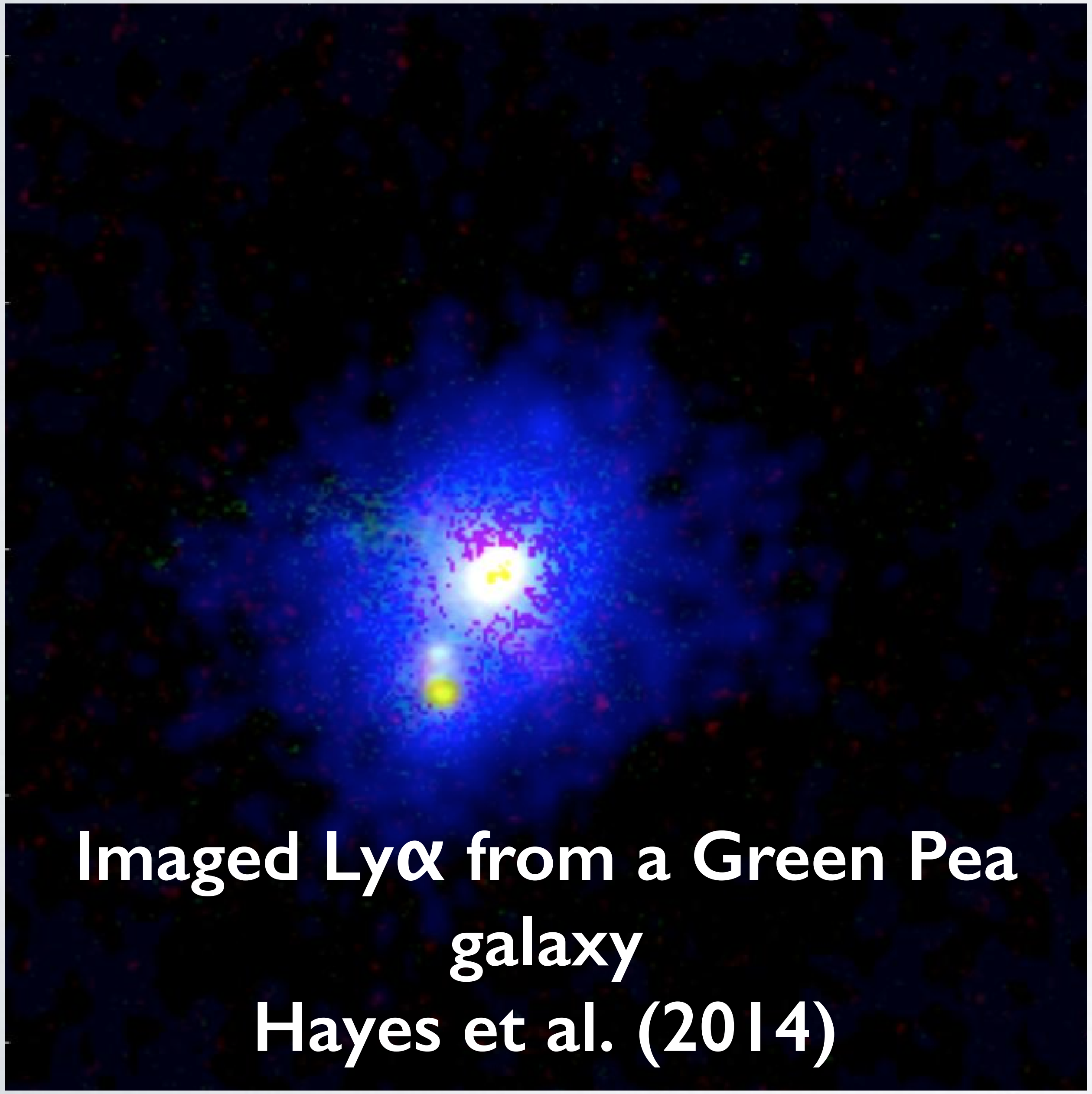
Local Laboratories for high-redshift astrophysics

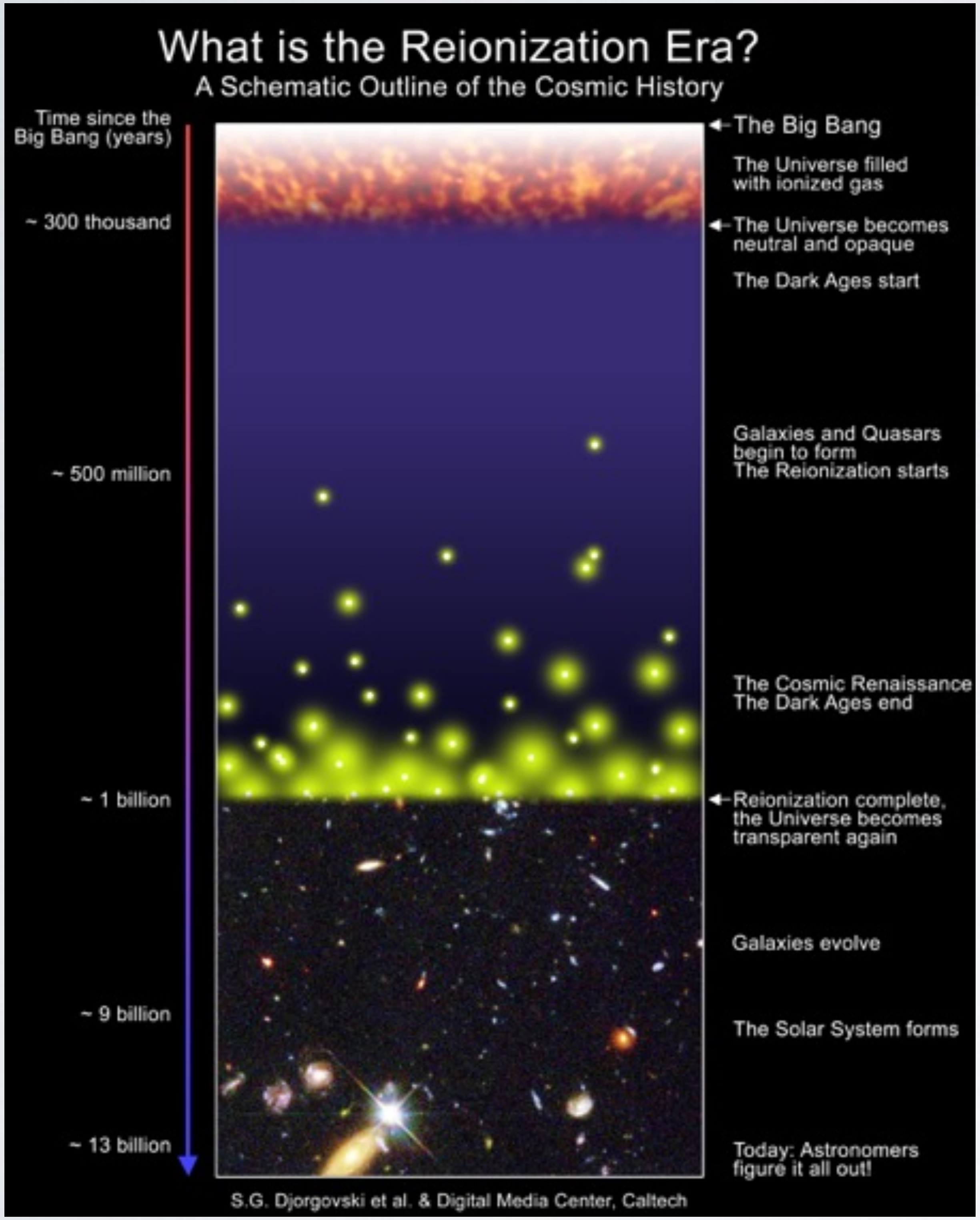
Testing theories of Lyα Escape (and more) in reionization-epoch analogs



Alaina Henry
(Goddard Space Flight Center)

Claudia Scarlata (U Minnesota)
Dawn Erb (UW Milwaukee)
Crystal Martin (UCSB)

The big picture of galaxies and IGM:



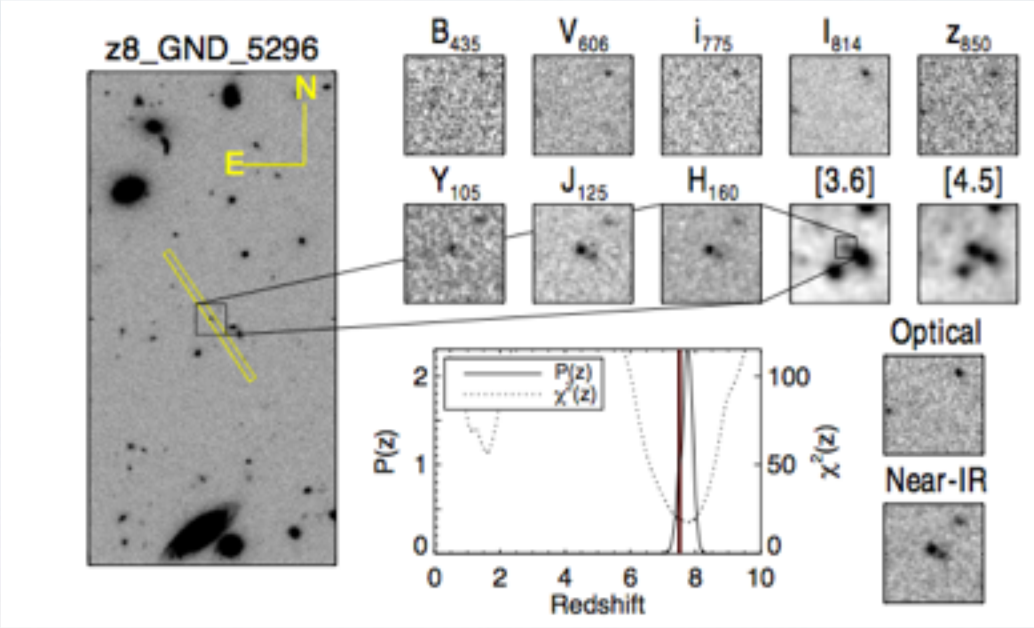
The astrophysical picture: key quantitative questions (to name a few)

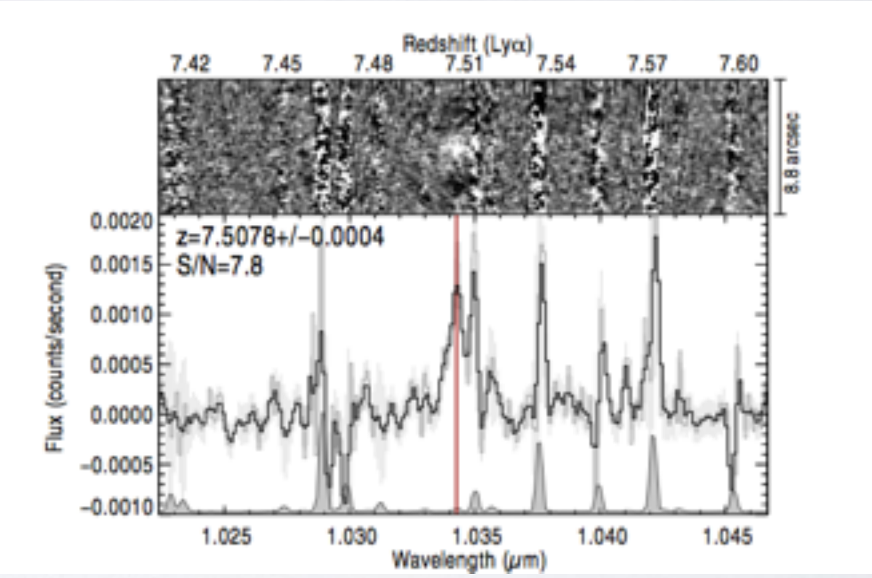
- When did the IGM become reionized, and what did it?
- What drives the rise and fall of the cosmic star-formation density?
- How does feedback from star-formation, SNe, supermassive black holes, and reionization shape our observations?
- How did the IGM become enriched in metals ?

One of the major legacies of HST is that we have produced a census of galaxy evolution. But, it has also brought into sharp focus what we don't know.

Even the best quality data is faint, redshifted into the infrared, and suffers from low spatial resolution.

- What is the escape fraction of ionizing photons?
- What is the best way to measure the metallicity of a galaxy?
- What are the properties of the stars in these galaxies?
- are their masses, SFRs, and dust measurements reliable?
- …..

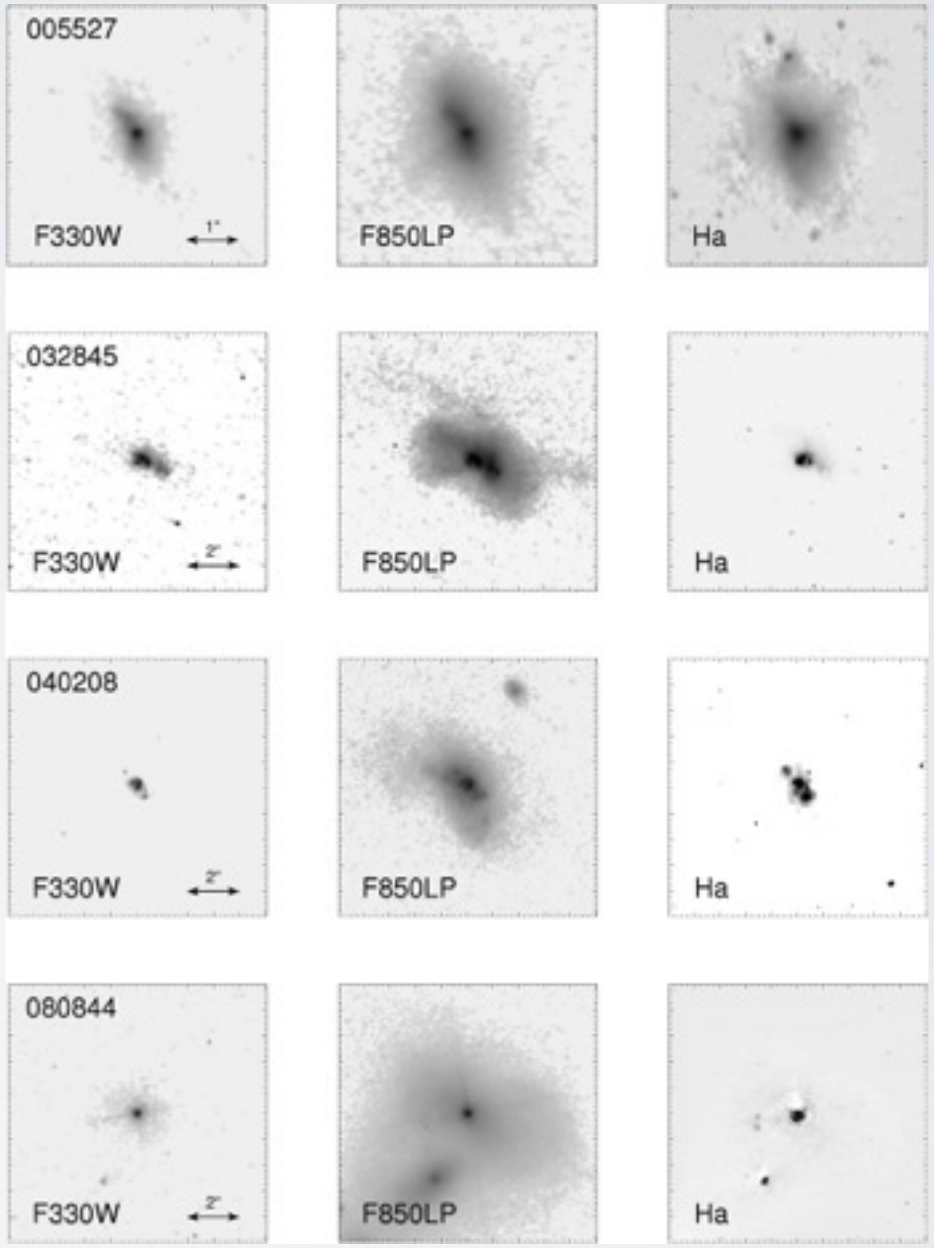




Finkelstein et al. (2013) — a spec-z record holder

Local Laboratories: Well-designed investigations into low-z galaxies can address some of these questions

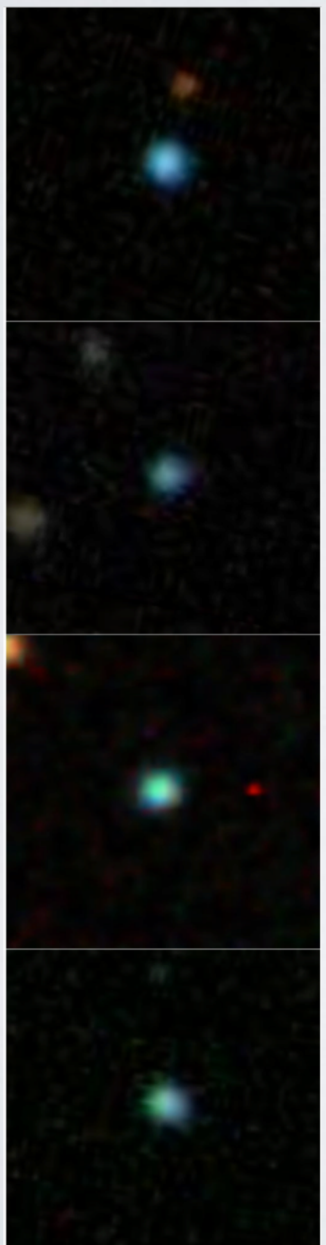
- While the physical conditions may be different in the early universe, the astrophysics is the same.
- With the SDSS + GALEX, around 2005, a team lead by Tim Heckman identified compact, UV luminous galaxies with properties — as far as they could tell— identical to Lyman Break Galaxies at z~3.
- New followup opportunities!

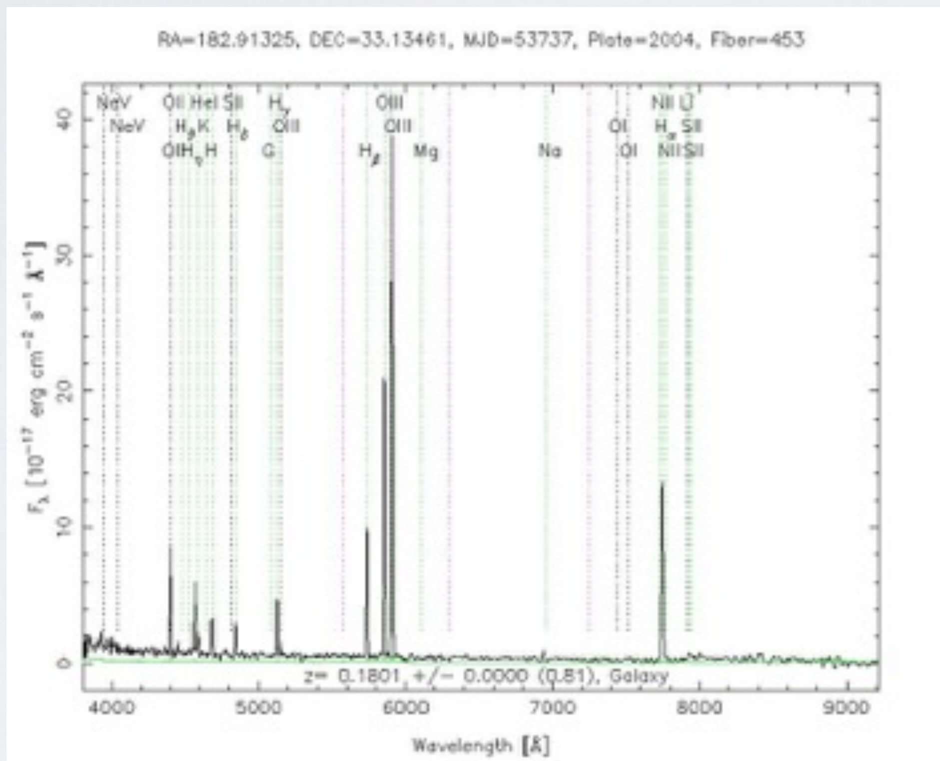


Lyman Break Analogs
Overzier et al. (2008)

“Green Peas” may be even better high-z analogs!

Lower metallicity, higher EWs and sSFR than most other nearby samples



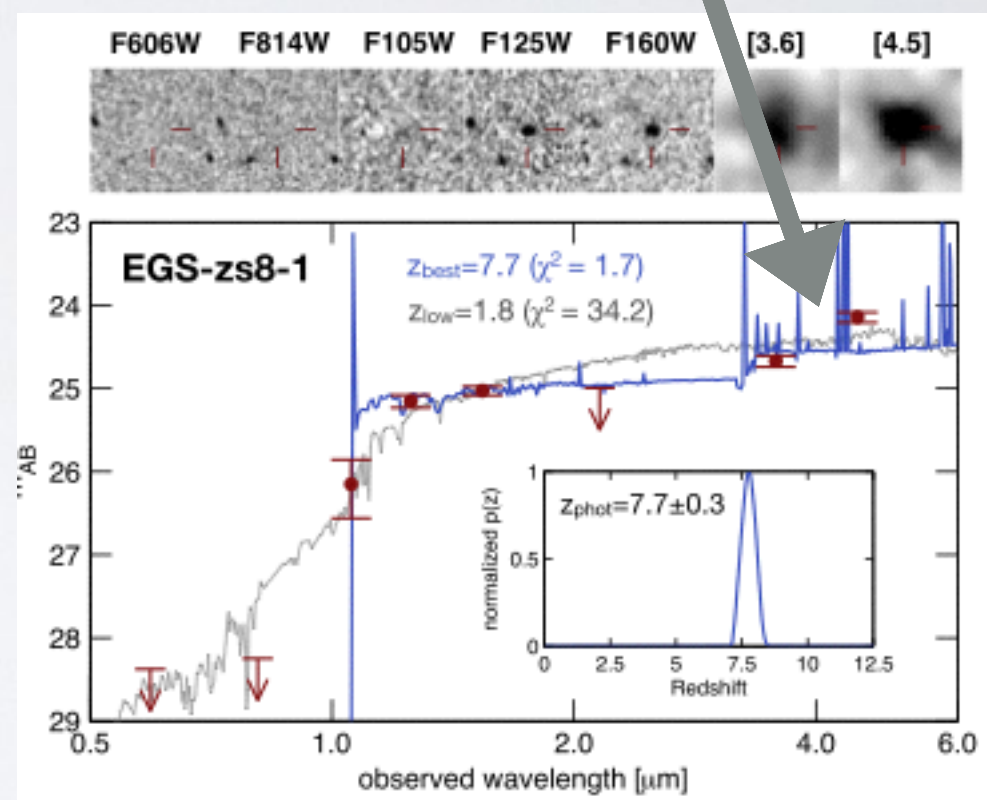


z~0.2

note: SDSS at low-z still much better than 10m Keck at intermediate-z

strong lines!

W([OIII]+Hb)~700 A

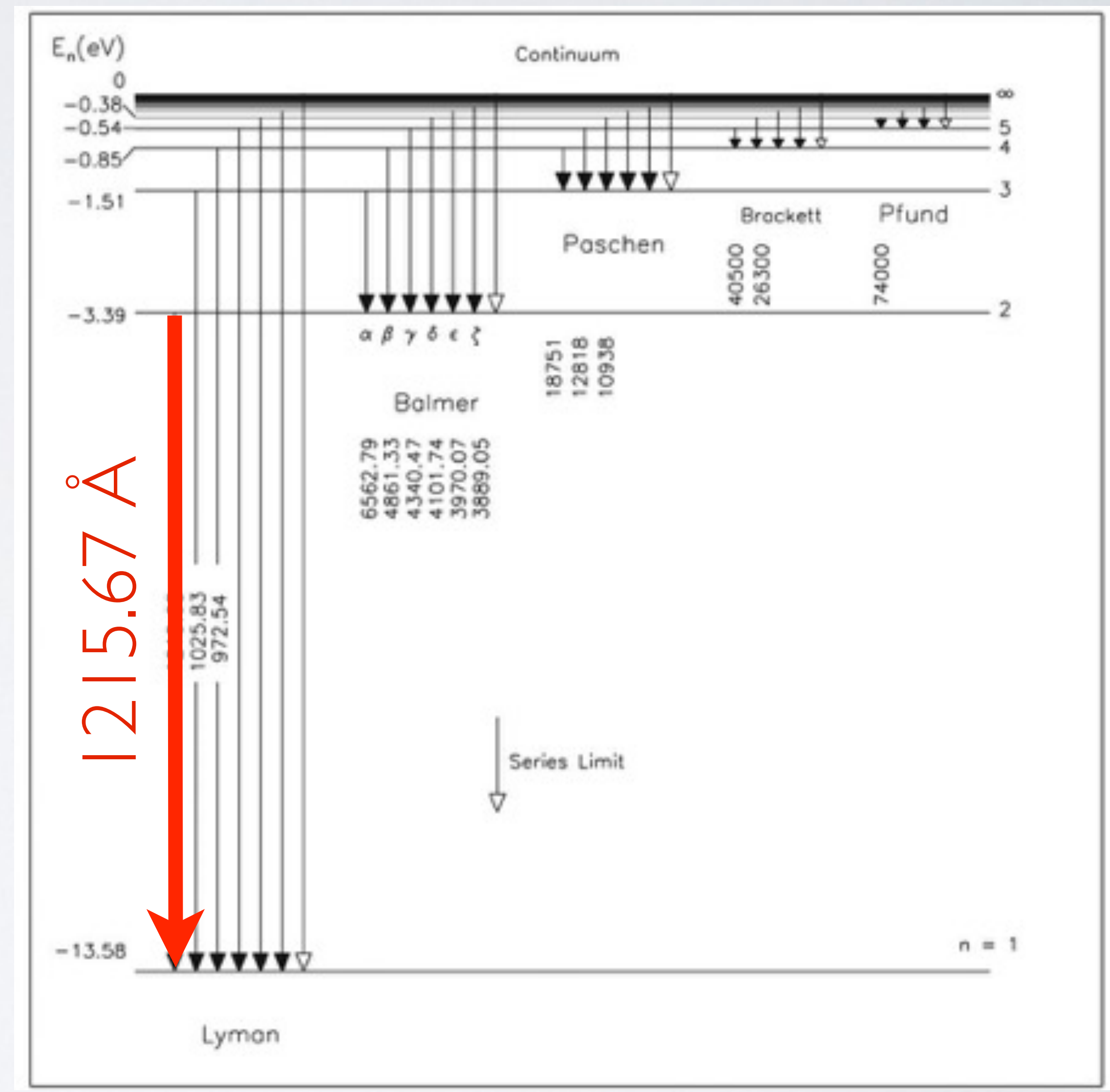


z~8 (Oesch et al. 2015)

Addressing Lyα output using Green Peas

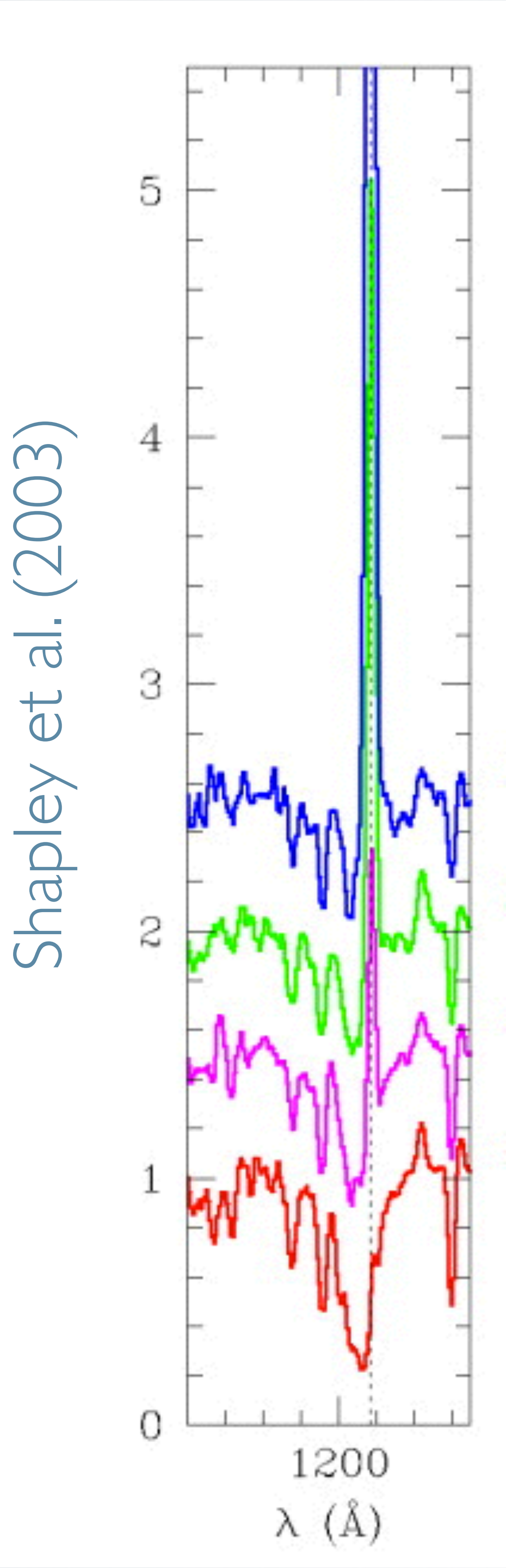
What is Lyα and what does it tell us?

- Formed in H II regions, when ionized H recombines.
- Recombination lines, like Lyα and Hα (Balmer) measure the number of ionizing photons produced by young, hot stars. Star Formation Indicators.
- 2/3 of all ionizing photons make Lyα. Should be very luminous.



Energy levels in the hydrogen atom

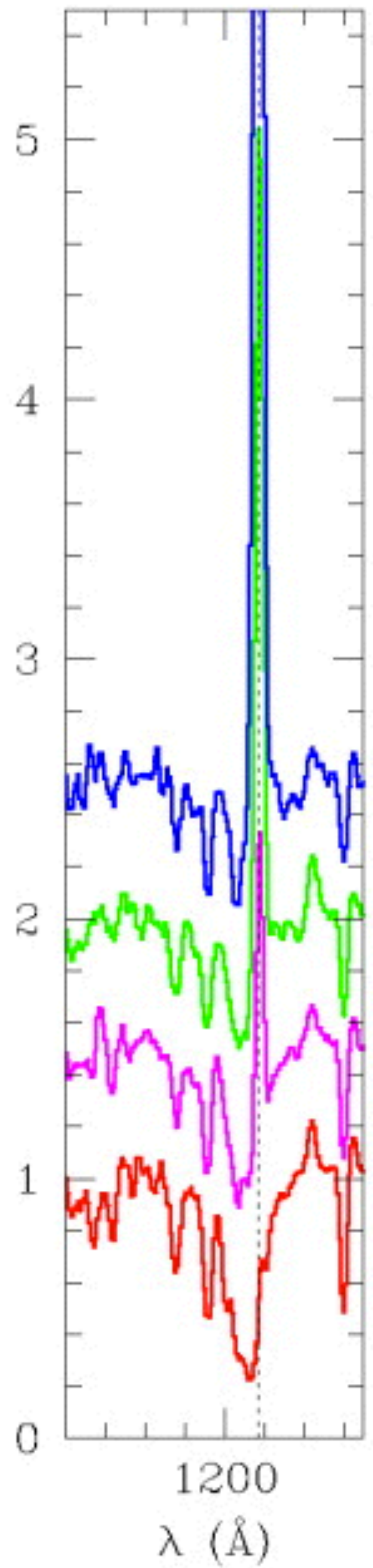
But Lyα is resonant....



- In the 1980's, *IUE* observations showed emission is much weaker than expected. Sometimes even in absorption.

- More common at higher redshifts, but still shows a wide range of strengths!

But Lyα is resonant....



Shapley et al. (2003)

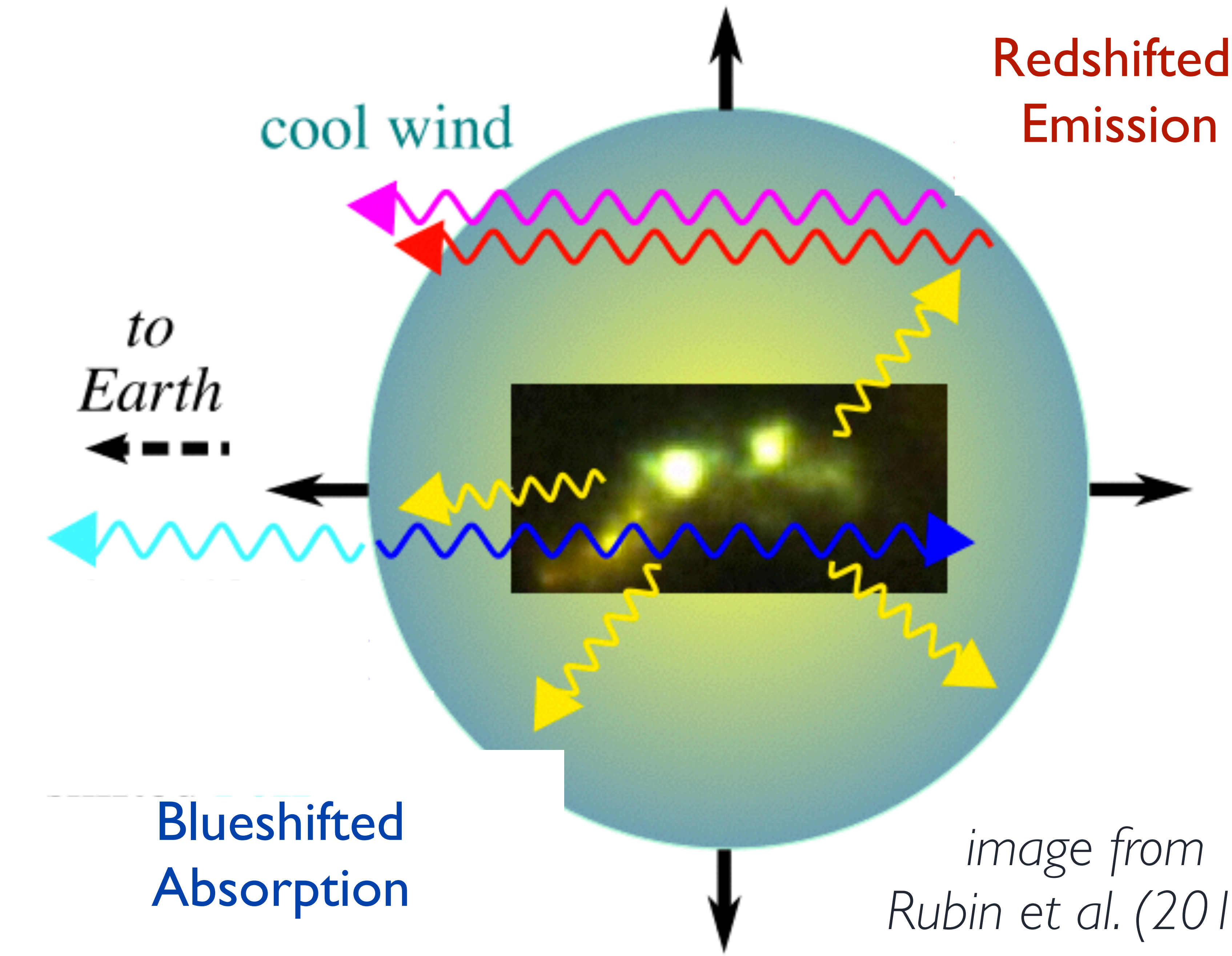
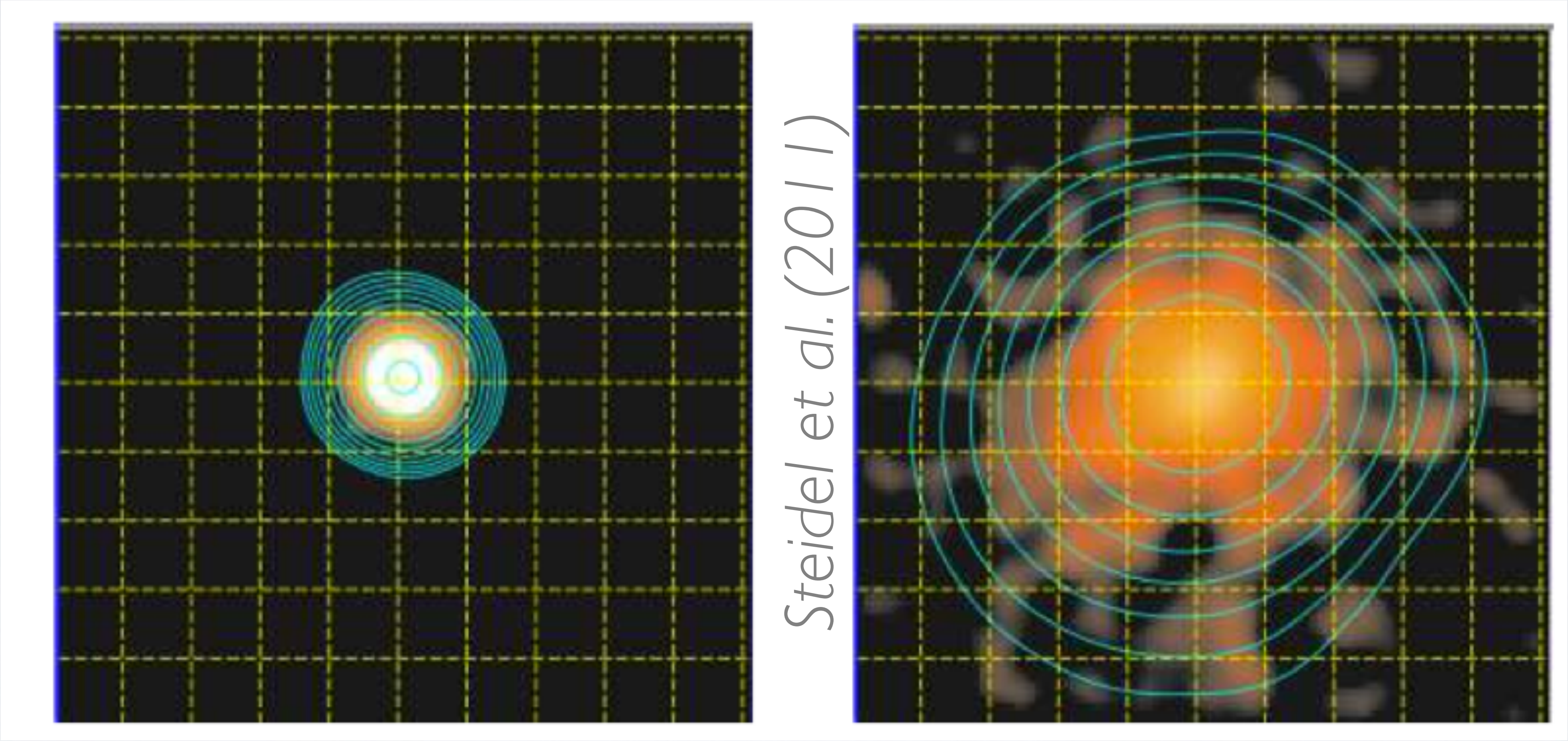


image from Rubin et al. (2011)

Wealth of Information from Lyα: Illuminates HI in the galaxy halo…

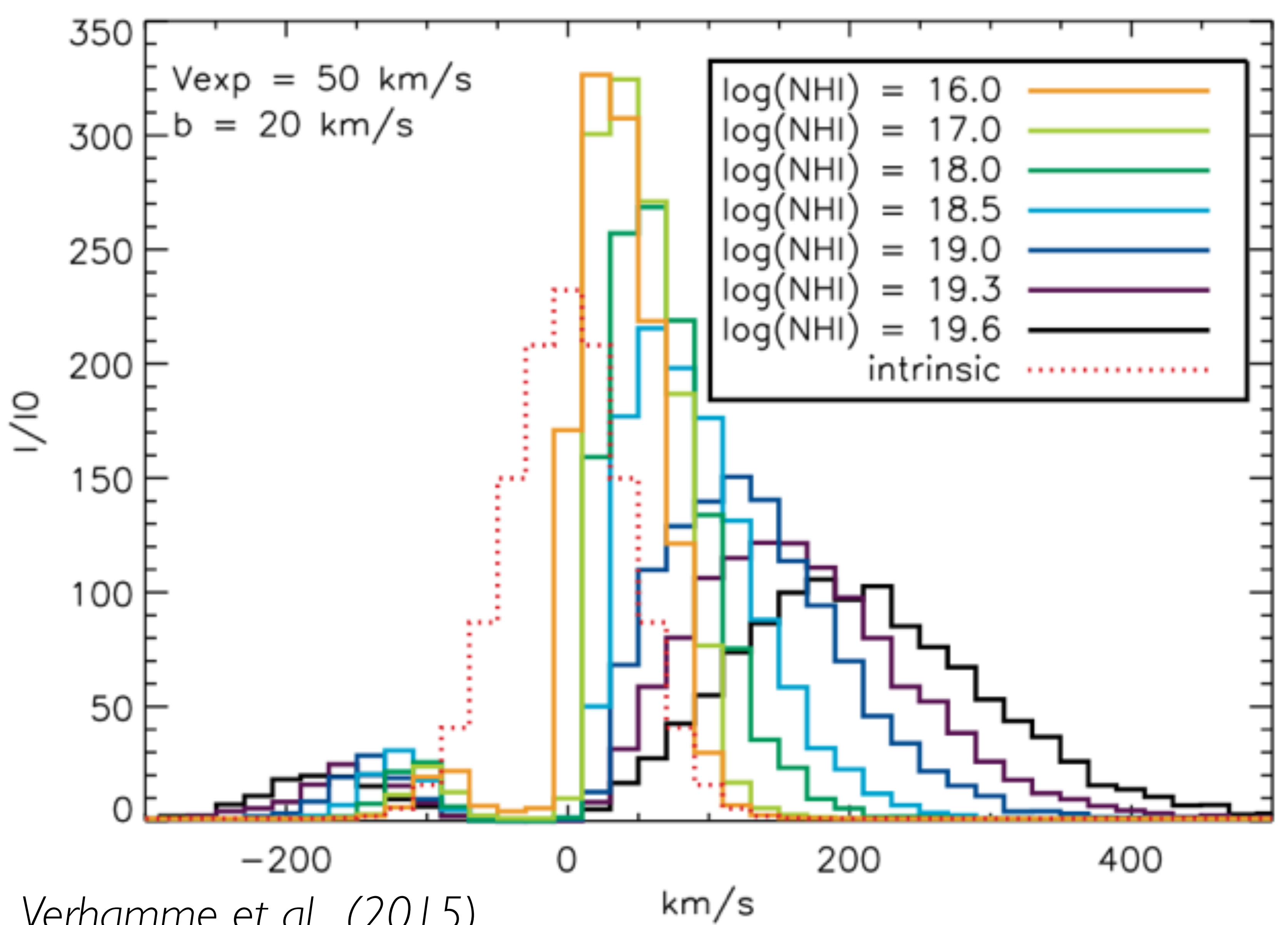
~100 kpc



Stellar Continuum

Lyα

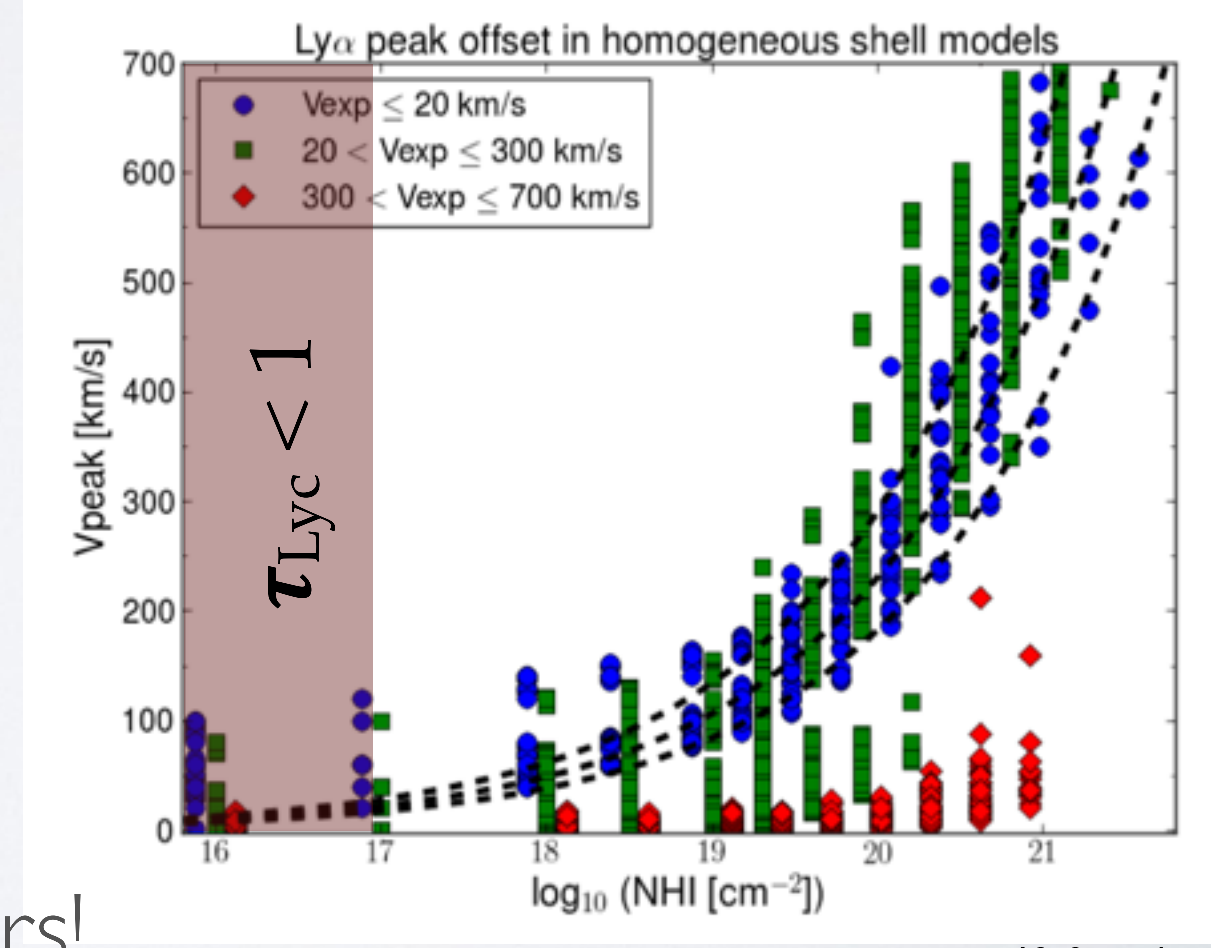
Wealth of Information from Lyα: Illuminates HI in the galaxy halo…



Verhamme et al. (2015)

… plus constrains circumgalactic gas properties

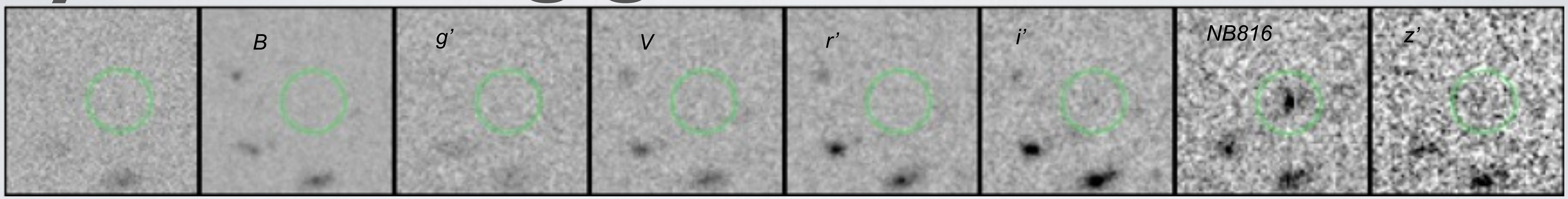
Wealth of Information from Lyα: Illuminates HI in the galaxy halo…



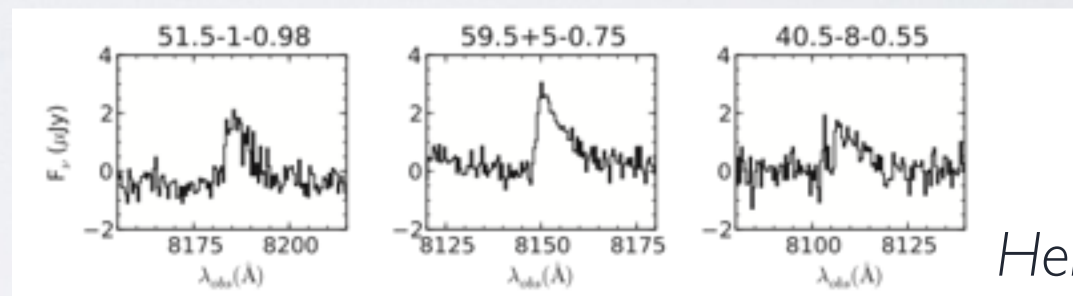
…and may identify LyC leakers!

Verhamme et al. (2015)

High redshift surveys are finding many Lyα emitting galaxies, out to z~6.5.

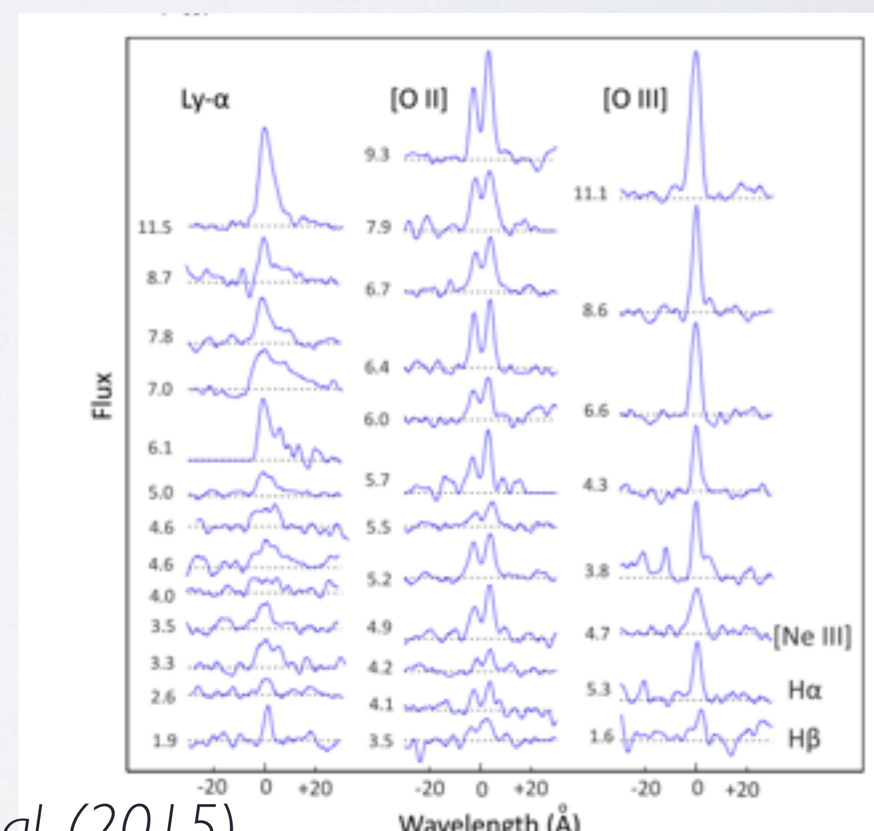


Ease of Observing:



Henry et al. (2012)

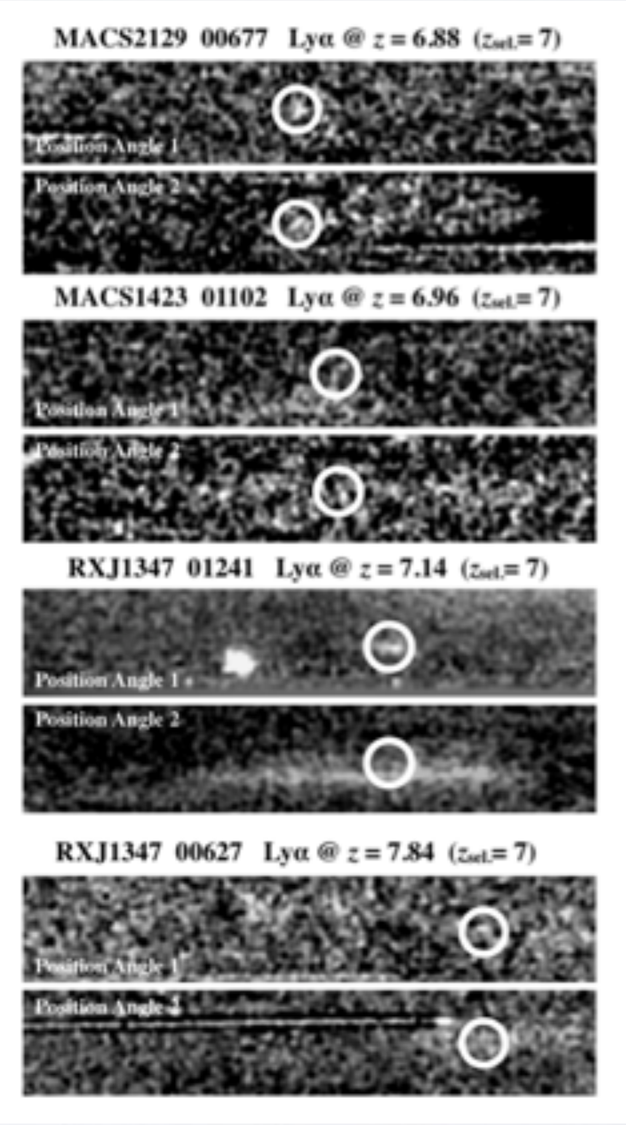
- often the strongest line
- Favorable rest-UV wavelengths (ground observable to high-z)
- fainter UV sources help constrain the ionizing photon budget



Dressler et al. (2015)

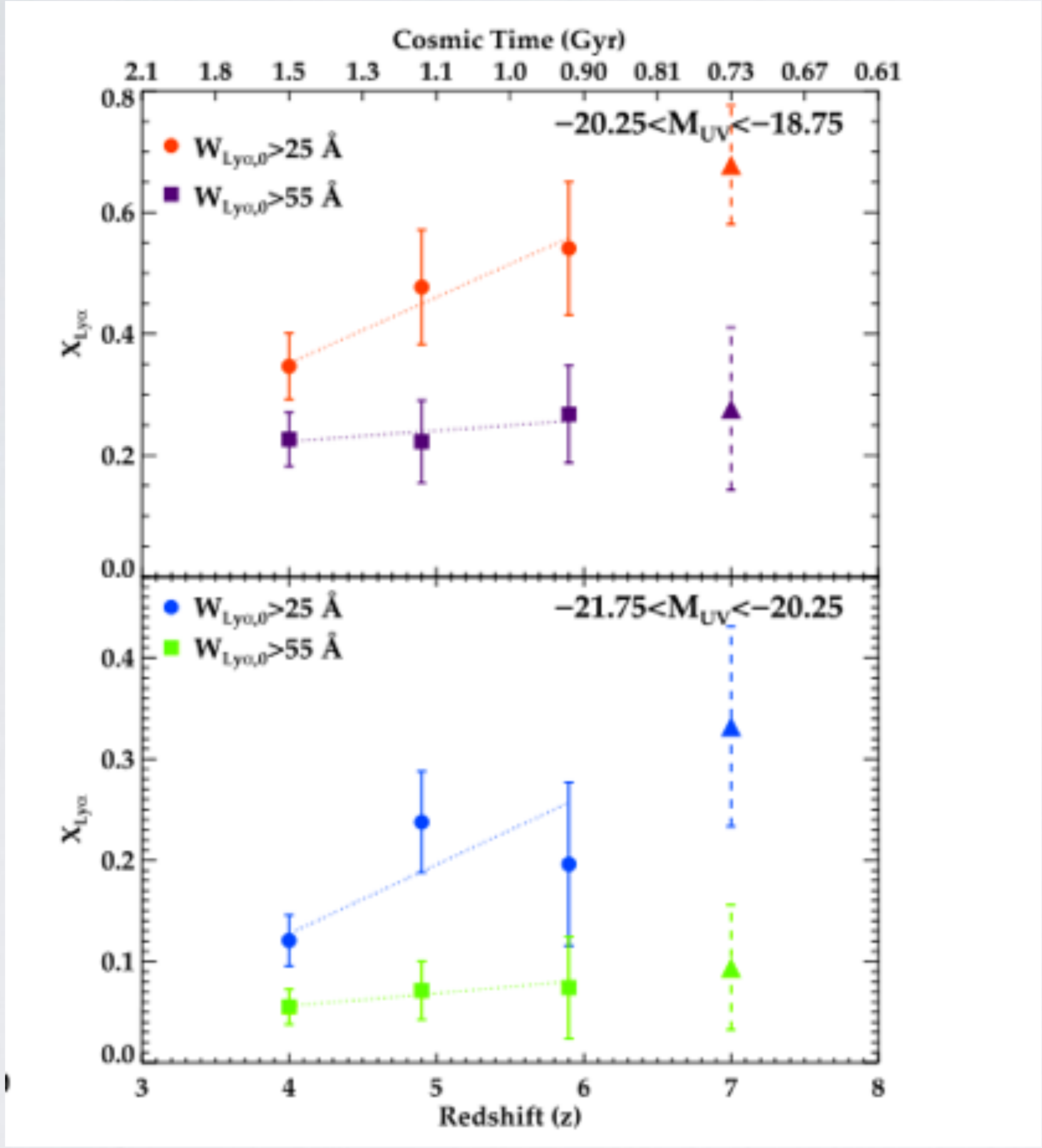
And Lyα detections during reionization (z~7-8)?

HST grism survey of 10 strong lensing clusters (from CLASH + Frontier Fields)

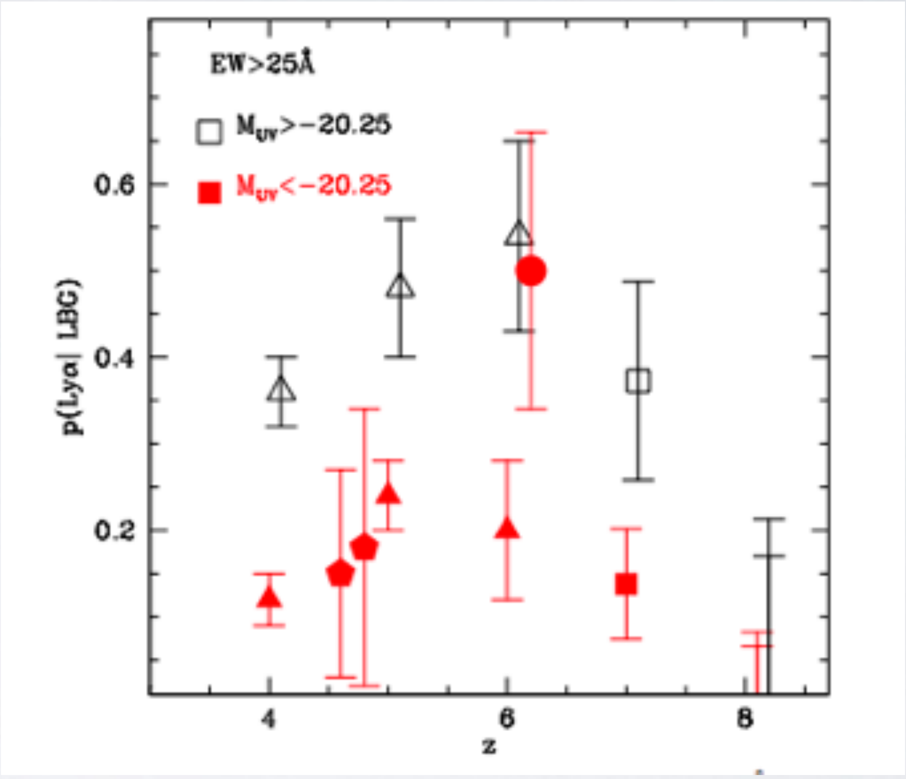


Schmidt et al. (2016, incl AH)

Can Lyα surveys constrain the IGM neutral fraction?



Stark et al. (2011)



Treu et al. (2013)

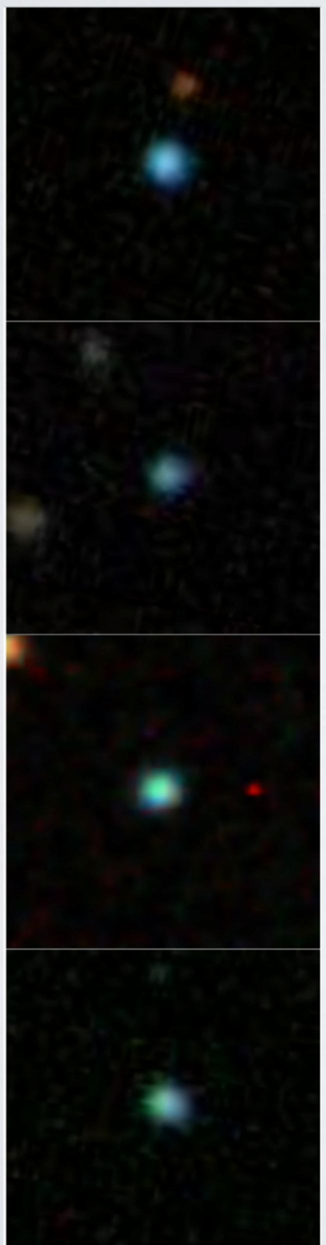
Lyα deficit at z>6 suggests partially neutral IGM. But what is the fiducial for measuring a deficit?

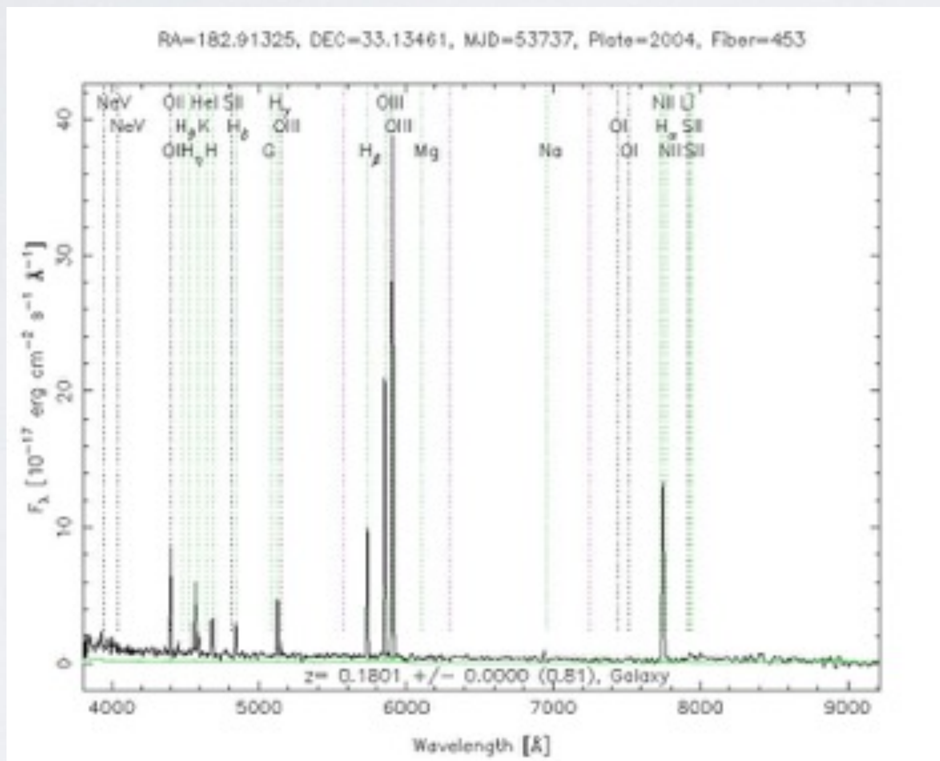
The data are going to get better with JWST and other new/big telescopes….
but we have to get smarter about Lyα

So how do we develop a predictive model for Lyα escape from galaxies?

“Green Peas” may be even better high-z analogs!

Lower metallicity, higher EWs and sSFR than most other nearby samples





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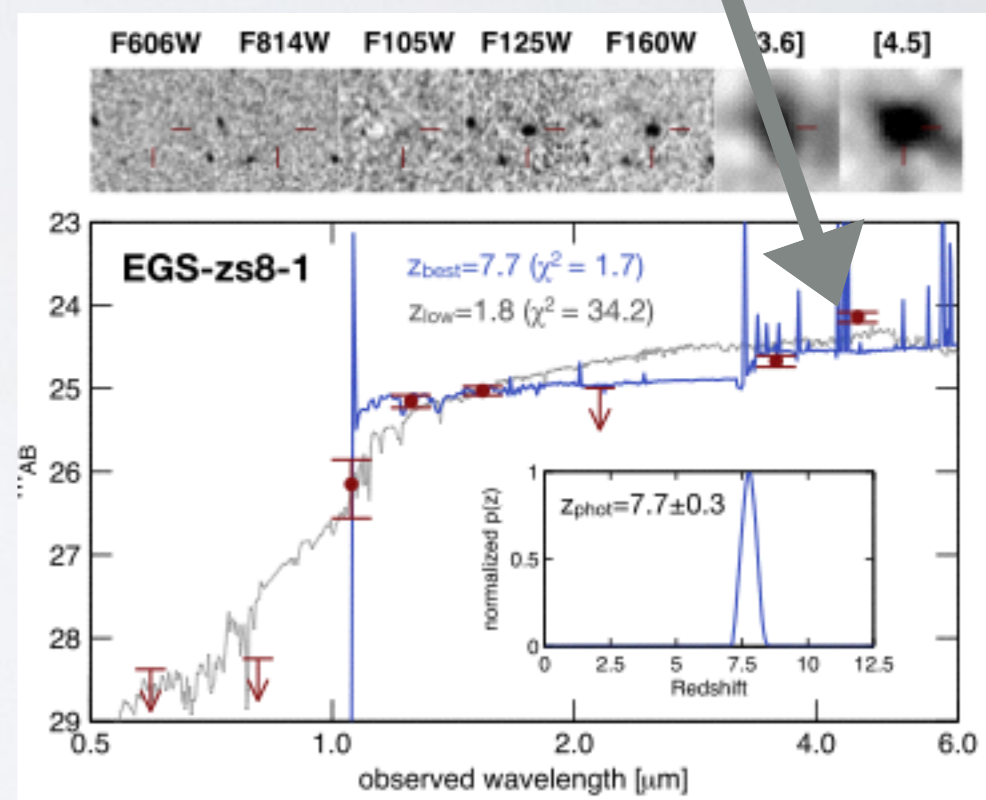
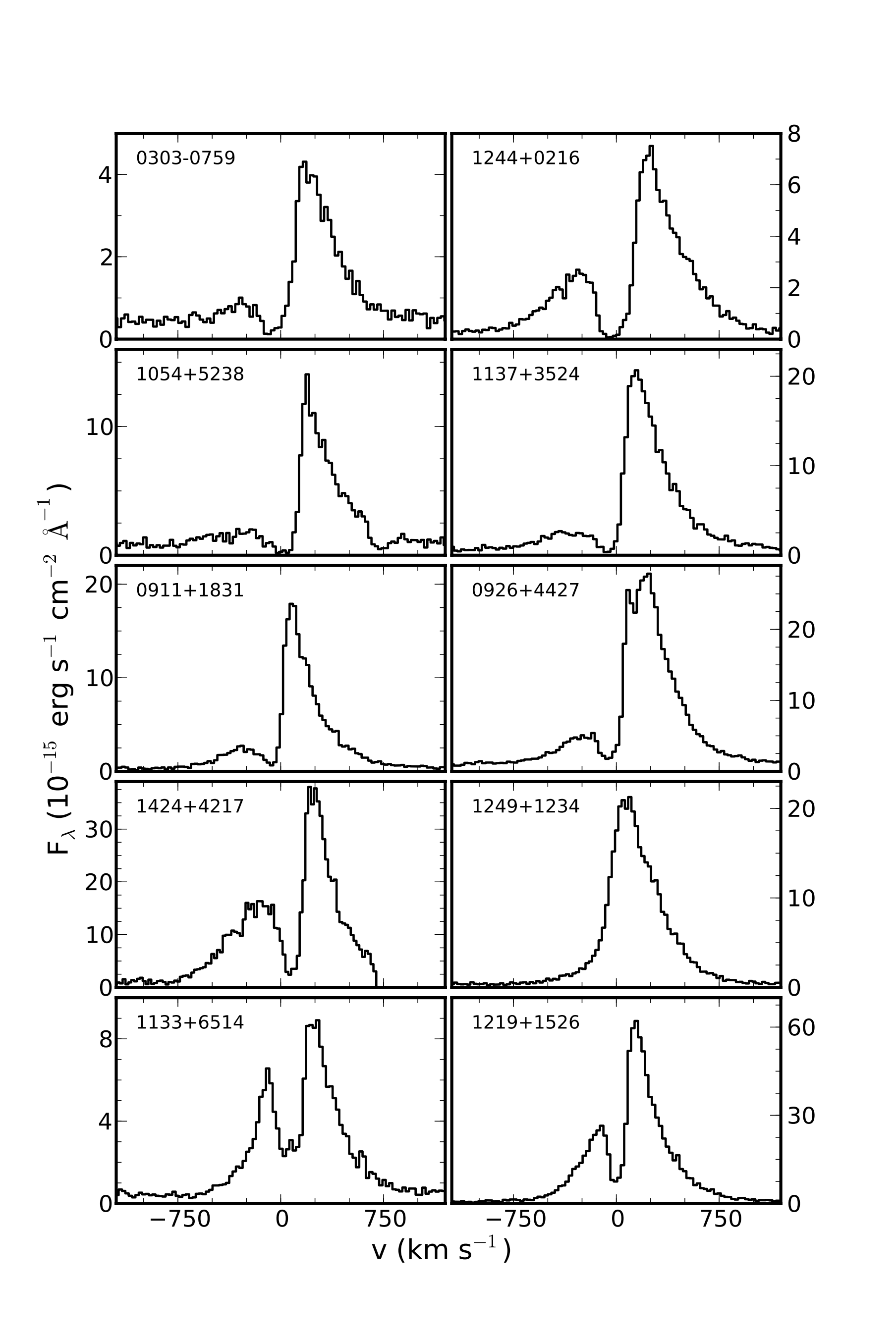


z~8 (Oesch et al. 2015)

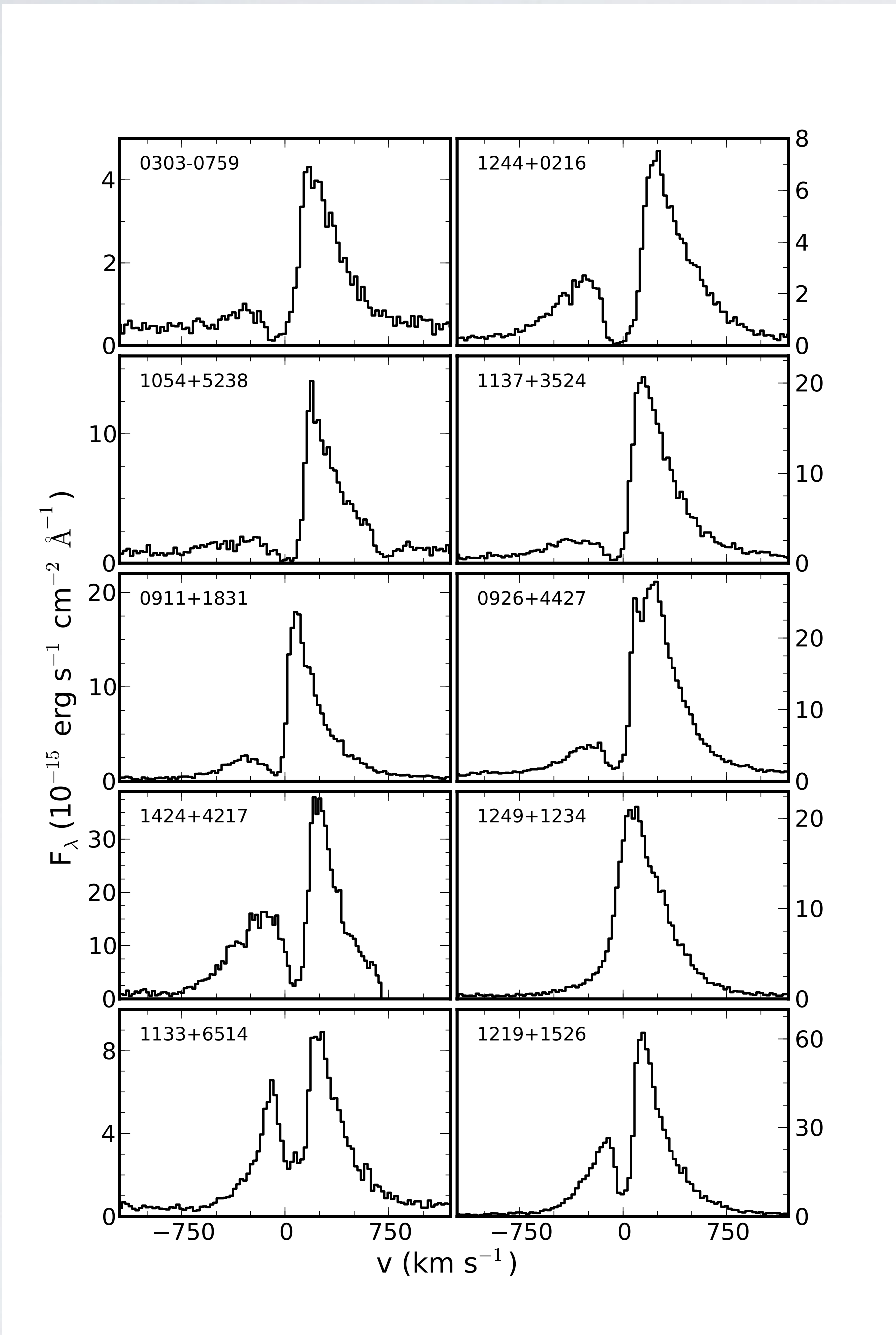
COS Lyα Spectra of Green Peas



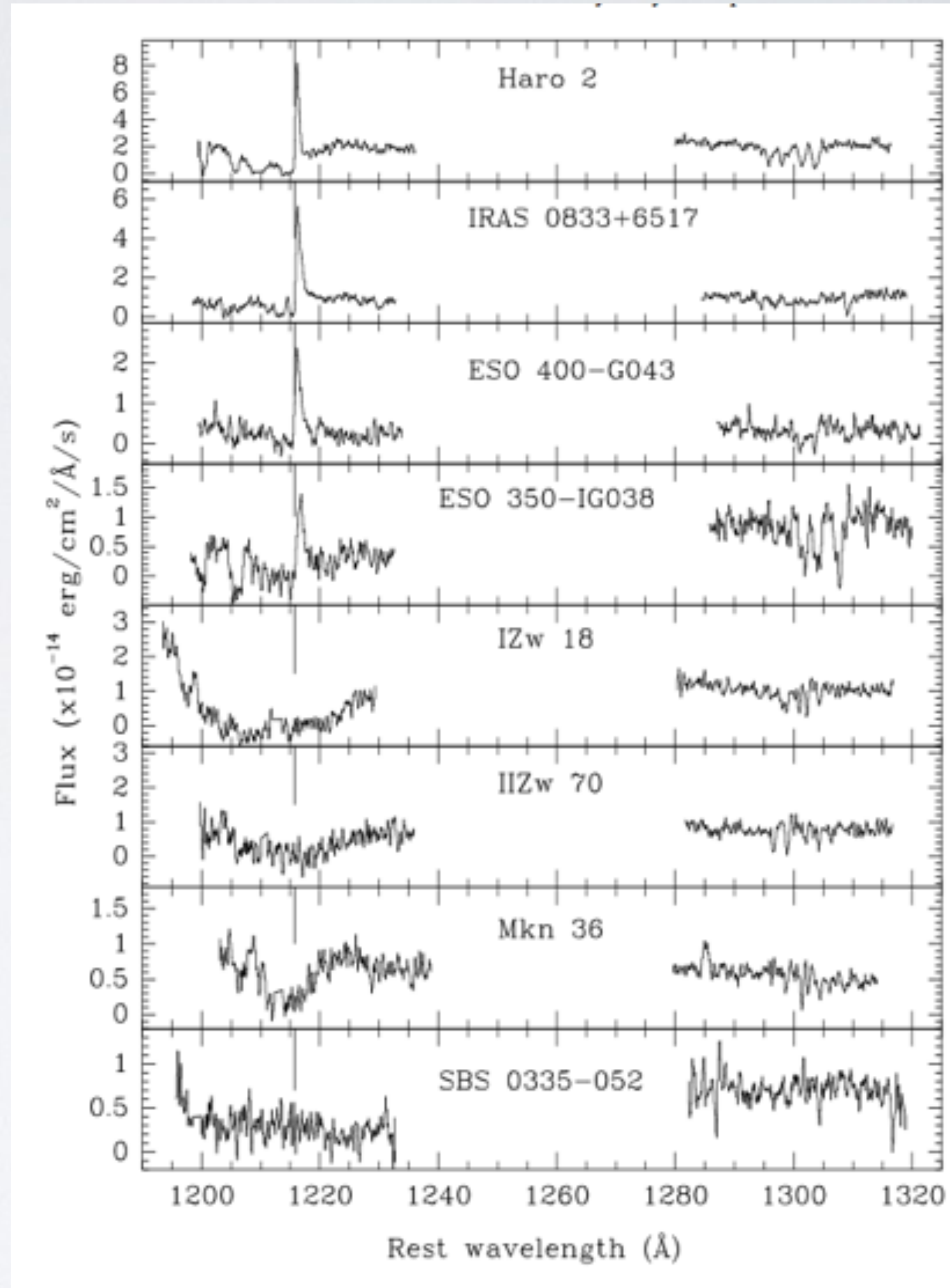
Henry et al. (2015)

- 9/10 double peaked when we observe with high spectral resolution
- Lyα has higher EW, luminosity than other nearby galaxies
- <u>more comparable to LAEs at z >~3</u>

COS Lyα Spectra of Green Peas

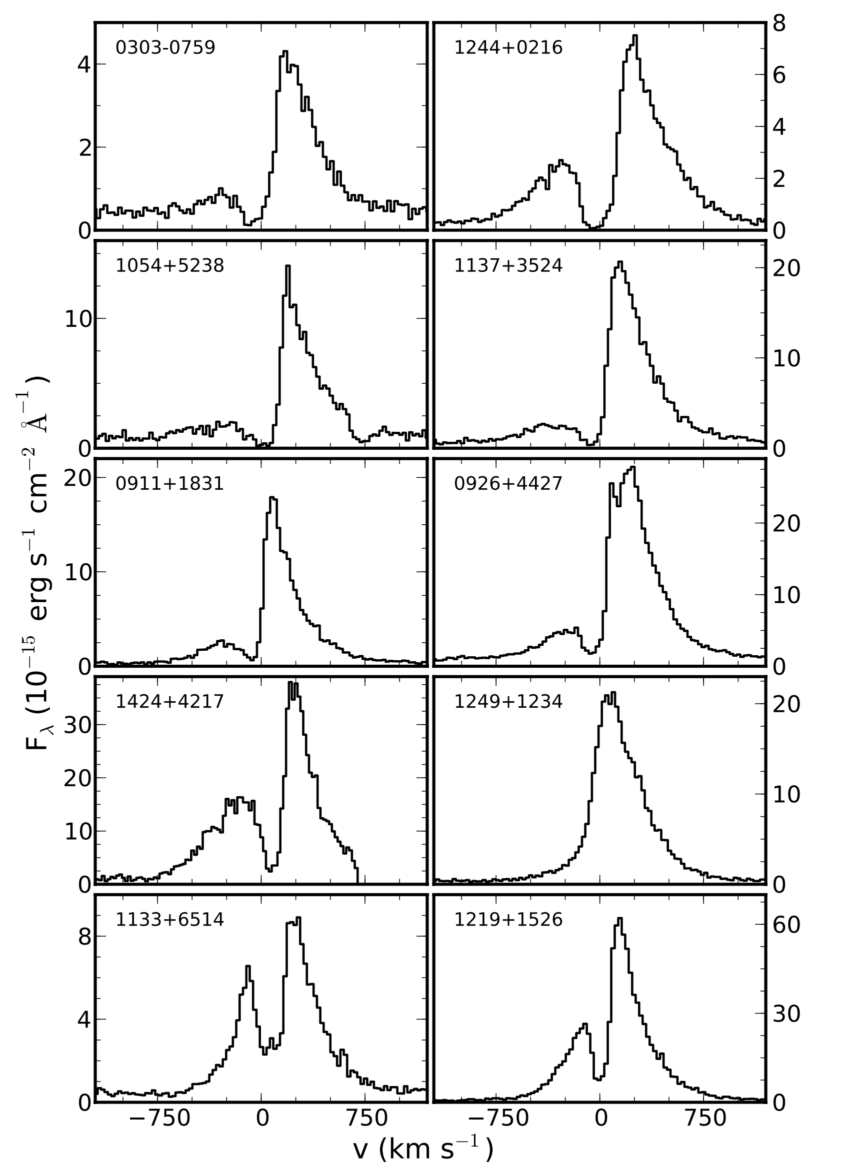


Henry et al. (2015)

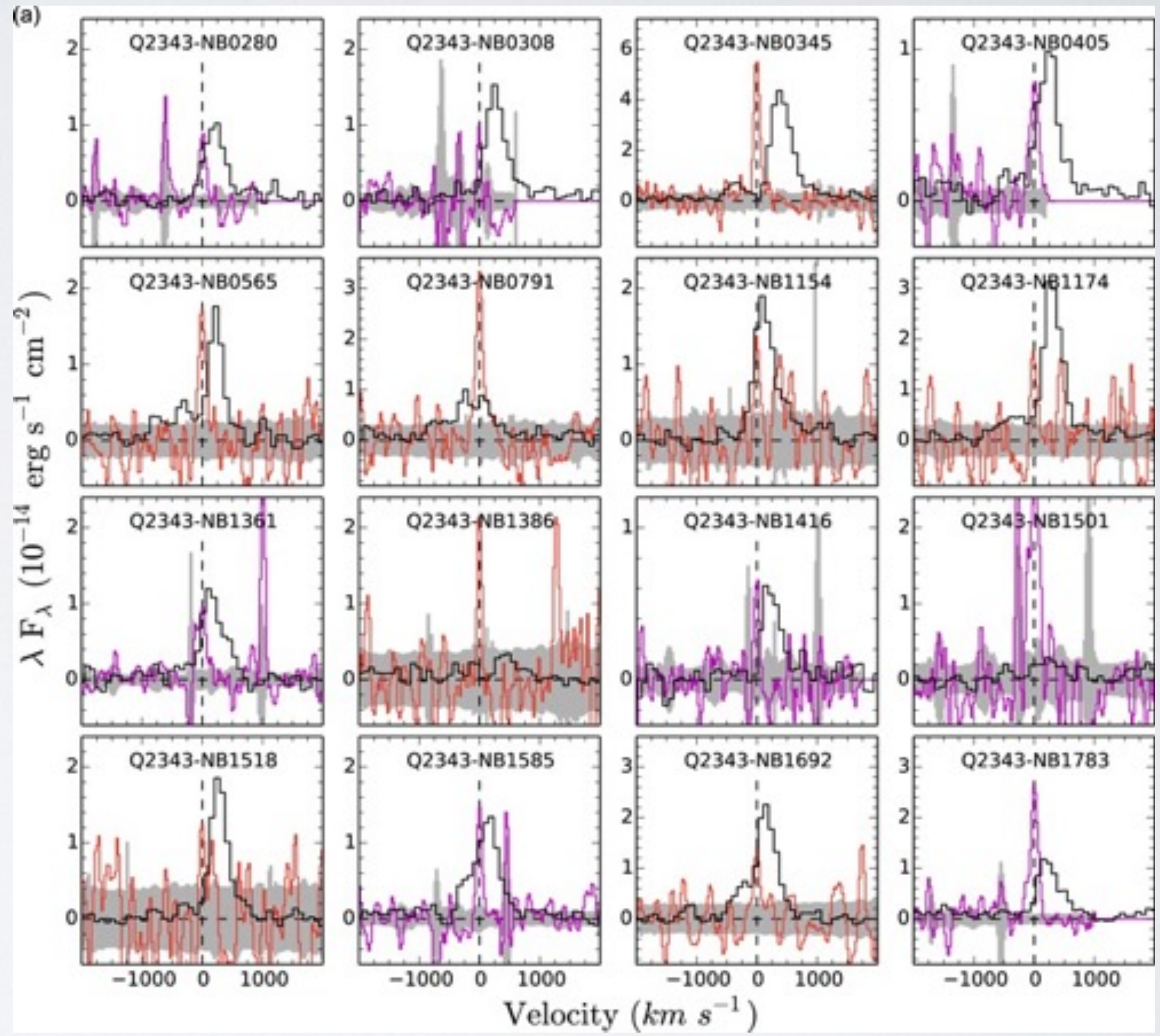


z~0 GHRS: Kunth et al. (1998)

COS Lyα Spectra of Green Peas

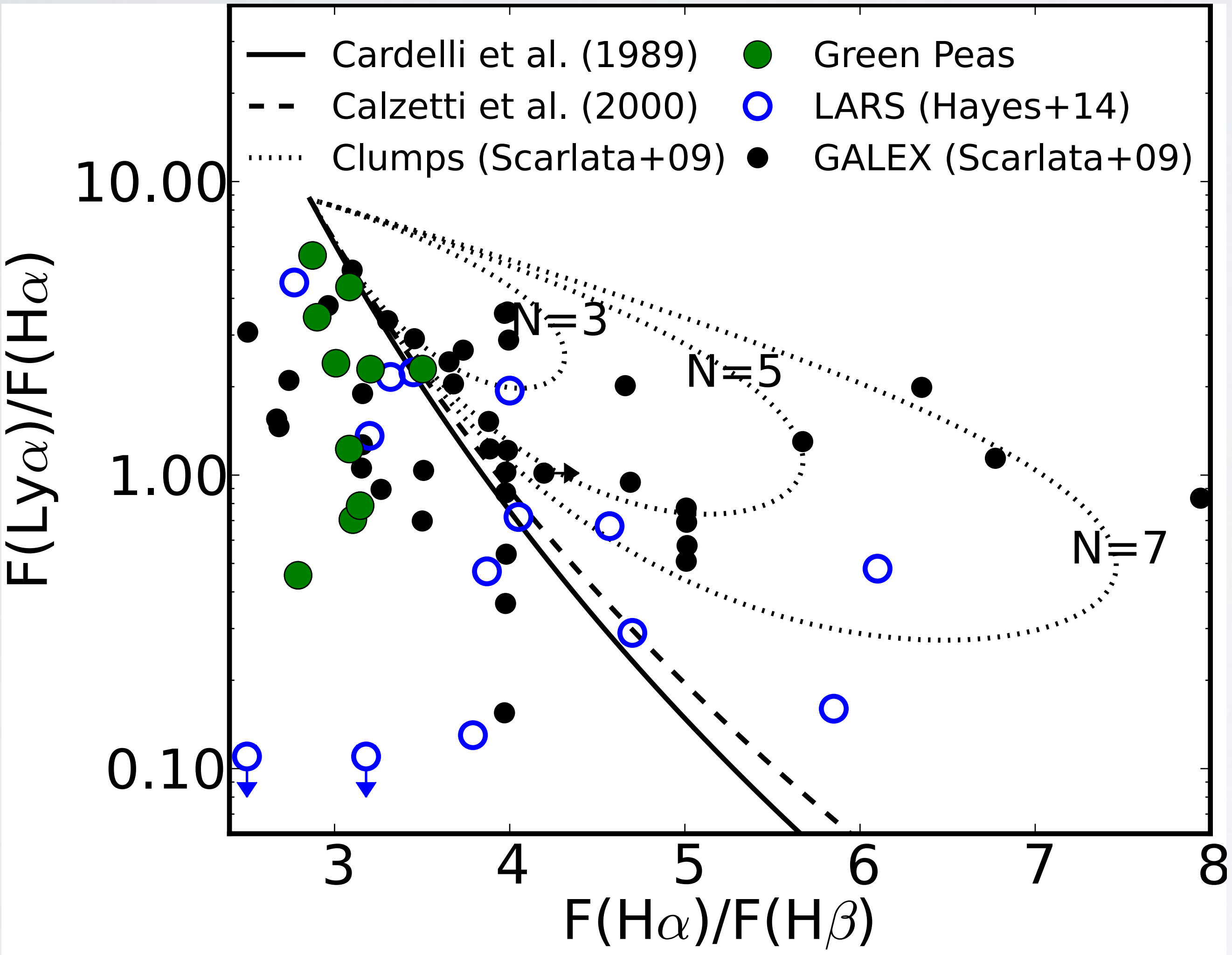


Henry et al. (2015)



z~2: Trainor et al. (2015)

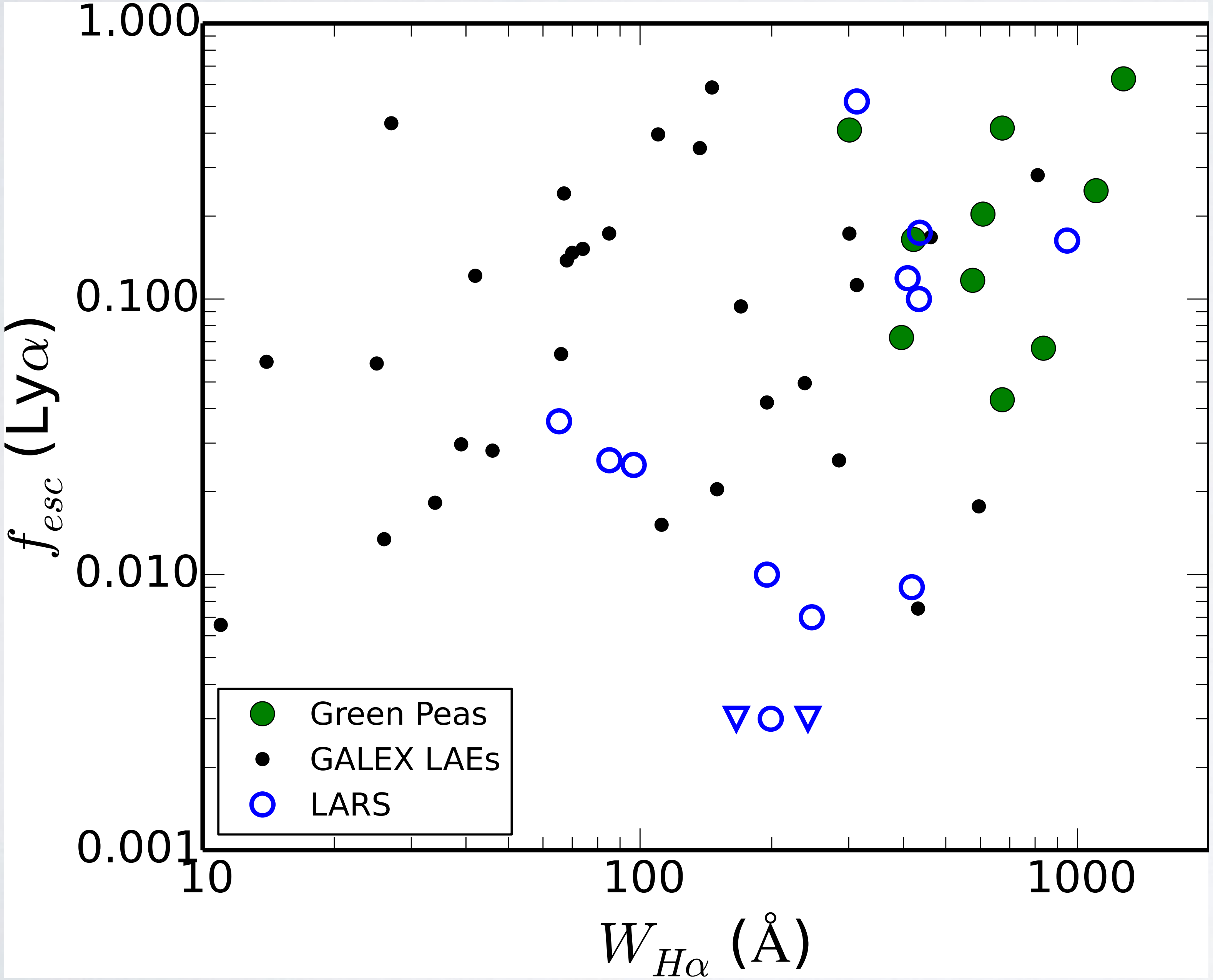
Still, only a fraction of the Lyα photons are escaping



Henry et al. (2015)

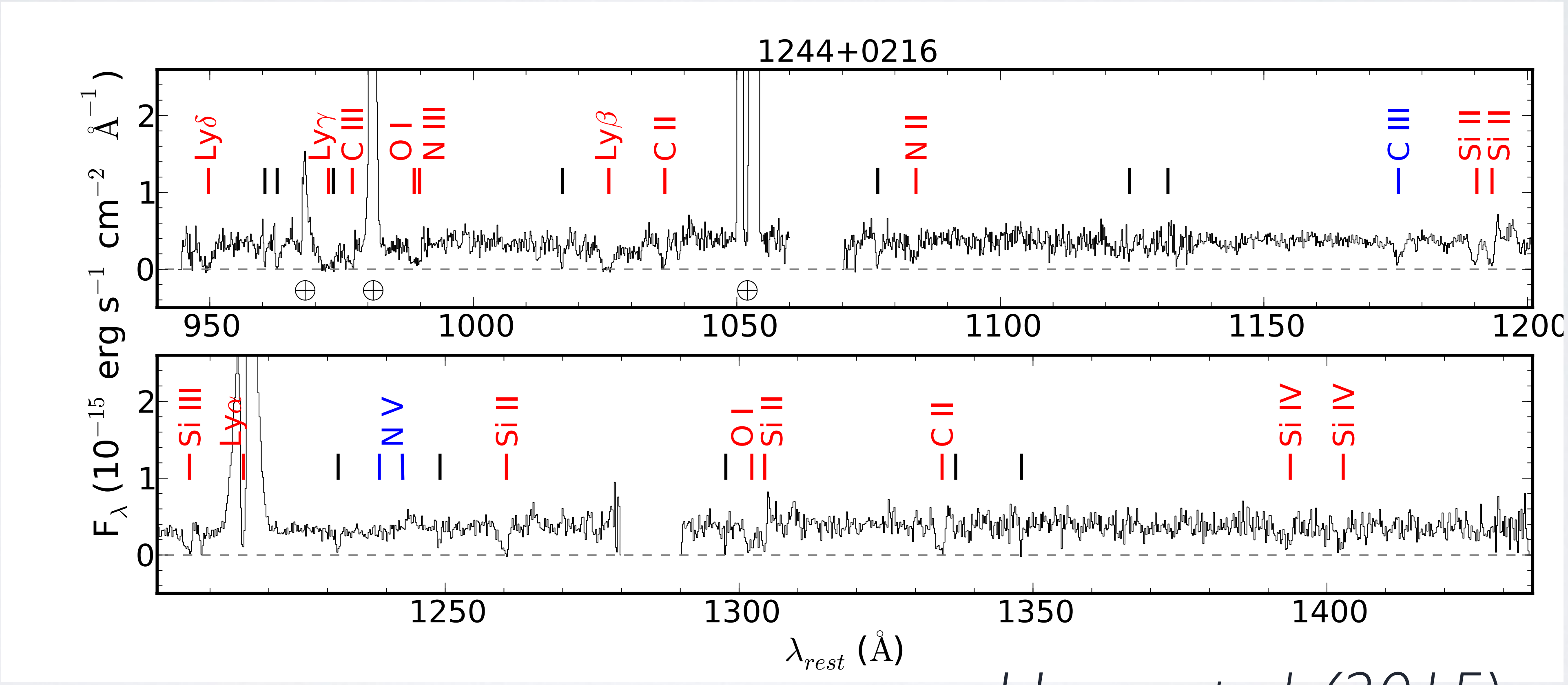
The range of Lyα / Hα flux ratios is not explained by extinction alone. $E(B\text{-}V)_{gas}$ is uniformly low.

More Lyα may escape when galaxies appear "younger."



But why?

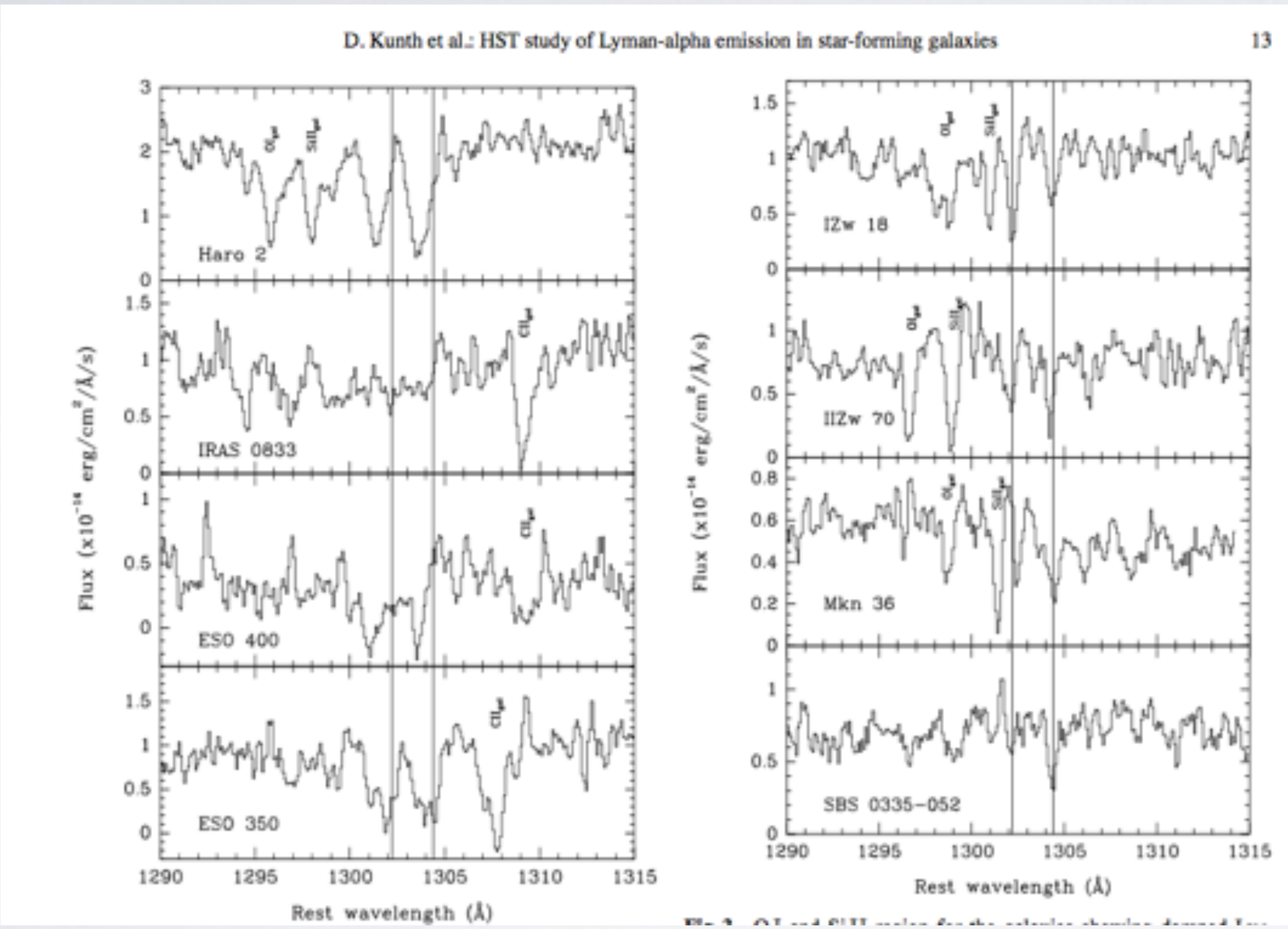
What is causing the variation in Lyα in these galaxies?



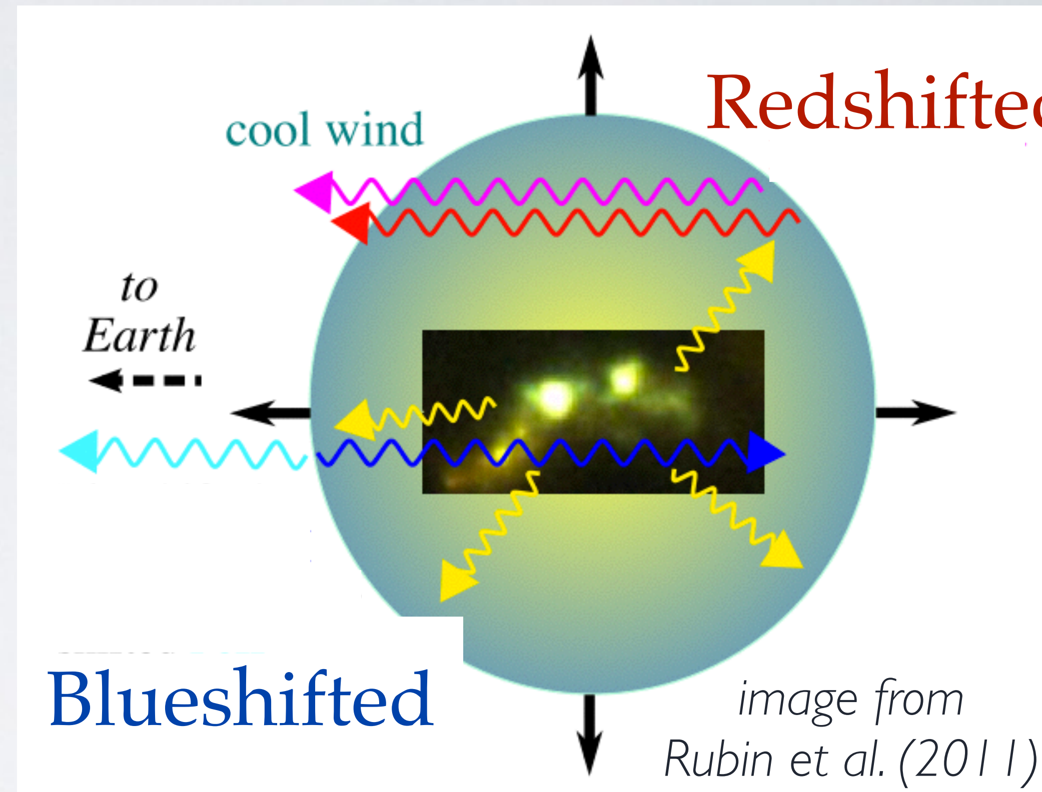
Henry et al. (2015)

Maybe the UV absorption lines can help us….

Test 1: Do outflows help Lyα escape?

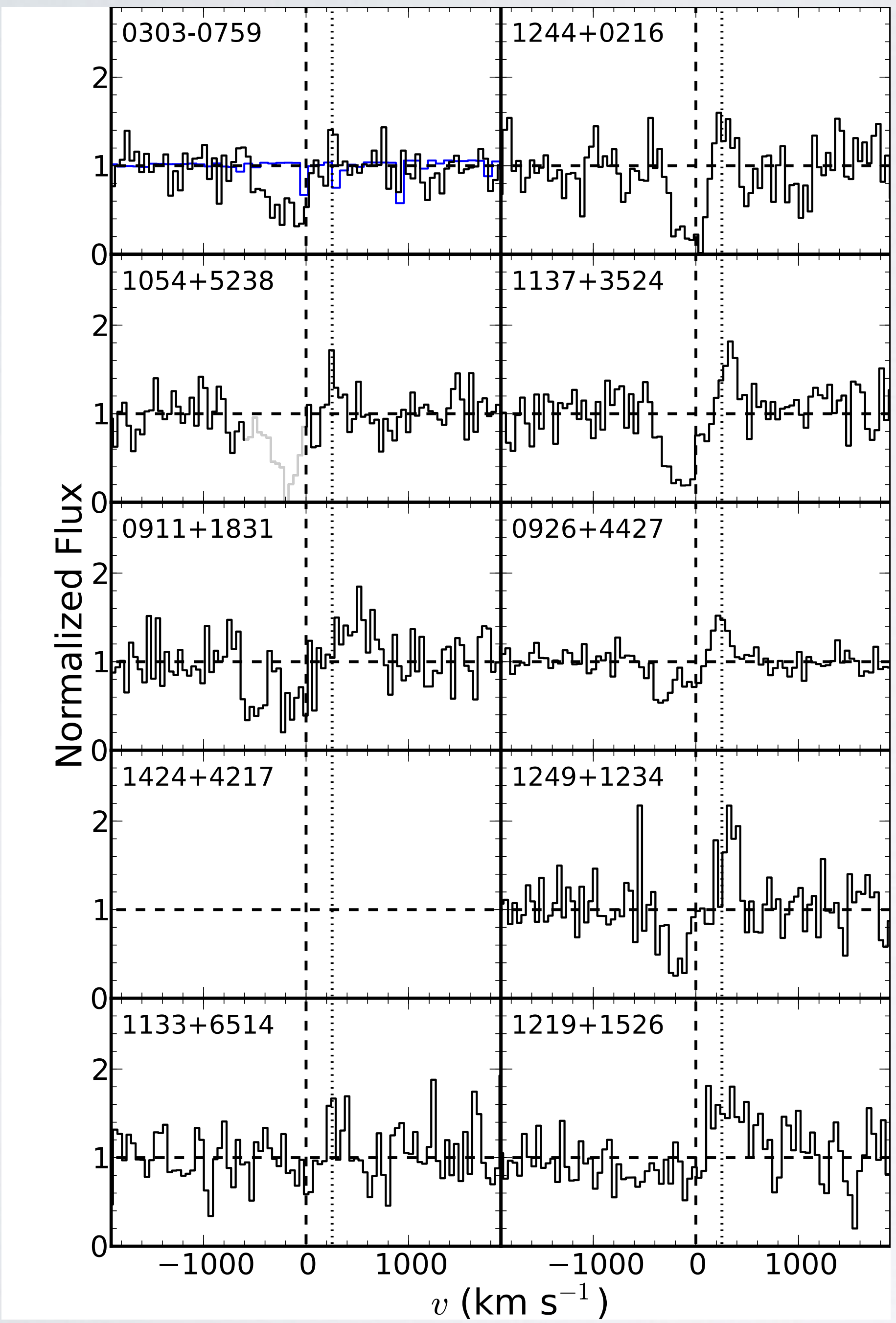


Kunth et al. (1998)



Hypothesis: Lyα escapes by scattering in outflowing HI gas, shifting out of resonance with the ISM (e.g Kunth et al. 1998).

We cover several low-ionization lines that trace neutral hydrogen



Henry et al. (2015)

e.g. C II 1334

E_{ion} = 11.3 eV

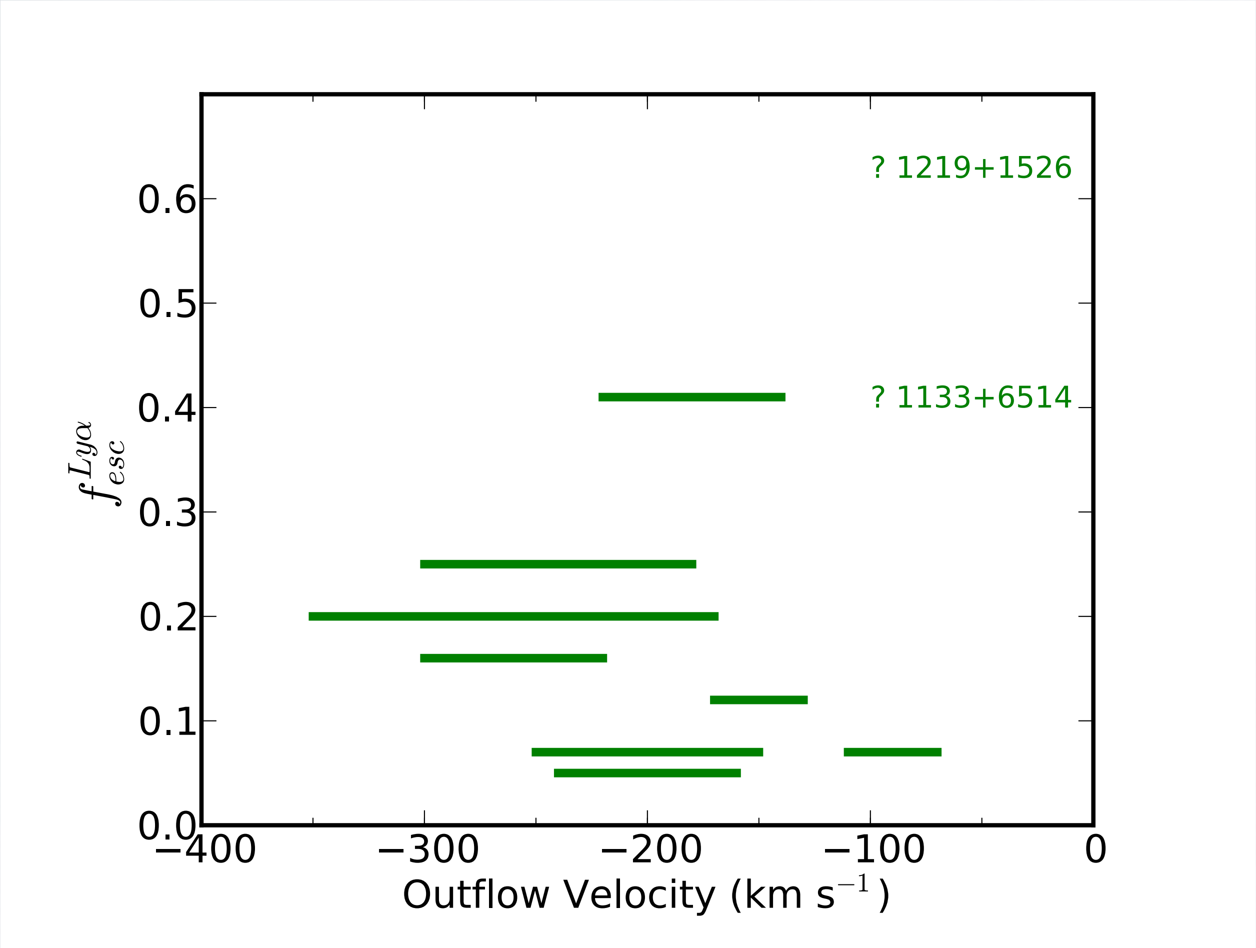
(C I → C II)

Si II 1190, 1193, 1260

E_{ion} = 8.1 eV

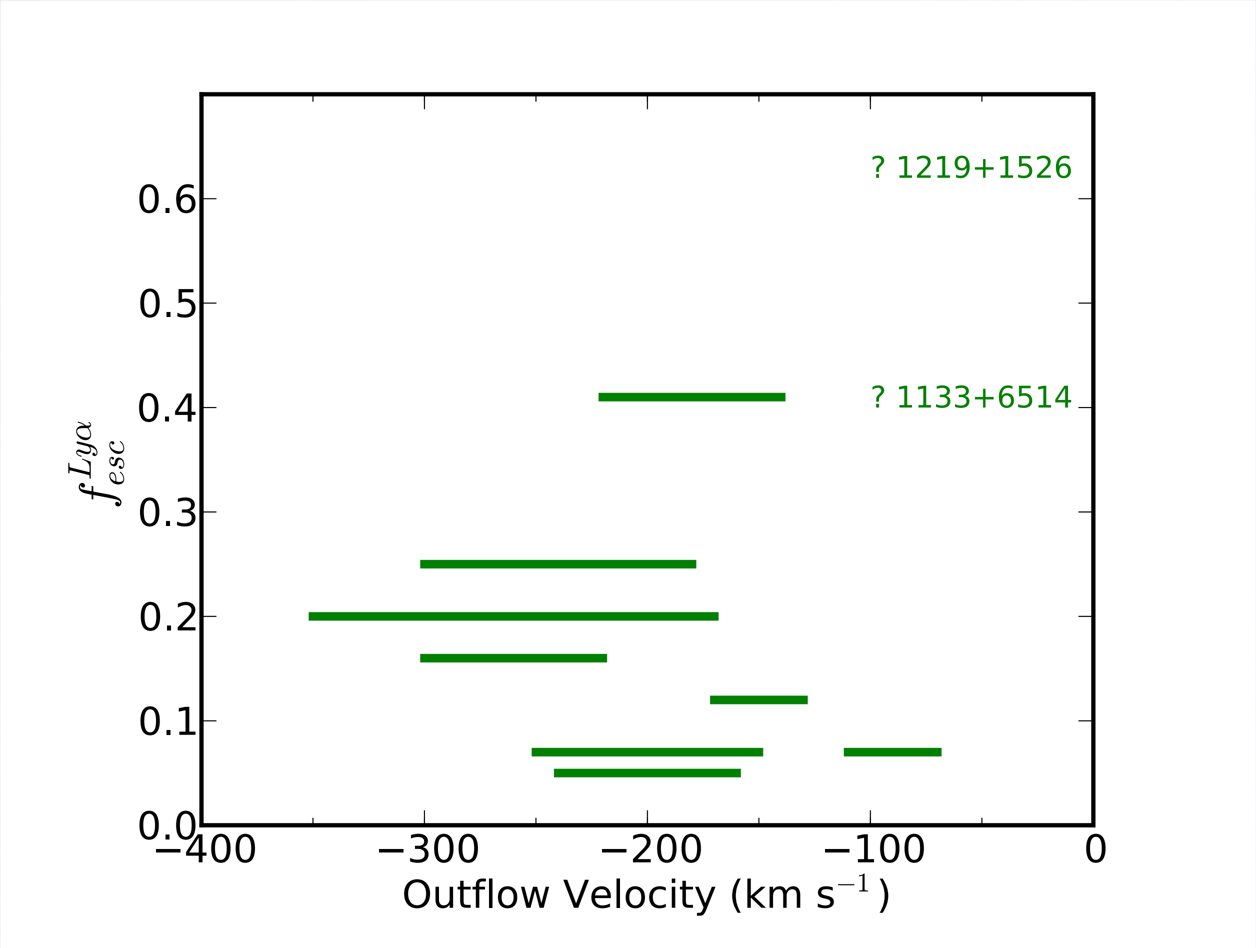
(Si I → Si II)

Test 1: Do outflows help Lyα escape?



Result: While the Green Peas all show Lyα and outflows, there is no correlation between the two.

Test 1: Do outflows help Lyα escape?



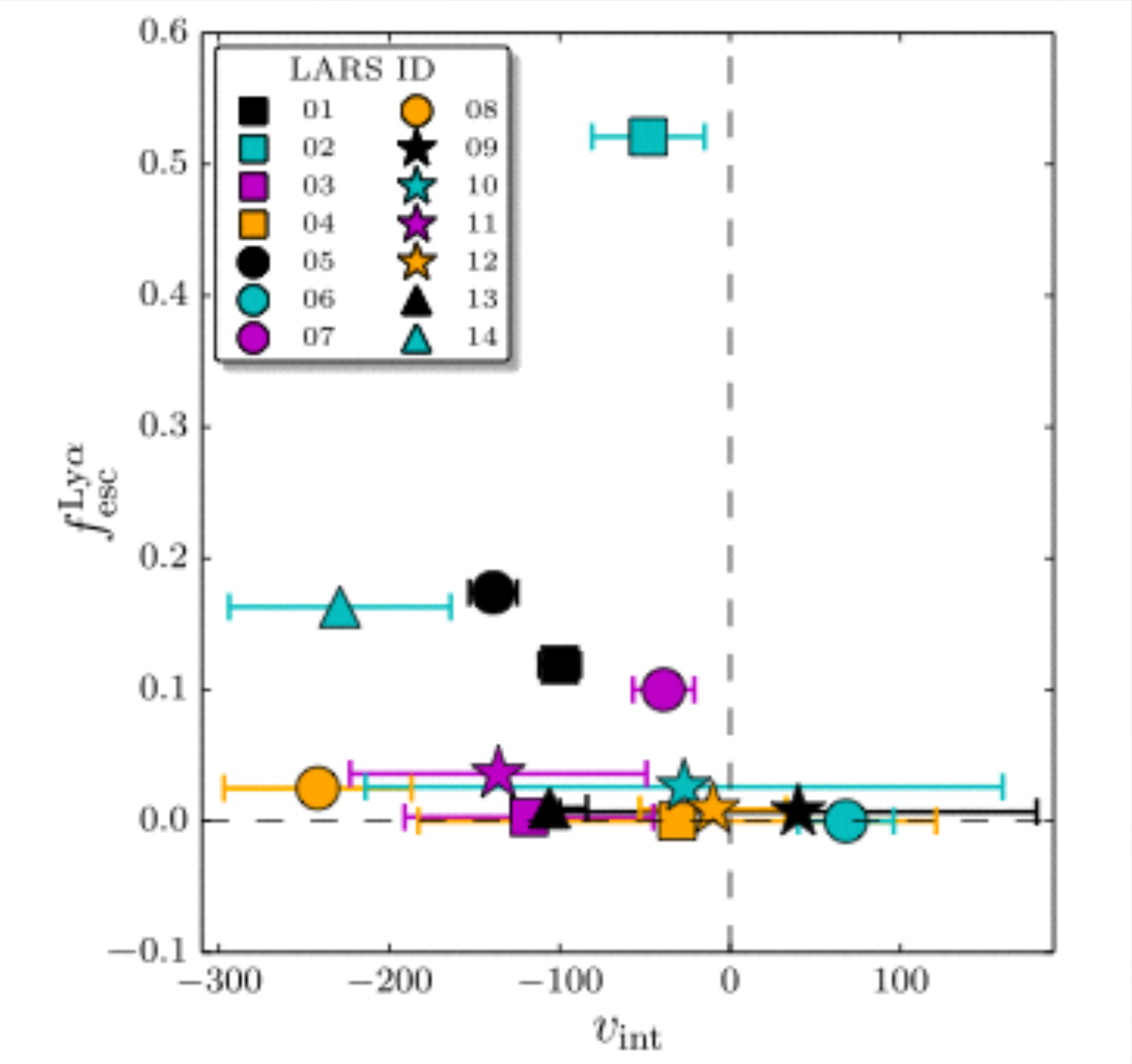


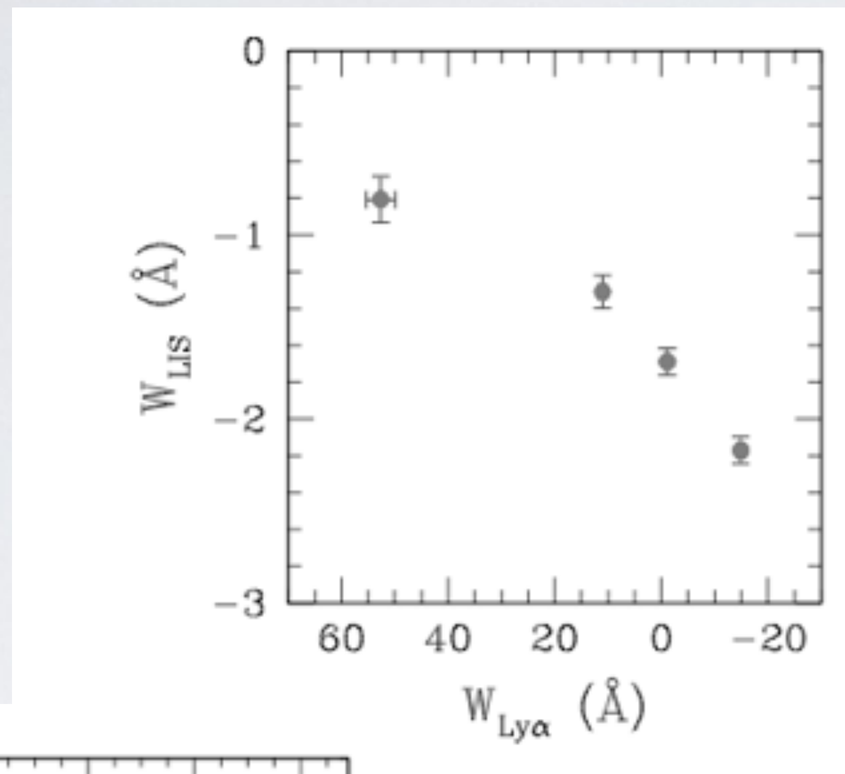
Figure 13. Plot of wind velocity vs. escape fraction $f_{\rm esc}^{\rm Ly\alpha}$ for the LARS sample. Escape fractions are global, imaging-derived values from Hayes et al. (2014).

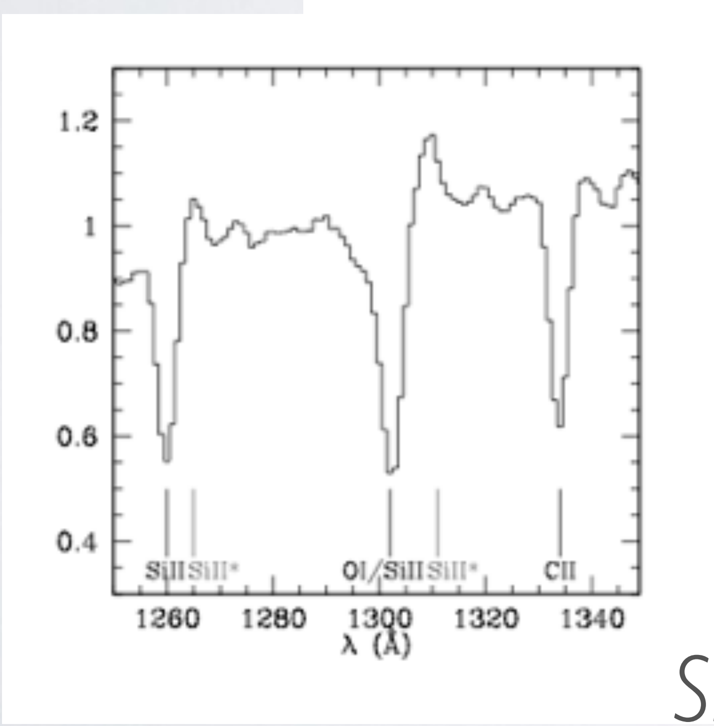
necessary but insufficient?

Rivera-Thorsen et al. (2015)

Test 2: Does Lyα escape through holes in the HI gas?

Data (z~3)





Shapley+03

Model

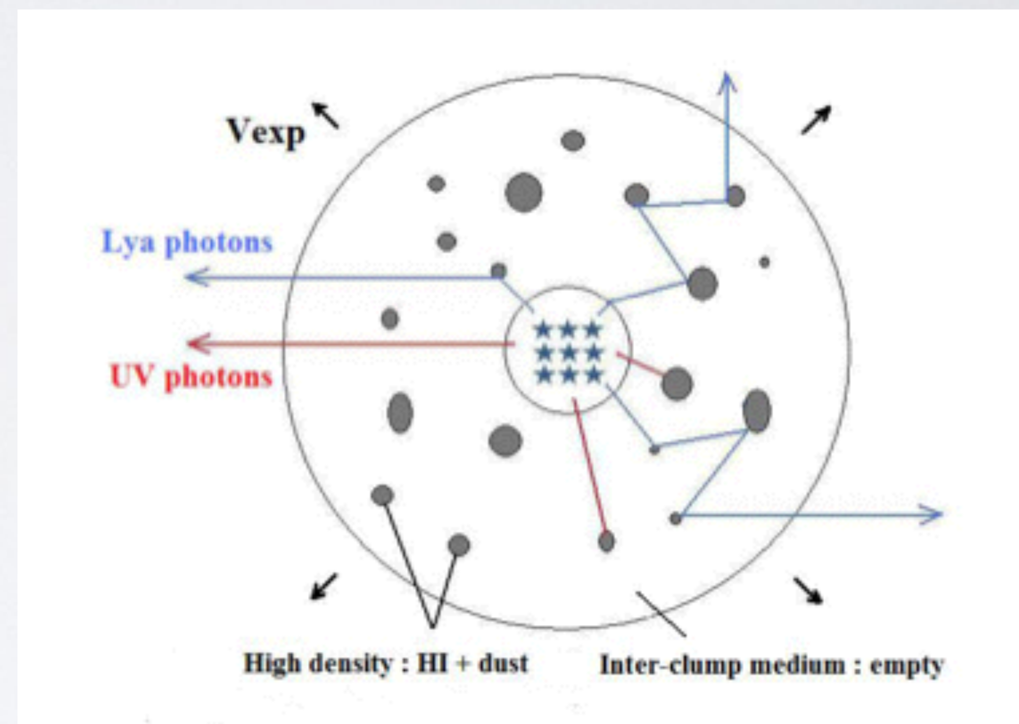
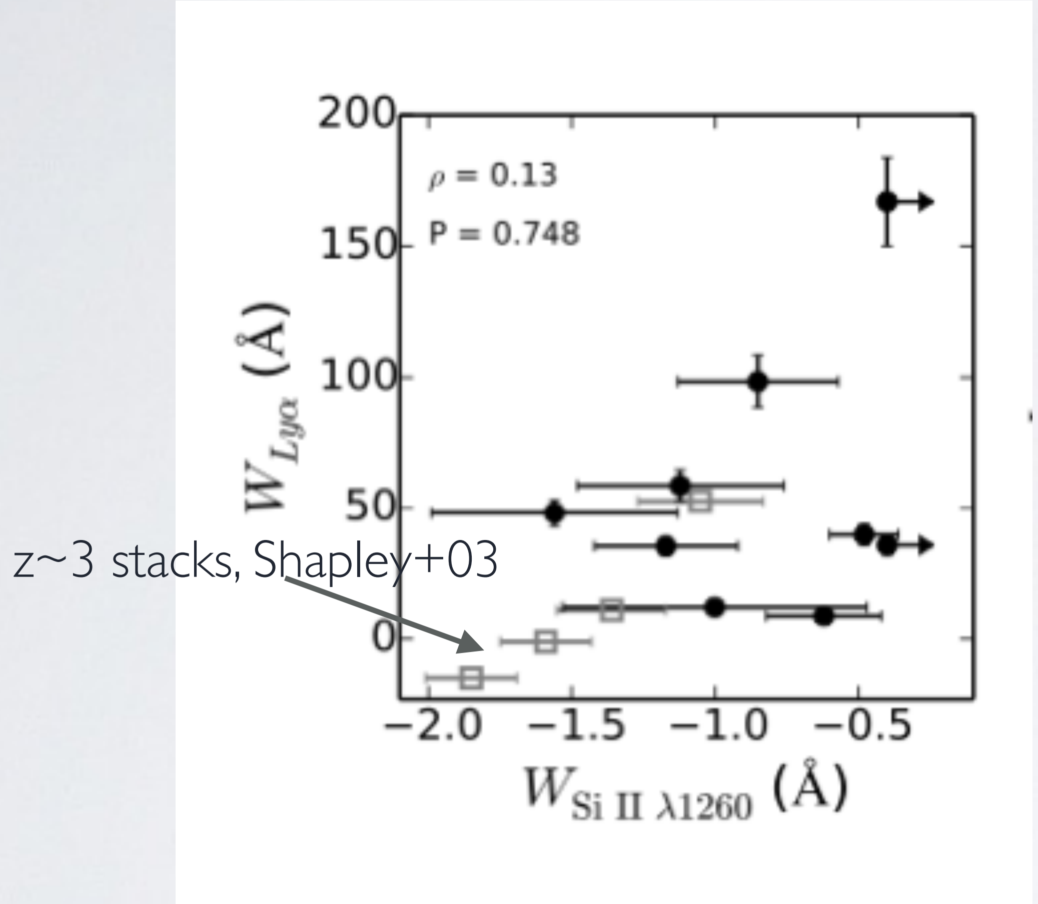


image from Duval et al. (2014)

Test 2: Does Lyα escape through holes in the gas?



Henry et al. (2015)

- Equivalent width trend confirmed…

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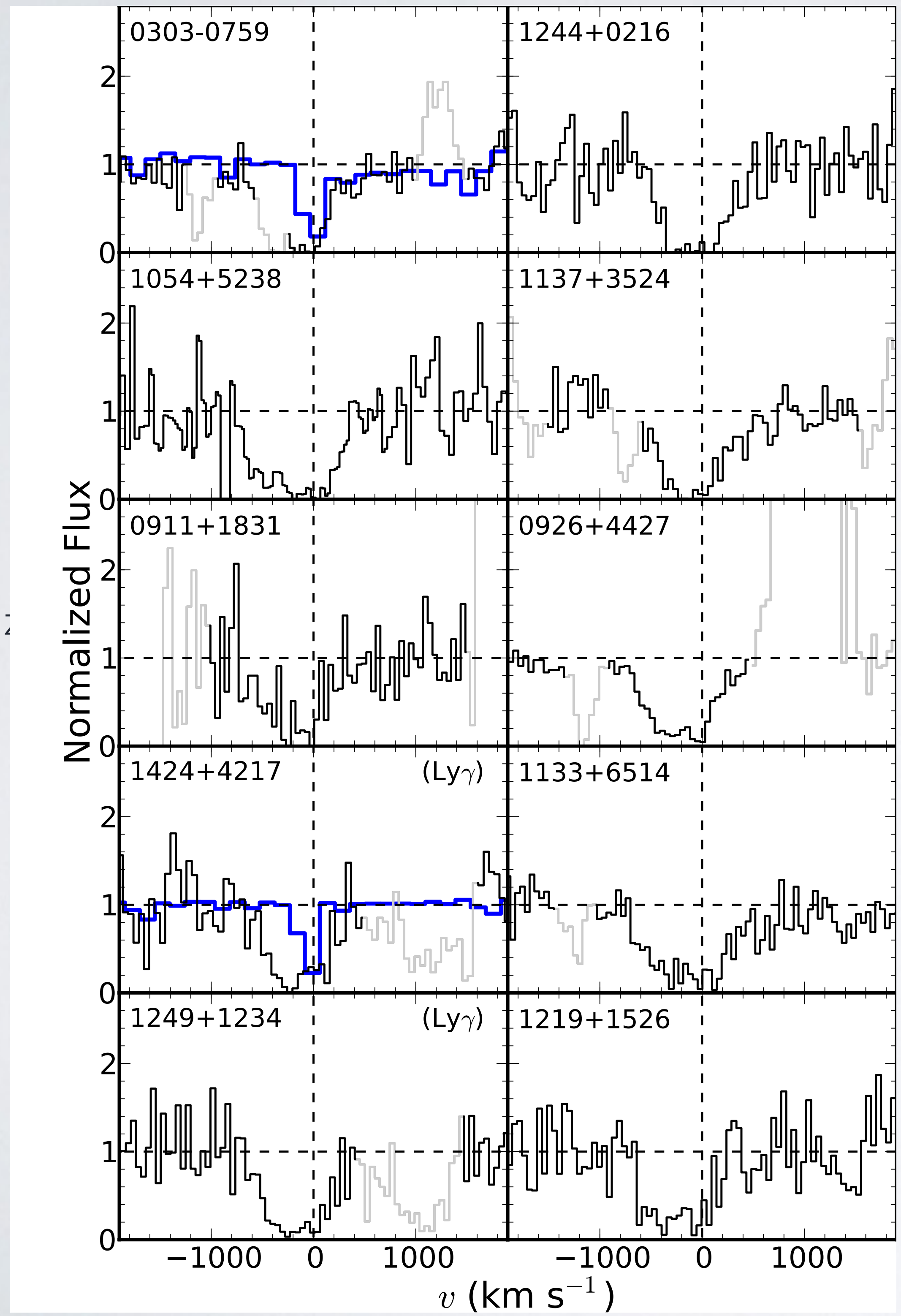
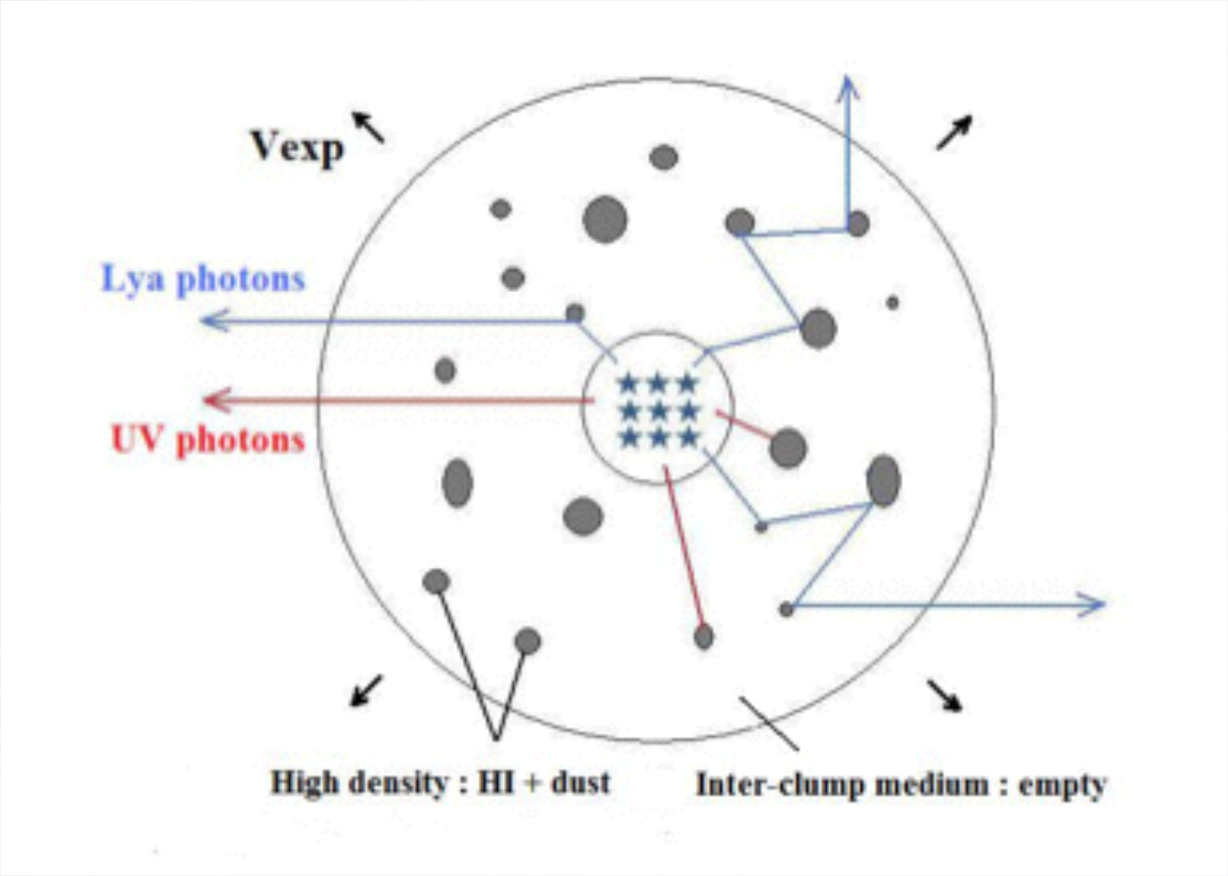


- Equivalent width trend confirmed…

- <u>But</u>: COS spectra show Lyman series absorption is opaque → HI covering near unity

HI gas is everywhere.

Test 2: Does Lyα escape through holes in the gas?



- There are no holes for Lyα to escape
- Two scenarios remain:

1. the clumps still exist, partially cover the galaxy, and give rise to detectable/saturated metal absorption. Surrounding HI saturates Ly series but metal density is too low to detect.

2. the medium is homogeneous and the metals are optically thin.

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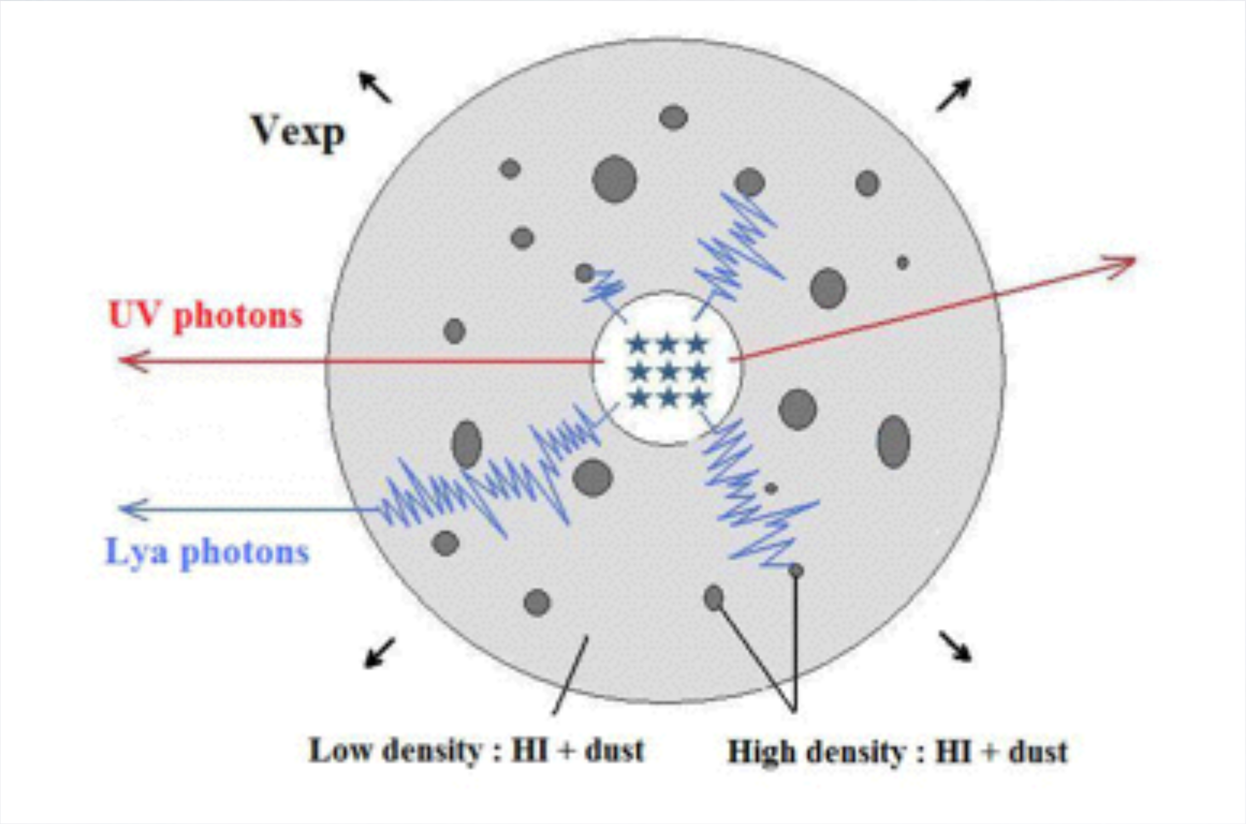

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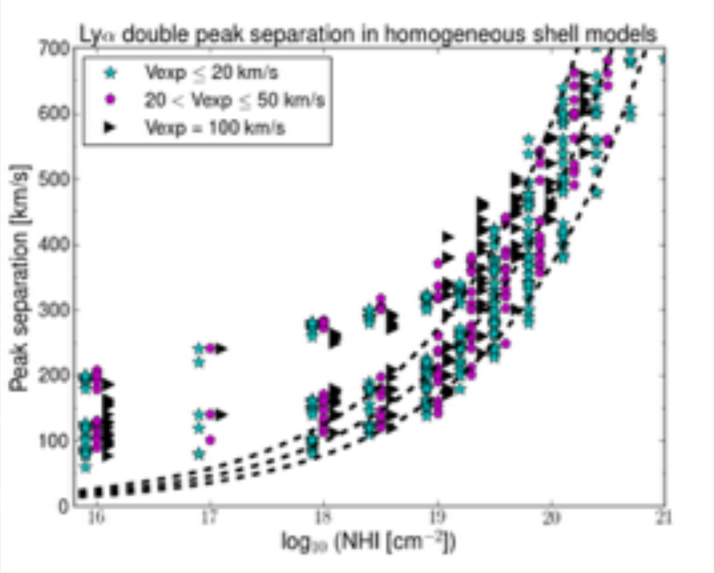
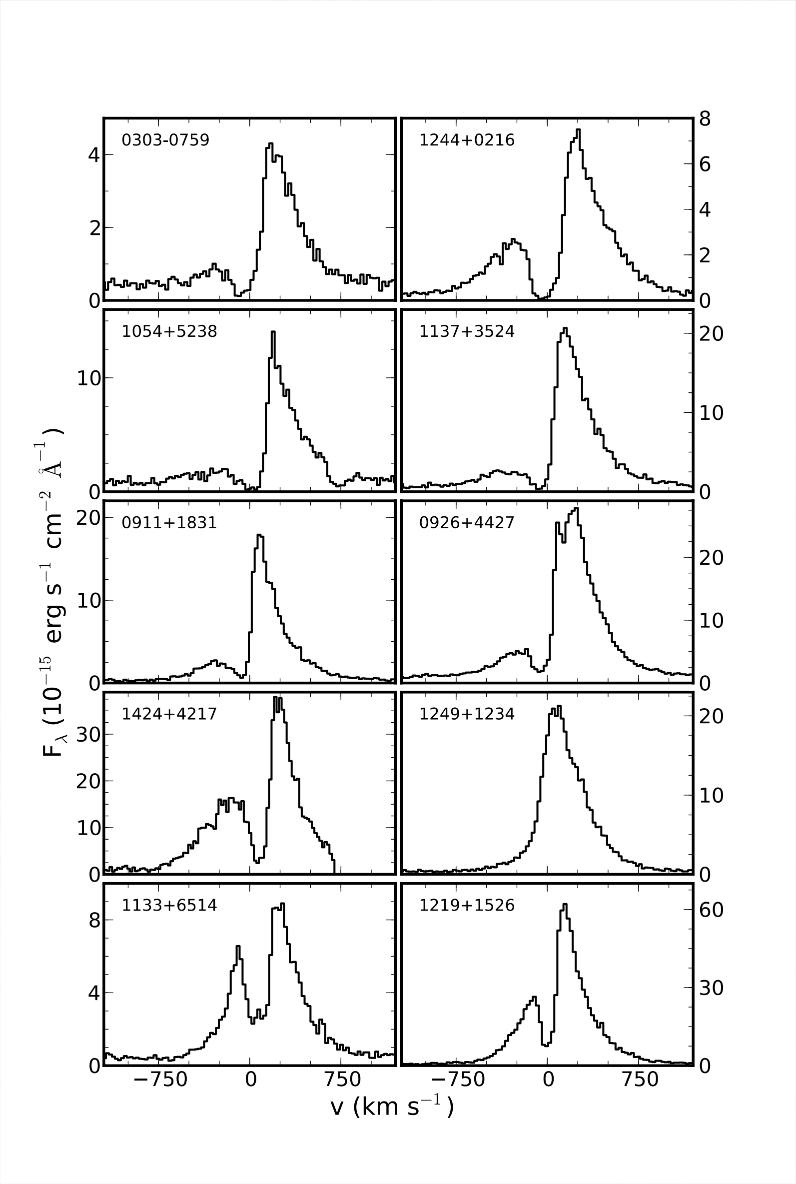
Test 3: HI gas density? (yes!)

- *<u>Hypothesis</u>*: Lyα escapes more easily when lower HI column density reduces the scattering.



Verhamme et al. (2015)



Henry et al. (2015)

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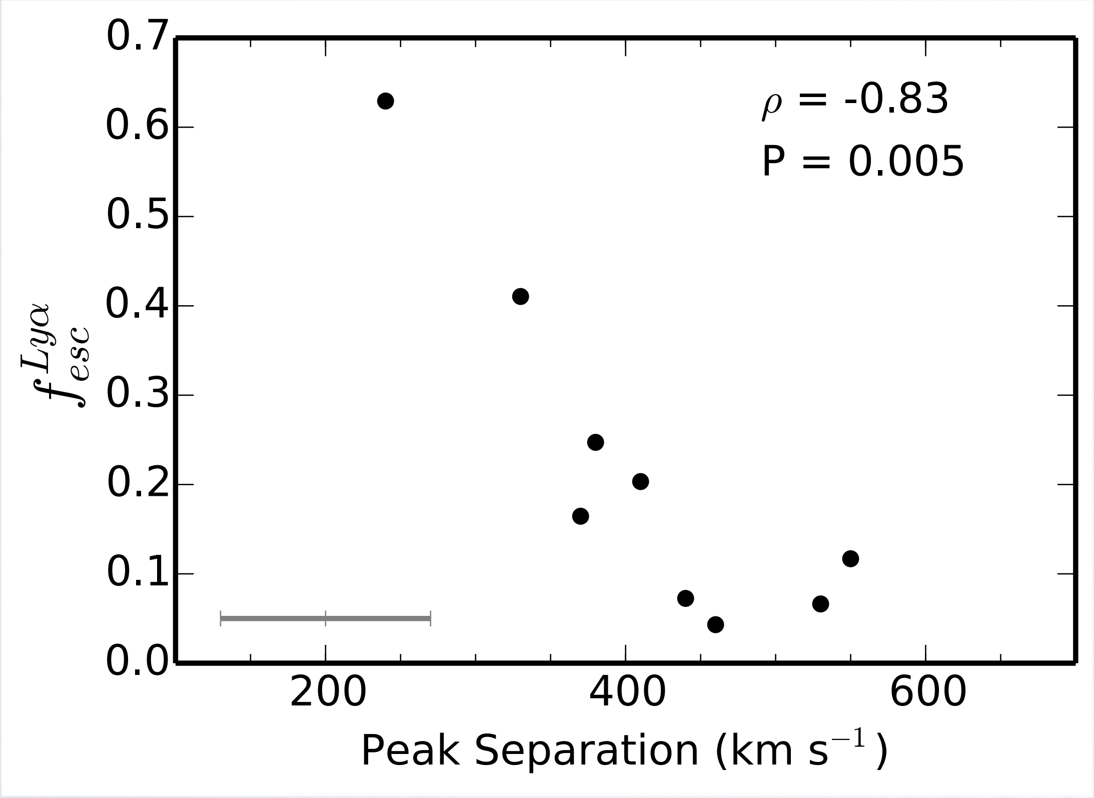
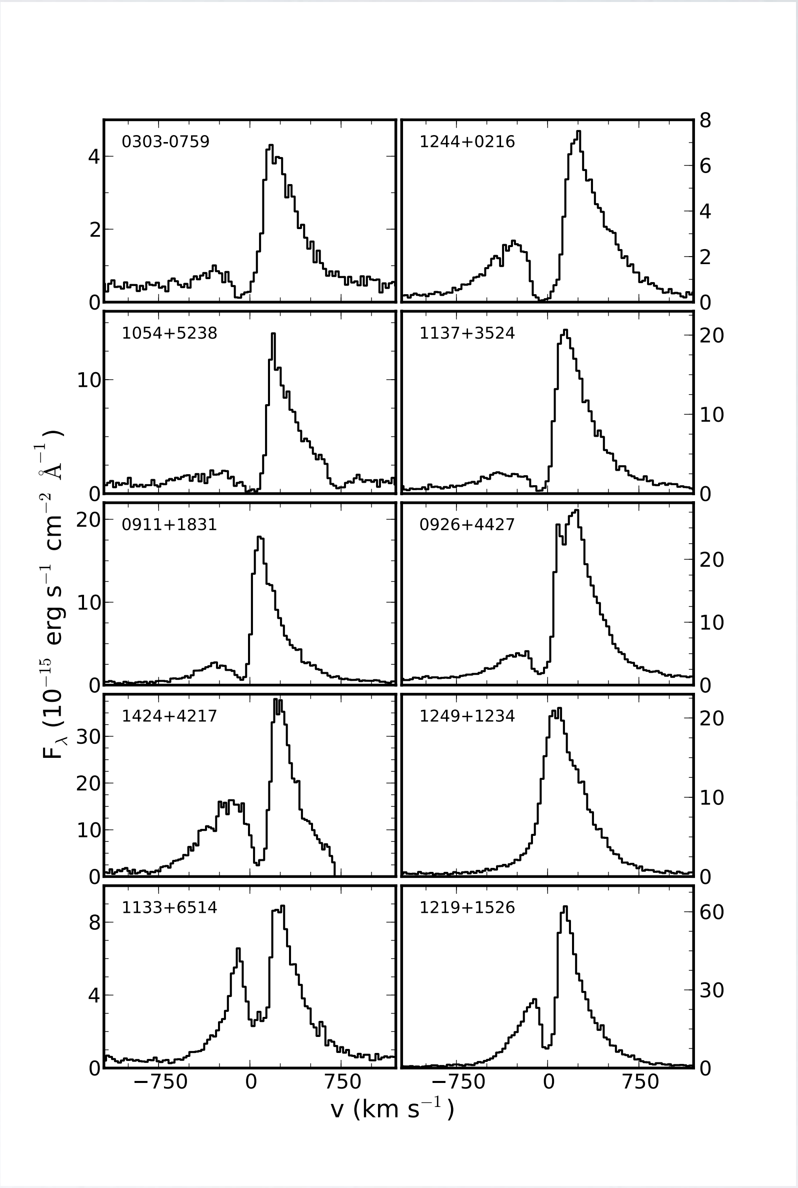




Henry et al. (2015)

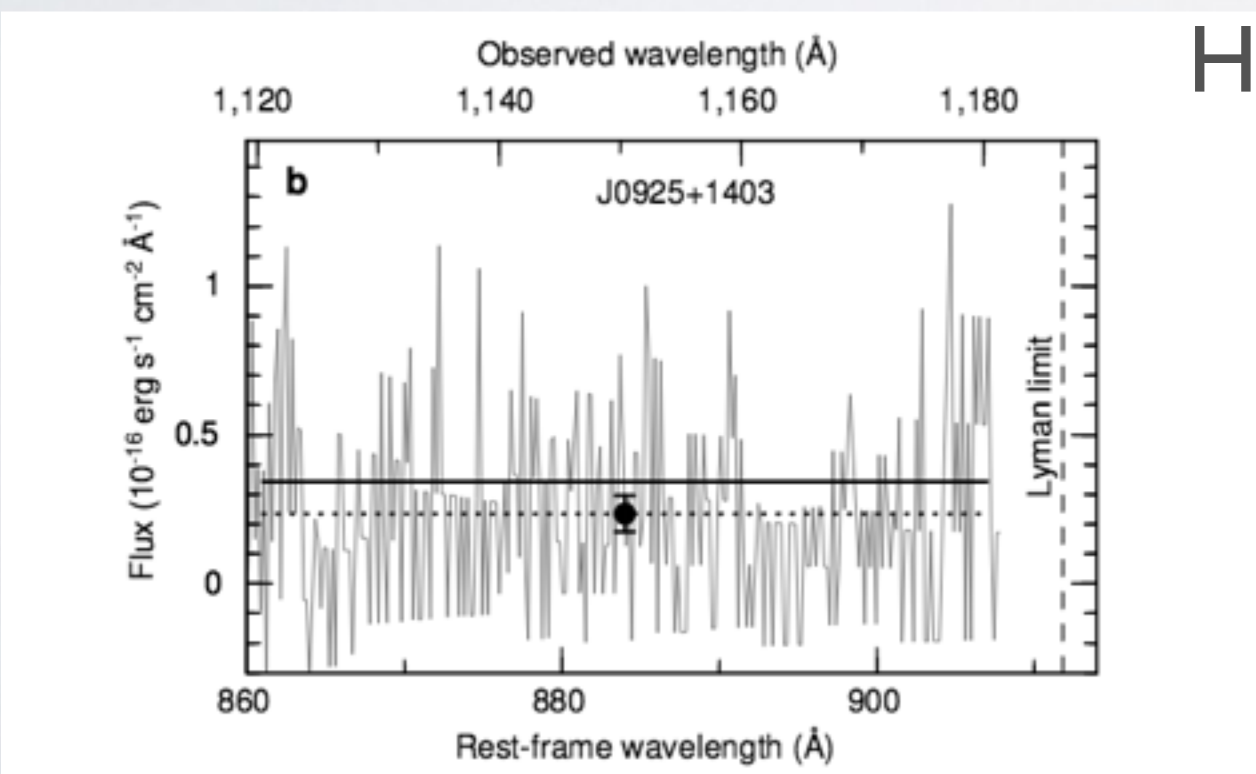
- *Result*: Lyα peak velocity separation, which is a signature of HI density correlates with the Lyα escape fraction.

What do these low-redshift Green Peas tell us about high-redshift galaxies?

What have we learned, that might be important at high redshift? (1)

The H I column densities seem to be low when Lyα is strong: 10^{16} -10^{20} cm^{-2}.

— potentially optically thin to hydrogen ionizing Lyman Continuum (LyC).



HST/COS direct detection of LyC (Izotov et al. 2016, Nature).

z~0.3

f_{esc}(Lyc) ~8%

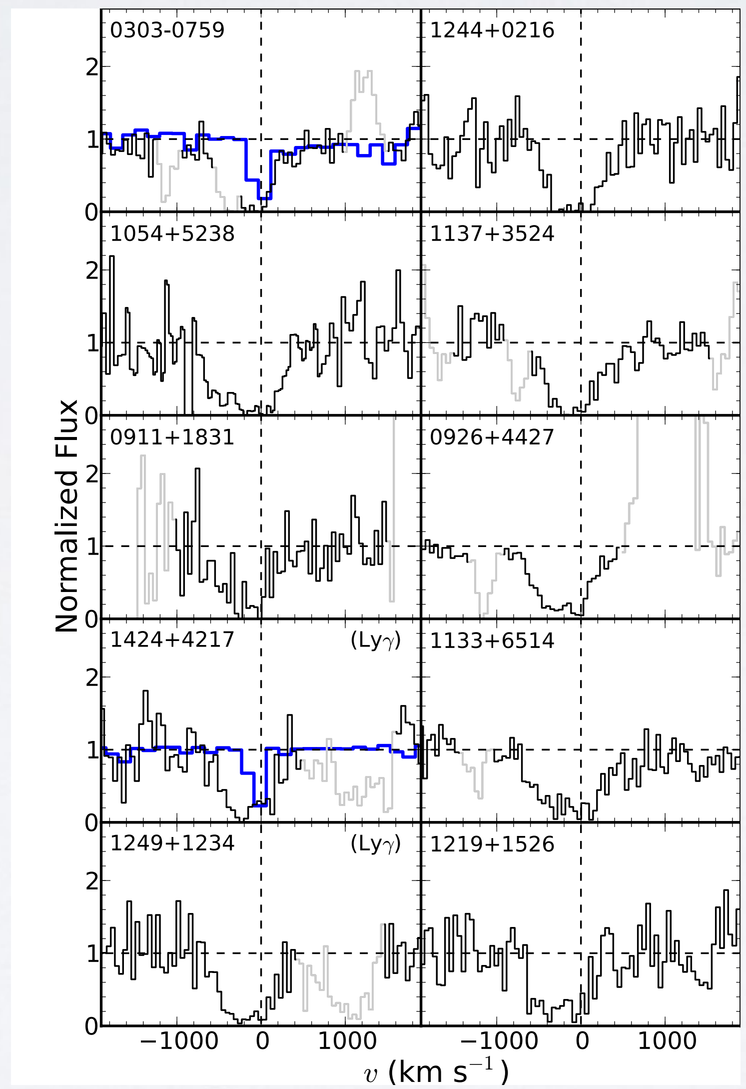
f_{esc}(Lyα) ~ 70%

$v_{peak\ separation}$ ~ 300 km s^{-1}

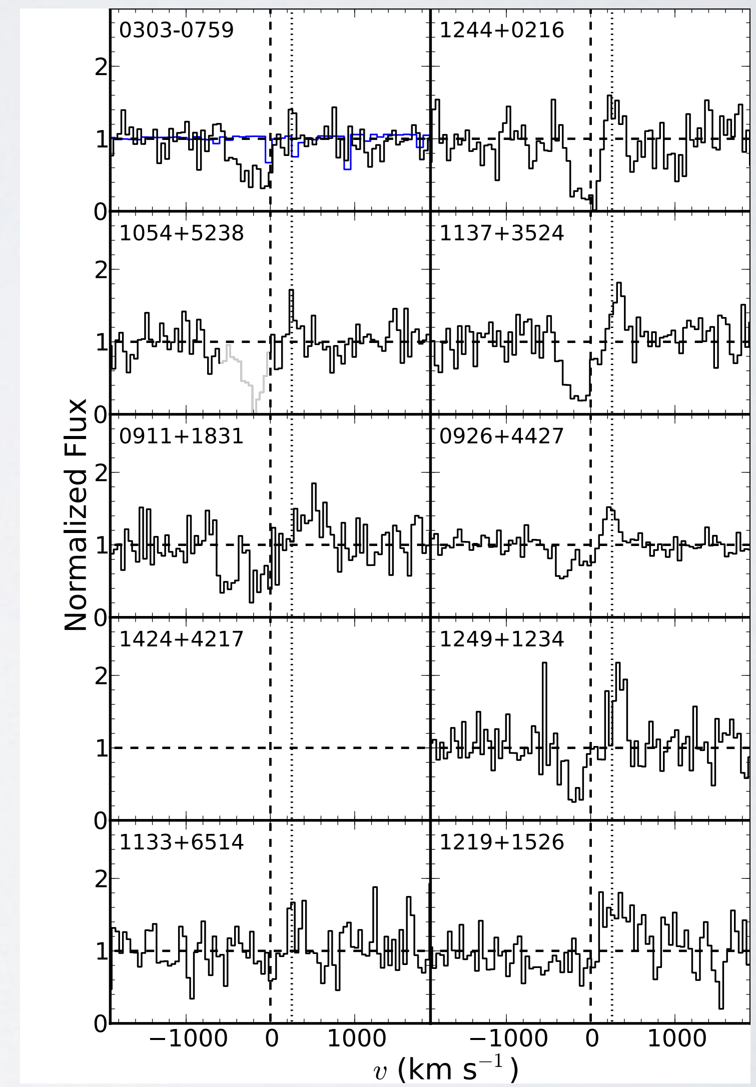
What have we learned, that might be important at high redshift? (2)

Observations of the H I Lyman series are important for quantifying the spatial distribution of gas

The residual H I that resides in the less-dense circumgalactic medium is still enough to influence the radiative transfer of Lyα



Ly β



C II

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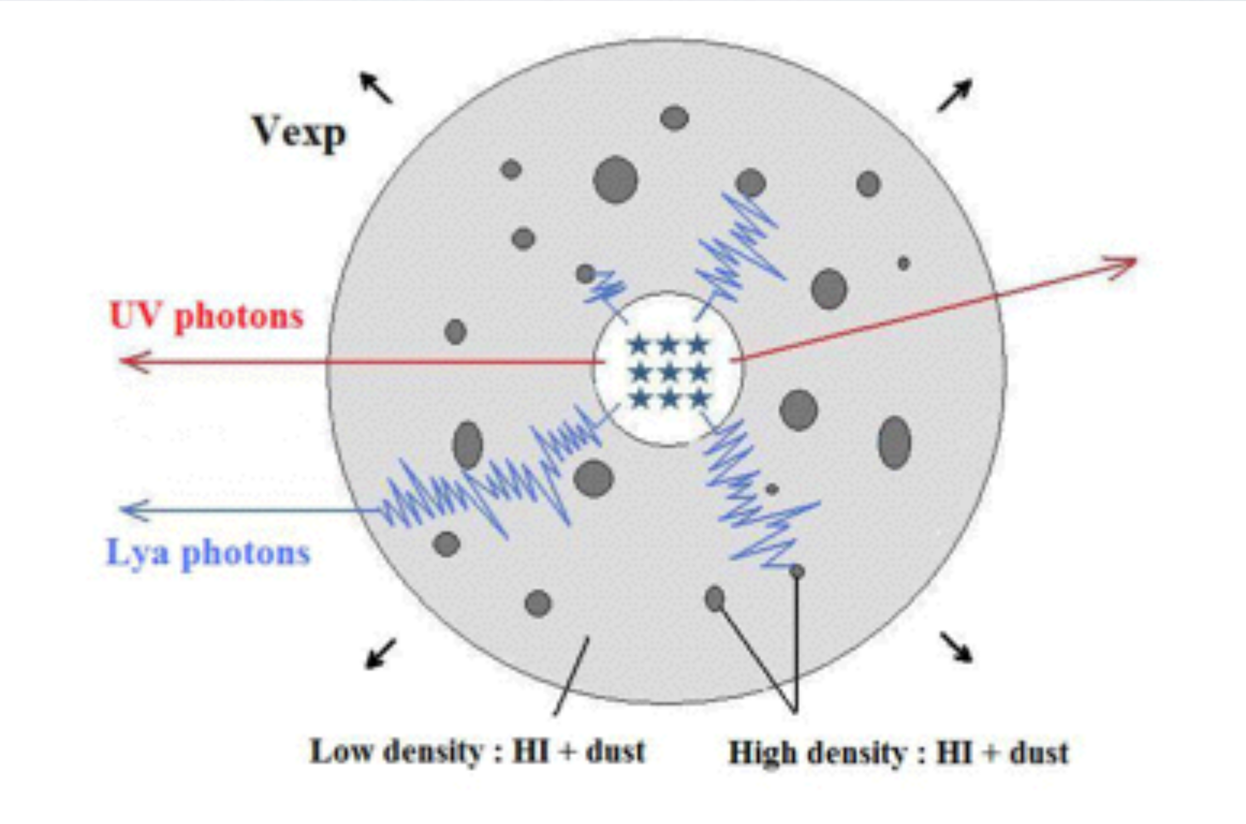


image from Duval et al. (2014)

Composite spectra of z~2 galaxies can probe the extreme UV (<1216 Å)

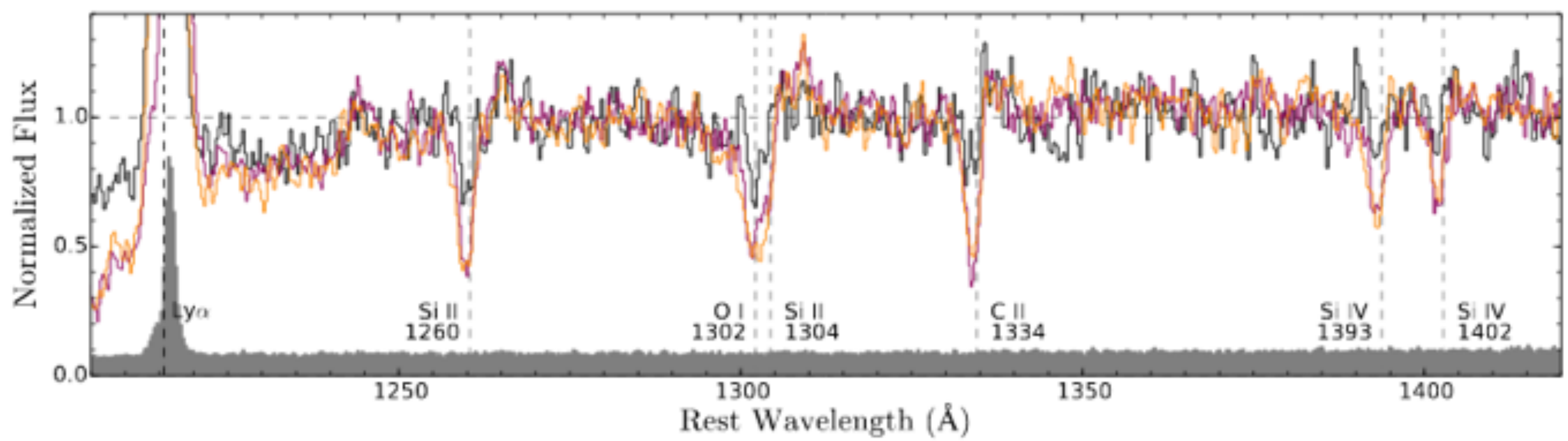
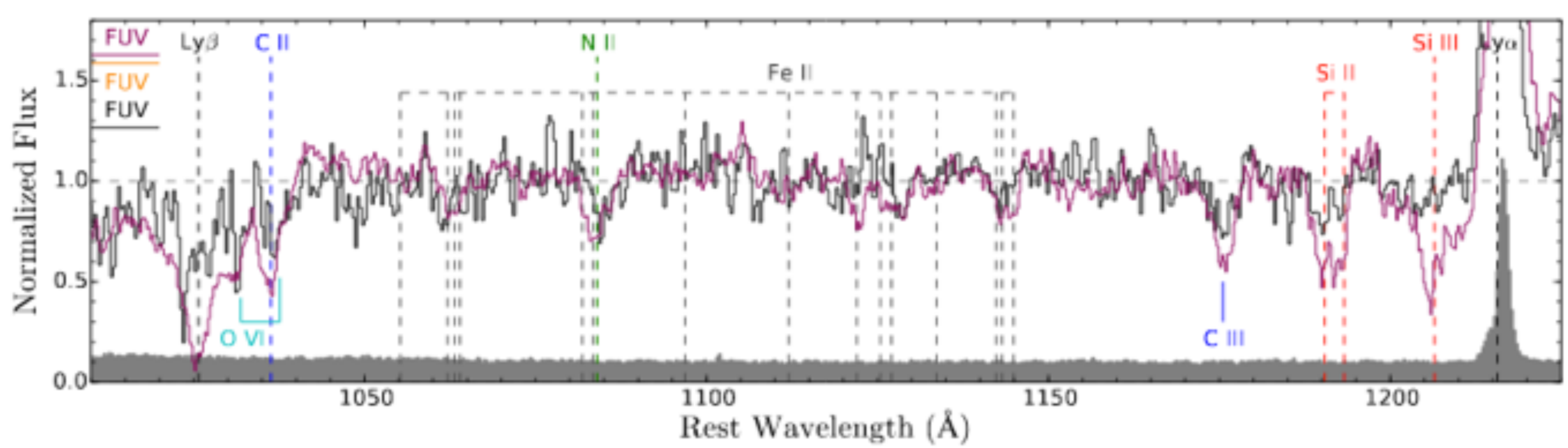


FIG. 20.— Composite rest-FUV continuum spectra (as in Fig. 19) normalized to a common f_{1325} continuum level (1250Å< λ < 1400Å). As in the preceding figures, the bootstrapped LAE error spectrum is in grey. The absorption lines displayed in Fig. 15 are here marked by vertical dashed lines. The two LBG samples (orange, purple) are highly consistent with each other and exhibit clear contrasts with the LAE sample, including significantly broader and deeper absorption profiles.

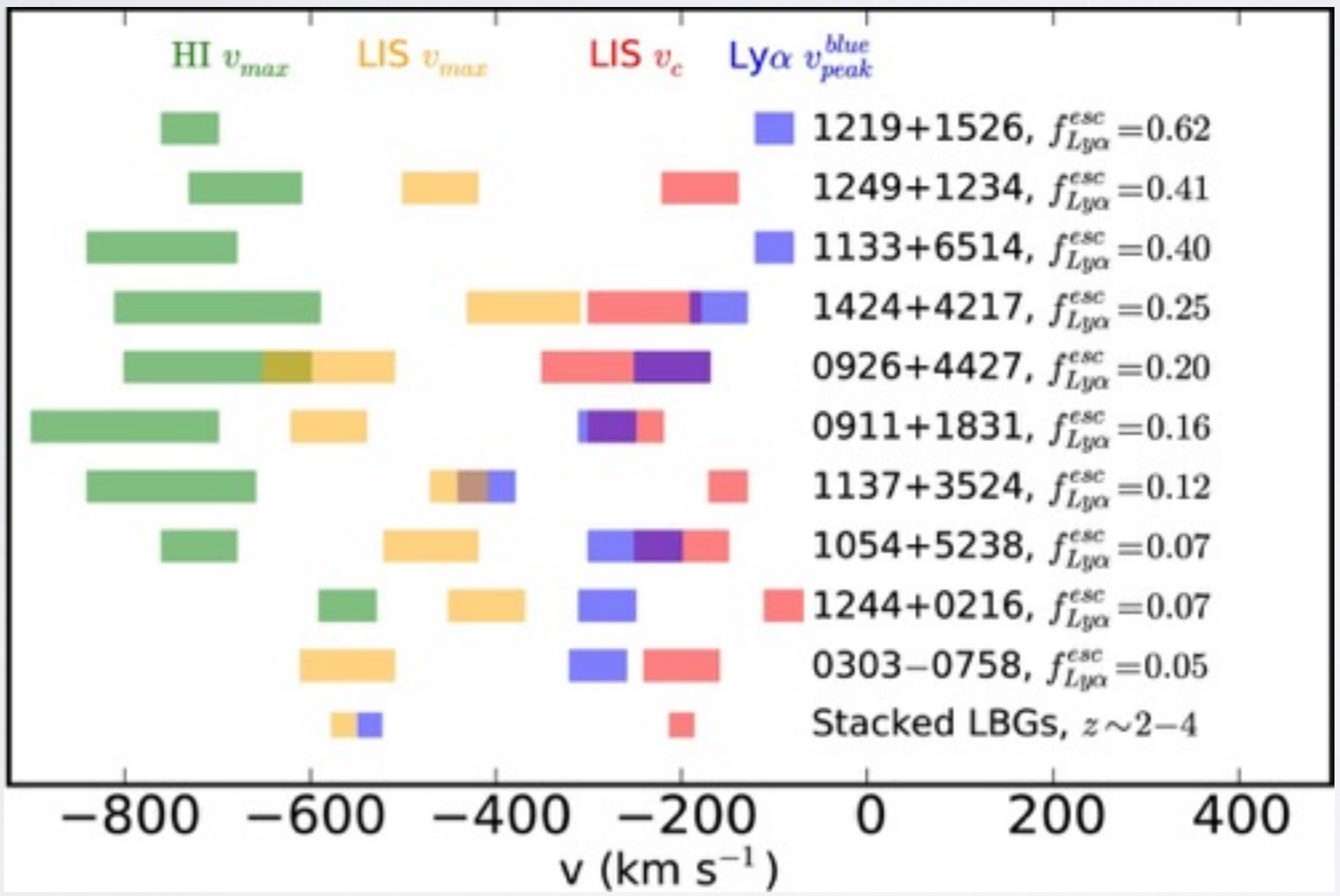


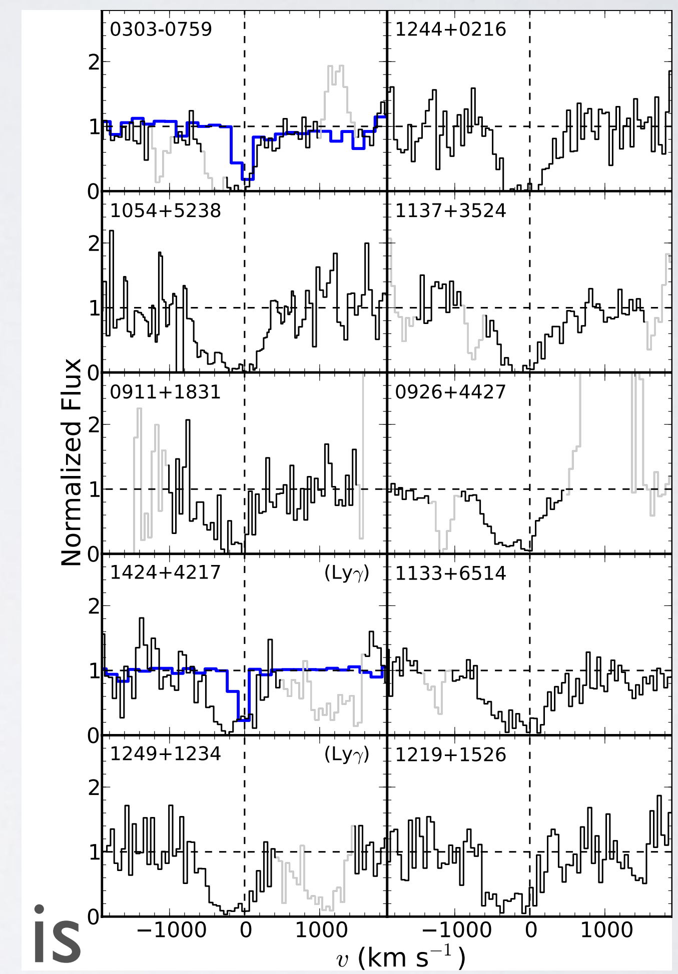
(Trainor et al. 2015)

What have we learned, that might be important at high redshift? (3)

Observations of the H I Lyman series are important for properly measuring the maximal outflow velocity.

Henry et al. (2015)





The maximum velocity reached in H I absorption is always greater than metals. Agrees with blue Lyα wing. Plus… obviously not a thin shell of gas.

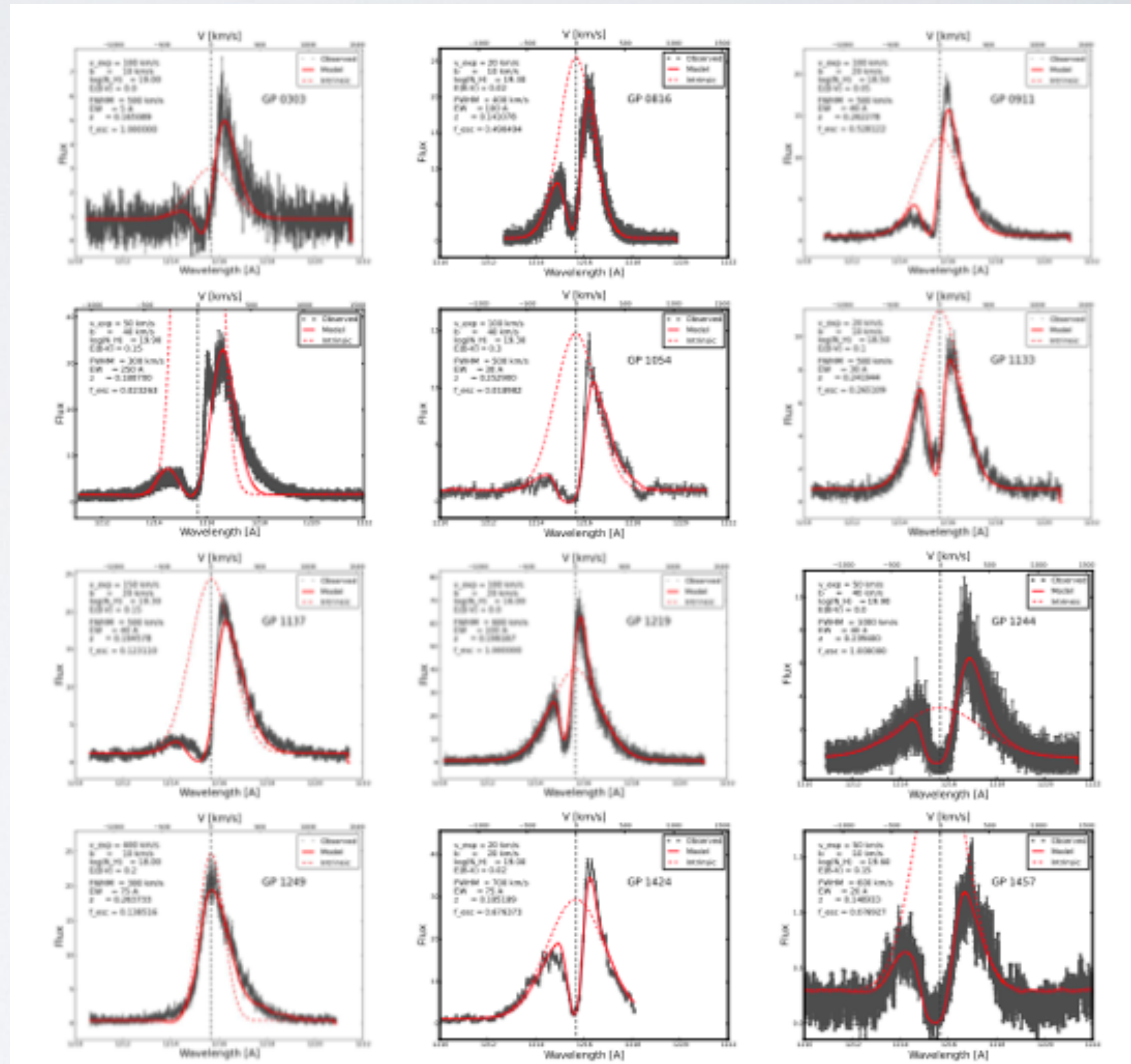
Ly β

What have we learned, that might be important at high redshift? (4)

Lyα Radiative transfer models that assume a thin H I shell may not work.

The high fidelity of the data, especially SDSS, place stringent constraints.

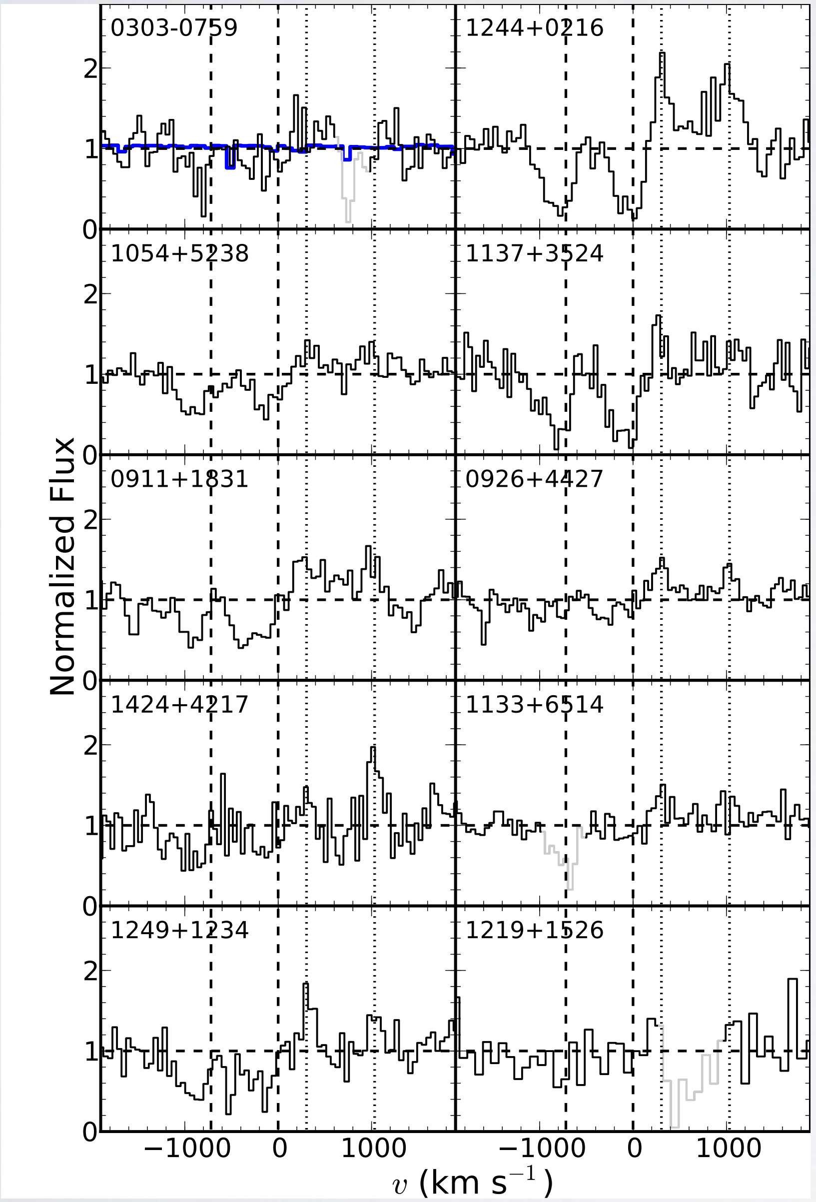
Fixing redshifts and FWHM to SDSS causes discrepancy. Double peaks prefer low outflow velocity, in conflict with COS spectra.



Orlitova et al. (+AH, in prep)

What have we learned, that might be important at high redshift? (5)

Emission filling must be accounted for,



Si II: Henry et al. (2015)

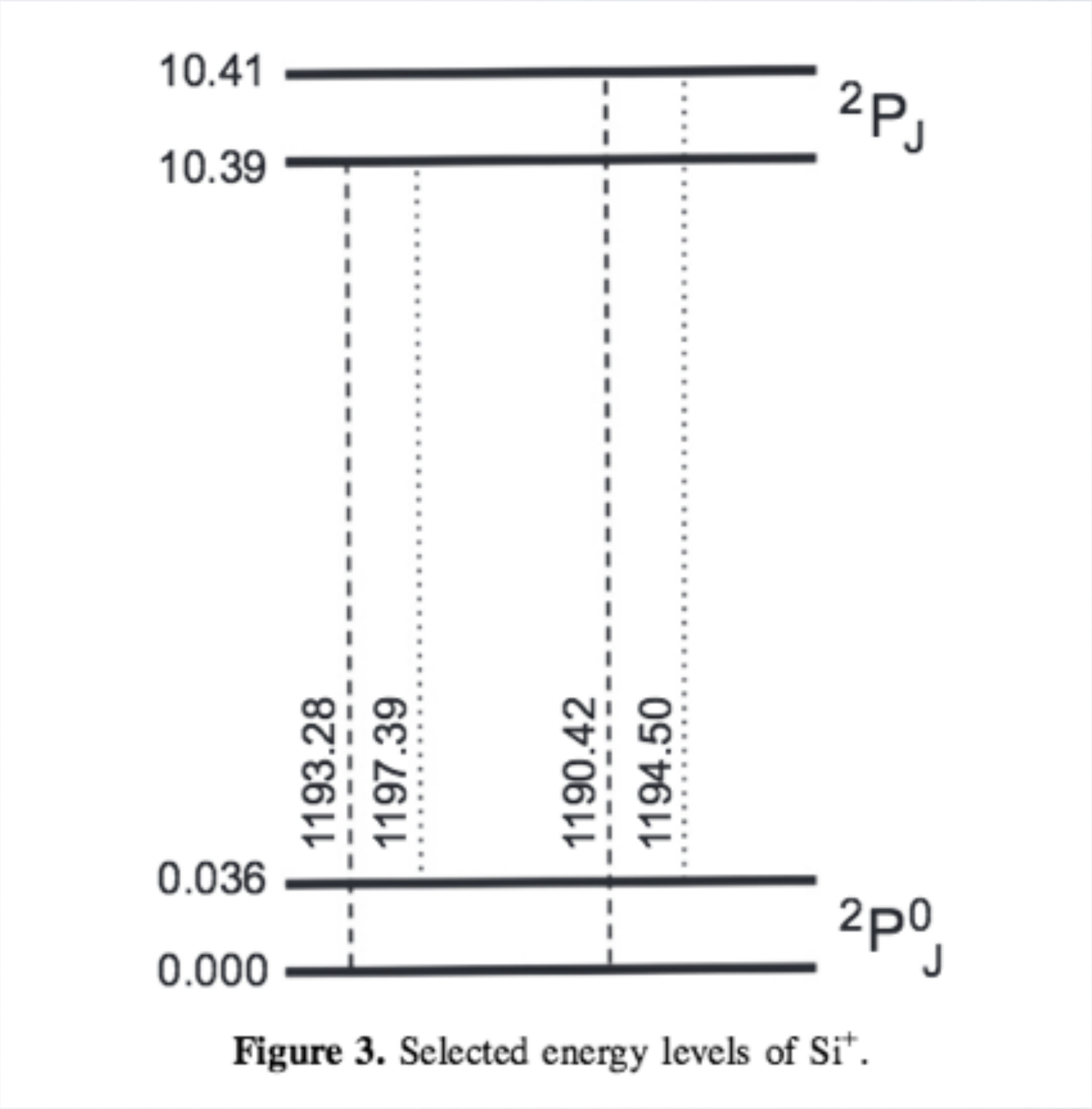
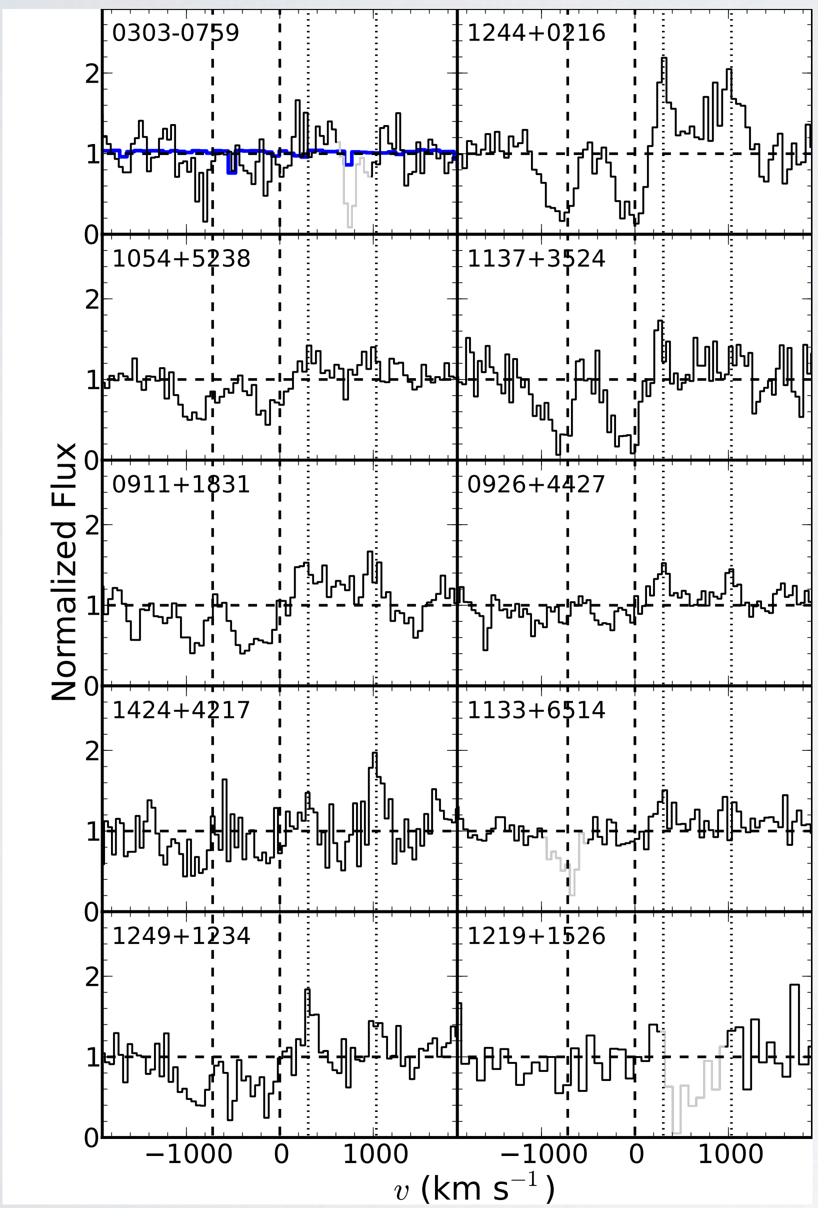


Figure 3. Selected energy levels of Si^+.

Scarlata & Panagia (2015)

What have we learned, that might be important at high redshift? (5)

Emission filling must be accounted for,



Si II: Henry et al. (2015)

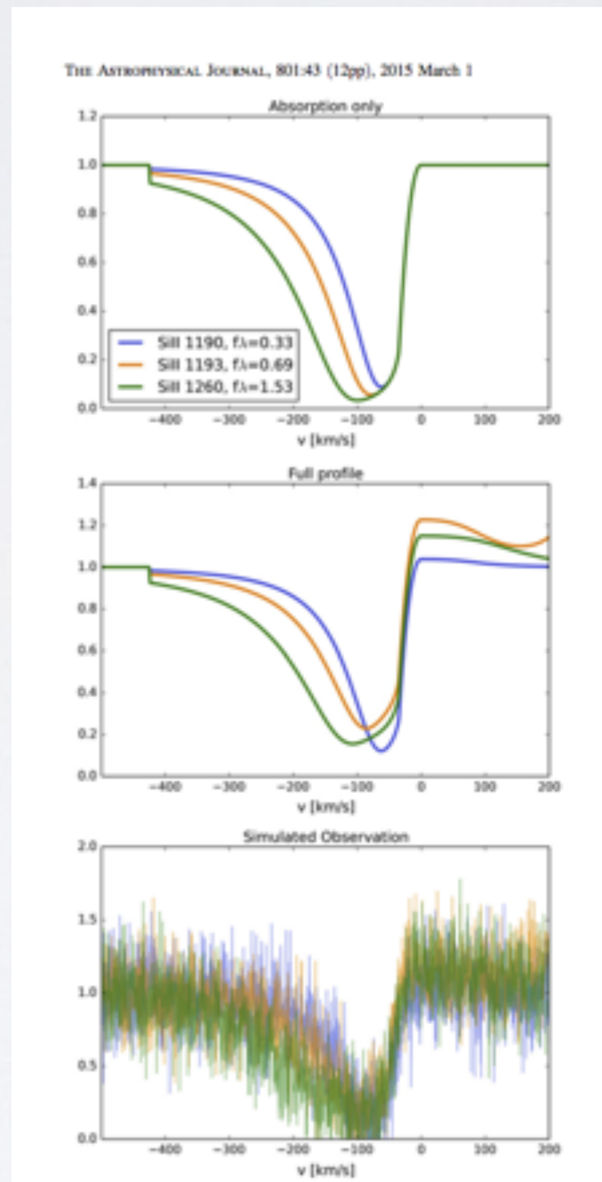


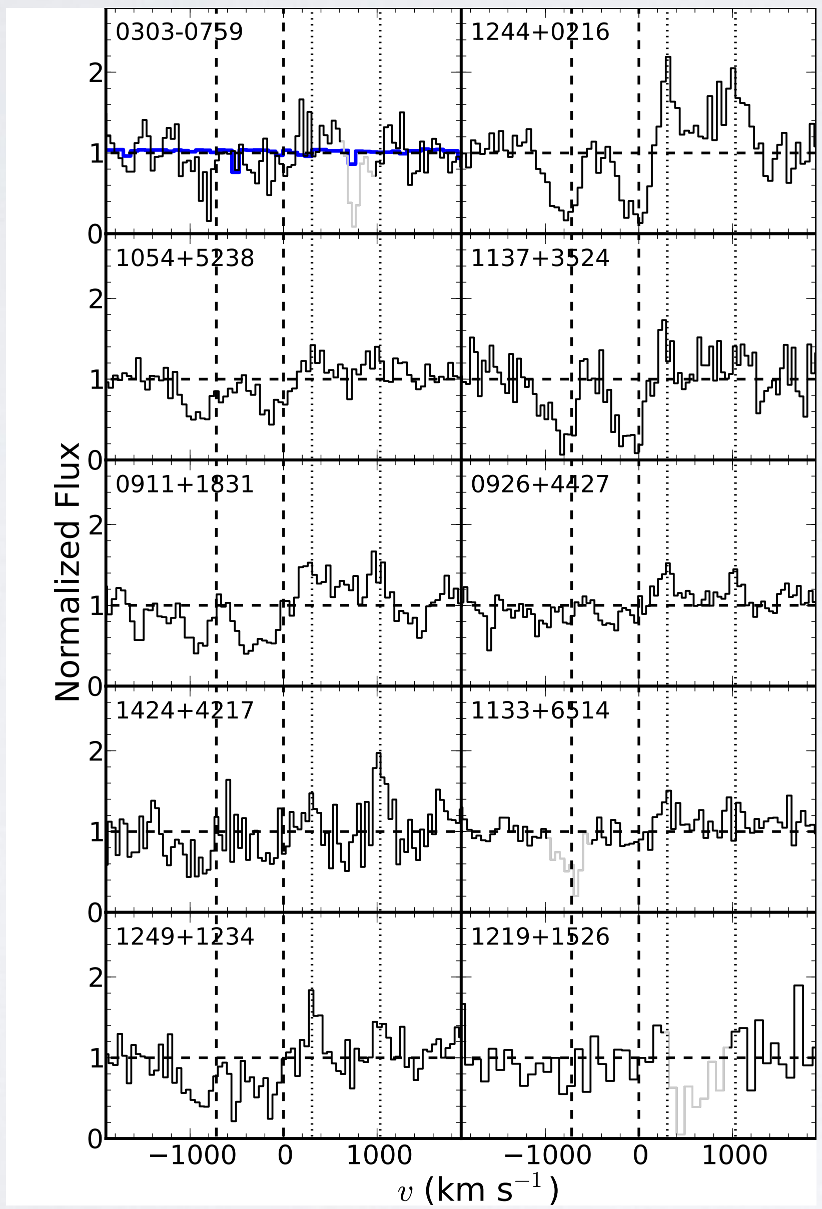
Figure 11. Neglecting emission filling of the absorption profiles can cause erroneous conclusions regarding the gas covering fraction. Top: absorption-only components of three resonant transitions of Si+, as indicated in the legend. The model correspond to a spherical envelope with $v_0 = 35$ km s^{-1}, $v_\infty = 450$ km s^{-1}, and $\tau_{1190Å} = 30$. When only the absorption components are considered, the profiles scale according to the value of $f\lambda$. Middle: full line profiles including the scattered re-emission component. Particularly at velocities close to zero, the profiles no longer scale as $f\lambda$. Bottom: simulated spectrum with 10% errors, and resolution of 30 km s^{-1}.

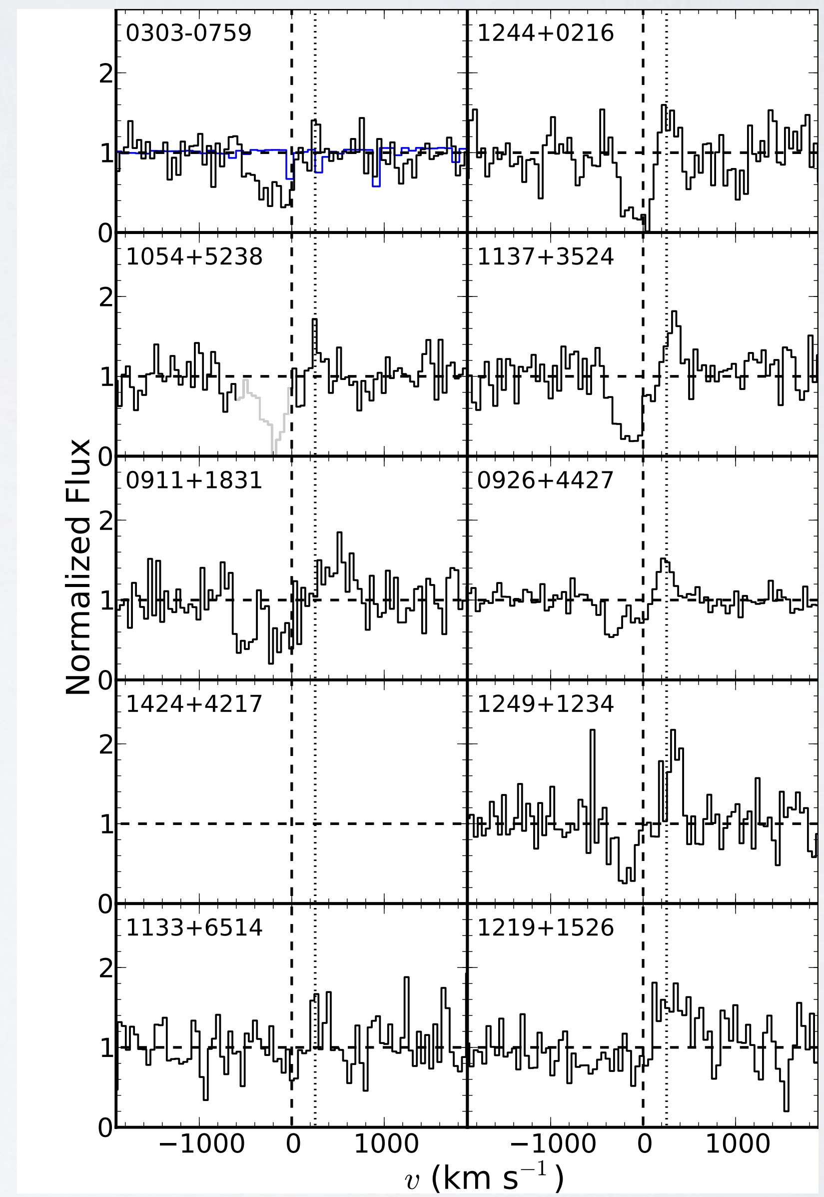
Multiple transitions in same ion, different oscillator strengths. Filling makes the lines look saturated even when they are optically thin. Particularly true for Si II ions probed by COS, and with large aperture.

What have we learned, that might be important at high redshift? (6)

Stacking spectra erases real variations.

Si II
1190, 1193
and Si II*



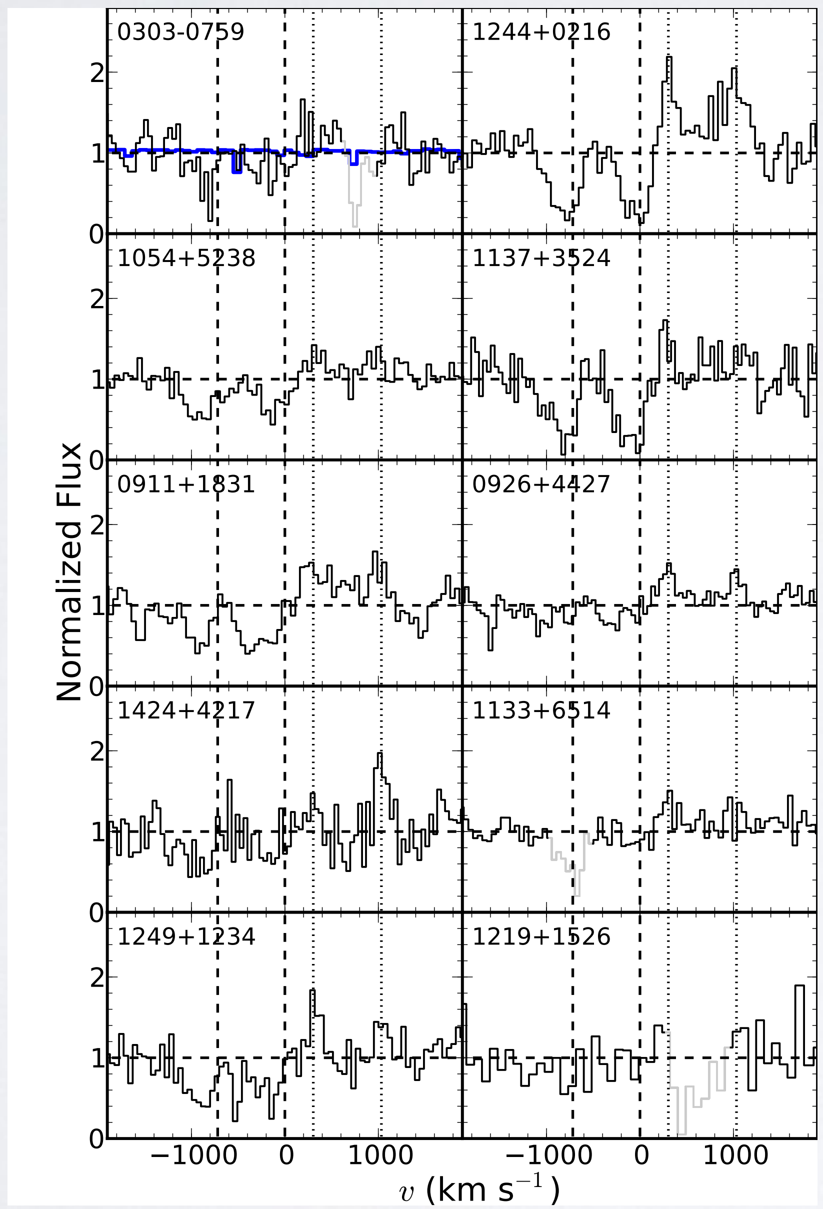


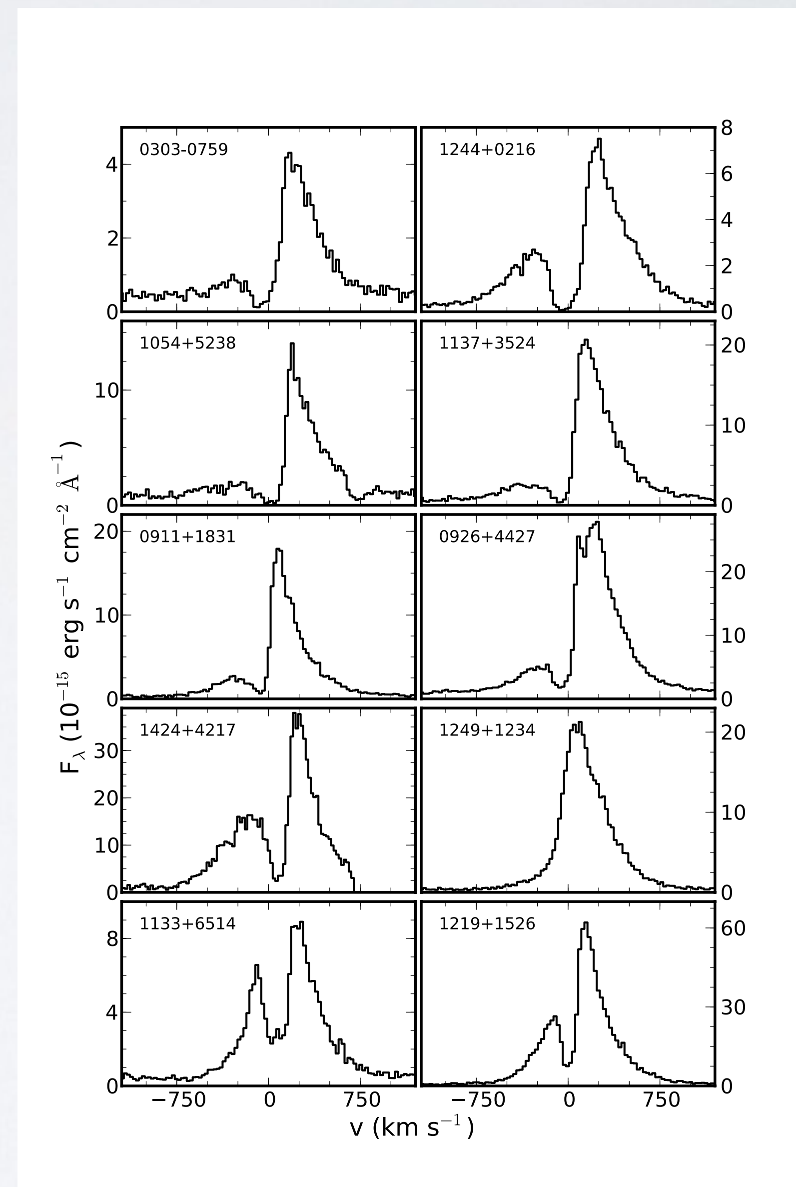
C II
1334
and C II*

Henry et al. (2015)

What have we learned, that might be important at high redshift? (7)

Spectral resolution better than ~100 km s^{-1} is important, for both Lyα and UV absorption lines.

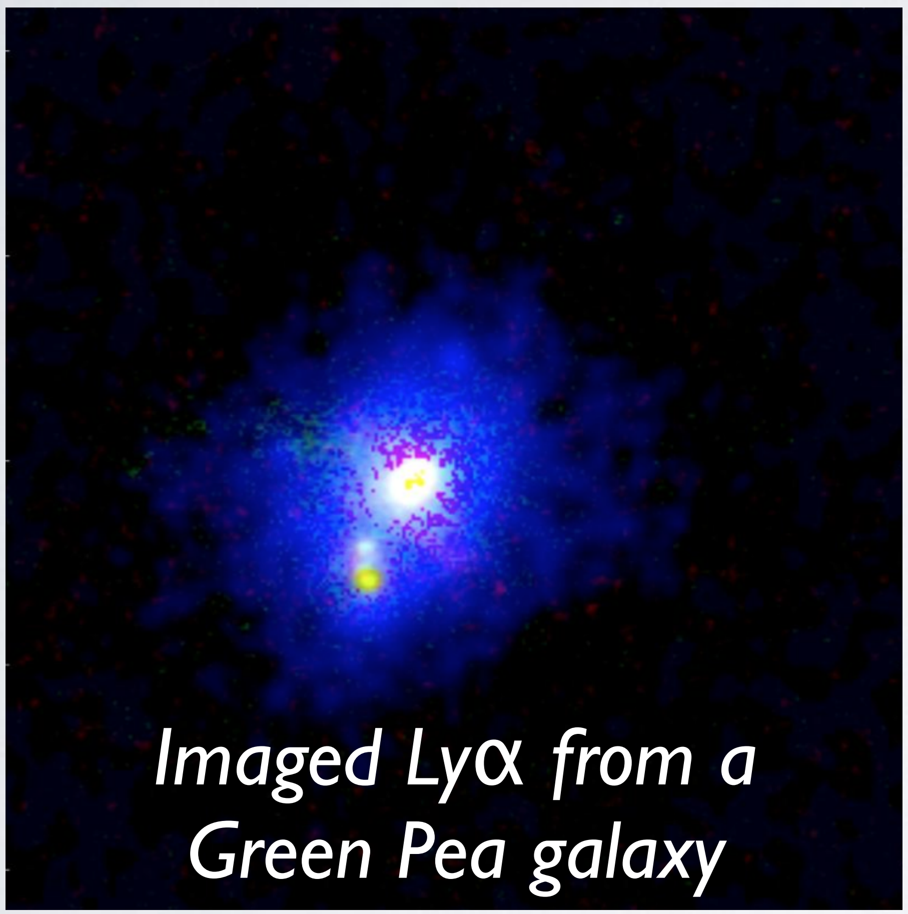




Henry et al. (2015)

What have we learned, that might be important at high redshift? (8)

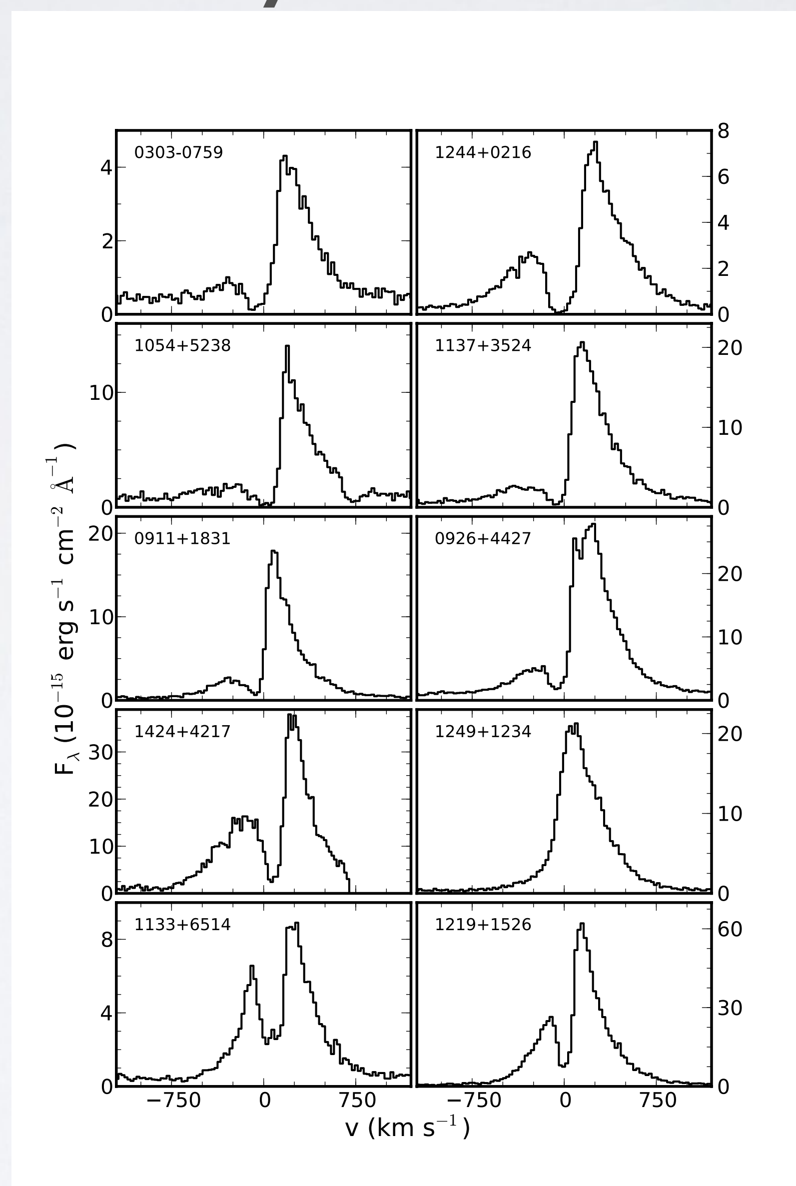
We must take extended Lyα emission into account.



Imaged Lyα from a Green Pea galaxy

Hayes et al. (2014)

extends far beyond stars/ HII regions

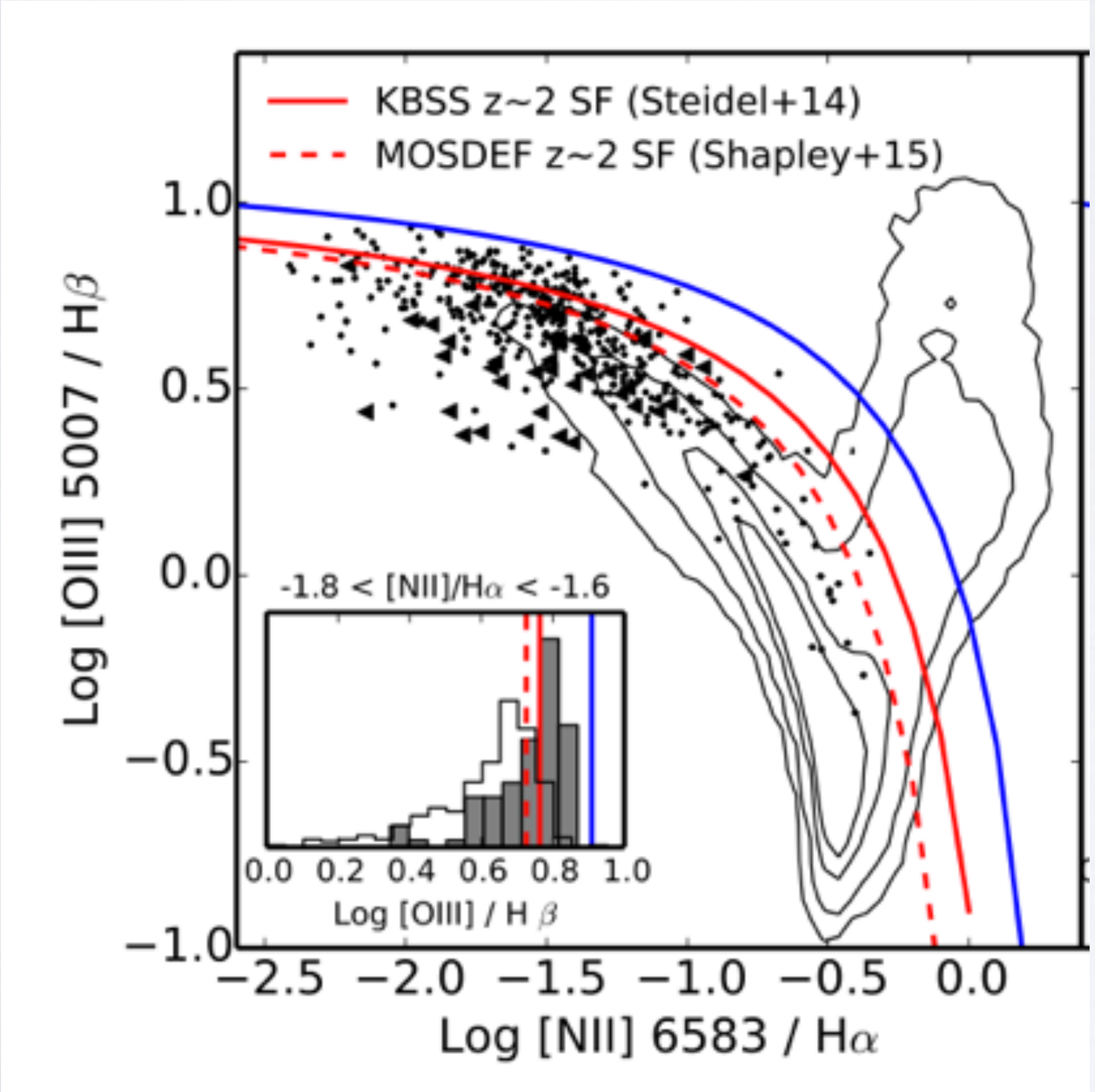


Henry et al. (2015)

if extended emission is part of a spherical outflow— the COS aperture losses could lie preferentially at v~0.

Finally (if I had more time) the Green Peas are really good for other things too!

Metal Abundance Diagnostics



Henry et al. (in prep)

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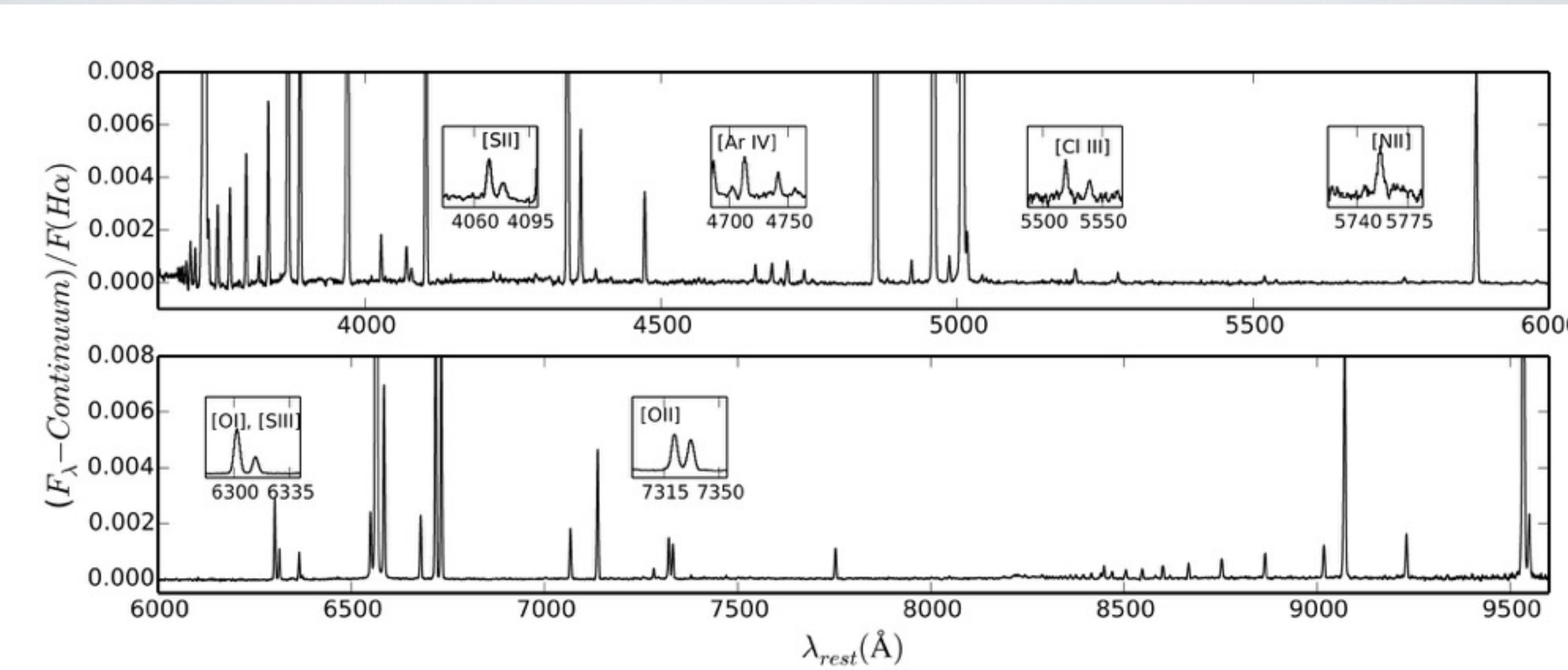
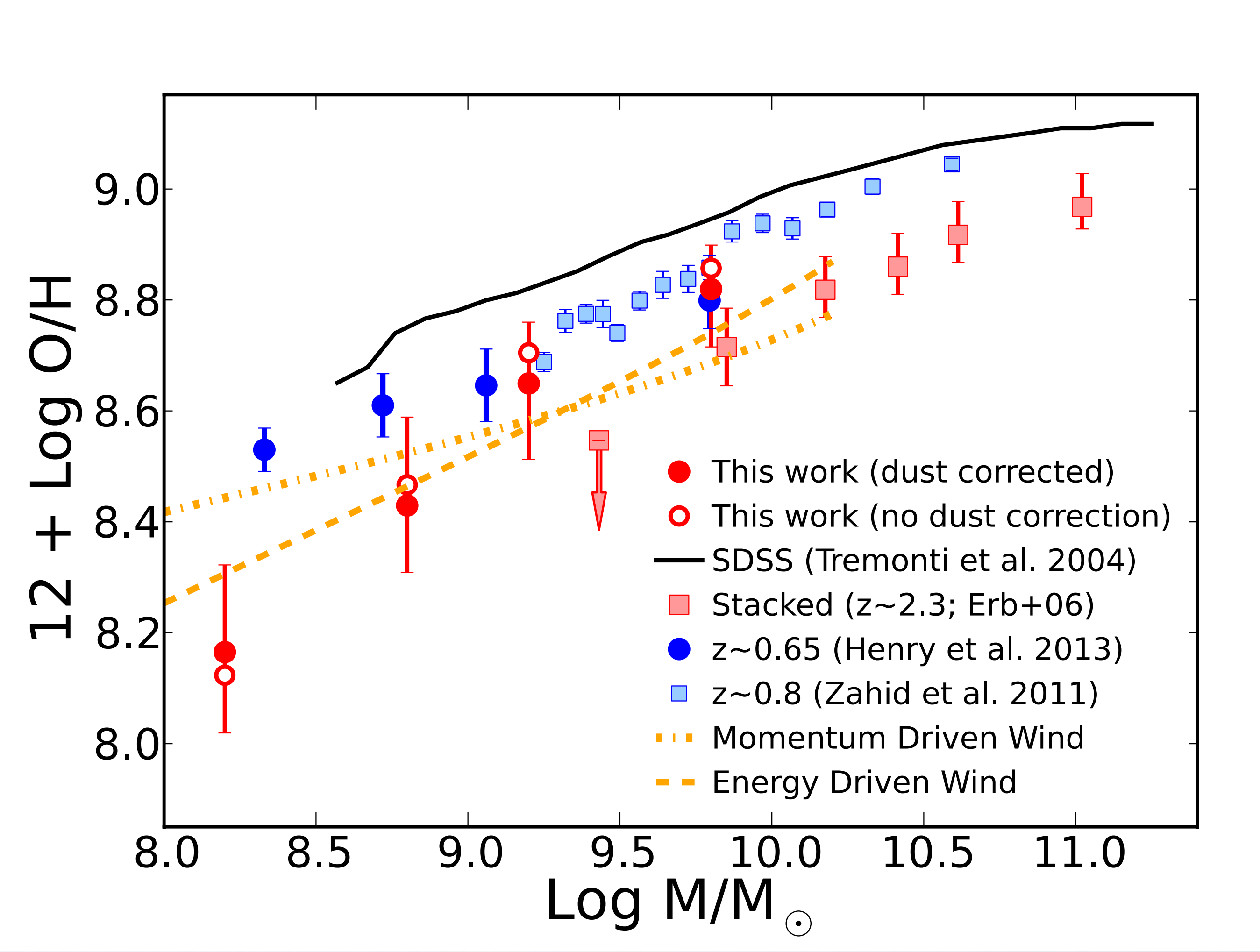
Metal Abundance Diagnostics



Henry et al. (in prep)

Finally (if I had more time) the Green Peas are really good for other things too!

Metal Abundance Diagnostics



Henry et al. (2013)

Conclusions

- Green Peas have taught us a lot about Lyα escape. Such as…
    - The range of Lyα escape is not explained by varying outflows or holes in the ISM/CGM.
    - HI column density seems to play the dominant role.
- We're learning a lot about how to proceed with high-redshift galaxies, where the data aren't that good, *yet.*
    - e.g. these data prove the importance of Lyman series absorption lines— we can't give up on them even though they're in the Lyα forest.
    - we're getting a sense of what kind of data/fidelity is needed to "break" the thin-shell Lyα RT models; we're now strongly motivated to treat the HI as an envelope.
    - we're learning about how spectral stacking washes out variations, and discovering details that lower resolution spectroscopy is missing.
- Low redshift analogs for high-redshift galaxies are really valuable, for more than just Lyα astrophysics. (Stay tuned!)