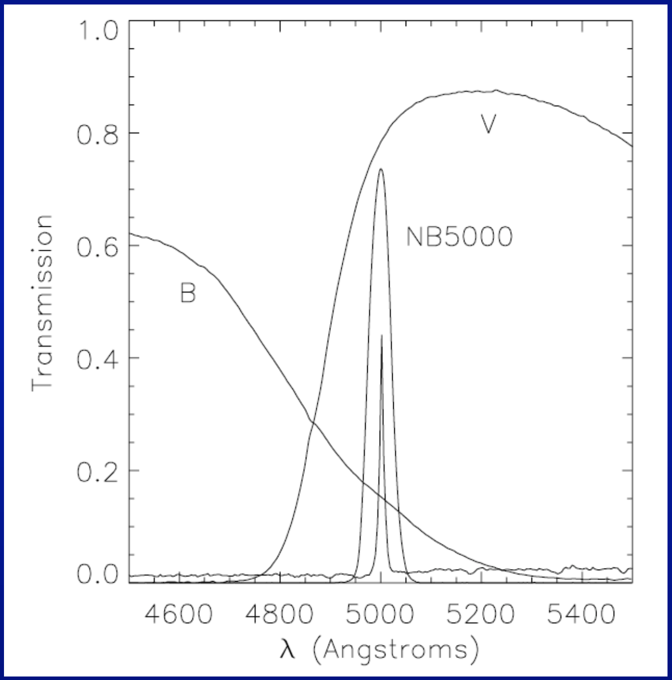
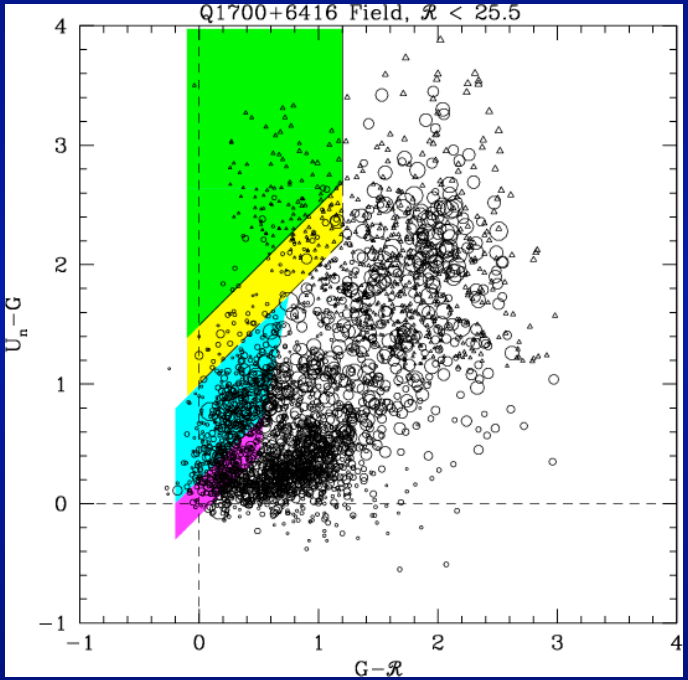
LAEs, LBGs and Related Objects

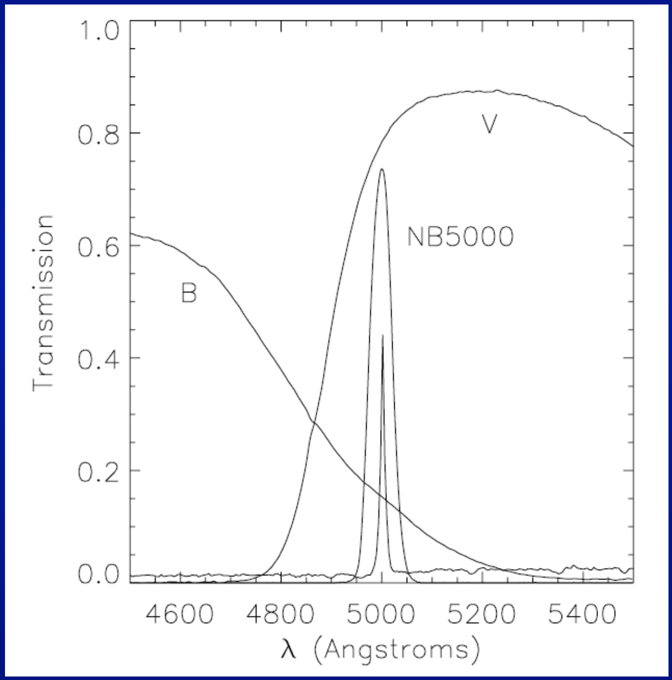


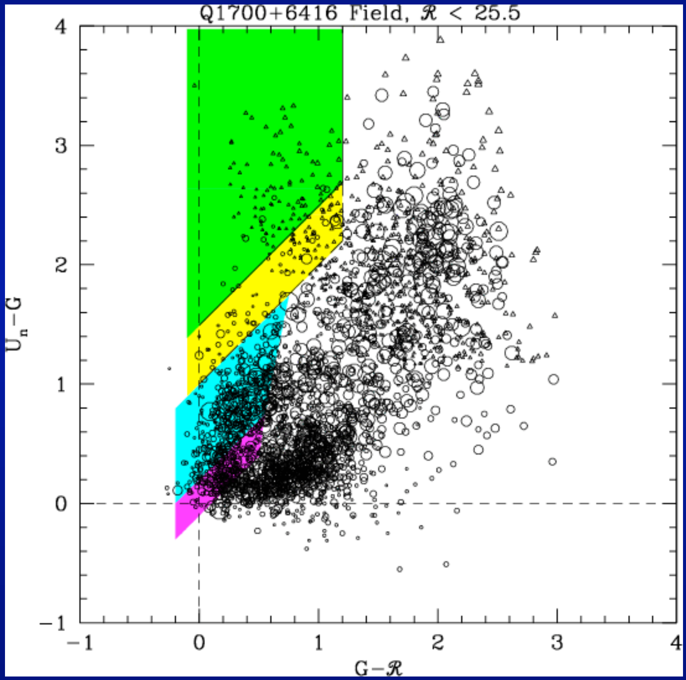


Alice Shapley (UCLA)

Collaborators: Kathy Kornei, Juna Kollmeier, Naveen Reddy, Anna Quider, Max Pettini, Chuck Steidel

Understanding Lyα Emission Using LBGs (and vice versa)





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Outline

- Is a comparison between LAEs and LBGs meaningful?

- LAE stellar populations within LBG samples.

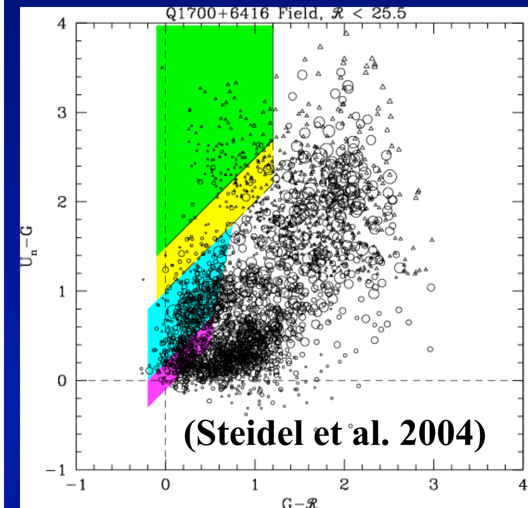
- Lyα emission and dust extinction – i.e., is the dust clumpy?

- Comparison between LBG spectra and Lyα radiative transfer models, both kinematic and spatial.

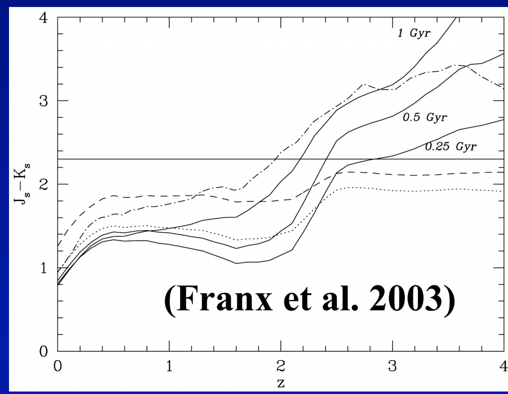
- The future.

LAEs vs. LBGs?

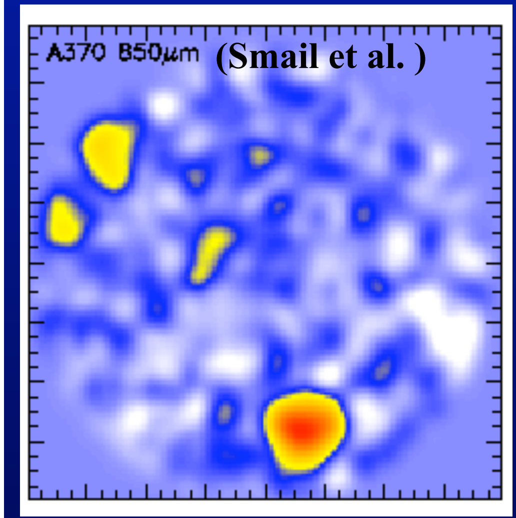
z>1.5 Galaxy Identification and Spectroscopy



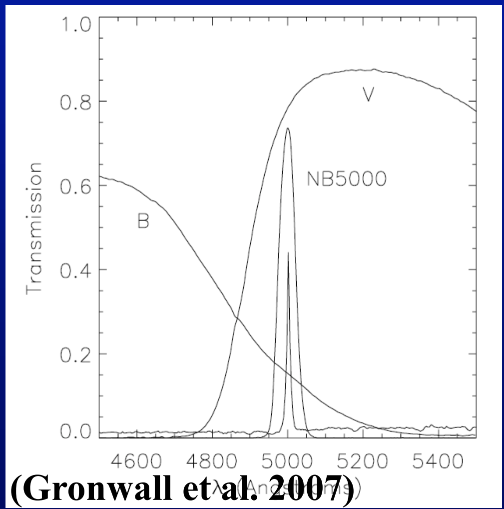
(Steidel et al. 2004)



(Franx et al. 2003)



(Smail et al.)

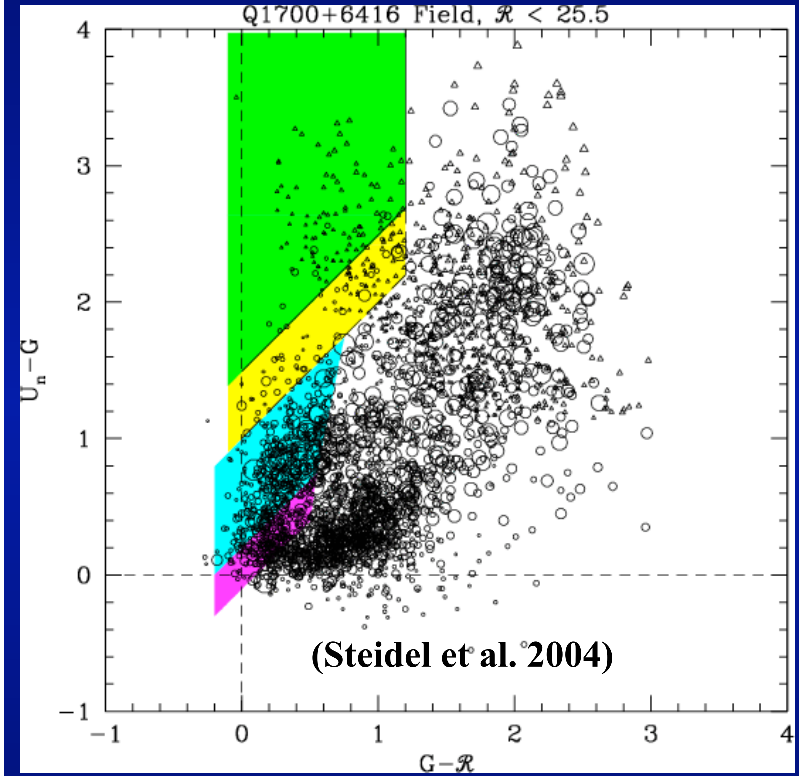


(Gronwall et al. 2007)

• Explosion of z>1.5 surveys. Unlike traditional magnitude-limited surveys, new results utilize several complementary selection techniques for finding high-z galaxies: UV (LBG), DRG, BzK, submm, Lyα emitters (alphabet soup!!)

• All color-based techniques are incomplete wrt star formation and stellar mass. NB and submm selection also only yield incomplete slices of the galaxy population at any given redshift.

Rest-frame UV selection

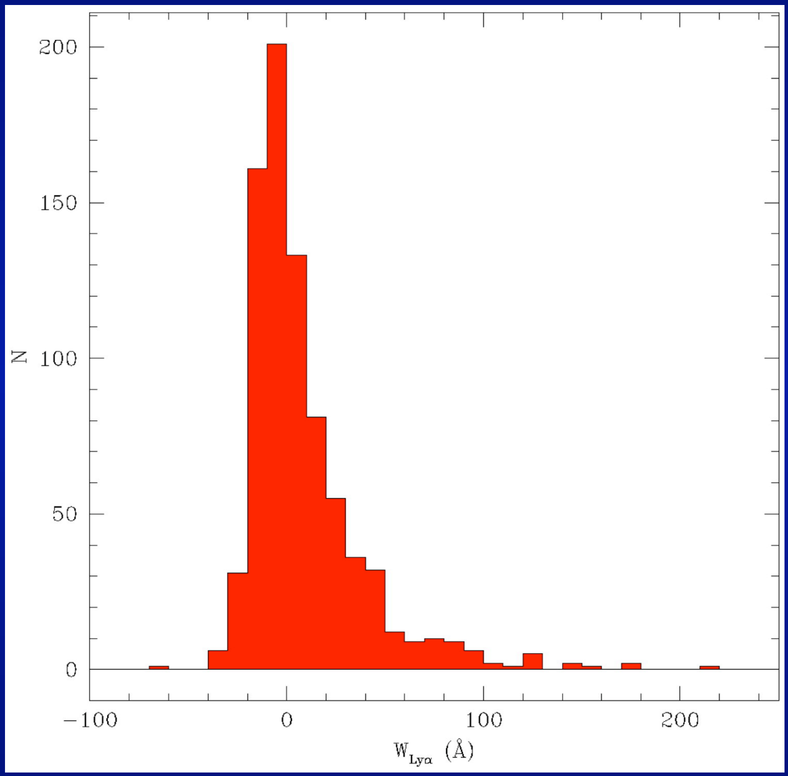


• LBG technique, and extensions to both lower and higher redshift (figure shows z~1.5-3.5), tuned to find galaxies with ongoing star-formation, and little to moderate extinction in the rest-UV (< × 100).

• We have learned much about the large-scale spatial distribution, luminosity function, dust content, stellar populations, metal content and star-formation properties of UV-selected galaxies from z~1.5 to z>6.

• Spectroscopic redshifts have been obtained for >2000 UV-selected galaxies at z~1.5-3.5 with $R_{AB} \leq 25.5$.

Rest-frame UV selection



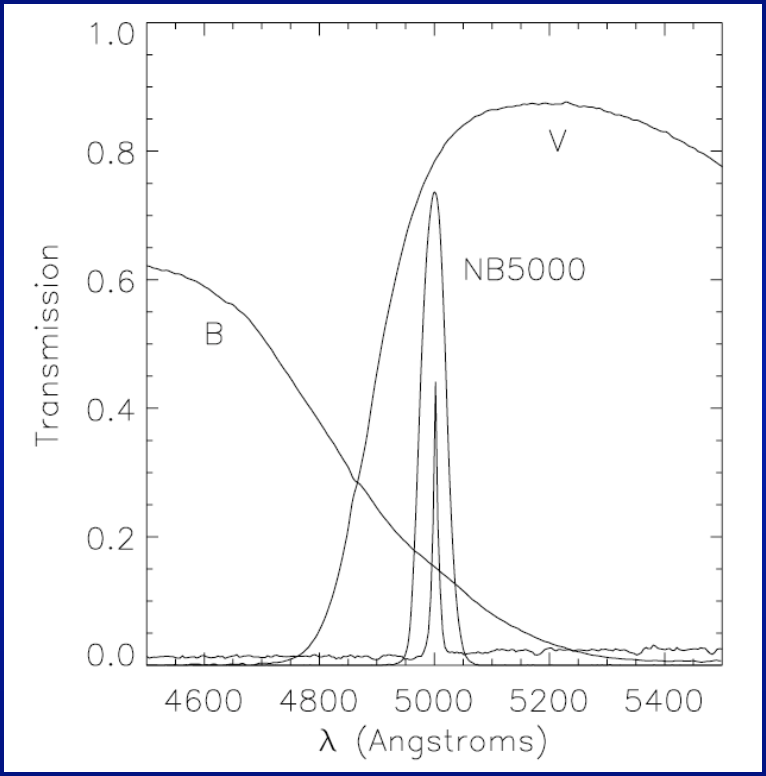
(Shapley et al. 2003)

- Rest-frame UV light is one of the defining characteristics of LBGs ($R_{AB} \leq 25.5$). Hence, rest-frame UV spectroscopy is an important component of their study.

- Lyα feature typically one of the strongest in the rest-frame UV of LBGs.

- ~25% of LBGs at z~3 have rest-frame EW(Lyα)>20Å, the typical limit for NB-selected LAEs at the same redshift. Lower fraction at z~2 (~10%, Reddy et al. 2008).

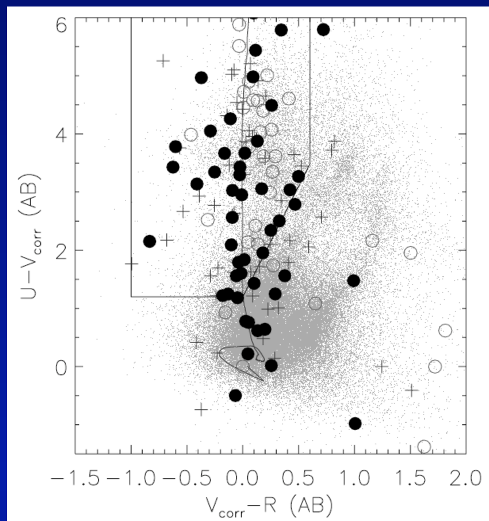
NB LAE selection

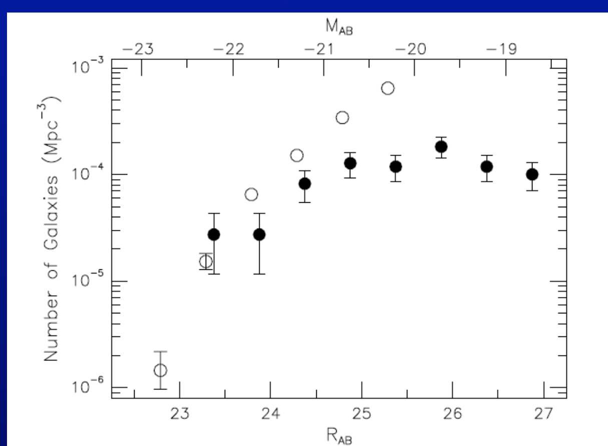


- NB selection of LAEs applied from z~2 to z>6.
- ID line emitters due to excess in NB vs. broadband filter.
- Lyα searches typically go down to EW=20 Å (rest).
- Given the nature of the search strategy, NB-selected LAEs are typically much fainter in the continuum than broad-band selected LBGs.

(Gronwall et al. 2007)

NB LAE selection





(Gronwall et al. 2007; Ouchi et al. 2008)

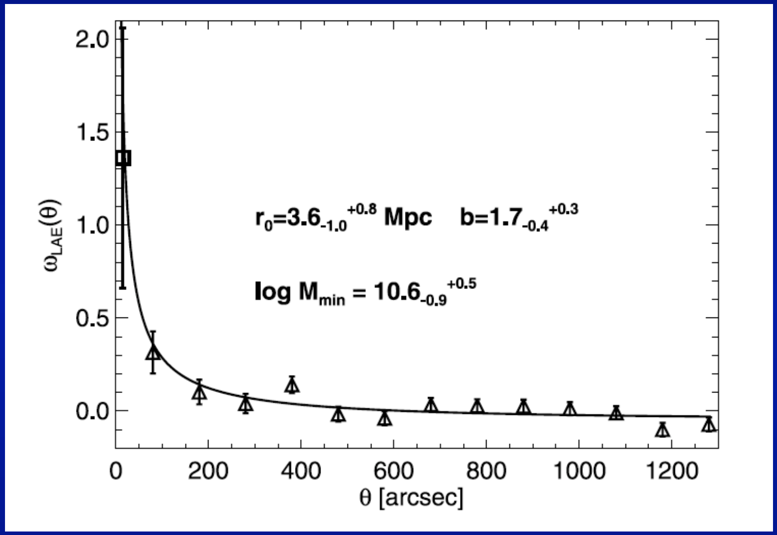
- **At z~3, rest-frame UV colors of LAEs overlap those of LBGs (filled symbols vs. selection box).**

- **Given the nature of the search strategy, NB-selected LAEs are typically *much* fainter in the continuum than broad-band selected LBGs.**

- **Median LAE magnitude for some studies (Gawiser et al. 2006) is R~27. Magnitude limit of LBG spectroscopic sample is R=25.5. L* is R~24.5 at z~3.**

- **If typical LAEs and LBGs have different stellar populations and spatial clustering properties, is it simply because LAEs are so much fainter?**

Galaxy Correlation Functions



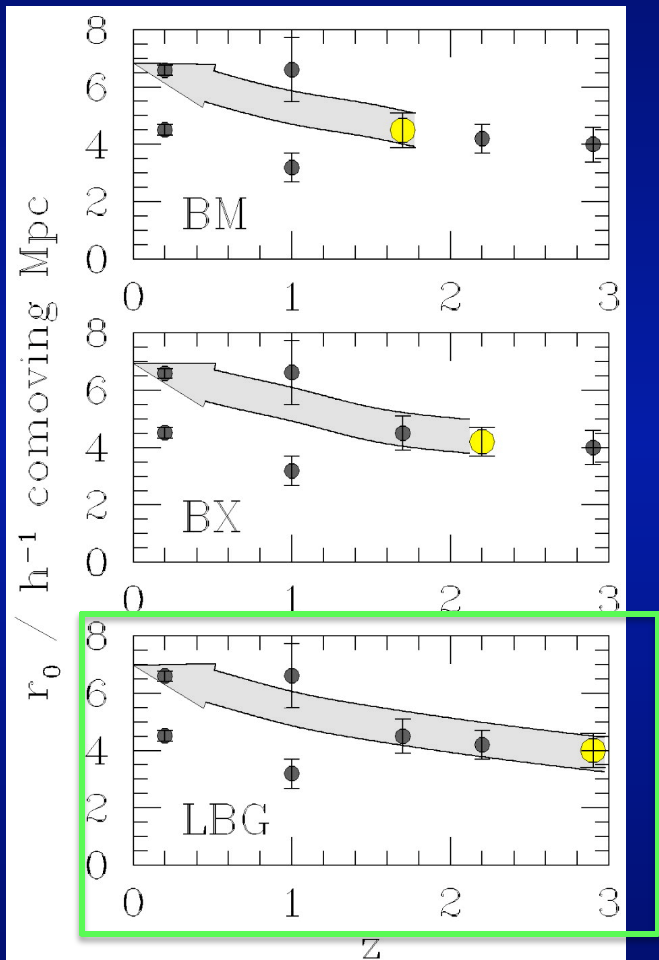
- Galaxy-galaxy correlation functions have been computed for both LAEs and LBGs.

- Based on angular correlation and redshift distribution, physical correlation length for LAEs is 3.7 Mpc, implying minimum dark-matter halo masses of $10^{10.6}\ M_{\odot}$.

- Space density of LAEs is only ~5% of that of halos with same clustering, uncertainty in how LAEs populate host DM halos, and the nature of their descendants.

(Gawiser et al. 2007)

Galaxy Correlation Functions



(Adelberger et al. 2005)

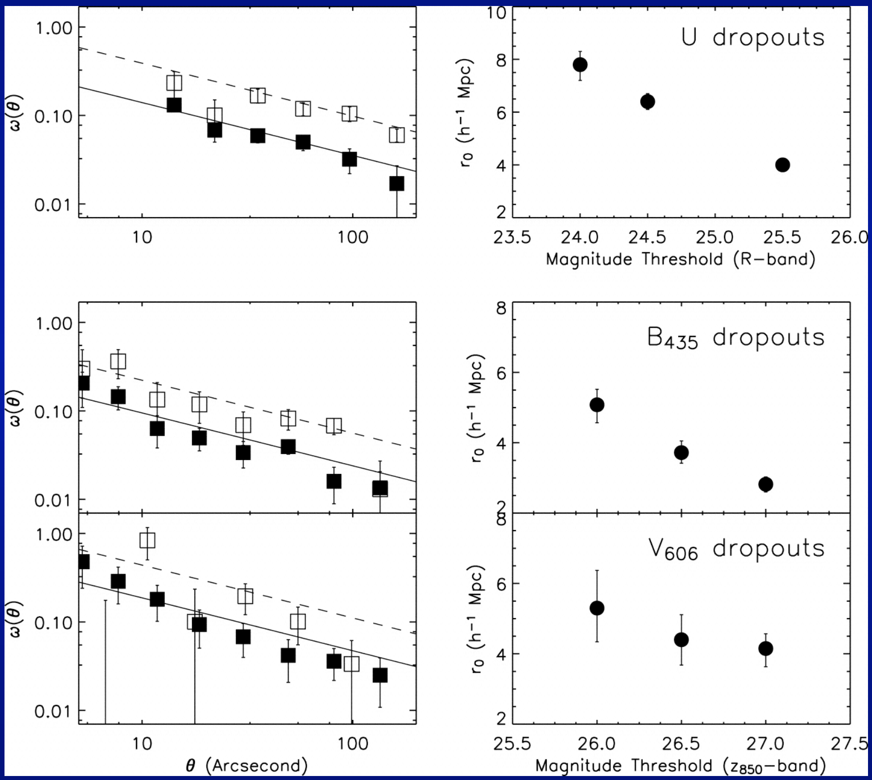
- **Galaxy-galaxy correlation functions have been computed for both LAEs and LBGs.**

- **Based on angular correlation and redshift distribution, physical correlation length for LBGs is 4.0 h^{-1} Mpc = 5.7 Mpc, implying minimum dark-matter halo masses of $10^{11.3} M_{\odot}$.**

- **Space density of UV-selected galaxies and DM halos that host them is comparable. High "duty cycle."**

- **Robust conclusion: LBGs and UV-selected galaxies at z~2 are progenitors of Milky-Way and more luminous galaxies in the local universe (Conroy et al. 2008).**

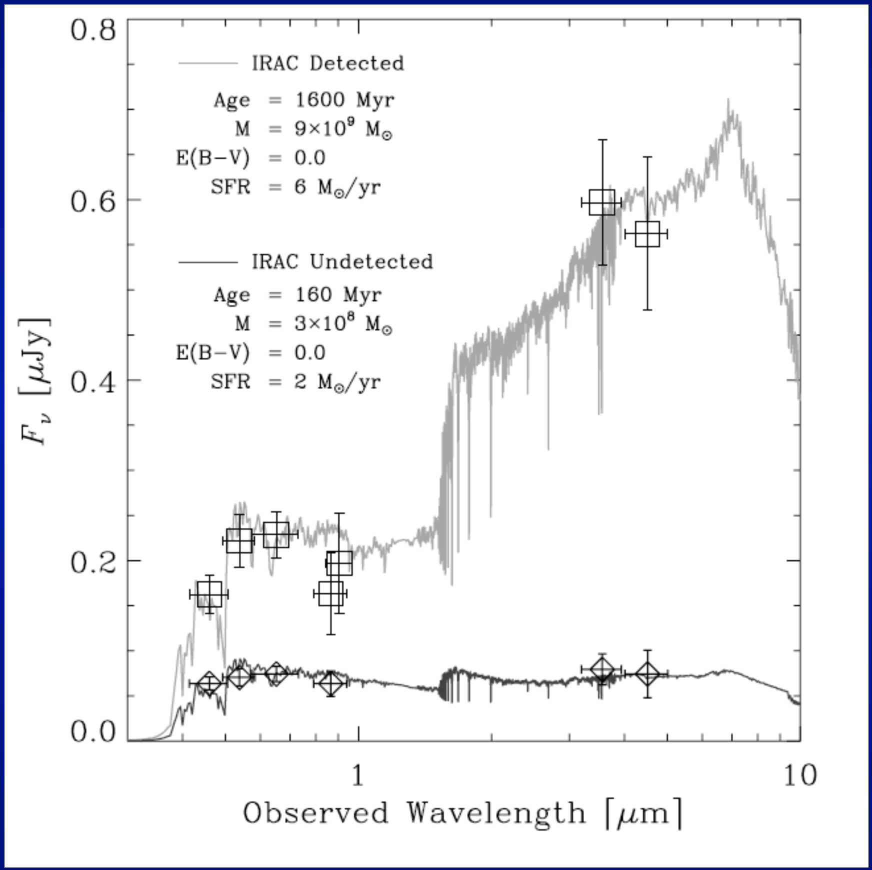
Galaxy Correlation Functions



(Lee et al. 2006)

- At the same time, multiple authors (Lee, Ouchi, Adelberger, Giavalisco) have found that clustering strength depends on UV-luminosity (optical magnitude).
- Lee et al. (2009) interpret luminosity-dependent clustering in terms of relationship between UV-luminosity and dark-matter halo mass.
- Relative clustering of LAEs and LBGs may simply reflect fact that faint galaxies are clustered less strongly than bright ones -- not indicative of Lyα –dependent trends.
- Unless we can understand how Lyα emission and luminosity are related.

Galaxy Stellar Populations

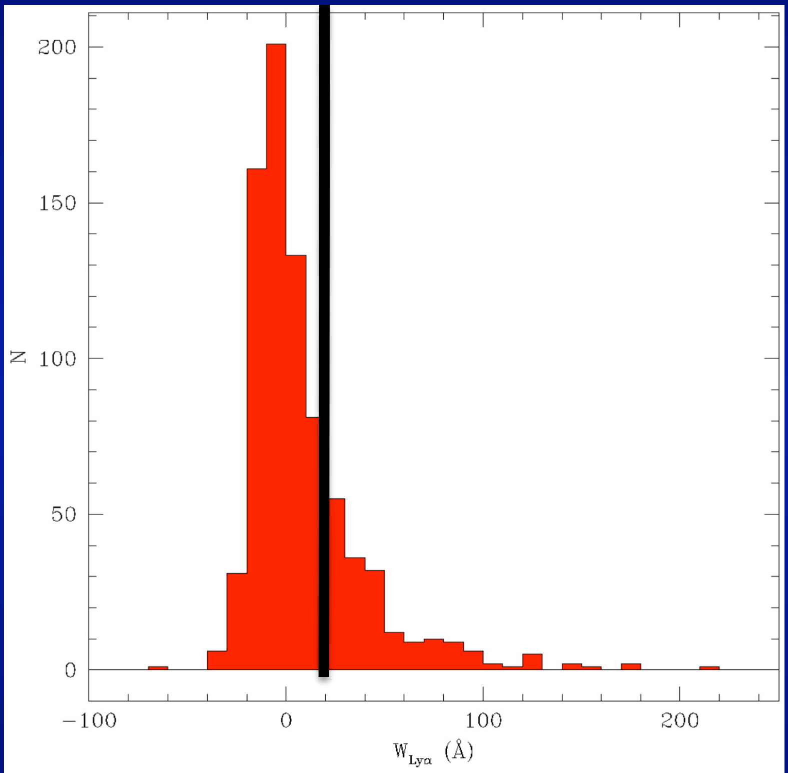


(Lai et al. 2008)

- By the same token, differences between "LAE" and "LBG" stellar populations may reflect many different factors, in particular different rest-frame magnitude ranges probed.
- LAEs have different stellar populations depending on whether or not they are detected with Spitzer/ IRAC (Lai et al. 2008). Diversity.
- Is it therefore meaningful to compare/contrast star-formation rates, stellar masses, E(B-V) and ages of "typical" NB-selected LAEs and color-selected LBGs?
- We will return to this question…

LAE/LBG Stellar Populations: A Controlled Comparison

LBG Lyα EWs



(Shapley et al. 2003)

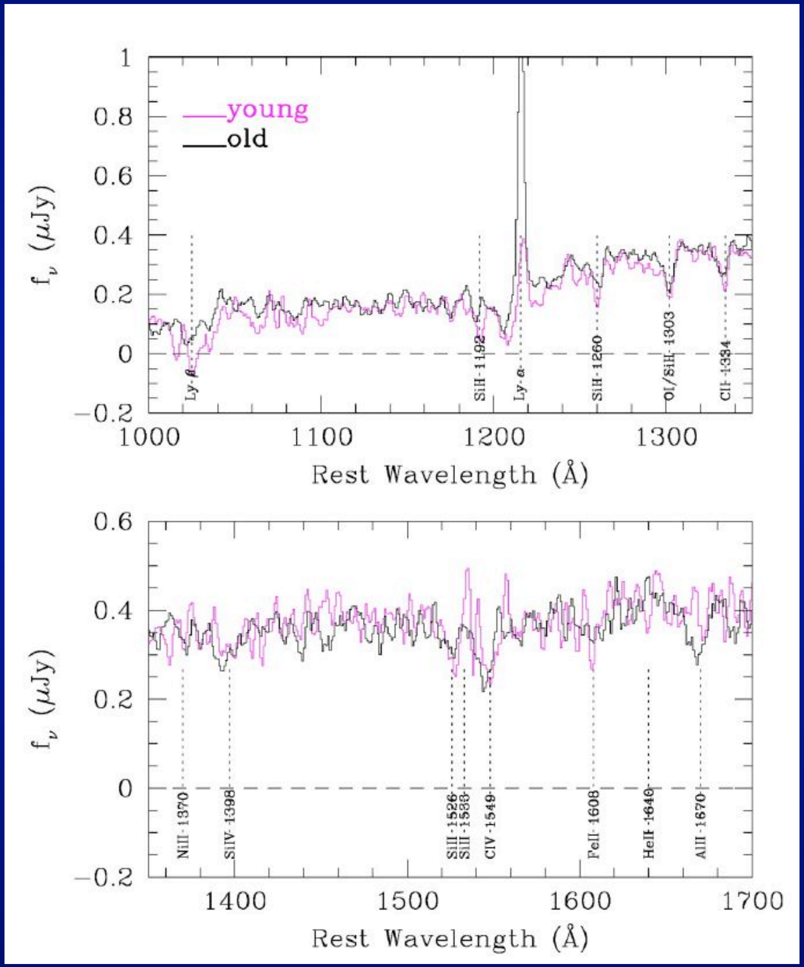
- The LBG technique yields objects spanning a broad range of Lyα properties, from strong absorption to strong emission.

- ~25% of LBGs at z~3 have rest-frame EW(Lyα)>20Å, the typical limit for NB-selected LAEs at the same redshift.

- Therefore, correlation of Lyα emission strength with other properties can be examined down to fixed magnitude/SFR/stellar mass limit.

- Properties of strong emitters can be differentiated as well.

z~3 LBG Stellar Populations & Lyα



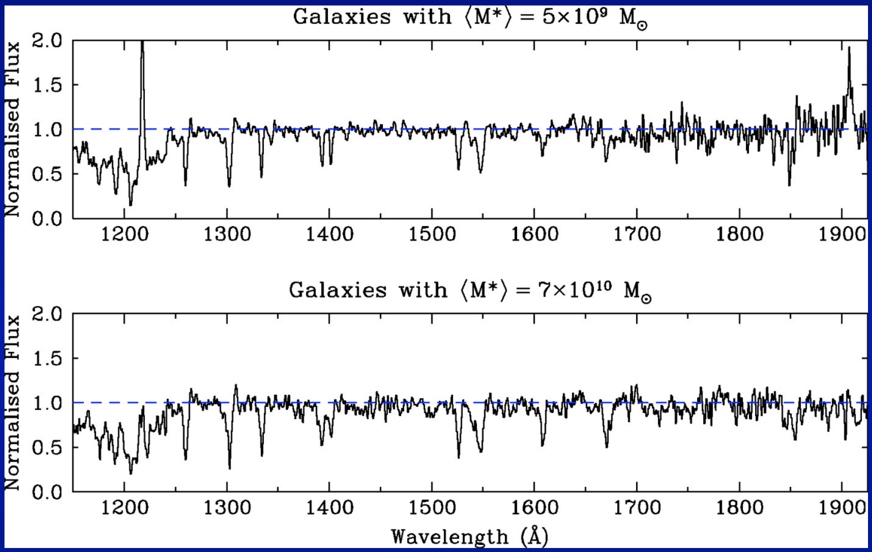
(Shapley et al. 2001)

- Based on a sample of 74 LBGs with Keck/NIRC UGRJKs photometry, "young" (≤35 Myr) and "old" (≥1 Gyr) rest-UV composite spectra constructed (N=16 for each composite).

- Younger galaxies characterized by weaker Lyα emission, redder UV continua, than older galaxies.

- Note: average composite spectrum of young/old objects not quite equivalent to average age as a function of EW(Lyα).

z~2 LBG Stellar Populations & Lyα



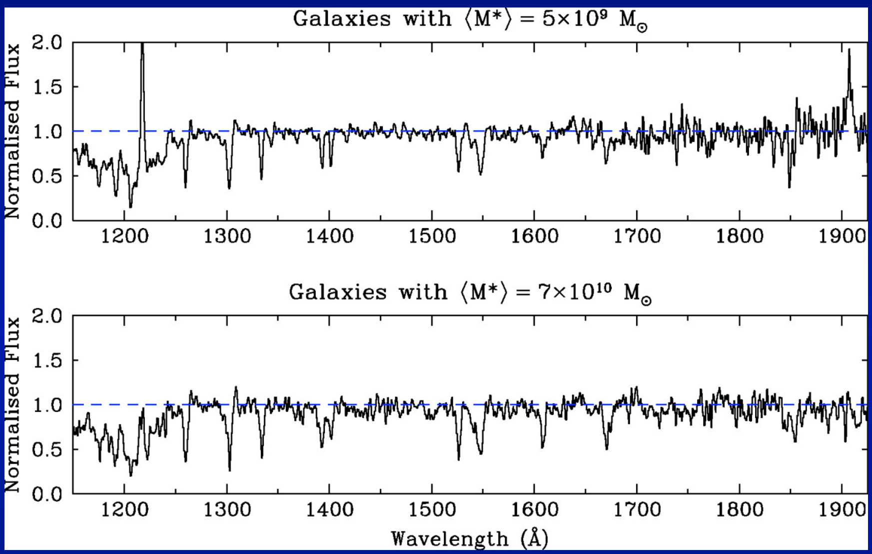
(Erb et al. 2006)s

- On the other hand, based on sample of ~100 UV-selected galaxies with stellar population models, Erb et al. (2006) constructed 6 composite spectra based on stellar mass.

- Found that 1/3 (N=30) of sample w/ lowest stellar mass has stronger Lya emission, lower metallicity than 1/3 (N=28) with highest stellar mass.

- Age and mass are strongly correlated. Higher stellar mass bin significantly older stellar population (×5).

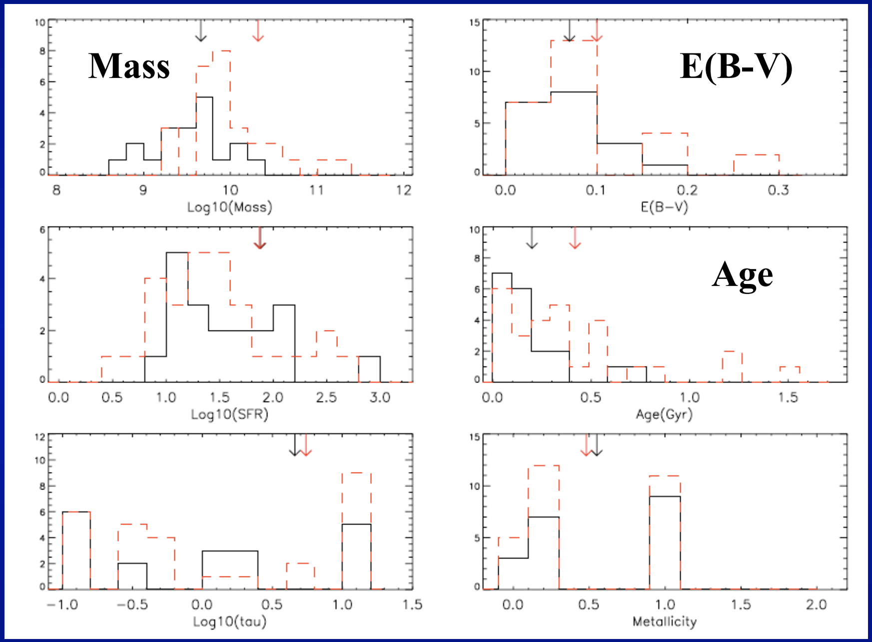
z~2 LBG Stellar Populations & Lyα



(Erb et al. 2006)

- Reddy et al. (2008) consider the stellar populations of strong (EW(Lyα)≥20 Å) emitters vs. the rest of the population.
- 139 z~2 UV-selected galaxies, 14 of which have strong Lyα emission.
- K-S tests indicate no significant differences in the stellar pops of strong emitters, relative to rest of sample.

z>3.5 LBG Stellar Populations & Lyα



- Sample of 47 LBGs at z=3.4-4.8 from the GOODS-S survey with multi-wavelength photometry and stellar population fits. 19 have Lyα emission; 28 have absorption or nothing.

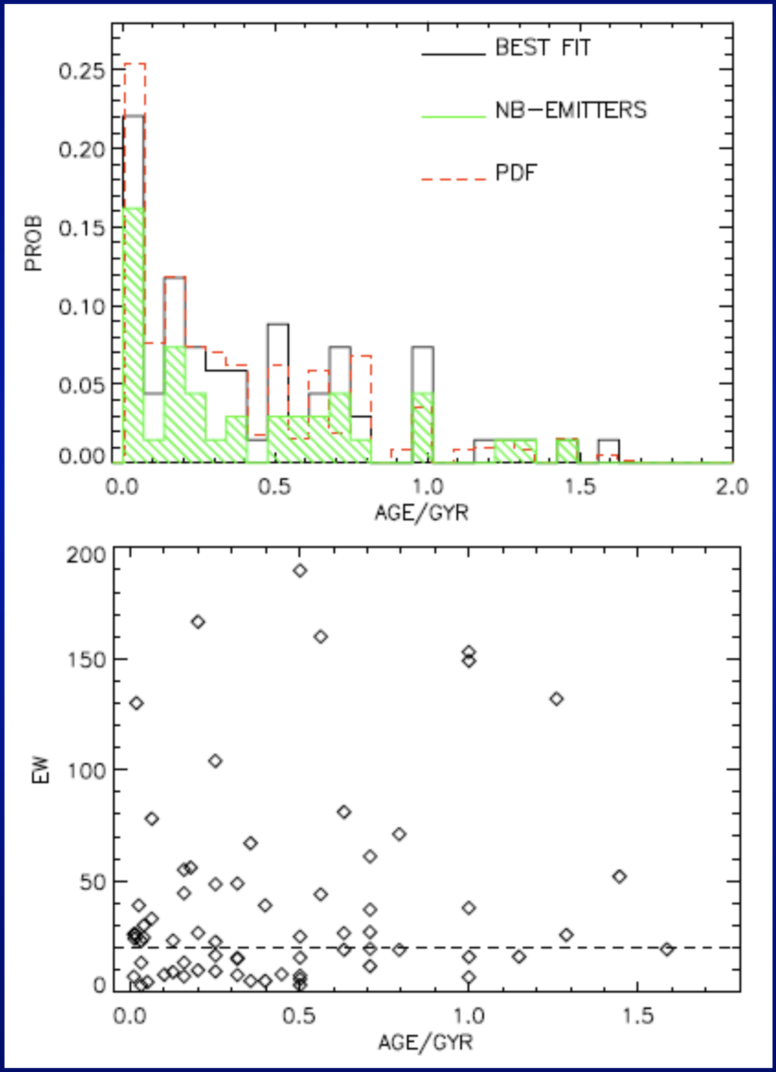
- Emitters significantly less massive and younger than non-emitters. Also less dusty.

Emitters: EW(Lyα)≥0

Non-Emitters: EW(Lyα)<0

(Pentericci et al. 2007)

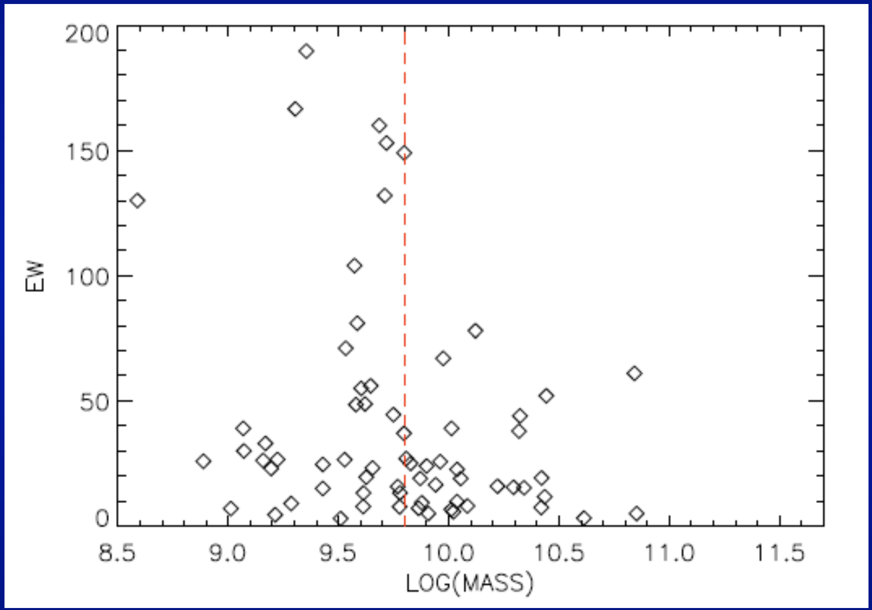
z>3.5 LBG Stellar Populations & Lyα



(Pentericci et al. 2009)

- Closer examination of galaxies with Lyα emission at z=3.5-6.5 in the GOODS-S field.
- All 68 have EW(Lyα)≥0. 38/68 have EW(Lyα)≥20 Å.
- Most fit by young stellar populations, but small, significant fraction fit by ~1 Gyr models. Small fraction have stellar mass $>10^{10}$ $M_{\odot}$.
- Lack of high stellar mass objects with strong emission.
- Strong Lyα emitters are a diverse population.

z>3.5 LBG Stellar Populations & Lyα



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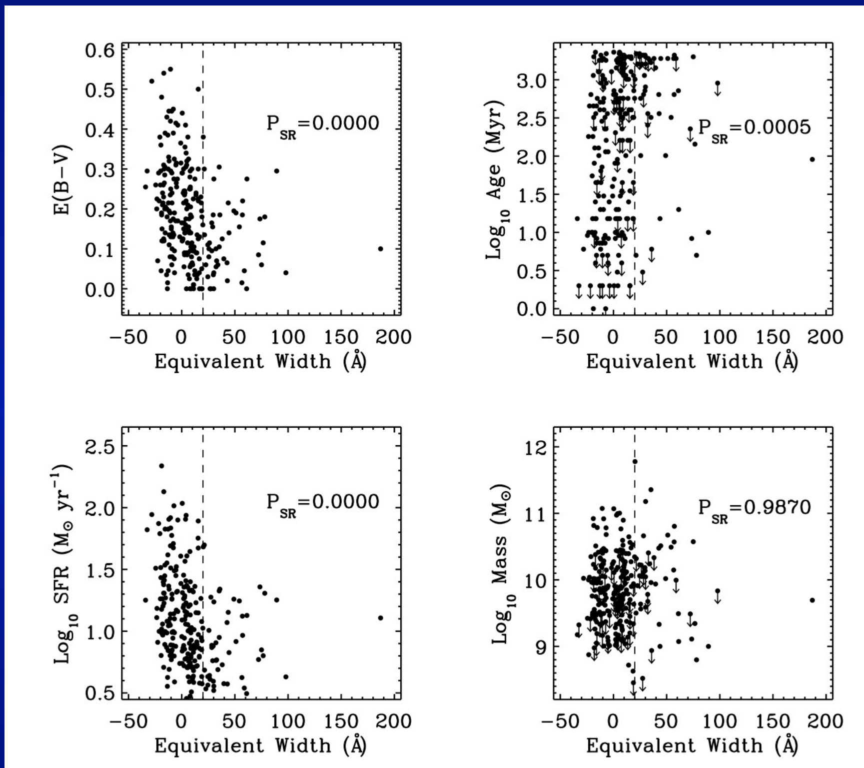
More systematic study at z~3

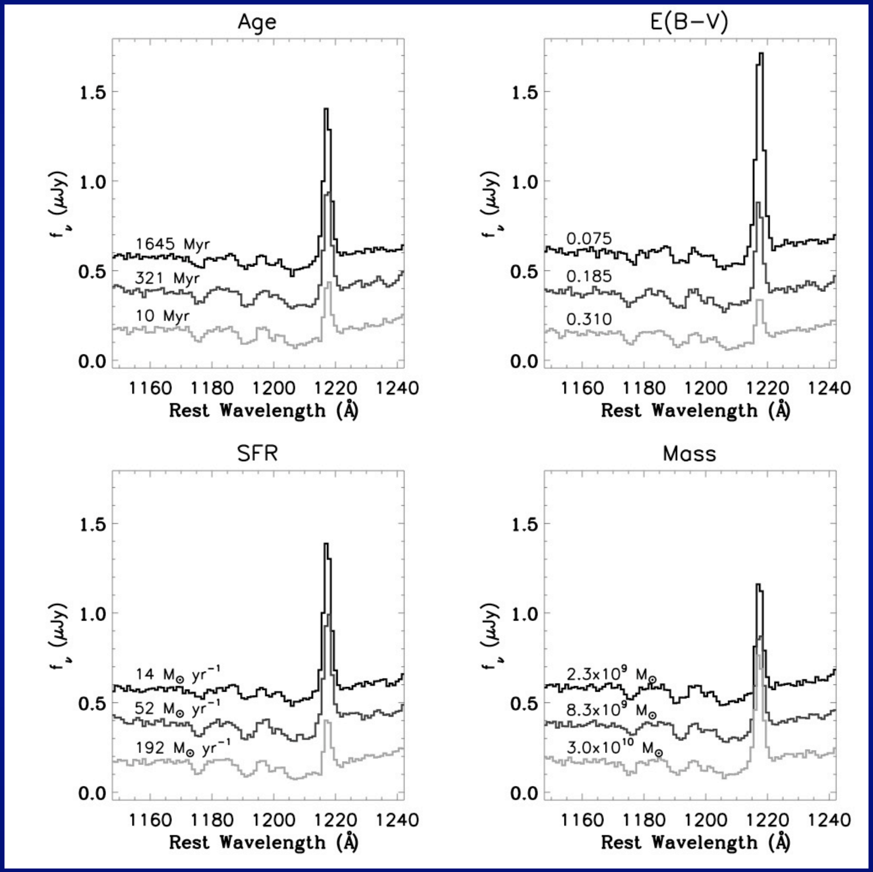


- **248 z~3 LBGs with both UV spectra and near/mid-IR photometry (stellar population fits).**
- **Considered (1) correlations between EW(Lyα) and stellar populations; (2) binary comparisons between "LAEs" and "non-LAEs."**
- **Correlations between EW(Lyα) and E(B-V), age, stellar mass, SFR.**

(Kornei et al. 2009)

- ★ **EW(Lyα) ↑ → E(B-V) ↓**
- ★ **EW(Lyα) ↑ → Age ↑**
- ★ **EW(Lyα) ↑ → SFR ↓**
- ★ **EW(Lyα) uncorr. with M_{star}**

More systematic study at z~3



(Kornei et al. 2009)

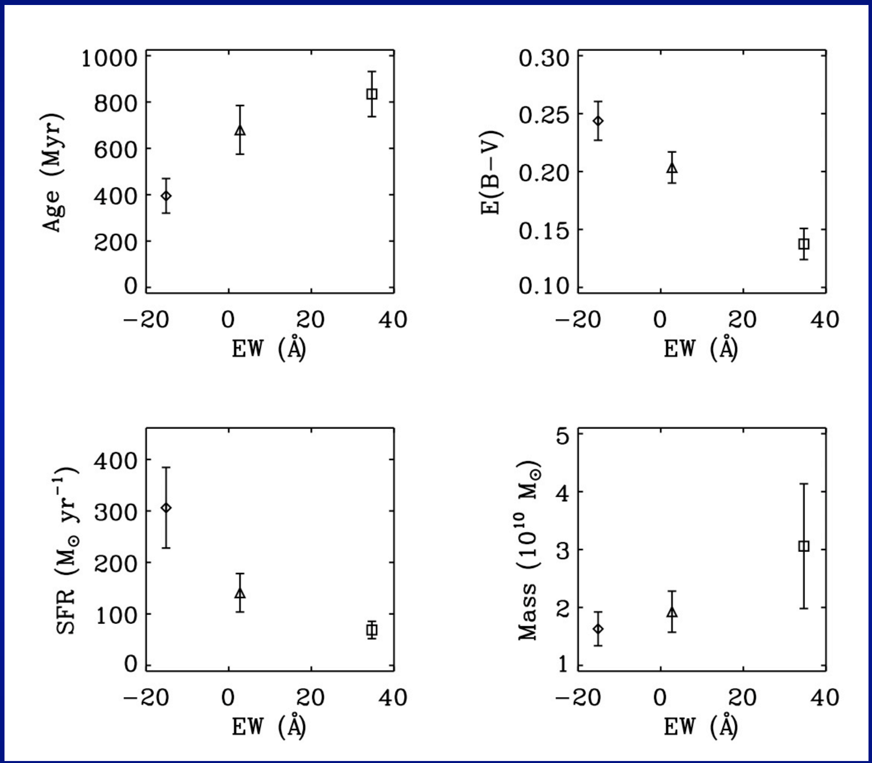
• 248 z~3 LBGs with both UV spectra and near/mid-IR photometry (stellar population fits).

• Considered (1) correlations between EW(Lyα) and stellar populations; (2) binary comparisons between "LAEs" and "non-LAEs."

• Composite spectra as a function of E(B-V), age, stellar mass, SFR.

★ EW(Lyα) ↑ ➔ E(B-V) ↓
★ EW(Lyα) ↑ ➔ Age ↑
★ EW(Lyα) ↑ ➔ SFR ↓
★ EW(Lyα) uncorr. with M_{star}

More systematic study at z~3



(Kornei et al. 2009)

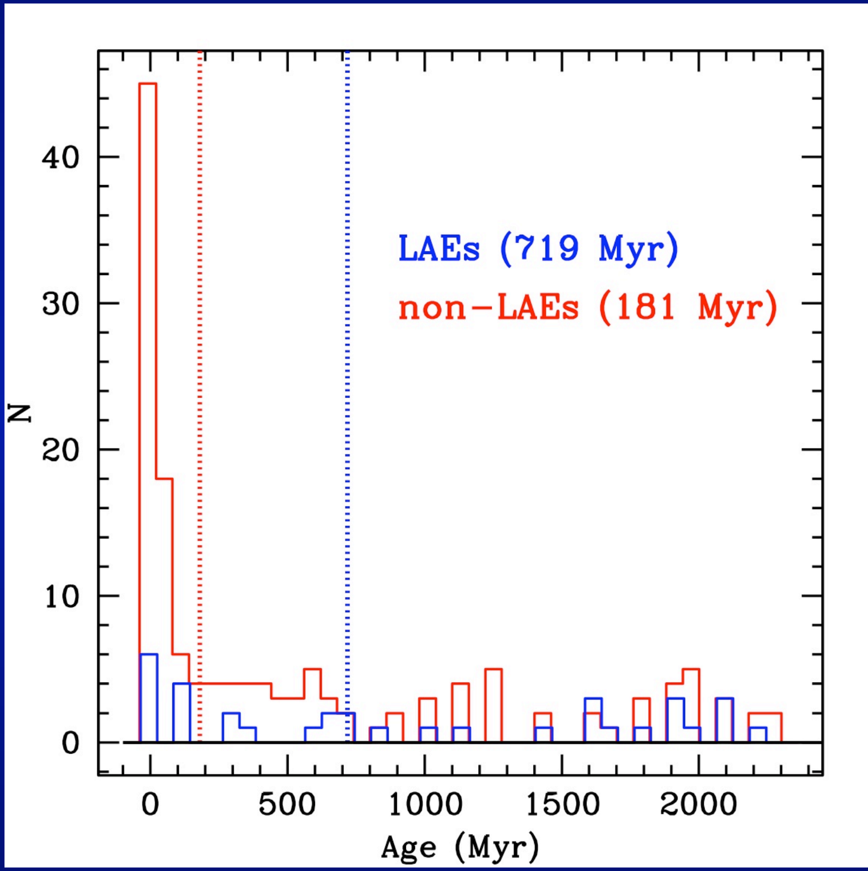
- 248 z~3 LBGs with both UV spectra and near/mid-IR photometry (stellar population fits).

- Considered (1) correlations between EW(Lyα) and stellar populations; (2) binary comparisons between "LAEs" and "non-LAEs."

- Average E(B-V), age, stellar mass, SFR as a function of EW(Lyα).

★ EW(Lyα) ↑ ➔ E(B-V) ↓
★ EW(Lyα) ↑ ➔ Age ↑
★ EW(Lyα) ↑ ➔ SFR ↓
★ EW(Lyα) uncorr. with M_{star}

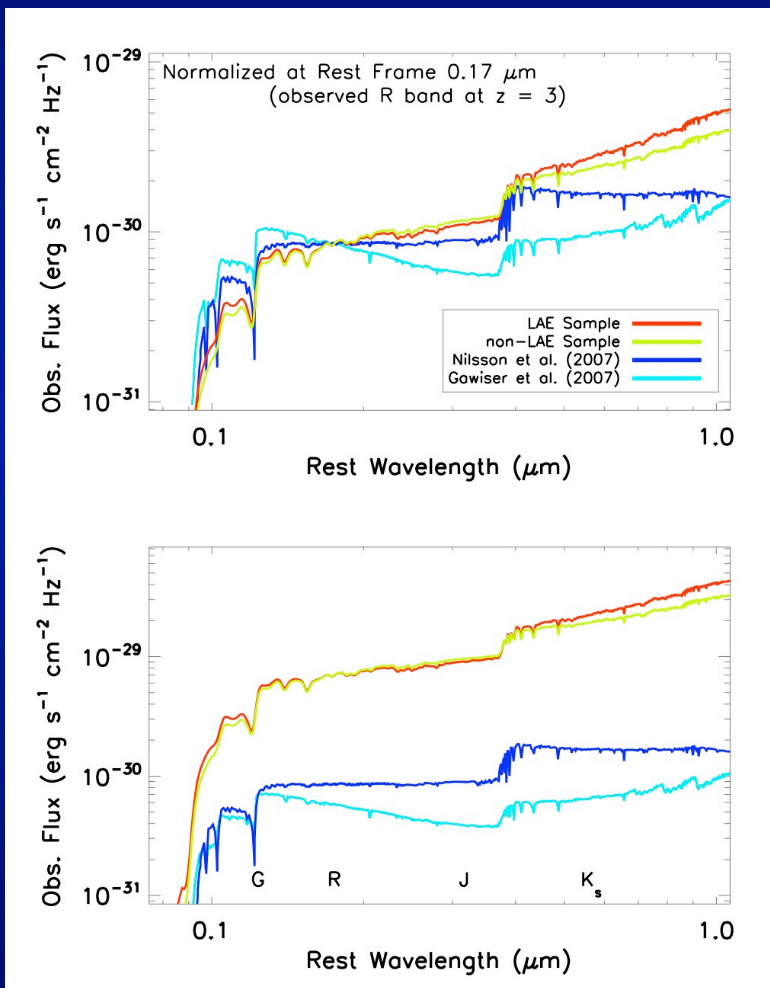
More systematic study at z~3



(Kornei et al. 2009)

- 248 z~3 LBGs with both UV spectra and near/mid-IR photometry (stellar population fits).
- Considered (1) correlations between EW(Lyα) and stellar populations; (2) binary comparisons between "LAEs" and "non-LAEs."
- Relative age distributions of LAEs and non-LAEs.

More systematic study at z~3



(Kornei et al. 2009)

- 248 z~3 LBGs with both UV spectra and near/mid-IR photometry (stellar population fits).

- Considered (1) correlations between EW(Lyα) and stellar populations; (2) binary comparisons between “LAEs” and “non-LAEs.”

- Average SEDs for LAEs, non-LAEs, and other, fainter LAE samples (Nilsson, Gawiser).

LBG/LAE stellar populations

- Results at z~2, 3, 4 and above apparently in contradiction?

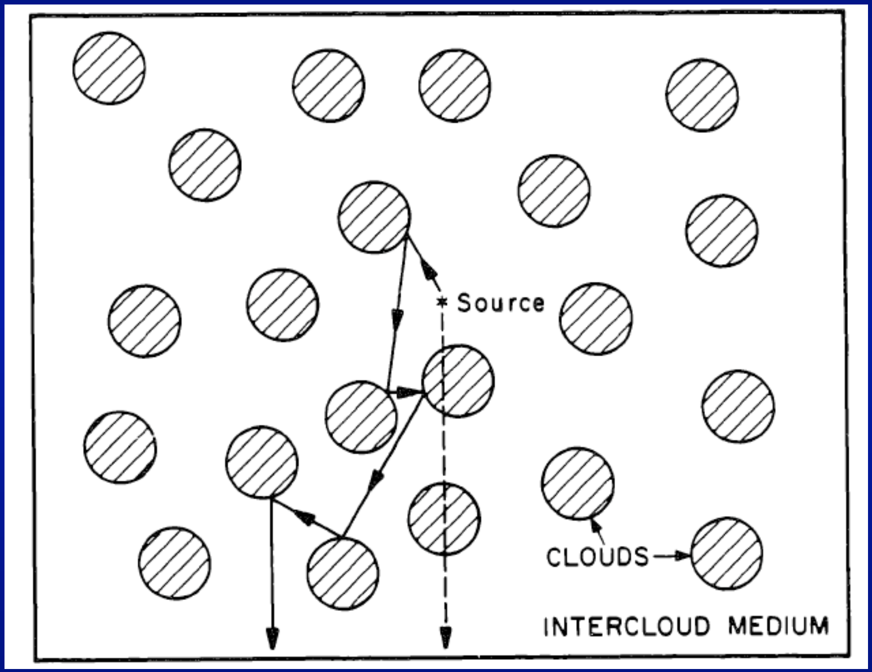
- At least partially due to non-uniformity of investigations: independent/dependent variable, EW(Lyα) range, sample selection effects.

- More in-depth analysis at z~3 confirms that LBG/LAEs are older on average (relative lack of objects with t≤100 Myr). Suggests that, among more luminous galaxies, evolution towards stronger Lyα emission.

- Strongest result at z≥3: EW(Lyα) and E(B-V) anti-correlated (more coming up).

Lyα: a probe of the dusty ISM

Lyα Radiative Transfer & Dust



(Neufeld 1991)

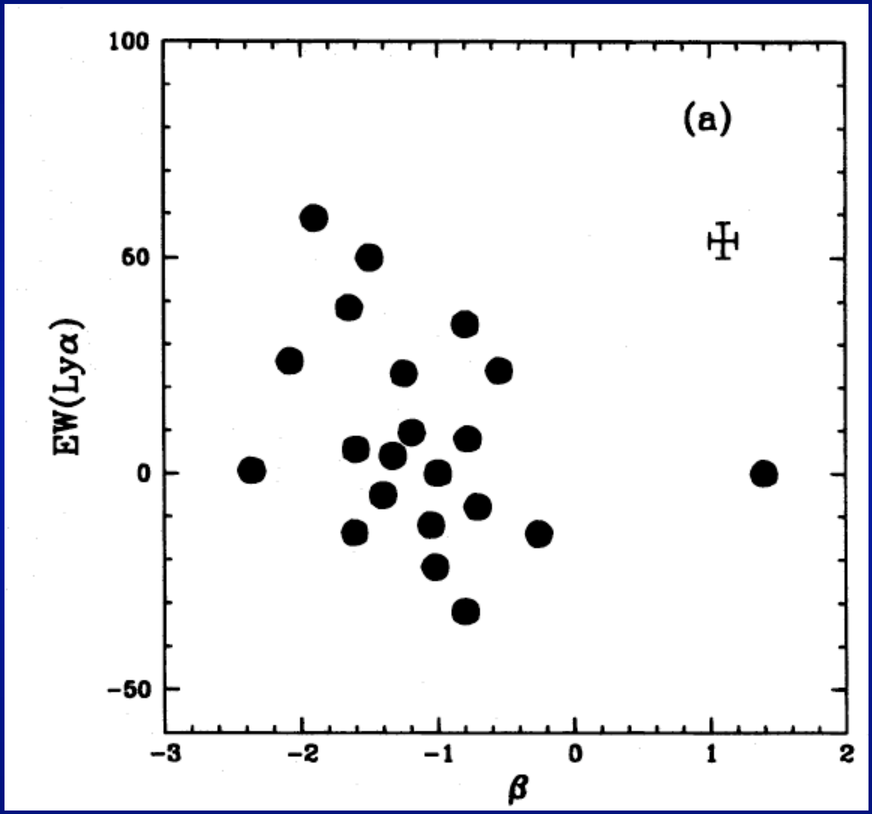
• In a uniform, neutral, dusty medium, Lyα will be preferentially attenuated relative to UV continuum.

• Resonant scattering of Lyα photons leads to effectively longer path length, greater probability of destruction.

• In multiphase medium (neutral, dusty clouds plus ionized, dust-free phase), Lyα photons spend most time in intercloud medium. Higher probability of escape → EW(Lyα) enhanced.

• Theory: Neufeld, Hansen & Oh

Lyα Radiative Transfer & Dust



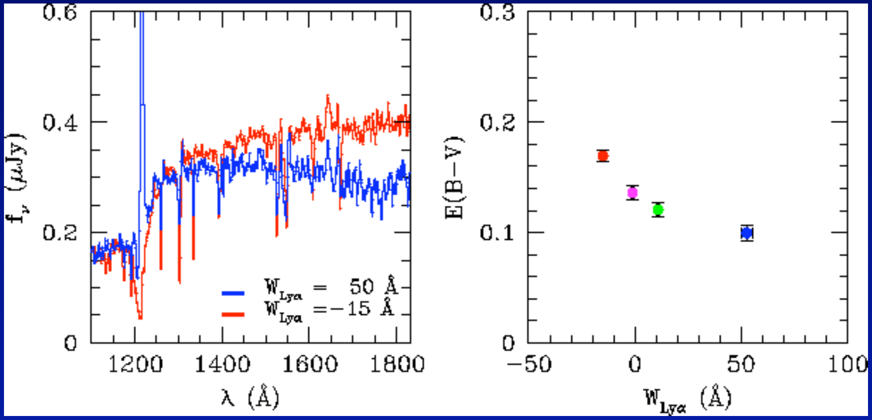
(Giavalisco et al. 1996)

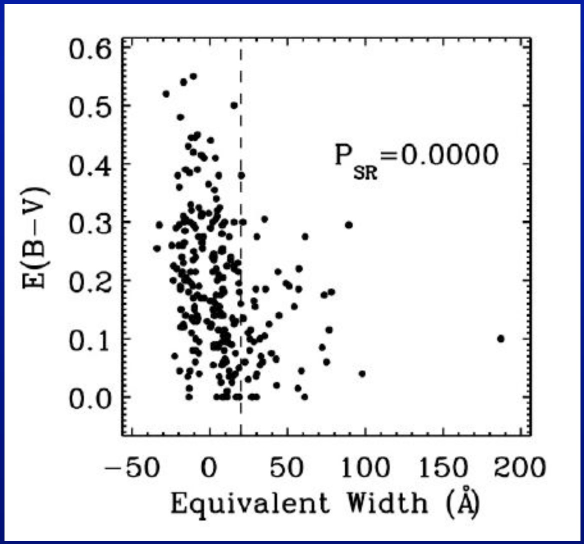
- Finkelstein et al. have advanced model of clumpy dust to explain high Lyα EWs of several z~4.5 LAEs that also appear reddened by dust.

- Cite evidence from Giavalisco et al. (1996): IUE spectra of 21 local starburst galaxies for which there is no significant correlation between EW(Lyα) and β (UV continuum slope).

- How does this evidence compare with what we measure in LBGs at $z \geq 3$?

<u>Lyα Radiative Transfer & Dust</u>





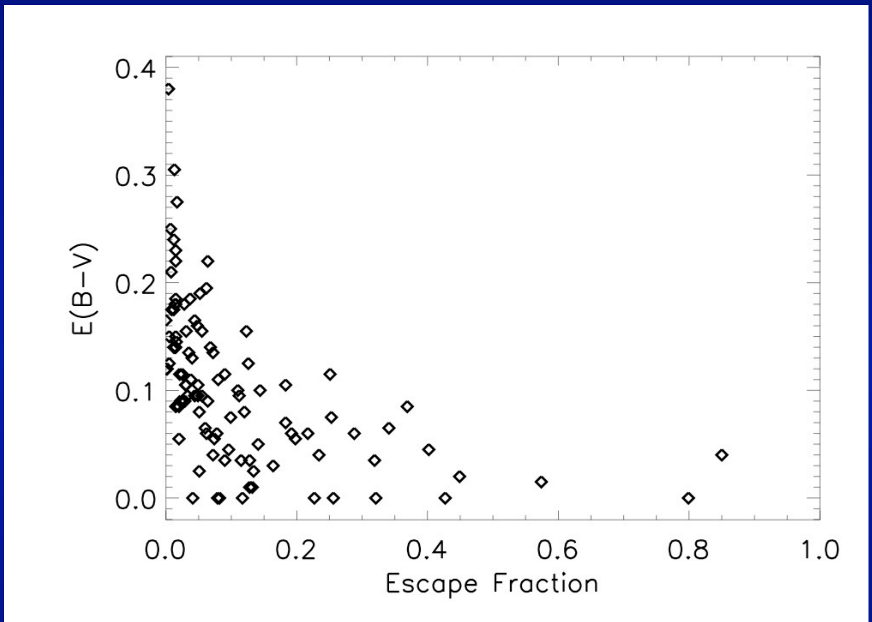
(Shapley et al. 2003, Kornei et al. 2009)

- In z~3 LBGs, there is a *significant* correlation between EW(Lyα) and E(B-V), such that EW(Lyα) increases as E(B-V) decreases.

- See also work by Pentericci et al. (2009), consistent results.

- Would such a correlation be expected if clumpy dust were dominant form of ISM?

Lyα Radiative Transfer & Dust



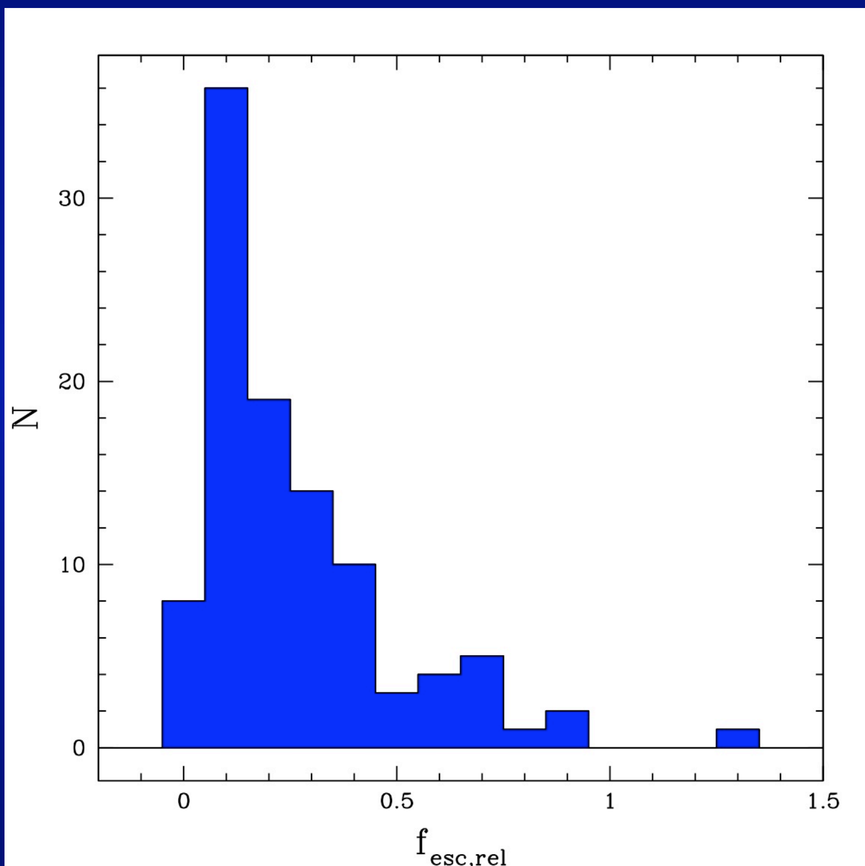
(Kornei et al. 2009)

- Also consider Lya escape fraction, $f_{esc,Ly\alpha}$:

$$f_{esc,Ly\alpha} = L_{Ly\alpha,obs}/L_{Ly\alpha,int}$$

- Measure $L_{Ly\alpha,obs}$. Infer $L_{Ly\alpha,int}$ based on SFR (i.e. SFR➔N_{ion}➔$L_{H\alpha}$ ➔$L_{Ly\alpha,int}$).
- Average value of $f_{esc,Ly\alpha}$ is ~10%. Strong correlation between $f_{esc,Ly\alpha}$ and E(B-V).
- See also comparisons of SFR(Lyα) vs. SFR(UV) in Gronwall et al. (2007) and Pentericci et al. (2009).
- Models of Verhamme et al. (2008) predict correlation between $f_{esc,Ly\alpha}$ and E(B-V).

Lyα Radiative Transfer & Dust



(Kornei et al. 2009)

- Can also investigate the *relative* extinction of Lyα and UV continuum photons, or relative escape fraction.

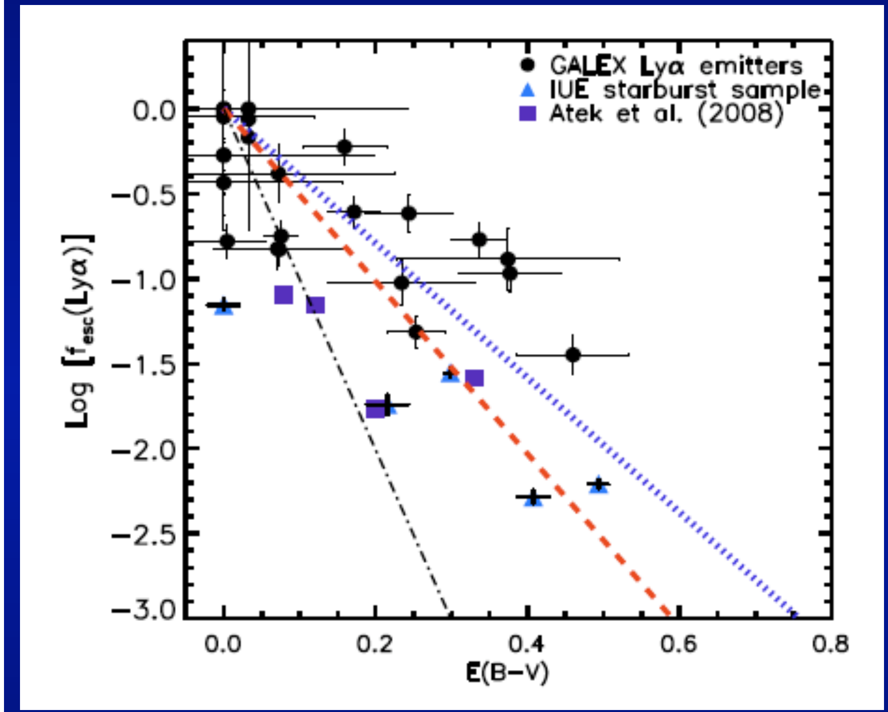
- Correct $L_{Ly\alpha,obs}$ using E(B-V) derived from UV-continuum slope or SED fitting.

$$f_{esc,rel} = f_{esc} \times 10^{0.4\,E(B-V)\kappa(1216)}$$

- If Lyα and UV continuum are attenuated with the same E(B-V), relative escape fraction is 1.

- We find average value of relative escape fraction is ~25%, i.e. Lyα is significantly *more* attenuated than UV continuum, consistent with simple expectations of Lyα radiative transfer.

Lyα Radiative Transfer & Dust



(Atek et al. 2009)

- In sample of 24 GALEX-selected LAEs at z~0.3, Atek et al. (2009) find anti-correlation between fesc and E(B-V). But see Deharveng et al. (2008).

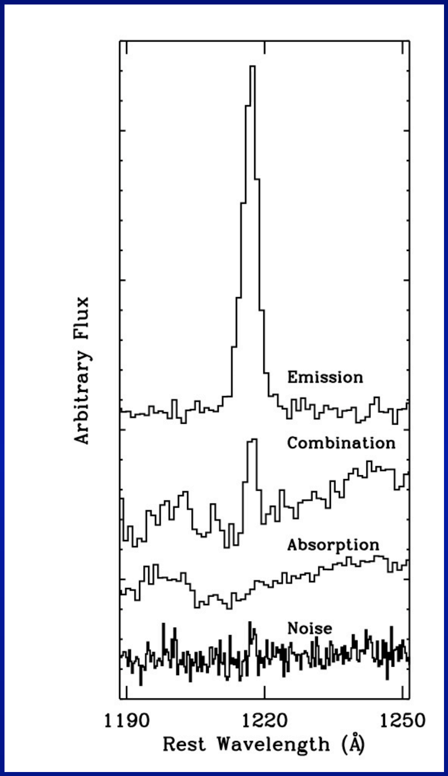
- However, relative escape fraction is not uniformly < 1, indicating Lyα is not always attenuated more than UV continuum.

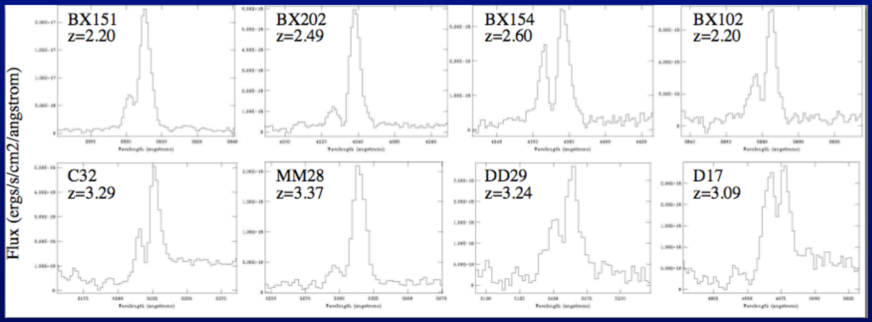
- Difference w.r.t. galaxies with Lyα emission in the LBG sample.

- Which sample is more representative of high-z LAEs? What are the implications for the structure of the ISM in high-redshift star-forming galaxies?

LBG Lyα Profiles and Radiative Transfer Models

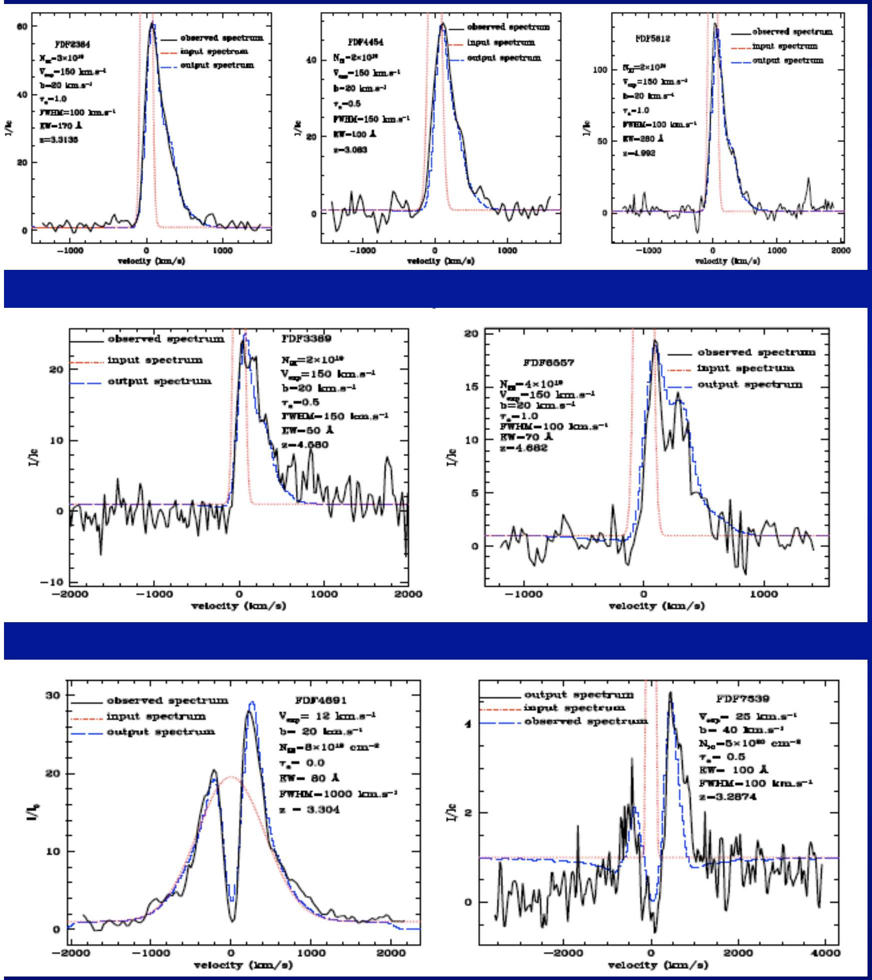
Lyα Radiative Transfer Models





- LBGs exhibit a wide variety of Lyα profile shapes.
- Range from symmetric to asymmetric emission, to emission/absorption, to pure absorption, to nothing.
- Velocity structure is sometimes complex, with multiple peaks.
- Explaining this diversity in Lyα profiles within the context of a unified model for Lyα radiative transfer is an important goal.
- In rare cases where spatial information is available, it offers additional constraints.

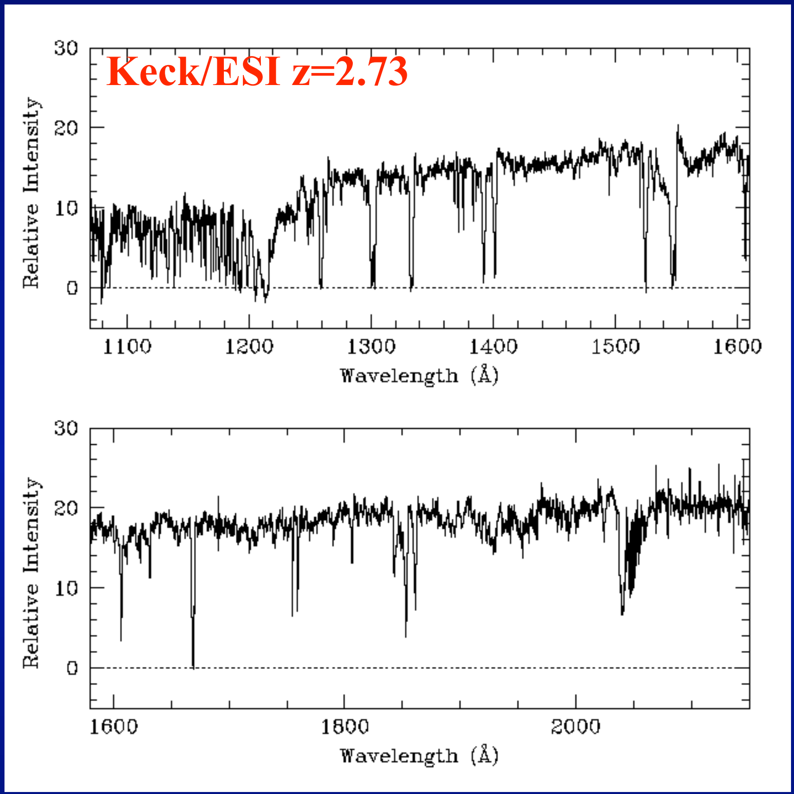
Lyα Radiative Transfer Models



(Verhamme et al. 2008)

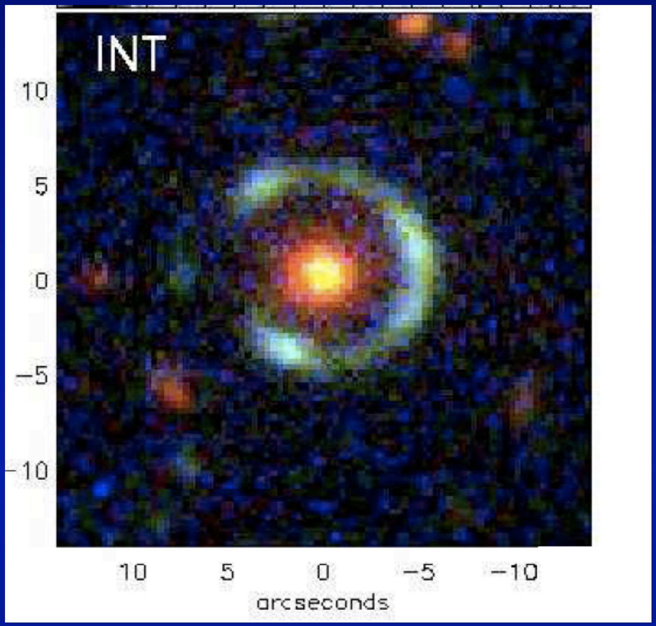
- Much recent progress in detailed radiative transfer models of Lyα emission.
- Model from Verhamme et al. (2006, 2008): 3D Monte Carlo radiative transfer code for predicting Lyα profiles given arbitrary gas density and kinematics.
- Comparison of models with 11 Lya profiles at z=3-5 from Tapken et al. (2007).
- Spectra modeled in the context of expanding thin, cold shells of HI, with varying column densities, expansion velocities, and dust content. Good fits obtained.

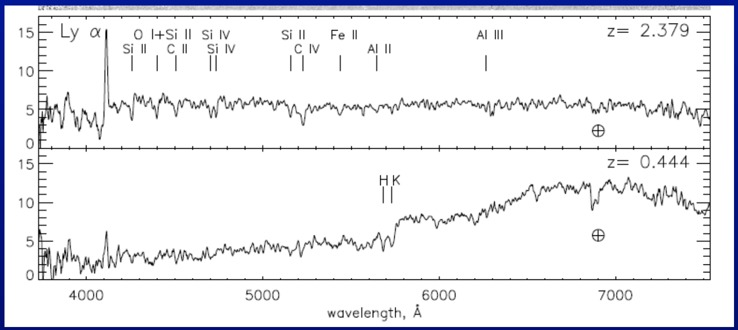
Gravitationally Lensed LBGs



- Gravitationally lensed LBGs provide an excellent opportunity for testing Lya radiative transfer models, because of the superior S/N and spectral resolution.
- For 10 years, MS1512-cB58 (z=2.73) was the single best example of a strongly-lensed LBG. Lyα profile modeled by Schaerer et al. (2008).
- There are limitations with a sample of one, when you want to generalize to the full population – i.e. how *typical* is cB58?
- Within the last few years, the number of strongly-lensed z≥2 galaxies has increased dramatically. New lensed galaxies are from SDSS and cluster surveys.

Gravitationally Lensed LBGs

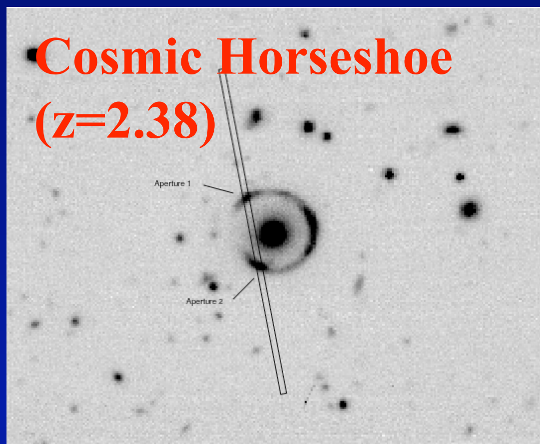


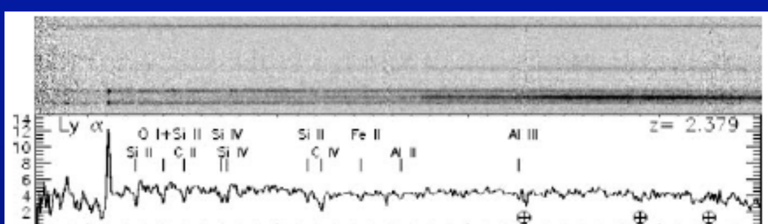


(INT imaging, SAO spectroscopy)

- New search technique in SDSS: look for multiple faint blue companions around luminous red galaxies.
- At least ~10 similar candidates, a few already spectroscopically confirmed, including the Cosmic Horseshoe, the Clone, 8:00 arc, Cosmic Eye.
- "Cosmic horseshoe," z=2.38, x25 magnification, R-mag ~19.5 (Belokurov et al. 2007; Dye et al. 2008), has Lyα in emission.

High-res Spectra of the Horseshoe





(Discovery spectrum from Belokurov et al. 2007)

- In a very superficial sense, the rest-frame UV spectrum of the Horseshoe is strikingly different from that of cB58.
- Lyα in emission; IS absorption lines weaker. Non-unity (~60%) covering fraction of cool gas is inferred.
- Offers opportunity to study the source of variations in rest-frame UV spectra in LBGs.

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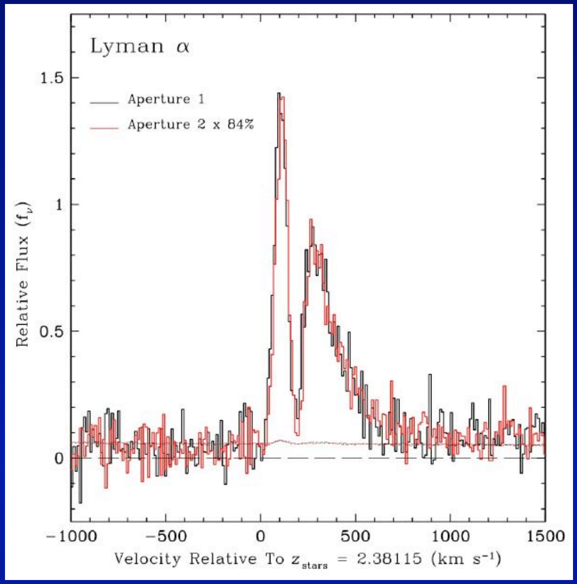
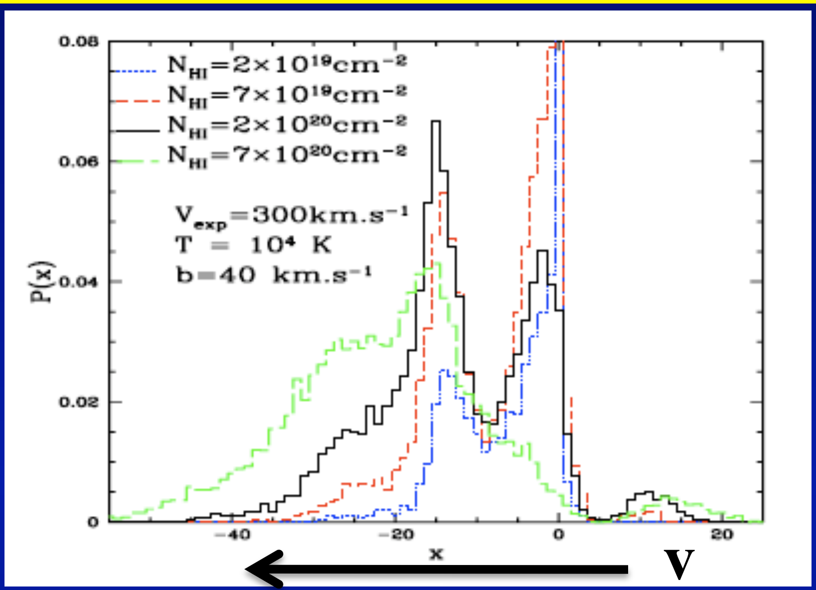


(Quider et al. 2009)



(Verhamme et al. 2006)

- Lyα is seen prominently in emission in Horseshoe spectrum. Profile double-peaked, and invariant between 2 apertures.
- Model from Verhamme et al. (2006) reproduces multi-peaked form of emission line, and gradual fall-off towards higher velocities. (Compare red curve).

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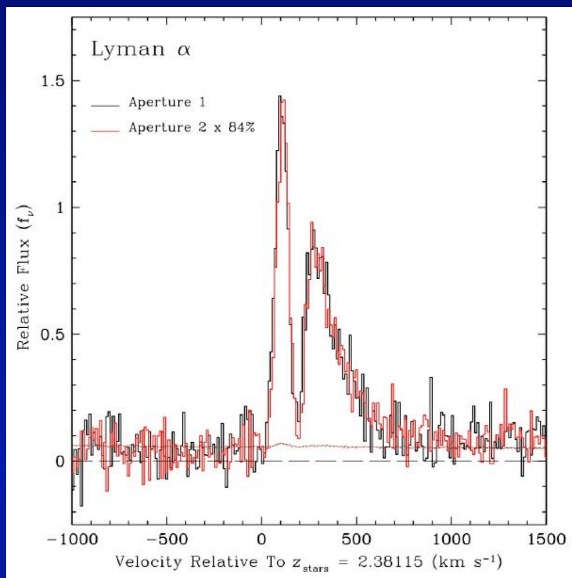

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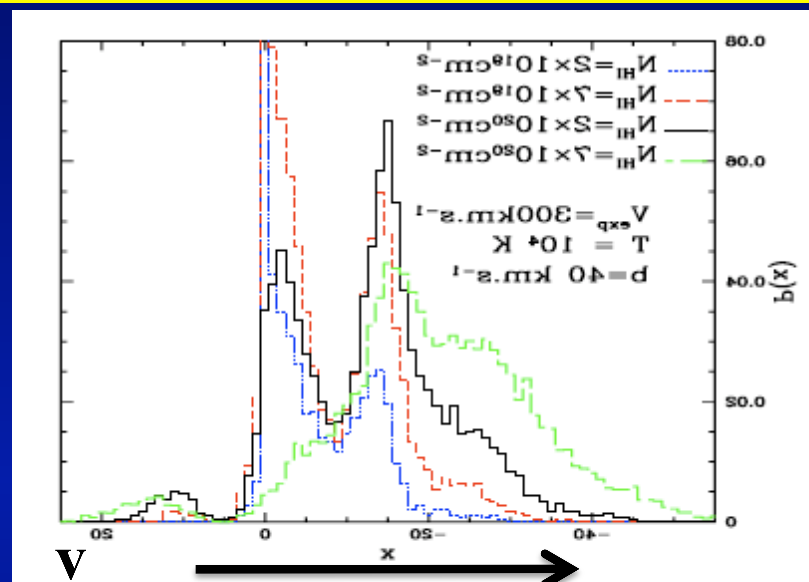

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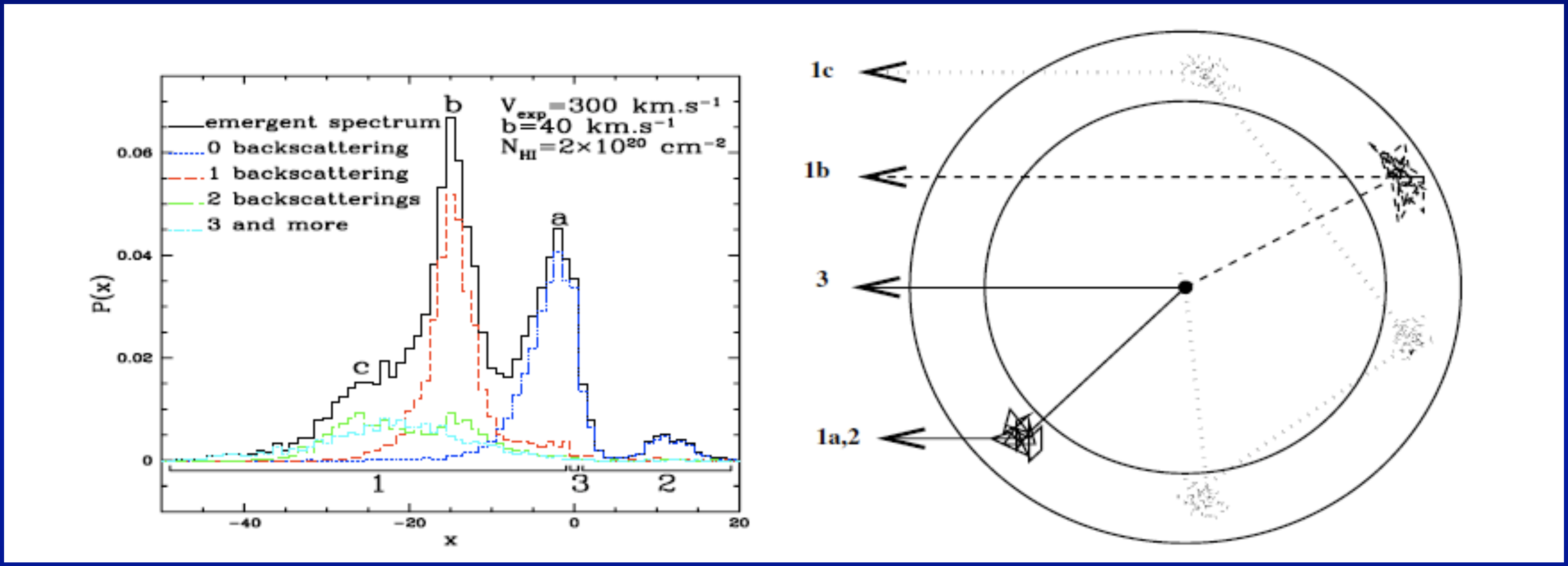
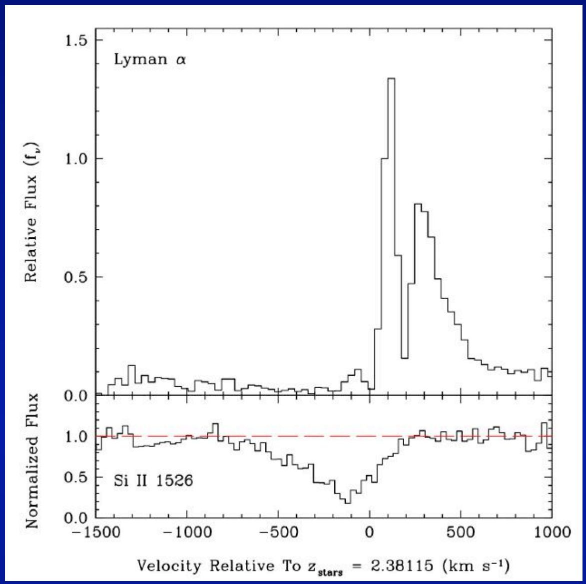
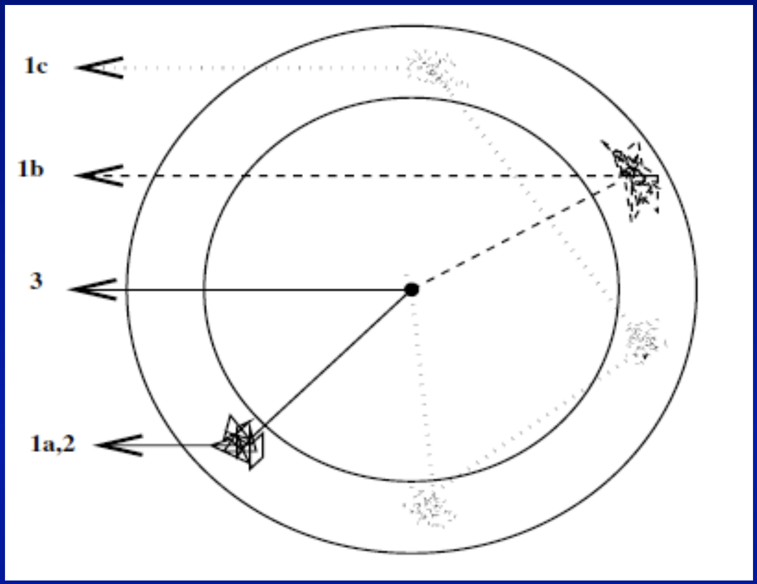


• Model from Verhamme et al.: 3D Monte Carlo radiative transfer code for predicting Lyα profiles given arbitrary gas density and kinematics. Different components of emergent profile correspond to photons that took different paths through an expanding shell (0, 1, 2, 3, backscatterings).

• Generic feature of models that yield multiple peaks: expanding shell has small velocity dispersion relative to expansion velocity.

High-res Spectra of the Horseshoe





(Quider et al. 2009)

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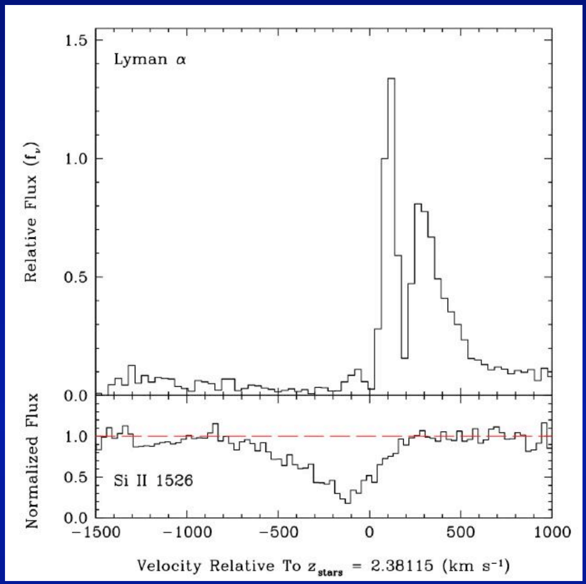
- However, we know based on metal interstellar absorption lines that outflowing interstellar gas has velocity dispersion at least comparable to the outflow speed, and extends over ~1000 km/s. In such cases, the models predict peaks become blurred, don't resemble Horseshoe Lyα spectrum.
- Fundamental problem with Lyα radiative transfer modeling.
- Shell model is not correct for high-redshift outflows!

High-res Spectra of the Horseshoe



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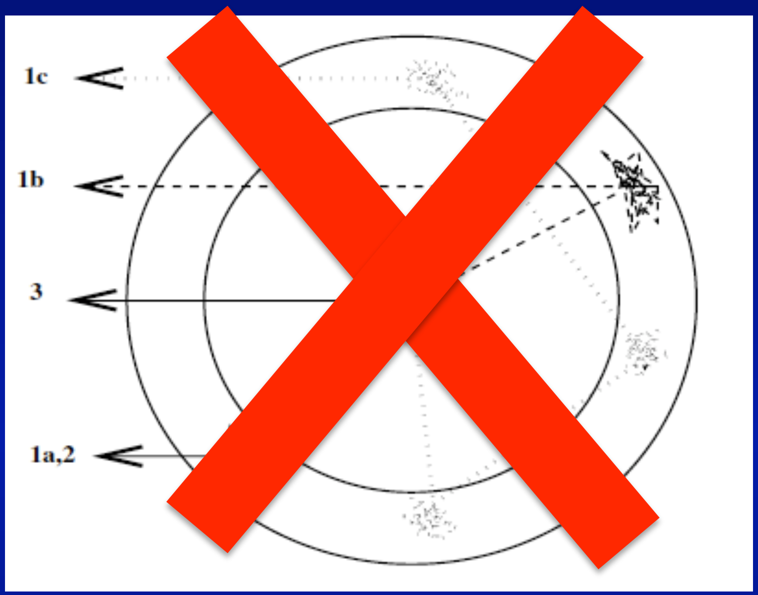

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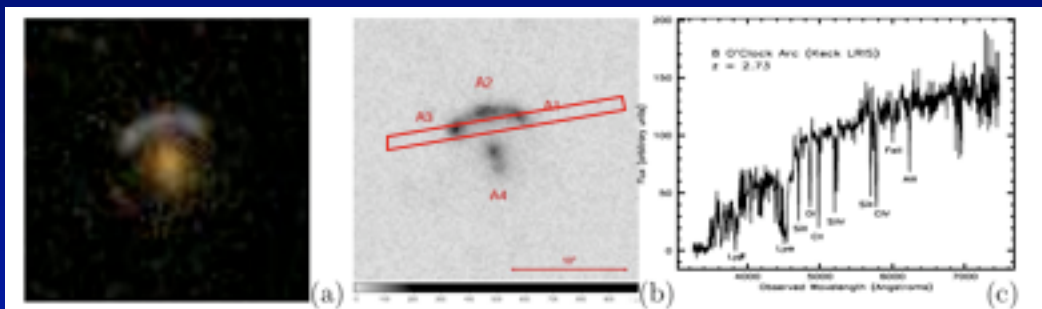
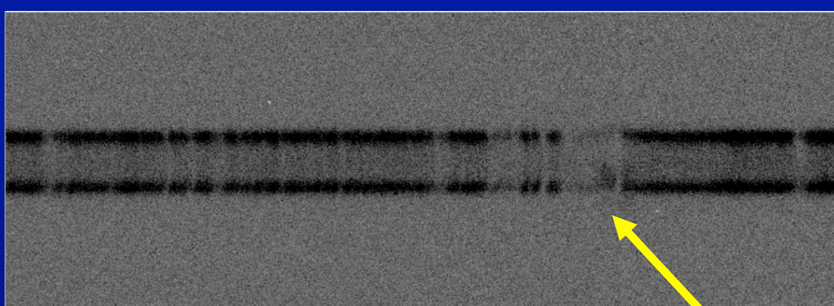
Spatial Variations in the 8:00 arc





Wavelength
(4000-4750 Å)

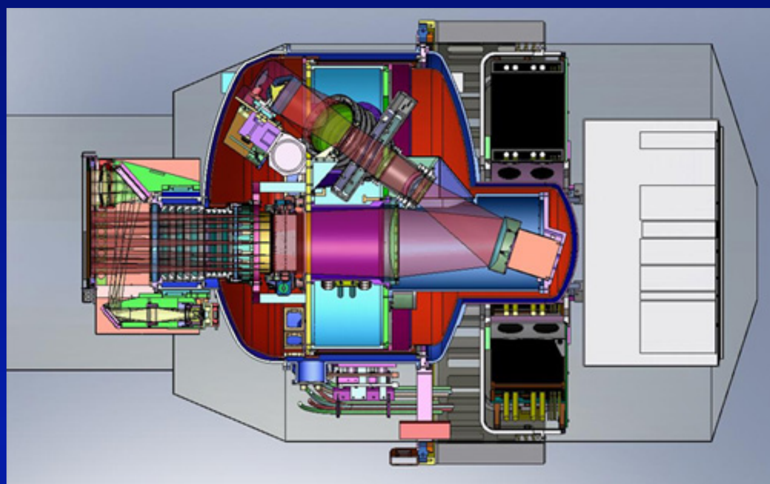
Blueshifted
Lyα

(Keck/LRIS-B, Shapley et al. 2009)

- “8:00 arc,” z=2.73, x12 magnification? R-mag ~19.2. Serendipitously discovered in SDSS. (Allam et al. 2007)
- Lots of multi-wavelength follow-up (HST, Spitzer), including deep, high-resolution spectroscopy.
- Recent paper by LRIS/NIRI optical/near-IR spectra (Finkelstein et al. 2009).
- We are analyzing Keck/ESI spectrum.
- Lyα shows spatial variations among the 3 different knots.

The Future

Future Observations



- Keck/MOSFIRE: Multi-Object Spectrometer for Infra-Red Exploration; co-Pis: McLean (UCLA) and Steidel (Caltech)
- Near-IR (0.9-2.5 μm) spectroscopy over 6.1’× 6.1’ FOV, one band (YJHK) at a time, multiplex advantage up to 46 slits using robotic, cryogenic configurable slit unit. R=2300-3300 with 0.7” slit .
- Planned first light in ~ 9 months.

MOSFIRE

http://www.astro.ucla.edu/~irlab/mosfire/

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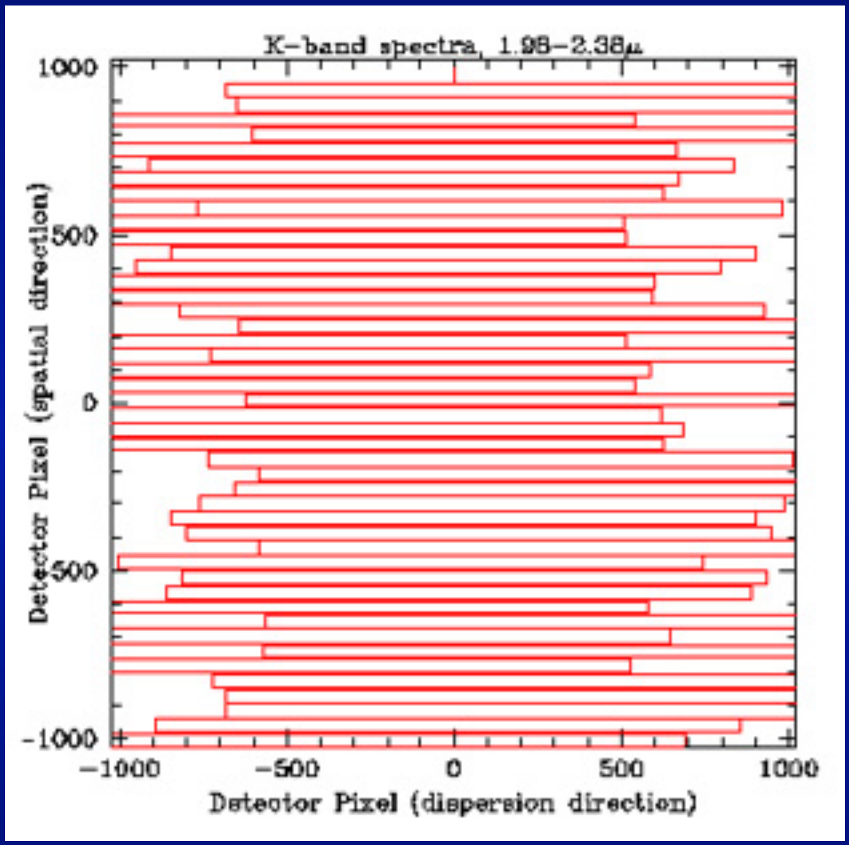

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2 Future Lyα-related Observations

• It is often asserted that objects with strong Lyα emission must be pristine, or at least relatively low-metallicity. THIS HAS NOT BEEN MEASURED. Deep, multi-object near-IR spectroscopy of high-redshift star-forming galaxies will demonstrate how EW(Lyα) and gas-phase metallicity are related.

• Fundamental input to Lyα radiative transfer models: nebular emission lines (Hα, [OIII]). Provide (1) systemic redshift (2) input velocity dispersion of Lyα photons (3) input ionizing flux.

Summary

• Comparison of LAEs and LBGs not meaningful unless it's controlled (magnitude, mass, etc.).

• LAE emitters appear to have bluer UV continua than non-emitters, with no evidence for clumpy dust.

• Definitive results await about stellar mass and age, and an evolutionary scenario for LBGs regarding Lyα emission. At z~3, LBGs appear to evolve towards stronger Lyα emission on average.

• Gravitationally lensed LBGs offer excellent test of Lyα radiative transfer models, calling the thin, expanding shell model into question.

• Next frontier: metallicities of strong Lyα emitters.