Emission lines in star-forming galaxies

Daniel Schaerer (Geneva Observatory & CNRS)

- *Introduction*
- *Properties of CIII] and CIV emitters at high redshift*
- *Compact strong emission line galaxies at z~0.3: analogs of the sources of cosmic reionization*
- *Conclusions*

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Star-forming galaxies at high redshift – overview of main information

Statistical properties:

- Number counts as fct of redshift
- Luminosity function (z) [continuum +certain emission lines]

- Star formation rate density (z)
- Stellar mass function (z)

- Sizes
- Clustering
- …

Physical properties:

- Stellar mass
- Star formation rate (SFR)
- Age of stellar population
- Dust attenuation

- **Metallicity**
- **ISM properties**
- **Radiation field**
- **Leakage of ionizing photons**
- Kinematics
- …

Spectroscopy -

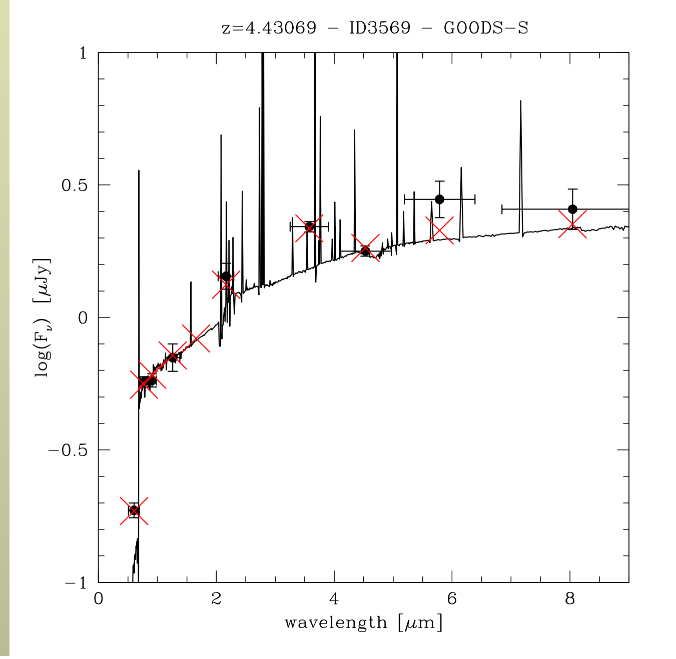
needs near-IR …up to 5-6 μm for high-z

- Dust mass
- Gas content
- Dark matter content?

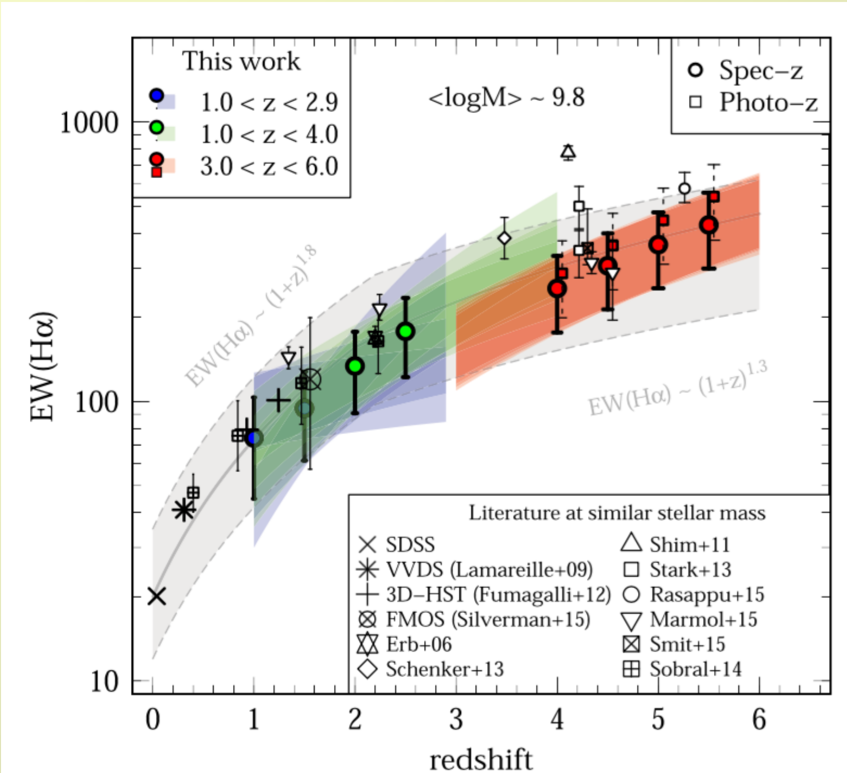
needs IR-mm data!

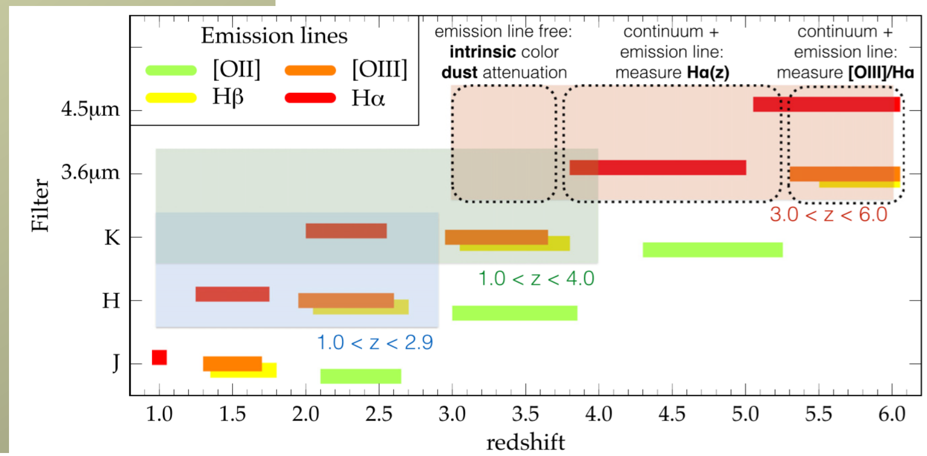
Redshift evolution of emission line strengths

Schaerer & de Barros (2009)
de Barros et al. (2014)



EW(Hα) traces specific star formation rate (sSFR=SFR/M*)

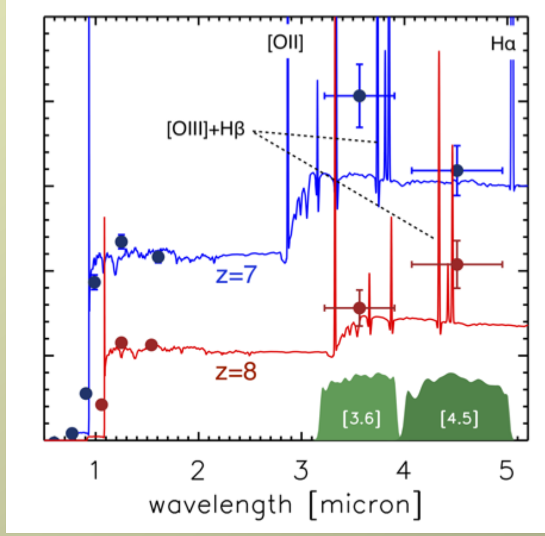




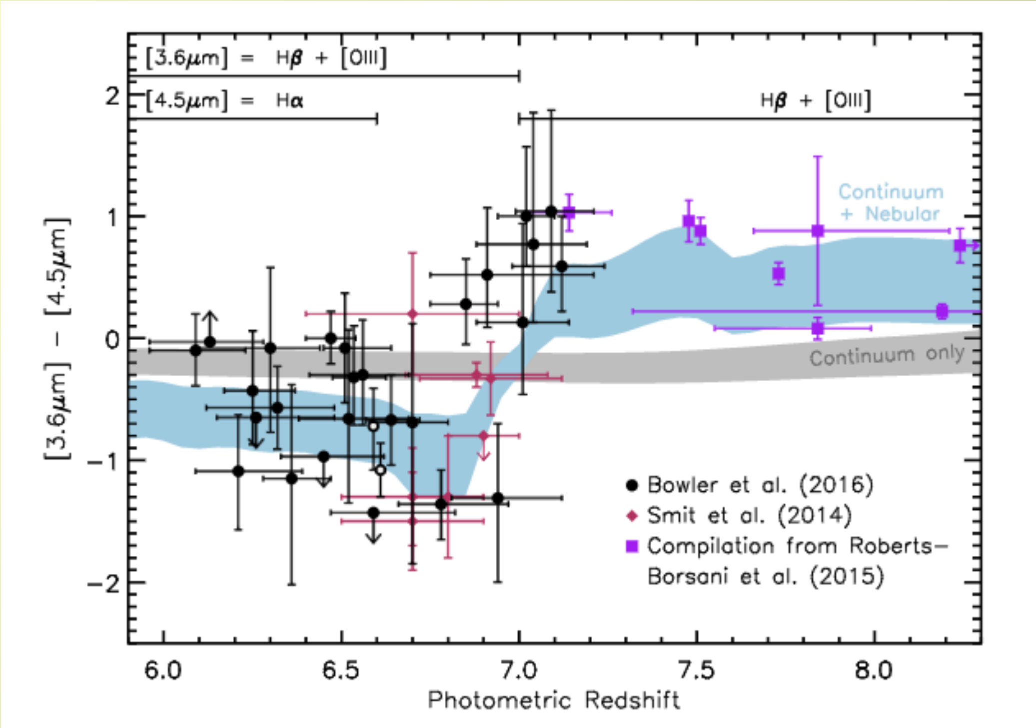
Faisst+2016

Redshift evolution of emission line strengths

Strength of [OIII]4959,5007 Å increases out to z~7



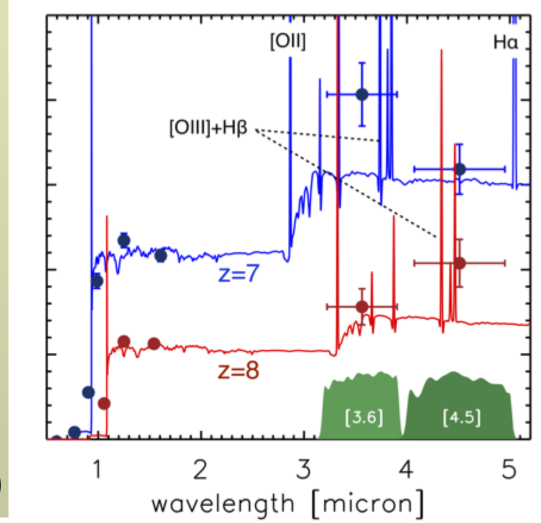
Labbé et al. (2012)



Bowler et al. (2017)

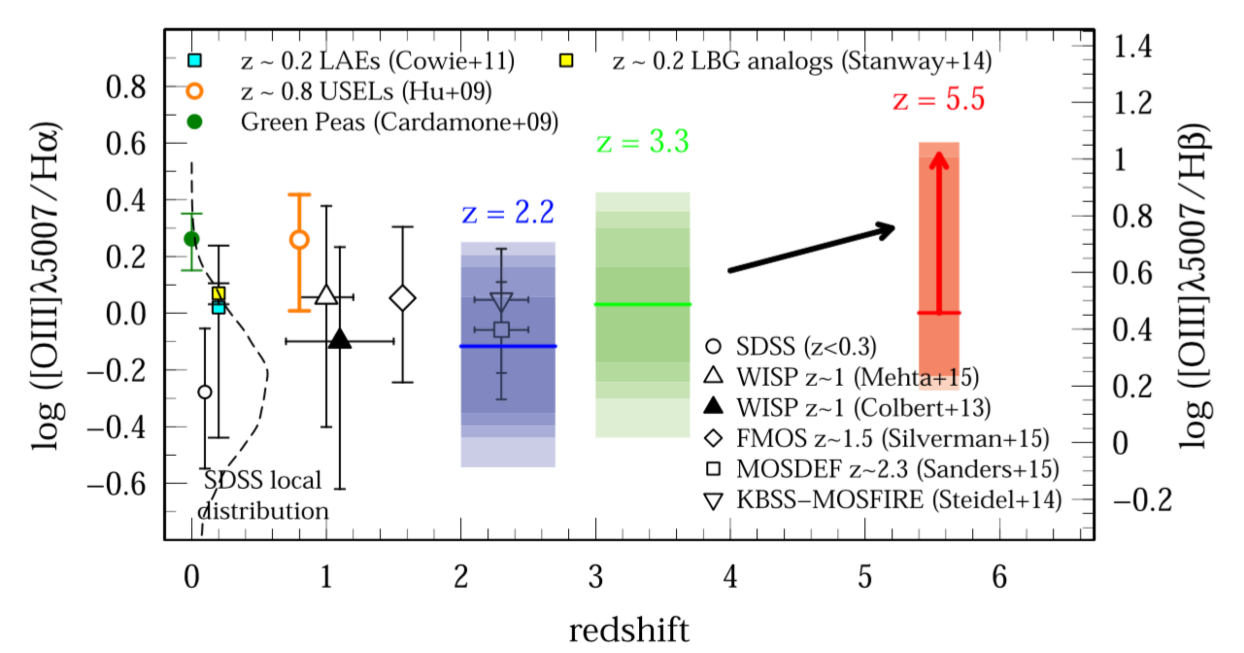
Redshift evolution of emission line strengths

Strength of [OIII]4959,5007 Å increases out to z~7
Possible increase of OIII/OII ratio with redshift
→ **Metallicity decreasing**
→ **+ increase of ionization parameter and ISM pressure ?!**
→ **Increased escape of ionizing photons?**

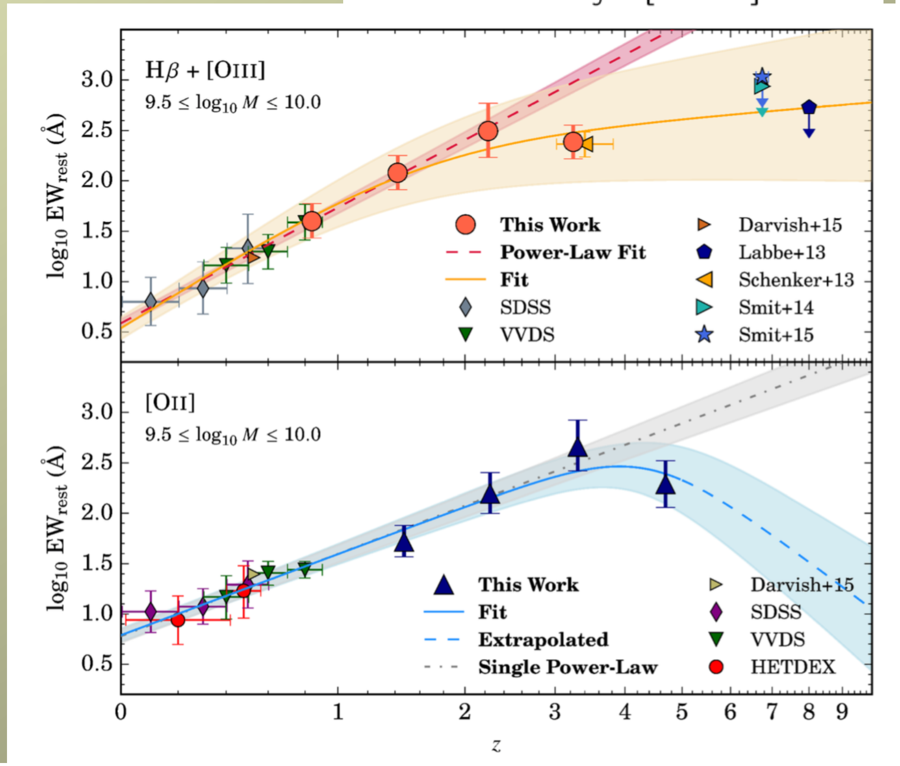


Labbé et al. (2012)

Faisst+2016



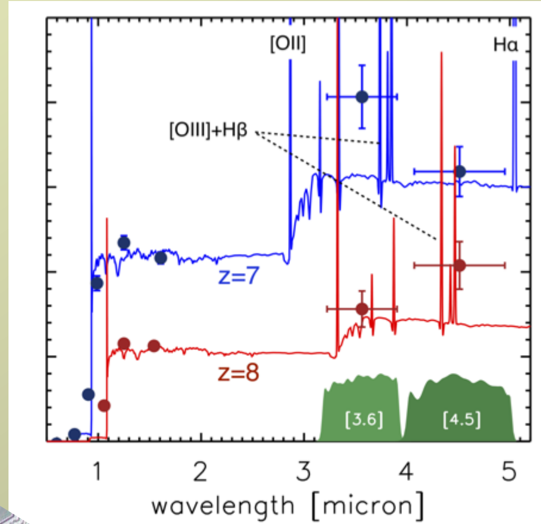
Khostovan+2016

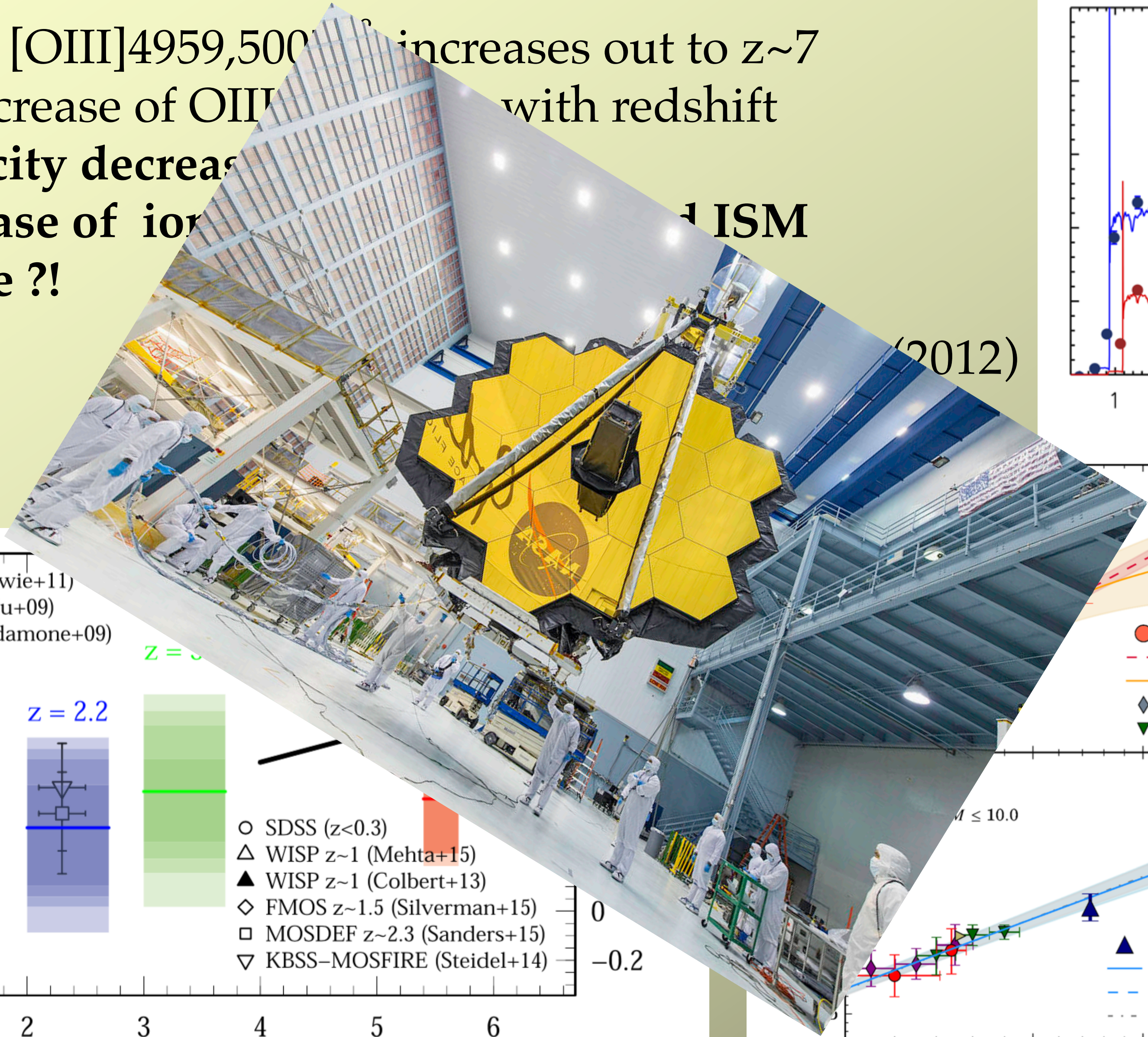


Redshift evolution of emission line strengths

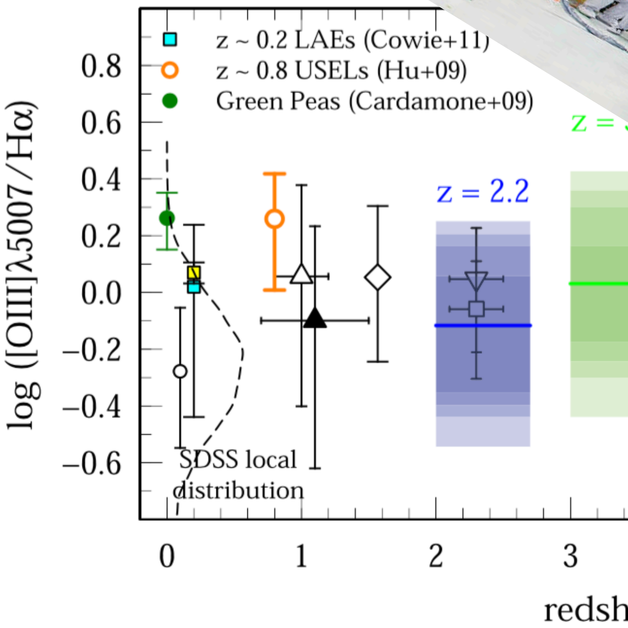
Strength of [OIII]4959,500 … increases out to z~7
Possible increase of OIII … with redshift
→ Metallicity decreas…
→ + increase of ion… …l ISM pressure ?!

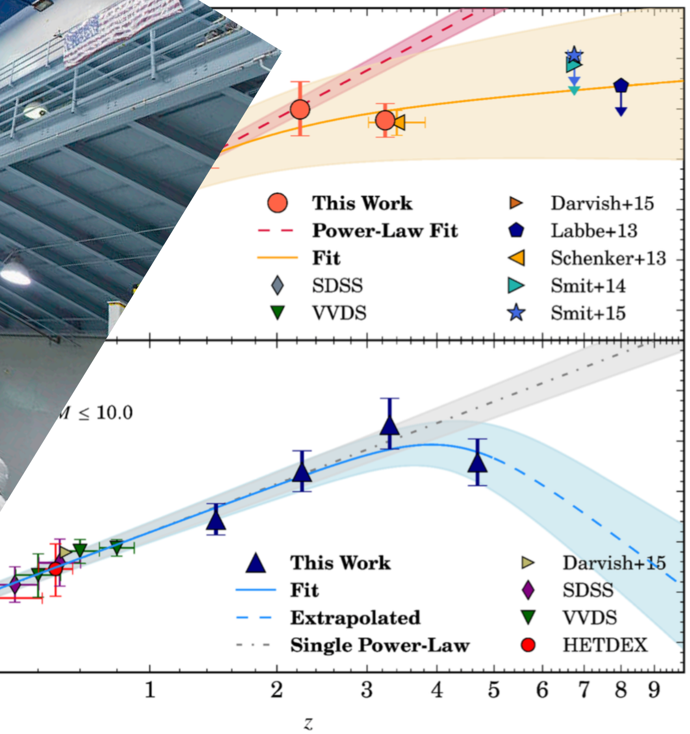
(2012)





Faisst+2016



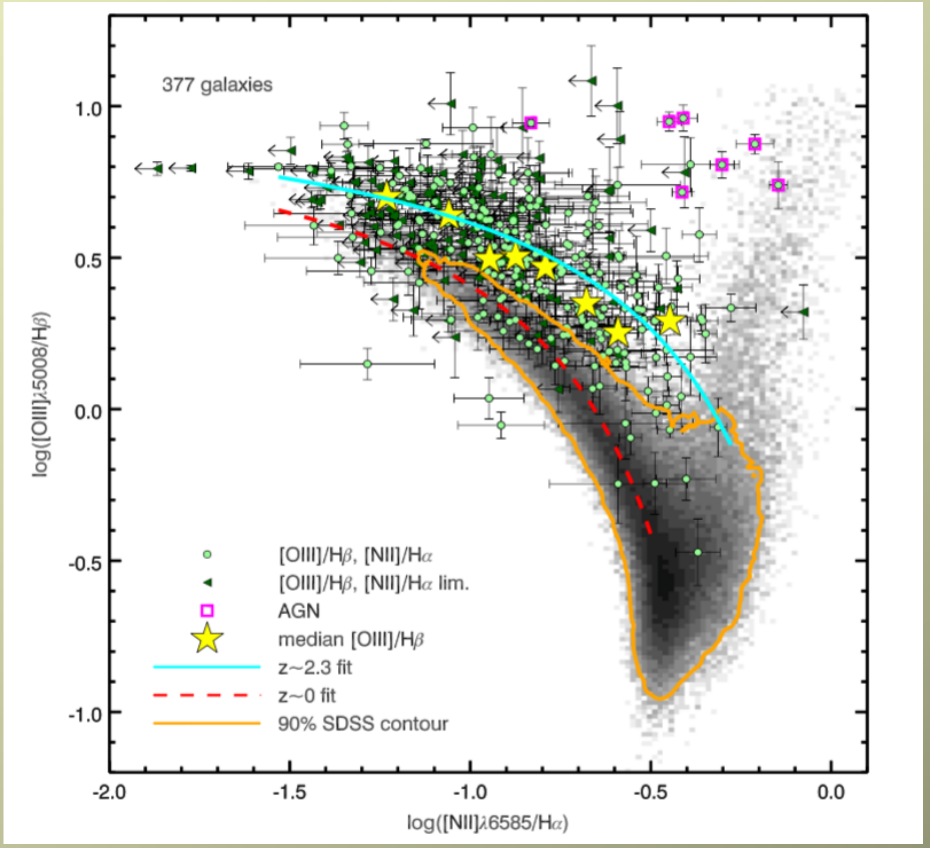


Restframe optical emission lines at z~2-3

Numerous studies on:
- Mass –metallicity relation, FMR
- ISM properties
- BPT diagrams, different emission line properties
- Kinematics

MOSFIRE@Keck → MOSDEF, KBSS surveys
KMOS@VLT

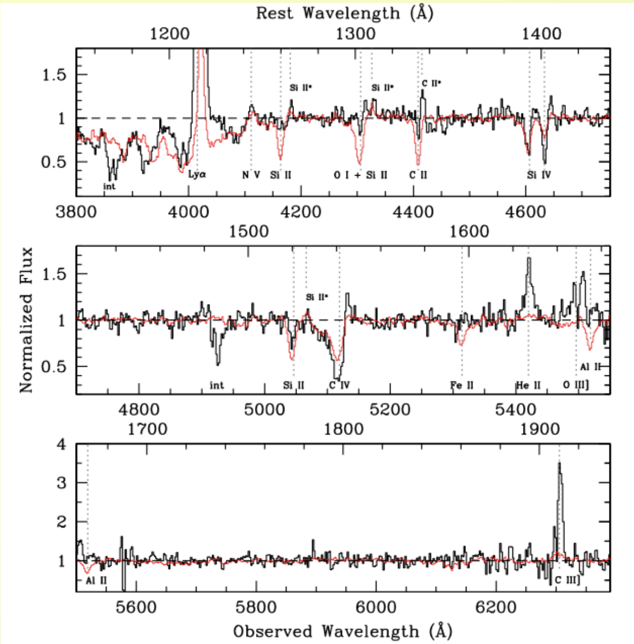
→ Many talks later …!



e.g. Strom et al. (2017)

Rest UV emission lines in z>2 galaxies

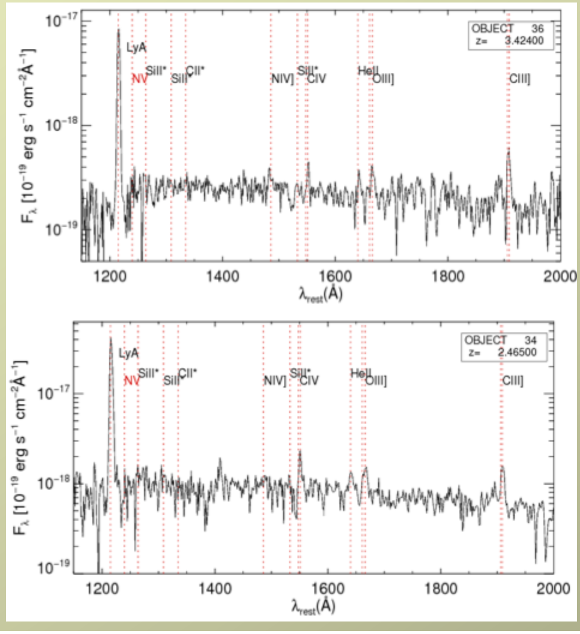
Lefèvre et al. (2014)

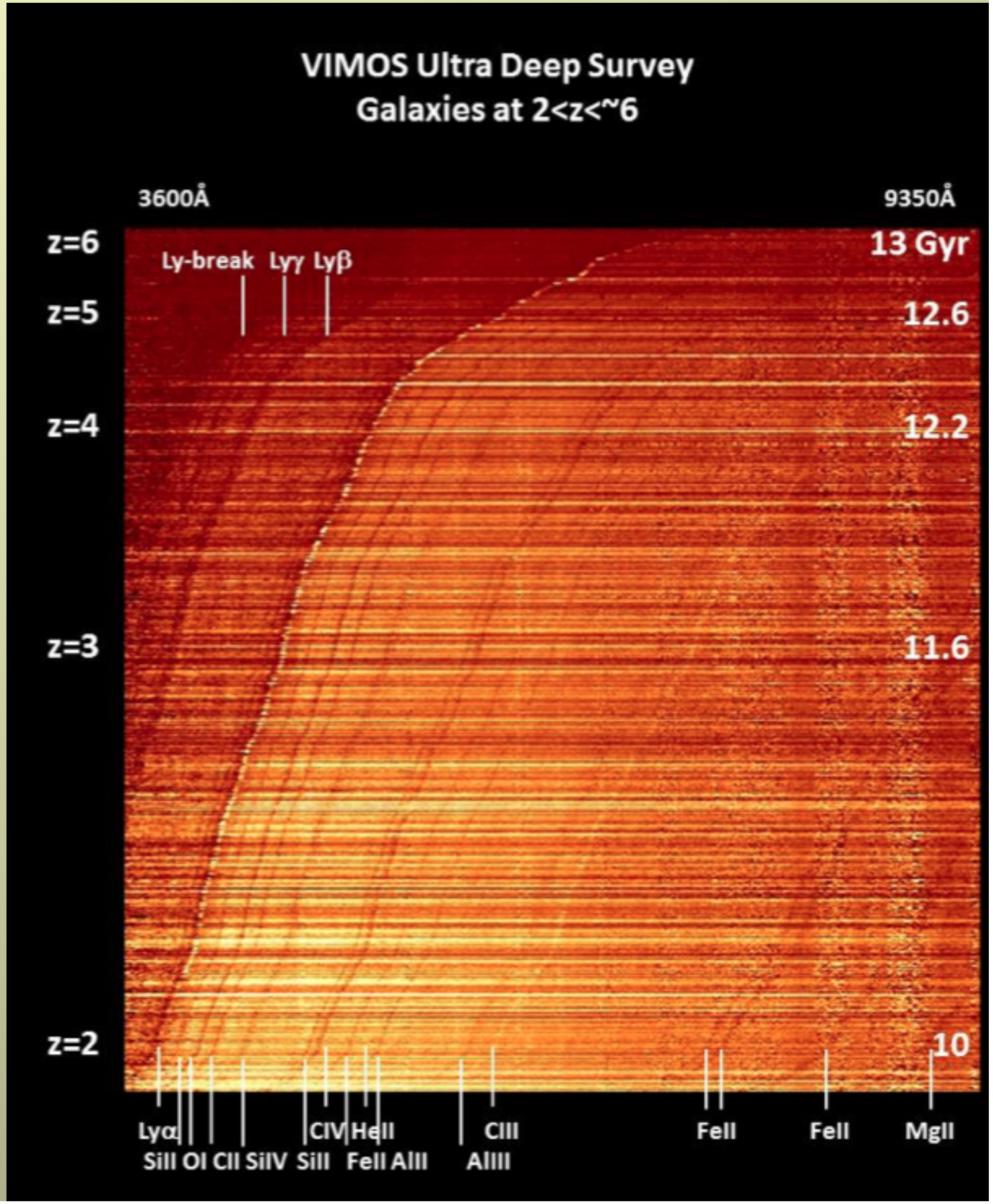


Erb et al. (2010)

Young, primeval galaxies at z~2-4 !?

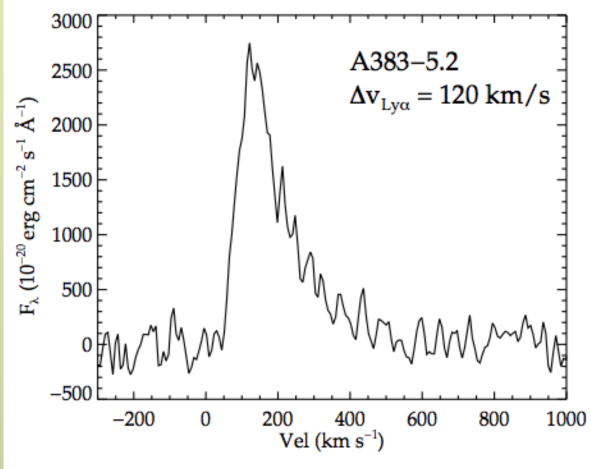
Amorin et al. (2015, 2017)

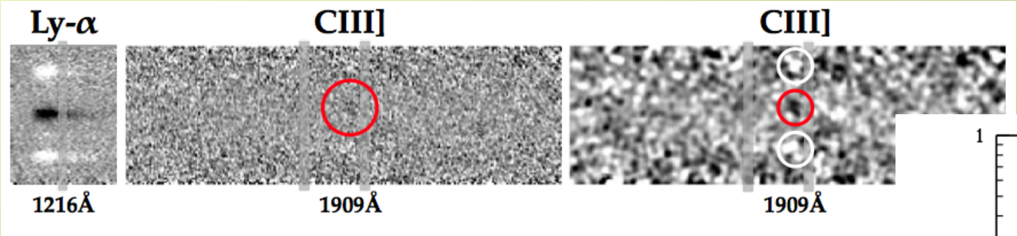


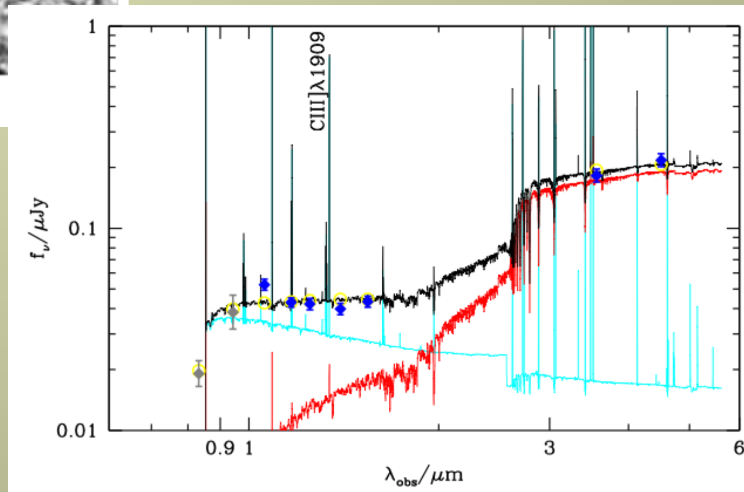


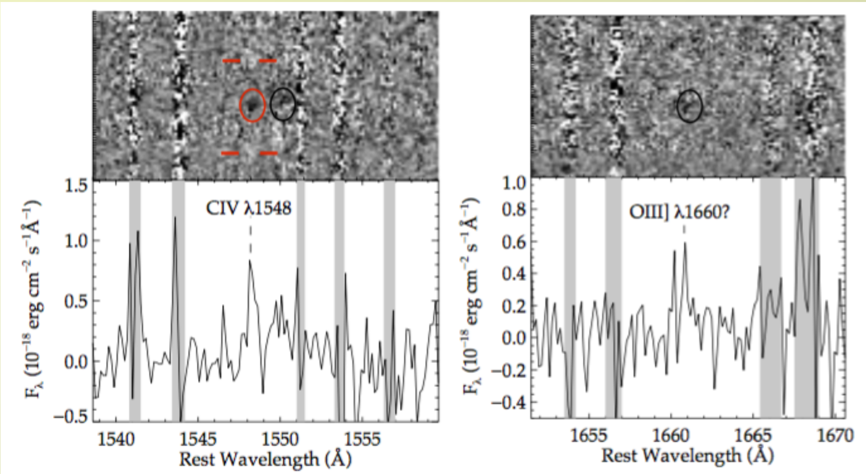
Rest UV emission lines in z>6 galaxies

- **CIII] 1909 line to replace Lyα for galaxies in epoch of reionization !?**
- First attempts to derive physical parameters (ISM, stellar populations,…)









Model fit to A383.5.2

$\log U$	$-1.70^{+0.49}_{-0.64}$
$\log(M_{*,young}/M_{*,tot})$	$-2.99^{+0.04}_{-0.03}$
$\log(Z/Z_\odot)$	$-1.33^{+0.27}_{-0.20}$
$\log(C/O)$	$-0.58^{+0.06}_{-0.06}$
$\log(age/yr)$	$8.72^{+0.10}_{-0.10}$
$\log(M_{*,tot}/M_\odot)$	$9.50^{+0.10}_{-0.10}$
$\log(SFR/M_\odot yr^{-1})$	$0.29^{+0.08}_{-0.08}$
$\hat{\tau}_V$	$0.05^{+0.05}_{-0.05}$

CIV 1550 line at z=7.045

→ **harder radiation field at high-z ?**

→ Low luminosity AGN ?

Stark et al. (2014, 2015)

Intererences from UV emission lines: the nature of CIII] and CIV emitters

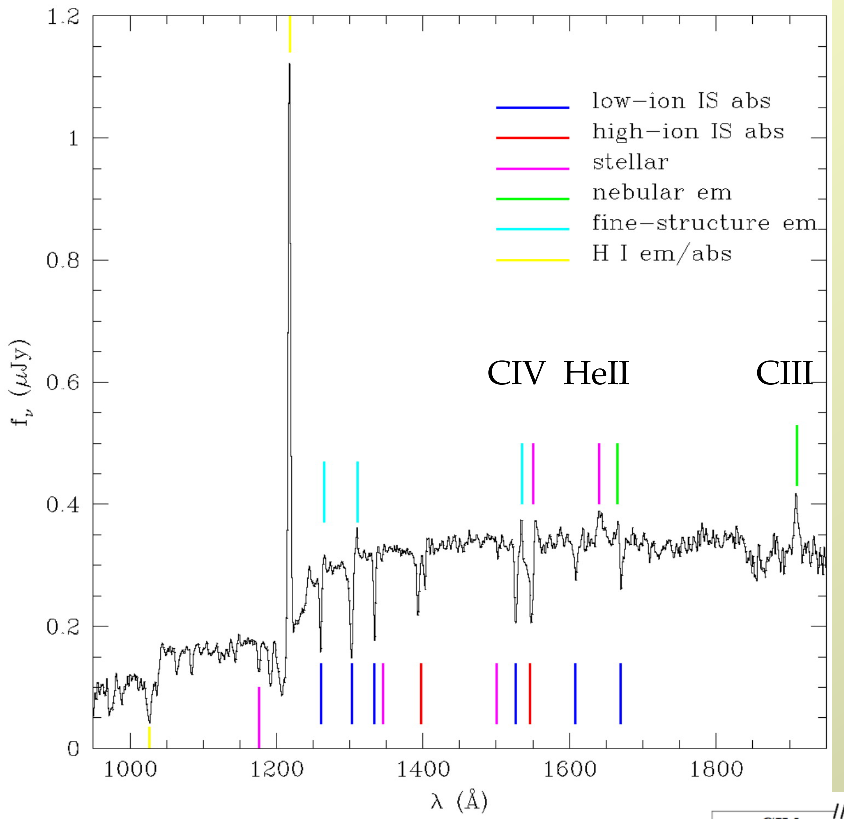
- The VIMOS Ultra Deep Survey: On the nature, ISM properties, and ionizing spectra of CIII] 1909 Å emitters at z=2-4

  Nakajima, Schaerer, Le Fèvre et al. (2017) – arXiv:1709.03990

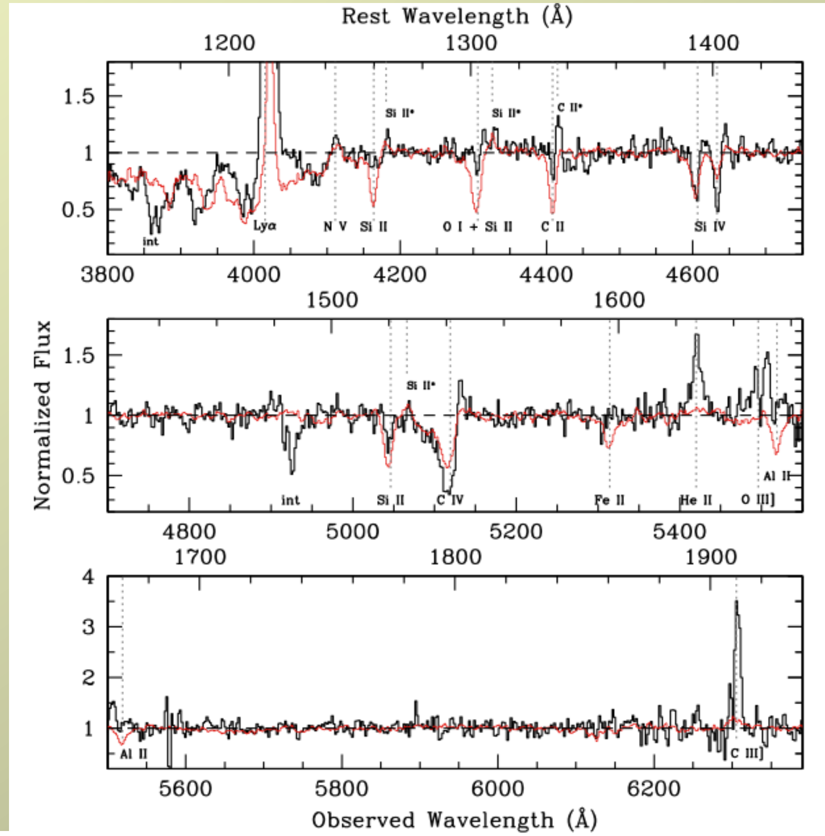
- The VIMOS Ultra Deep Survey: Statistical properties of CIII]–1909Å emitters in star-forming galaxies with 2 < z < 3.8 and evidence for AGN star-formation quenching

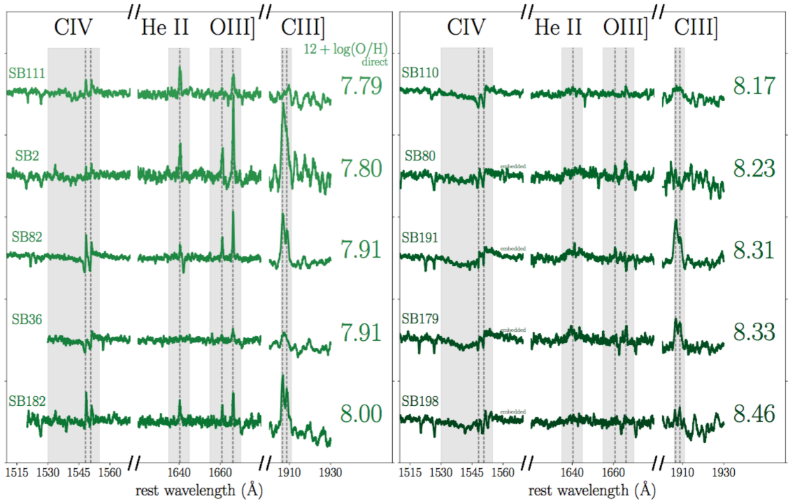
  Le Fèvre, Lemaux, Nakajima, Schaerer et al. (2017)

CIII] and CIV lines in star-forming galaxies



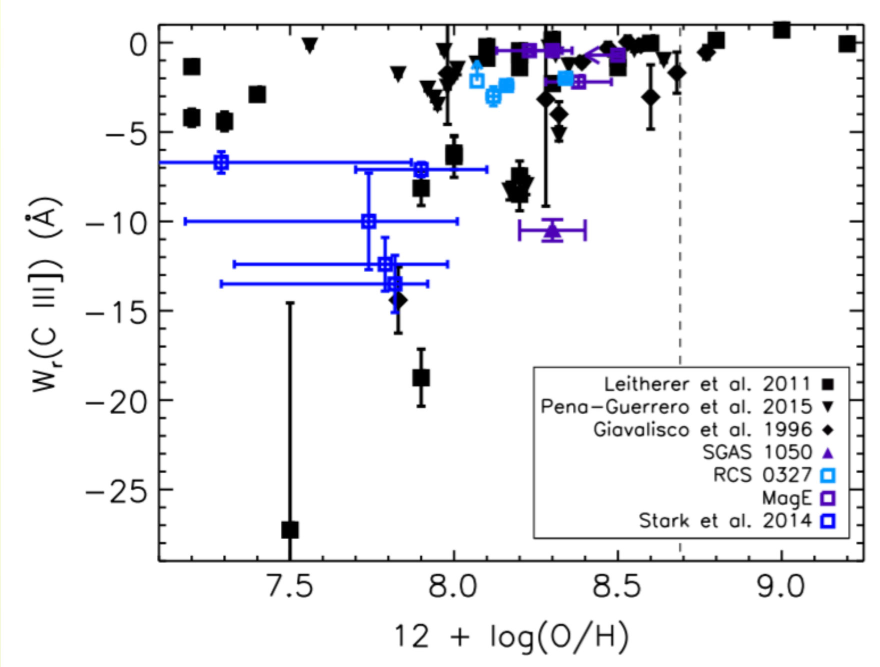
High-z:
Shapley et al. (2003)
Erb et al. (2010)

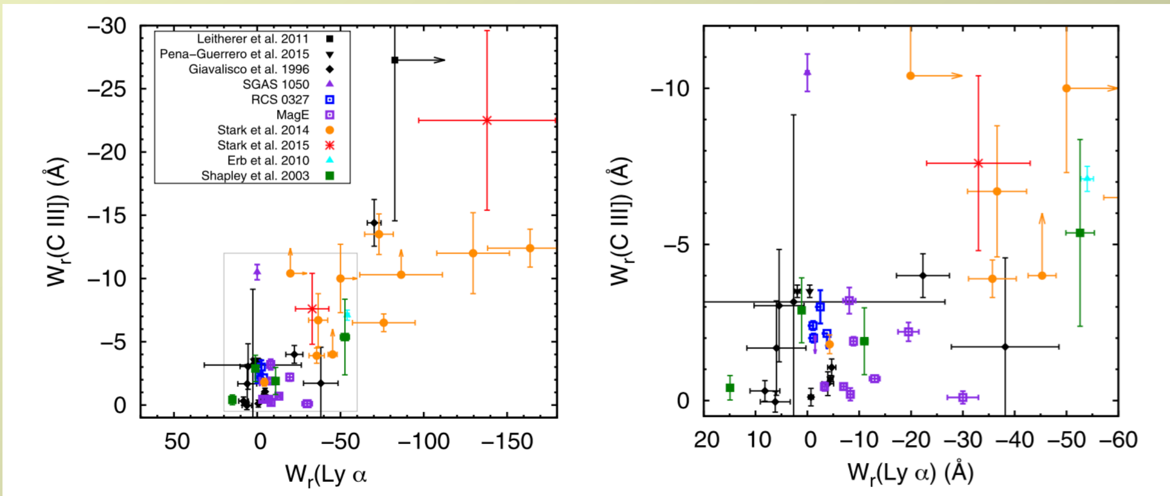




Low-z sources:
Senchyna et al. (2017)

CIII] and CIV lines in star-forming galaxies





Compilation from Rigby et al. (2015)

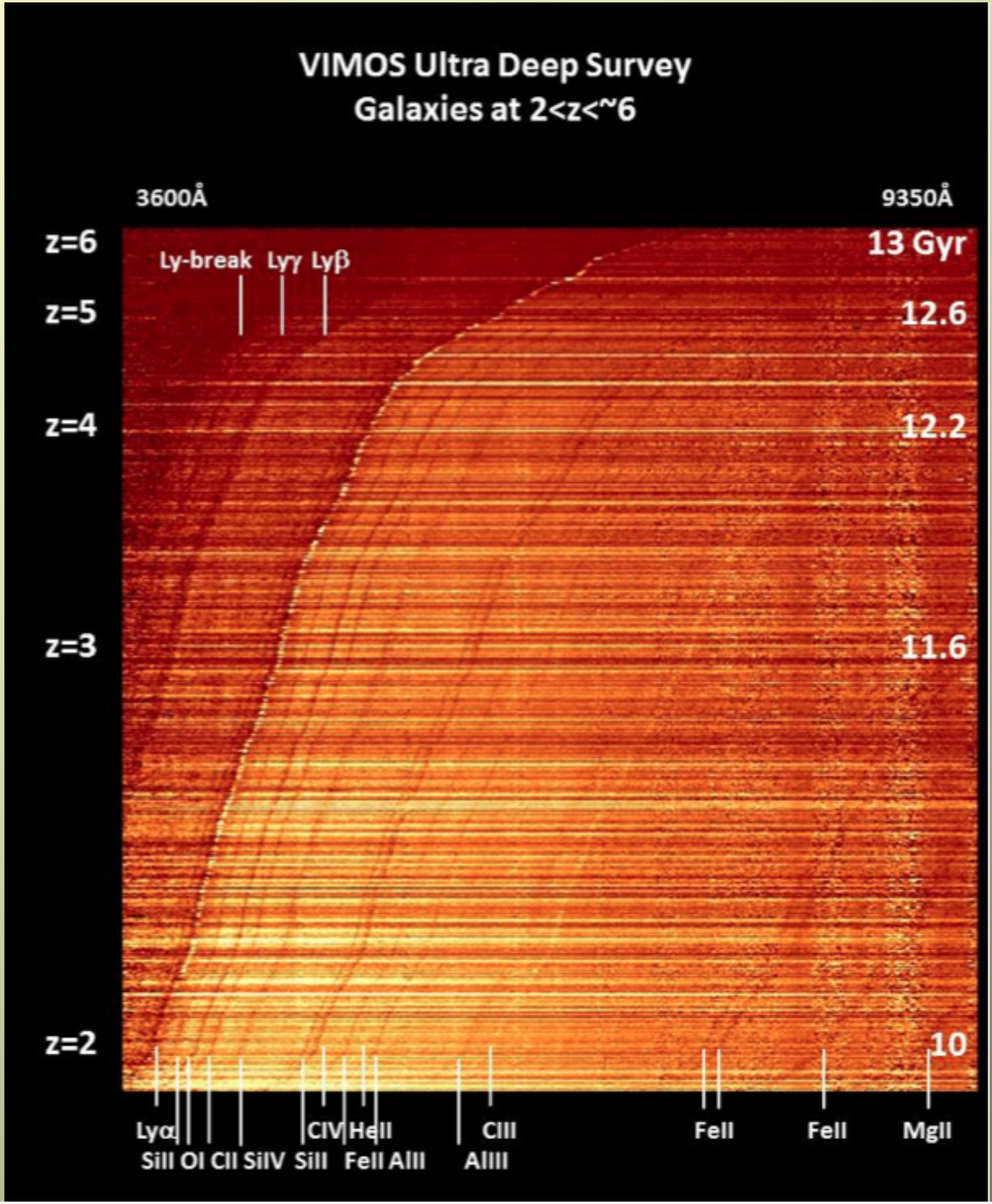
- **Does CIII]1909 primarily trace low metallicity?**
  Cf. CLOUDY modeling of Jaskot & Ravindranath (2016)
- **What explains a correlation between Lyα and CIII] ?**
- **ISM properties**

→ larger samples are needed !!

VUDS:
Survey of ~10’000 galaxies at z~2-6 within 1 deg2 on the VLT (14h integration)

COSMOS, ECDF, VVDS-02h fields

→ cesam.lam.fr/vuds



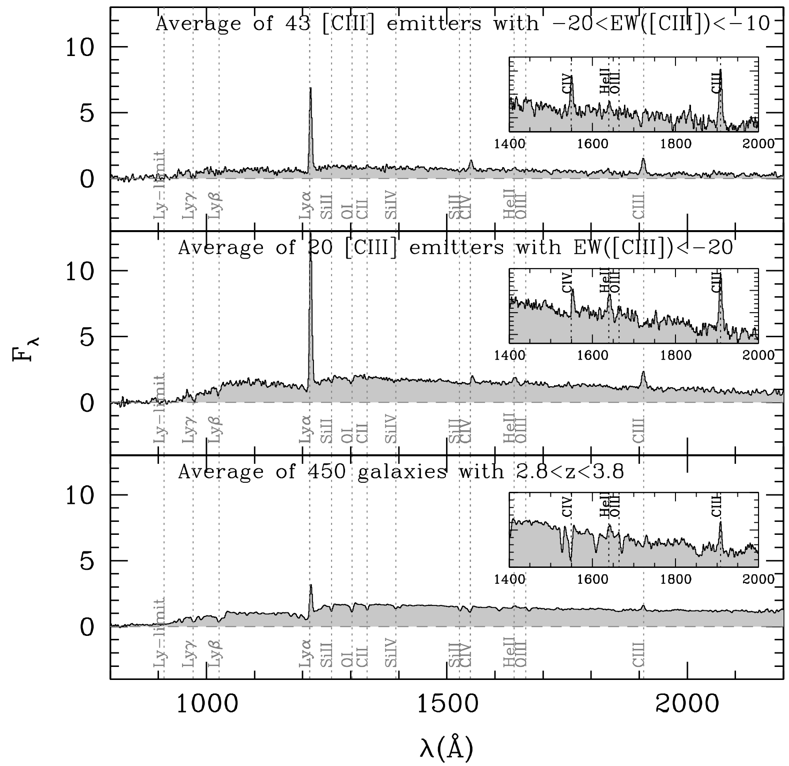
Lefèvre et al. (2014, 2015)

CIII] emitters in VUDS

- 2276 galaxies at z=2 – 3.8 (most with i_AB<=25)
- 43 % show EW(CIII)>3 Å (detection limit, for R~250)

→ Statistics of CIII] emission
→ Individual spectra and stacks
→ Measured lines: Ly**α**, NV, SiII, SiIII, NIV, CIV, HeII, OIII], NIII, SiIIII, CIII]

Le Fèvre, Lemaux, Nakajima, Schaerer et al. (2017)
Nakajima, Schaerer, Le Fèvre et al. (2017)



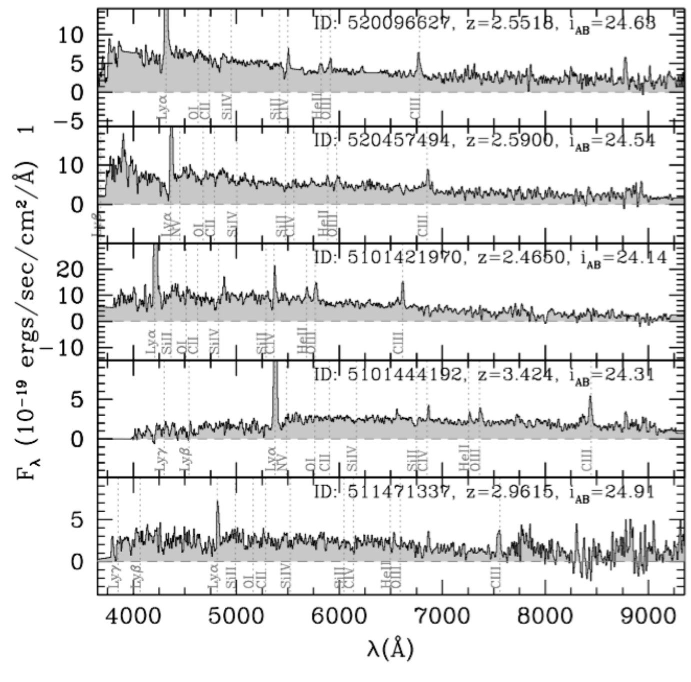
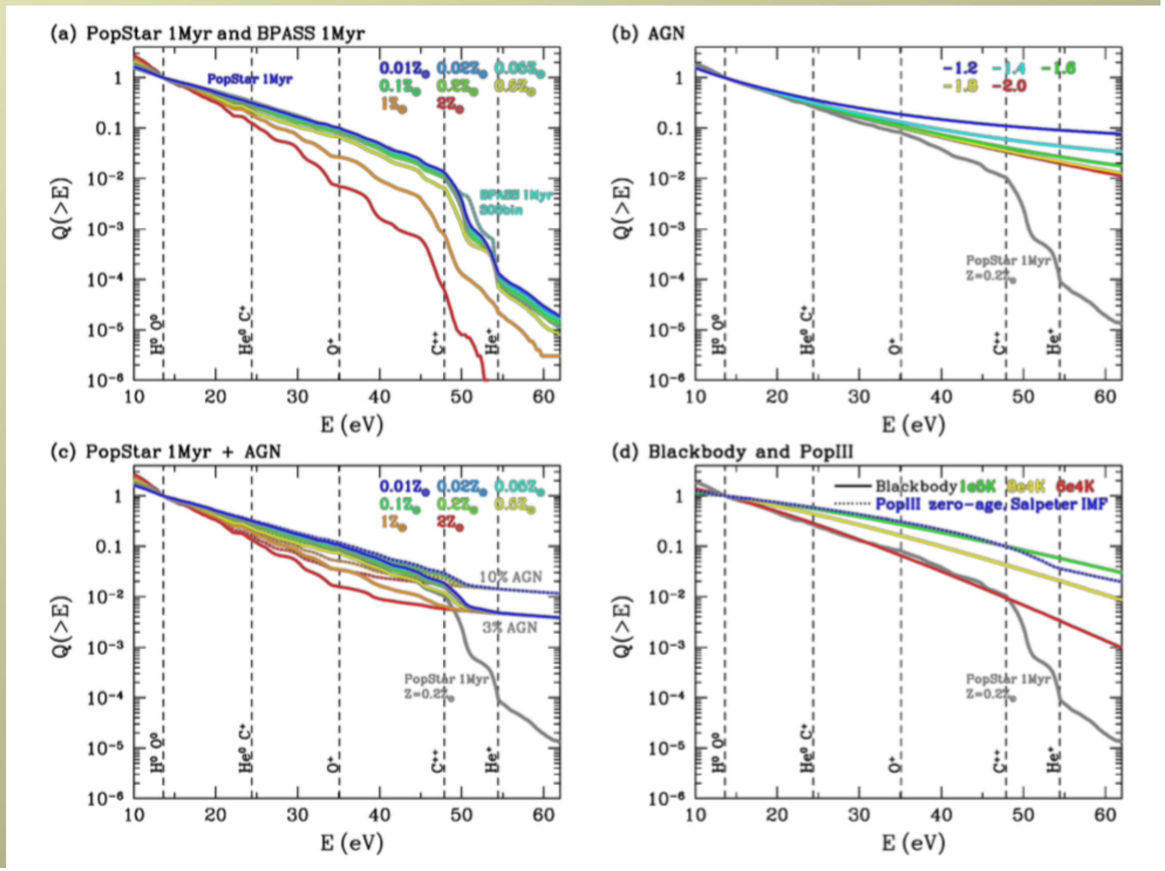


Fig. 2. Example VUDS spectra of CIII]1909 emitters with 10 < $W_{CIII]}$ < 20Å.

CIII] emitters in VUDS

Emission line modeling (using CLOUDY):

- Large grid with different radiation fields (SF, AGN and mix)
- Normal stellar populations and binary models (BPASS)
- Vast range of ionization parameters U
- Metallicities from 0.01 to 2 * solar
- Varying densities …



Nakajima et al. (2017)

CIII] emitters in VU

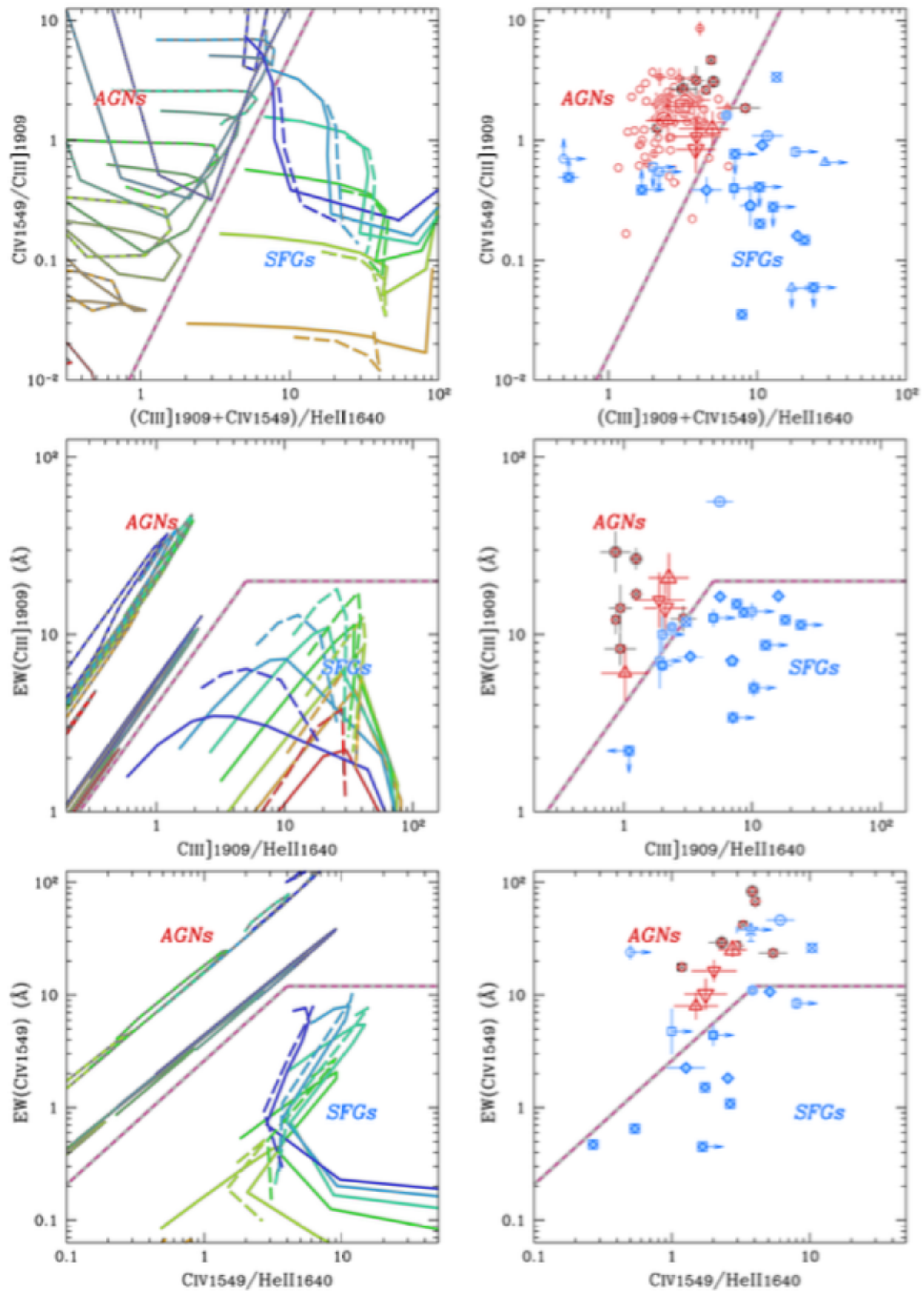
Emission line modeling (using CLOU

- Large grid with different radiation
- Normal stellar populations and bi
- Vast range of ionization parameter
- Metallicities from 0.01 to 2 * solar
- Varying densities …

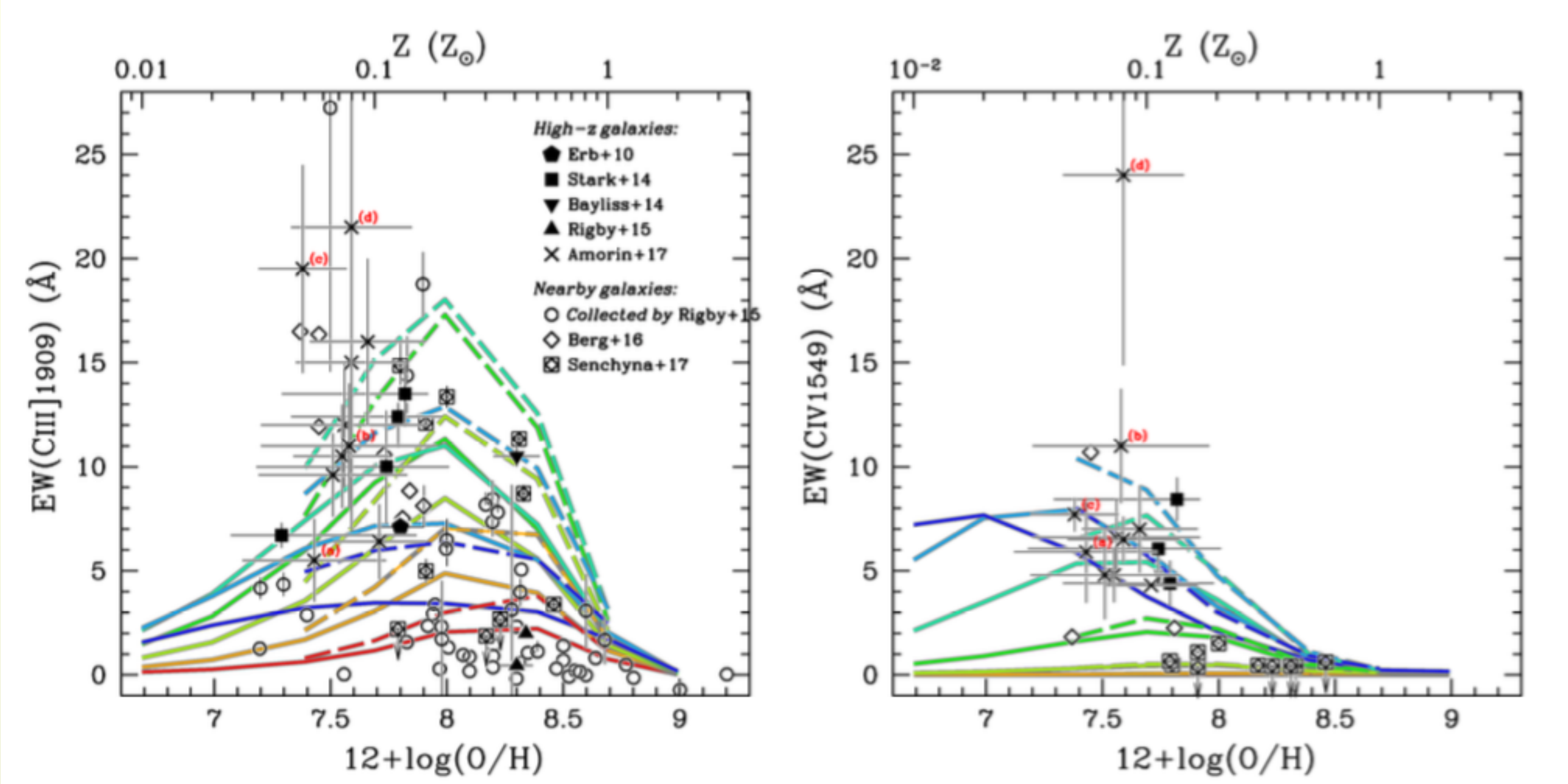
→ **Star-formation versus AGN diagnostics**

Cf. Feltre+ 2016, Gutkin+ 2016

Nakajima et al. (2017)



CIII] emitters in VUDS



… sources with known/estimated metallicity

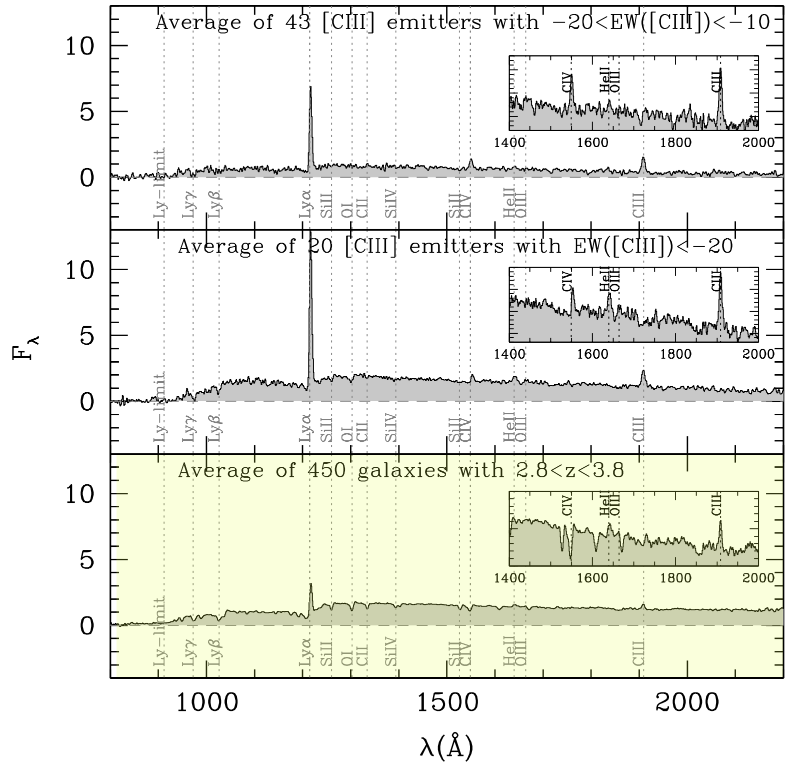
Nakajima et al. (2017)

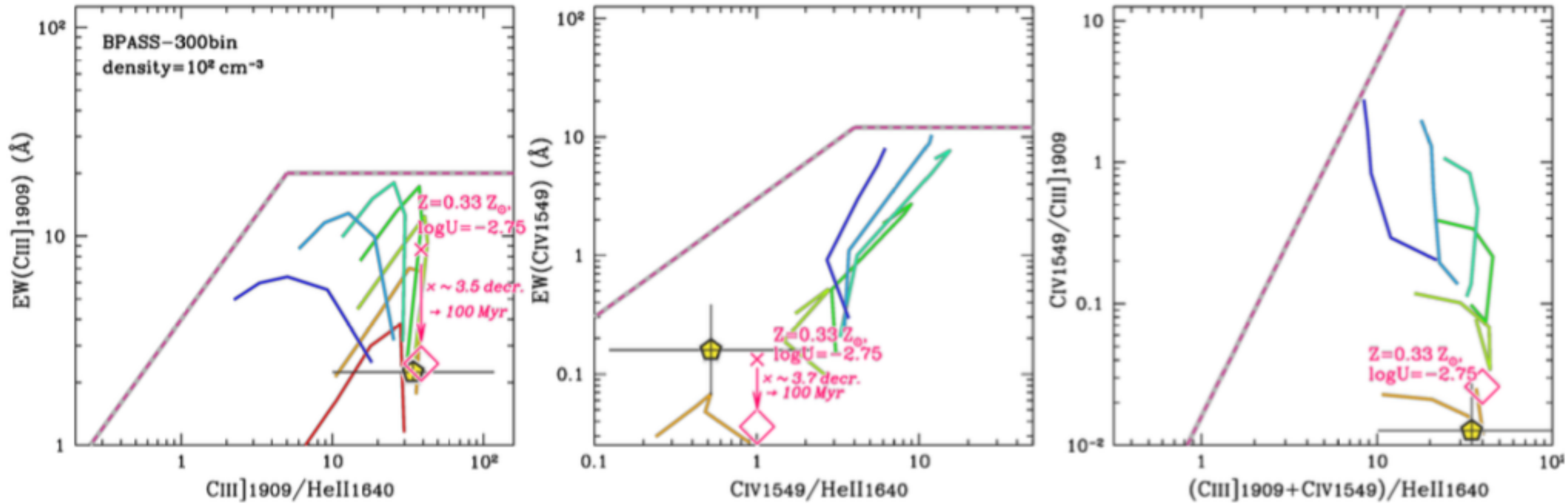
CIII] emitters in VUDS

Stack of all SF galaxies:

- *SF ionizing spectrum*
- Better agreement for BPASS models
- Metallicity ~ 0.3 solar
- Log(U) ~-2.5 to -3
- ~normal ionizing photon production

Nakajima et al. (2017)

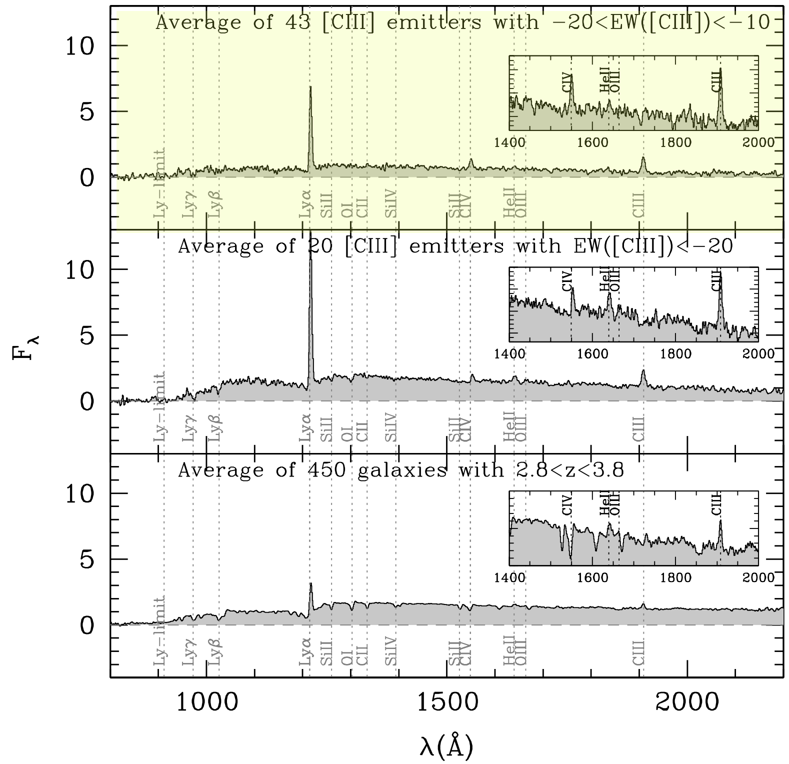




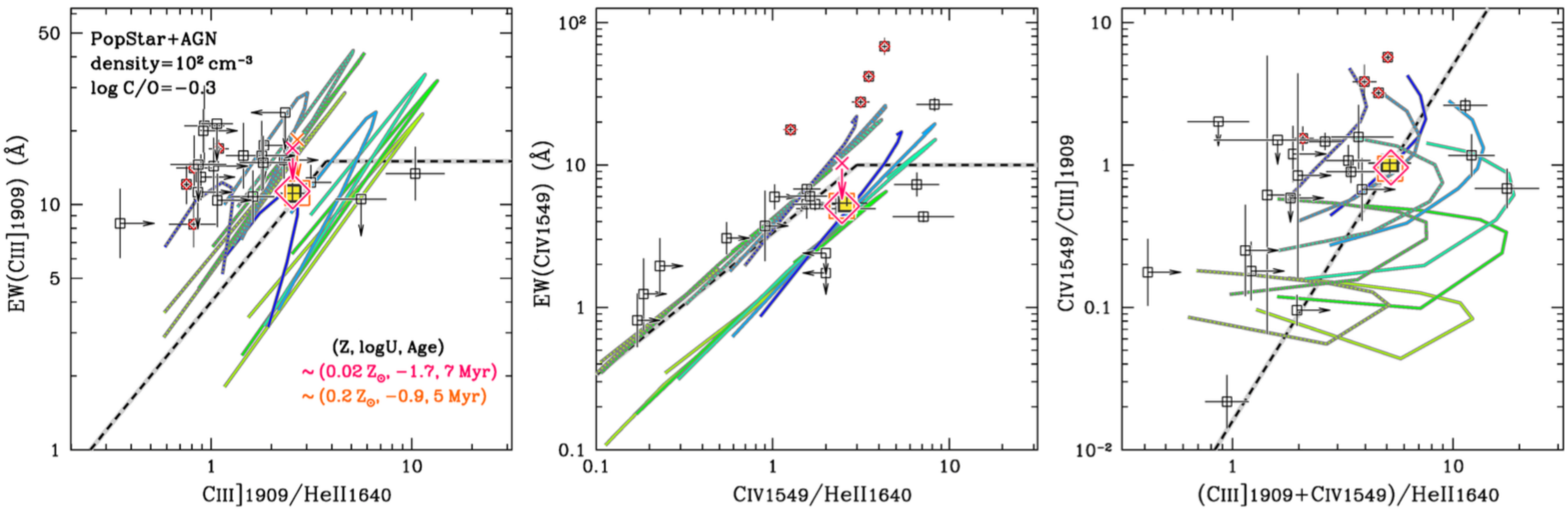
CIII] emitters in VUDS

« Intermediate » EW(CIII)~10-20 Å :

- SF + 7% AGN
- Metallicity ~ 0.2 solar, log(U) ~-1
- Some sources show evidence for enhanced C/O (cf. Amorin+ 2017)



Nakajima et al. (2017)



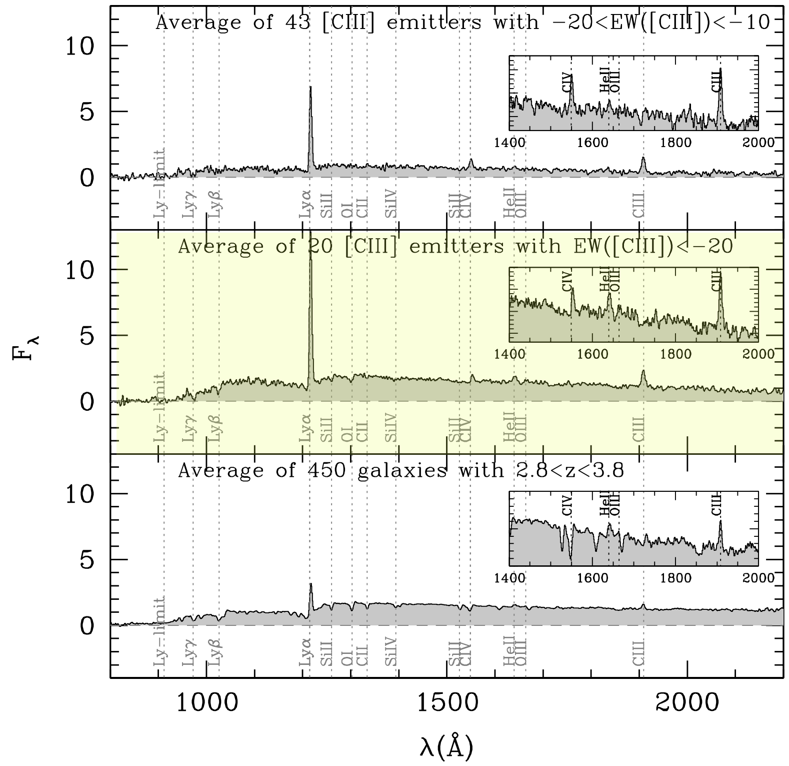
CIII] emitters in VUDS

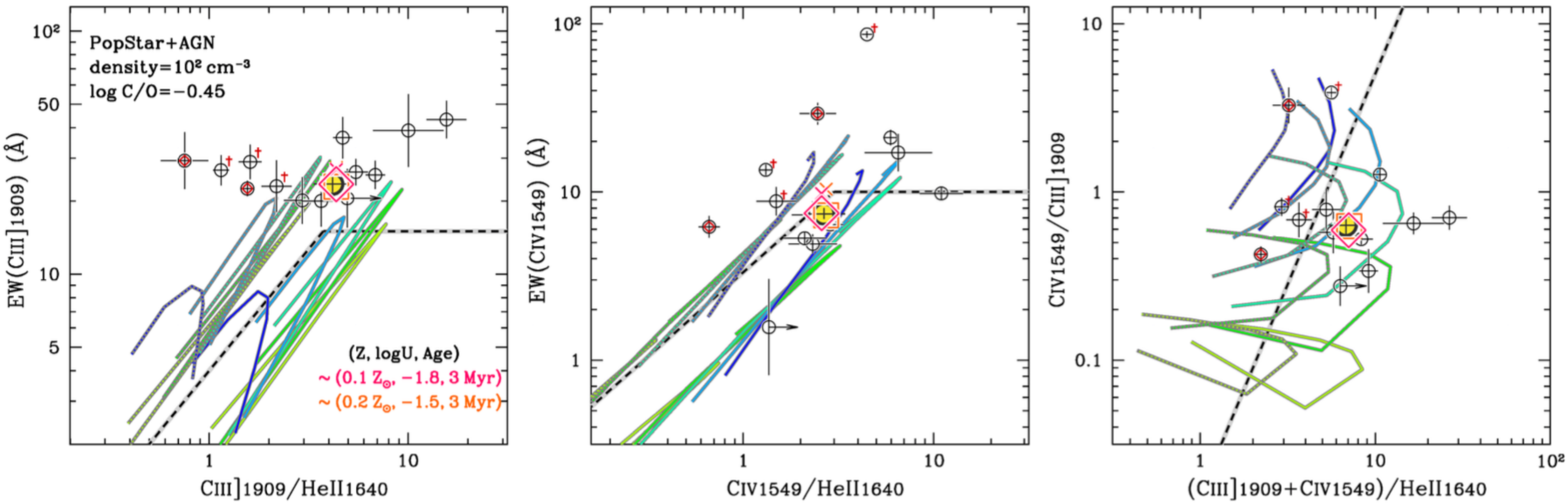
« Strong » CIII] emitters: EW>20 Å :

- SF + 8% AGN – very hard spectrum needed!
- Metallicity ~ 0.2 solar, log(U) ~-1.5
- Enhanced C/O (cf. Amorin et al. 2017)

→ rare sources !

Nakajima et al. (2017)



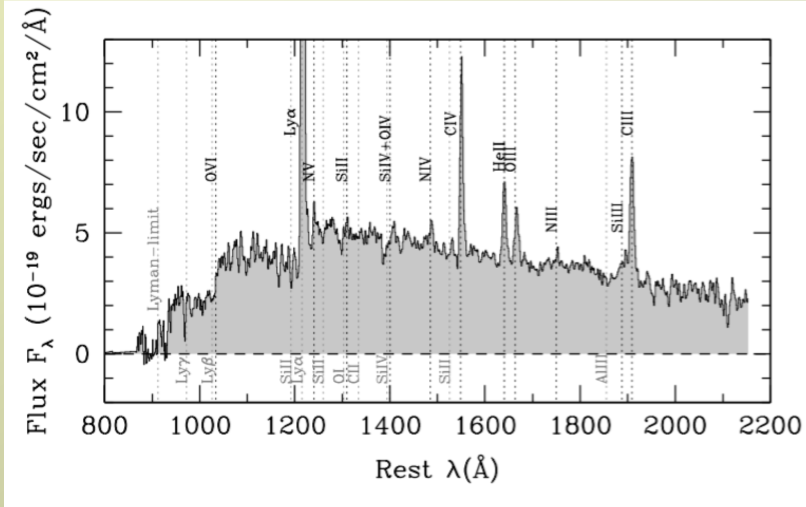


CIII] emitters in VUDS

« Strong » CIII] emitters: EW>20 Å :

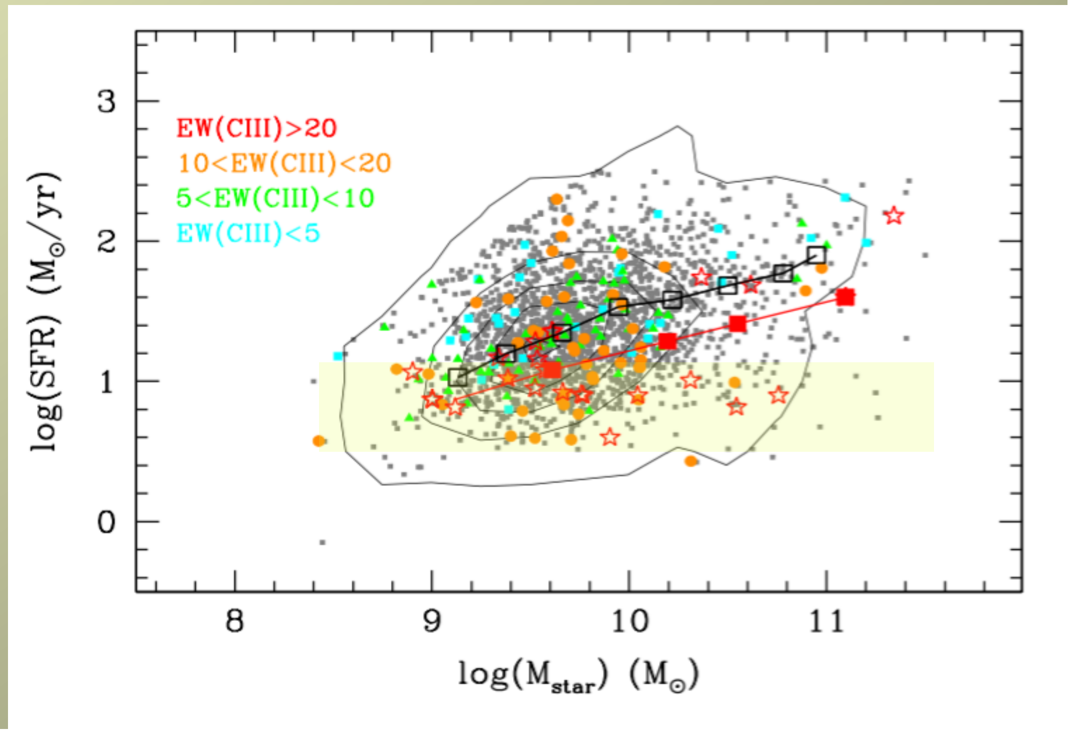
- SF + 10% AGN – very hard spectrum needed!
- Metallicity ~ 0.2 solar, log(U) ~-2
- Enhanced C/O

→ rare sources !



All indications compatible with AGN

Signature of quenching of star-formation by AGN !?



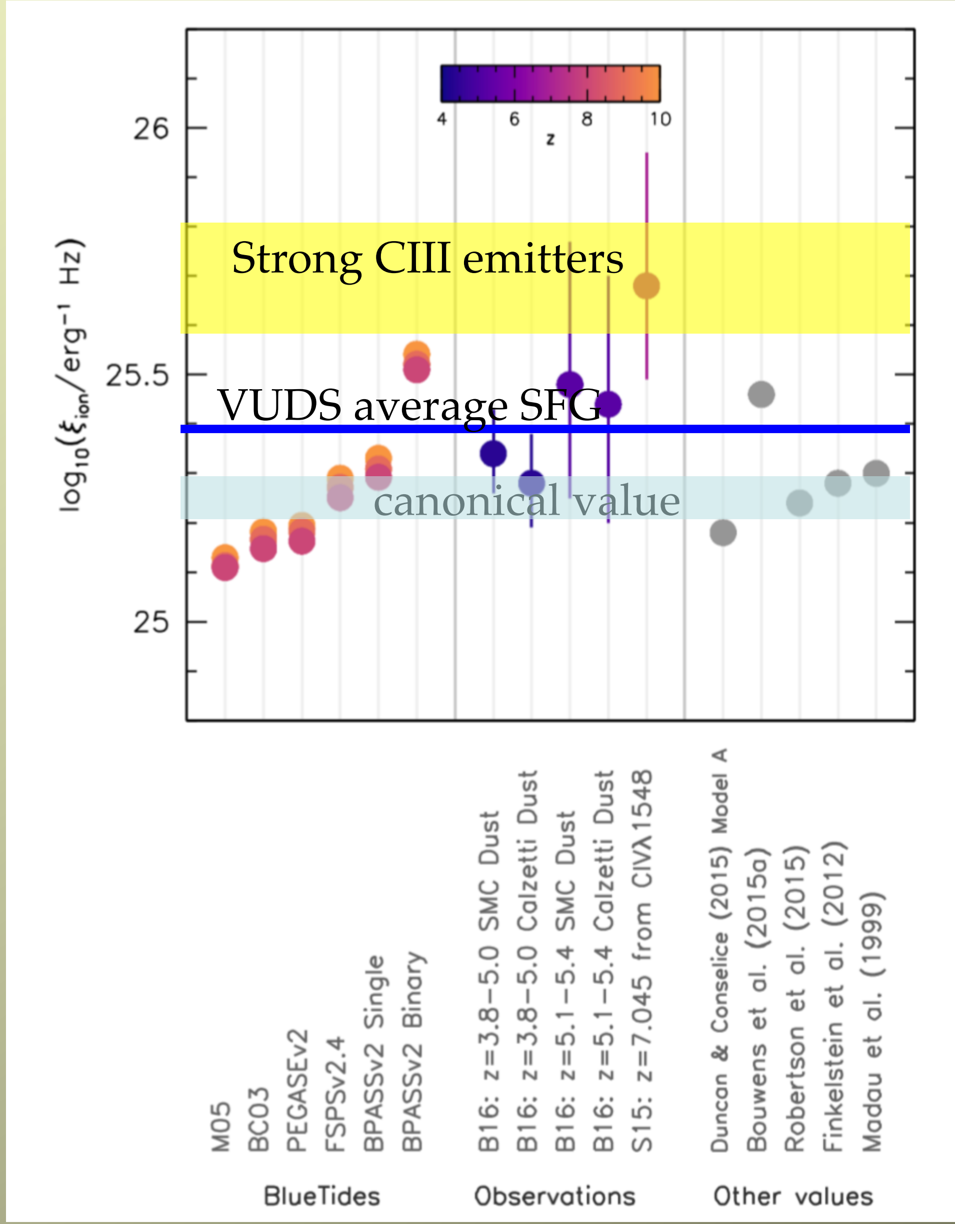
Nakajima et al. (2017)
Le Fèvre et al. (2017)

CIII] emitters in VUDS

Ionizing photon production:

ξ_{ion} = produced ionizing photons / UV luminosity

Constraints from modeling of emission lines and UV continuum



Nakajima et al. (2017)
Models from Wilkins et al. (2016)

Properties of Lyman continuum leaking galaxies and comparison with high-z star-forming galaxies

- Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2016, Nature 529, 178)
- Izotov, Schaerer, Thuan, Worseck, Guseva, Orlitova, Verhamme (2016, MNRAS 461, 3683)
- Schaerer et al. (2016, A&A 591, L8)
- Verhamme et al. (2017, A&A 597, A13)
- Chisholm et al. (2017, A&A, 605, A67)

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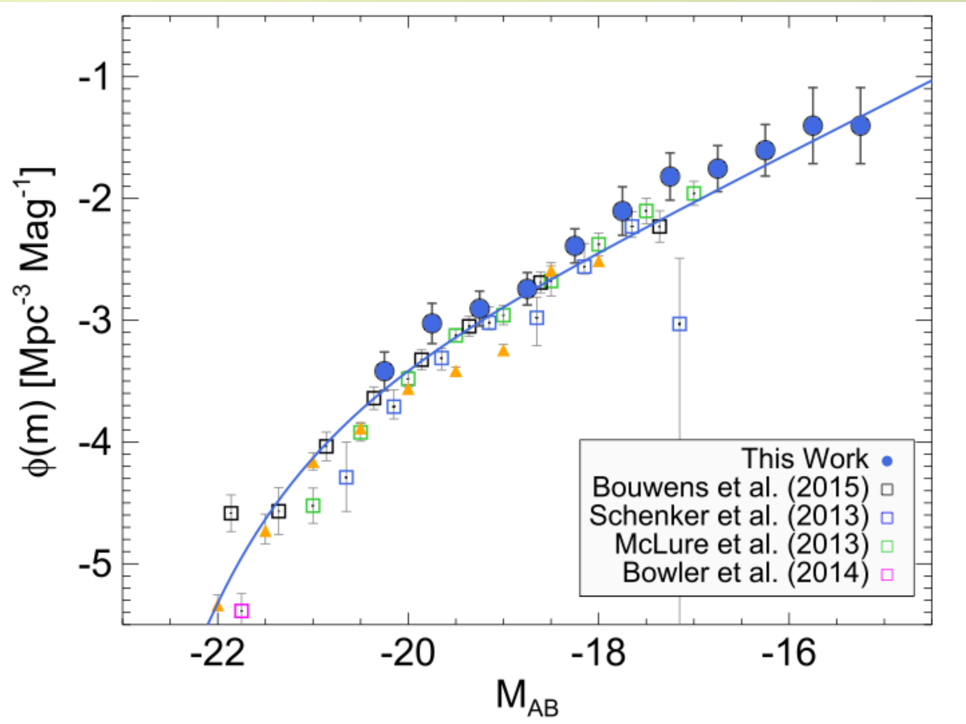
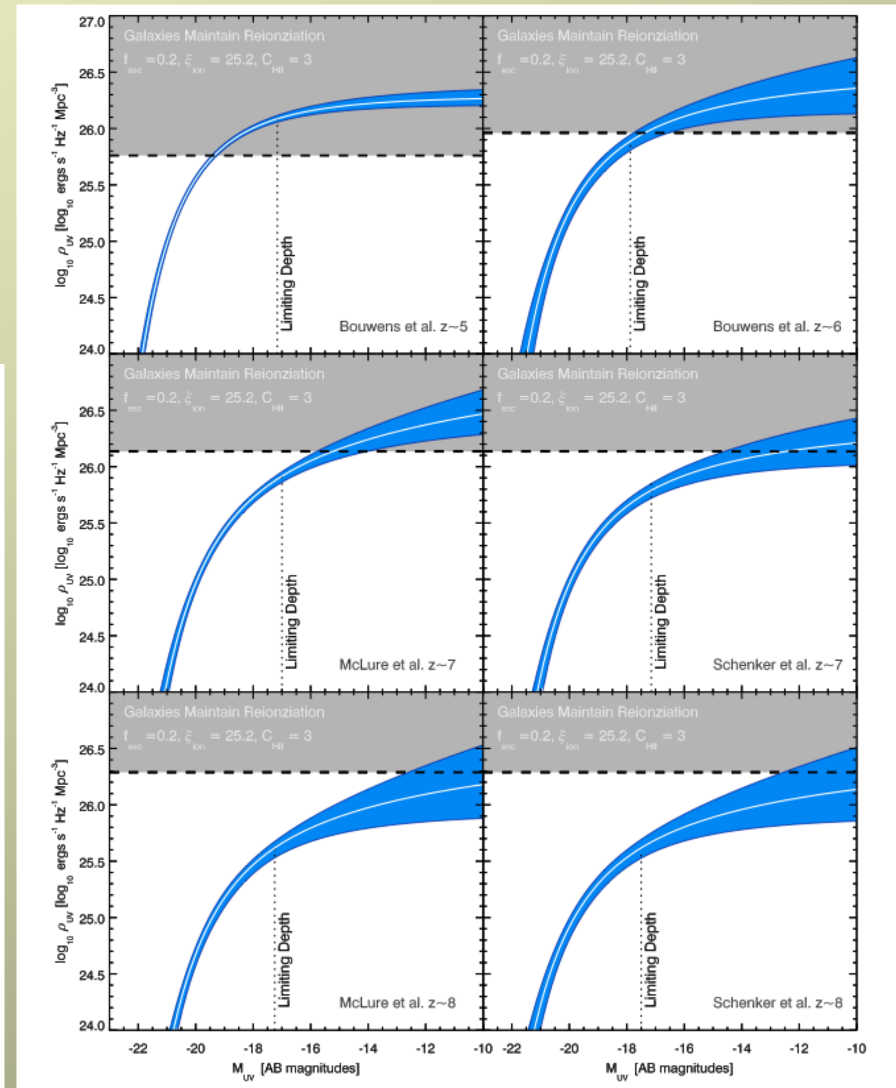
The quest for the sources of cosmic reionisation

- Faint, low mass galaxies thought to be main contributors to cosmic reionization
  → **Escape fraction of ~10-20% needed**



z~7 LF: Atek et al. (2015)



Robertson et al. (2013)

The quest for the sources of cosmic reionisation

- Faint, low mass galaxies thought to be main contributors to cosmic reionization

- Numerous searches for « Lyman continuum leakage » from star-forming galaxies at low and high-z
  → **sources elusive, so far!**

→ **New strategies needed**

  → **How to identity and find the sources of reionisation?**

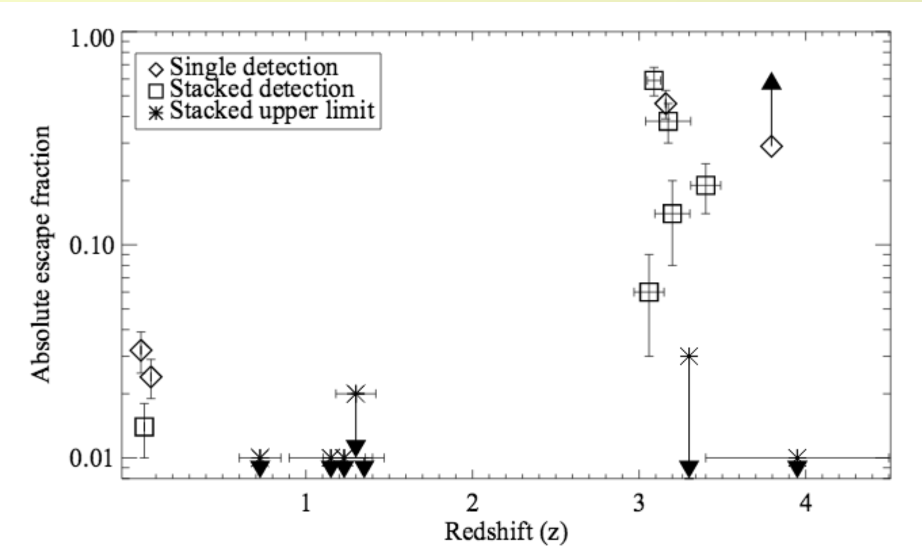
  → **Study their properties**

escape fraction

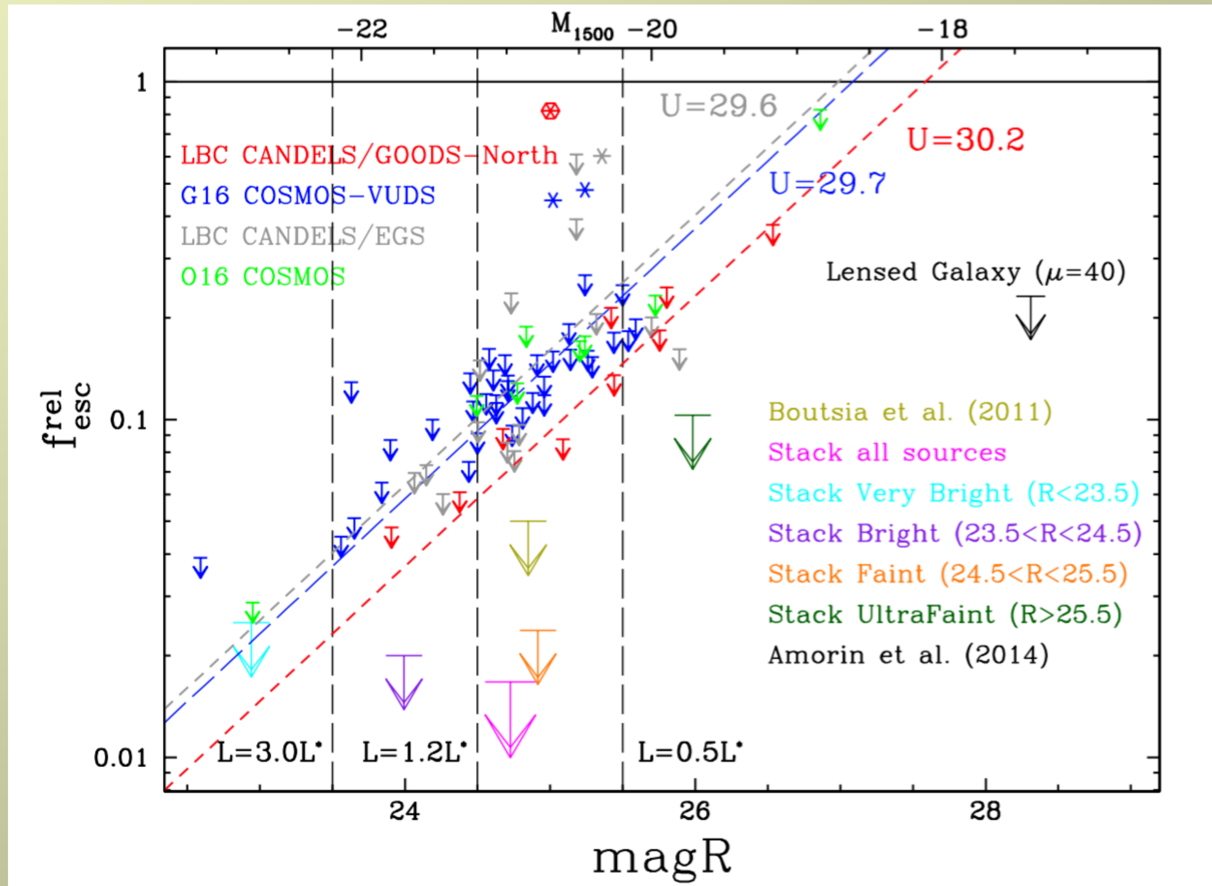
ionizing photons / UV luminosity

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

(Difficult) searches for Lyman Continuum leakers



Bergvall+ 2013



High redshift - z~3: Grazian+ 2016

The quest for the sources of cosmic reionisation - a recent breakthrough

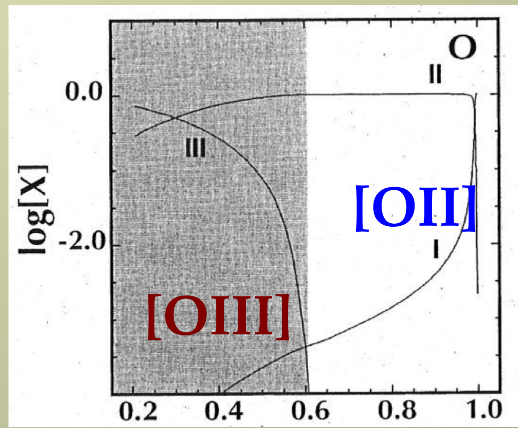
COS-HST cycle 22 program: *measure Lyman continuum and test indirect indicators*

Thuan, Izotov, Orlitova, Verhamme, Schaerer, Guseva
17 orbits, 5 galaxies

Object selection (from Sloan):

- **High [OIII]/[OII] ratio**
- **Compact SF galaxy – « Green Pea » like**
- z~0.3 and UV-bright for « easy » Lyman-continuum detection with COS

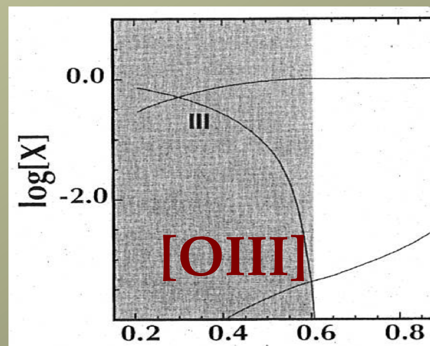
→ 5 galaxies selected



Strömgren radius ↑

G140M, G160M grism observations to cover:

- Lyman continuum
- Lyman alpha
- UV absorption lines

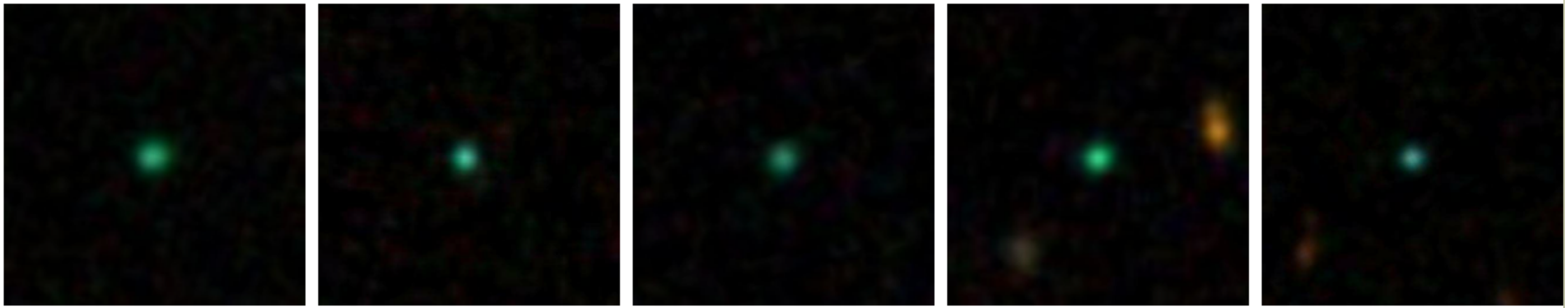


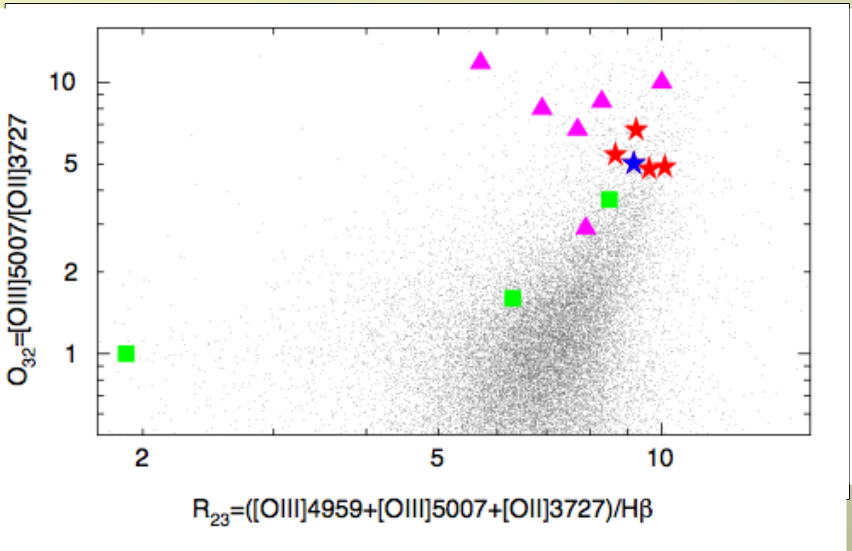
[OII] miss ing

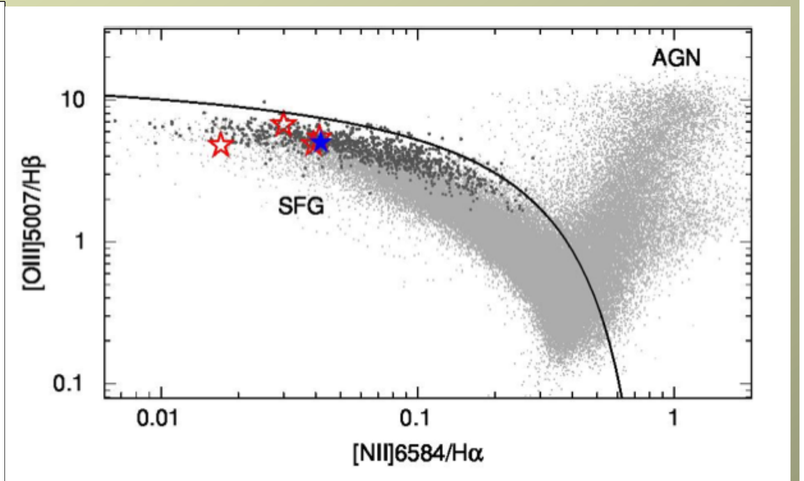
Strömgren radius ↑

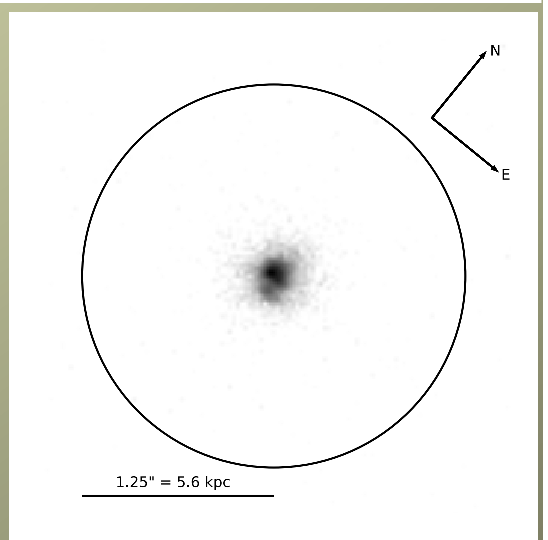
The quest for the sources of cosmic reionisation

Cycle 22 COS-HST program: *measure Lyman continuum and test indirect indicators* (Thuan, Izotov, Orlitova, Verhamme, Schaerer, Guseva)









Strong Lyman continuum leakers at z=0.3

Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2016)
Nature, 529, 178

LETTER

doi:10.1038/nature16456

Eight per cent leakage of Lyman continuum photons from a compact, star-forming dwarf galaxy

Y. I. Izotov[1], I. Orlitová[2], D. Schaerer[3,4], T. X. Thuan[5], A. Verhamme[3], N. G. Guseva[1] & G. Worseck[6]

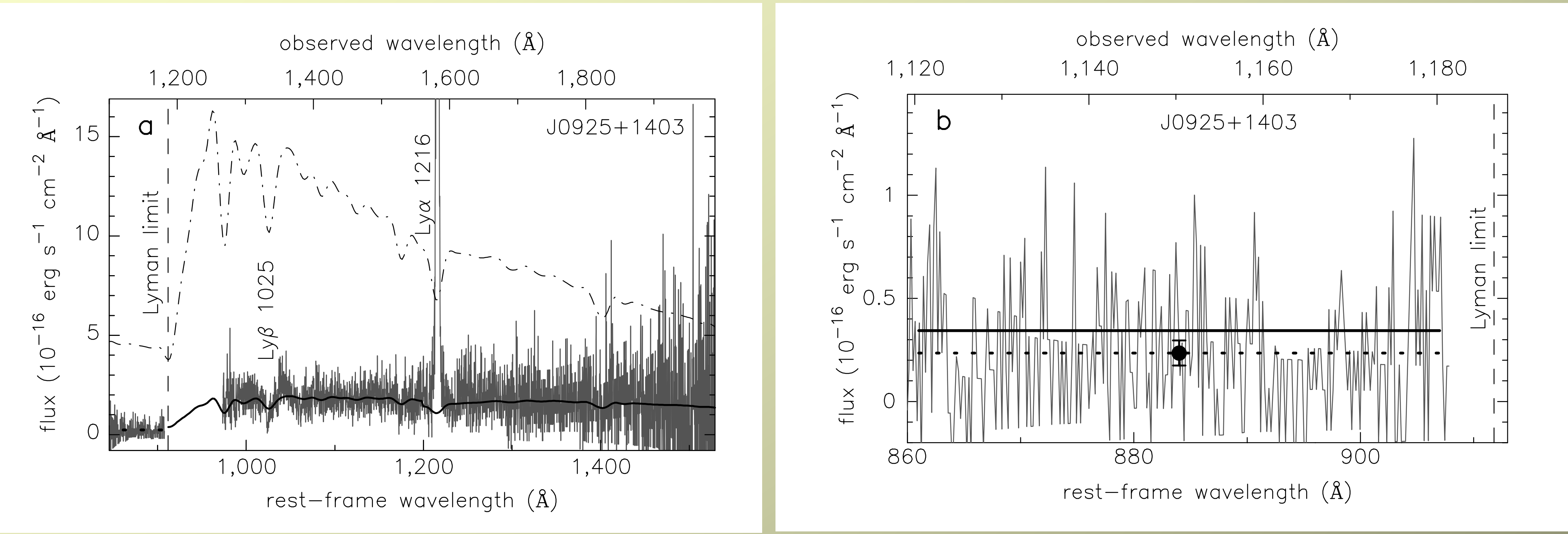
One of the key questions in observational cosmology is the identification of the sources responsible for ionization of the Universe after the cosmic 'Dark Ages', when the baryonic matter was neutral. The currently identified distant galaxies are insufficient to fully reionize the Universe by redshift $z \approx 6$ (refs 1–3), but low-mass, star-forming galaxies are thought to be responsible for the bulk of the ionizing radiation[4–6]. As direct observations at high redshift are difficult for a variety of reasons, one solution is to identify local proxies of this galaxy population. Starburst galaxies at low redshifts, however, generally are opaque to Lyman continuum photons[7–9].

star-formation rate, J0925+1403 shares many of the properties of high-redshift Lyman-α (Lyα) emitters.

GPs with $O_{32} \geq 5$ have been observed before by HST[17,18], but their low redshifts $z < 0.3$ were not optimal for Lyman continuum observations. The HST/COS observations of J0925+1403 were obtained on 28 March 2015 (program GO13744; PI, T.X.T.). The near-ultraviolet acquisition image shows the galaxy to have a very compact structure, with a half-light angular diameter of ~0.2″, much smaller than the spectroscopic aperture of 2.5″ (Fig. 2). This angular diameter corresponds to a linear diameter of ~1 kpc at the angular diameter distance

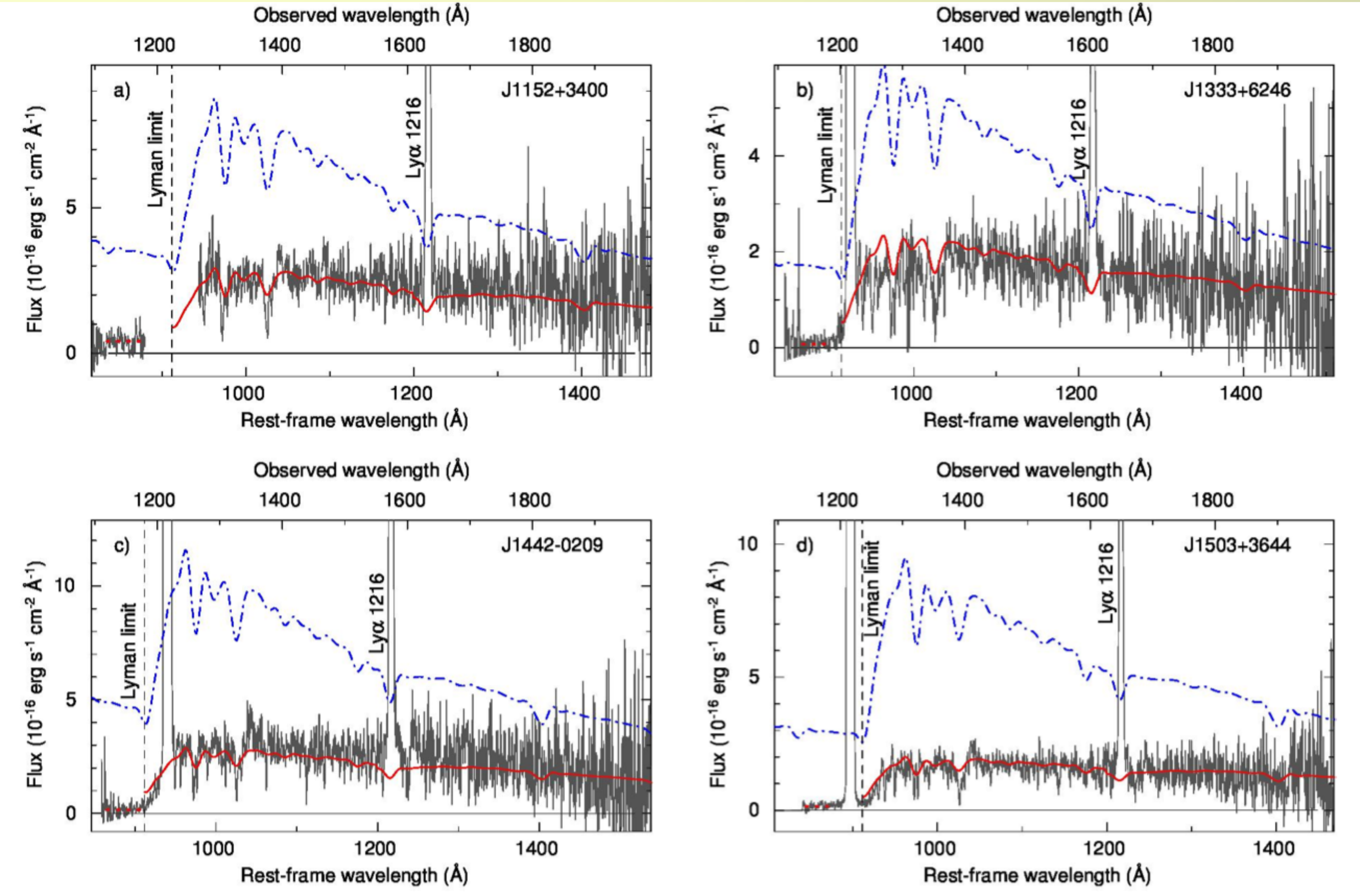
Strong Lyman continuum leakers at z=0.3

New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2016)



✔ Lyman continuum leakage

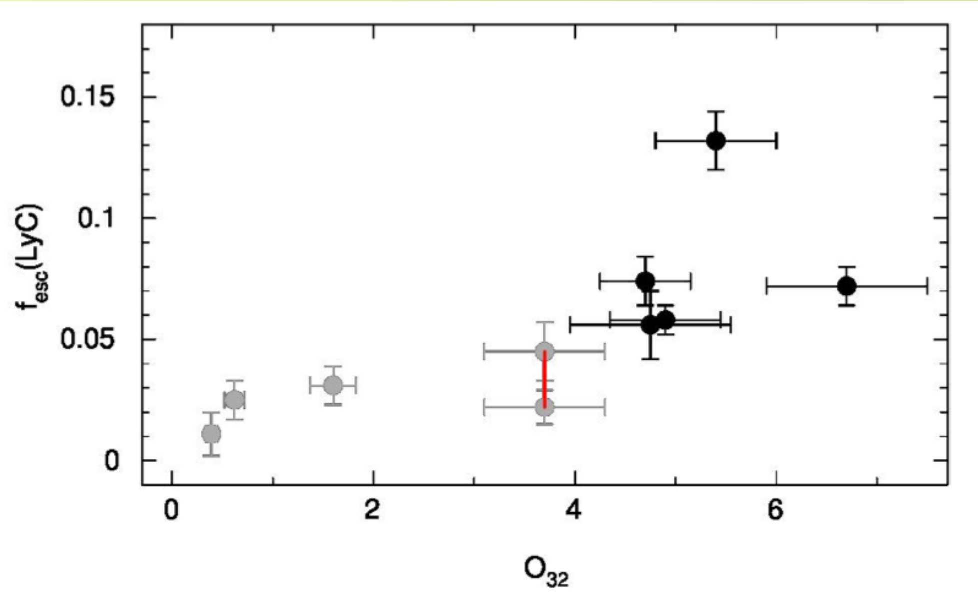
- 11.8 sigma detection $(3.43 \pm 0.29) \times 10^{-17}$ erg s^{-1} cm^{-2} $A^{\circ\,-1}$
- Absolute **fesc=7.8±1.1** % (highest so far at low redshift)



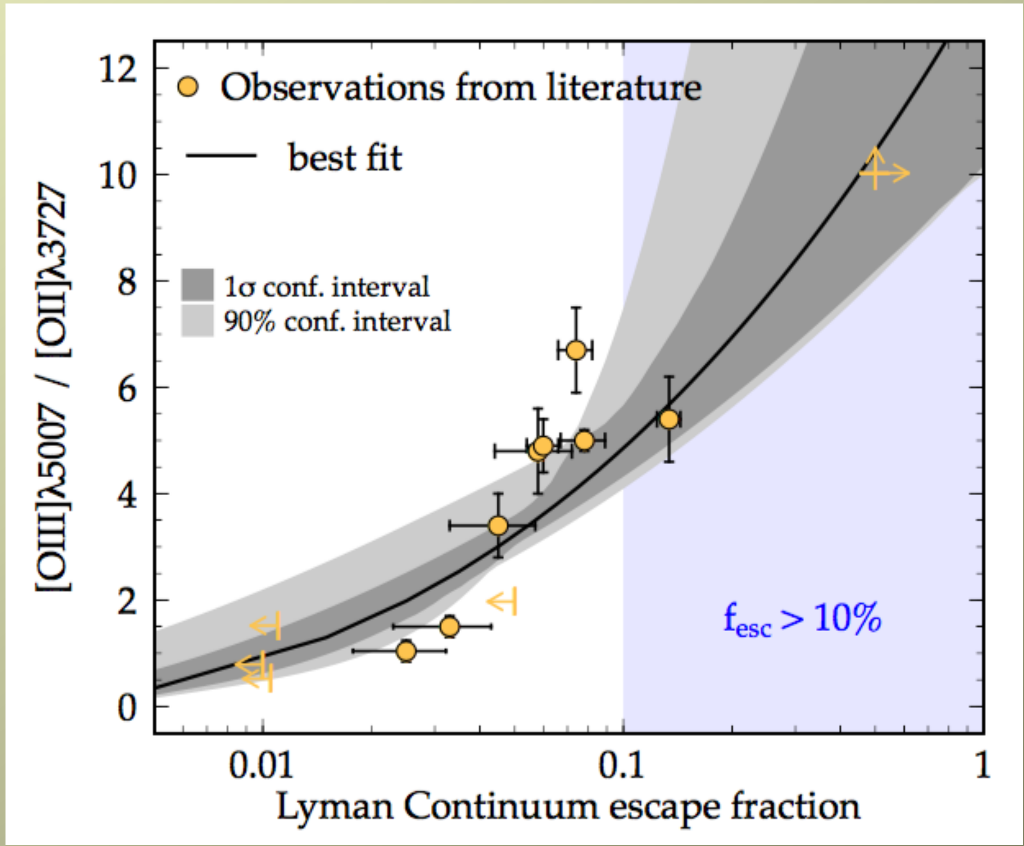
Larger sample: Izotov et al. (2016b) → **fesc=6-13** %

Strong Lyman continuum leakers at z=0.3

All known LyC leakers:
Correlation of fesc(Lyc) with O32
→ High OIII/OII is the best predictor of LyC escape fraction



Izotov et al. (2016b)



Faisst 2016

Lyman-alpha properties of Lyman continuum leakers

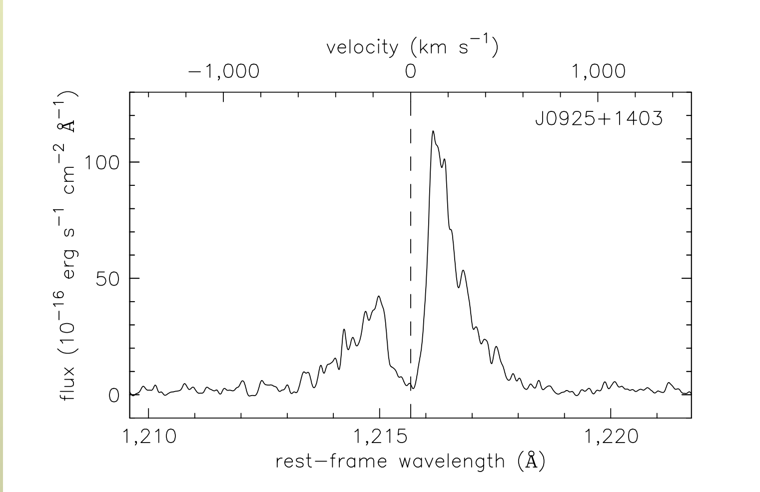
Verhamme et al. (2017, A&A 597, A13)

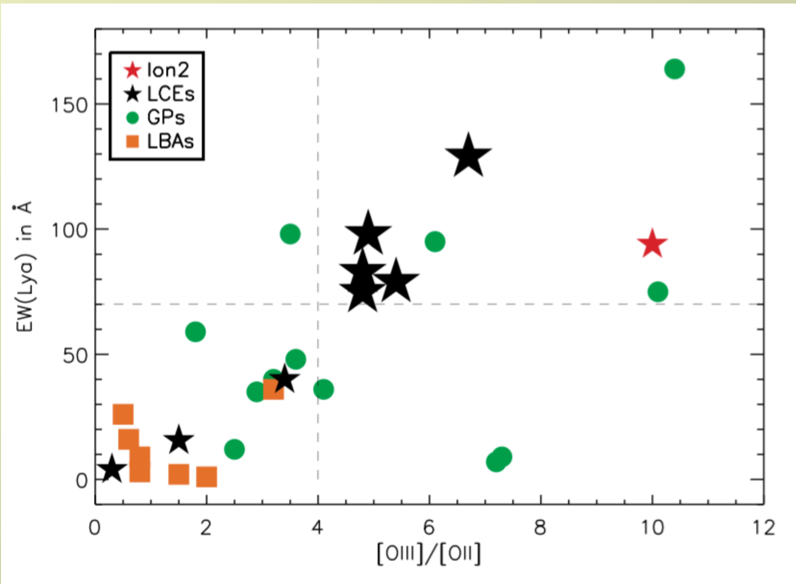
- **Strong Lyα emission (EW>70 Ang)**
- **Double-peaked profiles**
- **Small peak separation**

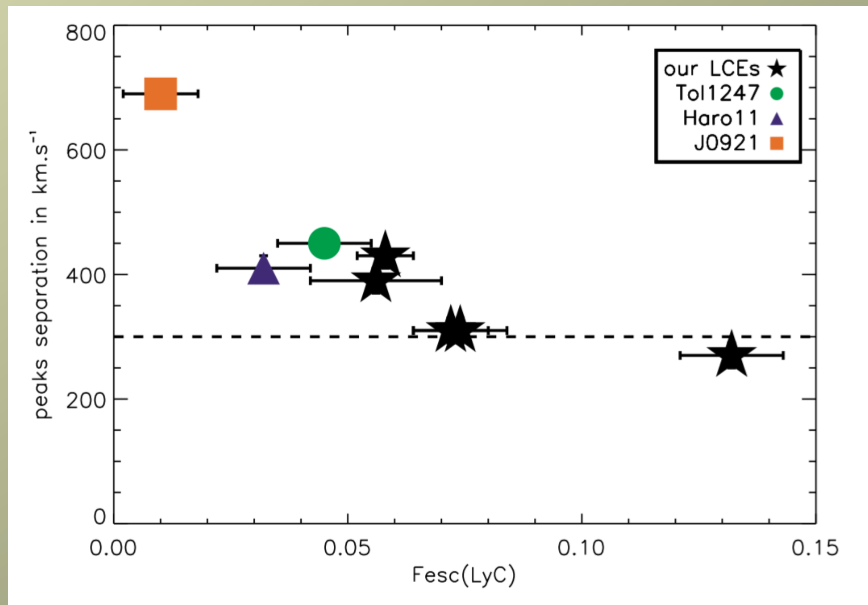
  as predicted by Verhamme et al. (2015)

→ **Intense star formation, low dust content**

→ **Low HI column density**







LyC leakers at z=0.3: comparison with high-z galaxies

→ Schaerer et al. (2016, A&A 591, L8)

*Best **high-z** Lyman continuum source:*

z=3.218 galaxy « Ion2 »in GOODS-S/Candels

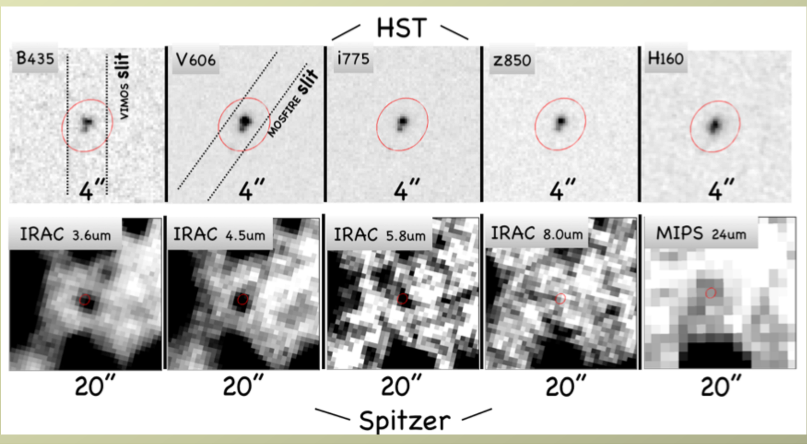
UV rest-frame mag_AB~24.5-25

→ Low metallicity (1/6 $Z_\odot$), ~low mass (1.6 10^9 $M_\odot$)

→ Strong Lya emission

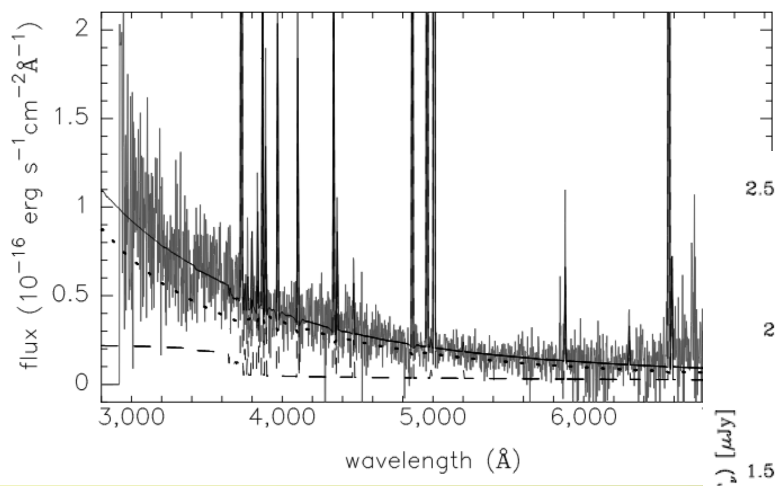
→ **High ratio [OIII]/[OII]>10, high [OIII]+Hb equivalent width (~1600 Ang)**

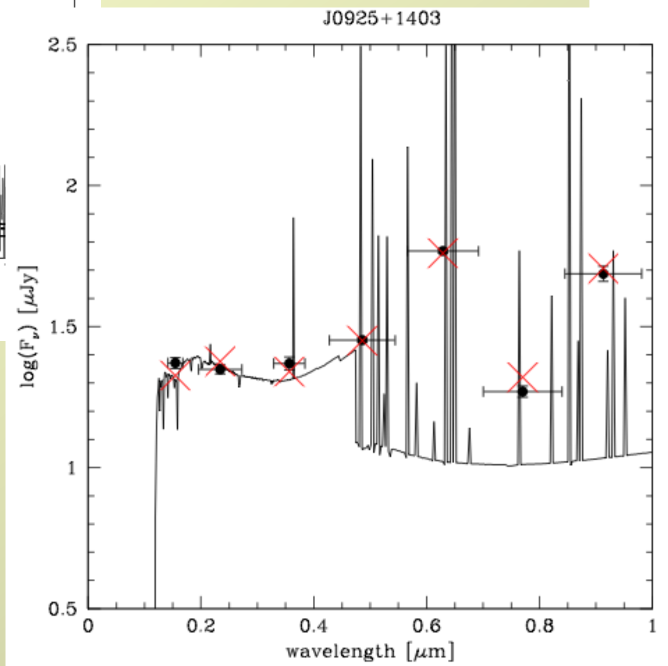
Vanzella et al. (2015), de Barros et al. (2016)

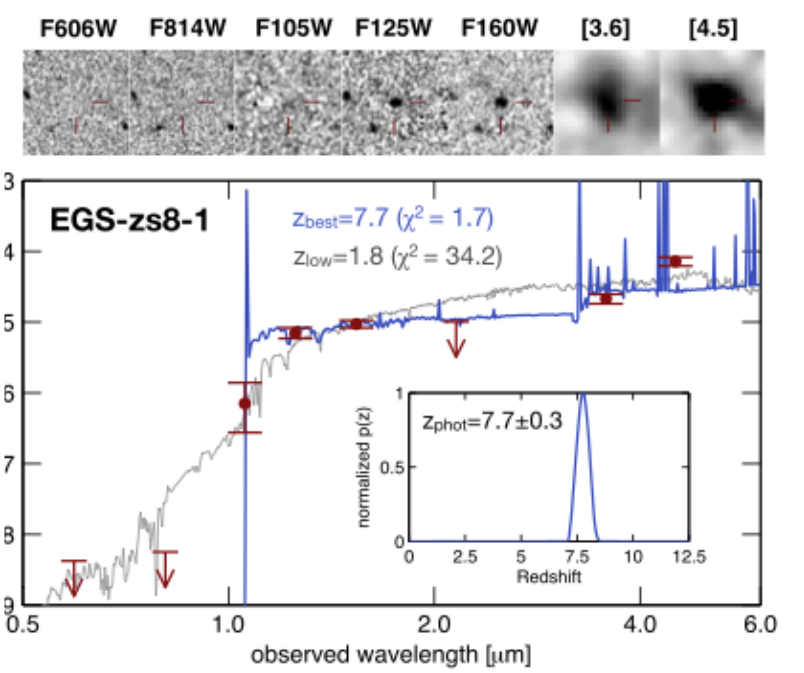


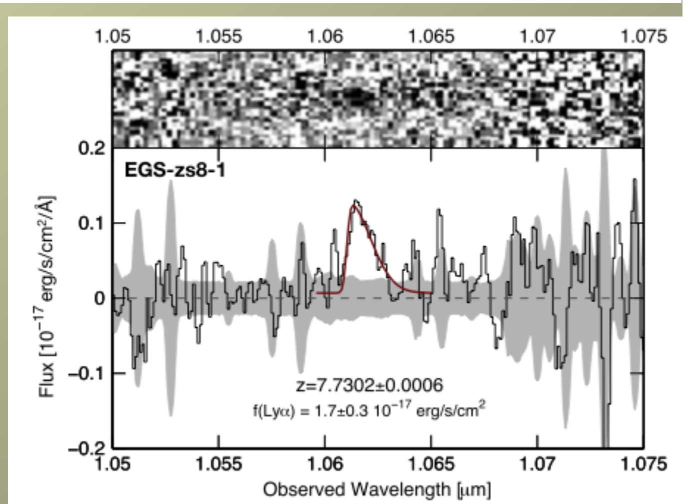
EL ratios, equivalent widths, stellar mass of our z~0.3 LyC leakers:
→ Comparable to Ion2

Strong Lyman continuum leakers at z~0.3
Comparison with high-z galaxies









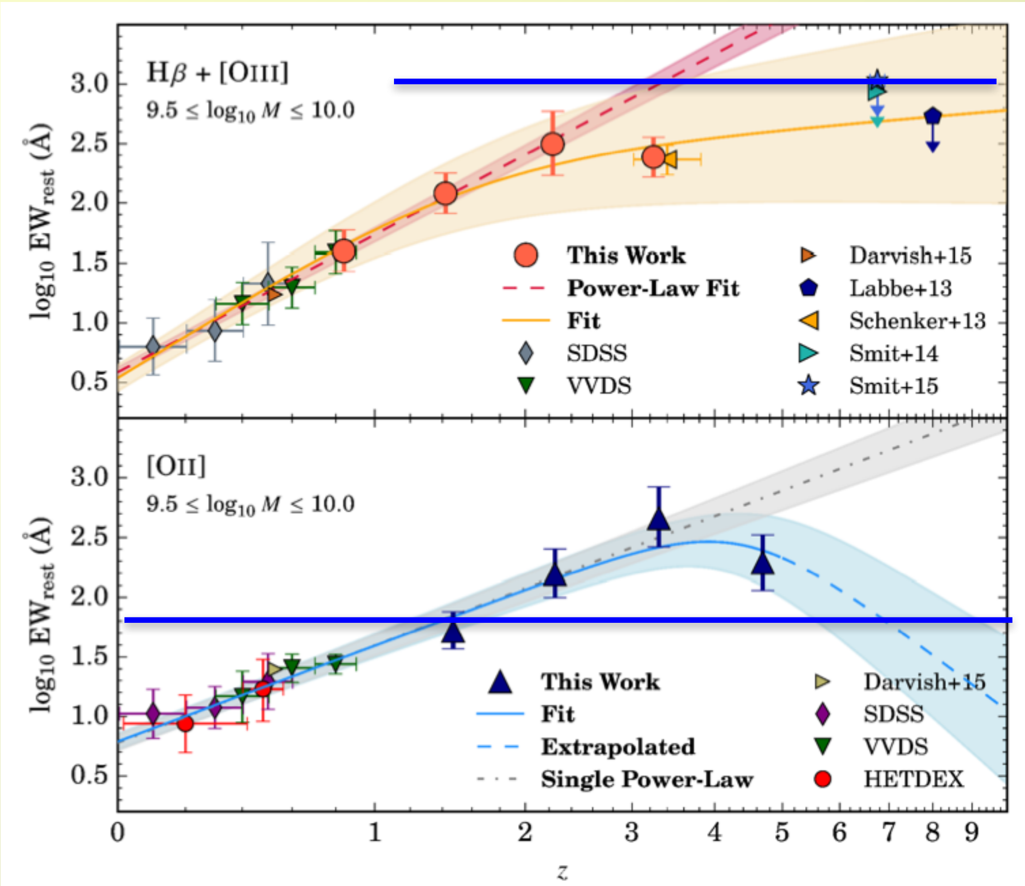
High equivalent widths:
EW(Ha)=730 Å
EW([OIII]4959+5007)=1480
…
→ Comparable to high-z galaxies

z=6.8: Schaerer et al. (2015)
Smit+ (2014)

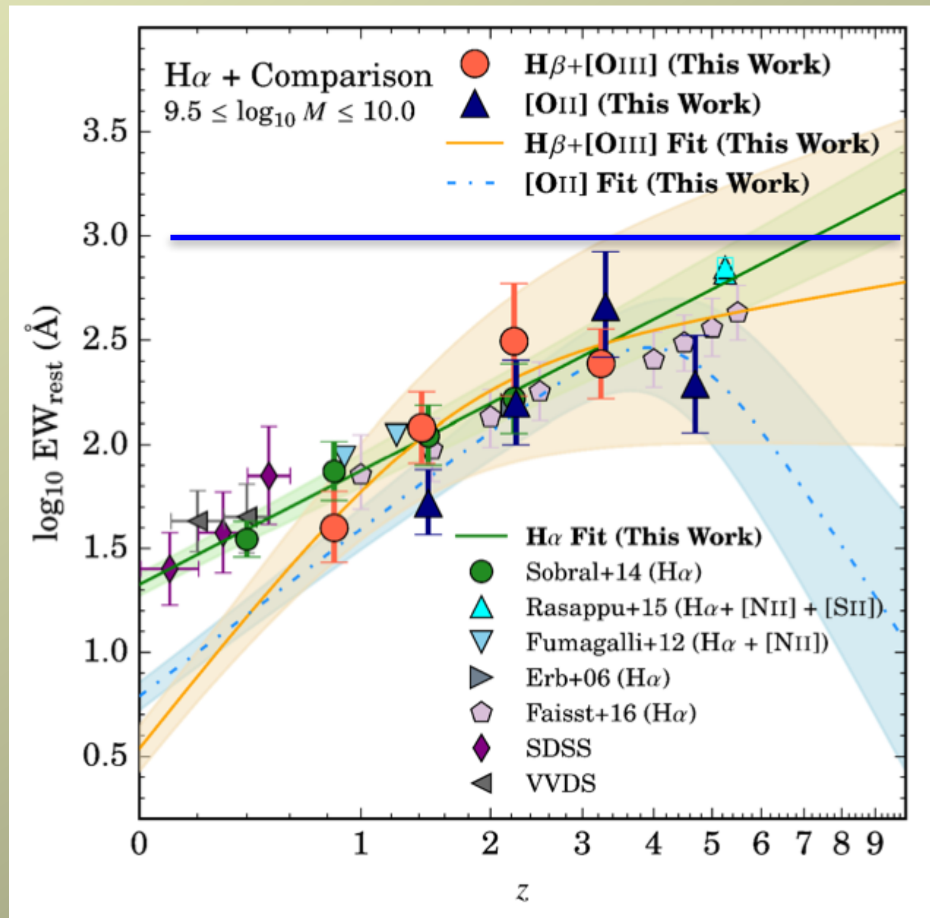
Izotov et al. (2016)

Oesch et al. (2015) z=7.73

Strong Lyman continuum leakers at z~0.3
Comparison with high-z galaxies



Khostovan et al. (2016)



Properties of **rare** z~0.3 leakers are comparable to **typical** z~7 galaxies

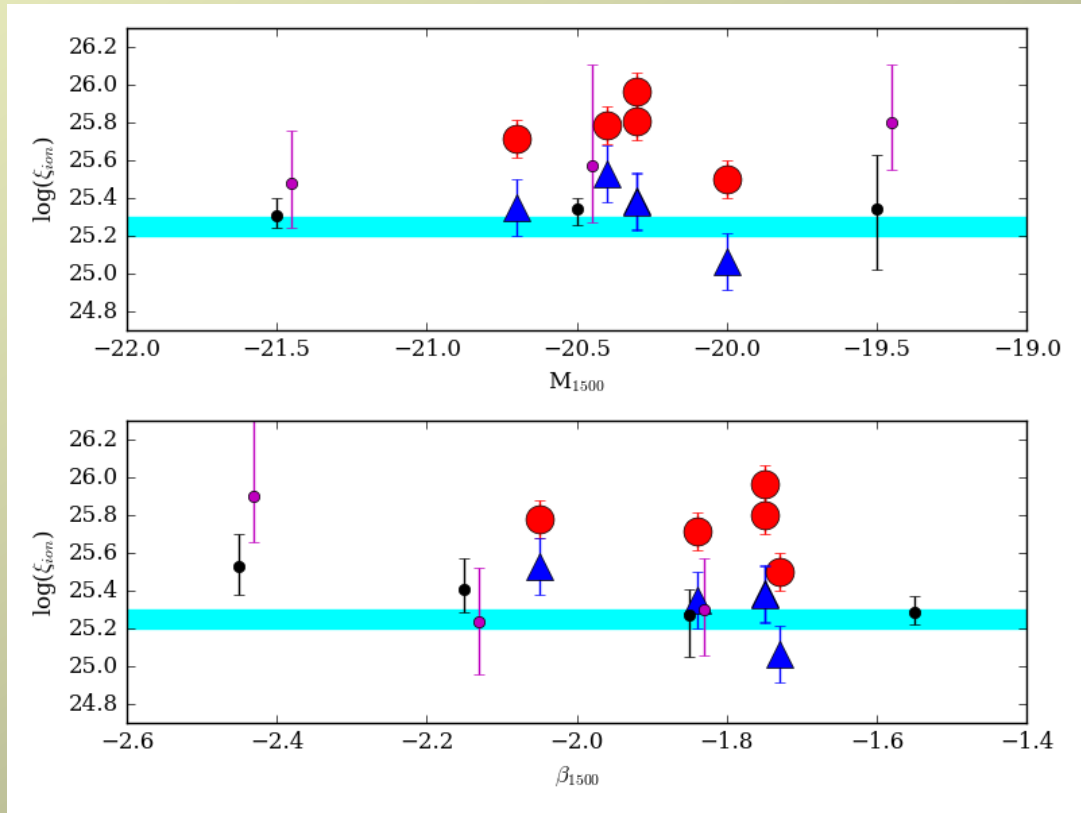
Lyman continuum leakers at z=0.3: Ionising photon production

Direct measure of ξ_{ion} :

→ **Factor ~2-5 times more ionizing photons produced** ***per unit UV luminosity than commonly assumed***

→ ***Intrinsic*** ξ_{ion} – corrected for extinction – is ~(1-2) times « standard » value

Best analogs for sources of cosmic reionisation



Schaerer et al. (2016)

Lyman continuum leakers at z=0.3: Ionising photon production

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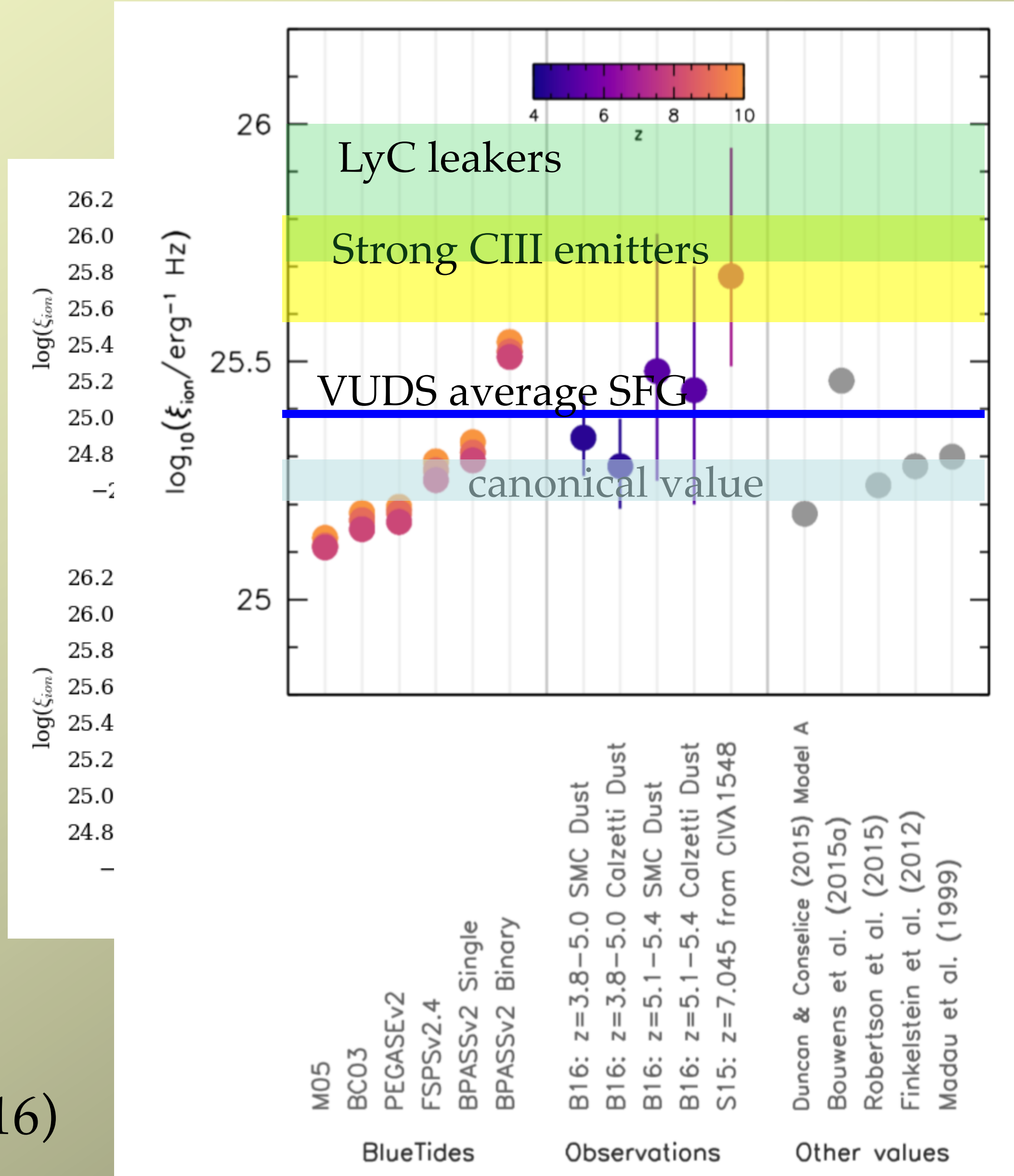
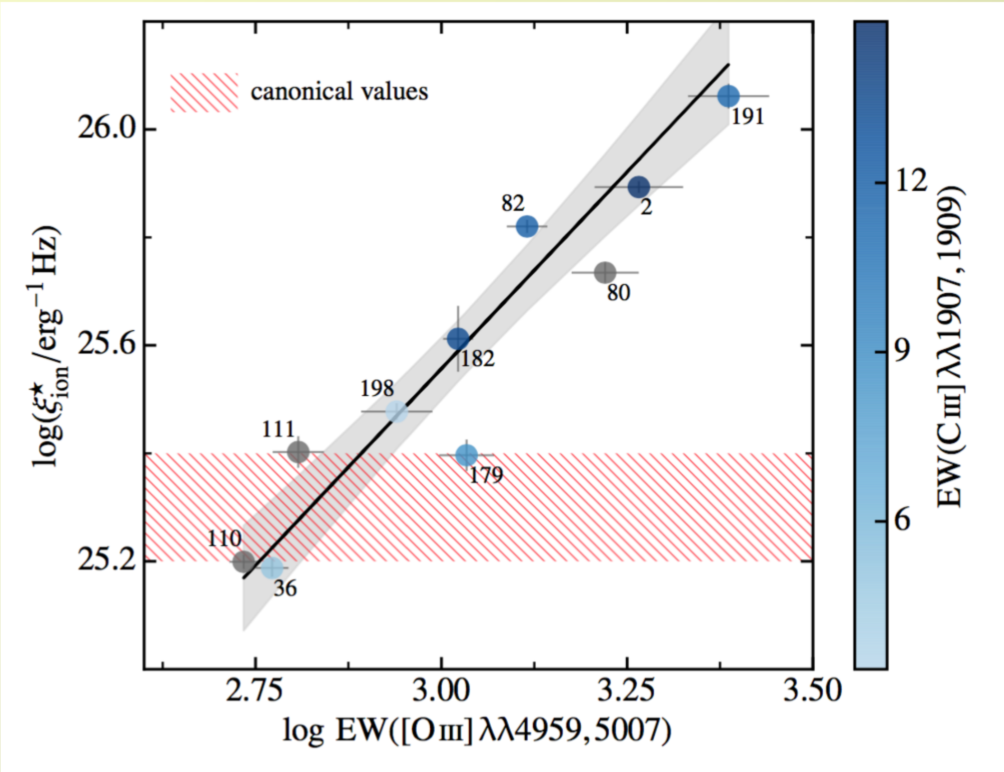
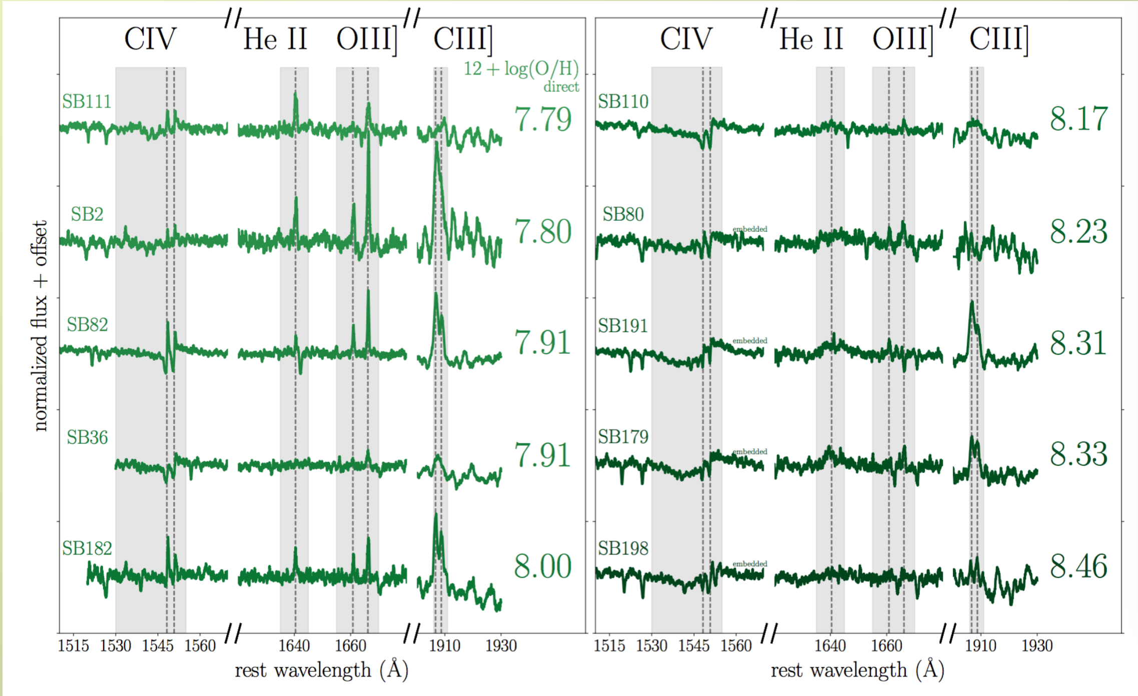


Cf. Wilkins et al. (2016)

Lyman continuum leakers at z=0.3: Ionising photon production

→ ξ_{ion} inferred from BEAGLE models





10 nearby SF regions/galaxies with nebular HeII emission

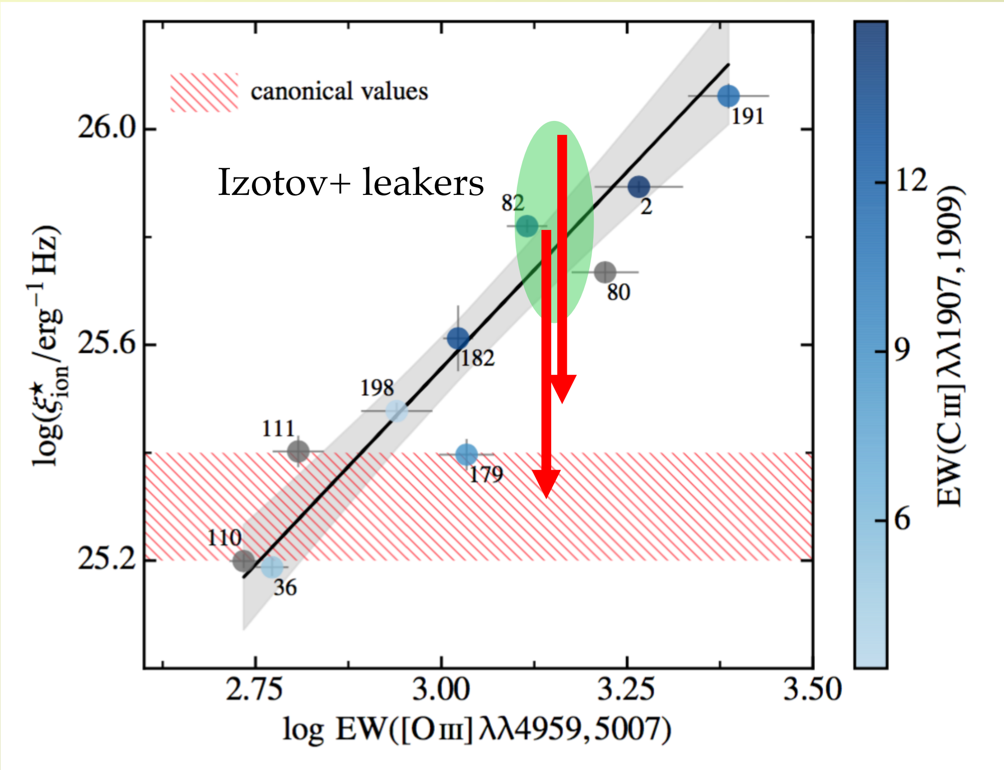
COS rest-UV spectra:

Senchyna et al. (2017)

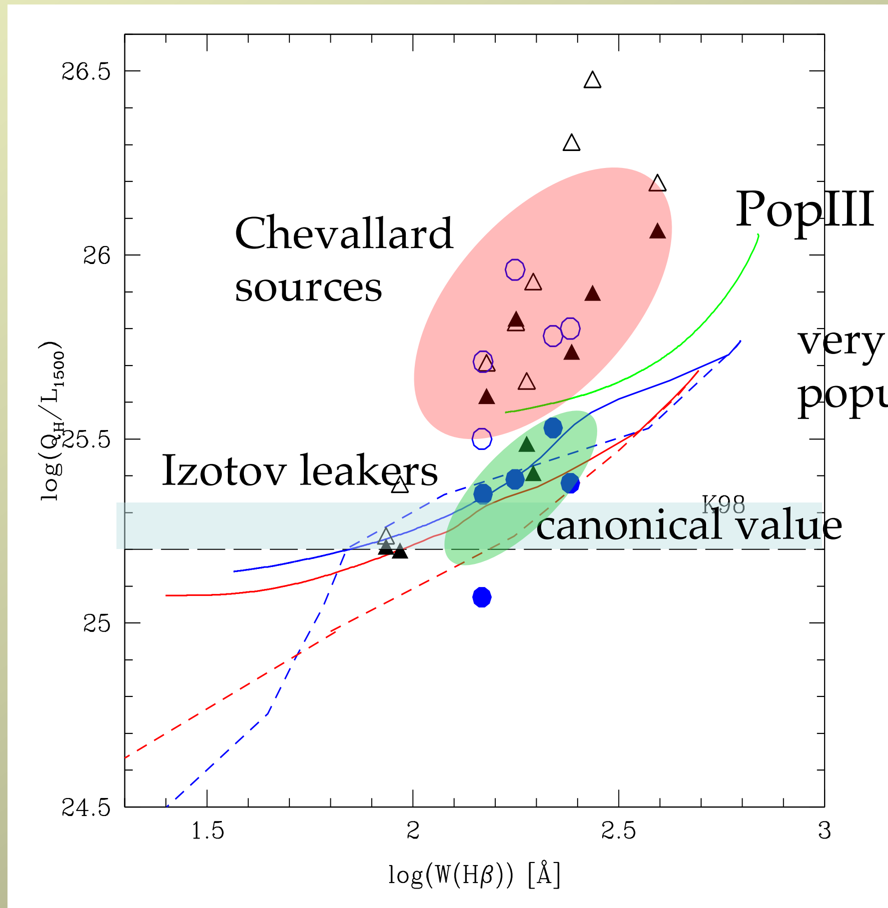
Chevallard et al. (2017)

Lyman continuum leakers at z=0.3: Ionising photon production

→ ξ_{ion} inferred from BEAGLE models



Chevallard et al. (2017)



Conclusions (I)

- **UV emission lines provide interesting constraints on:**
  - *Radiation field*: U, hardness, AGN/SF …
    Also ***ionizing photon production rate***
  - ISM properties: metallicity
    LyC continuum leakage ?!

- **VIMOS Ultra Deep Survey (VUDS):**
  - first statistics of CIII] emitters at z~2-4
  - Discovery of very strong CIII] emitters (EW>~20 Å)
    - Explained by SF + AGN (narrow line)
  - Discovery of sources with high C/O

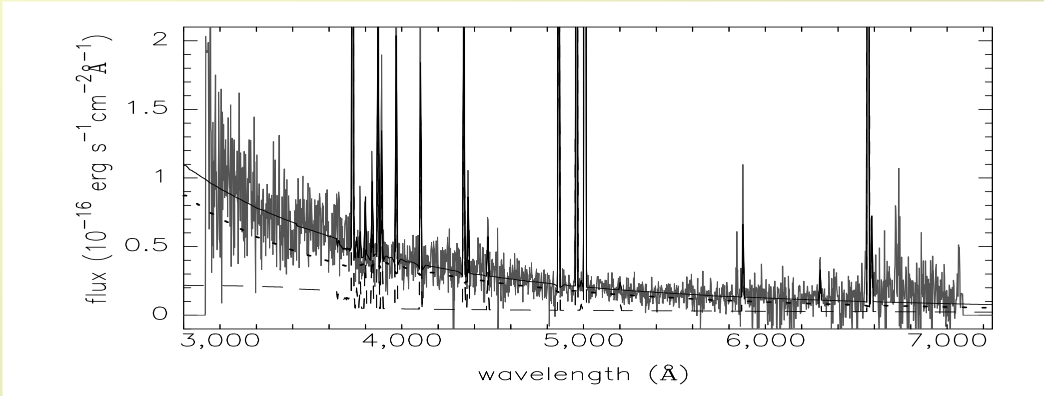
Conclusions (II)

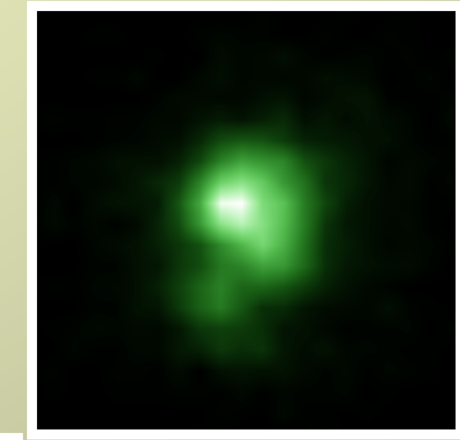
- Recent detection of strong Lyman continuum leakers:
  - **Confirms new selection criteria and their efficiency**
    High [OIII]/[OII] ratio & compact SF galaxy
    Narrow Lyman-alpha line profile + strong Lya emission
- *Currently known leakers are/have*
  - Compact, high SFR surface density
  - Strong emission lines (rest-optical and EW(Lya)>~70 Å)
  - (0.1-0.25) solar metallicity
  - ~low stellar mass (10^8-10^9) Msun
- LyC escape fraction correlates with O32

- Observed properties of the **rare** low-z leakers are very similar to **typical** high-z galaxies
- UV bright SF galaxies can contribute to cosmic reionisation

Properties of strong LyC leakers at z=0.3

J0925+1403
other properties

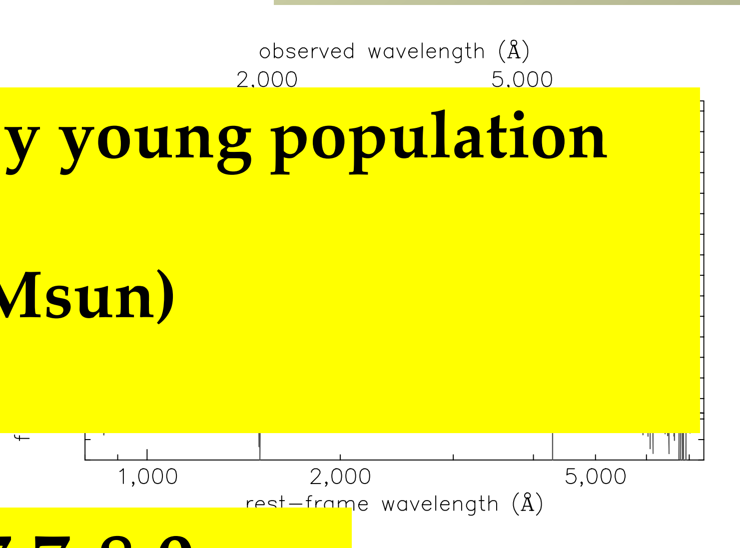




Extended Data Table 3 | Global characteristics of J0925+1403

Parameter	Value
$I_{H\beta}$†	
Redshi	
Lumino	
$L_{H\beta}$††	
SFR‡‡	
Q_H*	
Q_H(esc)	
t(burst)	
$M_y/M_\odot$	$(2.4 \pm 0.3) \times 10^8$
$M_*/M_\odot$	$(8.2 \pm 0.7) \times 10^8$

†Extinction-corrected flux densit
‡In units of Mpc.
††Extinction- and aperture-corre
‡‡Star-formation rate in $M_\odot$ yr^{-1}
*Q_H and Q_H(esc) are the number
**Burst age in Myr.



- **UV-optical spectrum dominated by young population (3-5 Myr)**
- **Low stellar masses (median ~10^9 Msun)**
- **High SFR (~14-40 Msun/yr)**

Metallicity 12+log(O/H)~7.7-8.0
~(0.12-0.25) solar