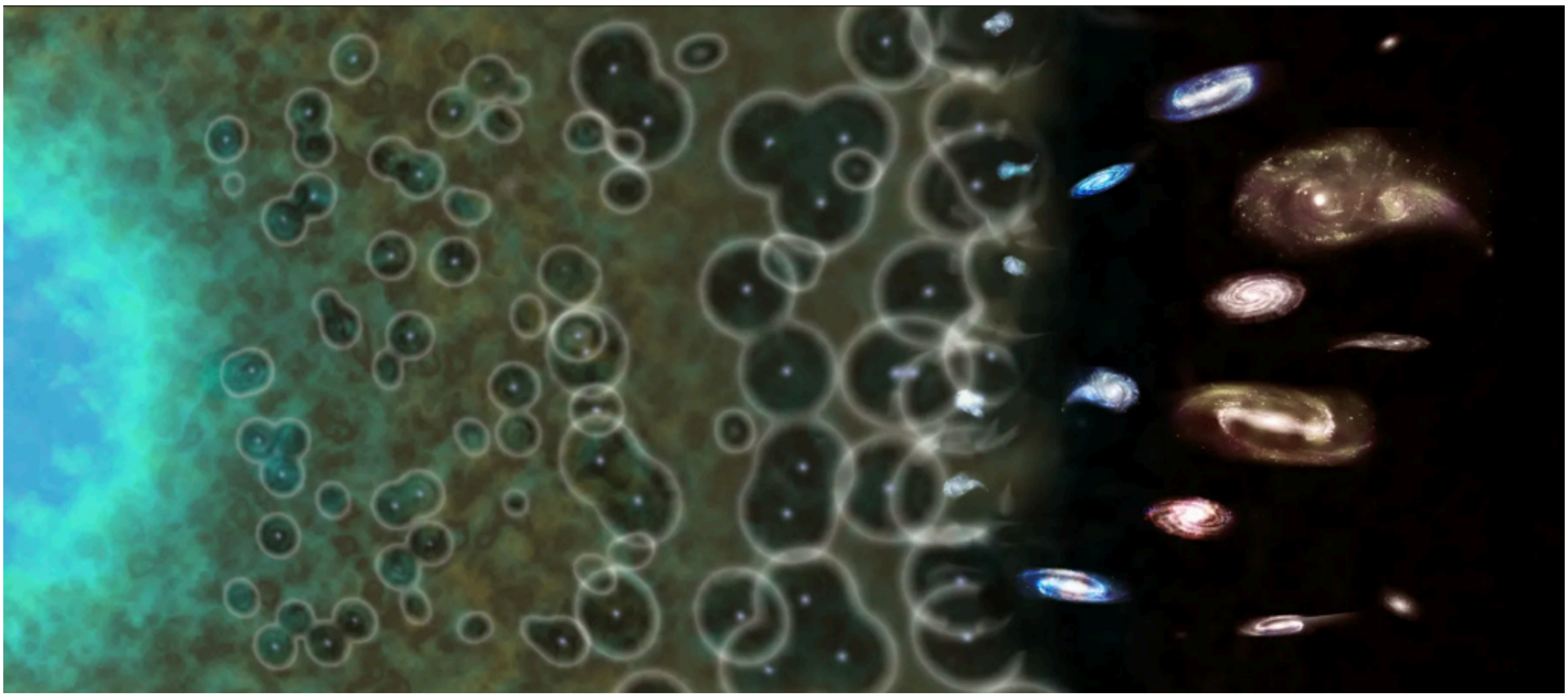
Review of UV/Continuum Attenuation…and The Production and Transmission of Lyα and Implications for the Escape of Ionizing Radiation

Naveen Reddy (University of California, Riverside)

Escape of Lyman Radiation from Galactic Labyrinths, Crete 2025



Outline of the First Part…

- What is the stellar attenuation curve?
- Why is it important?
- What does it depend on?
- What about the *nebular* attenuation curve?
- A “roadmap” of dust curves at high-redshift

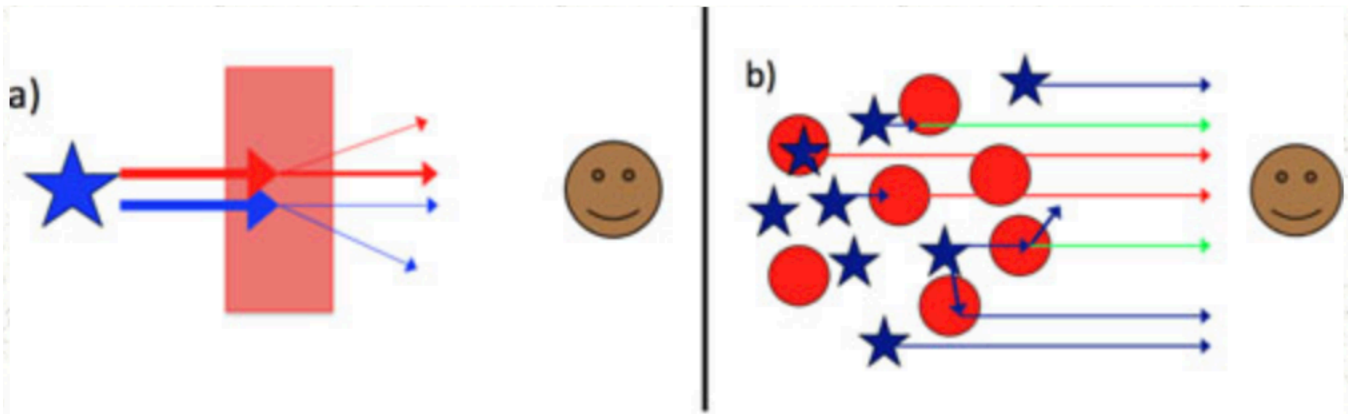
Definitions…

$$f(\lambda) = f_0(\lambda) \times 10^{-0.4A(\lambda)}$$

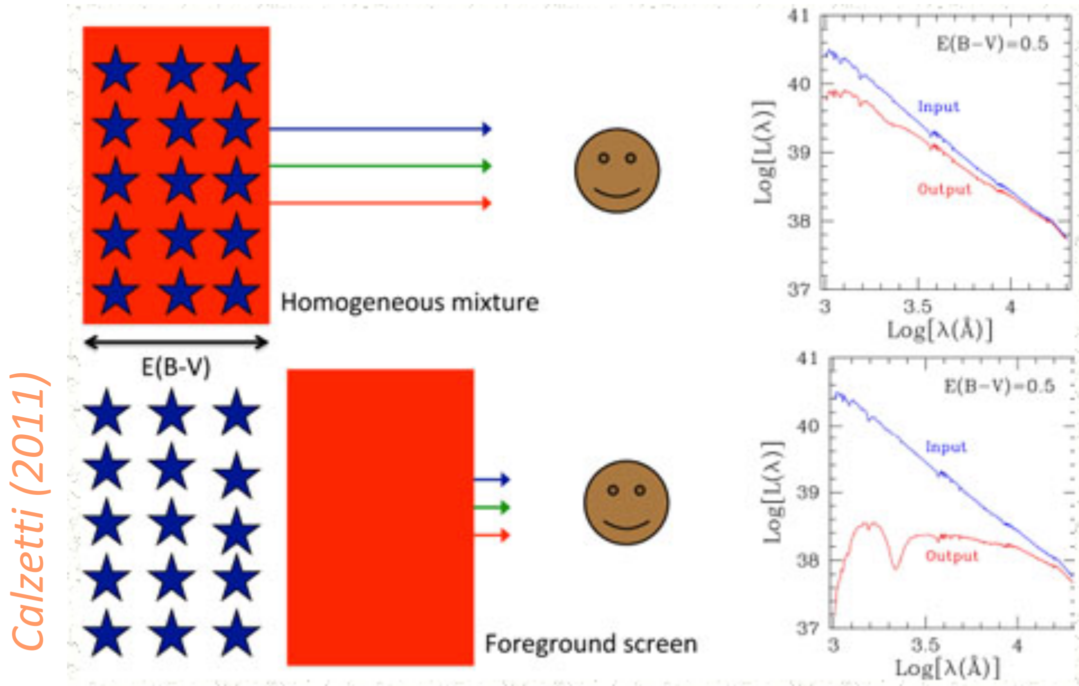
$$k(\lambda) \equiv \frac{A(\lambda)}{E(B-V)}$$

- Note that *E(B-V)* depends on the shape of the dust curve, *k*

- “Extinction” vs. “Attenuation”



Importance of the Dust "Curve"



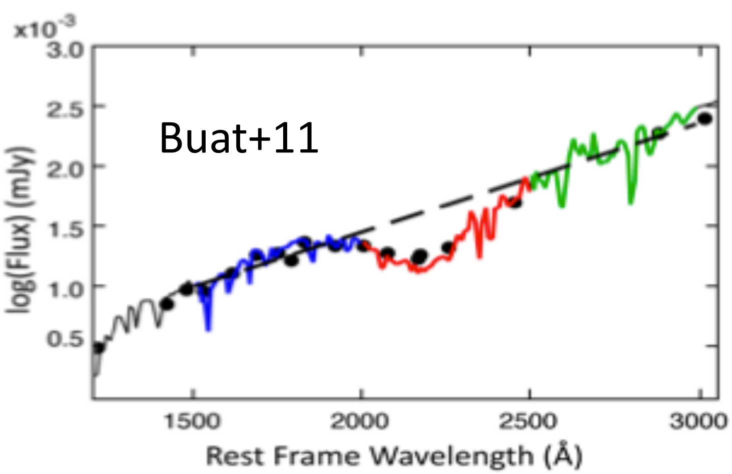
Important input to SED fitting

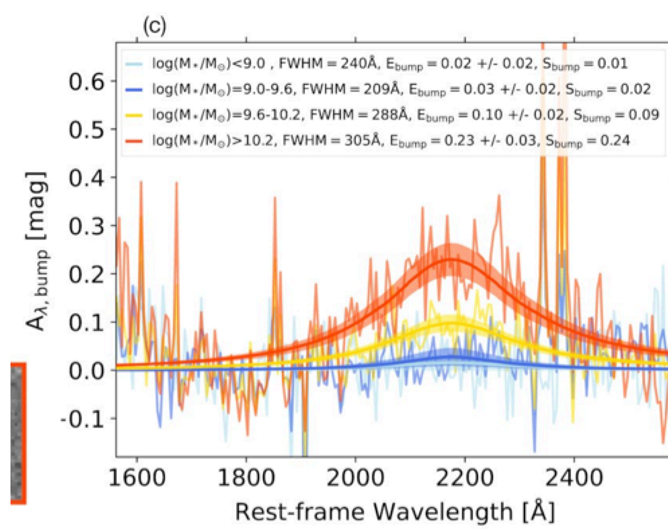
Needed to infer dust-corrected SFRs

Encodes info on the dust/stars geometry

Importance of Quantifying the Wavelength-Dependence of Dust Obscuration

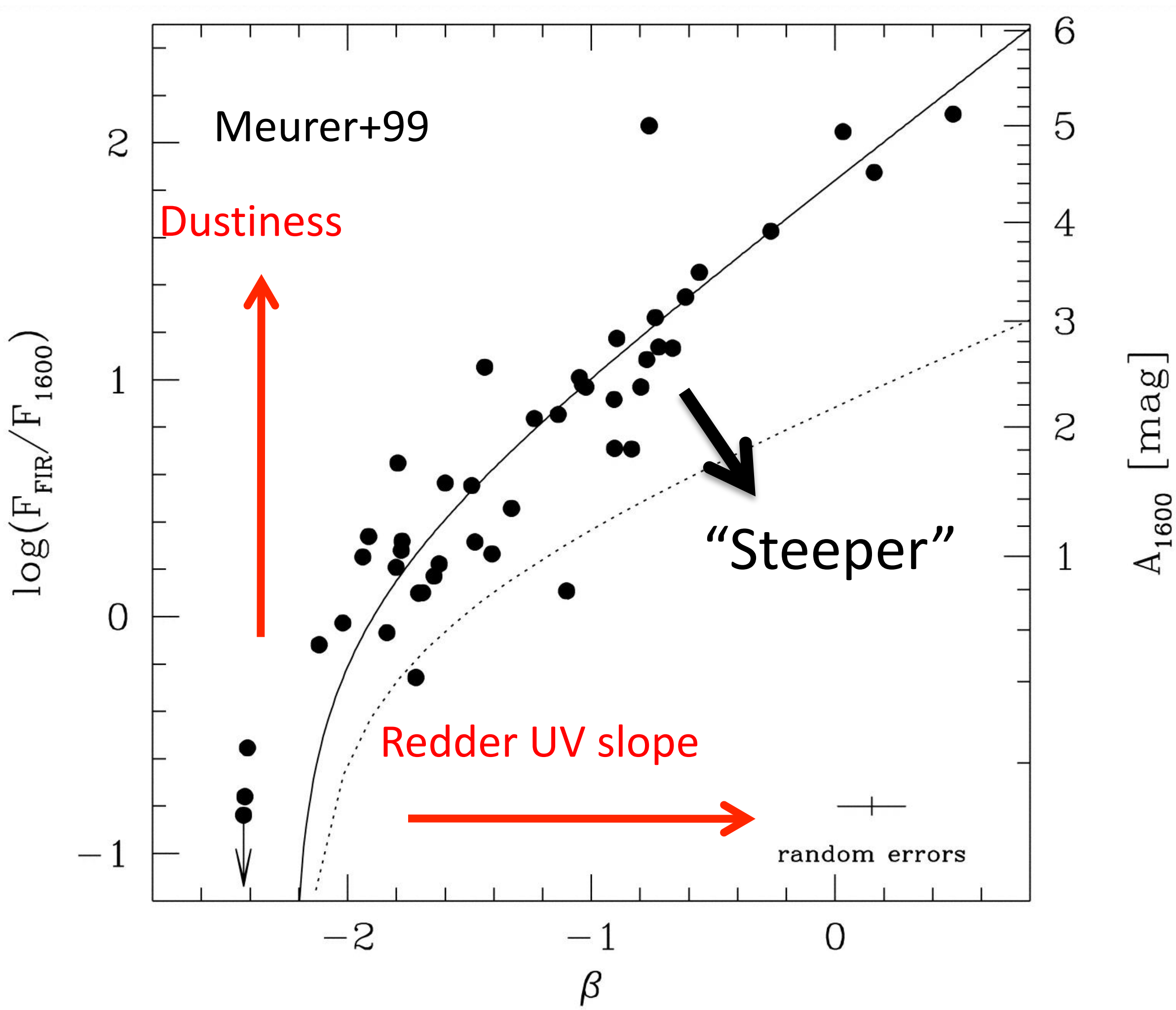
- [nebular attenuation curve:] Inferring the Physical Properties of the ISM based on rest-frame optical line ratios (e.g., ionization parameters, gas-phase metallicities, nebular reddening and recombination-line SFRs)
- Investigating the origin of the carriers of specific absorption features in the UV





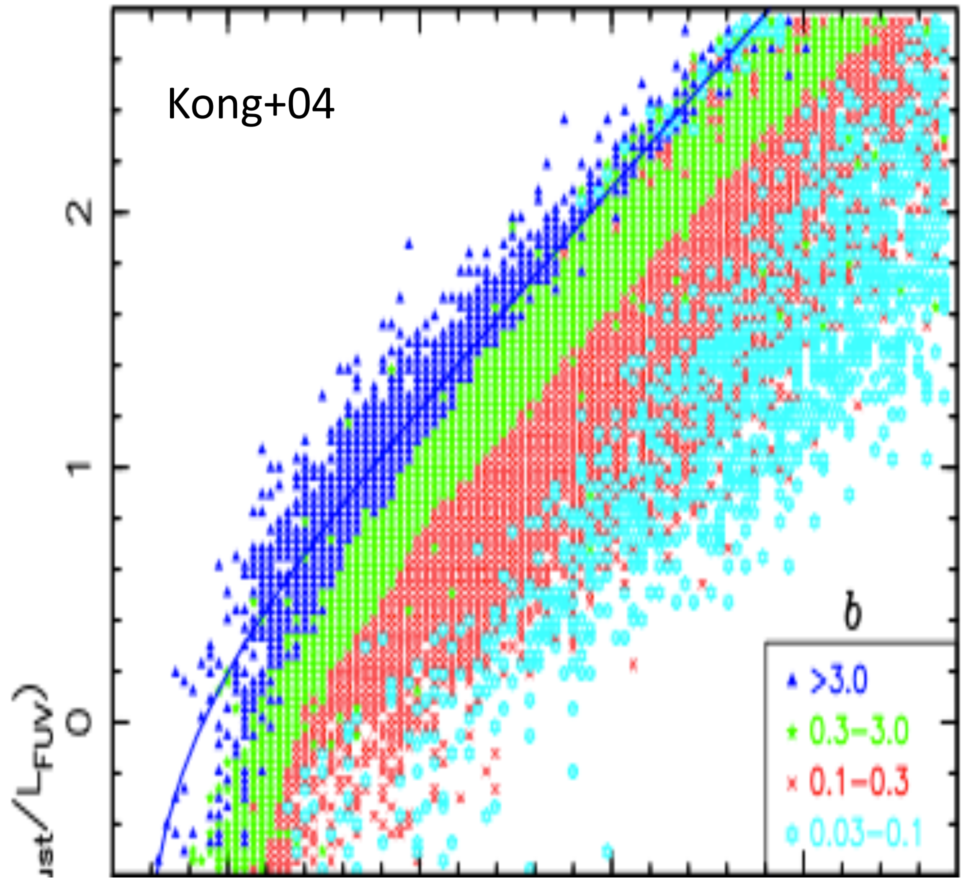
Shivaei+22

Investigating the Curve… often accomplished using the IRX-beta relation



Variations in the dust curve - SFH

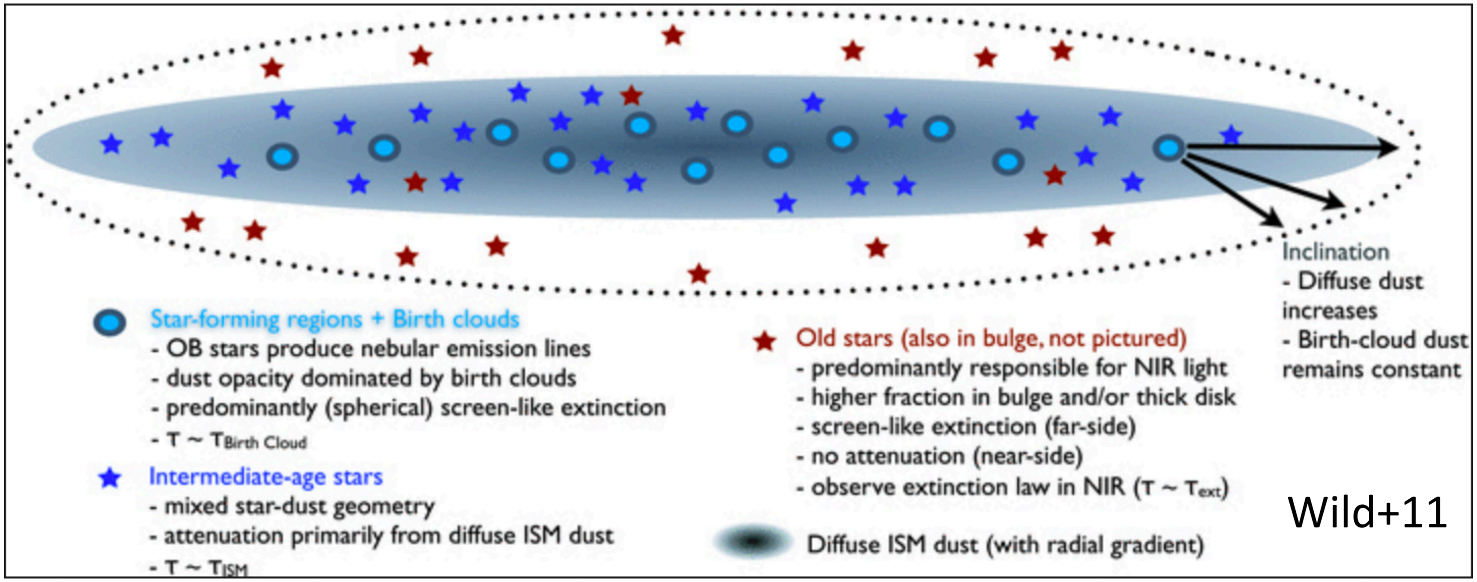
- Must take into account Star-formation history / Age / sSFR

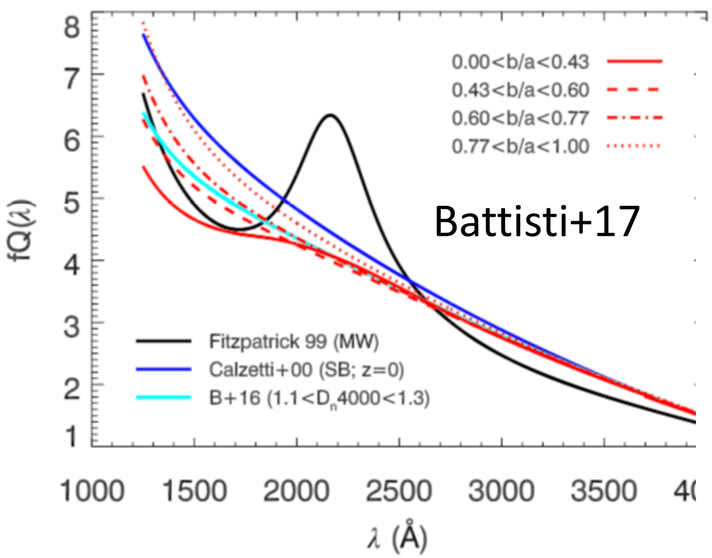


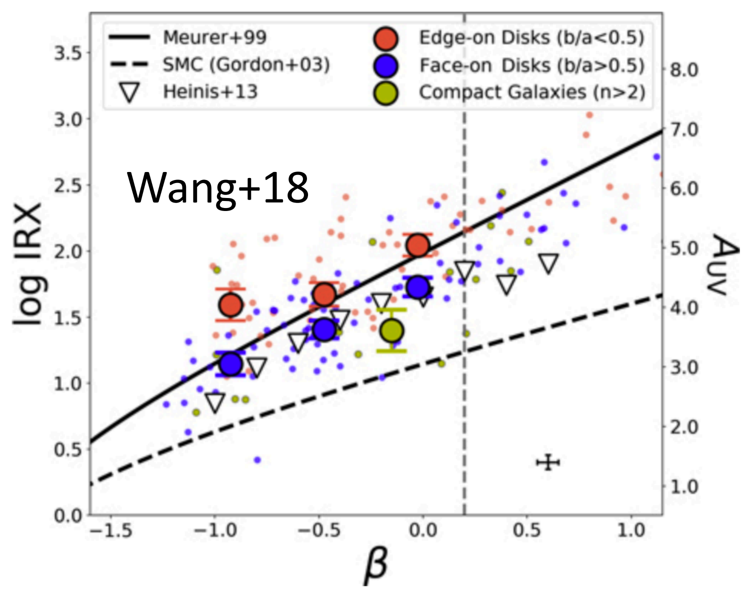
**Important to disentangle variations in stellar populations from changes in the shape of the dust curve

Variations in the curve - Inclination

- GEOMETRY





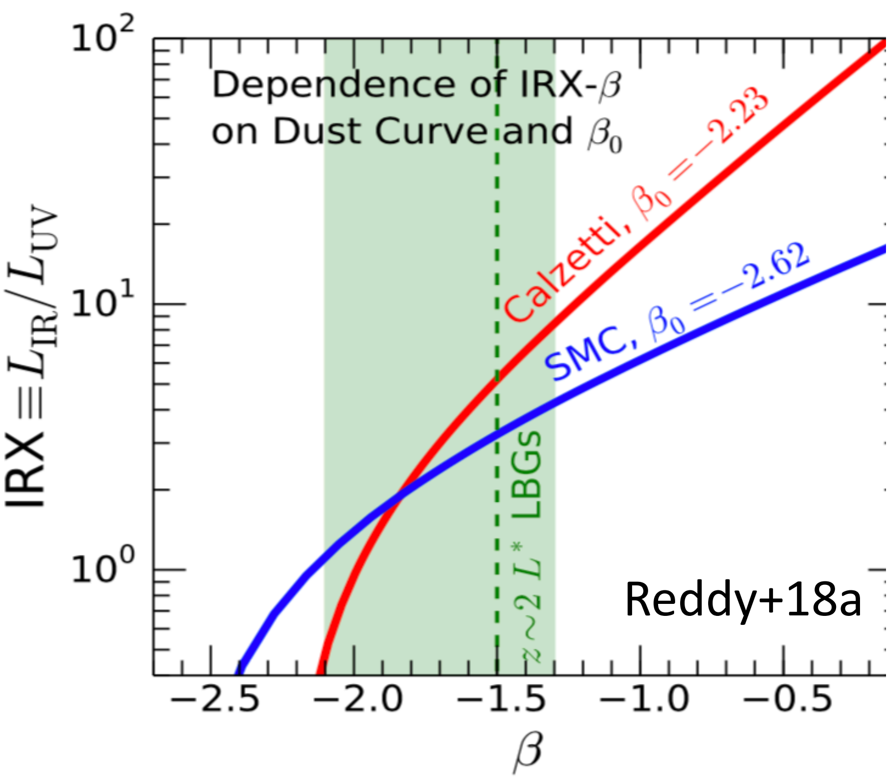


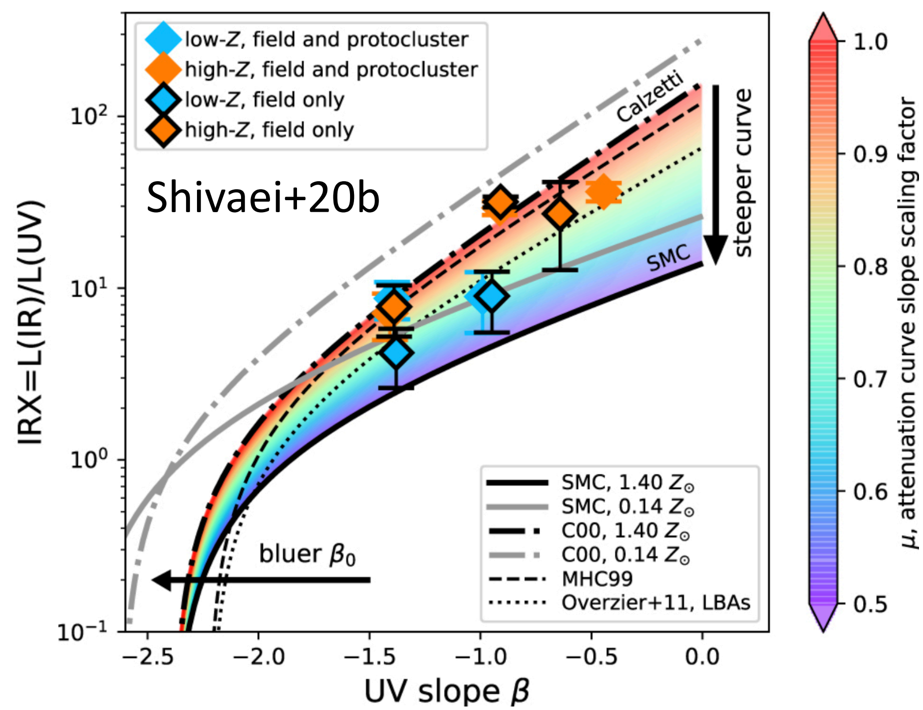
Geometrical effects may play a role in the “strength” of the 2175 bump

e.g., see also Narayanan+18

Variations in the curve - metallicity

- (Stellar) Metallicity (also related to SFH, sSFR, mass, etc.)

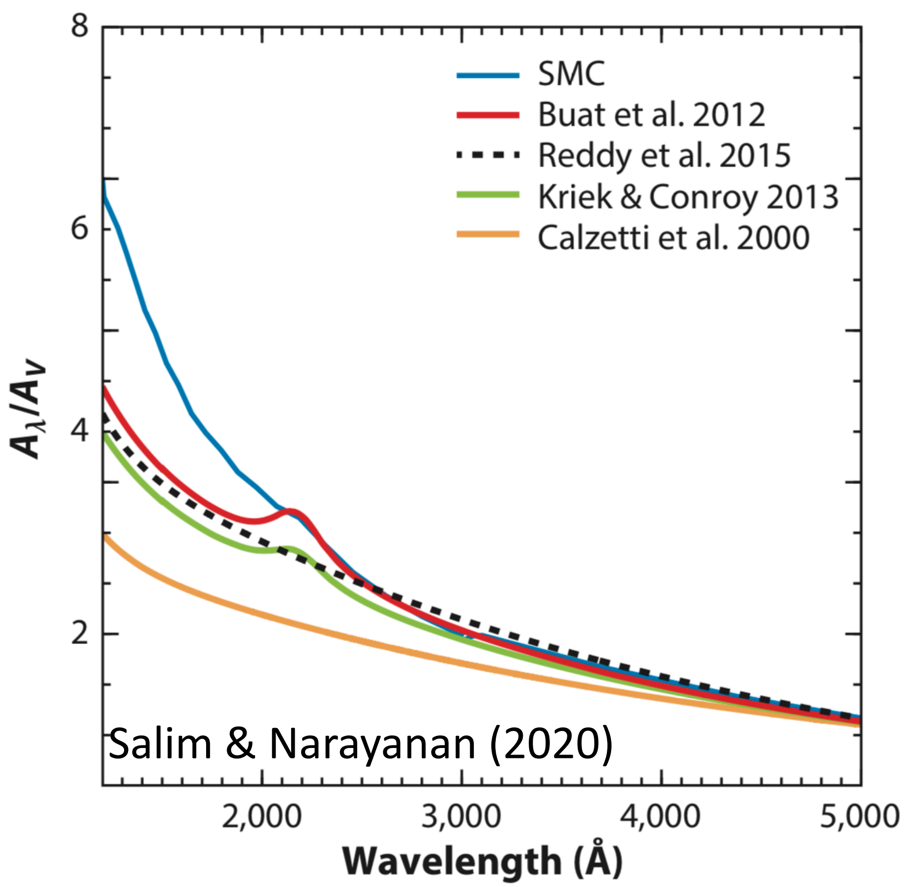


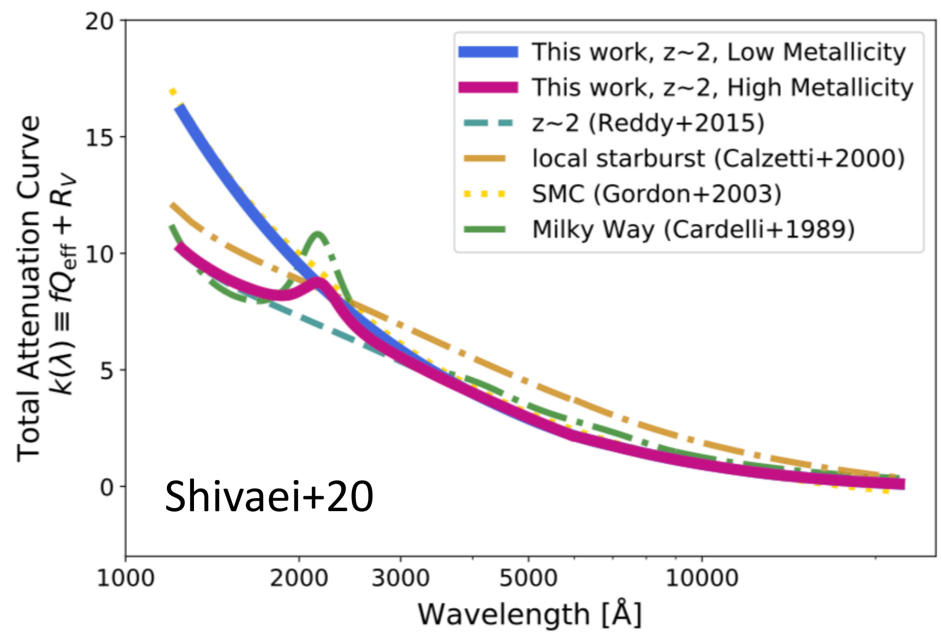


e.g., see also Wilkins+11, Boquien+12, Schaerer+13, de Barros+14, Zeimann+15

Going beyond IRX-Beta

- Constraints on the overall shape/normalization of the stellar attenuation curve (e.g., Noll+09, Kriek&Conroy13, Scoville+15, Reddy+15, Zeimann+15))



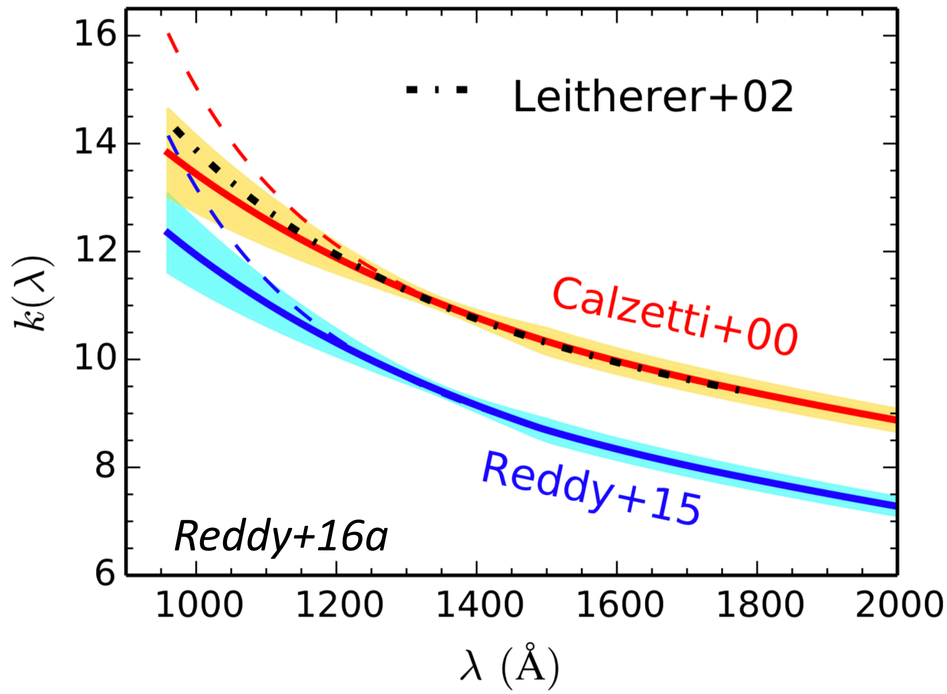


Curve intermediate between that of Calzetti and SMC for z~2 galaxies

Steepening of Curve at low mass/ low metallicity

The Far-UV Shape of the Dust Curve

- New constraints on the shape of the dust curve close to the Lyman Break

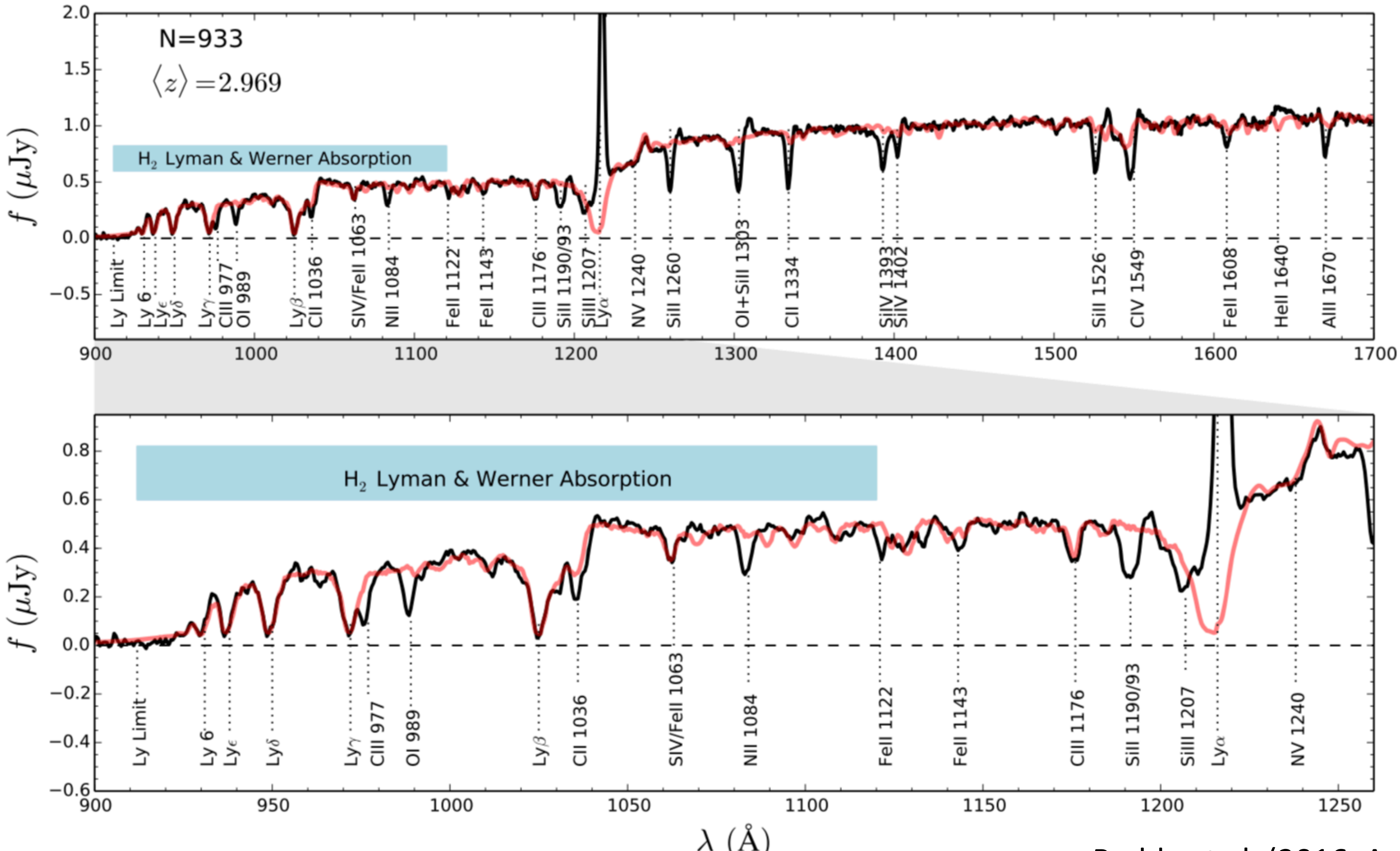


- Most dust curves, including that of Calzetti, have only been constrained above 1250 Angstroms

- New determination for z~3 LBGs suggests a shallower (less steep) wavelength dependence between 950 and 1250 A

May be used to assess attenuation of ionizing photons in low-column density ISM (<10^17.2 cm^-2) or in HII regions

Importance of the Dust "Curve" for Modeling Stellar Populations



Reddy et al. (2016, ApJ, 828, 108)

see also Reddy+16a,b; Steidel+18, Gazagnes+18, Reddy+22, …

What about the *nebular* attenuation curve?

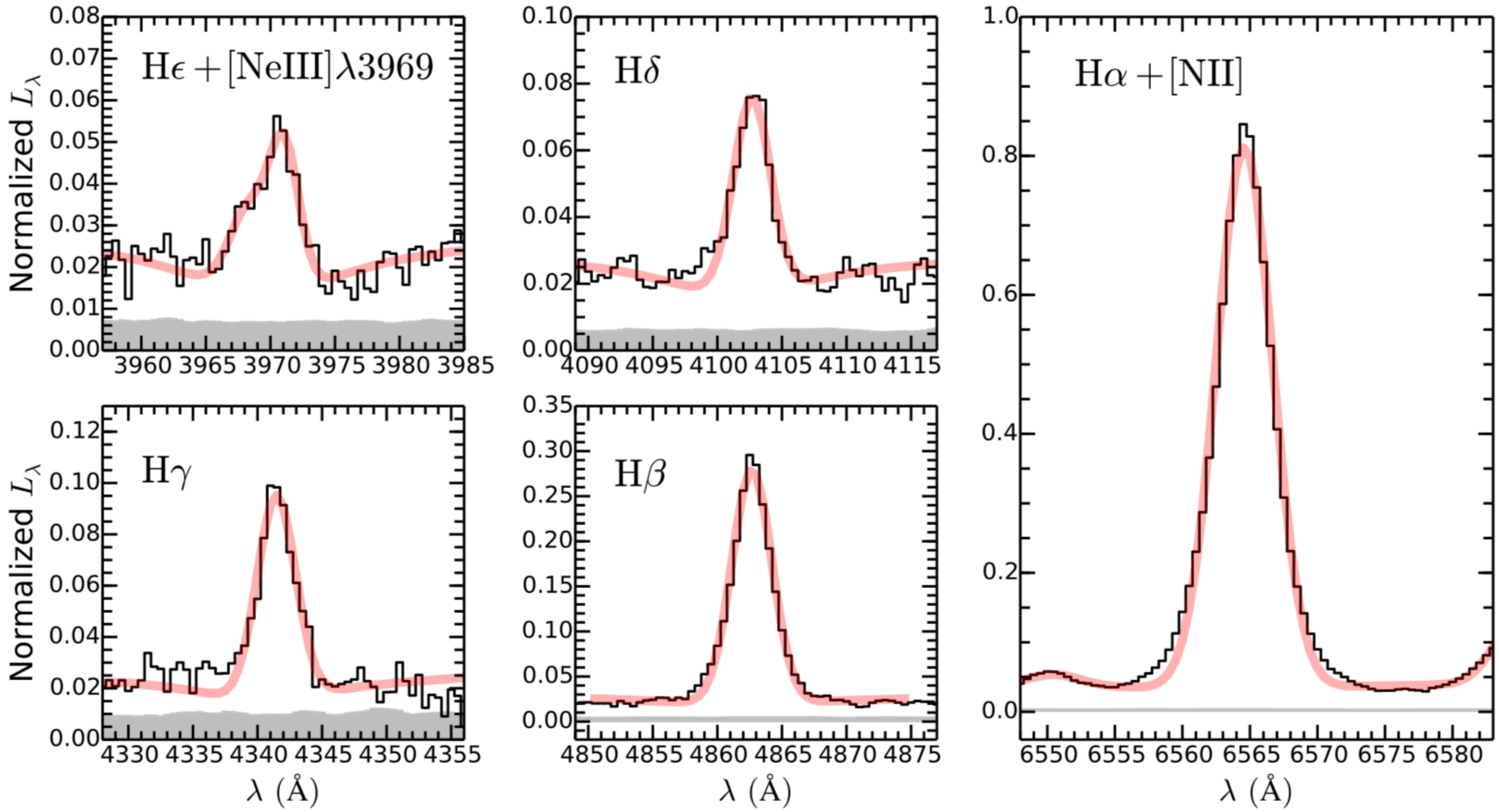
• Curve that applies for dust reddening along the lines-of-sight to the ionized ISM (i.e., towards massive stars)

• Required to interpret rest-frame optical line ratios to compute ISM physical properties

• *A priori* there is no reason why the curve should be the same as that affecting the stellar continuum (cov. fraction of dust/ geometry), MW extinction curve normally assumed

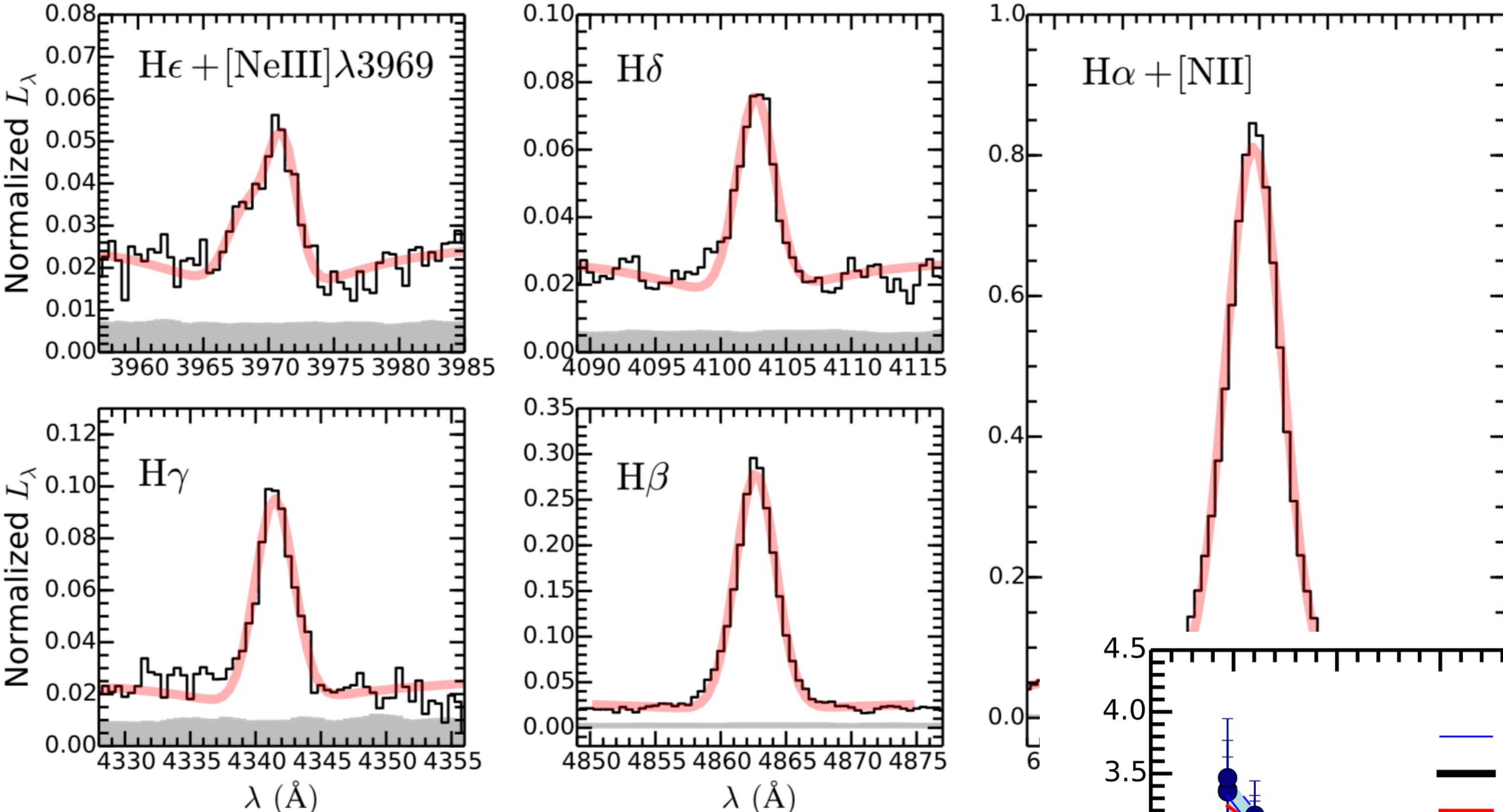
→ **can be investigated using multiple recombination line ratios**

What about the *nebular* attenuation curve?

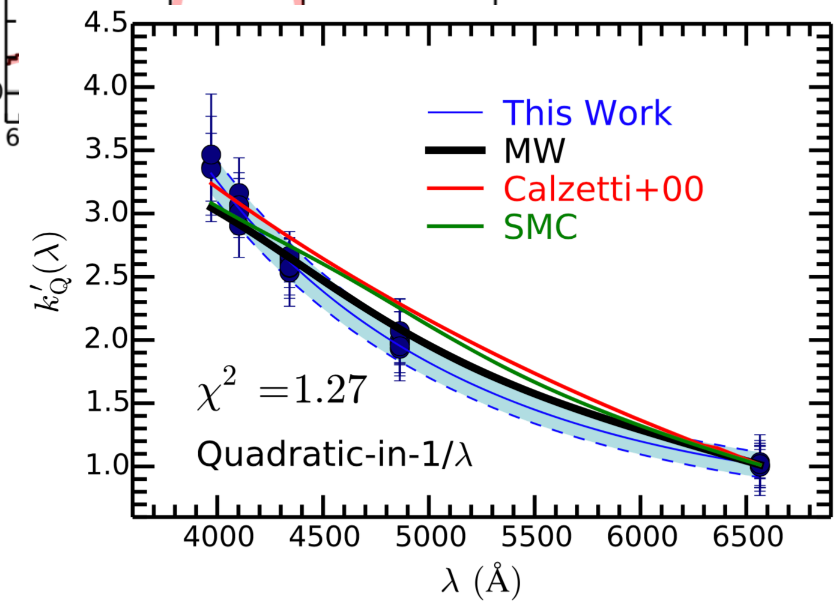


Reddy et al. (2020, ApJ, 902, 123)

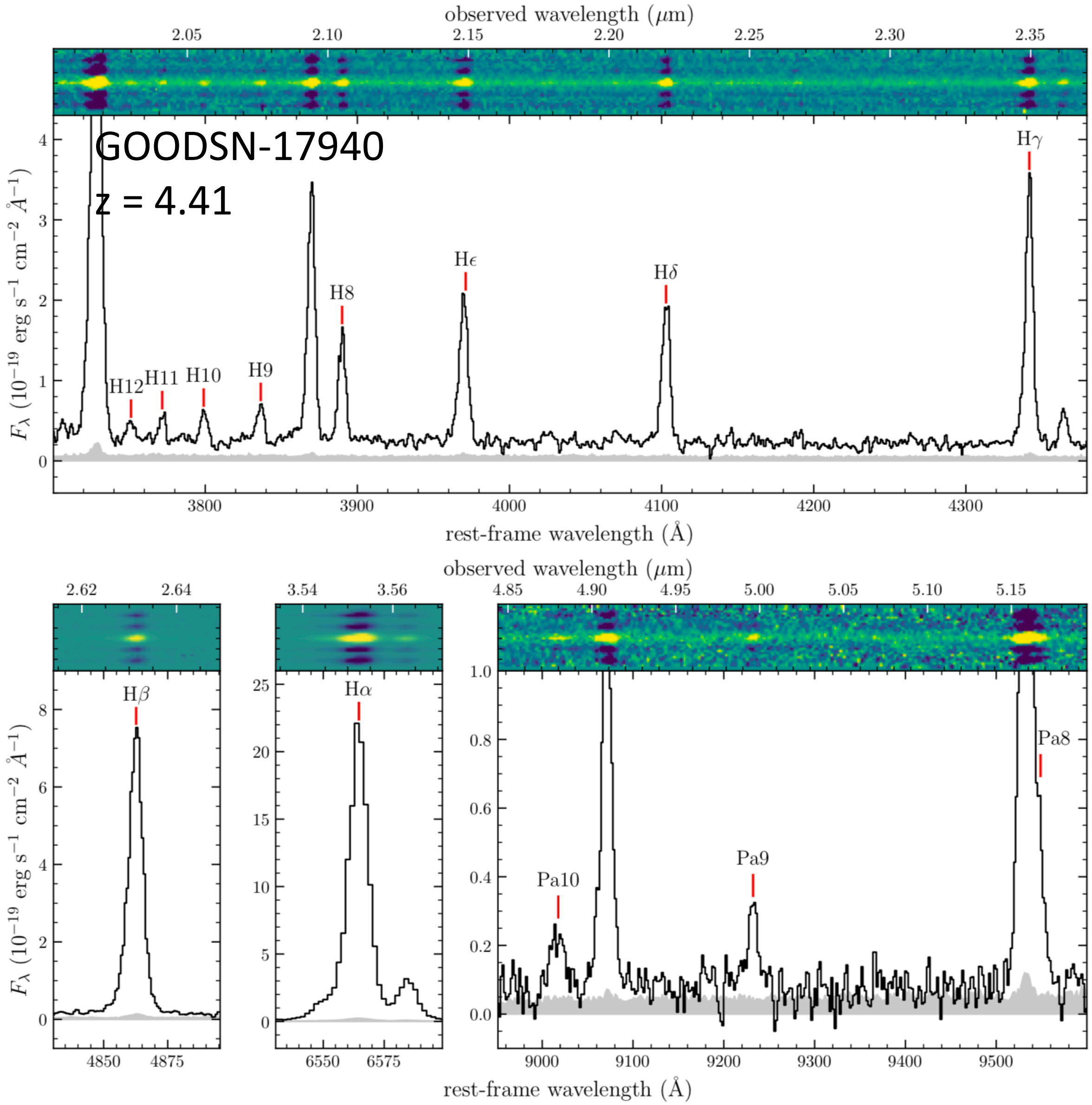
What about the *nebular* attenuation curve?



Reddy et al. (2020, ApJ, 902, 123)



What about the *nebular* attenuation curve?

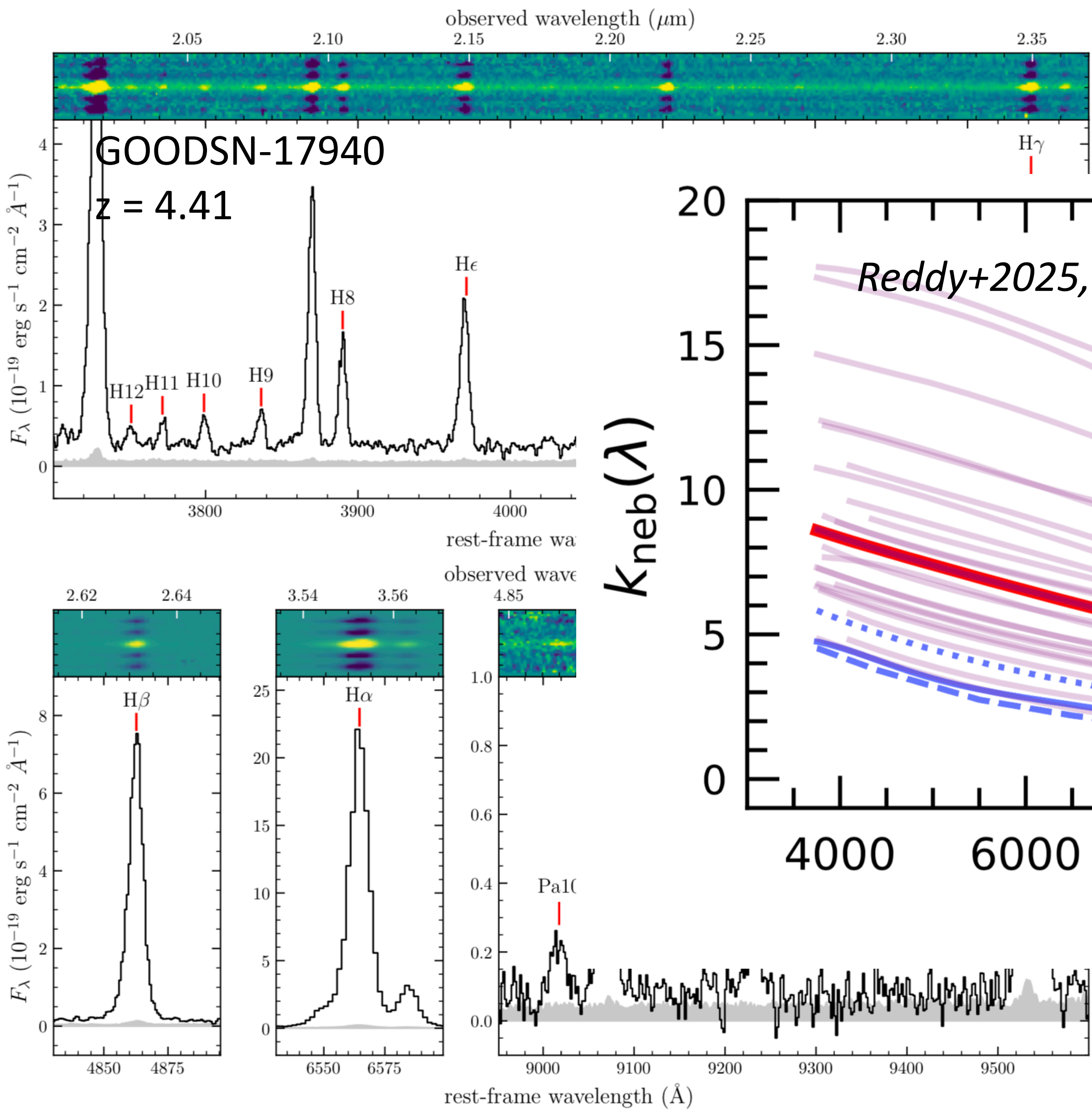


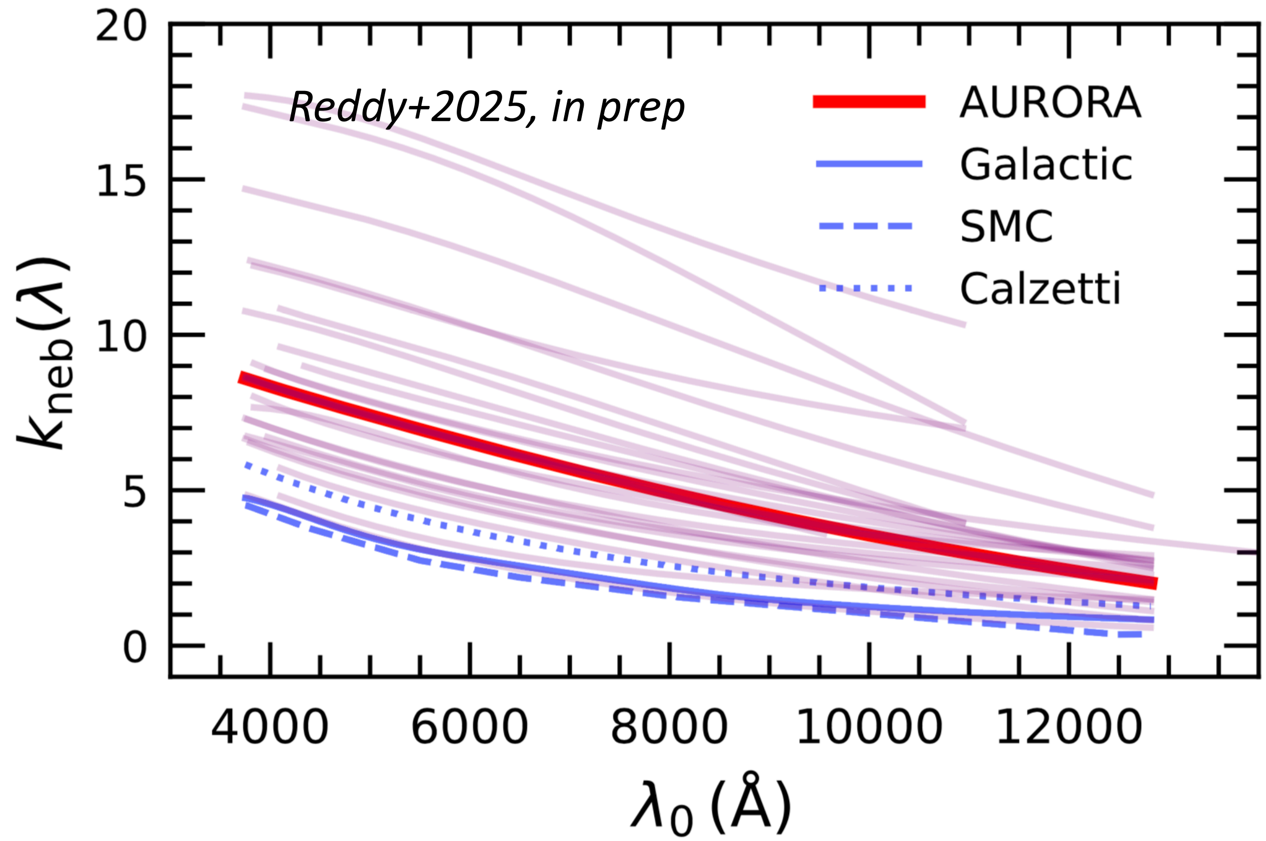
From the JWST Cycle 1 “AURORA” program

Sanders+24

What about the *nebular* attenuation curve?

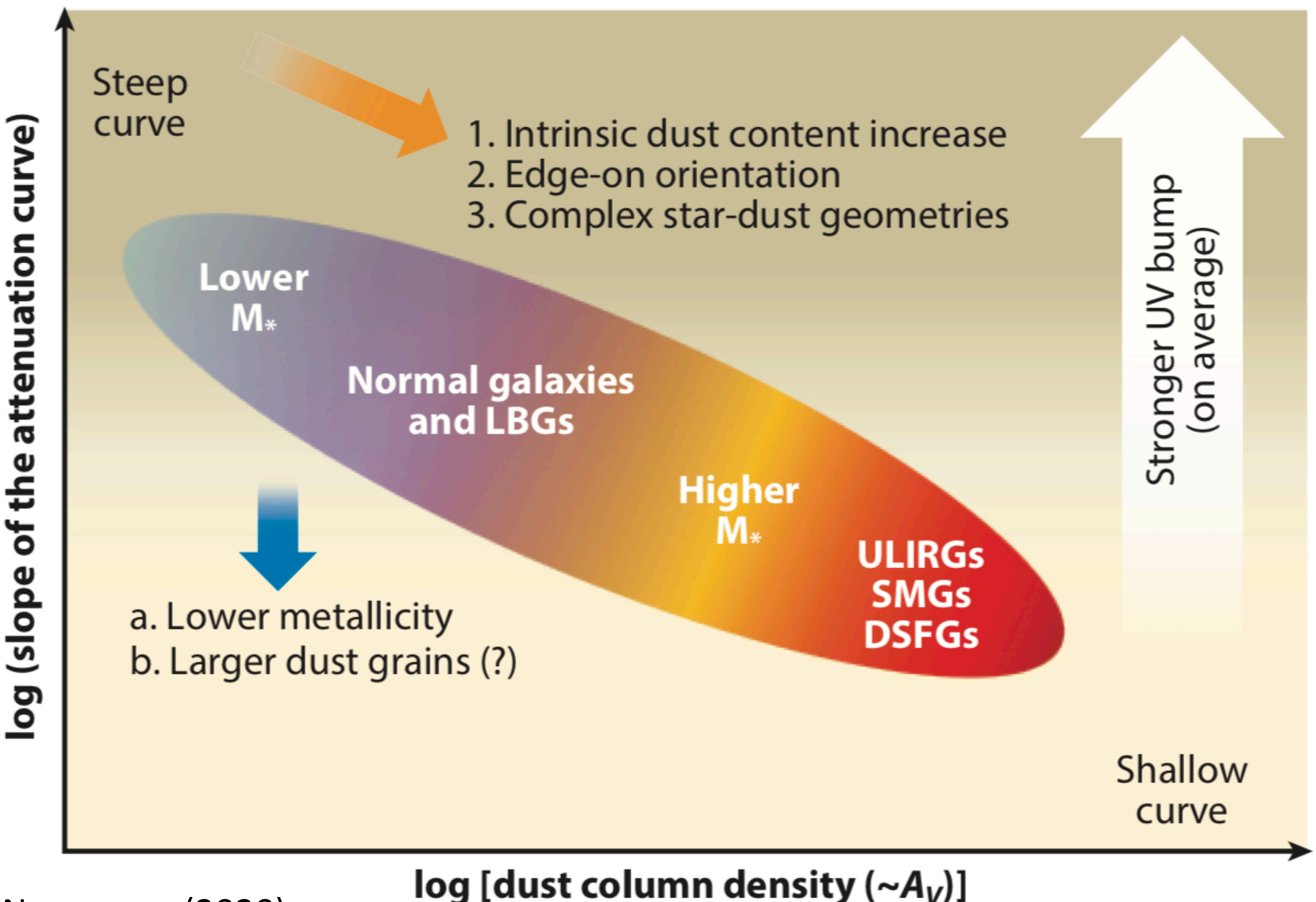
From the JWST Cycle 1 "AURORA" program





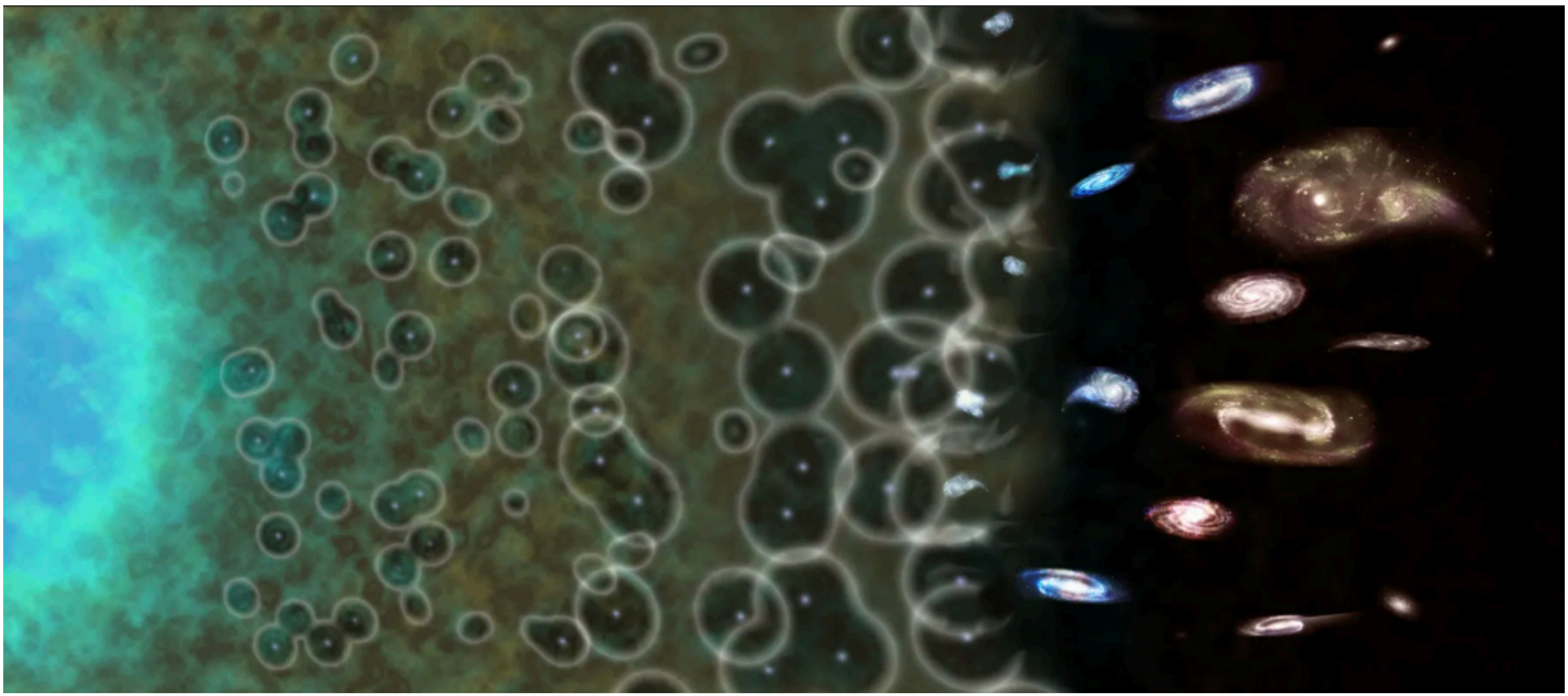
Sanders+24

A "Roadmap" for the Stellar Attenuation Curve at High Redshift



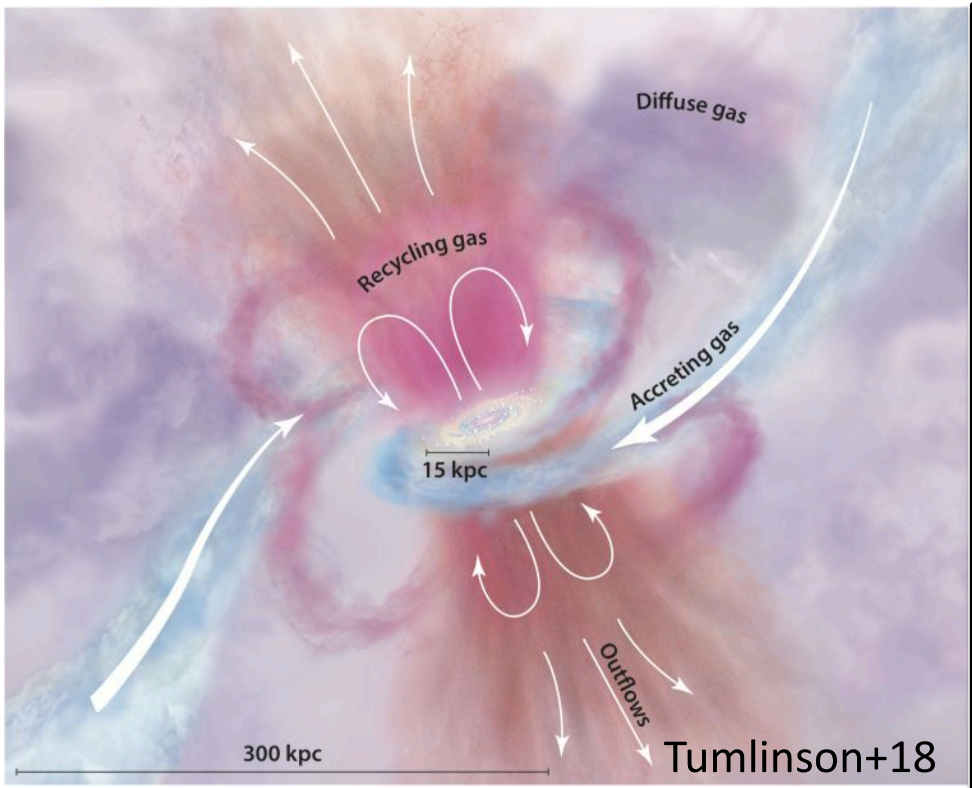
Salim & Narayanan (2020)

Part 2…
Effects of Stellar Population and Gas Covering Fraction on the Emergent Lya Emission

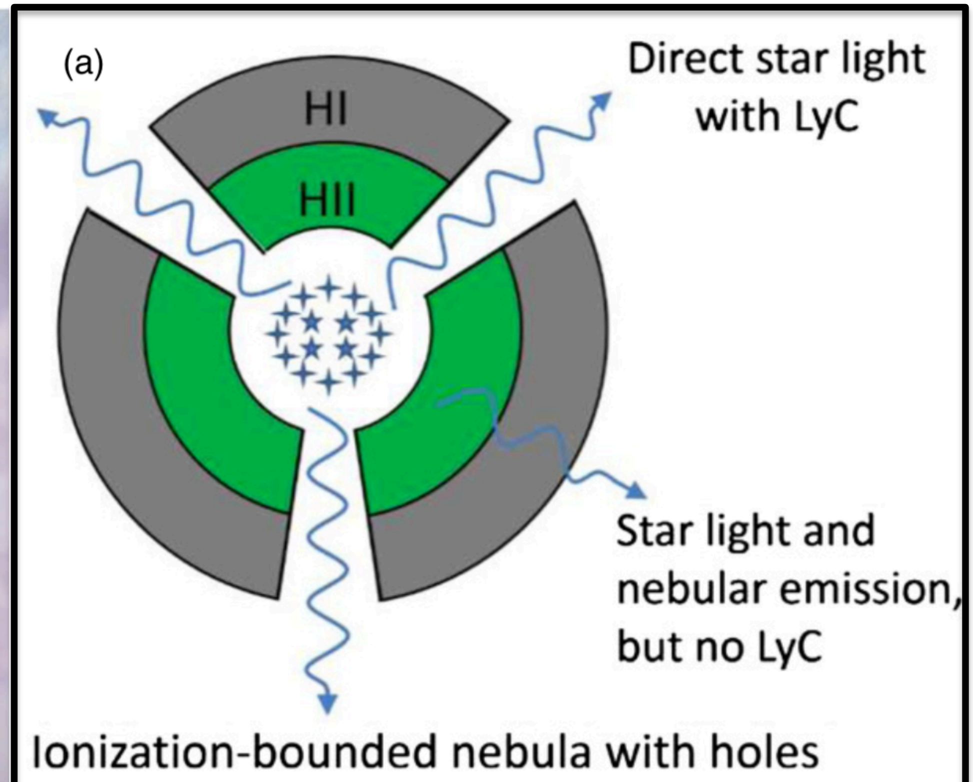


What processes facilitate the escape of ionizing (Lyman continuum) radiation?

OUTFLOWS → **POROUS ISM** (e.g., Ma+16)



Driven by Star-Formation-Rate Surface Density



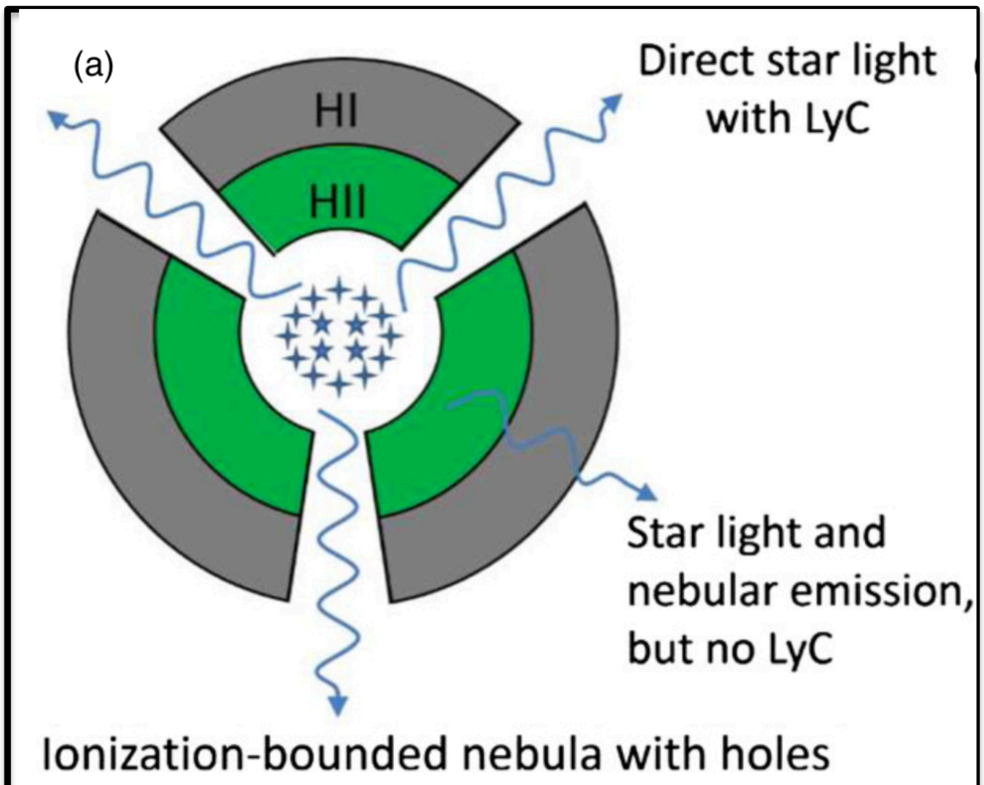
Zackrisson+13

Quantifying the mechanism for LyC escape

Difficulties in quantifying f_{esc} at z>2.7:

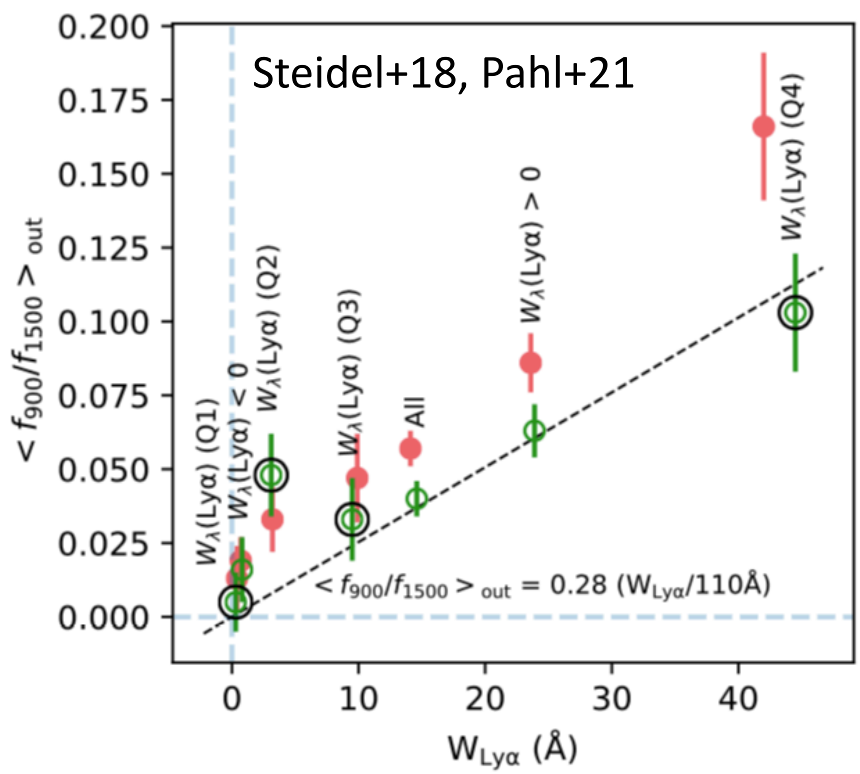
- signal is weak, particularly for fainter galaxies
- requires stacking to average over line-of-sight opacity variations

POROUS ISM



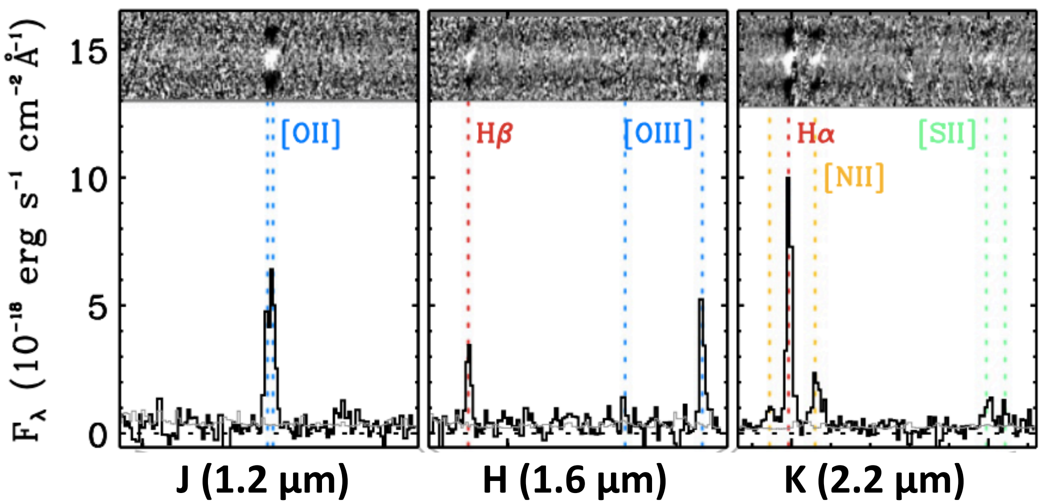
Zackrisson+13

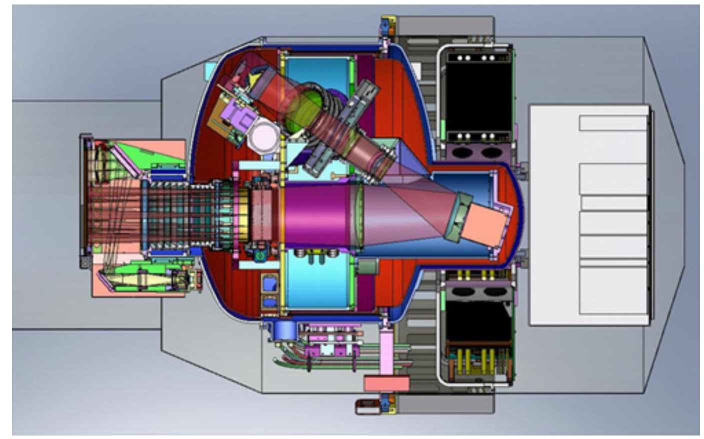
Lyman-alpha as potential proxy for LyC escape



The MOSFIRE Deep Evolution Field (MOSDEF) Survey

Survey paper: Kriek+2015



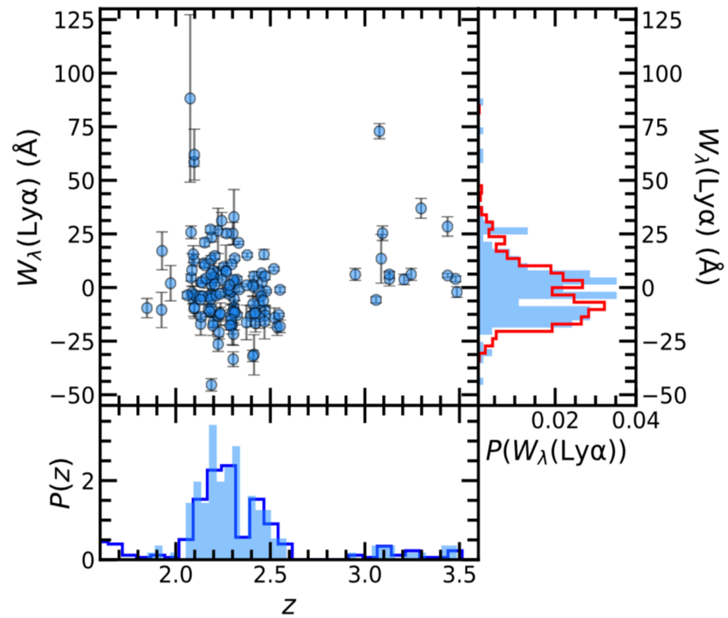


- Rest-frame optical spectra of ~ 1800 H-selected galaxies and AGNs
- $1.37 \leq z \leq 3.80$
- CANDELS fields
- 48.5 nights with MOSFIRE on Keck I (2012-2016)
- Collaboration between UC Riverside, UC Berkeley, UCLA, UC San Diego

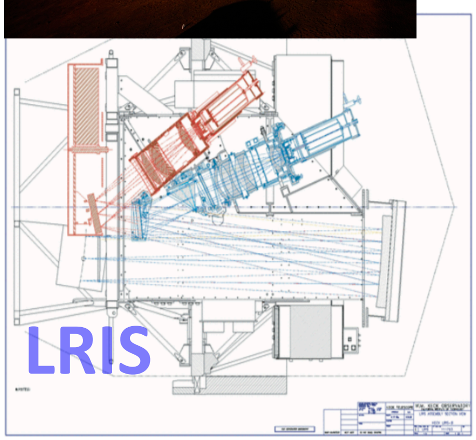
Keck/LRIS Followup (MOSDEF-LRIS Survey)

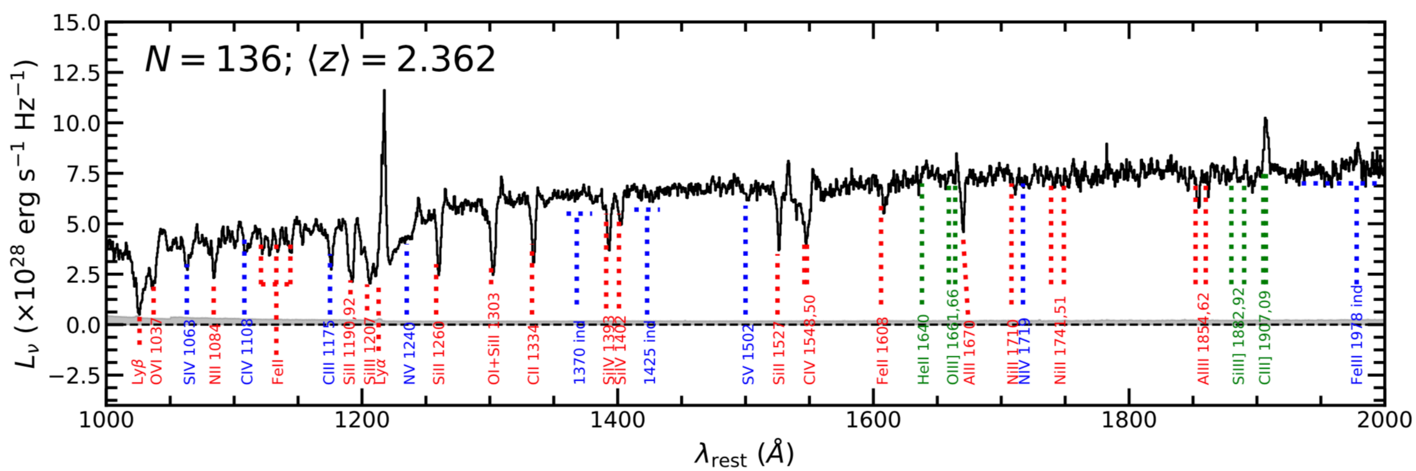
MOSDEF → **MOSDEF-LRIS**

LRIS followup of MOSDEF galaxies:
- 136 galaxies in final sample
- Complete coverage of Lyman-alpha at least Lyman-beta
- Removed AGN from sample
- Removed blended objects from the sample



~13% are LAEs





Production and Transmission of Lyα in z~2 Galaxies

Production

Model young stellar populations:
- Stellar Metallicities
- Ages
- Continuum Reddening, E(B-V)

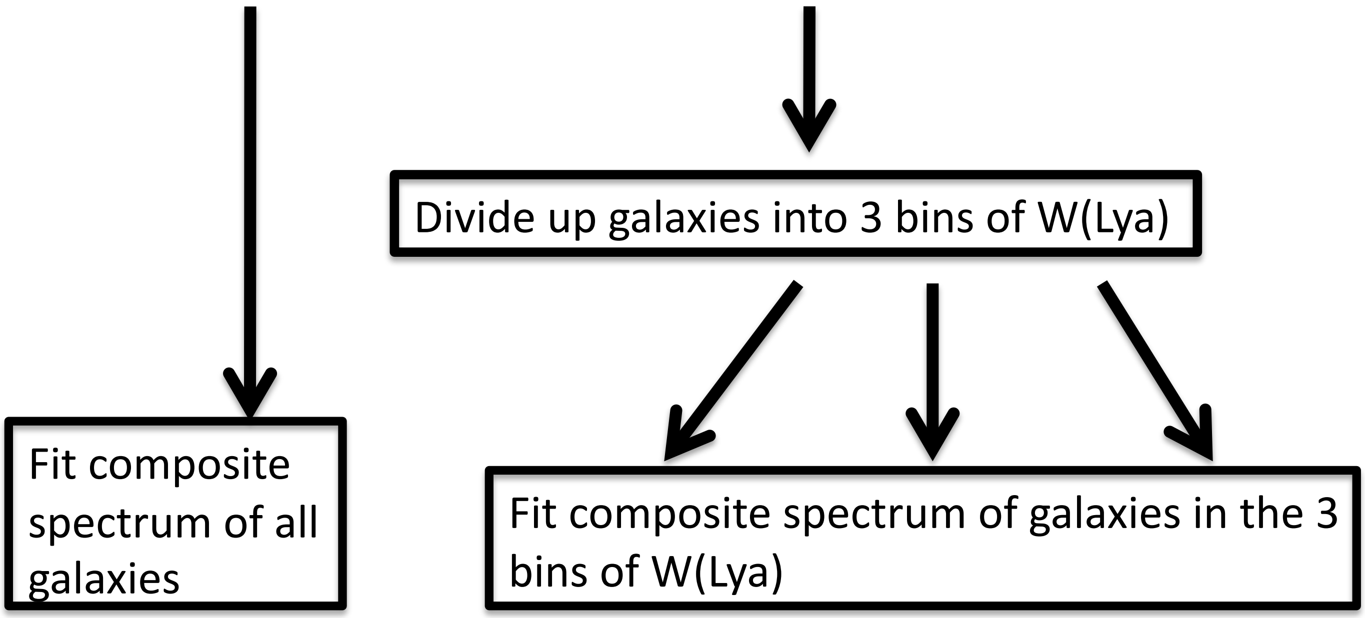
Response of ISM

Model Ionized ISM:
- Nebular Reddening, $E(B-V)_{neb}$
- Oxygen Abundance
- Ionization Parameter

Transmission

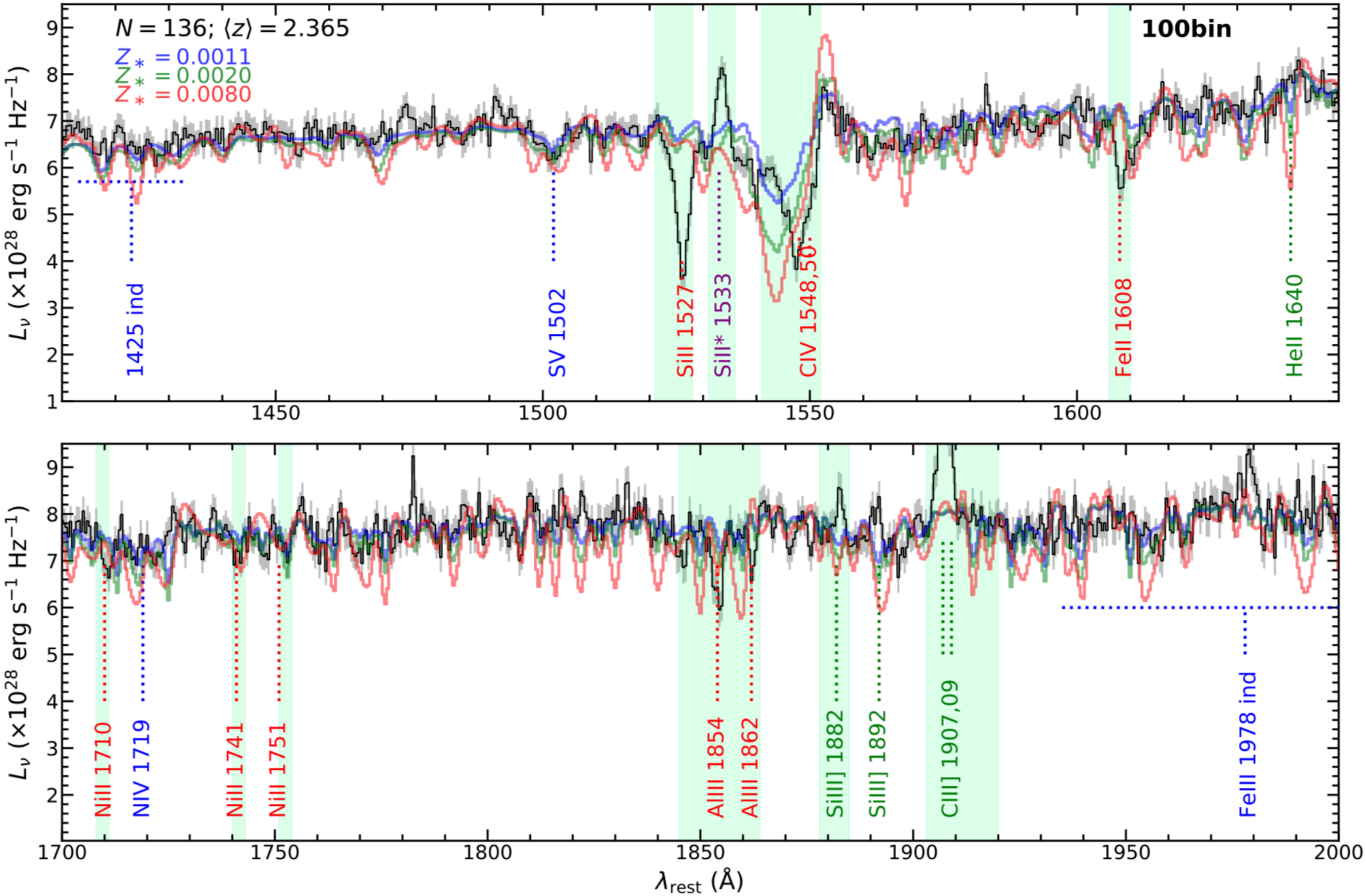
Model Neutral ISM:
- Line-of-sight Reddening, $E(B-V)_{los}$
- Column density
- Covering fraction

Spectral Modeling in bins of W(Lyα)



BPASS v2.2.1 models (Eldridge+17): includes the effects of stellar binarity; consider a range of ages and stellar metallicities

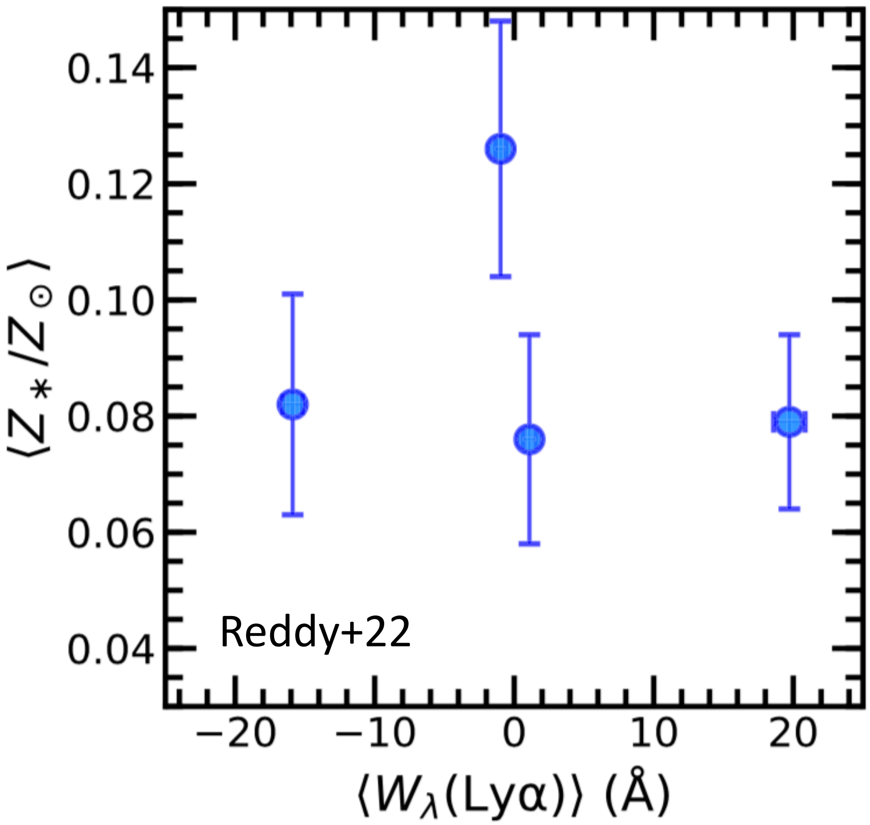
Properties of the Massive Stellar Populations

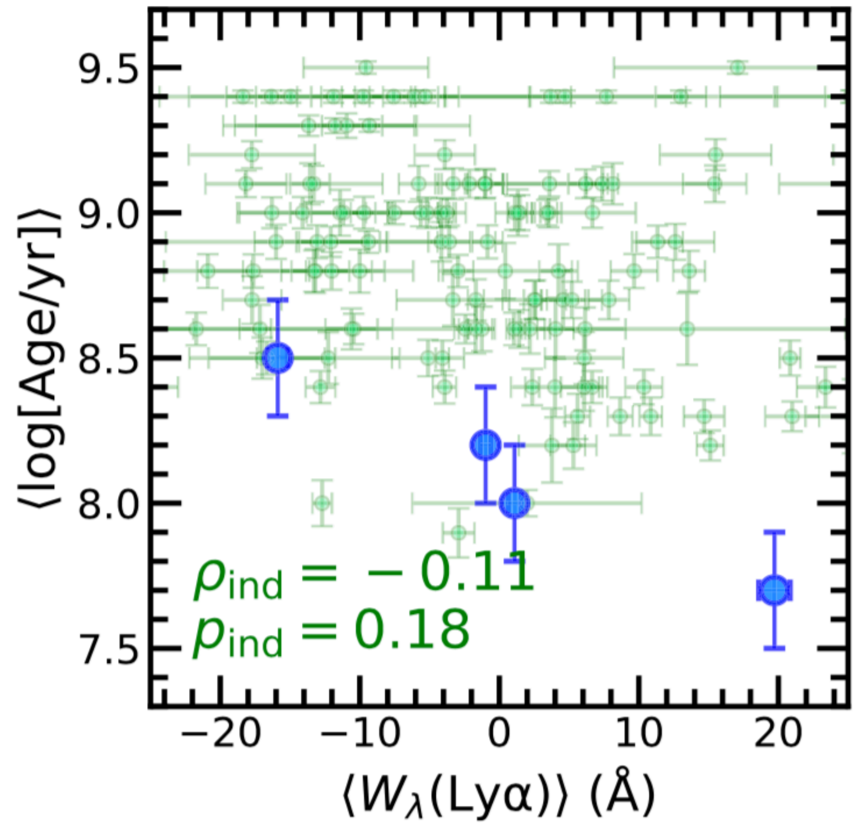


sub-solar metallicities favored (e.g., Steidel+16, Topping+20a)

Reddy+22

Properties of the Massive Stellar Populations



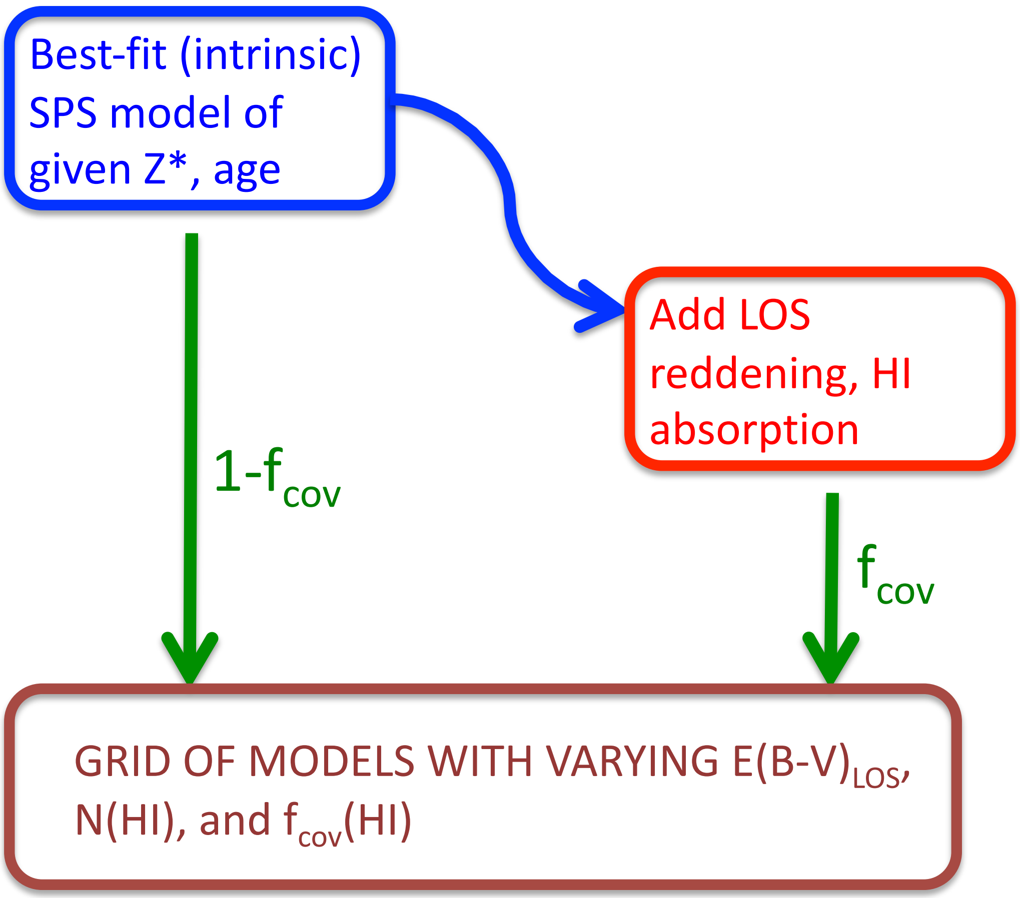


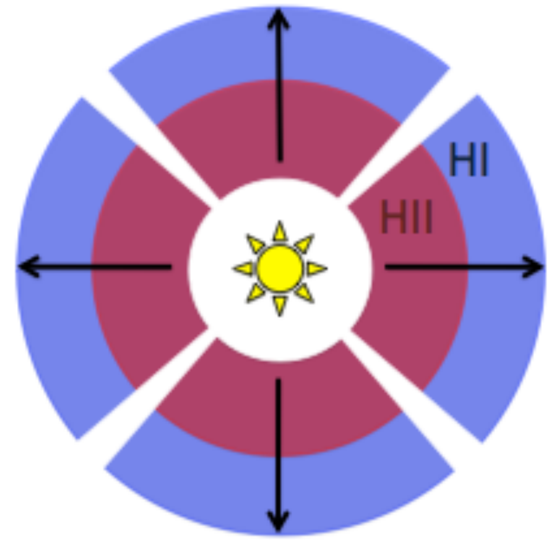
- No significant correlation between Z* and W(Lya)
- Only marginal anti-correlation
between age and W(Lya)

No significant change in hardness of ionizing spectrum

Variations in W within our sample are not driven by changes in stellar population

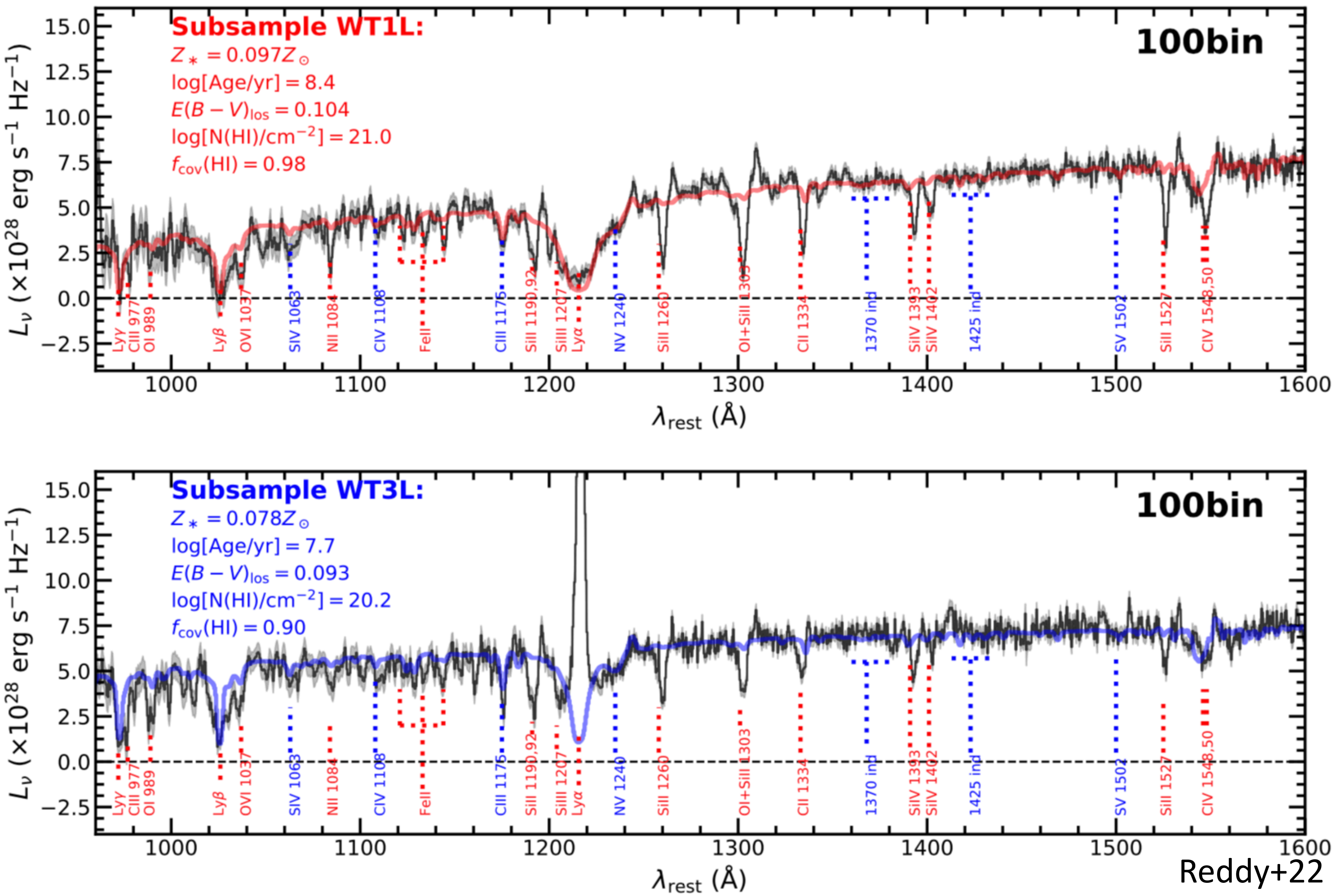
Properties of the Neutral ISM – Two-component modeling





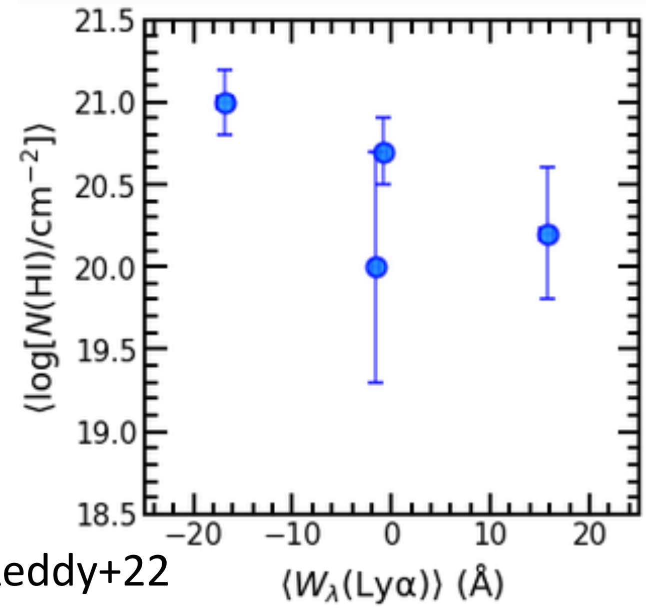
$$m_{\rm final} = f_{\rm cov}(\rm H\,I) \times m_{\rm H\,I} \times 10^{-0.4E(B-V)_{\rm los}k(\lambda)} + [1 - f_{\rm cov}(\rm H\,I)] \times m_0 .$$

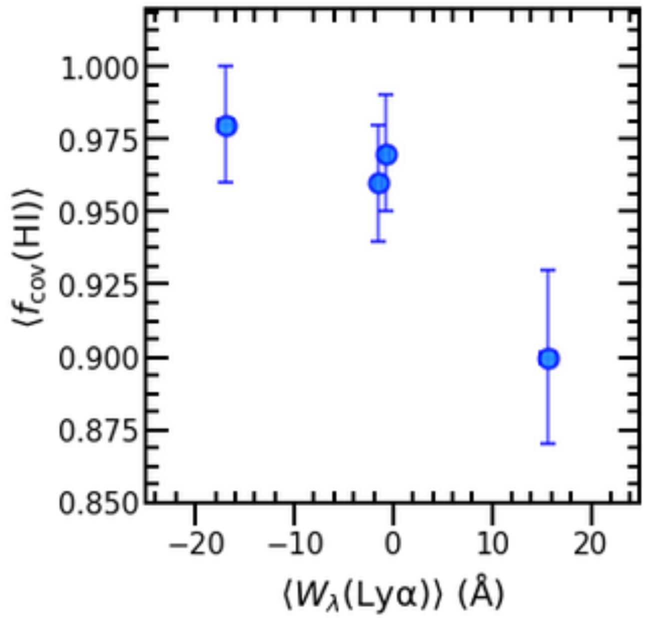
Properties of the Neutral ISM – Two-component modeling



Reddy+22

Properties of the Neutral ISM – Two-component modeling

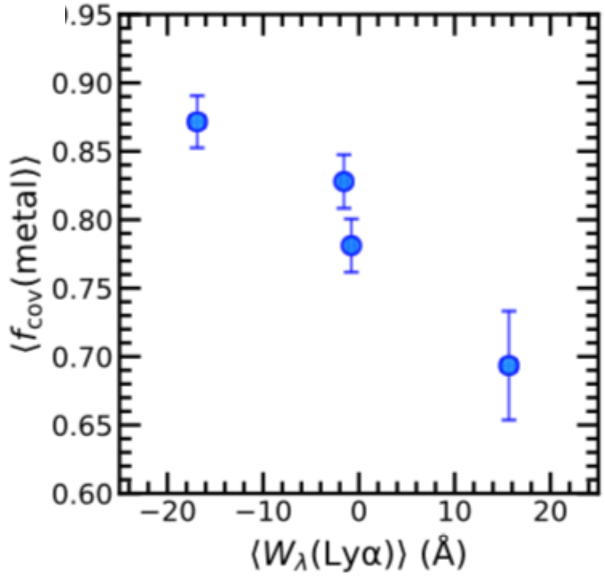




Reddy+22

N(HI) optically thick to LyC (and Lya) radiation

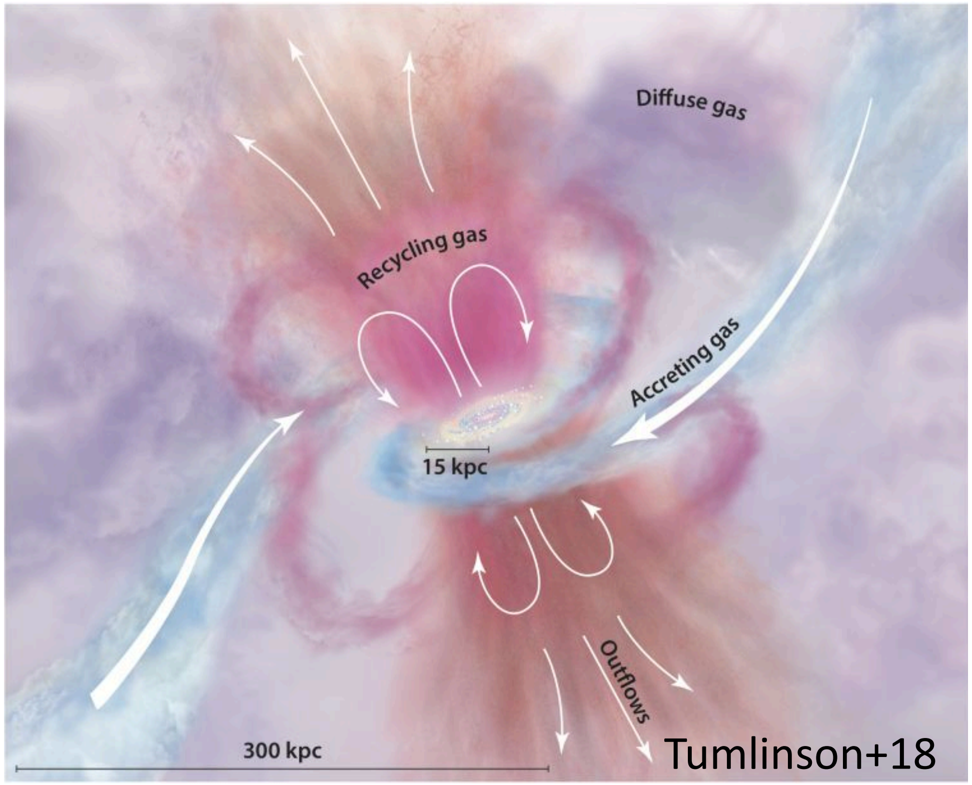
fcov anti-correlates with Lya



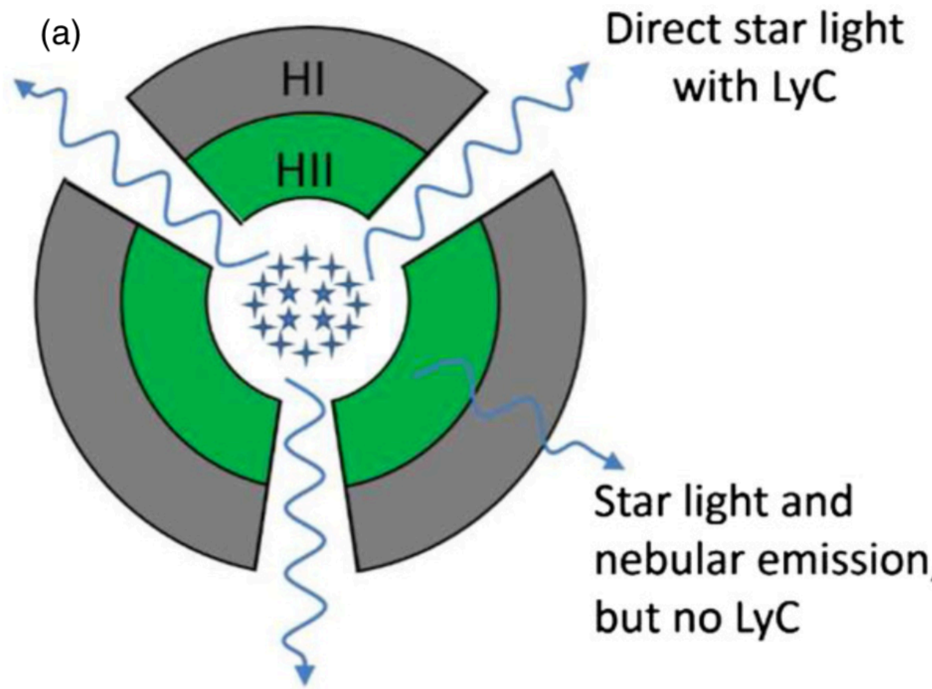
Strong anti-correlation between fcov(metal) and W(Lya)

What Influences Covering Fraction?

OUTFLOWS → POROUS ISM



Tumlinson+18



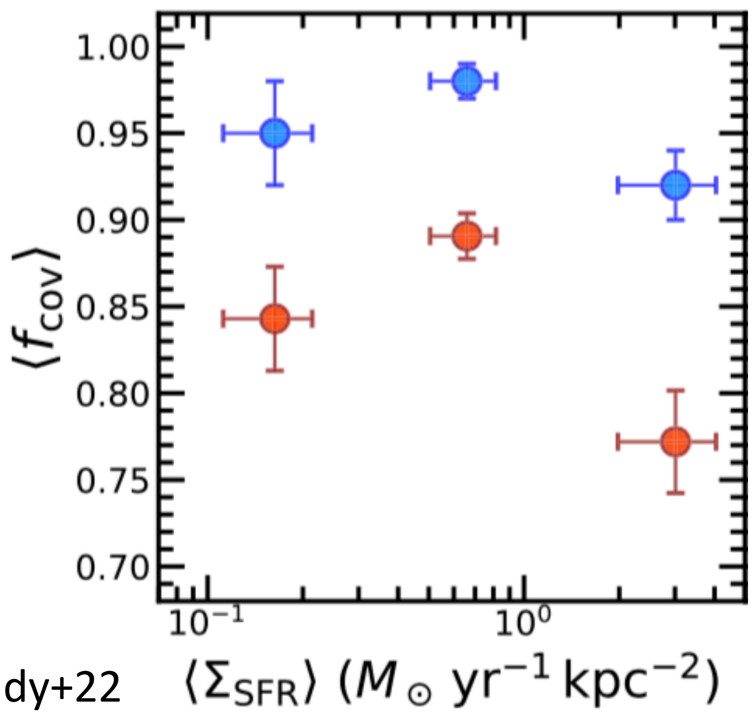
Ionization-bounded nebula with holes

Zackrisson+13

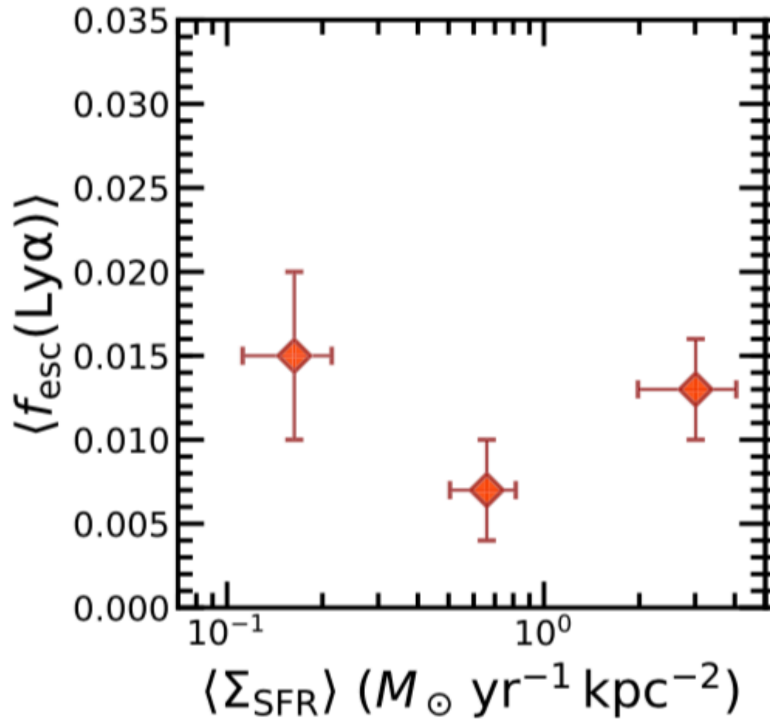
IS THERE A RELATIONSHIP BETWEEN Ly-alpha ESCAPE AND STAR-FORMATION-RATE SURFACE DENSITY?

$$\Sigma_{\rm SFR} = \frac{\rm SFR}{2\pi R^2}$$

Ly-alpha Escape vs. Star-formation-rate surface density



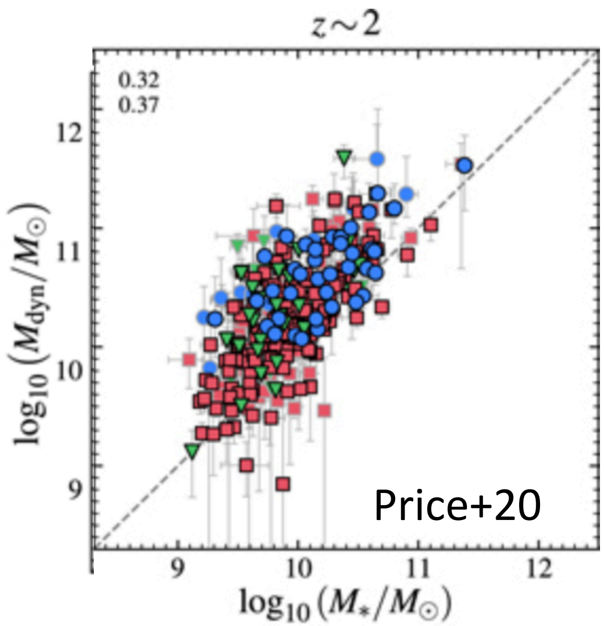
Reddy+22

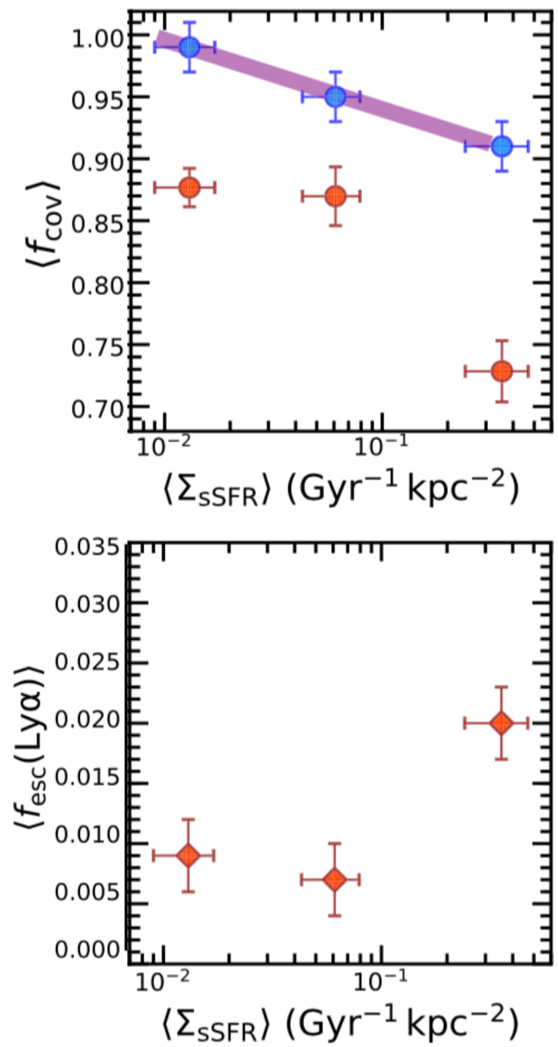


NO STRONG CORRELATION WITH SIGMA_SFR (at least over the dynamic range probed by our sample)

DOES ESCAPE FRACTION DEPEND ON SOMETHING ELSE AS WELL?

Escape Fraction and Gravitational Potential





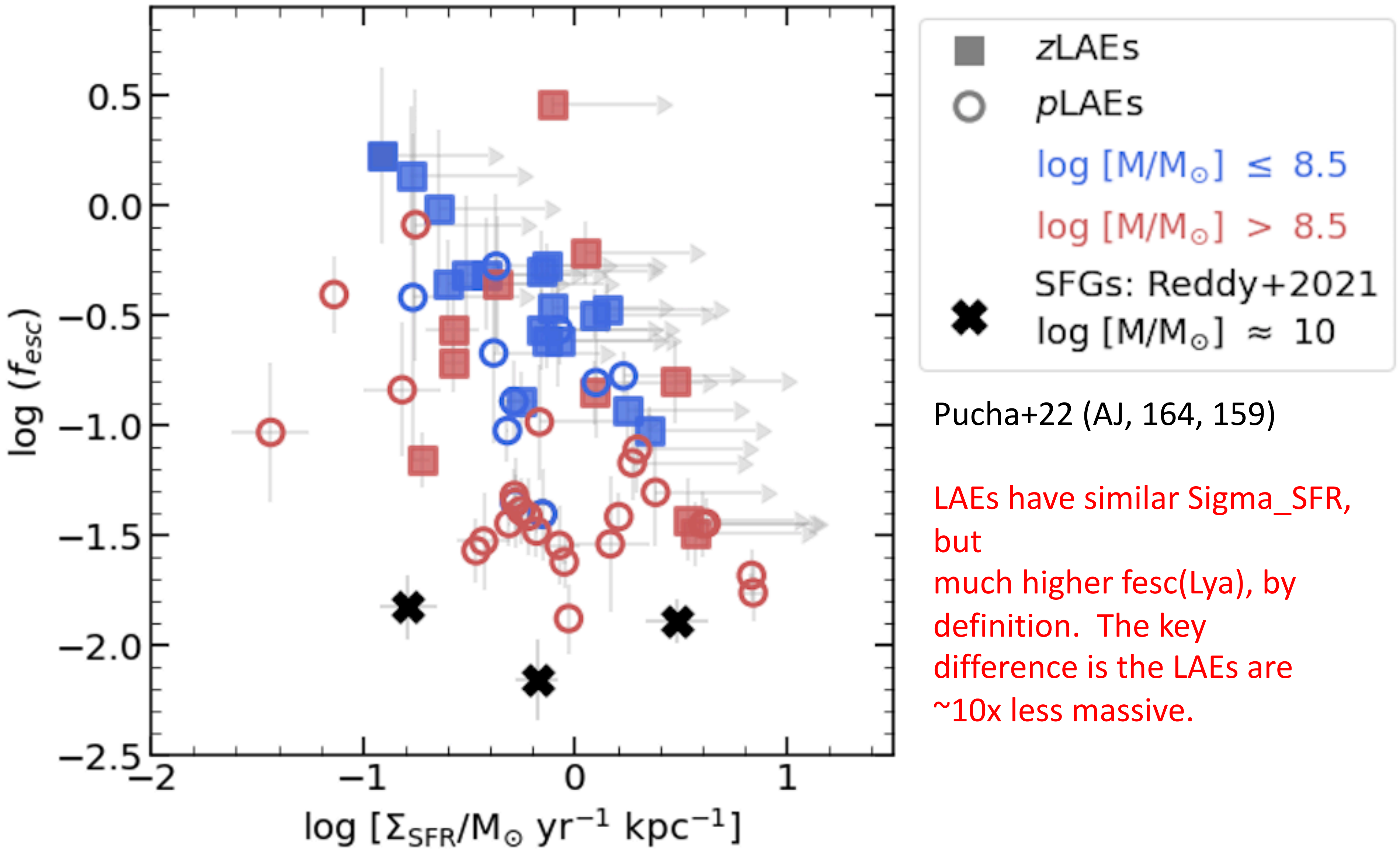
Stellar masses strongly correlate with dynamical masses

$$\Sigma_{\rm sSFR} = \frac{\Sigma_{\rm SFR}}{M_*}$$

RESULTS SUGGEST GRAVITATIONAL POTENTIAL MAY BE IMPORTANT FOR Lya ESCAPE

Reddy+22

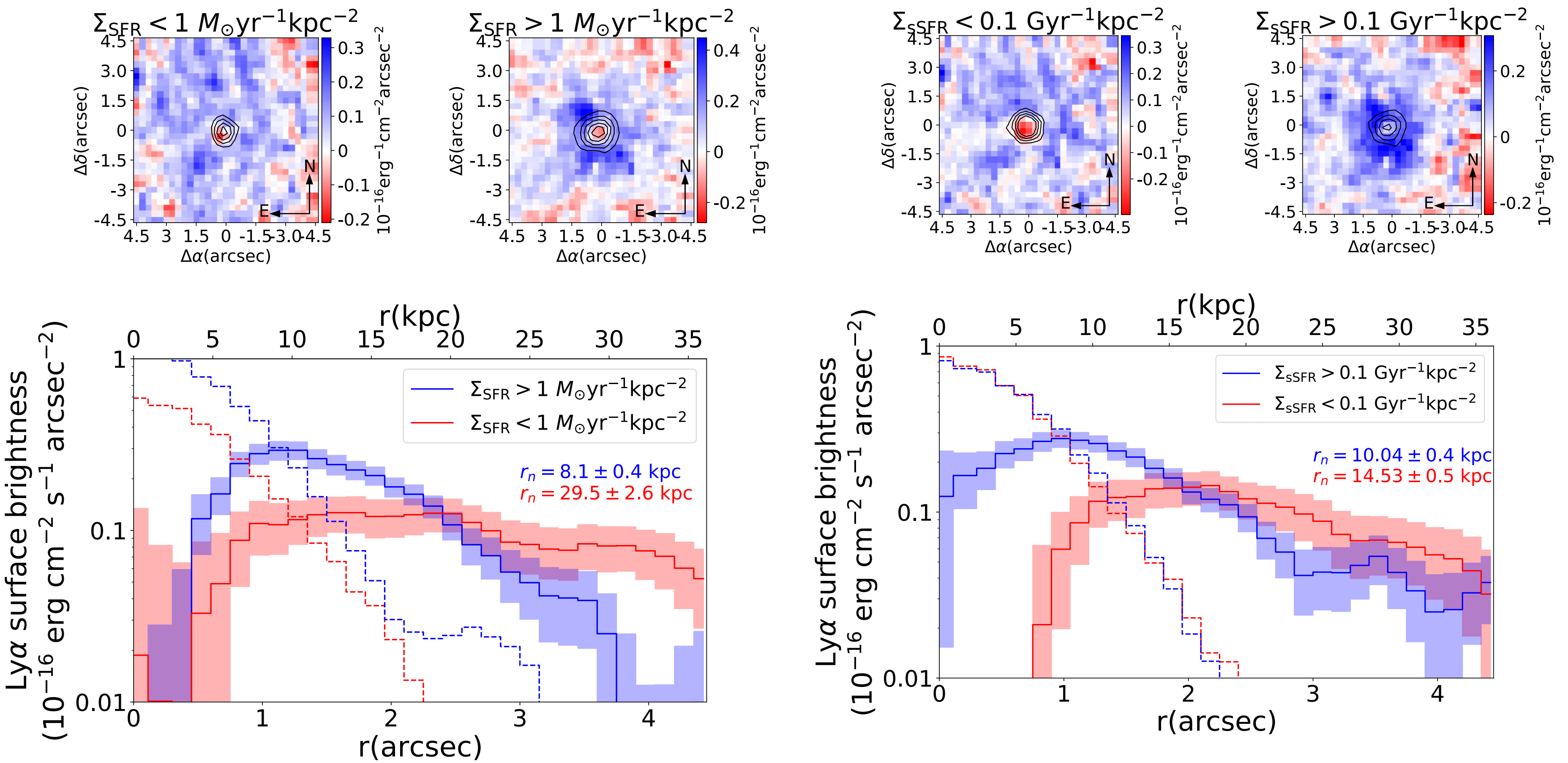
Importance of Gravitational Potential – Comparison with LAEs at similar redshifts



Pucha+22 (AJ, 164, 159)

LAEs have similar Sigma_SFR, but
much higher fesc(Lya), by definition. The key difference is the LAEs are ~10x less massive.

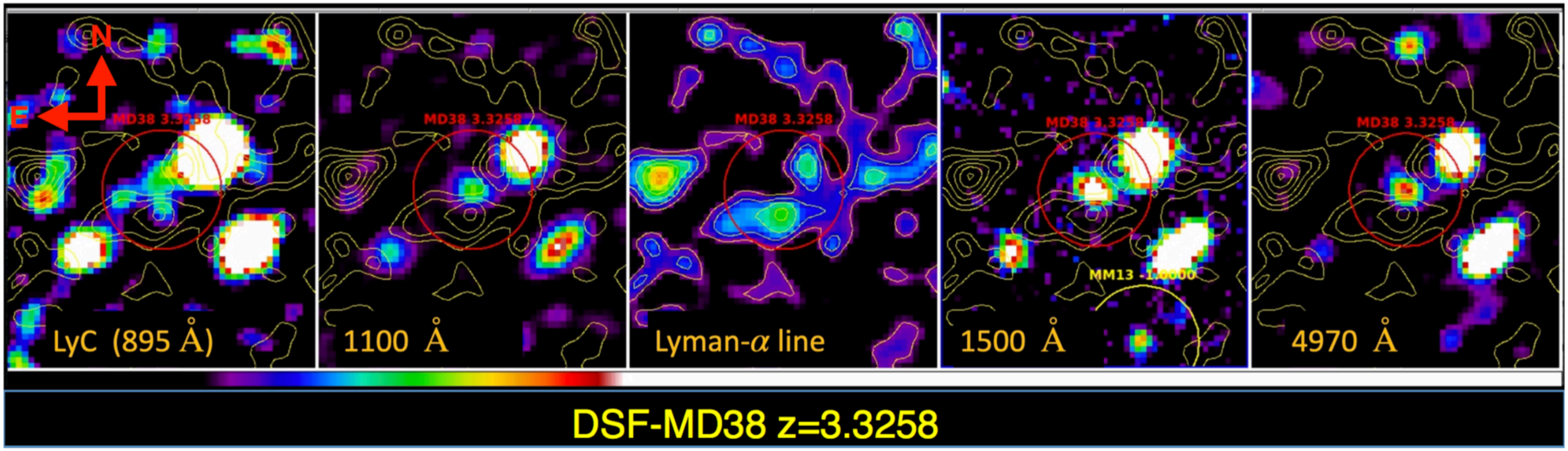
Importance of Gravitational Potential – Keck/KCWI Observations



Song+24 (ApJ, 969, 103)

Down-the-barrel Lya fraction much larger in galaxies with high Sigma_sSFR

Keck/KCWI Observations – Morphology of Lya and LyC Escape



Varying column density distribution towards continuum

Main "Takeaways" from Part 2…

• Even typical z~2 galaxies are "metal-poor" (~10% solar stellar metallicities); difficult to produce even more ionizing photons per unit SFR by going to metal-poorer or younger stellar populations

• Gas covering fraction is the primary factor in modulating W(Lya) within our sample

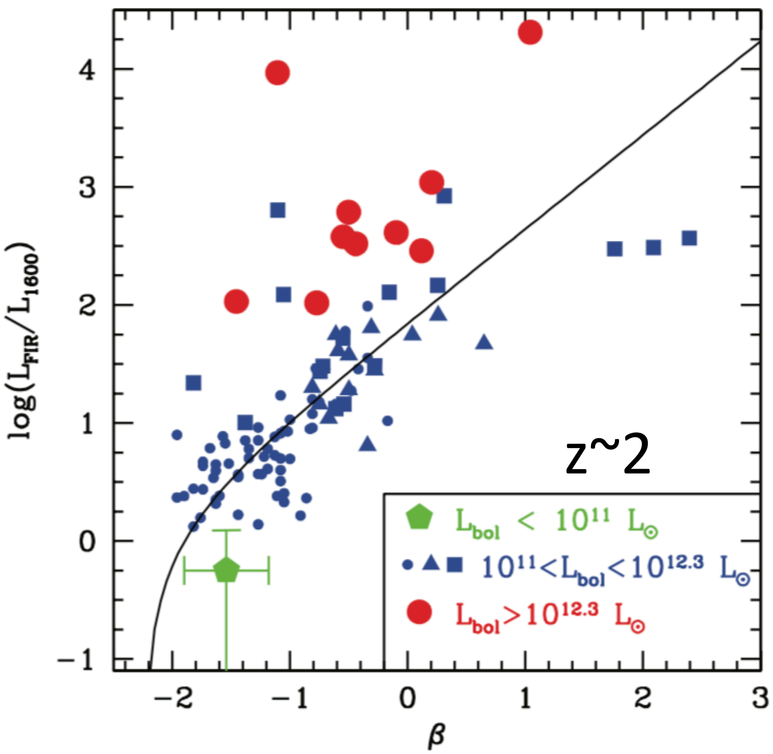
• Covering fraction appears to depend on more than just compactness of star formation. Gravitational potential may be an important factor.

Thank you!

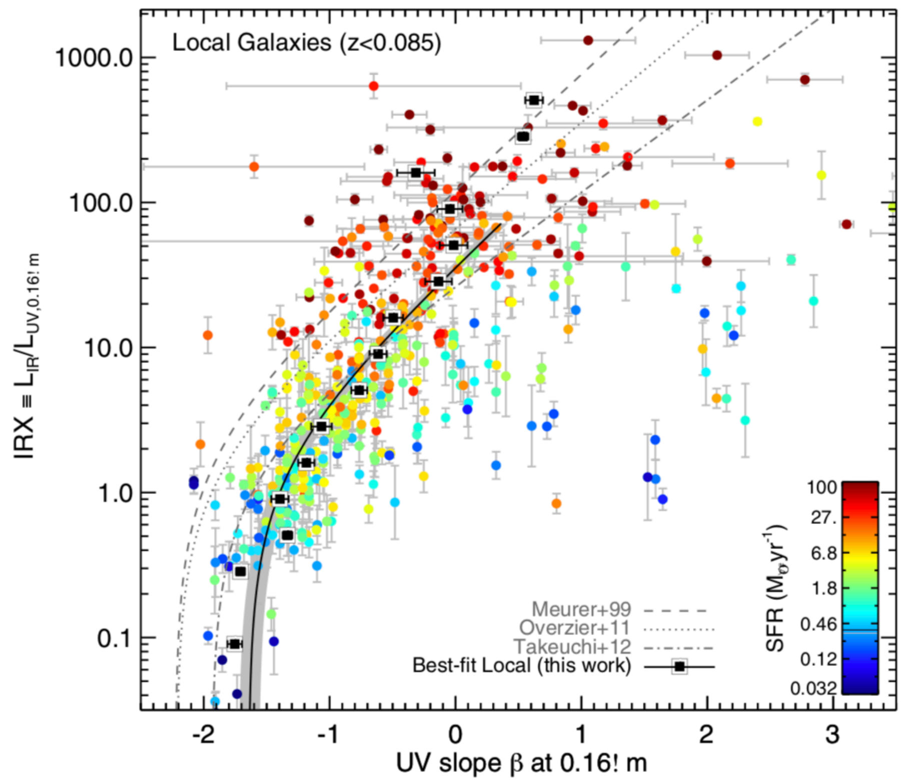
Backup Slides

Variations in the curve - Luminosity

- Luminosity (or total SFR)



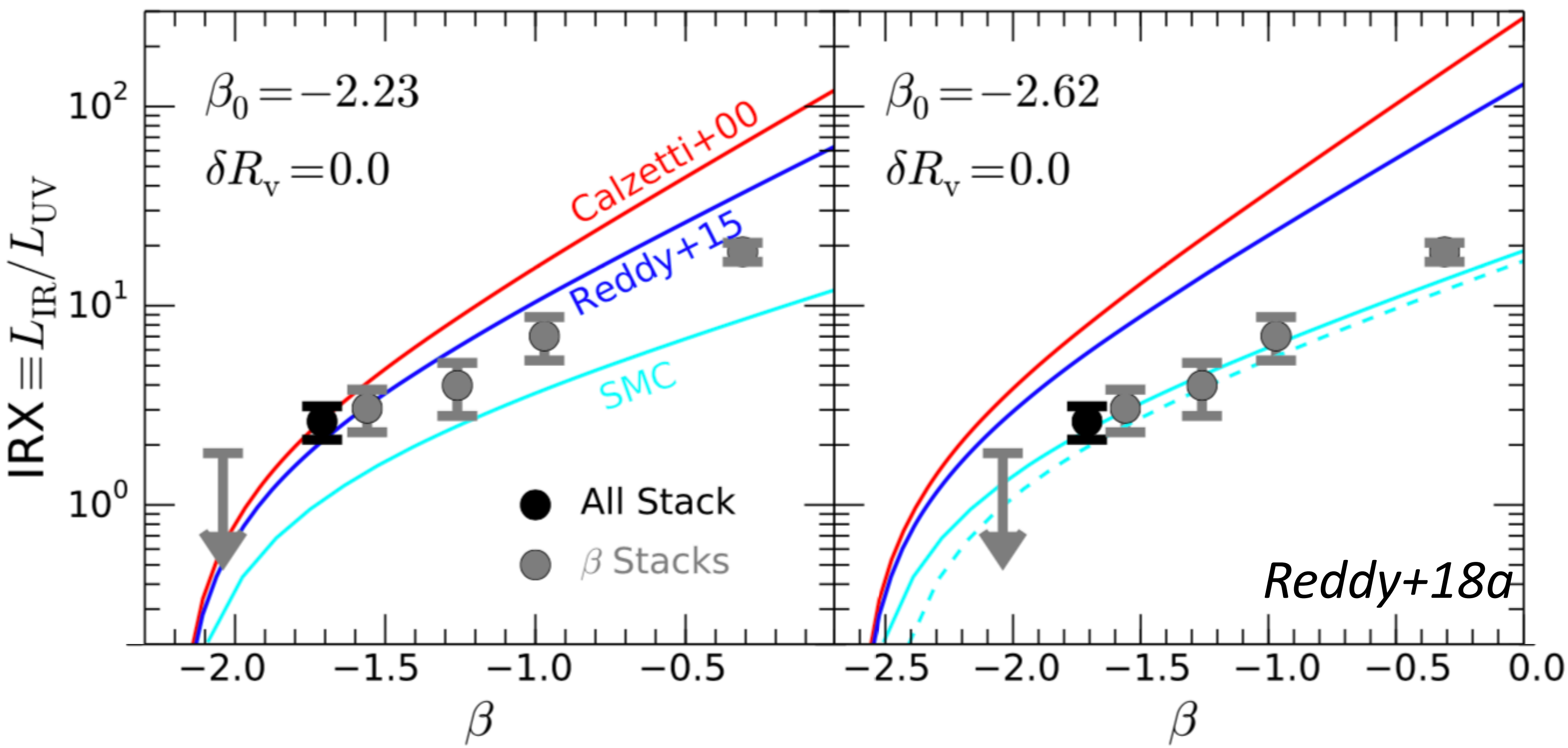
Reddy+06



Casey+14

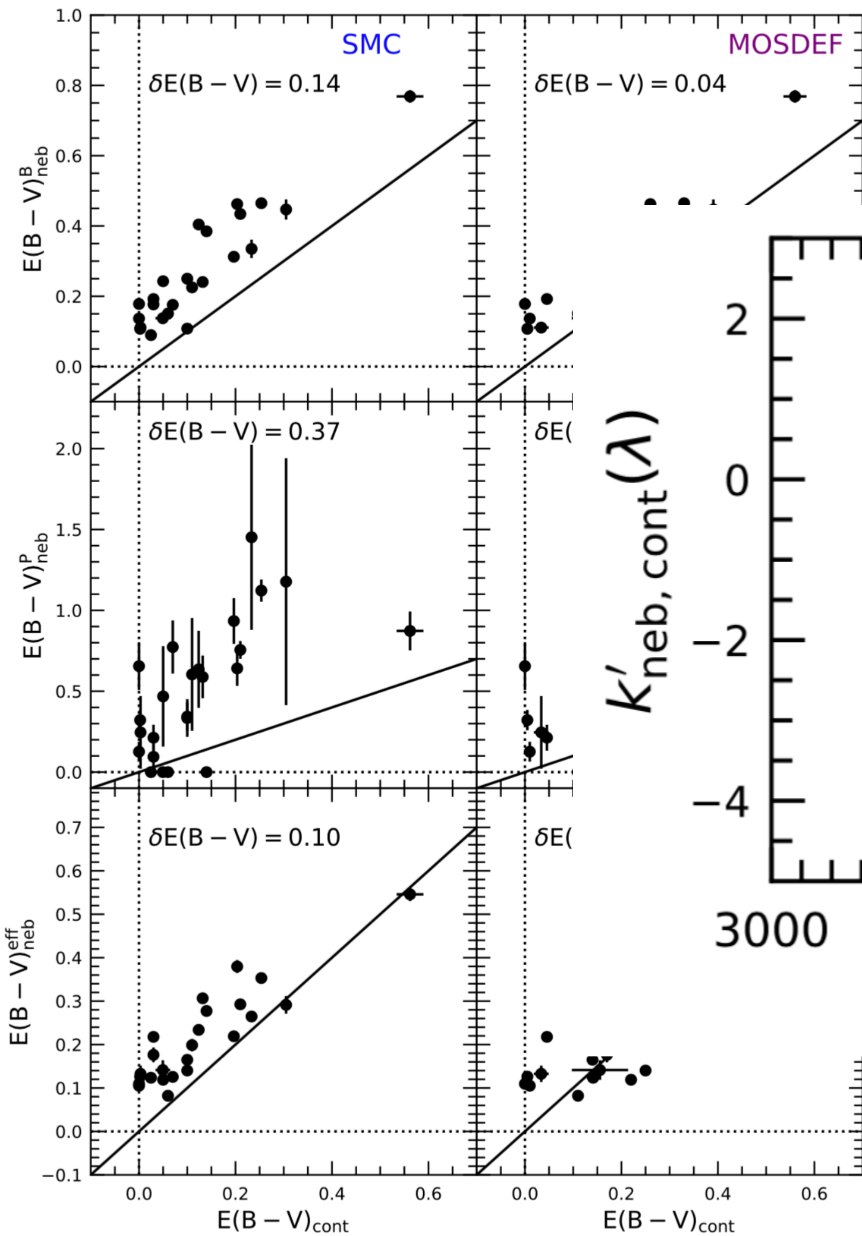
Variations in the curve - metallicity

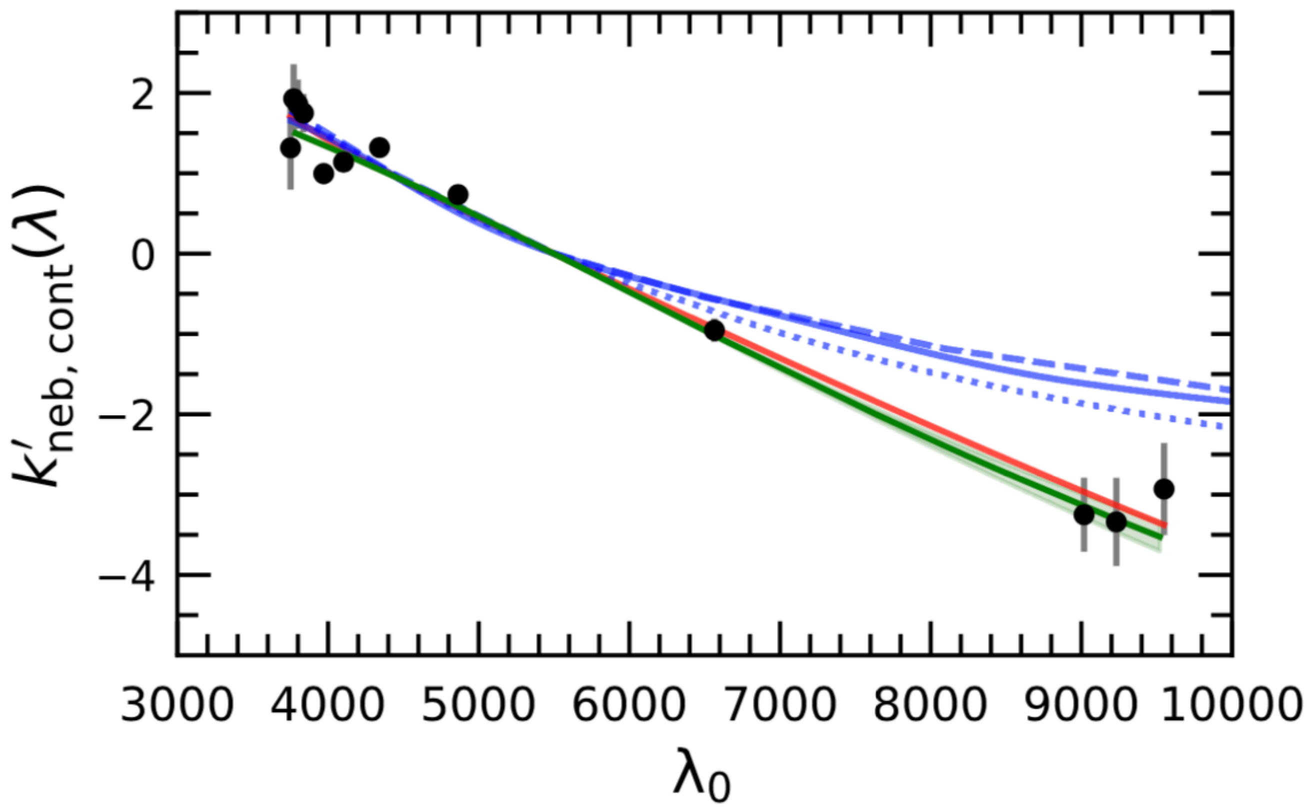
- (Stellar) Metallicity (also related to SFH, sSFR, mass, etc.)



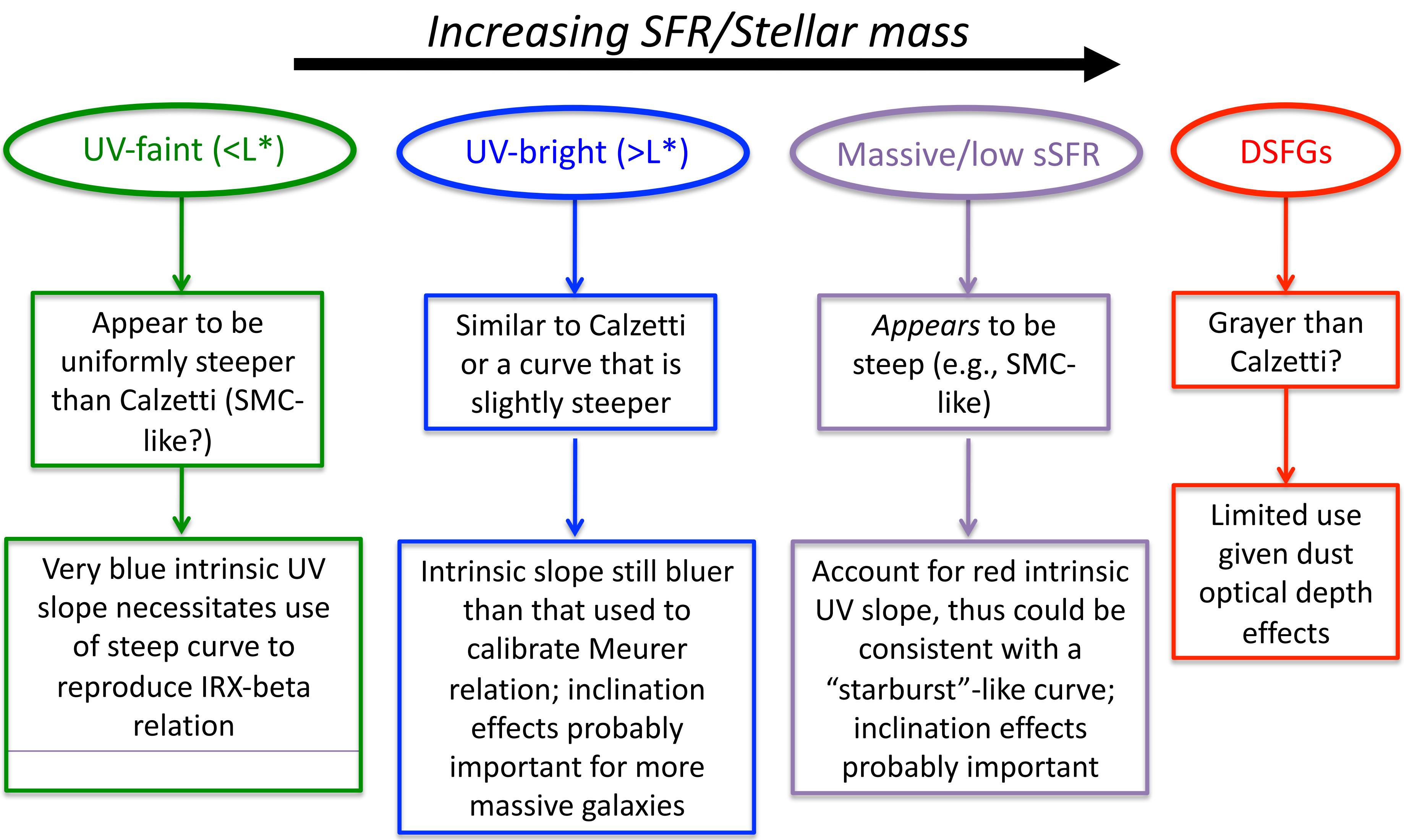
SMC applies best for high-z sub-solar metallicity stellar populations with blue intrinsic UV slopes

Differential Reddening between Lines and Continuum



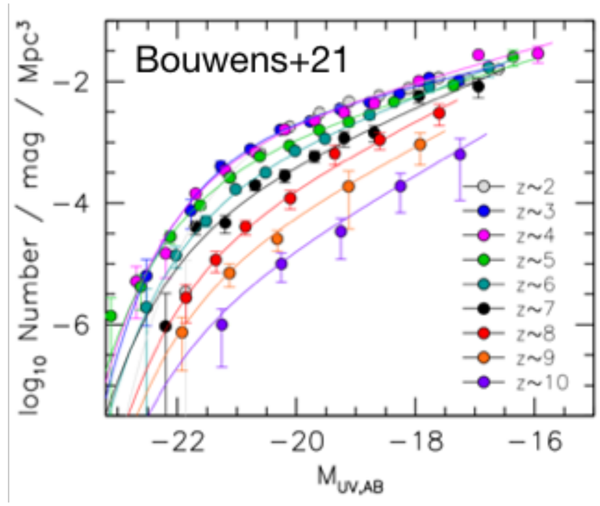


A “Roadmap” for the Stellar Attenuation Curve at High Redshift

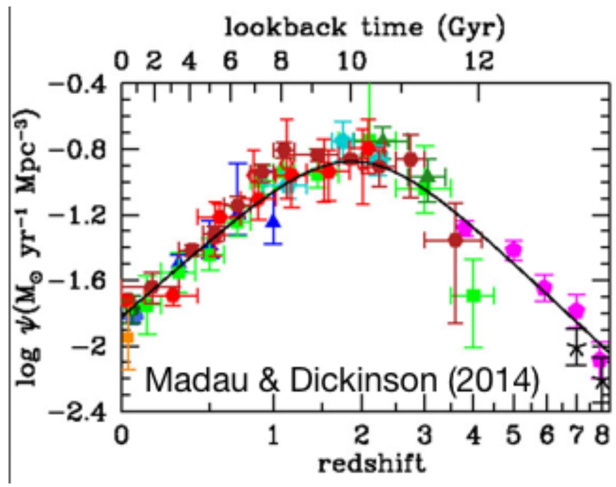


Are star-forming galaxies responsible for reionization?

•Is there a sufficient number of galaxies? **YES**

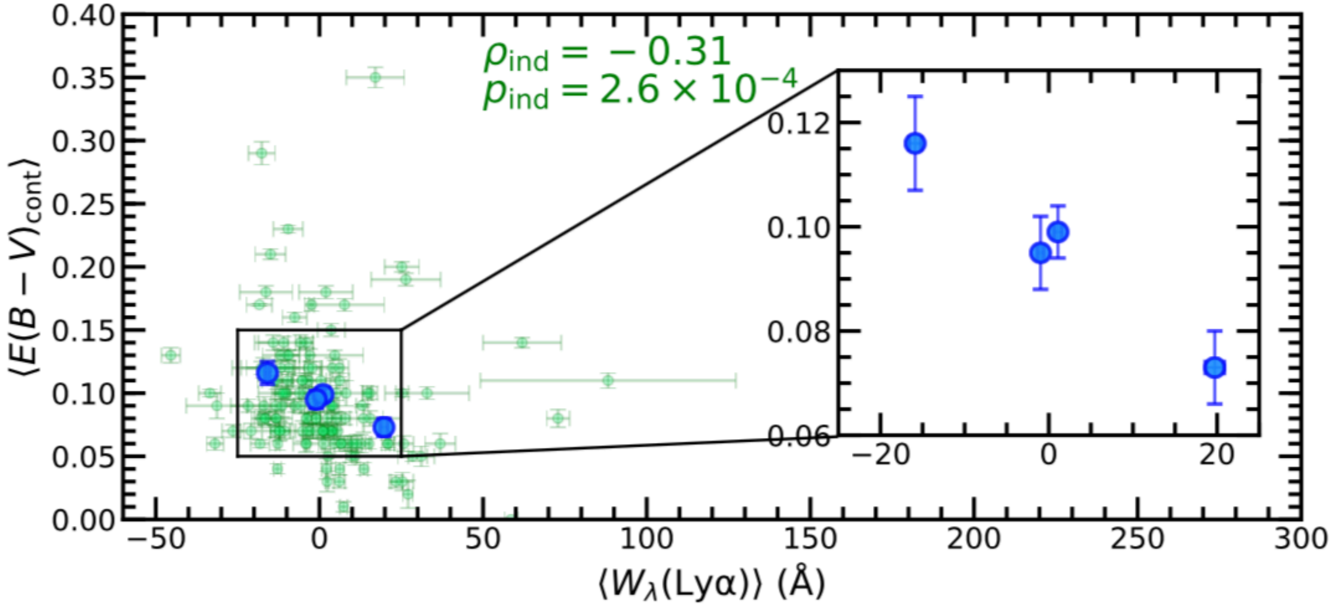


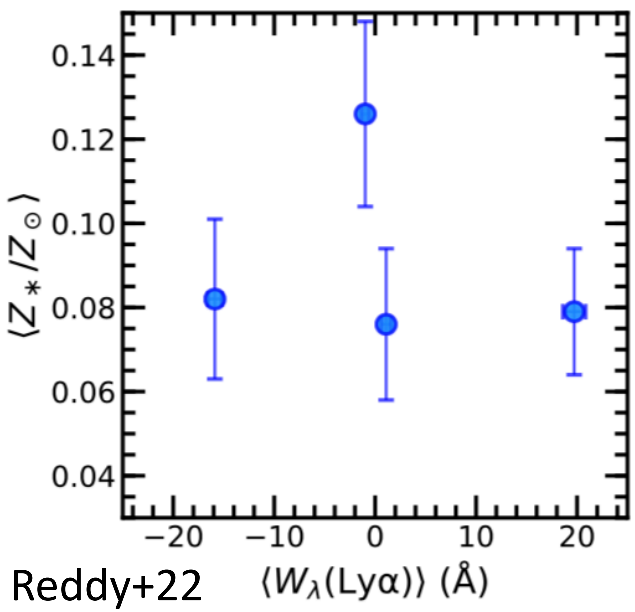
•Are enough ionizing photons produced? **YES**

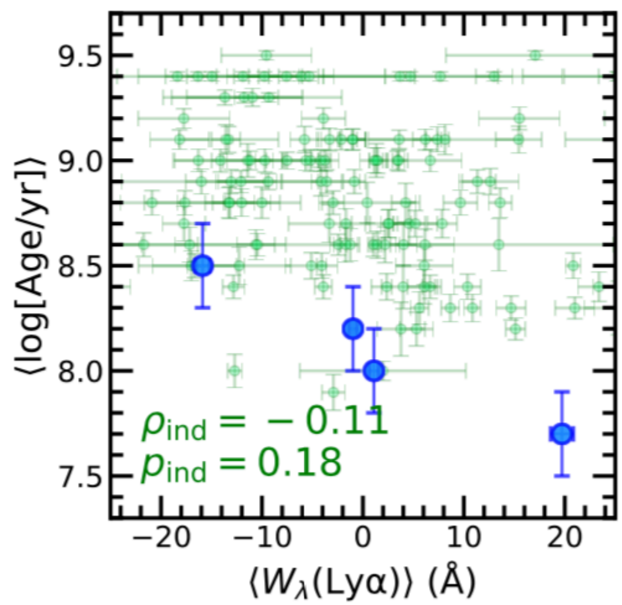


•Does a sufficient fraction of those photons escape? **MAYBE…**

Properties of the Massive Stellar Populations





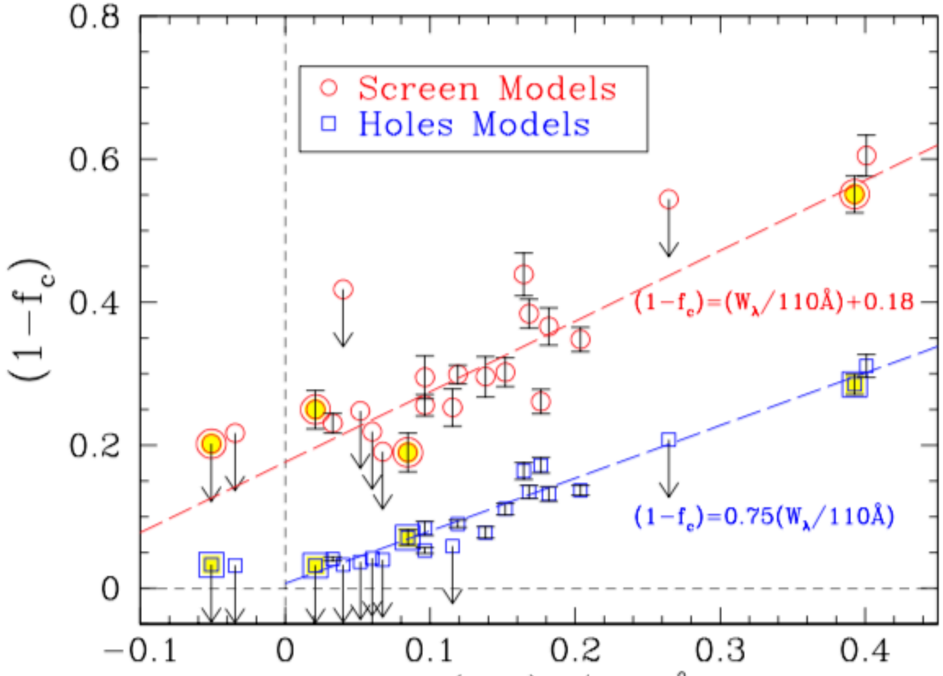


Reddy+22

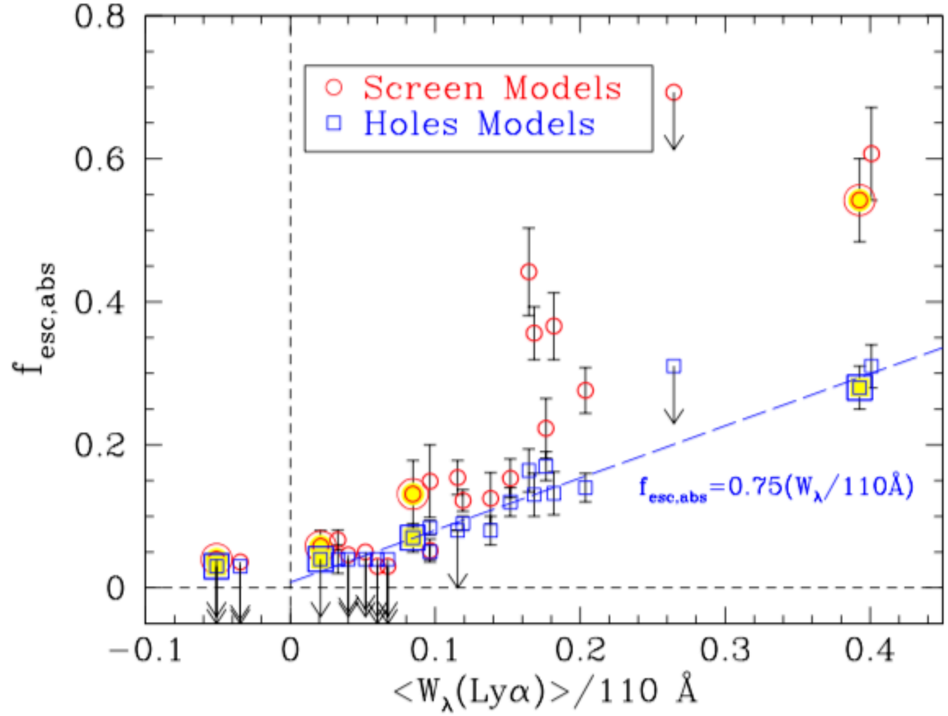
- No significant correlation between Z* and W
- Only marginal anti-correlation between age and W
- Significant anti-correlation between continuum reddening and W

Variations in W within our sample are not driven by changes in stellar population

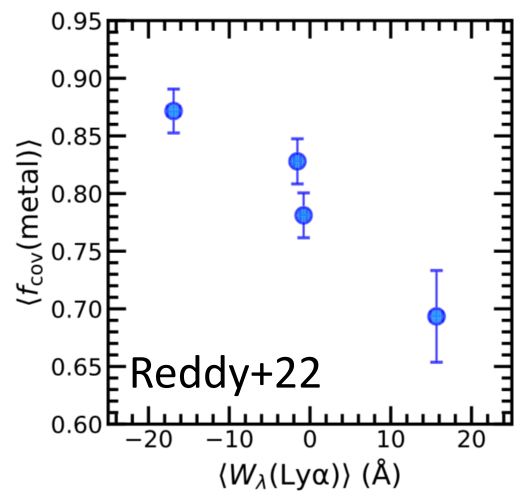
Does Covering Fraction Play a Role in Lya Escape? YES



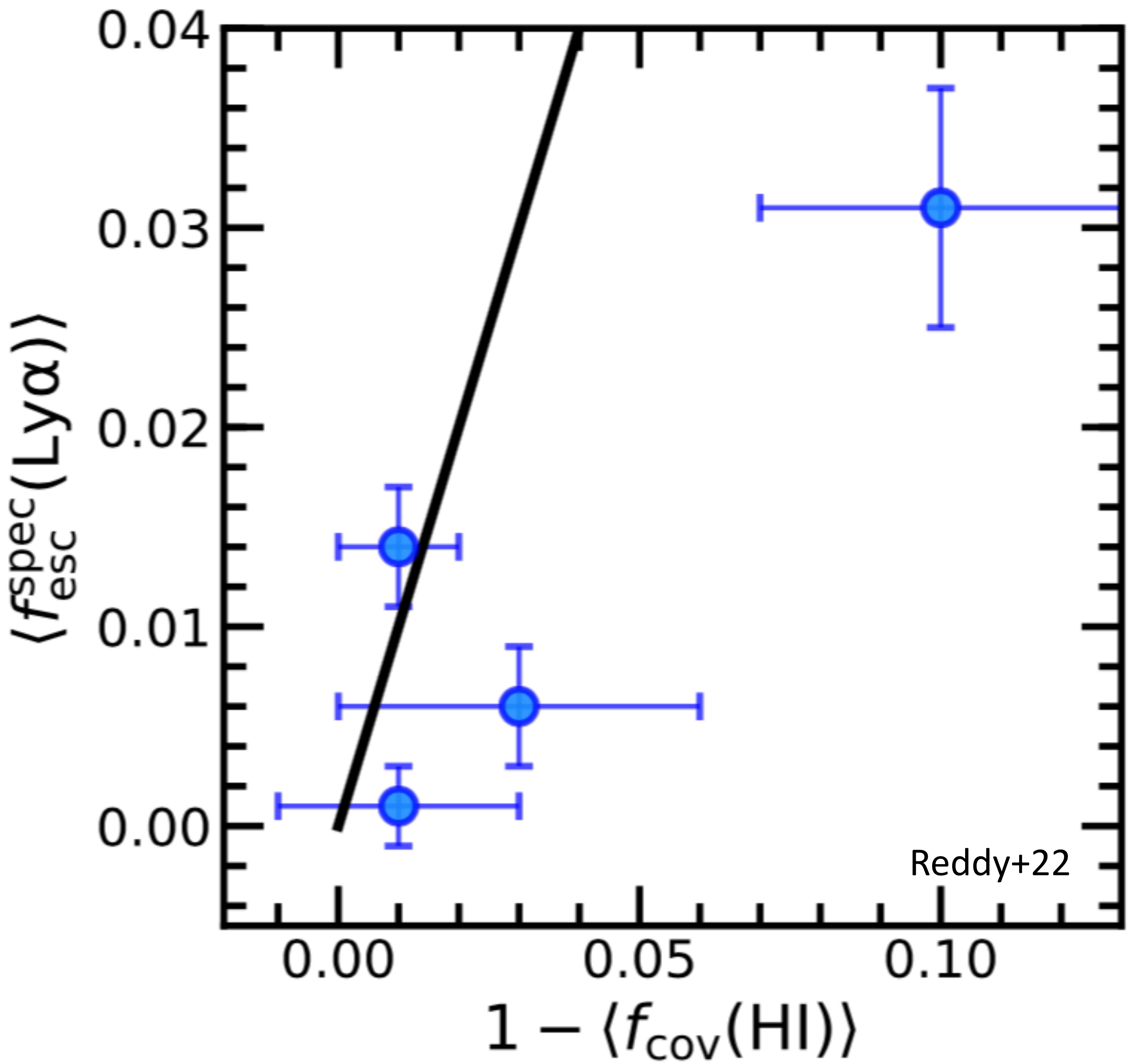
Steidel+18

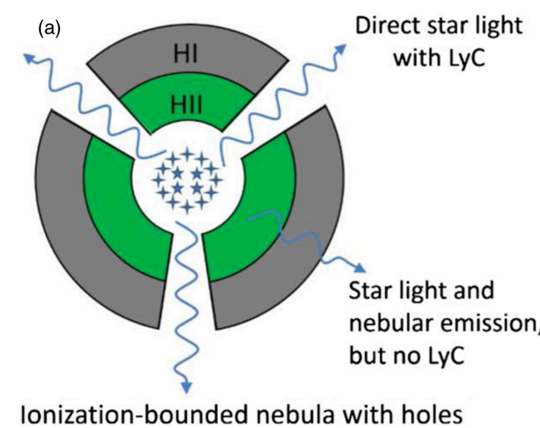


Fundamental Connection between ionizing escape fraction and HI gas covering fraction, W(Lya)



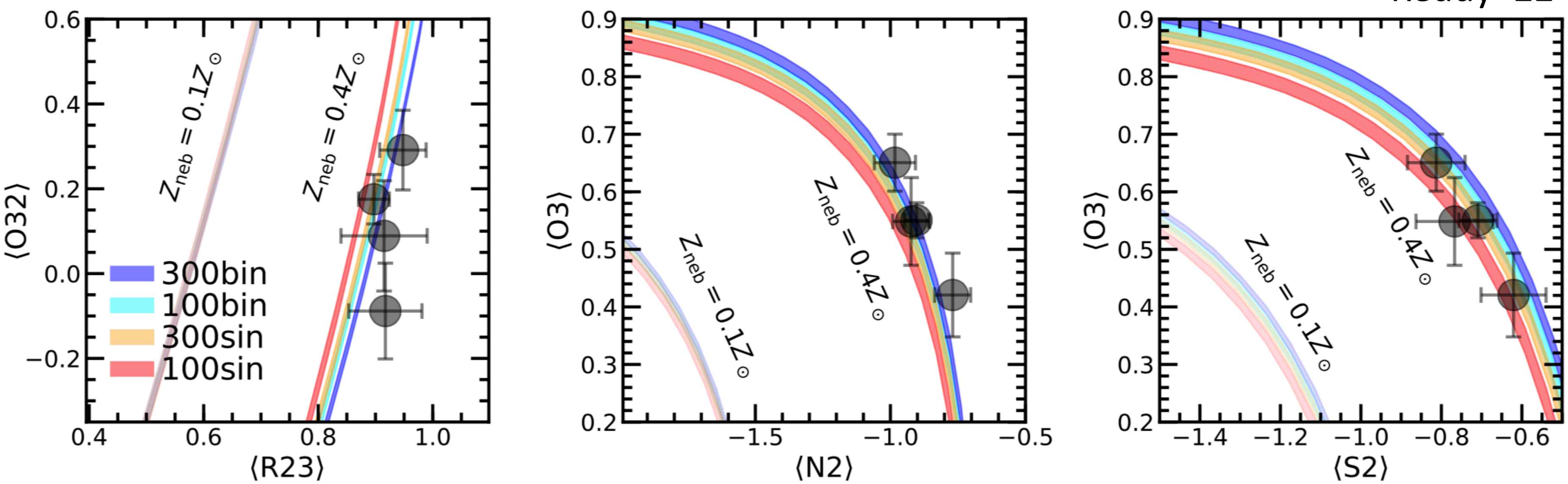
Does Covering Fraction Play a Role in Lya Escape? YES





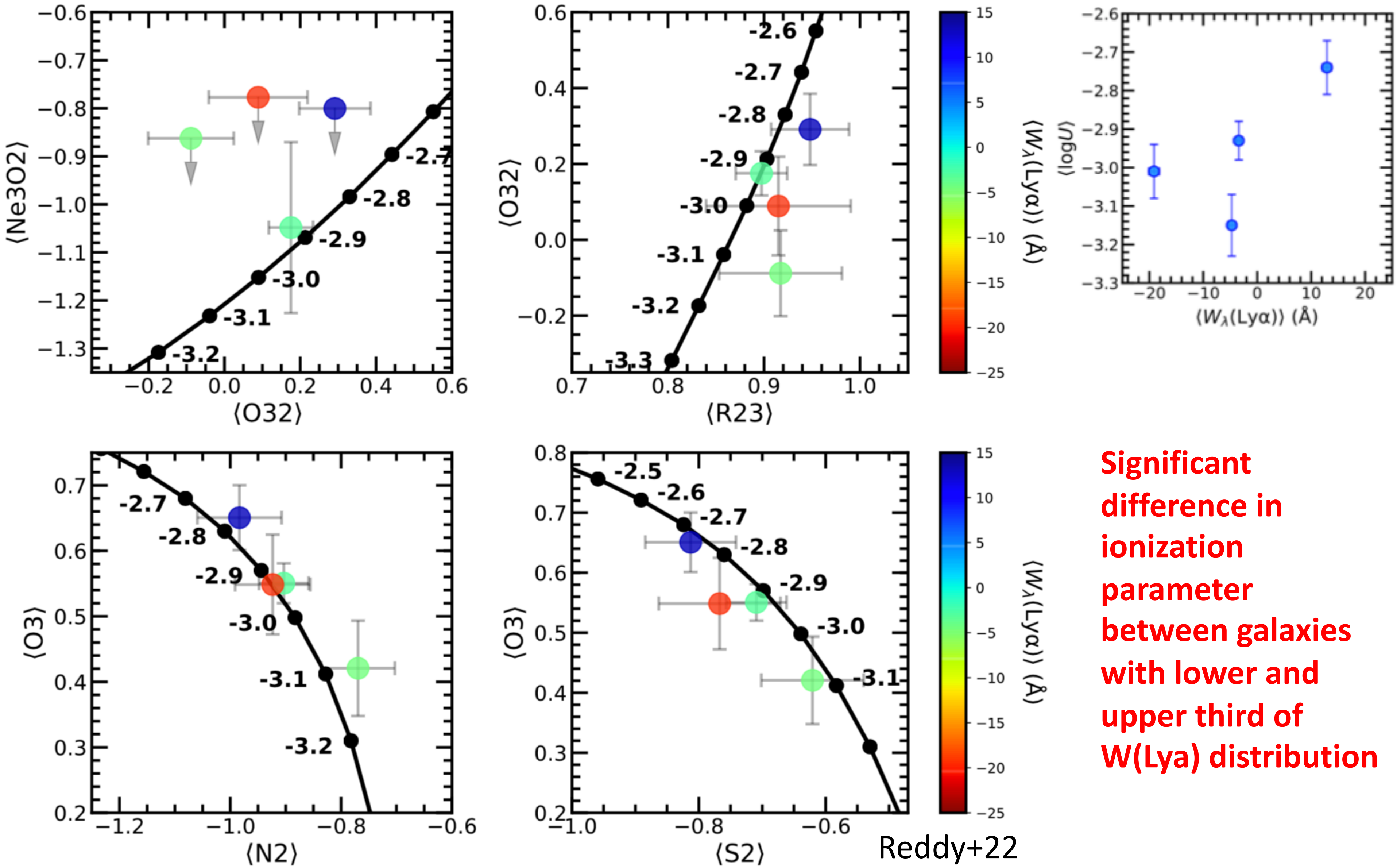
Properties of the Ionized ISM - CLOUDY Photoionization Modeling

Reddy+22



No significant difference in nebular metallicity (oxygen abundance) between galaxies with lower and upper third of W(Lya) distribution

Properties of the Ionized ISM - CLOUDY Photoionization Modeling

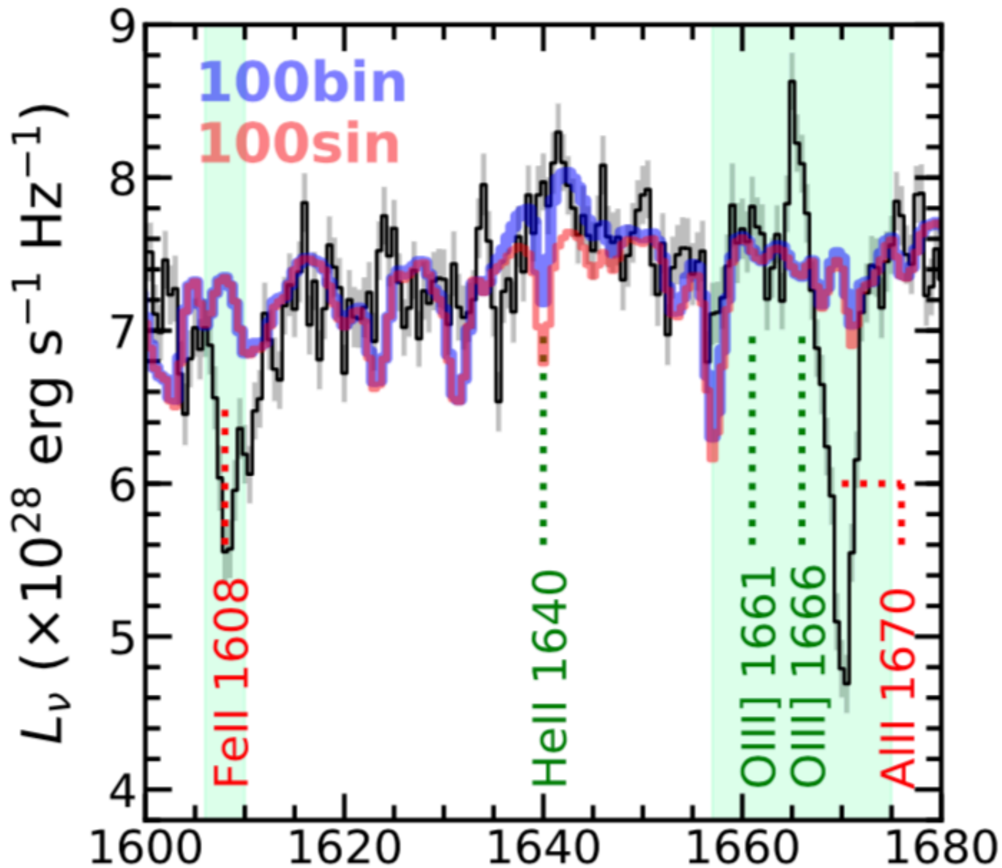


Significant difference in ionization parameter between galaxies with lower and upper third of W(Lya) distribution

Reddy+22

Constraints on Stellar Binarity

Single Stars	Binary Stars
↓	↓
Very little stellar He II	High stellar He II
↓	↓
High residual nebular He II	Low residual nebular He II
↓	↓
Inconsistent with predictions of CLOUDY modeling	**Consistent** with predictions of CLOUDY modeling



Reddy+22

Only binary models are able to self-consistently model the stellar and nebular HeII 1640 emission, independent of W(Lya)

Constraints on Stellar Binarity

Single Stars

↓

Very little stellar He II

↓

High residual nebular He II

↓

Inconsistent with predictions of CLOUDY modeling

Binary Stars

↓

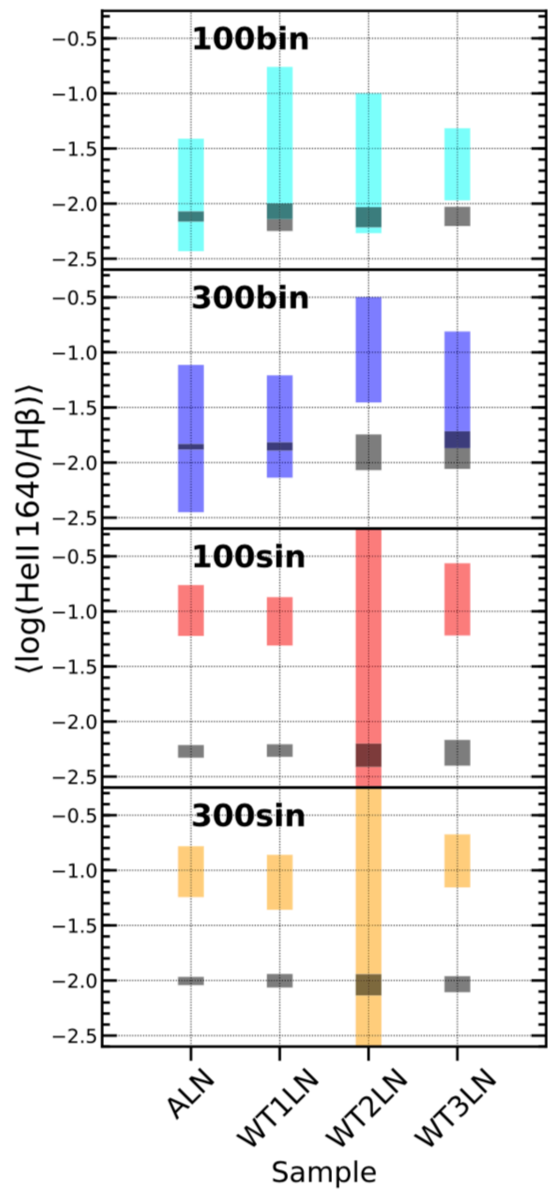
High stellar He II

↓

Low residual nebular He II

↓

Consistent with predictions of CLOUDY modeling



Only binary models are able to self-consistently model the stellar and nebular HeII 1640 emission, independent of W(Lya)