The MOSDEF Survey: A Stellar Mass–SFR–Metallicity Relation Exists at z ~ 2.3

Sanders+2018, APJ, 858, 99

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Presenter: N.Chen

Structure:

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- Observations, Data, and Measurements [4]
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Introduction

- The buildup of the gaseous and stellar content of galaxies is still not fully understood
- The connection between ISM abundance and baryon cycling

  → [MZR] The stellar masses (M_*) and oxygen abundances [12+log(O/H) or Z] of SFGs (Local)
- A secondary dependence of the z ~ 0 MZR on star formation rate (SFR)

  At fixed M_* , higher SFRs have lower metallicities → M_*—SFR—Z relation
- Mannucci+2010: the M_*–SFR–Z relation is redshift invariant at z < 2.5

  → Fundamental metallicity relation (FMR)

Questions: 1. Redshift invariant? 2. high-Z galaxies show a M_*–SFR–Z relation?

- No concensus has been reached (z > 1):

  Redshift invariant, An evolving M_*–SFR–Z relation
- Sanders+2015: z ~ 2.3 galaxies have lower metallicities than local at fixed M_* and SFR

- Difficulty in determine whether the MZR has a secondary SFR dependence at z > 1

  Several works have failed to detect any significant SFR dependence

  requires either high-precision measurements or large sample sizes to detect

- Previous: a single metallicity indicator (most often [NII] λ6584/Hα or R23

  based on large samples (> 100) with low S/N individual measurements, or small samples with moderate S/N measurements

- MOSDEF: multiple metallicity-sensitive emission-line ratios

$$\mathrm{O3} = [\mathrm{O\,III}]\,\lambda5007/\mathrm{H}\beta,$$

$$\mathrm{N2} = [\mathrm{N\,II}]\,\lambda6584/\mathrm{H}\alpha,$$

$$\mathrm{O3N2} = \mathrm{O3}/\mathrm{N2},$$

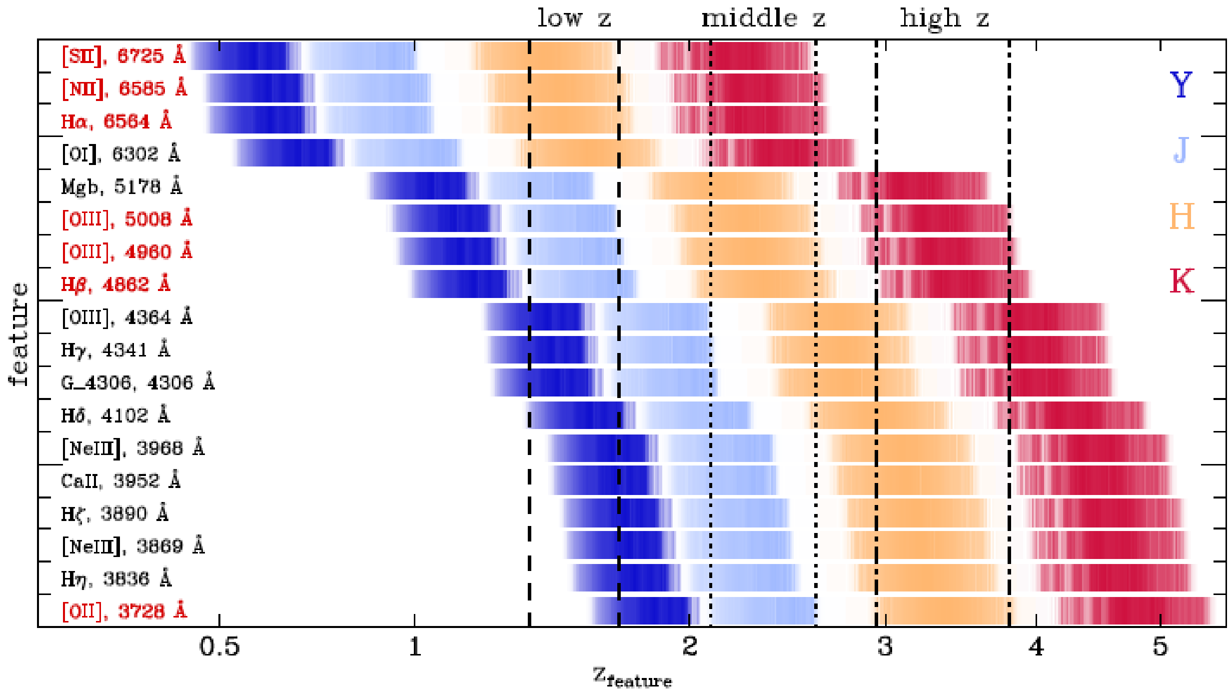
$$\mathrm{N2O2} = [\mathrm{N\,II}]\,\lambda6584/[\mathrm{O\,II}]\,\lambda\lambda3726,\,3729,$$

$$\mathrm{O32} = [\mathrm{O\,III}]\,\lambda5007/[\mathrm{O\,II}]\,\lambda\lambda3726,\,3729,$$

$$\mathrm{R23} = ([\mathrm{O\,III}]\,\lambda\lambda4959,\,5007 + [\mathrm{O\,II}]\,\lambda\lambda3726,\,3729)/\mathrm{H}\beta$$

"metallicity" to refer to the gas-phase oxygen abundance (12+log(O/H))

Observations, Data, and Measurements



1. The MOSDEF Survey

   ~ 1500 galaxies at $1.4 < z < 3.8$

2. Measurements and Derived Quantities
   - 2.1 Stellar mass

     FAST (exclude strong lines)

     Chabrier03, Calzetti+00 curve,

     solar metallicity, constant SFH
   - 2.2 Emission-line fluxes and Redshift

     Gaussian fitting (mostly single) [NII]+Hα: triple [OII]: double

     Redshift: the highest S/N line (Hα or [OIII]λ5007)
   - 2.3 Reddening Correction and Star Formation Rate

     SFRs were estimated using dust-corrected Hα luminosities

     Dust corrections were applied by Cardelli+89 Milky Way extinction curve

     N2O2, O32, R23: corrected; O3N2,N2,O3: uncorrected

     Uncertainties: dust curve, measurement uncertainties, silt loss (16%)

3. Sample selection

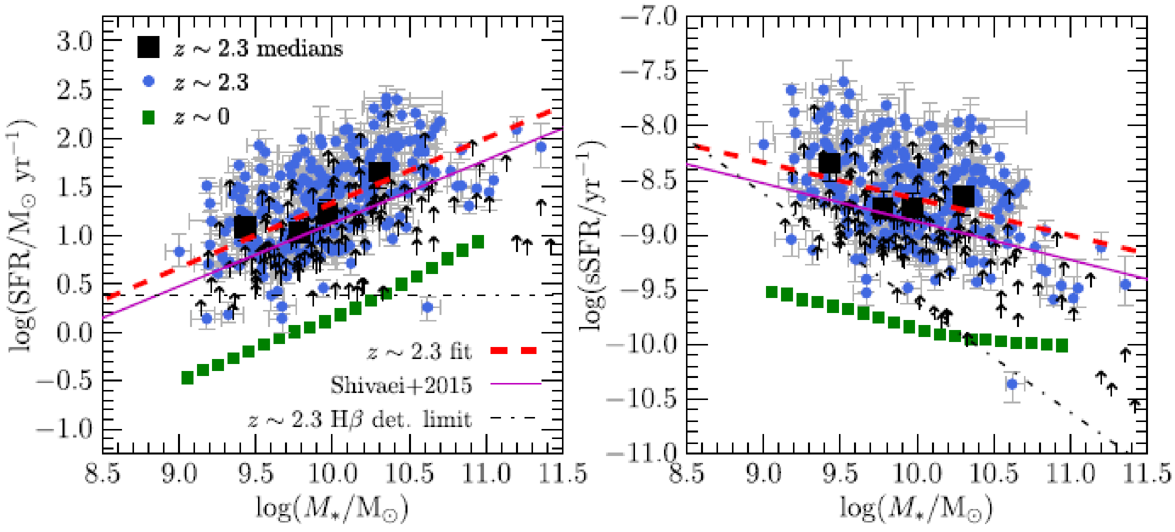
- 3.1 MOSDEF z ~ 2.3 Sample

  Criterion: 2.0 < z <2.7; $\log(M_*/M_\odot)$ > 9.0; Hα, Hβ: S/N > 3;

  → 260 galaxies at z_{med} = 2.29, $\log(M_*/M_\odot)$ = 9.0 — 11.4, SFR = 1.4 — 260 $M_\odot\ \mathrm{yr}^{-1}$

  Mass Completeness of MOSDEF:

  $\log(M_*/M_\odot)$ = 9.5



- 3.2 SDSS z ~ 0 Comparison Sample

  MPA-JHU: M_*, SFR, sSFR, emission-line ratios

  The z ~ 0 comparison sample has the same set of emission lines measured as the z ~ 2.3 sample and SFR measurements.

4. Metallicities

- N2, O3N2 indicators, Pettini and Pagel (2004)

$$12 + \log(O/H) = 8.90 + 0.57 \times \log(N2),$$ n = 143, Uncertainties: 0.14 dex, —2.5 < log(N2) < —0.3

$$12 + \log(O/H) = 8.73 - 0.32 \times \log(O3N2).$$ n = 126, Uncertainties: 0.18 dex, log(O3N2) < 2.0

- N2O2 indicator, Sanders + 17

$$12 + \log(O/H) = 8.94 + 0.73 \times \log(N2O2).$$ n=118, Uncertainties: 0.2 dex, —1.3 < log(N2O2) < 0.0

- O32 indicator, Jones + 15

$$12 + \log(O/H) = 8.3439 - 0.4640 \times \log(O32).$$ n=169, Uncertainties: 0.11 dex, —1.0 < log(N2) < 1.0

Each of the detected line-ratio subsets has median stellar mass in the range 9.9 < $\log(M_*/M_\odot)$ < 10.1 and median SFR within the range 22 < SFR/ $M_\odot\ \mathrm{yr}^{-1}$ < 32

5. Correcting for Diffuse Ionized Gas Contamination (f-factor)

- Sanders + 17: DIG a significant contaminant of global galaxy spectra at z ~ 0

  Local: $f = 0.55$ z ~ 2.3: negligible

6. Stacking Methodology

- For galaxies covers all emission lines mentioned ([OII], Hβ, [OIII], Hα, [NII]), $9.0 < \log(M_*/M_\odot) < 10.5$ (upper limit mass cut: avoid red star-forming, quiescent) → 195 galaxies
- 2 binning method: **a.** stellar mass **b.** sSFR + stellar mass
- **Composite spectra:** shift into rest frame, flux density → luminosity density (z_{spec}), dust correction was done separately based on Balmer decrement, separately normalized by Hα luminosity, take the median value

Table 1
Galaxy Properties and Emission-line Ratios from Stacks of $z \sim 2.3$ Star-forming Galaxy Spectra

N_{gal} [a]	$\log\left(\frac{M_*}{M_\odot}\right)$ [b]	SFR_{med} [c]	$\log\left(\frac{sSFR}{yr^{-1}}\right)$ [d]	log(N2)	log(O3)	log(O3N2)	log(N2O2)	log(O32)	log(R23)
				M_* stacks					
49	$9.0-9.62;\ 9.43^{+0.01}_{-0.03}$	$12.1^{+3.4}_{-1.2}$	$-8.34^{+0.16}_{-0.05}$	$-1.22^{+0.10}_{-0.05}$	$0.66^{+0.04}_{-0.02}$	$1.89^{+0.06}_{-0.10}$	$-1.13^{+0.20}_{-0.08}$	$0.28^{+0.10}_{-0.13}$	$0.93^{+0.04}_{-0.03}$
49	$9.62-9.89;\ 9.78^{+0.02}_{-0.01}$	$10.6^{+0.8}_{-4.4}$	$-8.75^{+0.03}_{-0.15}$	$-1.08^{+0.06}_{-0.09}$	$0.55^{+0.05}_{-0.02}$	$1.63^{+0.11}_{-0.07}$	$-1.12^{+0.09}_{-0.18}$	$0.07^{+0.16}_{-0.11}$	$0.89^{+0.06}_{-0.05}$
49	$9.89-10.13;\ 9.97^{+0.01}_{-0.04}$	$16.6^{+2.8}_{-6.8}$	$-8.75^{+0.11}_{-0.13}$	$-0.90^{+0.05}_{-0.06}$	$0.45^{+0.02}_{-0.04}$	$1.36^{+0.06}_{-0.06}$	$-0.93^{+0.13}_{-0.14}$	$-0.05^{+0.07}_{-0.17}$	$0.84^{+0.05}_{-0.05}$
48	$10.14-10.50;\ 10.30^{+0.01}_{-0.02}$	$45.1^{+14.9}_{-9.3}$	$-8.65^{+0.17}_{-0.07}$	$-0.71^{+0.03}_{-0.03}$	$0.37^{+0.02}_{-0.05}$	$1.09^{+0.03}_{-0.06}$	$-0.80^{+0.21}_{-0.15}$	$-0.20^{+0.23}_{-0.19}$	$0.83^{+0.07}_{-0.16}$
				M_*–ΔsSFR stacks: $\Delta\log(sSFR/yr^{-1}) < -0.2$					
30	$9.18-9.90;\ 9.72^{+0.04}_{-0.01}$	$5.7^{+0.2}_{-1.5}$	$-8.96^{+0.01}_{-0.12}$	$-1.05^{+0.10}_{-0.11}$	$0.43^{+0.04}_{-0.04}$	$1.49^{+0.13}_{-0.14}$	$-1.04^{+0.13}_{-0.16}$	$0.00^{+0.08}_{-0.11}$	$0.80^{+0.05}_{-0.04}$
30	$9.90-10.49;\ 10.04^{+0.02}_{-0.05}$	$11.1^{+1.9}_{-0.6}$	$-8.99^{+0.10}_{-0.01}$	$-0.79^{+0.09}_{-0.06}$	$0.34^{+0.04}_{-0.05}$	$1.14^{+0.06}_{-0.10}$	$-0.75^{+0.13}_{-0.09}$	$-0.11^{+0.04}_{-0.12}$	$0.76^{+0.05}_{-0.04}$
				M_*–ΔsSFR stacks: $-0.2 \leqslant \Delta\log(sSFR/yr^{-1}) \leqslant +0.2$					
34	$9.00-9.86;9.50^{+0.01}_{-0.03}$	$9.2^{+0.4}_{-2.1}$	$-8.53^{+0.03}_{-0.07}$	$-1.16^{+0.04}_{-0.17}$	$0.59^{+0.03}_{-0.04}$	$1.76^{+0.14}_{-0.07}$	$-1.09^{+0.10}_{-0.19}$	$0.21^{+0.09}_{-0.13}$	$0.88^{+0.03}_{-0.05}$
33	$9.86-10.47;\ 10.1^{+0.05}_{-0.01}$	$26.2^{+4.4}_{-0.1}$	$-8.68^{+0.07}_{-0.03}$	$-0.81^{+0.07}_{-0.04}$	$0.41^{+0.04}_{-0.04}$	$1.23^{+0.05}_{-0.08}$	$-0.83^{+0.11}_{-0.08}$	$-0.11^{+0.04}_{-0.09}$	$0.84^{+0.05}_{-0.02}$
				M_*–ΔsSFR stacks: $\Delta\log(sSFR/yr^{-1}) > +0.2$					
34	$9.20-9.92;\ 9.55^{+0.01}_{-0.05}$	$32.1^{+3.0}_{-4.1}$	$-8.04^{+0.07}_{-0.04}$	$-1.23^{+0.07}_{-0.10}$	$0.69^{+0.03}_{-0.01}$	$1.93^{+0.11}_{-0.08}$	$-1.22^{+0.11}_{-0.11}$	$0.25^{+0.15}_{-0.06}$	$0.97^{+0.03}_{-0.04}$
34	$9.92-10.5;\ 10.25^{+0.01}_{-0.03}$	$88.2^{+17.3}_{-1.0}$	$-8.30^{+0.12}_{-0.02}$	$-0.78^{+0.05}_{-0.05}$	$0.46^{+0.03}_{-0.03}$	$1.24^{+0.08}_{-0.05}$	$-0.97^{+0.07}_{-0.07}$	$-0.18^{+0.09}_{-0.06}$	$0.92^{+0.03}_{-0.04}$

Results

1. Mean z ~ 2.3 Relations

- In the lowest-mass bin, there is a selection bias (High SFR sample) because of Hβ detection limit. [Do not affect the conclusion]
- O3N2 and O32 are sensitive to the ionization parameter, containing both a high and low ionization energy ionic species. N2 is also sensitive to changes in ionization parameter, as well as the nitrogen abundance (N/H).
- A clear progression toward higher ionization parameter and lower N/O and N/H at fixed stellar mass from z ~ 0 to z ~ 2.3.

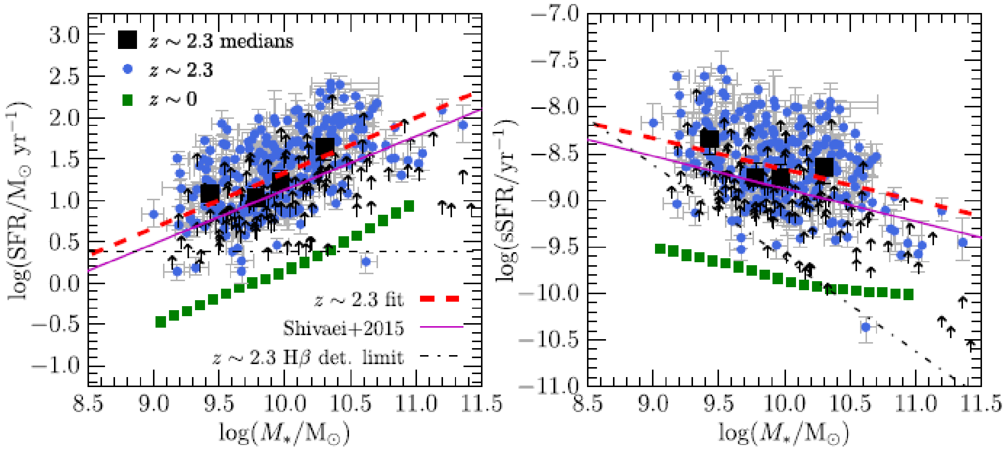
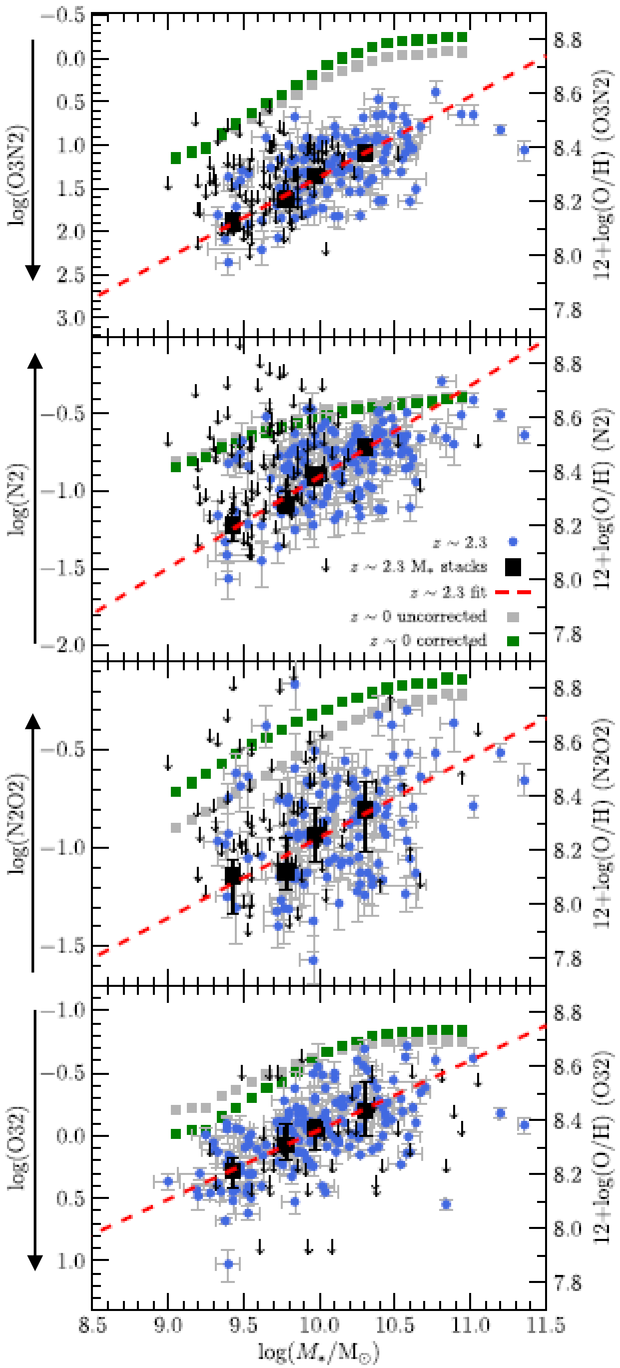


Table 2
Best-fit Linear Coefficients to $z \sim 2.3$ Galaxy Properties as a Function of Stellar Mass

Property	Slope	Intercept
Star Formation[a]		
SFR	0.67	−5.33
sSFR	−0.33	−5.33
Line Ratios[a]		
O3N2	−0.94	10.72
N2	0.59	−6.82
N2O2	0.41	−5.03
O32	−0.56	5.51
O3	−0.34	3.90
R23	−0.12	2.03
12+log(O/H)[b]		
O3N2	0.30	5.30
N2	0.34	5.01
N2O2	0.30	5.27
O32	0.26	5.79



- Ionization parameter anticorrelated to metallicity, while N/O, N/H are correlated to metallicity

  → lower metallicity at fixed M_* for galaxies at z $\sim$ 2.3
- Quantification:

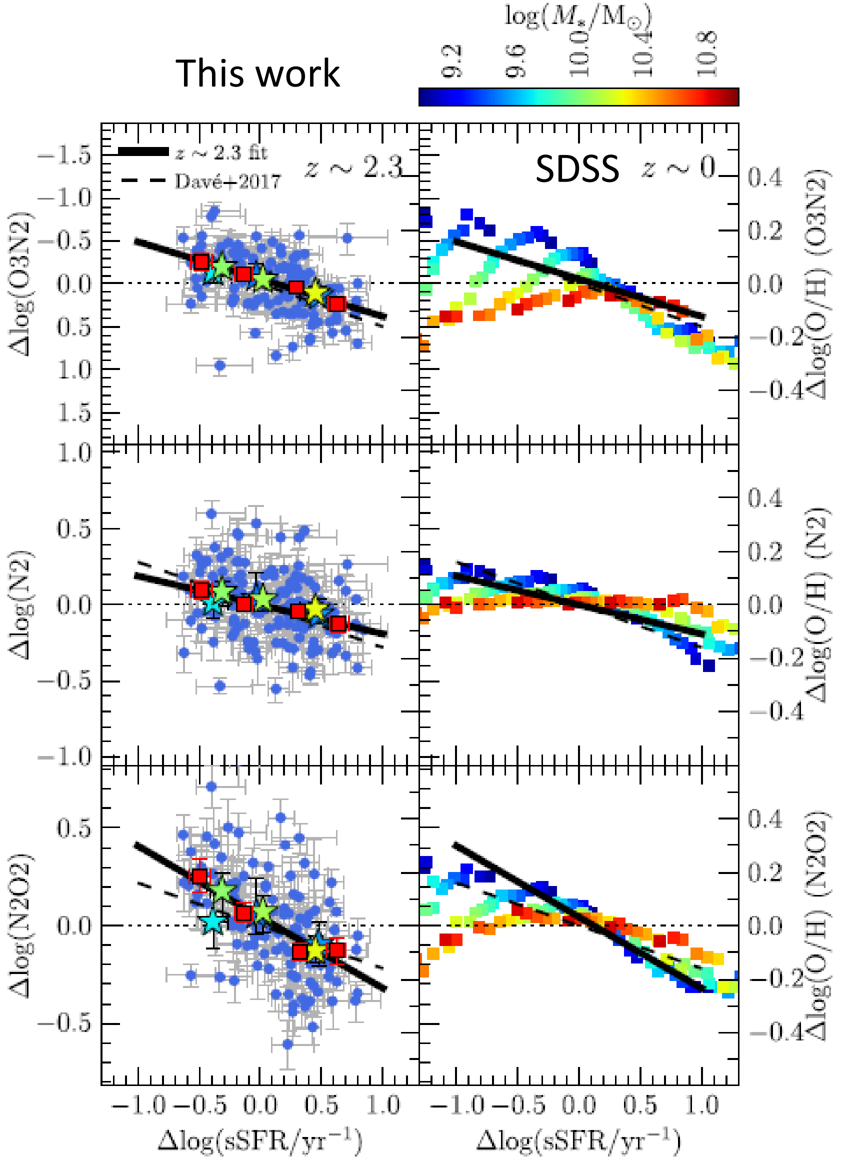
  All four panels are matched to the same range in metallicity (7.7 < 12+log(O/H) < 8.9)

  lower metallicities at fixed M_* by 0.37, 0.25, 0.46, and 0.25 dex on average for metallicities
- Potential problem:

  locally calibrated relations to estimate nebular metallicities in high-redshift galaxies (Discussion part)

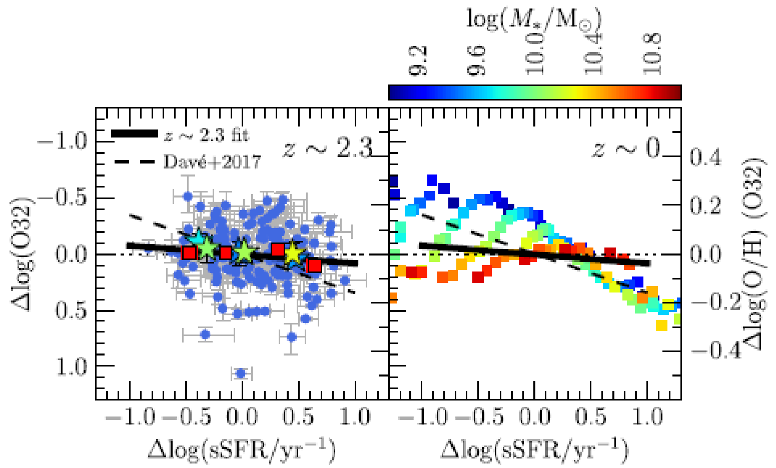
2. Is There SFR Dependence of the z ~ 2.3 MZR?

- Whether the metallicities of high-z galaxies display a secondary dependence on SFR at fixed M_*
  (Prerequisite of FMR)
- Residuals around the mean M_* relations for the line ratios, as a function of residuals around the mean M_* –sSFR relation (z ~ 2.3, 4 mass bin: 9.43, 9.78, 9.97, 10.30)
- The presence of a M_* –SFR–Z relation:
  O3N2 decreases with increasing metallicity, while N2 and N2O2 increase
- This is the first time that such a relation has been clearly demonstrated to exist at this redshift.
- The high-mass M_* –ΔsSFR stacks most clearly follow the same relation as the medians (the low-mass M_* –ΔsSFR are noisier)
- For SDSS data: show similar trends $\log(M_*/M_\odot)$ < 10.0 (decrease of disappearance of the SFR dependence at **high stellar mass** [larger than this work's range], Mannucci+2010)



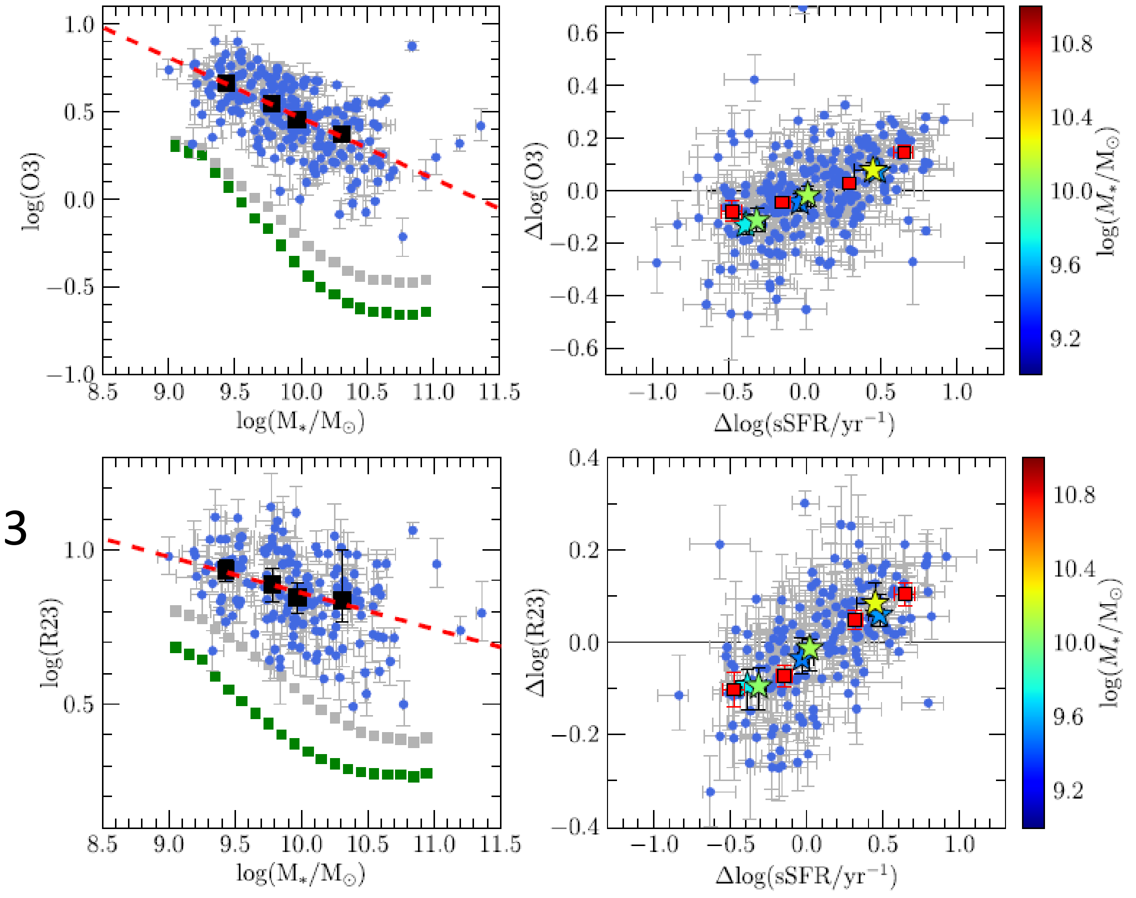
Line Ratio	Slope	r_s[a]	p-value[b]
O3N2	−0.14 ± 0.034	0.48	1.5×10^{-8}
N2	−0.11 ± 0.037	−0.32	8.6×10^{-5}
N2O2	−0.27 ± 0.067	−0.54	3.2×10^{-10}

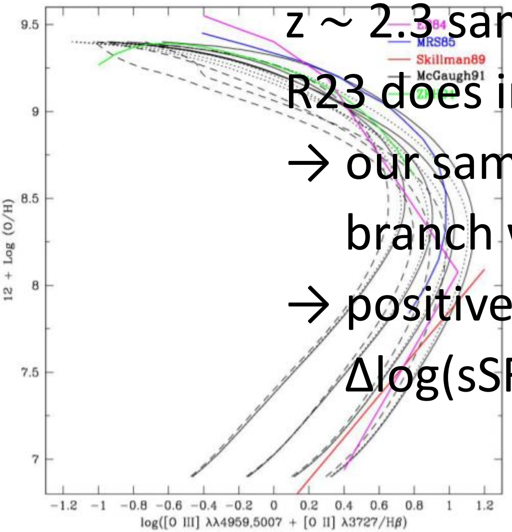
- O32 trend is not obvious in this study, while SDSS shows clear correlation. (Discussion part)



- O3 ratio is sensitive to ionization parameter and metallicity
  - a decrease in metallicity (increase in O3) as sSFR increases at fixed M_*

- R23 ratio is sensitive to O/H but has significant ionization parameter dependence
  - R23 is not a strong function of M_* for the z ~ 2.3 sample (turnover regime)
  - R23 does increase slightly with decreasing M_*
  - → our sample mostly lies on the upper metal-rich R23 branch where R23 increases with decreasing O/H
  - → positive correlation between Δlog(R23) versus Δlog(sSFR)





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34	9.20–9.92; $9.55^{+0.01}_{-0.05}$	$32.1^{+3.0}_{-4.1}$
34	9.92–10.5; $10.25^{+0.01}_{-0.03}$	$88.2^{+17.3}_{-1.0}$

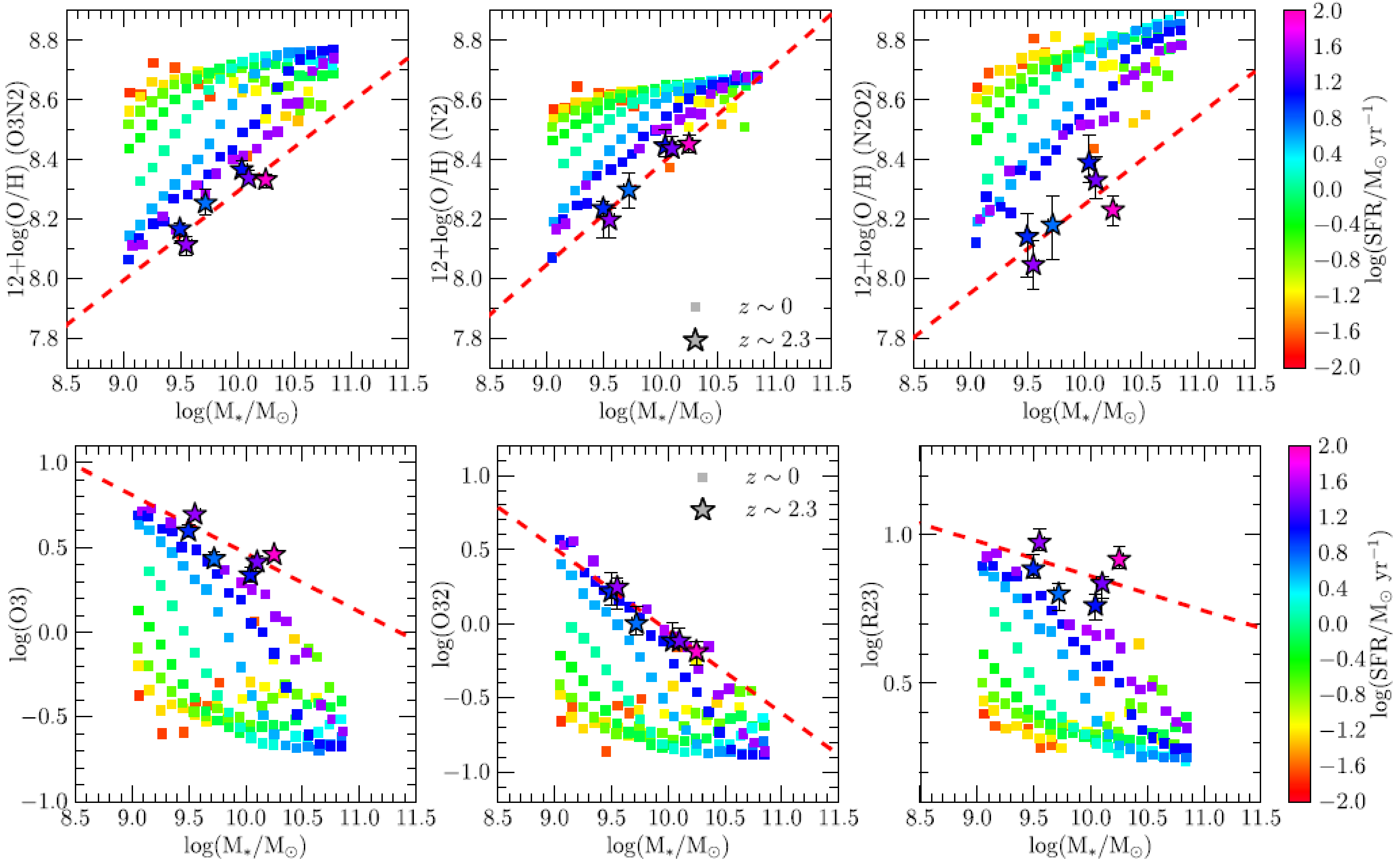
3. Do z ~ 2.3 Galaxies Lie on the z ~ 0 FMR?

- Test whether or a FMR exists that extends out to z ~ 2.3
- The highest-SFR/mass z ~ 2.3 stack, does not have any local analogue in the SDSS sample. However, all other z ~ 2.3 stacks have analogous z ~ 0 counterparts matched in M_* and SFR.

z ~ 2.3 galaxies display metallicities that are lower than their z ~ 0 counterparts by ~0.1 dex at fixed M_* and SFR

→ There is not a FMR that can simultaneously match the properties of star-forming galaxies from z ~ 0 out to z ~ 2.3 (argue against redshift invariance)

The z ~ 2.3 stacks display higher O3 and R23 than z ~ 0 stacks at fixed M* and SFR, suggesting higher excitation and lower metallicity at fixed M* and SFR at z ~ 2.3 (O32, discussion part)



Discussion

1. Potential Evolution in Metallicity Calibrations and Ionized Gas Physical Conditions

- Physical conditions of ionized gas in star-forming regions evolve with redshift
  No consensus: the ionization parameter, N/O ratio, the shape of the ionizing spectrum
  Consensus: electron density (increase with redshift, but no influence on this study)
- MOSDEF: high-redshift galaxies have elevated N/O at fixed O/H compared to $z \sim 0$ galaxies
  Explanations: high occurrence rate of Wolf–Rayet stars, pristine gas inflows
- Steidel+16: A harder ionizing spectrum at fixed nebular abundance in high-redshift star-forming regions
- Kewley+13,15,16: An elevated ionization parameter in high-redshift galaxies (Larger sSFR)

1.1 Nitrogen-to-Oxygen Ratio

- N/O ratio in this study: increasing sSFR at fixed M_*, higher O3N2, lower N2, and lower N2O2
- lower N/O at fixed O/H (Without metallicity variation) ?
  ↔ Wolf–Rayet stars scenario (Masters+14)
  ↔ high-redshift galaxies have higher N2 at fixed O3 compared to the $z \sim 0$ population

1.2 Ionization Parameter and Hardness of the Ionizing Spectrum

- Younger populations → lower Fe/O (time-delayed of Fe production) → harder spectrum → higher ionization parameter → higher O3 and O3N2 at fixed O/H

For N2, a harder ionizing spectrum increasing N2

- This may explain the trend on the ΔO3N2-ΔsSFR and ΔO3-ΔsSFR without the introduction of M_*–SFR–Z relation, but cannot explain that of ΔN2-ΔsSFR (harder ionizing spectrum cannot reproduce the observed result)

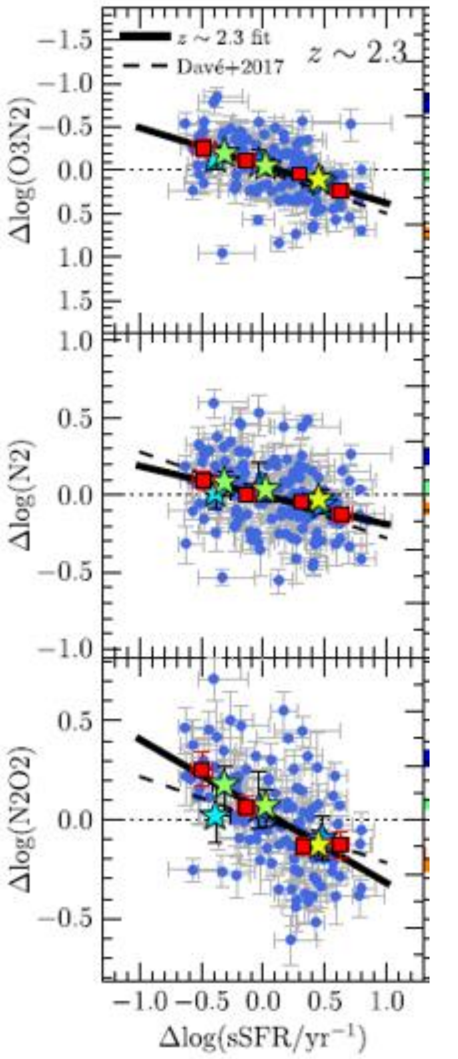
For N2, a higher ionization parameter decreases N2

- Fits the observation trends

But N2O2 may not be significantly affected by changes in the ionization parameter, since it is a ratio of two low-ionization lines with similar ionization energies.

- Ionization parameter is not the only influencing factor

The observed trends in O3N2, N2, N2O2, and O3 are primarily driven by metallicity variations, and that the z ~ 2.3 M_*–SFR–Z relation and evolution in O/H at fixed M_* and SFR are real.



2. Implications of the Evolution of the M_* –SFR–Z Relation

- The existence of a M_* –SFR–Z relation at z ~ 2.3 supports the theoretical prediction from analytical chemical evolution models and cosmological hydrodynamical simulations.

Cosmological hydrodynamical simulation (Dave + 17, long-dashed line)

- Δlog(O/H) v.s Δlog(sSFR), slope: −0.16 and independent of redshift
- Observation results located within 2σ of Dave+17, consistent
- Compare with z ~ 0 samples, requiring a recalibration of line ratio metallicity relations at high redshift

The ~0.1 dex offset (lower metallicity at high redshift)

- Gas reservoir theory: exceeding inflow (only feasible at z > 4, unlikely)

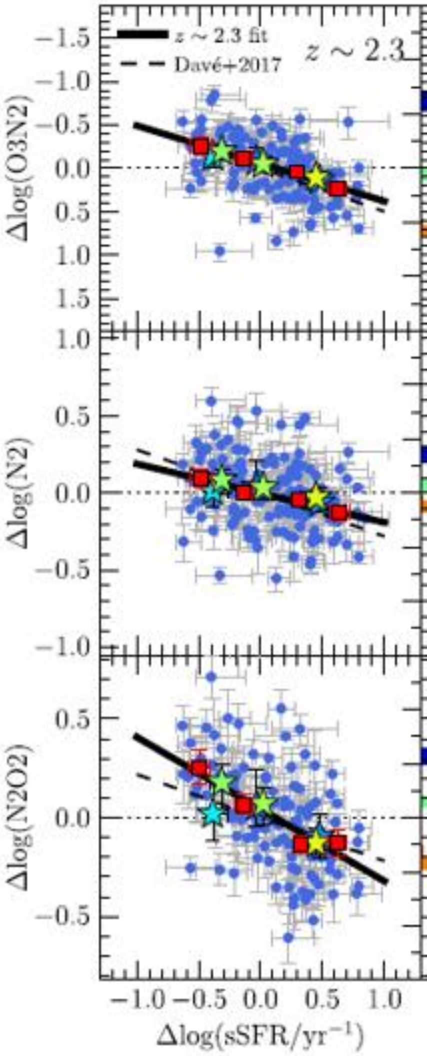
→ The evolving M_* –SFR–Z relation is related to gas properties.

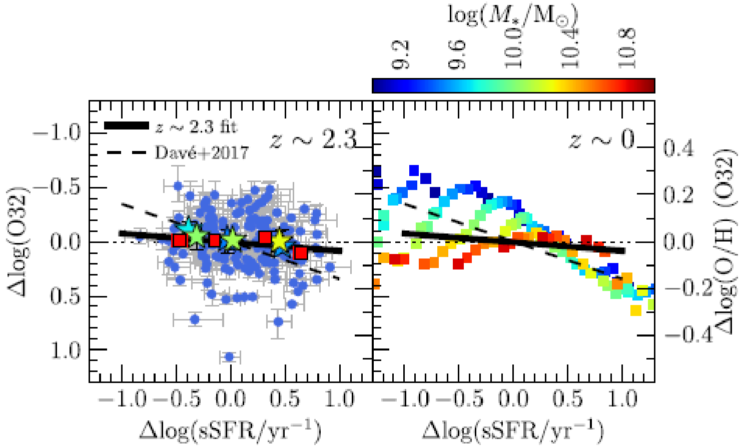
gas consumption timescale, the mass-loading factor (η=outflow rate/SFR)

lower metallicity → longer timescale → lower star formation efficiency ×

→ larger mass-loading factor ◯

Pristine gas accretion from the IGM is more important at high redshift than recycled gas accretion





3. The Inconsistency of Results Based on O32

- Dust correction curve should not be the case. (N2O2, R23)

A. Dependence of the shape of the attenuation curve on SFR

- Dust-correction recipe leads to either underestimated $E(B-V)_{gas}$ for z ~ 2.3 galaxies below the SFR–M_* relation, overestimated $E(B-V)_{gas}$ for objects above the SFR–M_* relation, or both.
  → At low Δlog(sSFR), overestimate of O32; At high Δlog(sSFR), underestimate of O32

B. O32 line's physics

- O32 directly probes the ionization parameter and is only sensitive to metallicity because of the anticorrelation between ionization parameter and metallicity.

  Ionization parameter does not depend on metallicity at z ~ 2.3 so strongly as local

A is most likely