Increasing the accuracy of metallicity measurements over the past 12 Gyr of cosmic history (z=0-4)

Ryan Sanders, UCLA

Baryons follow a complex cycle into and out of galaxies

Accretion of gas from the IGM

Star formation

Outflows

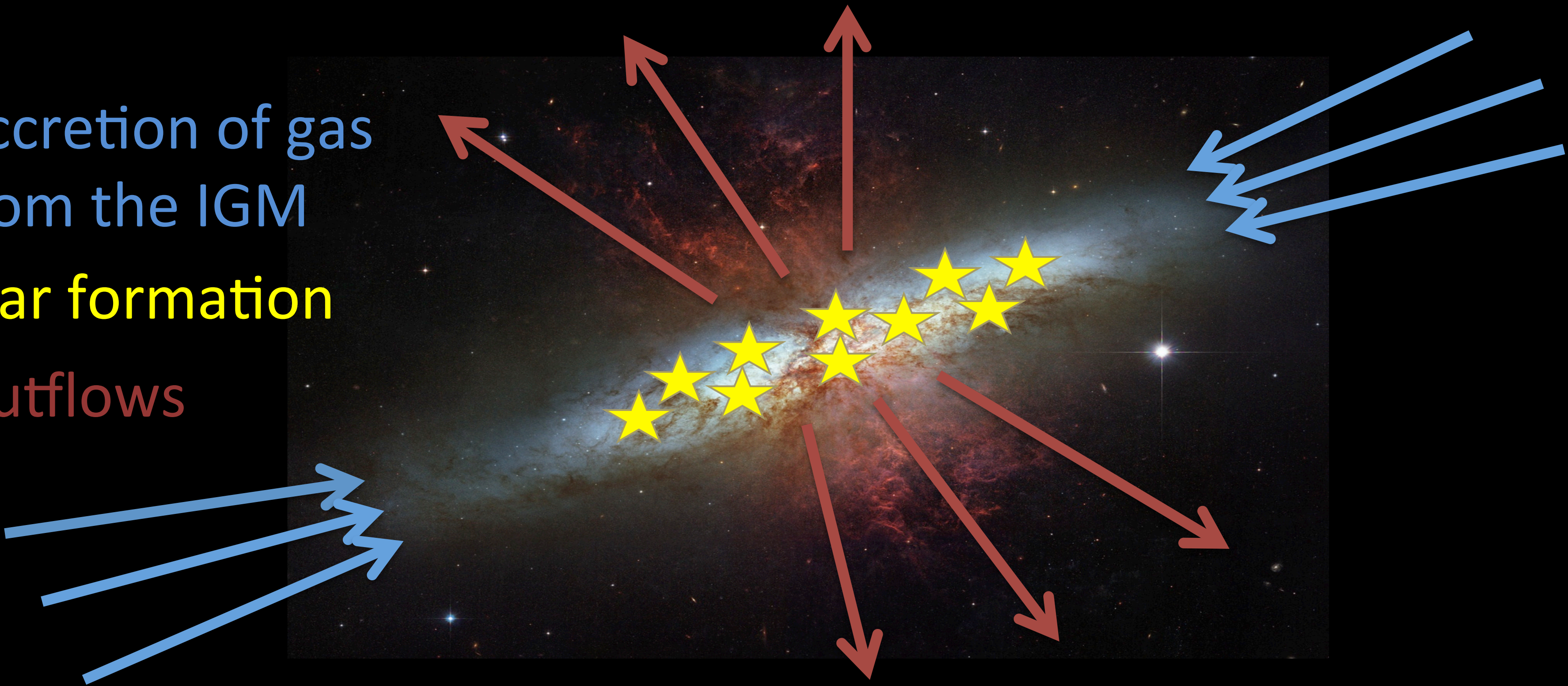

Image credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Baryons follow a complex cycle into and out of galaxies …and gas-phase metallicity is sensitive to this cycle

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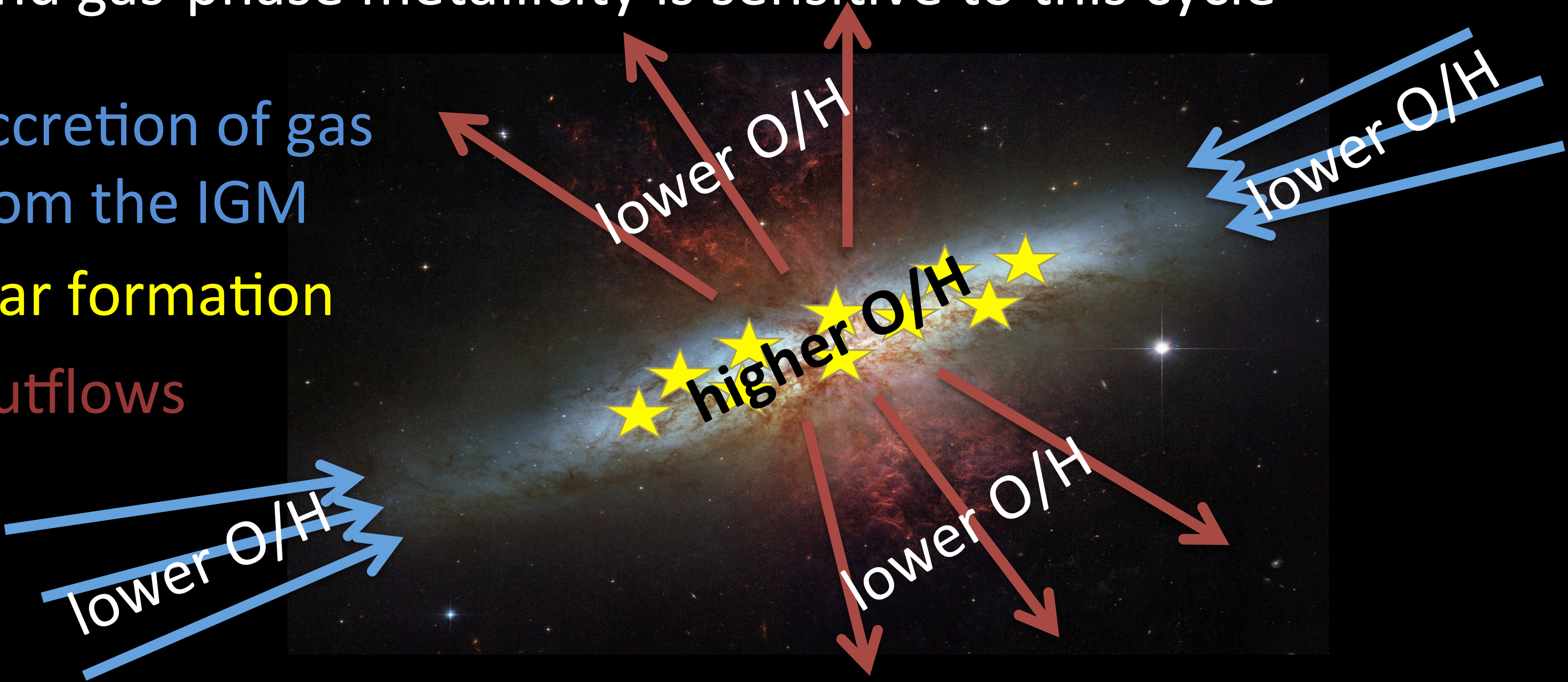
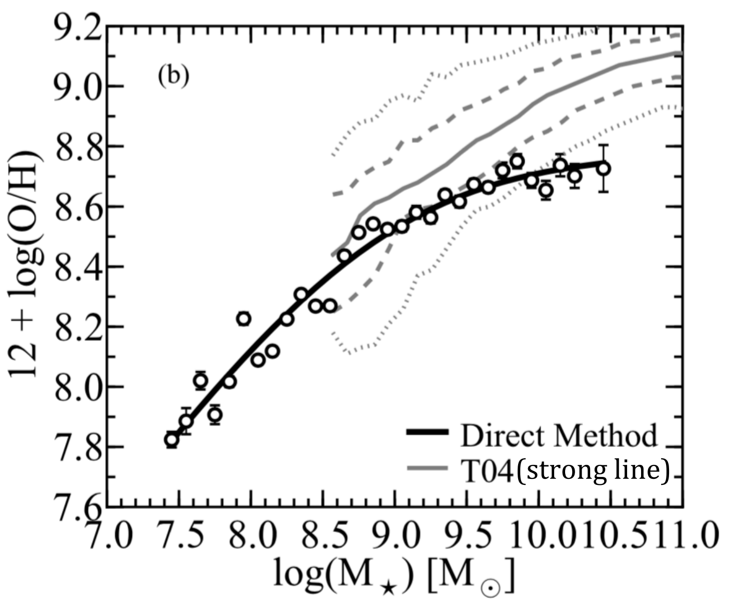


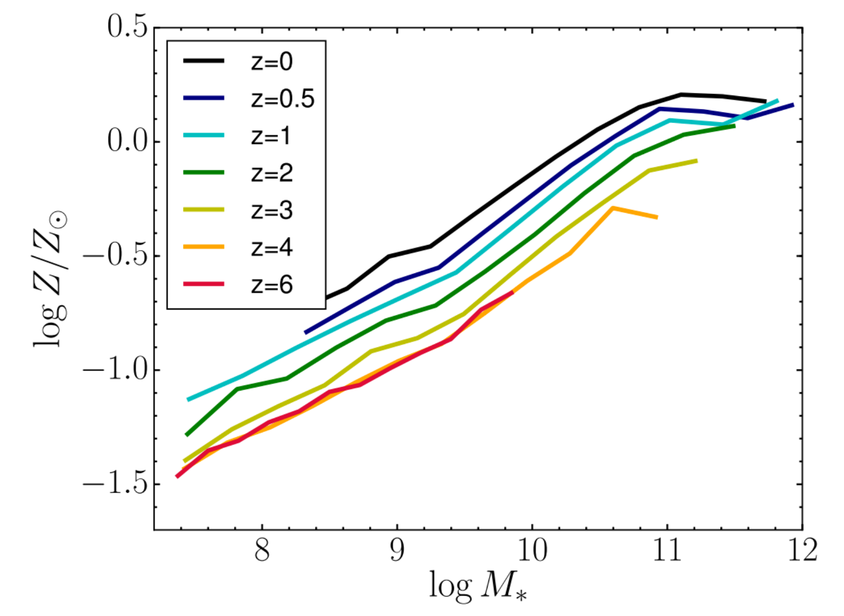
Image credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA)

Galaxy metallicity scaling relations are determined by the interplay of inflows, outflows, and star formation.

- Shape and normalization of the mass-metallicity relation (MZR) encodes the stellar mass dependence of the efficiency of galactic outflows
- Redshift evolution probes galaxy growth at multiple epochs in cosmic history



Andrews & Martini 2013
Tremonti+2004



mufasa: Davé+2017

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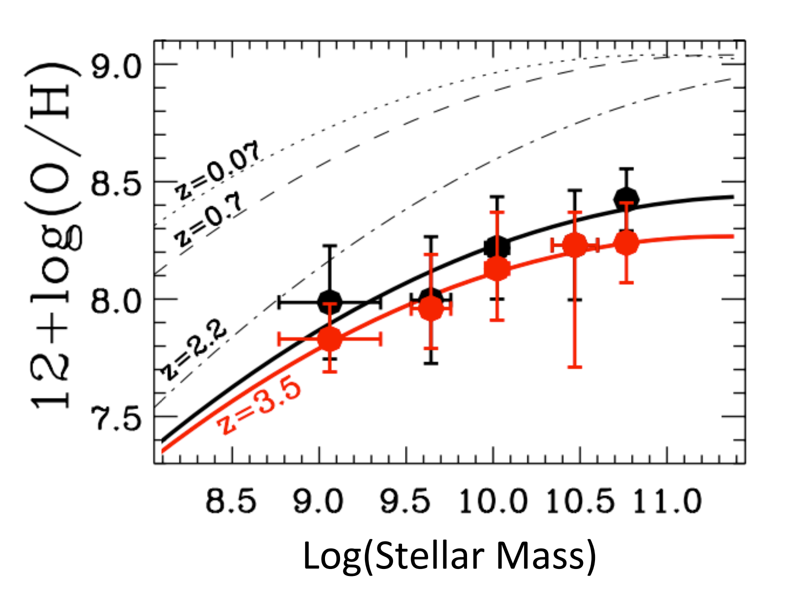
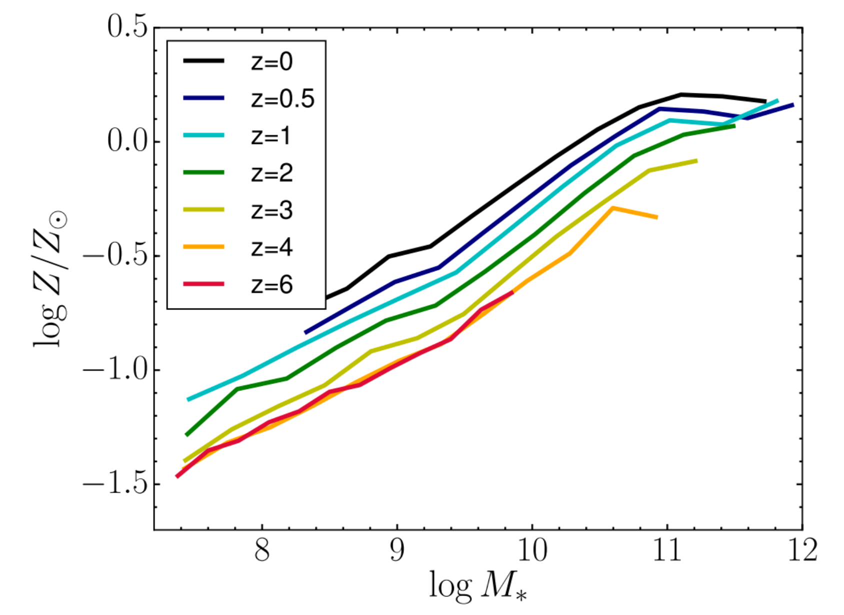


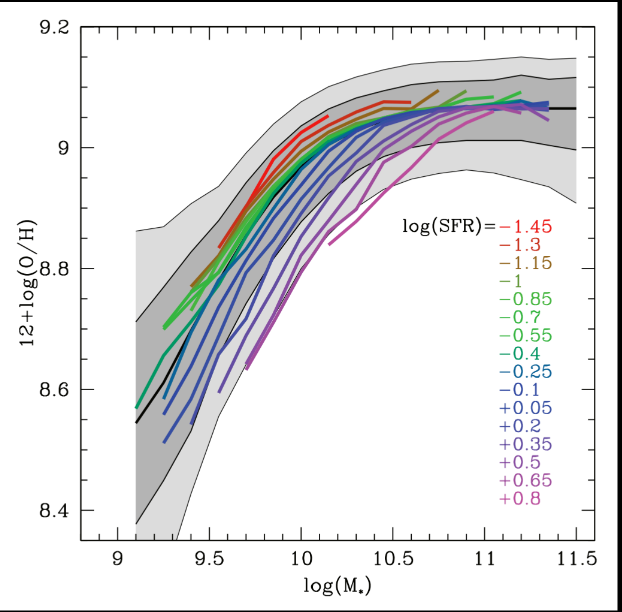
Troncoso+2014



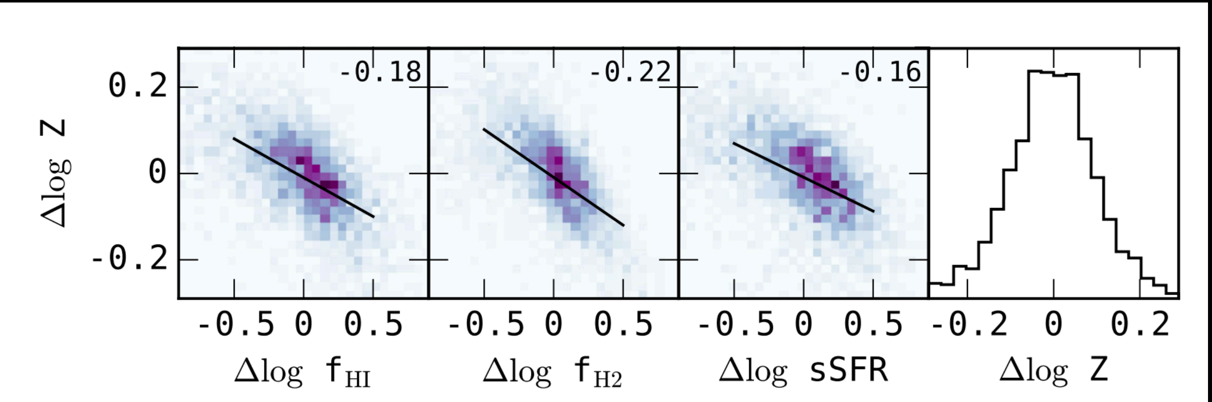
mufasa: Davé+2017

Galaxy metallicity scaling relations are determined by the interplay of inflows, outflows, and star formation.

- Higher order effects:
  - SFR dependence of the MZR ("Fundamental metallicity relation"; FMR)
  - Neutral and molecular gas (HI: Lara-López+2013, Bothwell+2013)



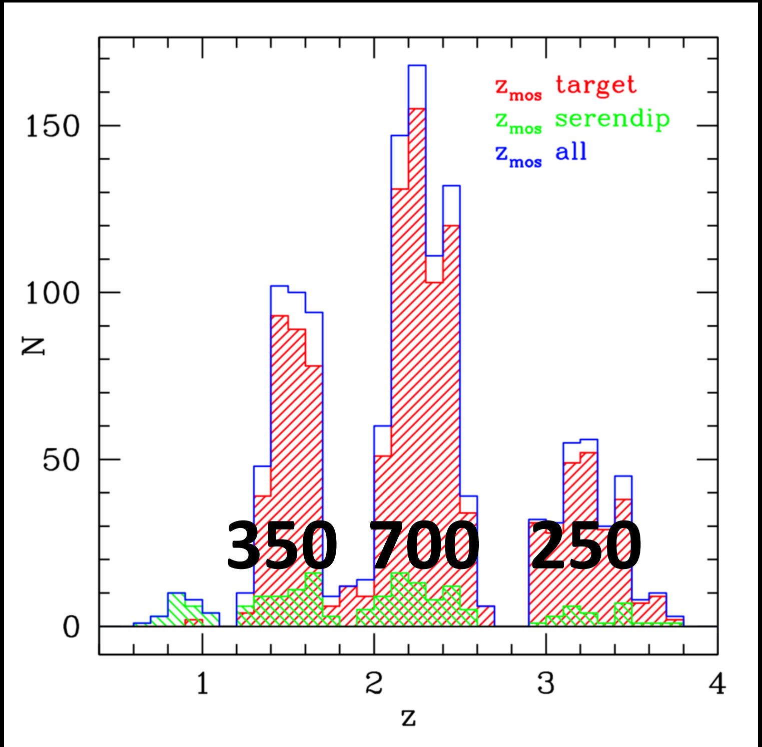
Mannucci+2010



mufasa: Davé+2017

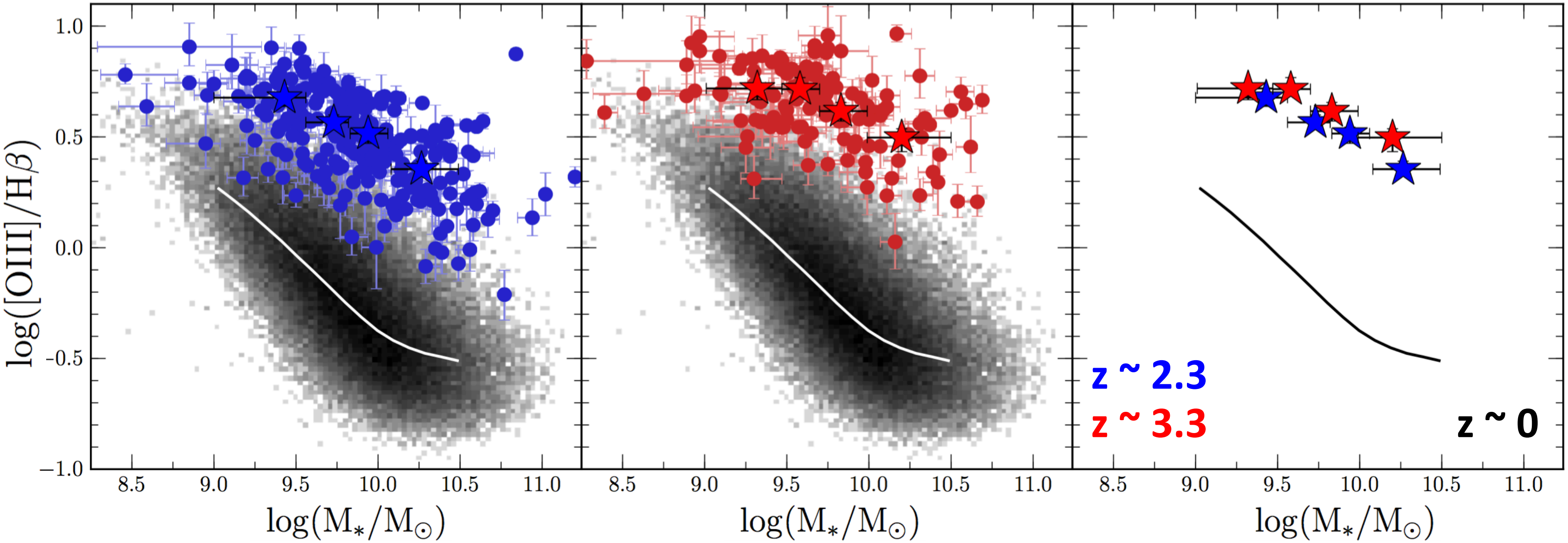
The MOSFIRE Deep Evolution Field survey

- Keck/MOSFIRE: high sensitivity, multiplexing, rest-frame optical spectra
- Rest-frame optical selected sample (observed H band/F160W)
- CANDELS fields with ancillary multi-wavelength data
- Large, representative sample of galaxies spanning a large dynamic range in stellar mass, SFR, and SED shape
- Multiple redshift ranges in order to study evolution



Observations completed in 2016: 1500 galaxies targeted, 1300 redshifts

Excitation at fixed stellar mass for z~2-4 star-forming galaxies with MOSDEF

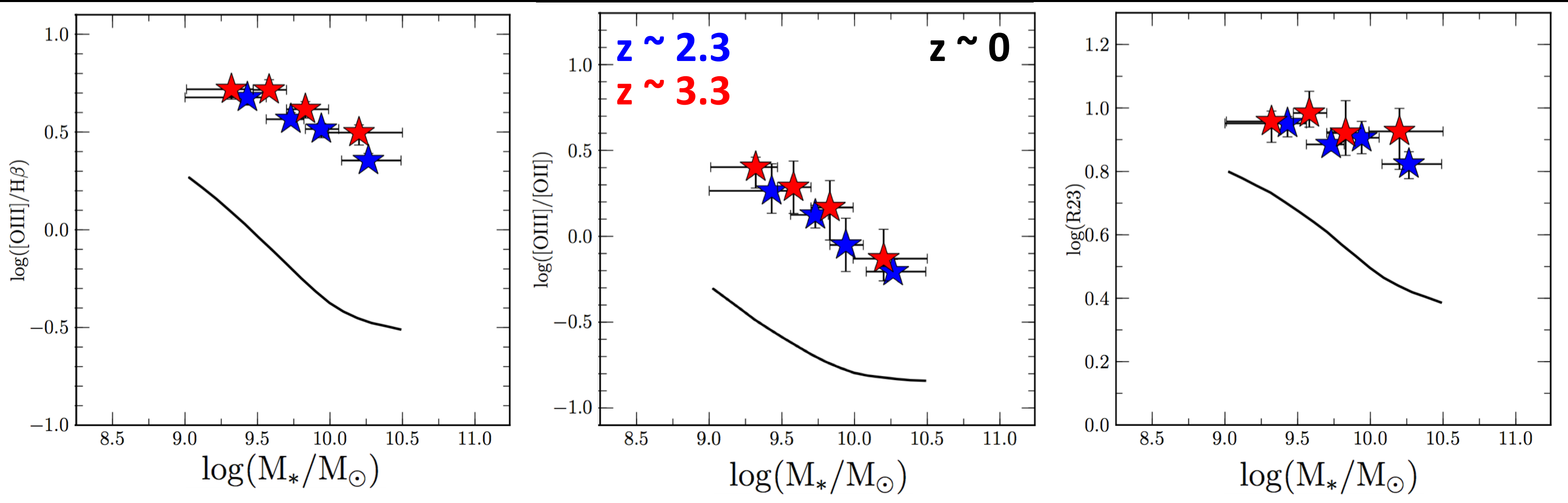


Sanders+, in prep.

Excitation at fixed stellar mass for z~2-4 star-forming galaxies with MOSDEF

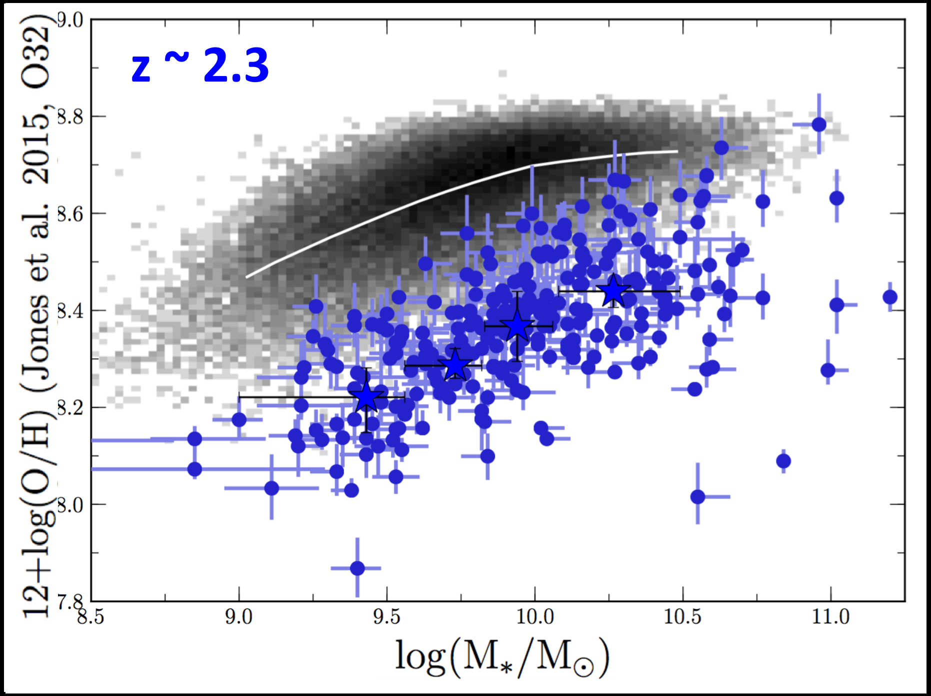
- -Significant excitation increase at fixed M_* from z~0 to z~2-4 (e.g., Steidel+2014, Holden+2016, Onodera+2016)
- -Slight increase in excitation at fixed M_* from z~2.3 to z~3.3

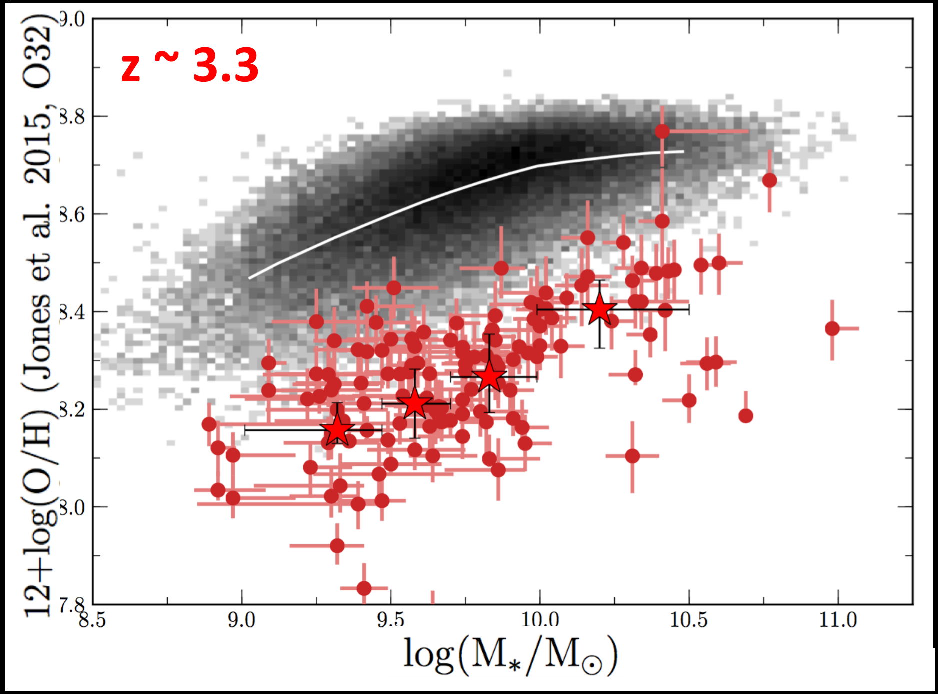
[OIII]/Hβ: [OIII]/[OII]: R23 = ([OII] + [OIII])/Hβ:



Sanders+, in prep.

An unprecedented view of the evolution of the MZR at z~2-4 with MOSDEF



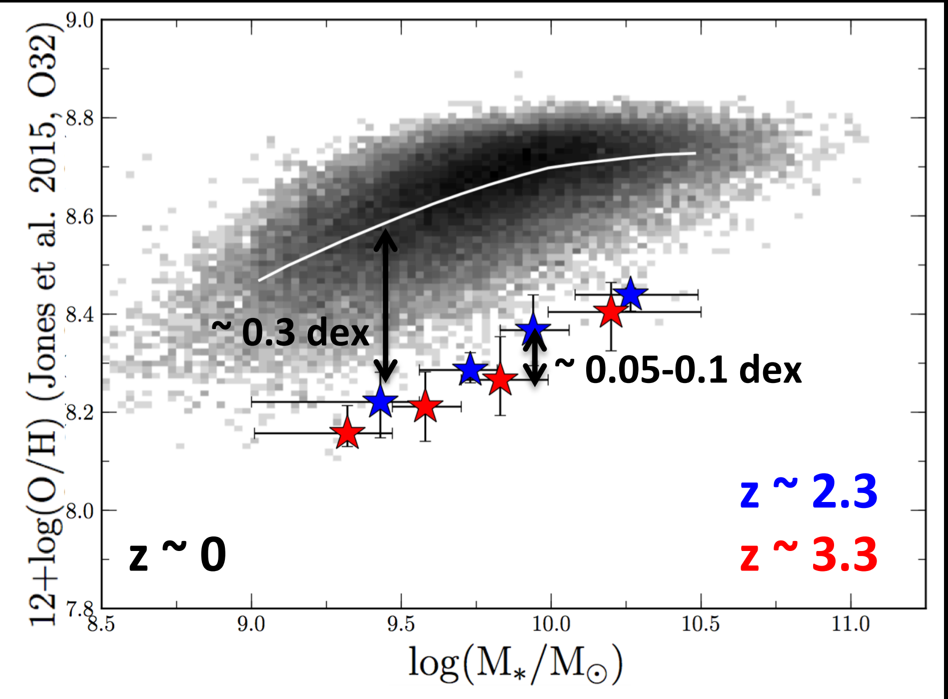


Sanders+, in prep.

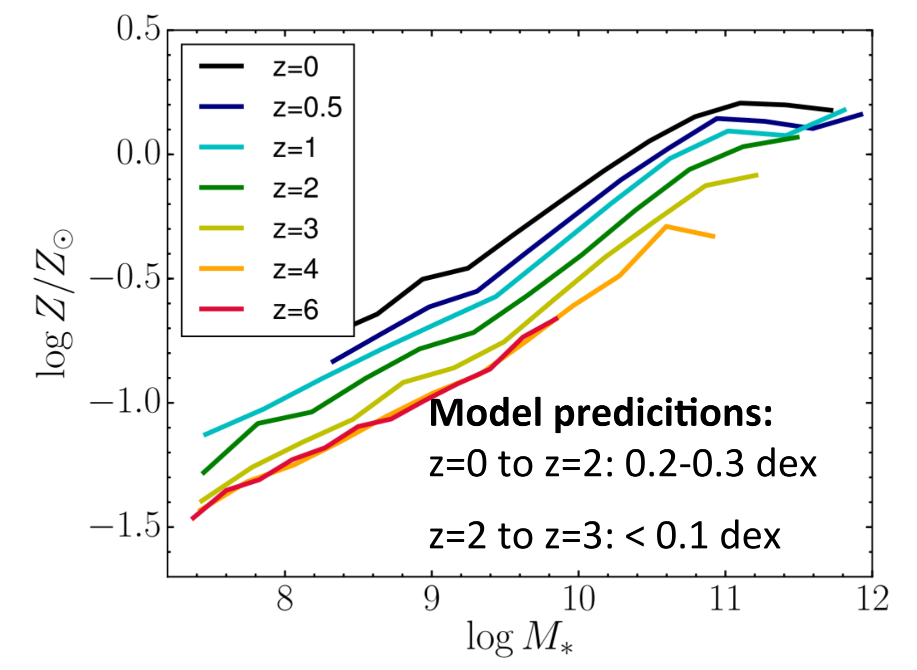
z = 2 – 2.6 sample:
- 270 individual detections
- 300 stacked in stellar mass bins

z = 3 – 3.8 sample:
- 134 individual detections
- 160 stacked in stellar mass bins

An unprecedented view of the evolution of the MZR at z~2-4 with MOSDEF

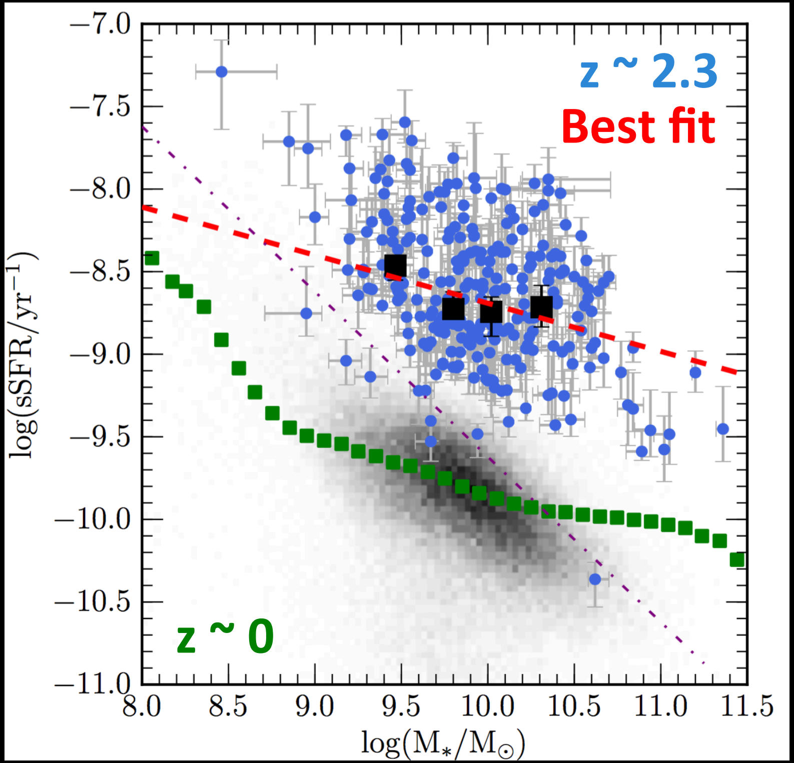


Sanders+, in prep.



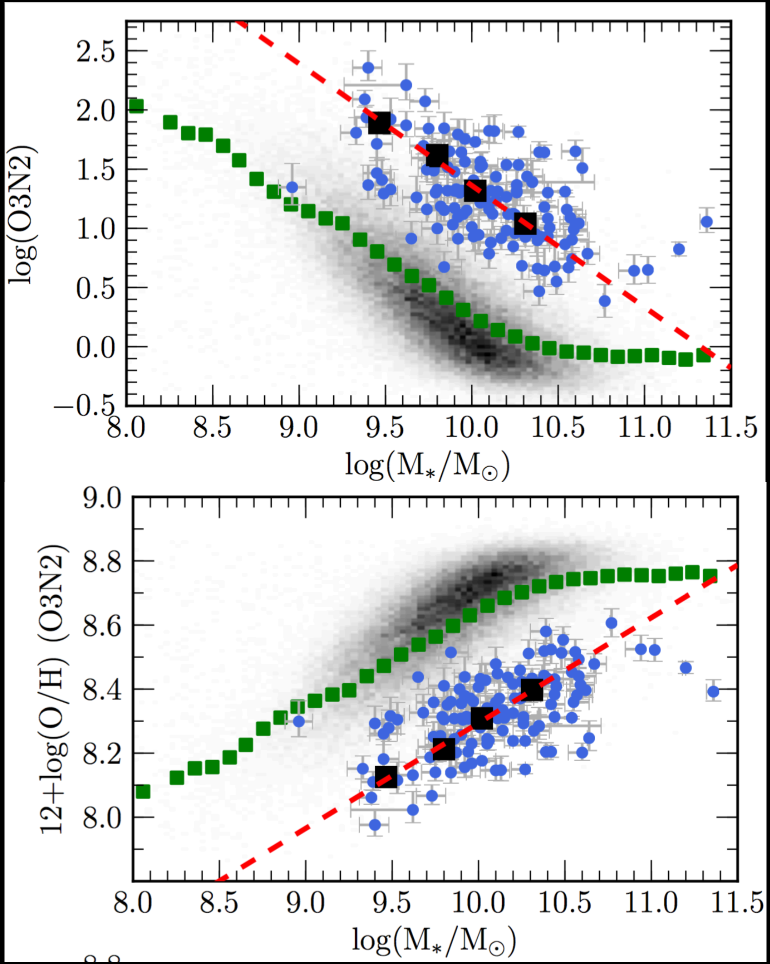
mufasa: Davé+2017

Searching for the FMR at high redshift: correlated scatter around mean scaling relations

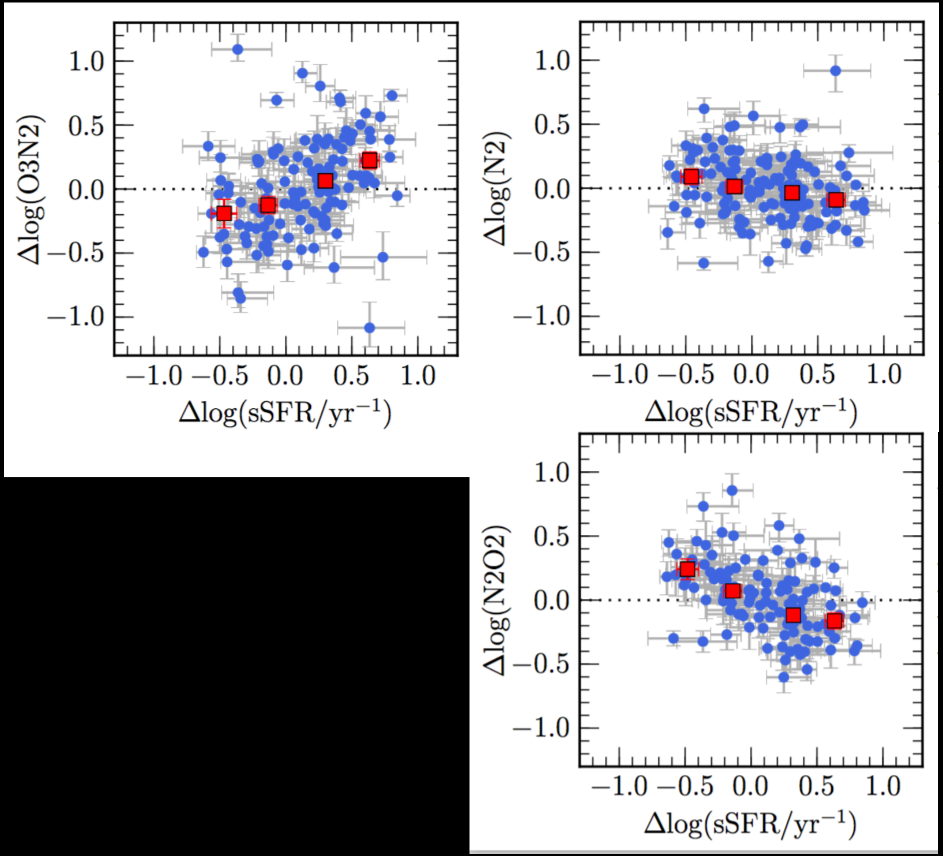


Sanders+, in prep.

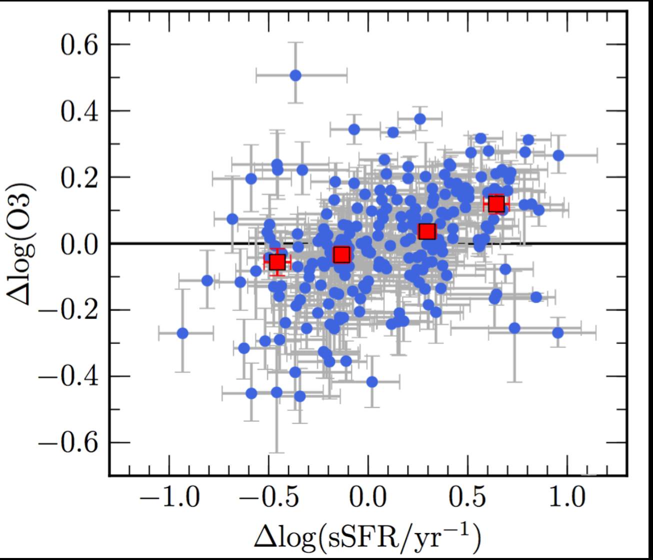
O3N2 = ([OIII]/Hβ)/([NII]/Hα)



SFR dependence of the MZR: a clear detection of an FMR at z~2.3



O3N2 = ([OIII]/Hβ)/([NII]/Hα)
N2O2 = [NII]/[OII]
N2 = [NII]/Hα
O3 = [OIII]/Hβ



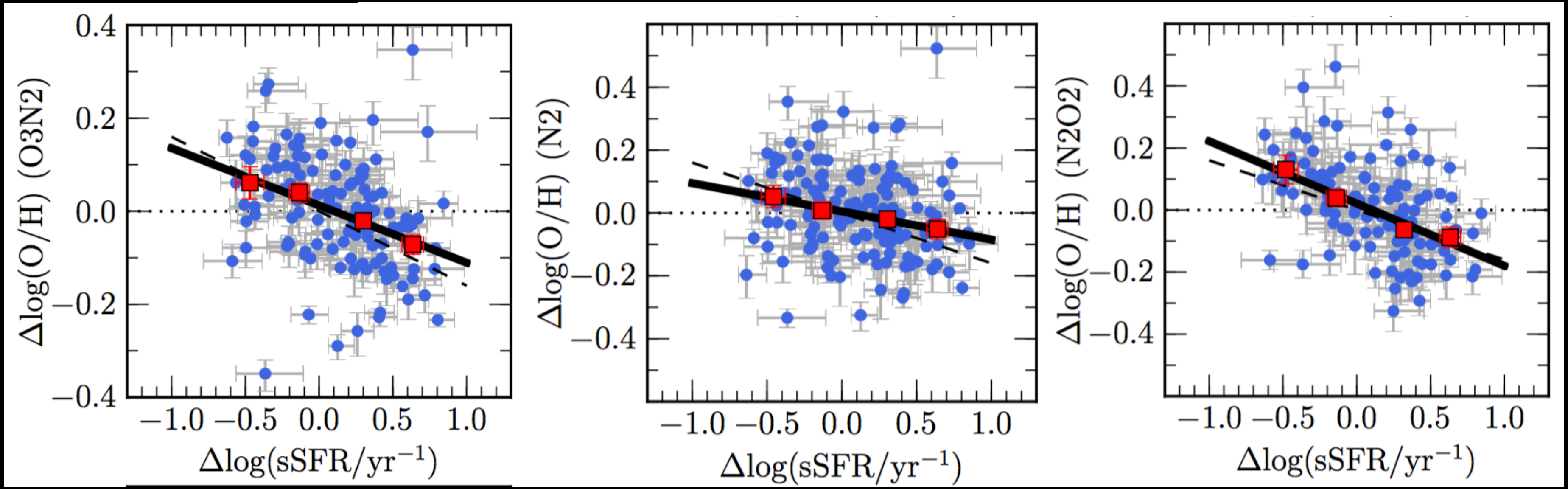
Sanders+, in prep.

SFR dependence of the MZR: a clear detection of an FMR at z~2.3

O3N2 = ([OIII]/Hβ)/([NII]/Hα)
slope = −0.12 ± 0.03

N2 = [NII]/Hα
slope = −0.09 ± 0.04

N2O2 = [NII]/[OII]
slope = −0.20 ± 0.05

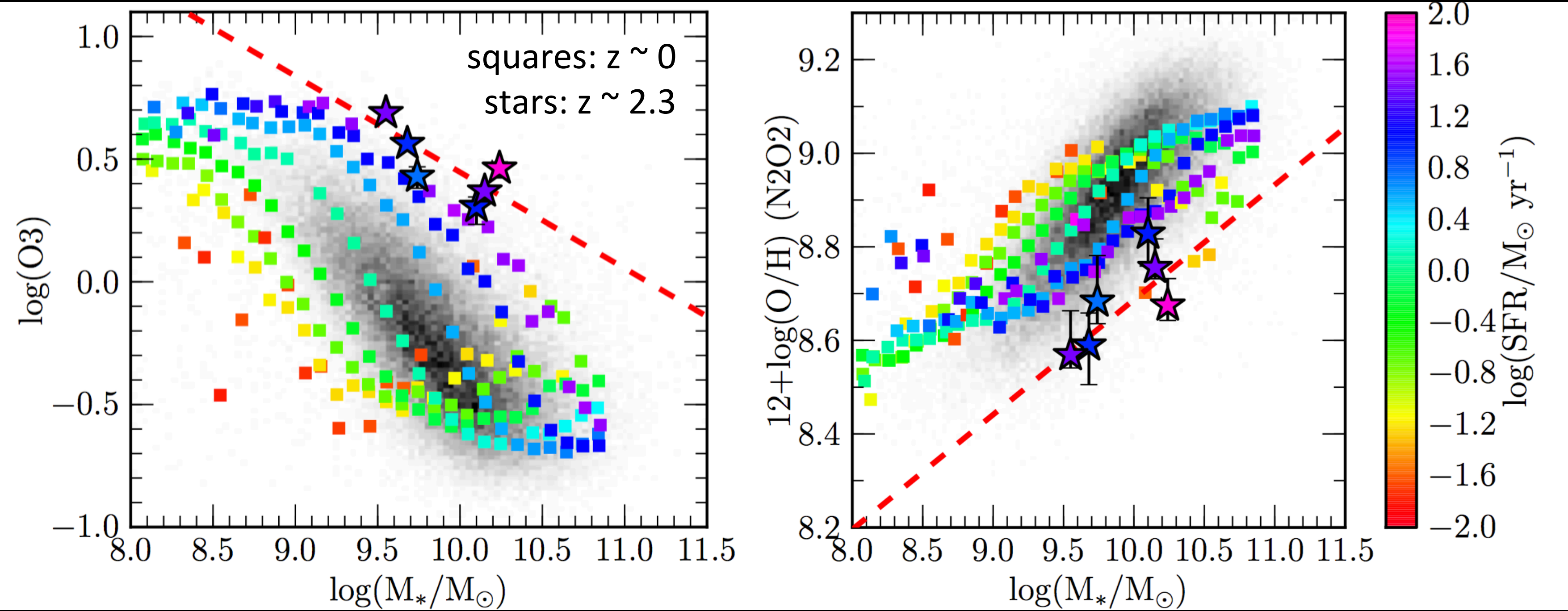


Sanders+, in prep.

mufasa: Davé+2017
predicted slope = −0.16

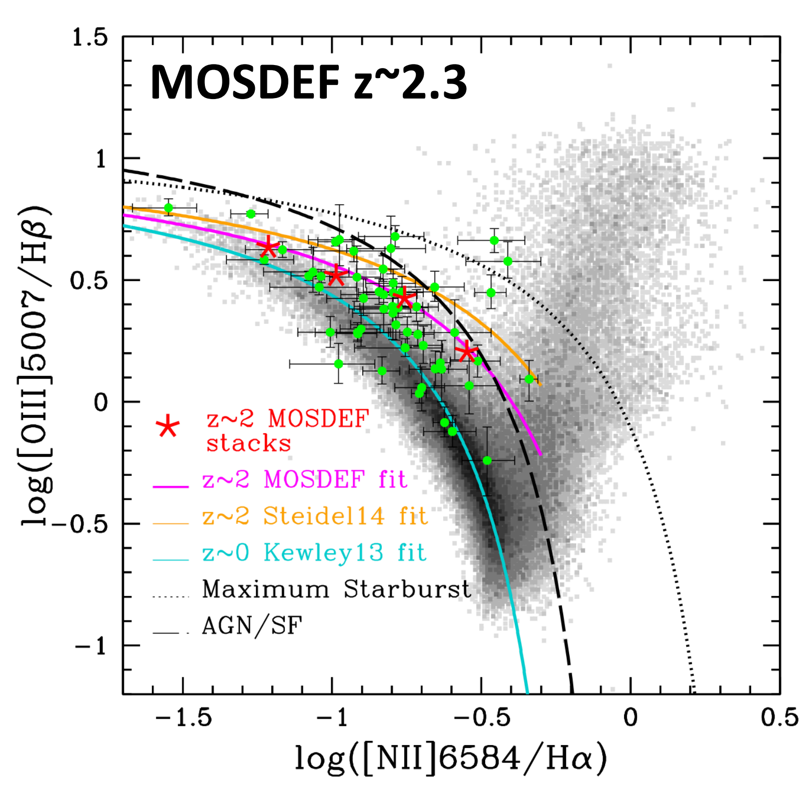
The FMR exists at z~2.3, but is it the same as at z~0?

-z~2.3 galaxies have ~0.1 dex lower metallicities at fixed M_* and SFR compared to z=0
-this offset is observed in both N/O and ionization parameter sensitive line ratios

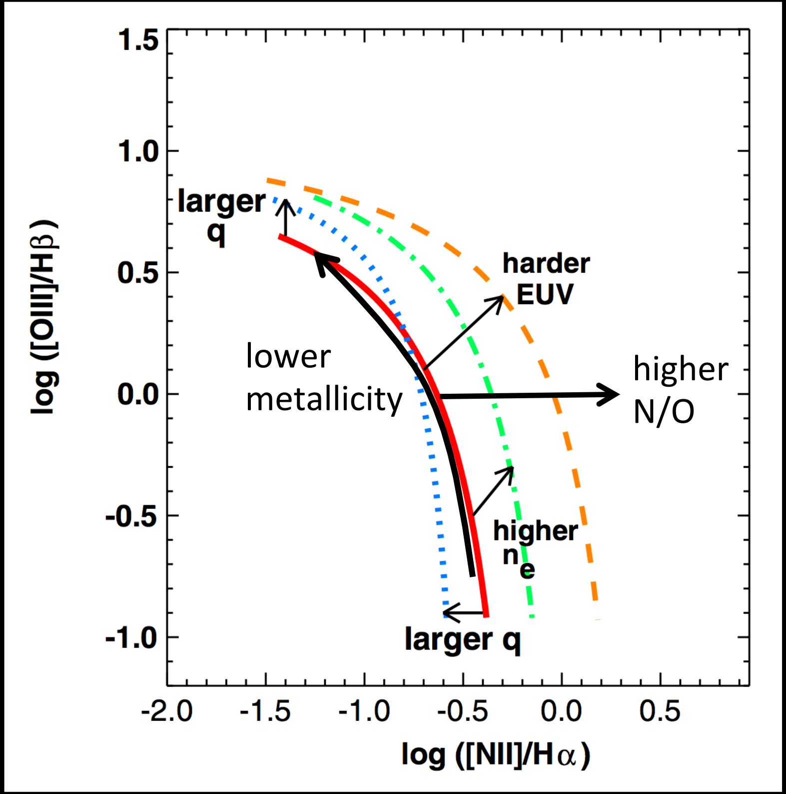


Sanders+, in prep.

Are local metallicity calibrations reliable at high redshifts?
Evolution in the physical conditions of ionized gas



Shapley et al. 2015



Kewley et al. 2013

A path forward for high-redshift metallicities: auroral-line measurements

- [OIII]λ4363/[OIII]λ5007 + [OIII]λ5007/Hβ

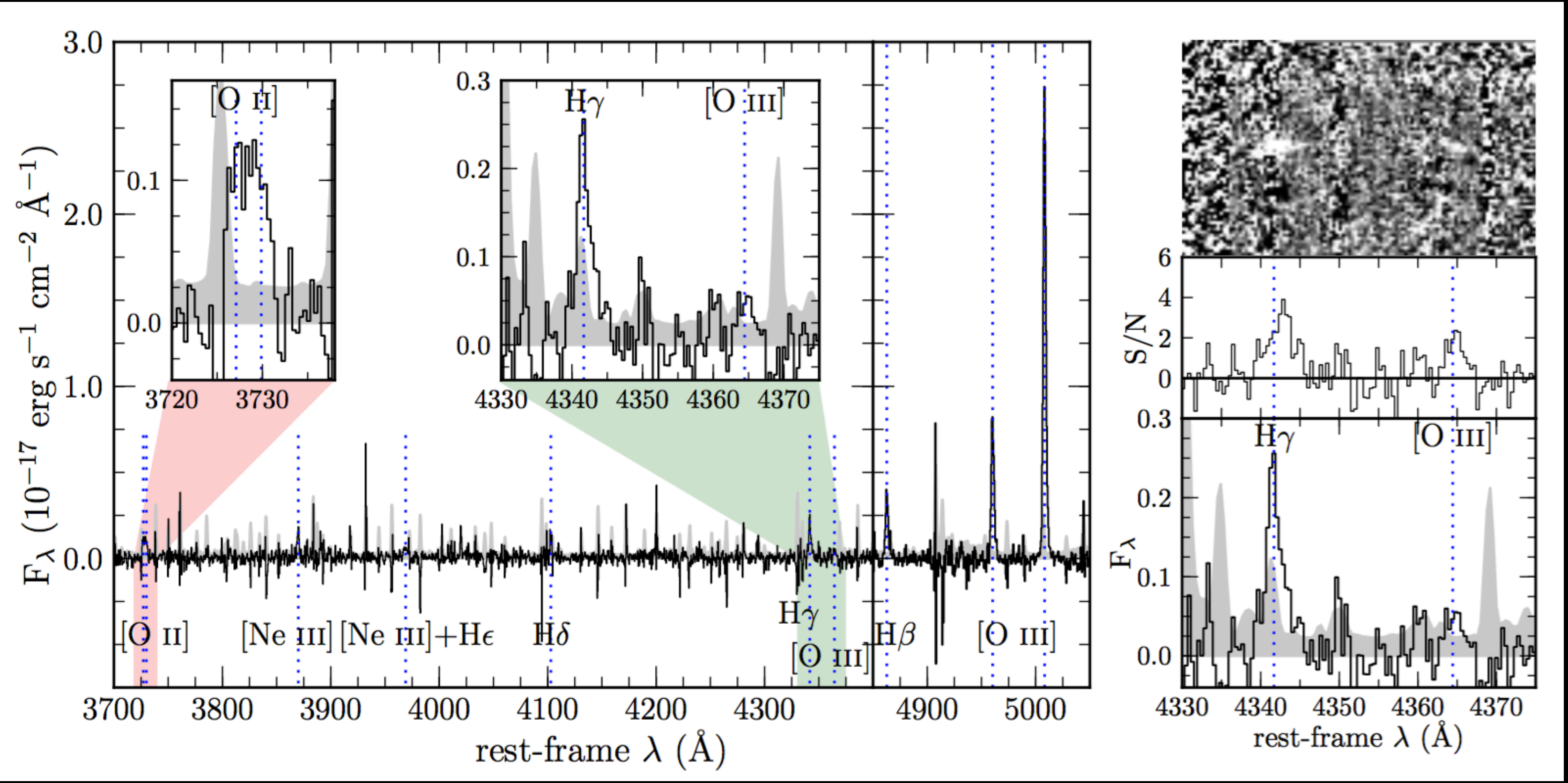
  → electron temperature and oxygen abundance

- Only depends on atomic physics, no dependence on strong-line calibrations

- Can be used to test and re-calibrate strong-line relations

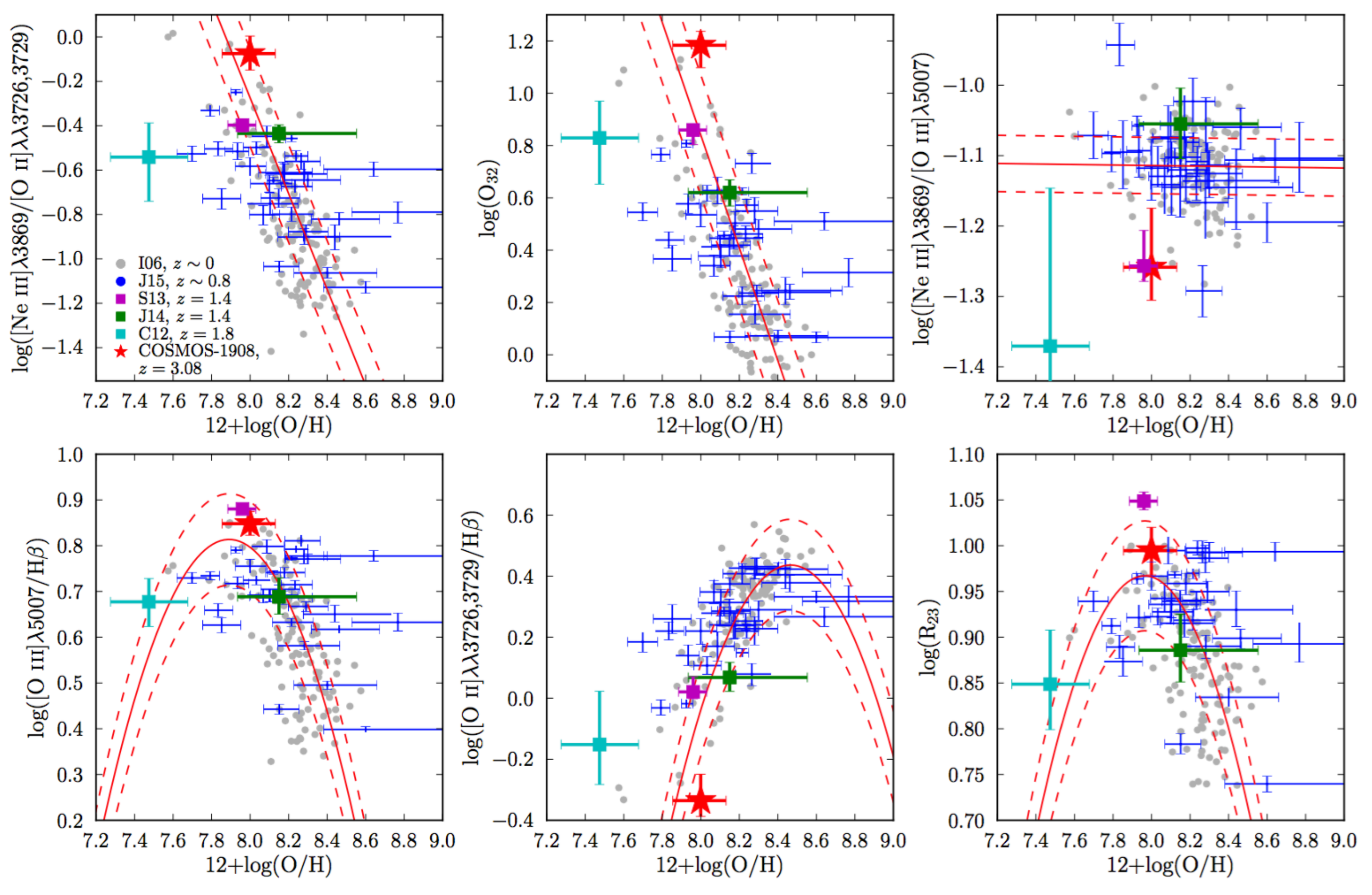
- But…100× weaker than [OIII]λ5007…can it be done at high-z?

A path forward: an auroral-line metallicity measurement at z=3.1



Sanders+2016b

A path forward for high-redshift metallicities: auroral-line measurements



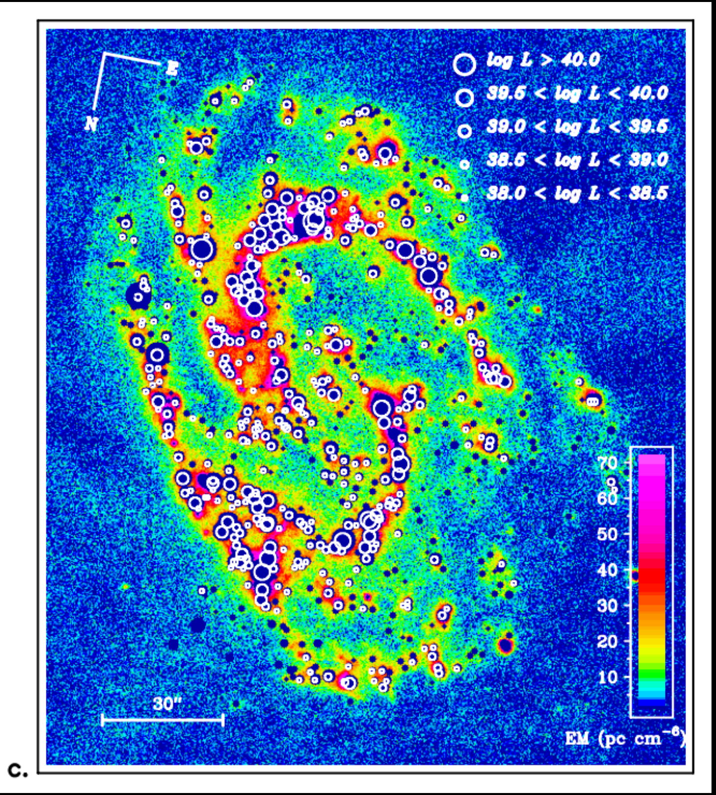
Sanders+2016b

What is in the emission-line spectrum of a star-forming galaxy?

Image credit: European Space Agency & NASA, K.D. Kuntz et al.

More than HII regions: Diffuse Ionized Gas (DIG) contamination

Narrowband Hα with HII regions removed:



Zurita+2000

Roughly half of all Hα emission in local star-forming spiral galaxies originates from diffuse ionized gas (DIG)

(Zurita+00, Oey+07)

DIG follows different emission-line ratio sequences than HII regions

(Zhang+17, Flores-Fajardo+09)

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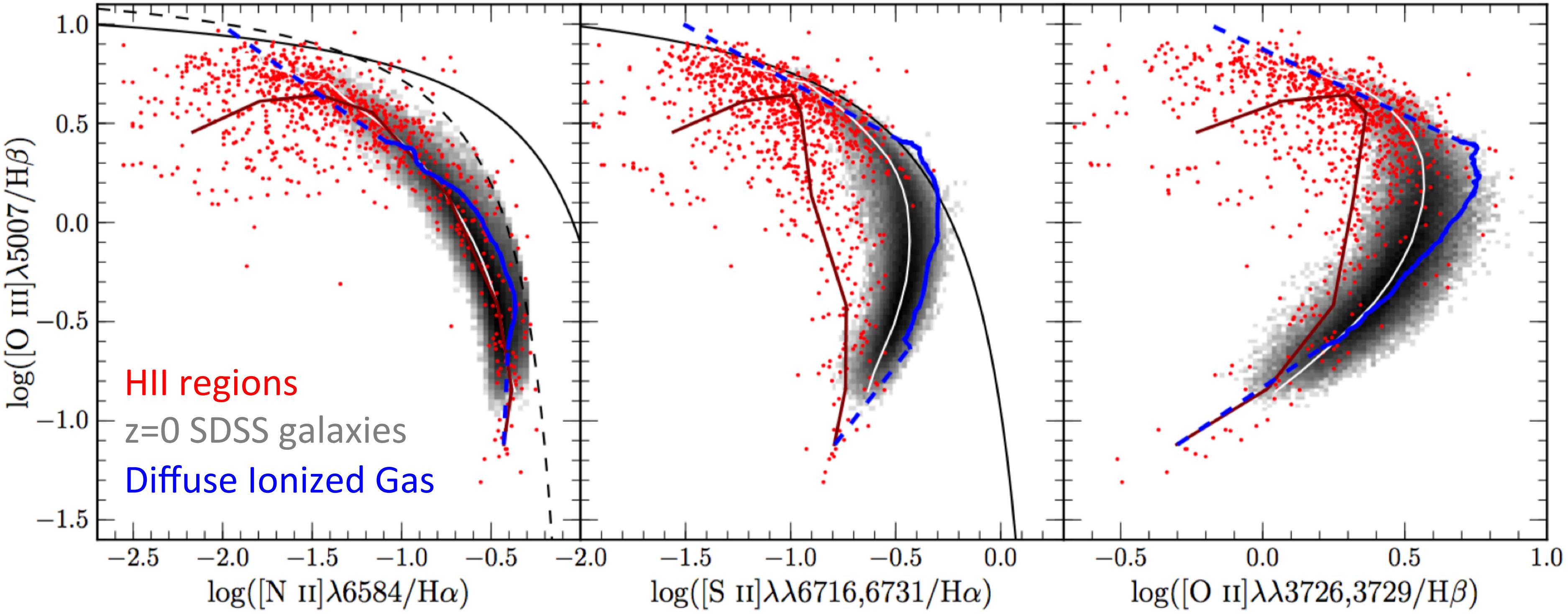

Sanders+2017, arxiv:1708.04625

Modeling galaxies as ensembles of line-emitting regions

Treat galaxies as collections of HII and DIG regions spanning a range of metallicities

Input HII region and DIG line ratios are based upon empirical datasets

1) Apply dust-reddening to each individual region
2) Combine light on a line-by-line basis
3) De-redden the global galaxy spectrum
4) Measure global galaxy properties (line ratios, electron temperature, metallicity)

Track strong and auroral emission lines

Compare properties derived from global galaxy spectrum to typical properties of the input HII region distribution

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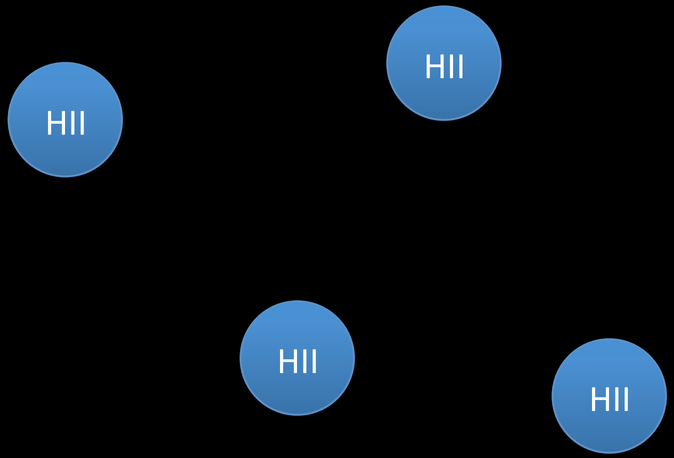

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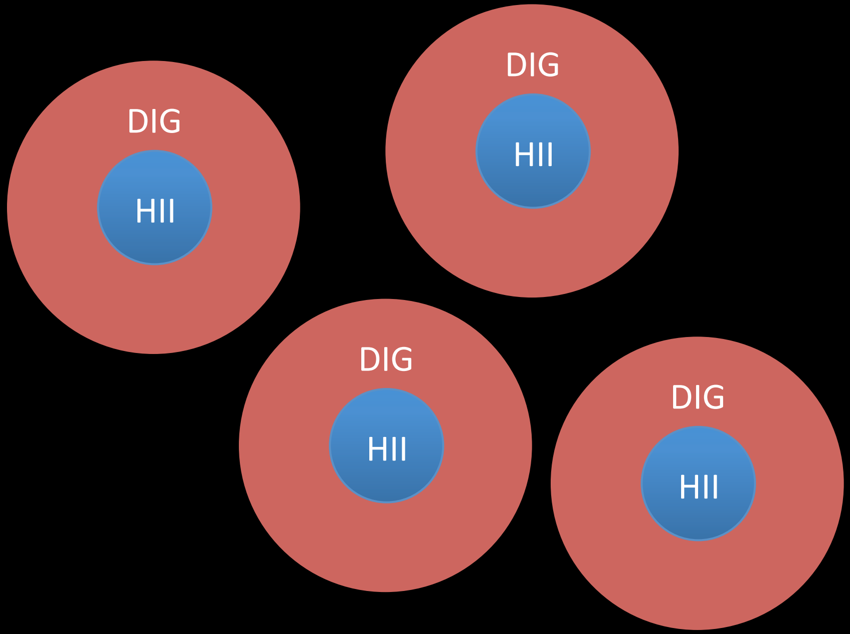

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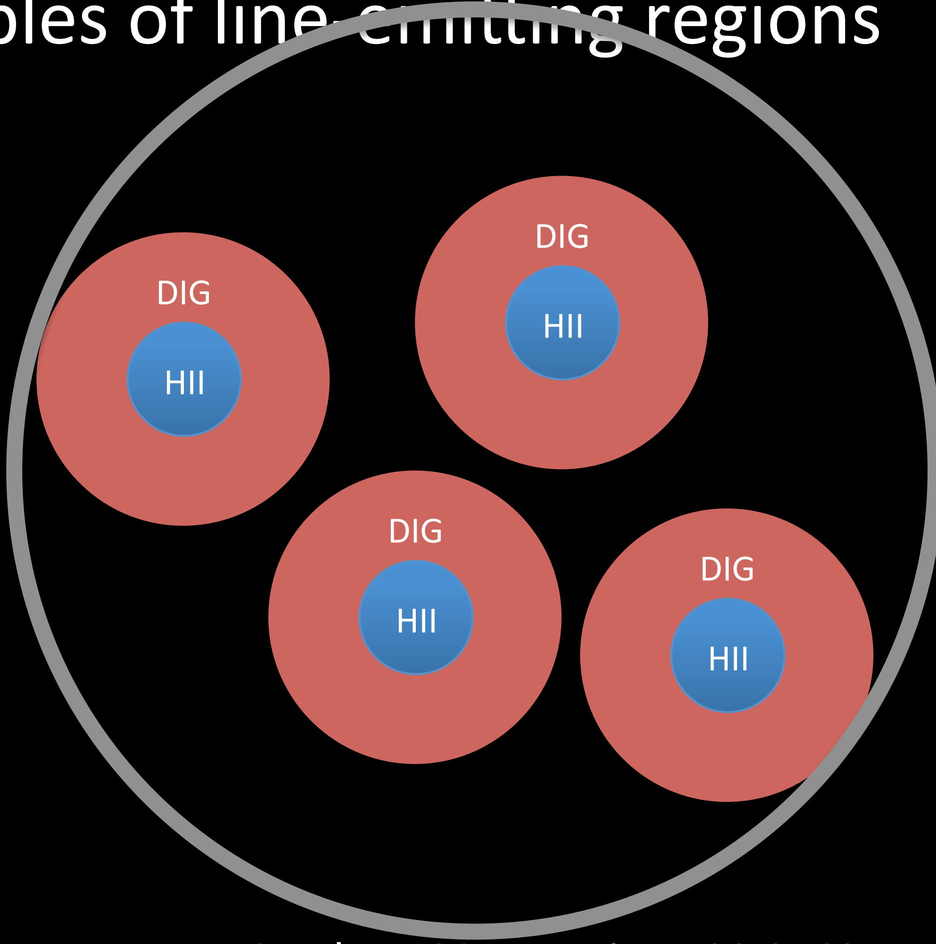

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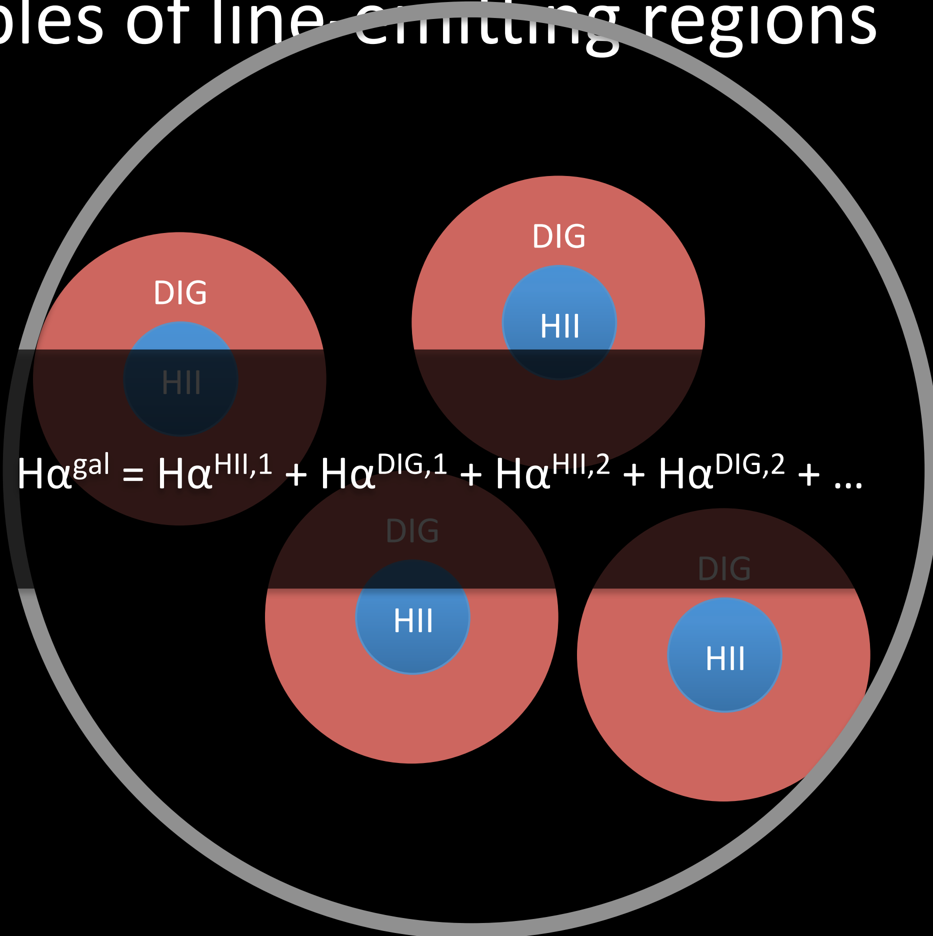
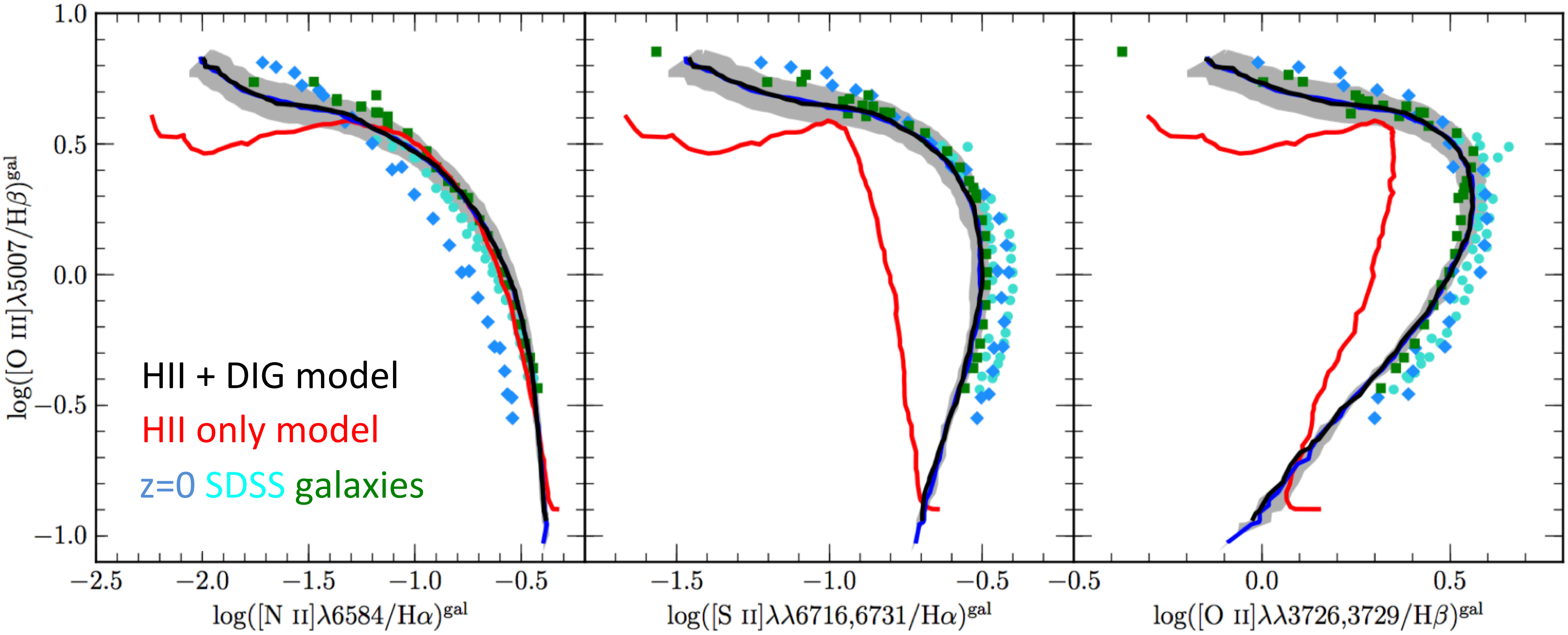


Sanders+2017, arxiv:1708.04625

Putting the models to the test: do they reproduce SDSS z=0 galaxies?



Sanders+2017, arxiv:1708.04625

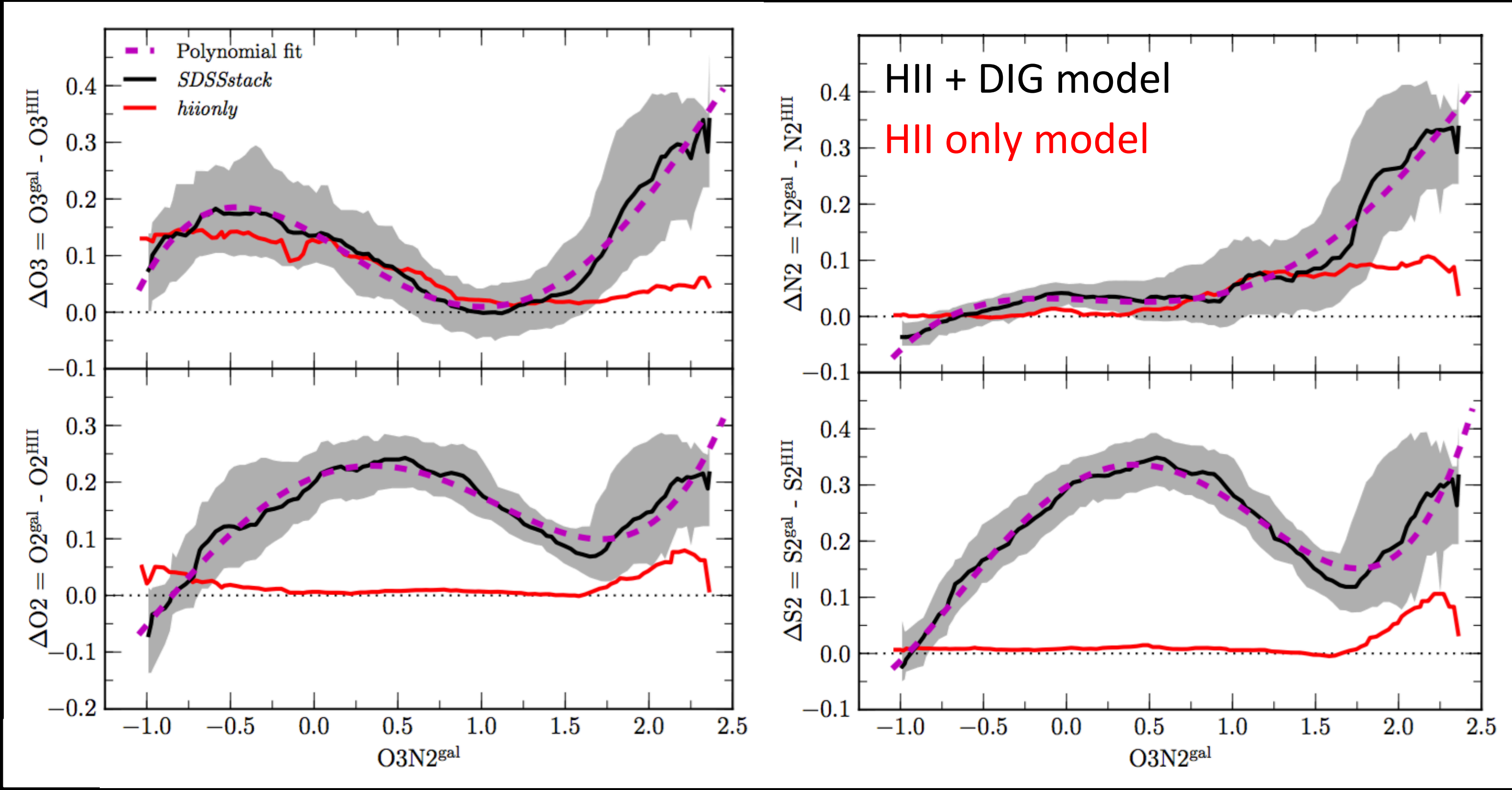
Biases in global galaxy properties from DIG contamination and flux-weighting effects: strong-line ratios

O3 = [OIII]/Hβ

O2 = [OII]/Hβ

N2 = [NII]/Hβ

S2 = [SII]/Hβ



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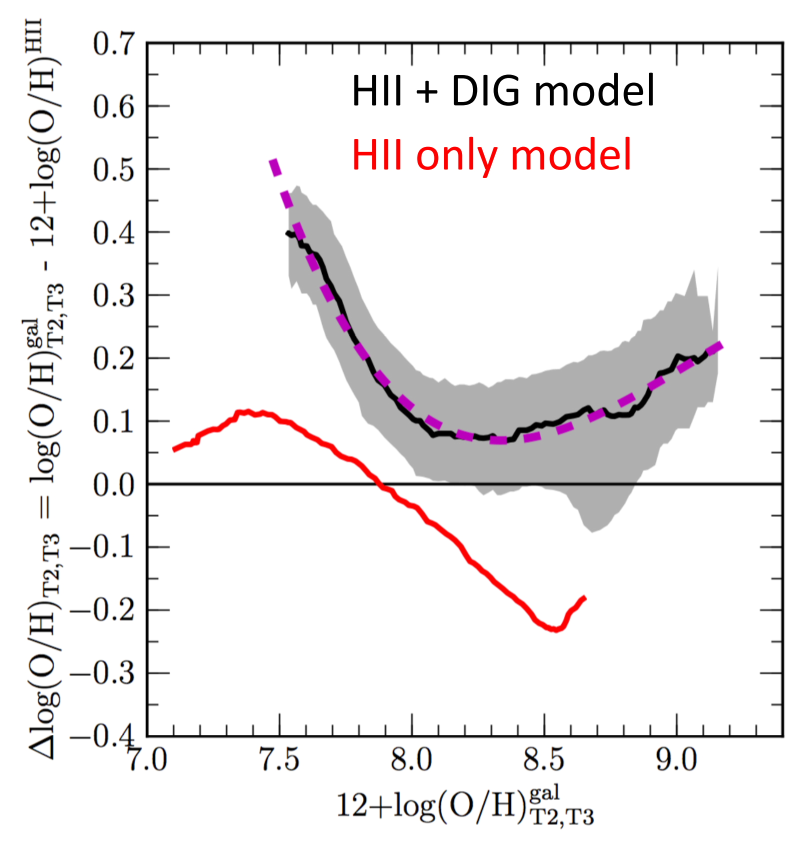

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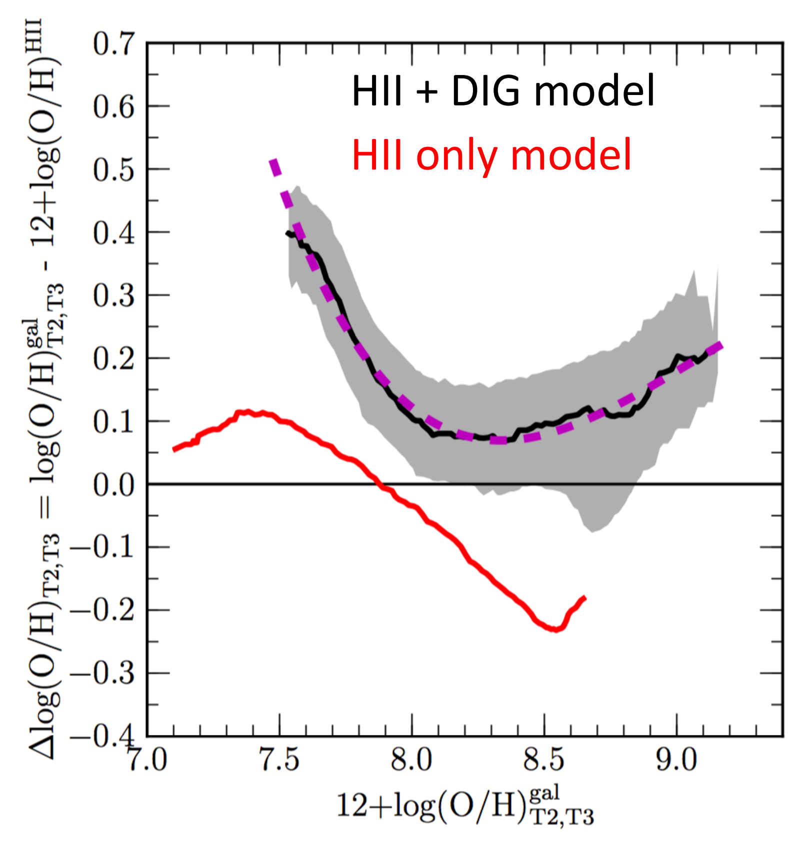


Sanders+2017, arxiv:1708.04625

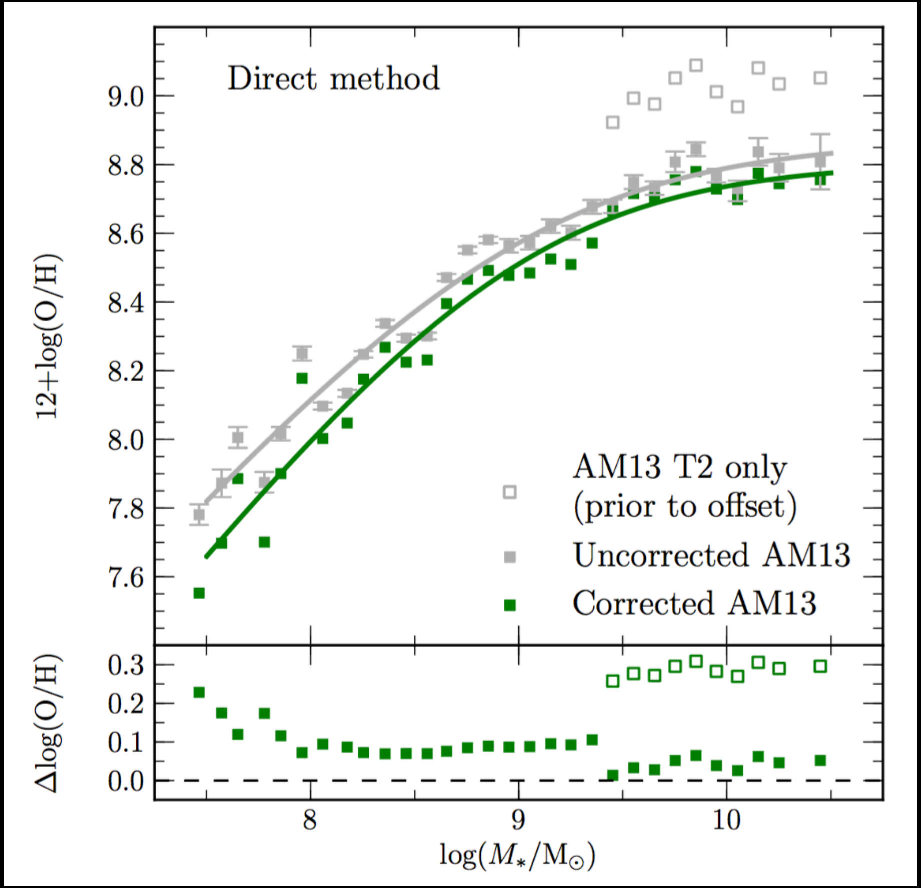
So you want to measure z~0 galaxy metallicities?

Plug your observed global galaxy line ratios into the Curti+17 calibrations!

BUT…

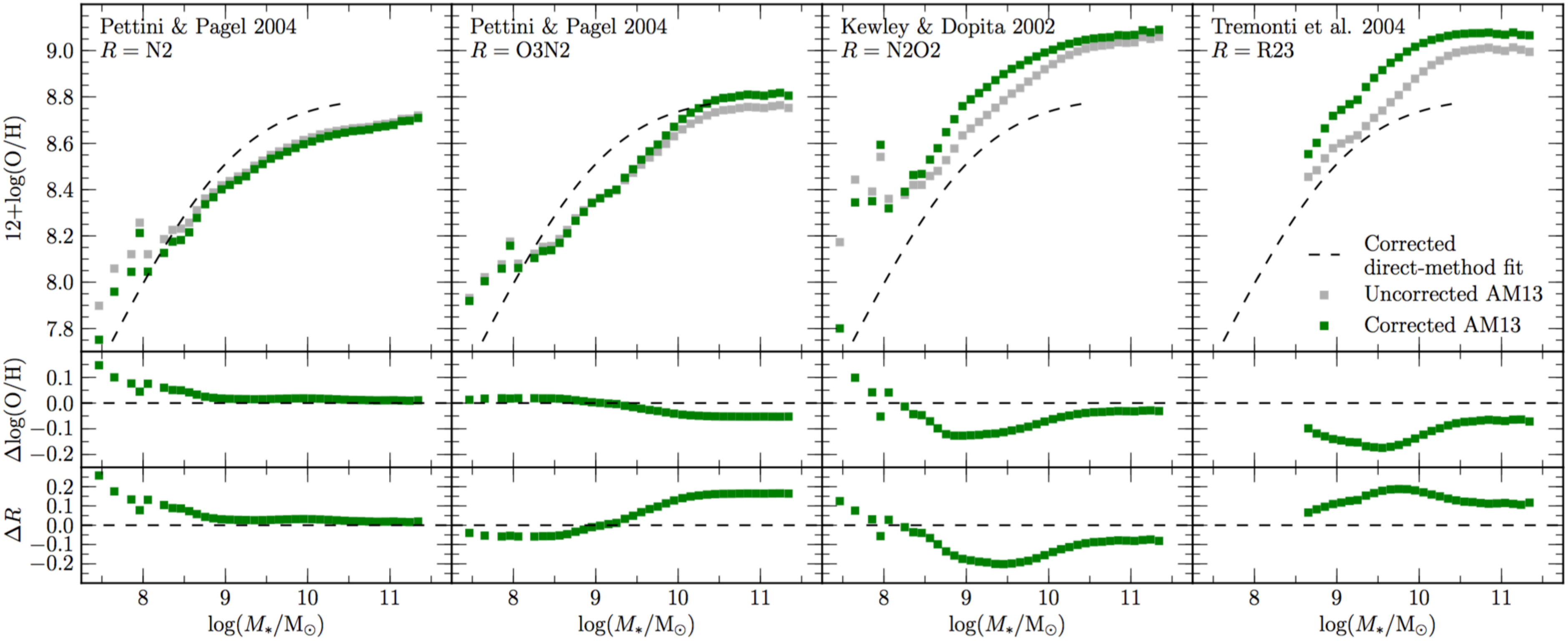
Make sure to correct the derived metallicity if you are interested in a measurement representative of the HII regions (e.g., for MZR, FMR studies, comparison to simulations)

Correcting the z=0 auroral-line mass-metallicity relation



Sanders+2017, arxiv:1708.04625

Correcting the z=0 strong-line mass-metallicity relation



Sanders+2017, arxiv:1708.04625

Summary and Conclusions

- Galaxy metallicity scaling relations, such as the mass-metallicity relation, provide valuable insight into the key processes governing galaxy growth
- Significant decrease in metallicity at fixed stellar mass from z~0 to z~3, but little evolution from z~2.3 to z~3.3
- An FMR clearly exists among SFR, M*, and metallicity for z~2.3 star-forming galaxies, but FMR may not be redshift invariant: high-redshift galaxies fall at lower metallicities than z=0 at fixed M_* and SFR
- Measurements of temperature-sensitive auroral lines at z>1 will pave the way for robust metallicity estimates at high redshifts; a significant observational investment in such a sample is required
  - JWST will make statistical samples of high-z galaxies with auroral line measurements a reality
- Robust metallicity estimates require a full understanding of the content of galaxy spectra
  - *Diffuse ionized gas contamination is a significant issue at z=0*
- Modeling galaxies as ensembles of HII and DIG regions successfully reproduces z=0 galaxy line-ratio properties and allows us to characterize and correct for biases in global galaxy metallicities