Galaxy Build-up at Cosmic Dawn:
Insights from Deep HST and Spitzer/IRAC Observations

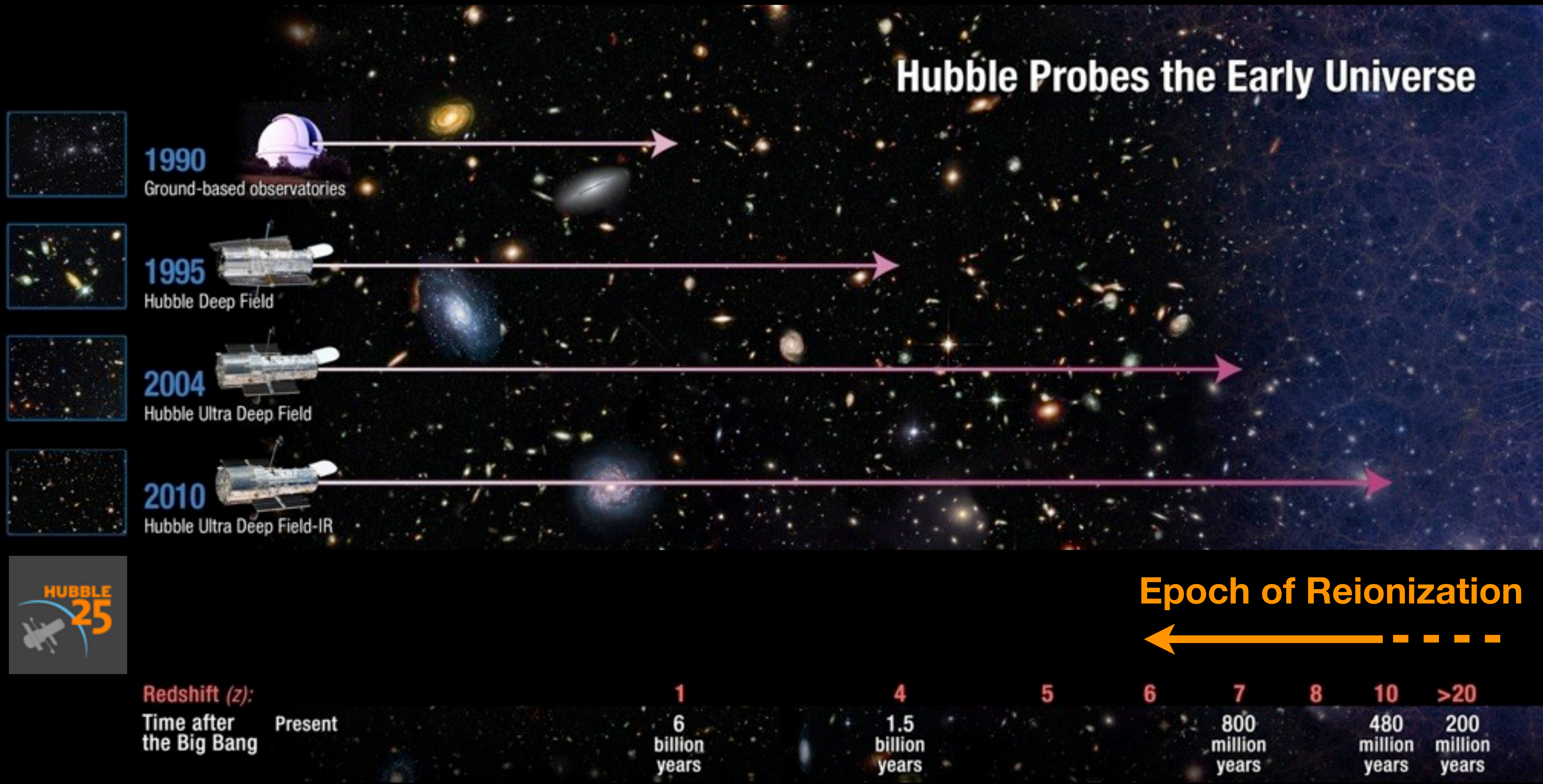
Pascal Oesch

Yale University → Geneva Observatory

in collaboration with **XDF Team+**: R. Bouwens, I. Labbé, G. Brammer, G. Illingworth, M. Franx, P. van Dokkum, D. Magee, V. Gonzalez, M. Trenti, C.M. Carollo, M. Stiavelli, R. Smit, L. Spitler, G. Fazio, M. Ashby, S. Willner, I. Momcheva, R. Skelton

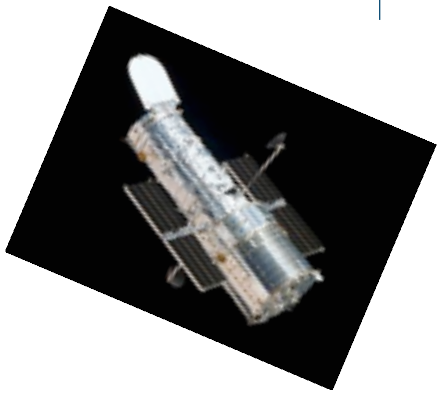
The history of astronomy is a history of receding horizons.

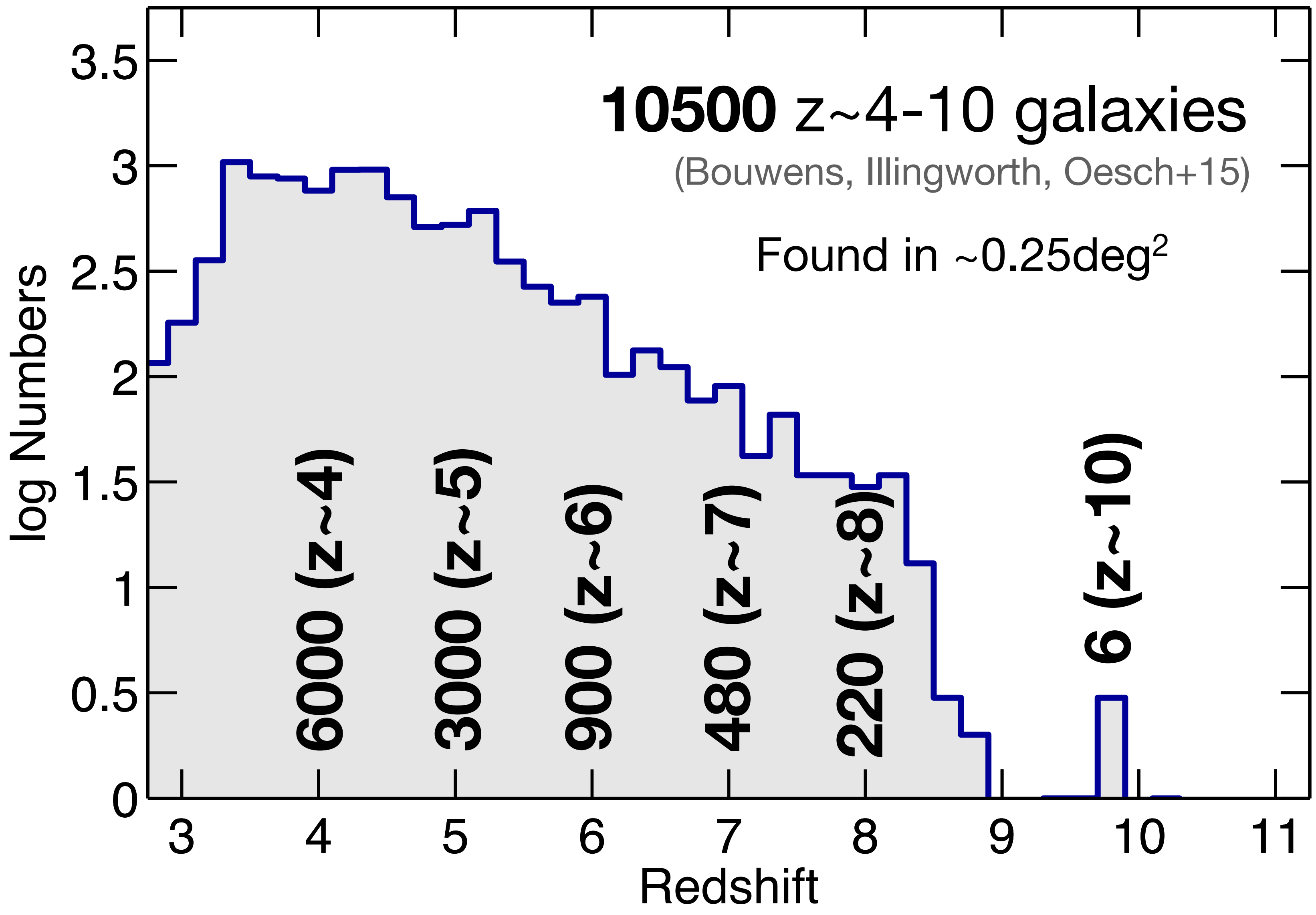
E. P. Hubble



Unprecedented Galaxy Samples at z>=4

(from HST's blank fields only)

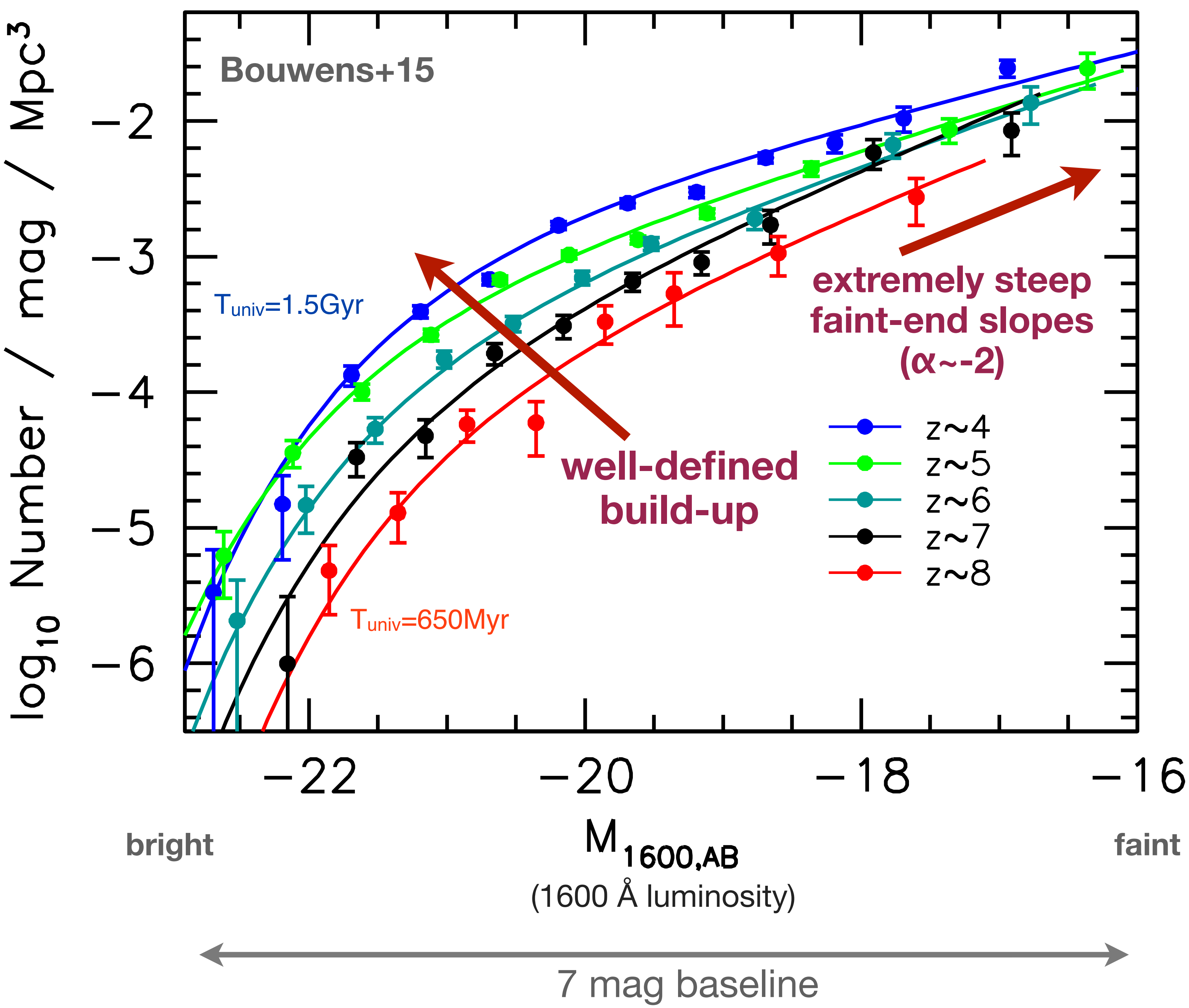




Almost 1000 galaxies in the epoch of reionization at z>6

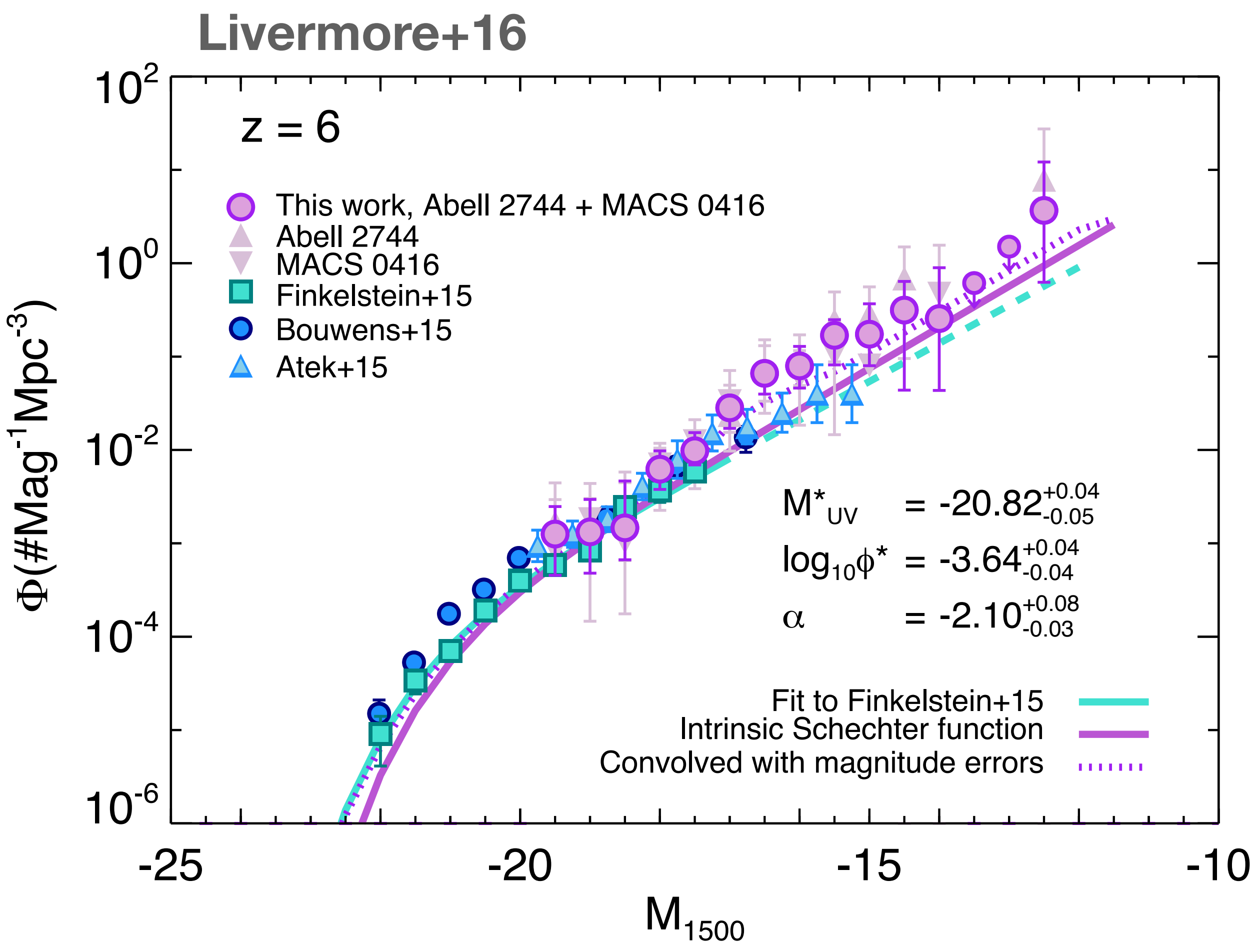
Current frontier: z~9-10

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, ...

The Hubble Frontier Fields: Extending Analyses to Fainter Luminosities

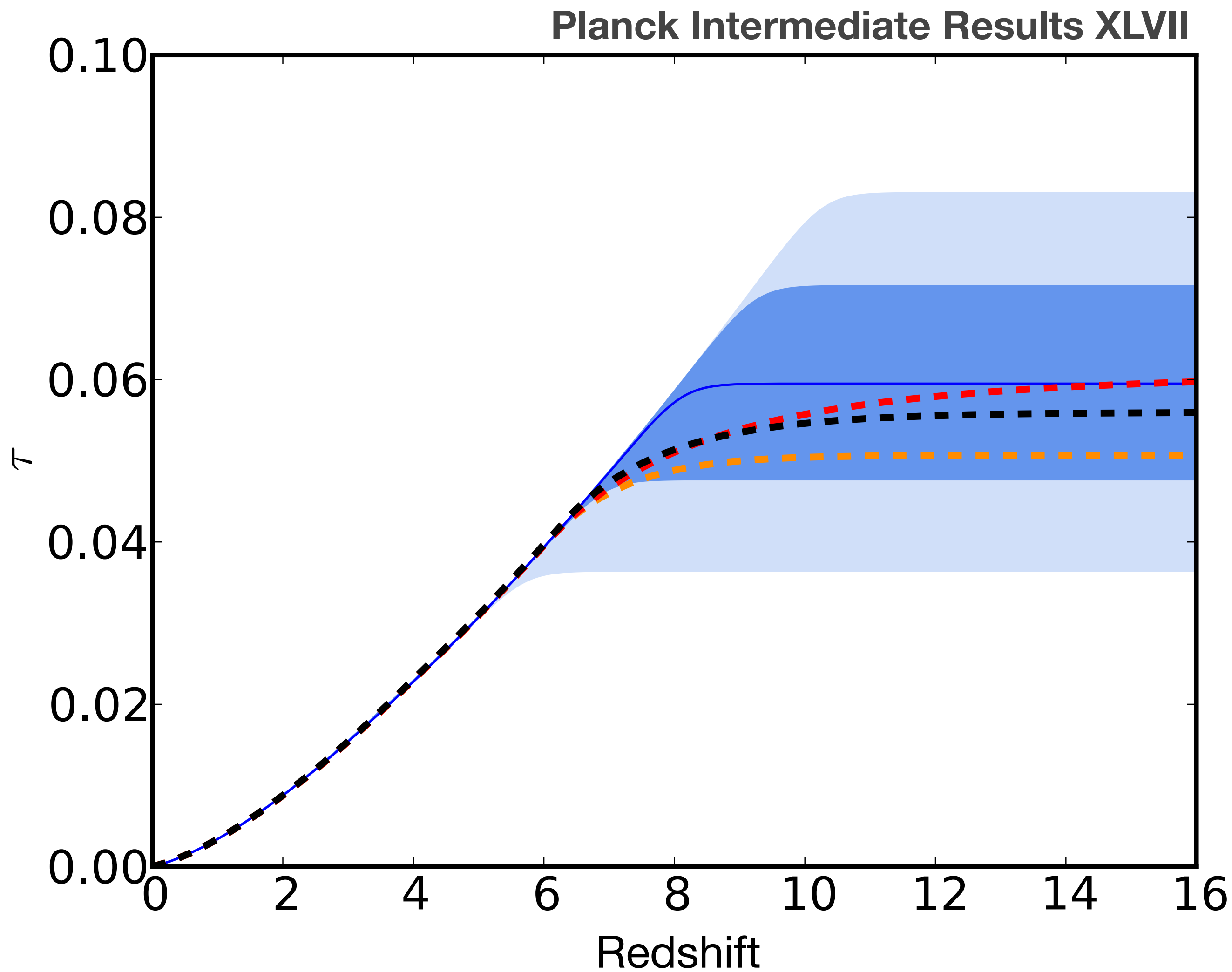


Using HFF dataset, some indication for continued steep increase in LF down to M_{UV}~-13.

Unclear, how much these LFs can be trusted given uncertainties in high-magnification regions (>10x)

See also: e.g. Atek+15ab, Ishigaki+15, Laporte+15, Castellano+16

Reionization by Faint Dwarf Galaxies

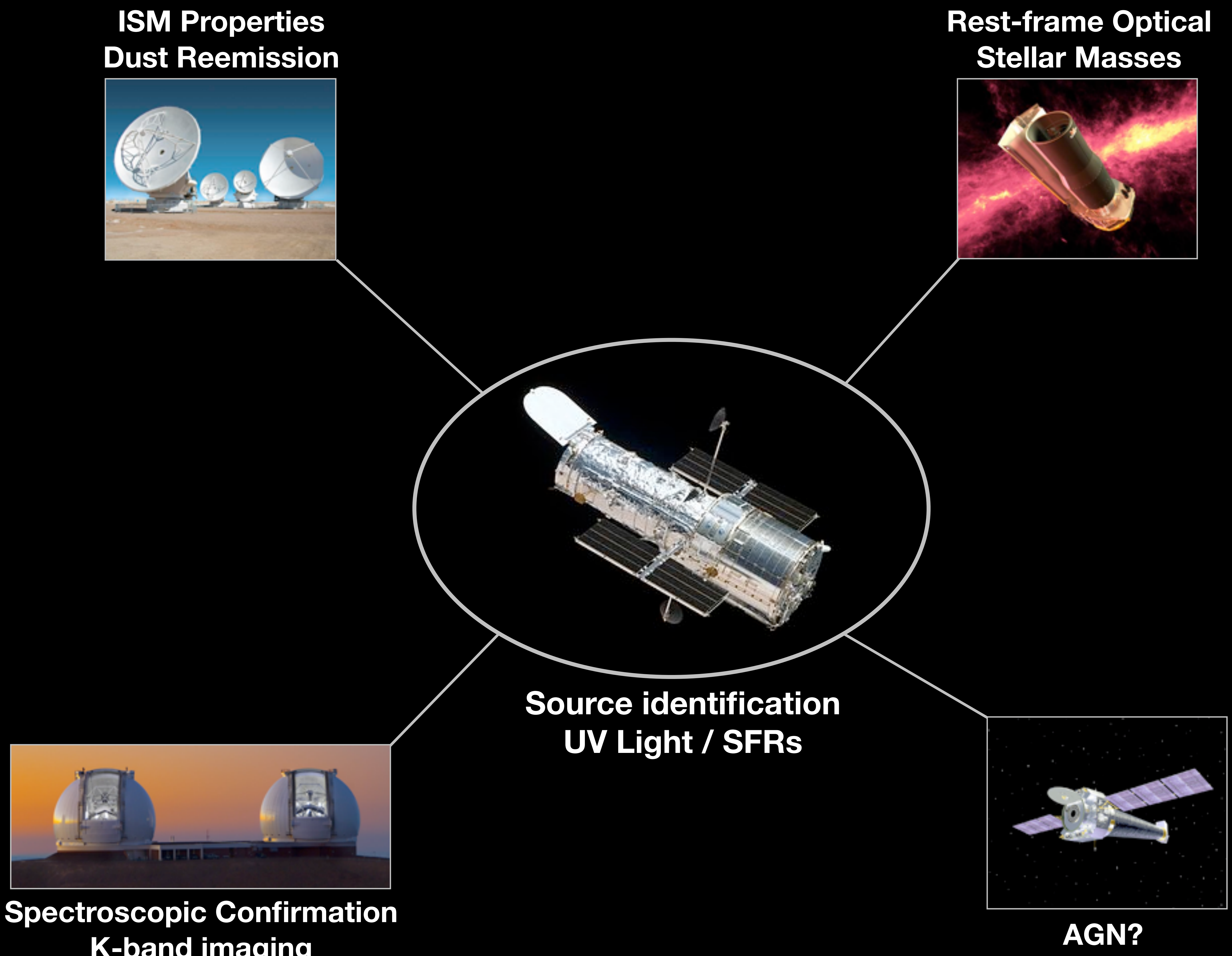


Dashed lines: different extrapolations of UV LFs by Bouwens+15, Robertson+15, Ishigaki+15

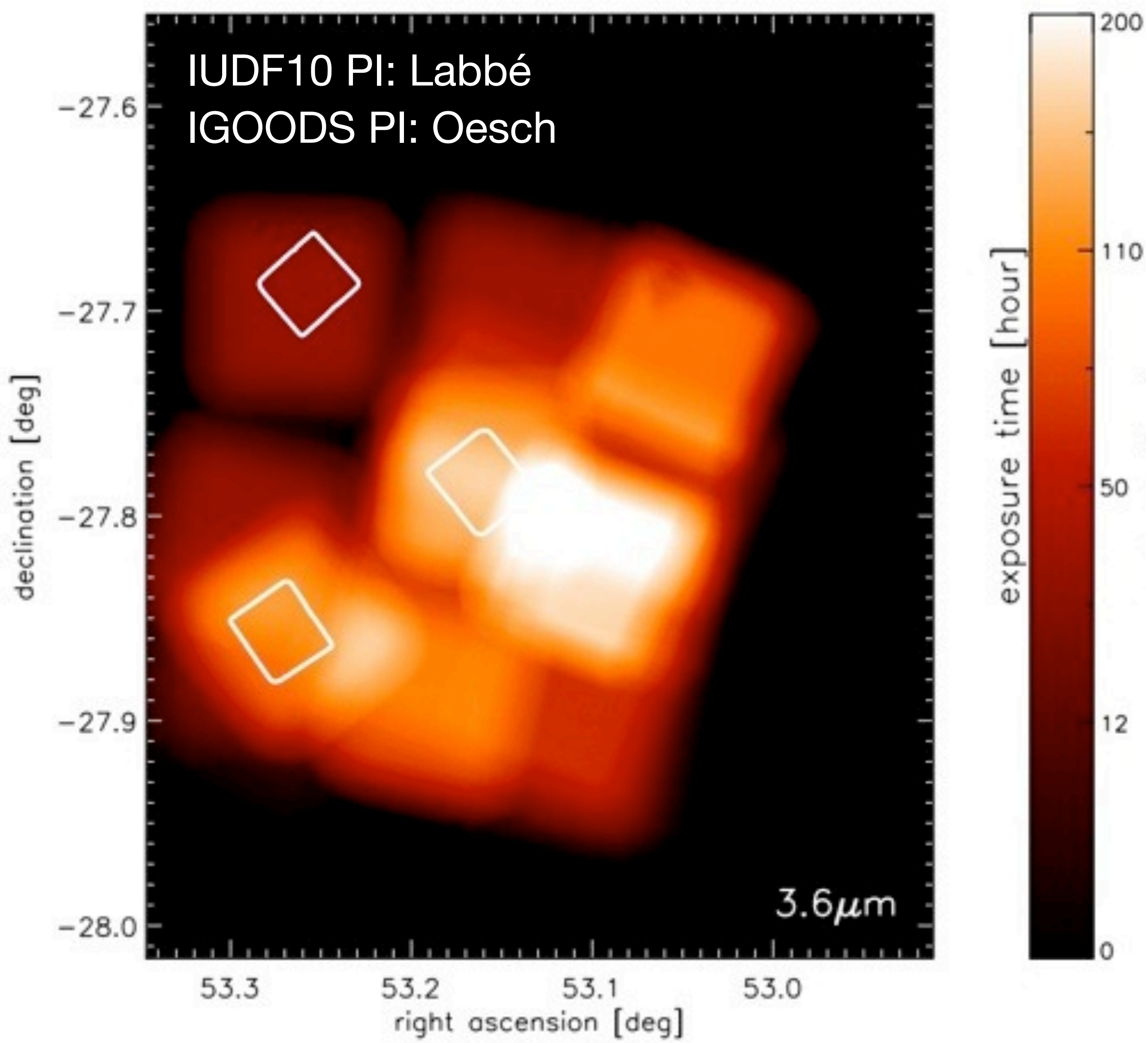
New Planck polarization results find: $\boldsymbol{\tau_e = 0.058 \pm 0.012}$, i.e. $\boldsymbol{z_{reion} = 8.2 \pm 1.1}$
Consistent with estimates from ultra-faint galaxy population.

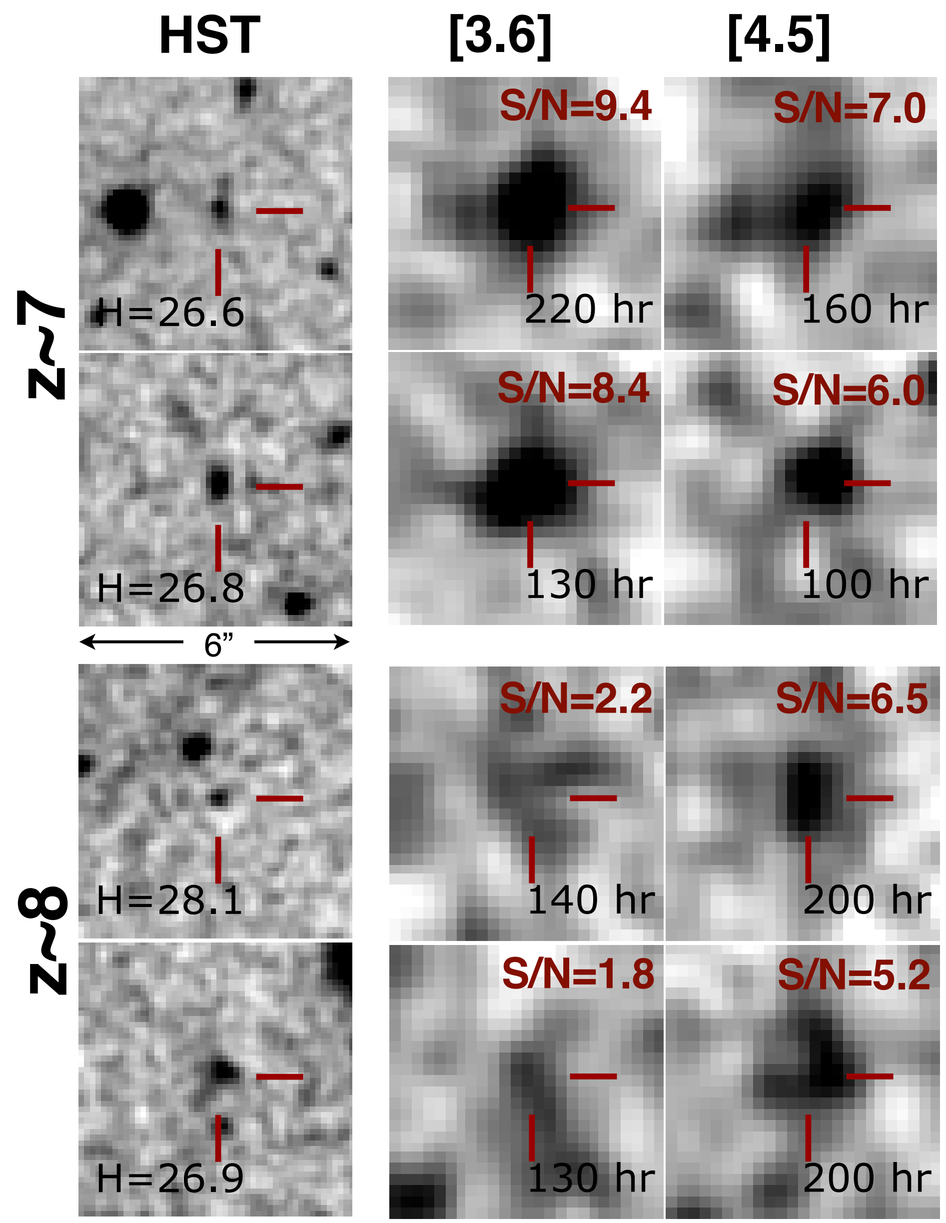
➡ **Was reionization driven by faint dwarf galaxies? Likely yes!**
Caveats: uncertainties in UV LF faint end slope and f_{esc}

See also: Oesch+09, Bouwens+12, Kuhlen+12, Finkelstein+12, Robertson+13/15


ISM Properties
Dust Reemission
Rest-frame Optical
Stellar Masses
Source identification
UV Light / SFRs
Spectroscopic Confirmation
K-band imaging
AGN?

Very Faint, Individually Detected z~7-8 Sources





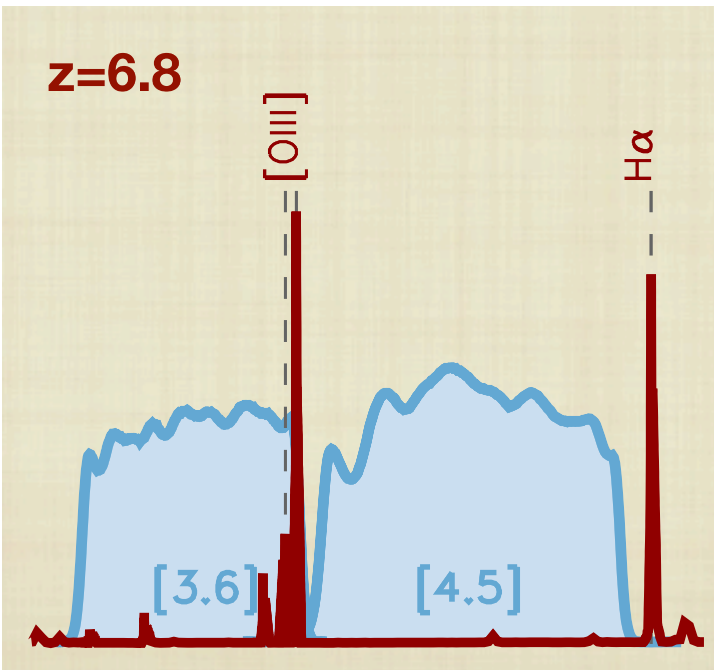
Labbe, Oesch+15

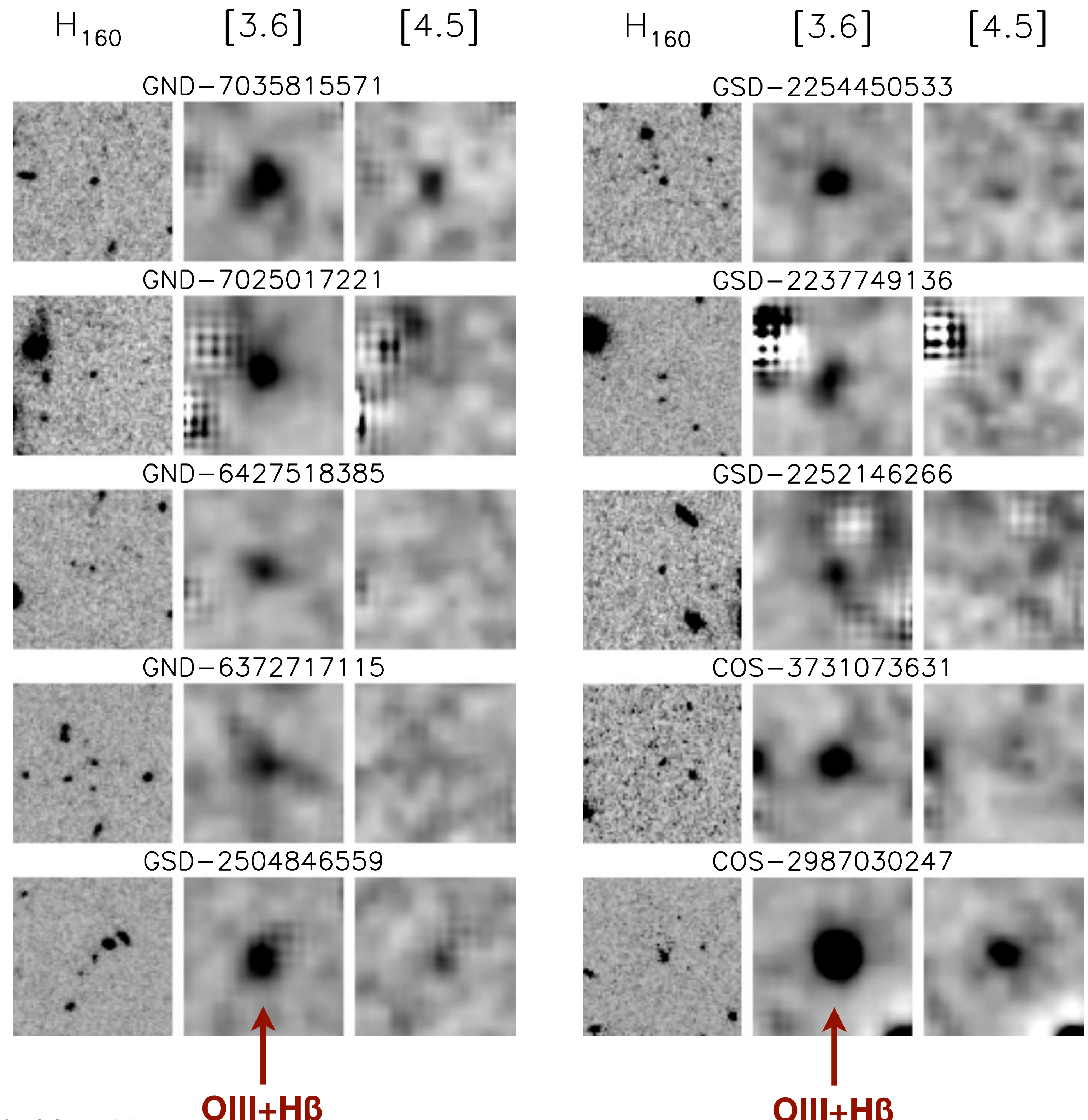
Small area over GOODS-S has 180-220 hour IRAC exposure times (27.4 mag, 3σ)

Ongoing program (**GREATS**; PI Labbe, 733 hrs) to push full GOODS-S+N Deep to this depth

Extremely Strong Lines are Ubiquitous at z>6

Smit et al. 2014, 2015





At z~6.8 Spitzer/IRAC [3.6] provides a clean probe of OIII+Hβ lines.

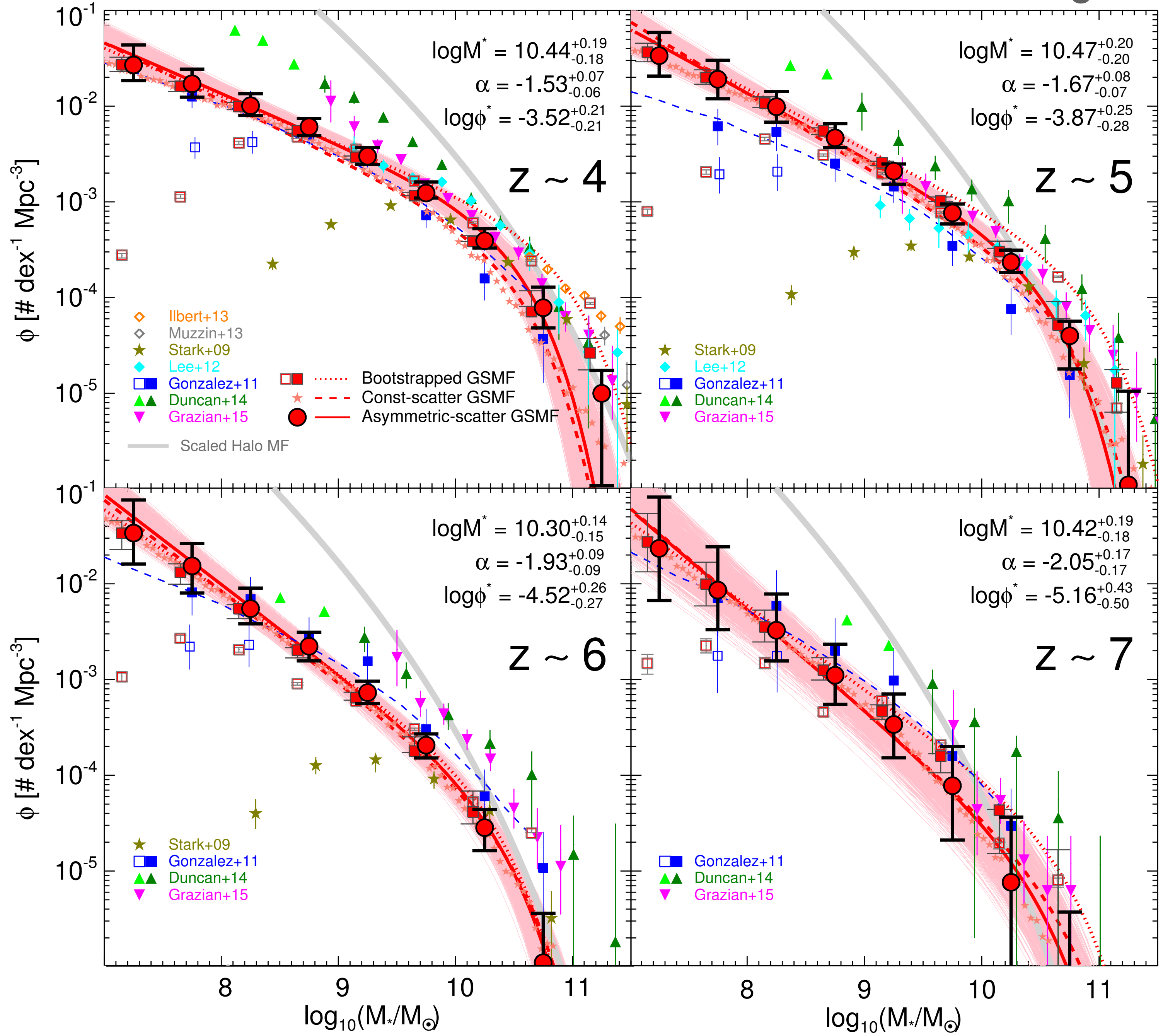
Extremely strong rest-frame EWs reaching over 1000 Å are common at these redshifts!

Needs to be accounted for in SED mass fits.

see also: Schaerer&deBarros09, deBarros+14, Shim+11, Labbe+13

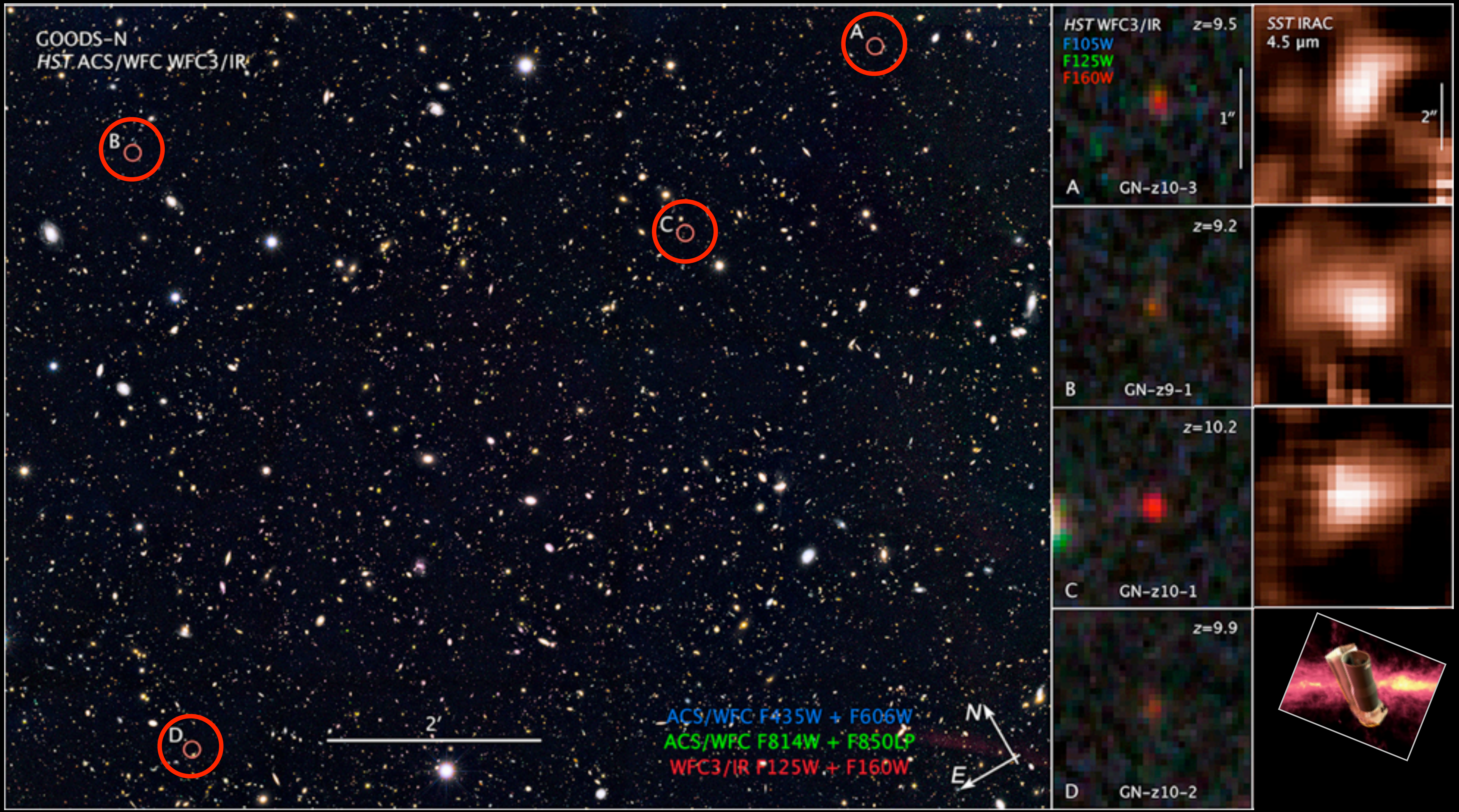
Galaxy Stellar Mass Functions at High Redshift

Song+16



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

Rest-Frame Optical Light of z~9-10 Galaxies

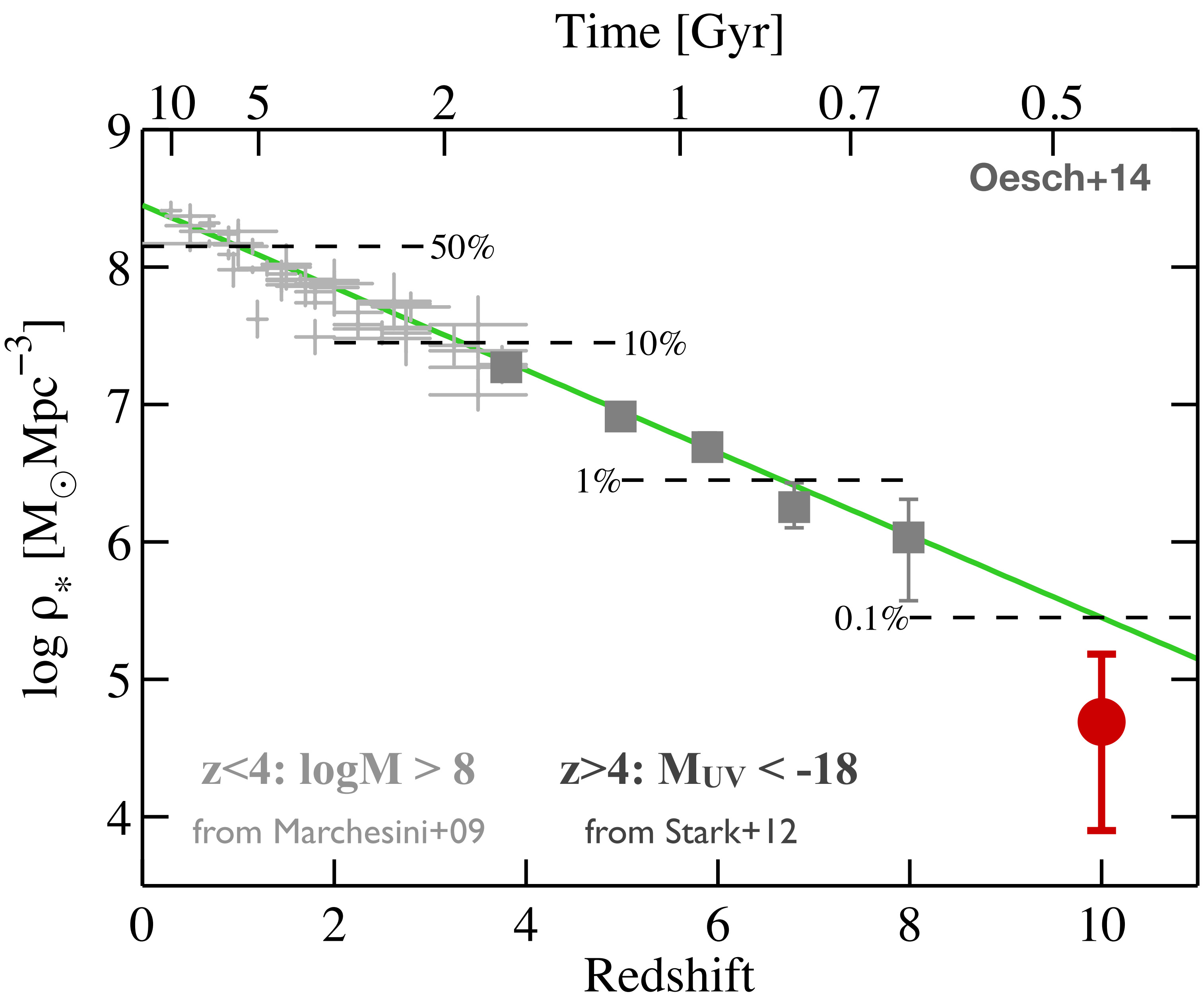


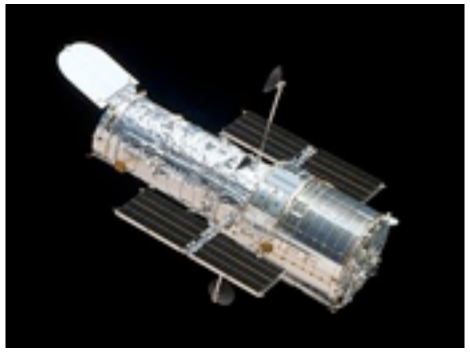
NASA and ESA

STScI-PRC14-05a

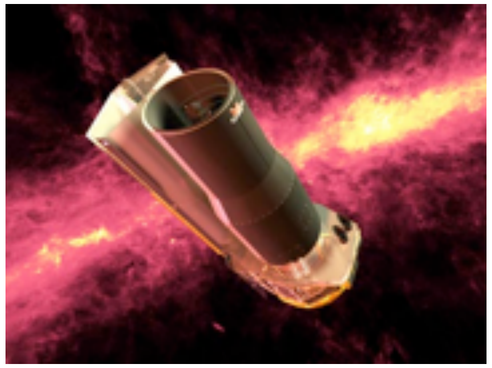
Powerful combination of HST and Spitzer to explore most distant galaxies

Stellar Mass Density Evolution to z~10





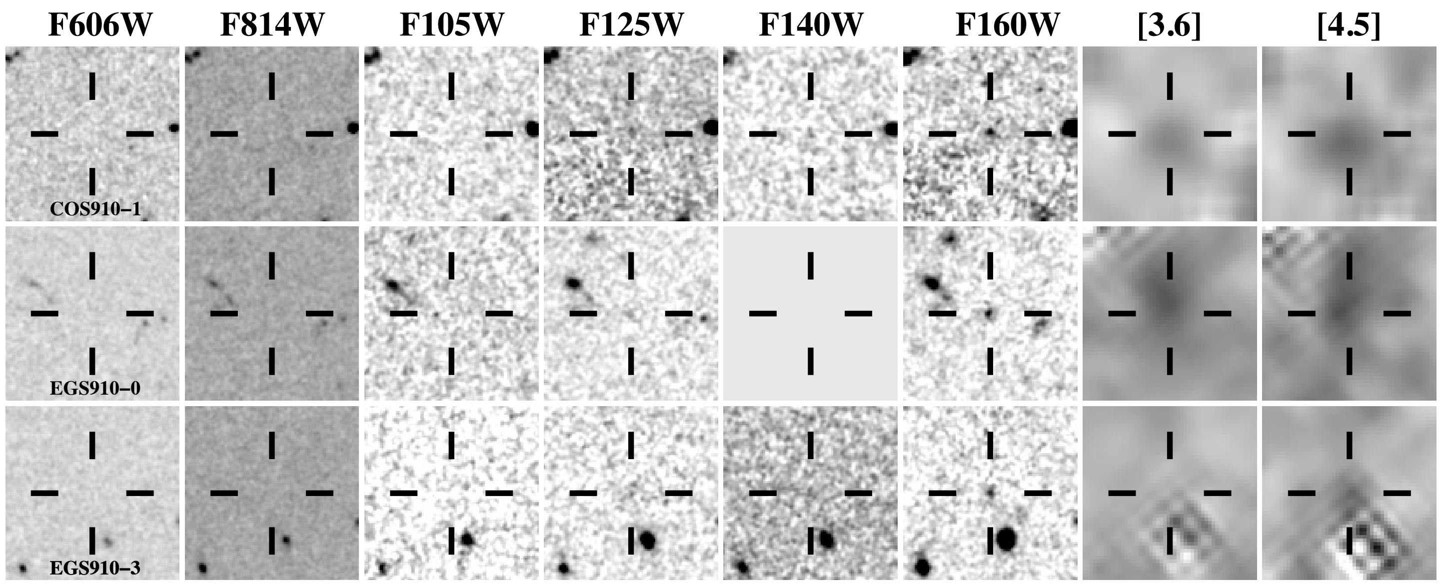
+



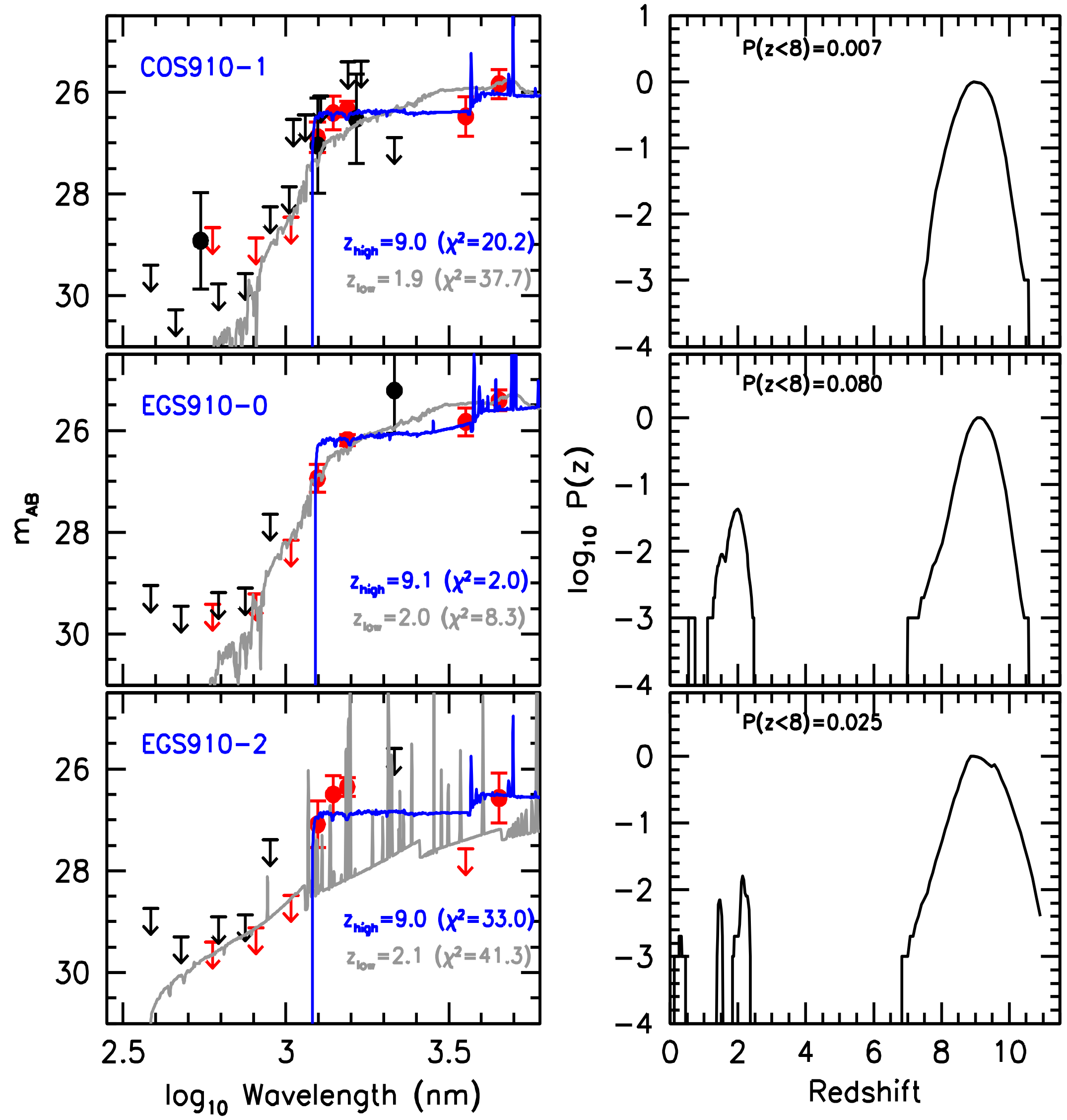
Luminosity limited SMD estimates at z>4 nicely match up with mass limited studies at z<4.

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.

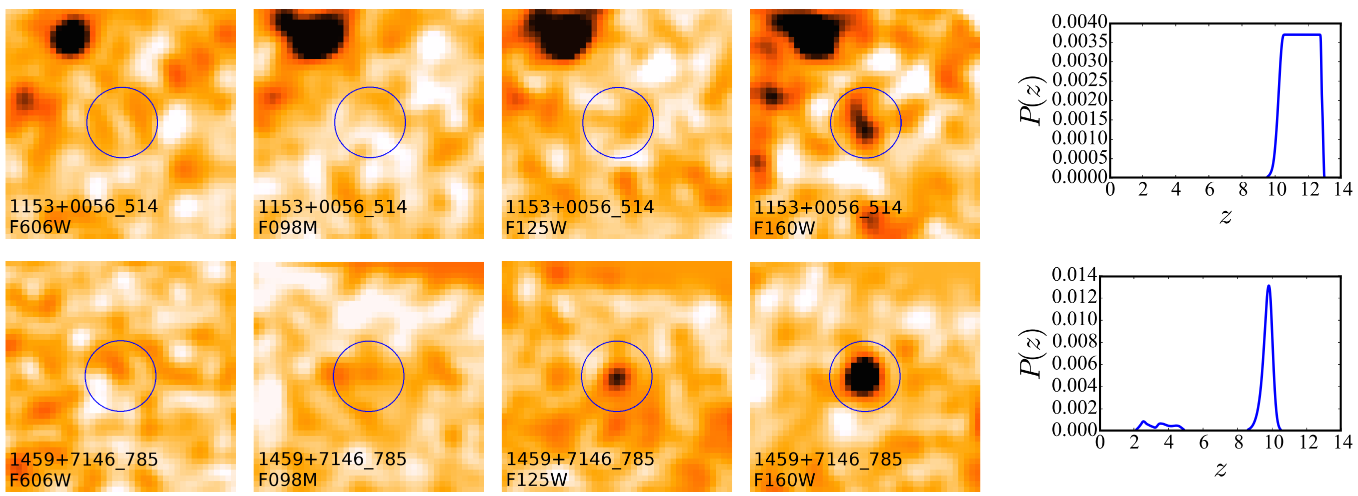
Increased z~9-10 Galaxy Sample: Full CANDELS + BORG



Bouwens+15



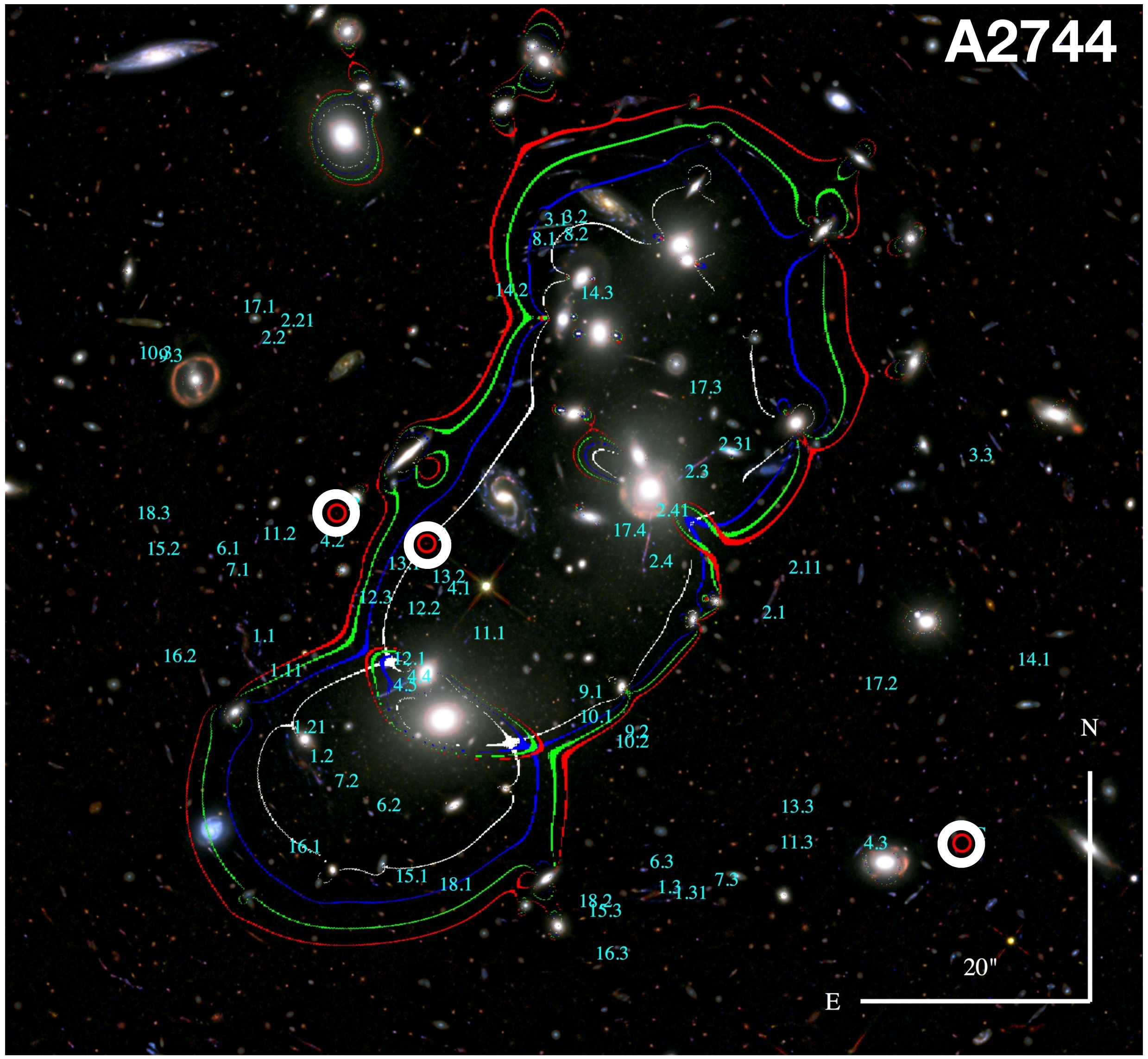
Calvi+15/Bernard+16

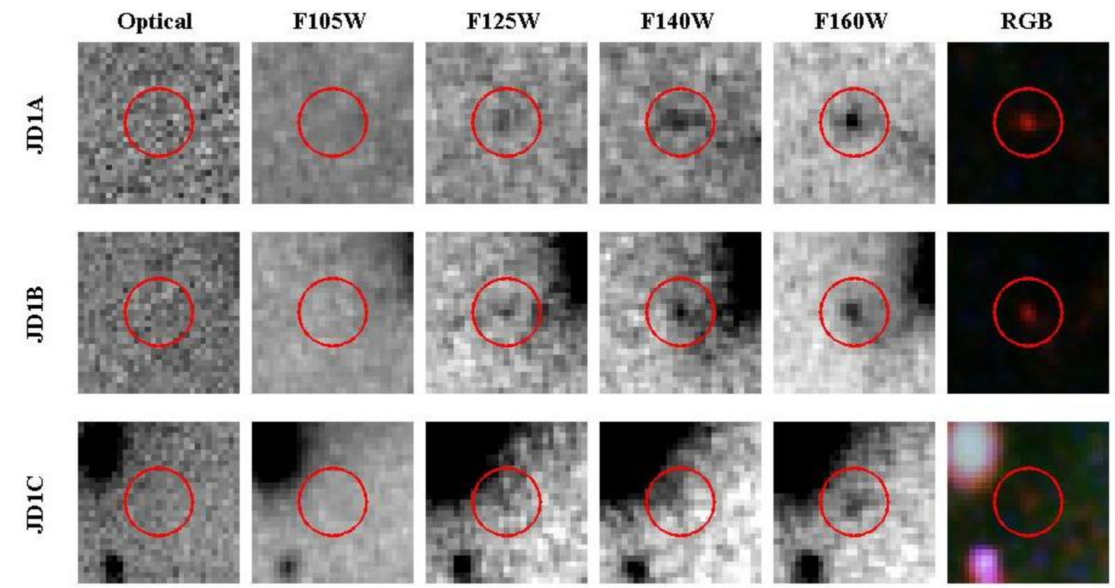


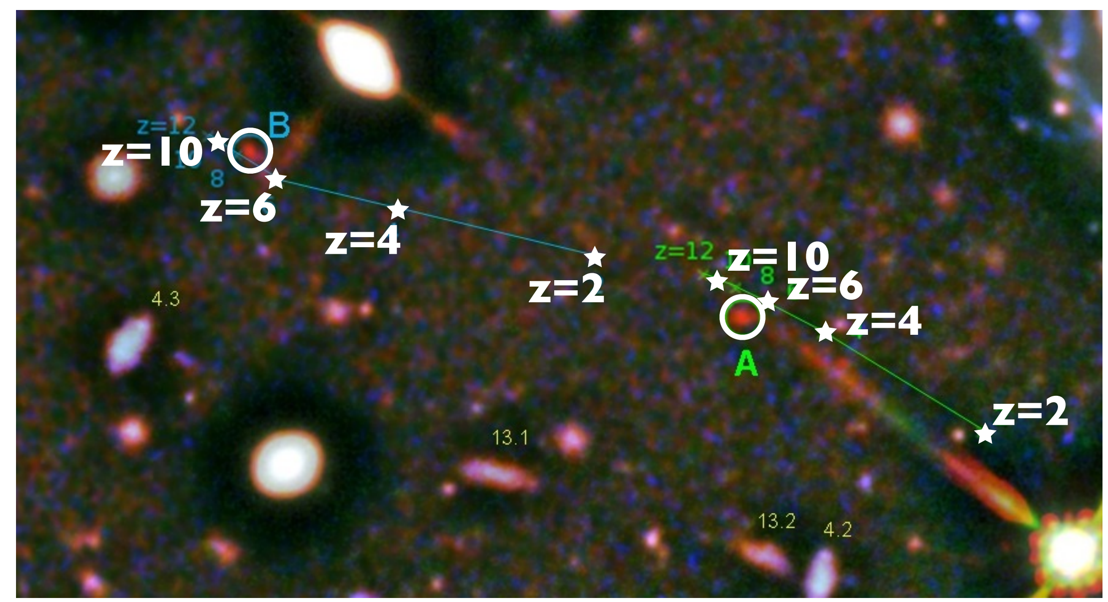
A handful new, bright, bona-fide z~9-10 candidates with H=26.0-26.5

Triply Imaged z~10 Candidate in First FF Cluster

Zitrin+14





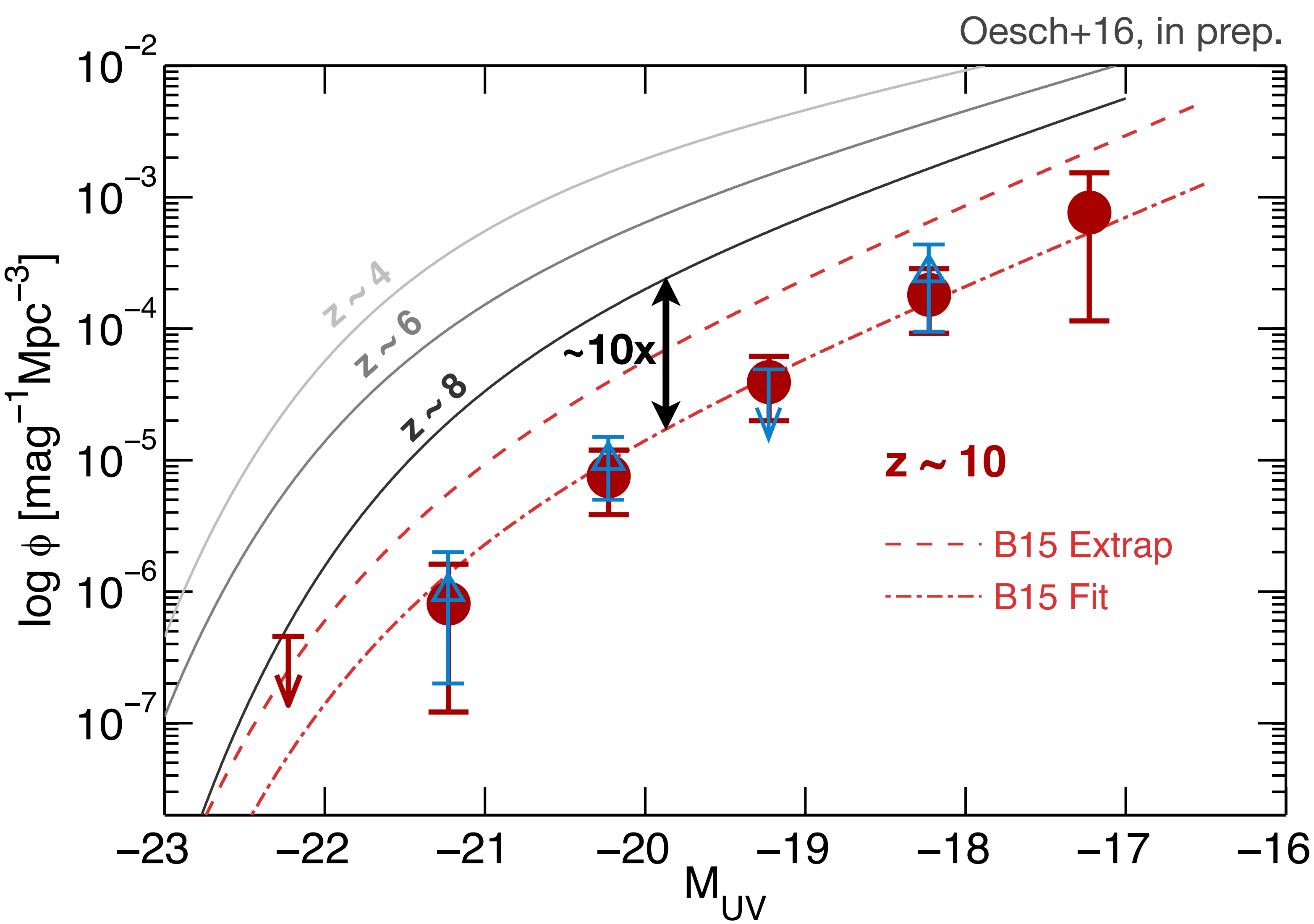


H = 29.9 mag (de-magnified)
zphot = 9.8+-0.4
magnification: 10-11x

strong geometric support of
high redshift solution of photo-z

(see also Oesch+15, McLeod+15, Ishigaki+15)

The UV Luminosity Function at the Cosmic Frontier

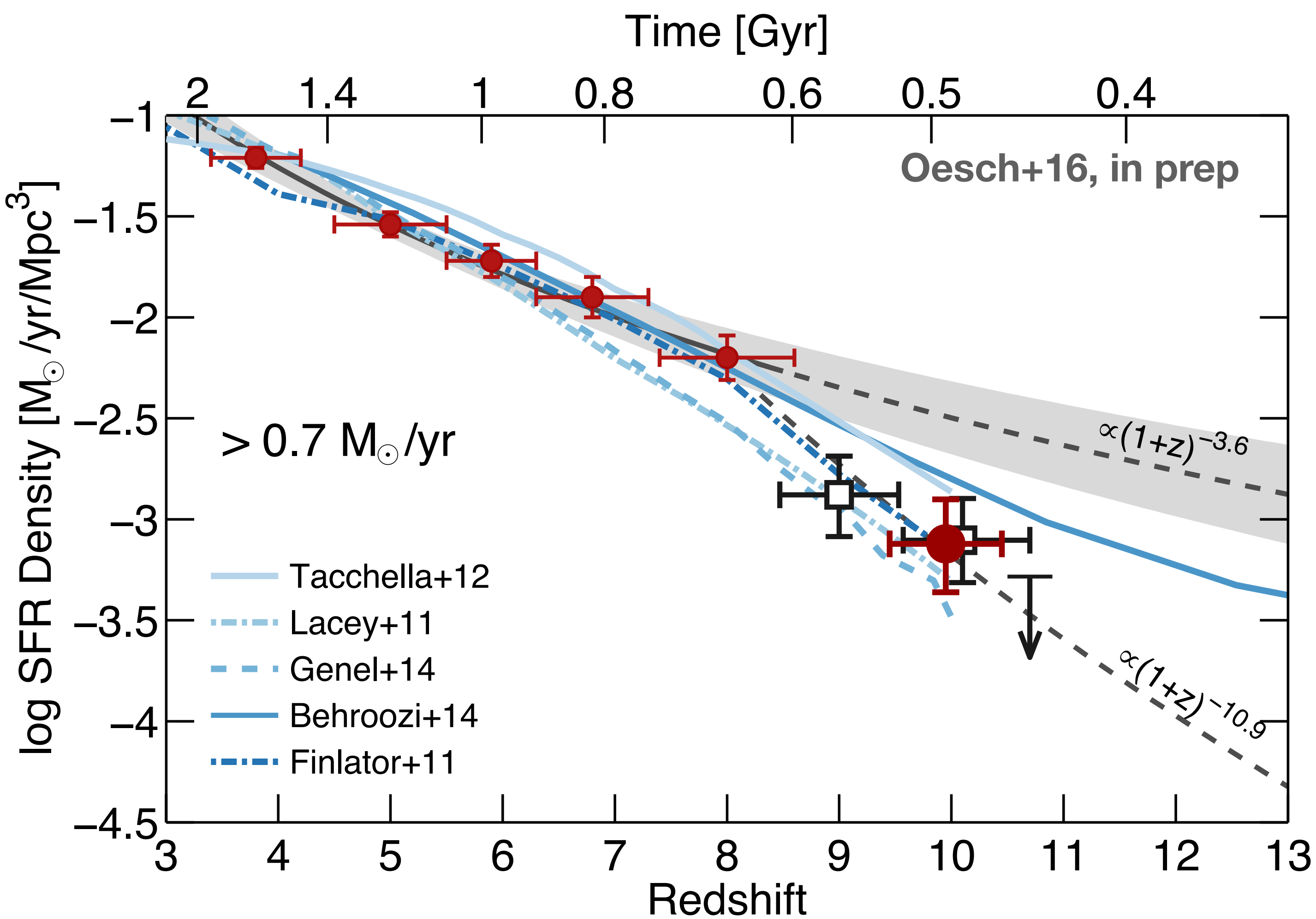


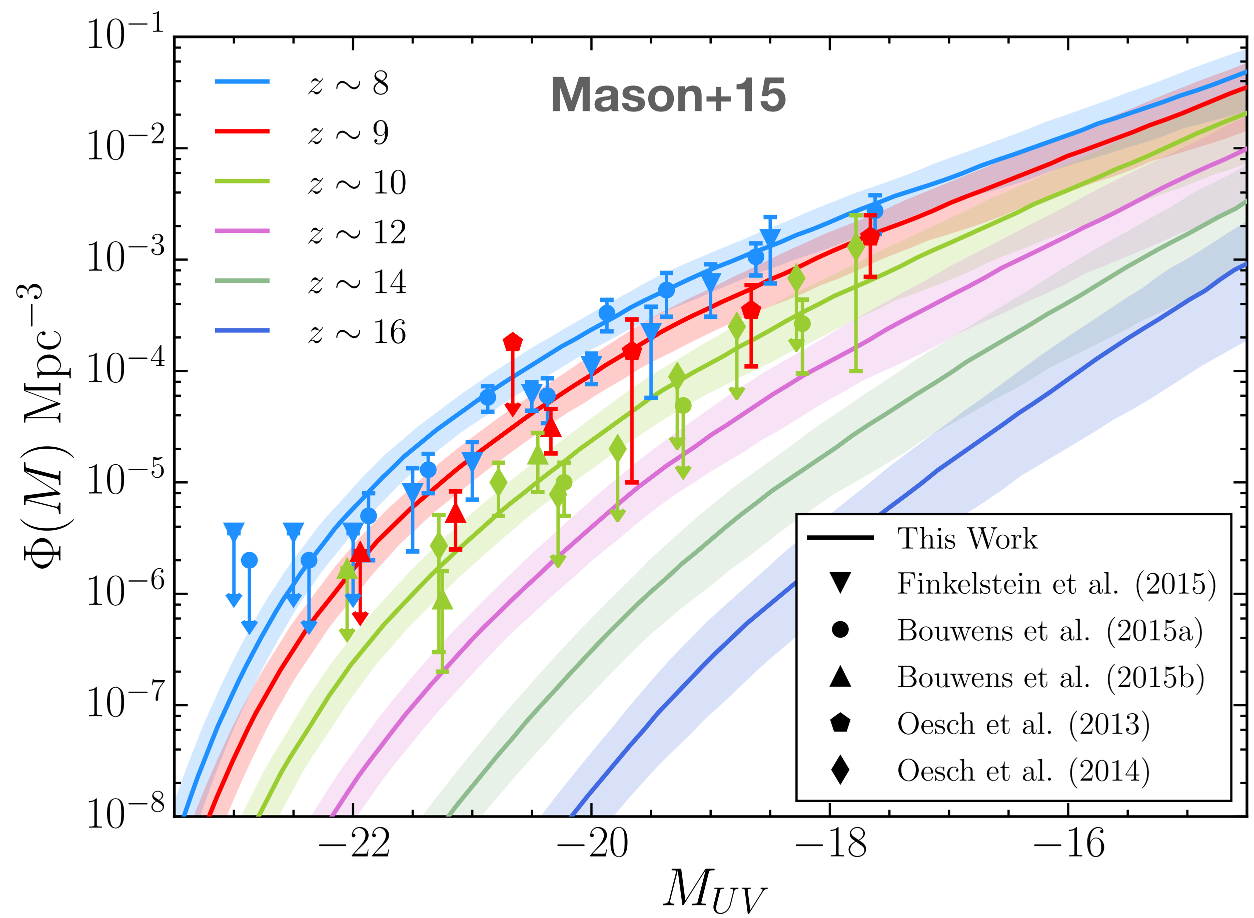
Including HFF galaxy candidates, now have a quite good estimate of the UV LF at z~10.

It lies a factor ~4-5x below the extrapolation from lower redshift trends.

Fast evolution from z~8 to z~10.

Rapid Decline Consistent with Models

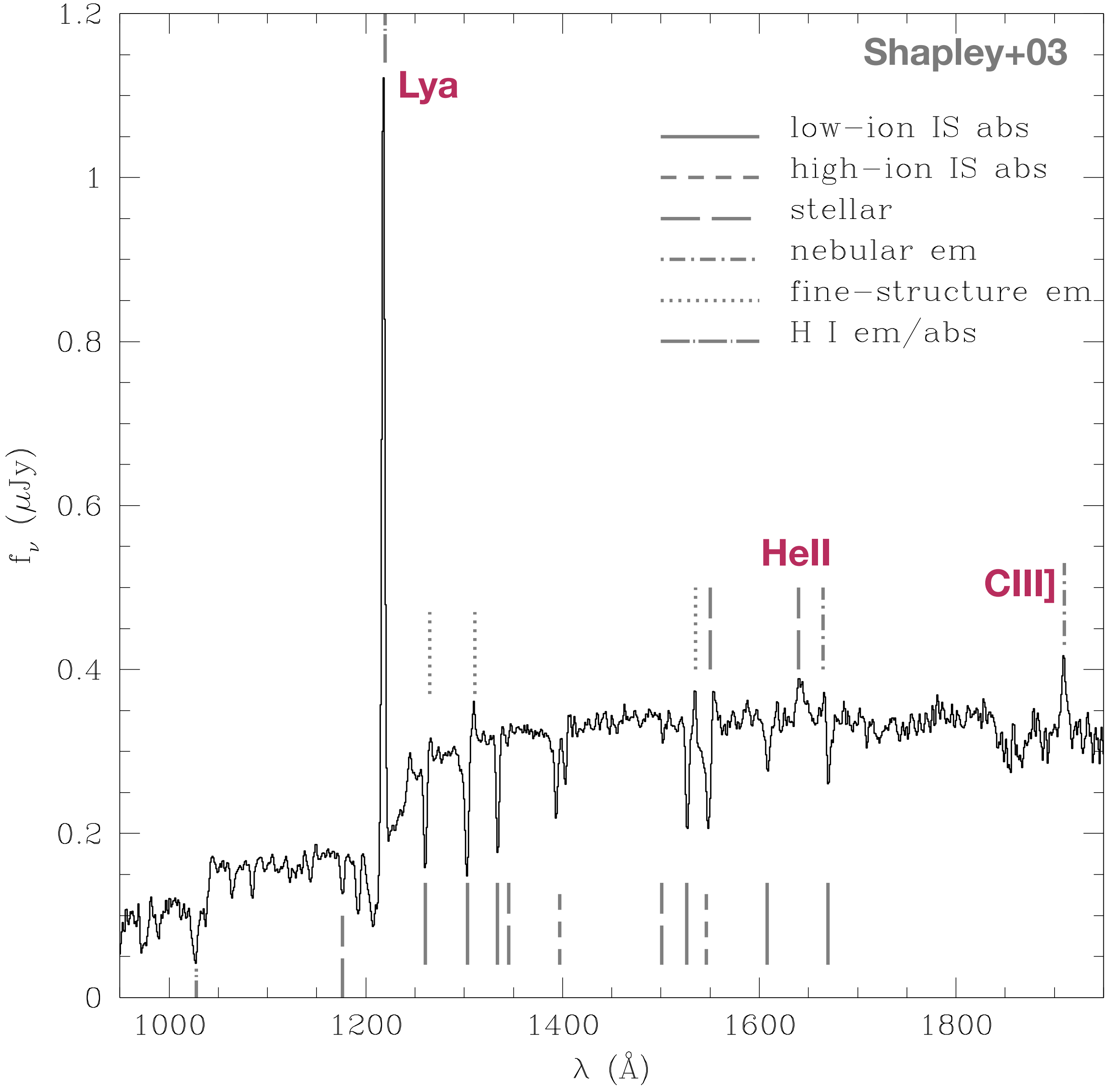




Rapid decline in the cosmic SFRD is consistent with most models, but there is a considerable range in predicted evolutions at z>8.

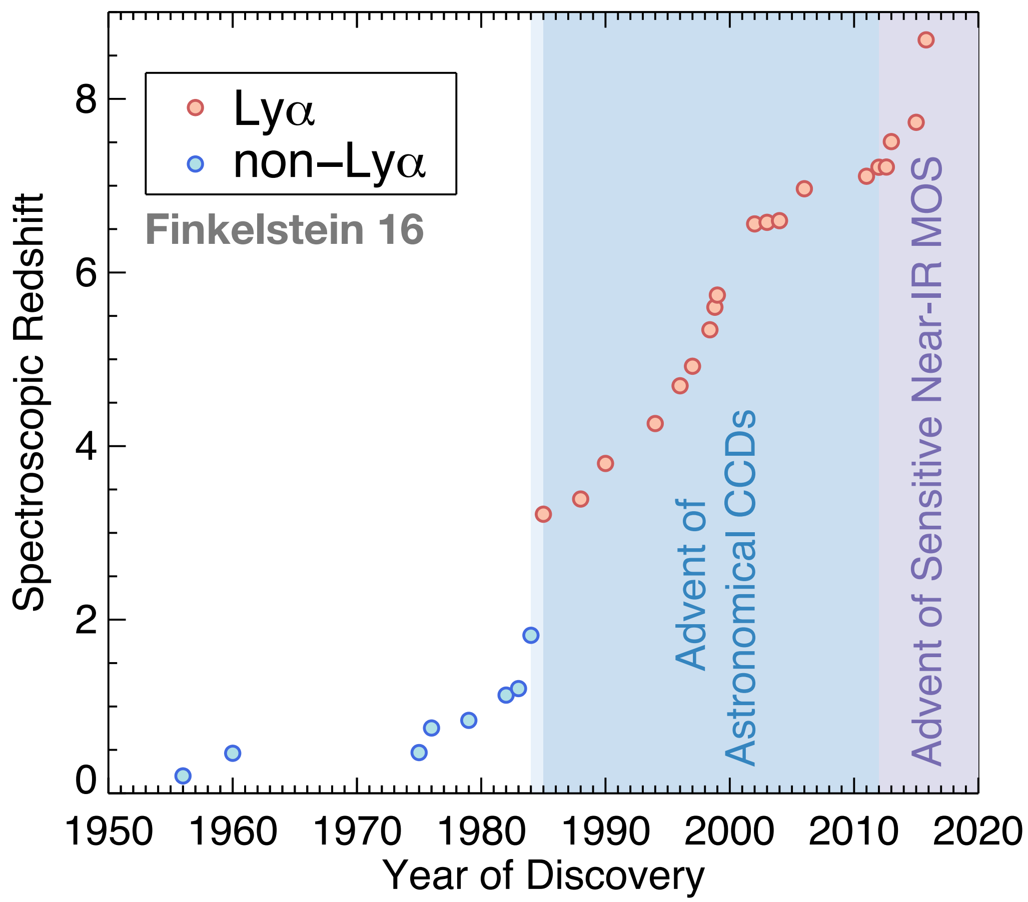
Need to understand this before launch of JWST to plan most efficient surveys!

Spectroscopic Features of High-z Galaxies

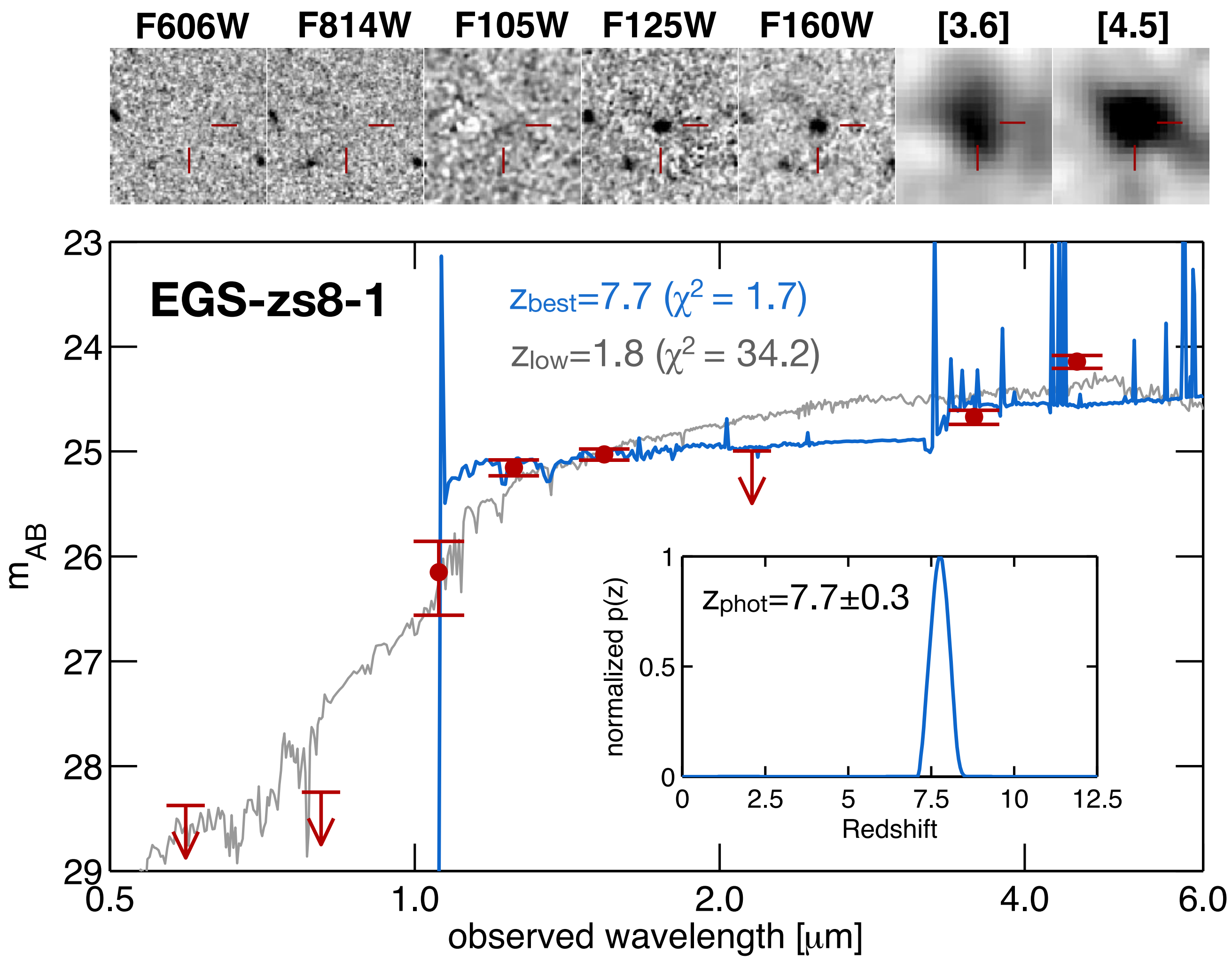


Lya is the most promising feature of high-redshift spectra

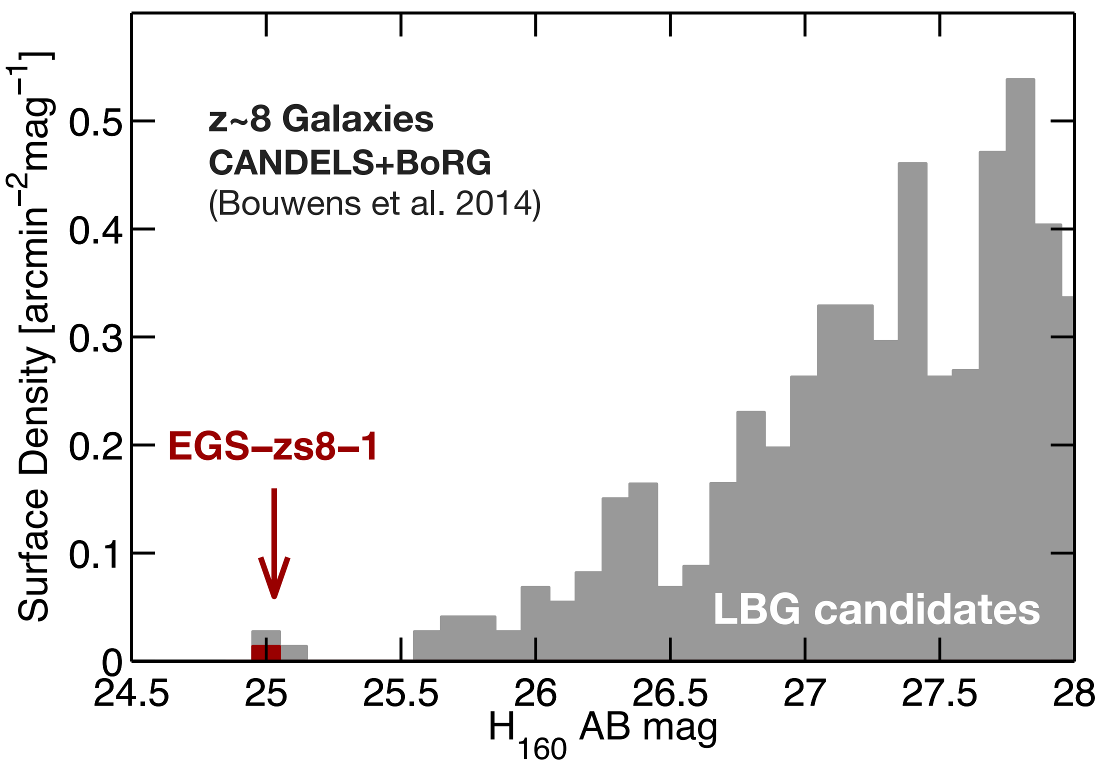
Other emission lines very weak, but possible to detect (e.g. Stark+15,16)



Bright z~8 Galaxies with Spectroscopic Redshifts



Small sample of four IRAC excess sources from CANDELS/WIDE
(see Roberts-Borsani+15)

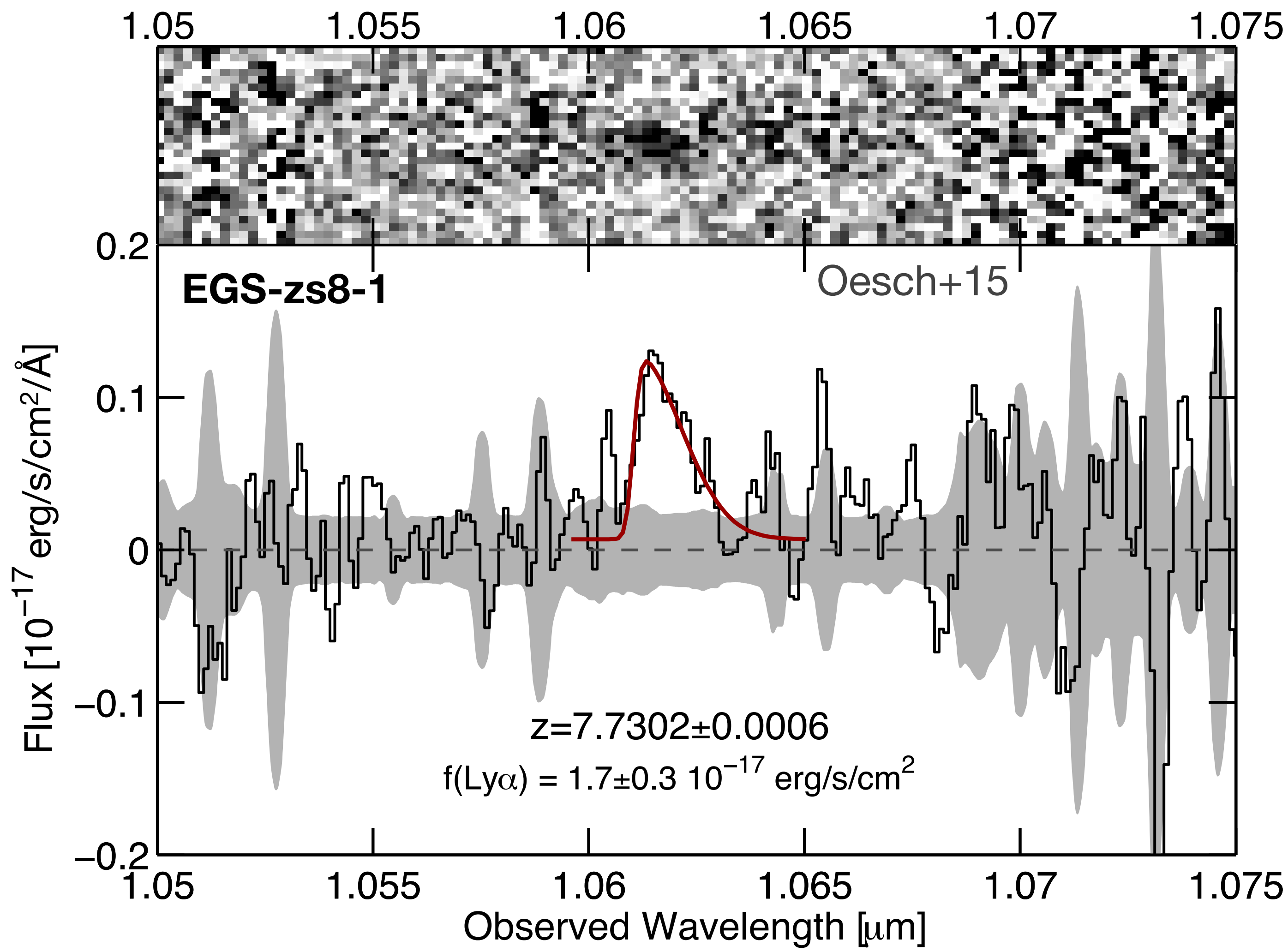


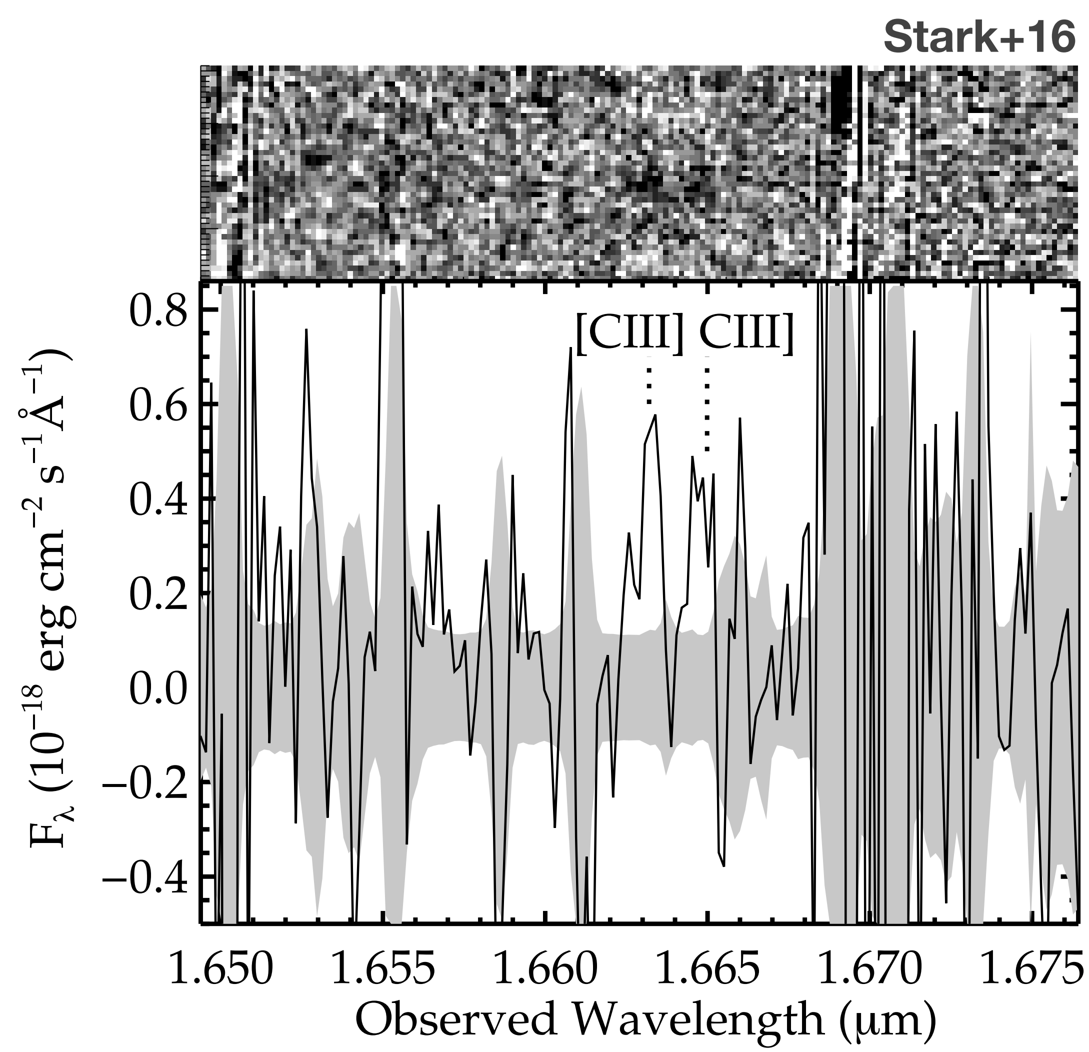
Spitzer/IRAC colors allow us to exploit very wide area imaging data to search for rare, ultra-luminous z~8 galaxy candidates with robust photometric redshifts

Bright z~8 Galaxies with Spectroscopic Redshifts

100% spectroscopic success rate via Lyα detection in such galaxies!

see: Roberts-Borsani+15 (z=7.48), Zitrin+15 (z=8.68), Stark+16 (z=7.15)



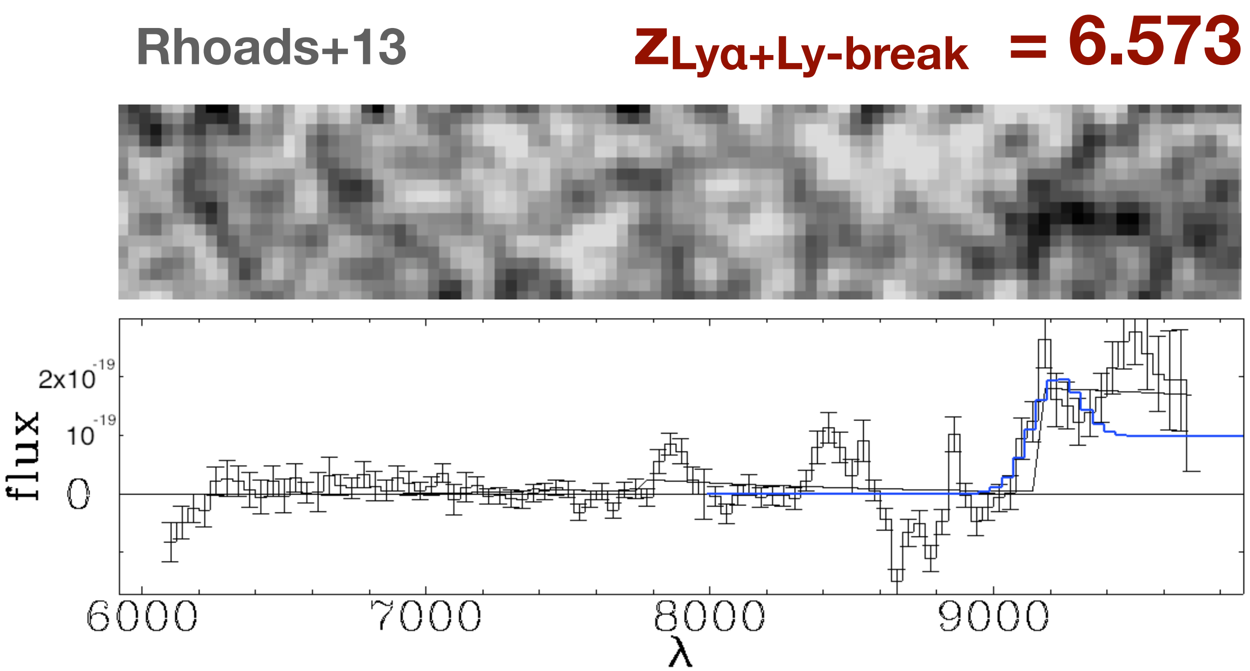


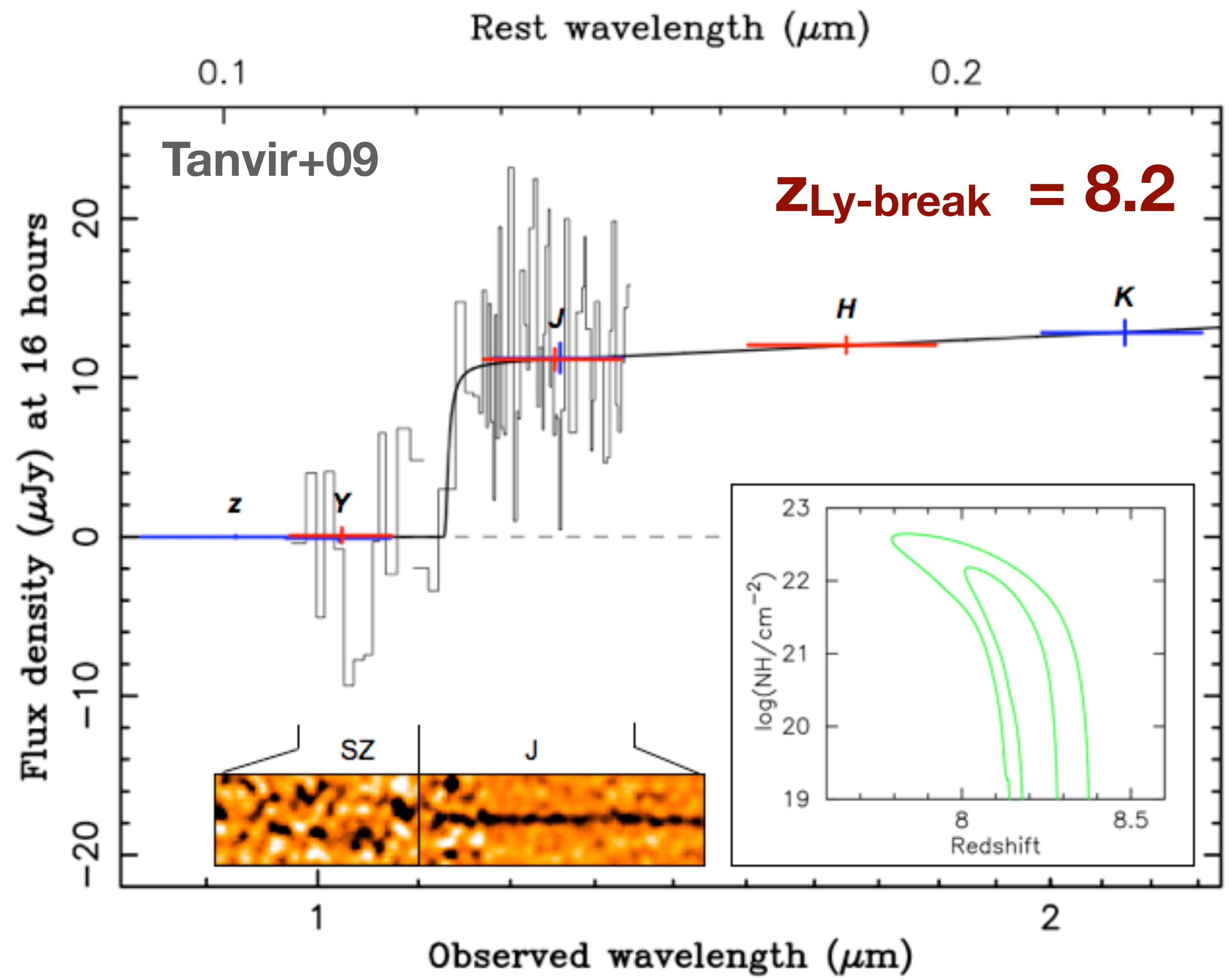
EGS-zs8-1 now has a three line redshift z=7.73.
Very high EW CIII] emission

Different Way Forward: Continuum Break Redshifts

If Lyα disappears, need different technique to measure redshifts:
continuum breaks (as done for QSOs)

Note: at z>6 these are the Lyα continuum breaks



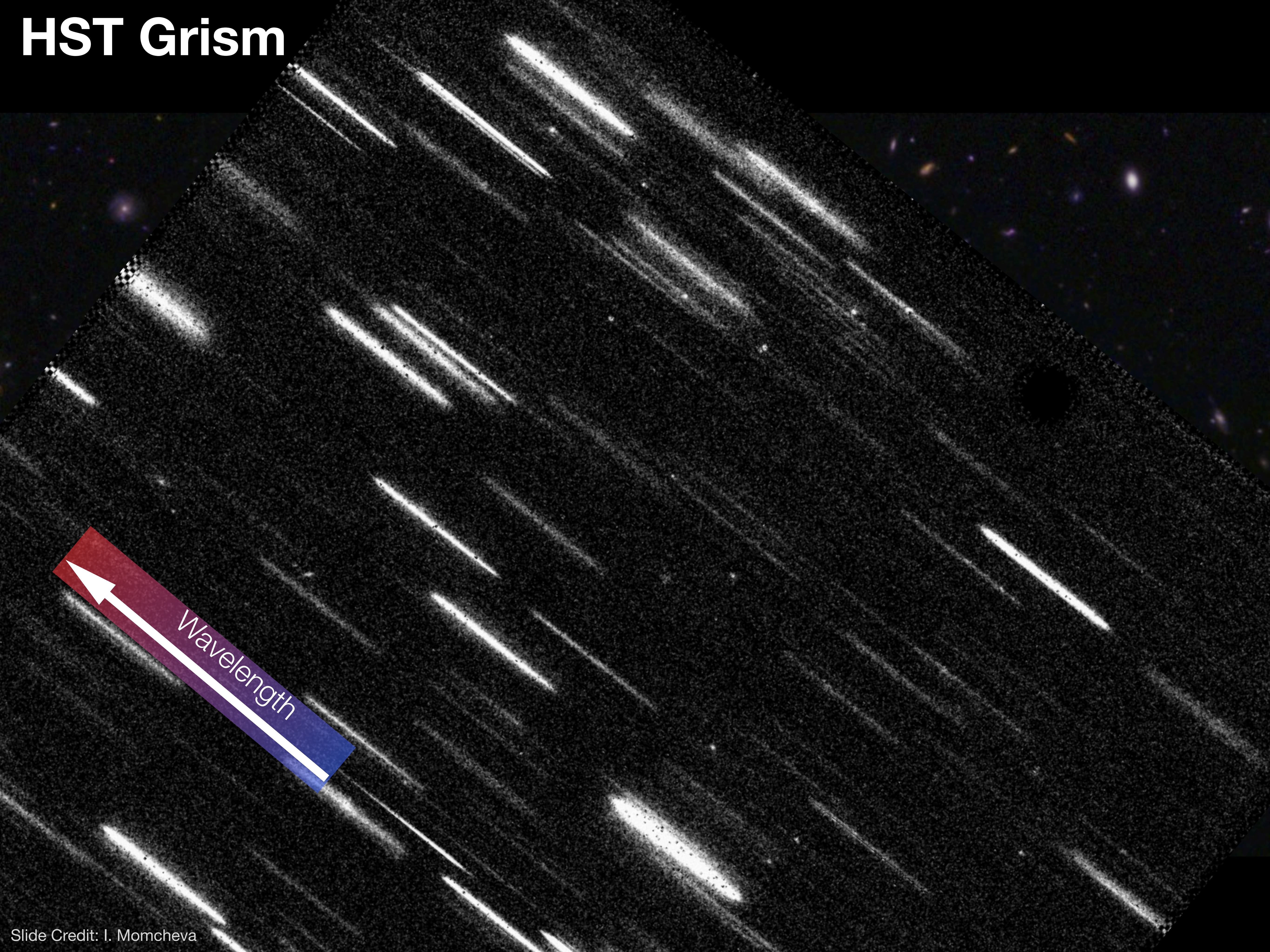


Problem: the background in the NIR is very high from the ground and faintness of galaxies compared to QSOs

HST Grism

Slide Credit: I. Momcheva

HST Grism



Slide Credit: I. Momcheva

HST Grism

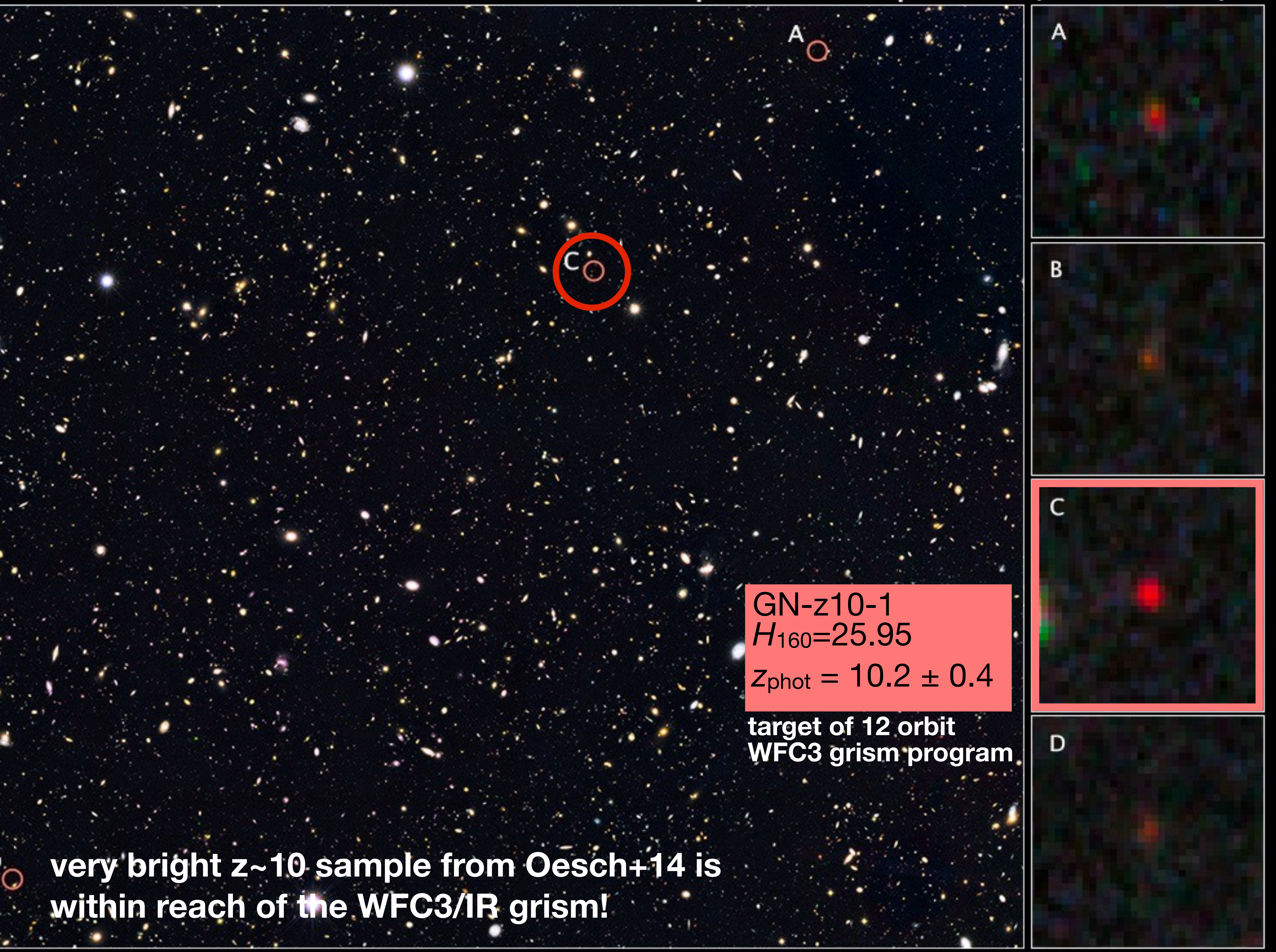
3D-HST

WISPS
WFC3 Infrared Spectroscpic Parallel Survey

GLASS
The Grism Lens-Amplified Survey from Space

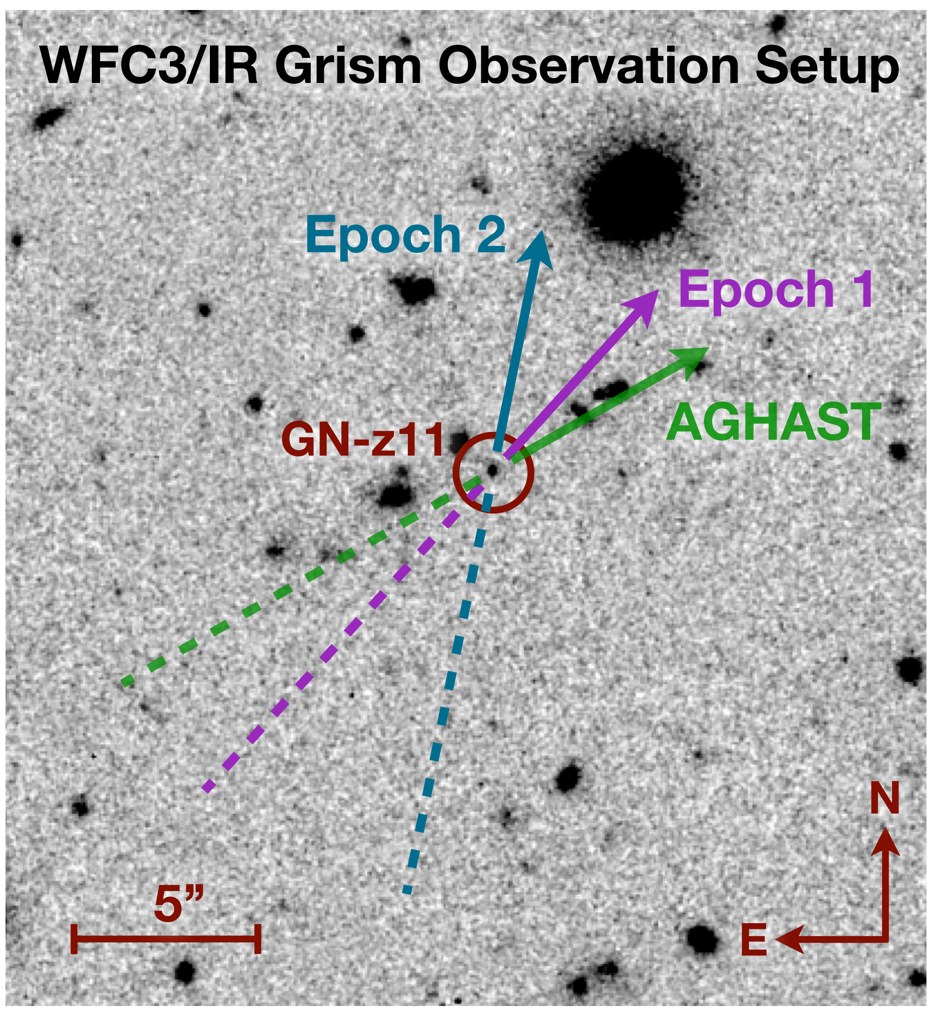
FIGS and others...

Slide Credit: I. Momcheva

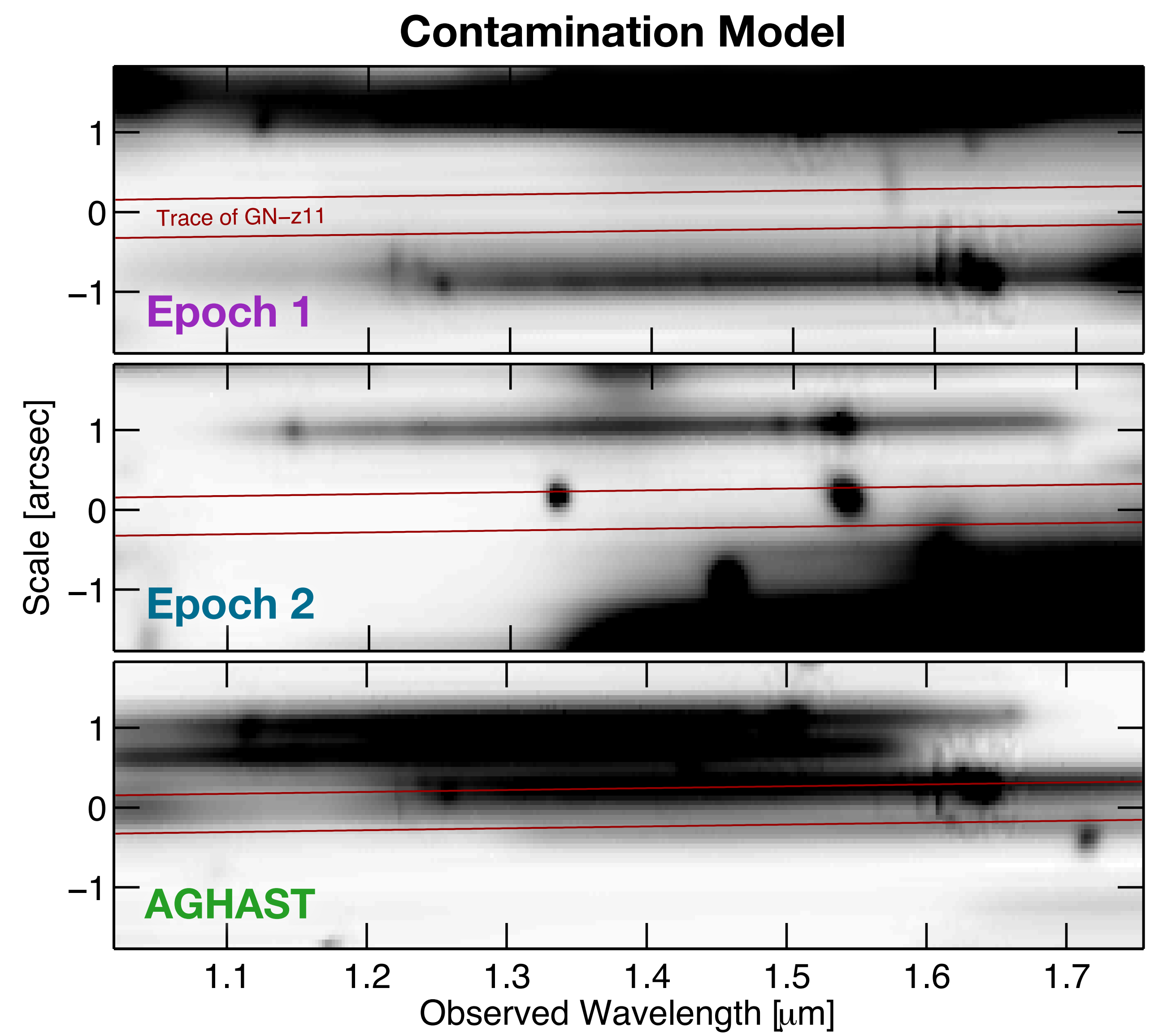

A
C
A
B
C
D
GN-z10-1
H_{160}=25.95
z_{phot} = 10.2 ± 0.4
target of 12 orbit
WFC3 grism program
very bright z~10 sample from Oesch+14 is
within reach of the WFC3/IR grism!

Neighbor Contamination in Grism Spectra

Even in a blank field, it's difficult to identify orientations with minimal contamination.
Previous AGHAST spectra heavily contaminated.

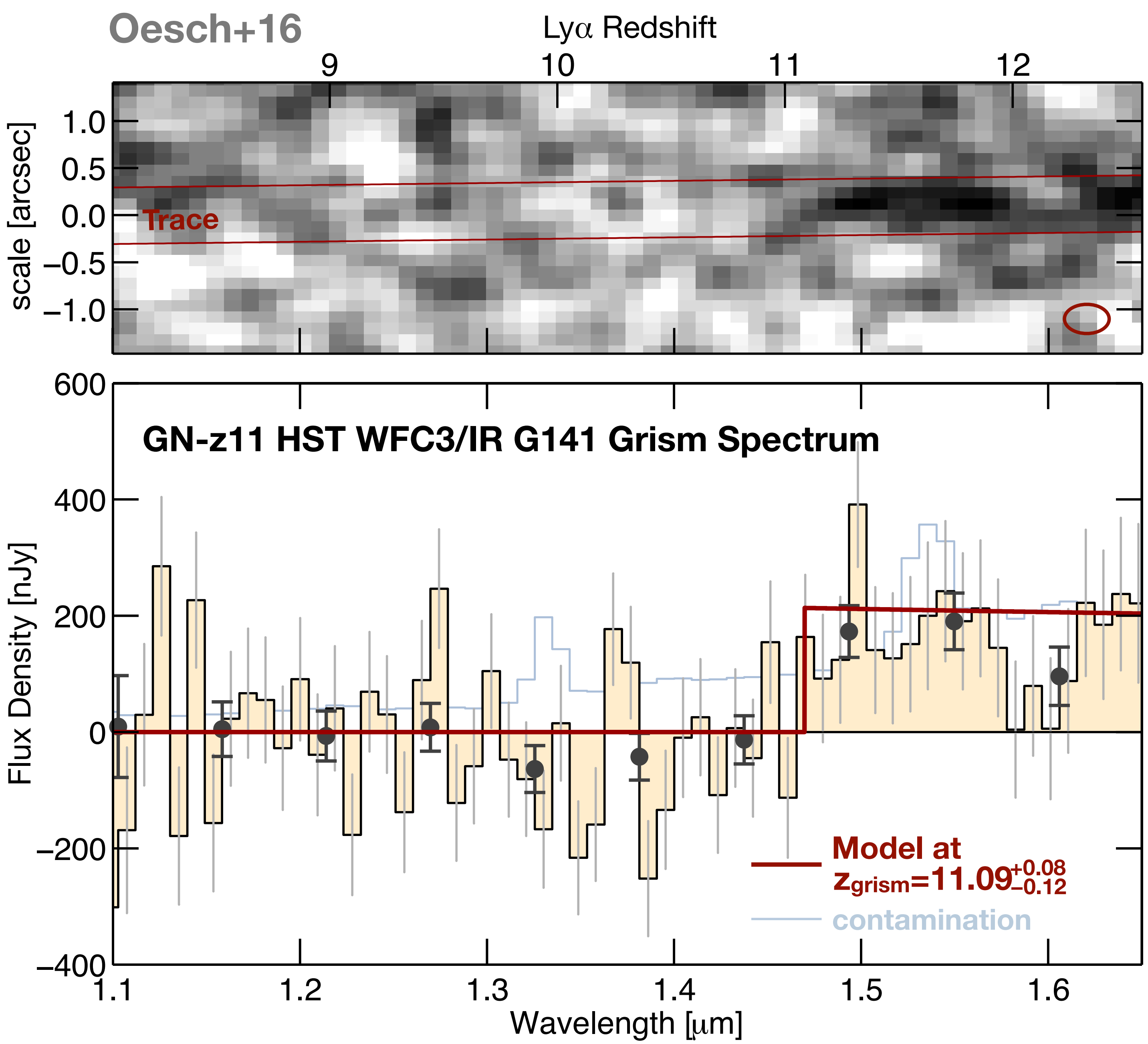


Oesch+16



Perform full 2D contamination modelling and neighbor subtraction
(based on 3D-HST grism pipeline; Brammer+12, Momcheva+15)

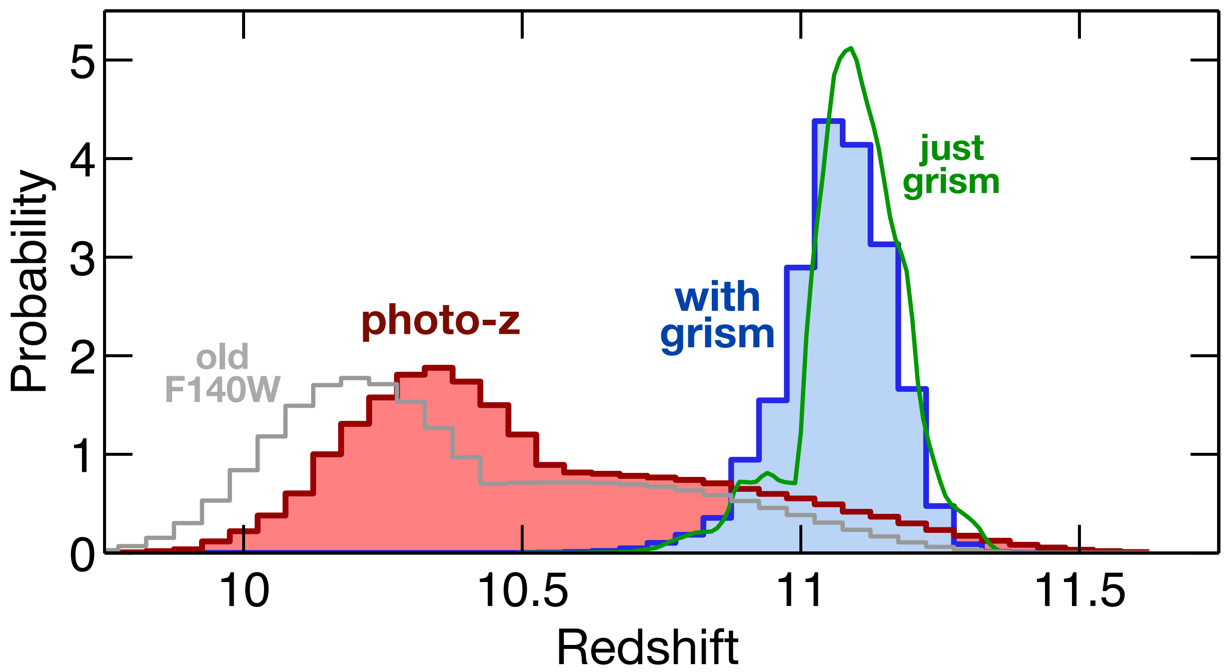
Lyman Break Detection at z=11

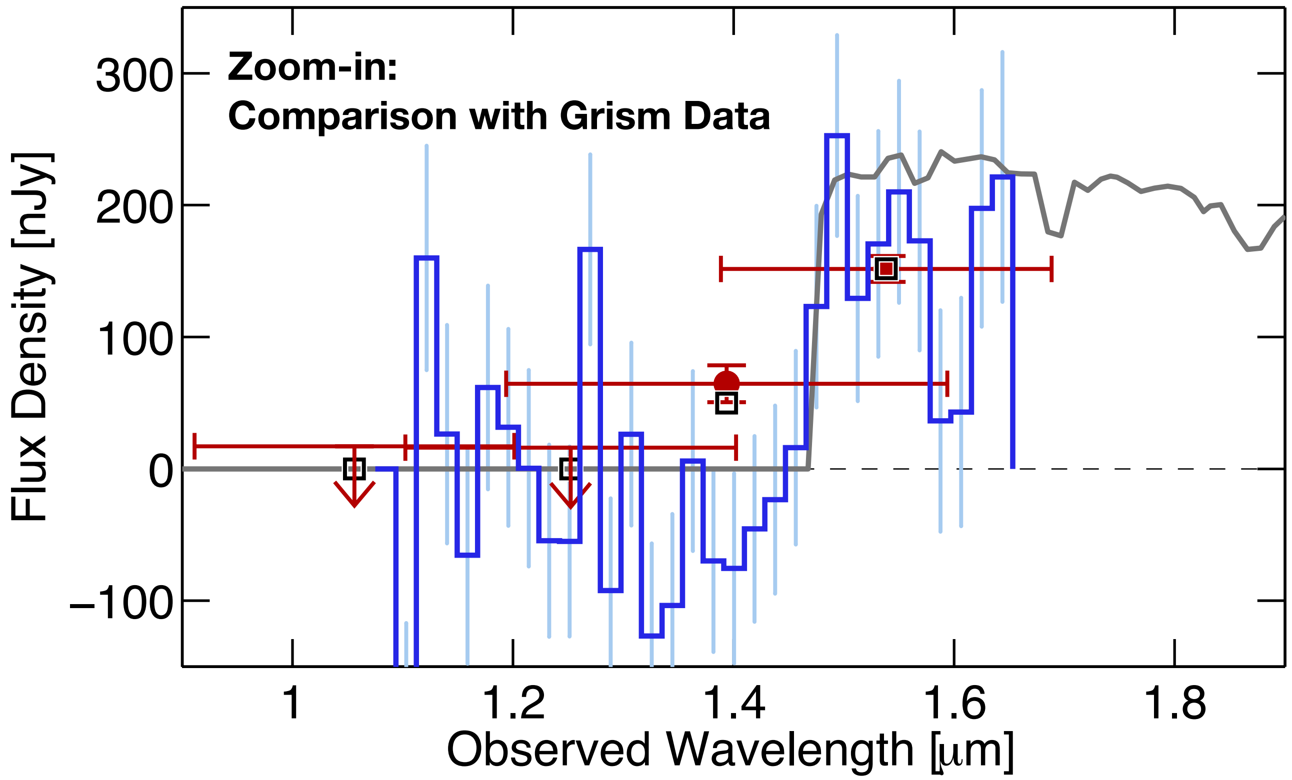


- Overall continuum detection ~5.5σ at λ > 1.47 μm
- Detected at 1-1.5σ per resolution element (91 Å)
- Detection in both epochs individually (but at low S/N)
- Break factor (f_{red}/f_{blue}) of >3.1 (2σ, 500 Å) rules out z~2-3 interloper
  (Maximally old BC03 model at z=2.7 a factor of <2.7 defined the same way)
- Rule out emission line contaminant
- Best-fit redshift: z=11.09+-0.10

The Higher Redshift

GN-z10-1 ➜ GN-z11

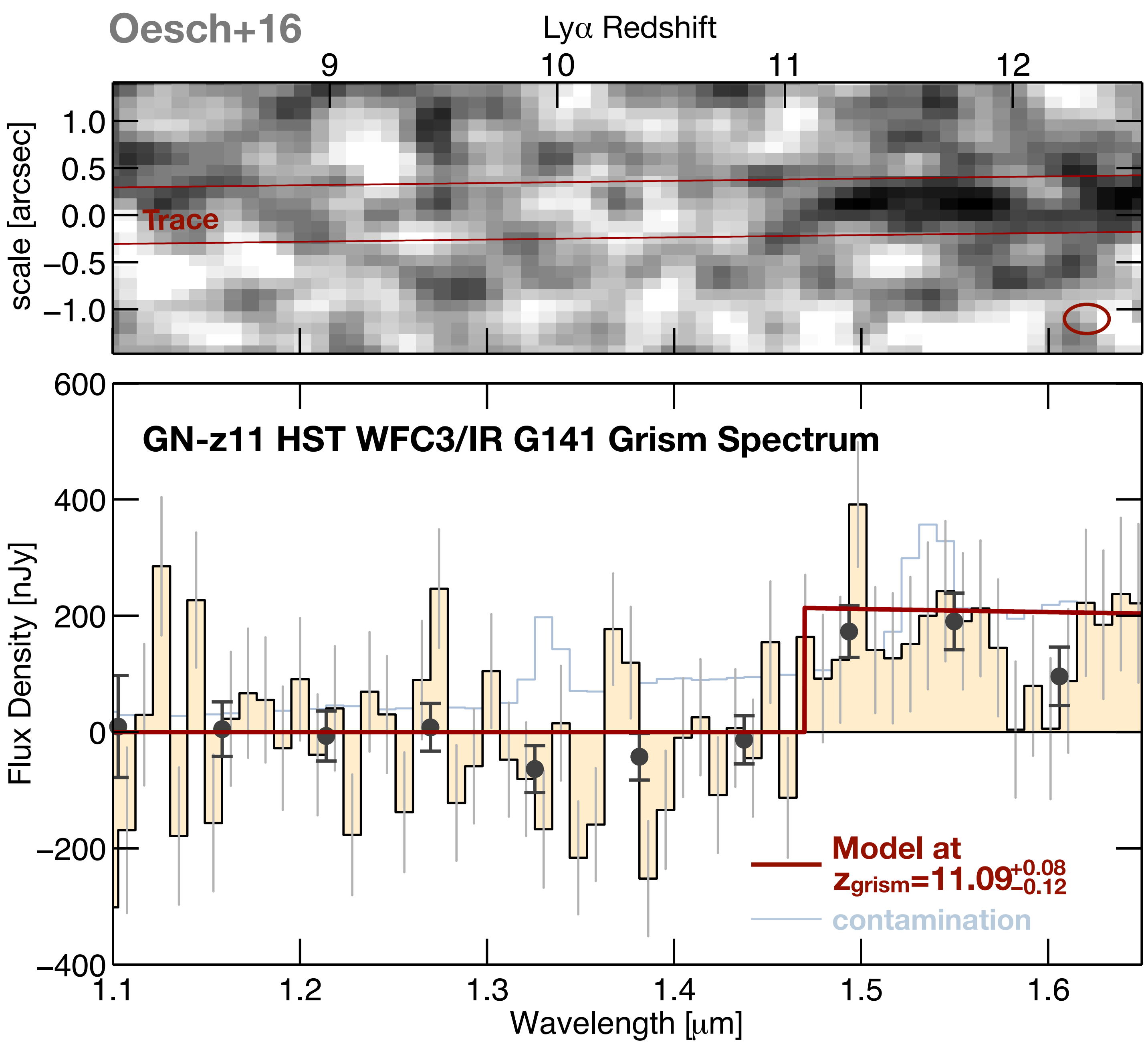




The grism data rules out the peak of the previous photometric redshift (z_{phot}=10.2).

Is consistent with high-end tail of photo-z and with the photometry.

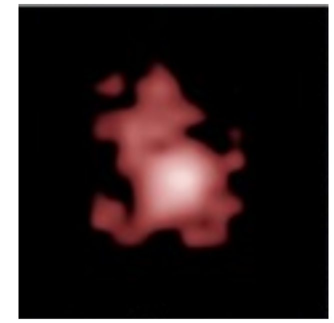
Better Spectrum Required?

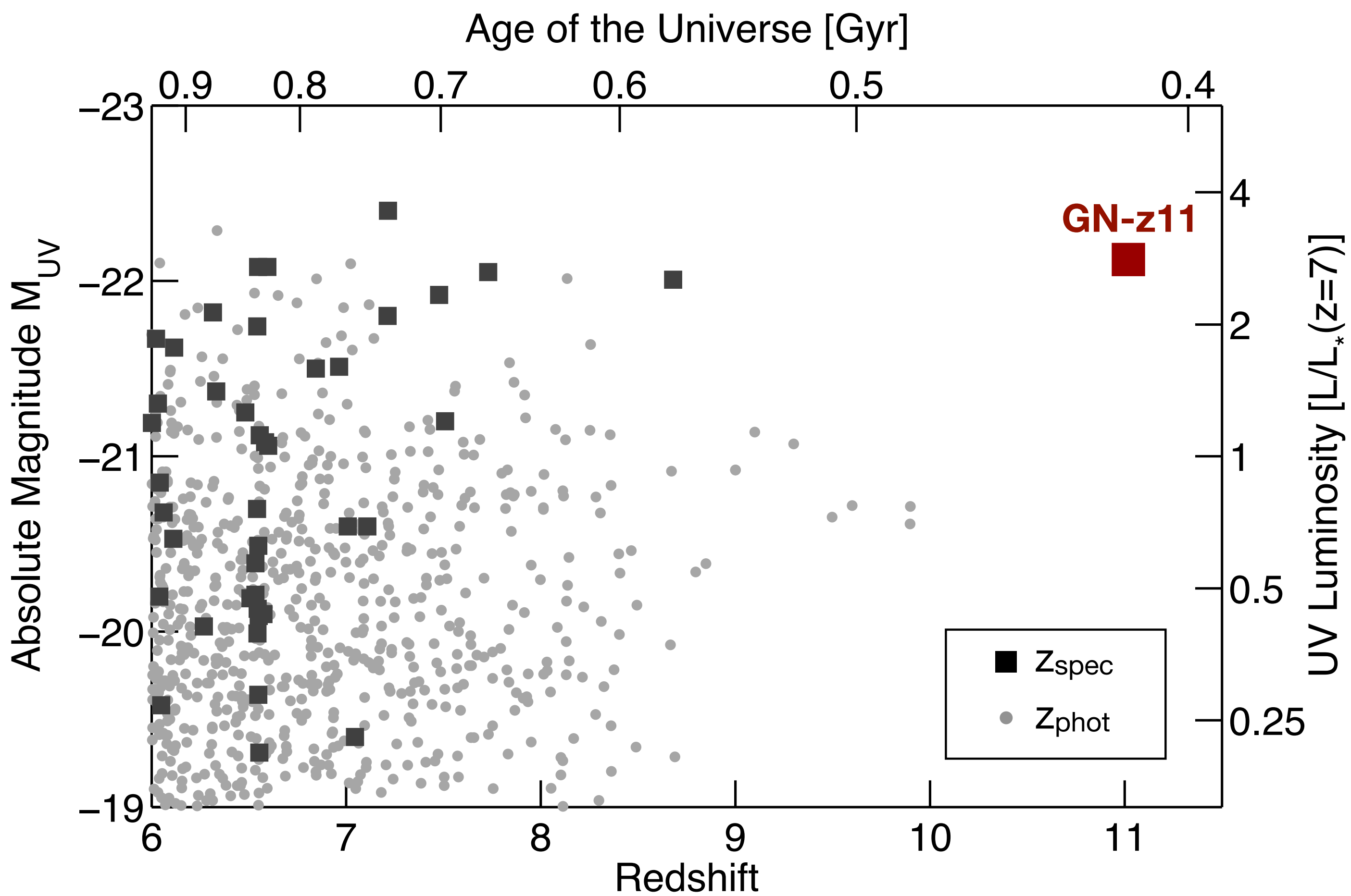


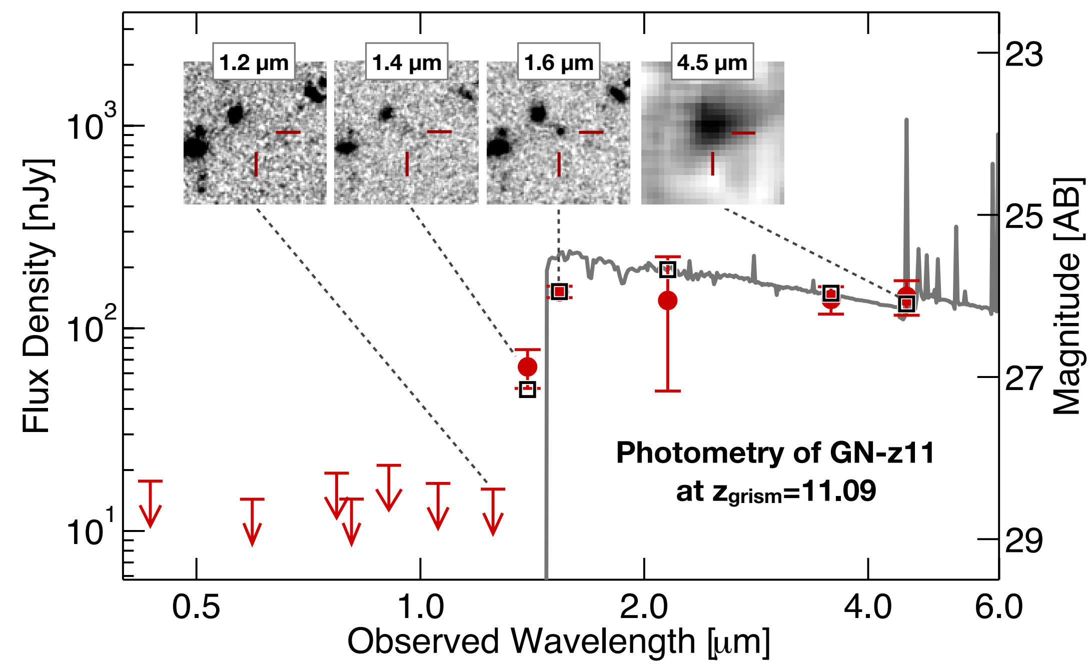
HST TAC comment:

"...the spectrum presented in Oesch et al. (2016) was not convincing..."

Physical Properties of GN-z11





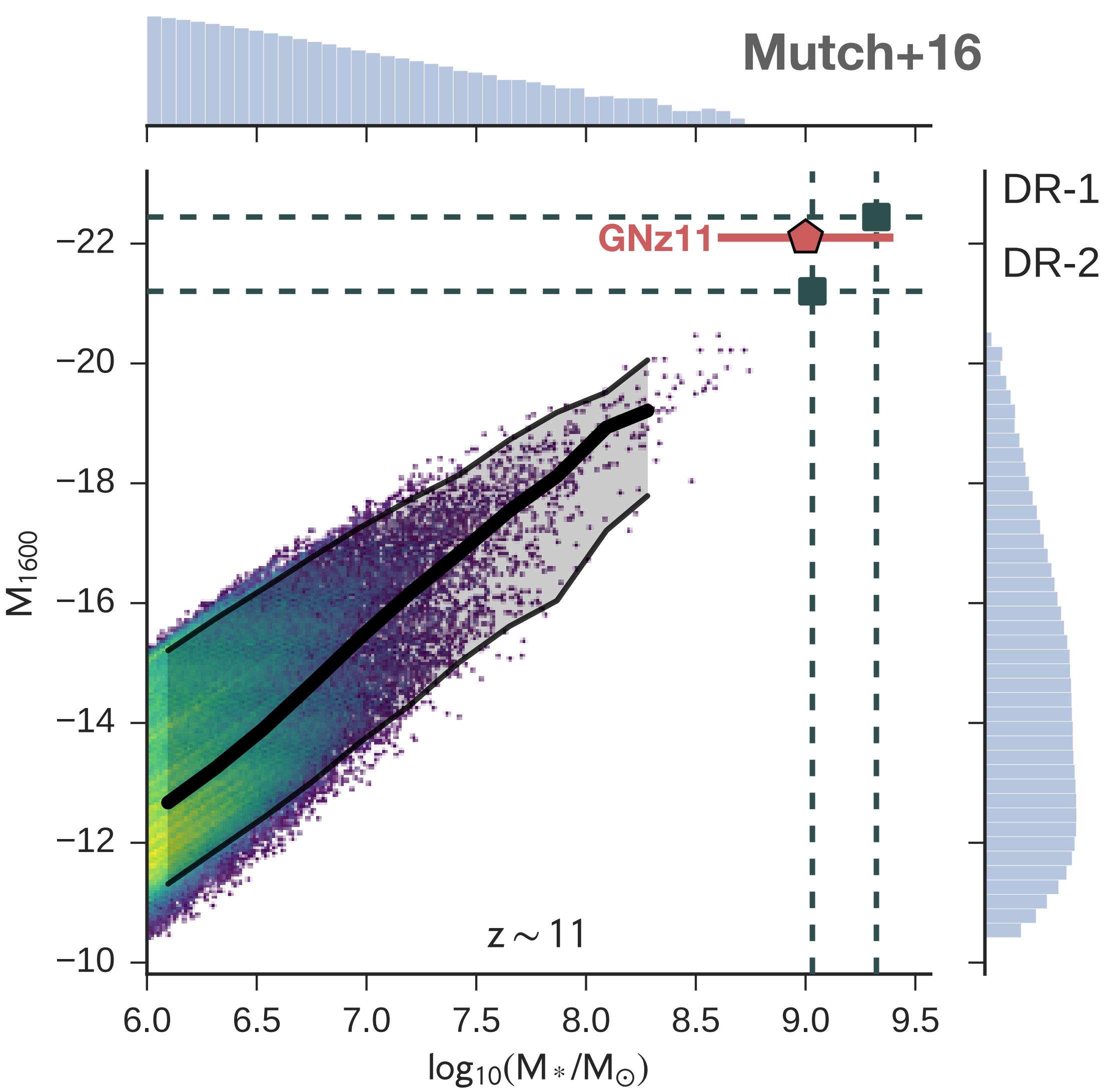


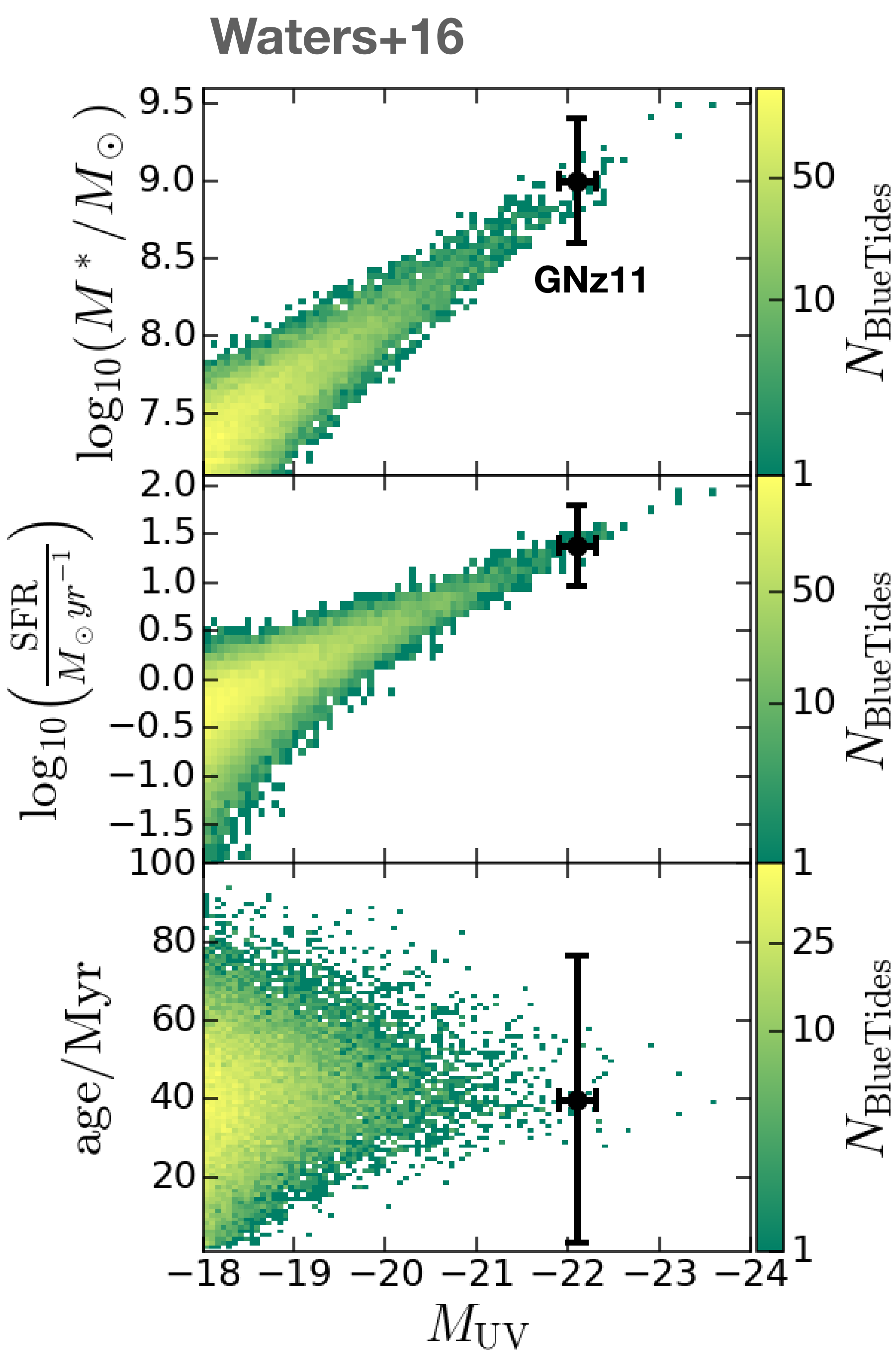
- UV luminosity ~ 3×$L^*(z=7)$
- Stellar mass ~ 10^9 $M_\odot$
- SFR~24 $M_\odot$/yr, age~40 Myr

R.A.	12 : 36 : 25.46
Dec.	+62 : 14 : 31.4
Redshift $z_{\rm grism}$	$11.09^{+0.08\,a}_{-0.12}$
UV Luminosity M_{UV}	-22.1 ± 0.2
Half − Light Radius[b]	0.6 ± 0.3 kpc
$\log M_{gal}/M_\odot$ [c]	9.0 ± 0.4
log age/yr [c]	7.6 ± 0.4
SFR	$24 \pm 10\ M_\odot\ {\rm yr}^{-1}$
A_{UV}	< 0.2 mag
UV slope β $(f_\lambda \propto \lambda^\beta)$	-2.5 ± 0.2[d]

Massive galaxy formation well under-way at z~11

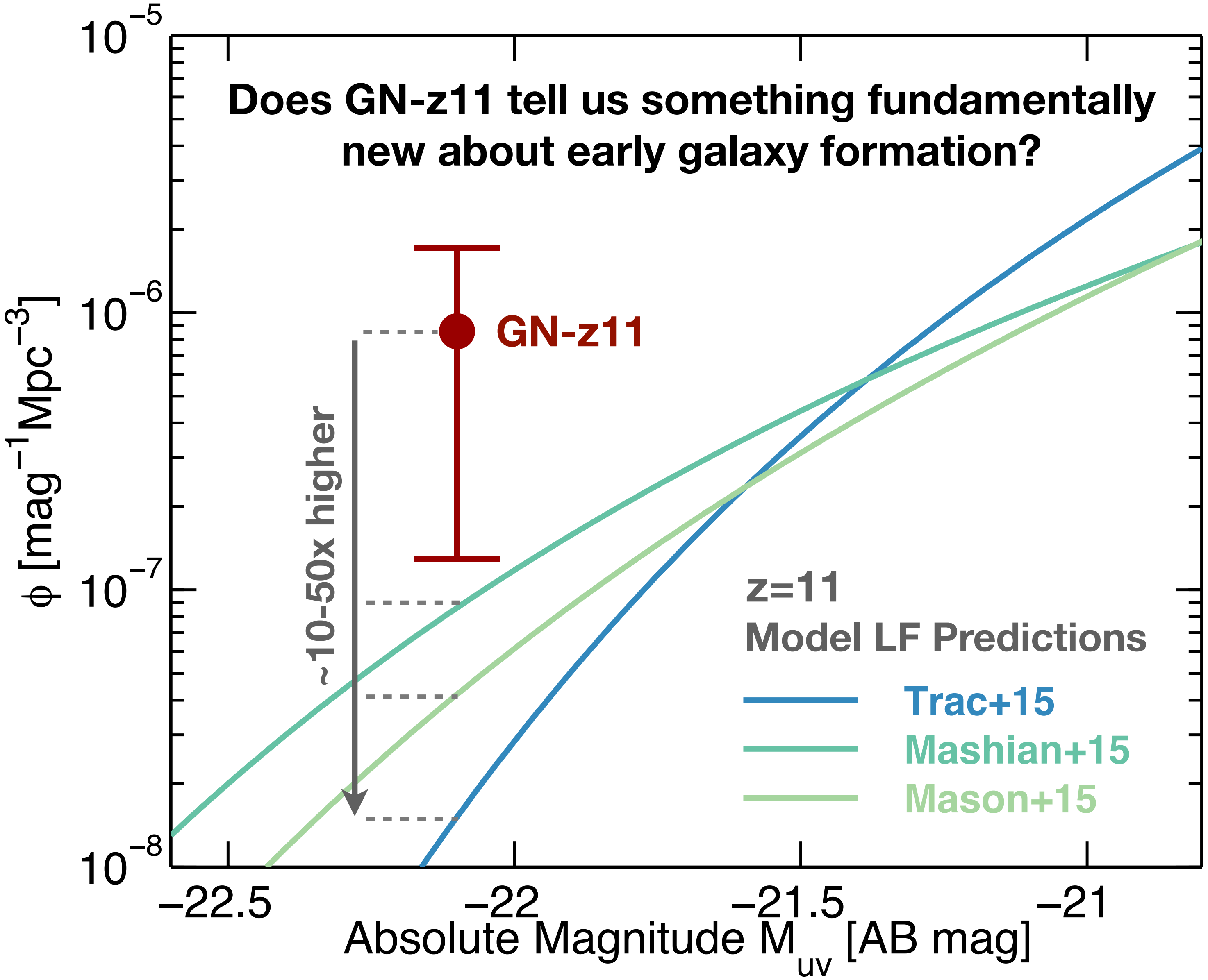
Physical Properties of GN-z11 in Line with Models





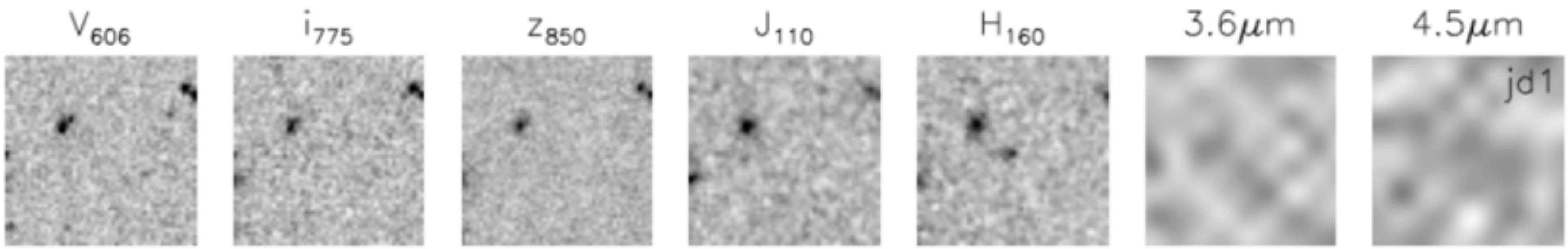
The derived physical properties (SFR, mass, and age) of GN-z11 are in very good agreement with expectations from large-volume simulations

GN-z11 is off the Charts

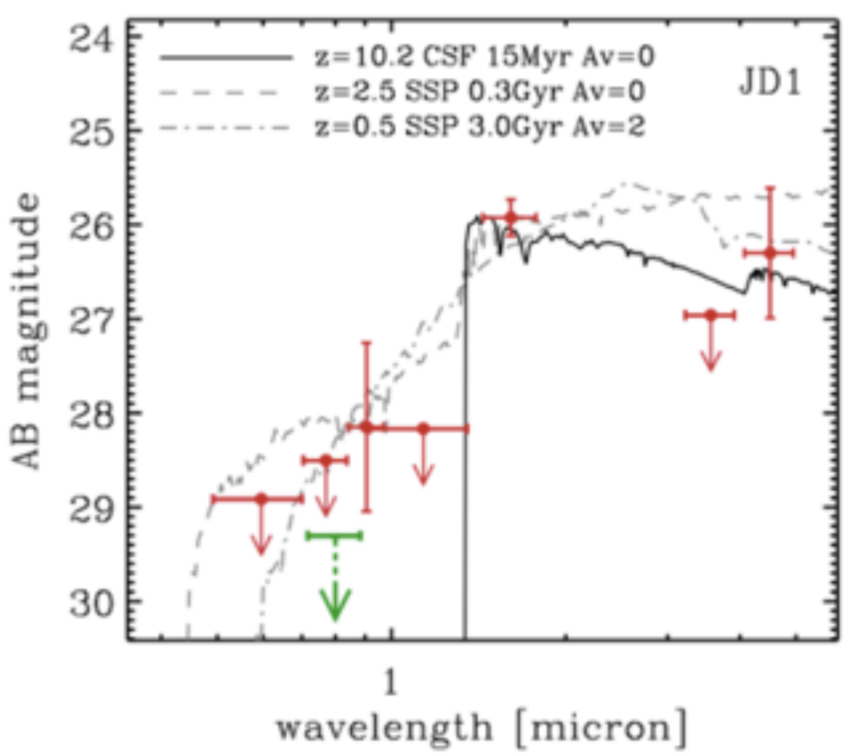


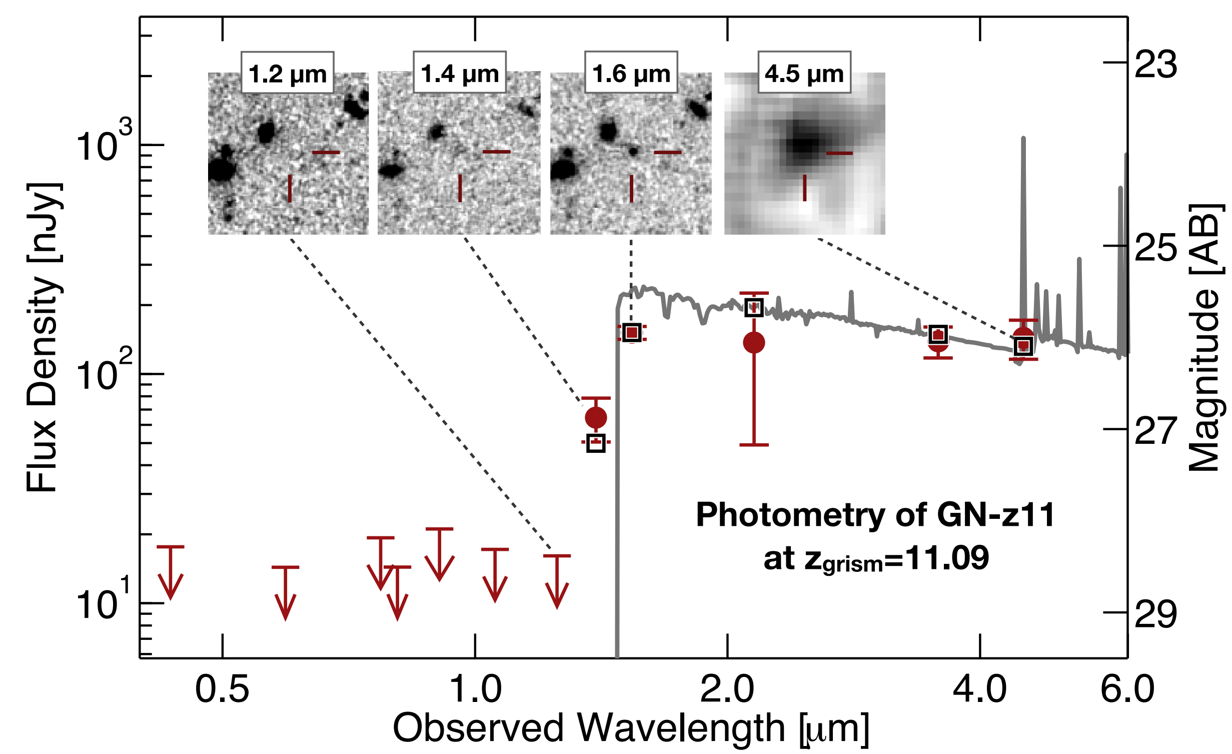
- Detection of GN-z11 in existing data is quite unexpected, given current models
- Expected to require 10-100x larger areas to find one such bright z~11 galaxy as GN-z11
- Difficult to draw conclusions based on one source. **Need larger survey!**

GN-z11 was "known" since 2008



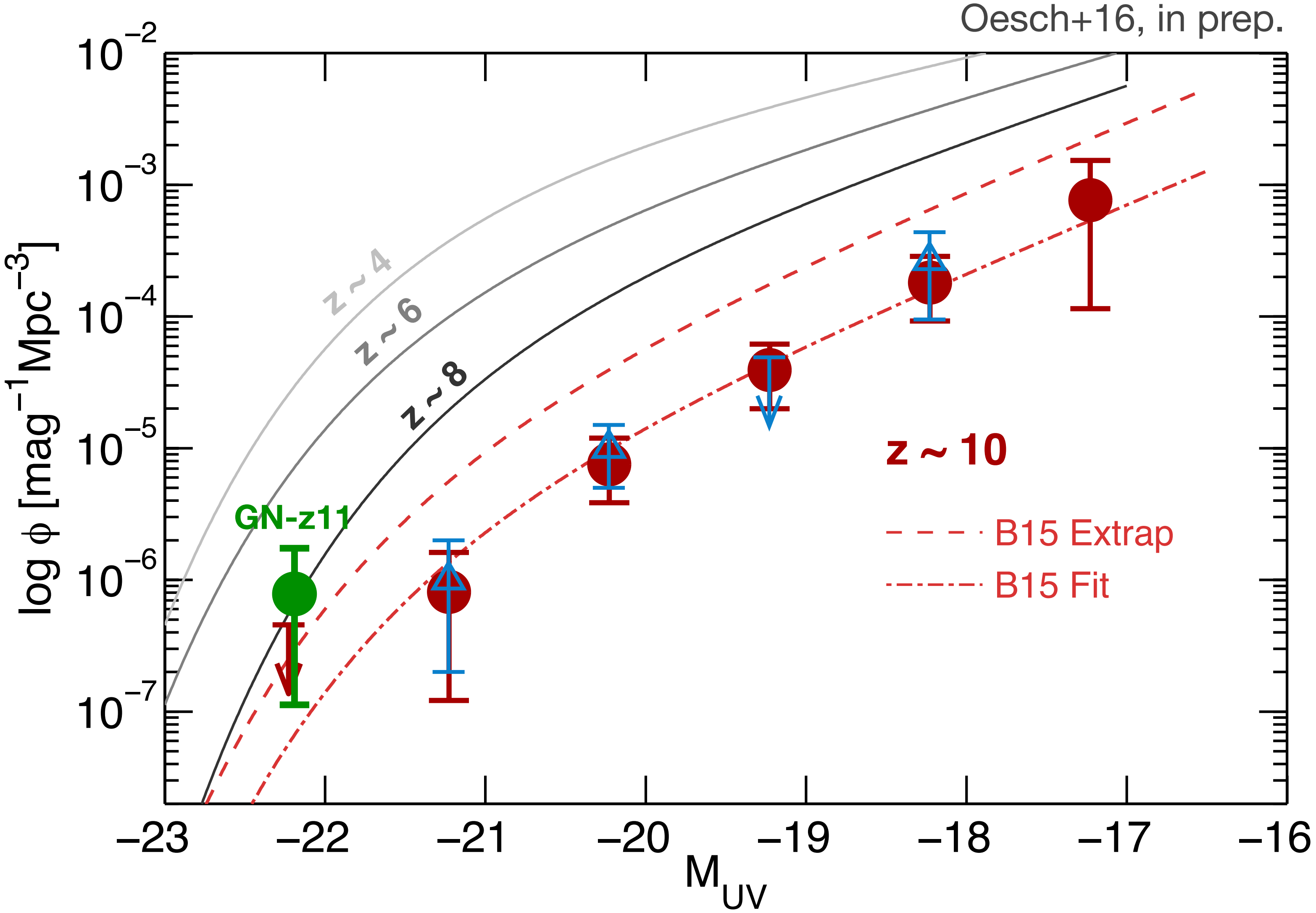
From presentation slides of Ivo Labbe in 2008





same photo-z as with new data, but was ruled out as not likely to lie at z>9 due to single band detection and its luminosity (Bouwens+10)

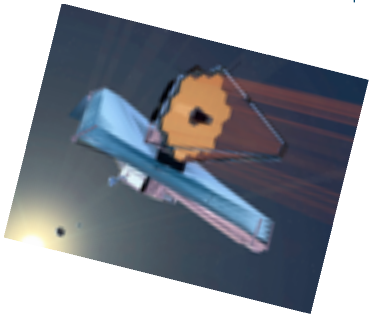
The UV Luminosity Function at the Cosmic Frontier



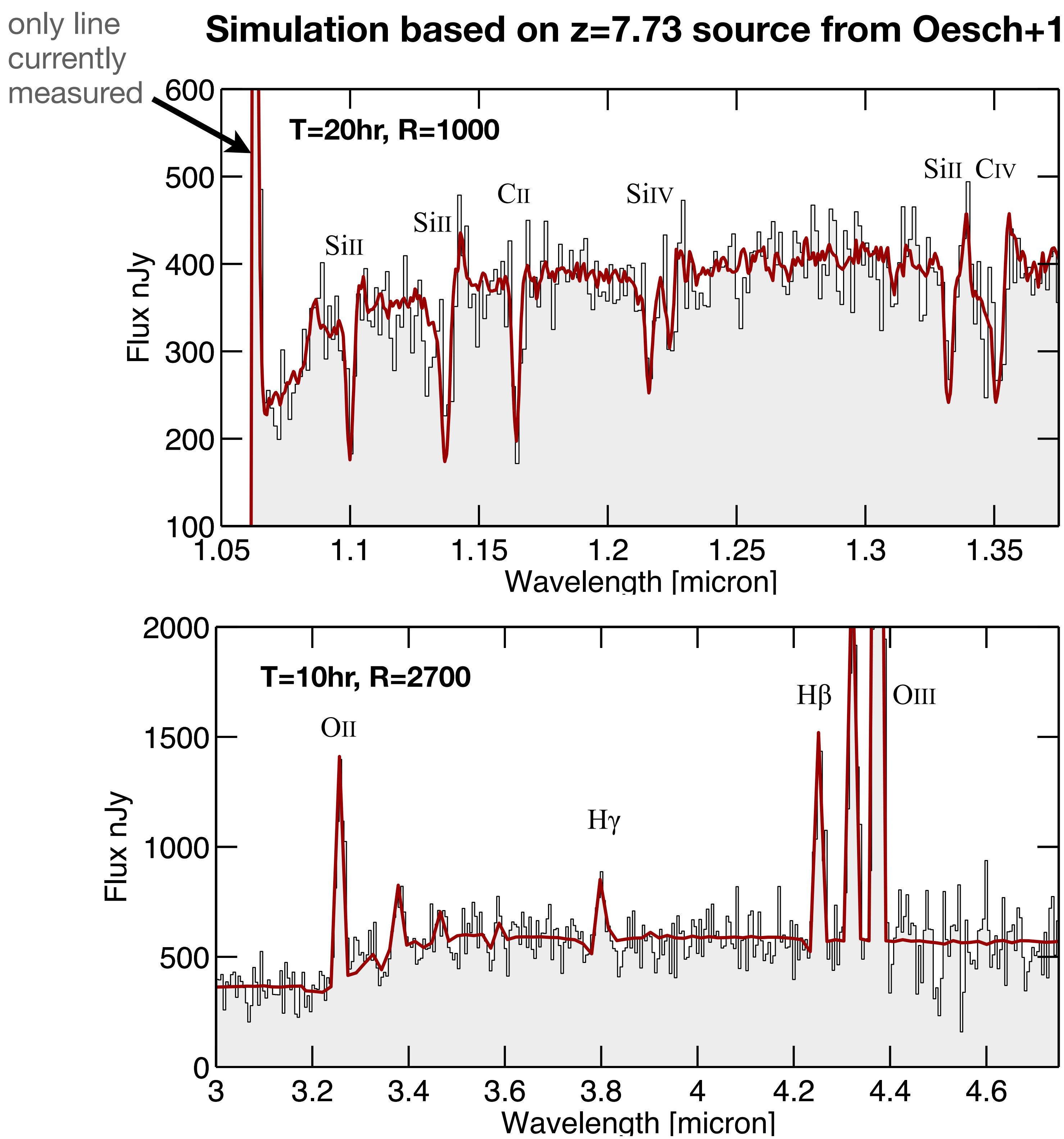
Slower evolution at the bright end of the UV LF?

➔ Need wider area NIR imaging data now to accurately determine number density of bright sources and to find such candidates for JWST follow-up

JWST/NIRSpec: Unprecedented Spectra



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?

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 (**>800 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
- The **cosmic SFRD** evolves **gradually at z~4-8,** then drops **rapidly at z>8** by a factor 10x in only 170 Myr
- 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!