Detection of Lyman continuum emission from distant star-forming galaxies

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Introduction

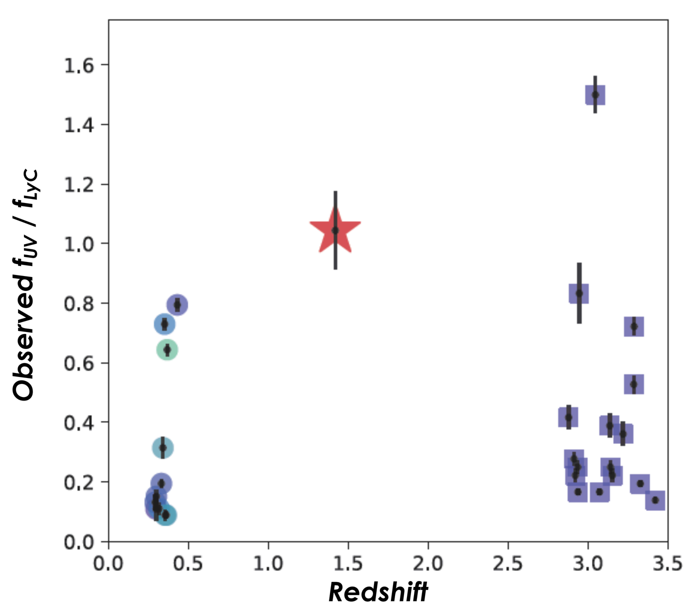
How was the universe reionized?

Approximately 1Gyr after the Big Bang, a primary phase transition occurred in the universe: the first atoms to form in the universe, neutral hydrogen, were ionized. Astronomers are uncertain of the source(s) of this ionizing radiation (i.e., Lyman Continuum, or LyC) during this epoch of reionization and continues to the present day. In the low-redshift universe, quasars and AGN are alone sufficient to maintain the ionized intergalactic medium (IGM), but in the early universe it is often assumed that the first stars in galaxies were sufficiently luminous and numerous to initiate reionization. However, it is impossible to directly confirm this assumption because the neutral hydrogen along the line of sight to these high redshift sources attenuates any escaping LyC emission.

The Need for Low-redshift Analogs

In lieu of direct detections, astronomers search for low and intermediate redshift *analogs* of the high redshift sources of LyC photons. To date, a small but growing number of low-redshift analogs have been identified but at higher redshift, when galaxies are intrinsically more gas-rich, star-forming, and lower metallicity, few been identified in the redshift range, 1<z<3 (Fig. 1), *Observations of escaping LyC in these intermediate-redshift analogs are essential for determining the physical characteristics of galaxies that could drive reionization.*

Figure 1: Despite decades of efforts with dedicated surveys, surprisingly few LyC-emitting star-forming galaxies (SFG) have been observed. Recently, Saha+2020 [1] discovered the first z~1 LyC Leaker. At right (red star) the observed UV-LyC flux observed for this source is presented in the context of *all* published LyC leakers in the literature. *Note the dearth of sources identified in the range 0.5<z<3.0.*



Constraining reionization with HST

The Hubble Space Telescope (HST) is the most advanced UV telescope currently in operation and the *only* space-based telescope capable of making direct detections of escaping LyC from 1<z<3 galaxies. Furthermore, the superior UV-optical imaging resolution of HST makes an ideal observatory with which to determine the way star-formation can produce the necessary conditions to enable LyC photons to escape into the IGM. Recently, as part of a large international team, the co-authors were awarded the largest (~3 weeks) proposal ever accepted to study LyC escape from 1<z<3 galaxies (UVCANDELS).

The program will observe 5 deep fields within the CANDELS+GOODS footprint using the LyC-sensitive WFC3/UV F275W. Considerable high-resolution data exists in these deep fields, including both HST optical and near-IR imaging and spectroscopy, and we will use these data to pre-select candidate LyC leakers. At present, only ~20% fraction of the total UVCANDELS have been obtained by HST (Epoch 1 and 2 in GOODS-North) and here, we report initial results in the search for escaping LyC using these data.

Selecting LyC-emitting Analogs

We used low-resolution grism spectroscopy (3DHST) and imaging (CANDELS) data to select two unique samples of SFGs. These criteria, and their scientific motivation, are defined as follows:

Primary Sample: SFGs were selected at $2.2 \leq z \leq 2.31$(and confirmed by the presence of nebular emission line(s); $EW_{[OII]} \geq 40$Å).At this redshift, F275W is *exclusively* sensitive to LyC emission. Furthermore, these SFGs were selected [OIII4959+5007Å]/[OII3727+3729Å]>5 [2], indicating they are currently undergoing a strong star-formation episode.

Secondary Sample: Redshift selection was extended as selected to include all SFGs at $1.9 \leq z < 3.0$ for which a single ($EW_{[OII]} \geq 40$) emission could be obtained from 3DHST.

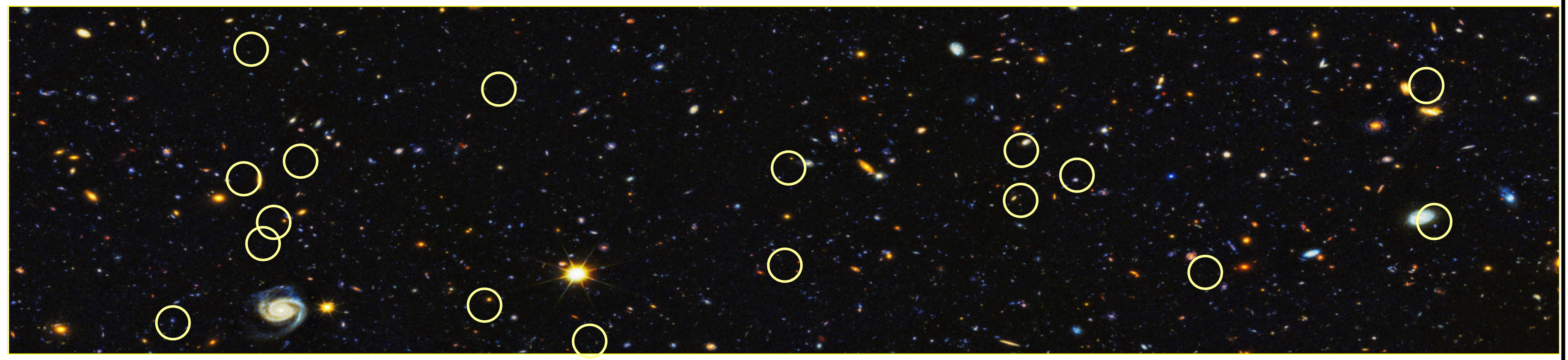


Fig. 2: UV-optical-near IR GOODS-North mosaic. Positions of a fraction of sample SFGs for are indicated in the field (adapted from HDUV) as yellow circles. Note these objects blue colors, clump-dominated or disturbed morphologies indicating or associated with active star formation.

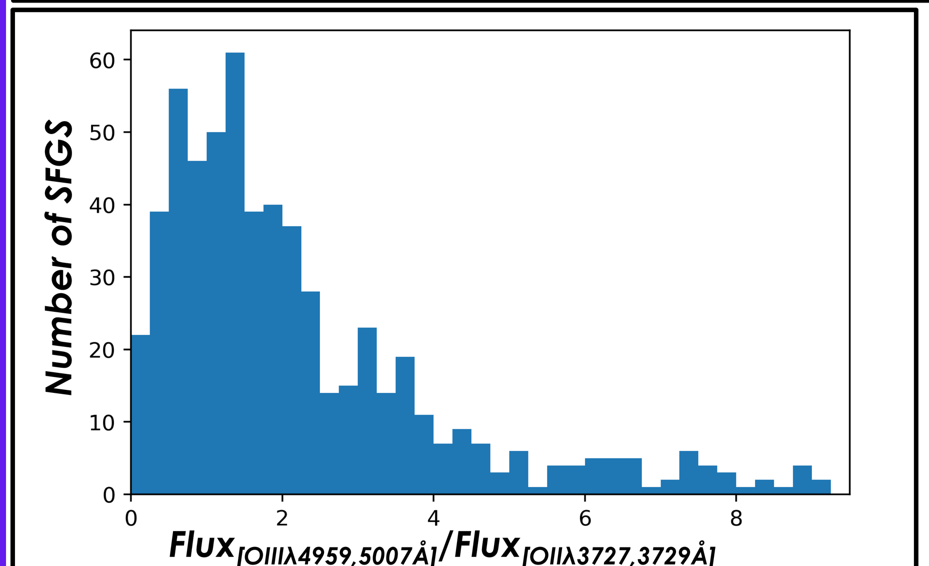


Fig. 3: [OIII]/[OII] 3DHST grism spectroscopy provides measurements of multiple strong nebular emission lines useful for selecting SFGs. The mean ratio peaks at ~1, but note the long tail towards more extreme star-formation.

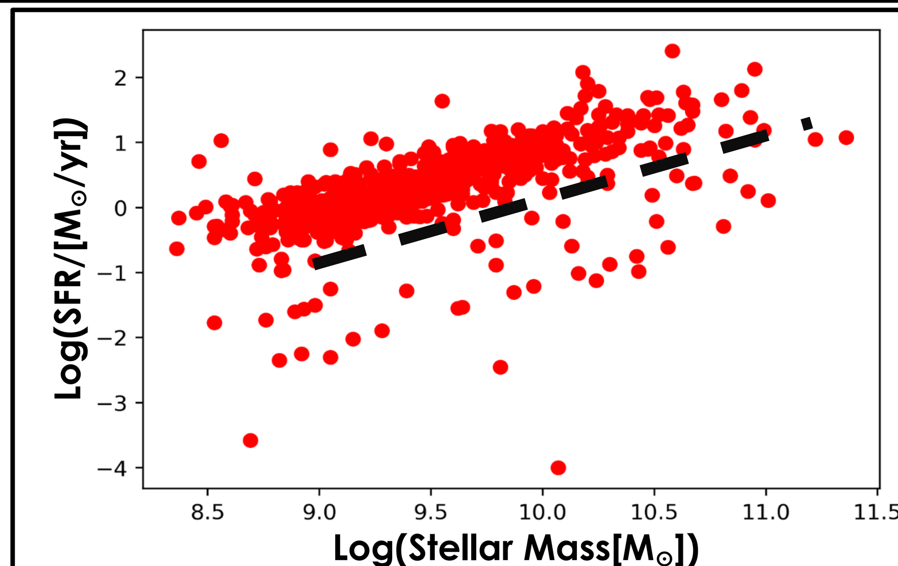


Fig. 4: SFR-Stellar Mass The secondary sample includes actively star-forming galaxies (red points), at an elevated rate relative to "star-forming main sequence" measured for z~2 galaxies (dashed, [3]).

Non-detection of LyC in extreme SFGs

In theory, extreme starbursts are the best candidates for reionization: they produce numerous LyC photons ($N \sim 10^{54} s^{-1}$ [4]), and strong feedback *should* clear pathways to allow LyC to escape into the IGM. We detected no significant LyC (F275W) flux from these rare sources in the field. Here we report the *relative escape fraction* for these sources, defined as:

$$f_{\rm esc,rel}^{\rm LyC} = \frac{(L_{\rm UV}/L_{\rm LyC})_{\rm int}}{(L_{\rm UV}/L_{\rm LyC})_{\rm obs}} \cdot \exp[\tau_{\rm IGM}],$$

We report measured limits to $f_{esc,rel}$, assuming a uniform IGM transmission (T~0.5%) and intrinsic UV-LyC ratio ($L_{UV}/L_{LyC} \sim 3$).

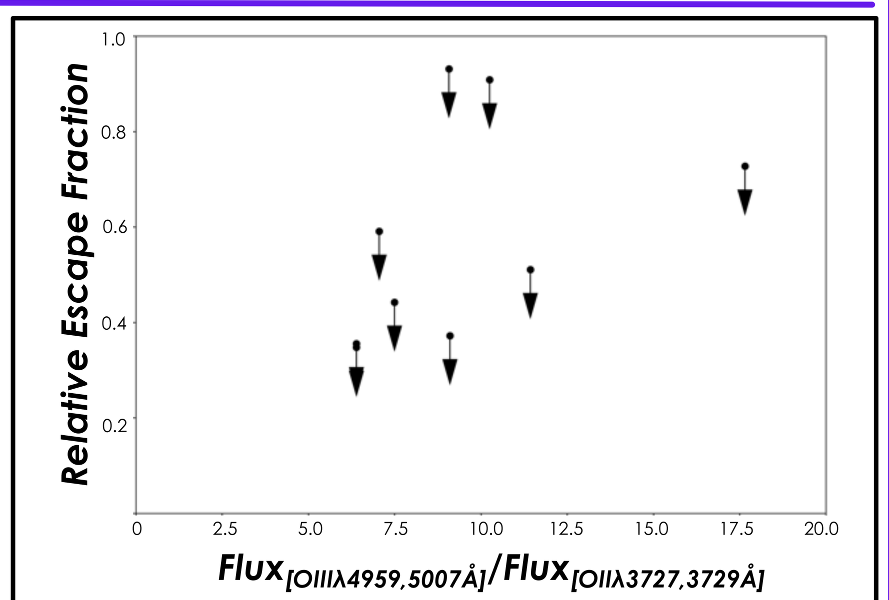


Fig. 5: UVCANDELS $f_{esc,rel}$ upper limits Of the 10 [OIII]/[OII]>5 SFGs in UVCANDELS, *none are individually detected as LyC leakers.*

Potential LyC Leakers

Recent results from the LZLCS survey suggests that LyC leakage is not exclusively associated with extreme star-formation; many galaxies could be detected with LyC *if* the channels through which this emission are preferentially oriented along the line of sight to the observers. To test this, we investigated a larger secondary sample of potential LyC leakers with weaker star formation properties. *For the first time, we have detected possible LyC emission from 12/609 sources at this redshift.* Note that UVCANDELS F275W imaging is not exclusively sensitive to LyC; non-ionizing emission may contaminate the LyC photometry. Accounting for this contamination in order to constrain $f_{esc,rel}$ will be completed in future work. In Figure 6 we present four of these new candidate LyC leakers.

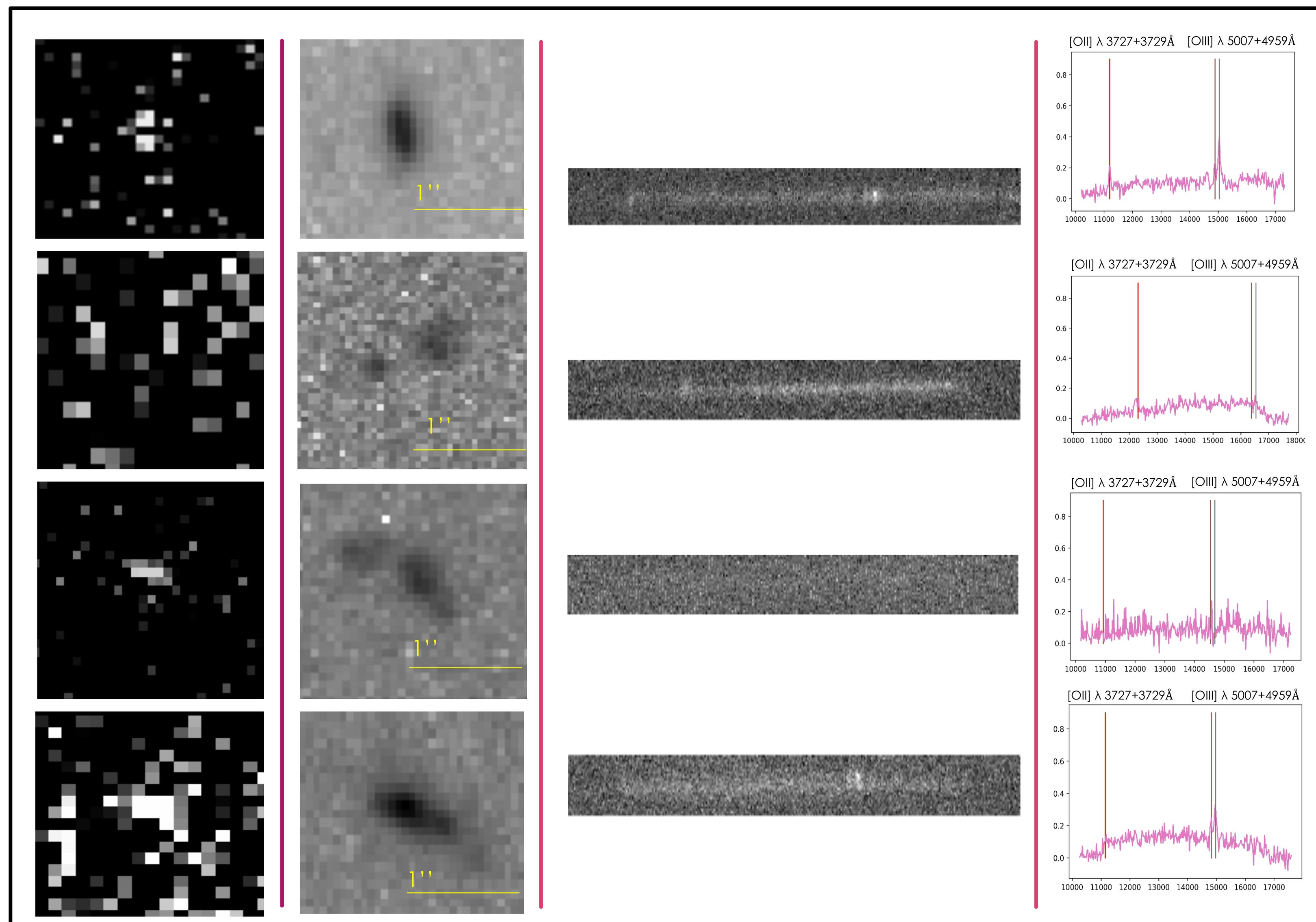


Figure 6: Imaging and Spectroscopy of LyC leaking candidates From left to right, we show in Column 1 and 2 the UVCANDELS F275W and CANDELS F606W images of four candidates, respectively. In Columns 3 and 4, 2D and 1D spectra are provided. The position of [OII] and [OIII] lines are overplotted on the 1D spectrum for reference.

Discussion

We have completed a preliminary survey of SFGs observed in the UVCANDELS GOODS-North field to identify low-redshift analogs to the sources of reionization. We summarize our conclusions from this novel analysis below:

- **We inspected ~610 SFGs using novel UVCANDELS F275W imaging of GOODS-North.** The preselection of the SFGs were informed by contemporary surveys of low-redshift LyC leakers. Future UVCANDELS data will increase the sample size to ~2200.
- **We find individual z~2 extreme SFGs ($f_{[OIII]}/f_{[OII]} > 5$) are *not* leaking LyC (f_{esc}<~30%).** The completeness limits of the UVCANDELS survey are insufficient to rule out a weaker contribution, but this results agrees with earlier work [5] suggesting that strong nebular emission is likely to be necessary, but not sufficient, for LyC escape.
- **We have identified a new population of 12 candidate LyC leakers.** Future work incorporating ground [6] and space-based UV imaging (cf. [7]) will be used to constrain the escape fraction of these sources and the contribution of their analogs to reionization.

References

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[4] Rutkowski, M.J. et al., ApJ, 819, 81
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