A Few Things we've Learned about High-Redshift Galaxies from Large Spectroscopic Surveys with Keck (KBSS, MOSDEF) and Open Questions

Naveen Reddy (UC Riverside, Sloan Fellow)

Collaborators:

KBSS
-Chuck Steidel
-Allison Strom
-Gwen Rudie
-Max Pettini

MOSDEF
-Alison Coil
-Mariska Kriek
-Bahram Mobasher
-Alice Shapley
-Brian Siana

TMT Forum 2016, Kyoto, Japan, 25 May 2016

A Few Topics of Interest

• Gas: how do galaxies exchange gas and metals with their surroundings?

• [Massive] stellar populations of high-redshift galaxies

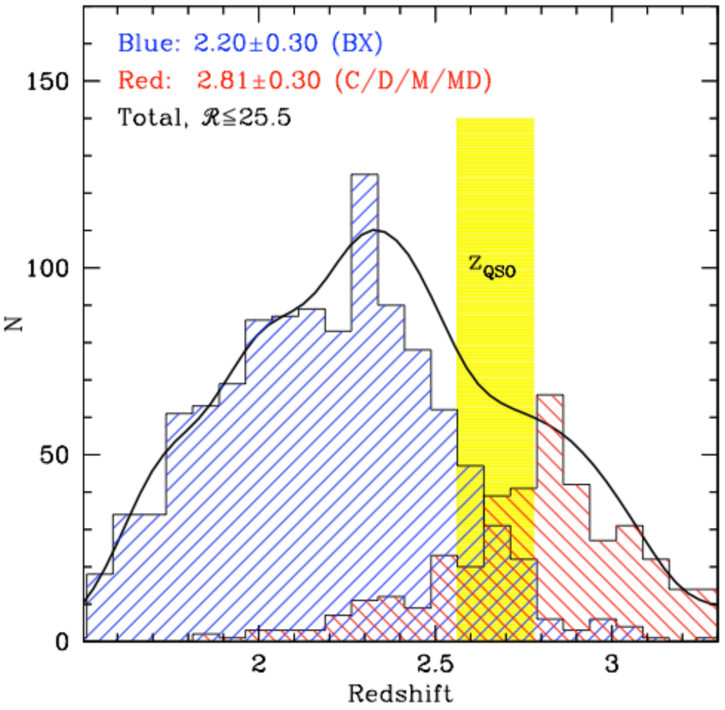
• Dust: how is it spatially distributed relative to stars in galaxies? What are the implications for discerning stellar populations at high-redshift?

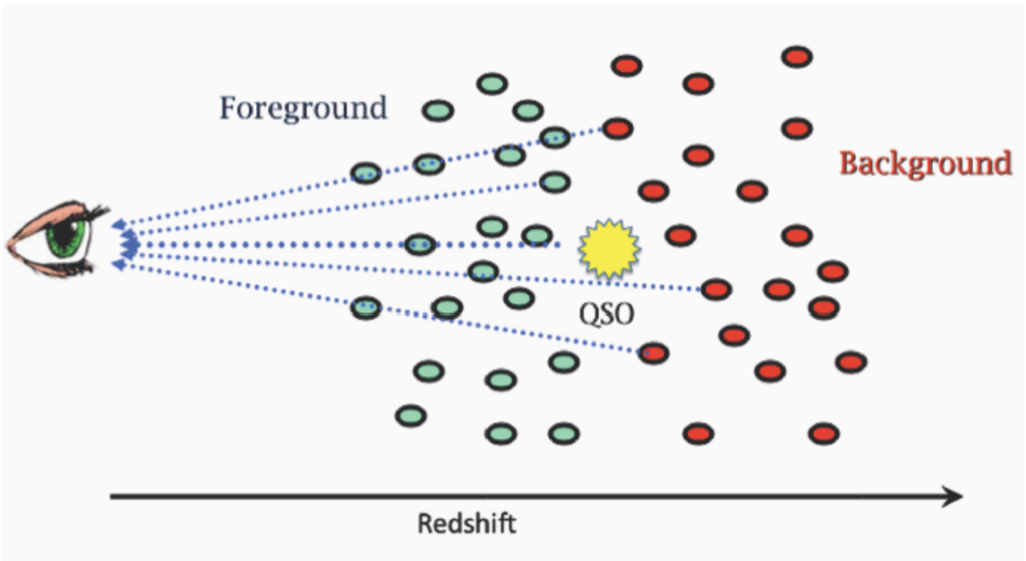
• Reionization: how do ionizing photons escape high-redshift galaxies?

• Things I won't talk about: dynamics, metallicities, ionization parameters, electron densities, …

The Keck Baryonic Structure Survey (KBSS)

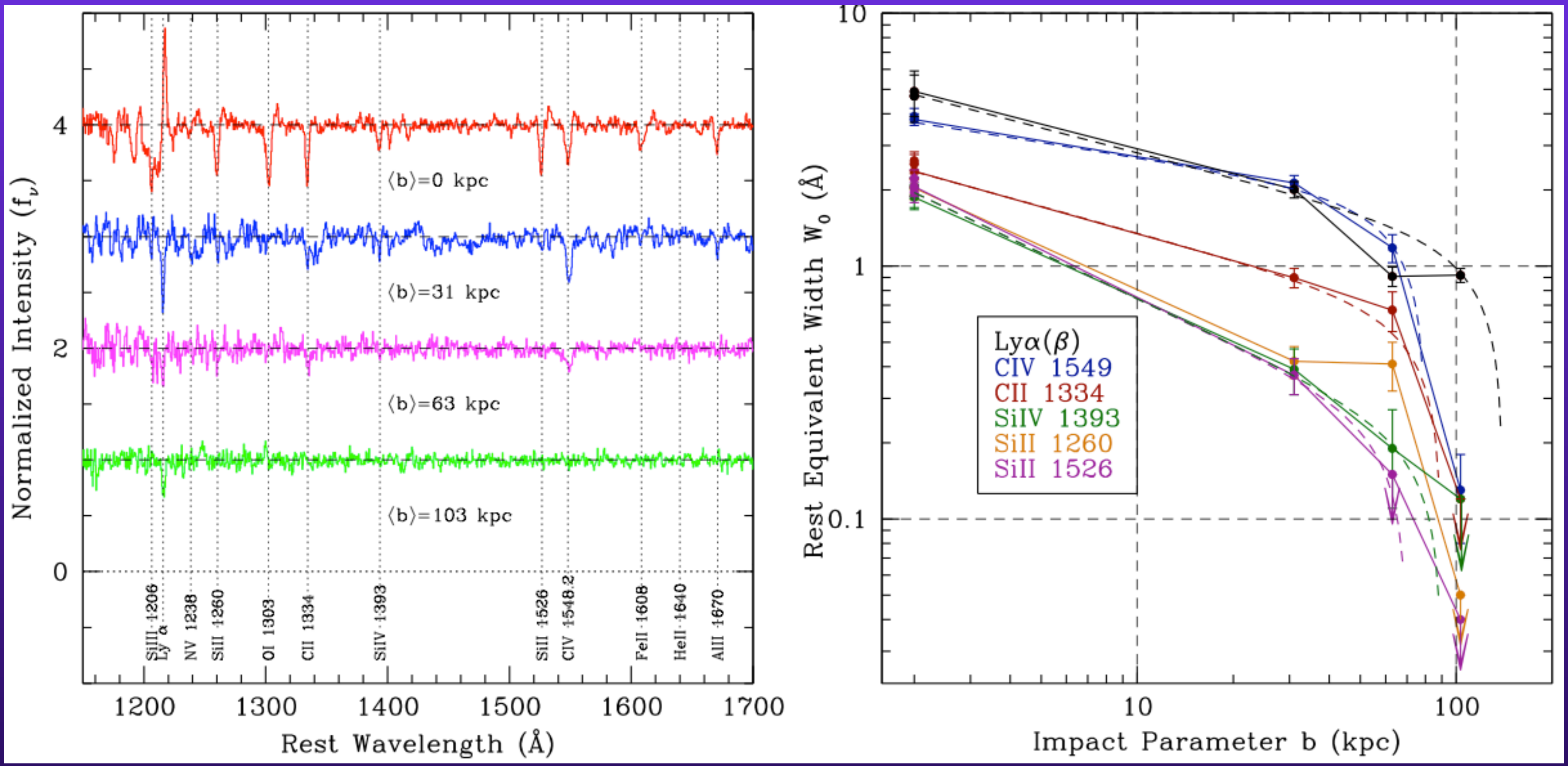
Chuck Steidel, Gwen Rudie, Allison Strom, Ryan Trainor, Naveen Reddy,
Alice Shapley, Dawn Erb, Max Pettini





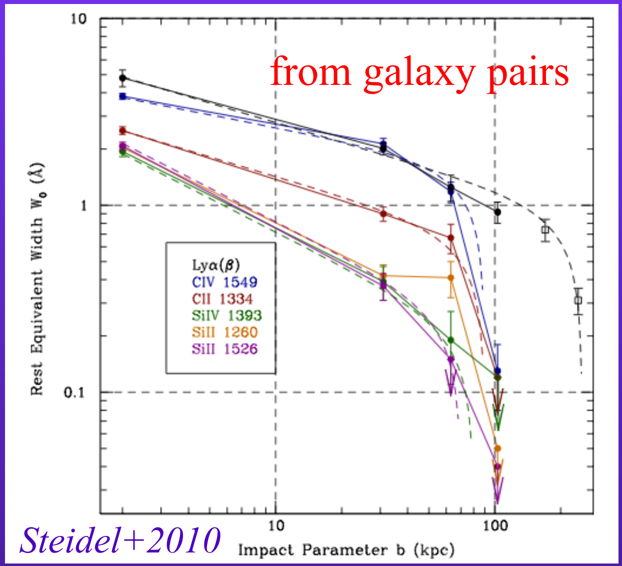
15 fields, 0.25 sq. degrees,
~2800 spectra <z>=2.4
~2300 UV spectra (LRIS-B)
~1100 rest-optical spectra (MOSFIRE)

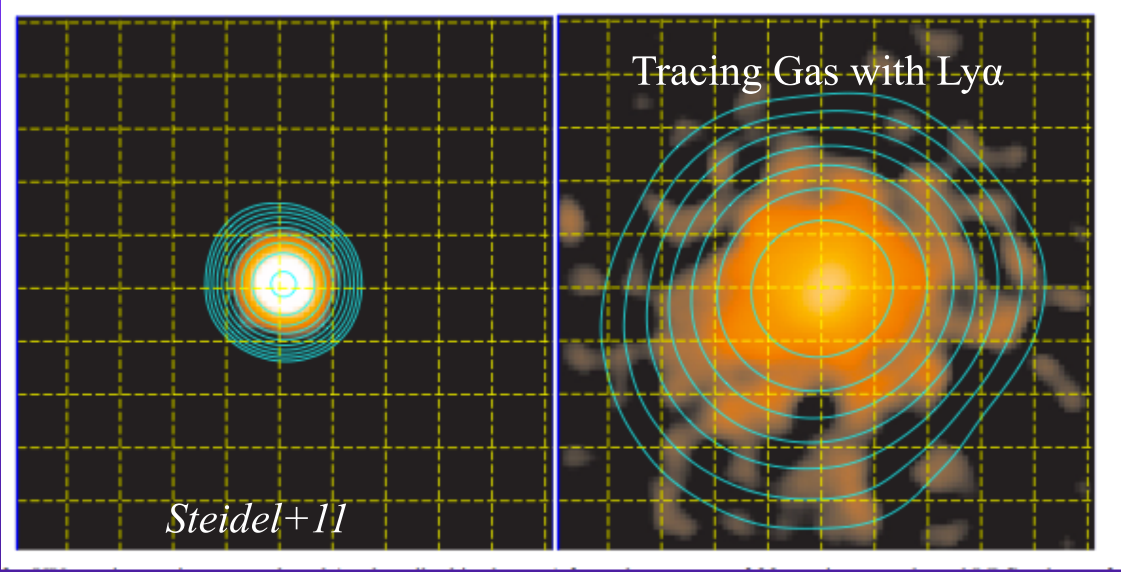
The Keck Baryonic Structure Survey (KBSS): Probes of CGM around high-redshift galaxies

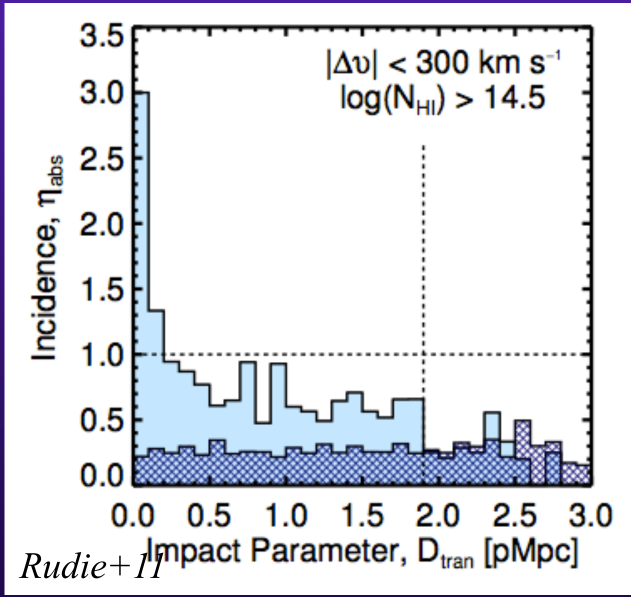


Steidel et al. (2010)

Gas Distribution around High-Redshift Galaxies



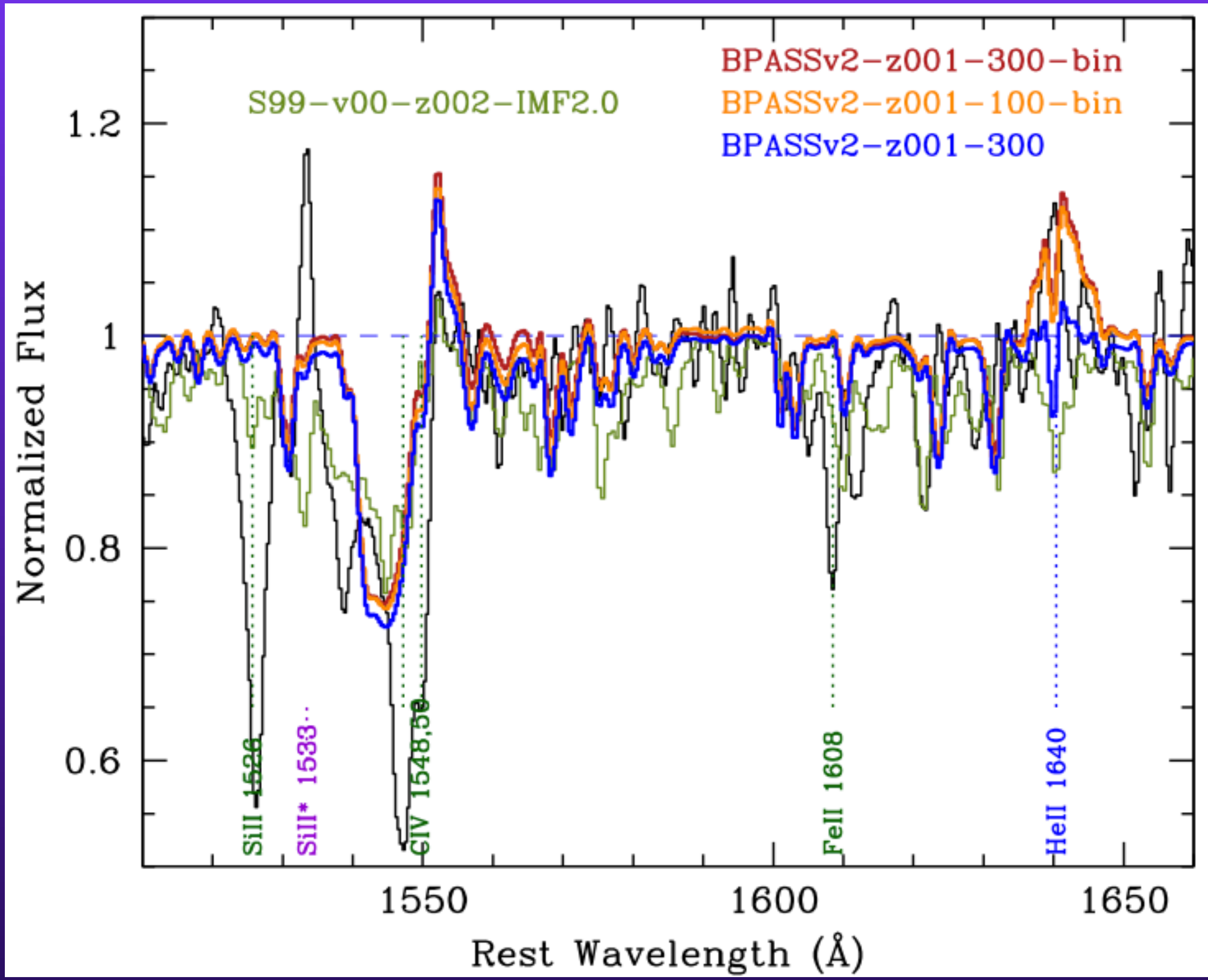




- *most* studies require large samples to average and increase S/N

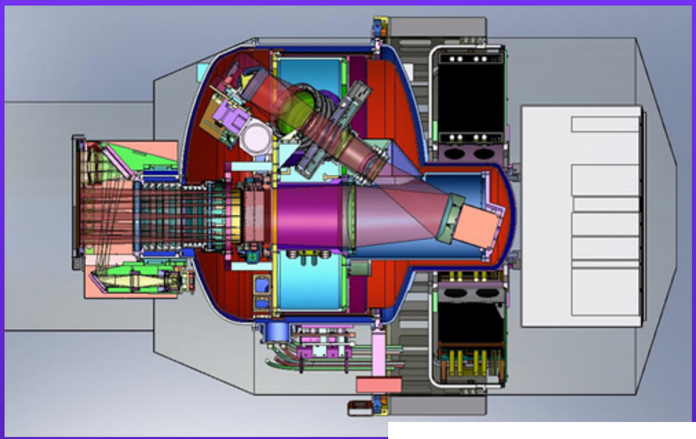
- gaseous halos for individual galaxies with TMT (equivalent of KCWI): see Chris Martin's talk

The Keck Baryonic Structure Survey (KBSS): Detailed Stellar Populations from Rest-UV Spectra



Steidel et al. (2016)

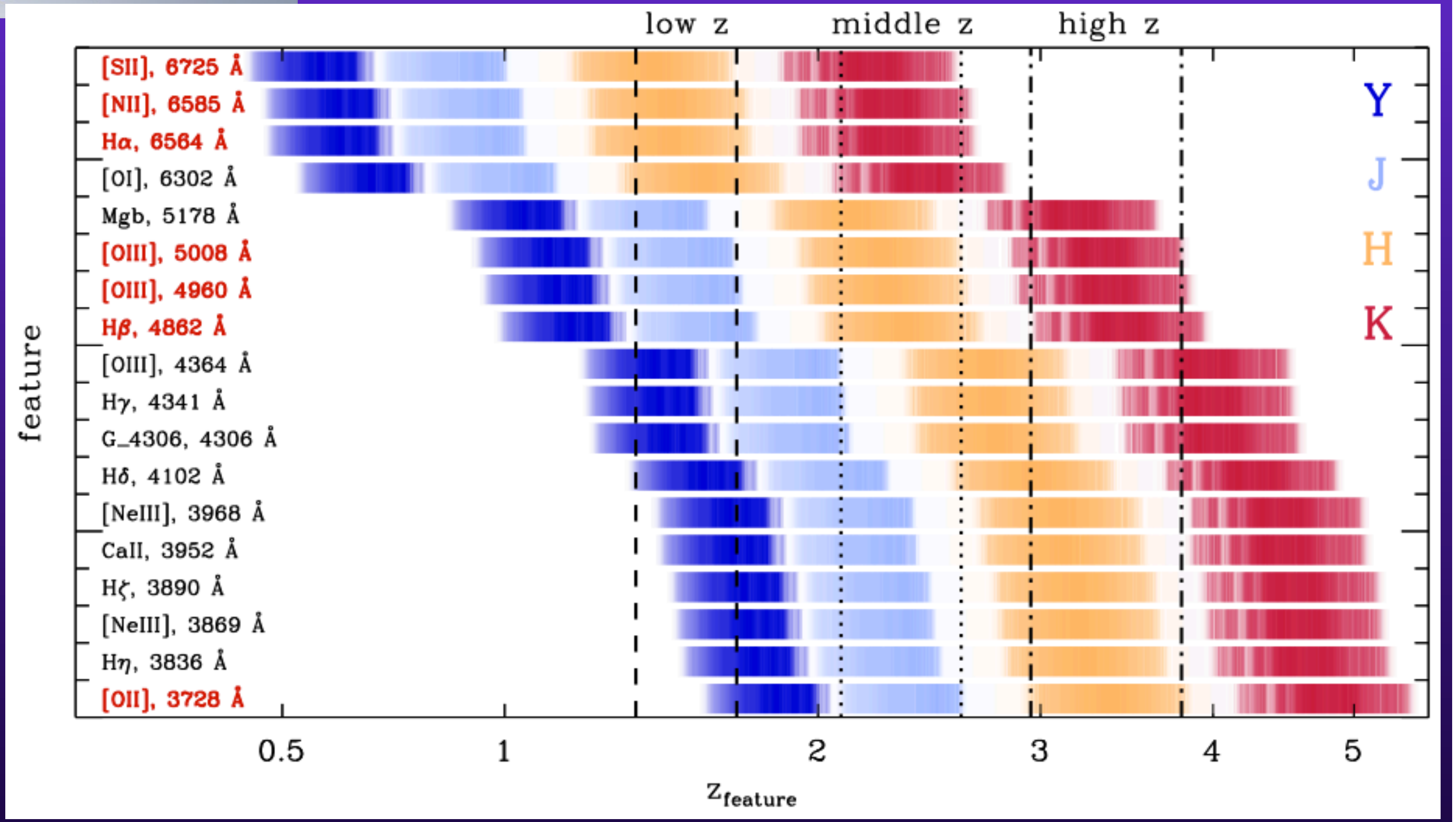
MOSFIRE Deep Evolution Field (MOSDEF) Survey



-Conducted using MOSFIRE on Keck (47 nights)
- MOS near-IR spectroscopy covering important nebular emission lines at 1.4<z<3.8
- H-band-selected

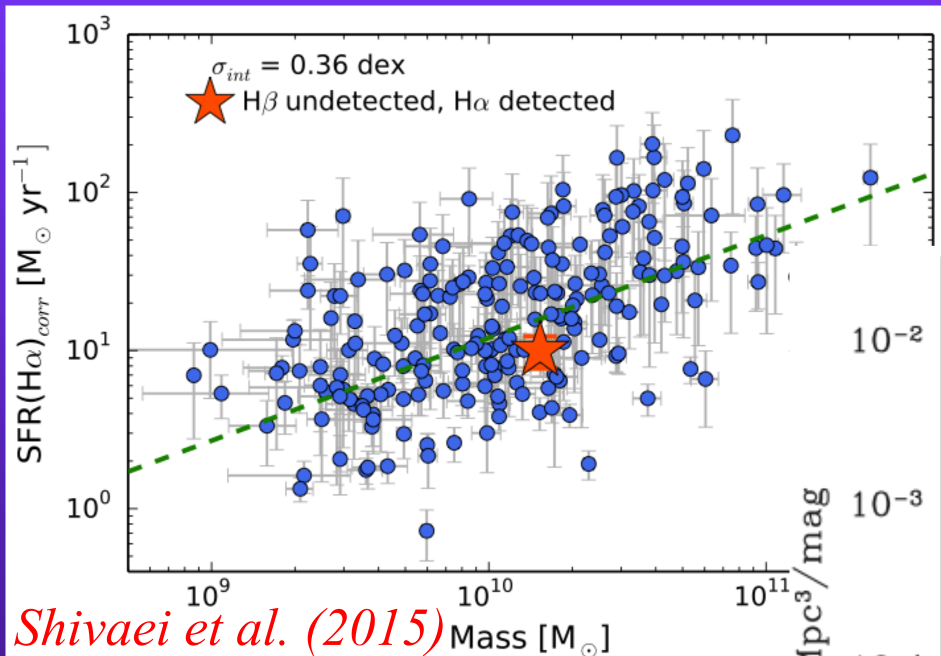
(1) large sample of objects (~1500) spanning full range of galaxy properties

(2) multiple redshifts to enable evolutionary studies



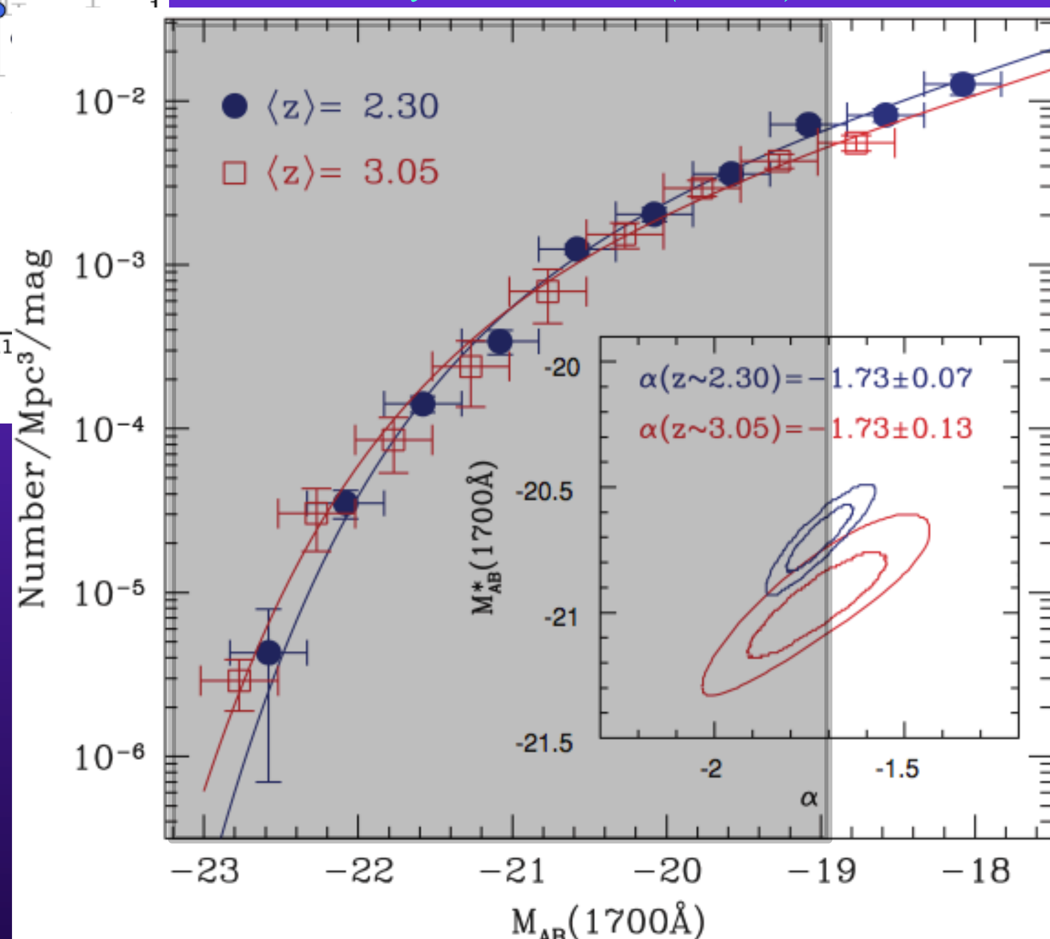
Kriek et al. (2015)

Sampling of "Typical" (L*) Star-Forming Galaxies at z~2

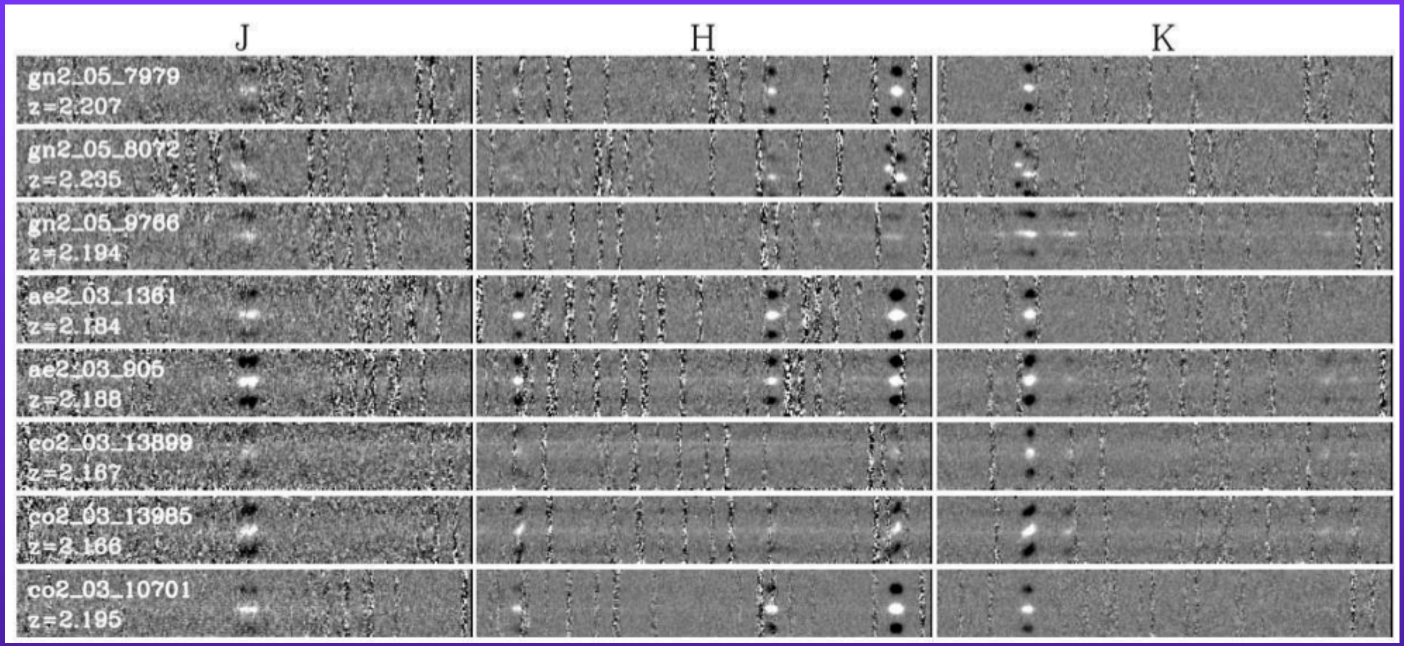


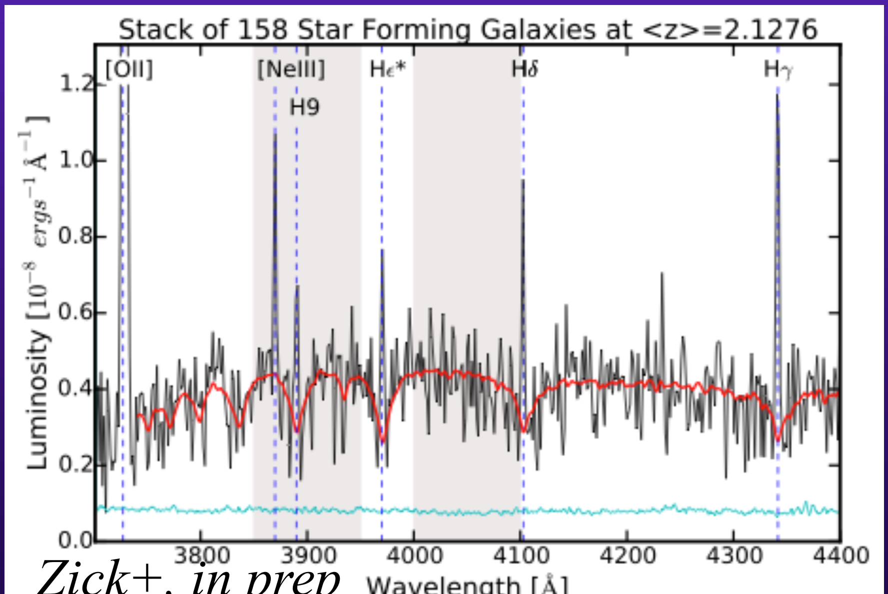
Shivaei et al. (2015)

Reddy & Steidel (2009)



MOSDEF Spectra

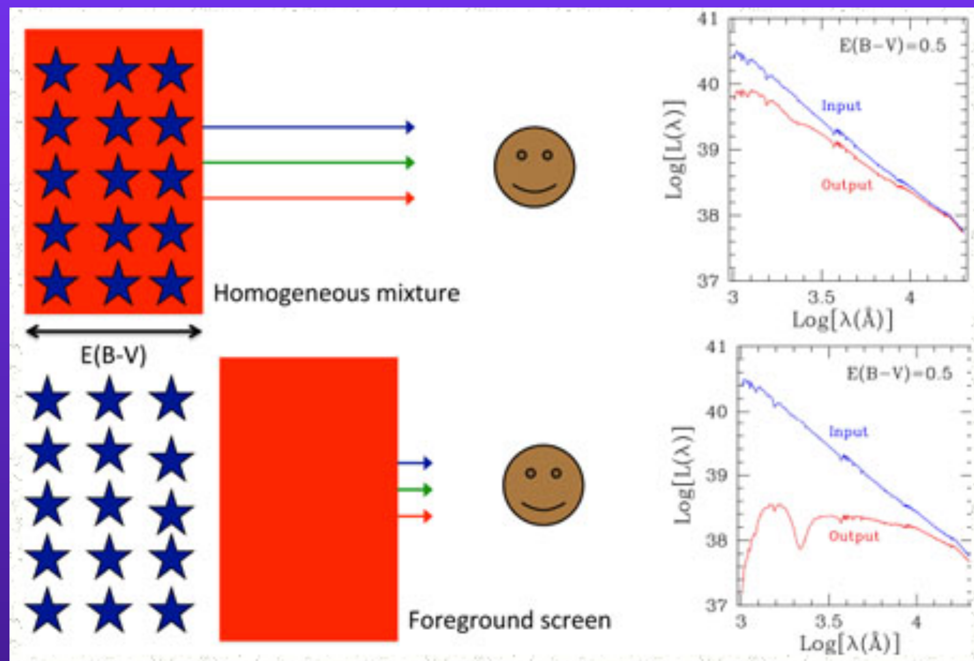




Zick+, in prep

Importance of the Dust "Curve" for High-z Galaxies

Calzetti (2011)



Important input to SED fitting

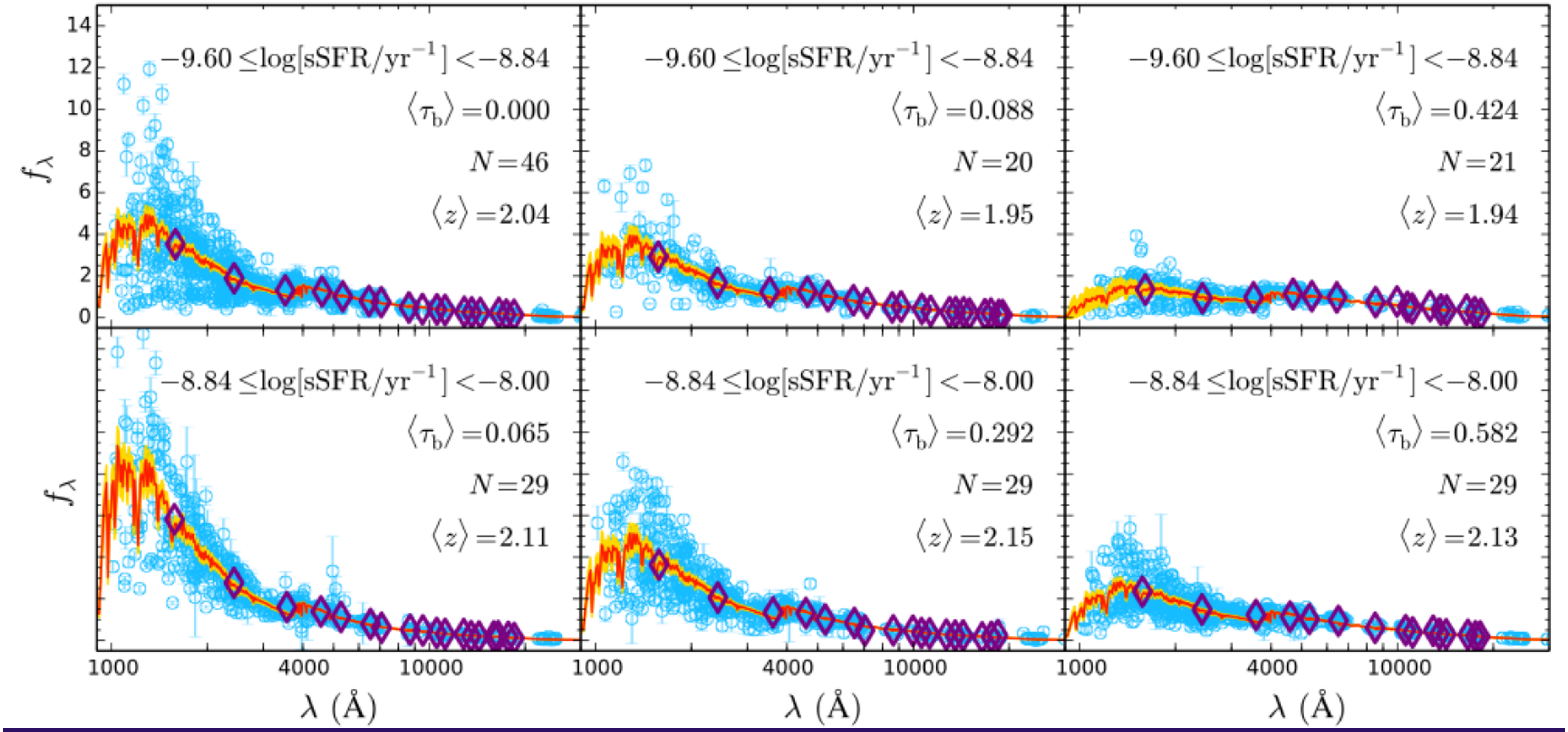
Needed to infer dust-corrected SFRs

Encodes info on the dust/stars geometry

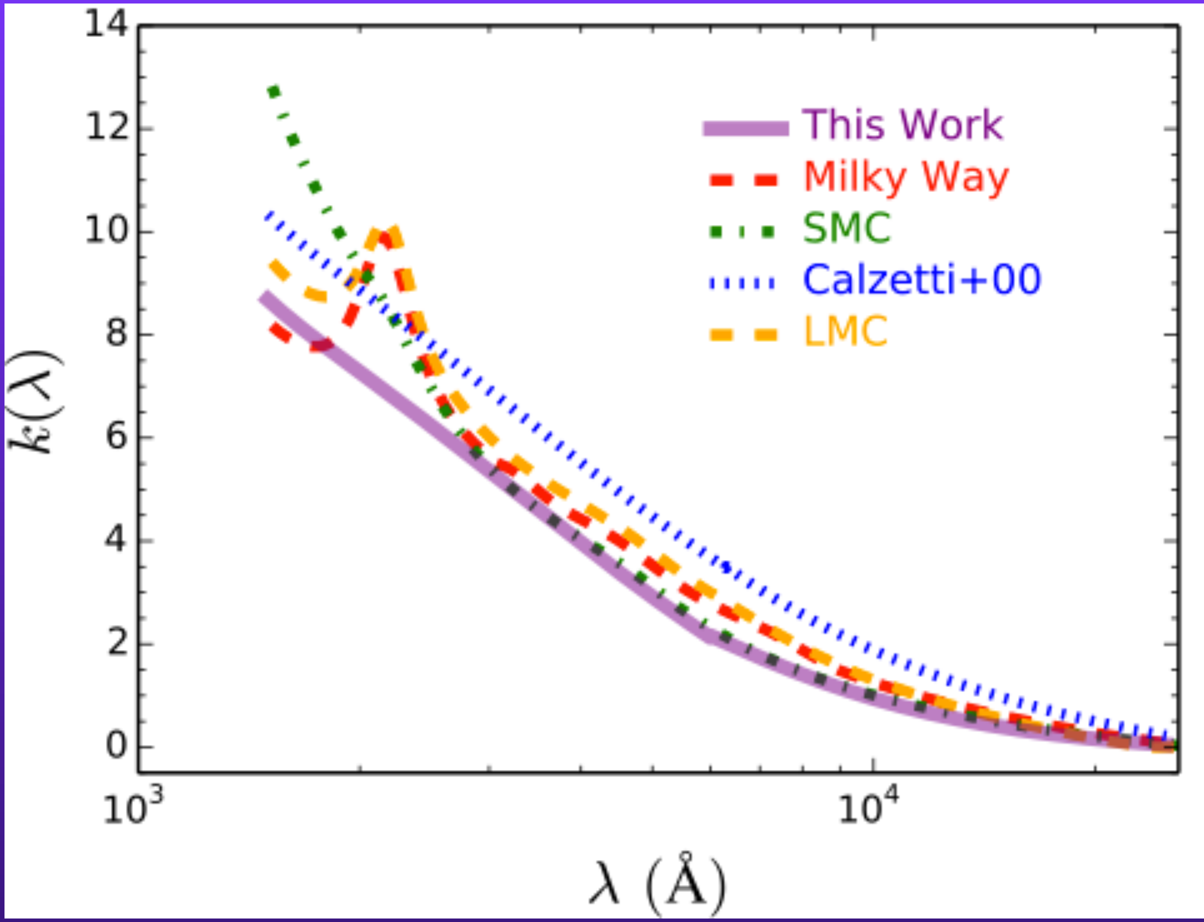
…combining UV and optical diagnostics of HII regions

Calculating the Attenuation Curve…

Ratios of Composites

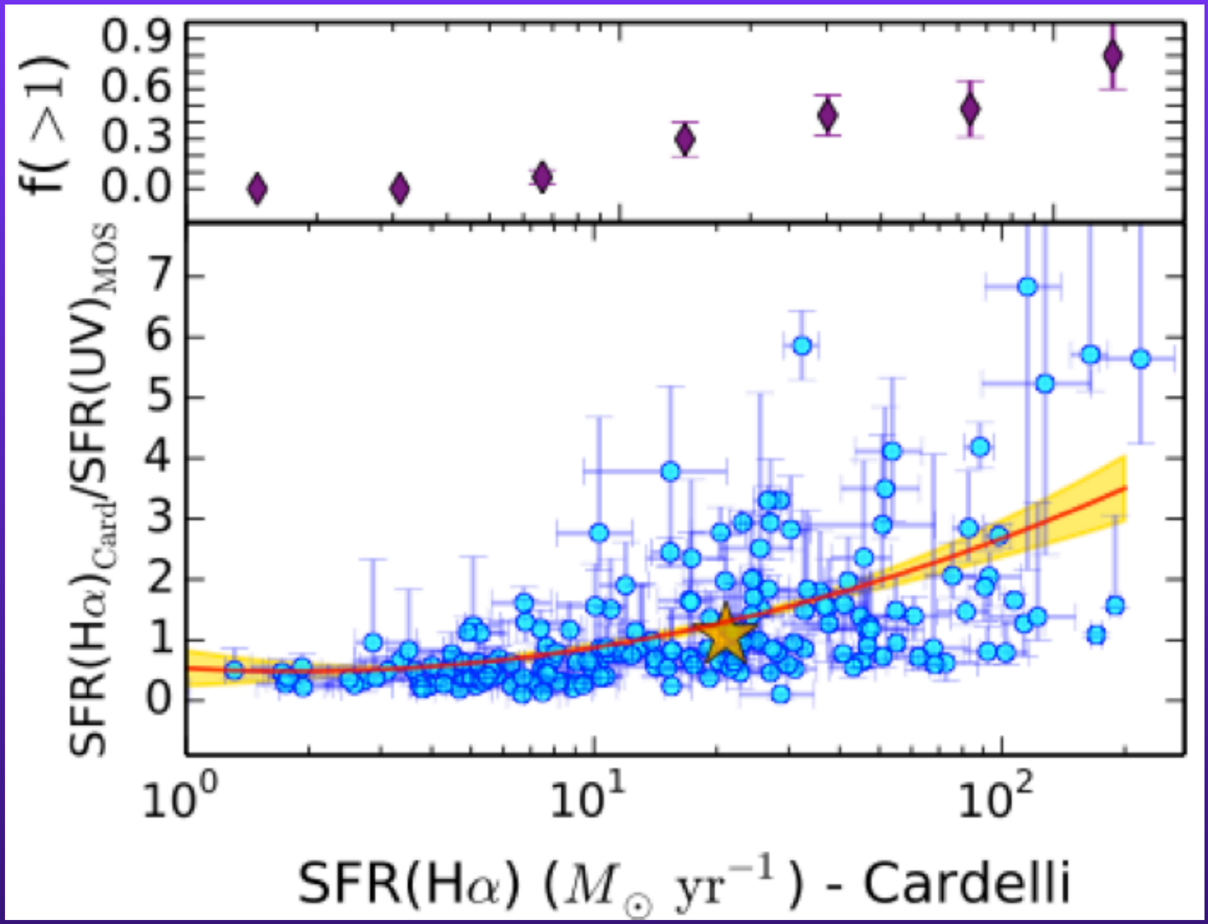


Comparison to other common curves



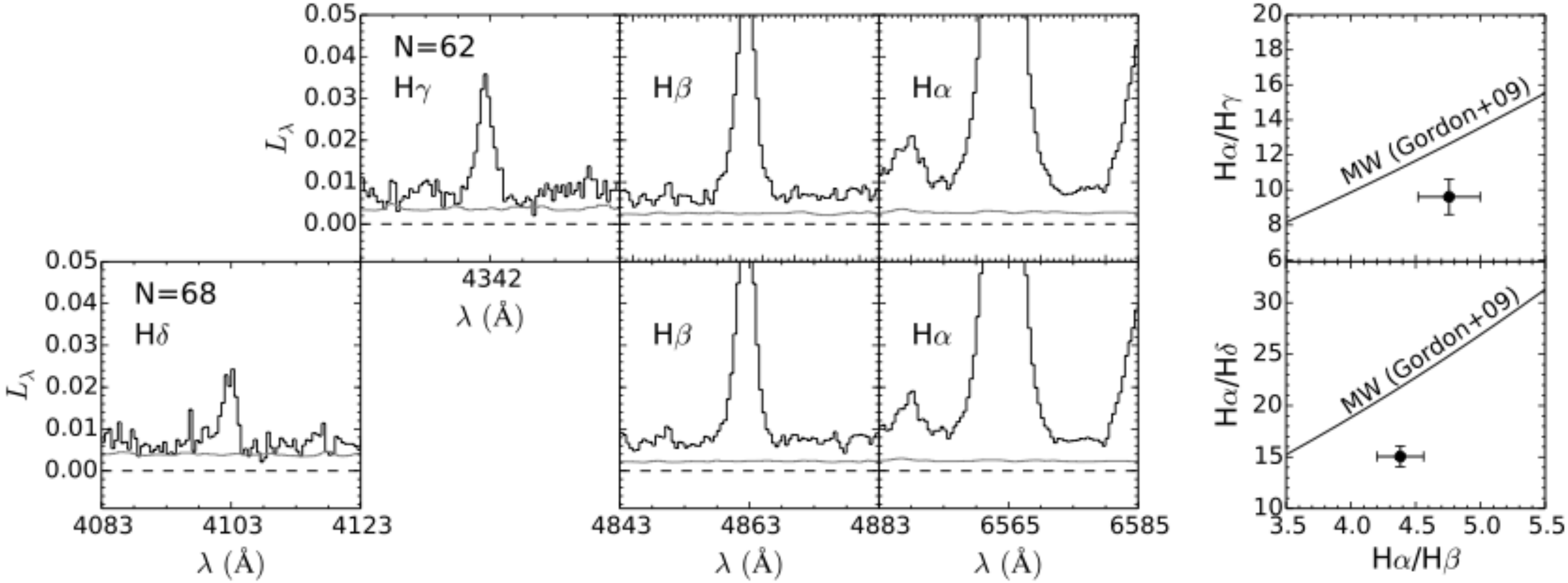
Similar in shape (and normalization) to SMC at λ>2500 Å
Similar in shape (but lower normalization) than Calzetti at λ<2500 Å

Implications for SFRs from Stellar Population Modeling



UV/SED-based SFRs *underpredict* total SFR above ≈ 20 $M_\odot$/yr

Shape of the Nebular Extinction Curve



Accurate Balmer absorption measurements required (i.e., deep ~8-10 hr TMT/IRMS spectra)

AO-Assisted MOS Spectroscopy on TMT

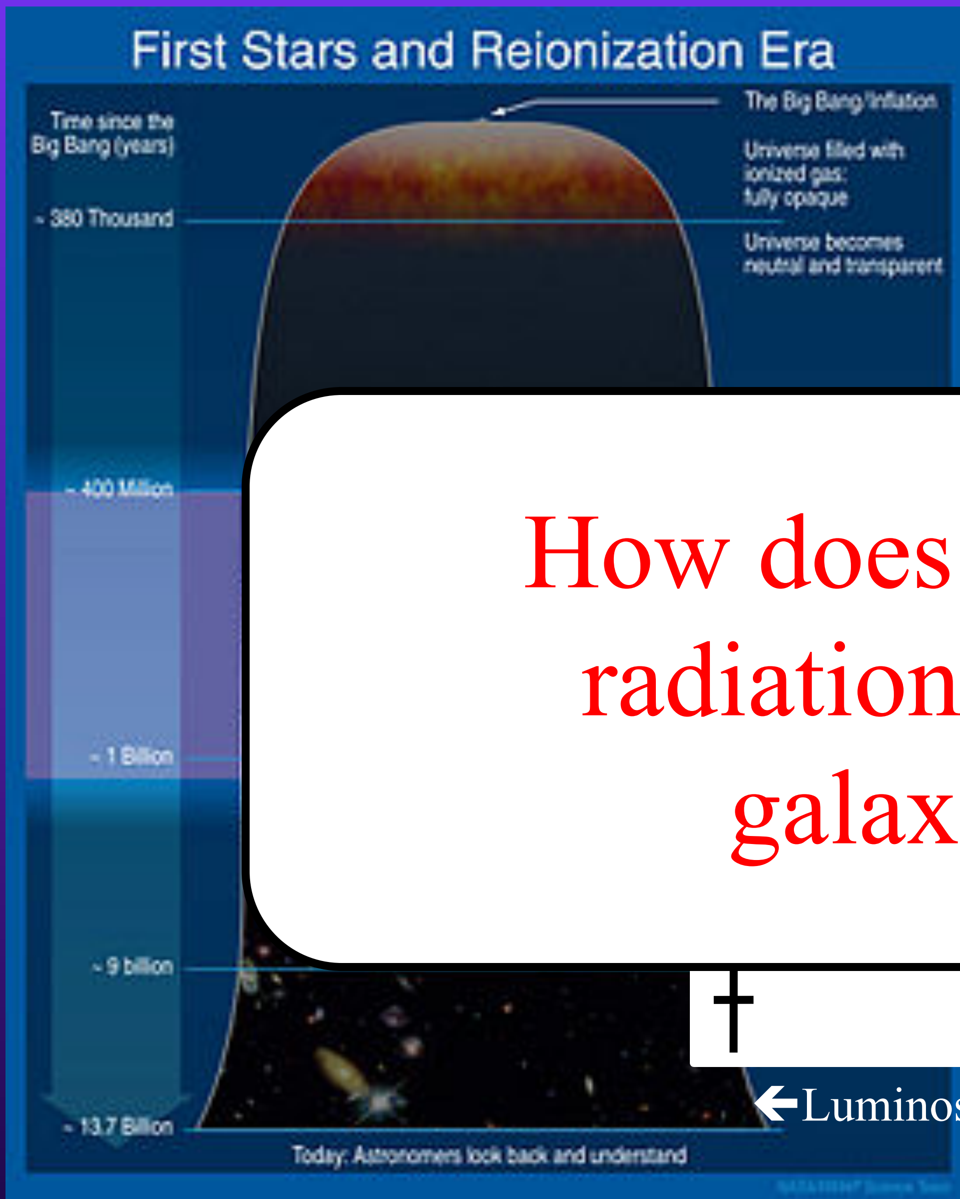
• Quantify dust attenuation in fainter galaxies, analogues of z>>2 galaxies

•Spatially-resolved extinction and far-UV maps will allow for a greater fidelity in studying SFR/dust correlations on an individual galaxy-by-galaxy basis

• Individual detections of weaker Balmer lines (and Balmer absorption through continuum detection) to constrain the shape *and scatter* of the dust curve relevant for the nebular regions of individual high-redshift galaxies

• MOSDEF science lays the groundwork for similar studies at higher redshifts with *JWST*/NIRSPEC

Important Period in History of Universe: Reionization

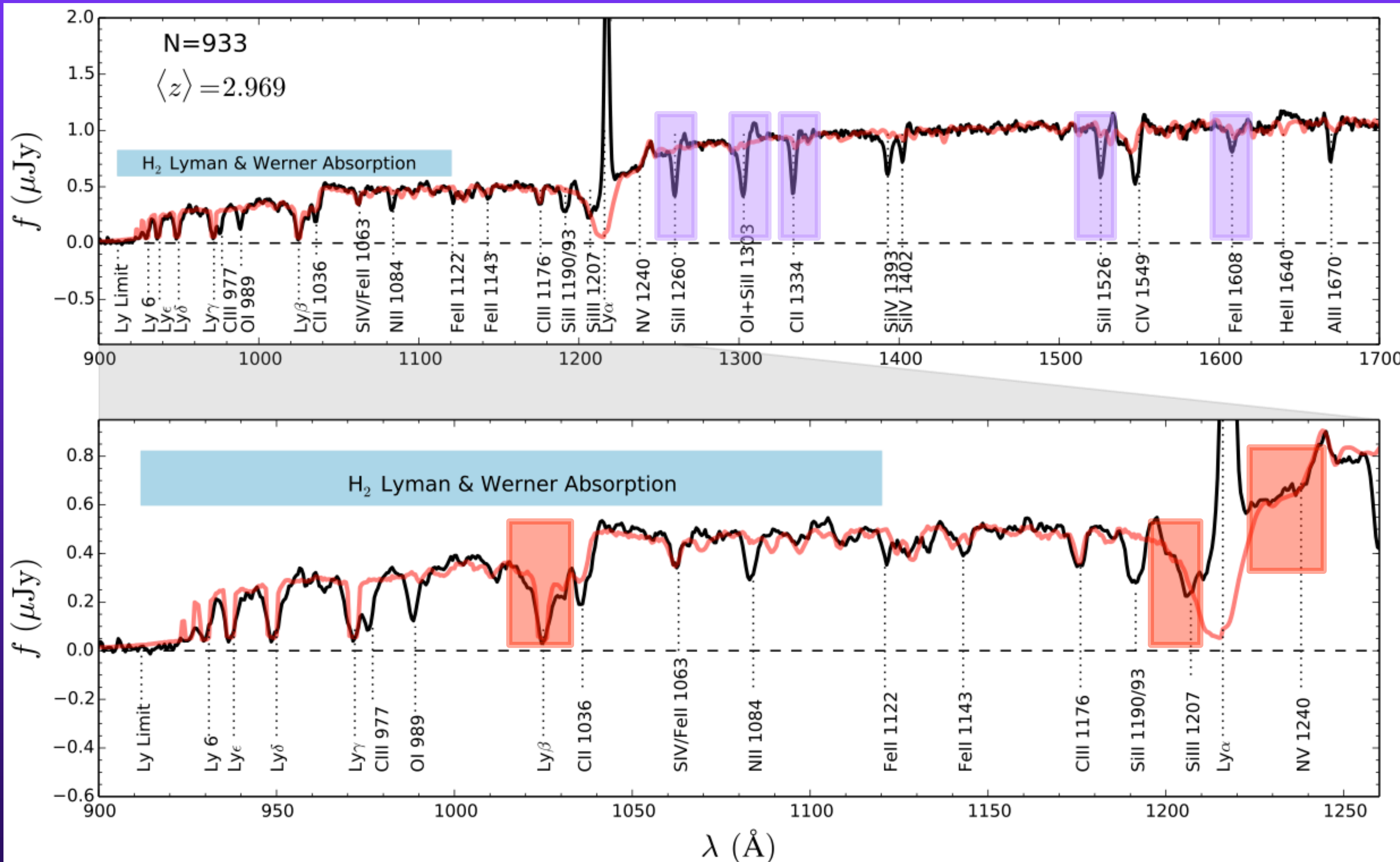


How does ionizing radiation escape galaxies?

← Luminosity

What does it take: lots of galaxies/AGN?

Composite Spectrum of 933 z~3 LBGs: fcov(HI) < 1

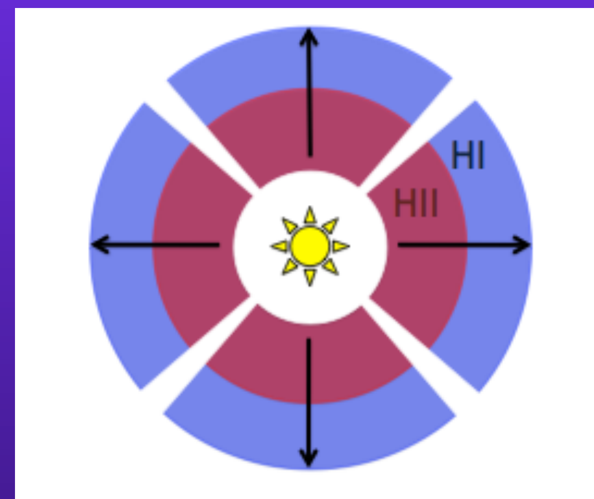


(1) Blue-shifted HI; (2) damping wings of Ly series lines; (3)non-zero residual flux at line centers: fcov(HI) < 1

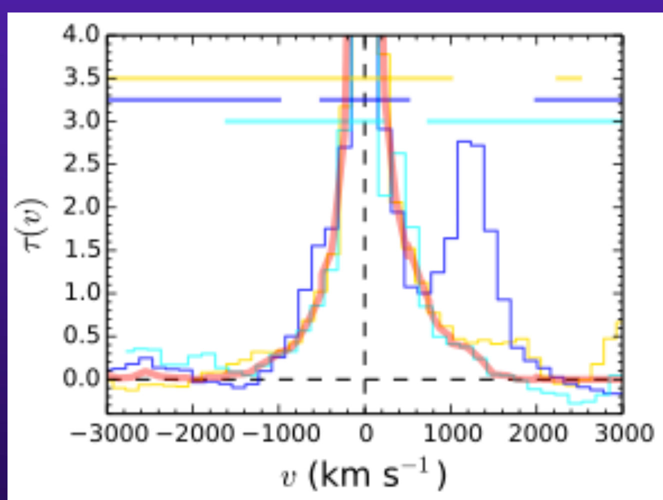
Spectral Modeling

Details of Model:

- Intrinsic Spectrum: Rix+S99, $0.28Z_o$, neb. continuum emission; constant SF

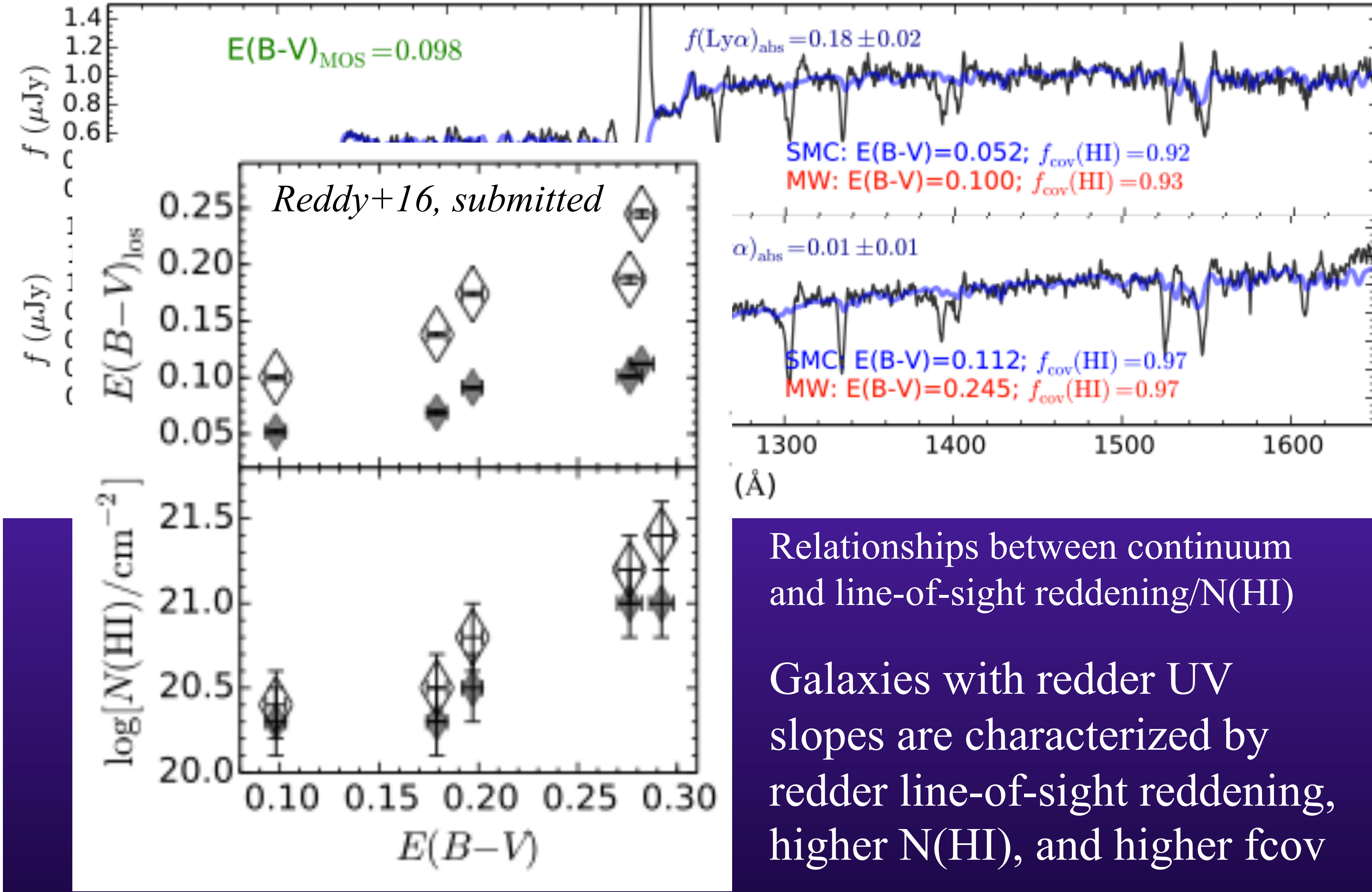


Reddened, and HI+H2 Absorbed spectrum



Fit to composites in bins of UV continuum reddening, while varying fcov

Spectral Modeling

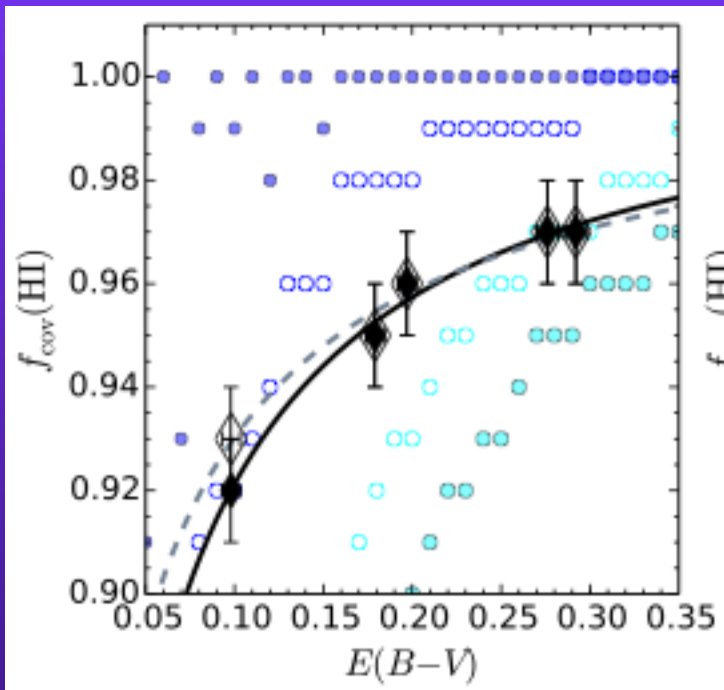


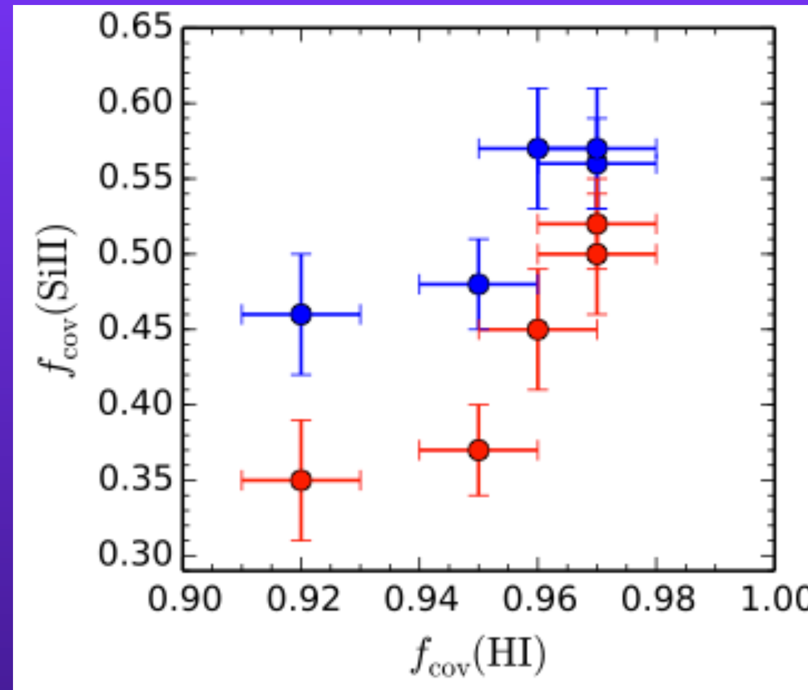
Relationships between continuum and line-of-sight reddening/N(HI)

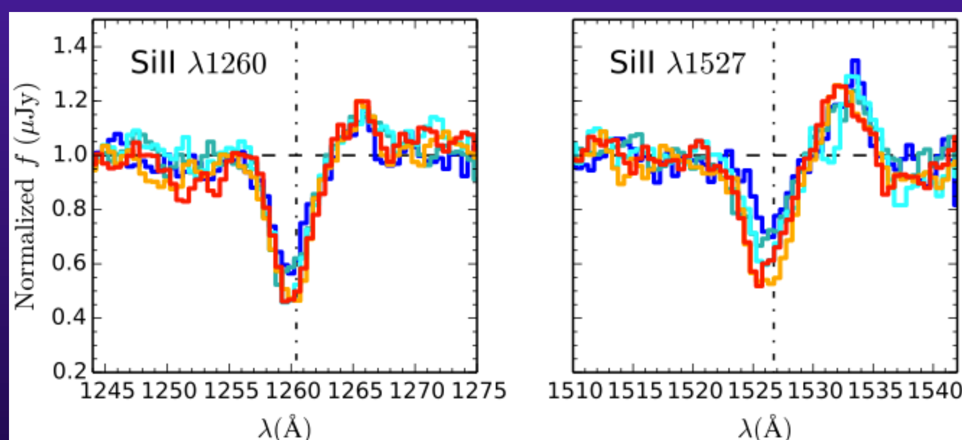
Galaxies with redder UV slopes are characterized by redder line-of-sight reddening, higher N(HI), and higher fcov

Relationship between Reddening and Covering Fraction

Reddy+16, submitted



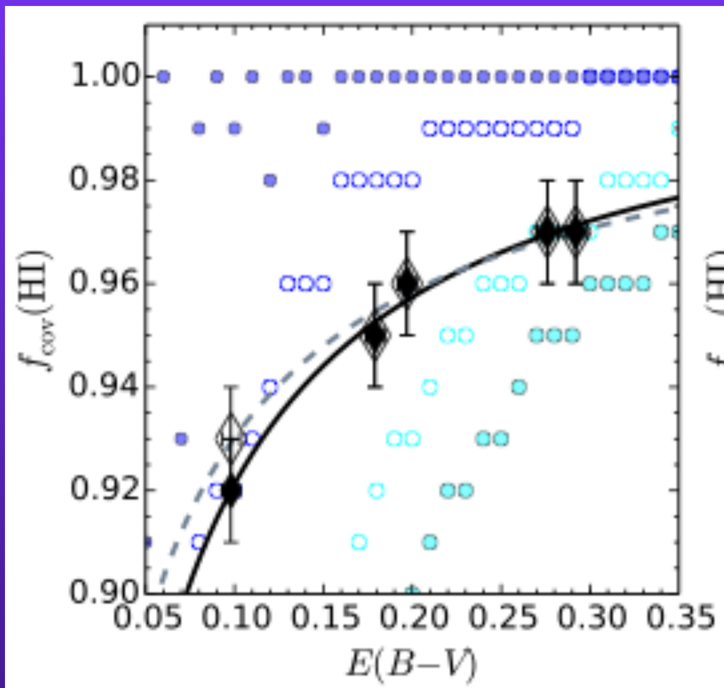




Reddy, Steidel, et al., submitted

Relationship between Reddening and Covering Fraction

Reddy+16, submitted



$$f(\mathrm{LyC})_{\mathrm{abs}} \approx 1 - f_{\mathrm{cov}}(\mathrm{H\ I}).$$

+

$$f_{\mathrm{cov}}(\mathrm{H\ I}) = 1 - \exp[a \times E(B-V)^b],$$

||

$$\frac{S(\mathrm{LyC})_{\mathrm{obs}}}{S(\mathrm{UV})_{\mathrm{obs}}} = \frac{S(\mathrm{LyC})_{\mathrm{int}}}{S(\mathrm{UV})_{\mathrm{int}}} \times \exp[-\tau_{\mathrm{IGM}}(\mathrm{LyC})] \times \exp[-\tau_{\mathrm{CGM}}(\mathrm{LyC})] \times \left[\frac{\exp[a \times E(B-V)^b]}{10^{-0.4k(\mathrm{UV})E(B-V)}}\right]$$

Reddy, Steidel, et al., submitted

Empirical Constraints on the Intrinsic LyC-to-UV Ratio

$(f900/f1500)_{obs} \sim 0.019 \pm 0.002$

IGM/ CGM

$(f900/f1500)_{cor} \sim 0.047 \pm 0.005$

E(B-V)~0.197 ± 0.005

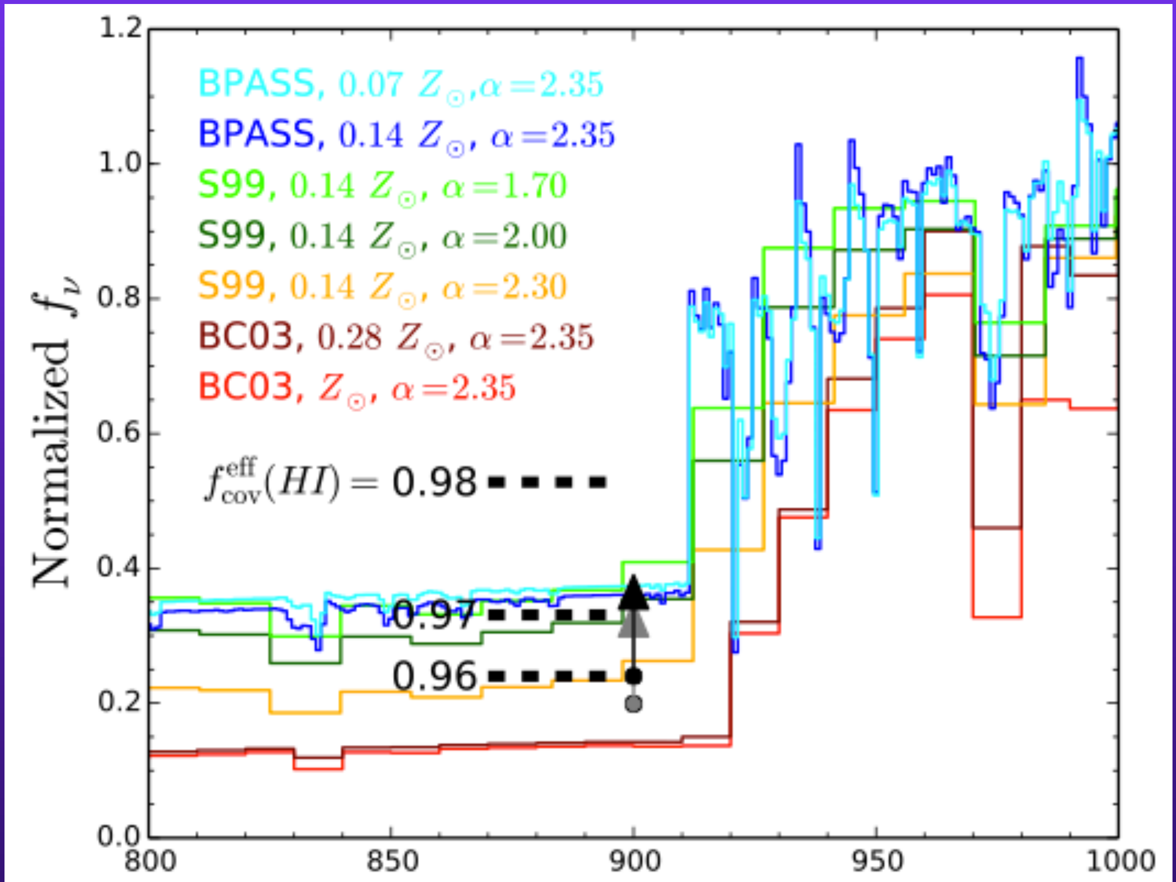
Model Prediction

$f_{cov}(HI) \sim 0.955 \pm 0.010$

$(f900/f1500)_{int} \sim 0.216 \pm 0.060$

Reddy, Steidel, et al., submitted

Comparison with Stellar Population Models



Reddy+16, submitted (ApJ)

Limit favors models that have weaker stellar winds, and shallow slope of the IMF, or QHE for massive stars

Comparison with Stellar Population Models

• Velocity distribution of gas along different sight-lines: high resolution optical IFU

• Still need large numbers of galaxies to average over forest stochasticity, but can we derive an empirical relation between depths of low-ionization and HI lines?

• Combine reionization with CGM/IGM studies: excess absorption as hindrance to ionizing photons; probe gaps in gas distribution for *individual* galaxies!

• High-S/N rest-UV and rest-optical spectra to provide additional constraints on massive stellar populations

Lessons/Directions for TMT

• Still room for large surveys, but TMT will open up avenues for detailed studies of the stellar populations, dust contents, and gas distributions in and around *individual* star-forming galaxies at high redshift

• Most information assembled for typical star-forming galaxies (L*, M*), but lacking for much more numerous low-mass galaxies at z>1.5

• Role of 8-10m class telescopes like Keck in the TMT-era: Keck already laying the groundwork for identifying objects for TMT follow-up