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PHOTOMETRIC AND SPECTROSCOPIC ANALYSIS OF LENSED RE-IONISING SOURCES AT THE FRONTIER OF THE UNIVERSE

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Abstract. Our team is performing an automatic search for very distant sources using HST, VLT, Magellan, Gemini, Spitzer and ALMA dataset around Frontier Fields aiming to study the nature and properties of sources during the epoch of reionization. In this paper, we report on our photometric sample selection, the photometric properties of our $z>6$ candidates and the evolution of galaxy number densities during the first billion years from a statistical point of view. Thanks to the huge depth of HST FF data, we identified several $z>7$ candidates selected in previous HST surveys as mid-z interlopers that could bias our conclusions on the evolution of the first galaxies. We also briefly discuss several interesting objects that will benefit from the arrival of the JWST. The spectroscopic follow-up has just started, and our team is observing a sample of $z>7$ sources with ground-based spectrographs in order to confirm the redshift of these objects and add robust constraints on their physical properties.

Keywords: Galaxies: distances and redshifts, Galaxies: evolution, Galaxies: formation, Galaxies: high-redshift, Galaxies: photometry, Galaxies: star formation

1 Introduction

Observations probing the edges of the visible Universe is one of the most intriguing challenges of the coming decade, particularly with respect to detecting the first galaxies at $z>12$ (Bromm & Yoshida 2011) and the first population III stars (eg. O'Shea & Norman 2007). Several telescopes and instruments are under development and have put these topics in their key objectives. Many surveys have been completed in order to push even further the observational limits of the Universe and to strongly increase the number of very high-redshift sources known ($z>6$). Ten years ago, only a dozen objects at $z>6$ had been discovered (Kneib et al. 2004), with none above $z>7.5$. Nowadays, the number of $z\sim6$, $z\sim7$, and $z\geq8$ galaxies selected in deep surveys count in the 1000s (e.g. Le Fèvre et al. 2015), several 100s (e.g. Bouwens et al. 2015) and $\sim$100 (e.g Oesch et al. 2014), respectively. Thanks to these huge numbers of objects, the evolution and properties of galaxies, as well as their contribution to the reionization process, are relatively well-constrained up to $z\sim6$, with many secure spectroscopic confirmations (Jiang et al. 2013; Smit et al. 2015). Beyond $z\sim6$, spectroscopic follow-up remains extremely challenging due to the decreasing mean brightness of these objects (Oesch et al. 2015; Watson et al. 2015). However, during the last year several groups have demonstrated that a type of very high-redshift candidates systematically shows bright emission lines (e.g. Oesch et al. 2015, Bouwens et al. 2014, Finkelstein et al. 2013) leading to the spectroscopic

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confirmation of objects up to z=8.7 (Zitrin et al. 2015; Roberts-Borsani et al. 2016). All these objects display two breaks : one between optical and NIR, the Lyman-break, and another one between 3.6 and 4.5μm, the 4000Å break that confirms the high-z hypothesis (Smit et al. 2014; Laporte et al. 2014).

In this paper, we report on the photometric selection of bright z>7 objects in the latest Hubble flagship program, the *Frontier Fields* (Lotz 2015), the statistical analysis of the sample and on the first stage of the spectroscopic follow-up.

2 The HST Frontier Fields

In October 2013, the *Hubble* Space Telescope started observations of six massive galaxy clusters as part of "The Frontier Fields" (hereafter FF, Lotz 2015), aiming to obtain the deepest data using strong gravitational lensing. The *Spitzer* Space Telescope is also involved allowing to increase the wavelength coverage with extremely deep data through 4.5μm. To date, four clusters have been fully observed by *Hubble* : Abell 2744, MACSJ0416.1-2403, MACSJ0717.5+3745 and MACSJ1149.5+2223 reaching depths of ≈29.0 AB at 5σ. Our group applied the Lyman Break Galaxy technique (LBG; Steidel et al. 1996) combining non-detections in F435W, F606W, F814W and detections in F125W, F140W, as well as color criteria to select the brightest $z \geq$6.5 candidates in all FF clusters. Compared to others groups, we add one more criteria on the size of the break between F814W and F125W (F814W-F125W > 4.0 mag) in order to remove extreme mid-z interlopers (Hayes et al. 2012, Fig. 1). In the following, we take benefit from public lens models provided in the framework of the Frontier Fields program by the CATS group (Richard et al. 2014; Jauzac et al. 2015).

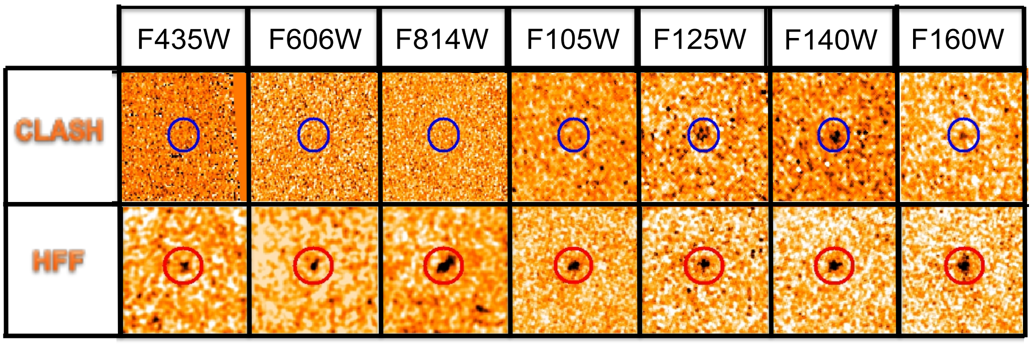

Fig. 1. Example of source selected as a good z ∼8 candidate and revealed as mid-z interloper by the *Hubble* Frontier Fields data. The first row shows the shape of this candidate in the CLASH data (Postman et al. 2012) and the second row shows the same object as seen by the Frontier Fields. The detections at ∼0.4, 0.6 and 0.8 μm demonstrates that this object is not at such high-redshift.

Finally, we selected 39, 22, and 39 z>6 candidates in Abell 2744 (Laporte et al. 2014; Zheng et al. 2014), MACS0416 (Laporte et al. 2015; Infante et al. 2015) and MACS0717 (Laporte et al. 2016) respectively. More particularly, we found one of the faintest galaxy at z>10 strongly amplified behind MACS0416 (Infante et al. 2015, see section 4) leading to a magnitude of M_{UV} ∼15.5.

3 Photometric Analysis of Frontier Fields samples

With the huge number of very high-z lensed galaxies selected in the Frontier Fields survey, we are able to put robust constraints on the faint end of the UV Luminosity Function (LF), and therefore constrain the contribution of the faintest galaxies to the reionization process. However, our selection is only based on photometric criteria (see previous section) and even by using additional criteria on the size of the break limiting the contamination by mid-z interlopers, it is crucial to take into account uncertainties on the photometric redshift to study the evolution of the UV LF. Therefore we used a MC method based on the redshift probability distribution for each source to compute the number density of galaxies in several redshift ranges (see Laporte et al. 2015 for a detailed description of the method). We adopted a Schechter parameterisation (Schechter 1976) and found a clear evolution of $\Phi^\star$, more especially between z ∼8 and 9 suggesting a strong decrease in the number of galaxies in this redshift interval, and a relatively small evolution of the faint-end slope α (Fig. 2). The parameterisation of the Schechter function we deduced from half of the Frontier Fields survey is reported in Table 1. We used this

Table 1. Schechter parameters for the UV LF at $z \sim$7, 8 and 9

$< z >$	$M^\star$	$\Phi^\star$	α
7	-20.33$^{+0.37}_{-0.47}$	0.37$^{+0.12}_{-0.11}\times10^{-3}$	-1.91$^{+0.26}_{-0.27}$
8	-20.32$^{+0.49}_{-0.26}$	0.30$^{+0.85}_{-0.19}\times10^{-3}$	-1.95$^{+0.43}_{-0.40}$
9	-20.45 (*fixed*)	0.70$^{+0.30}_{-0.30}\times10^{-4}$	-2.17$^{+0.41}_{-0.43}$

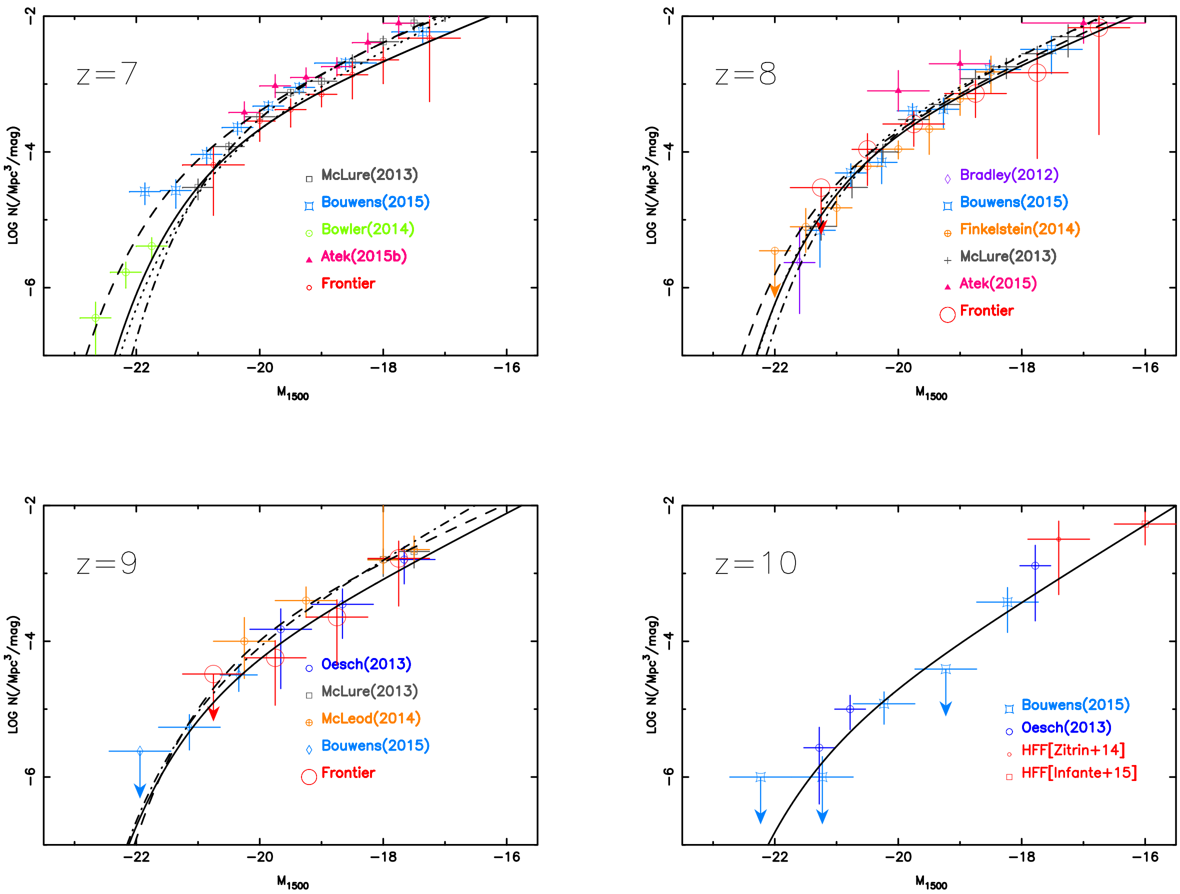

Fig. 2. Number densities and best-fit of the Luminosity Function at $z \sim$7, 8, 9, and 10 using the half of the Frontier Fields data. Our point (in red) are compared with results published in McLure et al. (2013); Bouwens et al. (2015); Bowler et al. (2014); Atek et al. (2015); Bradley et al. (2012); Finkelstein et al. (2015); Oesch et al. (2013); McLeod et al. (2015)

parameterisation to estimate the UV photons density produced by the galaxies at each redshift range covered by this survey, and compared these densities with the UV density required to keep the Universe reionized (Madau et al. 1999). As previously demonstrated, the UV photons density produced by the Lyman Break galaxies is not sufficient to explain the end of the reionization process at $z \sim$6 (Fig. 3), and therefore others contributors must be considered, such as the Gamma Ray Burst or AGN at very high-redshift.

We also took benefit from the large wavelength range covered by the Frontier Fields data to estimate the physical properties of our very high-z candidates using *iSEDfit* (Moustakas et al. 2013) as described in Infante et al. (2015). We confirmed the trend observed previously in the evolution of the Star Formation Rate (SFR) as function of galaxy mass as well as in the evolution of the size of galaxies as a function of the UV Luminosity at very high-redshift (see Fig. 6 and 10 of Laporte et al. 2016).

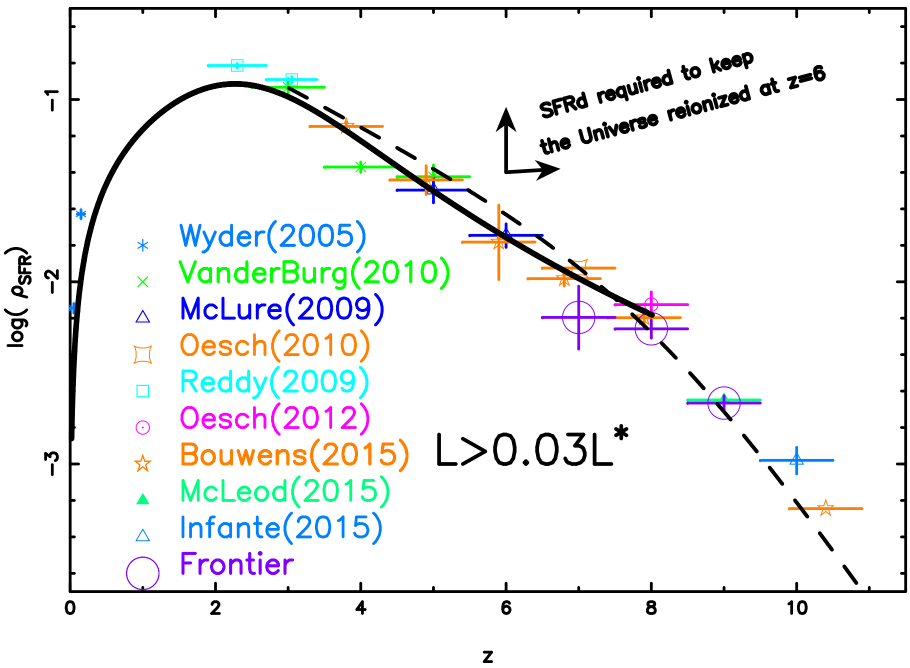

Fig. 3. Evolution of the SFRd including densities deduced from the half Frontier Fields data set. Two parameterizations are overplotted: the solid line shows the shape published in Cole et al. (2001) and the dashed line displays the evolution as seen by Ishigaki et al. (2015). The dark arrows show the SFR density required to keep the Universe reionized computed from Madau et al. (1999)

4 Spectroscopic follow-up

Our team just started a spectroscopic follow-up of all bright $z \geq 7.5$ objects with several ground based telescopes, such as the *Very Large Telescopes*, *Gemini*, *Magellan* and *Keck*. During the first stage of this program, we observed for $\approx$ 10 hours two of the brightest high-z candidates detected on the Frontier Fields images, namely Abell2744_Y1 (Laporte et al. 2014) and MACS1149_JD1 (Zheng et al. 2012), with MMIRS/Magellan. We reached a 2σ-sensitivity of 10^{-17} erg/s/cm^2 and detected no line. This non-detection is consistent with the non-detection observed in the GLASS survey (Treu et al. 2015; Schmidt et al. 2016) reaching a flux limit of 10^{-17} erg/s/cm^2 at 2σ. Others observations are already scheduled with X-Shooter/VLT to push the sensitivity to 2×10^{-18} erg/s/cm^2.

5 Conclusions

Thanks to the depth of the Frontier Fields survey images, we are able, for the first time, to give robust constraints on the extreme faint-end of the UV Luminosity Function up to $M_{1500}\sim$-15, and therefore start to reveal the role played by the faintest Lyman Break galaxies during the epoch of reionization. However, all these results must be taken with caution since they are based on photometric samples, which could be contaminated by mid-z galaxies displaying a SED similar to the very high-z objects SED. With current facilities, we are only able to observe the brightest objects in the first billion years of the Univers. But the arrival of the *James Webb Space Telescope* in 2018 or the first light of the *European Extremely Large telescope* in 2024 will allow us to explore by spectroscopy a new range of luminosity and therefore definitively determine the major contributors to the reionization process.

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References

Atek, H., Richard, J., Jauzac, M., et al. 2015, ApJ, 814, 69

Bouwens, R. J., Bradley, L., Zitrin, A., et al. 2014, ApJ, 795, 126

Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015, ApJ, 803, 34

Bowler, R. A. A., Dunlop, J. S., McLure, R. J., et al. 2014, MNRAS, 440, 2810

Bradley, L. D., Trenti, M., Oesch, P. A., et al. 2012, ApJ, 760, 108

Bromm, V. & Yoshida, N. 2011, ARA&A, 49, 373

Cole, S., Norberg, P., Baugh, C. M., et al. 2001, MNRAS, 326, 255

Finkelstein, S. L., Papovich, C., Dickinson, M., et al. 2013, Nature, 502, 524

Finkelstein, S. L., Ryan, Jr., R. E., Papovich, C., et al. 2015, ApJ, 810, 71

Hayes, M., Laporte, N., Pelló, R., Schaerer, D., & Le Borgne, J.-F. 2012, MNRAS, 425, L19

Infante, L., Zheng, W., Laporte, N., et al. 2015, ApJ, 815, 18

Ishigaki, M., Kawamata, R., Ouchi, M., et al. 2015, ApJ, 799, 12

Jauzac, M., Richard, J., Jullo, E., et al. 2015, MNRAS, 452, 1437

Jiang, L., Egami, E., Mechtley, M., et al. 2013, ApJ, 772, 99

Kneib, J.-P., Ellis, R. S., Santos, M. R., & Richard, J. 2004, ApJ, 607, 697

Laporte, N., Infante, L., Troncoso Iribarren, P., et al. 2016, ApJ, 820, 98

Laporte, N., Streblyanska, A., Clement, B., et al. 2014, A&A, 562, L8

Laporte, N., Streblyanska, A., Kim, S., et al. 2015, A&A, 575, A92

Le Fèvre, O., Tasca, L. A. M., Cassata, P., et al. 2015, A&A, 576, A79

Lotz, J. 2015, IAU General Assembly, 22, 2255460

Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648

McLeod, D. J., McLure, R. J., Dunlop, J. S., et al. 2015, MNRAS, 450, 3032

McLure, R. J., Dunlop, J. S., Bowler, R. A. A., et al. 2013, MNRAS, 432, 2696

Moustakas, J., Coil, A. L., Aird, J., et al. 2013, ApJ, 767, 50

Oesch, P. A., Bouwens, R. J., Illingworth, G. D., et al. 2013, ApJ, 773, 75

Oesch, P. A., Bouwens, R. J., Illingworth, G. D., et al. 2014, ApJ, 786, 108

Oesch, P. A., van Dokkum, P. G., Illingworth, G. D., et al. 2015, ApJ, 804, L30

O'Shea, B. W. & Norman, M. L. 2007, ApJ, 654, 66

Postman, M., Coe, D., Benítez, N., et al. 2012, ApJS, 199, 25

Richard, J., Jauzac, M., Limousin, M., et al. 2014, MNRAS, 444, 268

Roberts-Borsani, G. W., Bouwens, R. J., Oesch, P. A., et al. 2016, ApJ, 823, 143

Schechter, P. 1976, ApJ, 203, 297

Schmidt, K. B., Treu, T., Bradač, M., et al. 2016, ApJ, 818, 38

Smit, R., Bouwens, R. J., Franx, M., et al. 2015, ApJ, 801, 122

Smit, R., Bouwens, R. J., Labbé, I., et al. 2014, ApJ, 784, 58

Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17

Treu, T., Schmidt, K. B., Brammer, G. B., et al. 2015, ApJ, 812, 114

Watson, D., Christensen, L., Knudsen, K. K., et al. 2015, Nature, 519, 327

Zheng, W., Postman, M., Zitrin, A., et al. 2012, Nature, 489, 406

Zheng, W., Shu, X., Moustakas, J., et al. 2014, ApJ, 795, 93

Zitrin, A., Labbé, I., Belli, S., et al. 2015, ApJ, 810, L12