Exploring the High-Redshift Universe with HST

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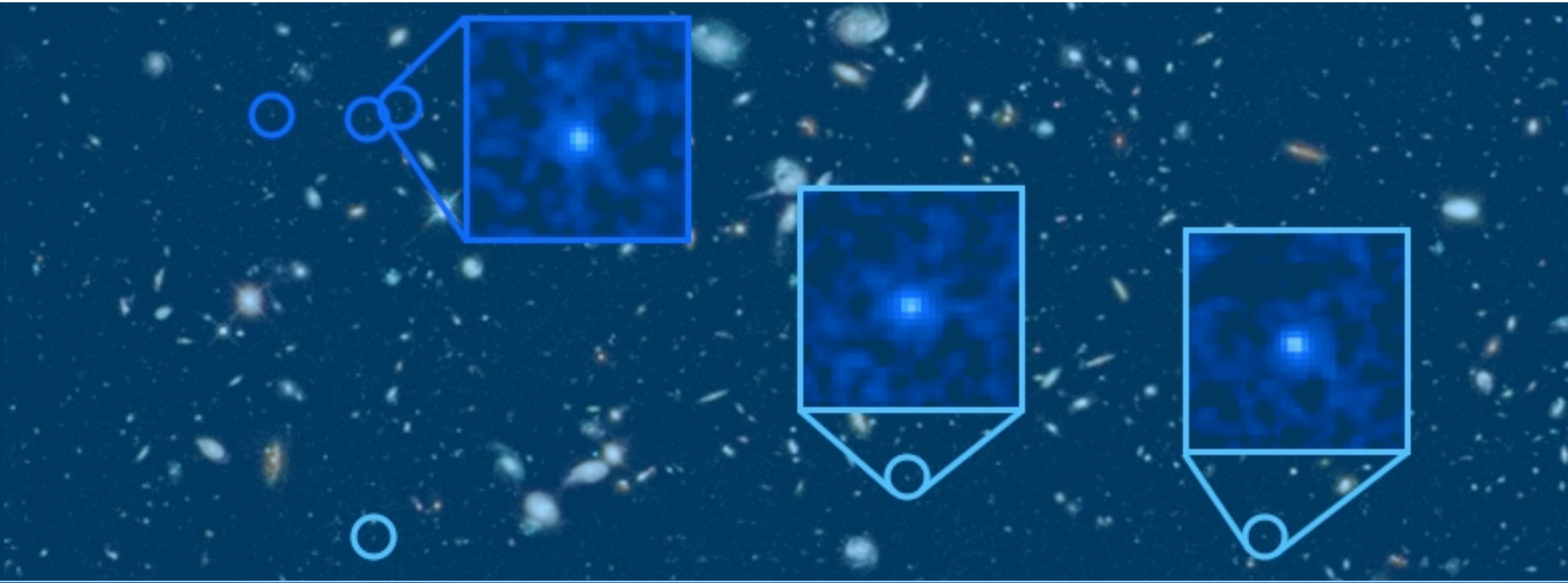
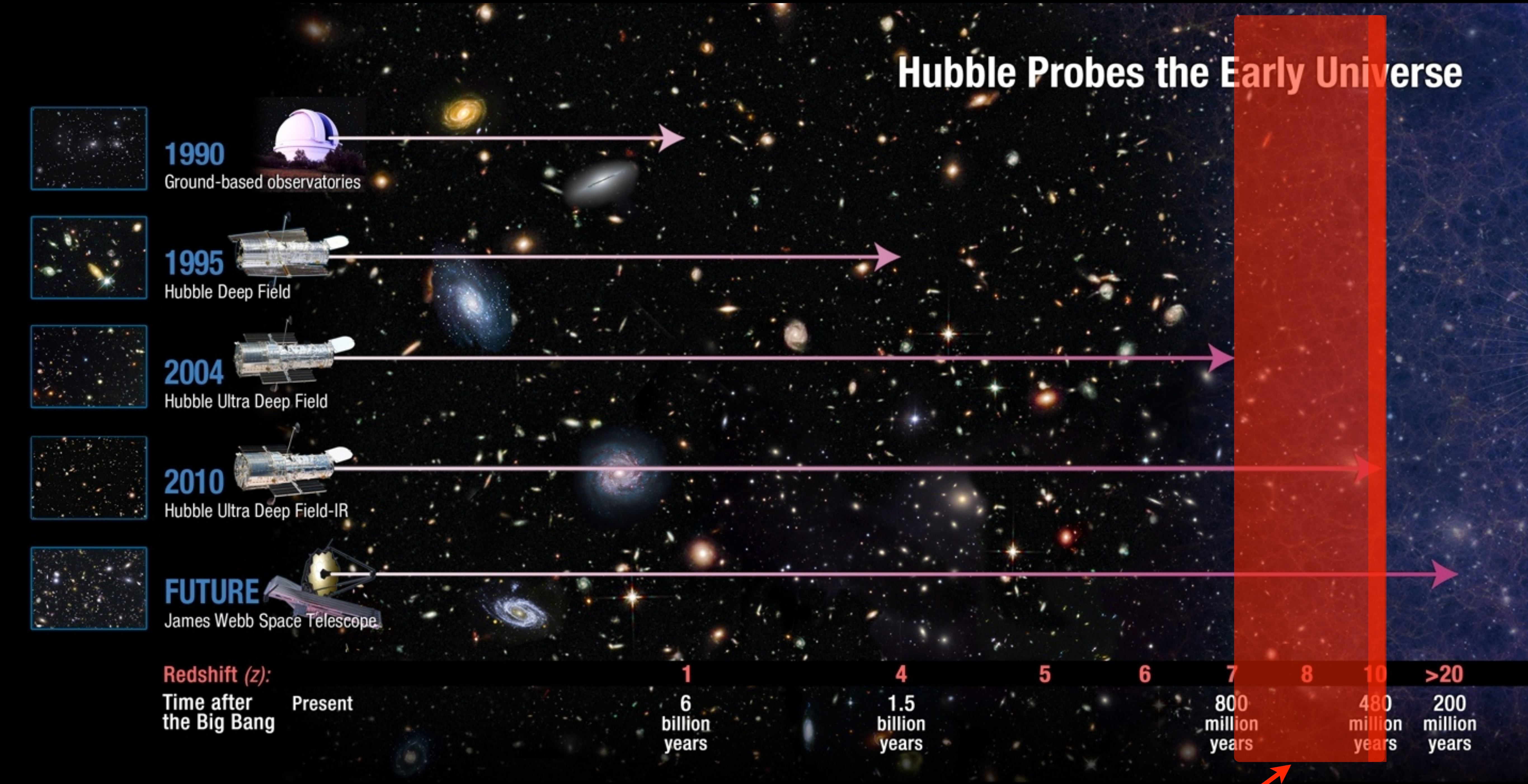
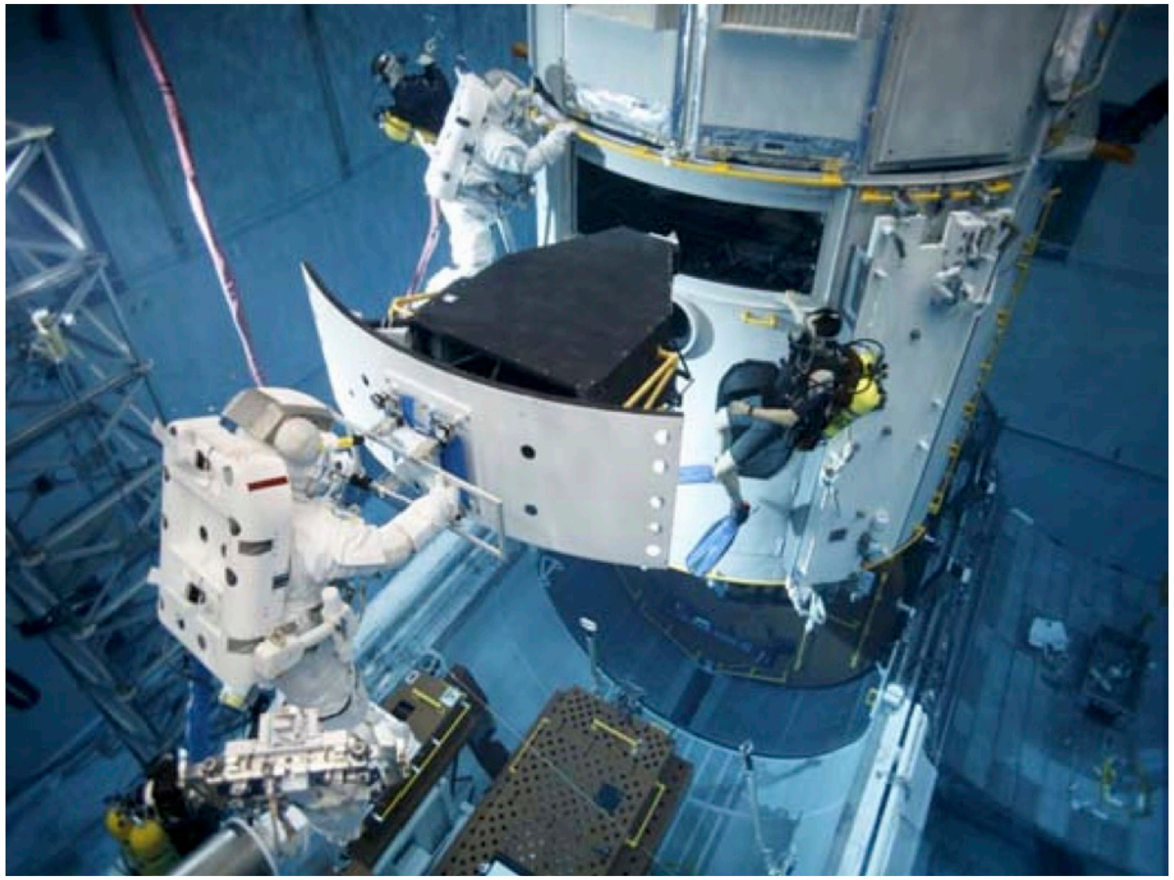


The Reionization Epoch with HST



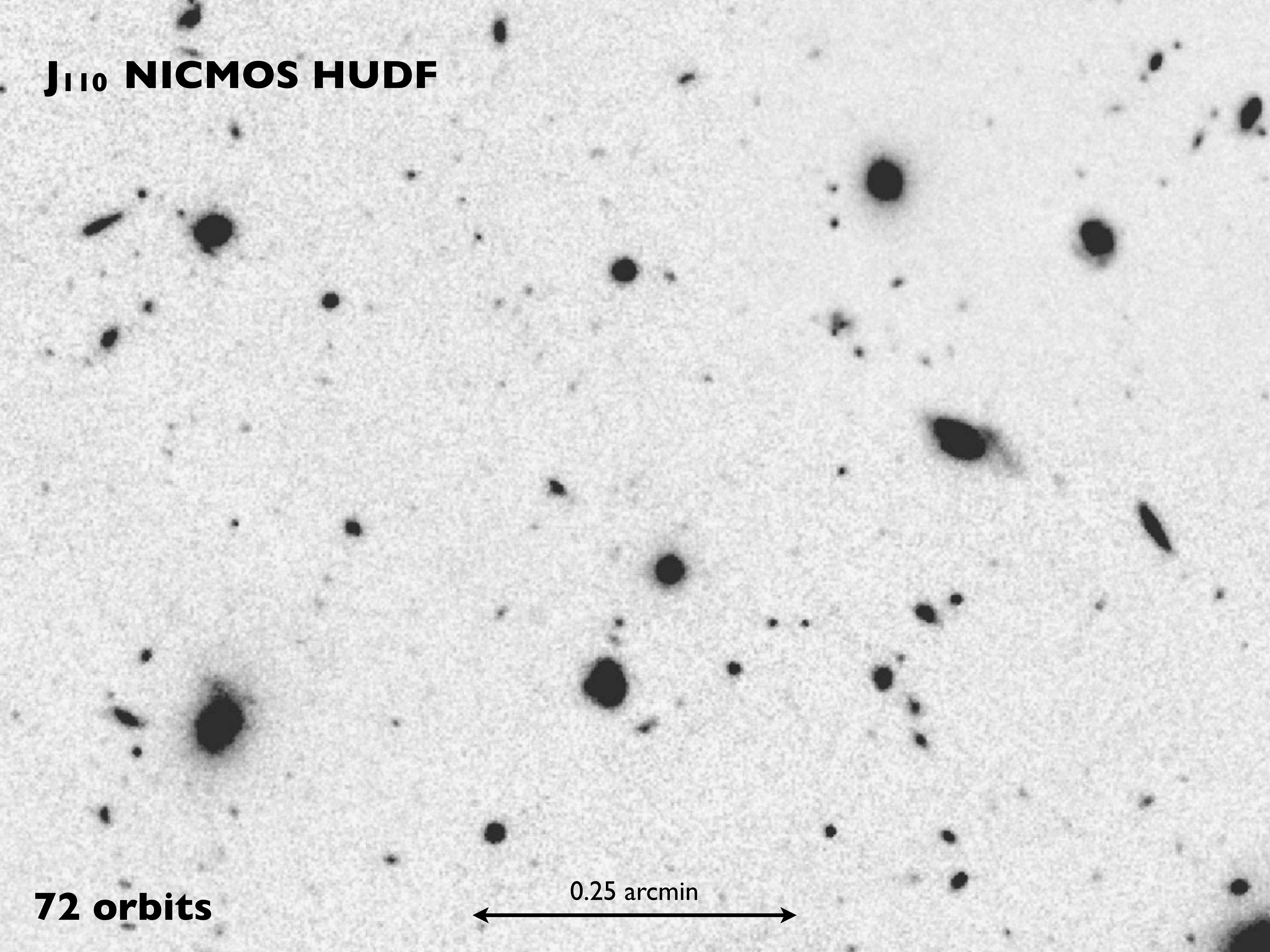
Here: Focus on Reionization by Galaxies and on Hubble's Horizon

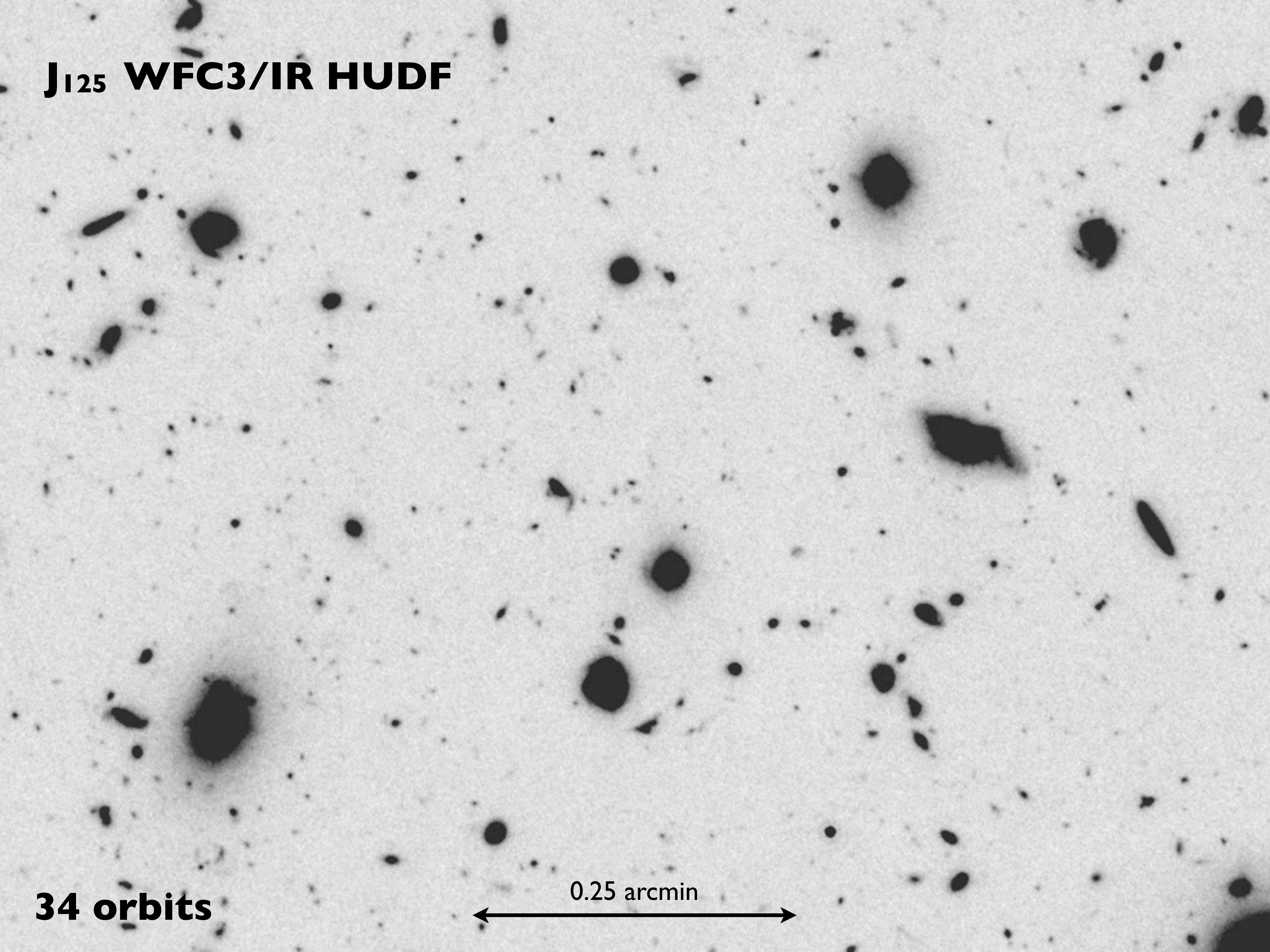
Installation of WFC3 on HST



- 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**

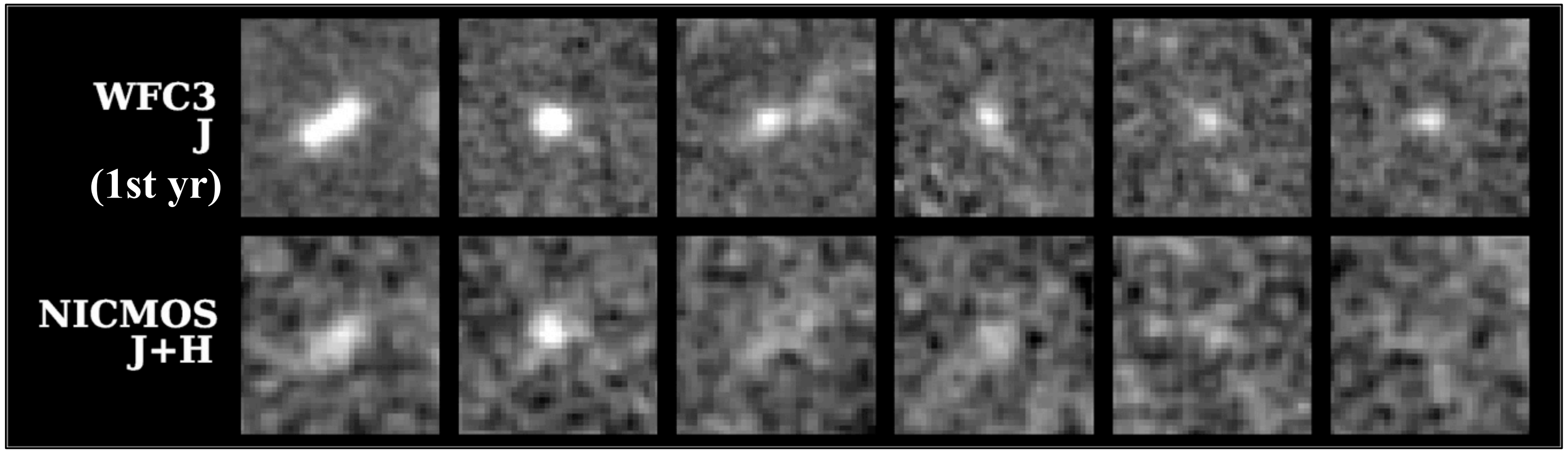

J_{110} NICMOS HUDF
72 orbits
0.25 arcmin


J125 WFC3/IR HUDF
0.25 arcmin
34 orbits

Progress on z>6.5 Samples with WFC3/IR

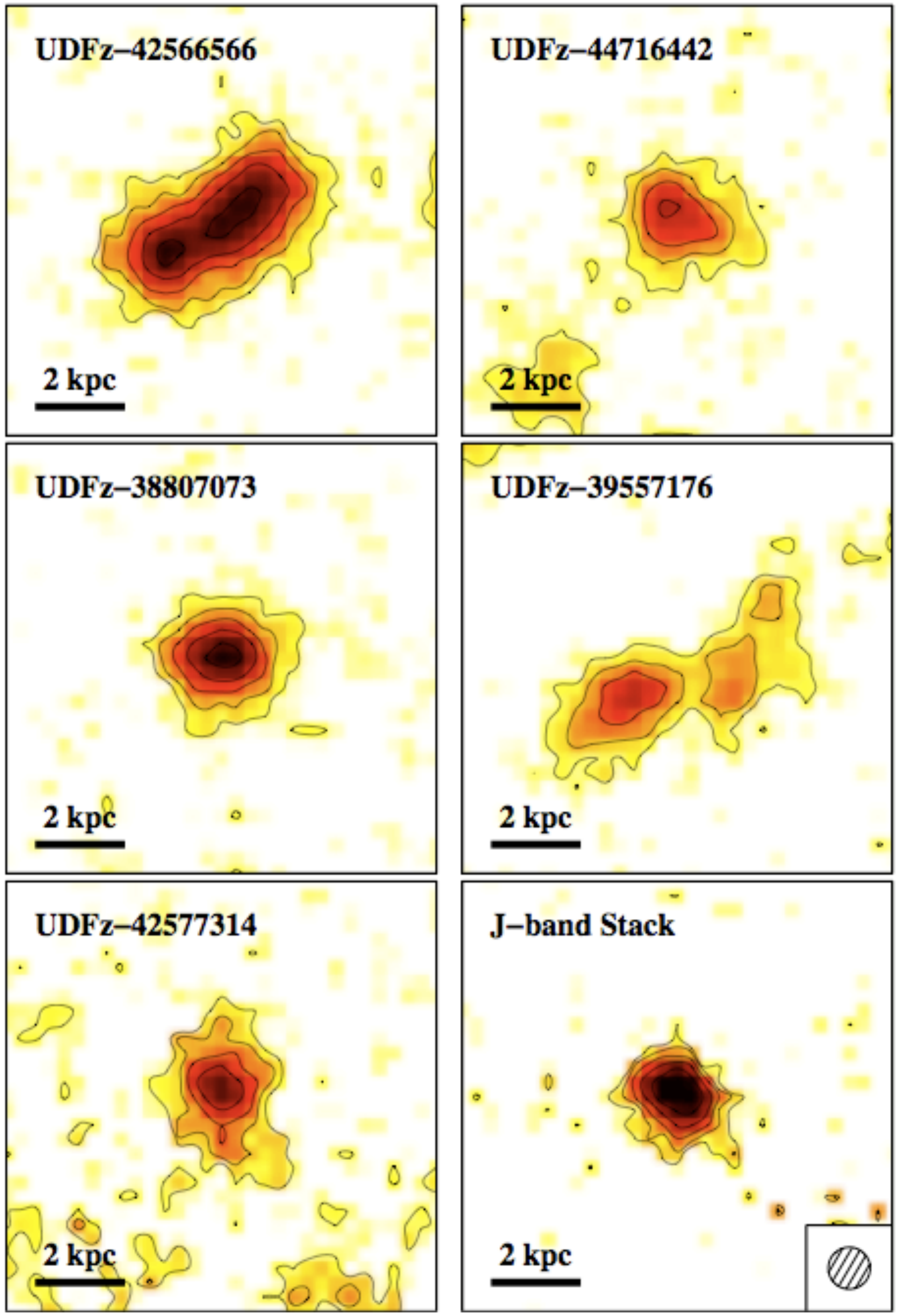
NICMOS: **12** galaxies (10 years of observations)

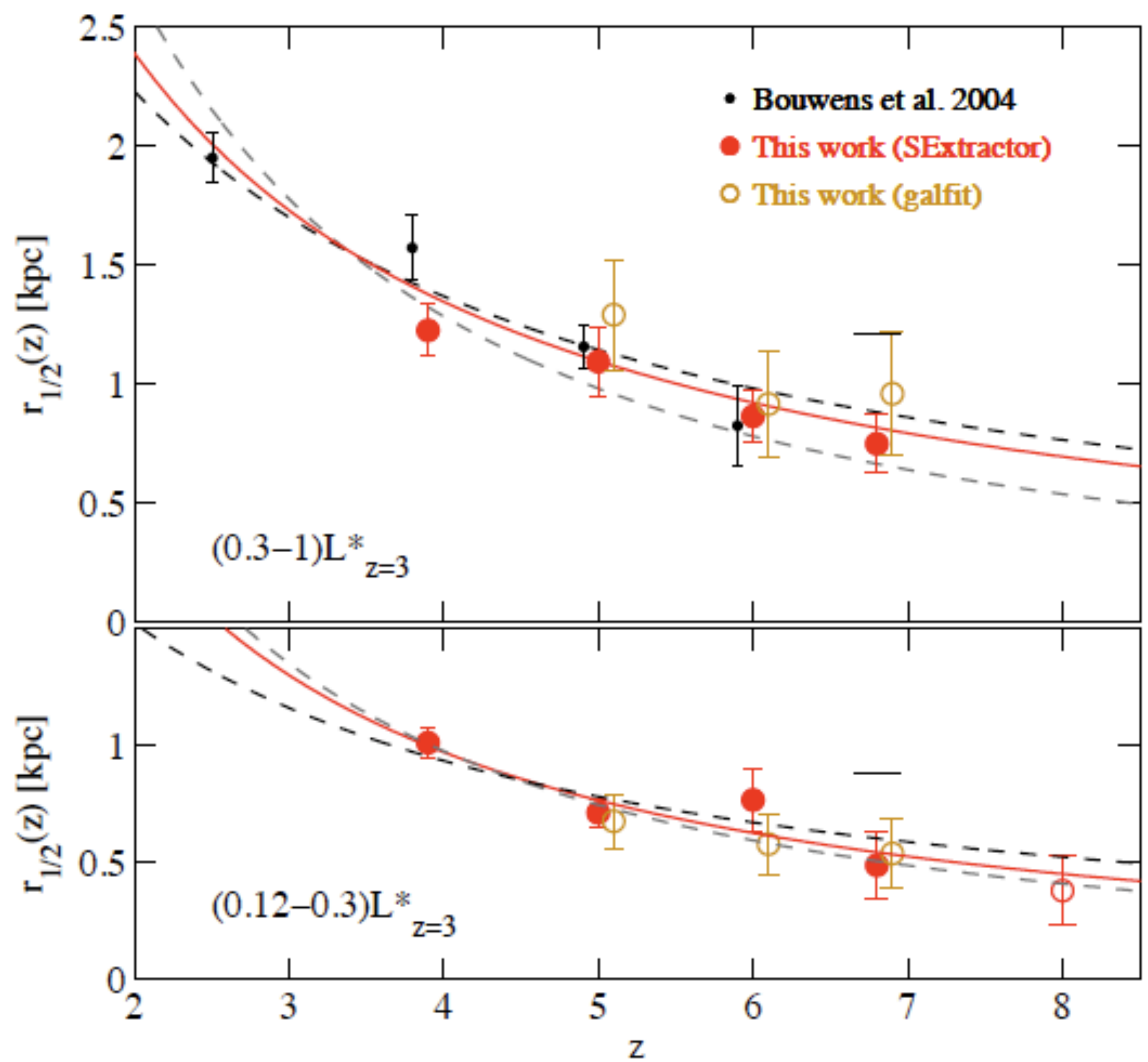
WFC3/IR: **20** galaxies (1st week of observations)



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

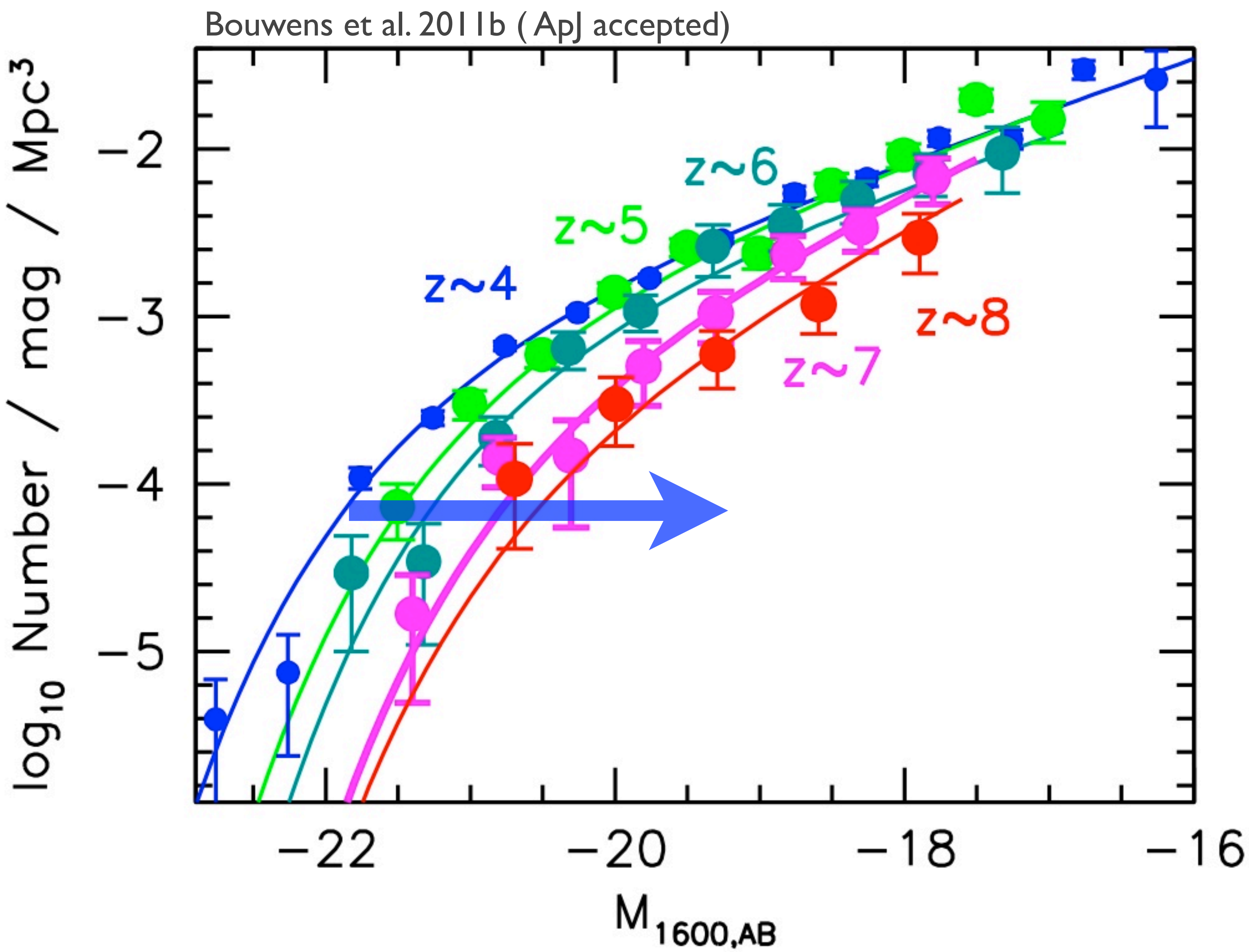
WFC3/IR's Resolution => Structure/Sizes





Oesch et al. 2010b

Evolution of UV LF to z~8



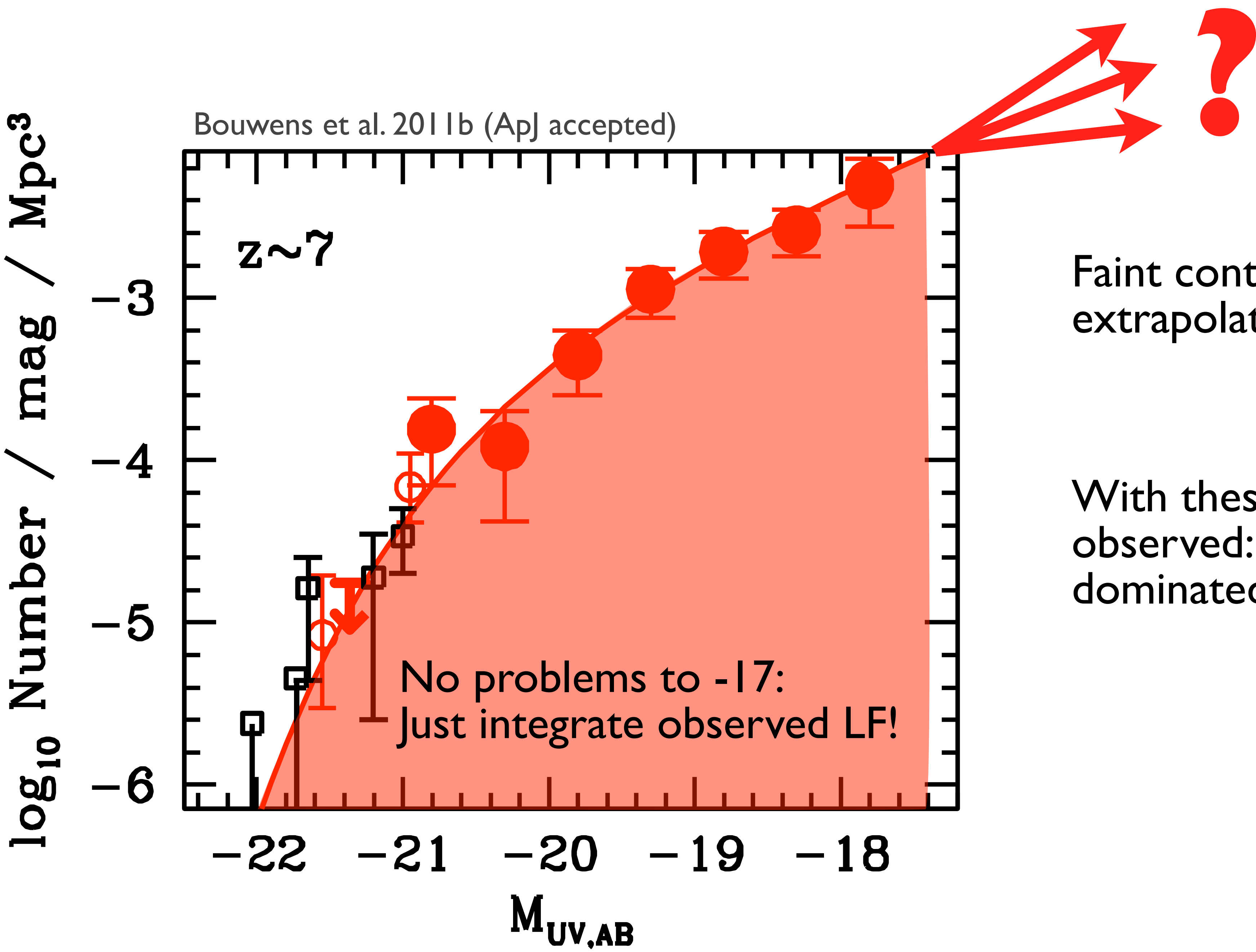
Main Evolution: only in M* (0.33 mag per unit z)

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

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

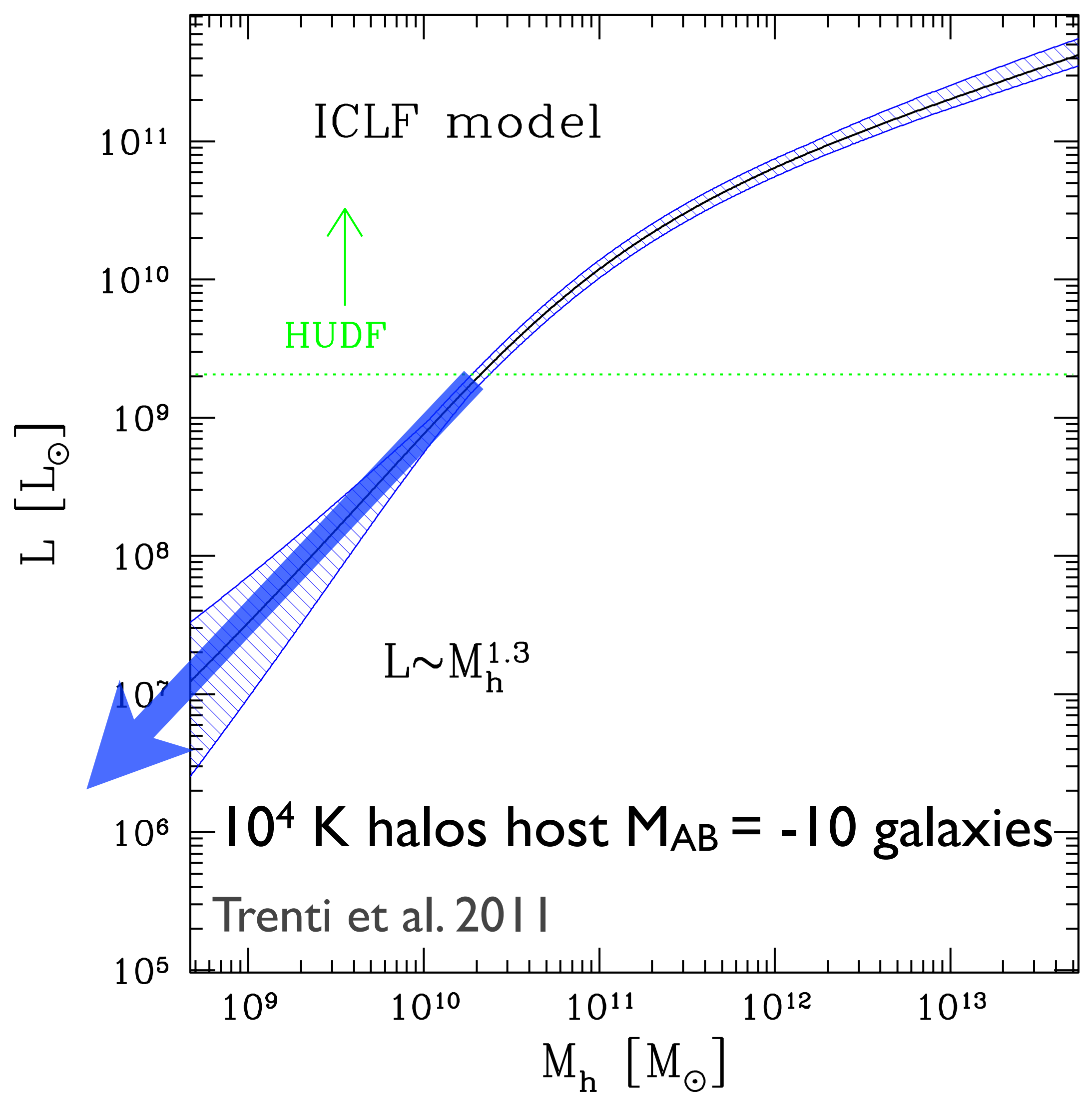


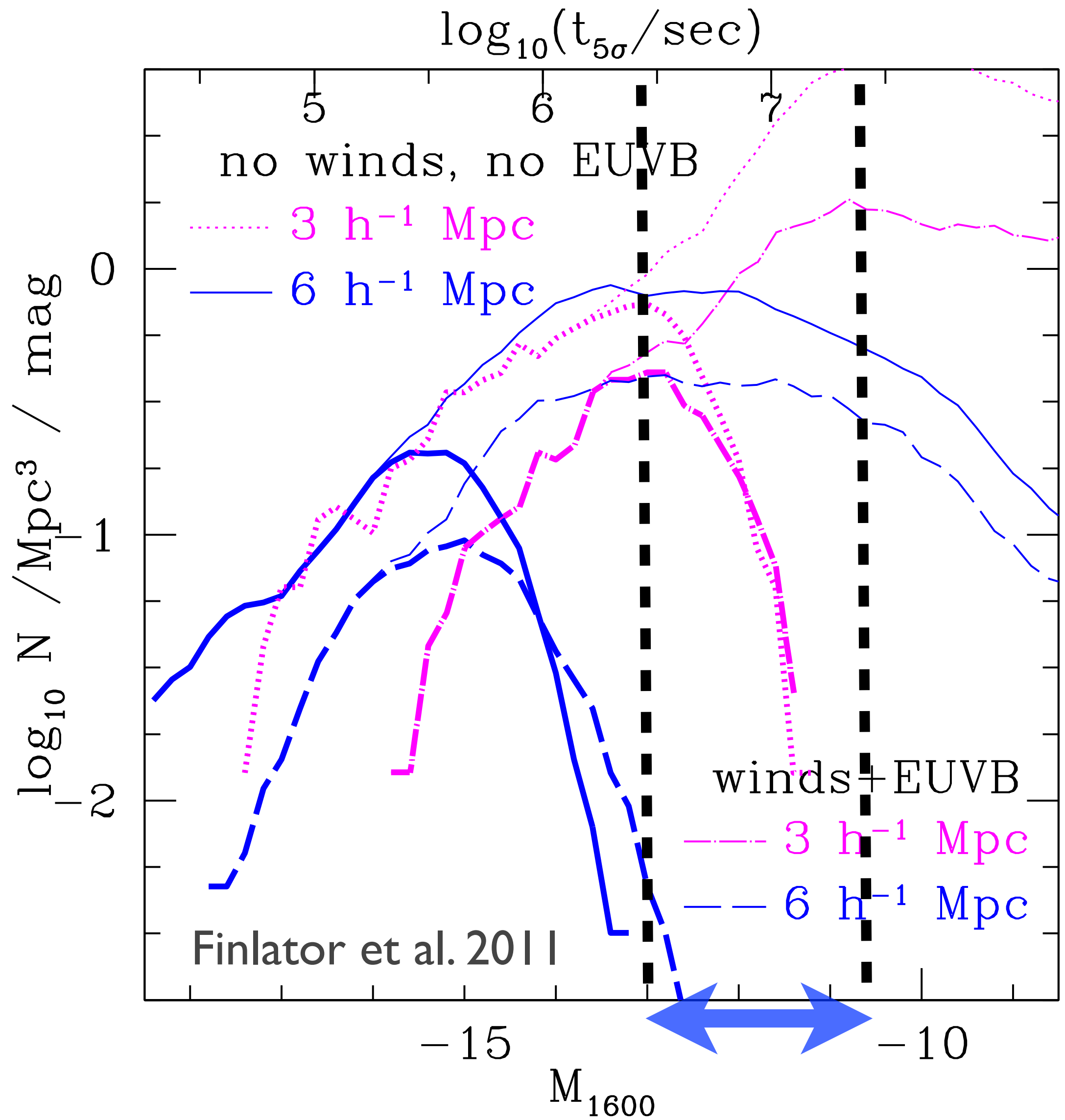
Faint contribution: Have to extrapolate to below detection limits

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

Where is the Faint-End Cutoff?

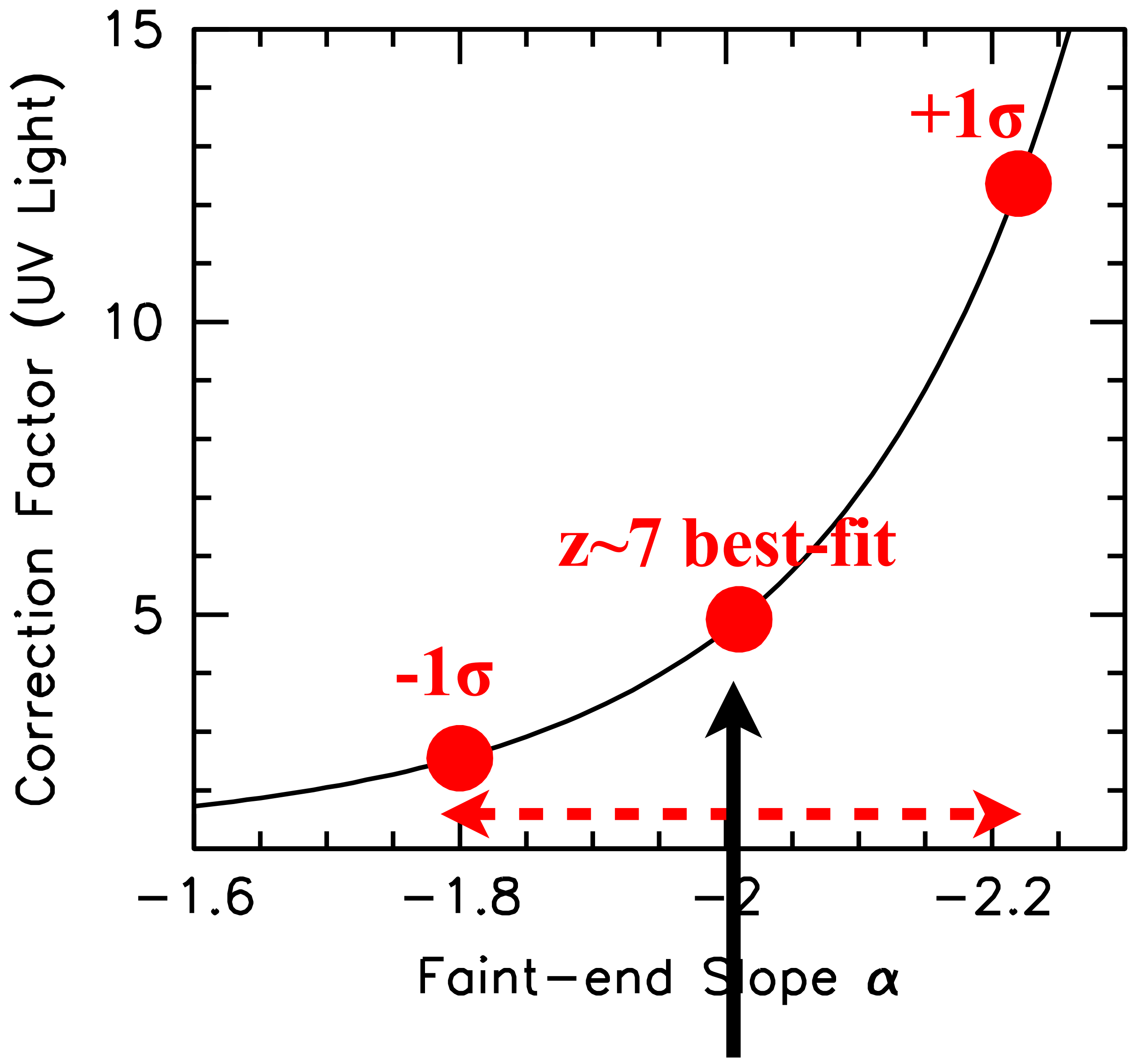
- Halos with T=$10^{4\text{-}5}$ K are affected by UV background
- Halos below T=10^4 K can only cool in H_2





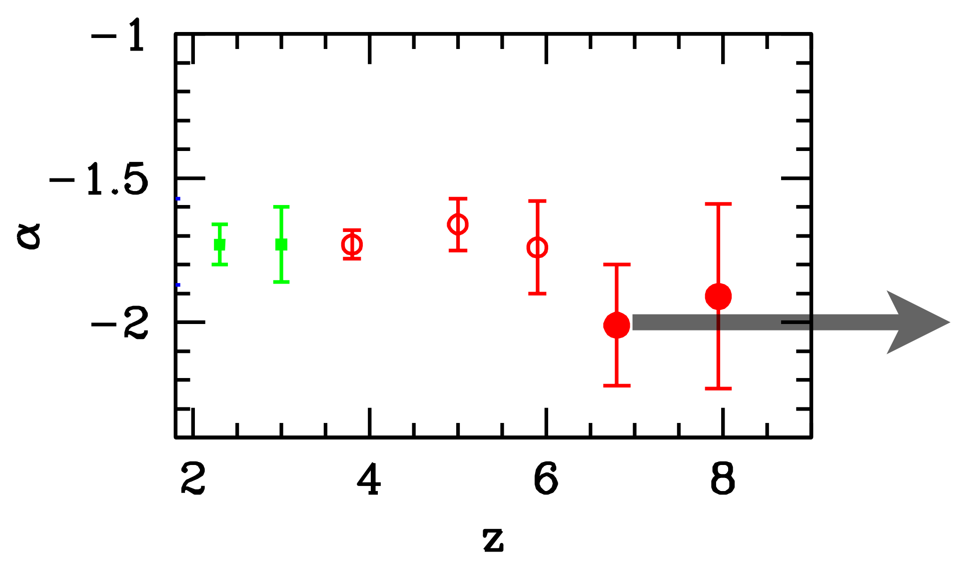
lower luminosity cut-off in the range: M_{AB} = -10 to -13
(but see also M. Kuhlen's talk!)

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
- Future effort: constrain this better!

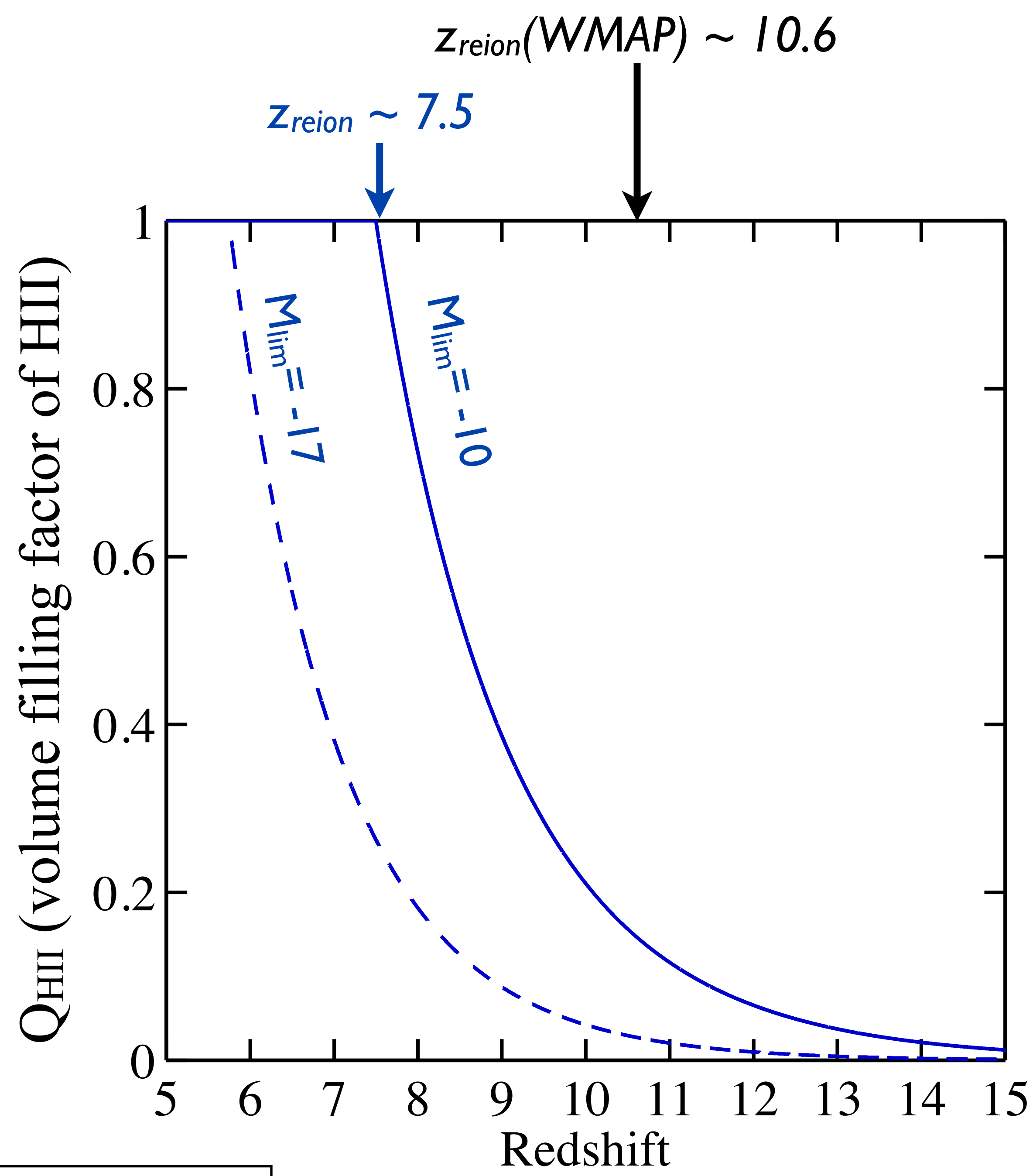


Inferred Reionization History

- 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**

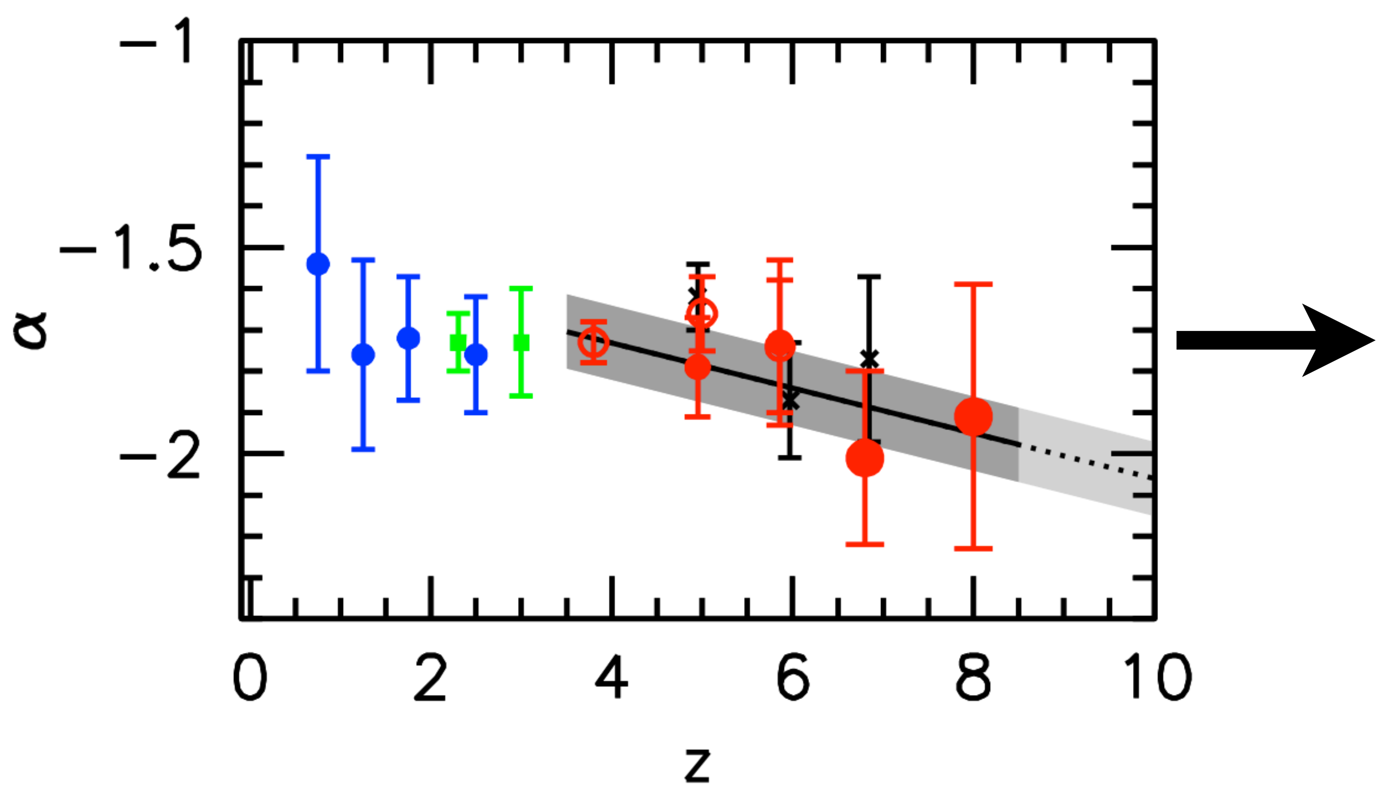
WMAP measurement: τ_e **= 0.088 ± 0.015**



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

Steepening in Faint-End Slope with Redshift?

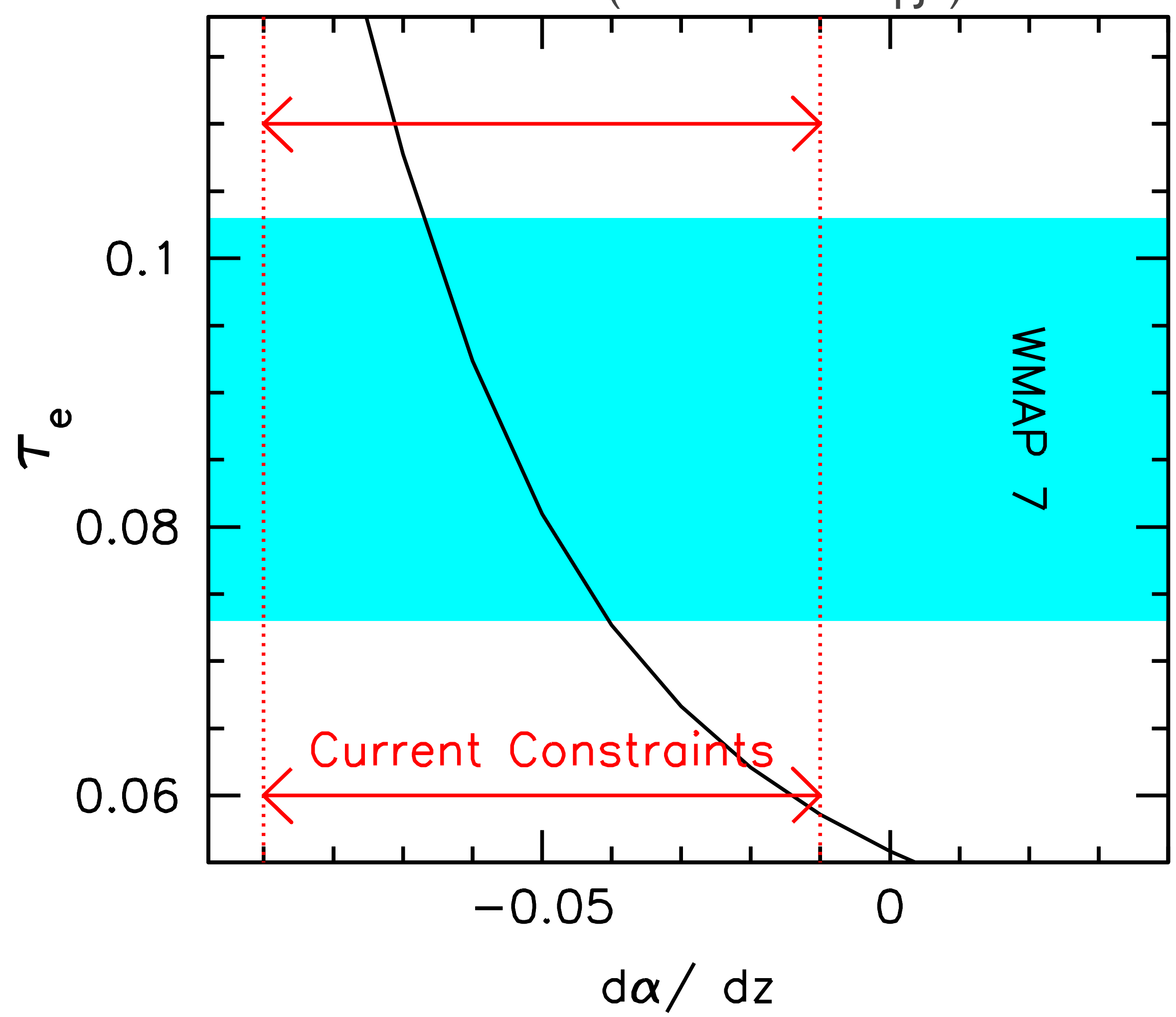
A possible way to get more photons



Tentative evidence for steeper faint-end slopes at higher z

(also seen in many simulations/theoretical models)

Bouwens et al. 2011c (submitted to ApJL)



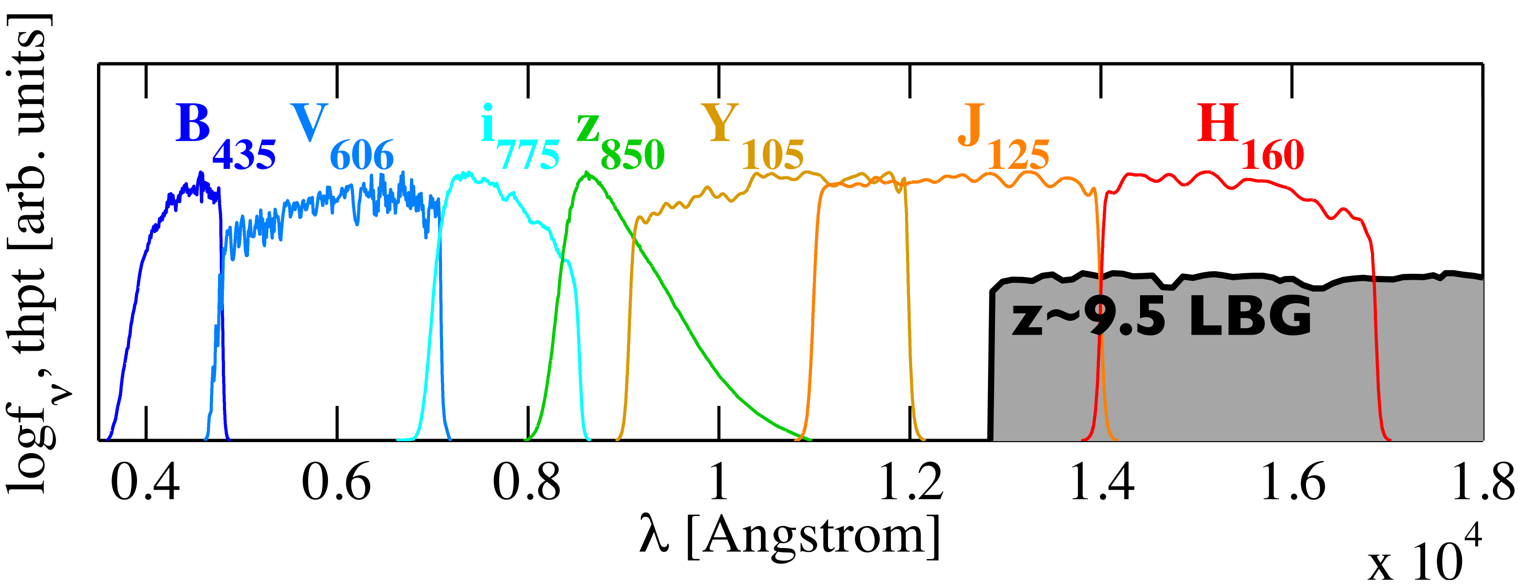
Required optical depths can be achieved since τ_e very sensitive to changes in faint end slope

- Thus: faint galaxies are consistent with being capable of driving reionization.
- **However:** Need to better constrain evolution of faint end slope with redshift!

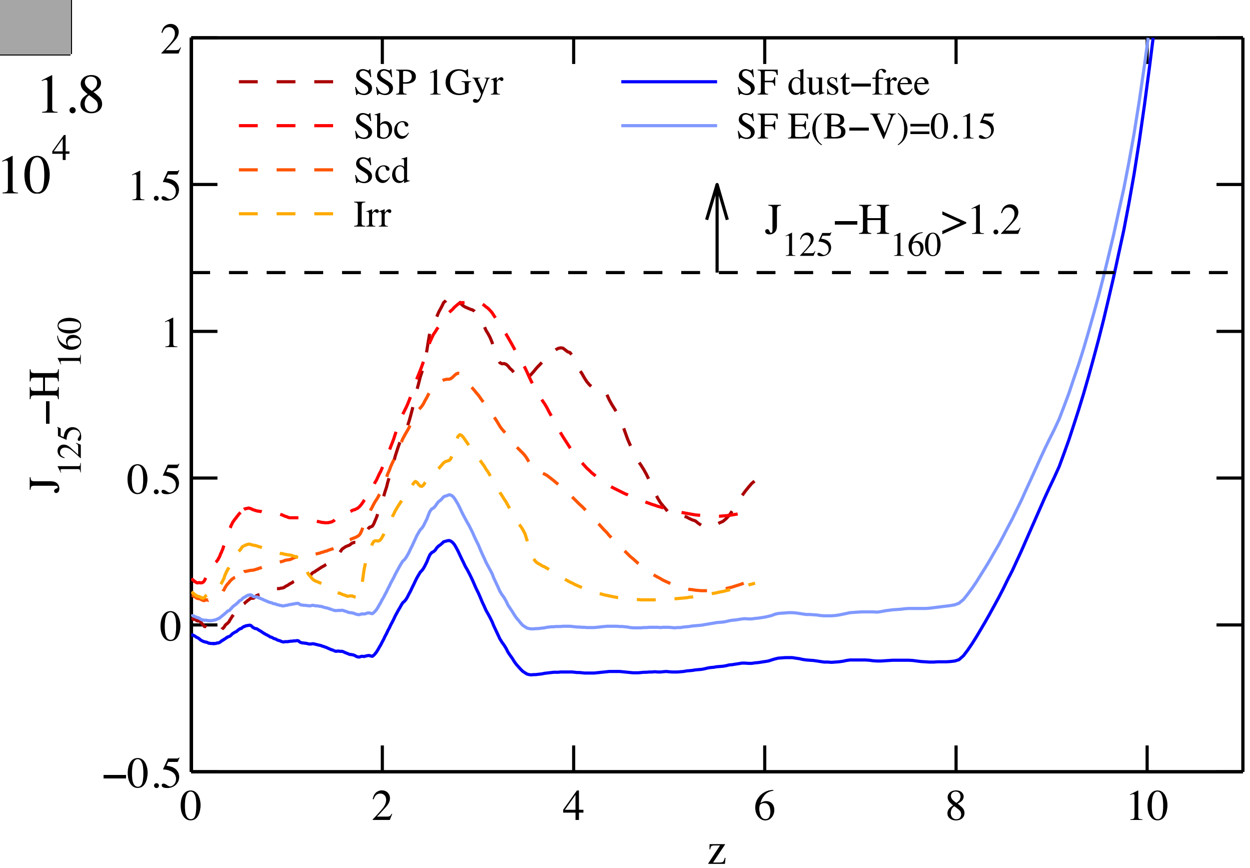
The Horizon of the Hubble Space Telescope: Constraints on the z~10 Galaxy Population

Pushing the Frontier to z~10

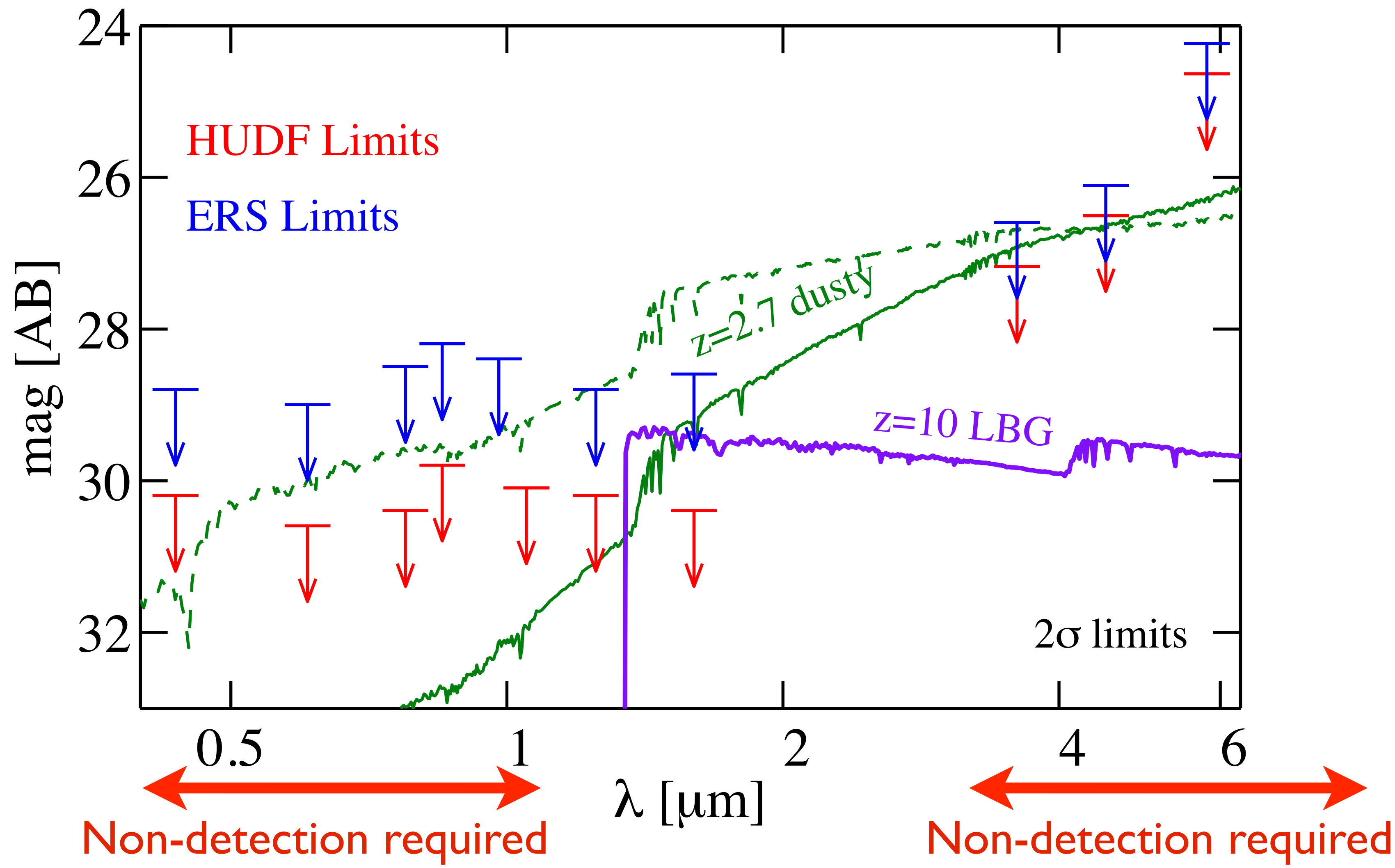
- At z~8: neutral IGM starts affecting J_{125}
- Can select z>9.5 galaxies as J-dropouts based on red J_{125}-H_{160} colors



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

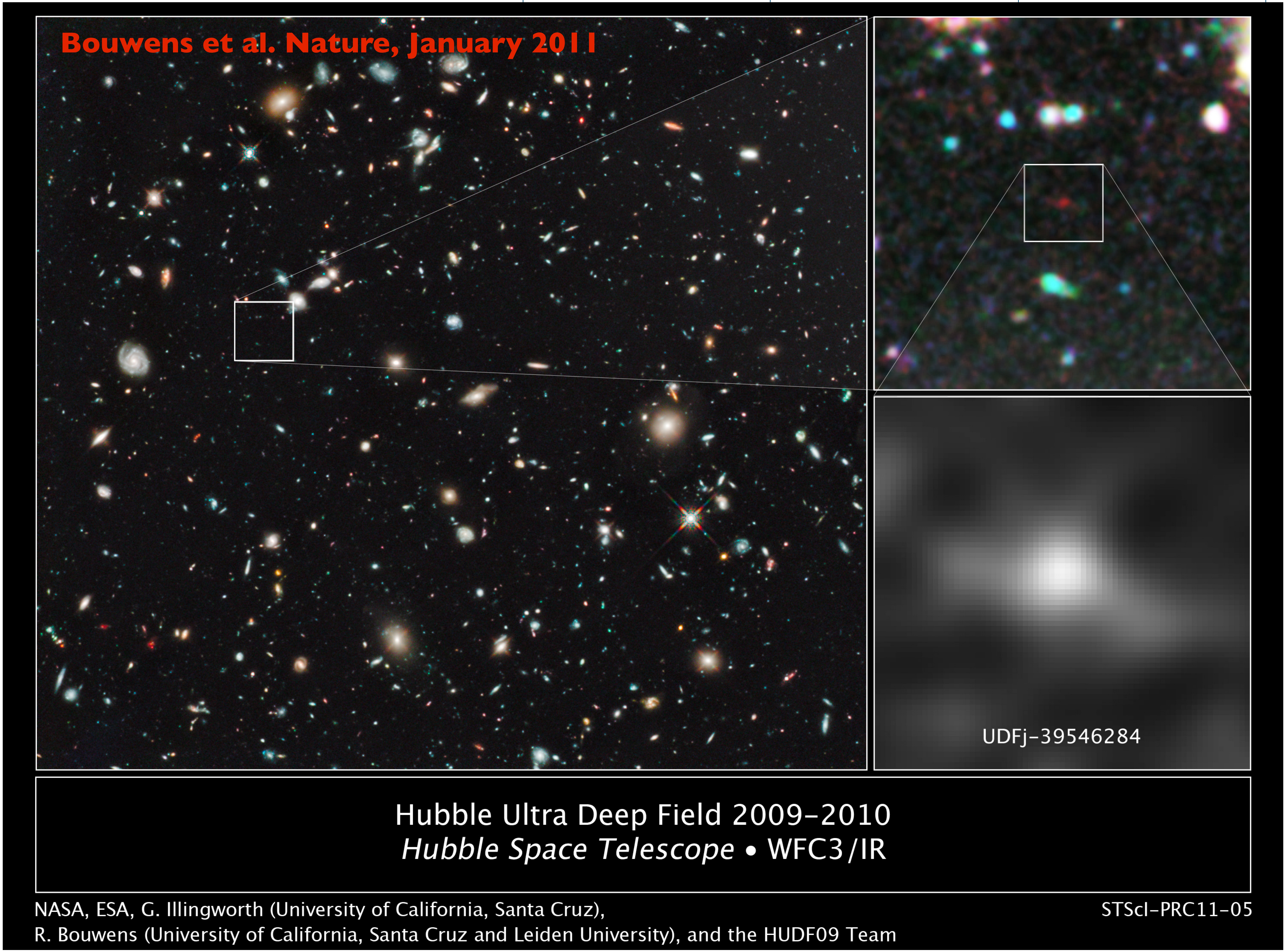


Requirements on Data

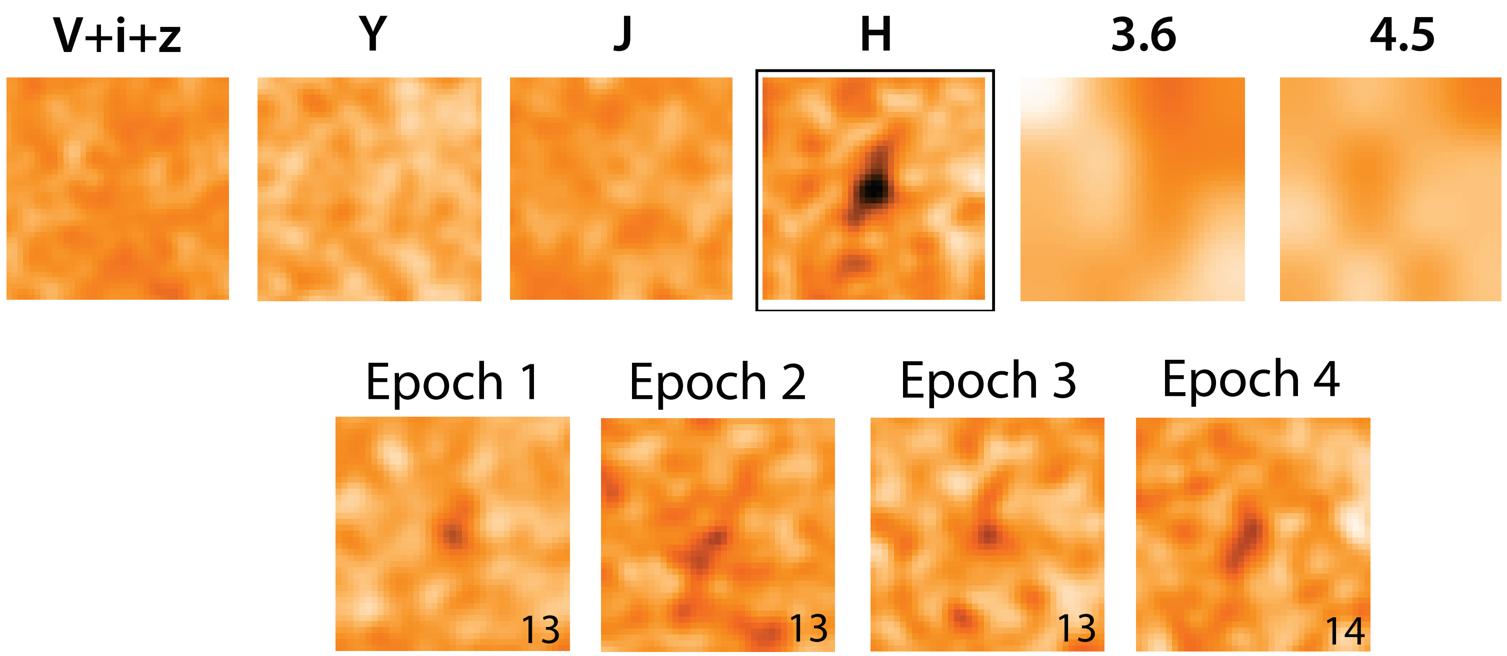


deep J_{125} and H_{160}

deeper data shortward of Lyα break

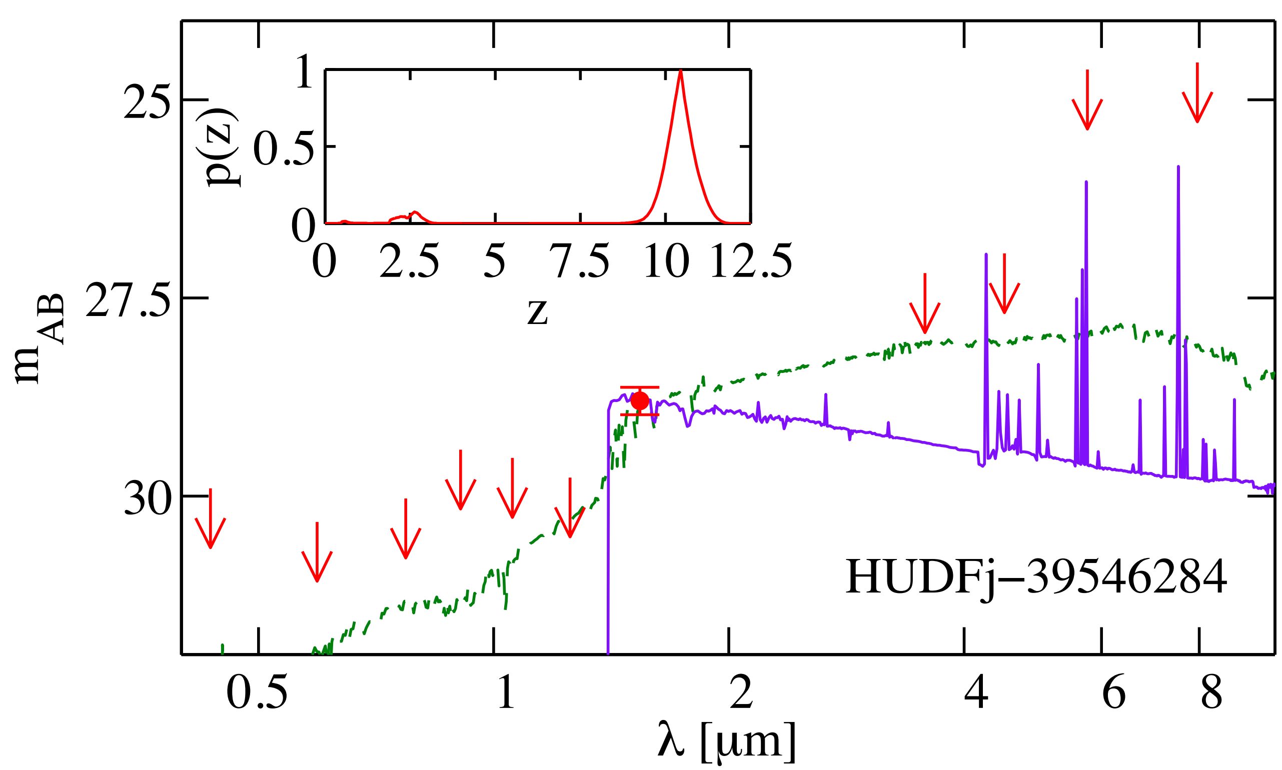

Bouwens et al. Nature, January 2011
UDFj-39546284
Hubble Ultra Deep Field 2009-2010
Hubble Space Telescope • WFC3/IR
NASA, ESA, G. Illingworth (University of California, Santa Cruz),
R. Bouwens (University of California, Santa Cruz and Leiden University), and the HUDF09 Team
STScI-PRC11-05

The z~10 Candidate in the HUDF

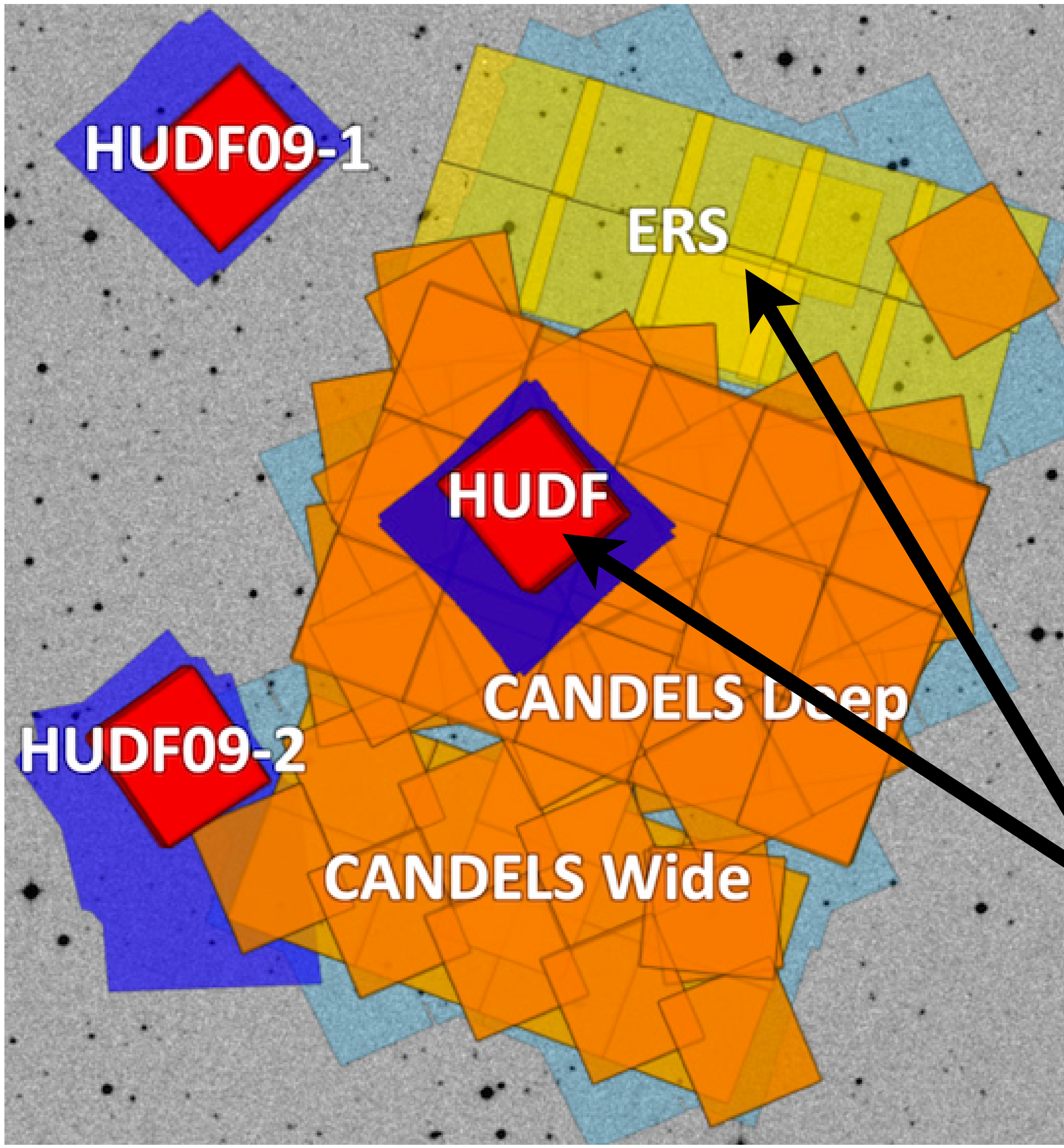


- Very faint: H_{AB}=28.8±0.2
- Small chance of being spurious:
  - It is detected at ~6σ
  - It is visible at >2.5σ in 4 independent splits of the data
- Blue UV continuum: not detected in very deep IRAC data

- 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



Extended z~10 Search

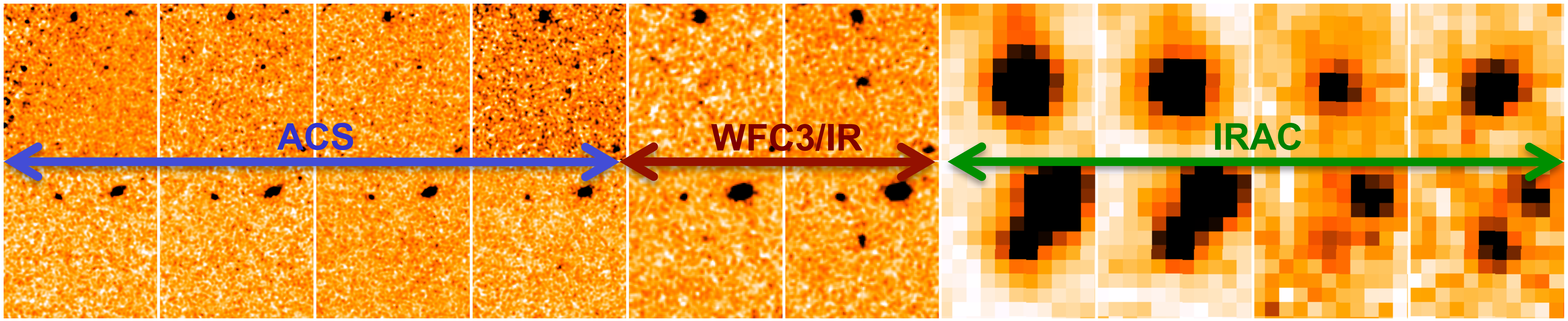


- CDFS offers perfect data for z~10 search
- Large amount of public optical (ACS) and NIR (WFC3) data
  - HUDF09
  - ERS
  - CANDELS (Deep & Wide)
- Total of 160 arcmin^2
- Reach to 26.9 - 29.4 AB mag

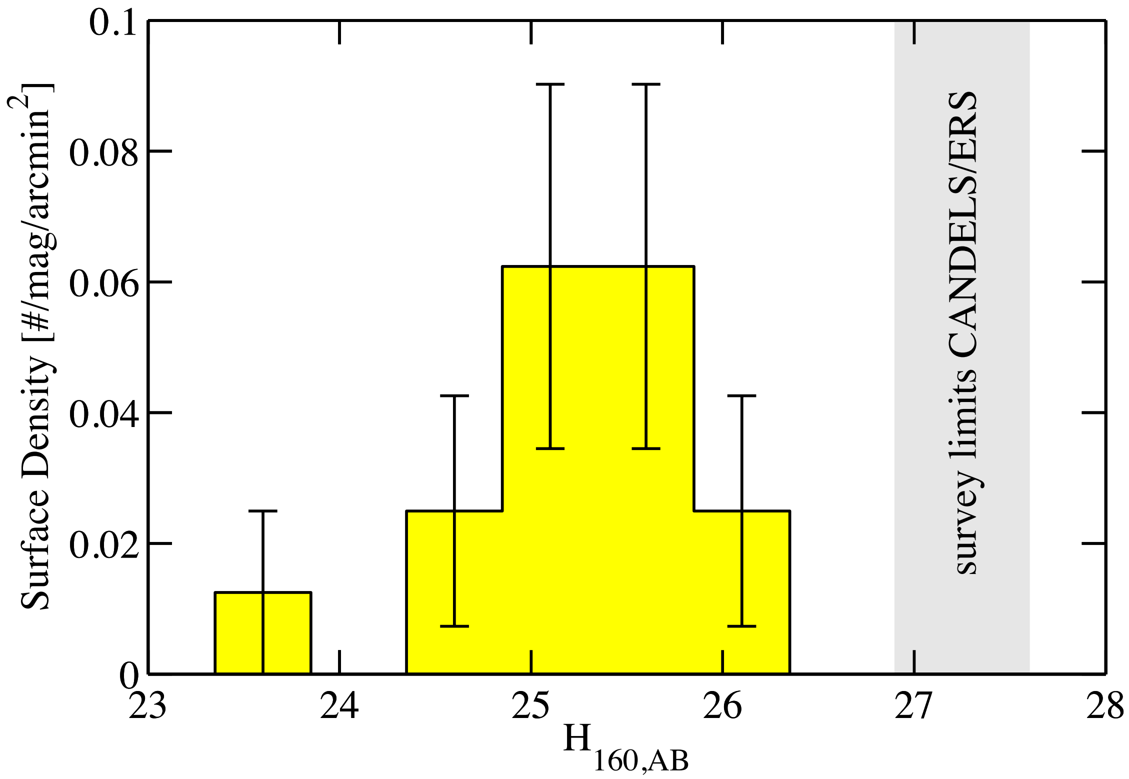
Our first analysis included only these two fields: Bouwens et al., Nature, 2011

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

Low-Redshift Contaminants



- 16 sources are found satisfying our HST selection criteria
- 15 out of these are dusty/evolved sources at intermediate redshift (z~2-4)
- These are identified by strong Spitzer IRAC detections (H_{160}-[3.6]>2)



Therefore: only our previous z~10 candidate from the HUDF found in full data

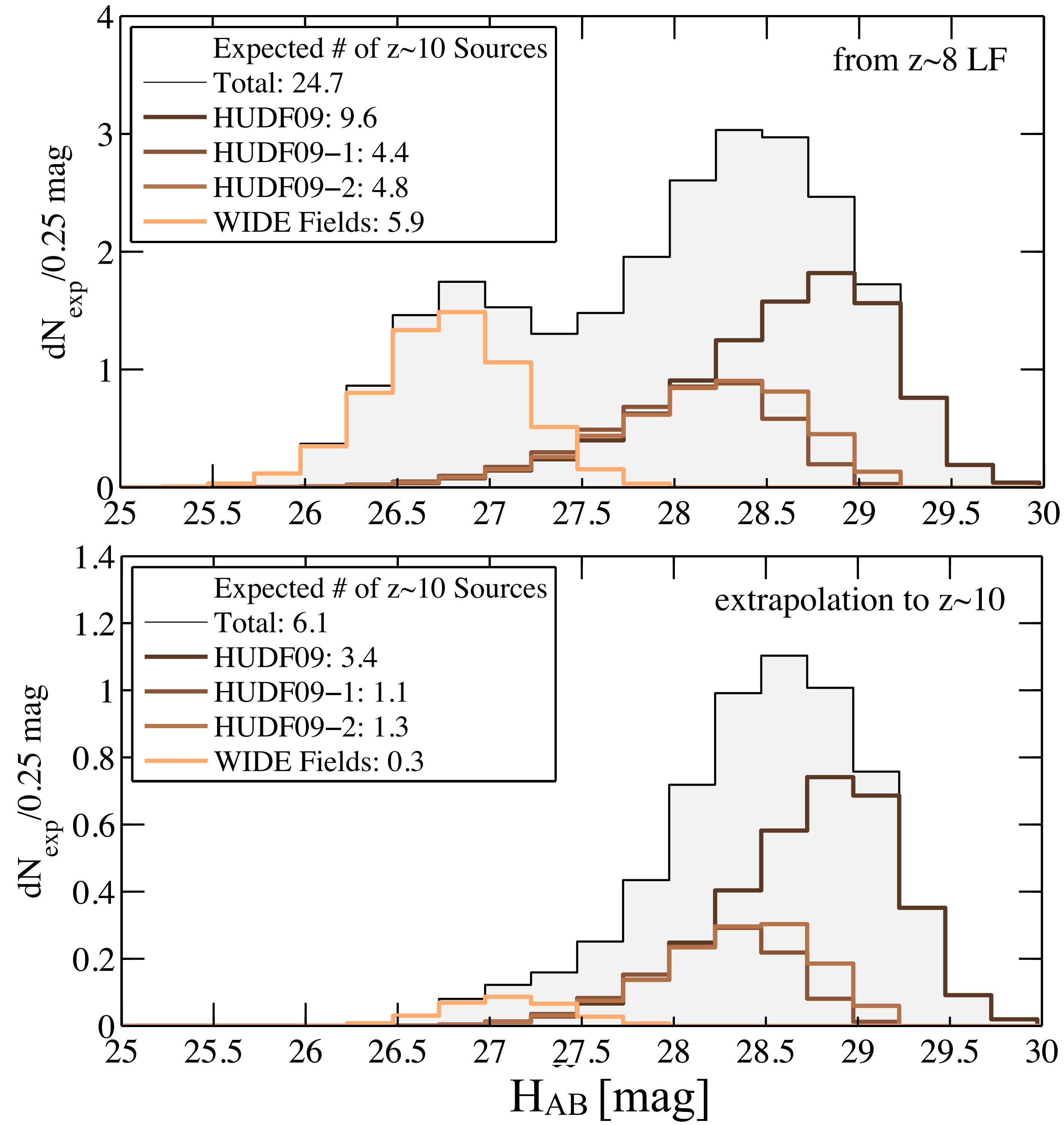
Such red intermediate redshift sources appear to have a peaked LF

However: Beware of z~10 selections without Spitzer coverage

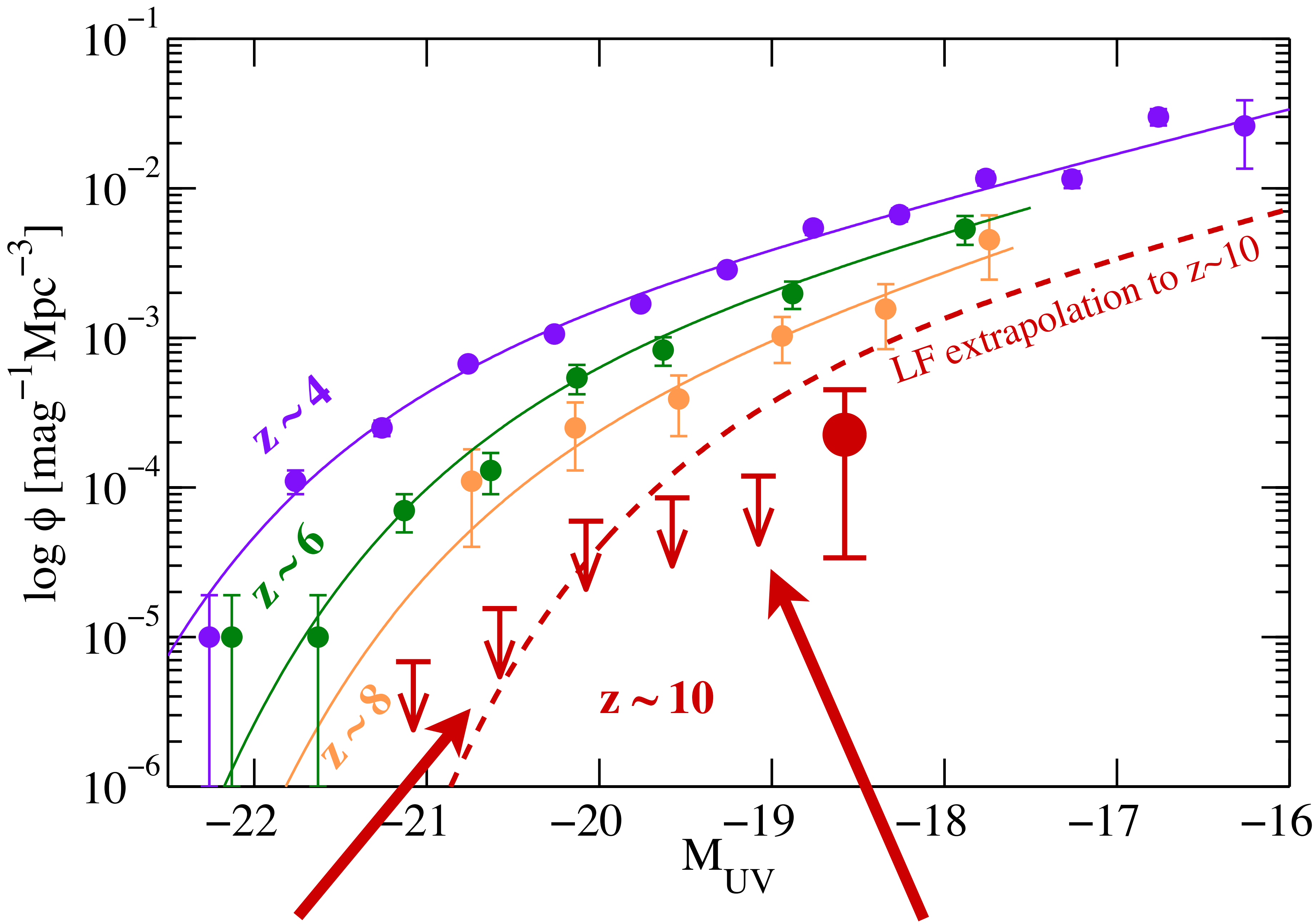
Constraints on z~10 LF

- Assume no evolution in galaxy population from z~8 to z~10:
  expect **25** z~10 sources
- Extrapolate low-z LF trends (c.f. Garth's talk) 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



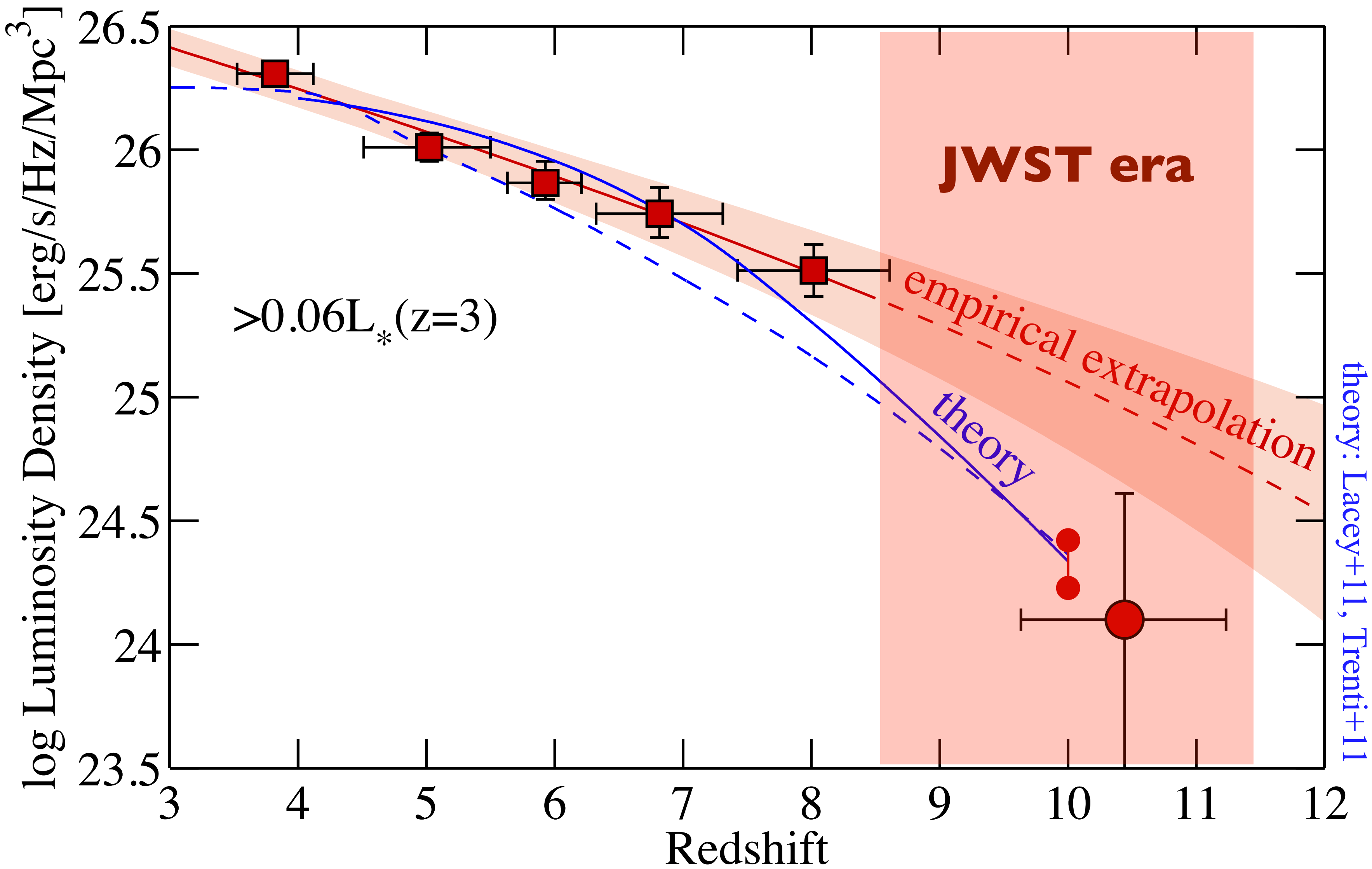
Constraints on z~10 LF (II)



Three Wide Fields:
limits are below z~8

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

But: result is still uncertain (due to only 1 detection)
needs confirmation with future deeper data (JWST!)

Summary

- The total flux density in ionizing photons is very sensitive to the faint-end slope. Given current uncertainties in the slope, deeper observations are absolutely necessary.
- The faint-end slopes measured at $z \geq 6$ are very steep and show weak trends to steepen towards high redshift. Therefore, galaxies below the current detection limits are consistent with being capable of reionizing the universe.
- Only 1 viable $z\sim10$ candidate identified so far in current WFC3/IR data over CDFS. The upper limits on the $z\sim10$ UV LF are significantly below extrapolation of observed trends
- Indicates accelerated evolution of UV LF at $M<-18$ at $z>8$, at 2σ significance, including cosmic variance. The 170 Myr from $z\sim10$ to $z\sim8$ appears to be a time of rapid change in the galaxy population.
- Need JWST to further constrain accelerated evolution. $z>8$ is JWST territory.