The importance of abundance ratios in interpreting high-z emission line spectra

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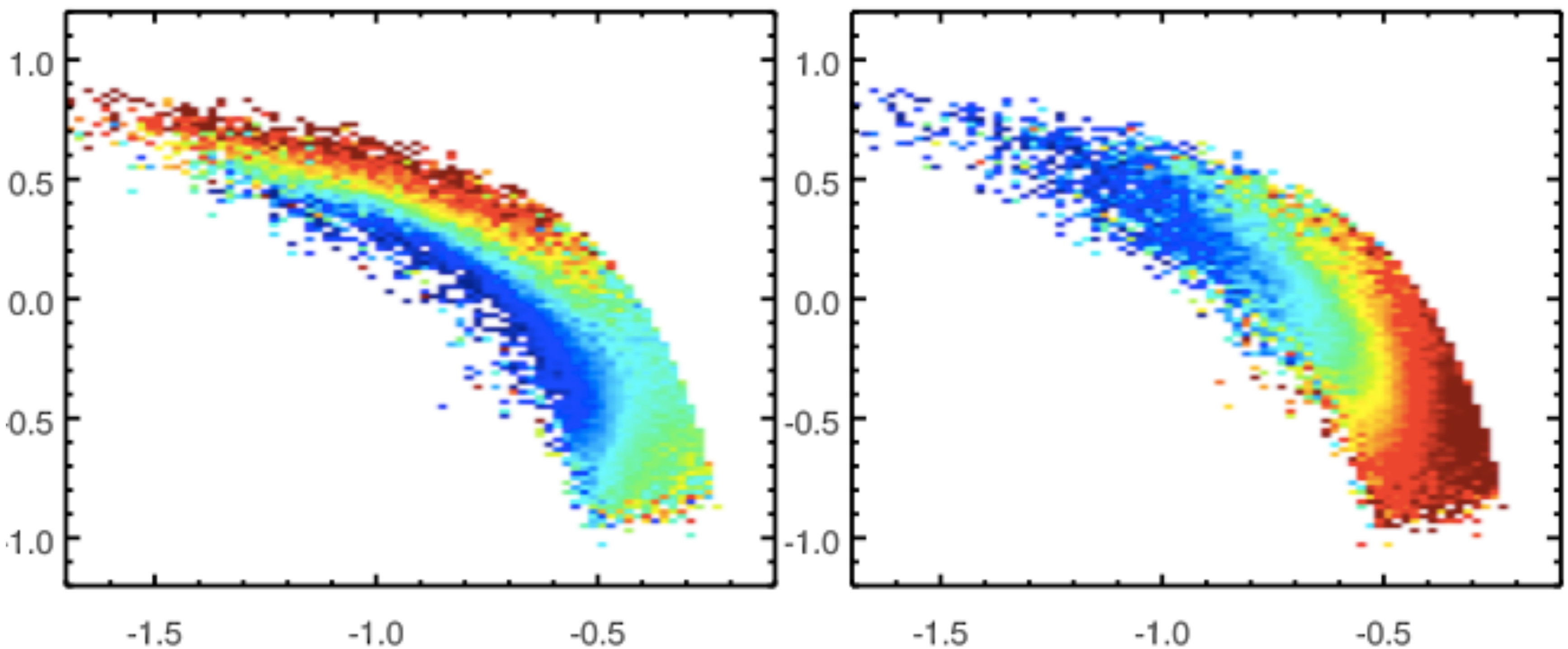
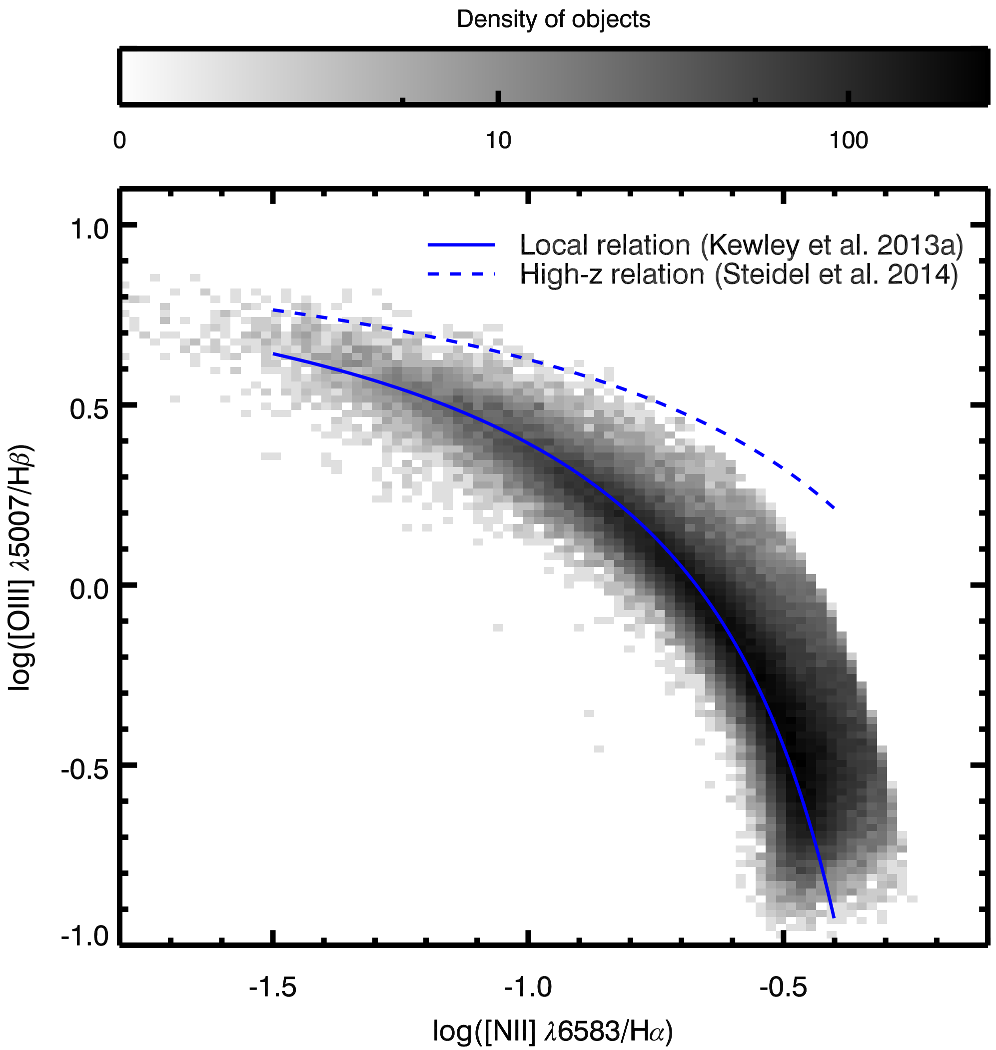
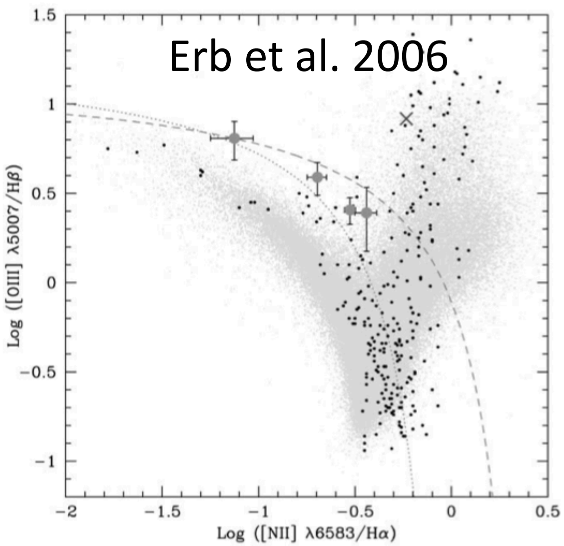


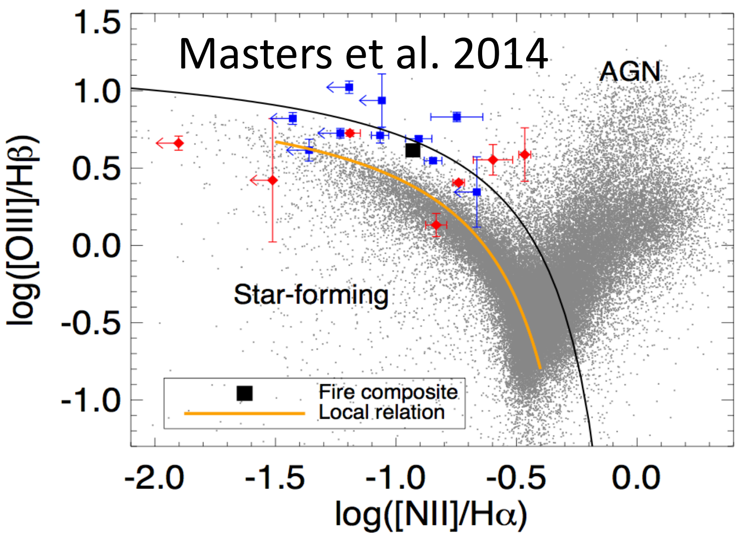
KICC workshop “Emission line galaxies with MOS” Sept. 19, 2017

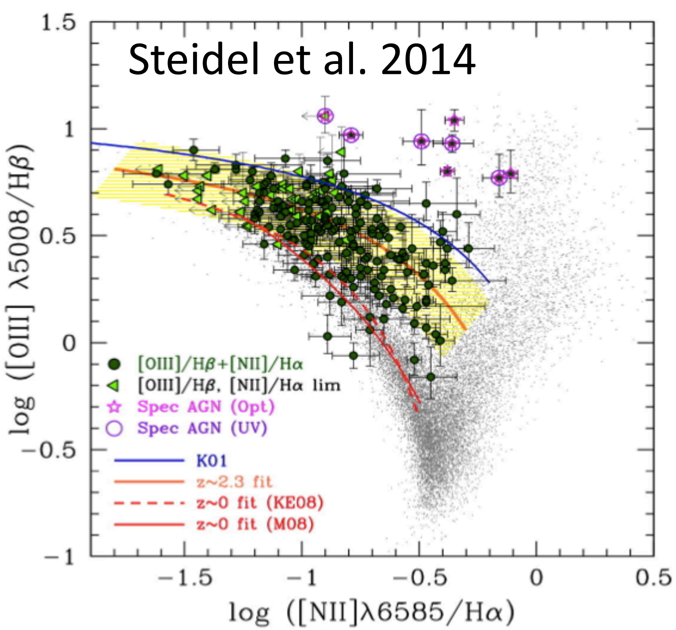
The Local "BPT" diagram

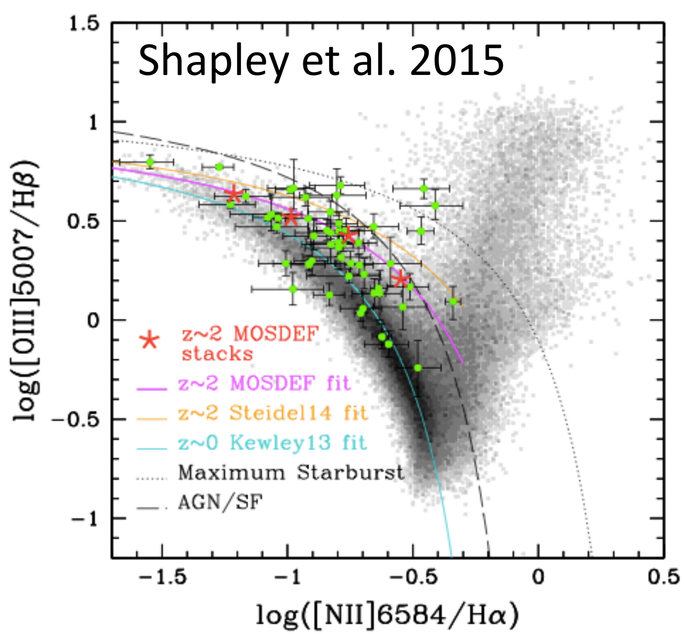


High-z galaxies *systematically* offset in O3N2



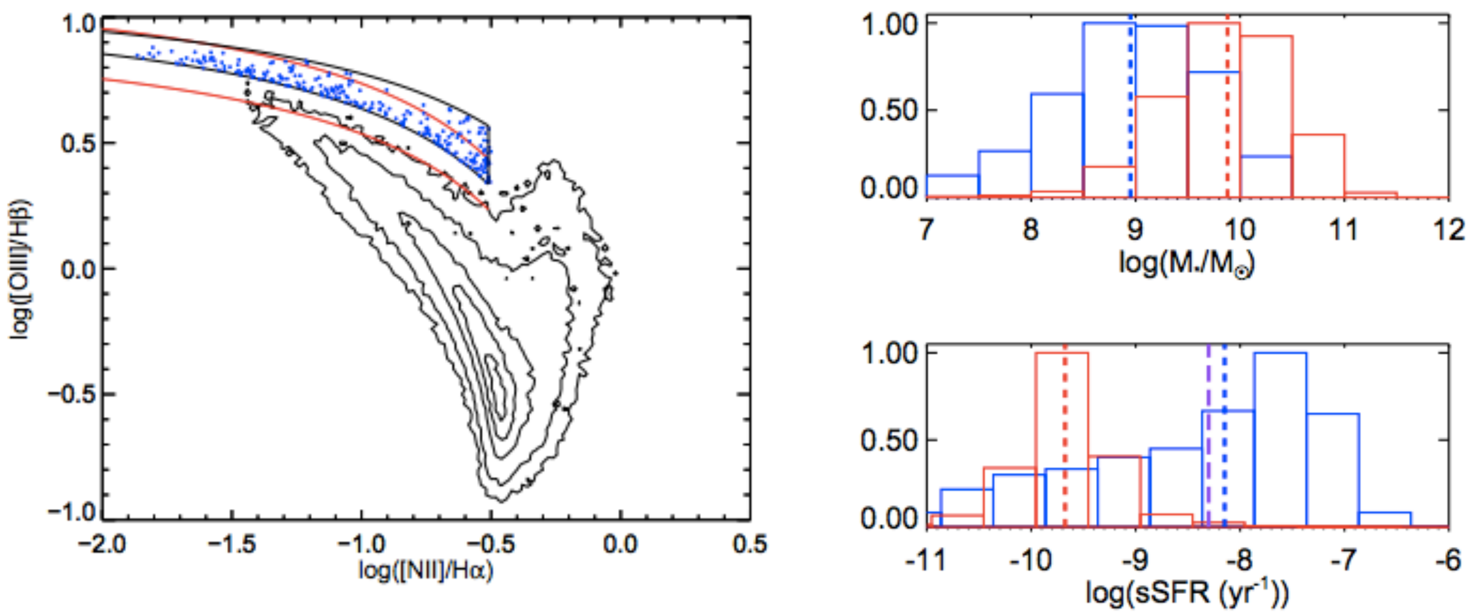






Local analogs

- A (rare) population of local galaxies exists that is remarkably similar in global properties to the high-redshift samples
  - E.g., the “green peas” (Cardamone et al. 2010)
  - Occupy same part of O3N2 diagram as high-z samples, with enhanced sSFRs & ionization parameters (Bian et al. 2016)



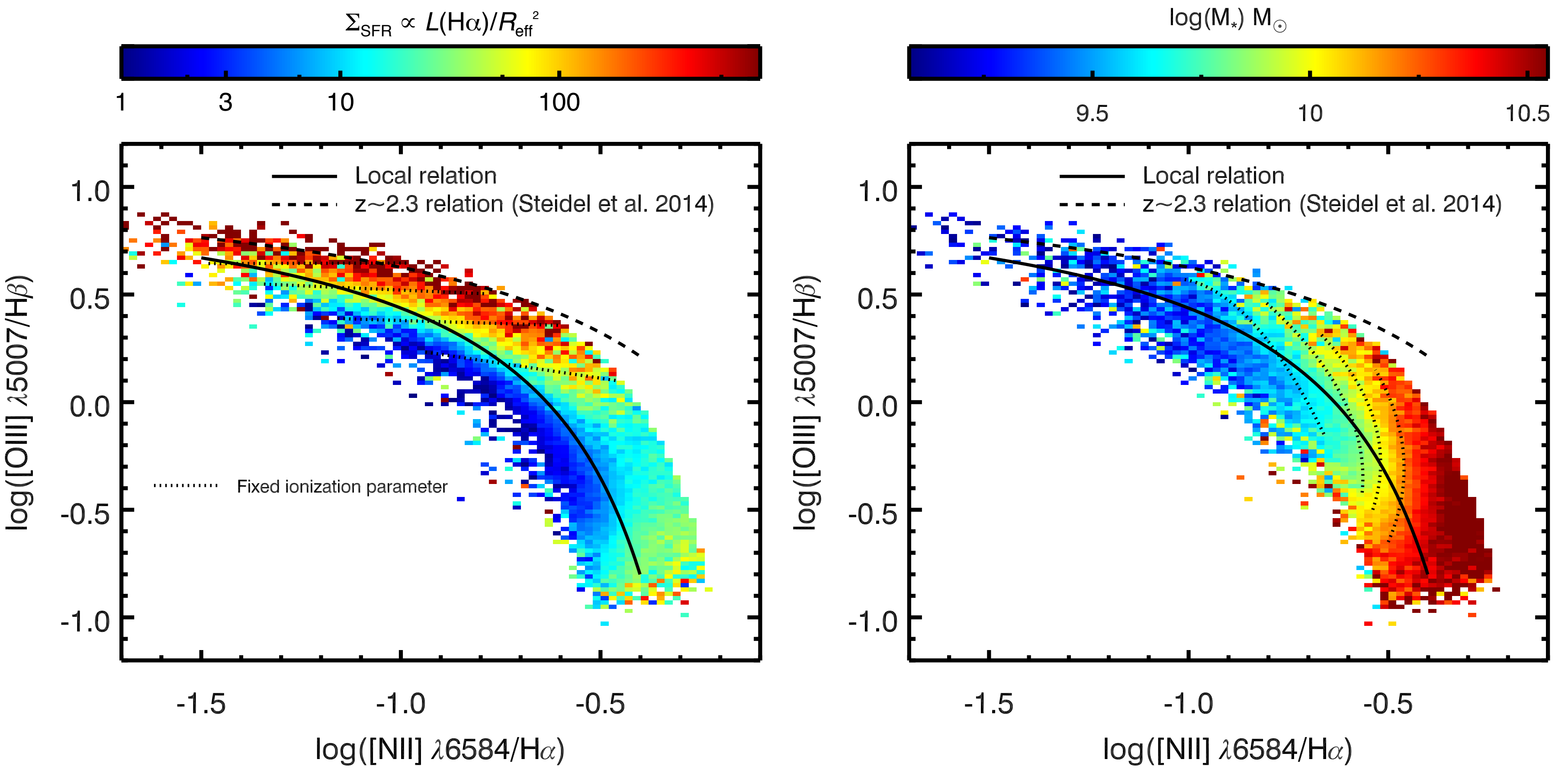
From Bian et al. 2016

Use empirical correlations in O3N2

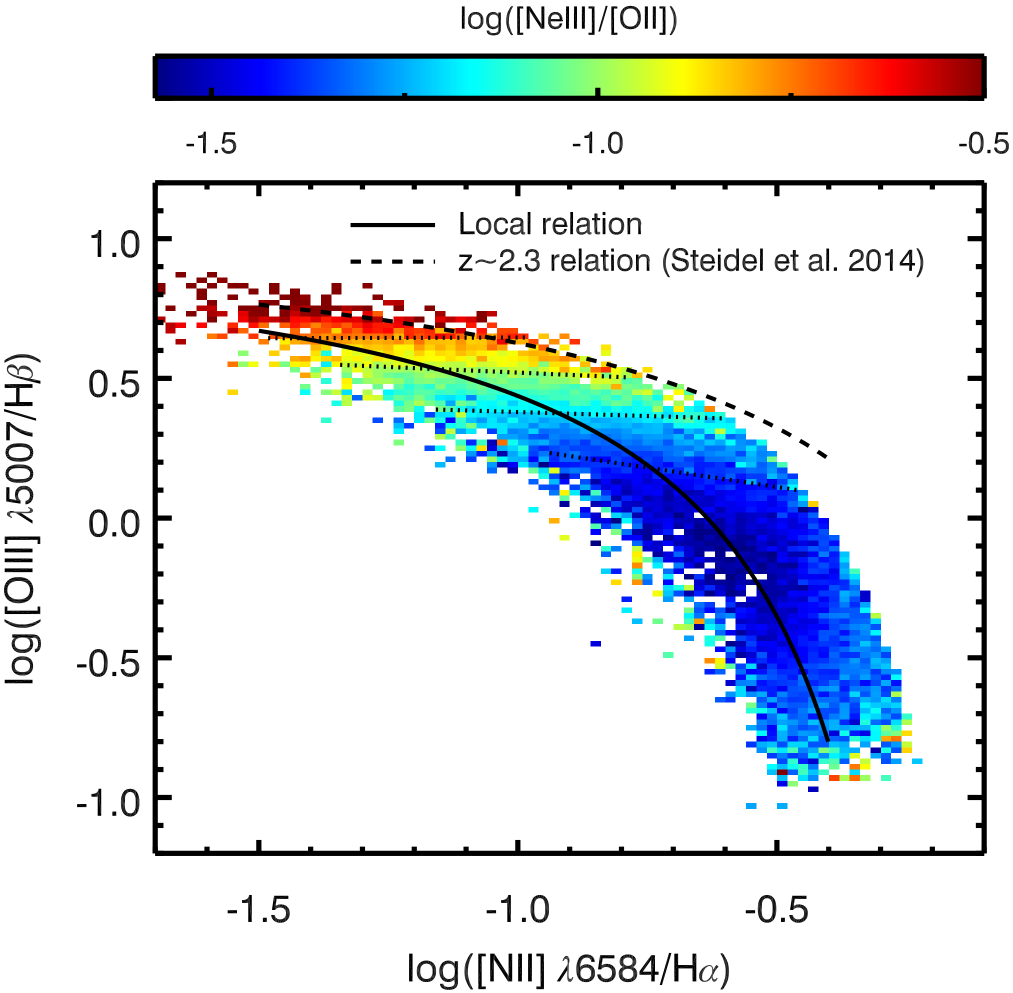
- Examine how measurable physical properties of SDSS galaxies correlate with position on the diagnostic diagram
  - SDSS data has the advantage of S/N and statistical power, contains numerous “analogs” to high-z galaxies
- Assume the same factors that cause local analogs to be offset in the O3N2 diagram drive the observed shift at high redshift

Masters et al. 2016 ApJ 828, 18

SFR density and stellar mass in O3N2

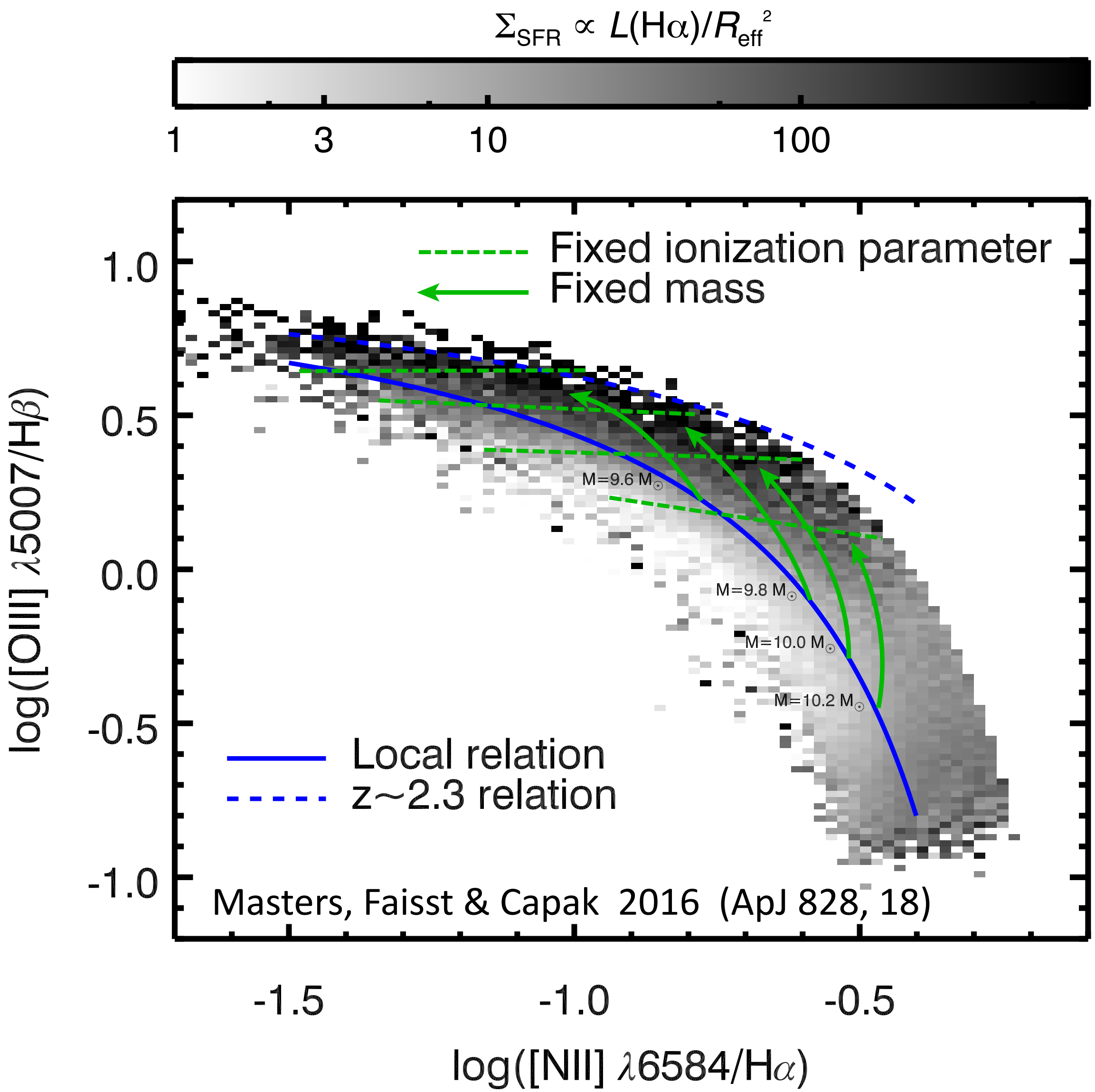


[NeIII]/[OII] in O3N2 space



[OIII]/Hβ closely linked to ionization parameter over most of the diagram

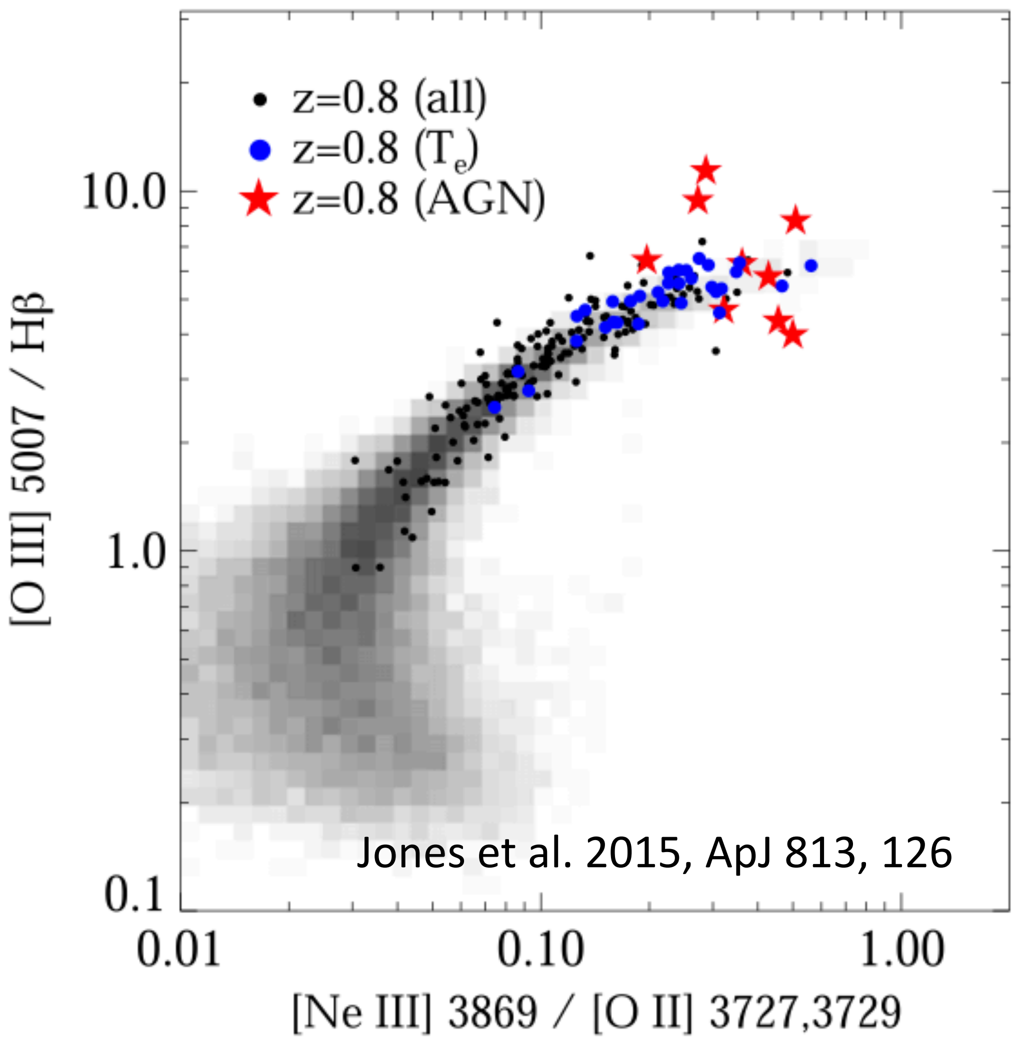
Putting it together



Interpretation

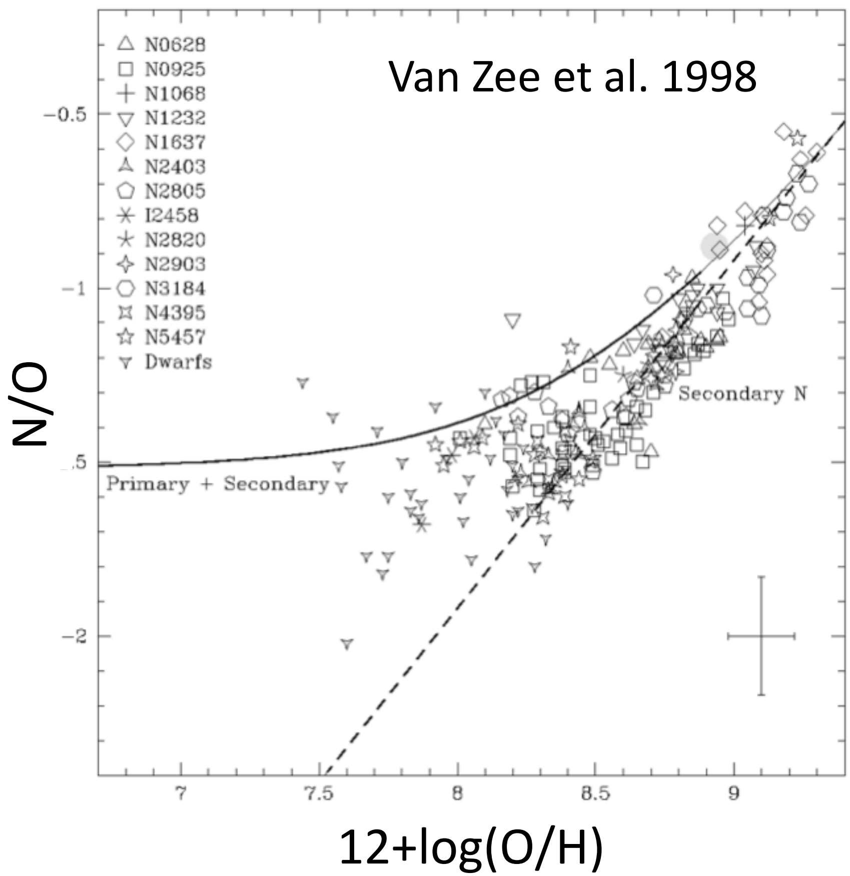
- Evolving BPT locus reflects changing mass-metallicity relation, which in turn reflects higher global SFR at high redshift
- But why does the position of the locus shift? Why don’t galaxies just move along the BPT locus with decreasing metallicity?

No shift in diagrams not involving N

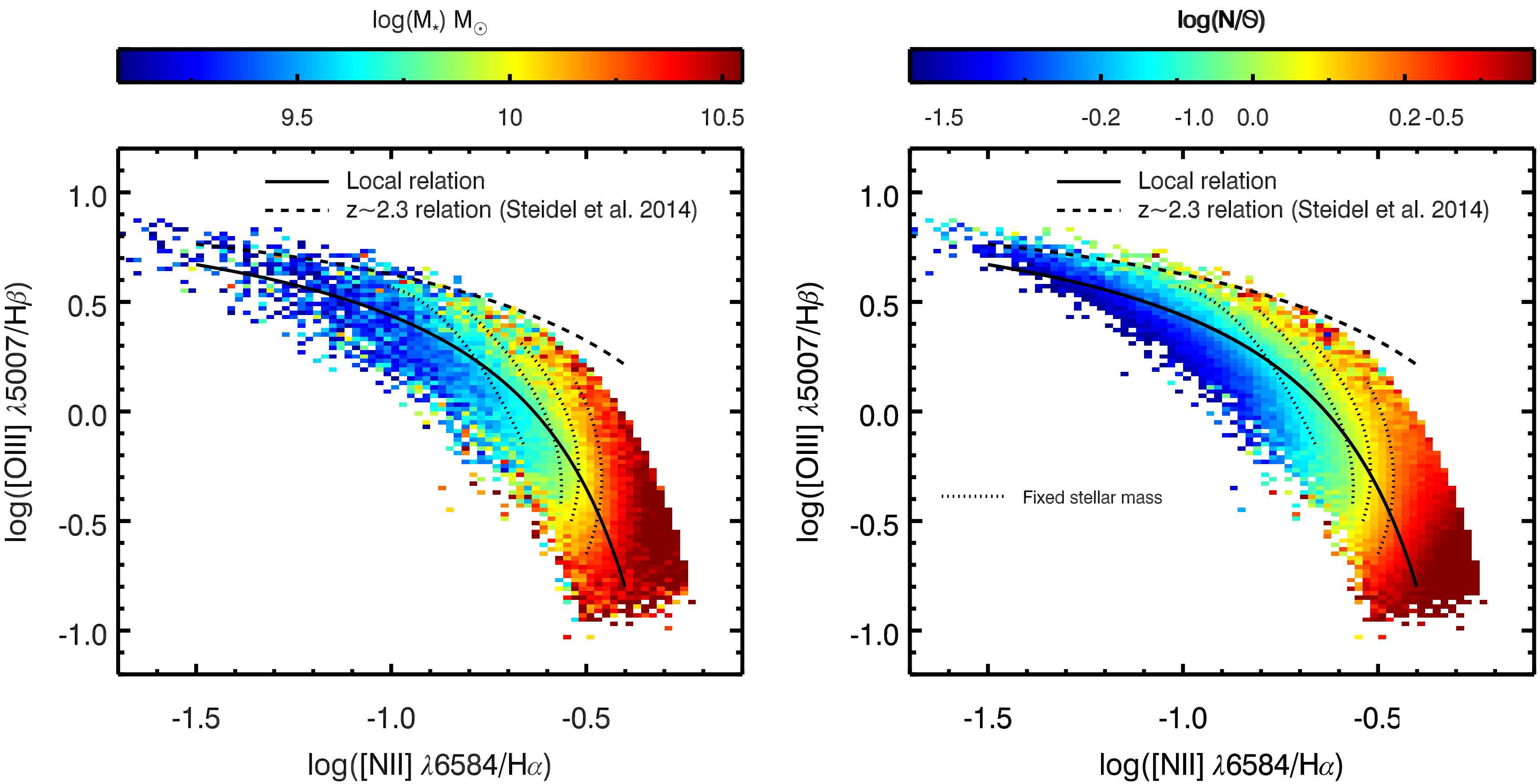


BPT diagram is sensitive to the N/O ratio

- N/O ratio directly impacts where galaxies fall on the x axis of the BPT diagram

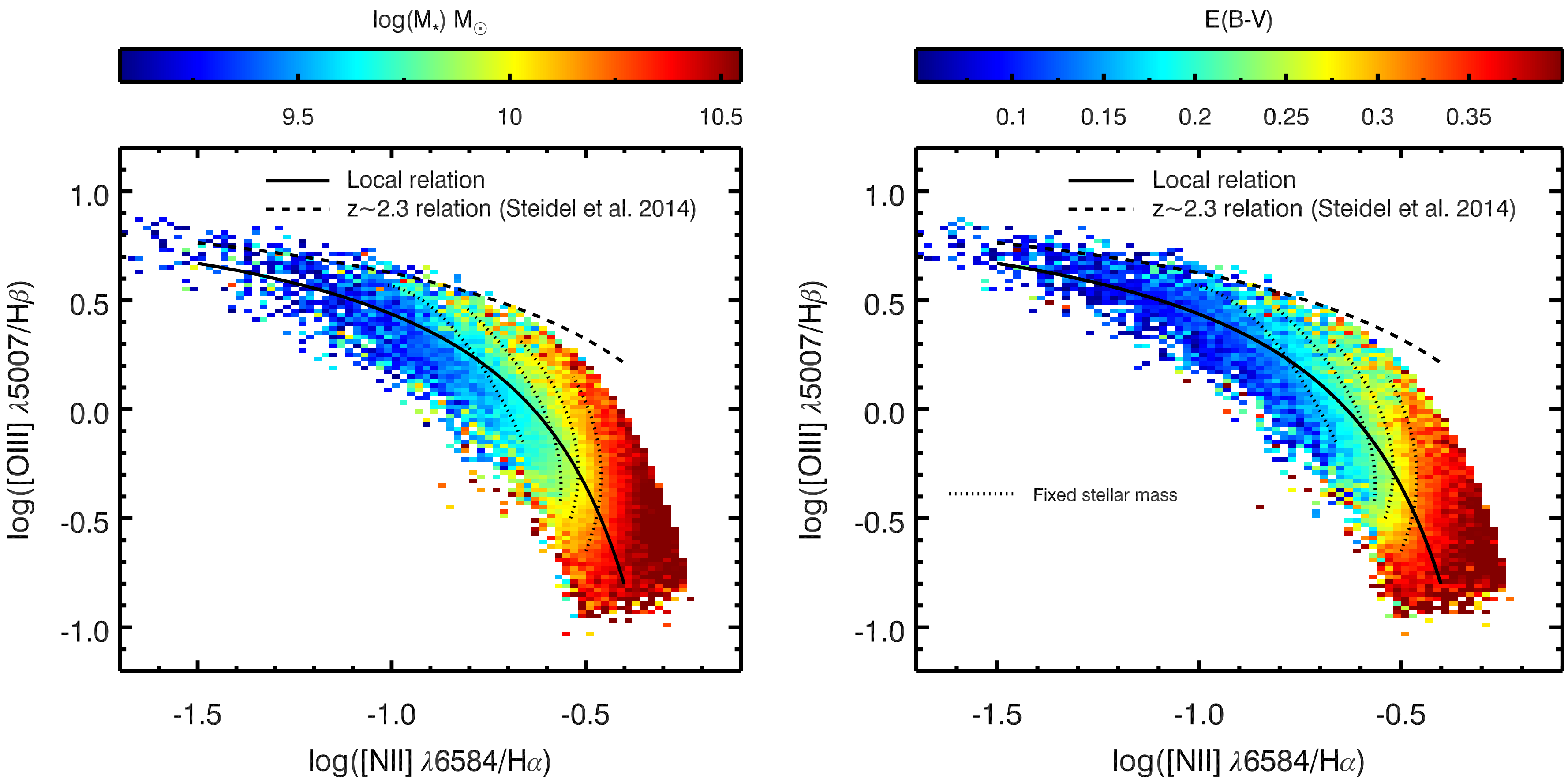


N/O ratio and stellar mass strongly correlated!



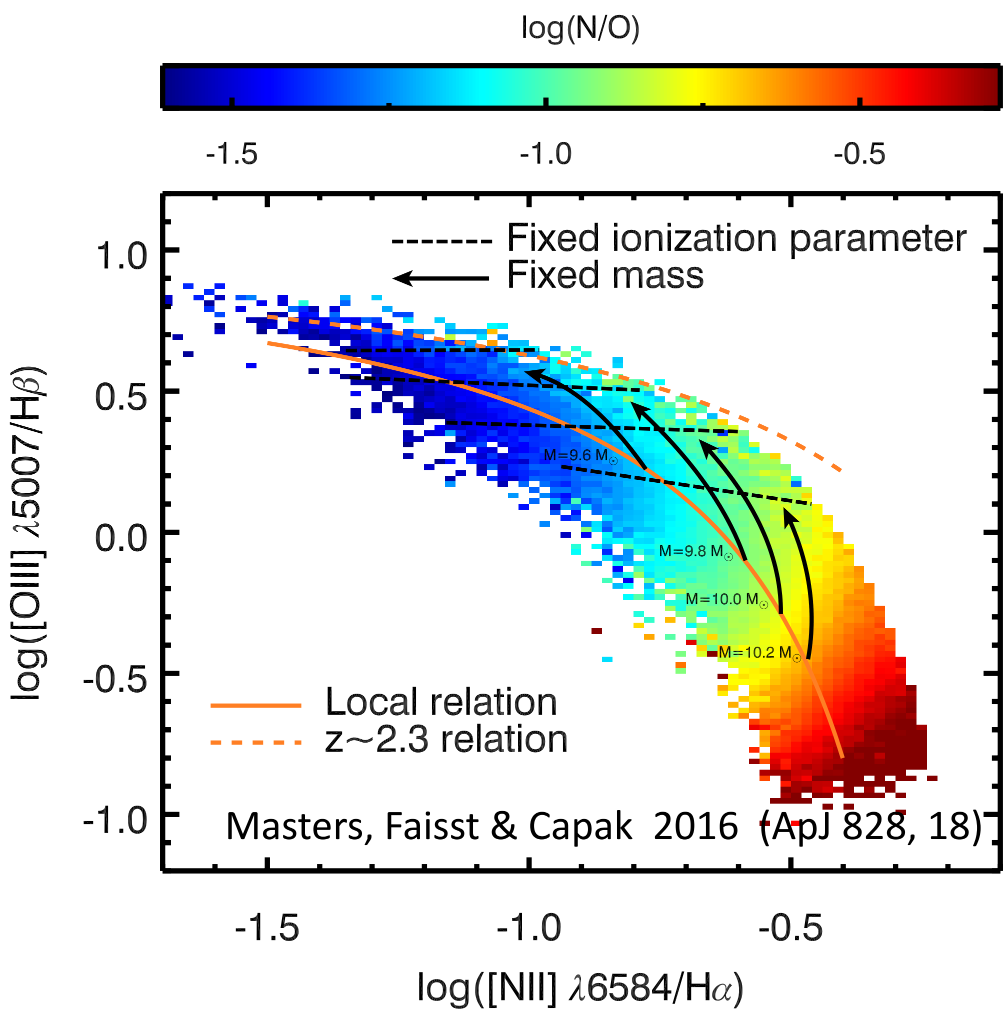
N/O ratio and stellar mass are distributed similarly across most of the diagnostic diagram, spanning a range of metallicities, SFRs, and ionization states – strong evidence that N/O-mass relation is more fundamental than N/O-metallicity

A quick aside on E(B-V)



E(B-V) from Balmer decrement shows a similar fundamental correlation with stellar mass, as also noted by Garn & Best 2010

Physical interpretation



At fixed [OIII]/Hβ, moving toward the high-z locus is associated with both higher stellar mass and N/O ratio

Why is N/O linked to mass?

- N/O ratio insensitive to inflows of H
  - Mostly insensitive to metal outflows as well
- O/H, in contrast, depends strongly on inflows
- Stellar mass of a galaxy is a rough measure of the past integral of chemical production through multiple stellar generations
  - N/O can be thought of as a marker of *chemical maturity*
  - Increases with secondary production of nitrogen through CN cycling in intermediate and massive stars

Conclusions

- Redshift evolution of line ratios in the BPT diagram arises naturally as a result of the evolution of the galaxy mass-metallicity relation
- Abscissa of BPT diagram ([NII]/Hα) is *sensitive to stellar mass* through its effect on the nitrogen-to-oxygen (N/O) abundance ratio
- N/O ratio is more fundamentally linked to stellar mass than to metallicity
- Nitrogen-based metallicity indicators should be viewed with caution – sensitive to N/O and hence mass
- Generally: galaxies with the same O/H at different redshifts are not the same

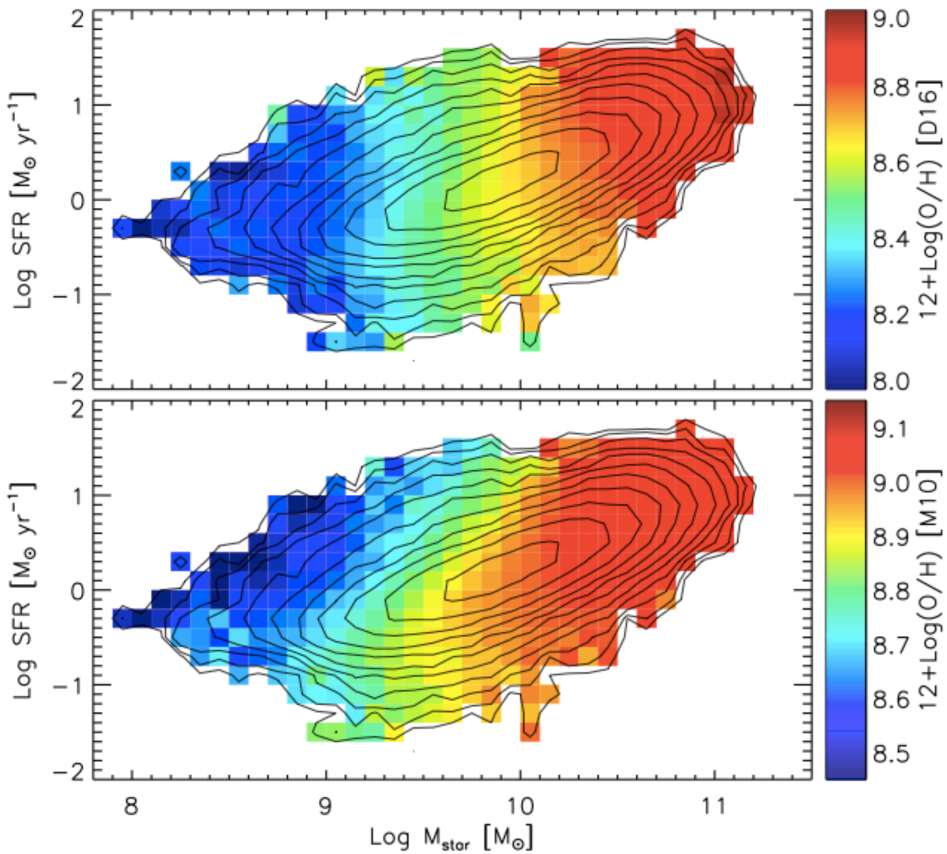
Implications for the Local FMR

A "fundamental metallicity relation" (FMR) has been proposed between mass, metallicity, and star formation rate (e.g., Mannucci 2010)

Top: Using new N/S-based metallicity calibration from Dopita et al. 2016 (primarily using the N/S ratio to measure metallicity)

Bottom: Using metallicity calibrations from Mannucci et al. 2010

The local FMR will appear weaker or absent when using nitrogen-based metallicity calibrations



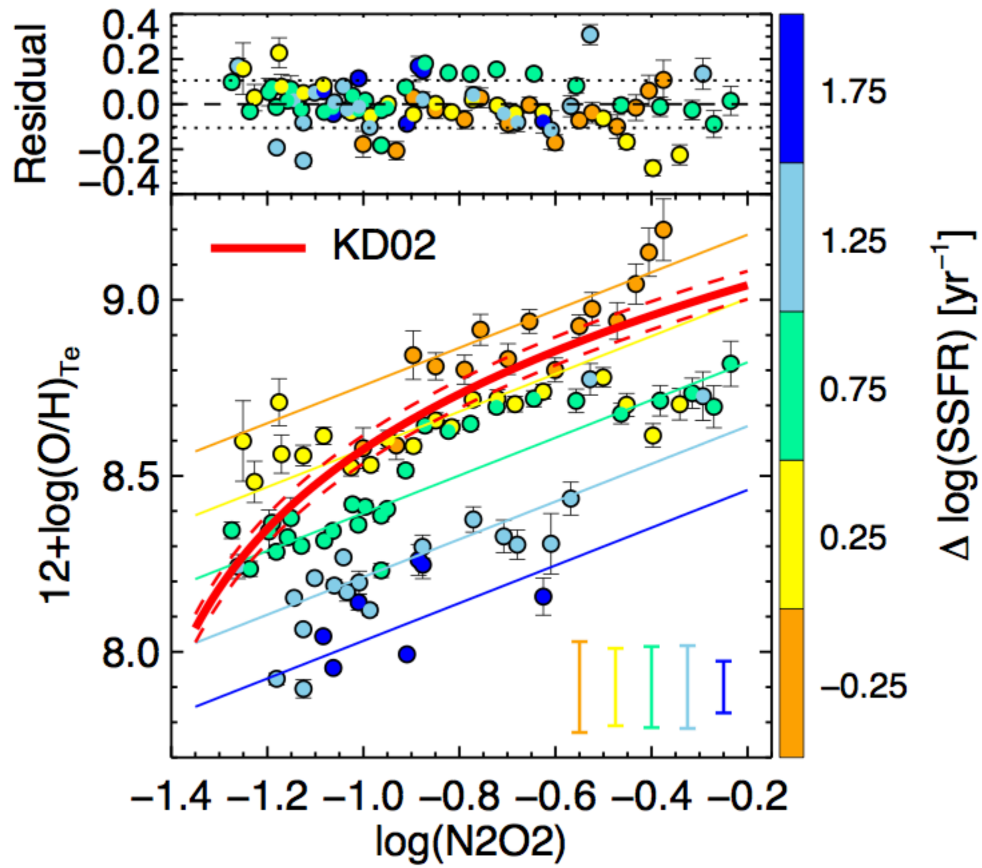
From Kashino et al. 2016, "Hide-and-Seek with the Fundamental Metallicity Relation"

Dissecting the BPT diagram

- Examine how four measurable galaxy physical properties correlate with position in the O3N2 diagnostic diagram:
  (1) Σ_{SFR}, using the proxy $L(H\alpha)/R_{eff}^2$
  (2) Ionization parameter, from [NeIII] λ3869/[OII] $\lambda\lambda$3726,3729 (Levesque & Richardson 2014)
  (3) N/O ratio, from the dust-corrected ratio [NII]λ6584/[OII]$\lambda\lambda$3726,3729
  (4) Stellar mass
- ~100,000 galaxies from SDSS used for this analysis
  – See Masters, Faisst & Capak 2016 for details

Dependence of N/O vs. O/H on sSFR

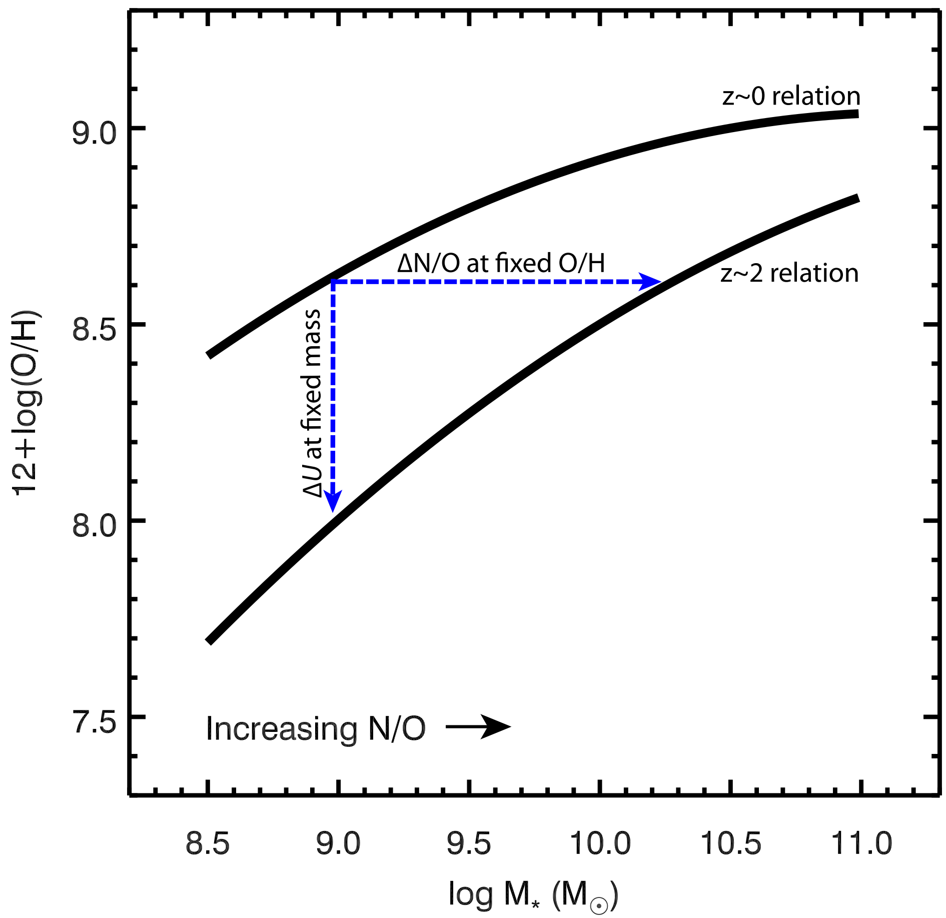
- The local N/O vs. O/H relation is found to have a strong secondary dependence on sSFR (e.g., Brown et al. 2016)
- N/O-mass relation does not show such a secondary dependence on sSFR



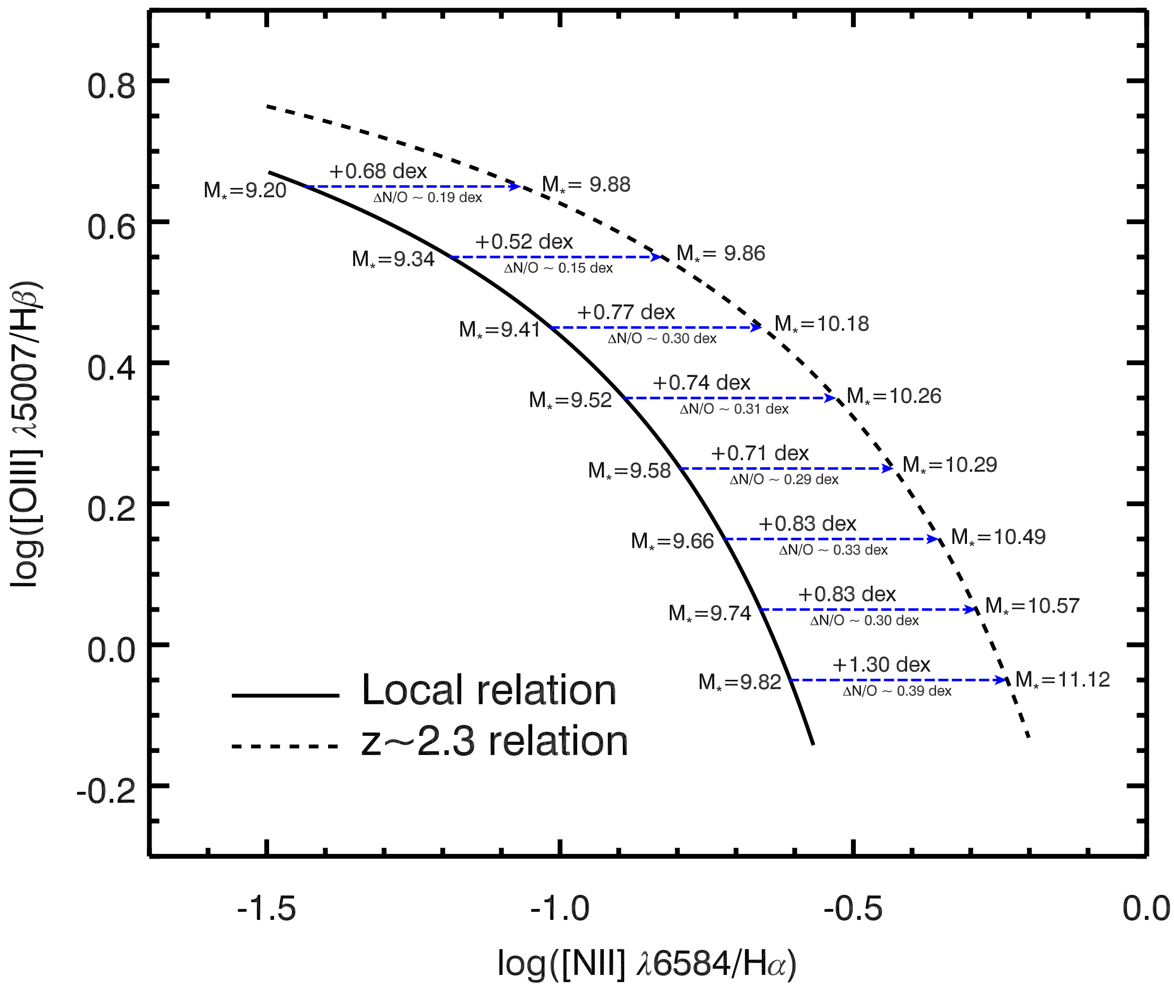
From Brown et al. 2016

N/O-M$_*$ relation + MZ evolution = BPT shift

High-z shift can be explained similarly



Mass in the BPT diagram at low/high-z



Measurements at z~2.3 from KBSS (Steidel et al. 2014)

Summary of physical interpretation

- At fixed mass at high redshift, metallicity is lower and ionization parameter is higher (evolution of the MZ relation)

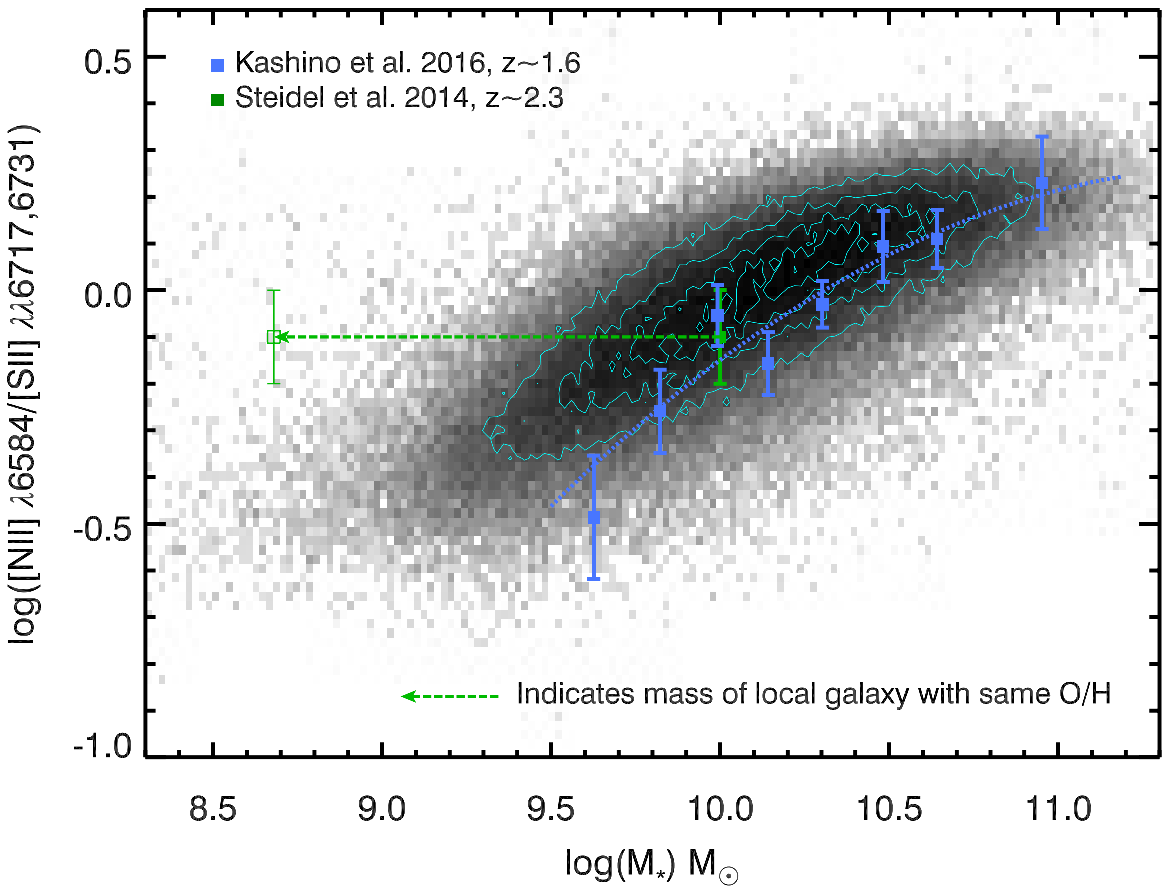
  $\longrightarrow$ Elevated [OIII]/Hβ at fixed mass

- At fixed [OIII]/Hβ at high redshift, both N/O ratio and stellar mass are higher

  $\longrightarrow$ Elevated [NII]/Hα at fixed [OIII]/Hβ ratio / metallicity

The O3N2 shift can be viewed as a consequence of the evolution of the mass-metallicity relation combined with the link between stellar mass and relative nitrogen abundance

N/S vs. stellar mass at high-redshift



Some evolution of the N/S-mass relation with redshift is observed, but not as much as would be expected from evolution of MZ relation if the N/O-O/H relation were invariant.

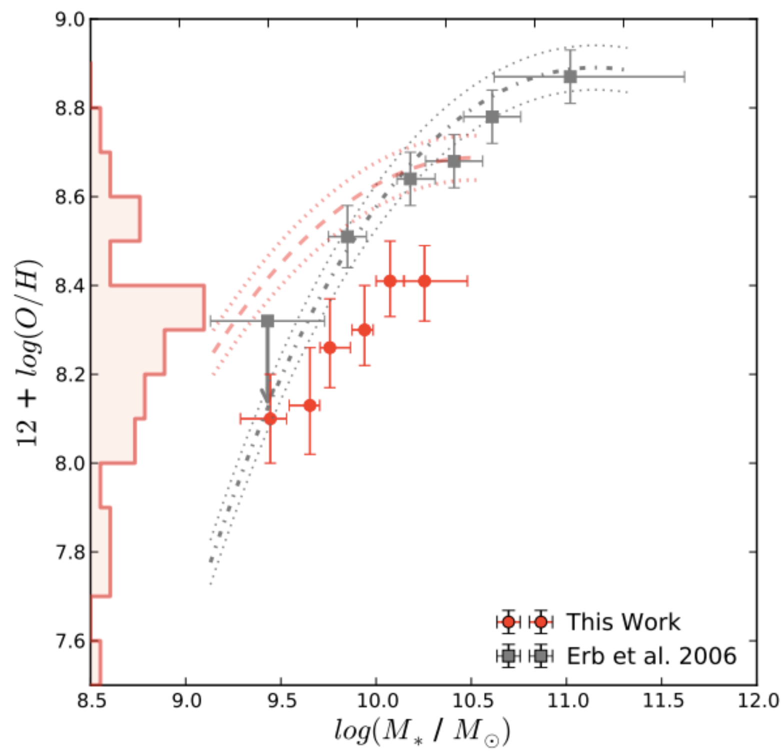
The production of nitrogen

- Nitrogen is produced in CNO burning in intermediate and high mass stars
- Which stars most effectively return nitrogen to the ISM and the relevant timescales are key uncertainties
- Extensive literature on the subject going back decades
  - E.g., Alloin et. Al. 1979, Vila Costas & Edmunds 1993, Henry et al. 2000, and references therein

Implications for metallicity calibrations

- Metallicity calibrations involving nitrogen depend on the scaling of N/O with O/H
- An N/O-mass relation implies that these calibrations are sensitive to *stellar mass* in addition to instantaneous gas-phase metallicity

Right: The z~2 MZ relation from Cullen et al. 2014 using calibration based on [OII], [OIII], and $H\beta$, compared with Erb et al. 2006 using [NII]/$H\alpha$



Diagnostics involving stellar mass evolve as well

This strong evolution in the O32 vs. mass diagram shows that high-z galaxies at a given mass have much higher ionization parameters than low-z counterparts.

From Sanders et al. 2016