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Fishing for Spectral Lines in High-Redshift Galaxies Lensed by Frontier Fields Clusters

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Abstract. The Hubble Frontier Fields, together with other cluster lensing surveys with Hubble, have revealed hundreds of high-redshift ($z \gtrsim 6$) dropout galaxy candidates. We summarize recent efforts taken to spectroscopically follow up magnified high-redshift galaxies behind those clusters and in the field, including our detection of Lyα emission from a redshift $z = 8.68$ object.

Keywords. cosmology: observations — galaxies: high-redshift — galaxies: evolution — galaxies: formation — gravitational lensing: strong

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Background It is by now well established that the Universe has become completely reionized by redshift ~ 6 (e.g. Fan *et al.* 2006). One of the main evidence for the evolving state of the intergalactic medium (IGM) at high redshift is the rapid decline observed in the visibility of Lyα λ1216 Å emission from photometrically-selected galaxies at $z \gtrsim 6$ due to resonant scattering by neutral Hydrogen.

Spectroscopy of high-redshift galaxies is crucial for understanding the physical properties of the first galaxies and the reionization process. Because of the scattering of Lyα emission, however, it is increasingly difficult to detect higher-redshift galaxies substantially above $z \sim 6$. Despite much observational effort with the largest telescopes, only about a dozen galaxies are spectroscopically confirmed above $z \sim 7$ (e.g. Ono *et al.* 2012, Vanzella *et al.* 2011, Schenker *et al.* 2014, Finkelstein *et al.* 2013, Oesch *et al.* 2015), and no Lyα had been seen above redshift $z \simeq 7.7$.

Due to the declining visibility of Lyα at higher redshifts, the most viable route for spectroscopically studying high-z galaxies is targeting alternative ultraviolet (UV) spectral lines, such as CIII] ($\lambda\lambda$1907, 1909 Å) and CIV ($\lambda\lambda$1548, 1550 Å). While typically ∼10 times fainter intrinsically than Lyα (Stark *et al.* 2014), due to the increasing fractions of neutral Hydrogen those UV lines should become apparently more prominent at higher redshifts when Lyα is completely attenuated by the intervening neutral gas. Recently Stark *et al.* 2015b and Stark *et al.* 2015a detected CIII] in a $z \simeq 6$ and $z \simeq 7.2$ galaxies, and CIV in a $z \simeq 7.05$ galaxy, with previous Lyα emission known, manifesting the potential of this observational route.

Our Keck / MOSFIRE Campaign Following this success we embarked (in 2014B) on a short campaign to search for CIII] and CIV emission in galaxies lensed by Hubble Frontier Fields, and CLASH (PI: Postman) clusters. The relative high density of targets concentrated in one field thanks to the lens magnification is especially beneficial in conjunction with the multi-slit capabilities of the Multi-Object Spectrometer For Infra-Red Exploration (MOSFIRE, McLean *et al.* 2012) on the Keck 1 telescope, to enhance chances for detection. This is particularly important, as unlike the 2-3 previous detections here we aimed to imitate future surveys without prior knowledge of the exact redshift (e.g. from Lyα) so that the chances for detection decrease both subjectively (it is more difficult to ascertain a few-sigma line detection and separate it from random noise) and statistically, given the distribution of skylines. Specifically, we targeted $\sim 20-30$ galaxies in the redshift range $\sim 6-9$, with higher priority given to brighter objects and those with better photometric redshifts. The typical integration time per field was around 2-3 hours, and up to 5 hours – reaching a 5σ flux limit of about 1.5×10^{-18} ergs cm^{-2} sec^{-1}. This flux limit is better than that obtained by Stark *et al.* in their previous detections, but here most of the objects are fainter and so in terms of equivalent width (EW) we were typically only sensitive to lines that are intrinsically stronger (higher EWs).

While no definitive line was detected in this campaign, several important conclusions were drawn: First, CIII] and CIV, albeit a promising route, are not necessarily less challenging to detect – in absence of exact redshift from other lines – than Lyα, at least not in the probed redshift $z \sim 7$. Second, it seems that unlike previous claims that fainter objects might actually show higher EWs, one should still prefer brighter objects also for UV line detection. Last, we managed to statistically fold our non-detections into an upper limit on the typical CIII] rest-frame EW in our sample, of ~ 26 Å (typical $M_{UV} \sim -19$). This was the first time CIII] was – to our knowledge – searched systematically in a statistical sample of high-redshift galaxies. Our results were summarized in Zitrin *et al.* 2015a.

Lyα at z=8.7 Are there other indicators that can guide us towards line detection aside for brightness? Recently, Roberts-Borsani *et al.* 2015 (see also Labbé *et al.* 2013, Smit *et al.* 2015), have used significantly red IRAC [3.6]-[4.5] colors indicative of strong emission lines to extract four $z > 7$ galaxies from the CANDLES fields, out of which three were targeted spectroscopically. Remarkably, all three showed Lyα emission despite being at $z > 7.5$ where the neutral Hydrogen fraction is believed to already be high enough to attenuate any such radiation. One of these three objects was targeted by us with MOSFIRE, EGS8p7, in which we detected Lyα at redshift $z = 8.68$ (Zitrin *et al.* 2015b) – becoming the highest spectroscopically confirmed object to date, and potentially challenging our understanding of reionization. It remains to investigate how frequent are such objects and what are the implications on our view on reionization.

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