THE MOSDEF SURVEY: DIRECT OBSERVATIONAL CONSTRAINTS ON THE IONIZING PHOTON PRODUCTION EFFICIENCY, ξ_{ion}, AT $z \sim 2$

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Abstract

- 674 galaxies, MOSDEF spectroscopy: Hα, Hβ, photometry: UV
- ξ_{ion} at z = 1.4 — 2.6, $\log(\xi_{ion}[Hz/erg]) = 25.06$ (25.34)
- Scatter: 0.28 dex
  - Observational uncertainties
  - Dust extinction
  - Galaxy-to-galaxy variations in stellar populations: IMF, stellar metallicity, star burst…
- ξ_{ion} ↑, higher ionization states, lower oxygen abundances, larger β
- ξ_{ion} $\nleftrightarrow$ BPT diagram
- If z > 6 galaxies keep same properties, A lower Lyman-continuum escape fraction is required.
- UV dust extinction can cause ~ 0.3 dex uncertainty in ξ_{ion}

Introduction

- Study of galaxy evolution ↔ Massive stars and surrounding gas
- Galaxy hydrogen-ionizing photon production rate → SFR, gas metallicity
- ξ_{ion}: The production rate of Lyman-continuum (LyC) ionizing photons per unit nonionizing UV continuum luminosity (1500 Å)
  - Ionizing photon production rate → metallicity, binarity, rotation
  - Most massive stars to less massive stars → IMF, SFH, age of the galaxy
- From ξ_{ion}, increase understanding of massive stellar population, galaxy evolution, stellar population synthesis (SPS) models.
- Determine whether star-forming galaxies are able to reionize the universe.
- Measurement of ξ_{ion}
  - 1. Indirect: SPS models → β- ξ_{ion} relations. $\log(\xi_{ion}[Hz/erg]) \sim 25.2 - 25.3$
  - 2. Direct: UV metal lines, f_{900}/f_{1500} (Lack of sample)
  - 3. Hα line: recombination

    Defects: Bouwens + 2016, Nakajima + 2016, Matthee + 2017, mostly using single line and do not consider dust obscuration.

  → Large and representative samples with spectroscopic Hα and Hβ observations to directly measure nebular line luminosity and properly correct for dust.

- MOSDEF: 673 galaxies at $1.37 < z < 2.61$
  - Hα, Hβ, [OII], [OIII], [NII]…
- 3D-HST photometry data

Goals:

- 1. Provide an observationally constrained canonical ξ_{ion} value for typical star-forming galaxies at z$\sim$2
- 2. To explore the origin of the observed scatter in the ξ_{ion} distribution of galaxies
- 3. To investigate the variations of ξ_{ion} with galaxy global properties, ISM characteristics, and redshift.

Data and Measurements

1. The MOSDEF survey (Kriek et al. 2015)

    4.5 yrs NIR spectroscopic survey

    ~ 1500 galaxies and AGNs in 5 CANDELS field

    H = 24.0 (z = 1.37—1.70), 24.5 (z = 2.09—2.61), 25.0 (z = 2.95—3.80)

2. Line Luminosities and Nebular dust correction
    - Emission line fluxes: Gaussian fitting
    - Silt loss: a standard star and match with 3D-HST
    - 673 galaxies with 3σ Hα detection and among them 451 have 3σ Hβ detection
    - Balmer decrement → dust attenuation

3. SED fitting and Stellar Dust Correction
    - Corrected for emission line contamination by MOSDEF spectra
    - BC03 models, Chabrier03, exponentially rising SFH (best for galaxies at z ~ 2), $Z = Z_{\odot}$ $(0.2 Z_{\odot})$
      Calzetti 2000 curve (SMC curve (Gordon et al. 2003))
    - SED fitting → $f_{v}(1500\text{Å}), E(B-V)$, UV slope (power-law function at 1268—2580 Å)

Inferring ξion

- $\xi_{ion} = \frac{N(H^0)}{L_{UV}}\ [s^{-1}/ergs^{-1}Hz^{-1}]$
- Conversion from Hα luminosity to $N(H^0)$
  - The rate of recombination balances the rate of ionizing photons
  - Related to election density and gas temperature
  - $N(H^0)[S^{-1}] = \frac{1}{1.36} \times 10^{12} L(H\alpha)\ [erg\ s^{-1}]$
  - Assumption 1: photoelectric absorption dominates the depletion of ionizing photons

    → negligible dust attenuation of ionizing photons internal to H II regions
  - Assumption 2: Hα-derived production rate of ionizing photons is the escape fraction of LyC photons (f_{esc}). A larger intrinsic ξ_{ion} (increase by 1/(1—f_{esc})).

    f_{esc} is calculated by E(B-V). The least dusty system (E(B-V) = 0) have f_{esc} = 0.3 (maximum)

    Average: f_{esc} = 0.04 (0.09) Calzetti + 2000 (SMC)

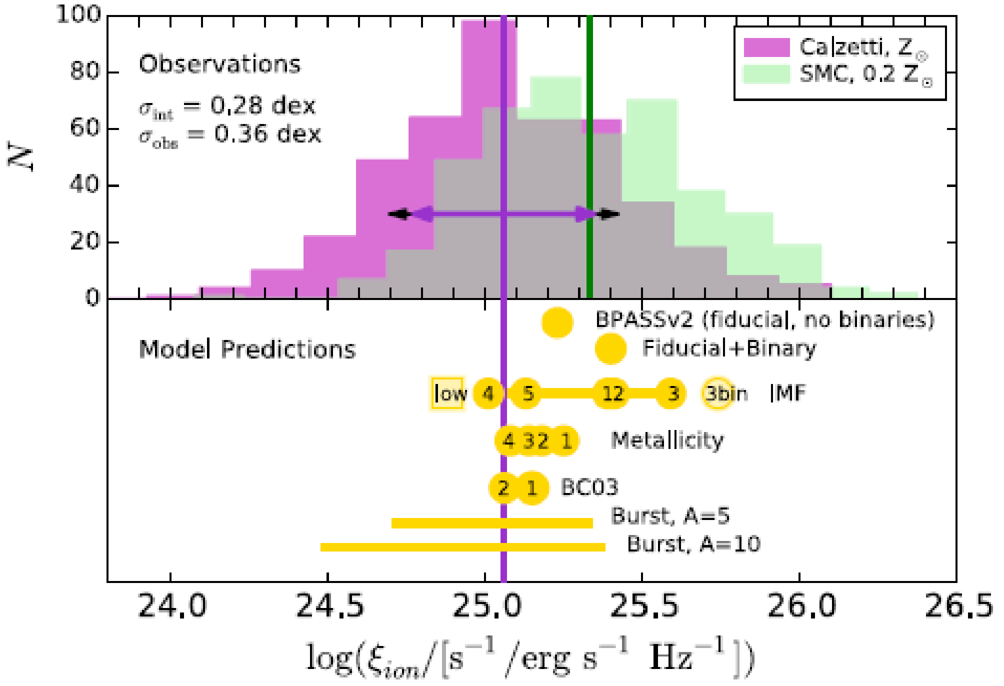
    f_{esc} do not significantly alter the result of this paper
- Large uncertainty: dust corrections to Hα and UV

Composite Measurements

- Hβ-undetected galaxies
  - Stacking technique with a wavelength grid $\delta\lambda = 0.5\ \text{Å}$
  - Hα, Hβ, [OIII], [NII]: single Gaussian profiles, [OII]: double Gaussian profiles
  - Initially normalizing individual spectra to their Hα/[OIII] luminosities, then create the composite spectrum from the normalized spectra

    → <Hα/Hβ>, <Hα/UV>, <[OIII]/Hβ>, <[OIII]/[OII]>

ξ_{ion} Distribution



Result:

Hα+Hβ: $\log(\xi_{ion}[Hz/erg]) = 25.10$ (25.33)

All galaxies: $\log(\xi_{ion}[Hz/erg]) = 25.06$ (25.34)

Subsamples at z1 = 1.4-2.0 and z2 = 2.0-2.6

z1: 25.05 (25.29)   z2: 25.13 (25.36)

- Assuming an SMC curve systematically increases ξ_{ion} by ~0.2 dex, indicating the sensitivity of ξ_{ion} measurements to the assumed UV attenuation curve.

Scatter:

- 0.36 dex (0.35 dex) for obs result + uncertainty in the Hα, Hβ luminosity (0.22 dex)

→ an "intrinsic" scatter of 0.28dex (0.26 dex) for the Calzetti (SMC) curve

1. Dust Attenuation Correction Uncertainties

- SMC curve has a bluer intrinsic UV slope, β (and hence, a higher attenuation at 1500 Å), is more appropriate for high-redshift galaxies (Reddy et al. 2017)
- Discrepancy increases with mass and dustiness
- Robertson et al. 2013, SPS models: $\log(\xi_{ion}[Hz/erg]) = 25.20$

  A higher (lower) ξ_{ion} results in a lower (higher) LyC photon escape fraction required for galaxies to maintain cosmic reionization

- A single attenuation curve for all types of galaxies is not realistic. (Mass, Dustiness…)

  Young galaxies → steeper Calzetti curve

  Reddy et al. (2017): SMC curve for massive galaxies at z ~ 2, younger → steeper

  This study: two single curves

- Galaxy-to-galaxy variation: estimate the uncertainty caused by a single attenuation curve

- Intrinsic: $\log(\xi_{ion}[Hz/erg]) = 25.13 \pm 0.21$
- Attenuate each individual galaxy with a different attenuation curve (Kλ)
- Recover the dust-corrected values with a single attenuation curve.

→ 0.16 dex toward higher ξ_{ion}, an uncertainty of ∼0.1 dex associated with the uncertainties in dust corrections

Cannot fully account for the scatter in ξ_{ion}

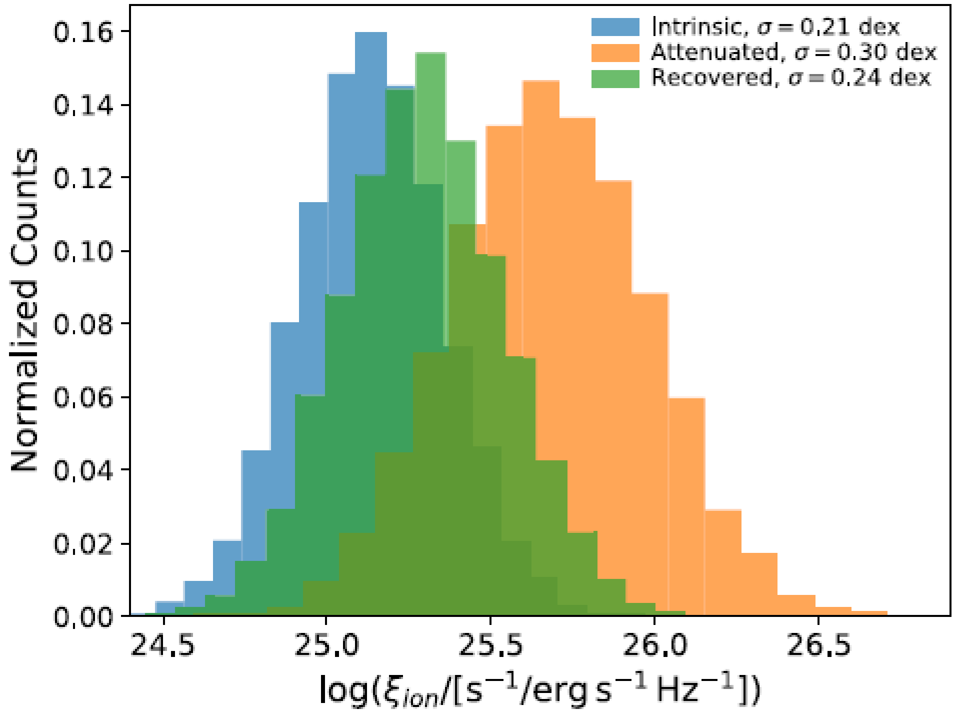


Figure 2. Simulation of a ξ_{ion} distribution with an intrinsic scatter of 0.21 dex. The simulated intrinsic distribution is shown in blue. To test the effect of the galaxy-to-galaxy variations of the dust attenuation curve on the ξ_{ion} scatter, we attenuated each object with a different attenuation curve (orange) and corrected the dust-obscured luminosities this time by assuming a single attenuation curve (green). The recovered scatter is larger than the intrinsic one, which introduces a ∼0.1 dex uncertainty in the measured scatter of the ξ_{ion} distribution.

2. Galaxy-to-galaxy Variations in Properties of Massive Star Populations

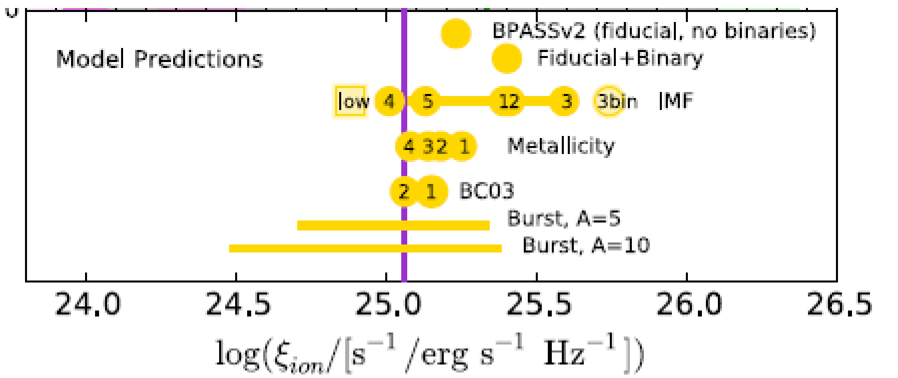
- Different properties of massive star populations, such as the shape of the IMF, star-burst metallicity, and binarity result in different ionizing photon production efficiencies.
- SPS models of BC03 and BPASSV2

BC03 + Salpeter IMF + Z = 0.02:

$$\log(\xi_{ion}[Hz/erg]) = 25.06$$

BPASSV2 + Salpeter IMF + Z = 0.02:

$$\log(\xi_{ion}[Hz/erg]) = 25.08$$



Binary are important sources of ionizing photons
Physically:
Mass and angular momentum transformation → increasing spin and mixing of layers, and efficient burning of hydrogen → Main-sequence lifetime
Model: increases, become hotter → increase ξ_{ion}
(50% increase by BPASSV2 model)

Bursts result in the largest change of ξ_{ion}
Onset of a burst, increasing ξ_{ion}
(Details in last presentation)

SPS Model	IMF	SFH	Z	Binary	$\log(\xi_{ion}/[s^{-1}/erg\ s^{-1}\ Hz^{-1}])$
BPASSv2 (Fiducial, F)	[a] $\alpha = -2.35$, $M_*^{max} = 100\ M_\odot$	Constant over 300 Myr	0.002 (0.15 $Z_\odot$)	No	25.23
(F)	(F)	(F)	(F)	Yes	25.40
(F)	$\alpha = -2.35$, $M_*^{max} = 300\ M_\odot$	(F)	(F)	Yes	25.59
(F)	(1) $\alpha = -2.35$, $M_*^{max} = 300\ M_\odot$ (2) $\alpha = -2.00$, $M_*^{max} = 100\ M_\odot$ (3) $\alpha = -2.00$, $M_*^{max} = 300\ M_\odot$ (4) $\alpha = -2.70$, $M_*^{max} = 100\ M_\odot$ (5) $\alpha = -2.70$, $M_*^{max} = 300\ M_\odot$	(F)	(F)	(F)	25.39 25.41 25.59[c] 25.01[c] 25.13
(F)	(F)	(F)	(1) 0.001 (2) 0.006 (3) 0.01 (4) 0.02	(F)	25.25 25.18 25.14 25.08
BC03	(F)	(F)	(1) 0.004 (2) 0.02	(F)	25.15 25.06
BC03	(F)	Burst (1)[b] $A = 5$, $D = 100$ Myr (2) $A = 10$, $D = 100$ Myr	0.004	(F)	[24.72–25.33] [24.49–25.37]

Stellar metallicity:

Lower Metallicity → higher ξ_{ion}

Physically: Low-metallicity stars have higher effective temperatures and harder ionizing spectra due to less metal blanketing. A larger mass of hydrogen and lower mass loss rate due to radiation pressure-driven winds lead to longer main-sequence lifetimes of low-metallicity massive star

Model: Changing the stellar metallicity from 0.07 $Z_{\odot}$ to 1.5 $Z_{\odot}$ results in a $\sim$50% change in ionizing photon production efficiency

IMF upper-mass cutoff and slope:

Model: 100 $\mathrm{M}_{\odot}$ to 300 $\mathrm{M}_{\odot}$, slope from α= – 2.7 to – 2.0 → 0.58 dex change in ξ_{ion}

(a larger fraction of hot and massive stars)

Largest value: $\log(\xi_{ion}[Hz/erg]) = 25.74$, Lowesr value: $\log(\xi_{ion}[Hz/erg]) = 24.88$

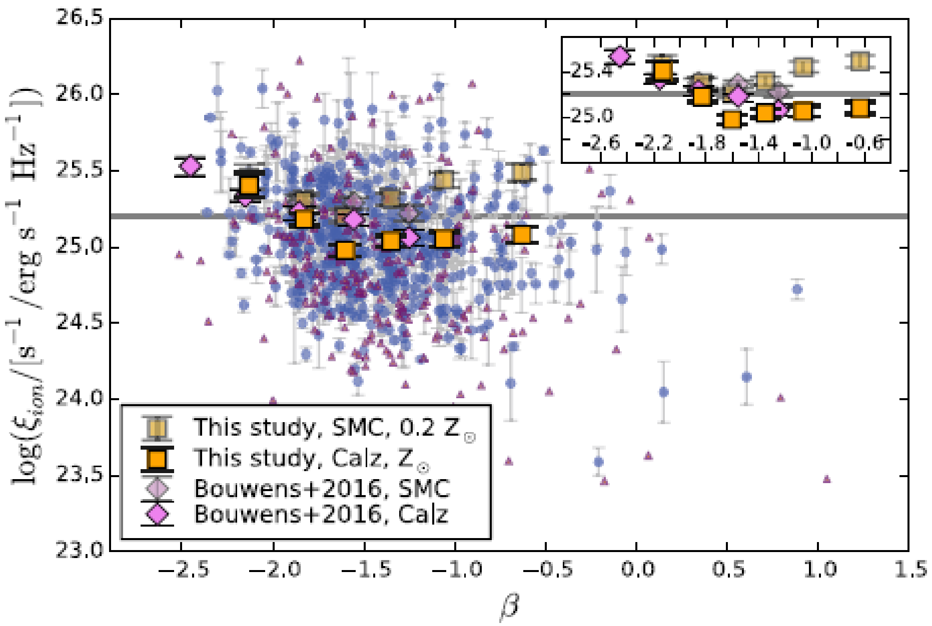
The 0.28 dex scatter in ξ_{ion} is partly affected by the variations in the stellar population of individual galaxies. It is not trivial to determine which model (or which dust attenuation curve) best describes the average properties of galaxies at z $\sim$ 2.

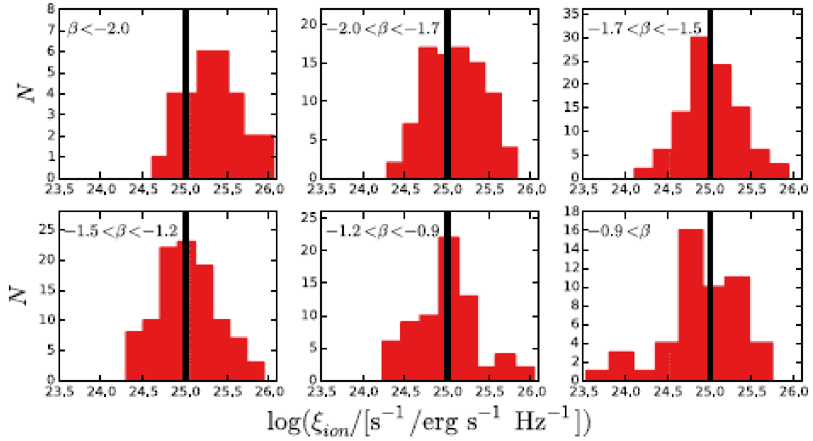
ξion Evolution with Galaxy Properties

The variations of ξ_{ion} as a function of stellar and gas properties

Blue circle: Hα+Hβ
Purple: Hβ-undetected

1. ξ_{ion} and UV Properties, Implications for Reionization
   - β at 1268—2580 Å
   - Based on Calzetti curve: $\xi_{ion} > -1.6$, constant
     $\xi_{ion} = -2.1$, increase by 0.5 dex
   - Similar to Bouwens+2016, an elevated ξ_{ion} in the galaxies with the bluest β
   - If galaxies at z > 6, have the bluest β and similar properties,
     → a lower escape fraction of ionizing photons is needed to reionize the universe





Bouwens et al. (2015)

- The evolution of the cosmic ionizing emissivity

== the number density of ionizing photons per second for reionizing hydrogen in the IGM (N_{ion})

- A product of three terms: the total UV luminosity density (ρ_{UV}), the ionizing photon production efficiency (ξ_{ion}), and the fraction of ionizing photons that escape into the IGM (f_{esc}).
- Conclusion: log(f_{esc} ξ_{ion}) = 24.50±0.1 is needed to reionize the IGM

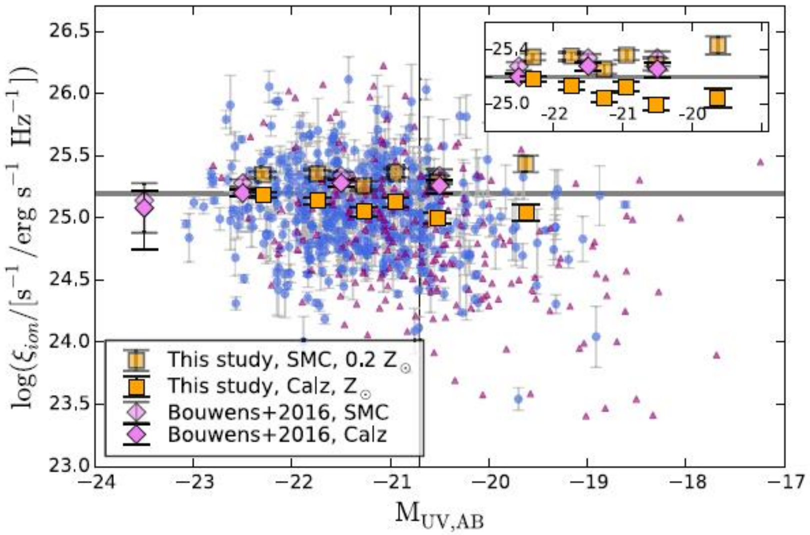
- → Suppose β = -2.1 subsample at z = 2 is representative of galaxies at z > 6,

$$\log(\xi_{ion}[Hz/erg]) = 25.32\ (25.39)$$

- → f_{esc} = 0.15 (0.13) ± 0.03, low LyC escape fraction than previously estimated

- Luv — ξ_{ion} relation: no significant trend

  Whether UV-faint galaxies also have higher ξ_{ion} (X)

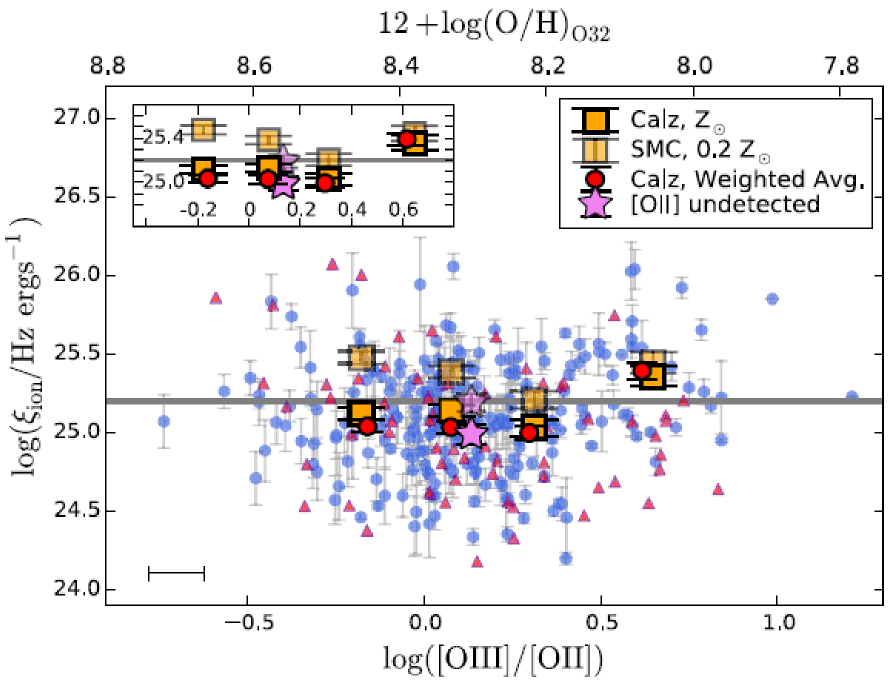


2. ξ_{ion} and ISM Properties: O32 and the BPT Diagram

ξ_{ion} as a function of O_{32}, O_3, N_2, BPT diagram

O_{32}:

- O_{32} implies the ionization parameter in H II regions
  ξ_{ion} is constant at $O_{32} < 3$ and increases by ~0.3 dex at $O_{32} \sim 5$.
- O_{32} can be explained by high ionization parameters, low metallicities, low mass (O32 and oxygen abundances, M_* anticorrelate with each other)
- SMC and Calzetti curve show greatest discrepancy at lowest O_{32} bin, **the dustier galaxies**
  → The systematic uncertainties associated with UV dust corrections
- Density-bounded HII region (fully ionized) → higher [OIII]/[OII], larger f_{esc} → larger ξ_{ion}



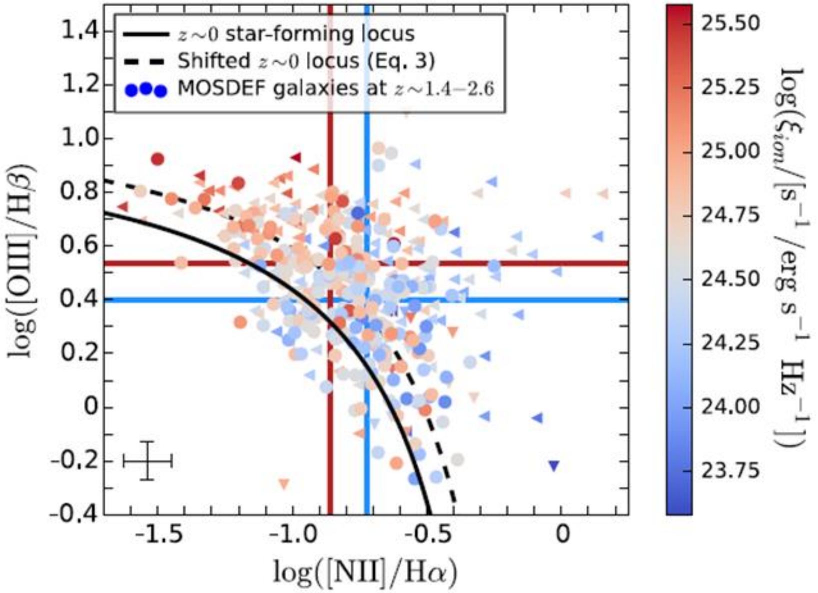
BPT-diagram

- ξ_{ion} is enhanced at high [O III]/Hβ and low [N II]/Hα

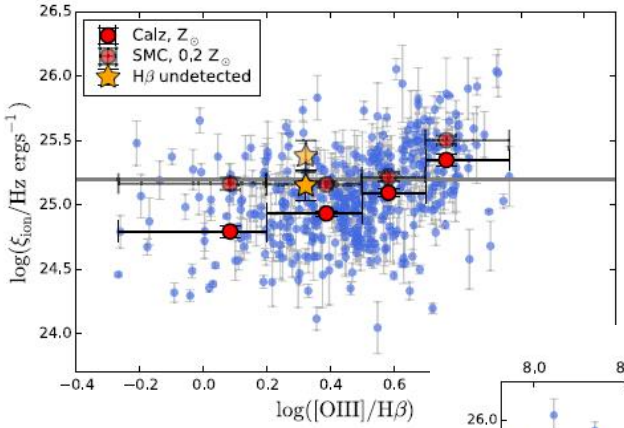
- Shifted sequence at z ~ 2

  125 galaxies on each side of the sequence

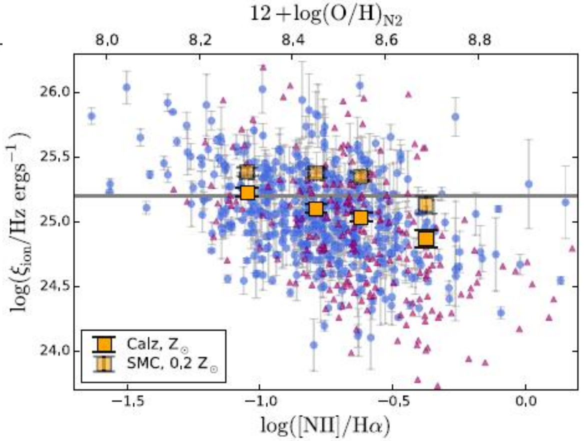
  No change in the hardness of the ionizing radiation with the offset from the z ~ 0 sequence



O_3: correlated



N_2: anti-correlated, larger change than SPS models predicted



In summary, an increase in ξ_{ion} in star-forming galaxies with high ionization parameter and at low metallicities

Comparison With Other Studies

- 2 redshift bin and $\log(M_*/M_\odot) < 10.3$
- Higher average mass than Bouwens+2016
- A mass dependency of ξ_{ion} at lower mass bin
  - Weak trend, similar to Wilkins+2016
- Comparison to Matthee+17
  - Matthee+17, No Hβ, same attenuation toward stellar and nebular
  - The average ξ_{ion} is highly affected by the dust correction method
- Comparison to Nakajima+16, Stark+15/17
  - LAE strong bias
  - Large [OIII]+Hβ EWs