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High Equivalent Width of Hα+[N II] Emission in $z \sim 8$ Lyman-break Galaxies from IRAC 5.8μm Observations: Evidence for Efficient Lyman-continuum Photon production in the Epoch of Re-ionization

ABSTRACT

We measure, for the first time, the median equivalent width (EW) of Hα+[N II] in star-forming galaxies at $z \sim 8$. Our estimate leverages the unique photometric depth of the *Spitzer*/IRAC 5.8μm-band mosaics (probing ≈ 5500 − 7100Å at $z \sim 8$) of the GOODS Reionization Era Wide Area Treasury from Spitzer (GREATS) program. We median stacked the stamps of 102 Lyman-break galaxies in the 3.6, 4.5, 5.8 and 8.0μm bands, after carefully removing potential contamination from neighbouring sources. We infer an extreme rest-frame $\mathrm{EW_0(H\alpha+[N\,II])} = 2328^{+1326}_{-1127}$ Å from the measured red $[3.6]-[5.8] = 0.82 \pm 0.27$ mag, consistent with young ($\lesssim 10^7$ yr) average stellar population ages at $z \sim 8$. This implies an ionizing photon production efficiency of $\log \xi_{\mathrm{ion},0}/\mathrm{erg\ Hz^{-1}} = 25.97^{+0.18}_{-0.28}$. Such a high value for photo production, similar to the highest values found at $z \lesssim 4$, indicates that only modest escape fractions $f_{esc} \lesssim 0.3$ (at 2σ) are sufficient for galaxies brighter than $M_{UV} < -18$ mag to re-ionize the neutral Hydrogen at $z \sim 8$. This requirement is relaxed even more to $f_{esc} \leq 0.1$ when considering galaxies brighter than $M_{UV} \approx -13$ mag, consistent with recent luminosity functions and as typically assumed in studies addressing re-ionization. These exceptional results clearly indicate that galaxies can be the dominant source of reionizing photons, and provide us with an exciting glimpse into what we might soon learn about the early universe, and particularly about the Reionization Epoch, from forthcoming *JWST*/MIRI and NIRCam programs.

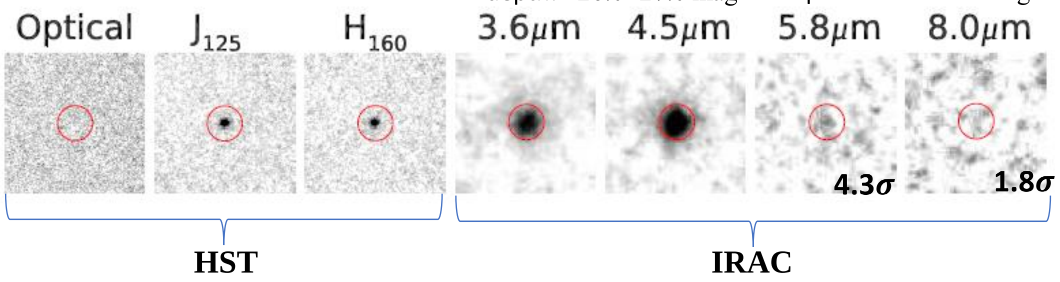
Constraining **Hα at z > 6** is quite challenging:

1. The flux densities in both the IRAC 3.6 and 4.5μm bands are enhanced by nebular emission lines. **Continuums or Emission lines ?**
2. Still unconstrained line ratios at these early epochs

At 7.0 < z < 8.7, [O III]+Hβ and Hα+[N II] drop into 4.5 and 5.8μm band, respectively. However, 5.8μm band suffer from lower sensitivities.
Solution: Combining the imaging available for samples of galaxies, and extracting their average properties.

Sample: 102 candidate LBGs at 7.3 < z_{phot} < 8.7, Y−dropout (Bouwens et al. 2015b)

Median stack: 2" diameter aperture depth: ~26.0−27.0 mag depth: ~23.0−24.0 mag



Stacking:
Excluding neighboring objects by **Mophongo** (Labbe et al. 2006);
For IRAC imaging, stacking was done after exluding neighbours.

Table 2. Flux densities for our median-stacked photometry

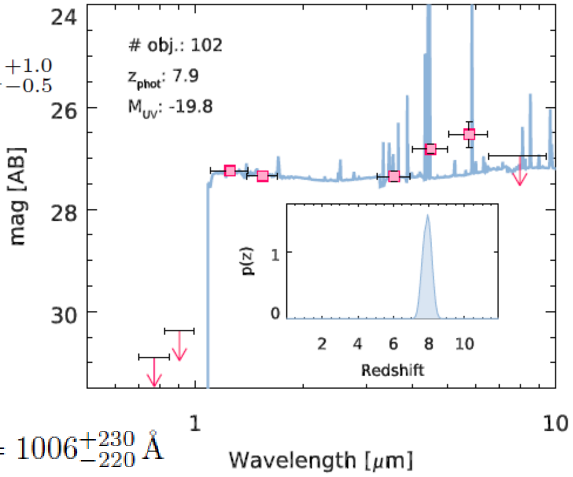
	V_{606} (nJy)	i_{775} (nJy)	z_{850} (nJy)	J_{125} (nJy)	H_{160} (nJy)	3.6μm (nJy)	4.5μm (nJy)	5.8μm (nJy)	8.0μm (nJy)
Stack	-0.4 ± 0.7	-0.5 ± 0.8	-1.3 ± 1.3	46.0 ± 2.4	41.8 ± 1.7	41.5 ± 3.9	68.0 ± 5.4	88.5 ± 20.3	56.3 ± 30.0

Note—We only list the flux densities in those bands available for at least 90% of the sources in our sample.

The aperture photometry was corrected to total using the median of the PSFs
Correction factors are 2.2, 2.2, 2.9 and 3.3 for the 3.6, 4.5, 5.8 and 8.0μm bands.

SED fitting result: (FAST)

$M_\star = 10^{8.12^{+0.86}_{-0.28}} M_\odot \quad A_V = 0.2^{+0.1}_{-0.2}$ mag $\quad \log(\mathrm{age/yr}) = 7.1^{+1.0}_{-0.5}$



Color:

1. The [3.6] − [5.8] = 0.82 ± 0.27mag

→ $\mathrm{EW_0(H\alpha+[N\ II])} = 2328^{+1326}_{-1127}$ Å

→ $\mathrm{EW(H\alpha)} = 1960^{+1089}_{-927}$ Å

$\log(L_{\mathrm{H\alpha}}/[\mathrm{erg\,s^{-1}}]) = 42.62^{+0.15}_{-0.23}$ SFR=$36^{+14}_{-15} M_\odot \mathrm{yr}^{-1}$

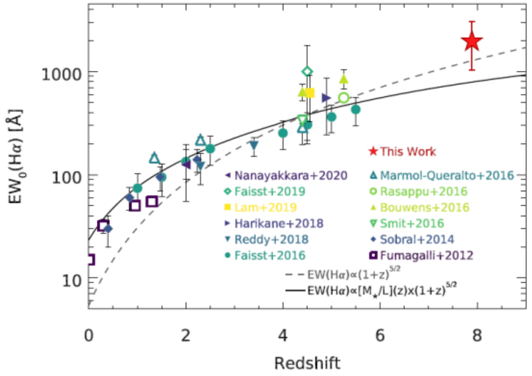
The first detection of Hα from broad-band photometry in normal star-forming galaxies at z > 6.5

2. The [3.6] − [4.5] = 0.54 ± 0.13mag → $\mathrm{EW_0([O\ III]+H\beta)} = 1006^{+230}_{-220}$ Å

Hα is very strong in these z~8 LBGs

3. The J − H = −0.10 ± 0.07mag → β ~ -2.4, blue UV slope

Evolution of the EW(Hα):

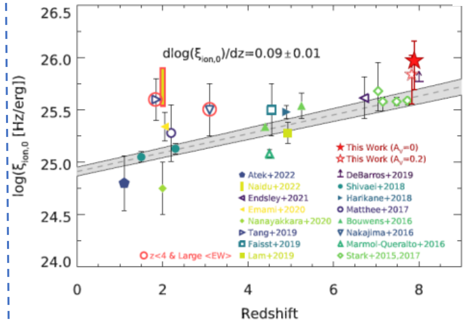


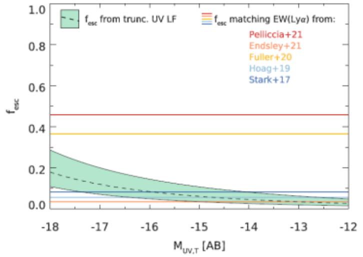
Overall agreement, but 1σ above the expected values from sSFR ∝ $(1+z)^{5/2}$ (Dekel et al. 2013) → Personal comment: bias from 10 very bright sources in the COSMOS and UDS fields

Implications on reionization:

$\xi_{ion} = \frac{\dot{N}_{ion}}{L_{UV}}\ [erg^{-1}\ Hz]$ $\quad L(H\alpha)\ [erg\ s^{-1}] = 1.36 \times (1 - f_{esc})\ 10^{-12}\ \dot{N}_{ion}\ [s^{-1}]$

$\dot{N}(H^0) = \rho_{UV} \xi_{ion} f_{esc}$ $\quad \mathrm{EW_0(Ly\alpha)_{intrinsic}} = 517^{+287}_{-244}$ Å





Escape fractions f_{esc} ~ 10% are sufficient for star-forming galaxies to fully ionize the neutral H at z ~ 8 through escaping LyC radiation.

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The star formation burstiness and ionizing efficiency of low-mass galaxies

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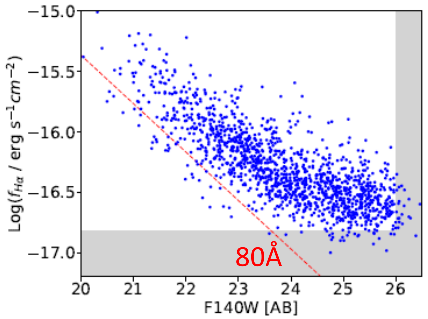
ABSTRACT

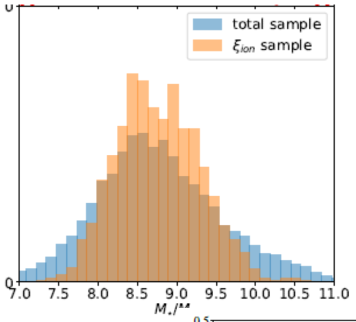
We investigate the burstiness of star formation and the ionizing efficiency of a large sample of galaxies at $0.7 < z < 1.5$ using *HST* grism spectroscopy and deep ultraviolet (UV) imaging in the GOODS-N and GOODS-S fields. The star formation history (SFH) in these strong emission line low-mass galaxies indicates an elevated star formation rate (SFR) based on the Hα emission line at a given stellar mass when compared to the standard main sequence. Moreover, when comparing the Hα and UV SFR indicators, we find that an excess in $SFR_{H\alpha}$ compared to SFR_{UV} is preferentially observed in lower-mass galaxies below 10^9 M$_\odot$, which are also the highest-EW galaxies. These findings suggest that the burstiness parameters of these strong emission line galaxies may differ from those inferred from hydrodynamical simulations and previous observations. For instance, a larger burstiness duty cycle would explain the observed $SFR_{H\alpha}$ excess. We also estimate the ionizing photon production efficiency ξ_{ion}, finding a median value of $\mathrm{Log}(\xi_{ion}/\mathrm{erg}^{-1}\ \mathrm{Hz}) = 24.80 \pm 0.26$ when adopting a Galactic dust correction for Hα and an SMC one for the stellar component. We observe an increase of ξ_{ion} with redshift, further confirming similar results at higher redshifts. We also find that ξ_{ion} is strongly correlated with $EW_{H\alpha}$, which provides an approach for deriving ξ_{ion} in early galaxies. We observe that lower-mass, lower-luminosity galaxies have a higher ξ_{ion}. Overall, these results provide further support for faint galaxies playing a major role in the reionization of the Universe.

Target: Galaxies at $0.7 < z < 1.5$ down to a stellar mass of $10^8 M_\odot$

Observation: 3D-HST (Spectroscopy, Momcheva et al. 2016)

HDUV legacy survey (UV imaging, Oesch et al. 2018)





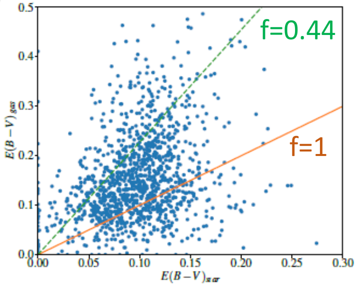
Dust attenuation correction:

Nebular, Domínguez et al. 2013:

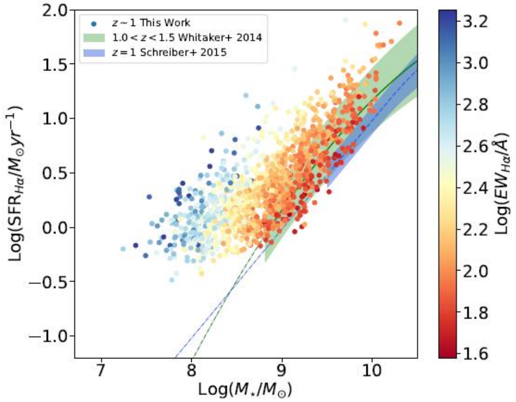
Balmer decrements vs. galaxy stellar mass

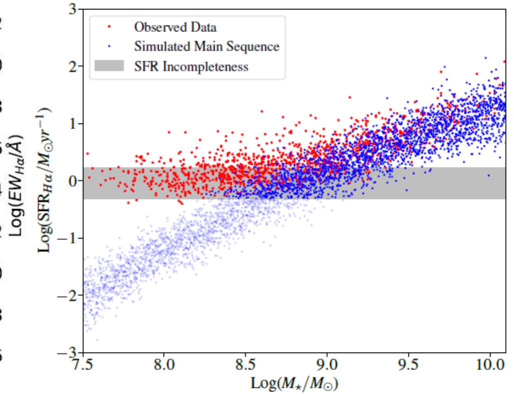
Stellar, UV slope β:

Assuming an intrinsic UV slope of β_0=-2.62 (Reddy et al. 2018a)



Star formation burstiness in low-mass galaxies:





SFMS:

The observed flattening of the slope towards low-mass galaxies is likely the result of Hα flux incompleteness. However, the deviation from the main sequence is much larger at low mass, as the highest EWHα values are observed at lower masses.

↔ Other UV or SED-based SFR indicators found no evidence of increasing scatter towards lower masses, nor evidence for an enhanced Hα luminosity compared to UV

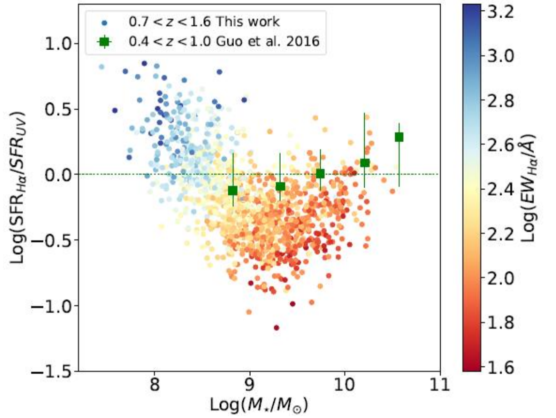
Hα v.s UV:

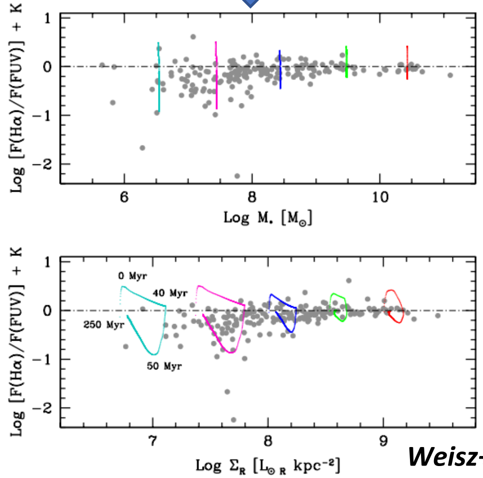
The SFR$H\alpha$/SFRUV ratio differ from the model in Weisz+12 with burst episodes lasting less than 10 Myr and a period of 250 Myr between bursts.

Also, high-EWHα galaxies have the highest SFR$H\alpha$/SFRUV

(i) a larger τ in the exponential SF; (ii) a shorter period between successive SF bursts.

(iii) IMF (binary stars, higher mass end)



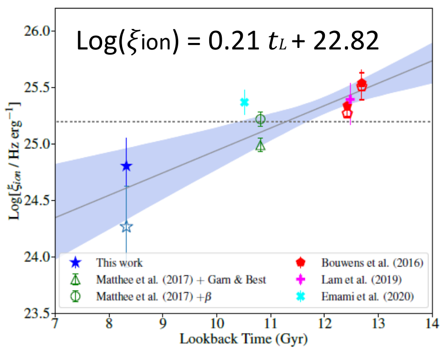


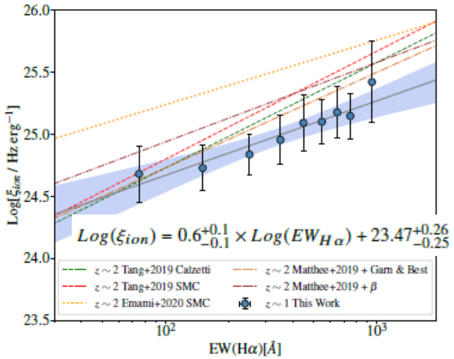
Weisz+12

ξ_{ion}: the production rate of Lyman-continuum photons (λ < 912 Å) per unit Ultra-Violet (UV) continuum luminosity measured at 1500 Å.

$$\xi_{ion} = \frac{\dot{N}_{ion}}{L_{UV}}\ [erg^{-1}\ Hz] \qquad L(H\alpha)\ [erg\ s^{-1}] = 1.36 \times (1 - f_{esc})\ 10^{-12}\ \dot{N}_{ion}\ [s^{-1}]$$

It is also found that ξion is anti-correlated with stellar mass and absolute UV magnitude





Other Recent studies: low-mass galaxies are more representative of the galaxy population at the epoch of reionization and take charge of reionization.

Implication:

The classical value of Log(ξion) = 25.2, based on massive galaxies, may not hold in low-mass galaxies.

Variations of the escape fraction in low-mass galaxies, driven by supernovae explosions of massive stars