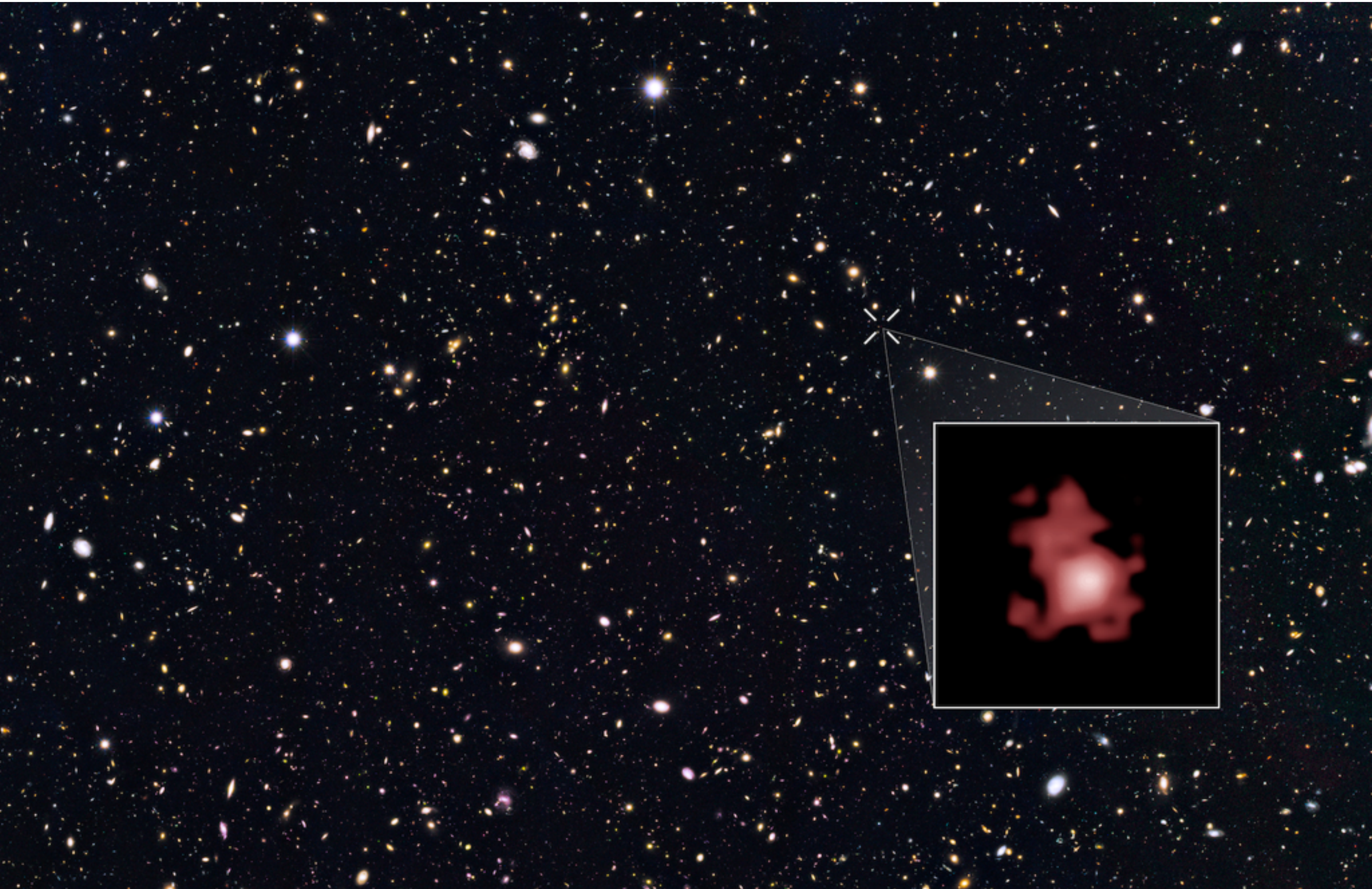
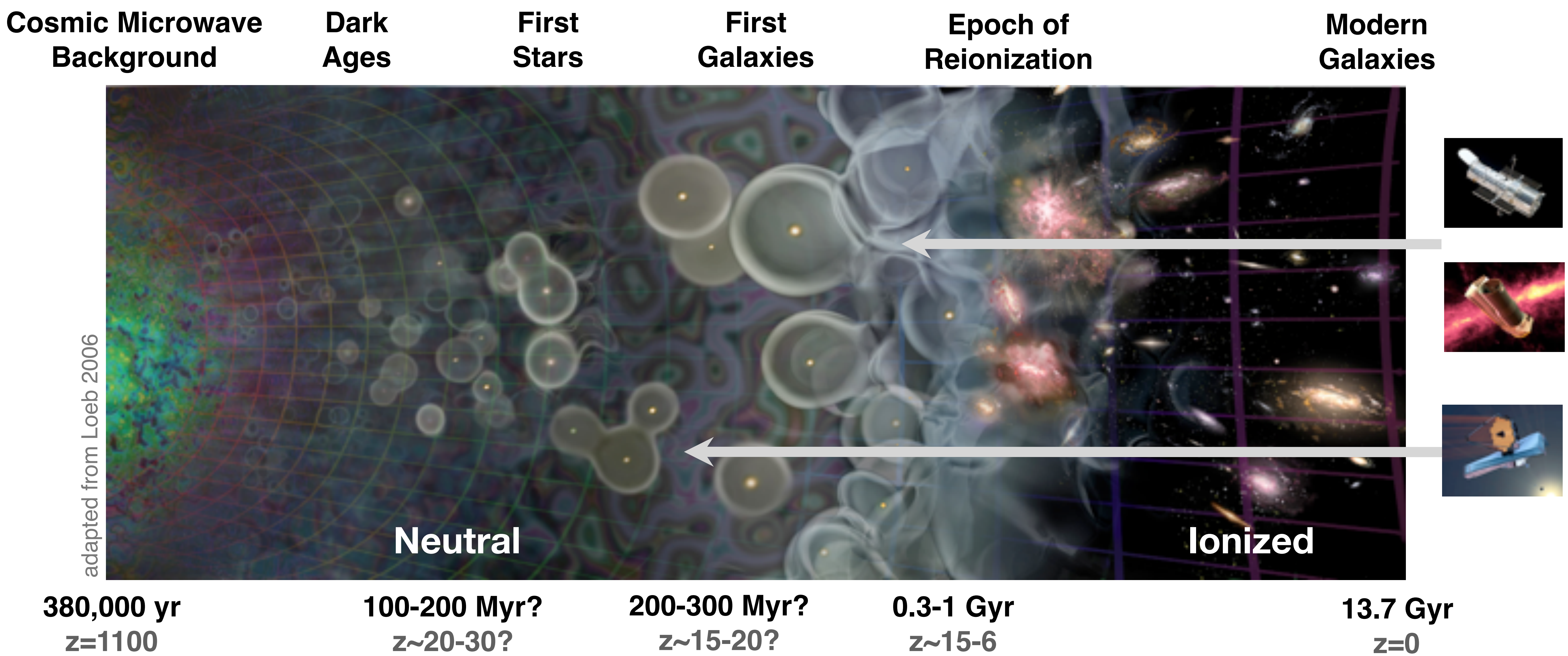
Galaxy formation in the epoch of reionization

Ivo Labbé, Leiden University, July 5 2016



Galaxies at cosmic dawn



- Identify and characterize our cosmic origins when universe was only few% of its present age
- Early universe is an good testbed for theoretical models (closer to initial conditions, simpler physics)
- Probe galaxies at <1Gyr to understand cosmic reionization (last major phase transition of Hydrogen). Were there enough ionising photons?

Did Galaxies Reionize Universe?

ionizing emissivity

$$\dot{n}_{\rm ion} = f_{\rm esc}\, \xi_{\rm ion}\, \rho_{\rm UV}$$

1) abundance of (low luminosity) sources integrated UV luminosity density $\rho_{\rm UV}$

2) stellar populations Lyman-continuum photon production efficiency ($\xi_{\rm ion}$) per UV-continuum luminosity

3) Escape fraction of Ly-c photons $f_{\rm esc}$ (see Erik Zackrisson's talk)

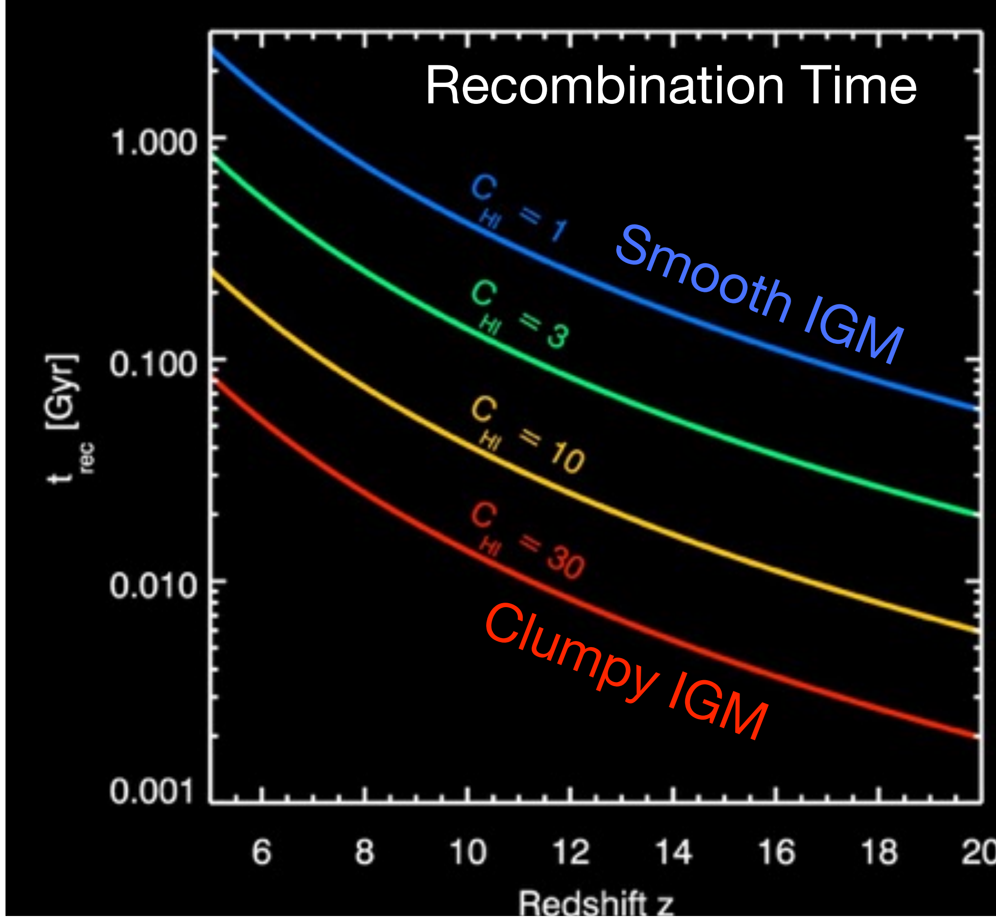
4) Optical depth of electron scattering to CMB: τ

$$\dot{Q}_{\rm HII} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H}\rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}}$$

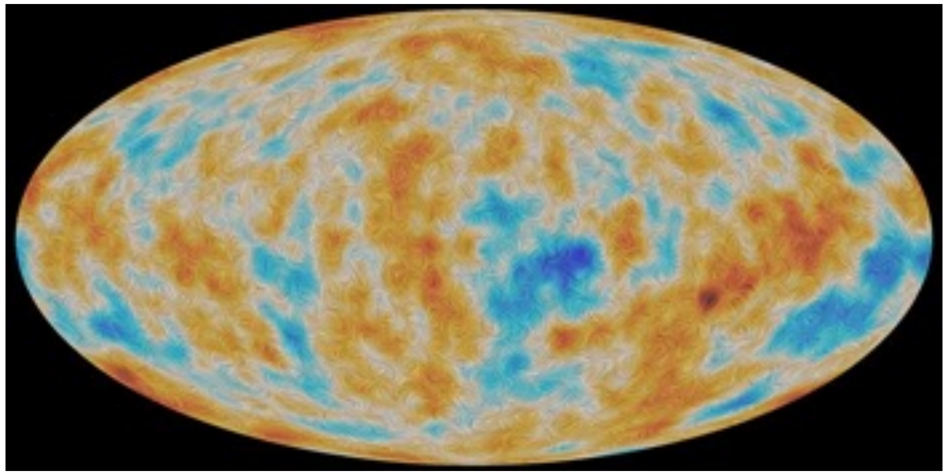
Ionizing photon production rate (density)

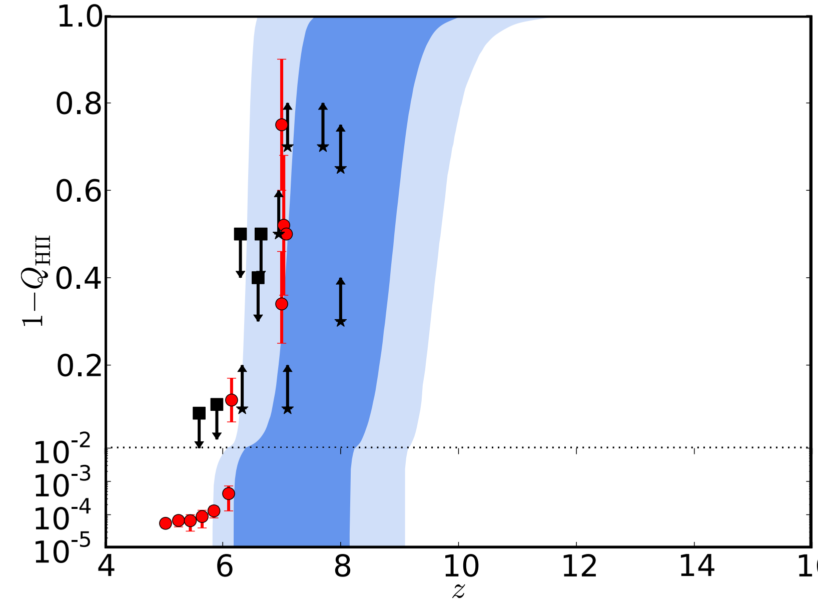
Comoving H density

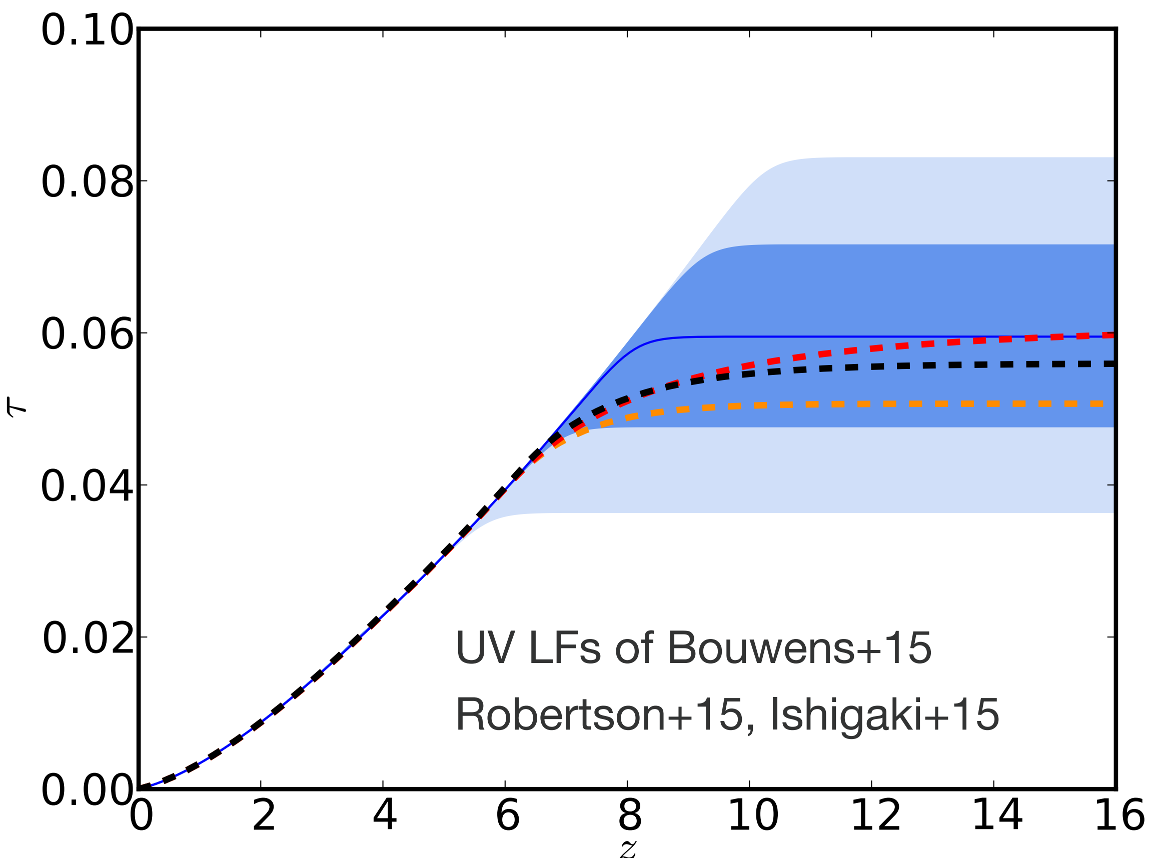
Recombination time

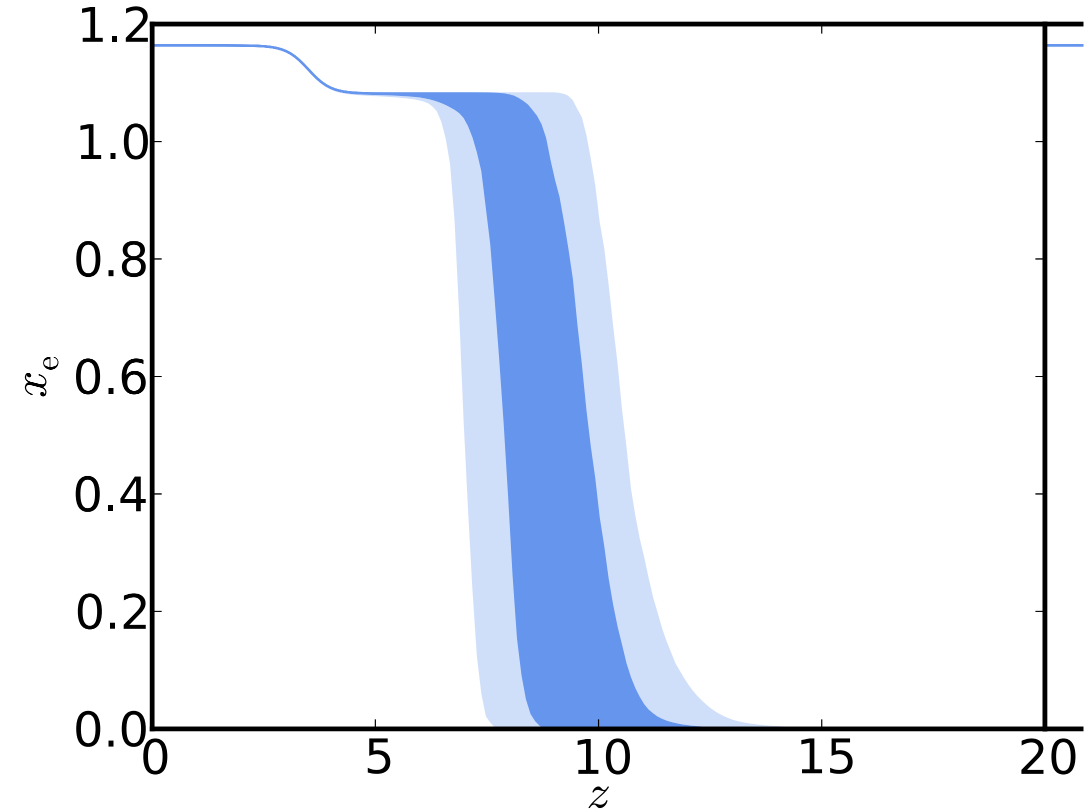


Planck Intermediate Results XLVII arxiv:1605.03507v2



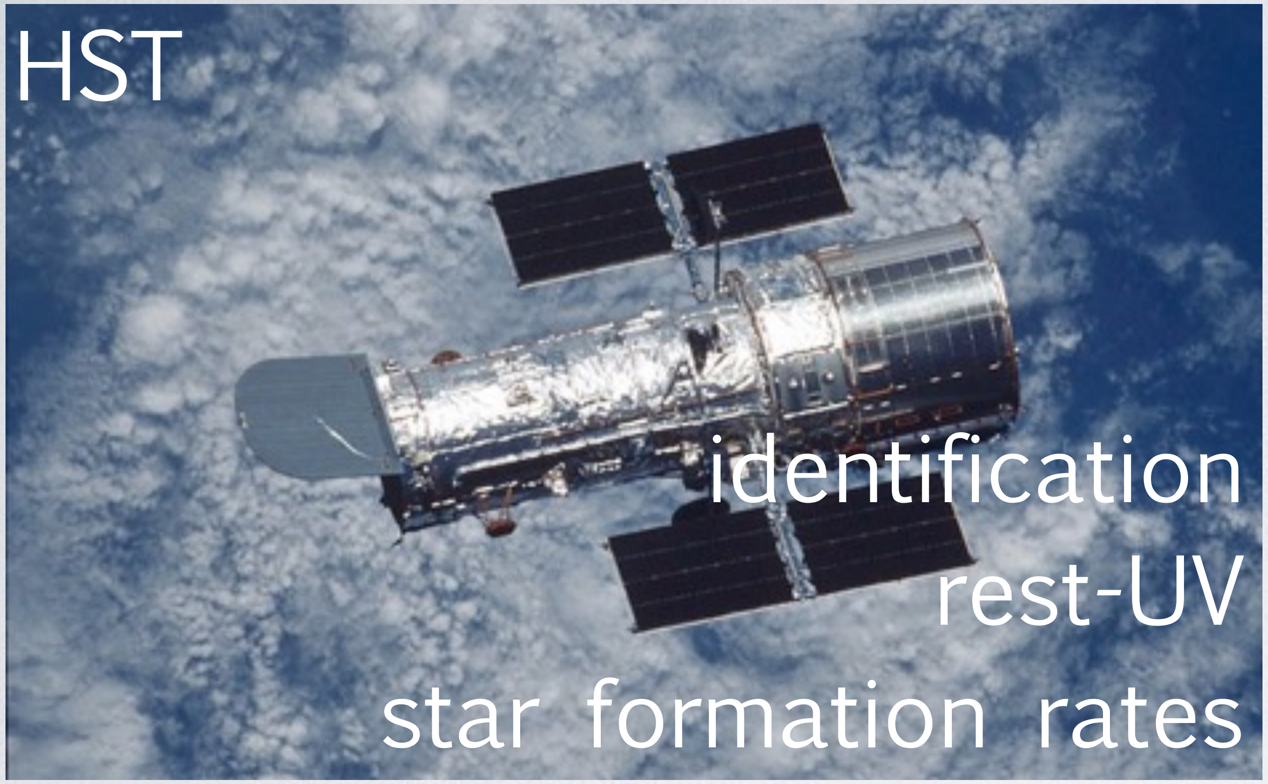


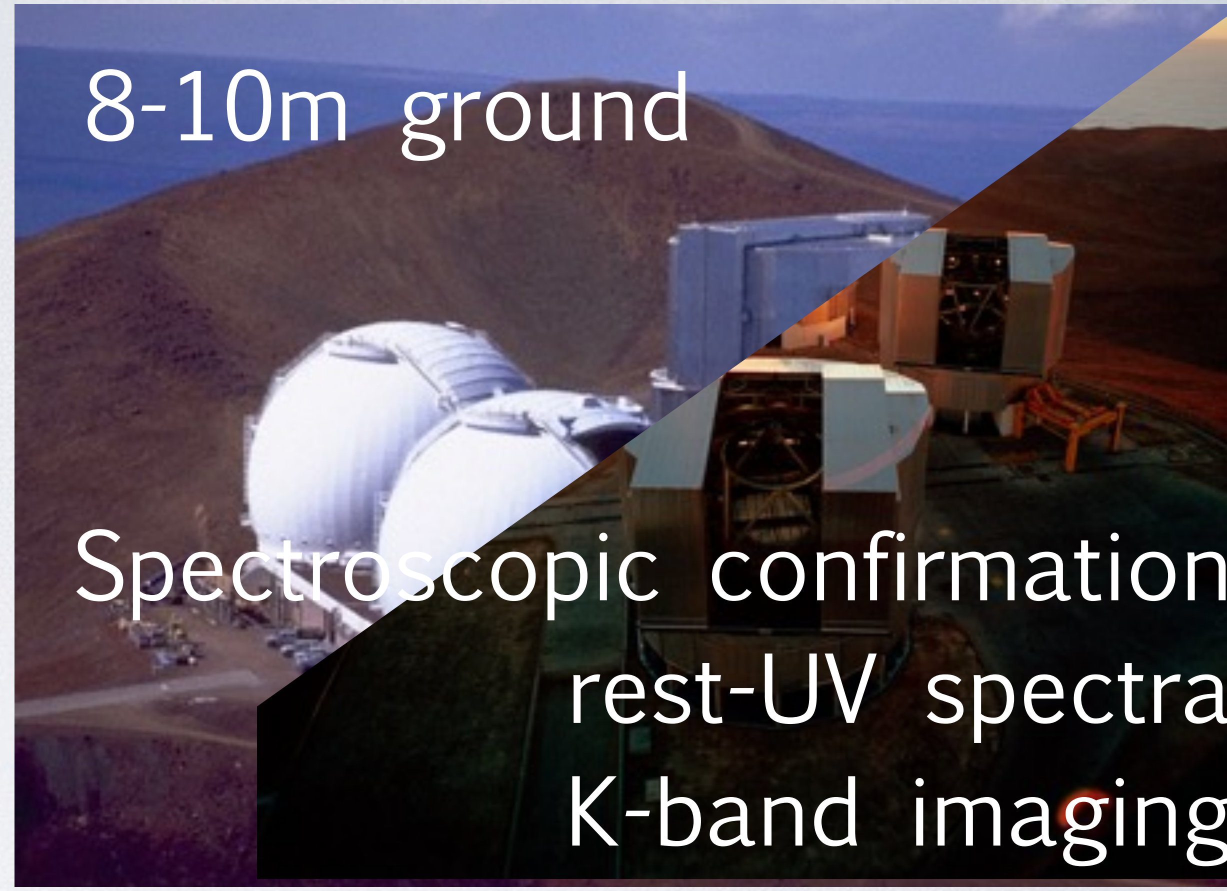


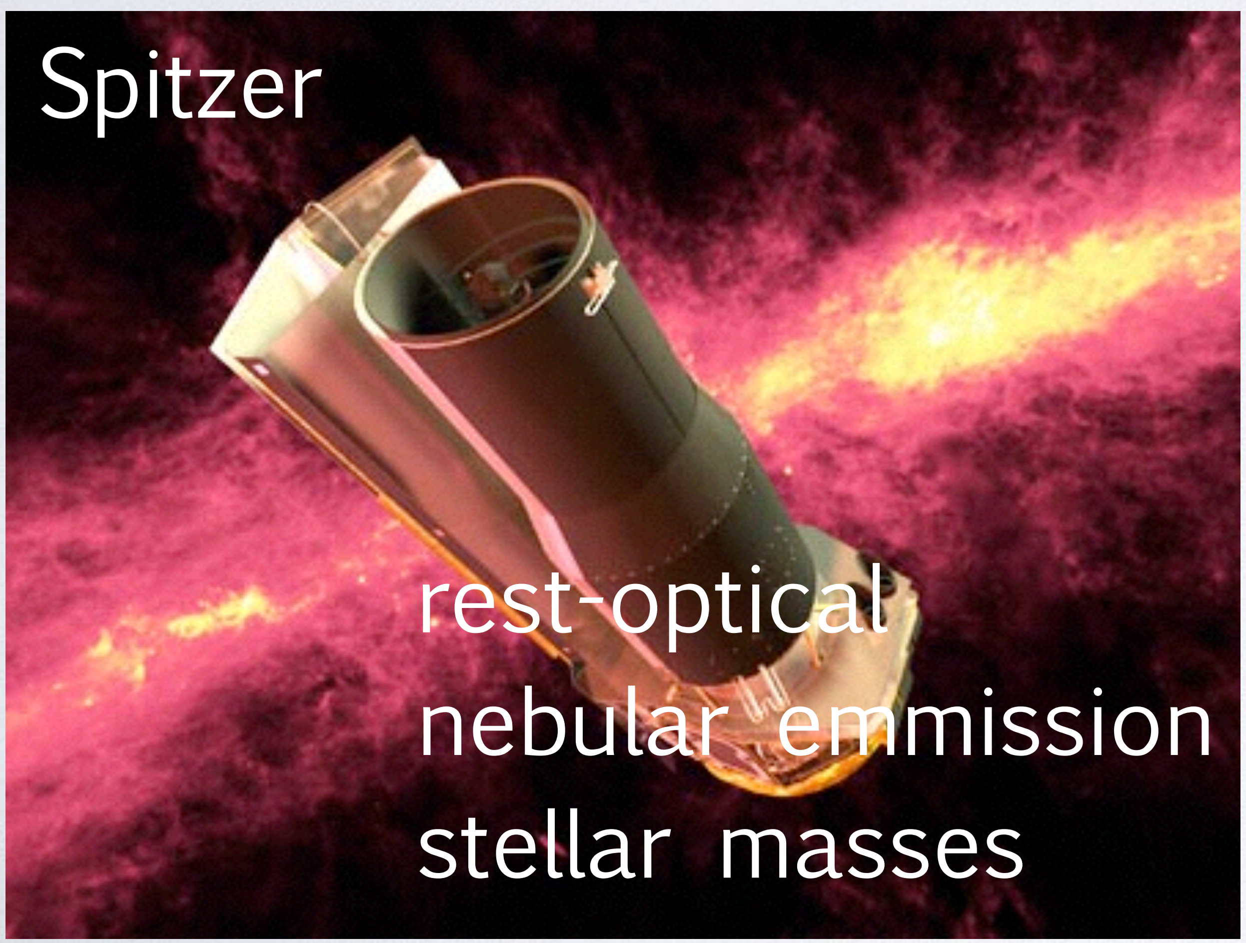


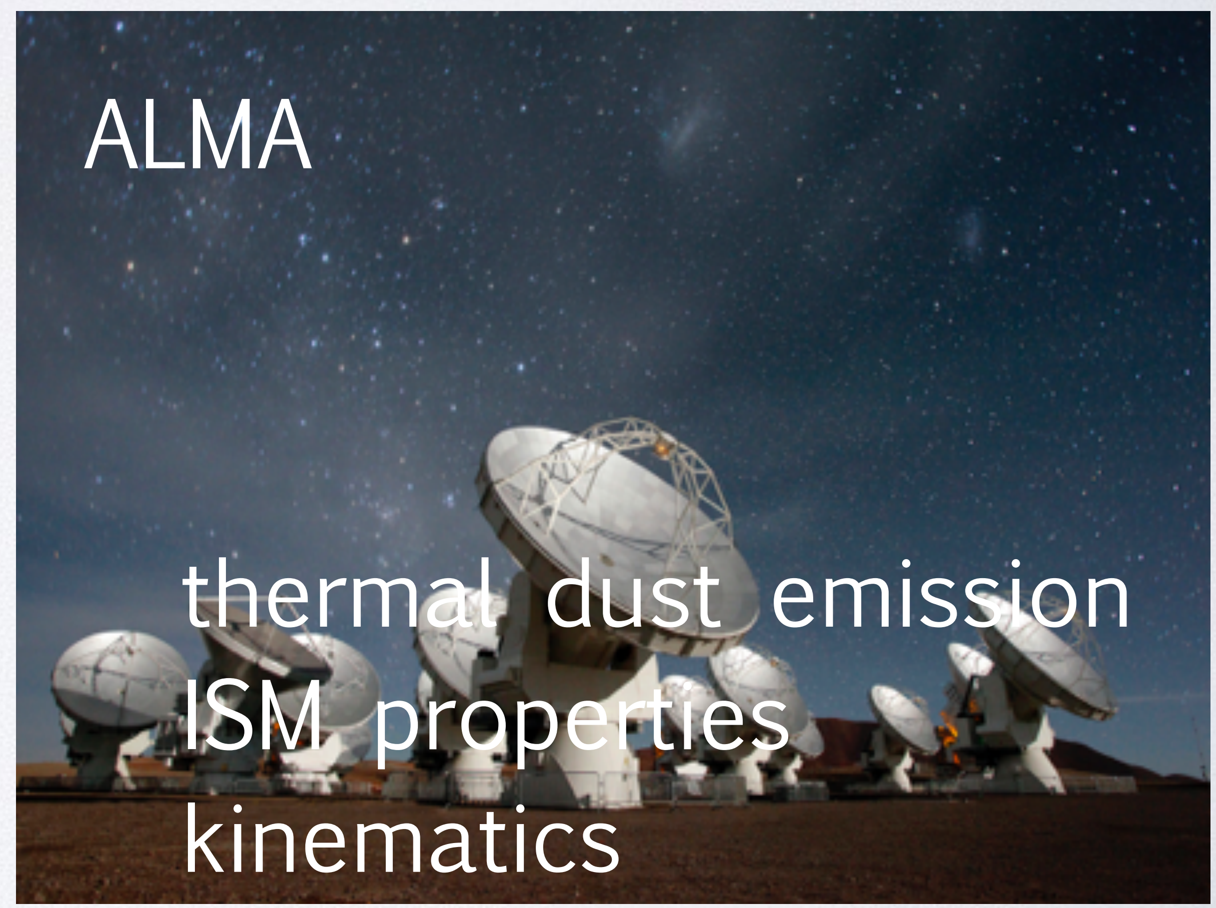
New Planck polarization results: **τ = 0.058 ± 0.012**, **z=8.2±1.1**

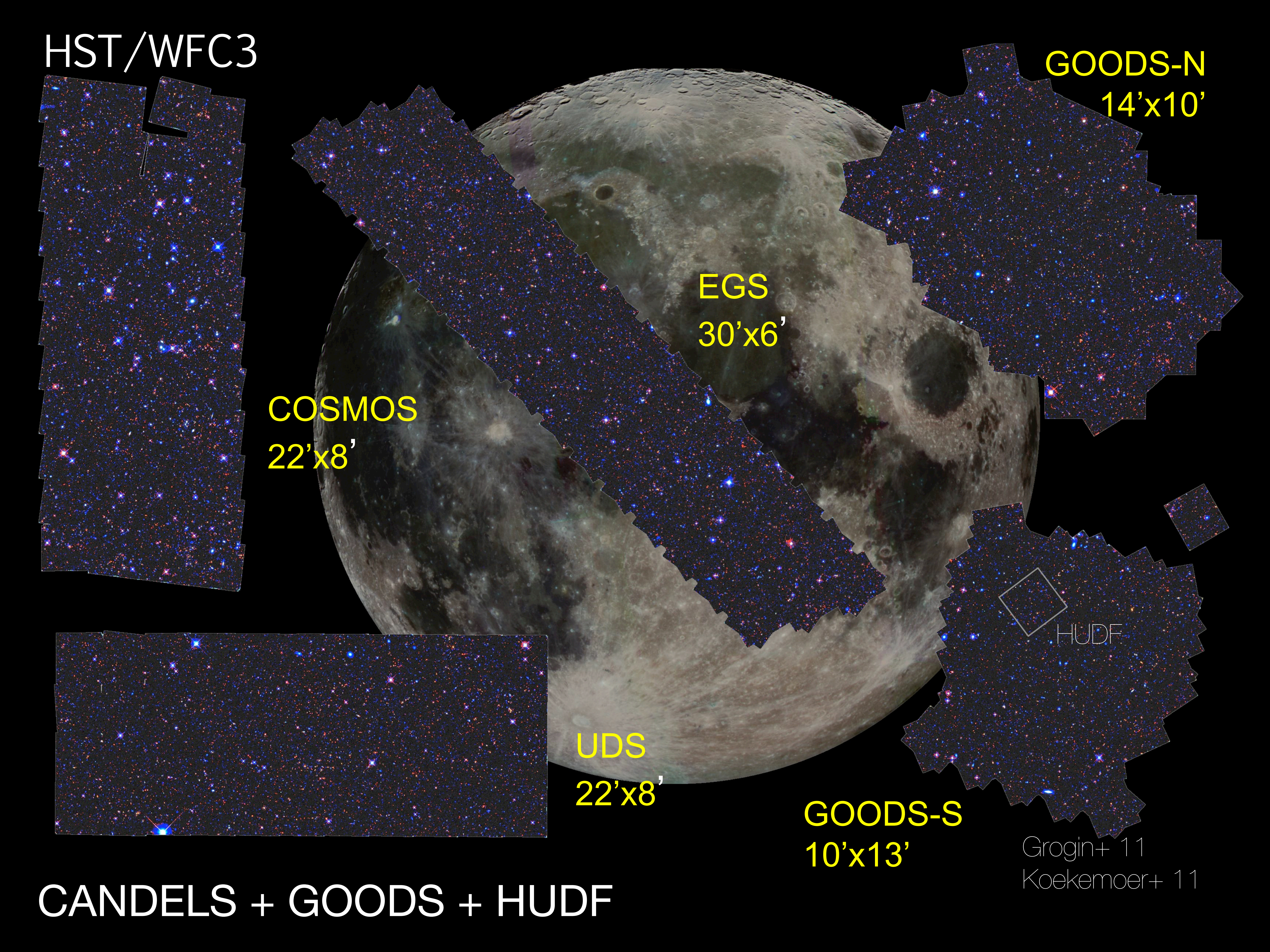
Good agreement with faint galaxies for reasonable $f_{esc}\,\xi_{ion}\,\rho_{UV}$


HST
identification
rest-UV
star formation rates

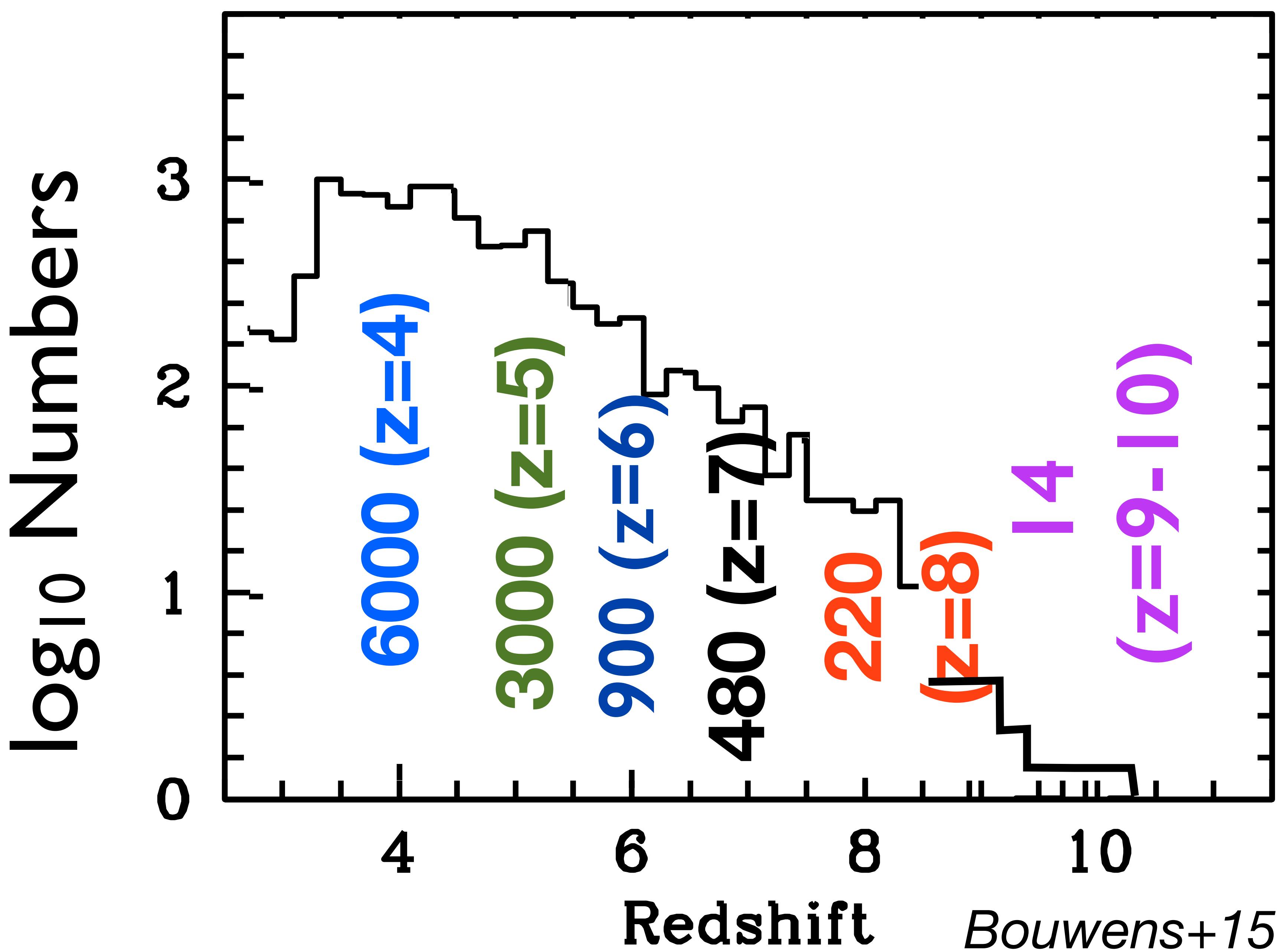

8-10m ground
Spectroscopic confirmation
rest-UV spectra
K-band imaging


Spitzer
rest-optical
nebular emmission
stellar masses


ALMA
thermal dust emission
ISM properties
kinematics


HST/WFC3
GOODS-N
14'x10'
EGS
30'x6'
COSMOS
22'x8'
HUDF
UDS
22'x8'
GOODS-S
10'x13'
Grogin+ 11
Koekemoer+ 11
CANDELS + GOODS + HUDF

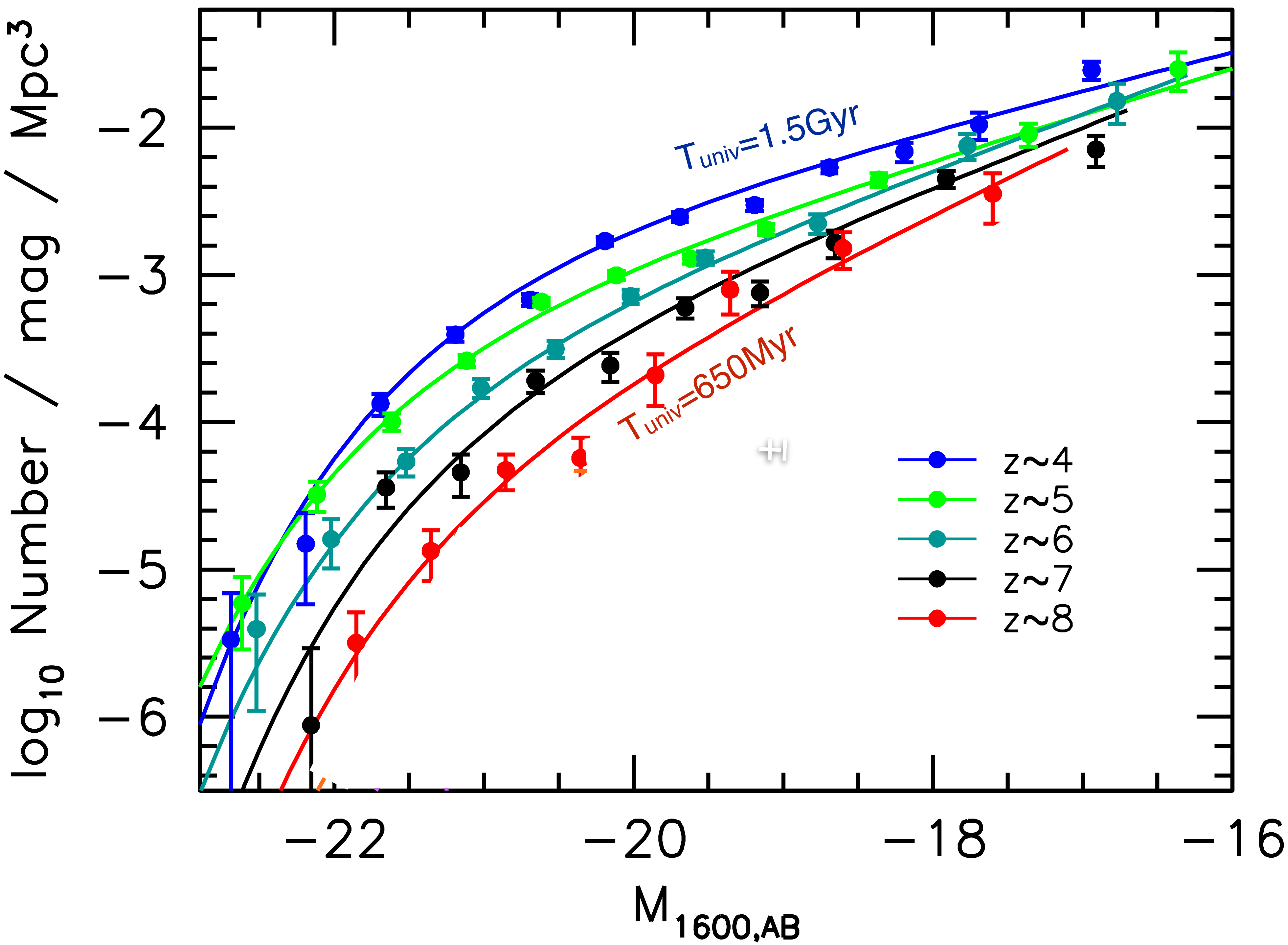
10500 galaxies candidates at z~4-10



Almost 1000 galaxies in the epoch of reionization at z>6
Current frontier: z~9-10

The evolution of the UV luminosity function

(HUDF/XDF, parallels, 5 CANDELS Fields)



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

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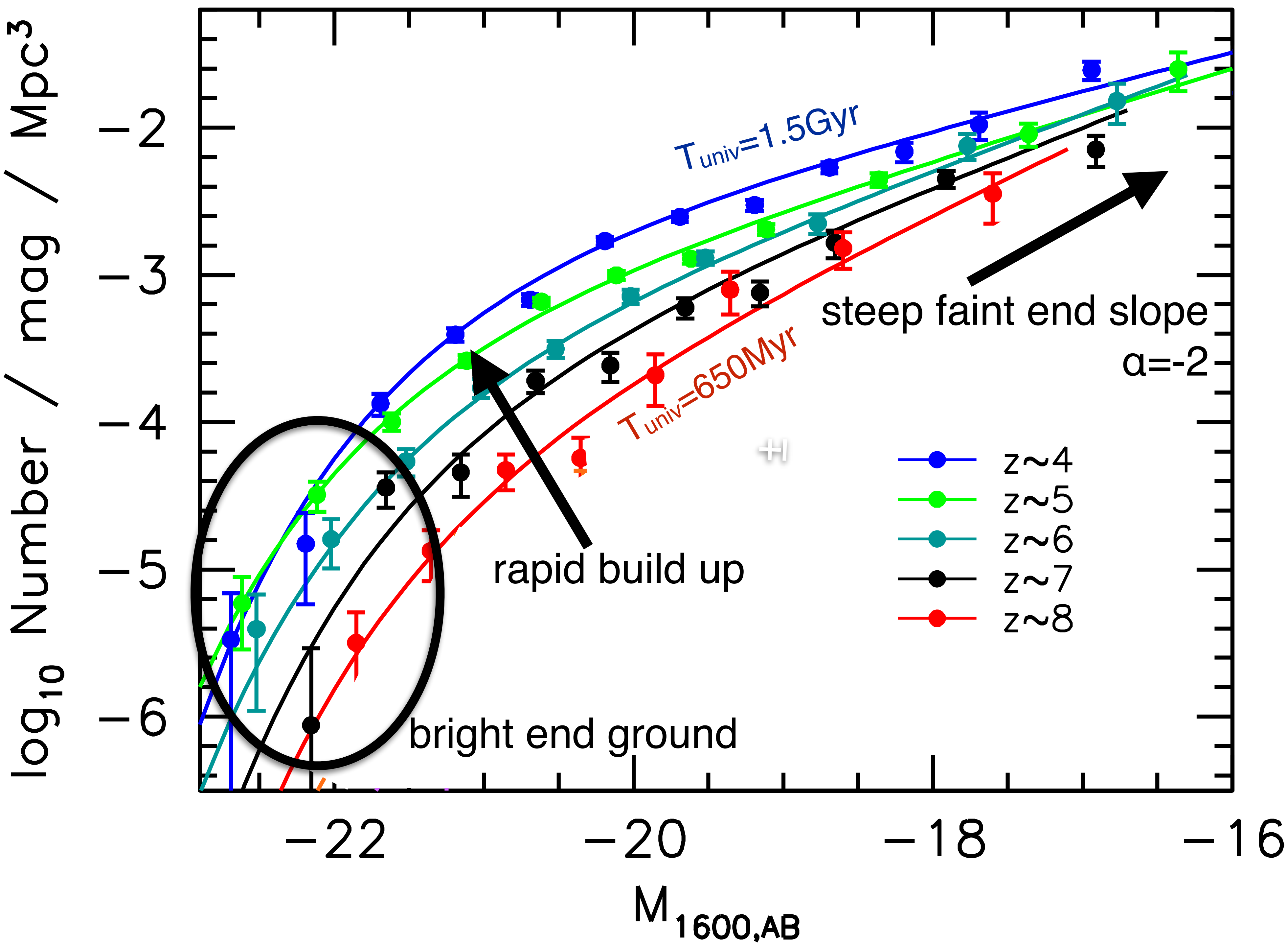
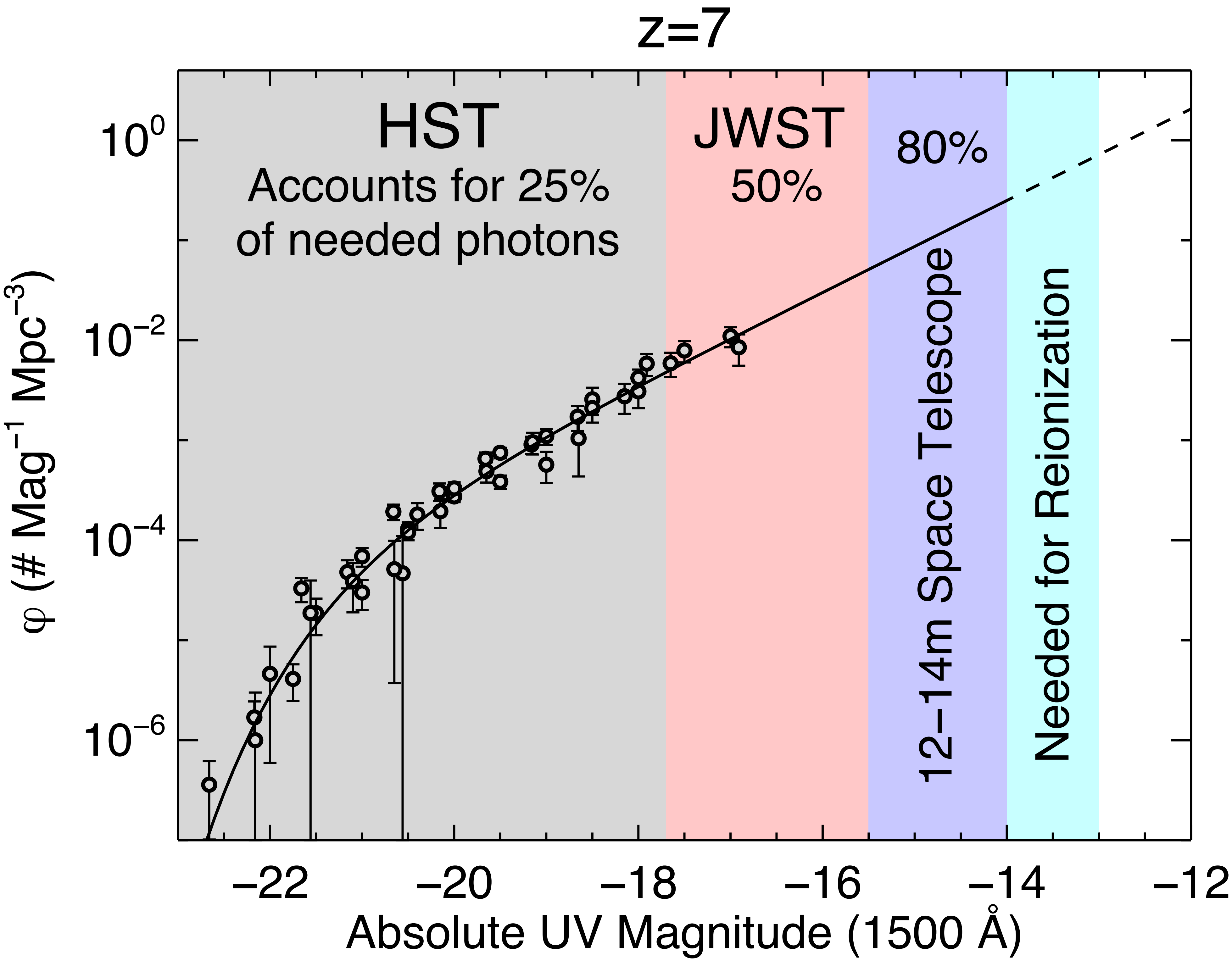


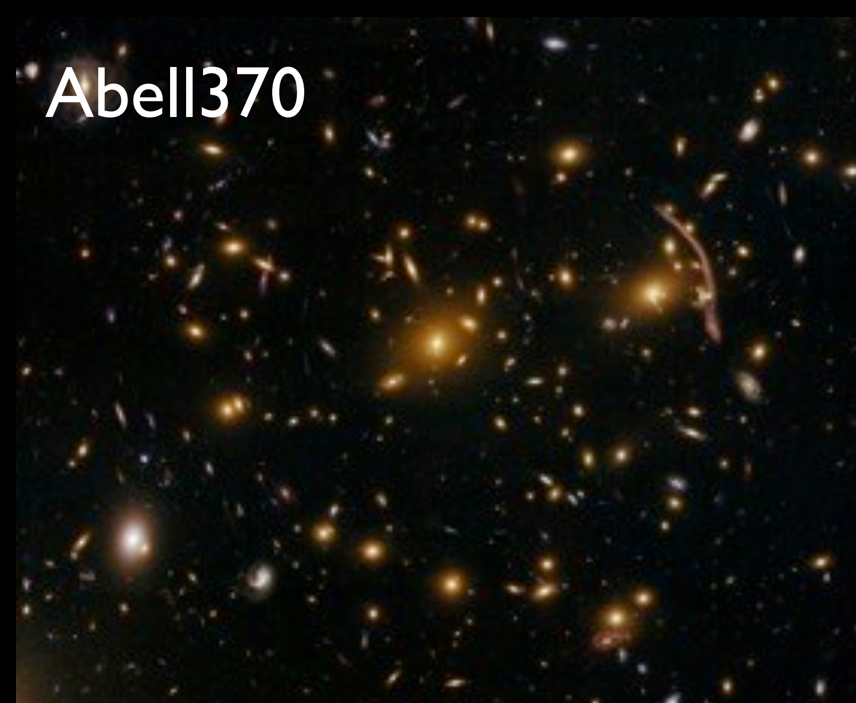
see also: Oesch+10a/12, Bouwens+10a,11,12; Bunker+10, Finkelstein+10/14, Wilkins+10/11, McLure +10/13, Yan+12, Bradley+12

Fraction of UV luminosity function directly observed



Finkelstein+16

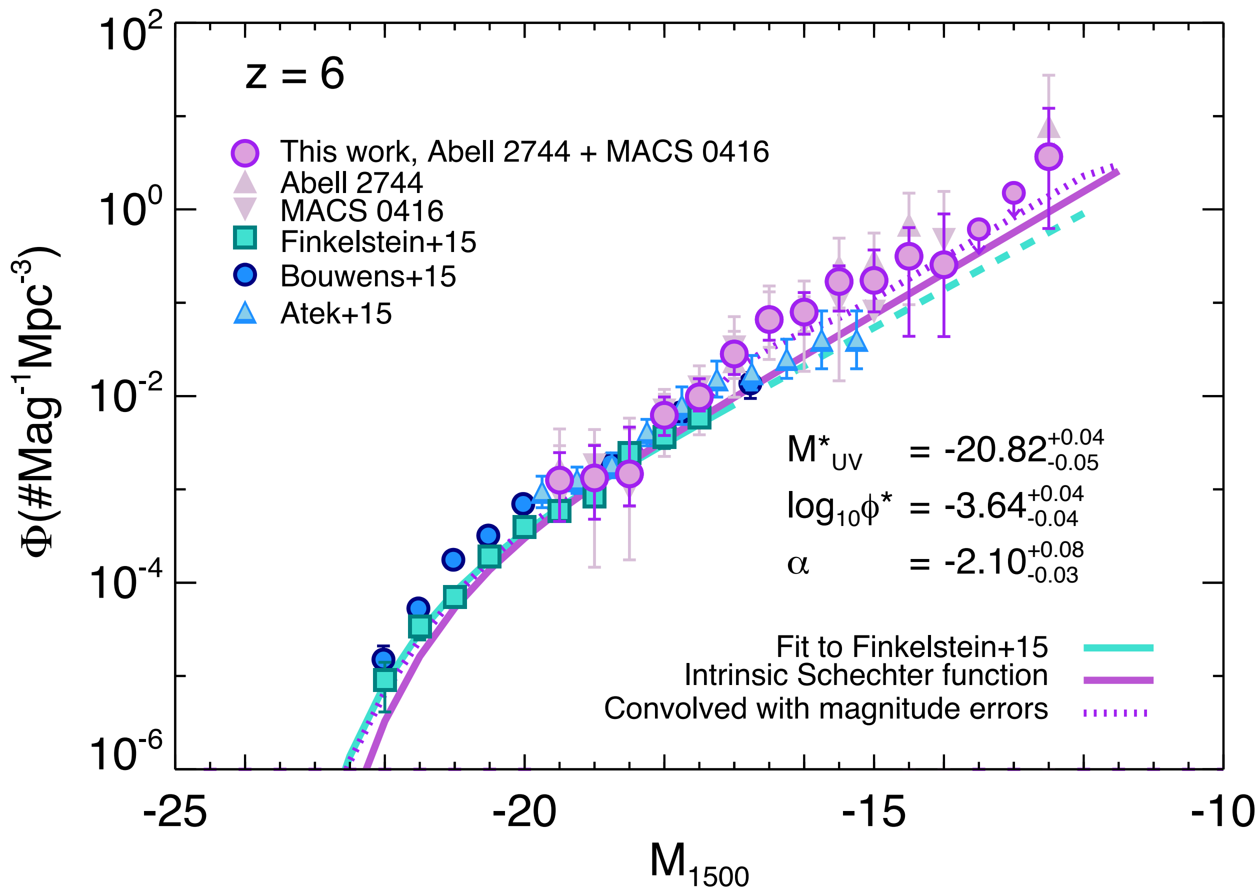
The Hubble Frontier Fields

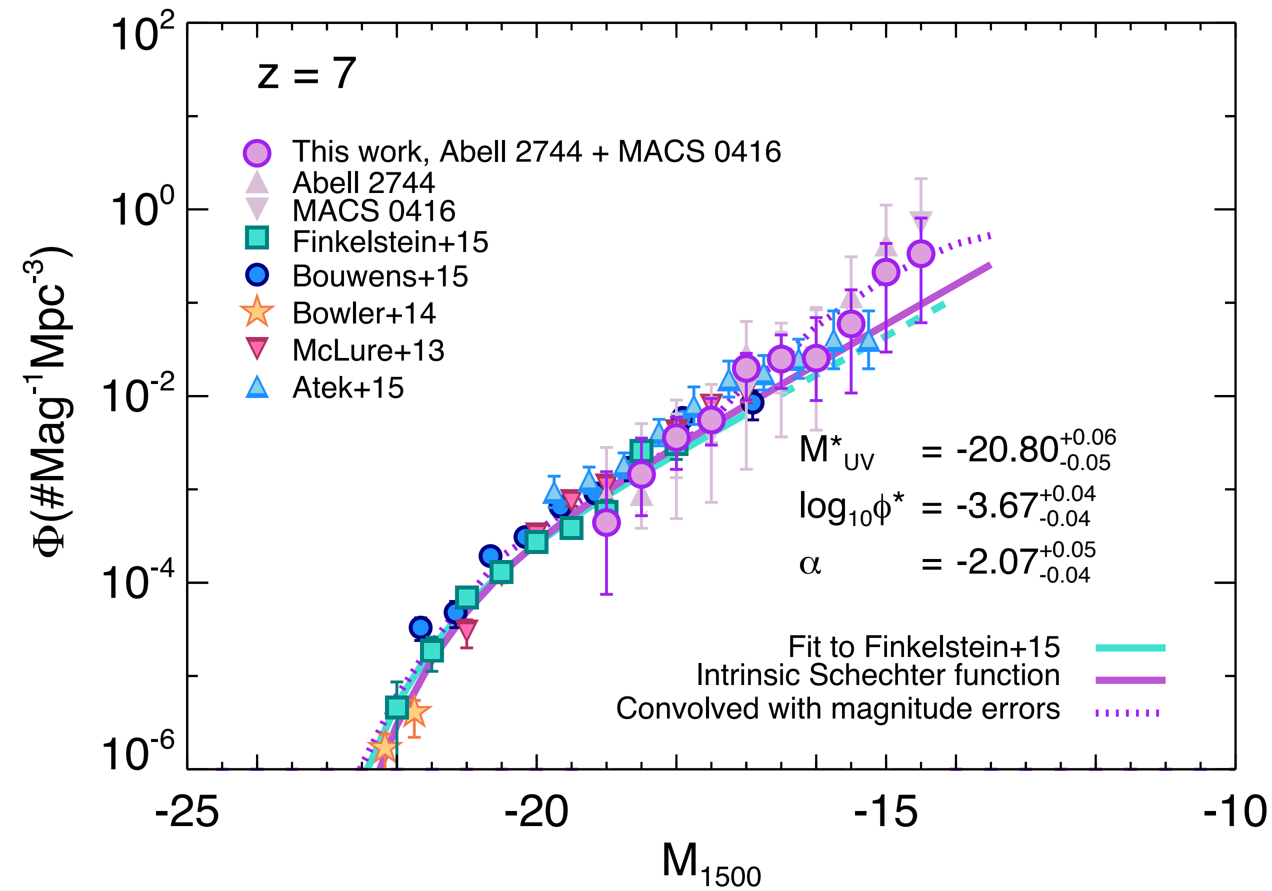


The Hubble Frontier Fields

Extending Analyses to Fainter Luminosities…

Livermore+16



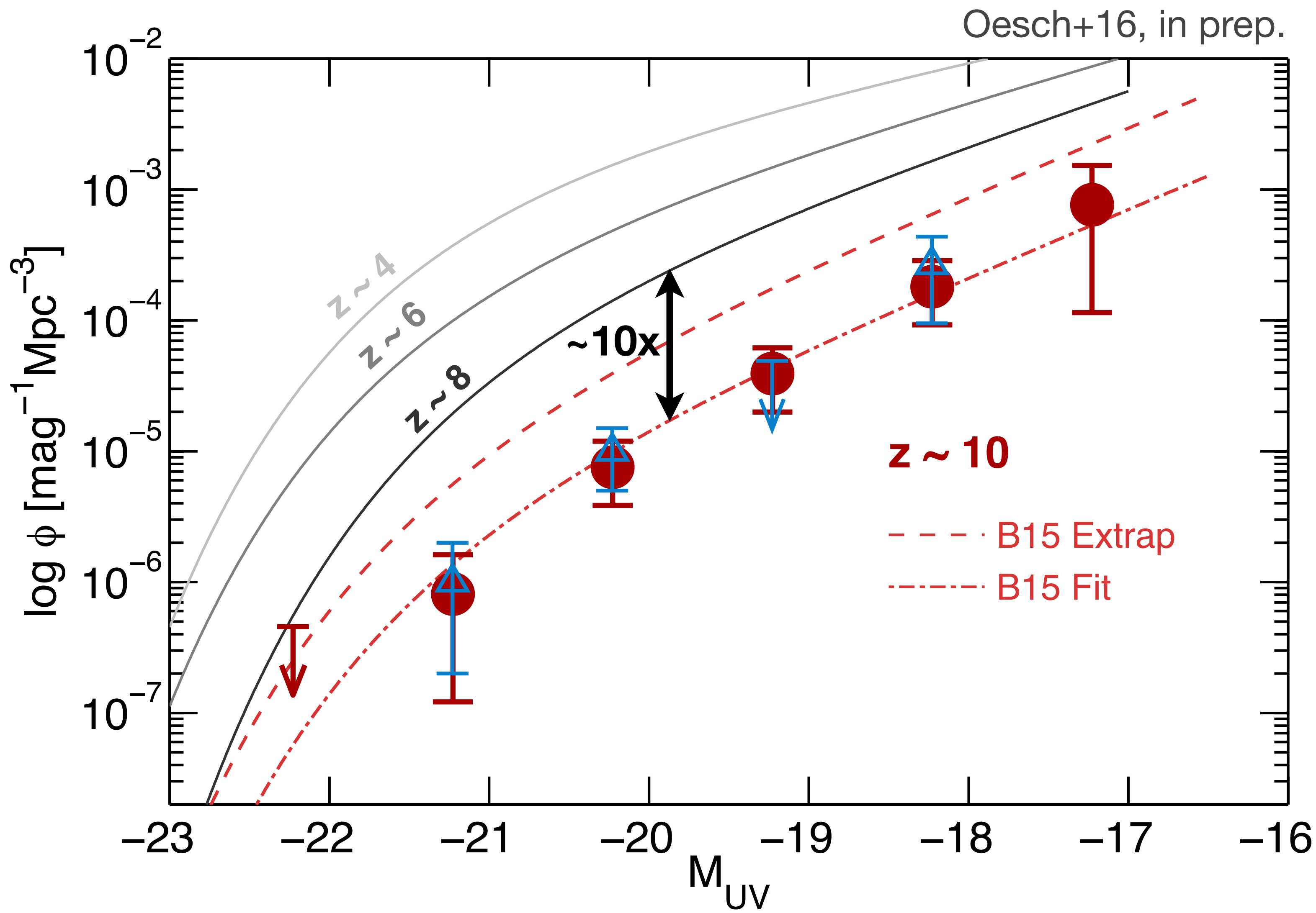


apparent continued steep increase in LF down to M_{UV} ~-13

caution: unclear how much these LFs can be trusted given uncertainties in high-magnification regions (>10x)

The Hubble Frontier Fields

And higher redshifts z=9-10…

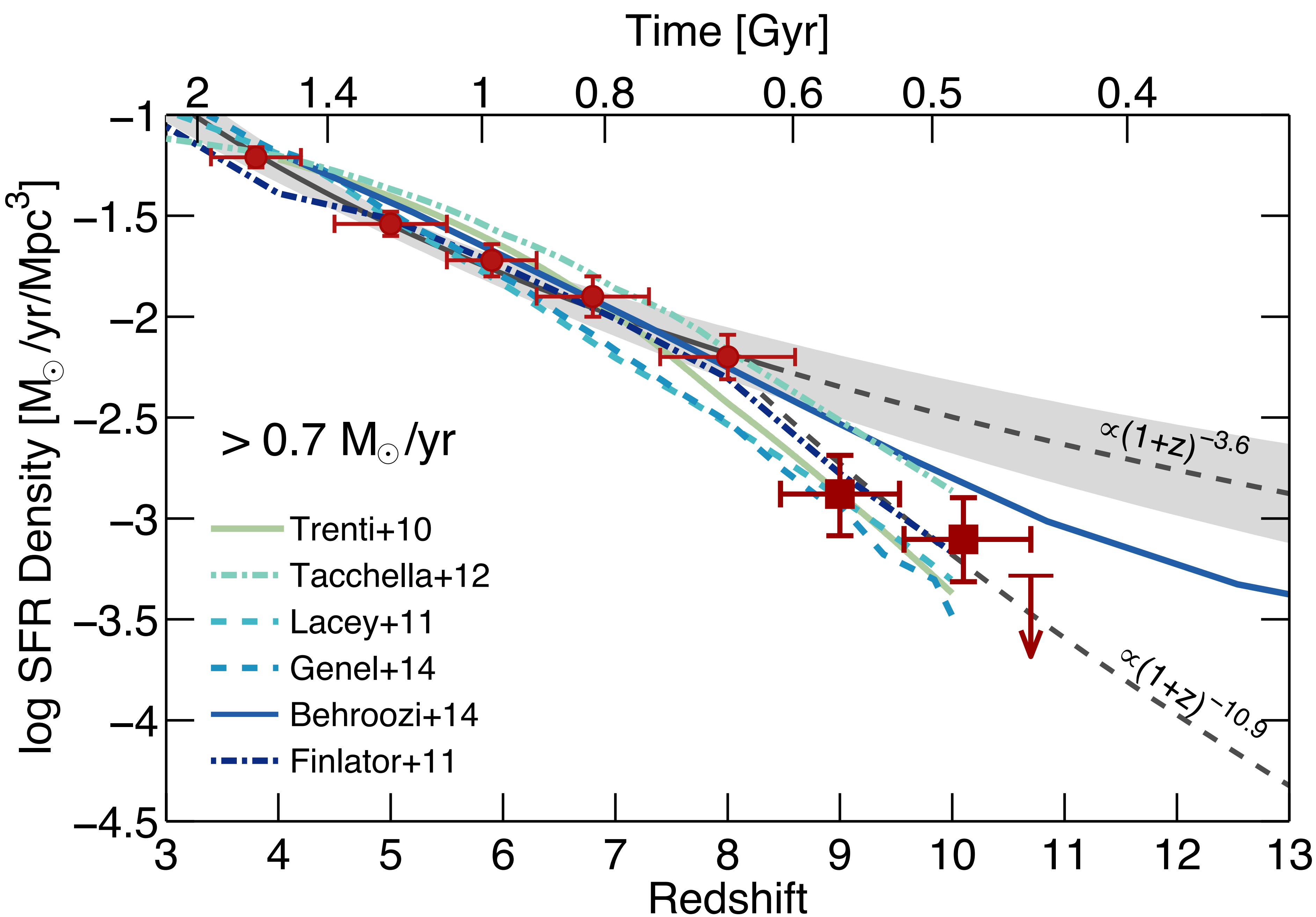


Including HFF galaxy candidates a decent estimate of the UV LF at z~10.

continued rapid evolution to z~10.

See also McLeod+16   *bright end at z=9-10 see Michele Trenti's talk*

Rapid Decline in SFRD towards high redshift

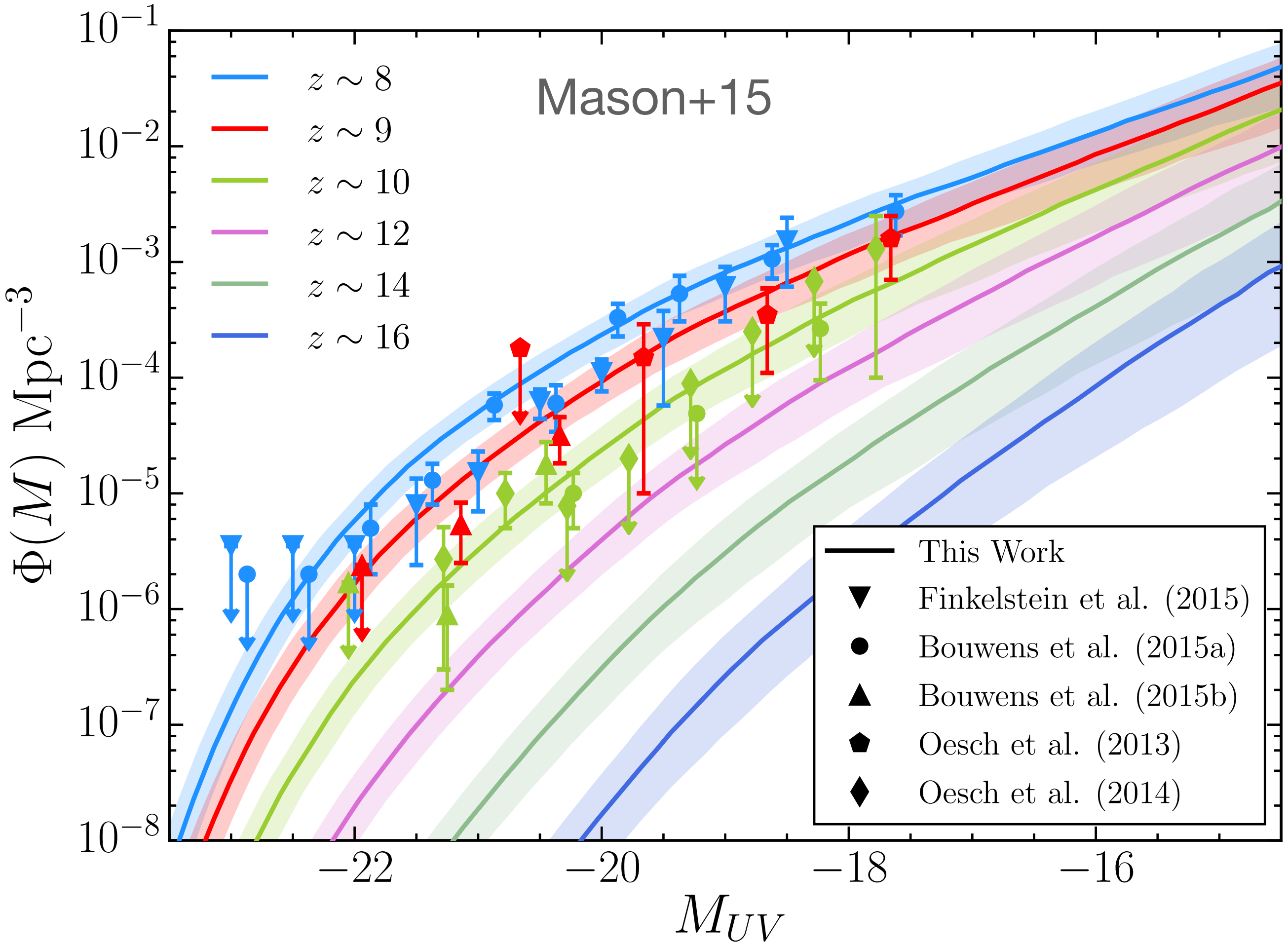


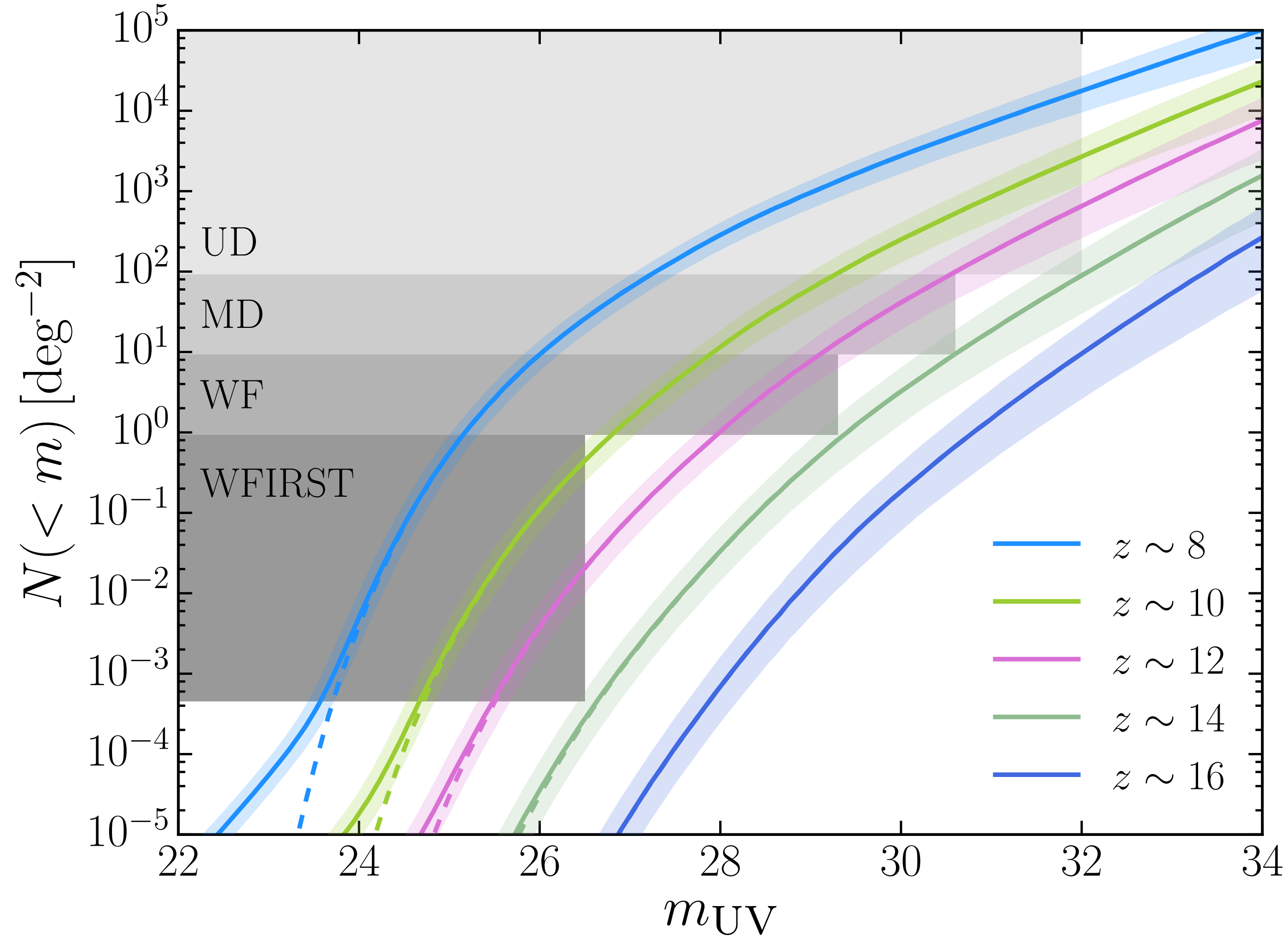
Rapid decline in the cosmic SFRD is consistent with most models

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!

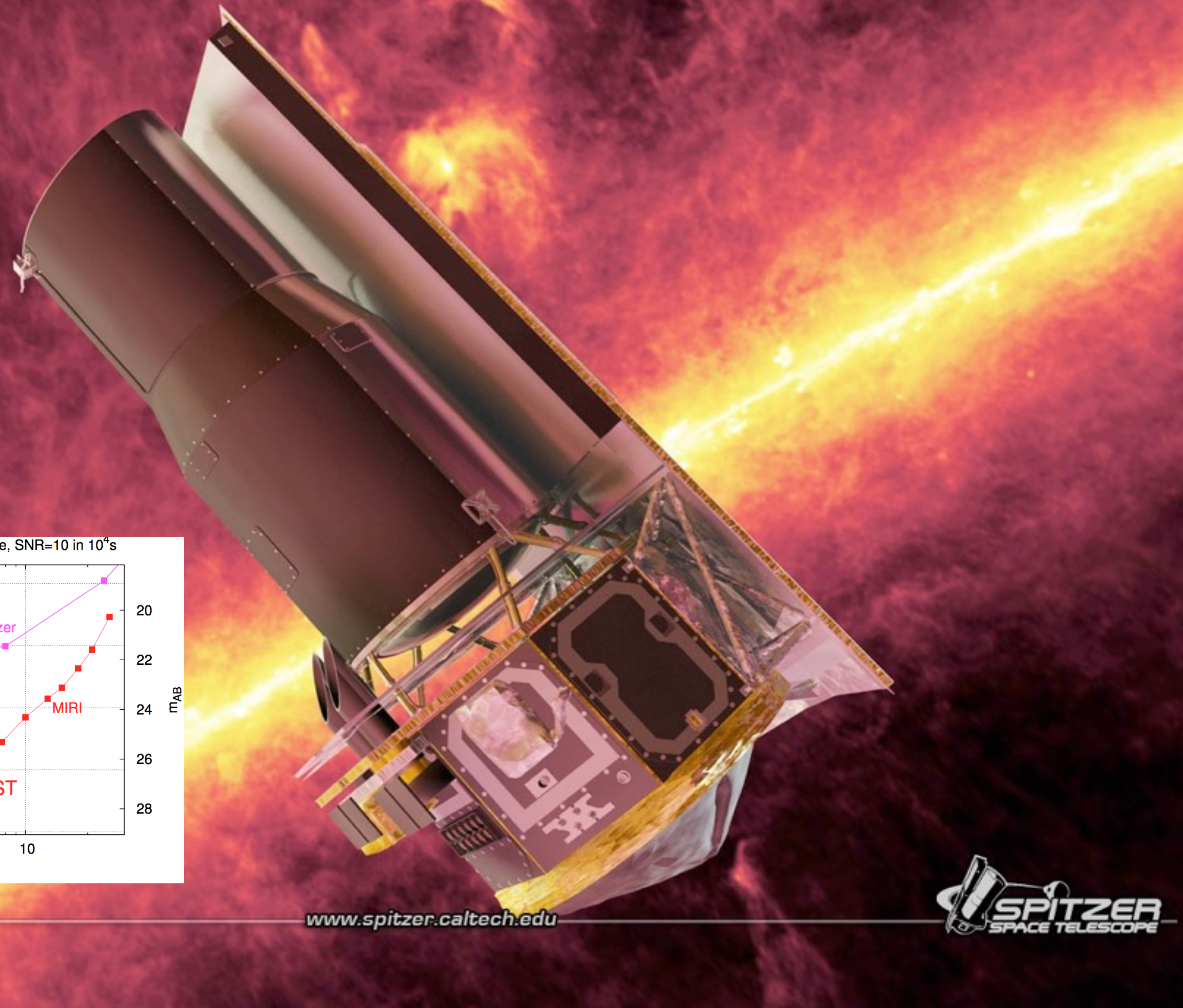
Predictions at z > 10 for JWST

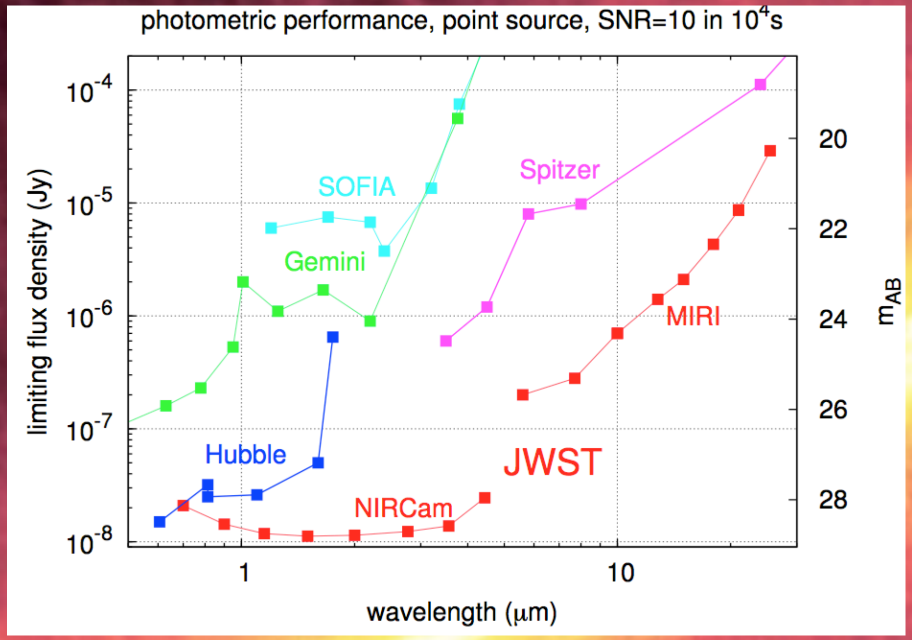




Despite decline: most models predict deep JWST/NIRCam observations will reach to z~15

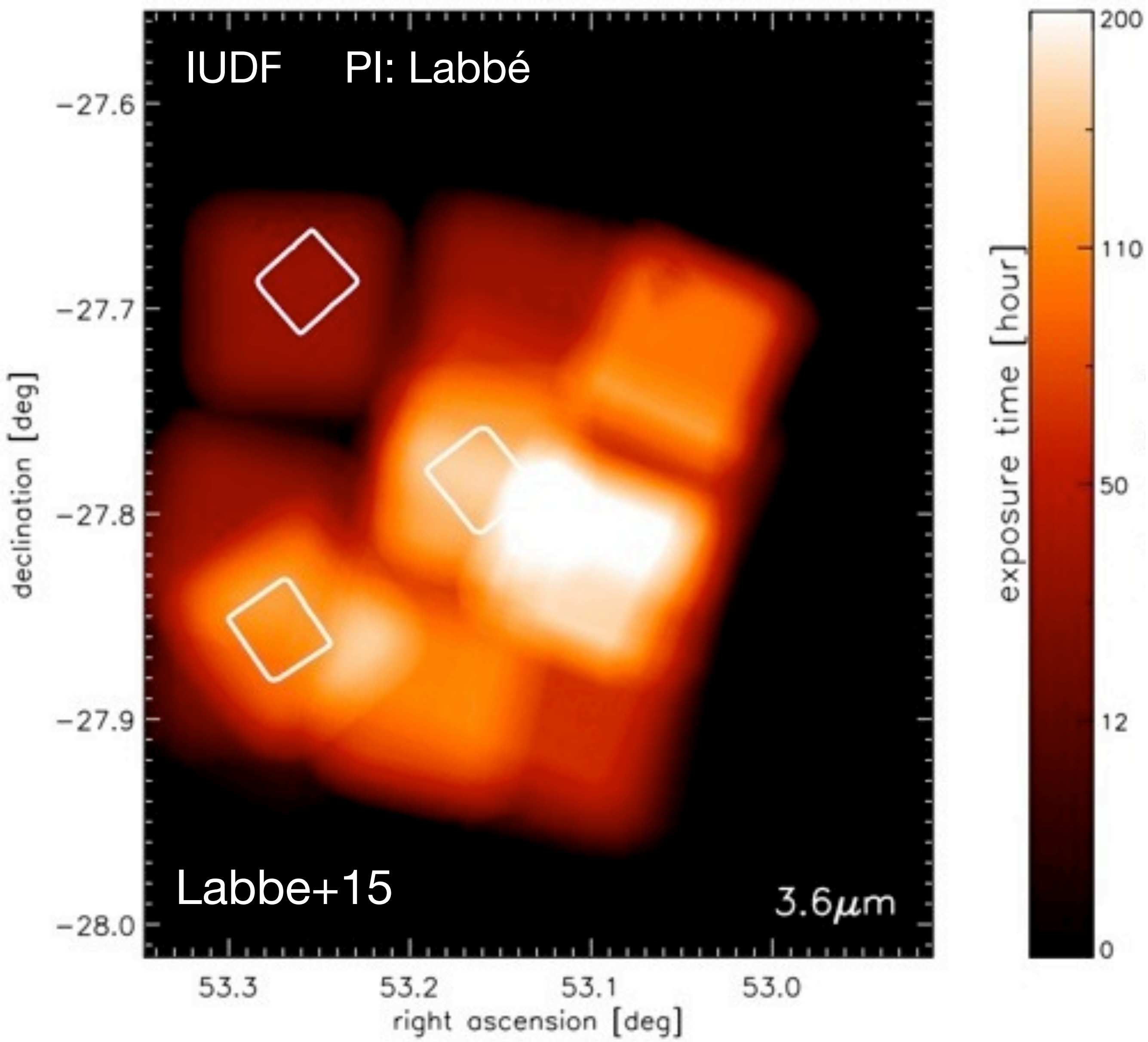
Spitzer/IRAC stellar masses and emission lines

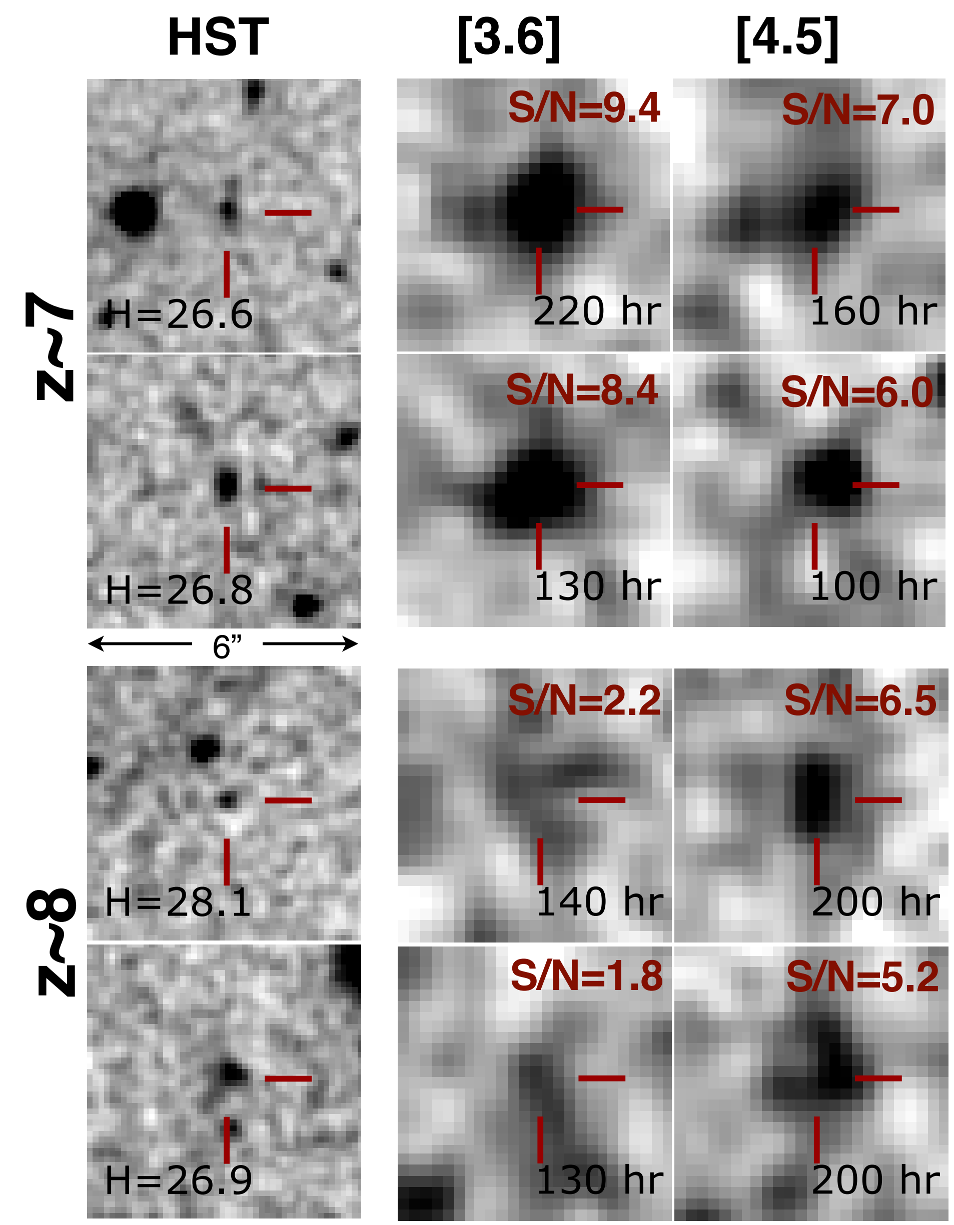




Matched HST + IRAC data are key

Very Faint, Individually Detected z~7-8 Sources





Labbe, Oesch+15

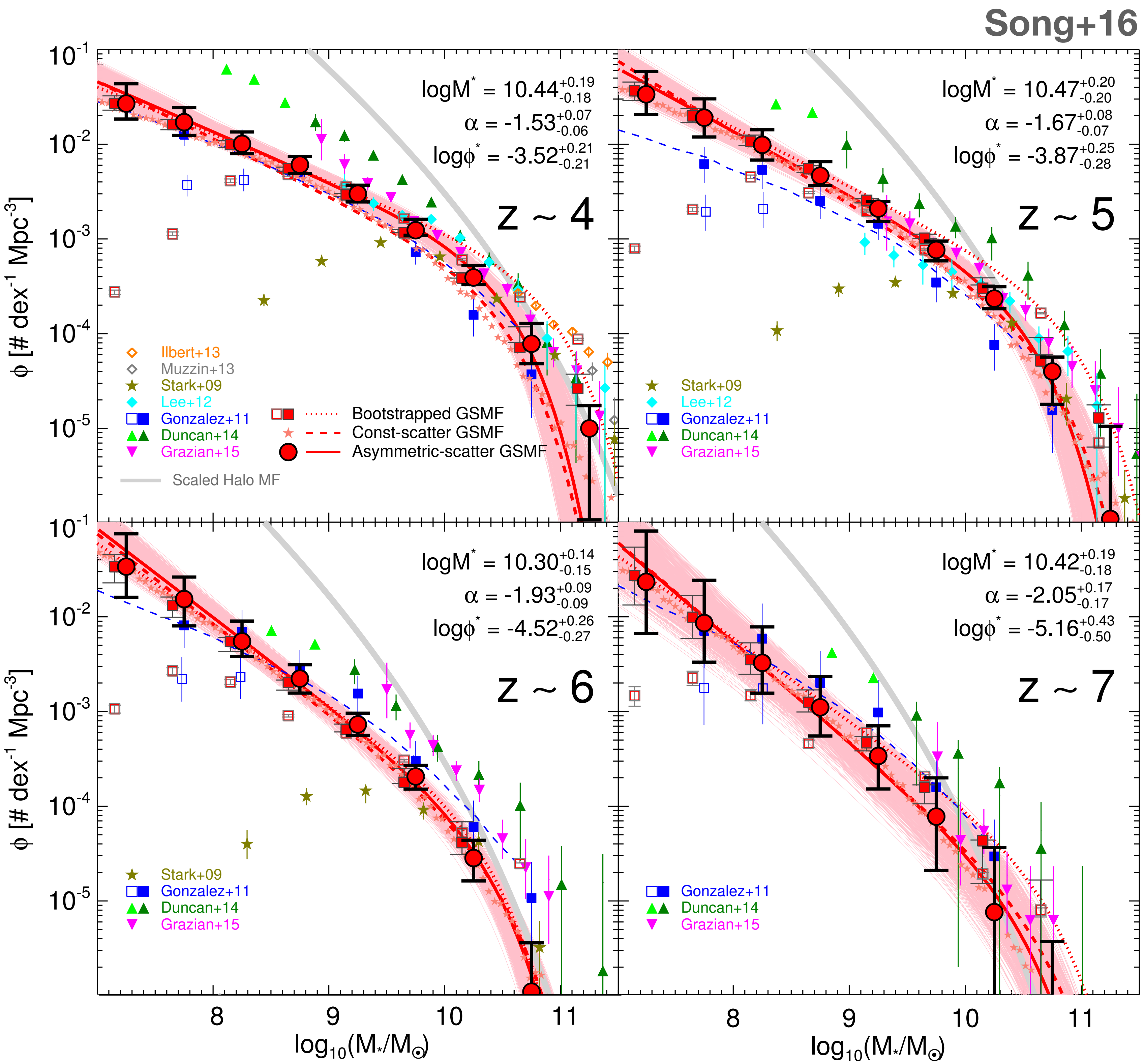
Small area over GOODS-S has 180-220 hour IRAC exposure times (27.4 mag, 3σ)

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

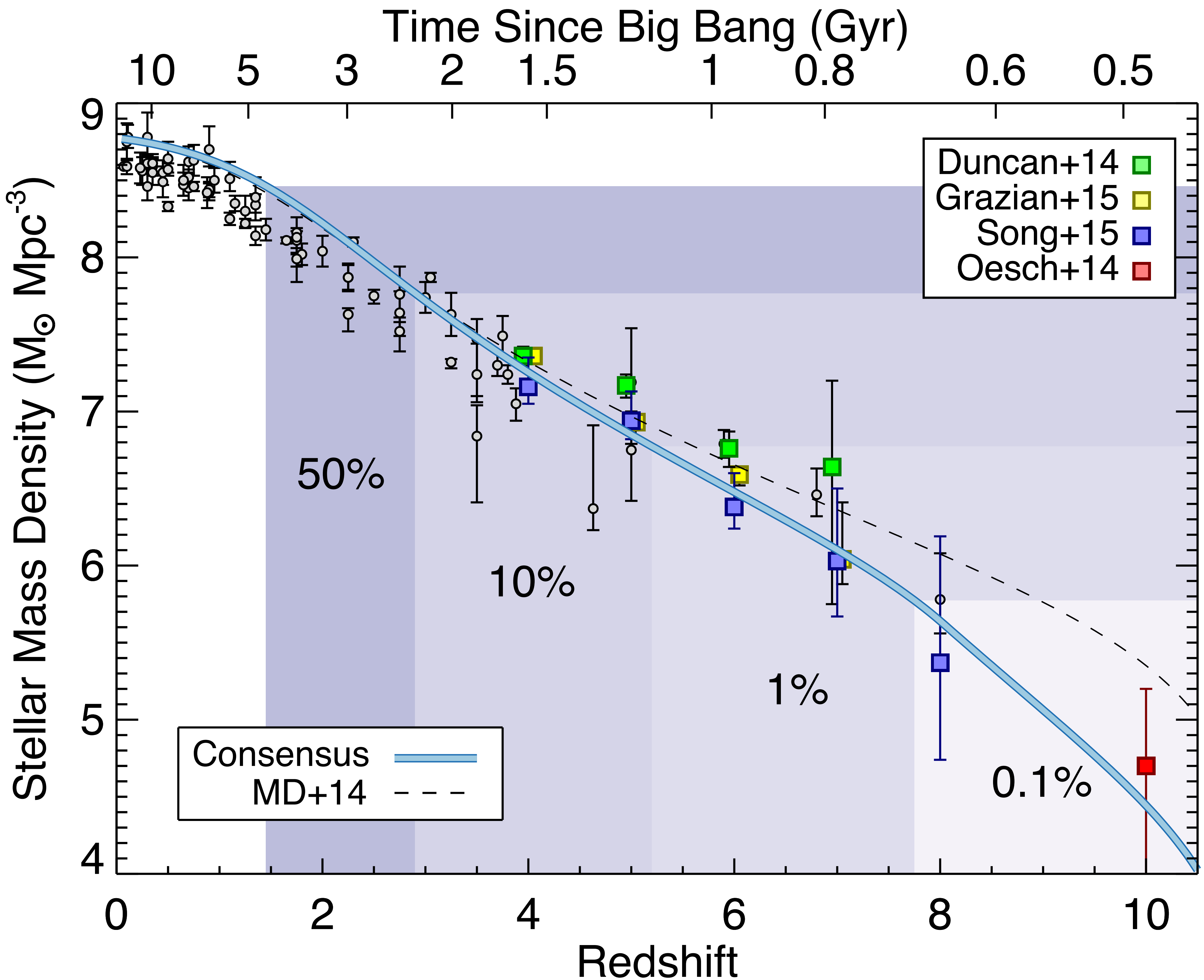
data release fall 2016

see also Karina Caputi’s Talk

Evolution of the Galaxy Stellar Mass Functions to High Redshift

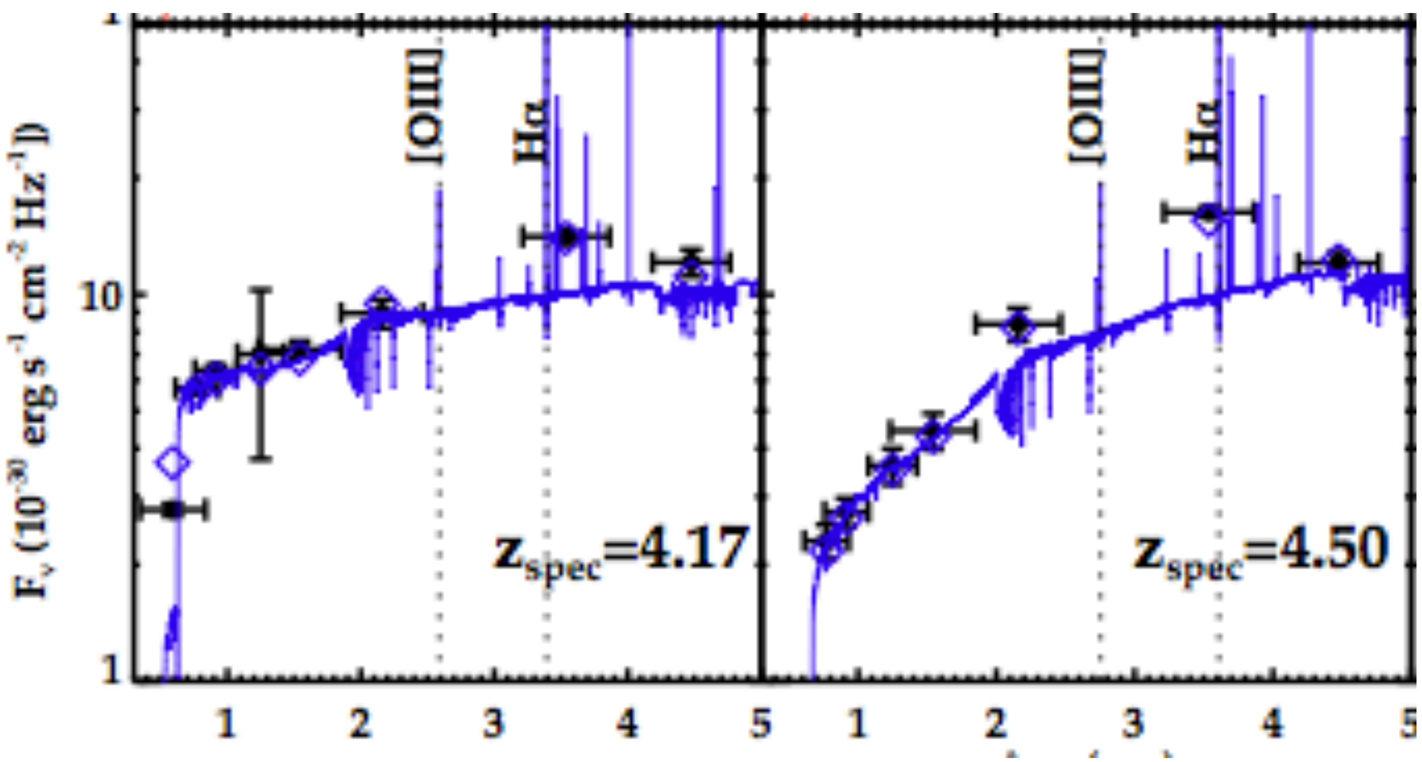


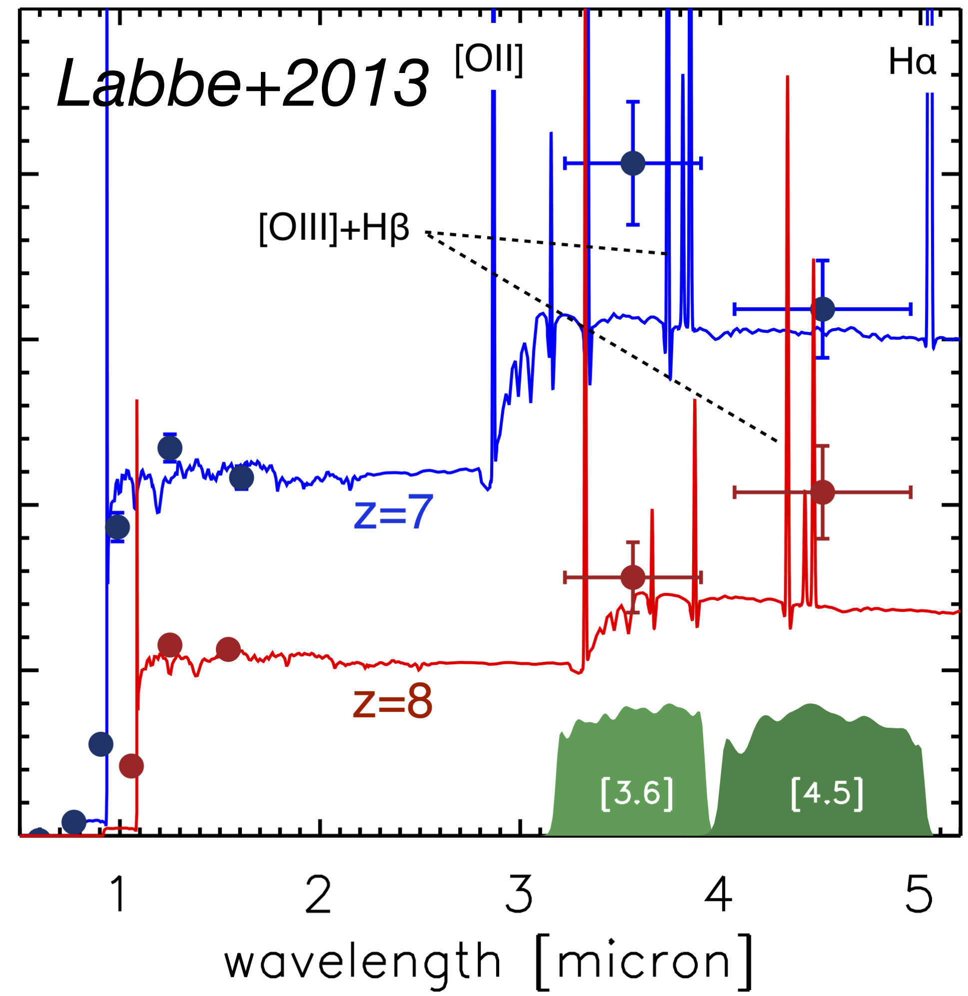
The Evolution of the Total Stellar Mass Density



Caveat: very Strong Nebular Lines are Ubiquitous at z>4

Stark+2013 z_{spec}=3.8-5.0





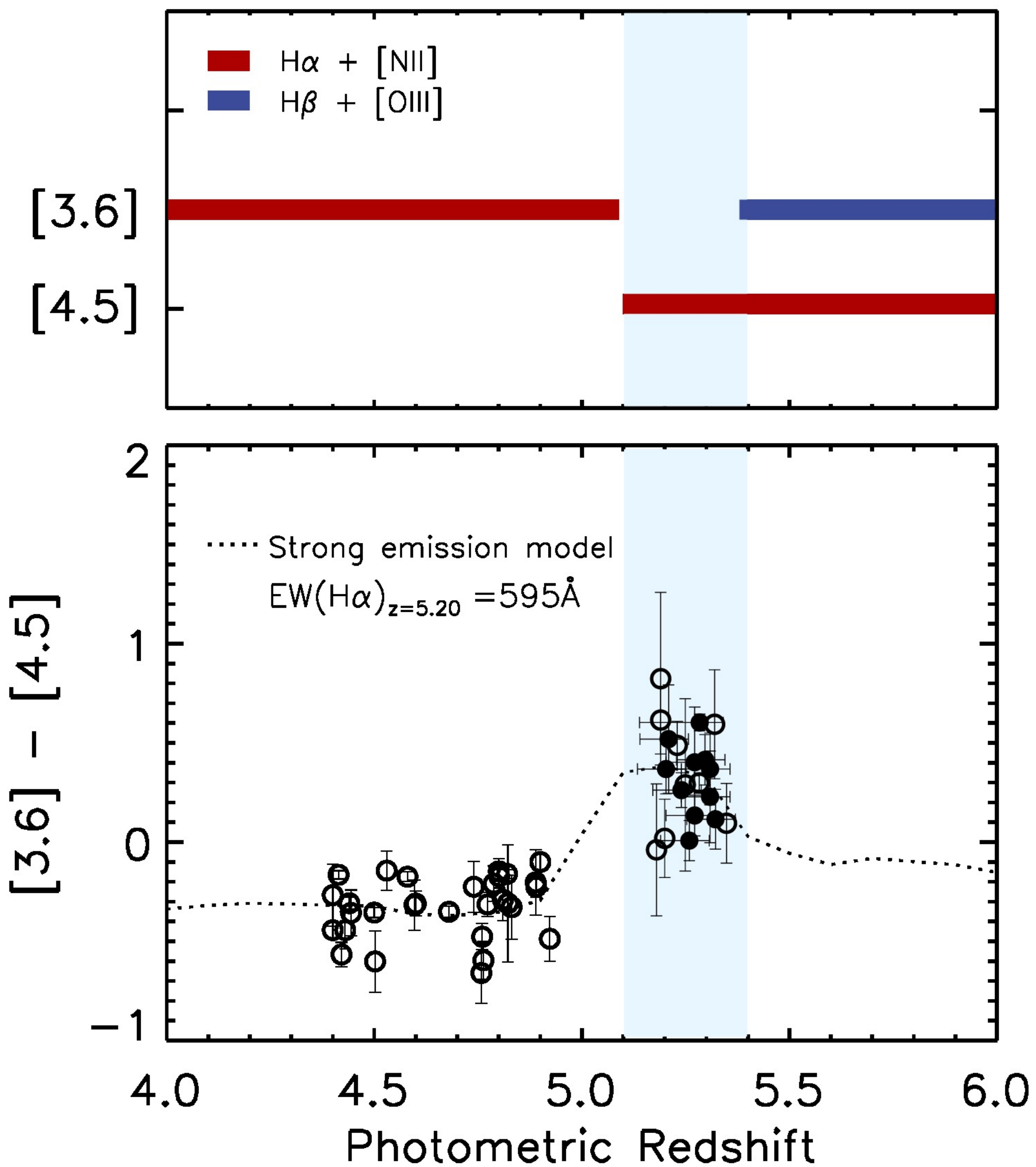
Rest-frame EW Ha+[SII]+[NII] ~ 400A at z~4.5

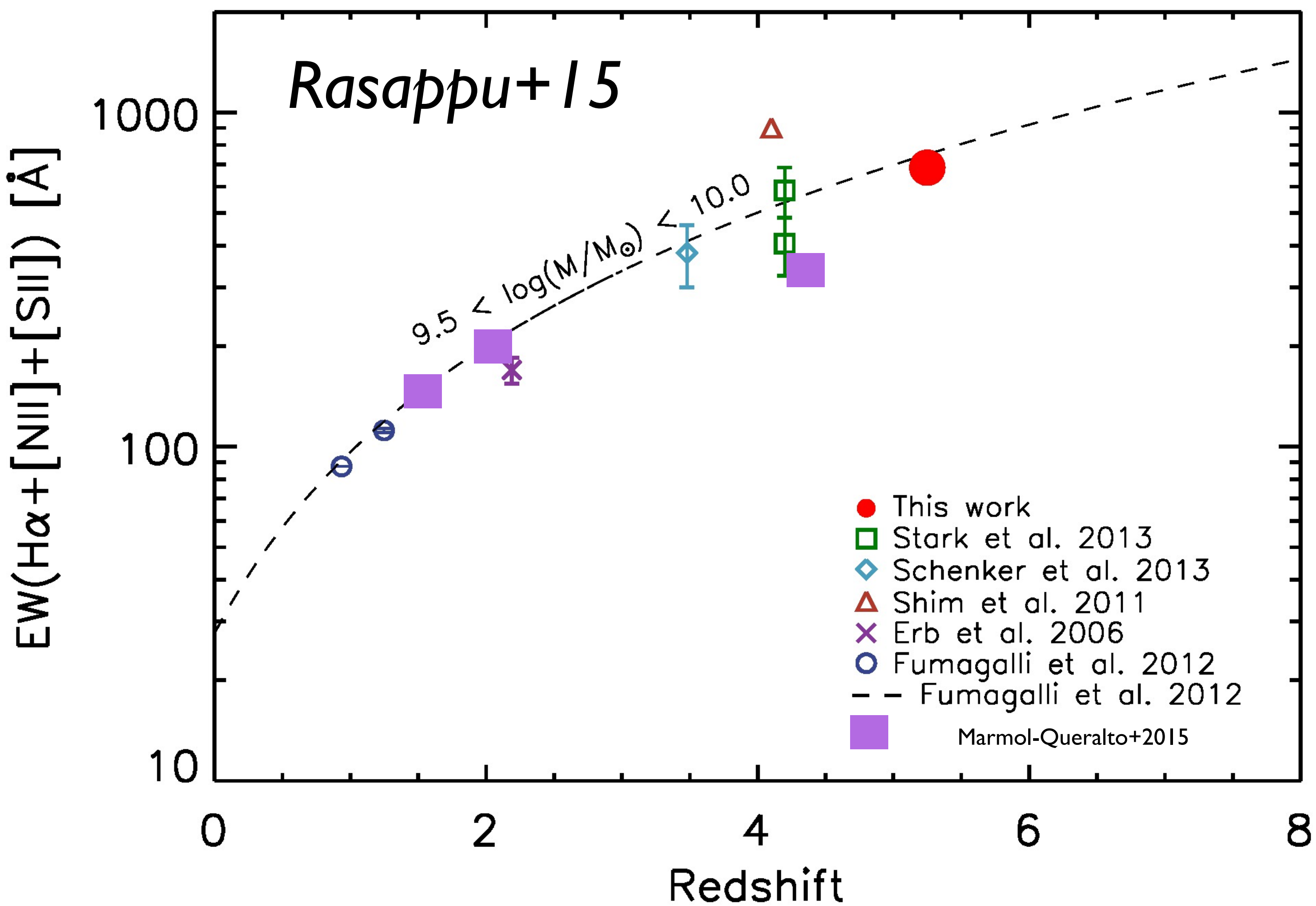
Rest-frame EW Hb+[OIII] ~ 700A at z~7-8 (>1000A are common)

Easily detectable with JWST!

e.g., see also: Schaerer & deBarros09, de Barros+14, Shim+11

IRAC colors encodes useful information!





Ha+[NII]+[SII] at z~5.3 EW$_0$ ~ 600A

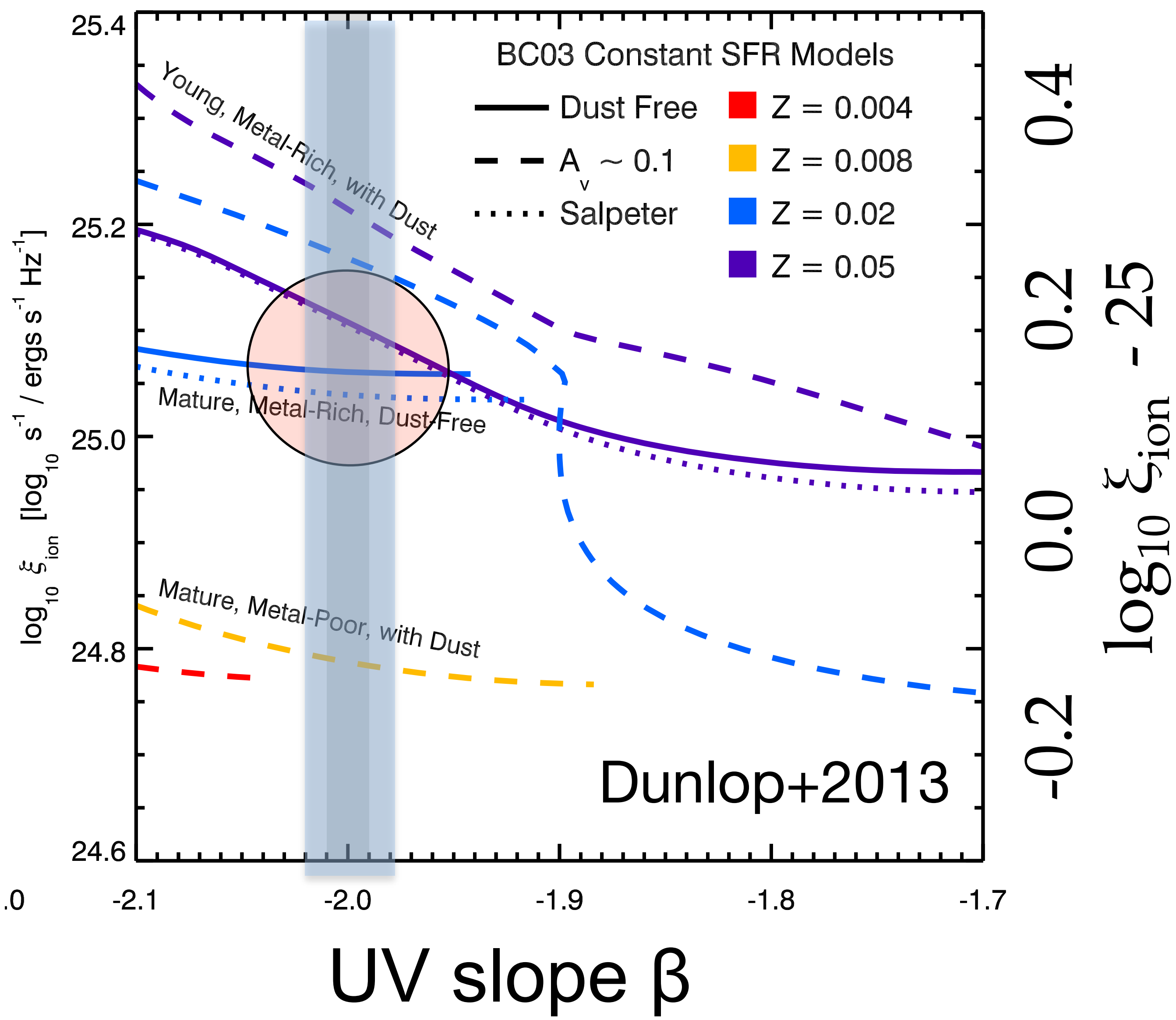
see also Marmol-Queralto+2015

more examples: Smit+2015

- SFR vs stellar mass
- dust law
- bustiness / ionising photons

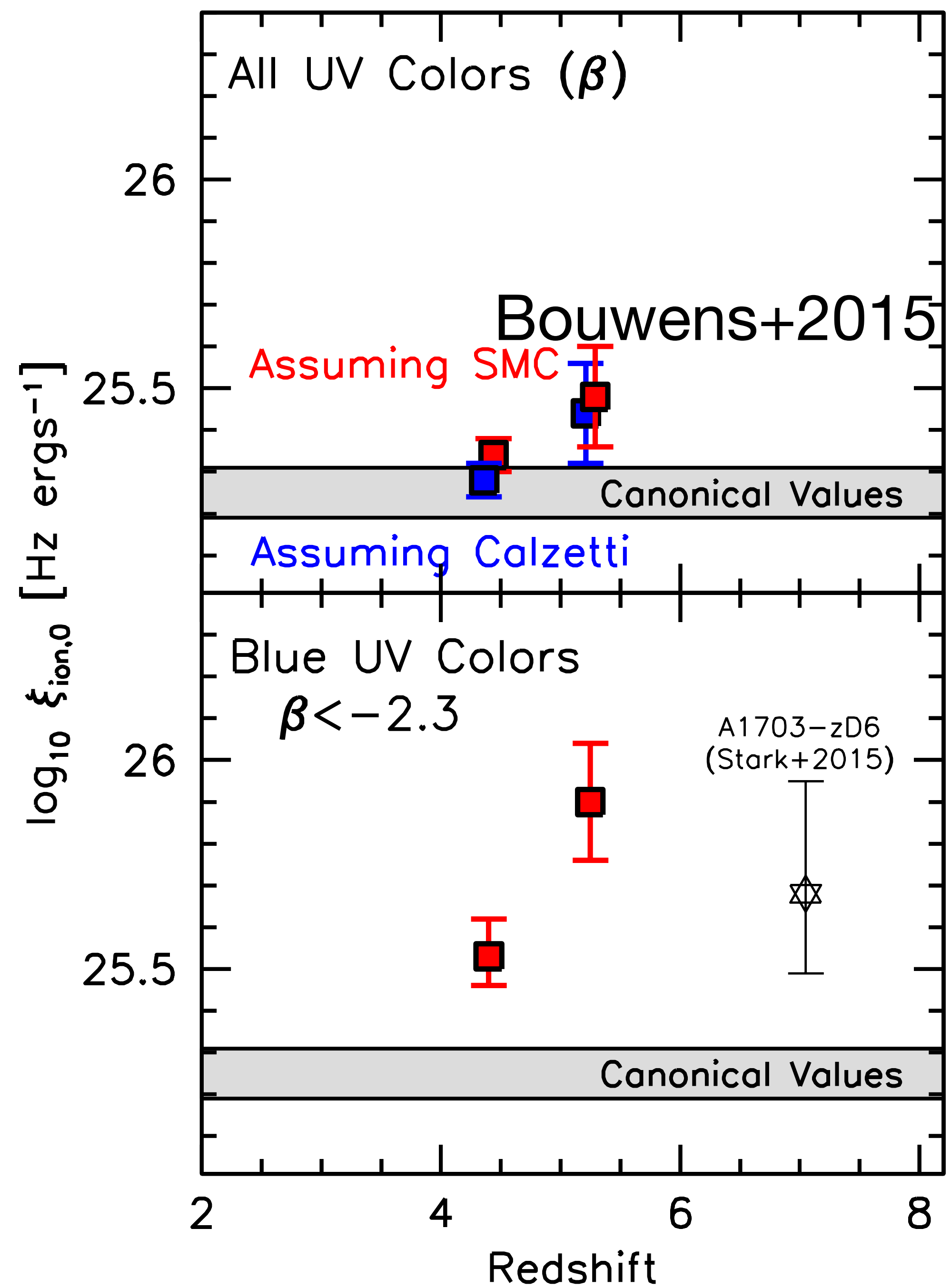
Constraints on Ionizing-to-UV photon ratio ξ_{ion}

from inferred UV slope



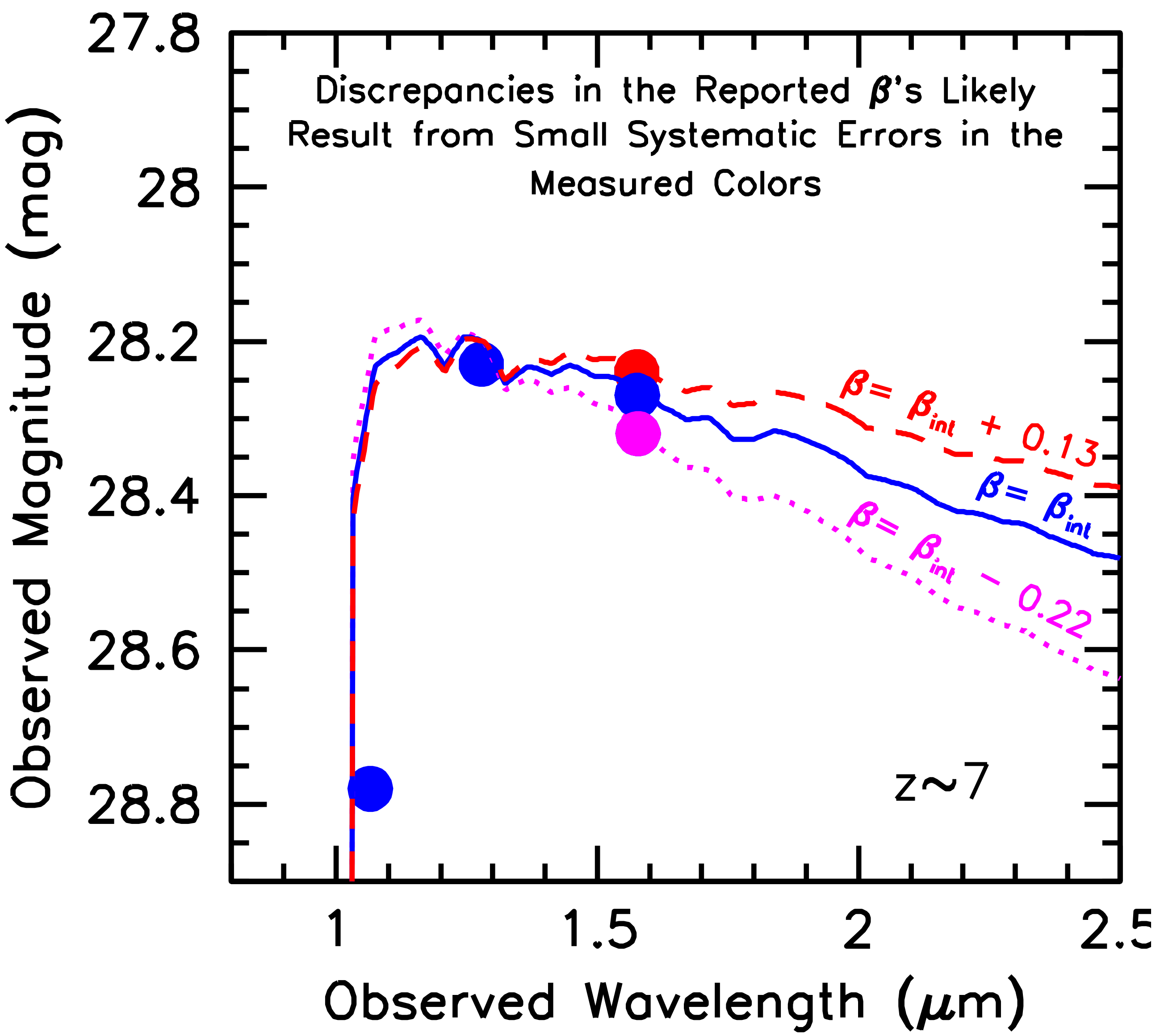
degenerate with age, metallicity, dust
stellar population details (binaries etc)

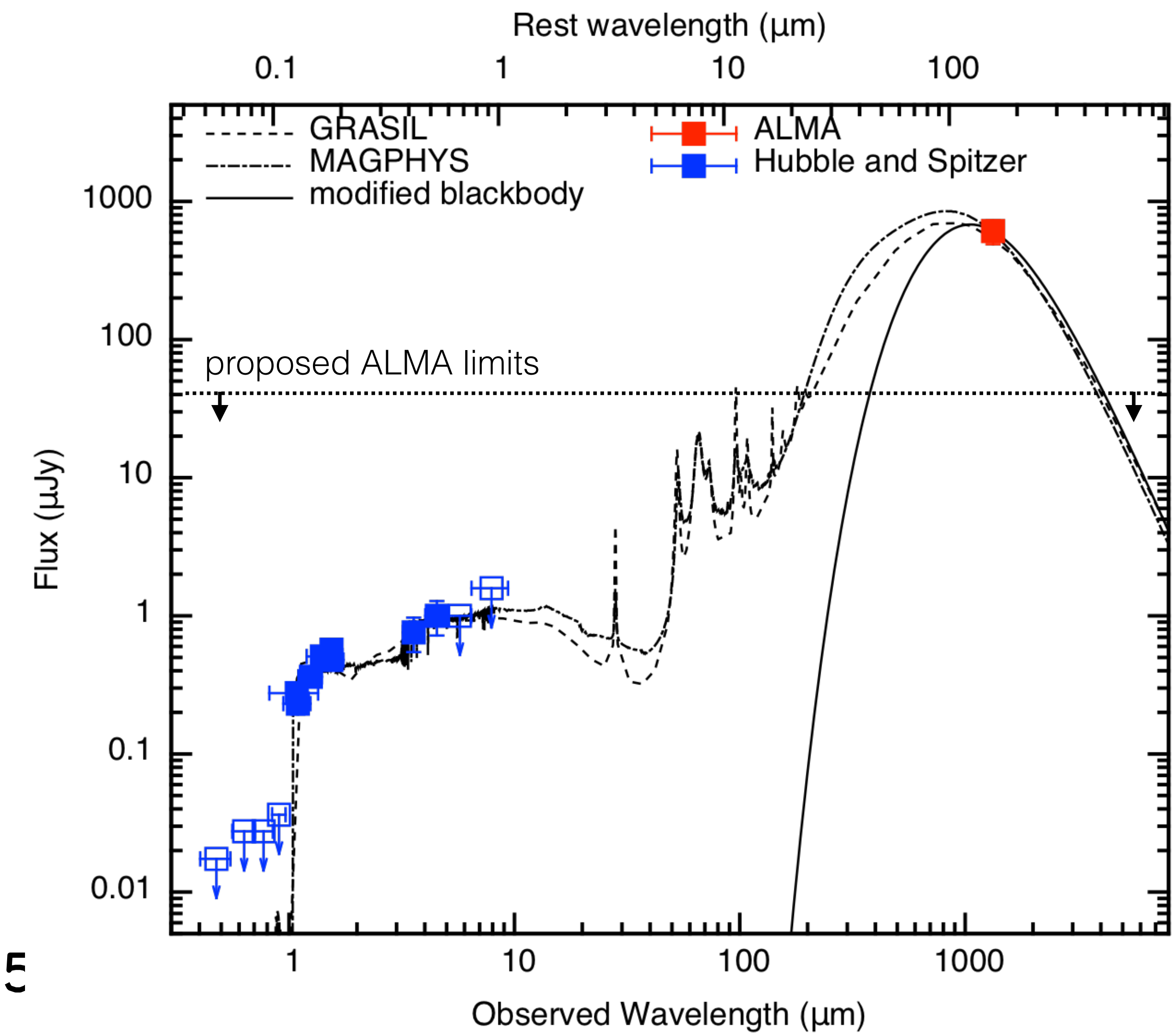
from inferred Hα



some dependence on dust

Dust inferred from UV colors



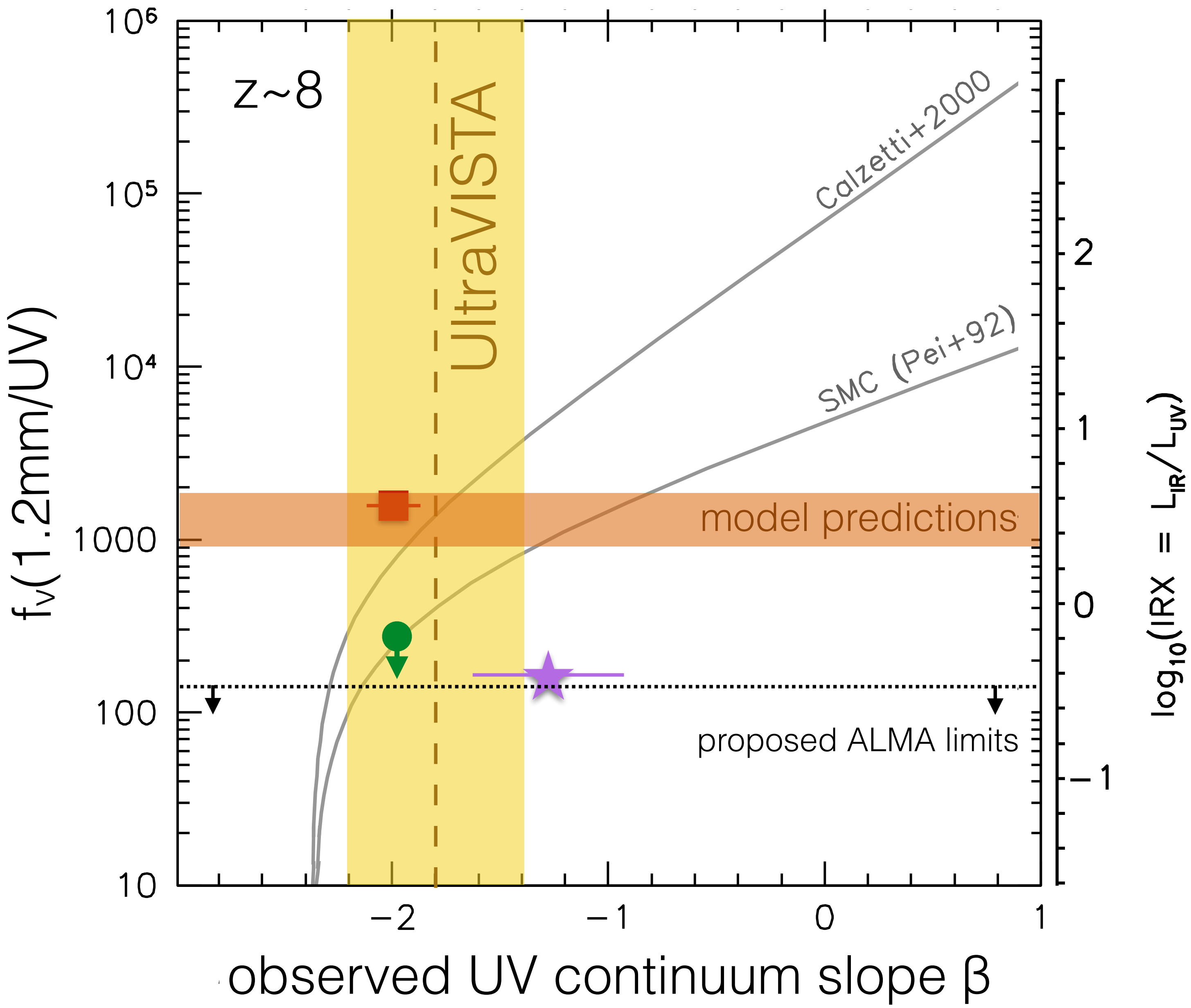


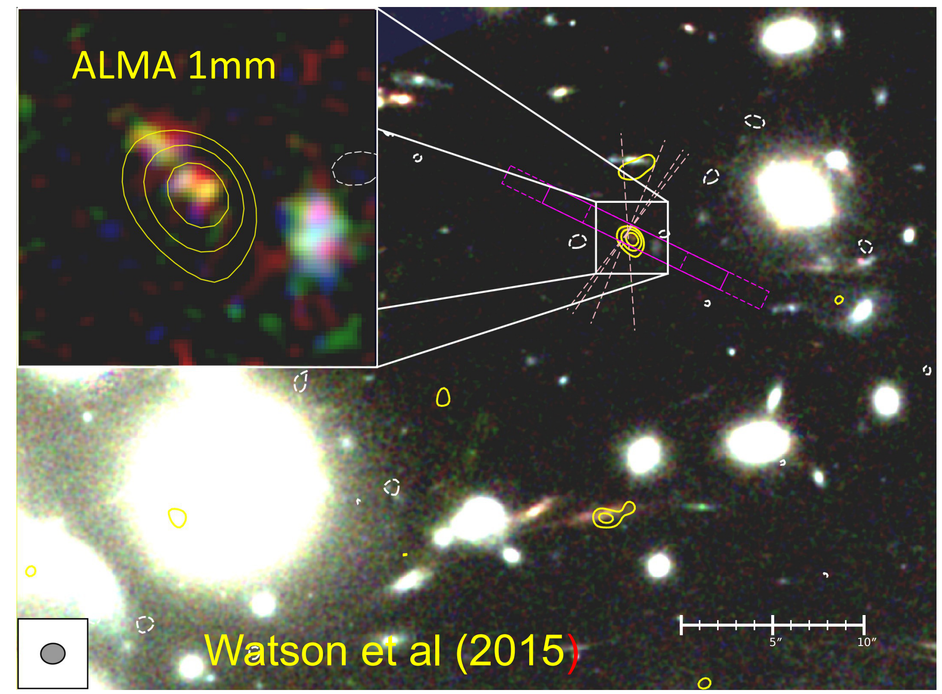
z=7.5 (lensed) galaxy A1689-zD1 Watson+2015).

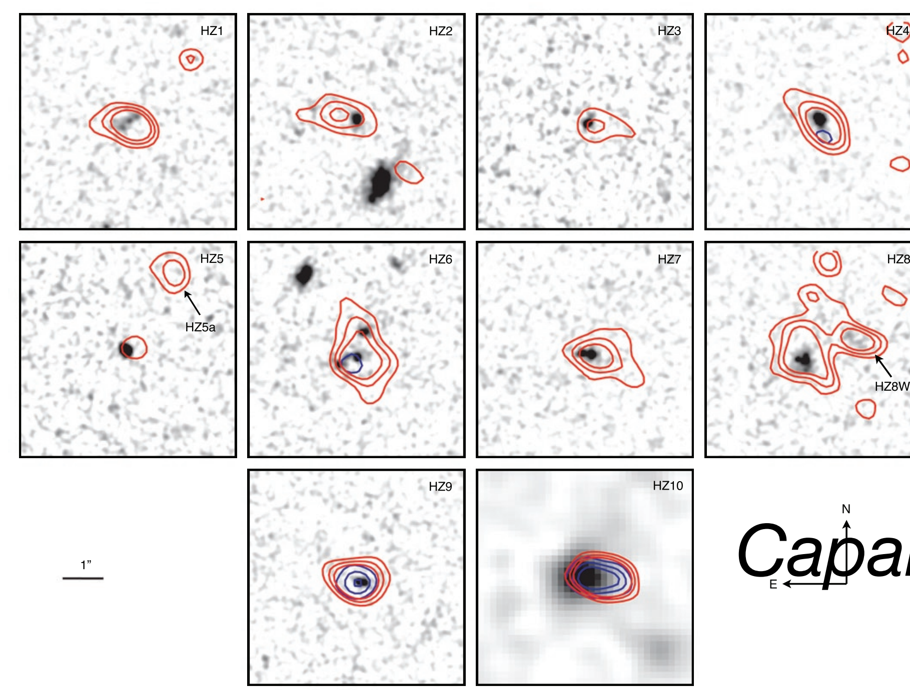
relies on IRX-beta relation: untested at z > 3

Test with ALMA

ALMA results: dust not important at high redshift?







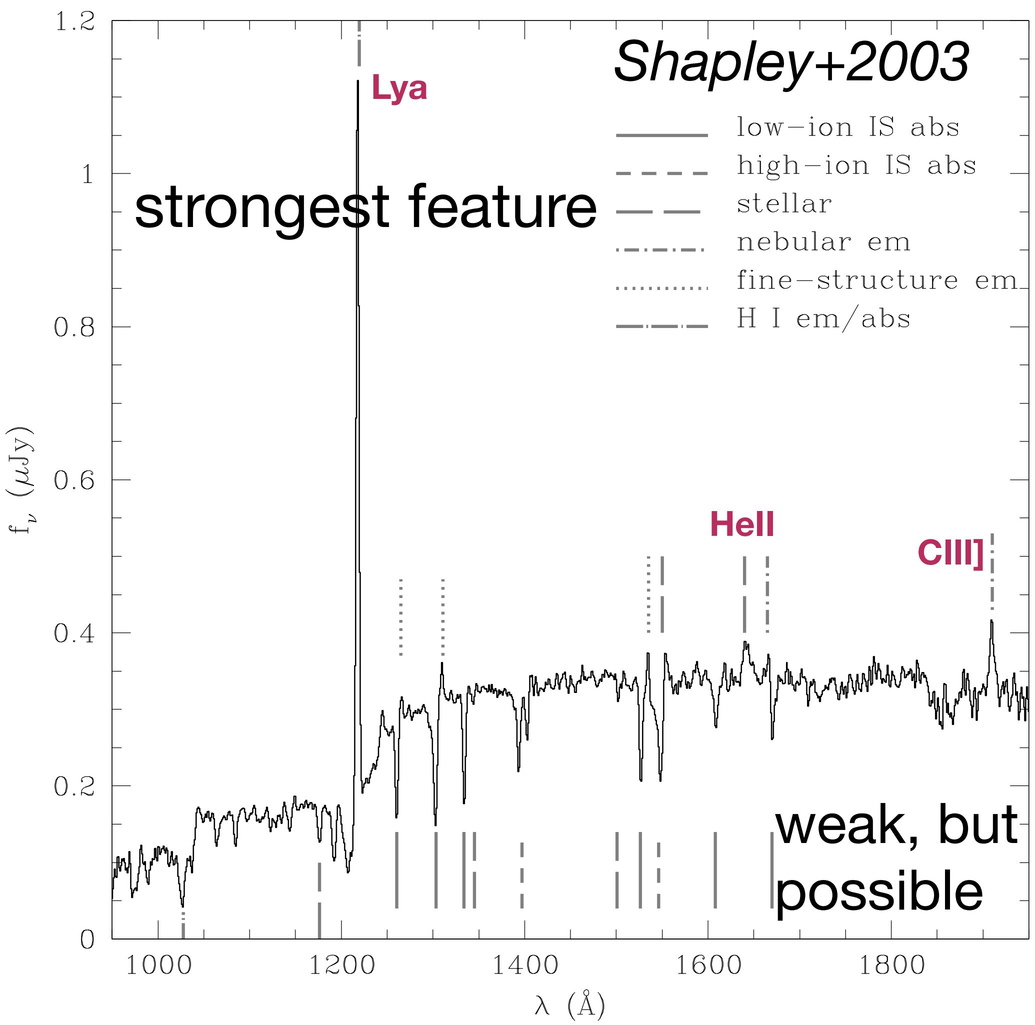
Capak+15

current situation not entirely clear:

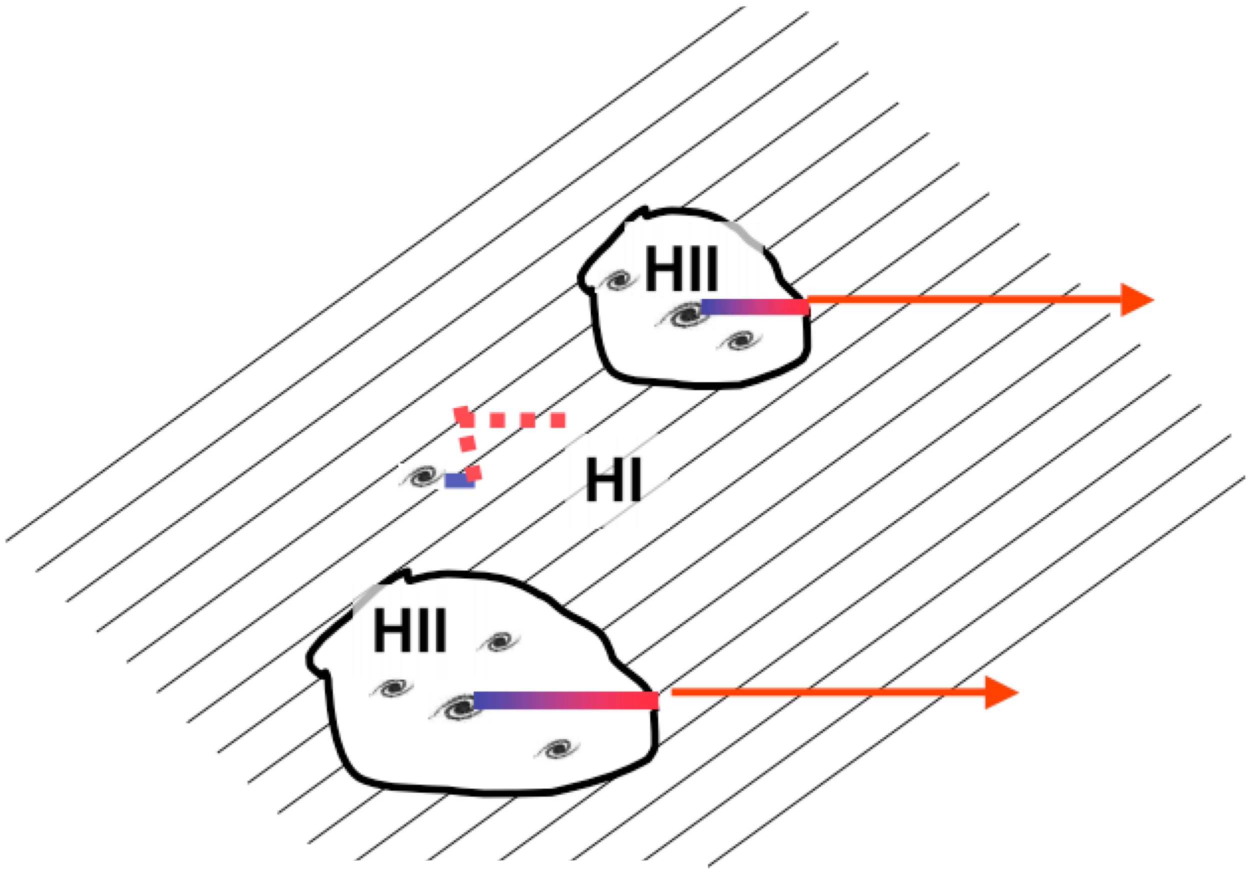
- ALMA dust continuum at z>4 lower than expected *(Capak+2015,Bouwens+2016)*
- significant source to source scatter (c.f. Watson)
- CII 158 micron cooling line easily detected in z=5-6 LBGs (e.g. Capak+15)

Groundbased spectroscopy

- ionising continuum
- kinematics
- ISM
- Ly-α demographics



Lyα fraction as a Probe of Reionization

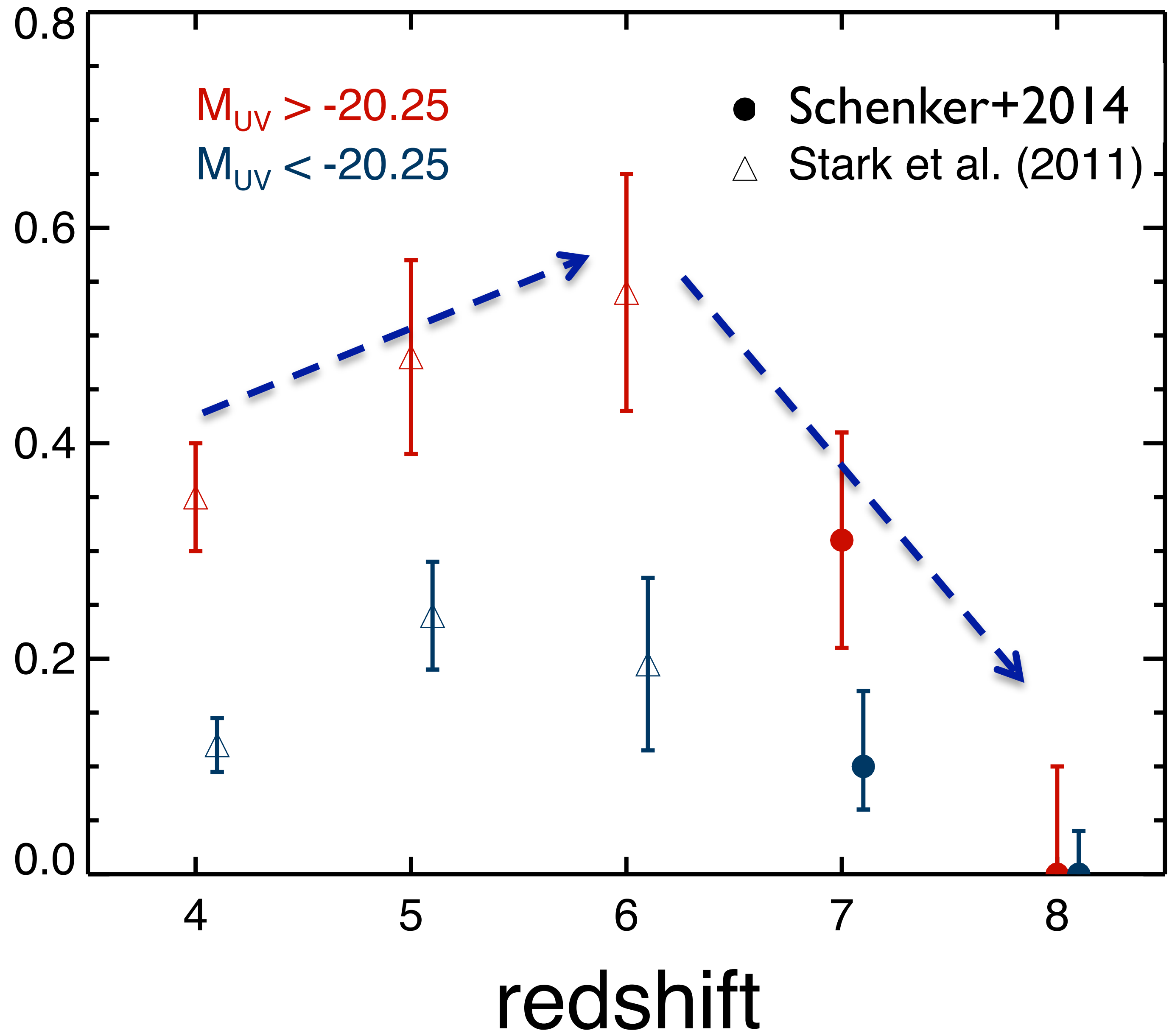


Dijkstra+2014

- Lyα resonant scattered by neutral H reduces visibility
- epoch of reionization IGM becomes significantly neutral: implies sudden drop in Lyα fraction
- unless galaxy lies in an ionized bubble

Lyα fraction declines sharply for z > 6

Fraction of galaxies with Lyα EW > 25 A

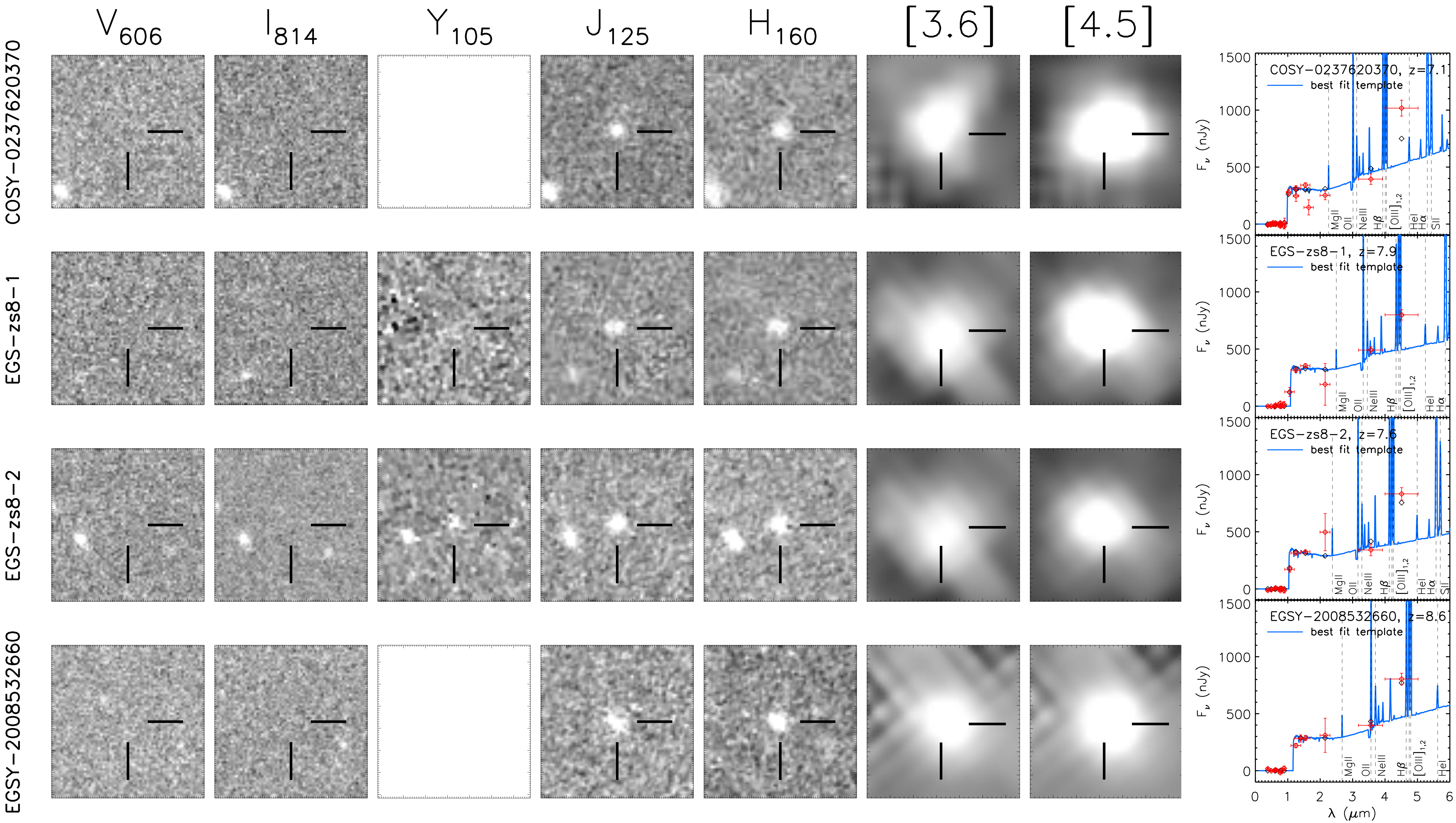


see also Pentericci+2014,2015; Tilvi+2014; Treu+2013; Stark+2010; Fontana+2010; Caruana+2014; Ono+2012

Inferred x(HI) depends on details of

- residual neutral HI inside the bubbles (or self shielding Lyman limit systems)
- redshift evolution of ionising photon production + escape fraction.
- velocity offset of Ly−α

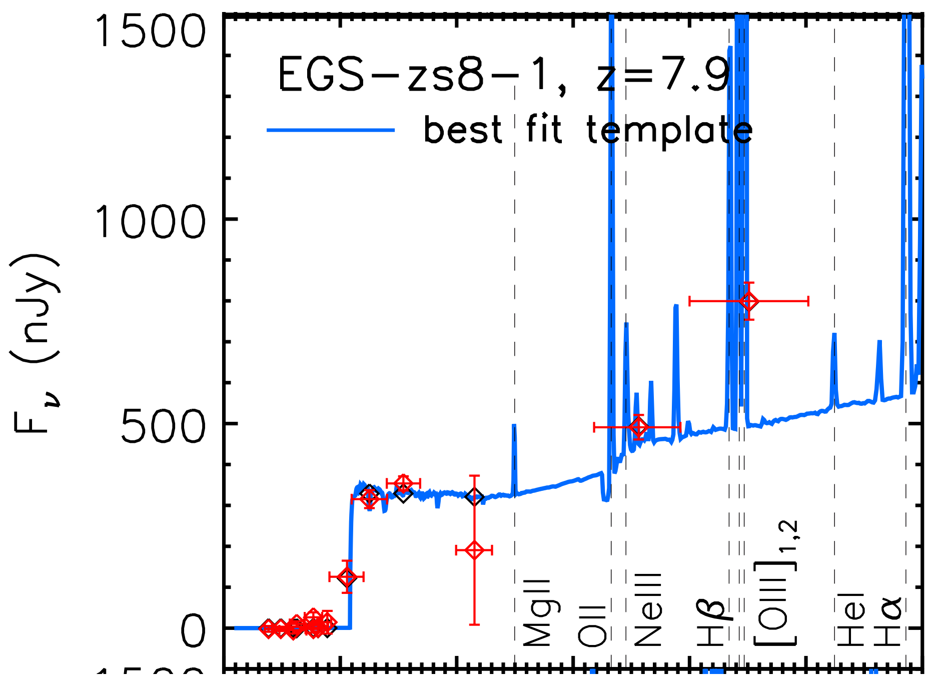
using IRAC excess to select bright 7 < z < 9 galaxies with extreme emission lines

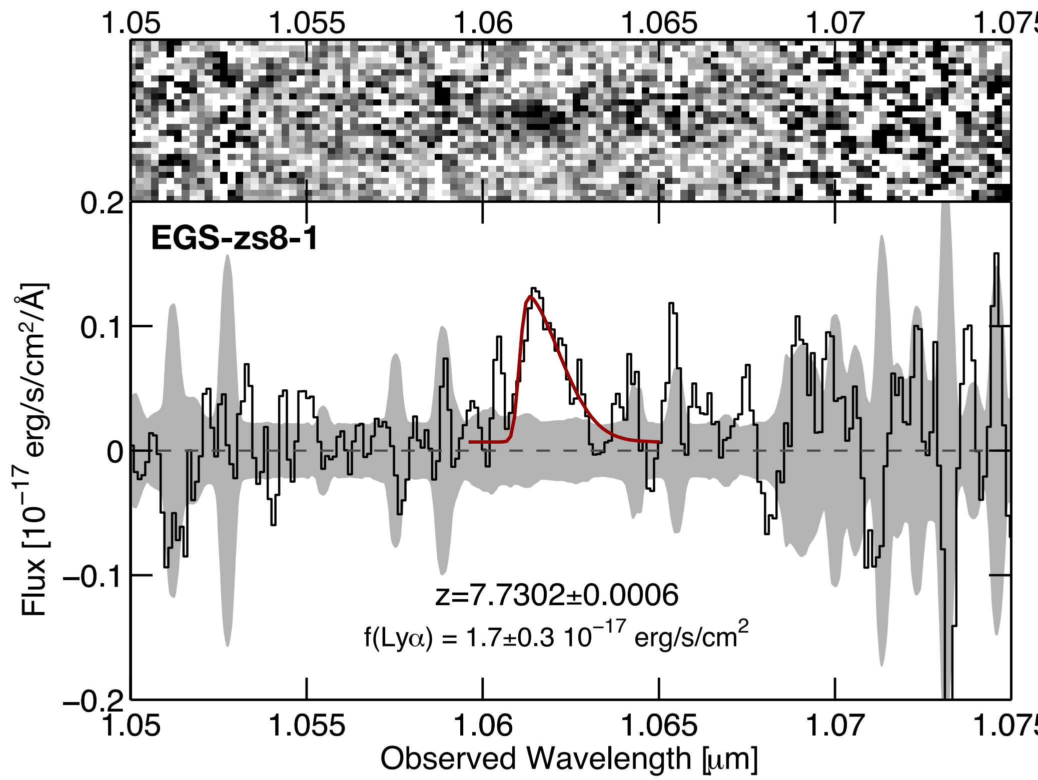


[OIII]+Hβ boost 4.5 micron band

Roberts-Borsani+2015

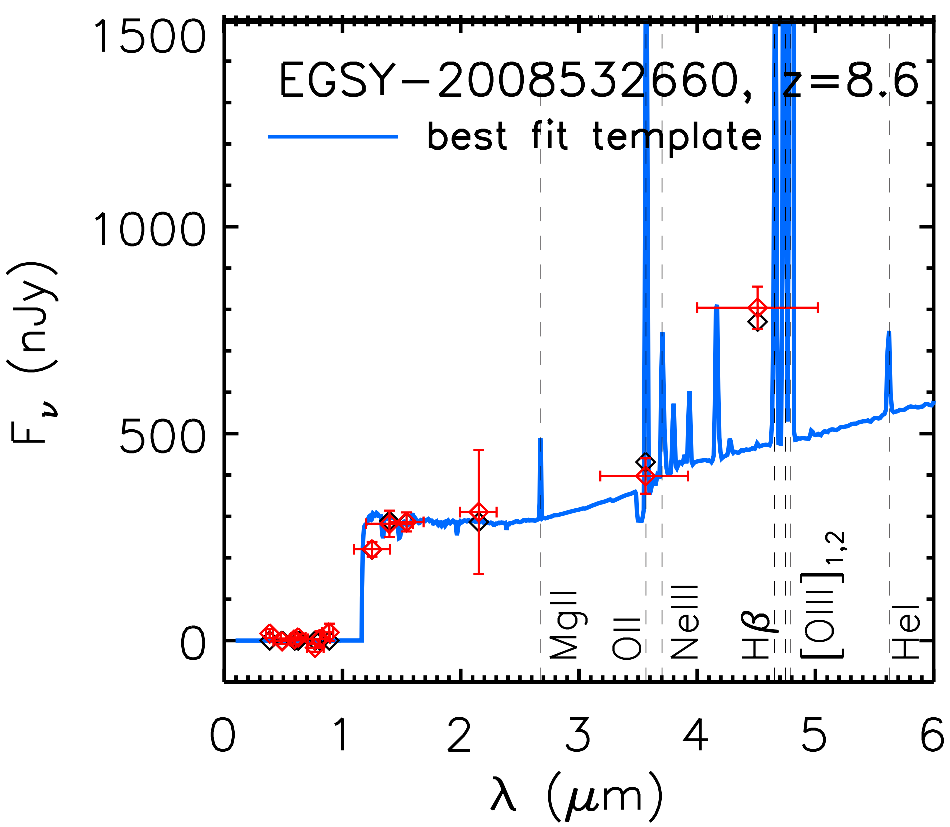
all 4/4 sources show show strong Ly-a: two redshift records

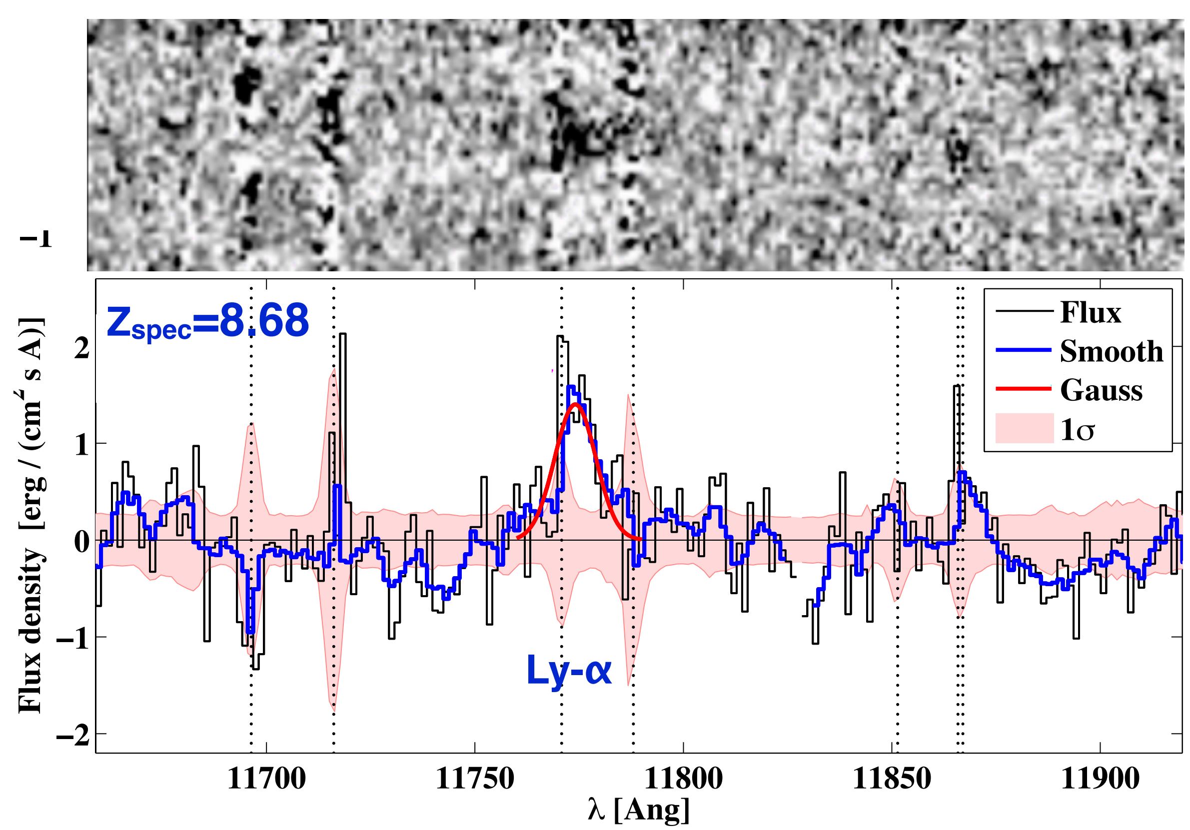




z_{spec}=7.73

Oesch+2015



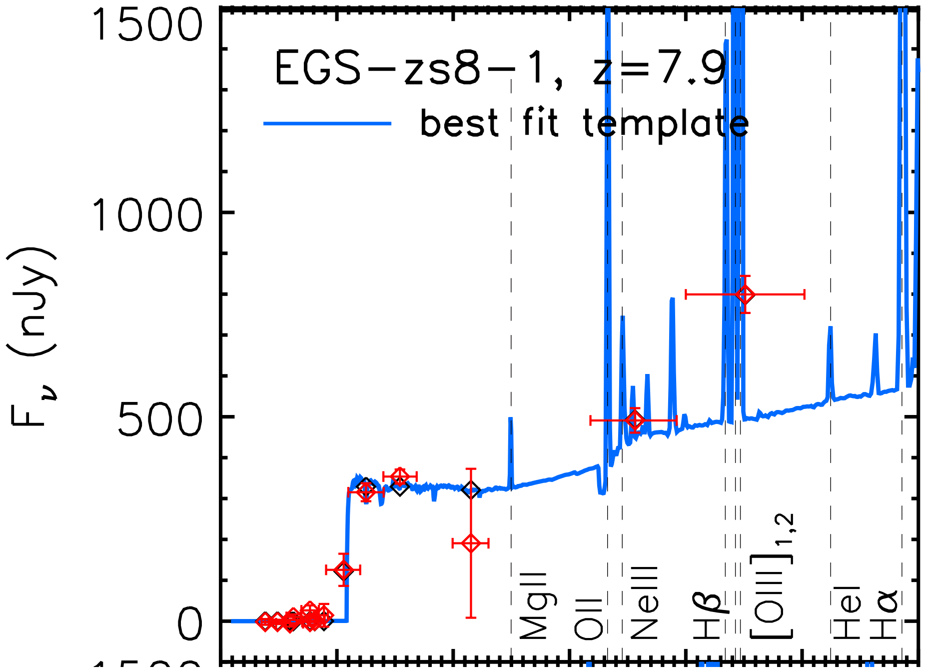


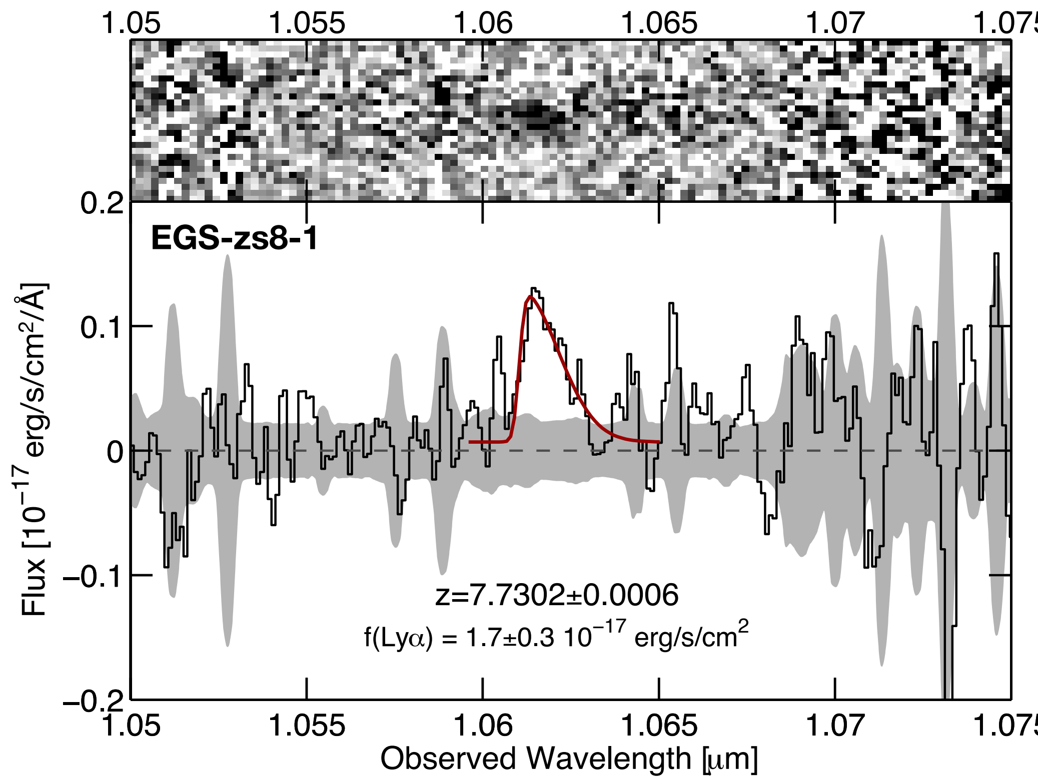
z_{spec} = 8.683

Zitrin+2016

see also Stark+2016,Roberts-Borsani+2016

How can this be? Intense radiation field from CIII] + [OIII]+Hβ EW





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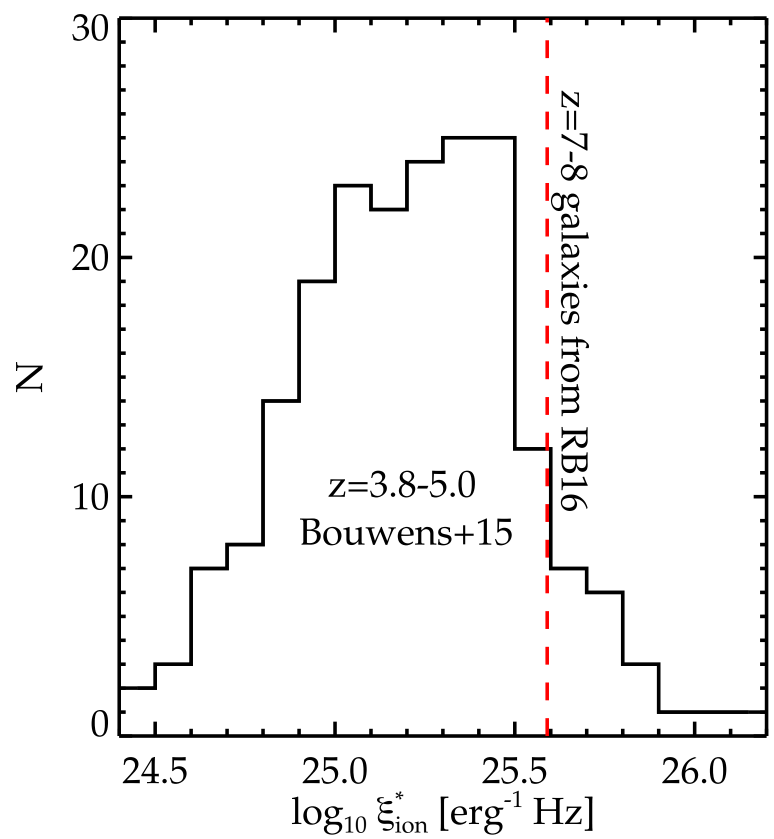
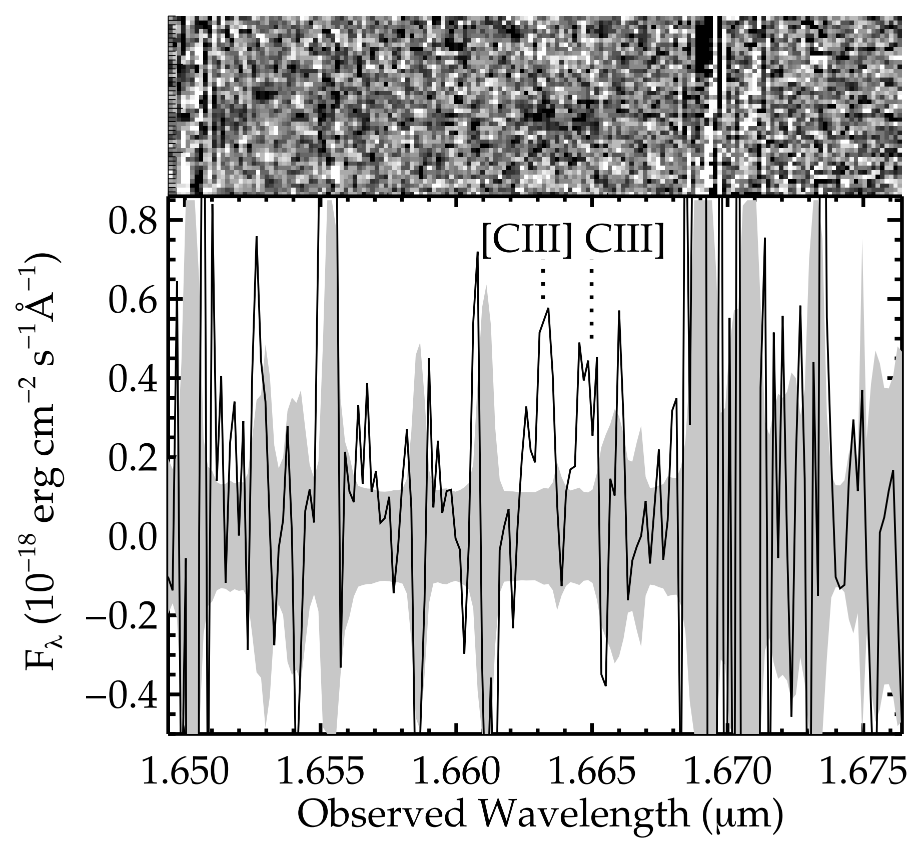
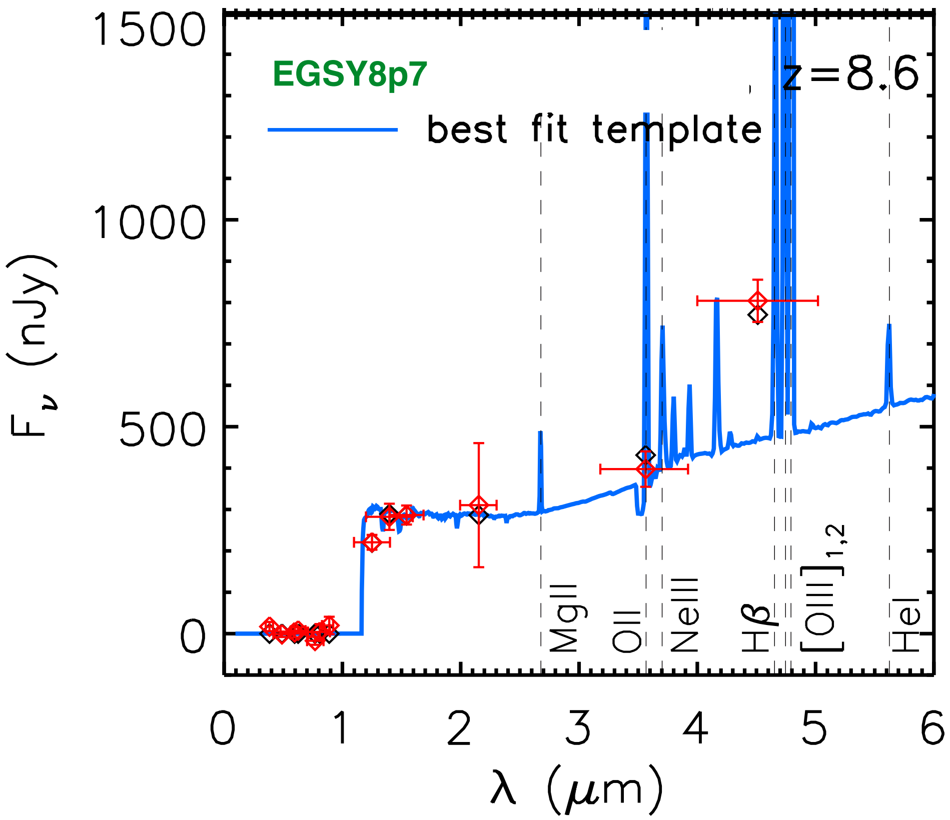


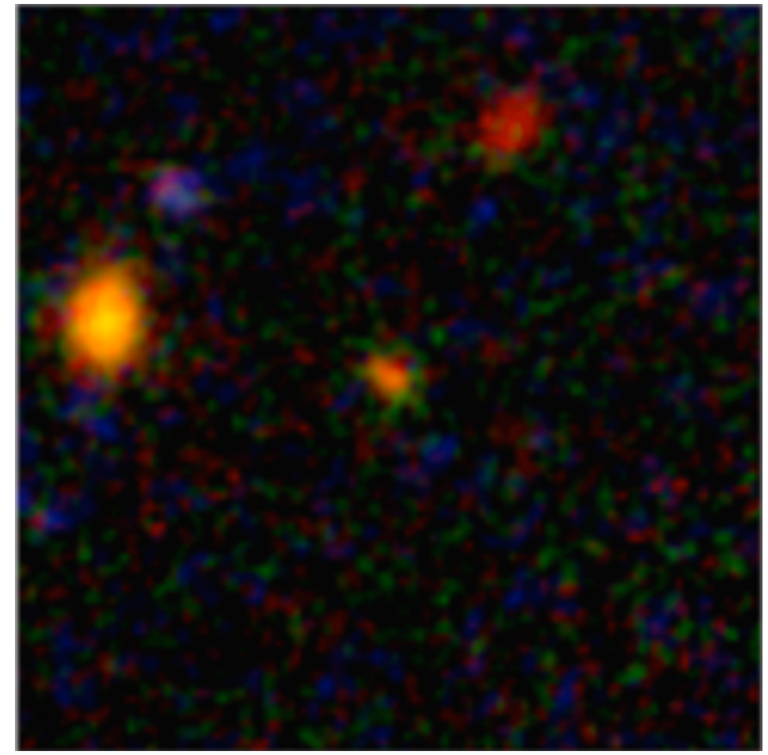


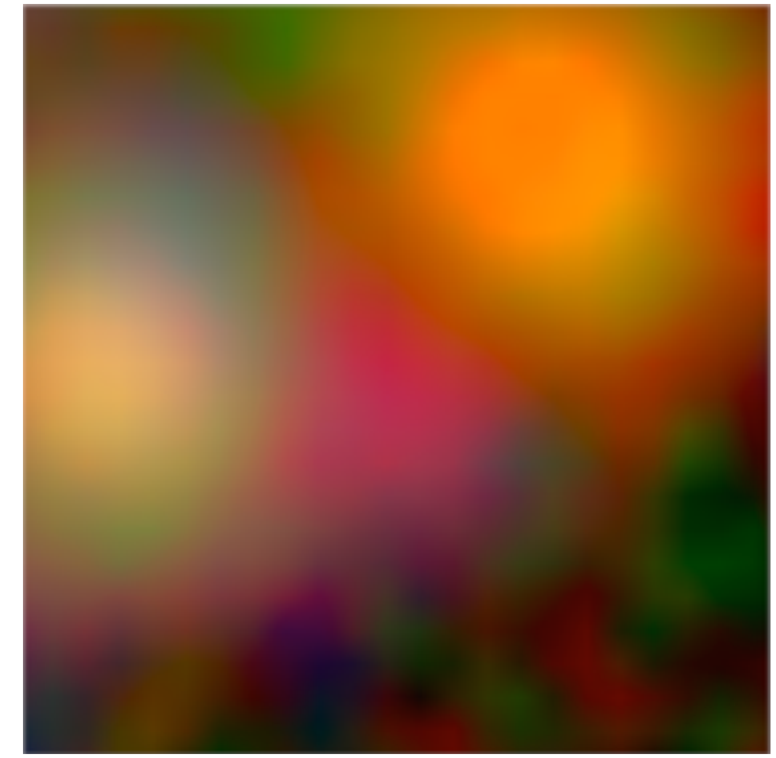
Stark+2016

strong CIII] doublet

also large velocity offset Ly-α







f(Ly-a) = 1.7e-17 ergs/etc

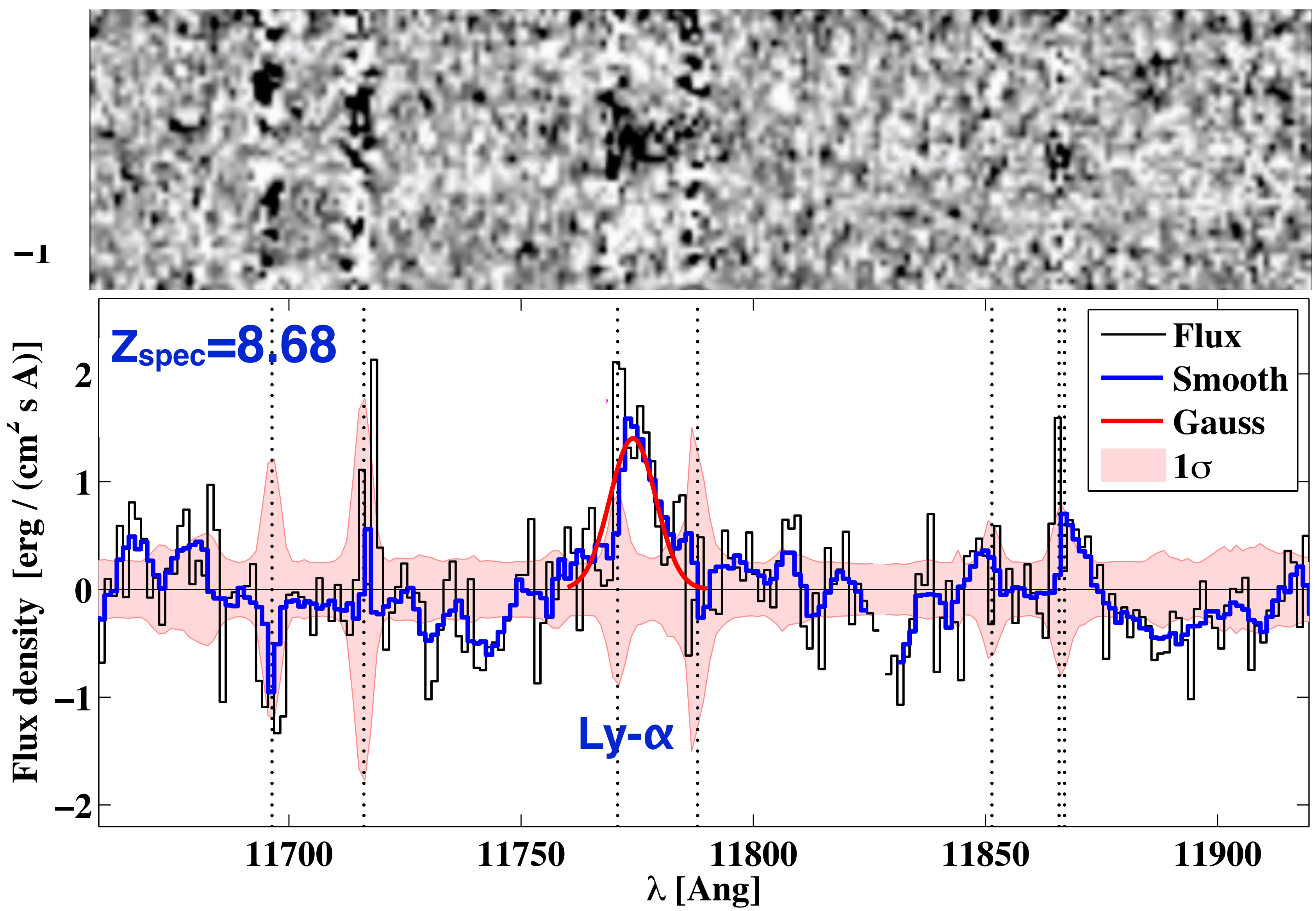
EW_0 Ly-a = 28A

z = 8.683

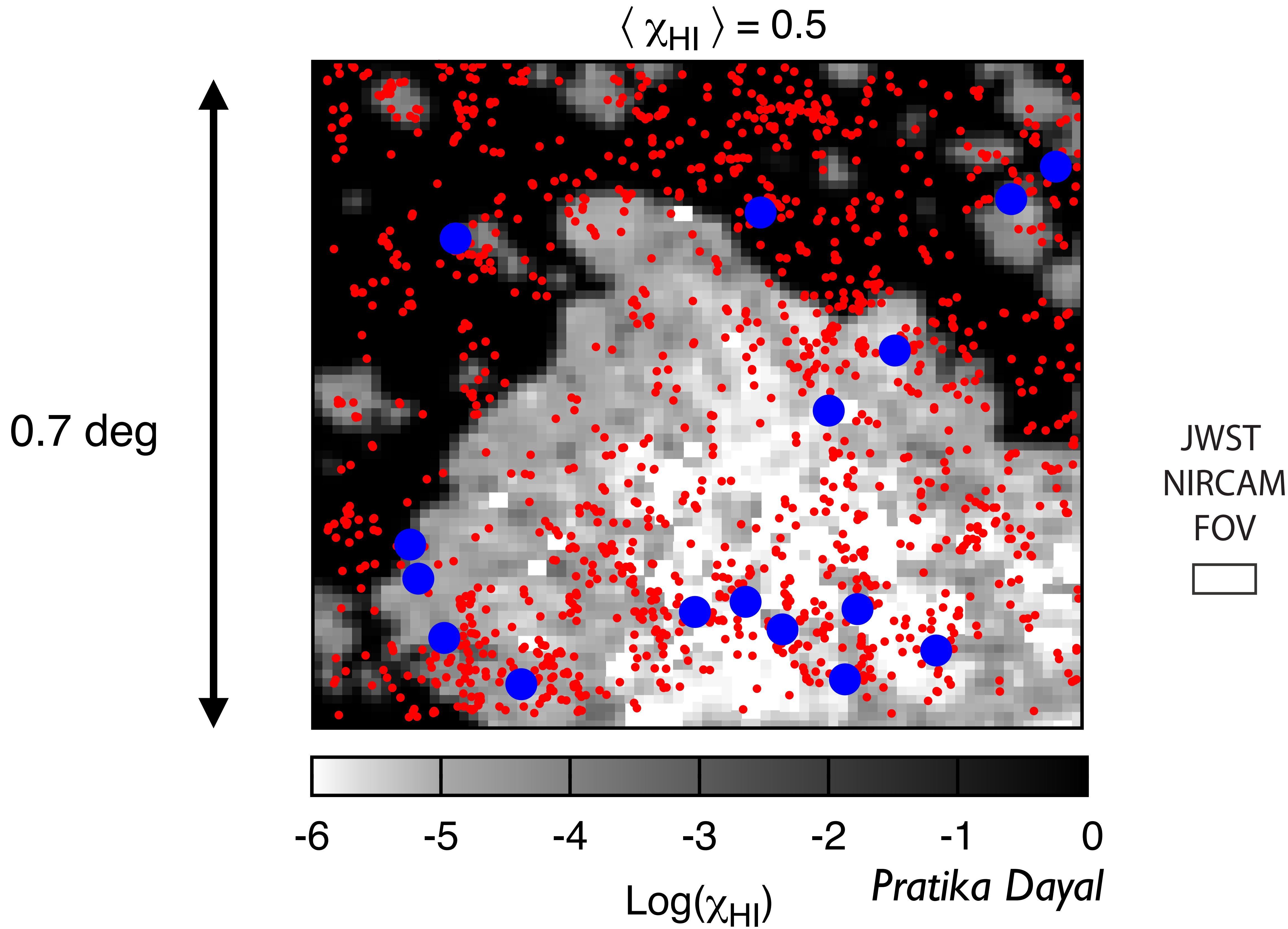
log M ~ 10^{10} M*

SFR_{cor} ~ 150 M*/yr

EW_0 [OIII]+Hb ~ 1000A

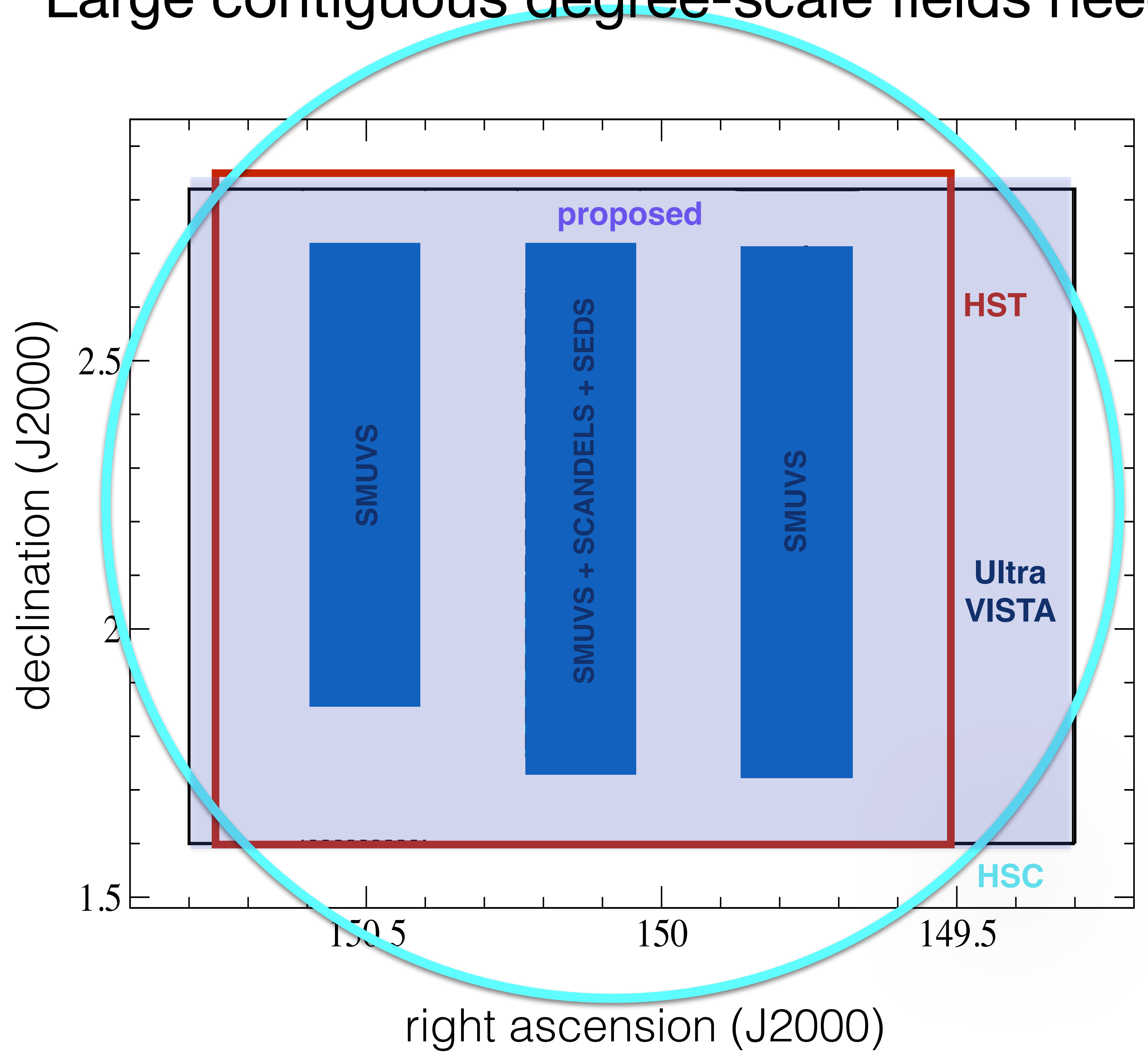


Massive galaxies as signposts of patchy accelerated reionization



Need large volumes to study!

Large contiguous degree-scale fields needed

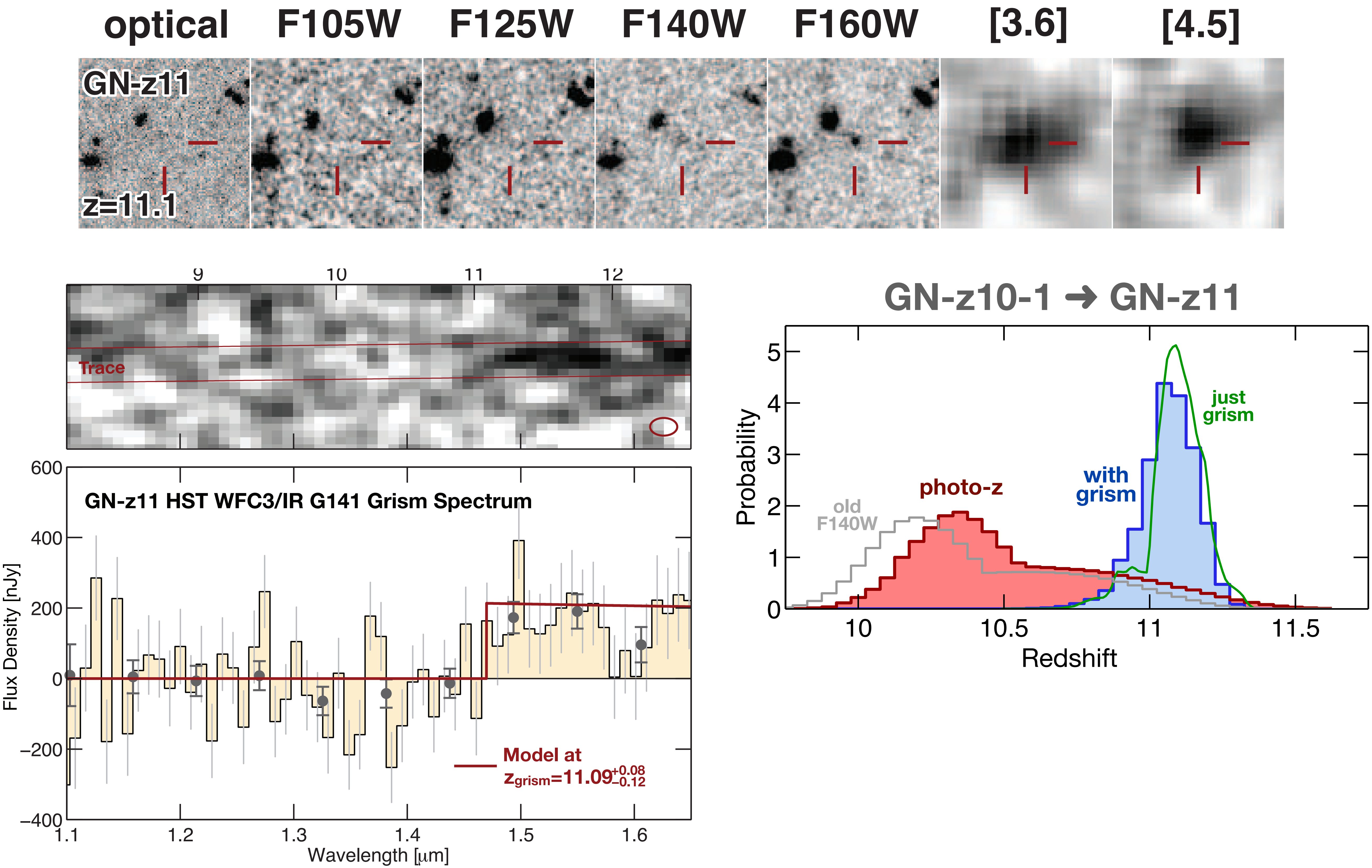


Approved UltraVISTA extensions in near-IR, IRAC still needed

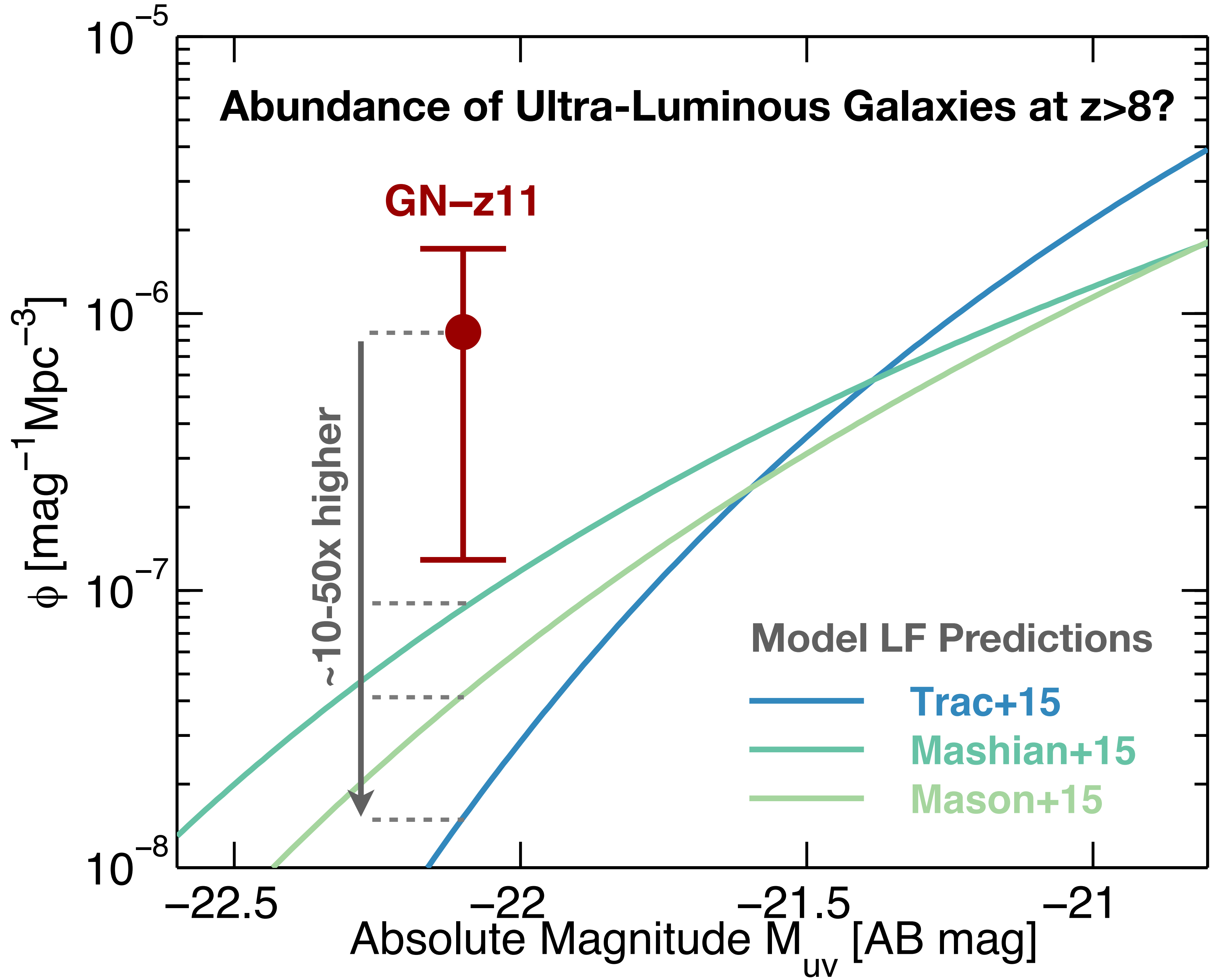
Will not be done by JWST, critical for follow up

A luminous, massive galaxy at z=11.09

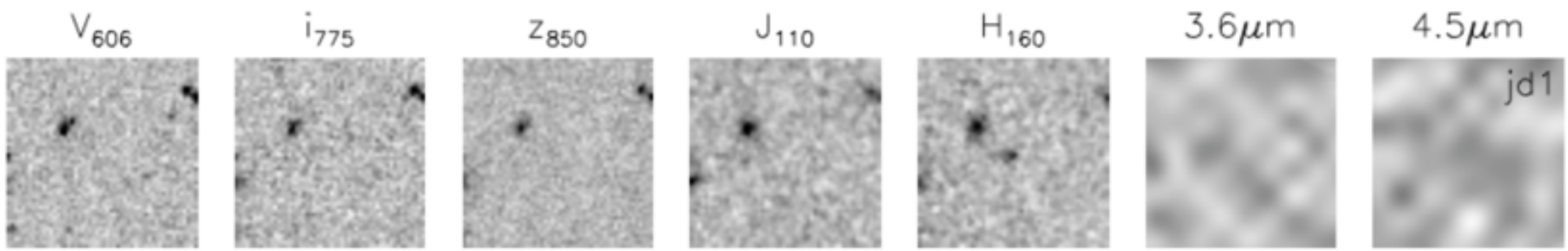
Lyman Break detected at z=11

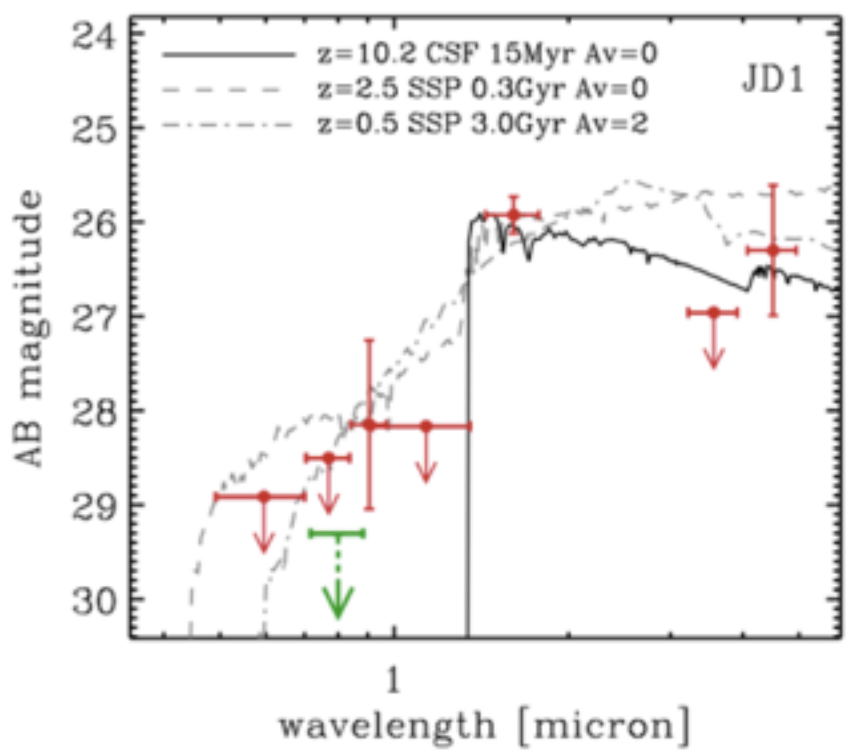


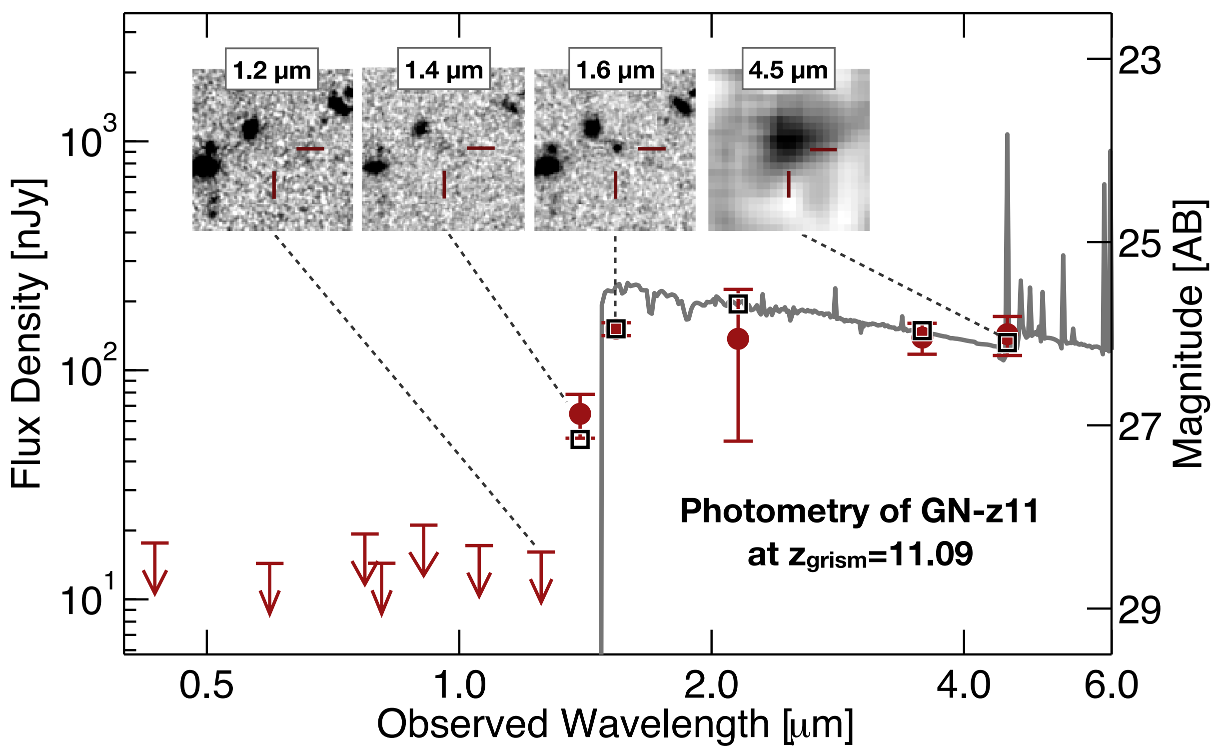
Unexpected in such a small volume



GN-z11 was "known" since 2008

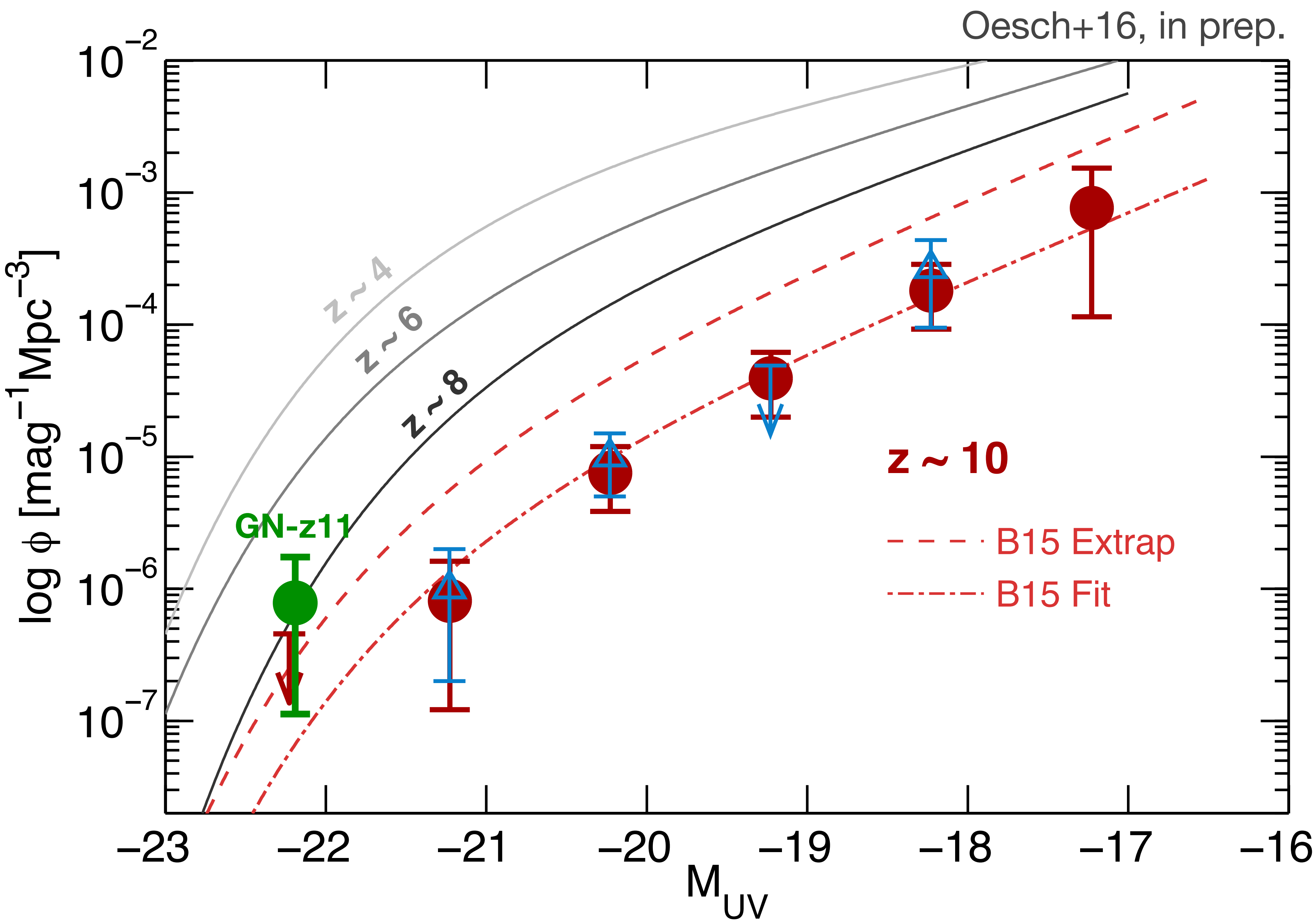






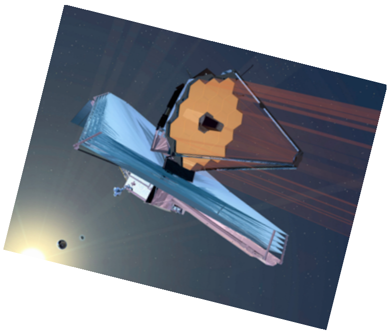
same photo-z as with new data, but was ruled out as not likely to lie at $z>9$ due to single band detection and its luminosity (Bouwens+10)

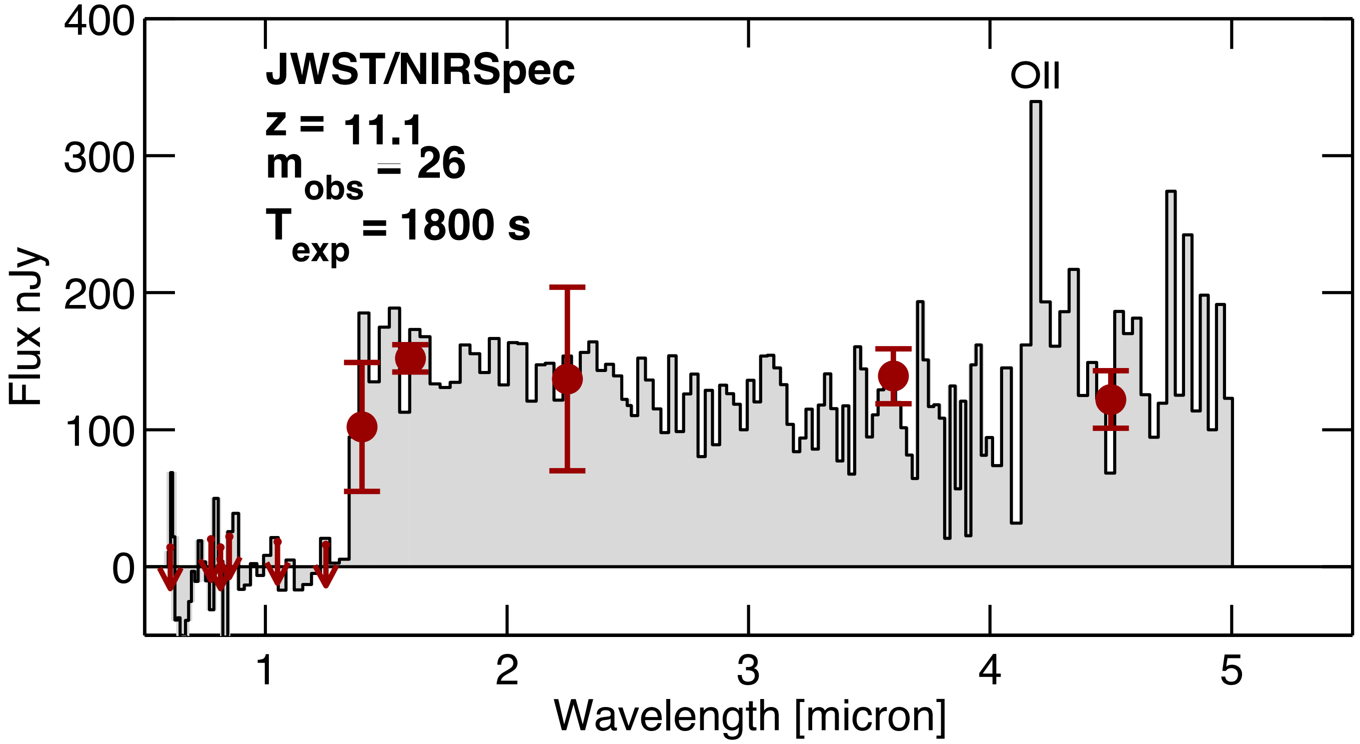
Slower evolution at the bright end of the UV LF?



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

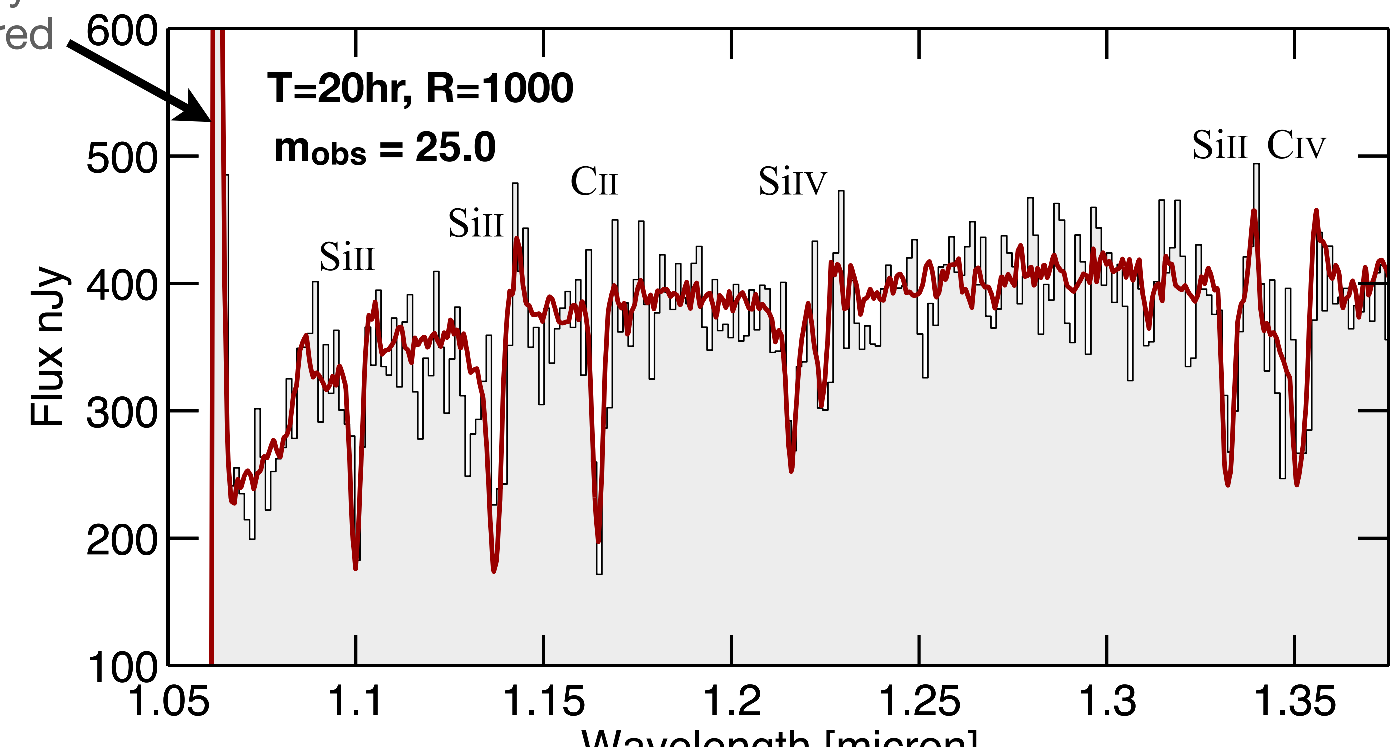
JWST/NIRSpec: Unprecedented Spectra





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, OIII out to z~9
- Current, bright z~9-10 galaxies will also be very quick to spectroscopically confirm
- For brightest targets, like the recently confirmed target EGS-zs8-1 at z=7.73, we will even be able to measure absorption lines individually
- Are working on collecting largest possible samples of very bright galaxies at z>=8

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>4, 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 $\alpha = -2$) and evolved quickly.

- CMB constraints imply lower instantaneous reionization redshift z=8.2 ➔ 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

- Strong emission lines inferred from IRAC and strong CIII] at z=7-8: unusual stellar populations, intense radiation fields and high ξ_{ion}

- surprising Ly-α detections at z>7 to z=8.68: patchy reionization? Large fields need to be studied!

- Will be able to do detailed astrophysics with JWST/NIRSpec: ionization state, SFR, metallicity, dynamical state

- 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!