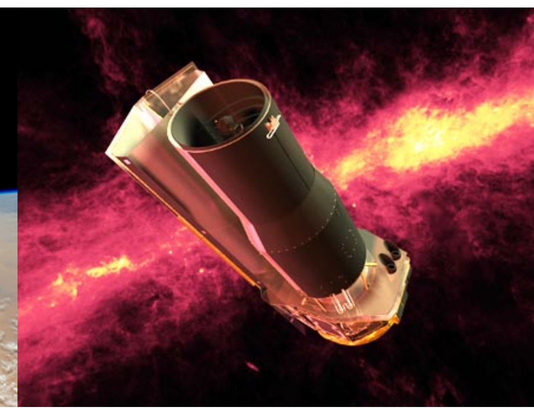
Key Results on Dust Attenuation and Ionizing Escape/Gas Covering Fractions at z~2-3

Naveen Reddy

Emission Line Galaxies with MOS, *18 Sep 2017*





MOSDEF: Shapley, Kriek, Coil, Mobasher, Siana, …

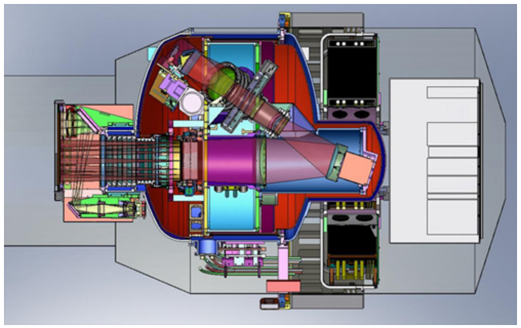
HDUV Legacy Survey: Pascal Oesch, Rychard Bouwens, …

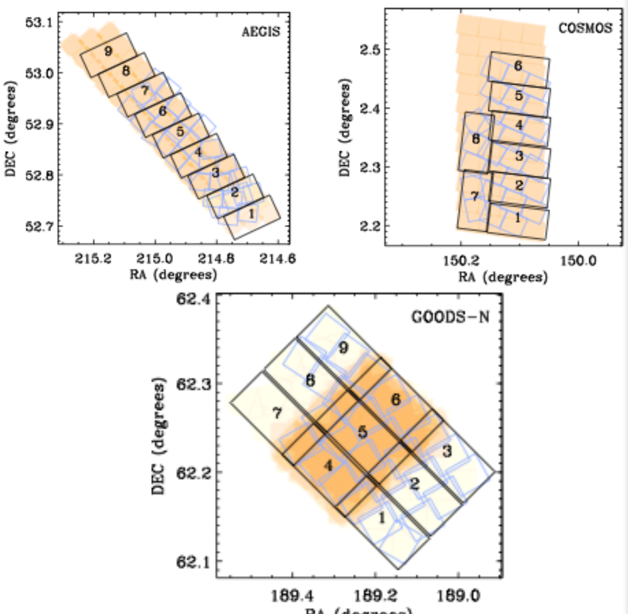
KBSS/KLCS Survey: Chuck Steidel, Milan Bogosavljevic, Max Pettini, …

ASTRONOMY UCR

MOSDEF

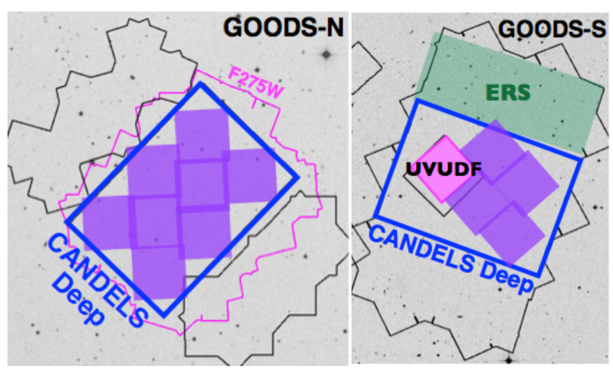
Keck/MOSFIRE rest-optical spectroscopy of galaxies at the cosmic "peak"





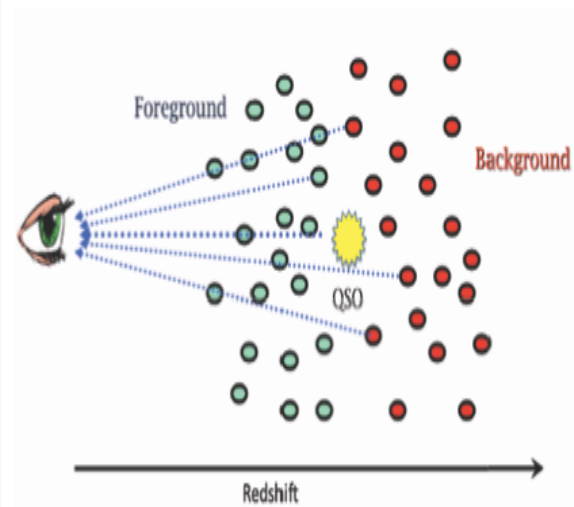
HDUV Legacy

HST WFC3/UVIS imaging of the GOODS fields; LBG selections to faint limits at z~0.5-3.0

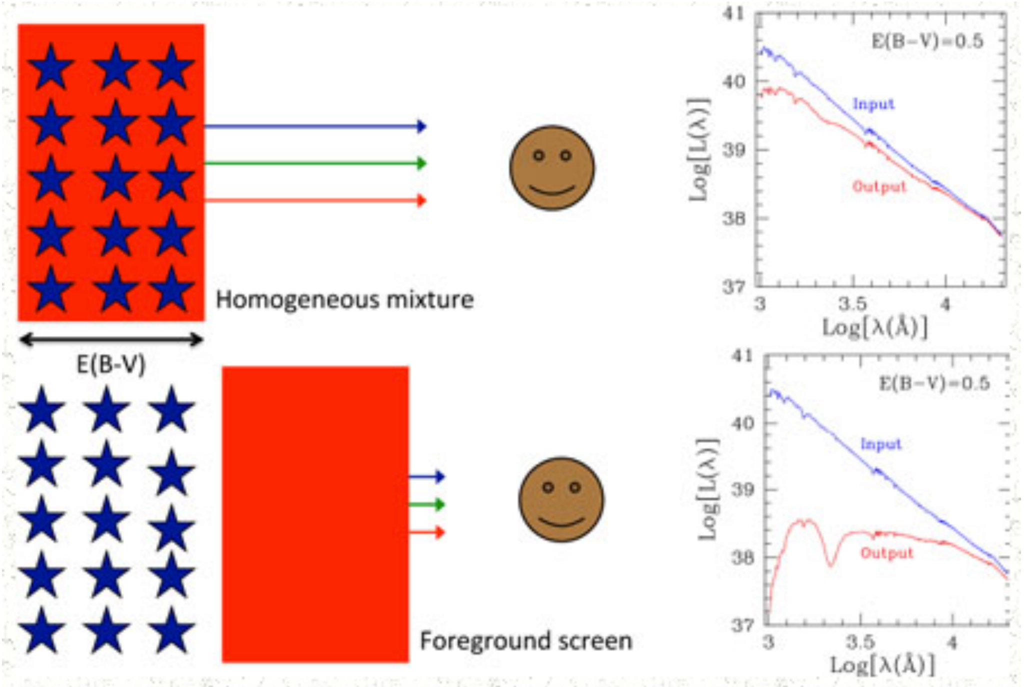


KLCS

Keck/LRIS rest-UV spectroscopy of galaxies at the cosmos "peak"



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



Calzetti (2011)

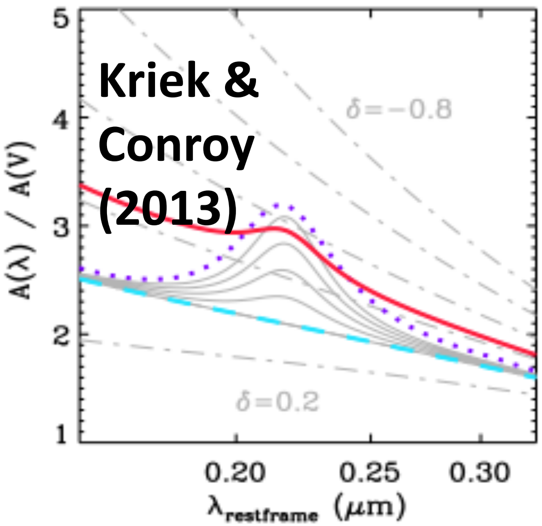
Important input to SED fitting

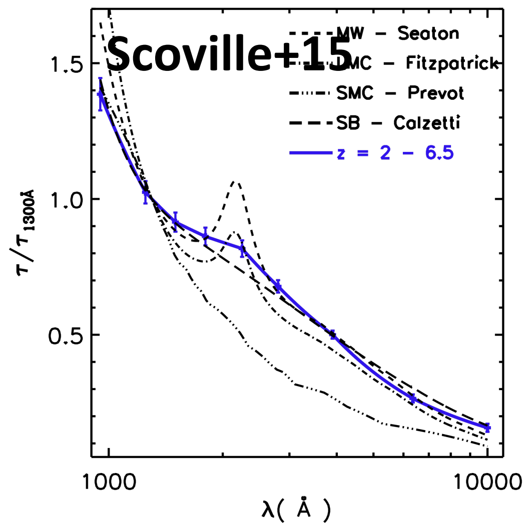
Needed to infer dust-corrected SFRs

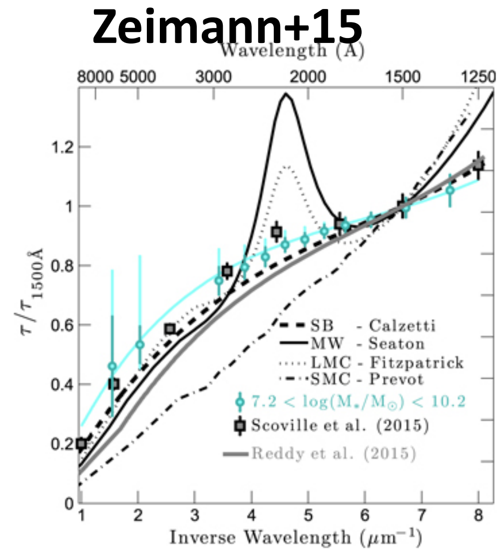
Encodes info on the dust/stars geometry

Recent High-Z Constraints on the Dust Curve

Noll+09, Buat+11,12, Kriek & Conroy (2013), Scoville+15, Salmon+15, Zeimann+15







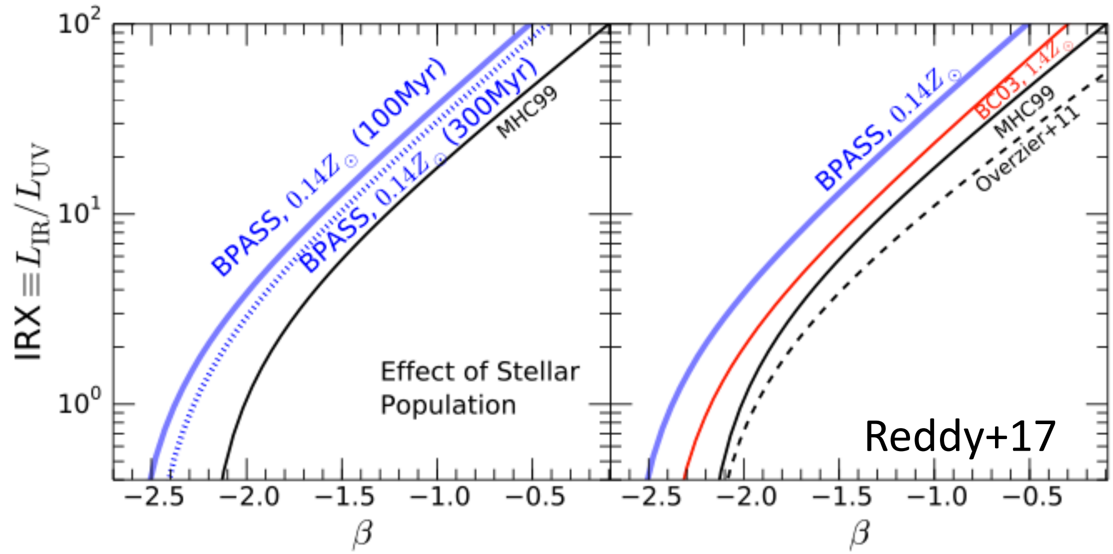
Based on photometry, UV/optical spectroscopy, and/or comparison to stellar templates

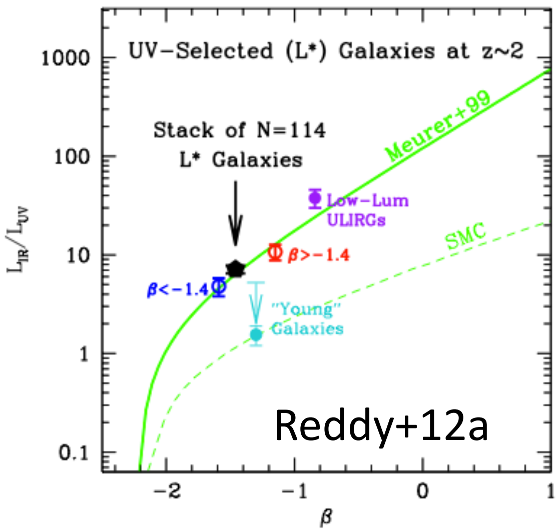
CAN WE DO BETTER?

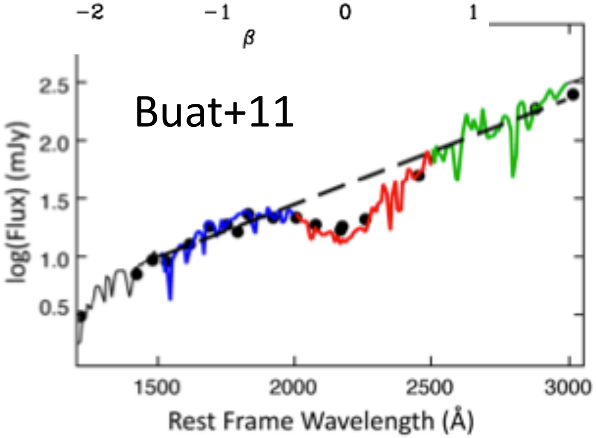
Proxies for Dust at High Redshift

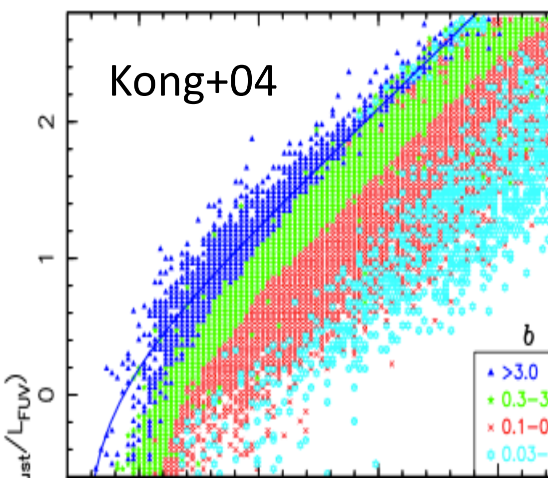
UV Slope

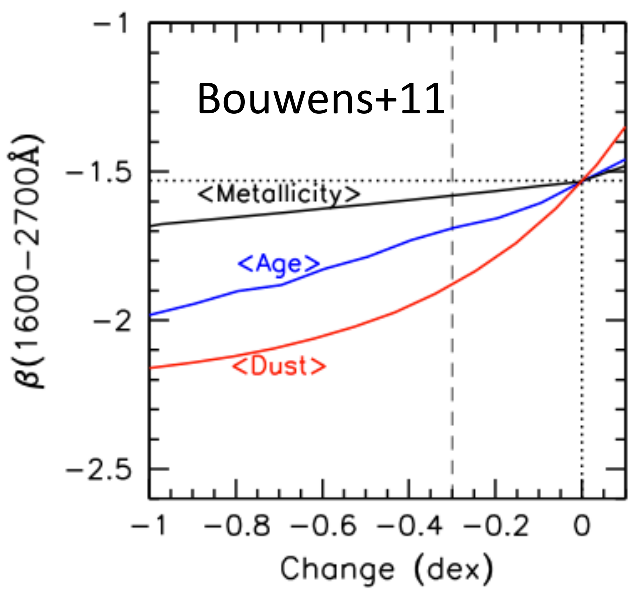
sensitive to age, metallicity, and SFH; measurement can be complicated by presence of 2175 A feature







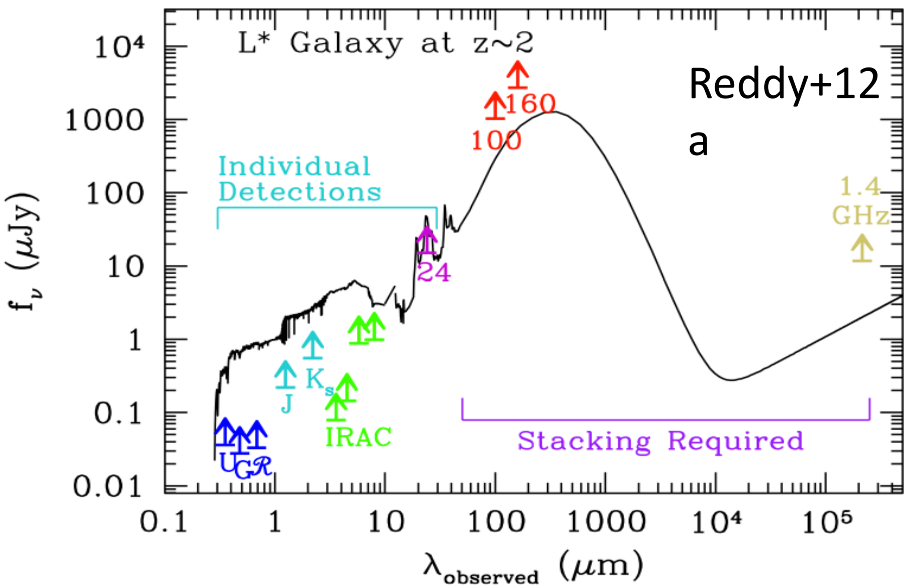


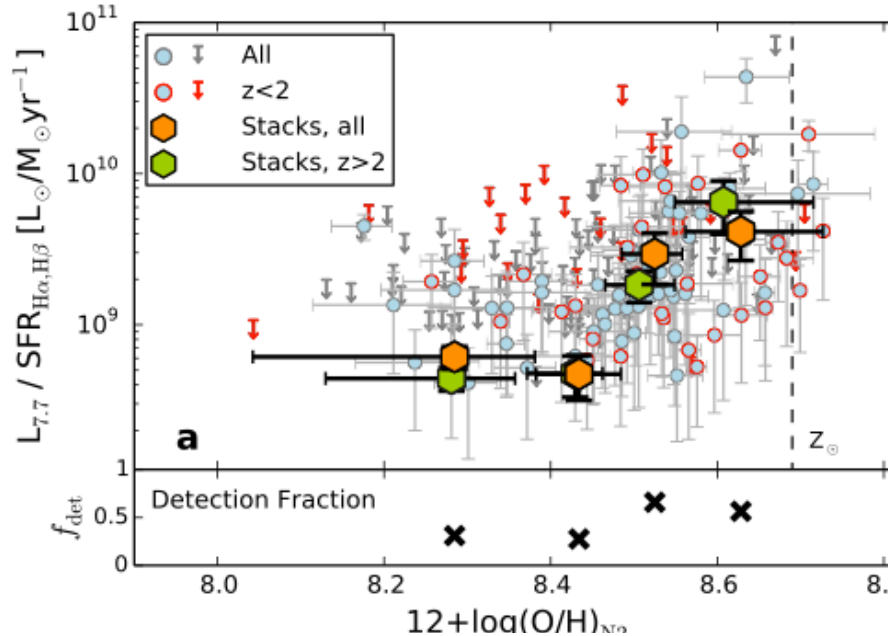


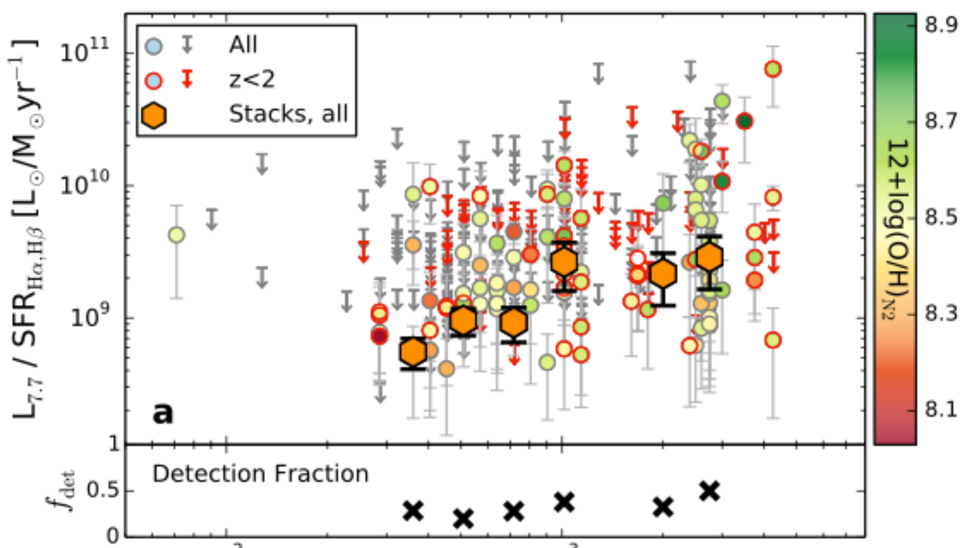
Proxies for Dust at High Redshift

Mid- and Far-IR

observations not sensitive enough to detect typical star-forming galaxies at z>1.5 (requires lensing)





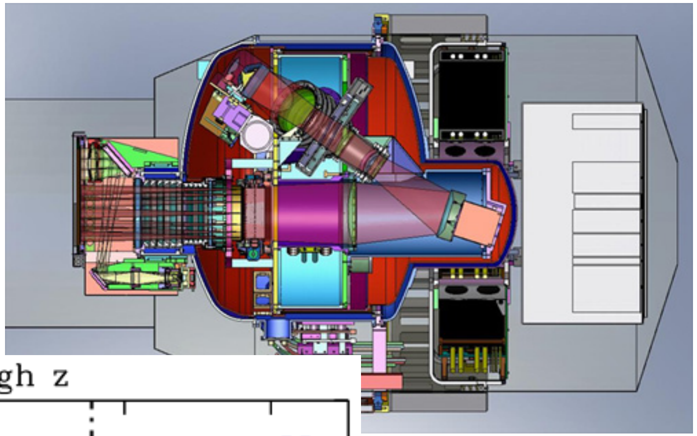


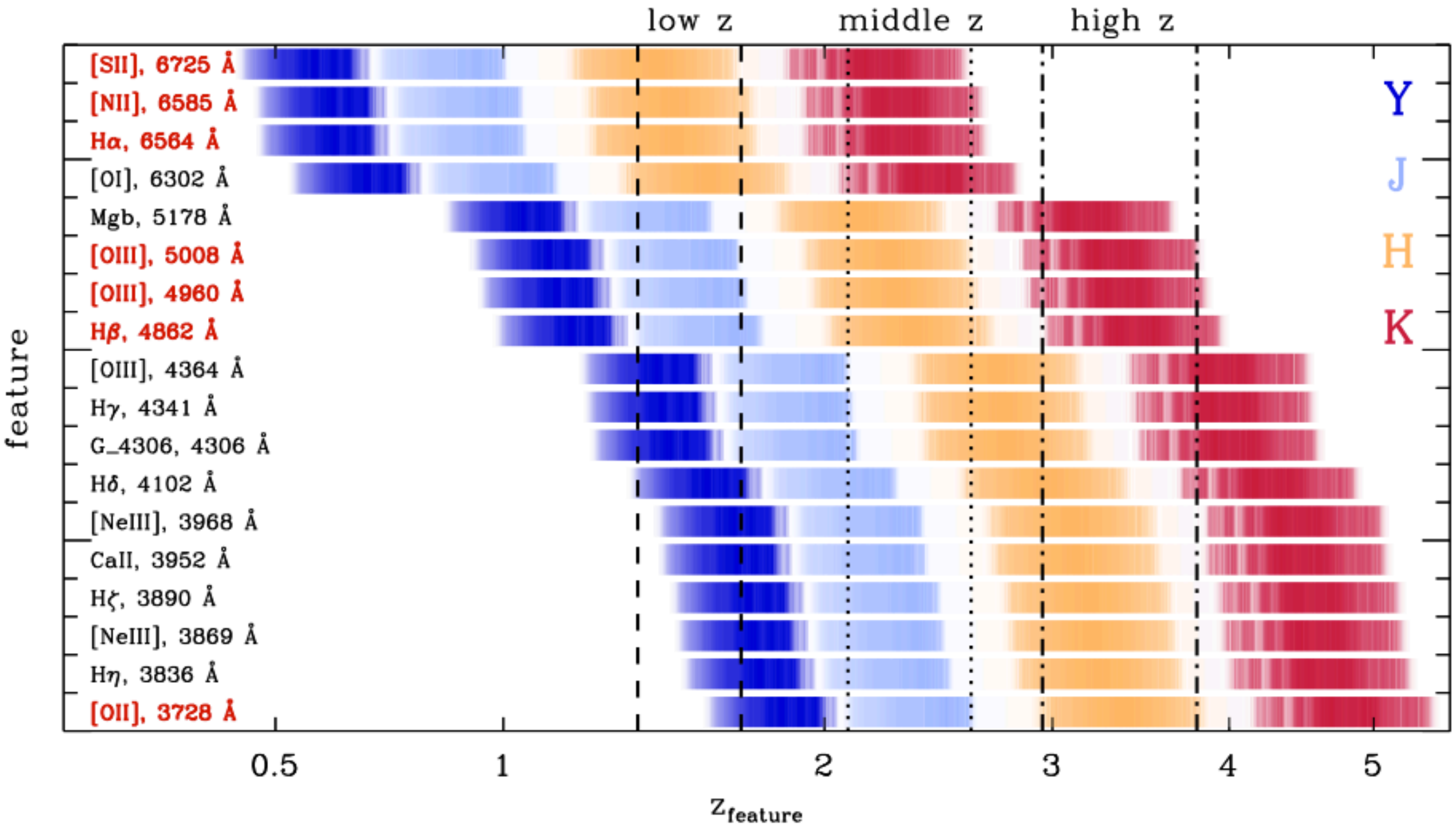
Shivaei+17

A New Avenue to Exploring Dust at High Redshifts using HI Recombination Lines

BALMER DECREMENTS

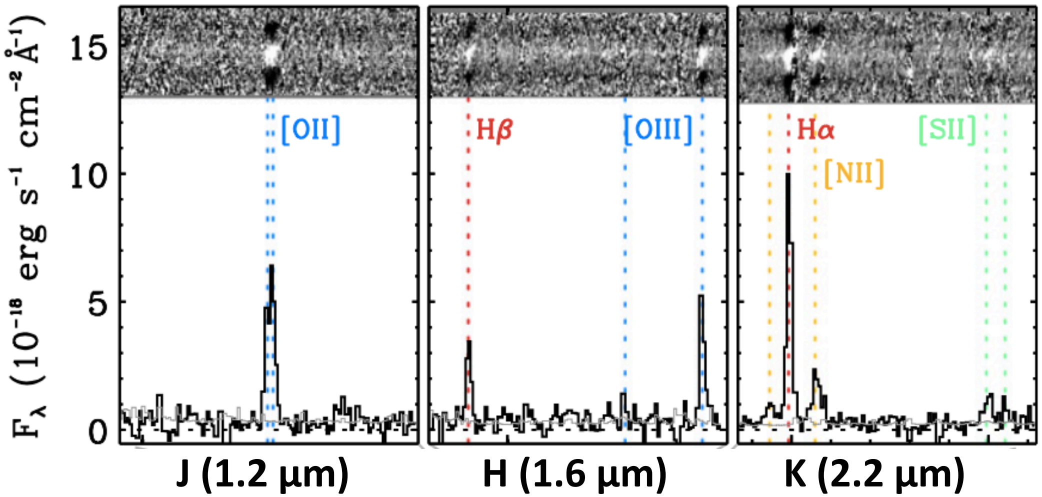
(e.g., Calzetti et al. 1994, Kennicutt et al. 2009, Groves et al. 2012, etc...)

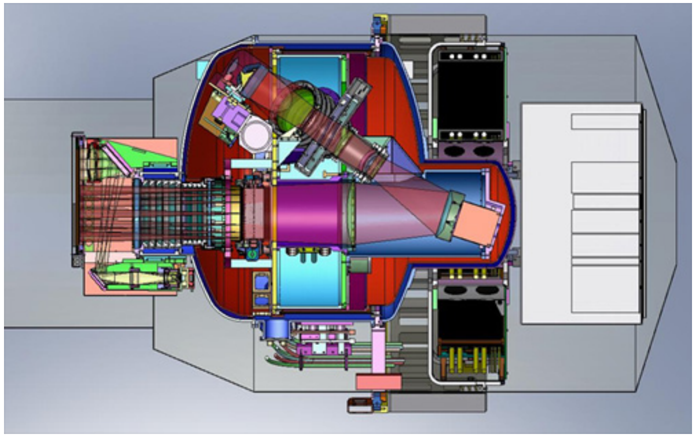




MOSFIRE Deep Evolution Field (MOSDEF) Survey

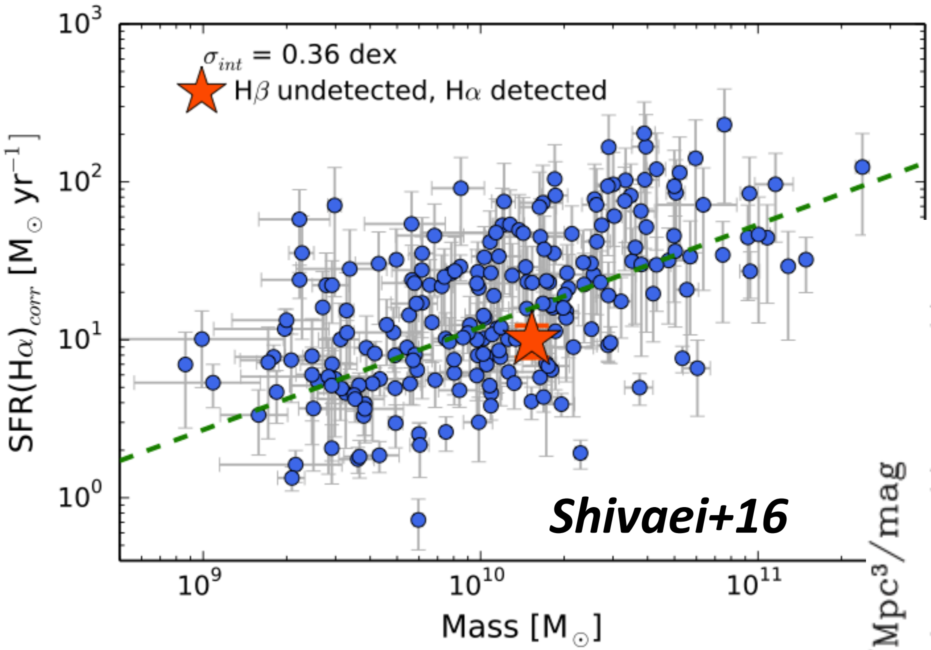
Survey paper: Kriek+2015

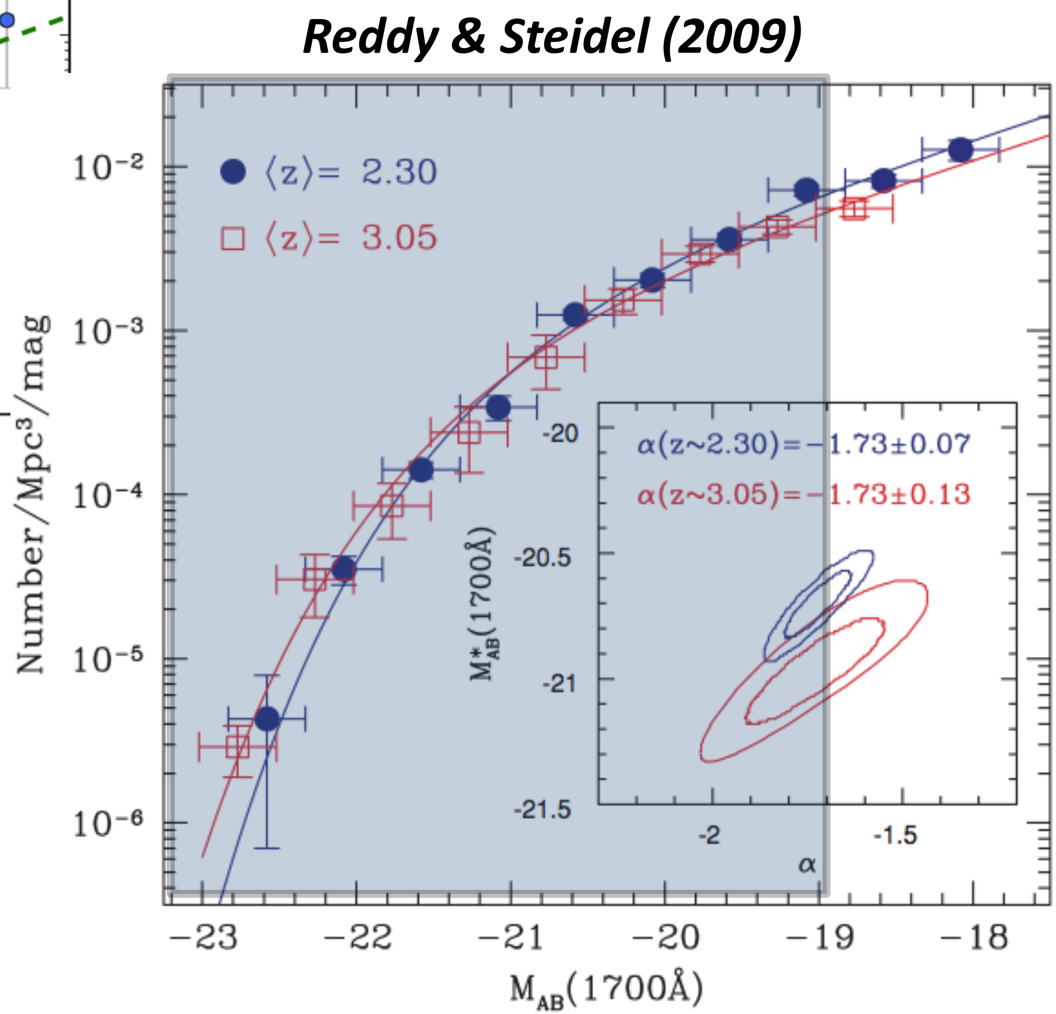




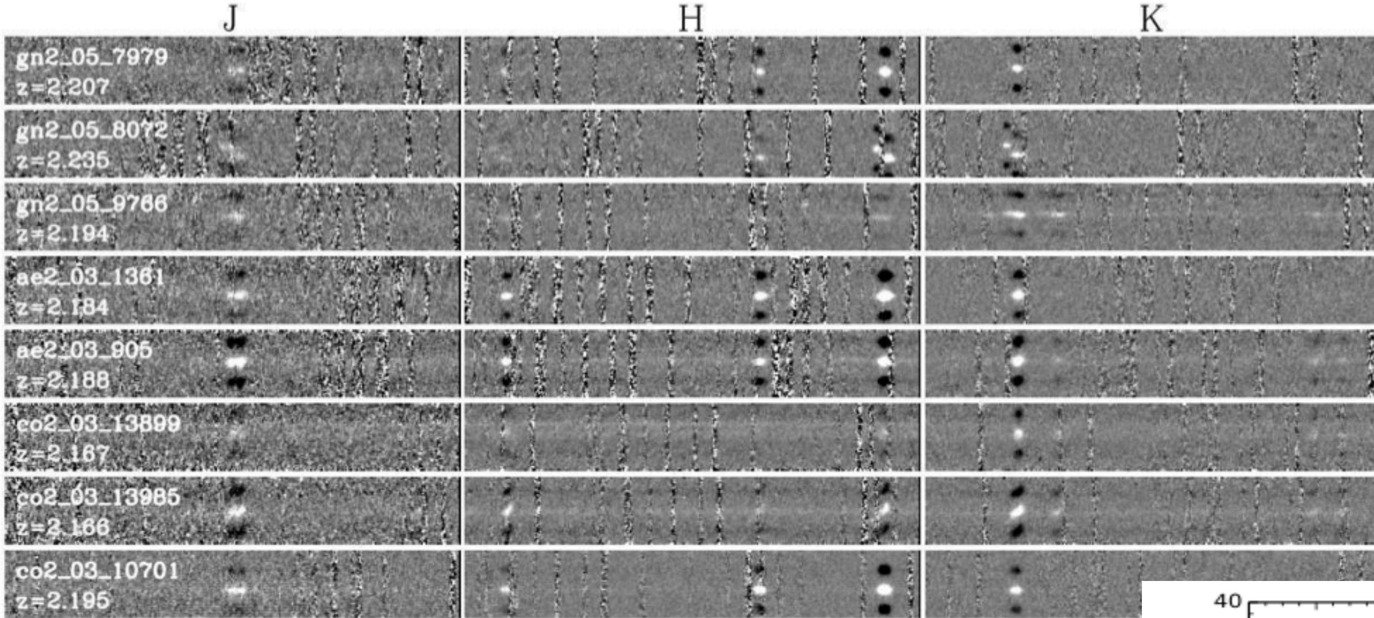
- Rest-frame optical spectra of ~ 1800 H-selected galaxies and AGNs
- $1.37 \leq z \leq 3.80$
- CANDELS fields
- 48.5 nights with MOSFIRE on Keck I (2012-2016)
- Collaboration between UC Berkeley, UCLA, UC San Diego, UC Riverside

MOSDEF Sampling of "Typical" Star-forming Galaxies at 1.4<z<3.8



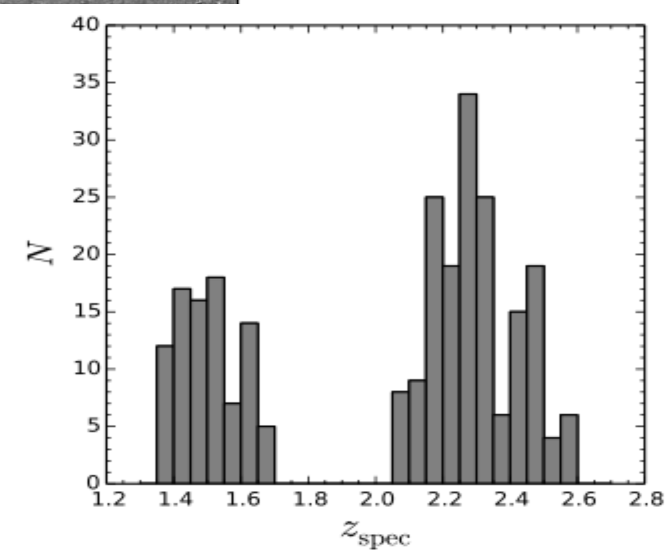


Balmer Decrement Measurements



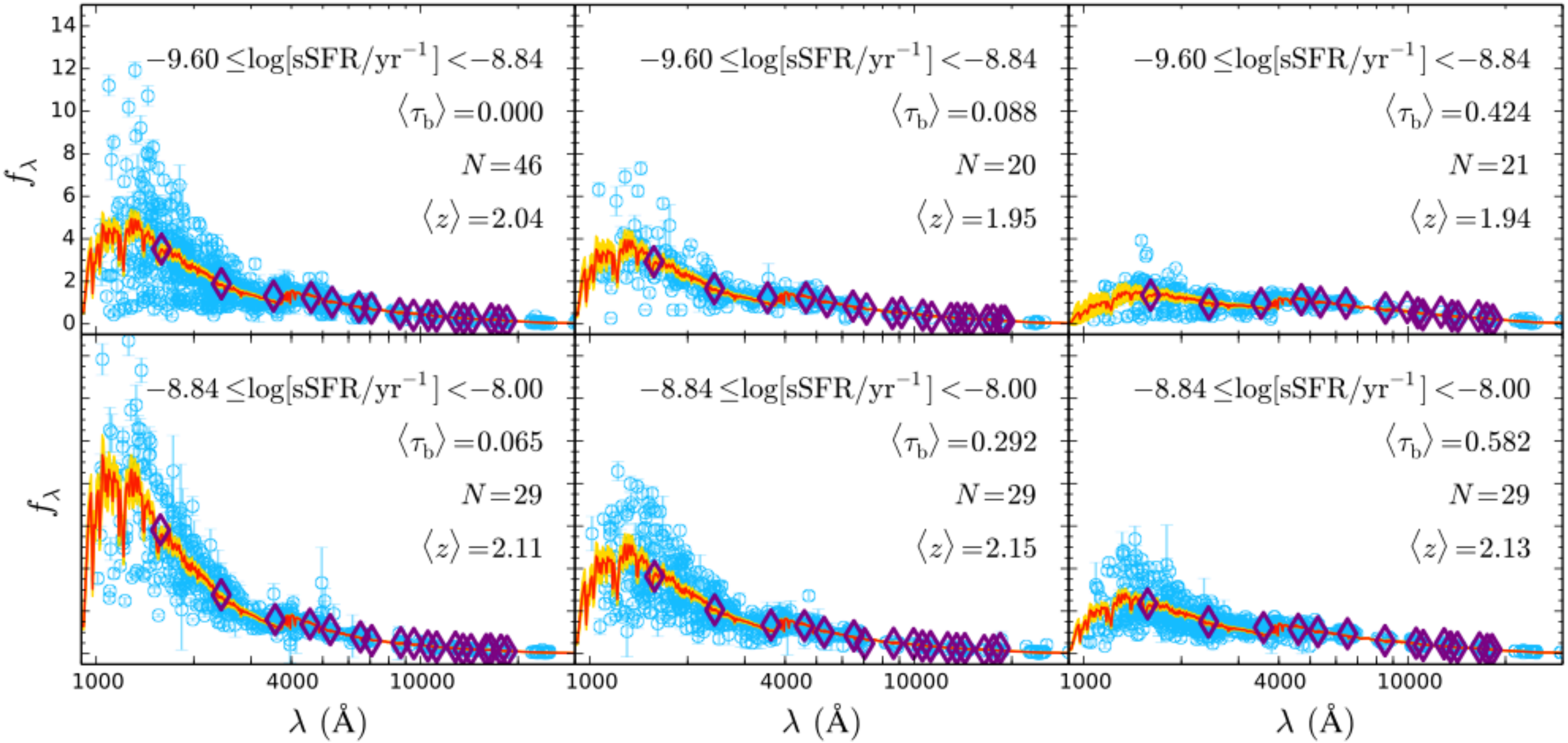
$$\tau_{\rm b} \equiv \ln\left(\frac{{\rm H}\alpha/{\rm H}\beta}{2.86}\right)$$

224 star-forming galaxies at z_{spec}= 1.36 – 2.59



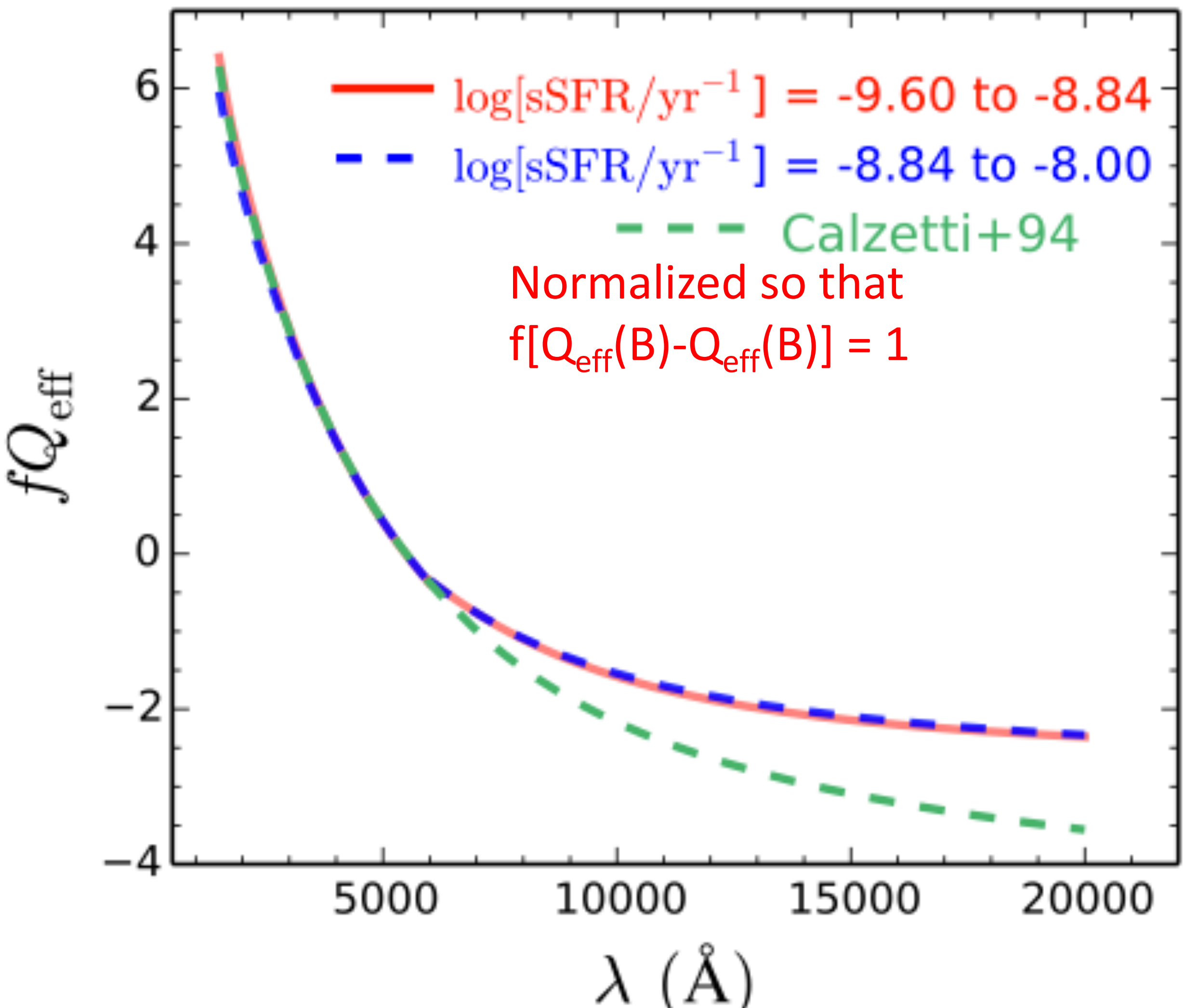
Calculating the Attenuation Curve

Ratios of Composite SEDs in bins of Balmer optical depth



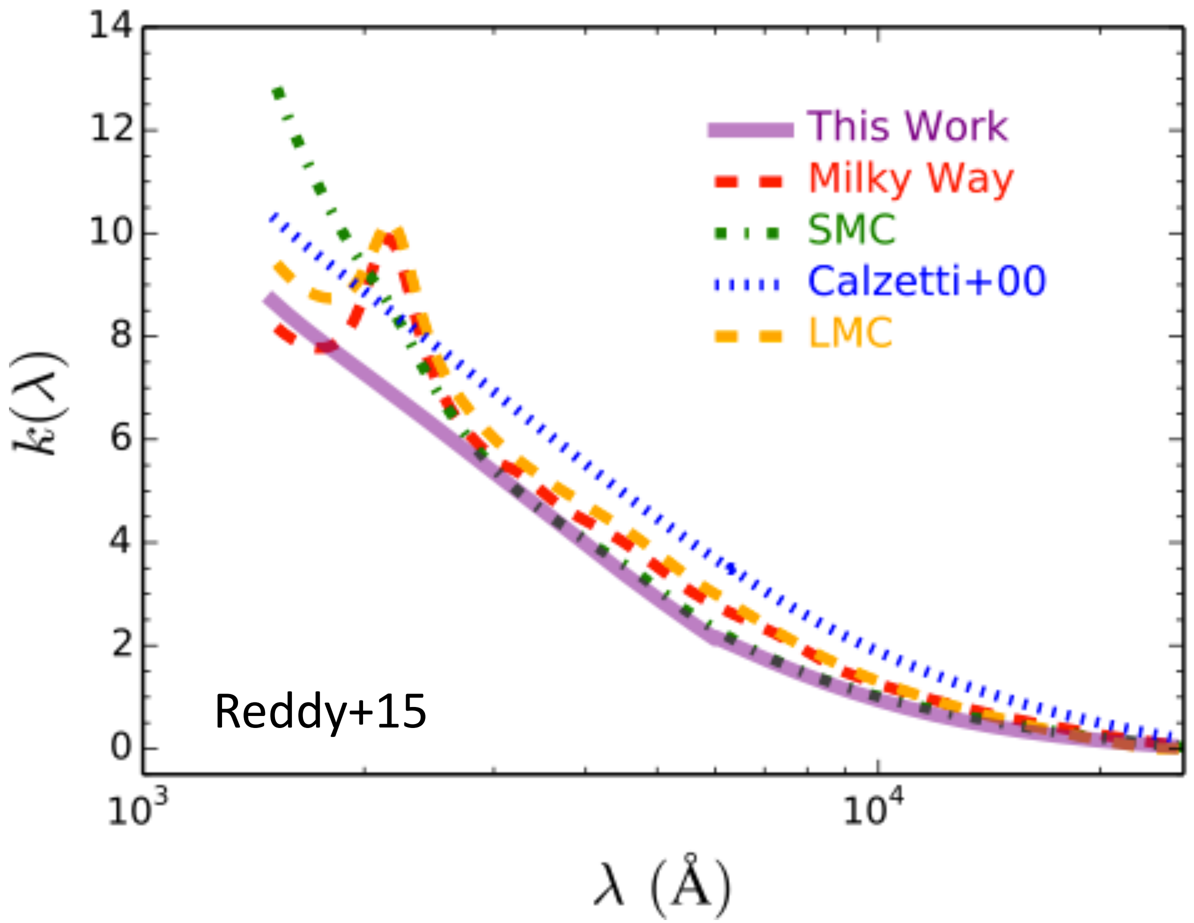
Calculating the Attenuation Curve…

Normalization (Rv)…



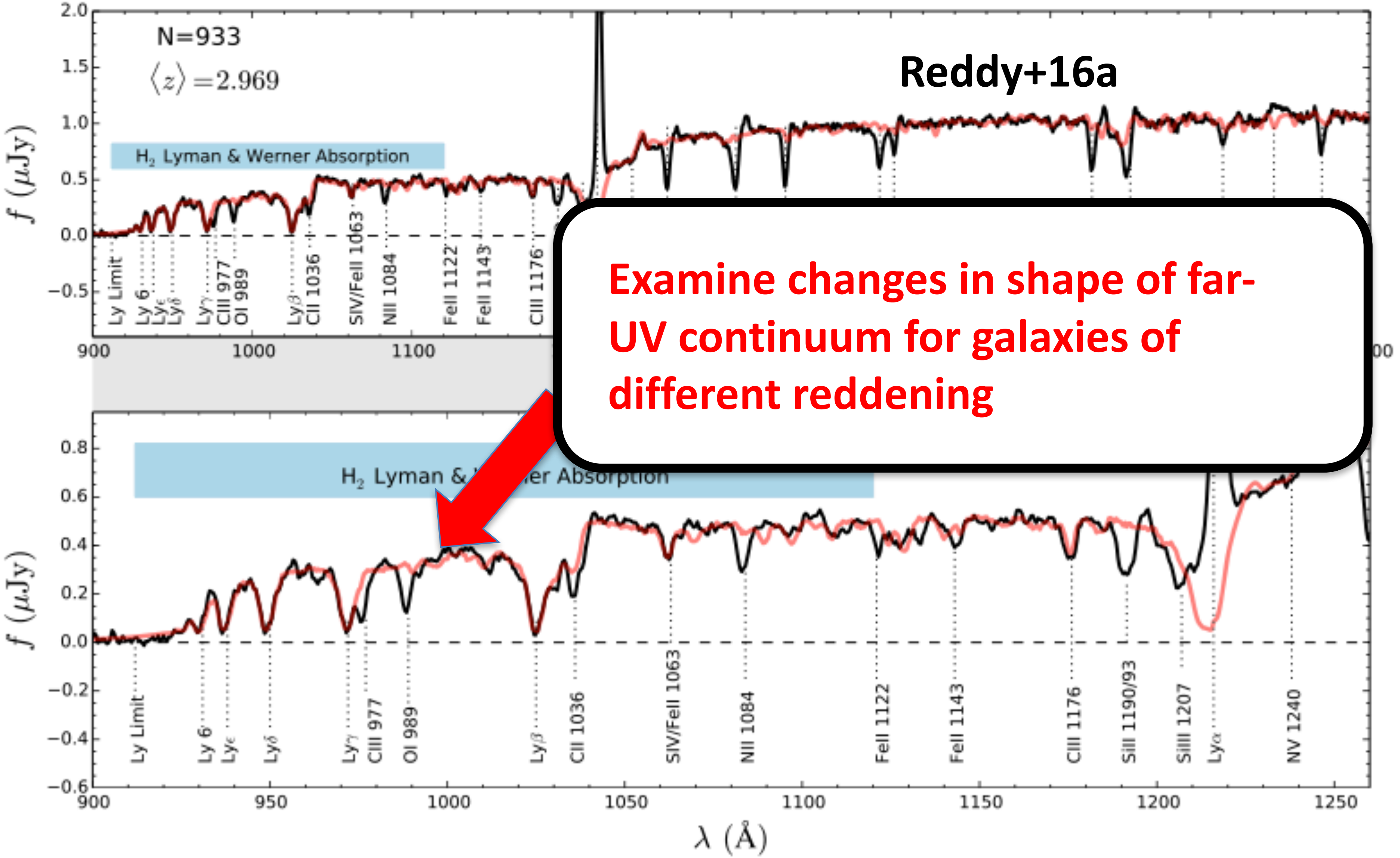
Renormalized so that $fQ_{\mathbf{eff}}(\lambda \rightarrow 2.85\ \mu m)=0$

Systematic uncertainties of $\Delta R_V \approx 0.4$



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

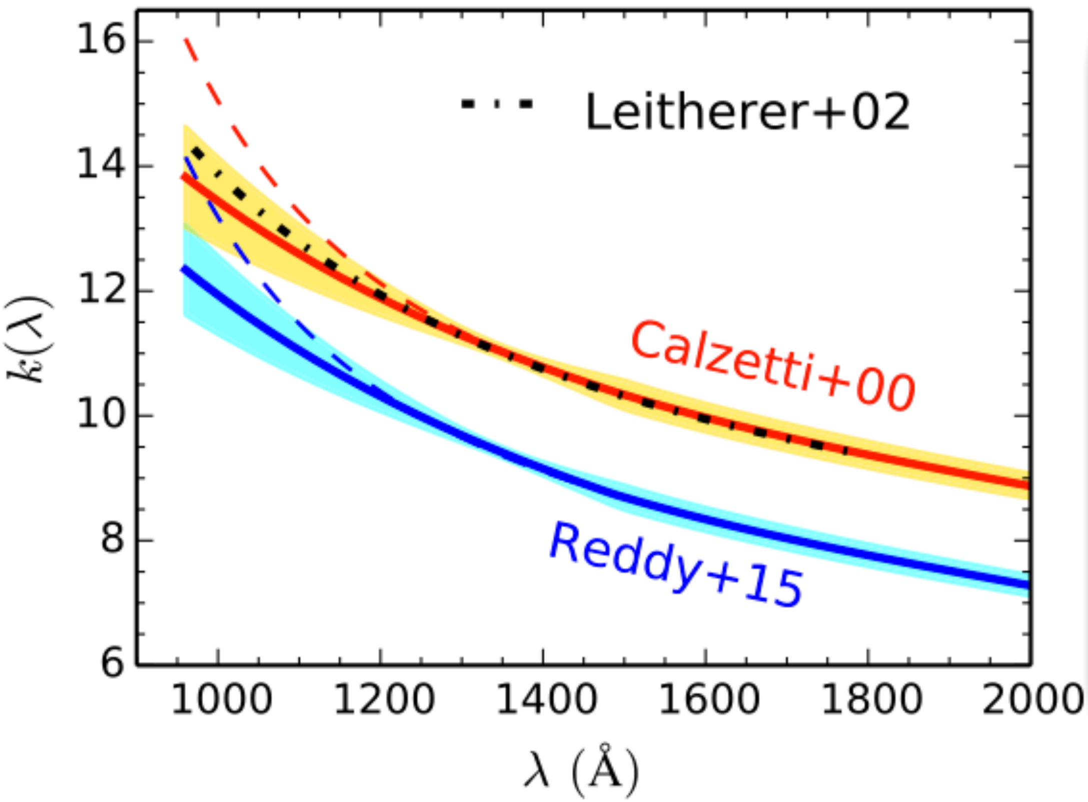
Extension of the Curve to the Lyman Break



Examine changes in shape of far-UV continuum for galaxies of different reddening

Extension of the Curve to the Lyman Break

Factor of ~2 lower attenuation for typical E(B-V) at the Lyman break relative to simple extrapolations of attenuation/extinction curves



Practical Uses:

- **Evaluating attenuation of ionizing photons**
- **Evaluating attenuation in low column density ISM of high-redshift galaxies**

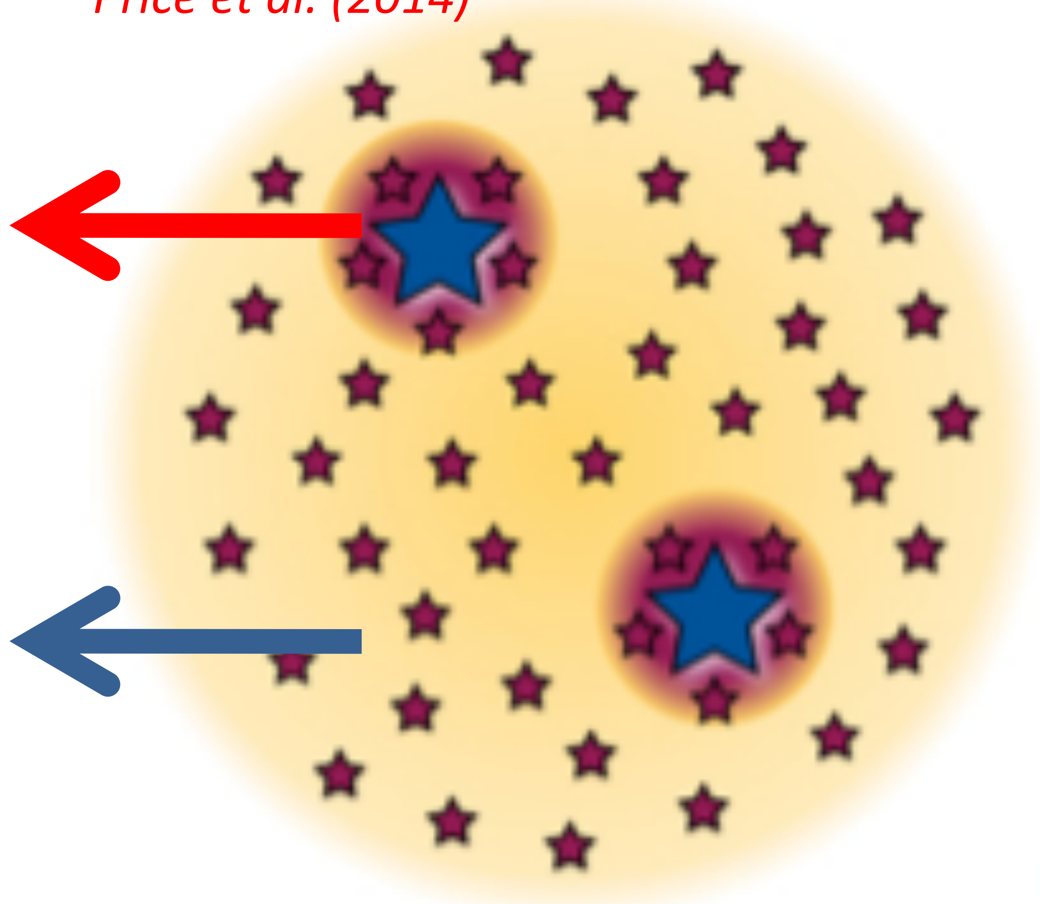
Reddy+16a

Reddening of Lines vs. Continuum

Price et al. (2014)

LOCALLY:

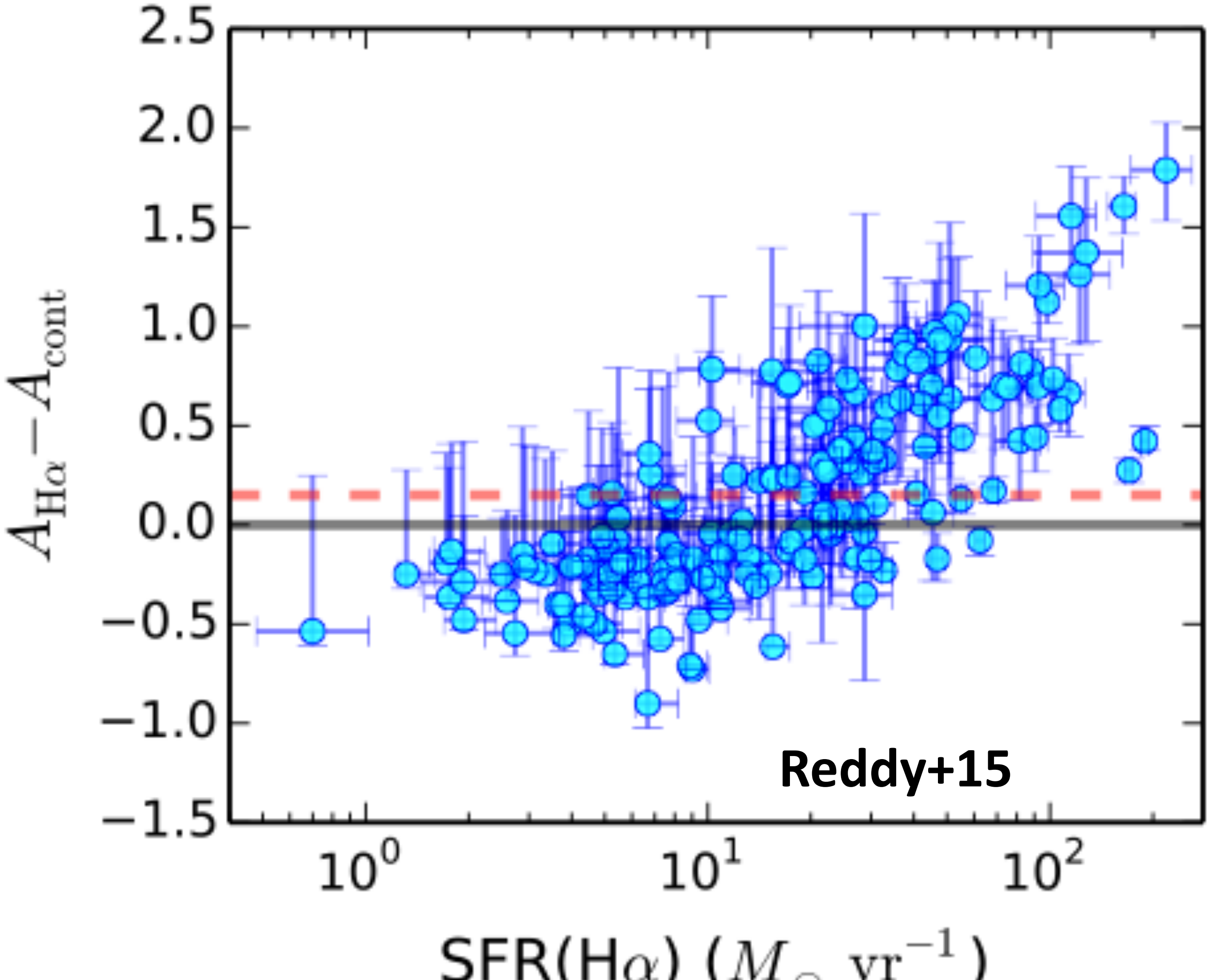
Higher attenuation towards lines-of-sight to massive stars



(e.g., Fanelli et al. 1988, Calzetti et al. 1994, Mas-Hesse & Kunth 1999, Kreckel et al. 2013)

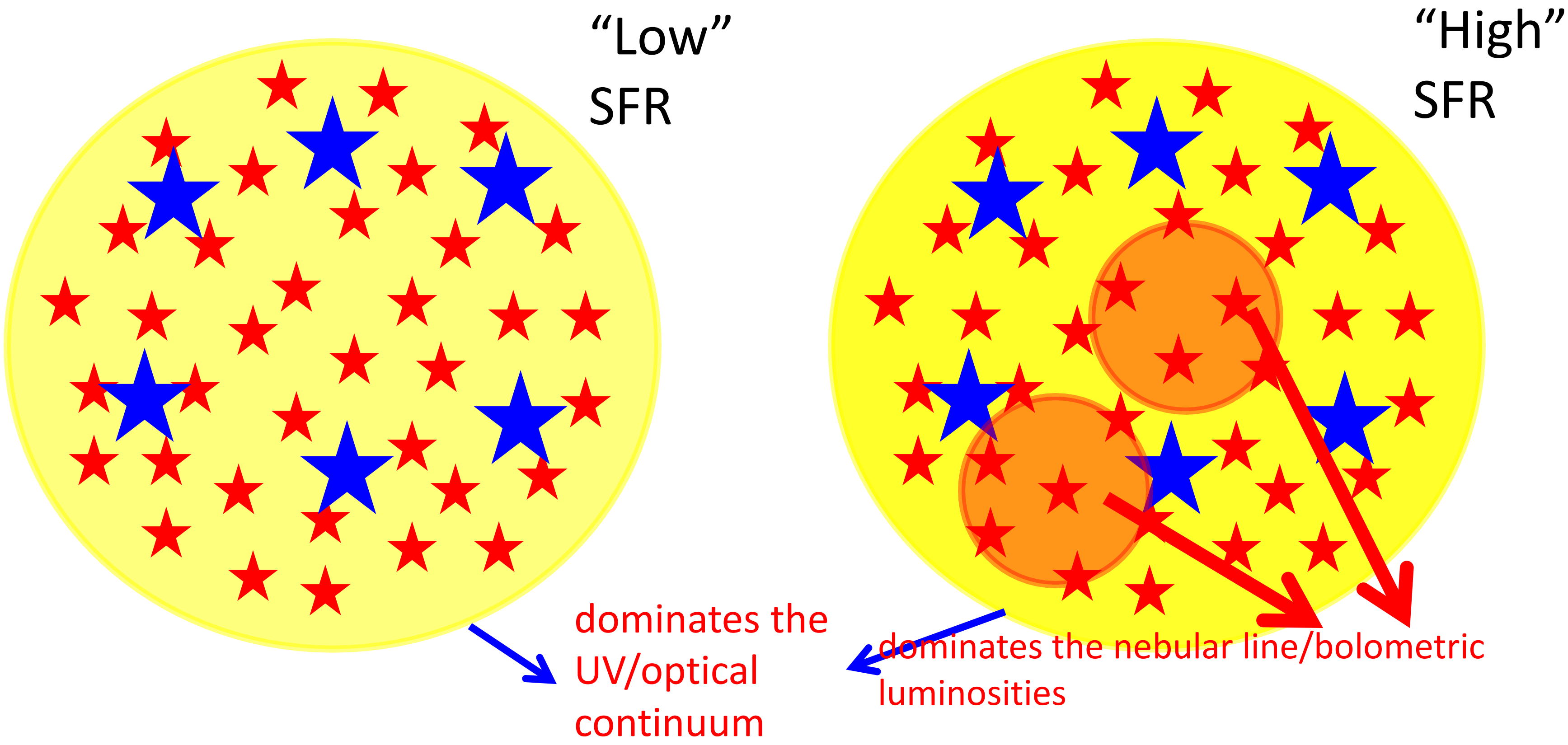
Color Excess of Ionized Gas vs. Stellar Continuum

Assumes Cardelli+89 (Galactic) extinction curve

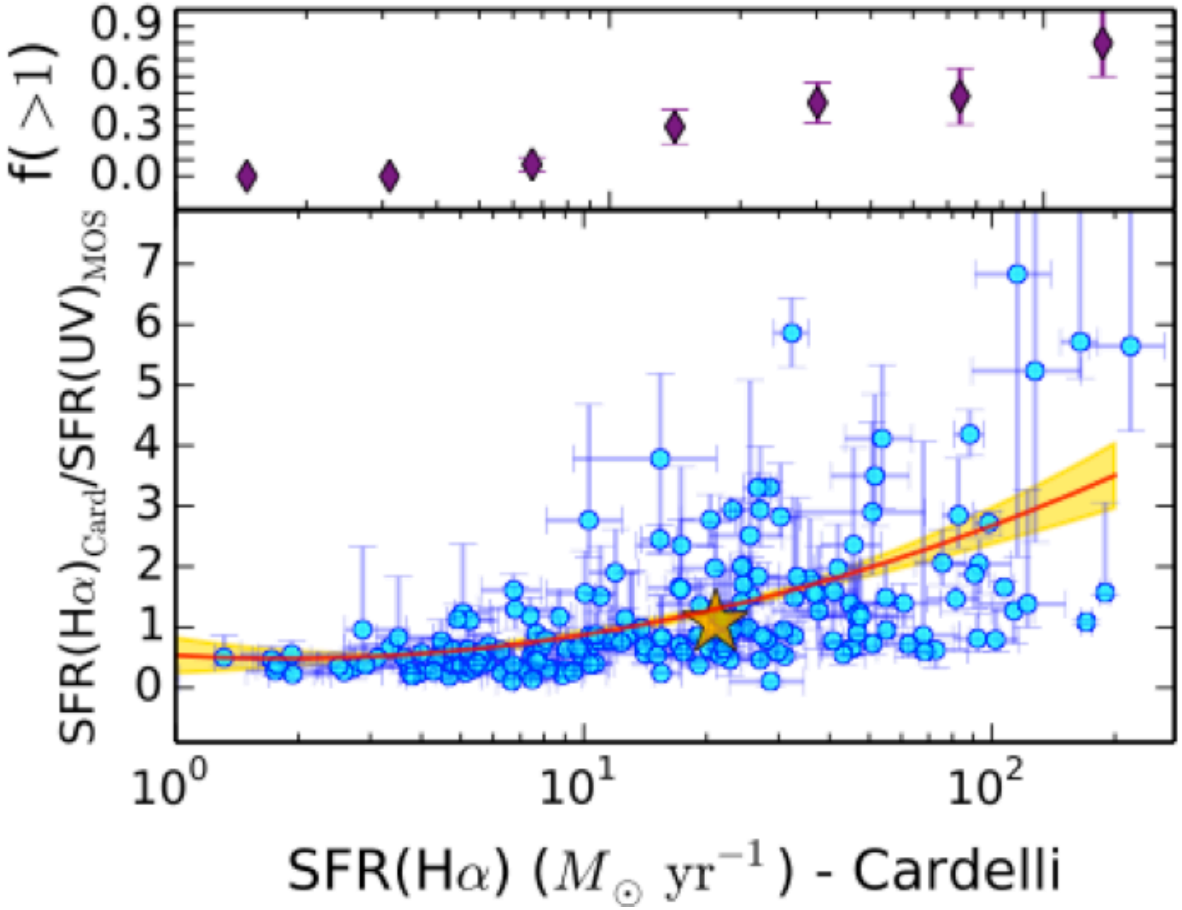


A Possible Physical Interpretation

At high-z: stars of all masses are attenuated by same amount, with larger contribution of dust-enshrouded SF at higher SFRs

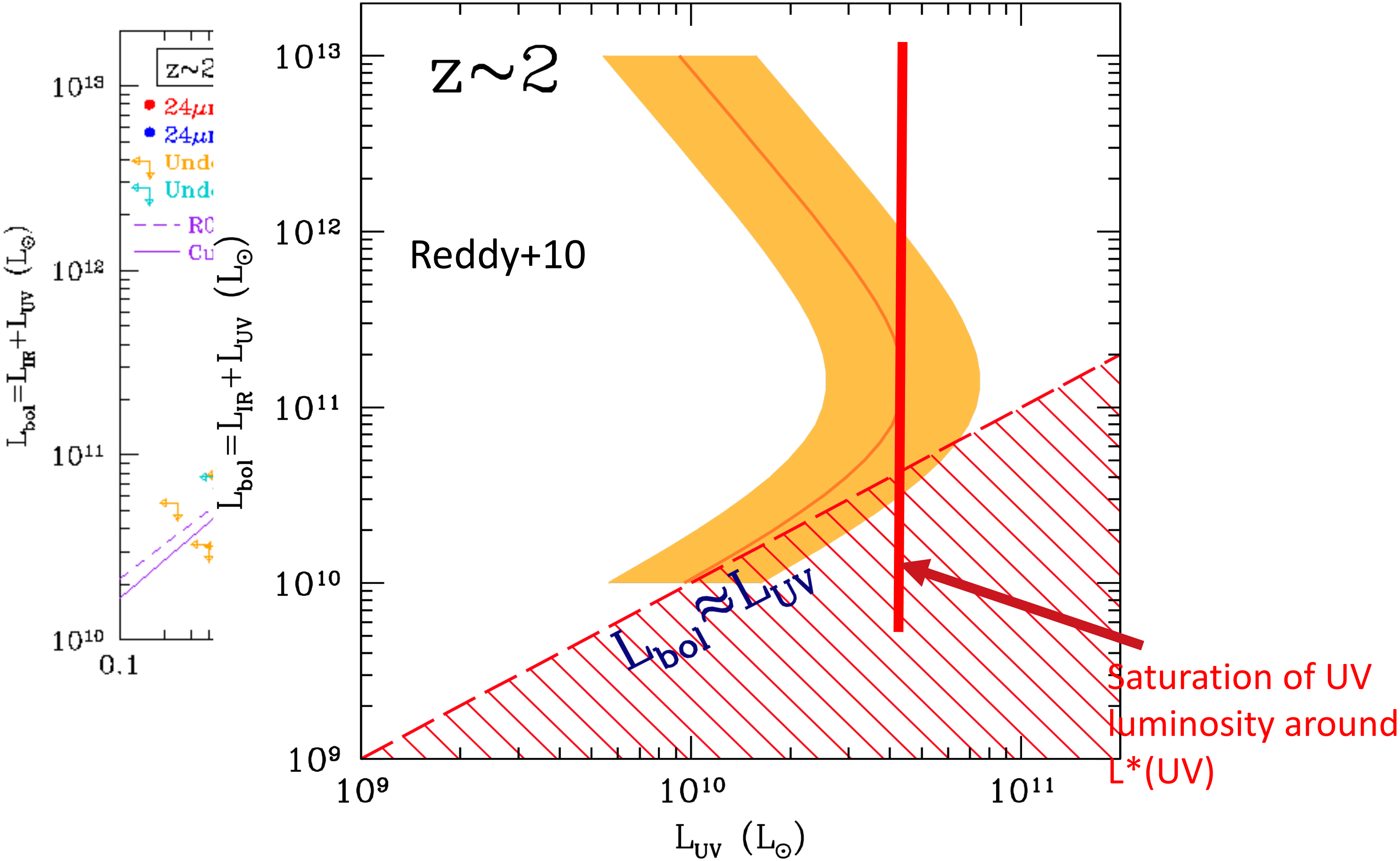


Implications for SFRs from the UV or SED-fitting

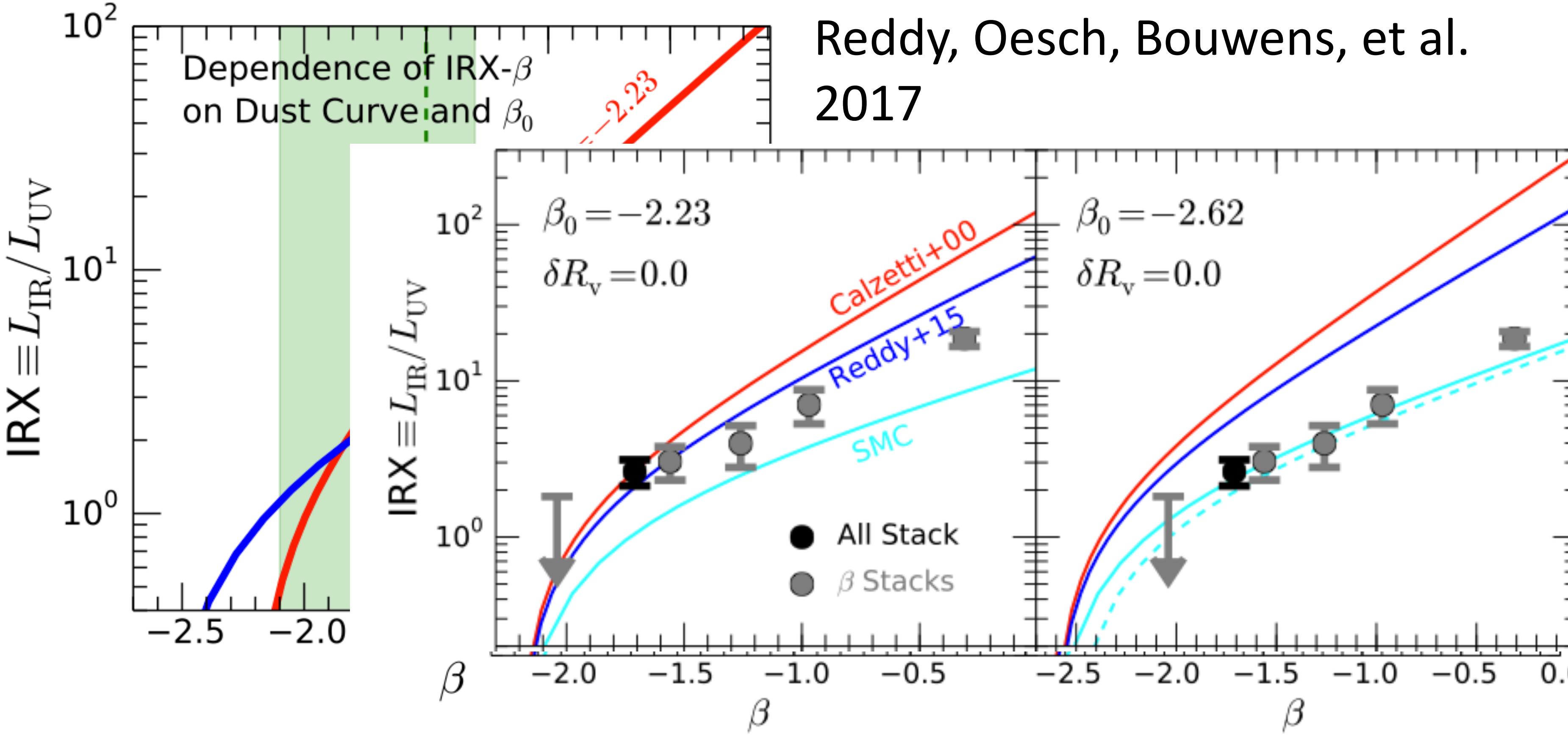


UV/SED-based SFRs *underpredict* total SFR above ≈ 20 $M_\odot$/yr

Similar “Saturation” seen with IR vs. UV-based SFRs



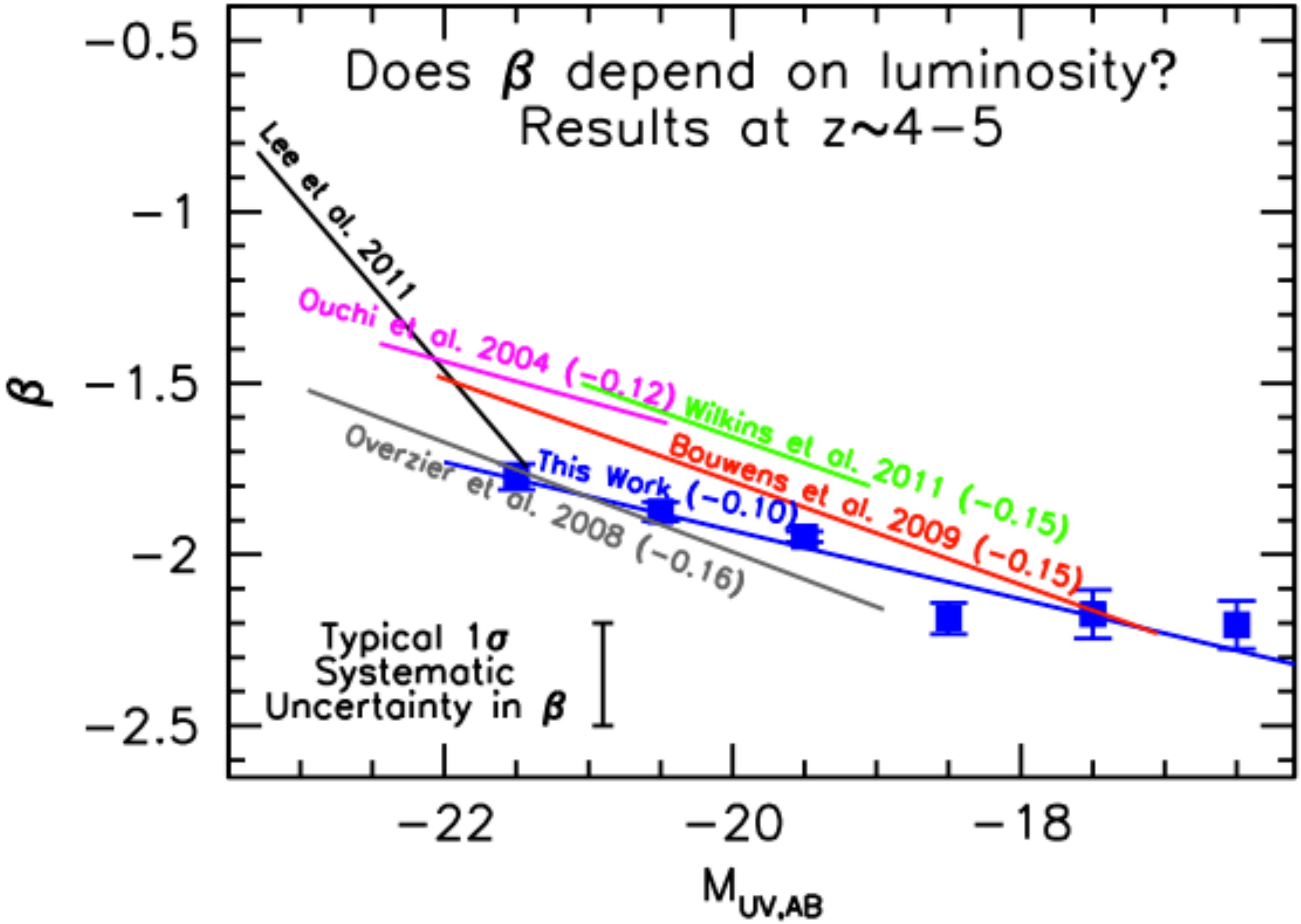
Recent Results from the HDUV Survey



Reddy, Oesch, Bouwens, et al. 2017

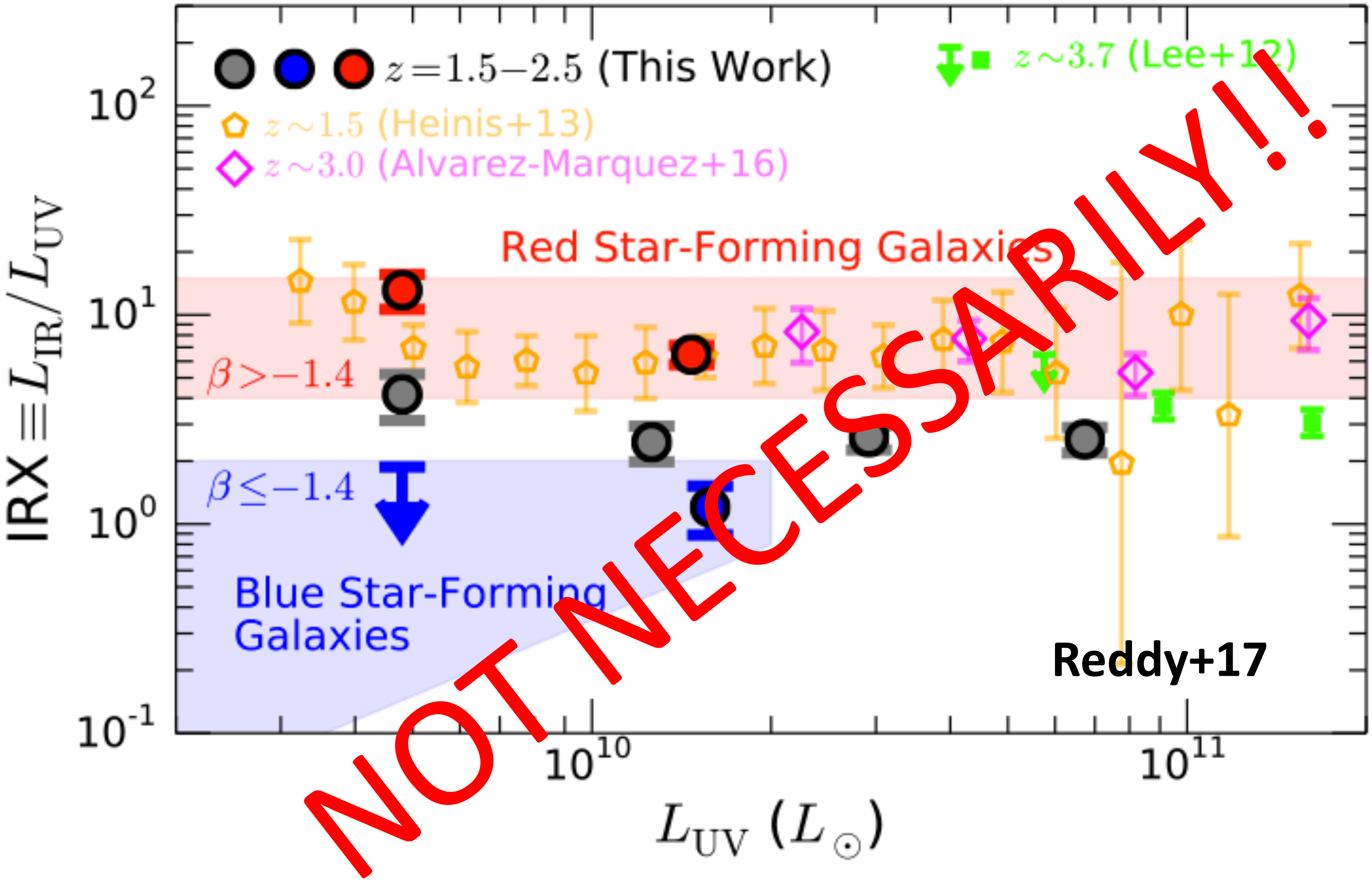
SMC best reproduces the IRX-β Relation for sub-solar metallicity stellar populations

Are sub-L* galaxies less dusty?



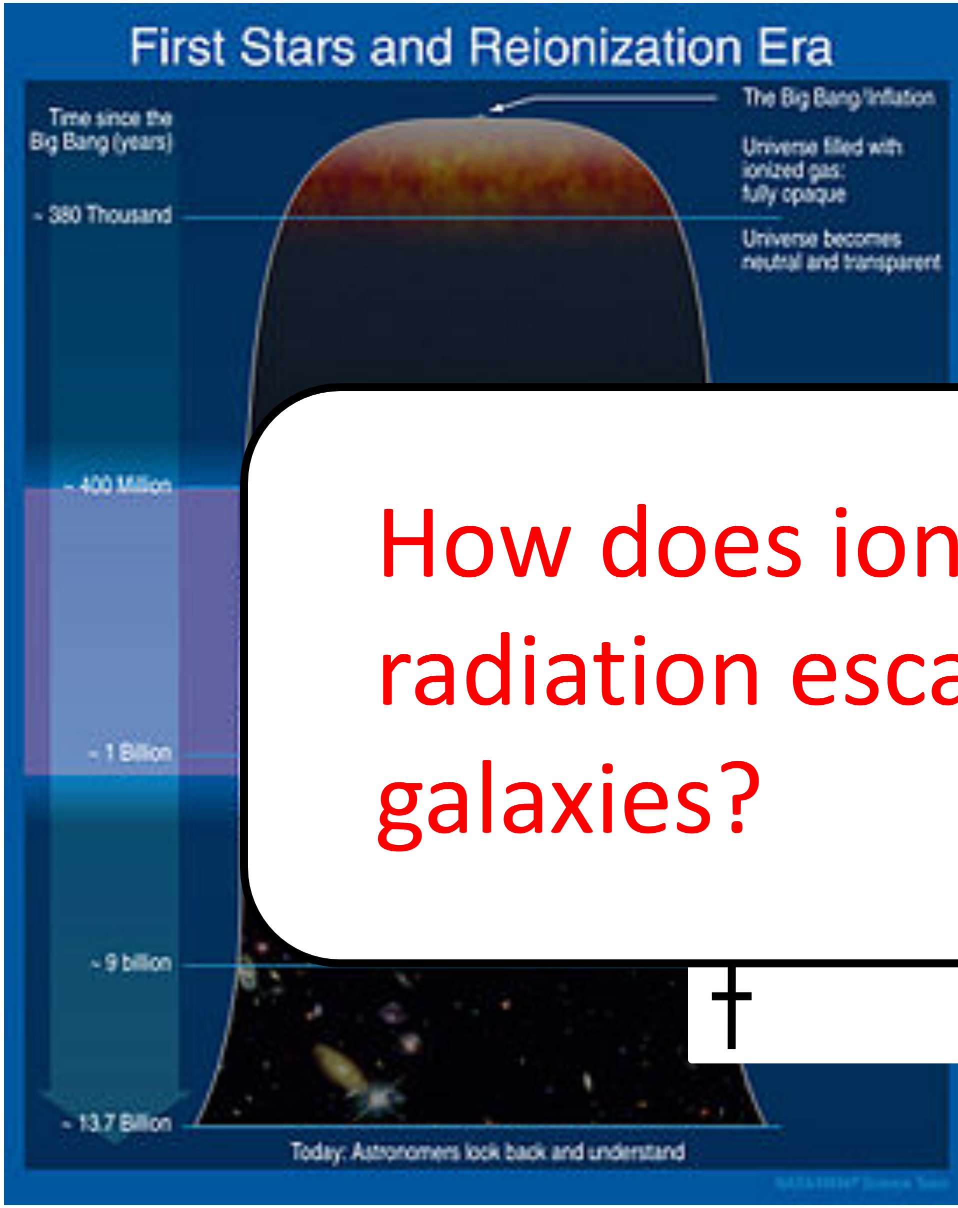
Bouwens+11

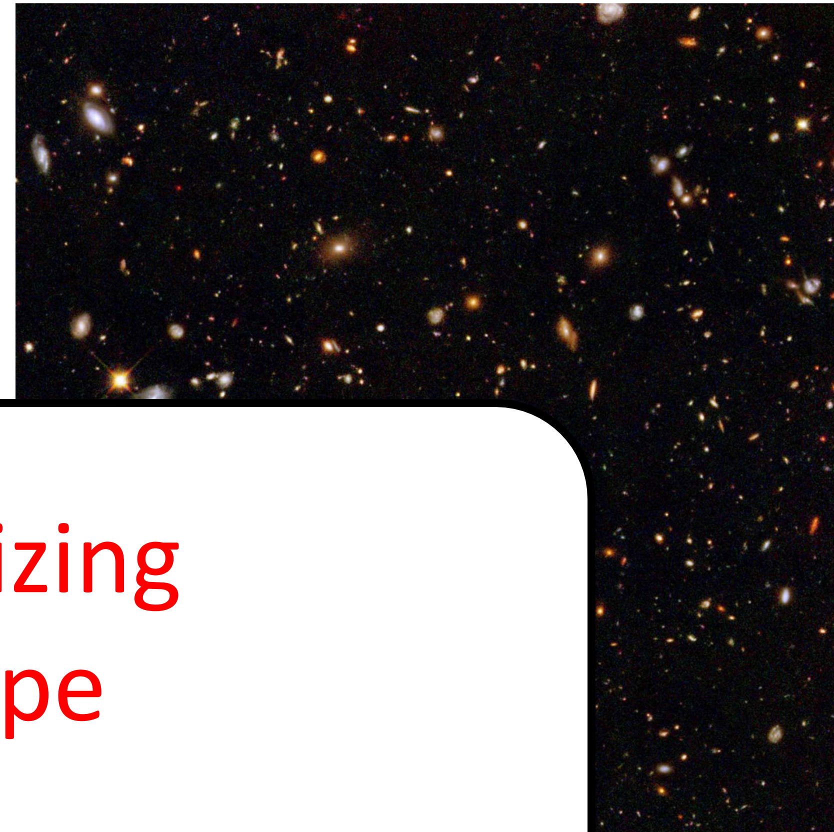
Are sub-L* galaxies less dusty?



Rapid Dust Enrichment for CCSNe (Todini & Ferrara 2001)

Epoch of Reionization

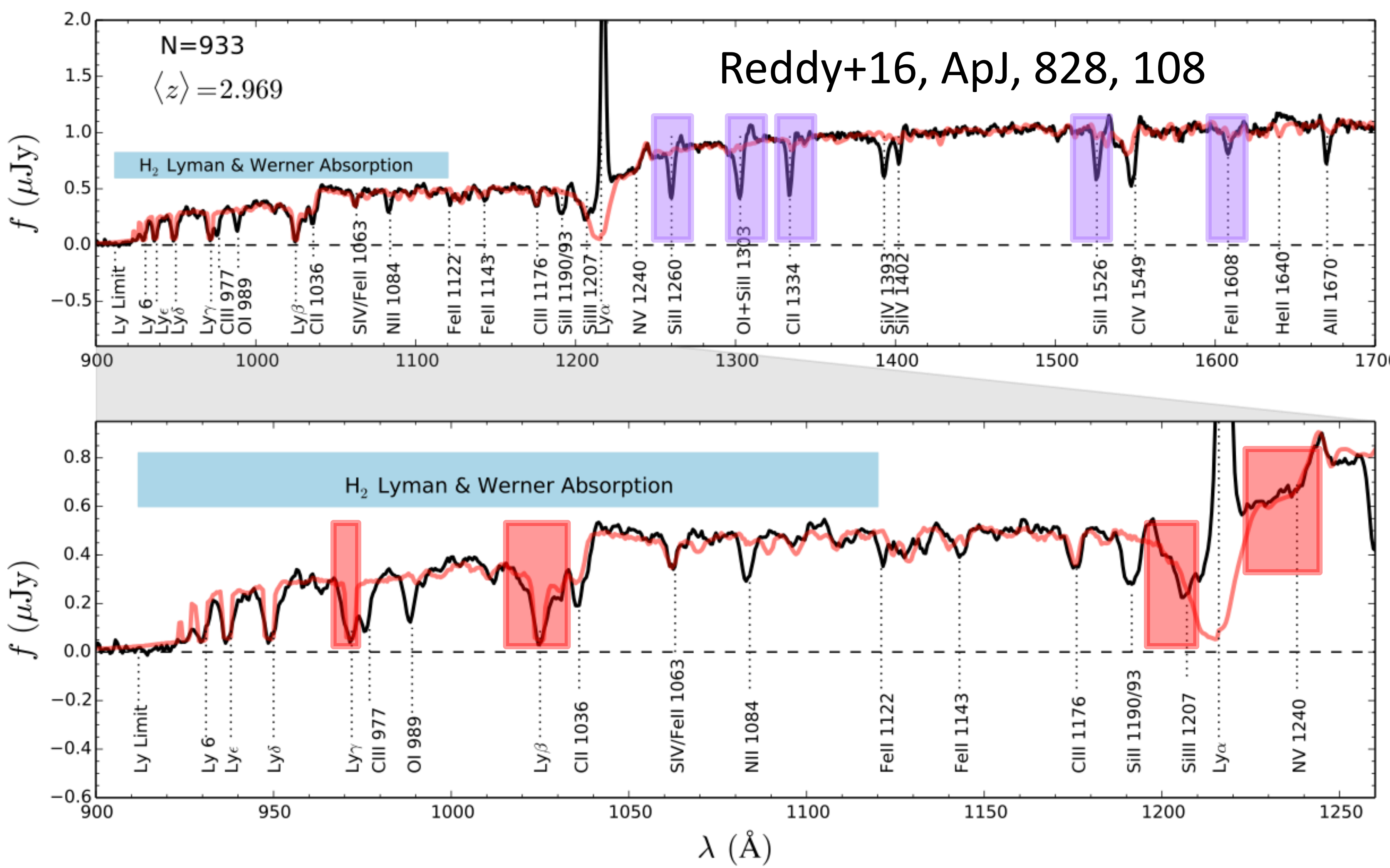




How does ionizing radiation escape galaxies?

What does it take: lots of galaxies/AGN?

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



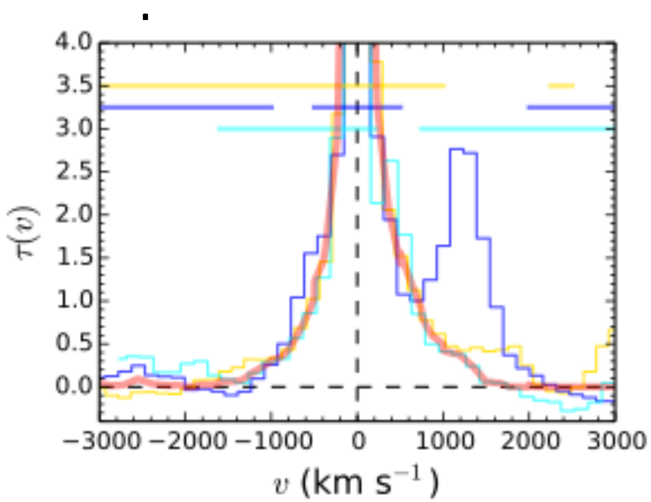
(1) Blue-shifted HI; (2) damping wings of Ly series lines; (3)non-zero residual flux at line centers: fcov(HI) < 1

Spectral Modeling

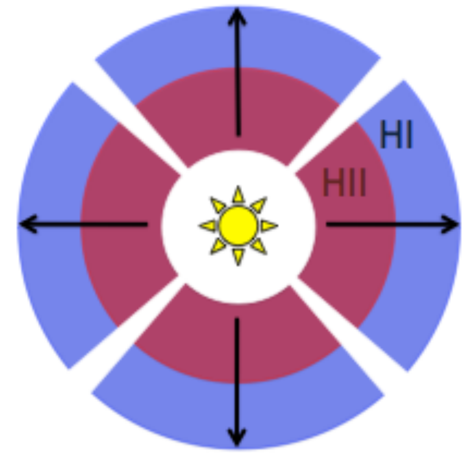
Details of Our "Two Component" Model:

- Intrinsic Spectrum: Rix+S99, $0.28Z_{o}$, neb. continuum emission; constant SF

LOS Reddened, and
HI+H2 Absorbed

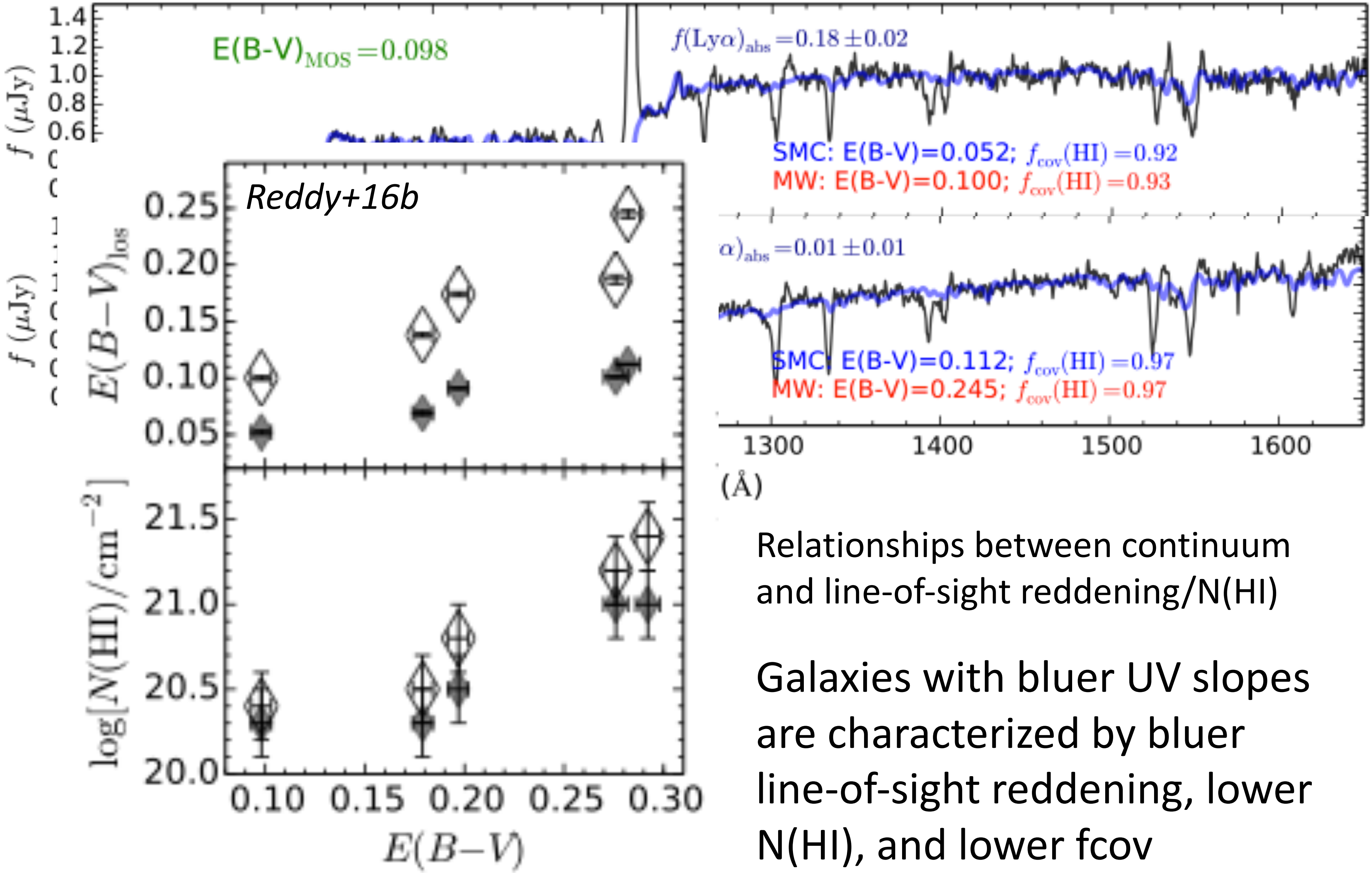


Fit to composites in bins of UV continuum reddening, while varying fcov



Gnedin+08, Razoumov &Sommer-Larsen+10, Zackrisson+13, Ma+16, Dijkstra+16

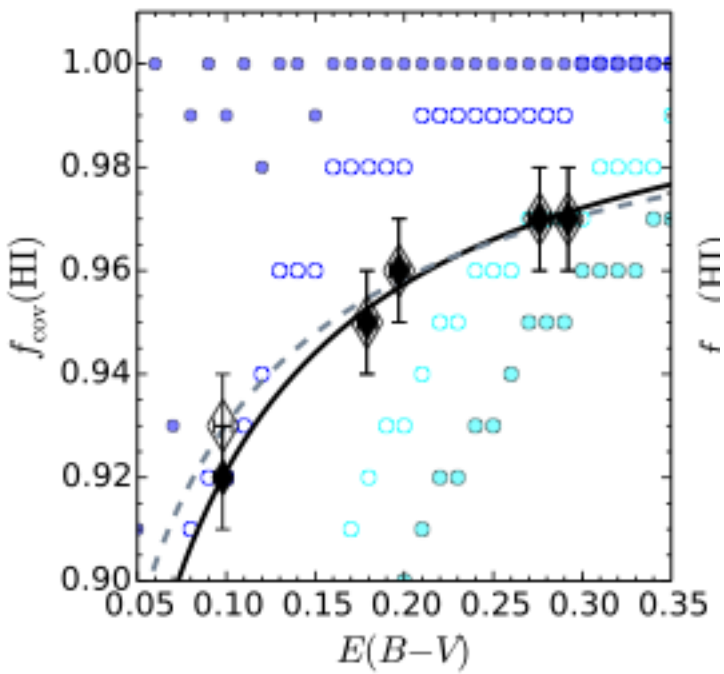
Spectral Modeling



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

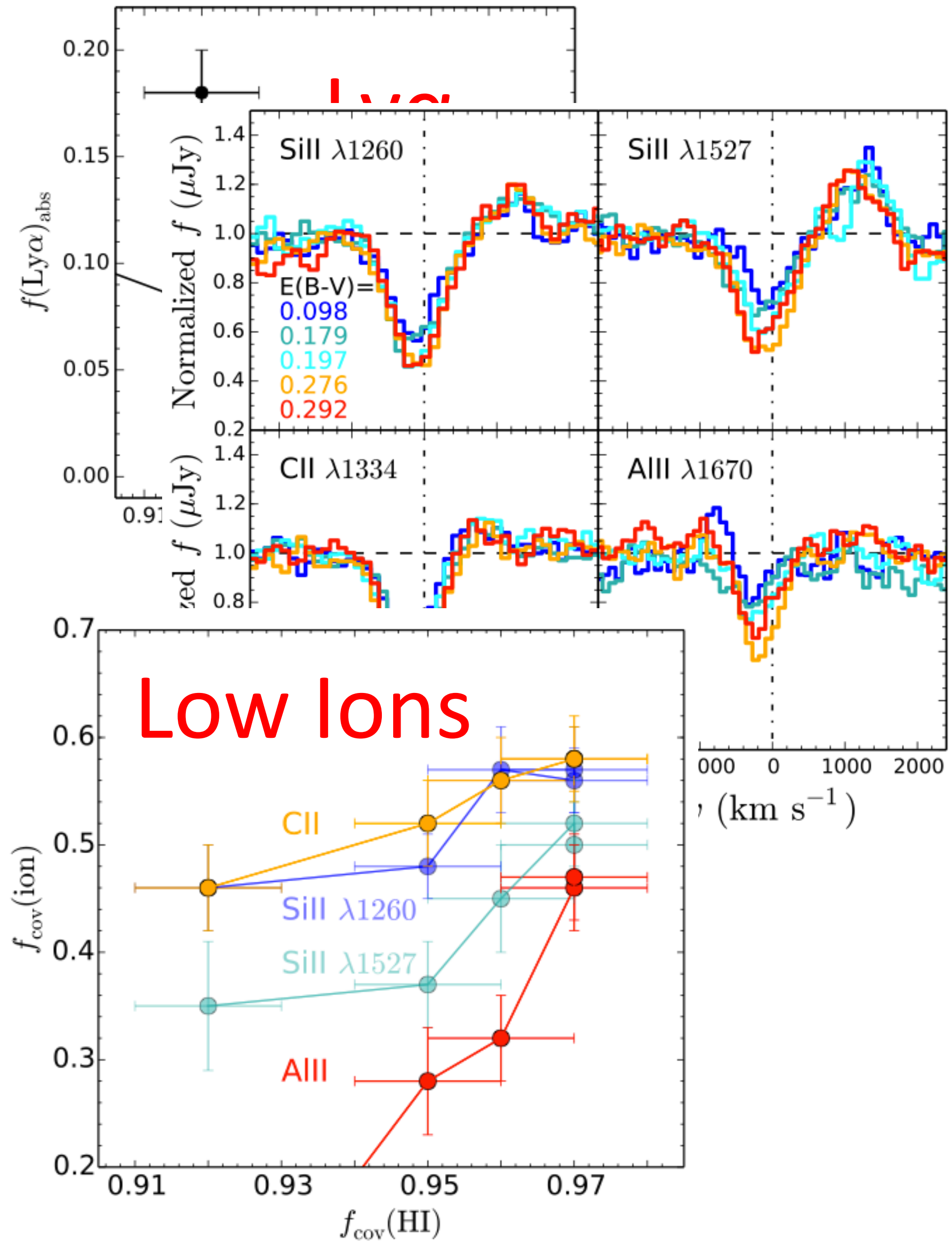
Galaxies with bluer UV slopes are characterized by bluer line-of-sight reddening, lower N(HI), and lower fcov

Relationship between Reddening and Covering Fraction



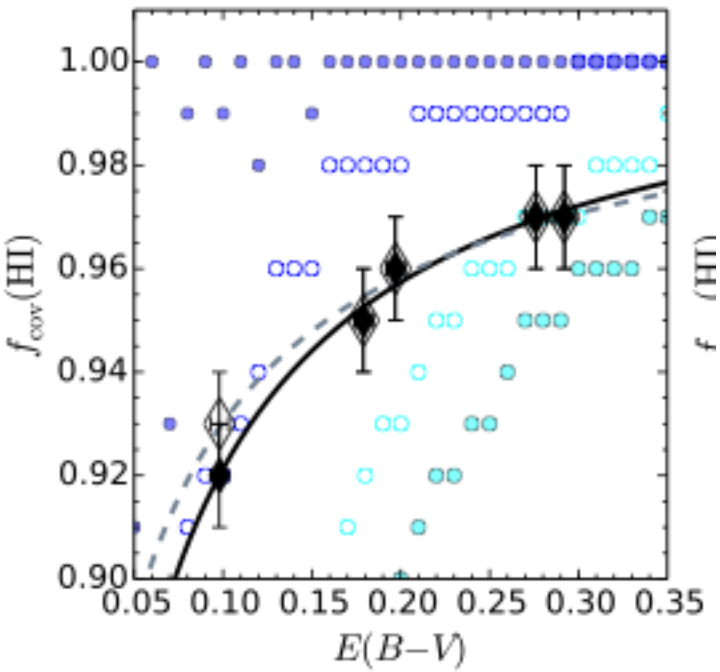
Reddy+16, ApJ, 828, 108

Low-ionization interstellar absorption lines systematically *underpredict* covering fraction…



Relationship between Reddening and Covering Fraction

Reddy+16, ApJ, 828, 108



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

+

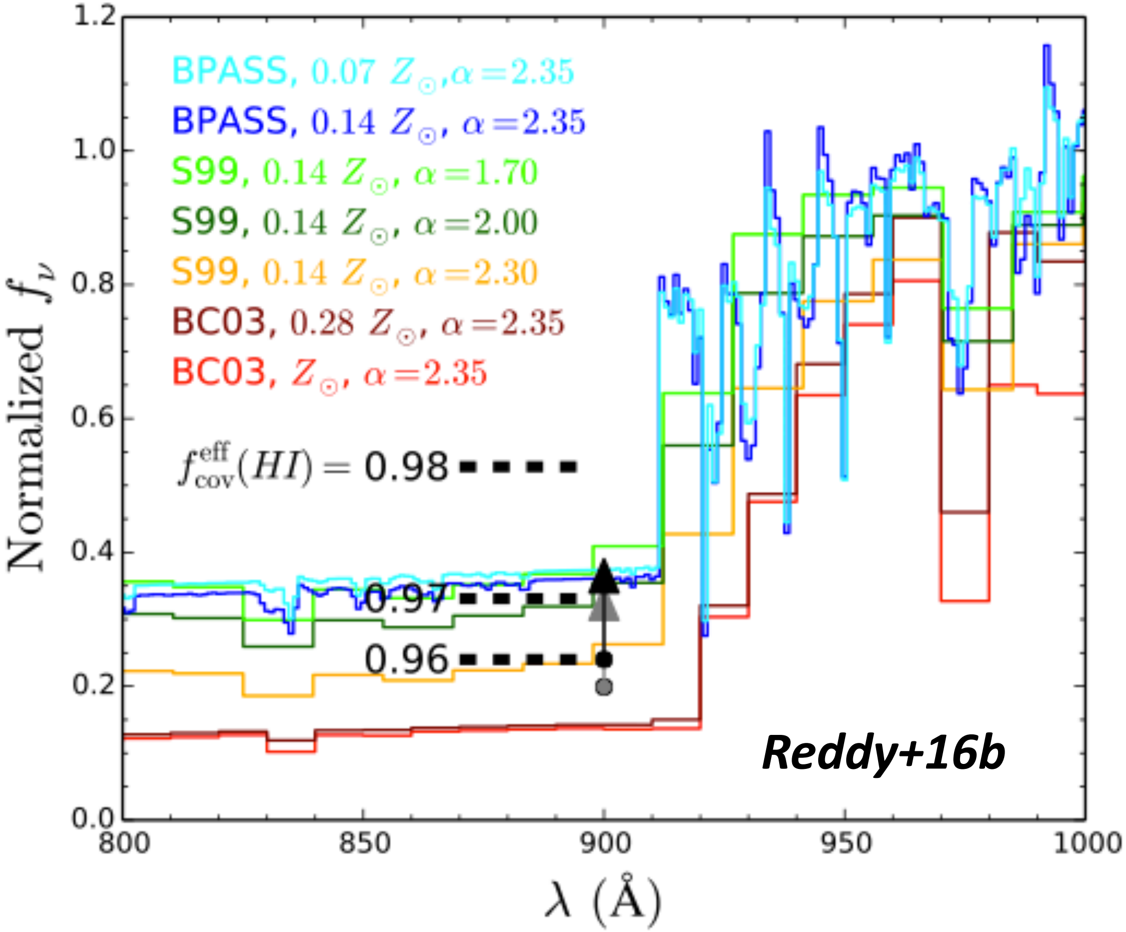
$$f_{\rm cov}(\mathrm{H\,I}) = 1 - \exp[a \times E(B-V)^b],$$

=

$= \xi_{\rm ion}$

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

Comparison with Stellar Population Models

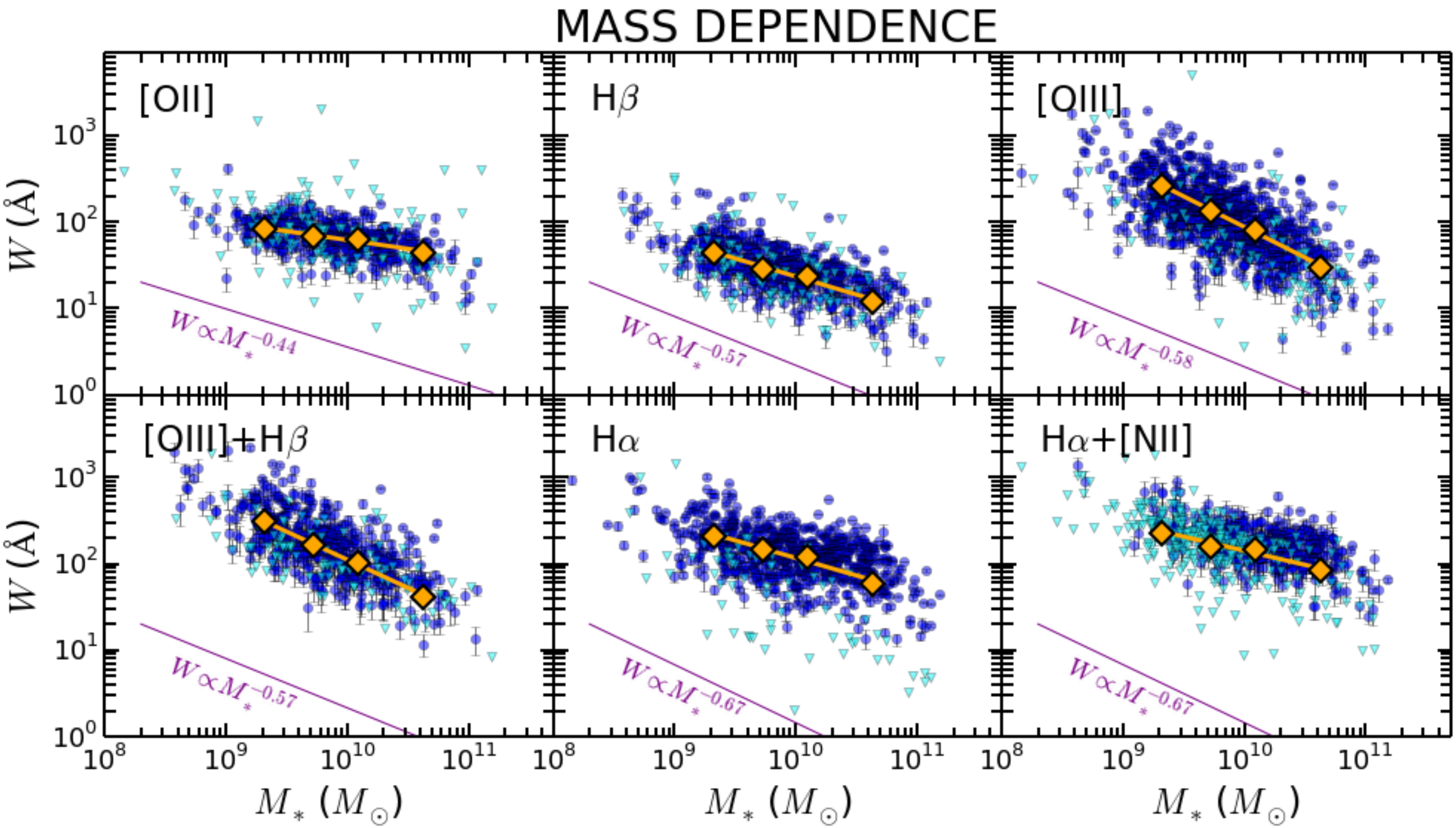


$(f900/f1500)_{int} \gtrsim 0.240 \pm 0.047$

Galaxies with *large* covering fractions provide the most sensitive constraints on the intrinsic LyC production rate

Limit favors models that include weaker stellar winds, a shallower IMF, and/or stellar rotation/binarity

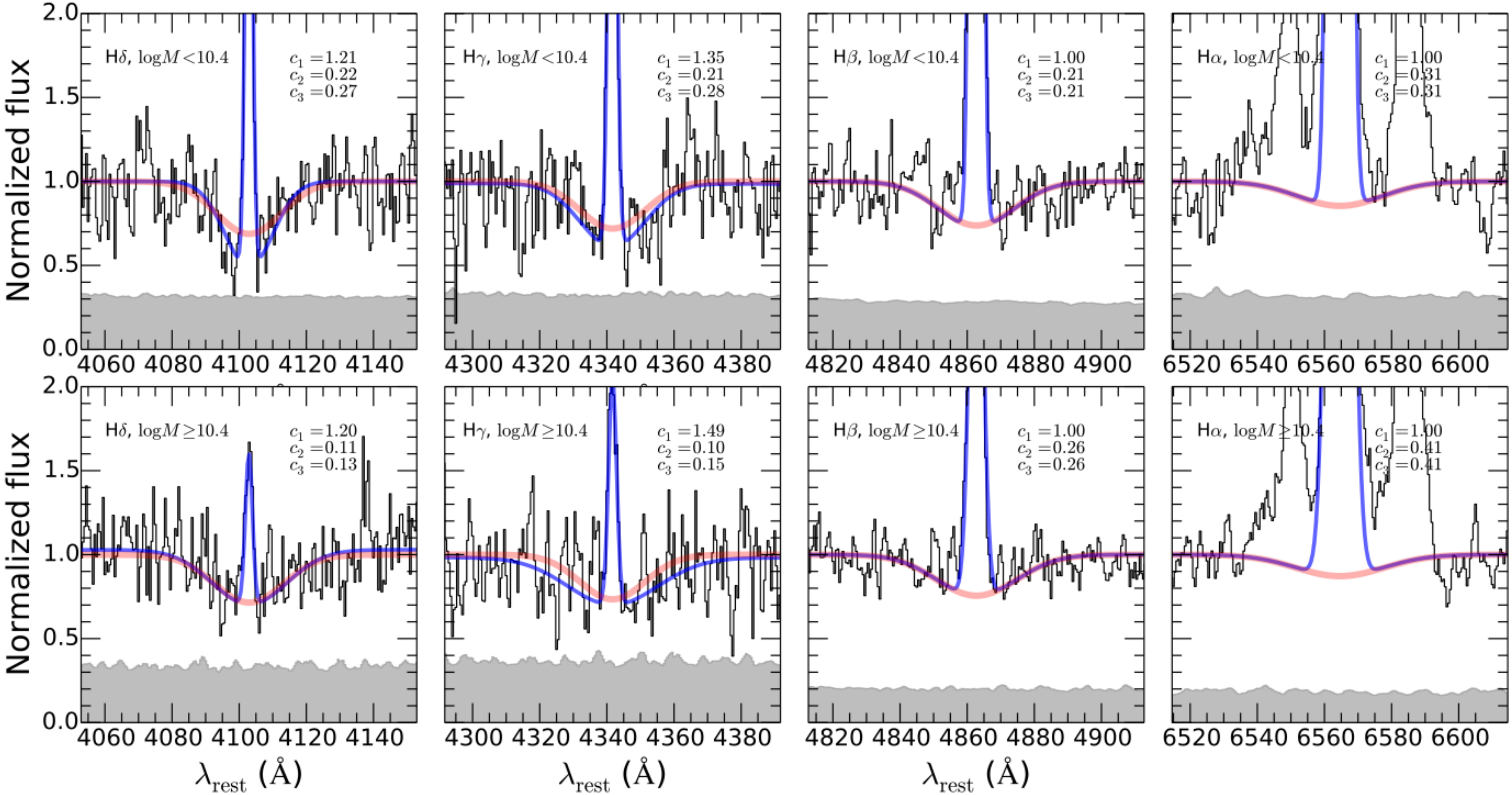
EW Measurements from MOSDEF



Reddy+, in prep

MOSDEF: Multiple Balmer Emission Lines

R~3500



Conclusions

- Large sample of Balmer decrements aids in calculating the attenuation curve *relevant for the stellar continuum:*
    - Difference in total attenuation increases with SFR
    - Data suggest a moderately reddened stellar population that dominates the UV/optical SED, and a second, dustier population, that dominates the line/bolometric luminosities at higher SFRs **[Reddy et al. 2015, ApJ, 806, 259]**
    - SMC curve appears to be most appropriate for sub-solar metallicity stellar populations at high-redshift **[Reddy et al. 2017, ApJ, submitted]**

- Modeling of z~3 LBG spectra to obtain empirical constraints between reddening and gas covering fraction:
    - Photoelectric absorption dominates the depletion of LyC photons
    - Modeling can be used to predict observed LyC-to-UV flux ratios or, alternatively, constrain ionizing stellar populations at high redshift **[Reddy et al. 2016a, ApJ, 828, 107; Reddy et al. 2016b, ApJ, 828, 108]**