Theoretical prediction for the detectability of z > 7 nebular lines

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Shimizu et al, 2015, arxiv:150900800

Our goal of this study

Breaking the highest redshift record
using nebular lines rather than Lyman break

- ✓ What objects will we target?
- ✓ How will we observe these objects?

From theoretical point of view,
we predict the detectability of higher-z objects
using future telescope!

Contents

- Alternative lines instead of Lyα Line for higher-z galaxy survey
  ⇒ CIV1549Å & CIII]1909Å Lines

- Motivation

- Simulation

- Results
  - ✓ Prediction for observed line fluxes ($z > 7$)
  - ✓ Line luminosity functions ($z > 7$)
- Conclusion

Alternative Lines Instead of Lyα Line

The spectroscopic survey using Lyα might be difficult at z>8.
← Lyα attenuation by IGM is significant at z>6

⬇

It appears to be important to consider the detectability of alternative lines instead of Lyα line

Alternative line candidates

- ✓ [CII]157μm
- ✓ [OIII]88μm, [OIII]52μm

➡ ALMA

- ✓ CIV1549Å, CIII]1909Å
- ✓ [OII]3727Å, [OIII]5007Å
- ✓ Hα, Hβ

➡ Keck, VLT, Subaru, JWST, TMT, E-ELT

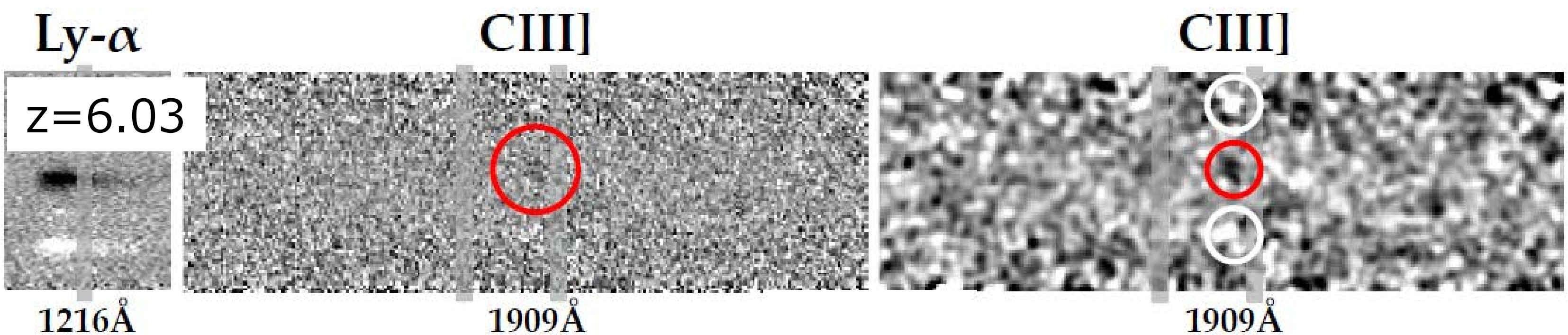
TMT can cover only CIV1549Å and CIII]1909Å at z>7,
Thus, we focus on only these lines in this talk.

TMT coverage : CIV 1549Å (< z=15), CIII] 1909Å (< z=12)

CIV1549Å & CIII]1909Å Lines

- CIII]1909 emission have already been detected in two high-z (z=6.03, 7.213) galaxies

- There are many observation of CIII]1909A at low-z.



- CIV1549 emission also have been detected in high-z and low-z galaxies.

Stark et al.2014a,2014b

CIV 1549Å & CIII]1909Å lines can be strong candidates for the future surveys.

Motivation of This Study

✓ We want to confirm high-z (z>8) galaxy redshift with spectroscopic survey using some lines except for Lyα.

✓ We want to know CIV 1549 Å and CIII]1909 Å lines are reasonable to study high-z galaxies using TMT.

Using cosmological simulations with cloudy calculation, we explore the detectability of the two lines

Cosmological Hydrodynamic Simulation

- Cosmology (Plank 1st year)

  $$(\Omega_m \Omega_\lambda, \Omega_b, h, \sigma_8) = (0.3175, 0.6825, 0.049, 0.6711, 0.8344)$$

- Simulation code :Gadeget3

  radiative cooling/heating, star formation, SN & galactic wind feedback, radiation pressure, AGN like feedback (Okamoto et al.2008, 2009, 2014)

This code can reproduce many observational results from low-z to high-z.

- ✓ Stellar mass function ($0 < z < 7$)
- ✓ Star formation history
- ✓ Mass-metallicity relation
- ✓ Downsizing
- ✓ Star formation efficiency (M_*/M_{halo}: Moster plot)

- Post process
  - ✓ Intrinsic SED (Stellar continuum+ nebular continuum & line)
  - ✓ Dust attenuation + Dust emission

- Simulation setup

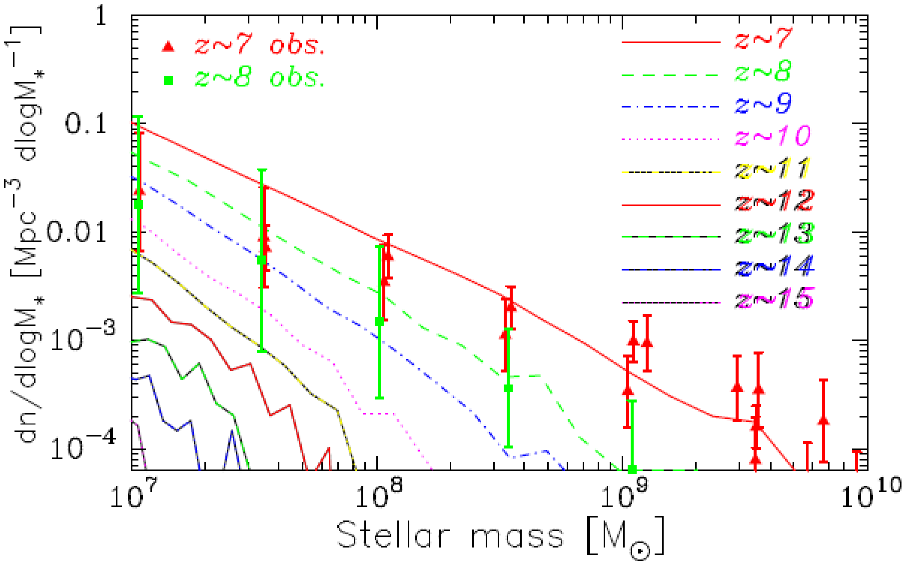
Boxsize :	$50 Mpc^3/h^3$
Number of particles :	2×1280^3
M_{dm} :	$4.4 \times 10^6 M_{sun}$
M_{gas} :	$8.1 \times 10^5 M_{sun}$

→

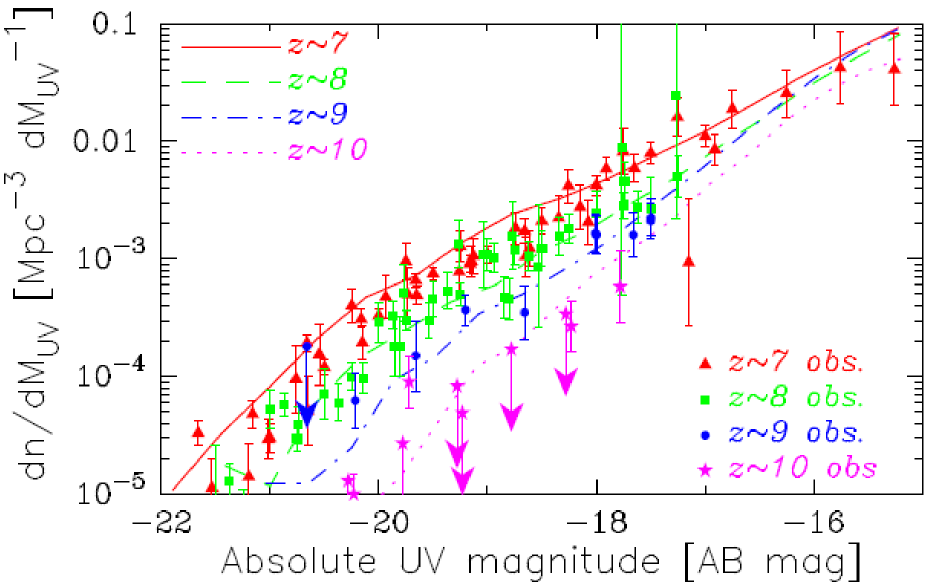
Minimum halo mass: $\sim 10^8 M_{sun}$
Minimum stellar mass: $\sim 10^6 M_{sun}$
Spatial resolution: 2 ckpc

Comparison with Observations

Stellar mass functions



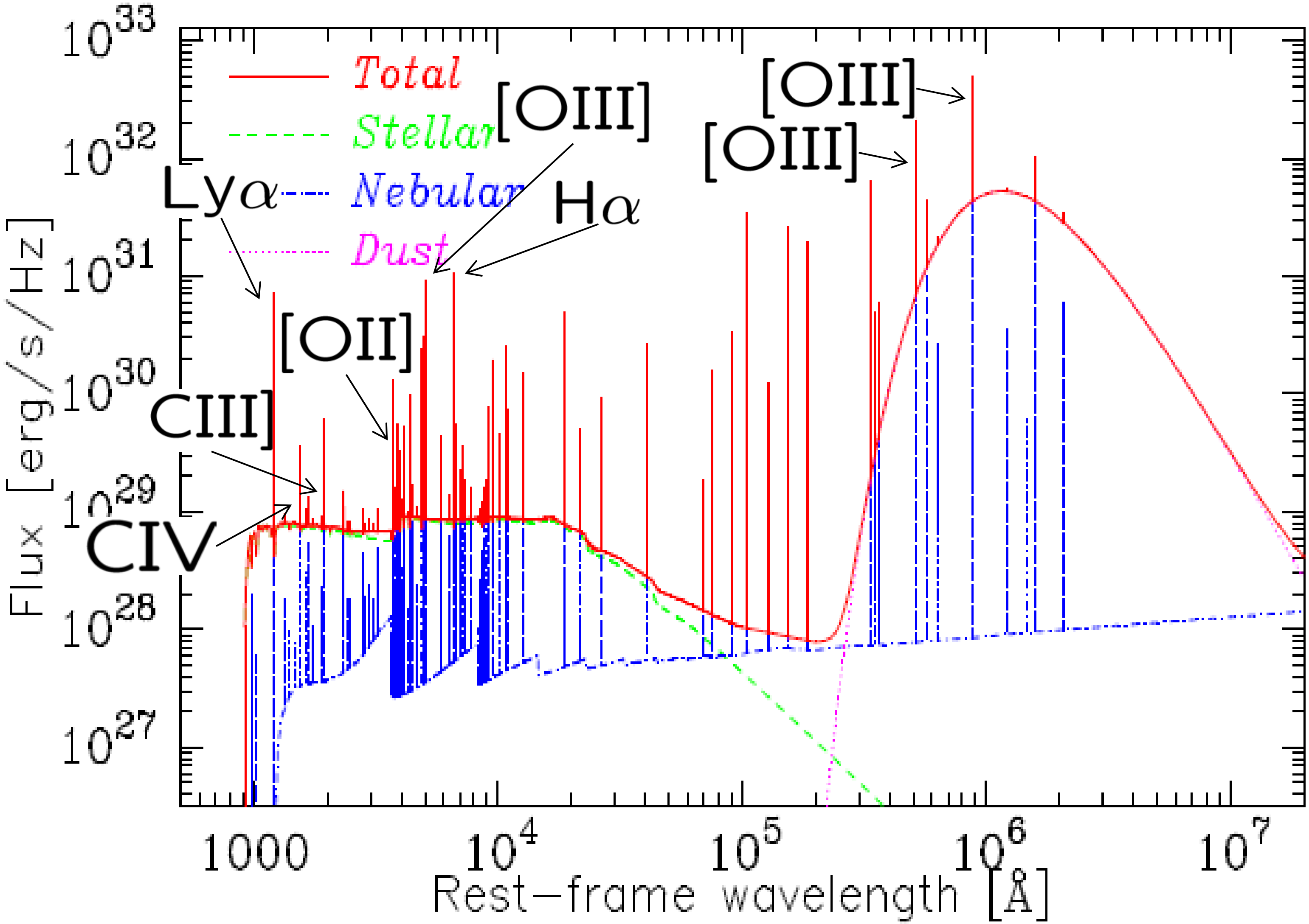
UV functions



Our model (code) reproduce observations at high-z well.
Afterward, we use this data-set to explore high-z (z>7) galaxies.

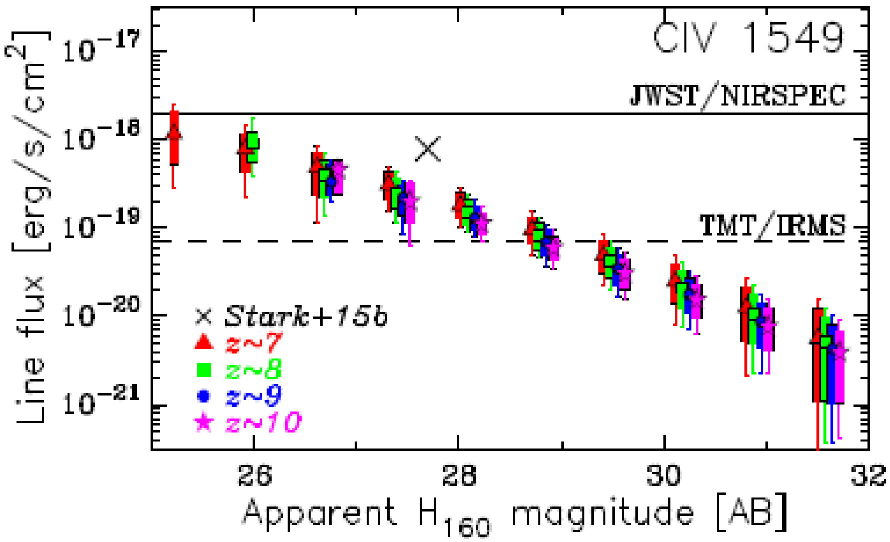
Example of High-z Galaxy SED

Stellar continuum+ nebular continuum & line + dust emission

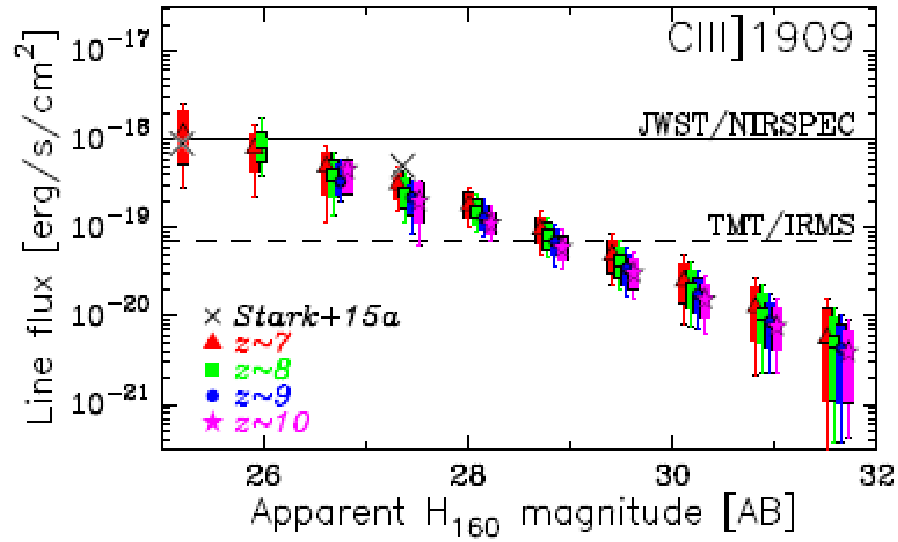


Prediction for CIV and CIII] line from z~7 to z~10

CIV 1549Å



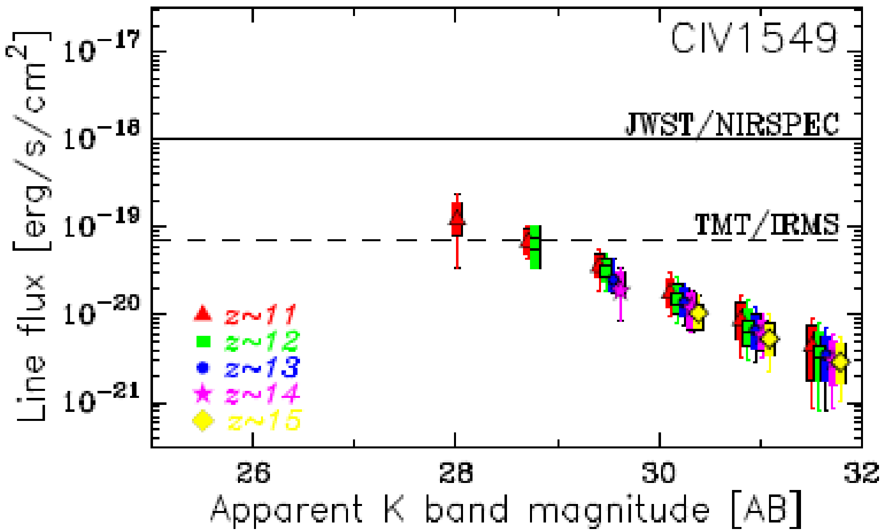
CIII] 1909Å



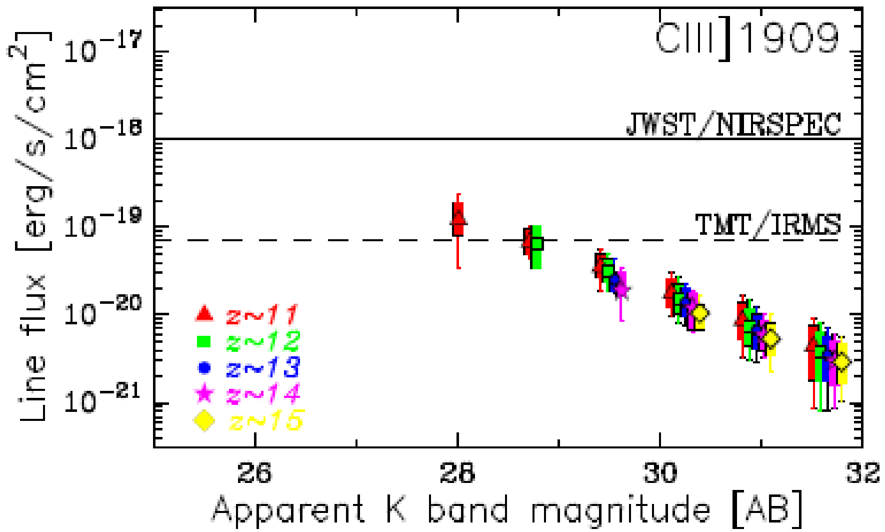
- Line fluxes strongly correlate with the H band (UV) magnitude.
- There is no line flux evolution from z ~ 7 to z~10.
  - ⇒ We are able to detect these line even z ~ 10.
- CIV 1549Å and CIII] 1909Å lines of brighter galaxies (H < 28) can easily be detected by TMT.

Prediction for CIV and CIII] line at z > 10

CIV 1549Å



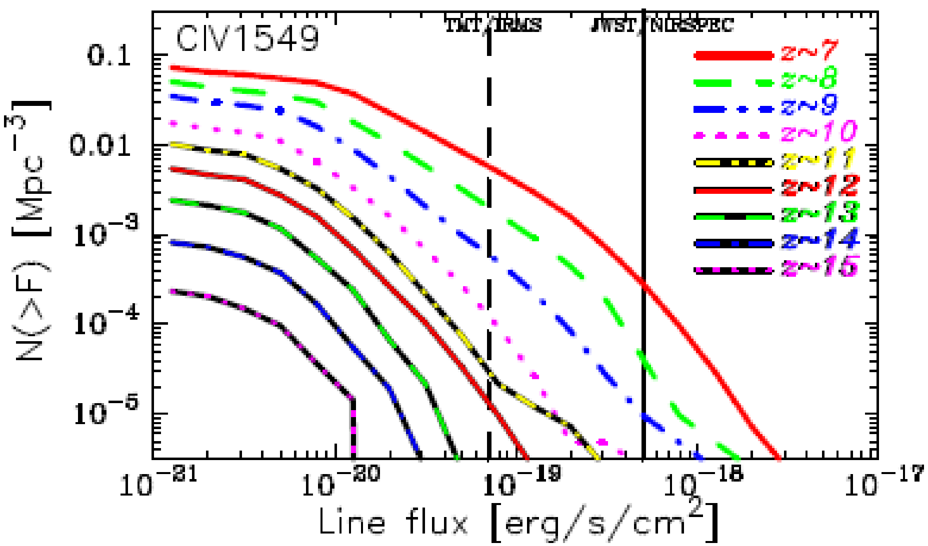
CIII] 1909Å



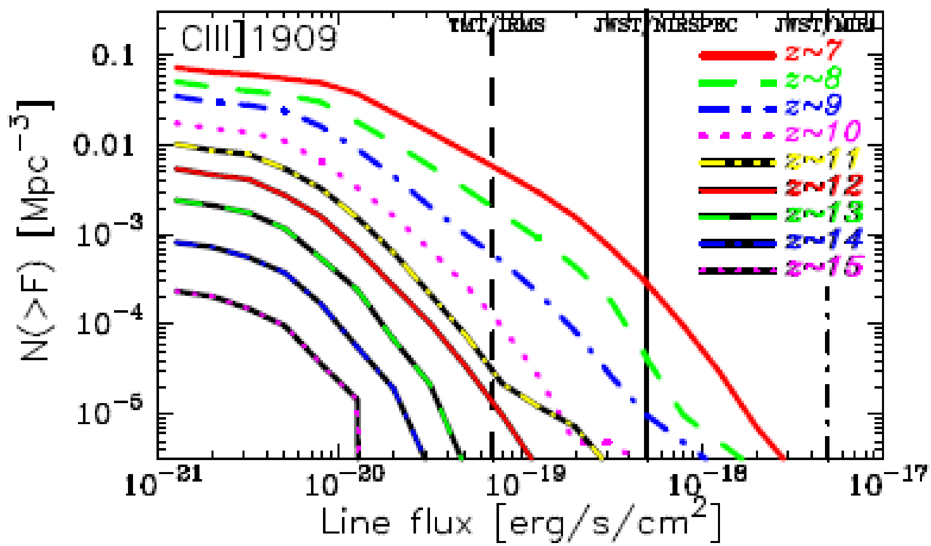
- Line fluxes also correlate with the K band (UV) magnitude.
- There is also no line flux evolution even at z > 10.
- The number of bright lines (> 10^{-19} erg/s/cm^2) is small.
  This is because we simulate with very small simulation box.
  If simulation box is large enough to form high sigma objects, brighter galaxies are appeared.
  ⇒ We are probably able to detect these line even z > 10.
- CIV 1649Å and CIII] 1909Å lines of brighter galaxies (H < 28) can easily be detected by TMT.

Prediction for CIV and CIII] Line Luminosity Functions at z > 7

CIV 1549Å



CIII] 1909Å



One or more CIV 1549Å and CIII] 1909Å emitters at z < 12 can be detected by TMT if the survey volume is about 10^5 [Mpc^3] which is equivalent to > 200 FOVs of the TMT.

A wide imaging survey with the WFIRST and the FLARE is very useful to discover very higher-*z* line emitters.

Summary

- Our simulation reproduce high-z (z > 7) Universe well.
  - ✓ Stellar mass function, UV luminosity function, etc

- Our line flux prediction also reasonable.
  - ✓ [OIII]88μm line at z=7.212 has already been detected as we predicted.

- CIV1549Å, CIII]1909Å are good target for TMT/ELT
  - ✓ The line fluxes of galaxies with H<28 or K<28 are greater than 10^{-19} erg/s/cm^2.
    ⇒ TMT can detect these lines!

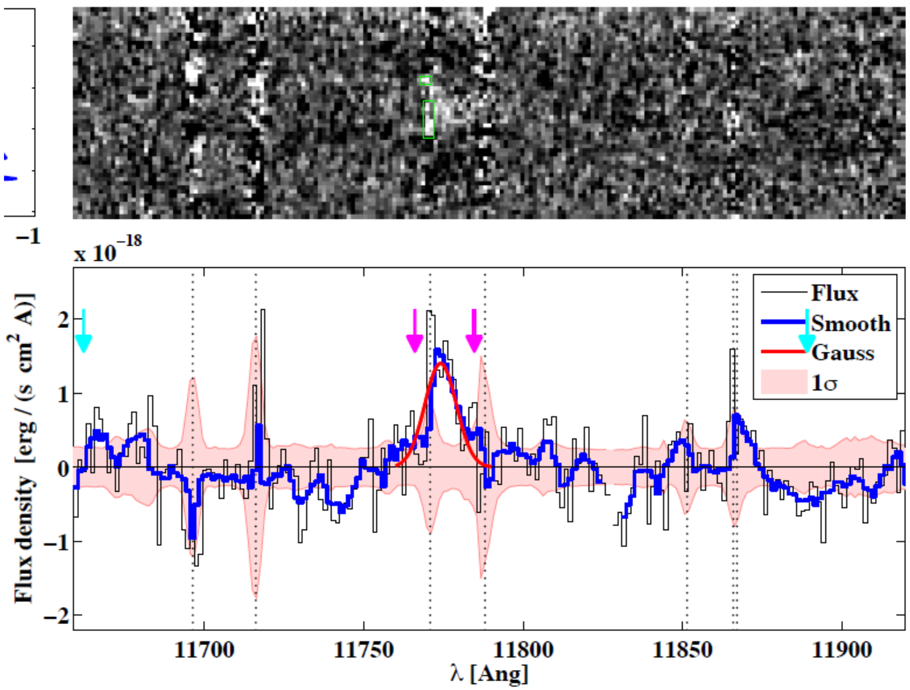
- WFIRST and FLARE will discover many galaxies at z=10~15
  - ✓The follow-up survey is necessary with the TMT
  - ✓CIV and CIII] are good target for the TMT.

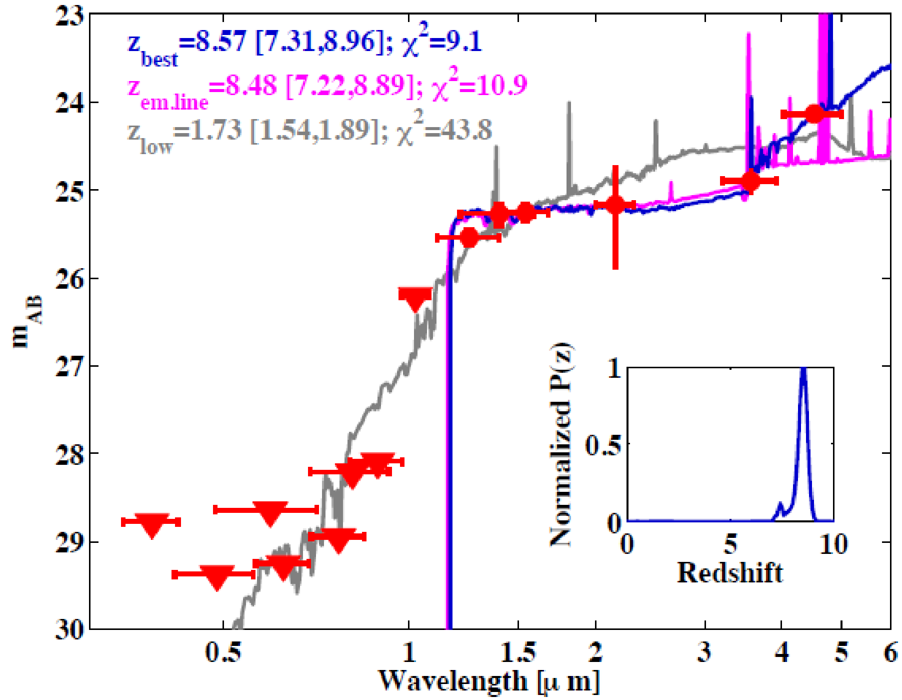
Using these lines, the redshifts of a lot of high-z galaxies will be confirmed! Moreover, these physical properties also might be revealed.

Appendix

Spectroscopic Survey for High-z Galaxies

In order to identify the object redshift,
we need to observe Lyα (or another) line or Lyman break feature.



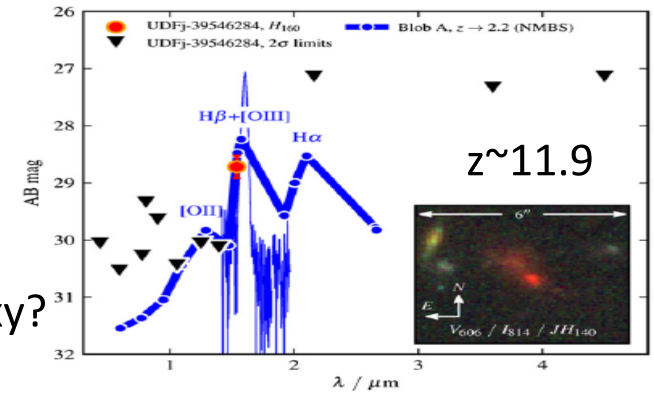


Zitrin et al.2015

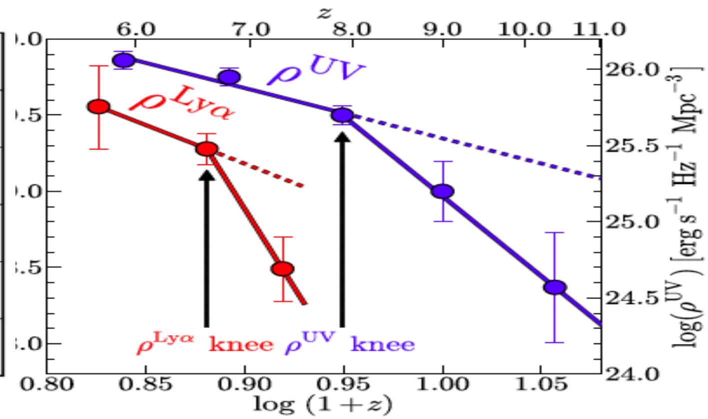
The most distant redshift confirmed galaxy
with using Lyα (z=8.68).

Observational Difficulty for z>8 galaxies

z=2.2 galaxy?

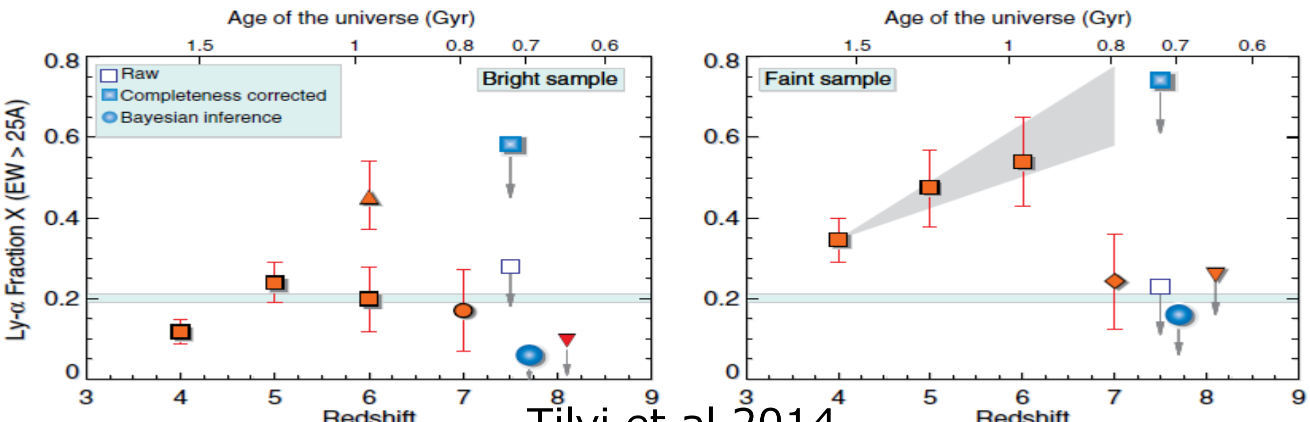


Brammer etal.2013



Konno et al.2014

nLAE/nLBG

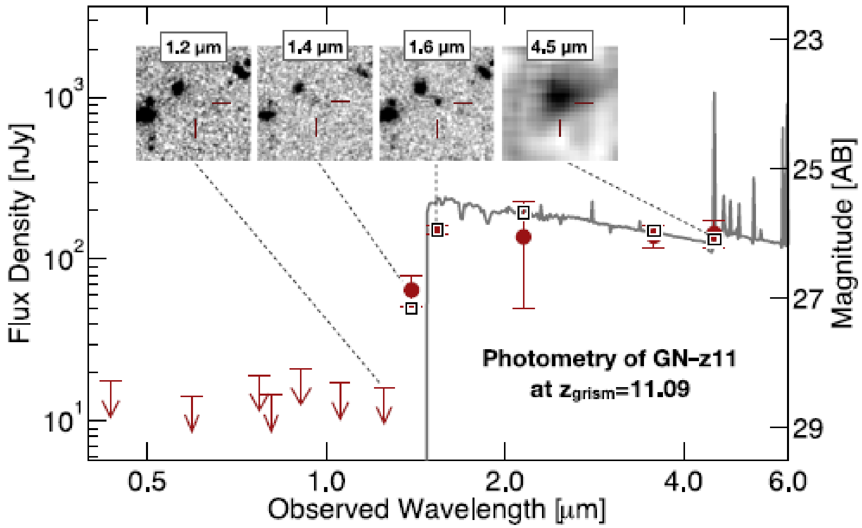


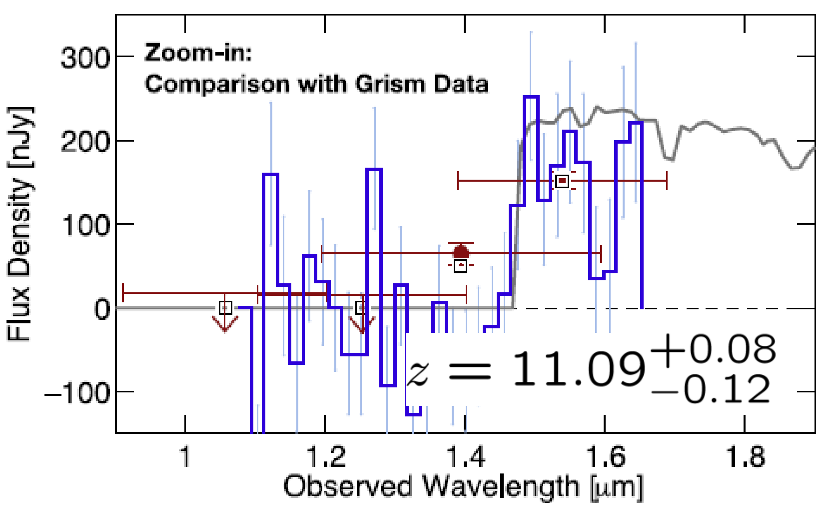
Tilvi et al.2014

- Almost all spectroscopic z>8 Lyα survey have failed
- The fraction of high-z galaxies with detectable Lyα emission decreases from z=6
- These imply that Lyα attenuation by IGM is significant at z>6

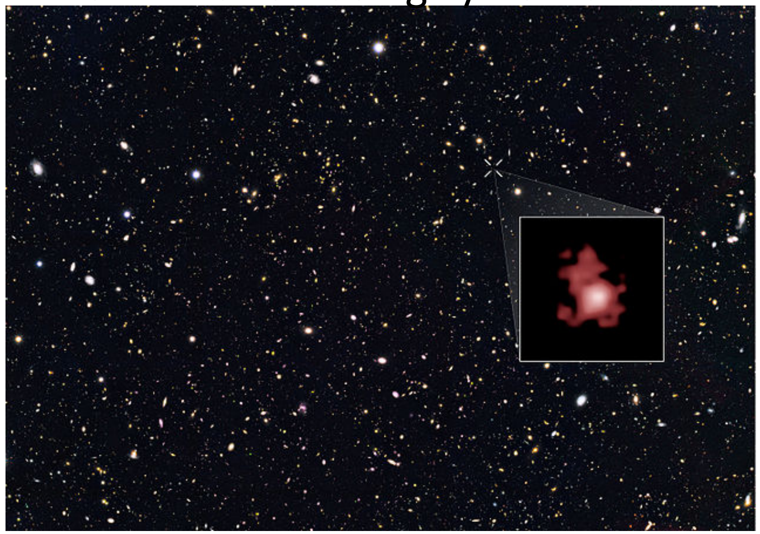
Most distant confirmed galaxy?

GN-z11
Oesch et al. 2016

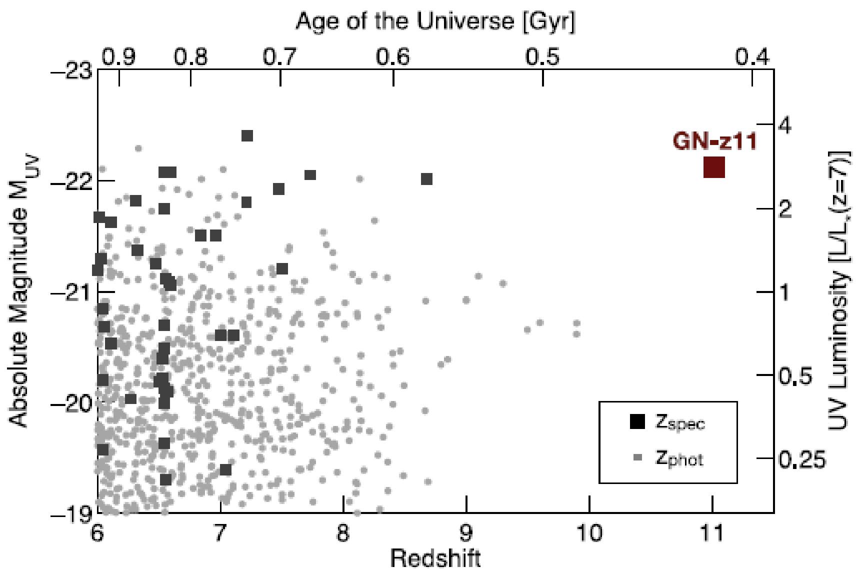




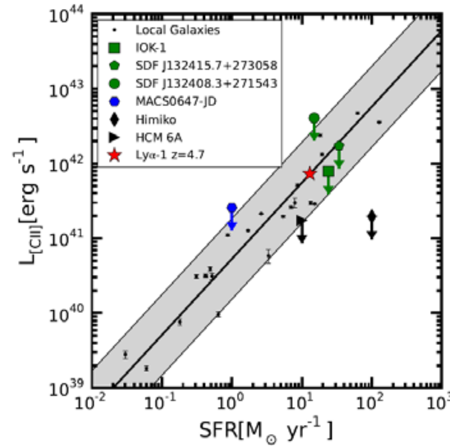
Confirmation using Lyman break



http://hubblesite.org



[CII]157μm Line

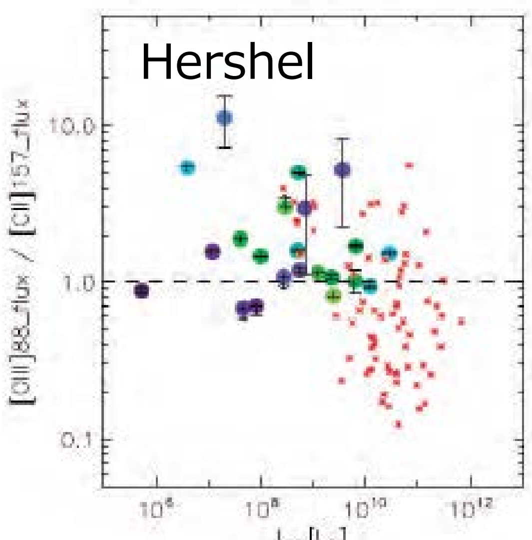


- One of brightest line in IR region
- Good target for ALMA
- Almost all survey have failed to detect [CII]157μm line in high-z Lyα emitters (LAEs)
  ⇒ This fact disadvantages because the fraction of young galaxies like LAEs increases at higher-z
- The line originates mainly from photo-dissociation region (PDR)
  ⇒ Theoretical prediction for the line is very difficult because excitation mechanism in PDR is very complicate.

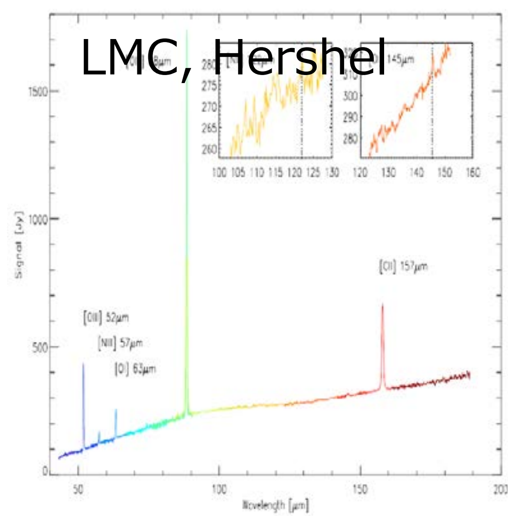
[OIII]88μm Line

- The line emits from HII region
  ⇒ Excitation mechanism is simpler than that in PDR
  ⇒ Theoretical prediction is easier than [CII]157μm line

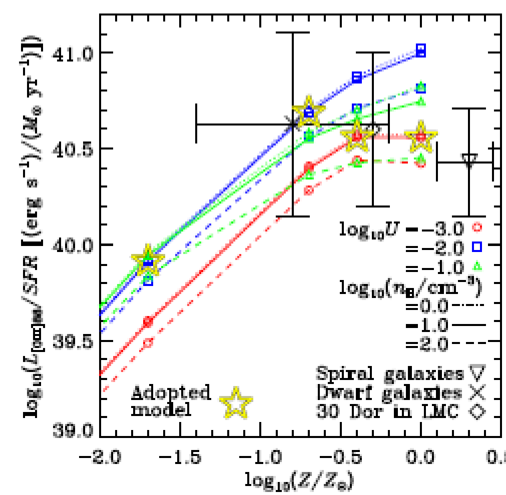
- The line luminosity of lower-Z galaxy is brighter than [CII]157μm line.
  ⇒ This advantages to explore higher-z galaxy



Madden et al.2012

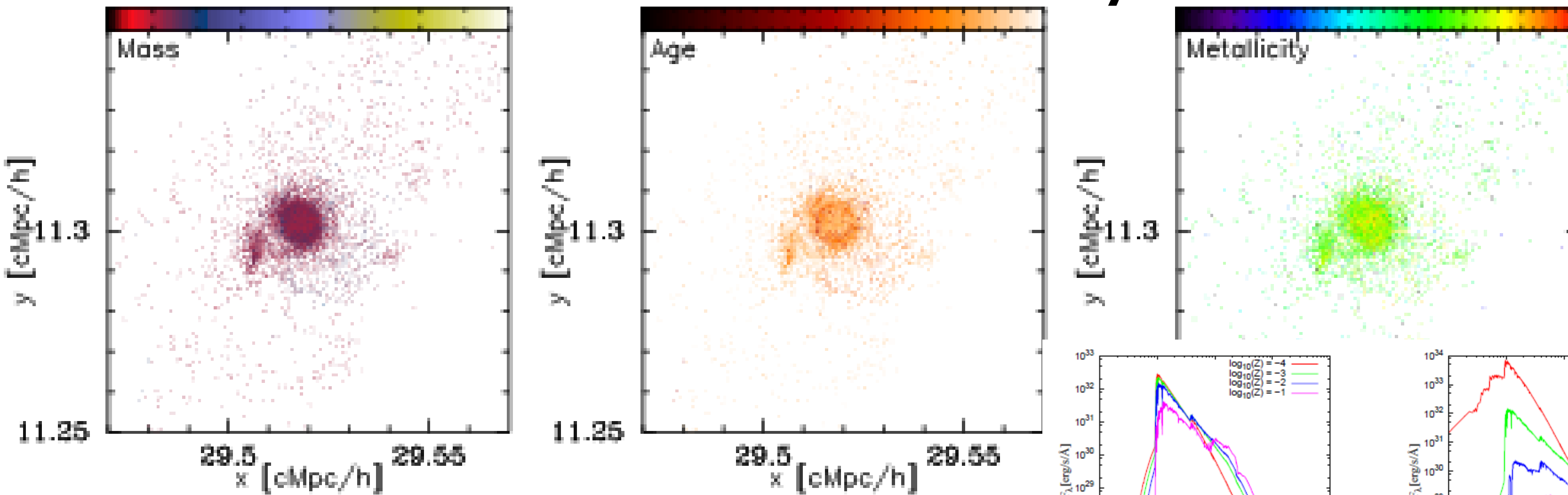


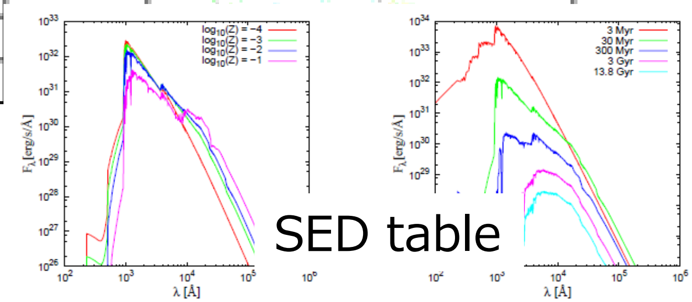
Lebouteiller et al. 2012



Inoue, IS et al.2014

Calculation of Galaxy SED





SED table

Calculation of intrinsic SED of galaxy

A) Calculation SED table (continuum, nebular continuum, line) using PEGASE2
A) Calculation each star particle SED
B) Summation each star particle SED to obtain galaxy SED
C) We assume case B Hydrogen recombination (Hα, Hβ, Hγ)
D) The other (metal) lines are calculated with $L_{line} = C_{line}(Z)L_{H\beta}$ based on Inoue, IS et al.2014 (CLOUDY calculation)

Intrinsic SED = stellar continuum + nebular continuum & line

Calculation of Galaxy SED

Calculation of dust attenuation at UV (= 1500A)

$$f_{\mathrm{UV}} = \frac{1-\delta}{2}(1 + e^{\tau_{\mathrm{d}}}) + \frac{\delta}{\tau_{\mathrm{d}}}(1 - e^{\tau_{\mathrm{d}}})$$

$$\tau_{\mathrm{d}} = \frac{3\Sigma_{\mathrm{d}}}{4as} \Leftarrow \Sigma_{\mathrm{d}} = e_{\tau}\frac{M_{\mathrm{metal}}}{\pi r_{\mathrm{half}}^2}$$

M_{metal}, r_{half} → Using simulation

δ:slab fraction,(0~1) , a:dust grain size (0.05 μm), s:dust grain density (2.5 g/cm^3)

We choose the value of δ, e_{τ} to reproduce UV luminosity function.

Calculation of dust attenuation at the other wavelength

- Calzetti law (Calzetti et al. 2000)

Calculation of dust attenuation for line

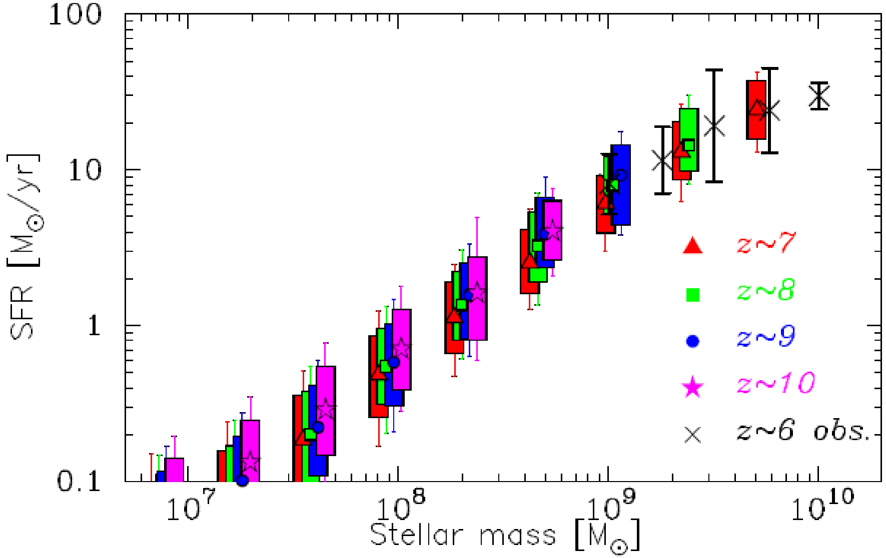
- Calzetti law, e.g., $E(B - V)_{*} = 0.44E(B - V)_{\mathrm{gas}}$

Calculation of IGM absorption (λ < 1216A)

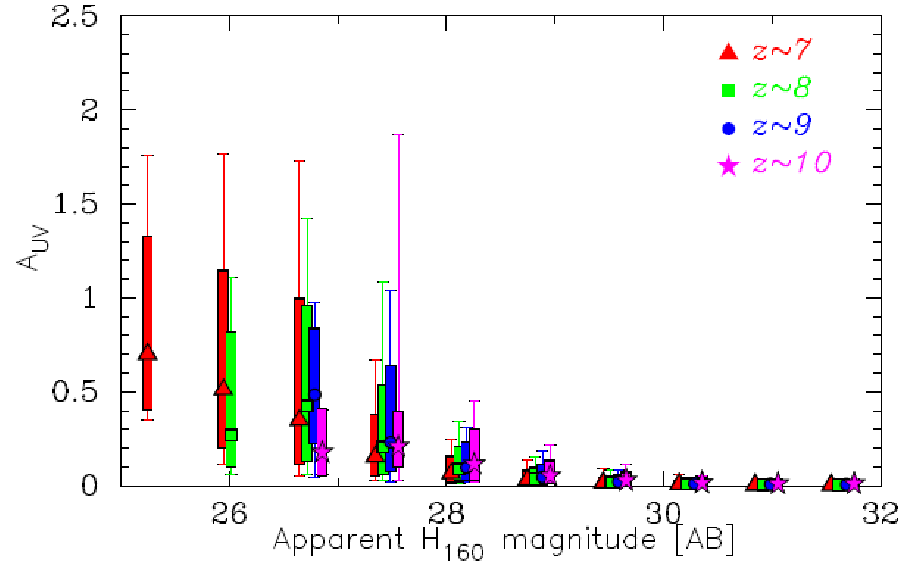
- Madau 1994

Simulation Results

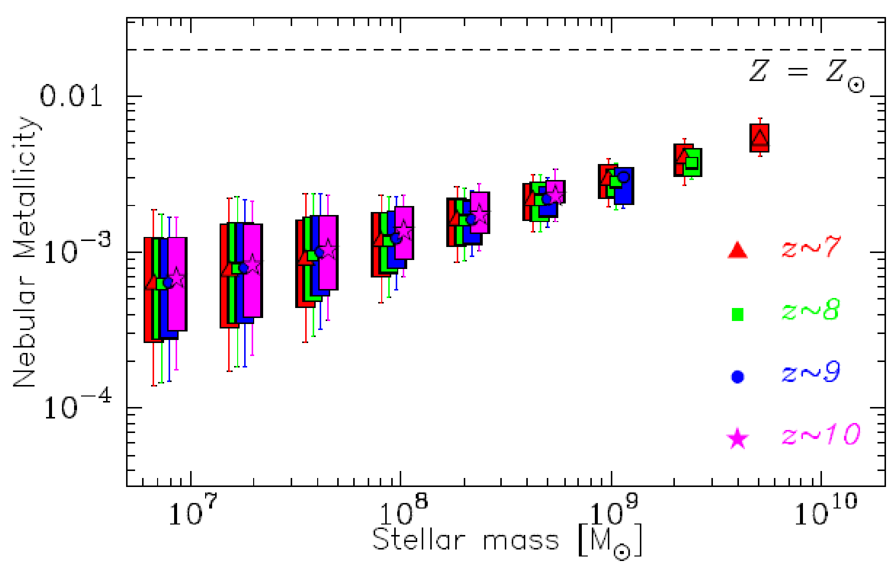
Stellar mass-SFR



UV attenuation

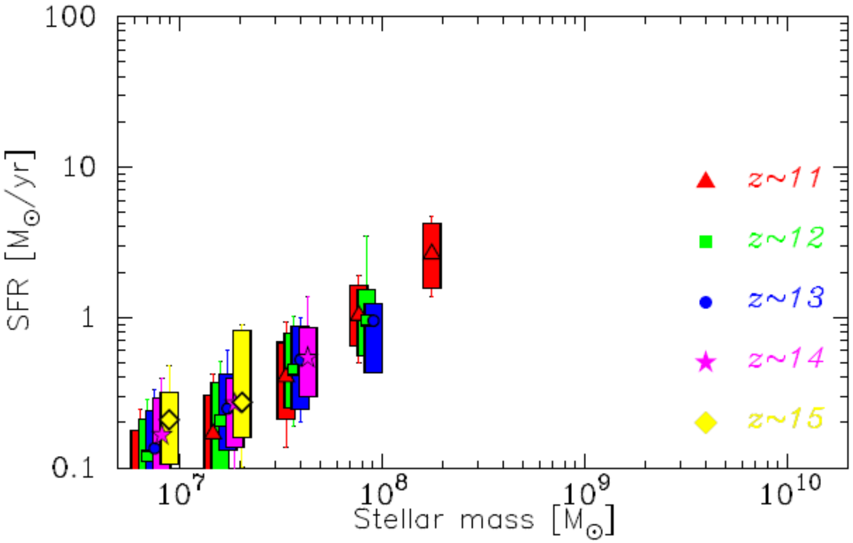


Metallicity

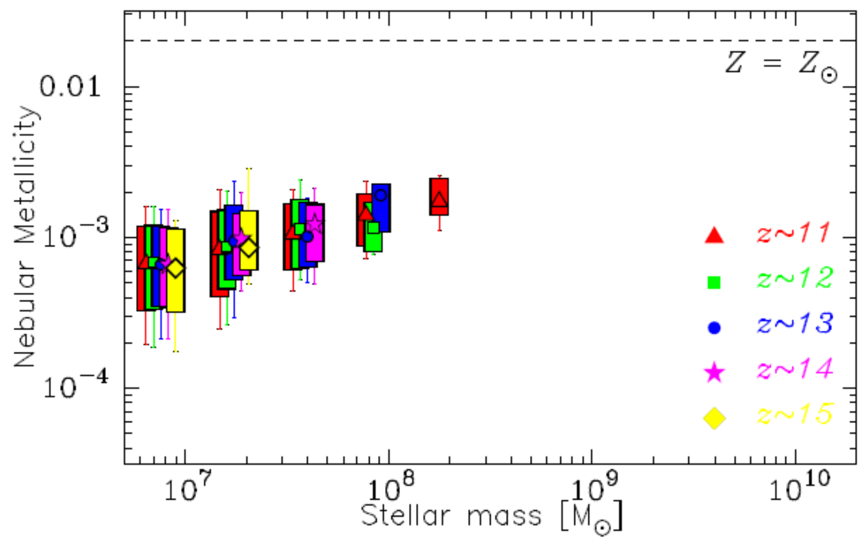


Simulation Results

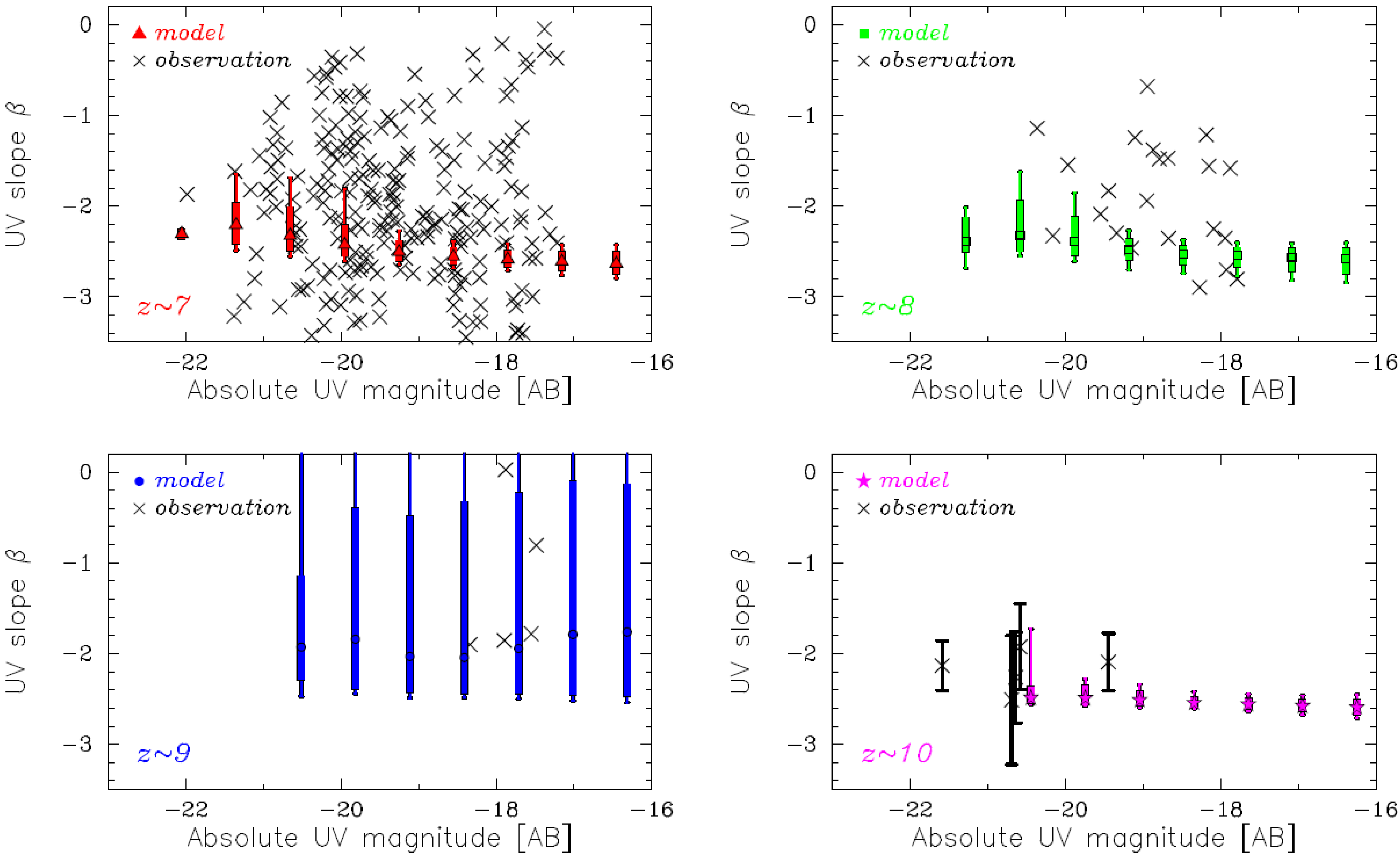
Stellar mass-SFR



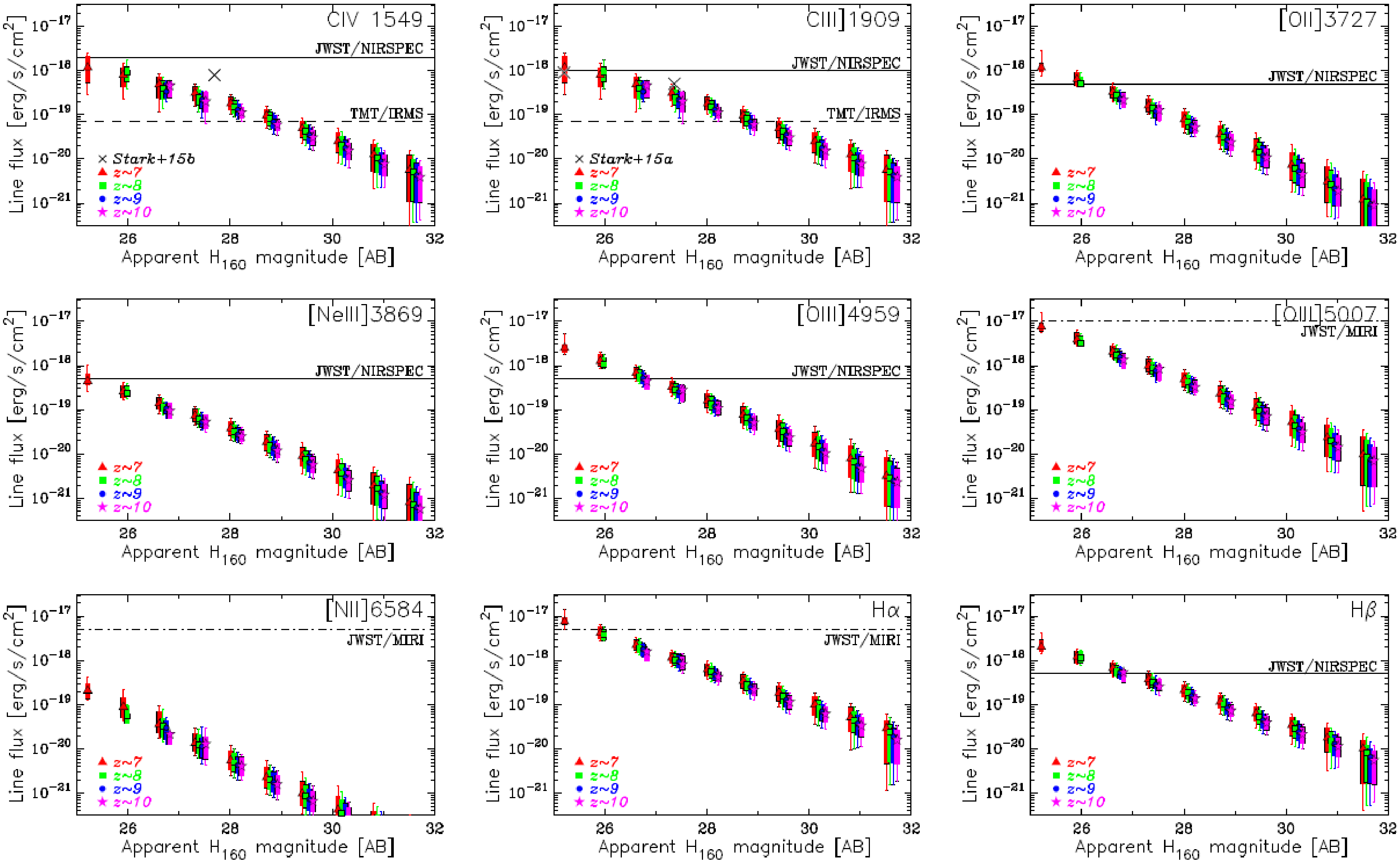
Metallicity



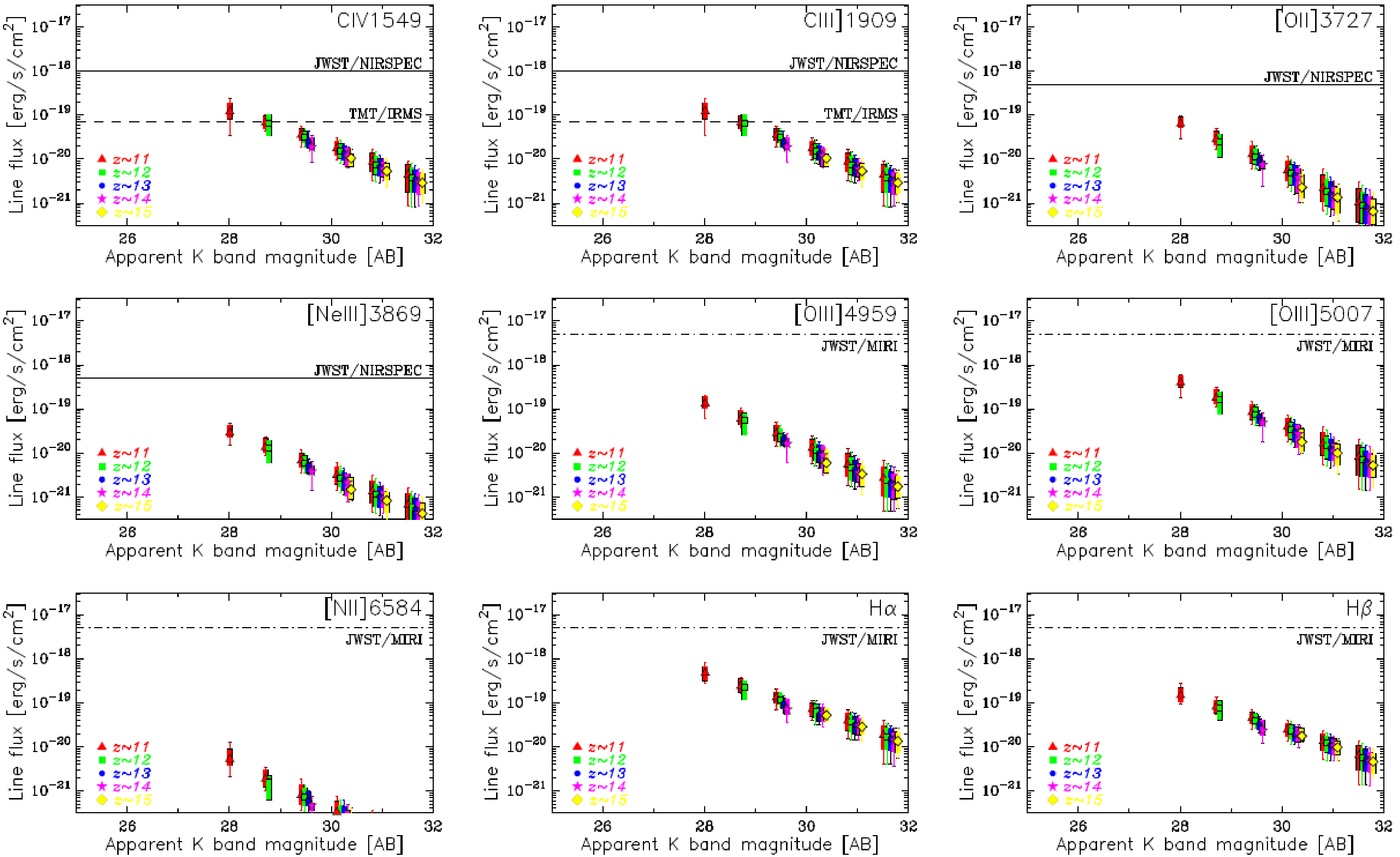
Simulation Results



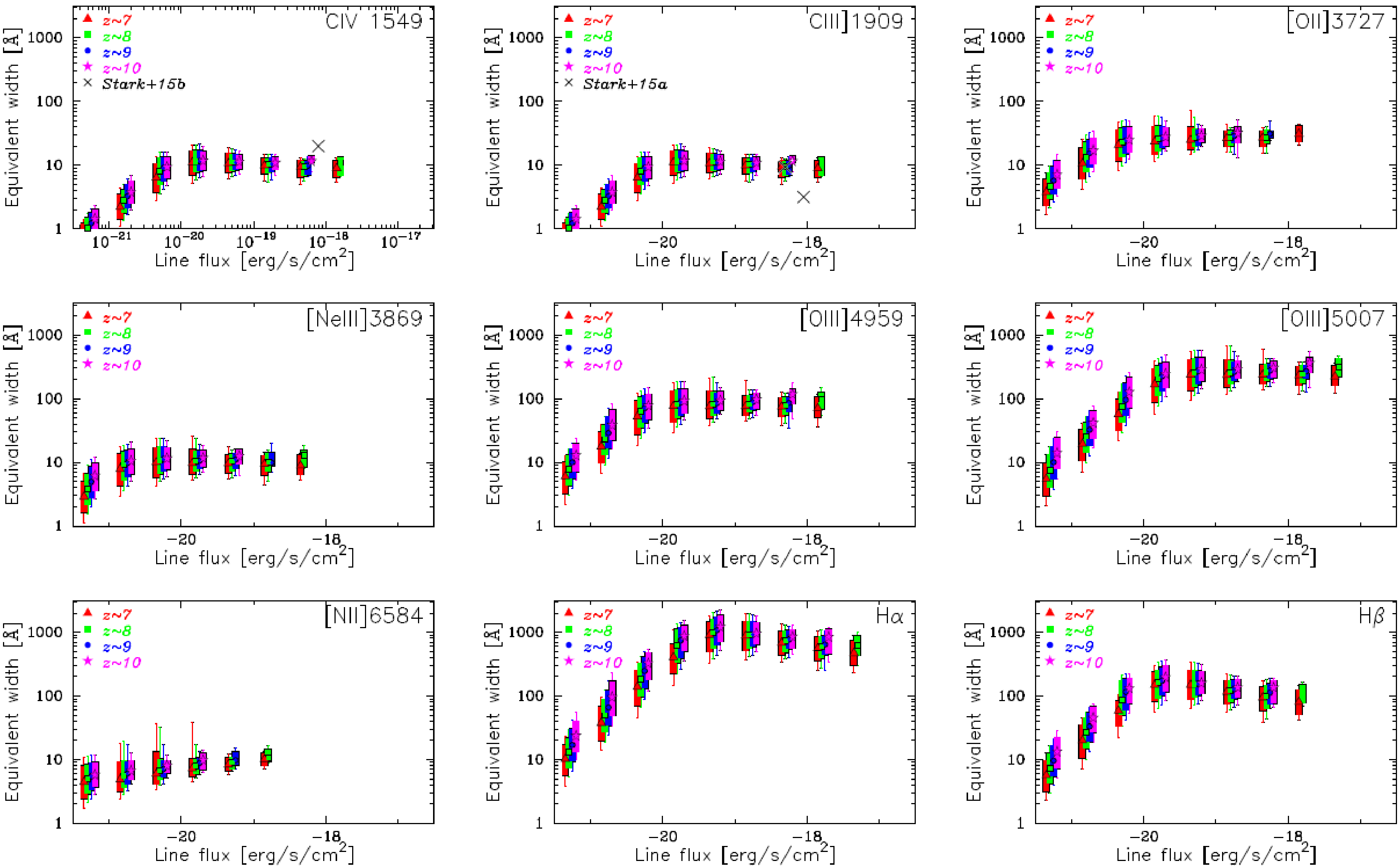
Prediction for some important line fluxes



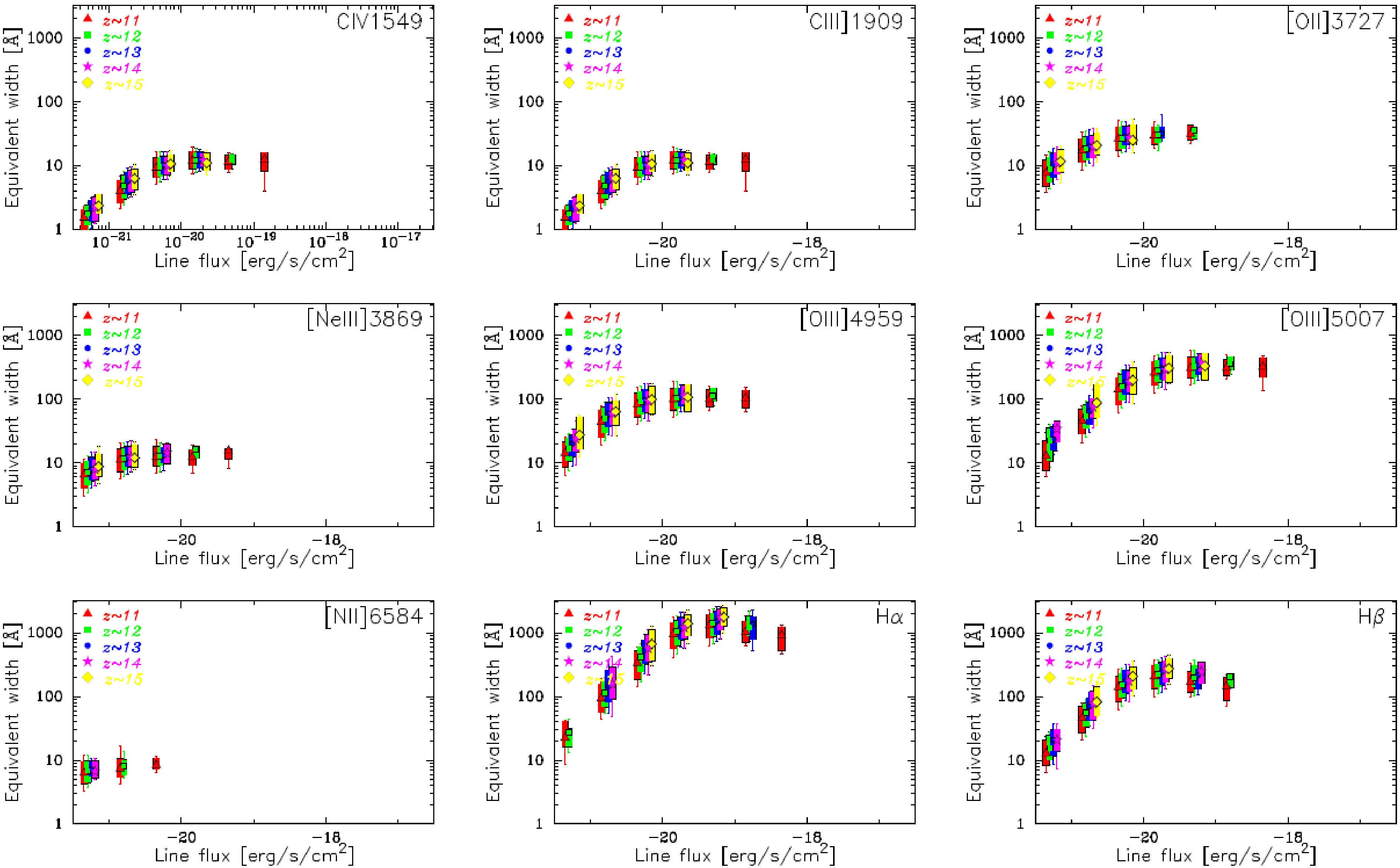
Prediction for some important line fluxes



Prediction for some important line EWs

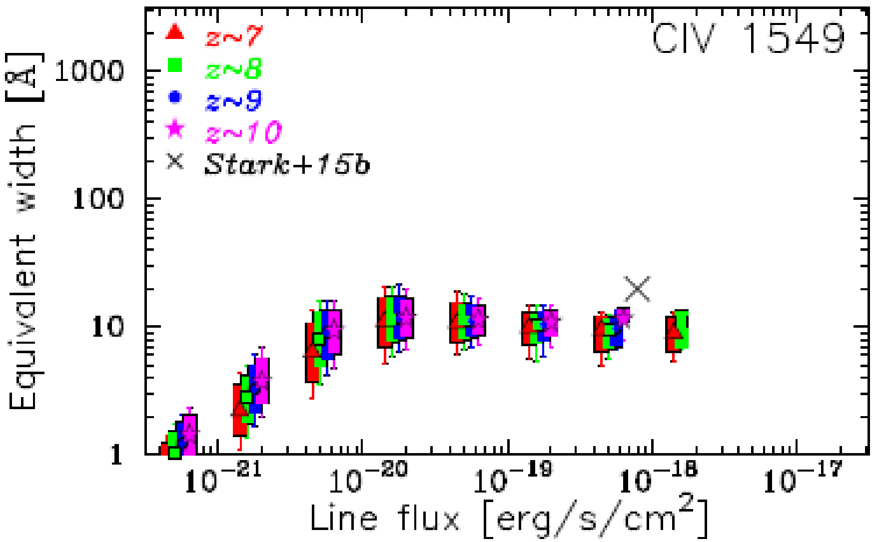


Prediction for some important line EWs

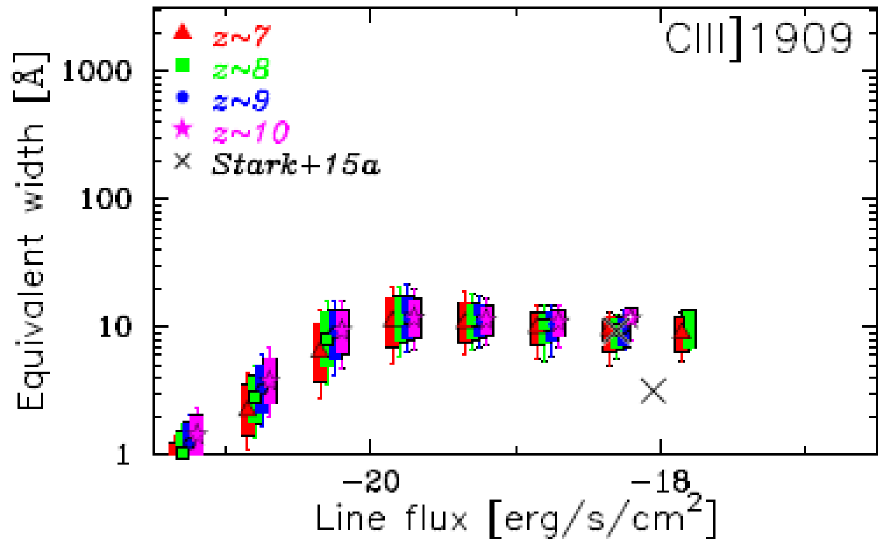


Prediction for CIV and CIII] line from z~7 to z~10

CIV 1549 Å



CIII] 1909 Å



In the fainter line fluxes (less massive galaxies) regime (<10^{-20} erg/s/cm2)

The EWs are proportional to their line fluxes

⇒ the current SFR divided by an average of SFR over a certain time duration

= SFR/< SFR >

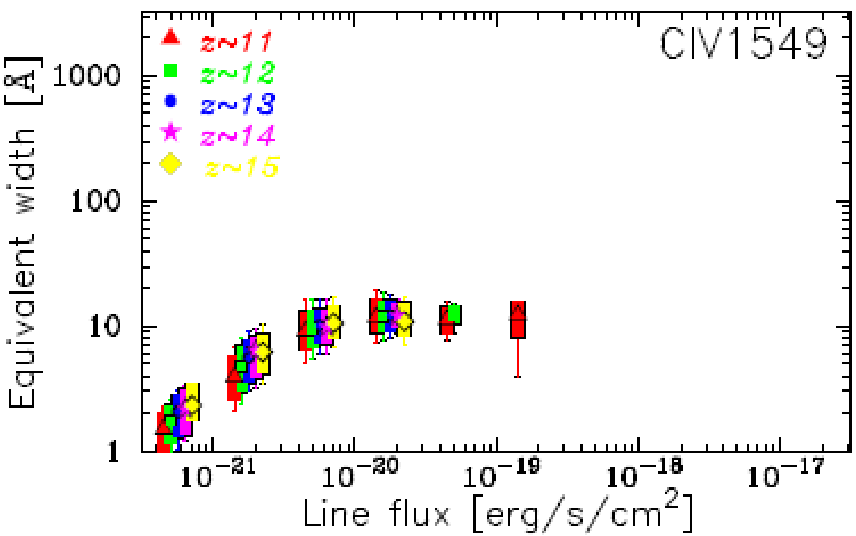
In the brighter line fluxes (massive galaxies) regime (>10^{-20} erg/s/cm2)

EWs are almost constant (or very slowly decrease with increasing line fluxes)

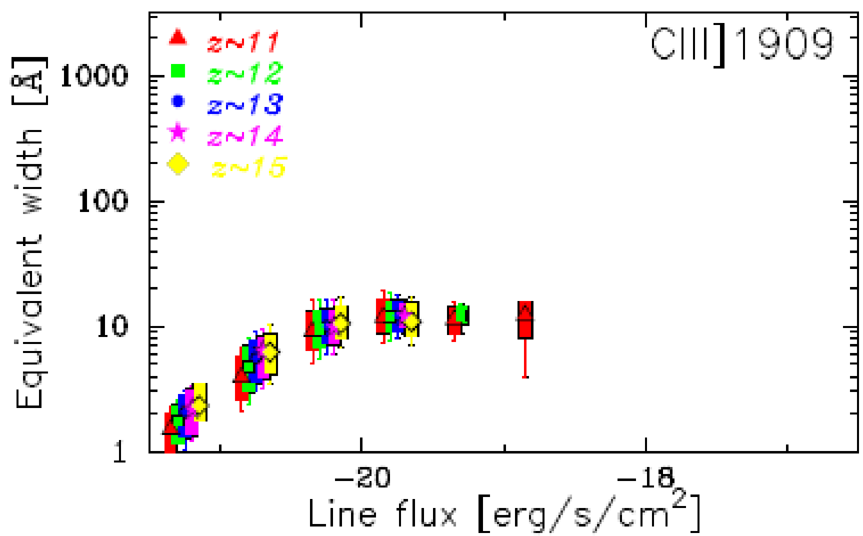
⇒ These galaxies are in an on-going star-formation episode (or starburst) and their EW (or SFR/< SFR >) reaches an asymptotic value.

Prediction for CIV and CIII] line at z > 10

CIV 1549Å



CIII] 1909Å



Same trend can be seen in cases of z < 10 galaxies.

Prediction for CIII]1909 Å