Reconstructing the Observed Ionizing Photon Production Efficiency at $z \sim 2$ Using Stellar Population Models

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Abstract

- ξ_{ion}: ionizing photon production efficiency

  A key to the completion of the reionization of the Universe
- KECK/MOSFIRE (ZFIRE) and ZFOURGE
- 130 Hα emitters at z ~ 2

  Mass: $9.0 < \log(M_*/M_\odot) < 11.5$

  Ionizing efficiency (median): $\log(\xi_{ion}[Hz/erg]) = 24.8 \pm 0.5$ (a typical value at z ~ 2 Universe)
- BPASSv2.2.1 and Starburst99 stellar population models
  - Model galaxies with same degree of ionizing efficiency (< 25.0) and parametric star-formation-histories (SFHs) have low Hα EW and redder colors
  - If star-bursts were introduced to SFHs make up this dispersion but random distribution of star-bursts in evolutionary time are unlikely to explain the observed distribution
- 1. Our observed sample is specially selected based on their past SFH
- 2. Stellar models require additional mechanisms

Introduction

- The reionization of the Universe starts at z = 20 ~ 6

  ↖ The escape of ionizing photons (Lyman continuum leakage) from young stars

- ξ_{ion}: the production rate of Lyman-continuum photons (λphoton < 912 Å) per unit Ultra-Violet (UV) continuum luminosity measured at 1500 Å.
  - A measure of hydrogen ionizing to non-ionizing photon production rates

    → the ratio of massive to less massive stars in stellar populations

- ξ_{ion}+ UV luminosity density + escape fraction of ionizing photons

  → picture of how galaxies drove the reionization of the Universe

- Direct measurement of ξ_{ion} ×, alternatively the rest-UV continuum slope (β) → ξ_{ion}

  * β is also sensitive to dust, metallicity, and SFHs

- Dust free Case B recombination:

  Hα emission ∝ the number of Lyman continuum photons

2 Problems:

- Hα contaminated by [NII]

  → empirical or model calibrations (local) ↔ not suitable at $z > 2$ (line ratios evolving)

- Accurate dust corrections to UV and nebular Hα flux require a combination of multi-wavelength photometry and Balmer line ratios

- → Spectroscopic measurements are crucial

Sample Selection and Results

1. Survey description

- ZFIRE-COSMOS, all 134 (130) galaxies with Hα detections (S/N > 5)
  - 1.90 < z < 2.67
  - 4 AGN contamination, $\log(M_*/M_\odot)$ > 9.3, Ks < 24.11, no biases compare to parent ZFOURGE sample.

2. ξ_{ion} computation and dust corrections

- $\xi_{ion} = \frac{N(H)}{L_{UV}}\ [Hz/erg]$
  - N(H) is the production rate of H ionizing photons per s
  - L_{UV} is the intrinsic UV continuum luminosity at 1500 Å.
- L_{UV} is derived from ZFOURGE photometry using FAST++ (Schreiber et al. 2018b)
  - A power law function at 1400—1600 Å with slope β
  - BC03 + Chabrier03 + Truncated SFH (constant + exponentially declining) + Calzetti00 + Z=0.004 ~ 0.02
- N(H): dust free Case B, $n_e = 10^3 cm^{-3}$, T = 10000K [No escape of ionizing photons]

$$N(H) = \frac{L(H\alpha)}{C_B}[s^{-1}] \qquad C_B = 1.36 \times 10^{-12} erg$$

- Balmer decrement: stack MOSFIRE H band observation or Hβ detections

Set Name	N of galaxies	UV luminosity dust correction law	Hα luminosity dust correction law	Balmer decrement from	Median $\log_{10}(\xi_{ion}$ [Hz/erg])
Set A	130	Calzetti et al. (2000)	Cardelli et al. (1989)	Hα SFR stacks	24.83 ± 0.49
Set A	130	Calzetti et al. (2000)	Cardelli et al. (1989)	β stacks	24.77 ± 0.43
Set A	130	Calzetti et al. (2000)	Cardelli et al. (1989)	UV magnitude stacks	24.73 ± 0.49
Set A	130	Calzetti et al. (2000)	Cardelli et al. (1989)	Stellar mass stacks	24.79 ± 0.44
Set A	130	Calzetti et al. (2000)	Cardelli et al. (1989)	[O III]λ5007/Hα stacks	24.76 ± 0.45
Set A	130	Calzetti et al. (2000)	Cardelli et al. (1989)	UV+IR SFR stacks	24.68 ± 0.46
Set B	49	Calzetti et al. (2000)	Cardelli et al. (1989)	Individual observations	24.79 ± 0.58

3. The observed distribution of ξ_{ion}

- A slight bias towards low ξ_{ion} compared to Shivaei + 2018 (MOSDEF)
- 80% of the sample fall below log10(ξ_{ion} [Hz/erg]) = 25.2 (Robertson + 2013, reionize the Universe by z ~ 6)
- Brown shading: BPASS model, with $Z_{\odot}$, binary star constant SFH

[differences in the stellar population/ISM properties, calibration uncertainties, and/or the choice of the dust attenuation curve]

- Compare to other research

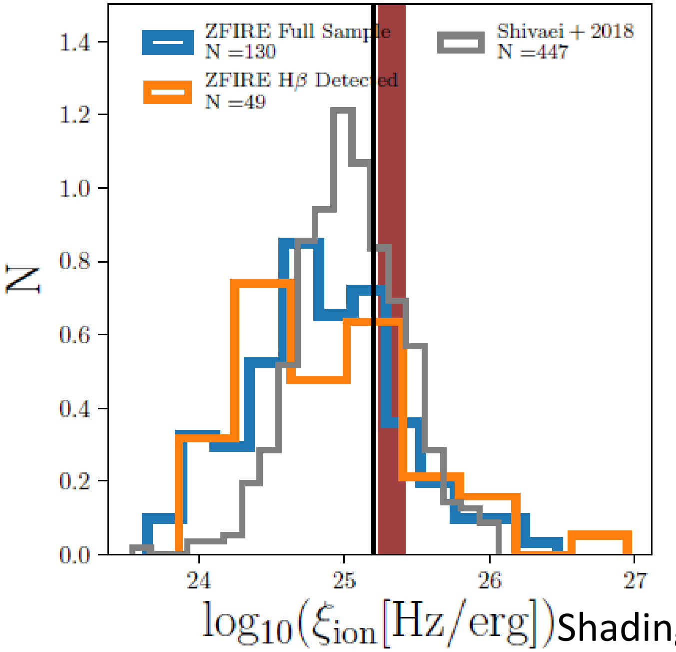
Tang + 2016: Low mass [OIII] emit

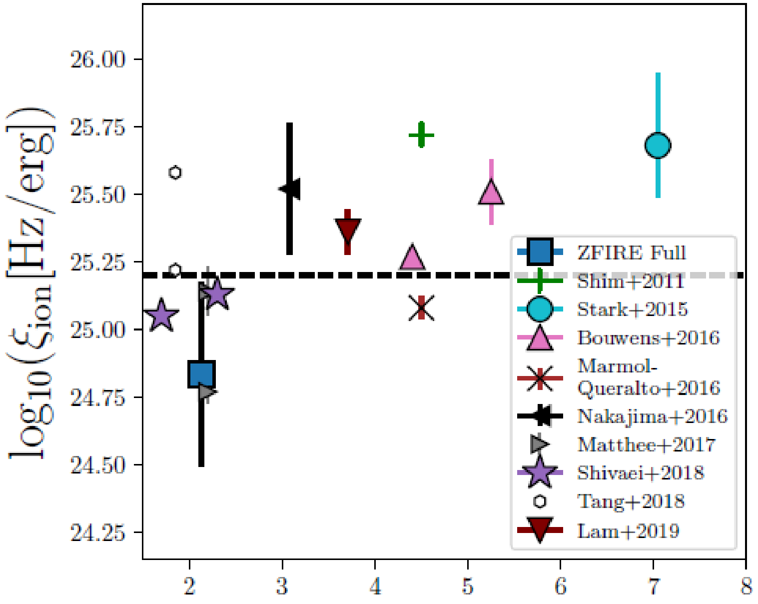
Nakajima + 2018: Lyα emitters

- Lower than other z > 4 surveys

A redshift evolution

Biases in sample selection





Shading: BPASSv2.2.1 binary stellar population model

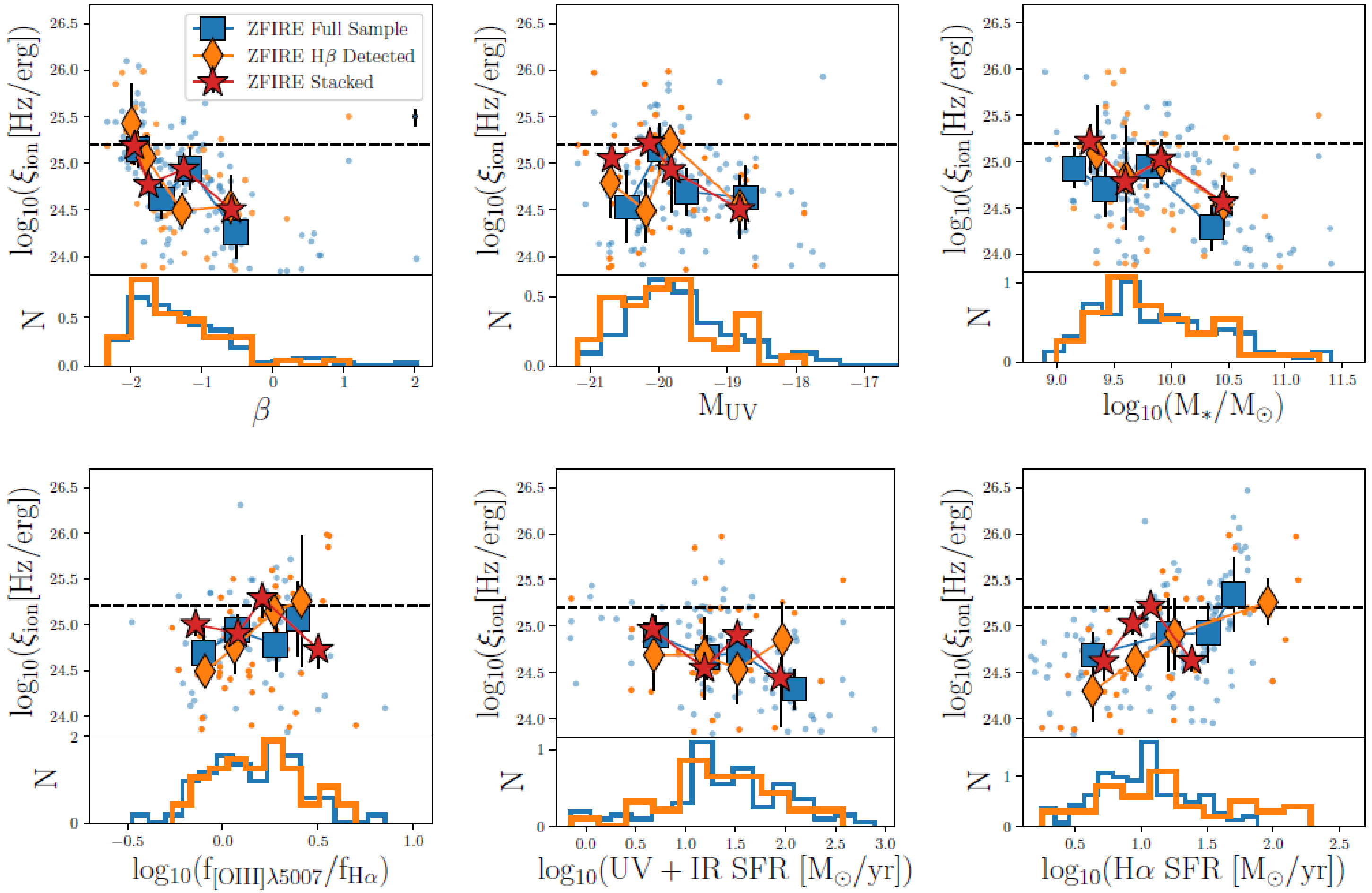
Analysis

1. Observed correlation of ξ_{ion}

   (a) A moderate negative correlation between β and ξ_{ion}
   (Such a trend has also been observed at z ~ 2 and at z ~ 4)

   (b) No correlation between Muv and ξ_{ion}.

   (c) A negative correlation between stellar mass and ξ_{ion}
   But cannot make strong conclusions on the excess of ξ_{ion} in the lowest mass bin



(d) [OIII]/Hα: 58 galaxies with [OIII] (S/N>3), Set B galaxies (detected Hβ) show a moderate positive correlation of ξ_{ion} with [OIII]5007/Hα ratio. Galaxies with higher ionization parameters tend to have higher ξ_{ion}

(e) UV+IR SFR: Negative correlation in set A galaxies but no correlation in set B galaxies

(f) Hα SFR: Both set A and B galaxies show a statistically significant moderate positive correlation

2. Combining ξ_{ion} with Hα EW and optical colors

- Diagnostics of sSFR

- Hα lines: young O-type stars with M > 20M⊙ Hα continuum: Red giant stars with 0.7 < M < 3
  UV continuum: O and B type stars with M > 3M⊙ [340]—[550] color: bluer to redder stars
- → Hα EW, ξ_{ion}, [340]—[550] color are sensitive to the SFH/age of a stellar population and may make stronger constraints on the nature of the stellar populations.

- 77 galaxies without contamination from surrounding objects
- Using ZFOURGE photometry to calculate Hα EW (Q: Why not directly use the MOSFIRE K band?)
  - Compare with 38 galaxies with confident K band continuums → $\Delta \log_{10}(EW) = -0.02$

2.1 Simple parametric SFHs using BPASS stellar population models

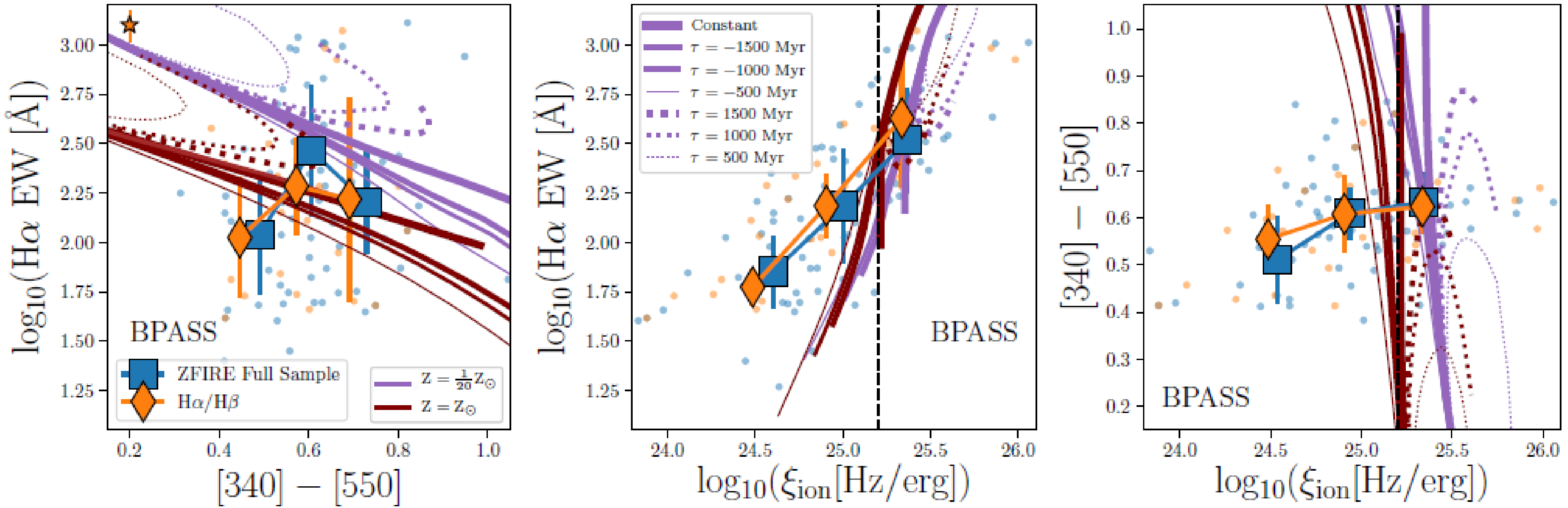
Figure (a): there is a fraction of galaxies with lower Hα EWs and/or bluer optical colors than what is expected from the BPASS models. [explained by random star-bursts over smooth SFHs]

Figure (b): galaxies with higher Hα EWs show higher ξ_{ion} values (diverge from Hα EW < 2.25Å)

Figure (c): galaxies with higher ξ_{ion} show slightly redder optical colors → high ξ_{ion} system dominated by the older populations → the relative strength of the star-burst compared to the past SFH should be low (if high ξ_{ion} caused by star-burst)

Figure (b) and (c): the predicted ξ_{ion} values are consistently too high for the observed Hα EW and rest-frame optical colors

- Simple parametric SFHs on average is accurate → Star-burst contribution? (z ~ 2)



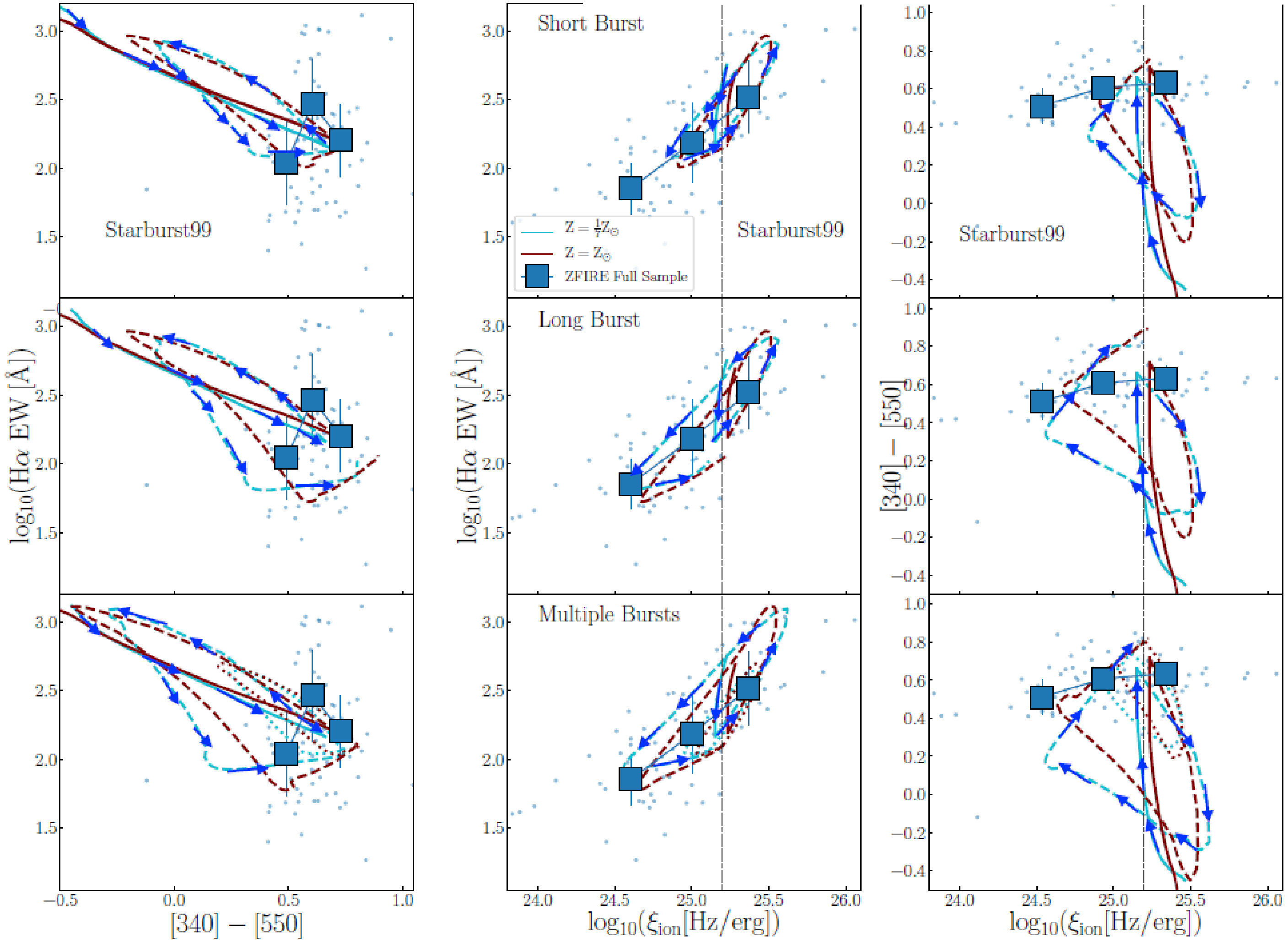
2.2 Star bursts using Starburst99 stellar population models

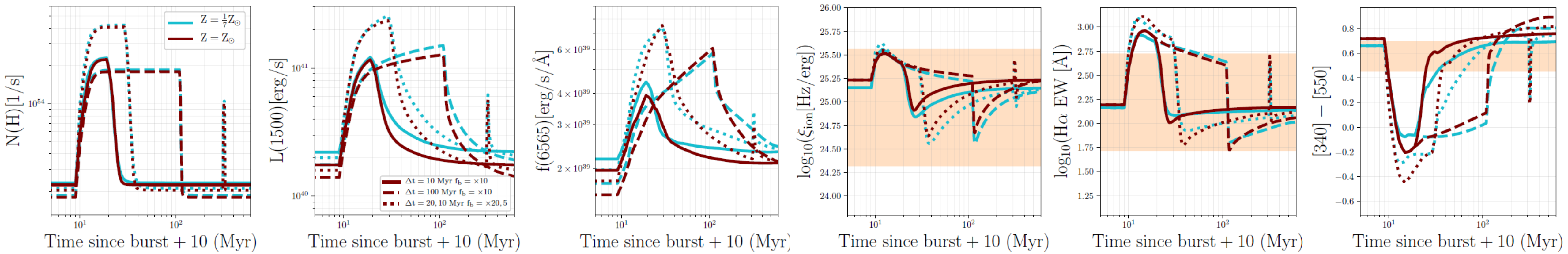
Name	Burst Time[a] (Myr)	Burst Strength	Burst Length (Myr)
Short	2500	×10	10
Long	2500	×10	100
Multiple	2500	×20	20
	2800	×5	10
Simulations[b]	200-3000	×5 − 100	10 − 100

[a] Defined from the onset of star-formation.
[b] 2 − 10 bursts are chosen randomly within these parameters to construct the SFH.

3 different burst scenarios

- Short star-bursts fail to reproduce the observed redder colors of the galaxies.
- Long lived bursts produce post starburst tracks that could explain a majority of galaxies with low ξ_{ion} and low Hα EWs.
- By invoking star-bursts with varying strengths and lengths, the observed distribution at z ~ 2 could be reproduced.





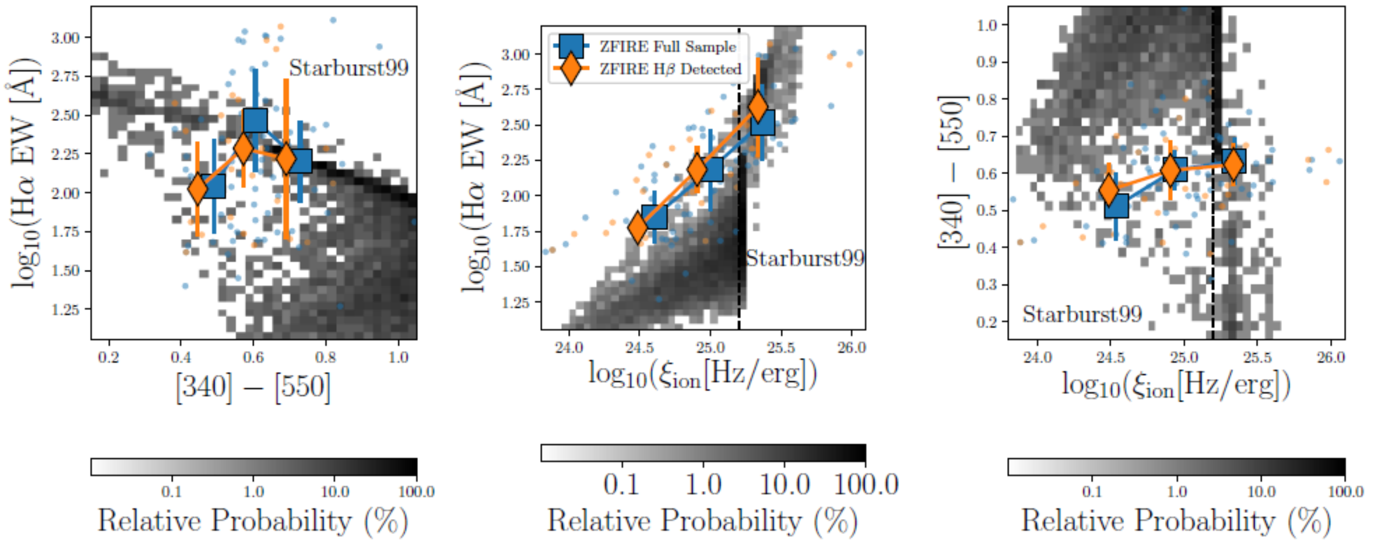
Parameter change:

- The Hα EW and ξ_{ion} increase rapidly to their maximum values within ~ 3Myr, while UV luminosity takes ~ 10 Myr to stabilize.
- Hα timescale: ~ 10 Myr, UV timescale: ~ 100 Myr, 6565Å continuum timescales: few 100 Myr
- The [340]—[550] color: an almost instantaneous shift to blue colors at the onset of the starburst, then turn redder within a very short time-scale in the post star-burst phase.
- Metallicity have a weak influence

- Starburst ↔ Observation
  - 10000 sample simulation

  It is unlikely to preferentially observe galaxies with high Hα EWs, low ξ_{ion}, and blue optical colors.

- Future work: SED-fitting based SFH



Discussion

1. Observed correlations of ξ_{ion}

- Enhancement of ξ_{ion} when β < -1.5, reach $\log(\xi_{ion}[Hz/erg]) = 25.2$ at β = -2
- Expected an continuous enhancement for galaxies with β < -2 (z > 6 galaxies have bluer UV slopes)
- An evolution of ξ_{ion} with UV magnitude is currently not favored $\not\rightarrow$ faint UV sources provide an additional contribution to reionization through elevated production of ionizing photons

  (UV Bright V.S. UV faint contribute to the reionization of the universe)
- Stellar mass: no constraints on whether there is an enhancement of ξ_{ion} at $\log(M_*/M_\odot)$ < 9.0
- Shivaei + 2018, high R32, high [OIII]/Hβ, low N[II]/Hα (high Ionizing parameter, low metallicity) → high ξ_{ion}, can be explained by current physics
- ξ_{ion} is a proxy of sSFR. It is reasonable that ξ_{ion} shows a flat distribution with the SFR (SFMS)

- Additional discussion: dusty star-forming system ?

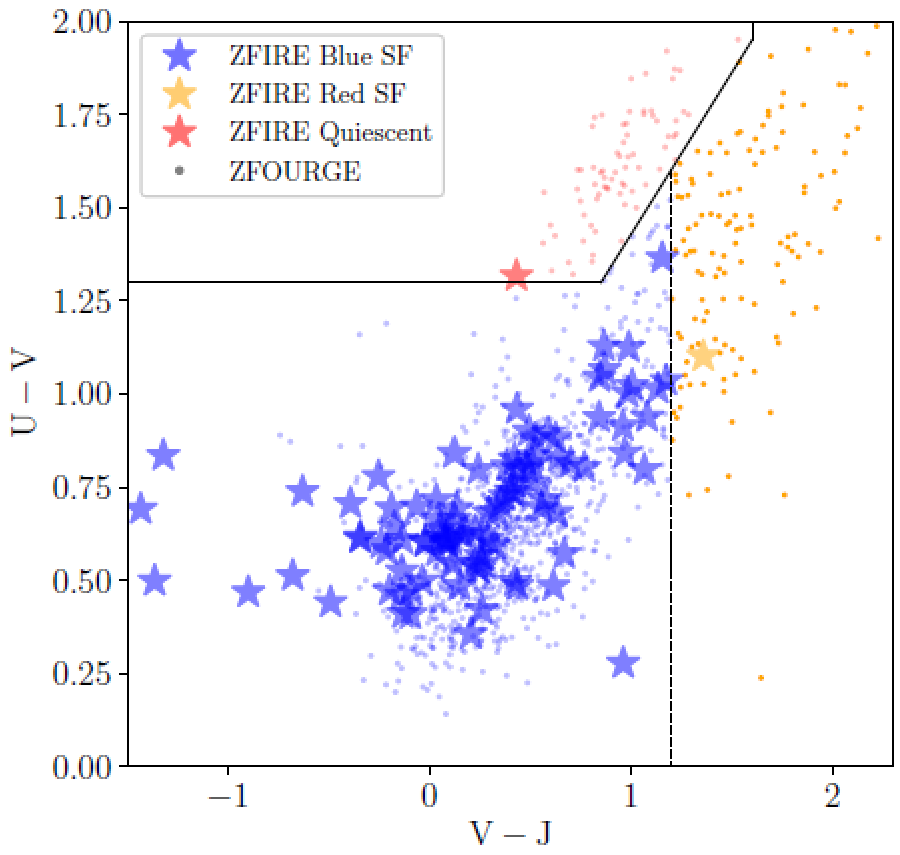
2. The completeness of our observed sample

- EAZY derived UVJ color diagram (rest-frame)

The majority of galaxies used in this analysis are blue star-forming systems.

The lack of red star-forming galaxies in sample may translate to a lack of galaxies with low sSFRs. (Low Hα EW and Low ξ_{ion}). Still not able to explain the trends in model.

In this paper, can rule out selection effects (?)



3. Dust related uncertainties

- $\sim$ 84% lower than $\log(\xi_{ion}[Hz/erg]) = 25.2$
- Similar to Shivaei + 18

- The choice of the dust attenuation curve (< 0.2 dex errors)
- Nebular and stellar components (extra extinction)

- Need multiple Balmer emission line ratios

4. z evolution of ξ_{ion}

- z ~ 2 measurements are ~ 0.5 dex smaller than that of z ~ 4 → redshift evolution

→ Exponentially rising SFHs or star-burst at z ~ 4; Exponentially declining SFHs at z ~ 2

Starburst effect ? (would drive ξ_{ion} to increase rapidly, but…)

- Model: the time window in which ξ_{ion} reach $\log(\xi_{ion}[Hz/erg])$ > 25.5 is very short

4.1 Selection effects in high-z ξ_{ion} estimates

- Difference in selection between z ~ 2 and z > 4 (Shim + 11, Bouwens + 16)
- z ~ 7, extreme [OIII]+Hβ emitters → high ξ_{ion} (not typical)
- z > 4 photometry, bias to strong Hα+[NII] (Spitzer/IRAC).

    Hard ionizing radiation → contamination from [NII] → Overestimate of Hα
- z > 4 spectroscopy, selection bias
- Need deeper spectroscopic explorations of the z > 4 Universe

4.2 Expectation from current stellar population models

- Kewley et al. 2019 current limitations of stellar population models.
- X-binaries and stripped stars increase the production of ionizing photons → such phenomenon are important in high-z galaxies
- Shallower slopes at the high mass end of IMF at high-z universe.

→ ξ_{ion} is reasonable to systematically increase with redshift

Model differences

- BPASS models show a higher ξ_{ion} at fixed metallicity compared to Starburst99 models
- BPASS: low Z → high ξ_{ion}
- Starburst99: low Z → low ξ_{ion}. (W-F stars effects, BPASS models even have W-F stars at low metallcity)