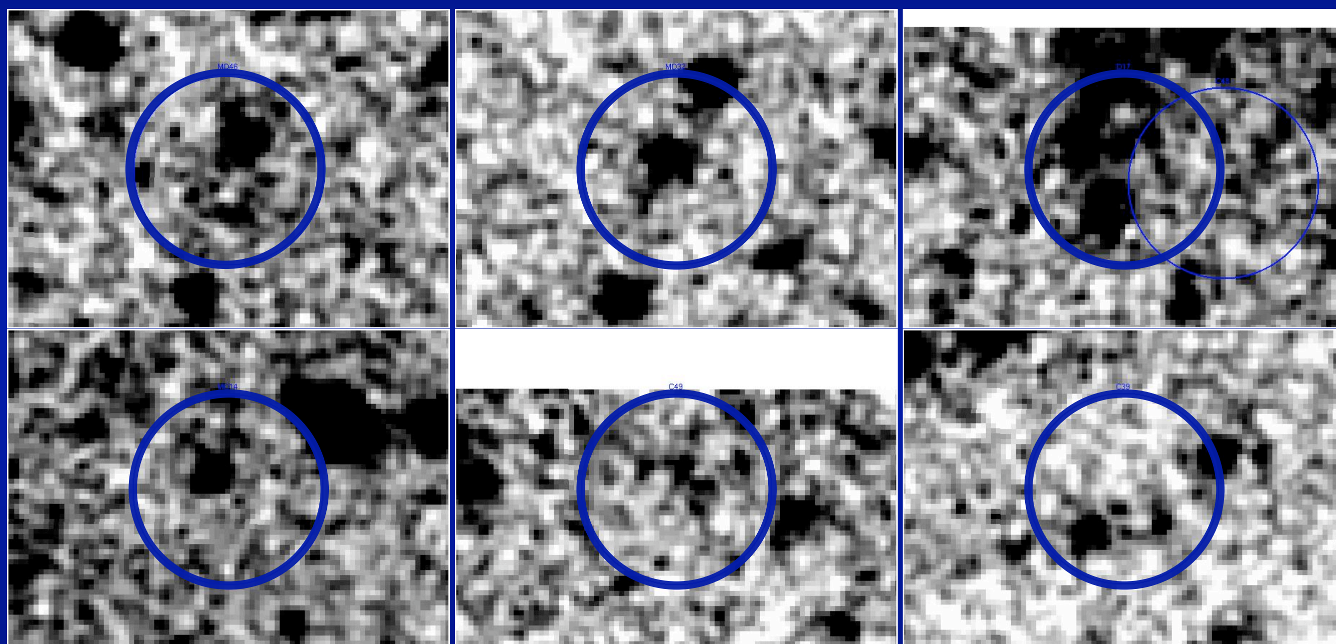
Imaging Lyman Continuum Emission from Galaxies at z~3



Alice Shapley (UCLA)

Collaborators: Chuck Steidel, Milan Bogosavljevic, Max Pettini, Dawn Erb, Naveen Reddy

See also: poster by Iwata, and Iwata et al. 2008 (astro-ph/0805.4012)!!!

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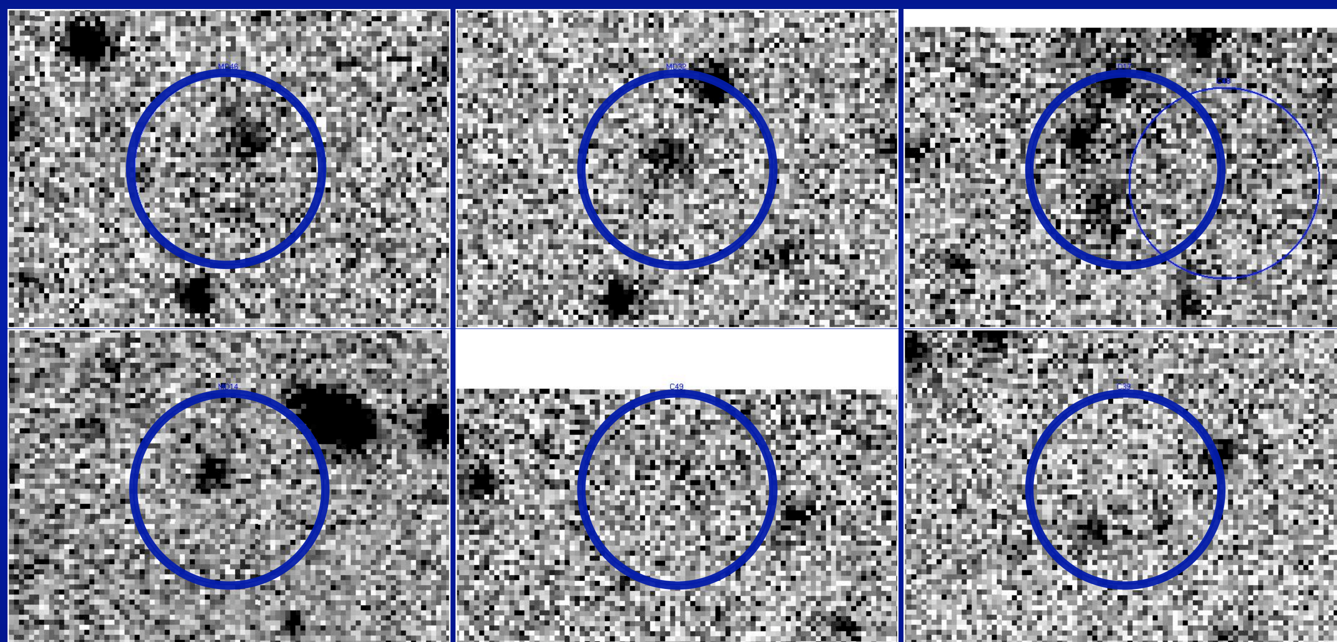

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Origin of the Ionizing Background

- Ionization rates of HI and HeII in the IGM are controlled by amplitude and spectrum of background radiation field between 1 and 4 Rydbergs

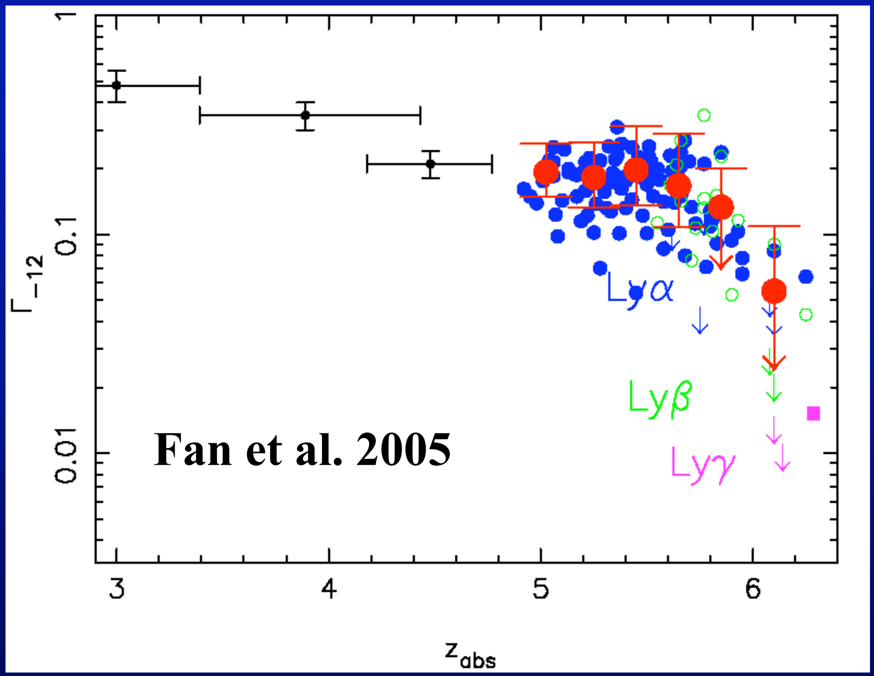
- Nature of the ionizing background important for understanding reionization and inferring physical properties of Lyα forest

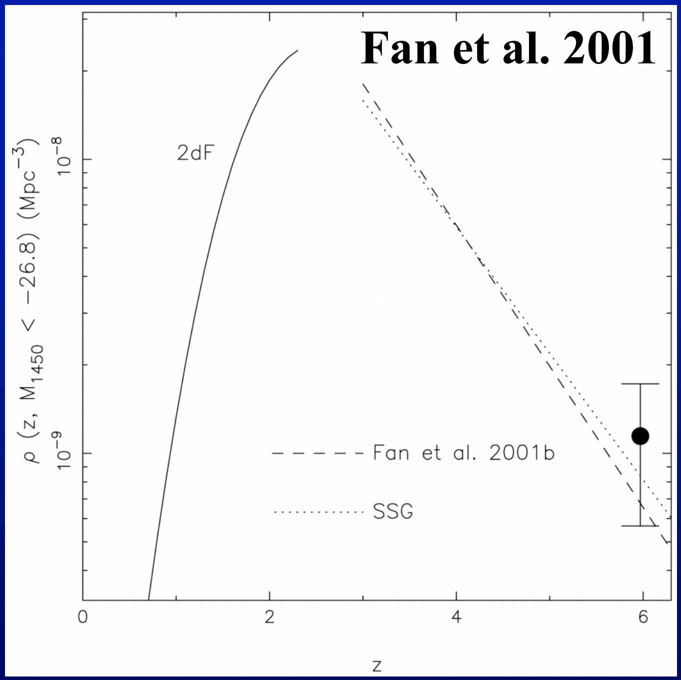
- Fundamental questions: How did the universe transform from having a neutral to highly ionized IGM? What are the relative contributions of QSOs and galaxies to the ionizing background as a function of redshift? What is f_{esc} in galaxies?

- Today's question: what is the observed spatial distribution of ionizing radiation in galaxies at z~3, and how does this constrain models of the escape fraction?

Origin of the Ionizing Background

The drop-off in QSO number density at high redshift, compared with ionizing background, implies QSOs can't dominate by z~5 (McDonald & Miralda-Escude 2001). At z>3, galaxies become dominant contributors to ionizing background. Determining process through which radiation escapes galaxies is crucial.





Definitions of f_{esc}

Lyc=880-910 Å

UV=1500 Å

- What is f_{esc}?

$$f_{esc} = \frac{L_{lyc,out}}{L_{lyc,in}} = \exp(-\tau_{ISM,lyc})$$

- What is $f_{esc,rel}$ and why?

$$f_{esc,rel} = f_{esc} \times \left(\frac{L_{UV,out}}{L_{UV,in}}\right)^{-1} = f_{esc} \times \exp(\tau_{ISM,UV})$$

Useful for deriving global quantities, such as $J_{912,gal}$, based on LBG UV luminosity function

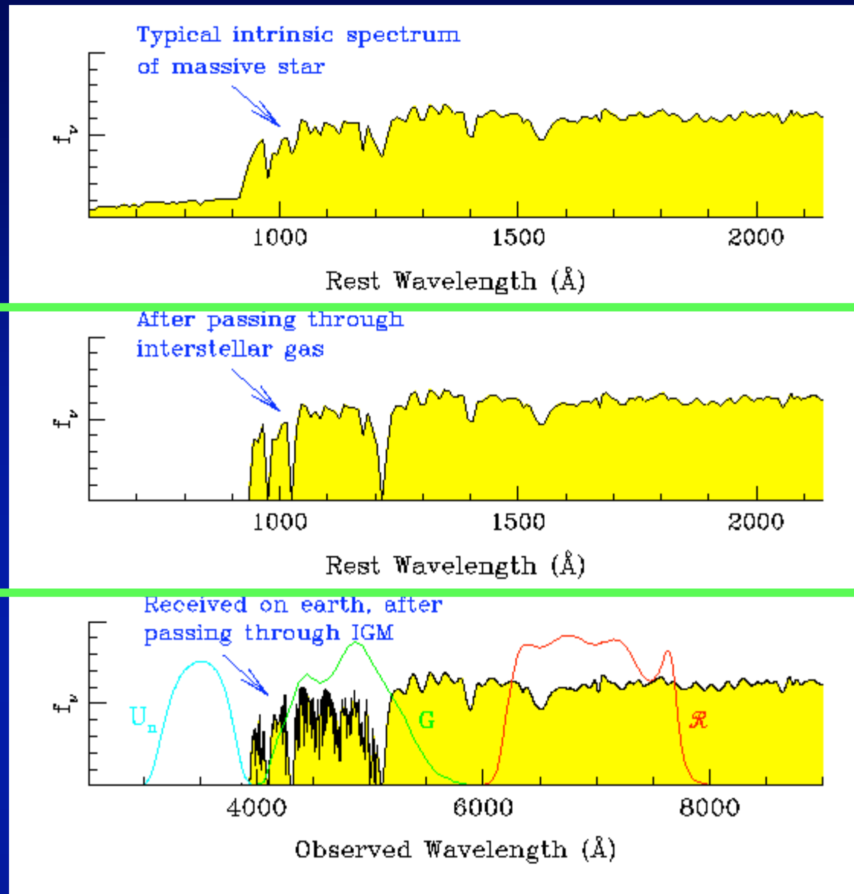
- $f_{esc,rel}$ can be re-written:

$$f_{\rm esc,rel} = \frac{(L_{1500}/L_{900})_{\rm int}}{(f_{1500}/f_{900})} \exp(\tau_{\rm IGM,900})$$

Stellar pop. models:1.5-5.5 → $(L_{1500}/L_{900})_{\rm int}$

We measure this → (f_{1500}/f_{900})

Simulations of z~3 IGM opacity in Lyc range → $\tau_{\rm IGM,900}$



$$f_{\rm esc,rel} = \frac{(L_{1500}/L_{900})_{\rm int}}{(f_{1500}/f_{900})} \exp(\tau_{\rm IGM,900})$$

Stellar pop. models:1.5-5.5

We measure this

Simulations of z~3 IGM opacity in Lyc range

Search for Ly-Cont Emission

z<3:

- **Local starburst observations dominated by upper limits, e.g. HUT spectra at z~0, f_{esc}<0.01-0.15 (Leitherer et al. 1995, Deharveng et al. 2001)**

- **Controversial result about Haro 11 (local dwarf starburst). Bergvall et al. 2006 report FUSE detection of Lyman continuum implies f_{esc}~0.04-0.11 -- challenged by Grimes et al. (2007)**

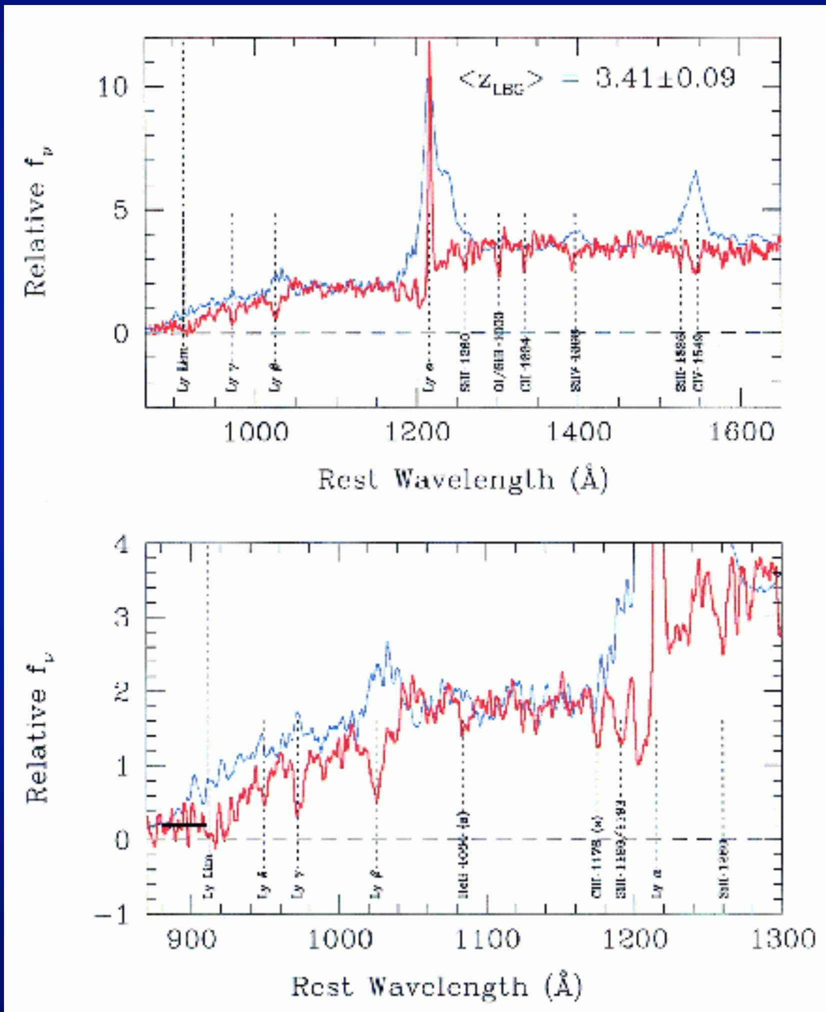
- **z~1 observations: HST/STIS UV (λ_{obs}~1600Å) imaging of star-forming galaxies at z=1.1-1.7 (Malkan et al. 2003, Siana et al. 2007). Probe rest-frame 700 Å. Non-detections, limits on $f_{esc,rel}$<0.1-1.0.**

z~3:

- **Multiple groups reported non-detections of various types: individual spectra (Giallongo et al. 2002), SED modeling (Fernandez-Soto et al. 2003), NB imaging (Inoue et al. 2005)**

- **Our group has composite and individual spectroscopic detections**

Detection of Ly-Cont Emission?



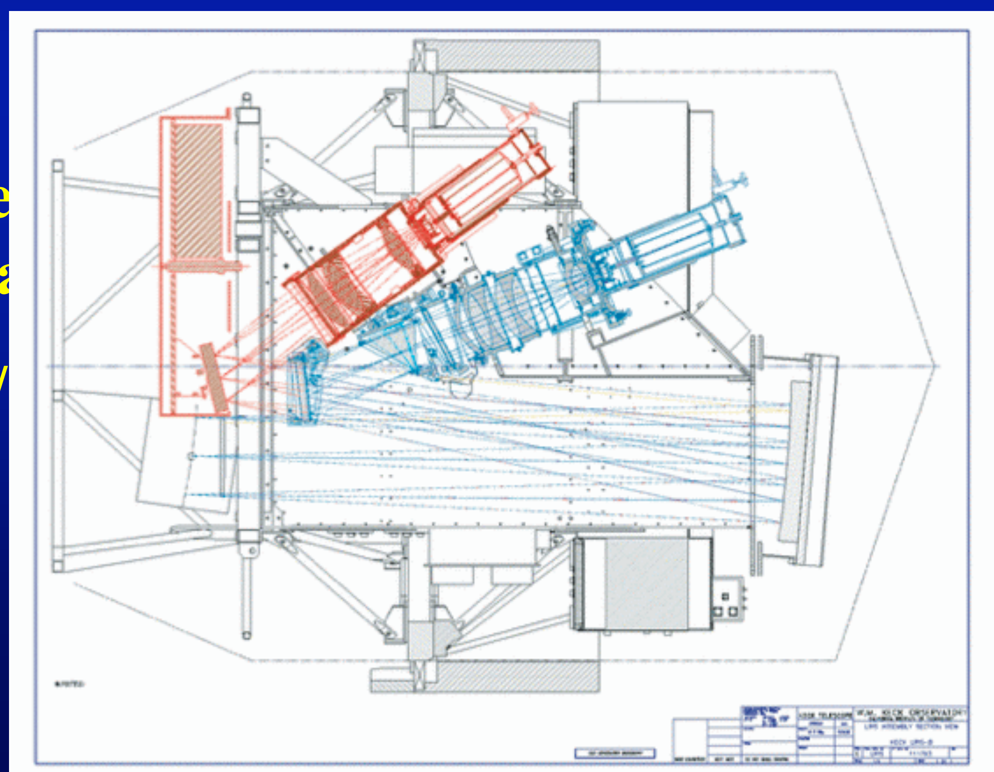
(Steidel et al. 2001)

LBG Composite Spectrum

- 29 gals at <z>=3.4+/-0.09
- Significant Ly-cont flux in composite spectrum → 5 times more ionizing flux than QSOs at z~3
- Bluest quartile in $(G-R)_0$, strong Lyα emission: is it a fair sample?

Individual Ly-C Detections

- Deep Keck/LRIS spectra for a sample of 14 objects (1 mask)
- Red side: detailed obs of interstellar lines (17 hr, 2x resolution)
- Blue side: sensitive observations of Lyman Continuum region (22 hr, 8 hr with New Blue Camera, 1.3x resolution)
- Ionizing flux ... hy?
- F_{900}/F_{1500} (i.e ... alaxies --> significant gal...
- Ratio of F_{900}/ ... es lower than that in Steidel



Individual Ly-C Detections

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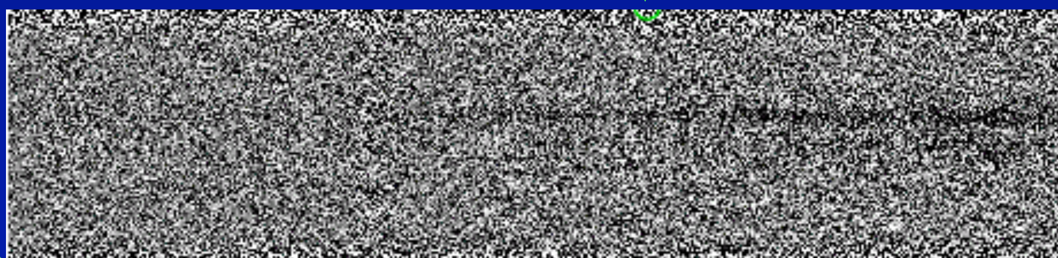
- Red side: detailed obs of interstellar lines (17 hr, 2x resolution)
- Blue side: sensitive observations of Lyman Continuum region (22 hr, 8 hr with New Blue Camera, 1.3x resolution)
- Ionizing flux is detected for 2 out of 14 objects. Why?
- F_{900}/F_{1500} (i.e. F_{lyc}/F_{UV}) quite large for these two galaxies --> significant galaxy-to-galaxy variation in f_{esc}?
- Ratio of F_{900}/F_{1500} in average spectrum is four times lower than that in Steidel et al. (2001)

Detections: 2D Spectra

Lyman limit, 912 Å



3350 Å 3950 Å

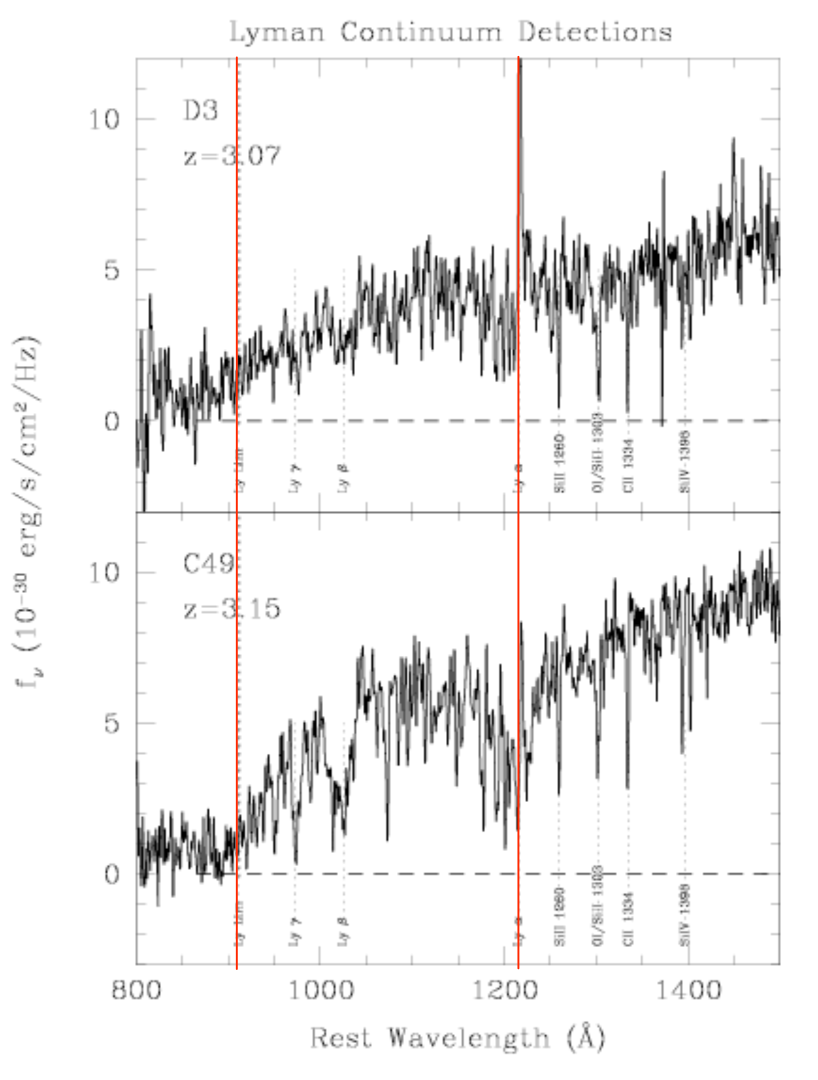
D3, z=3.07
Rs=23.37

Lyman limit, 912 Å

3350 Å 3950 Å

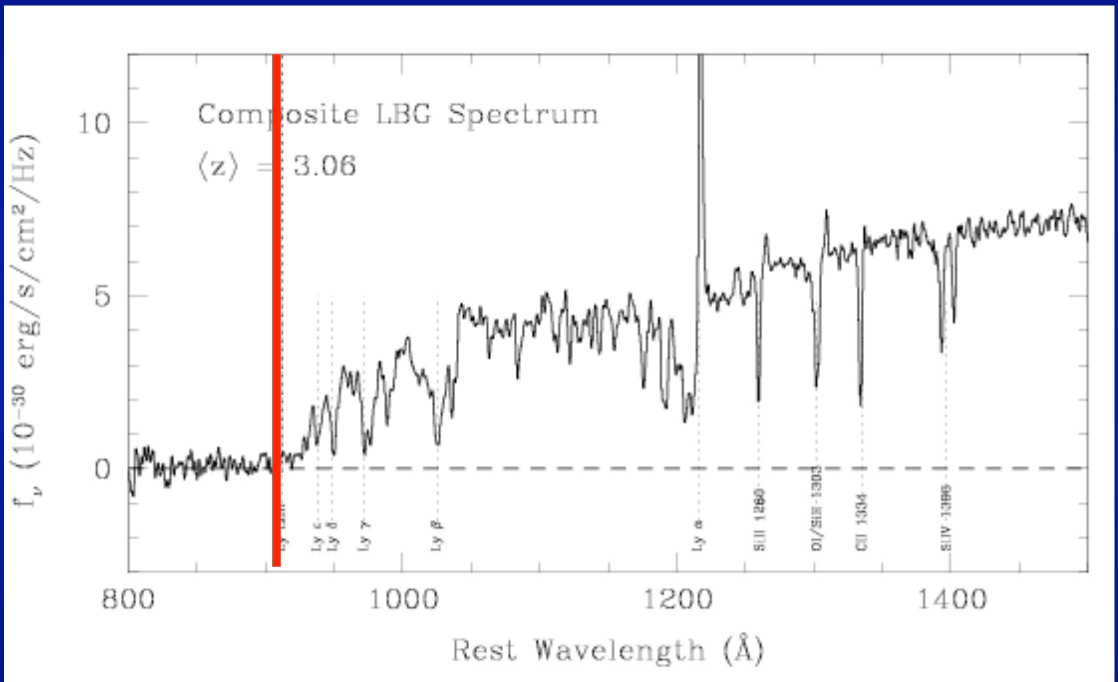
C49, z=3.15
Rs=23.85

Detections: 1D Spectra



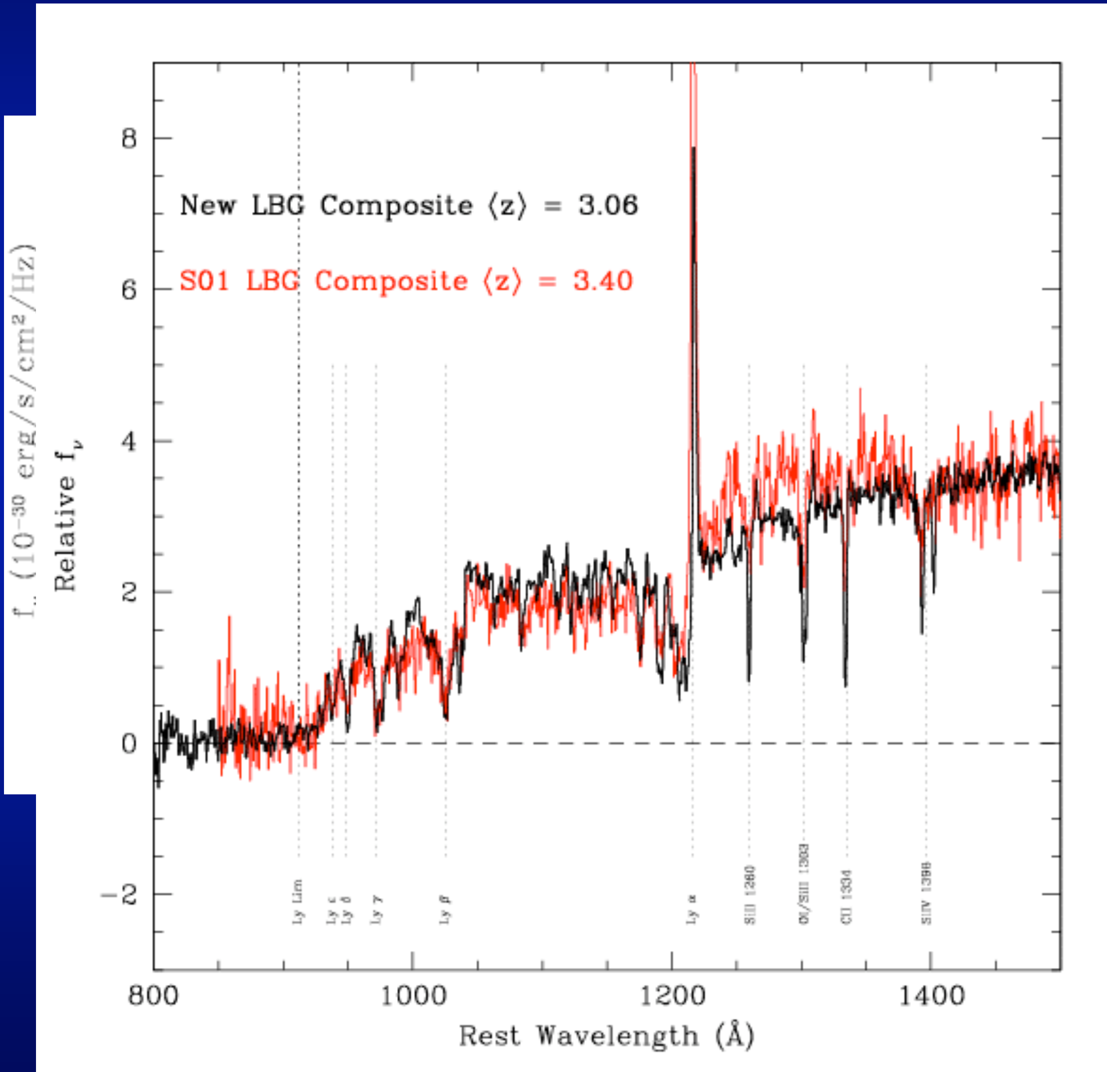
- D3, double, z=3.07, Rs=23.37 F_{1500}/F_{900}=7.5 if you add F_{1500} from both components
- C49, z=3.15, Rs=23.85 F_{1500}/F_{900}=12.7
- Both objects have very high $f_{esc,rel}$, >65%, f_{esc}>15%
- Yet, they have very different properties: D3 is reddest object in sample, C49 is one of bluest. D3 has very deep absorption lines (high covering fraction), C49 has much weaker absorption lines. D3 has double morphology.

The Average Spectrum



- F_{1500}/F_{900}=58, four times larger than S01, IGM correction implies $F_{1500}/F_{900,corr}$=22, and $f_{esc,rel}$=14%, f_{esc}=4%.
- Assuming F_{1500}/F_{900} is representative, use it to convert LBG 1500Å luminosity function into 912Å luminosity function/density → ε(912), J_{912} and Γ
- Obtain $J_{912}=2.6\times10^{-22}$ erg $s^{-1}cm^{-2}Hz^{-1}sr^{-1}$, and $\Gamma\sim6\times10^{-13}$ s^{-1}, more consistent with recent estimates (Bolton et al. 2005) of Γ(z=3) based on Lyα forest optical depth

The Average Spectrum



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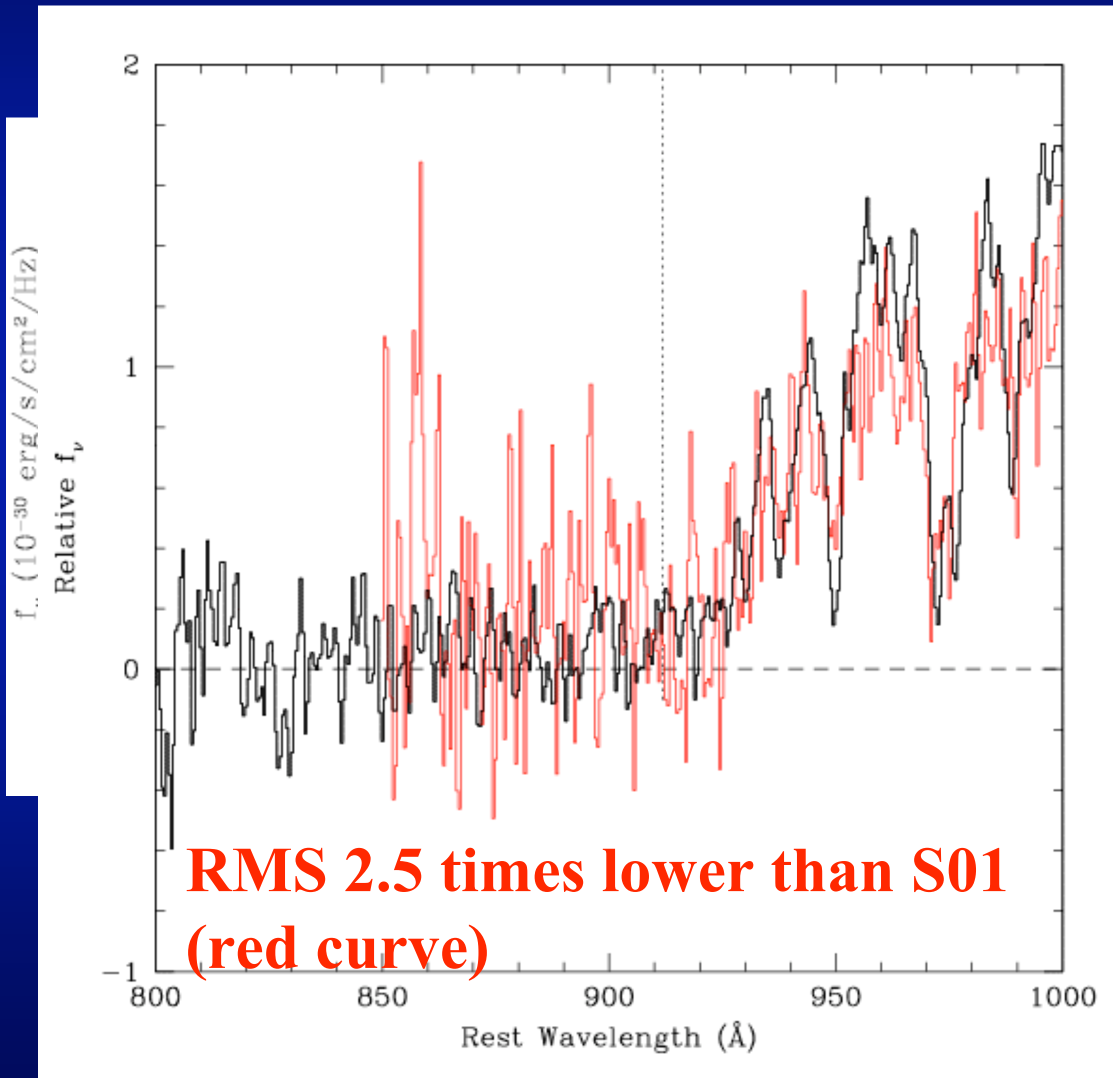

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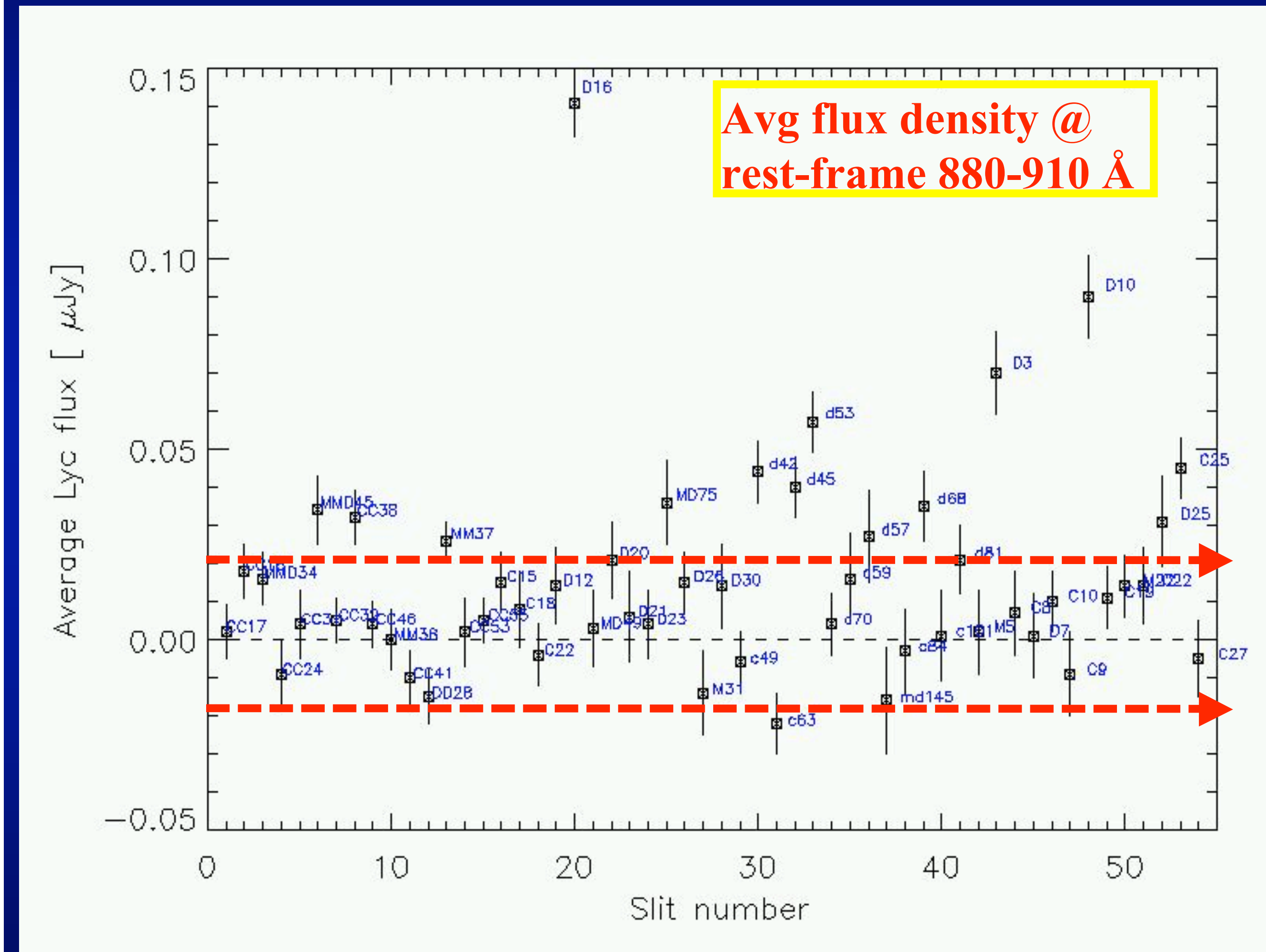
One Way Forward



(Bogosavljevic, Steidel, Shapley, Reddy 2009, in prep)

Much larger sample of Keck/LRIS-B Ly-cont spectra:

Figure shows ~40% of sample with <z>=3.0

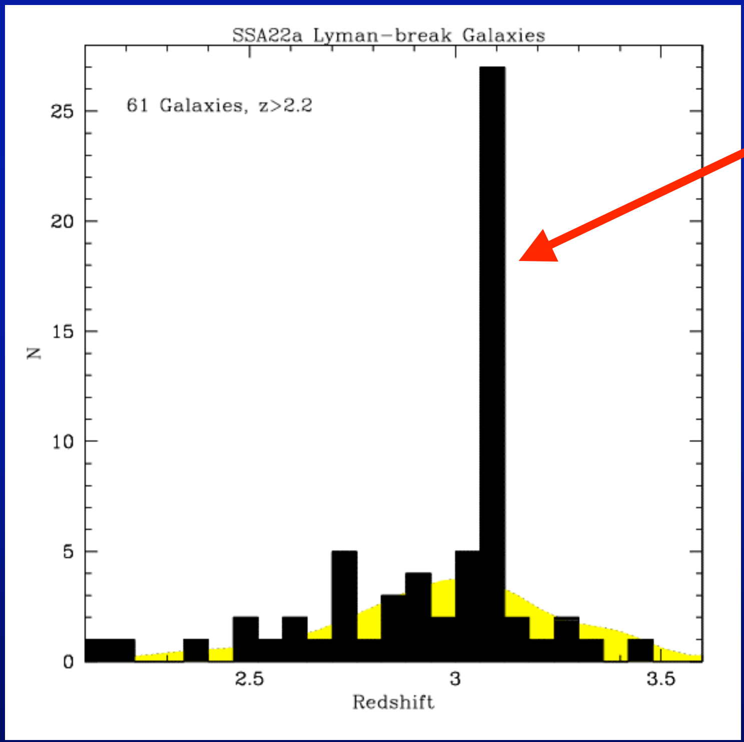
Total sample ~125 objects, 9 masks drawn from several fields (10 nights of observing)

A New Technique

- Using spectroscopy is one way of detecting escaping Lyman continuum emission
- Drawbacks: Sky-subtraction systematics, spectroscopic flatfielding difficult, ~~differential refraction~~ (not an issue any more, but what about intrinsic offsets?)
- Also, desirable to determine spatial distribution of ionizing radiation, how Lyman continuum emission distributed relative to UV non-ionizing flux and Lyα.
- Narrow-band imaging, just below the Lyman limit, provides complementary technique for detecting escaping ionizing radiation (e.g., Inoue et al. 2005)
- Why narrow-band? At z~3, Lyman continuum mean free path is only $\Delta z=0.18$ (~40 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.

A New Technique

- BUT….Narrow-band imaging just below Lyman limit is not very efficient if all galaxies are at different redshifts.
- Solution:

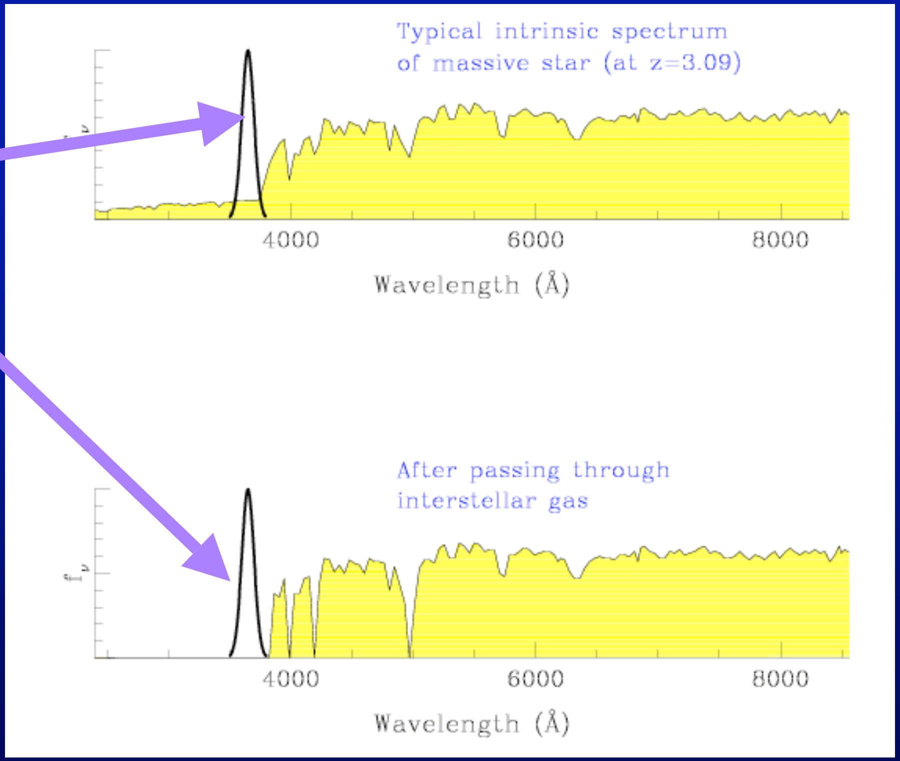


SSA22a field, the very field where we did spectroscopy, contains a redshift overdensity of factor of ~6, with 26 galaxies at z=3.09±0.03.

A New Technique

• It gets better! To image at 880-910Å, an ideal filter would cover roughly 3600-3700Å. It turns out that Andrew Blain had independently designed a filter to probe Lya emission at z~2. This is the very filter required to probe just below the Lyman limit at z=3.09!

Special filter probes right below the Lyman limit, within one Lyman continuum mean free path. Perfect for galaxies contained in the significant spike.



A New Technique

- The final advantageous circumstance is access to imaging with LRIS-B, which has unmatched sensitivity in the ~3600Å wavelength range. Most sensitive imaging instrument at this wavelength on any large telescope.

- In August 2005 and June 2008, we used dichroic capabilities of LRIS-B spectrograph on Keck I telescope to obtain 13.2 hours of Lyman continuum imaging in this 3650/100Å filter on the blue side, and 9.4 hours of Lyα imaging on the red side. LRIS field contains 22 LBG targets at $z=3.09\pm0.03$, 43 LAEs most likely in the spike, 5 LBGs at $z>3.12$.

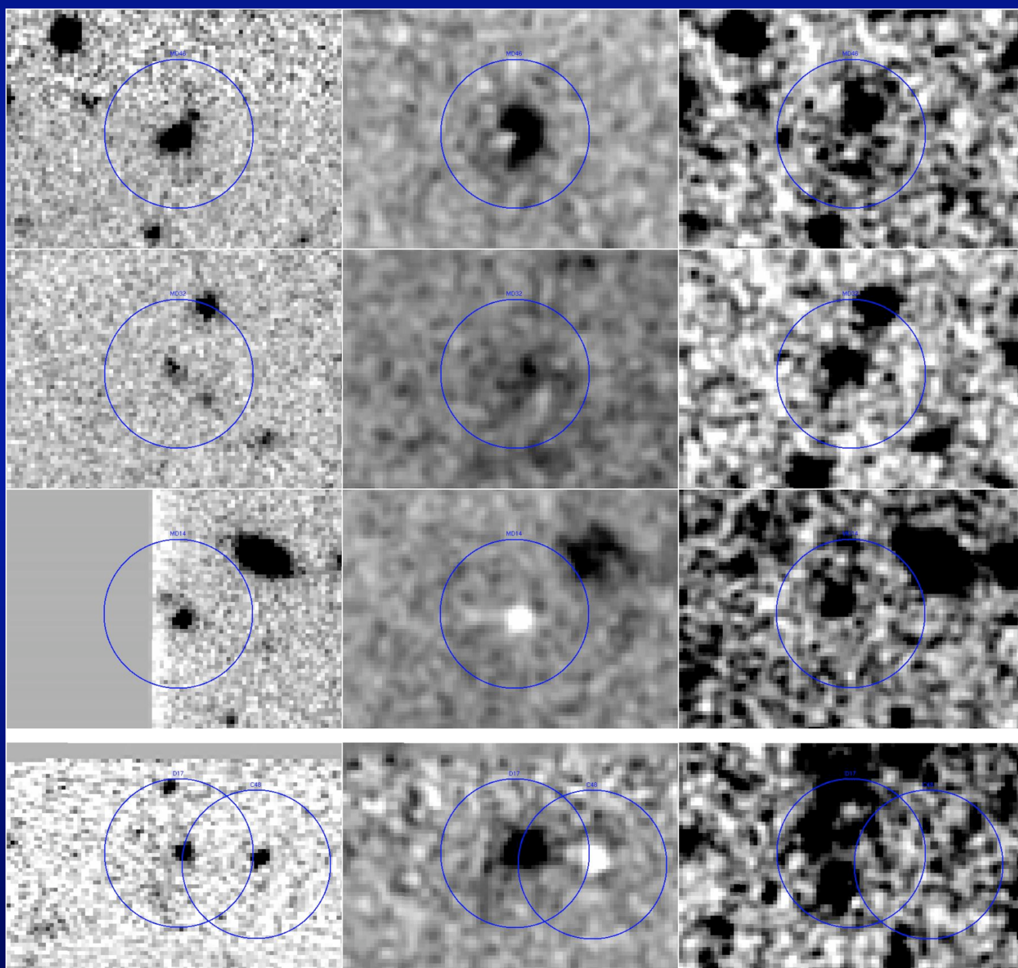
- Depth of Lyman continuum images is 29.15 mag/arcsec^2 (1σ), comparable to depth of spectra.

- We have detections!

- Also, see poster/paper by Iwata et al., based on Subaru/SUPRIME-CAM data, with 3590/150 filter, depth= 28.6 mag/arcsec^2 (astro-ph/0805.4012)

NB Imaging: Examples

Rs-band **Lyα NB** **Ly-cont NB**



MD46, z=3.091, Rs=23.30

MD32, z=3.102, Rs=25.41

MD14, z=3.094, Rs=24.14

D17, z=3.098, Rs=24.27

$(m_{Rs,AB}^{*}=24.54)$

NB Imaging: Early Results

- The LRIS-B/NB imaging technique has yielded individual Ly-cont detections for 5 (out of 22) LBGs contained in the SSA22a protocluster and 2 additional LBGs at higher z (one is C49).

- There are 43 galaxies in the spike that have been selected by their Lyα emission, some of which have spectroscopic redshifts (Matsuda et al. 2005). 15 are detected in Ly-cont (13 unique).

- In most cases, the distribution of light in the Lyman continuum filter appears different from that in the Rs-band (UV non-ionizing continuum). In some cases, the Lyman continuum appears to trace the edges of the Lyα emission (speculative!!). Important to determine what is coming from actual targets vs. what is associated with neighboring galaxies.

- Iwata et al. (2008) show that avg. F_{1500}/F_{900}=4.9 for 7 LBG detections, even smaller for LAEs: challenge for IGM and stellar population models.

Summary & Future directions

• Ly-cont spectroscopic samples on the order of N=100 have now been collected with Keck/LRIS-B/ADC.

• At the same time, NB imaging tuned to the Lyman limit is very efficient in fields containing protoclusters at z~3.

• Individual LBGs and LAEs detected in deep Ly-cont NB imaging in the SSA22a field. Spatial distribution of ionizing radiation is complex. On average, detected objects have very high ratios of F_{900}/F_{1500} (Iwata et al. 2008).

• Compare with theoretical predictions for relative Lyα/Ly-cont/UV-cont light distributions, and ratio of F_{900}/F_{1500}.

• Apply to other fields, e.g. Q1549, z_{spike}=2.85, n_{LBG}=26, n_{LAE}=67, NB filter with λ=3420+/=60 Å.