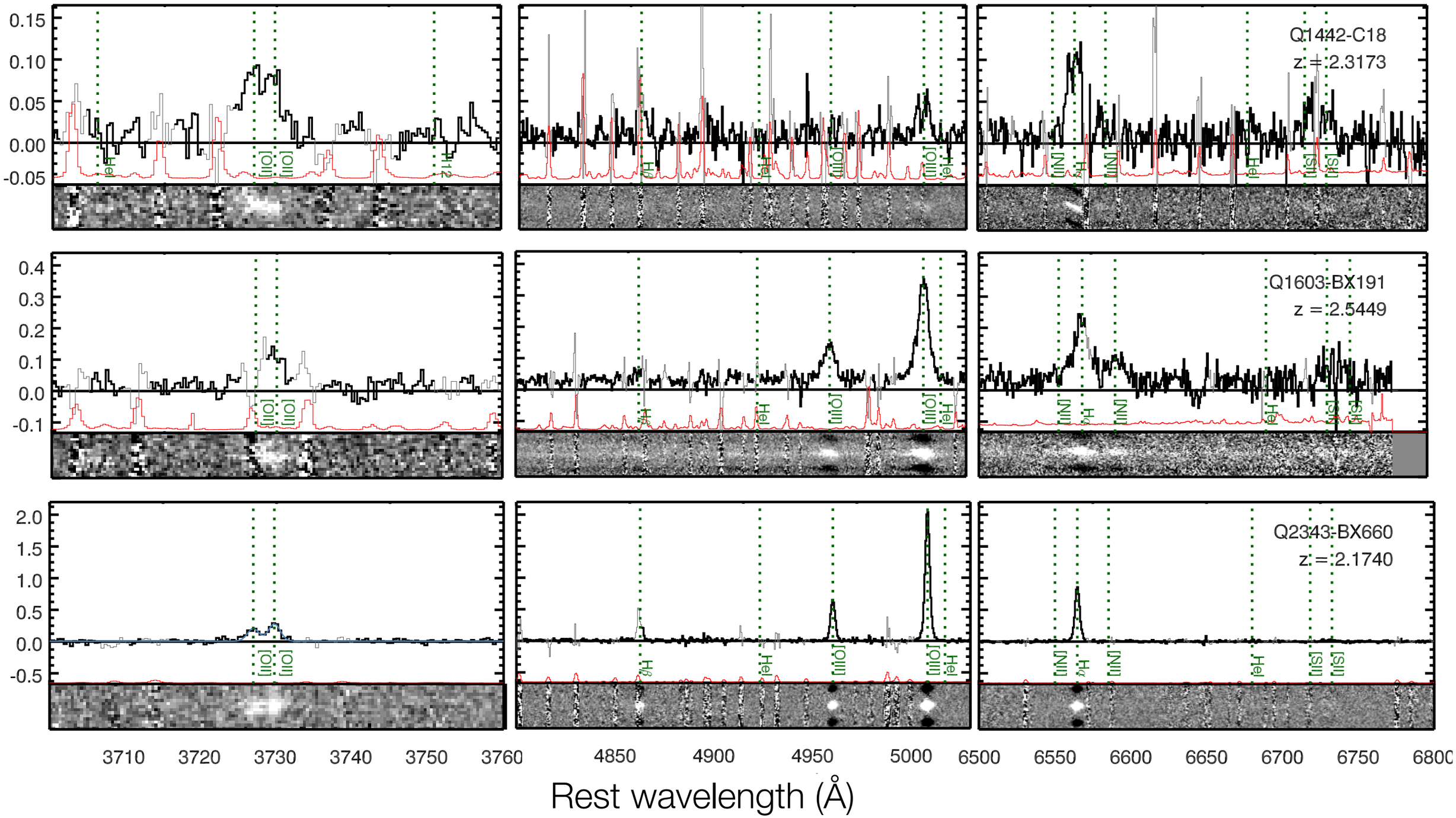
Nebular emission line ratios in z~2-3 star-forming galaxies: ionization, excitation, and N/O ratios in KBSS-MOSFIRE

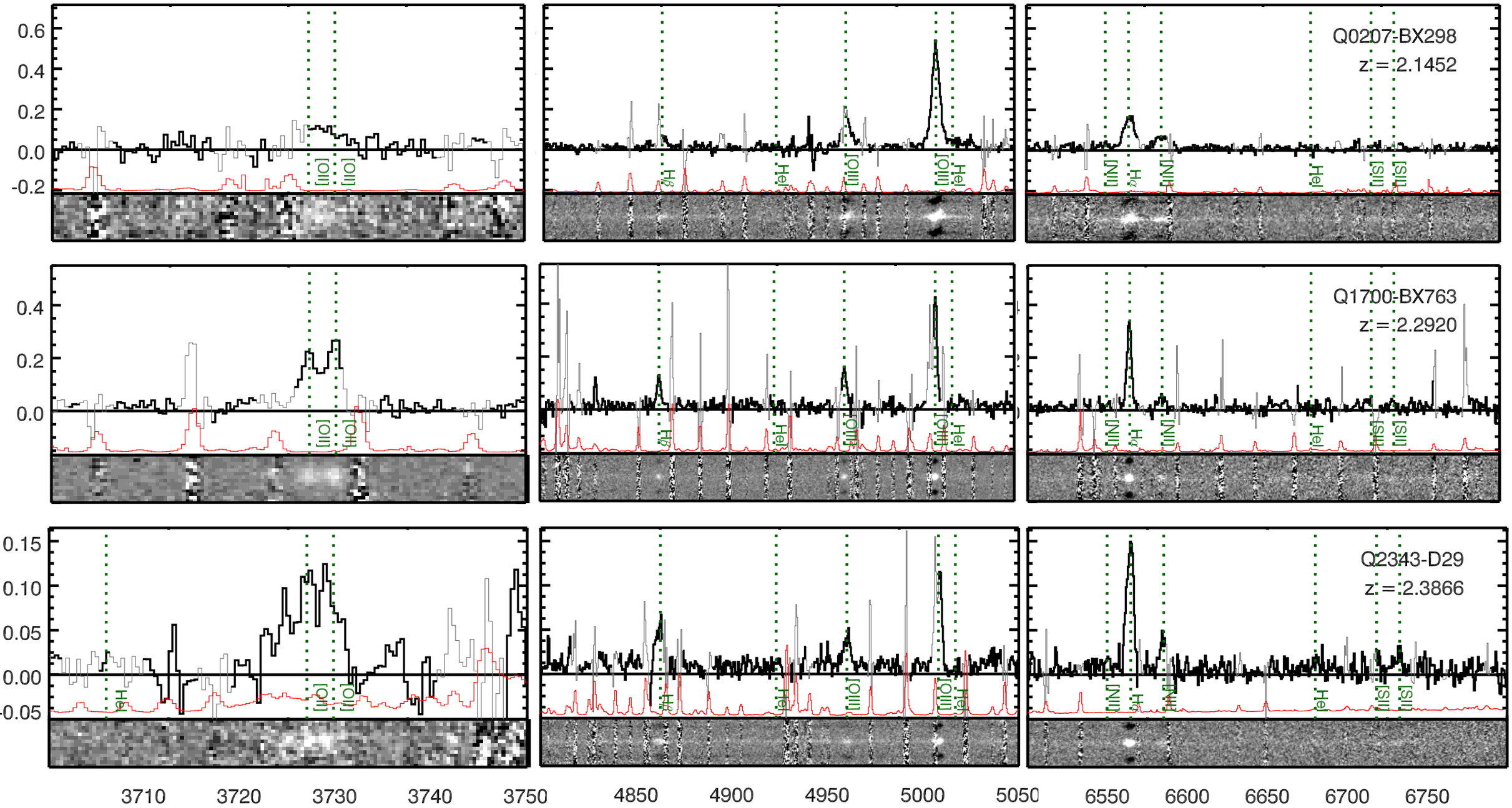
Allison Strom (Caltech)

Chuck Steidel (Caltech)
Gwen Rudie (Carnegie)
Ryan Trainor (UC Berkeley)
Max Pettini (IoA Cambridge)
Naveen Reddy (UC Riverside)

Good SNR rest-optical spectra available for individual galaxies



Good SNR rest-optical spectra available for individual galaxies



Keck Baryonic Structure Survey (KBSS)

Centered on 15 of the brightest quasars in the sky (total area = 0.24 deg^2)

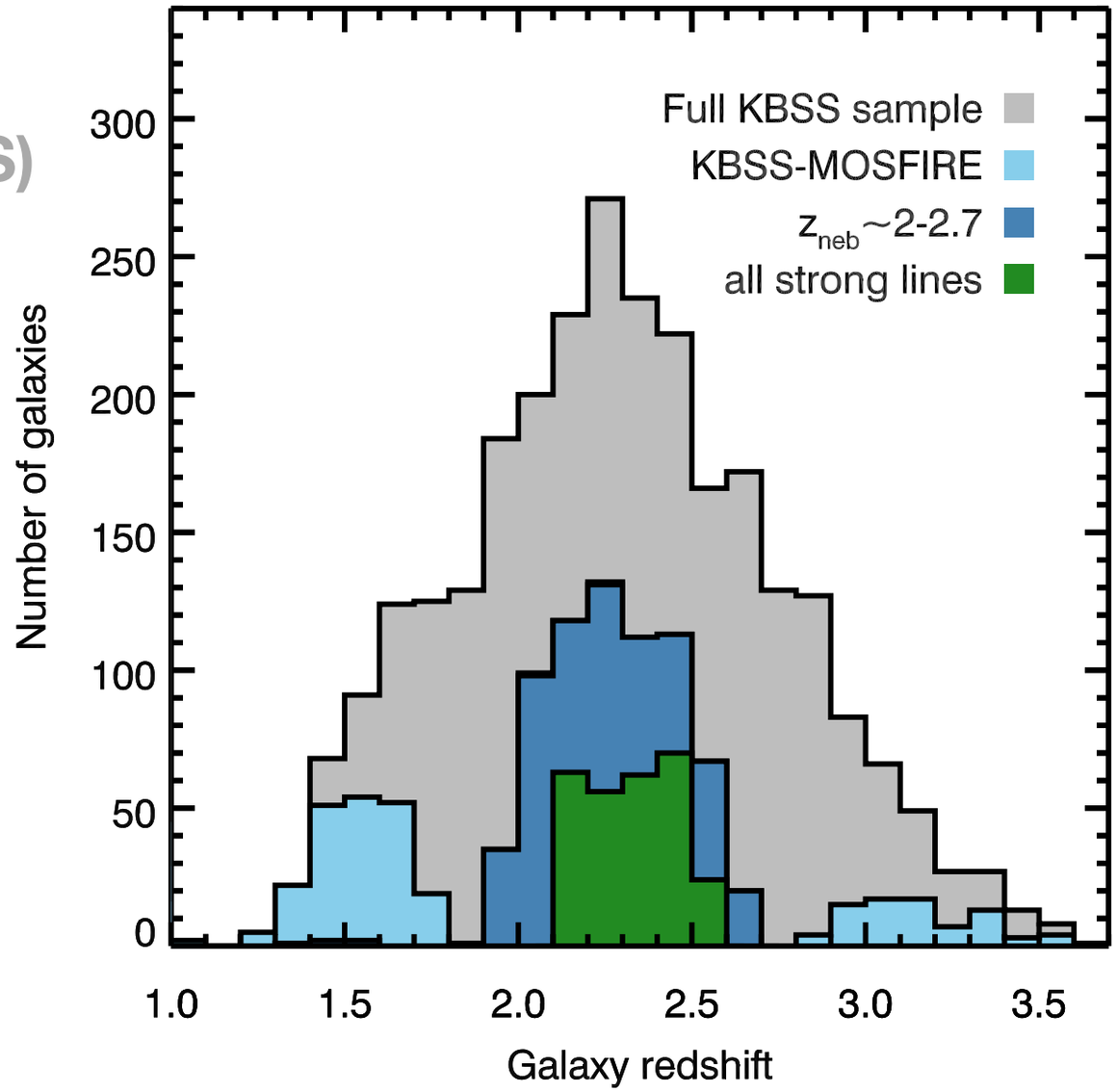
Spectroscopic observations:

- **2354 with rest-UV spectra (LRIS)**
- **1097 with rest-optical spectra**

  40 nights with MOSFIRE since commissioning in June 2012

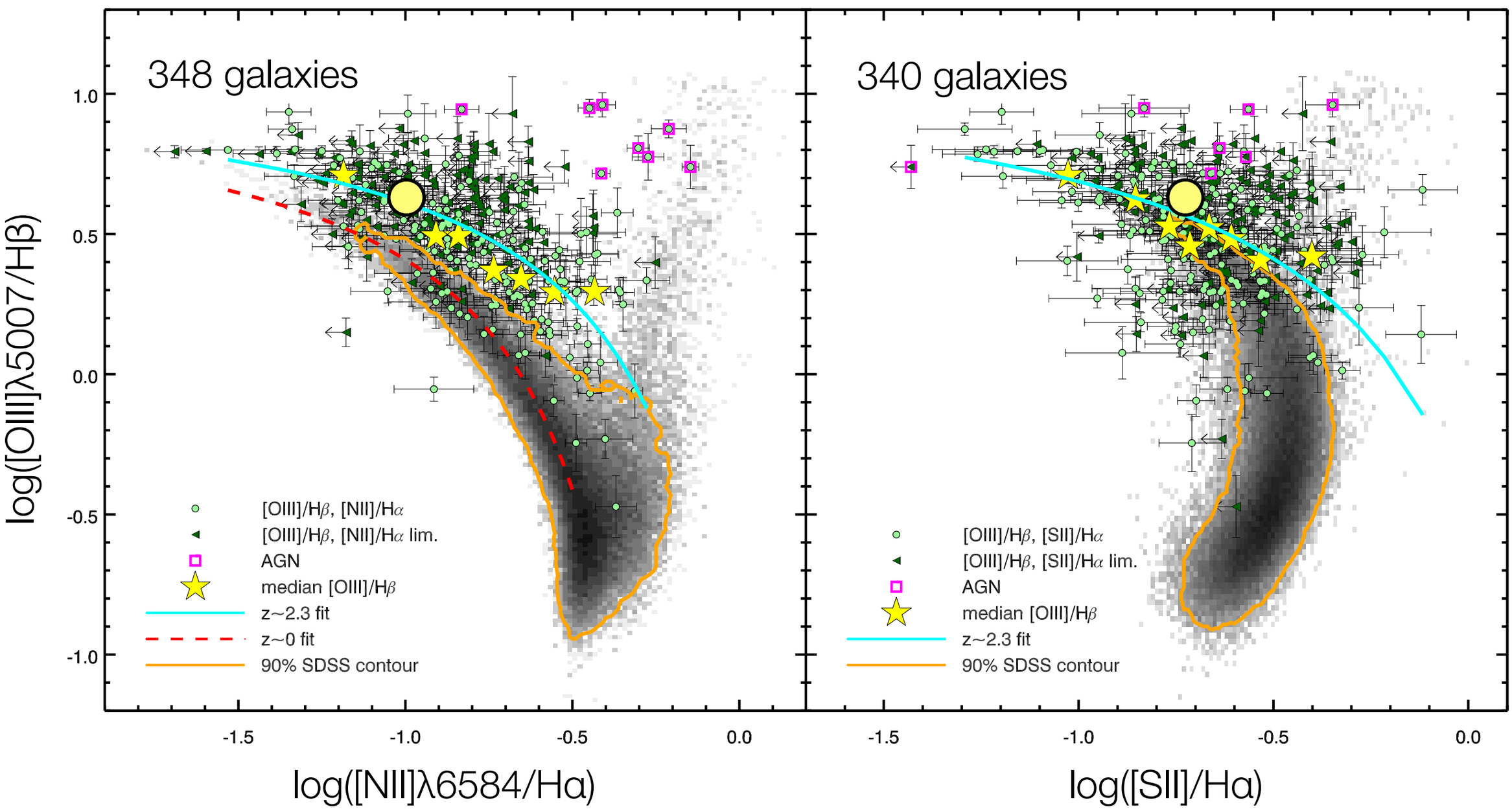
>700 galaxies with $z \simeq 2$-2.7 have at least one MOSFIRE spectrum

275 galaxies with good detections of many of the strong diagnostic emission lines

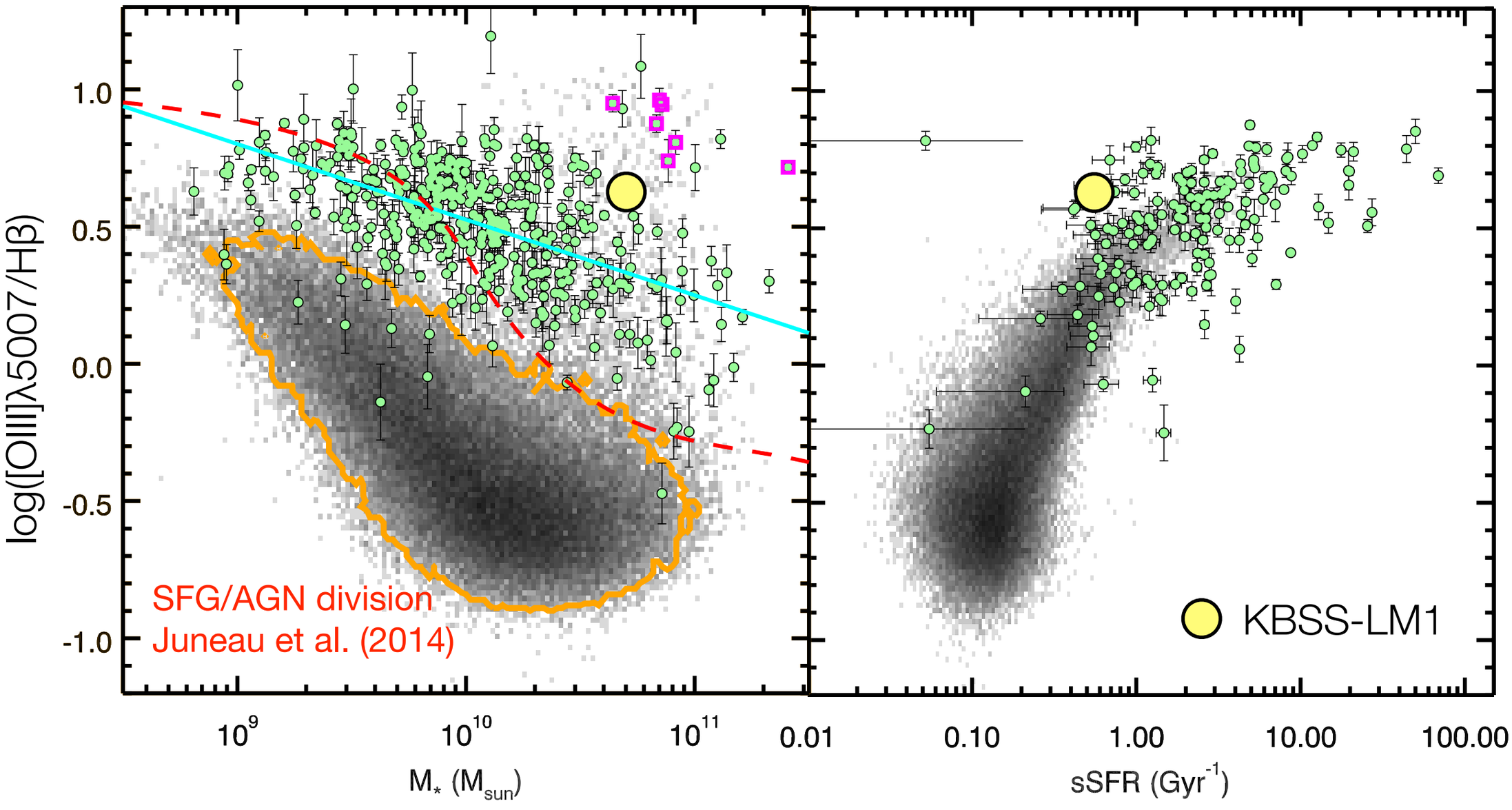


BPT diagrams for z~2-3 star-forming galaxies

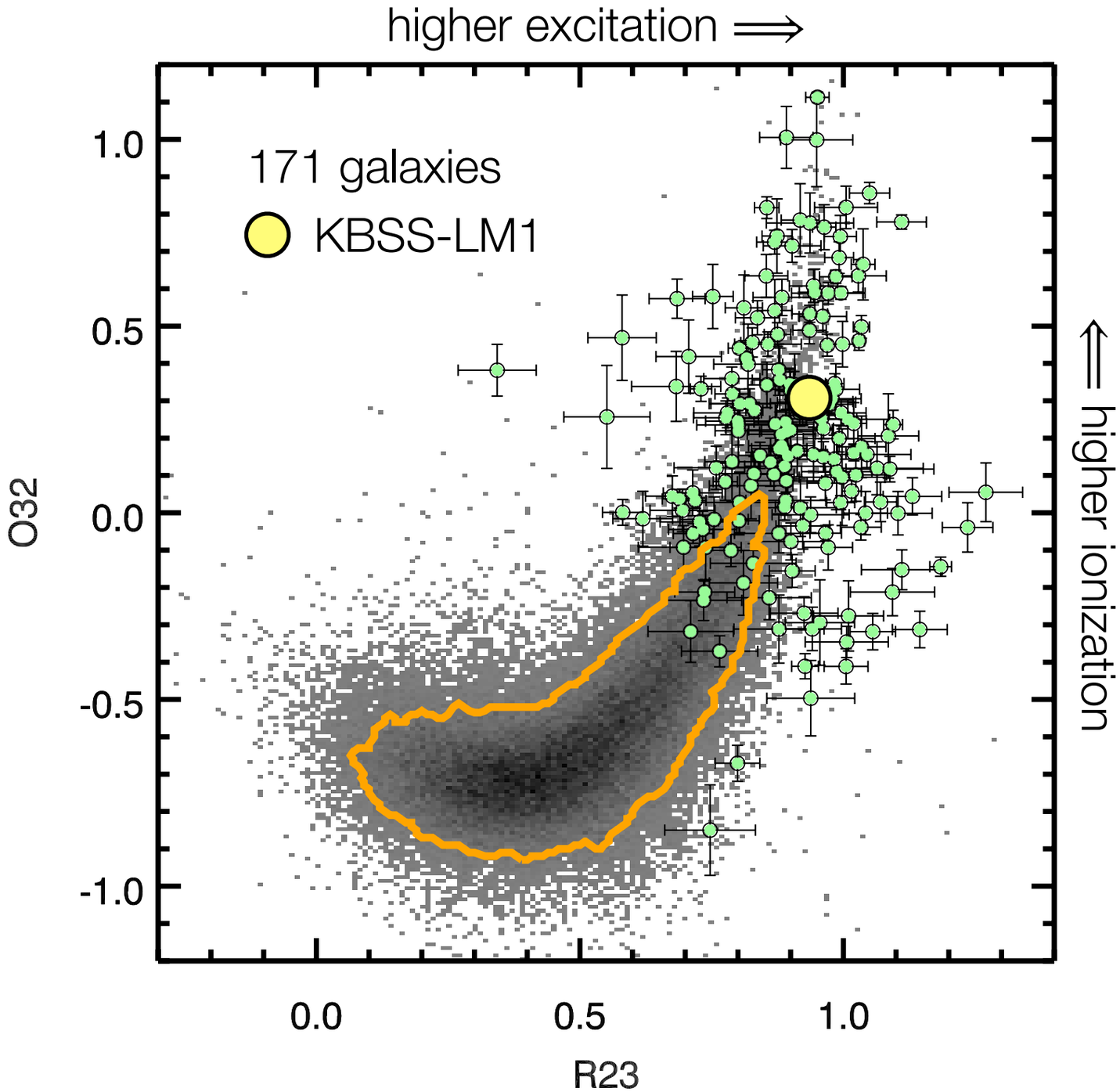
Strom et al. (in prep.)

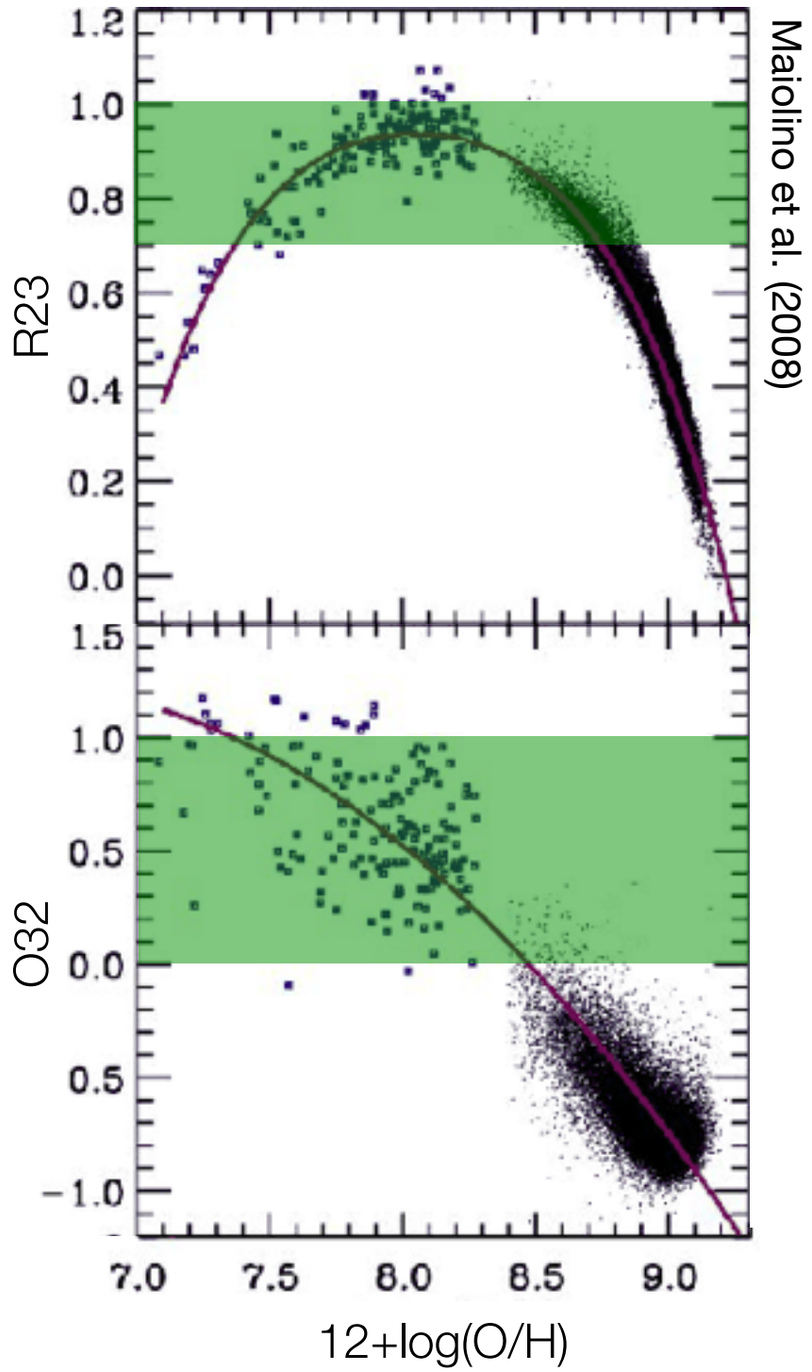


[OIII]λ5007/Hβ with galaxy properties

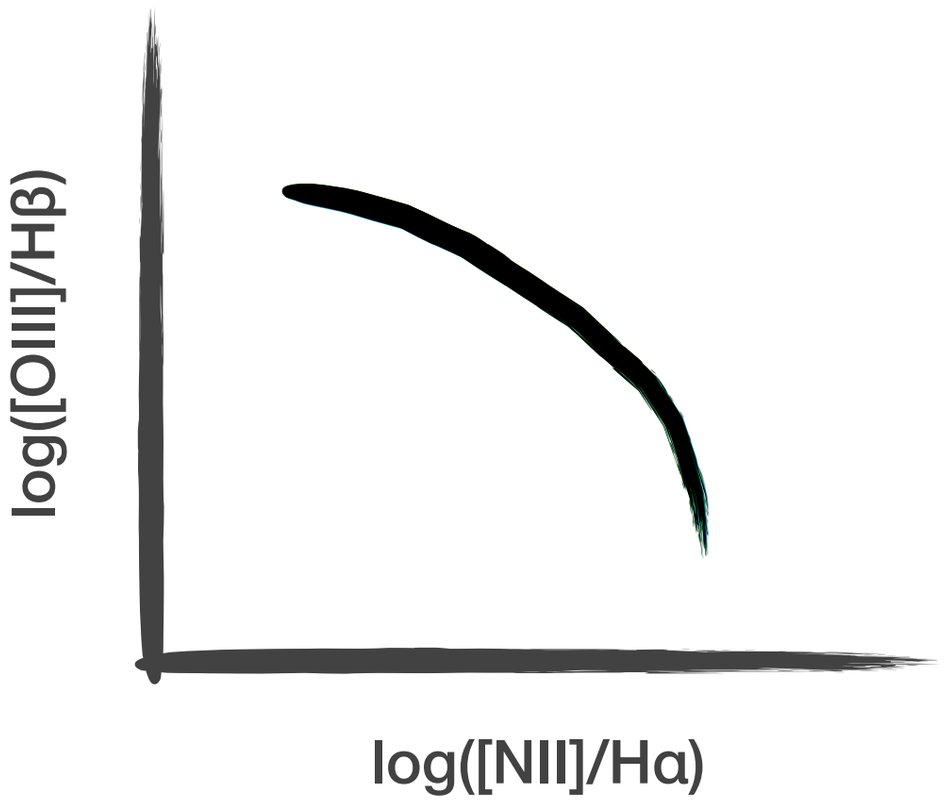


O32 vs. R23: powerful probe of ionization and excitation





How can we collectively explain these observations?



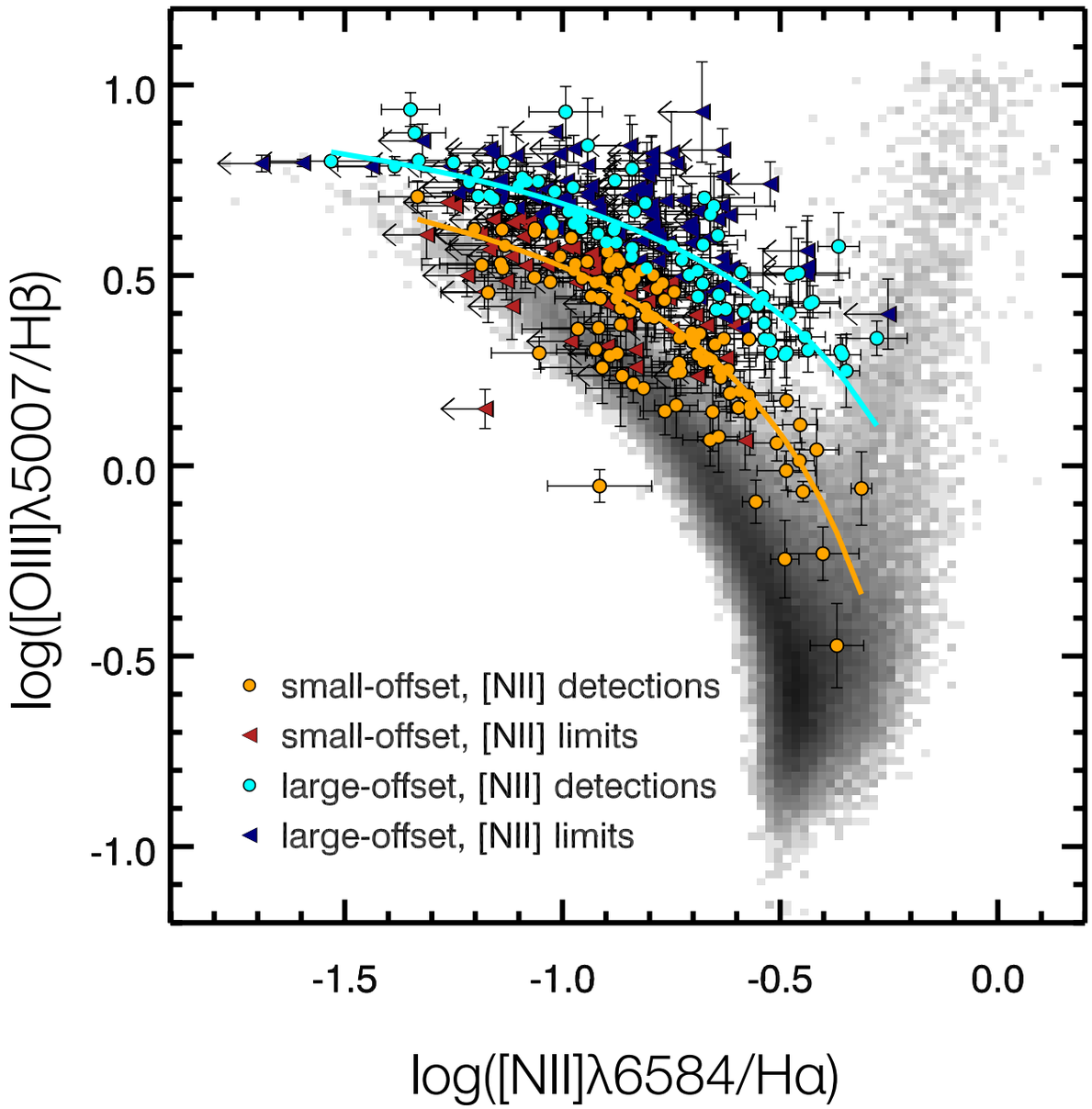
harder ionizing radiation

more ionizing photons
(e.g., Kewley+15)

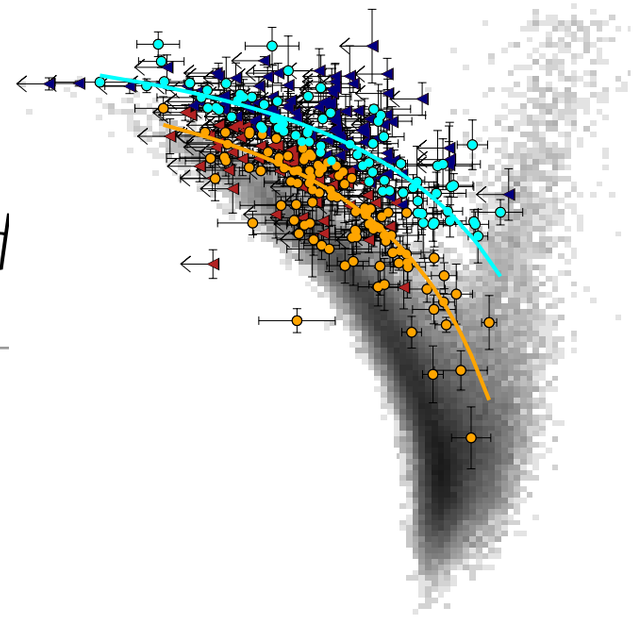
enhanced N/O at fixed O/H
(e.g., Masters+14, Shapley+15, Sanders+16, Masters+16)

Properties of large-offset galaxies reveal important differences

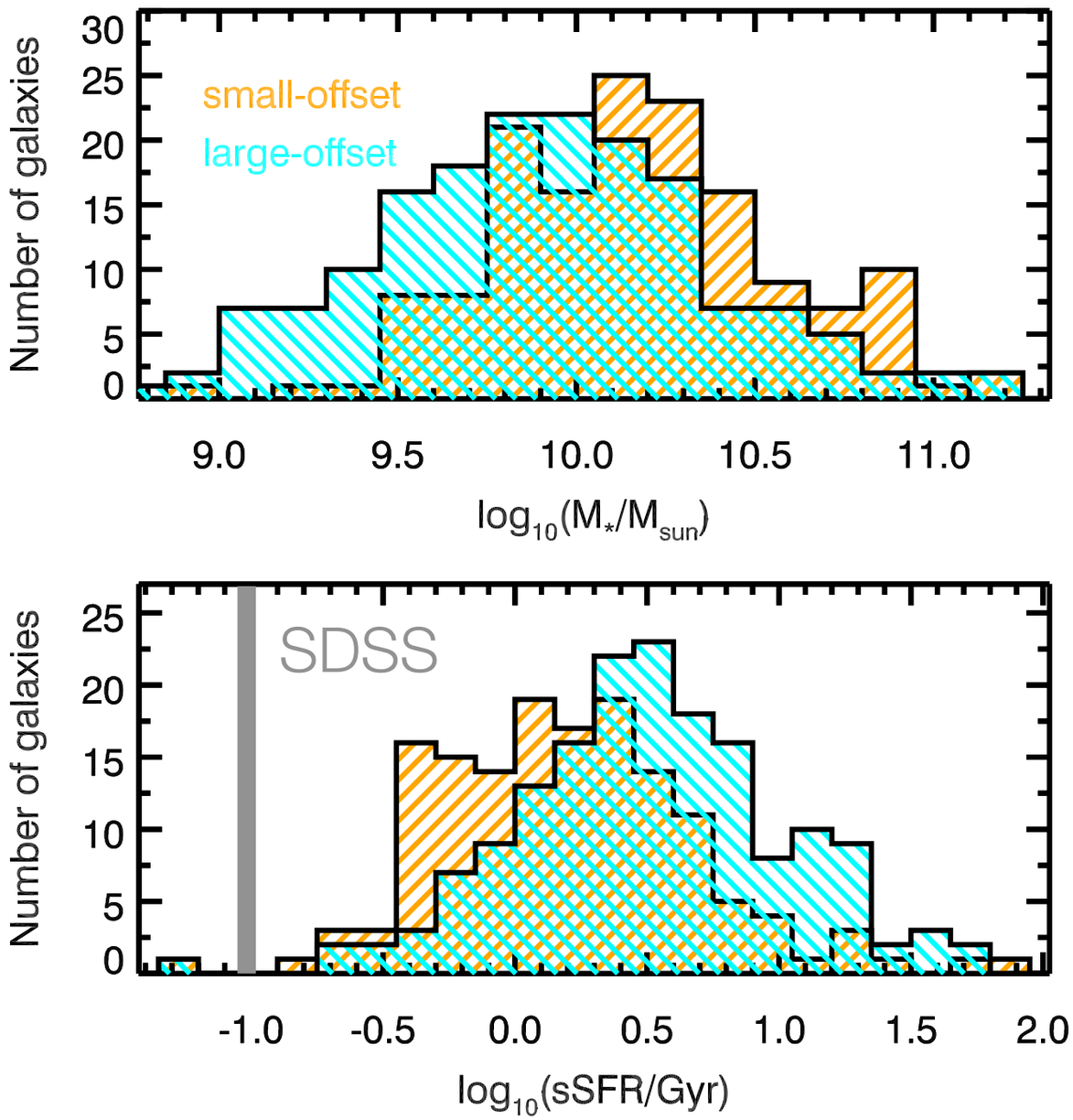
Strom et al. (in prep.)



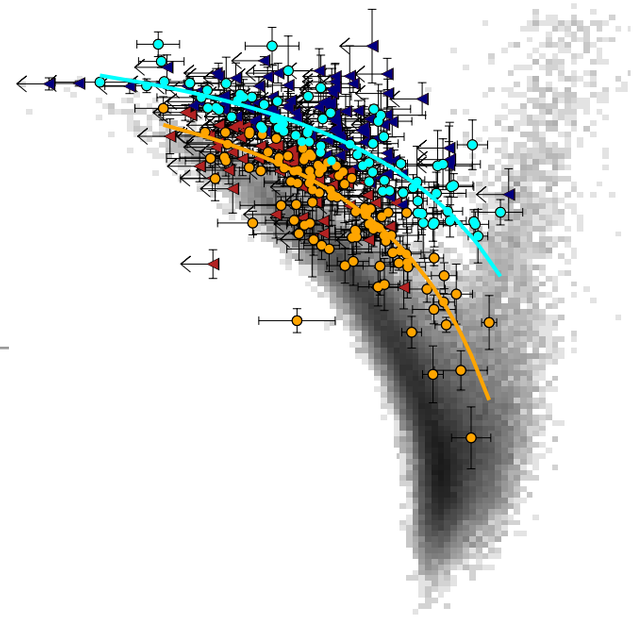
Large-offset galaxies less massive, but more SF-dominated



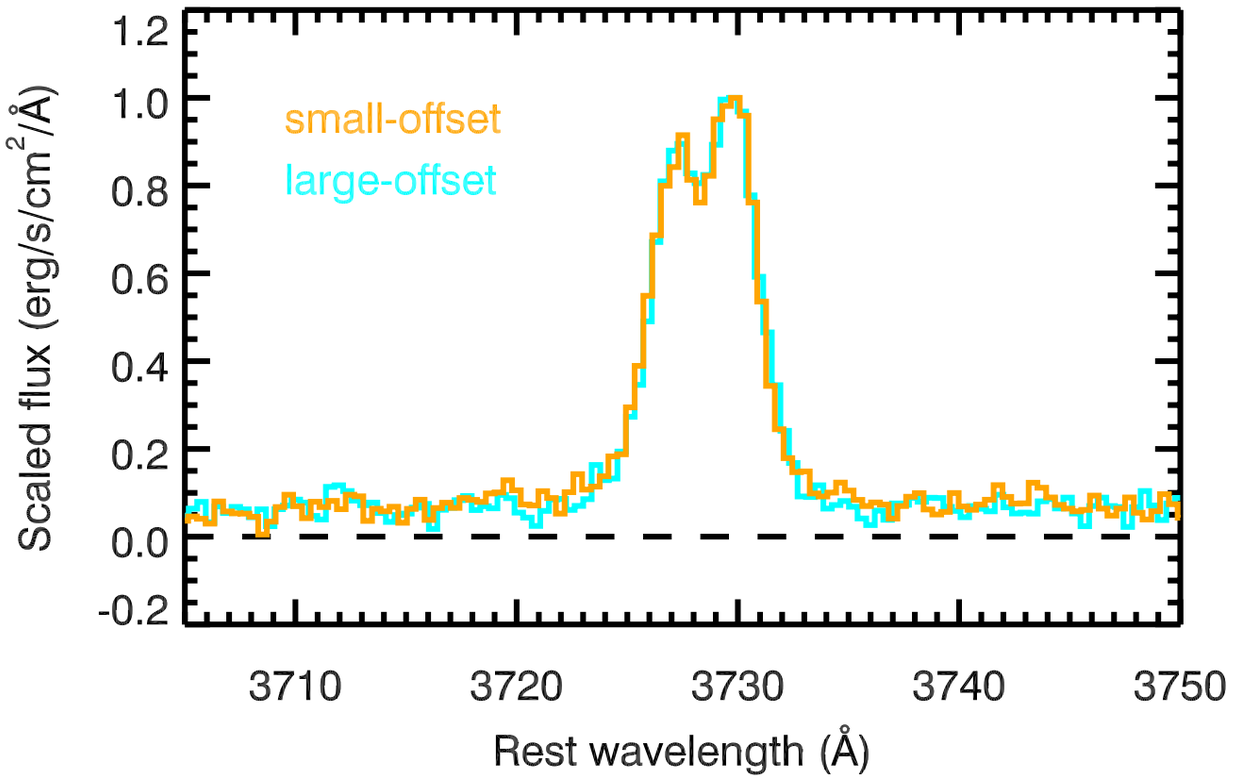
Strom et al. (in prep.)



KBSS-MOSFIRE galaxies have similar densities



Strom et al. (in prep.)

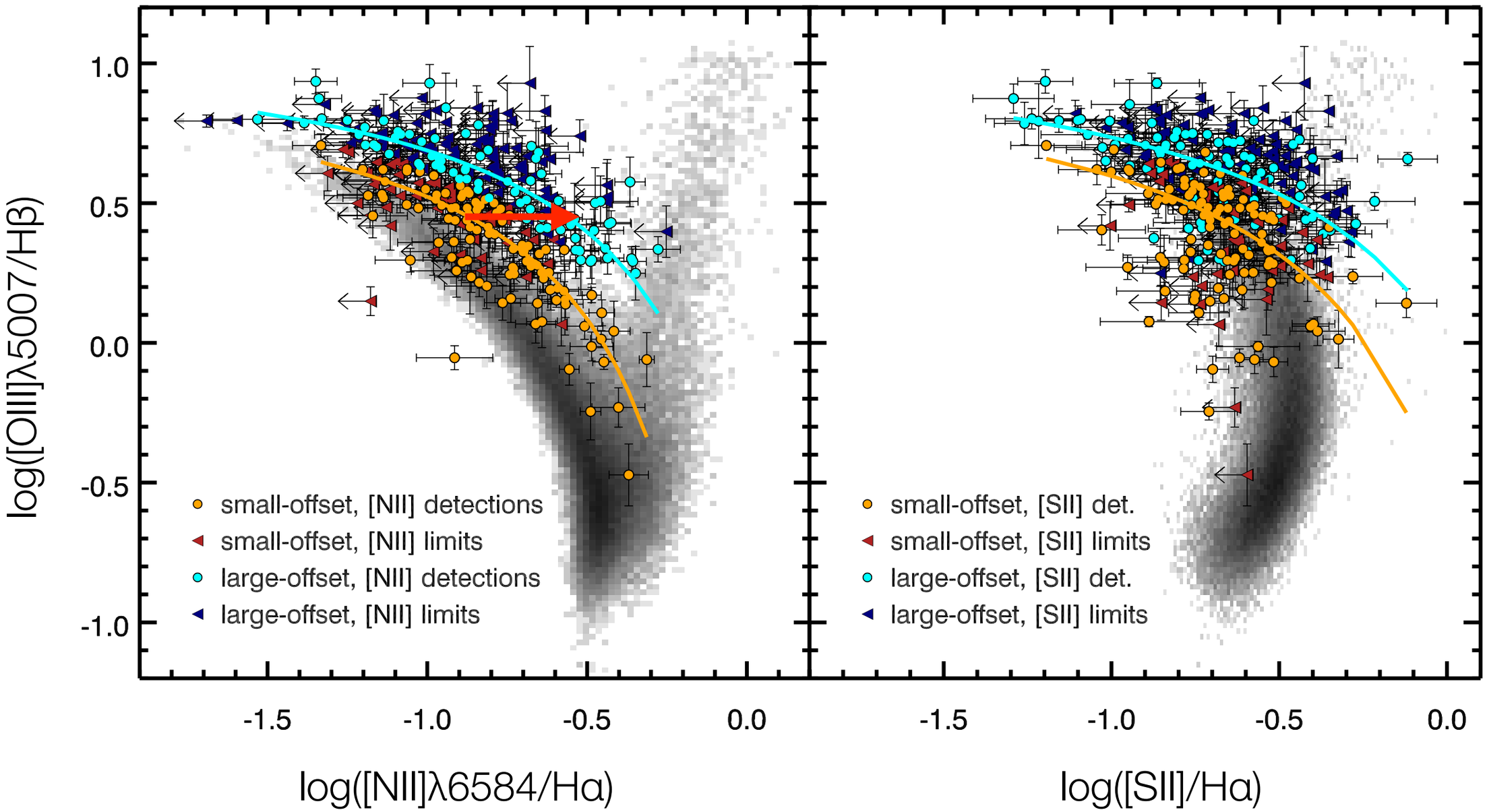


$$n_{e,\mathrm{small}} = 290^{+39}_{-36}\ \mathrm{cm}^{-3}$$

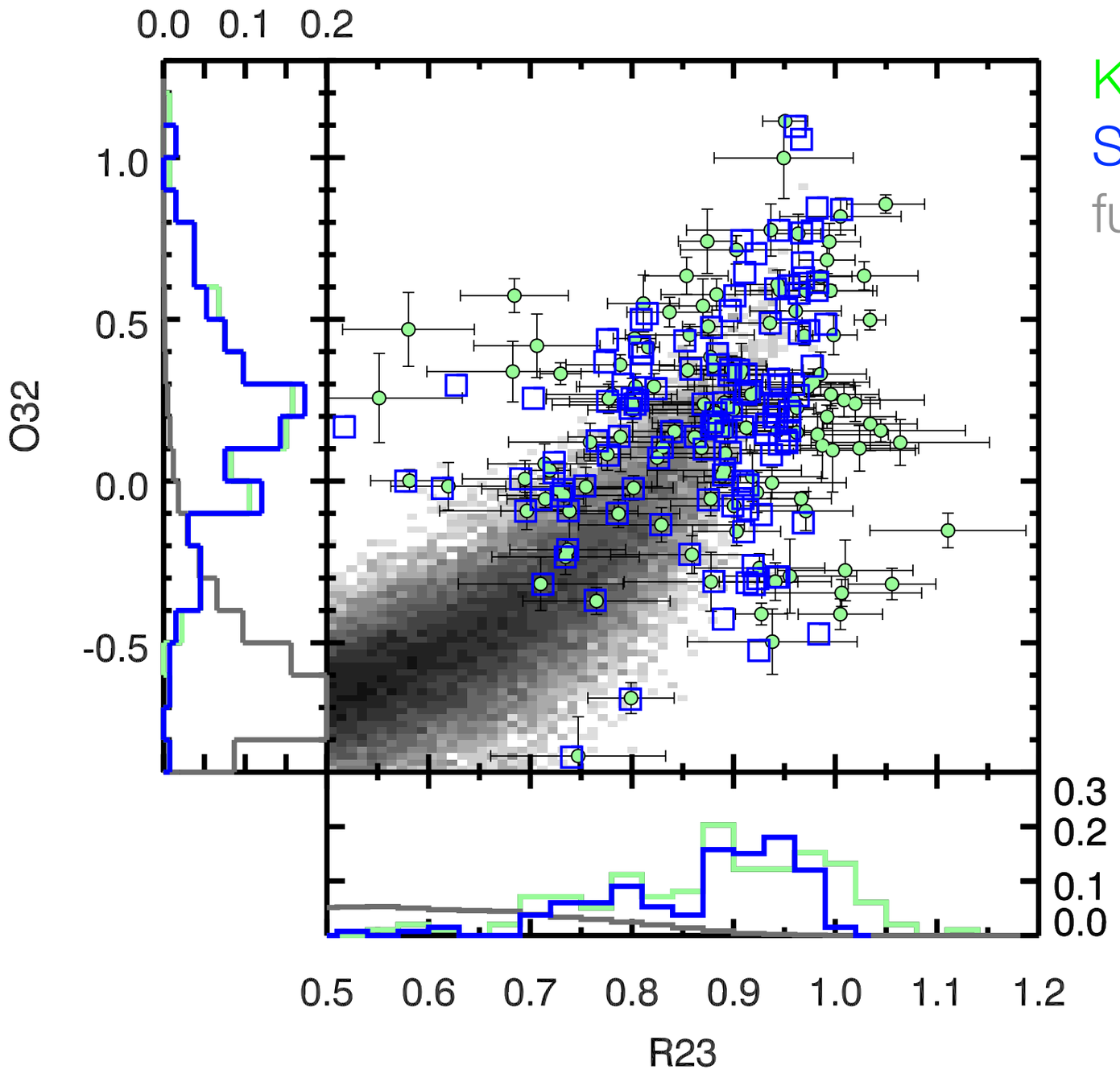
$$n_{e,\mathrm{large}} = 232^{+34}_{-32}\ \mathrm{cm}^{-3}$$

Evidence for higher excitation at fixed gas-phase abundance

Strom et al. (in prep.)



SDSS "twins" selected to match KBSS-MOSFIRE in O32 and R23



Strom et al. (in prep.)

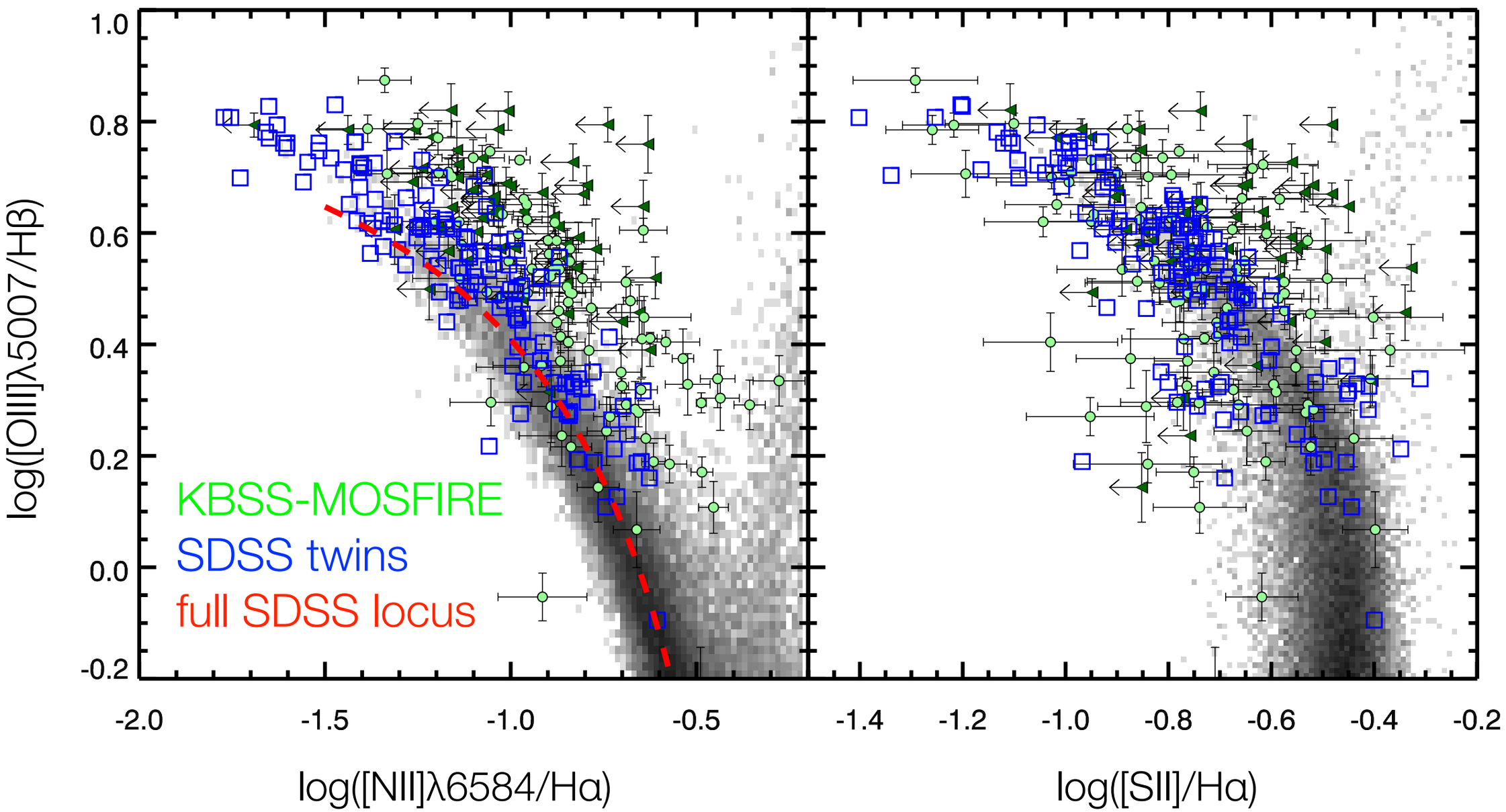
KBSS-MOSFIRE

SDSS twins

full SDSS sample

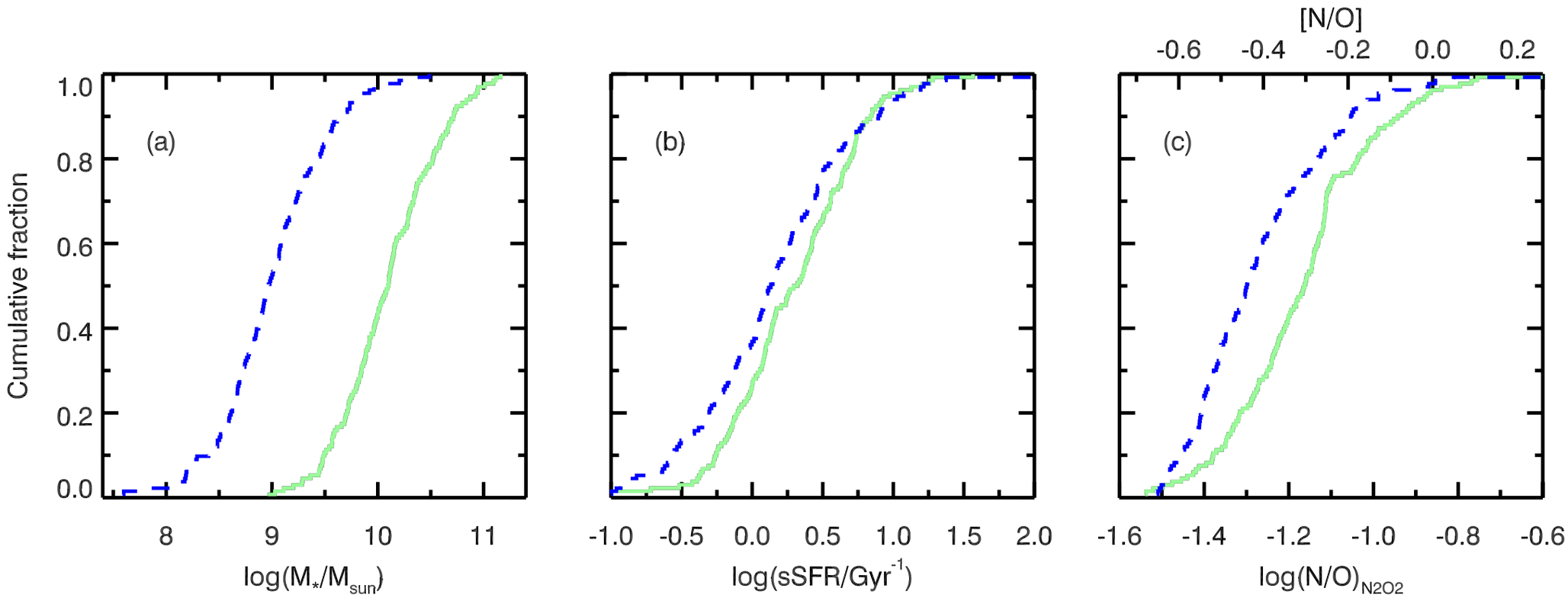
High-z galaxies still exhibit offset in N2 BPT

Strom et al. (in prep.)



Offset consistent with an increase in N/O

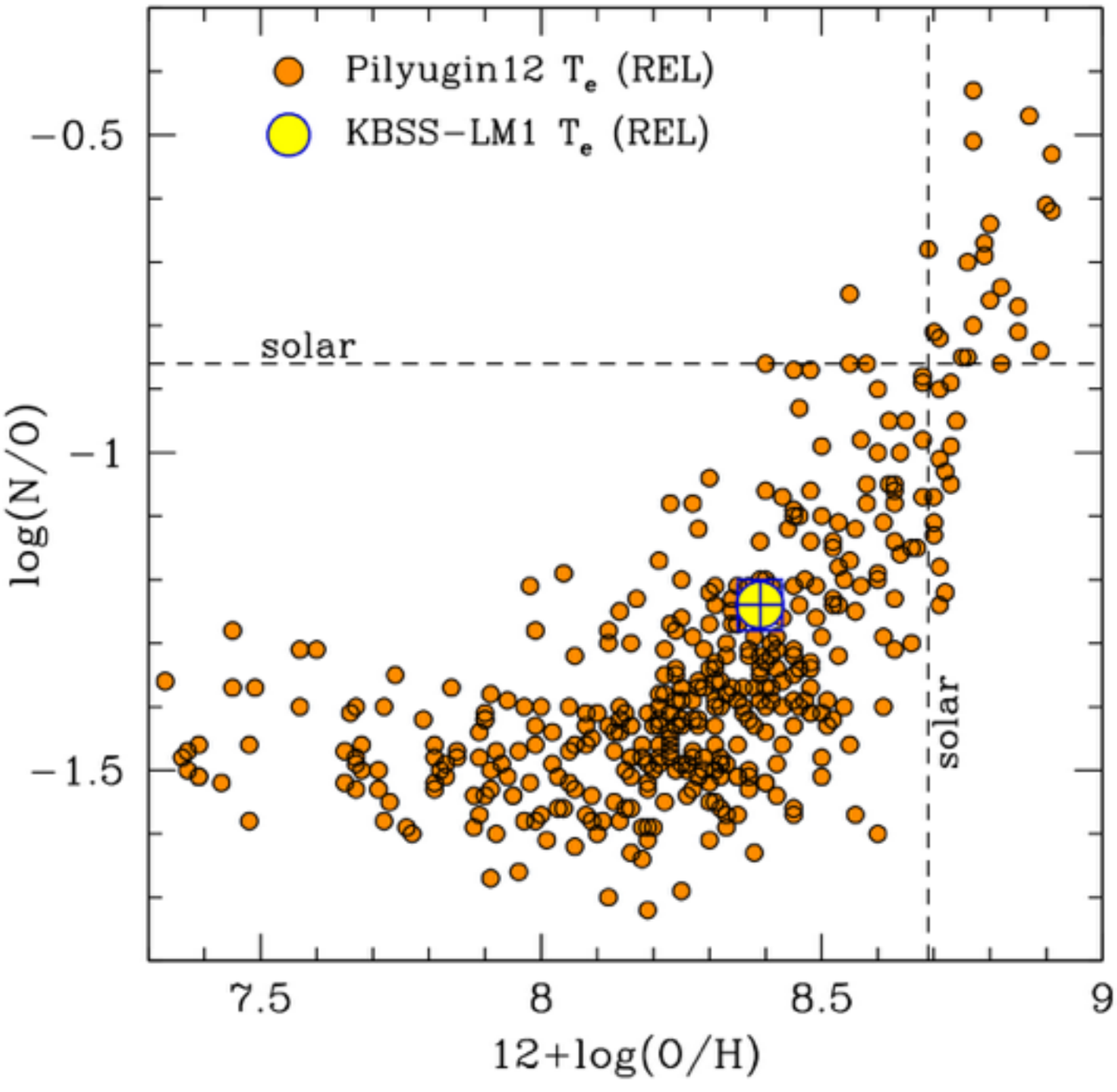
Strom et al. (in prep.)



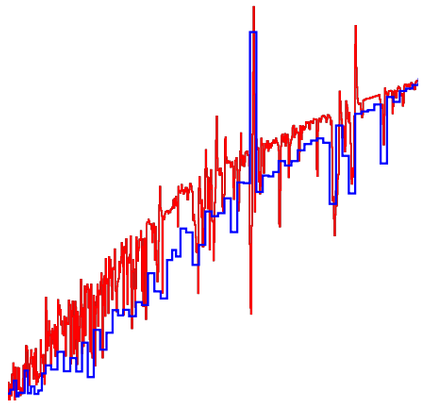
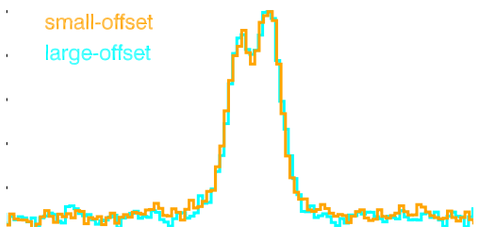
- **KBSS-MOSFIRE galaxies**
  - are **10 times more massive** than **SDSS twins**
  - have **higher sSFRs** than **SDSS twins**
  - have **higher N/O ratios** than **SDSS twins**

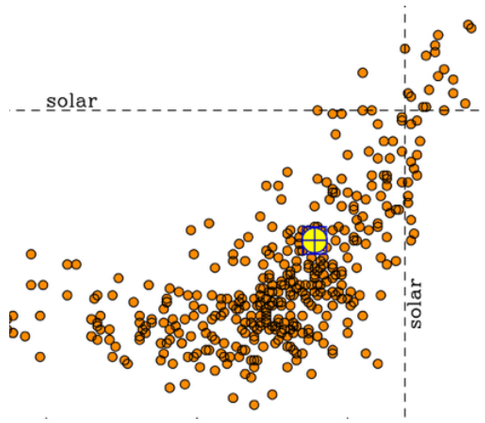
Evidence for similar abundance patterns in all galaxies

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

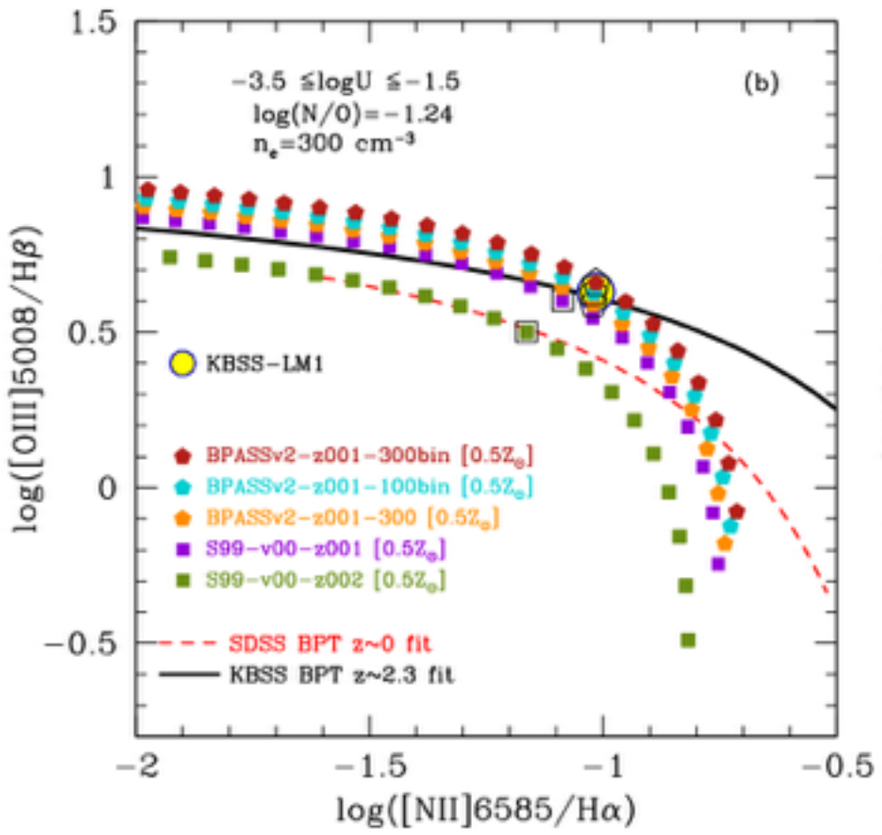


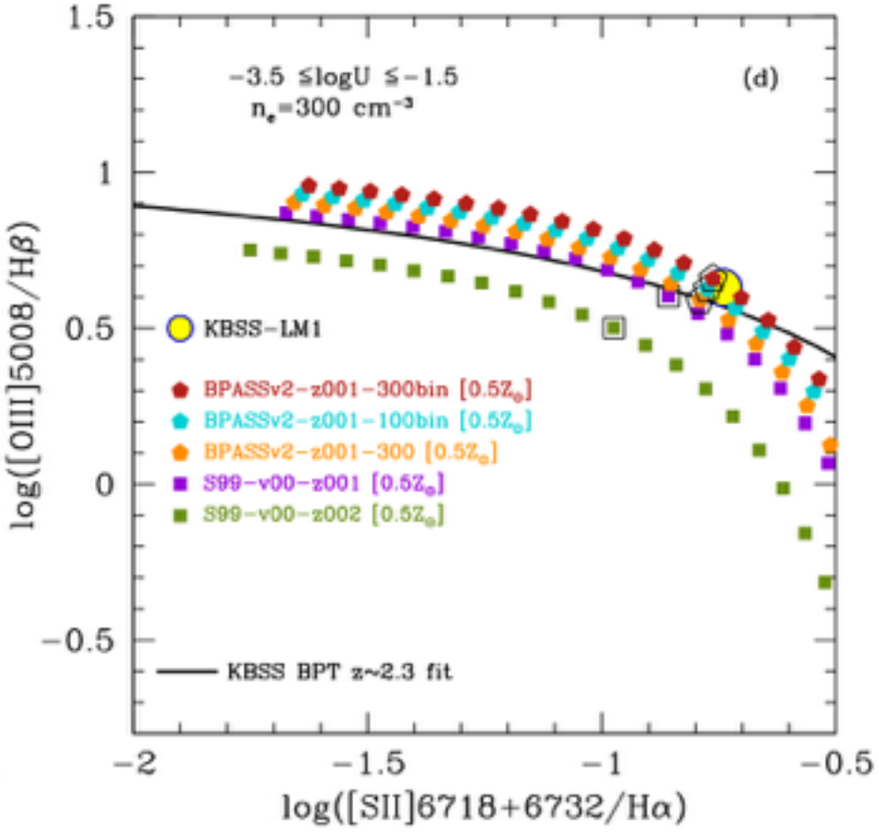
Contraining log(U) and Z_{neb} with photoionization models

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

+ 

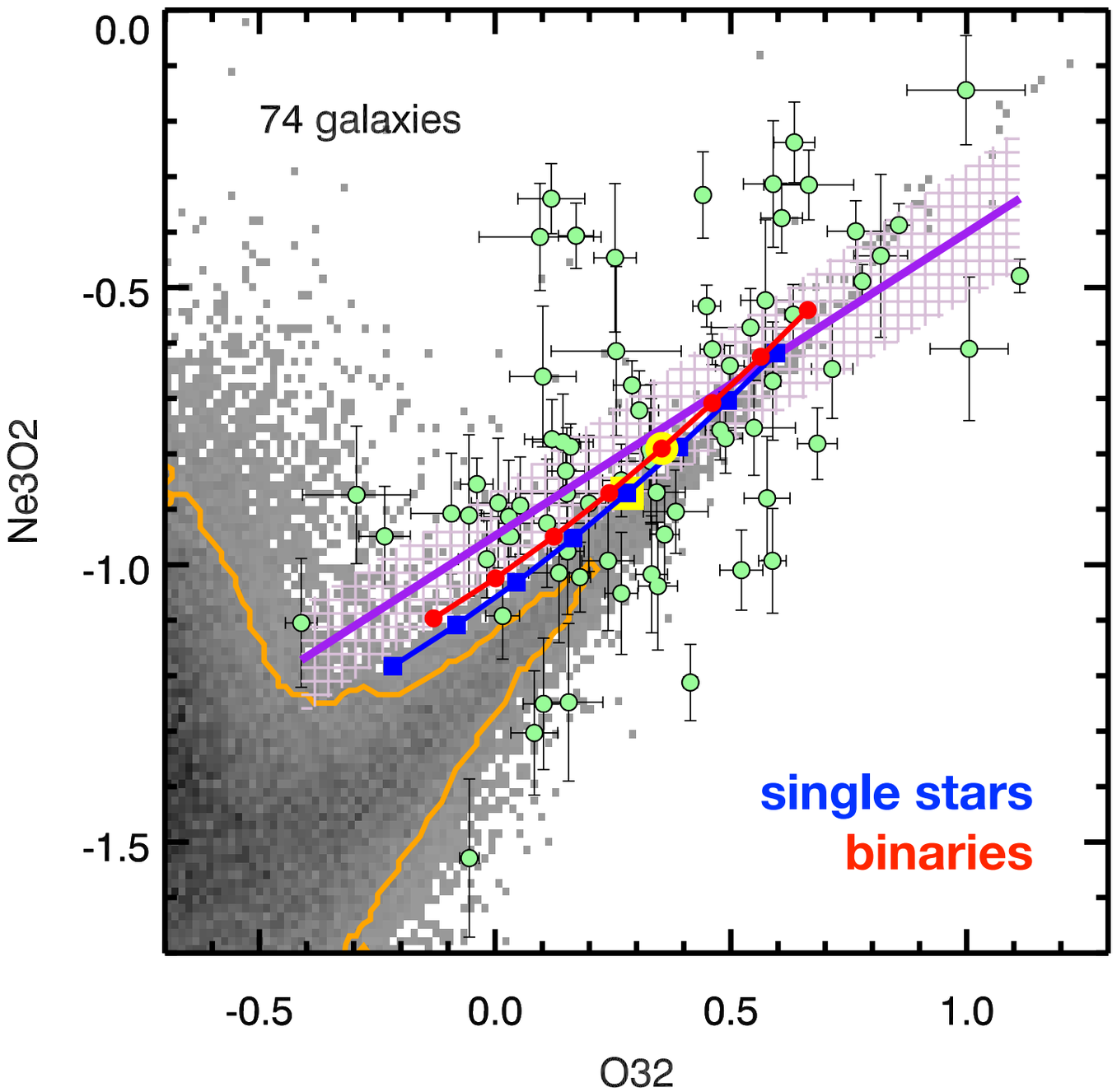
shape of EUV **electron density** **N/O ratio**





Ionization parameter with Ne3O2 and O32

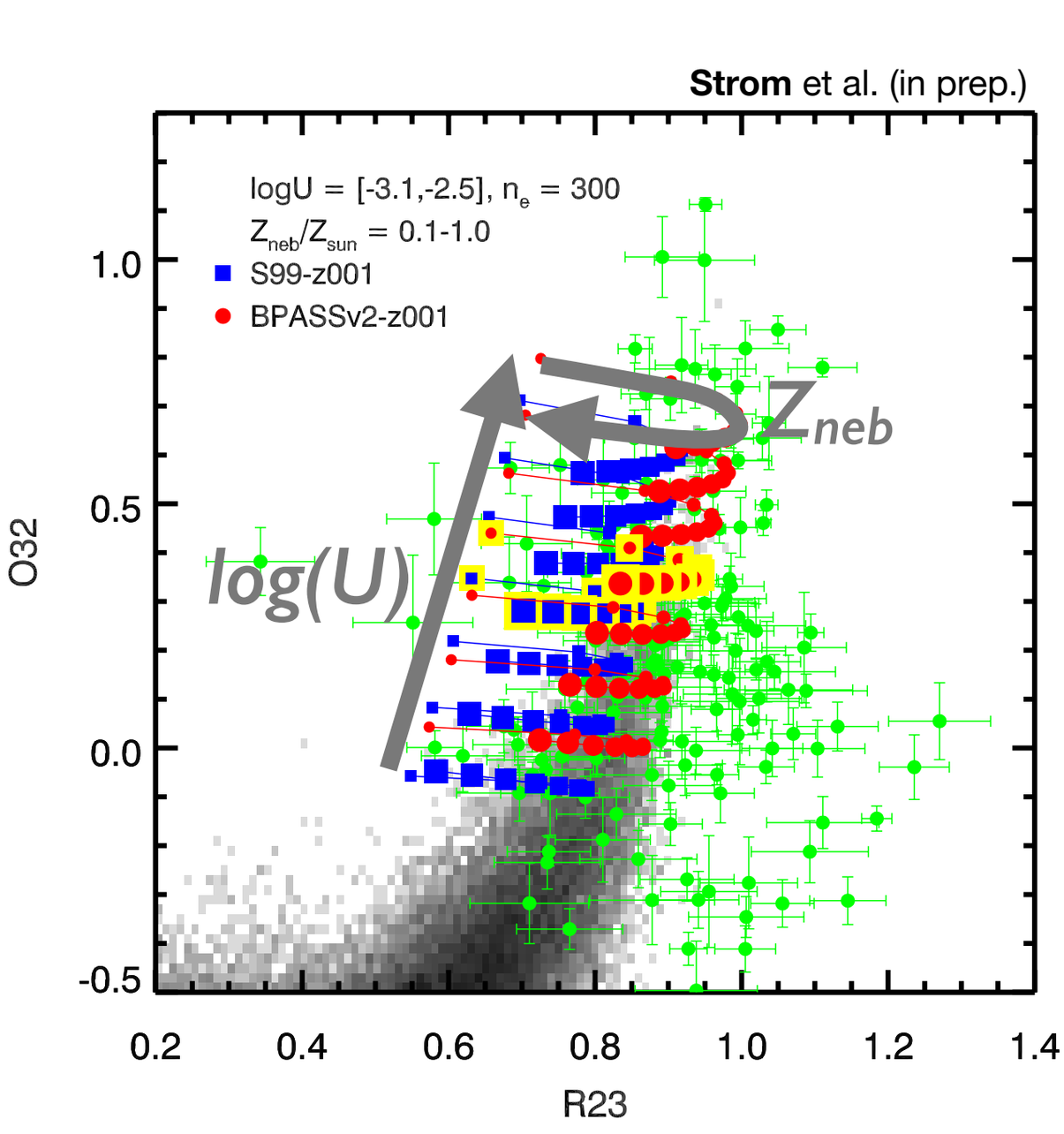
Strom et al. (in prep.)

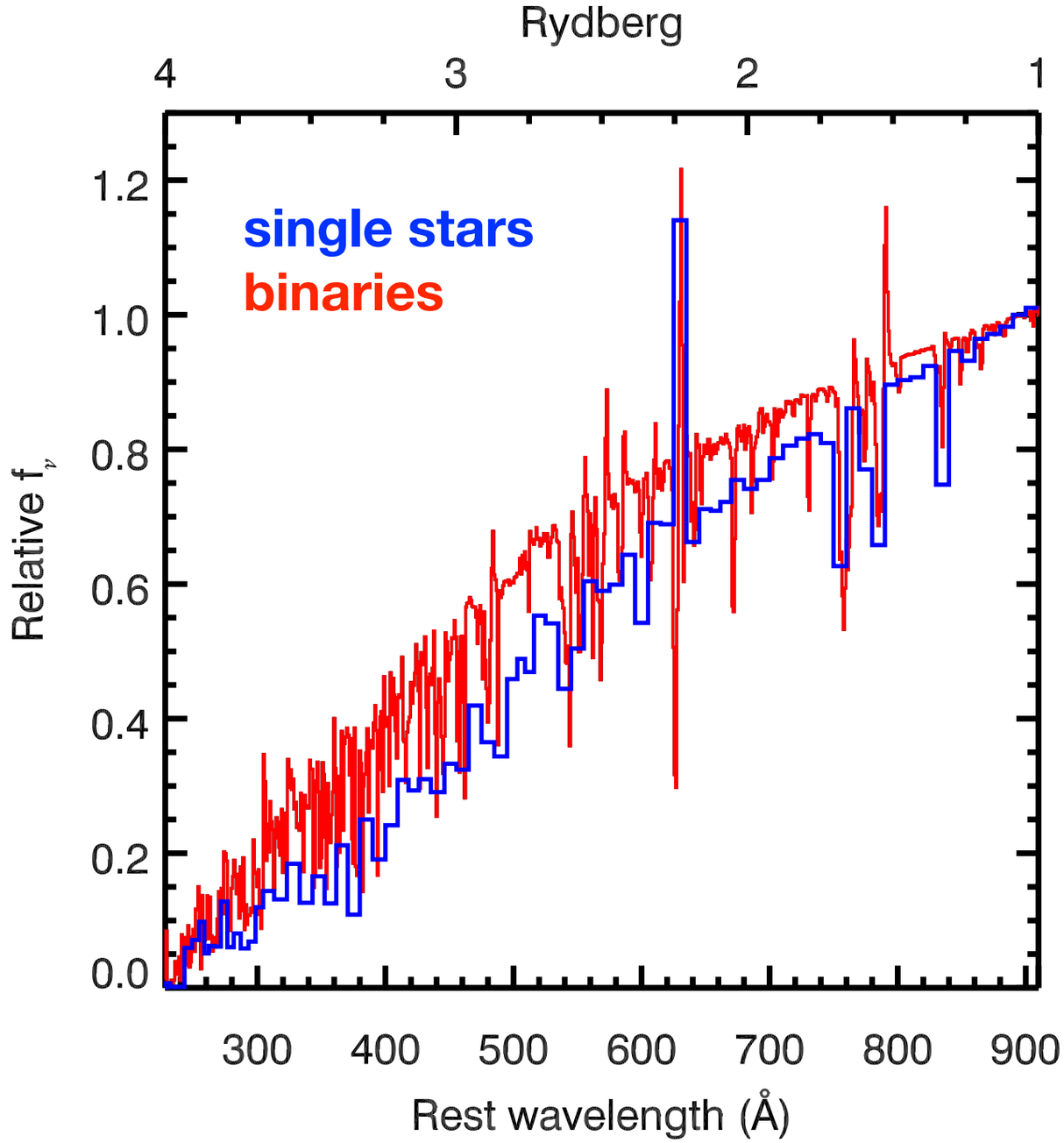


$$U = n_\gamma/n_H \approx n_\gamma/n_e$$

- O32 and Ne3O2 relatively insensitive to changes in gas-phase metallicity
- $\log(U)_{KBSS} = [-3.1,-2.5]$
- $\log(U)_{SDSS} = [-3.5,-3.3]$

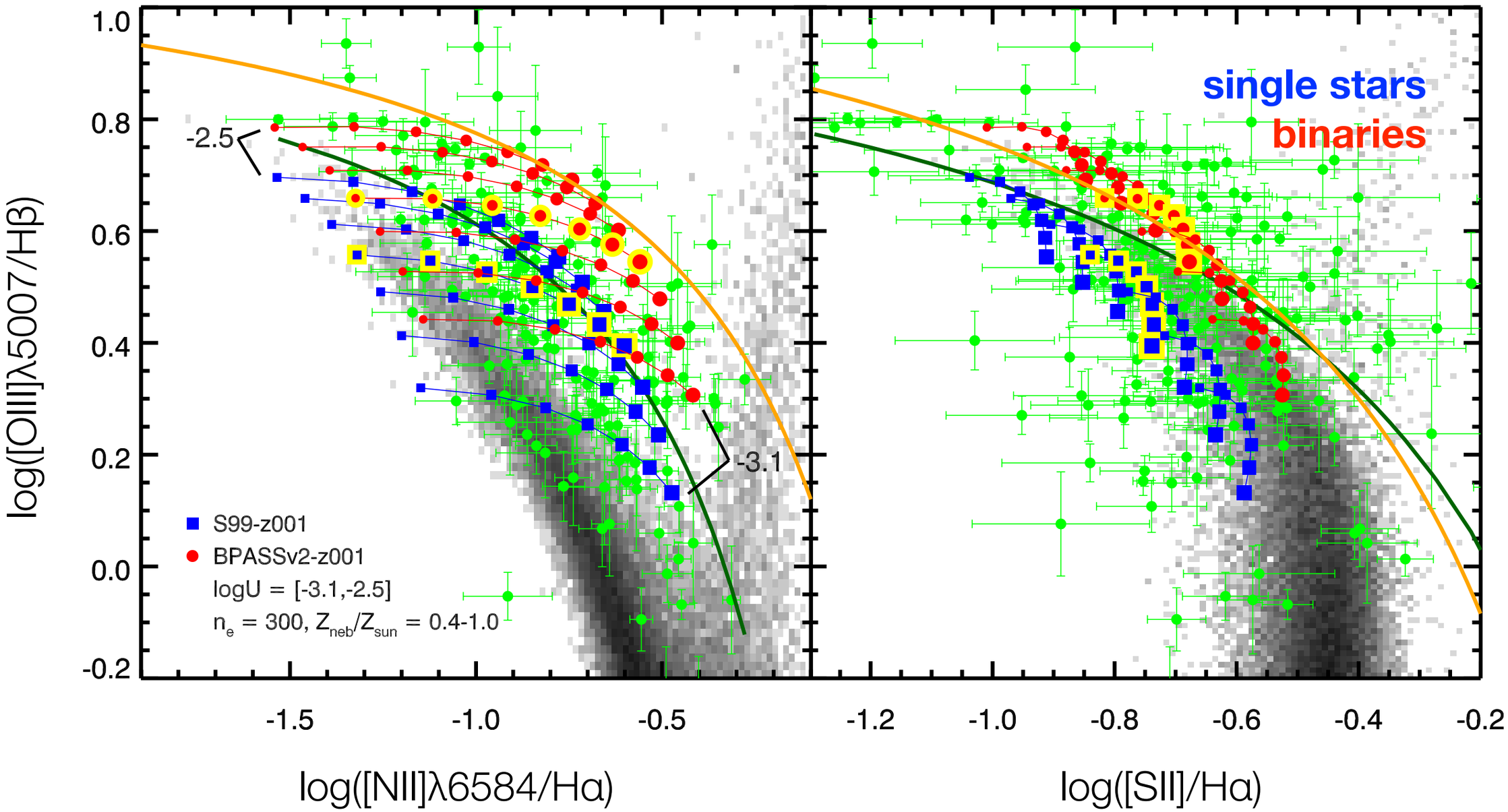
R23 sensitive to shape of EUV ionizing radiation





Harder EUV spectra naturally reproduce range of observations

Strom et al. (in prep.)



Compared to z~0, high-redshift star-forming galaxies…

1. Have **higher R23 and [OIII]/Hβ**, consistent with **harder EUV radiation**

2. Have **higher N/O** and are **10 times more massive** than *z*~0 galaxies matched in O32 and R23 (ionization and excitation)

3. Are well-described by models with **moderate gas-phase abundance** and **apparently metal-poor stars**

Galaxies at *z*~2-3 have **higher O/Fe ratios** than typical *z*~0 galaxies as a result of **substantially more rapid star-formation histories**

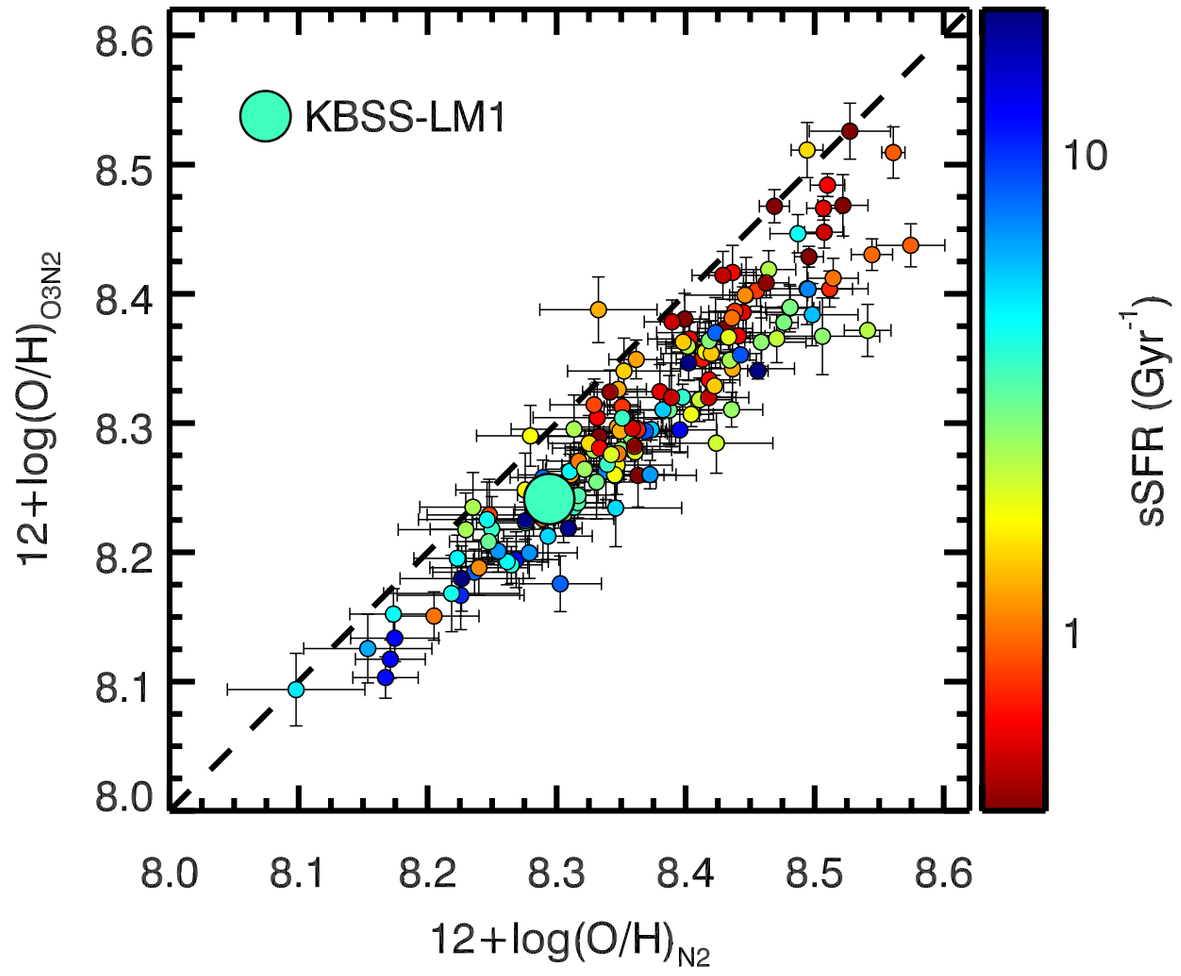
Impact of star formation history on nebular diagnostics

- Significant recent star formation will cause higher excitation at fixed gas-phase abundance

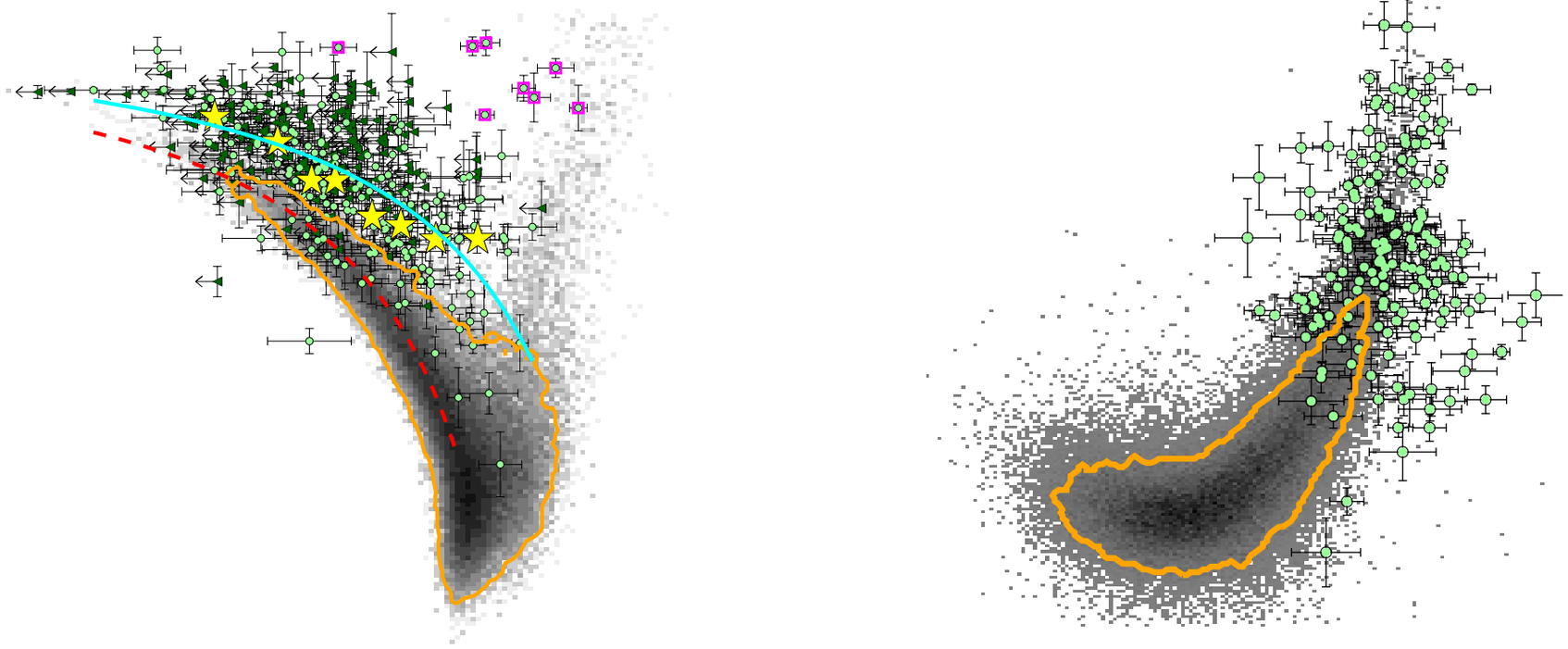
- Strong-line calibrations rely on the underlying correlation between
  1. shape of the ionizing radiation (related to stellar metallicity)
  2. gas-phase metallicity

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

- Must carefully choose local “analogs”!



High-redshift galaxies are different in important ways



1. Typical high-*z* galaxies have “hotter” stars due to effects of binary evolution that are most important at low stellar metallicities (and high O/Fe)

2. High O/Fe ratios likely to occur when recent star formation dominates contributions to ISM chemistry (via CCSNe), as in systems with high sSFR

3. Scarcity of massive SF-dominated galaxies at *z*~0 presents challenges for establishing appropriate nebular diagnostics for high-*z* galaxies