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Star-forming dwarf galaxies at z <1 in the VUDS survey: new insights on the low-mass end of the mass-metallicity relation

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VUDS | VIMOS Ultra Deep Survey

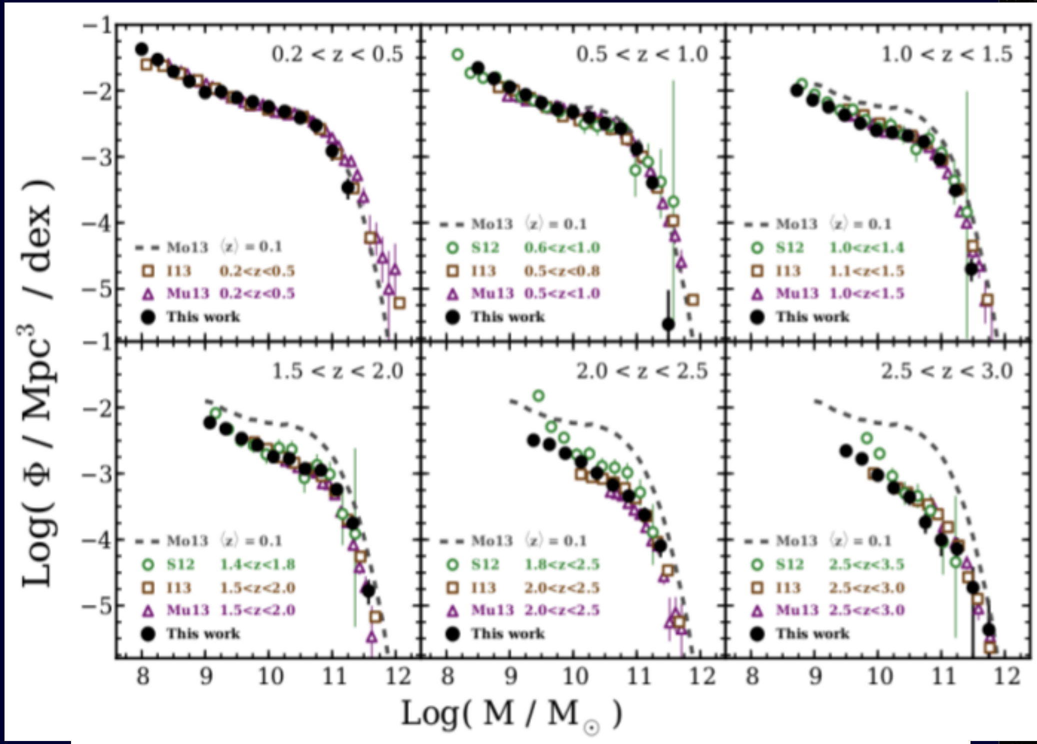
Main references : A.Calabrò et al. 2017
E.Pérez-Montero et al. 2014

Cambridge, 20 September 2017

Low mass galaxies : cosmological context

$M_* < 10^9\ M_{sun}$ e $M_B > -18$ (Thuan & Martin +81)

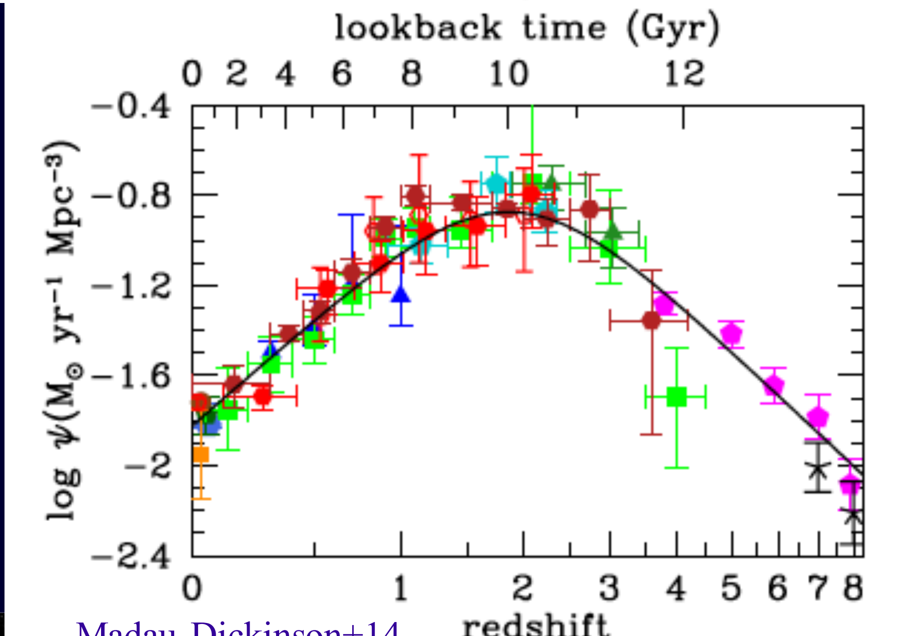
- They are the most abundant type of galaxies in the Universe at all redshift (Santini+12)
- Key object for reionization era (Reddy & Steidel +09, Bouwens +16)



Star Forming Dwarf Galaxies (SFDGs) :

- Low-mass
- They show bright emission lines in their optical spectra (e.g.,[OIII], Hα)
- Bursty SFH implying high SSFR
- Low metallicity , small sizes, high gas content

- Ideal laboratories to study the properties of ISM (metallicity, ionization) that are more common in the early universe.



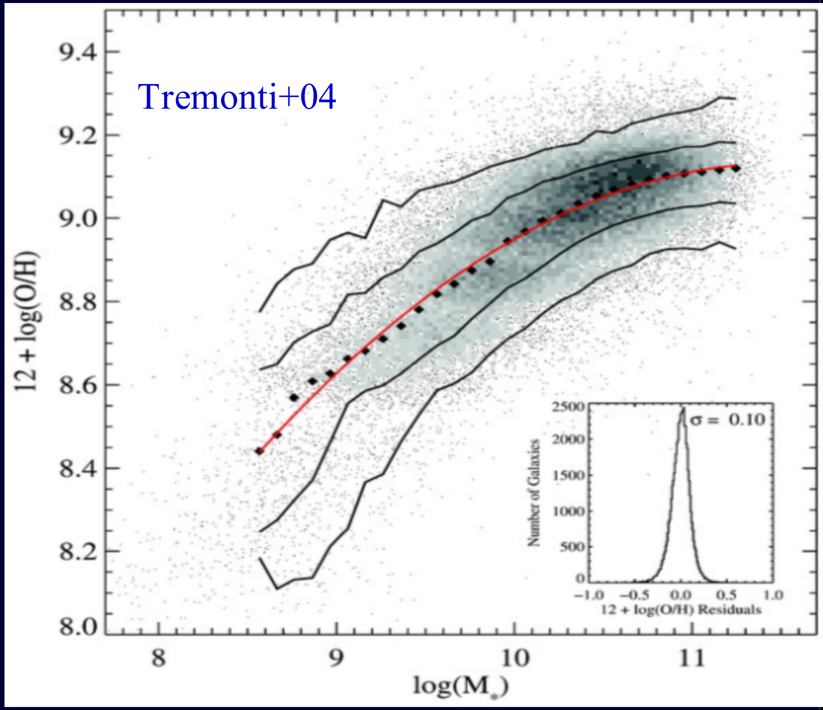
Madau-Dickinson+14

Main goals of this work :

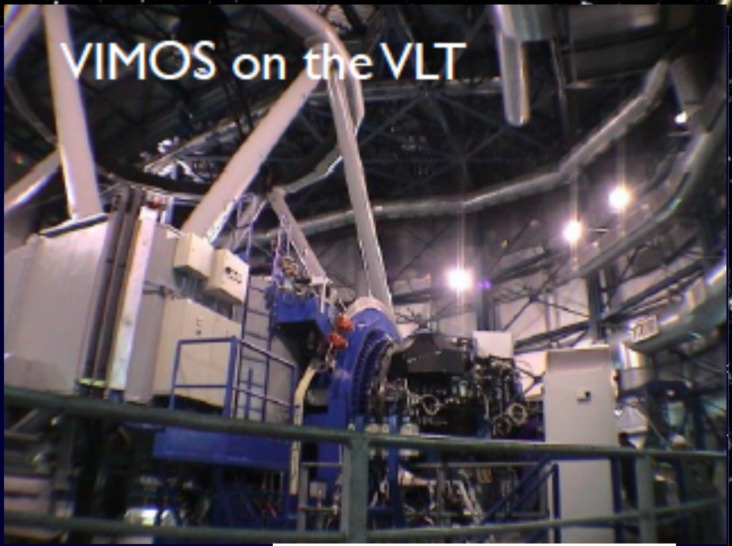
- Characterization of physical properties (e.g., SFR, EWs, line ratios, sizes, stellar masses) and chemical abundances of low-mass star forming emission-line galaxies out to redshift 1

- key scaling relations (metallicity, stellar mass and SFR) in the low-mass regime and comparison with model predictions and other observations.

- Example **: the Mass-Metallicity relation,** tracing the assembly and chemical evolution of galaxies

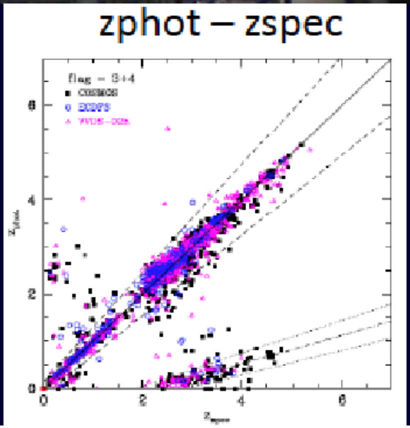


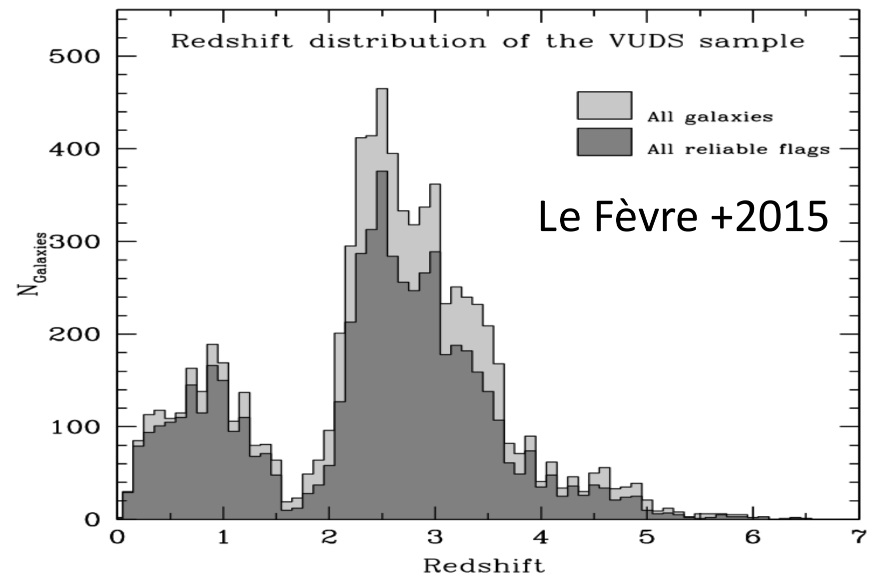
… and deep spectroscopy → VIMOS Ultra Deep Survey (VUDS)

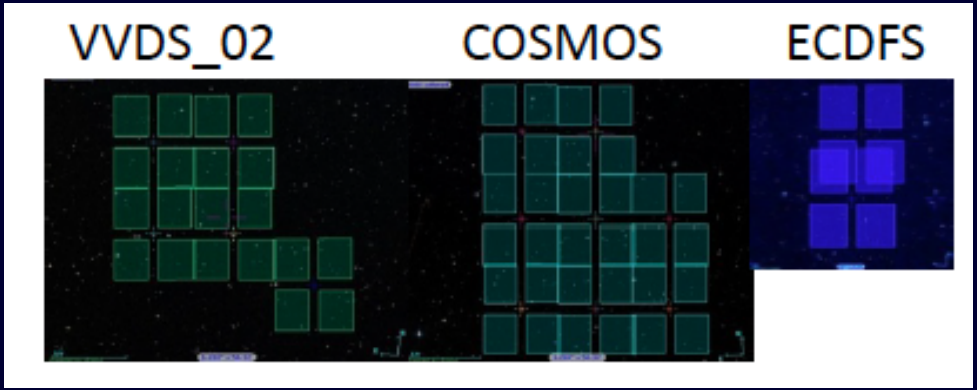


OVERVIEW (details in Le Fèvre +2014)

- ESO Large Program: 640h
- Focused on $2<z<6$
- Wide field: 1 deg^2
- 10,000 galaxies
- 14hr integration over 3600-9300 Å
- 3 fields: mitigate cosmic variance
- Selection: photo-z + SED + colors, $23 \leq i_{AB} \leq 25$
- 2000 galaxies with z_{spec}=0-1.5







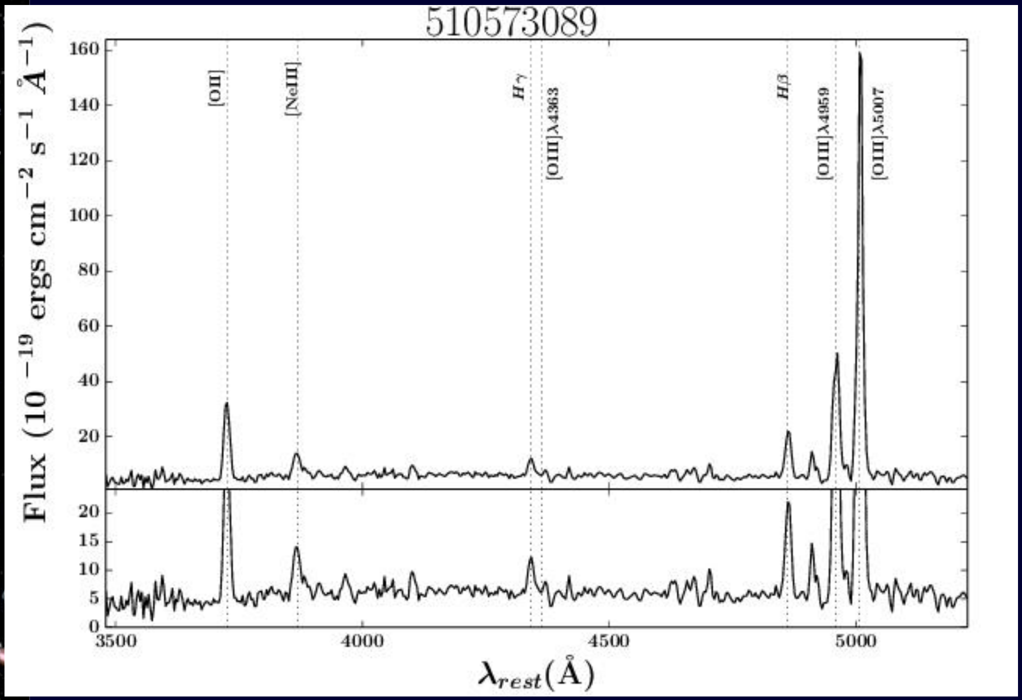
Selection of galaxies

We applied the following selection criteria :

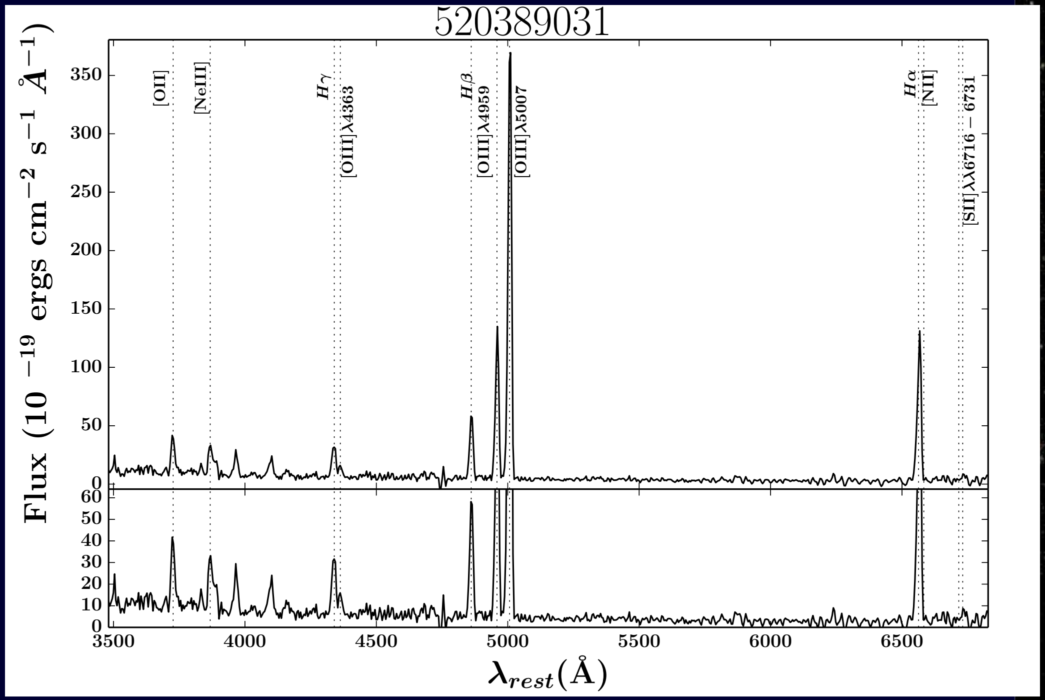
- reliability flags 3 and 4 (at least 95% probability the redshift to be correct)
- redshift in the range $0.13 < z < 0.88$
- detection of at least [O II]λ3727 Å, [O III]λλ4959-5007 Å, Hβ and/or Hα

★ 168 selected galaxies (76 COSMOS, 28 ECDFS, 64 VVDS-2h)

★ Representative of low-mass emission-line galaxies at $0.13 < z < 0.88$ and $23 < I_{AB} < 25$



Flat and faint continuum, high S/N



Lower redshift galaxy with Hα in the spectrum

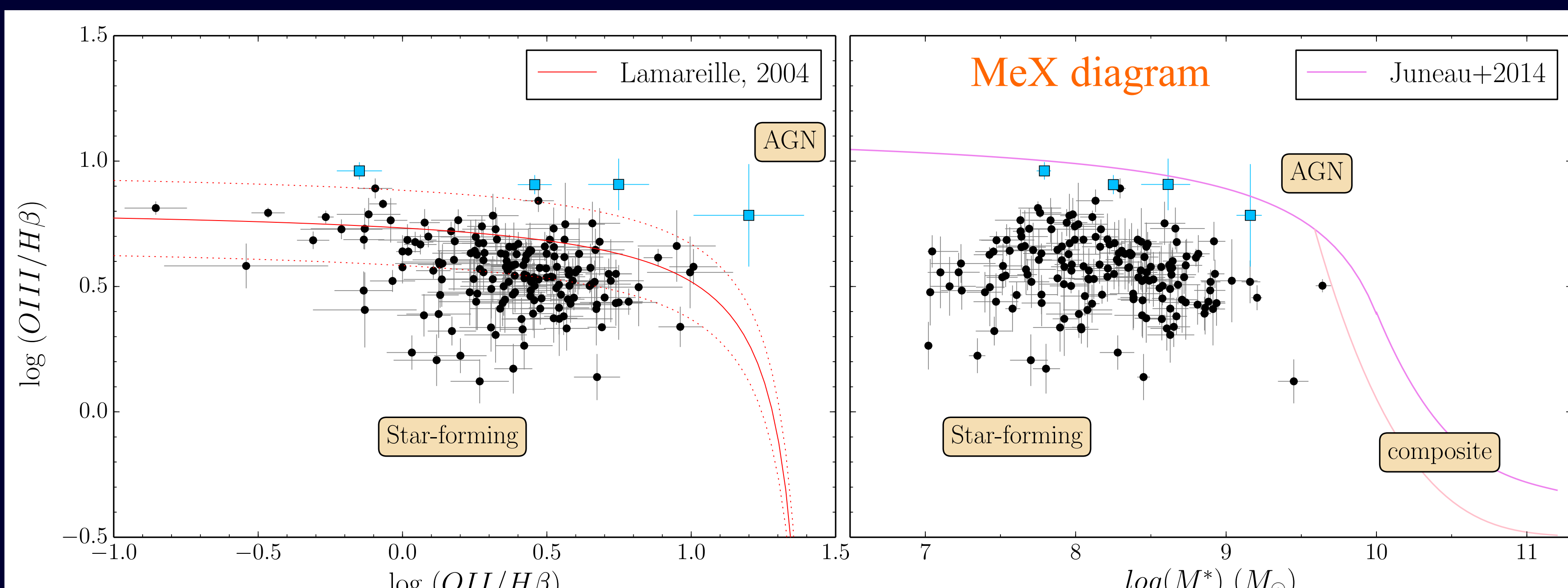
AGN removal

Star-forming or AGN ?

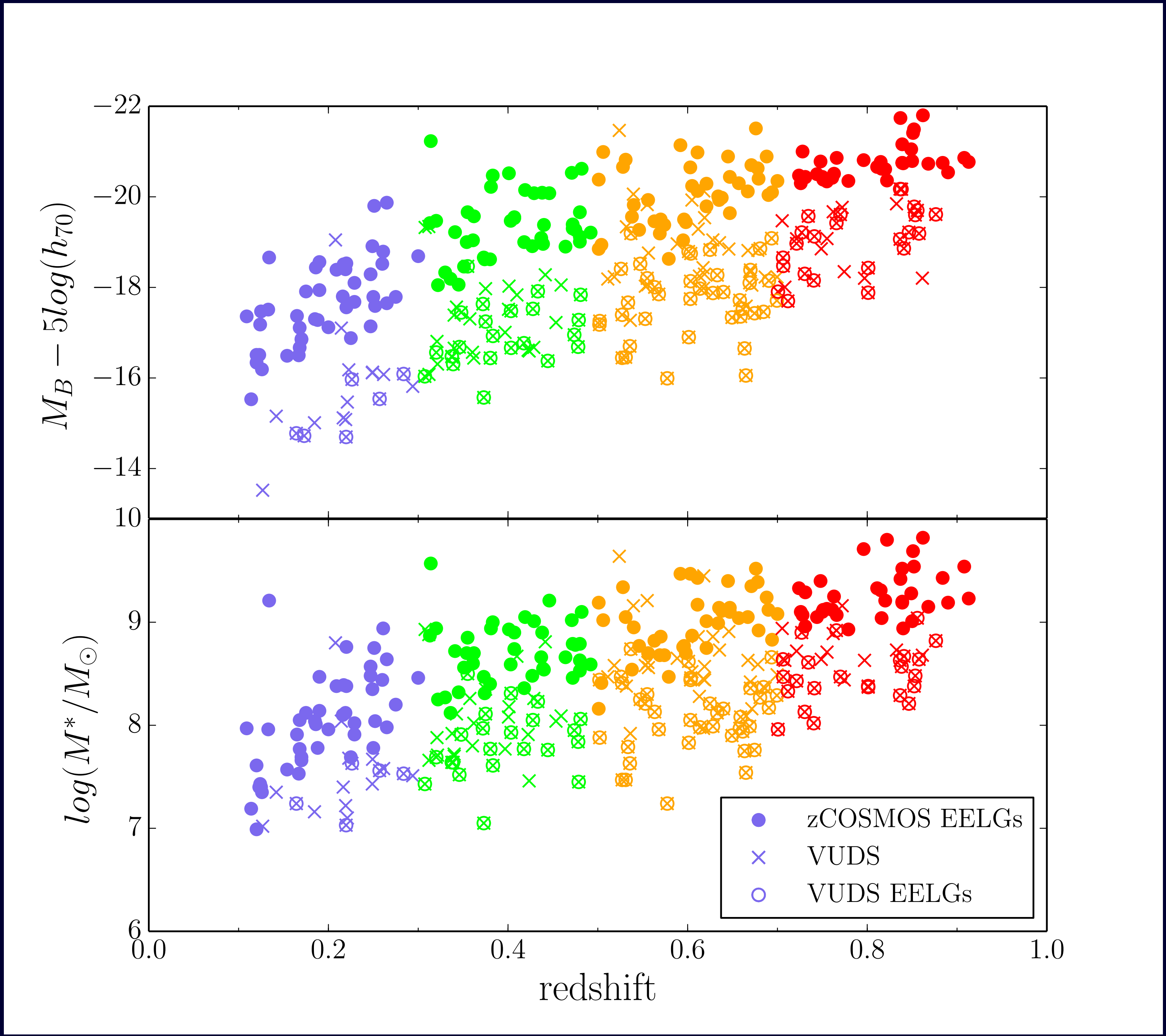
- No X-ray sources
- No hard-ionization lines (e.g. Ne V)
- No broad Balmer lines
- Stellar ionization from diagnostic diagrams: compare line ratios with empirical predictions

164 Genuine star-forming galaxies

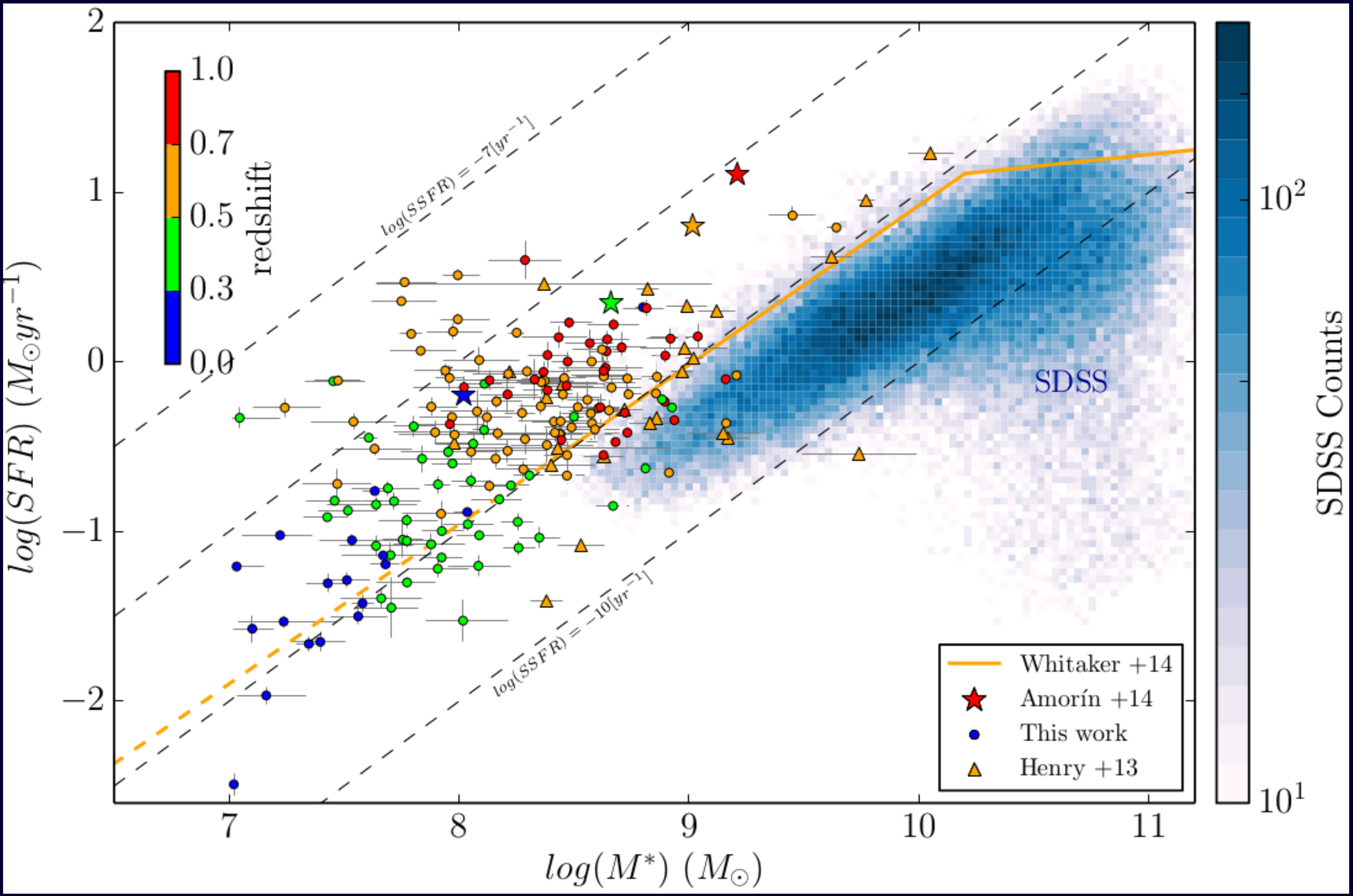
- We exclude 4 galaxies from the original sample



Low mass and faint galaxies



SFR vs Stellar mass



⋆ Higher SFRs per unit mass compared to local star-forming galaxies (SDSS)

⋆ Subset of galaxies above the MS by ~1 dex

→ higher specific SFR (SSFR)

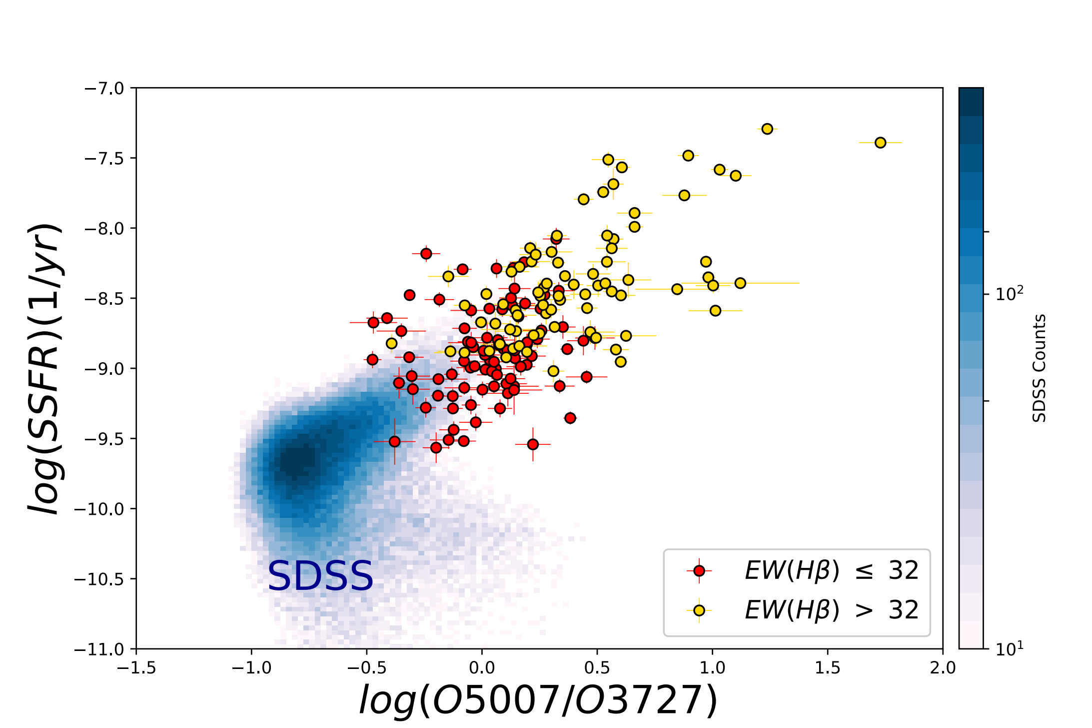
EELGs (Extreme emission line galaxies)

- OUR DEFINITION : high equivalent width (EW) of the optical emission lines (EW[O III]>100 Å, Amorin +14, 15)

- higher surface densities, lower starburst ages, and lower gas metallicities than the average population of star-forming dwarfs (Terlevich+91, Kniazev+04 ; Cardamone+09; Amorin+10, Atek+11; van der Wel+11; Maseda+14)

- host the most powerful supernova explosions (Chen+13; Leloudas+15).

- [O III]λ5007/[O II]λ3727 > 5, reaching values up to 60, allowing radiation to escape and ionize the surrounding ISM (Nakajima & Ouchi 14, Jaskot&Oey 14).



- contribute to the reionization of the Universe, providing up to 20% of the total ionizing flux at $z \sim 6$ (Robertson+15; Dressler+15, Vanzella +16)

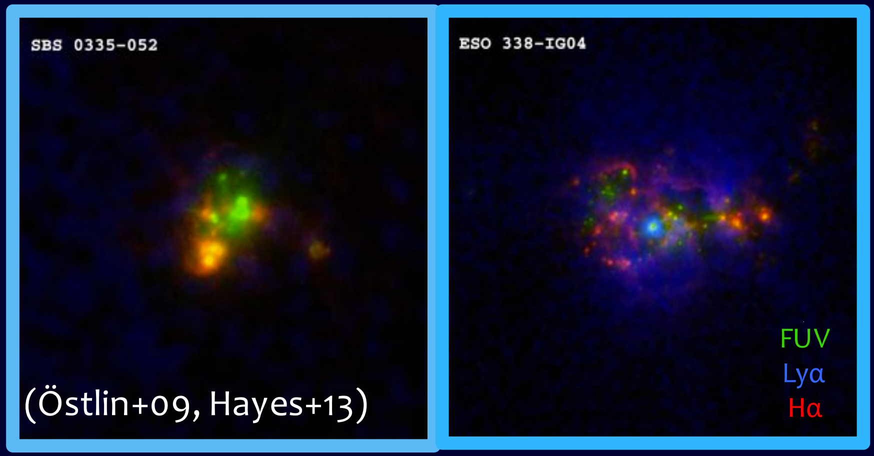
- **50 % of our sample are EELGs**

Local analogs of LyC galaxies

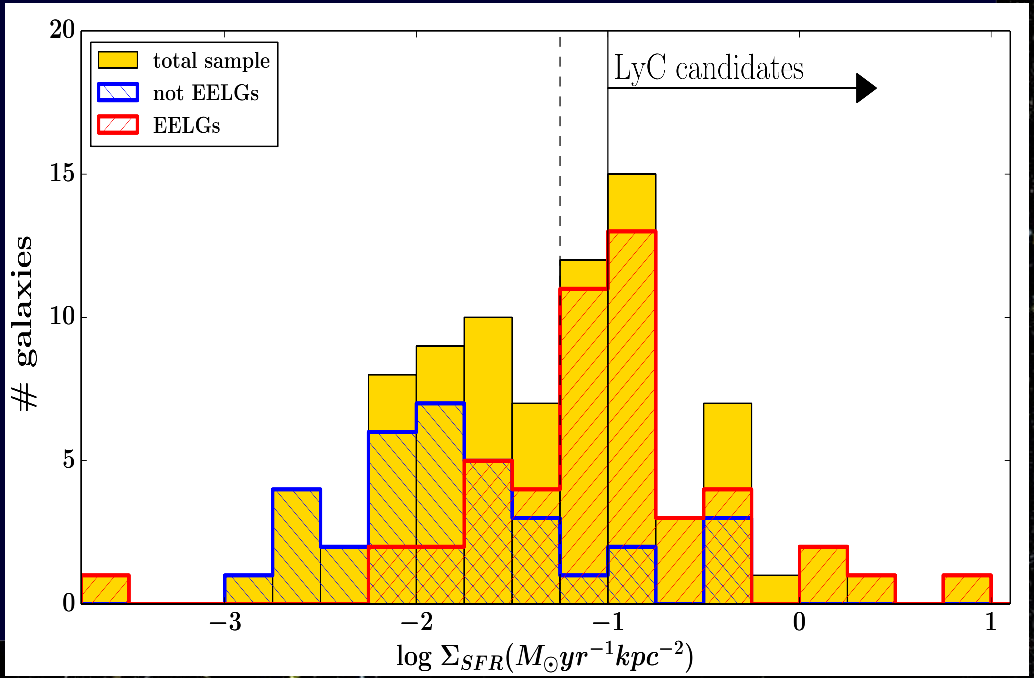
- local candidates for LyC leakers (e.g., Green Peas; Jaskot & Oey 14); detections using UV spectroscopy (Izotov +16, Schaerer+16)

- intermediate ($z \sim 3$) redshift (de Barros +16; Vanzella +16); detections using UV spectroscopy (Izotov +16)

- strongly ionized outflows ubiquitous in galaxies with high SFR per unit area ($\Sigma_{SFR} \geq 0.1\ M_{\odot} yr^{-1} kpc^{-2}$; Heckman+11; Sharma+16)



- 30 SFDGs show Σ_{SFR} higher than the lower limit of Sharma+16. Most of them (25) are EELGs
- 7 EELGs with high Σ_{SFR} also present high EW(Hβ) (> 100 Å) and high [O III]5007/[O II]3727 ratio (> 4)

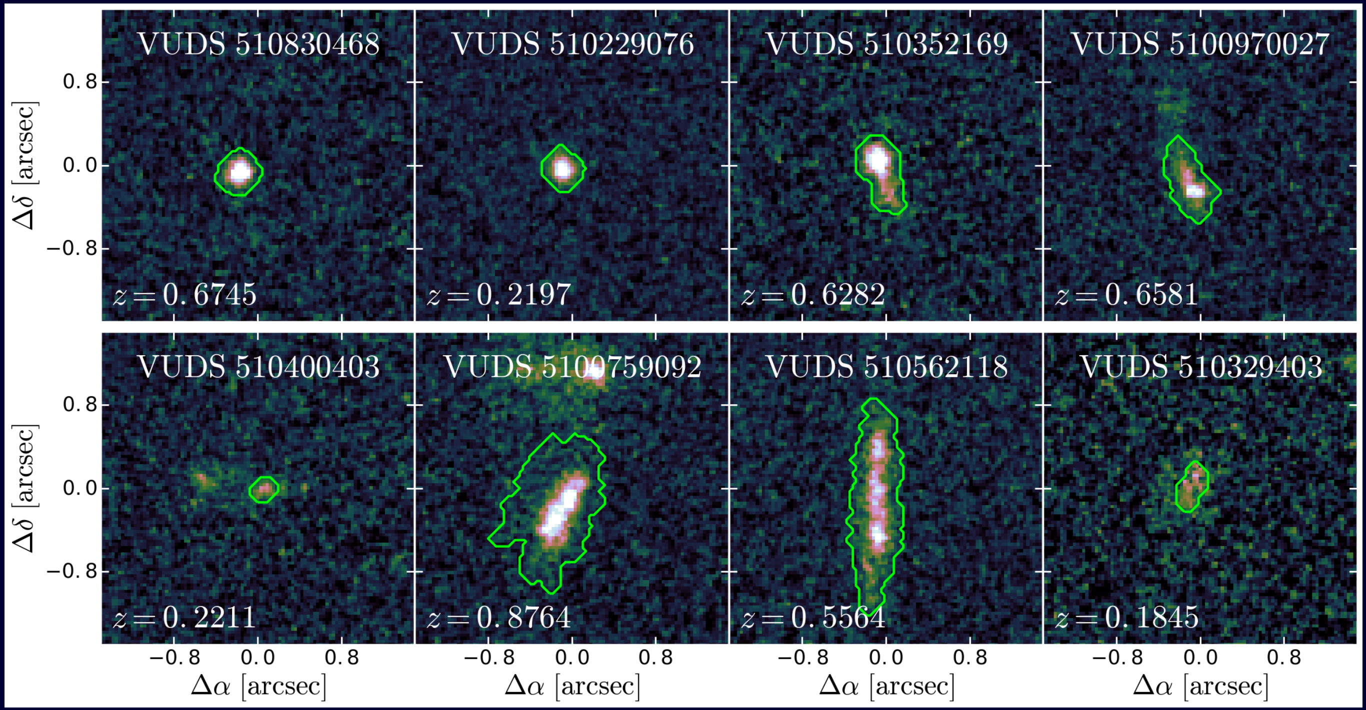


The sizes and morphologies of our galaxies

Sizes :

- Very compact galaxies ($r_{e,med}$=1.2 kpc)
- Relatively high **gas-fractions** (assuming a general Kennicutt-Schmidt law)

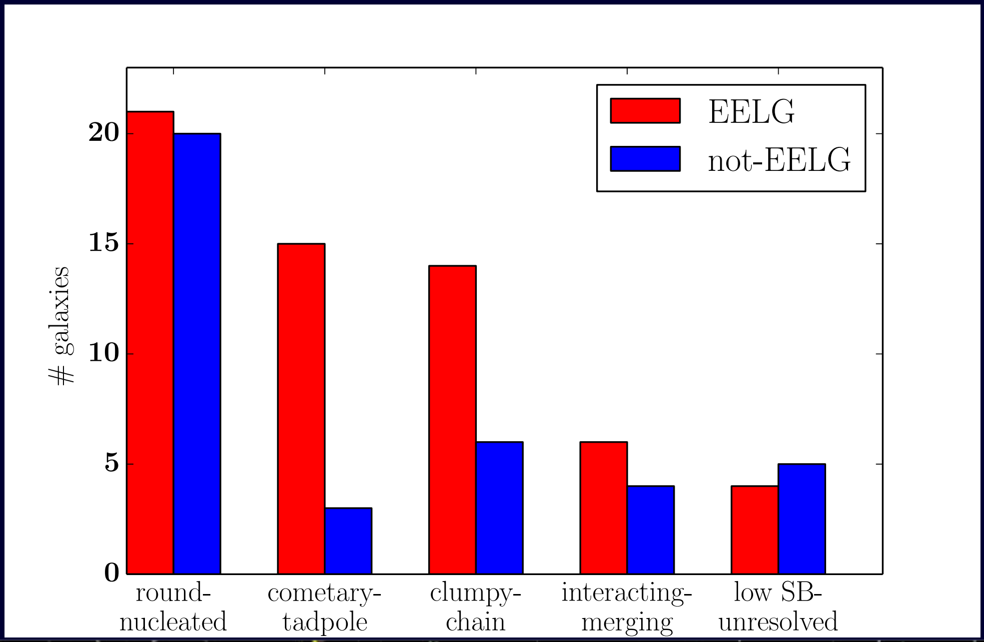
HST i band



Four morphological classes (Amorin et al. 2015) :

- Round-nucleated
- Cometary-tadpole
- Clumpy-chain
- Merger-interacting

EELGs have on average disturbed morphologies



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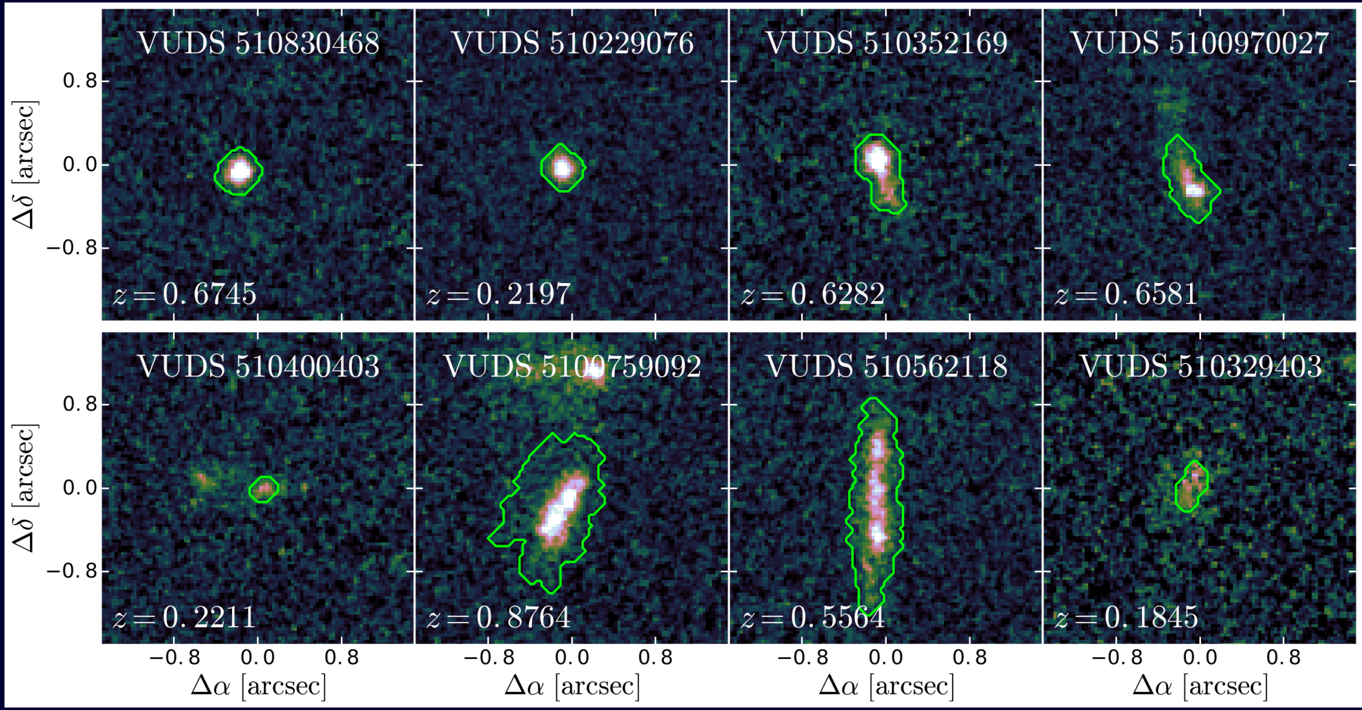

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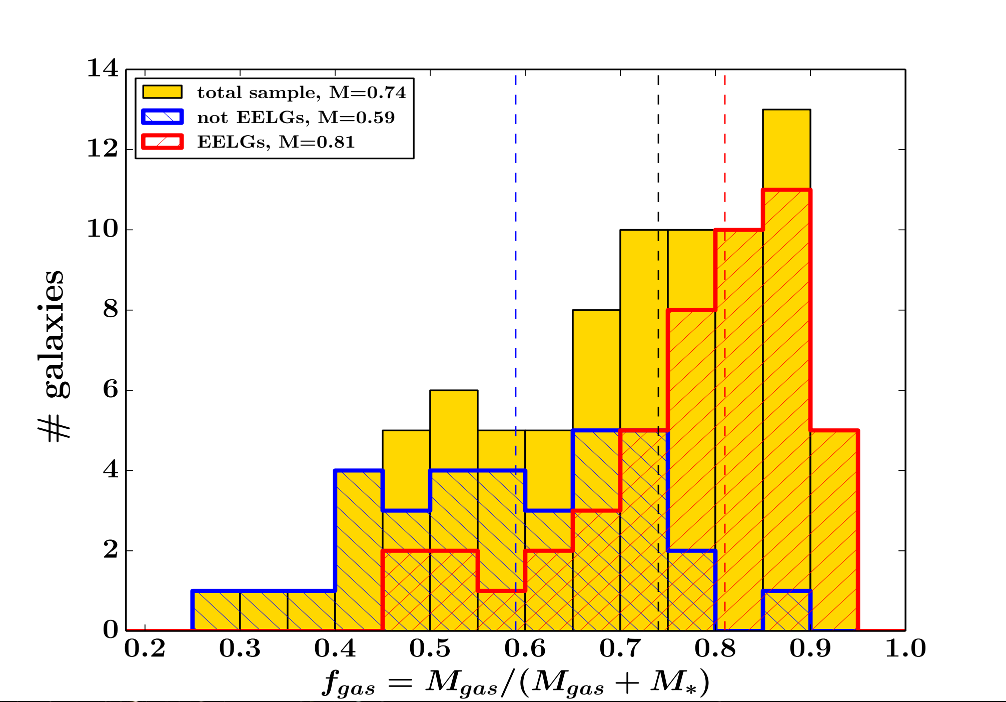


… our methodology → HII-CHI-mistry

- Python script (Pérez-Montero+14) to derive oxygen and nitrogen abundances and ionization from a set of emission lines
- 300 models covering a wide range of 12+log(O/H), log(N/O) and log(U) using CLOUDY v13.03 (Ferland et al. +13) and POPSTAR (Mollá et al. +09)

[OII] 3727
[OIII] 4363
[OIII] 5007
[NII] 6584
[SII] 6717+6731

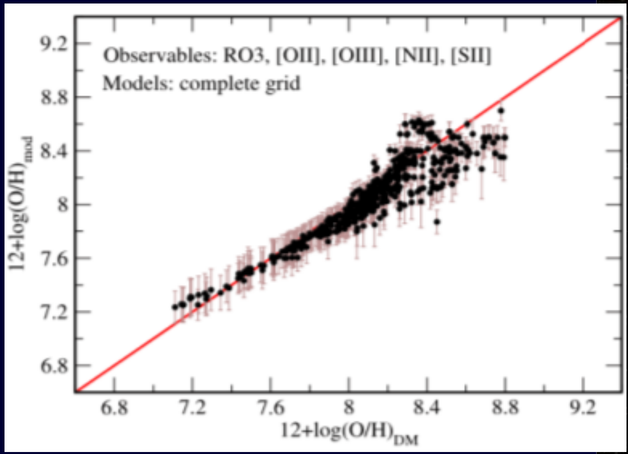
→

12+log(O/H)
log(N/O)
log U

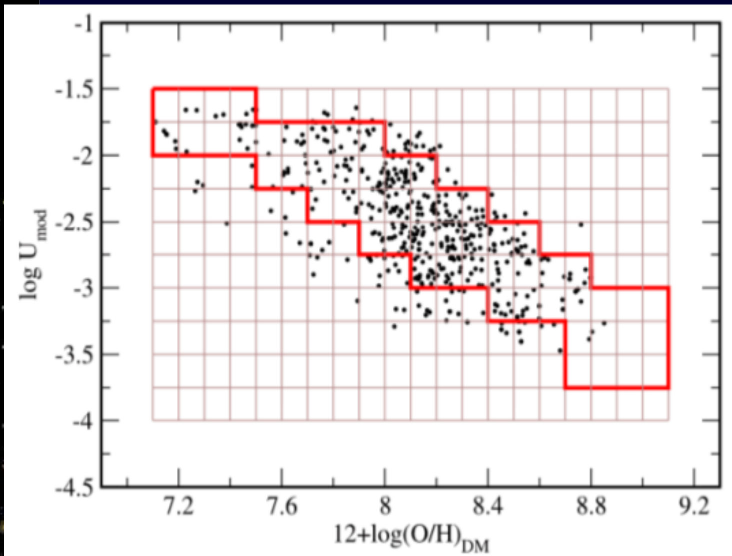
- χ^2 -based

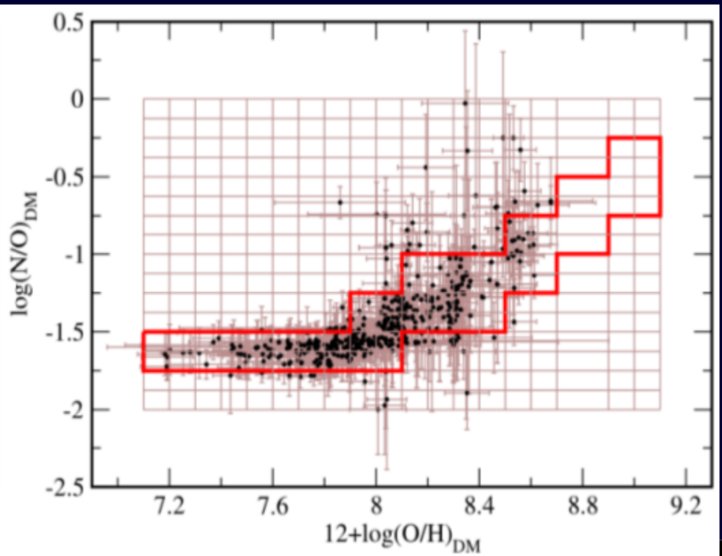
$$log(N/O)_f = \frac{\Sigma_i log(N/O)_i/\chi_i}{\Sigma_i\ 1/\chi_i}$$

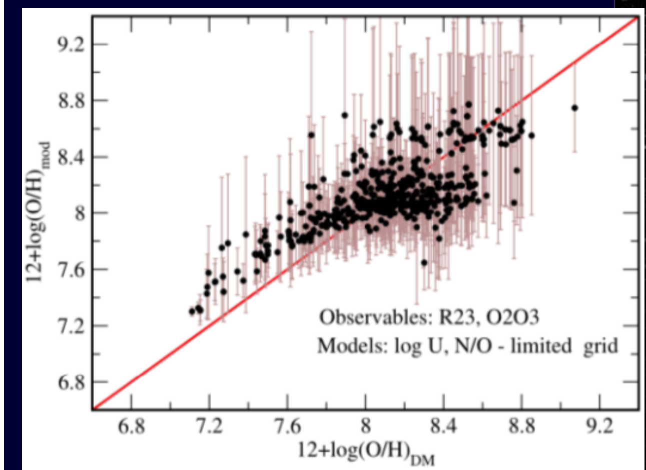
$$\chi_i^2 = \Sigma_j \frac{(O_j - T_{ji})^2}{O_j}$$



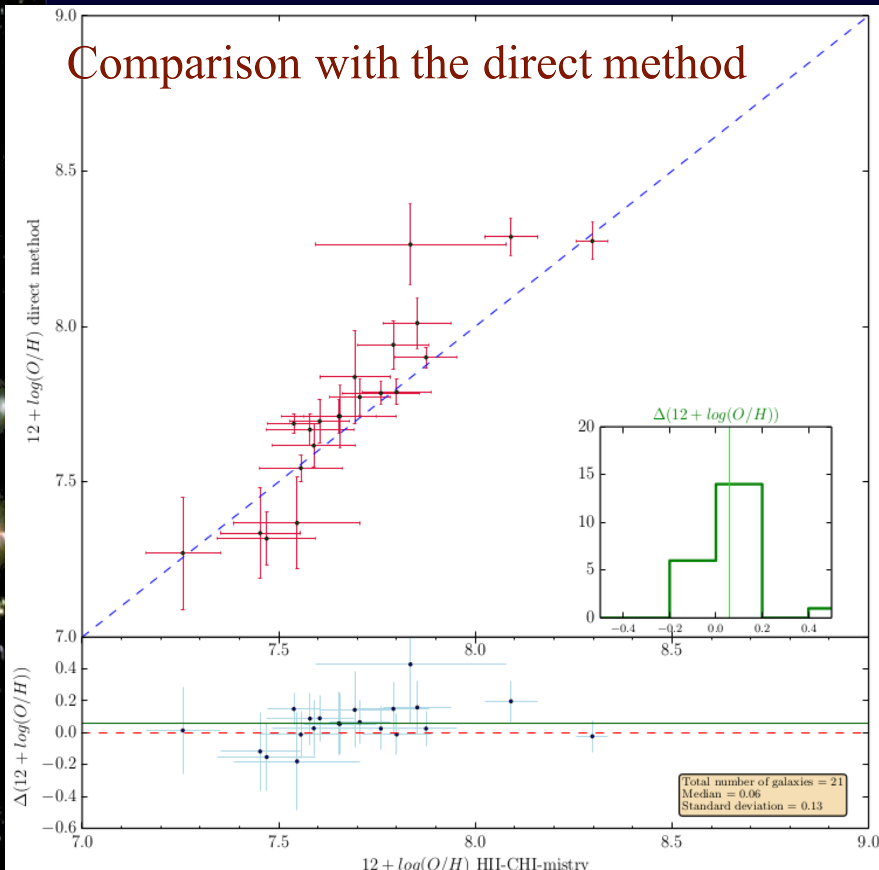
- First time applied to redshift 0 < z < 1
- Consistent with the T_e method over the entire range

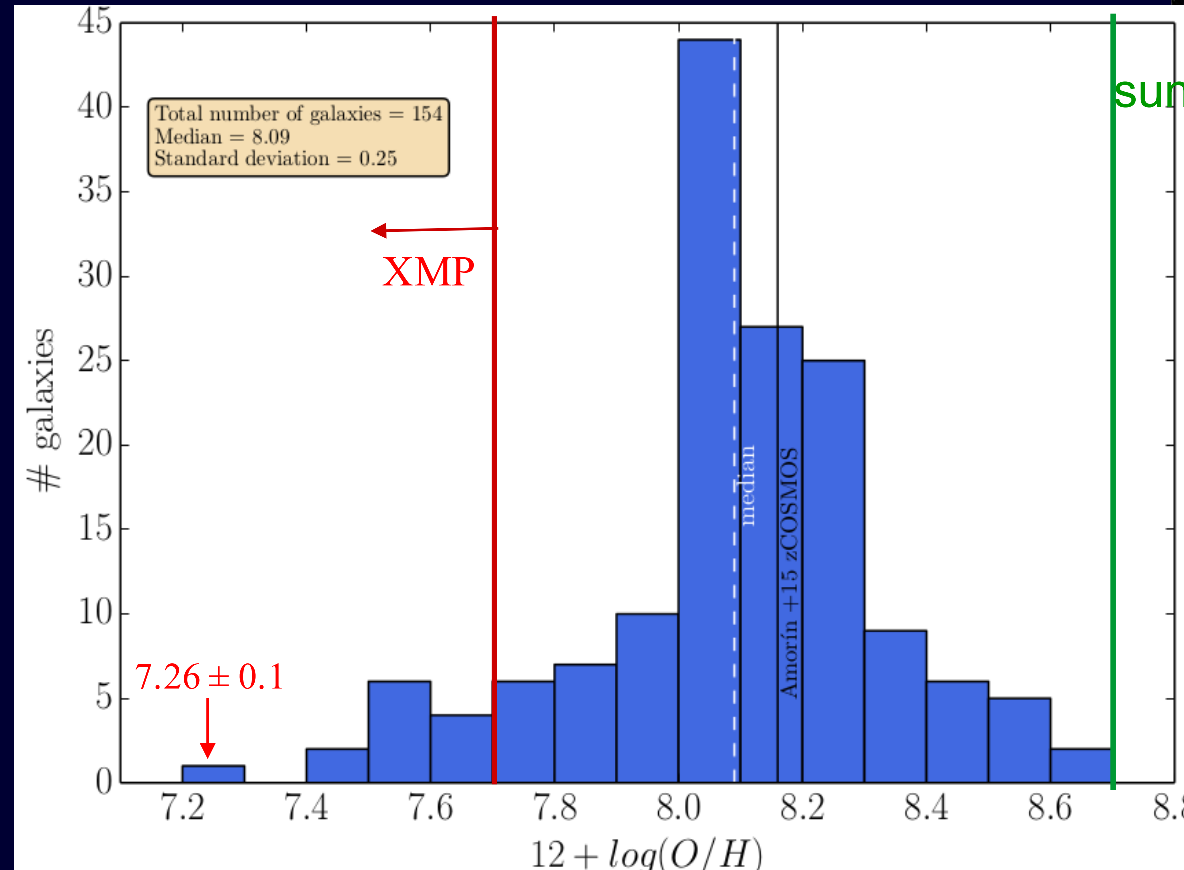






Oxygen abundance

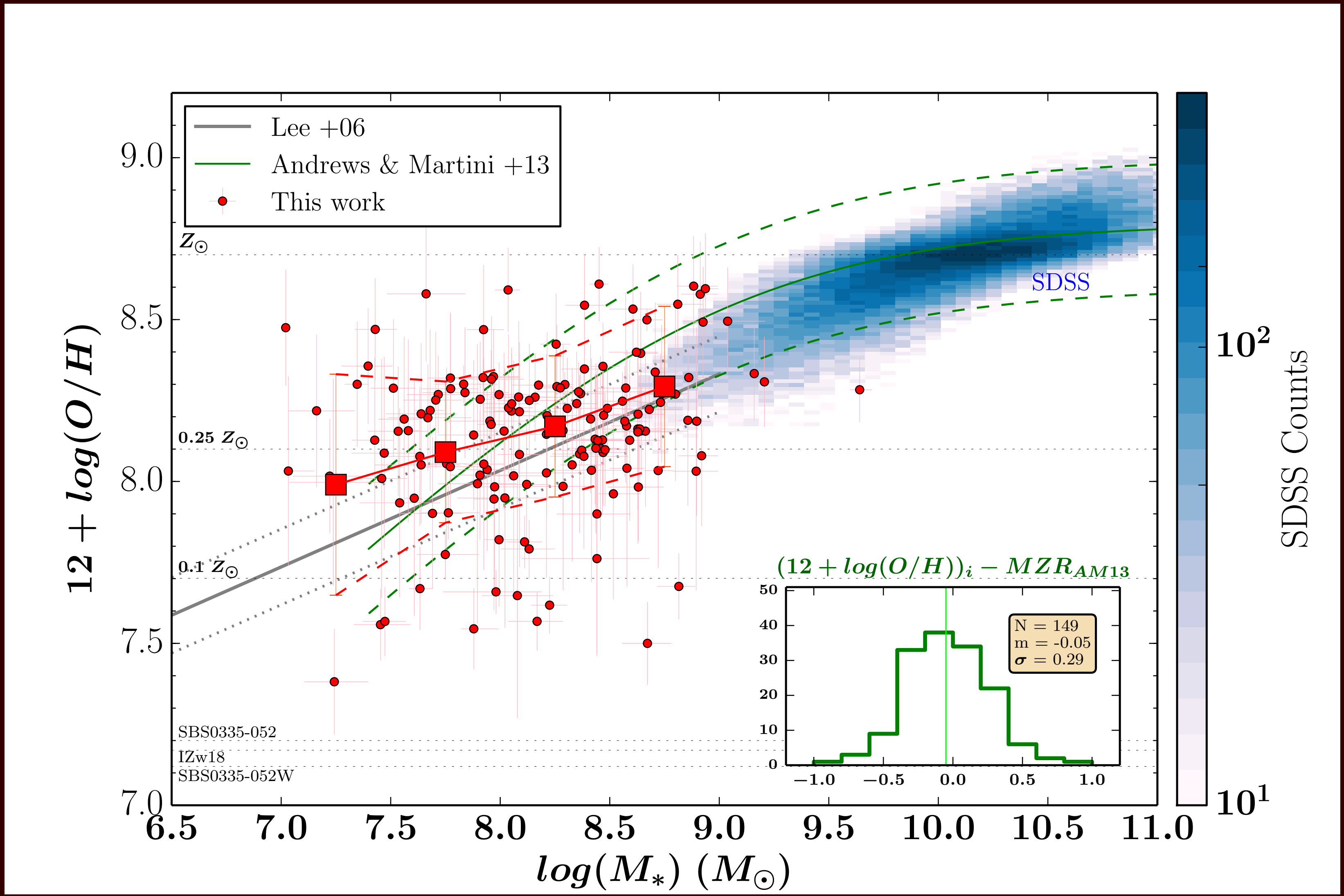




The oxygen abundances of 19 galaxies with O4363 detection are consistent with the direct method.

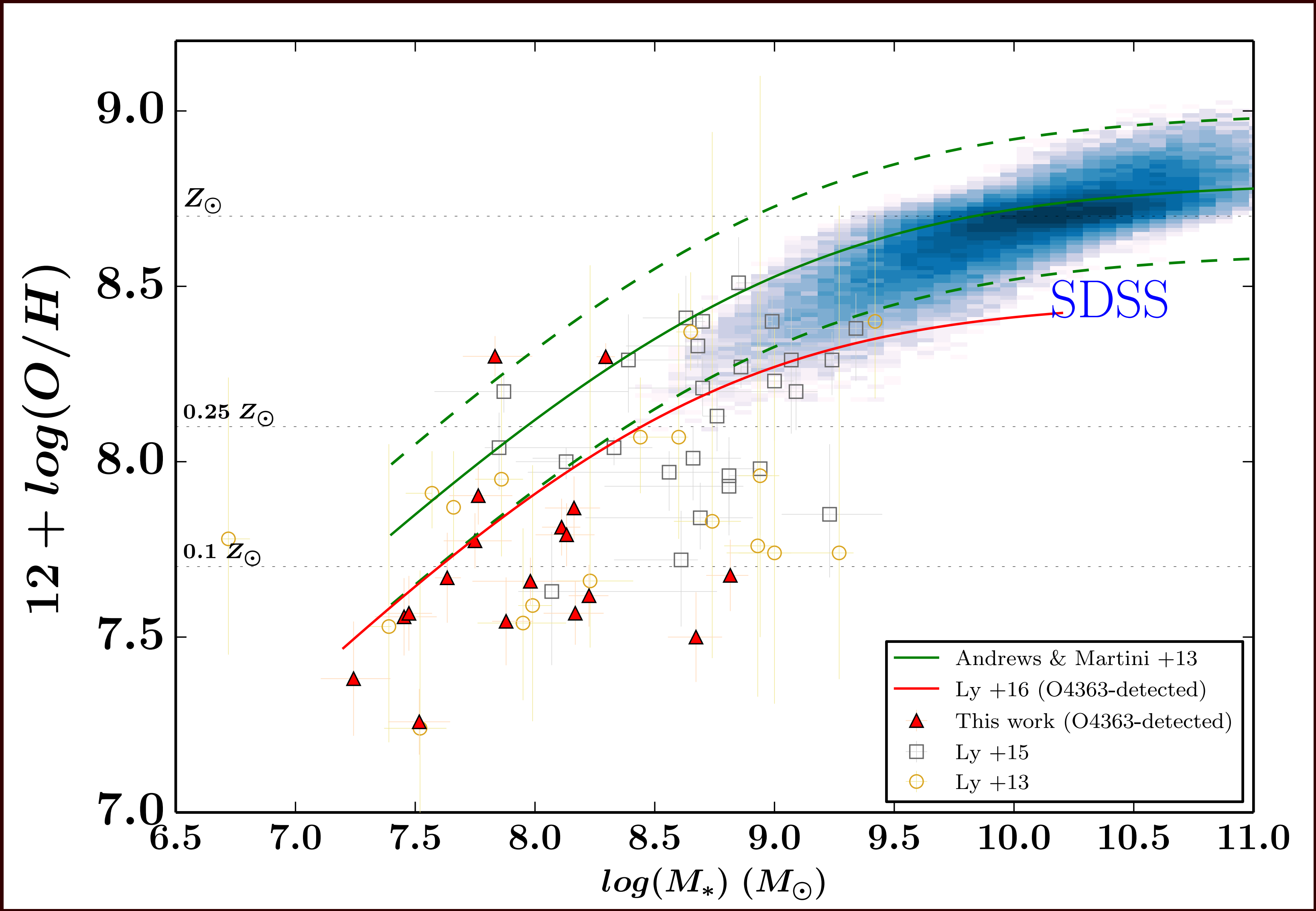
- 8 galaxies are extremely metal poor (XMP) ($Z < 1/10\ Z_{sun}$, Kunth & Östlin 2000)
- VERY RARE in the Local Universe (~0.01% in SDSS; Filho+13) , first discoveries at $z > 0.3$
- The youngest and chemically un-evolved star-forming galaxies that can be studied locally. Local analogs of star-forming galaxies at high redshift.

Results 1 / 3 : 12+log(O/H) vs Stellar mass



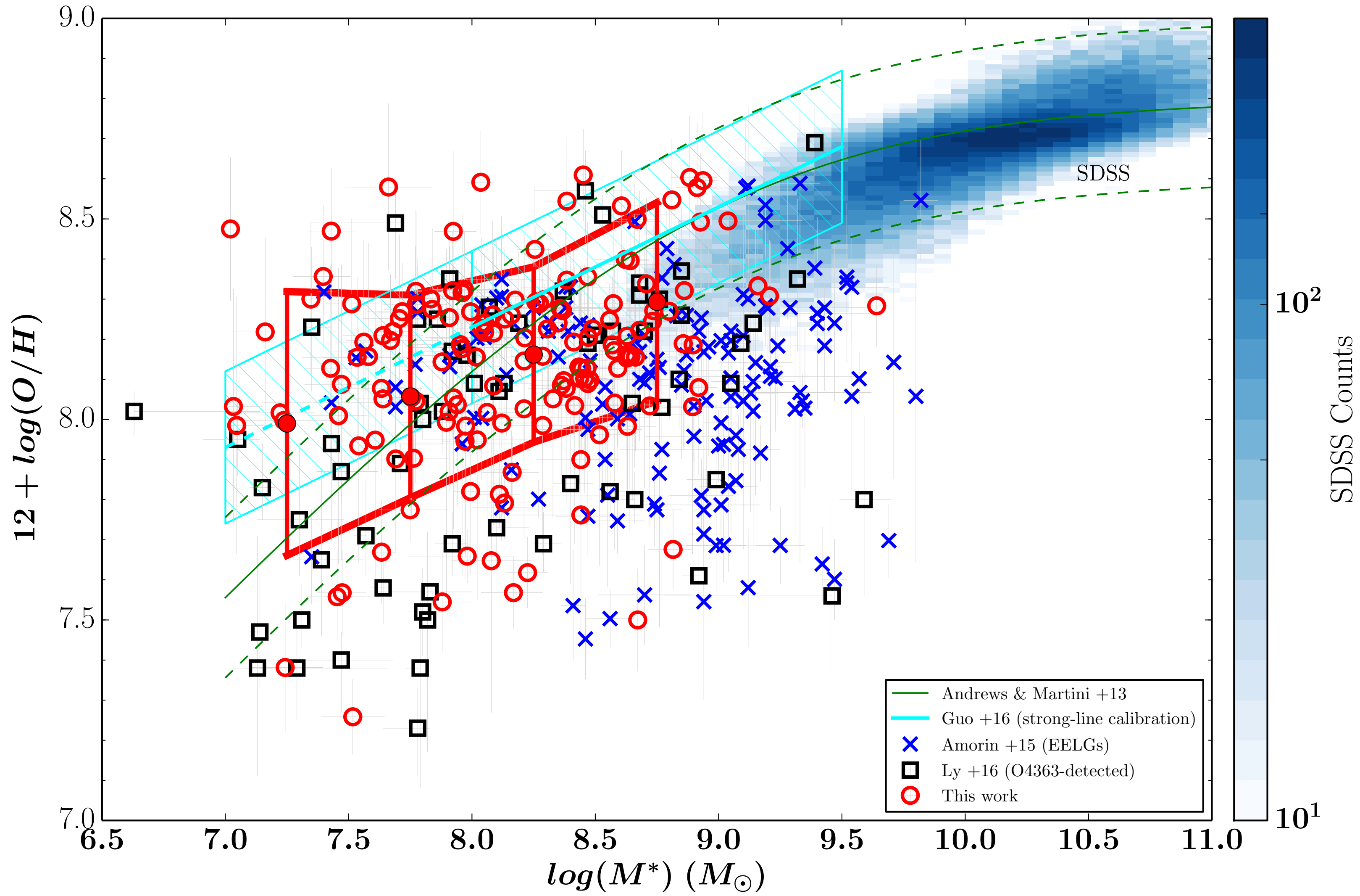
- Our trend is generally consistent with the T_e-based MZR
- We favour a shallow decrease of Z with mass
- The dispersion increases toward lower masses

Results 2 / 3 : The MZR of galaxies with O4363 detection



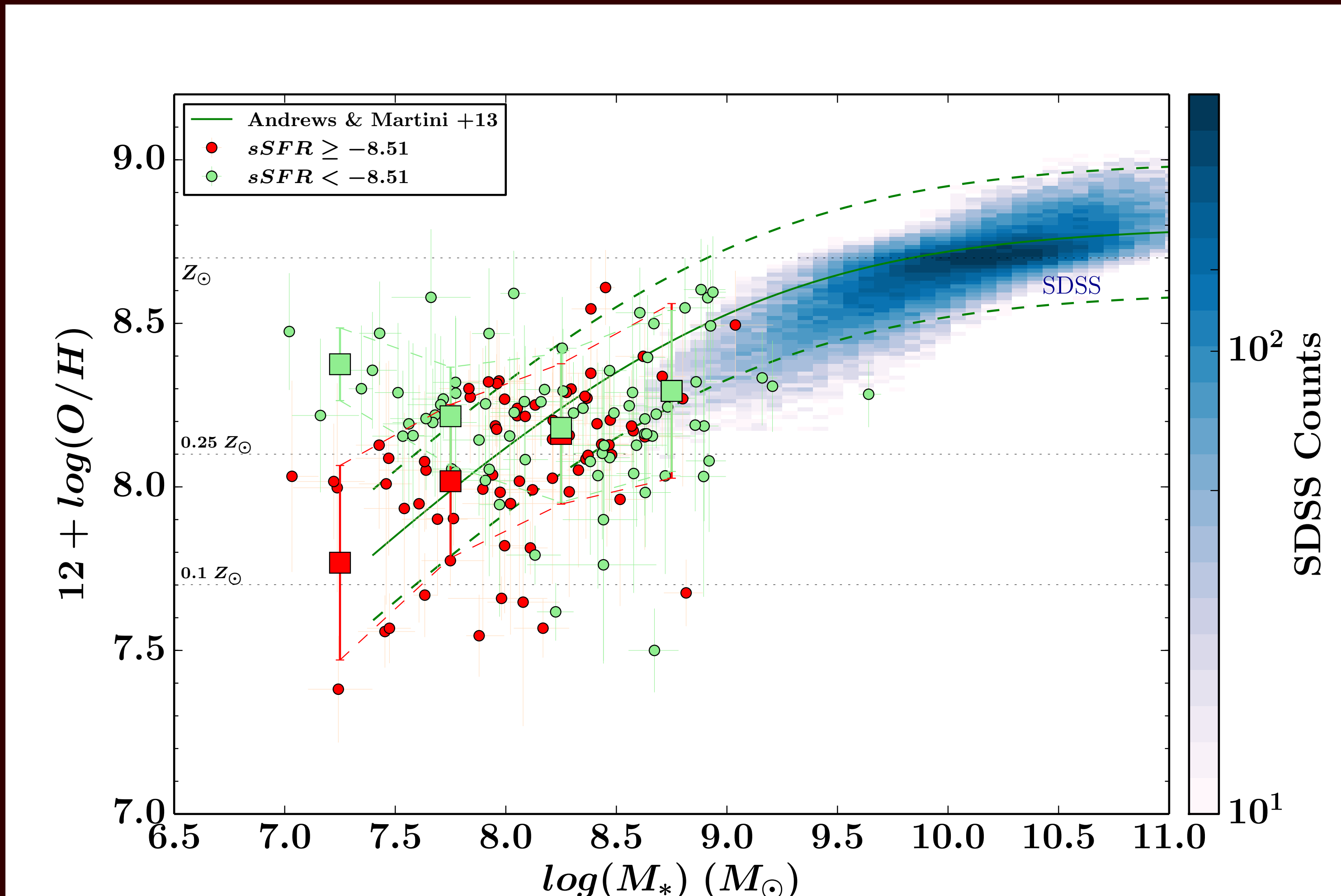
- O4363 tends to select galaxies with lower metallicities

Results 2 / 3 : Comparison with other samples



- Slope of our MZR is more consistent with Guo et al. 2016 than Andrews & Martini 2013 for SDSS galaxies

Results 3 / 3 : Dependence of the MZR on the sSFR



In the low-mass end :

higher metallicity → lower SFR

lower metallicity → higher SFR

Underlying population of more evolved dwarfs (Zahid et al. 2012), driving the slope and dispersion of the MZR ?

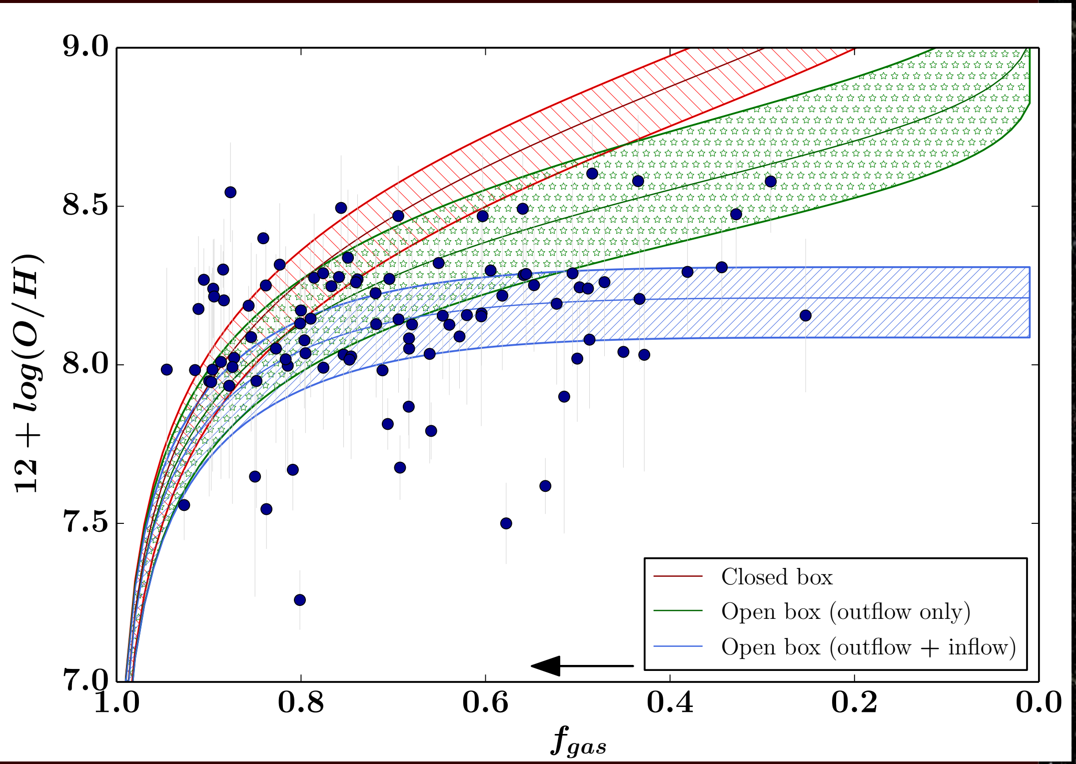
Constraining chemical evolution models for dwarfs

What regulates the star formation and chemical evolution ?

Simple models of chemical evolution : (Kudritzki +15)

Assumptions:

- gas outflows and inflows occur at a constant fraction of the SFR (η and Λ)
- outflowing gas has the same metallicity of the remaining gas reservoir
- only metal-free gas accretion
- fraction of stellar mass returned to the ISM through winds = 0.18 (Ascasibar+15, Sanchez-Almeida+15)
- Instantaneous mixing and recycling approximation
- oxygen yield : $0.008 < \mathcal{Y}_0 < 0.010$ (Zahid+12)



☞ average error on f_{gas} ~ 0.2 dex

model	η	Λ
CLOSED-BOX	0	0
OUTFLOWS	$2 < \eta < 4$ (Wuyts+14, Sanchez-Almeida+14)	0
OUTFLOWS+INFLOWS	$2 < \eta < 4$	$\eta + 0.95$ (Wuyts+12)

The outflows + inflows models are preferred to close-box models

Summary

- I have presented the discovery of one of the largest and more representative samples of star-forming dwarf galaxies at intermediate redshift $0.13 < z < 0.88$.

- New constraints to the low-mass end of key scaling relations between mass, metallicity and SFR. Significant variations in sSFR are primary responsible of the increasing scatter and moderate slope towards low masses in the MZR.

- Comparison between simple chemical evolution models and observations : Gas flows (both inflows and outflows may play a key role)

- Sample of EELGs as best candidates of low-redshift analogs of Lyman-continuum leaking galaxies (LyC), which reionized the universe at redshift 6-8

… Thanks for your attention