Credit: A. L. Strom and T. A. Rector

rethinking metallicity

the quest to measure abundance scaling relations at cosmic noon

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CARNEGIE SCIENCE

PRINCETON UNIVERSITY


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Z


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Z
HII region physics
molecular gas tracers
ISM
star and planet formation

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feedback
nucleosynthesis
stars
rotation and winds
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Z
feedback
nucleosynthesis
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cosmology tracers
galaxies
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star formation histories
CGM and IGM enrichment
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Z


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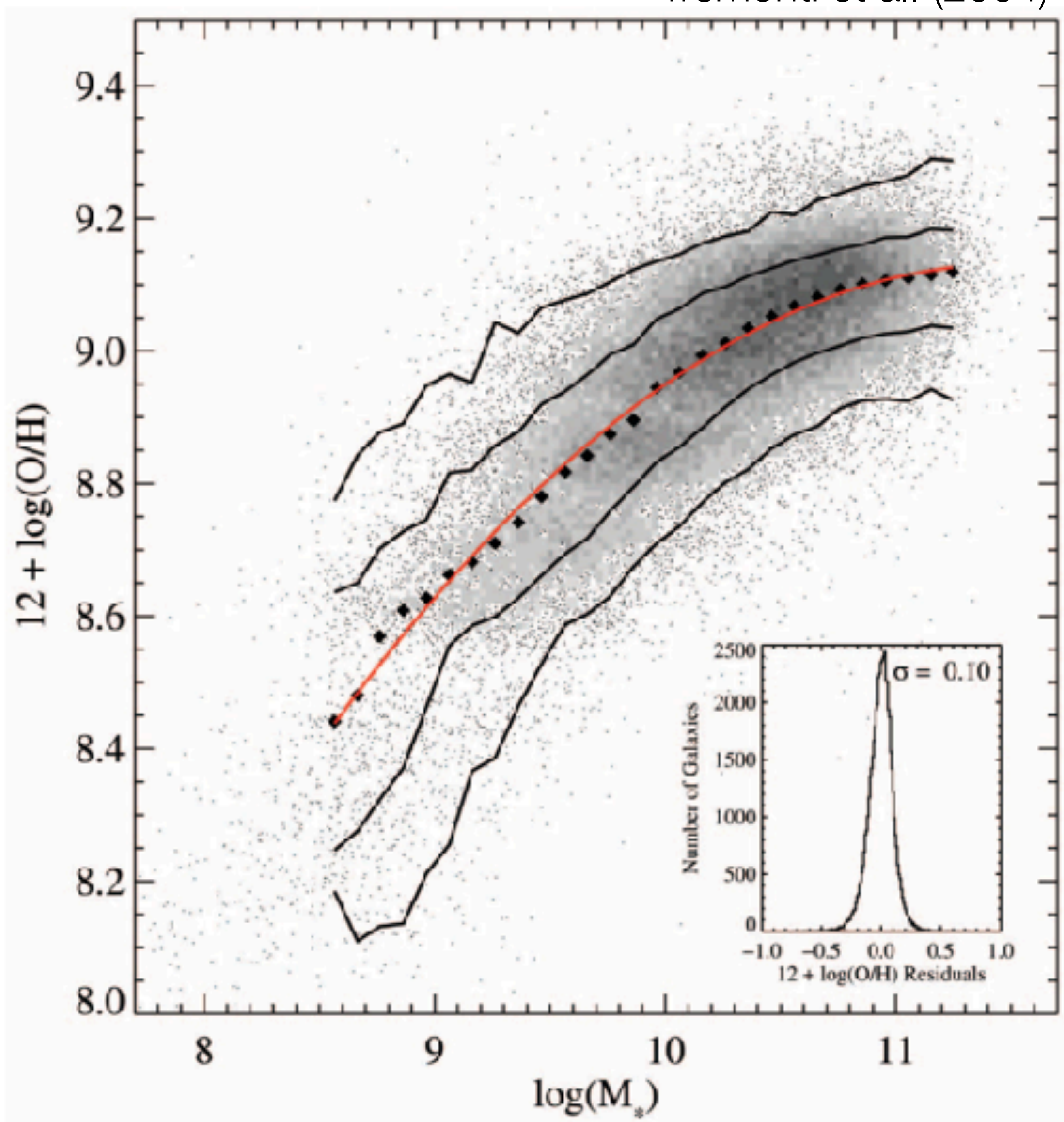
Z


Credit: A. L. Strom and T. A. Rector
Z=1-X-Y

The mass-"metallicity" relation encodes details of galaxy assembly

Tremonti et al. (2004)



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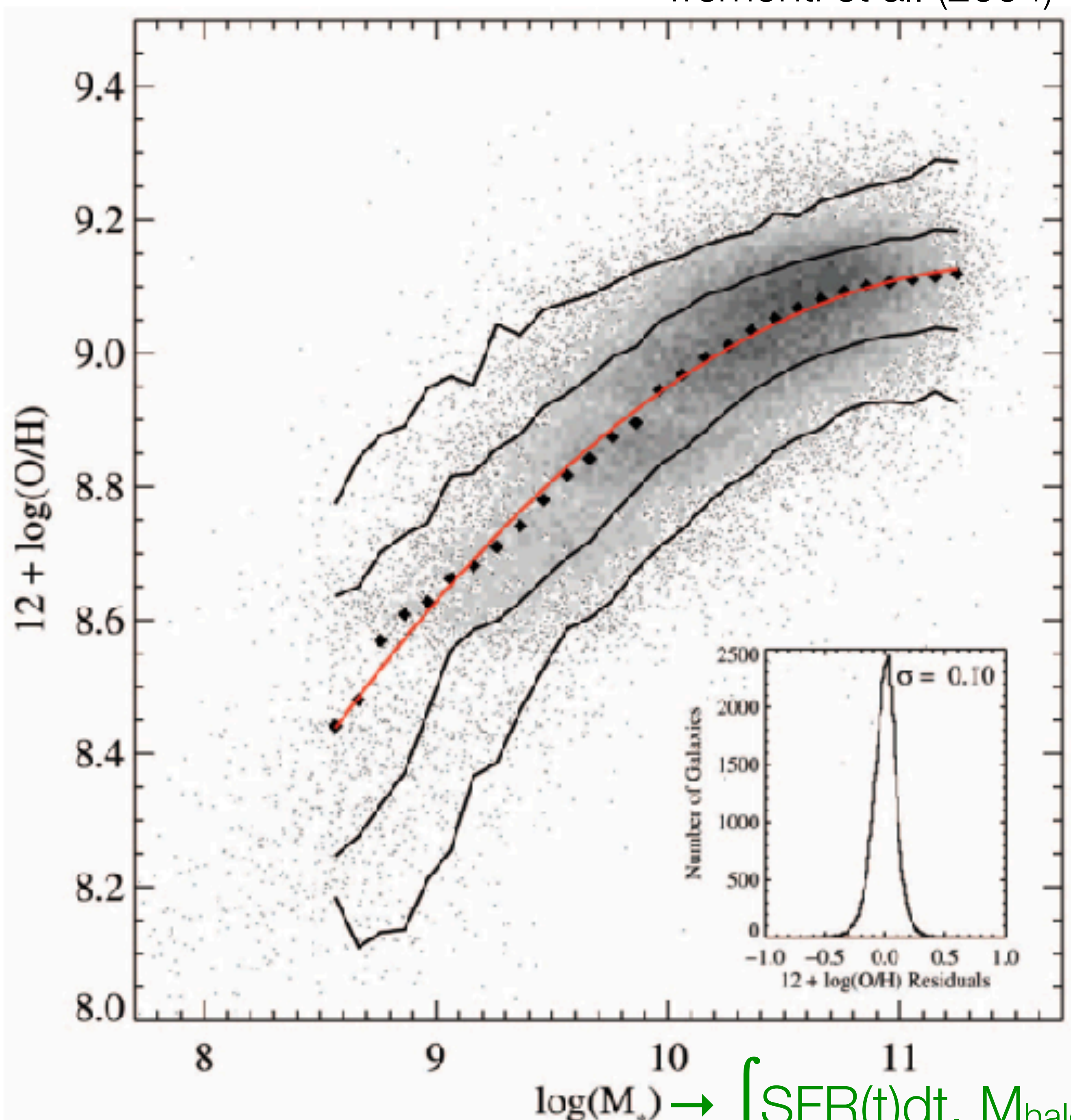

$\rightarrow \int SFR(t)dt$, M_{halo}, age

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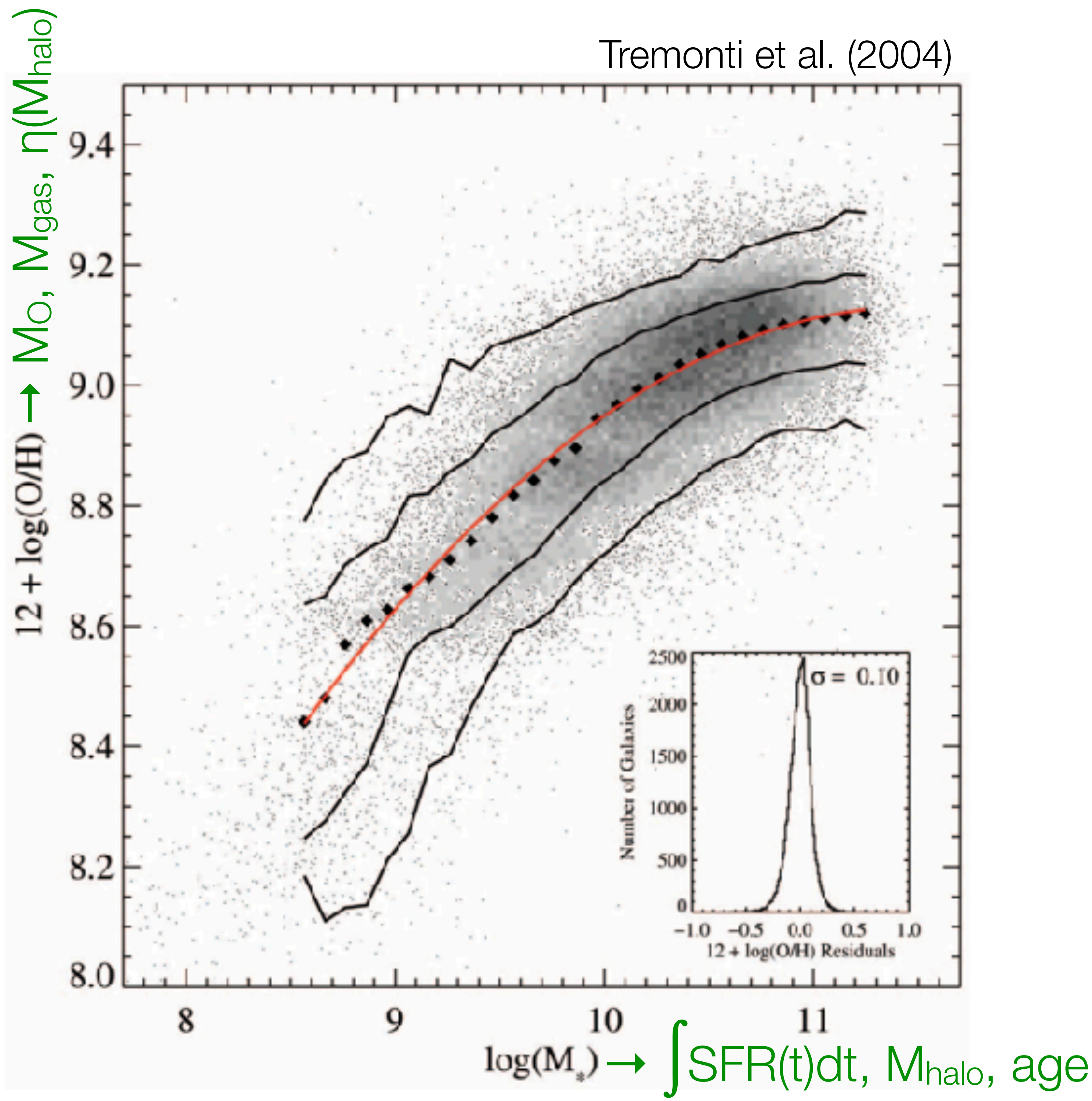

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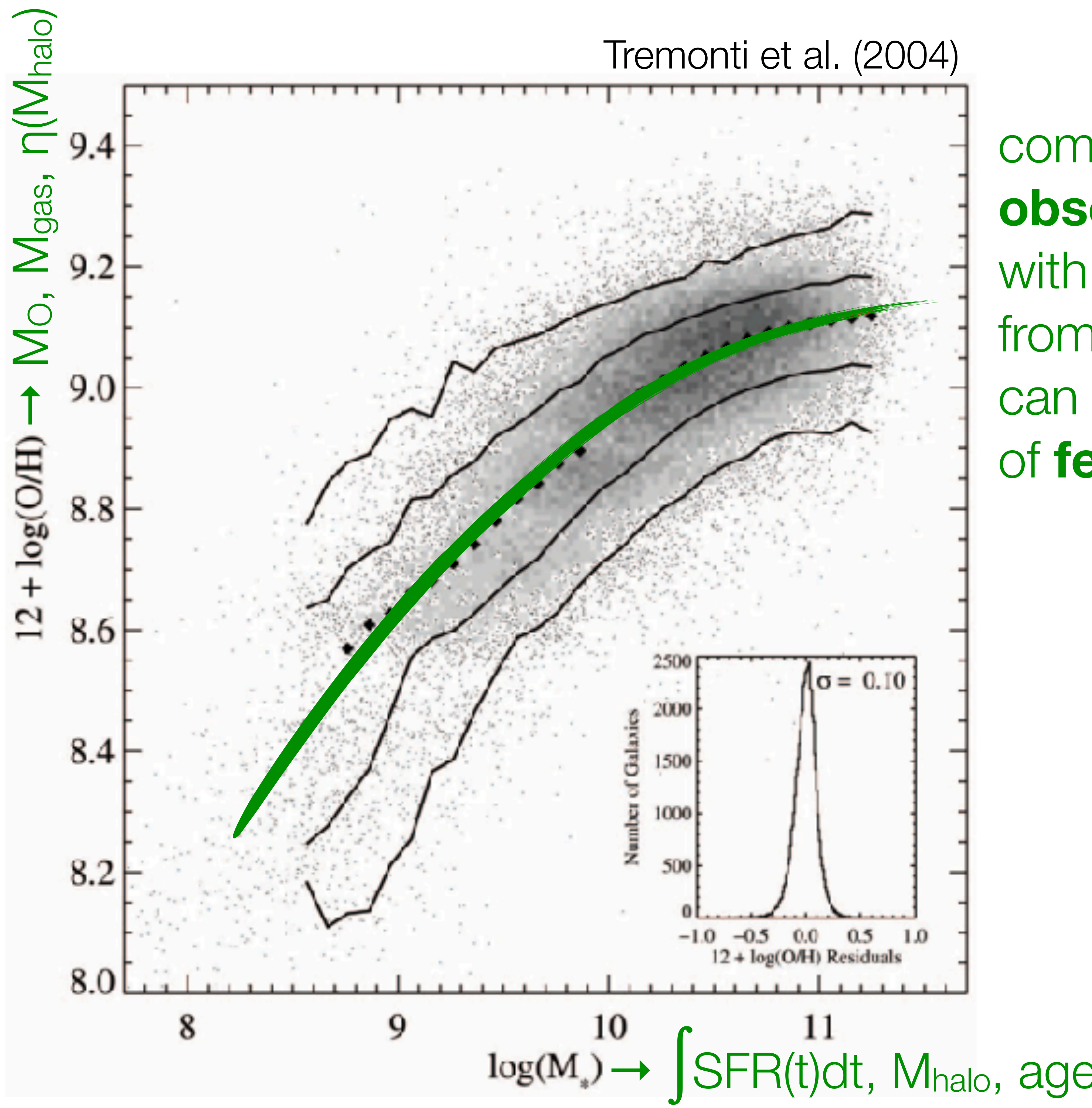
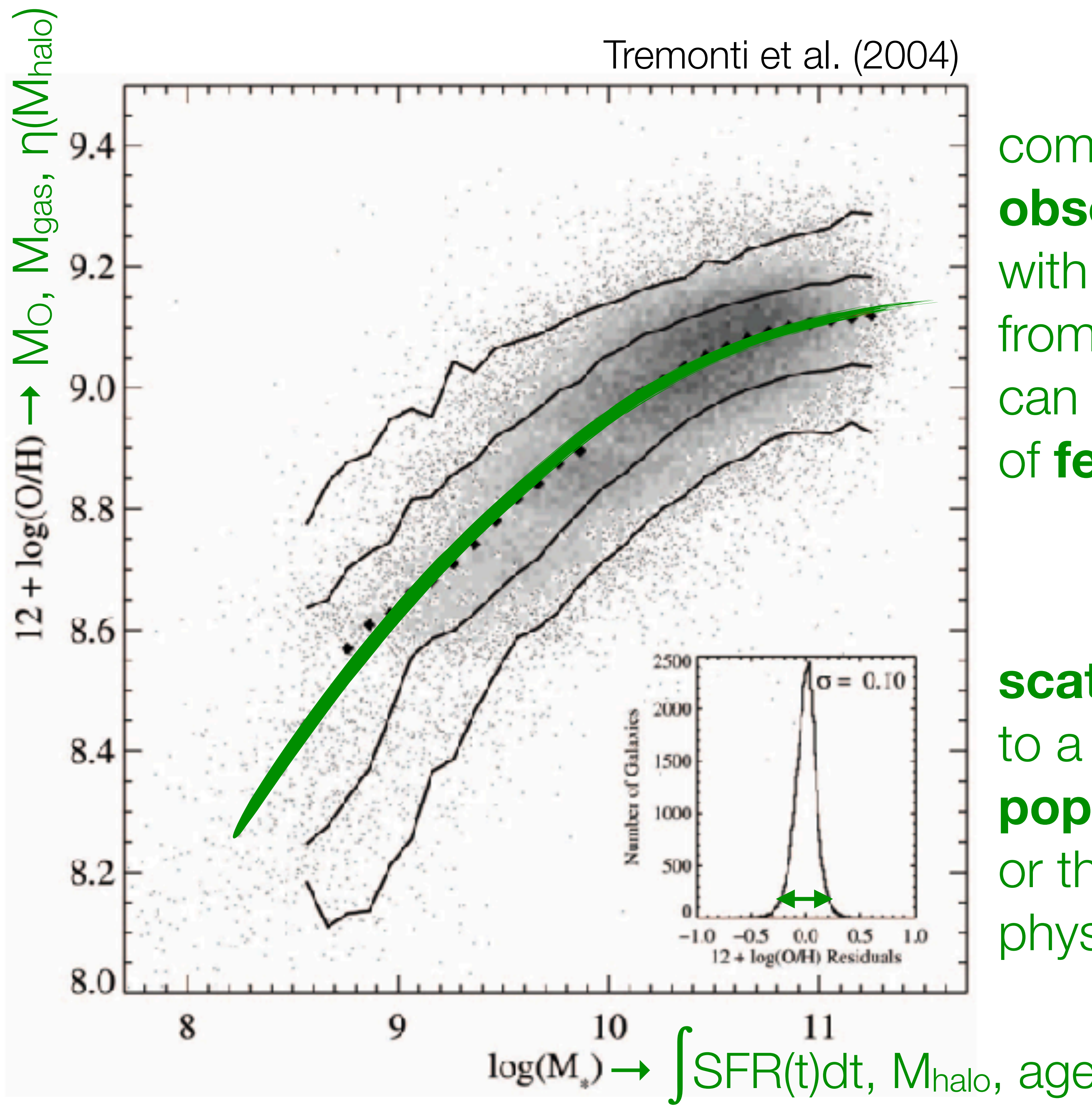


comparing the **observed shape** with predictions from **simulations** can serve as a test of **feedback models**

The mass-"metallicity" relation encodes details of galaxy assembly

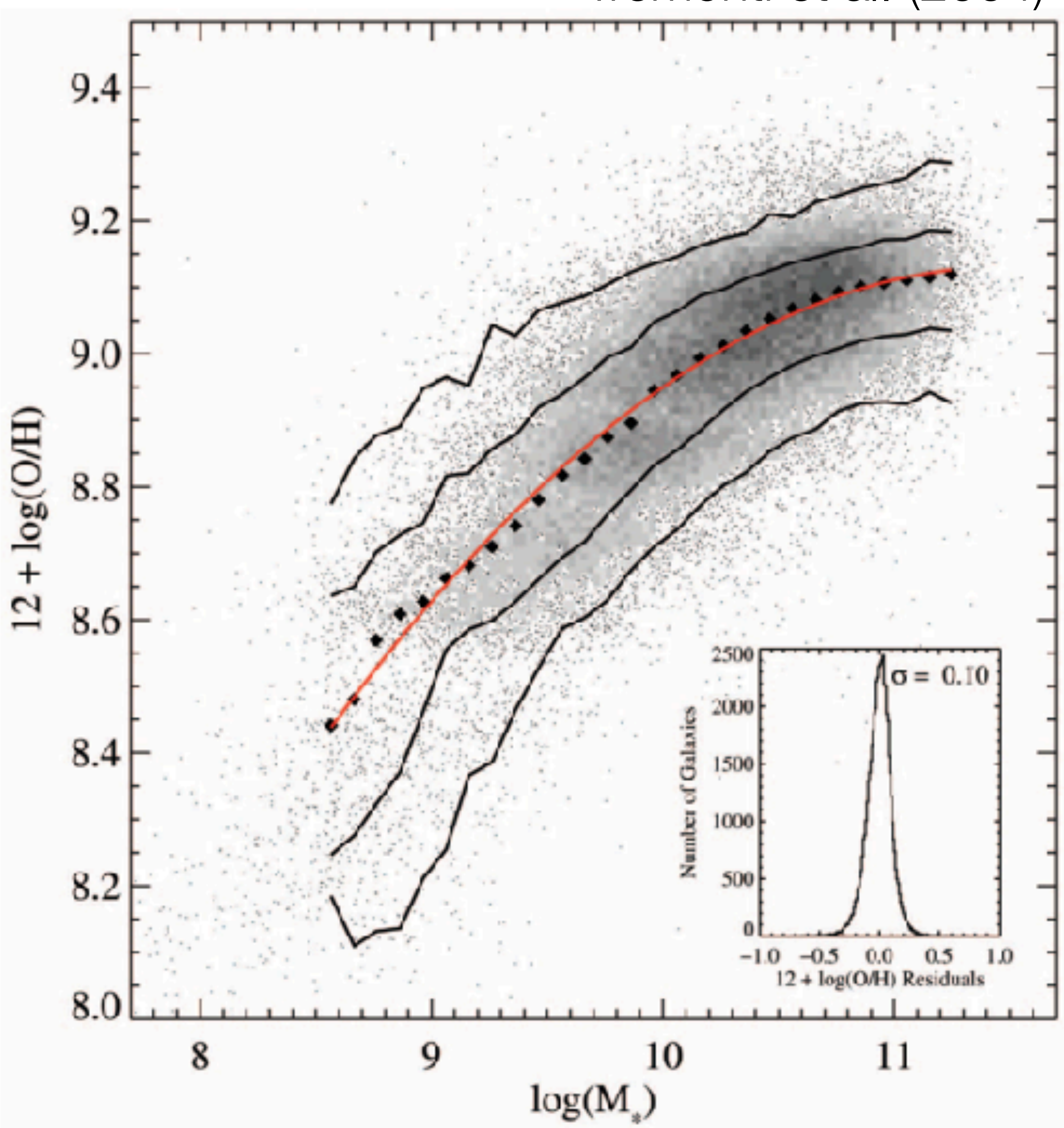


comparing the **observed shape** with predictions from **simulations** can serve as a test of **feedback models**

scatter may be tied to a **third parameter**, **population diversity**, or the **timescale** of physical processes

We see a correlation using multiple tracers of enrichment

Tremonti et al. (2004)



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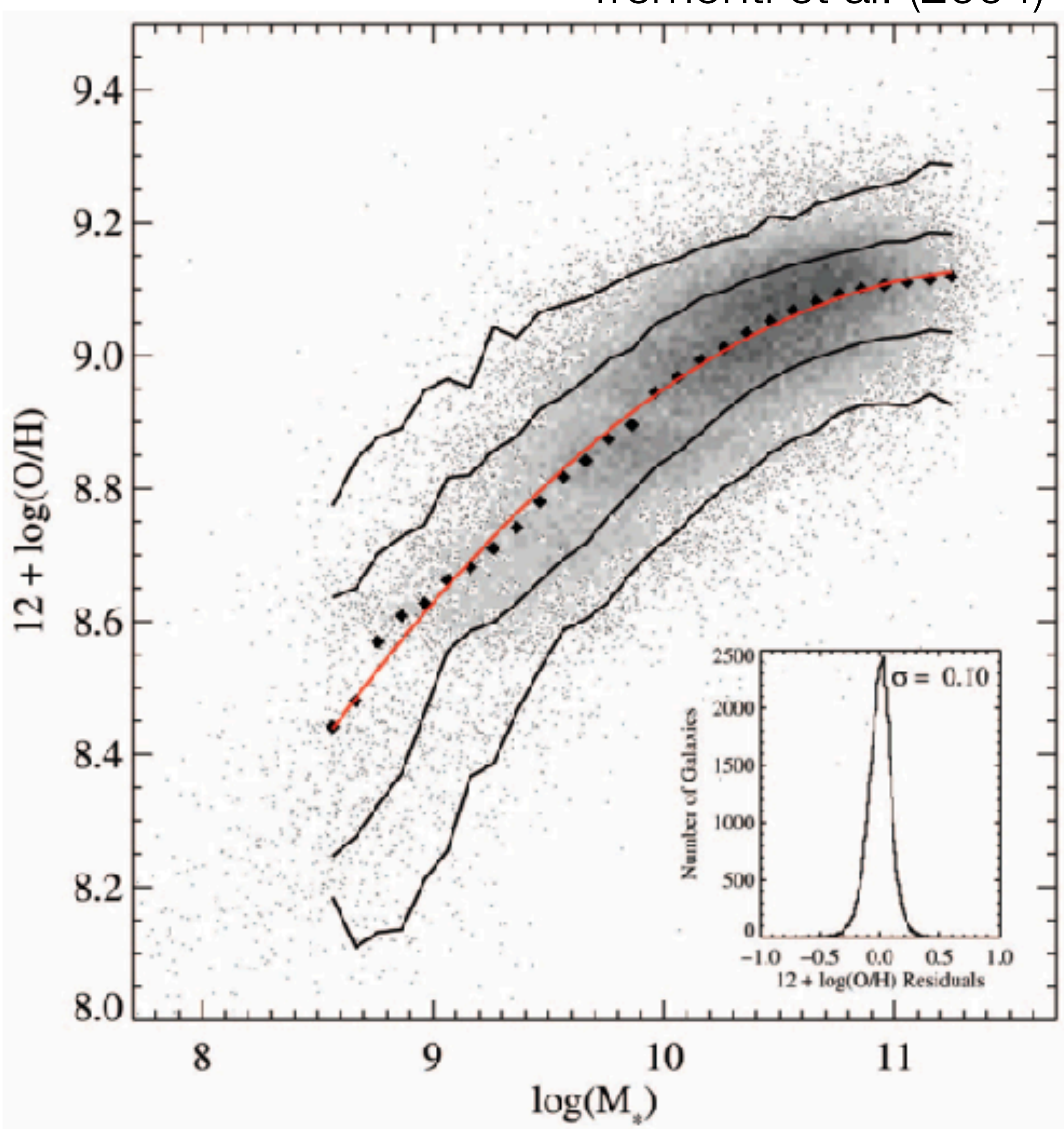
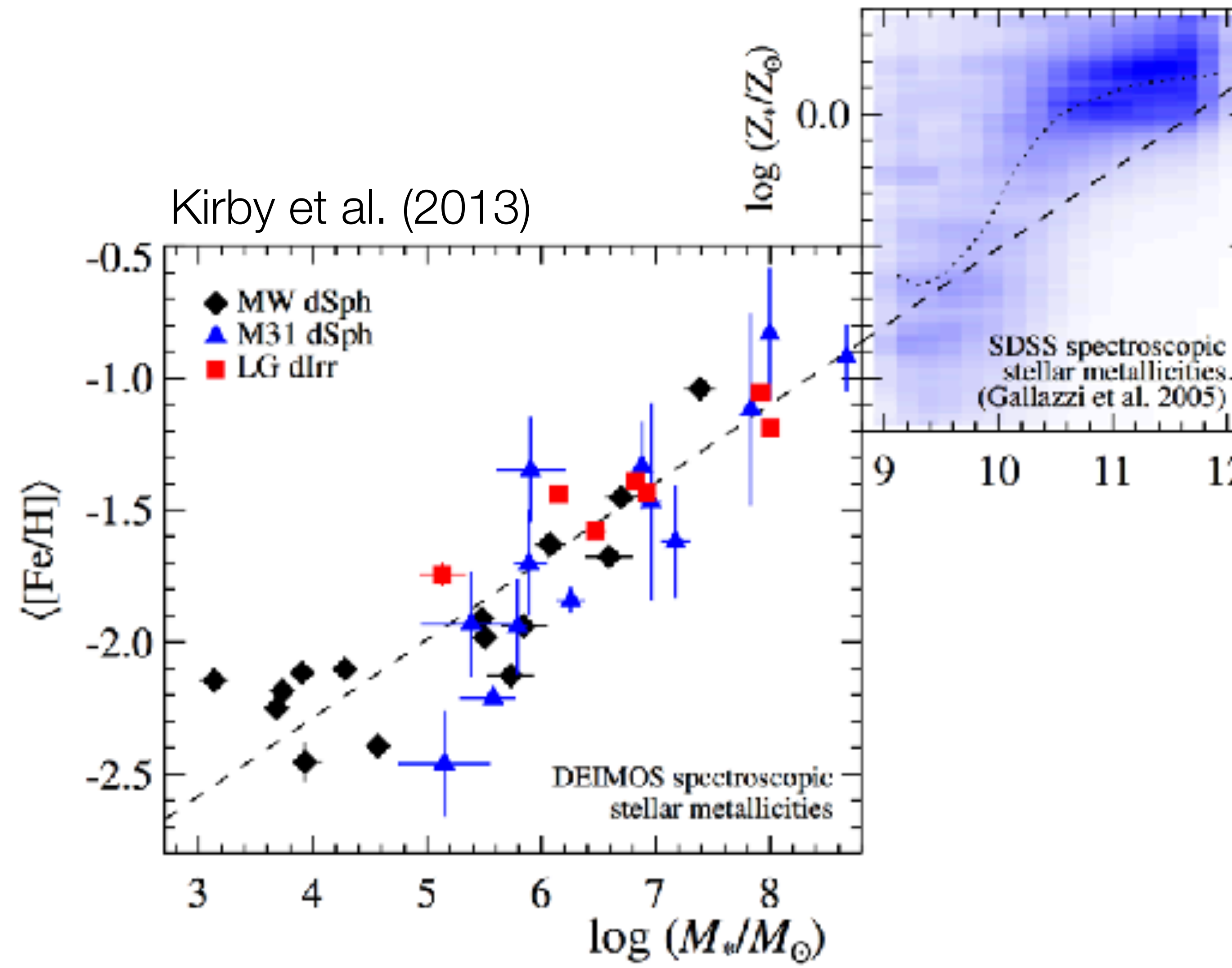


Kirby et al. (2013)



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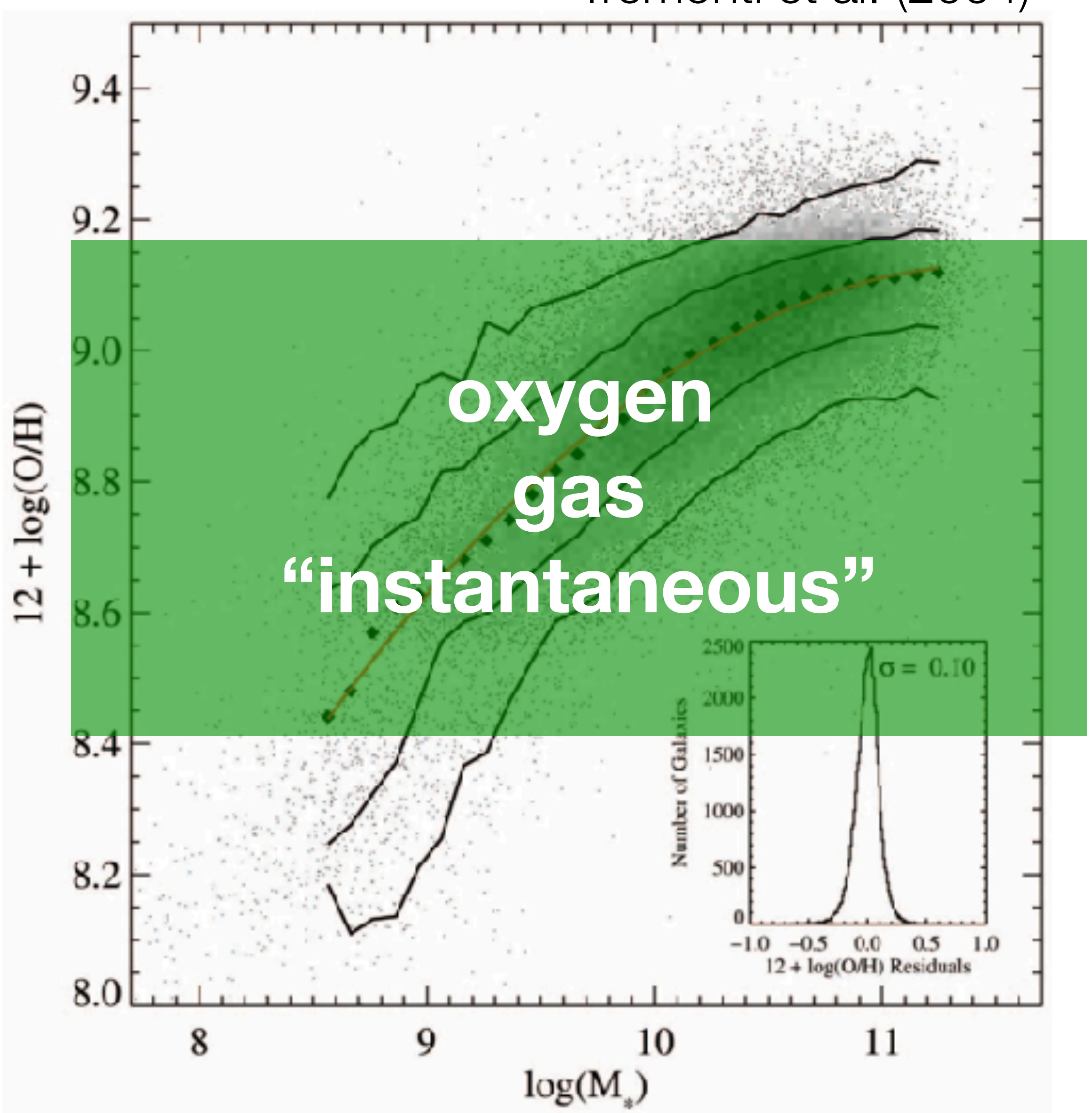

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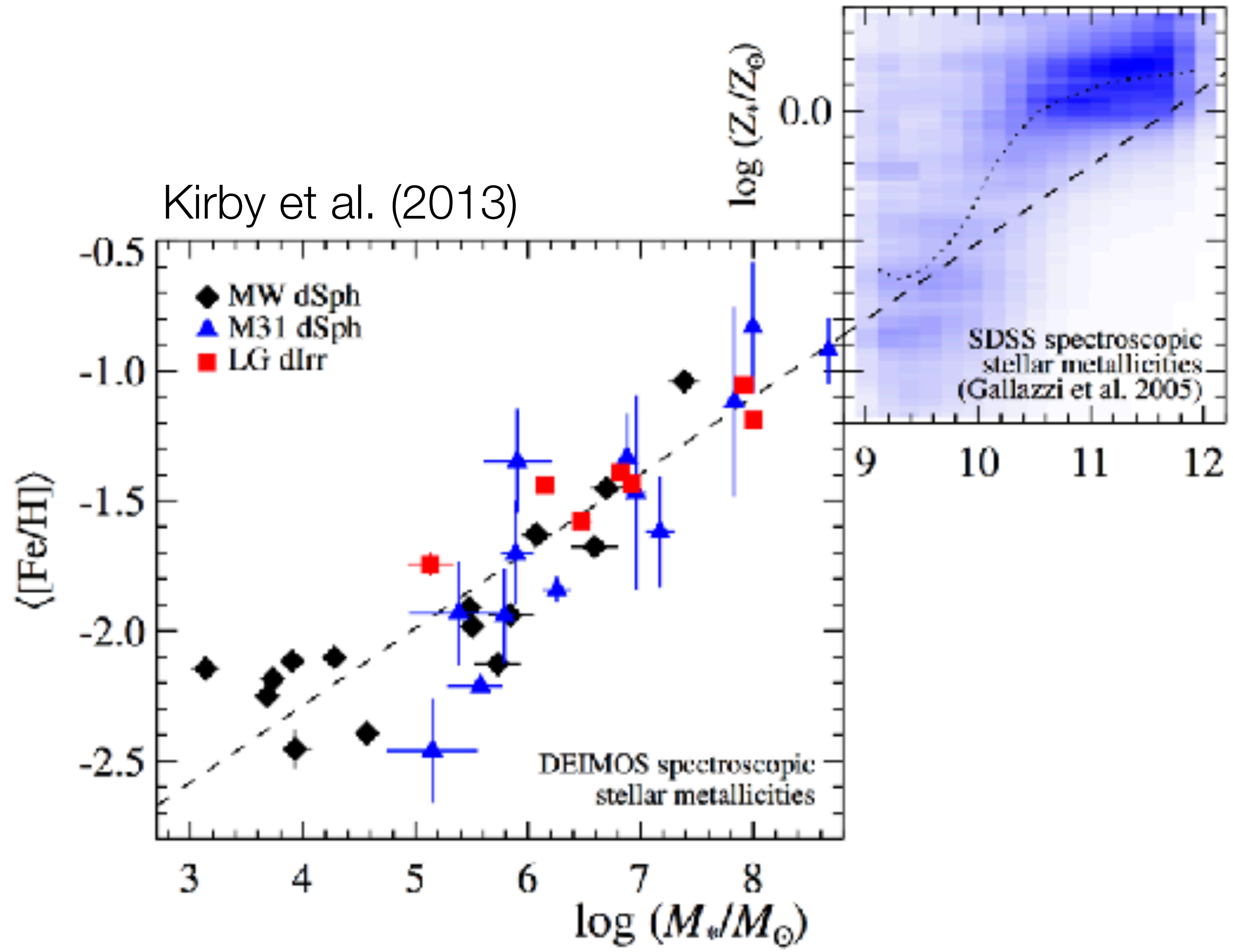

We see a correlation using multiple tracers of enrichment

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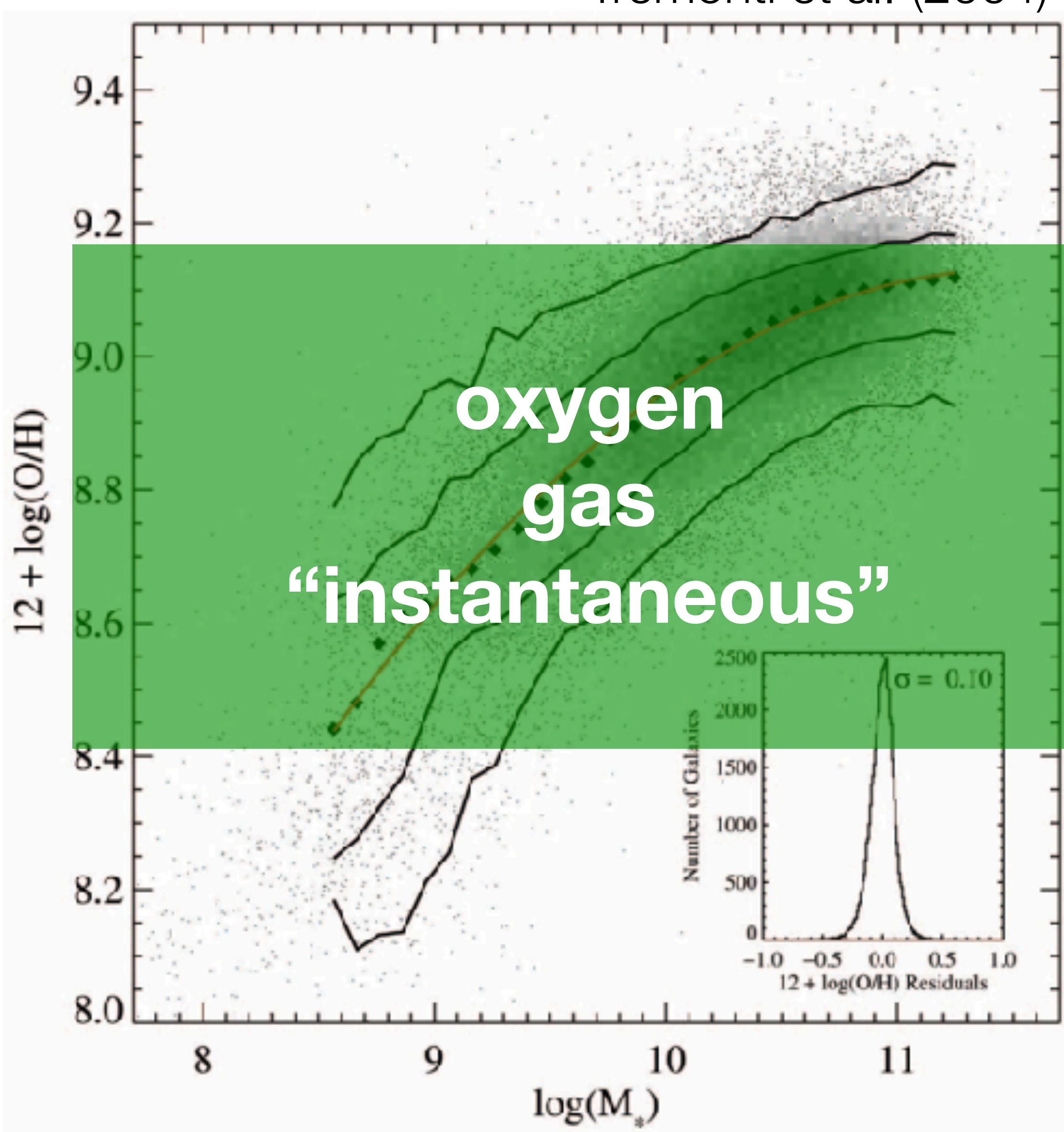
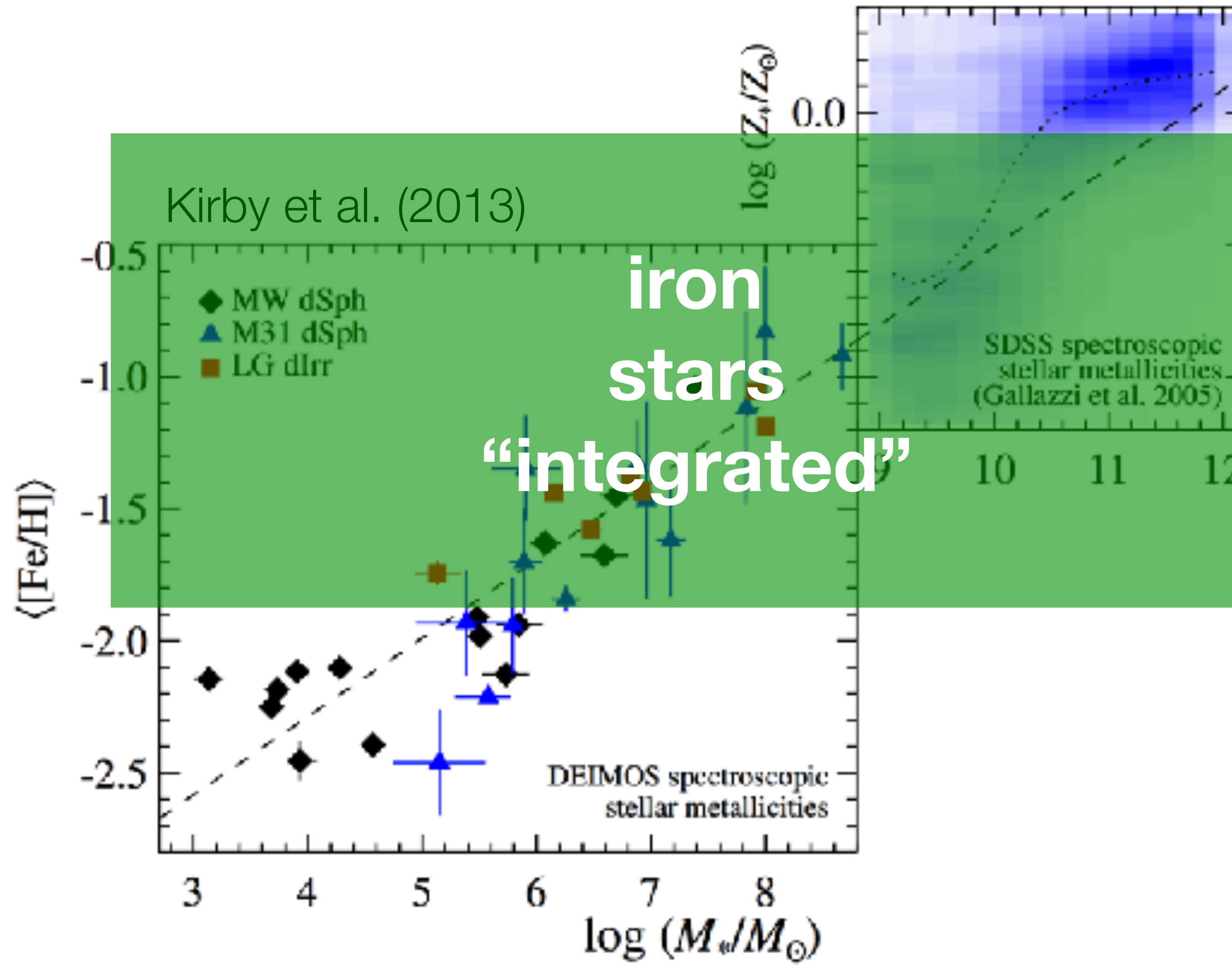


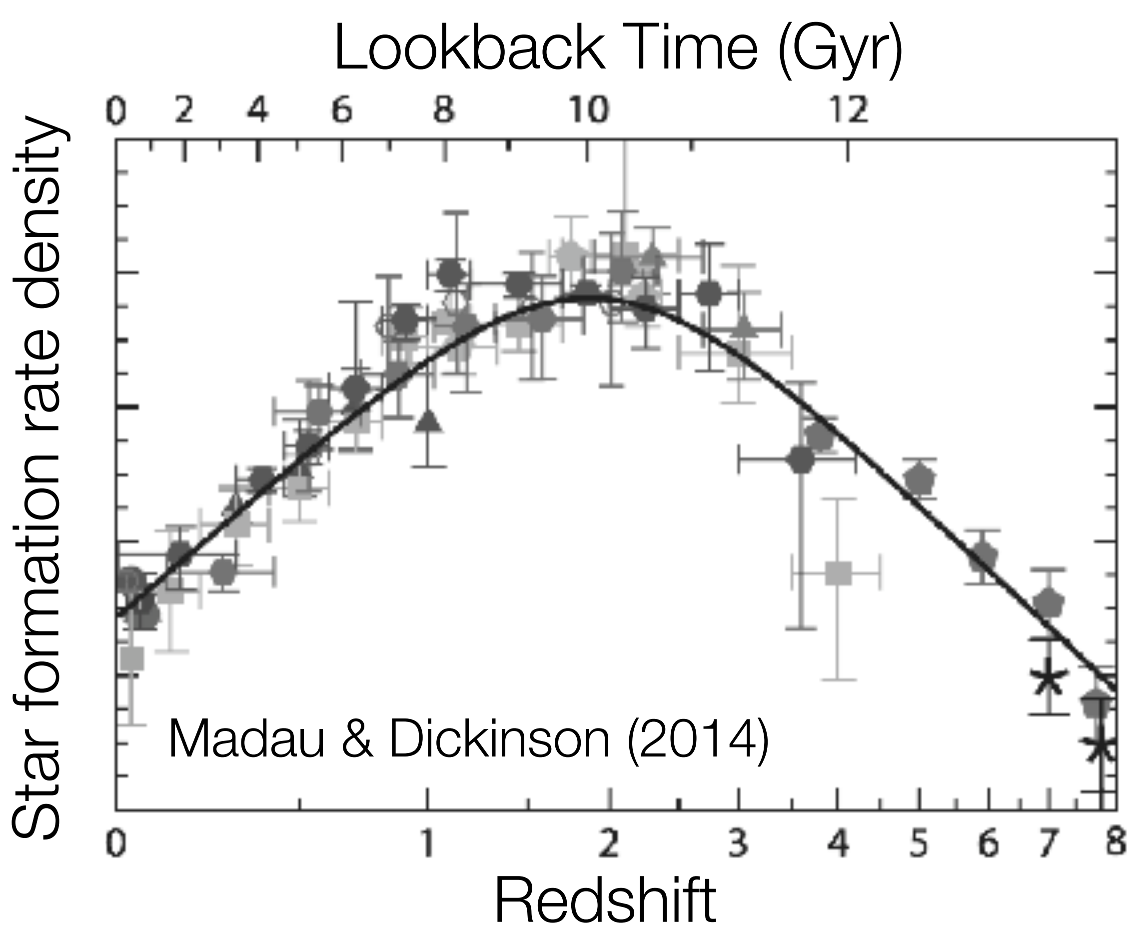
oxygen
gas
“instantaneous”

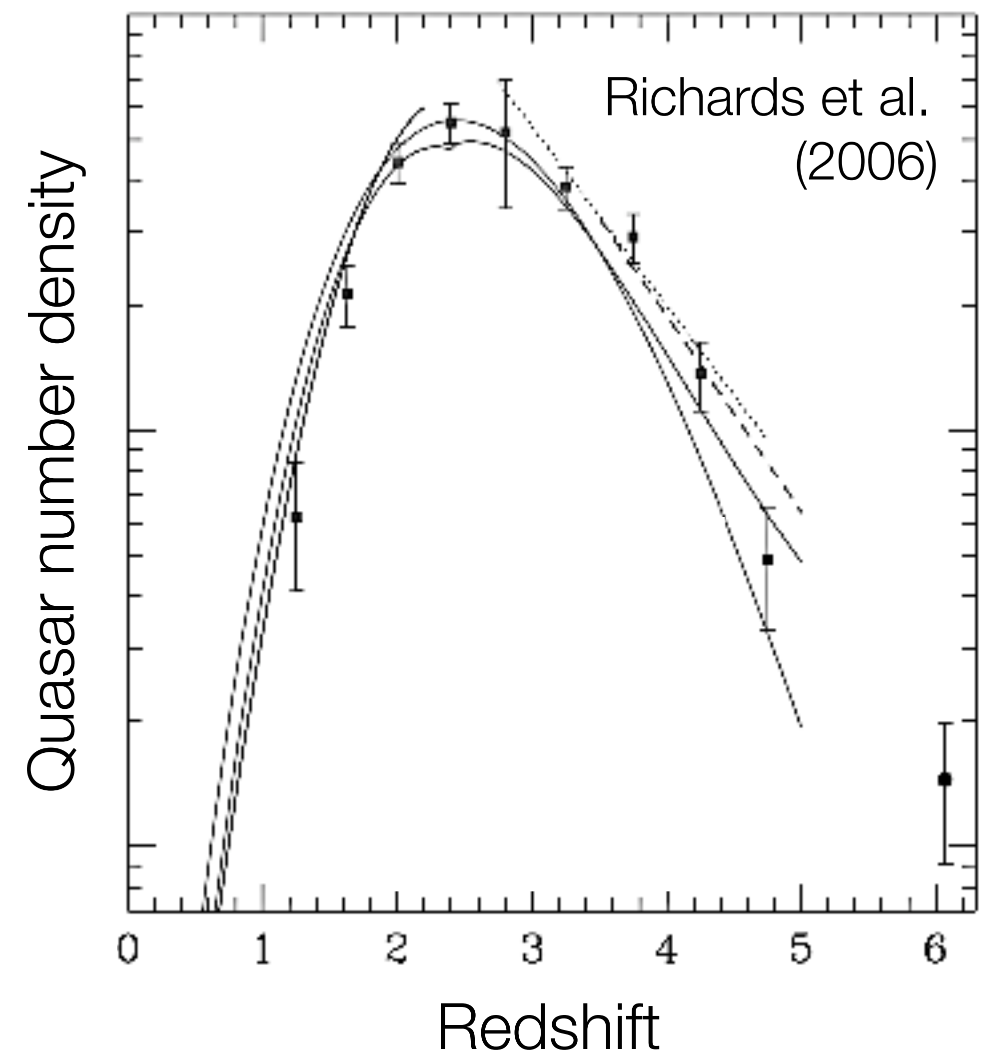
Kirby et al. (2013)



iron
stars
“integrated”

Most of the universe's stars were formed (quickly) in the past





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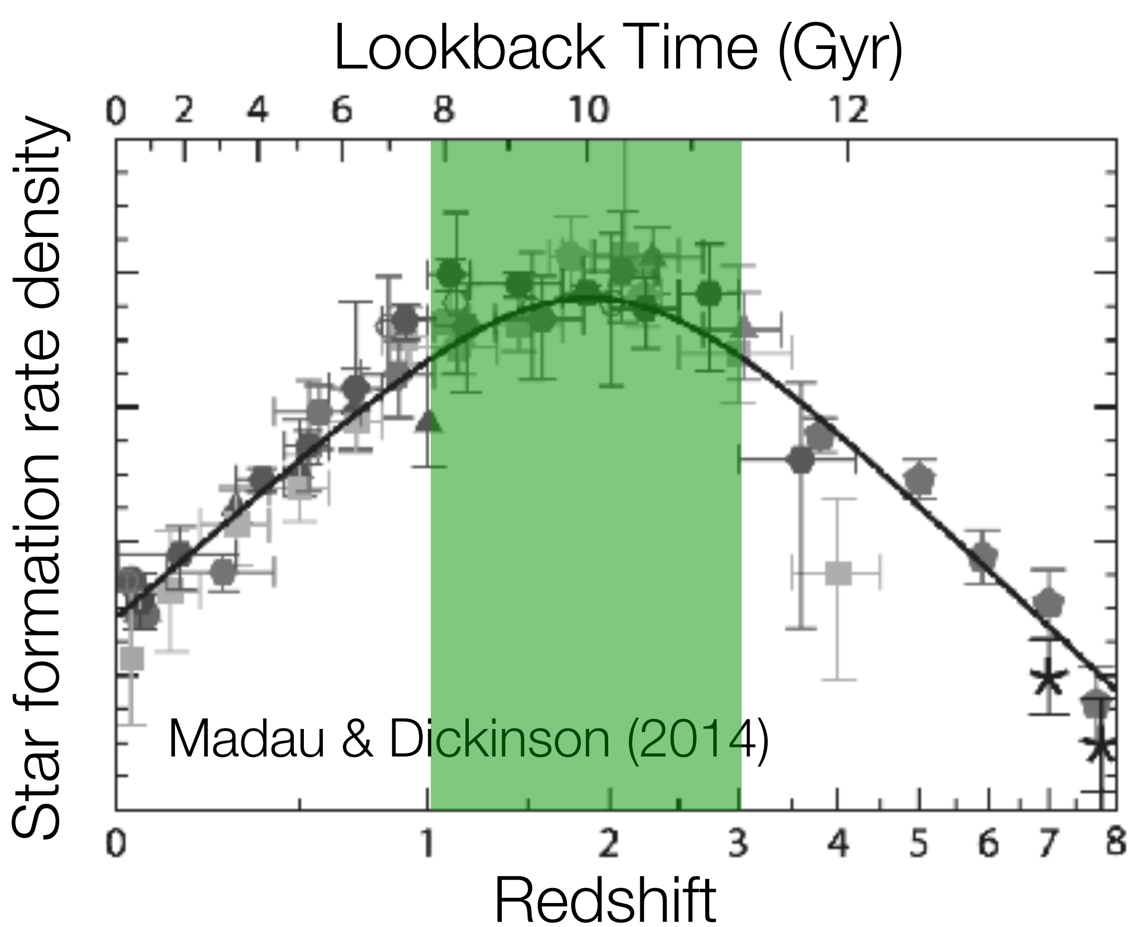
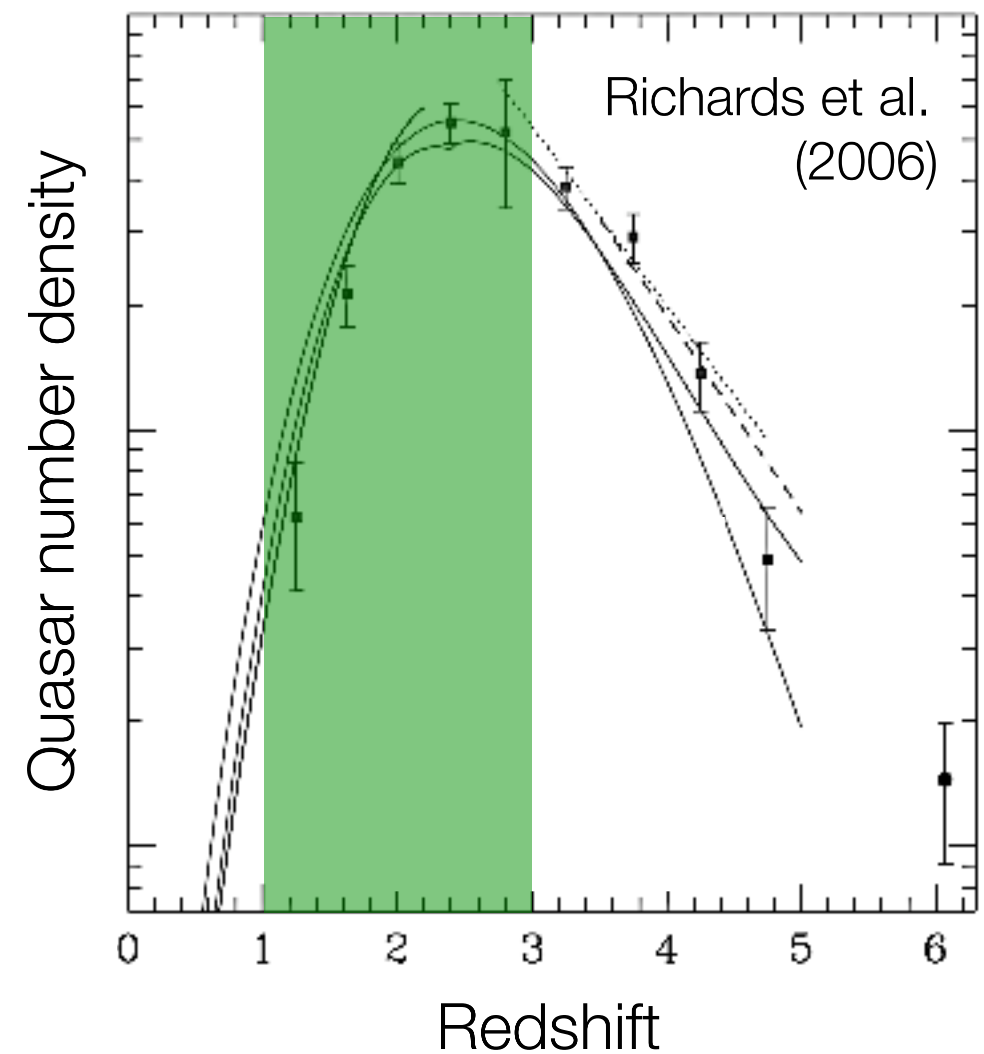
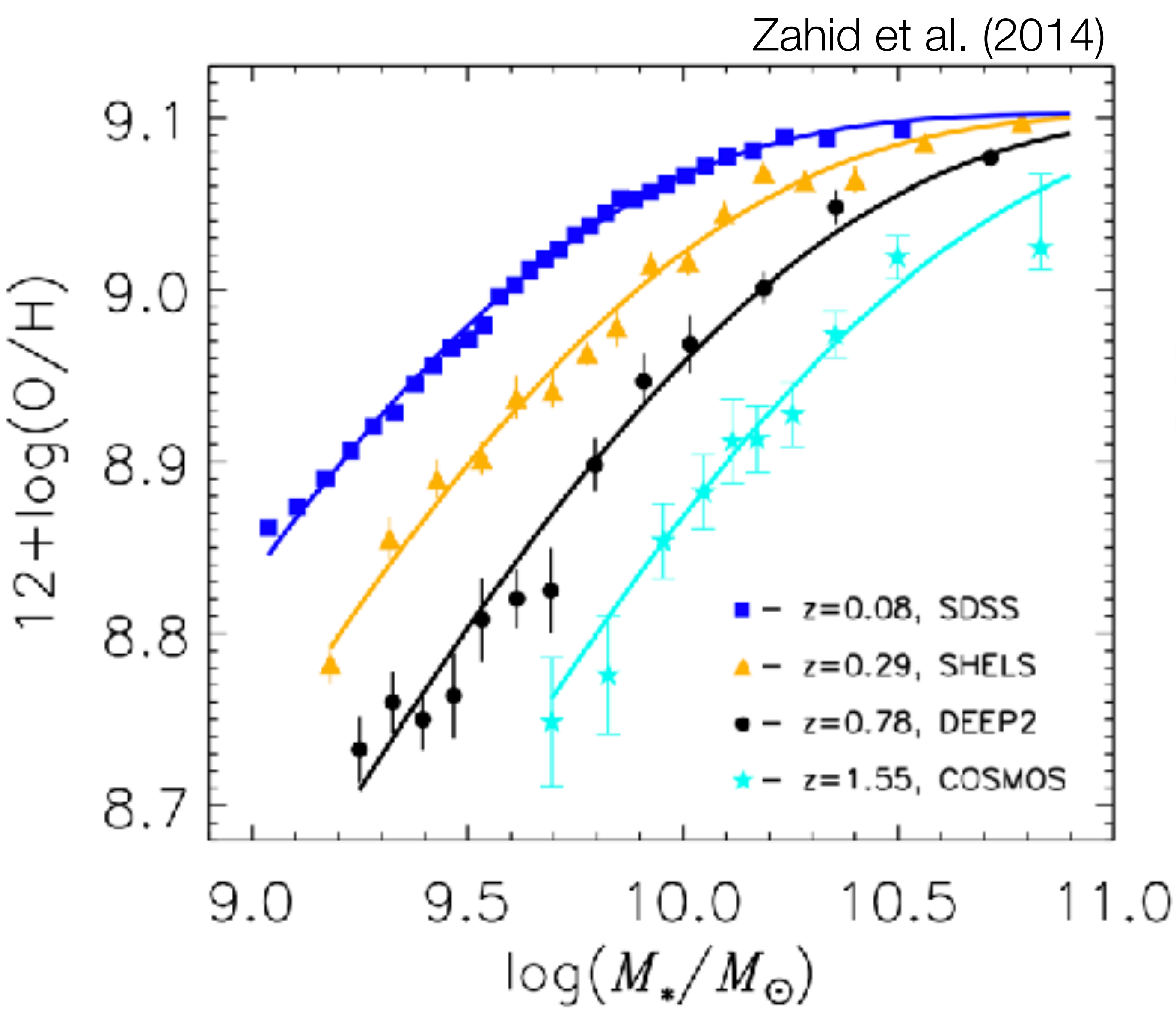
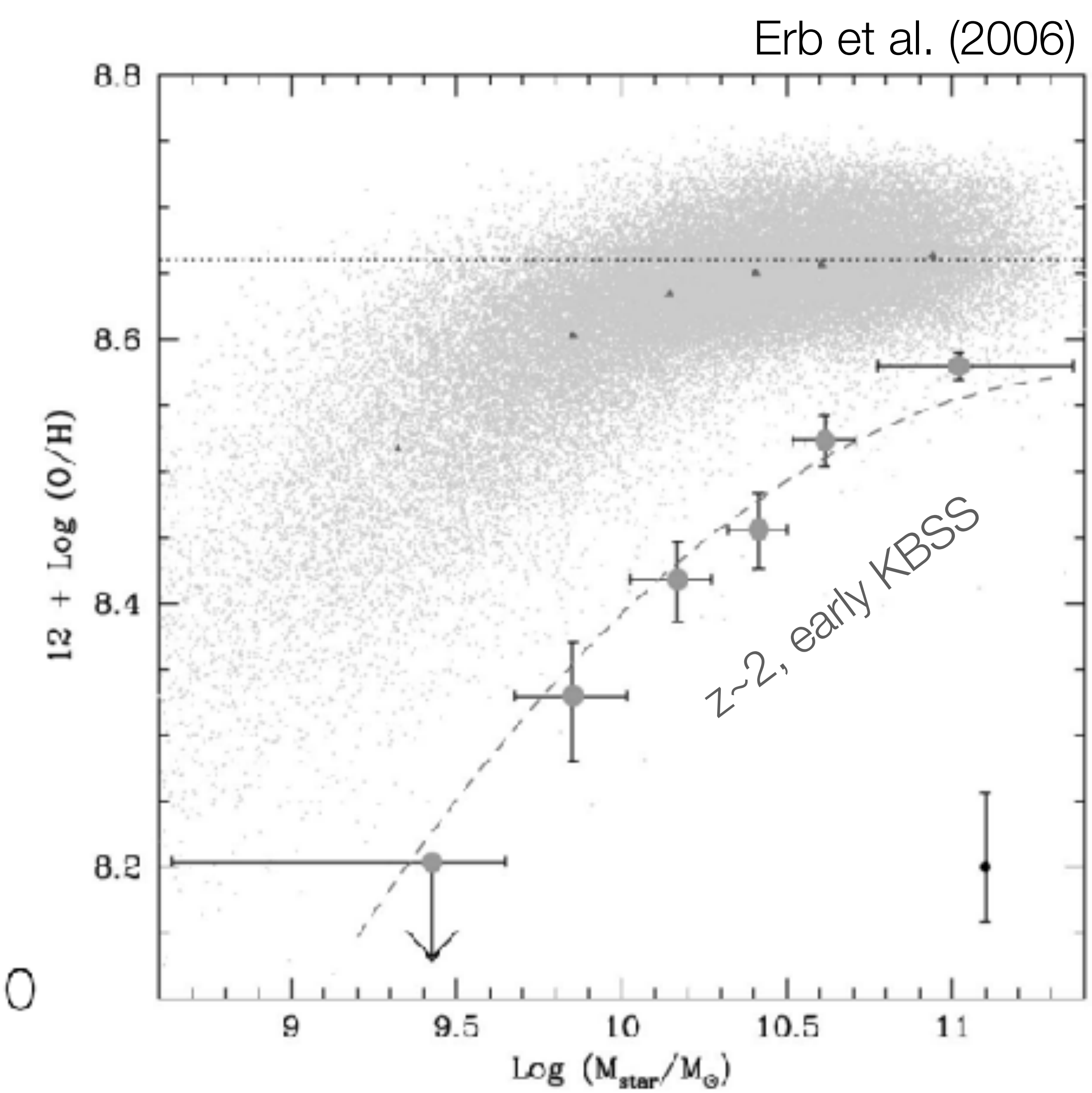




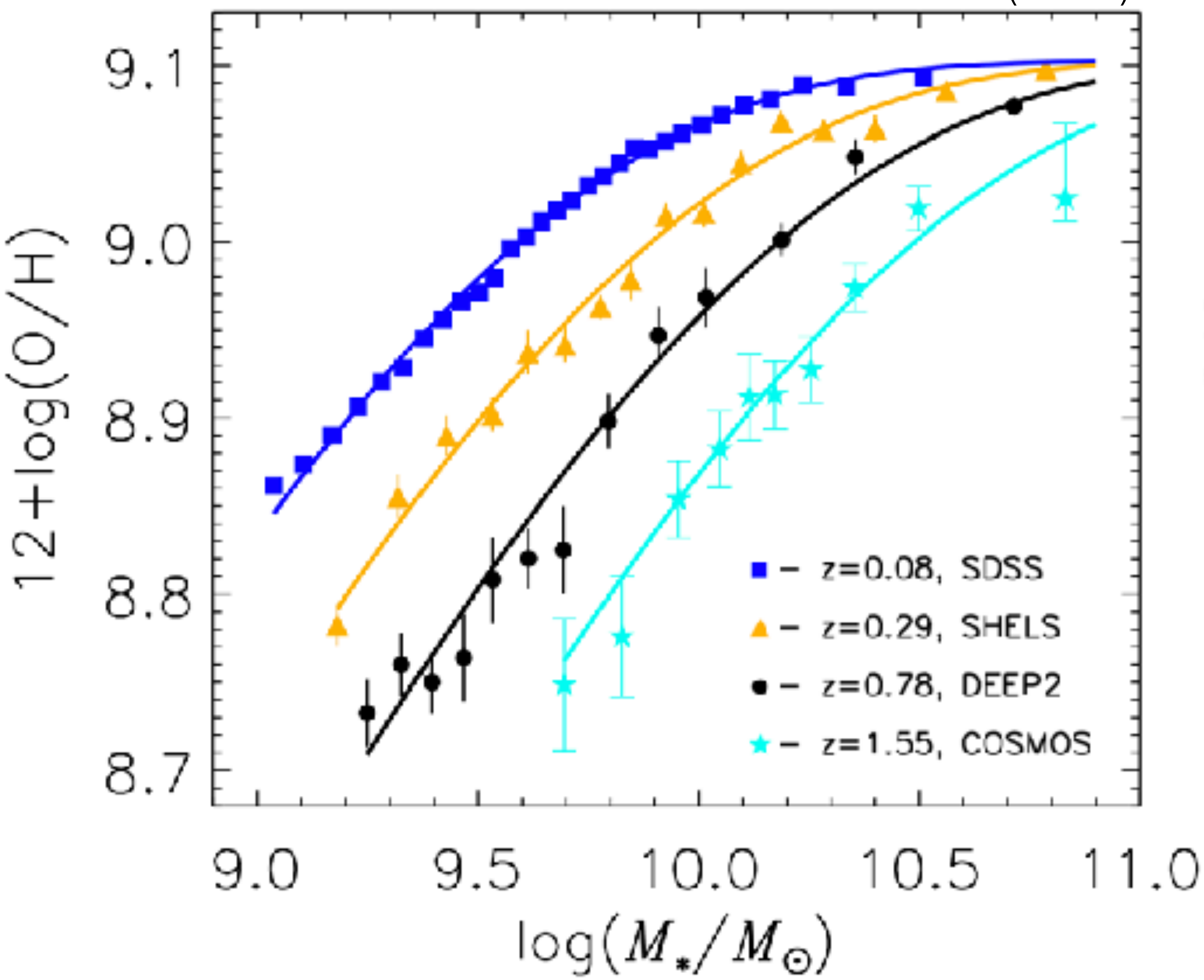
Differences with redshift offer clues regarding early galaxy formation



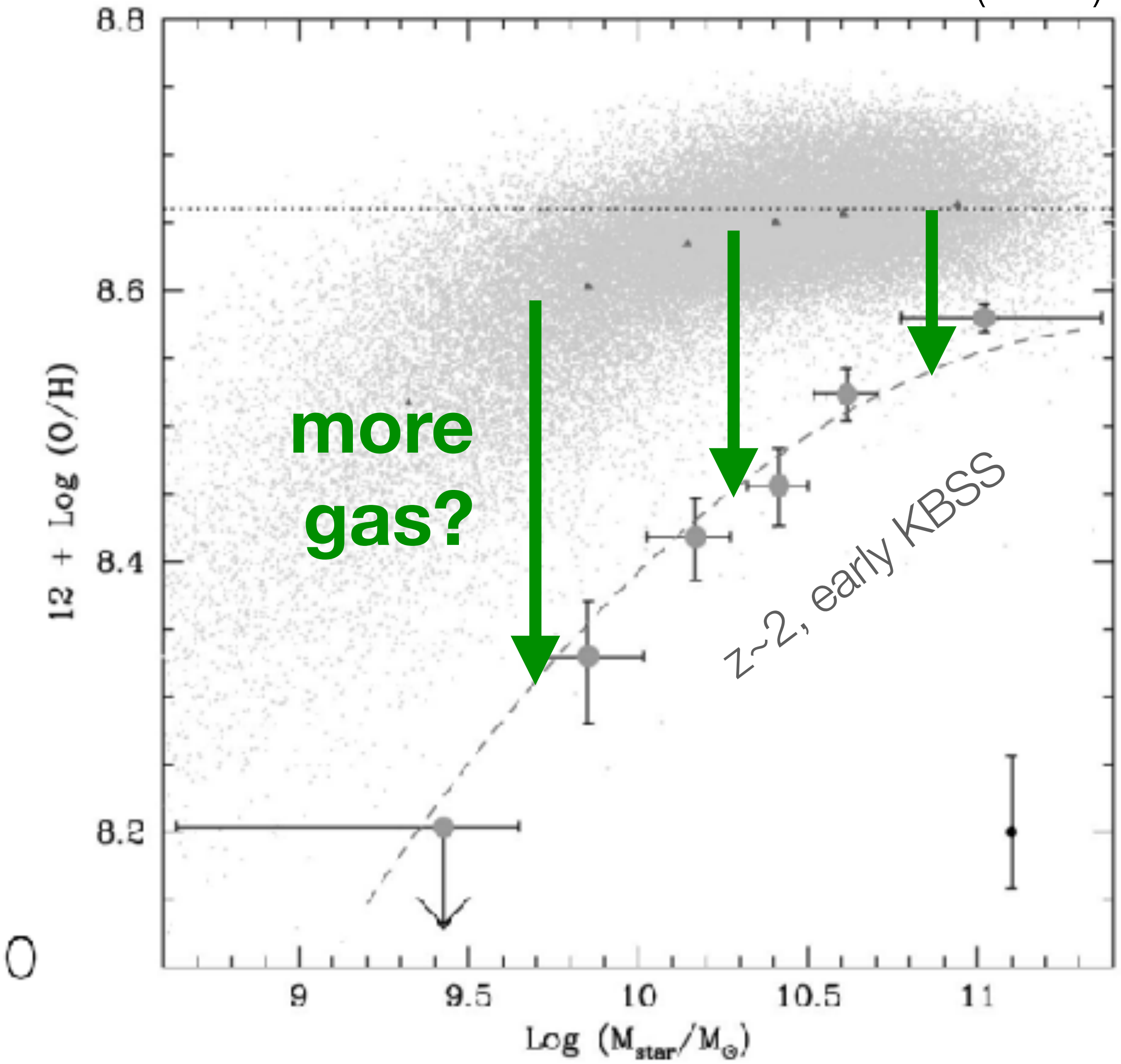


Differences with redshift offer clues regarding early galaxy formation

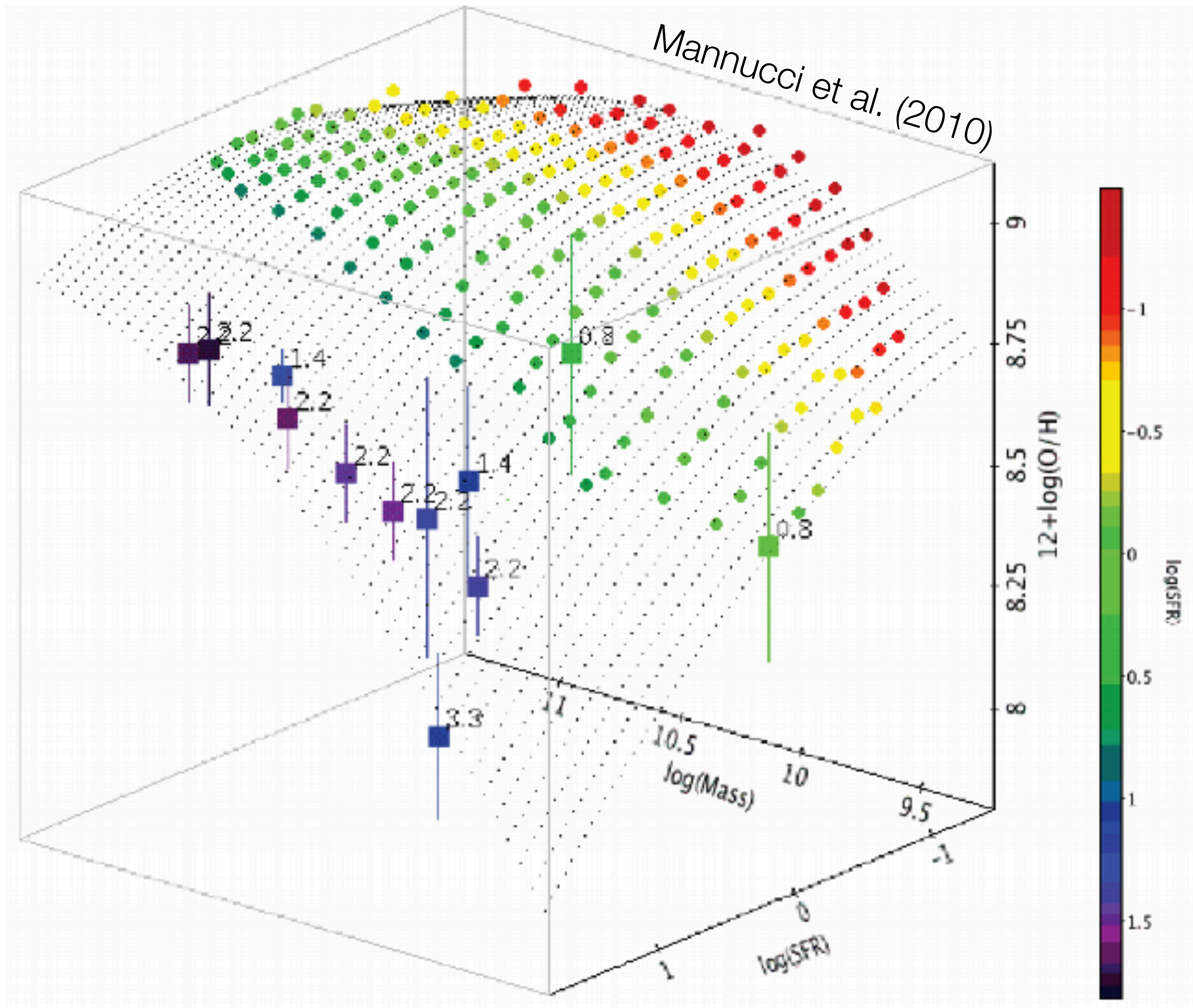
Zahid et al. (2014)



Erb et al. (2006)



Debate remains regarding implications of a M★-Z-SFR surface



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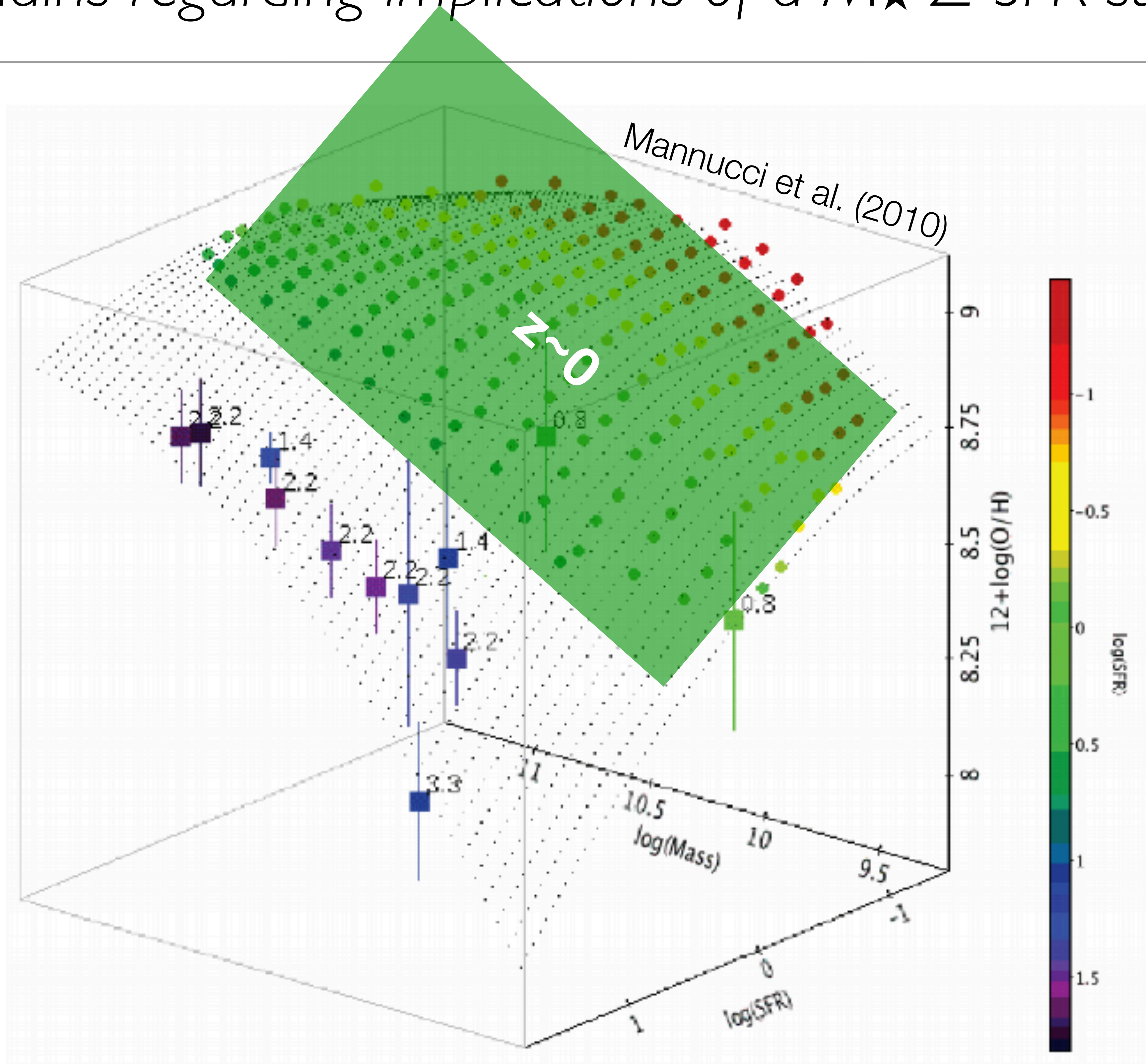

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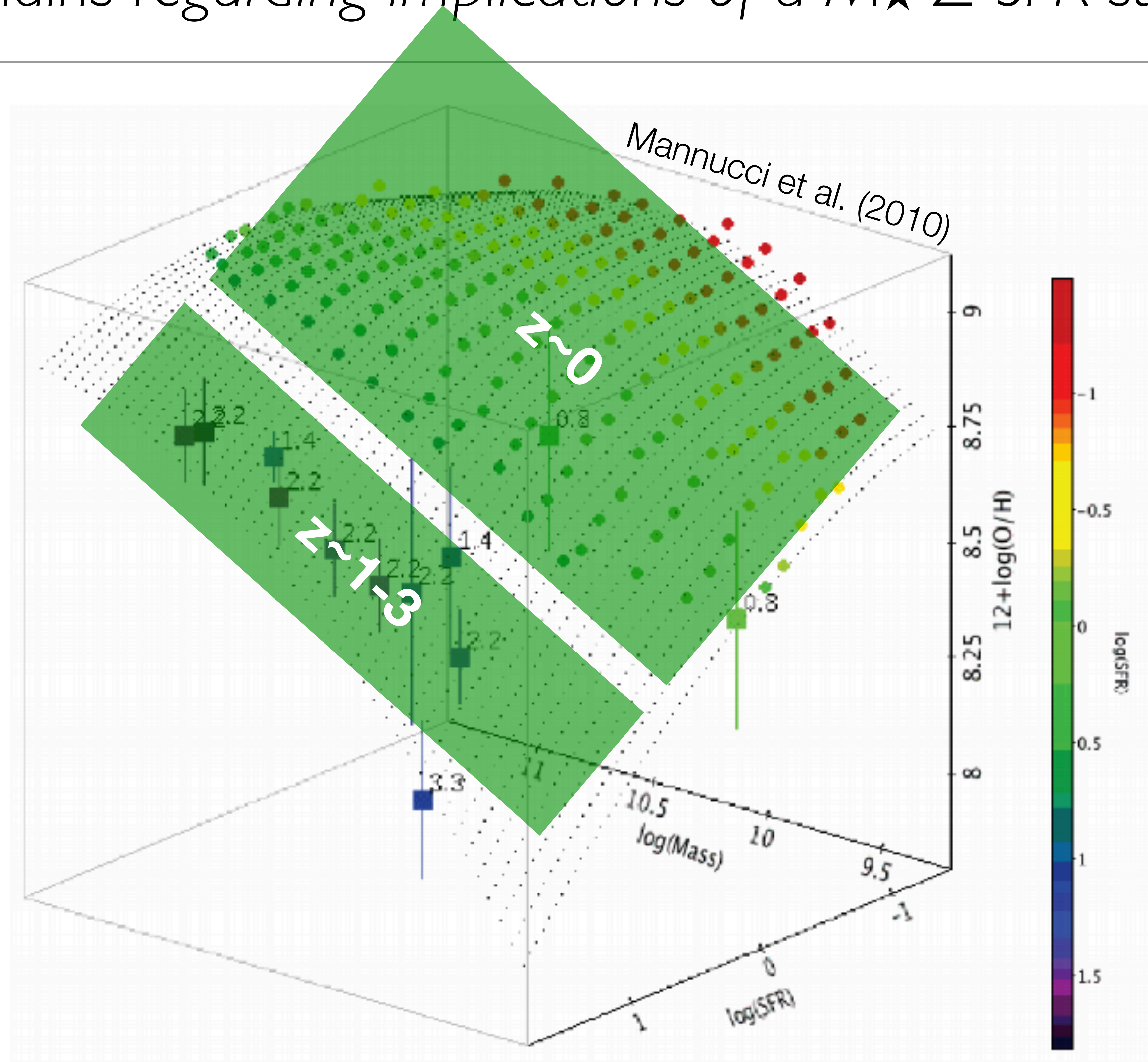
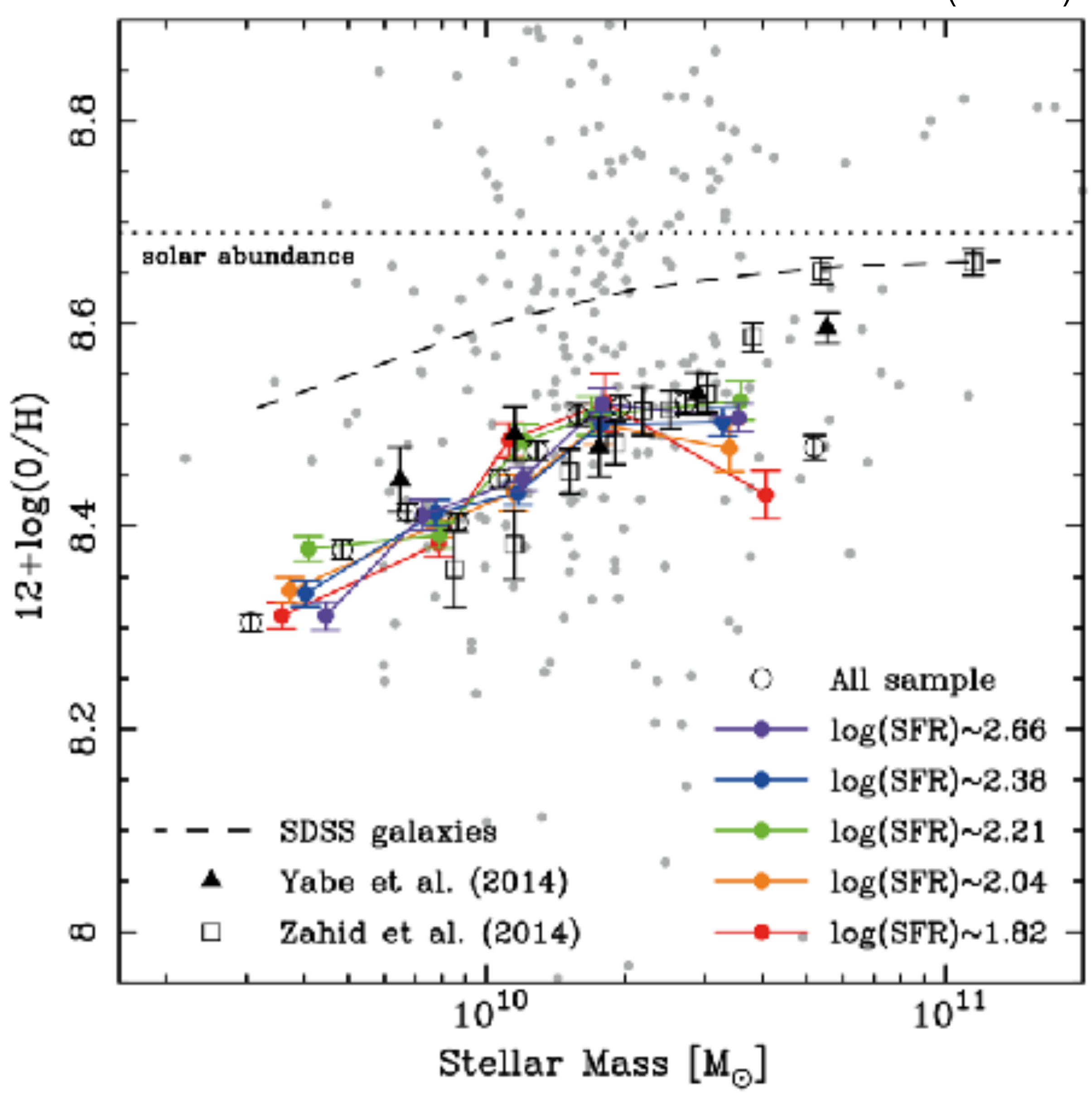
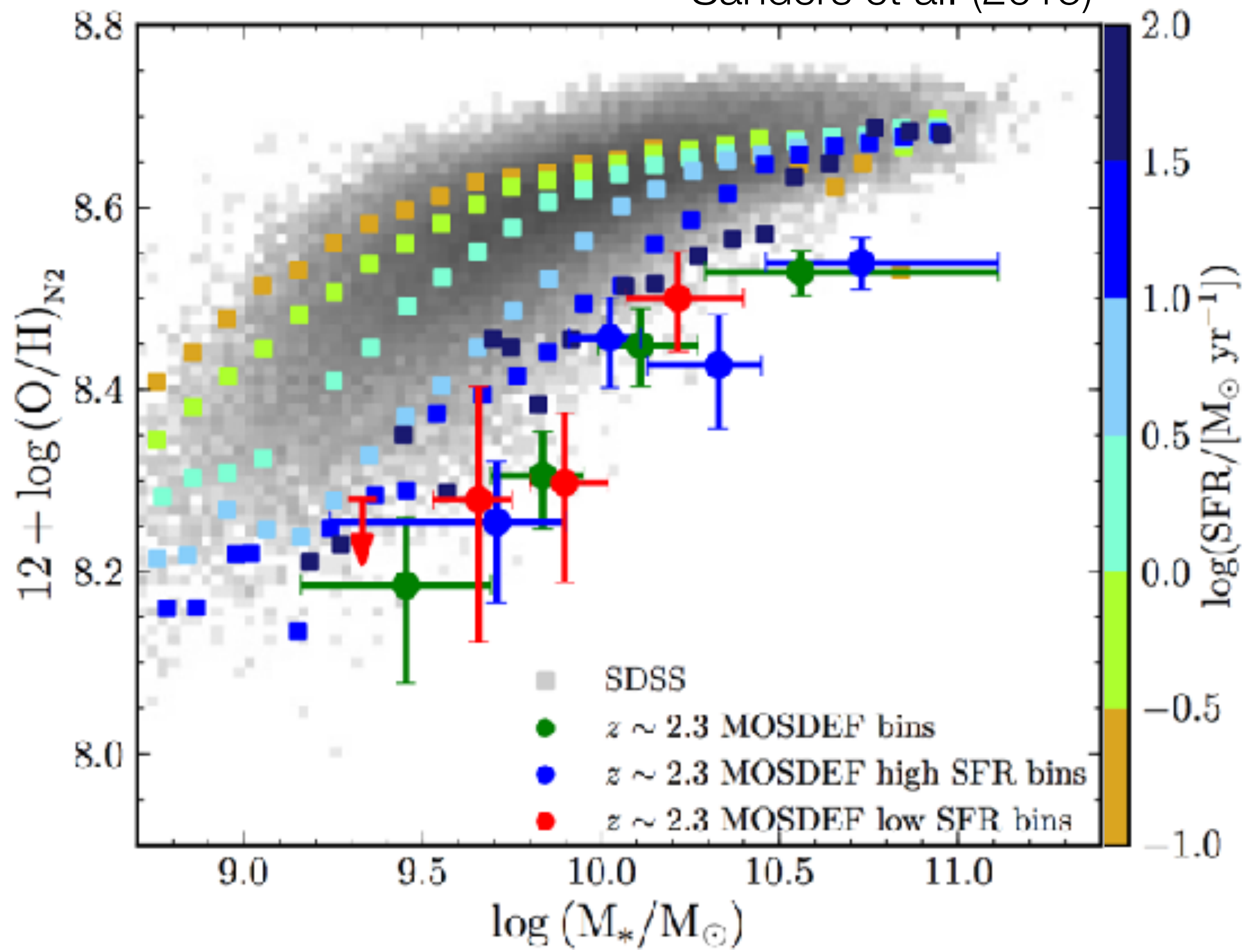


Debate remains regarding implications of a M★-Z-SFR surface

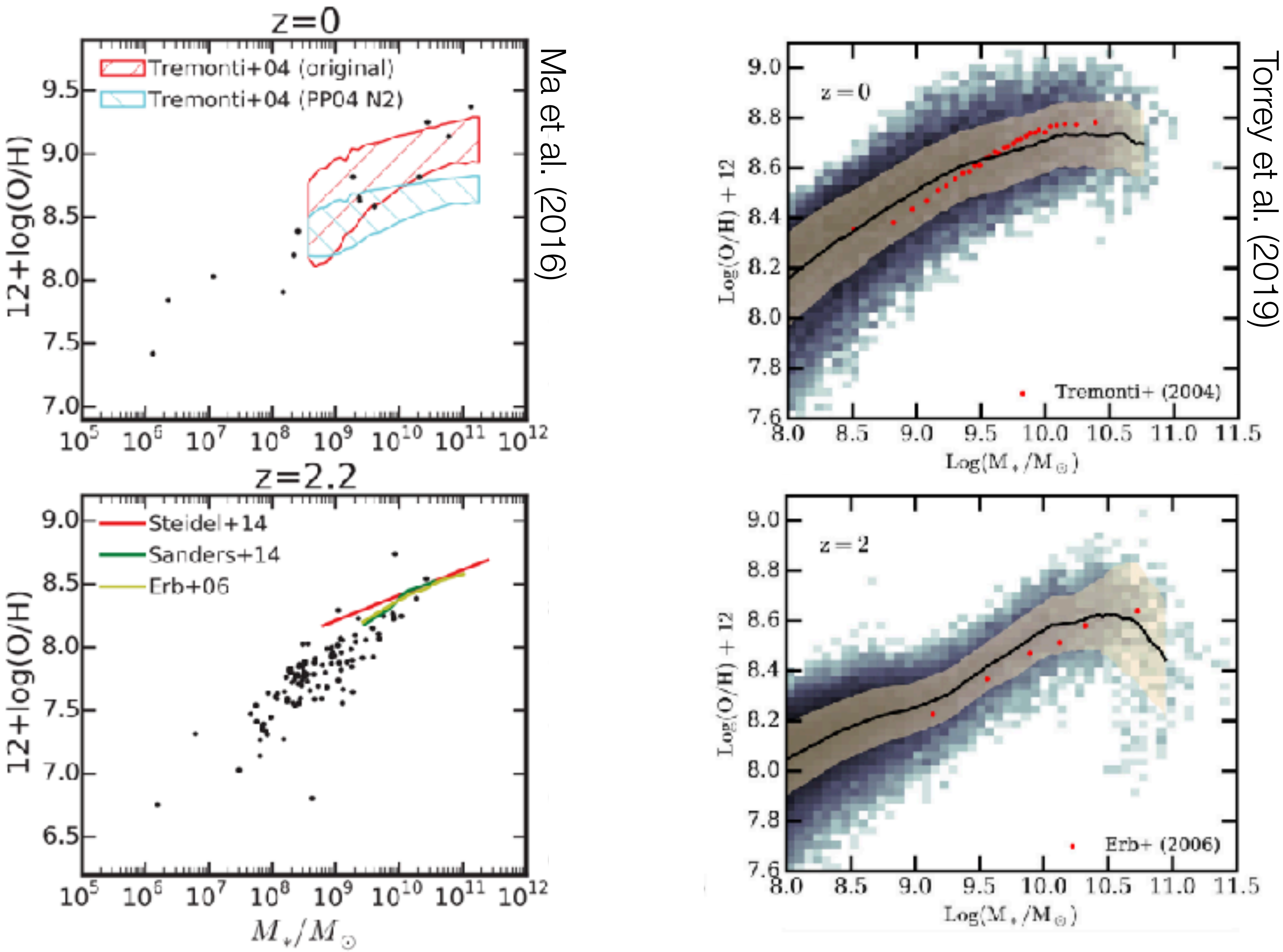
Yabe et al. (2015)



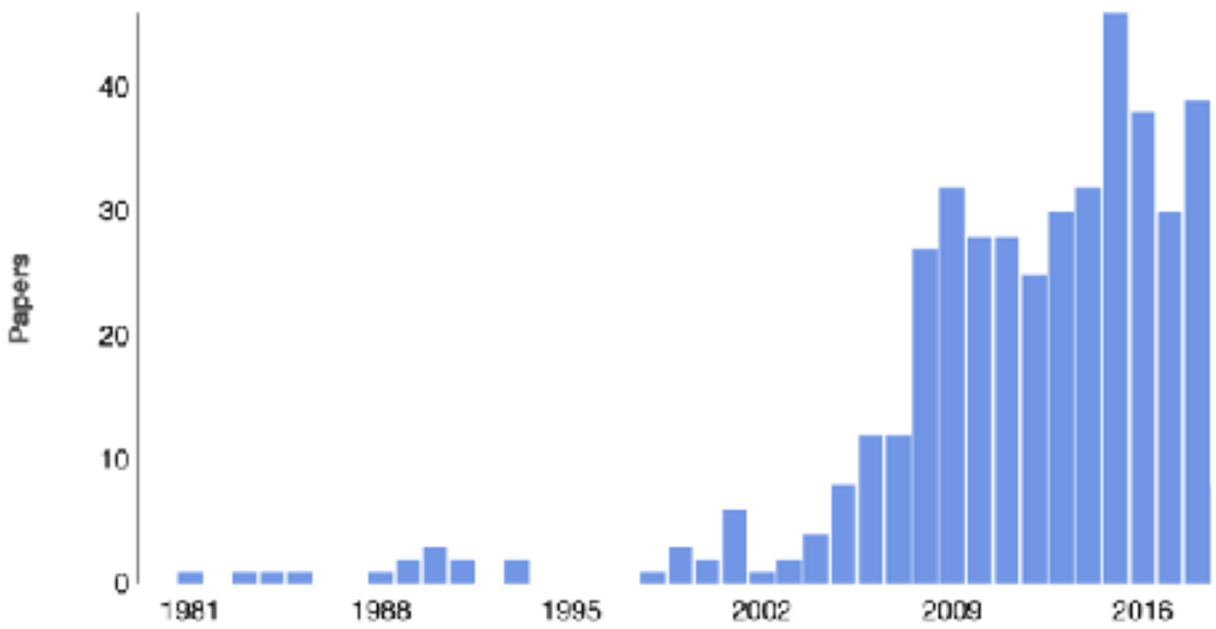
Sanders et al. (2015)

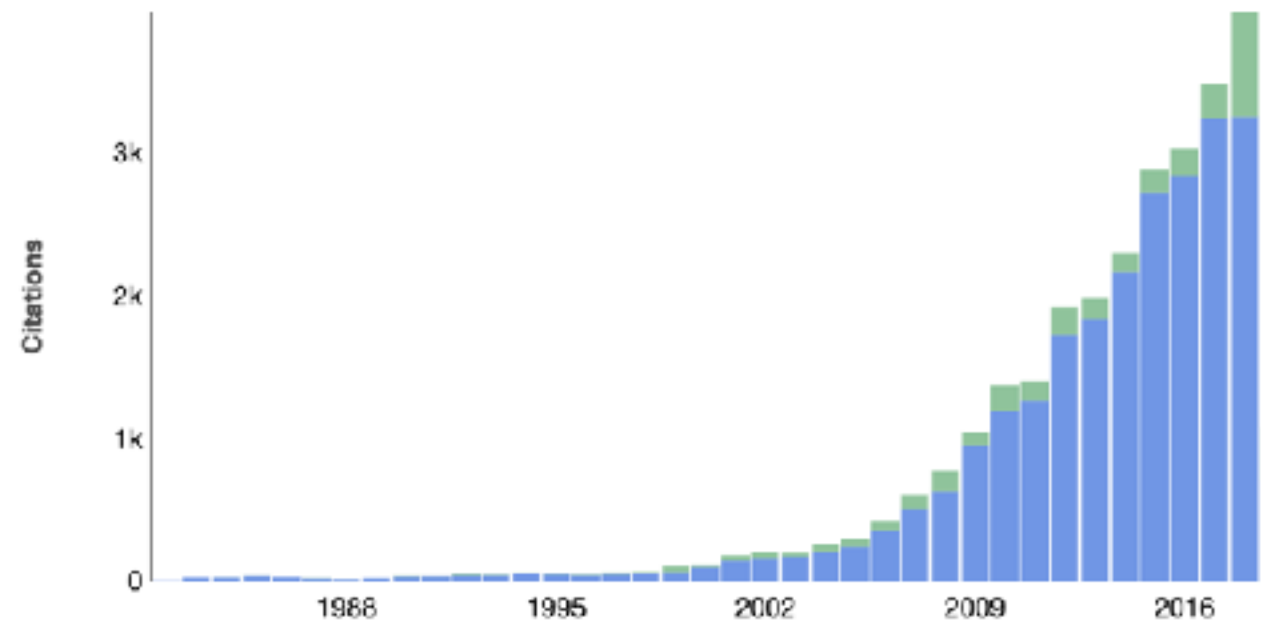


Simulations connect feedback physics to observed galaxy enrichment



Astronomers love (writing about) the MZR





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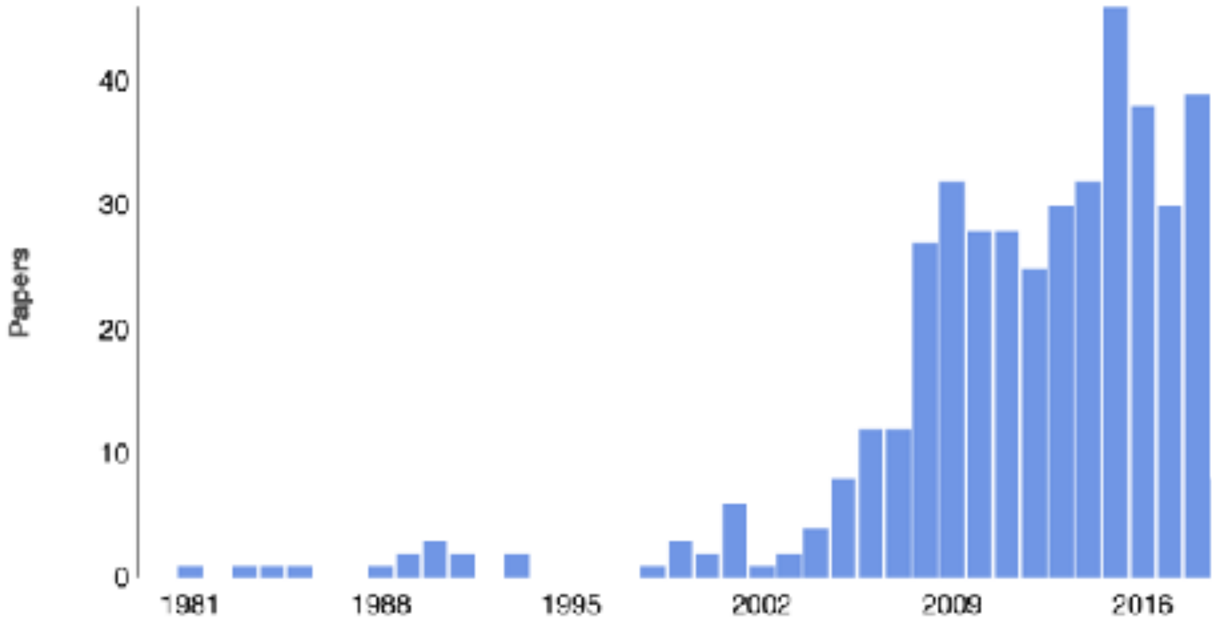
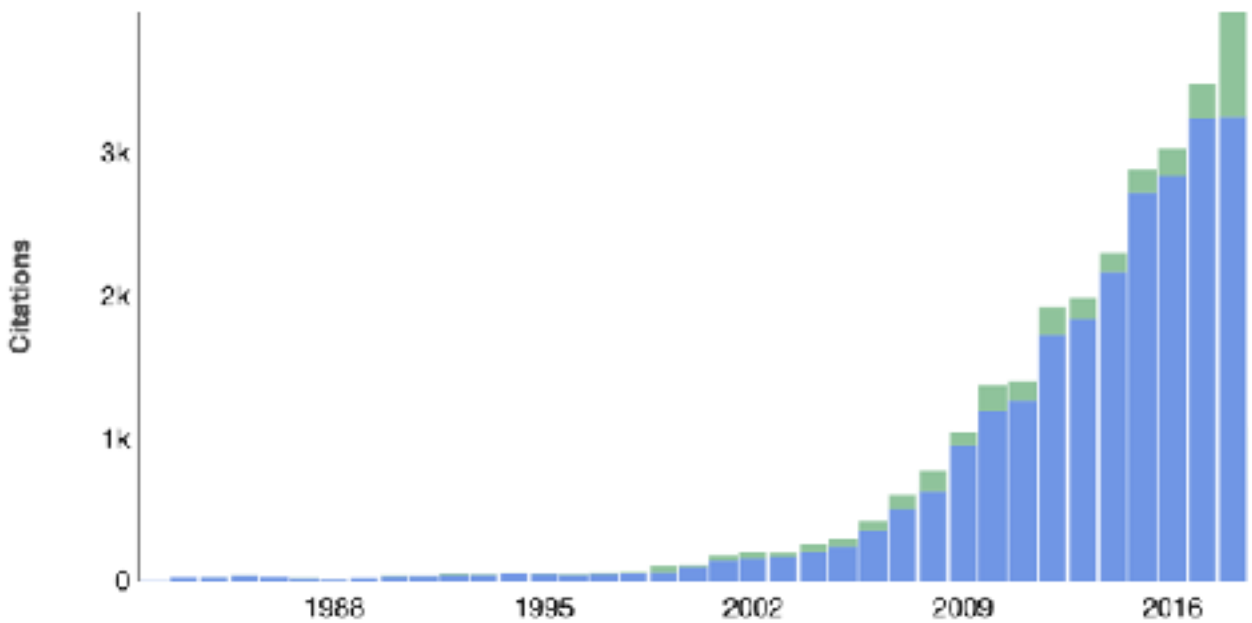
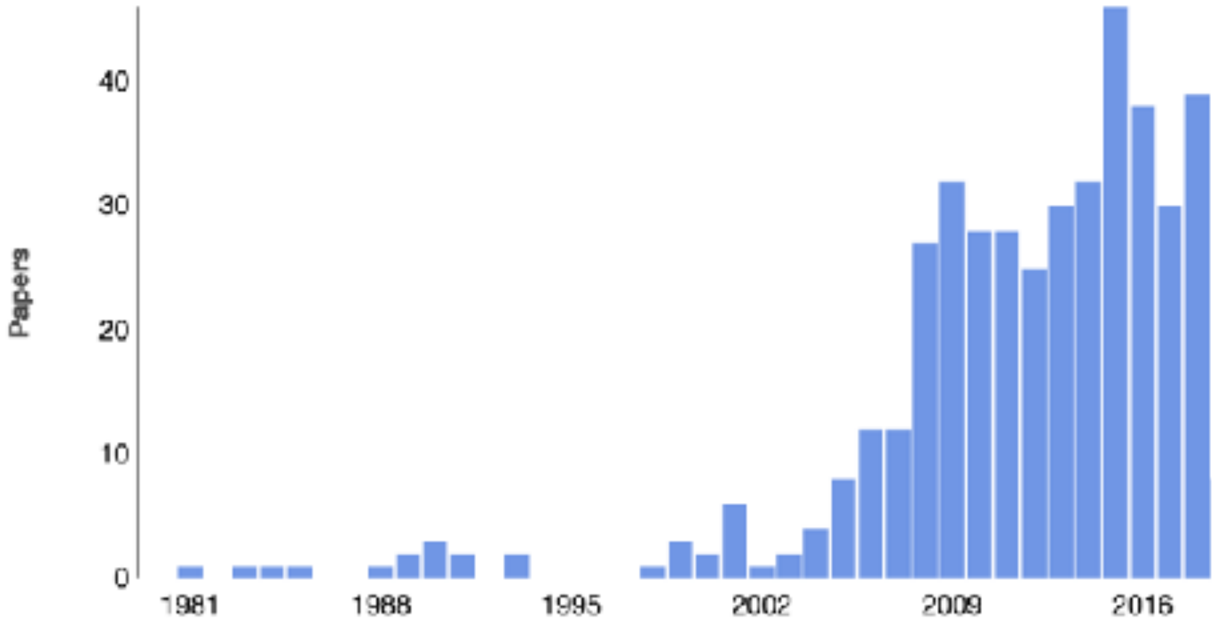
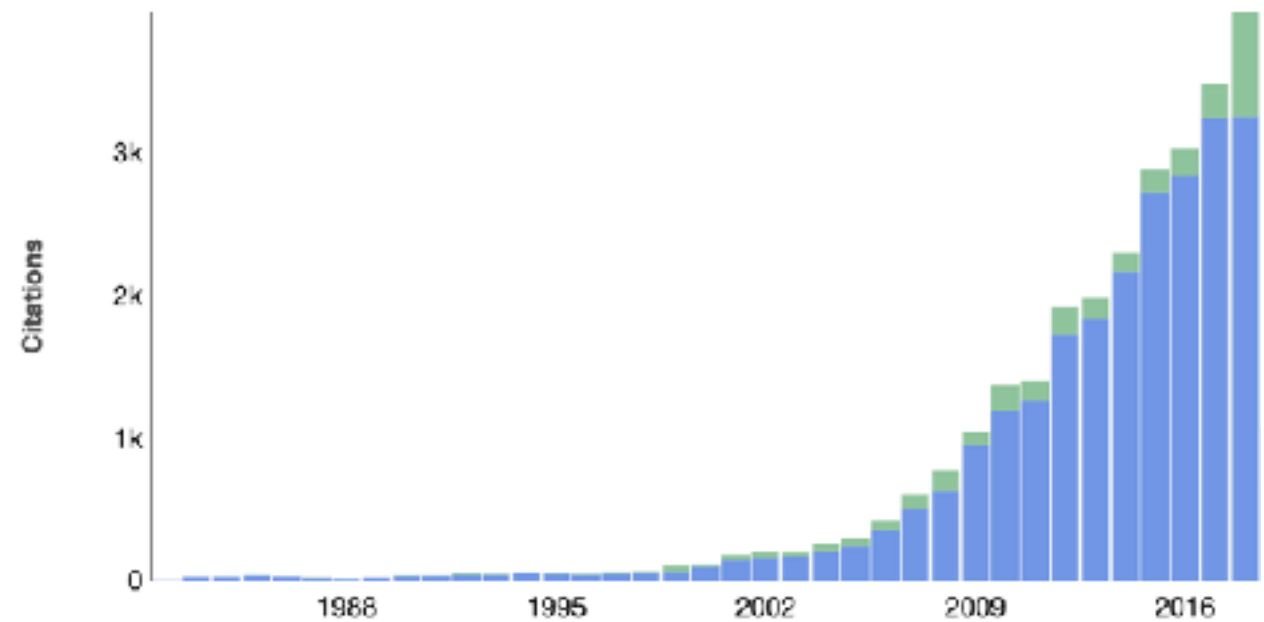




Two questions I want to consider today

Astronomers love (writing about) the MZR

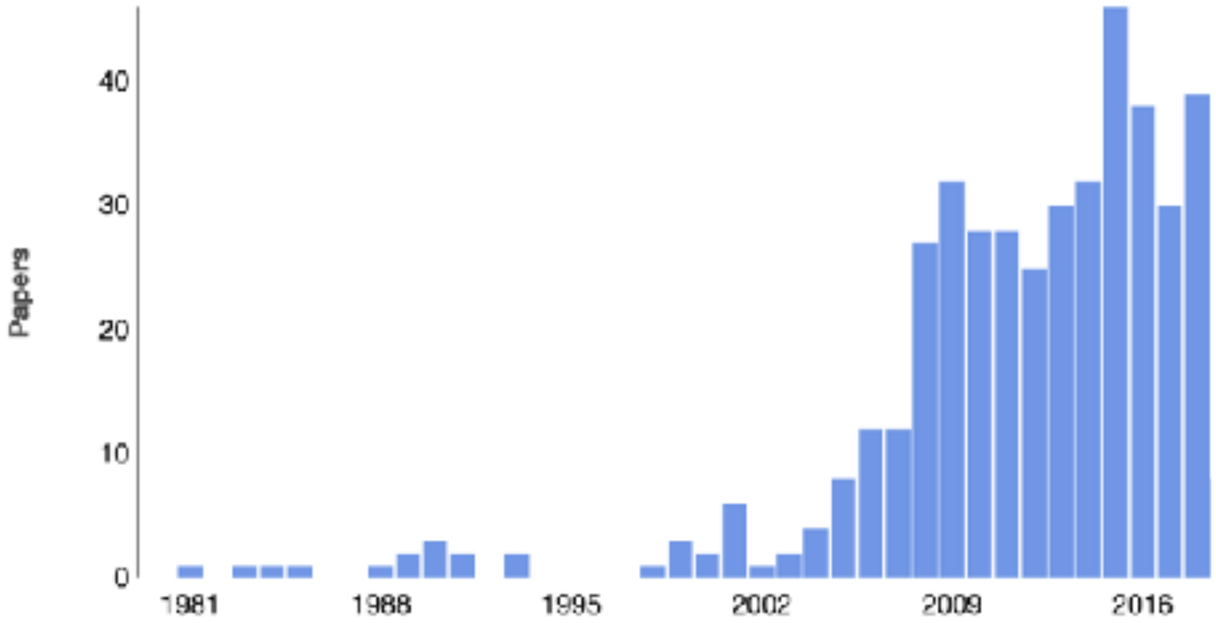


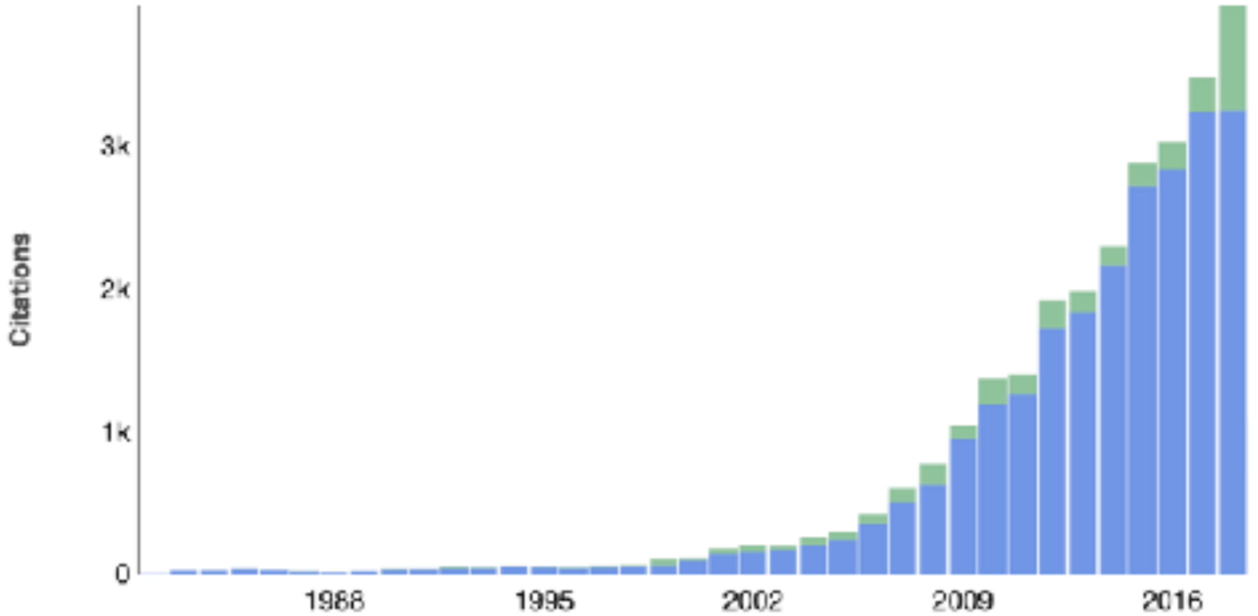


Two questions I want to consider today

1. What is the least biased way to measure enrichment using common observables?

Astronomers love (writing about) the MZR



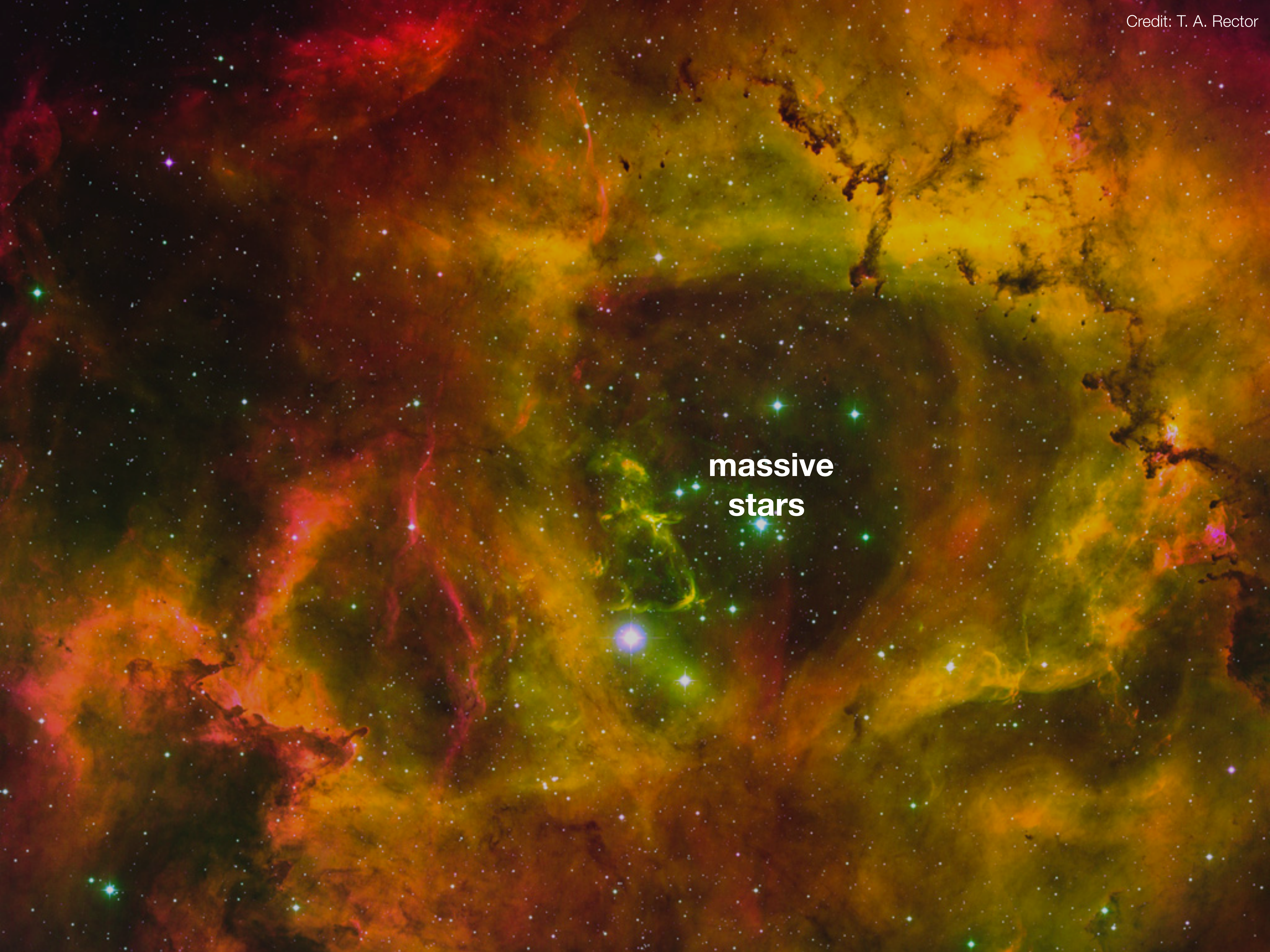


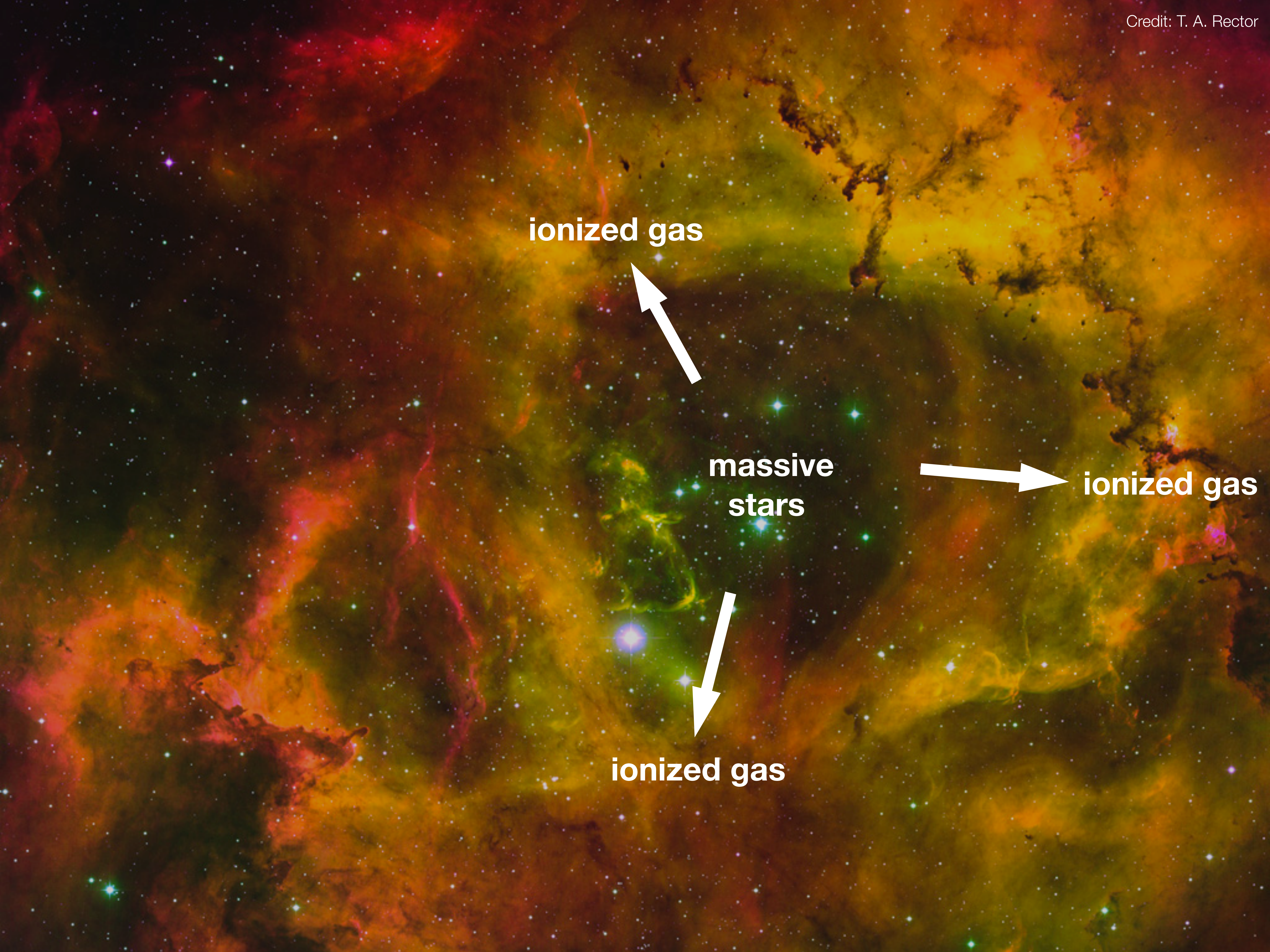
Two questions I want to consider today

1. What is the least biased way to measure enrichment using common observables?
2. What parameters are most important for learning about galaxy assembly?

1. ***What is the least biased way to measure enrichment using common observables?***


Credit: T. A. Rector

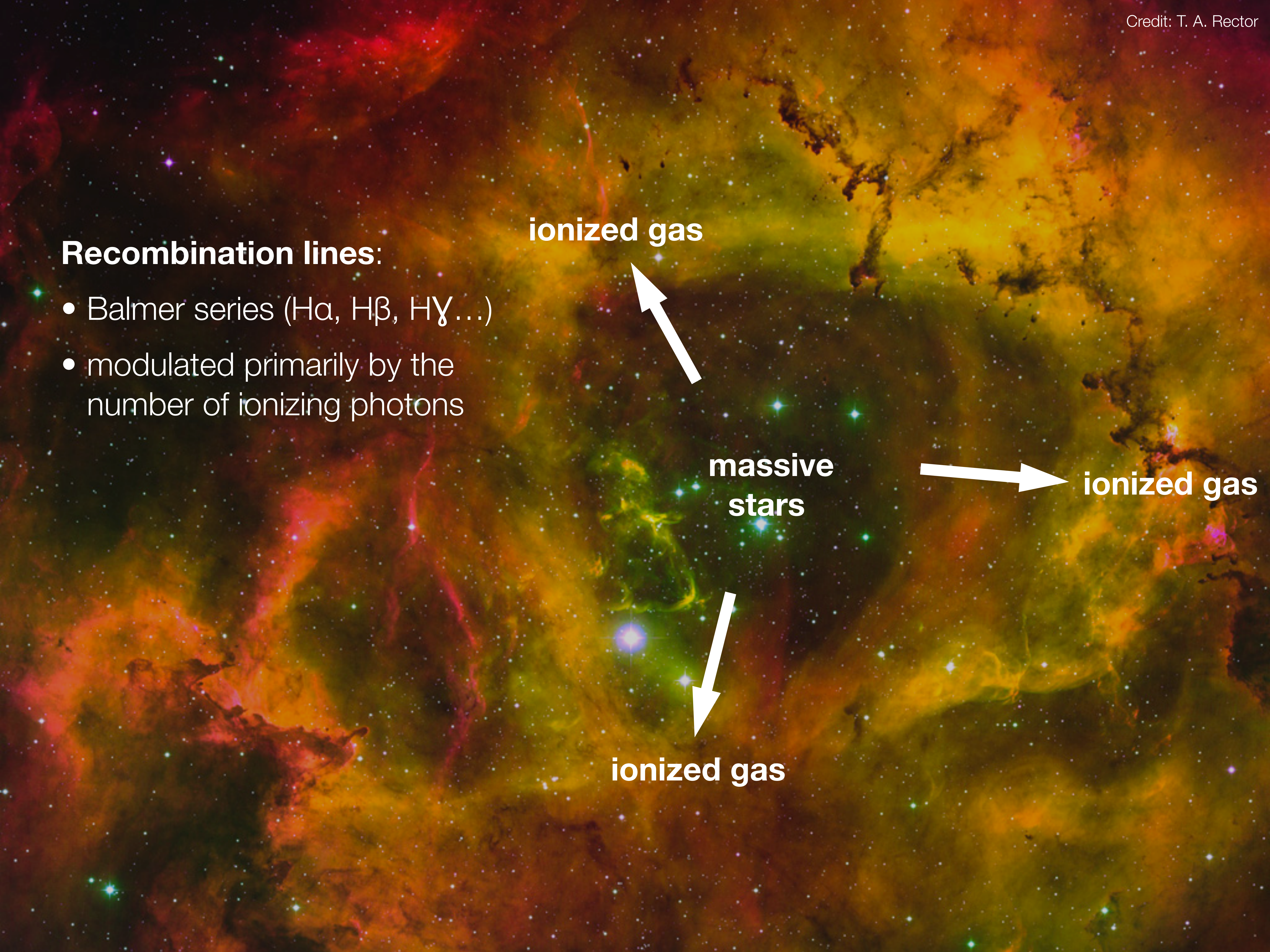

Credit: T. A. Rector
massive
stars

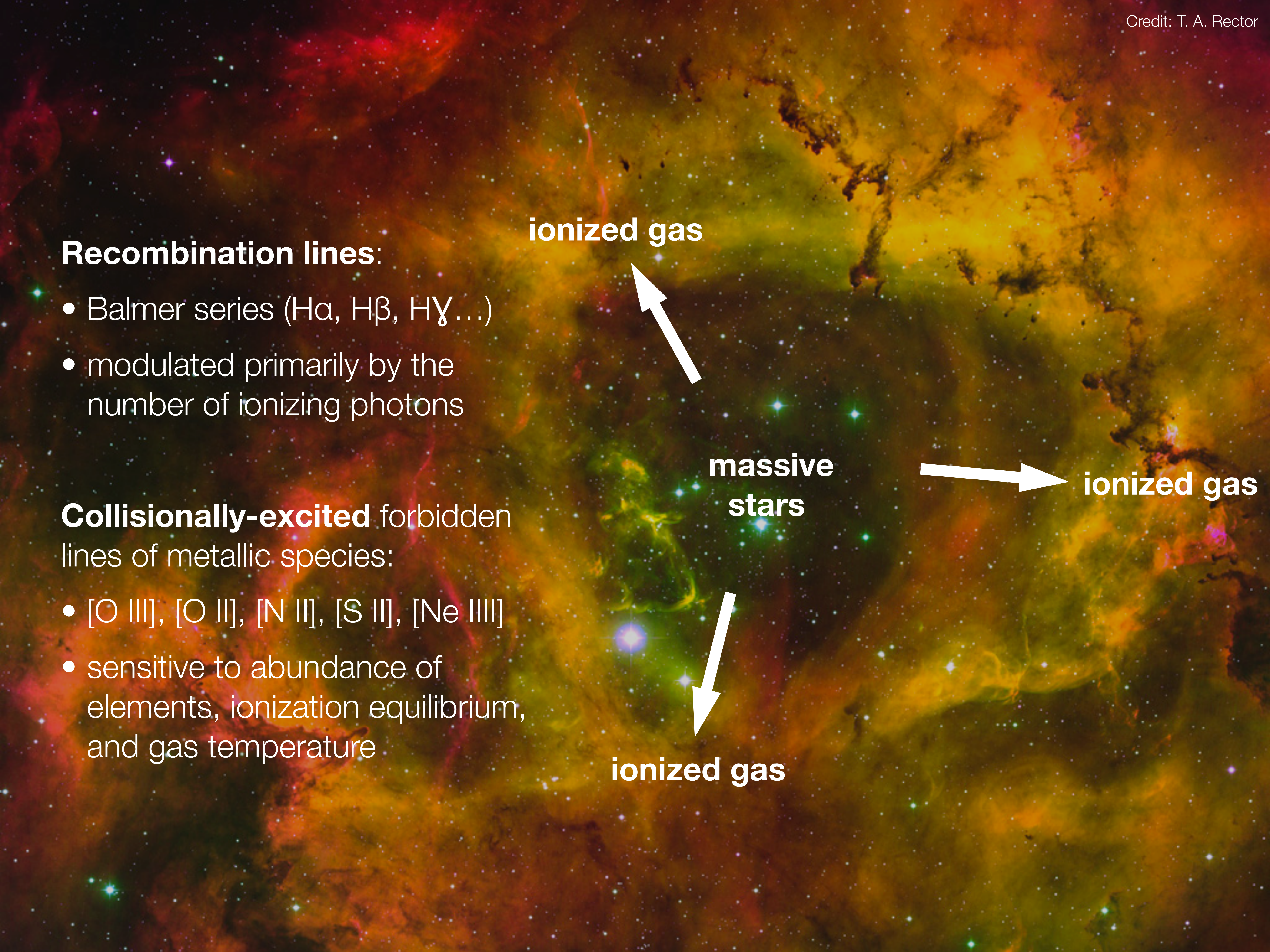


Credit: T. A. Rector
ionized gas
massive stars
ionized gas
ionized gas

Recombination lines:

- Balmer series (Hα, Hβ, Hɣ…)
- modulated primarily by the number of ionizing photons





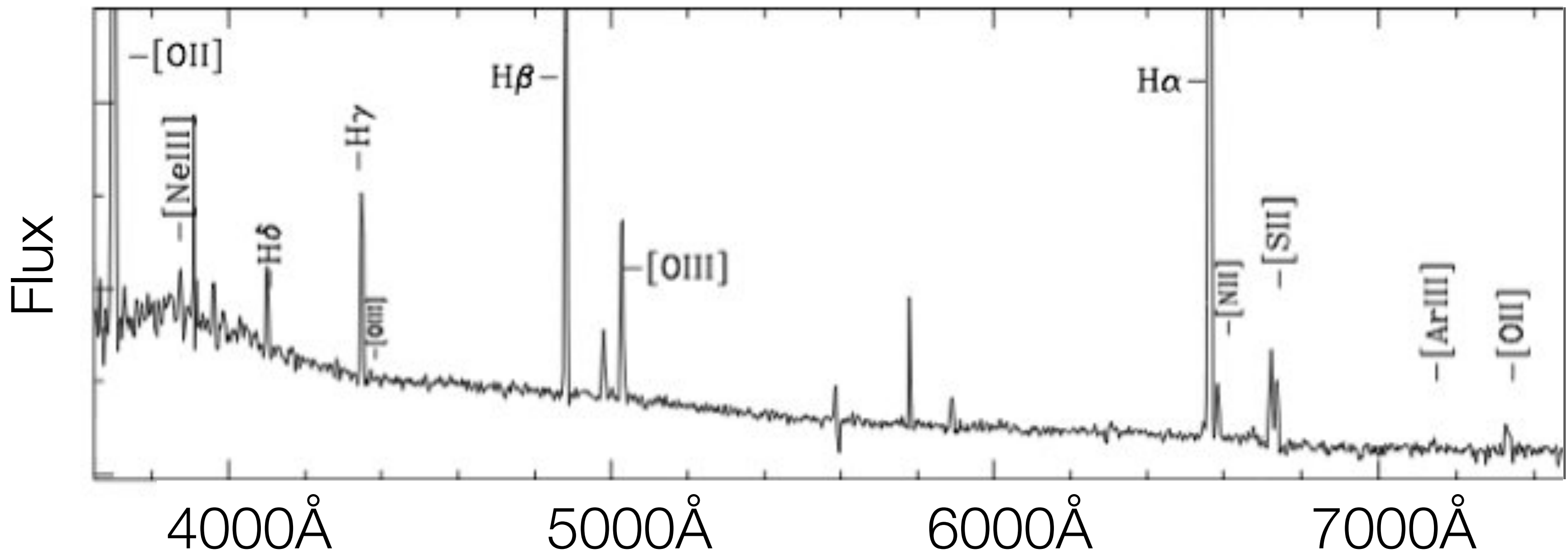
Recombination lines:

- Balmer series (Hα, Hβ, Hɣ…)
- modulated primarily by the number of ionizing photons

Collisionally-excited forbidden lines of metallic species:

- [O III], [O II], [N II], [S II], [Ne IIII]
- sensitive to abundance of elements, ionization equilibrium, and gas temperature

HII region spectra depend on detailed astrophysics



- **Electron density:** lines with similar excitation energies, but different critical densities, including [OII]λλ3727,3729, [SII]λλ6717,6731
- **Electron temperature:** lines from same ion with different excitation energies, including [OIII]λ4363/[OIII]λ5007, but also need low-ionization zone temperature
- **Abundance ratios:** N2O2=[NII]λ6584/[OII]λλ3727,3729 assuming N/O=N^+/O^+
- **Ionization parameter:** emission from different ions of the same element, including [OIII]λ4959,5007/[OII]λλ3727,3729

Empirical diagnostics relate observables to (gas-phase) O/H

Temperature-sensitive **auroral lines are often inaccessible or absent** from spectra of faint, distant, and/or metal-rich objects

Instead, ratios of strong emission lines are used to construct **metallicity (O/H) calibrations** based on (what is hopefully) a representative sample

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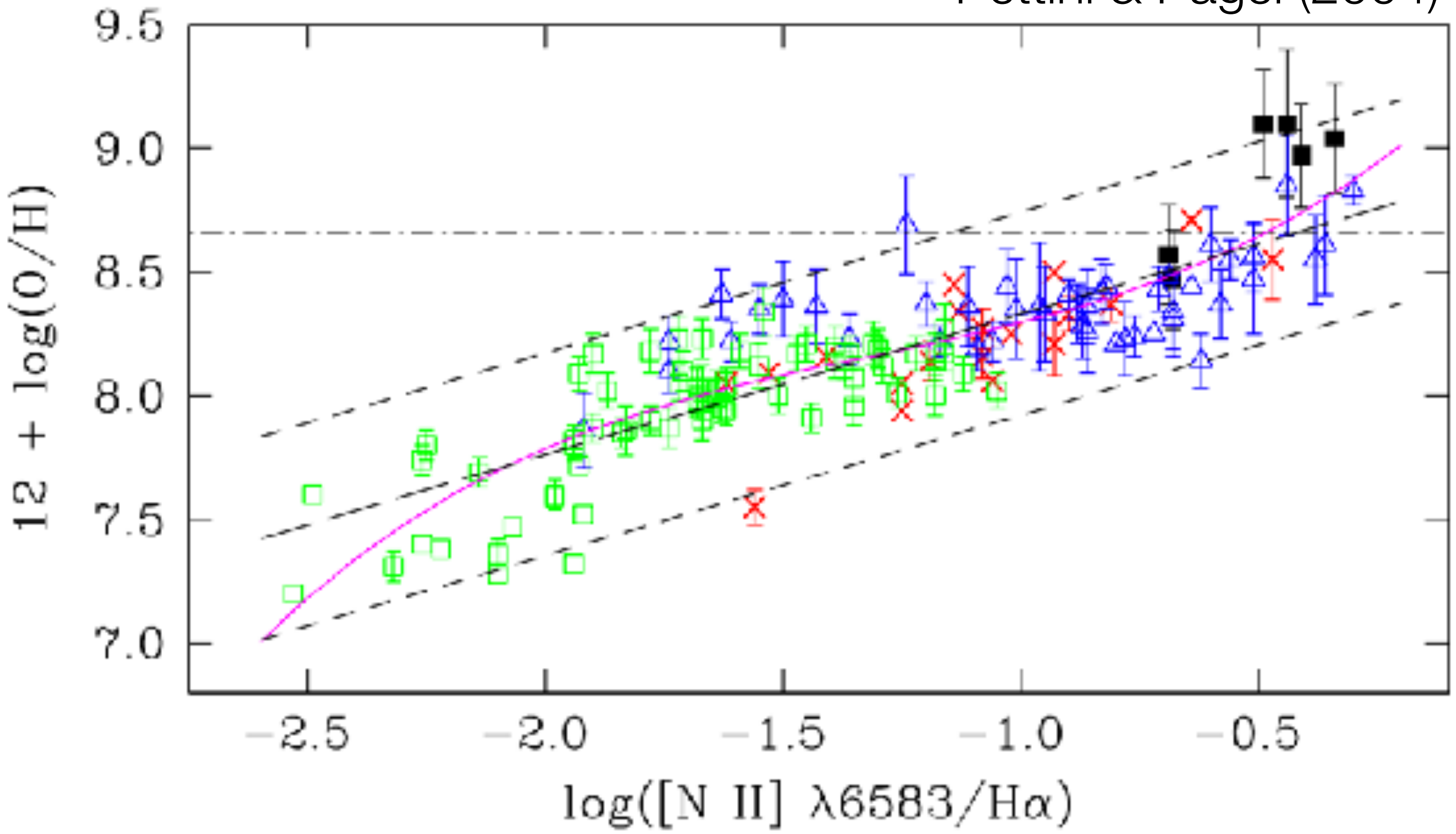
Pettini & Pagel (2004)



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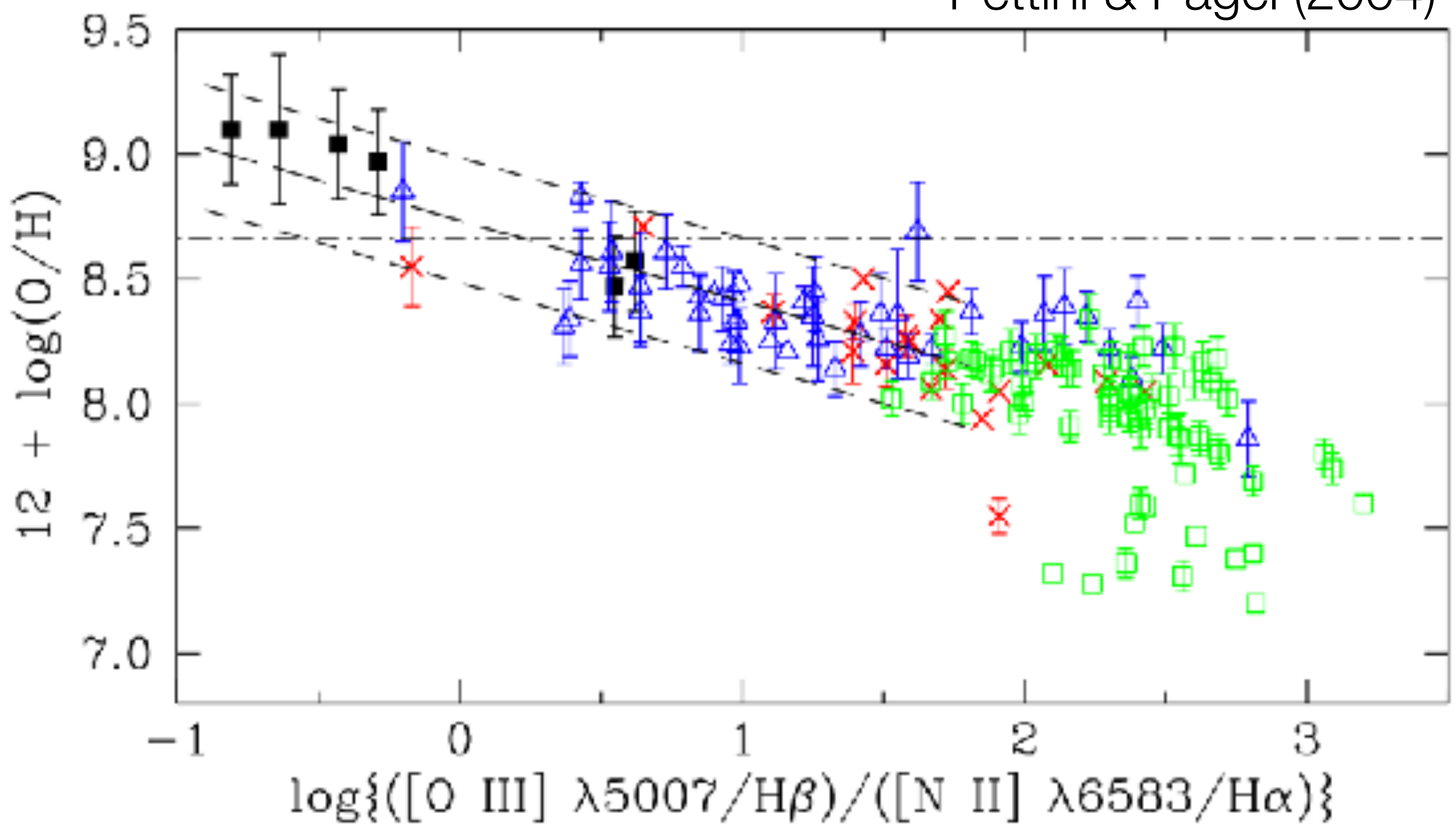

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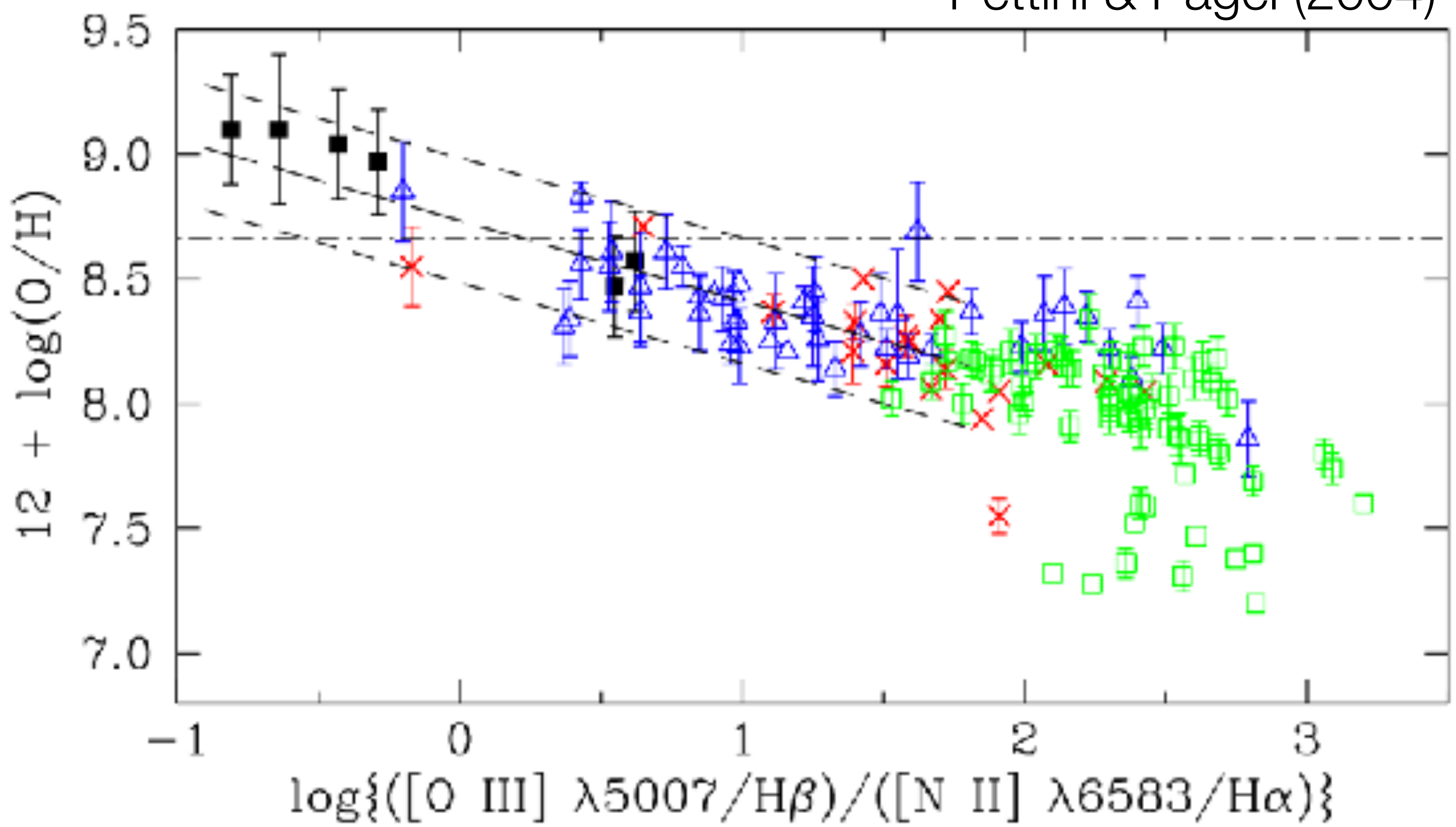
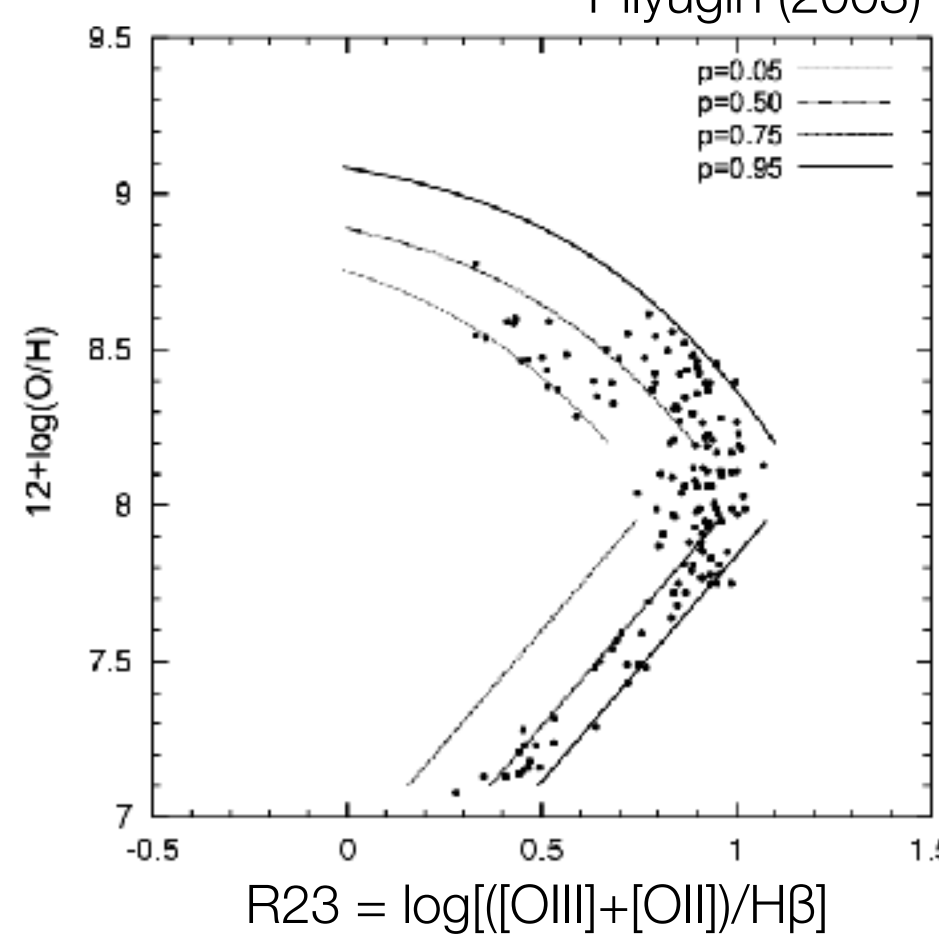
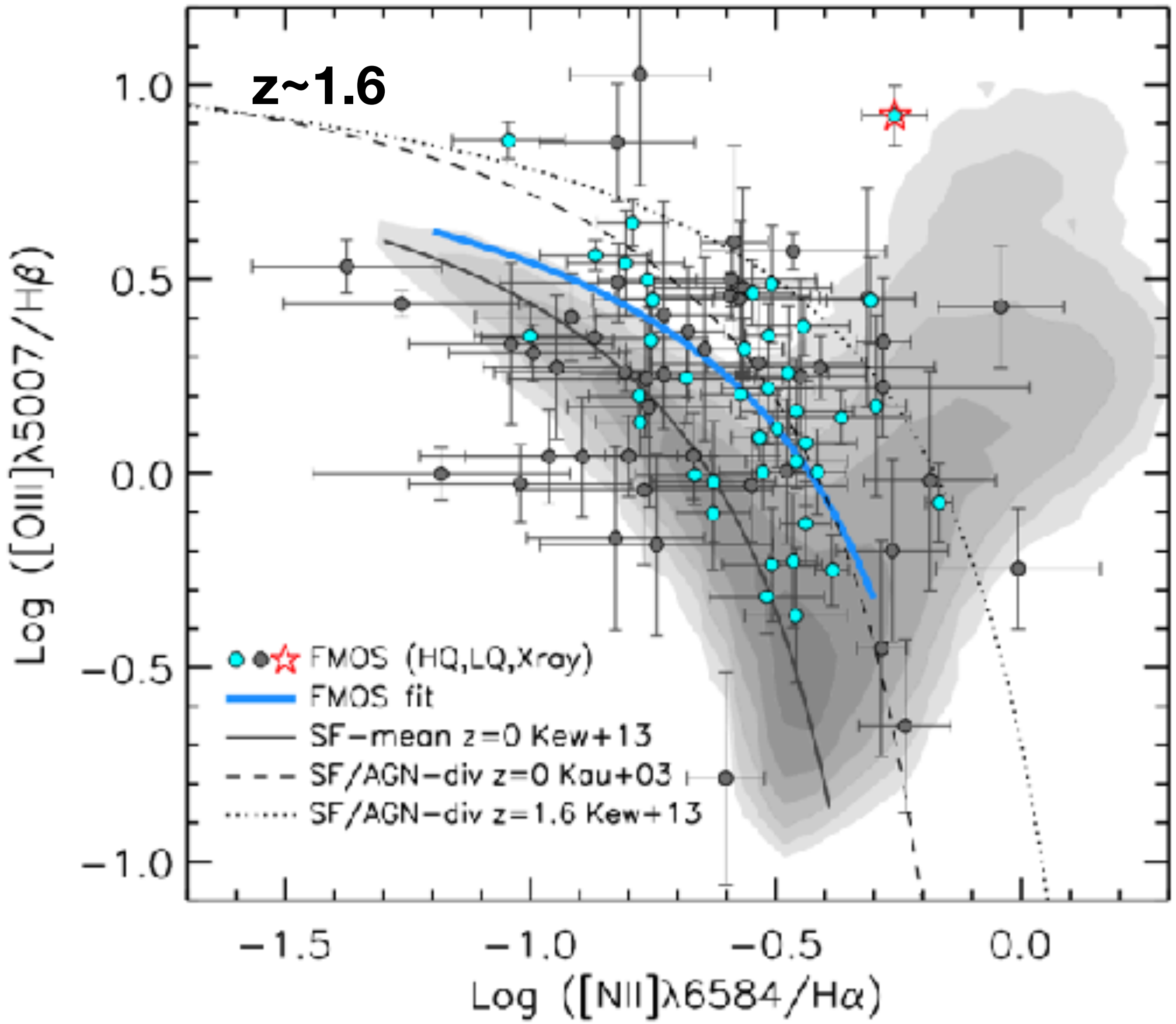


Pilyugin (2003)

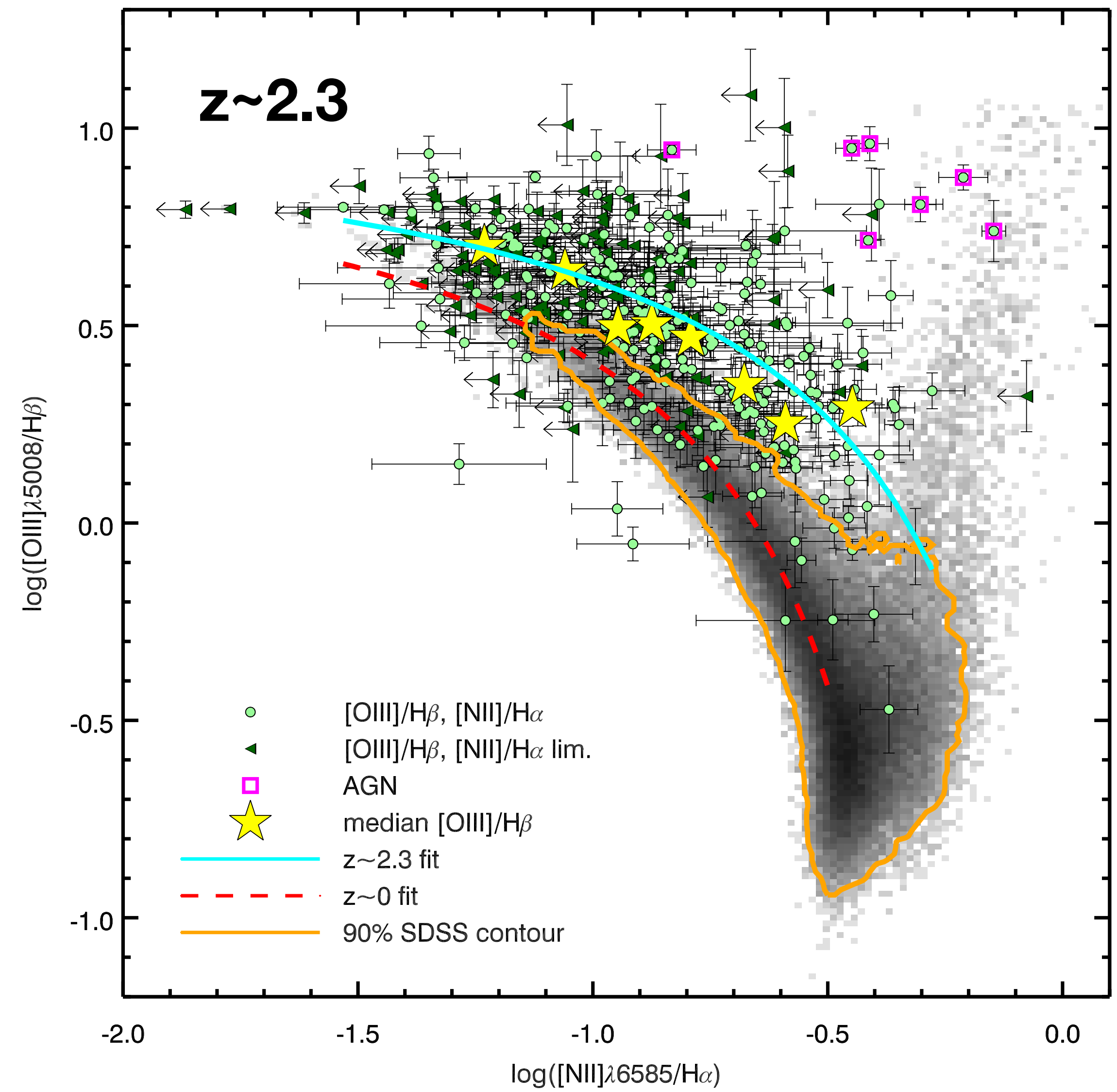


But high-z galaxies have notably different spectra from galaxies today

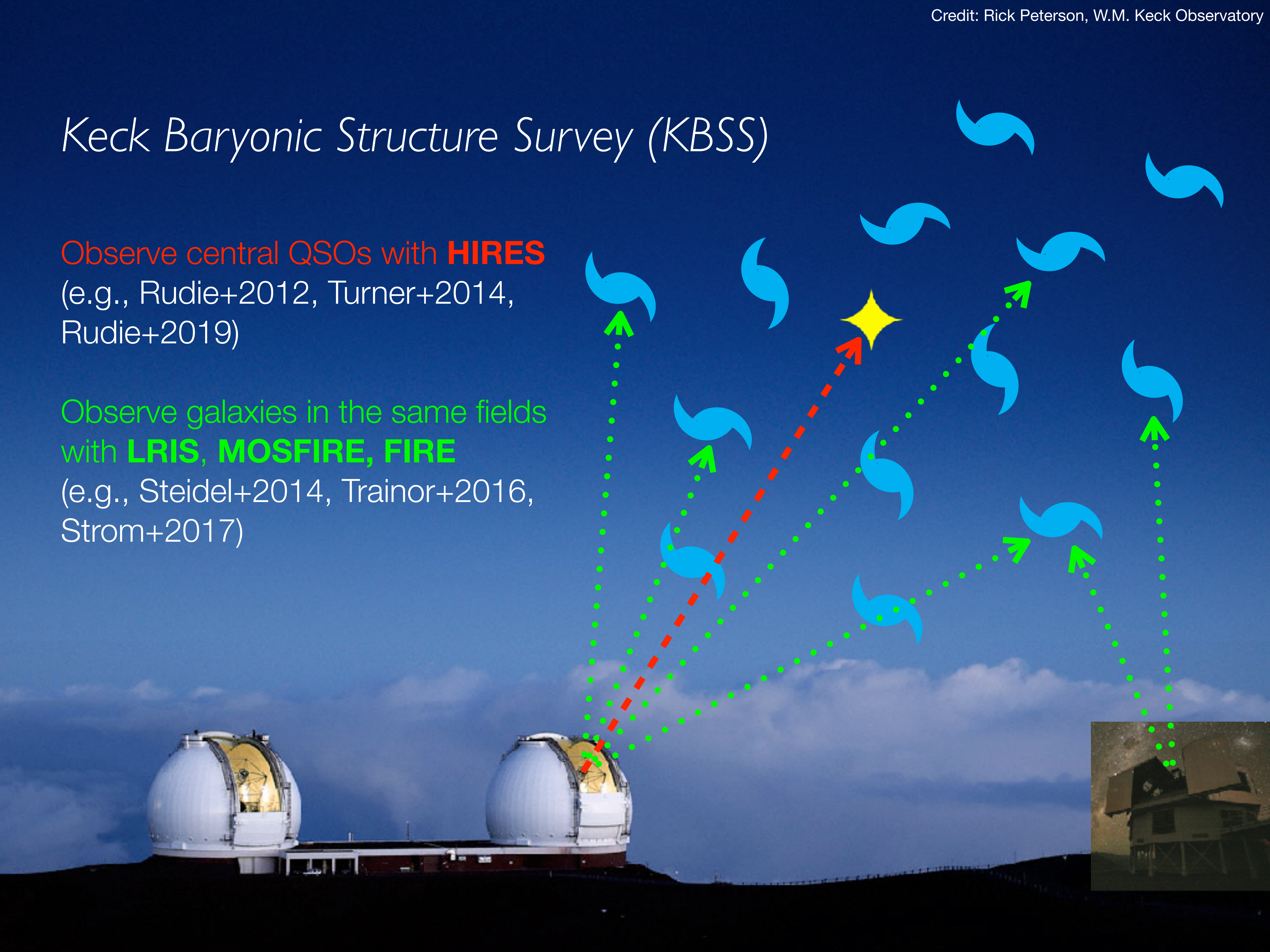
FMOS-COSMOS: Kashino et al. (2017)



KBSS: Strom et al. (2017)



Fortunately, samples at $z>1$ now have high-quality data that allow them to be studied independent of the $z\sim0$ context


Credit: Rick Peterson, W.M. Keck Observatory
Keck Baryonic Structure Survey (KBSS)
Observe central QSOs with HIRES
(e.g., Rudie+2012, Turner+2014, Rudie+2019)
Observe galaxies in the same fields with LRIS, MOSFIRE, FIRE
(e.g., Steidel+2014, Trainor+2016, Strom+2017)

Keck Baryonic Structure Survey (KBSS)

15 separate survey fields centered on bright quasars, with a total area = 0.24 deg^2

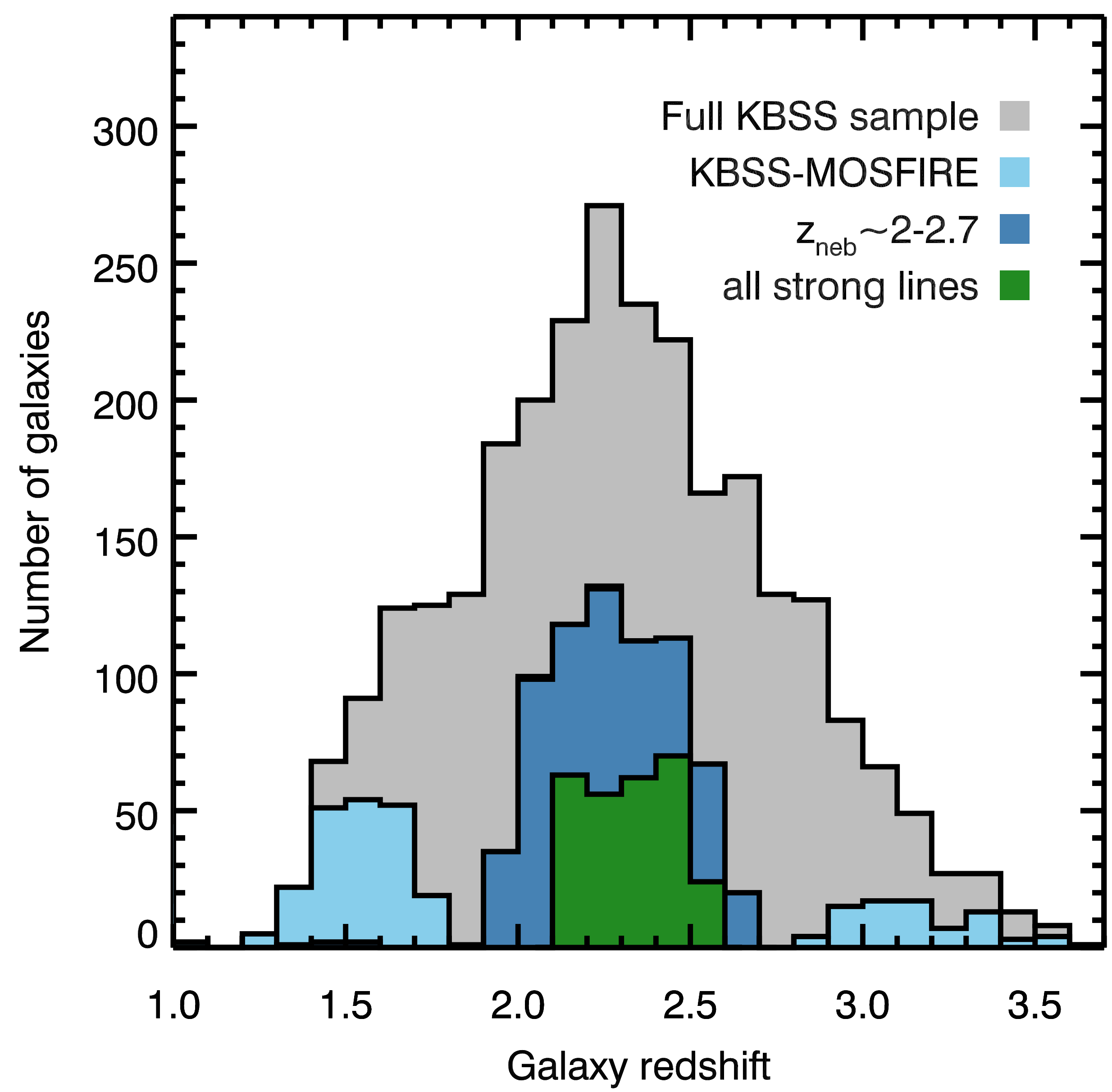
Rest-UV color-selection (BX/BM + RK)

Rich spectroscopic dataset:

- **~2700 with rest-UV spectra**
- **~1300 with rest-optical spectra**

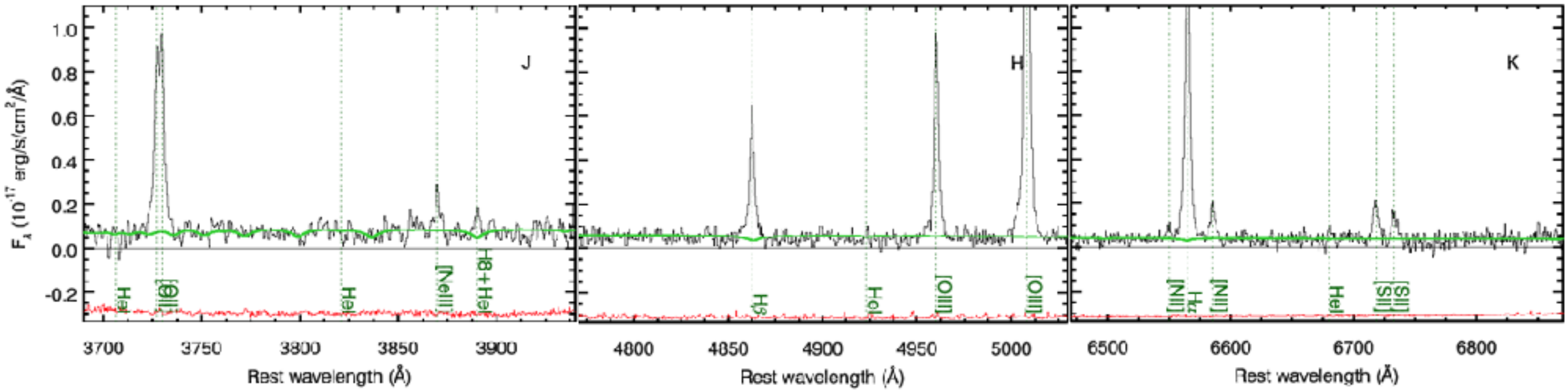
>700 galaxies with z≃2-2.7 have at least a partial rest-optical spectrum

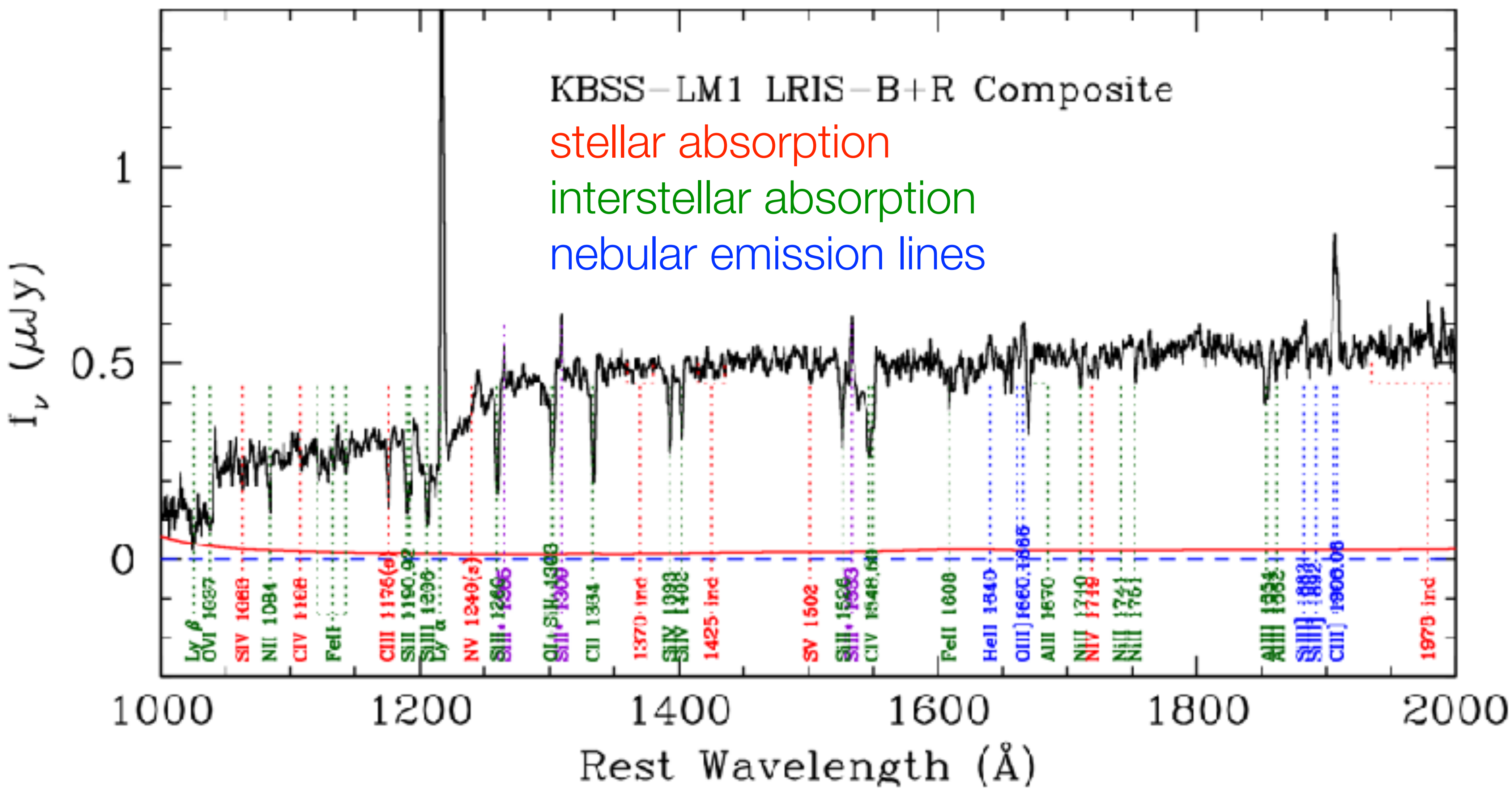
~300 galaxies with good detections of many of the strong rest-optical diagnostic emission lines



KBSS-LM1: the same 30 galaxies at z~2.4

Steidel, **Strom**, et al. (2016)





Totals

MOSFIRE:
30 x ~5 hr/band
@ R ~ 3660

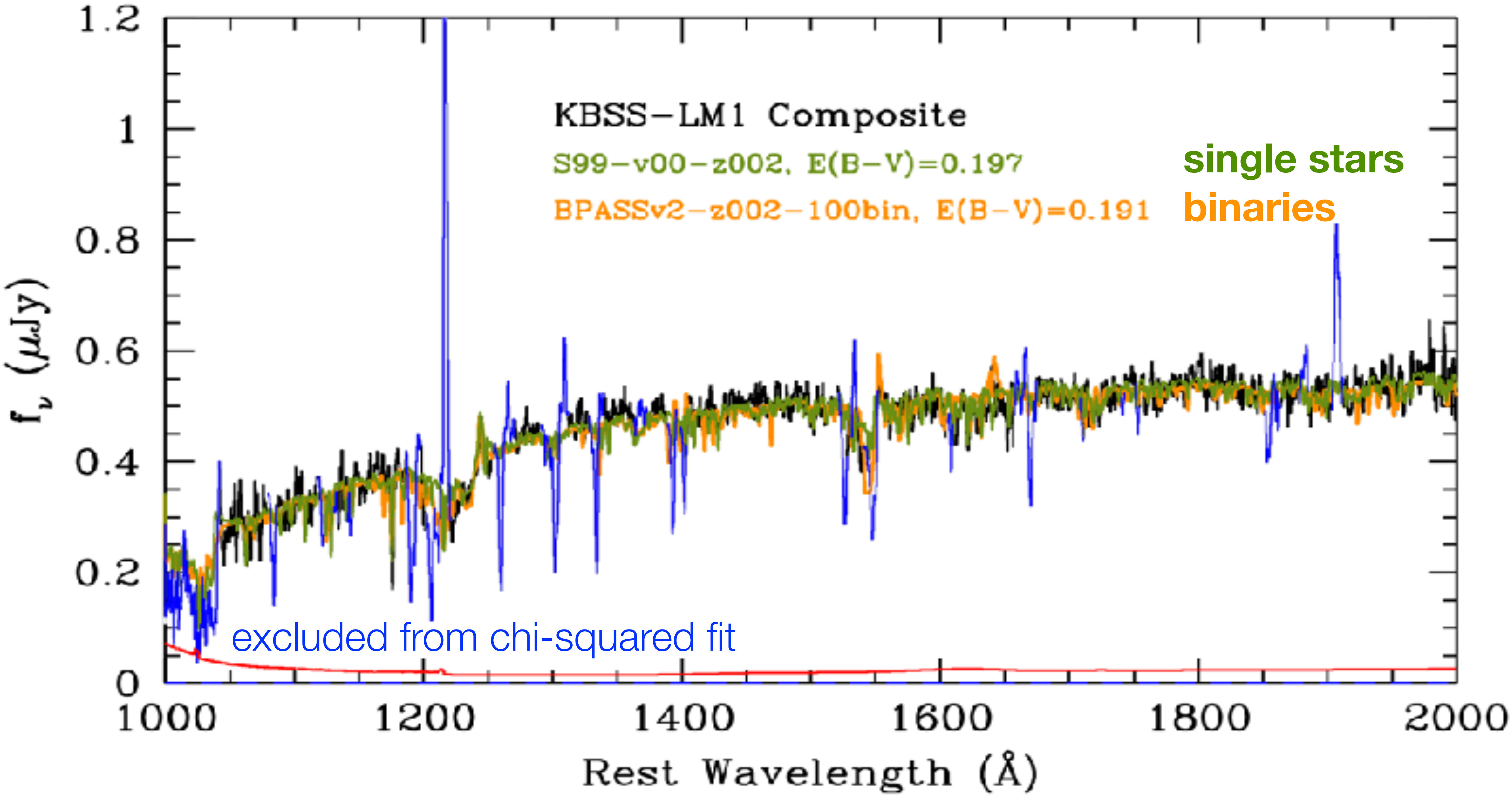
LRIS-B+R:
30 x ~10 hr
@ R ~1500

A useful guiding principle

Since the same stars are responsible for **both** the rest-UV and rest-optical spectra we observe, any physical model(s) of high-z galaxies must also account for **both**

Massive stars in z~2-3 galaxies appear to be Fe-poor

Steidel, **Strom**, et al. (2016)



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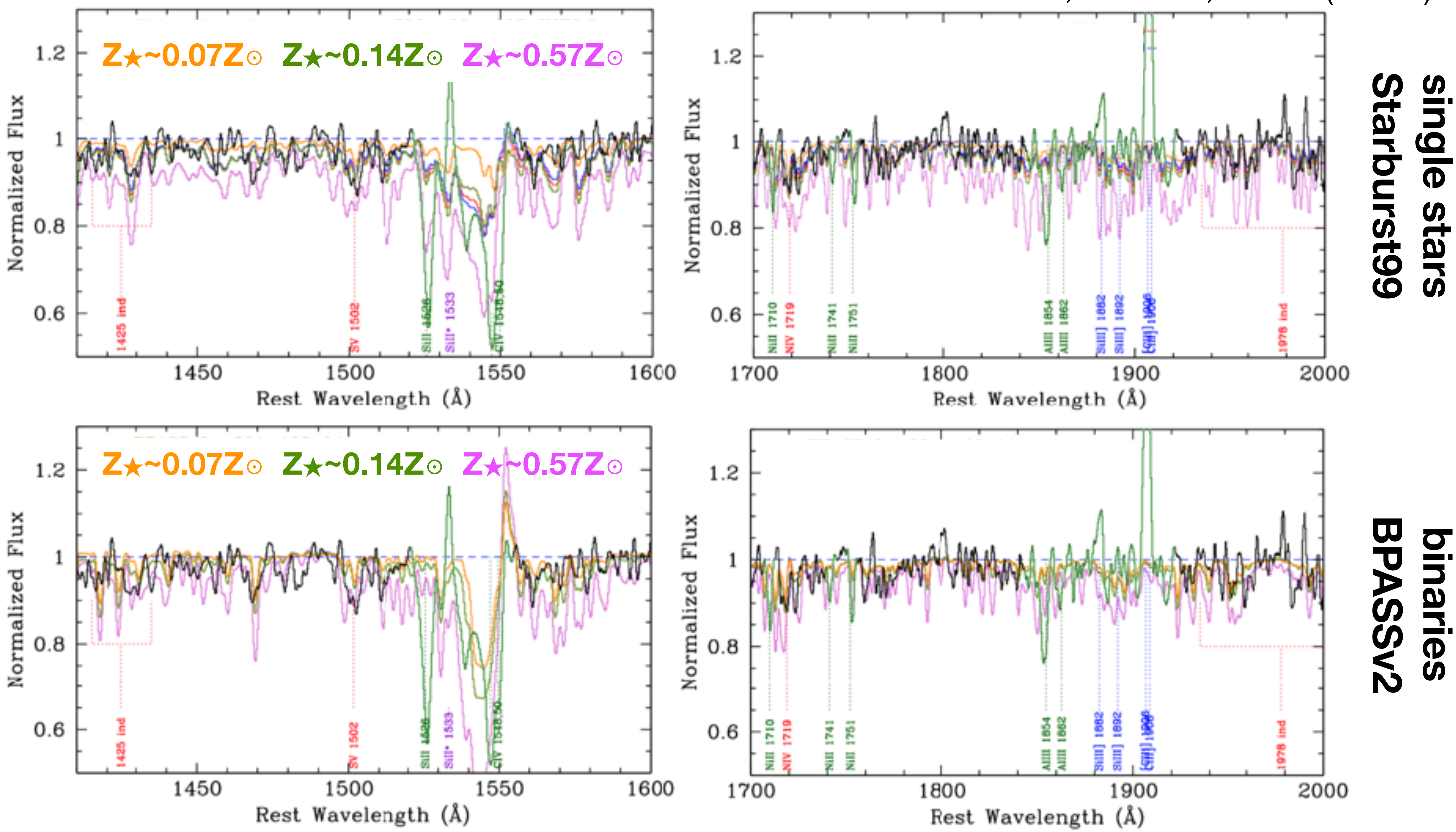
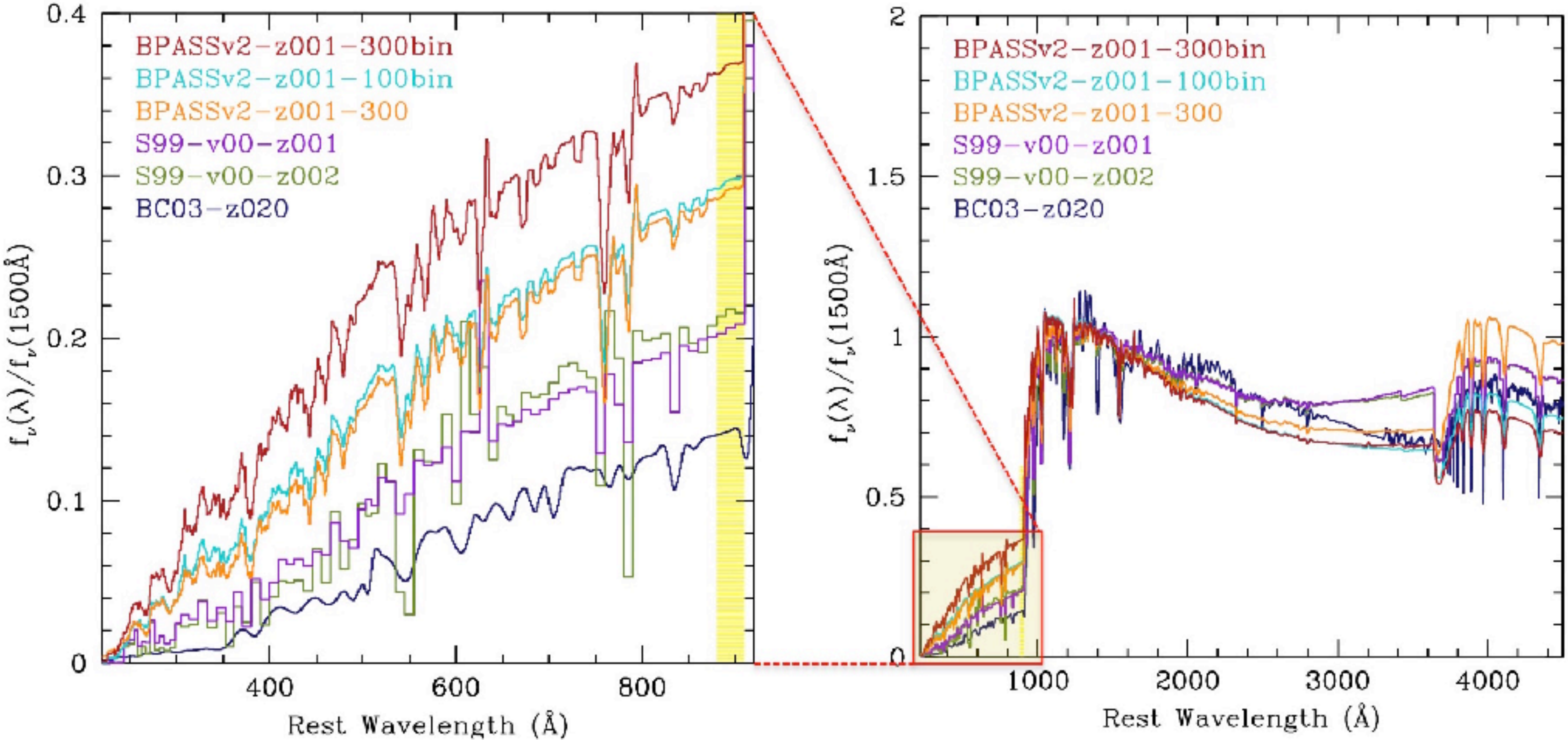
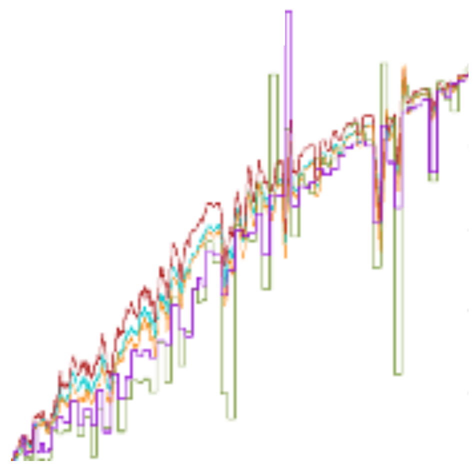
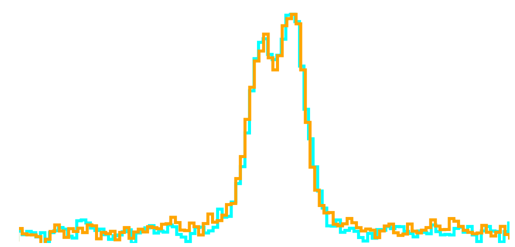


The predicted EUV radiation varies substantially between models



Comparing observations of stars and nebulae in three "easy" steps

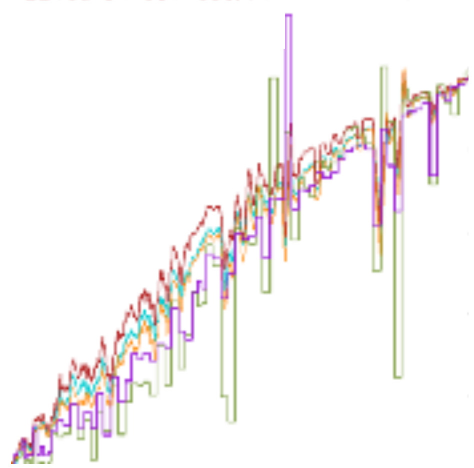
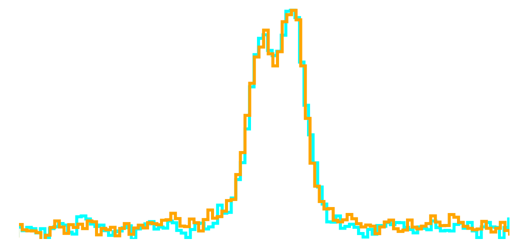
line ratios
f(U, Z) =  +  + ???

shape of EUV
Fe-poor stars

electron density
n_e = 300 cm^{-3}

abundance ratios
e.g., N/O vs. O/H

Comparing observations of stars and nebulae in three "easy" steps

line ratios f(U, Z) =  +  + ???

shape of EUV
Fe-poor stars

electron density
n_e = 300 cm^{-3}

abundance ratios
e.g., N/O vs. O/H

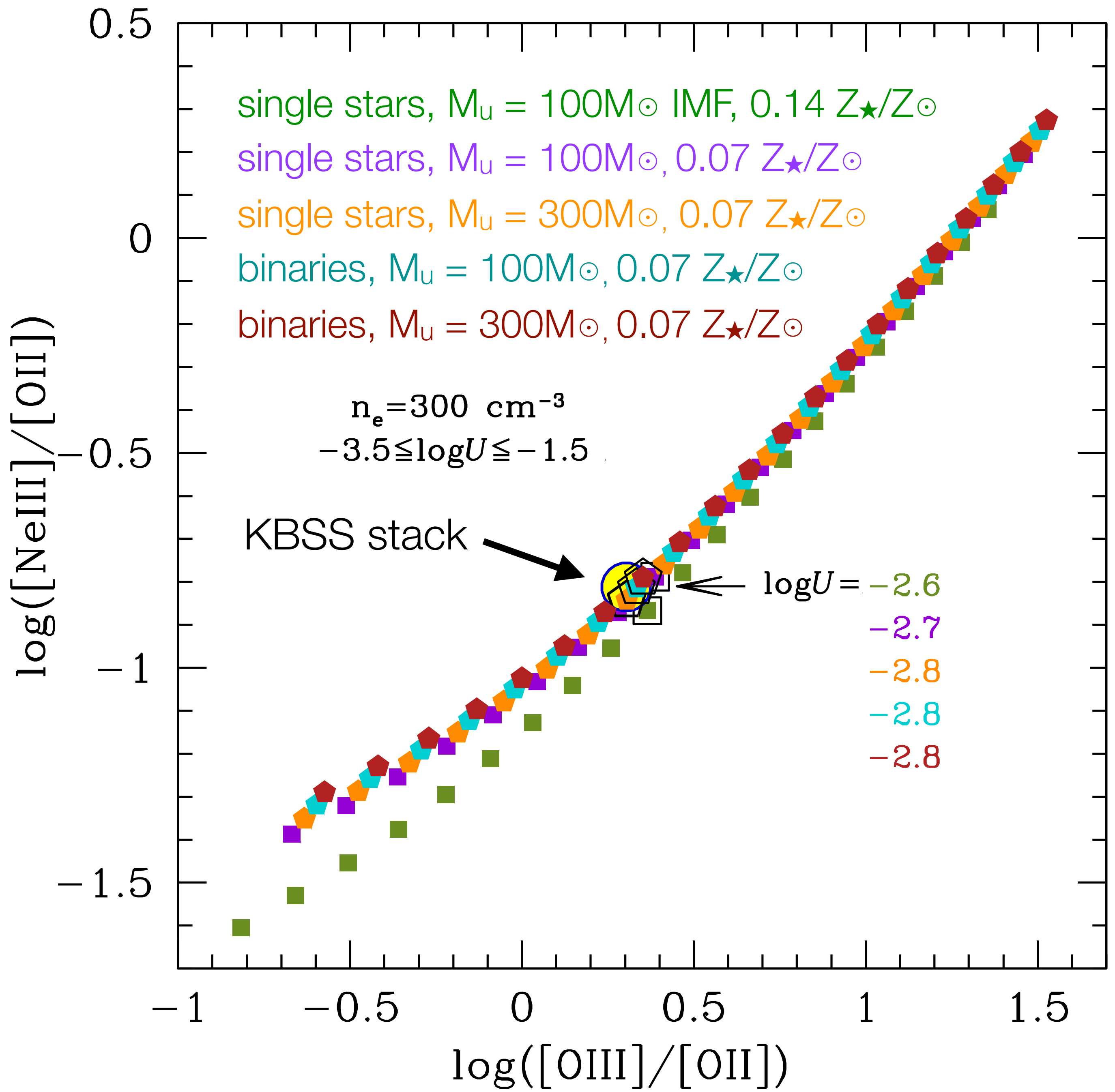
Considerations

Stellar atmospheres care mostly about Fe, so **$Z_\star$ traces Fe/H**
Gas cooling is largely regulated by O, so **Z_{neb} traces O/H**

Different $Z_\star$ and Z_{neb} imply O/Fe different from solar, but **not** gas and stars with different O/H or Fe/H!

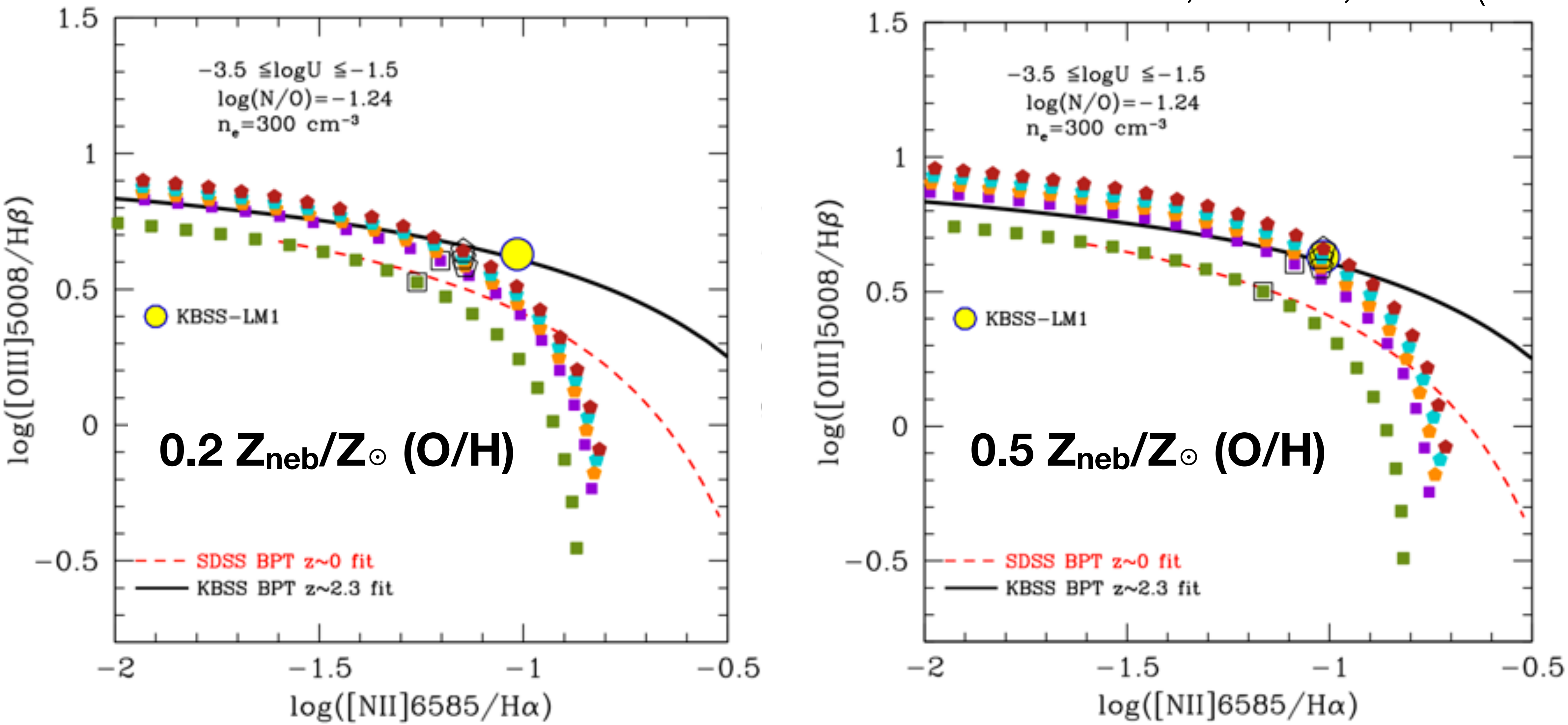
Step one: *set ionization parameter using O32 and Ne3O2*

Steidel, **Strom**, et al. (2016)



Step two: *identify likely O/H by matching line ratios*

Steidel, **Strom**, et al. (2016)



single stars, M_u = 100$M_\odot$ IMF, 0.14 $Z_\star/Z_\odot$

single stars, M_u = 100$M_\odot$, 0.07 $Z_\star/Z_\odot$

single stars, M_u = 300$M_\odot$, 0.07 $Z_\star/Z_\odot$

binaries, M_u = 100$M_\odot$, 0.07 $Z_\star/Z_\odot$

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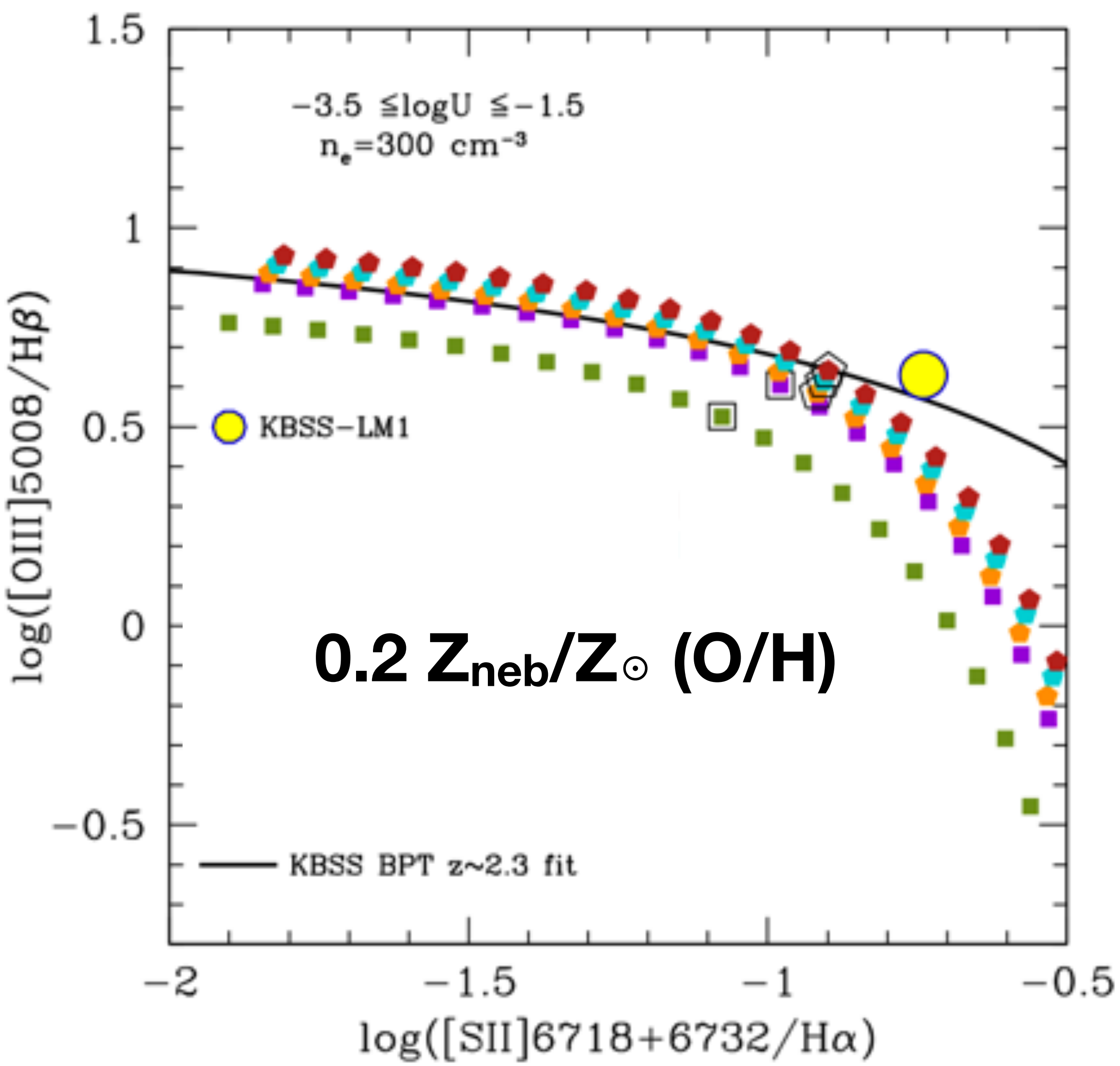
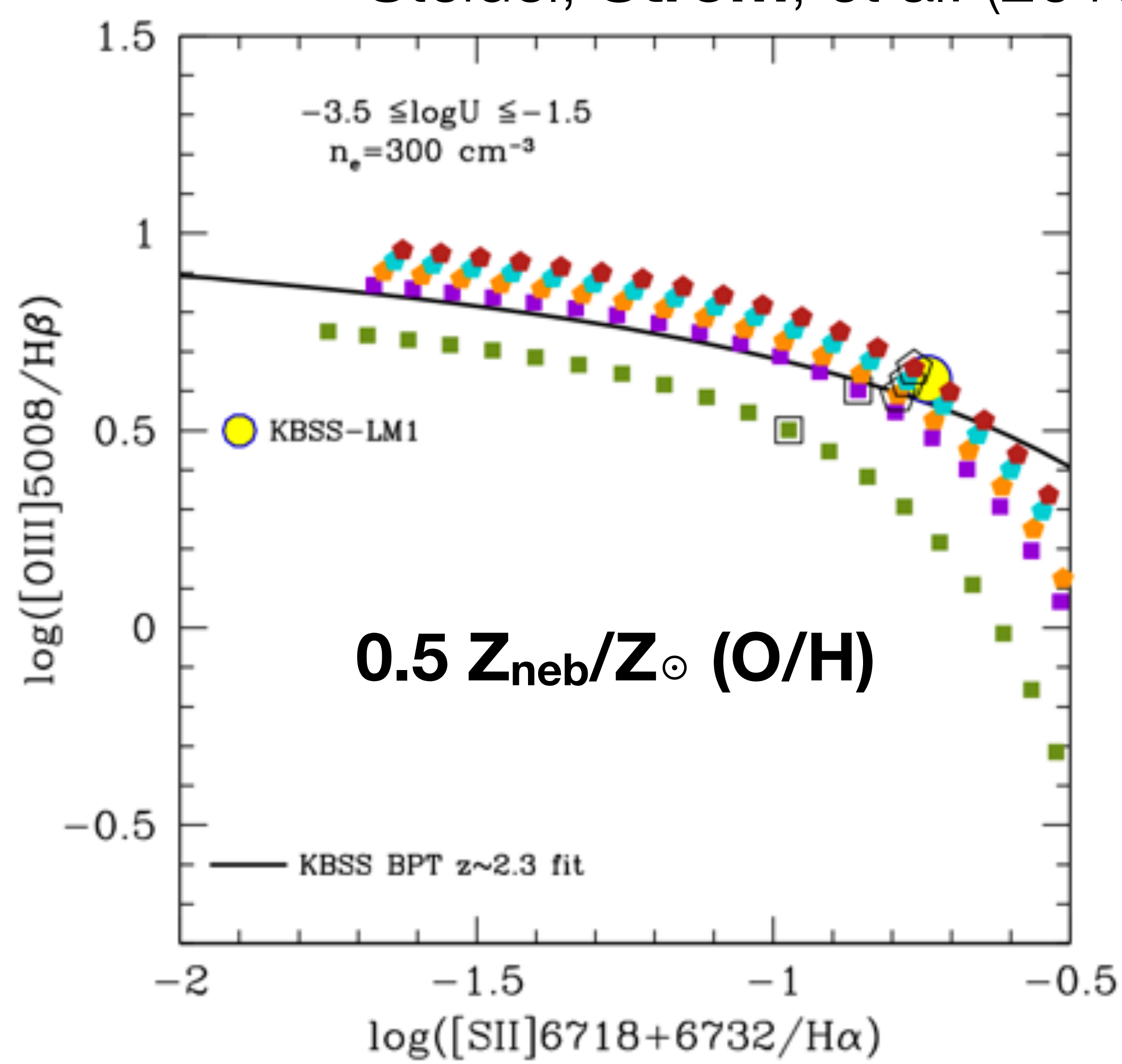
Step two: *identify likely O/H by matching line ratios*

Steidel, **Strom**, et al. (2016)





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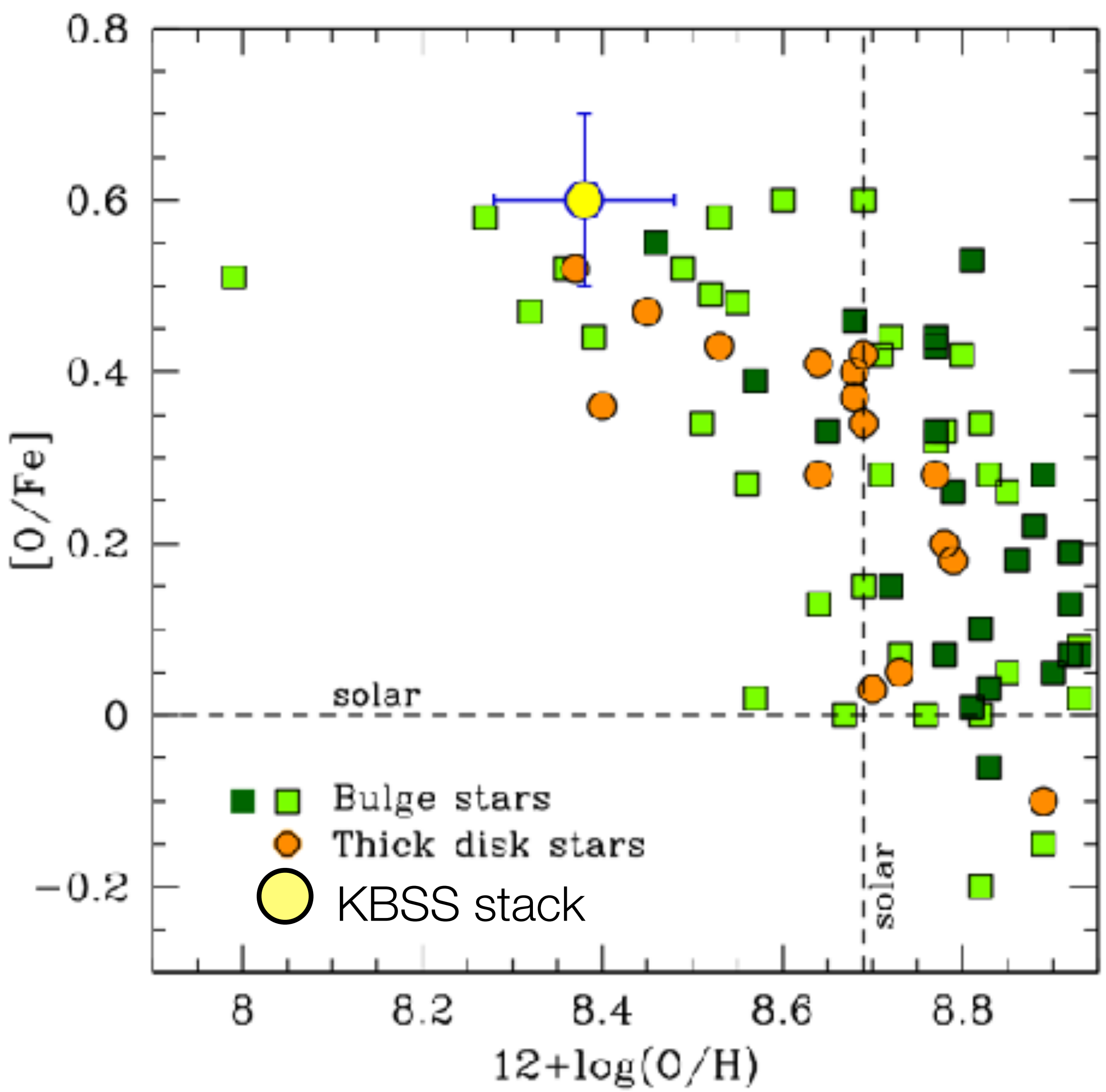
binaries, M_u = 100M⊙, 0.07 $Z_\star/Z_\odot$
binaries, M_u = 300M⊙, 0.07 $Z_\star/Z_\odot$

High-z galaxies have O/Fe similar to bulge+thick disk stars

Steidel, **Strom**, et al. (2016)



KBSS stack:

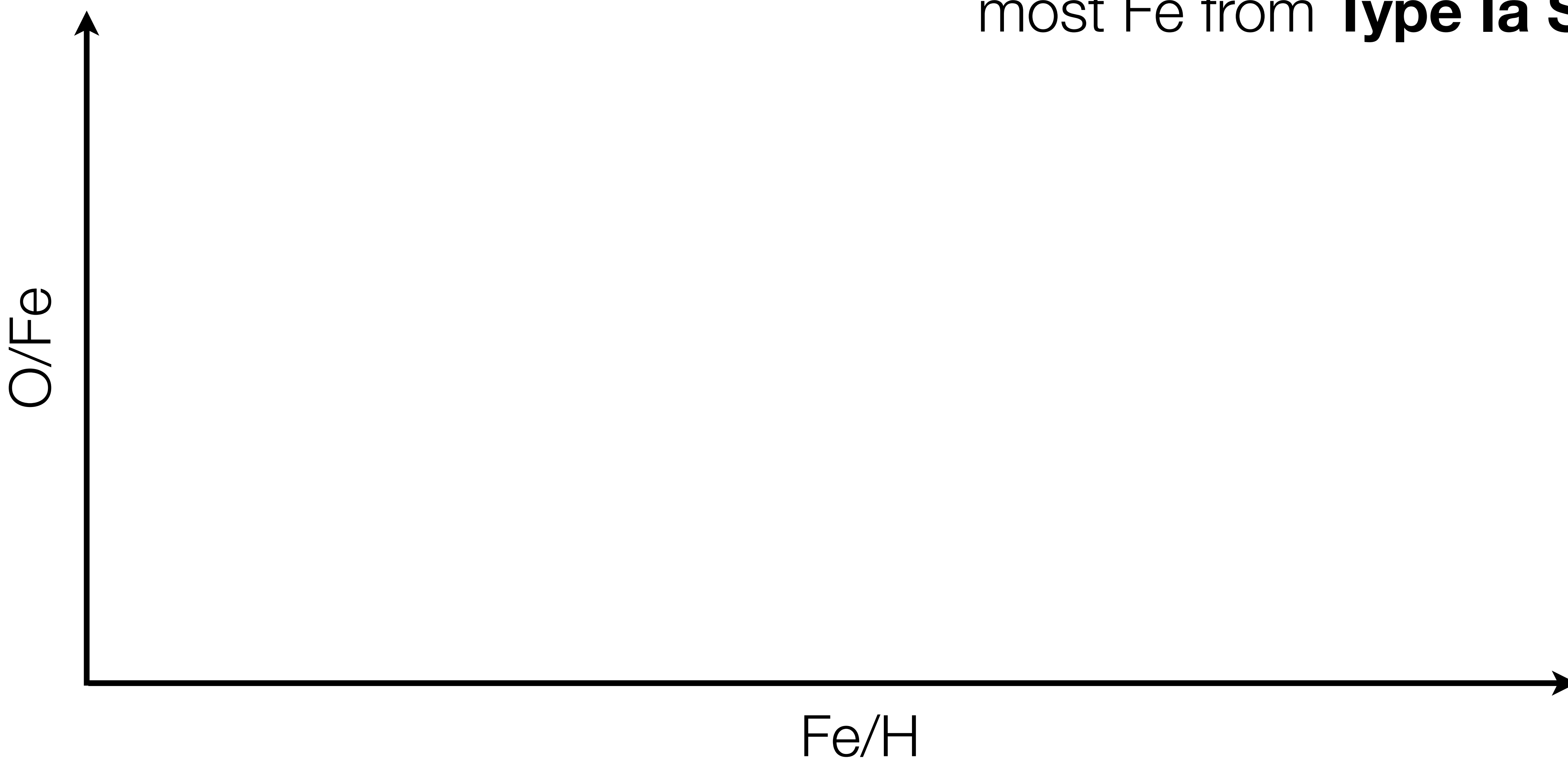
O/Fe ~ 4-5(O/Fe)$_\odot$

Consistent with predictions from Nomoto+06 for Fe-poor core-collapse SNe

Elevated O/Fe also observed in the centers of giant ellipticals (e.g., Thomas+10, Conroy+14, Segers+16)

Star-formation history determines chemical abundance patterns

most O from **core-collapse SNe**
most Fe from **Type Ia SNe**



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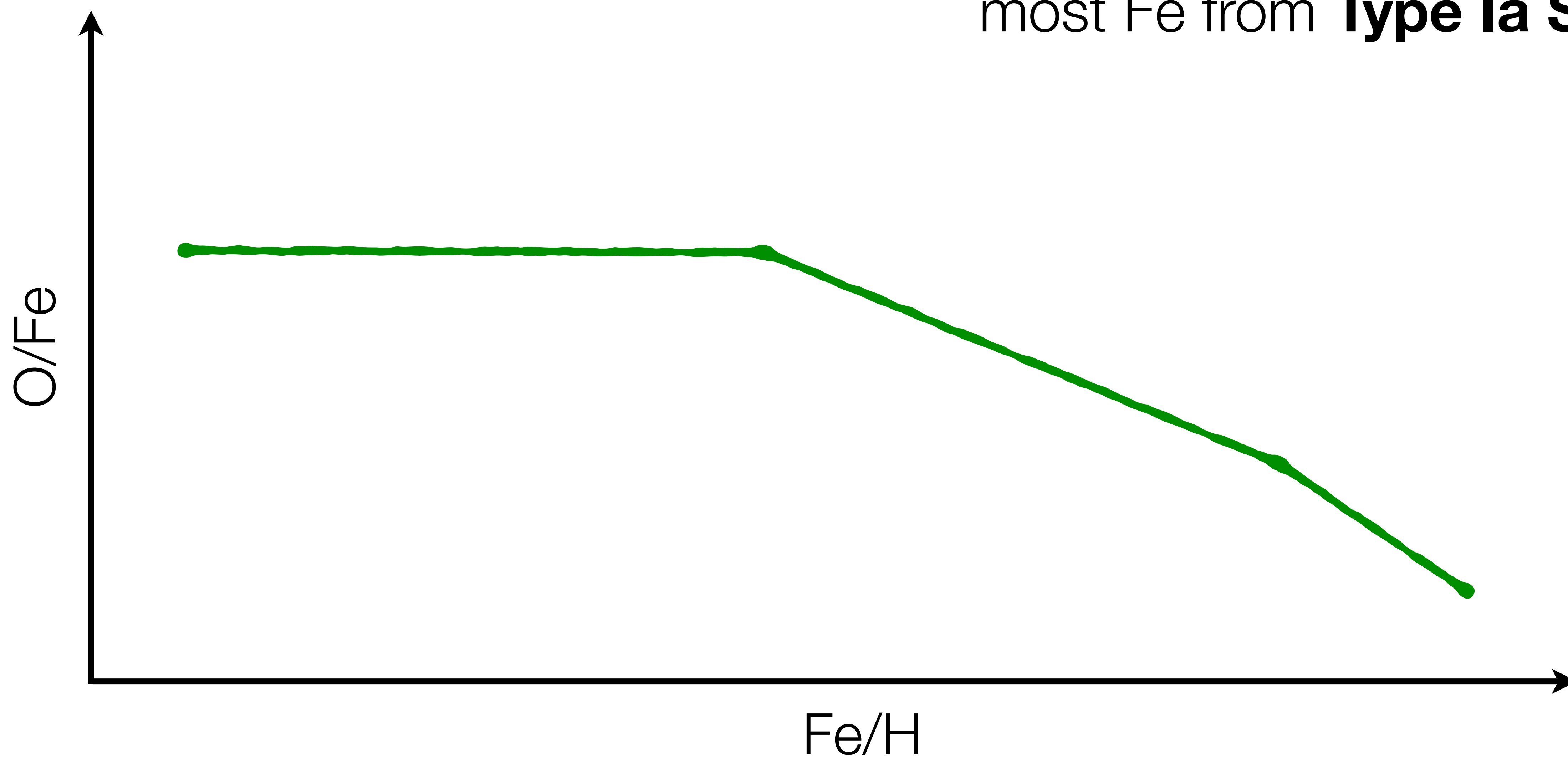

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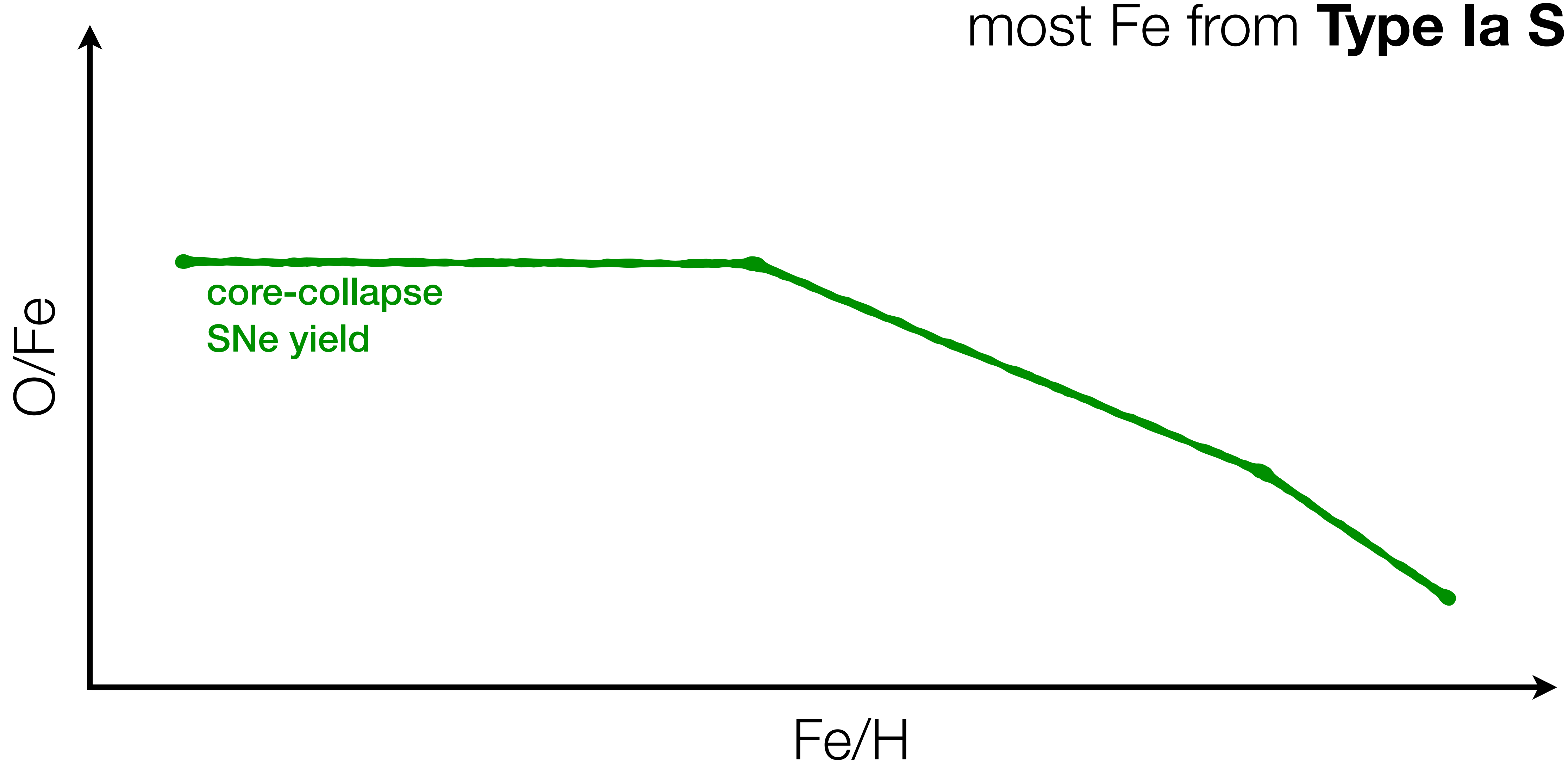

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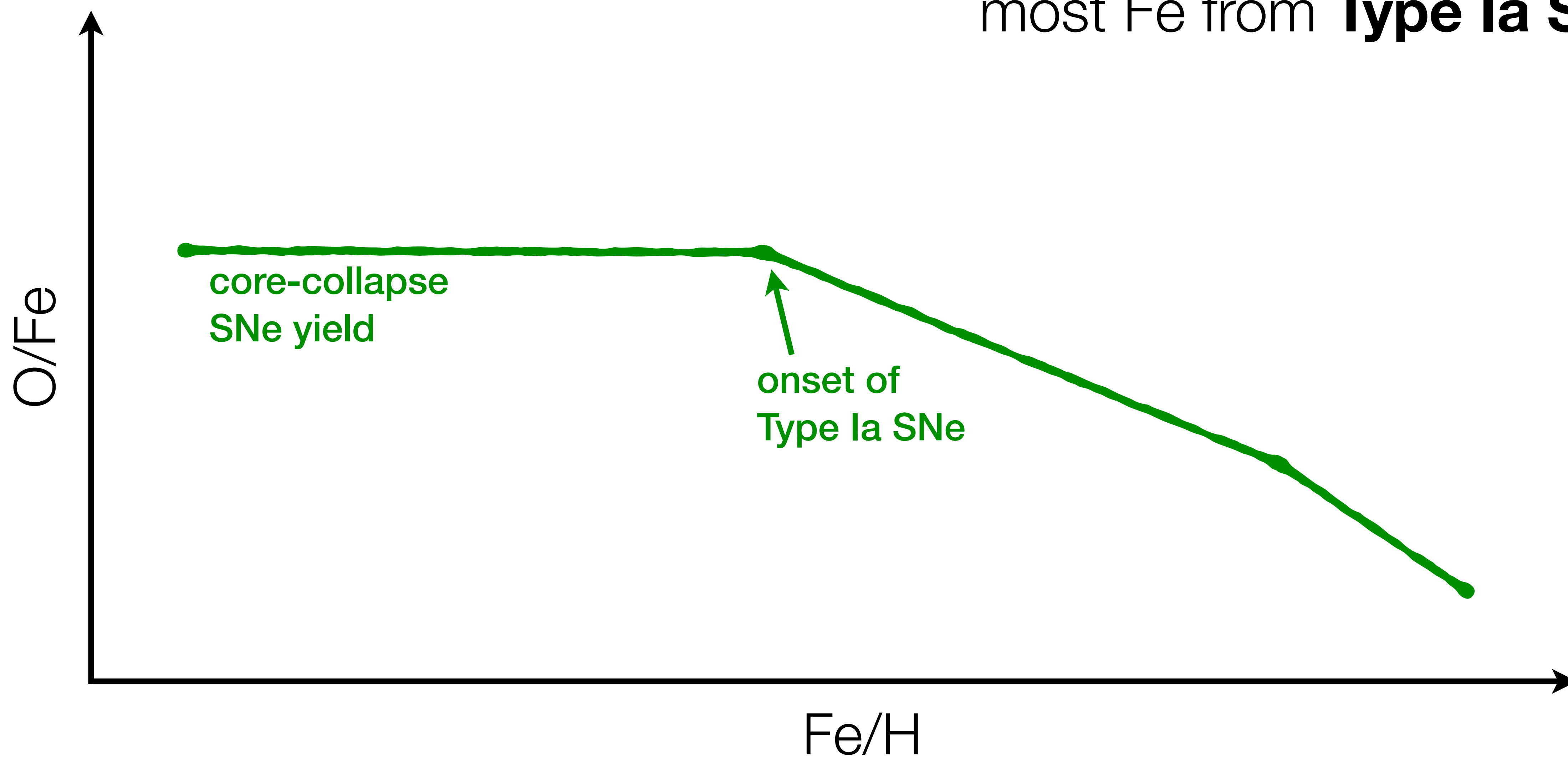
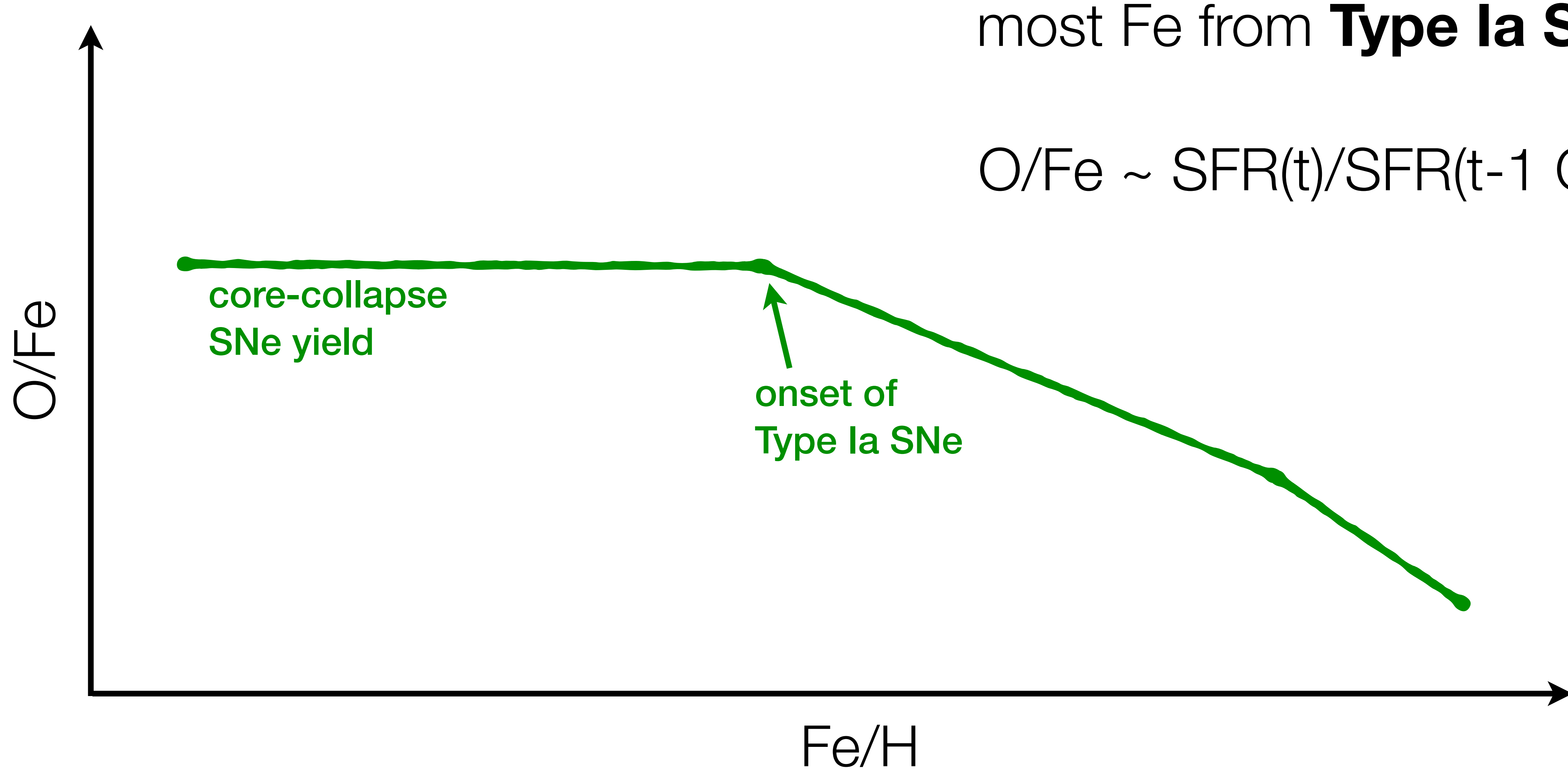


Star-formation history determines chemical abundance patterns

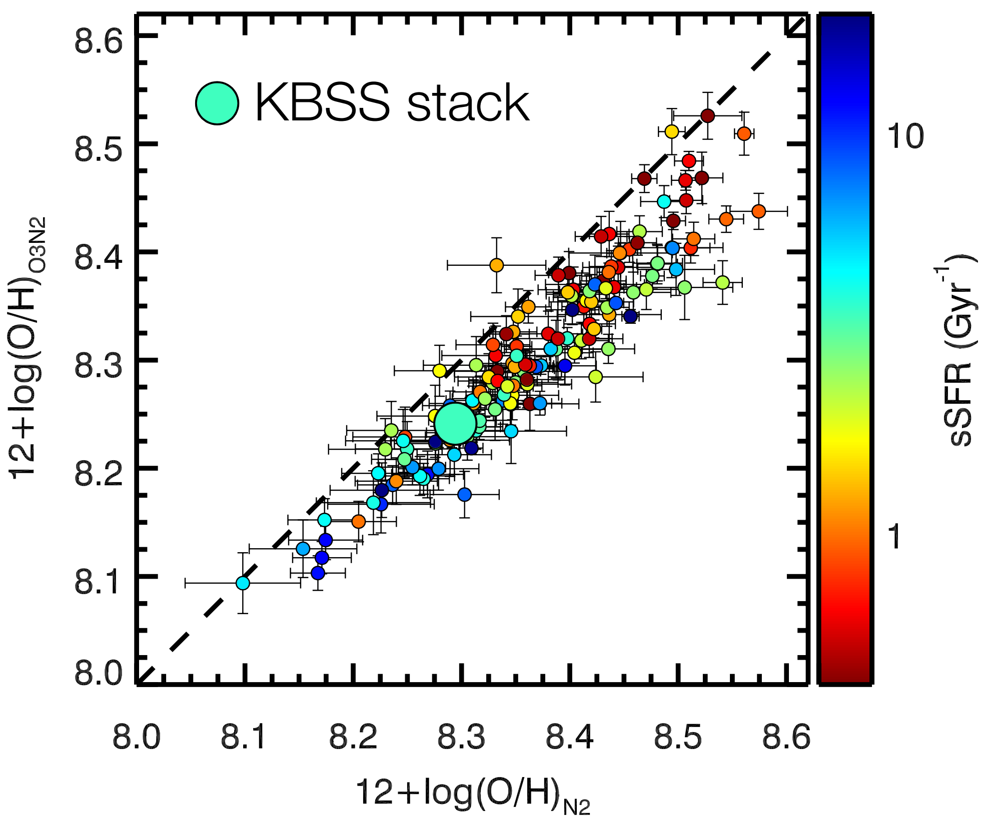
most O from **core-collapse SNe**
most Fe from **Type Ia SNe**

O/Fe ~ SFR(t)/SFR(t-1 Gyr)



Differences in star formation history impact O/H diagnostics

High α/Fe due to young galaxy ages or rising star formation histories will result in different strong line ratios at fixed O/H



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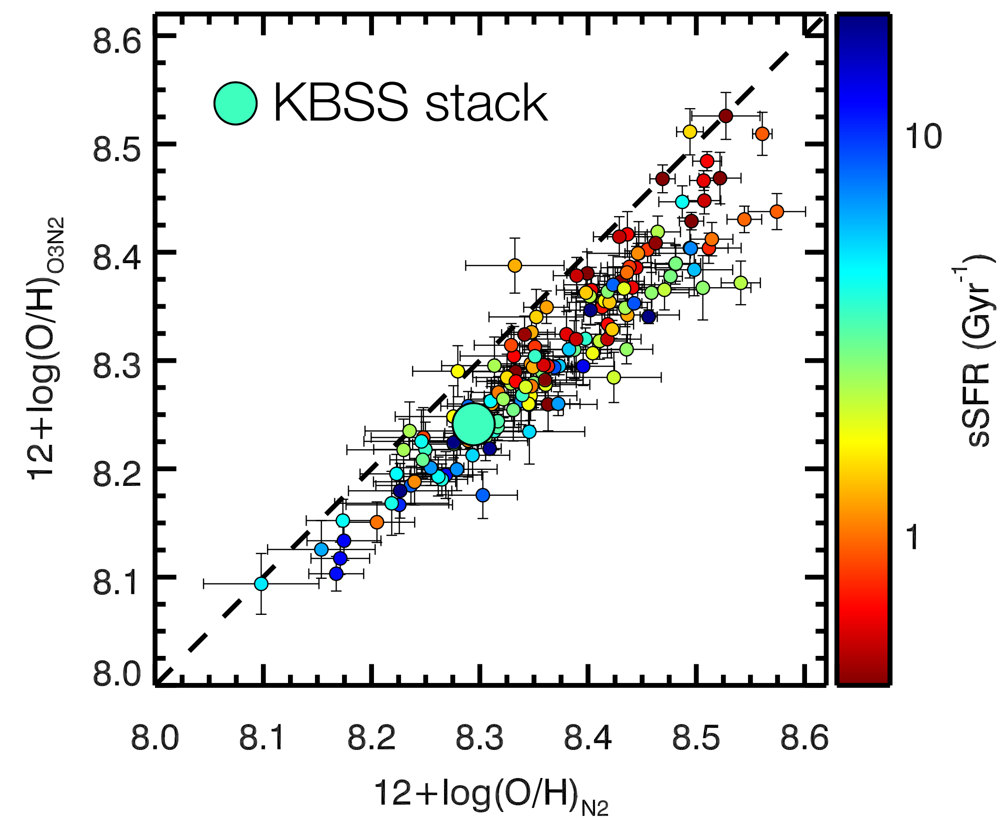
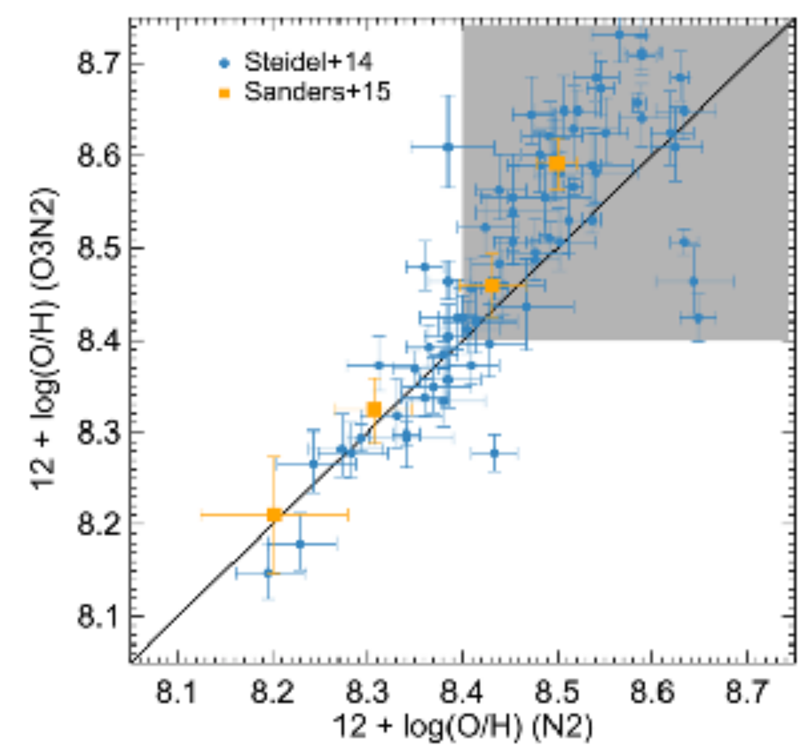


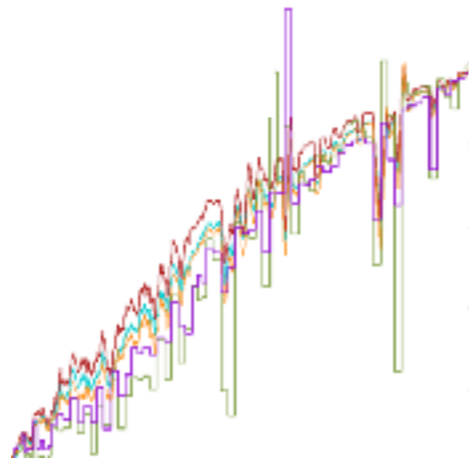
There are no nearby massive stars (or stellar pops) with moderate-to-high O/H <u>and</u> high α/Fe on which to base a new empirical calibration



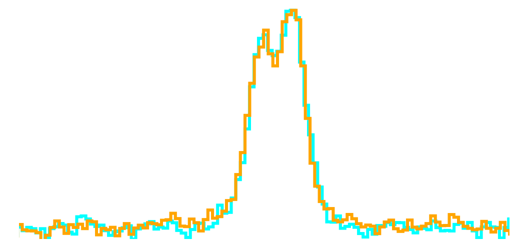
Bian+2018

Measuring physical conditions using only emission lines

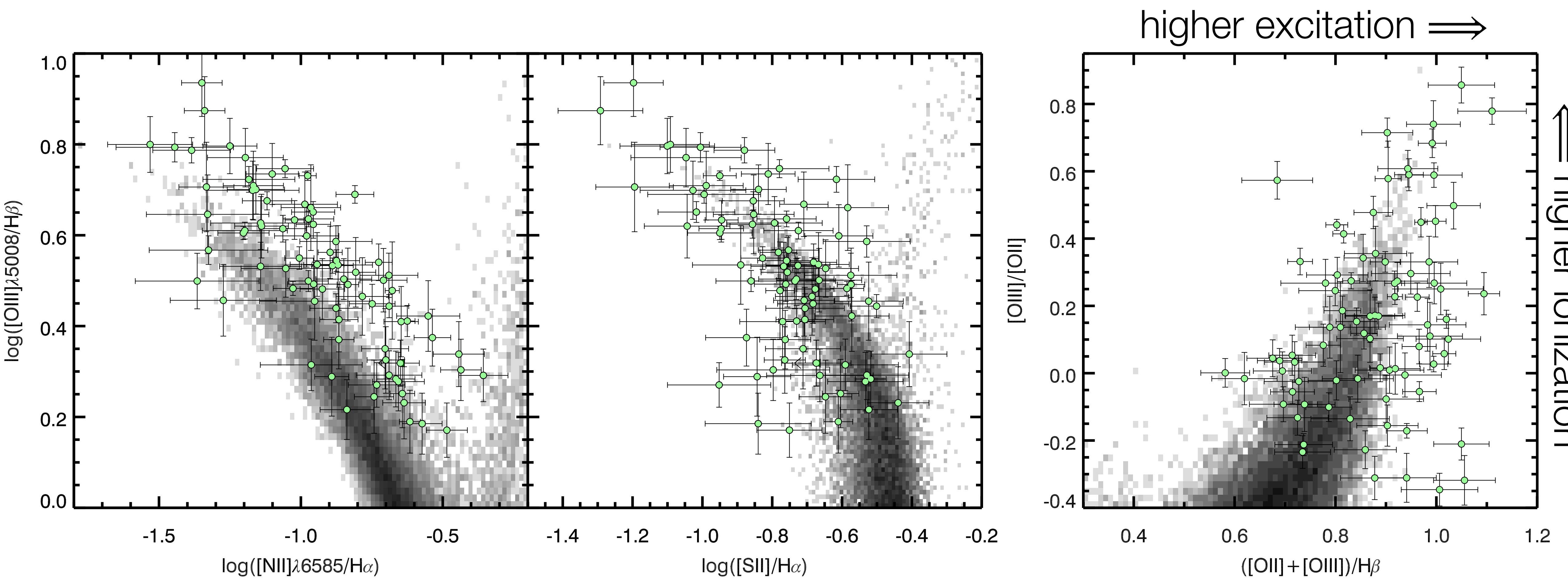
line ratios
f(U, Z_{neb}, $Z_\star$) =



\+



\+ ???



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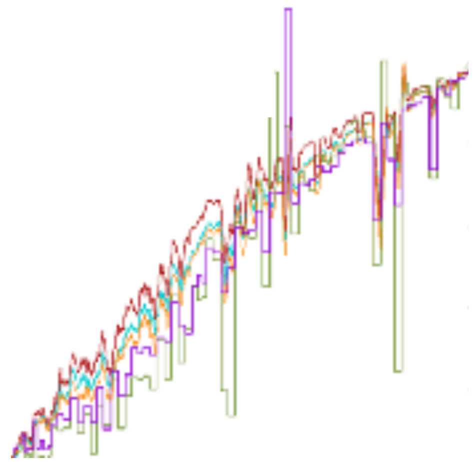
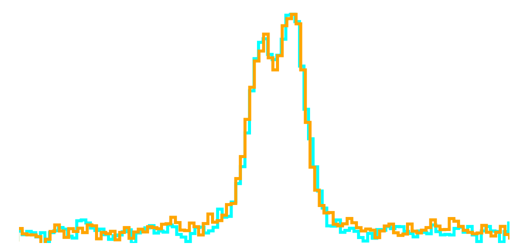
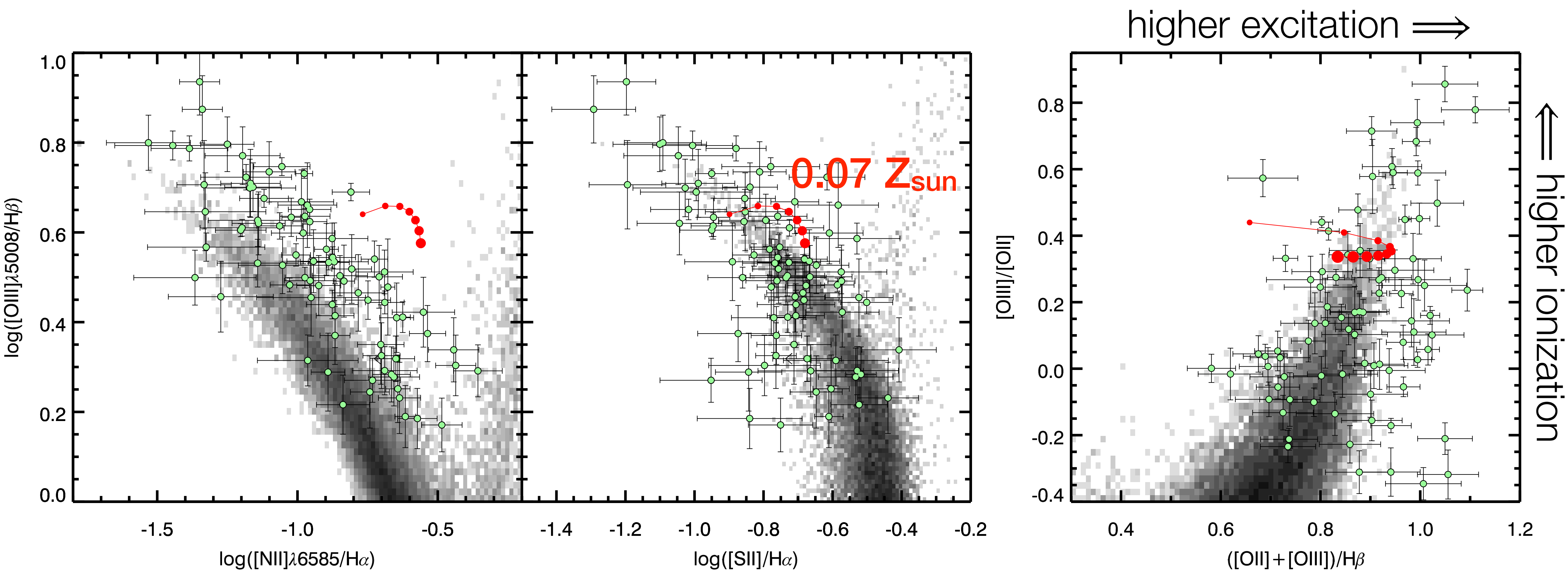
f(U, Z_{neb}, $Z_\star$) =  **+**  **+ ???**



Measuring physical conditions using only emission lines

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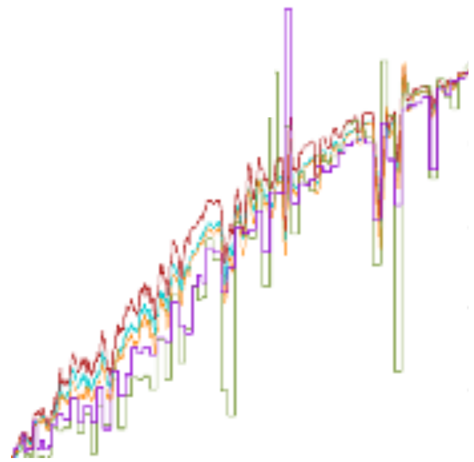

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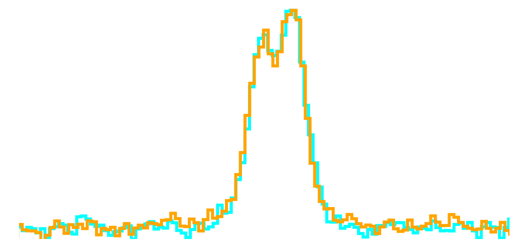

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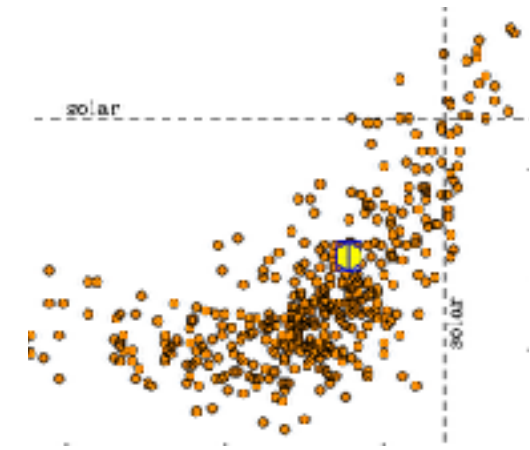

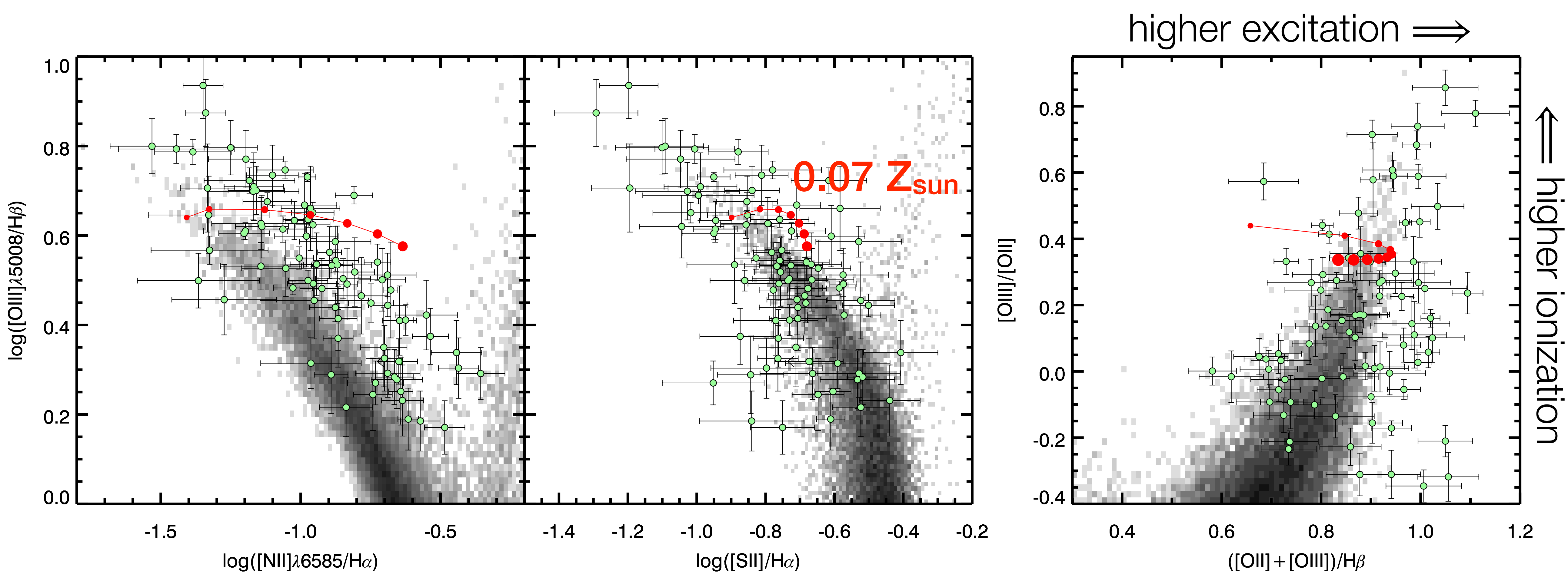

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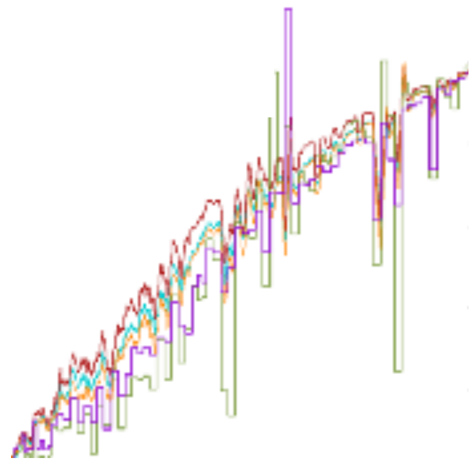
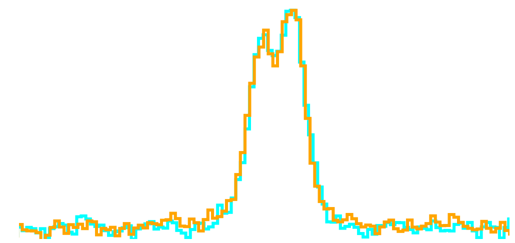
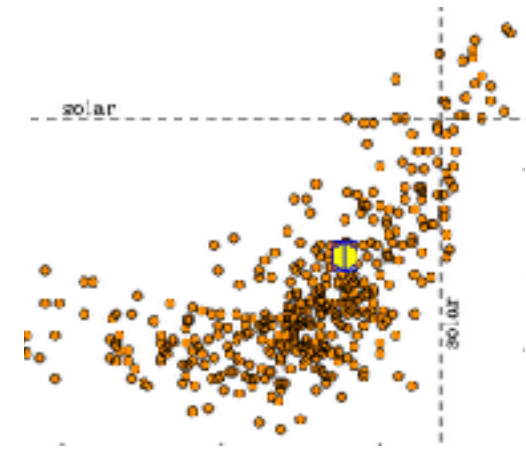
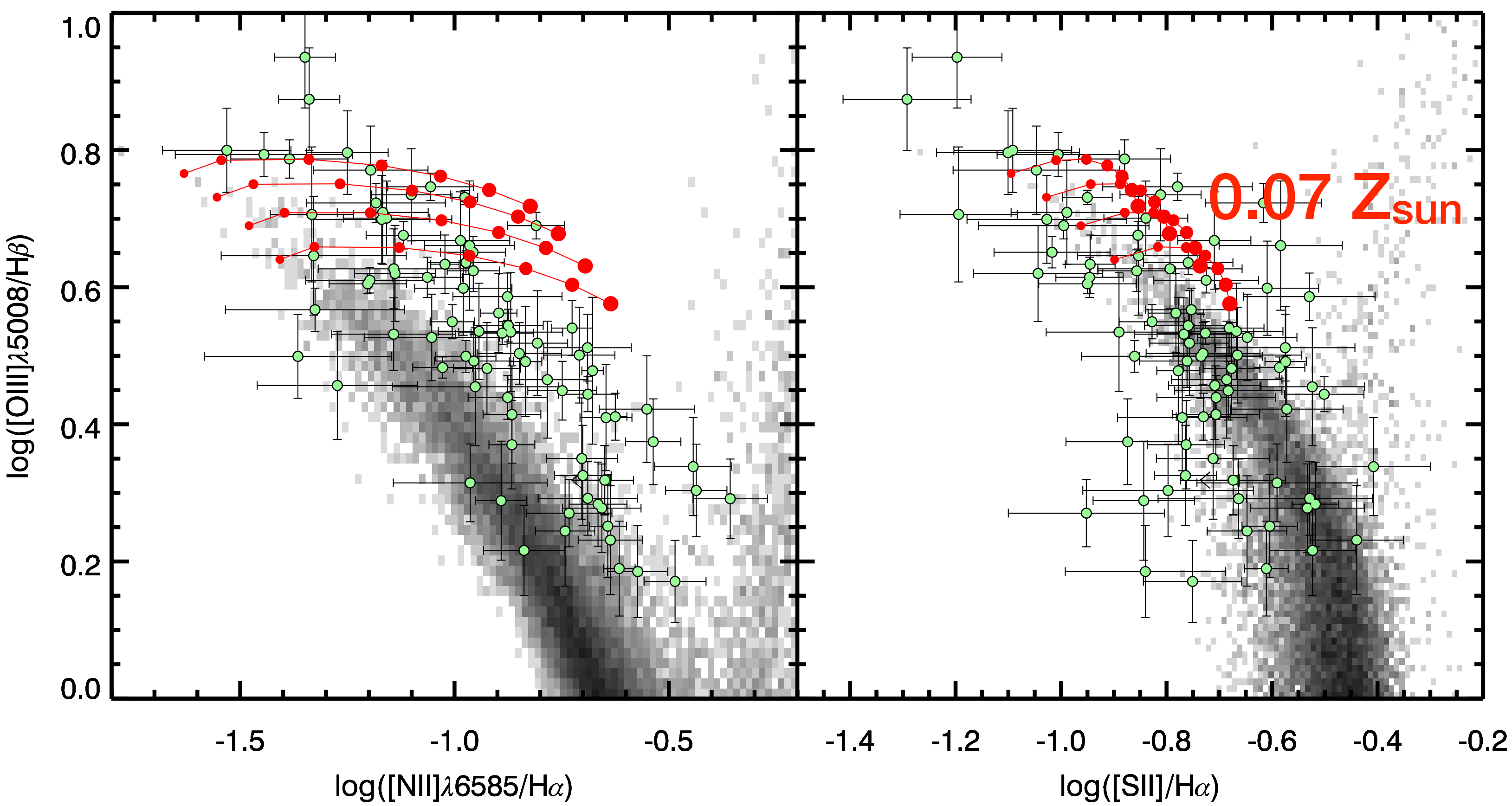
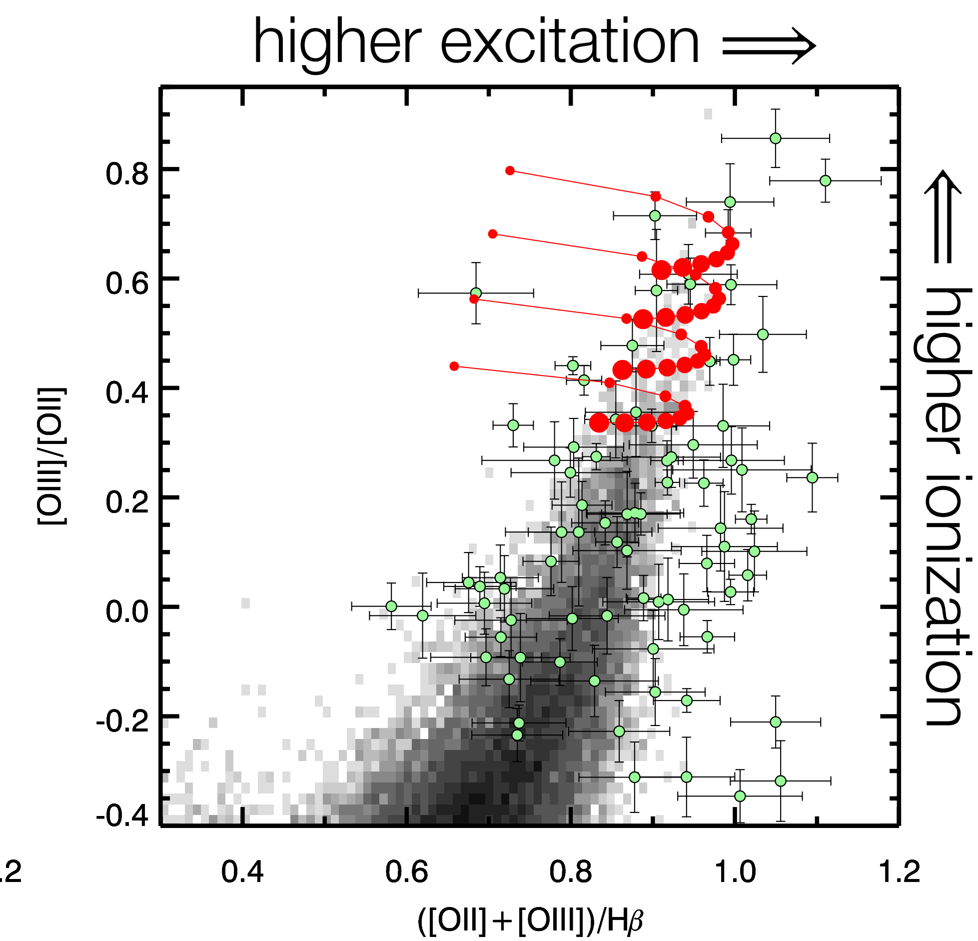
f(U, Z_{neb}, $Z_{\star}$) =  +  + 





Measuring physical conditions using only emission lines

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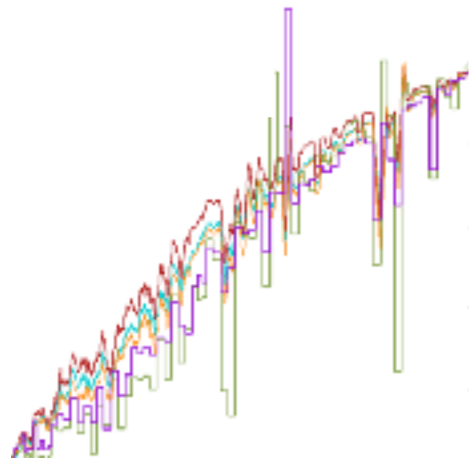

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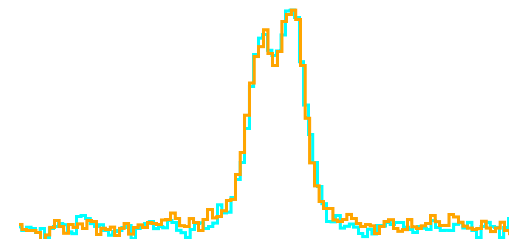

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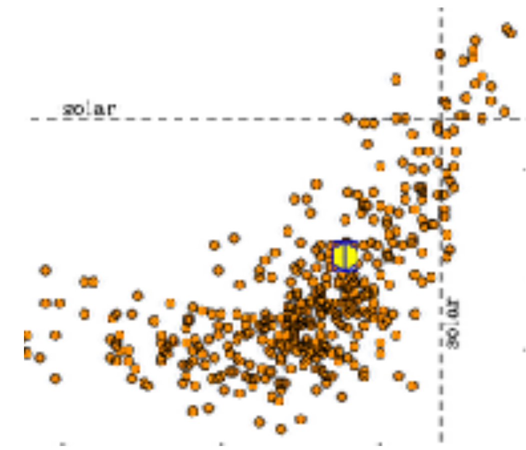

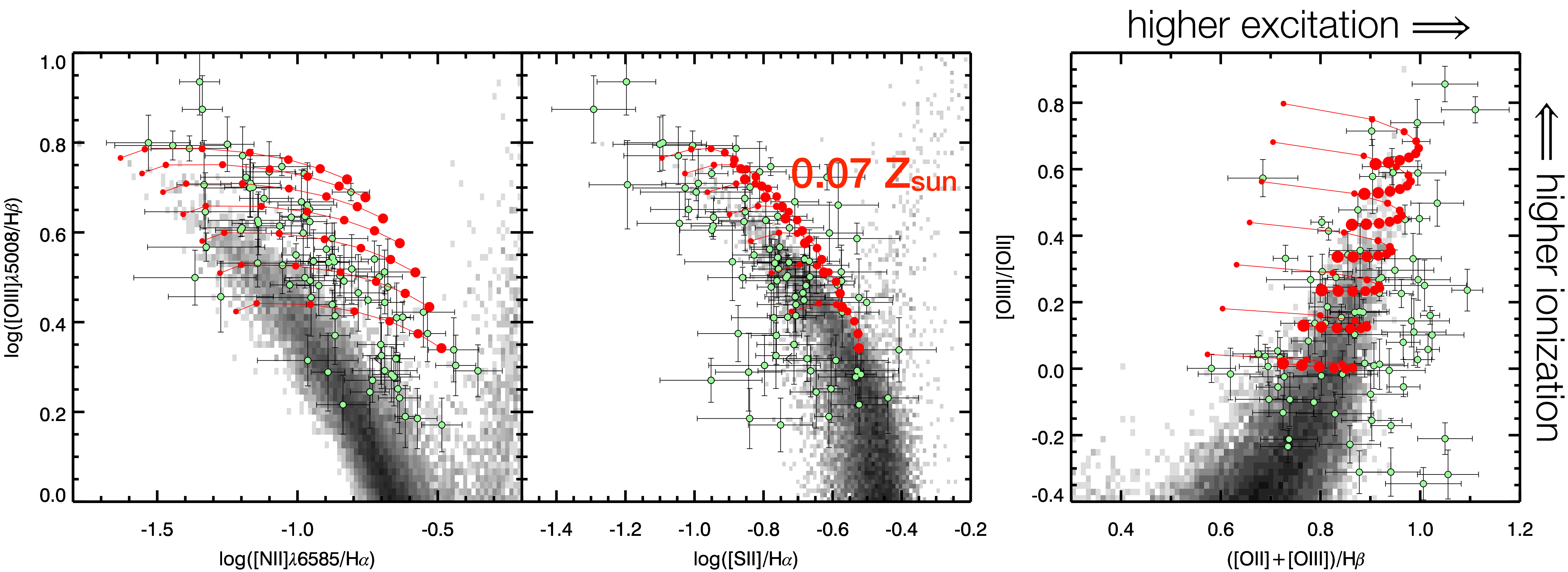

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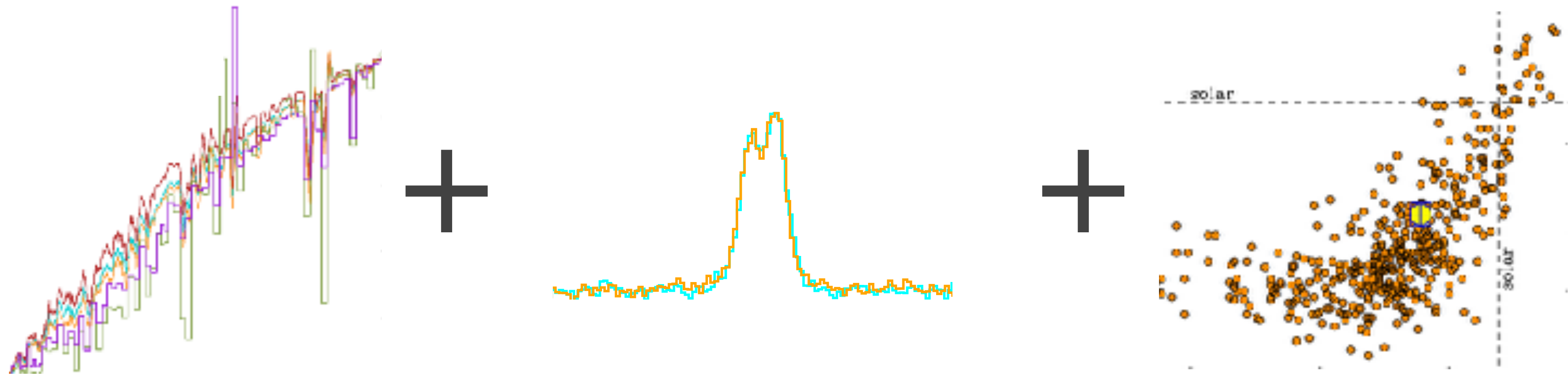

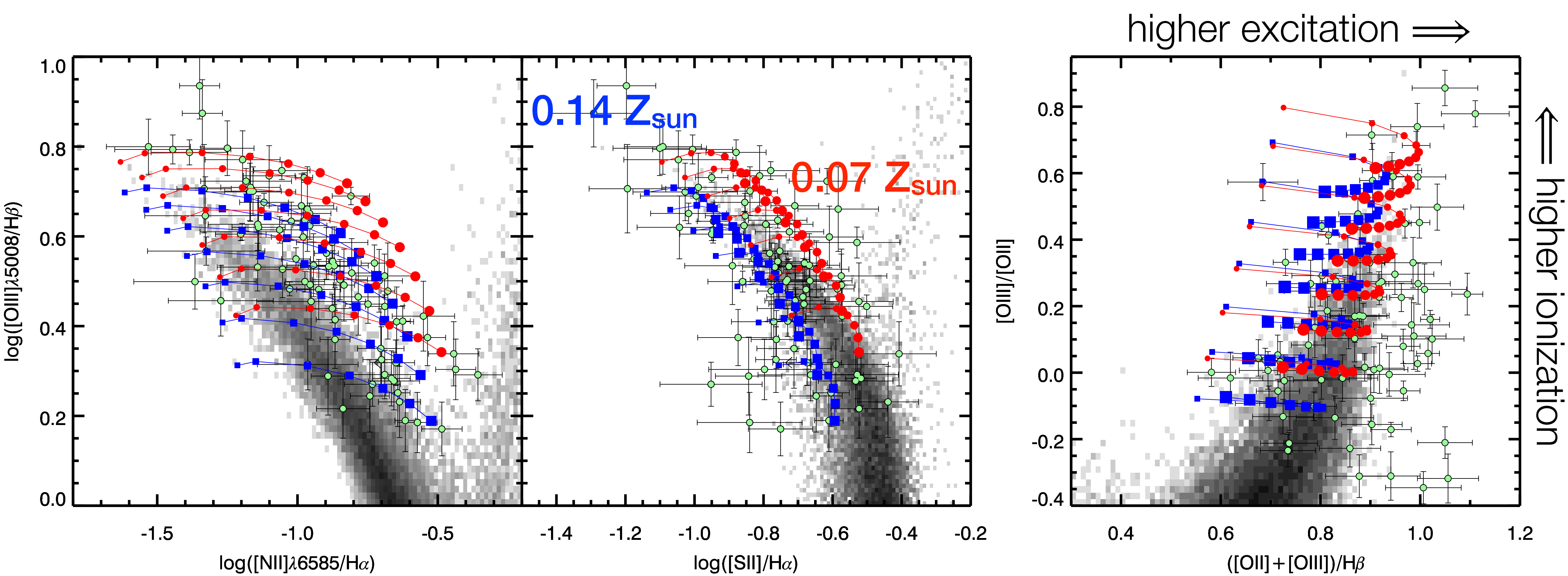

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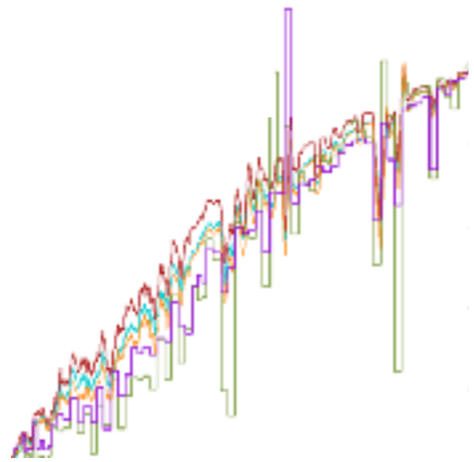
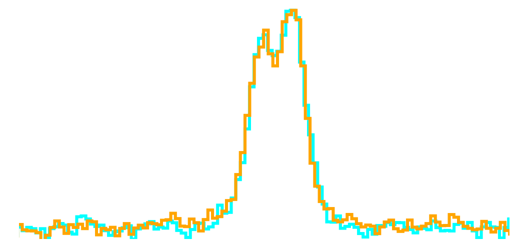
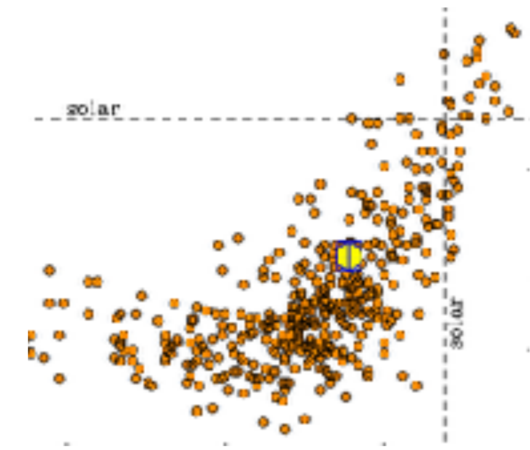
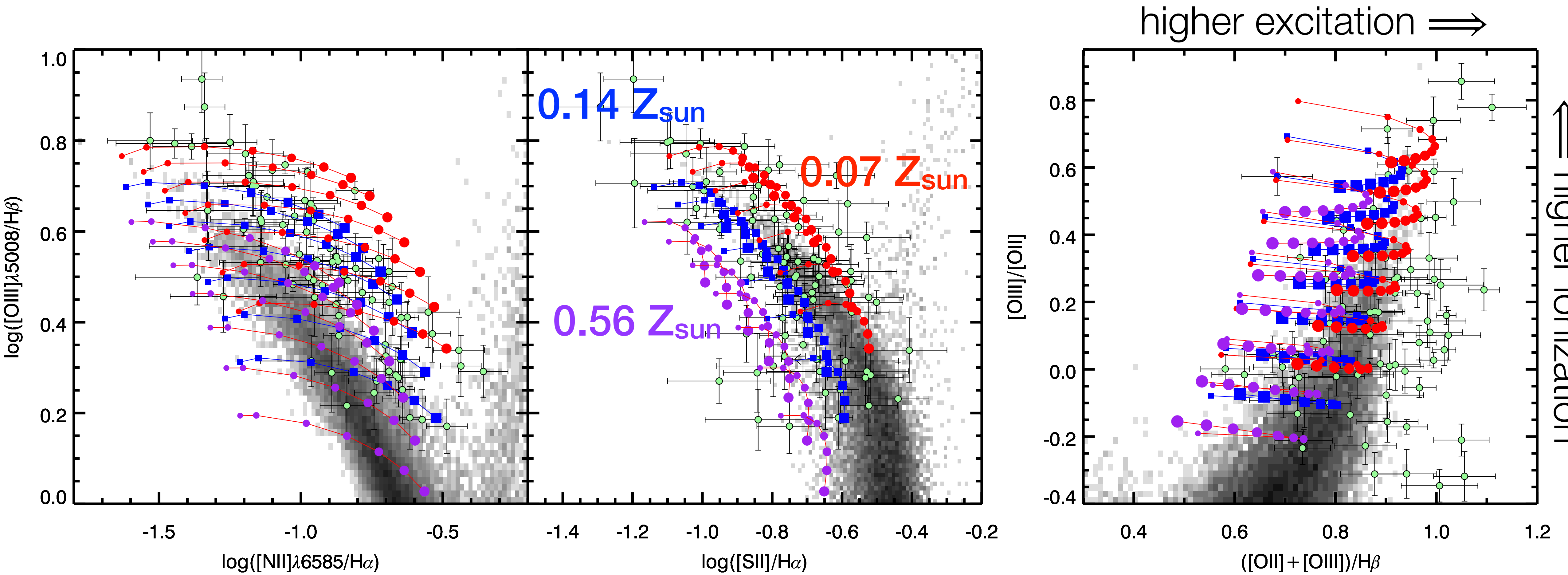
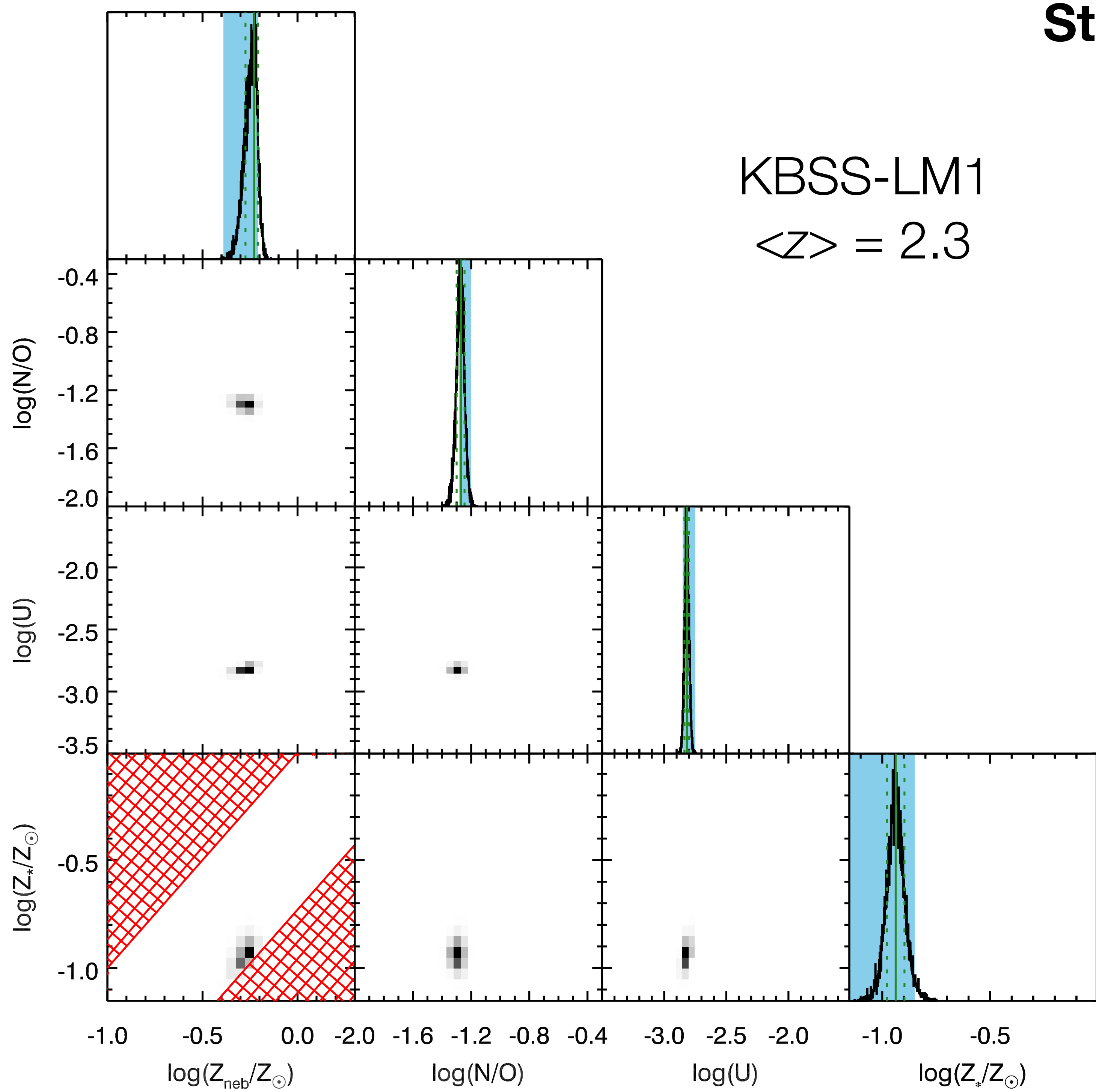
f(U, Z_{neb}, $Z_\star$) =  **+**  **+** 



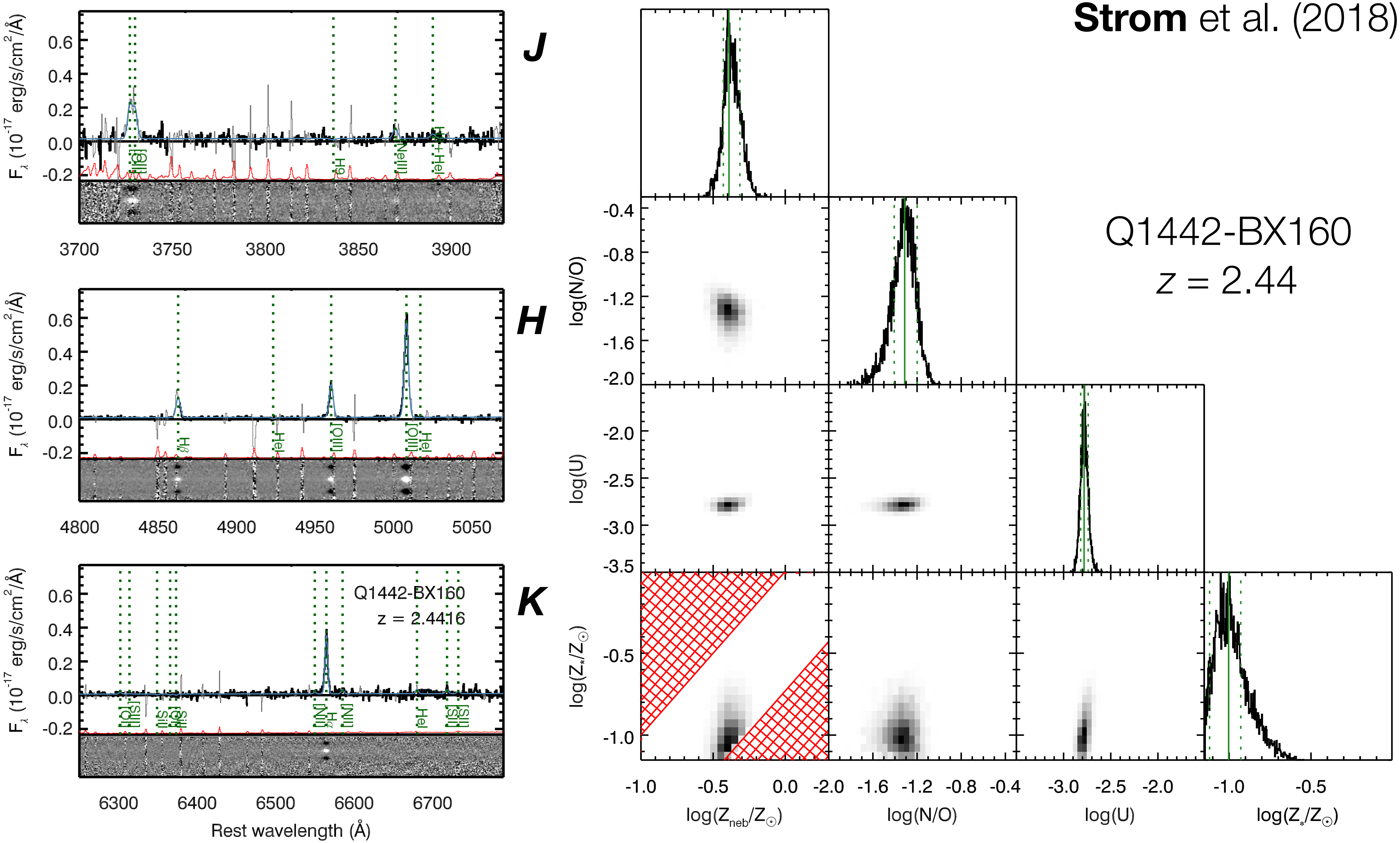
Testing the photoionization model method using the LM1 composite

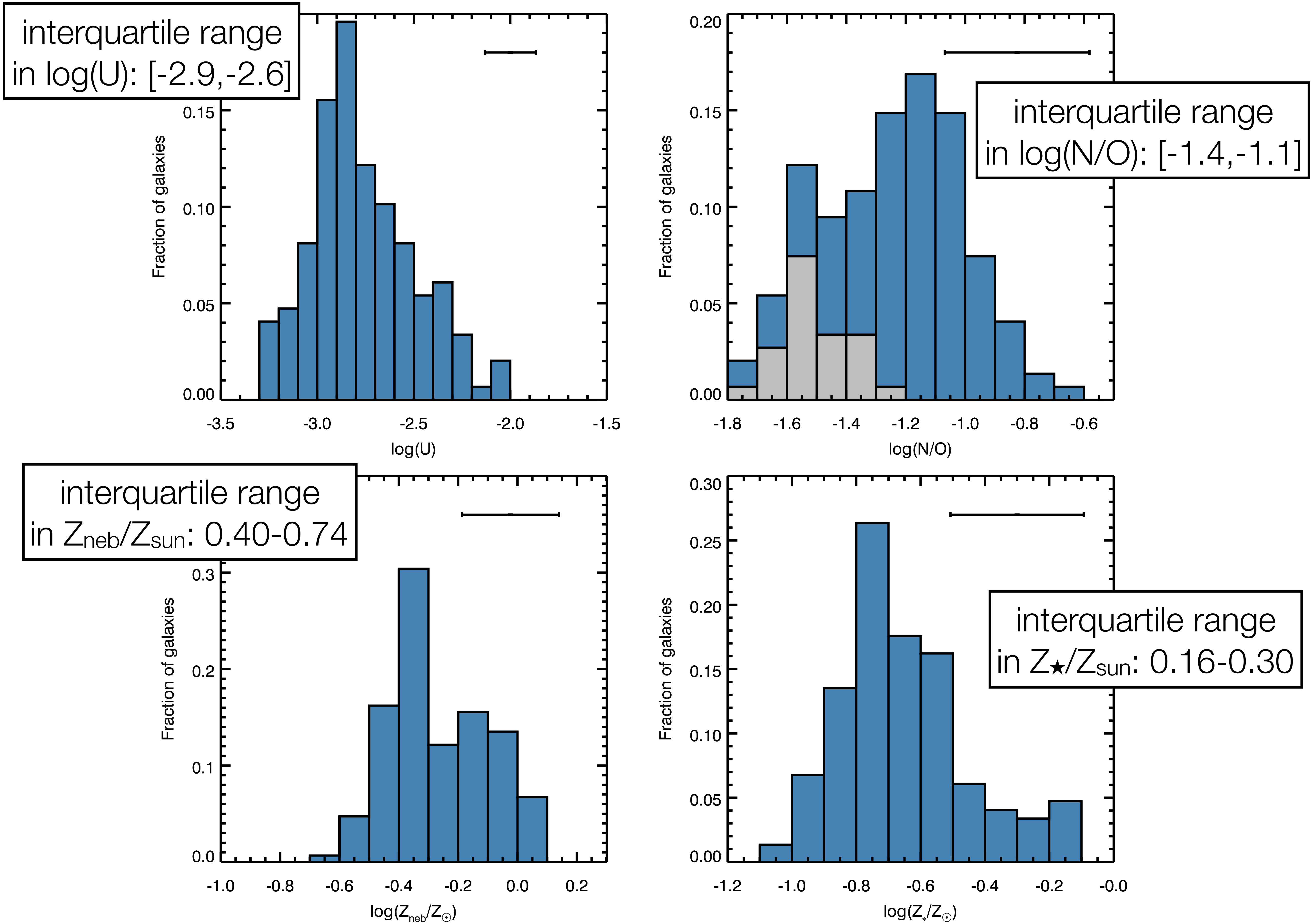
Strom et al. (2018)



Measuring O/H, N/O, U and Fe/H for individual galaxies

Strom et al. (2018)

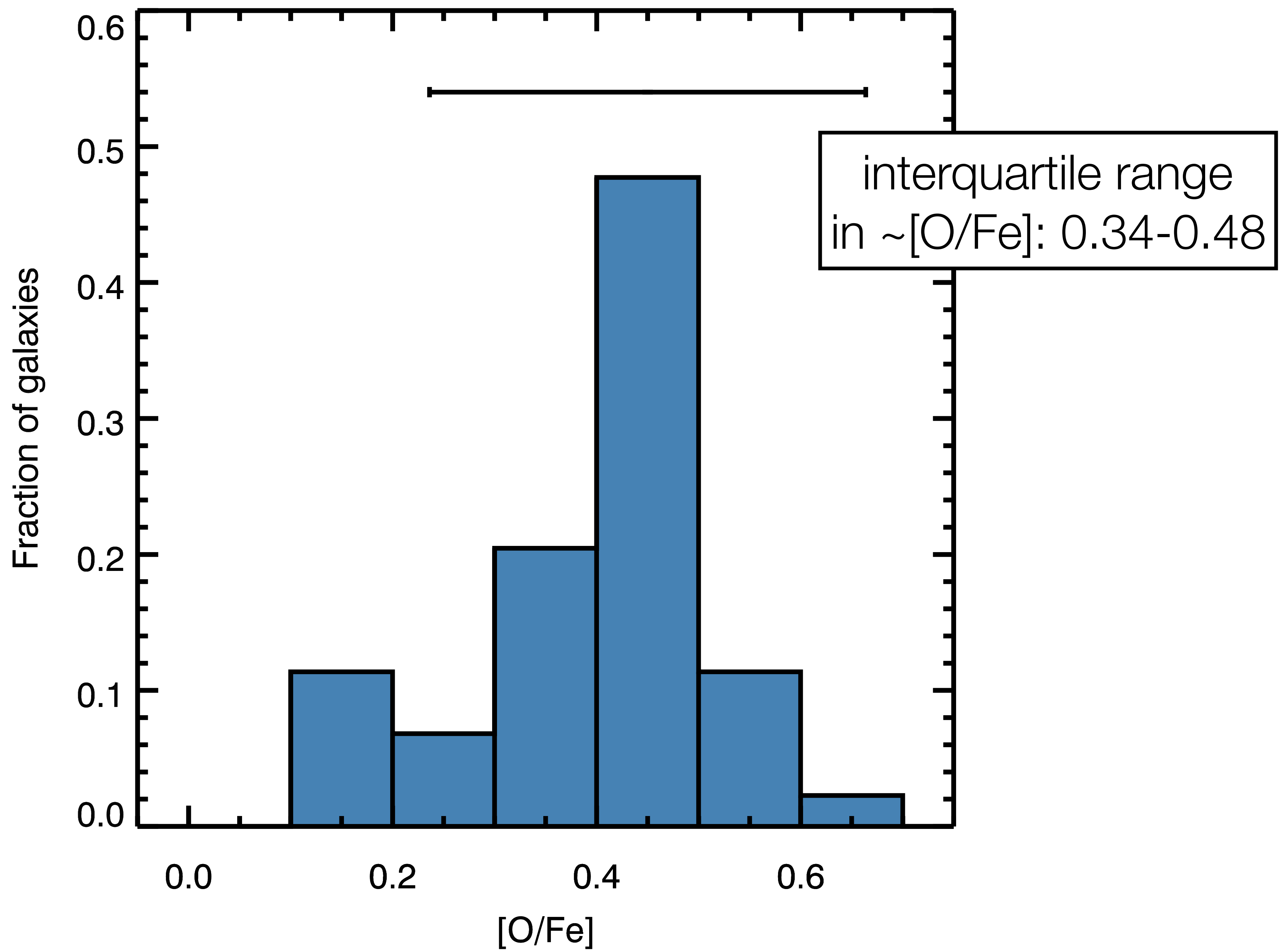




Strom et al. (2018)

Most high-z star-forming galaxies show high O/Fe in their ISM

Strom et al. (2018)



1. ***What is the least biased way to measure enrichment using common observables?***

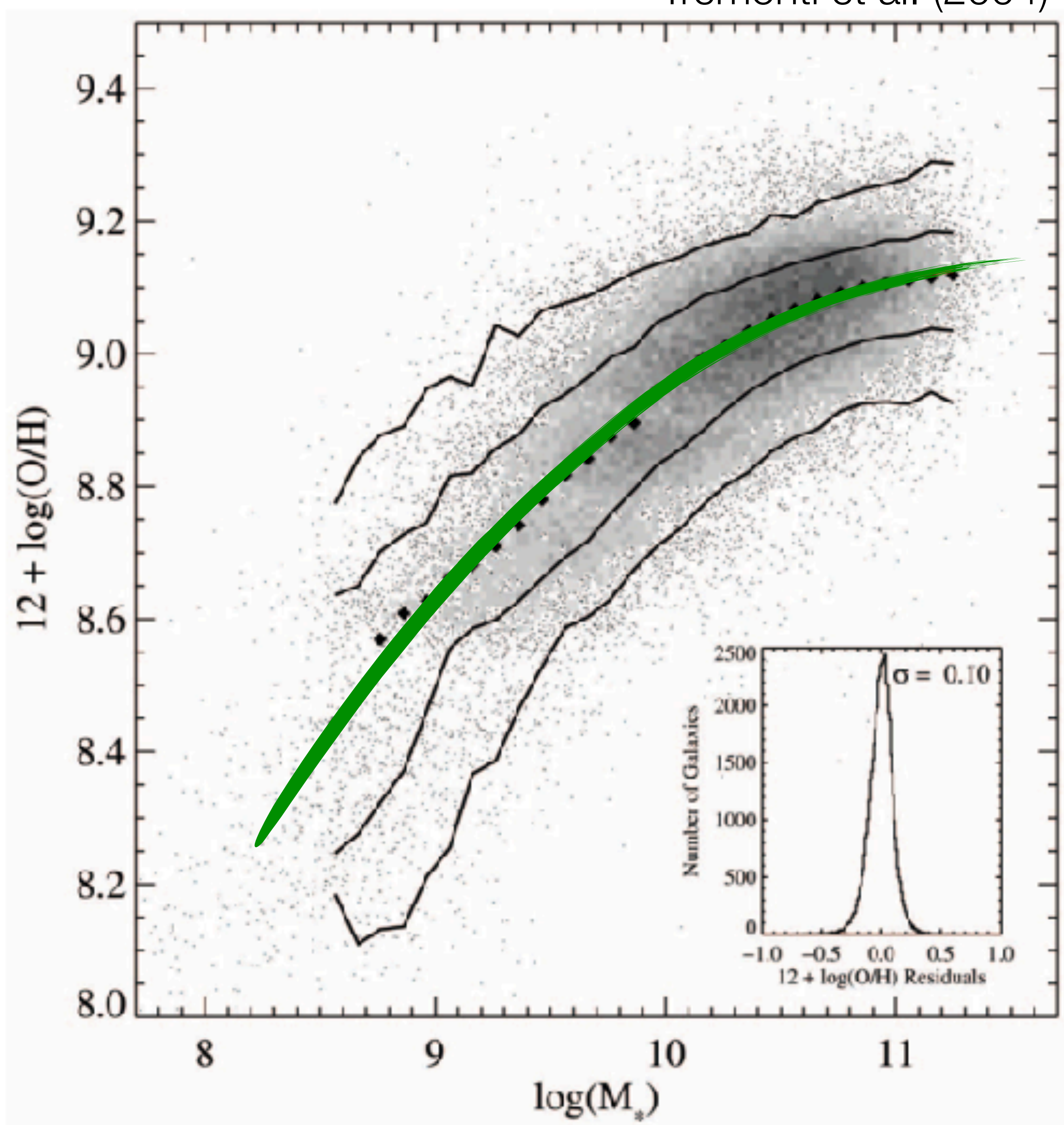
1. ***What is the least biased way to measure enrichment using common observables?***

Because the most common observables are sensitive to multiple astrophysical parameters, the best method is one that accounts for **all** of those parameters.

2. ***What parameters are most important for learning about galaxy assembly?***

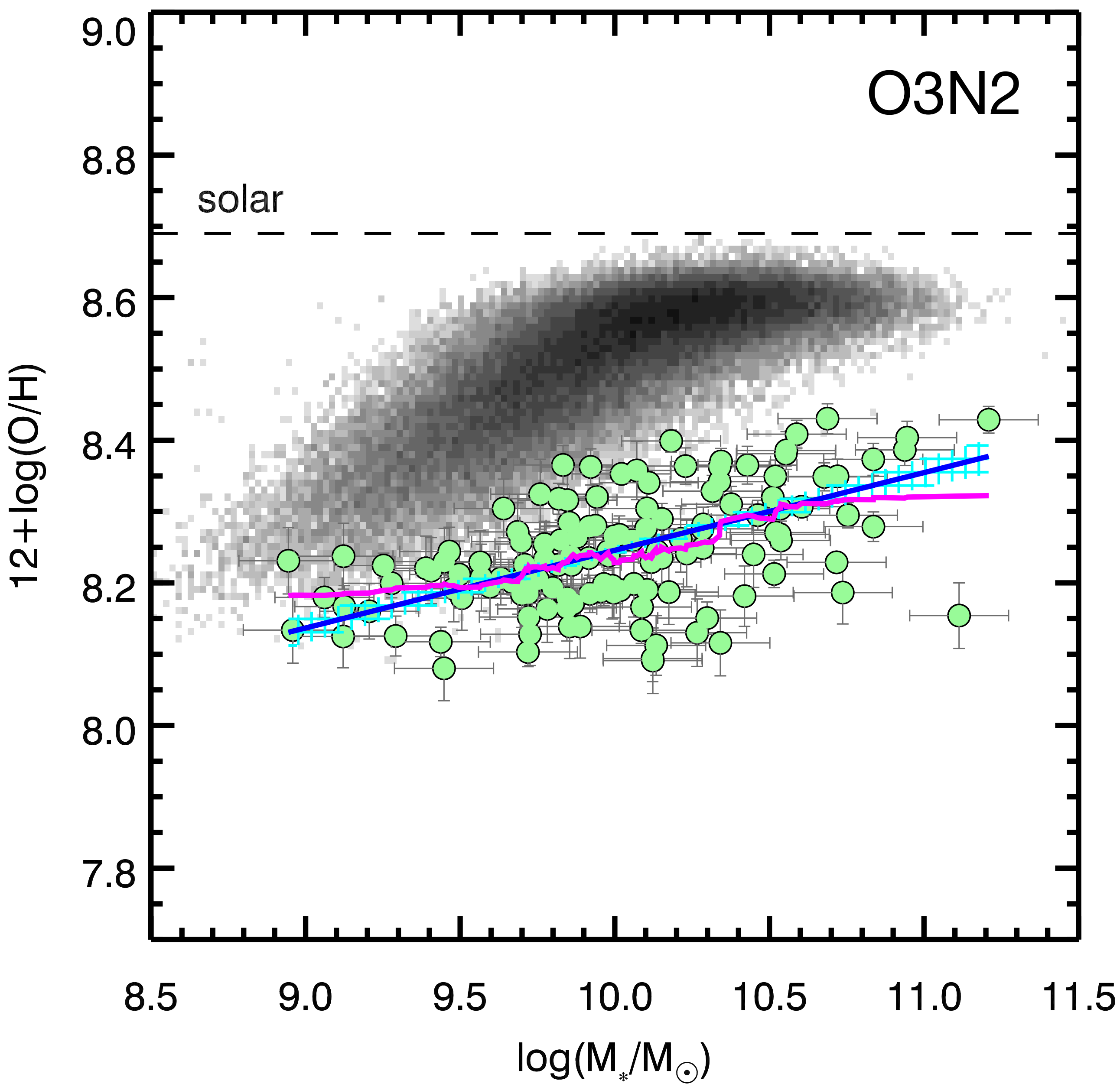
Can define a scaling relation with normalization, slope, and scatter

Tremonti et al. (2004)



The mass-"metallicity" relation you measure depends on the method

Strom et al. (2019, in prep.)



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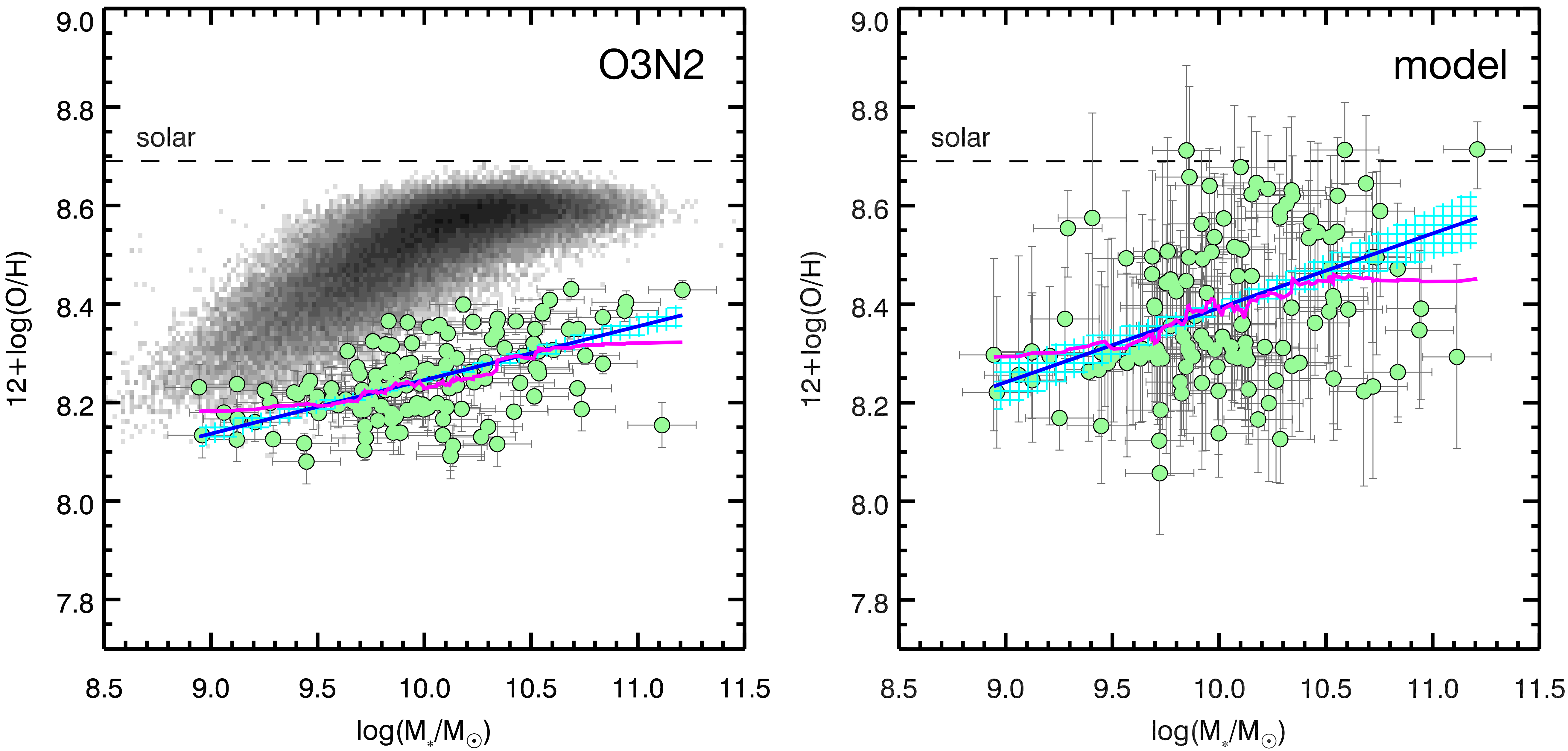
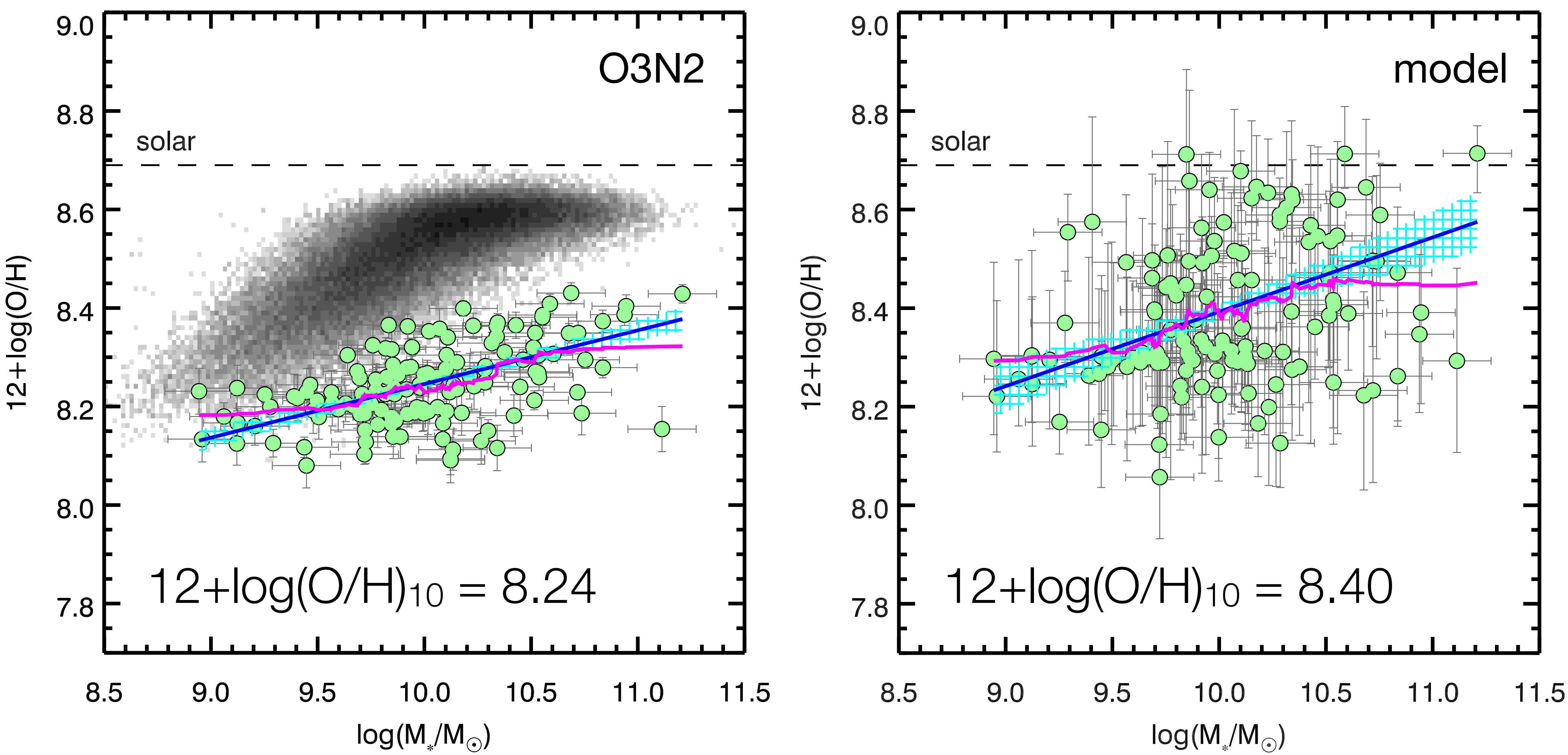


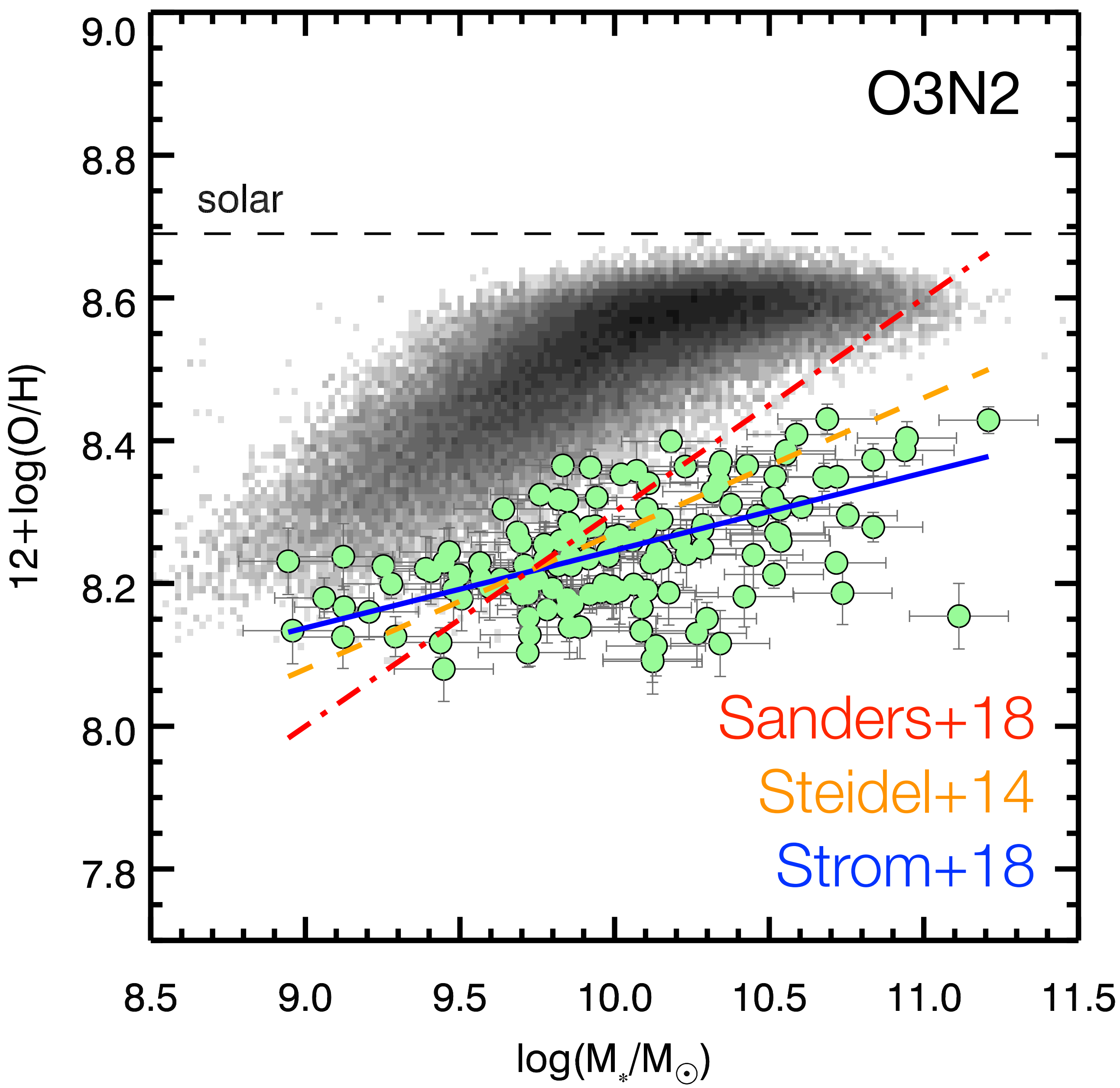
*Which **normalization** you report depends on implicit abundance scale*

Strom et al. (2019, in prep.)



*The measured **slope** of the scaling relation can differ dramatically*

Strom et al. (2019, in prep.)



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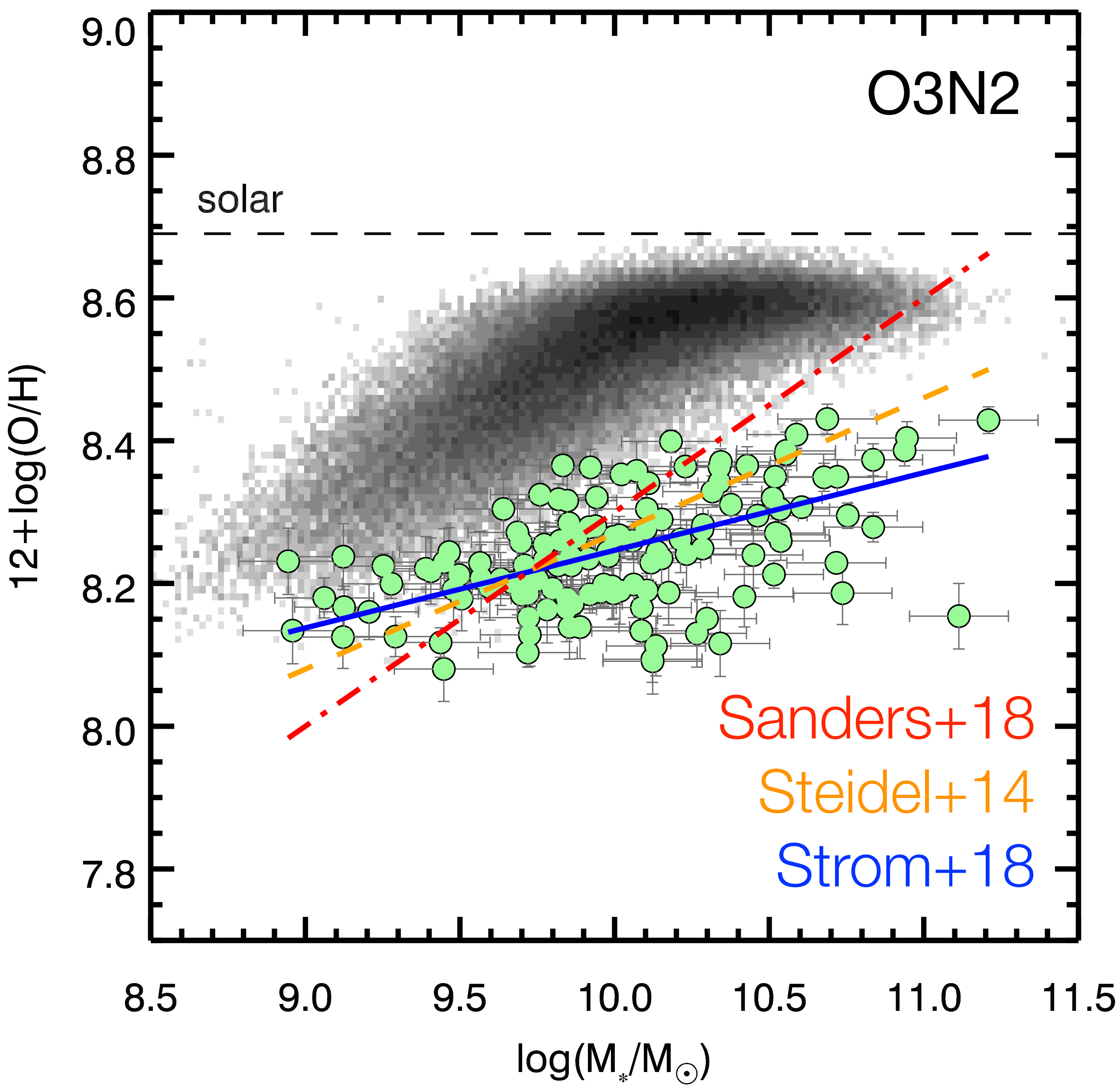

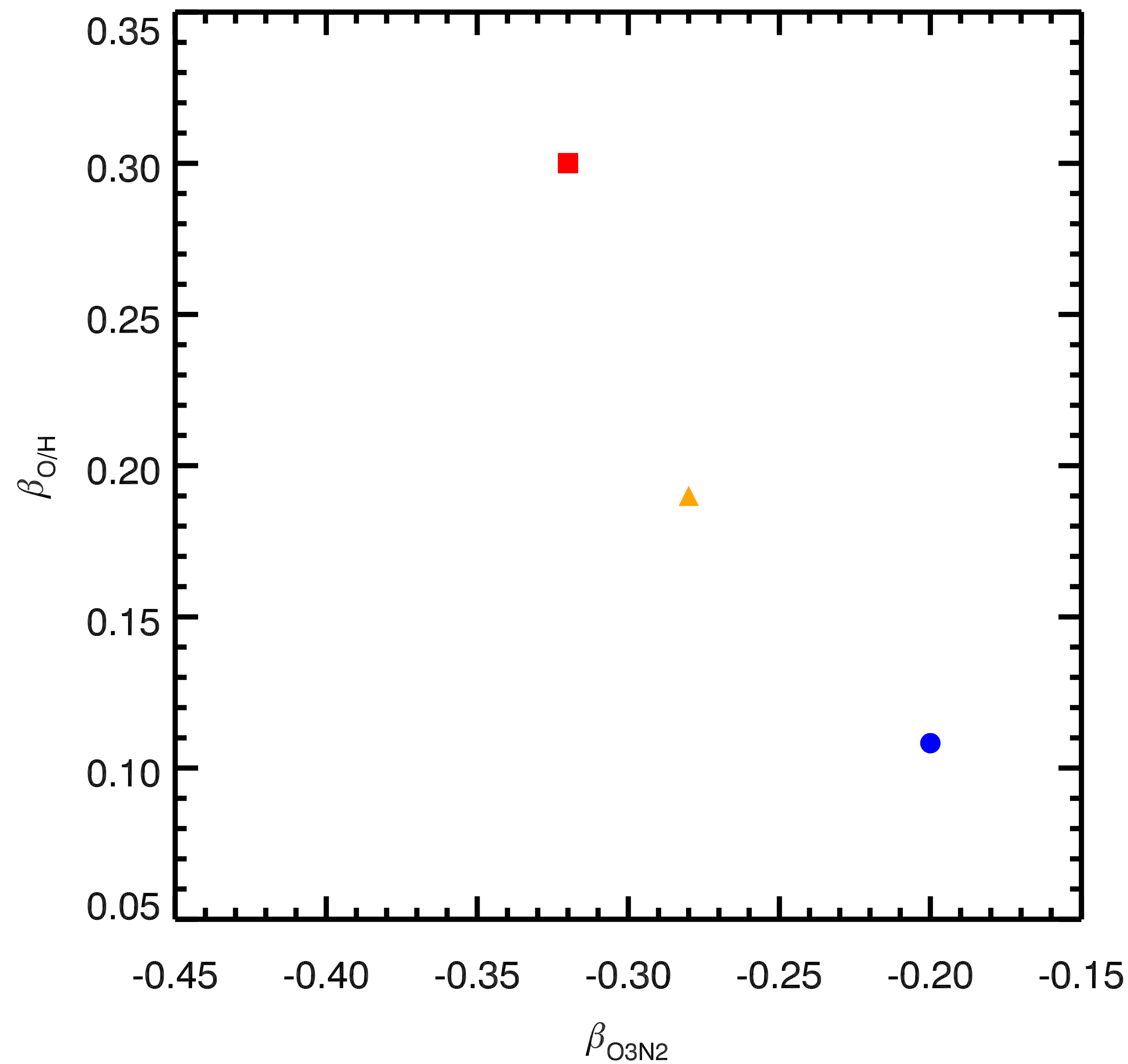

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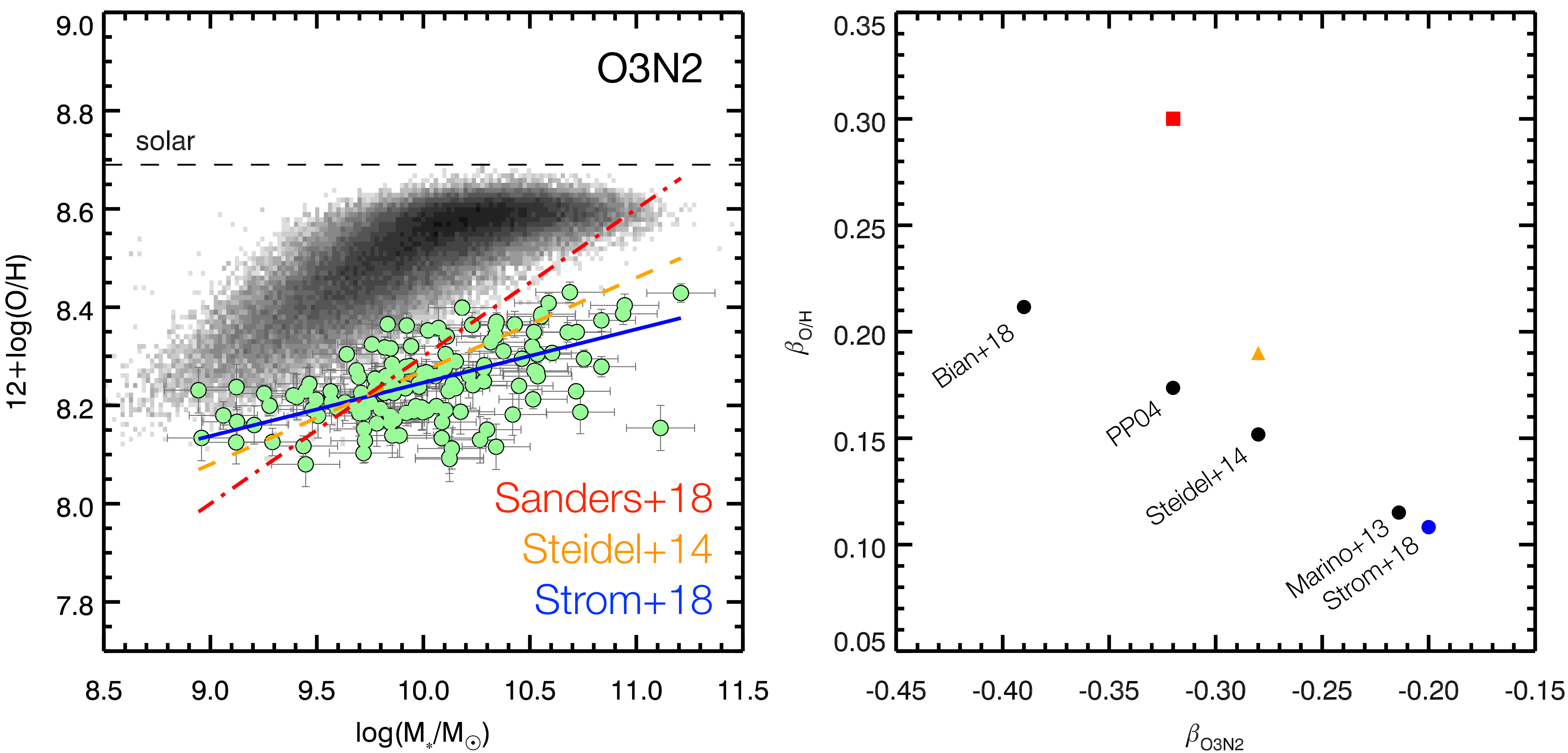
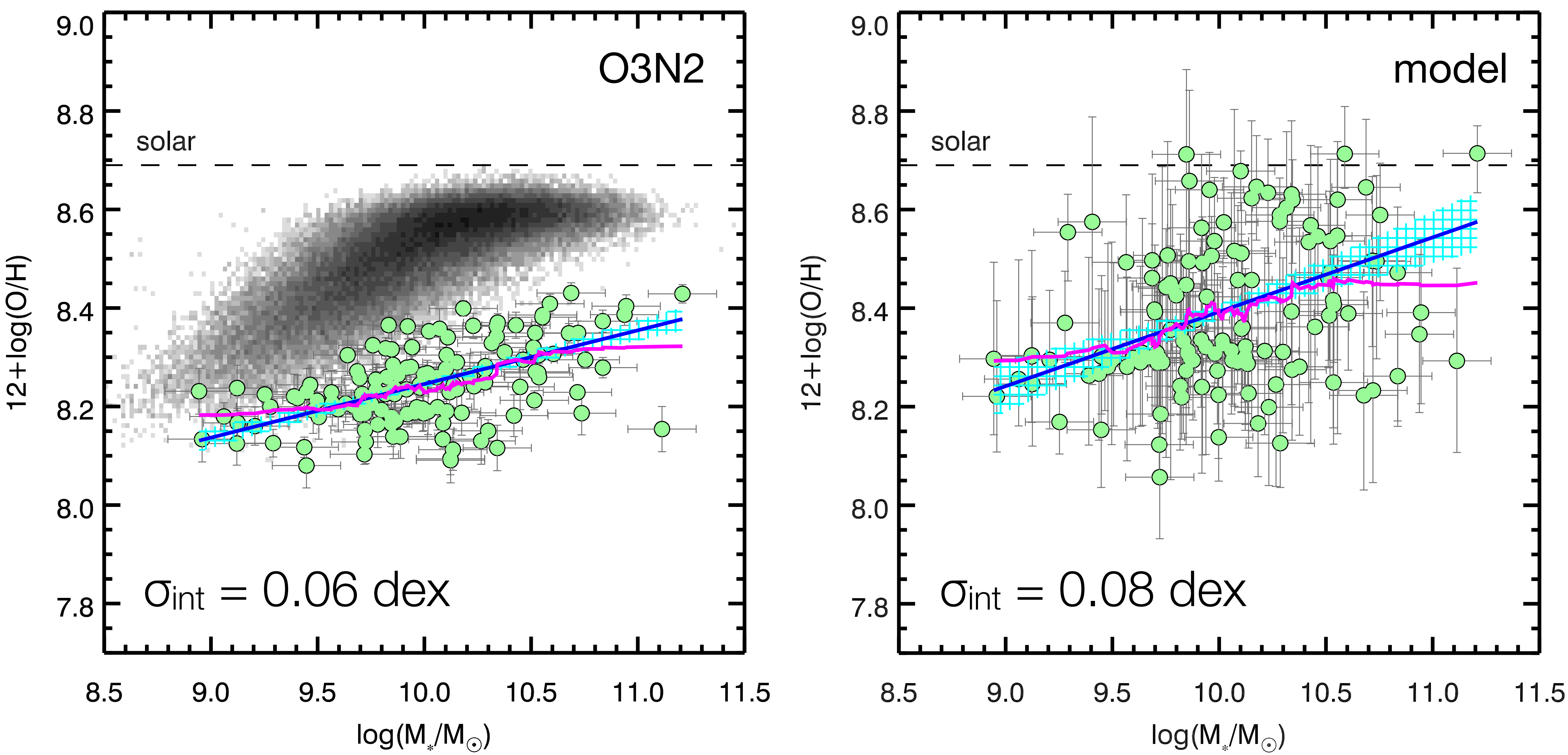


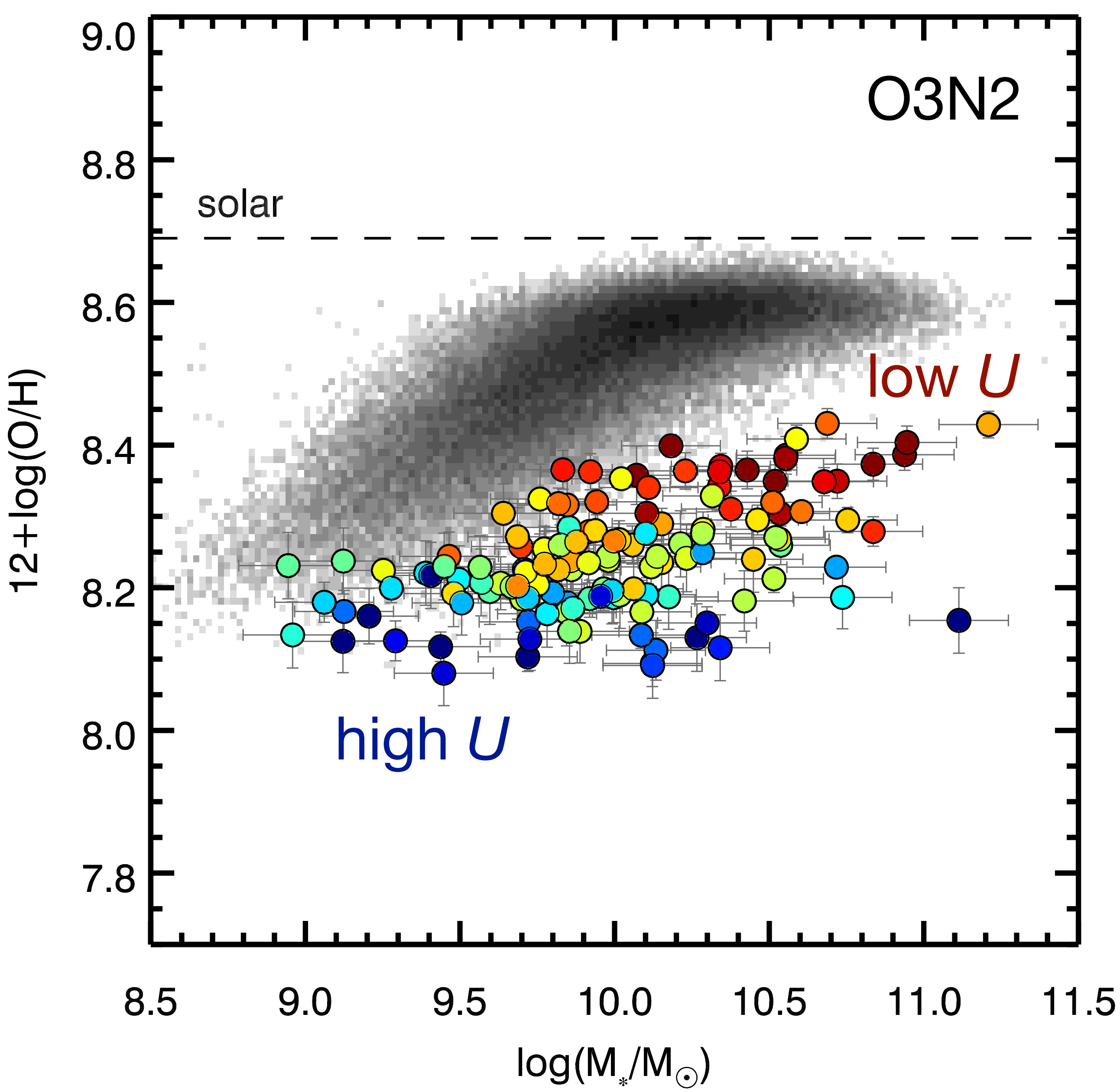
*The **scatter** in the relation is larger than previously measured*

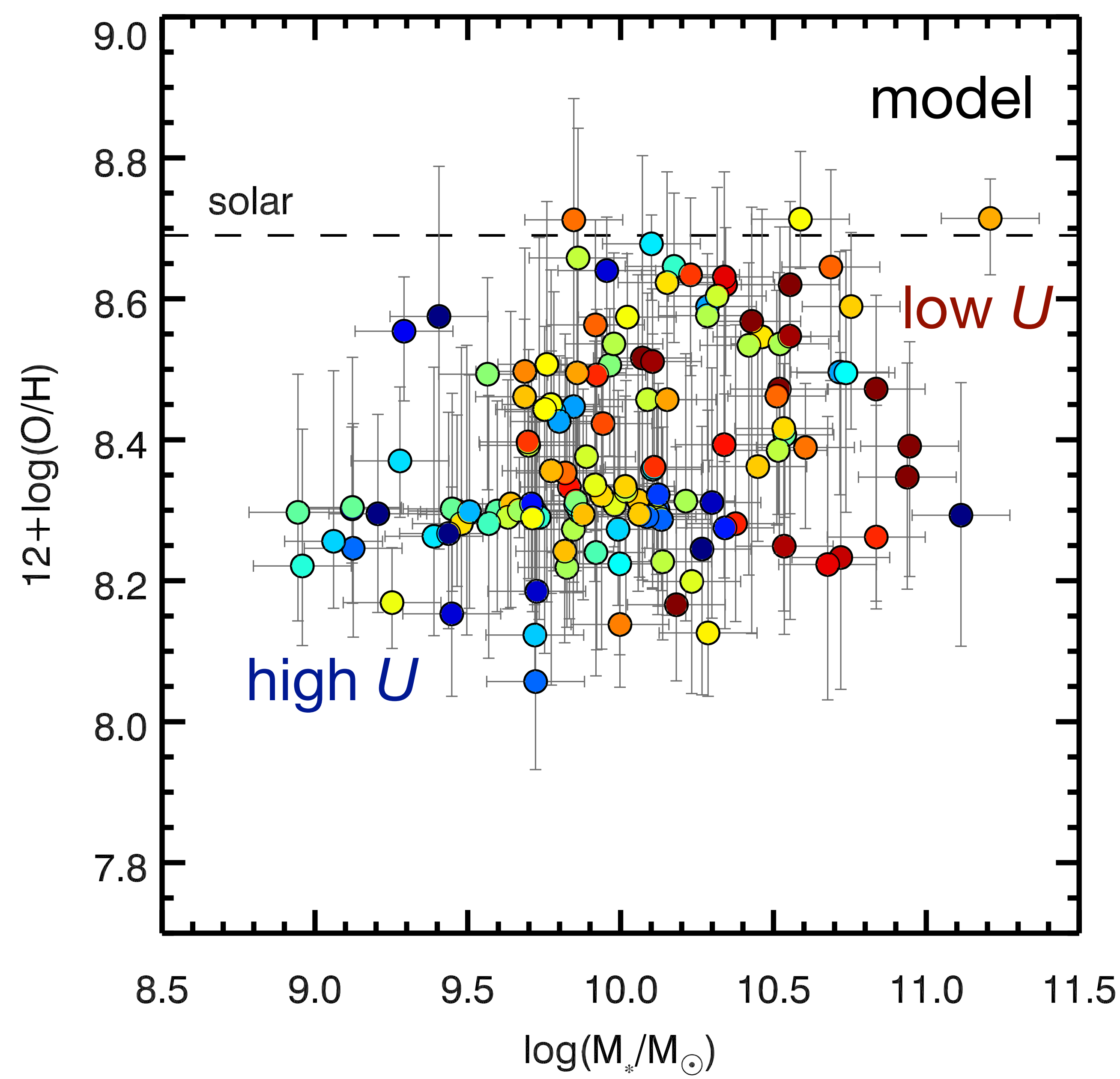
Strom et al. (2019, in prep.)



Scatter in strong-line relations suppressed due to secondary parameters

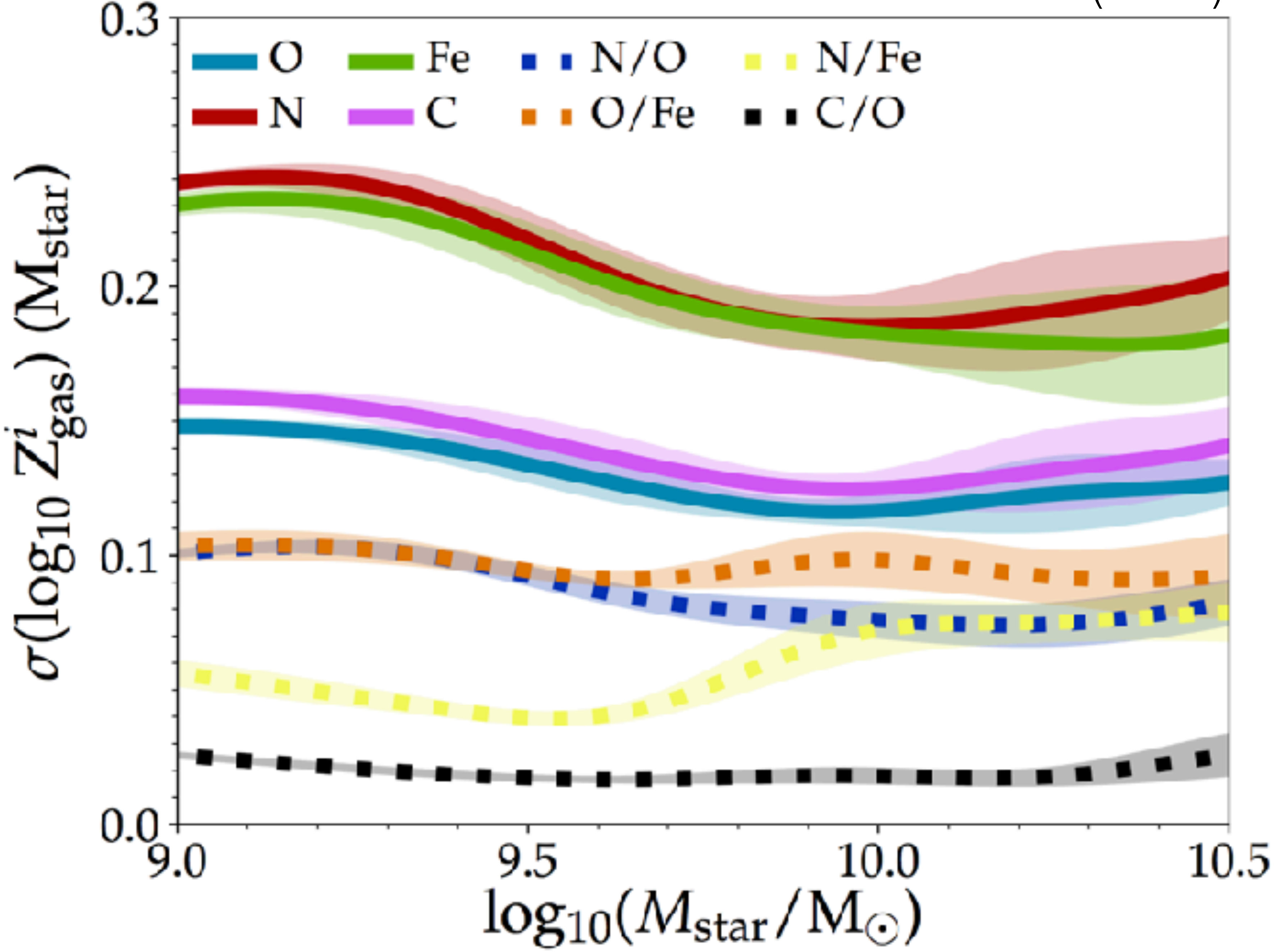
Strom et al. (2019, in prep.)





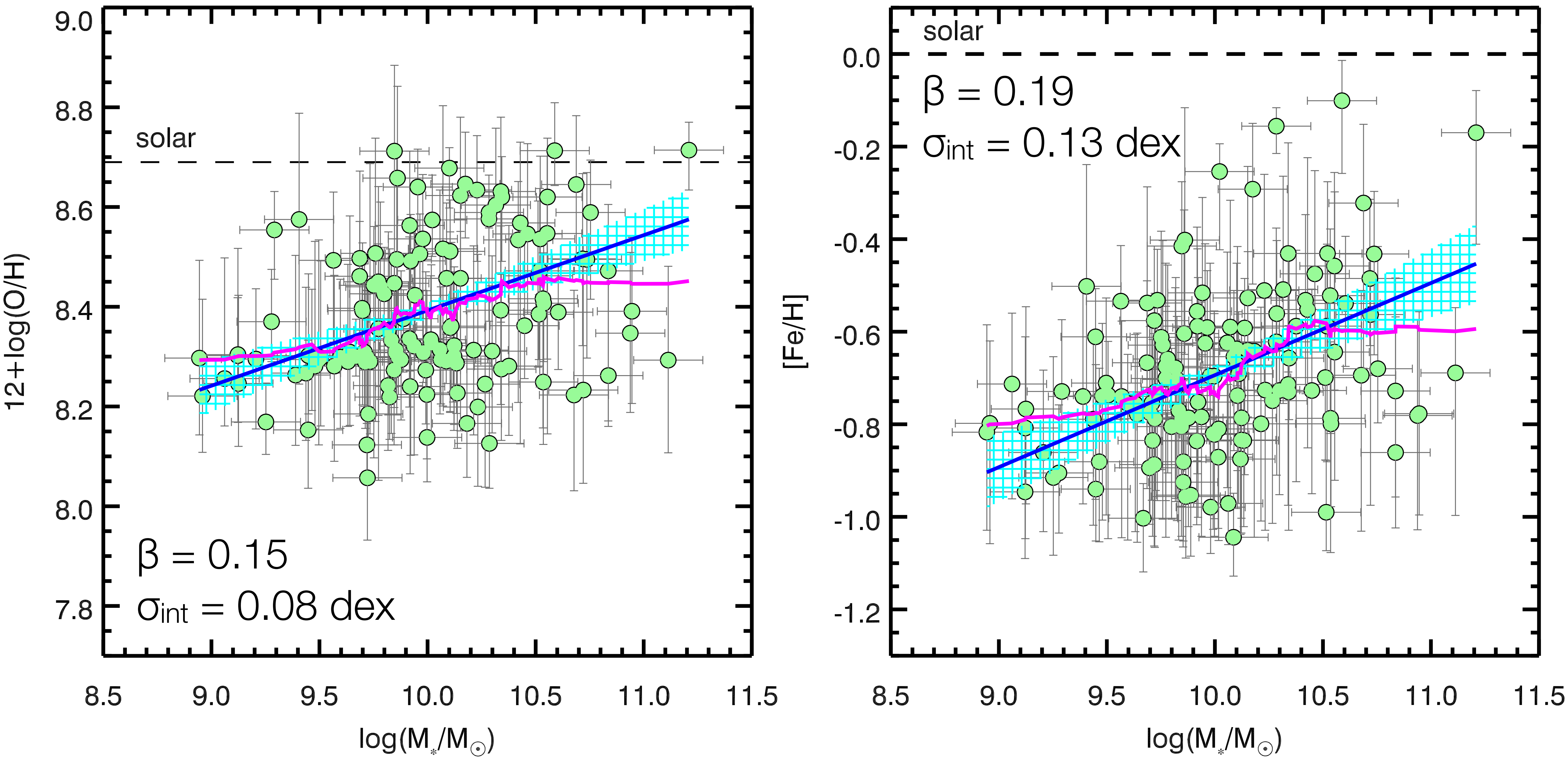
Accurate estimates of scatter can help probe assembly timescales

Matthee et al. (2018)



Stellar mass-Fe/H relation is steeper, has larger scatter

Strom et al. (2019, in prep.)



2. ***What parameters are most important for learning about galaxy assembly?***

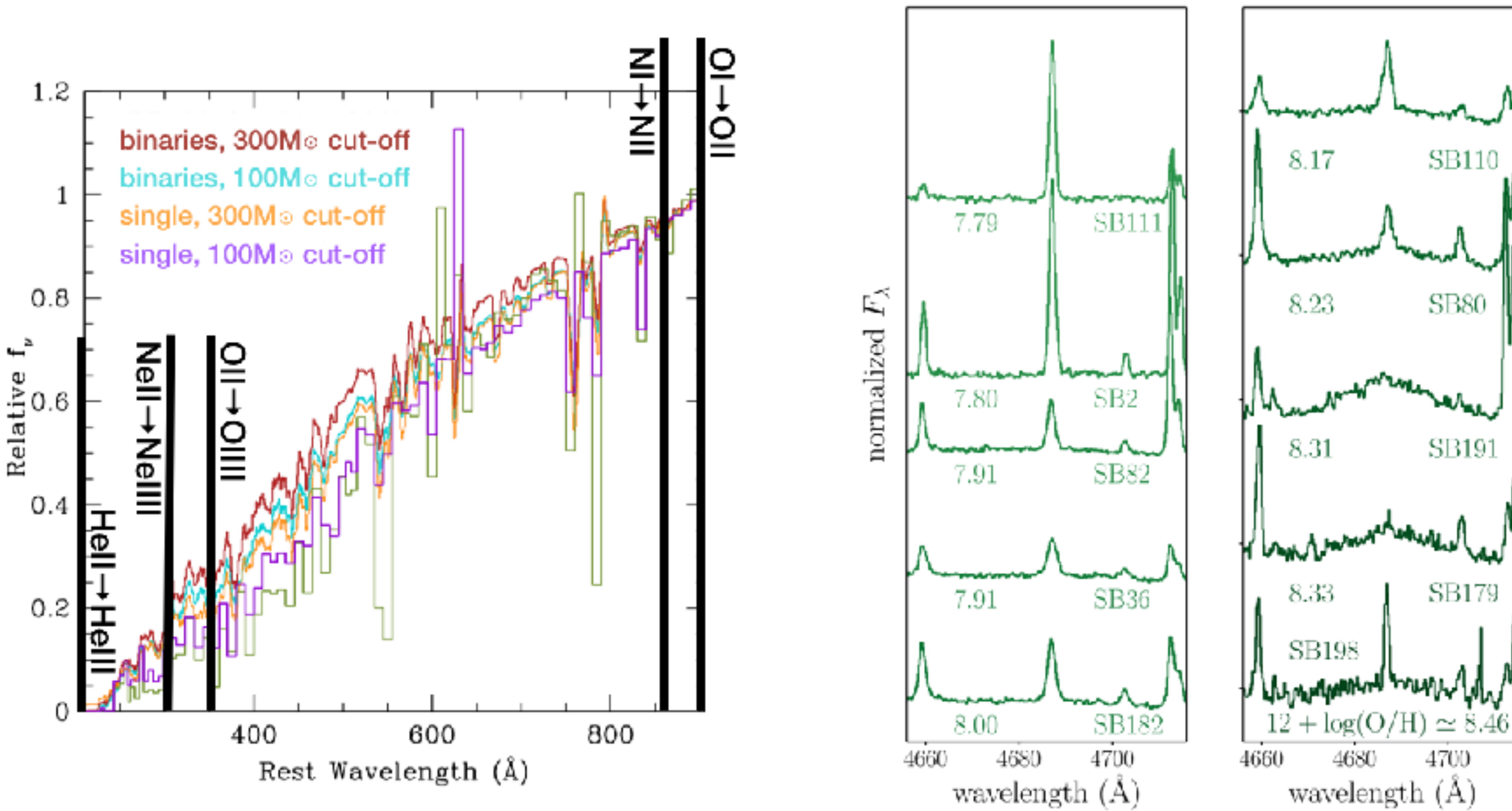
2. *What parameters are most important for learning about galaxy assembly?*

Measuring the normalization, slope, and **scatter** for **multiple** elements and secondary parameter relations provides the most comprehensive view.

What we need moving forward

1. Photoionization model method(s) we trust
2. Large galaxy samples across redshift

We can build better models now, using existing facilities

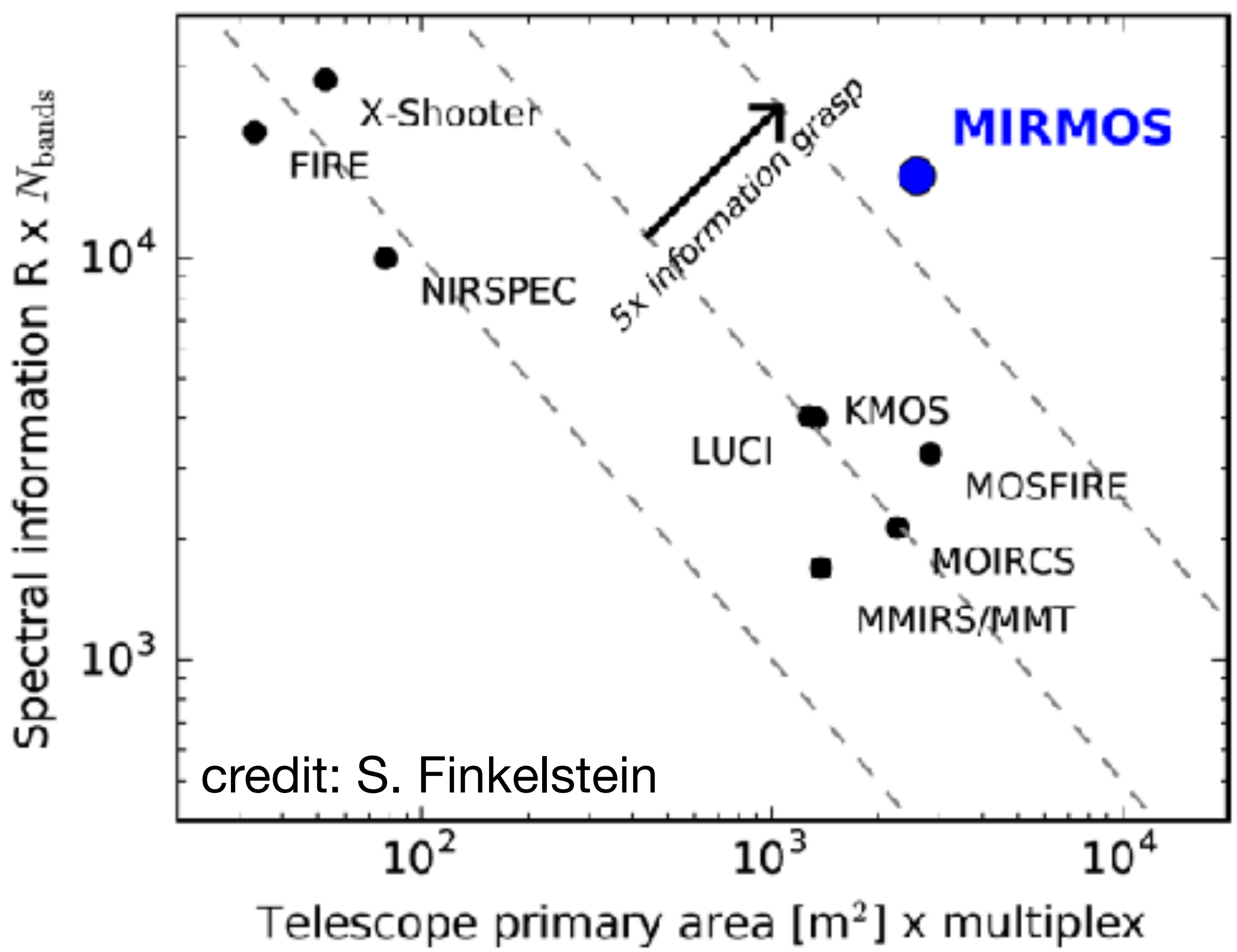


Senchyna et al. (2017)

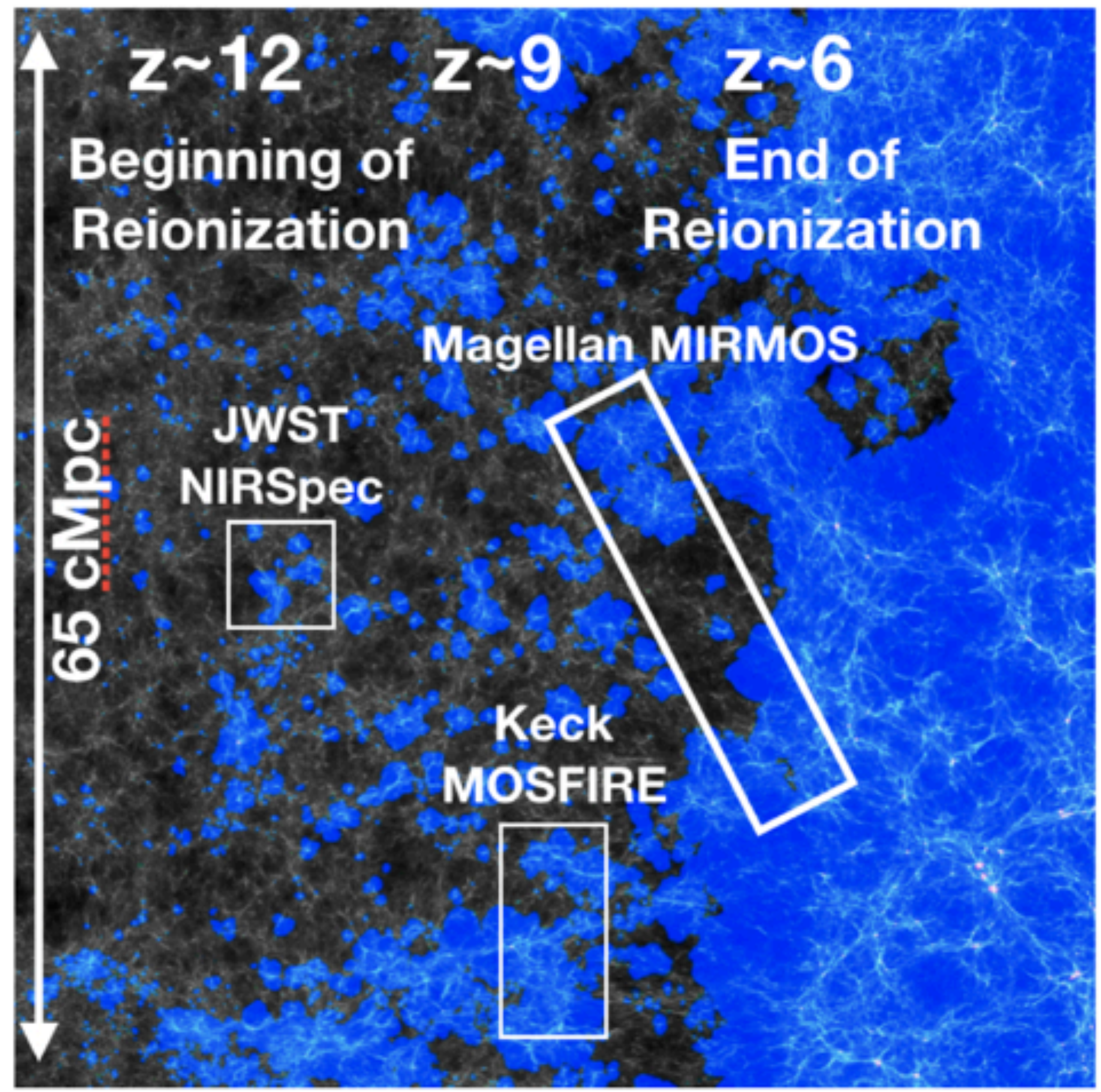
We can use **high-resolution, high-S/N spectra of local analogs** to constrain the ionizing radiation fields of massive stars

Despite past efforts, still work to be done at cosmic "noon"

MIRMOS: proposed NIR MOS+IFU at Magellan that will observe 0.95-2.5 μm simultaneously for 120 objects at a time

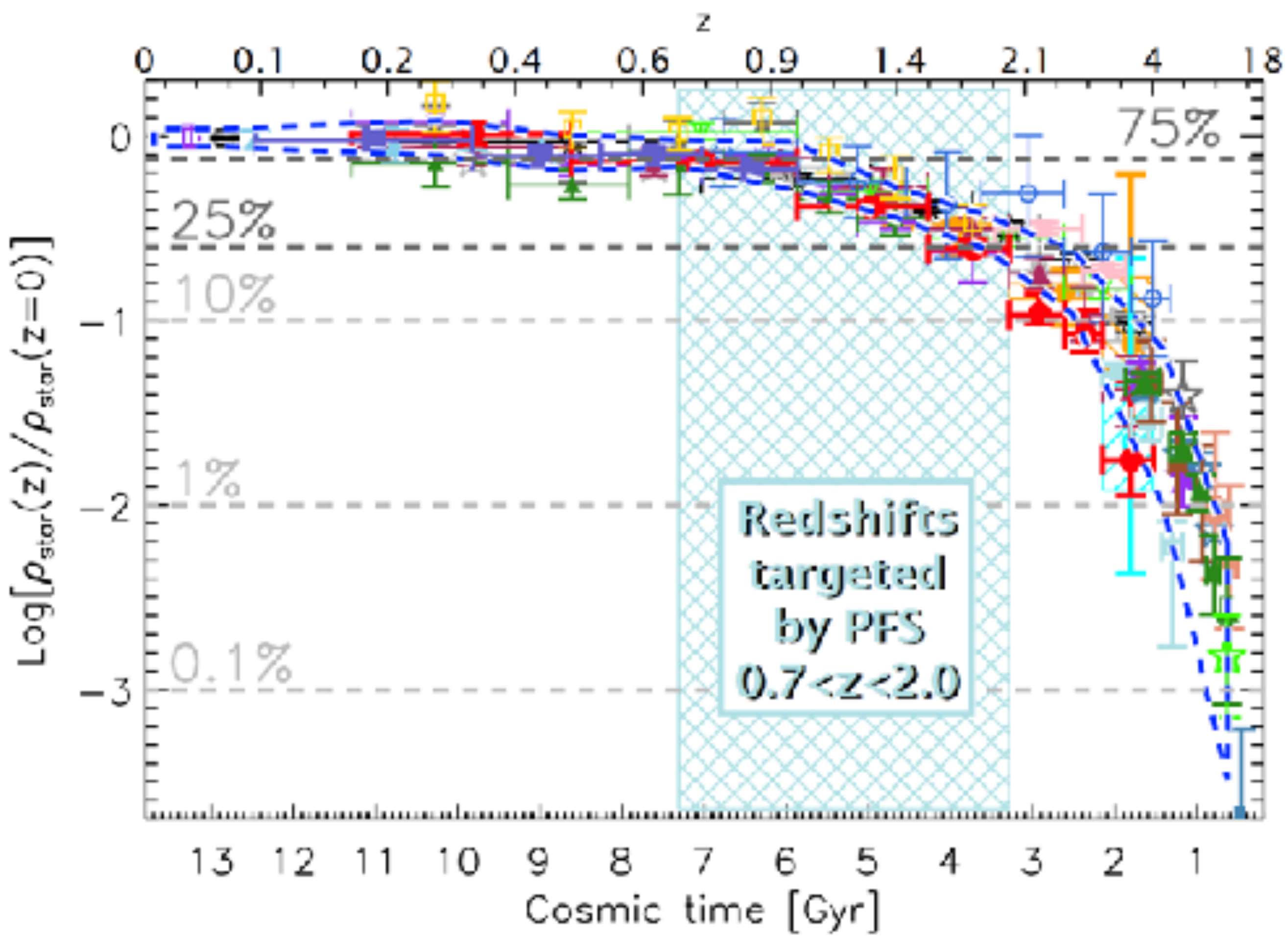


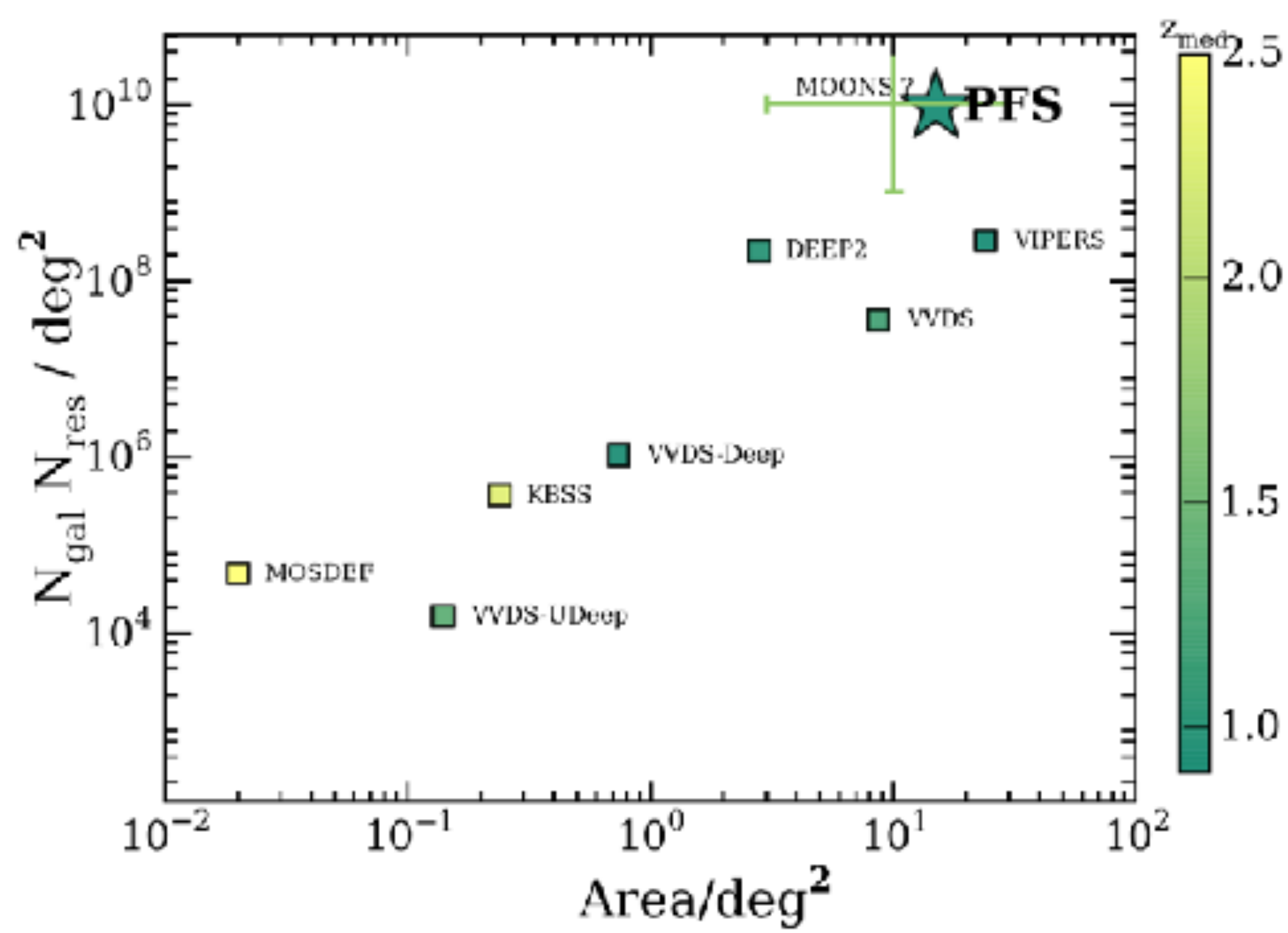
Cosmic Dawn II simulation from Ocvirk et al. (2018)



Subaru/PFS will provide unprecedented view of cosmic "afternoon"

- 2400 fibers across a 1.3 deg diameter field-of-view
- Observed wavelength coverage from 0.38-1.26 μm
- Can observe
  - [SII] up to z~0.8
  - [OIII] up to z~1.5
  - [OII] up to z~2.4

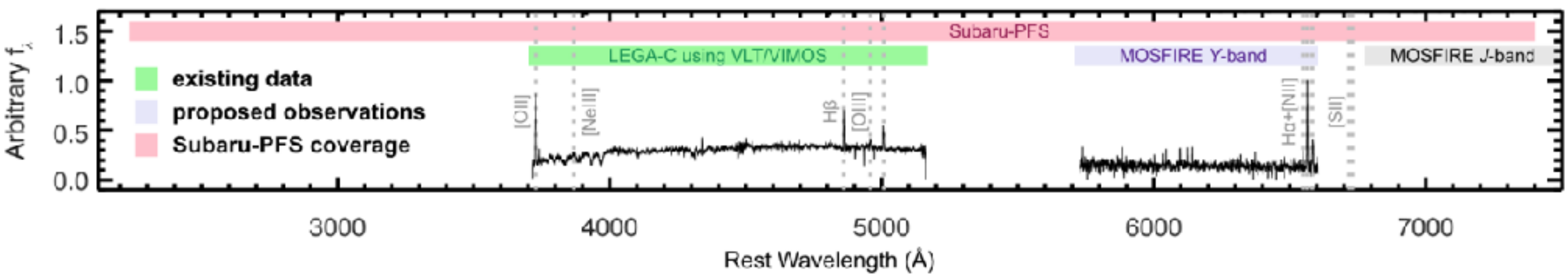


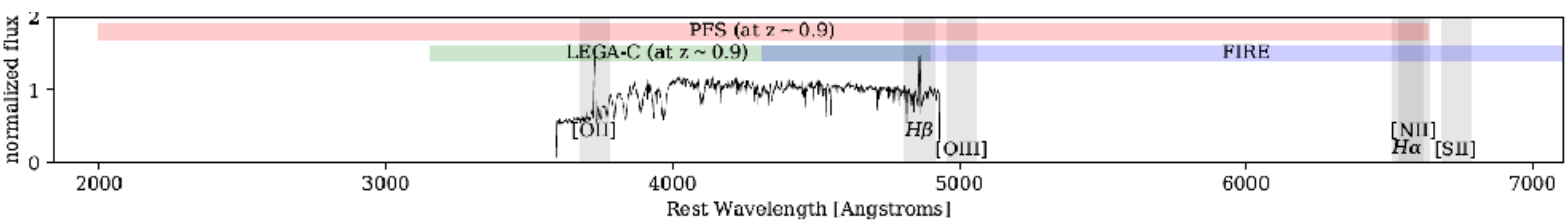


Preparing for Subaru/PFS with z~1 samples

Helton, **Strom** et al. (in prep.)

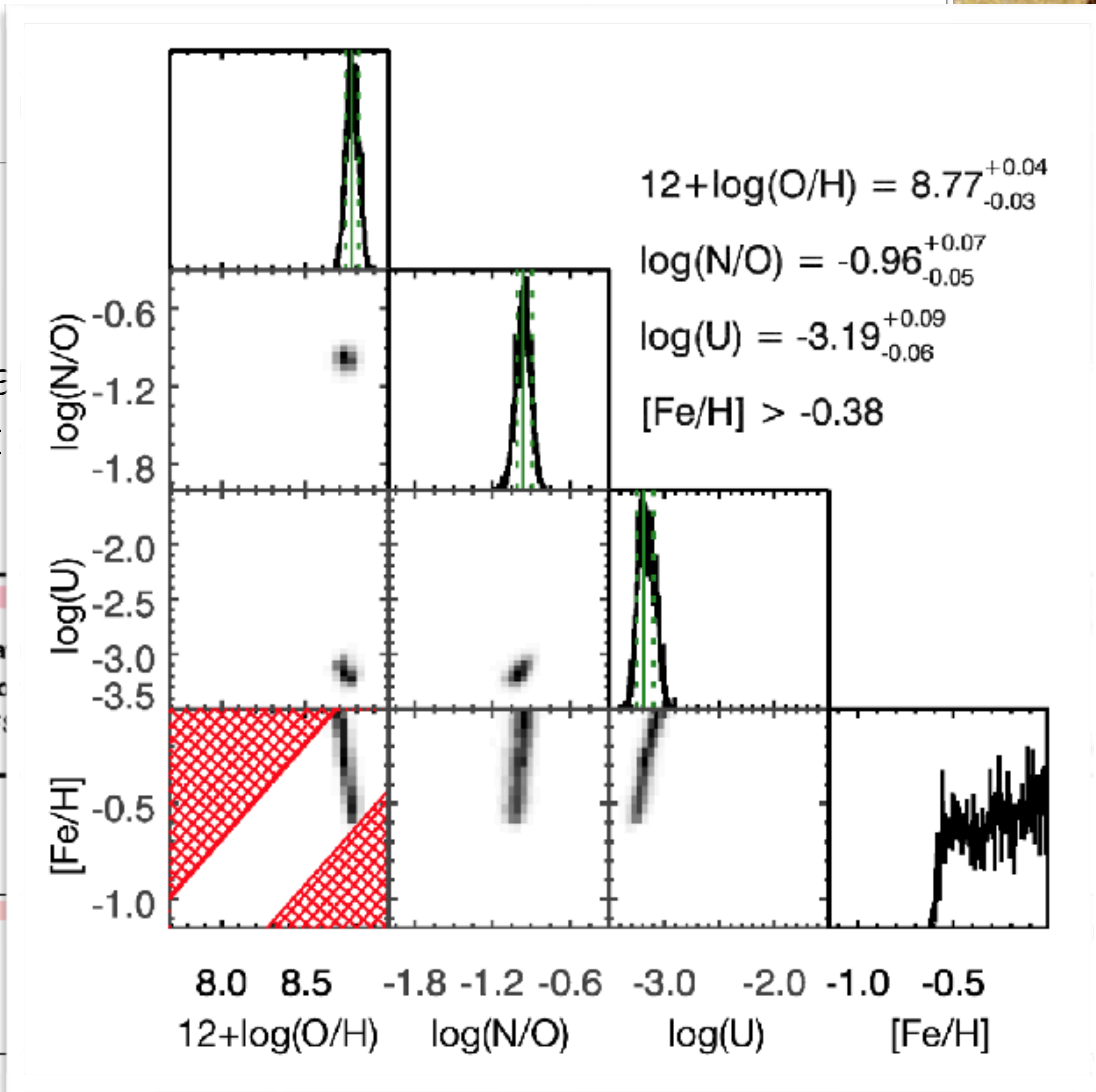
15 galaxies at *z*~0.9 with Keck/MOSFIRE *Y*-band spectra
9 galaxies at *z*~0.7 with Magellan/FIRE spectra



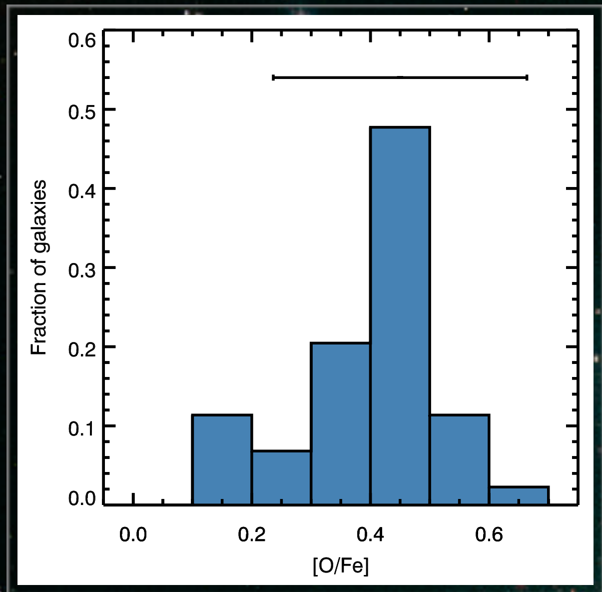


Preparing

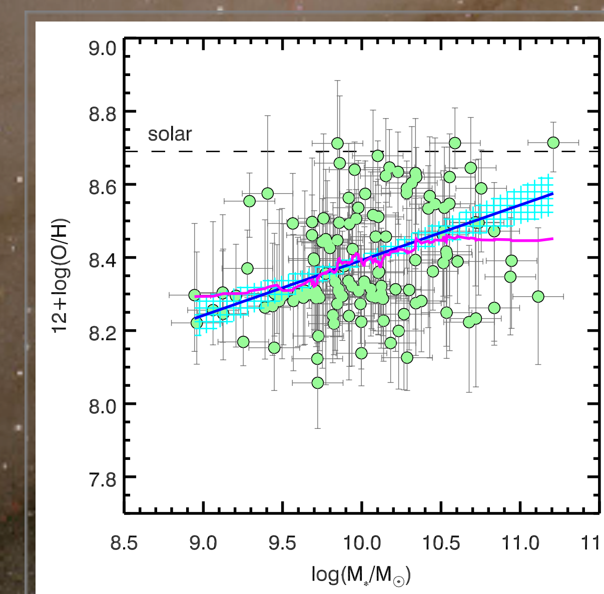
15 galaxies a
9 galaxies at



Credit: A. L. Strom and T. A. Rector



Models designed to jointly reconcile the rest-UV and rest-optical spectra of z~2-3 galaxies reveal **moderate O/H** enrichment, but **low Fe/H**



The same models result in a z~2 M_*-O/H relation that has **more scatter**, **higher normalization** and may be **shallower** relative to strong-line methods

To make progress and prepare for future datasets, we need to: account for **degeneracies between parameters**, devise **better massive star models**, address **abundance scale discrepancies**