The Interstellar Medium in [OIII]-selected Star-forming Galaxies at z∼3.2

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Abstract

- Keck/MOSFIRE: [OIII] galaxies at z ~ 3.2
- Gas metallicity: $\begin{cases} Low\ stellar\ mass: 12 + log(O/H) = 8.07 \pm 0.07 \\ High\ stellar\ mass: 12 + log(O/H) = 8.31 \pm 0.04 \end{cases}$
- No systematic bias in the selection of star-forming galaxies. (Compare to UV, Lyα)
- Ionization parameters and gas metallicities are similar to SFG at z ~ 2

  → No strong redshift evolution in the ISM conditions

  → SFR at a fixed stellar mass also do not significantly change
- The stellar mass is the primary quantity to describe the evolutionary stages of individual galaxies at z > 2

Introduction

- High-z galaxies have different ISM conditions comparing to local galaxies
  - On BPT-diagram, high-z has higher [O III]/Hβ ratios with respect to [N II]/Hα
  - On Mex-diagram, high-z has higher [O III]/Hβ ratios at a fixed stellar mass
  - A result of lower gas metallicities, higher ionization parameters, harder spectra of ionizing sources
- M_*—gas metallicity relation: SFG at high-z have lower gas metallicities at a fixed mass
- Strong emission line ratios → gas metallicities is probably not suitable for high-z
- Studies of ISM and M_*—gas metallicity is important at z > 3 because the cosmological inflow is prominent. Metal content can reflect inflow/outflow processes.
- SFGs at z > 3 has limited sample sizes and sample bias (UV-selected, less dusty systems)

  → rest-frame optical emission lines (ELGs)
- HST/H-band grism: z ~ 1-2 ELGs, low mass, starburst with [O III]/Hβ ≥ 5 (similar to LAEs)
- NB filter: SFGs at high-z show brighter [O III] emission lines and can be observable
- [O III]——SFMS at z > 3; [O III] ELGs have similar M_*, SFR, Dust extinction as Hα at z ~ 2.2

  → [O III] can be a tracer of SFGs at high-z
- This paper: [O III] at z ~ 3.24 selected by COSMOS-HiZELS, KECK/MOSFIRE H and K-band

Sample Selection, Observations, and Reduction

1. Selection of candidate at z ~ 3.24
   - HiZELS (NB surveys, UKIRT and Subaru) —COSMOS2015 catalog (NB_K, 2.121μm)
   - Selection: NB to BB, Σ is introduced to quantify the significance of an NB excess relative to 1σ photometric error

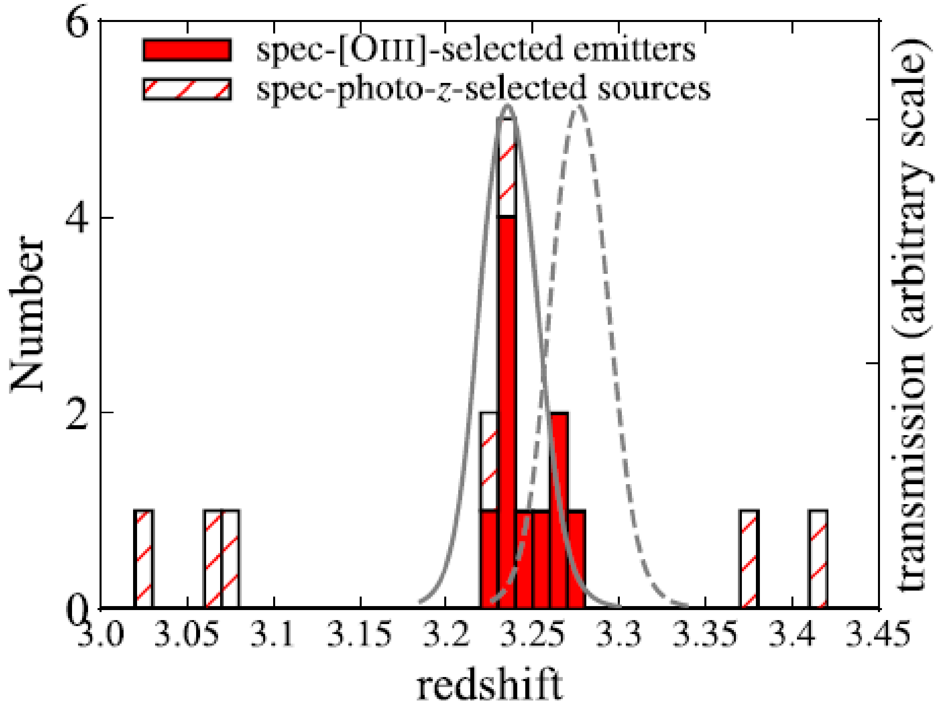
$$\Sigma = \frac{1 - 10^{-0.4(K-\mathrm{NB})}}{10^{-0.4(\mathrm{ZP}-\mathrm{NB})}\sqrt{\pi r_{\mathrm{ap}}^2(\sigma_{\mathrm{NB}}^2 + \sigma_K^2)}}, \qquad \mathrm{EW}_{\mathrm{rest}} = \Delta_{\mathrm{NB}}\frac{f_{\mathrm{NB}} - f_{\mathrm{BB}}}{f_{\mathrm{BB}} - f_{\mathrm{NB}}(\Delta_{\mathrm{NB}}/\Delta_{\mathrm{BB}})},$$

   - Criteria: Σ > 3 and EW_{rest} > 19 Å, 2.8 < z_{phot} < 4.0
   - 174 [O III] NB candidates emitters at z ~ 3.24 in COSMOS

2. H and K Band Spectroscopy with Keck/MOSFIRE
   - R = λ/Δλ ~ 3600, Slit width ~ 0".7, 120 mins—K-band, 90 mins—H-band, FWHM ~ 0".7—1".0
   - First detection: 10 NB candidates + 10 photometric sources with K < 24 mag at 3.0 < z_{phot} < 3.5

3. Data reduction and Analyses
   - Pipeline: MosfireDPR
   - Telluric correction & flux calibration: A0V star, HIP43018

- All 10 candidate emitters show [O III] doublets (100% detection) at z = 3.23—3.27 + Hβ + [O II]
- 7 photometric targets shows [O III] doublets (70% detection)
- The Correction factors for different seeing conditions in H (1.22±0.04) and K (0.89±0.03) bands
- Calculating emission line fluxes: Gaussian fitting by SPECFIT
  - Assuming [O III]λ5008/[O III]λ4960 = 3.0, Zspec is calculated by 5008.24Å, velocity dispersion
  - Fitting Hβ and [O II] and weak lines HeII, [Ne III]
- [O III] λ5008 with S/N > 20, and Hβ, [O II], Ne[III] S/N > 3
- Velocity dispersion (140—310 km/s) → No AGN



Curve: Transmission line of NB

4. Stellar Absorption Correction for Hβ

$$F_{H\beta,corr} = F_{H\beta,obs} + 2\,(\text{Å}) \times (1 + z) \times f_c\,,$$

- Correction factors ~ 1.0—1.2

5. Estimation of Physical quantities

- SED fitting: EAZY + FAST for 14 photometric bands in the COSMOS2015 catalog with emission lines subtraction ([O III], Hβ, [O II])
- SED models: Fixed Zspec, IMF: Chabrier 2003, Dust extinction: Calzetti 2000, Exponentially declining SFH, 3 Metallicities
- SFR_{SED} — UV continuum (SED fitting result)

  Dust extinction correction: $A_{\rm FUV} = 3.4 + 1.6\beta.$ β is the UV slope $f_{\nu,\rm int} = f_{\nu,\rm obs}\ 10^{0.4A_{\rm FUV}}.$
- SFR_{UV} is derived from r-band

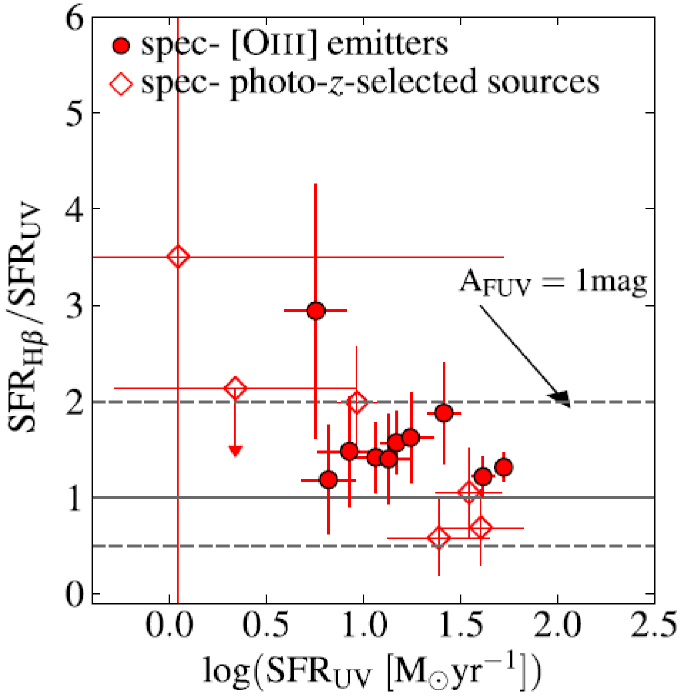
$$\mathrm{SFR}\ \ (M_\odot\ \mathrm{yr}^{-1}) = \frac{4\pi D_L^2 f_{\nu,\rm int}}{(1+z)\times 8\times 10^{27}\ (\mathrm{erg\ s^{-1}cm^{-2}Hz^{-1}})} = \frac{L(1600\text{Å})}{8\times 10^{27}\ (\mathrm{erg\ s^{-1}Hz^{-1}})},$$

/1.7 (Chabrier IMF)

- SFR_{SED} shows + 0.25dex over SFR_{UV}
- $SFR_{H\alpha}$ from Hβ, dust correction from UV slope + Calzetti 2000, with Hα/Hβ=2.86, E(B-V)nebular = E(B-V)stellar

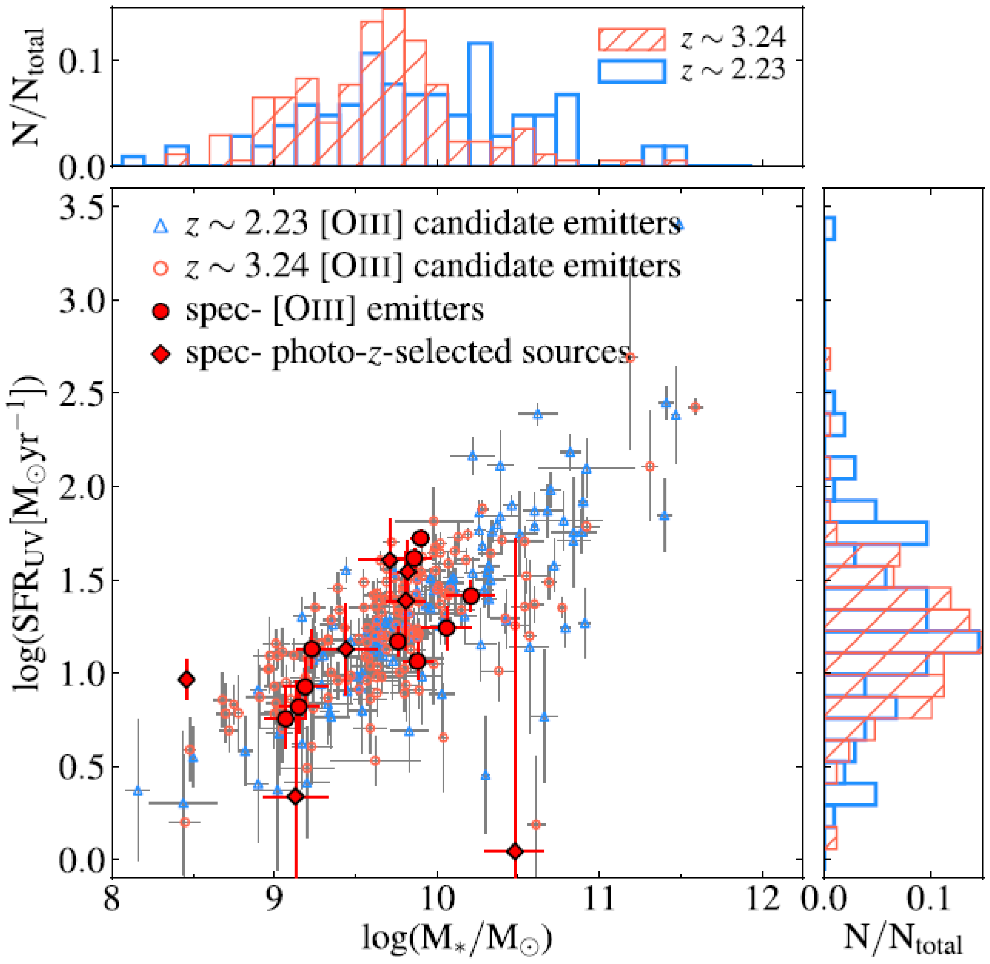
$$\log(\mathrm{SFR_{H\alpha}}/M_\odot\ \mathrm{yr}^{-1}) = \log(L_{\rm H\alpha}/\mathrm{erg\ s^{-1}}) - 41.27.$$

- $SFR_{H\alpha}/\ SFR_{UV}$ = 1.6±0.2 (due to dust correction based on UV-β)



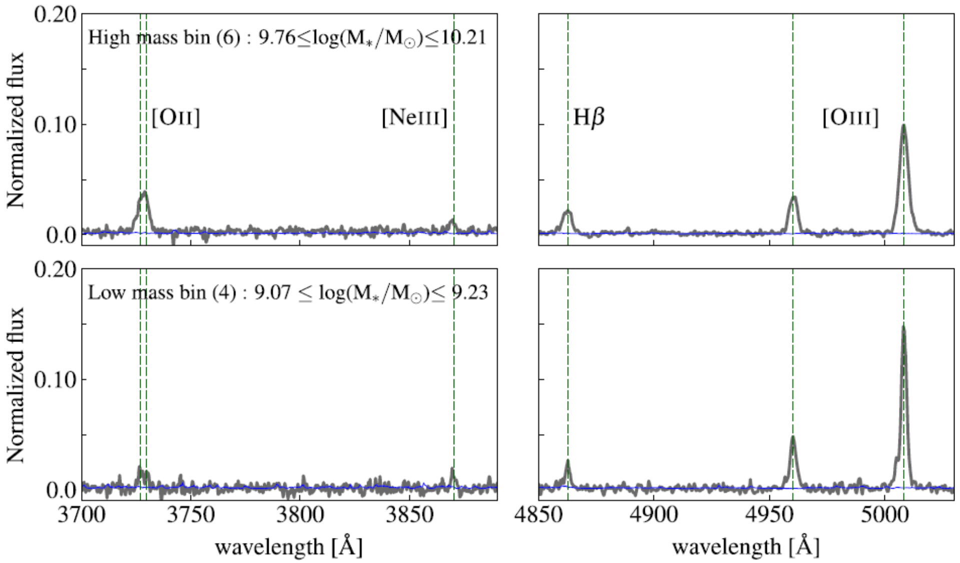
6. Stellar Mass-SFR Relation

- No bias compare to the parent sample → normal SFGs
  [O III] at z ~ 2.23 are from NB_H (117)
- [O III] emitters at z ~ 2.23 and 3.24 show similar SFRs
- [O III] emitters at z ~ 3.24 tend to have lower mass



7. Stacking Analysis

- 10 [O III] emitters $\begin{cases} 9.76 < \log(M_*/M_\odot) < 10.21 \\ 9.07 < \log(M_*/M_\odot) < 9.23 \end{cases}$
- Stacked spectra

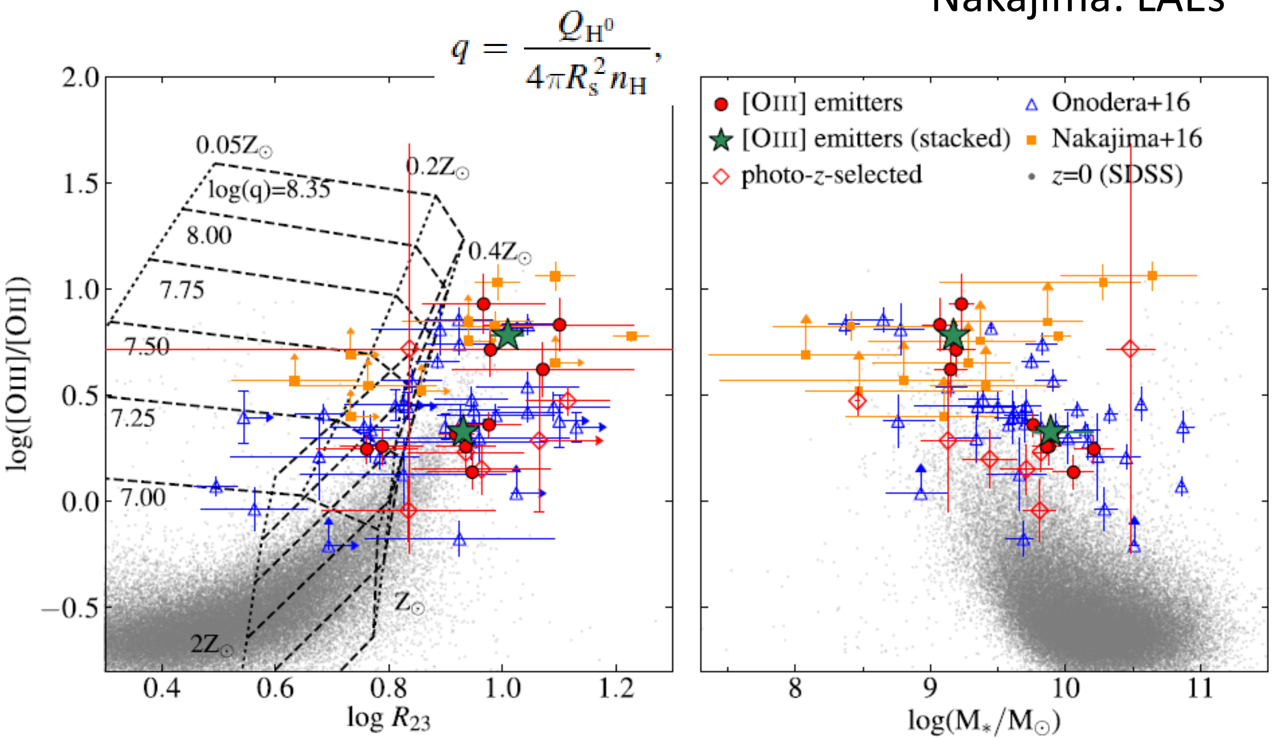


ISM Conditions of [OIII] Emitters

1. Line Ratios and M_* dependence at z > 3

- $R_{23}(([OIII]+[OII])/H\beta)$ ratio to $[OIII]/[OII]$ ratio + Model from **MAPPING V**
- R_{23} sensitive to gas metallicities, $[OIII]/[OII]$ sensitive to ionization parameter

Onodera: UV-SFGs
Nakajima: LAEs



Result:

- Compare to SDSS data (local)

High-z SFGs have higher [OIII]/[OII] ratio

The ionization states of high-z SFGs are higher

- **Massive [O III] emitters → SFGs**
- **Low mass [O III] emitters → LAEs**

The selection based on the [O III] emission line strength does not cause any significant bias in terms of the ISM conditions

2. Metallicity Estimation with the Empirical Calibration Method

The empirical relations between the gaseous metallicities and six line ratios (Curti et al. 2017)

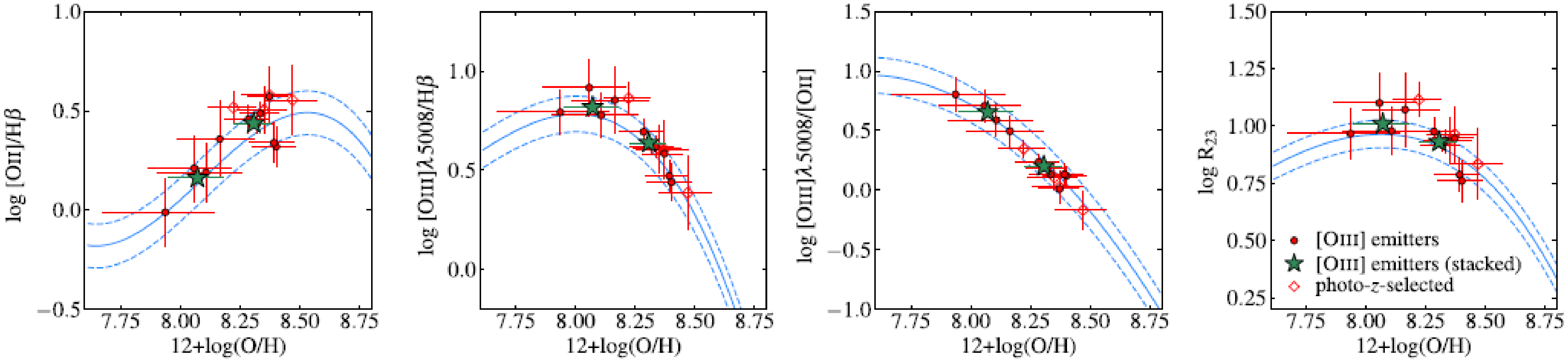
- [O III], Hβ, [O II] S/N > 3
- 4 line ratios → best-fit metallicity

$$\chi^2 = \sum_{i=1}^{N} \frac{(\log R_{i,\rm obs} - \log R_{i,\rm fit})^2}{\sigma^2_{i,\rm obs} + \sigma^2_{i,\rm int}},$$

Table 2. Best-fitting coefficients and rms of the residuals for calibrations of metallicity diagnostics given by equation (5). The σ parameter is an estimate of the dispersion along the log(O/H) direction in the interval of applicability given in the *Range* column.

Diagnostic	c_0	c_1	c_2	c_3	c_4	rms	σ	Range
R_2	0.418	−0.961	−3.505	−1.949		0.11	0.26	7.6 < 12+log(O/H) < 8.3
R_3	−0.277	−3.549	−3.593	−0.981		0.09	0.07	8.3 < 12+log(O/H) < 8.85
O_{32}	−0.691	−2.944	−1.308			0.15	0.14	7.6 < 12+log(O/H) < 8.85
R_{23}	0.527	−1.569	−1.652	−0.421		0.06	0.12	8.4 < 12+log(O/H) < 8.85
N_2	−0.489	1.513	−2.554	−5.293	−2.867	0.16	0.10	7.6 < 12+log(O/H) < 8.85
O_3N_2	0.281	−4.765	−2.268			0.21	0.09	7.6 < 12+log(O/H) < 8.85

- The four line ratios of galaxies are well fitted by their empirical relations within 1σ errors.
- The physical conditions of H II regions do not evolve with redshifts at a fixed metallicity, this paper use the locally calibrated empirical relations to estimate gas metallicities



3. Mass-Metallicity relation at z > 3

- More massive galaxies have higher metallicities
- No difference between [O III] emitters and UV-selected SFGs at mass range $9.0 < \log(M_*/M_\odot) < 10.2$

- A larger sample and a larger massive range is required for comparison

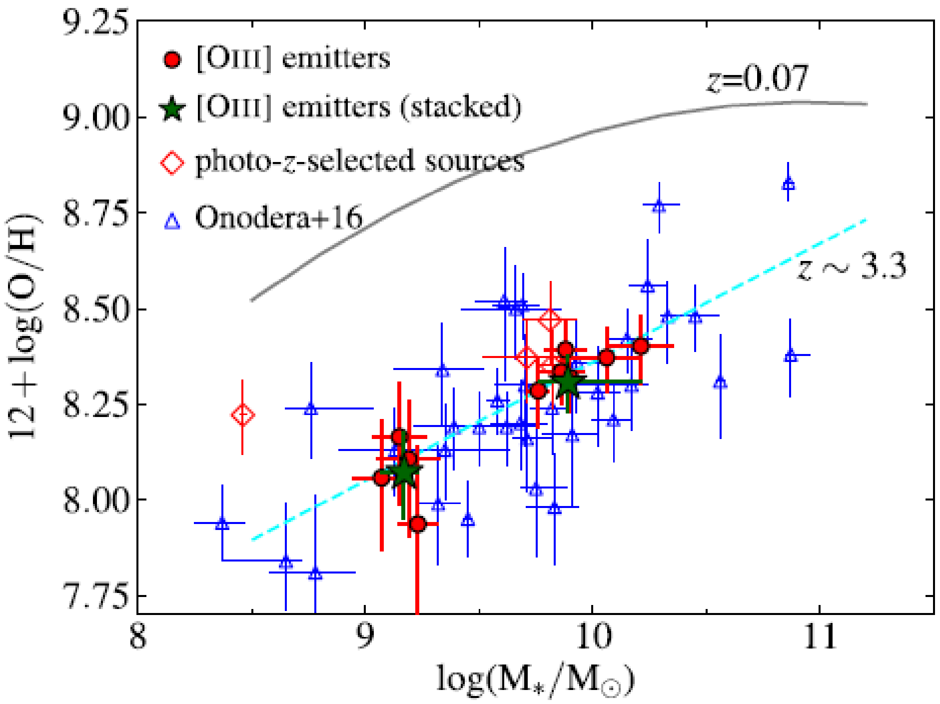


Figure 7. Relation between stellar mass and gas metallicity for our sample at $z \sim 3.2$ and the UV-selected galaxies at $z \sim 3$–3.7 from Onodera et al. (2016). The solid curve represents the mass–metallicity relation at $z = 0.07$ (Maiolino et al. 2008). The dashed curve represents the best-fitted mass–metallicity relation at $z \sim 3.3$ from Onodera et al. (2016). Our targets are well below the mass–metallicity relation of the local star-forming galaxies. Comparing with the UV-selected galaxies at the same epoch, there is no clear difference of gas metallicities at a fixed stellar mass between the two samples. Our [O III] emitters follow the best-fitted relation by Onodera et al. (2016).

Comparison with Star-forming Galaxies at z ~ 2

1. Metallicity Calibration Based on Photoionization Modeling

- Calibration model: KK04
- A. Ionization parameter (q) to O_{32} (y=log(O_{32}))

$$\log(q) = \{32.81 - 1.153y^2 + [12 + \log(\mathrm{O/H})] \times (-3.396 - 0.025y + 0.1444y^2)\} \times \{4.603 - 0.3119y - 0.163y^2 + [12 + \log(\mathrm{O/H})](-0.48 + 0.0271y + 0.02037y^2)\}^{-1},$$

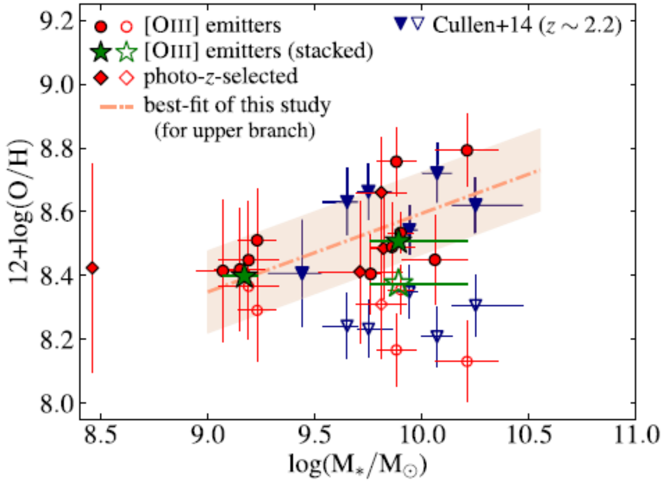
- B. Gas Metallicity (12+log(O/H)) to R_{23} (x=log(R_{23}))
  Upper: 12+log(O/H) > 8.4   Lower: < 8.4

$$12 + \log(\mathrm{O/H})_{\mathrm{upper}} = 9.72 - 0.777x - 0.951x^2 - 0.072x^3 - 0.811x^4 - \log(q) \times (0.0737 - 0.0713x - 0.141x^2 + 0.0373x^3 - 0.058x^4),$$

- Iterative manner of A and B

$$12 + \log(\mathrm{O/H})_{\mathrm{lower}} = 9.40 + 4.65x - 3.17x^2 - \log(q)(0.272 + 0.547x - 0.513x^2),$$

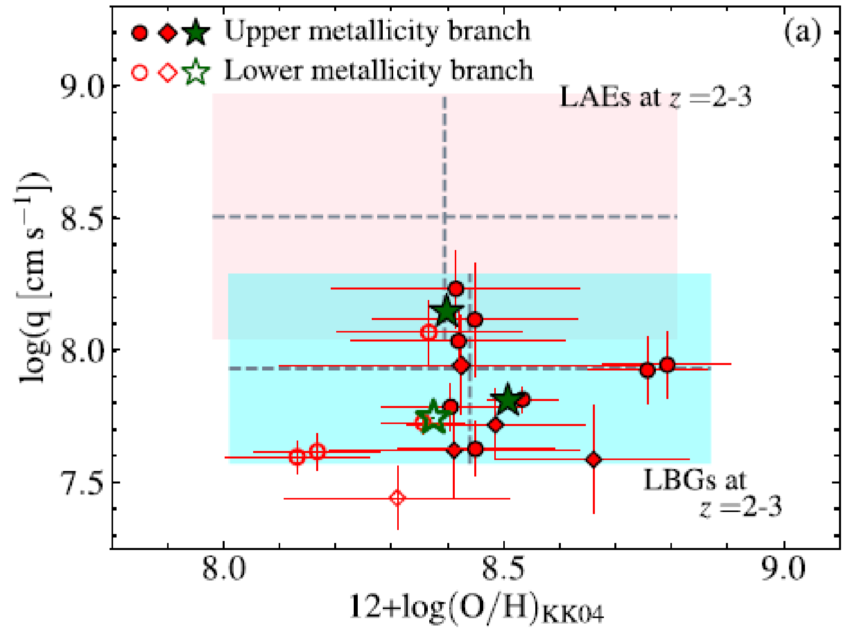
- [N II]/[O II] is needed to determine metallicity branch, this paper uses the upper branch



Blue shaded: LBGs (2<z<3)
Red shaded: LAEs (2<z<3)

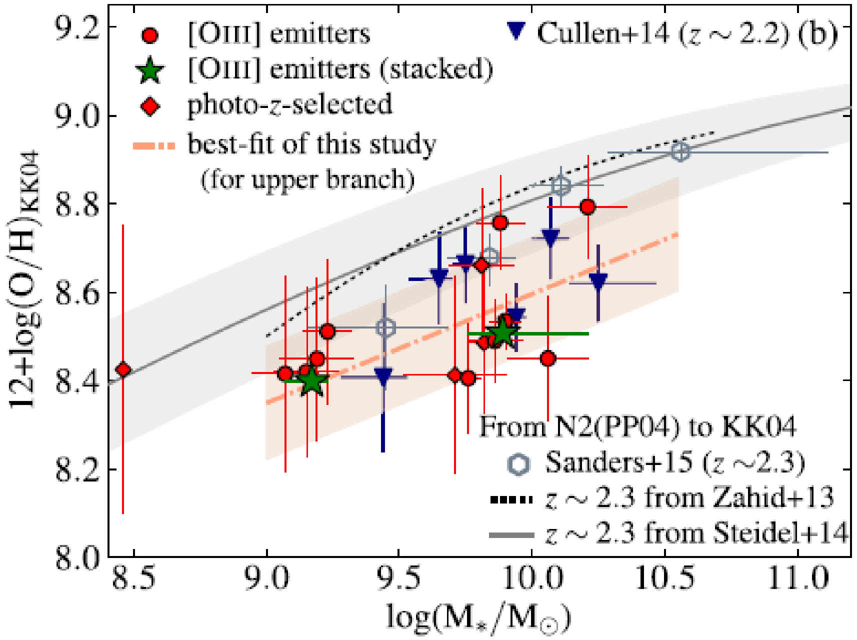
2. Comparison of the Ionization Parameter and Gas Metallicity

- Some sources have the same solution at the two branches, indicating that they lie at the crossover metallicity.
- The sample at z ~ 3.2 shows gas metallicities and ionization parameters similar to those of the LBGs at z∼2–3 (Nakajima & Ouchi 2014)
- The redshift evolution of ISM conditions is unlikely to be strong between z∼3.2 and z∼2



3. Comparison of Mass–Metallicity Relation

- Comparison at z ~ 2,
  Cullen+14 (3D-HST grism, KK04), consistent
  Others PP04 to KK04, higher gas metallicity for former researches (Systematic differences due to correction)
- The sample at z∼3.2 has similar ionization parameters and gas metallicities as star-forming galaxies at z∼2 at a fixed stellar mass under the same calibration method.



4. ISM Conditions and Star-forming Activity between z ~ 3.2 and z ~ 2

- From 2.6 and 4.1 & 4.2, the properties of star-forming galaxies at $z \sim 2.0$–3.2 (the difference of cosmic age of $\sim$1.3 Gyr) are primarily determined by their stellar masses rather than cosmic epoch.
- The individual galaxies should experience significant growth in their stellar masses

  → gas accretion is really strong at that epoch
- Onodera et al. (2016) shows a similar result

  It needs supports from the gas mass measurement to get the inflow and outflow of gas and constrained gas model.