First galaxies: observations
Lecture 3

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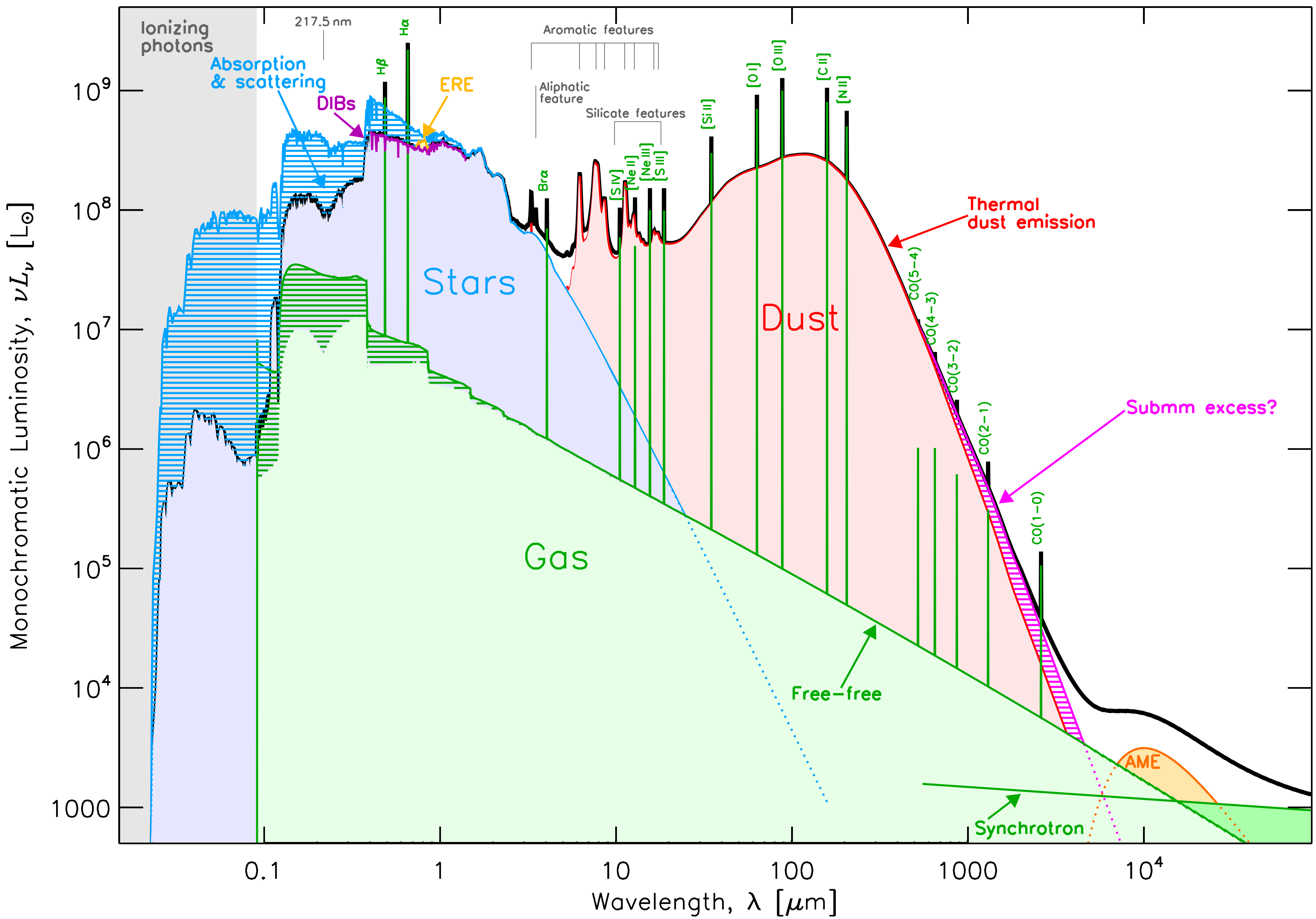
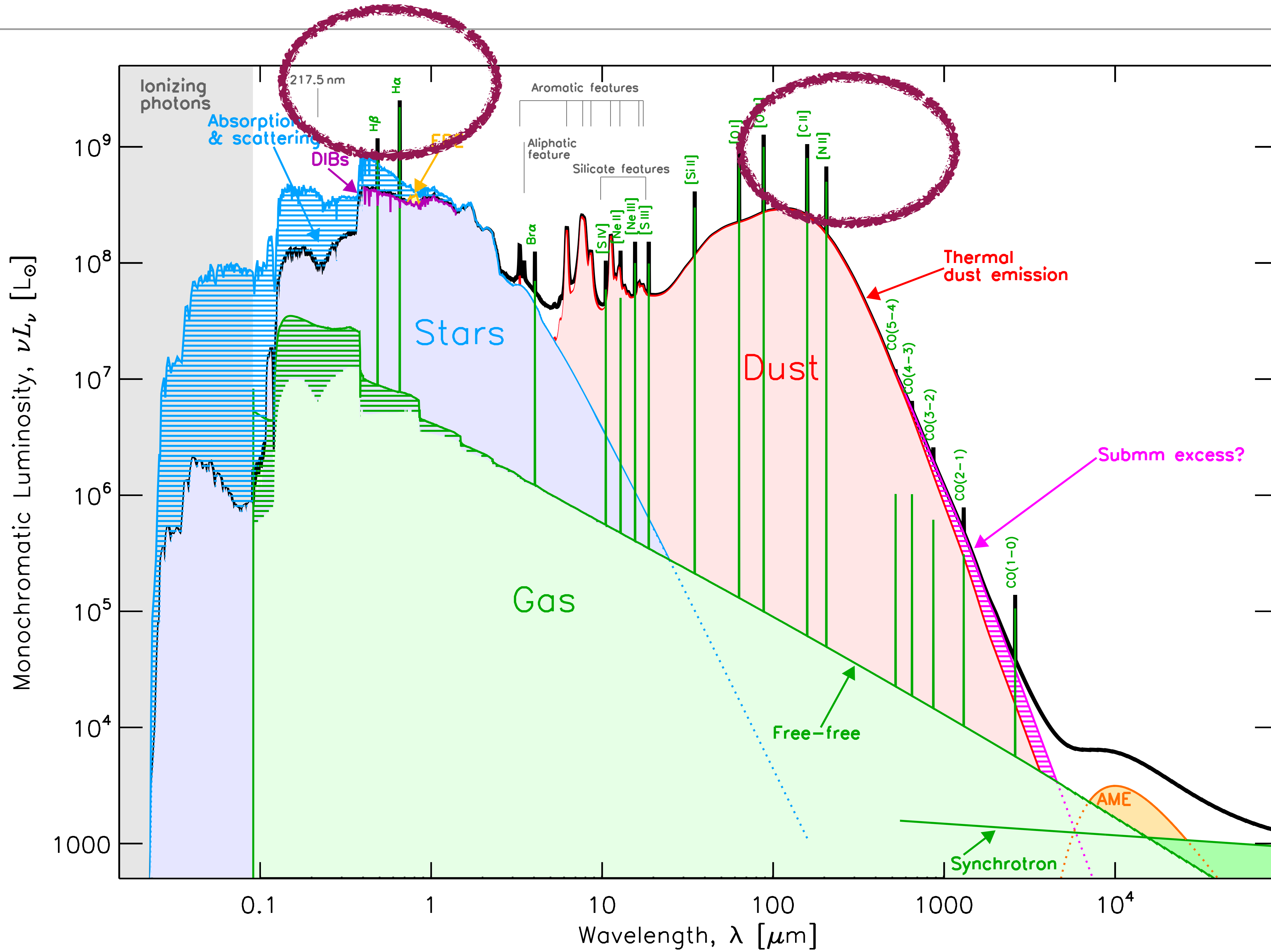
The spectral energy distribution



Adapted from Galliano et al. 2018

The spectral energy distribution



Adapted from Galliano et al. 2018

Overview

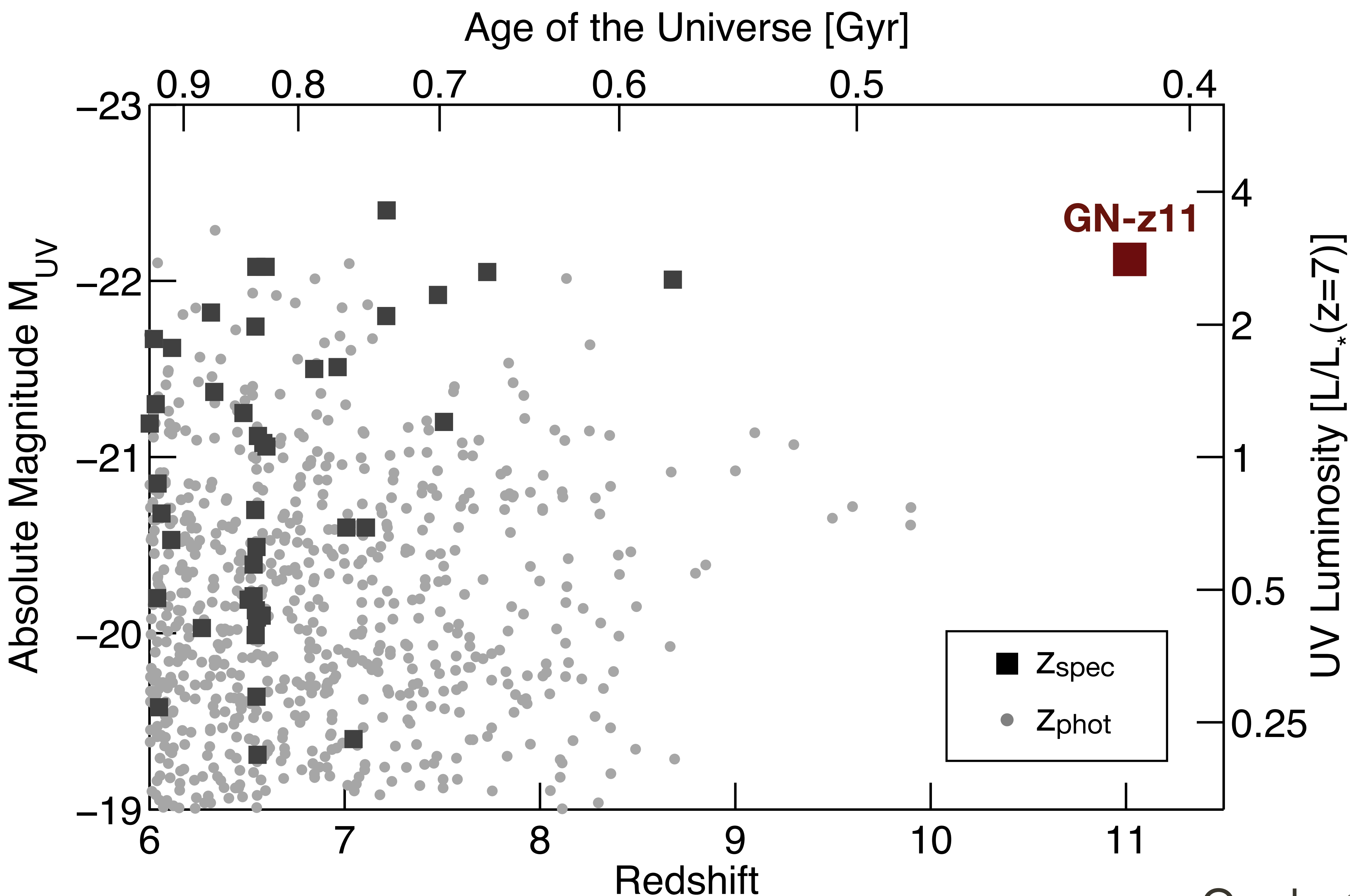
Lecture 1: Detection methods and the galaxy census

Lecture 2: Dust and stellar mass

Lecture 3: Optical and sub-mm spectroscopy

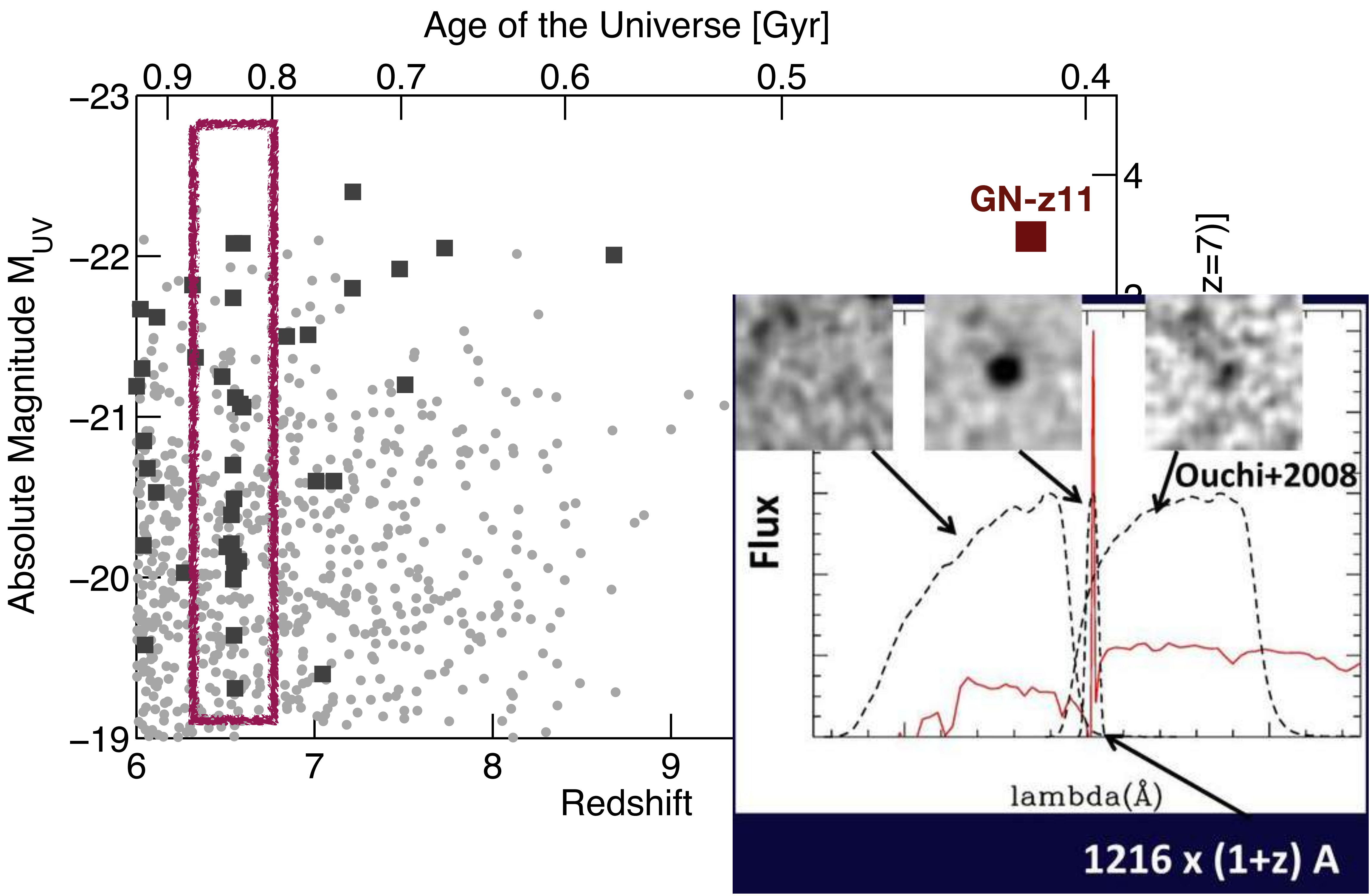
- Spectroscopic confirmations
- Lyman alpha and the IGM neutral hydrogen fraction
- [CII] emission: origin and detections
- Potential for kinematics
- High ionisation lines

Spectroscopic confirmation of galaxies in the EoR



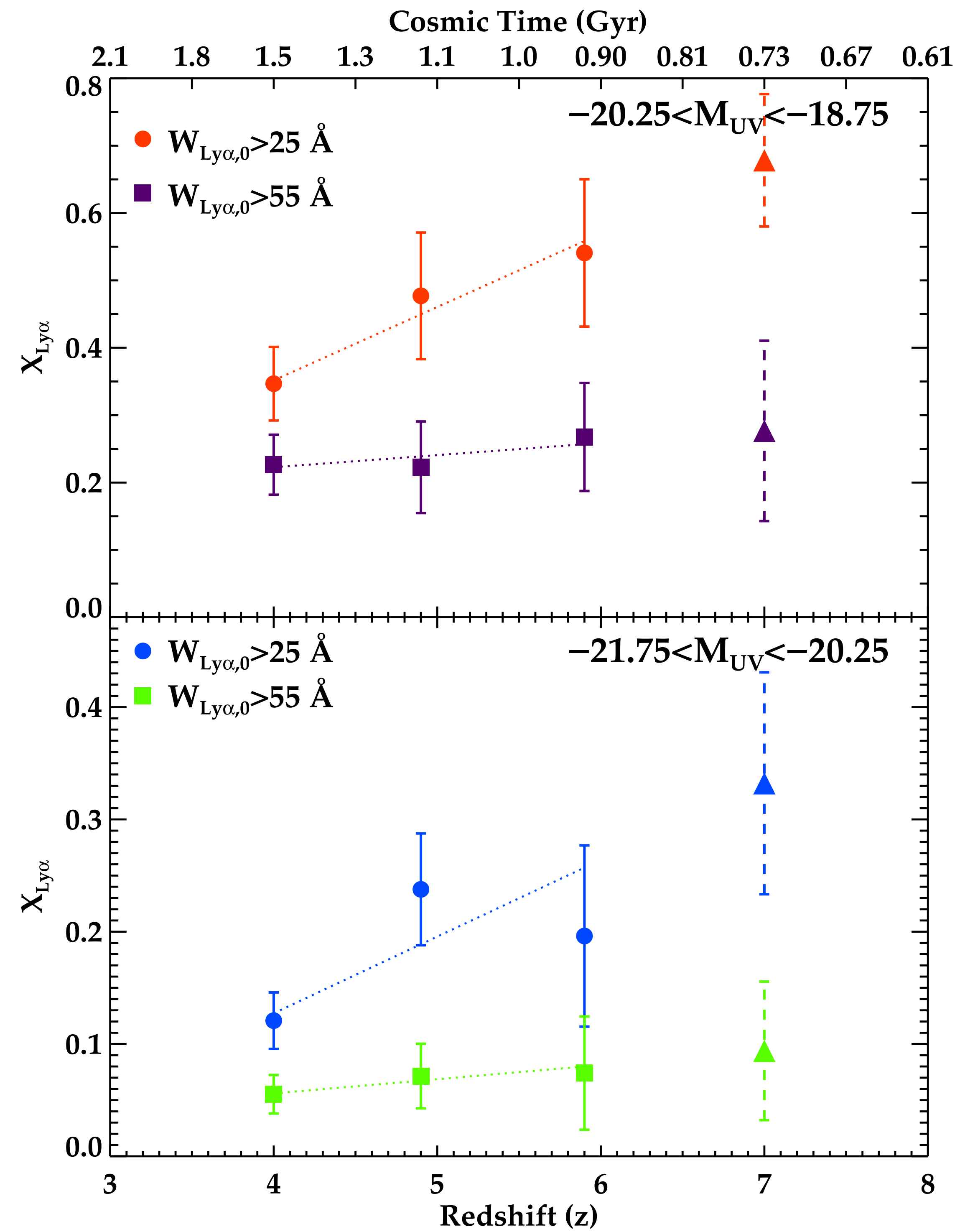
Oesch et al. 2016

Spectroscopic confirmation of galaxies in the EoR



Lyman-α z=3-6

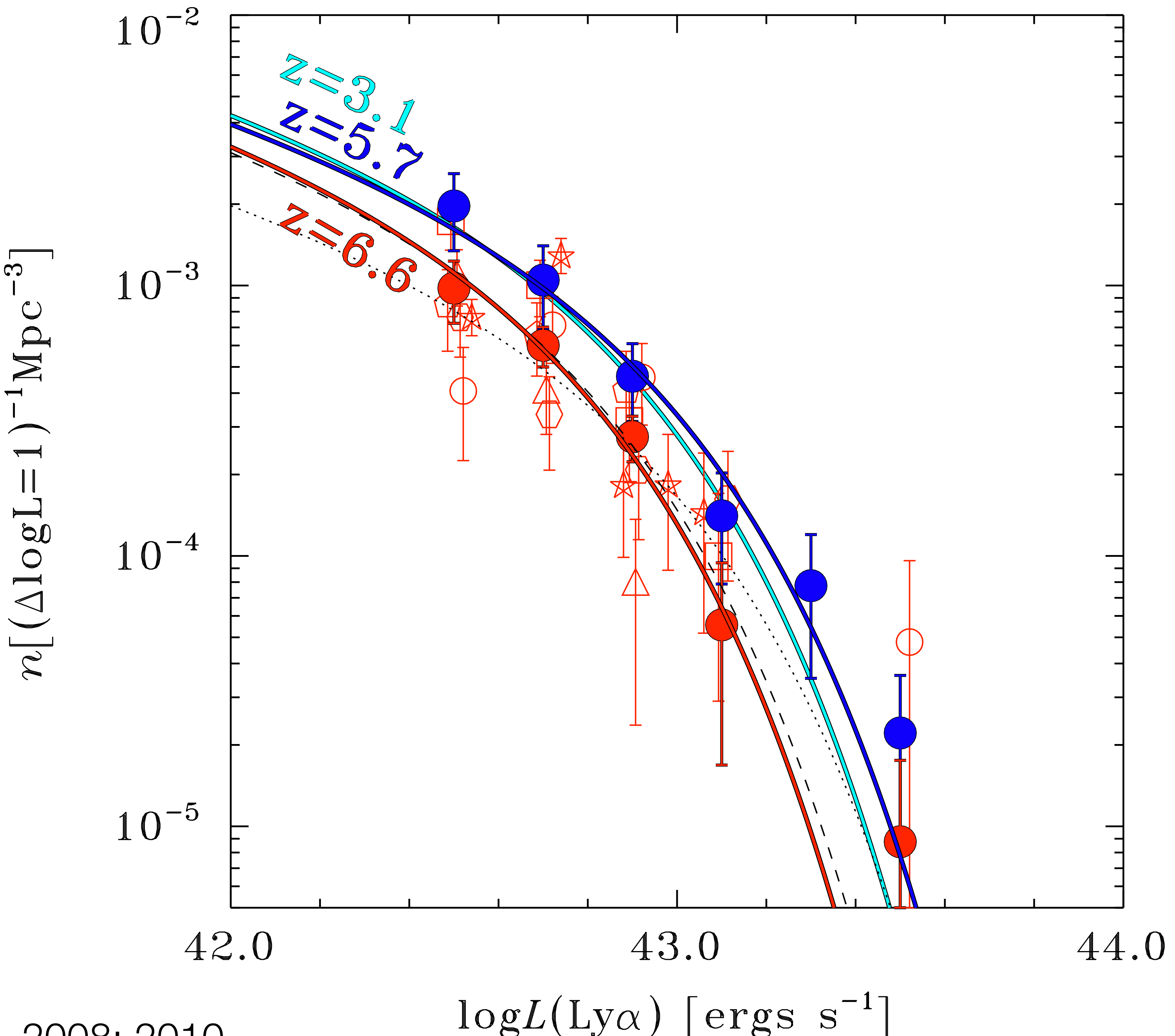
- Lyα at 1216Å is the intrinsically the brightest emission line in the spectrum of SF galaxies
- Due to resonant scattering the Lyα fraction goes down. Lyα is mainly observed in low-mass, low metallicity systems



Stark et al. 2011

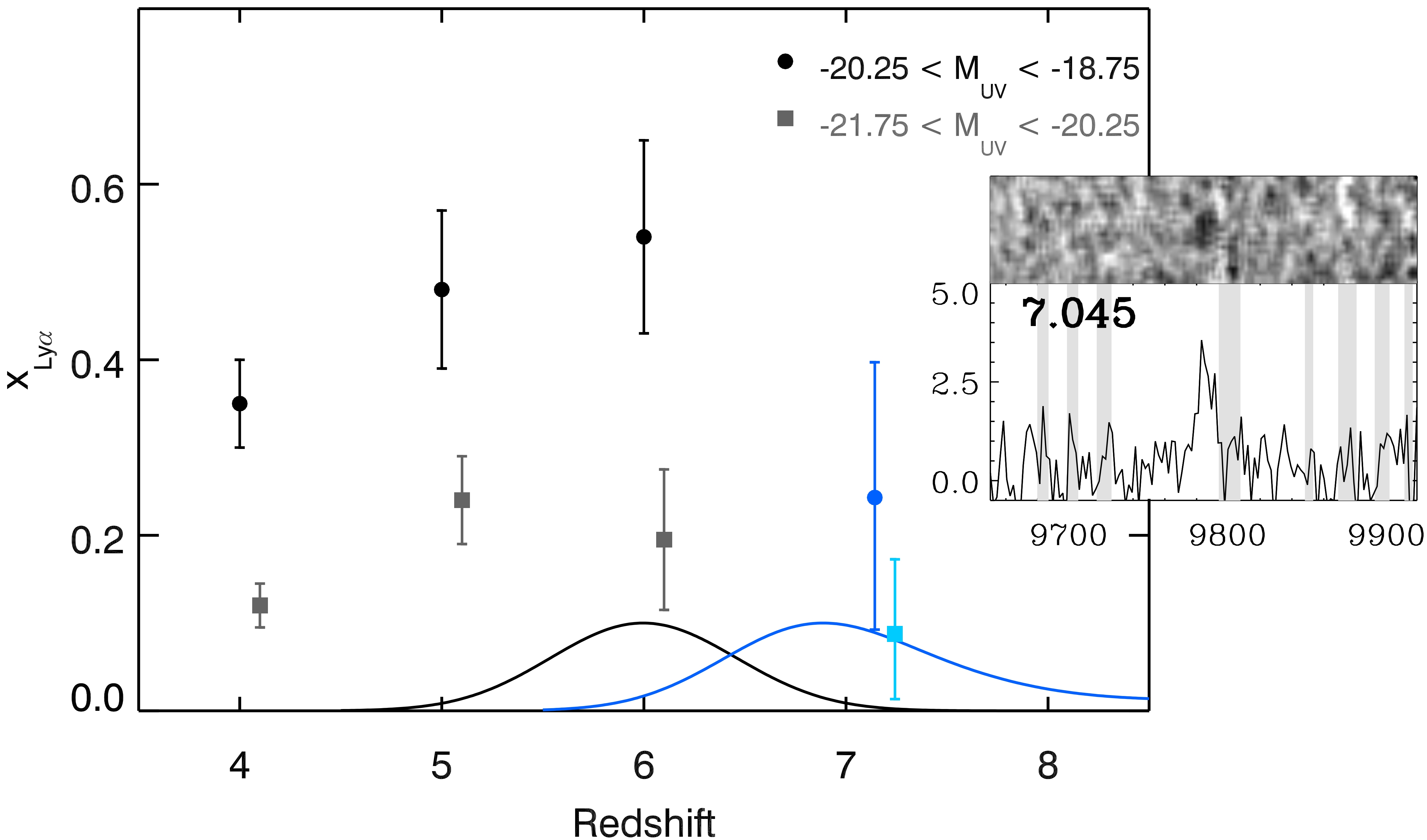
Lyman-α z=3-6

LAE luminosity function: no evolution from z=3.1 to z=5.7 - unlike strong evolution of LBGs



Ouchi et al. 2008; 2010

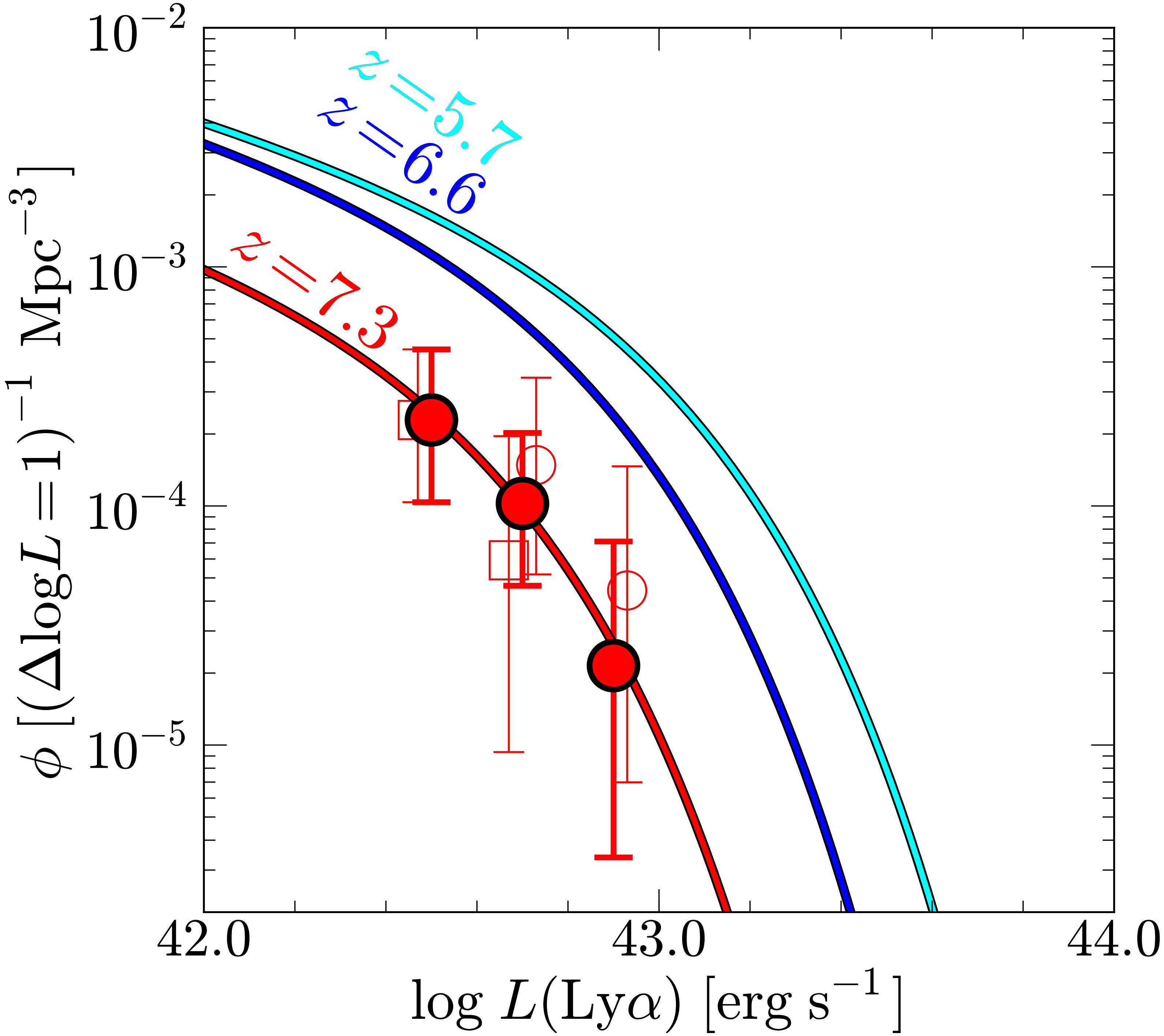
Lyman-α z>6



Schenker et al. 2013

Lyman-α z>6

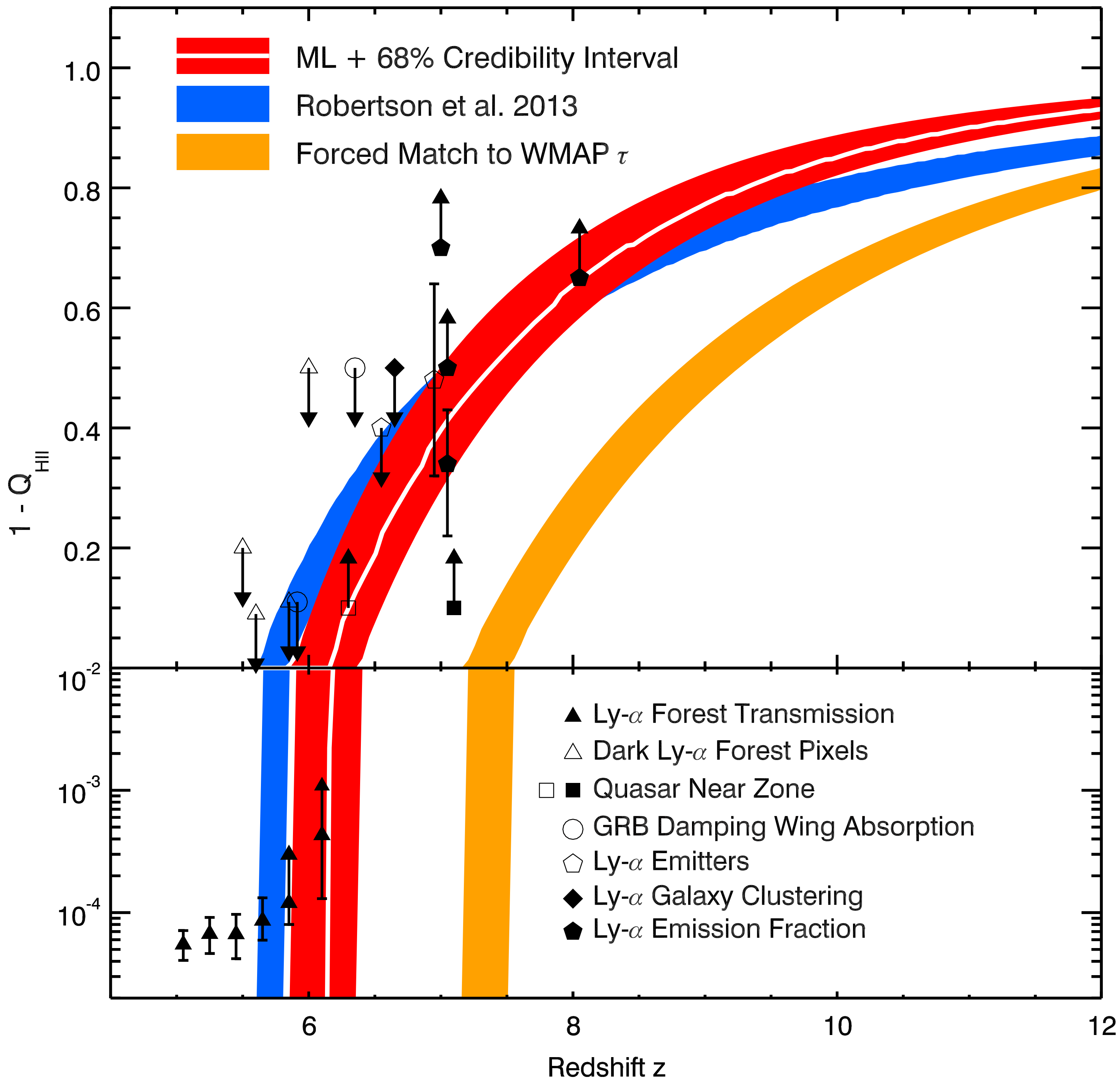
Consistent results from LBG follow-up and LAE narrowband sources



Konno et al. 2014

Neutral Hydrogen fraction of the IGM

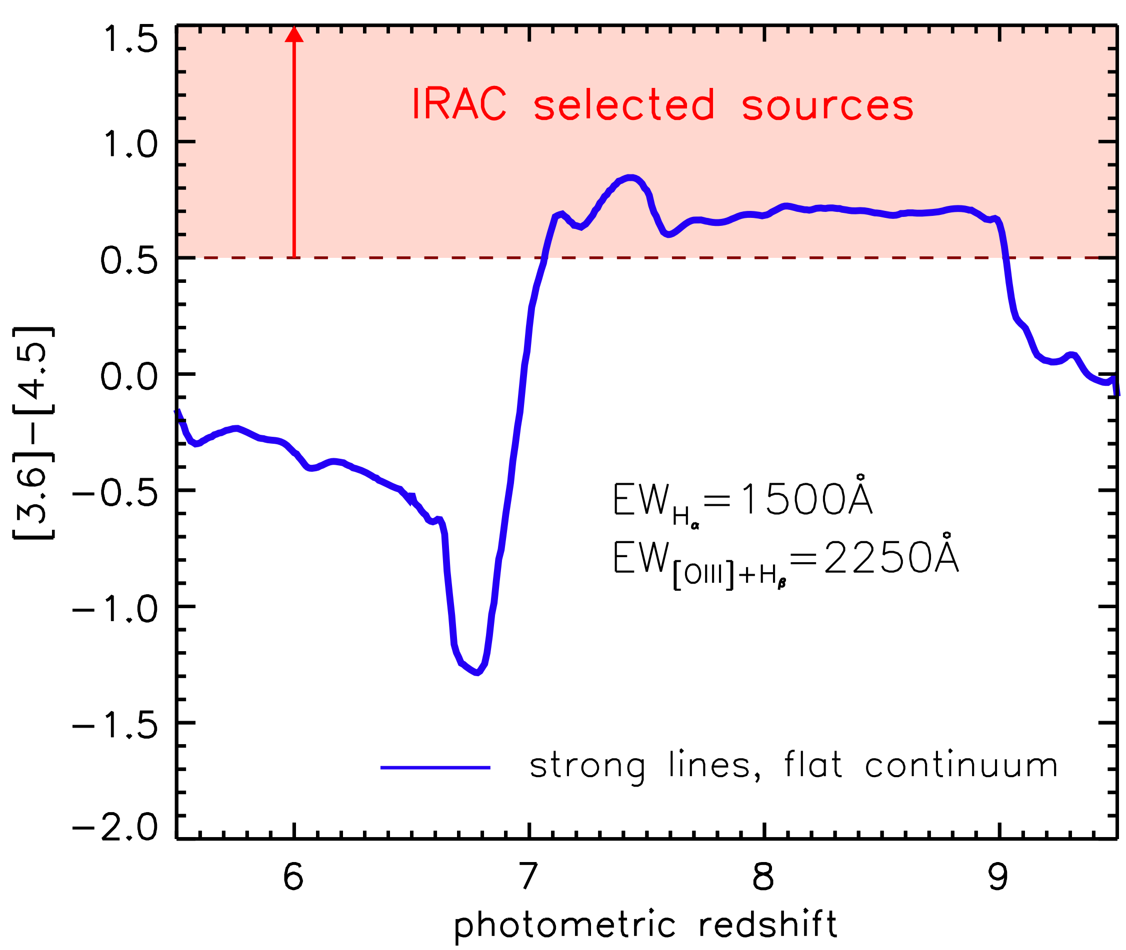
Rapid change of the IGM neutral Hydrogen fraction between z=6 and z=7-8

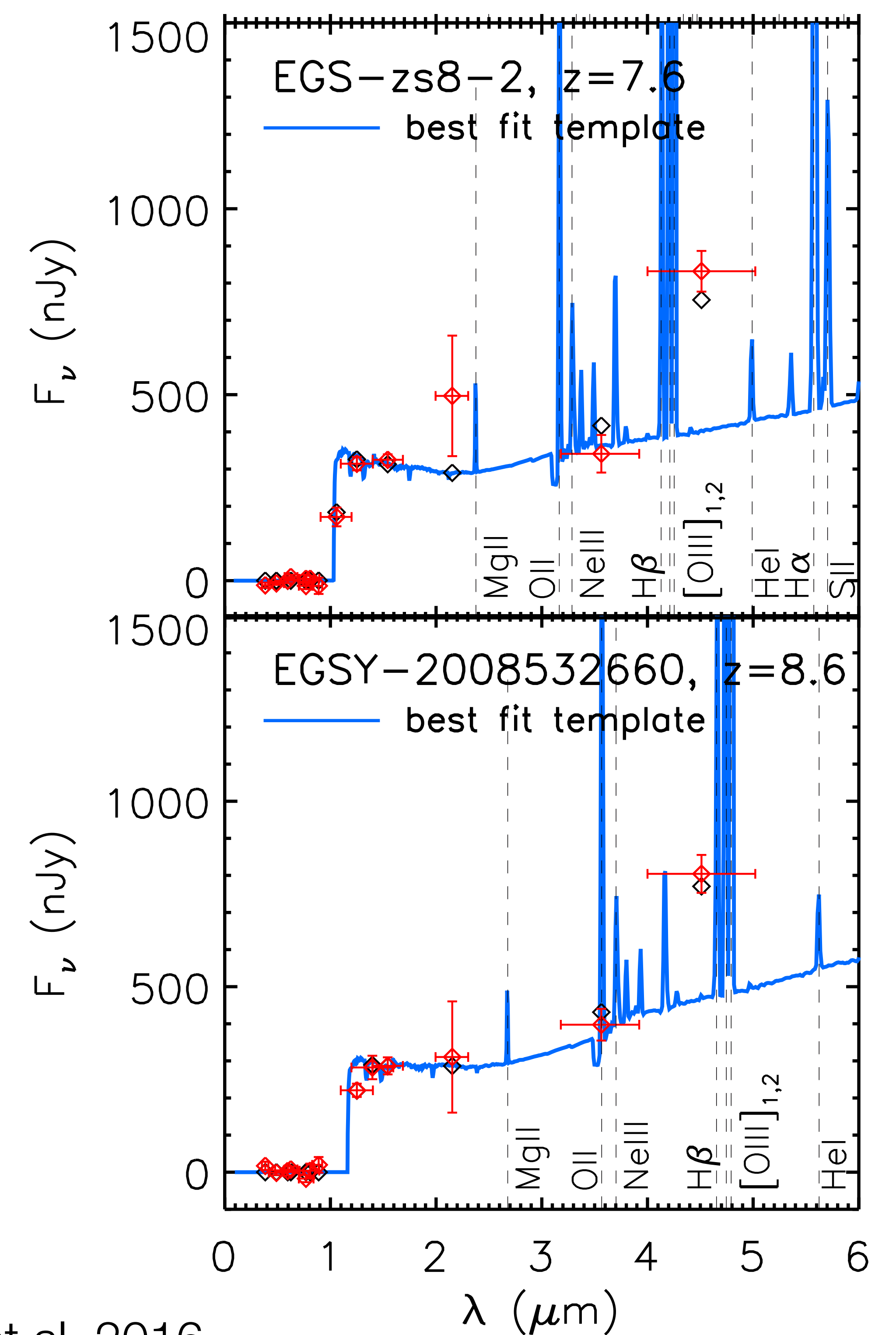


Robertston et al. 2015

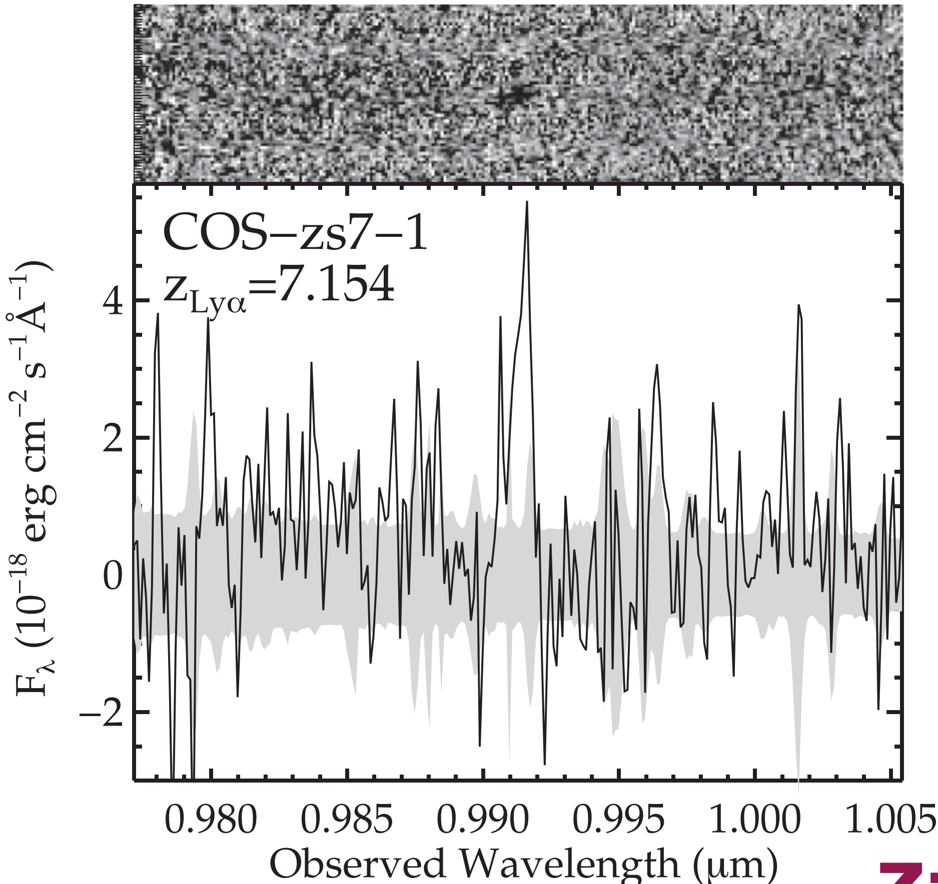
Is this the case for all z>7 LBGs?

Detection of new, extreme Spitzer [OIII] line emitters at z>7



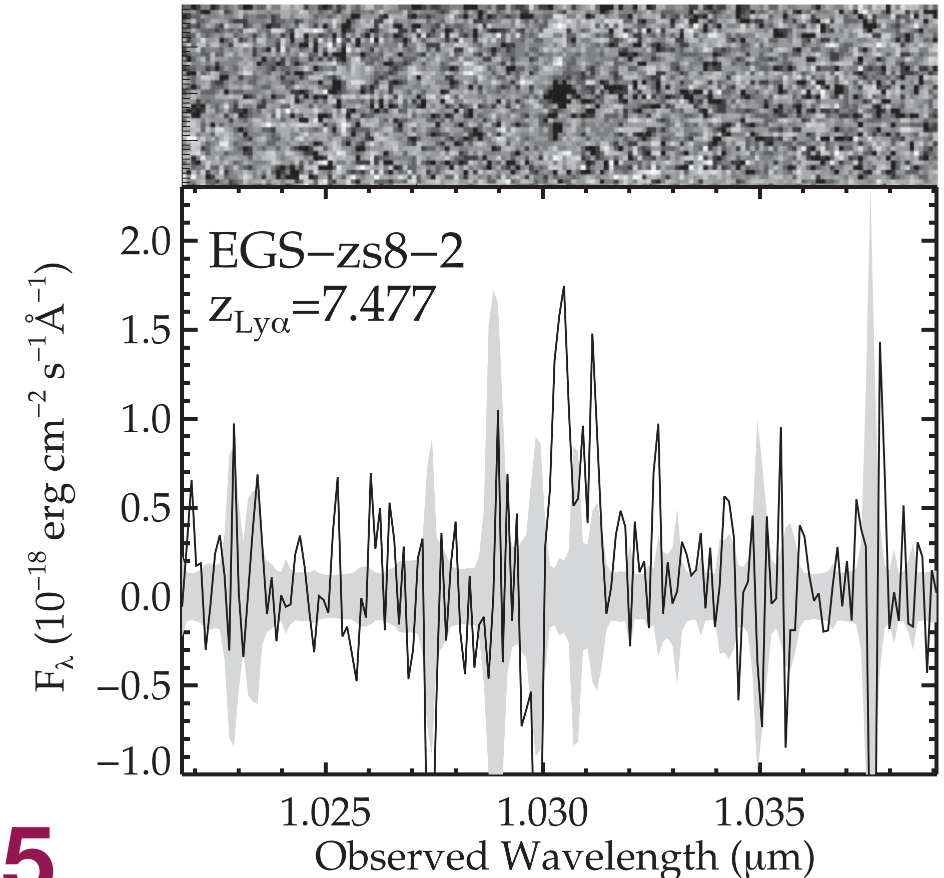


Roberts-Borsani et al. 2016

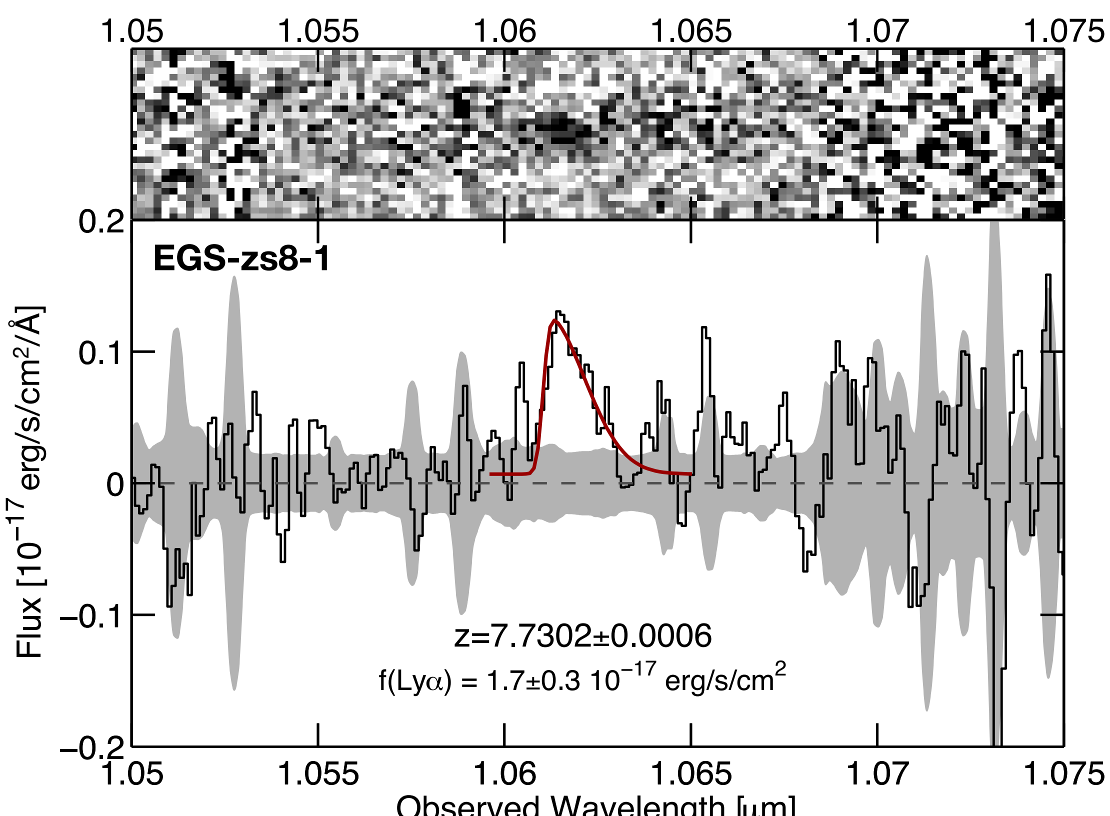


z=7.15

Stark et al. 2017

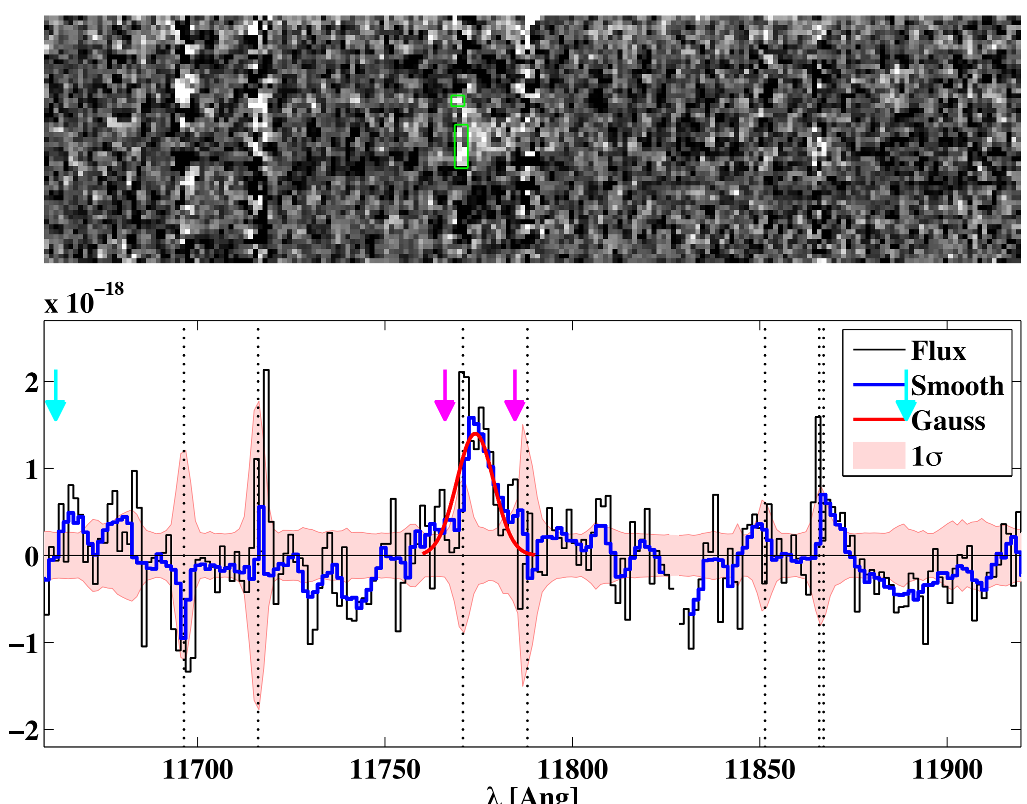


z=7.48



z=7.73

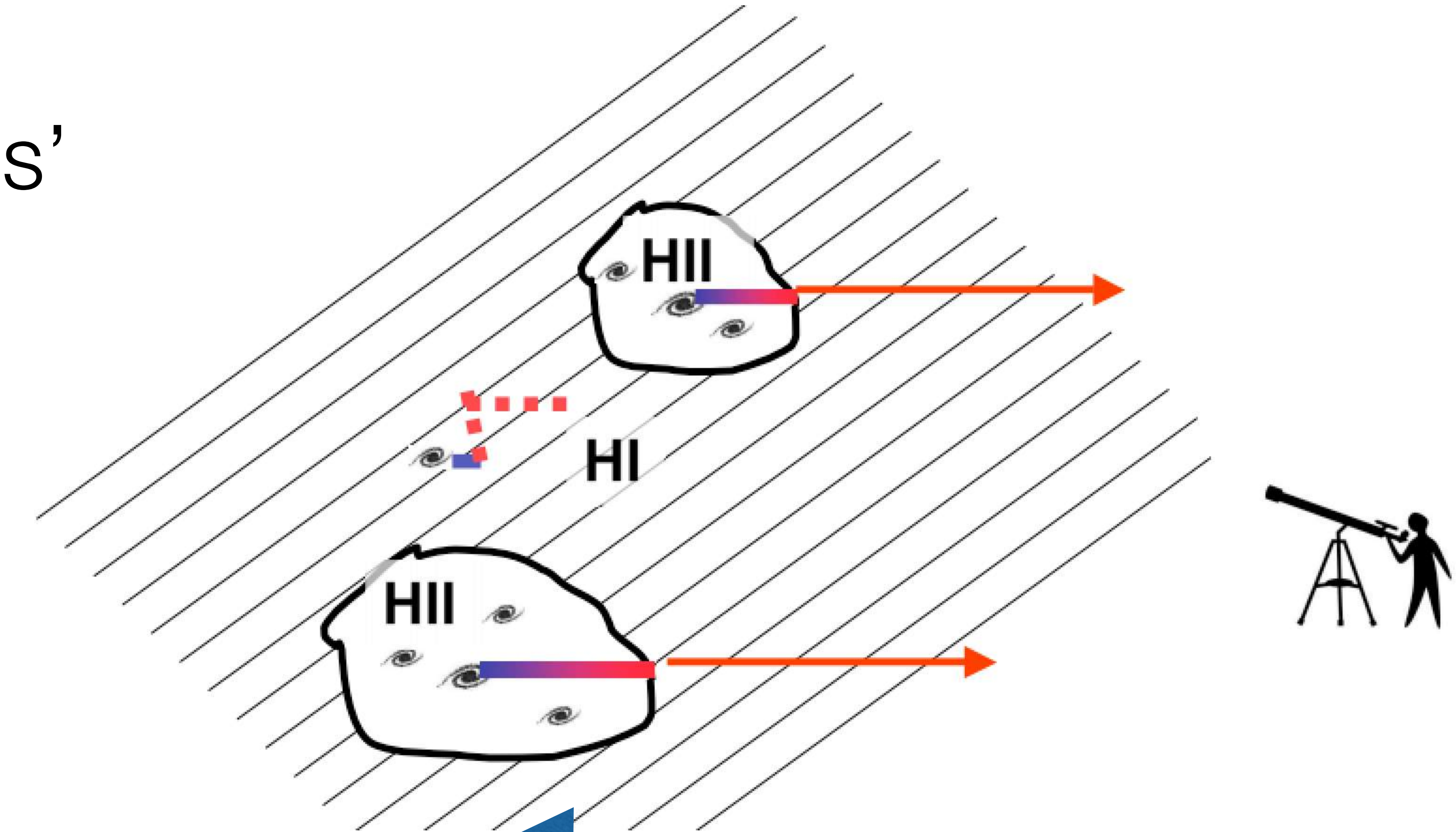
Oesch et al. 2015



Zitrin et al. 2015

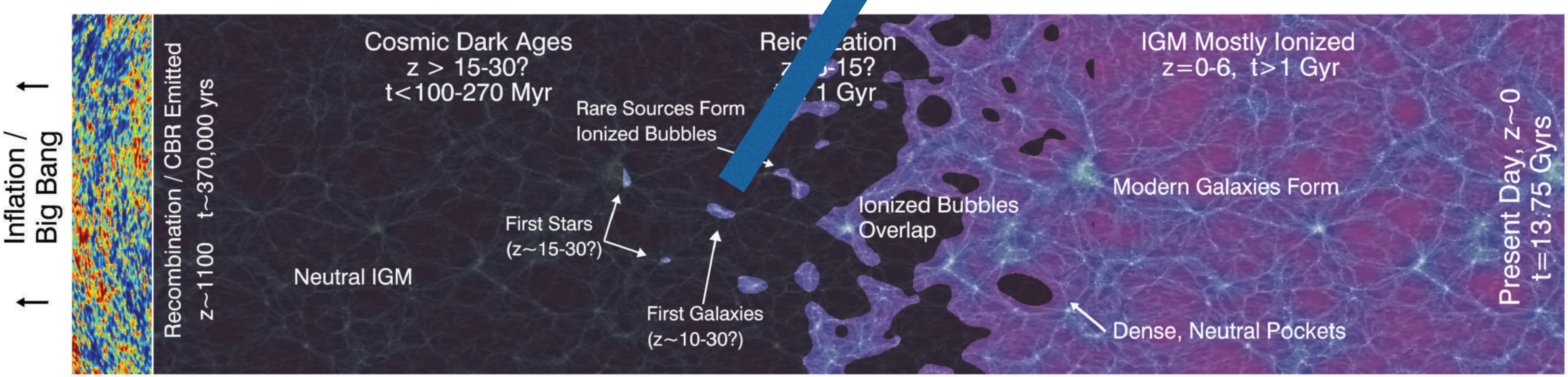
z=8.68

Ionised ‘bubbles’



Dijkstra et al. 2014

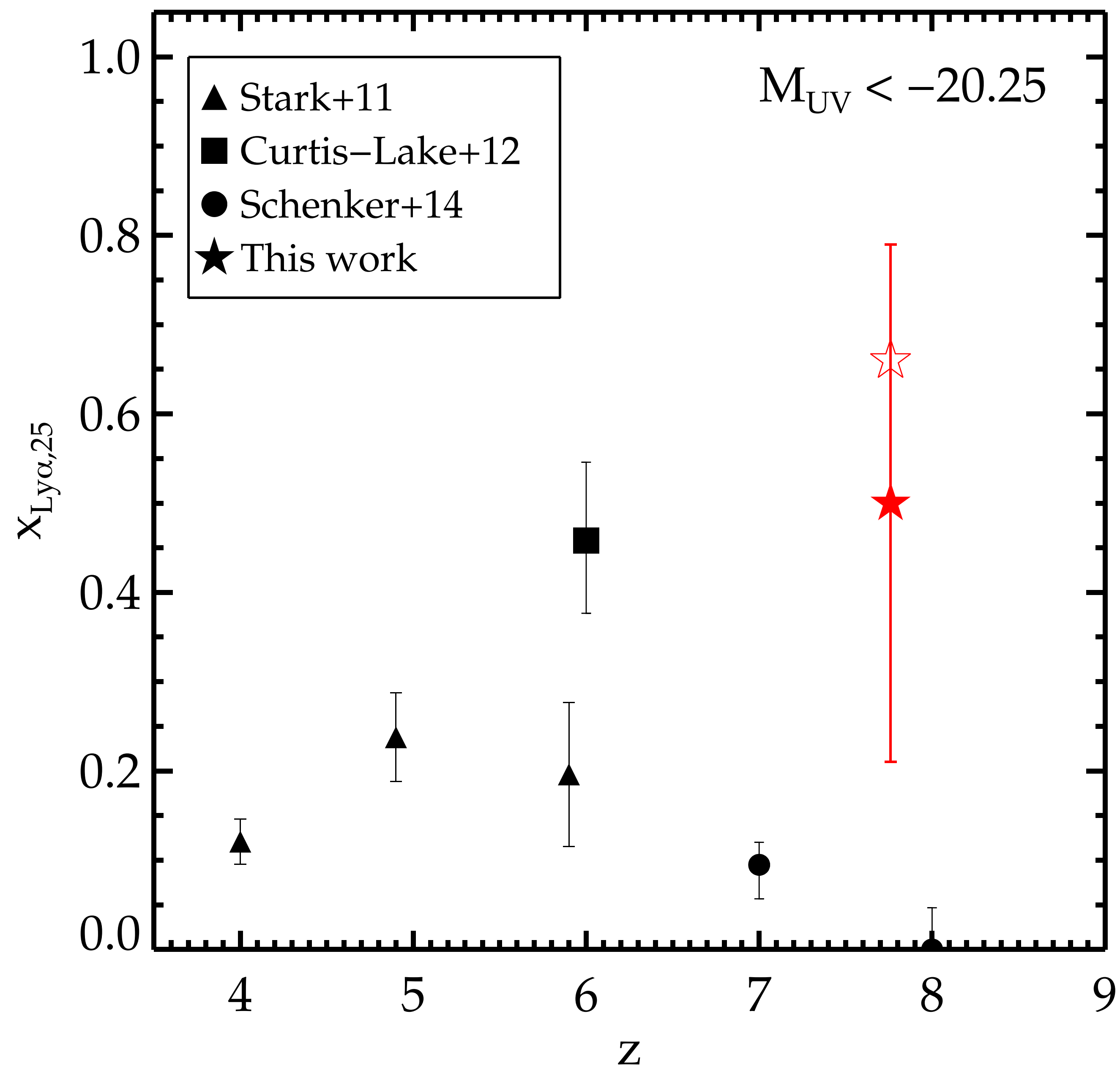
Robertson et al. 2010



What makes these sources special?

Two possibilities:

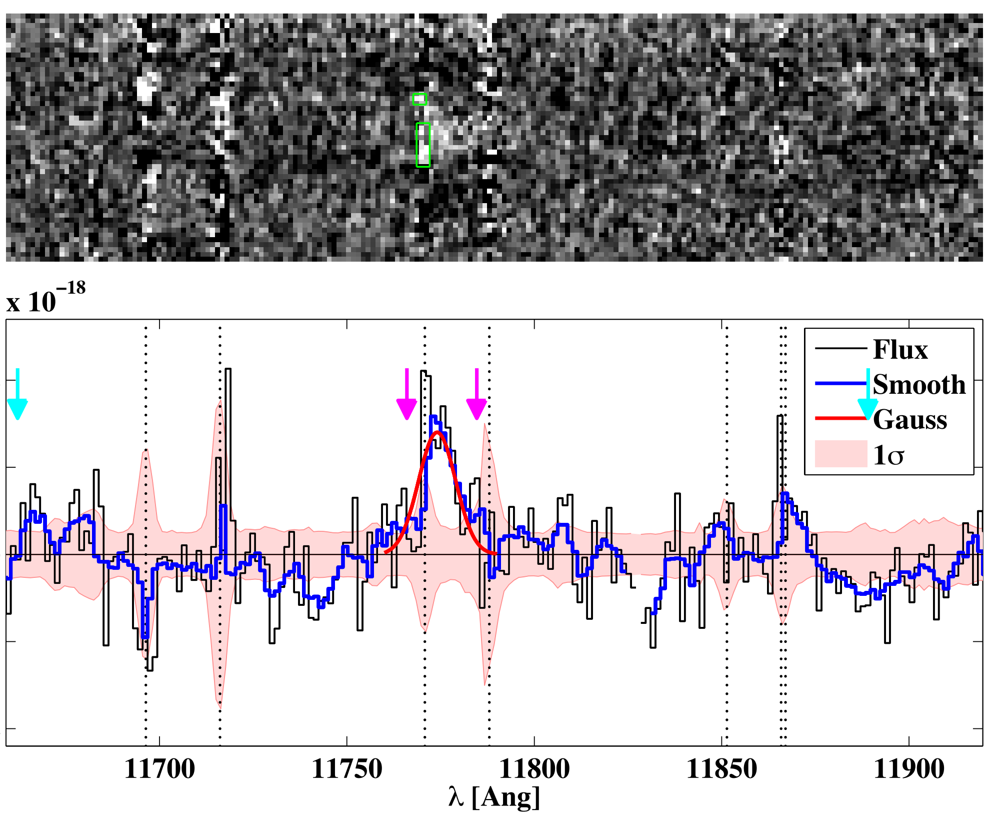
- These sources are selected on [OIII] - the source of ionising photons can potentially create an ionised bubble
- These sources are bright (>L*) and therefore likely live in overdens regions - dens regions might reionise first

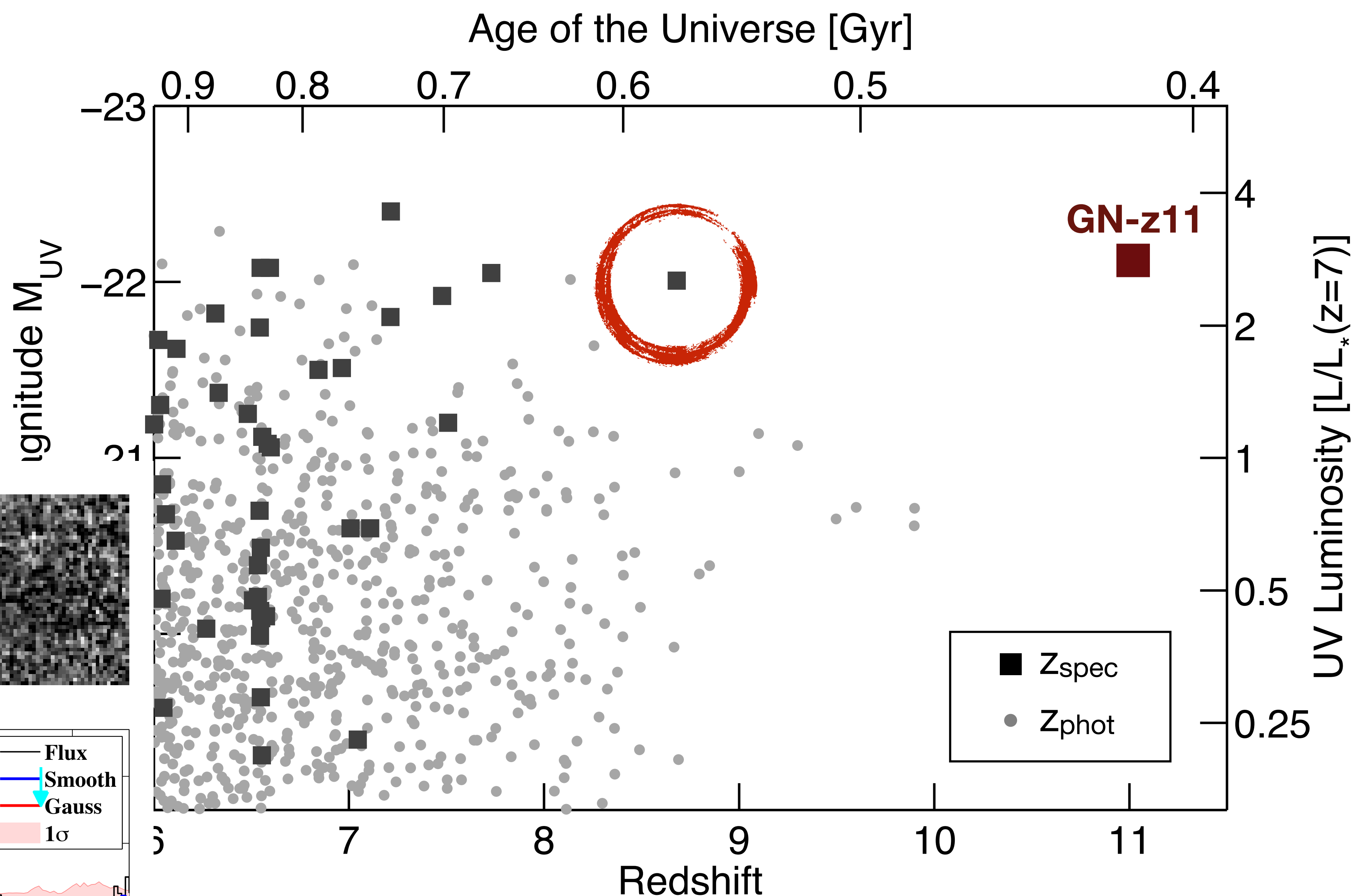


Stark et al. 2017

Spectroscopic confirmation of galaxies in the EoR

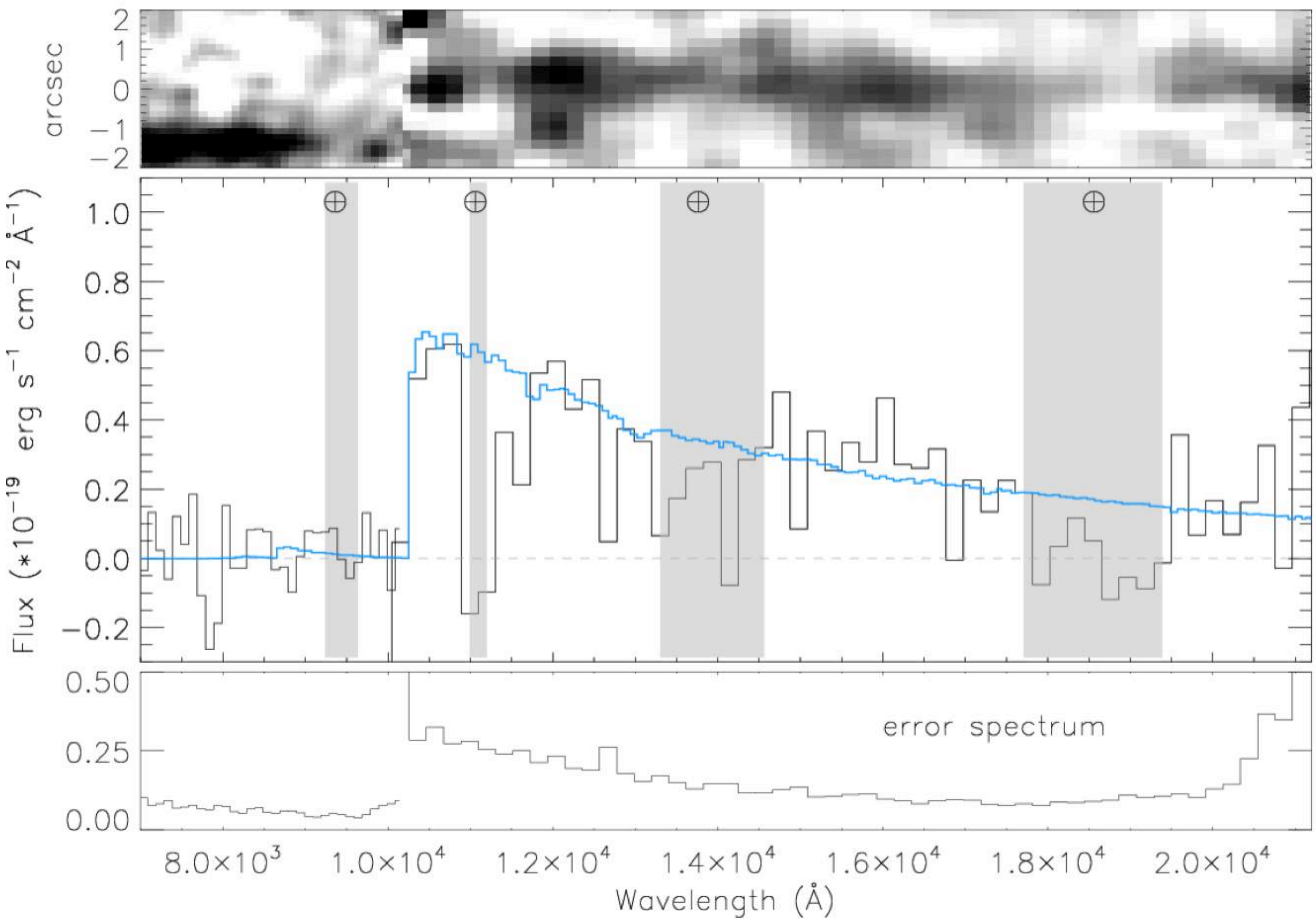
Zitrin et al. 2015





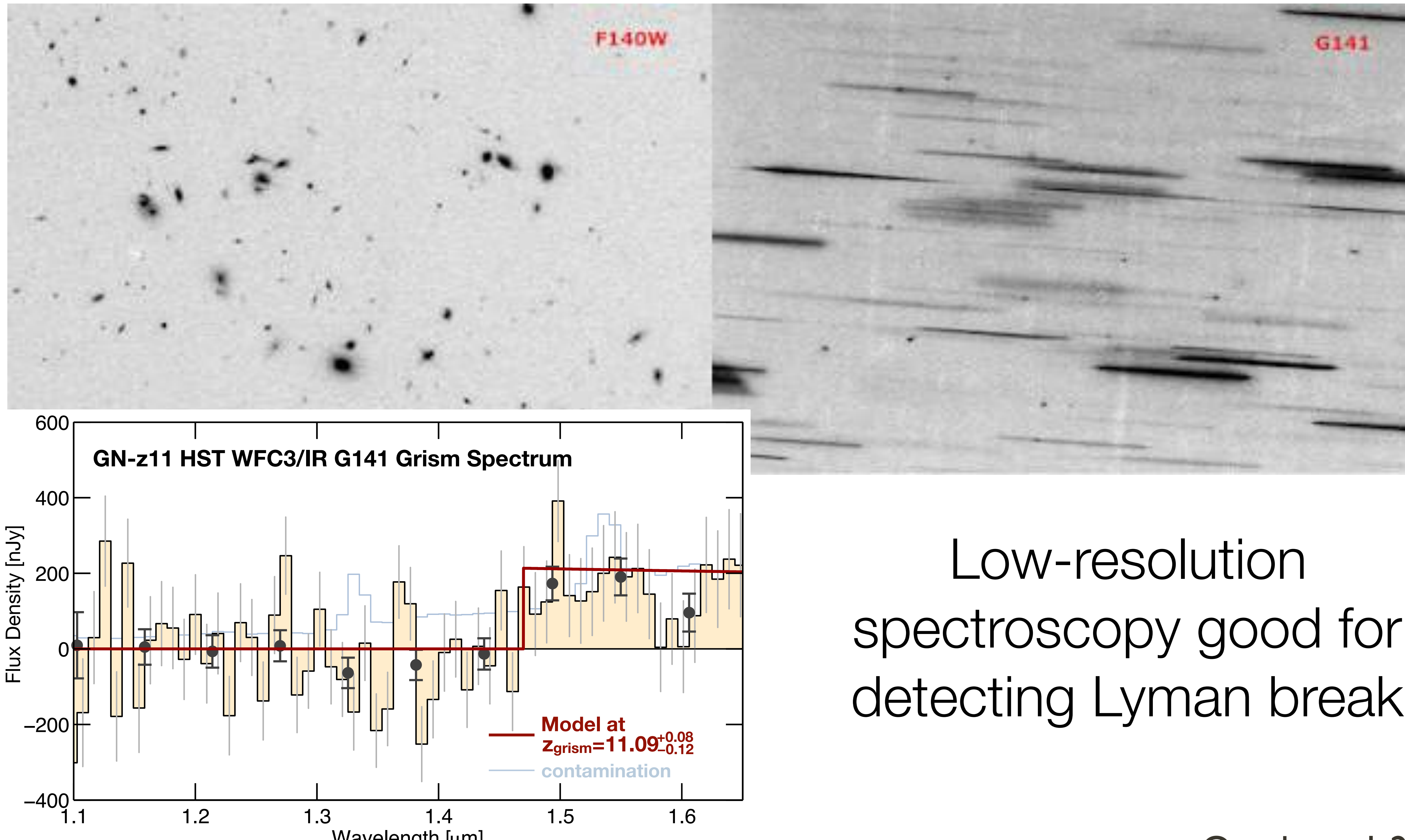
Oesch et al. 2016

Lyman Break spectroscopy



Watson et al. 2015

Grism spectroscopy



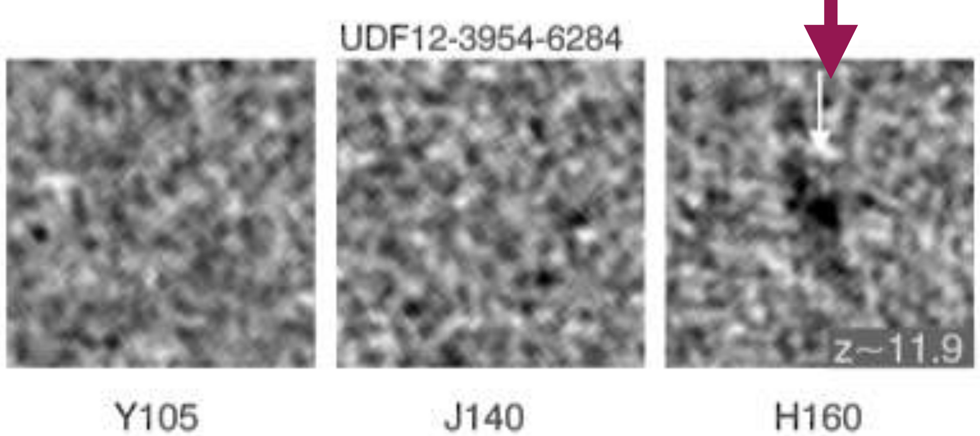
Low-resolution spectroscopy good for detecting Lyman break

Oesch et al. 2016

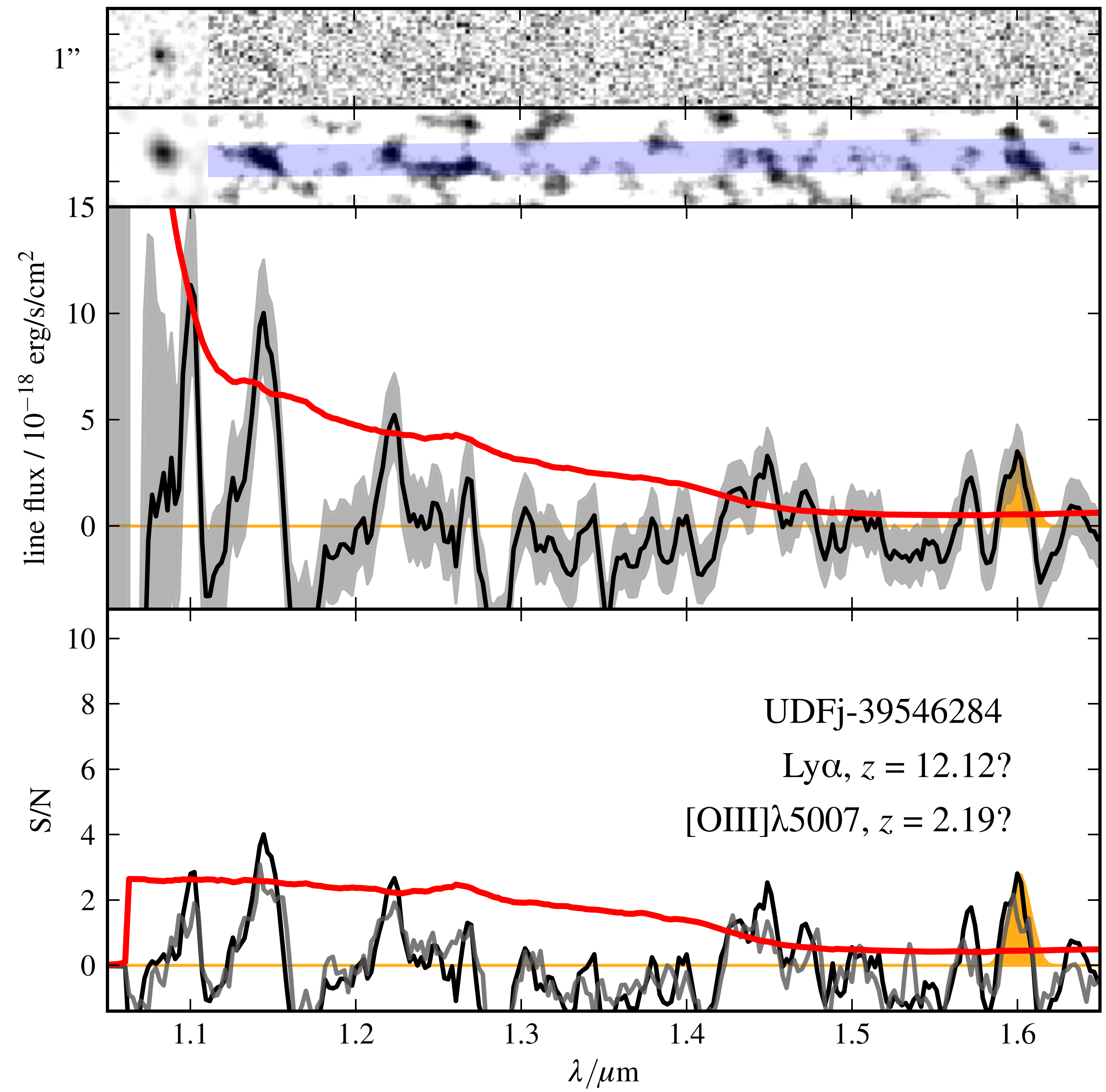
Grism spectroscopy

For single band detections low redshift line emitters are a new class of interloper

[OIII] at z=2

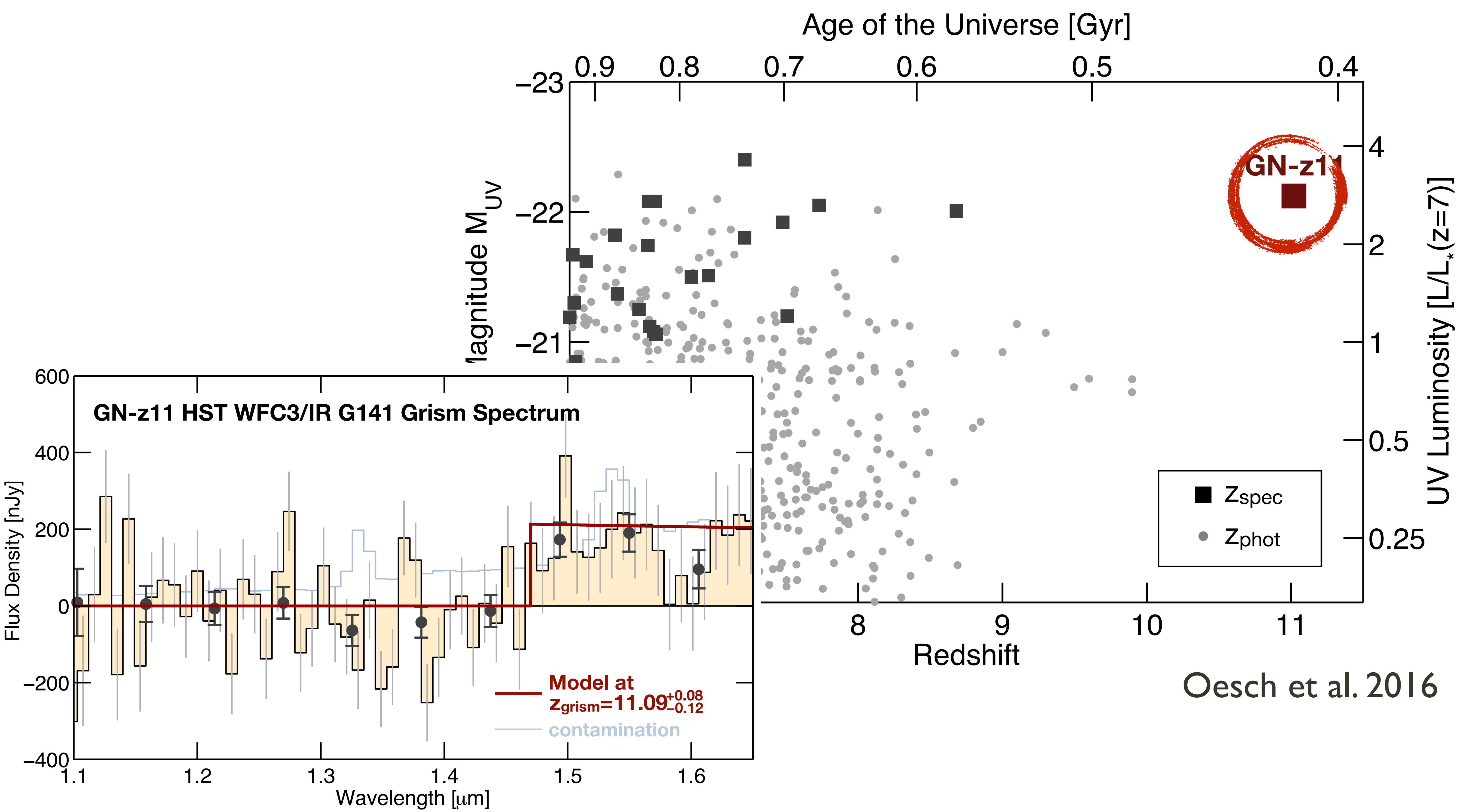


Bouwens et al. 2011; Ellis et al. 2013



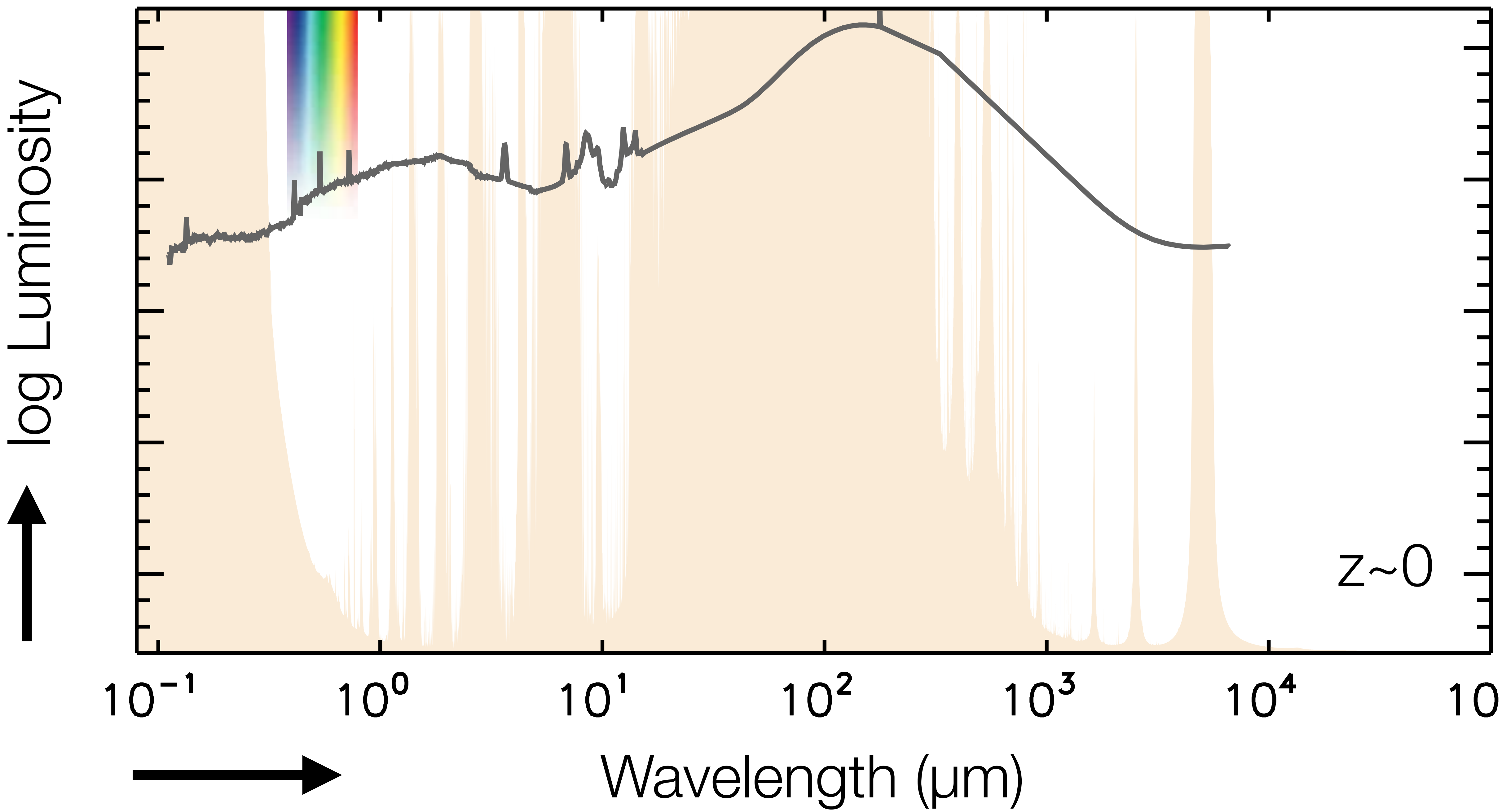
Brammer et al. 2013

Spectroscopic confirmation of galaxies in the EoR

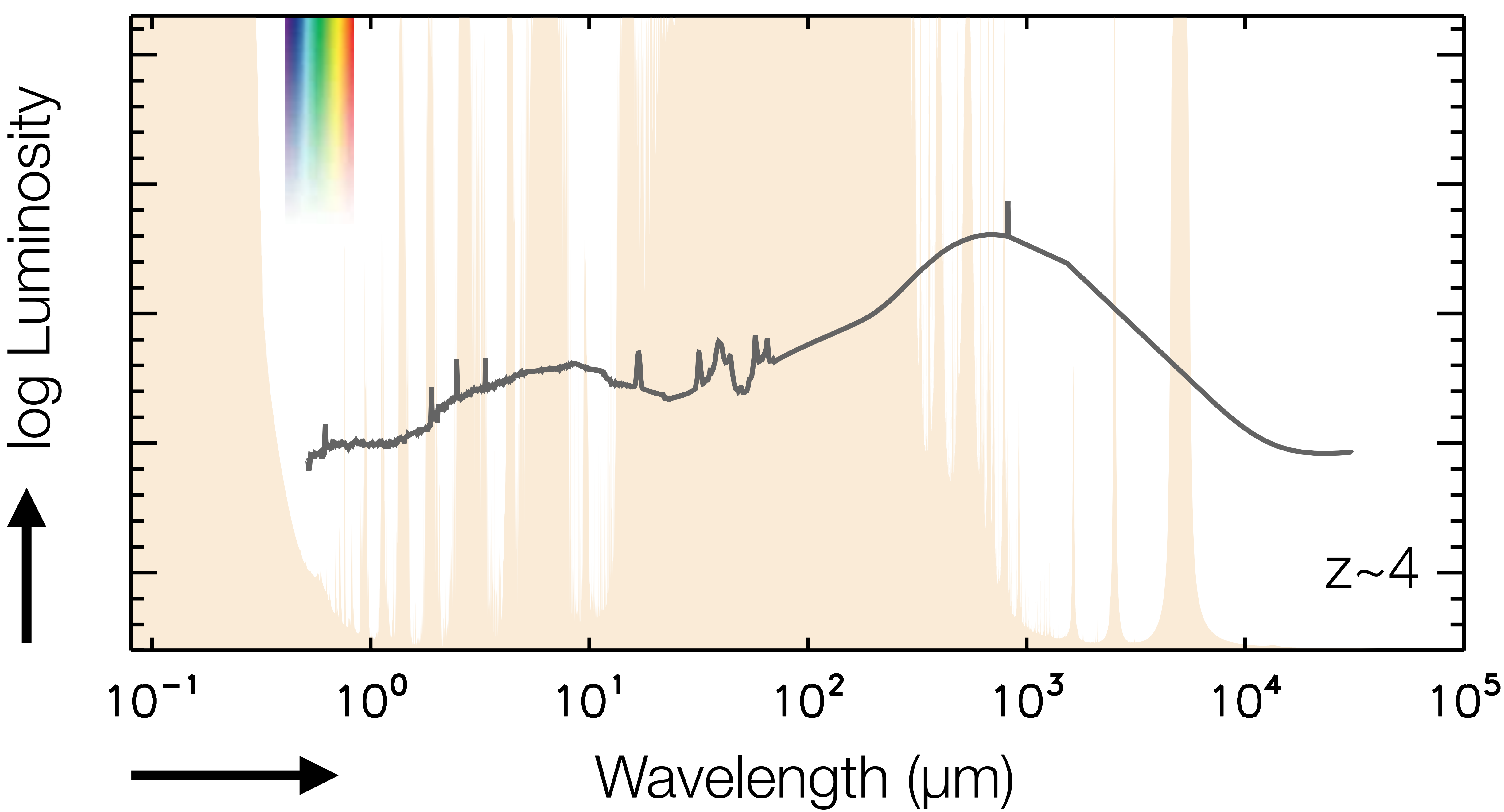


Oesch et al. 2016

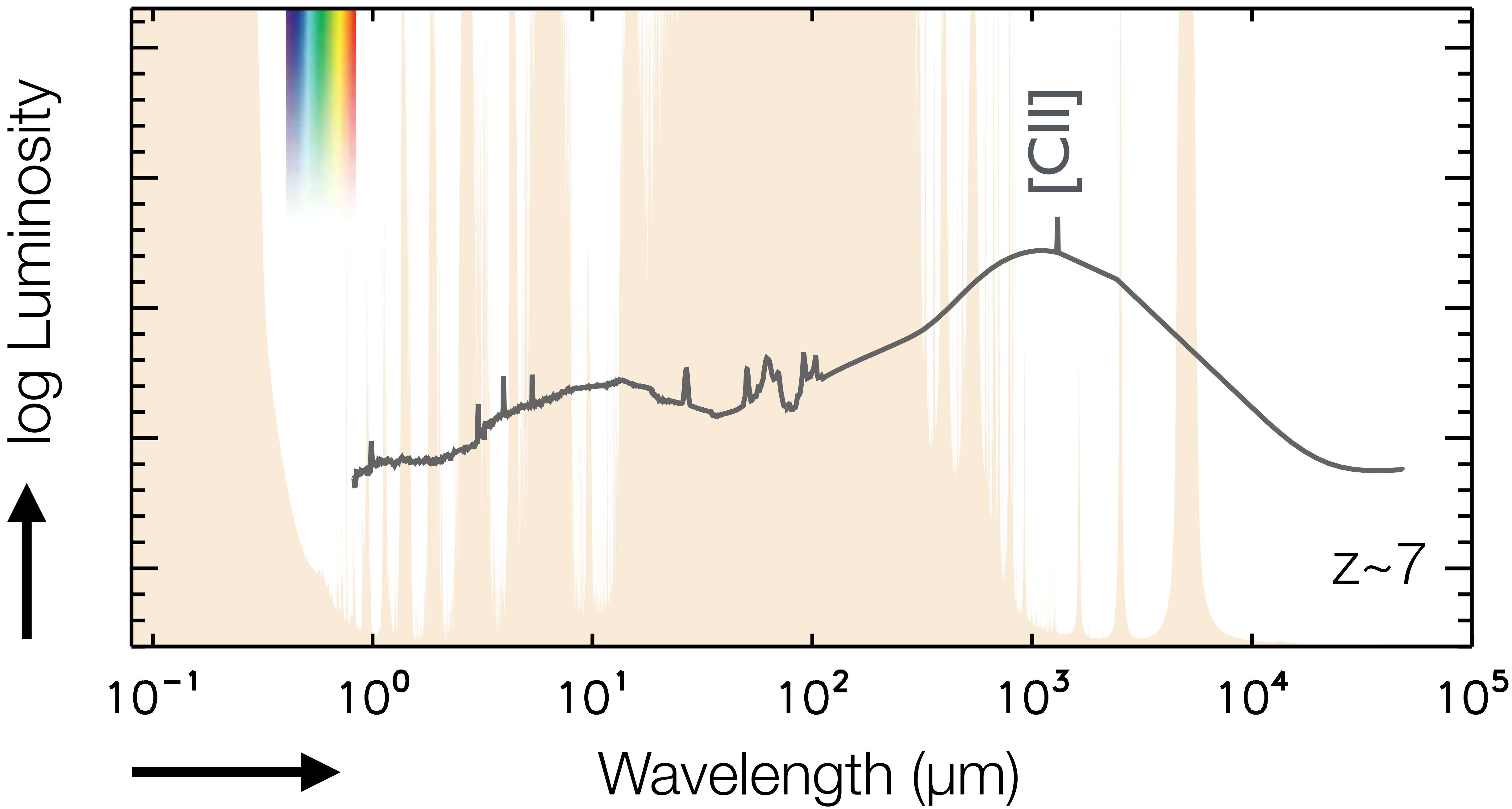
Low- and high-redshift spectroscopic tracers



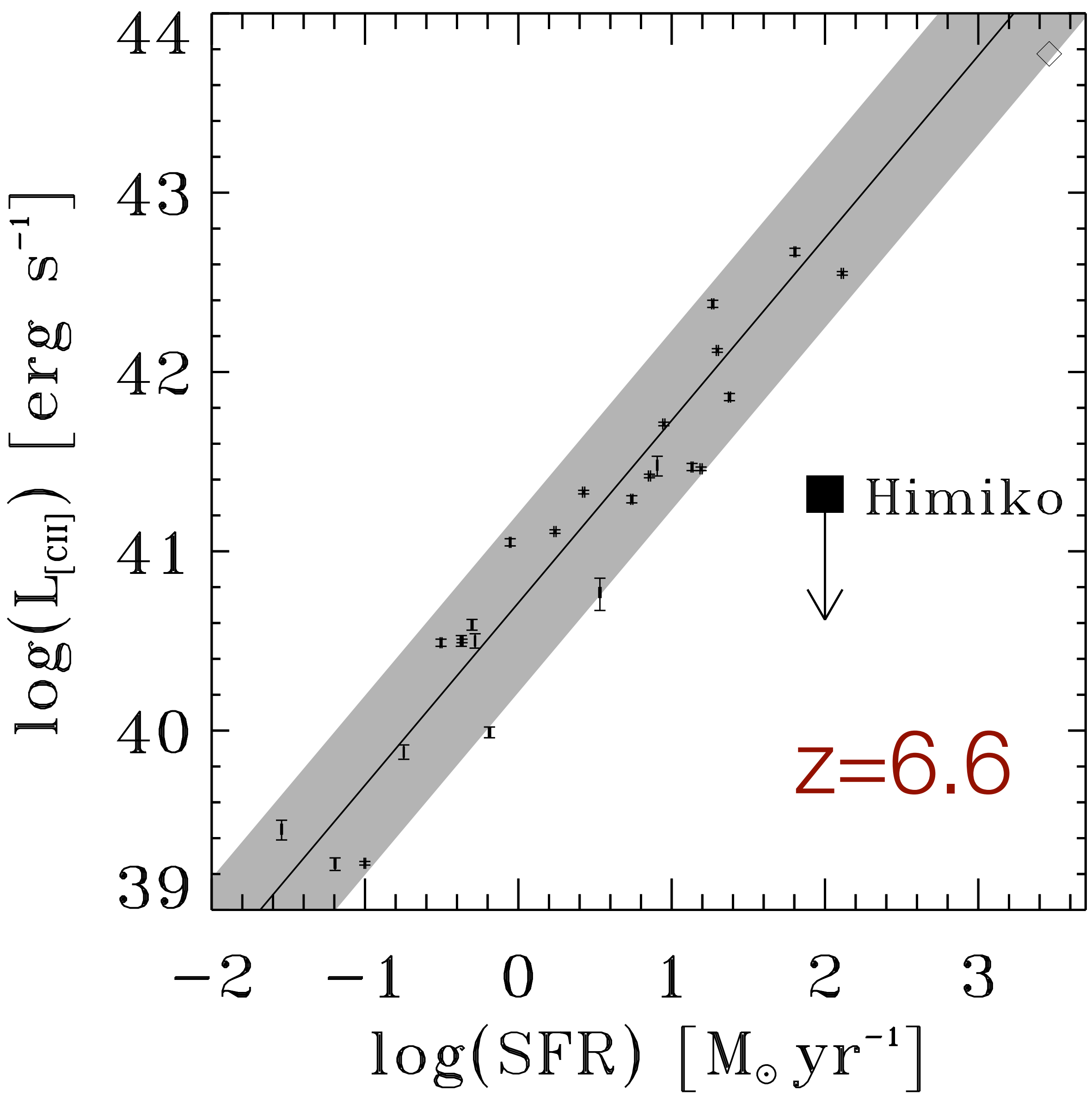
Low- and high-redshift spectroscopic tracers

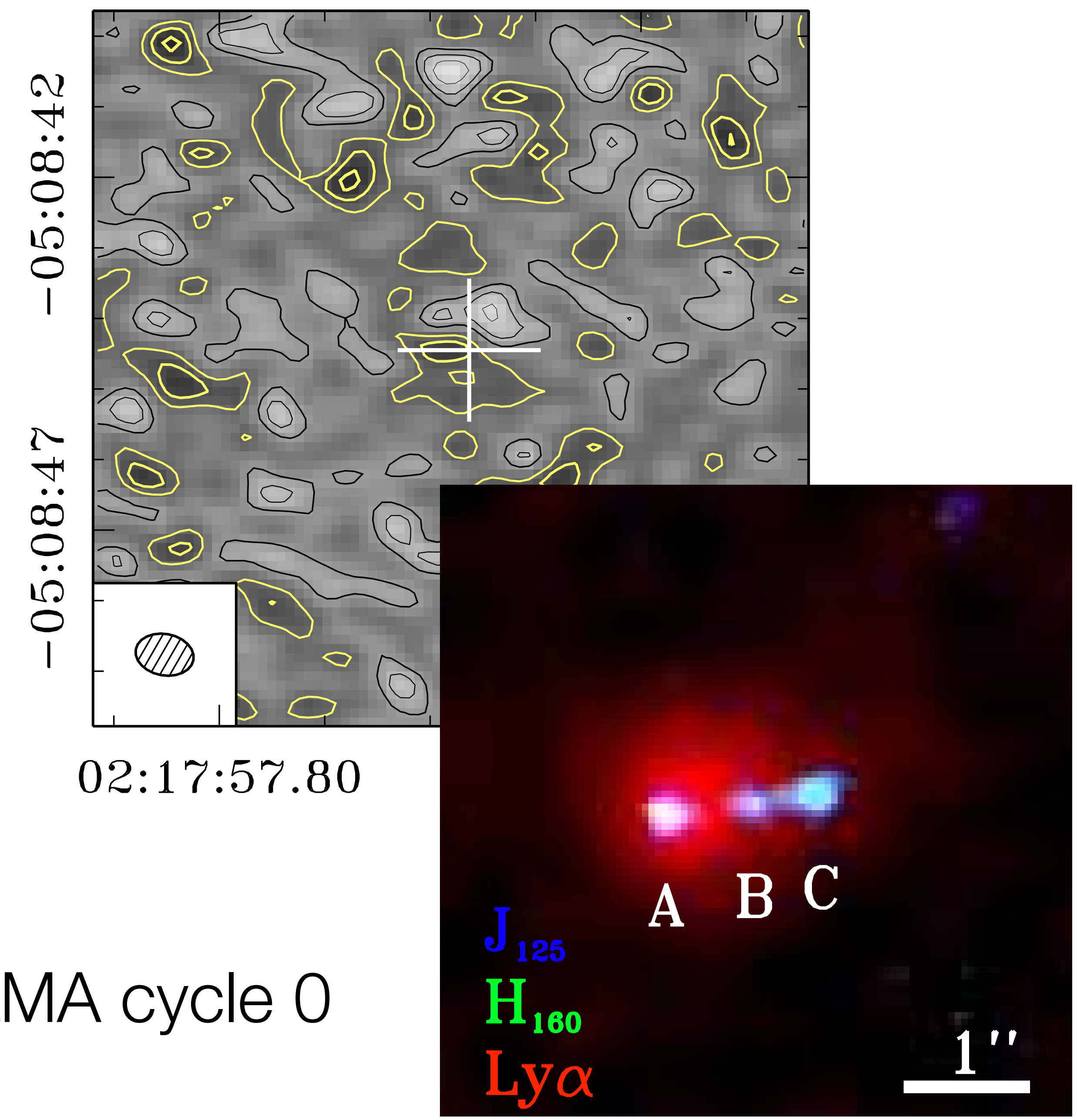


Low- and high-redshift spectroscopic tracers



ALMA as a redshift machine?





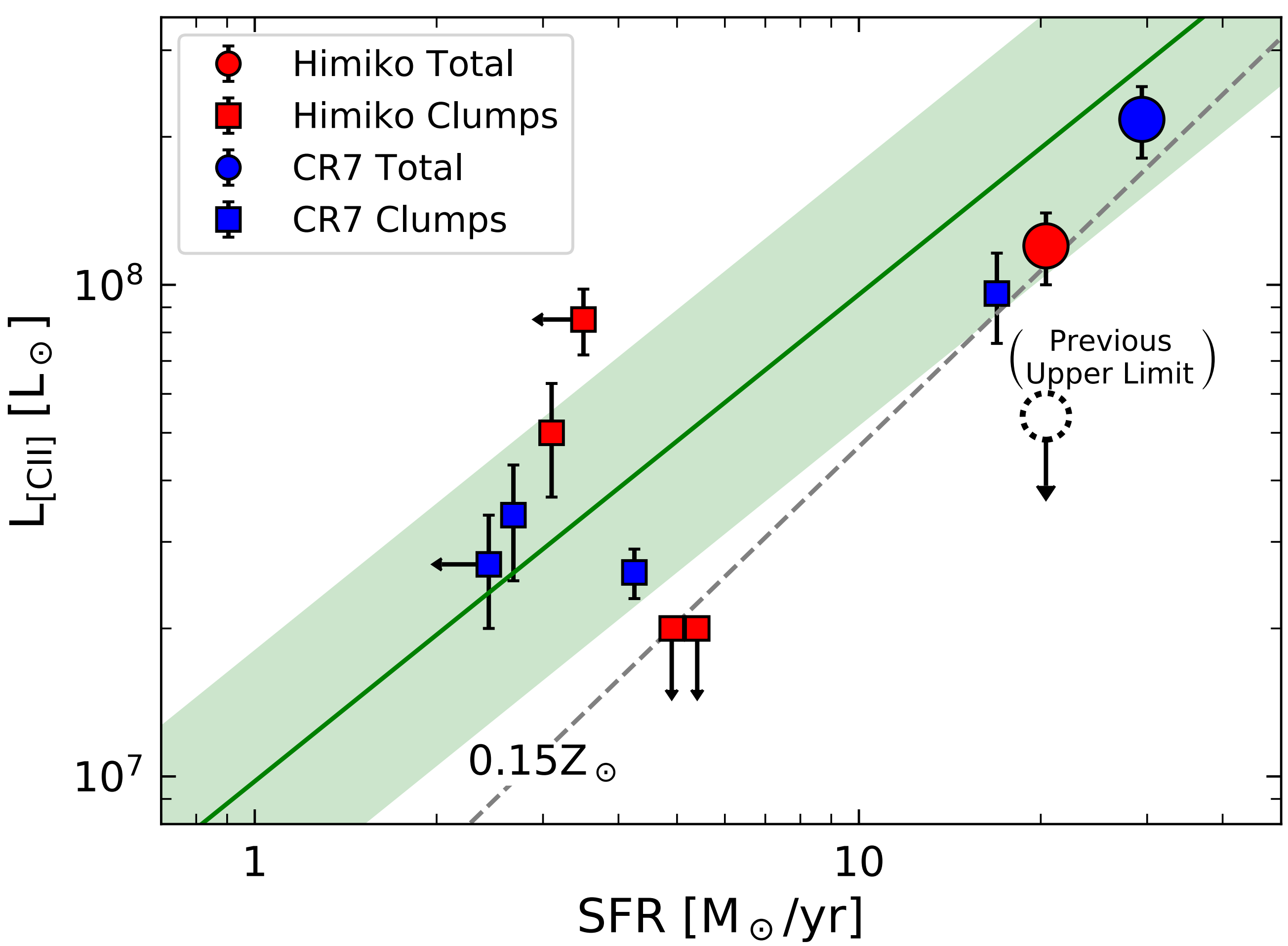
ALMA cycle 0

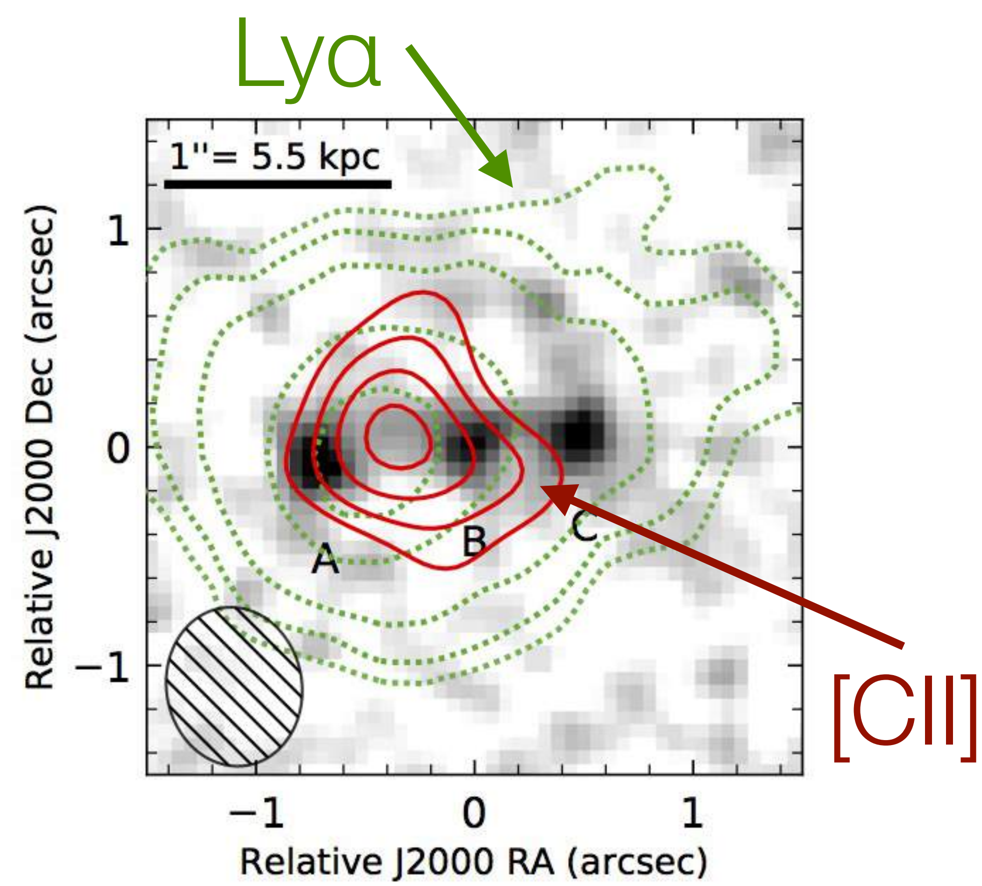
Ouchi et al., 2013

see also Ota et al. 2014, Maiolino et al. 2015

Himiko revisited: faint but detectable [CII]

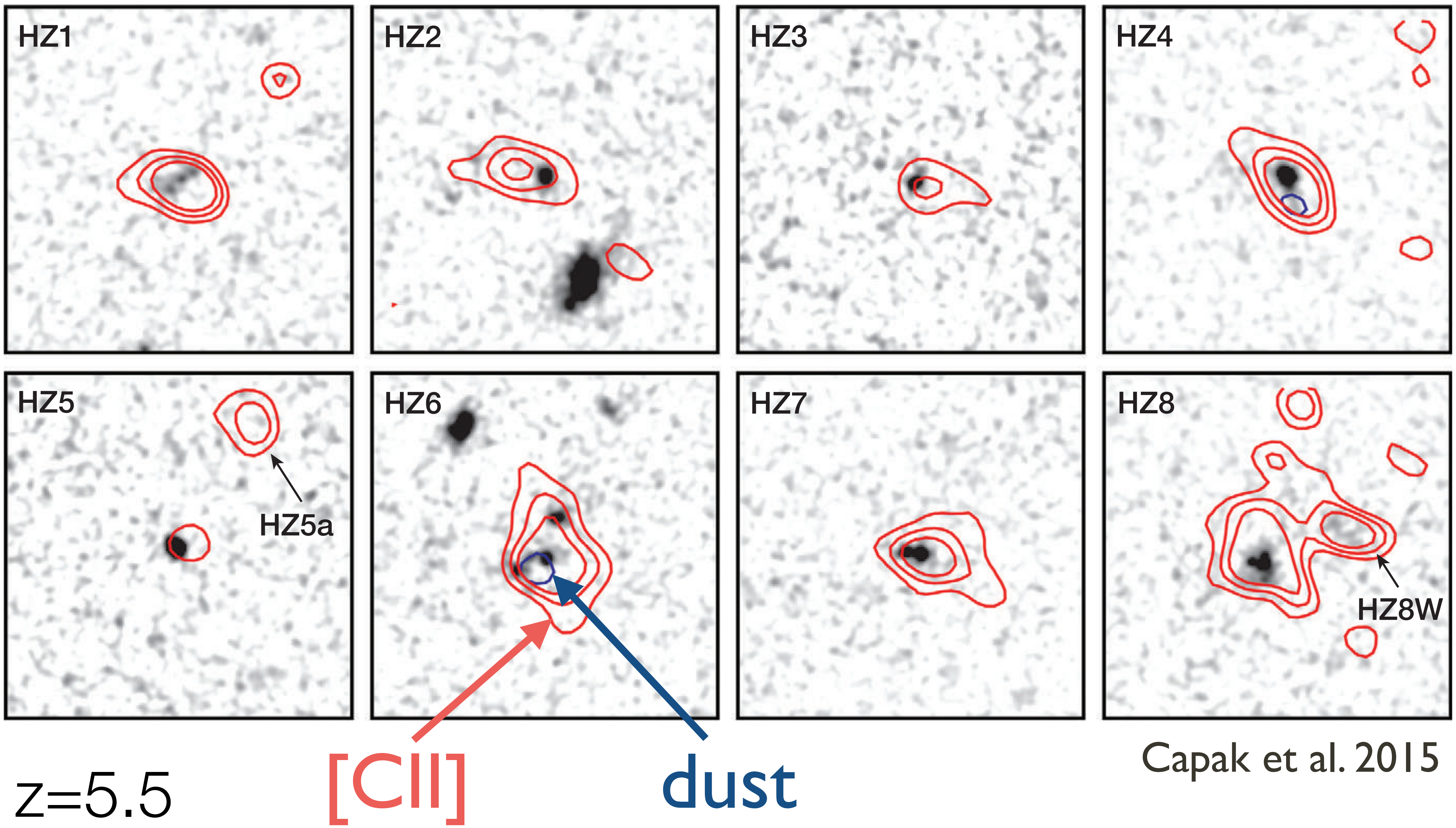
Low surface-brightness [CII] at the origin of SFR-$L_{[CII]}$ scatter?





Carniani, Maiolino, Smit & Amorin, 2017

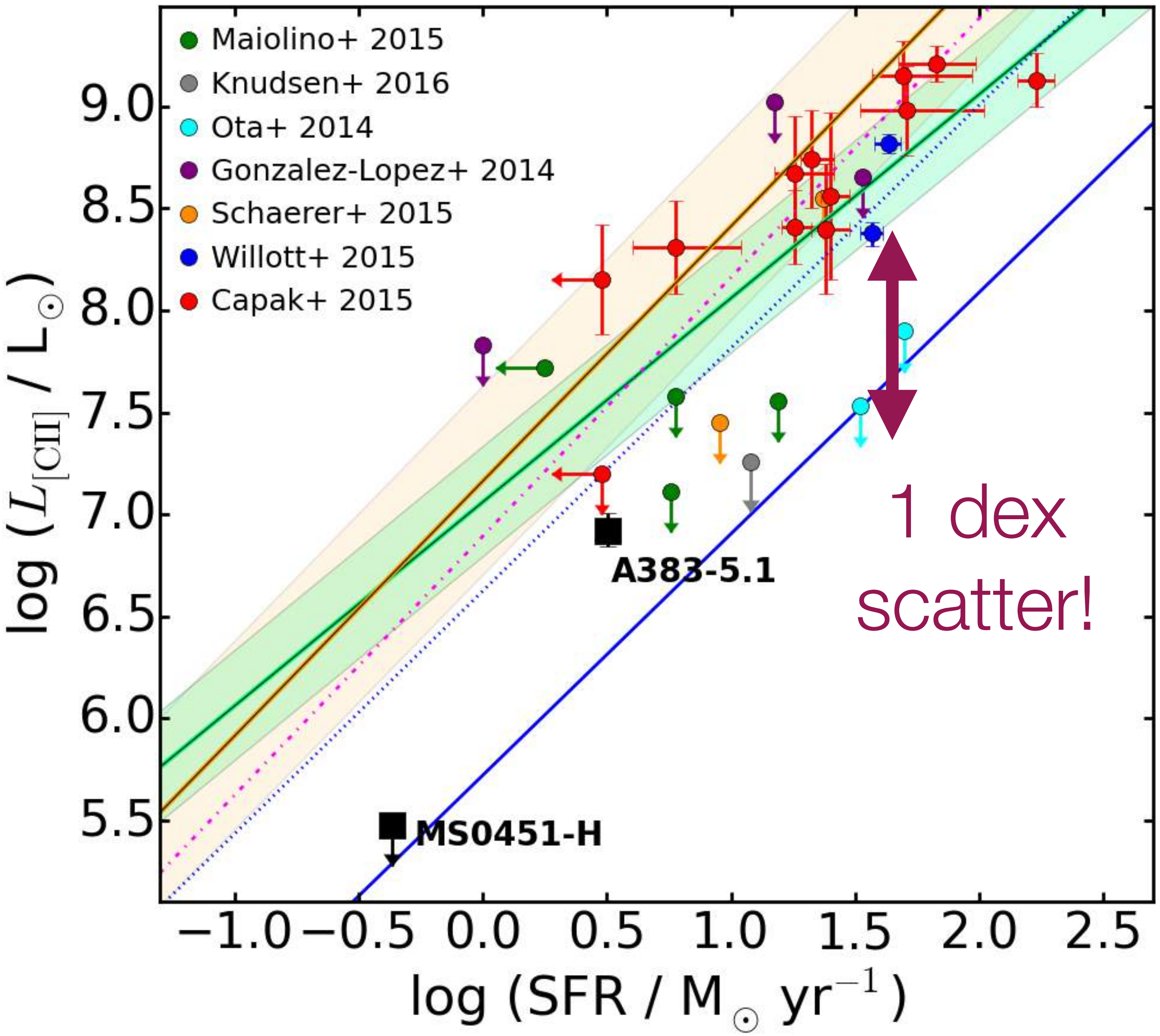
ALMA [CII] (non)detections



Capak et al. 2015

z=5.5

ALMA [CII] (non)detections

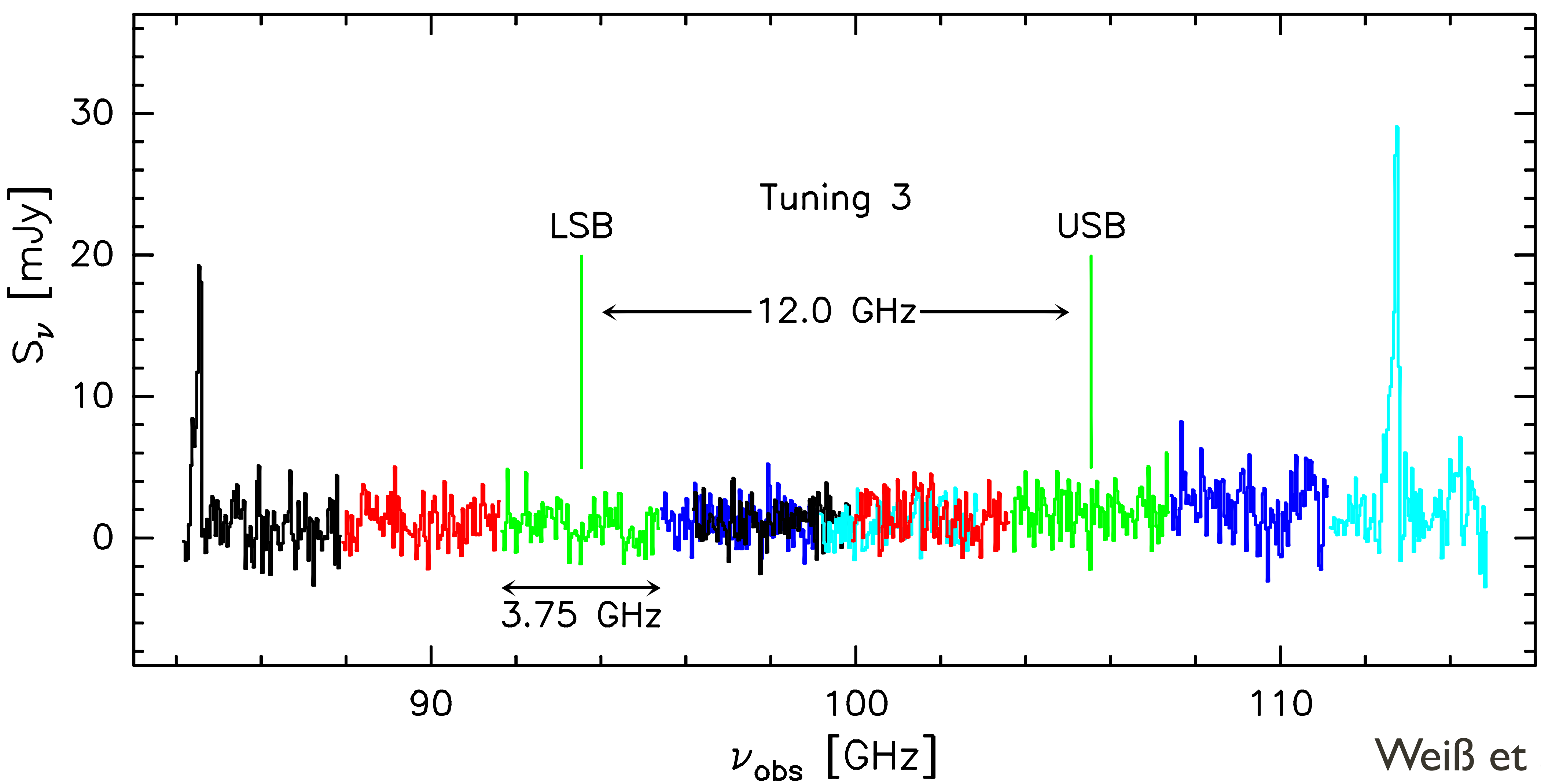


Knudsen et al. 2016

A potential difference between Lyα emitters and non-Lyα emitters?

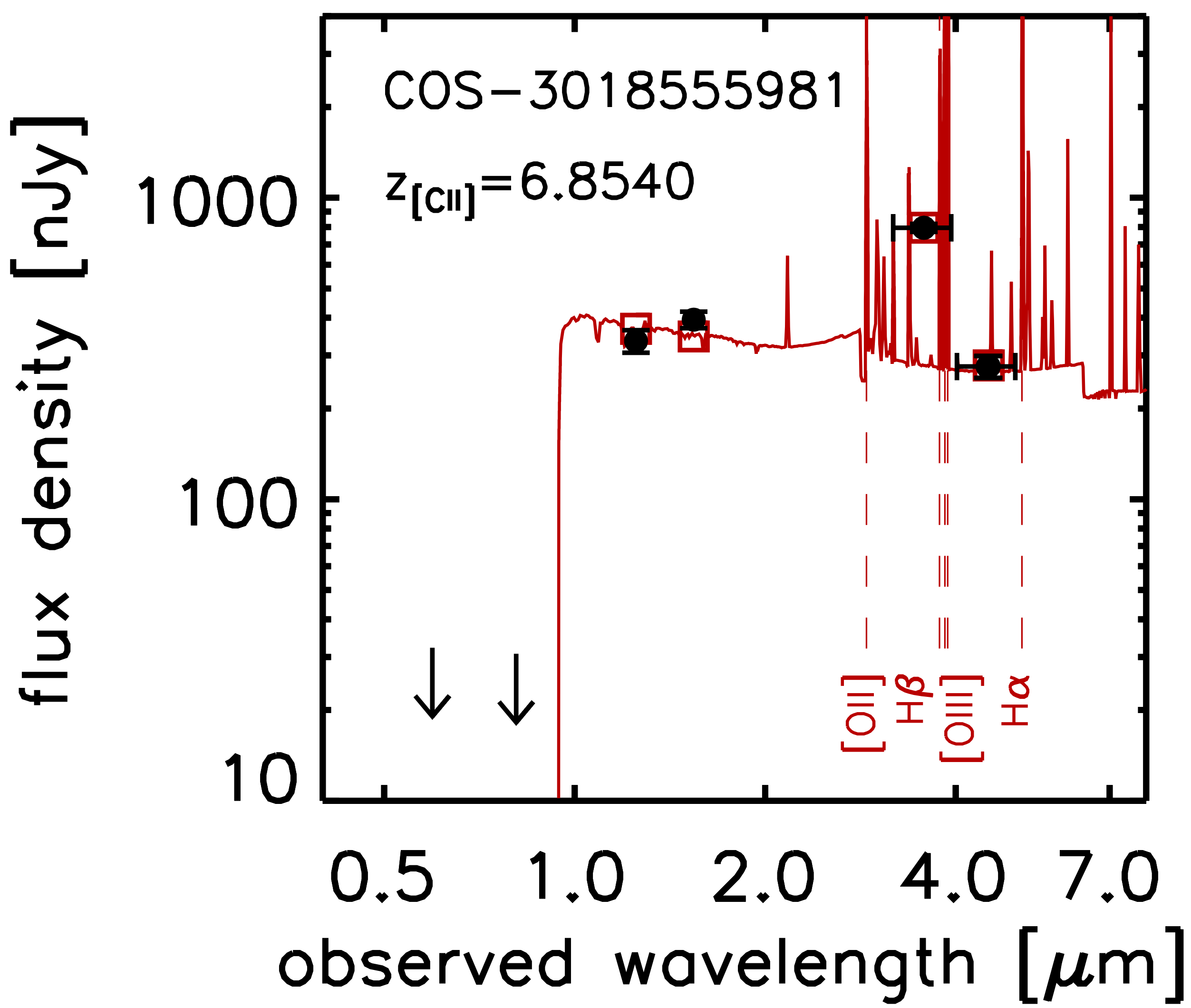
ALMA as a ‘redshift machine’

Uncertainty in photometric redshift requires a (long) scan of the frequency range



Weiß et al. 2013

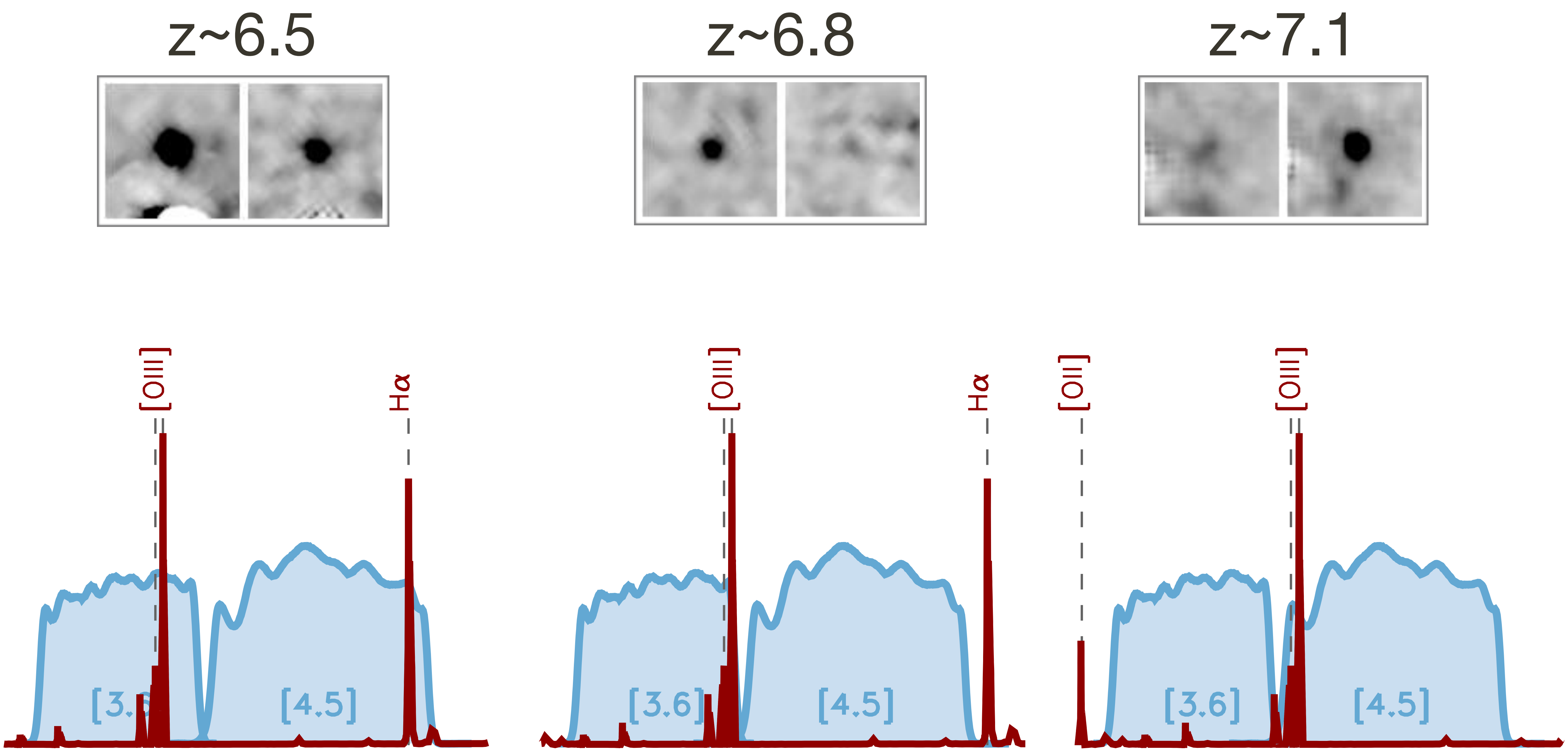
High-EW [OIII] emitters



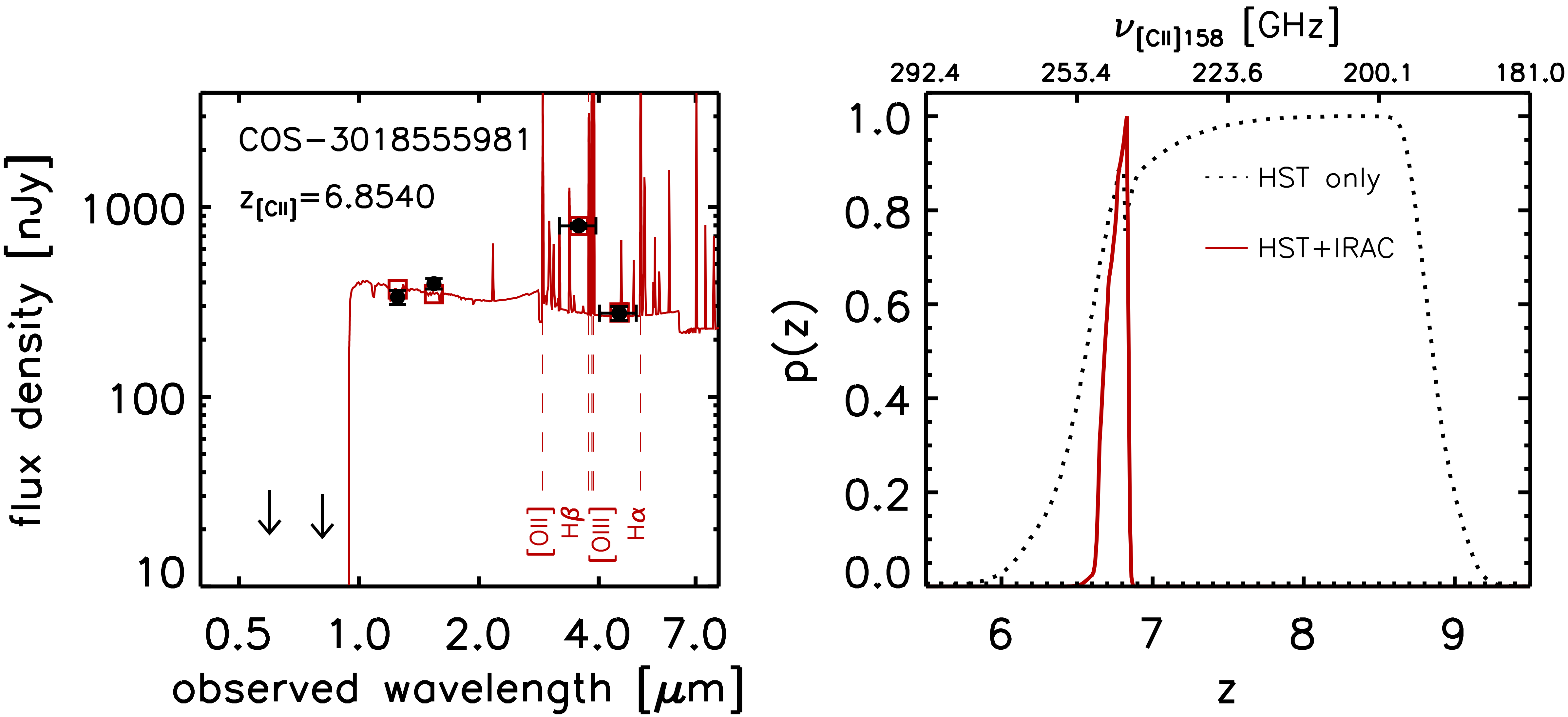
- Colour offers only occur in certain redshift bands - extra constraints on the redshift probability distribution!

Smit et al., 2014; 2015, Roberts-Borsani et al. 2016

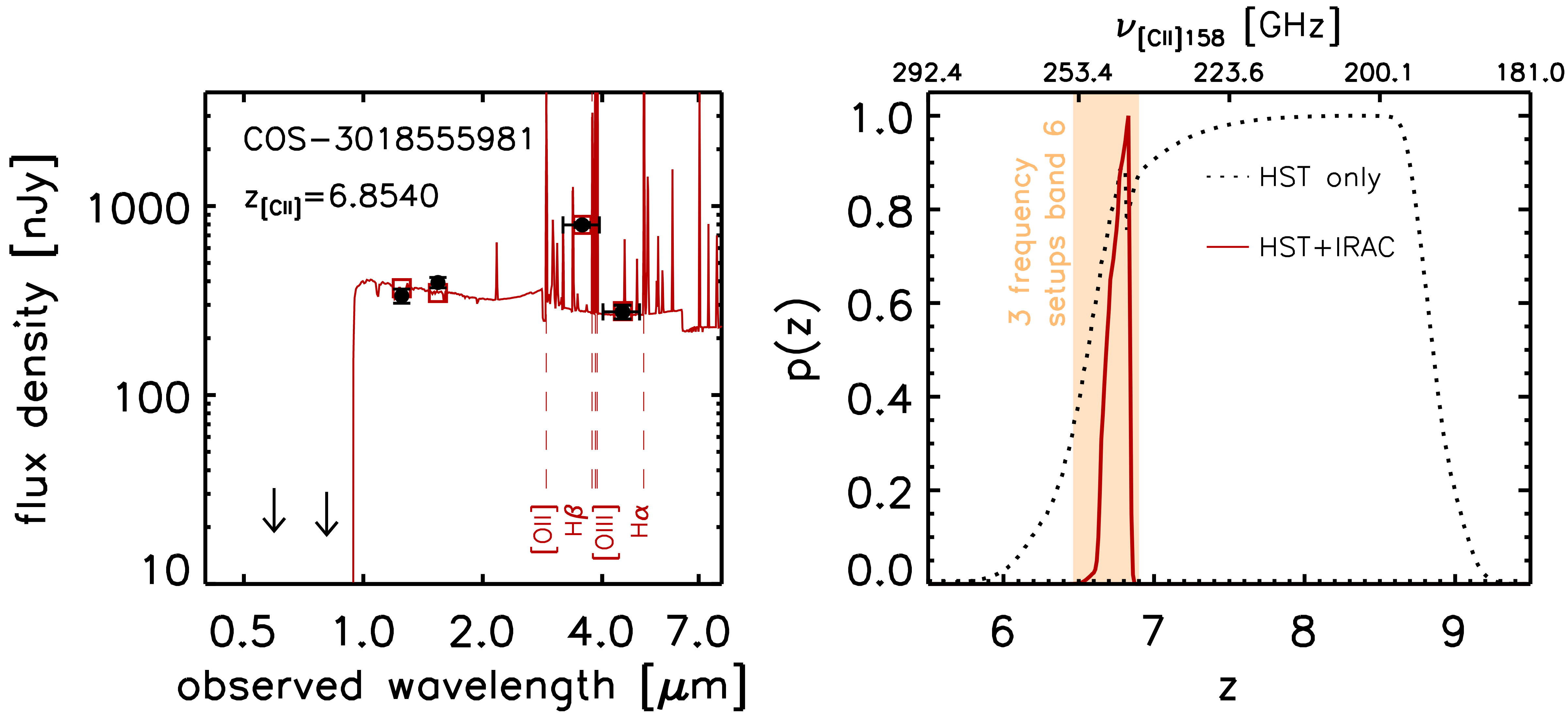
Emission line signatures of Hα, [OIII]



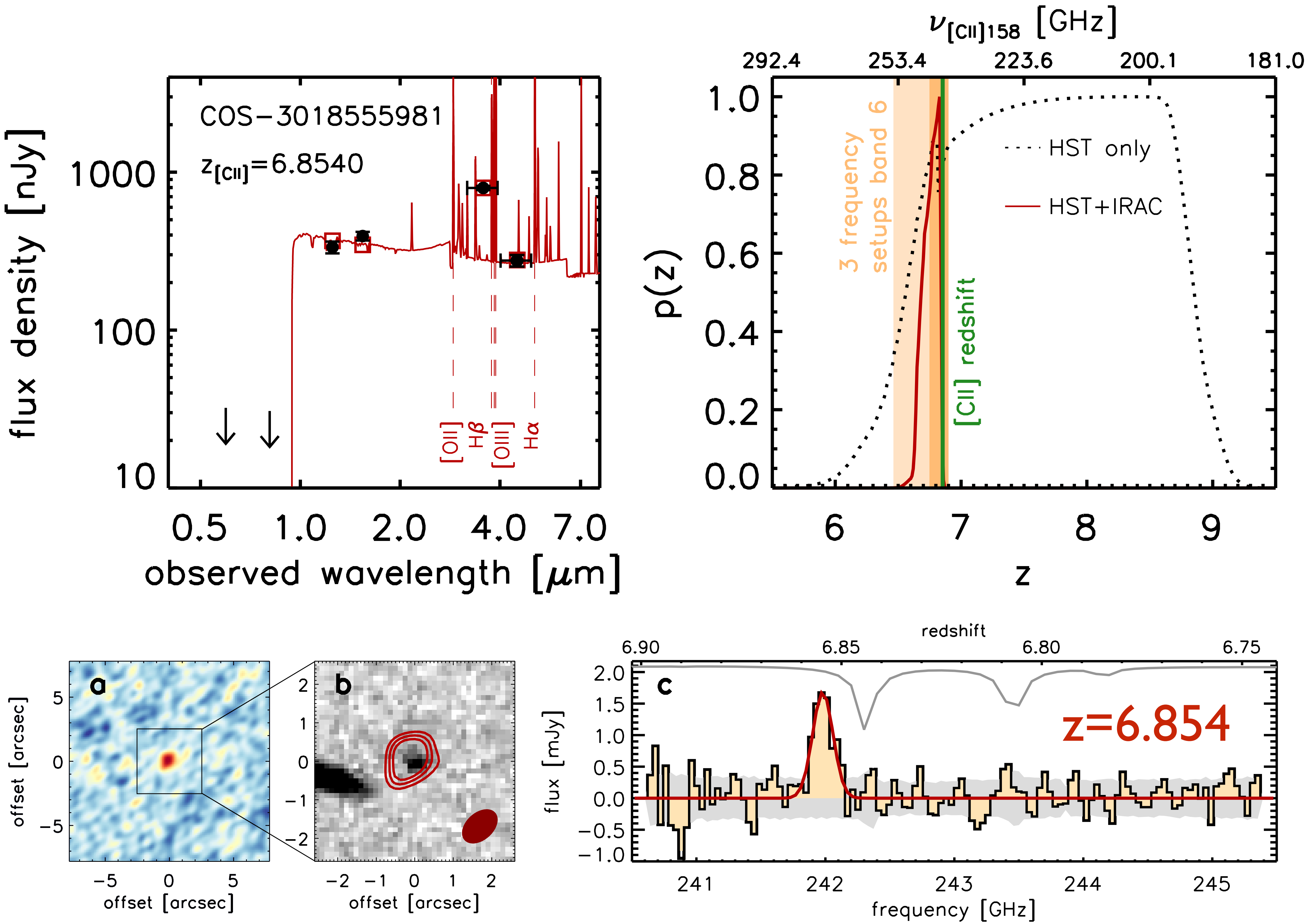
Smit et al. 2015



Smit et al. 2015

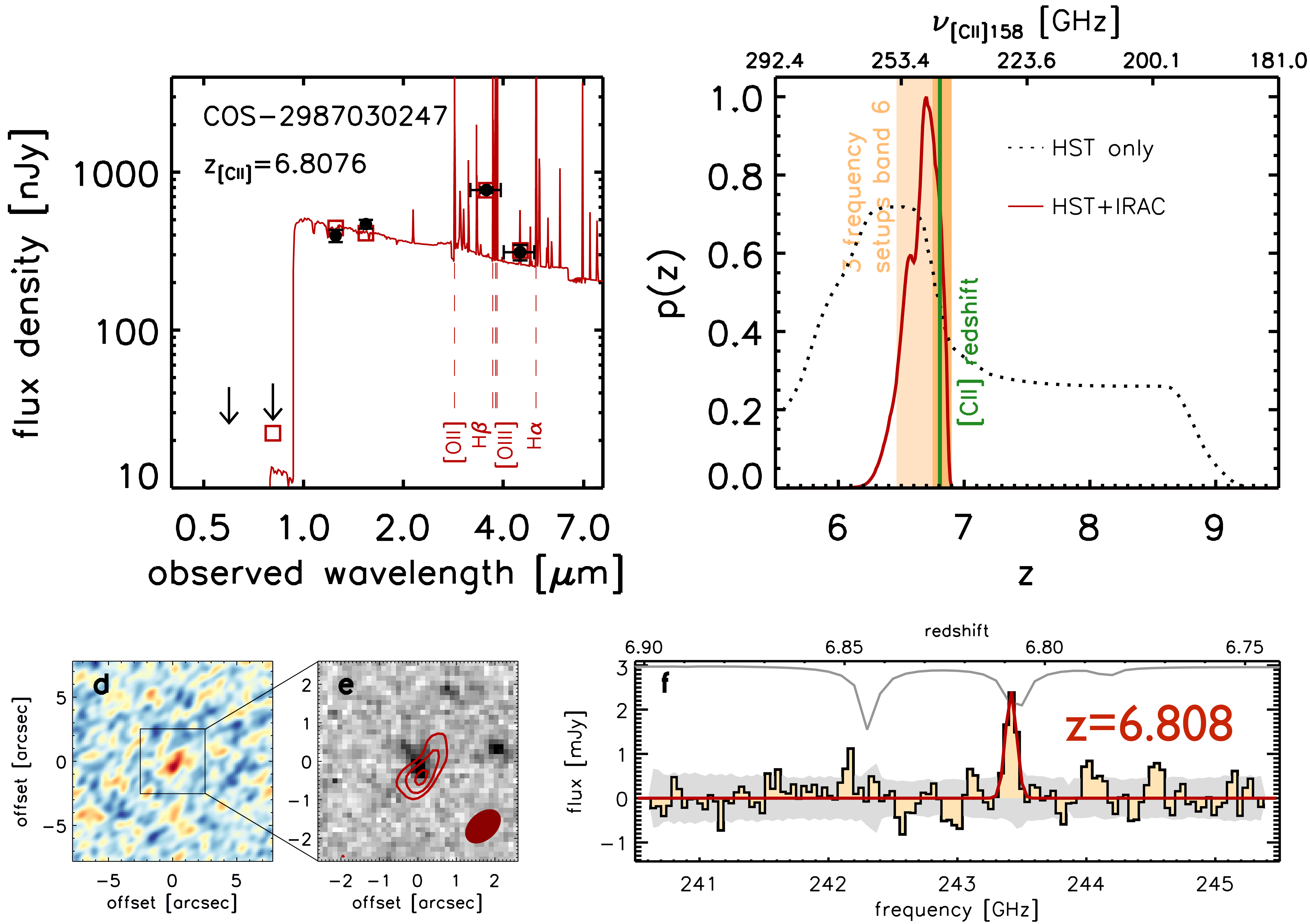


Smit et al. 2015



>8 sigma - 24 min on source!

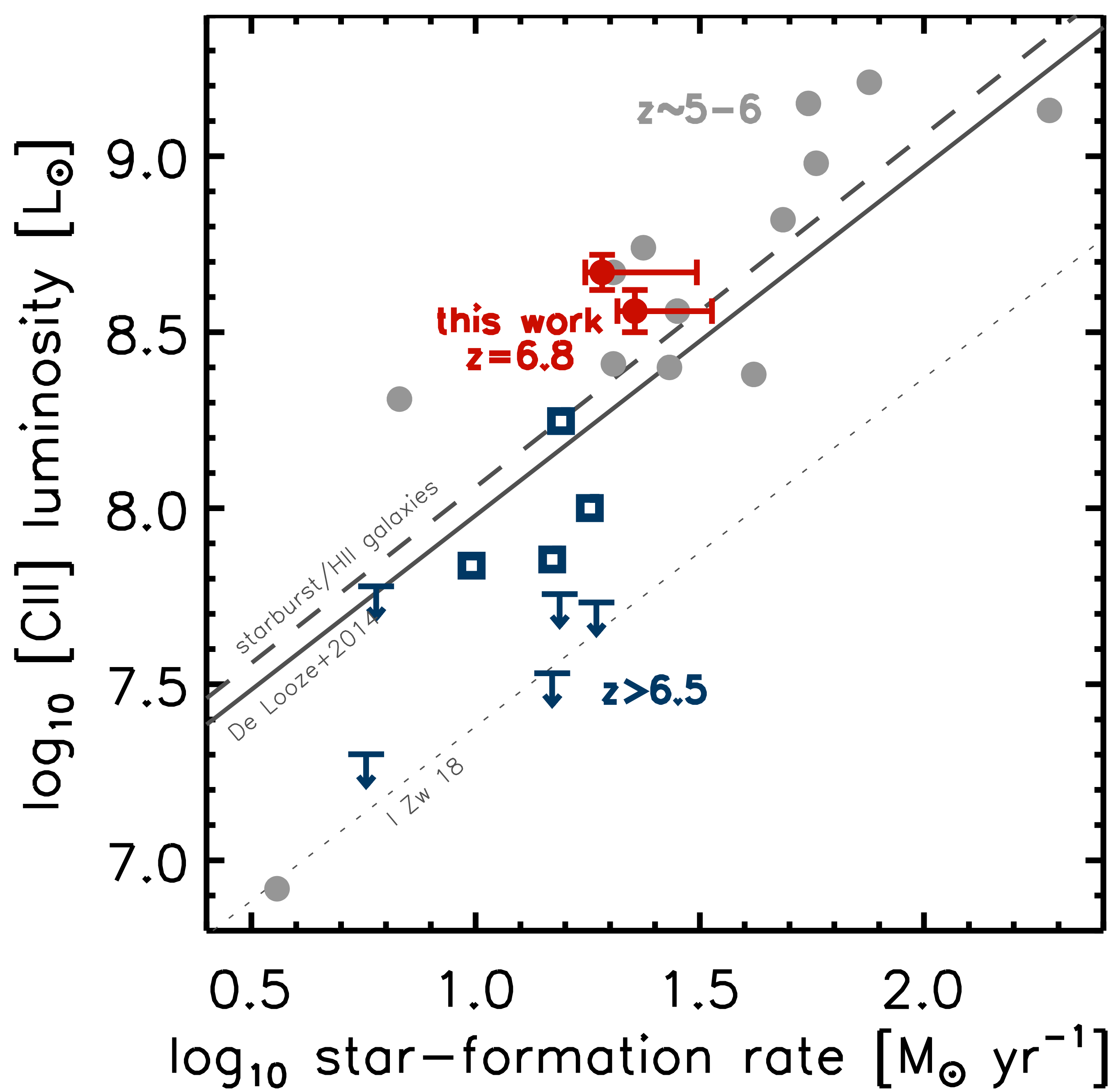
Smit et al. 2018



Smit et al. 2018

ALMA spectroscopic confirmations

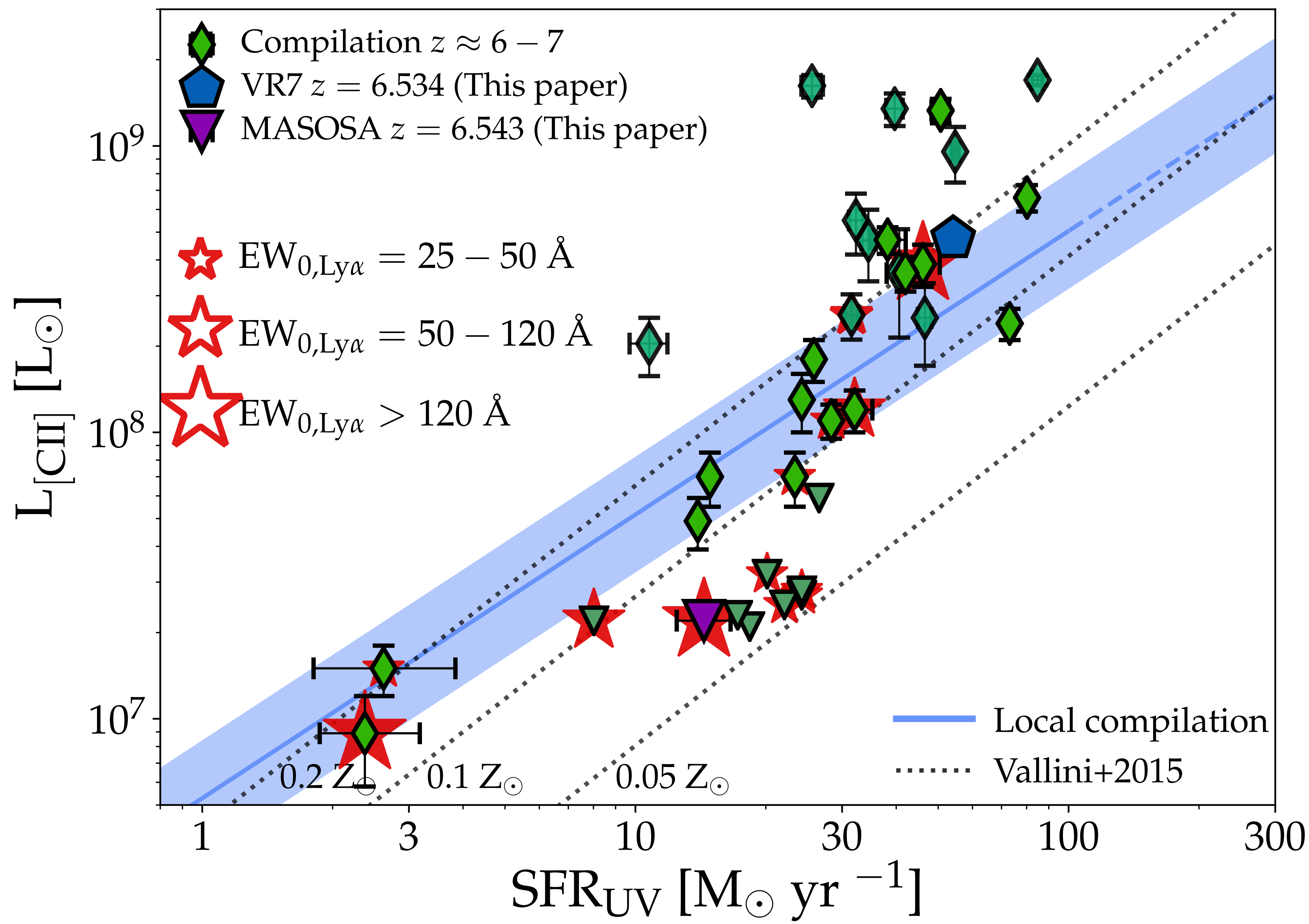
- Not selected on Lyα: implications for stellar population or gas column density?
- Modestly red UV-continuum slopes and bright Luv: more evolved/ dustier galaxies?



Smit et al., 2018

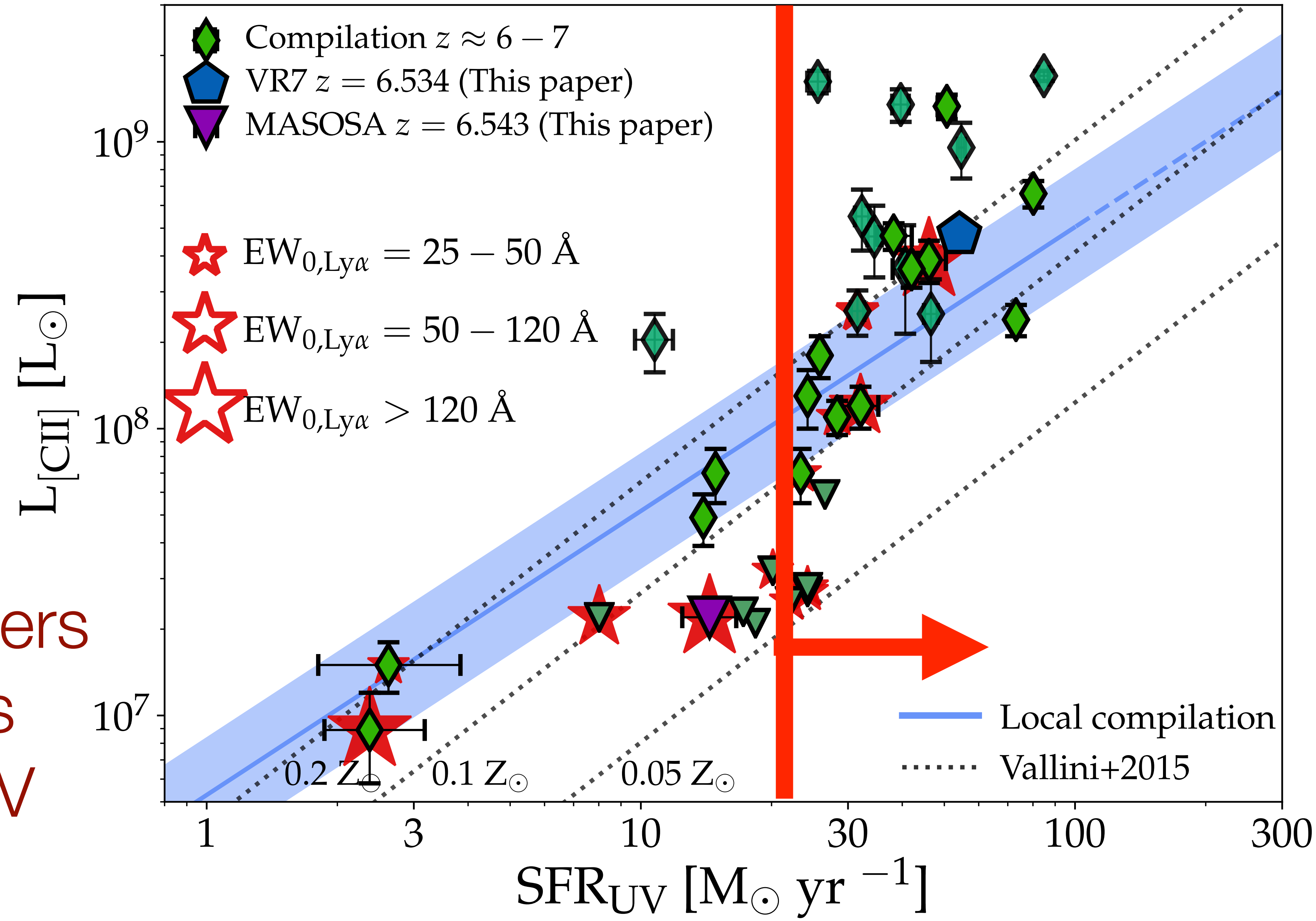
What produces bright [CII] emission?

Bright [CII] can appear in sources with red and blue UV slopes, and even in high-EW Lyα emitters!



Matthee et al. 2019

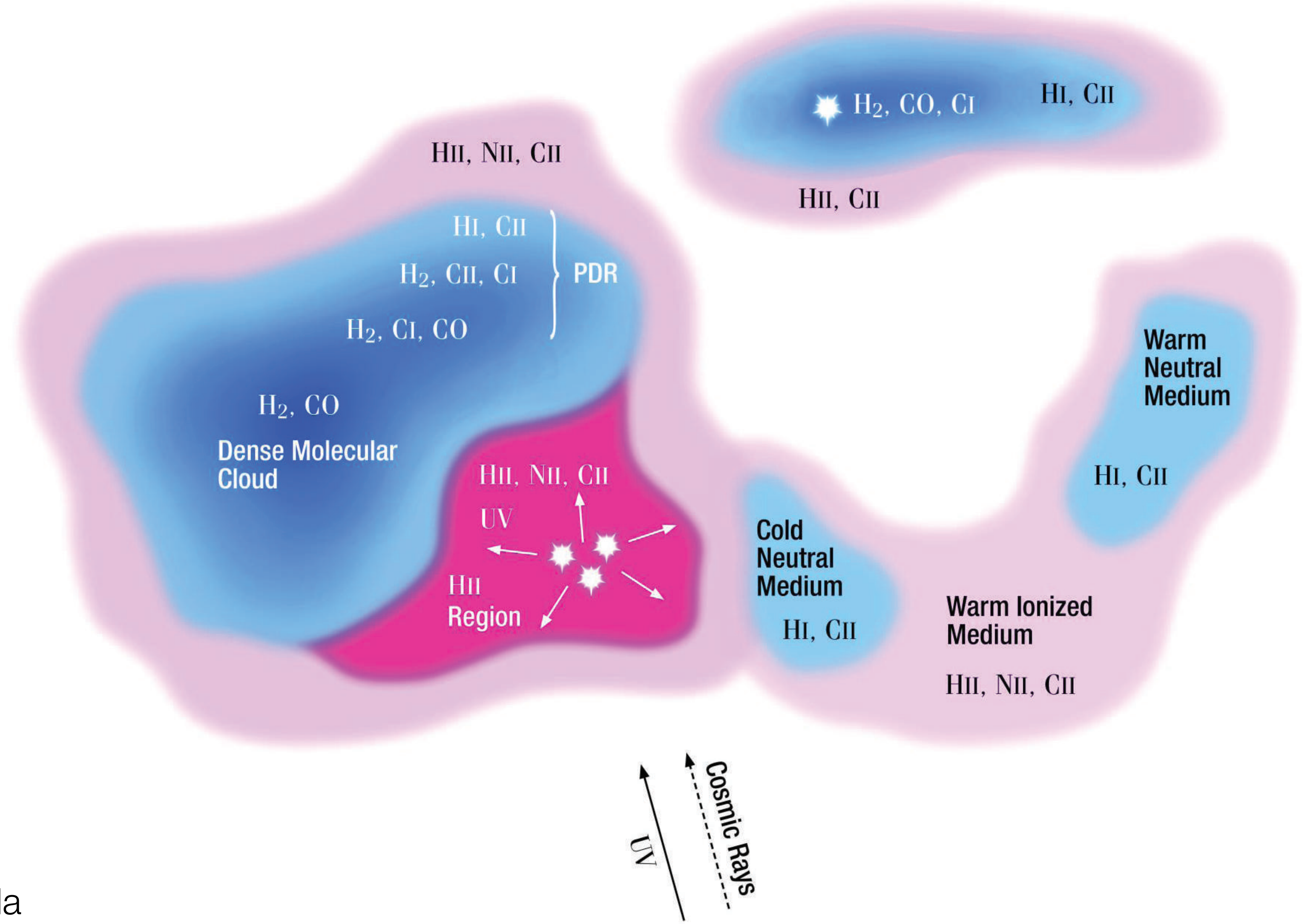
What produces bright [CII] emission?



Bright [CII] emitters almost always show bright UV luminosity: $SFR_{UV} > 20\ M_\odot/yr$

Matthee et al. 2019

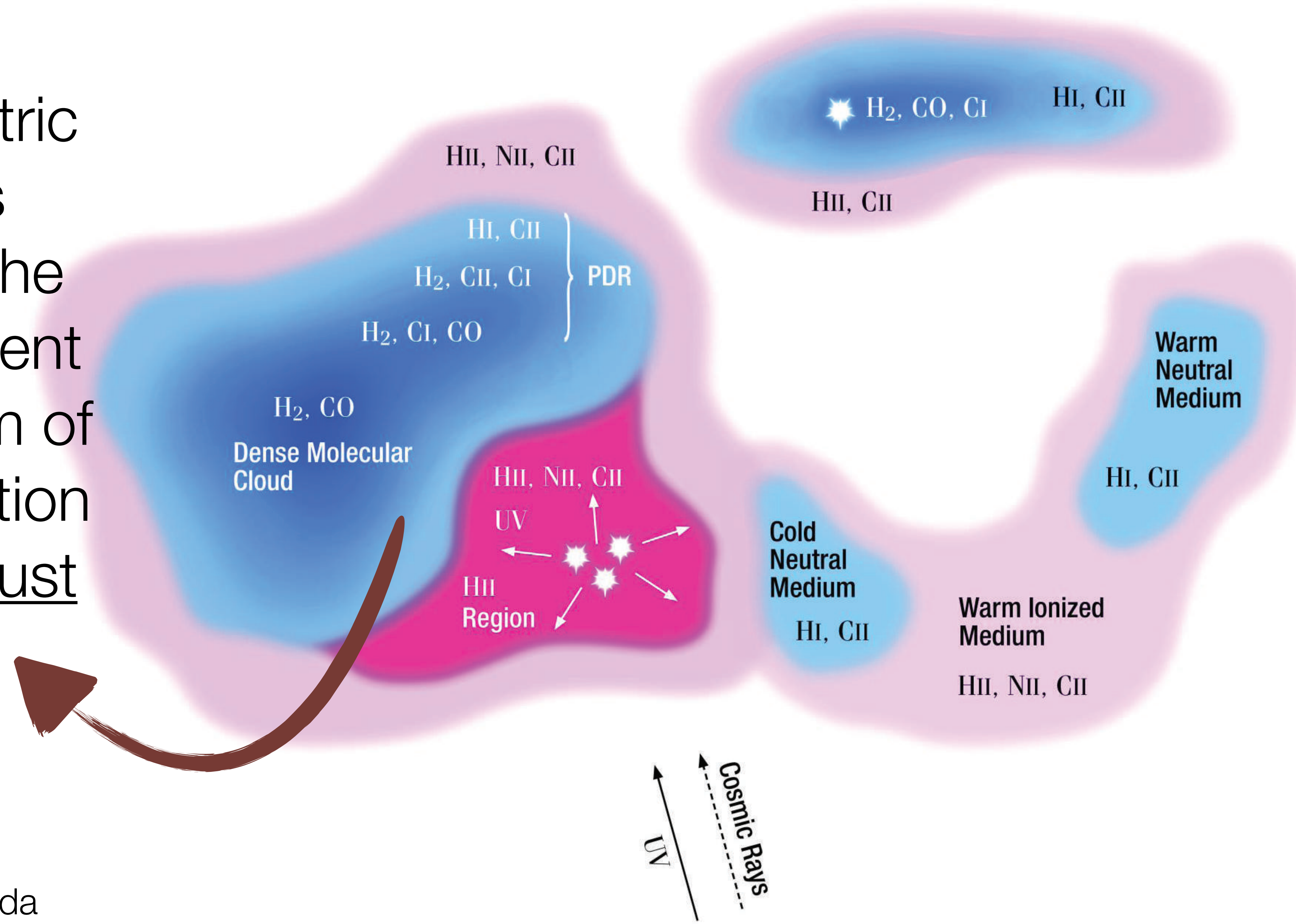
Origin of [CII] in the interstellar medium



Credit: Jorge Pineda

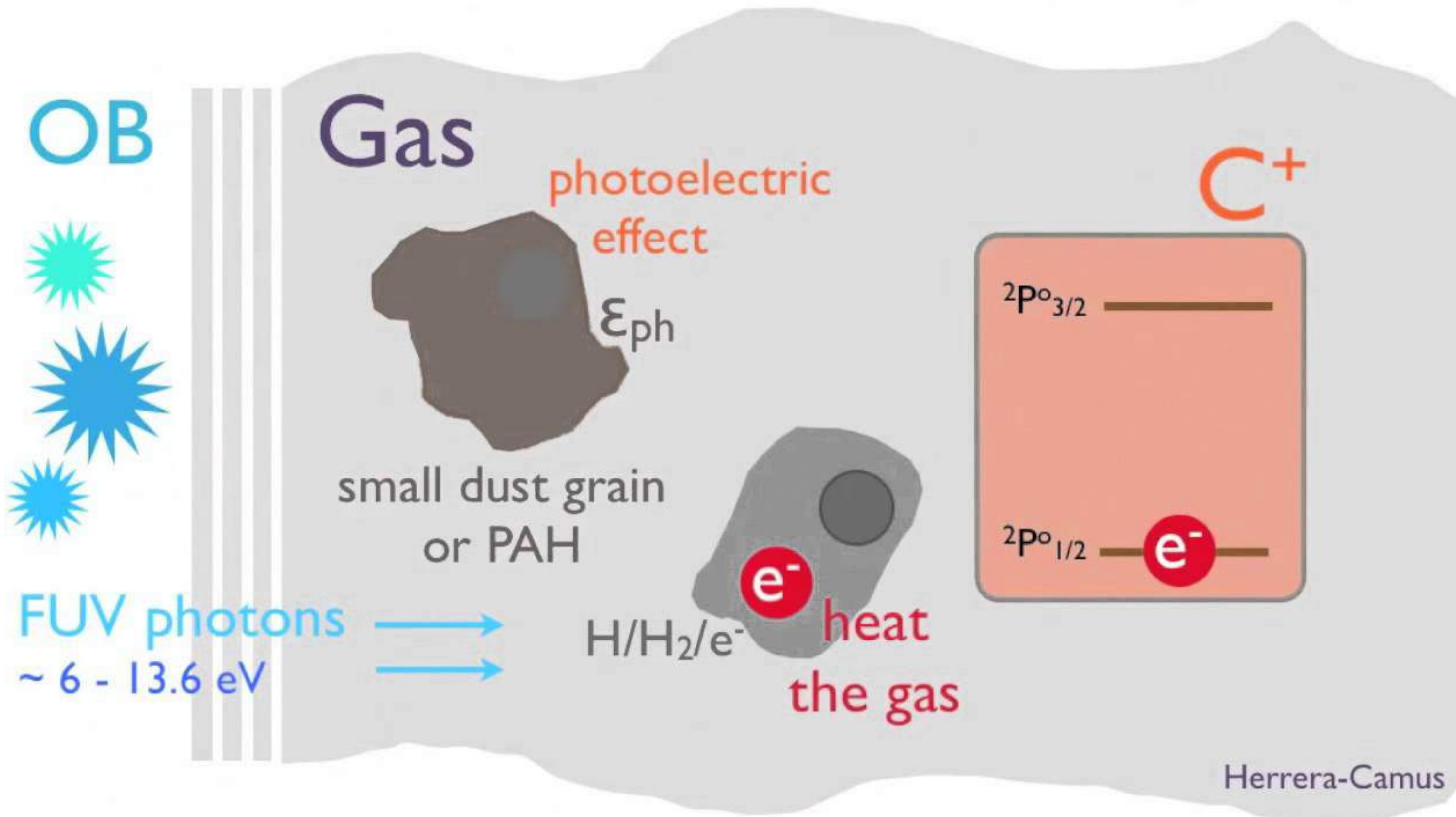
Origin of [CII] in the interstellar medium

Photoelectric effect is perhaps the most efficient mechanism of [CII] excitation → need dust



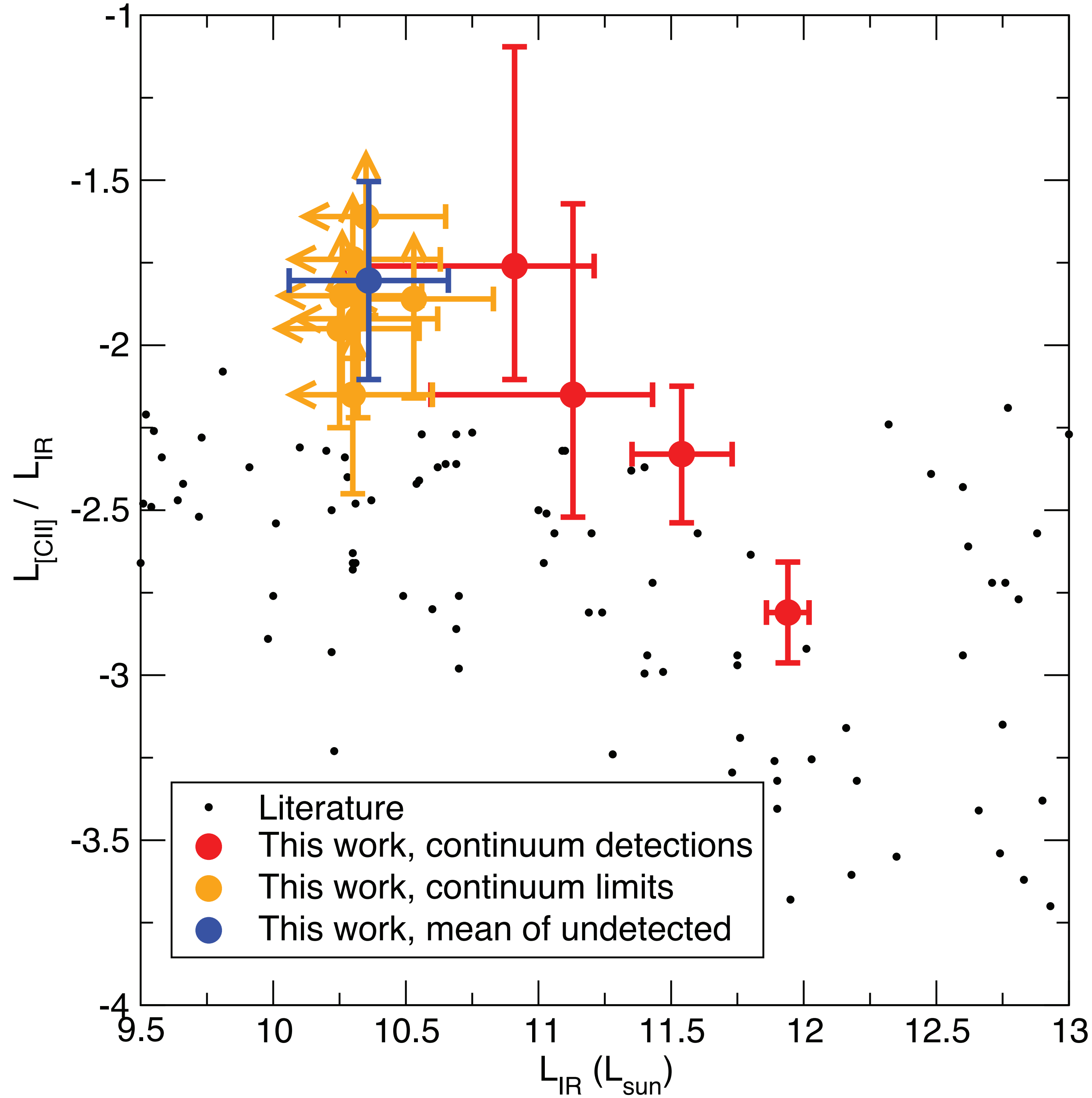
Credit: Jorge Pineda

Photo-electric effect



[CII] more easily excited in some sources?

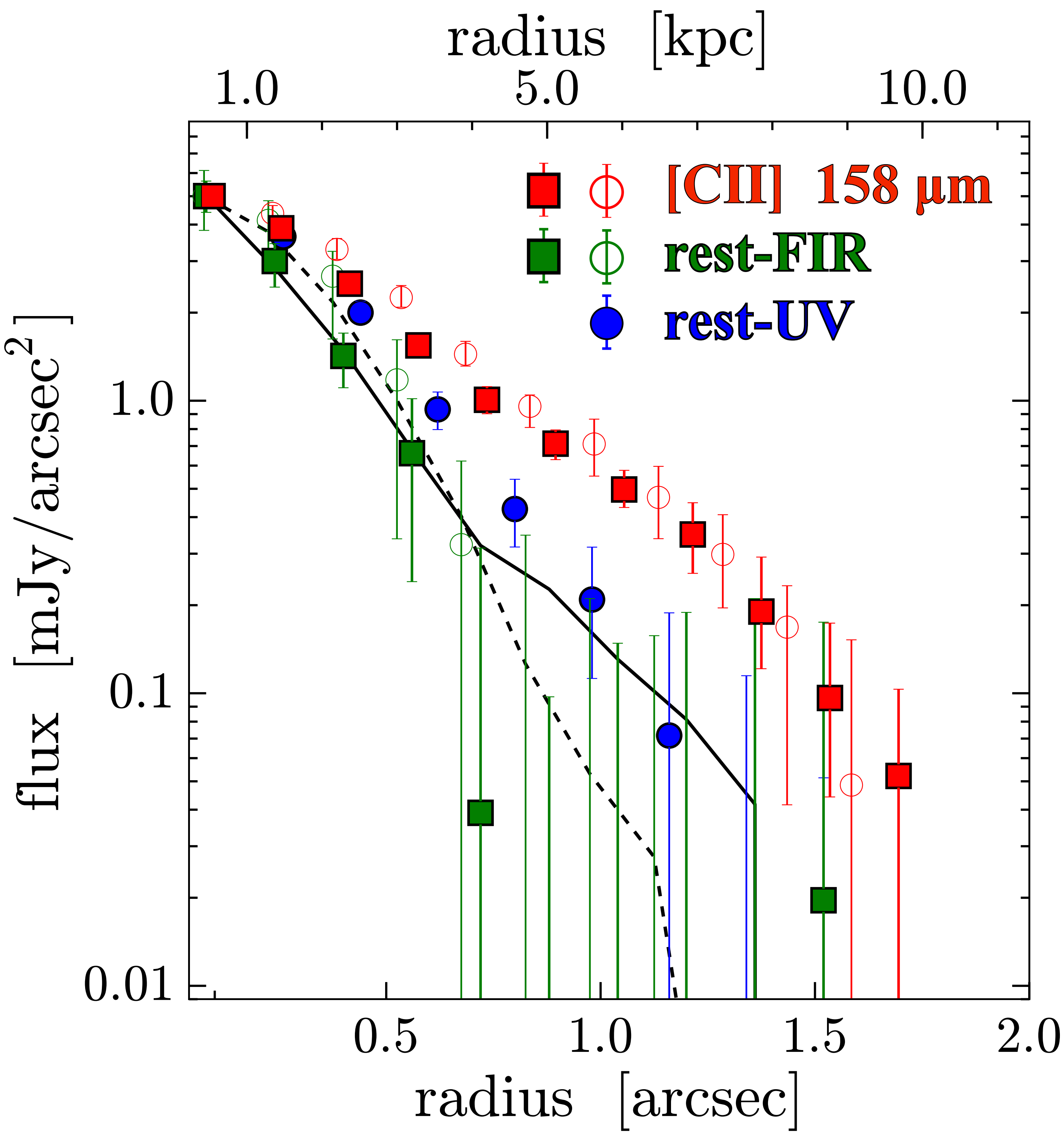
One possible explanation is a higher gas-to-dust ratio: UV light penetrates further into the photo-dissociation region surrounding SF



Capak et al. 2015

[CII] ‘halos’?

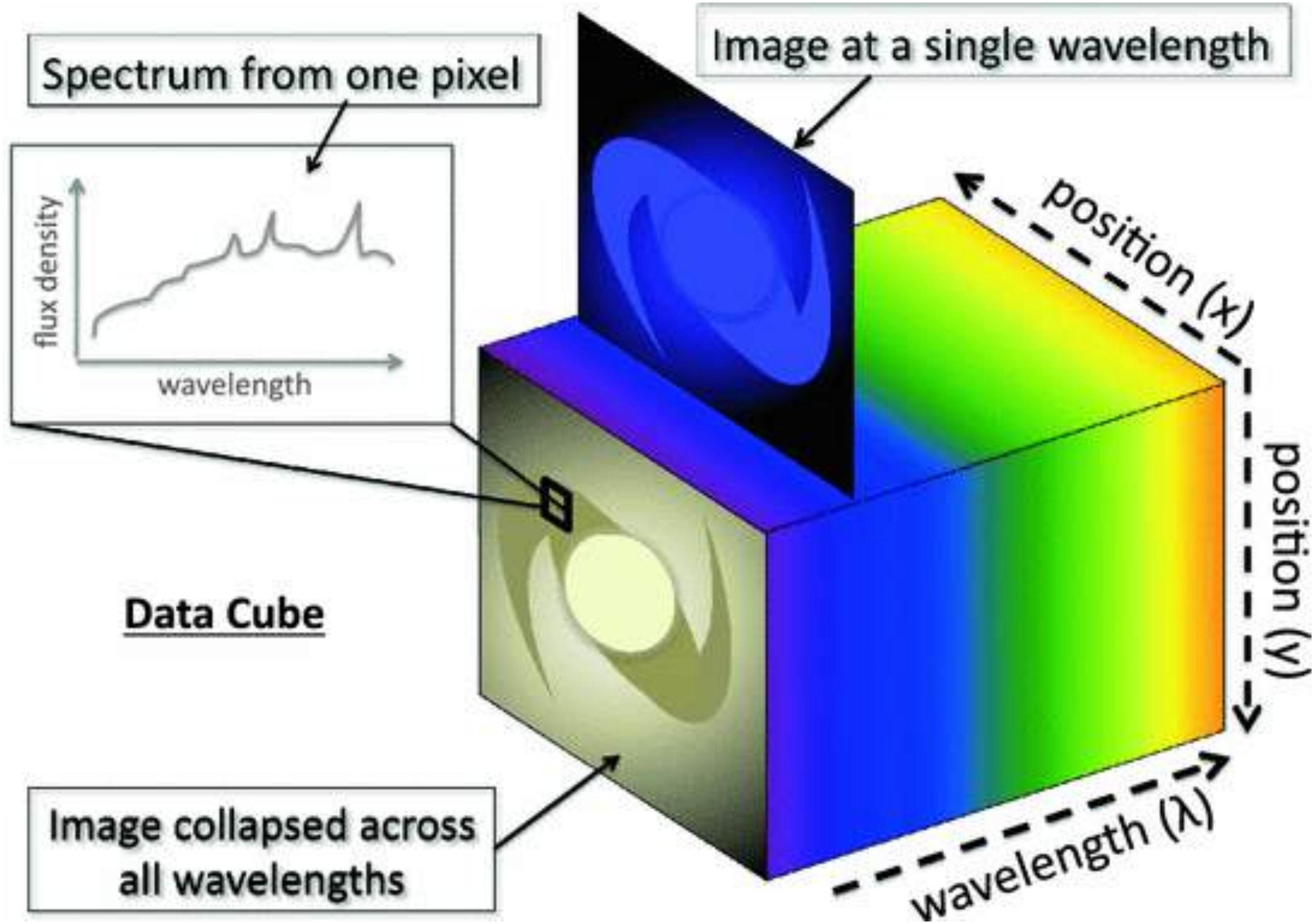
Stacking of z=5-7 sources: [CII] contribution from diffuse gas in the circumgalactic medium (CGM)? Evidence for outflows?



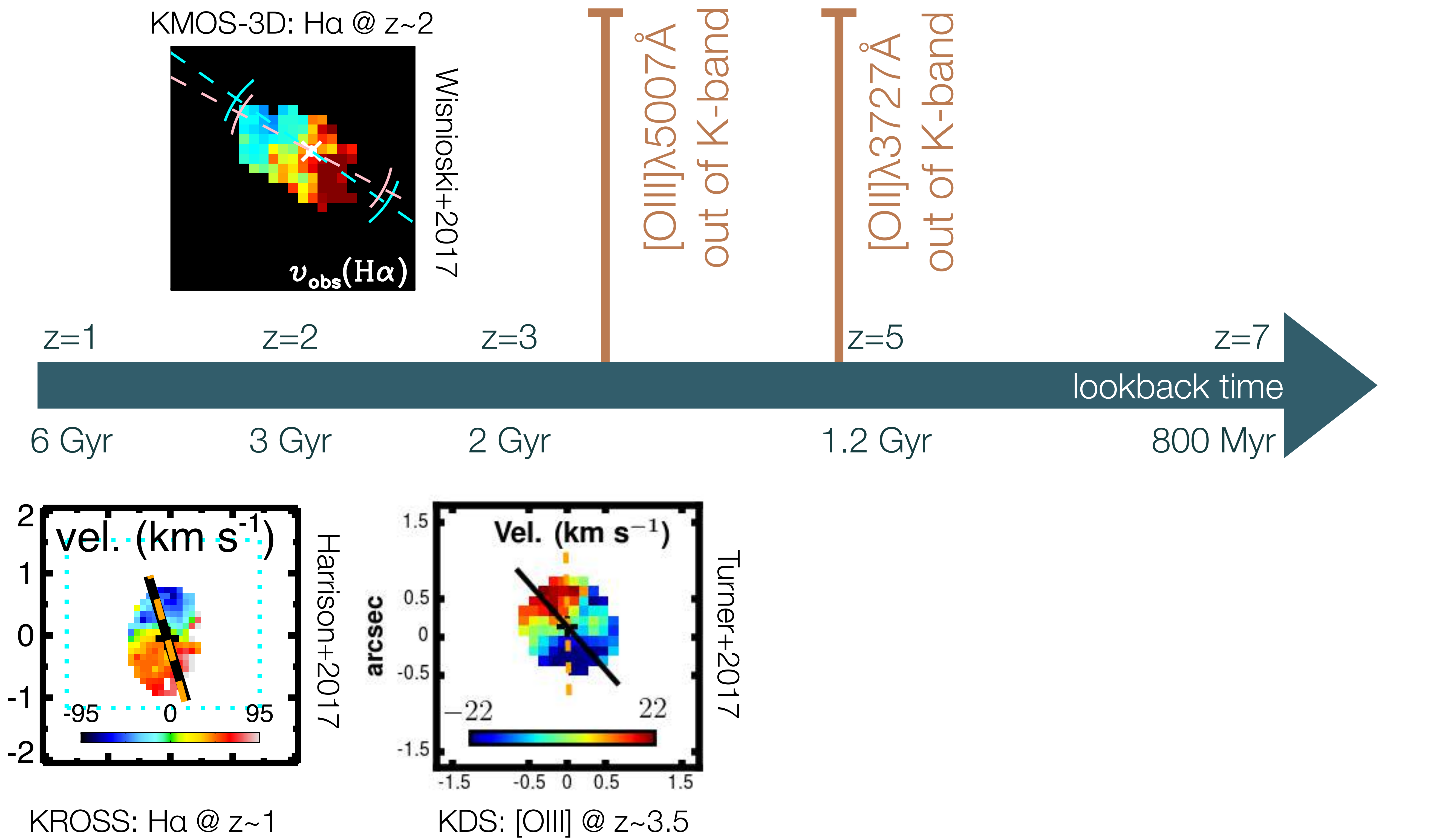
Fujimoto et al. 2019

The potential for kinematics from ALMA

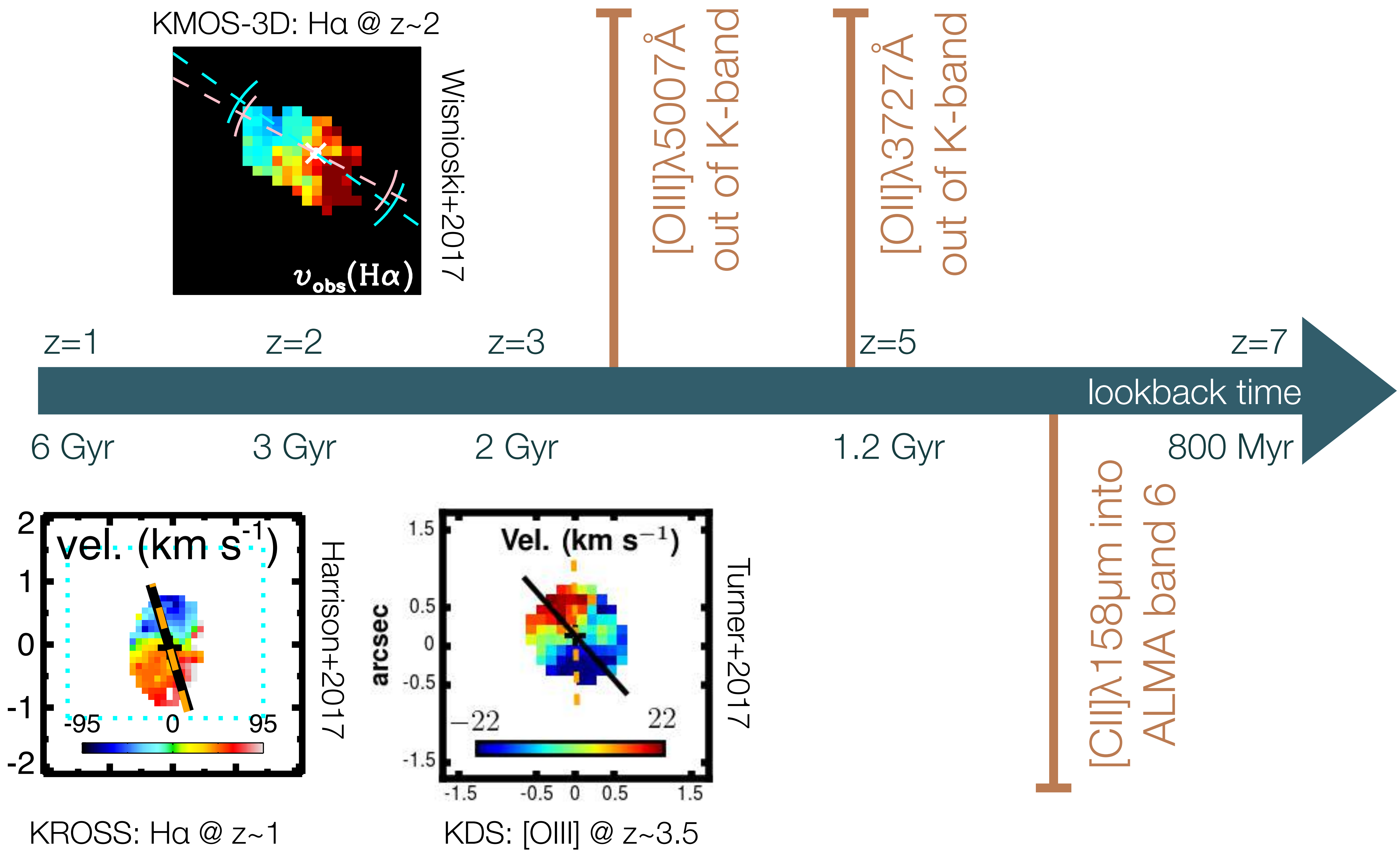
IFU spectroscopy



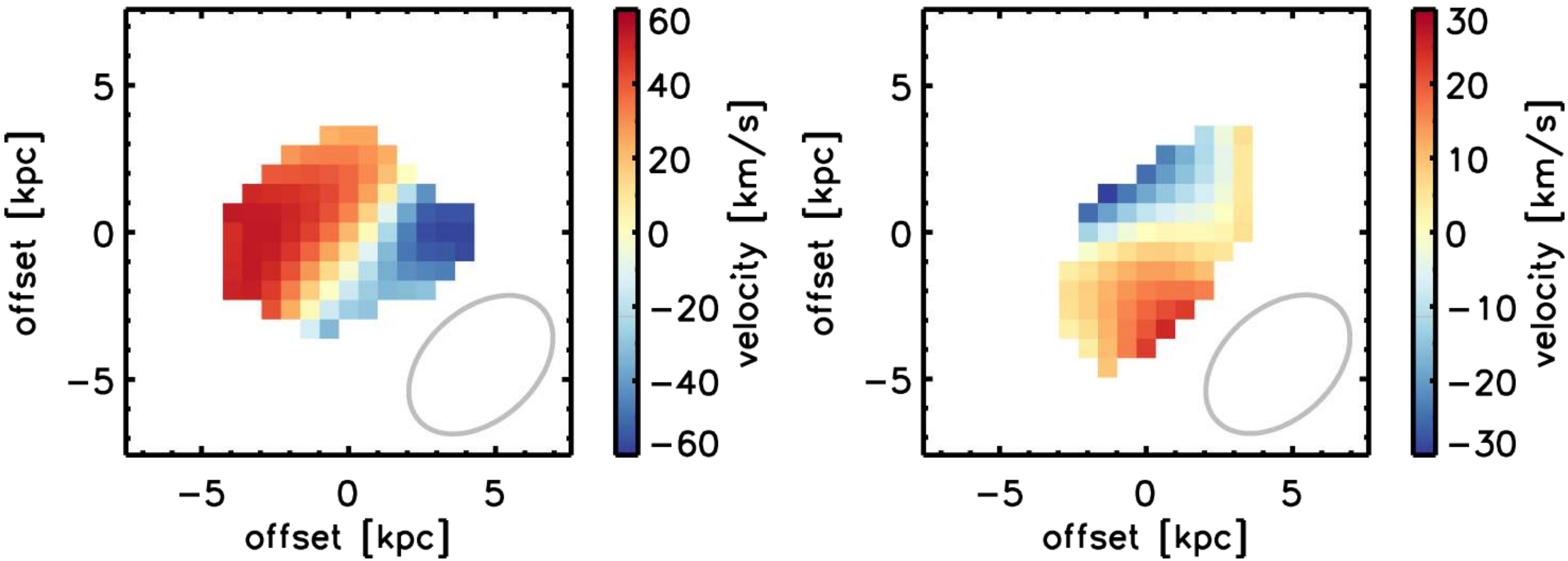
The promise of ALMA for kinematics using [CII]



The promise of ALMA for kinematics using [CII]



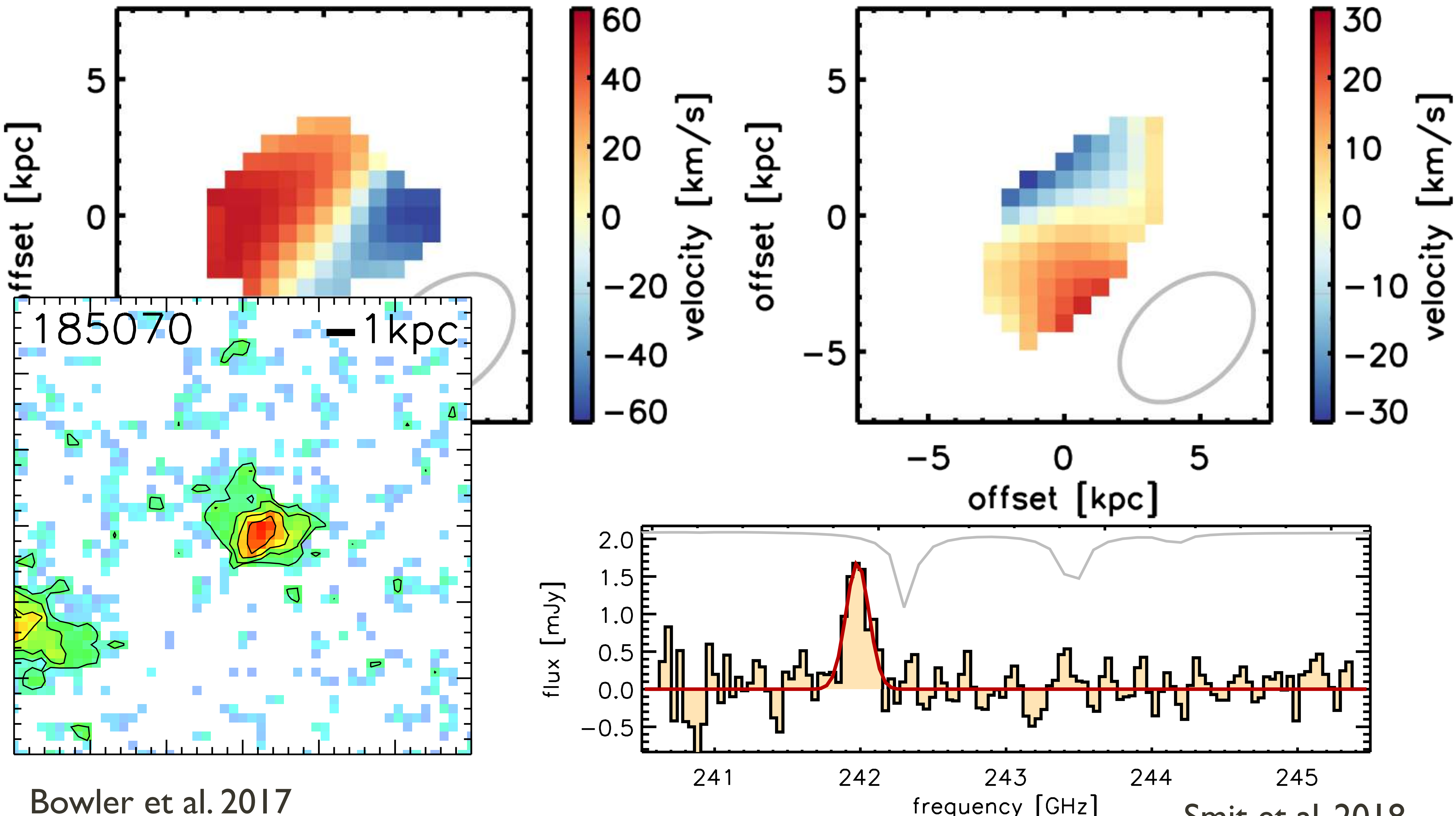
First low-resolution kinematic measurements



Smooth accretion from the cosmic web as an important mechanism for galaxy growth at z~7?

Smit et al. 2018

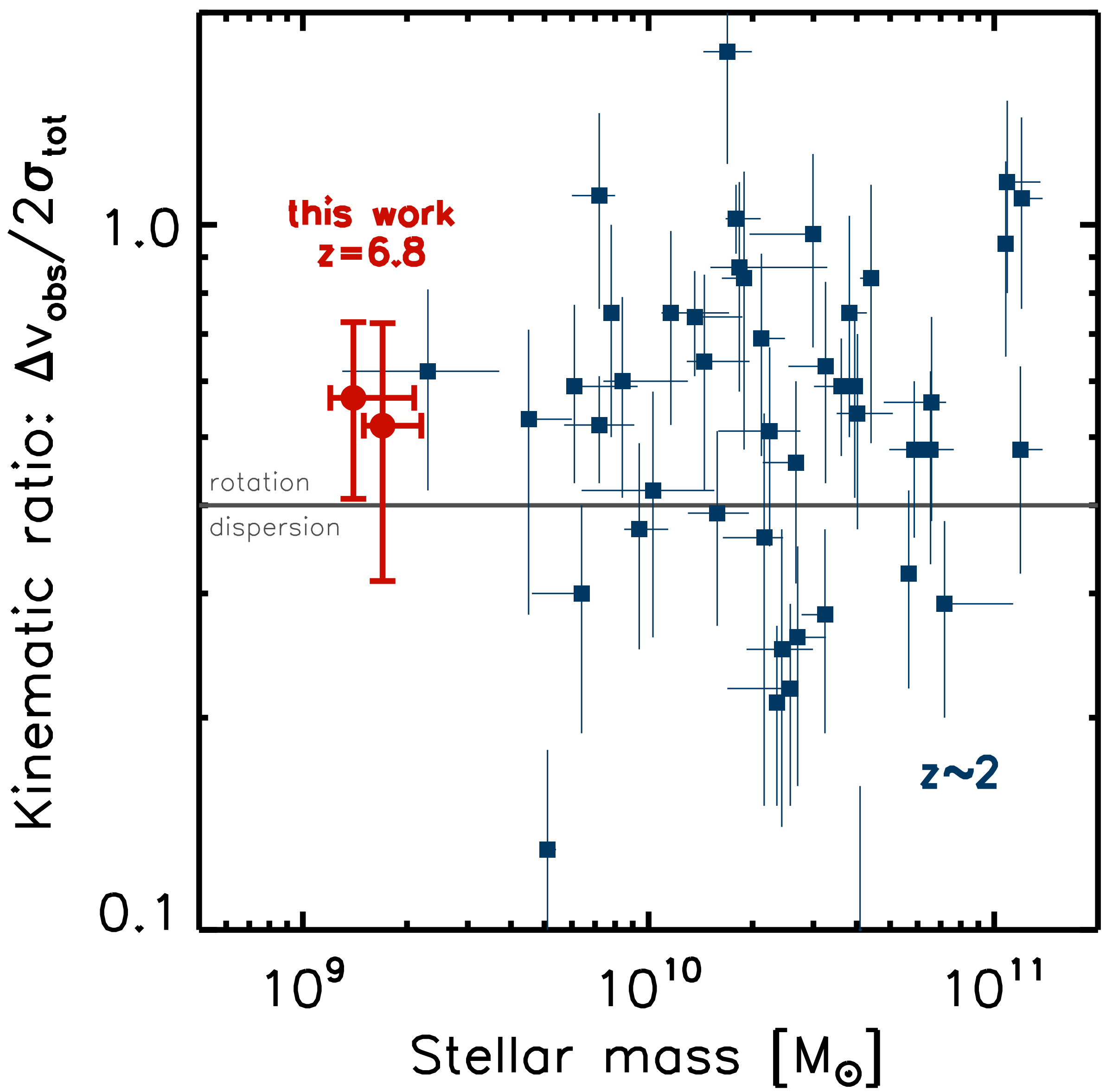
First low-resolution kinematic measurements



Bowler et al. 2017

Smit et al. 2018

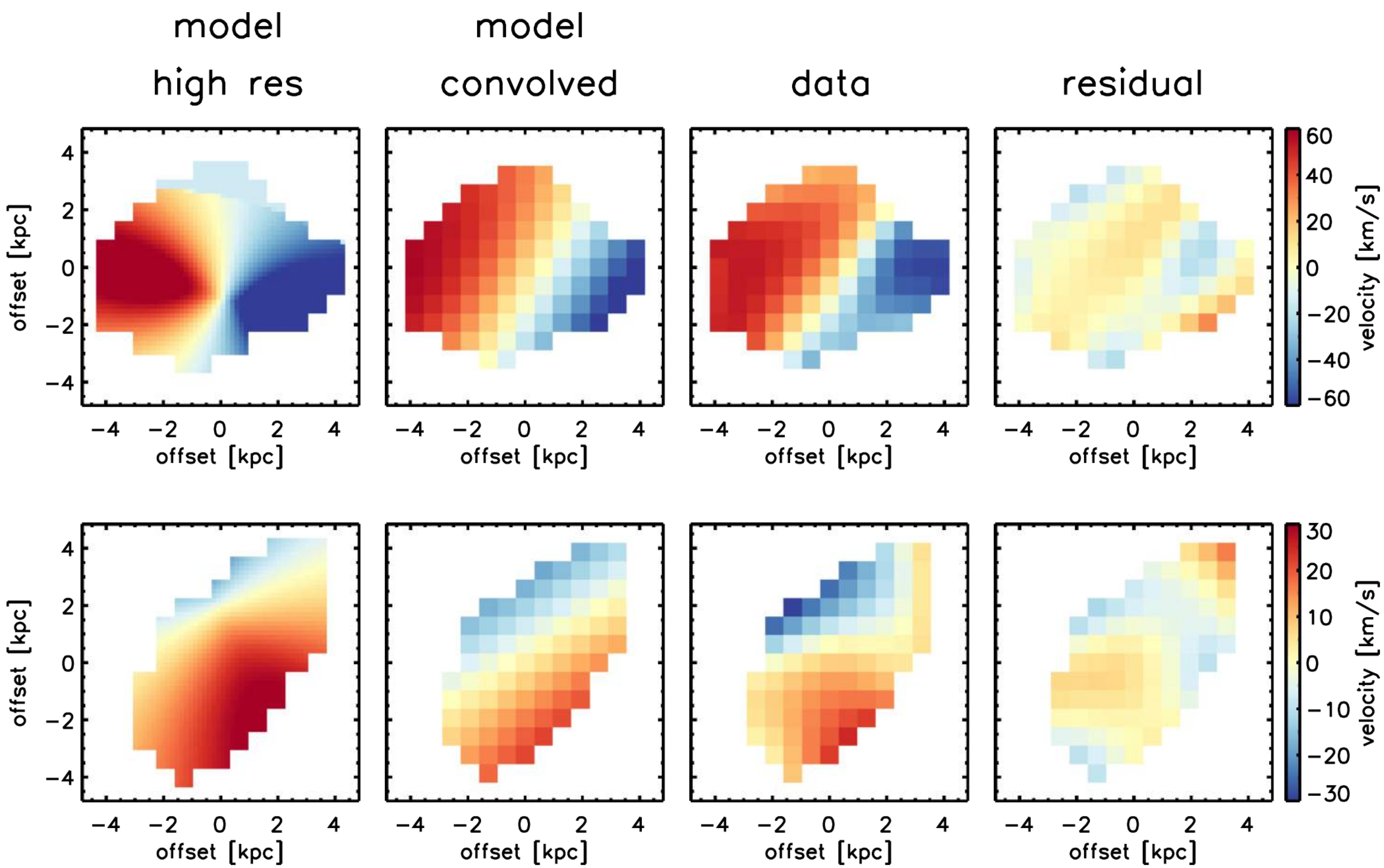
First low-resolution kinematic measurements



Observational classification indicates likely 'rotation-dominated' systems

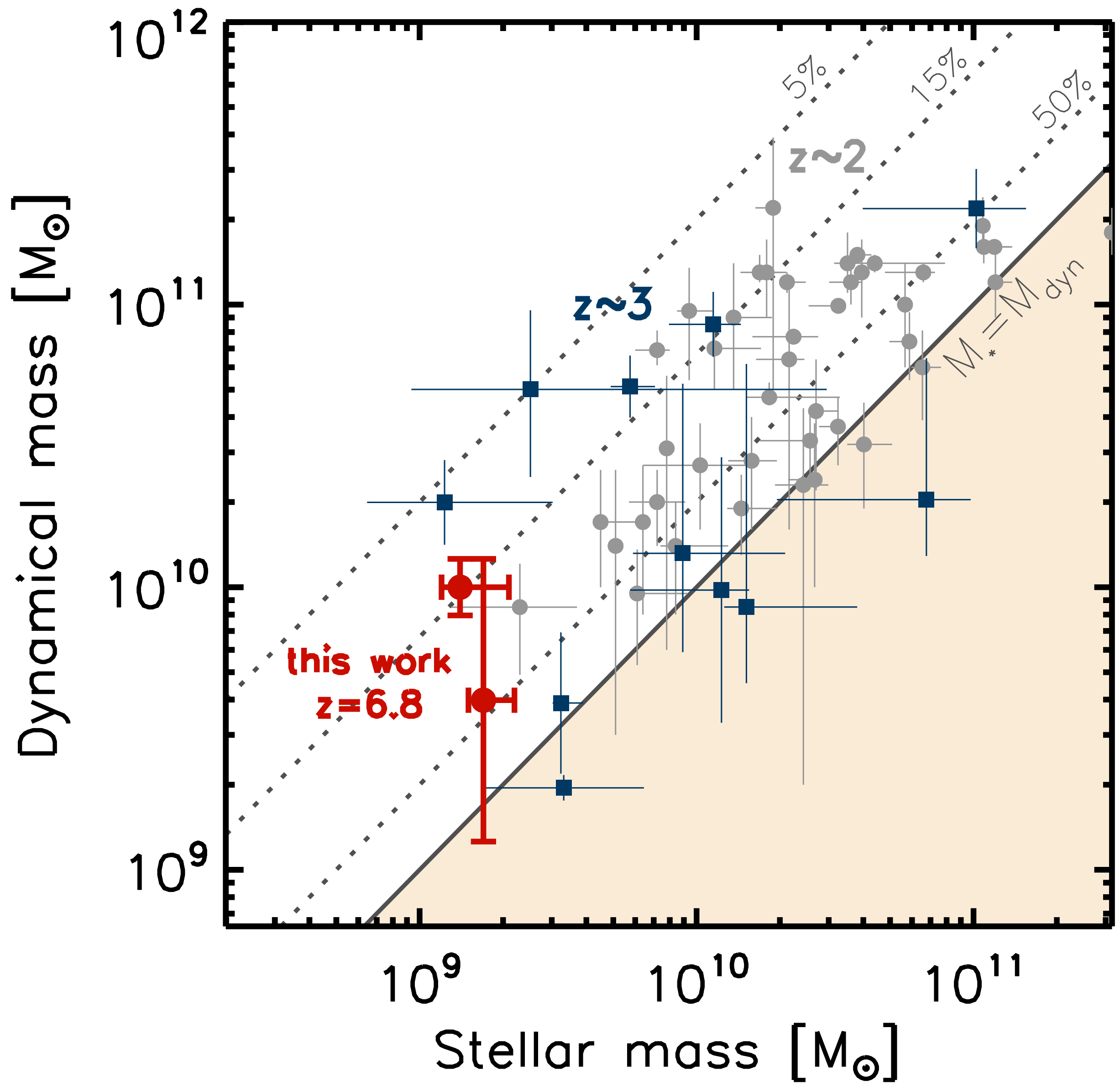
First low-resolution kinematic measurements

Disk model works well, however mergers or gas outflows are still possible



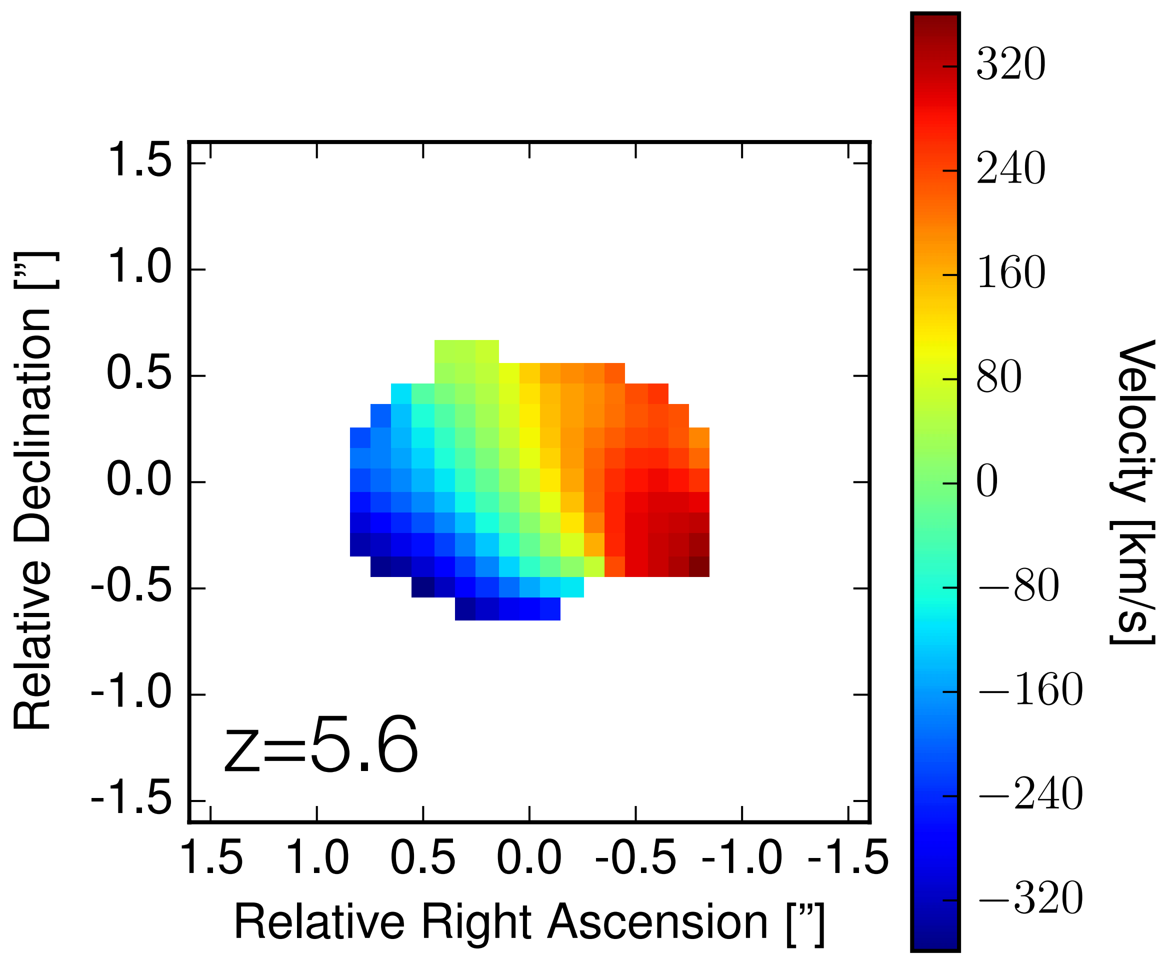
Dynamical masses from [CII]

15-50% stellar mass fraction suggest gas rich systems - similar to z~2-3 star-forming disks

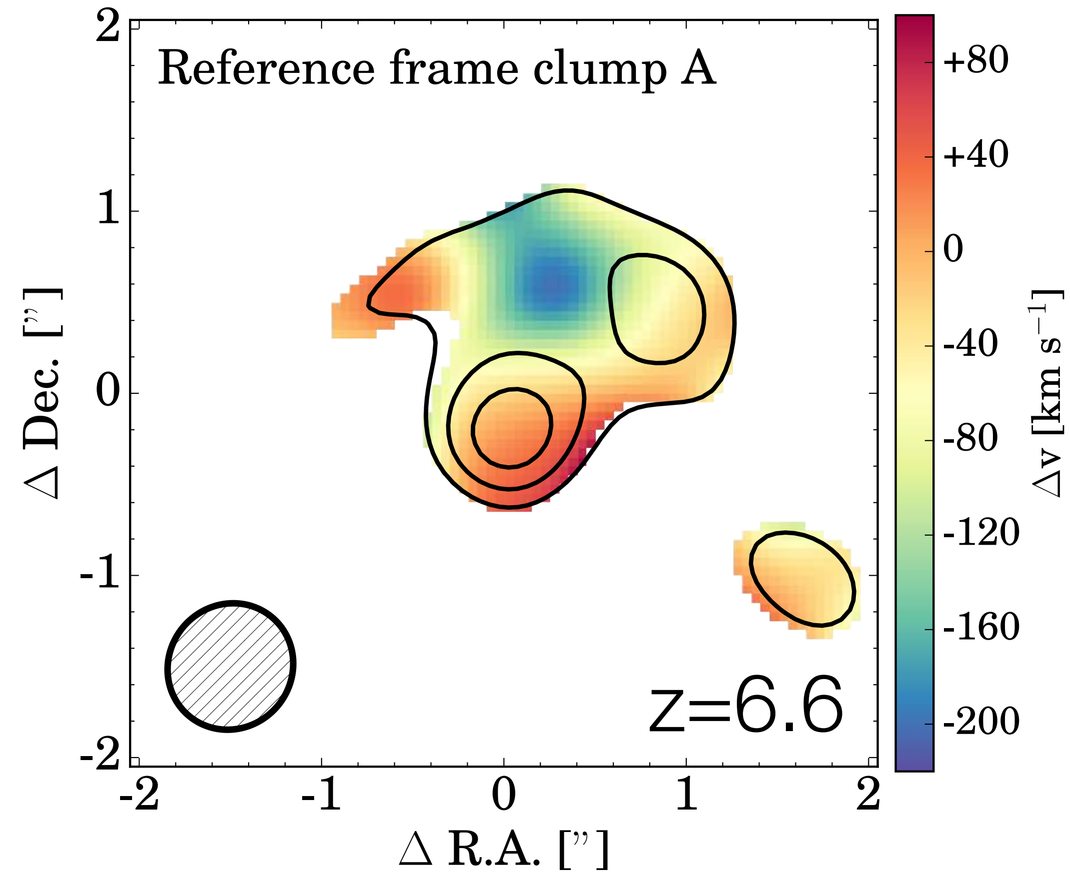


Smit et al. 2018

Rotation vs. chaotic motion



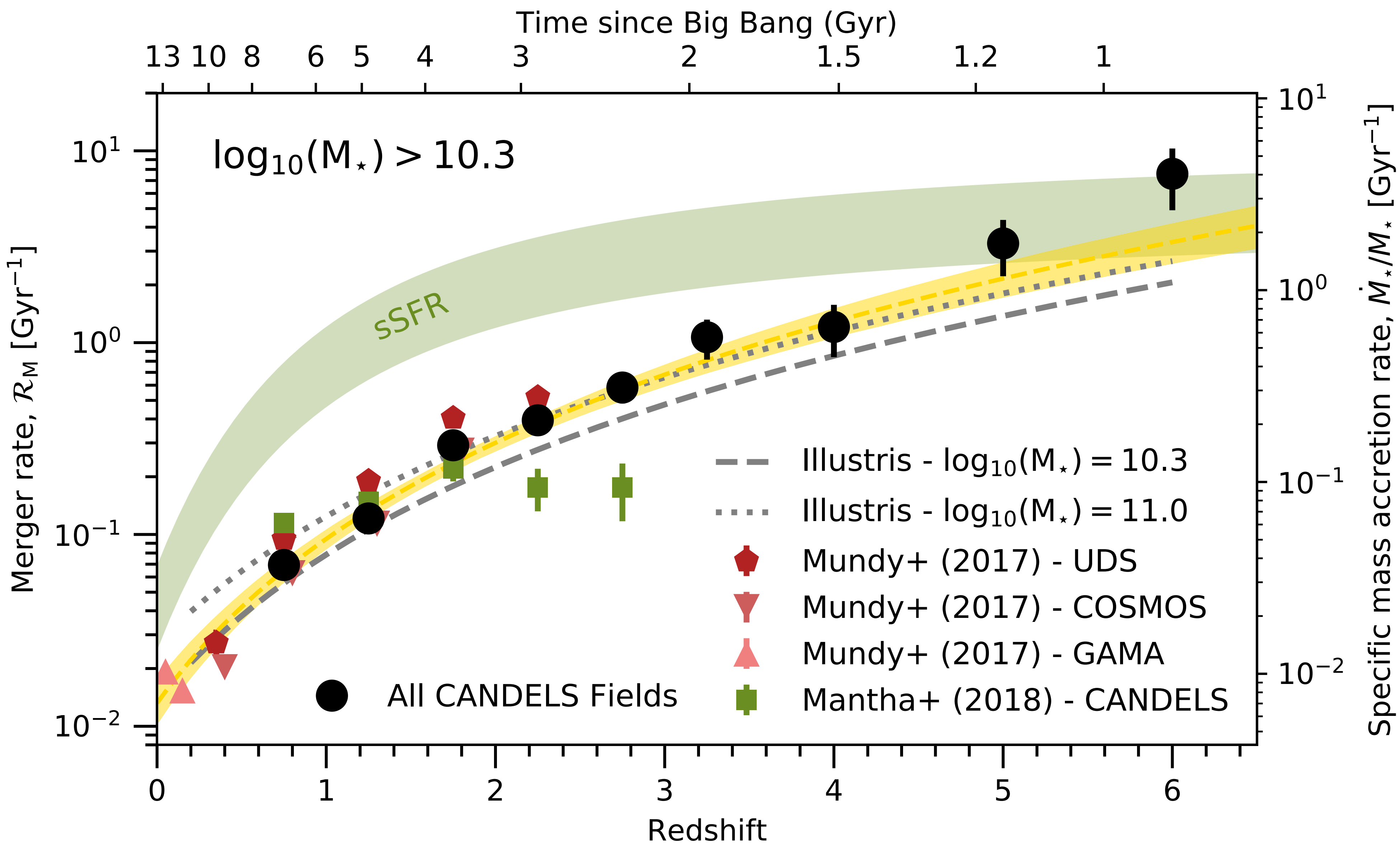
Jones et al., 2017



Matthee et al., 2017

What fraction of the galaxy population is chaotic vs. settled?

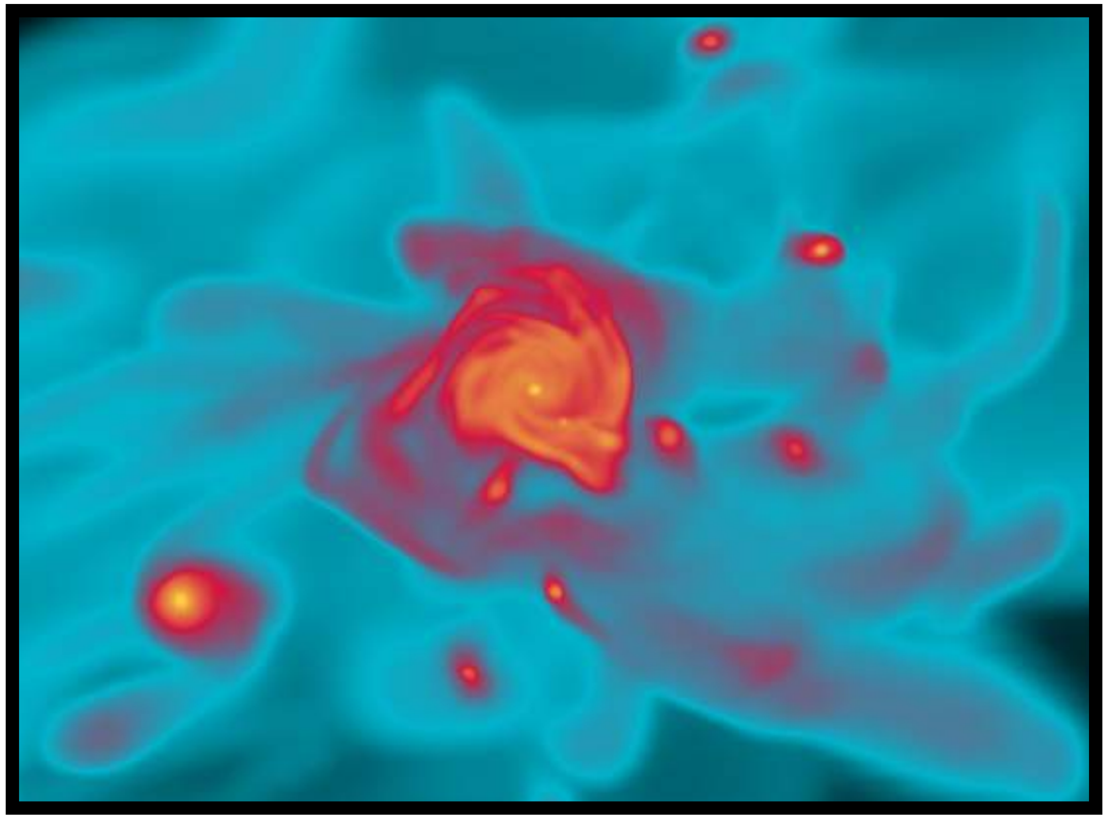
Contribution of mergers vs smooth accretion



At z>6 mergers and smooth accretion might contribute equally to stellar mass growth

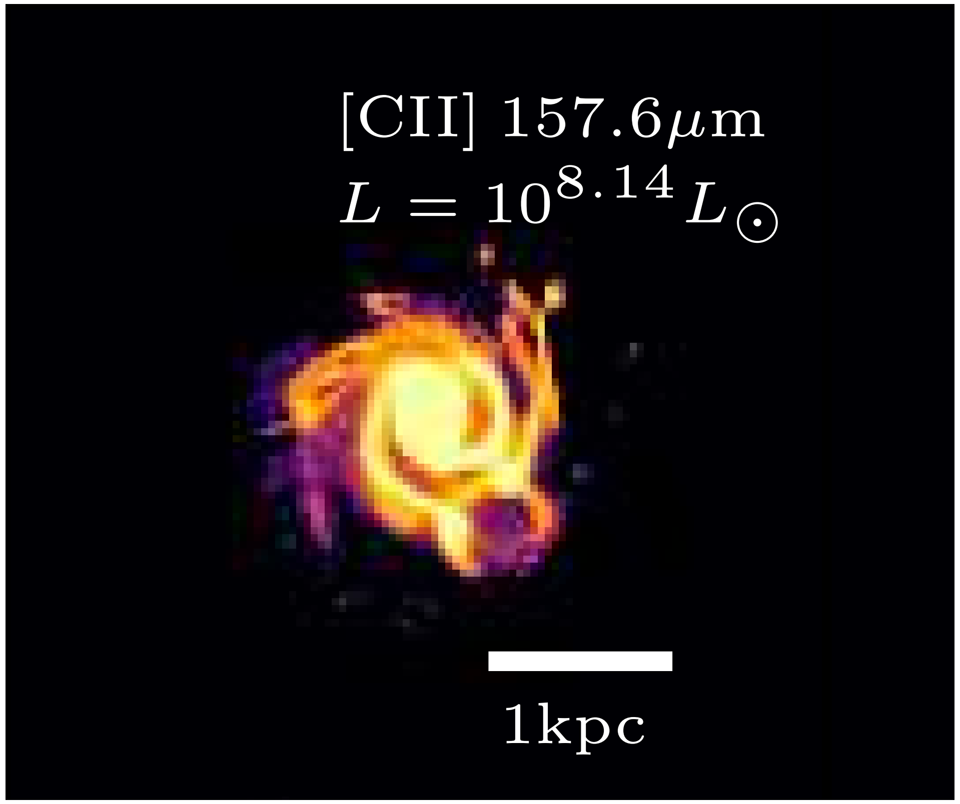
Duncan, et al., 2019

Simulation predictions for [CII]



Pallottini, et al., 2017;2019

Simulations predict highly time variable morphologies, but ordered rotation is common

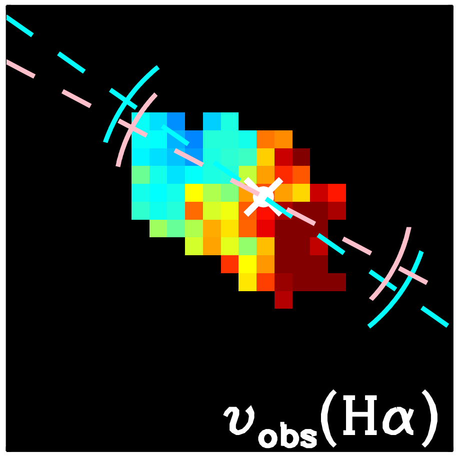


Katz, et al., 2019

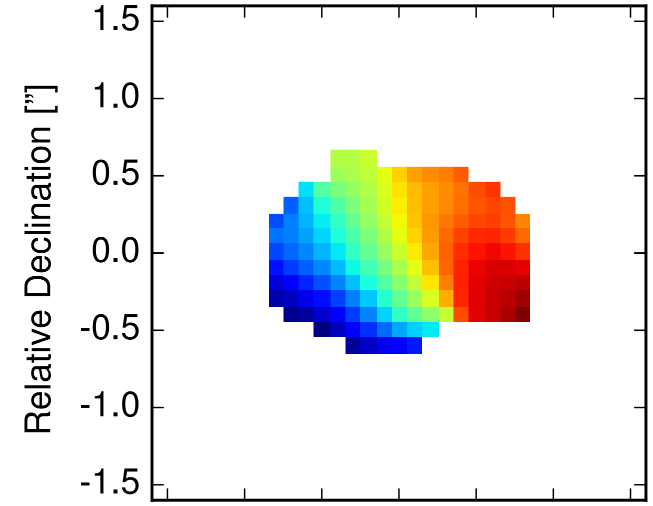
see also Pawlik et al. 2011, Romano-Diaz et al. 2011, Feng et al. 2015

The promise of ALMA for kinematics using [CII]

KMOS-3D: Hα @ z~2



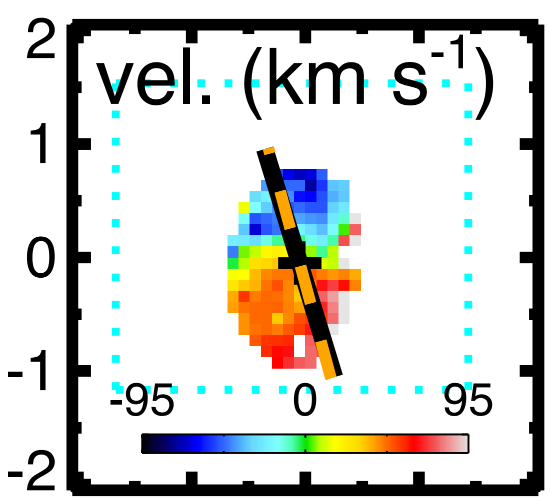
Wisnioski+2017



z=1 z=2 z=3 z=5 z=7

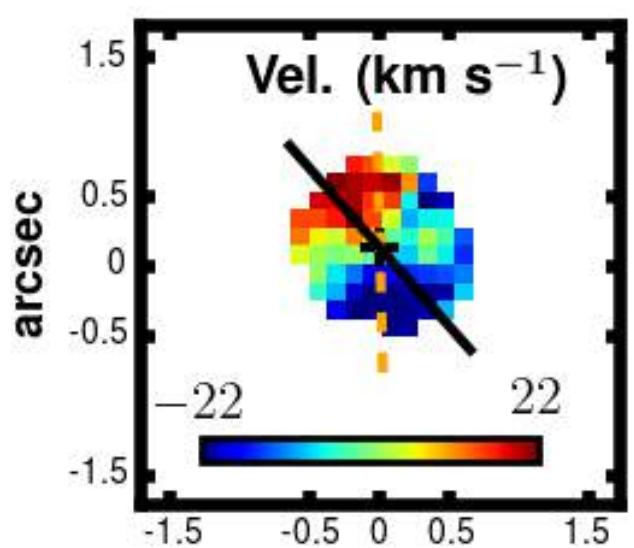
lookback time

6 Gyr 3 Gyr 2 Gyr 1.2 Gyr 800 Myr



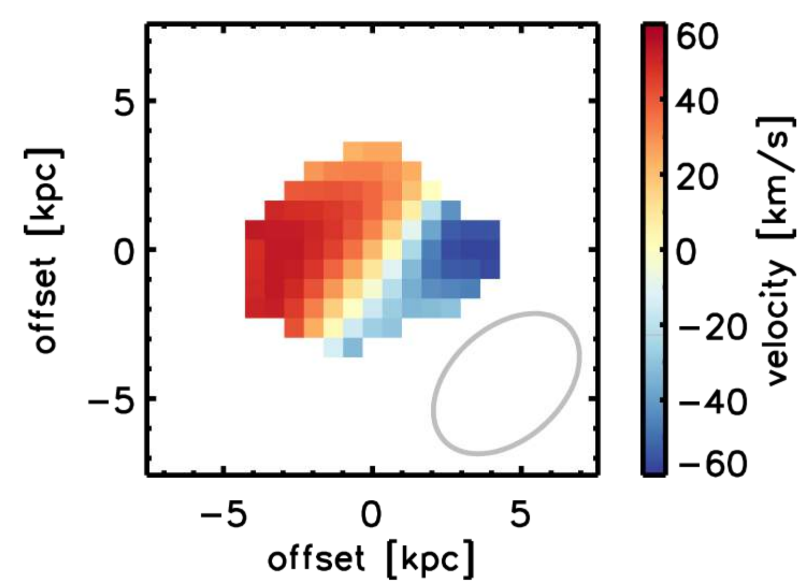
Harrison+2017

KROSS: Hα @ z~1



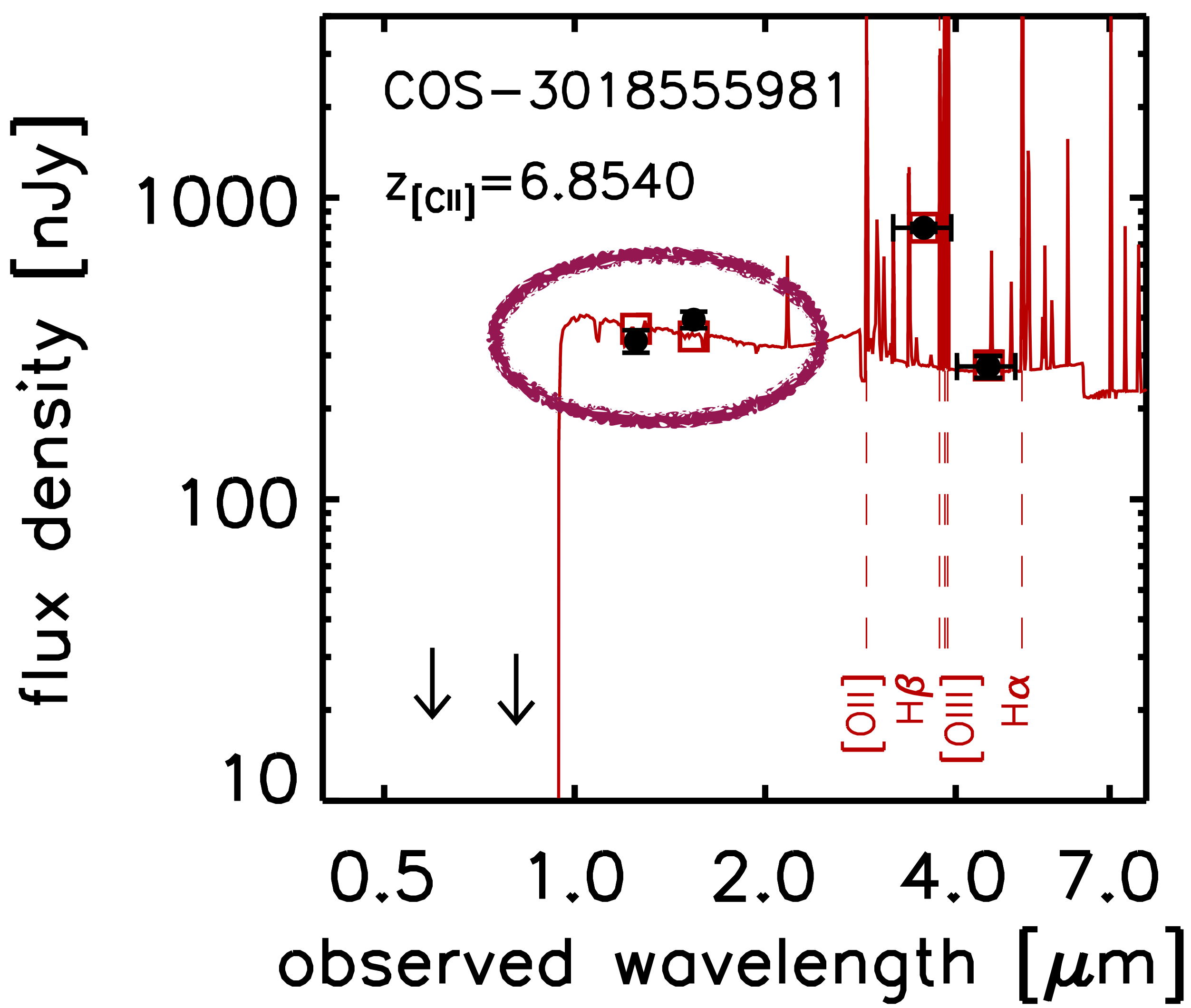
Turner+2017

KDS: [OIII] @ z~3.5



Highly ionised gas from spectroscopy

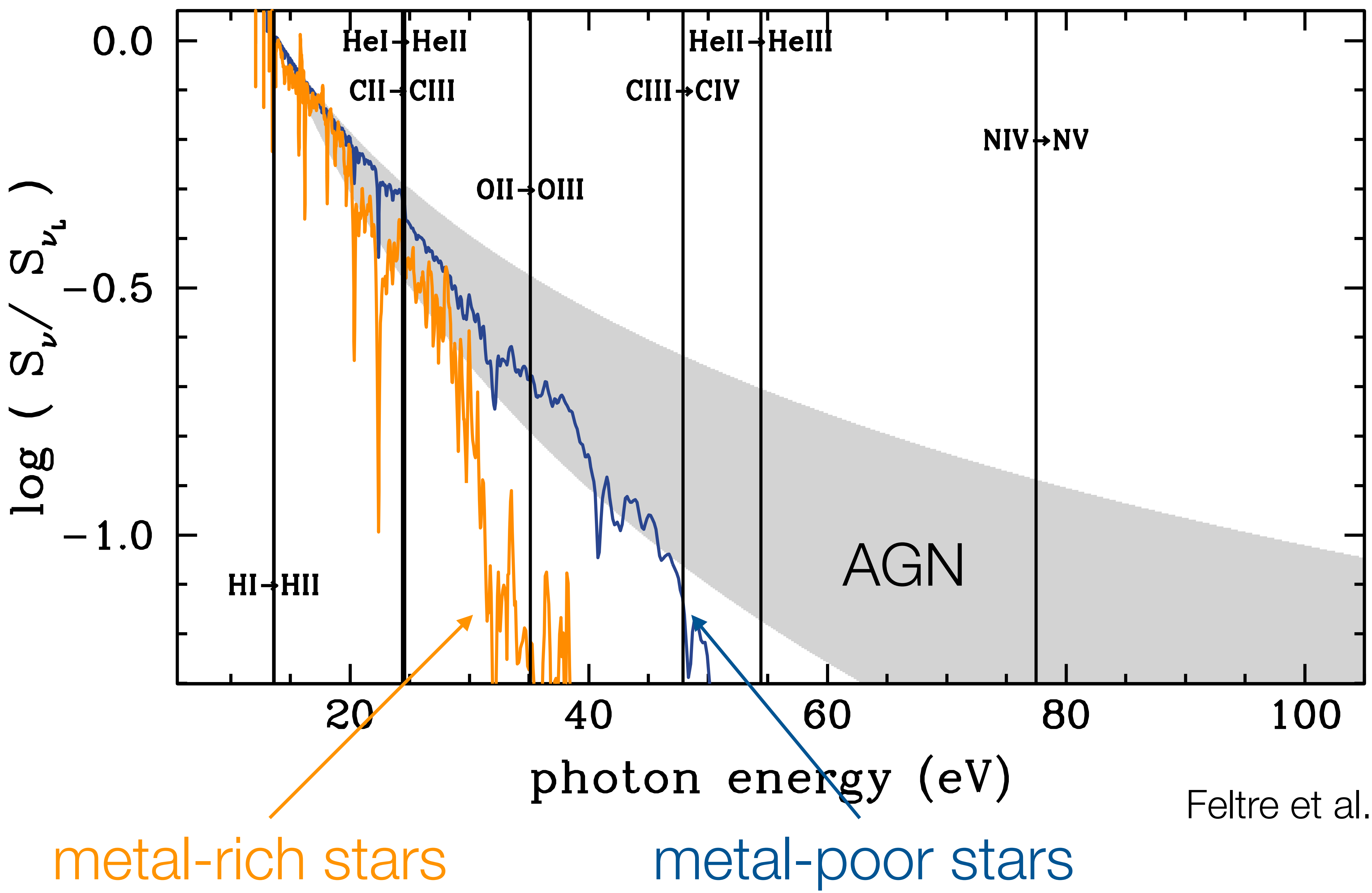
High-EW [OIII] emitters



- Given the measurements of high-EW ionisation lines from Spitzer we might also expect fainter lines in the rest-frame UV

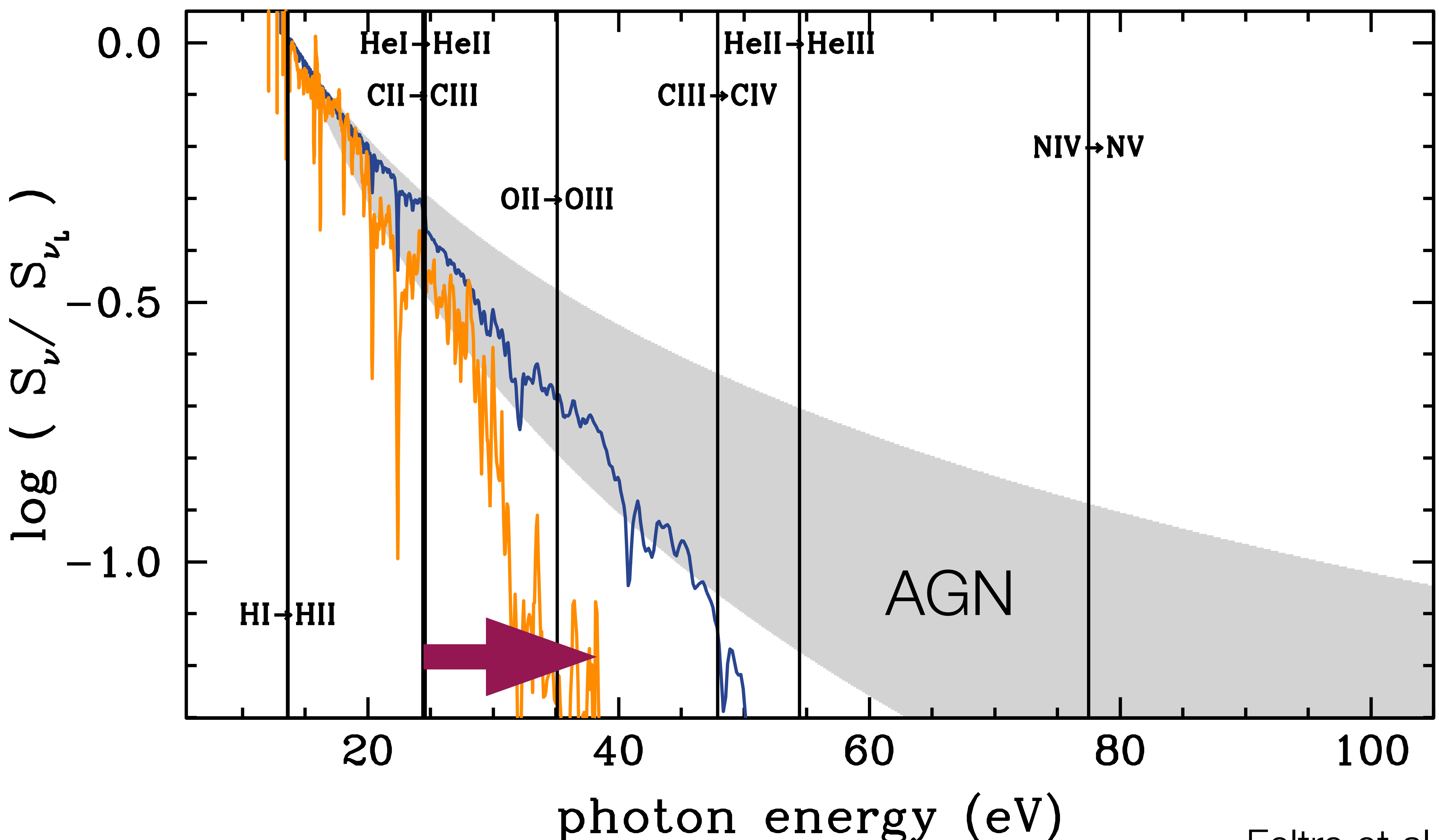
Smit et al., 2014; 2015, Roberts-Borsani et al. 2016

The origin of ionising photons



Feltre et al., 2016

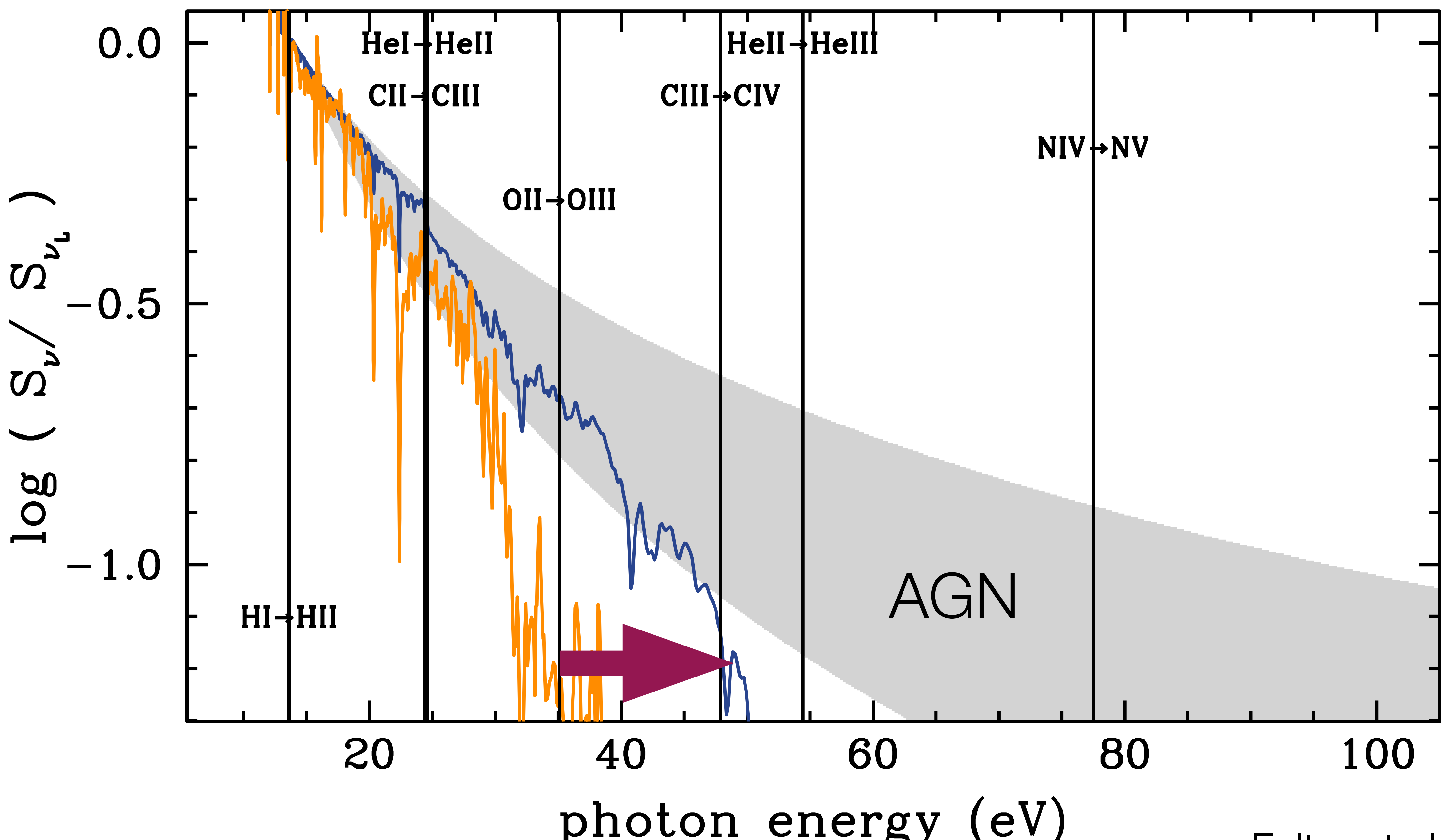
The origin of ionising photons



Feltre et al., 2016

Expect CIII] 1907,1909Å

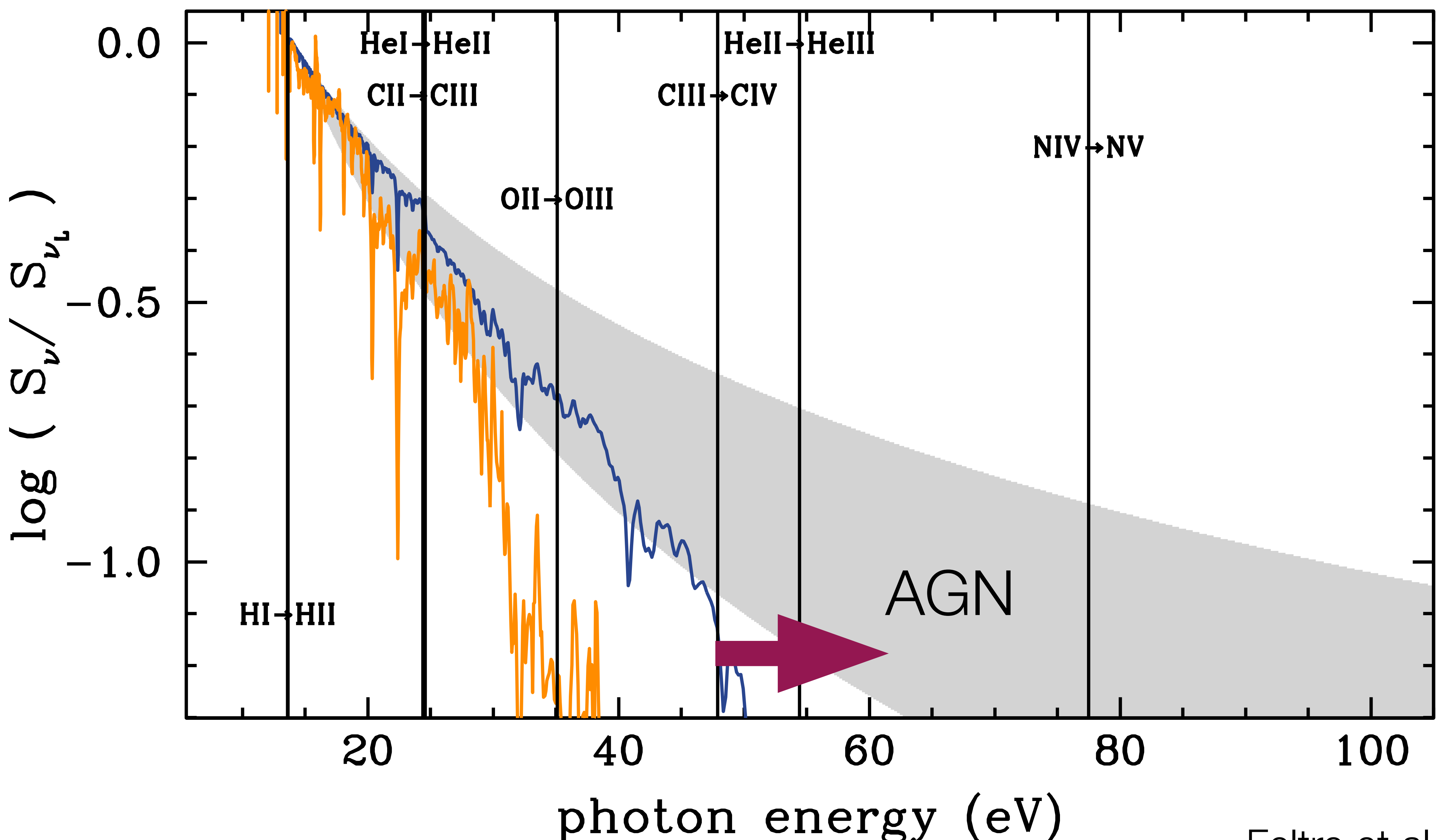
The origin of ionising photons



Feltre et al., 2016

Expect [OIII] 1661,1666,5007Å and 88μm

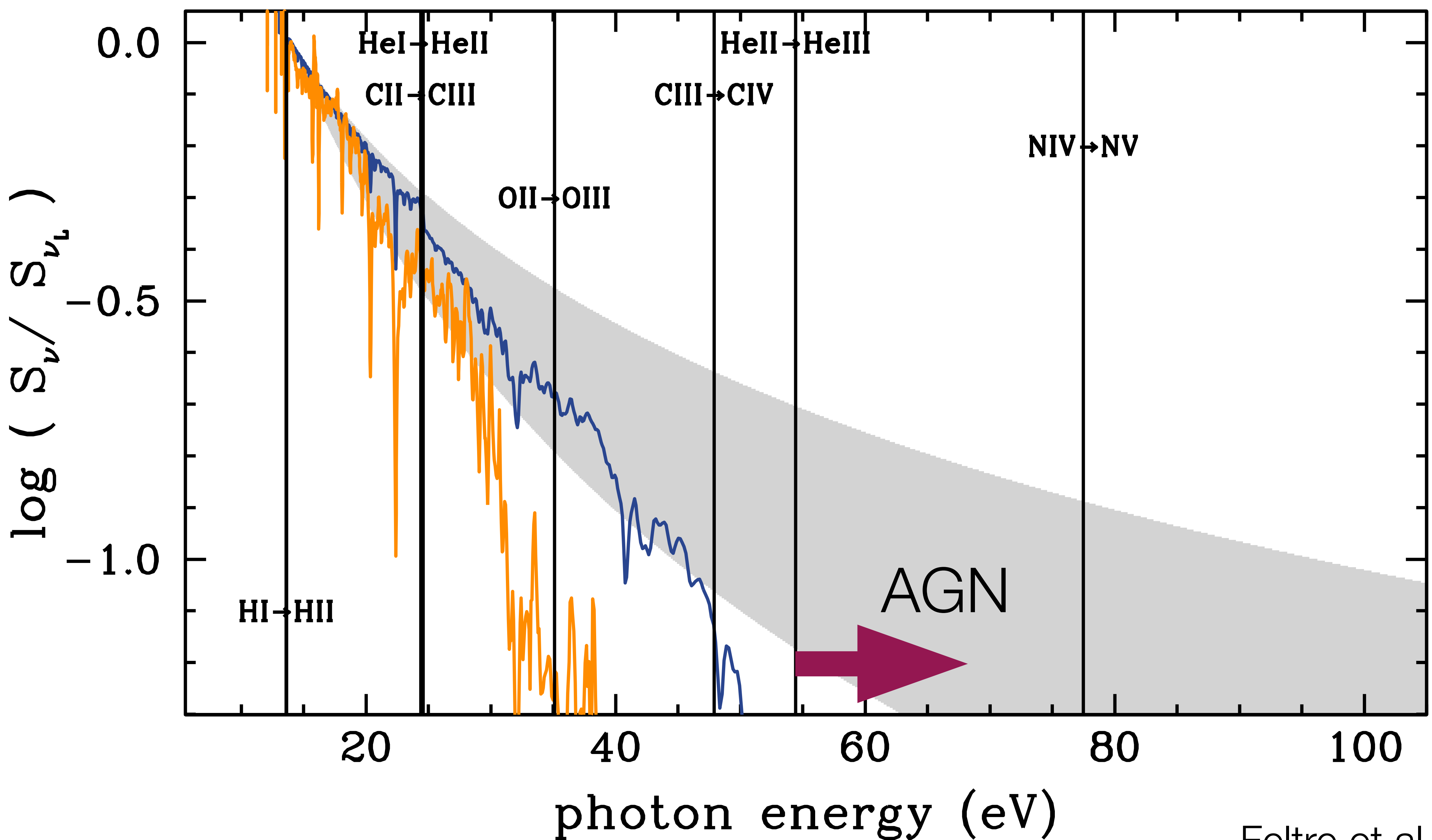
The origin of ionising photons



Feltre et al., 2016

Expect CIV 1548,1550Å

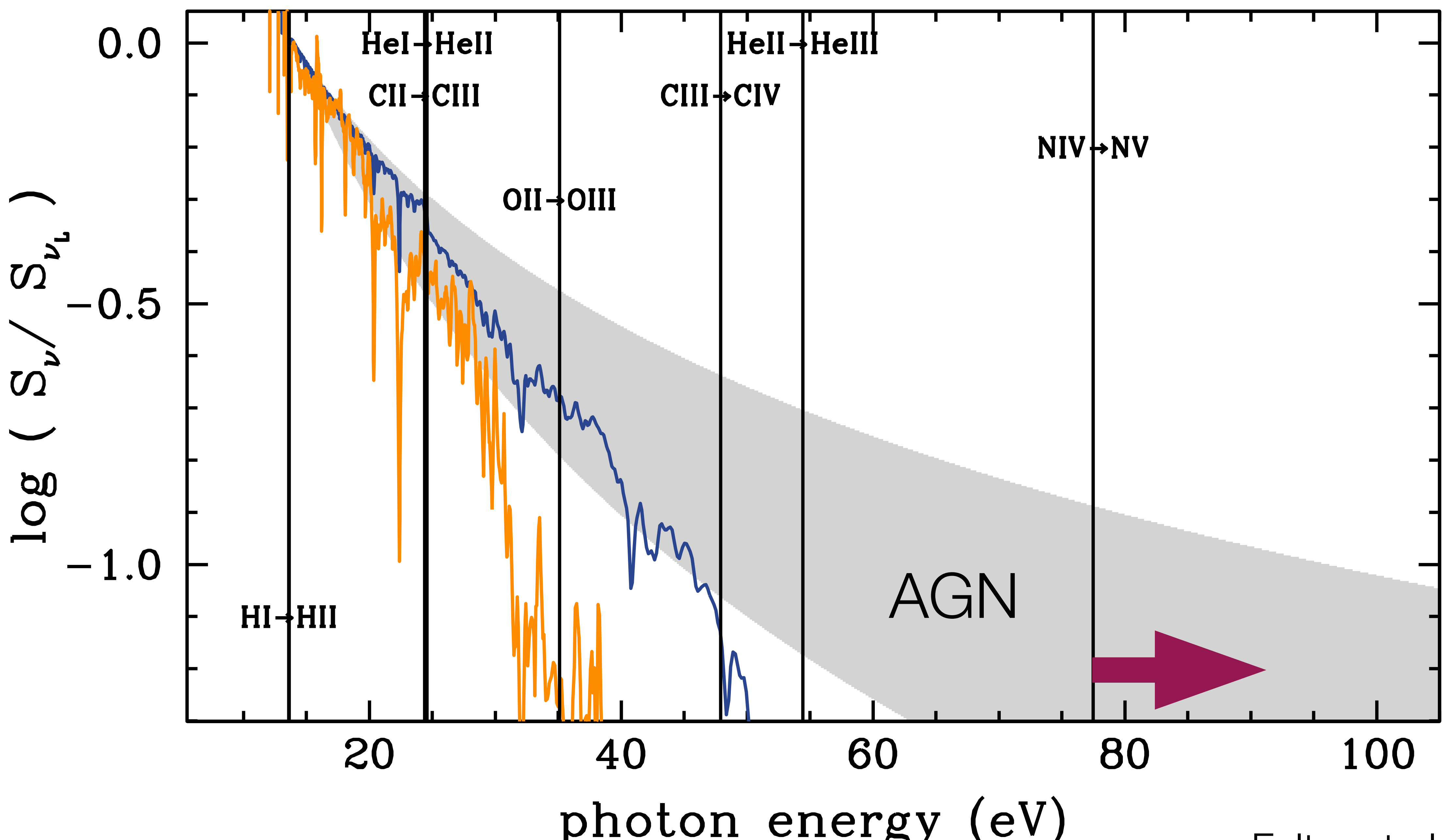
The origin of ionising photons



Feltre et al., 2016

Expect HeII 1640Å

The origin of ionising photons

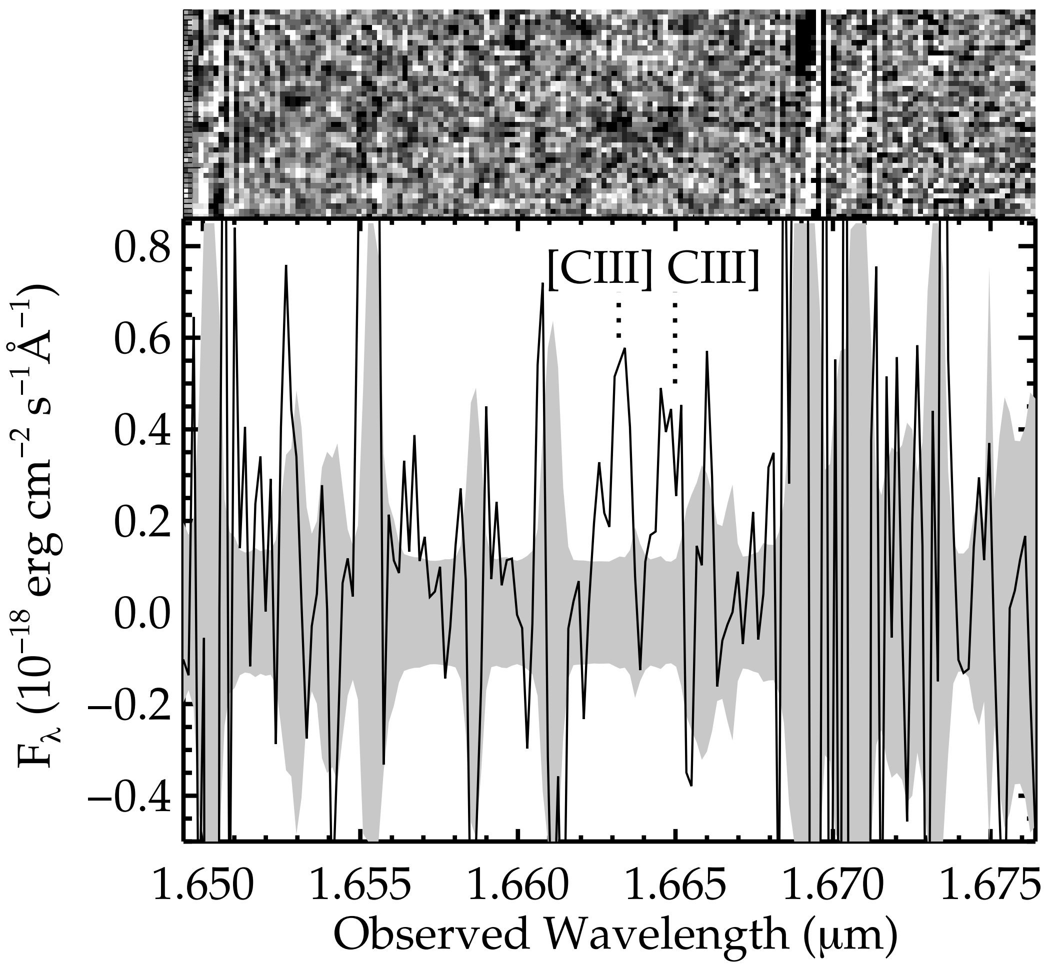


Feltre et al., 2016

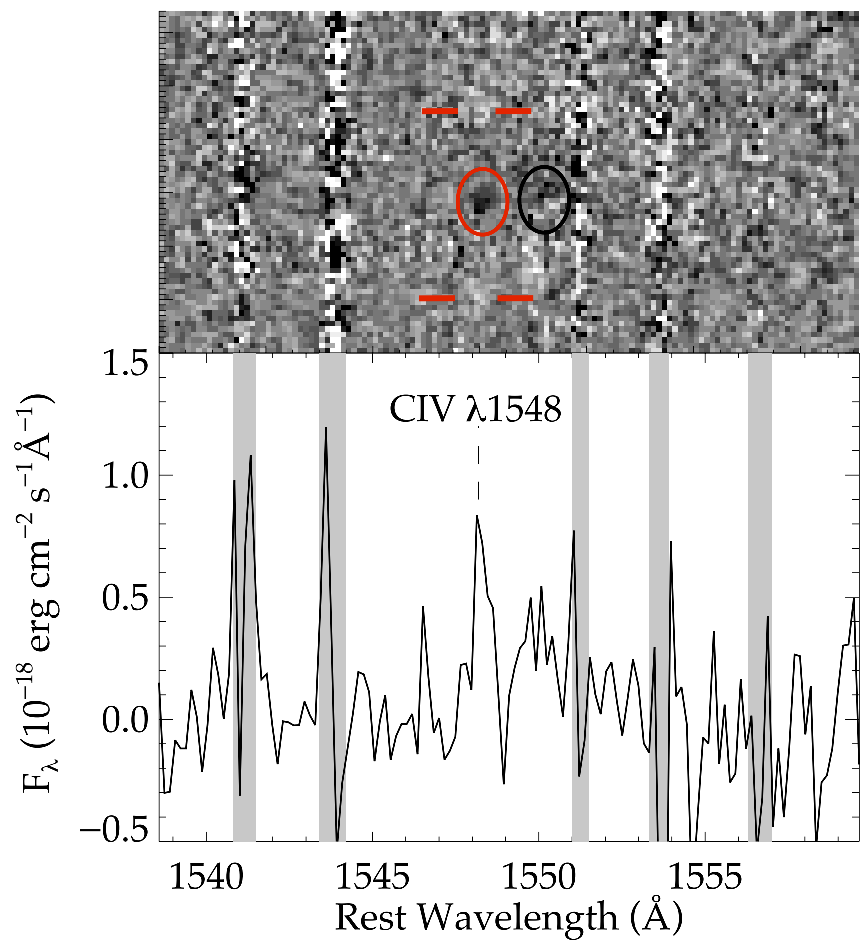
Expect NV 1238,1243Å

High ionisation lines found at z~6-8

CIII] @ z=7.73



CIV @ z=7.05

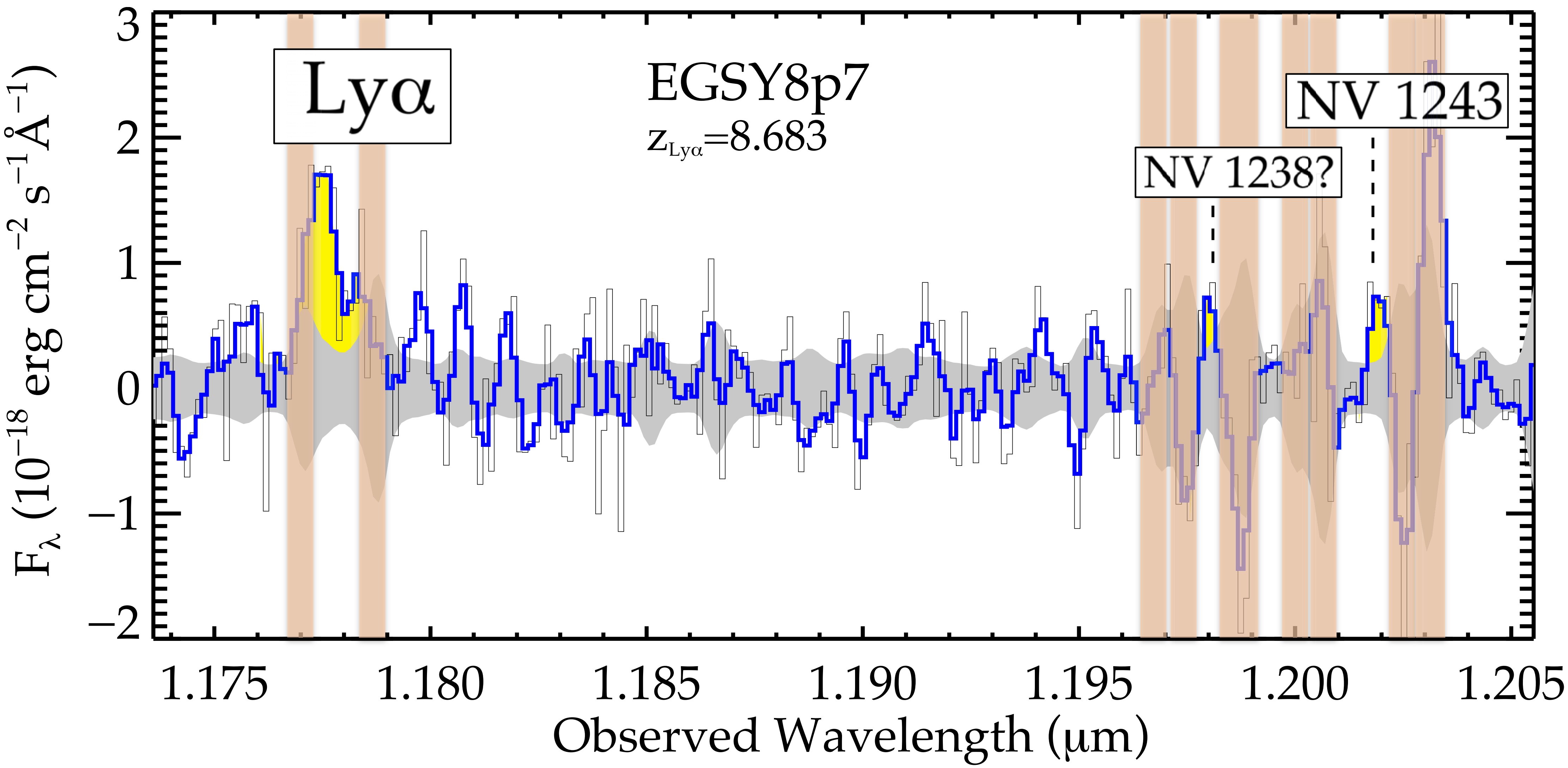


Stark et al. 2015; 2017

see also Shibuya et al., 2017; Zabl et al., 2015

High ionisation lines found at z~6-8

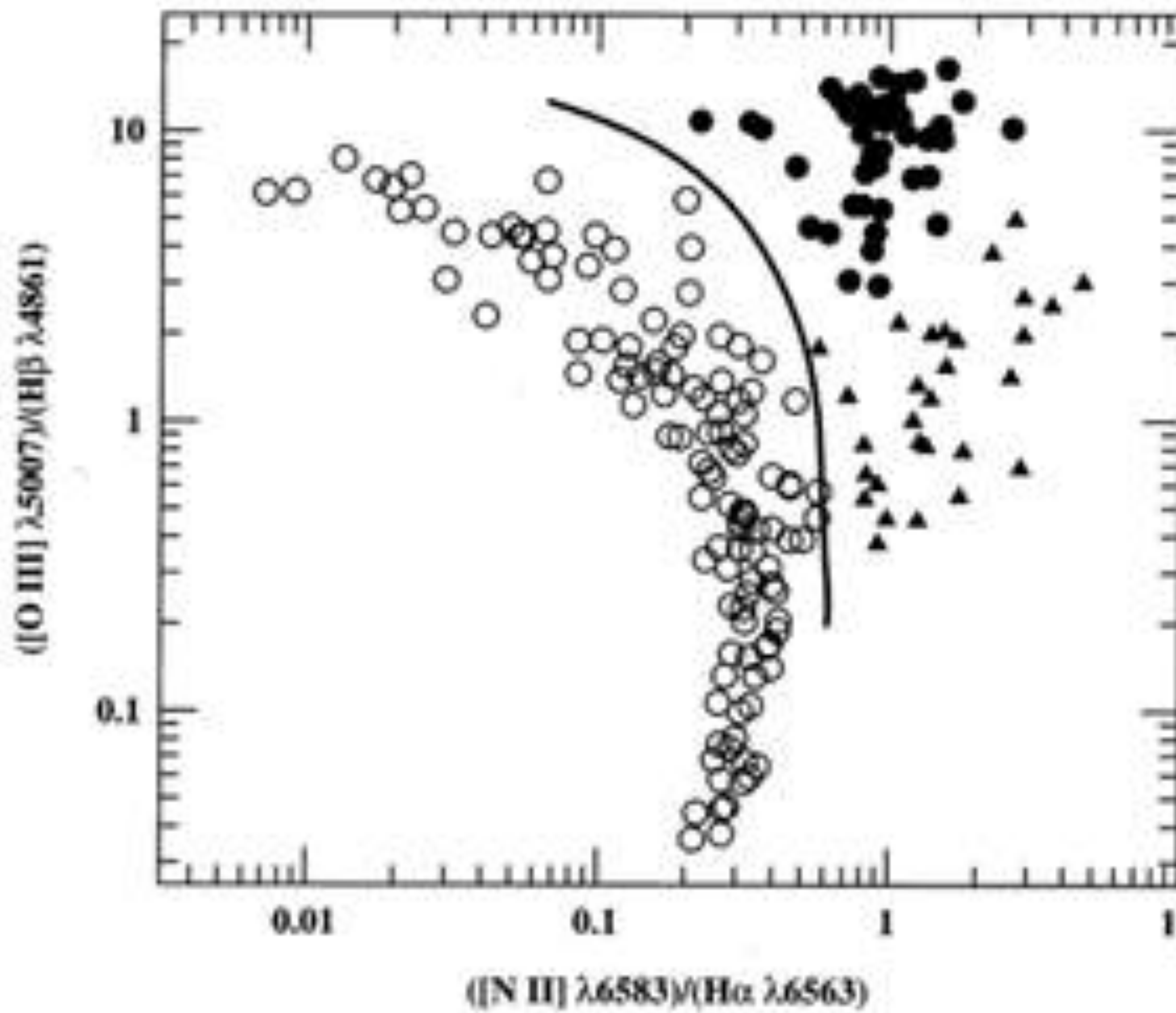
NV @ z=8.68



Mainali et al. 2018

Classic BPT

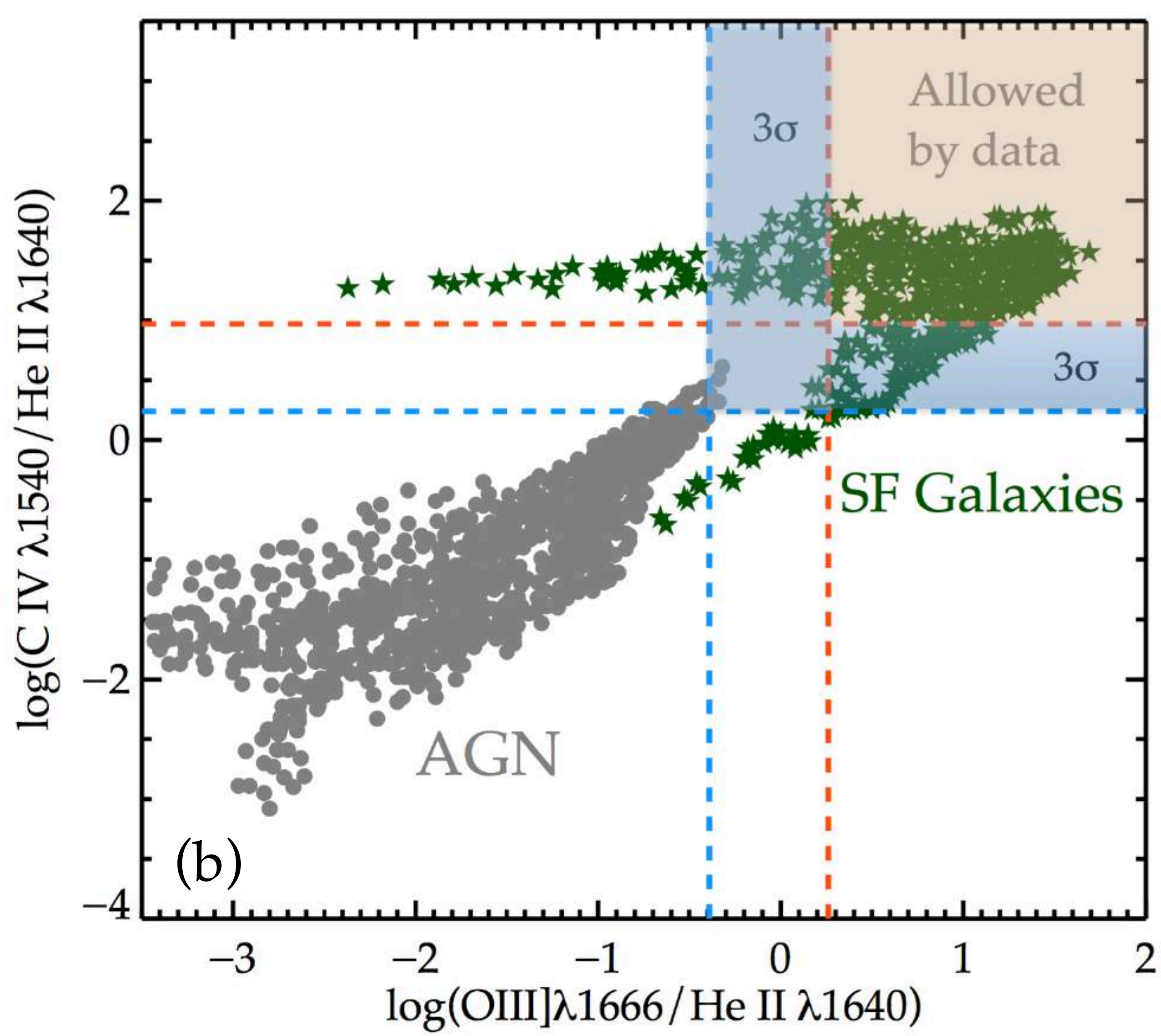
Rest-frame optical lines have well-studied line ratios to discriminate between AGN and star formation



Baldwin, Phillips & Terlevich

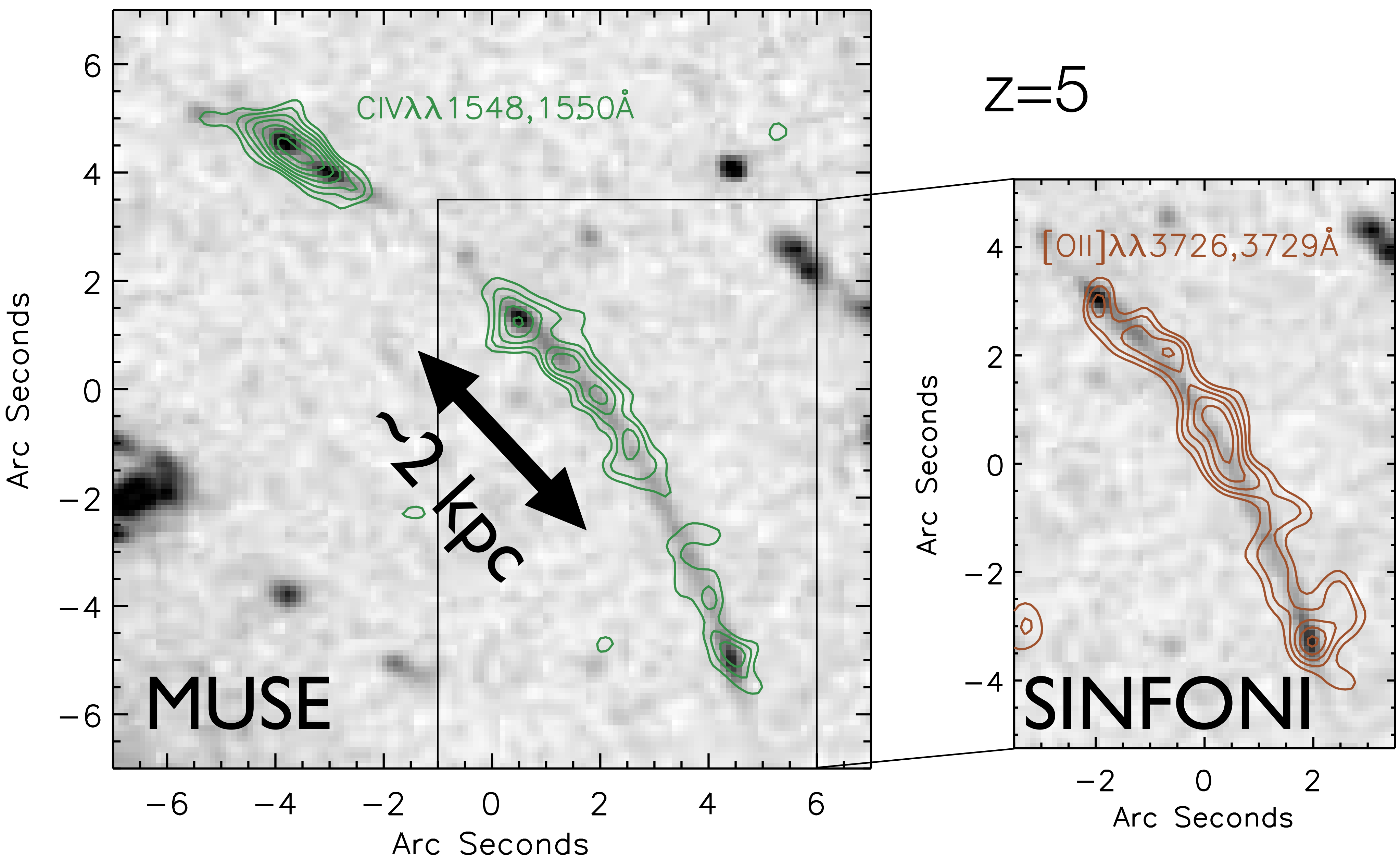
Photoionisation modelling

- New development of line ratio diagnostics in the rest-frame UV can replace the BPT diagnostics to differentiate between AGN & star-formation
- Most z>6 galaxies with deep rest-frame UV spectroscopy indicate likely SF origin of photons



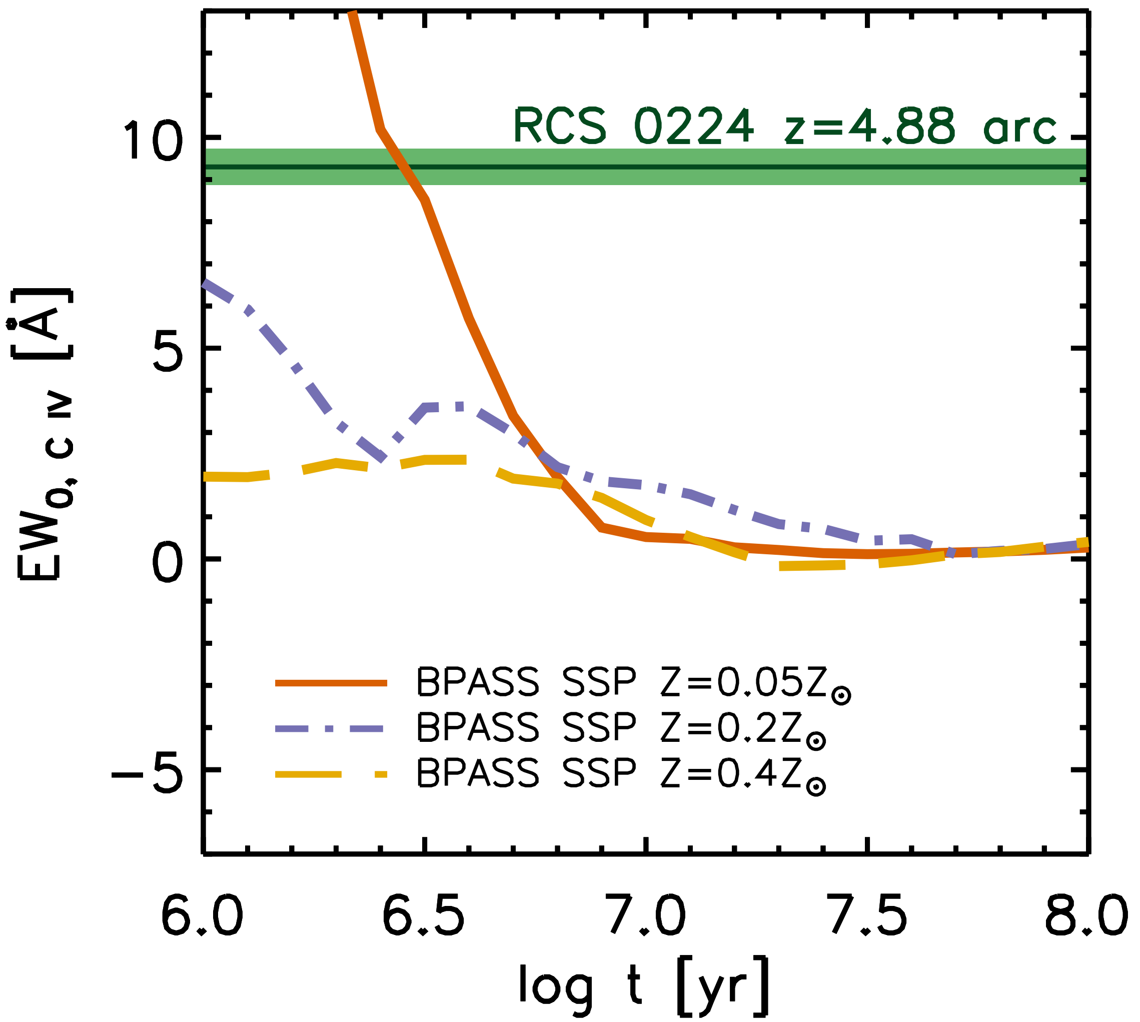
Feltre et al. 2016; Mainali et al. 2017

The spatial distribution of CIV lines with lensing



Smit et al., 2017

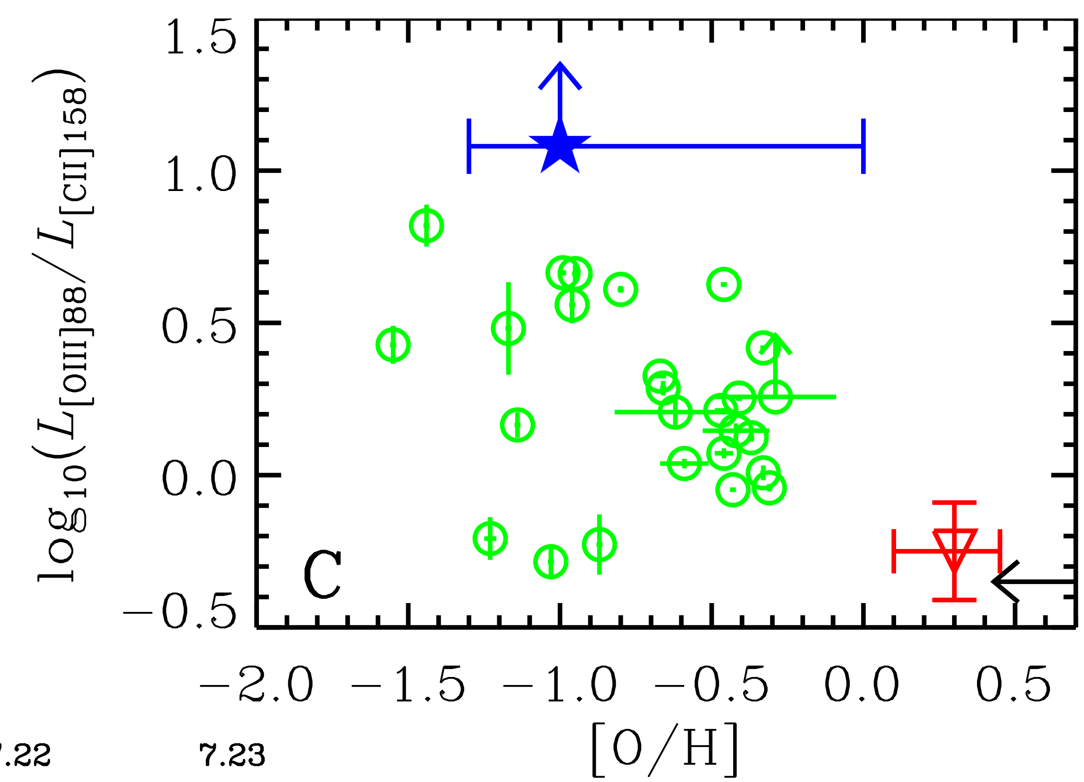
The origin of ionising photons

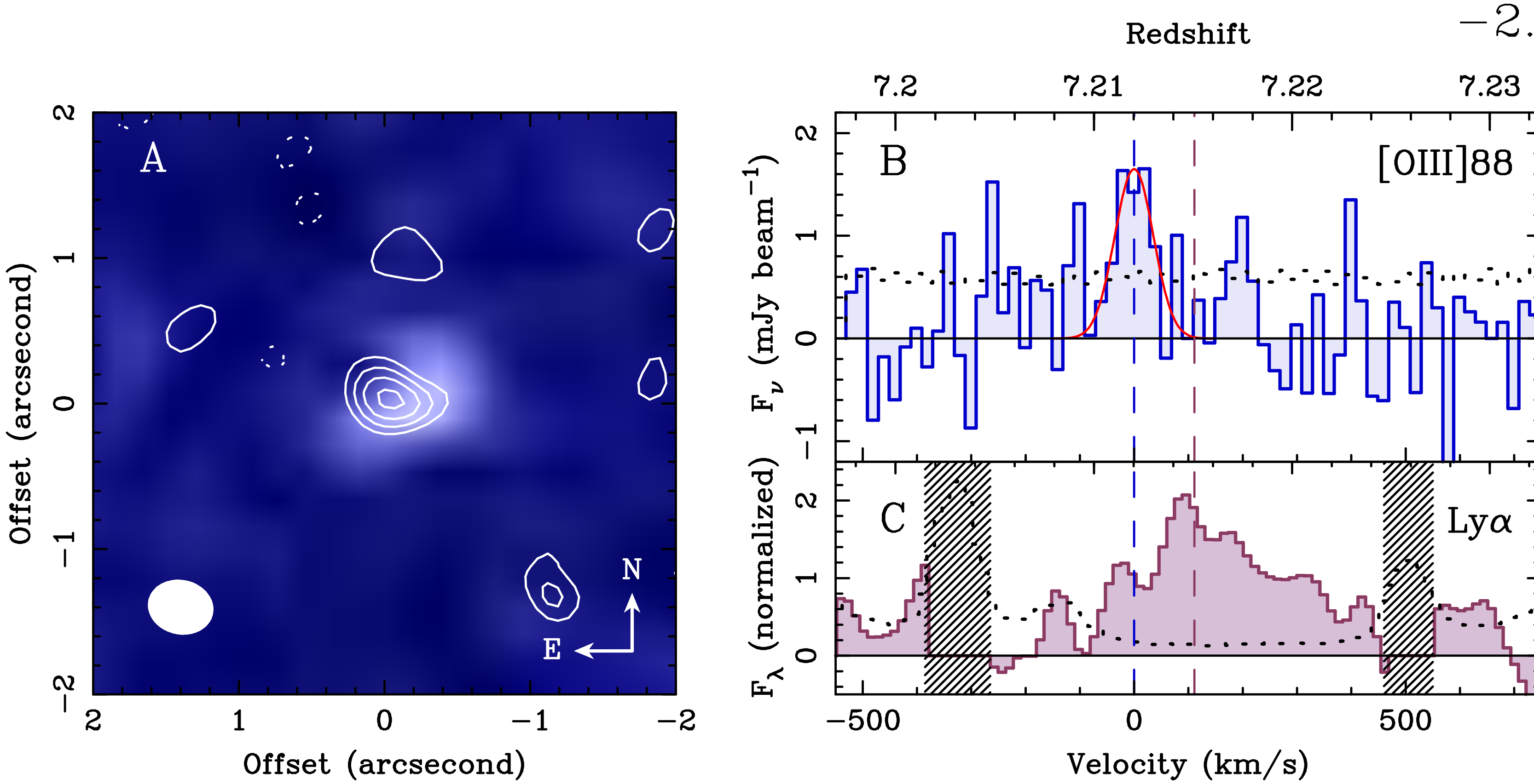


- BPASS models including binary rotation needed for high CIV EW
- Young ages and low metallicity stellar population (<5% solar)

ALMA observations of highly ionised lines

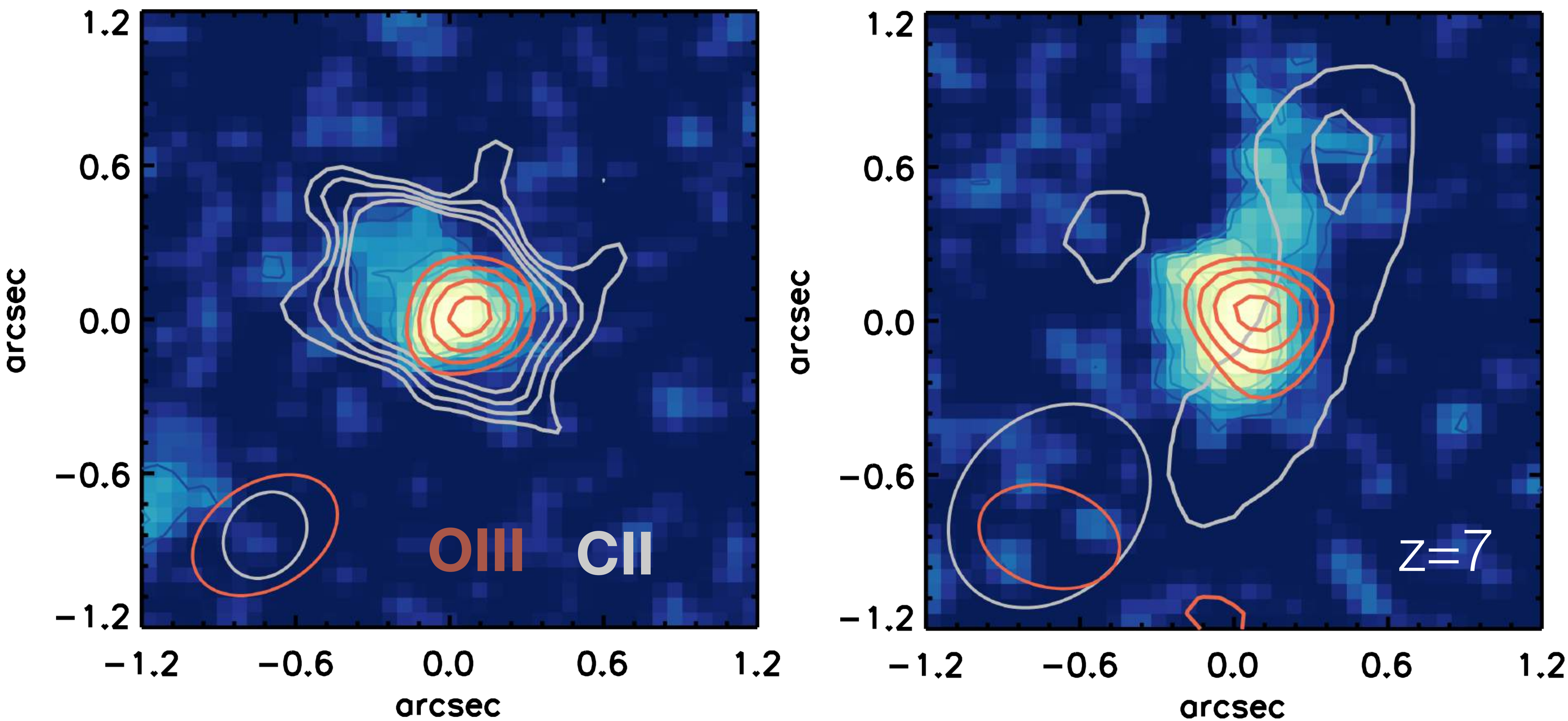
[OIII]/[CII] traces the volume filling factor of (highly) ionised gas



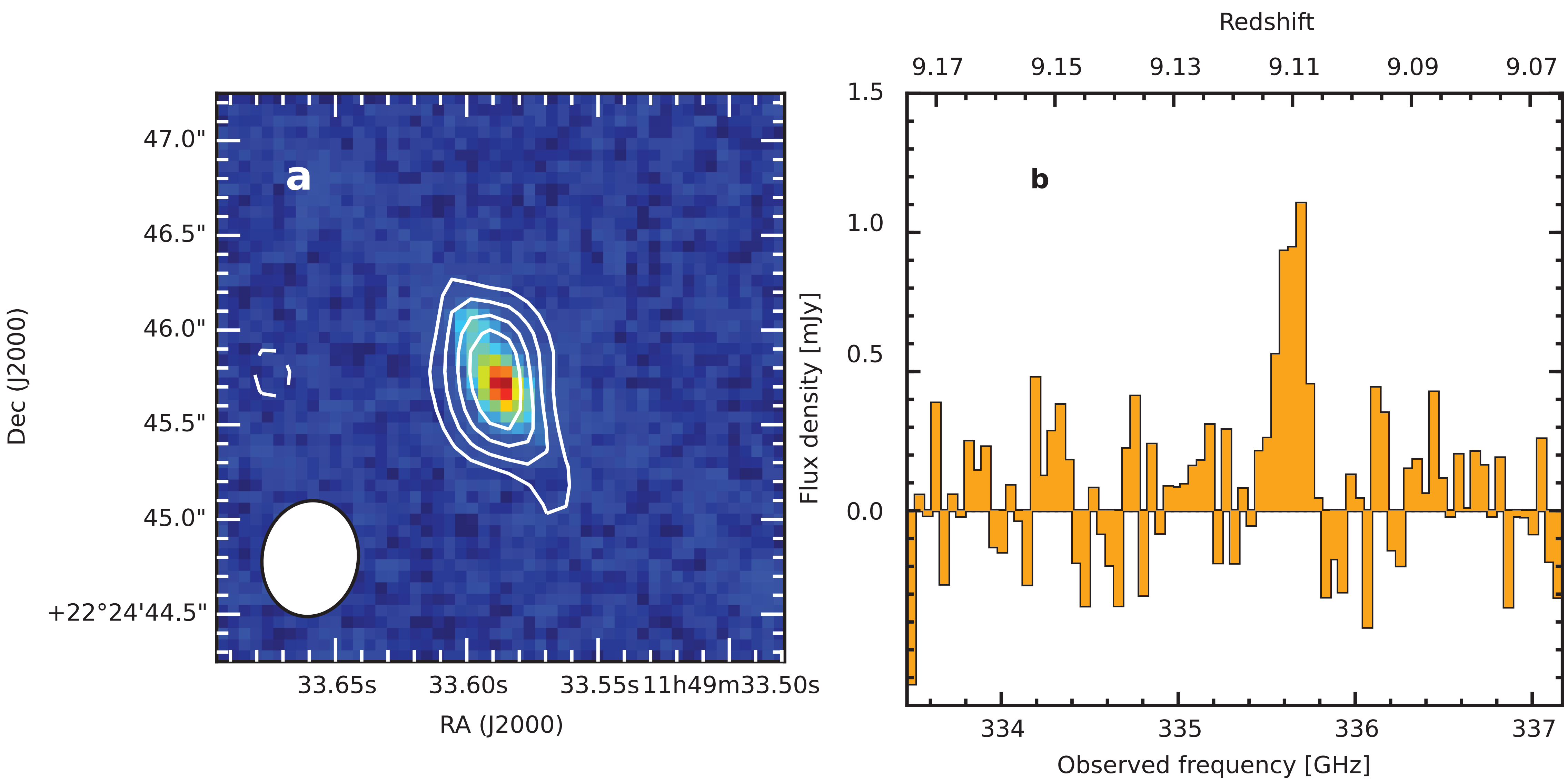


Inoue et al., 2016

OIII emission linked to UV bright star-formation?



Spectroscopic line record with ALMA



ALMA showing it's real potential: [OIII] at z=9.11!!

Hashimoto et al., 2018

Summary

- Lyα is now found deep in the Epoch of Reionisation - potentially emerging from ionised bubbles
- ALMA is starting to take over as the main way of obtaining spectroscopic confirmations
- Bright and extended [CII] emitters are now found in the Epoch of Reionisation - kinematics of these galaxies could suggest turbulent rotating systems 800 million years after the Big Bang
- Detection of high-ionisation lines indicate a hard radiation field in the highest redshift galaxies - star-formation is a likely origin, but some evidence for AGN too!