MOSDEF: Measurements of Balmer Decrements and the Dust Attenuation Curve at High Redshift

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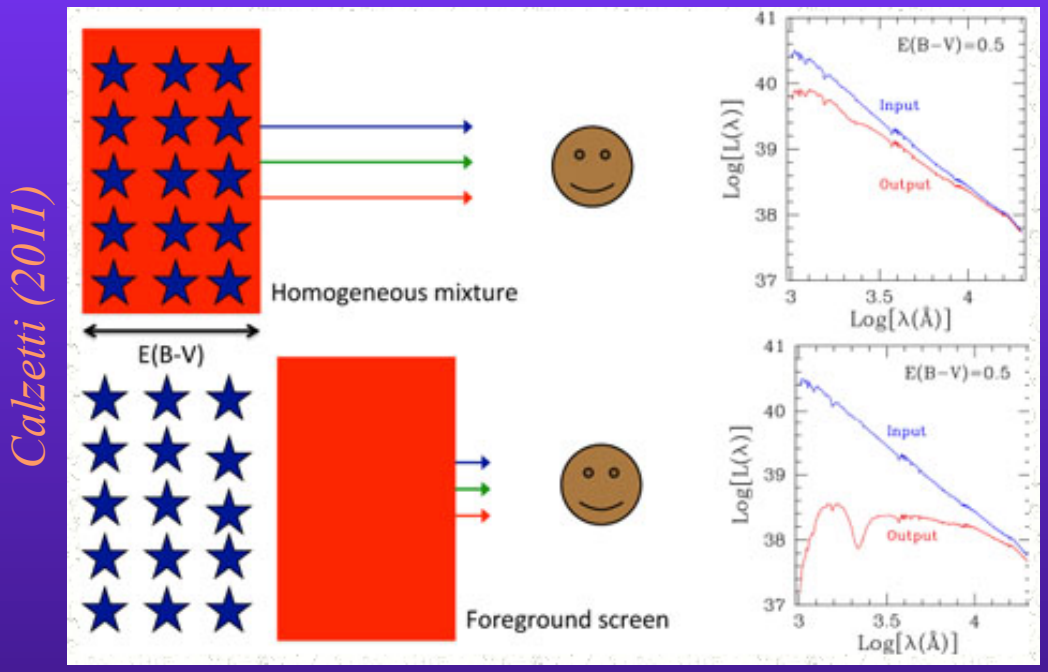
Irene Shivaei (UCR)

Understanding Nebular Emission in High-Redshift Galaxies; Carnegie, 17 July 2015

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



Important input to SED fitting

Needed to infer dust-corrected SFRs

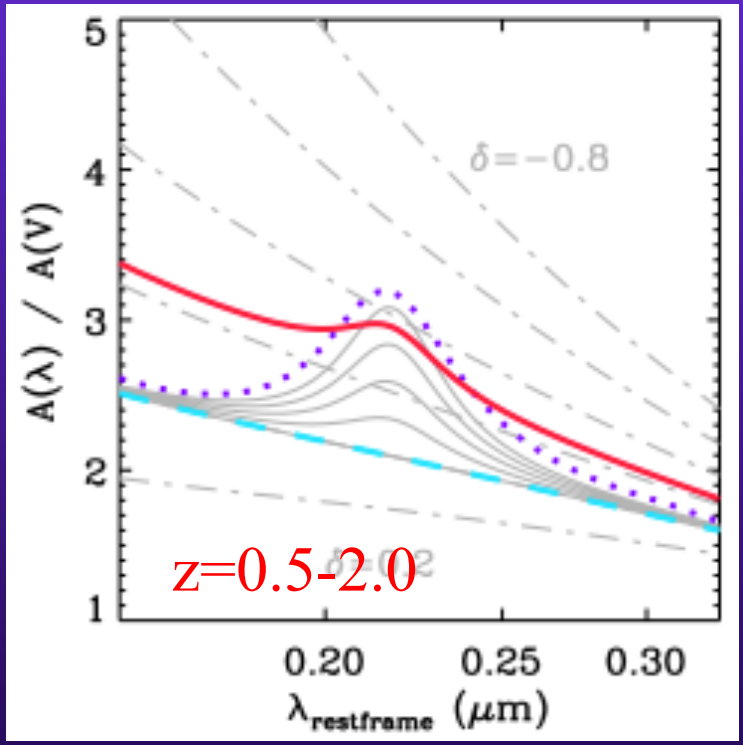
Encodes info on the dust/stars geometry

…combining UV and optical diagnostics of HII regions

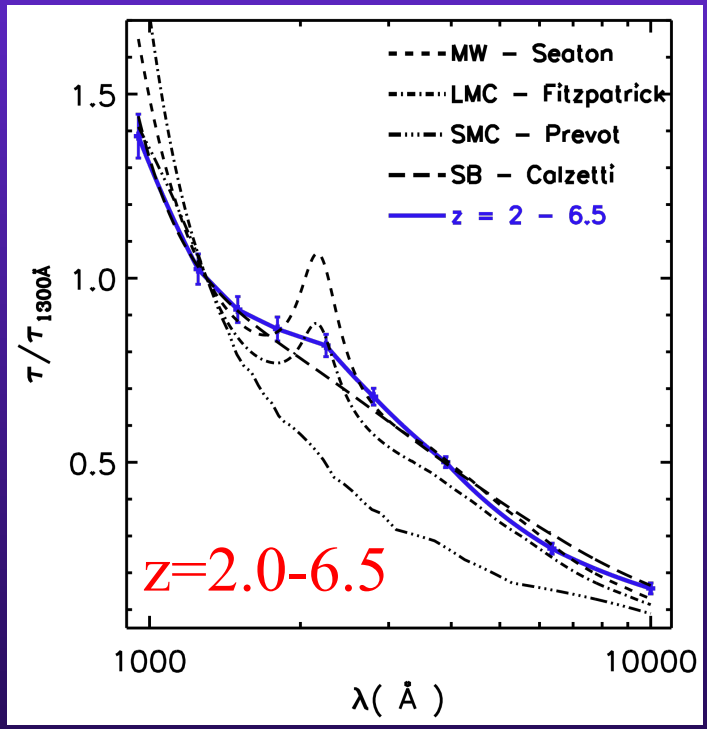
Recent High-Z Constraints on the Dust Curve

- Noll+09
- Buat+11,12
- Kriek & Conroy 2013
- Scoville+15

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



Kriek & Conroy (2013)



Scoville+15

Proxies for Dust at High-z

• UV Slope: sensitive to age, metallicity, and star-formation history; measurement can be complicated by presence of 2175 Å absorption feature

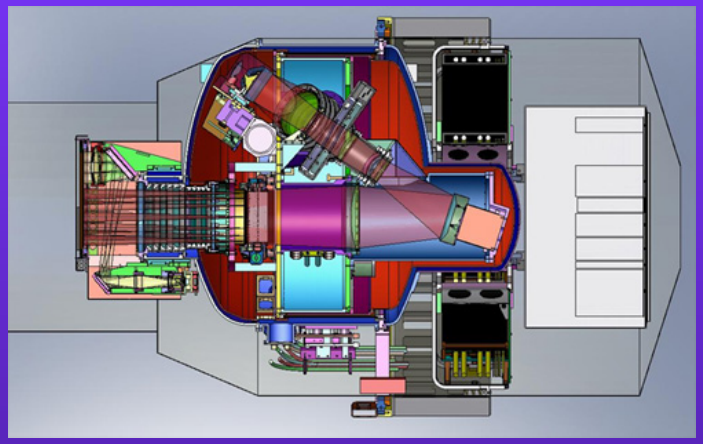
• Far-IR Measurements: only available for more luminous and dusty galaxies (ALMA helping this to some extent)

➔ need tracers that are less sensitive to stellar population parameters (age and star-formation history), probe star formation on short timescales, and can be measured for individual typical star-forming galaxies at high redshift

BALMER DECREMENTS

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

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

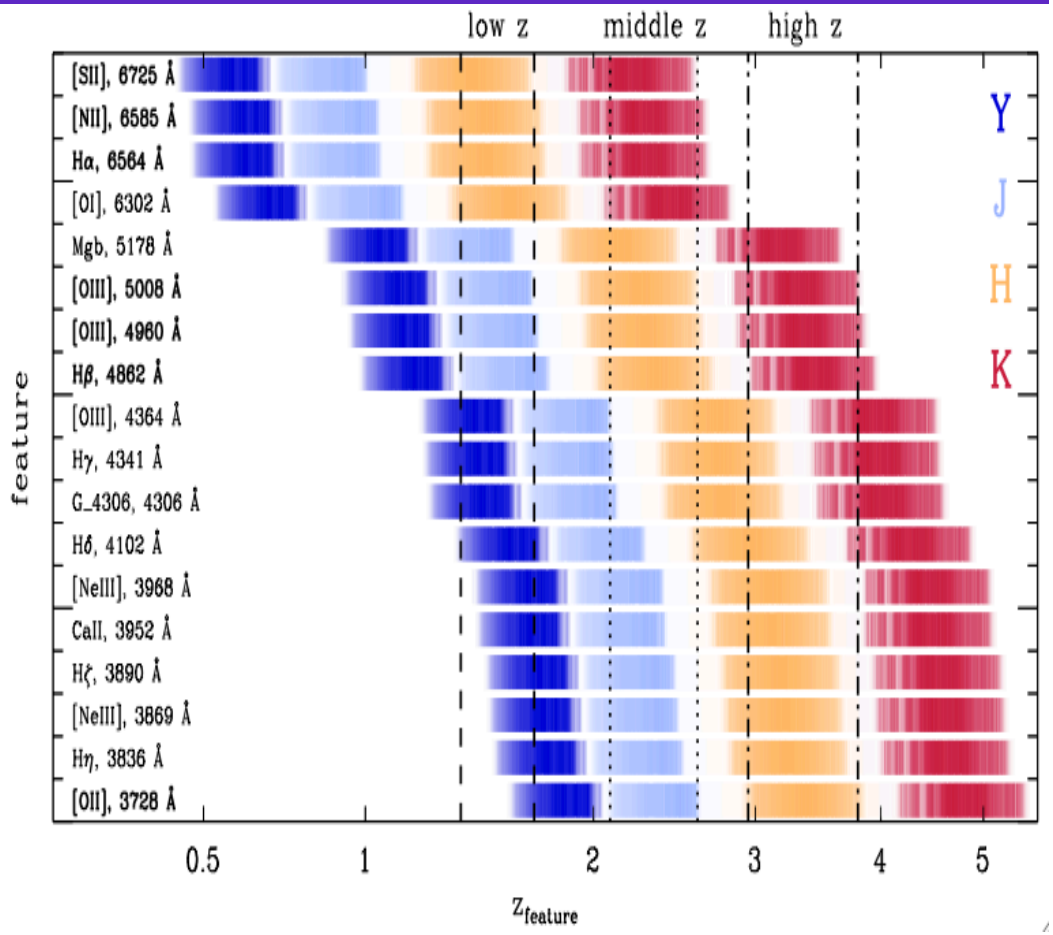
Transformative survey:

(1) H band-selected rest-optical spectroscopy covering strongest em/abs features with high resolution to characterize gaseous/ stellar contents of galaxies

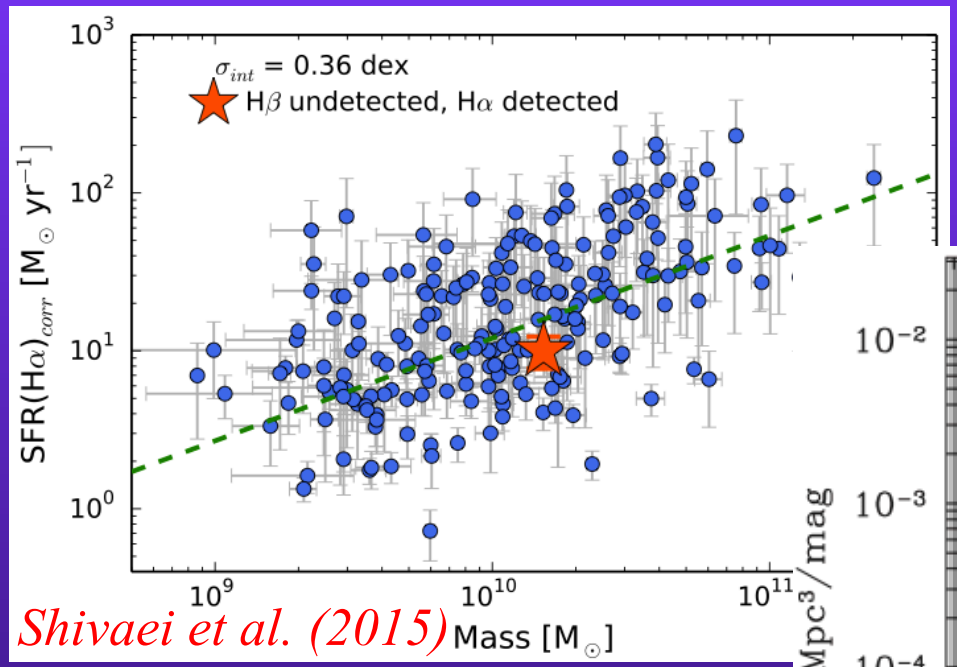
(2) large sample of objects (~1500) spanning full range of galaxy properties

(3) multiple redshifts to enable evolutionary studies

Kriek et al. (2015)

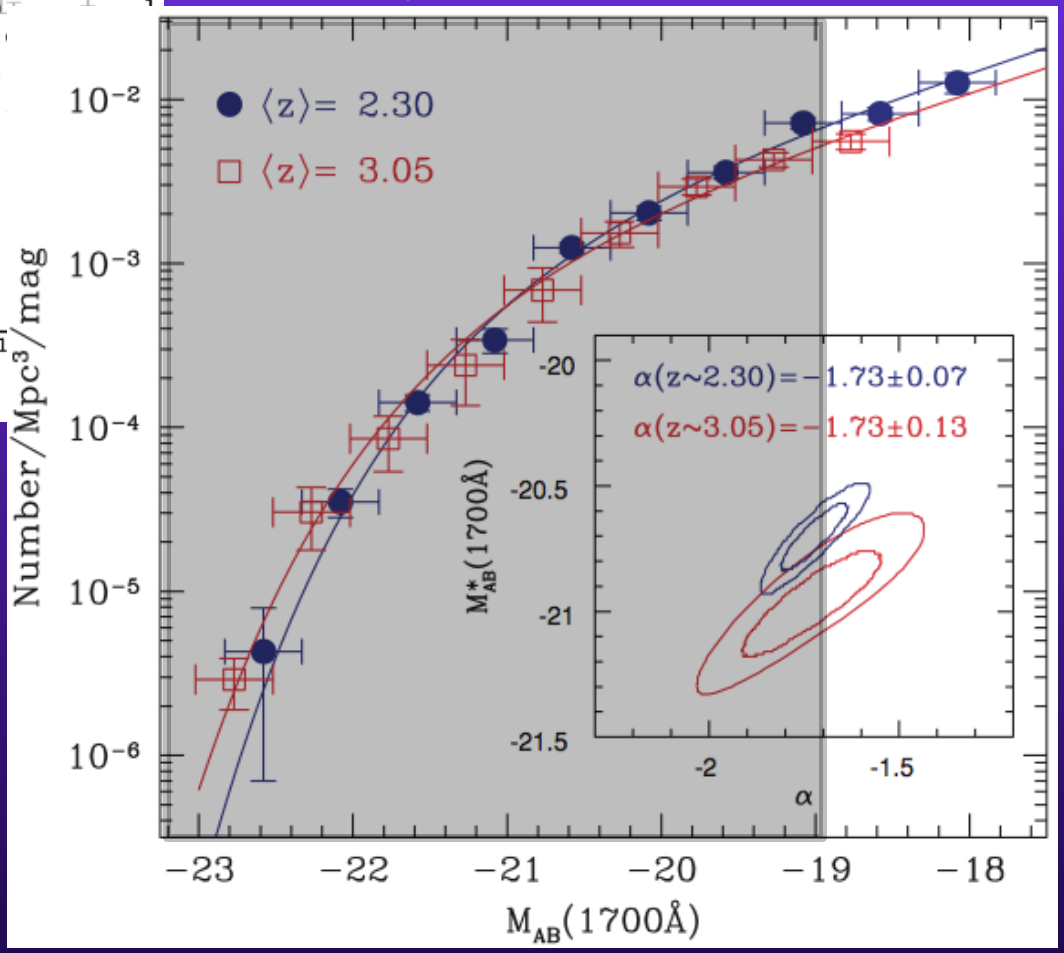


Sampling of "Typical" Star-Forming Galaxies at z~2

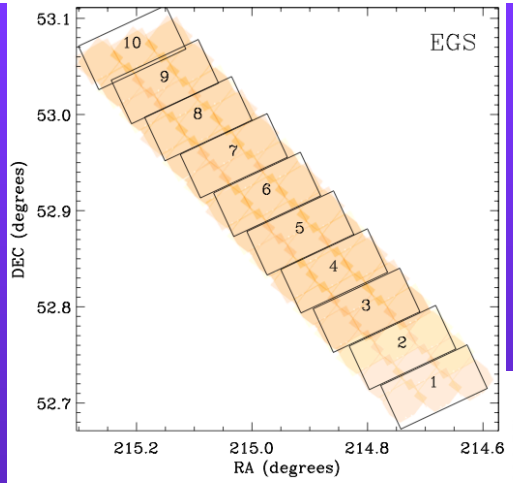


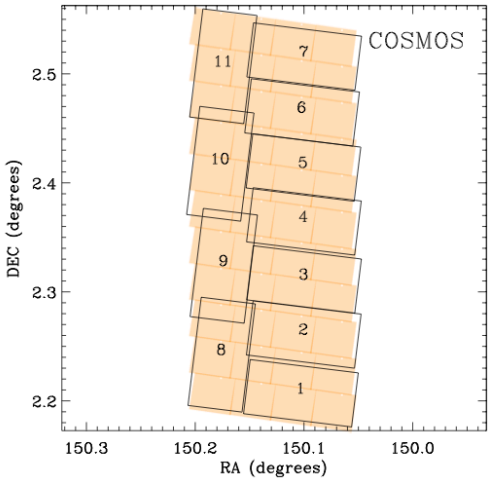
Shivaei et al. (2015)

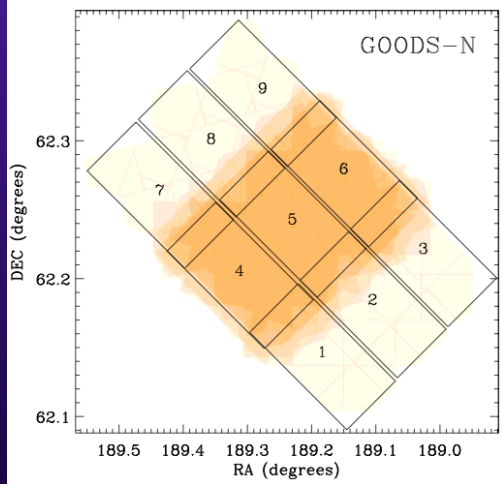
Reddy & Steidel (2009)

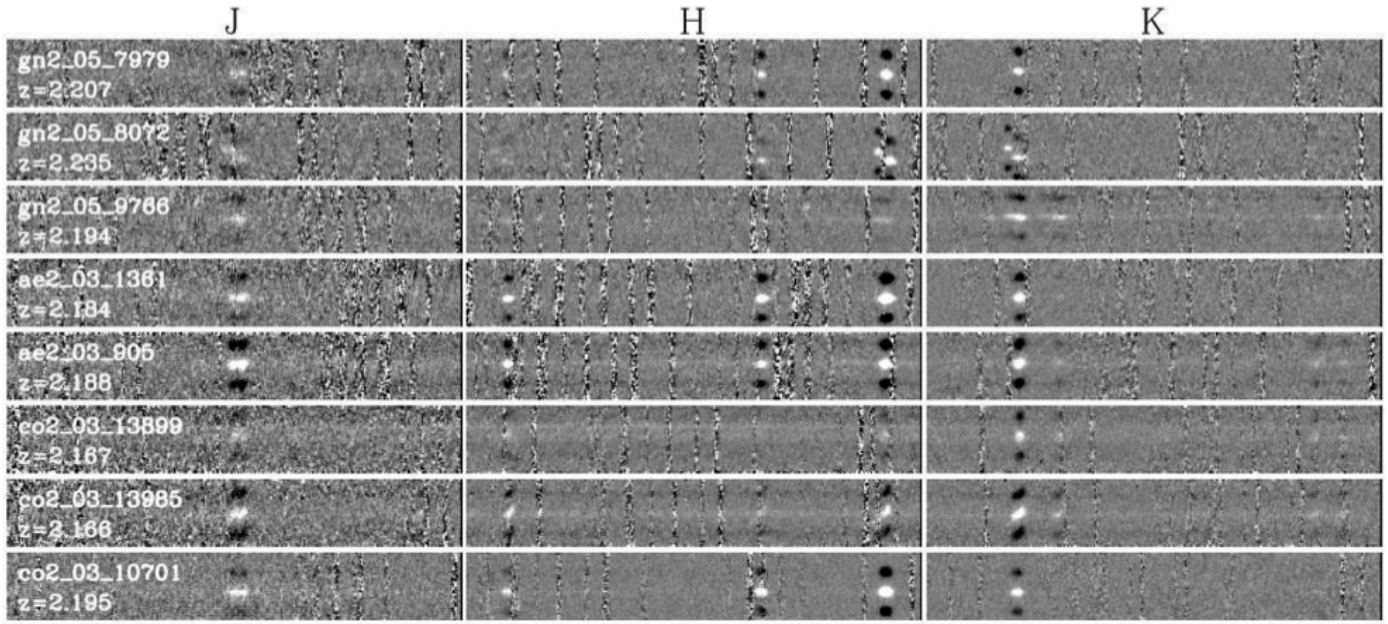


MOSDEF Fields/Spectra





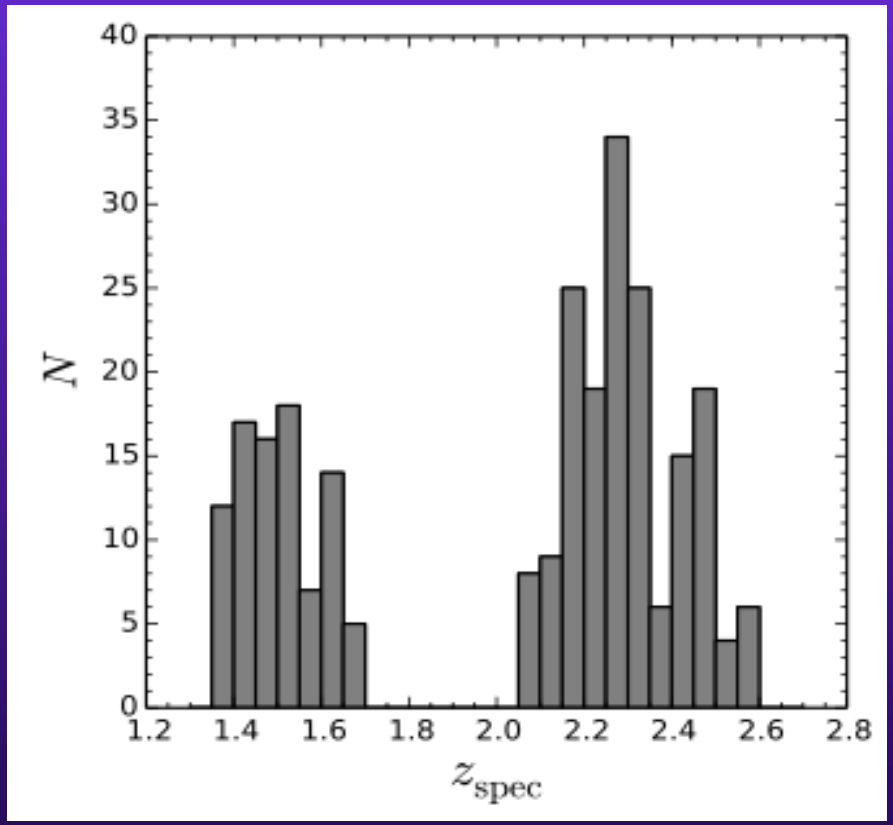


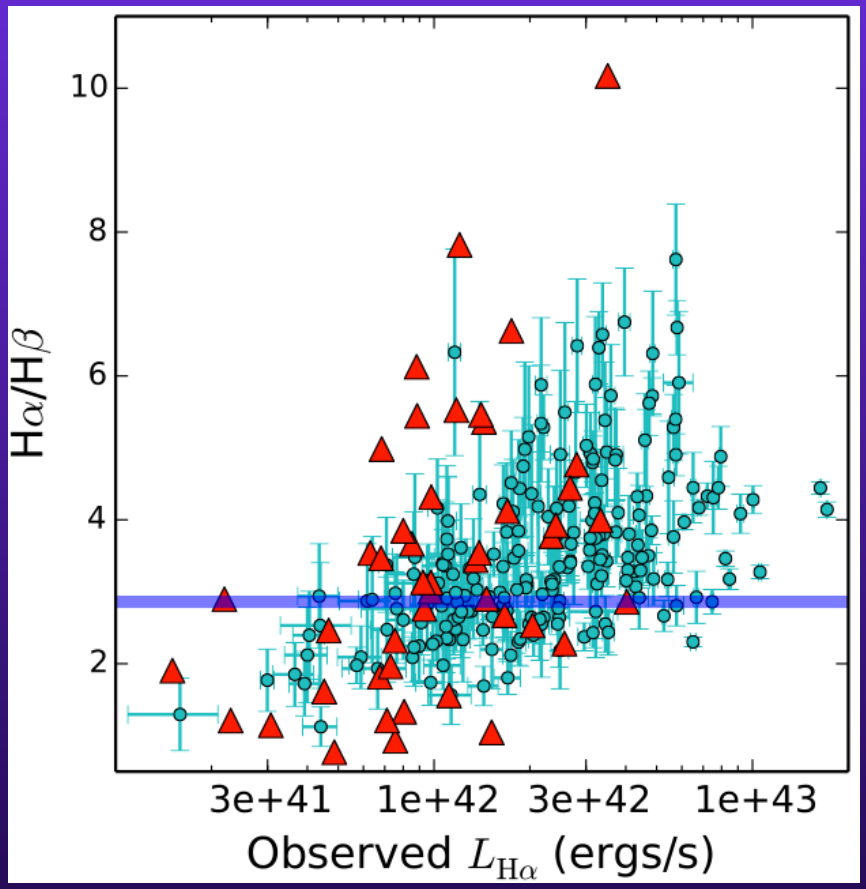


Balmer Decrement Measurements

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

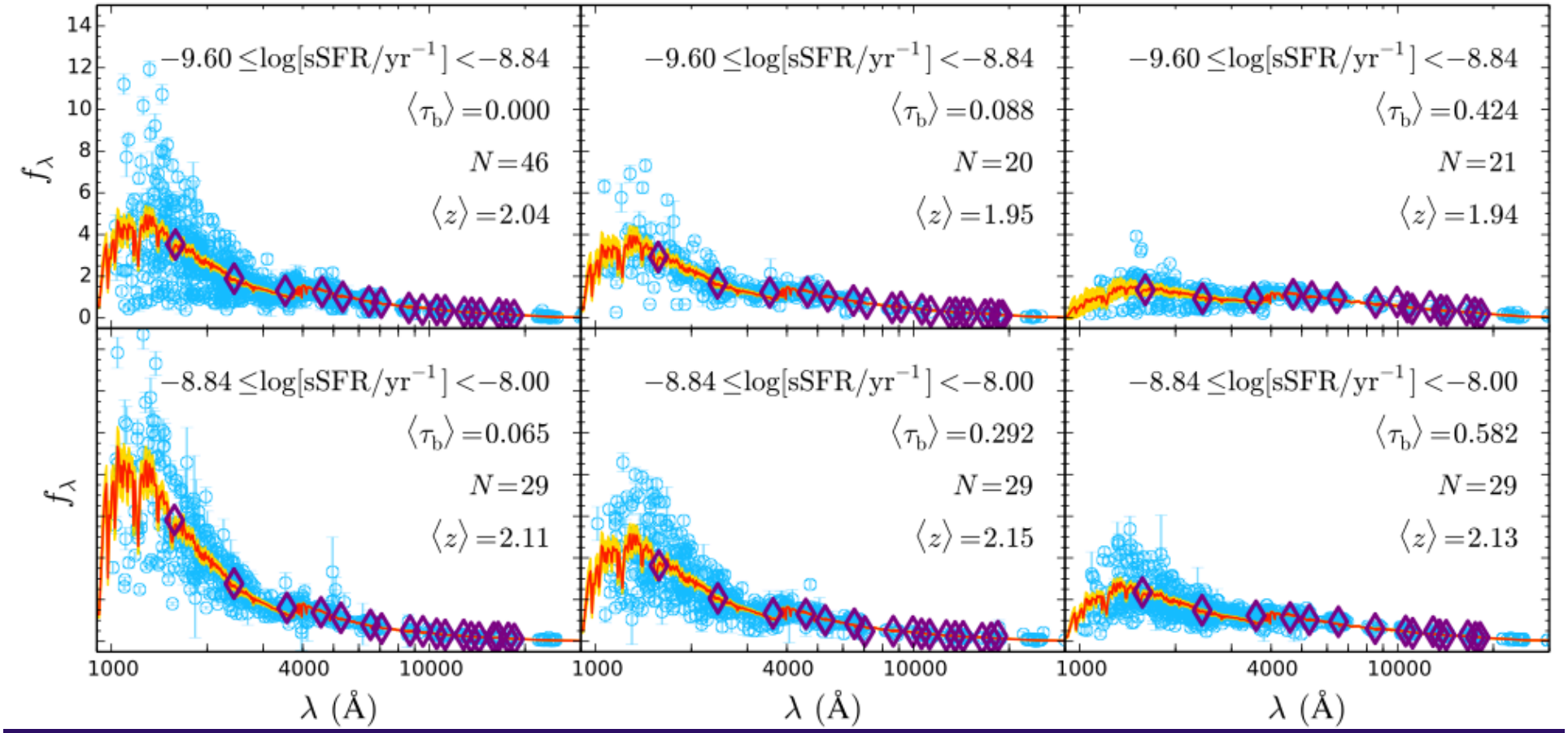
224 star-forming galaxies
at z_{spec} = 1.36 – 2.59





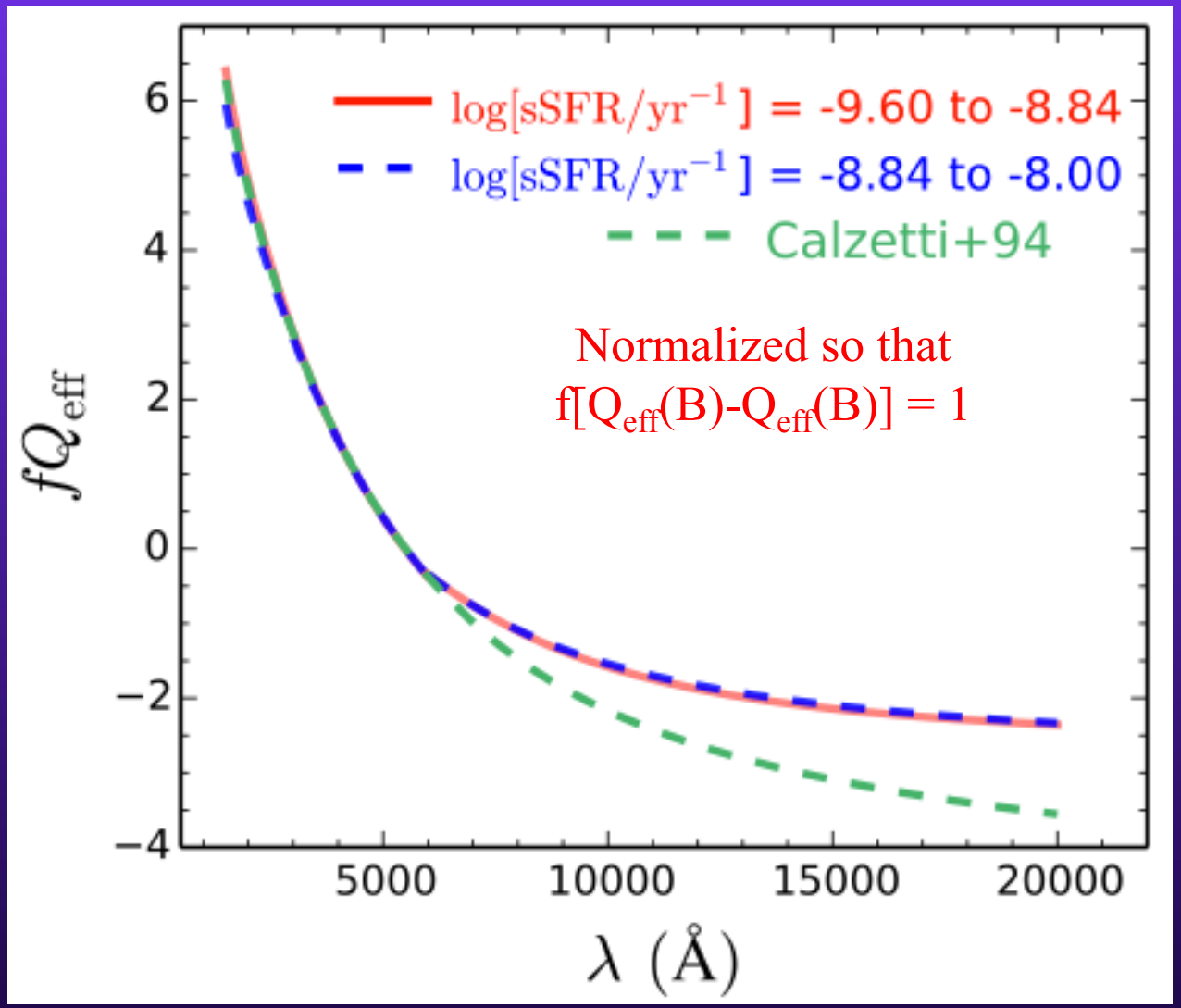
Calculating the Attenuation Curve…

Ratios of Composites



Calculating the Attenuation Curve…

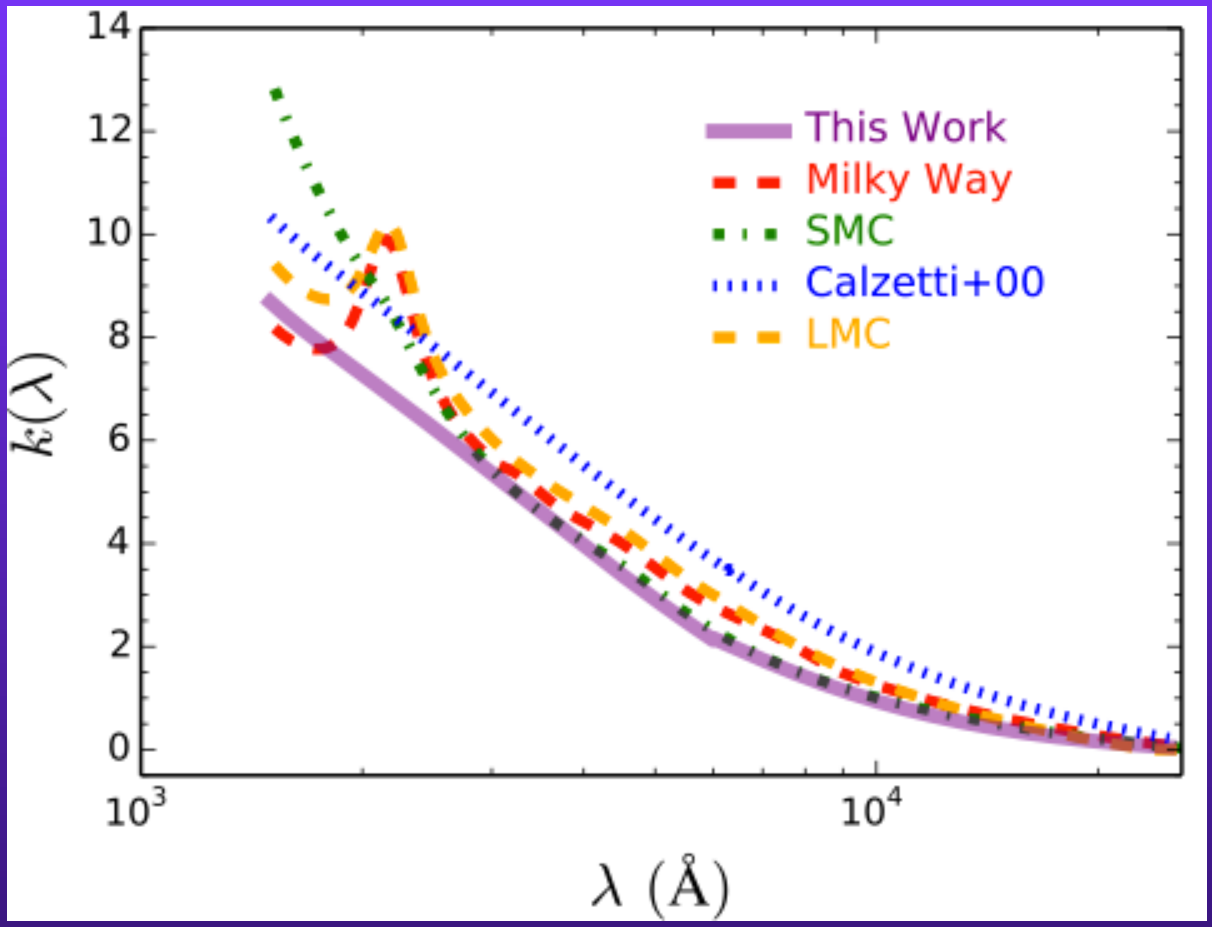
Normalization (R_V)



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

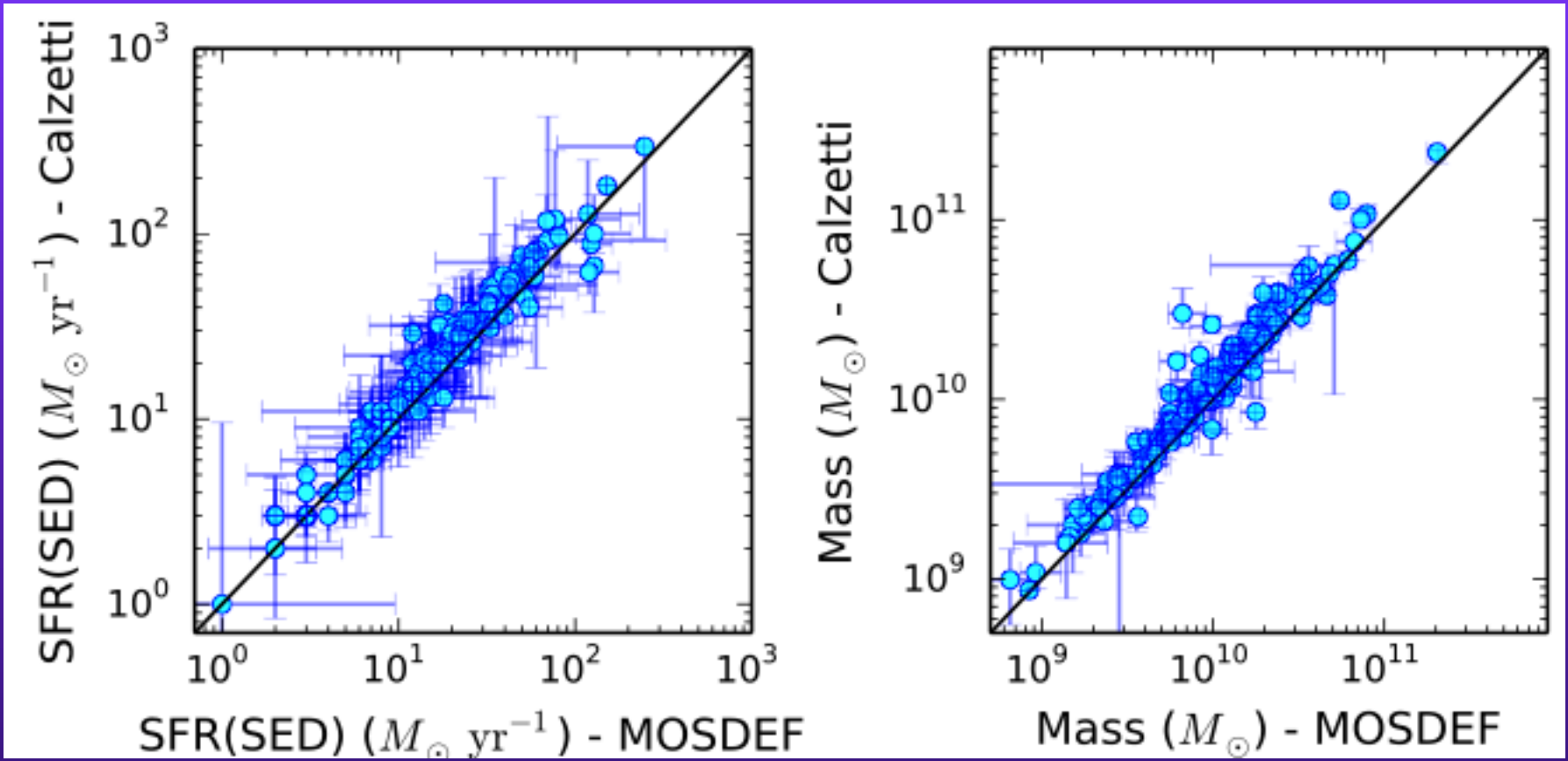
Systematic uncertainties of $\Delta R_V \approx 0.4$

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 SFR(SED) and M*

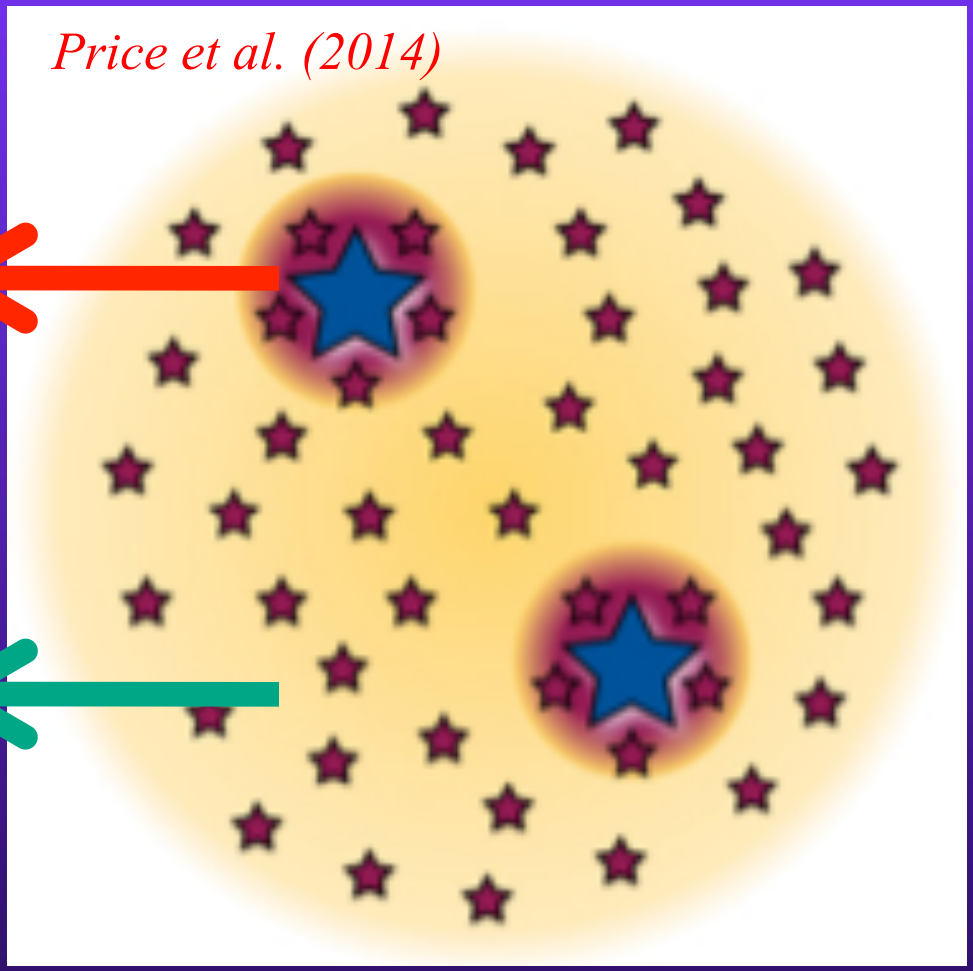


≈20% lower SFRs with new curve

$\Delta\log(M^*/M_\odot) = 0.16$ dex

Color Excesses of the Ionized Gas vs. Stellar Continuum

Higher attenuation towards lines-of-sight to massive stars

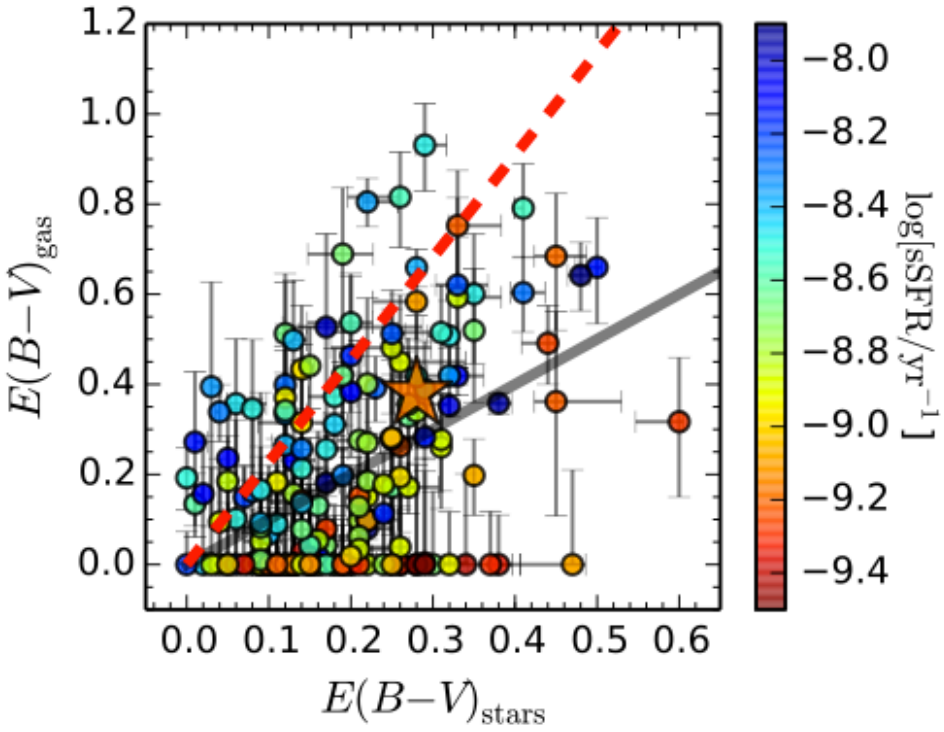


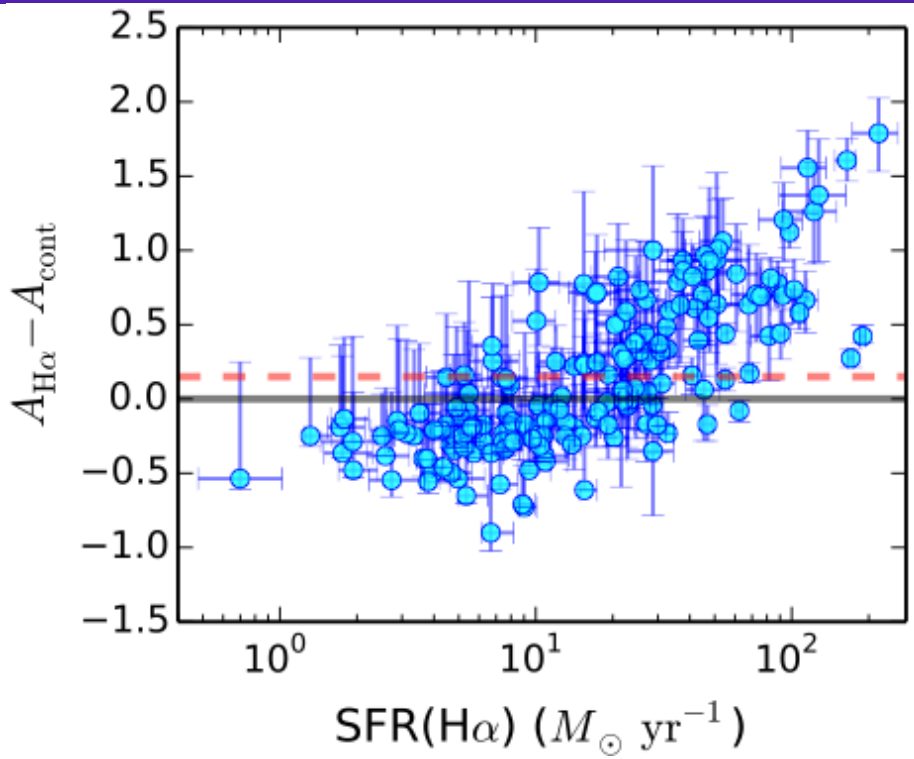
(e.g., Fanelli et al. 1988, Calzetti et al. 1994, Mas-Hesse & Kunth 1999, Kreckel et al. 2013)

Color Excesses of the Ionized Gas vs. Stellar Continuum

$$E(B-V)_{\rm gas} = \frac{2.5}{k(\mathrm{H}\beta) - k(\mathrm{H}\alpha)} \log_{10}\left(\frac{\mathrm{H}\alpha/\mathrm{H}\beta}{2.86}\right)$$

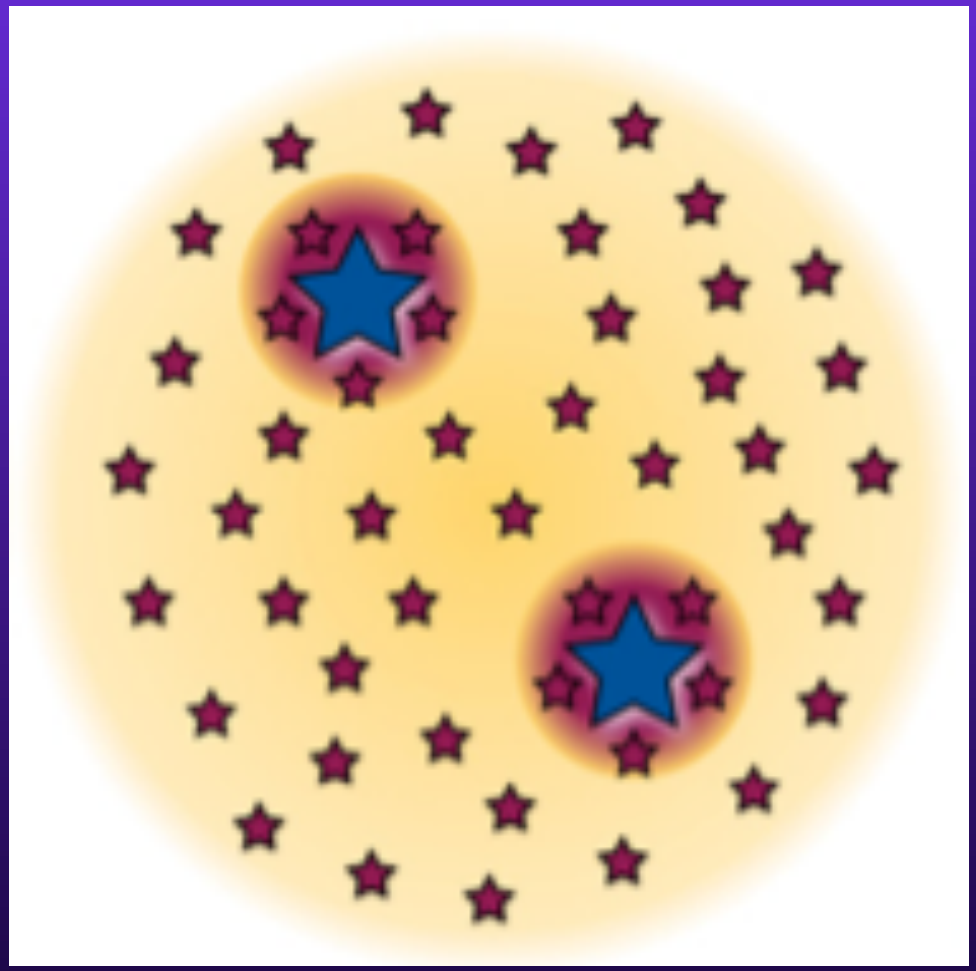
Assumes Cardelli+89 (Galactic) extinction curve





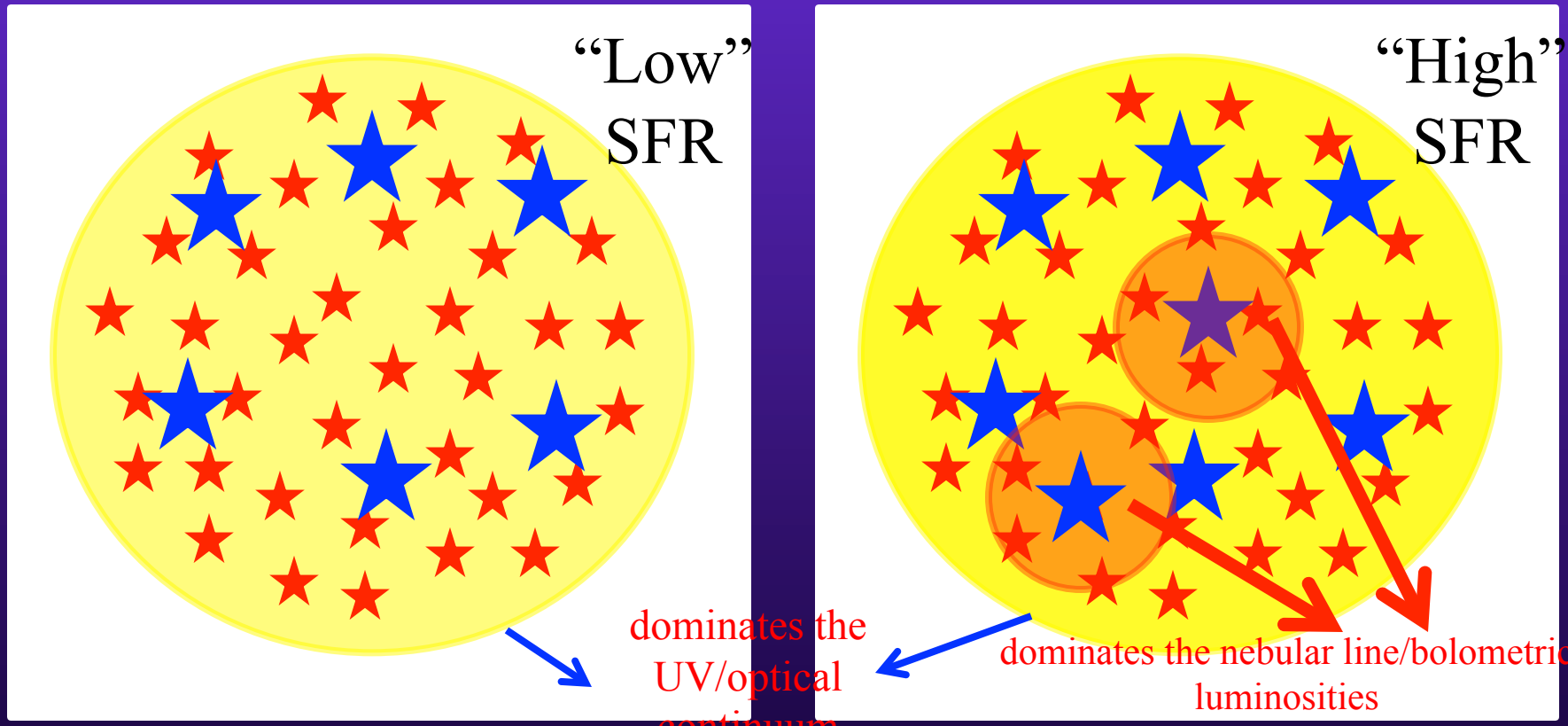
A Possible Physical Interpretation

Locally…ionizing stars found in parent birth clouds

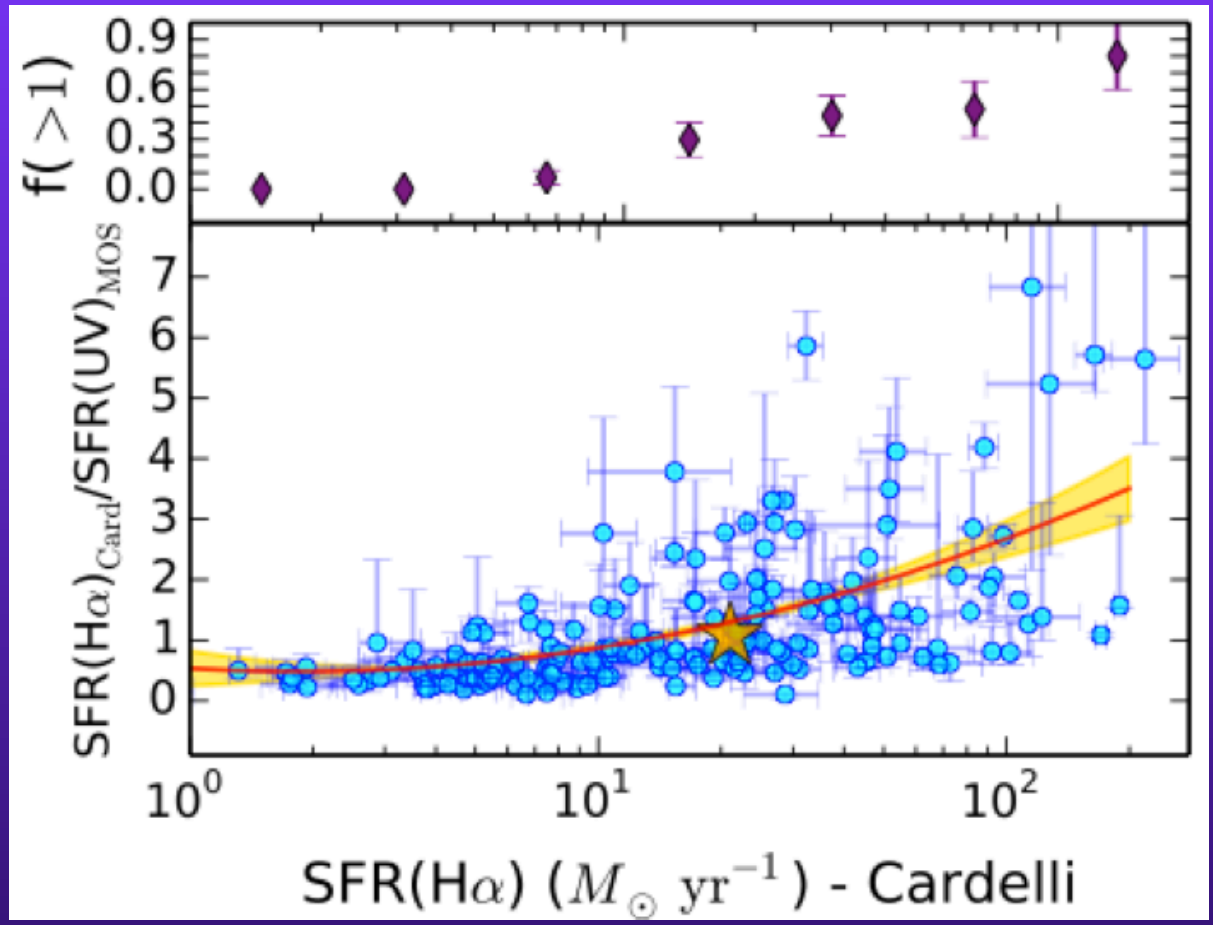


A Possible Physical Interpretation

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



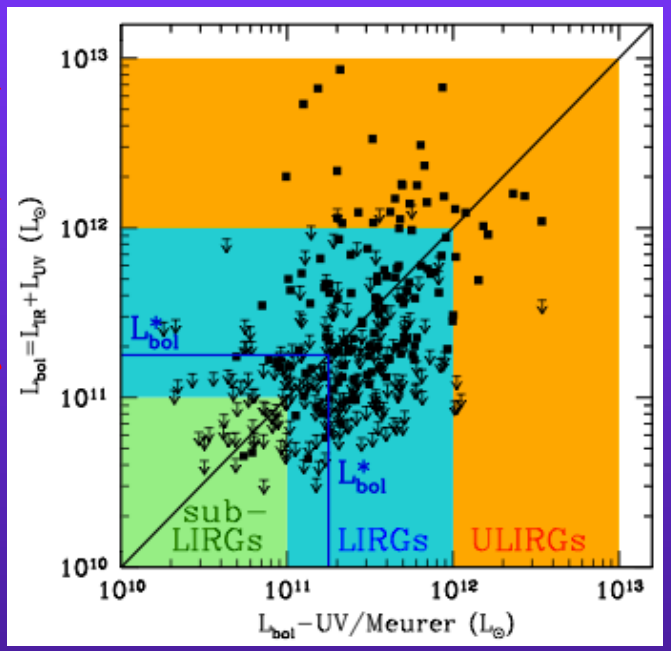
Implications for SFRs from the UV or SED-fitting



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

Similar "Saturation" seen with IR vs UV-based SFRs

Reddy et al. (2010)



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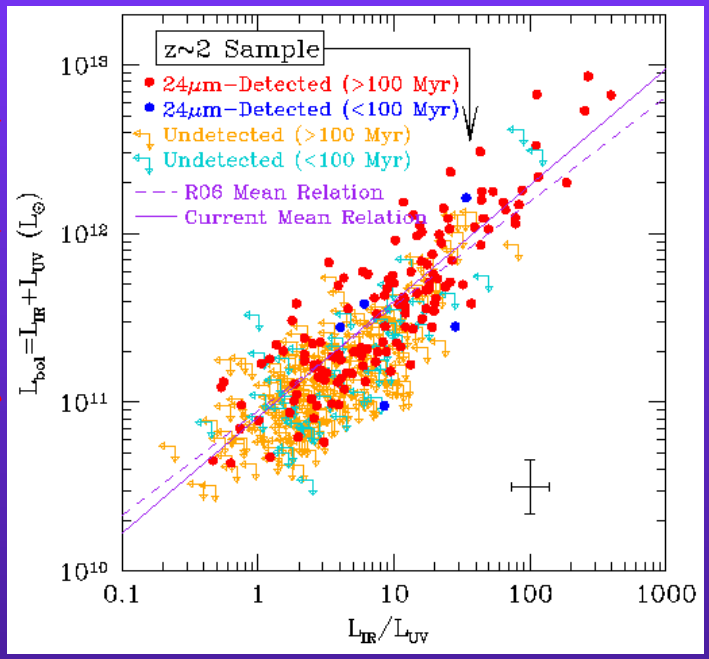

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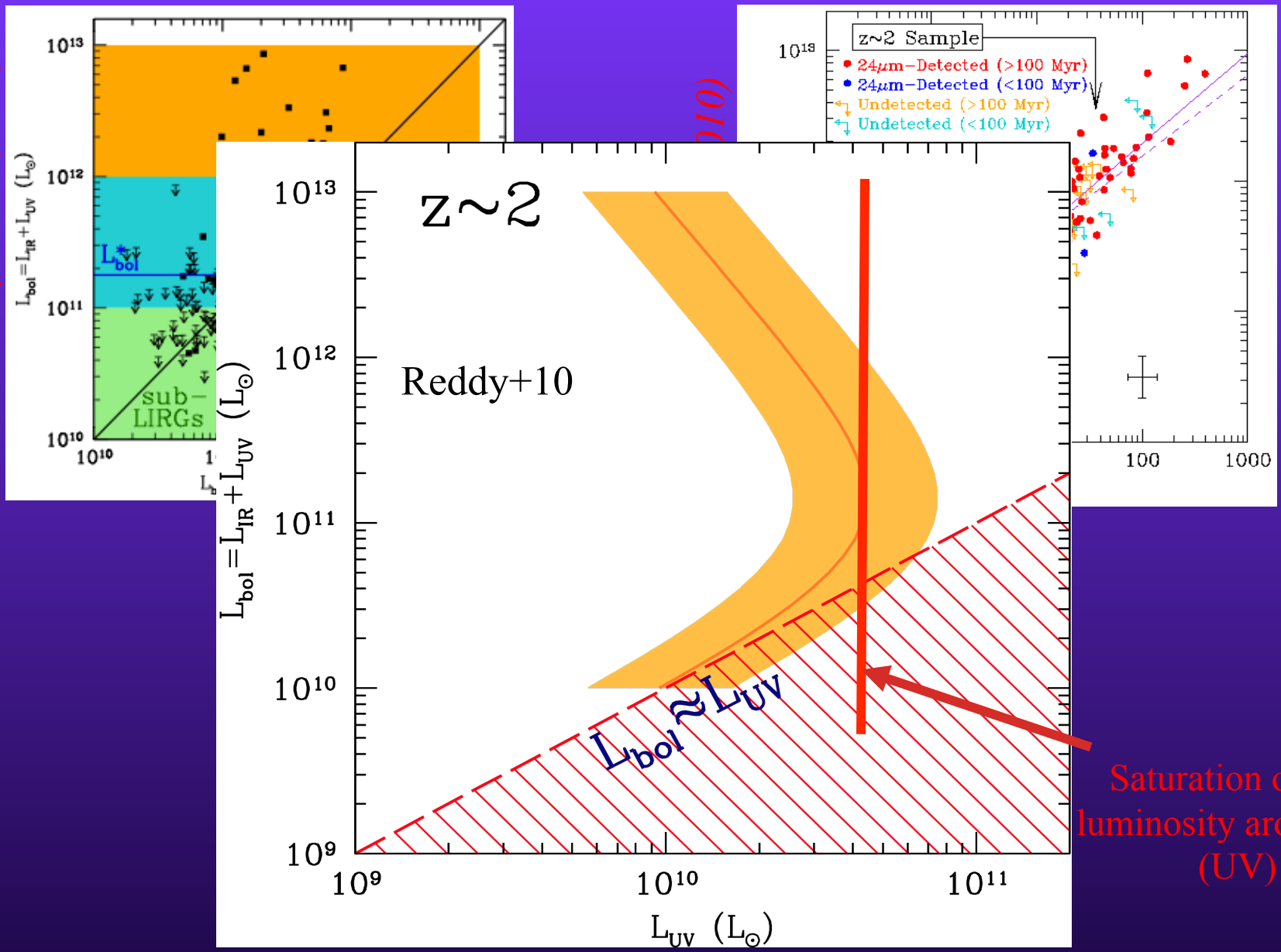


Future Work

- Incorporate mid- and far-IR data

- Larger sample will enable studies of stellar attenuation curve as a function of other galaxy properties (e.g., SFR)

- Relationship between attenuation curve shape/ normalization and resolved color maps

- Multiple Balmer emission lines

Conclusions

• Large sample of Balmer decrements aids in calculating the attenuation curve *relevant for the stellar continuum*

• Attenuation curve found here is similar to SMC at longer wavelengths (λ>2500 Å), and similar in *shape,* but with different *normalization*, than Calzetti+00

• New curve implies SFR ≈20% lower, and log M* that are 0.16 dex lower, than those obtained with the Calzetti relation

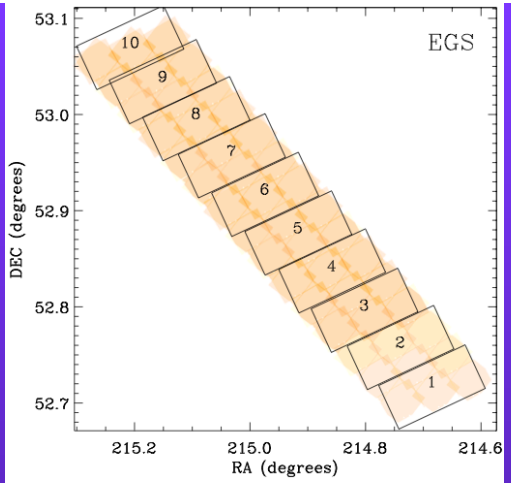
• Difference in the color excess (and total attenuation) of the ionized gas and stellar continuum correlates strongly with sSFR and SFR, with higher SFR galaxies exhibiting the largest differences

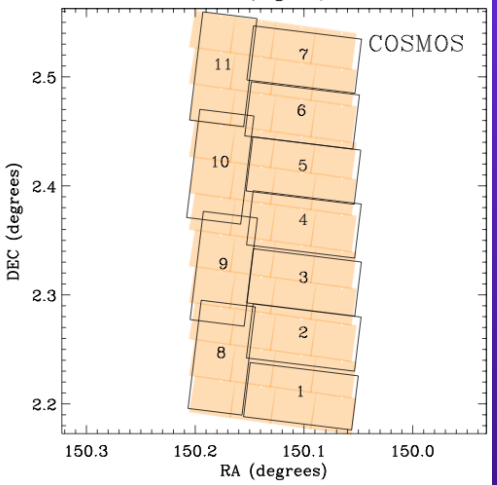
• Data suggest a physical interpretation where galaxies consist of moderately reddened stellar population that dominated the UV through near-IR continuum, and a second, dustier population, that begins to dominate the line and bolometric luminosities at higher SFRs.

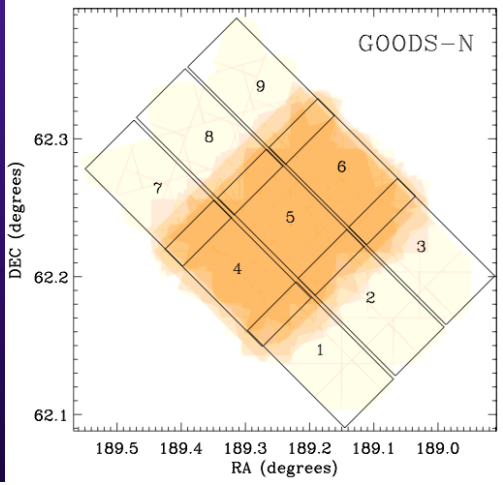
Reddy et al. 2015, ApJ, 806, 259

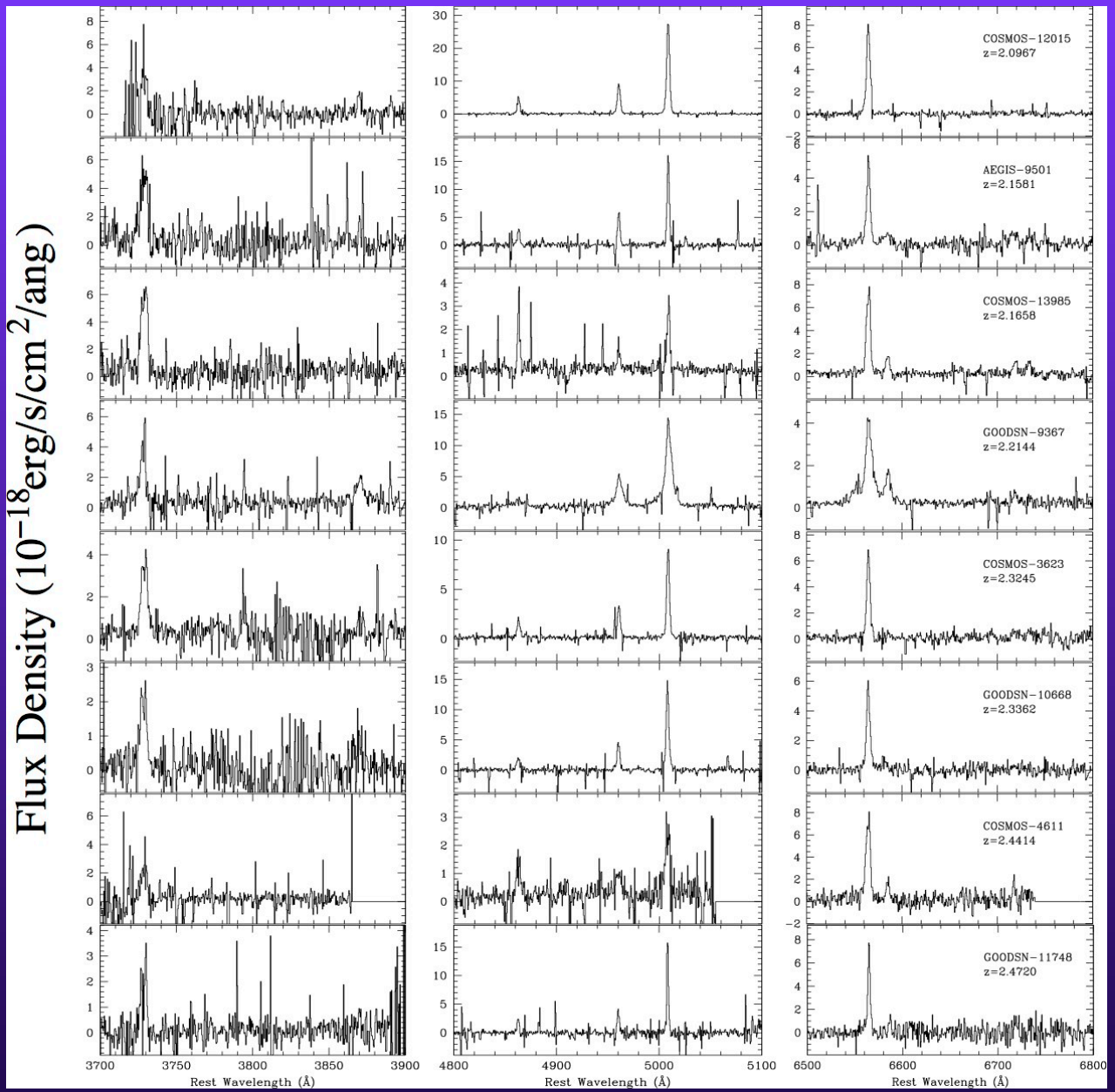
Extra Slides

MOSDEF Fields/Spectra









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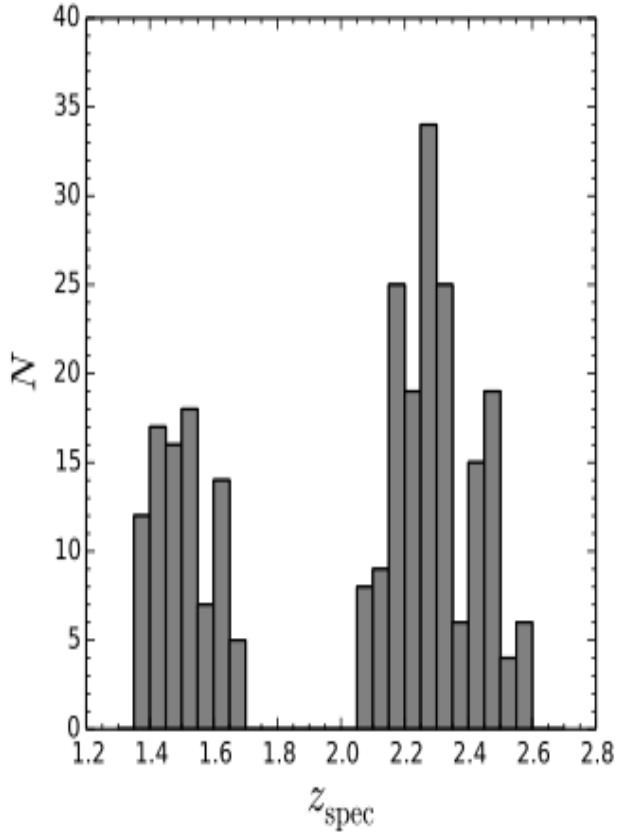
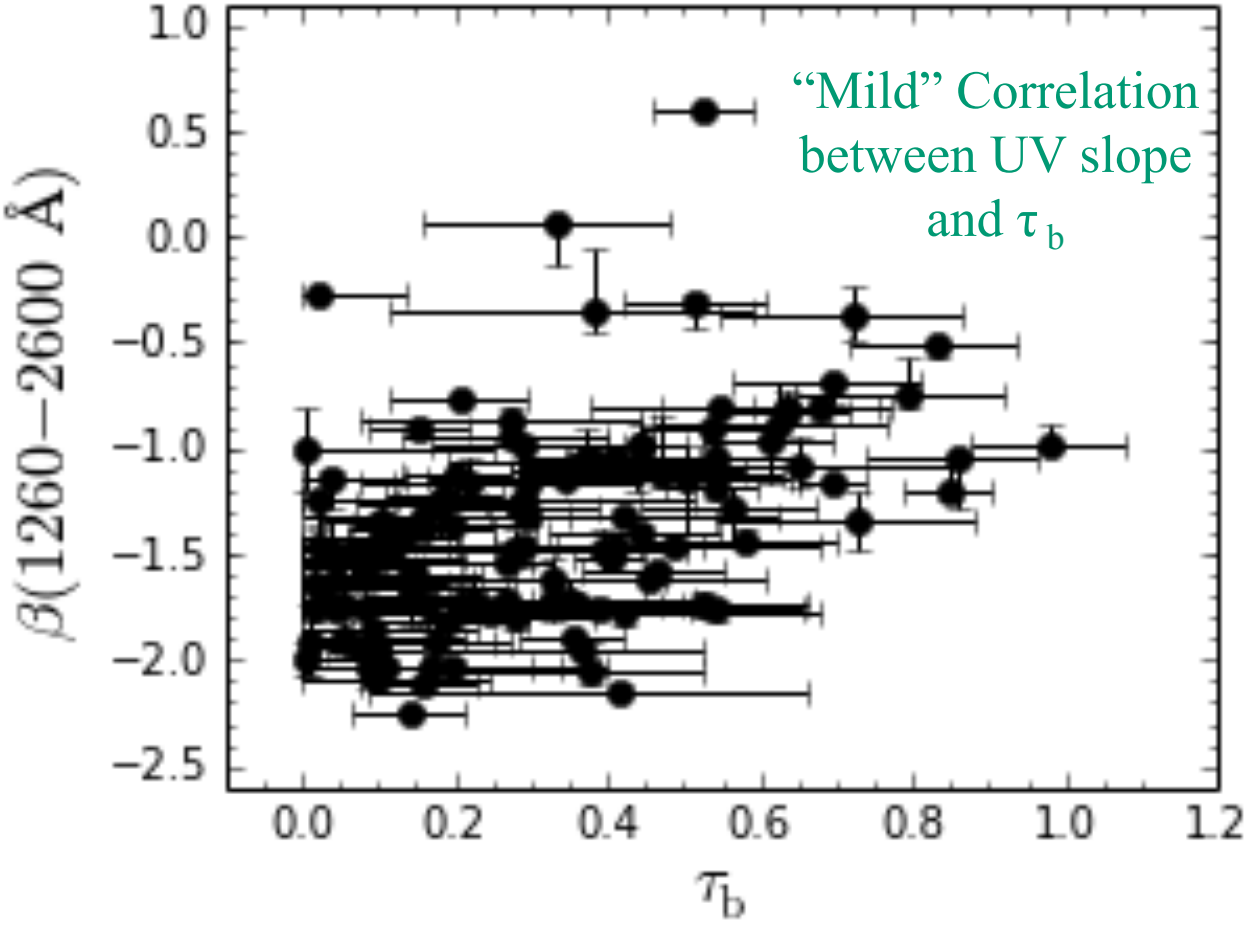
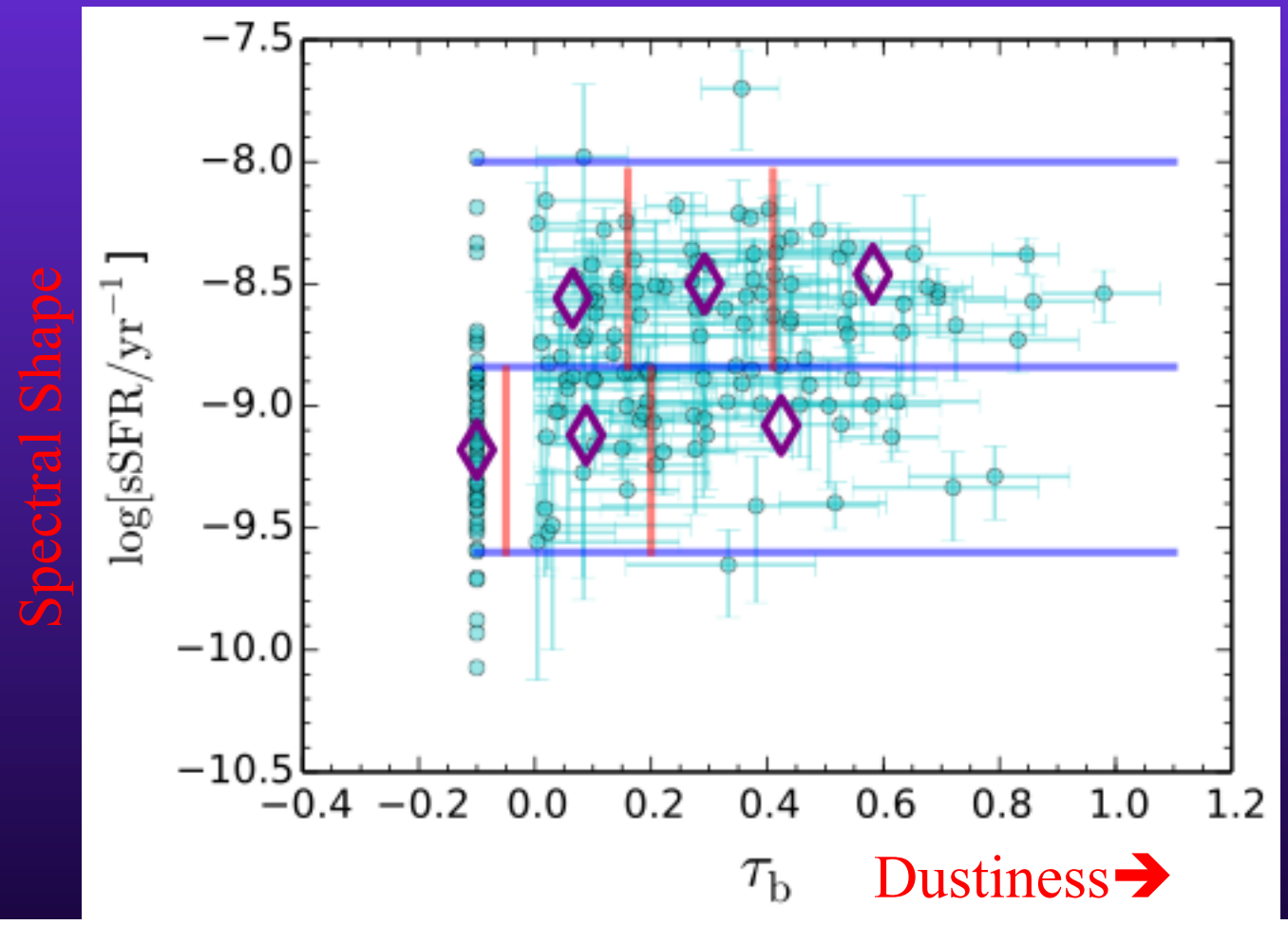




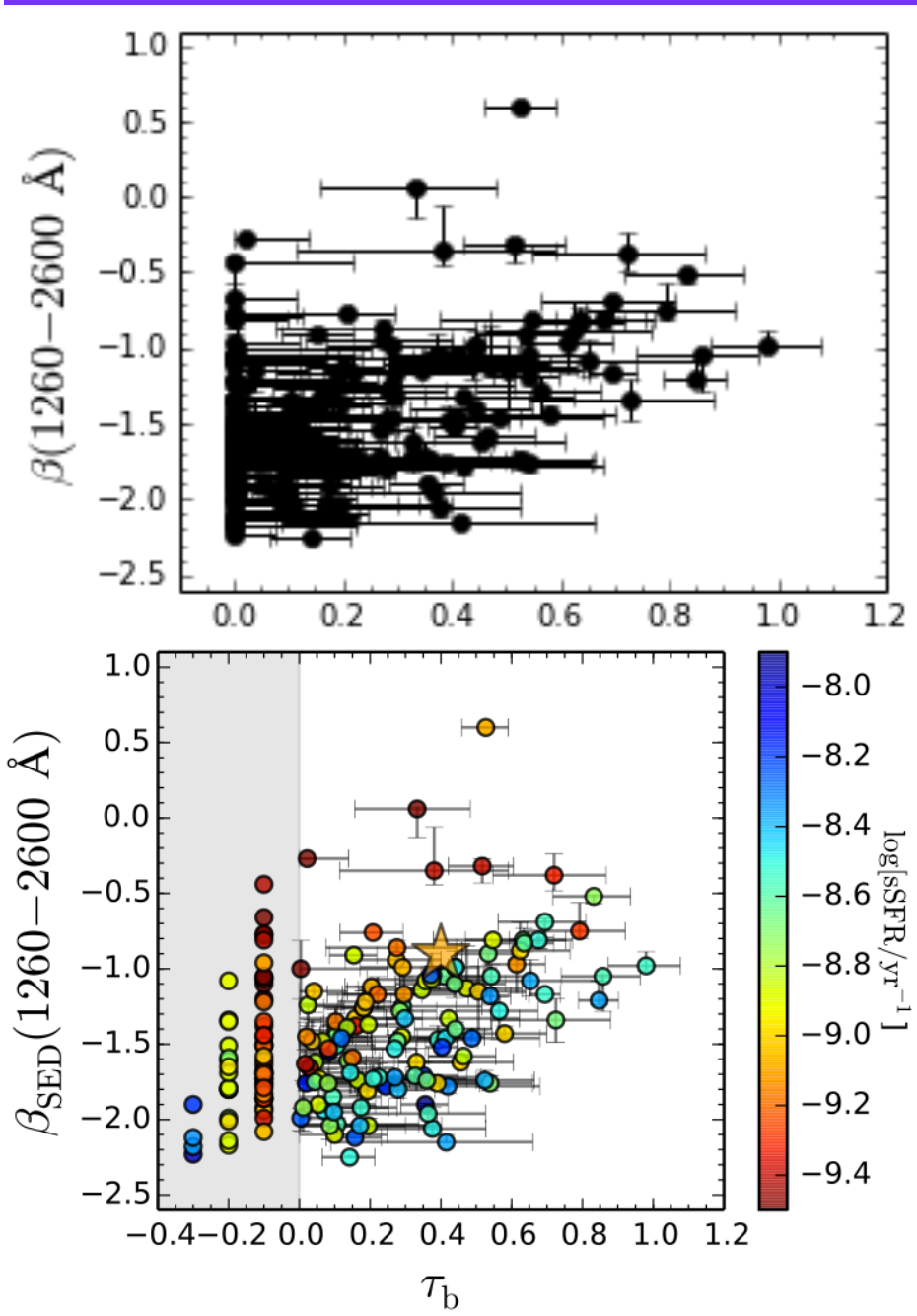
Calculating the Attenuation Curve

Ratios of Composites

Limit to Galaxies of Similar Spectral Shapes

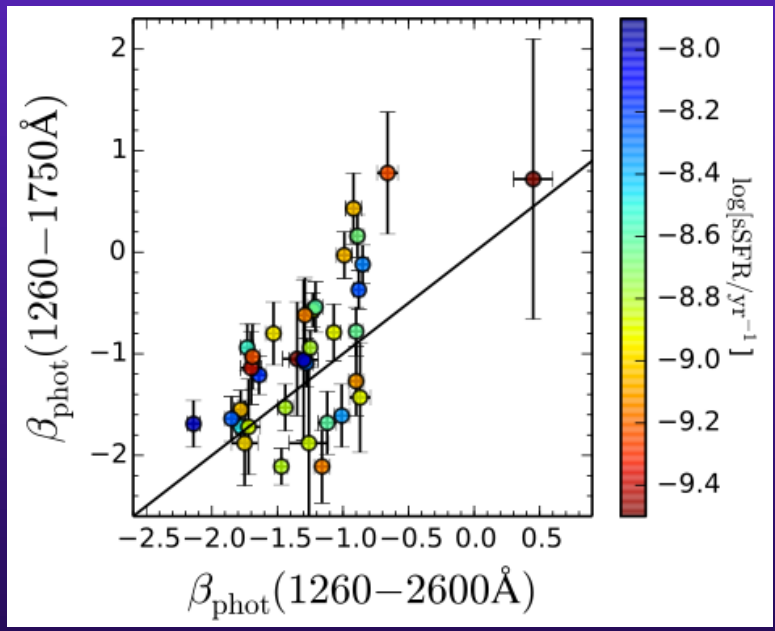


Effects of Star Formation History

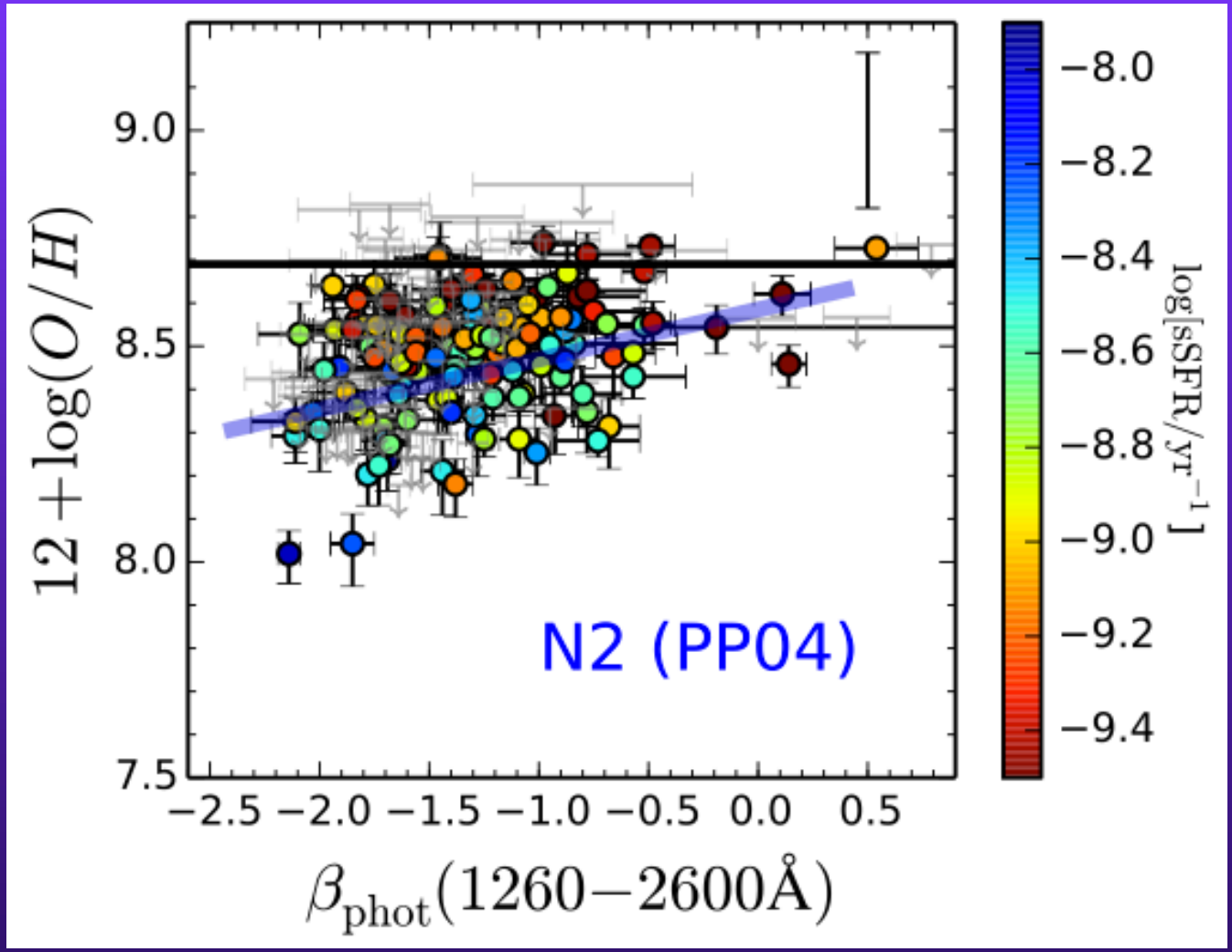


- "sequence" of β vs. τ_b with sSFR
- are A stars contributing to near-UV flux?

unlikely…

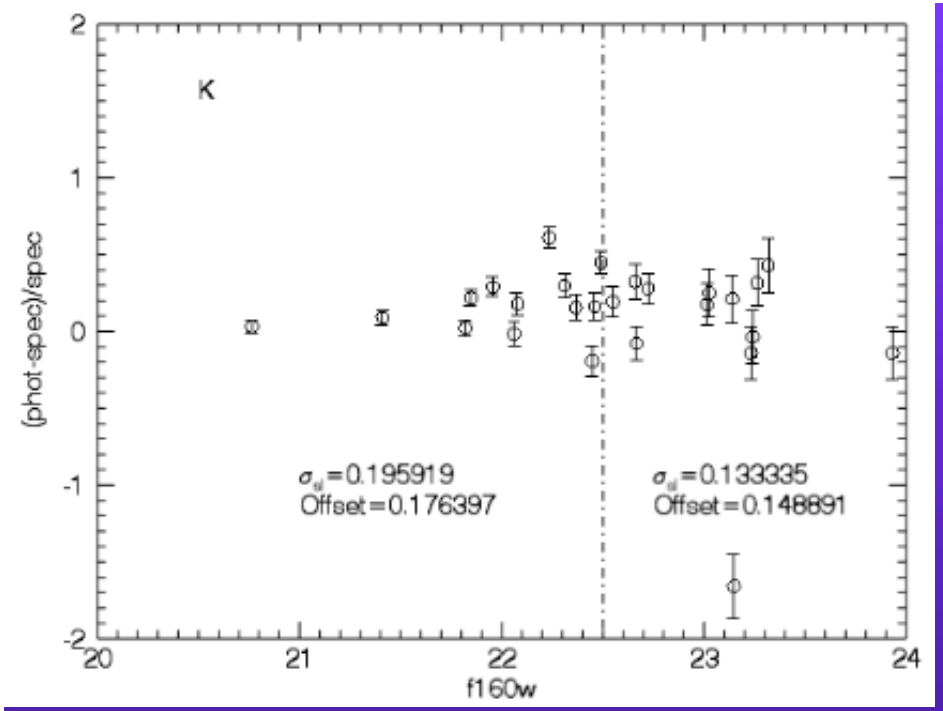


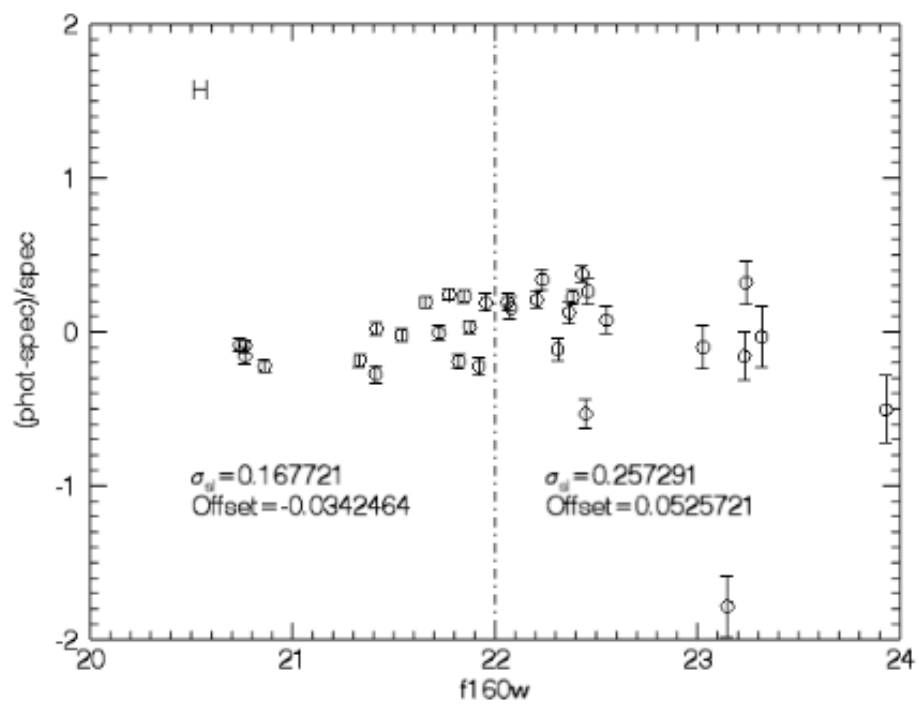
Effects of Metallicity?

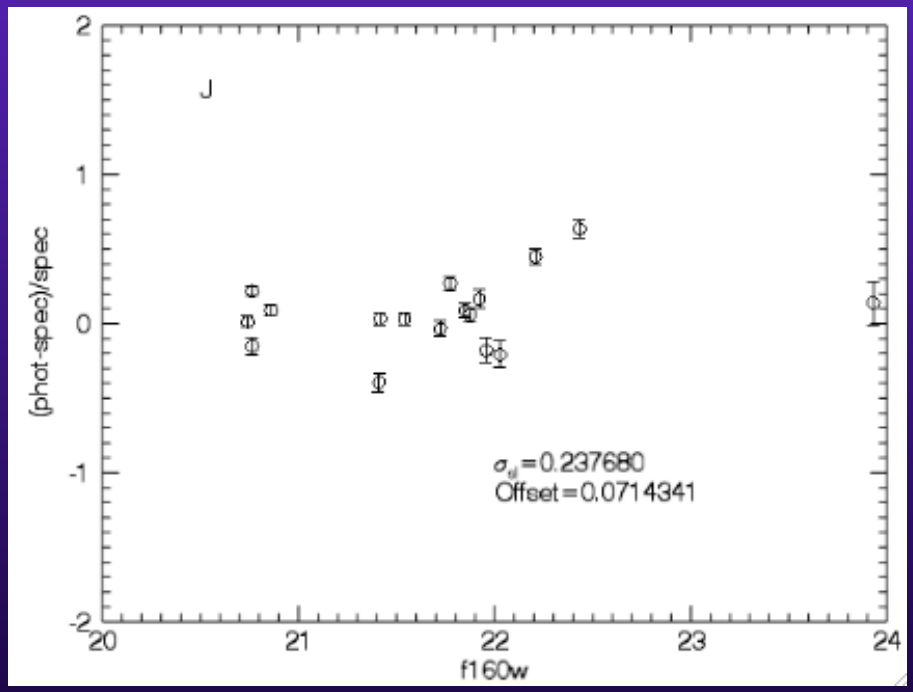


Range of metallicity implies $\Delta\beta_{\rm int} \approx 0.2$

Slit Losses


K
(phot-spec)/spec
f160w
σ_{sl}=0.195919
Offset=0.176397
σ_{sl}=0.133335
Offset=0.148891


H
(phot-spec)/spec
f160w
σ_{sl}=0.167721
Offset=-0.0342464
σ_{sl}=0.257291
Offset=0.0525721


J
(phot-spec)/spec
f160w
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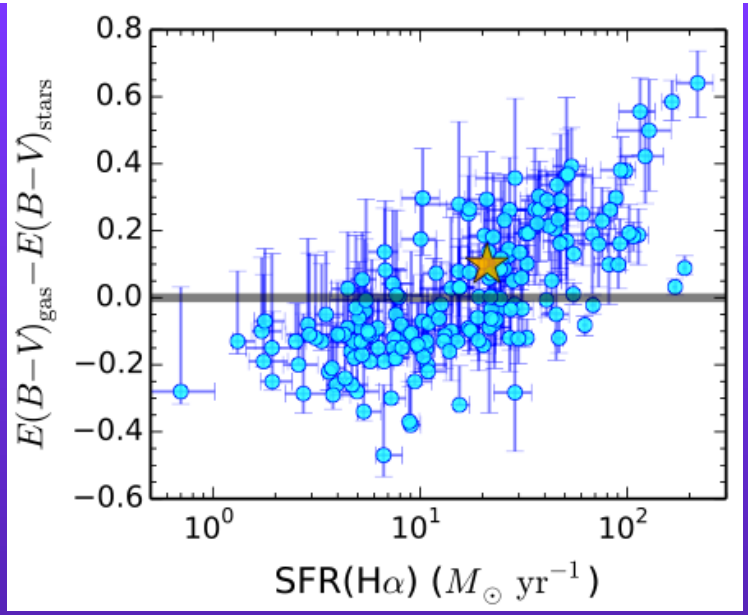
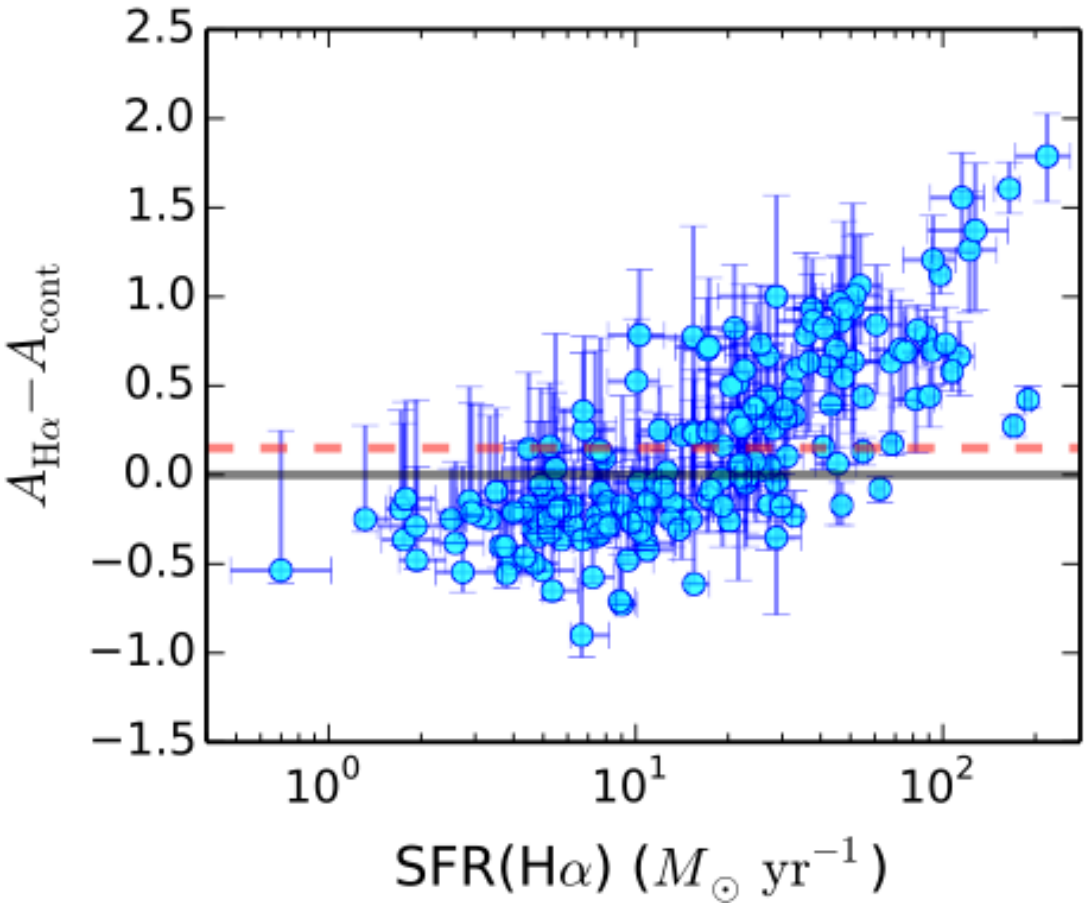
Offset=0.0714341

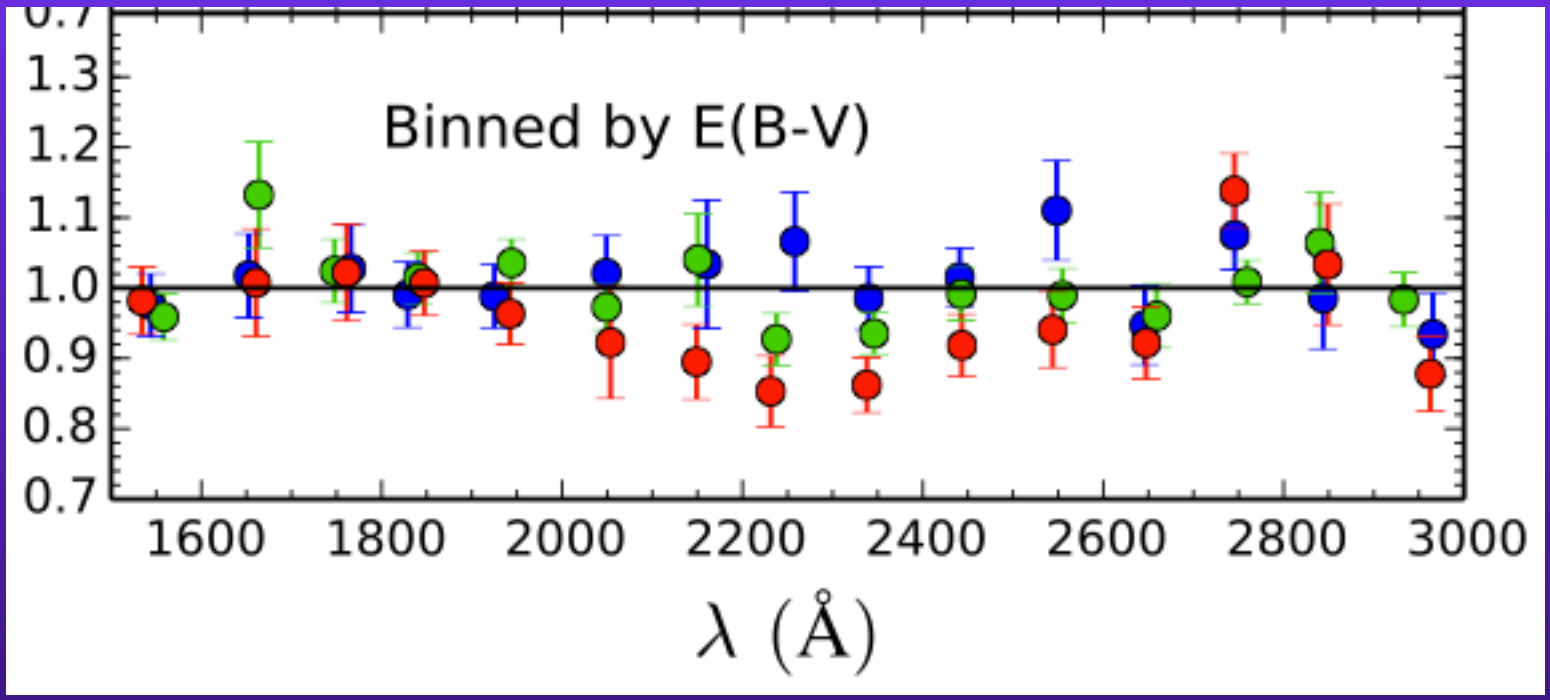


Dependence of the Difference in *Color Excess* on SFR

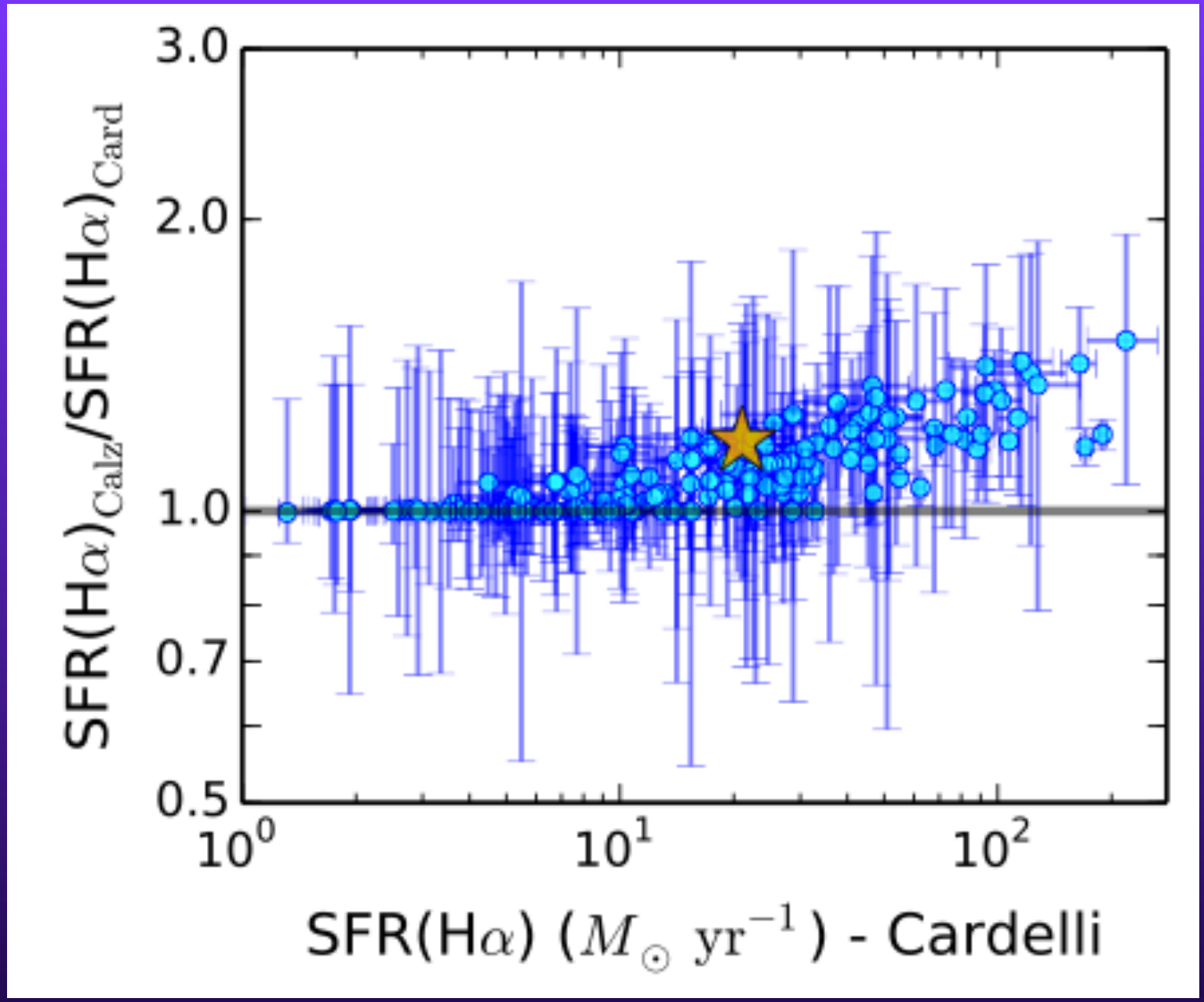
Dependence of the Difference in *Total Attenuation* on SFR



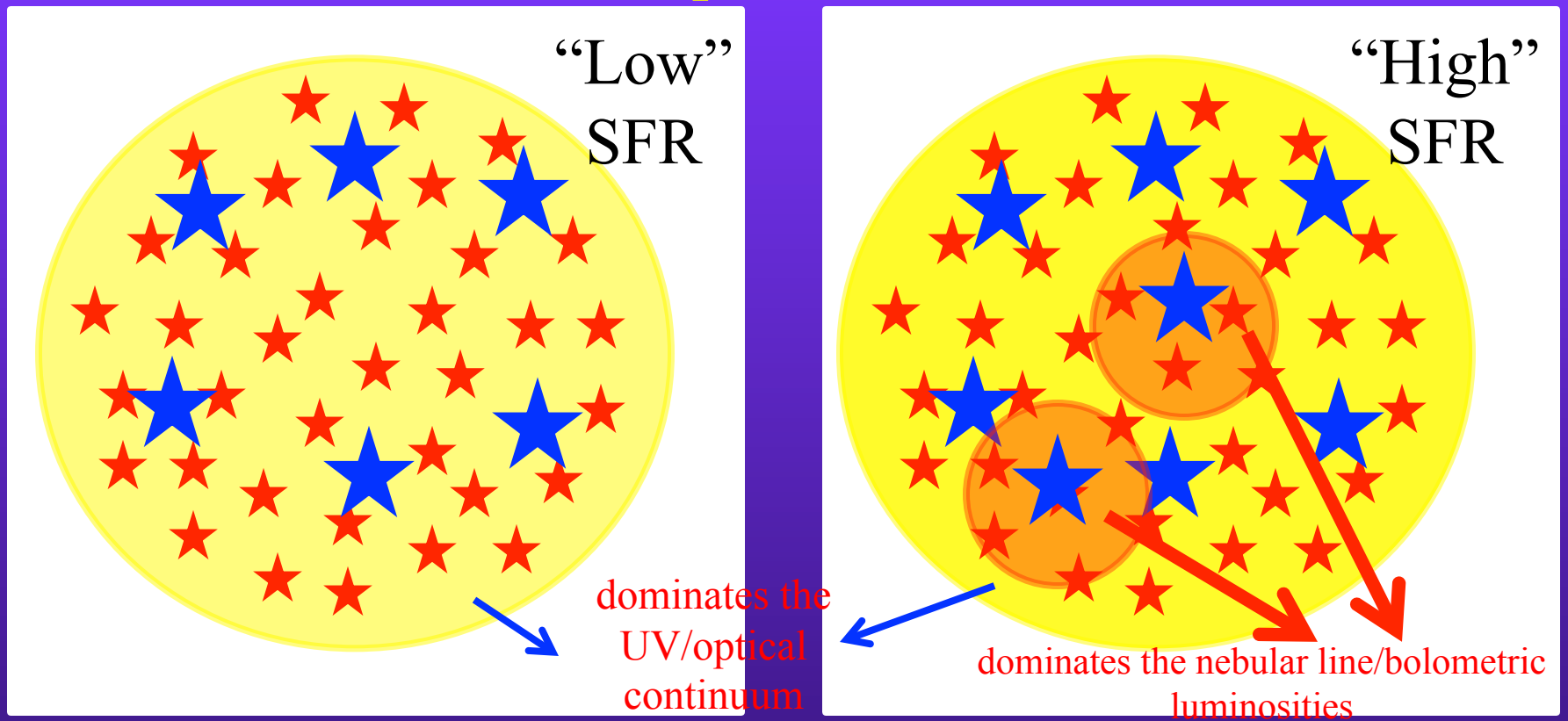
Excess UV Absorption at 2175 Å?



Marginal (3σ) significance

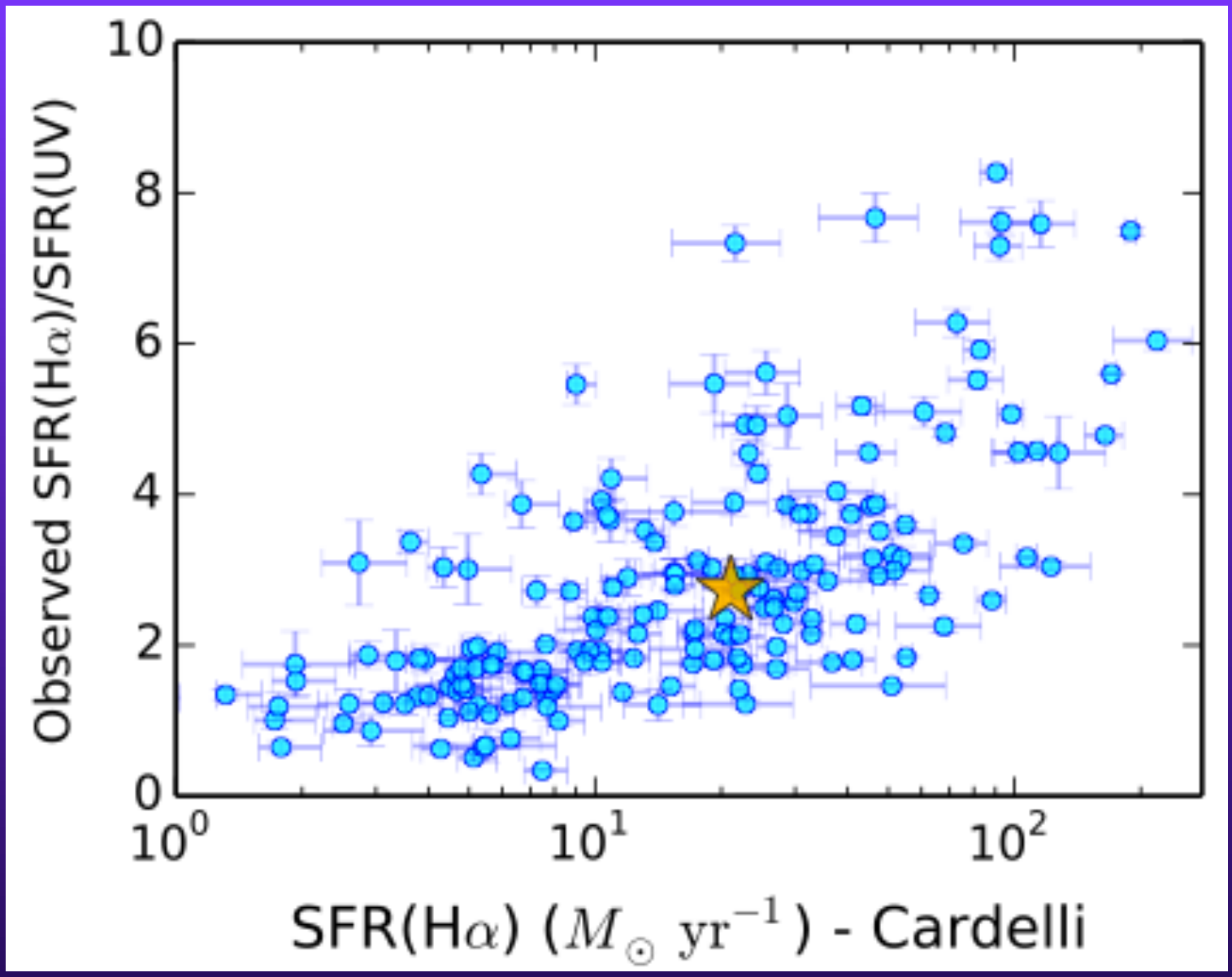

3.0
2.0
1.0
0.7
0.5
10^0
10^1
10^2
$\mathrm{SFR(H}\alpha)_{\mathrm{Calz}}/\mathrm{SFR(H}\alpha)_{\mathrm{Card}}$
SFR(Hα) ($M_\odot$ yr^{-1}) - Cardelli

Implications



SFR(SED) and SFR(UV) may underpredict total SFR at even "modest" levels

Appropriate attenuation curve to use for HII regions? Gray at low SFR, MW/SMC at high SFR?


Observed SFR(Hα)/SFR(UV)
10
8
6
4
2
0
10^0
10^1
10^2
SFR(Hα) ($M_\odot$ yr^{-1}) - Cardelli