Low Mass Galaxies in the Reionization Era

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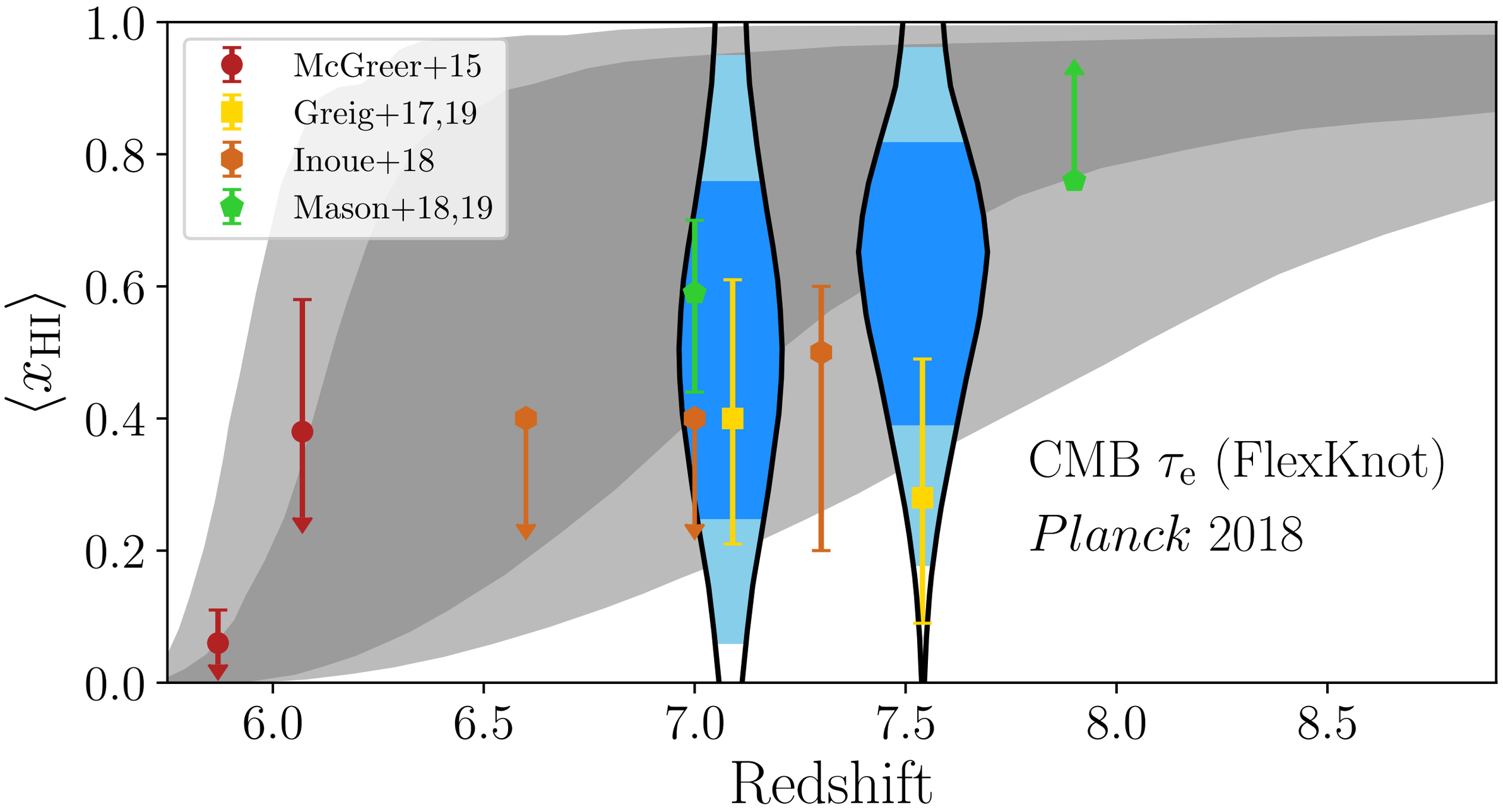
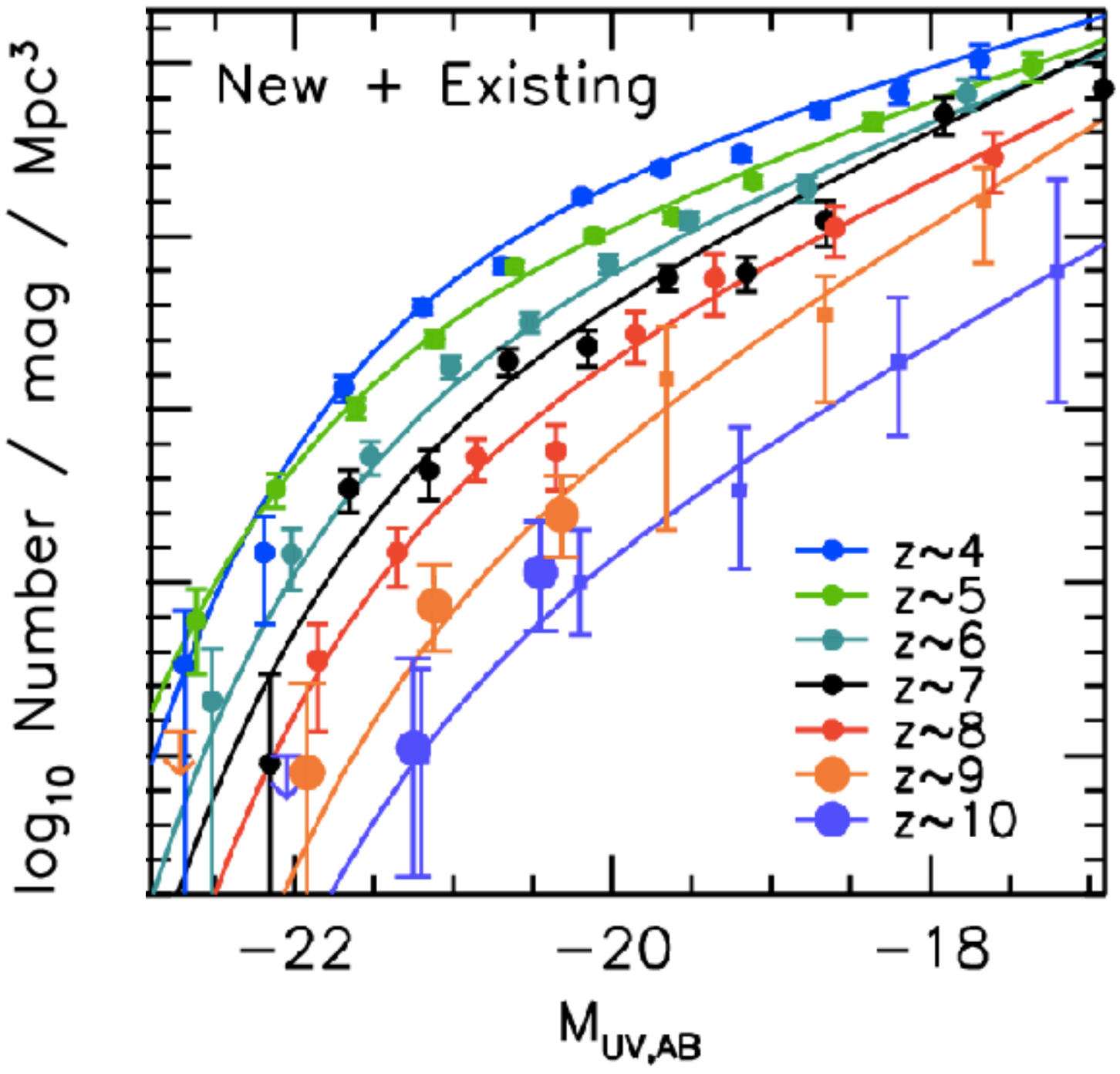
Reionization History



F. Davies 2019

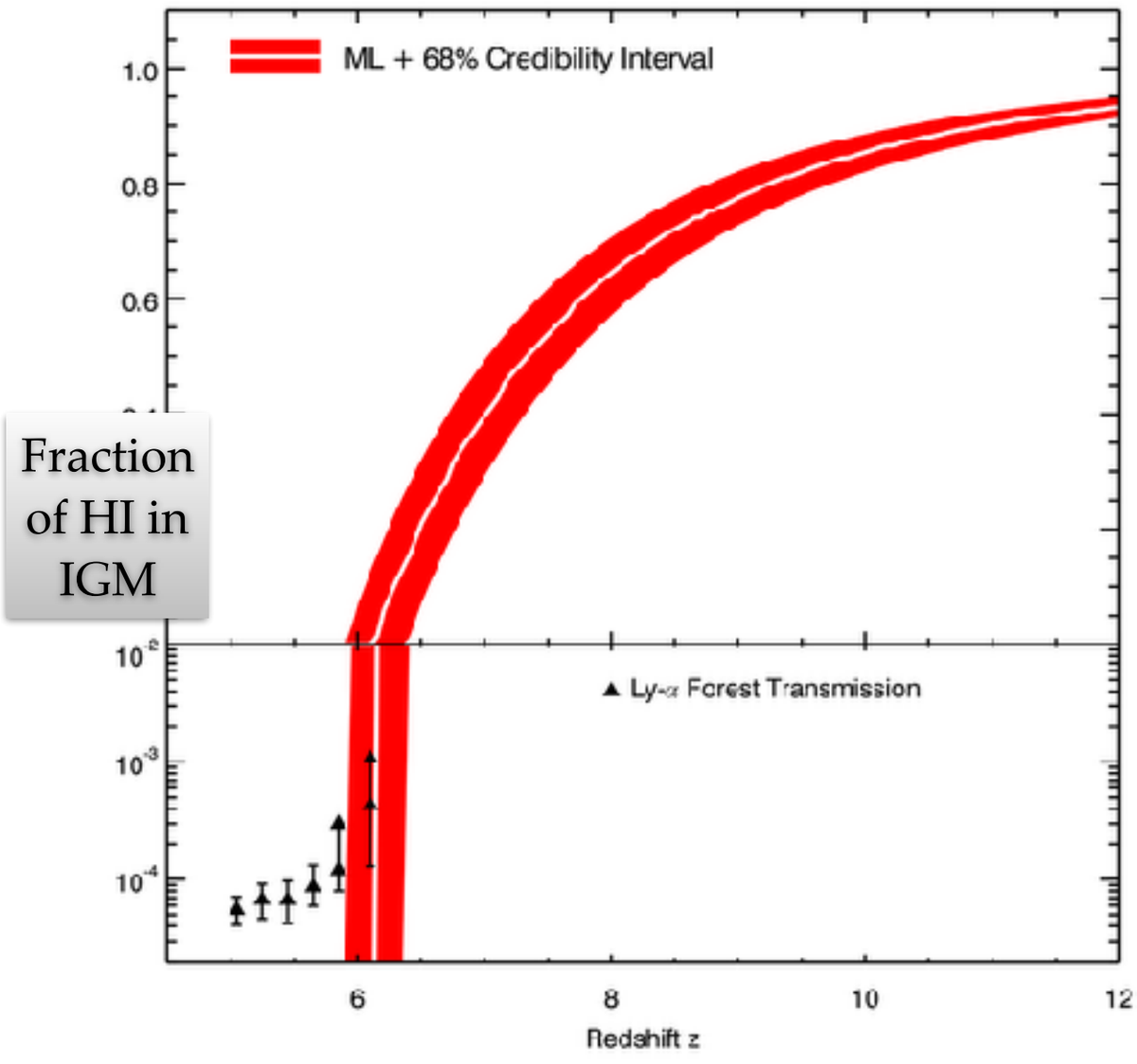
Galaxies in the Reionization Era



- Large samples of galaxies at 4<z<10.
- Can this population plausibly achieve reionization by z~6?

Bouwens+2019

Contribution of Galaxies to Reionization

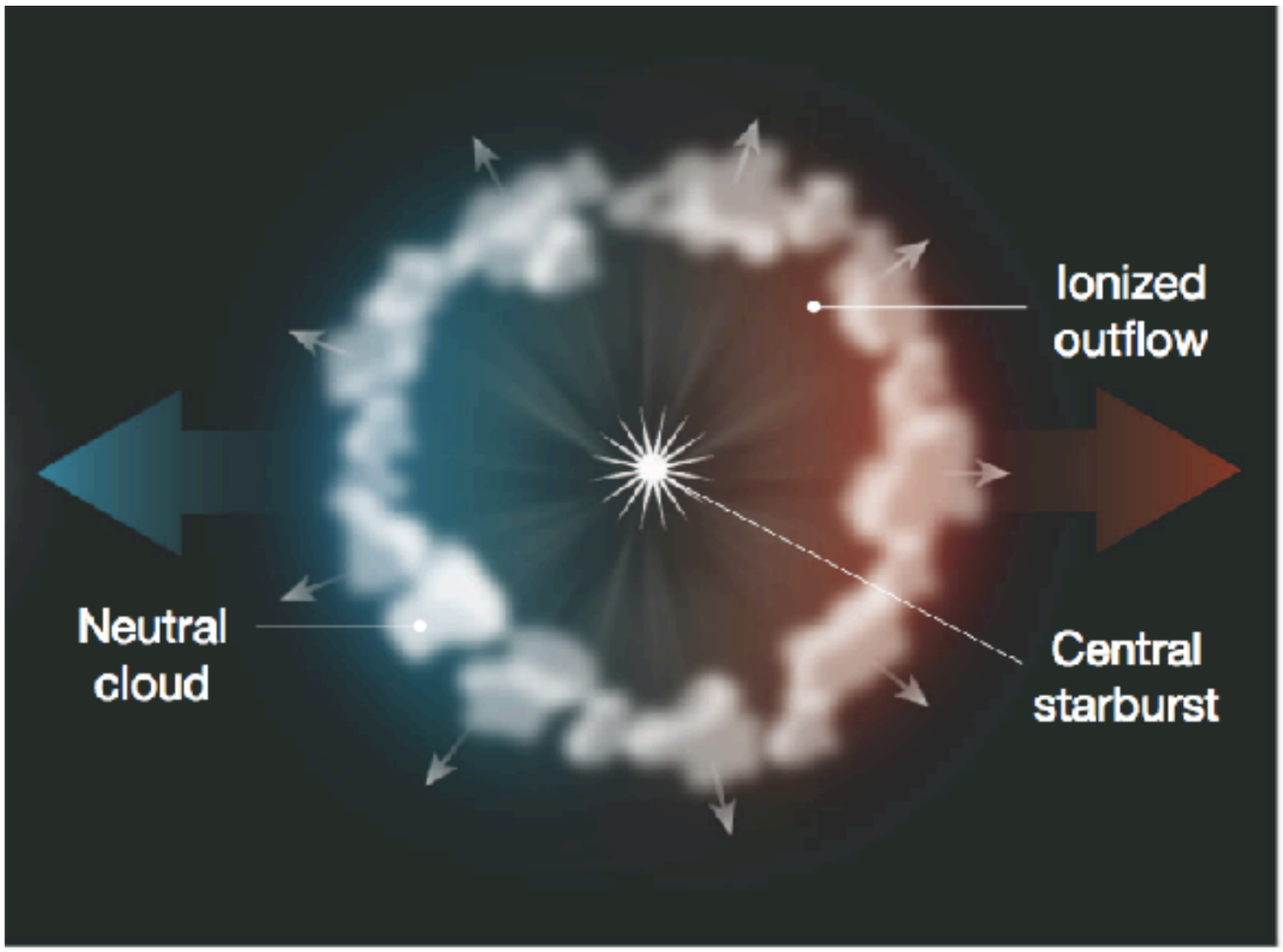


- Ionizing photon output possibly sufficient, provided luminosity function rises steeply to M_{UV}=-13.

Robertson et al. 2015

Caveats to this Picture: (I) Ionizing Photon Production

Erb 2015

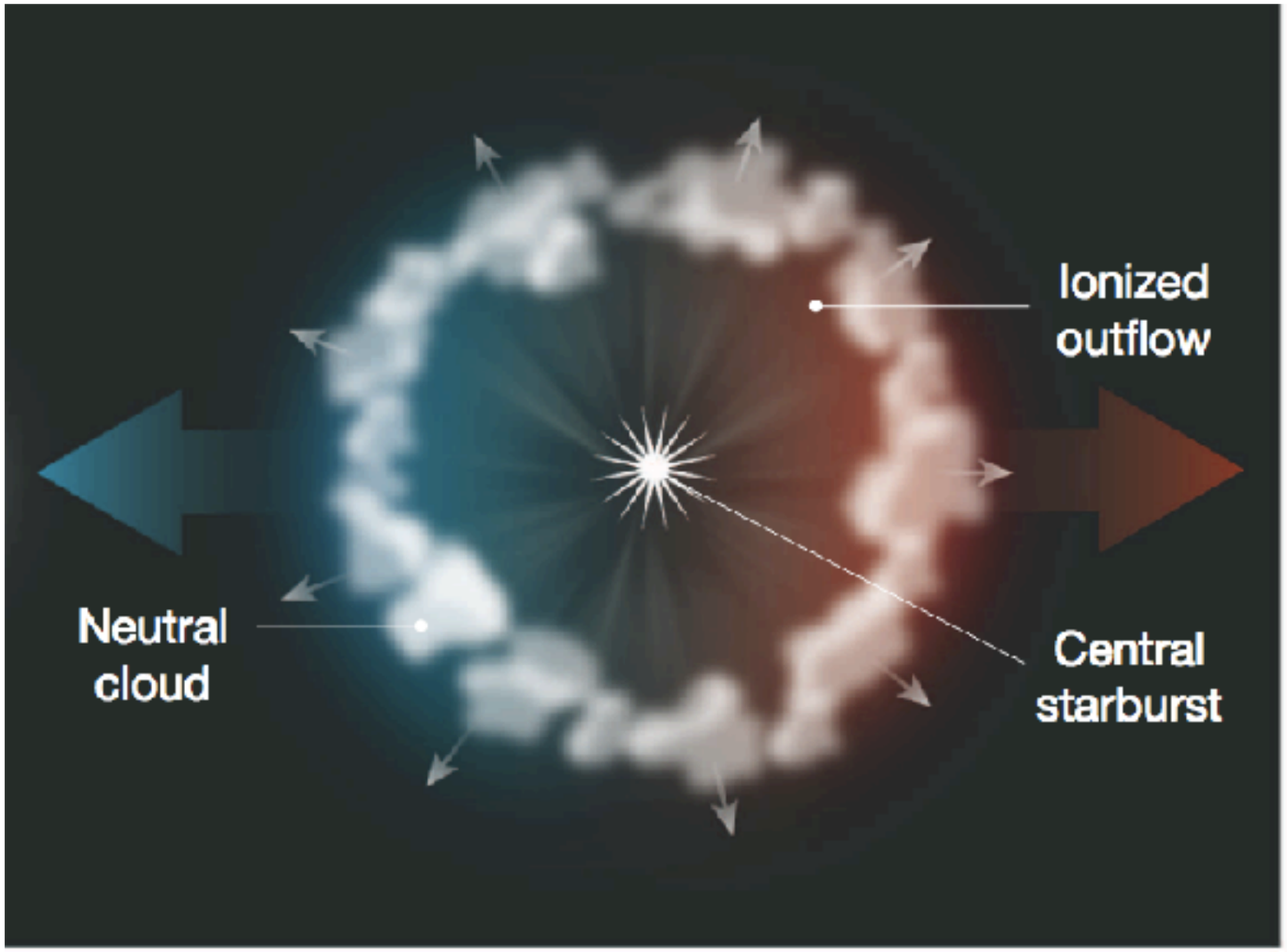


Hubble detects galaxies at ~1500Å, need to convert this to ionizing radiation (<912Å).

Conversion depends sensitively on metallicity / age of stellar population — very poorly understood at z>6.

Caveats to this Picture: (II) Ionizing Photon Escape

Erb 2015



For galaxies to achieve reionization, we require ~20% of ionizing radiation to escape through galaxies.

Such large escape fractions very rarely seen in typical galaxies at z~3.

Caveats to this Picture: (II) Ionizing Photon Escape

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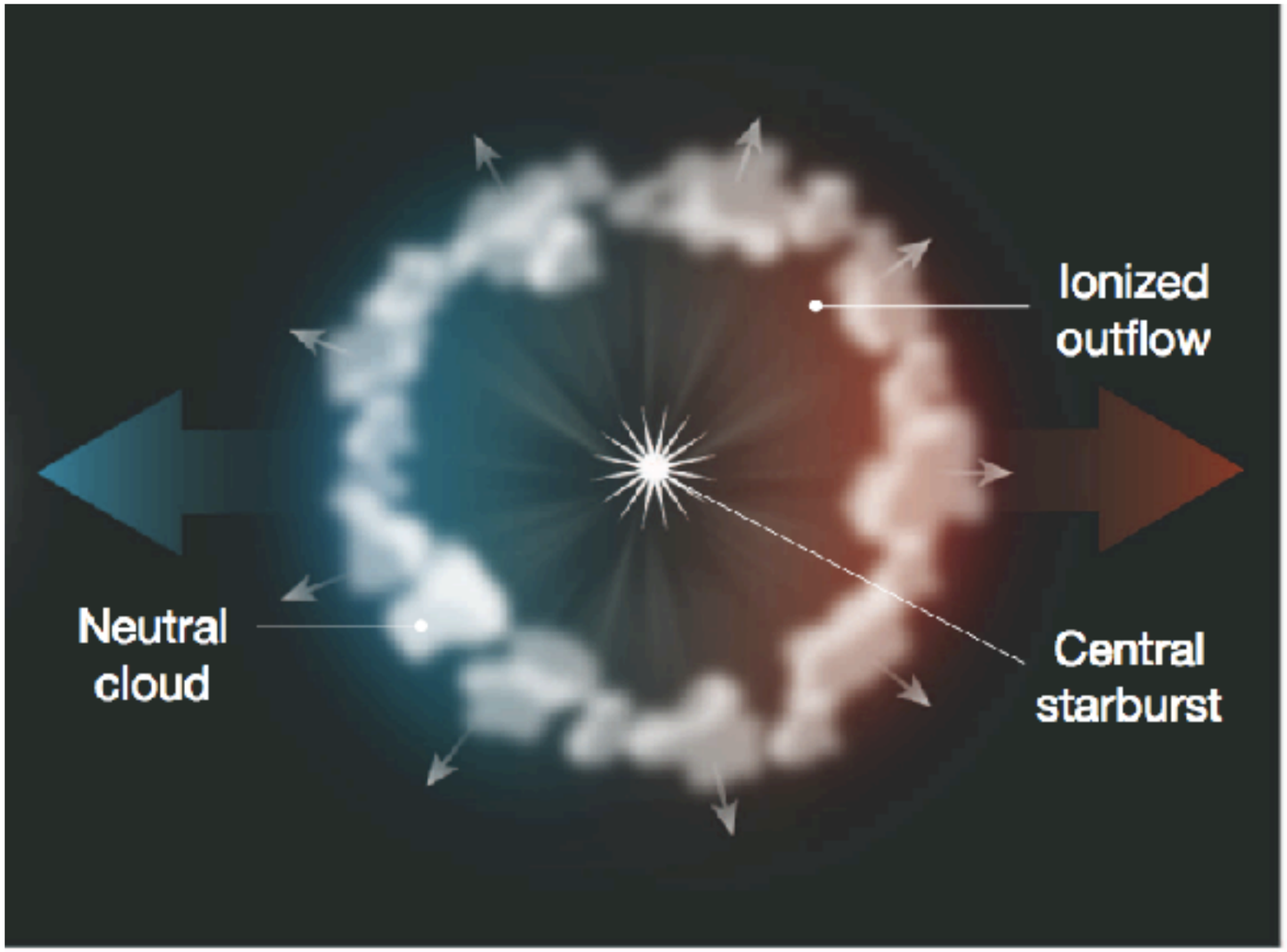
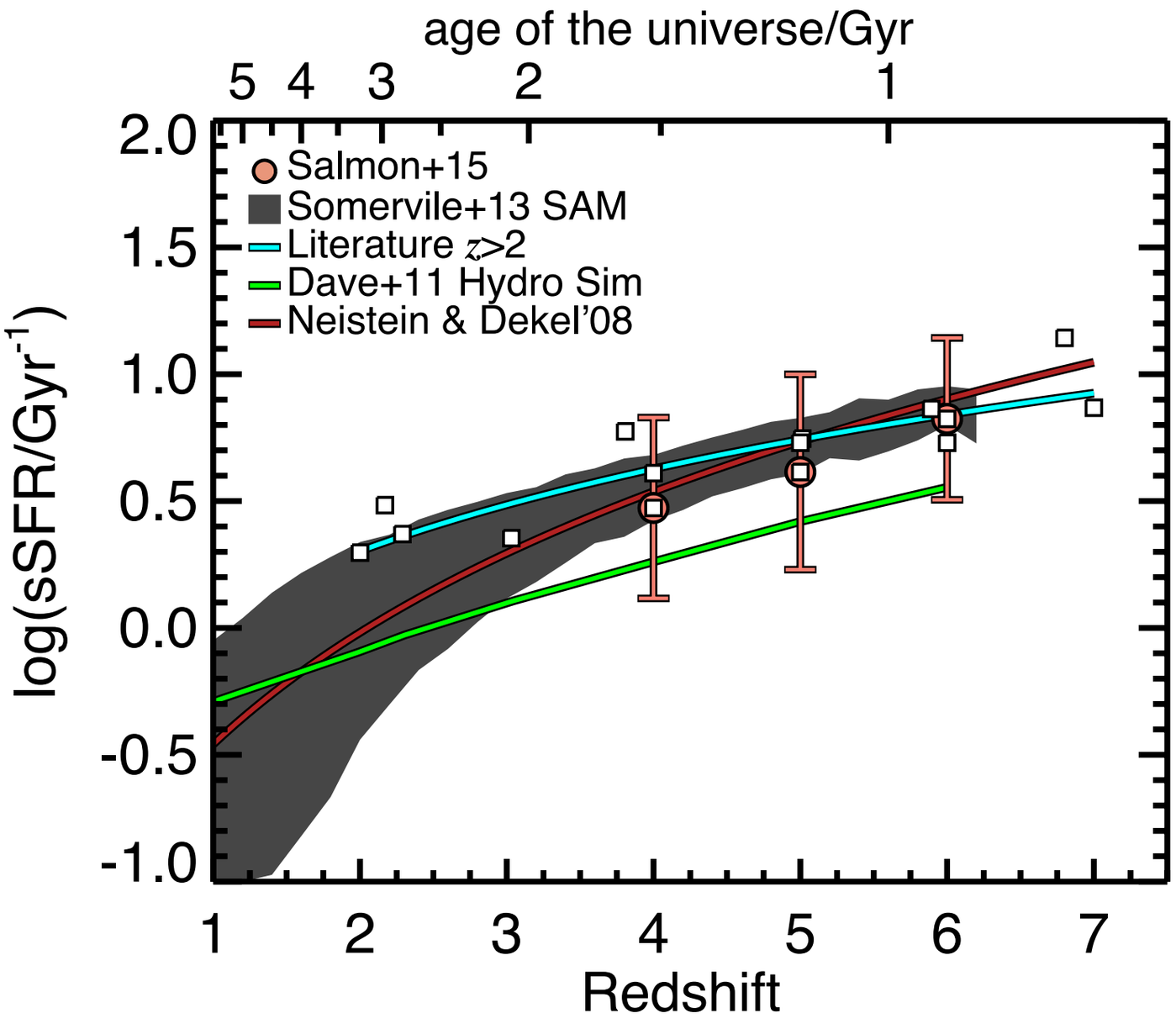


For galaxies to achieve reionization, we require ~20% of ionizing radiation to escape through galaxies.

Such large escape fractions very rarely seen in typical galaxies at z~3.

Efforts focused on understanding of how physical properties of z>6 galaxies compare to those which are common at z~3.

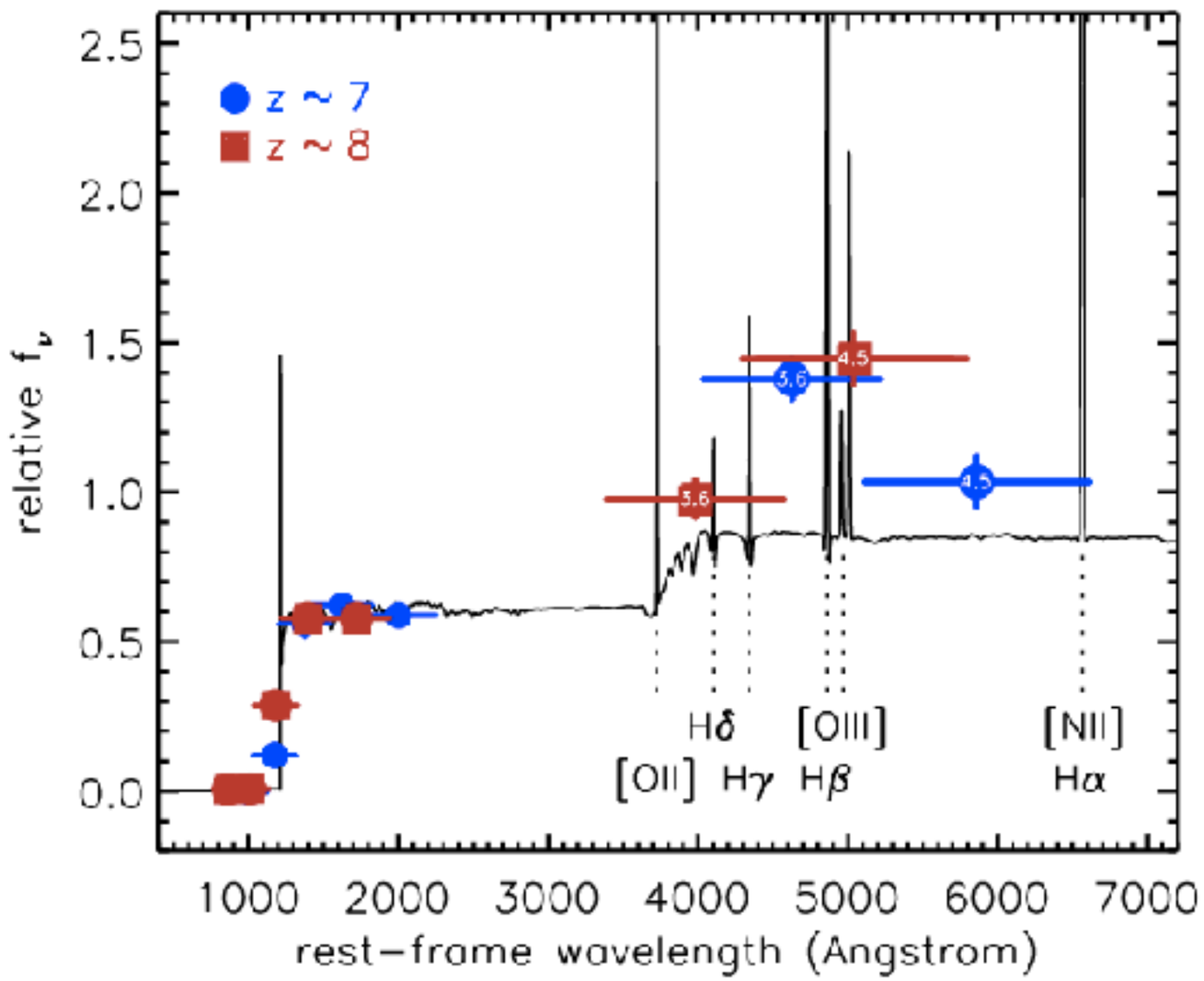
Specific star formation rates are large



Specific star formation rates ($SFR/M_\star$) in z~7 galaxies are ~5x greater than at z~2.

Stark 2016 ARAA, adapted from Salmon+15

Strong [OIII] Emission Lines



Strong [OIII]+Hβ emission evident in composite SEDs of galaxies z~7-8.

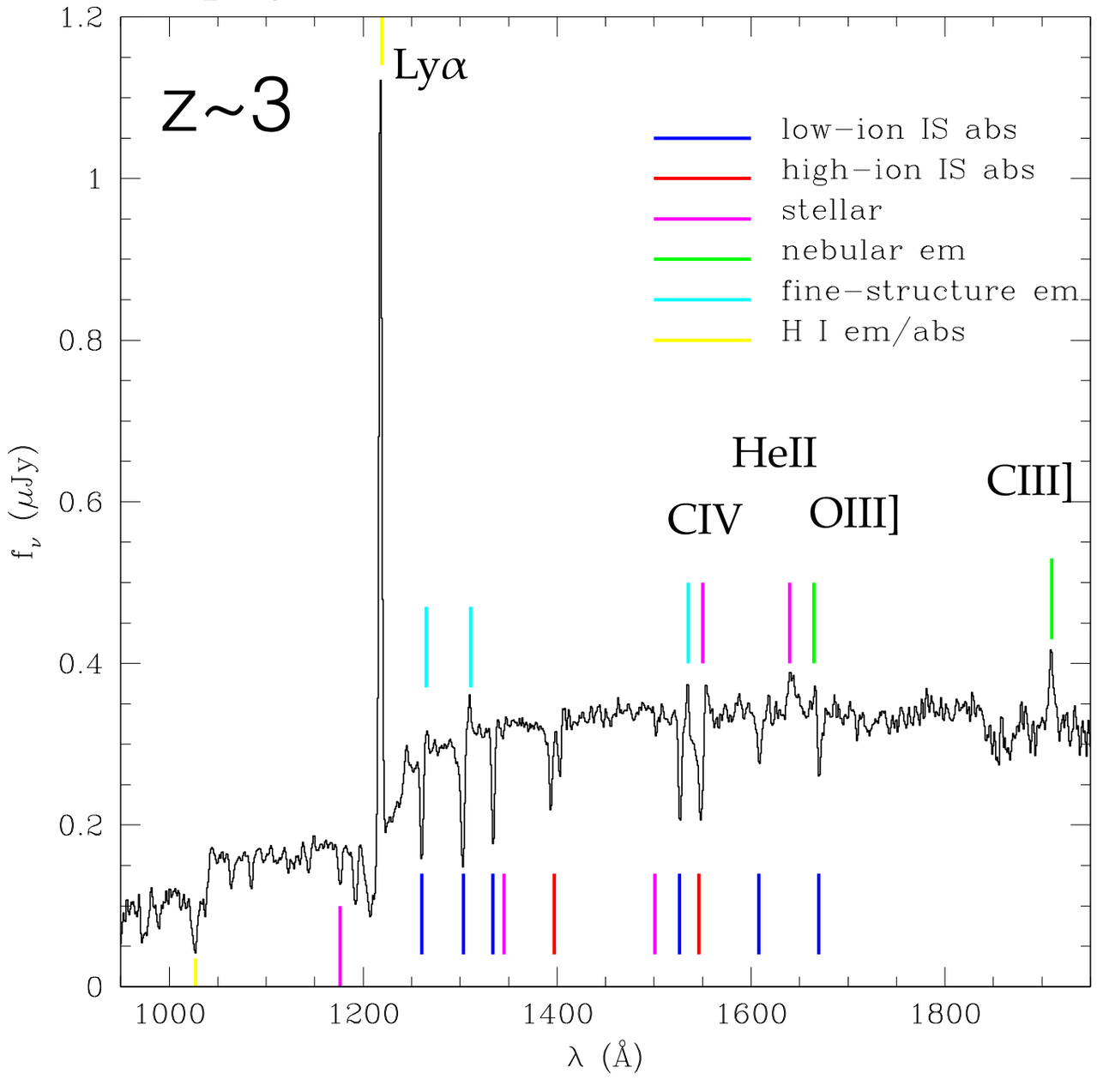
- $EW_{[OIII]+H\beta}$=670 Å is average
- Many systems with $EW_{[OIII]+H\beta}$=1000-3000 Å

Signpost of galaxies undergoing burst/upturn in star formation — much more common at z>6.

Labbé et al. 2013, ApJL, 777, 19

What can we learn from ground-based spectra of z>6 galaxies?

Shapley et al. 2003



Attention focused on UV nebular lines, which are very faint in typical z~3 galaxies.

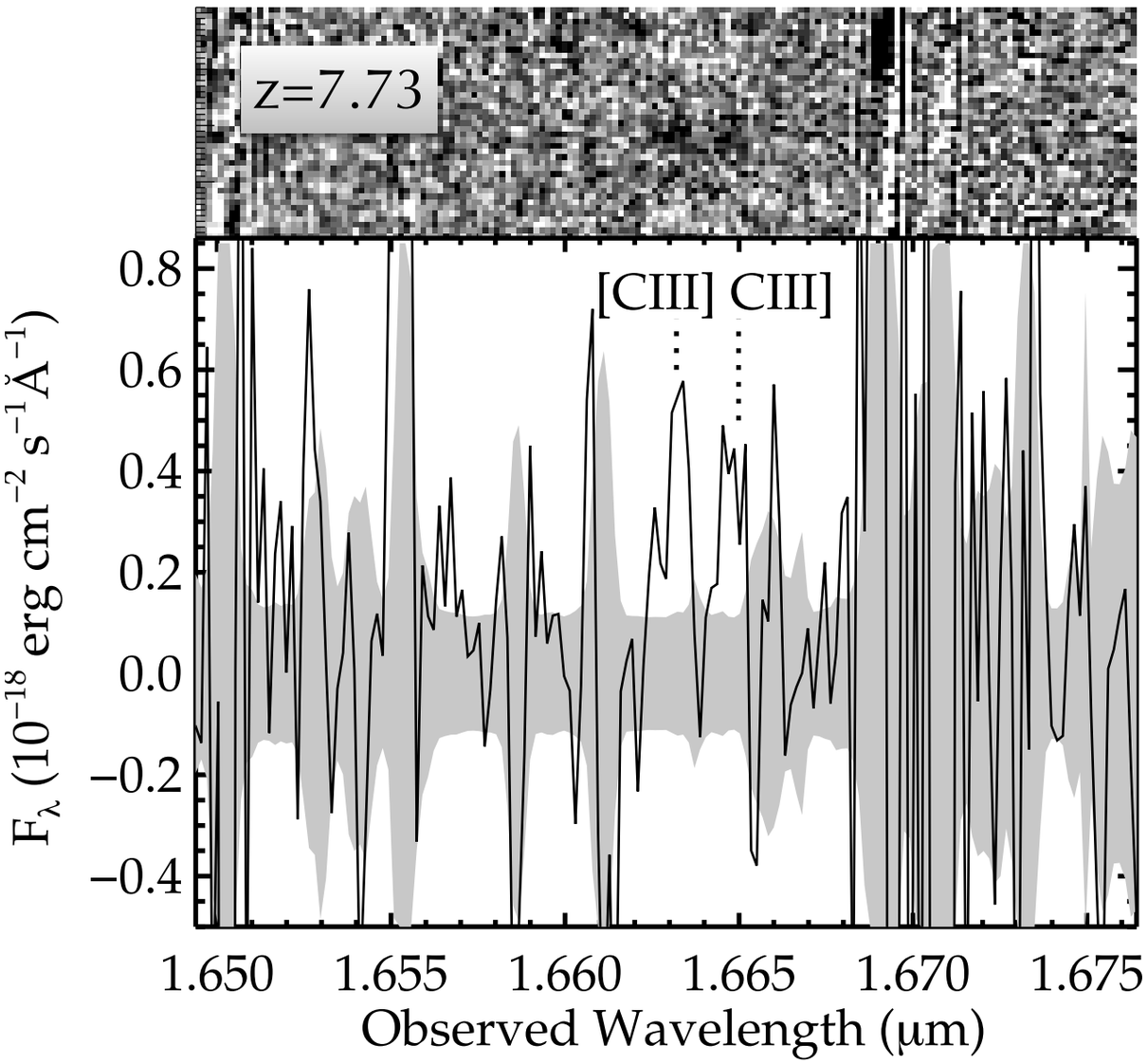
$EW_{CIII]} = 1.7$ Å

$EW_{HeII} = 1.3$ Å

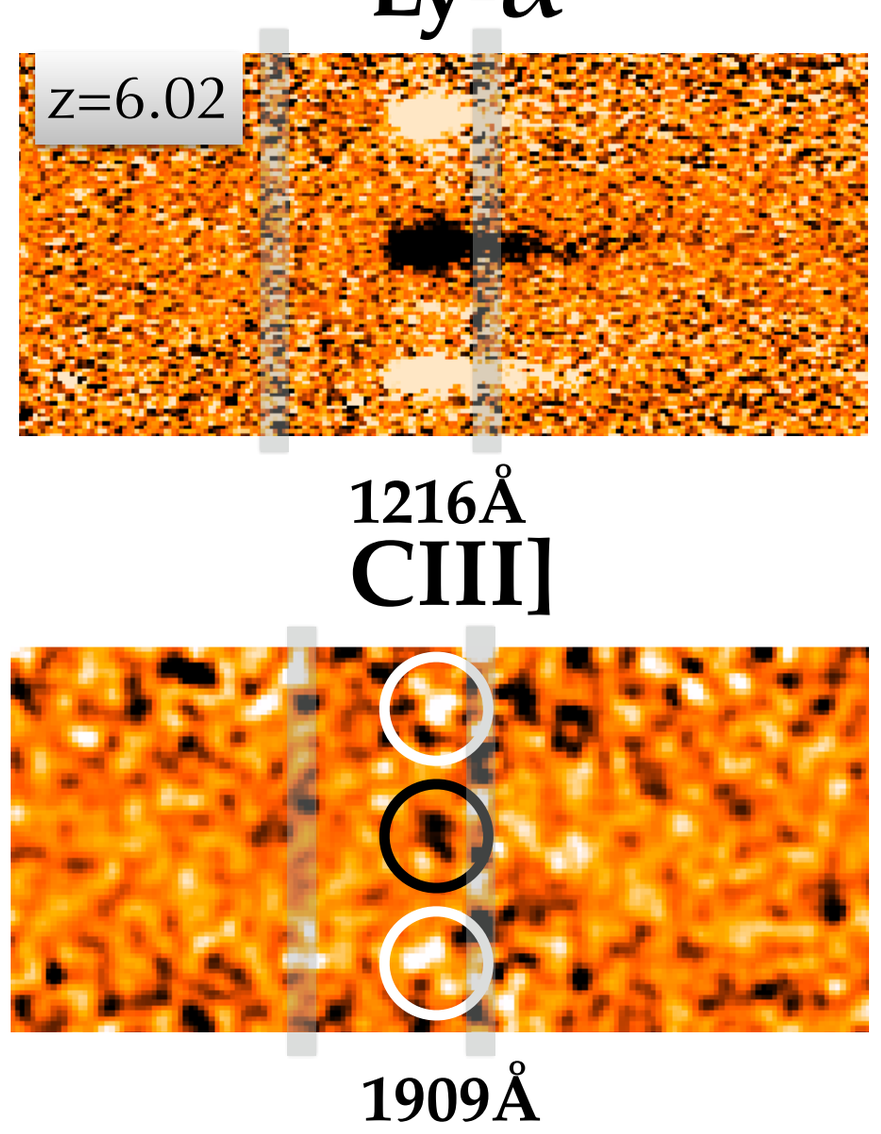
$EW_{OIII]\lambda 1661+1666} = 0.2$ Å

CIII] Emission is Strong at z>6

Stark+17



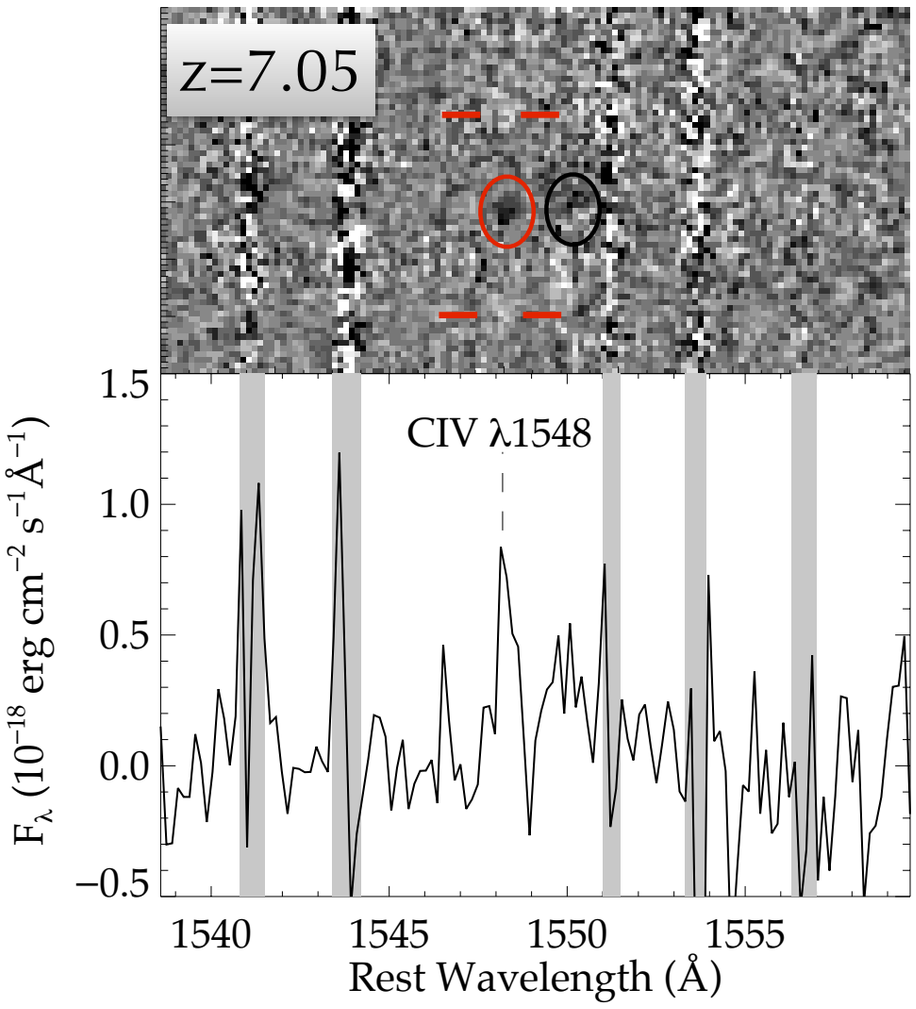
Stark+15a



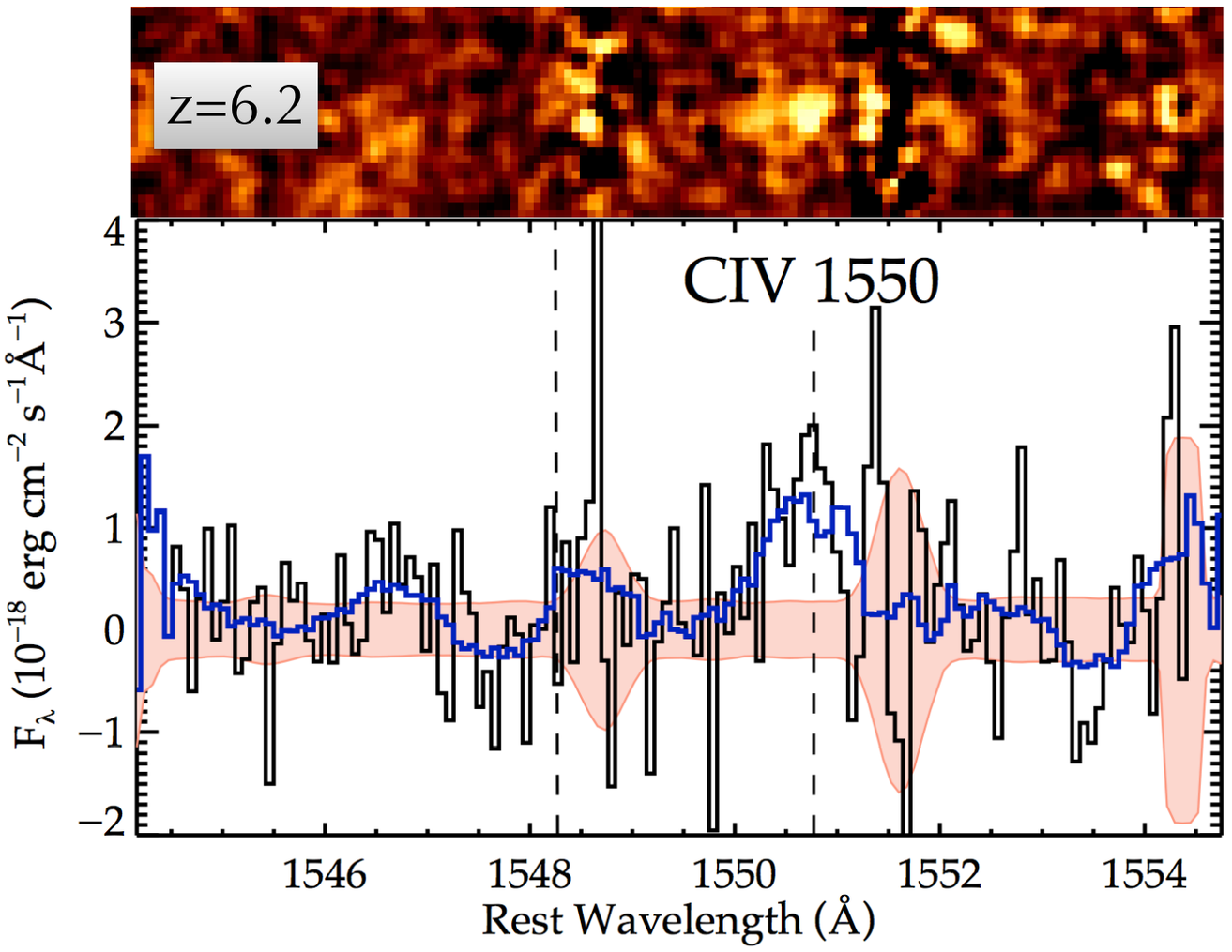
- CIII] equivalent widths of ~20Å in galaxies at z=6.02, z=7.73, z=7.47.
- More than 10x greater than average value at z~3.

CIV Emission is Strong at z>6

Stark+2015b



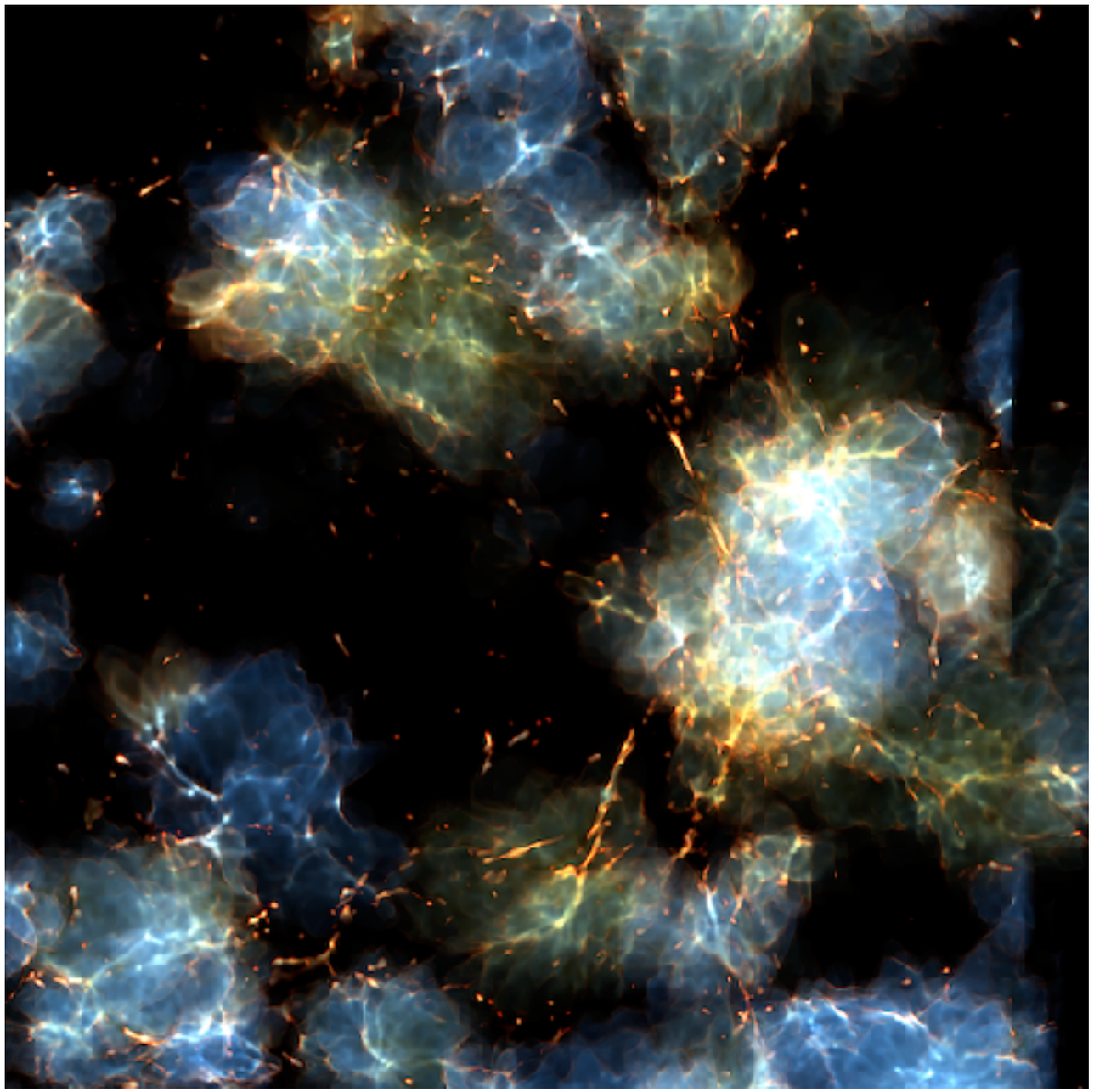
Mainali+2017 (see also Schmidt+2017)



Intense CIV emission (EW ~ 20Å) in gravitationally lensed galaxies

Requires hard ionizing spectrum capable of triply ionizing carbon — typically signature of AGN, here metal poor stars may be responsible.

Implications for Early Galaxies and their Contribution to Reionization



credit: Wise, Cen, and Abel

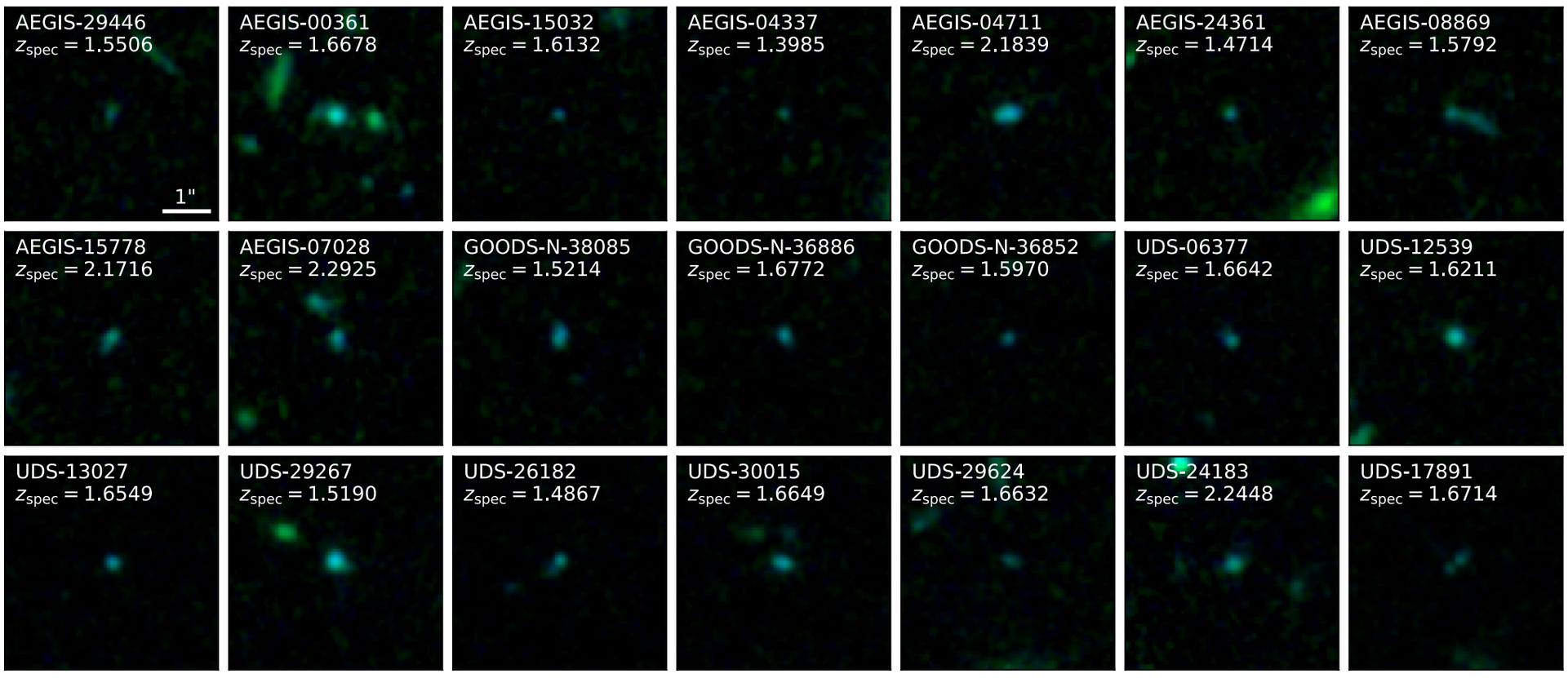
- What is the production efficiency of ionizing photons (ξ_{ion}) in z>6 galaxies

- Is the ISM of z>6 galaxies conducive to escape of ionizing radiation?

- Why do we see such strong CIII]+CIV emission?

Insight from Low Mass Star Forming Galaxies Undergoing Bursts at z~0.1-2

Tang, Stark, Chevallard, & Charlot 2019

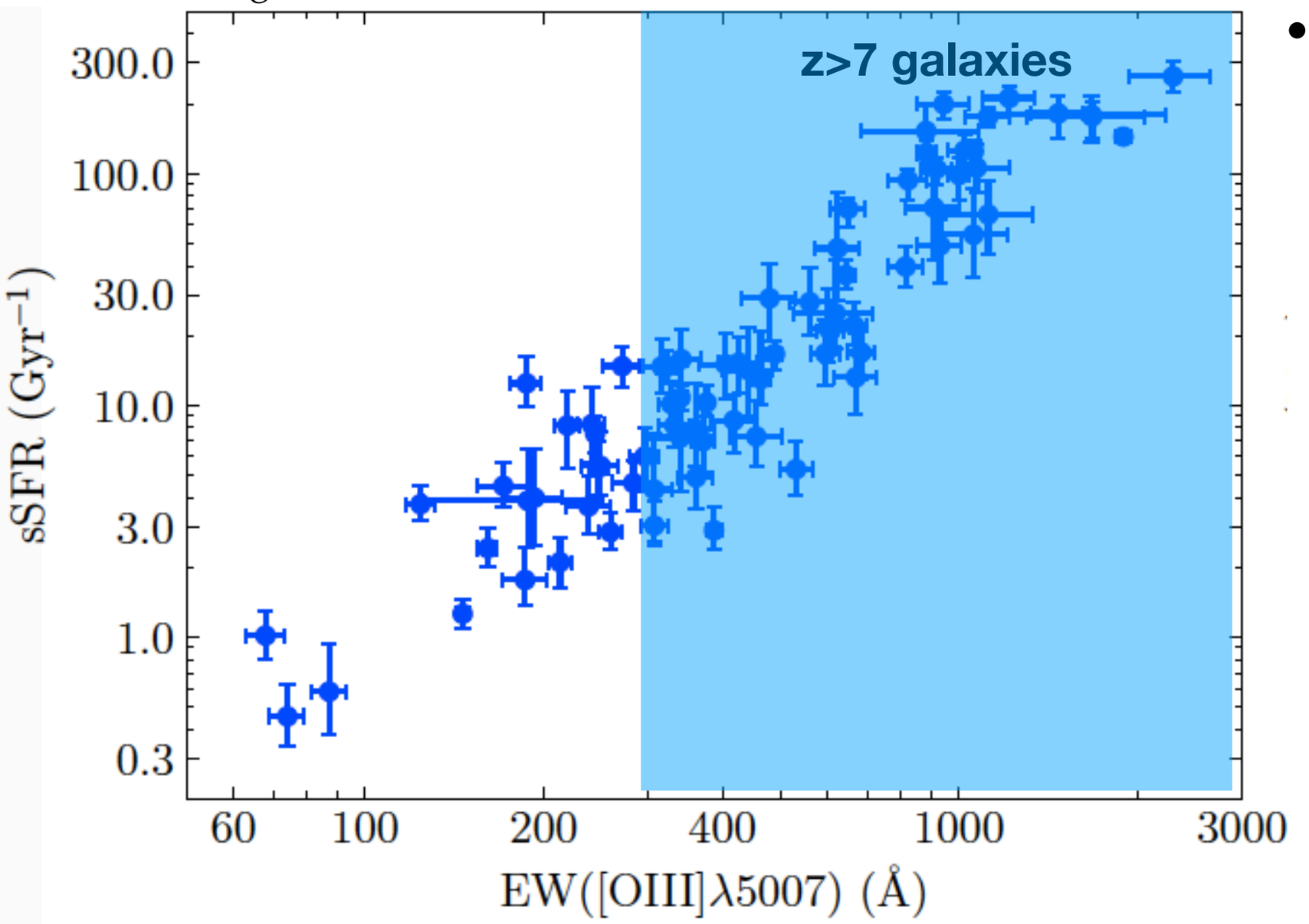


- Large (~150 hours) spectroscopic survey of z~2 galaxies with similarly large [OIII] EW (extreme emission line galaxies) as at z>7.

- Compare to similar samples at z~0.1-0.3 in SDSS.

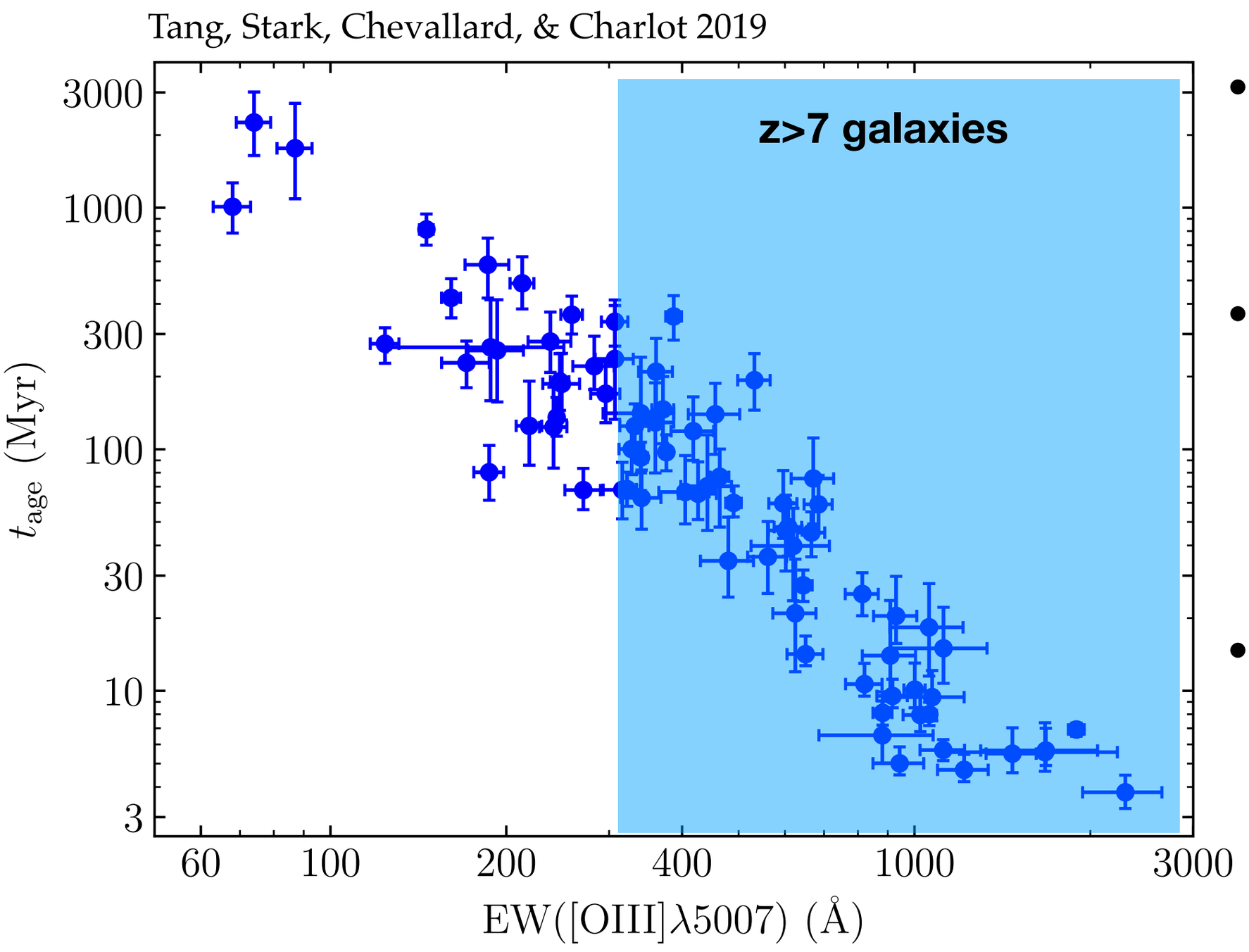
Sample of Low Mass Galaxies

Tang, Stark, Chevallard, & Charlot 2019



- Higher [OIII] EW corresponds to high sSFR and young stellar population.

Sample of Low Mass Galaxies



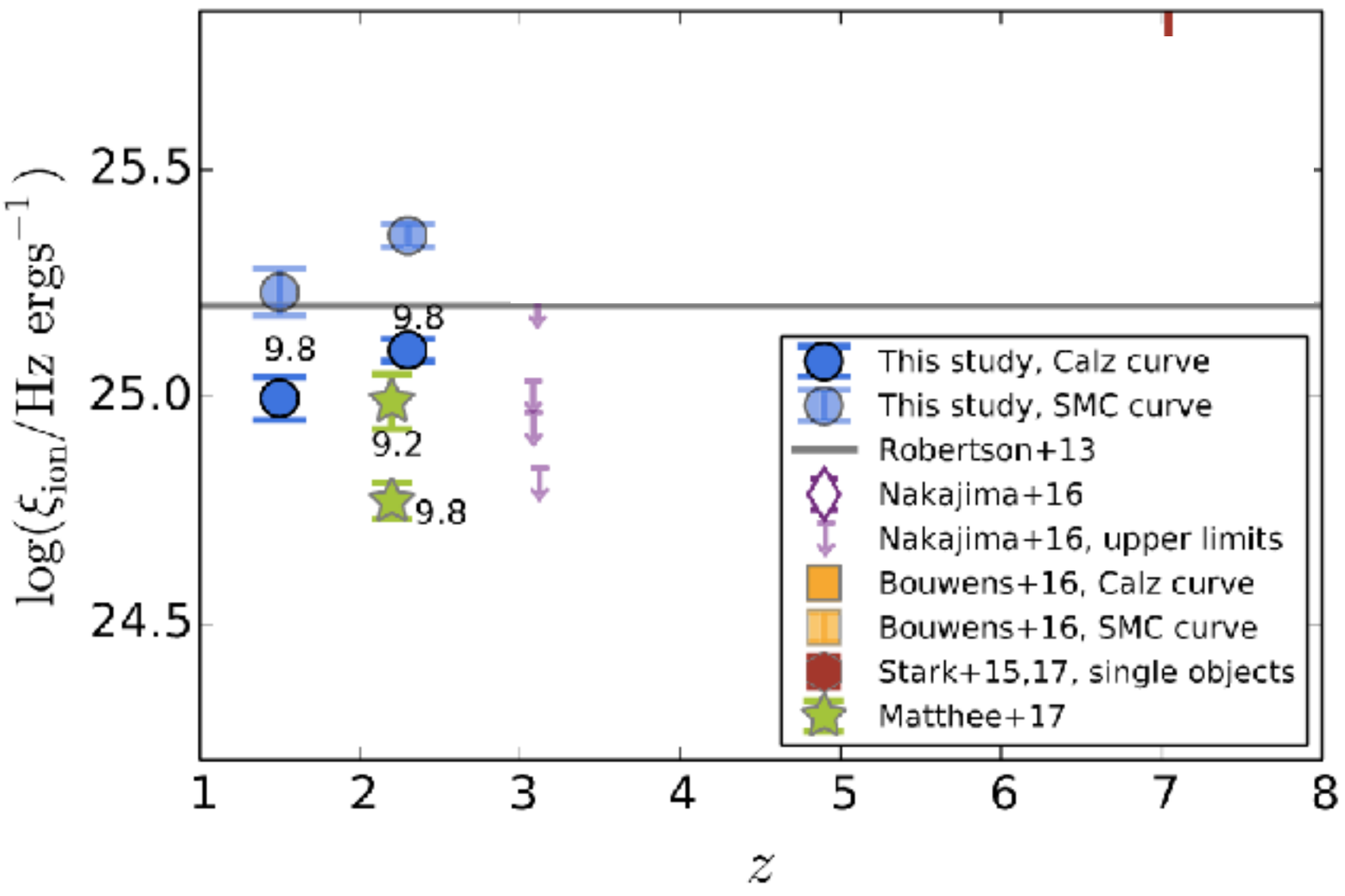
- Higher [OIII] EW corresponds to younger stellar population.
- Probe phases just after a burst of star formation in dwarf galaxy, when feedback strong and radiation field intense.
- Test if this brief window coincides with enhanced ionizing photon production and escape.

(I) Ionizing photon production in low mass galaxies with large sSFR?

- Production efficiency of ionizing photons, defined as ξ_{ion}=Ionizing photon production rate / $L_{UV.}$

Ionizing Production Efficiency at z~2

Shivaei+2018

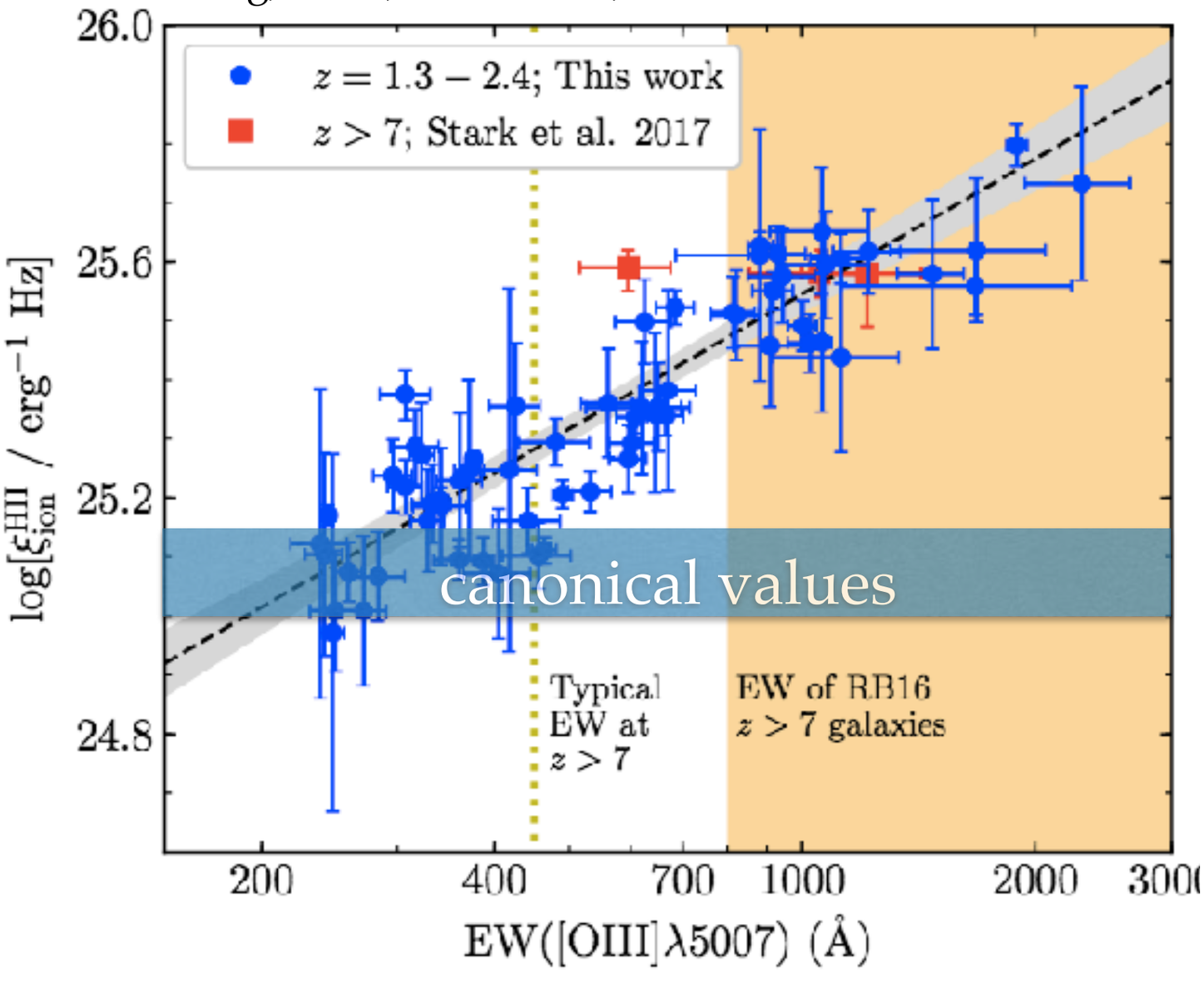


- State of the art from MOSDEF survey targeting massive star forming galaxies at z~2 with lower sSFR and [OIII] EW~120Å.
  - log ξ_{ion}=25.1

- Do young/hot stellar populations that emerge immediately after burst power harder radiation field with larger ξ_{ion}?

Ionizing Production Efficiency

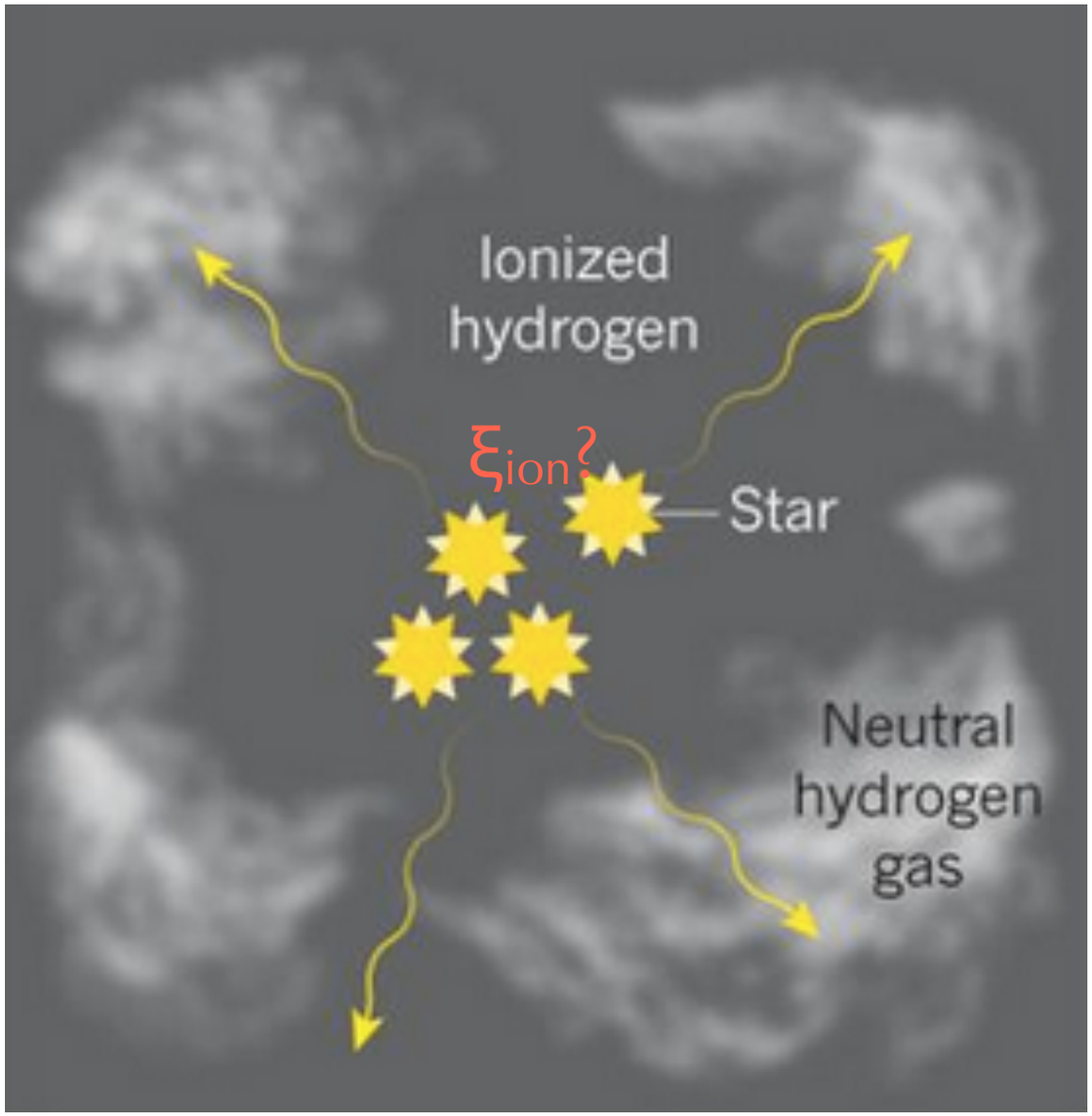
Tang, Stark, Chevallard, & Charlot 2018



- ξ_{ion} scales with [OIII] EW at z~2, reaching large values in the galaxies with large [OIII] EW that are common at z~7.

- Most extreme line emitters produce 4x more ionizing photons relative to L_{UV} than typical z~2 galaxies.

Ionizing Production Efficiency in Low Mass Galaxies undergoing Bursts



- There is a window after a burst where stellar populations characterized by very hot effective temperatures — power harder ionizing spectrum with larger ξ_{ion}.
- These type of galaxies appear fairly common at z>6 — important to consider these bursts when calculating contribution of galaxies to reionization.

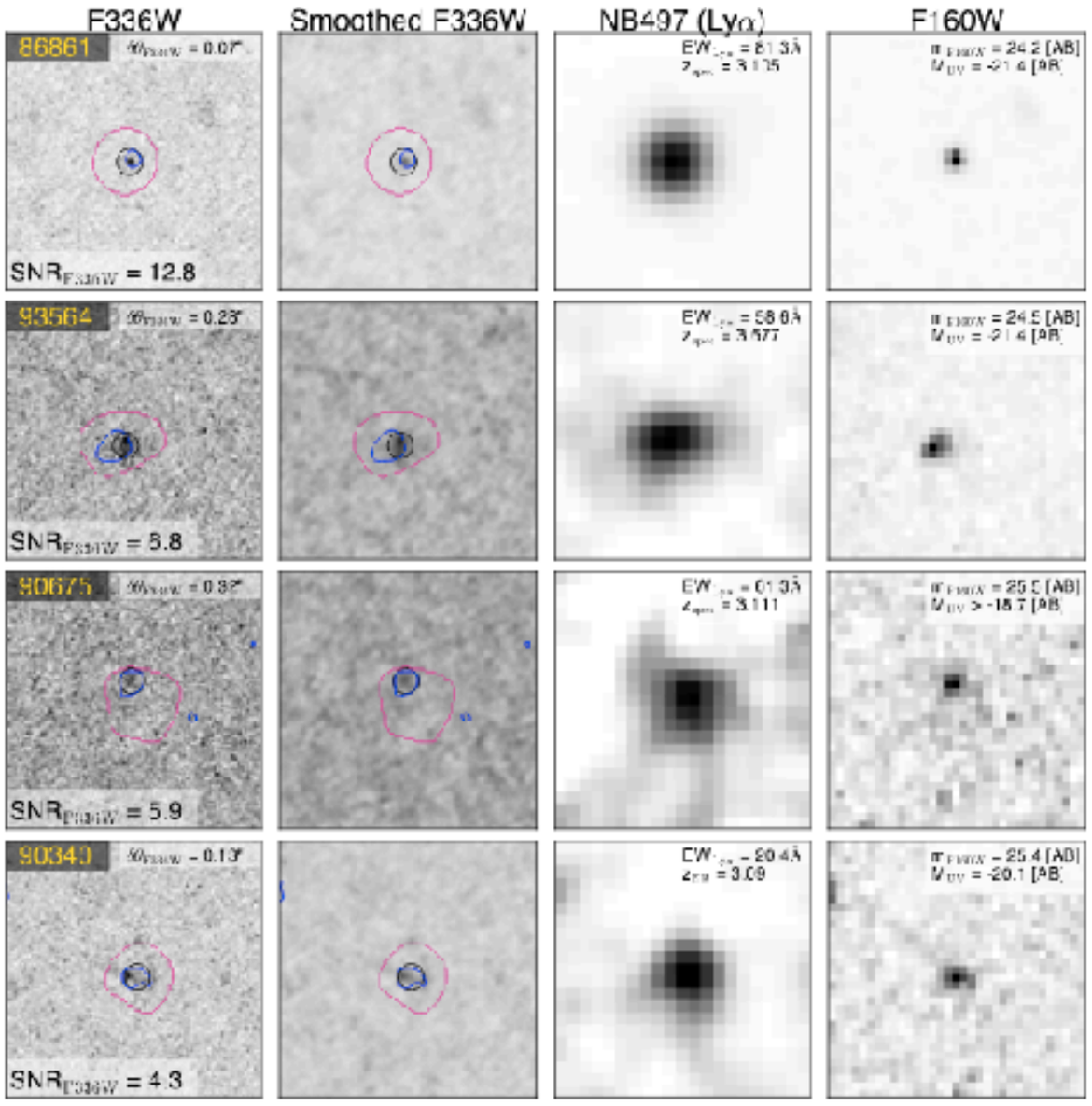
(II) Ionizing photon escape in low mass galaxies with large sSFR?

Does this energetic phase also lead to more highly ionized ISM that may be more conducive to ionizing photon escape?

Ionization state of ISM can be constrained by flux ratio of [OIII] and [OII] — the O32 ratio.

Ionizing Photon Escape and O32

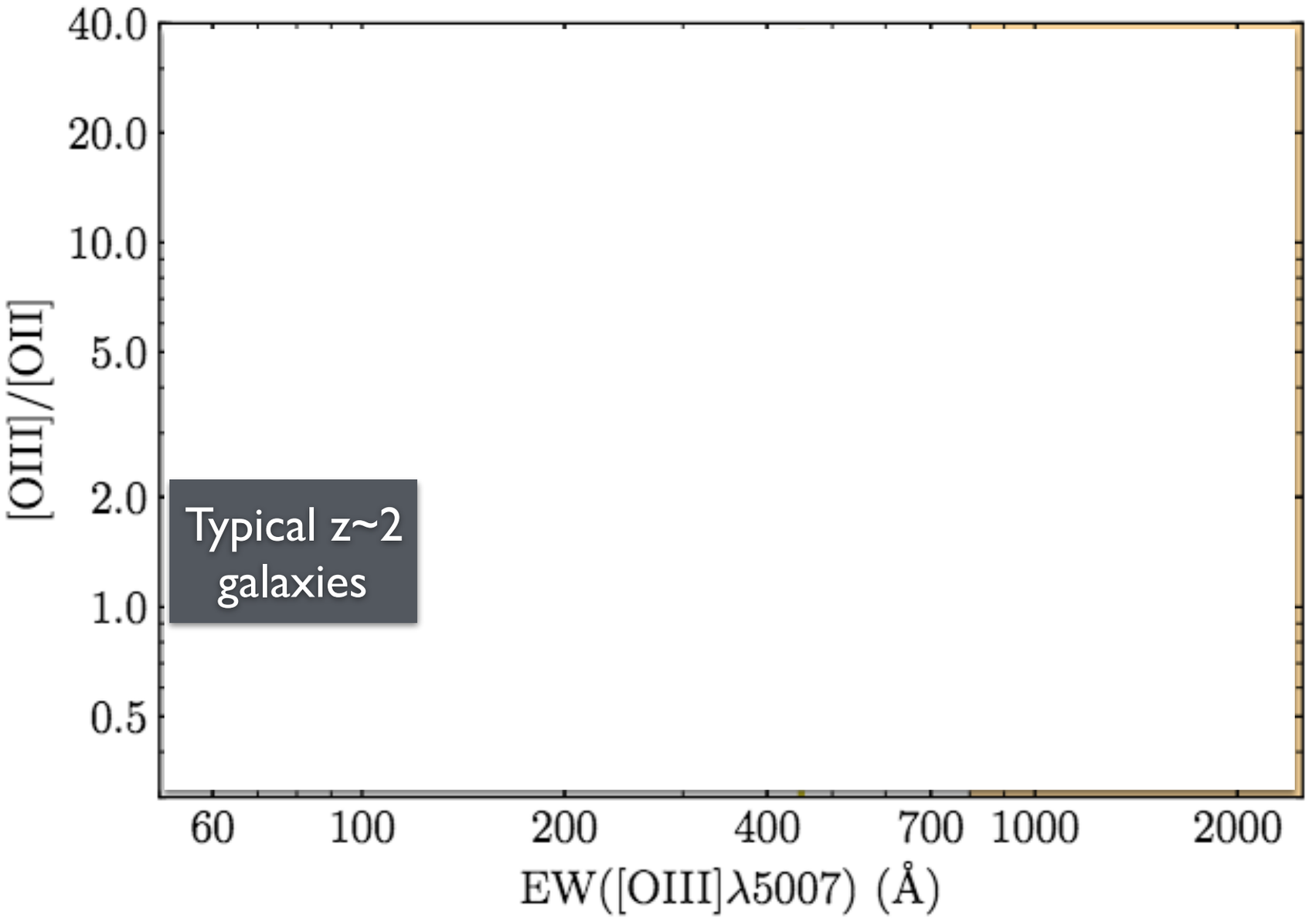
Fletcher et al. 2019



- Samples of galaxies with significant ionizing photon escape fractions now emerging at z~0 and z~3.

- Galaxies with largest ionizing photon escape fractions often associated with very highly ionized ISM (O32>8).

ISM Conditions after Burst in Low Mass Galaxies



ISM Conditions after Burst in Low Mass Galaxies

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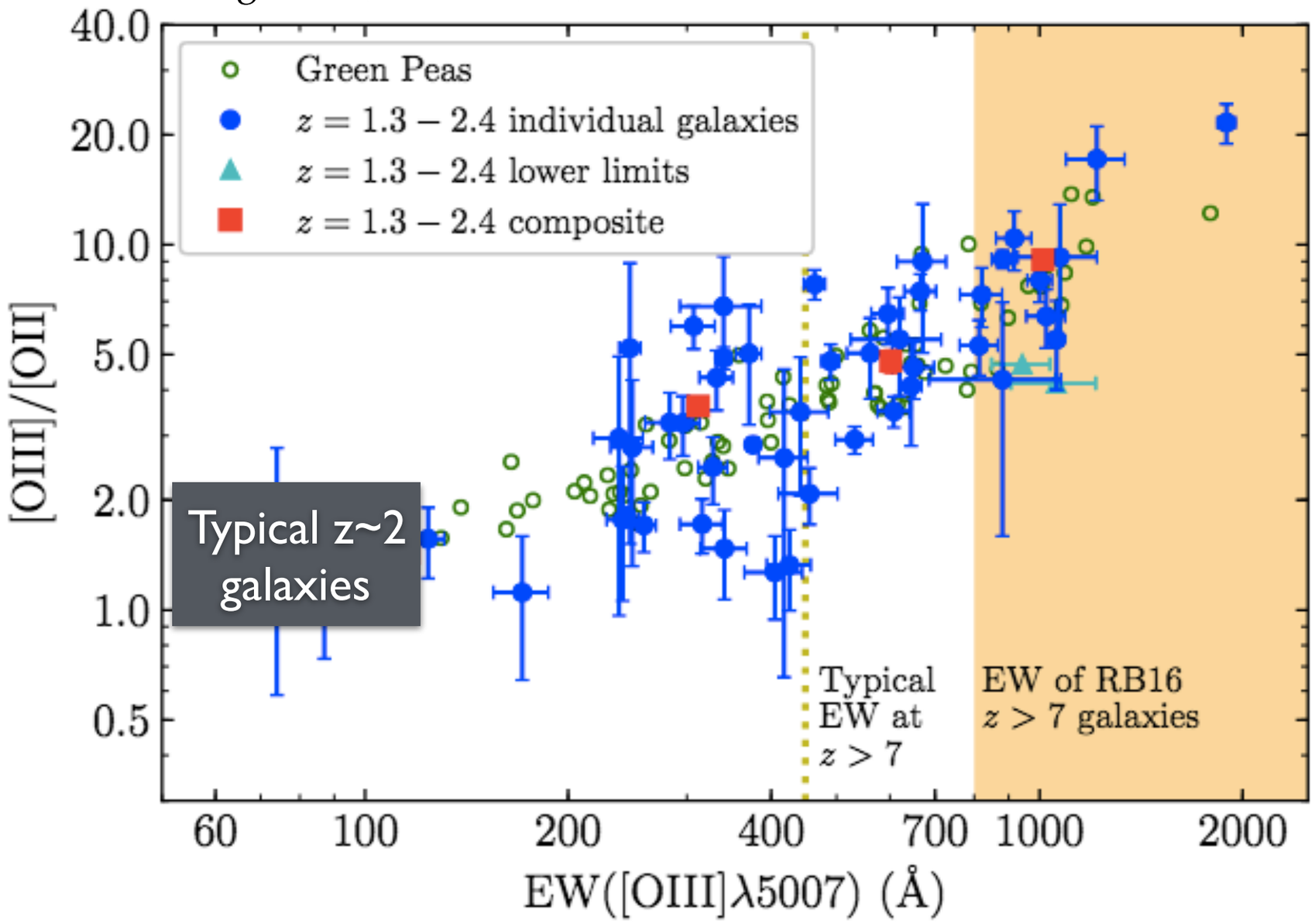
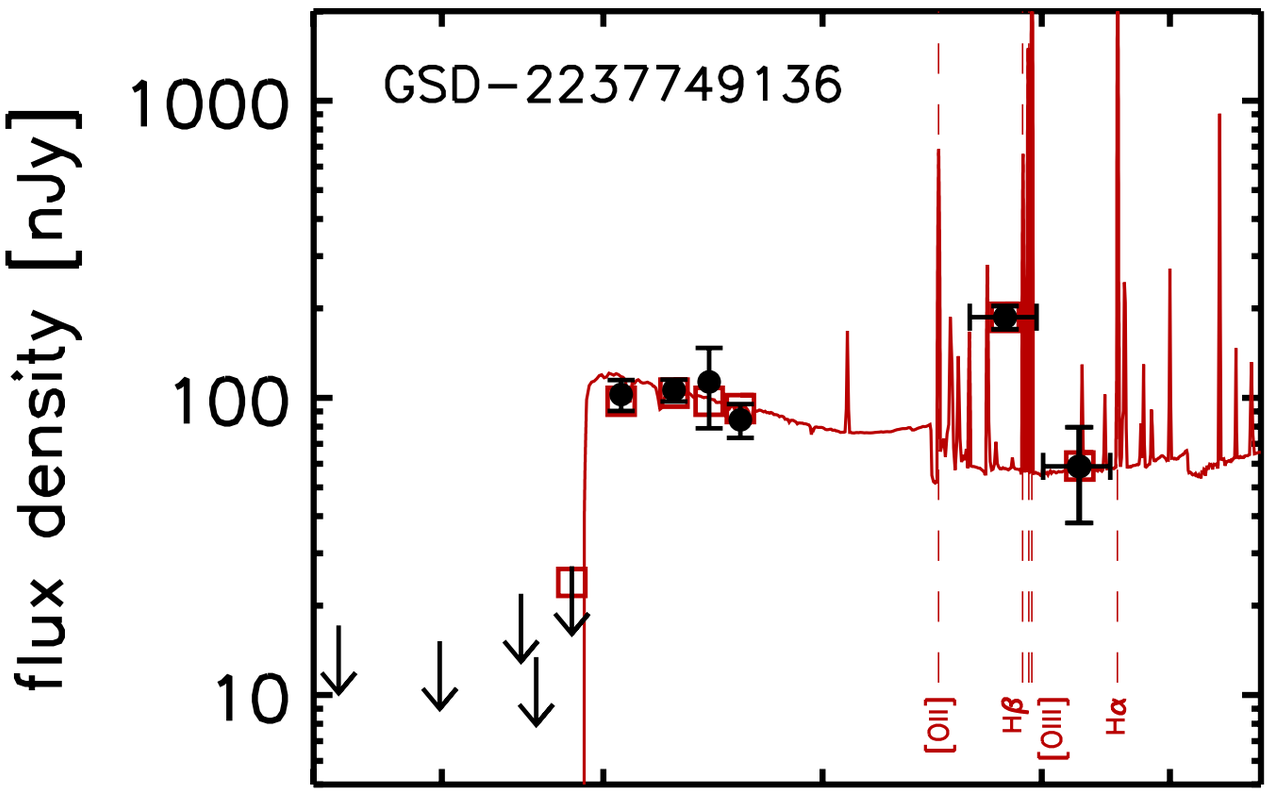


- Very large O32 ratios common in galaxies with large [OIII] EW.

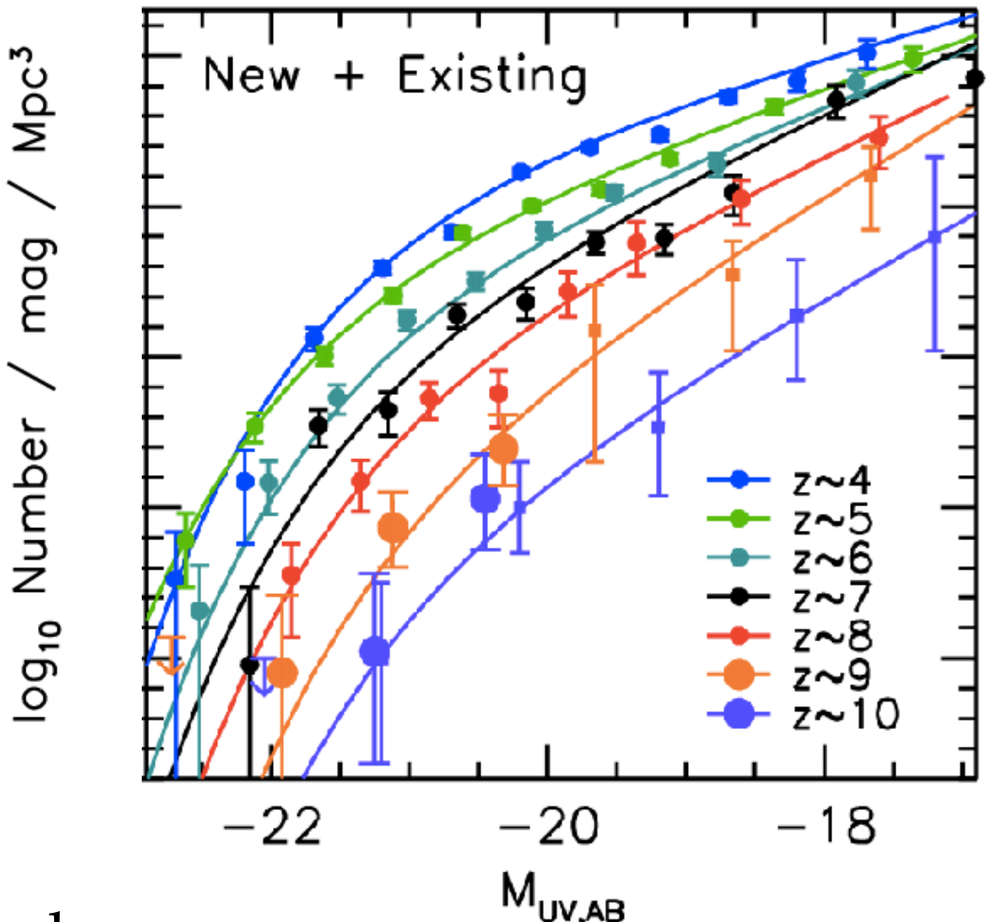
- Very highly ionized ISM that tends to be associated with large f_{esc} is commonplace just after a burst of star formation.

Implications for Contribution of z>6 Galaxies to Reionization

Smit+15, ApJ, 801,122



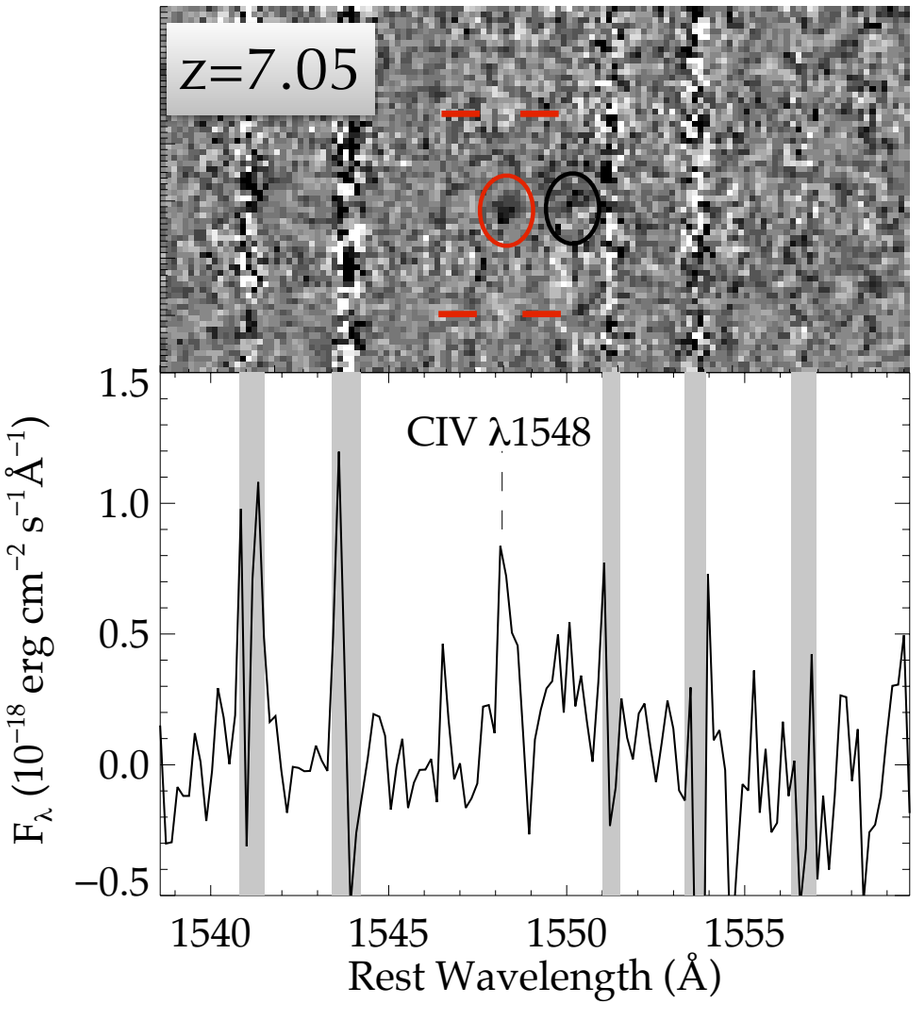
Bouwens+2019



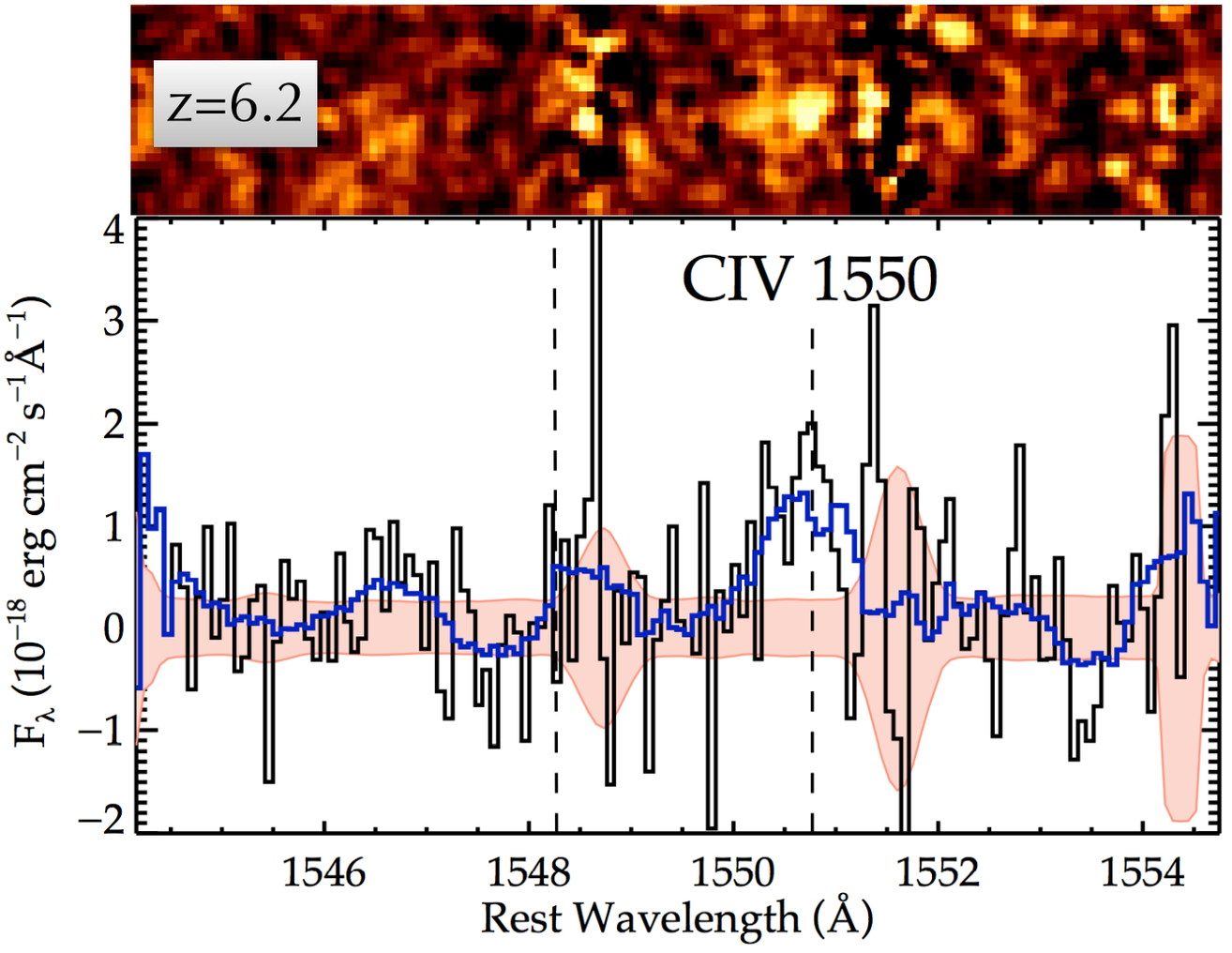
- Low mass galaxies undergoing bursts are commonly seen at z>6.
- During this phase, galaxies are very effective ionizing agents - both in the production and escape of their ionizing radiation.
- Not all galaxies at z>7 are in this phase — need to calculate duty cycle, mass dependence.

What do CIII] and CIV detections tell us about early galaxies?

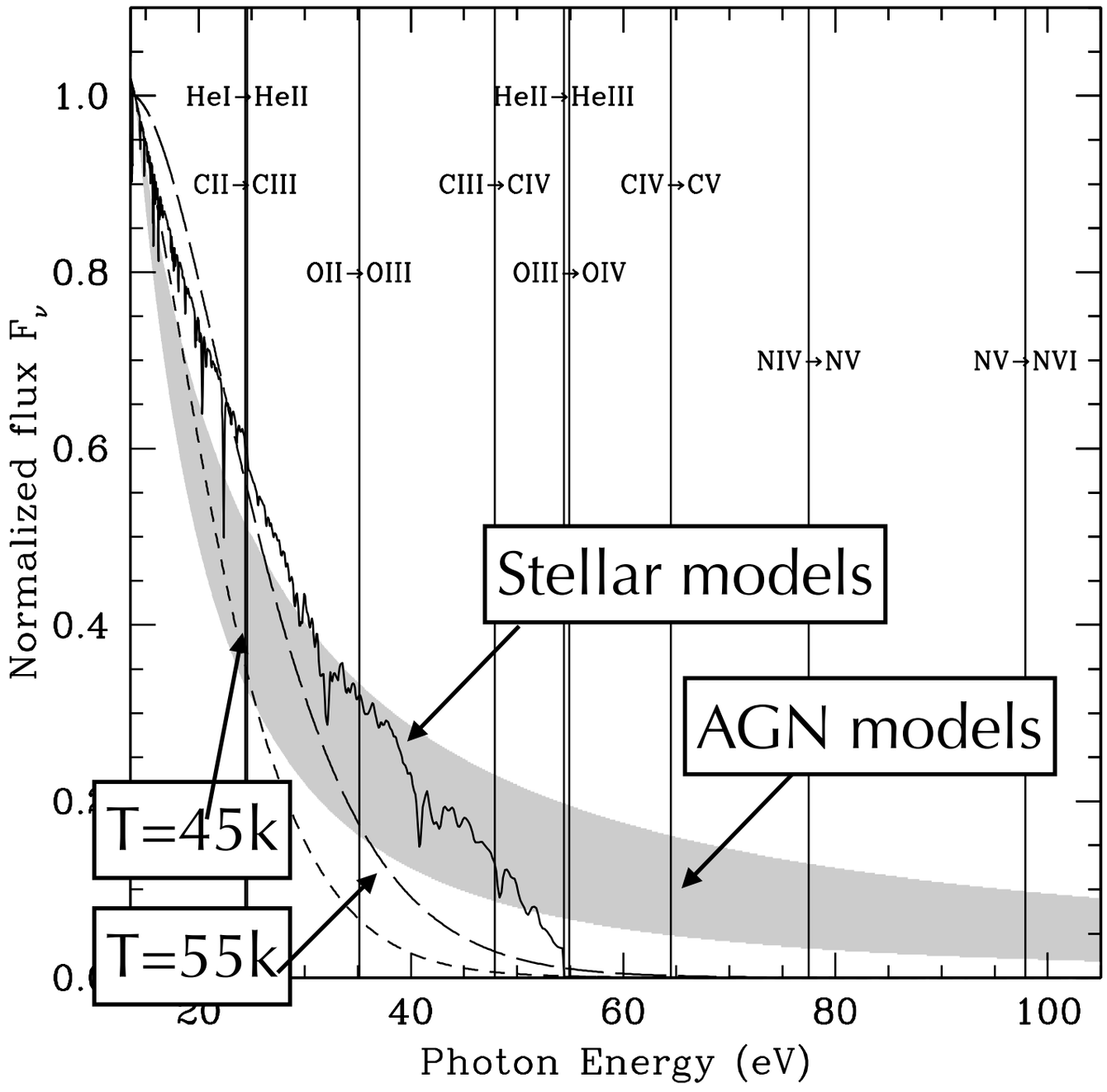
Stark+2015b



Mainali+2017 (see also Schmidt+2017)



Tension in Interpretation of UV Line Emission

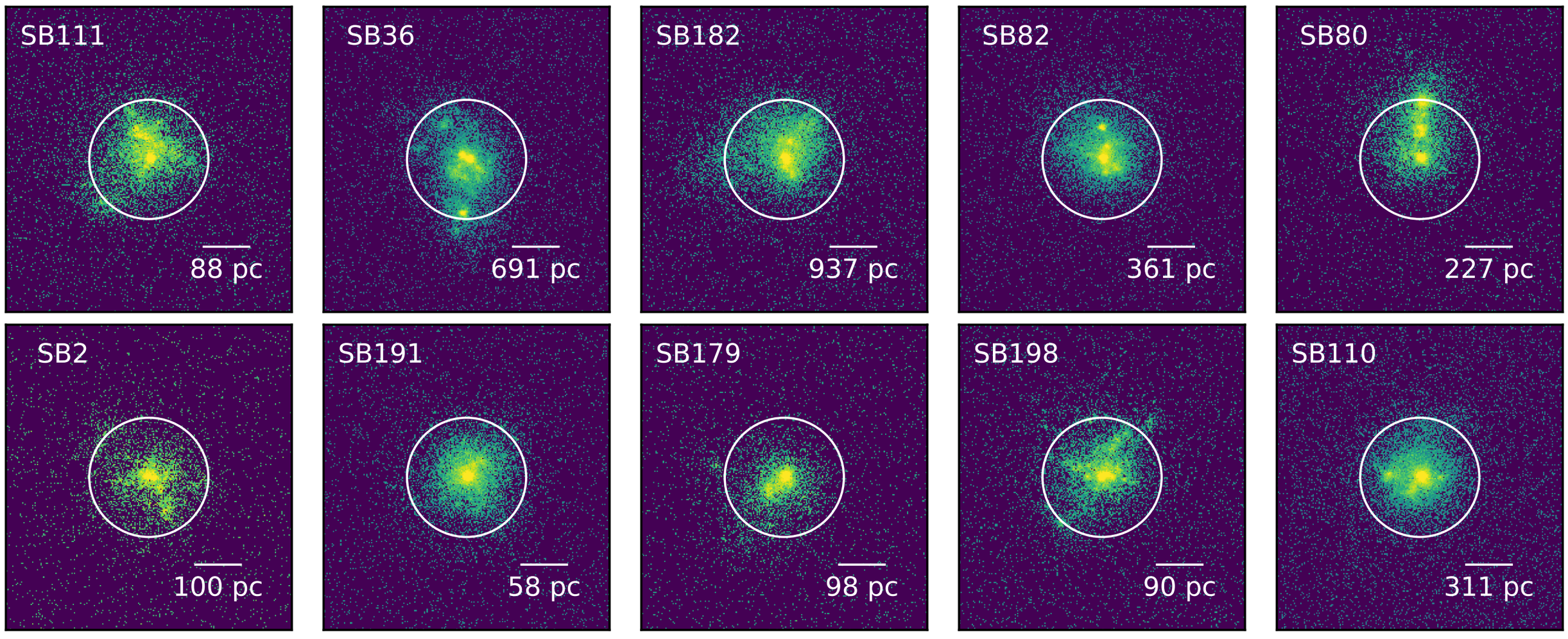


Stark+15b

- Some find very low metallicity stars (12+log O/H=7.05; 2% solar metallicity) required to power CIV emission (Stark+2015b).
- Others have argued that AGN are required (Nakajima+2018).
- Tension reflects poor understanding of EUV radiation field powered by metal poor massive stars.

One Way to Address This Tension: UV Spectroscopy of Nearby Metal Poor Star Forming Galaxies

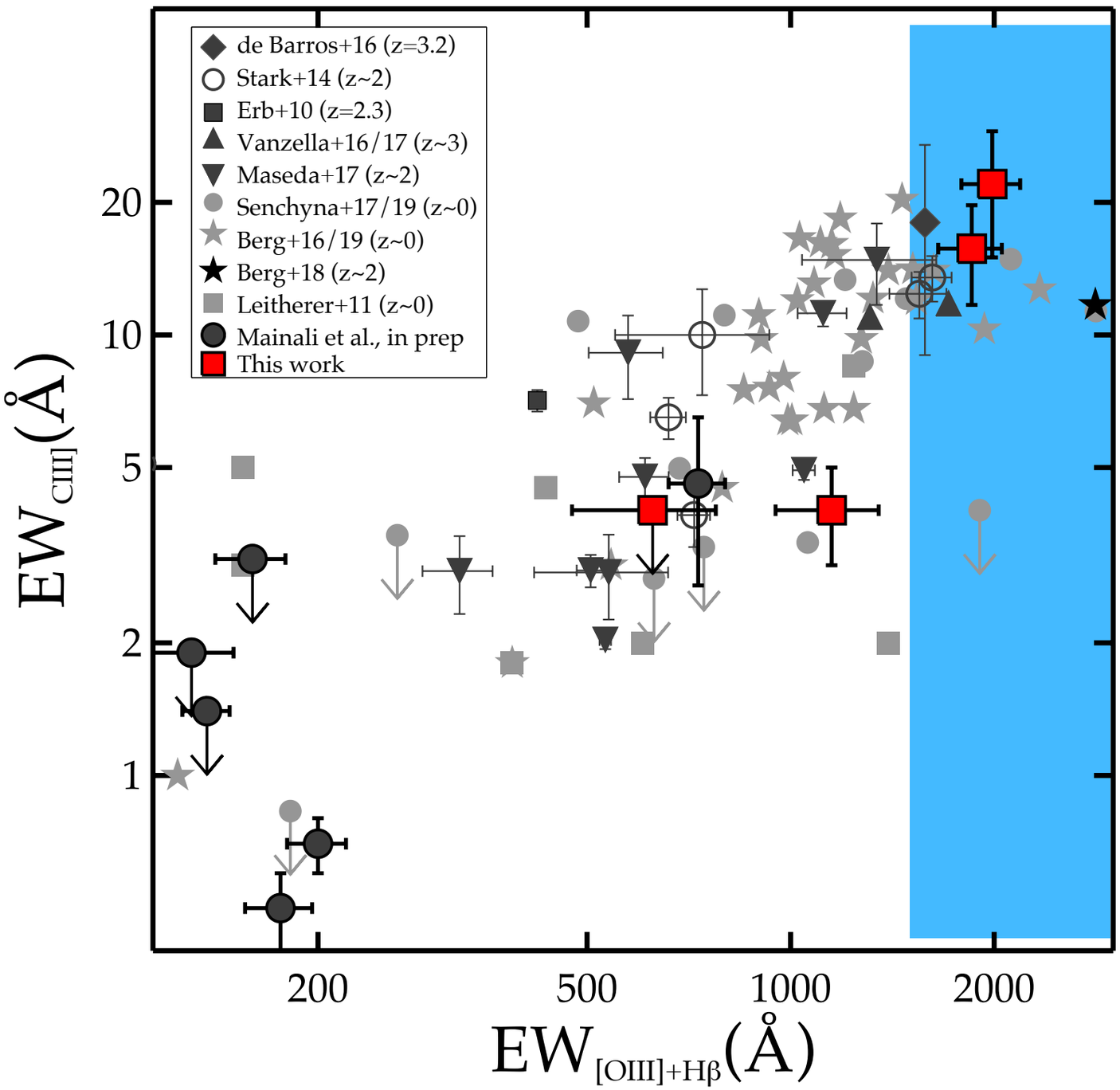
Senchyna+17, 19b



- HST Cycle 23-27 programs to obtain COS UV Spectra of z<0.01 galaxies
  - Can we find galaxies with the CIII] and CIV line intensities we see at z>6?
  - What stellar populations and gas conditions support strong CIII] and CIV?

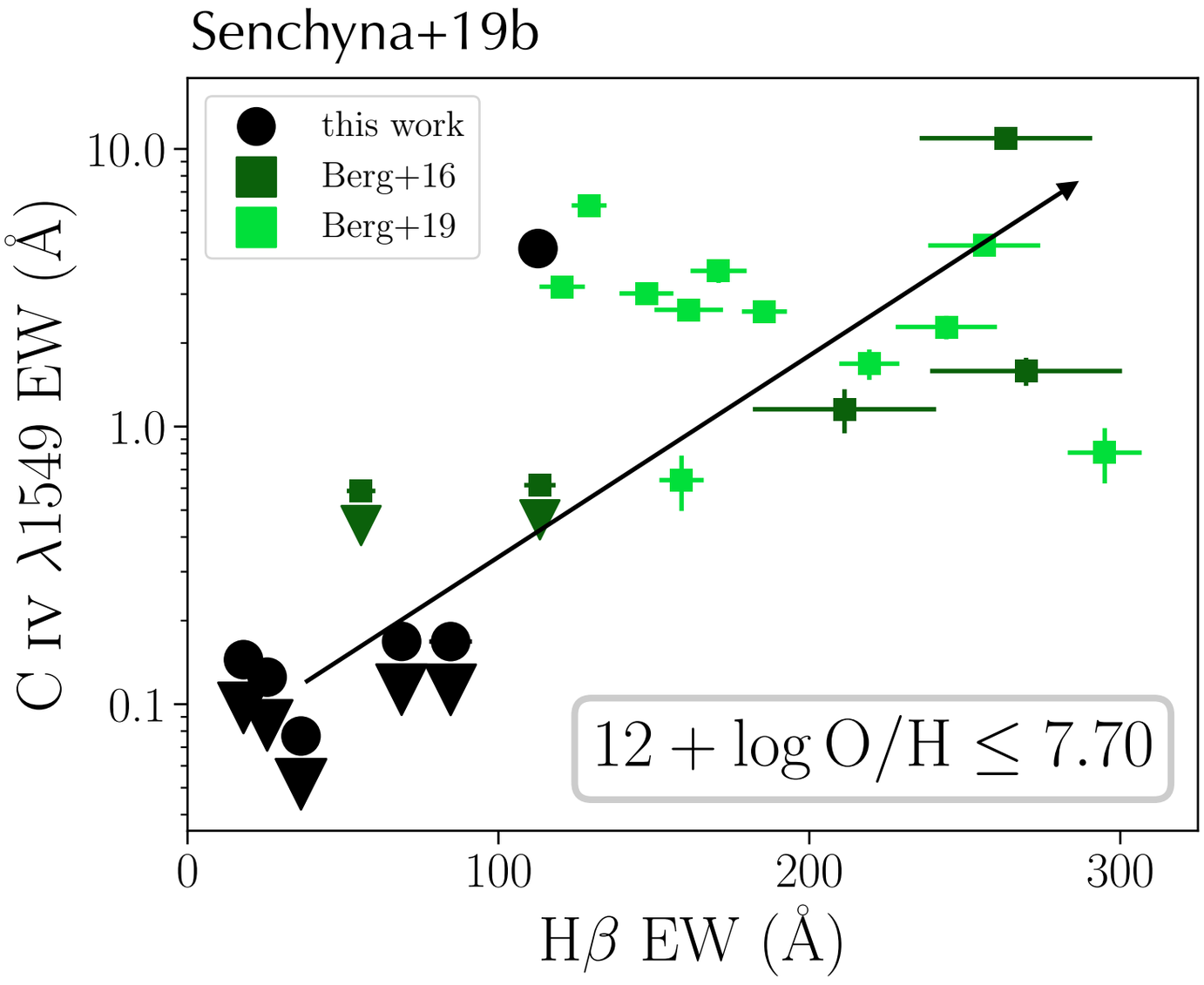
The Nature of Strong UV Line Emitters

Mainali+2019



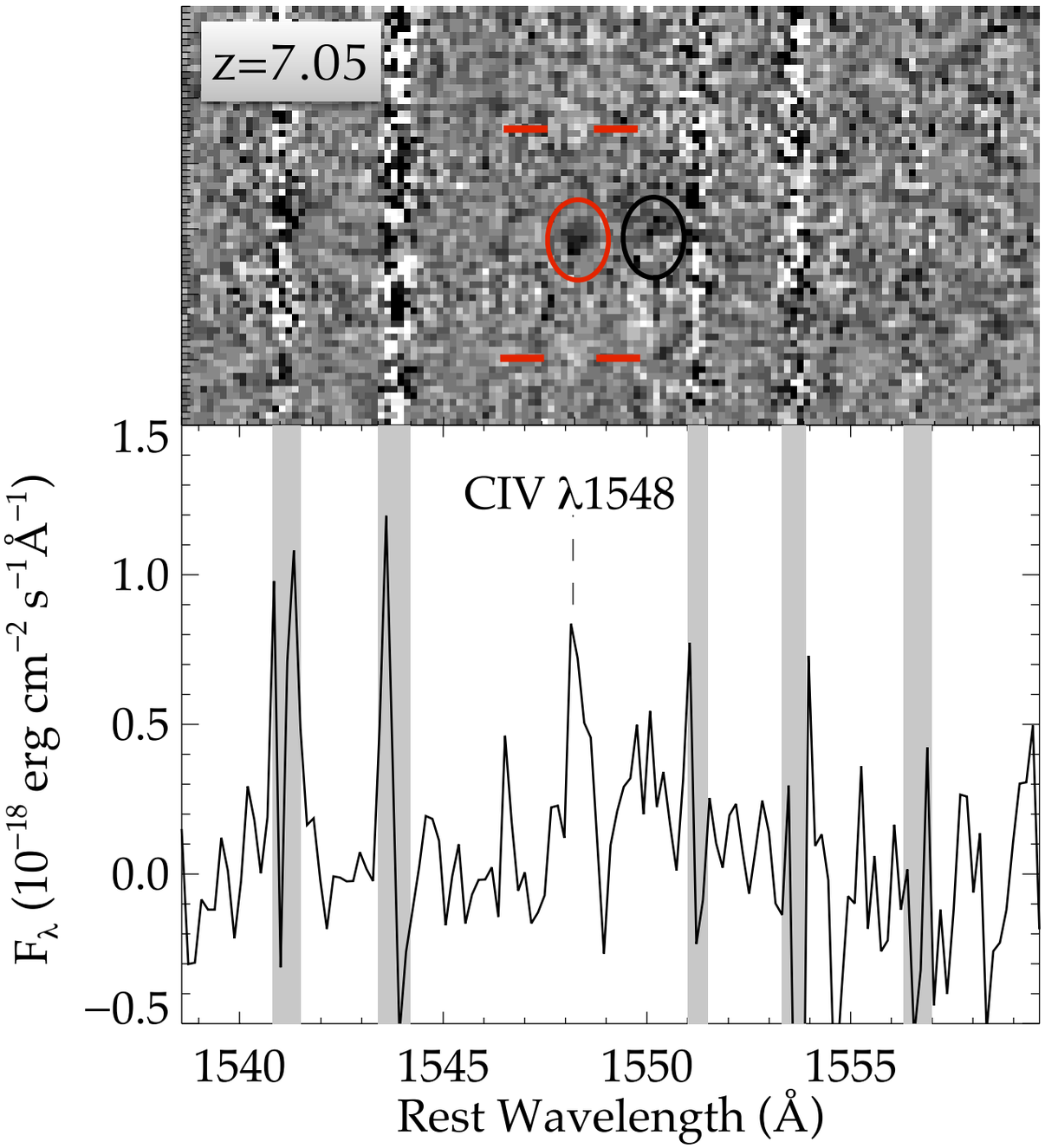
- CIII] emission increases with [OIII] EW, reaching values seen at z>6 in galaxies with [OIII] EW > 1500Å.

The Nature of Strong UV Line Emitters



- CIV emission requires lower metallicities (0.01-0.1 $Z_\odot$) but also requires very young stellar populations that appear in window after a burst of star formation.

Interpretation of z>7 UV Metal Line Detections

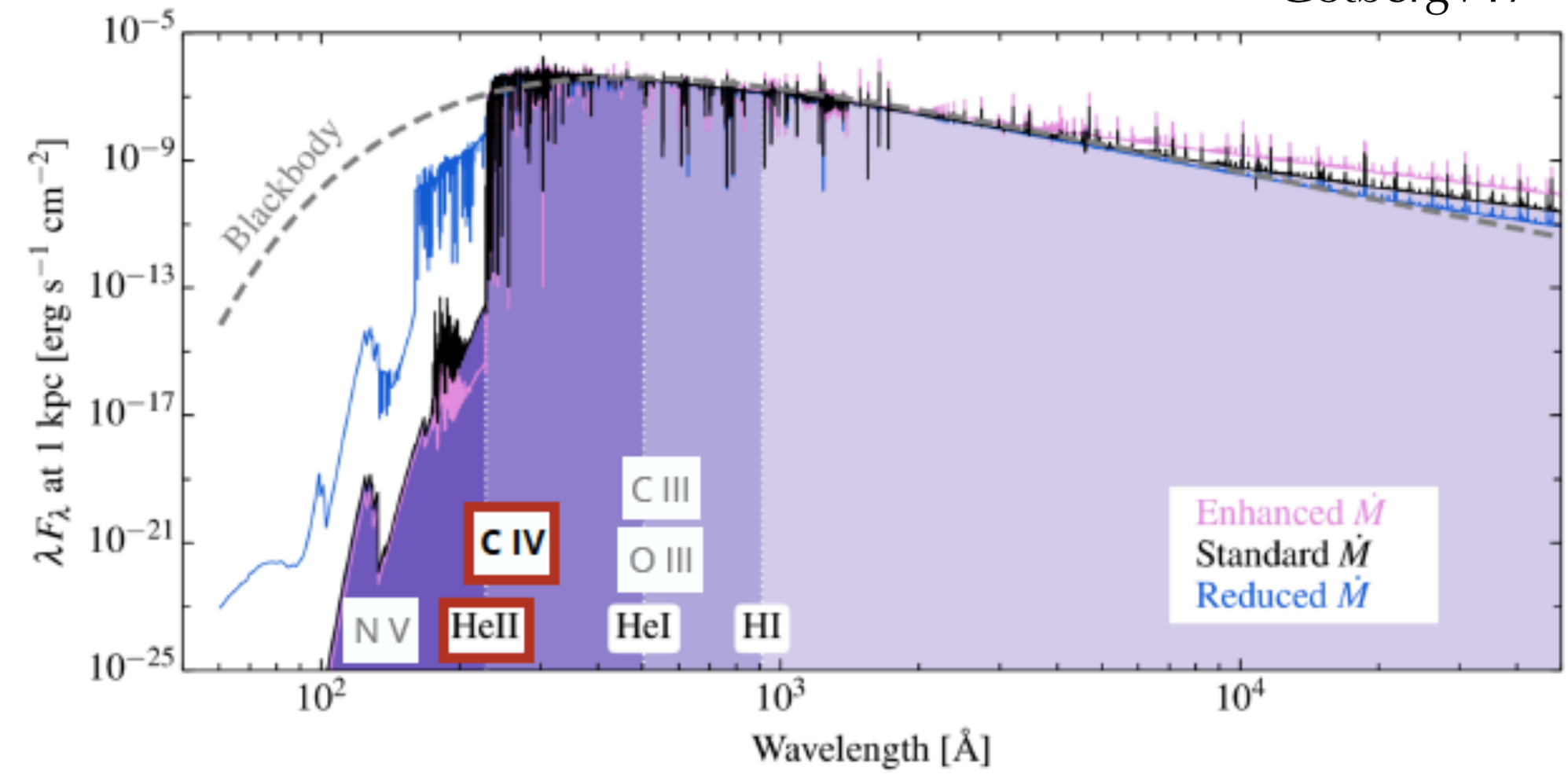


Increased incidence of CIV and CIII] detections at z>6 is to be expected!

Reflects lower metallicities and younger stellar populations (i.e., larger sSFR) present in reionization-era galaxies.

Are Stellar Population Models Equipped to Interpret Galaxies in this Metallicity Regime?

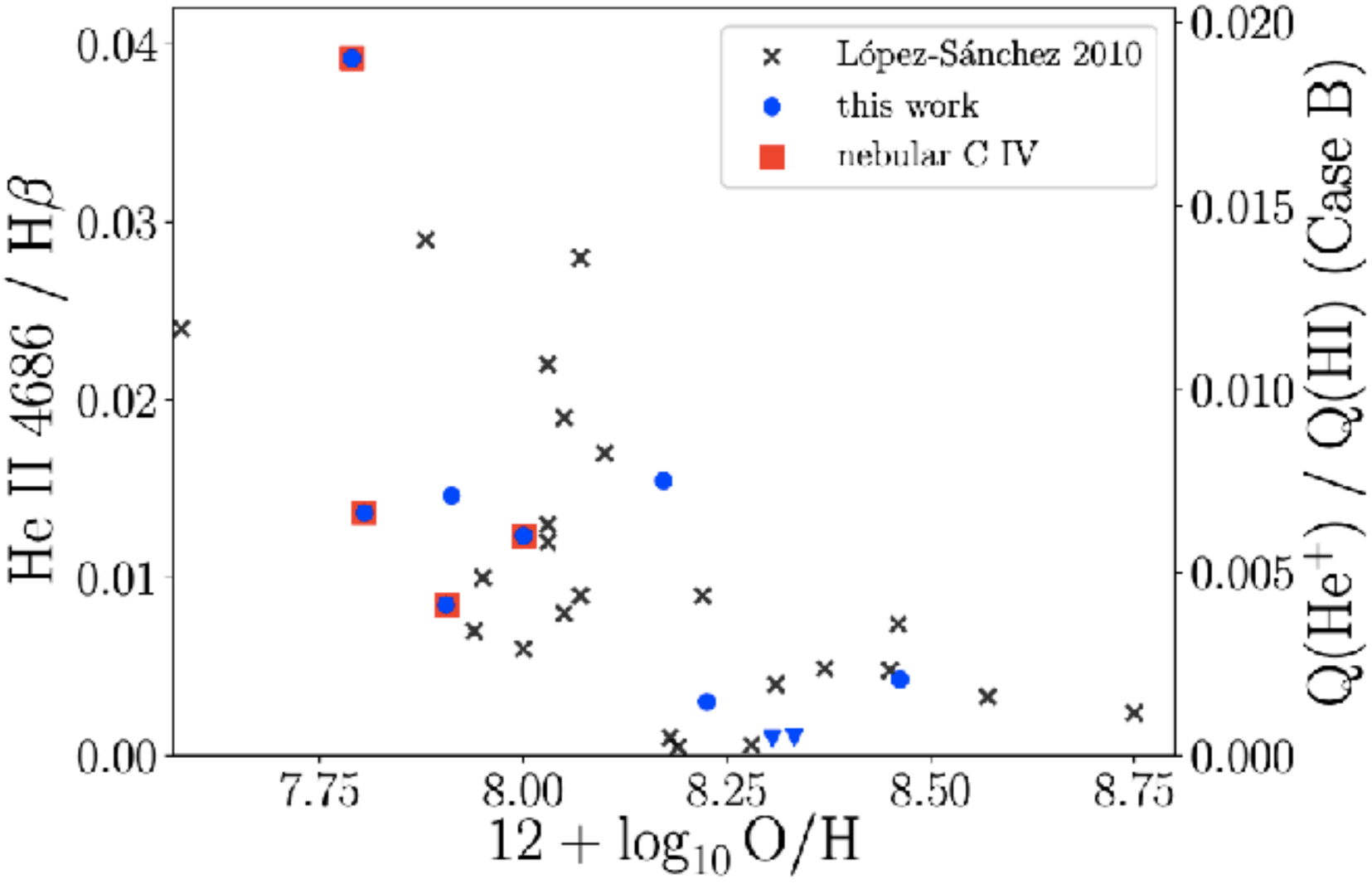
Götberg+17



- Stellar population models anchored by resolved studies in Local Group — entirely theoretical for massive stars at sub-SMC metallicities that appear common at z>6.

- As a result, emergent EUV radiation field very uncertain at low metallicity!

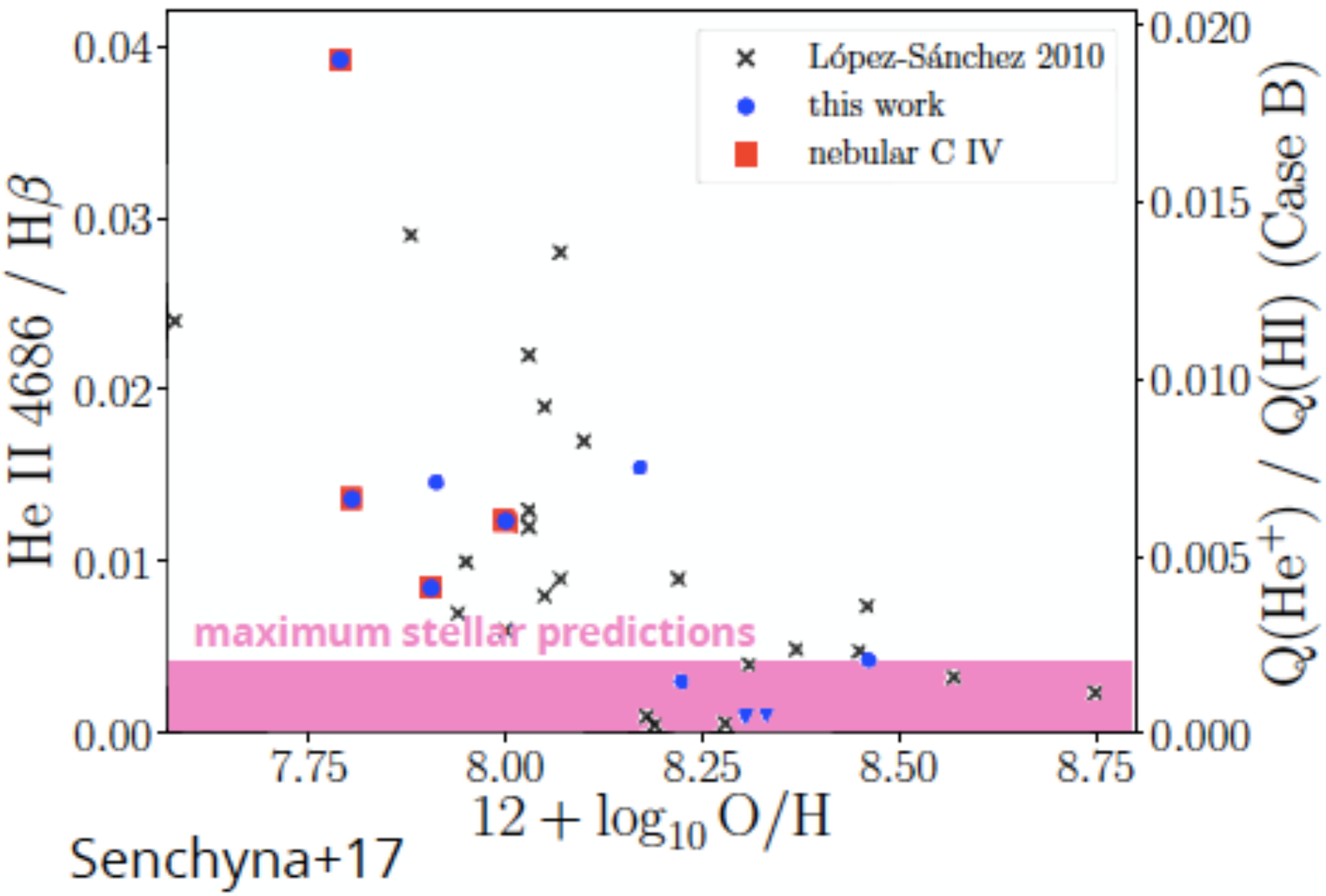
A Stress Test of Stellar Population Models at Low Metallicity with Nearby Star Forming Galaxies



Senchyna+17

- Strength of He II emission sensitive to hardness of ionizing spectrum.
- Data imply harder spectra at lower metallicities.
- Can models reproduce EUV spectral shape?

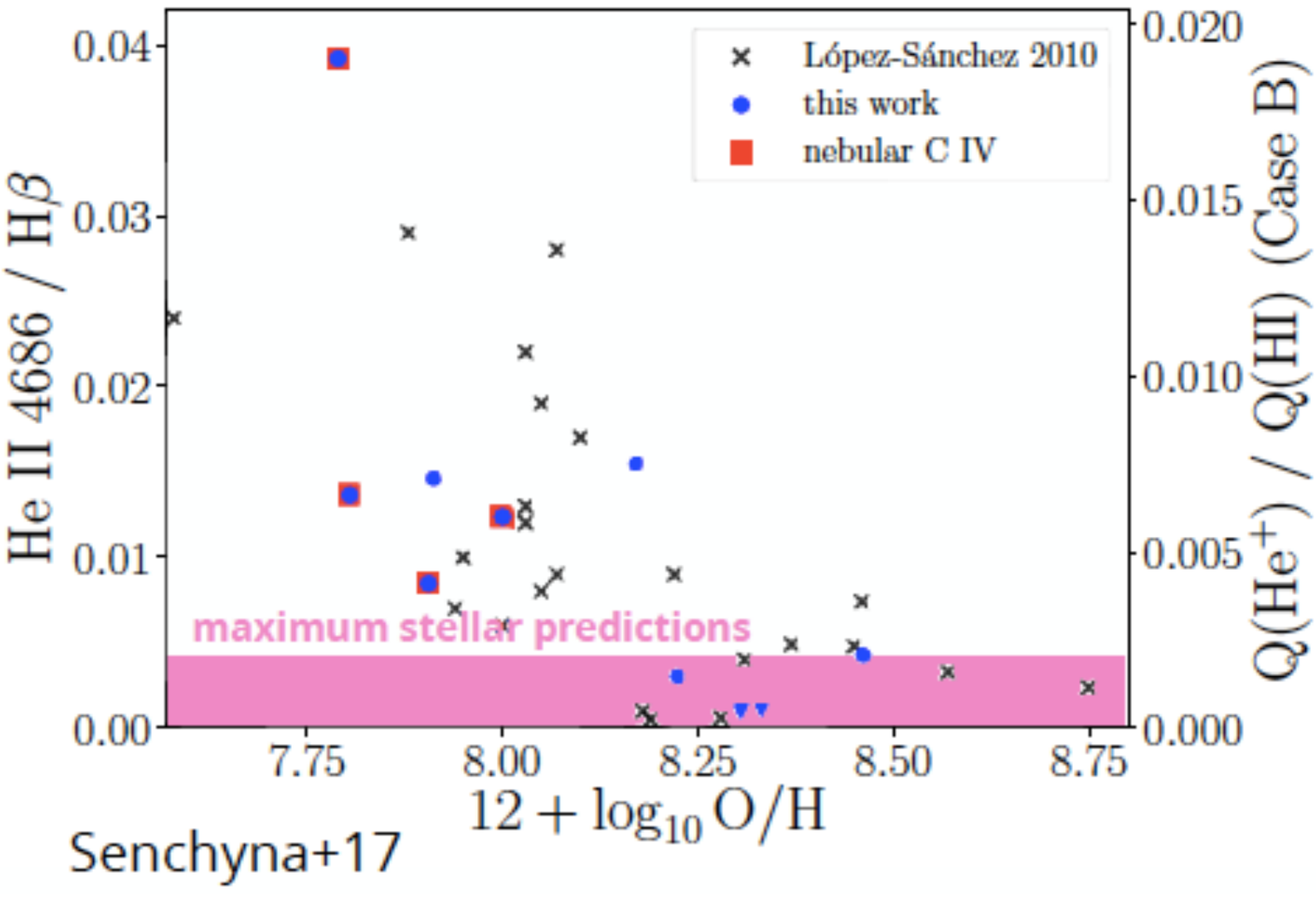
Stellar Population Models at Low Metallicity



Senchyna+17

- Models cannot match He II strengths, indicating shortfall of He^+ ionizing photons (>54.4 eV).

Stellar Population Models at Low Metallicity



Senchyna+17

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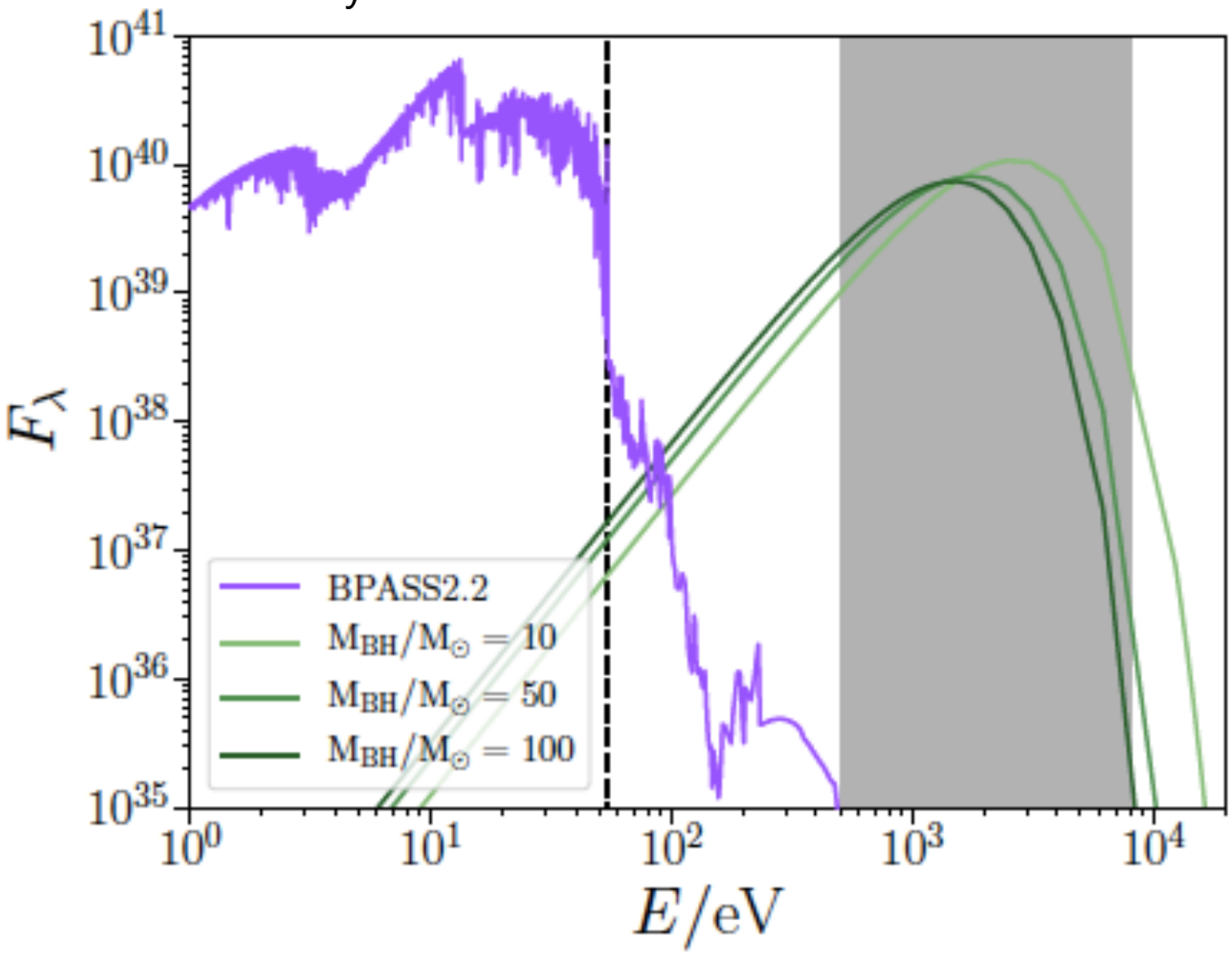
- HMXBs?

Stellar Population Models at Low Metallicity

Senchyna+2019c



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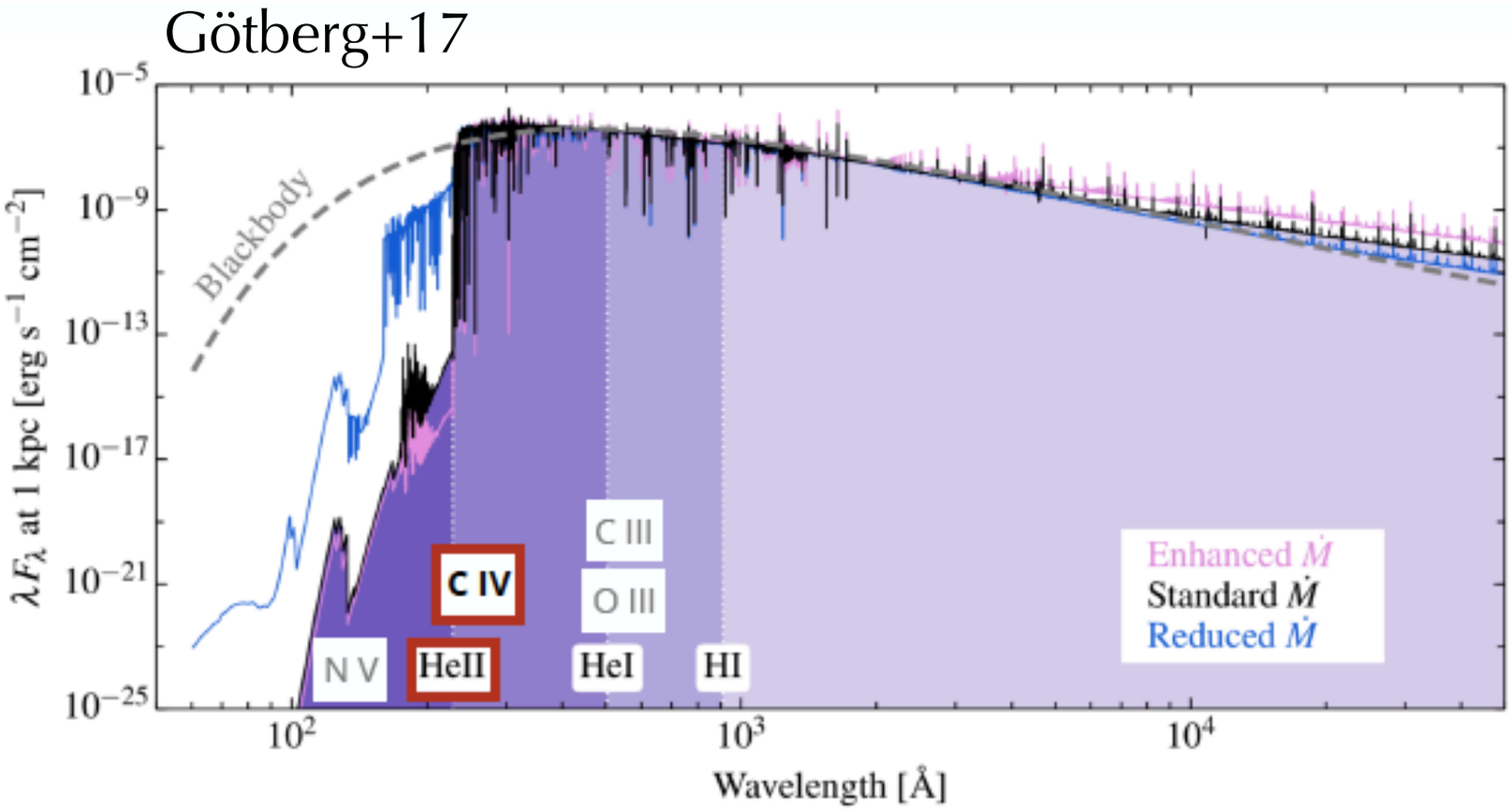
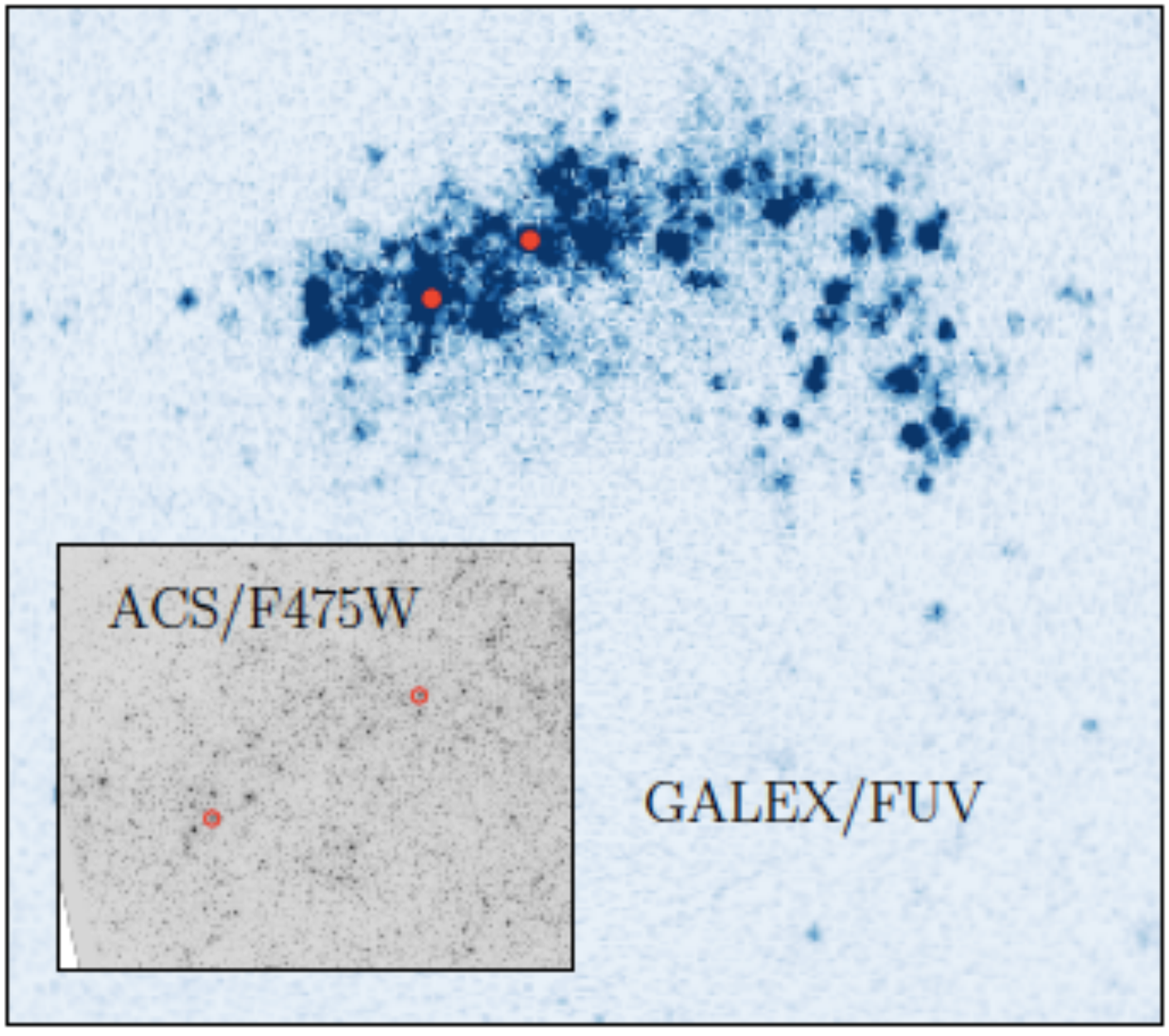
  - HMXBs?
    - No, very inefficient producers of He^+ ionizing photons.

Stellar Population Models at Low Metallicity



- Models cannot match He II strengths, indicating shortfall of He^+ ionizing photons (>54.4 eV).
  - HMXBs?
    - No, very inefficient producers of He^+ ionizing photons (Senchyna+2019c).
  - Stellar wind prescriptions wrong at low metallicity?

Improving Stellar Wind Prescriptions at Low Metallicity: COS Spectra of Massive Stars in Leo A



- Deep COS spectra of two massive stars in Leo A approved in cycle 27 (PI: Senchyna)

- Will test stellar wind scalings at the sub 10% solar metallicity level for the first time, providing direct way to improve stellar population synthesis models in regime critical for JWST.

Summary

- Galaxies at z>6 have different spectral properties than those at z~2-3 — intense nebular line emission powered by very young stellar populations, as expected for systems following an upturn/ burst of star formation.

- These low mass galaxies undergoing a burst are likely to be very efficient ionizing agents at z>6, with enhanced production and escape of ionizing radiation.

- Detection of strong CIV emission at z>6 appears to be powered by very low metallicity massive stars (2% solar metallicity), similar to lowest metallicity star forming galaxies known locally.

- Stellar population synthesis models fail at low metallicity. Must be addressed soon in nearby dwarf galaxies if we are to reliably interpret hundreds of spectra at z>6 JWST will soon deliver.