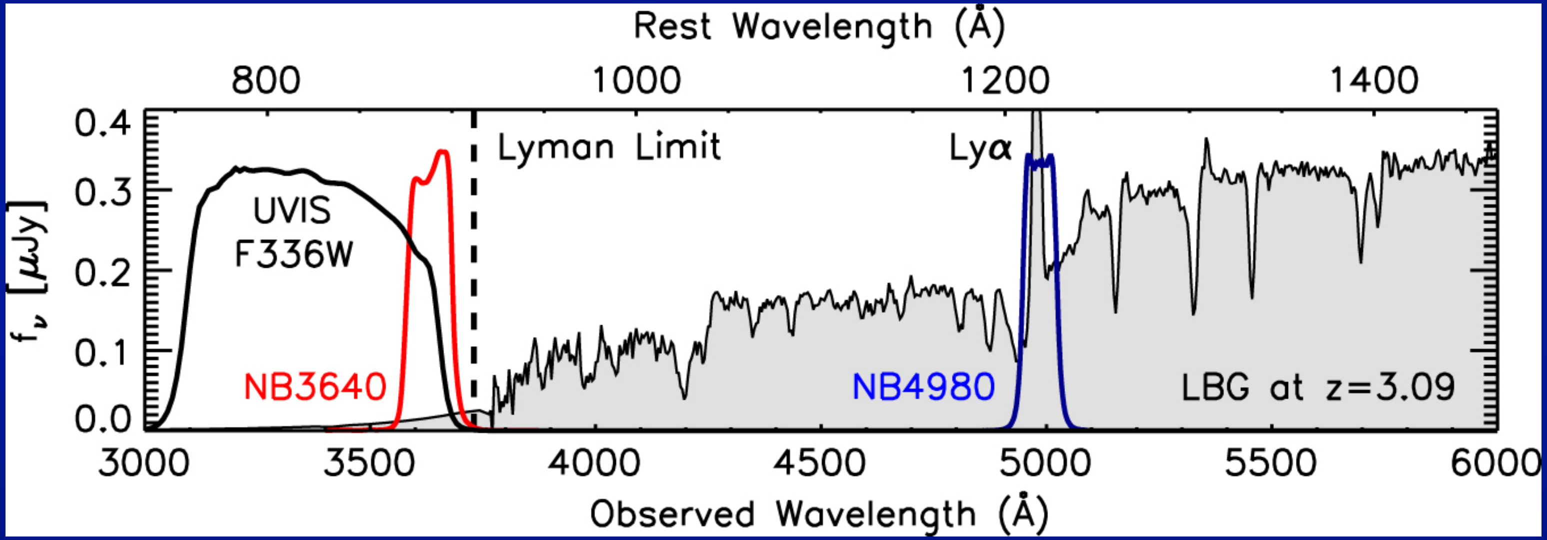
Radiation from High-Redshift Sources and the Release of Ionizing Photons

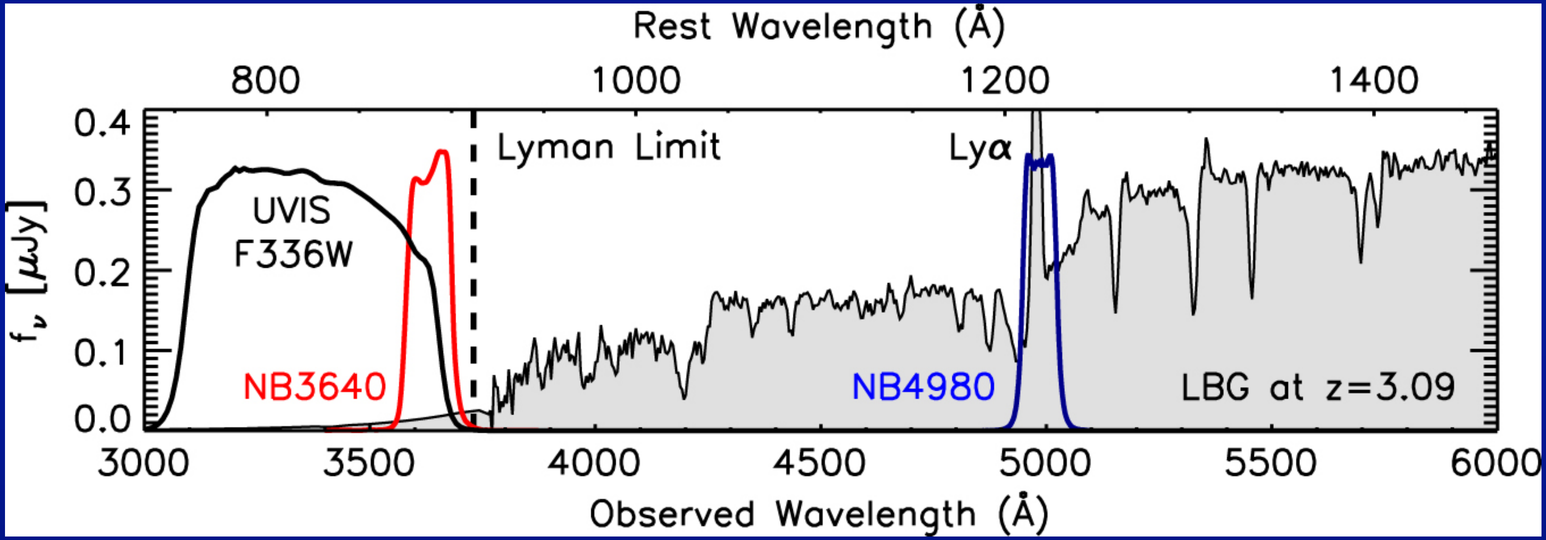


(Siana et al. 2015)

Alice Shapley (UCLA)

Collaborators: Brian Siana, Robin Mostardi, Daniel Nestor, Chuck Steidel, Naveen Reddy, Max Pettini

Direct Measurement of the Escape of Ionizing Radiation from Galaxies at High Redshift



(Siana et al. 2015)

Alice Shapley (UCLA)

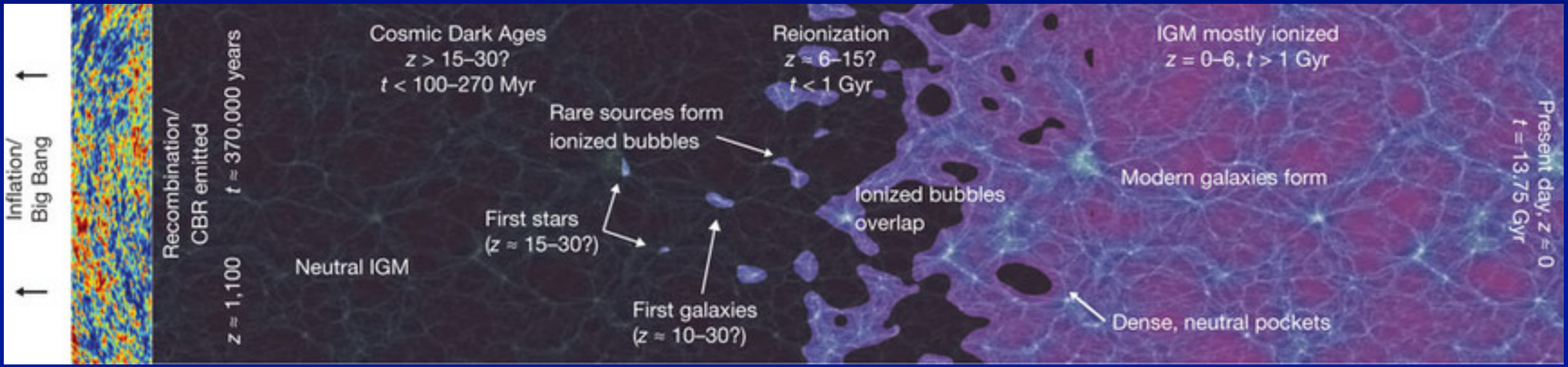
Collaborators: Brian Siana, Robin Mostardi, Daniel Nestor, Chuck Steidel, Naveen Reddy, Max Pettini

Overview

- Reionization and The Big Picture.
- Direct measurements of f_{esc} from star-forming galaxies.
- The future.

The Big Picture

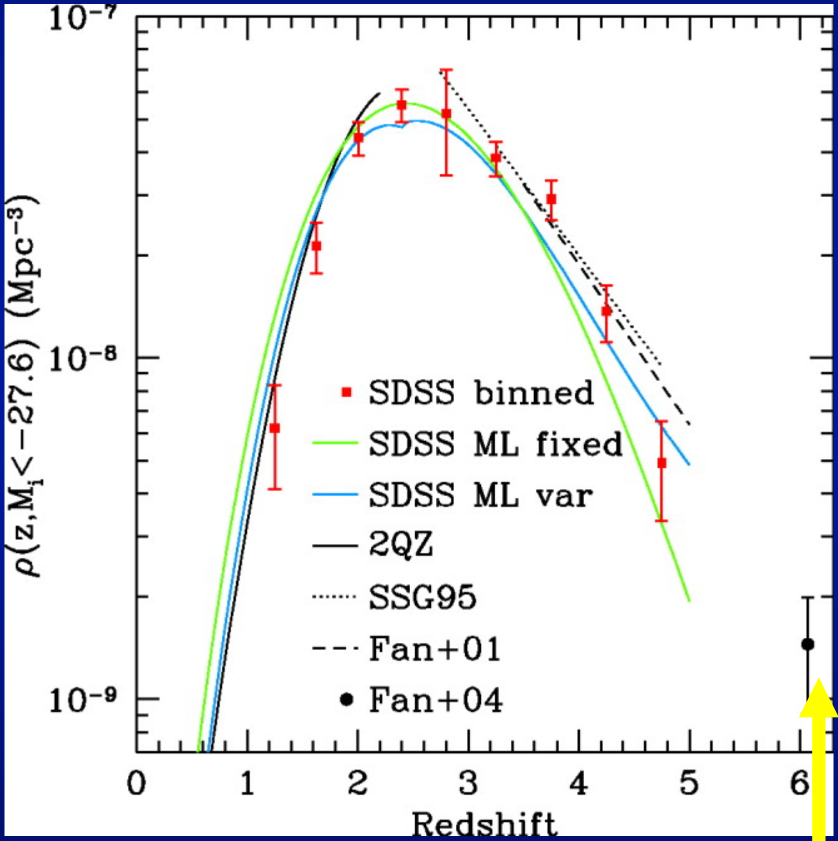
Cosmic Timeline & Reionization



- **Much theoretical work (simulations and semi-analytic models) on the process of reionization.**
- **Observations (CMB, z~6 QSOs, galaxy Lyα emission statistics) tell us about the beginning and end of reionization.**
- **Planned 21-cm experiments.**

(Robertson et al. 2010)

Sources of Ionizing Photons

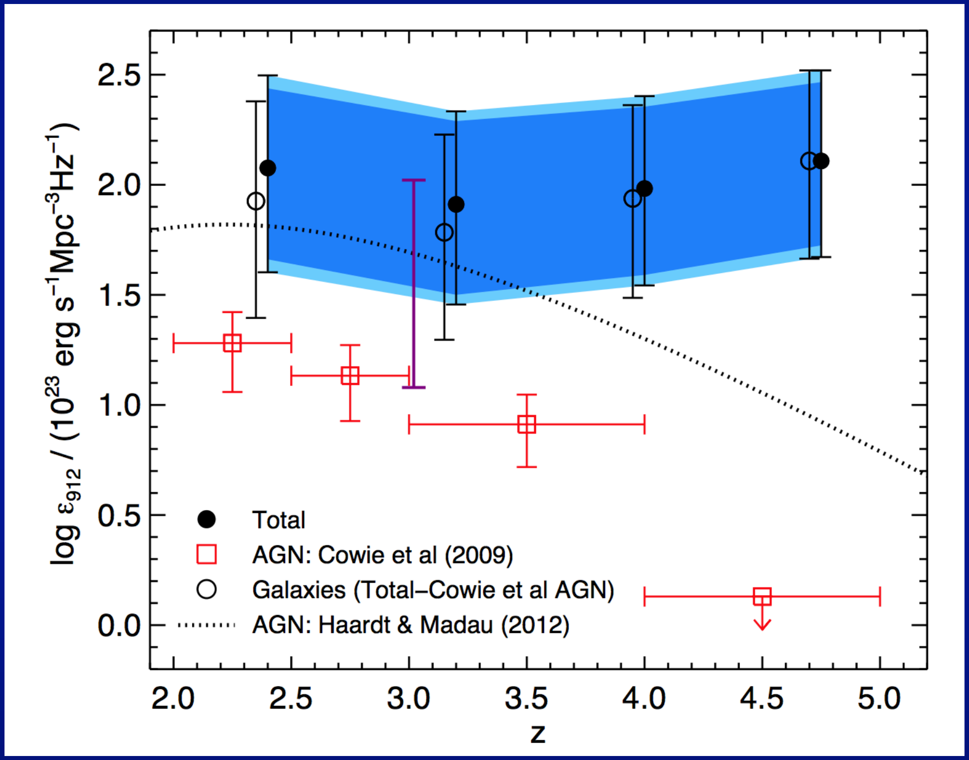


(Richards et al. 2006)

Epoch of Reionization

- While they are very luminous, quasars are also very rare.
- Furthermore, the number density of optically luminous QSOs appears to drop off from from a peak level at z~2, both towards higher and lower redshifts.
- Number density of faint QSOs at z~4-6 is uncertain, but reasonable estimates of QSO contribution at these redshifts suggests they are not important.

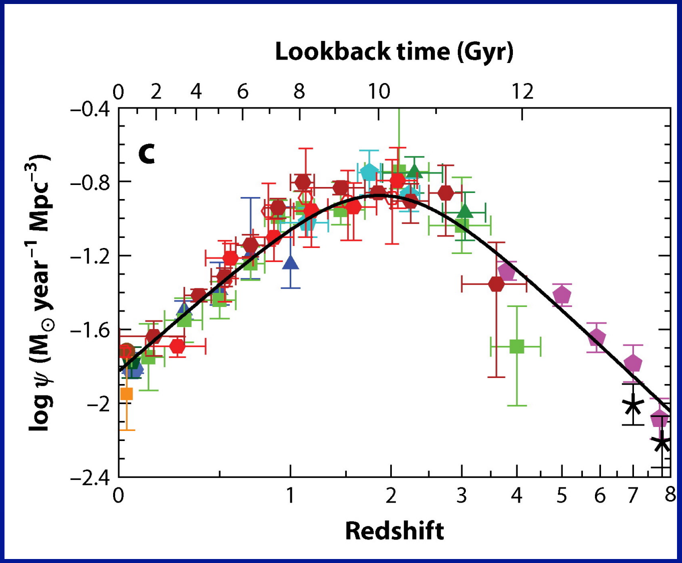
Sources of Ionizing Photons



- At the same time, the rate at which the ionizing background evolves is much more gradual.
- When the intergalactic medium (IGM) became reionized, there were probably not enough quasars to do the job.
- Therefore, we must understand the contribution of galaxies to reionization and to the ionizing background over a large range in redshifts.

(Becker & Bolton 2013)

Sources of Ionizing Photons



Evolution of the global density of star formation in the universe, based on non-ionizing UV light.

(Madau & Dickinson 2014)

- Critical questions: What are the sources that reionized the universe? What is the ionizing photon production rate from galaxies and their contribution to the global ionization rate of hydrogen?

- To answer these questions, we must chart the abundance and star-formation rates of galaxies as a function of redshift, and estimate f_{esc}, the escape fraction of ionizing photons from star-forming galaxies.

Simple Models of Reionization

- Evolution of ionized fraction of the universe is described as a balance between ionization and recombination (e.g., Robertson et al. 2015):

$$\dot{Q}_{\rm HII} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H} \rangle} - \frac{Q_{\rm HII}}{t_{\rm rec}}$$

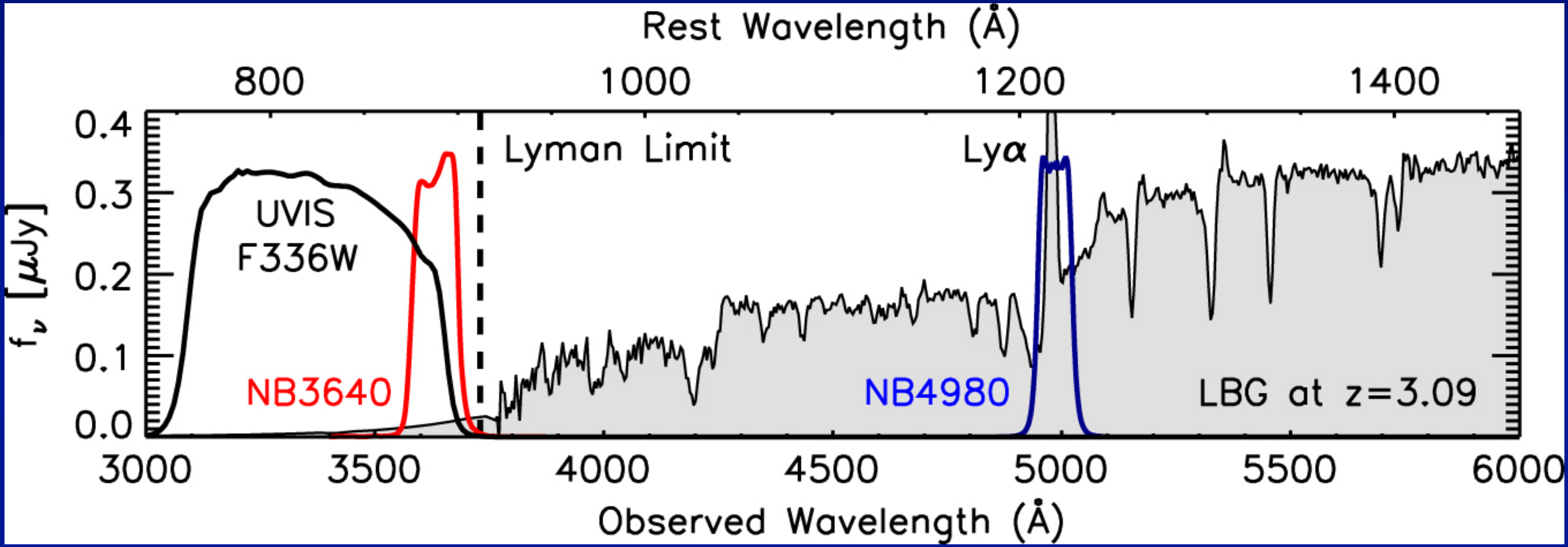
- The ionizing photon production rate is expressed as:

$$\dot{n}_{\rm ion} = f_{\rm esc} \xi_{\rm ion} \rho_{\rm SFR}$$

- The evolution of the ionized fraction directly follows from *ndot*$_{\rm ion}$. $\rho_{\rm SFR}$ follows from measured UV luminosity function. $\xi_{\rm ion}$ follows from population synthesis models. Realistic estimates of $f_{\rm esc}$ are critical for understanding how $Q_{\rm HII}$ evolves.

Direct Measurements of f_{esc}

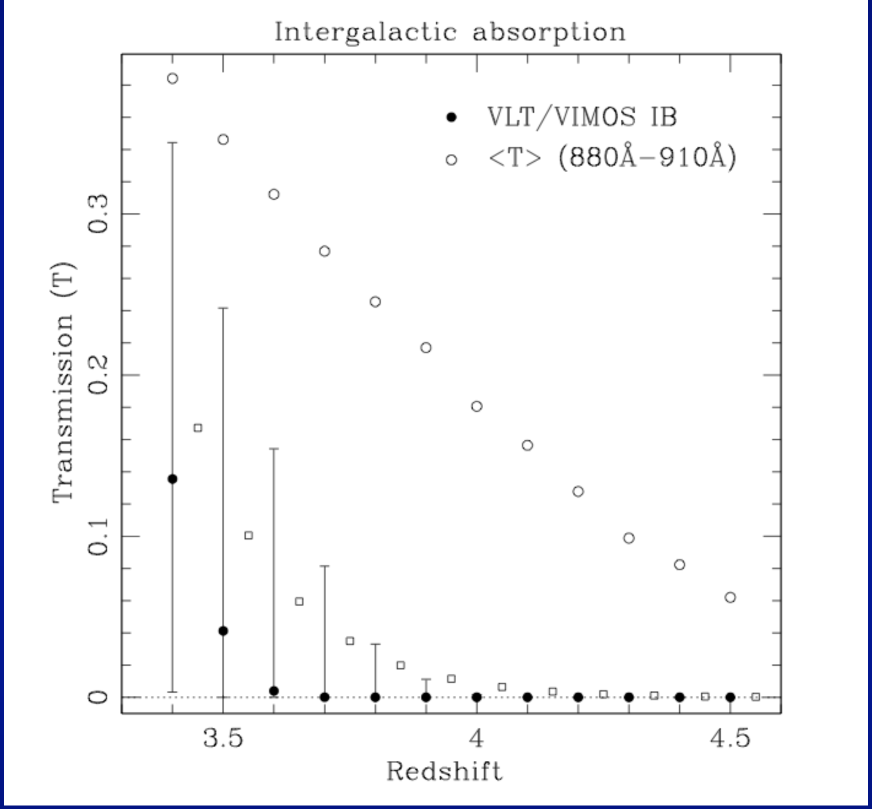
What is a direct measurement?



(Siana et al. 2015)

- Spectroscopy: Spectroscopy below the Lyman limit at 912 Å.
- Imaging: Broadband or narrowband image entirely below the Lyman limit at 912 Å.

Measuring f_{esc}



- Unfortunately, at the epoch of reionization, the Lyα forest is so thick that it is impossible to determine f_{esc} directly from z>6 (or even z>4) galaxies.

- Solution: measure f_{esc} from lower-redshift galaxies, relate these sources to objects at z>6 (see Heckman's talk).

- Highest practical redshift for direct f_{esc} measurements is z~3.5.

Transmission of ionizing photons.(Vanzella et al. 2012)

Definitions of f_{esc}, etc.

- What is f_{esc}?

$$f_{esc}(\mathrm{LyC}) = \frac{L_{LyC,out}}{L_{LyC,in}}$$

LyC=880-910 Å

- How are f_{esc} and $f_{esc,rel}$ related?

$$f_{esc,rel}(\mathrm{LyC}) = \frac{f_{esc}(\mathrm{LyC})}{f_{esc}(1500)}$$

$$f_{esc}(\mathrm{LyC}) = f_{esc,rel}(\mathrm{LyC}) f_{esc}(1500)$$

$$f_{esc,rel}(\mathrm{LyC}) = \frac{f_{900}/f_{1500}}{(L_{900}/L_{1500})t_{IGM}}$$

$f_{esc,rel}$ useful for deriving global quantities, such as ε_{LyC}, based on LBG UV luminosity function

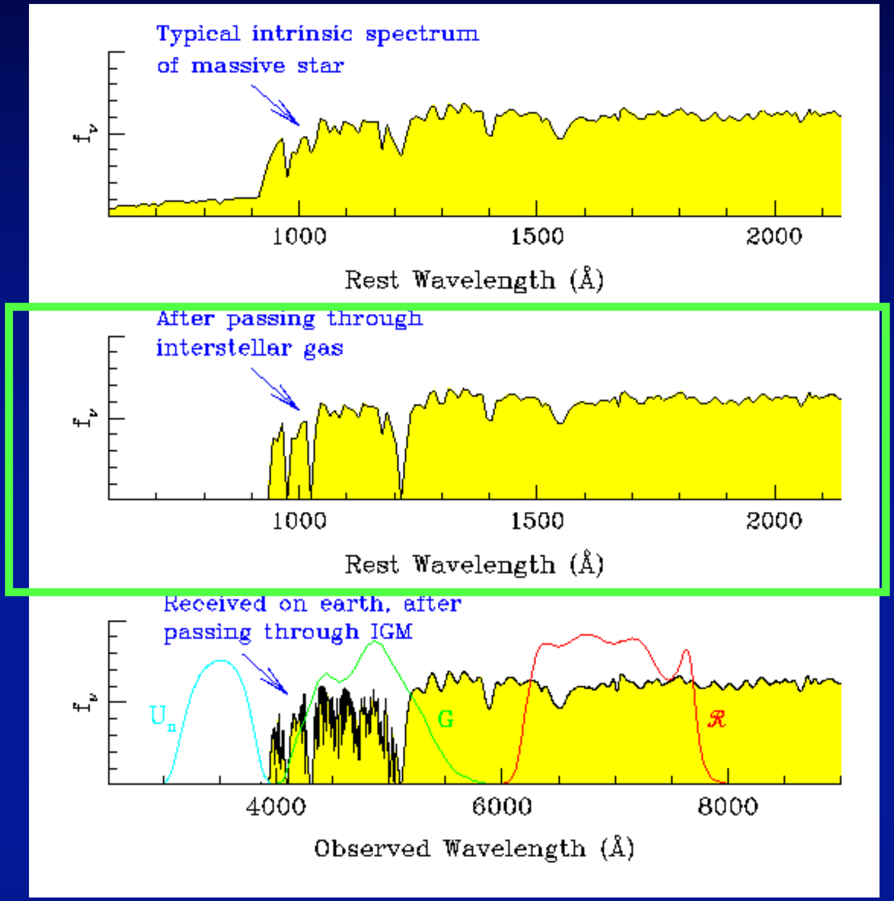
- Can be re-arranged:

$$f_{900}/f_{1500} = f_{esc,rel}(\mathrm{LyC})(L_{900}/L_{1500})t_{IGM}$$

We measure this

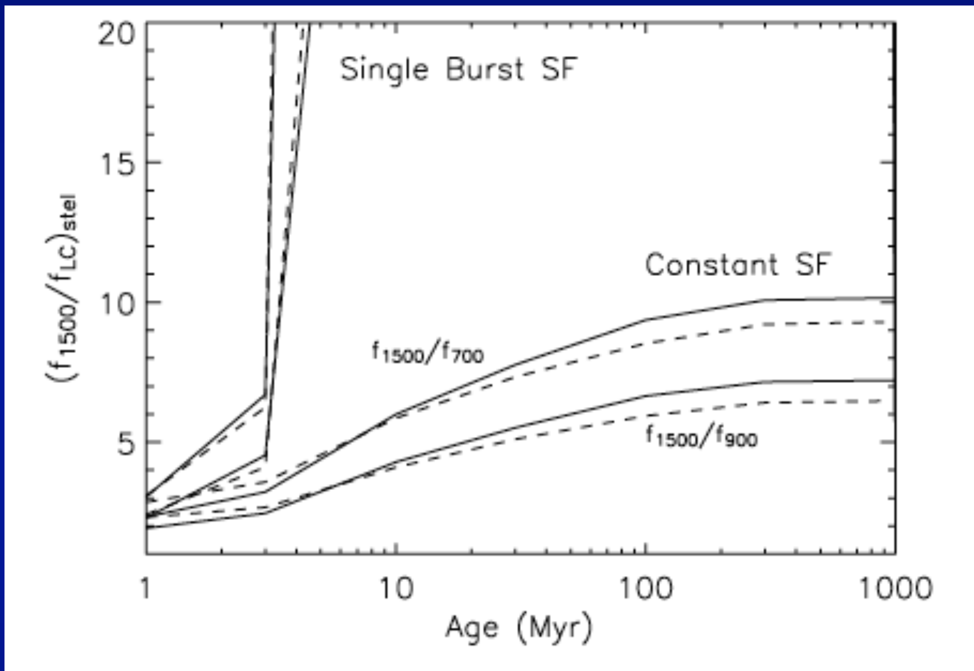
Stellar pop. models:1.5-8

Simulations of z~3 IGM opacity in LyC: 0.17-0.55



$$f_{esc,rel}(\mathrm{LyC}) = \frac{f_{900}/f_{1500}}{(L_{900}/L_{1500})t_{IGM}}$$

Intrinsic L_{UV}/L_{LyC}



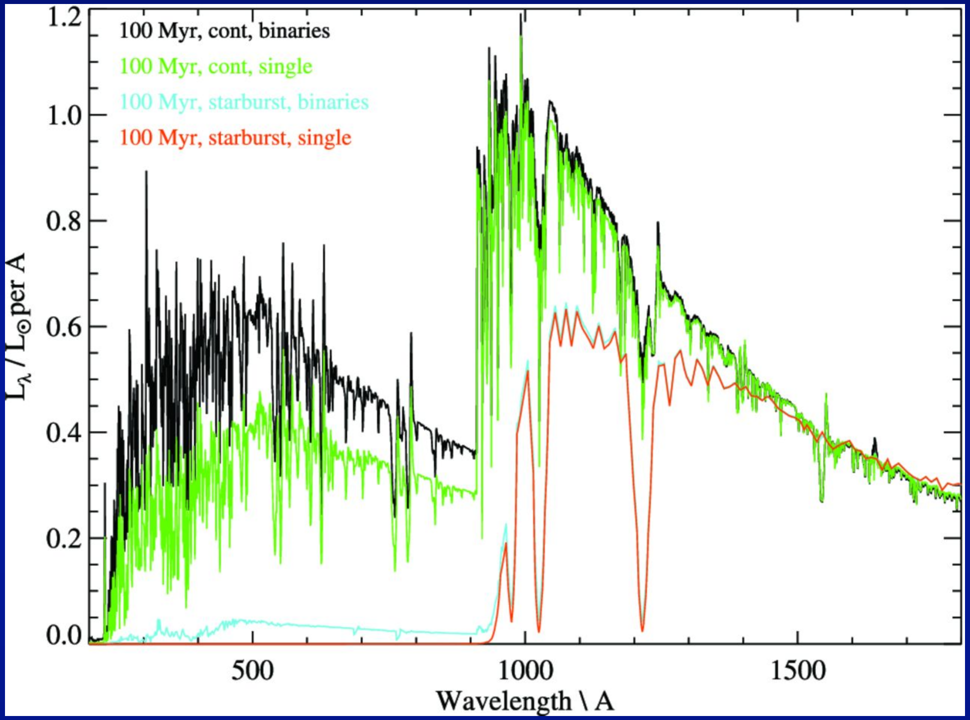
(Siana et al. 2007)

- Key for estimating f_{esc} is an assumption about the intrinsic ratio of non-ionizing UV (i.e. "UV," 1500 Å) and ionizing-UV (i.e. "LyC," 900 Å) flux density, L_{UV}/L_{LyC}.

- BC03 Stellar population synthesis models predict L_{UV}/L_{LyC}~7 for reasonable assumptions of ages, metallicities, and IMFs.

- Recall: We evaluate "UV" at ~1500Å, and "LyC" at ~900Å (880-910 Å).

Intrinsic L_{UV}/L_{LyC}



(Stanway et al. 2016)

- **Key for estimating f_{esc} is an assumption about the intrinsic ratio of non-ionizing UV (i.e. "UV," 1500 Å) and ionizing-UV (i.e. "LyC," 900 Å) flux density, L_{UV}/L_{LyC}.**

- **BPASS and S99 models suggest a lower ratio of L_{UV}/L_{LyC} (~4) when evolution of interacting binaries and stellar rotation are included. Lower for lower metallicity (~3), different IMF.**

Global Implications

• Compute ε_{Lyc} (ionizing luminosity density), based on ε_{UV} (non-ionizing UV luminosity density) and $\langle F_{UV}/F_{LyC} \rangle$, corrected for IGM absorption:

$$\epsilon_{\rm LyC} = \left(\frac{F_{\rm UV}}{F_{\rm LyC}} \right)^{-1}_{\rm corr} \int_{L_{\rm min}}^{L_{\rm max}} L \, \Phi \, dL$$

• For ε_{UV}, integrate luminosity function of population of interest (e.g., Reddy et al. 2008 for LBGs; Ouchi et al. 2008 for LAEs).

• ε_{Lyc} is directly related to $\textit{ndot}_{ion}$

Global Implications

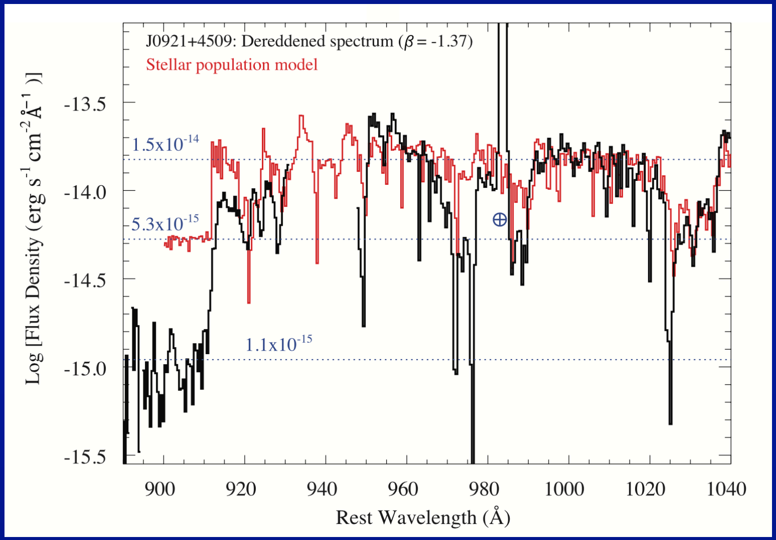
- **Based on ε_{LyC} and Δl_{mfp} (mean free path for ionizing photons at z~3), compute contribution from LBGs to the global hydrogen ionization rate, Γ.**

$$\Gamma(z) \approx \frac{\sigma_{\rm H\,I}\Delta l(\nu_{\rm H\,I}, z)\epsilon_{\nu_{\rm H\,I}}(z)}{h(\alpha_{\rm H\,I} + 3)}$$

σ_{HI}=hydrogen ionization cross-section; Δl= mean free path; $\varepsilon_{\nu HI}$=ionizing luminosity density (ε_{LyC}); h=Planck's constant; α_{HI}=spectral index of ionizing radiation.

z~0 LyC Measurements

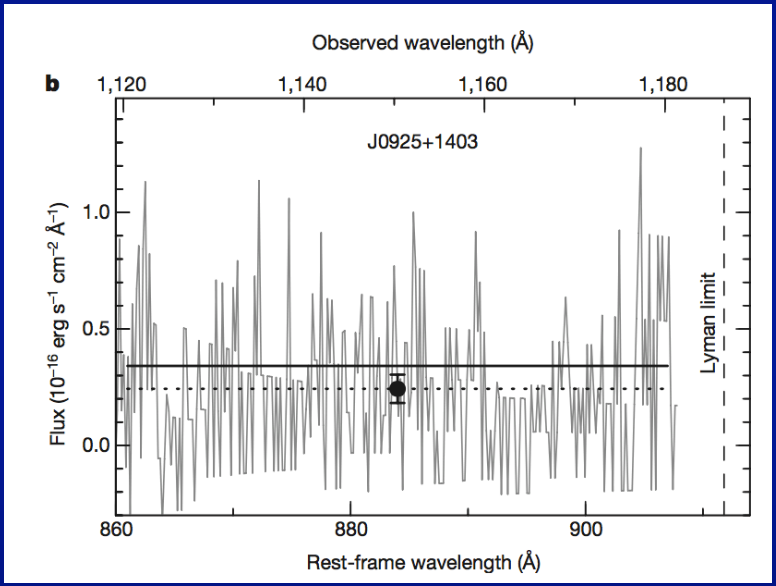
(Borthakur et al. 2014)



- **For ~2 decades, no convincing direct detections of LyC emission from local galaxies or z~1-2.**
- **Haro 11 (controversial; Bergvall et al. 2006, Grimes et al. 2007; Leitet et al. 2011).**
- **Borthakur et al. (2014): z=0.23 starburst (SFR~50 M_{sun}/yr), very compact; blueshifted ISM lines indicate non-unity covering fraction. *HST/COS spectrum covers 890-1040 Å, implies f_{esc}~1%.***

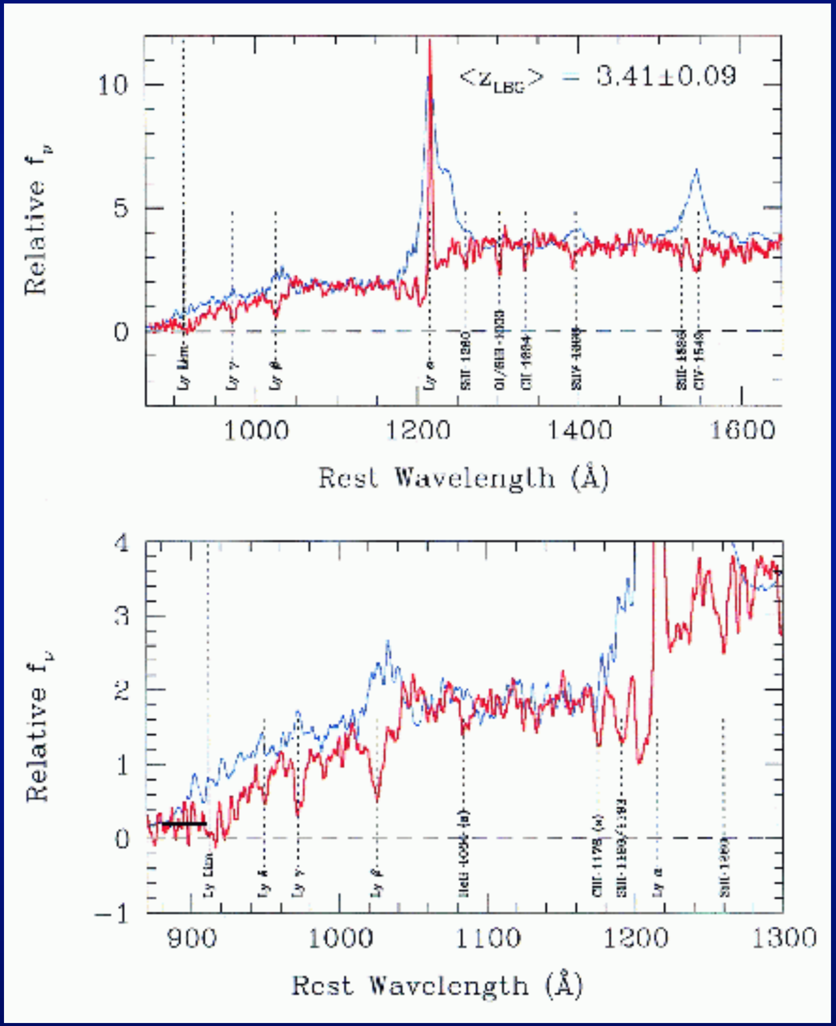
z~0 LyC Measurements

(Izotov et al. 2016a)



- **For ~2 decades, no convincing direct detections of LyC emission from local galaxies or z~1-2.**
- **Haro 11 (controversial; Bergvall et al. 2006, Grimes et al. 2007; Leitet et al. 2011).**
- **Izotov et al. (2016a): z=0.3 "Green Pea" galaxy (strong rest-optical emission lines, compact), low-metallicity. *HST/COS spectrum implies f_{esc}~8%.***
- **Leitherer et al. (2016) present 2 HST/COS LyC detections at z=0.04-0.05, *f_{esc}~2.5-4.5%.***
- **Izotov et al. (2016b): 4 additional z~0.3 objects with *f_{esc}~6-13%* based on HST/COS.**

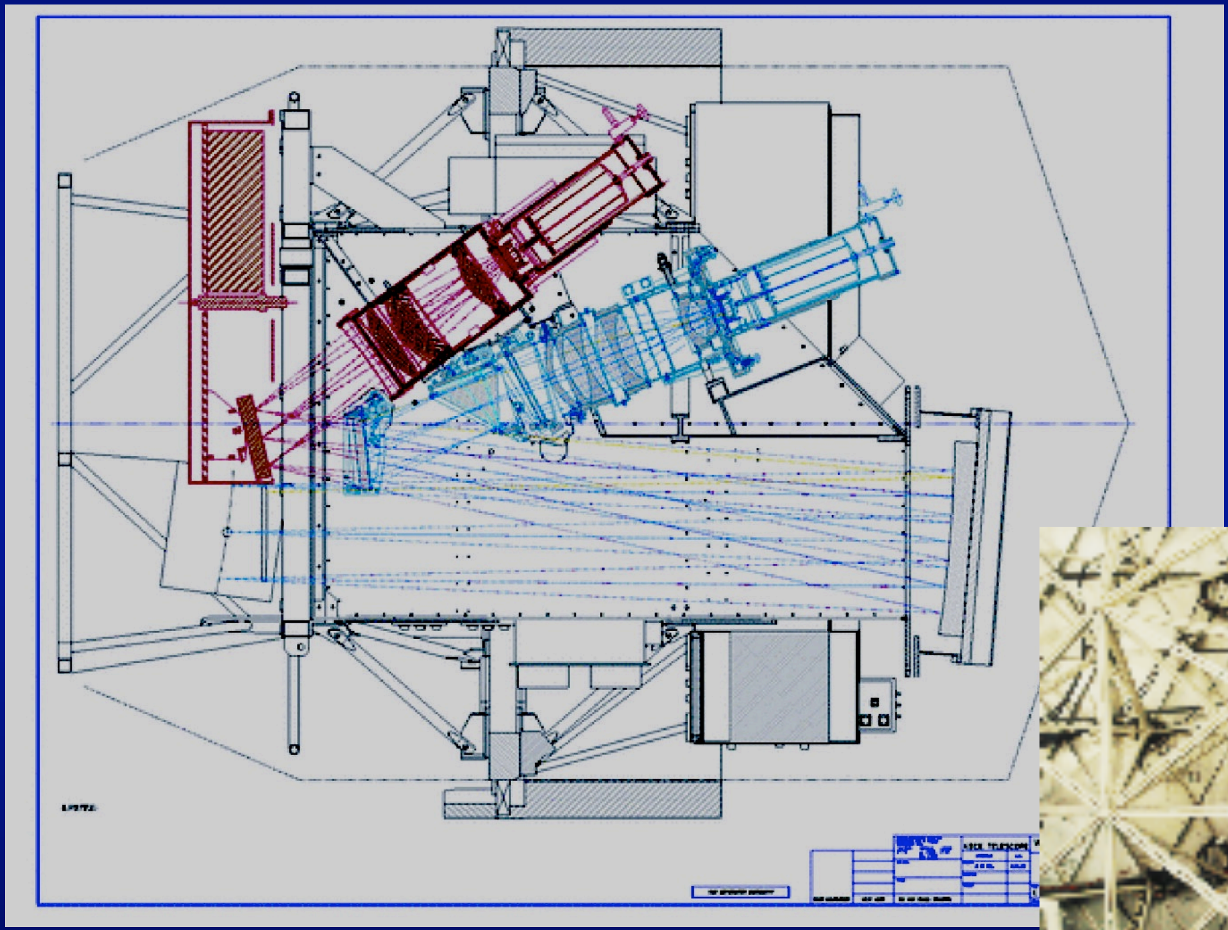
First Detection of z~3 LyC Emission?



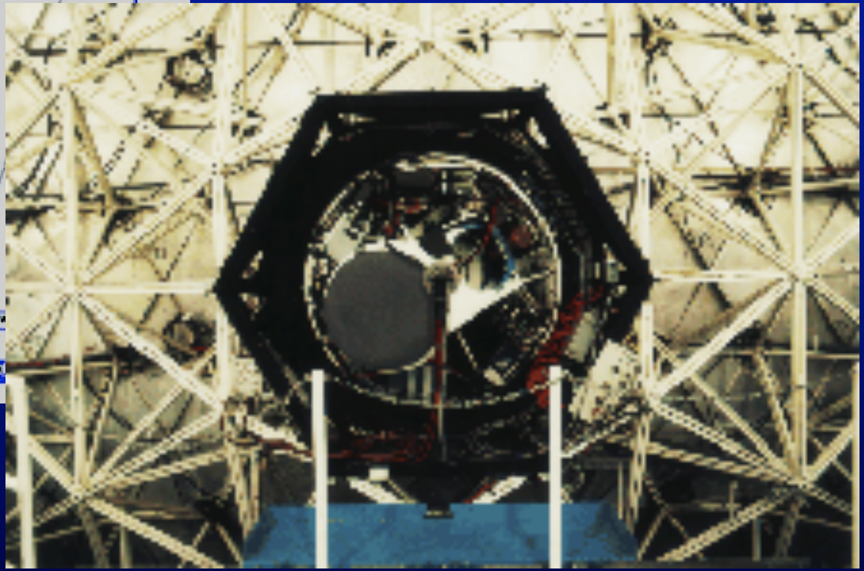
(Steidel et al. 2001)

- First reported detection of LyC emission at high redshift in Steidel et al. (2001).
- Composite spectrum: 29 LBGs at <z>=3.4+/-0.09
- Apparently significant LyC flux in composite spectrum → 5 times more ionizing flux than QSOs at z~3
- Probably spurious.

Measuring Galaxy Spectra: Keck/LRIS



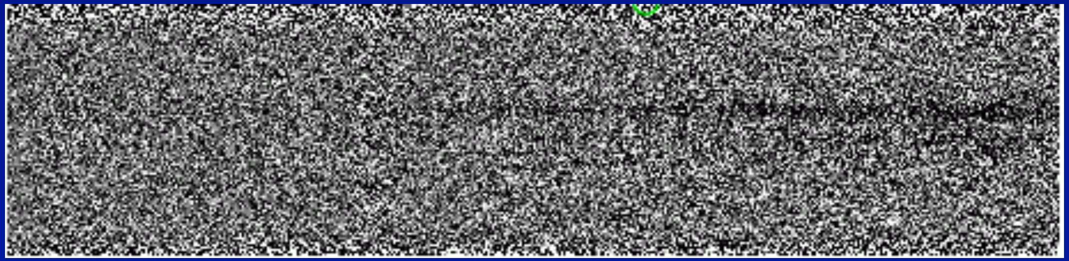
- Low Resolution Imaging Spectrometer (LRIS), a *dichroic* spectrograph sensitive to optical light
- Light is split into blue and red portions, sent to 2 different detectors



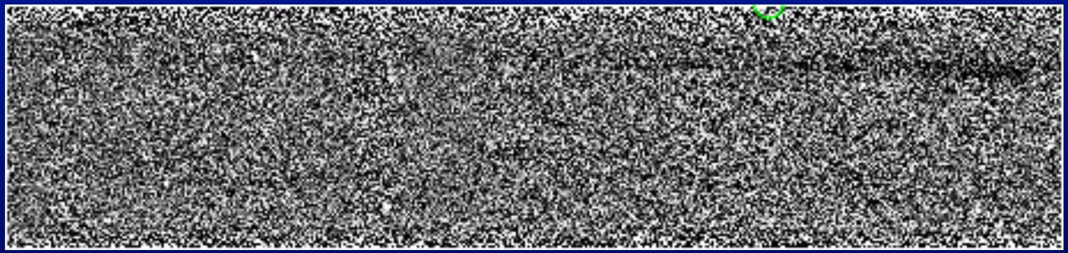
(LRIS at the Cassegrain focus behind the Keck primary mirror, P. Shopbell)

More apparent z~3 LyC Detections

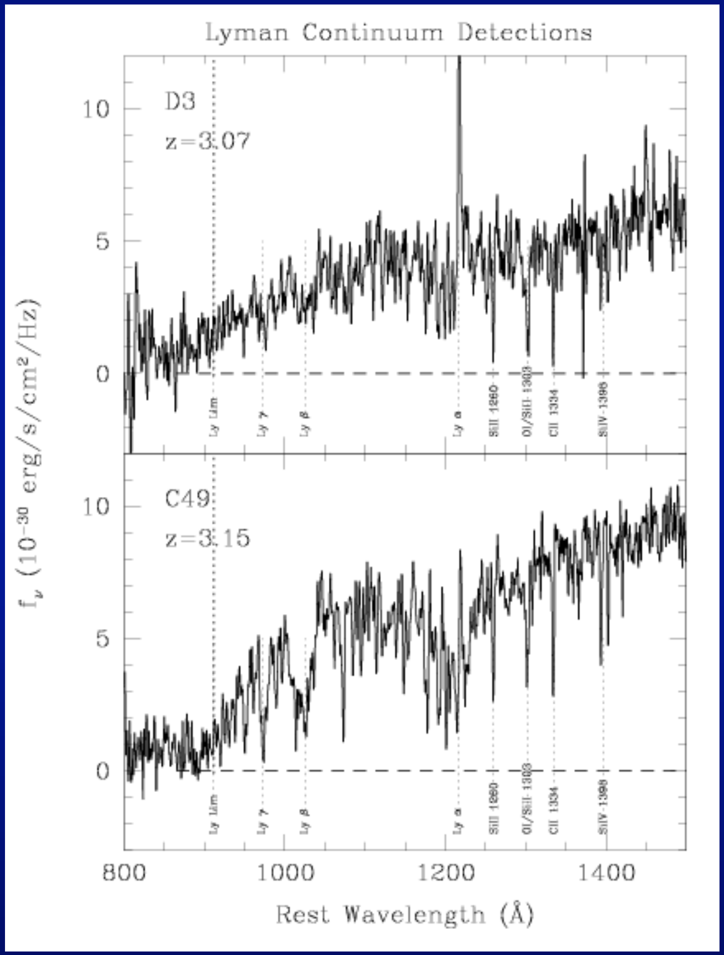
Lyman limit, 912 Å



Lyman limit, 912 Å



Wavelength (3350-3950 Å)

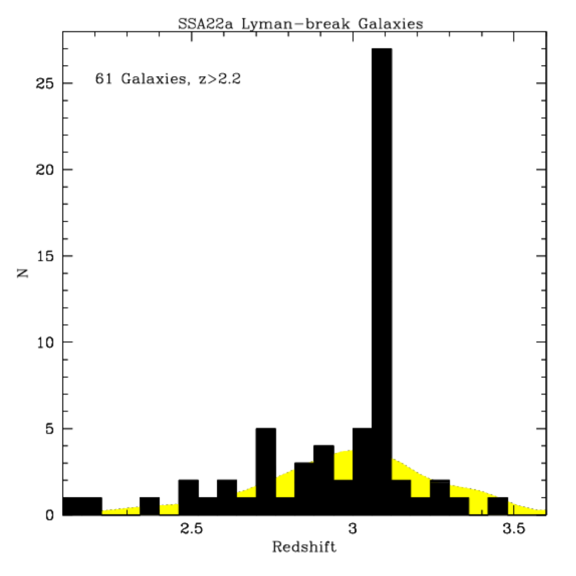


(Shapley et al. 2006)

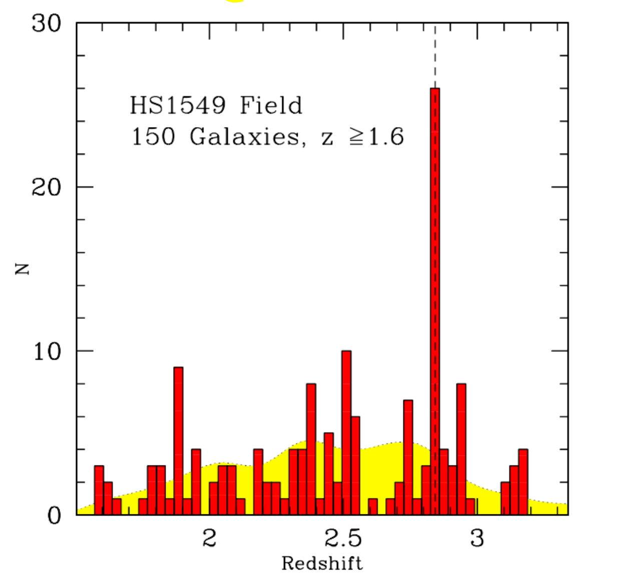
Narrowband Imaging and z~3 LyC

- Narrowband imaging, just below the Lyman limit, provides complementary technique for detecting escaping ionizing radiation
- Why narrowband? At z~3, LyC mean free path is only Δz=0.35 (~80 Å rest frame), so it's important to probe just below the Lyman limit. Broadband filter would tell you more about IGM opacity than escape fraction.
- Protoclusters are efficient targets for narrowband imaging (lots of LBGs and LAEs at the same redshift):

SSA22a



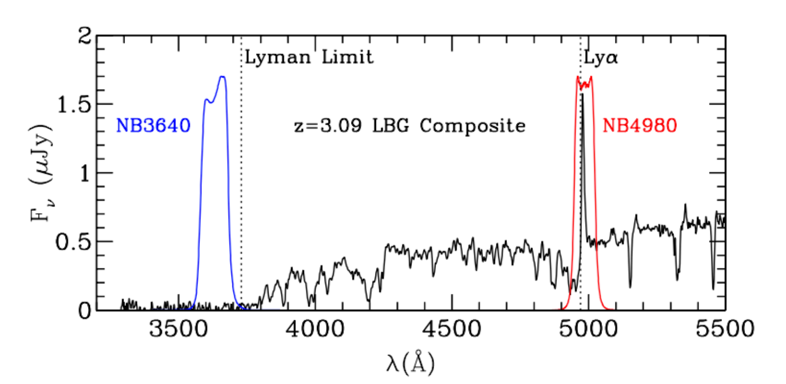
Q1549



Narrowband Imaging and z~3 LyC

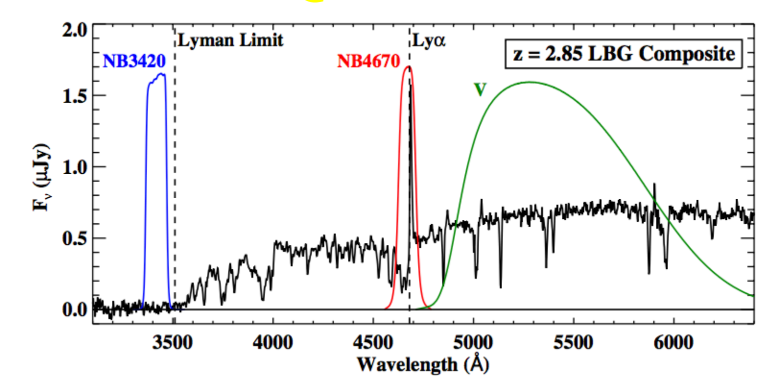
- Narrowband imaging, just below the Lyman limit, provides complementary technique for detecting escaping ionizing radiation
- Why narrowband? At z~3, LyC mean free path is only Δz=0.35 (~80 Å rest frame), so it's important to probe just below the Lyman limit. Broadband filter would tell you more about IGM opacity than escape fraction.
- Protoclusters are efficient targets for narrowband imaging (lots of LBGs and LAEs at the same redshift):

SSA22a



(Nestor et al. 2011)

Q1549

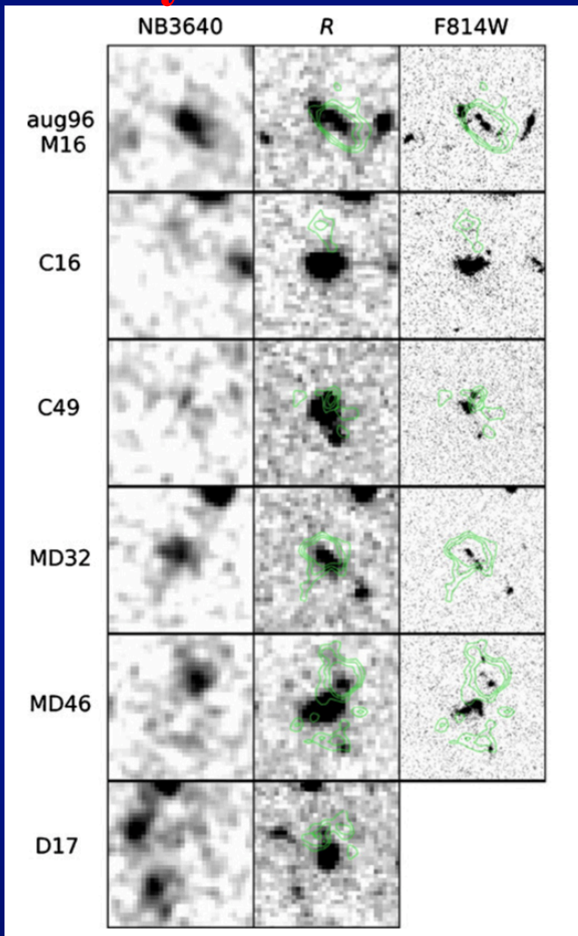


(Mostardi et al. 2013)

- See also work by Iwata et al. (2008), Micheva et al. (2015).

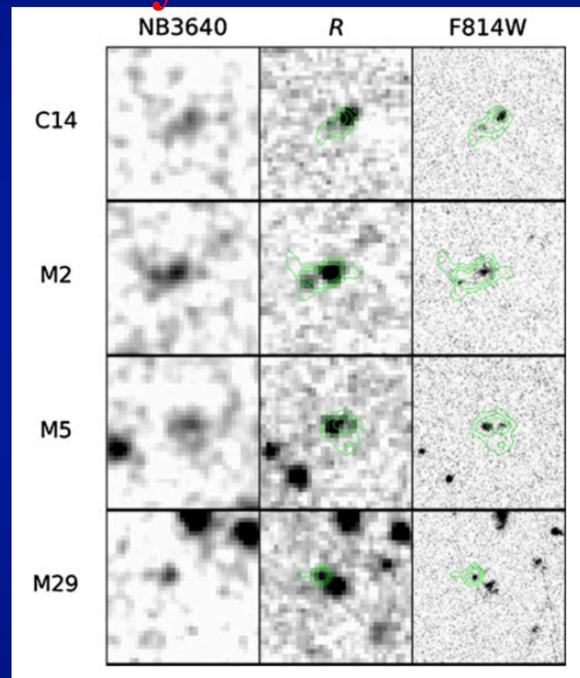
Narrowband Imaging and z~3 LyC

LyC UV



SSA22a

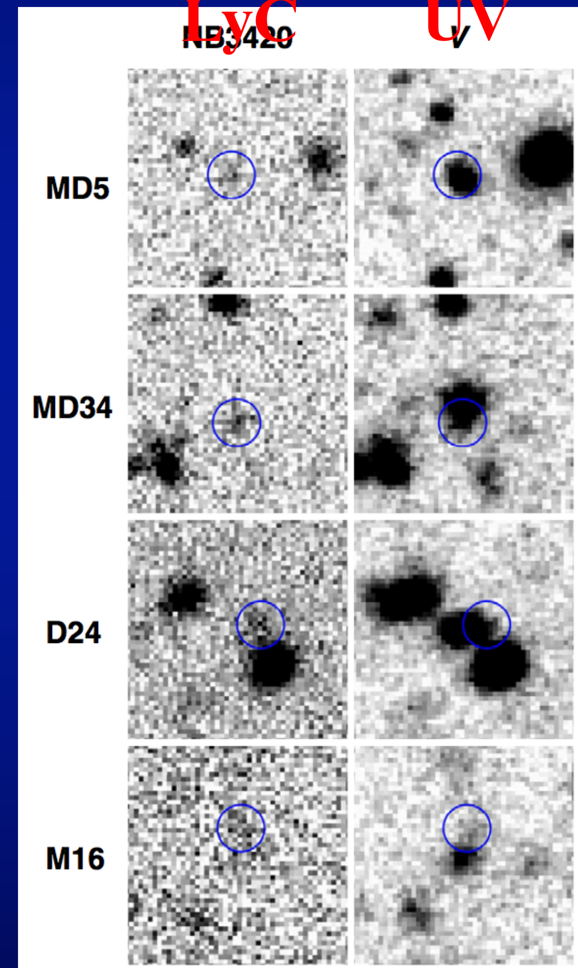
LyC UV



(Nestor et al. 2013)

Q1549

LyC UV

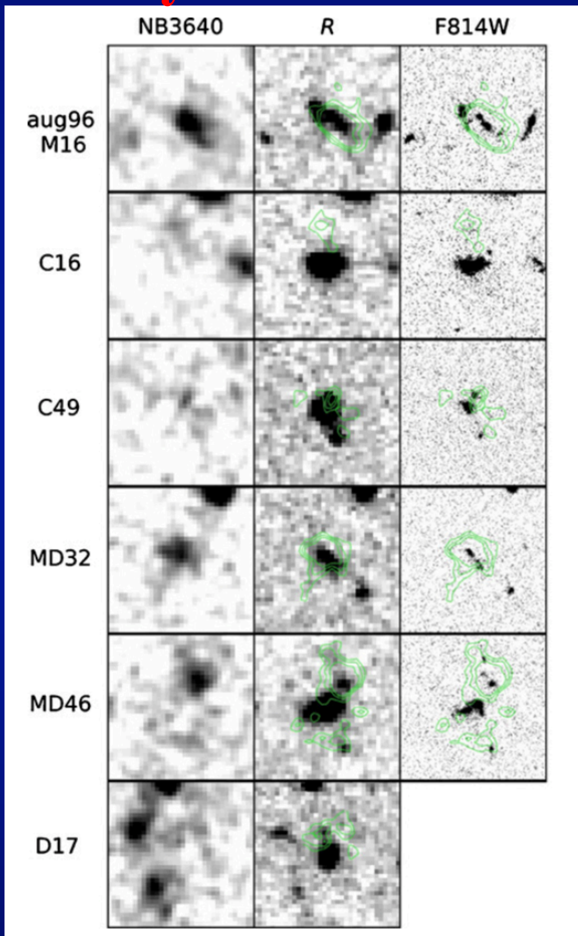


(Mostardi et al. 2013)

- LBG/LAE LyC detection rate is 10-20%

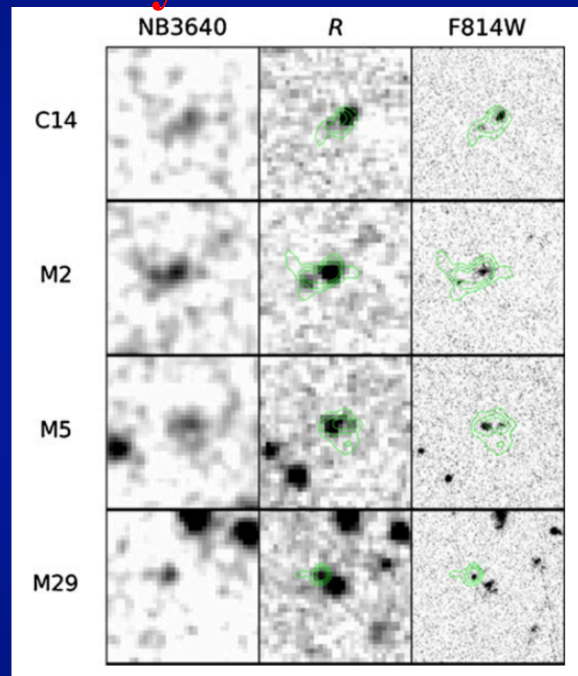
Narrowband Imaging and z~3 LyC

LyC UV



SSA22a

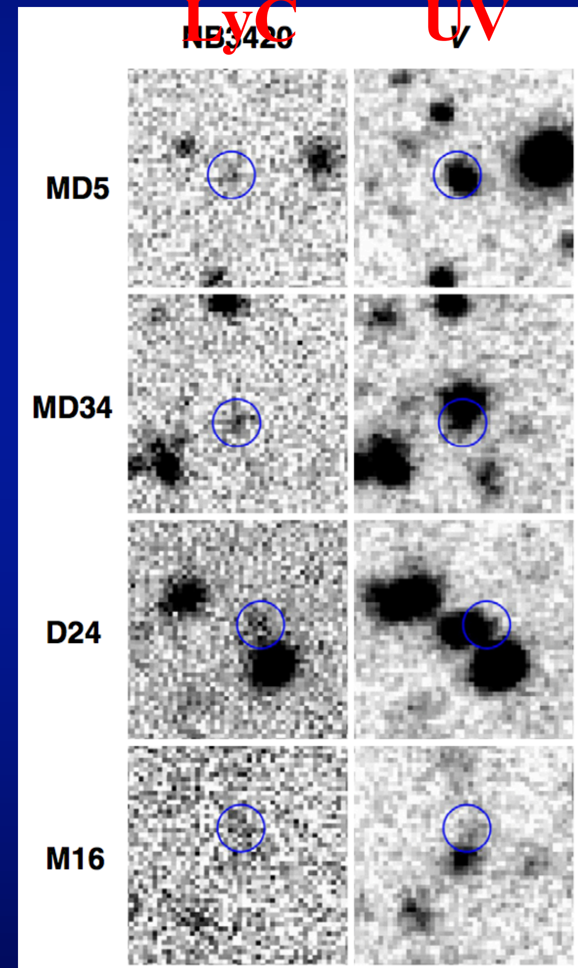
LyC UV



(Nestor et al. 2013)

Q1549

LyC UV



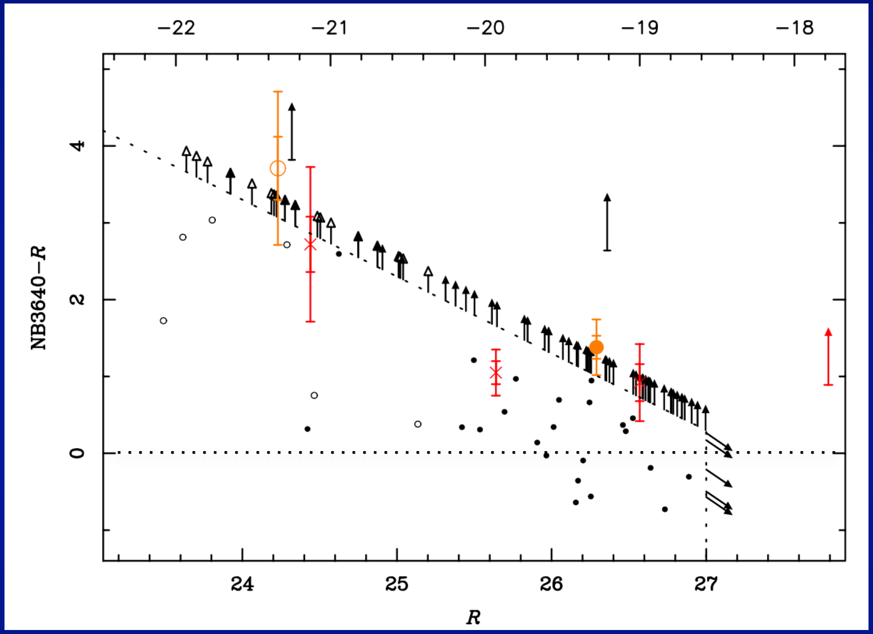
(Mostardi et al. 2013)

- NB3640/NB3420 (i.e., LyC) emission frequently appears offset from non-ionizing UV continuum (0.3”-1.3”).

Narrowband Imaging and z~3 LyC

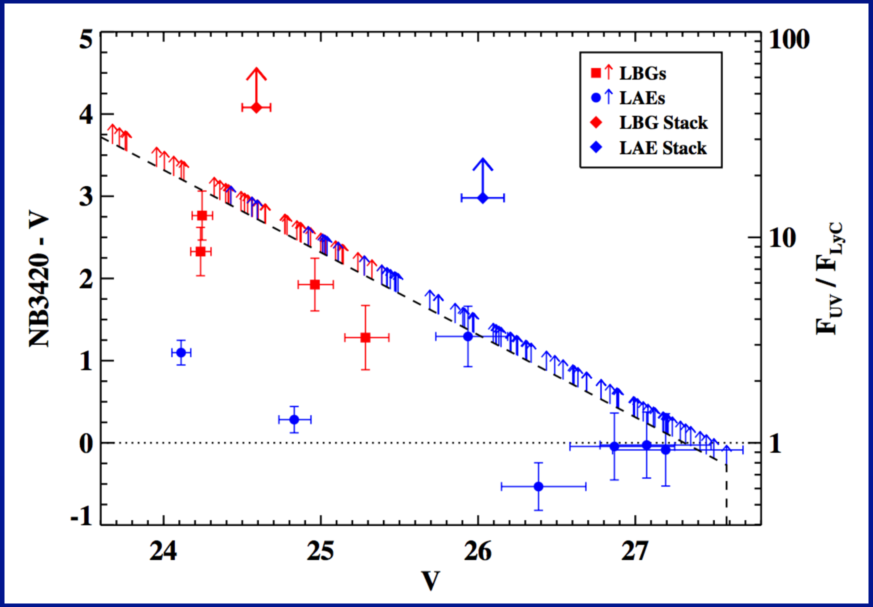
UC/LyC

SSA22a



(Nestor et al. 2013)

Q1549

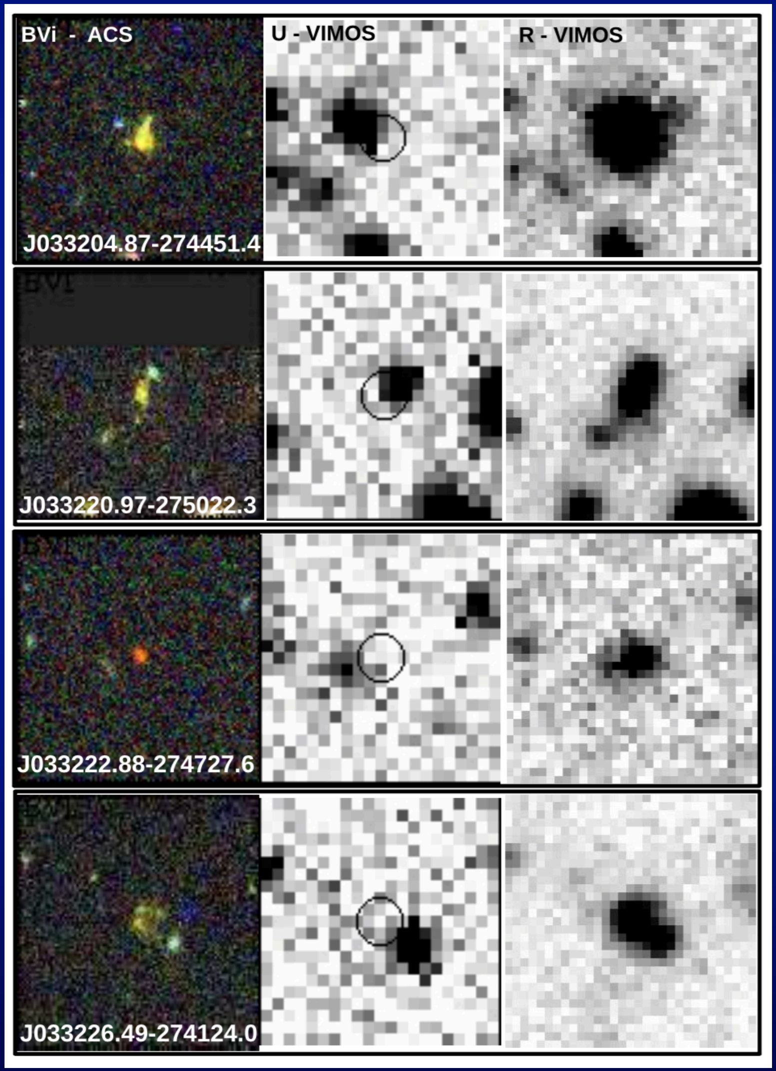


(Mostardi et al. 2013)

- UV/LyC ratios are uncomfortably small for some LAEs. NB3640-R, or NB3420-V colors ~0 are not easy to explain with stellar population synthesis models. Too blue. Exotic stellar populations (Inoue et al. 2011)?

What about contamination?

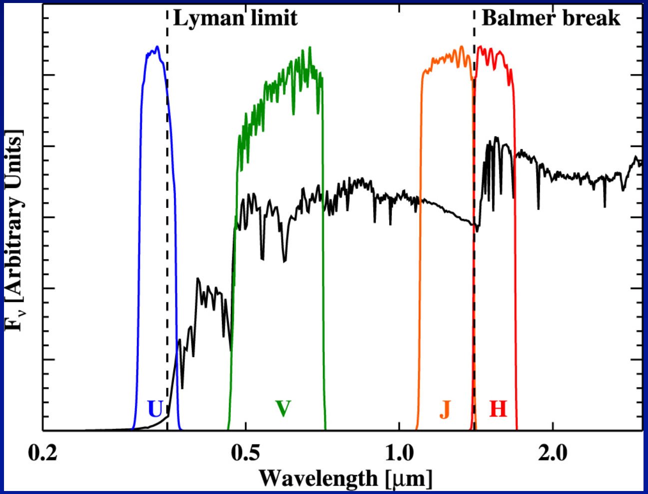
LyC UV



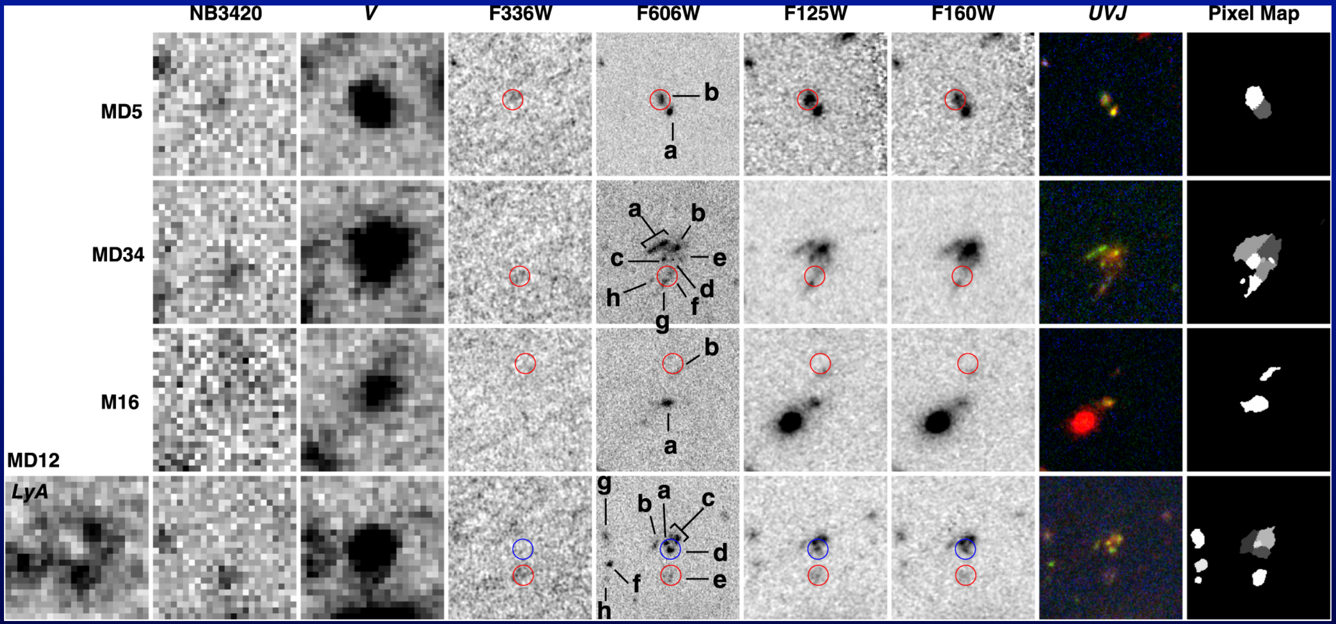
(Vanzella et al. 2012)

- Vanzella et al. (2012): HST imaging shows that apparently offset sources of LyC at z~3 are actually low-redshift interlopers (photometric redshifts).
- Ionizing radiation from a source at z~3 corresponds to the same wavelength as non-ionizing radiation from a source at, e.g., z~2.
- HST resolution required to show what's going on.
- In ground-based studies, we could only make a *statistical* correction for contamination.

What about contamination?

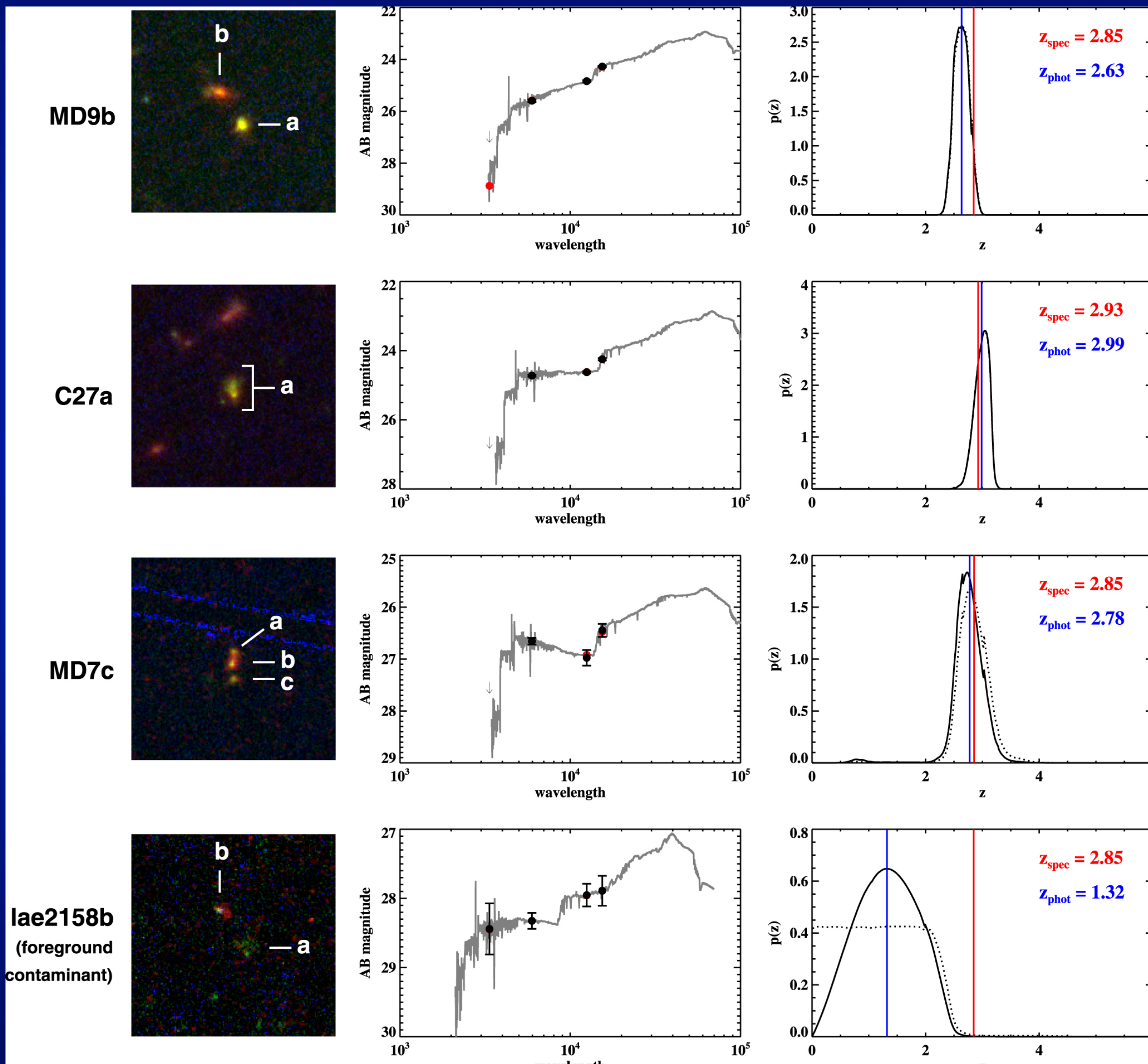


- We imaged 4 LBGs and 12 LAEs in Q1549 with apparent LyC detections using *HST* UVJH.
- Photometric redshifts for each subcomponent.
- J and H bracket Balmer break at z~3.



(Mostardi et al. 2015)

What about contamination?

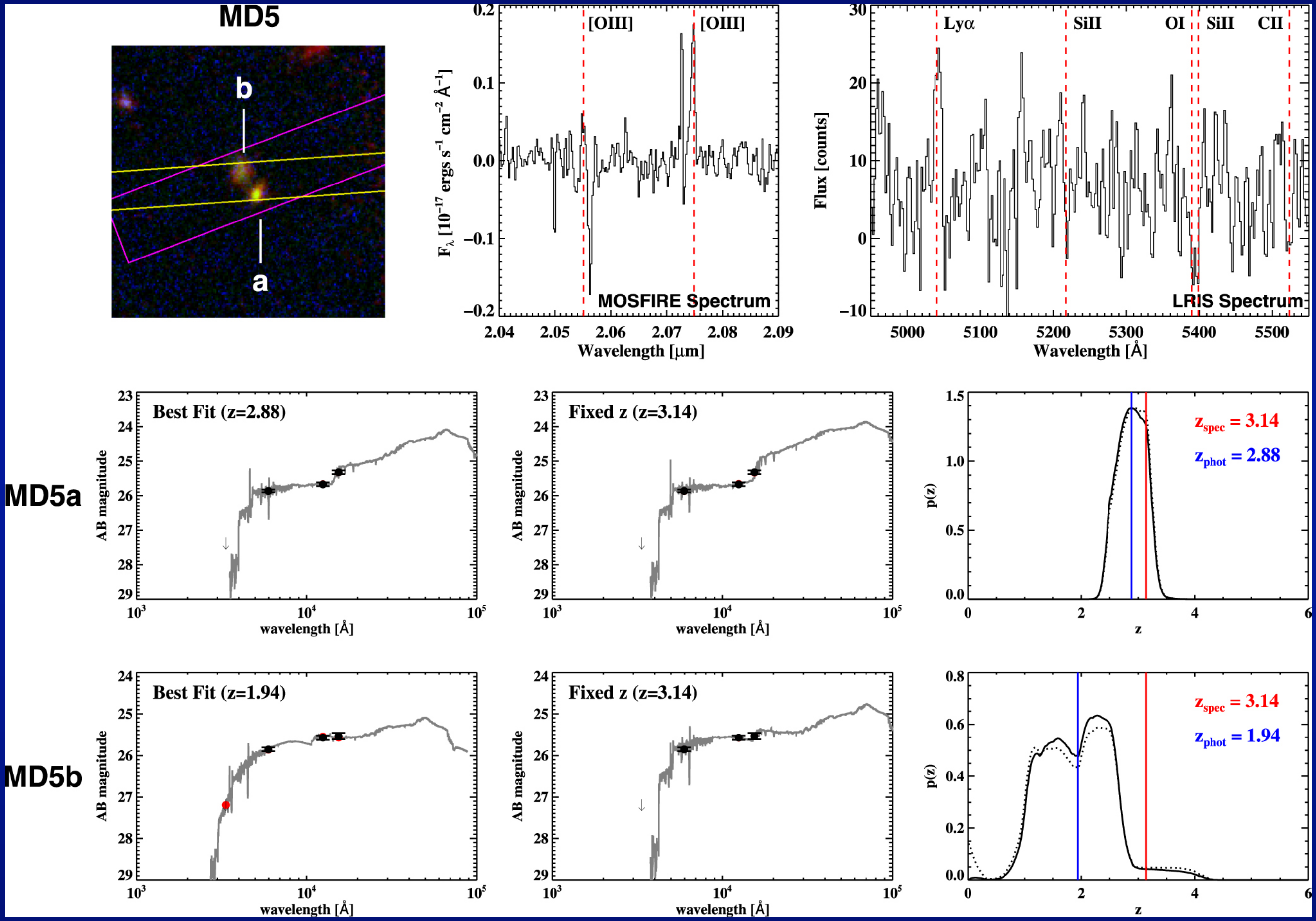


(Mostardi et al. 2015)

- Galaxies are typically lumpy!
- Examples of subcomponent SEDs.
- VJH colors of contaminant stand out from those of z~3 objects.
- These z~3 examples don't have LyC detections.

What about contamination?

(Mostardi et al. 2015)

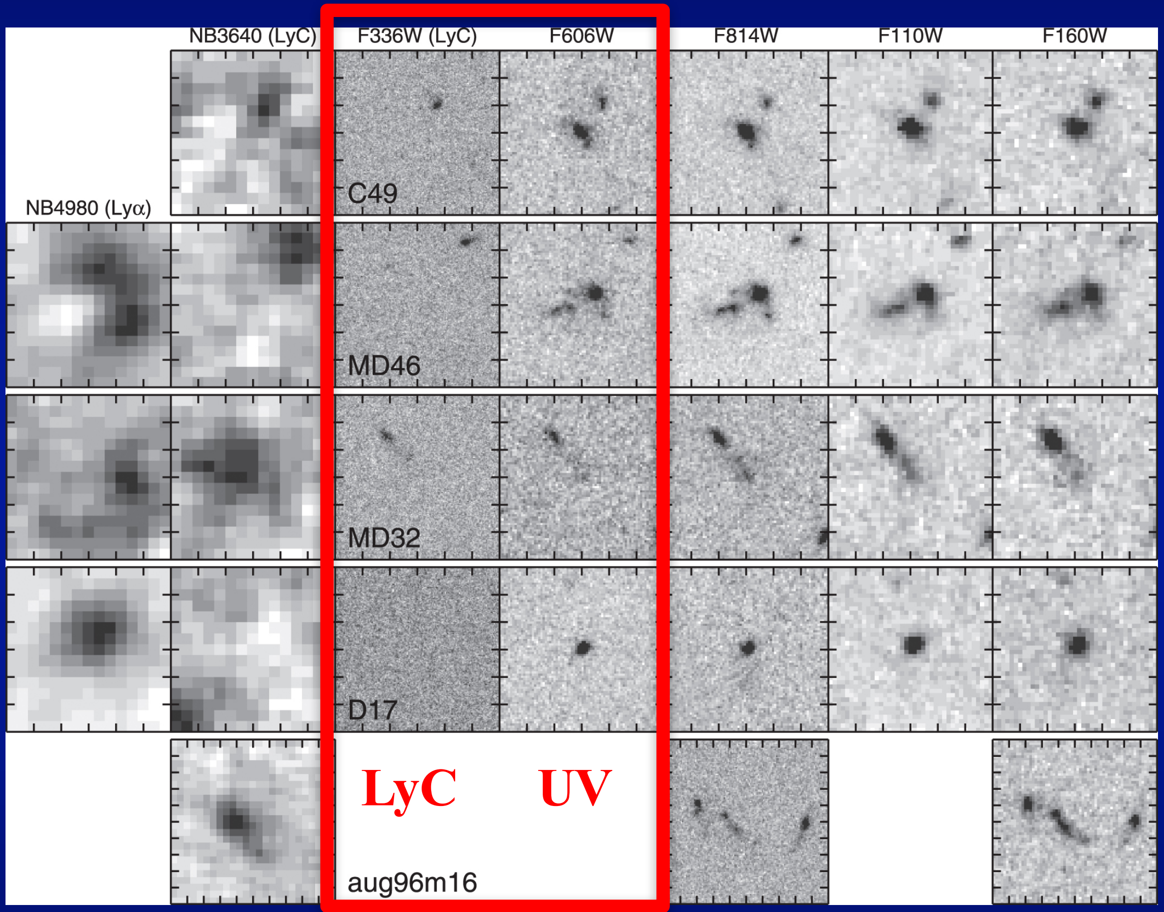


Two clumps, separated by 0.58”.

- One object out of 16 has robust LyC detection not due to obvious foreground contamination: MD5.
- Two components. Need to show definitively that MD5b is at z=3.15.

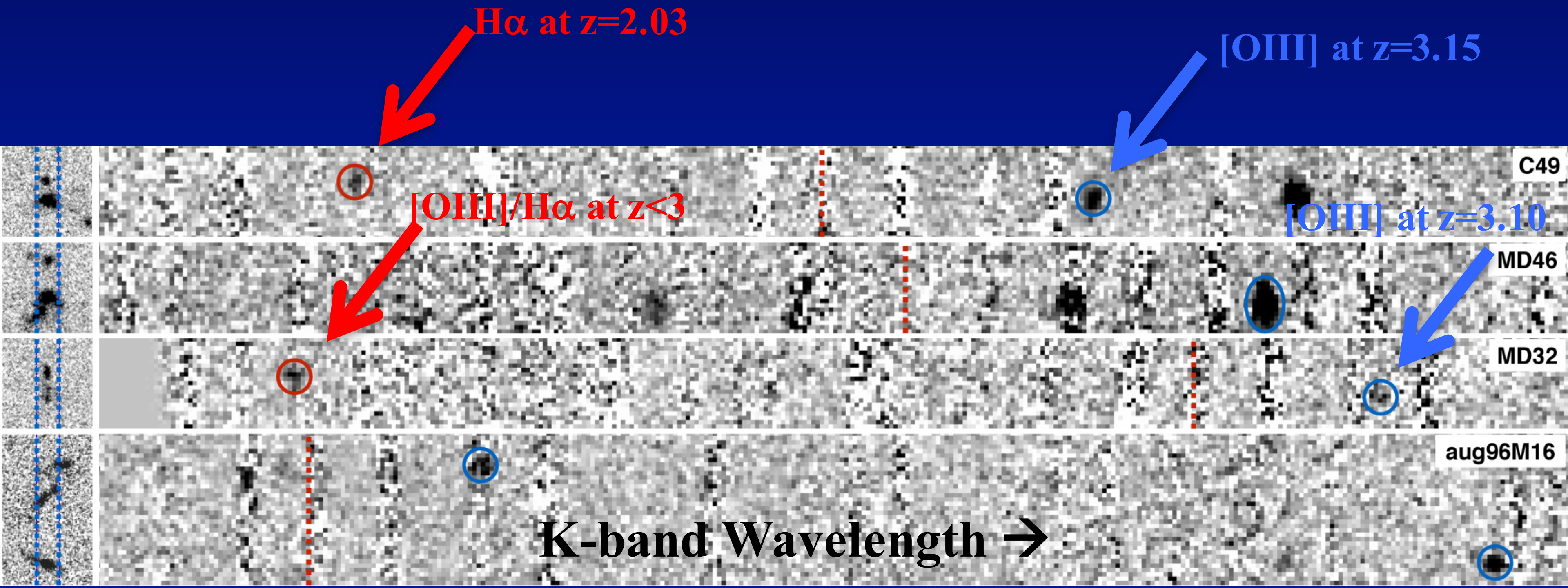
What about contamination?

(Siana et al. 2015)



- HST UVIJH imaging in SSA22a plus near-IR spectroscopy.
- Clumpy morphologies revealed by HST. Apparent LyC emission only associated with one of the clumps.

What about contamination?



(Siana et al. 2015)

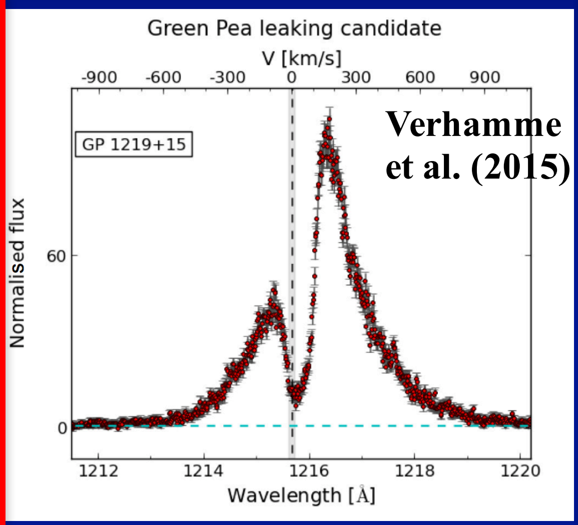
- Keck/NIRSPEC spectra of C49 and MD32 show evidence for low-redshift interlopers. Offset is ~0.5”. Difficult to resolve in optical data, for MD32 in particular.
- Contamination is very important! HST/AO spatial resolution required, or excellent near-IR seeing.

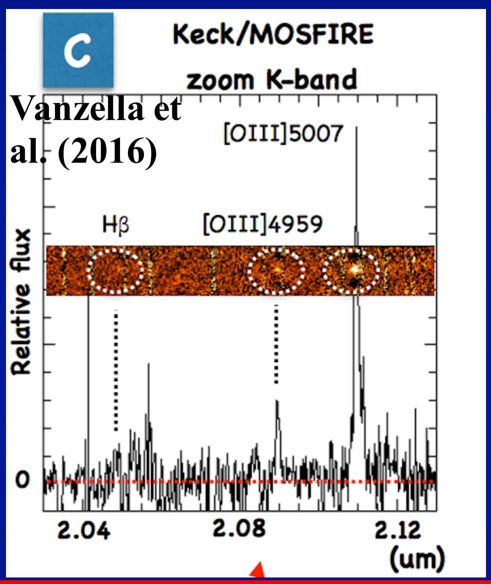
What about contamination?

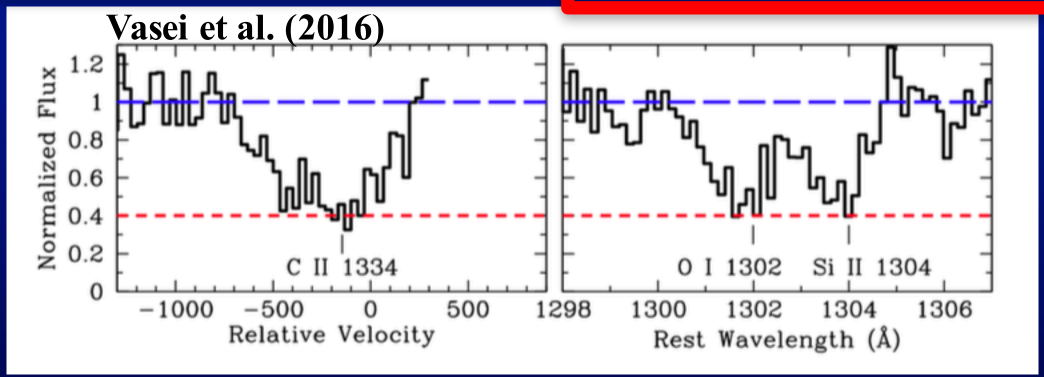
- Contamination rate is comparable to detection rate.
- Ground-based, seeing-limited observations (imaging and spectroscopy) cannot be interpreted without HST-level spatial resolution.
- A spectroscopic or photometric redshift is required for each subcomponent associated with LyC emission.
- Premature to calculate global quantities (ε_{LyC}, Γ, $\dot{n}_{ion}$ *ndot*$_{ion}$), relate z~3 "leaker" properties to those of potential z>6 LyC leakers.

Predicting LyC

- How to predict which objects are "leakers" based on non-ionizing emission?



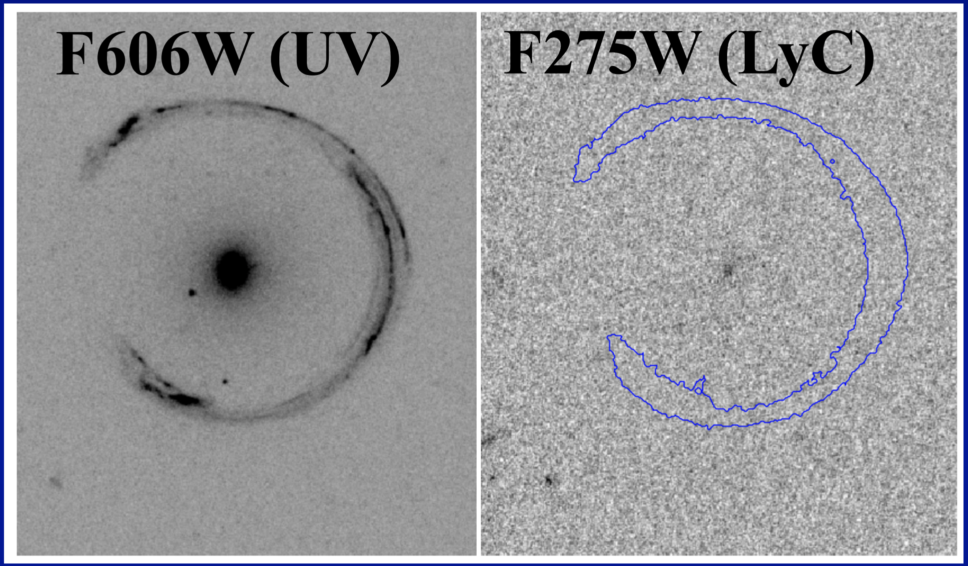


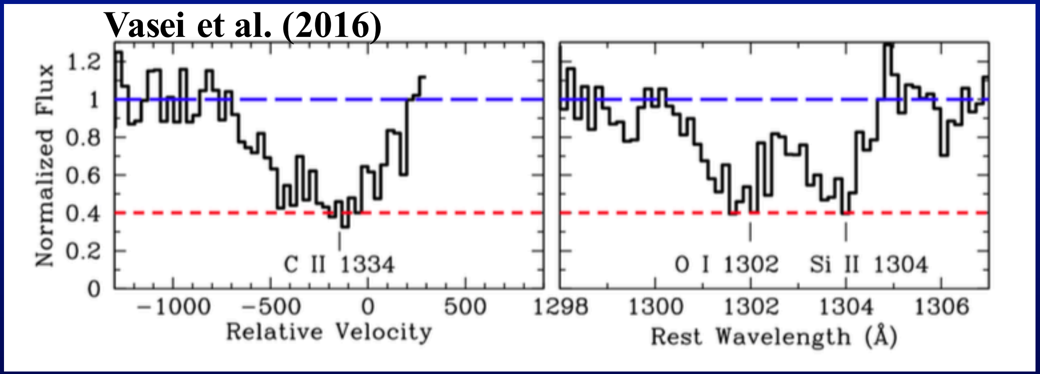


- **Lyα emission with significant flux at systemic and negative velocities?**
- **Interstellar absorption lines that are saturated but not black (non-unity covering fraction)?**
- **High [OIII]/[OII] ratios indicative of density-bounded HII regions?**

A Cautionary Tale

- How to predict which objects are "leakers" based on non-ionizing emission?



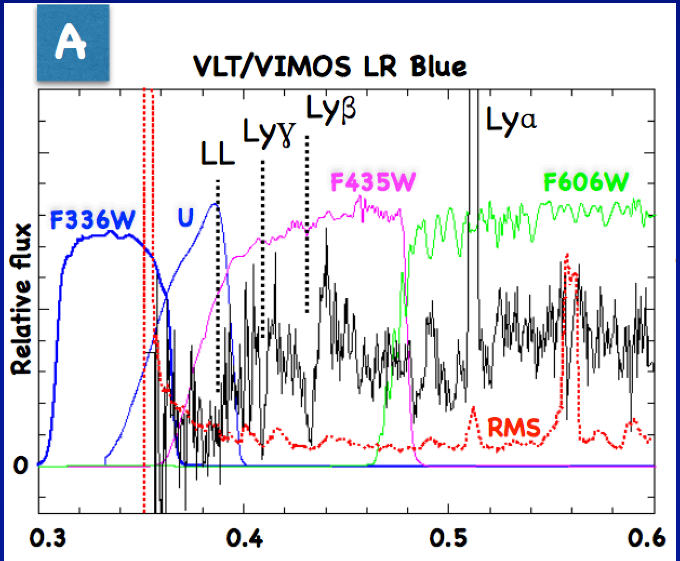


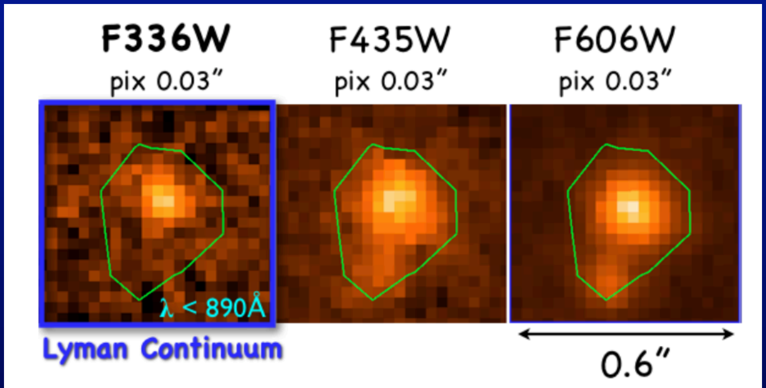
- Cosmic Horseshoe, lensed galaxy at z=2.38.
- Interstellar absorption lines that are saturated but not black (non-unity covering fraction)?
- HST F275W imaging reveals upper limit on LyC emission, $f_{esc,rel}$=0.08, 5 times lower than predicted by ISM lines.

Some Hope: Ion2

- Ion2 (z=3.2, in GOODS-S) has both deep spectrum and HST imaging.

(Vanzella et al. 2016)





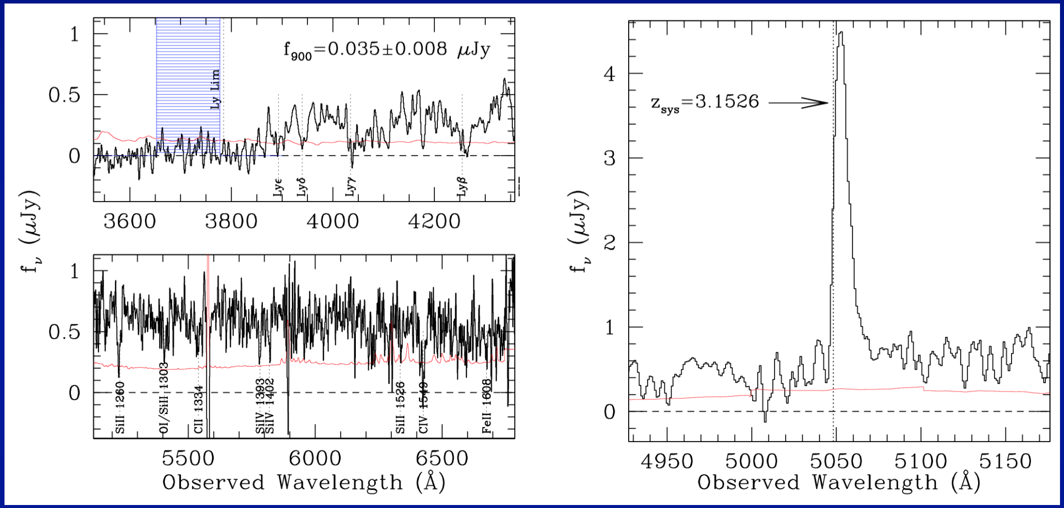
- Spectrum and ground-based U-band imaging suggests LyC emission.

- HST imaging shows that F336W (i.e., LyC) is associated with bright component at z=3.2.

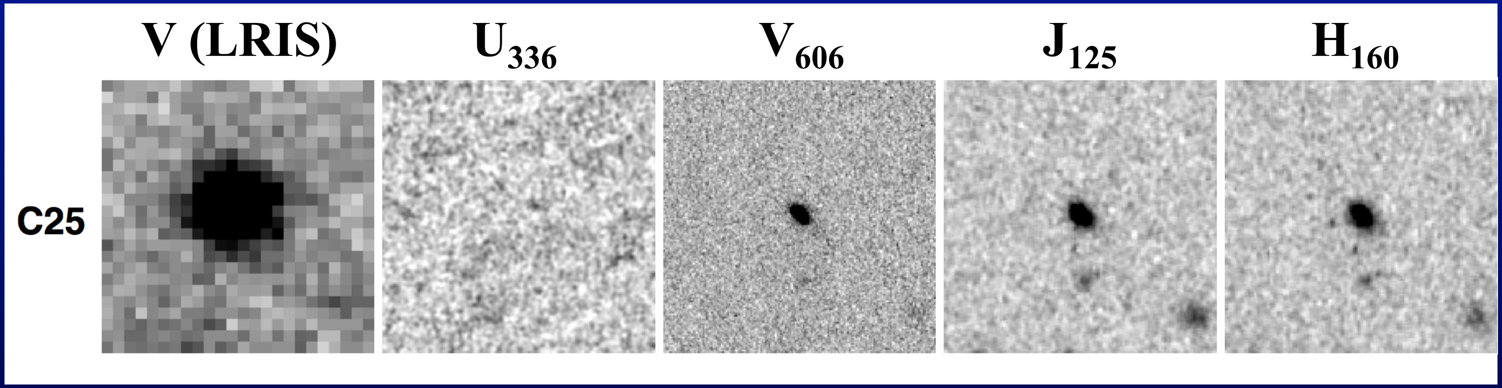
Some Hope: Q1549-C25

(Shapley et al. 2016)

- **Q1549-C25 (z=3.15) has both deep spectrum and HST imaging.**

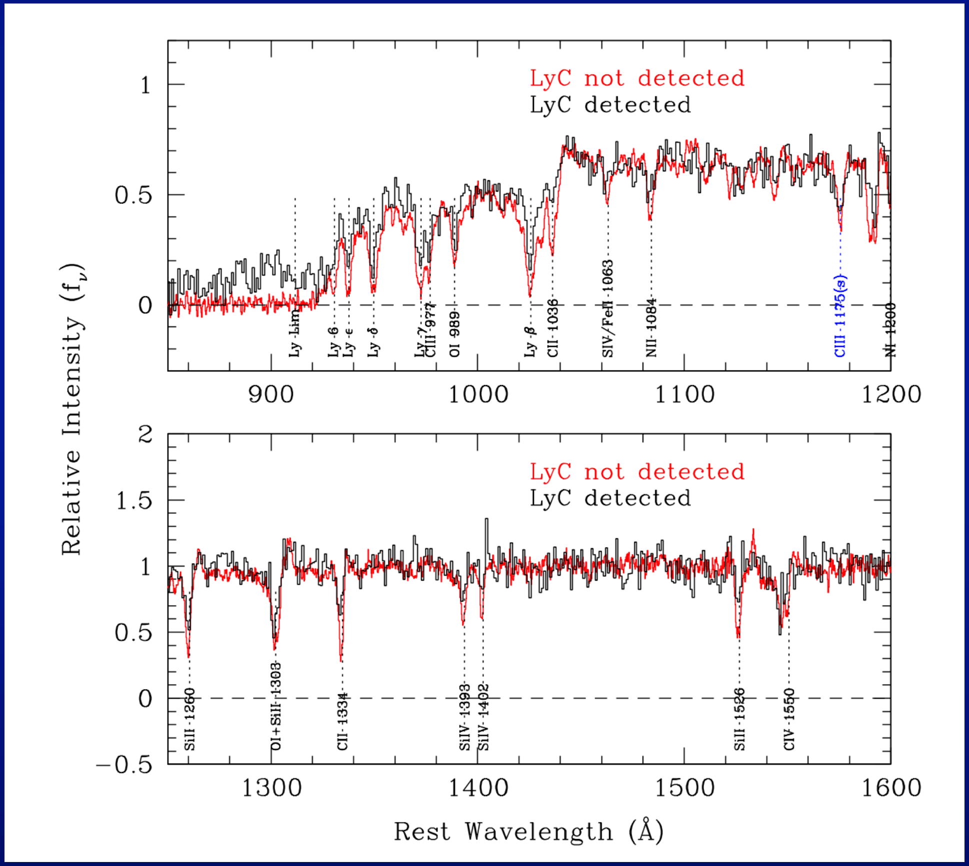


- **Spectrum suggests LyC emission (4.4σ).**
- **HST imaging shows that there is no contamination.**



What's next?

- Requirement: promising sample of LyC detections, HST follow-up.



- Steidel et al. (in prep.): Sample of 124 LBGs with ~8 hour Keck/LRIS spectra covering the LyC region.
- 13/124 apparently detected spectroscopically in LyC.
- Follow up with HST UVJH imaging, determine contamination rate.
- Other spectroscopy: LRIS, MOSFIRE.
- *Increase current robust LyC sample by an order of magnitude.*

Closing remarks

• Identifying the sources responsible for reionizing the intergalactic medium (IGM) is an important goal for observational cosmology.

• Direct measurements of leaking LyC are only possible at $z<3.5$.

• Contamination from lower-redshift sources is a huge challenge to overcome when making this measurement.

• We need a much larger sample of robust detections to calculate global ionization-related quantities and relate $z<=3$ leaking galaxies to those observed during reionization.

• We have identified the ideal $z\sim3$ sample for follow-up with *HST*.

• Why is this so hard? For V~26 (median LAE), even assuming only factor of ~3 Lyman break:

- f_{esc}=100%, t_{IGM}=100%: $m_{900,AB}\sim27.2$
- f_{esc}=100%, t_{IGM}=50%: $m_{900,AB}\sim28$
- f_{esc}=10%, t_{IGM}=50%: $m_{900,AB}\sim30.5$