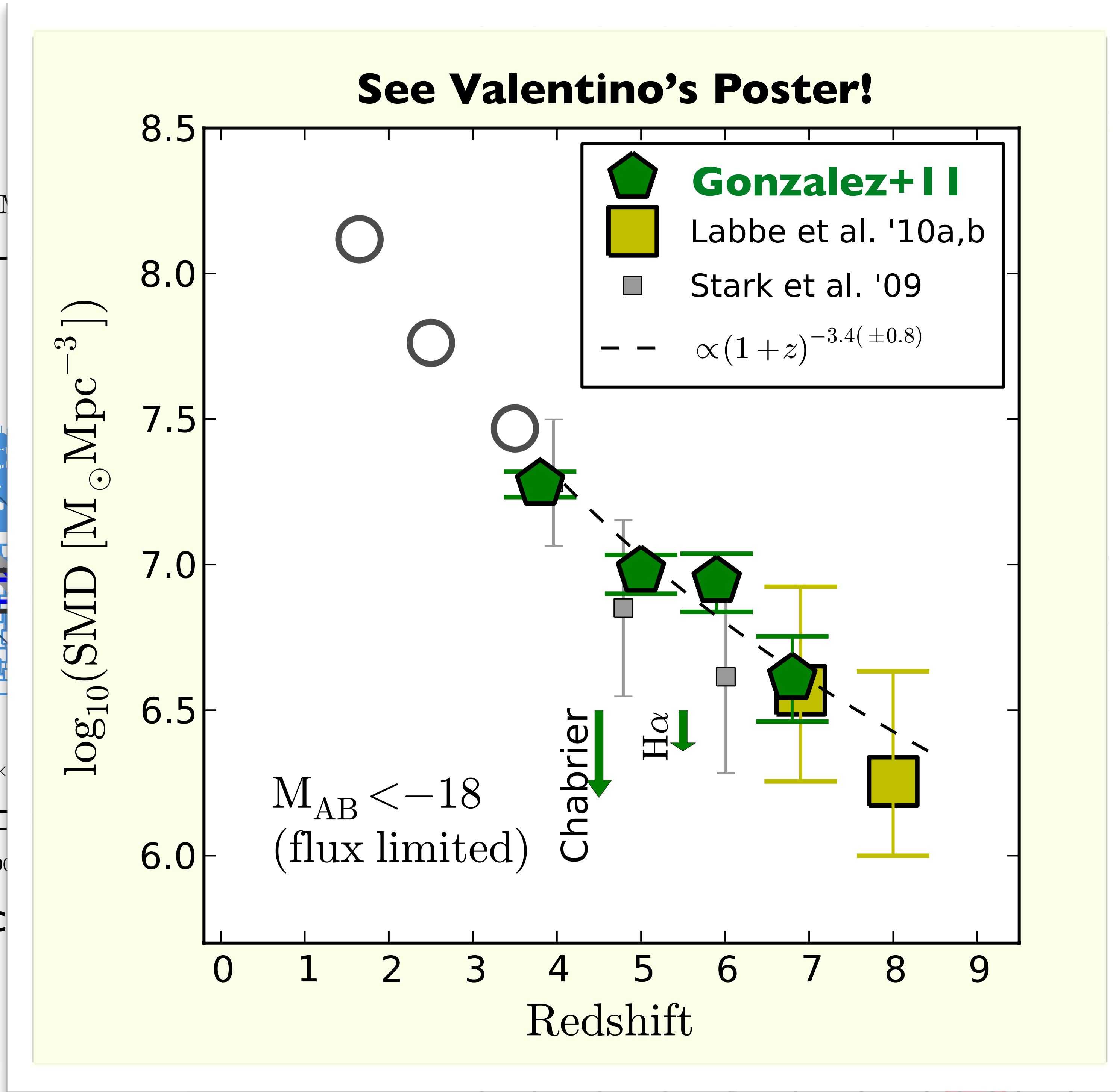
strong spectral break: indicates ages>~300 Myr,
i.e. onset of SF at z>~12

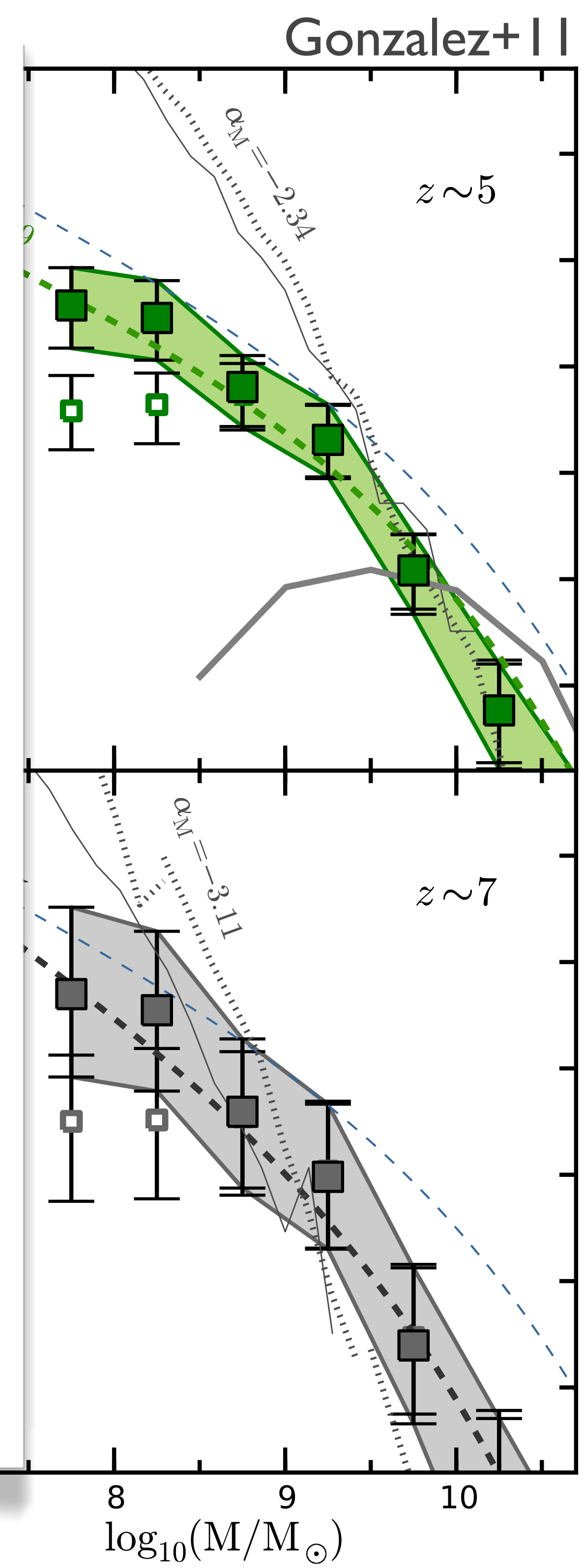


Evolution of the Mass Function



UV luminosity c
relatively well with



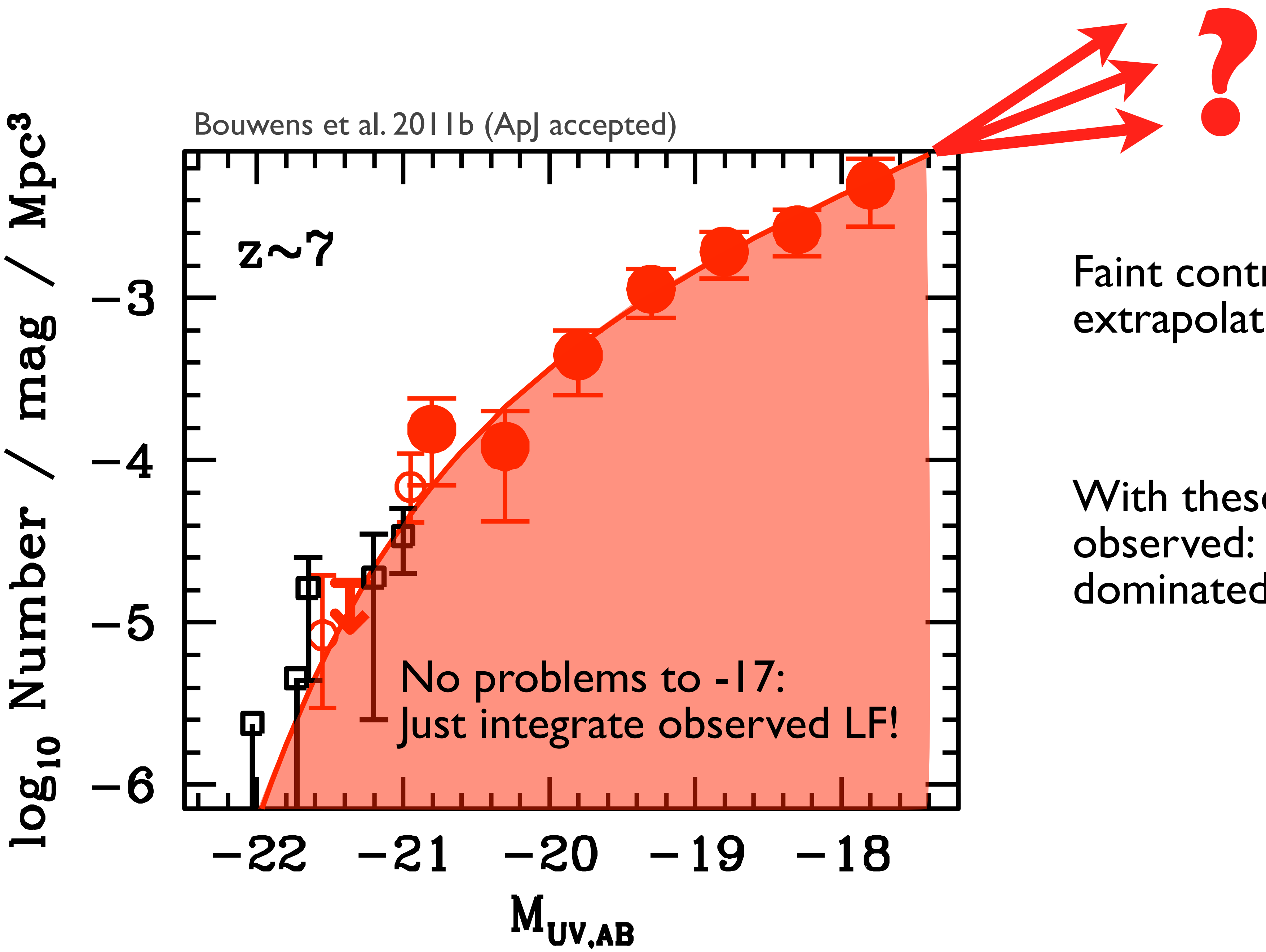


Are Galaxies Responsible for Cosmic Reionization?

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

The Ionizing Flux Density from Galaxies

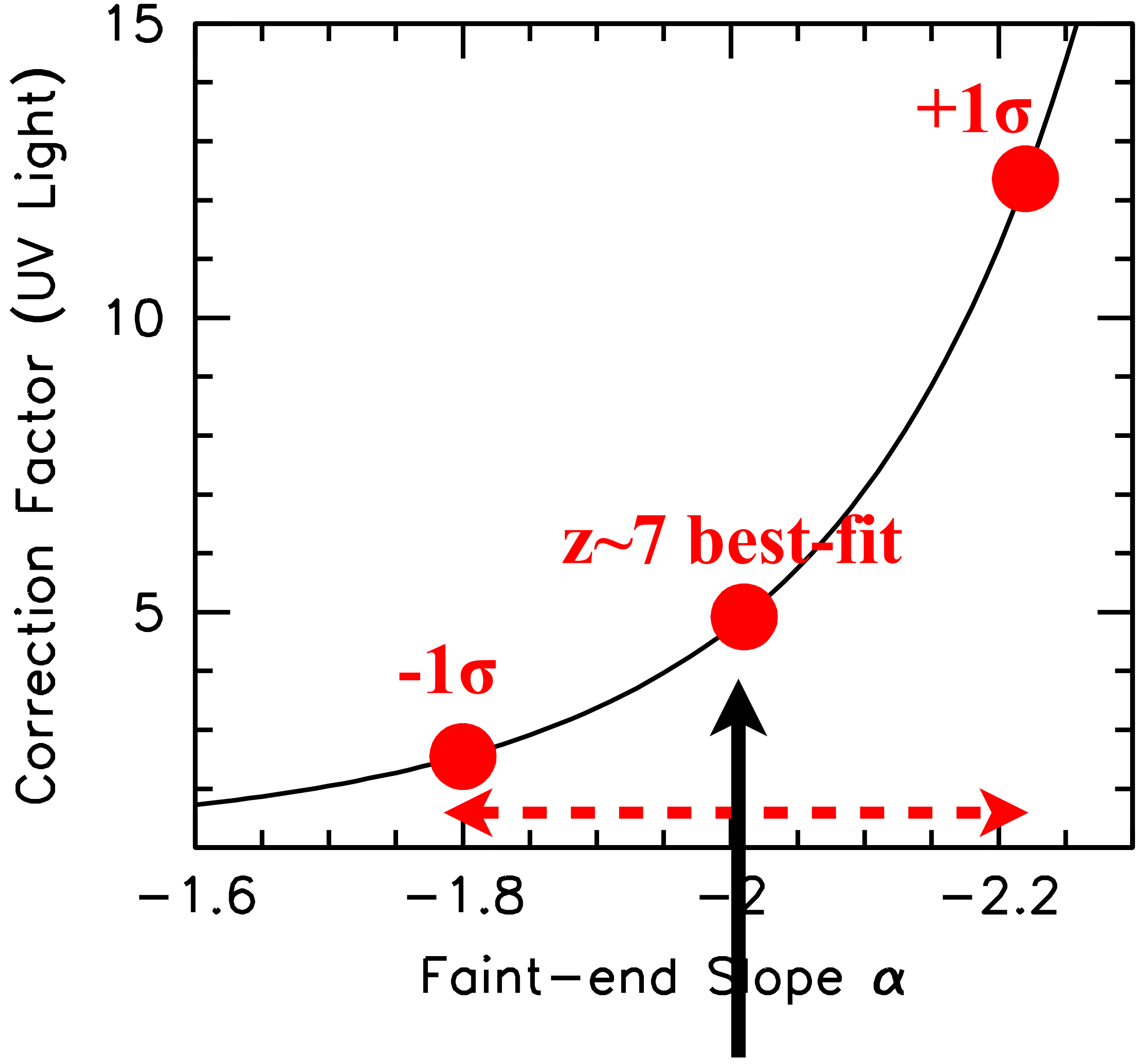
$$\phi(M_{1400}) \xrightarrow{\text{integrate}} \rho_{L1400} \xrightarrow{\langle N_{\gamma<912}/N_{\gamma1400}\rangle} \dot{N}_{ion}^{int} \xrightarrow{f_{esc,rel}} \dot{N}_{ion}$$



Faint contribution: Have to extrapolate to below detection limits

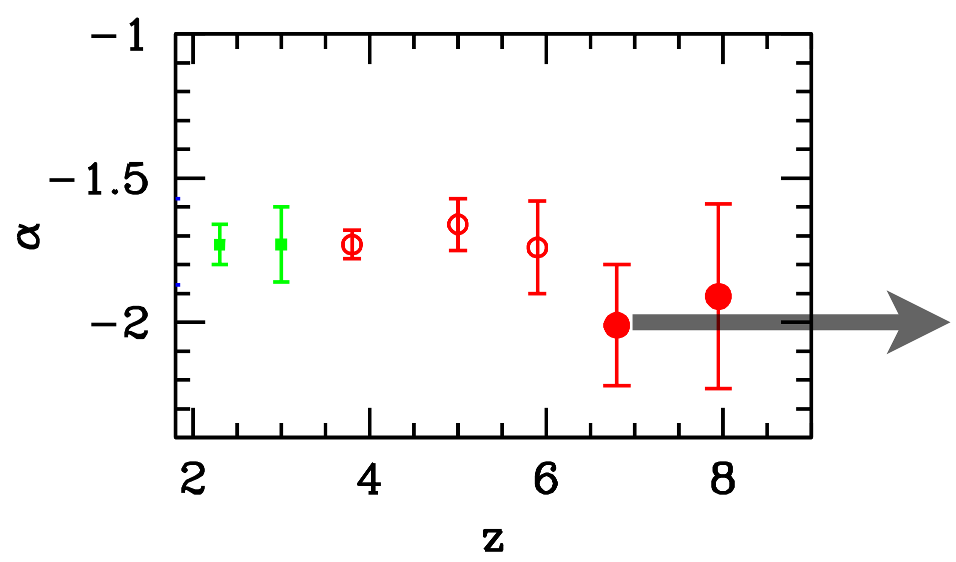
With these steep faint-end slopes as observed: luminosity density completely dominated by faint galaxies

Correcting from Observed to Total LD



Assume α = const
and extrapolate LF trends

- Total: integrated down to M = -10
- Corrections change by almost an order of magnitude within currently allowed 1σ range of faint-end slope



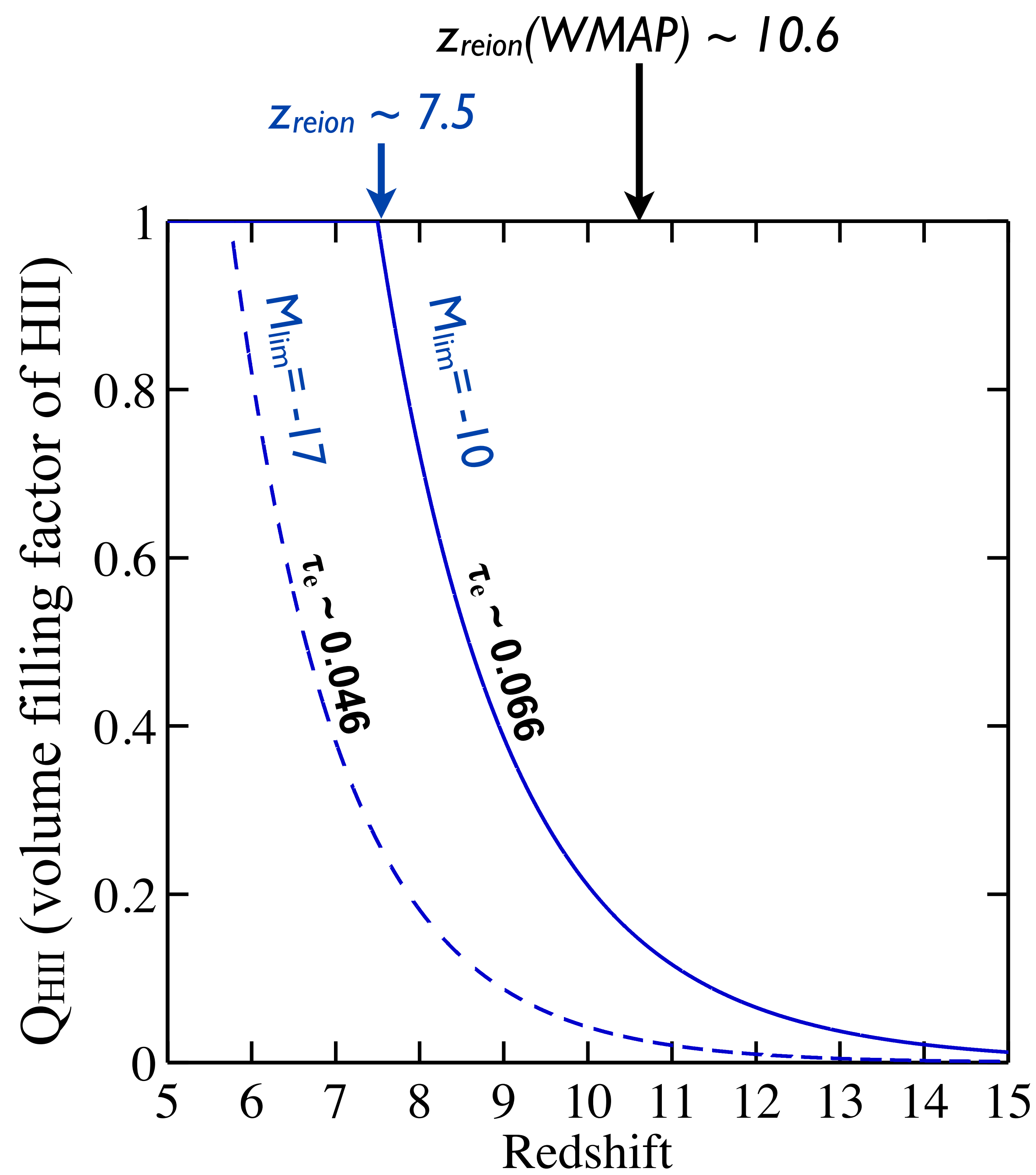
Inferred Reionization History

- 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: τ_e **~ 0.066**

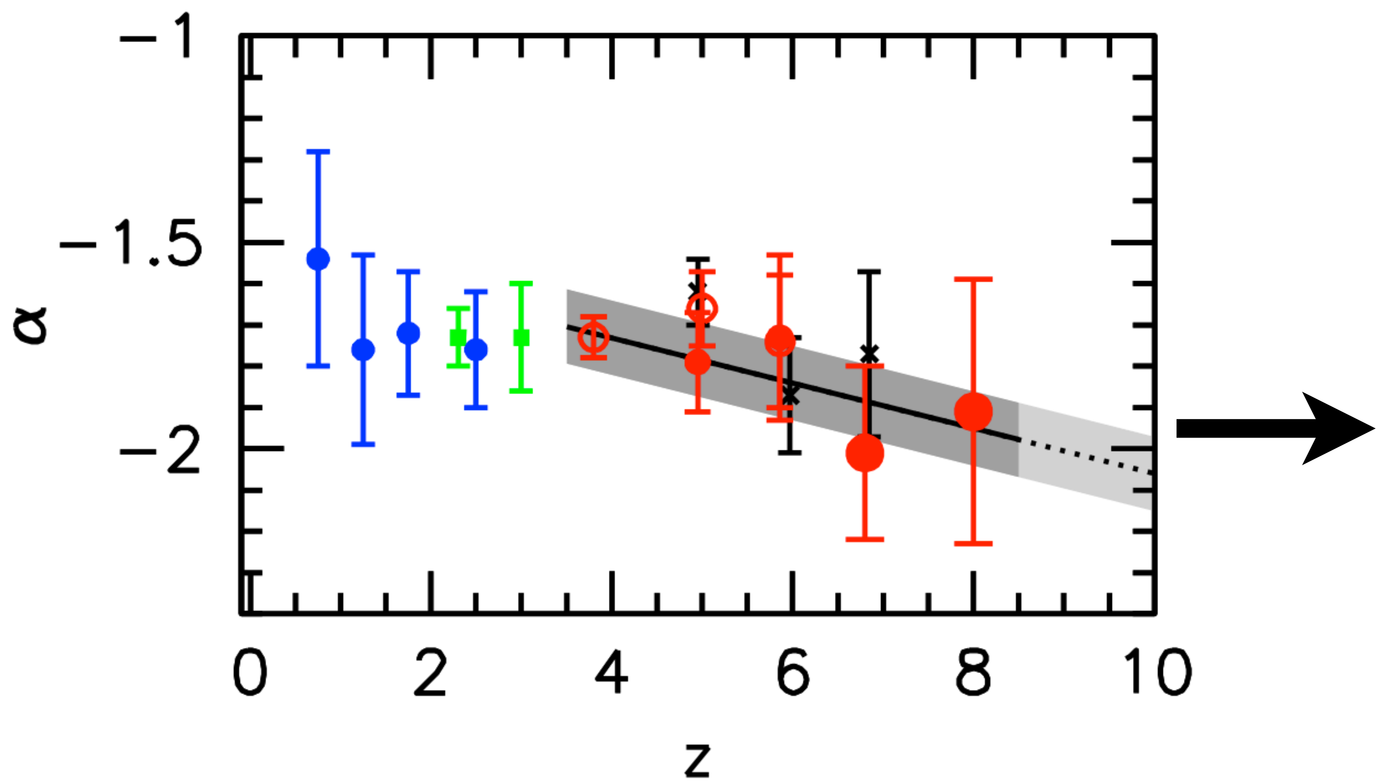
WMAP measurement: τ_e **= 0.088 ± 0.015**

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

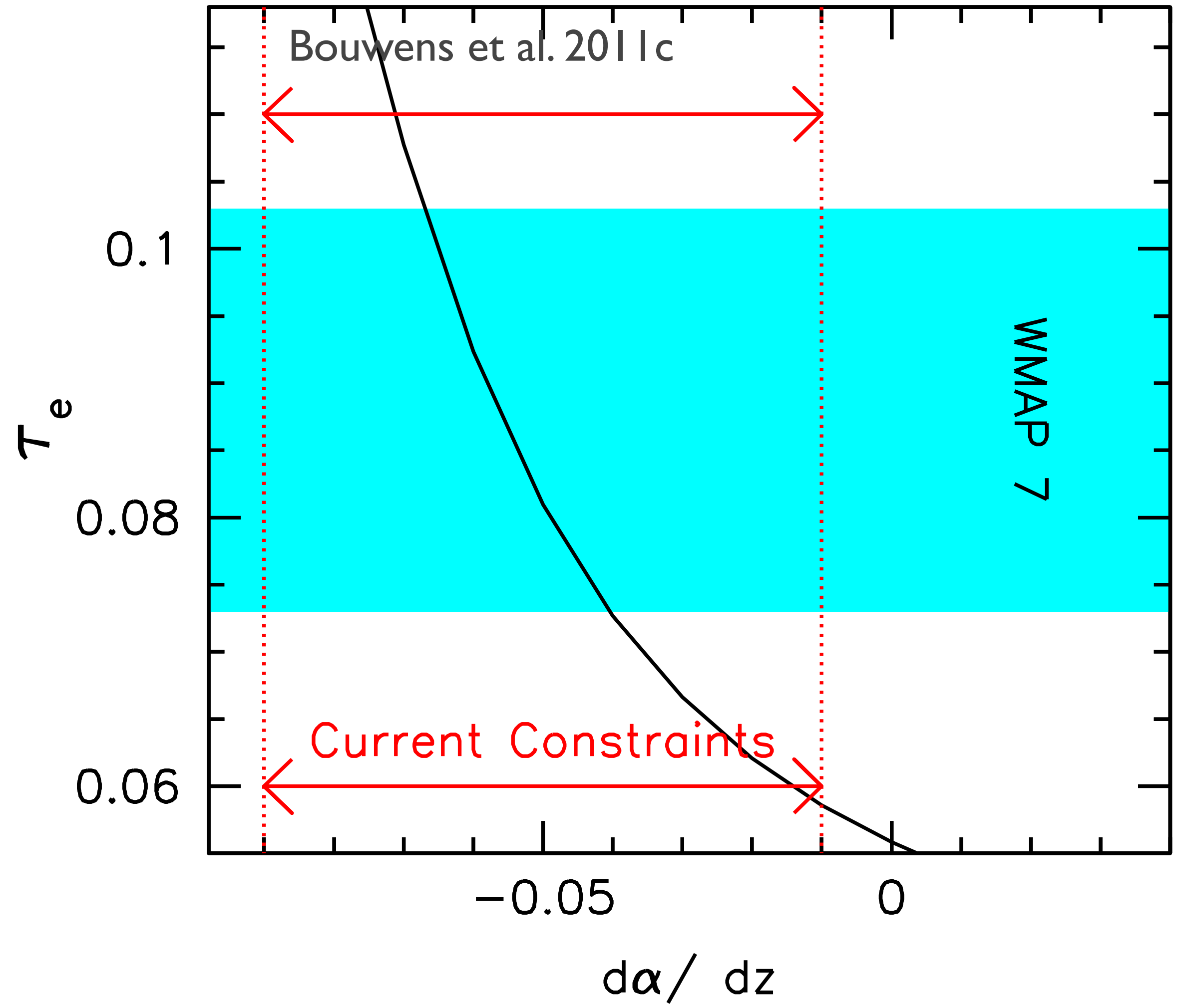


Additional assumptions:
clumping factor = 3
relative escape fraction = 20%

Steepening of Faint-End Slope with Redshift?



Extrapolate steepening of faint-end slope into EoR



Required optical depths can be achieved since τ_e very sensitive to changes in faint end slope

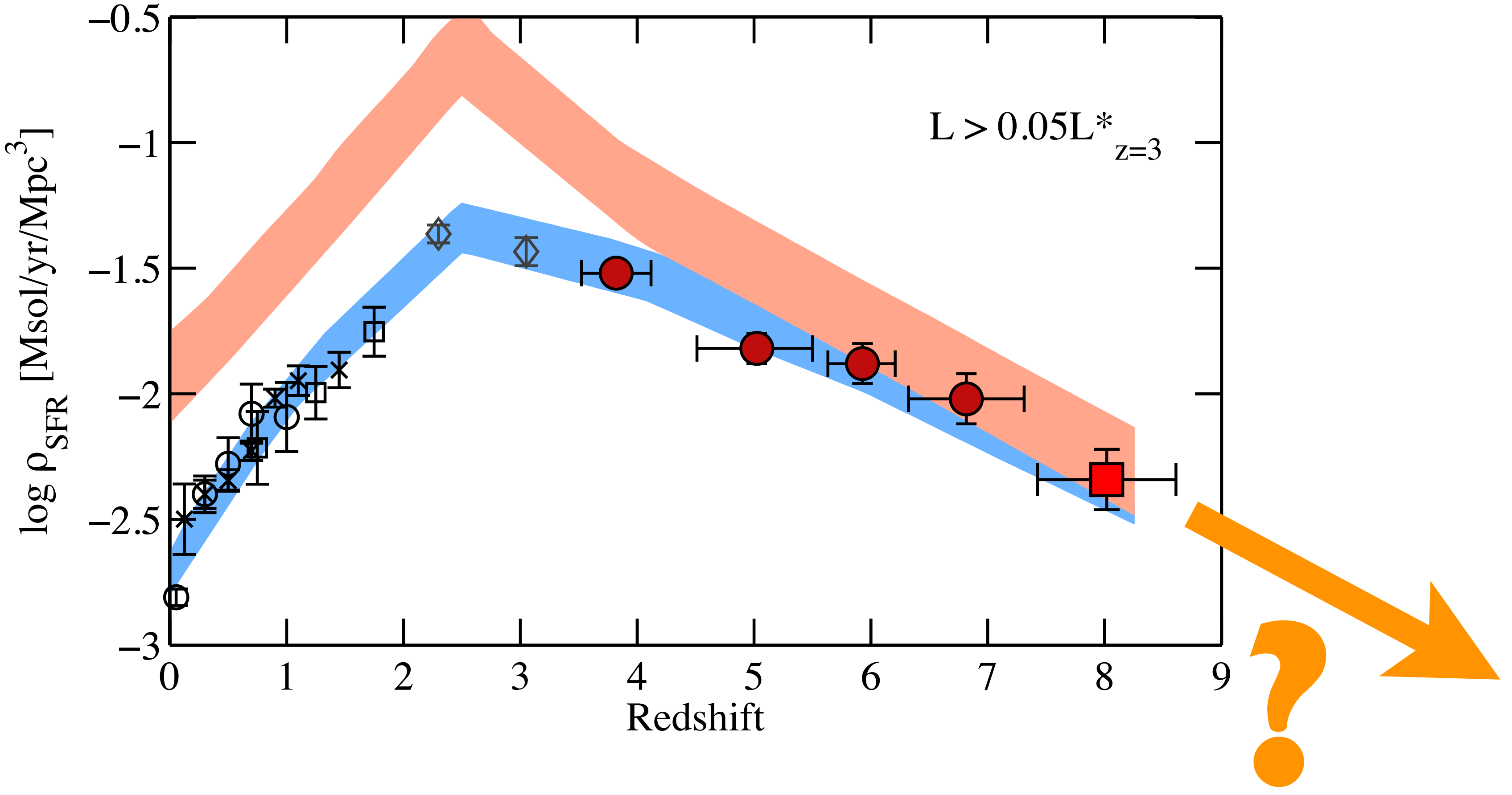
➡ Thus: faint galaxies are consistent with being capable of driving reionization.

➡ **However:** Need better constraints on evolution of faint end slope with redshift!

Other possibility for more ionizing photons: evolving escape fraction, e.g. Kuhlen & Faucher-Guiguere 11

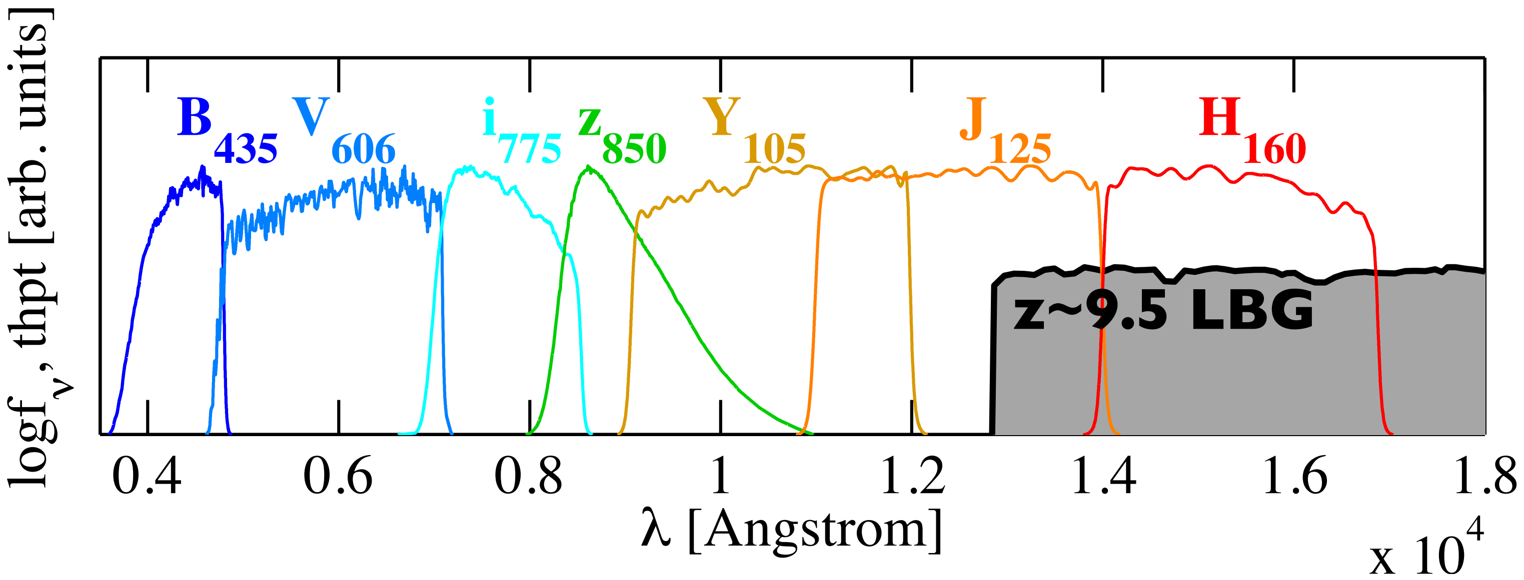
So Far:

Galaxy build-up is remarkably smooth (and predictable) from z~8 down to z~3-4

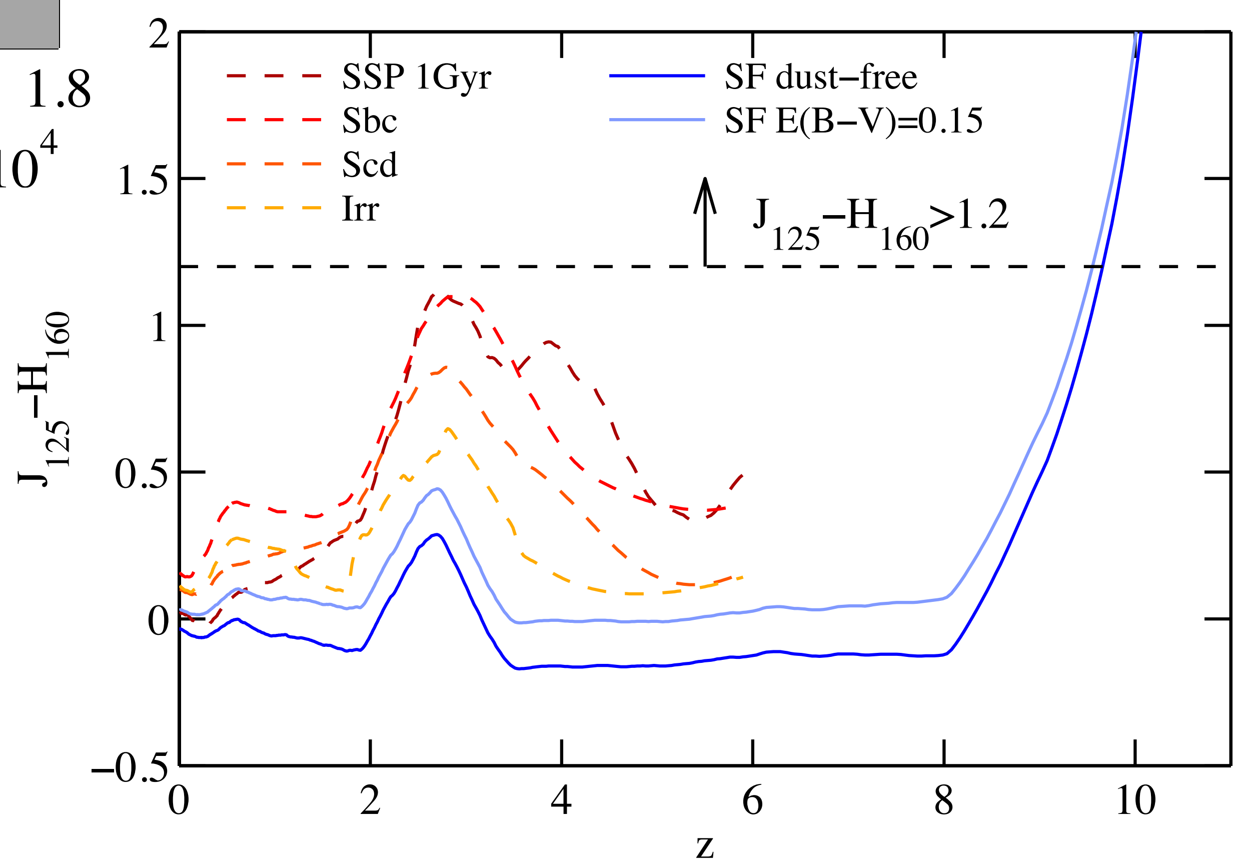


HST Can Push the Frontier to z~10

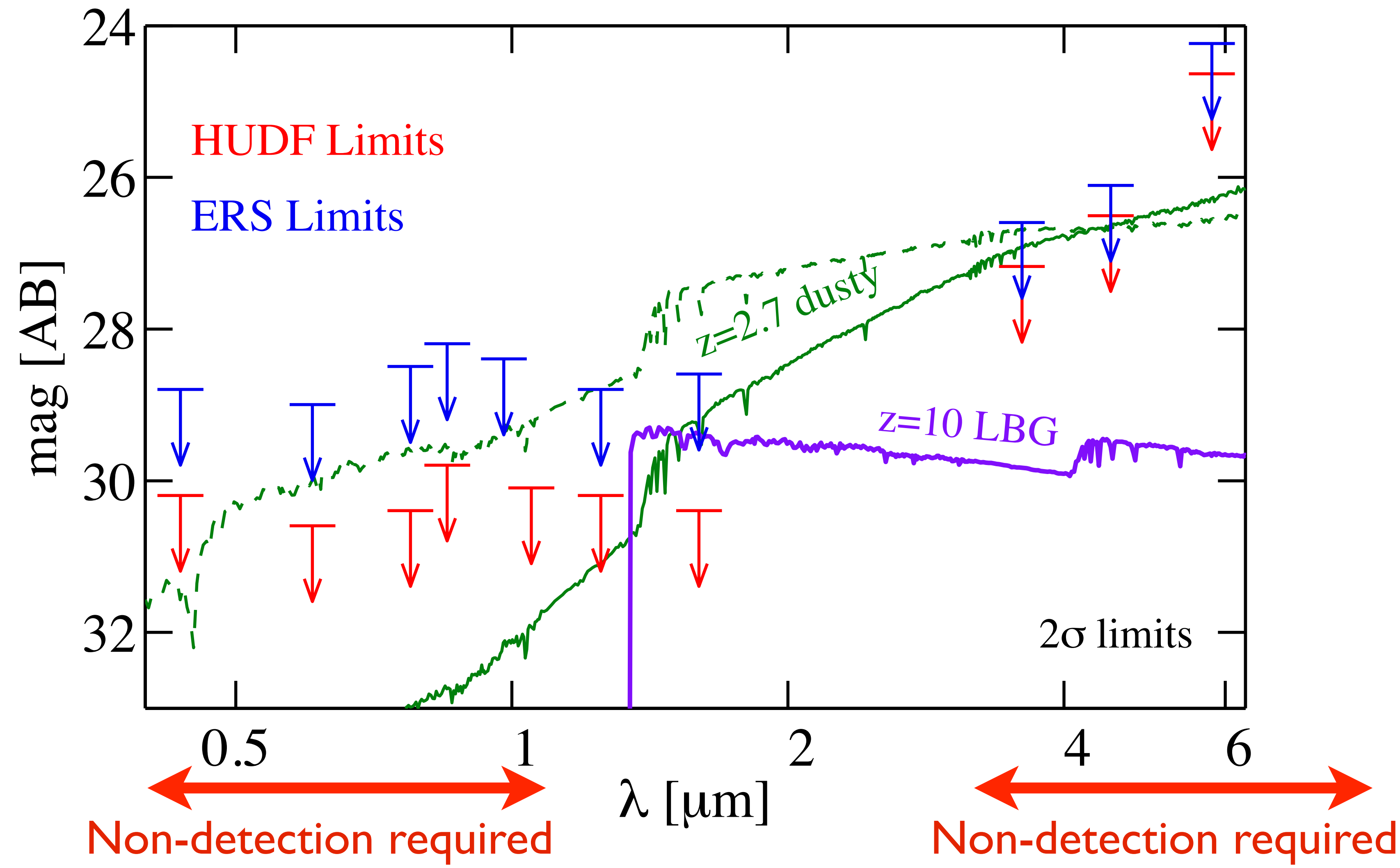
- At z~8: neutral IGM starts affecting J_{125}
- Can select z>9.5 galaxies as J-dropouts based on red J_{125}-H_{160} colors



- Very challenging:
  - z~10 galaxies expected to be extremely faint
  - single band detections
  - low-z dusty galaxies can exhibit similar colors

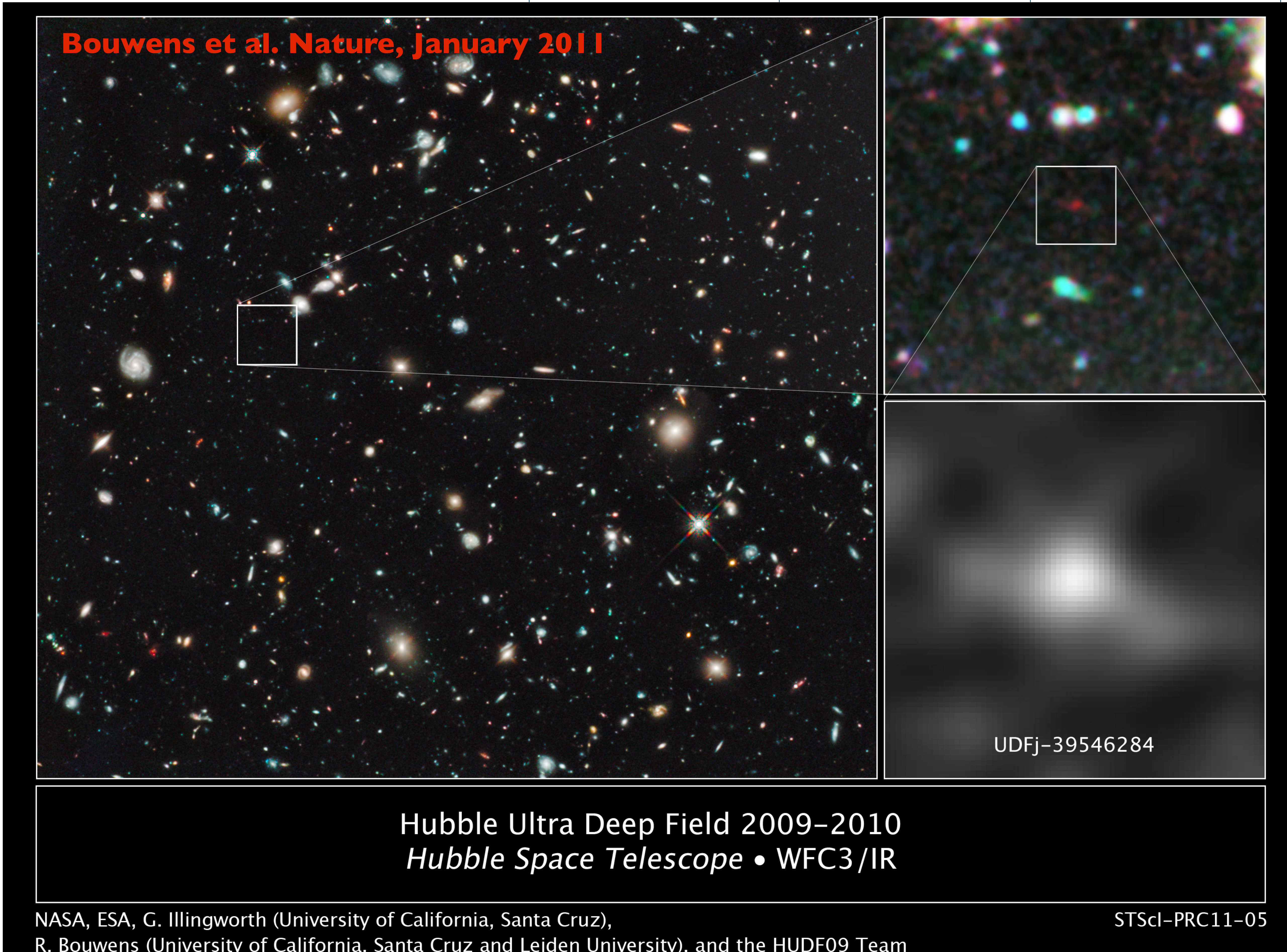


Requirements on Data

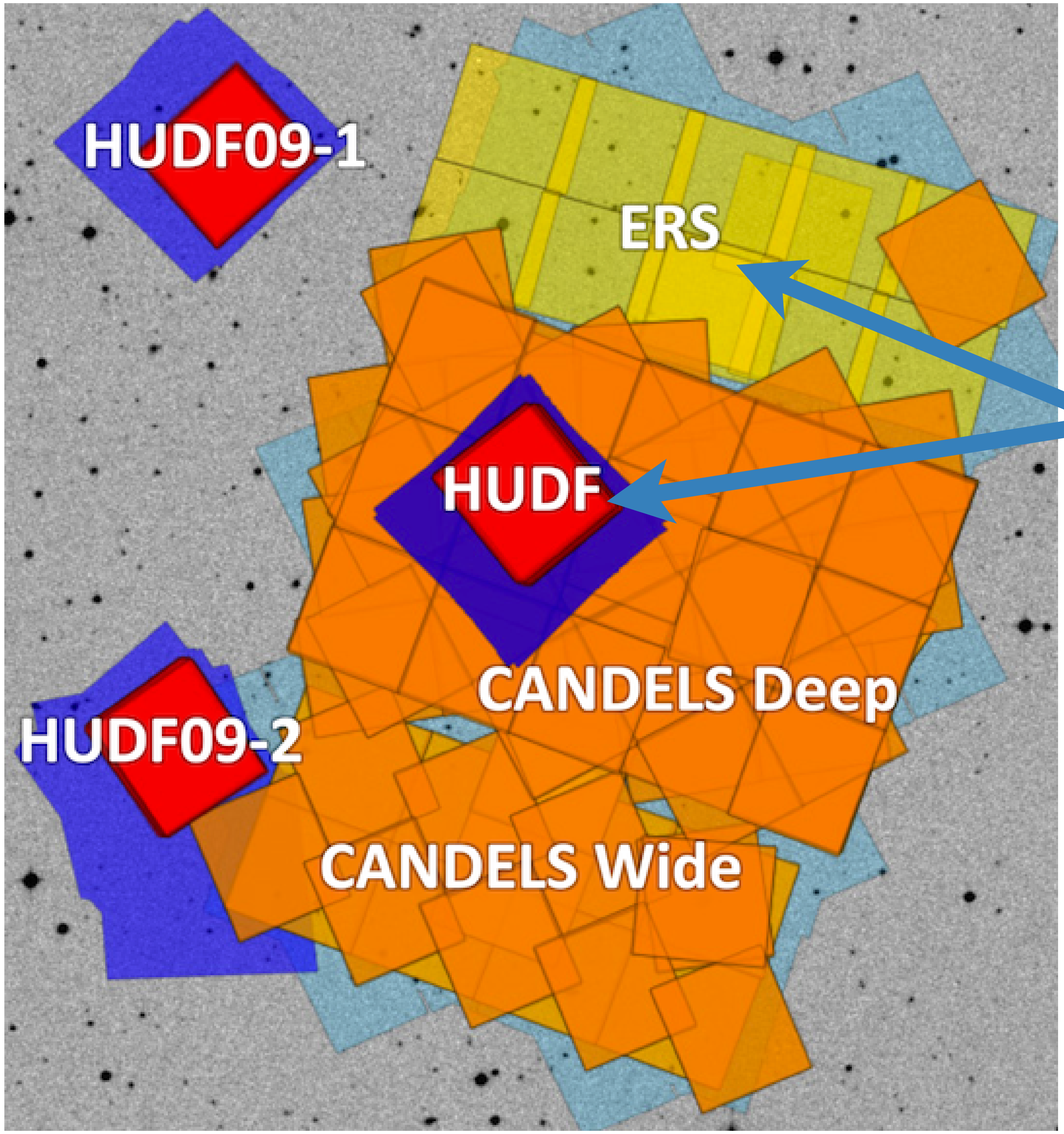


deep J_{125} and H_{160}

deeper data shortward of Lyα break


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

Extended z~10 Search



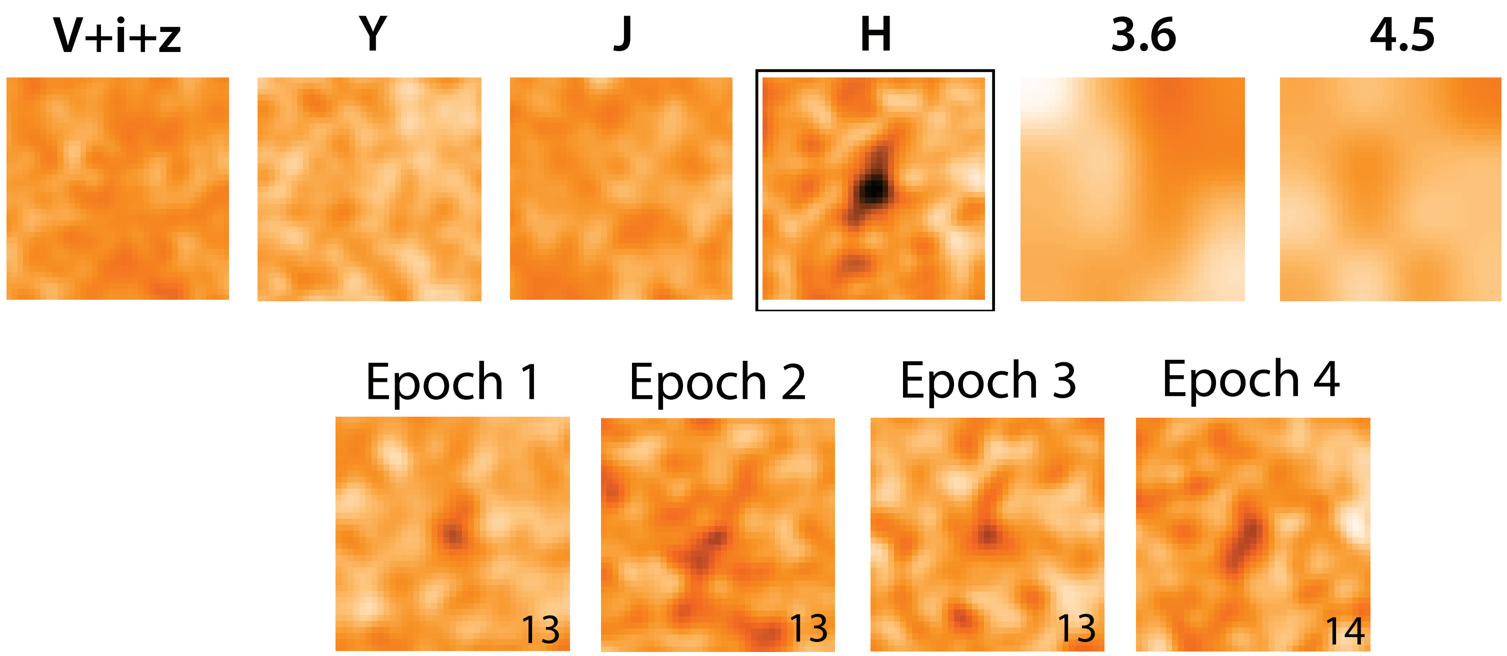
Our first analysis included only these two fields: Bouwens et al., Nature, 2011

Now extended to full WFC3/IR data available over CDFS, including CANDELS

➡ More than triple the search area both for bright and faint sources

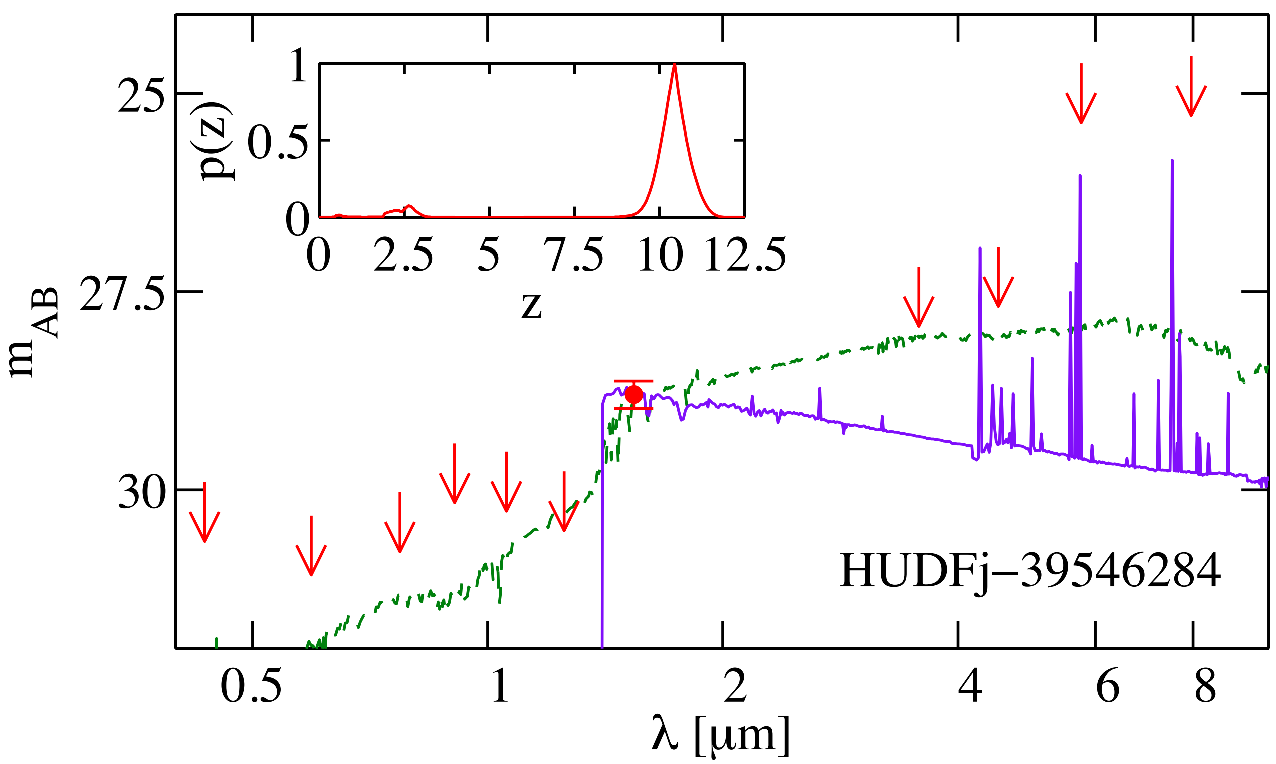
➡ Still: only **one** candidate at >5sigma in whole search field!
(after removing z~2-3 dusty galaxies based on extremely red H-IRAC colors)

The z~10 Candidate in the HUDF

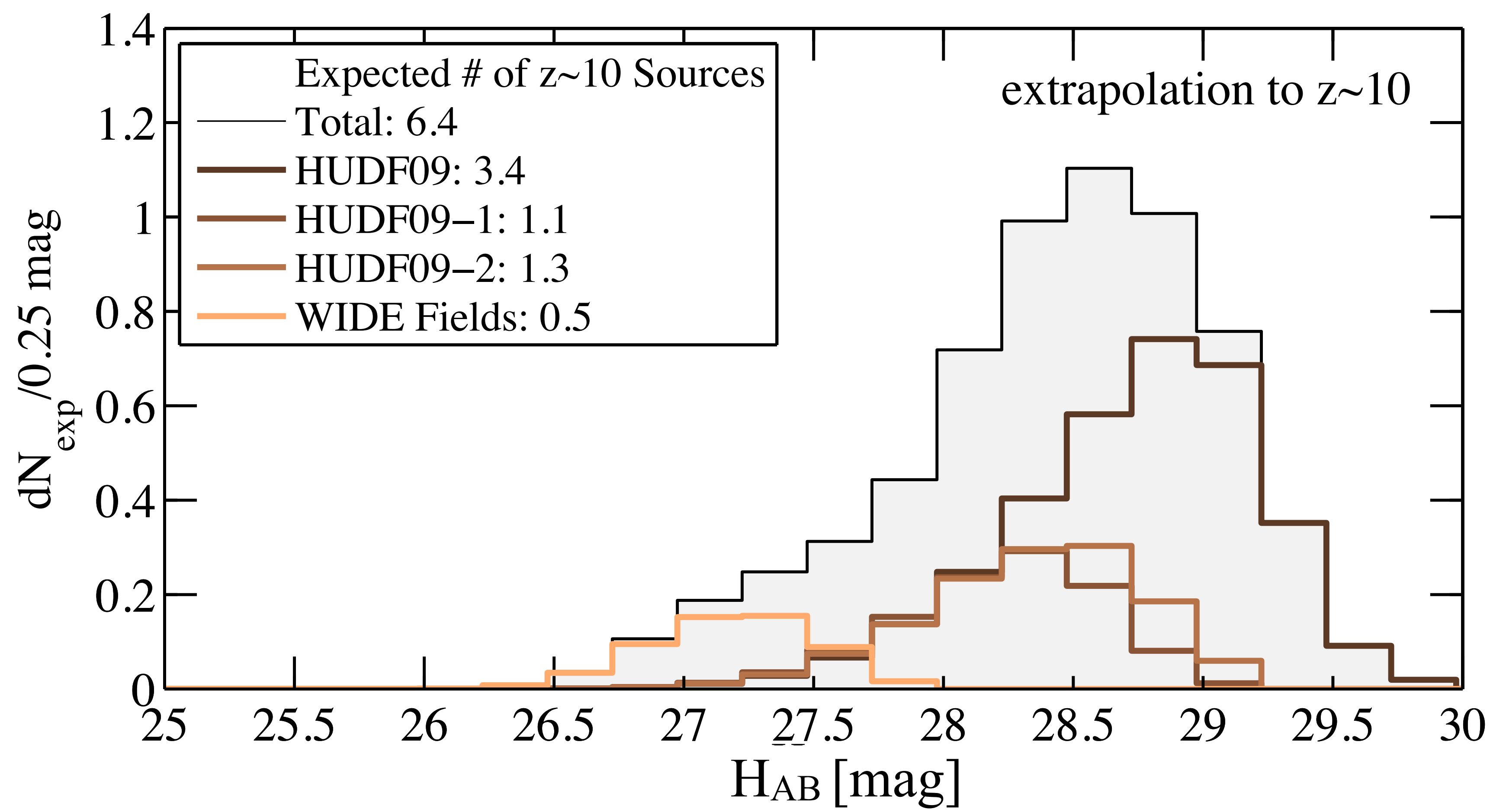


- Very faint: H_{AB}=28.8±0.2
- Small chance of being spurious:
  - It is detected at ~6σ
  - It is visible at >2.5σ in 4 independent splits of the data
- Blue UV continuum: not detected in very deep IRAC data

- z_{phot} = 10.4±0.4
- Small (<~10%) chance of being a low-z contaminant
- Planned HST data might help to further strengthen the high-z solution



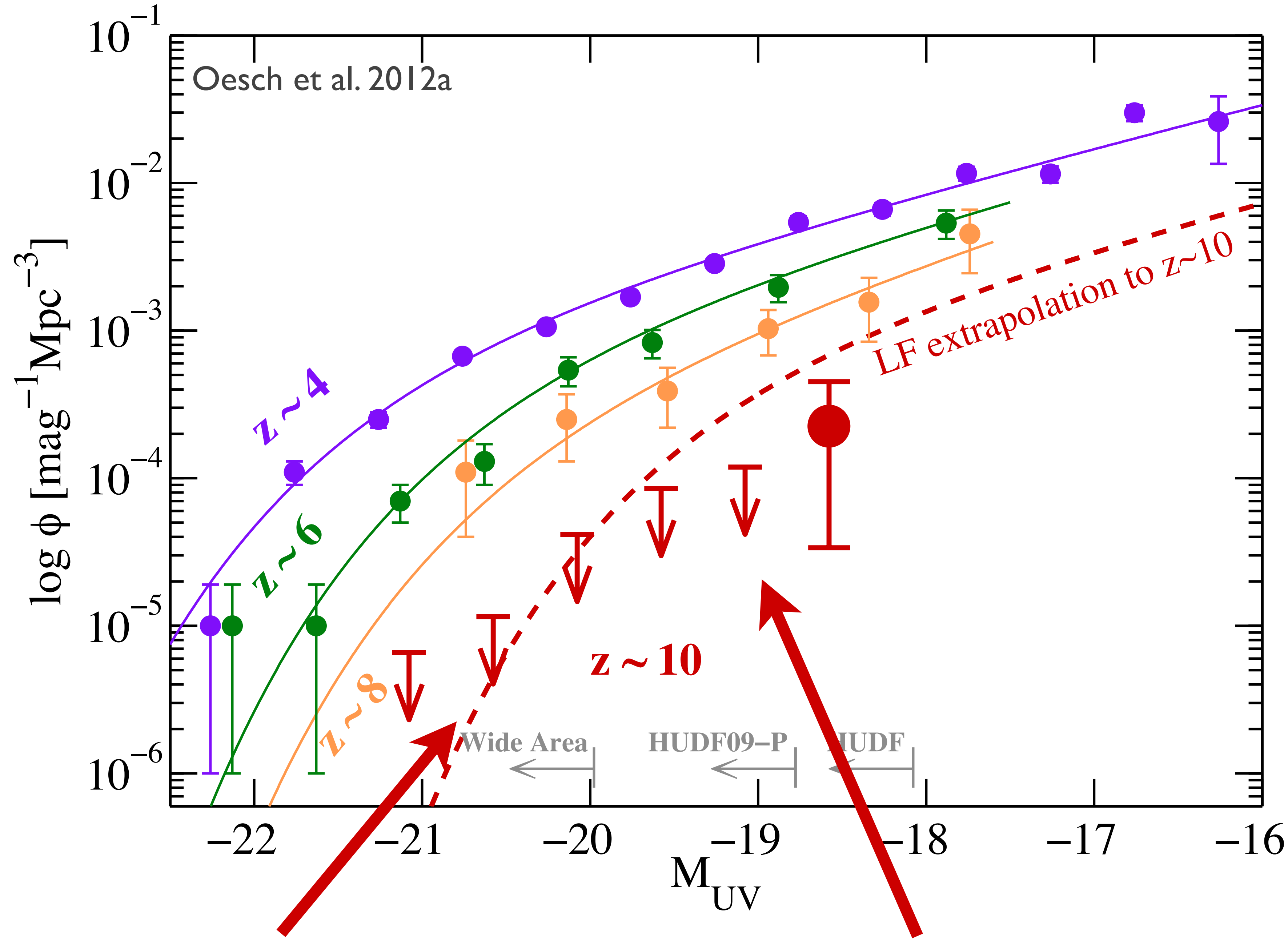
Constraints on z~10 LF



- Extrapolate low-z LF trends to z~10: expect to see **6** sources
- Even including cosmic variance: chance of finding one when expecting 6 is only ~6%

➡ Accelerated evolution of UV LF detected at ~2σ

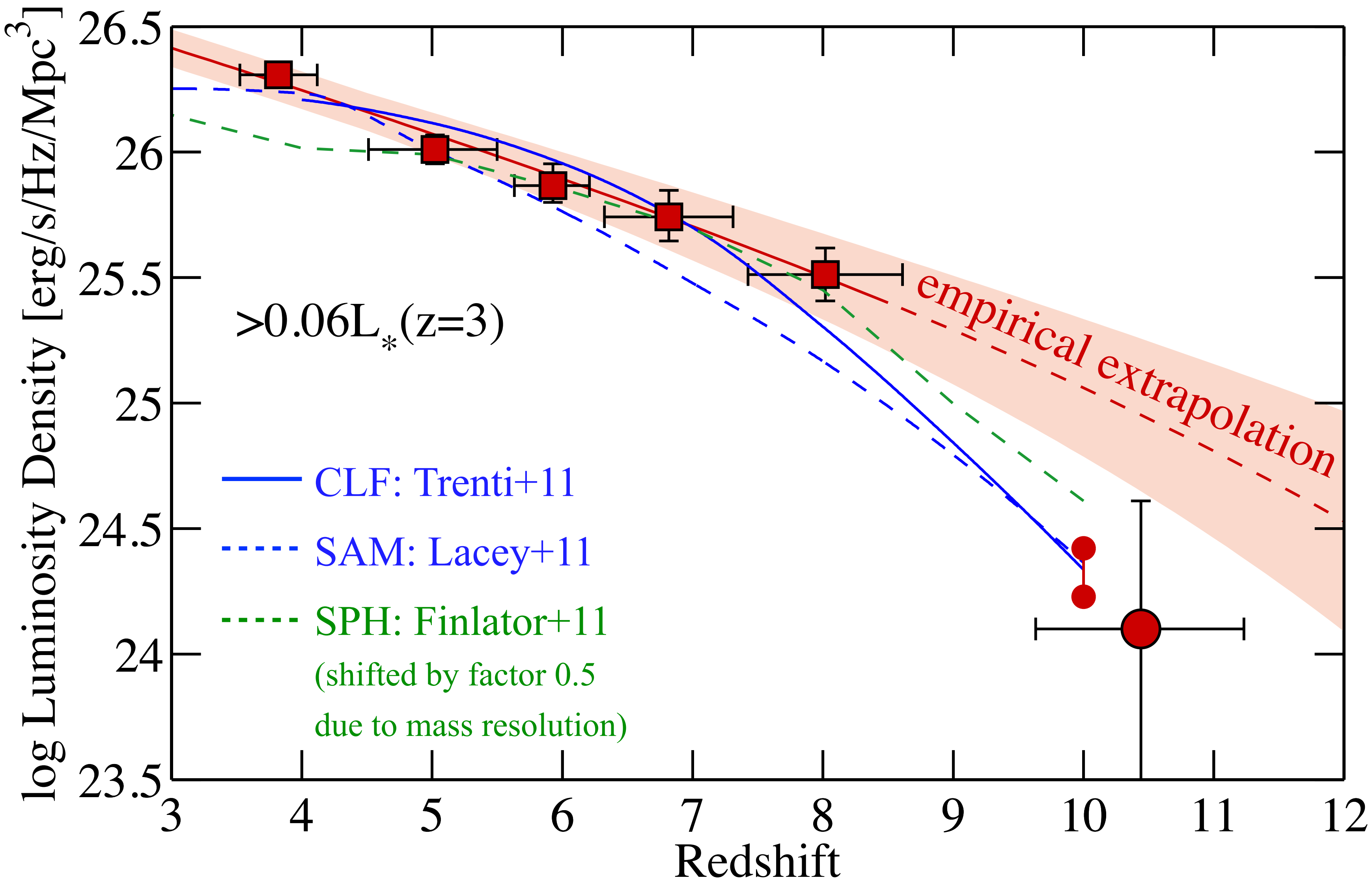
Constraints on z~10 LF (II)



Three Wide Fields:
limits are below z~8 LF

Three HUDF09 Fields:
z~10 limits are below extrapolation

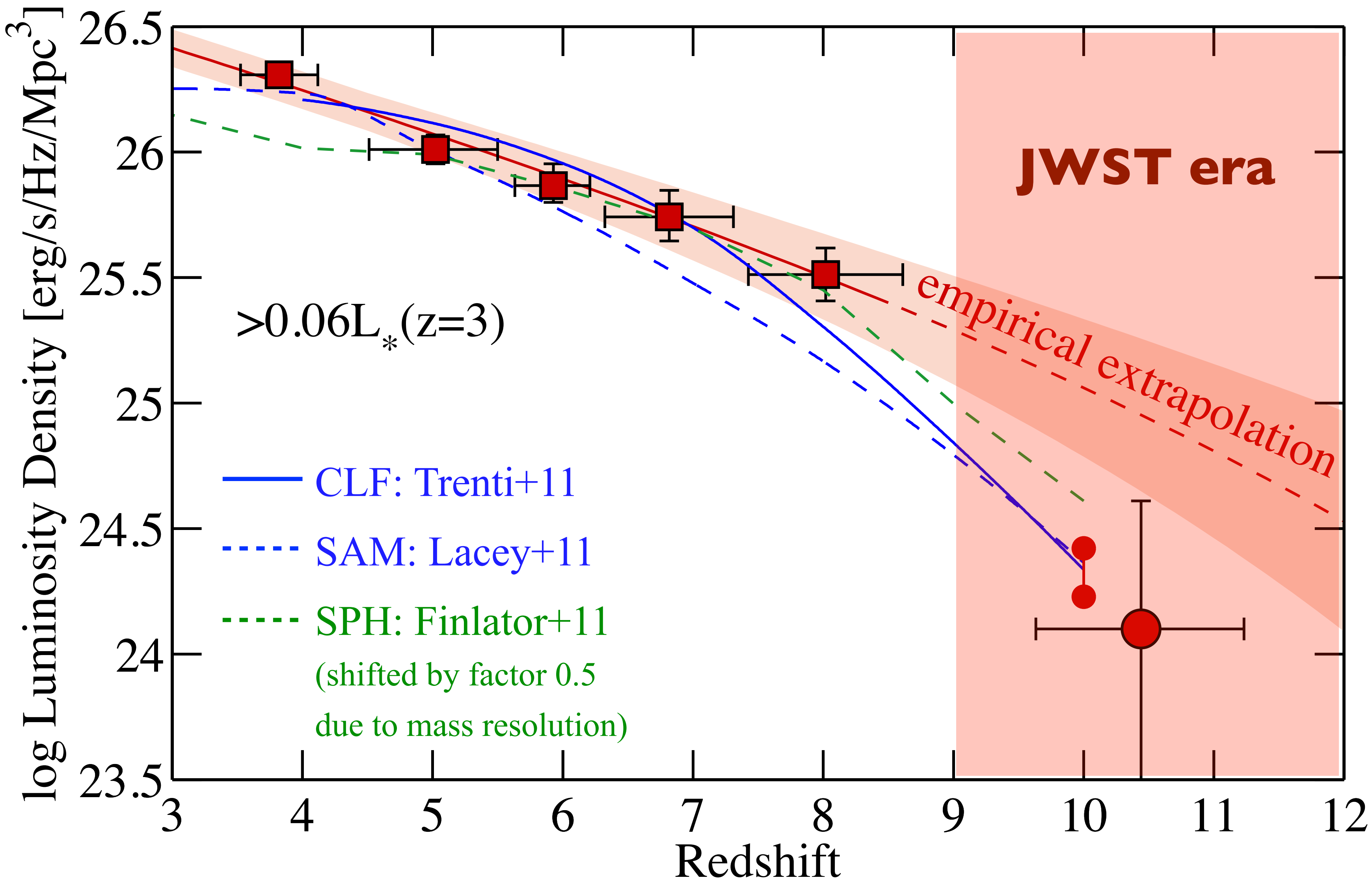
Accelerated Evolution of the UV Luminosity



Rapid build-up of UV luminosity in galaxies within only 170 Myr

A number of very different theoretical models reproduce such a drop to z~10: thus most likely driven by evolution of underlying DM halo mass function

Accelerated Evolution of the UV Luminosity



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 (at z>9 JWST!)

Summary

- WFC3/IR has opened up the window to very efficient studies of z>6.5 galaxies: by now, we have identified >100 galaxy candidates at these redshifts; one 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 relatively tight UV color-magnitude relation is found in z>4 galaxies, with a constant slope but evolving normalization: at z~7 galaxies are essentially dust-free.
- Spitzer IRAC has detected the rest-frame optical light of galaxies out to z~8: we can start to study the build-up of the stellar mass densities out to these redshifts
- The faint-end slopes measured at z≥6 are very steep and show weak trends to steepen towards high redshift. If true, galaxies below the current detection limits are consistent with being capable of reionizing the universe, with high enough τ_e.
- From the one z~10 candidate identified so far in current WFC3/IR data over CDFS. The upper limits on the z~10 UV LF are significantly below extrapolation of observed trends. ➡ Accelerated evolution is most likely explained by growing DM halo MF
- Need JWST to further constrain accelerated evolution. z>9 is JWST territory.