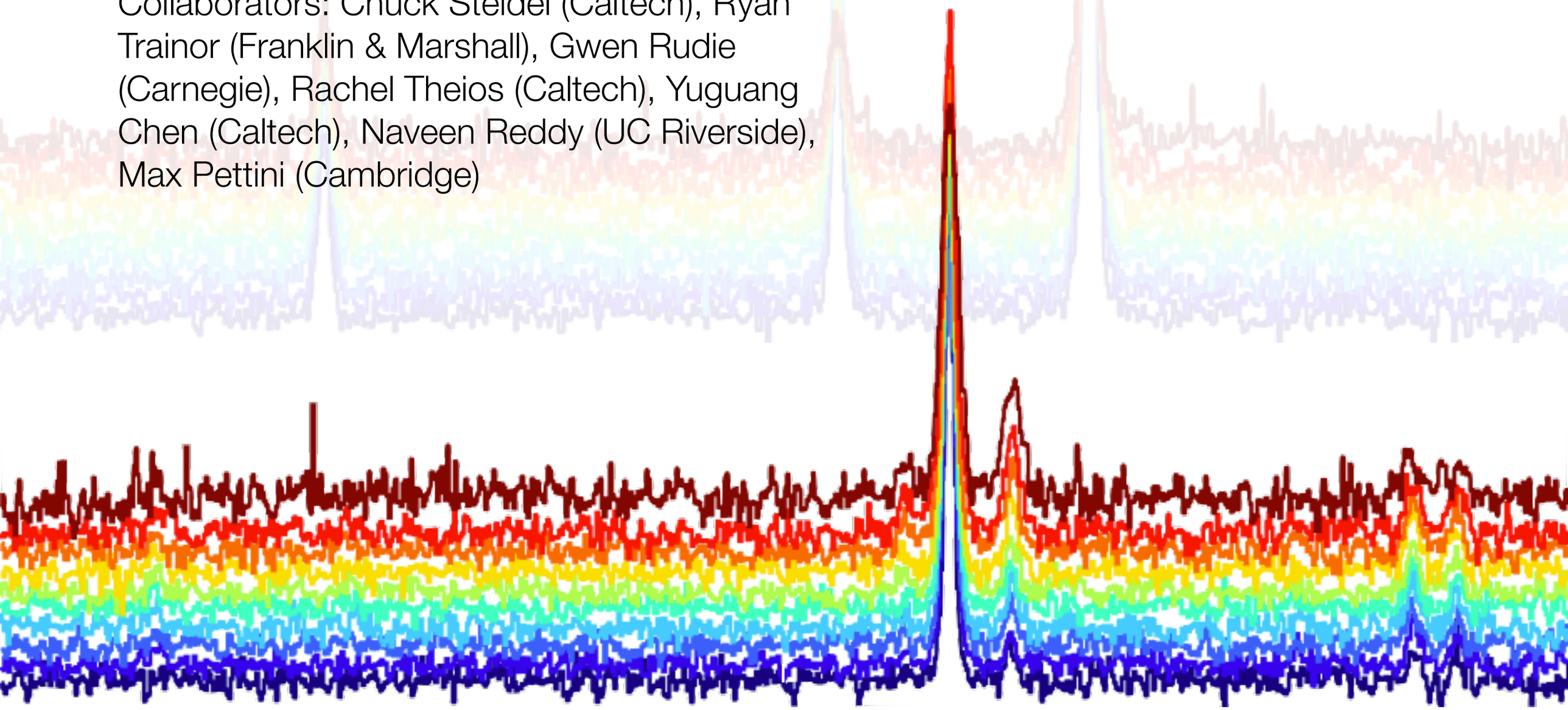
The Keck Baryonic Structure Survey

what we learn by combining the rest-UV and rest-optical spectra of high-redshift star-forming galaxies

Allison Strom (Carnegie)

Collaborators: Chuck Steidel (Caltech), Ryan Trainor (Franklin & Marshall), Gwen Rudie (Carnegie), Rachel Theios (Caltech), Yuguang Chen (Caltech), Naveen Reddy (UC Riverside), Max Pettini (Cambridge)



Credit: T. A. Rector

Massive stars are one of the central engines of the baryon cycle

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massive stars

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Massive stars are one of the central engines of the baryon cycle

ionized gas

massive stars

ionized gas

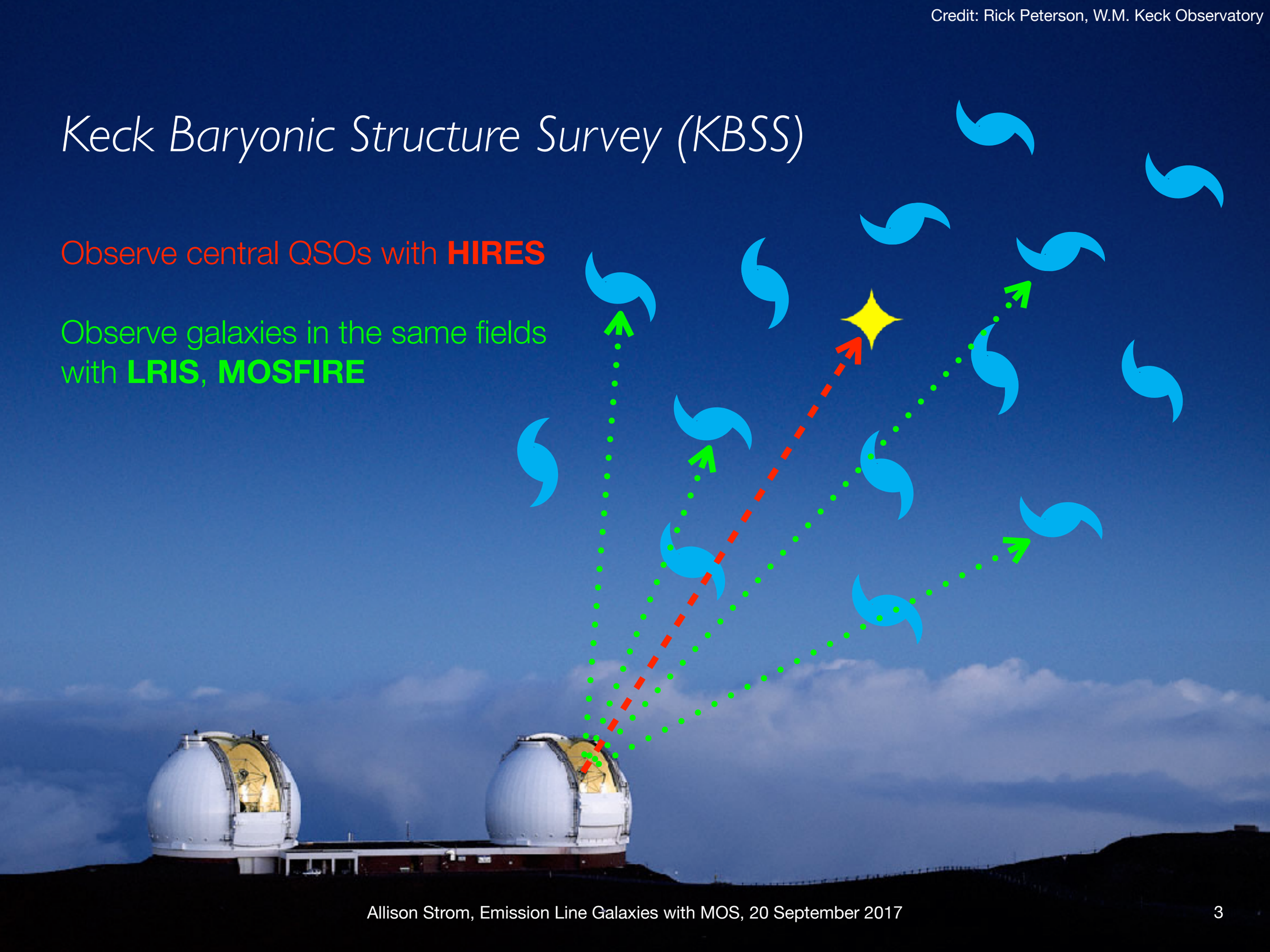
ionized gas

Credit: Rick Peterson, W.M. Keck Observatory

Keck Baryonic Structure Survey (KBSS)

Observe central QSOs with **HIRES**

Observe galaxies in the same fields with **LRIS**, **MOSFIRE**



Keck Baryonic Structure Survey (KBSS)

15 separate survey fields, with a total area = 0.24 deg^2

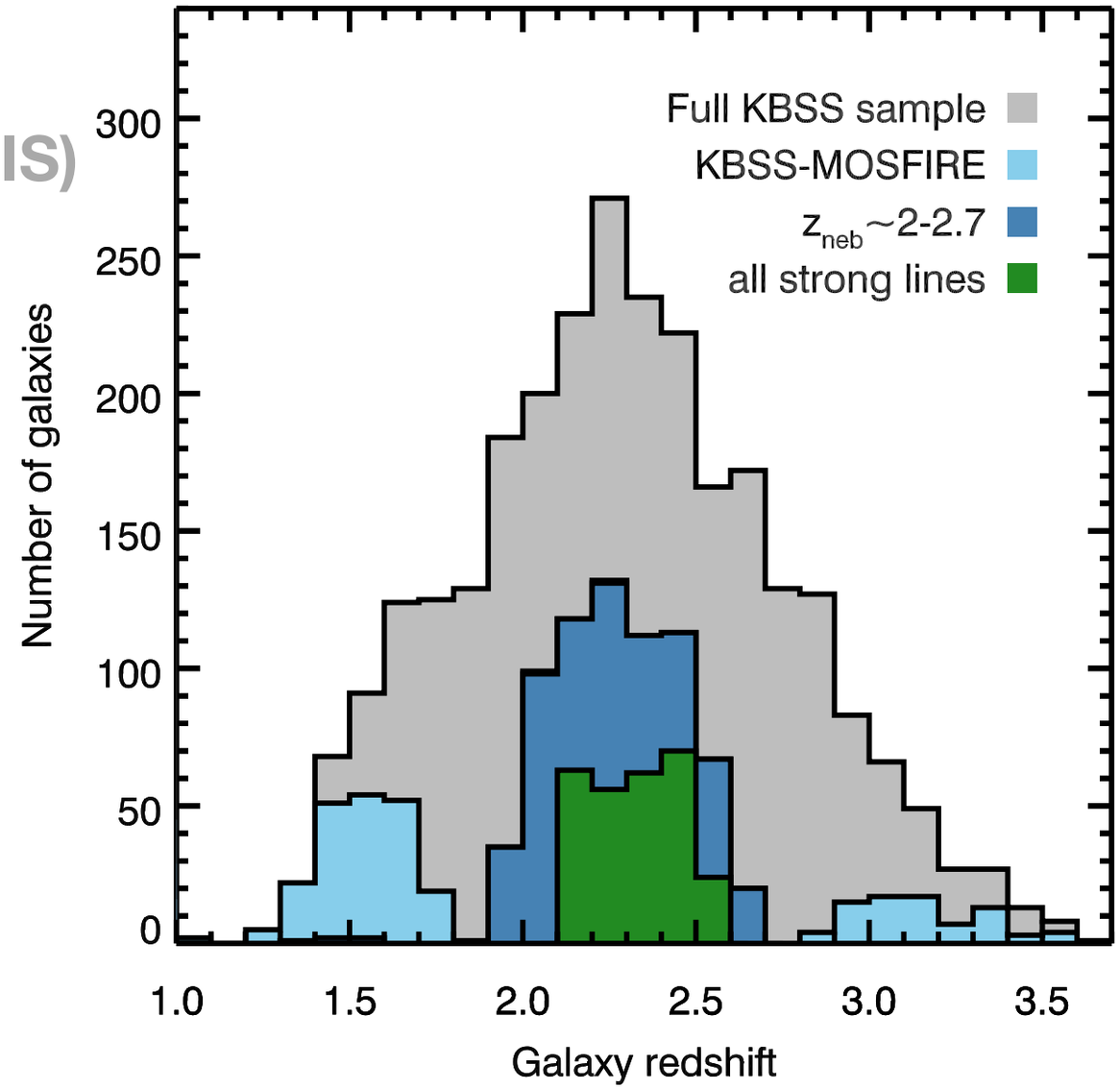
Spectroscopic observations:

- **~2700 with rest-UV spectra (LRIS)**
- **~1300 with rest-optical spectra**

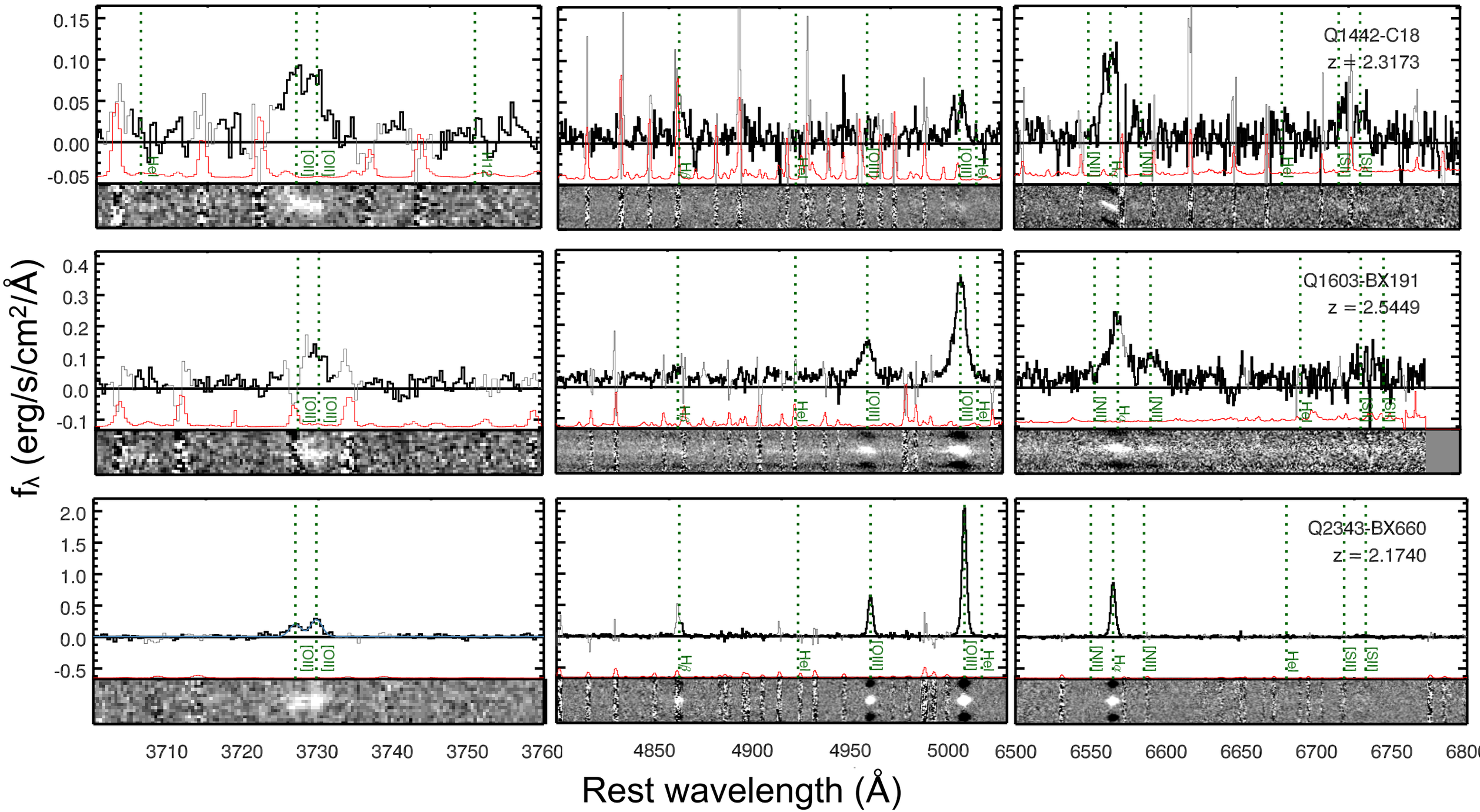
  61 nights with MOSFIRE since commissioning in June 2012

>700 galaxies with z≈2-2.7 have at least one MOSFIRE spectrum

~300 galaxies with good detections of many of the strong diagnostic emission lines in J, H, and K



KBSS galaxies exhibit striking variation in nebular properties



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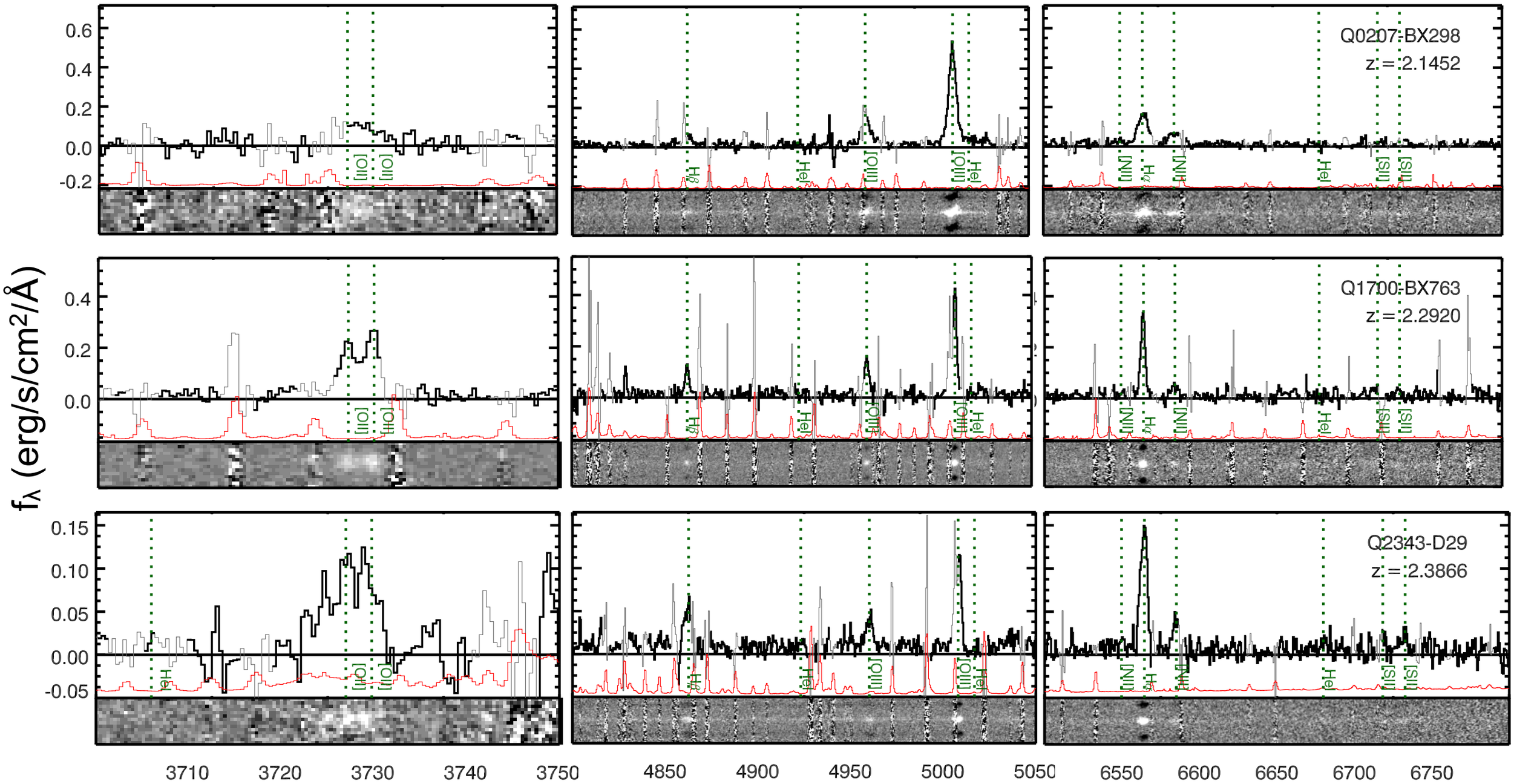
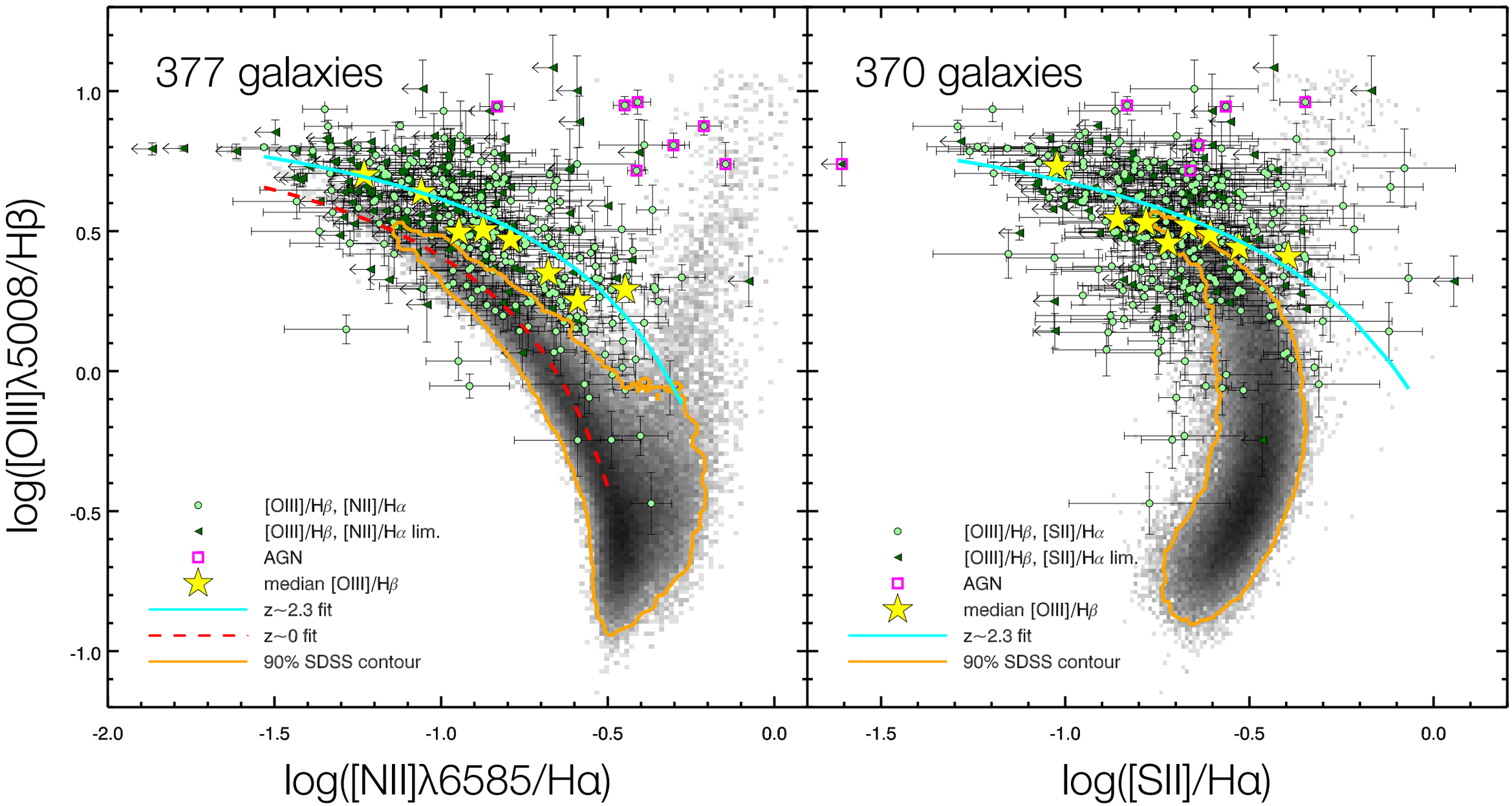


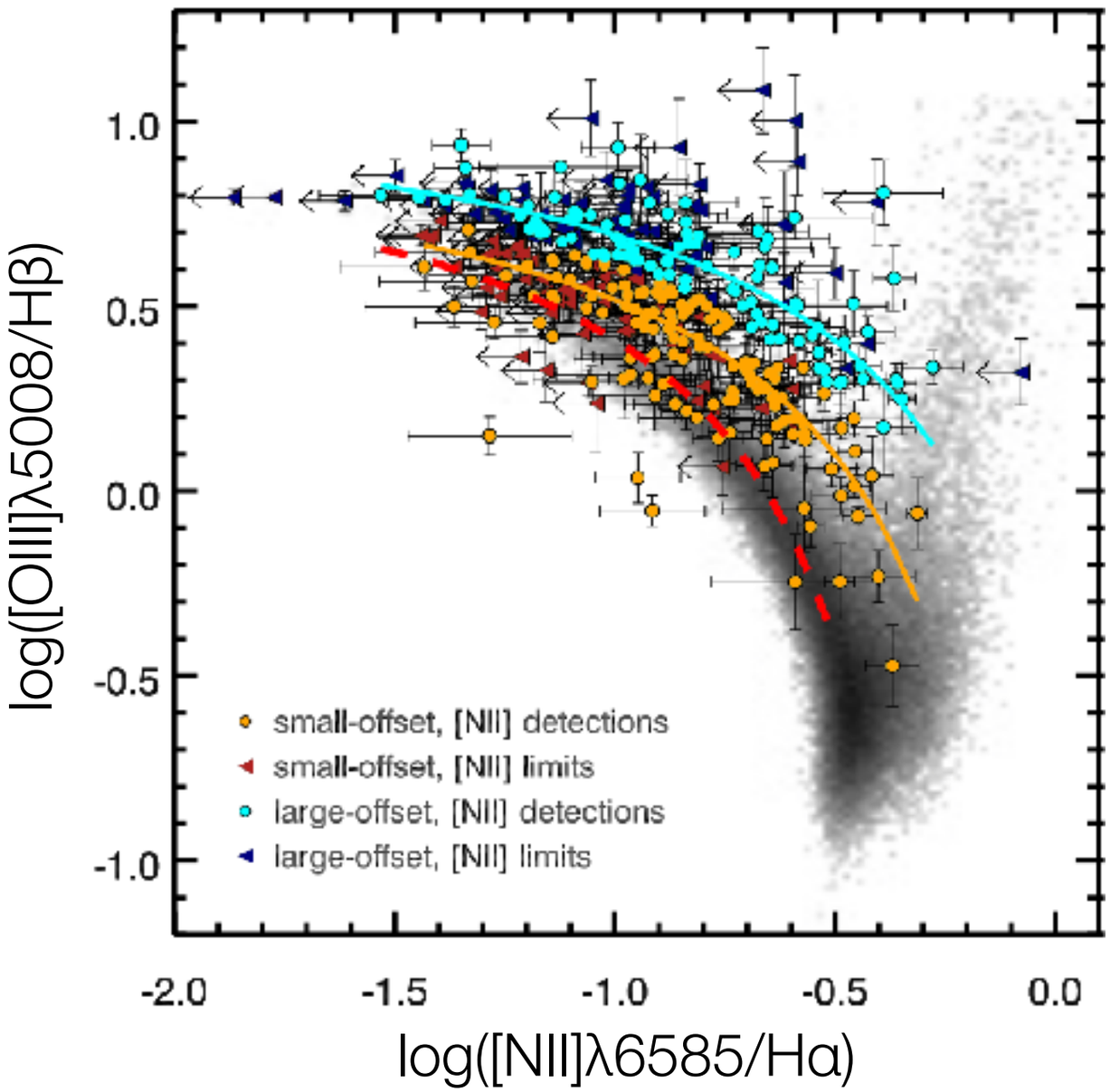
KBSS galaxies in the N2-BPT and S2-BPT diagrams

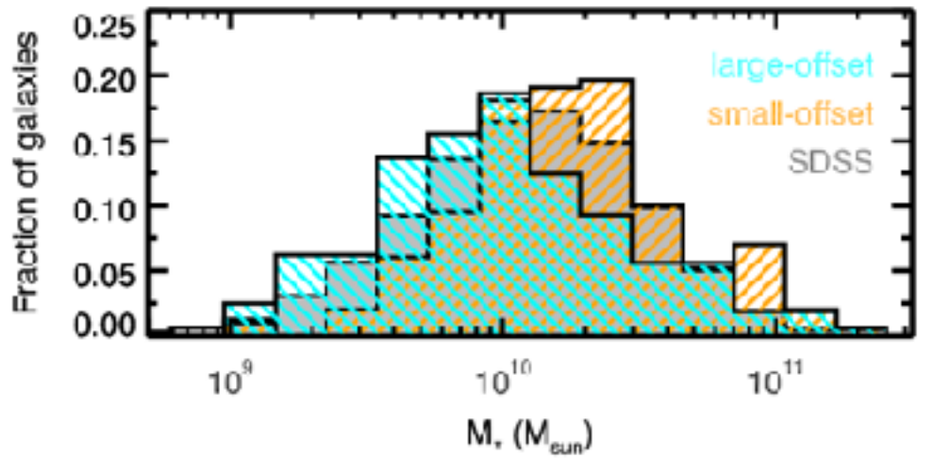
Strom et al. (2017)

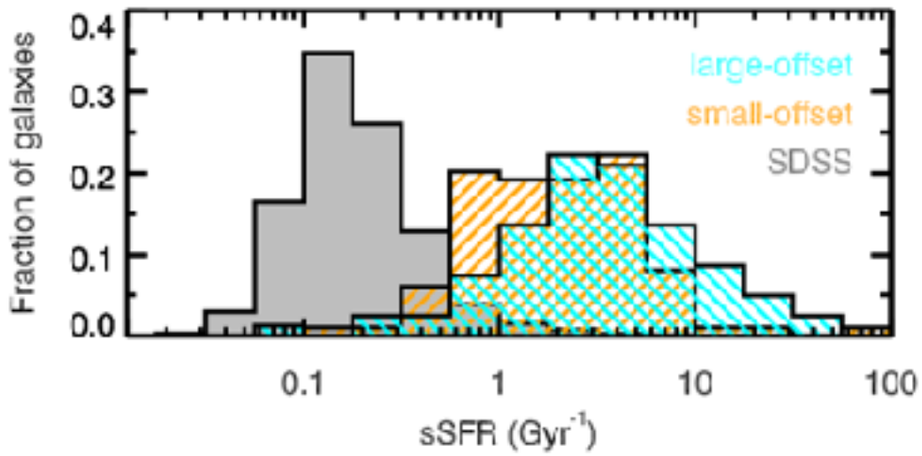


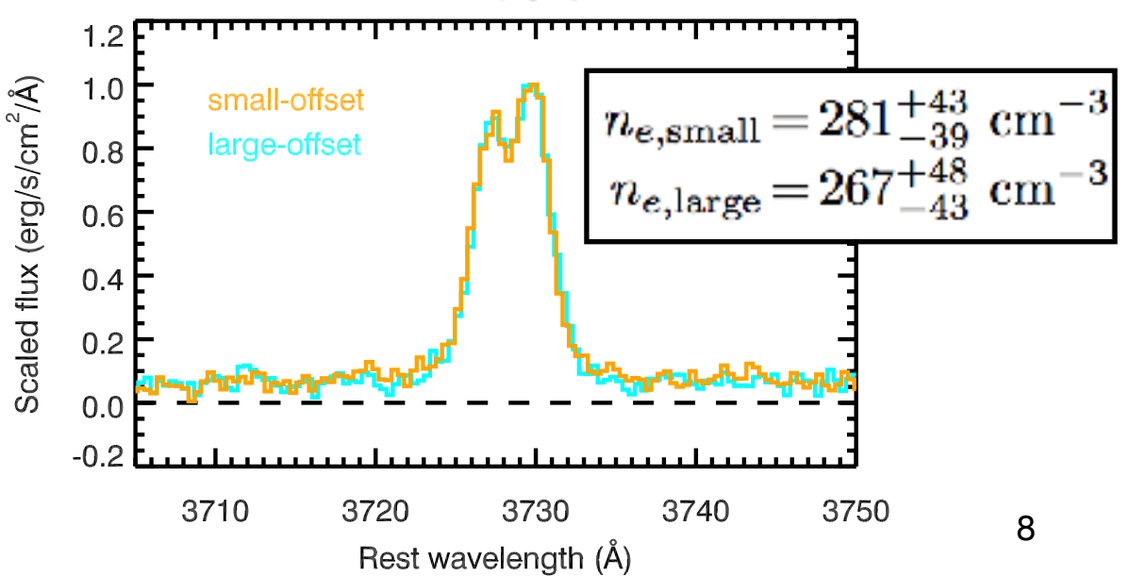
High-z trends differ from those observed in SDSS galaxies

Strom et al. (2017)





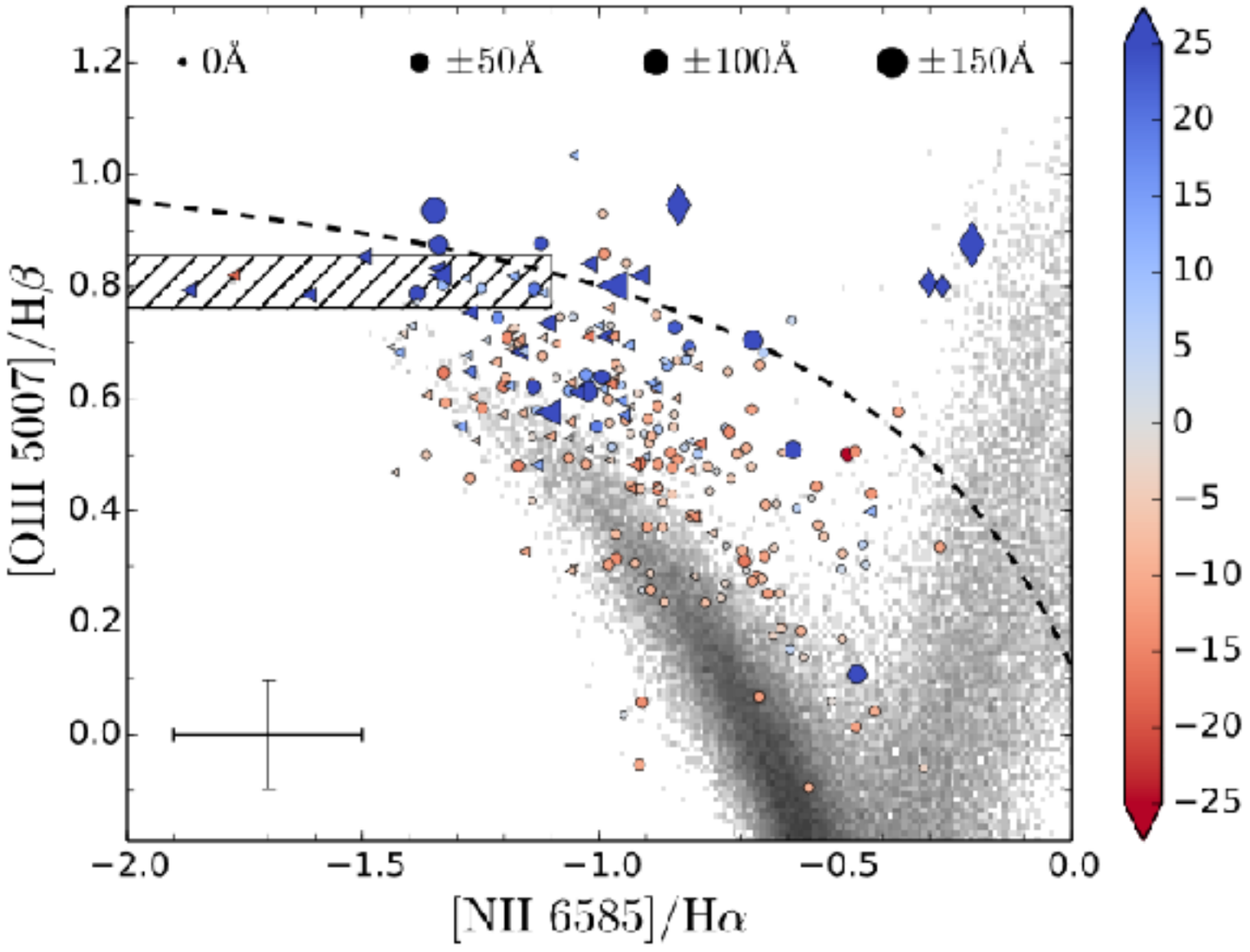




Lyman-α-selected galaxies in KBSS

FRANKLIN & MARSHALL COLLEGE

Trainor, ALS, et al. (2016)



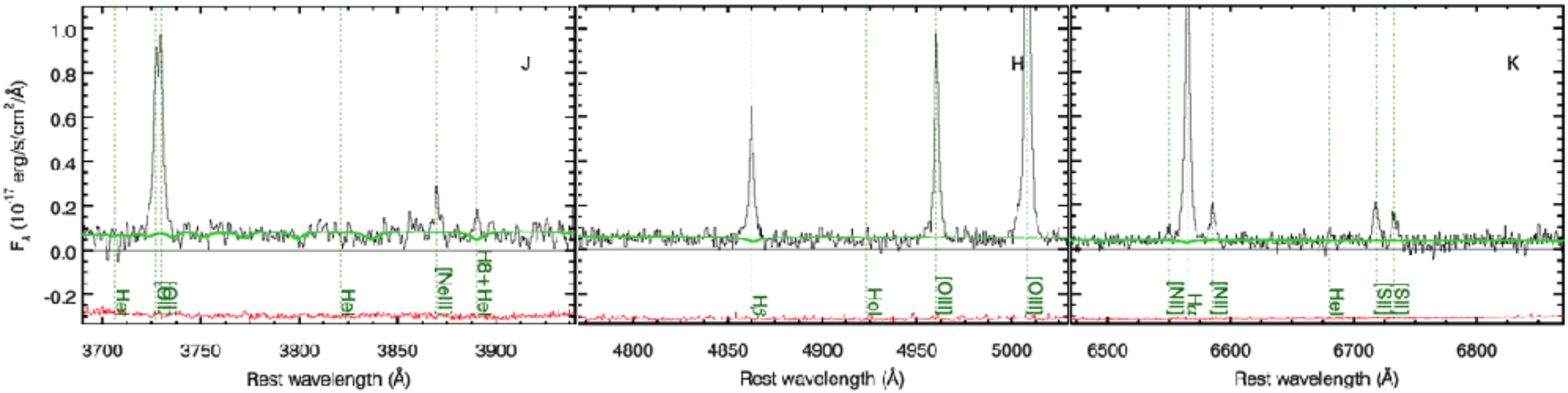
EW(Lyα) depends strongly on ionization/excitation properties

Average faint galaxies consistent with highest-ionization LBGs (see also Erb+2015)

See also Nakajima+2013, 2016; Kojima+17 (but note difference in M_{UV})

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

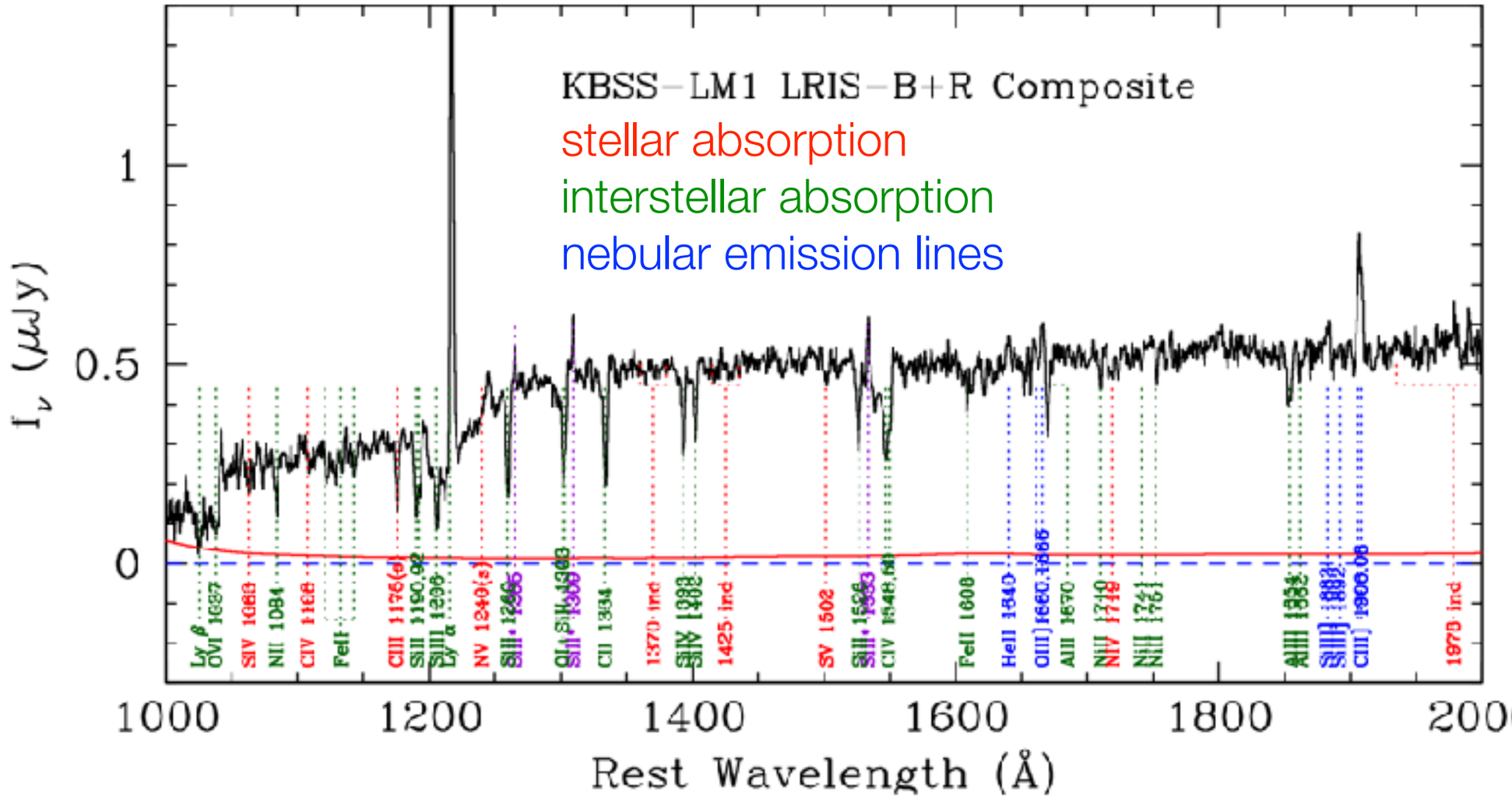
Steidel, **Strom**, et al. (2016)



Totals

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

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

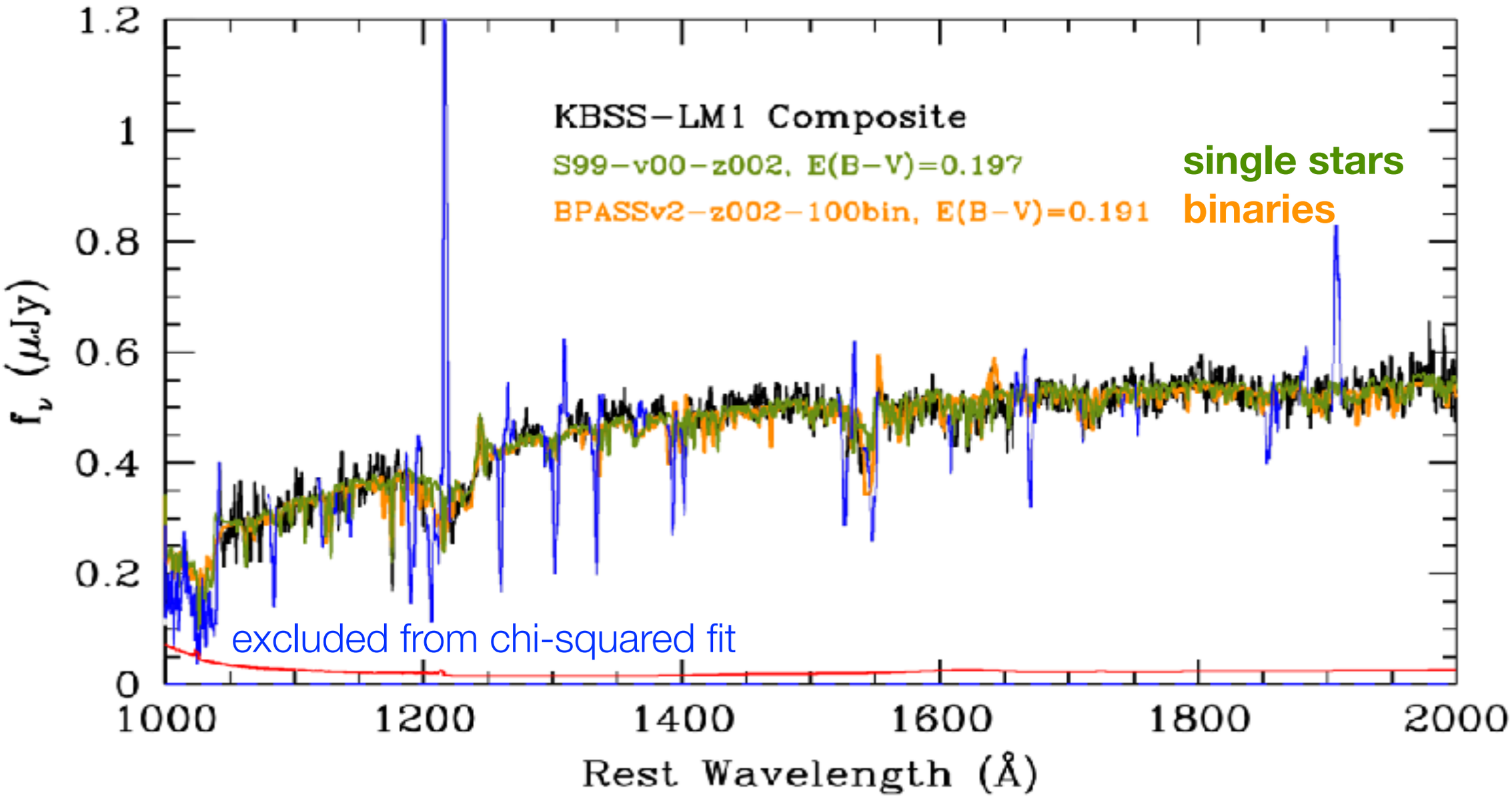


Basic Premise

Since the same stars are responsible for ***both*** *the rest-UV and rest-optical spectra we observe, any physical models(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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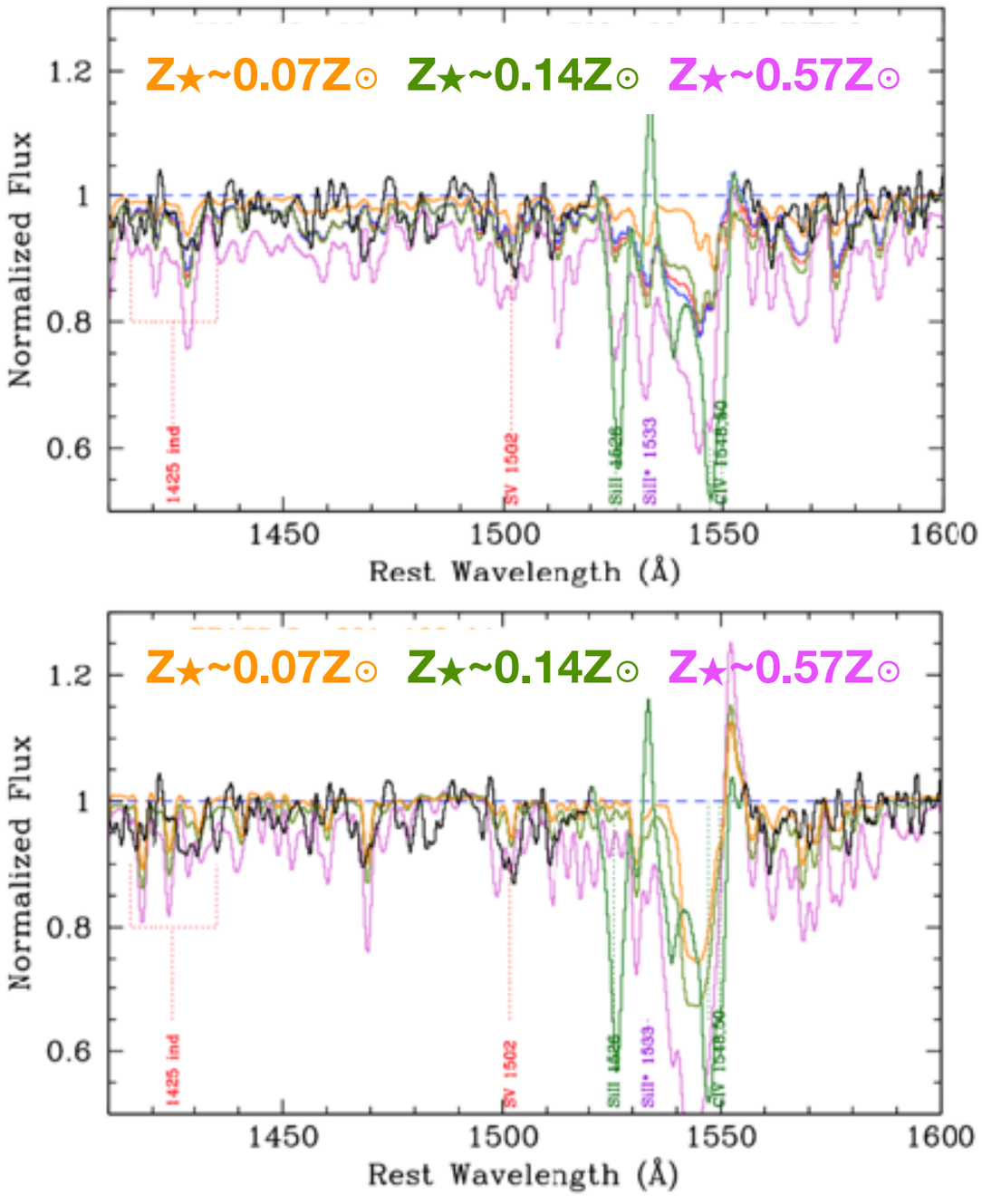
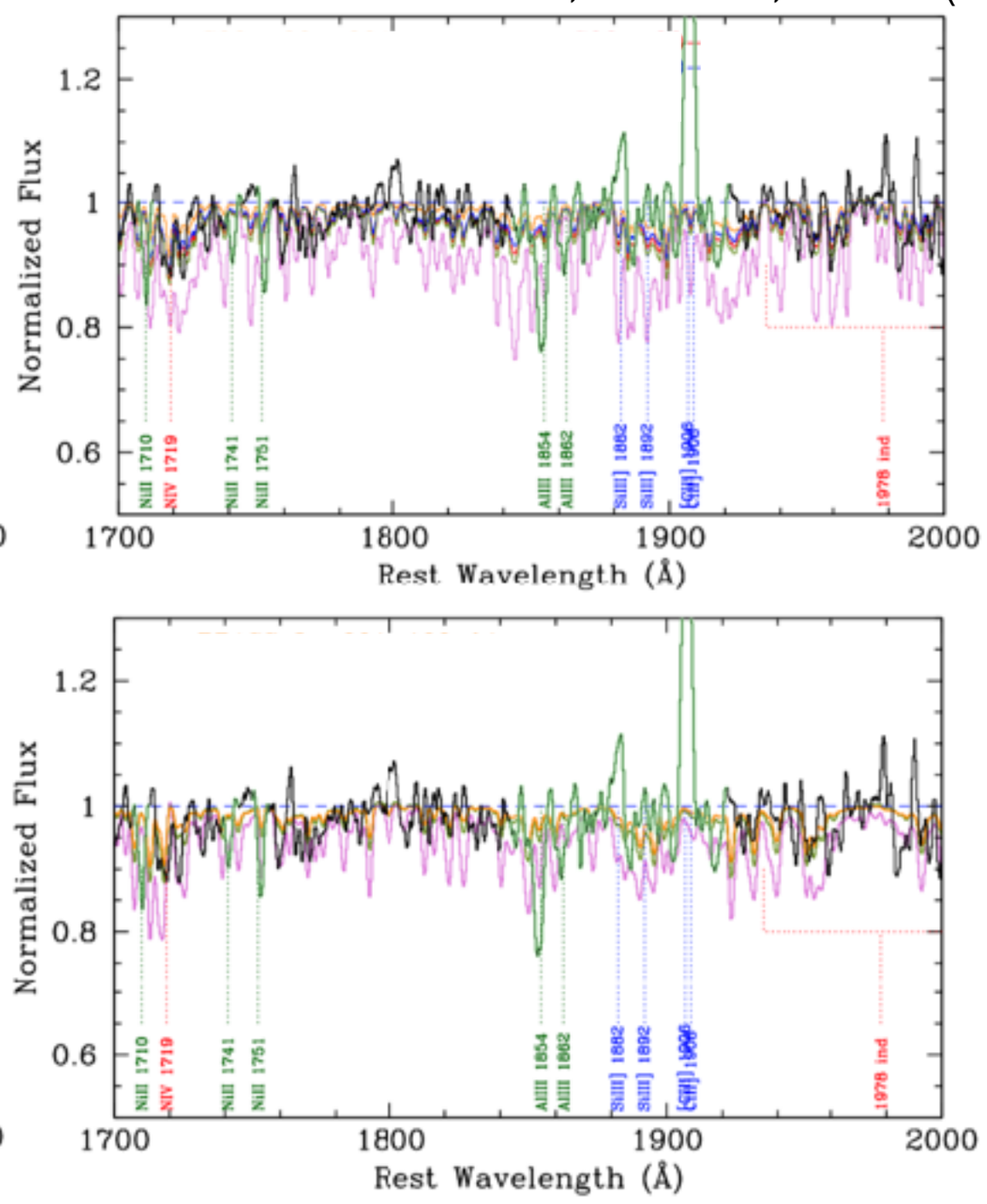
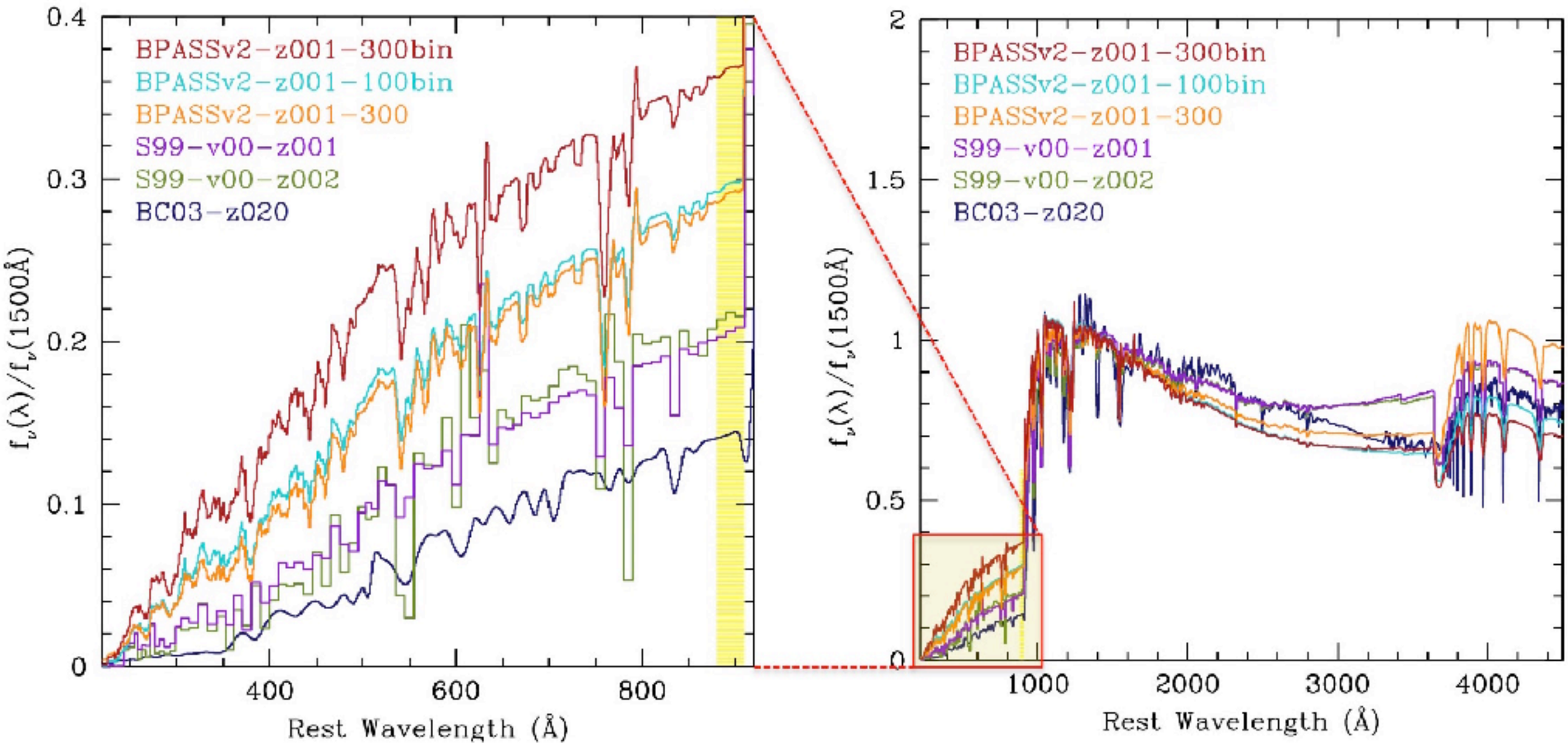




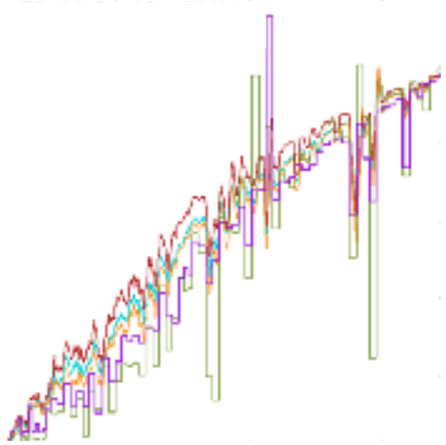
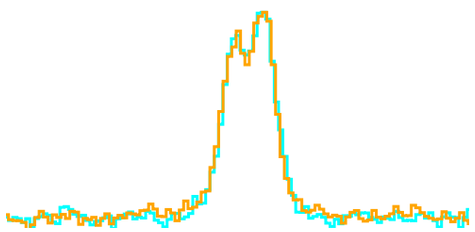
single stars
Starburst99

binaries
BPASSv2

The predicted EUV radiation varies substantially between models



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

line ratios
f(U, Z_{neb}) =  +  + ???

shape of EUV
Fe-poor stars

electron density
n_e = 300 cm^{-3}

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

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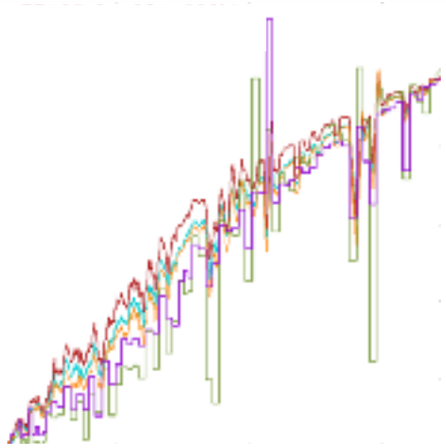
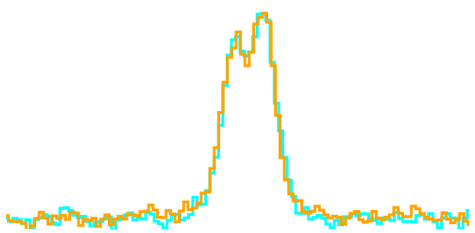
line ratios $f(U, Z_{neb})$ =  +  + ???

shape of EUV
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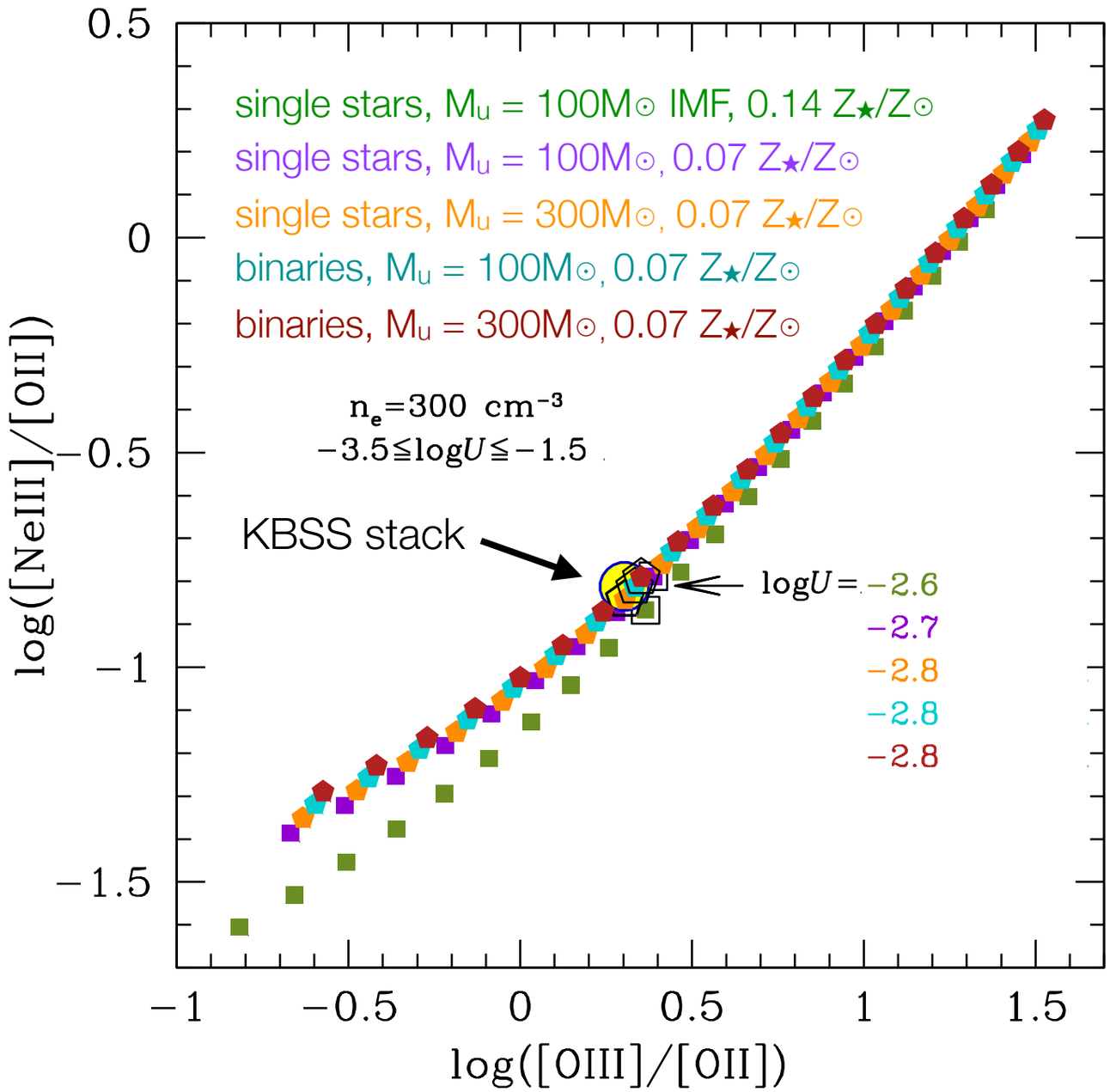
Considerations

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!

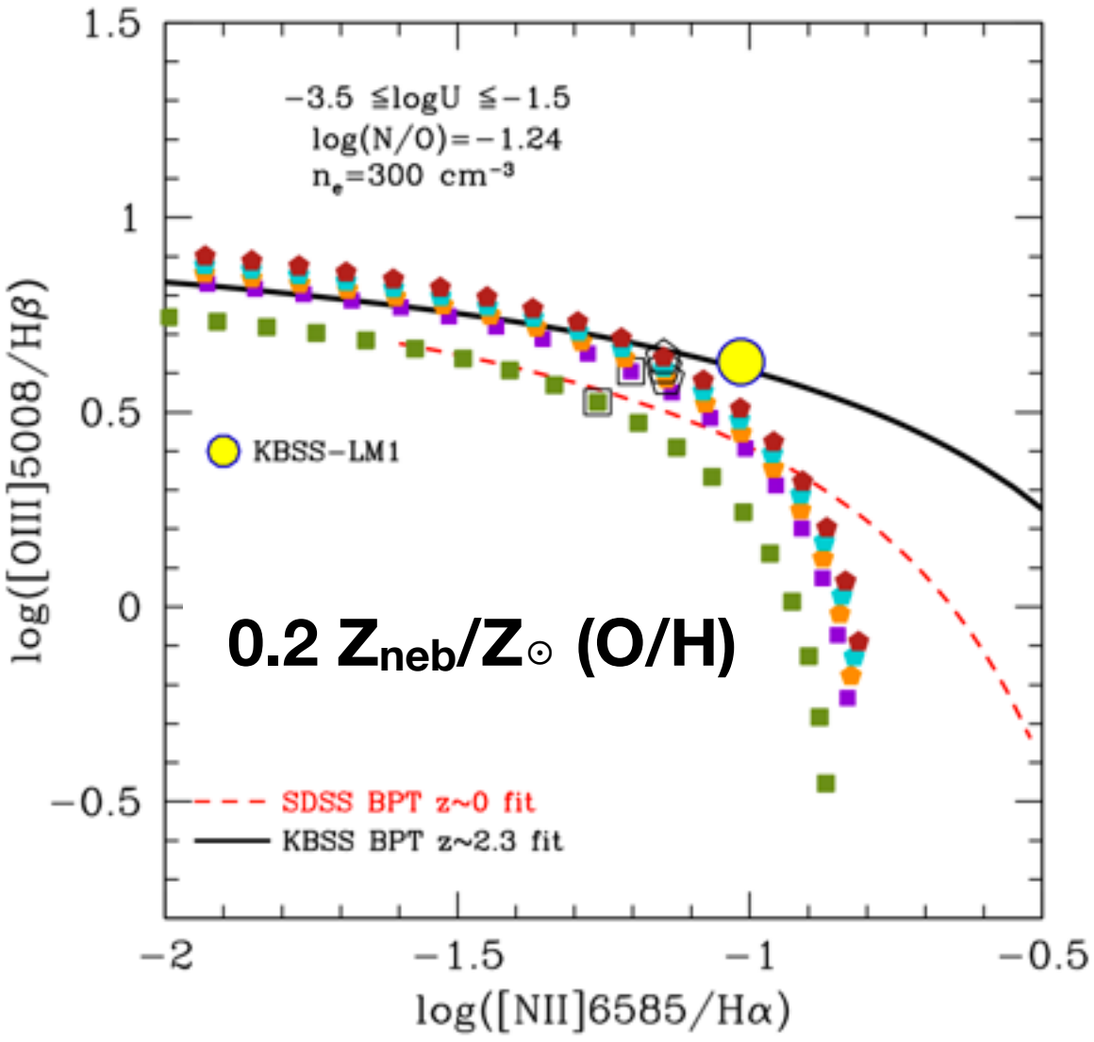
Step one: *set ionization parameter using O32 and Ne3O2*

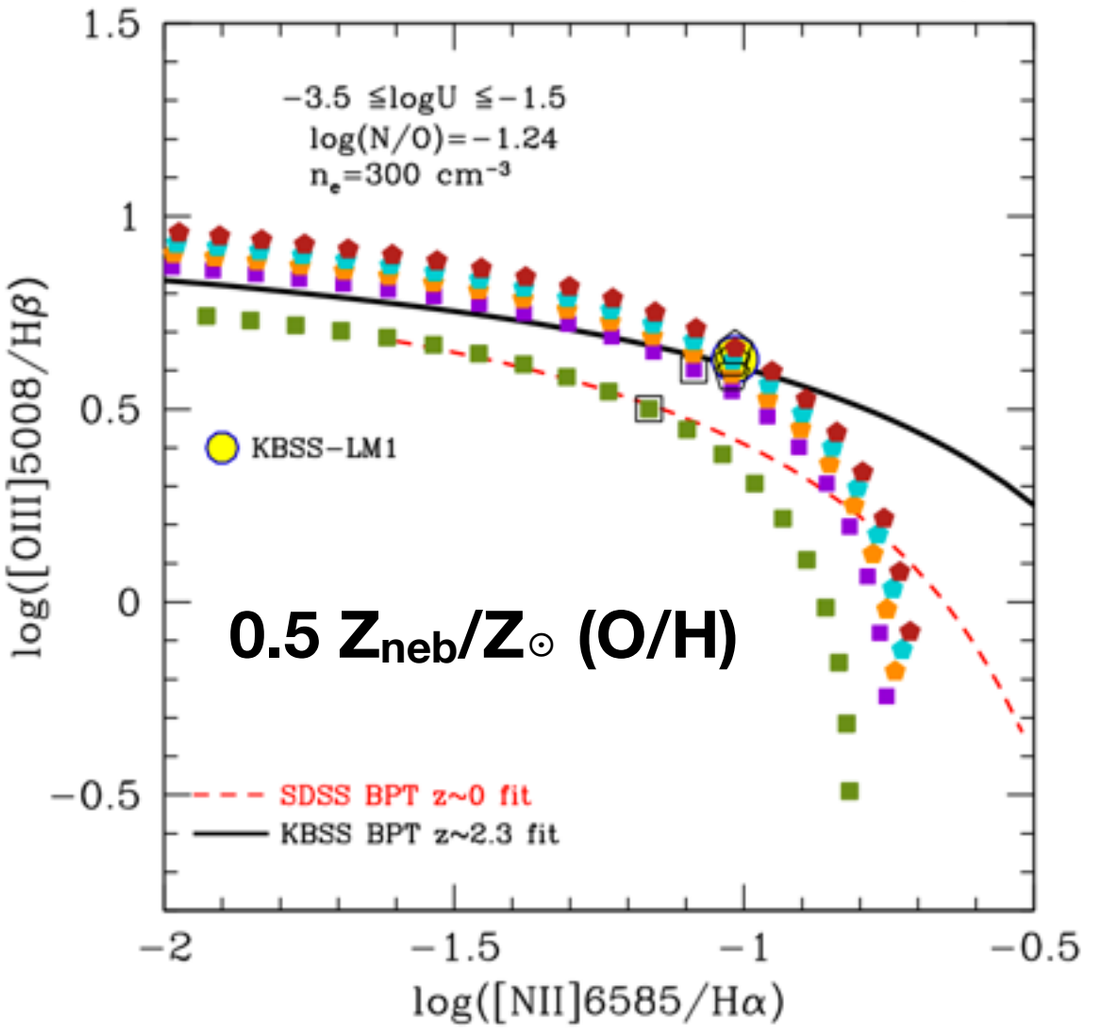
Steidel, **Strom**, et al. (2016)



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

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





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

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

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

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

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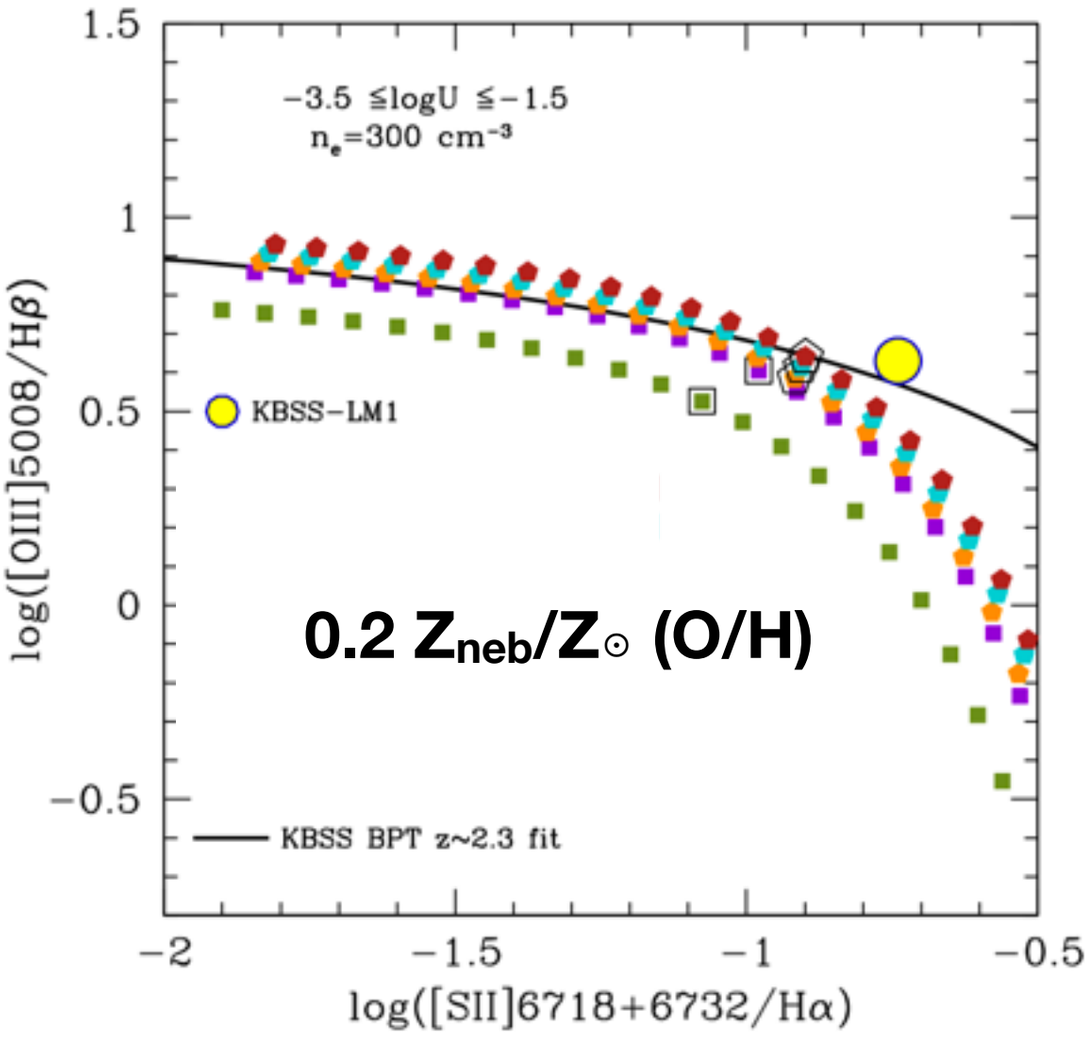

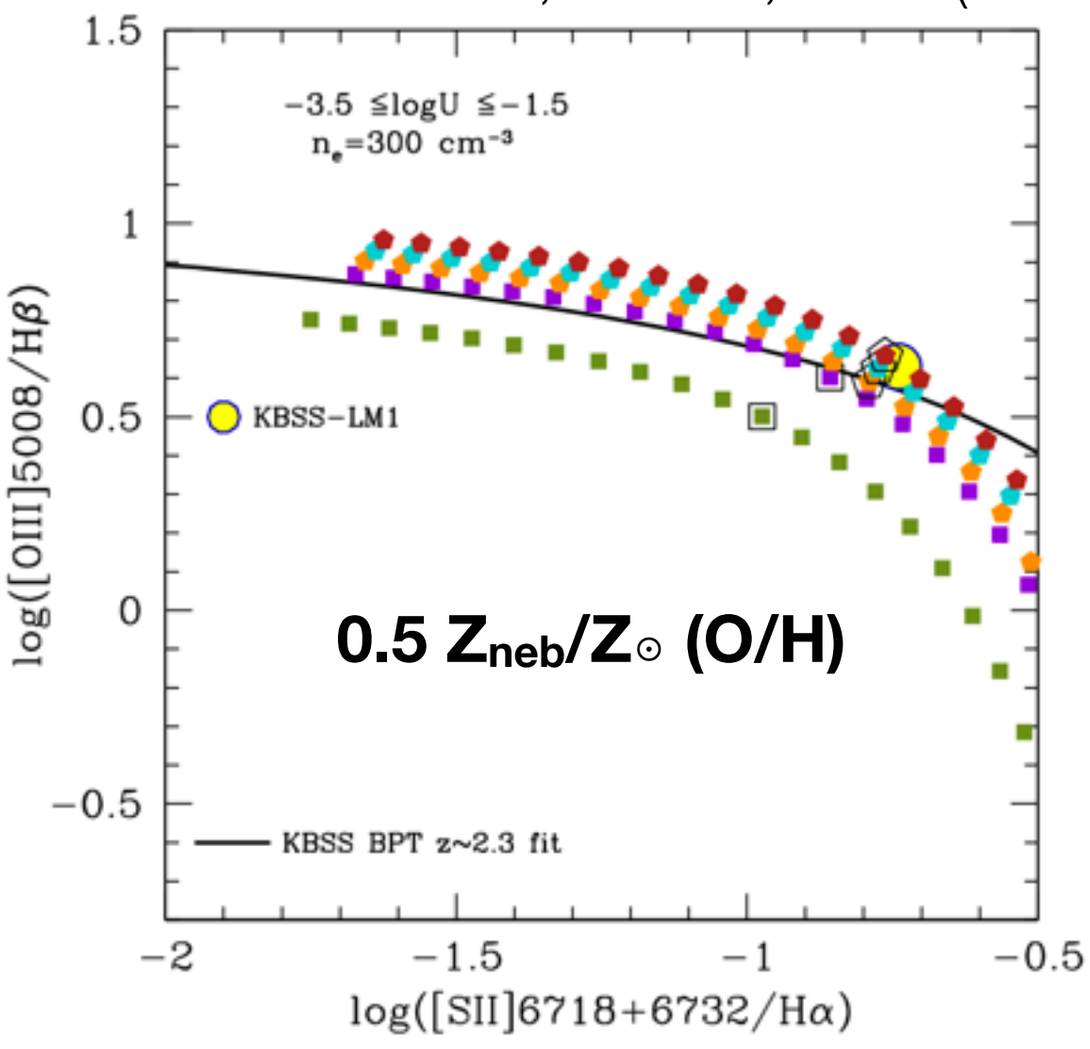

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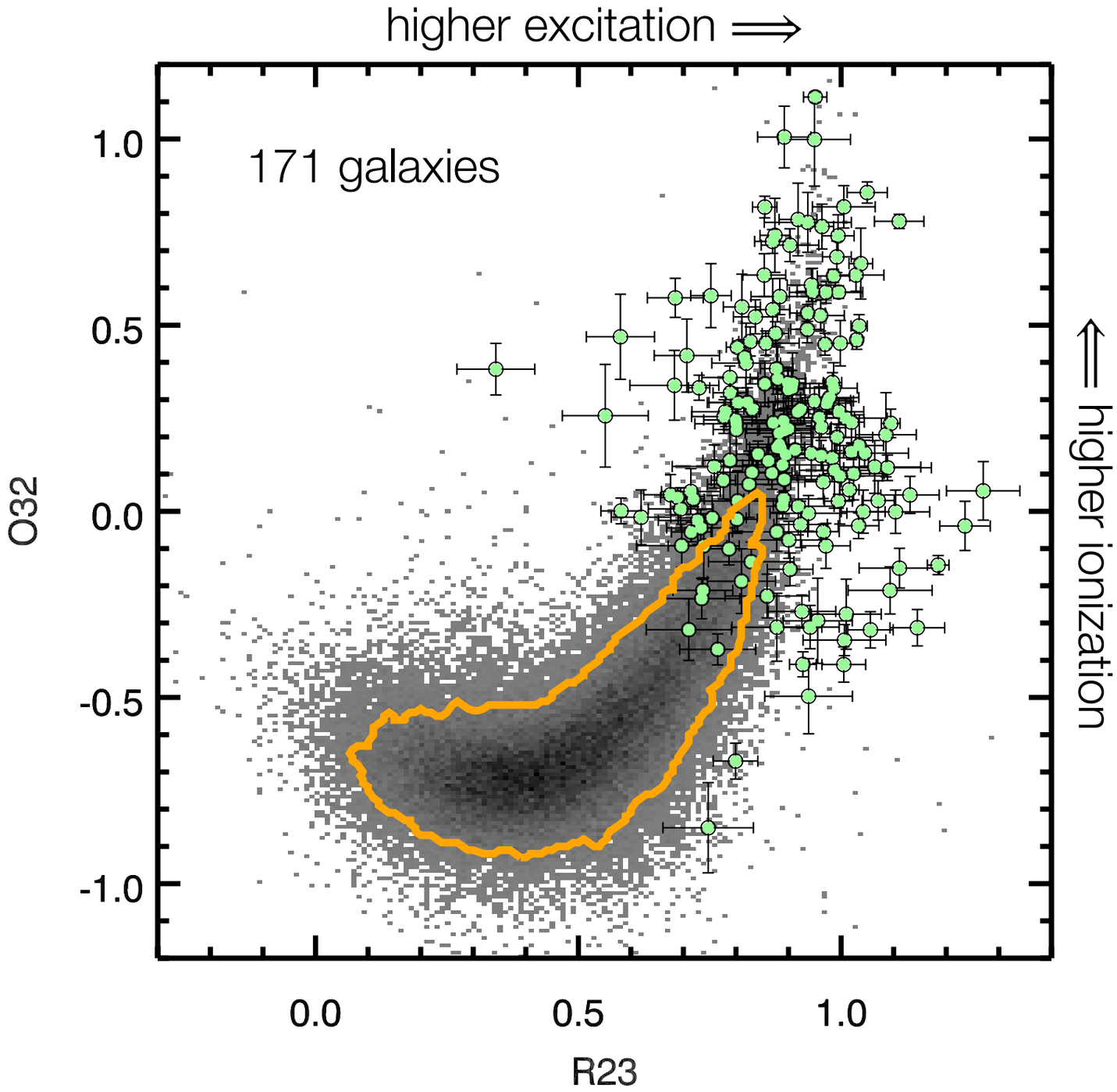
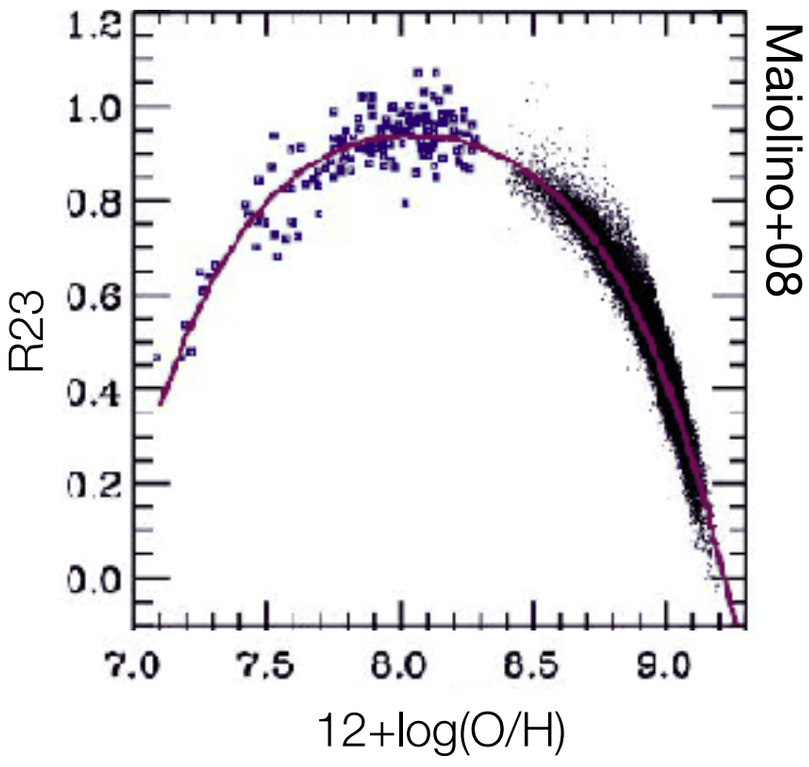
Step three: *constrain shape of ionizing radiation field*



O32 = [OIII]/[OII]
traces ionization state

R23 = ([OIII]+[OII])/Hβ
used to estimate oxygen abundance



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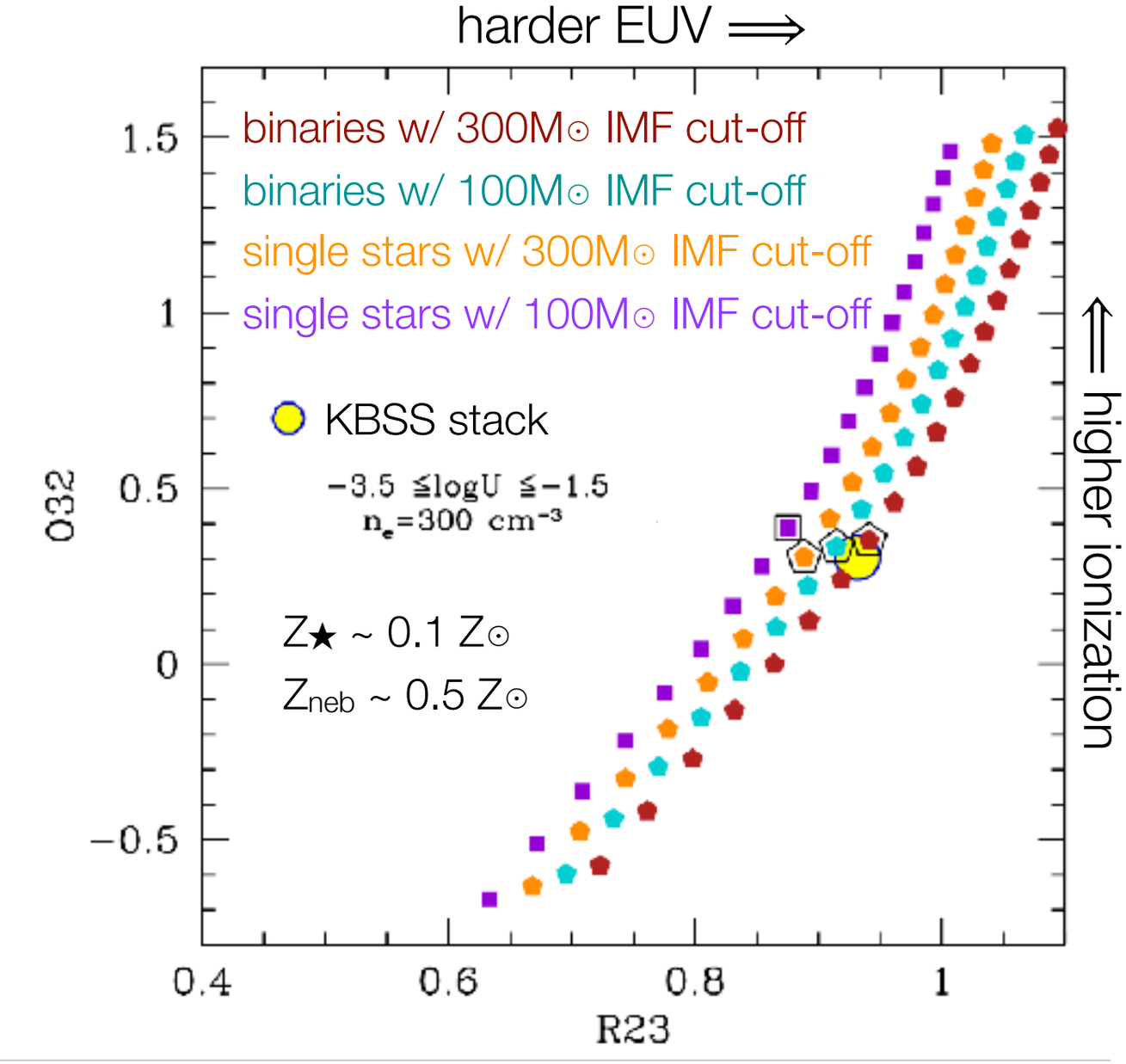

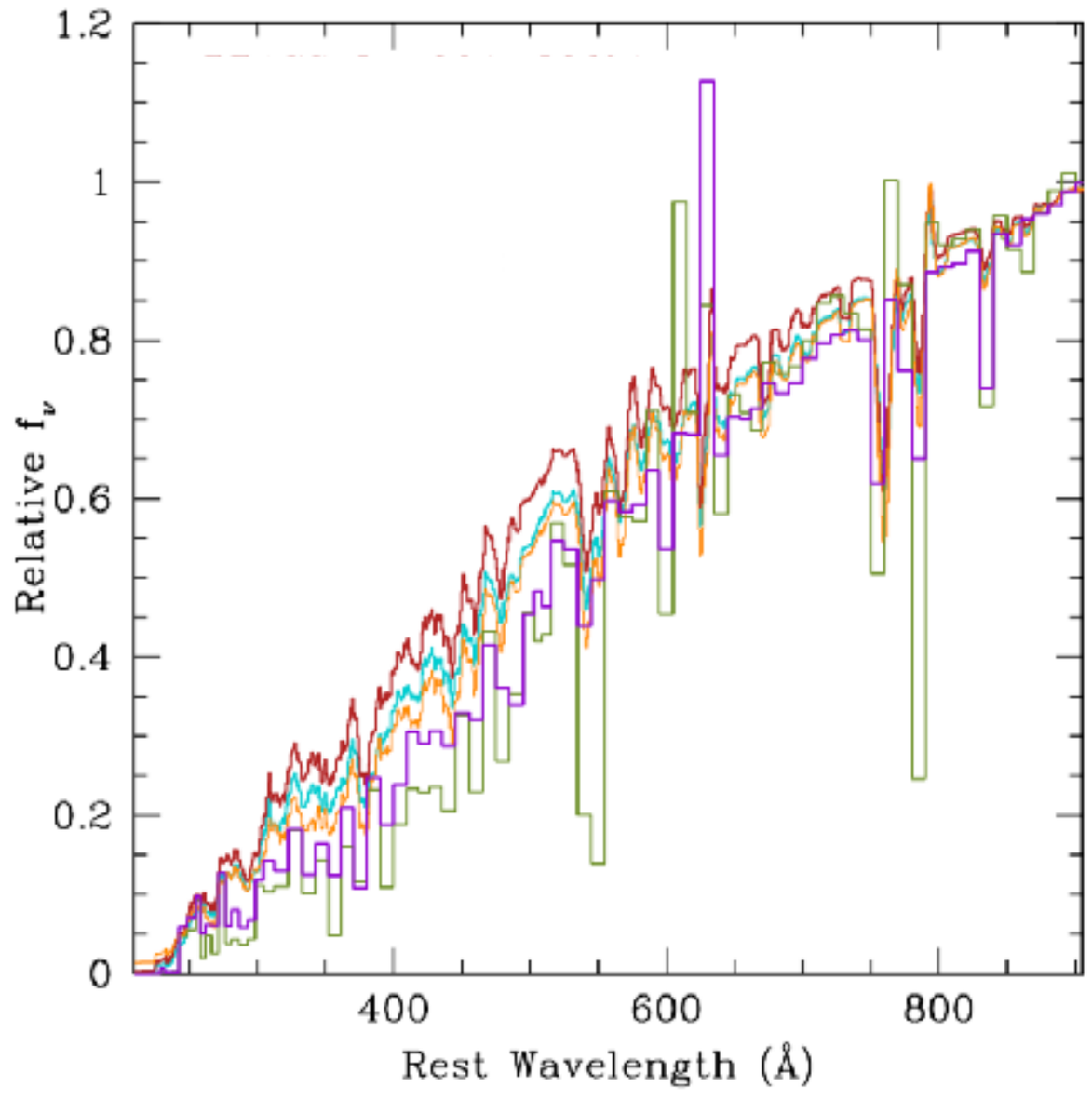

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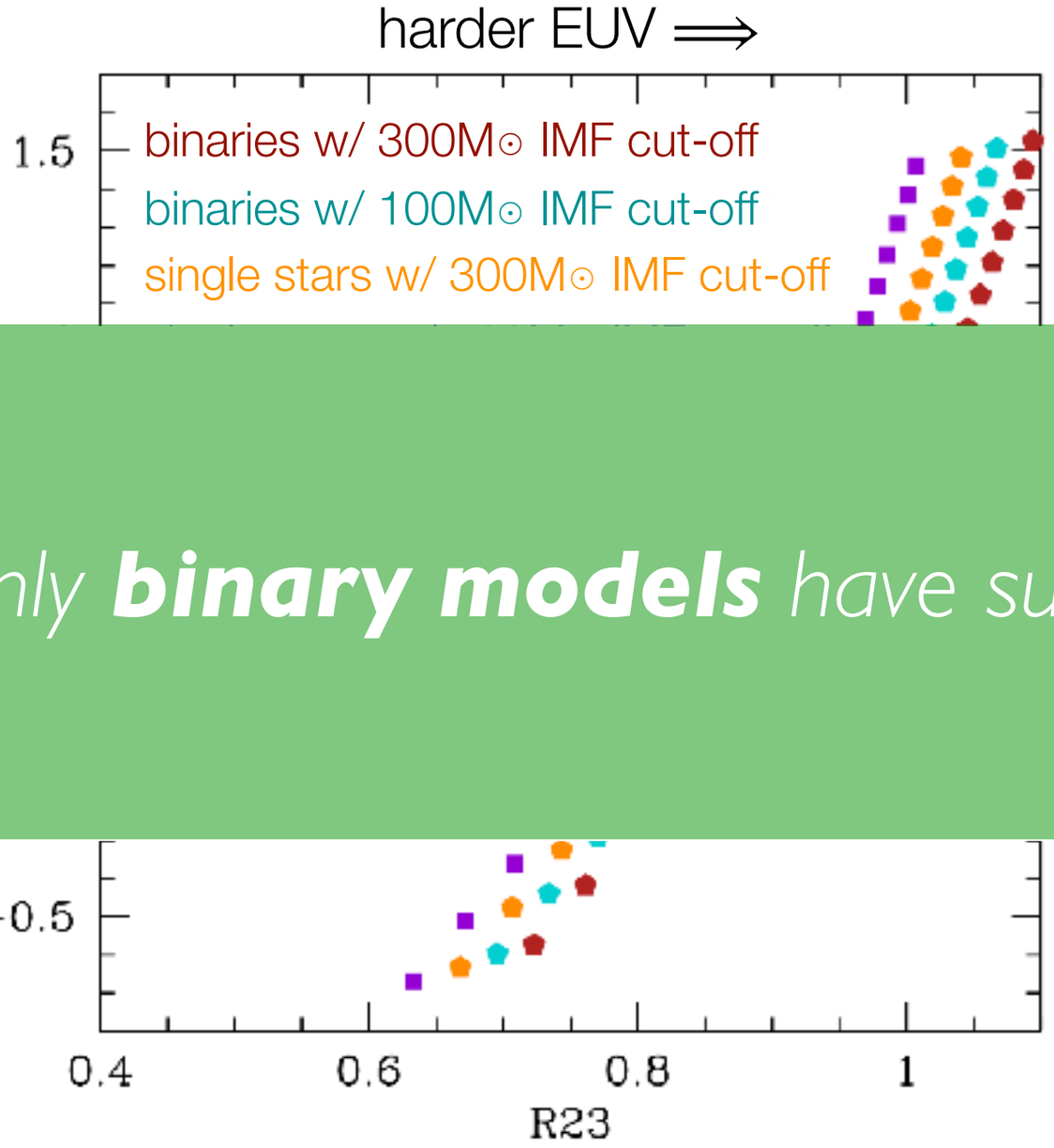
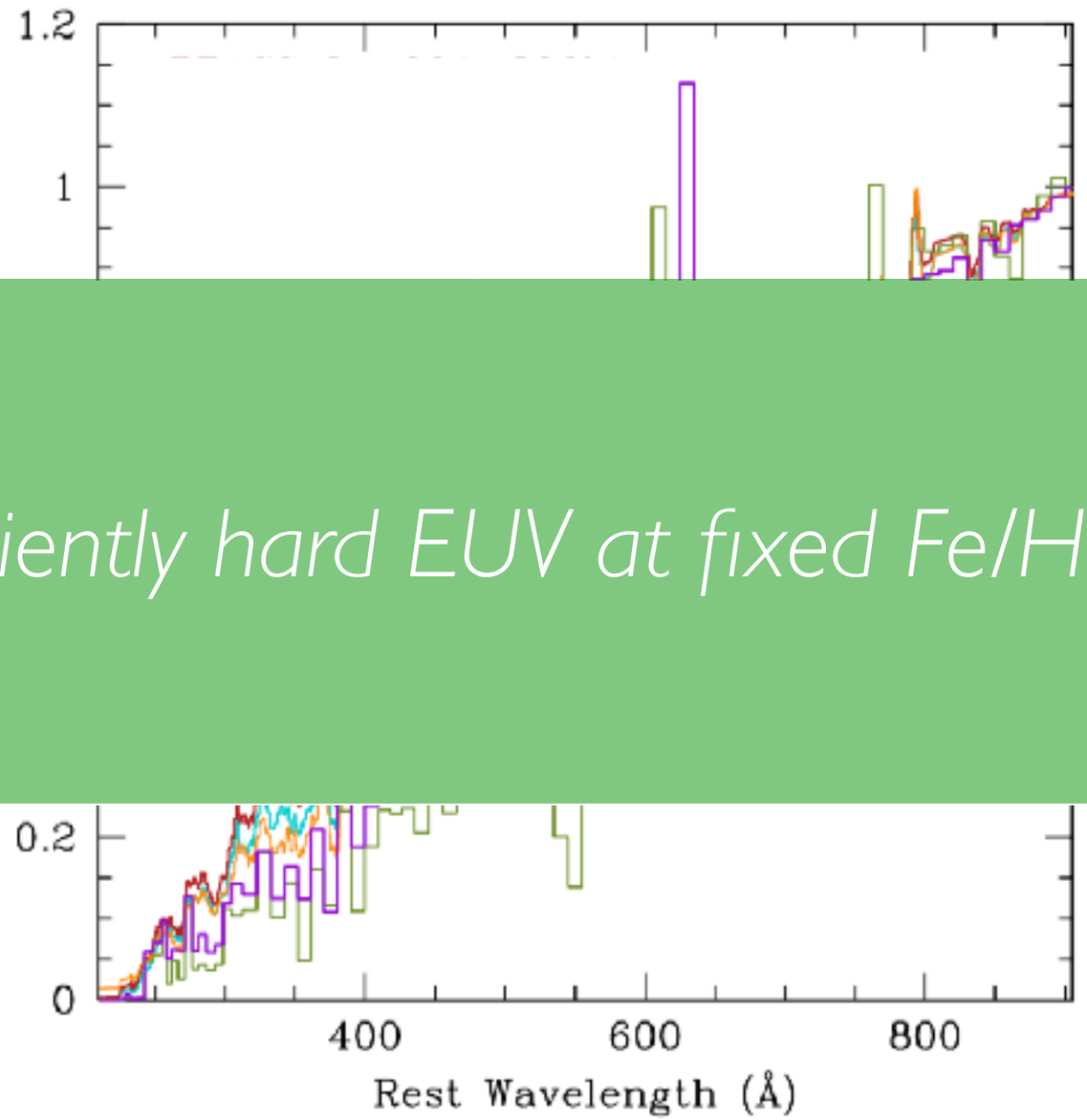
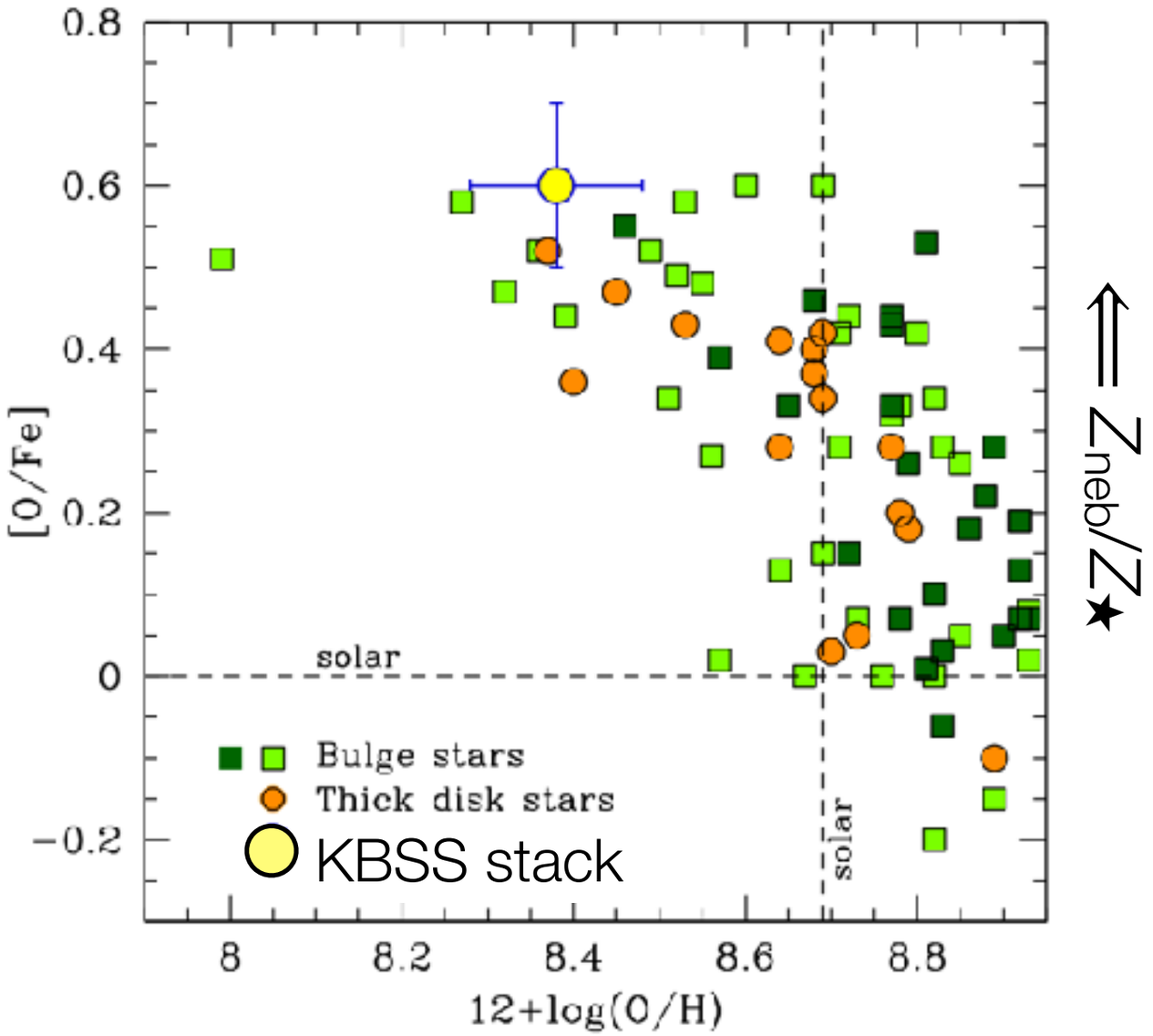




*Only **binary models** have sufficiently hard EUV at fixed Fe/H.*

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)⊙

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., Conroy+14, Segers+16)

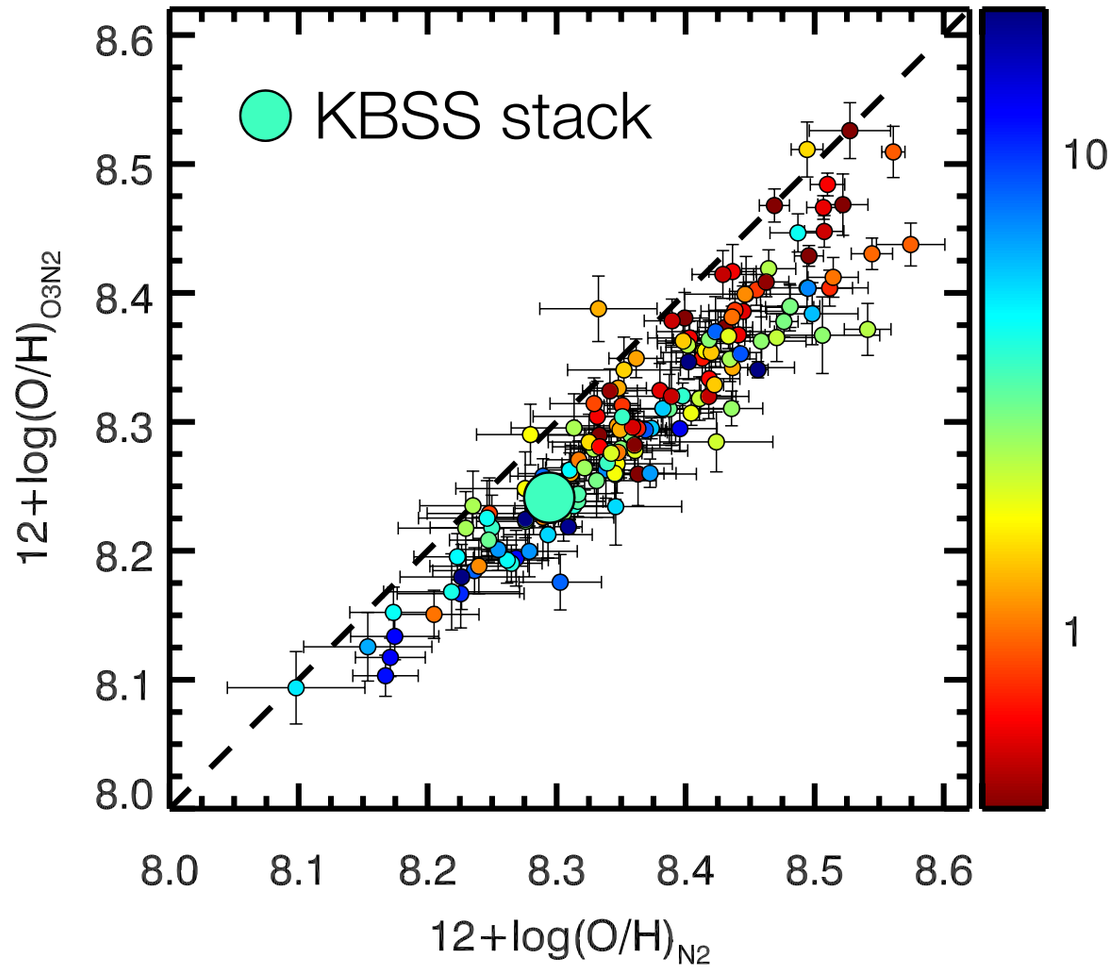
Impact of star formation history on metallicity diagnostics

Young galaxy ages and/or rising star formation histories will result in higher excitation (i.e., O3 and R23) at fixed O/H

Strong-line calibrations rely on the underlying correlation between

1. shape of the ionizing radiation (Fe/H)
2. gas-phase C/H, N/H, and O/H

Local metallicity calibrations will be inconsistent for high-*z* galaxies, especially at high 12+log(O/H)



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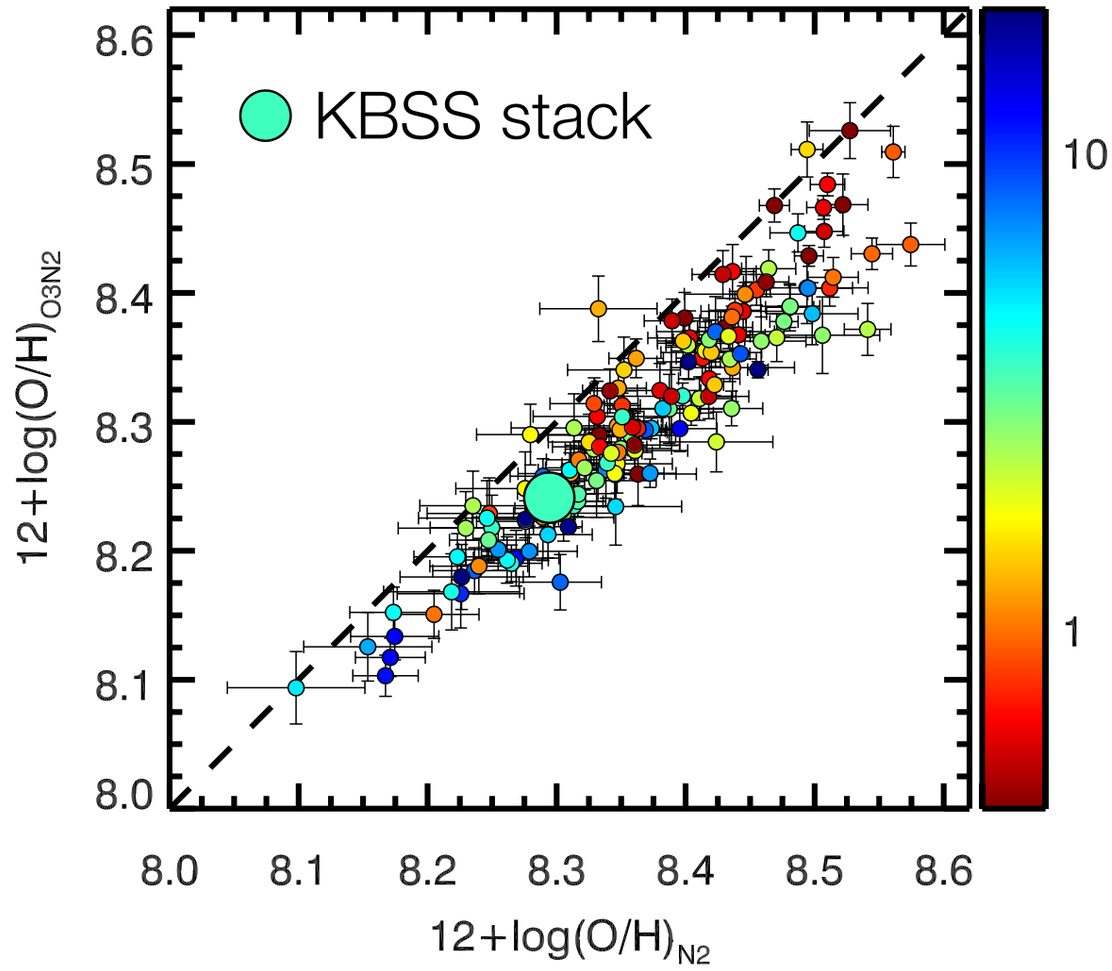
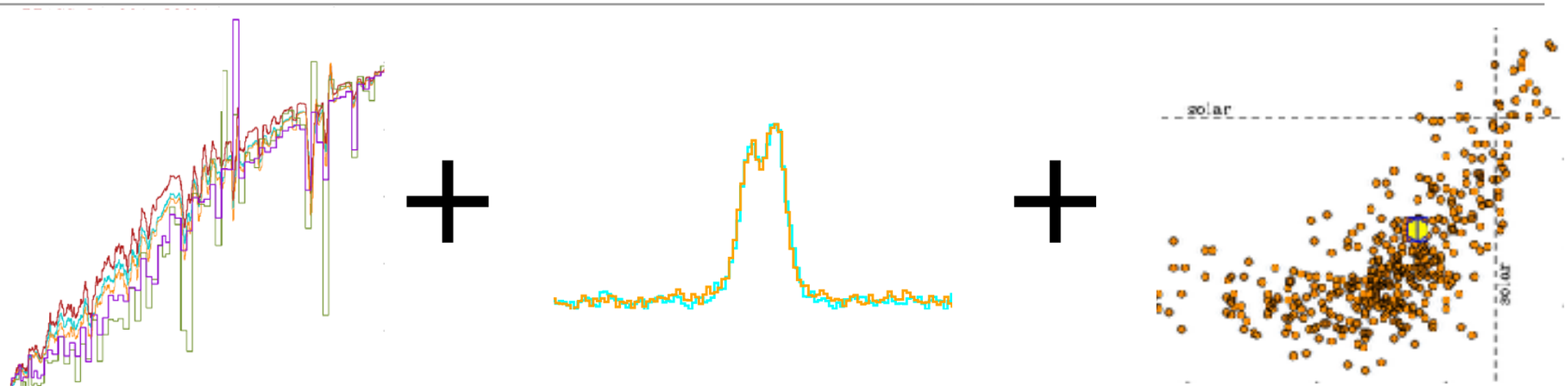


But photoionization models can help!

Measuring physical conditions using photoionization models

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

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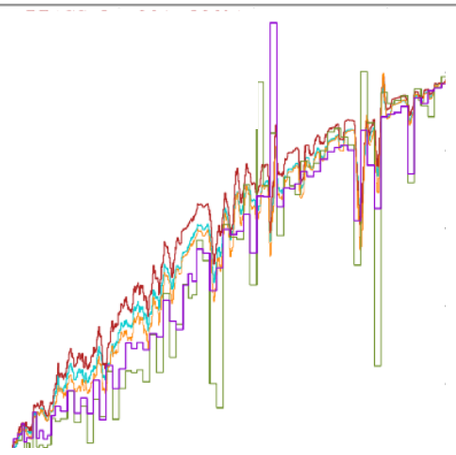

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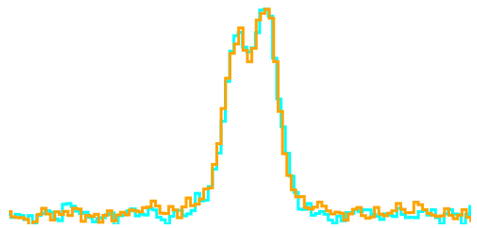

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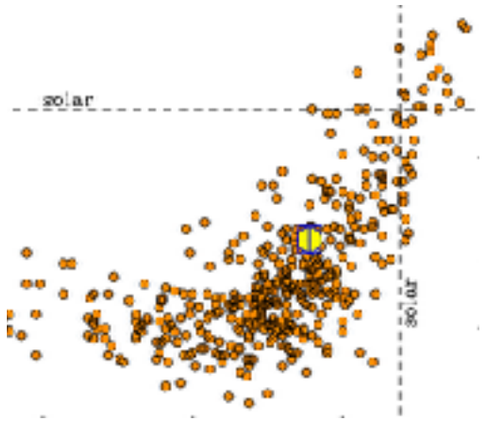
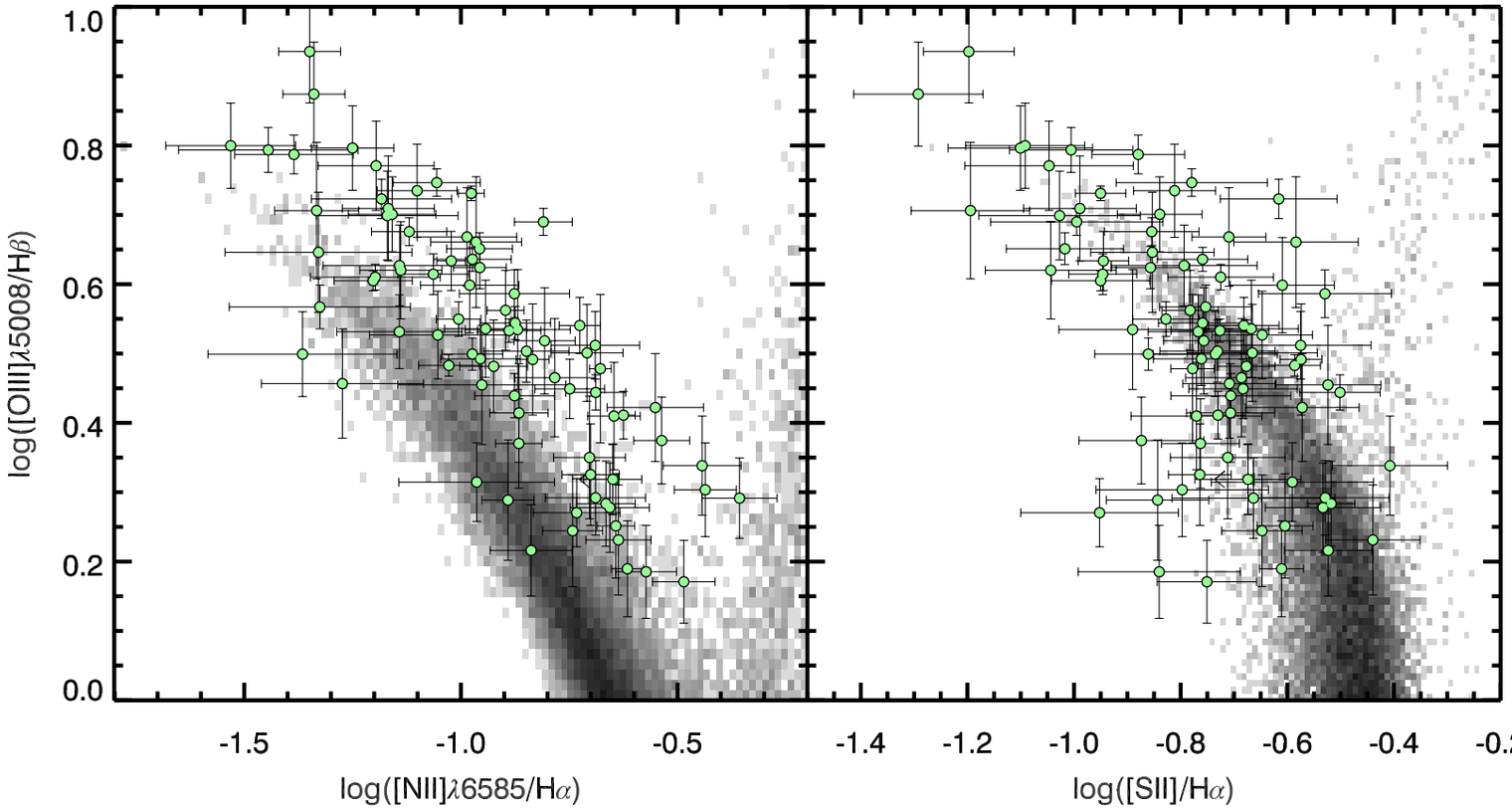
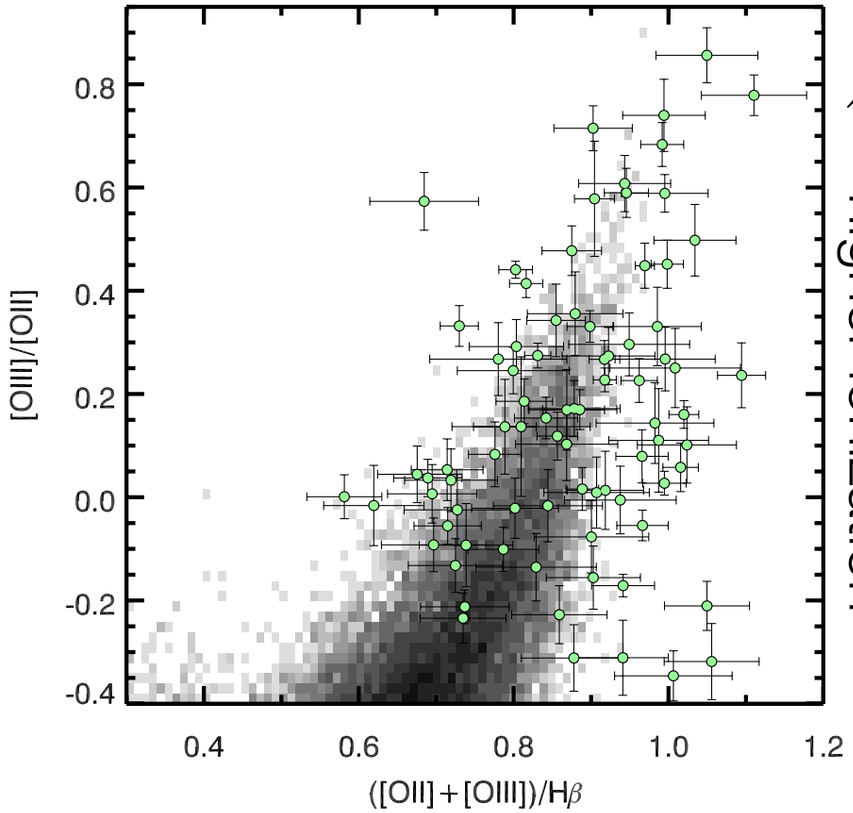


higher excitation ⟹





⟸ higher ionization

Measuring physical conditions using photoionization models

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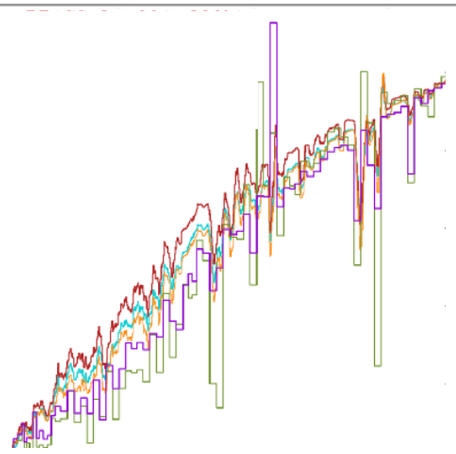

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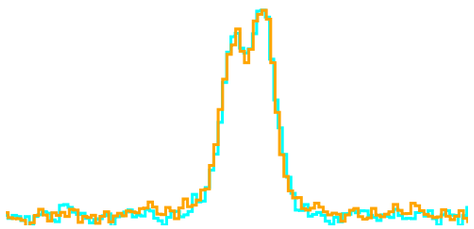

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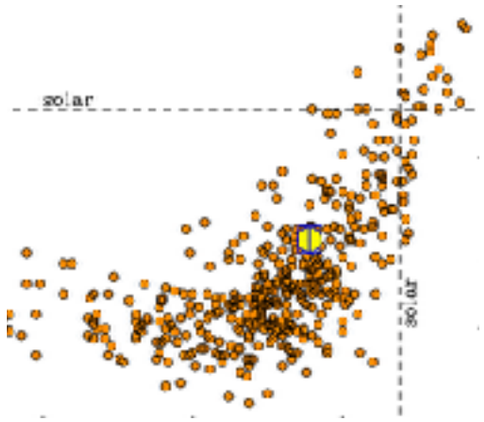

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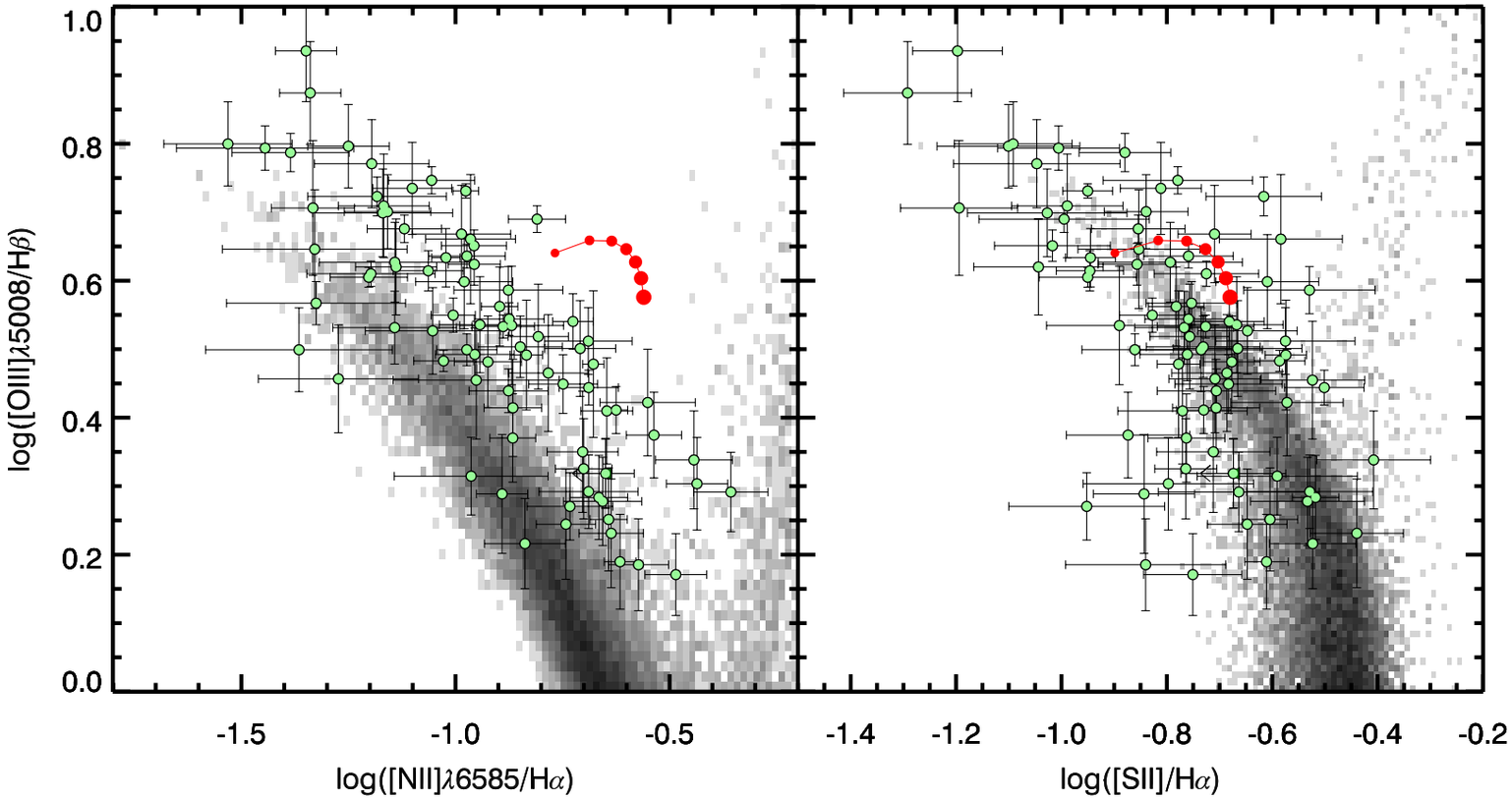

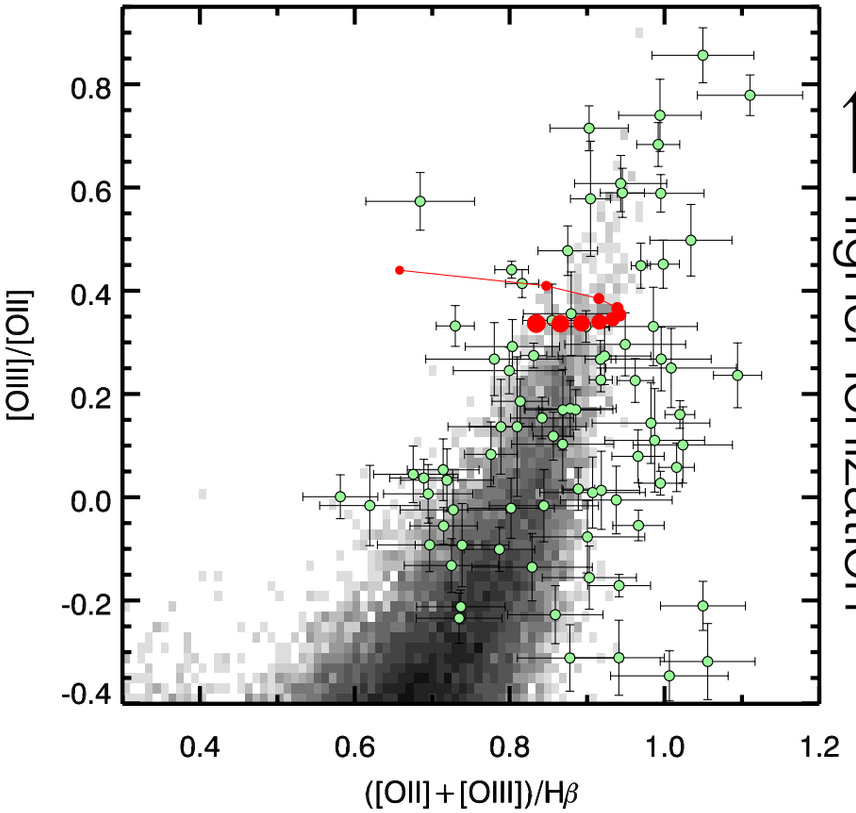

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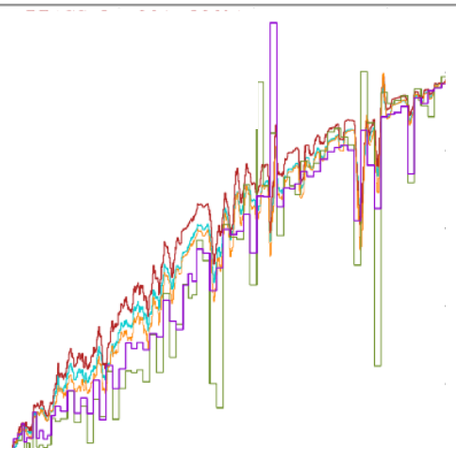

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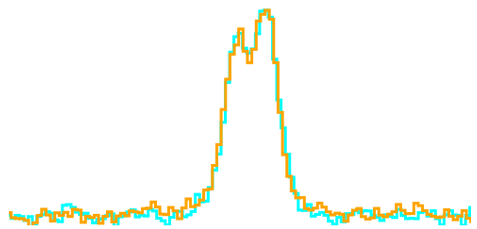

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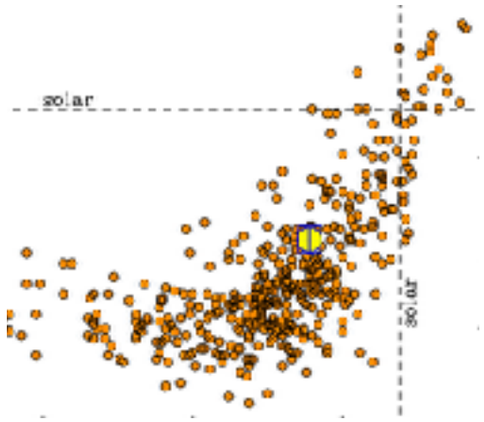
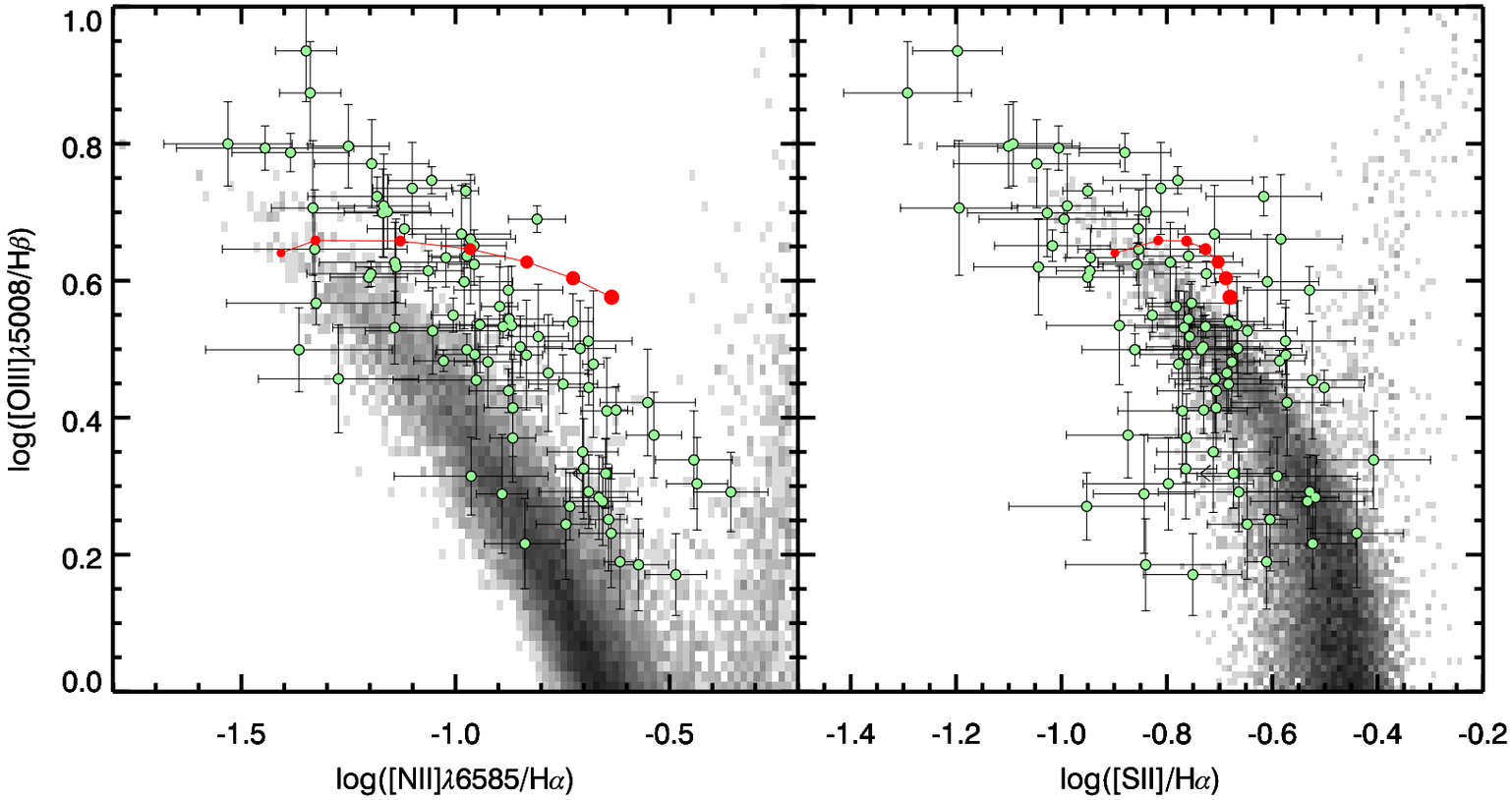
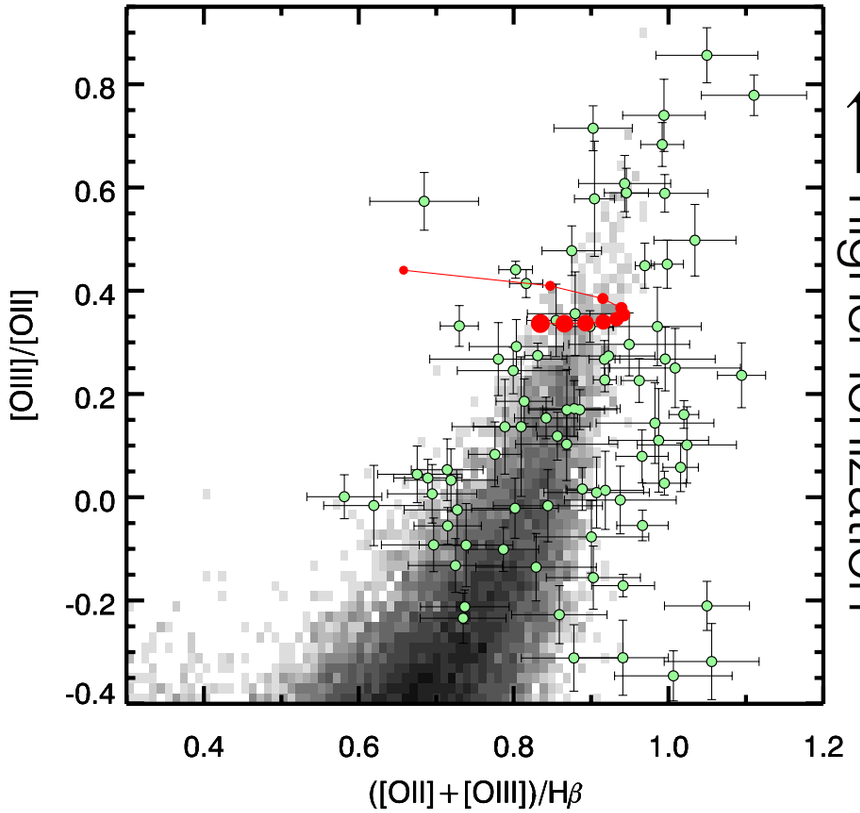


higher excitation ⟹

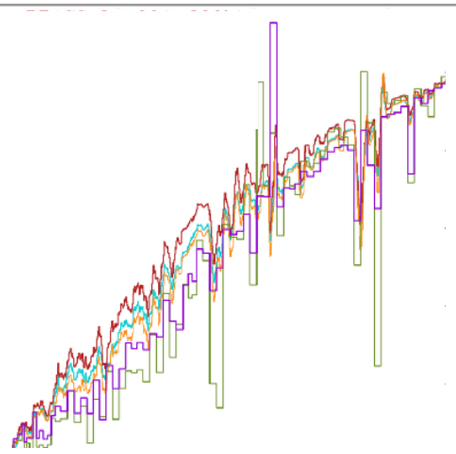




⟸ higher ionization

Measuring physical conditions using photoionization models

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



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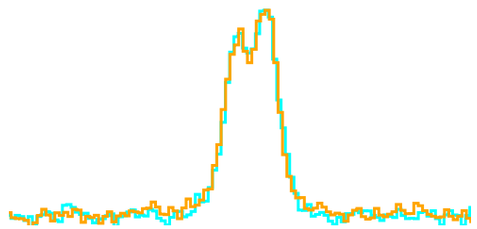

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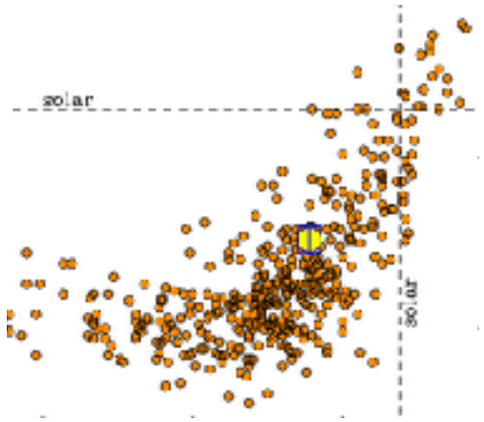
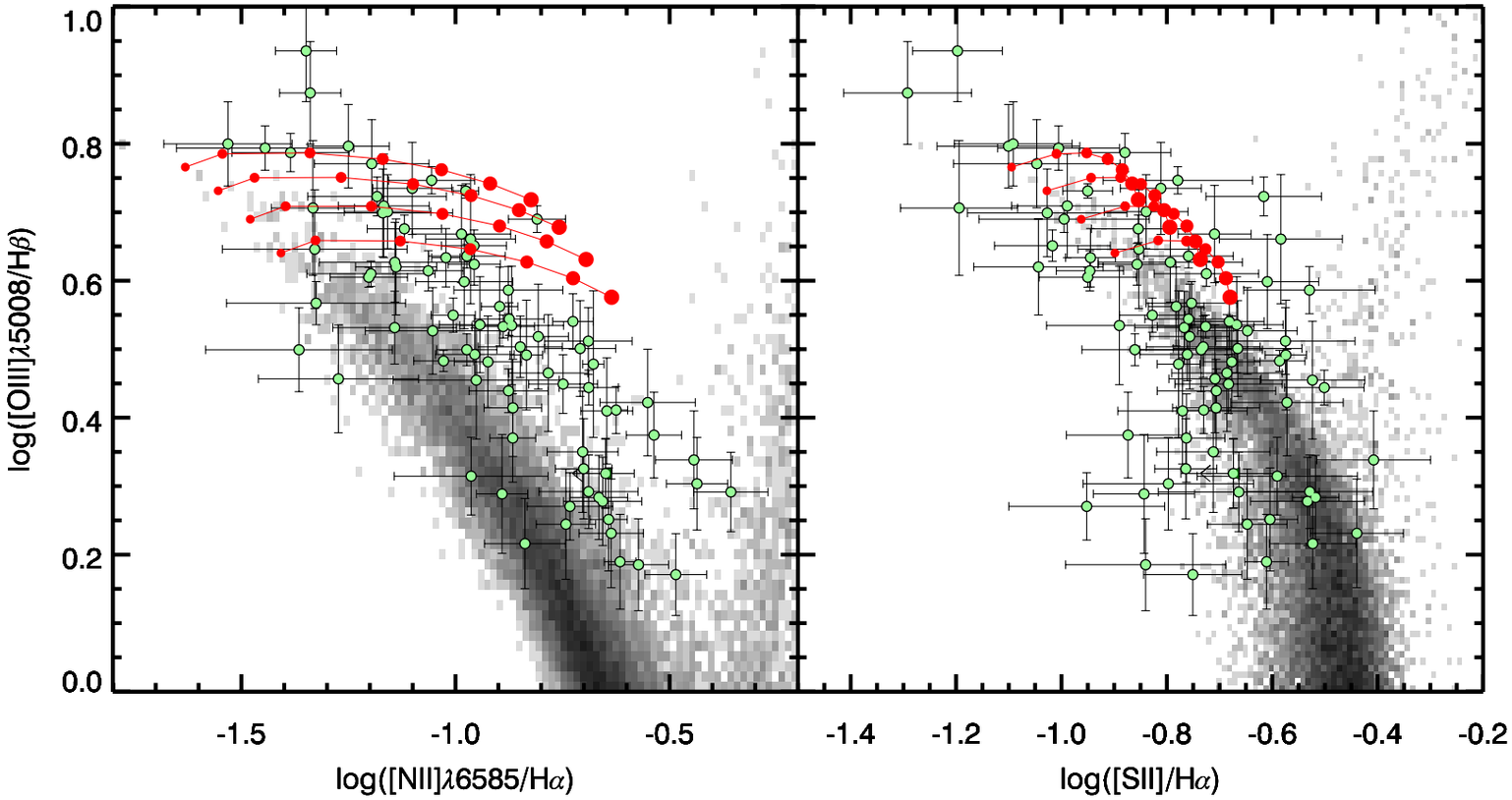
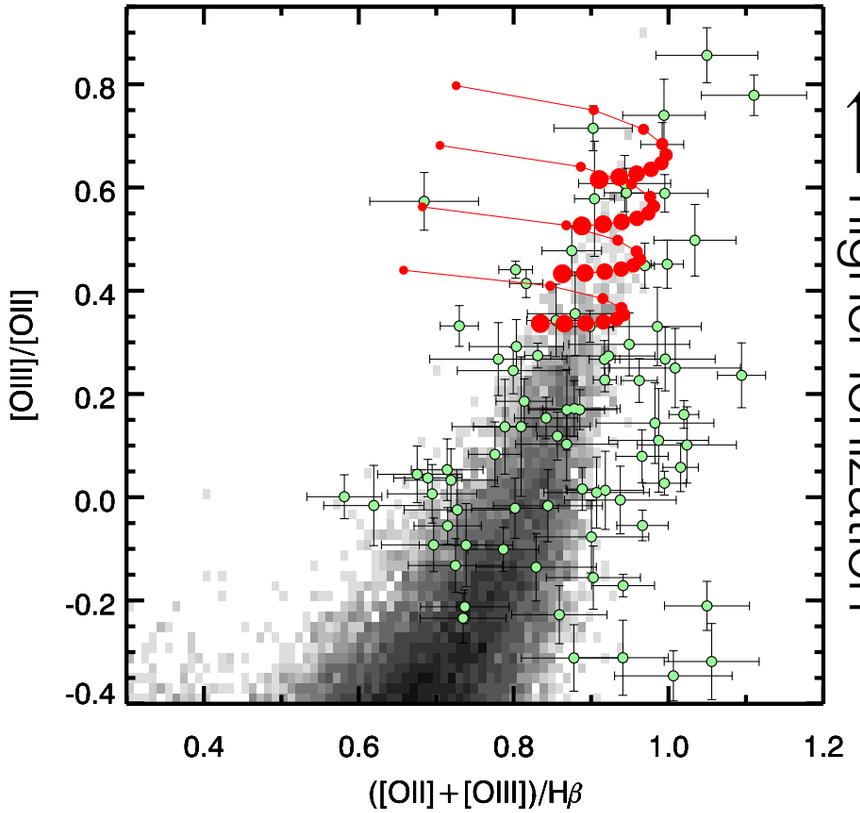


higher excitation ⟹





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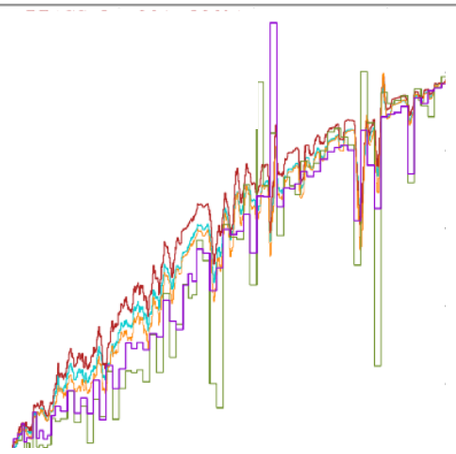

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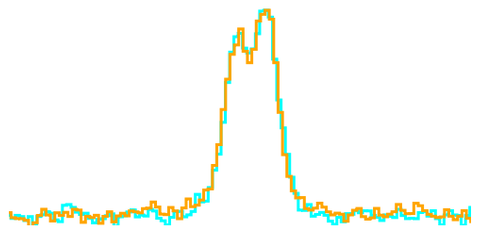

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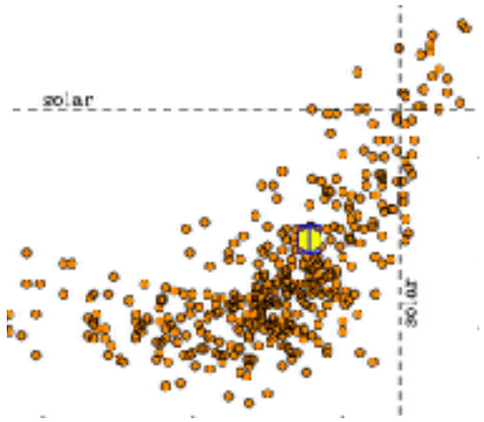
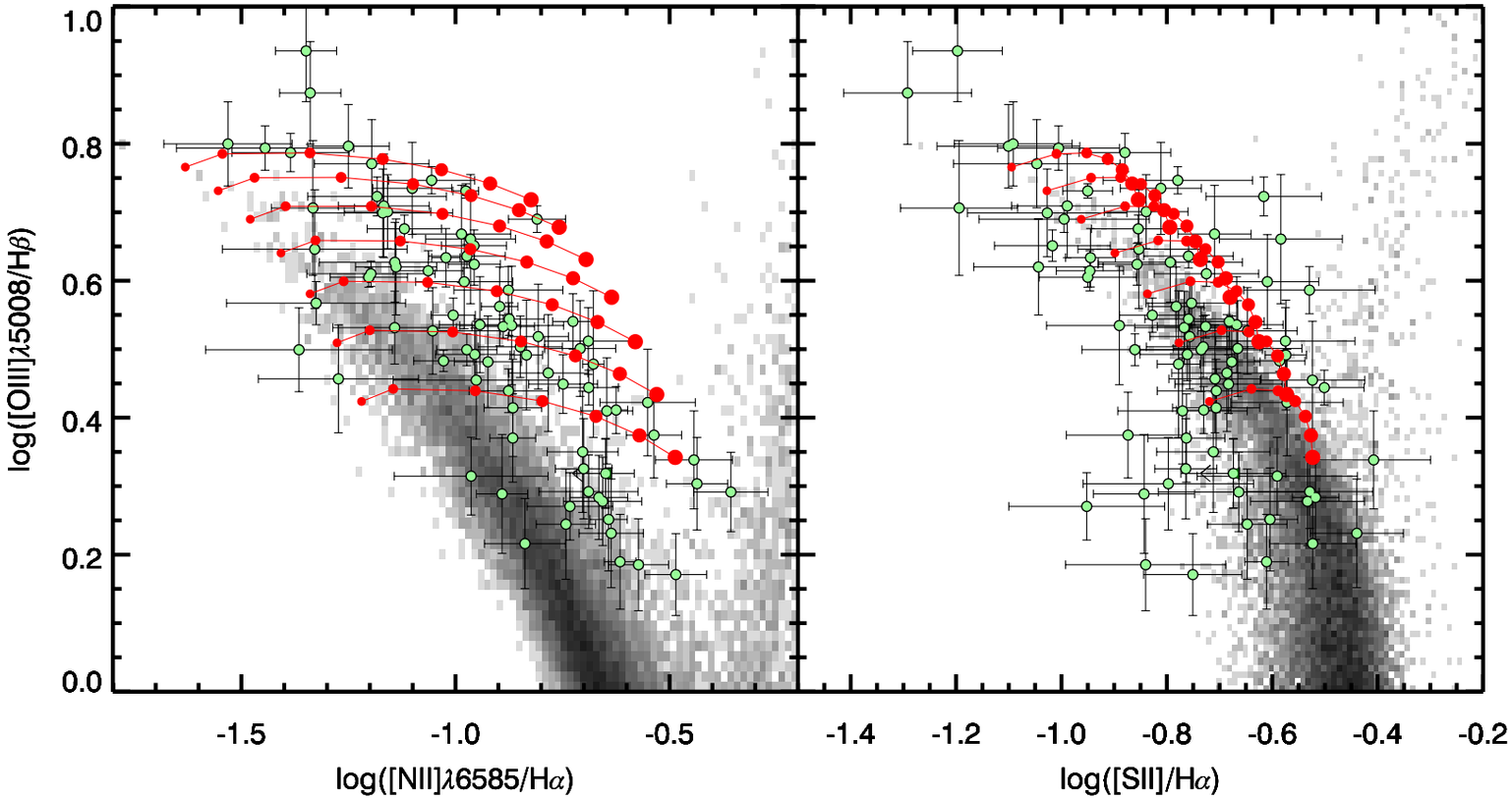
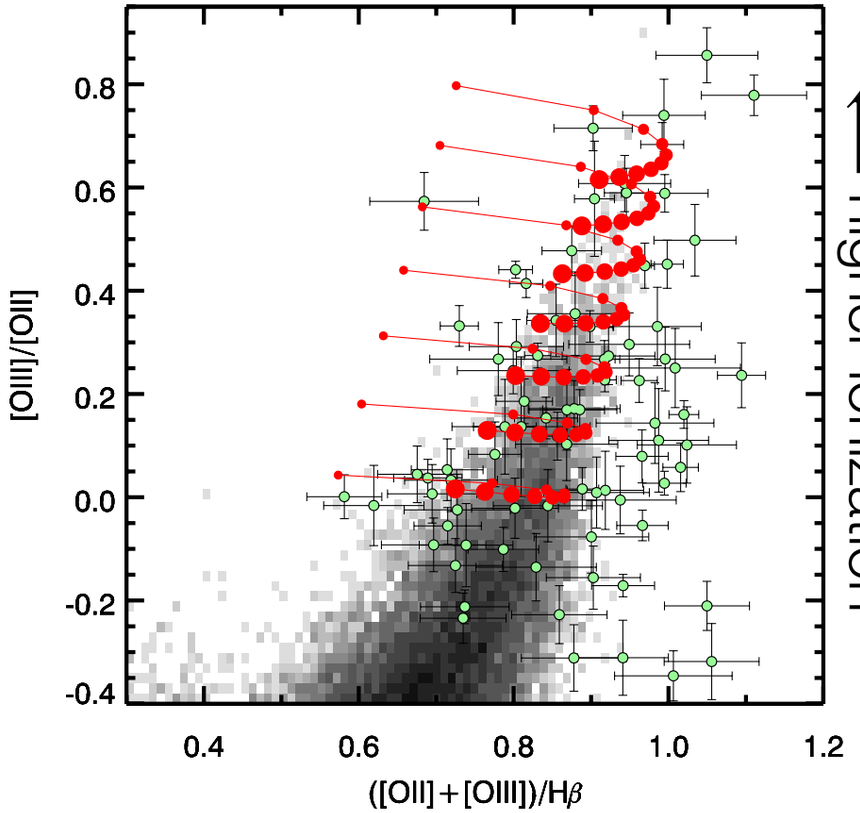


higher excitation ⟹





⟸ higher ionization

Measuring physical conditions using photoionization models

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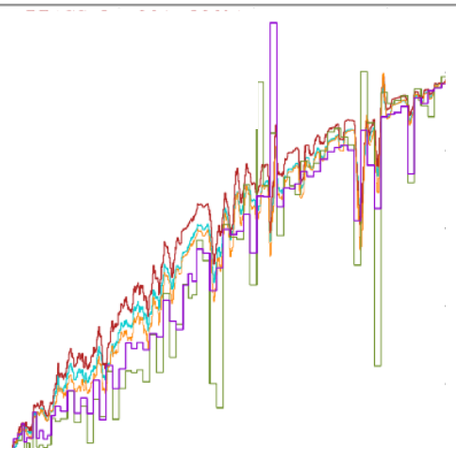

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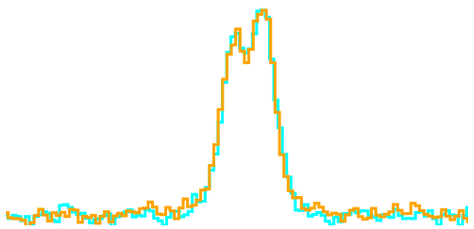

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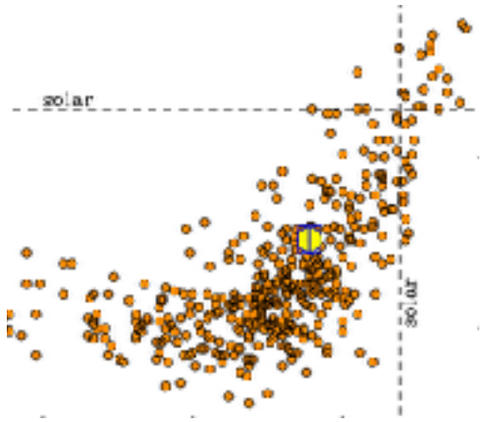
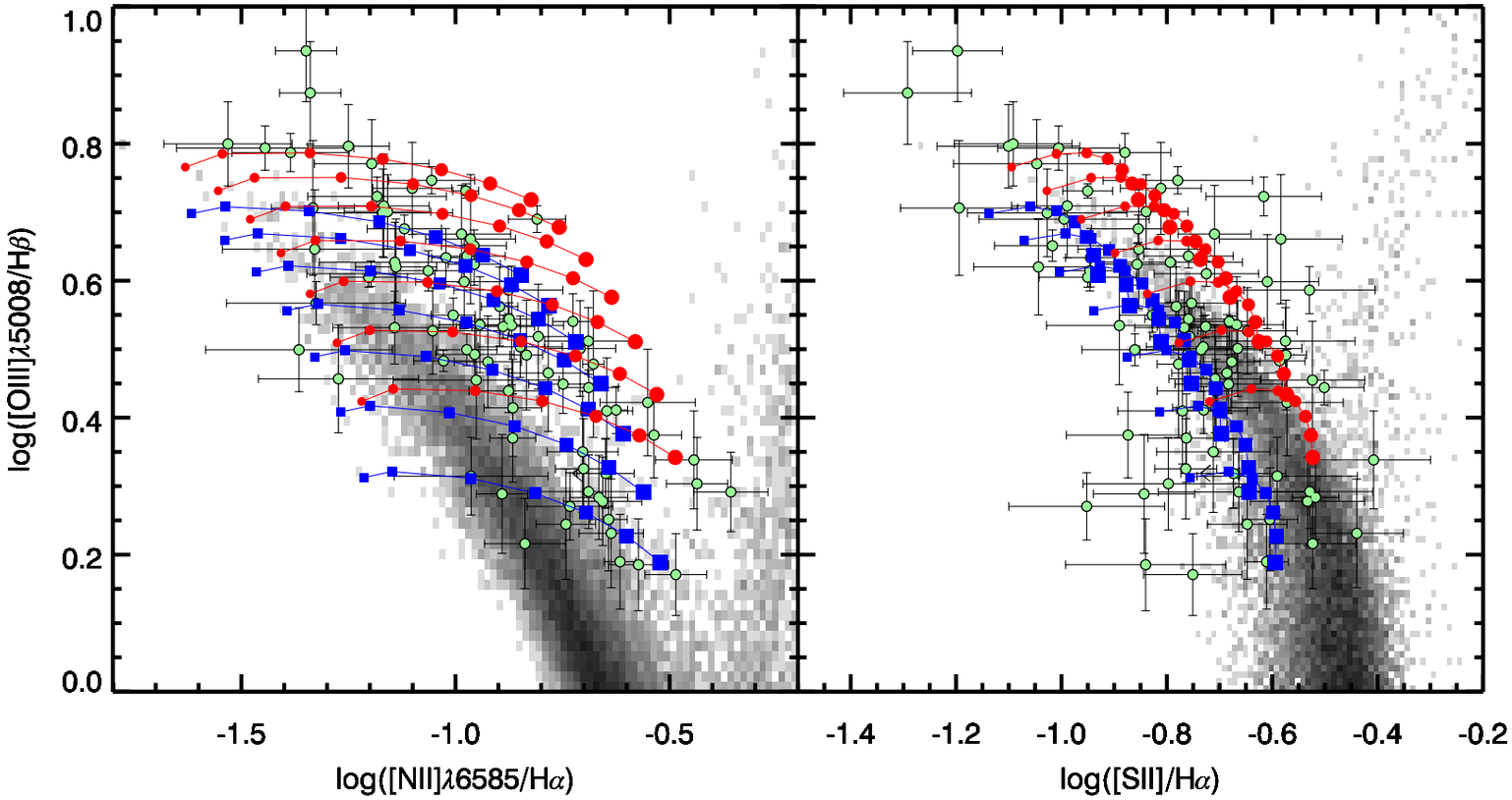
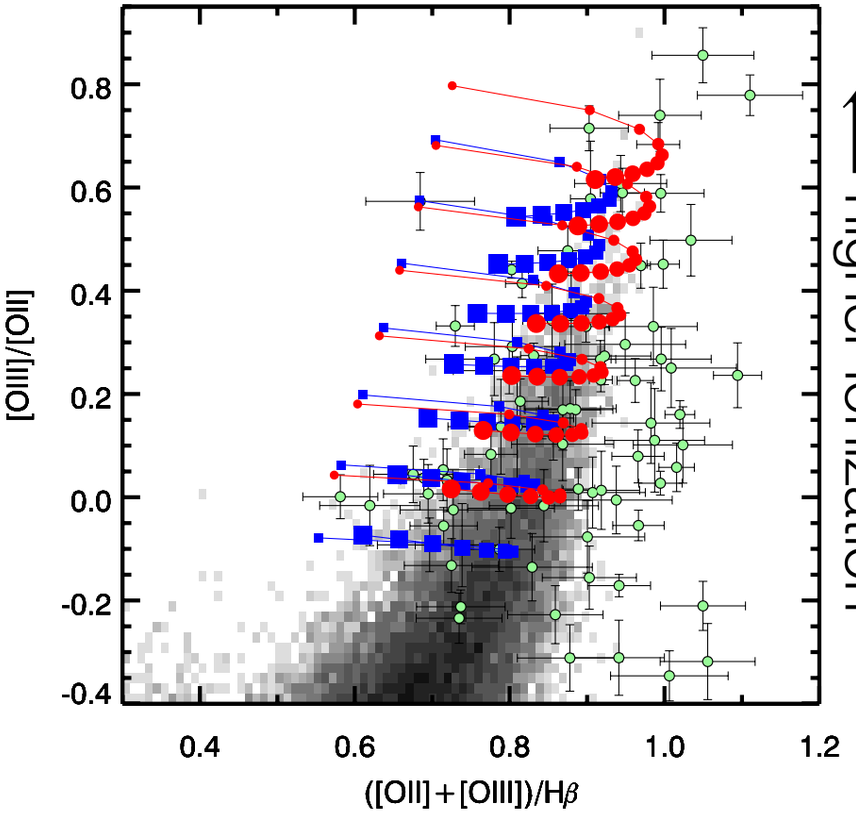


higher excitation ⟹





⟸ higher ionization

Measuring physical conditions using photoionization models

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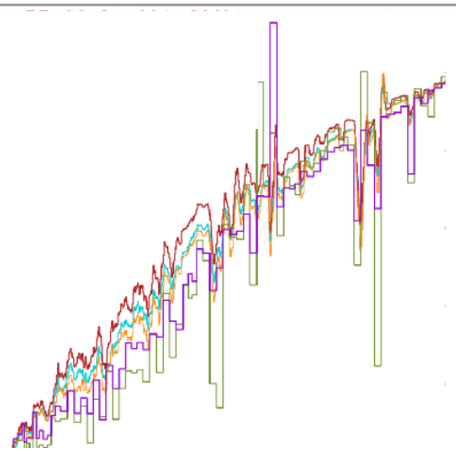

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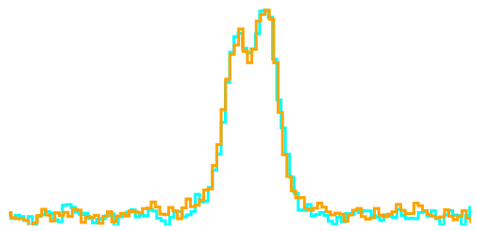

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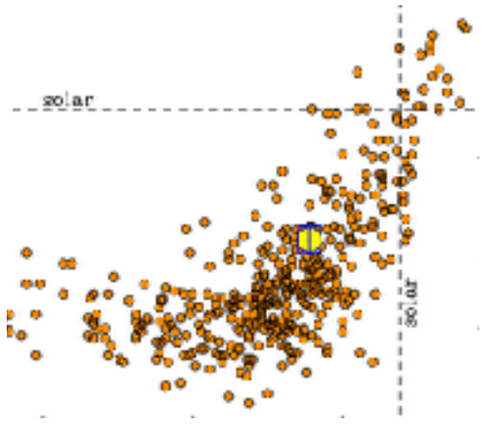
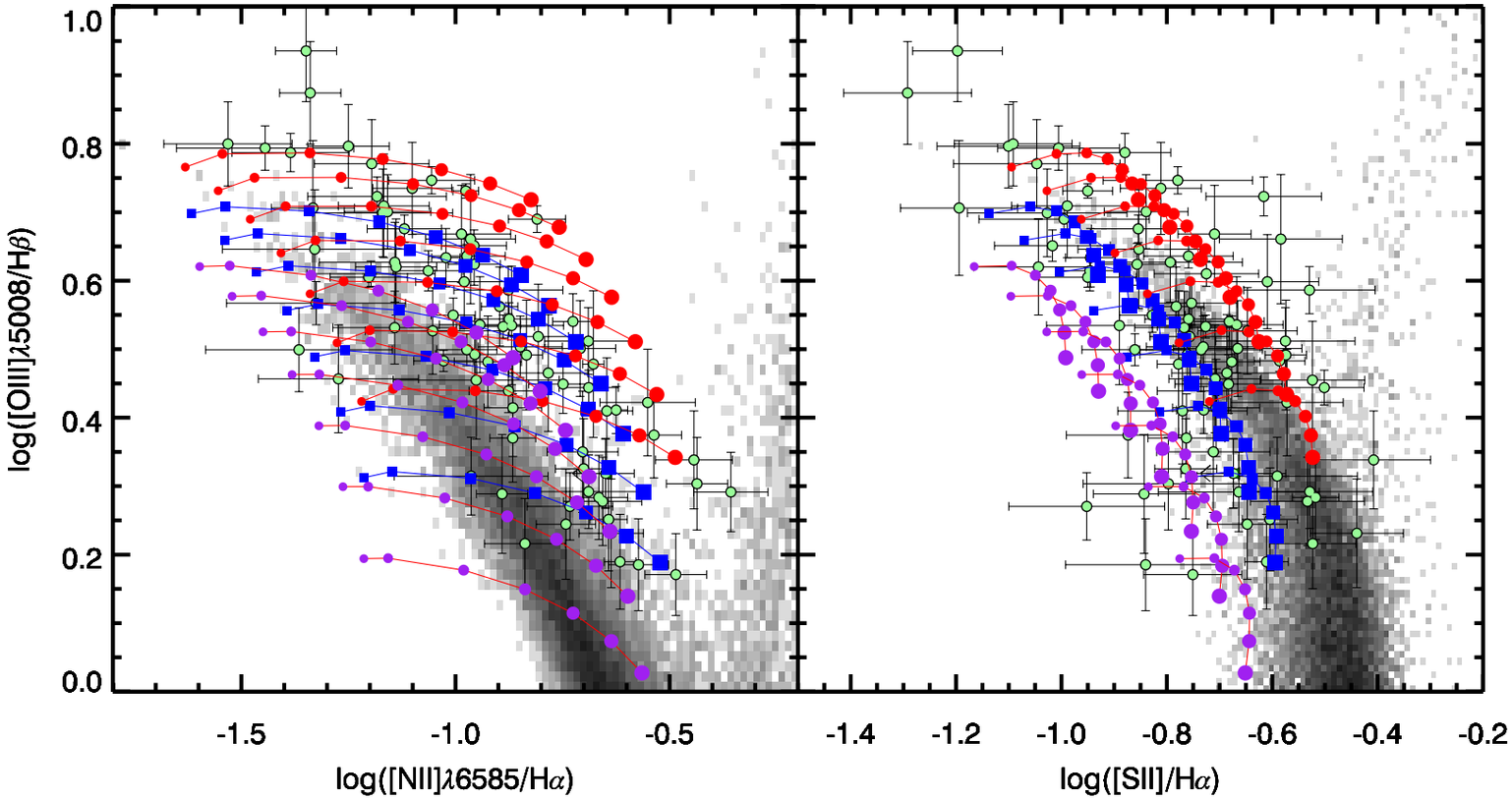
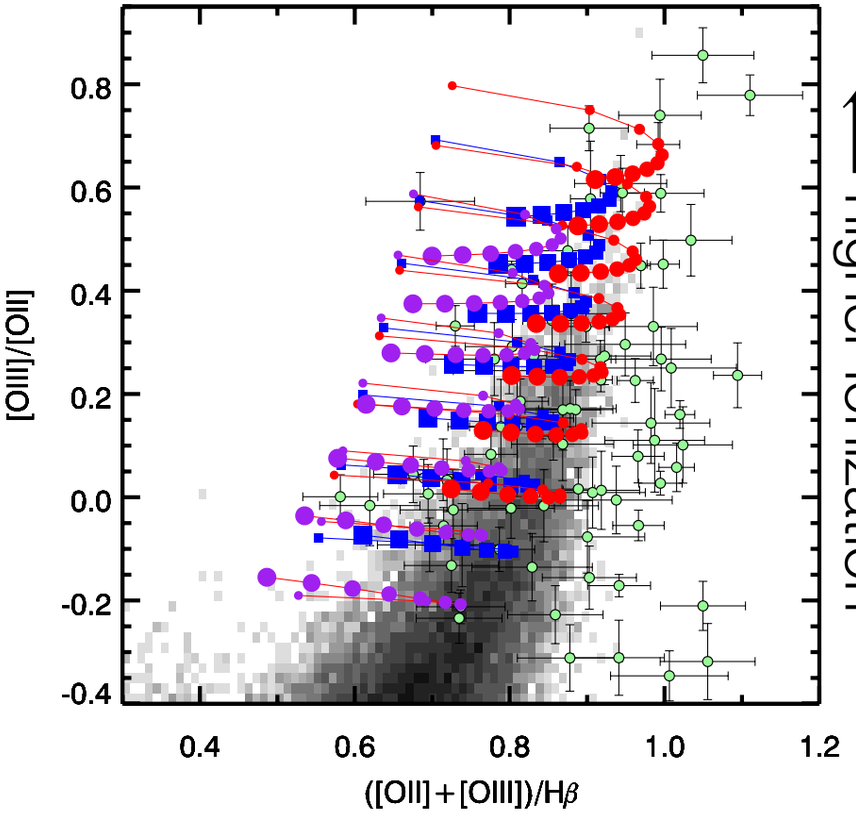


higher excitation ⟹

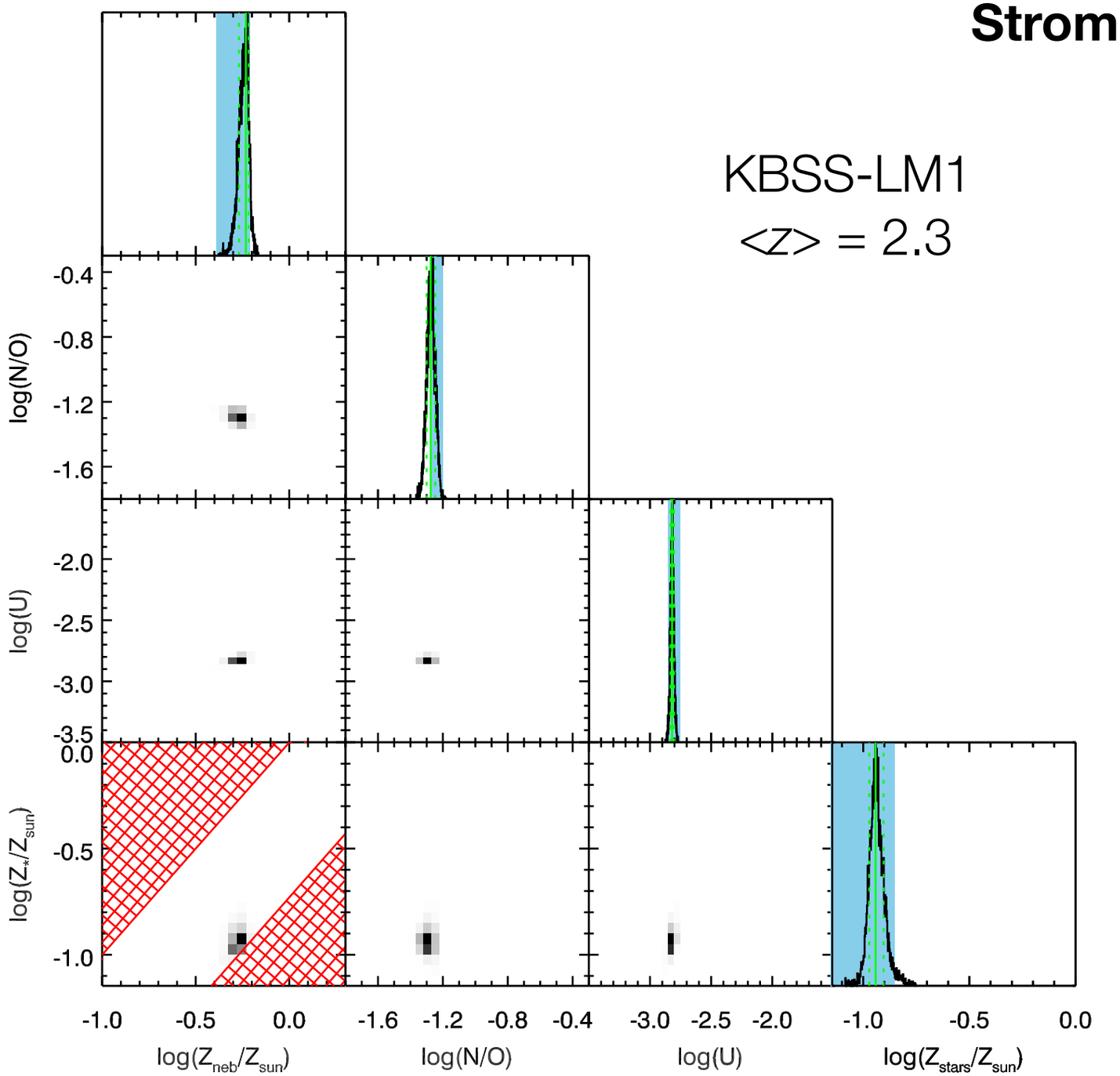




⟸ higher ionization

Testing the photoionization model method using the LM1 composite

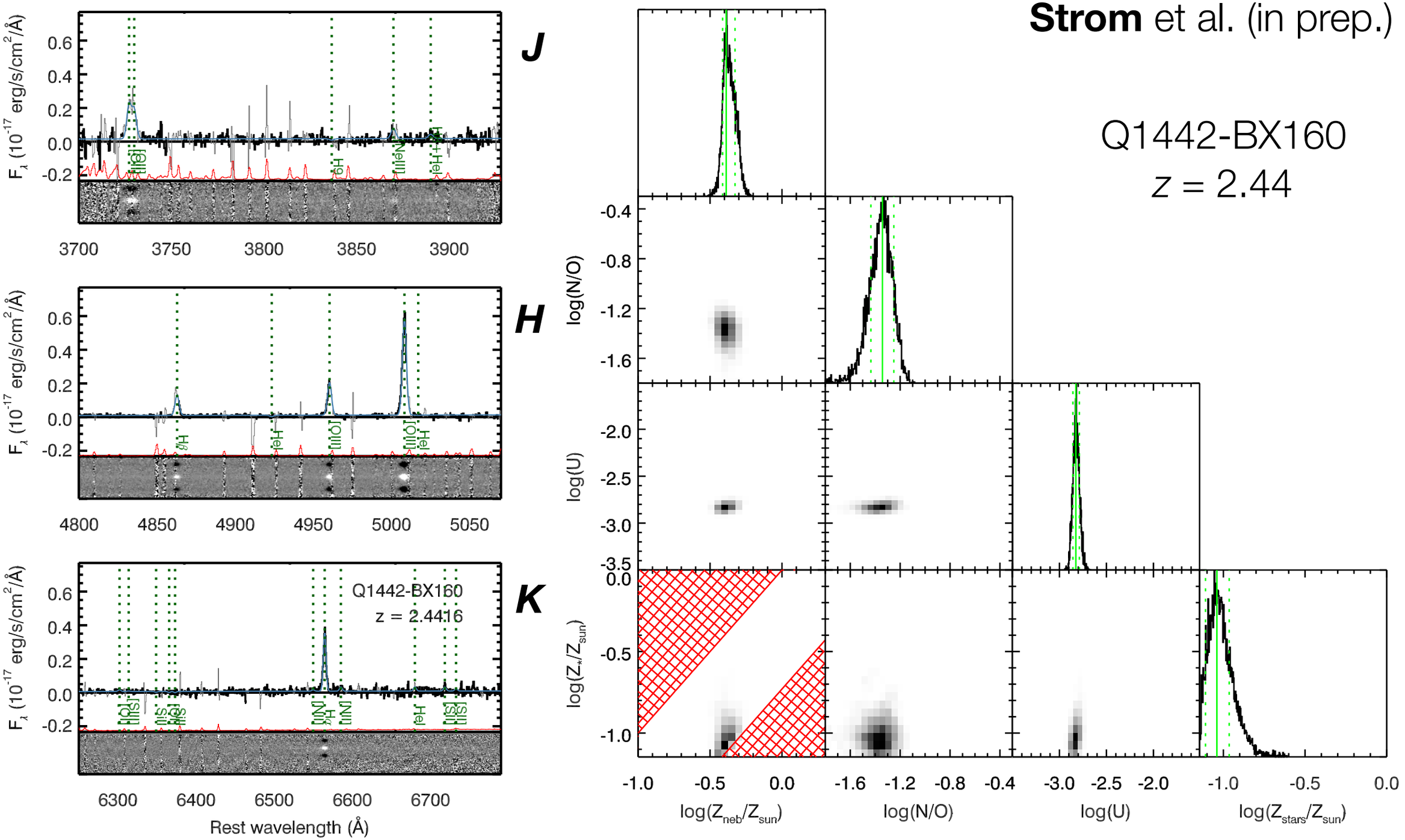
Strom et al. (in prep.)



KBSS-LM1

<z> = 2.3

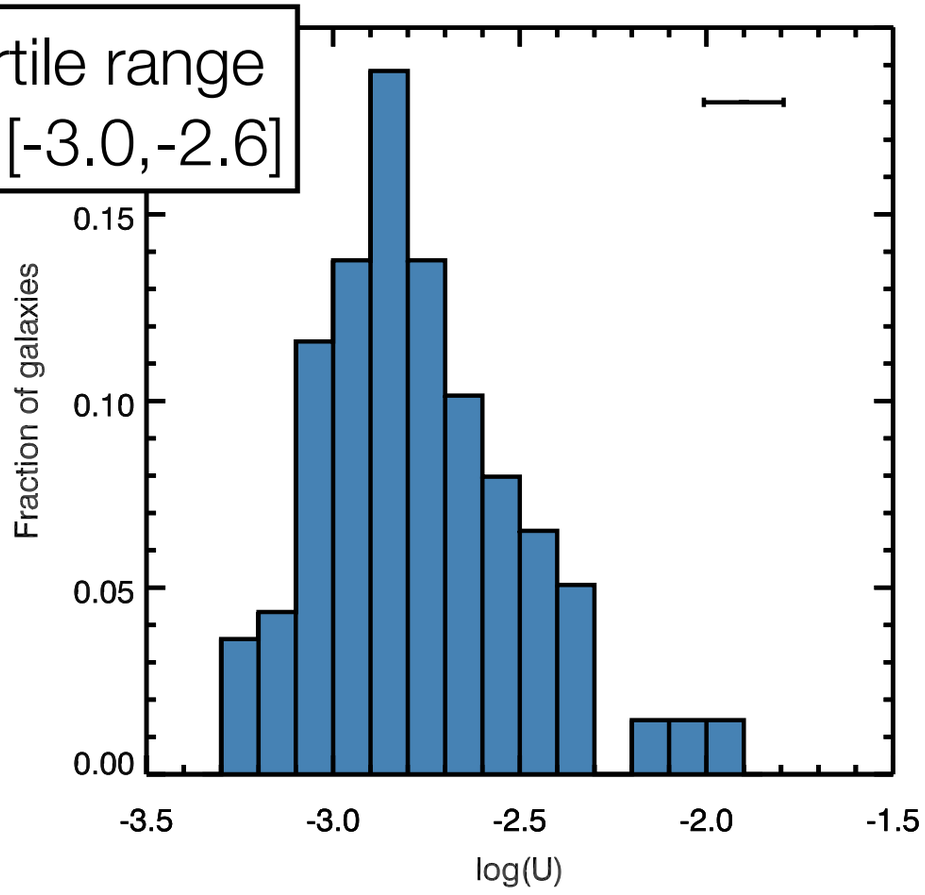
Measuring Z_{neb}, N/O, U and $Z_\star$ for individual galaxies

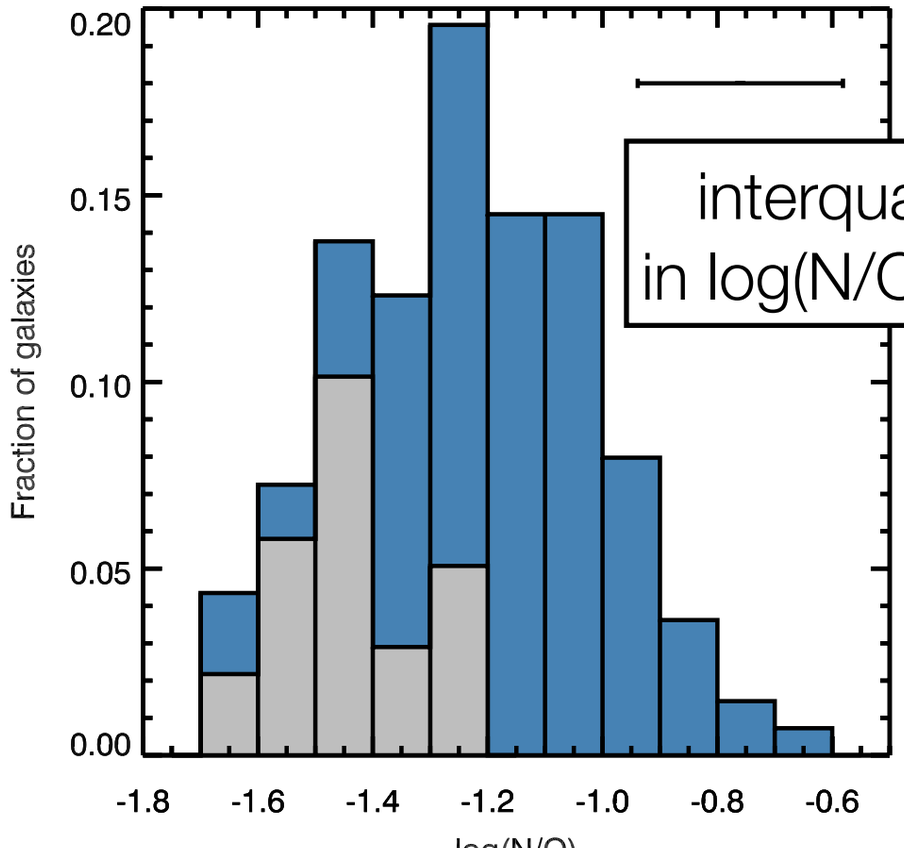


Strom et al. (in prep.)

Q1442-BX160
$z = 2.44$

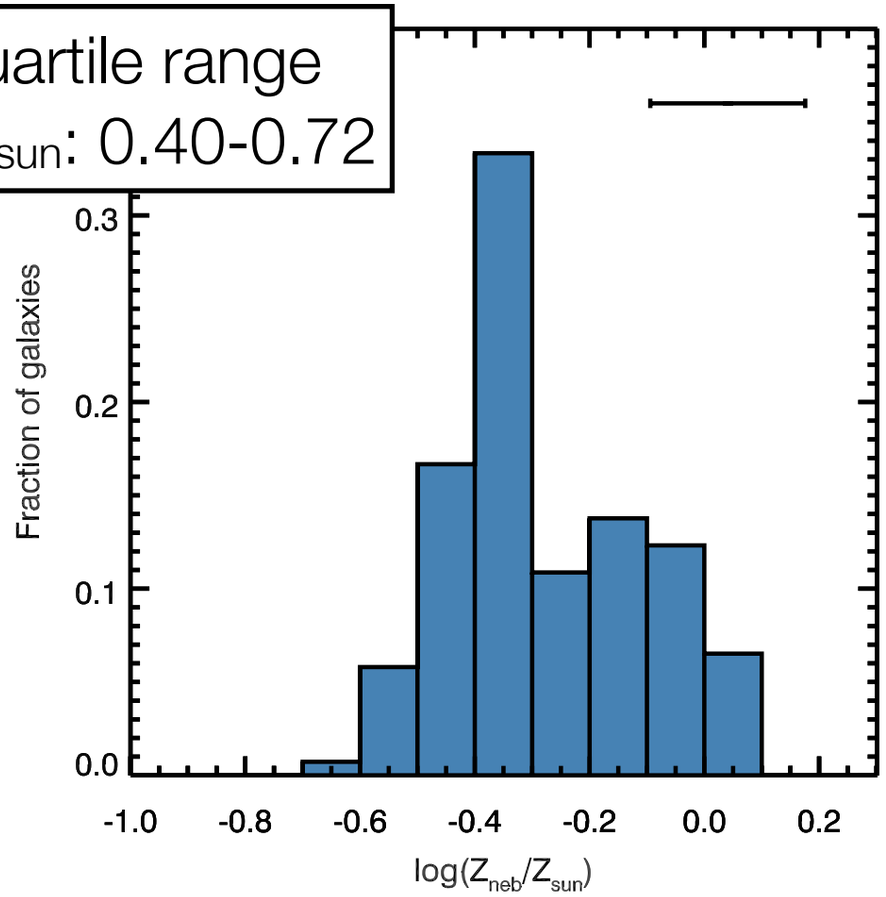
interquartile range
in log(U): [-3.0,-2.6]

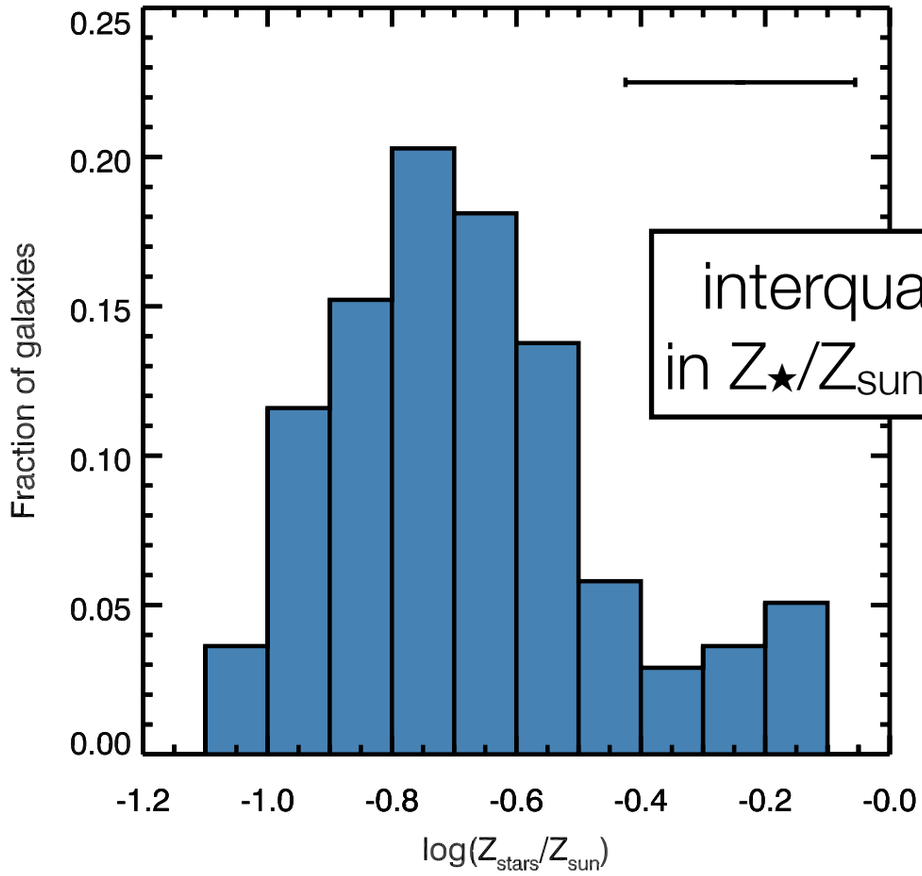




interquartile range
in log(N/O): [-1.4,-1.1]

interquartile range
in Z_{neb}/Z_{sun}: 0.40-0.72



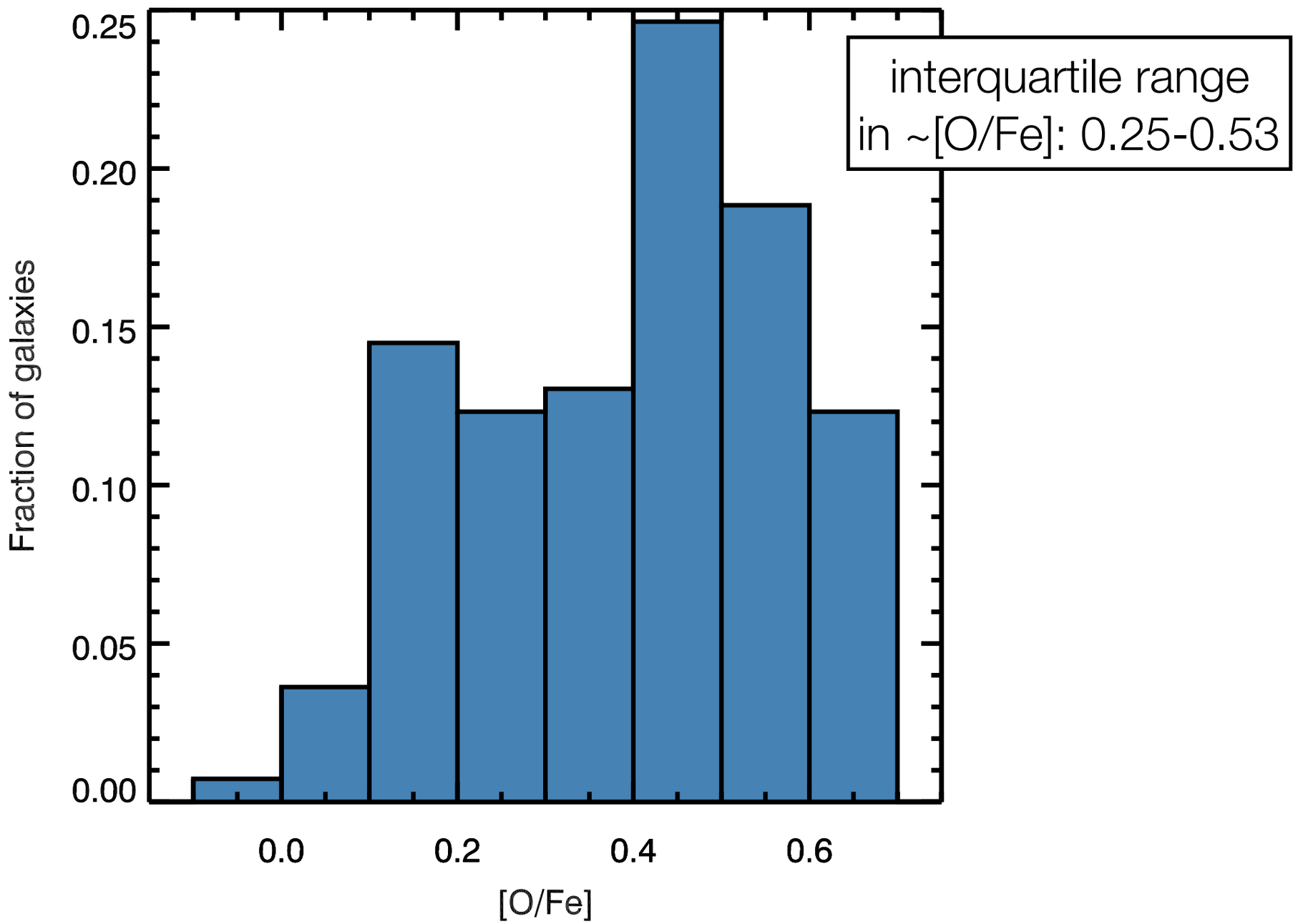


interquartile range
in $Z_{\star}/Z_{sun}$: 0.14-0.29

Strom et al. (in prep.)

Evidence for super-solar O/Fe in the ISM of high-z galaxies

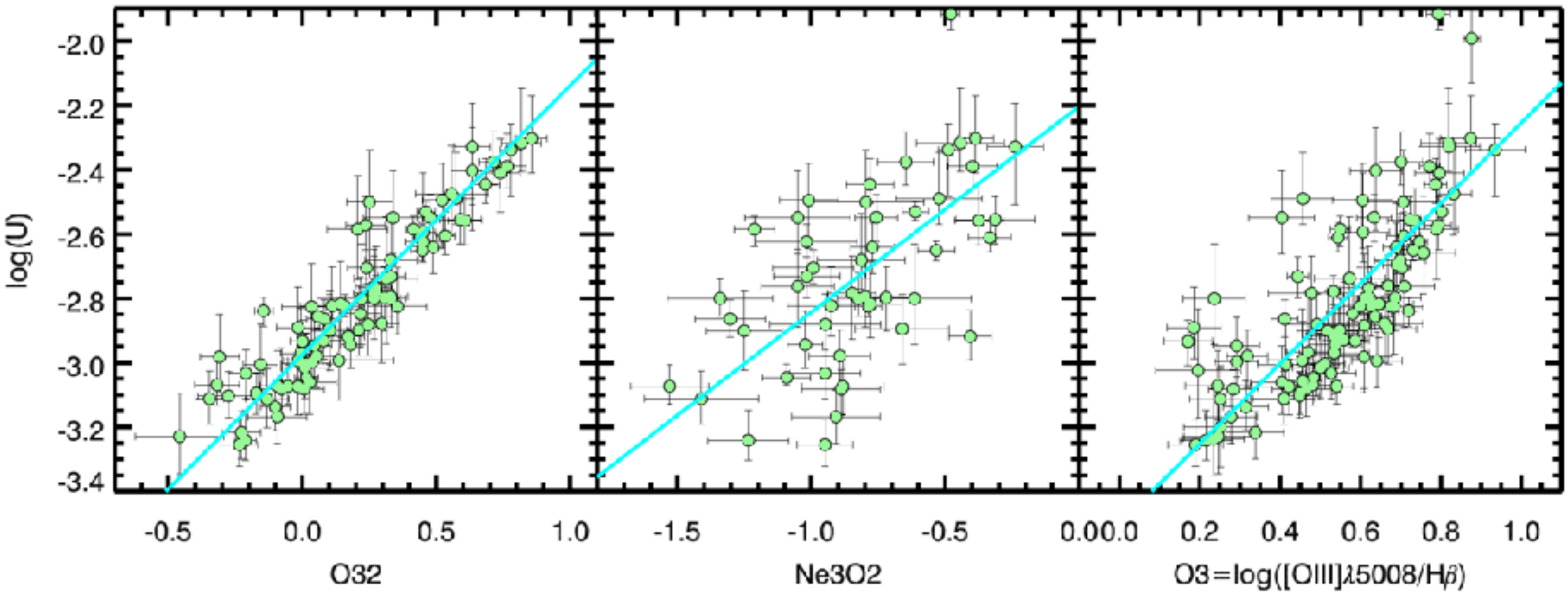
Strom et al. (in prep.)



Ionization parameter is strongly correlated with nebular spectrum

Strom et al. (in prep.)

calibrations from this work

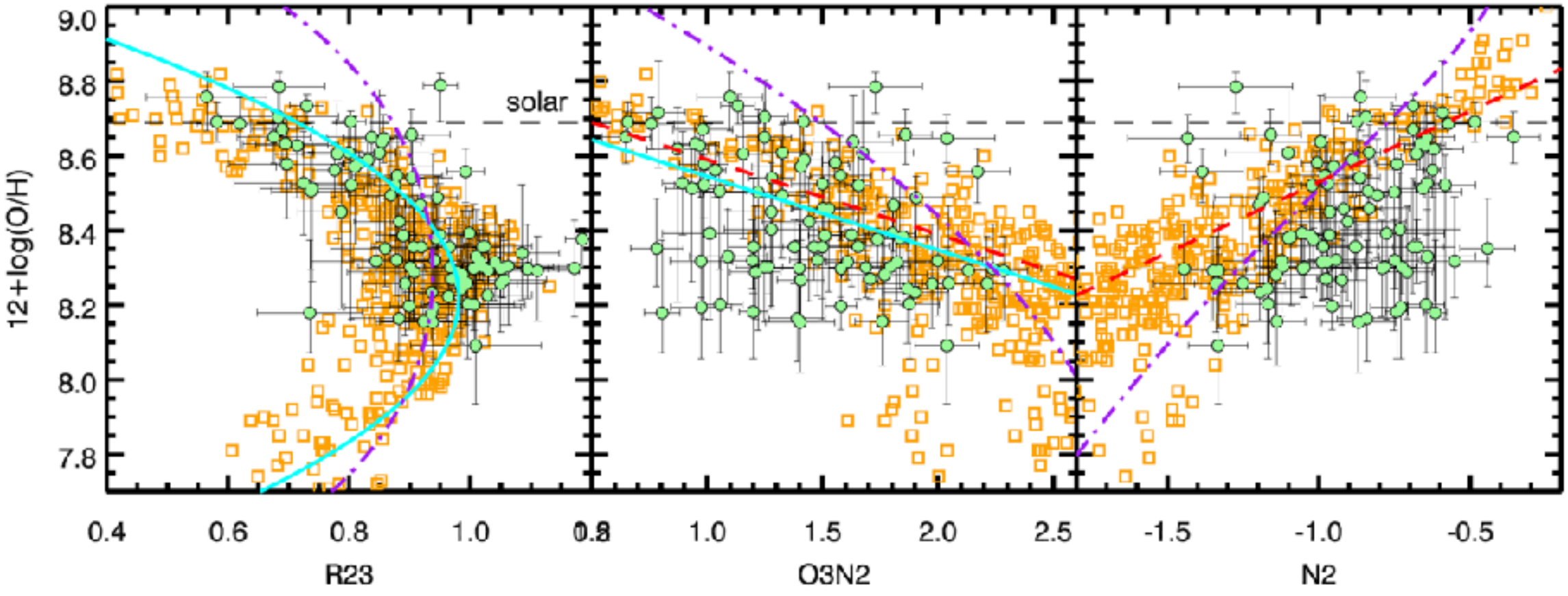


Ionization parameter is the most precisely-determined parameter for over 80% of ***z*~2-3 KBSS galaxies**

Common strong-line indices are (relatively) insensitive to O/H

Strom et al. (in prep.)

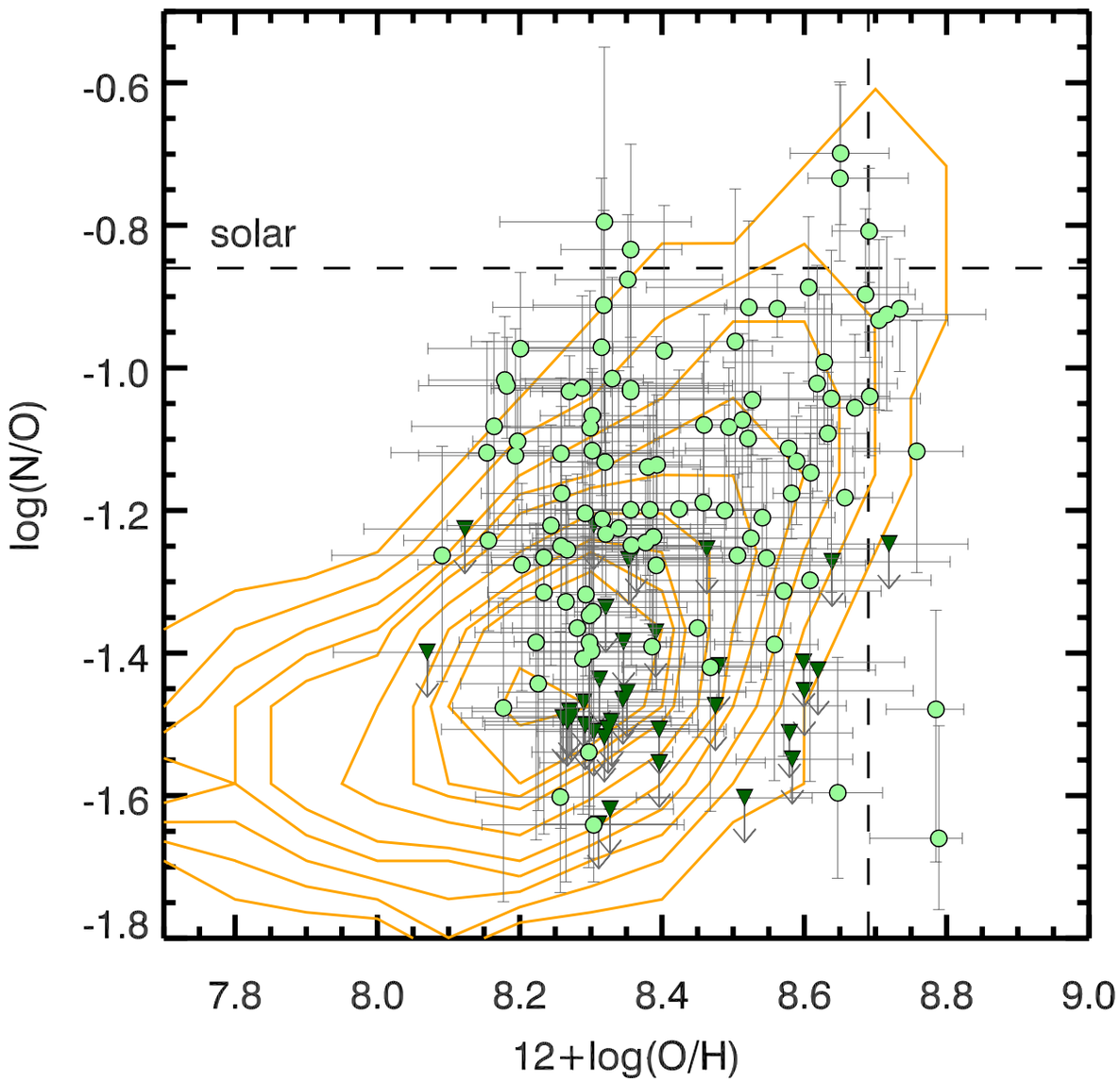
Maiolino+2008
Strom+2017 (based on *z*~0 HII regions)
calibrations from this work



There are still important differences in the way the **nebular spectra of high-*z*** galaxies respond to physical conditions compared to **local HII regions**

Confirming the existence of a single N/O-O/H relation

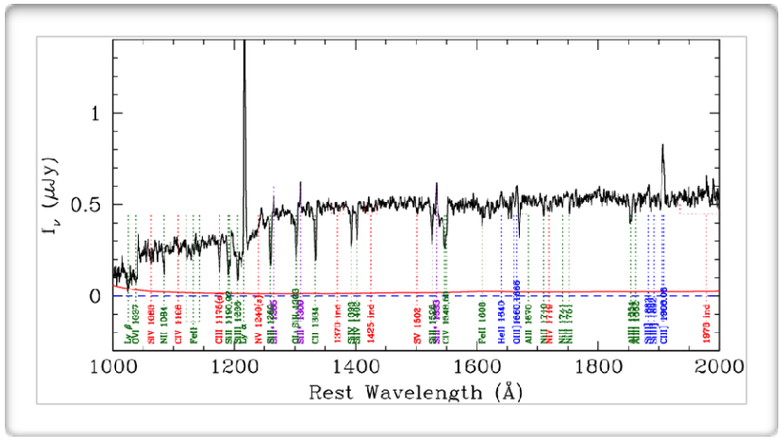
Strom et al. (in prep.)

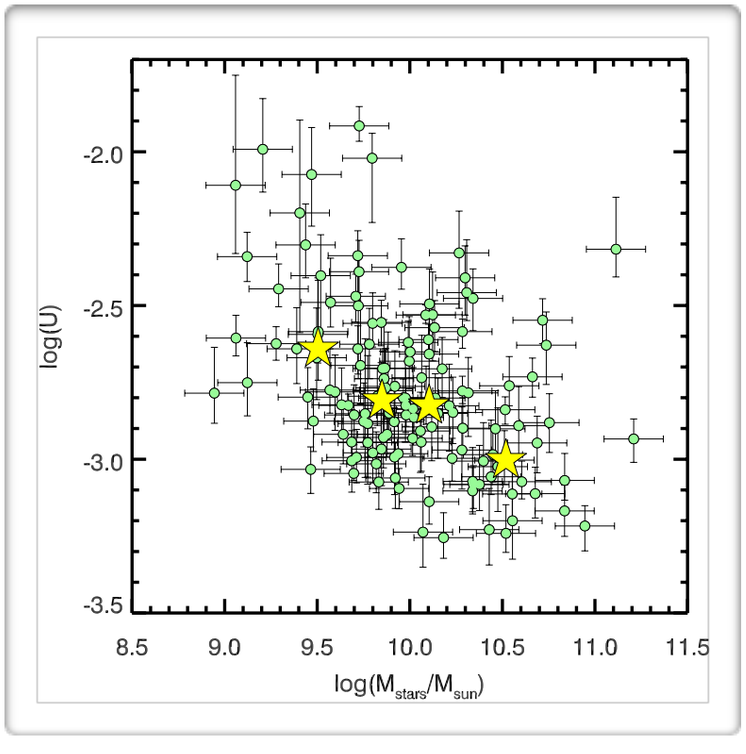


There is a large amount of scatter (a factor of ~2-3!) in log(N/O) at fixed 12+log(O/H) for both **local HII regions** and **high-*z* star-forming galaxies**

Questions for the future

1. *Can we test stellar models using UV+optical spectra of individual galaxies?*
2. *When does this framework break down for galaxies with different SFHs?*
3. *How important are parameter degeneracies when measuring scaling relations?*

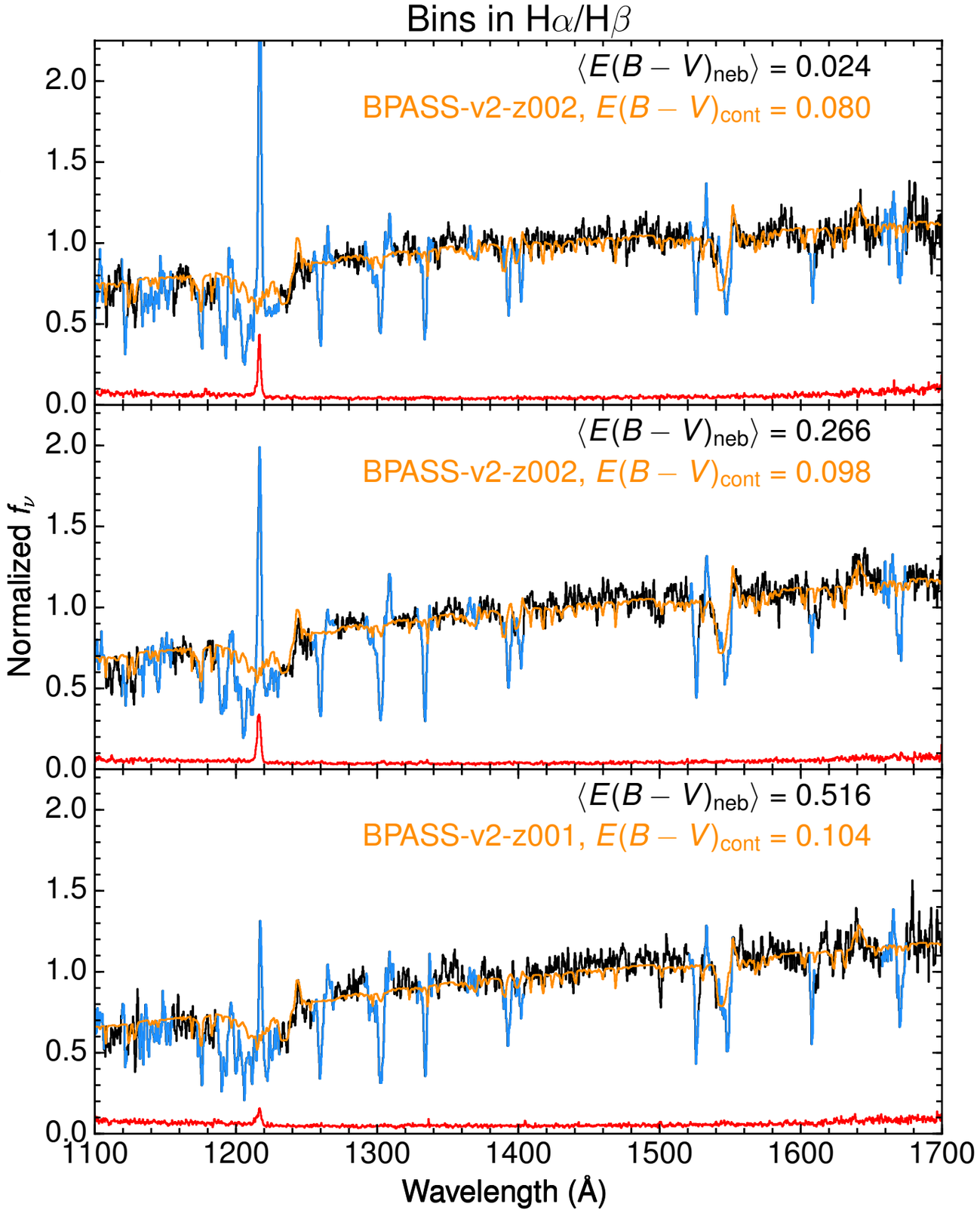




UV+optical dust probes

Theios, Steidel, ALS, et al. (in prep.)

Caltech



Credit: Rick Peterson, W.M. Keck Observatory

What we've learned from the ***Keck Baryonic Structure Survey*** *so far:*

1. *Jointly modeling the rest-UV and rest-optical spectra of z~2-3 galaxies reveals* ***moderate O/H*** *enrichment, but relatively* ***low Fe/H***

2. *Strong-line ratios from z~2-3 galaxy spectra are* ***more sensitive to ionization and excitation*** *than the overall chemical enrichment of the gas (O/H)*

3. ***Abundance patterns*** *(O/Fe, N/O, C/O) determined from UV+optical spectra provide clues about assembly history and stellar populations in young galaxies*

4. *Studies of* ***z~2-3 galaxies are a test-bed for future investigations*** *of z>3 galaxies, where complete rest-UV-optical spectra await JWST*