Our Current View of Galaxy Build-up at Cosmic Dawn

6th Subaru Conference Hiroshima

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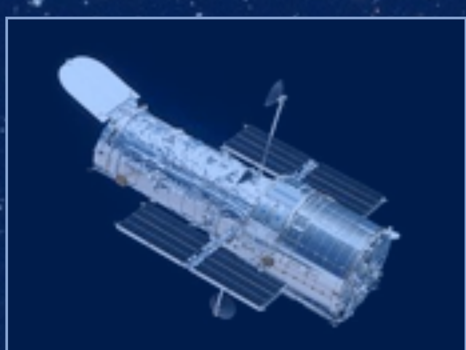
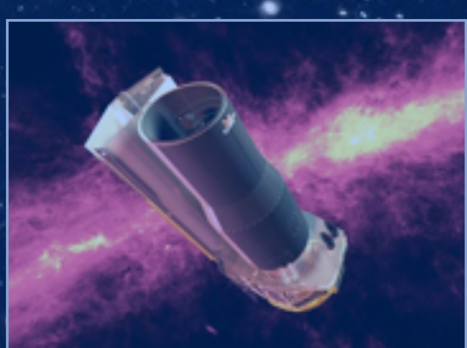
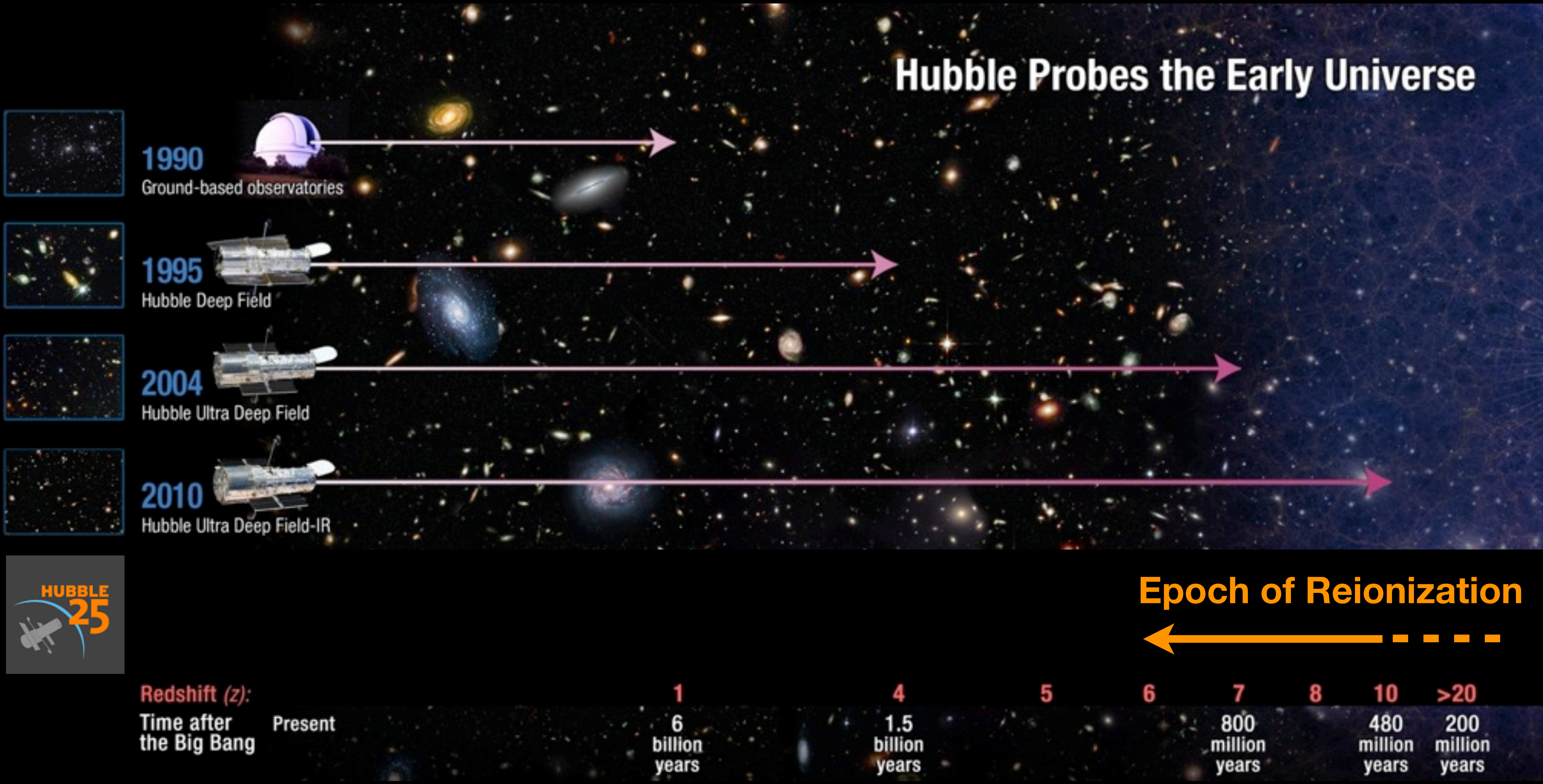




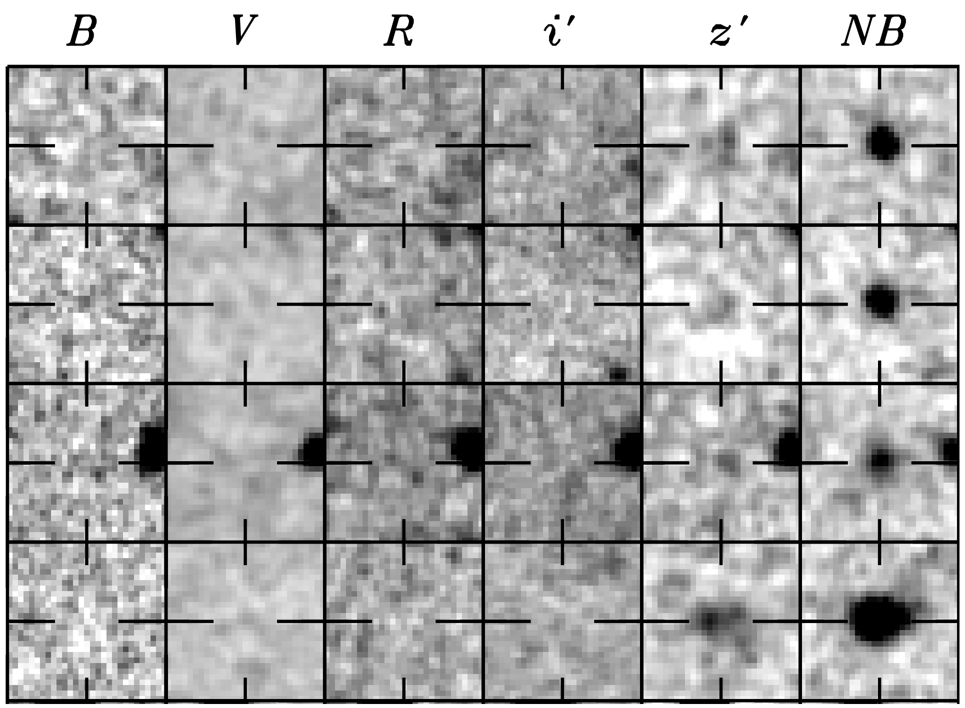
The history of astronomy is a history of receding horizons.
E. P. Hubble



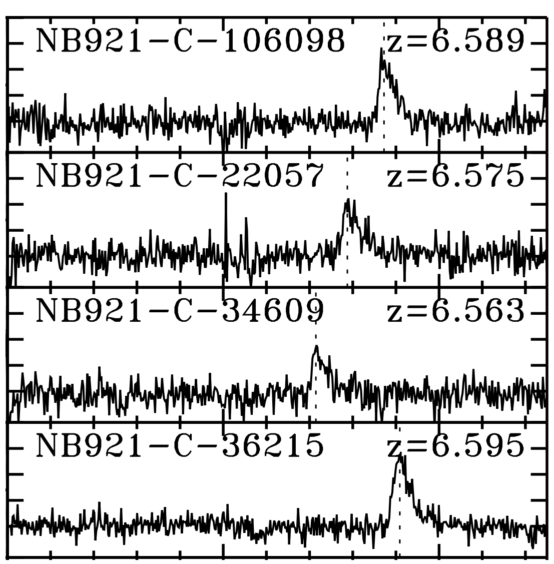
Epoch of Reionization

Identifying Galaxies at High Redshifts

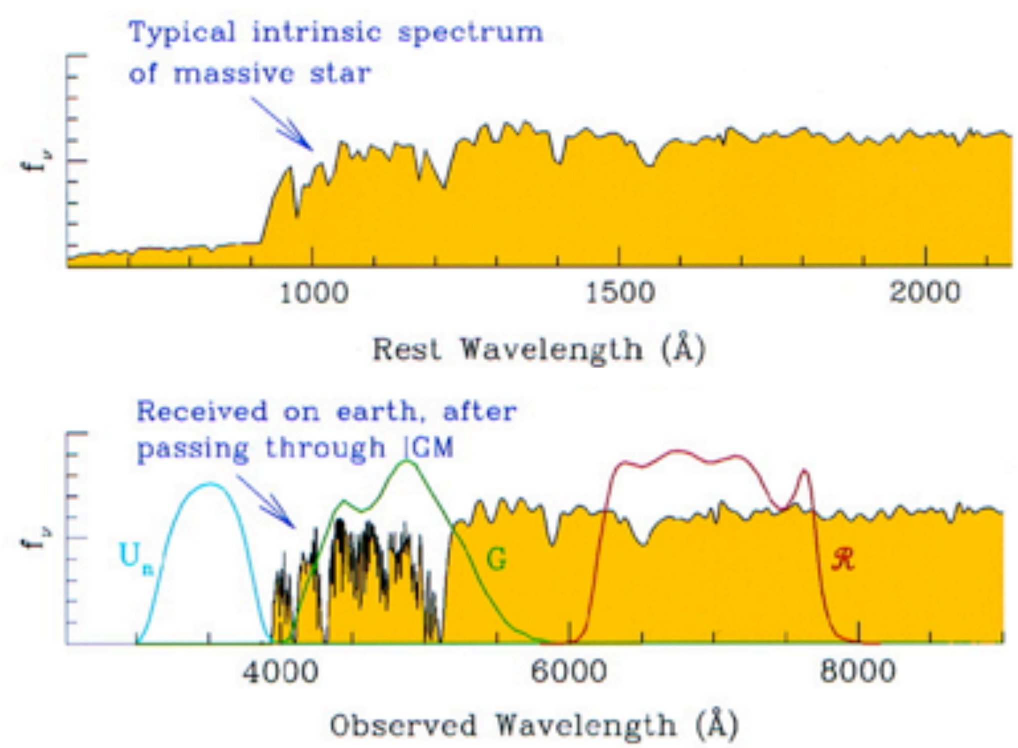
Lyα Emitters

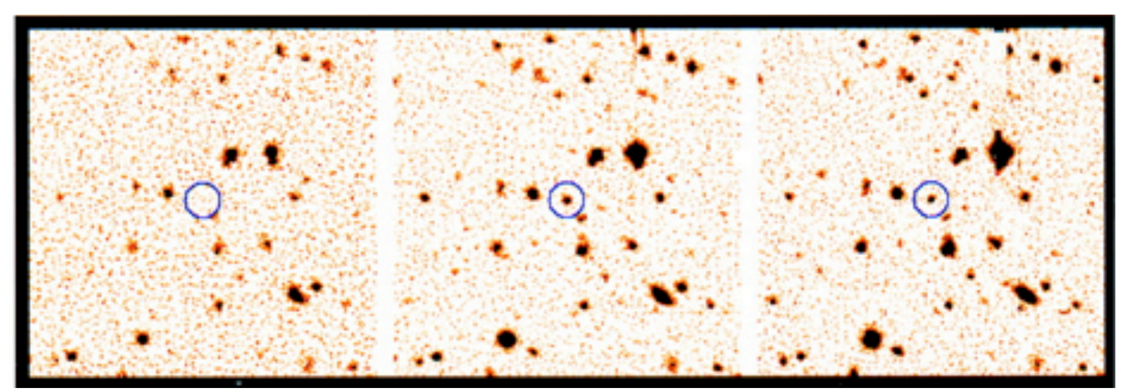


Ouchi+12



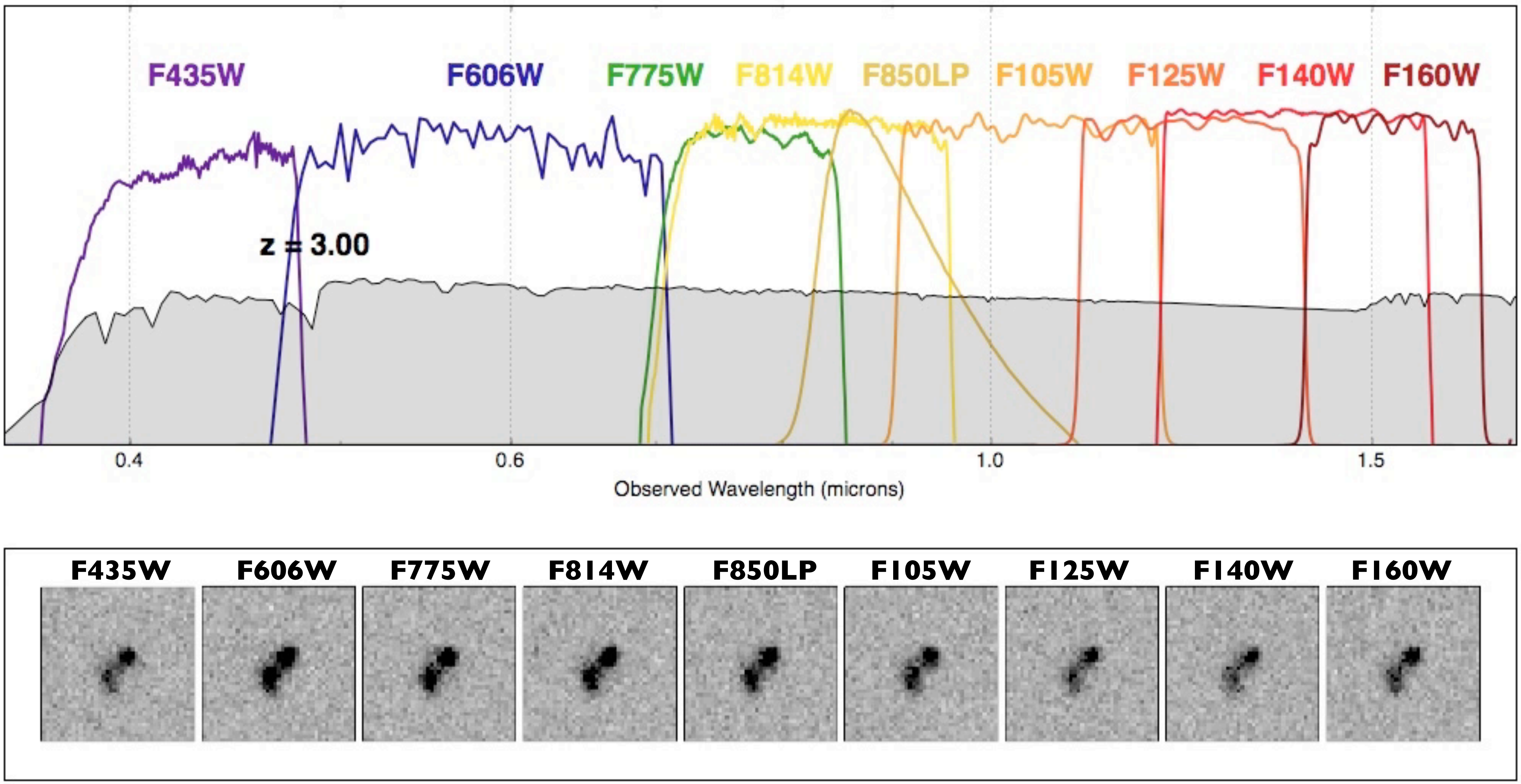
Lyman Break Galaxies





Steidel+99

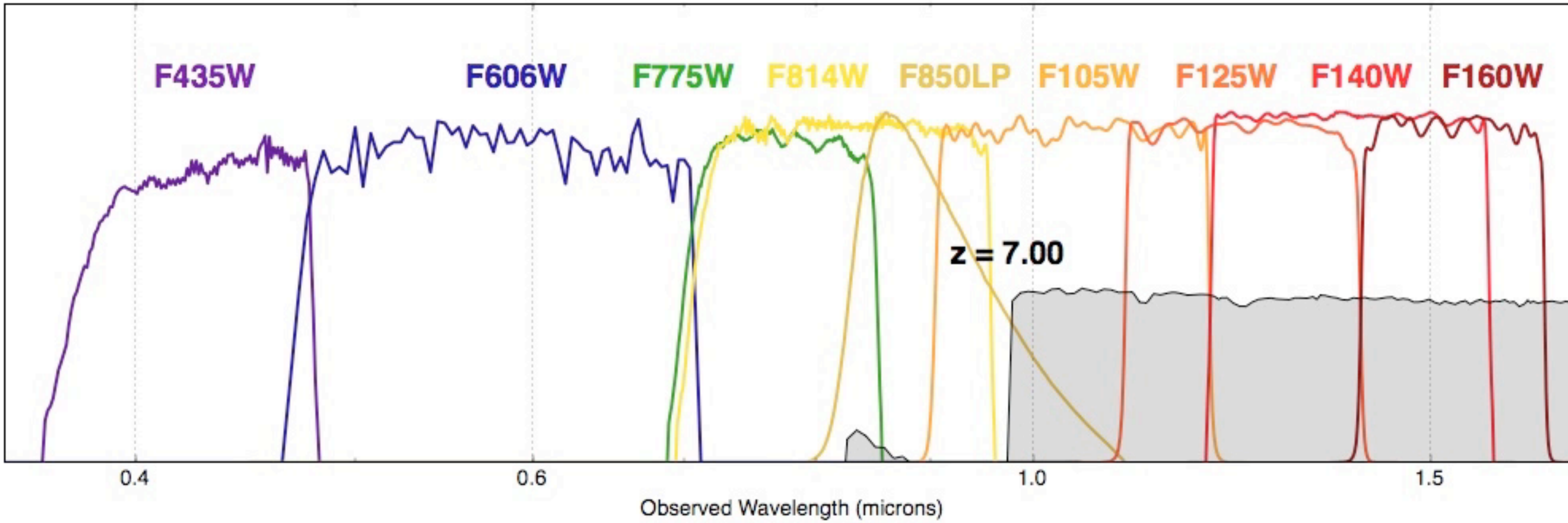
LBGs with HST: efficient detection out to z~10-12

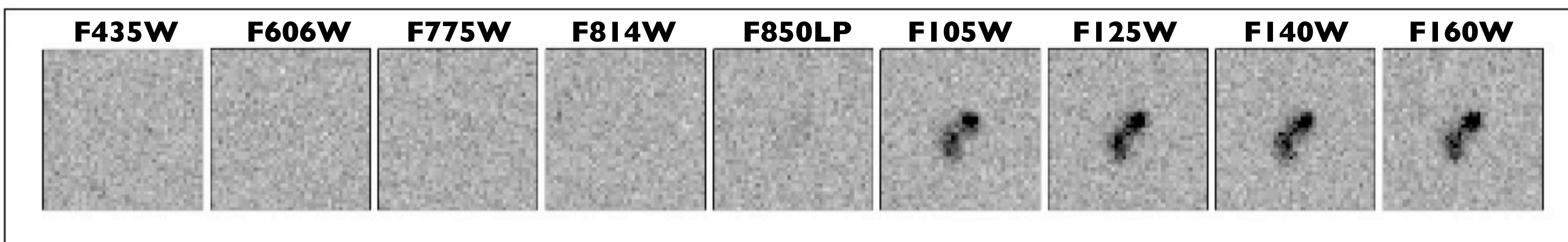


optical ACS

near-IR WFC3/IR

LBGs with HST: efficient detection out to z~10-12

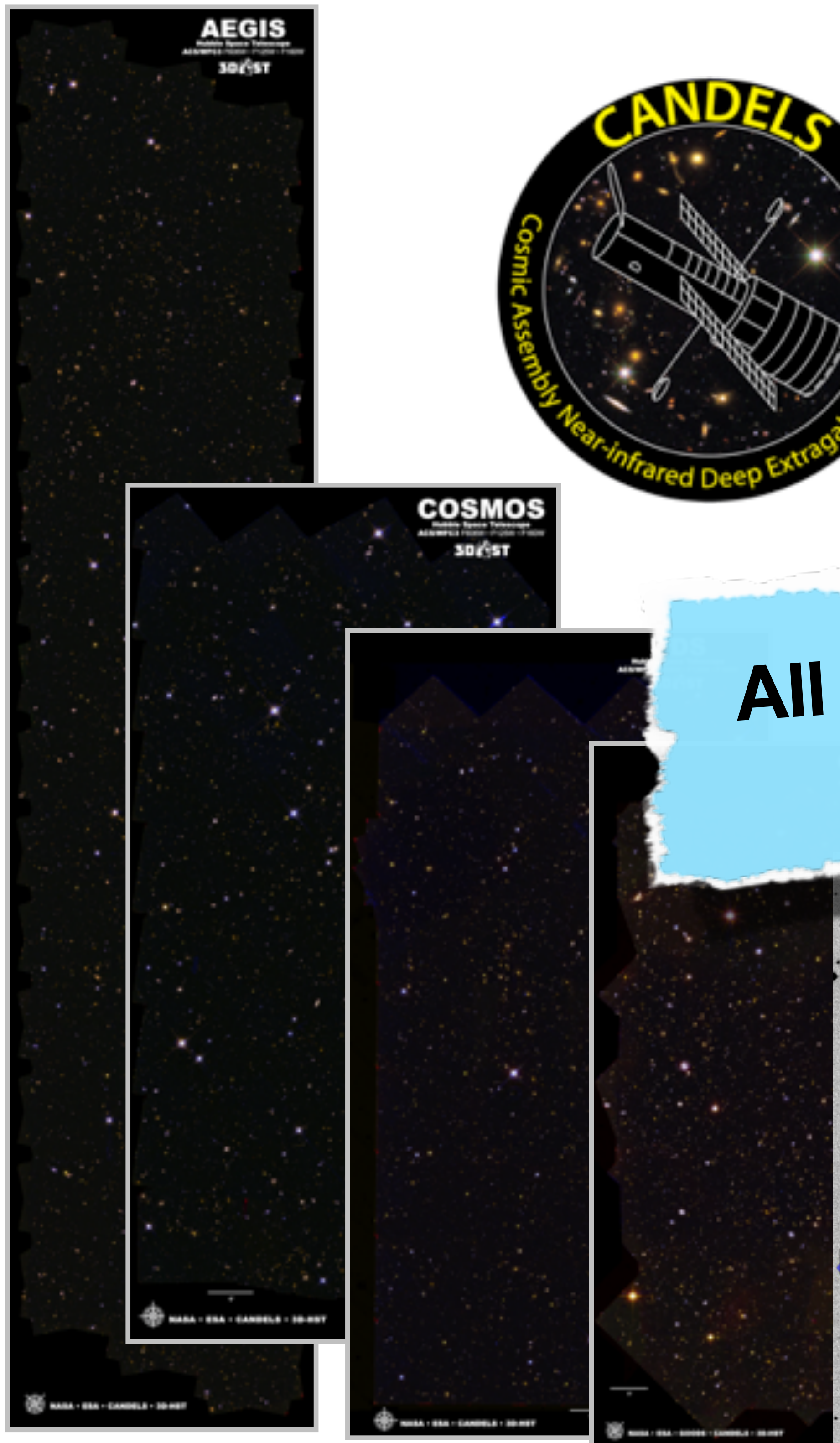




optical ACS

near-IR WFC3/IR

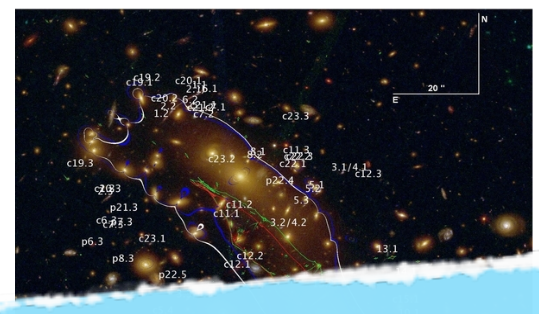
Multi-Tiered Dataset for High-z Studies



CANDELS

Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

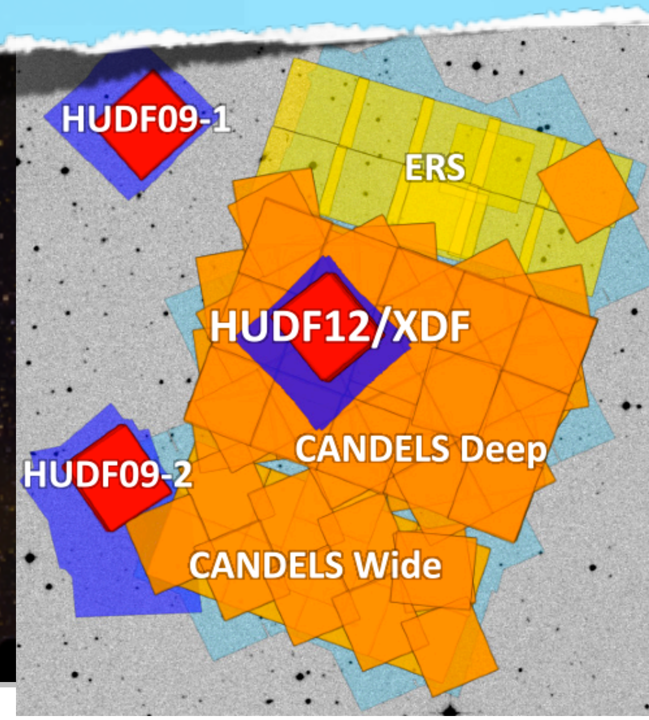
CLASH



FRONTIER FIELDS

x12

All these HST fields combined: <0.5 deg^2



RELICS

REIONIZATION LENSING CLUSTER SURVEY

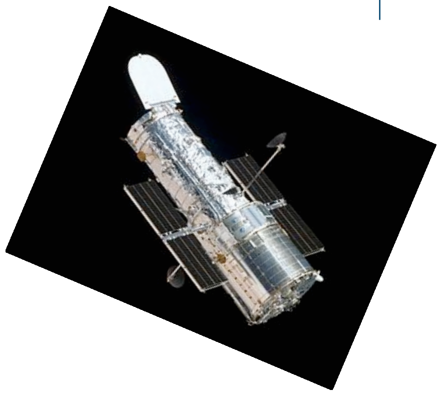
x41

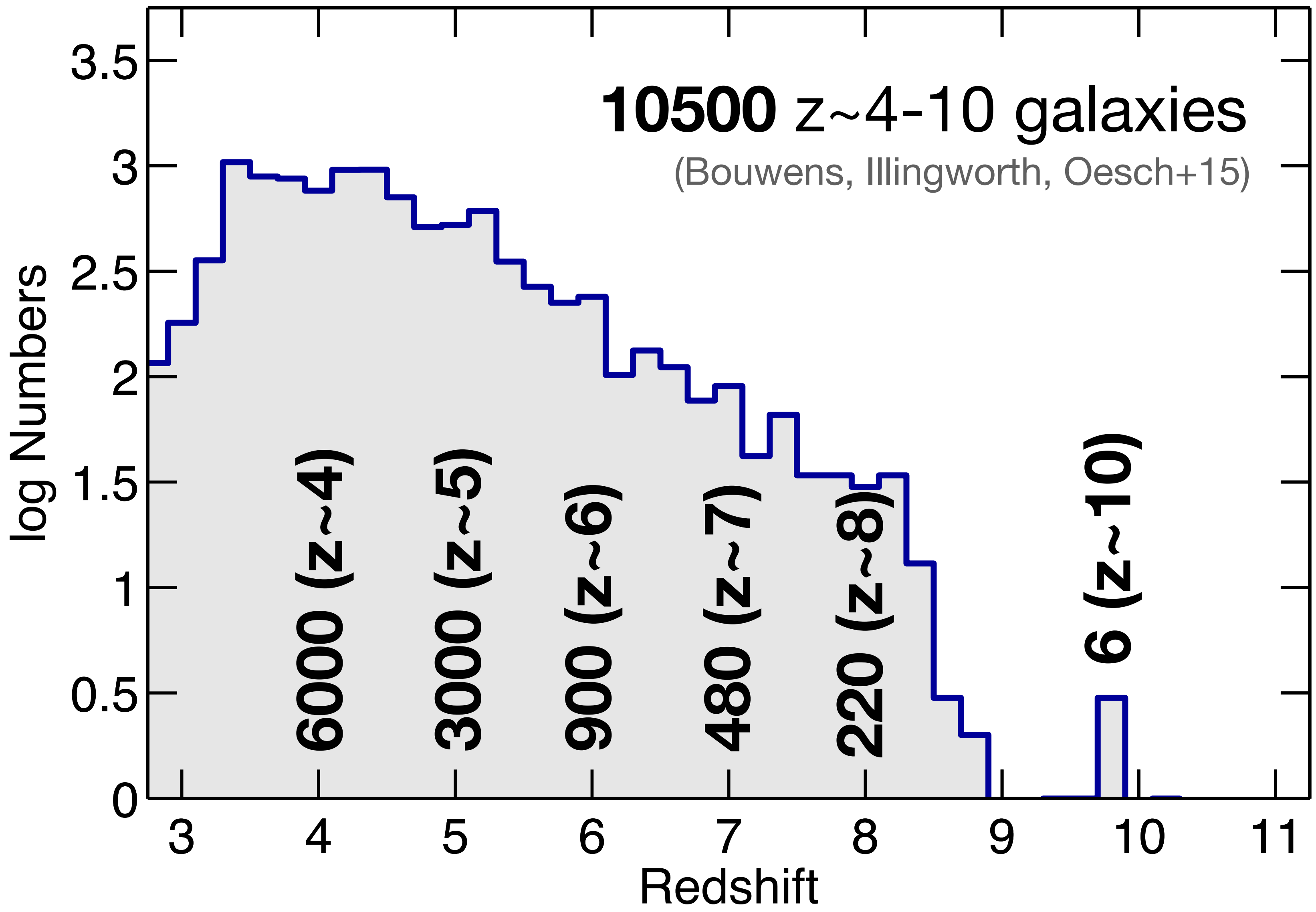
WFC3 BoRG SURVEY

Pure Parallel

credit color images: I Momcheva+3DHST

Unprecedented Galaxy Samples at z>=4
(from HST's blank fields only)



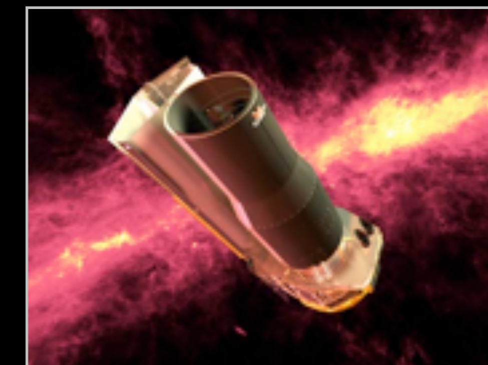


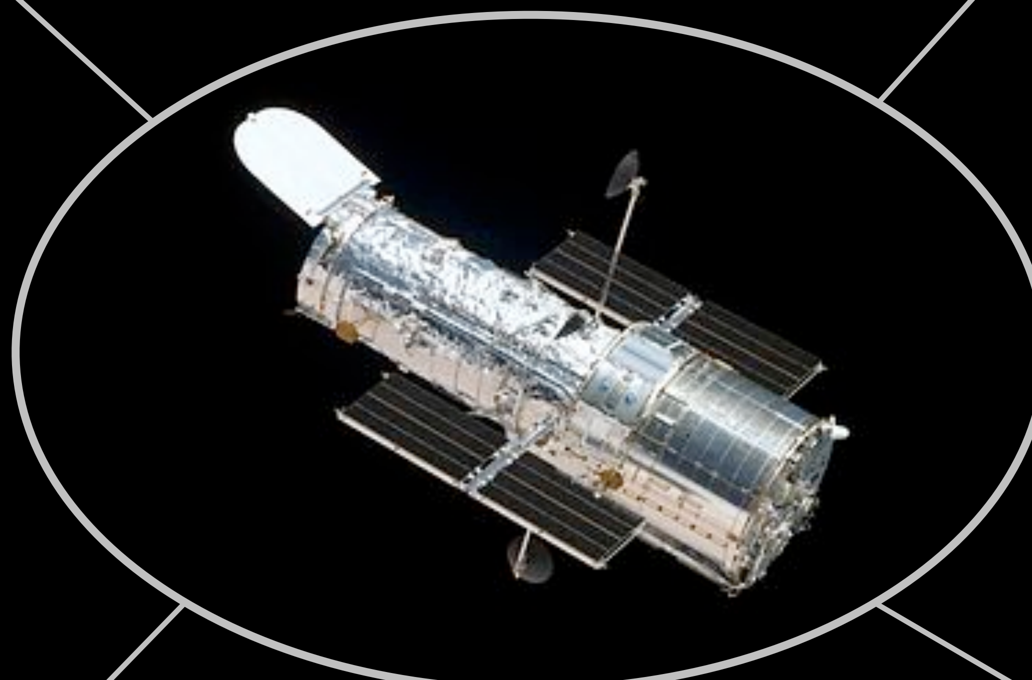
Almost 1000 galaxies in the epoch of reionization at z>6

Current frontier: z~9-10

ISM Properties
Dust Reemission

Rest-frame Optical
Stellar Masses





Source identification
UV Light / SFRs

Spectroscopic Confirmation
K-band imaging

AGN?

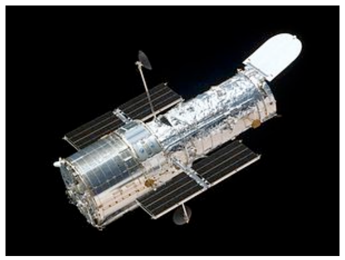
Our Multi-Wavelength Census of Early Galaxies

ALMA/NOEMA:

cold gas

dust re-emission

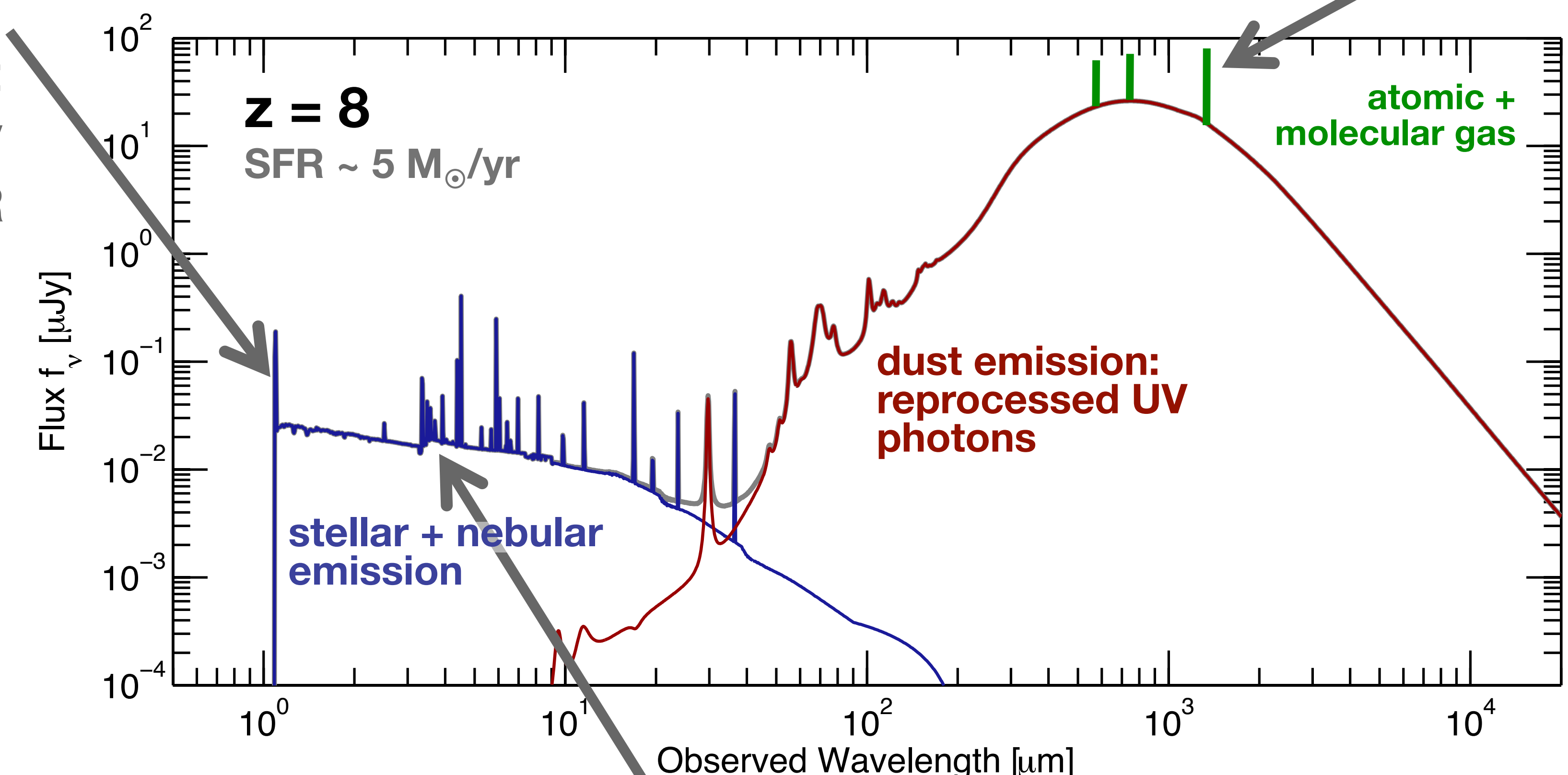
closes energy balance



HST:

rest-frame UV

un-obscured SFR



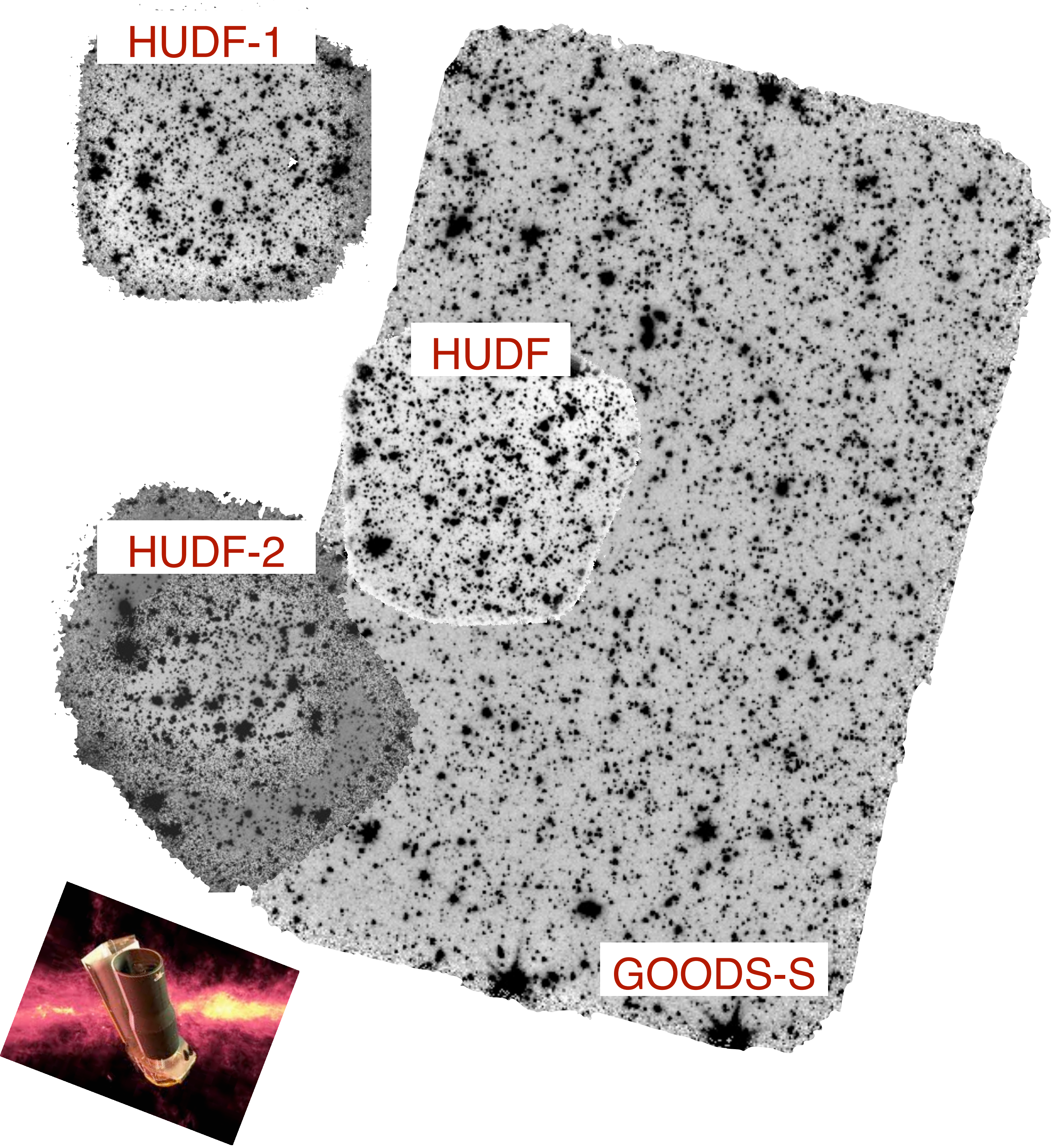
Spitzer:

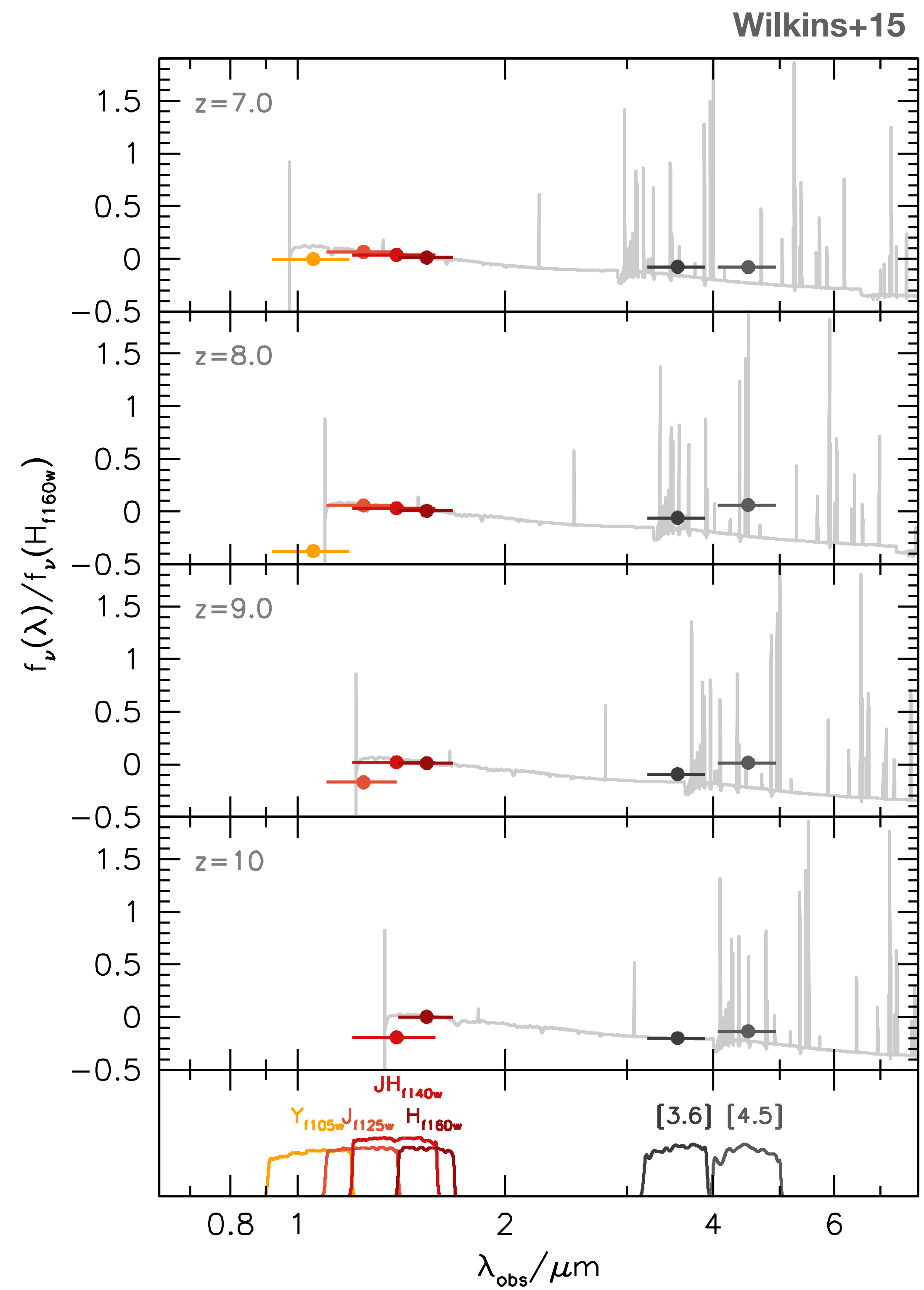
rest-frame optical imaging

stellar masses

(rest-frame optical emission lines!)

Matched Deep IRAC Data: Stellar Masses

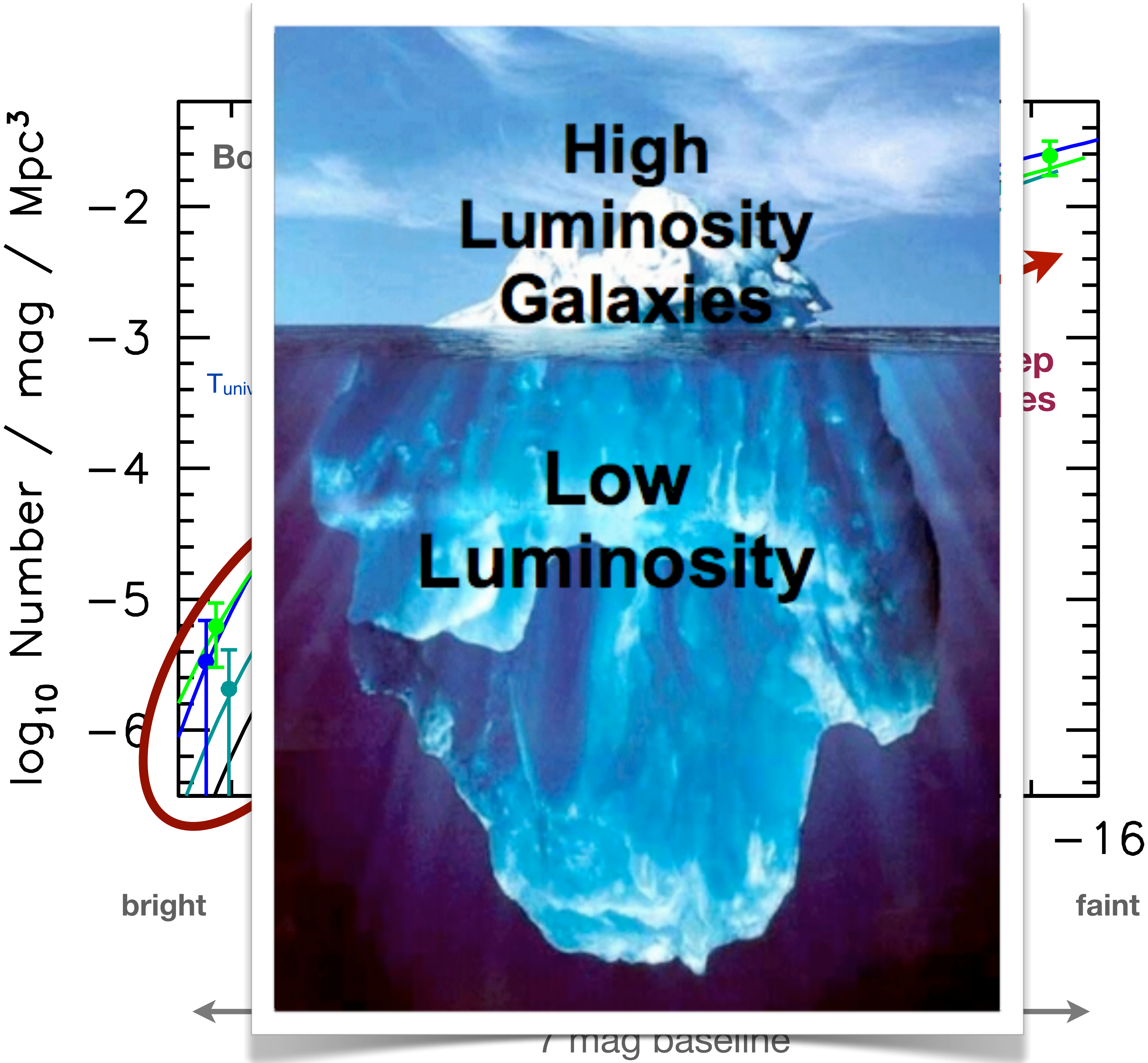




What can we learn about these early galaxy populations?

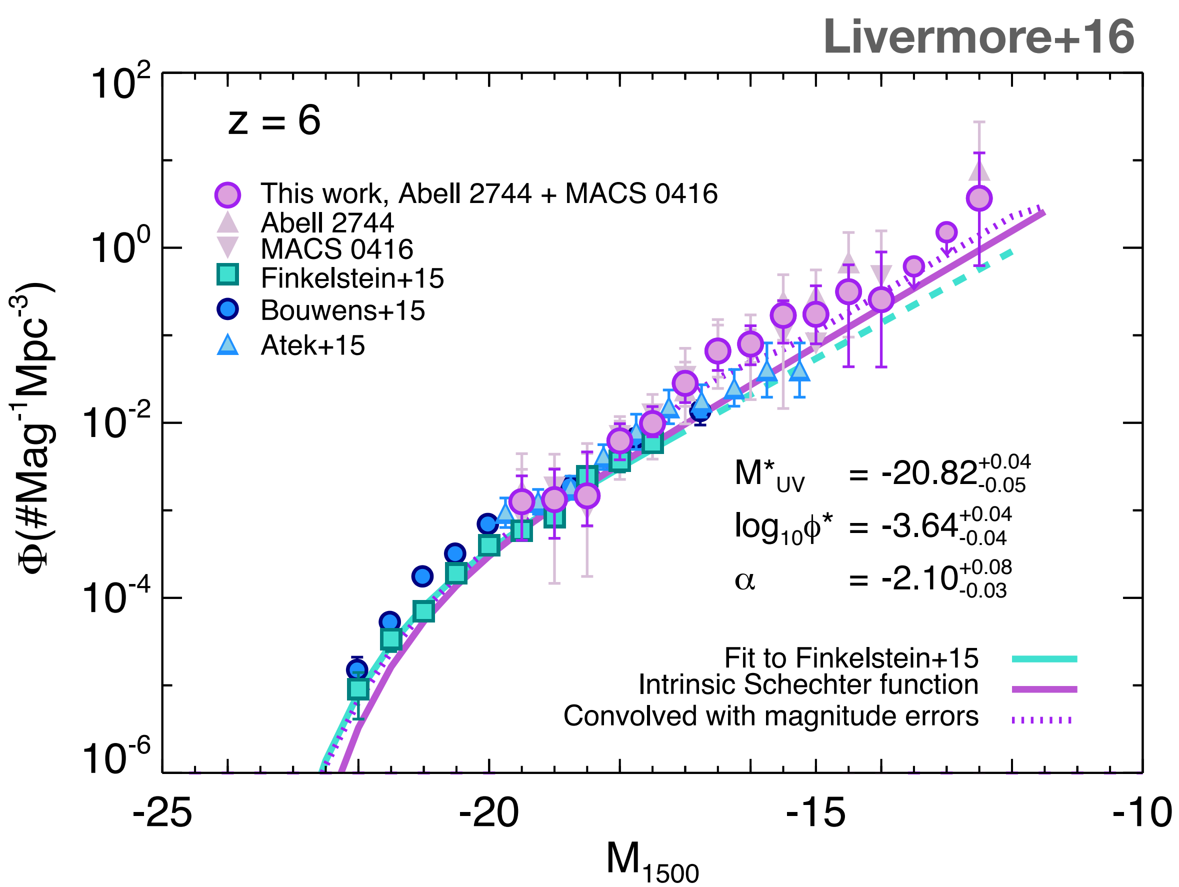
→ Some Science Highlights

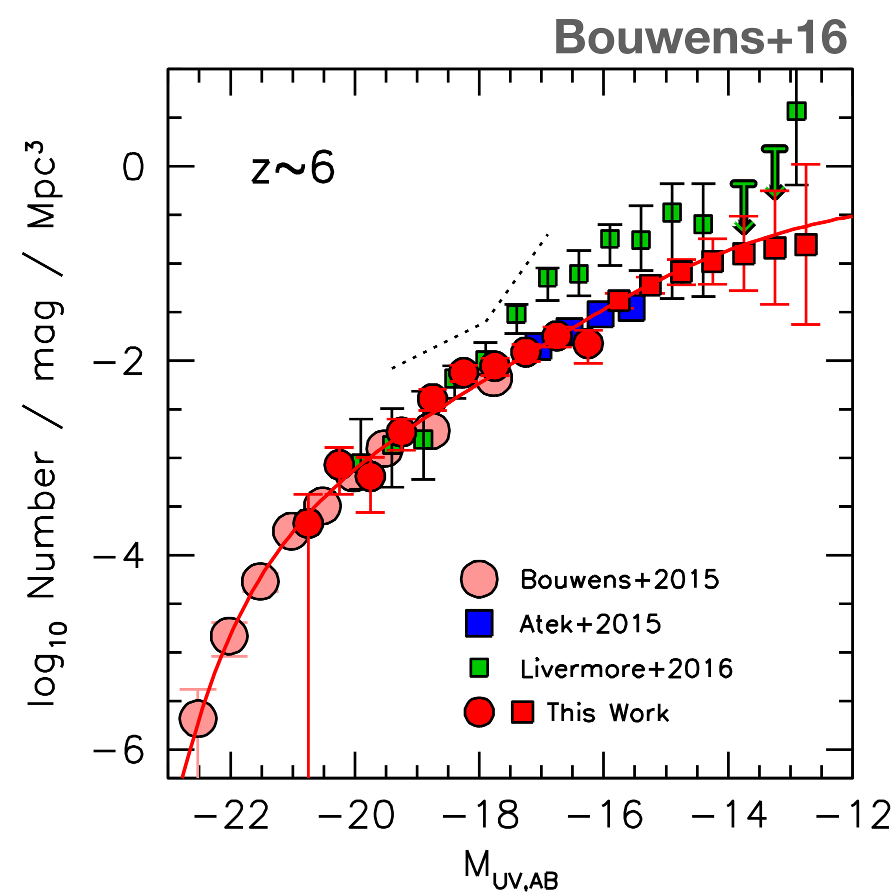
The Evolution of the UV Luminosity Function to z~8



See also: e.g. Oesch+10a/12, Bouwens+10a,11,12; Bunker+10, Finkelstein+10/14, Wilkins+10/11, McLure+10/13, Yan+12, Bradley+12, ...

New Frontier: Faint-End Cutoff/Turnover?

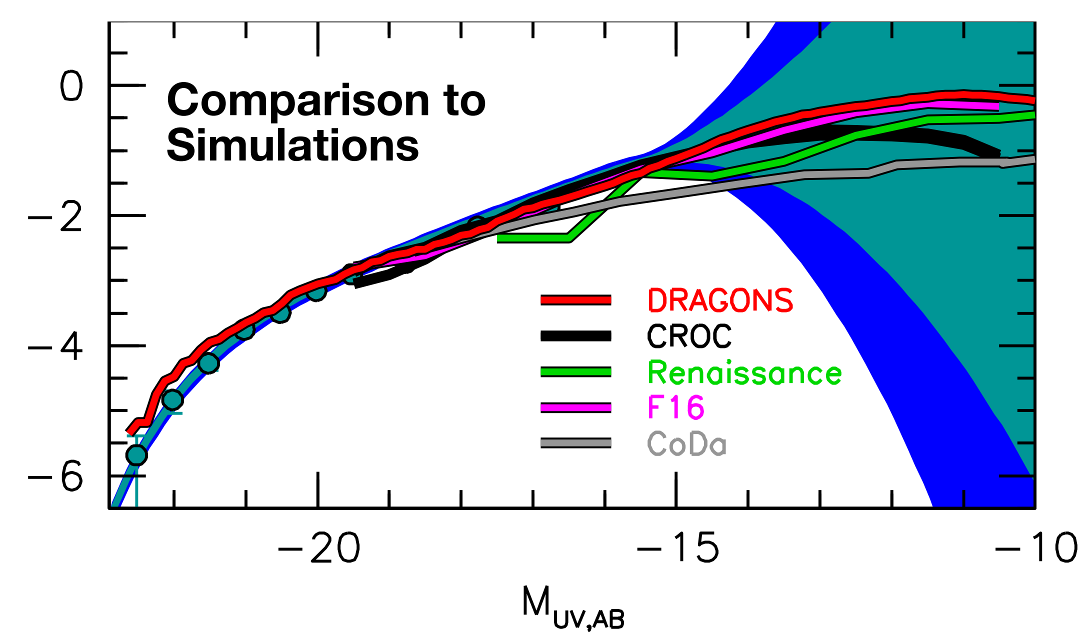




Hubble Frontier Fields: can probe possible turn-over in LF at faint luminosities thanks to lensing

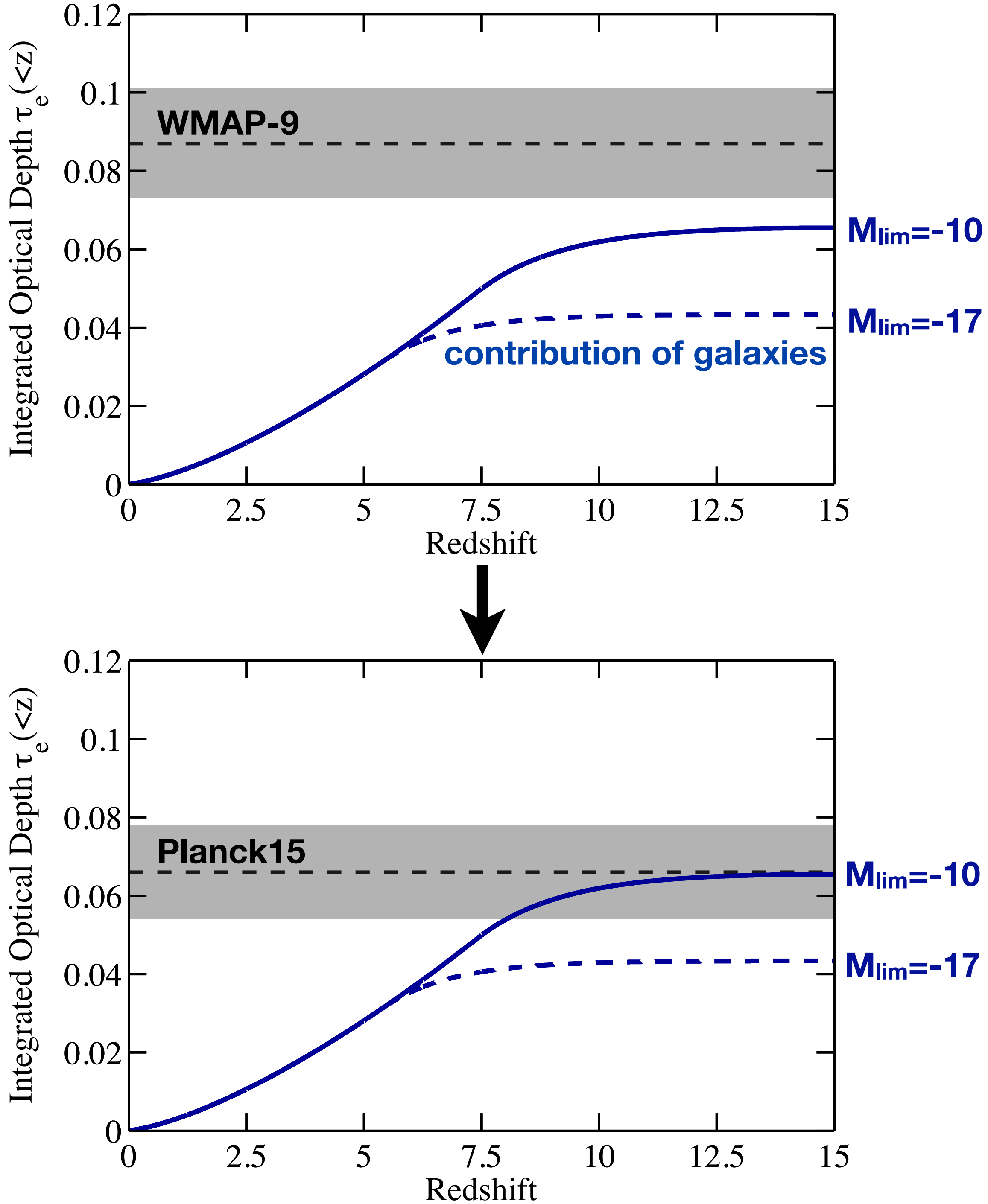
Some debate in the literature, due to uncertainties associated with lensing and size distribution of faint galaxies

clear: LF continues steep at least to Muv~-14

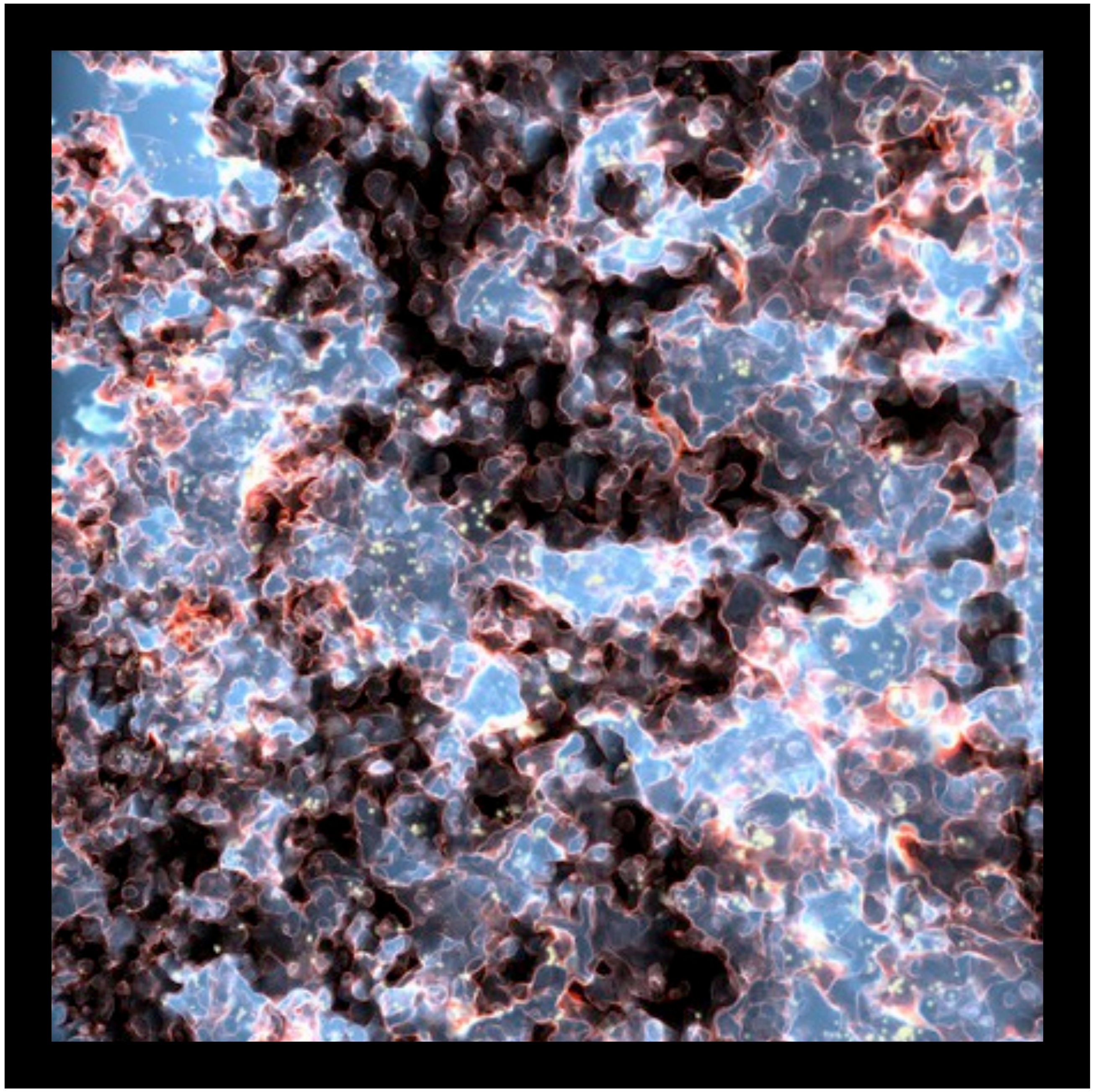


See also: e.g., Alavi+14 , Atek+15, Ishigaki+15, Laporte+16

Did Galaxies Reionize the Universe?

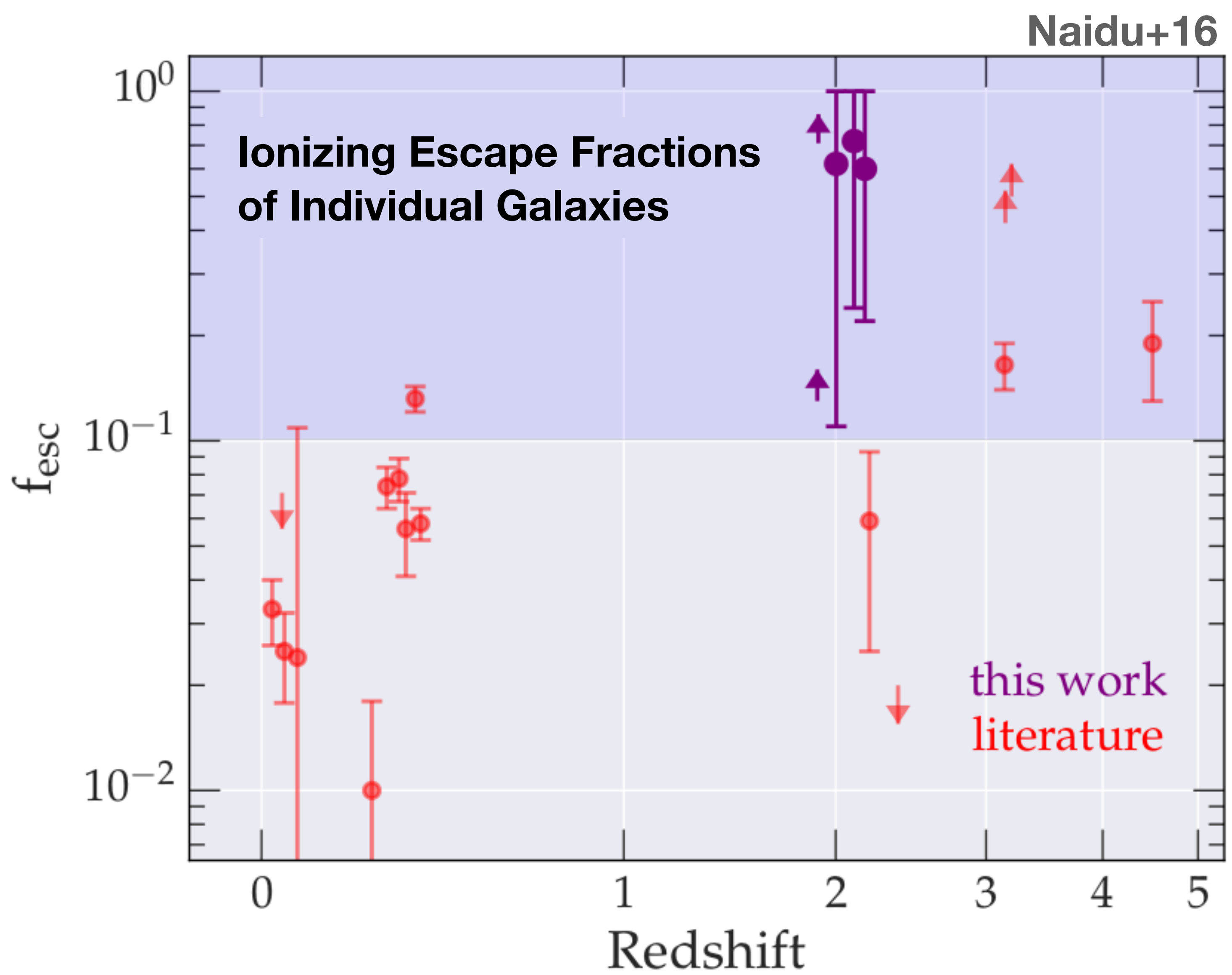


simulation: Alvarez et al. 2009



New Planck polarization results find: τ_e = **0.058±0.012**, i.e. z_{reion} = **8.2±1.1**
Consistent with estimates from ultra-faint galaxy population.

Escape of Ionizing Photons?

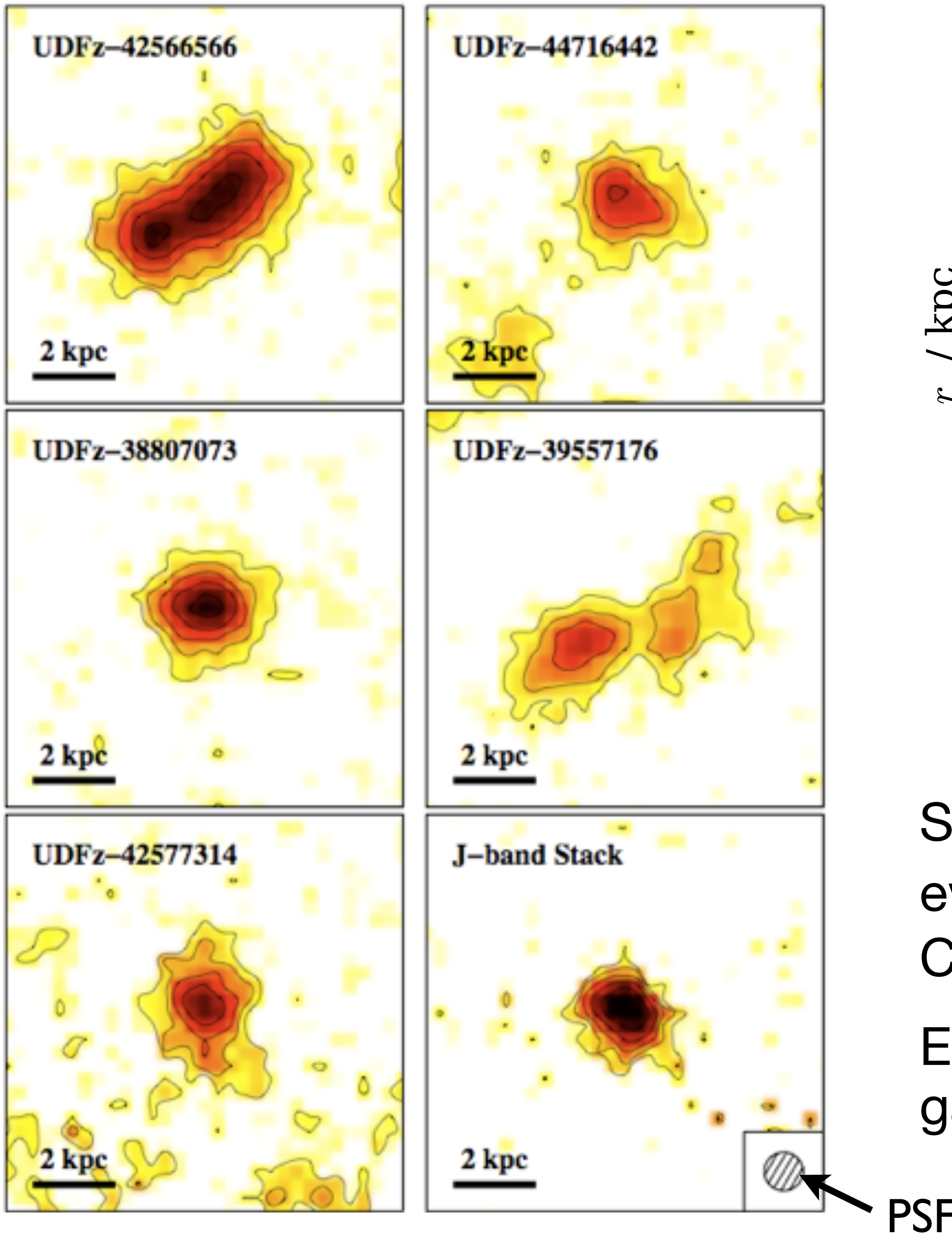


>10%: needed for reionization by galaxies

Escape fraction of ionizing photons is the most uncertain parameter for reionization studies.

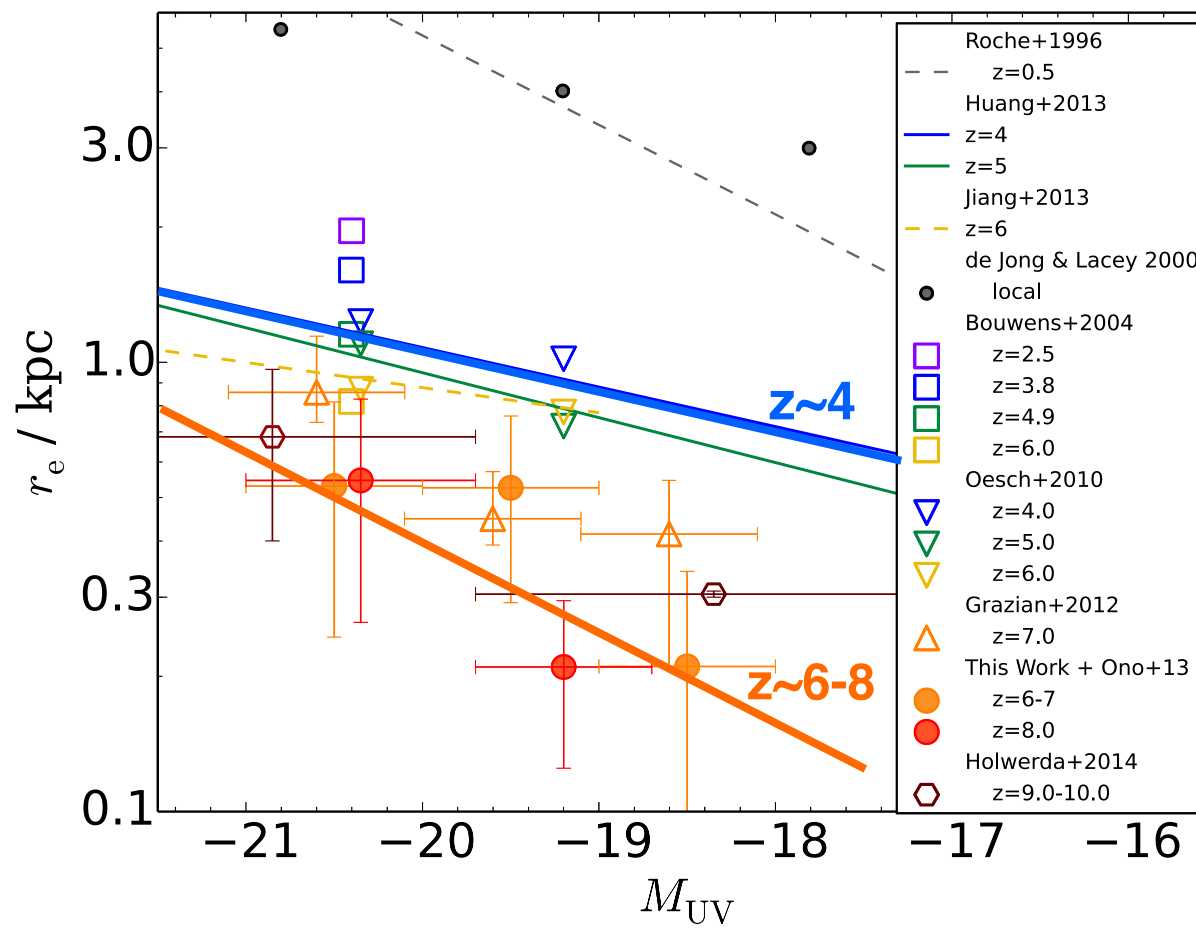
Recent progress: some sources at high redshift certainly have high enough fesc

High-Redshift Galaxies Resolved with HST



Oesch et al. 2010b

Kawamata+15



Sizes of LBGs in first 2 Gyr of cosmic time evolve as: $\mathbf{r_{1/2} \sim (1+z)^{-1}}$
Consistent with constant L at fixed halo mass.

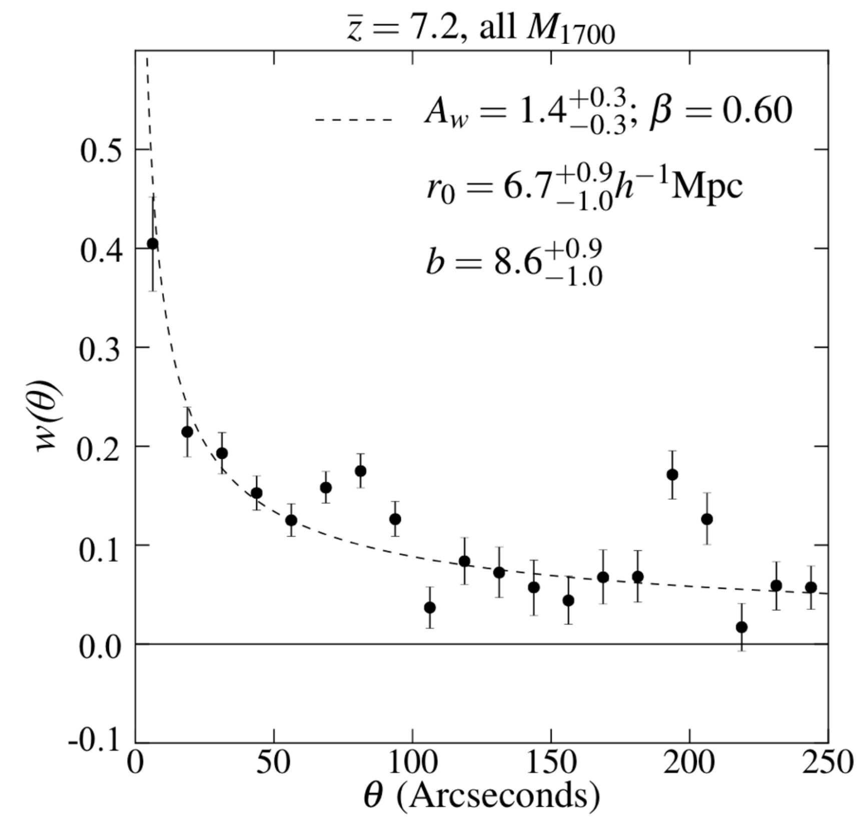
Evidence for extremely small sizes of faint galaxies at z~6-8 (e.g. Bouwens+16, Kawamata+15)

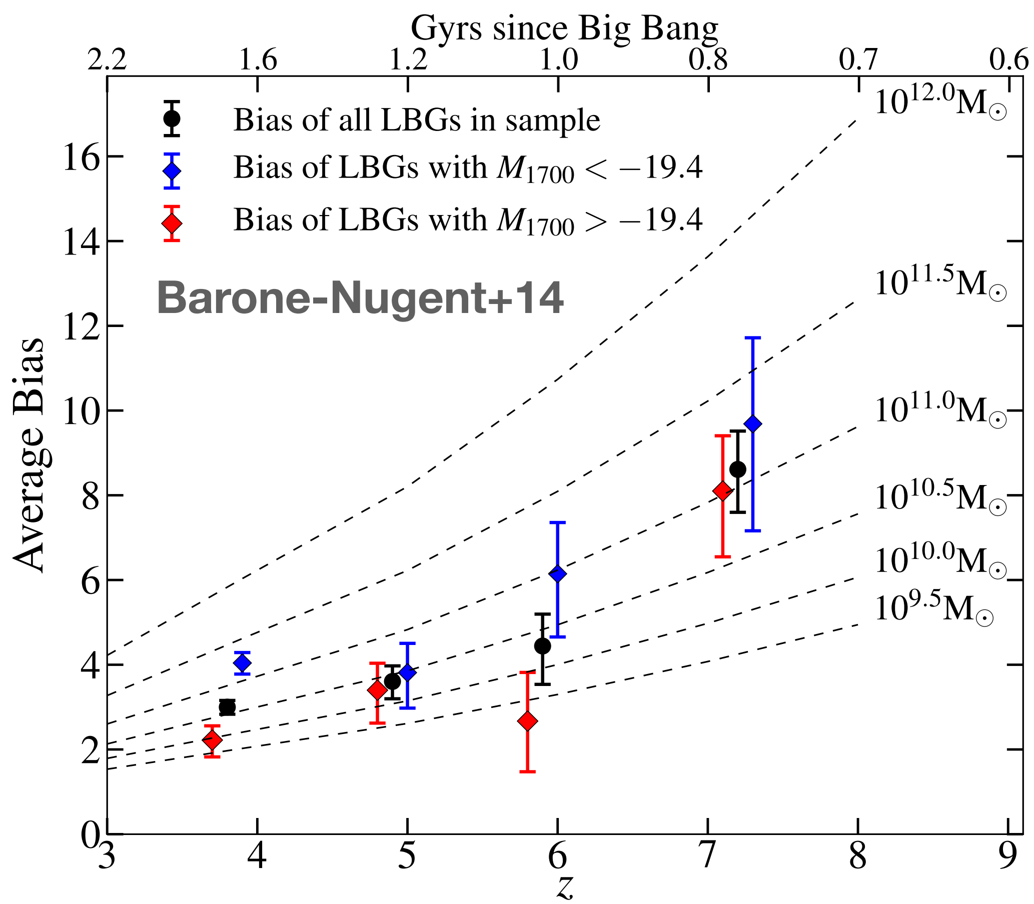
see also: Ferguson+04, Bouwens+04, Ono+12, Holwerda+14, Curtis-Lake+14

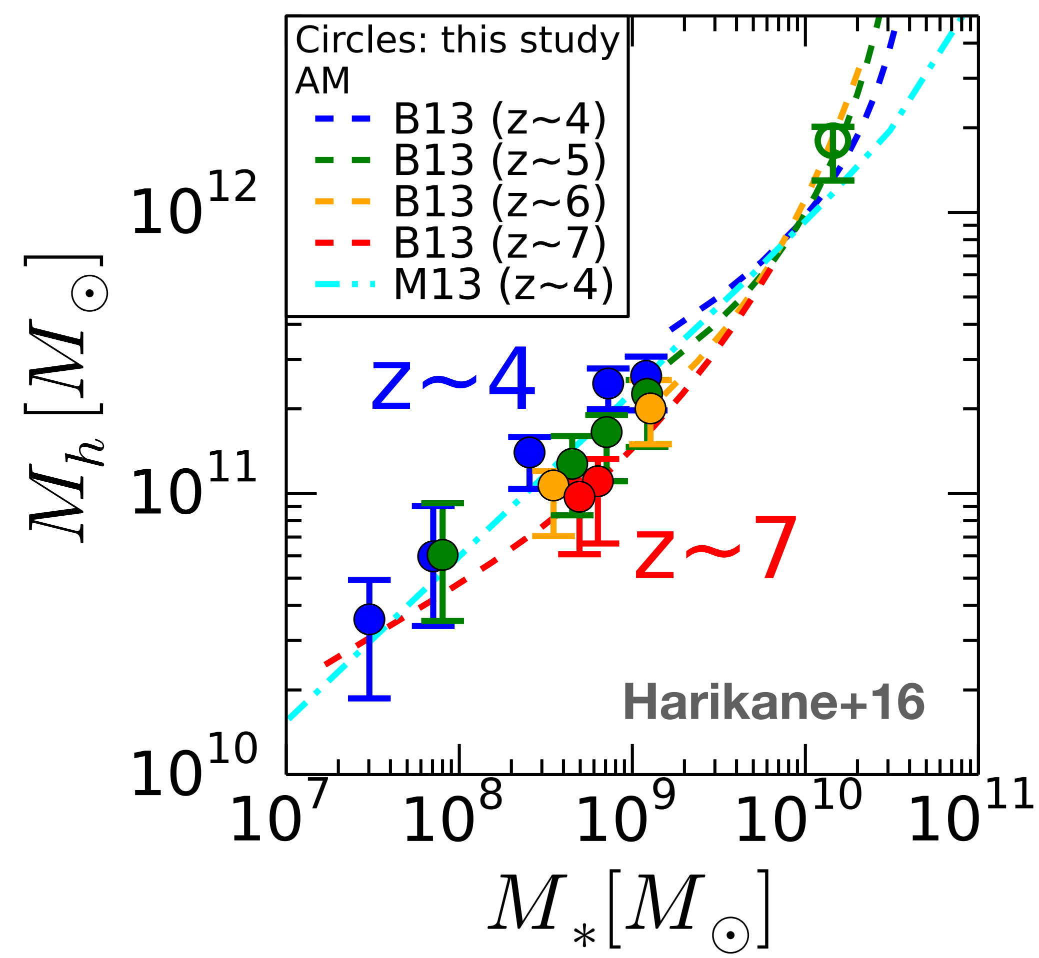
Large Samples → Clustering

Fundamental quantity to measure:
stellar-mass to halo-mass relation

First estimates based on M_{UV} selected
samples through clustering

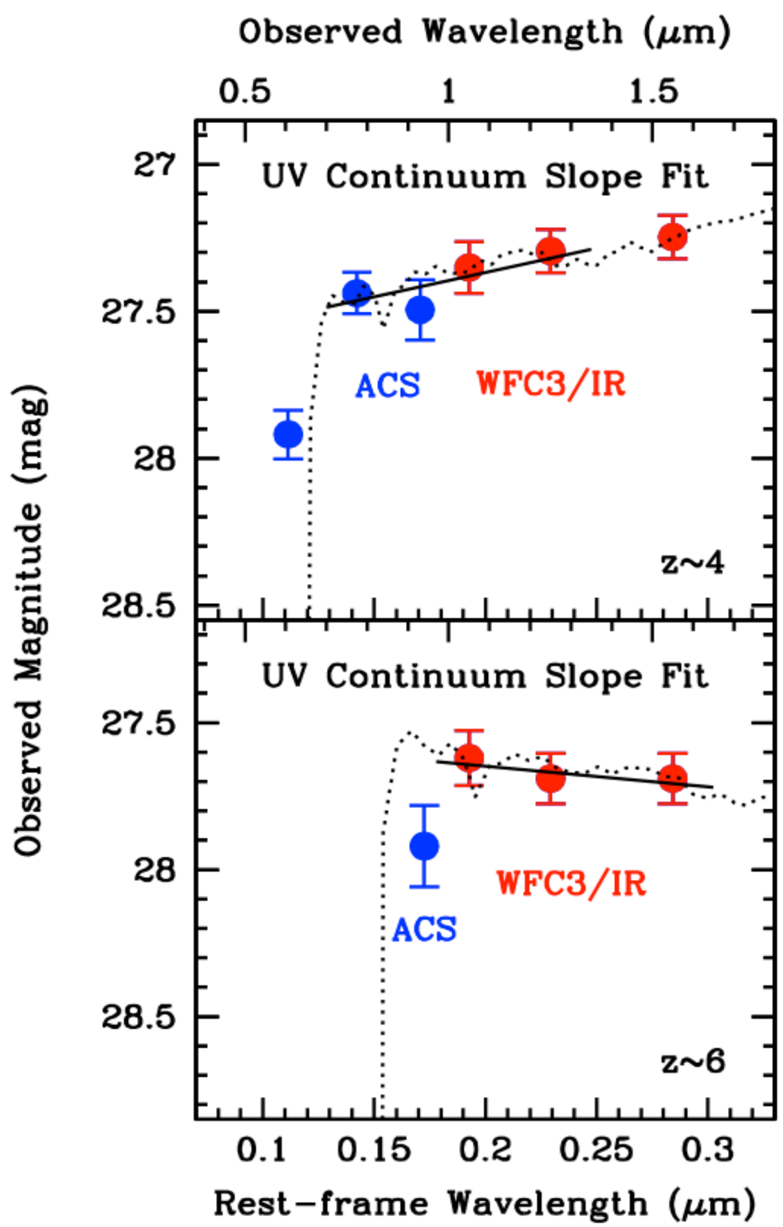






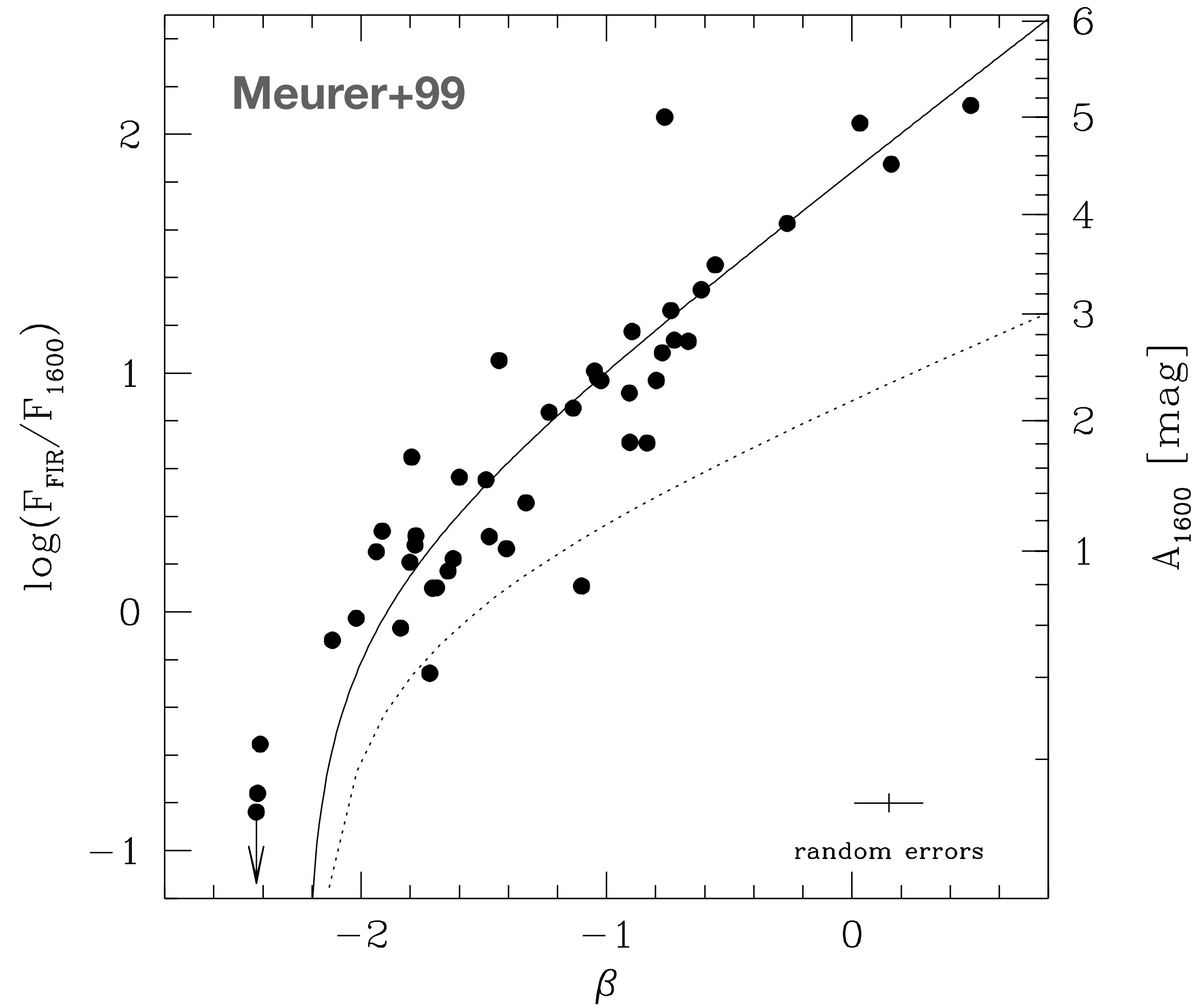
see also: Lee+12, Overzier+11

Rest-Frame UV Colors of Galaxies at z>4



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

β=UV continuum slope

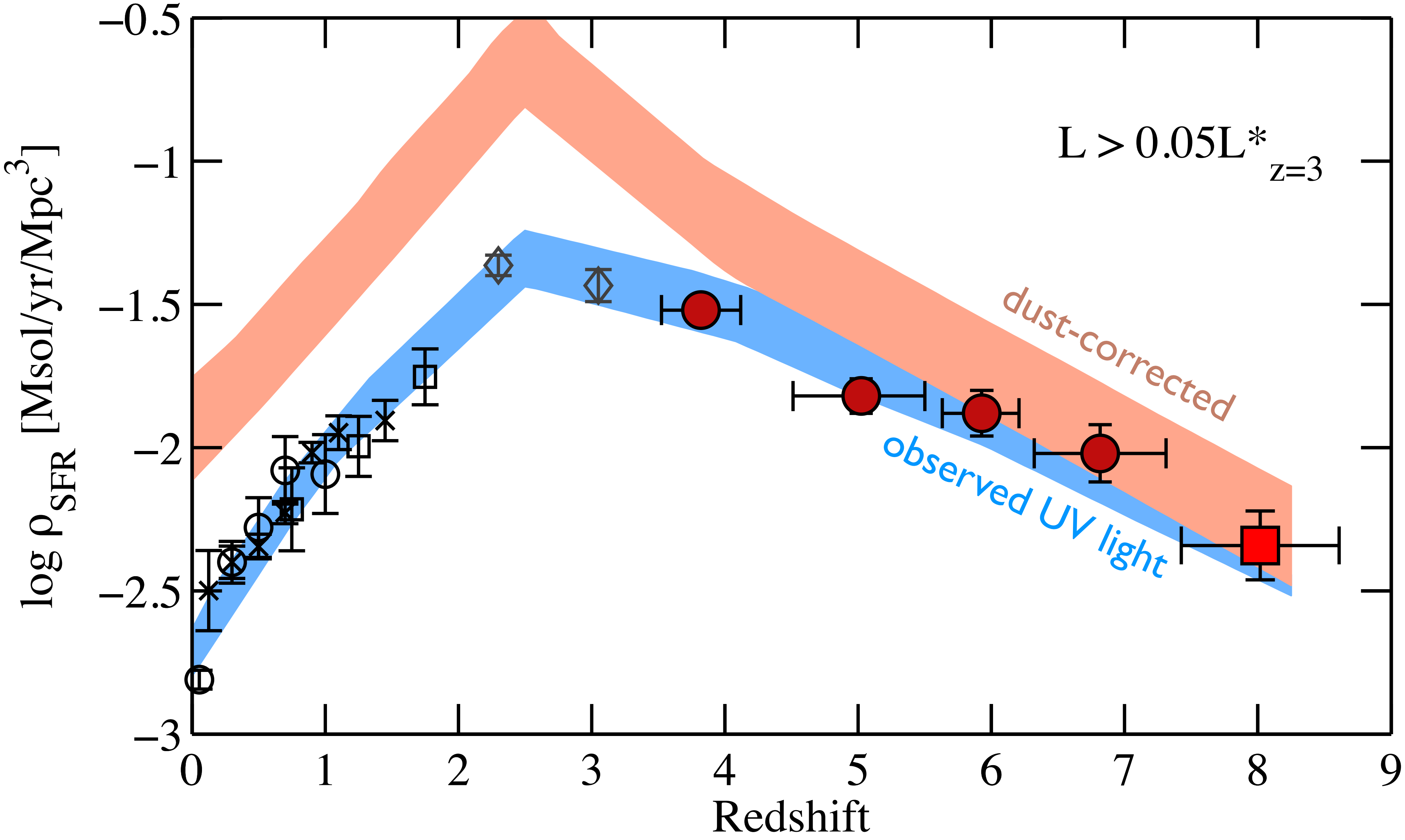


UV continuum slopes have so far been used for dust corrections at z>3 based on local relations!

See also: Wilkins+11, Dunlop+12/13, Castellano+11, Bouwens+09/10, Finkelstein+10/12, Rogers+13/14

Cosmic SFR Density

Use UV continuum slope measurements to correct for dust extinction:
→ cosmic SFR density

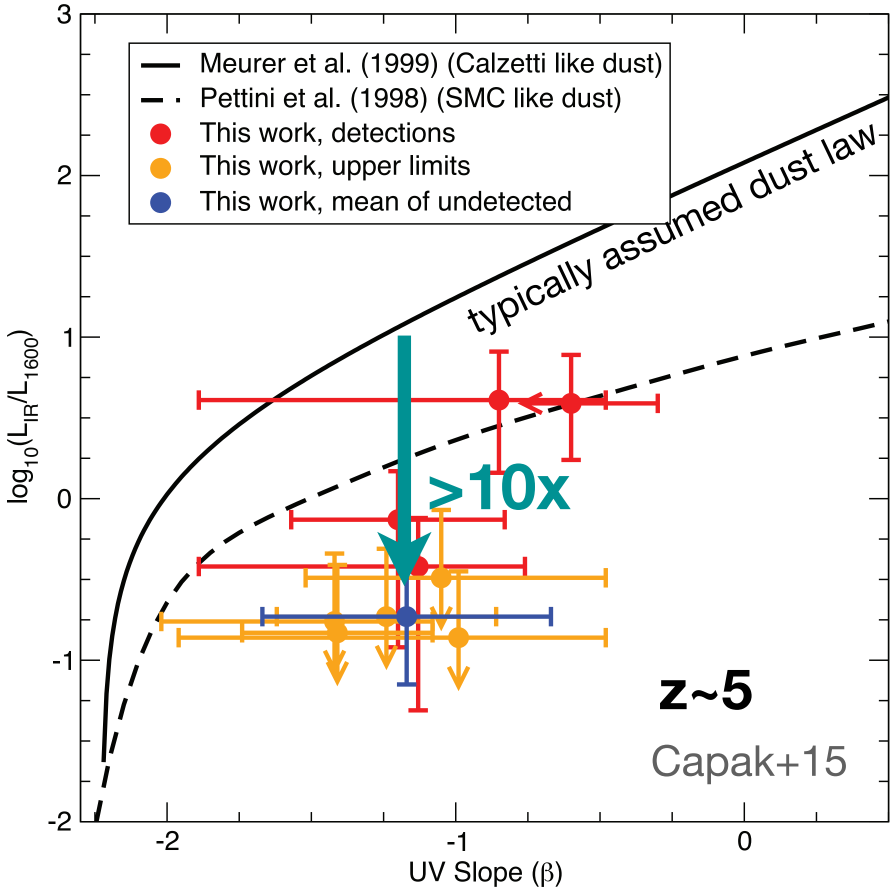


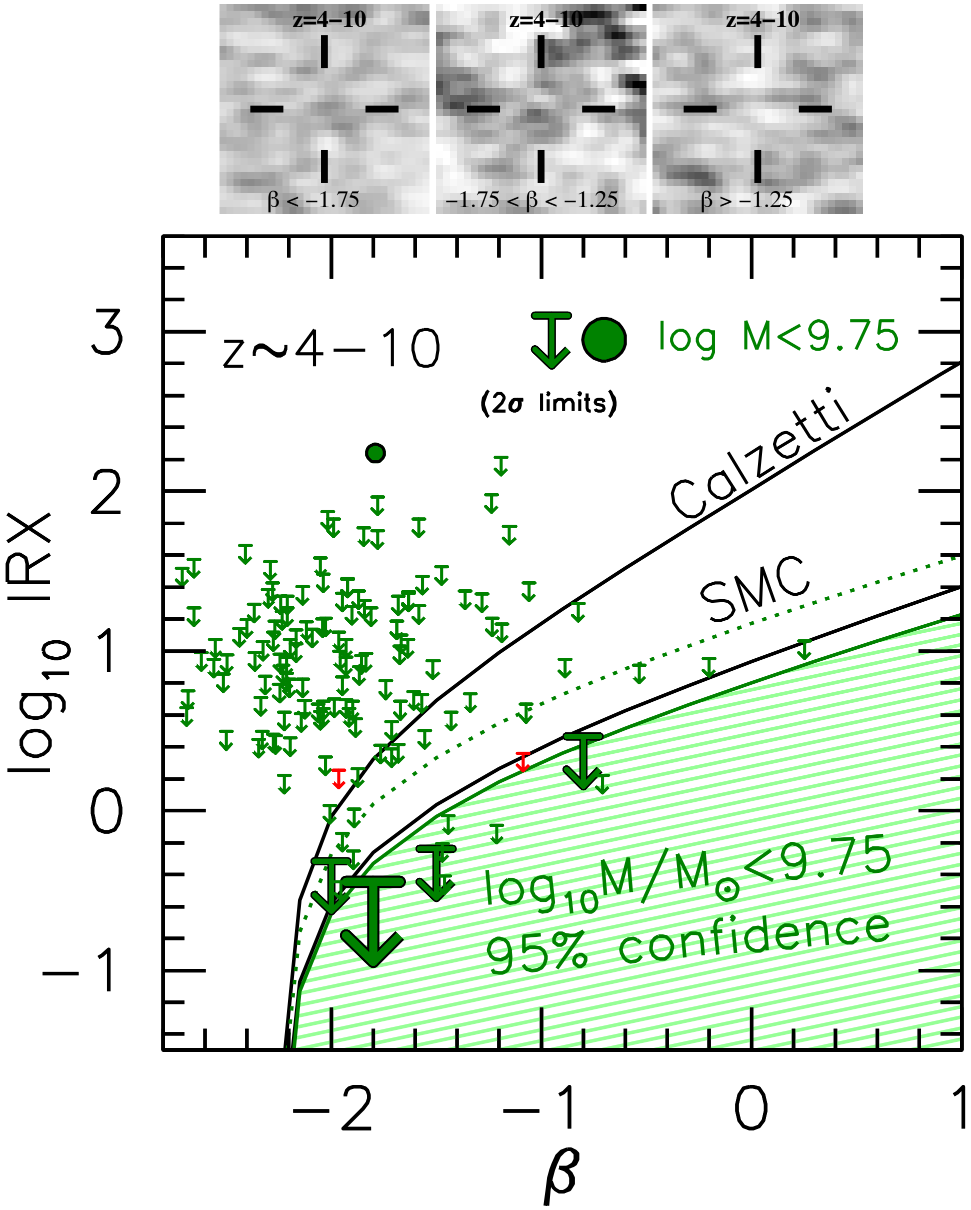
Remarkably smooth build-up of cosmic SFRD at z~8 to z~2-3
Below z~4, dust-obscured SFR dominates

see also e.g. Bouwens+07; Oesch+10d; Bouwens+11,15; Bunker+10, McLure+11,13, Finkelstein+12,14, Schenker+13, ...

First ALMA Constraints on LBG Dust Reemission

Much less emission than expected!
Less dust than we thought from UV slopes?

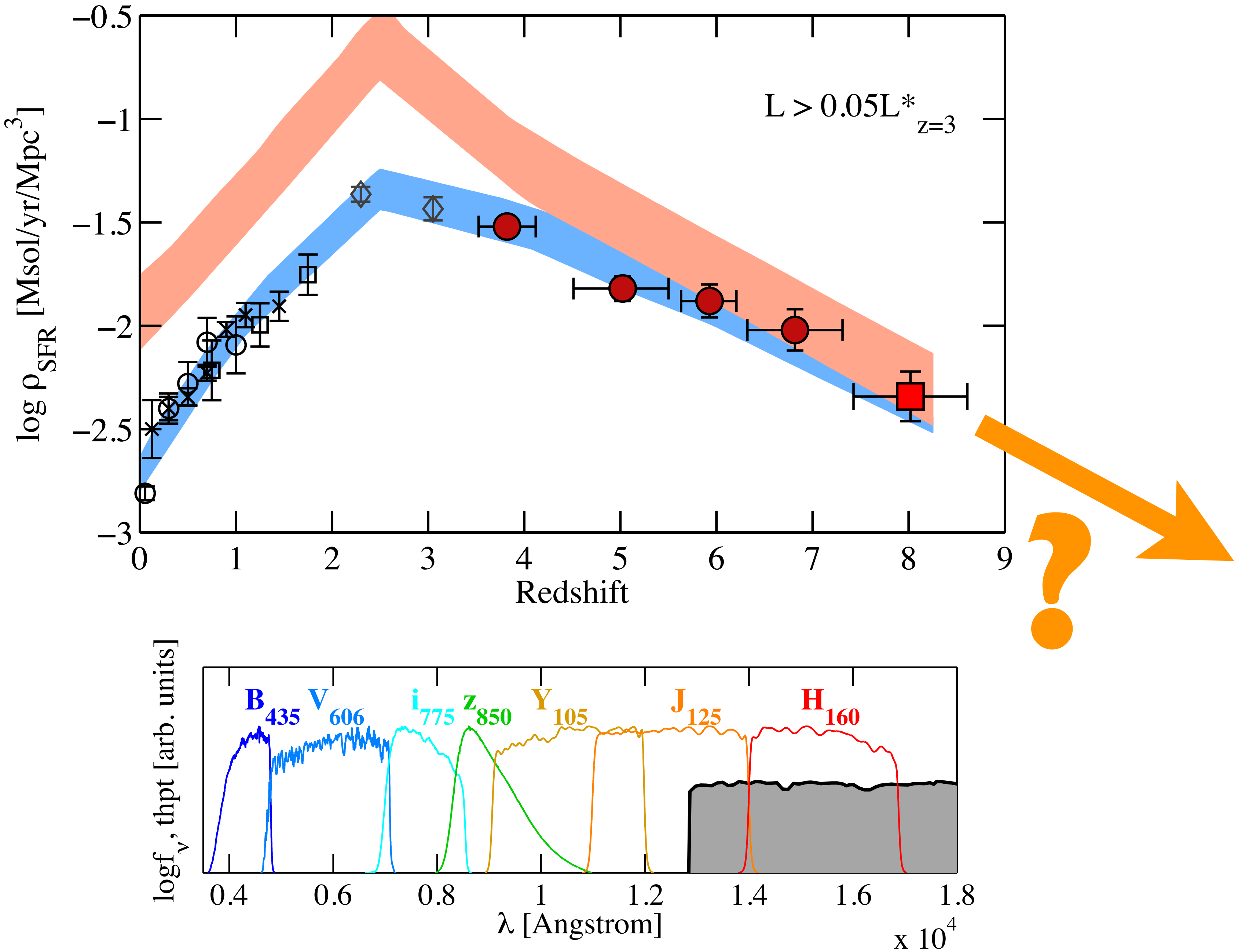




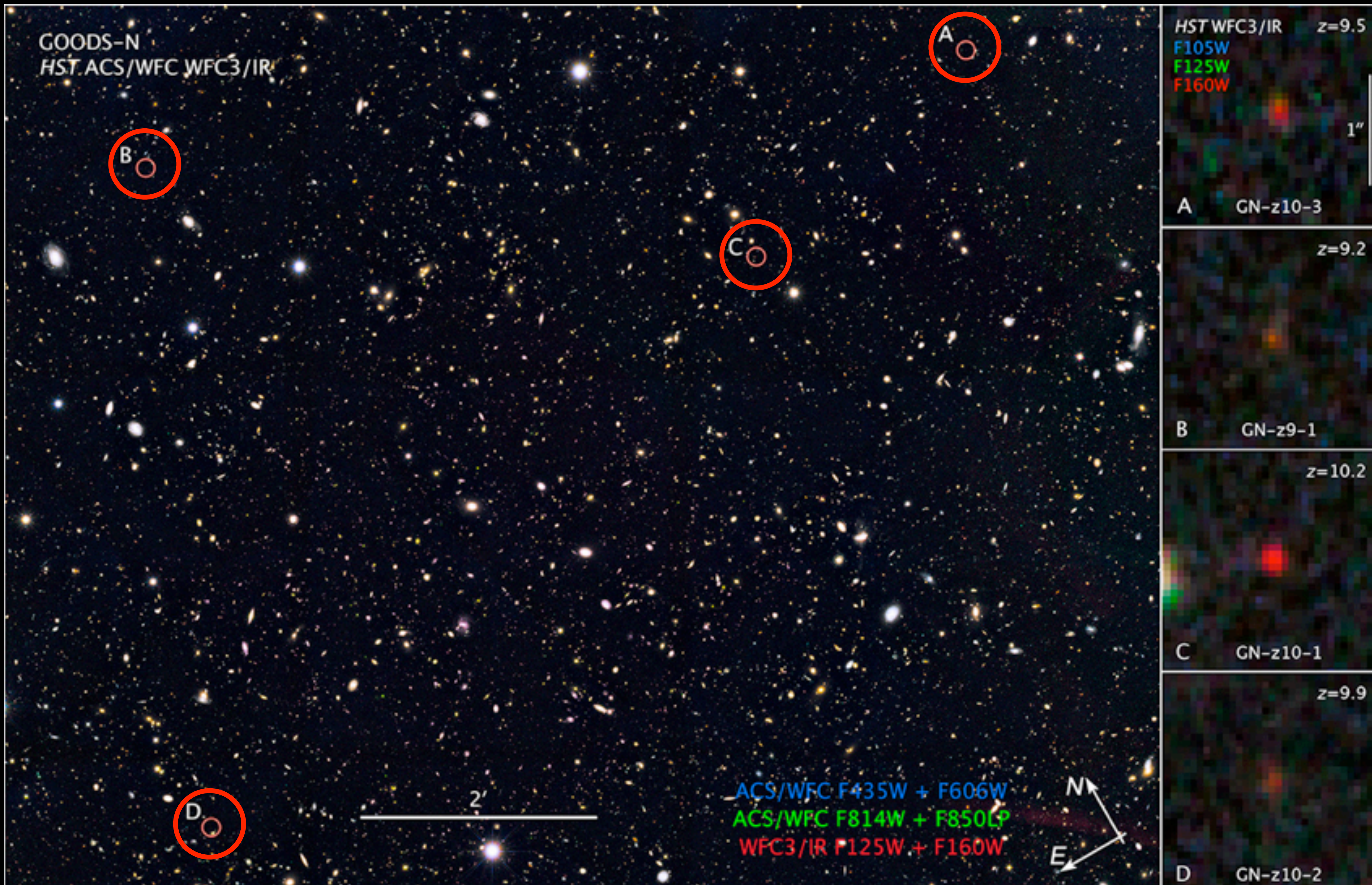
Bouwens+16
see also Dunlop+16

Probing the Frontier of Galaxies

HST can detect galaxies out to z~10-12



Sample of 4 Bright z~9-10 Galaxy Candidates



H=26.8

H=26.6

H=26.0

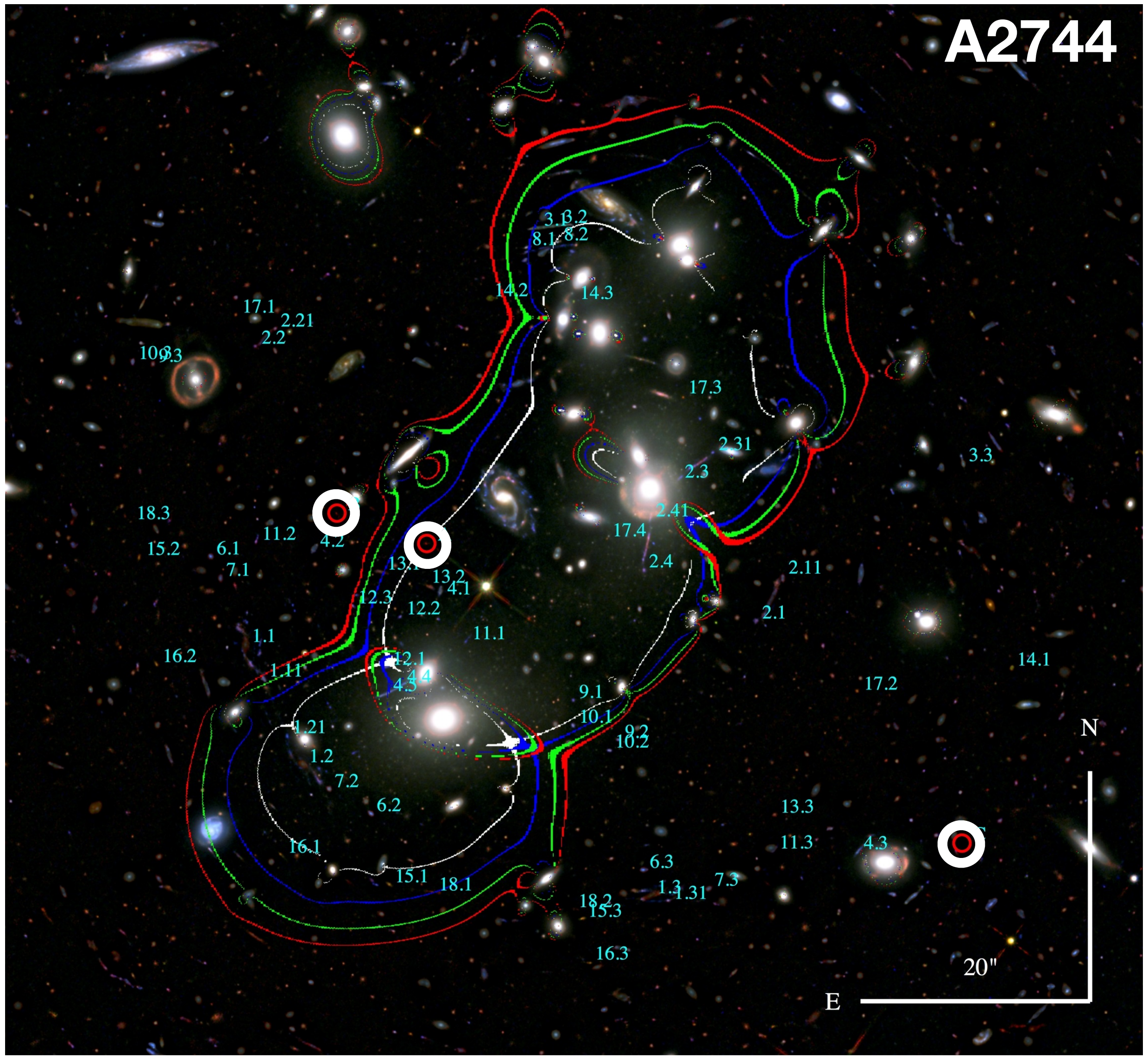
H=26.8

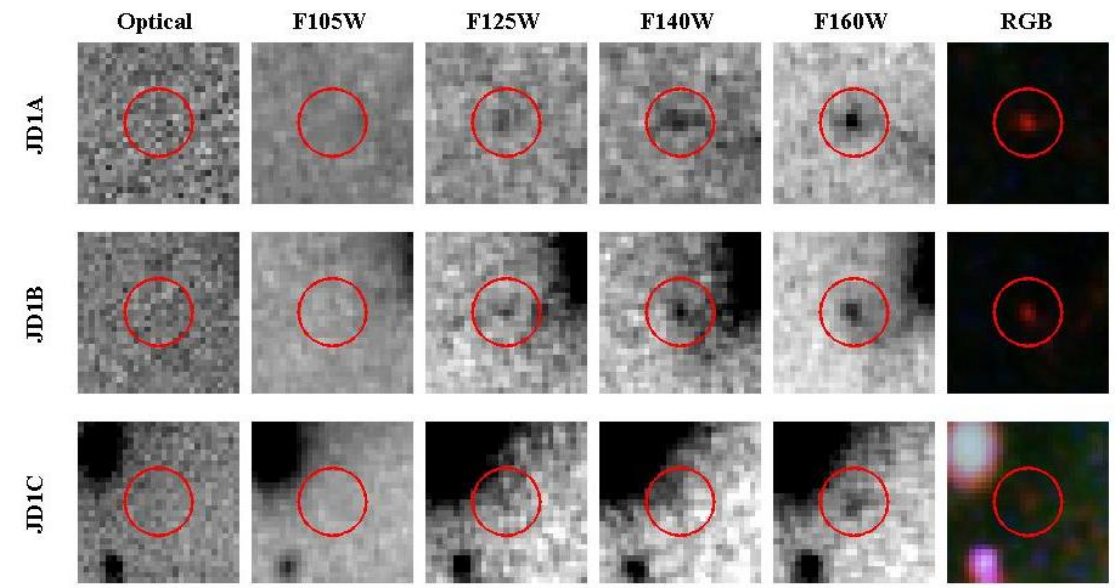
NASA and ESA

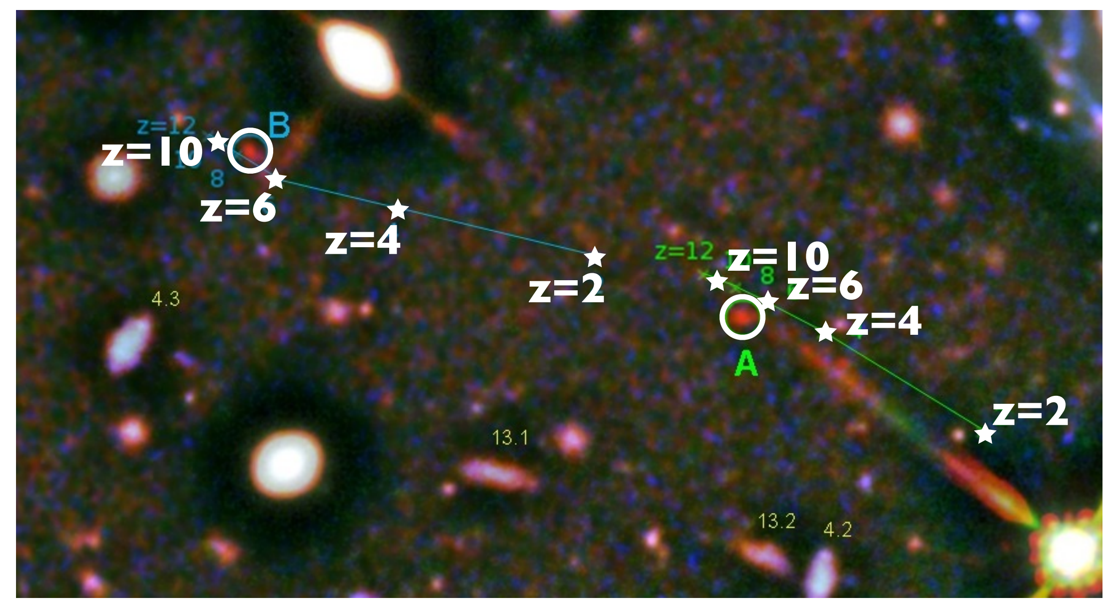
STScI-PRC14-05a

Triply Imaged z~10 Candidate in First FF Cluster

Zitrin+14 (see also Oesch et al. 2015)







H = 29.9 mag (de-magnified)

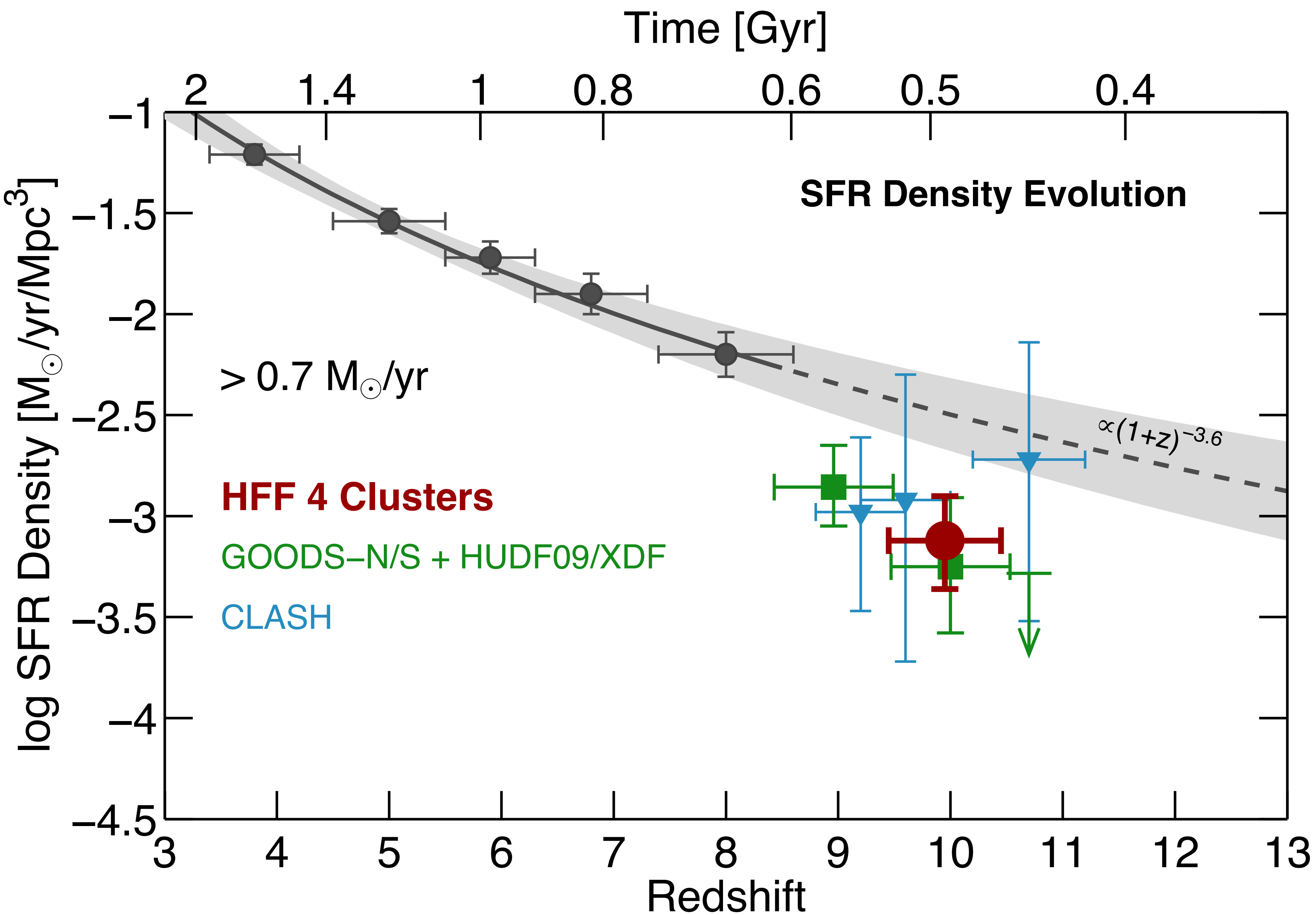
zphot = 9.8+-0.4

magnification: 10-11x

strong geometric support of high redshift solution of photo-z

FRONTIER FIELDS

SFRD Evolution at z>8

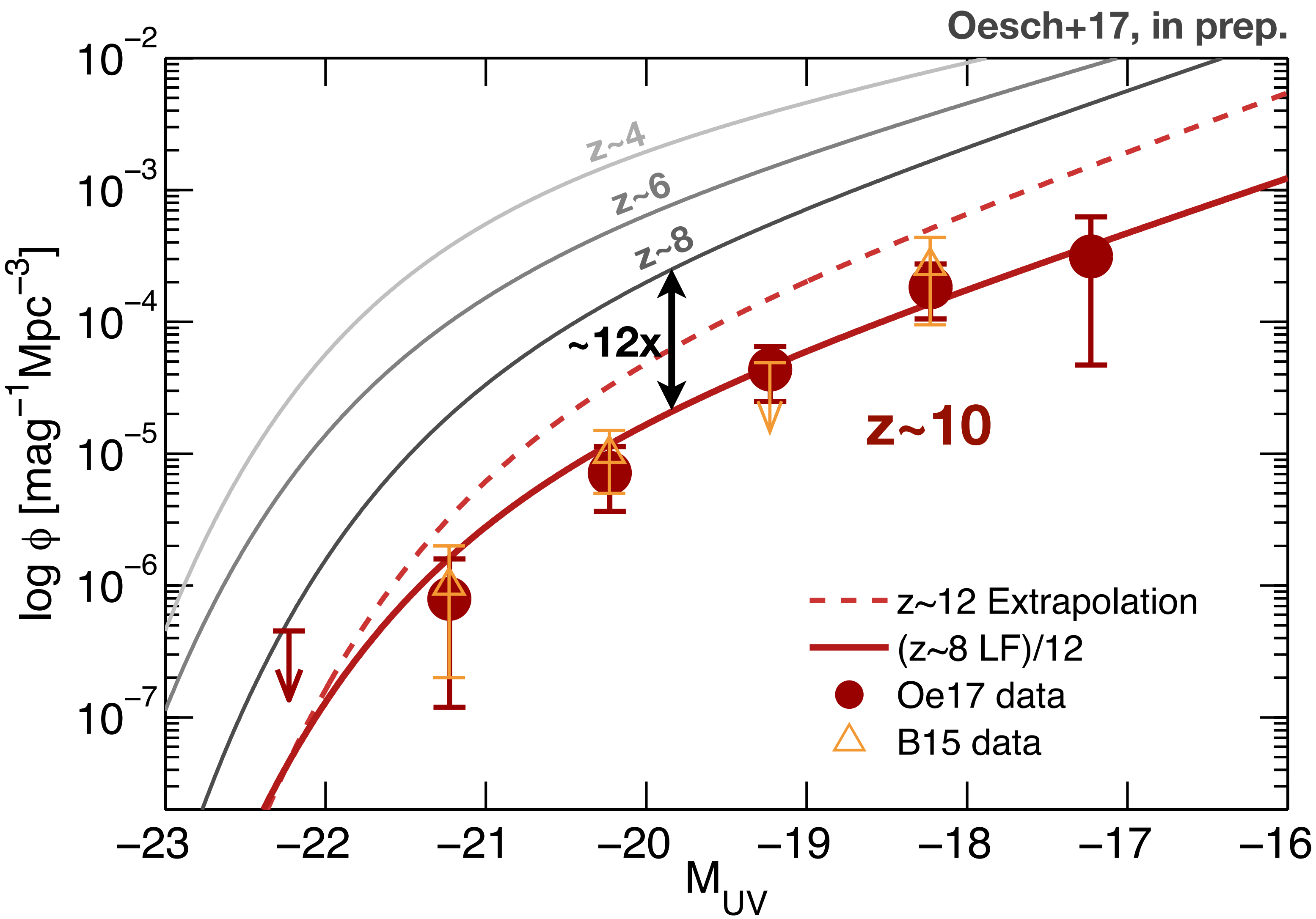


Full analysis of first 4 HFFs confirms: SFRD evolves very rapidly beyond z~8

but see McLeod+16

see also: Zheng+12, Coe+13, Bouwens+13/15, Ellis+13, McLure+13, Ishigaki+14

The UV Luminosity Function at the Cosmic Frontier



Including HFF galaxy candidates, now have a quite good estimate of the UV LF at z~10.

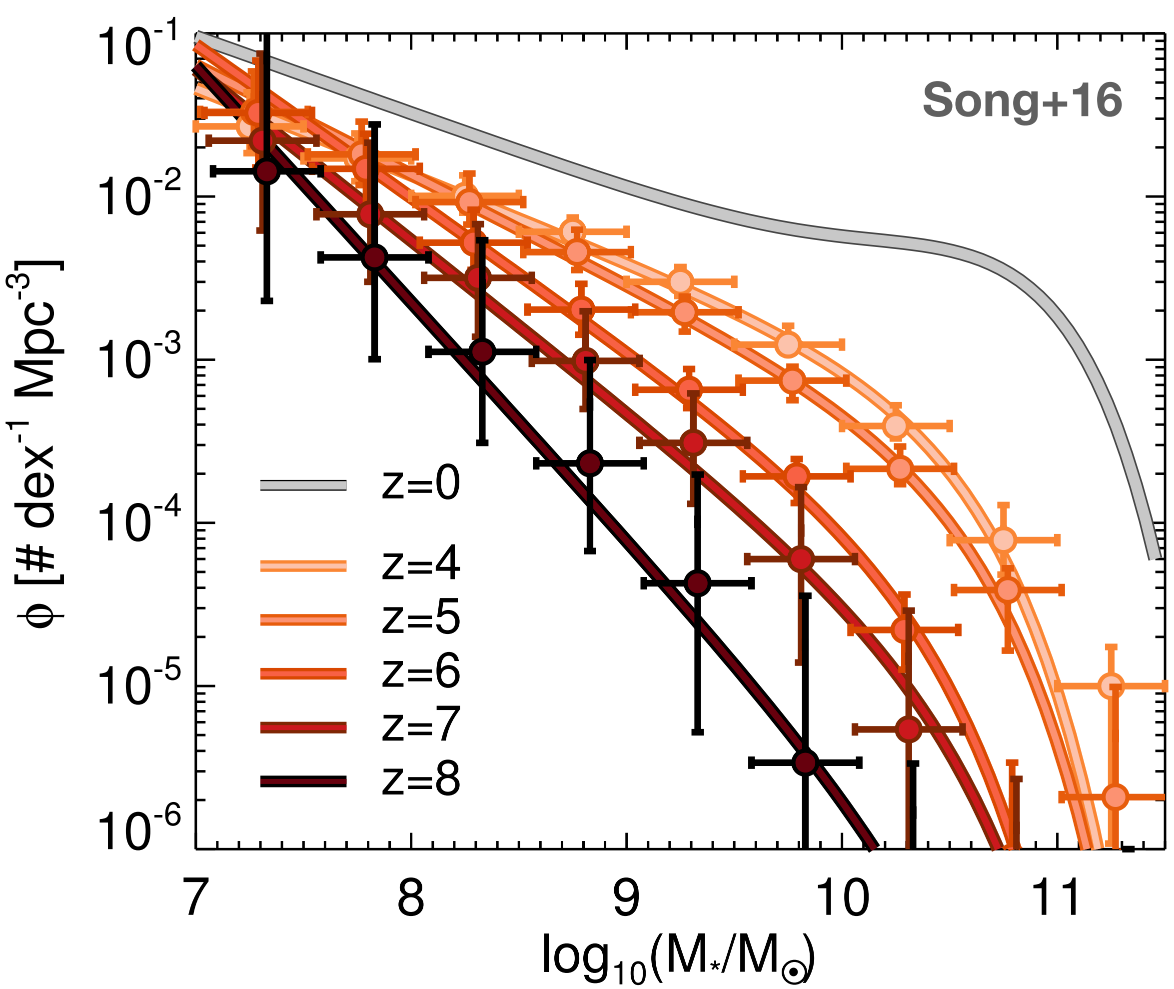
It lies a factor ~12x below the z~8 UV LF measurement at all luminosities

Confirms fast evolution from z~8 to z~10.

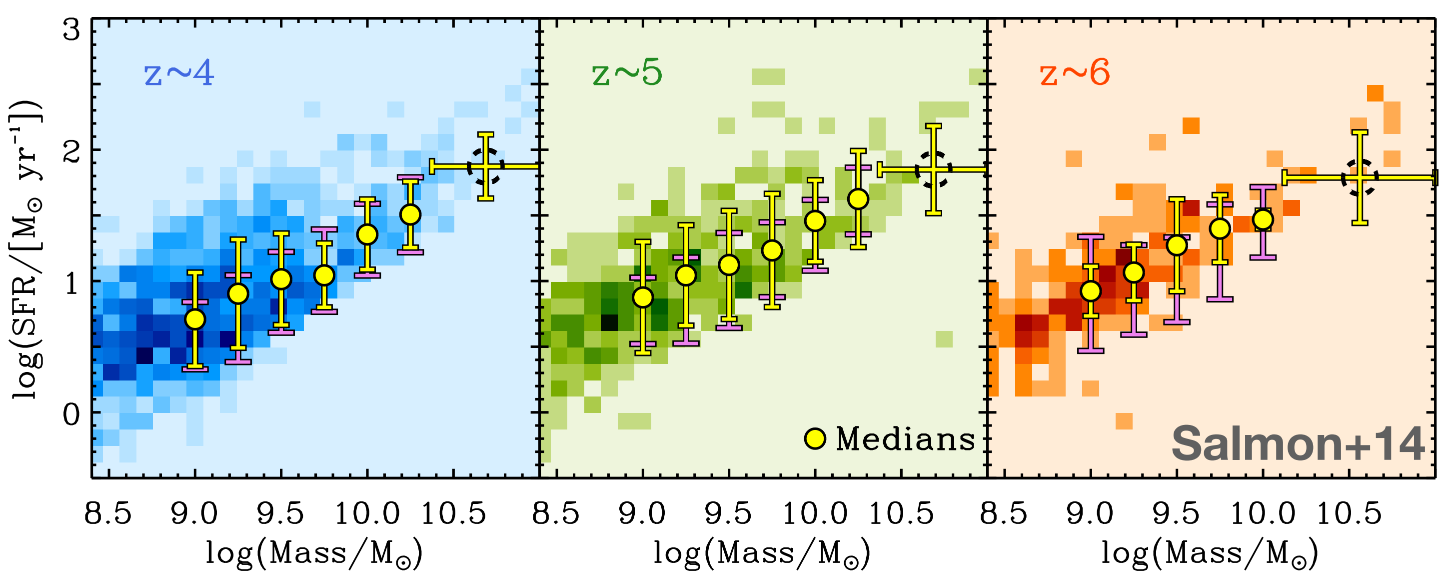
Stellar Mass Build-up

Making use of HST+Spitzer imaging over CANDELS
(and accounting for rest-frame optical emission lines):

estimates of the stellar MF out to z~8

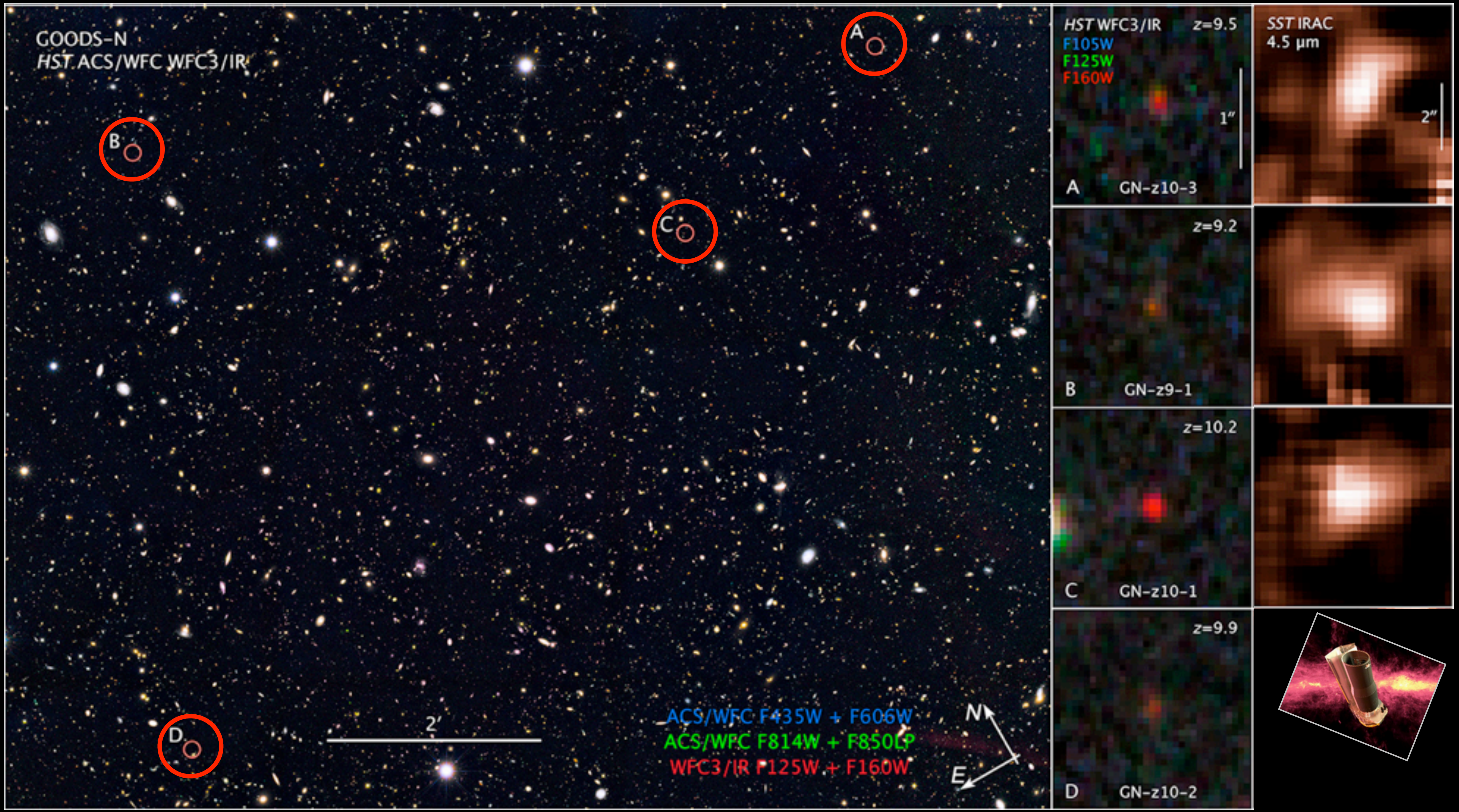


“main sequence” of star-formation at z~4-6



see also: Grazian+15, Caputi+15, Duncan+14, Ilbert+13, Muzzin+13, Gonzalez+11, Lee+12

Sample of 4 Bright z~9-10 Galaxy Candidates

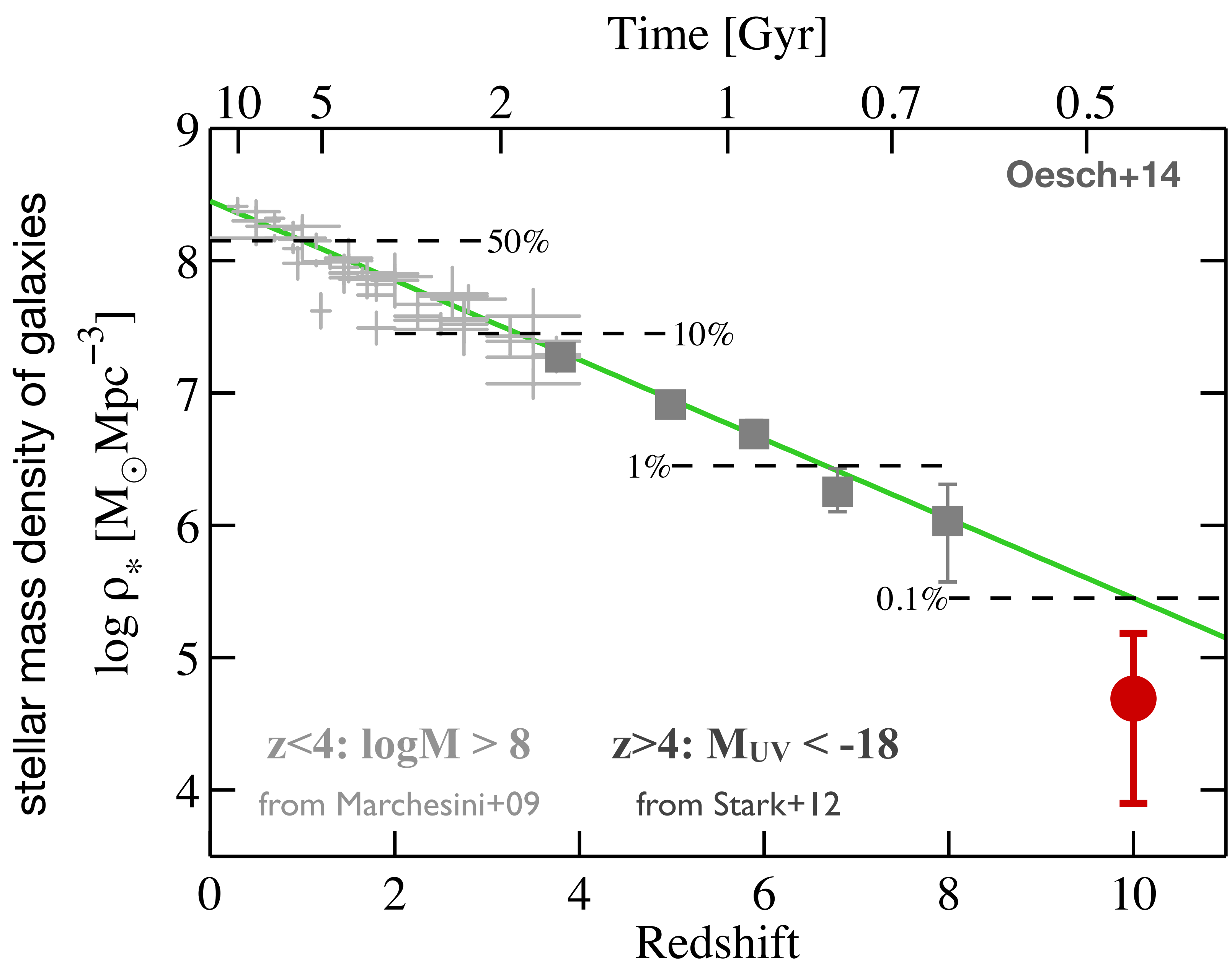


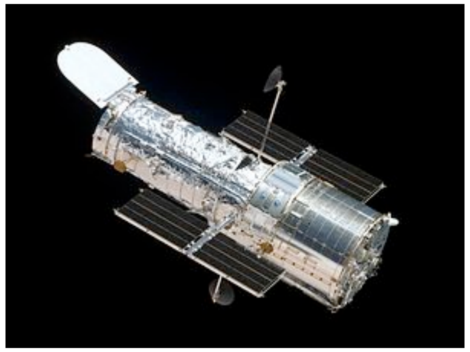
NASA and ESA

STScI-PRC14-05a

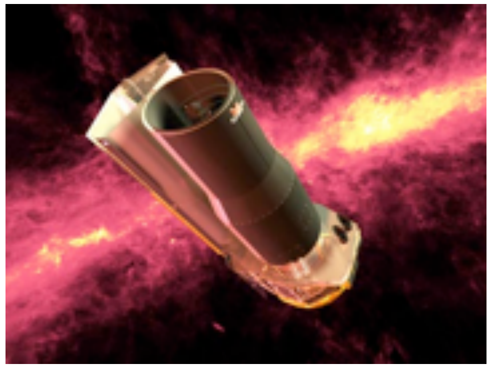
Powerful combination of HST and Spitzer to explore most distant galaxies

Stellar Mass Density Evolution to z~10



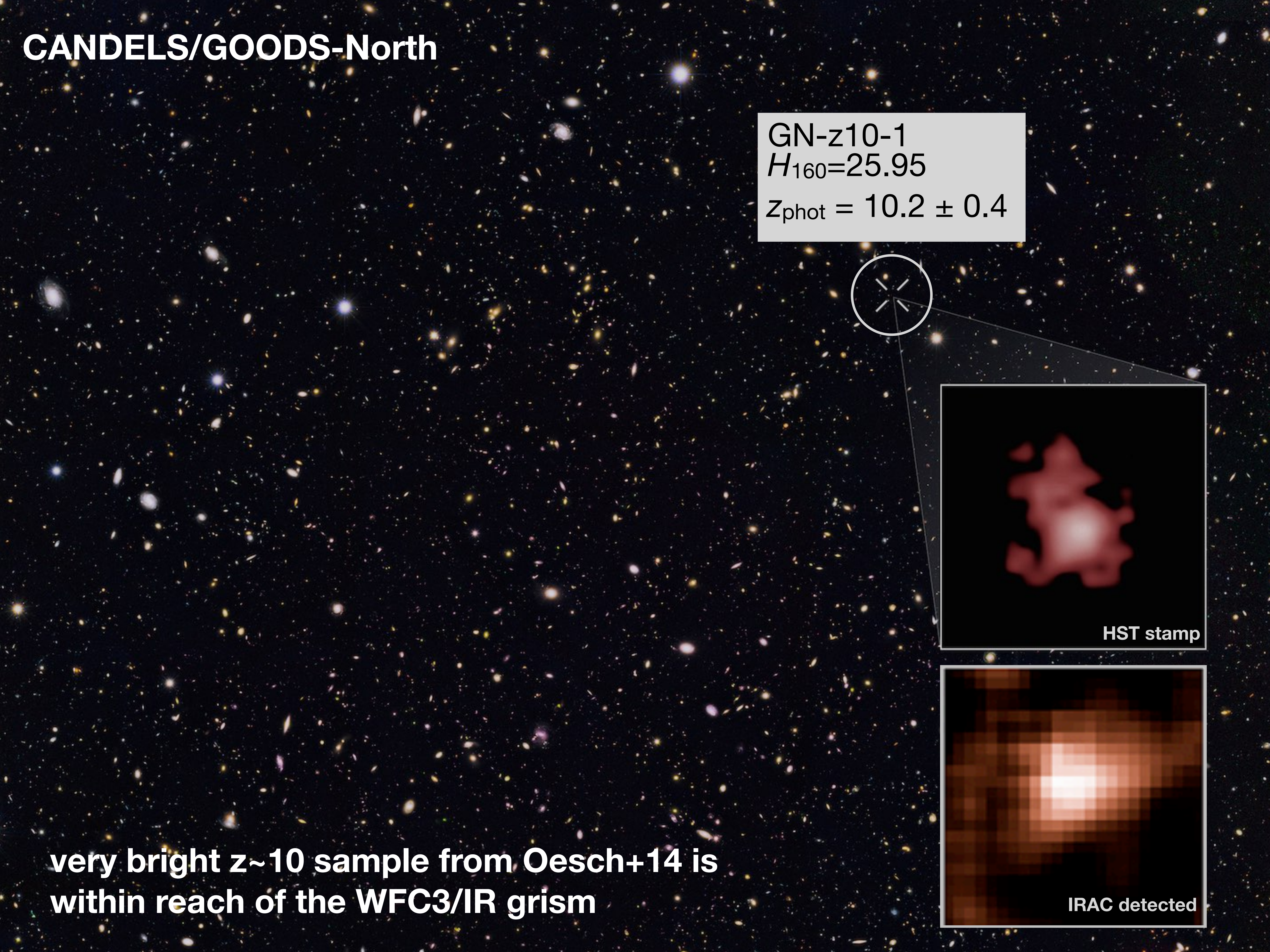


+

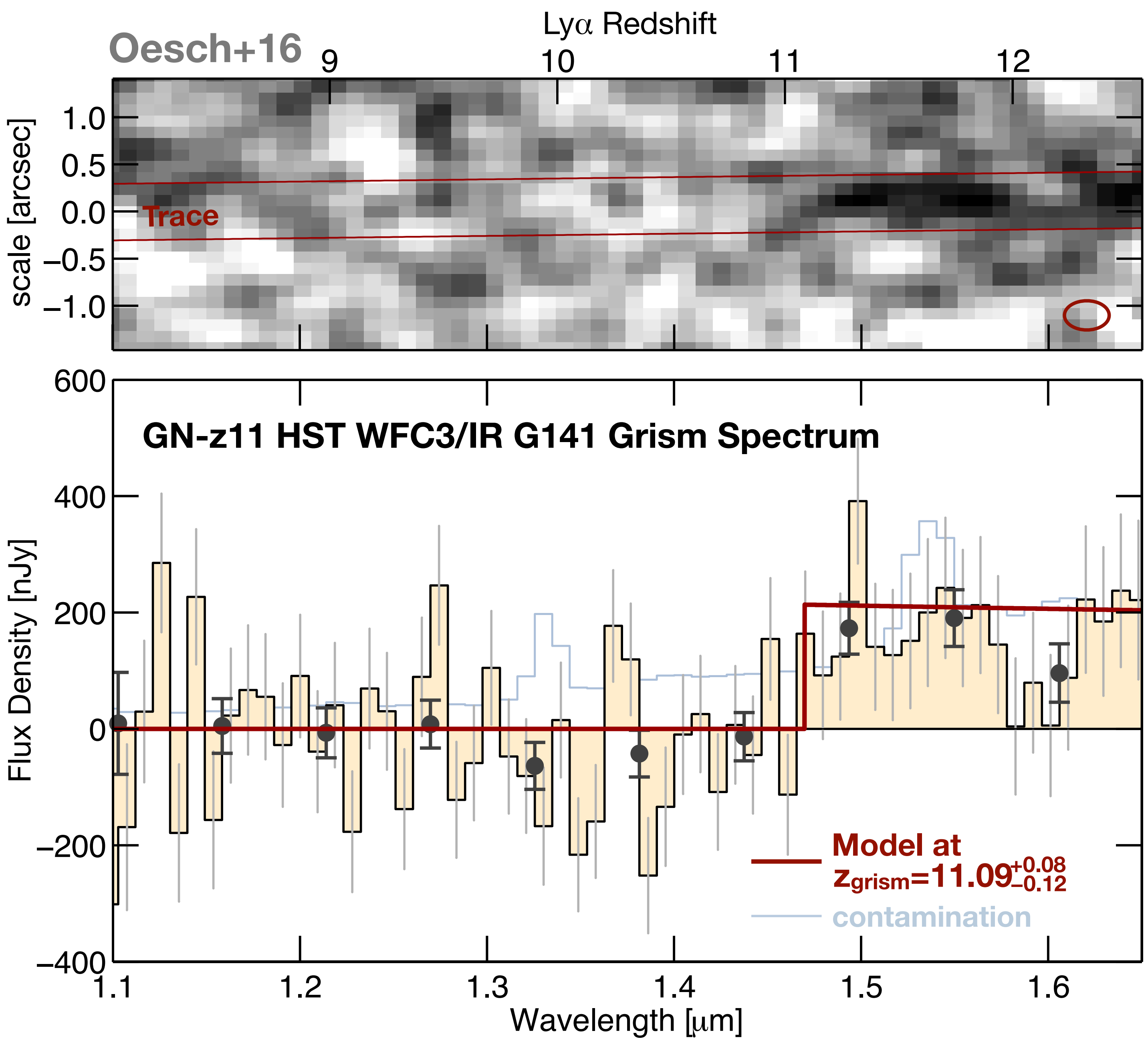


Stellar mass density estimates at z>4 nicely match up with mass limited studies at z<4.

Are witnessing the assembly of the first 0.1% of local stellar mass density.
The first two Gyr are a very active epoch of galaxy assembly.


CANDELS/GOODS-North
GN-z10-1
H_{160}=25.95
z_{phot} = 10.2 ± 0.4
HST stamp
IRAC detected
very bright z~10 sample from Oesch+14 is
within reach of the WFC3/IR grism

Lyman Break Detection at z=11



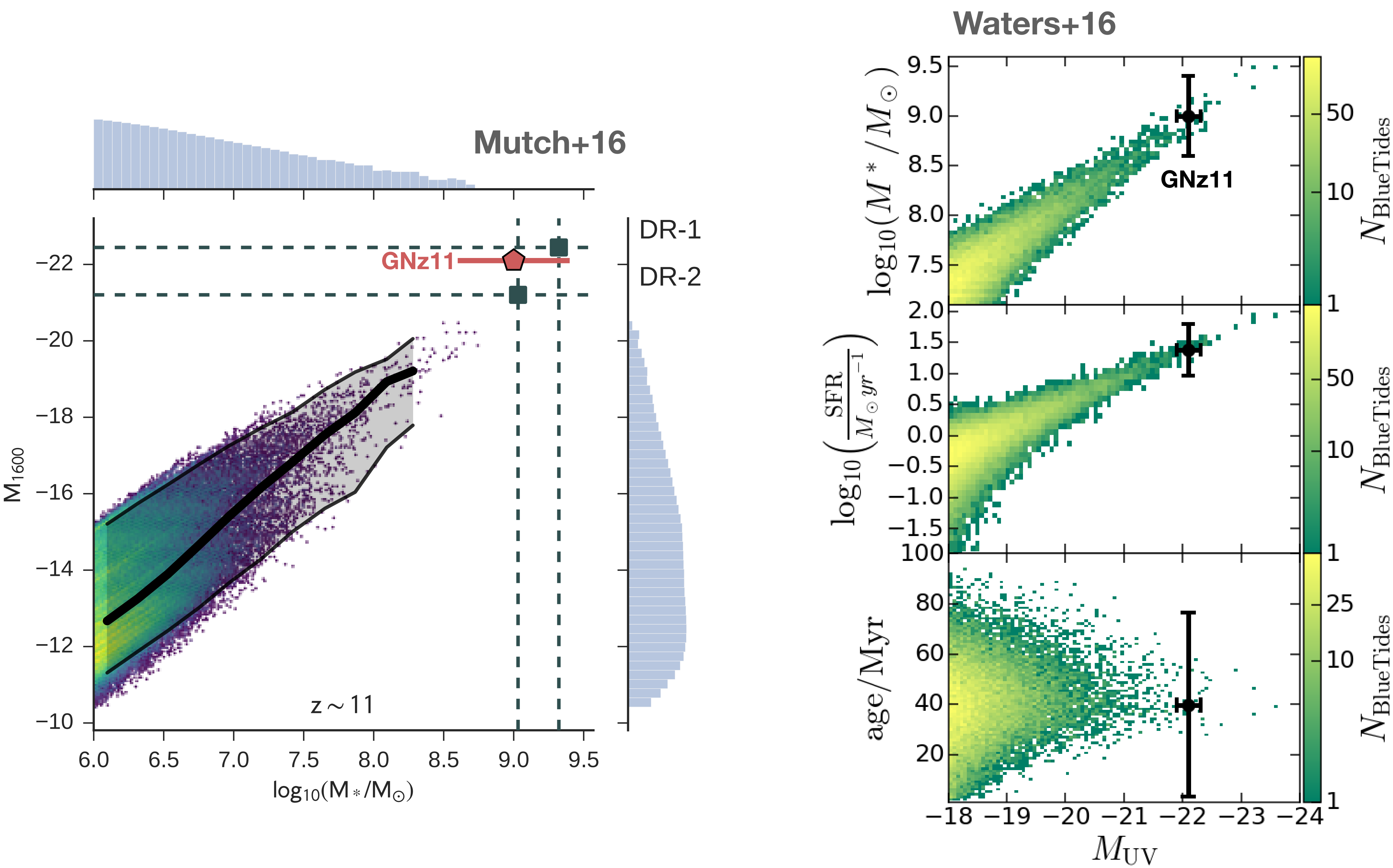
- 12 orbits of HST grism spectra with WFC3/IR
- Detect UV continuum (at 5.5σ) and a break at λ > 1.47 μm
- Rule out potential lower redshift solutions (quiescent galaxy at z~2 or strong emission line source)
- Best-fit redshift: z=11.09+-0.10

GN-z10-1 → GN-z11

Most distant source ever seen

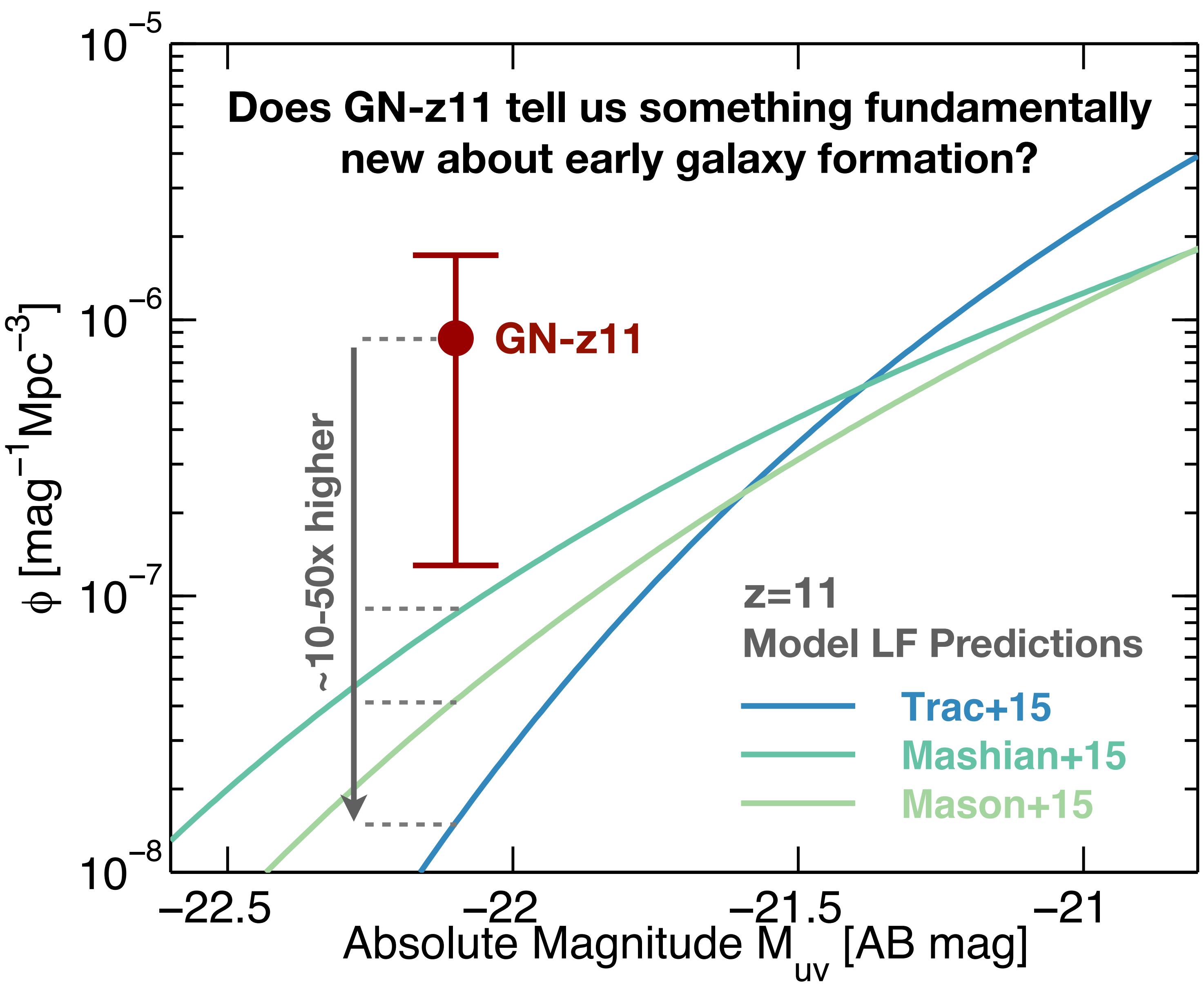
Build-up of massive galaxies well underway at 400 Myr after Big Bang

Physical Properties of GN-z11 in Line with Models



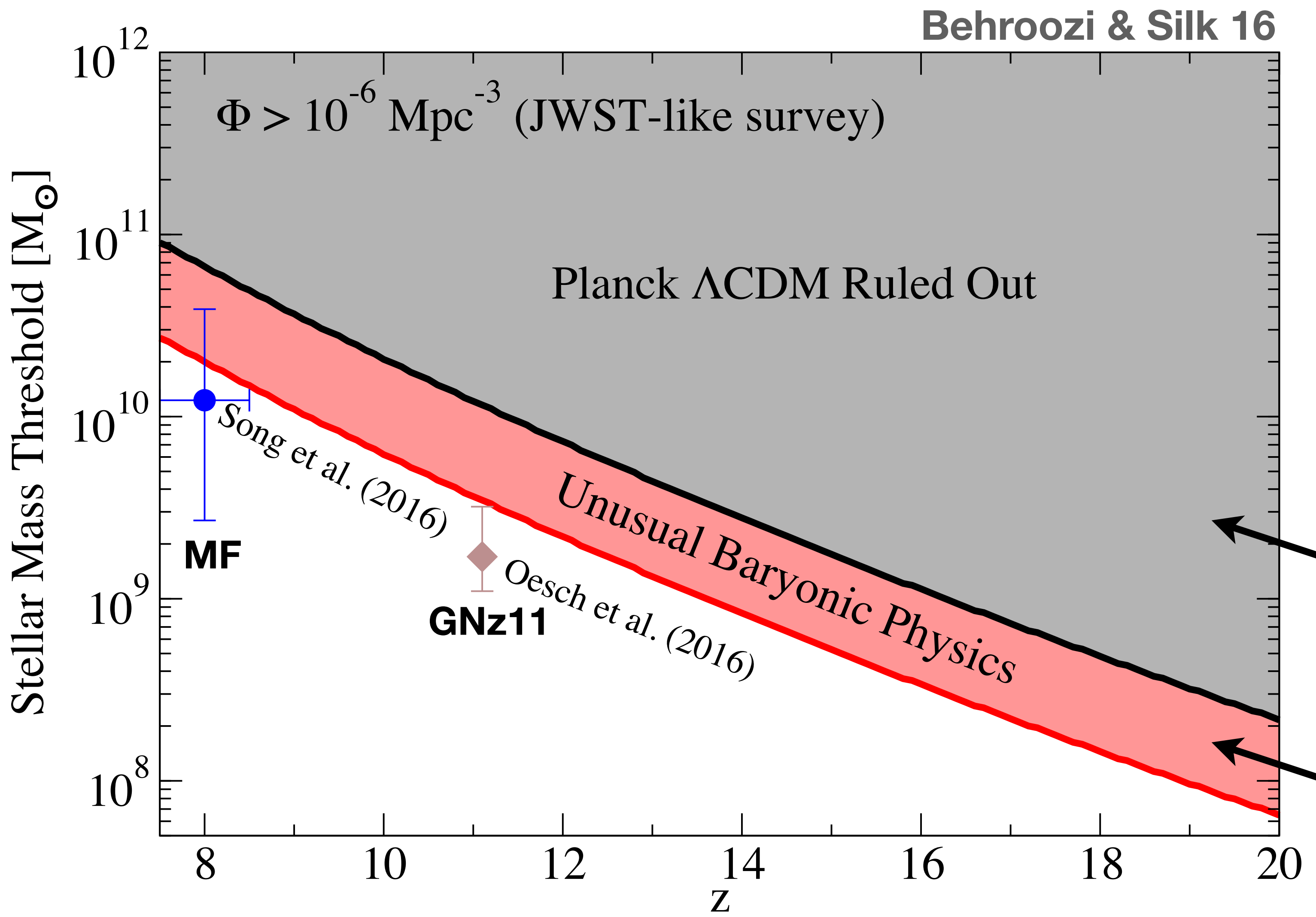
The derived physical properties (SFR, mass, and age) of GN-z11 are in very good agreement with expectations from large-volume simulations

GN-z11 is off the Charts



- Detection of GN-z11 in existing data is quite unexpected, given current models
- Expected to require 10-100x larger areas to find one such bright z~11 galaxy as GN-z11
- Difficult to draw conclusions based on one source. **Need larger survey!**

Changing Physics at Highest Redshifts?

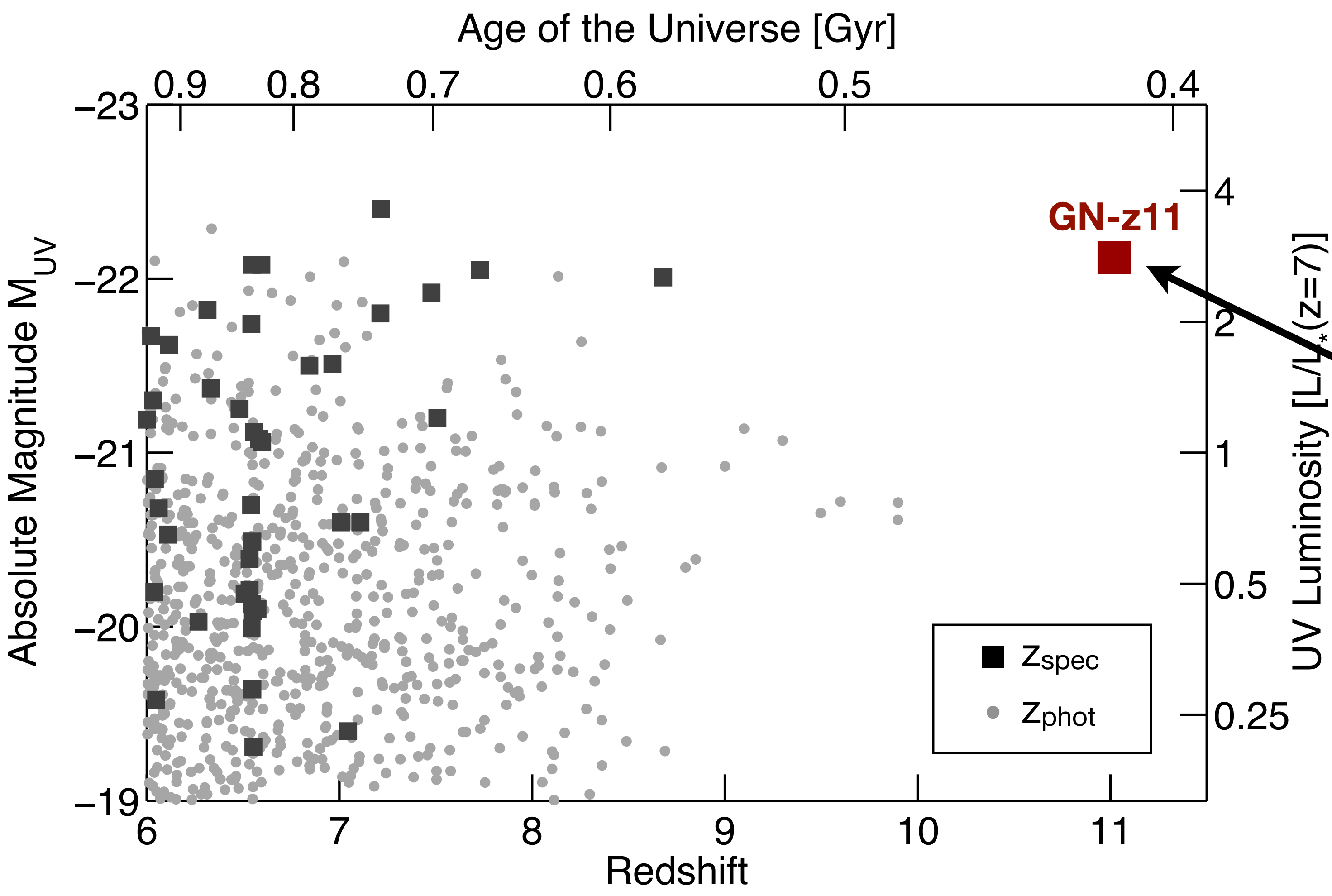


Would need more baryons than available in DM haloes

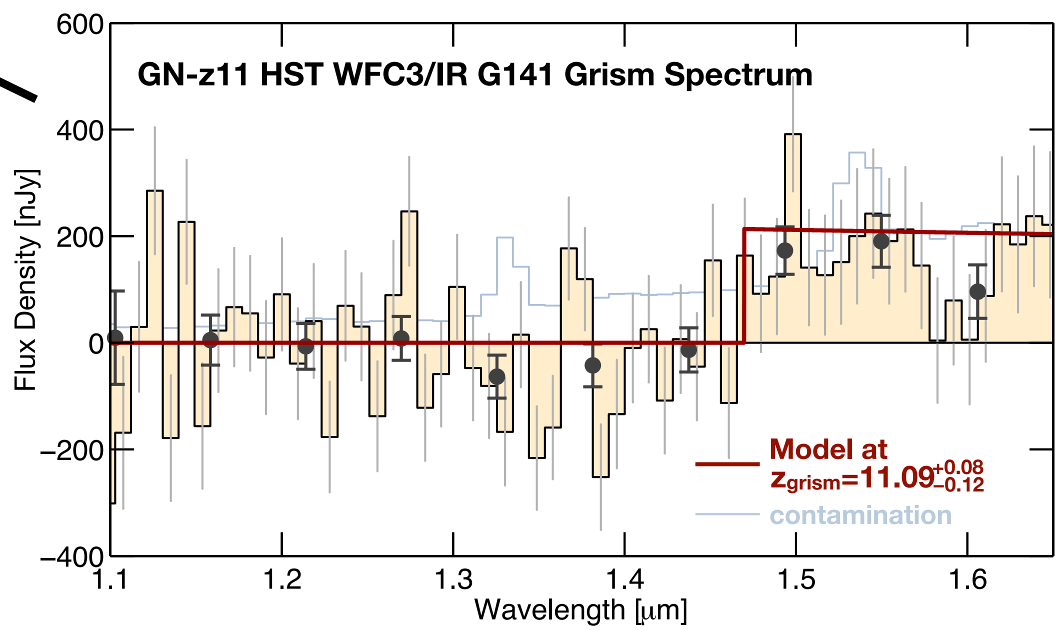
Would need higher star-formation efficiencies than found at lower redshift

Massive galaxies found in current surveys at high redshift are still compatible with "standard" picture of galaxy formation.

The Current Spectroscopic Frontier

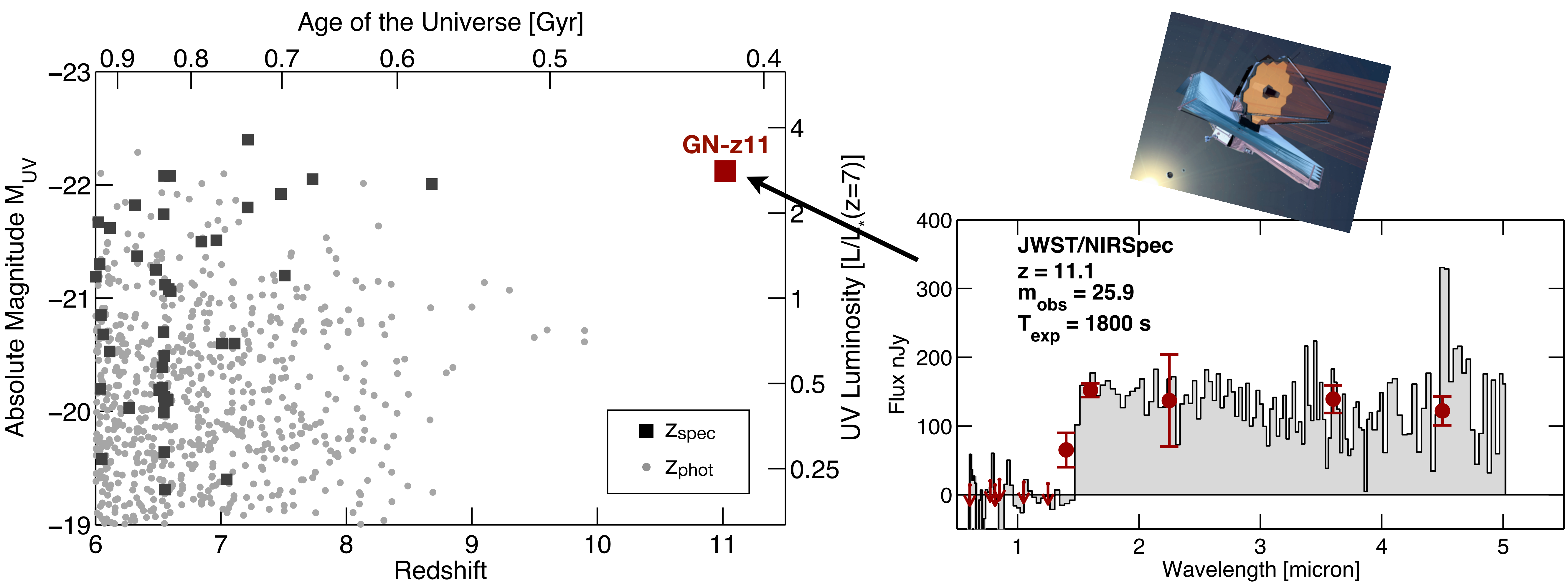


GN-z11 is by far the most distant known source



With surprising discovery of GN-z11,
HST+Spitzer have already **reached into JWST territory**

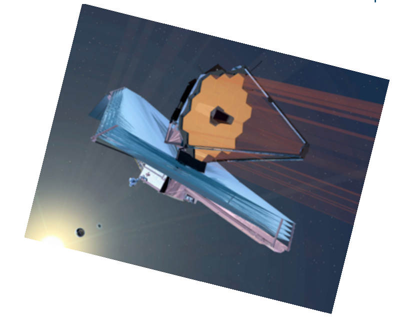
Moving Forward with JWST NIRSPEC



However, JWST spectroscopy will completely **revolutionize** this field!

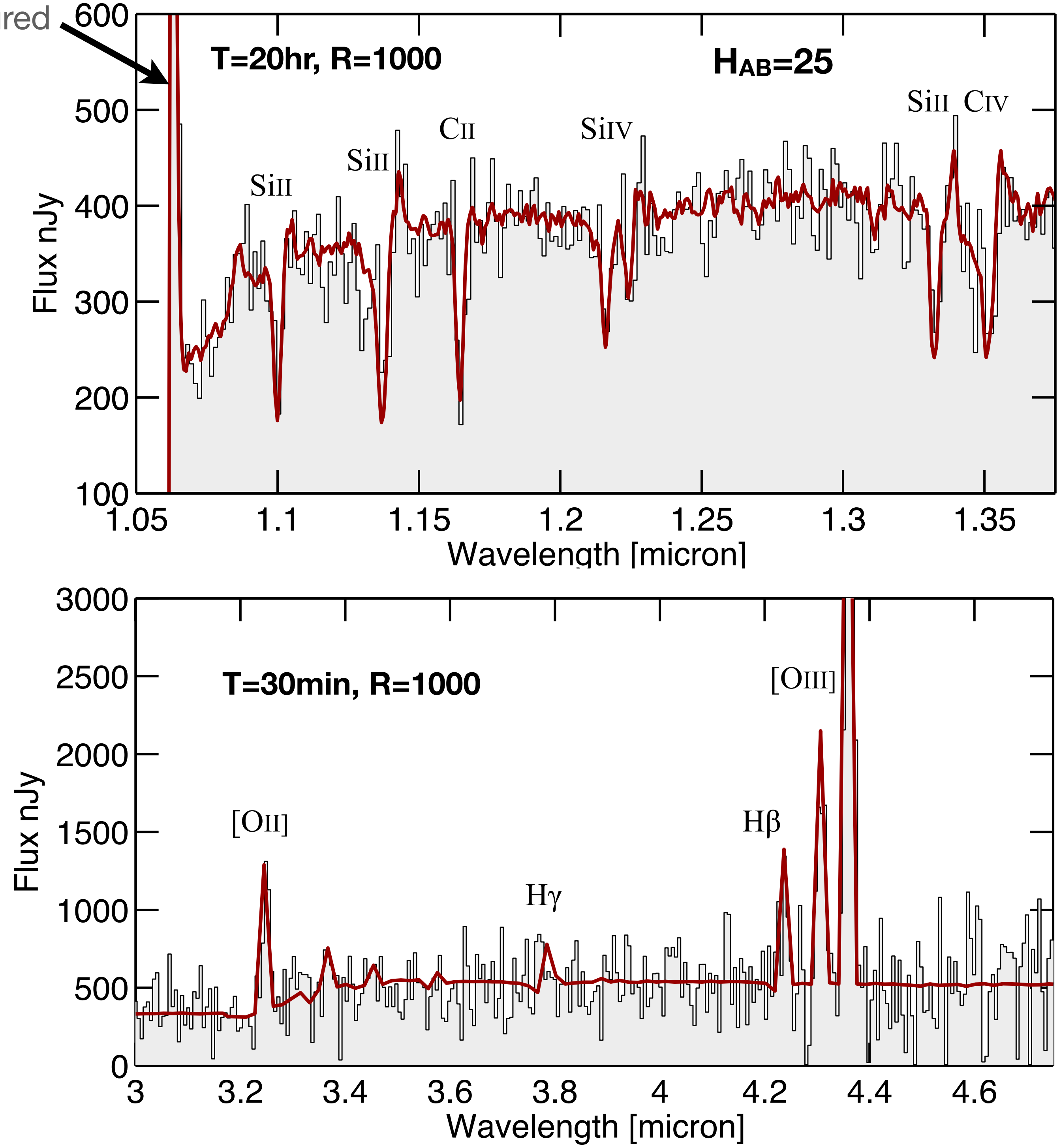
JWST can in principle get spectroscopic redshifts for every single source currently known with HST

JWST/NIRSpec: Unprecedented Spectra



only line currently measured

Simulation based on z=7.73 source from Oesch+15



- JWST will be extremely efficient in spectroscopic characterization of z>7 galaxies
- For brightest targets, like the recently confirmed target EGS-zs8-1 at z=7.73, we will even be able to measure absorption lines

What is the ionization state of gas in early galaxies?

What is their dynamical state?

How fast did they build up their metals?

Wide area surveys like HSC are critical to find bright targets that will provide unique information with JWST spectra

Summary

- **Deep imaging with HST** enabled the detection of an unprecedented sample of galaxies at z>3 (11'000), and extended our frontier into the heart of the cosmic reionization epoch (**~1000 galaxies at z~7-10**). Cosmic Frontier: **z=11.1**

- The **UV LF is extremely steep** during the reionization epoch (faint end slopes as steep as $\alpha = -2$) ➔ ultra-faint galaxies likely main drivers for reionization

- Combination of very deep **HST and IRAC** data allow us to measure rest-frame optical colors and **stellar mass build-up** from z~10 to z~3-4. We now explored **97% of cosmic history** in build-up of star-formation and mass

- Discovery of **GN-z11 in current search area is surprising** according to models: **Need larger area surveys** to confirm the number densities of bright galaxies at z>10. Needs to be done now with HST, likely won't be done with JWST!

- Finding **bright galaxies at high redshift** (e.g. with HSC) is crucial for JWST: these sources will give access to **unique information with spectroscopy**