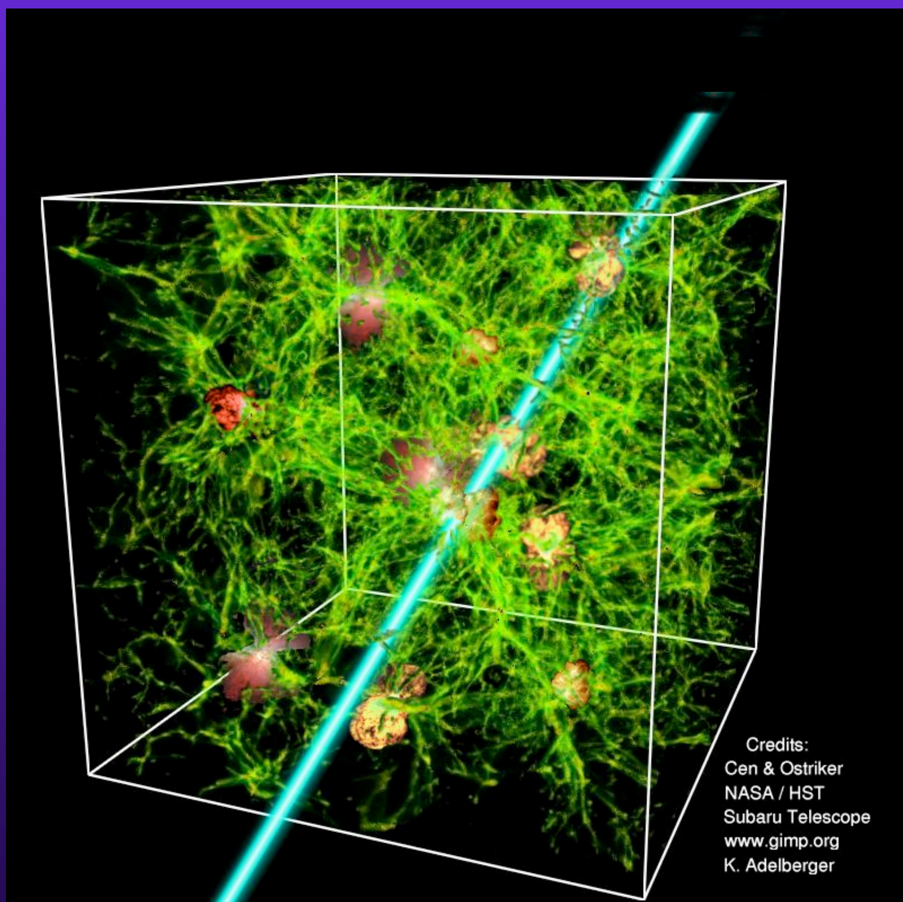
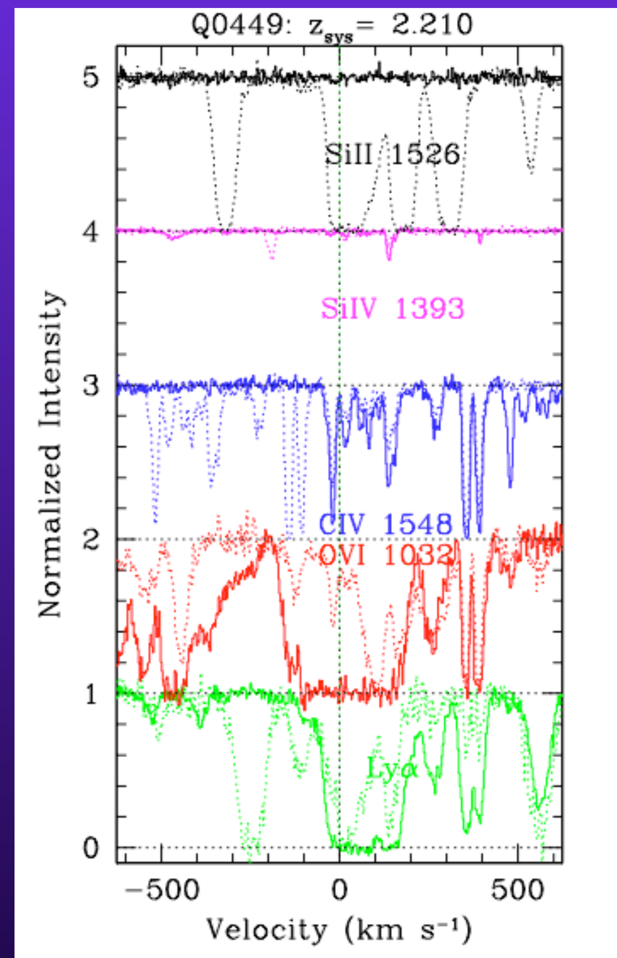
Observations of Feedback Processes in High Redshift Galaxies

C. Steidel (Caltech)



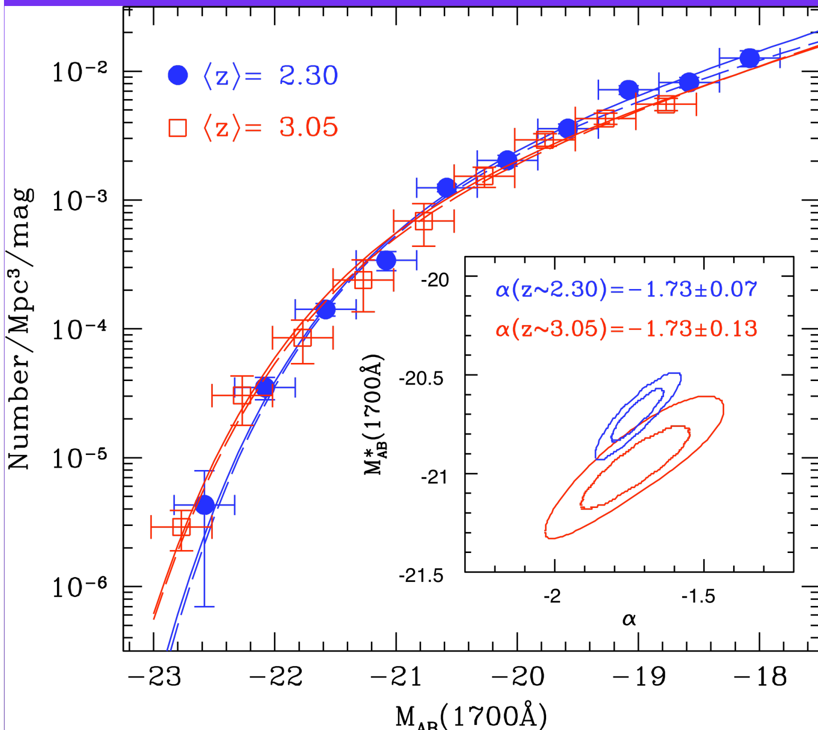


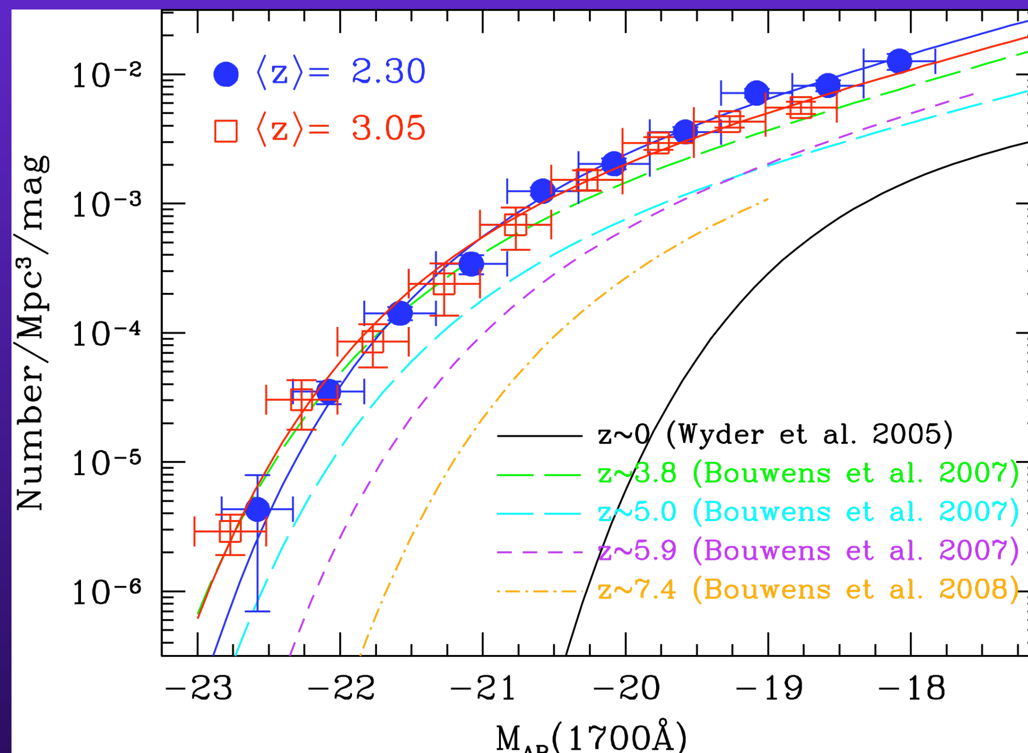
IAP Colloquium, July 2008

Outline

- Given the focus at this meeting on high redshift objects (z>3):
  - What have we learned (at somewhat lower redshift) that might be useful to know about “LBGs” and other denizens of the high-z universe?
  - What kinds of objects:
    - leak gas, metals to the IGM
    - produce H-ionizing photons that contribute significantly to the metagalactic radiation field?
      - Not the objects that reionized the universe; the ones that keep it ionized!
  - How might one map out a more complete picture of the whole complicated (but lovable!) mess of galaxies/AGN and the IGM?

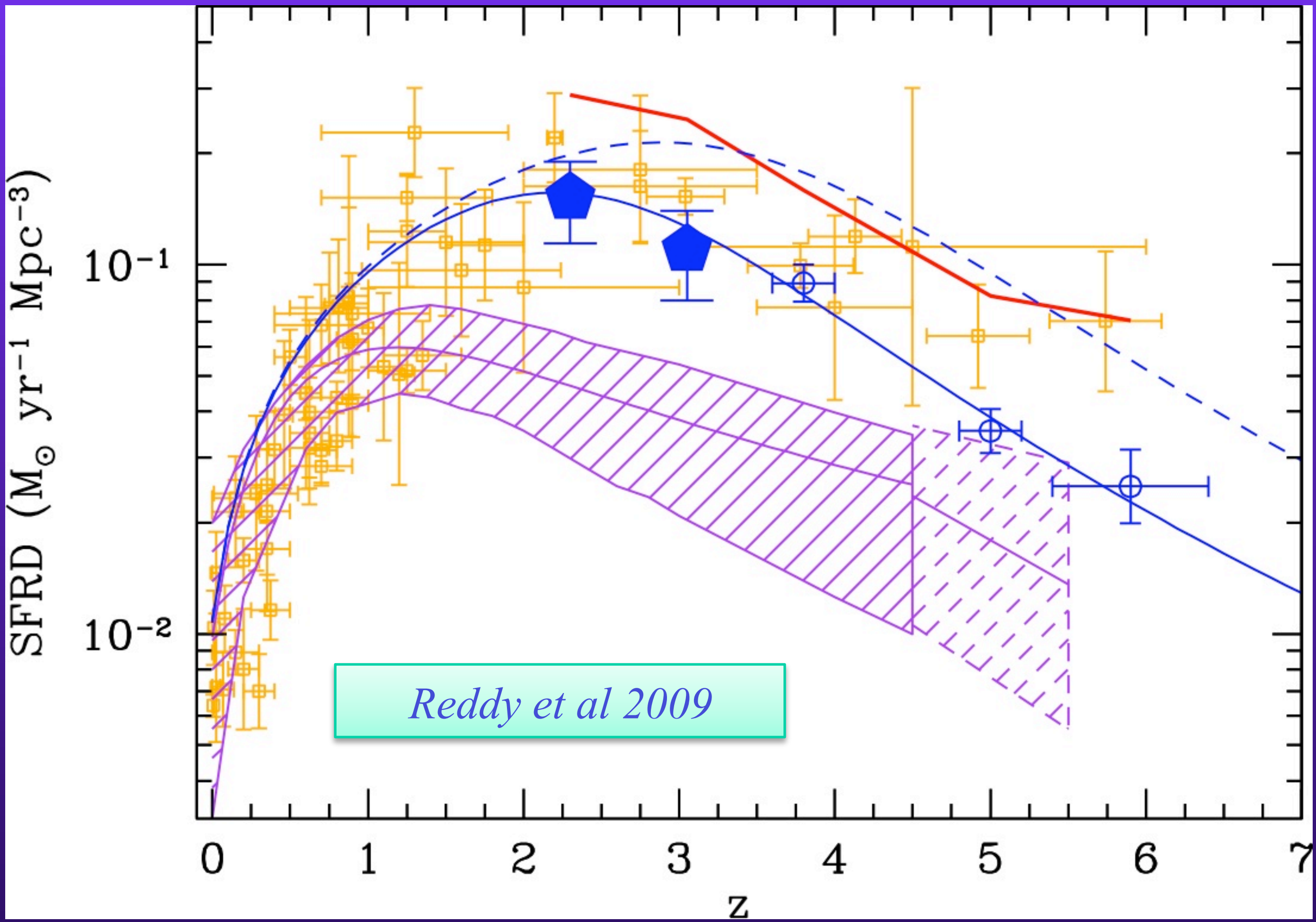
Far-UV LFs vs. Redshift





Reddy et al 2009

Why Bother With "Low" Redshift?



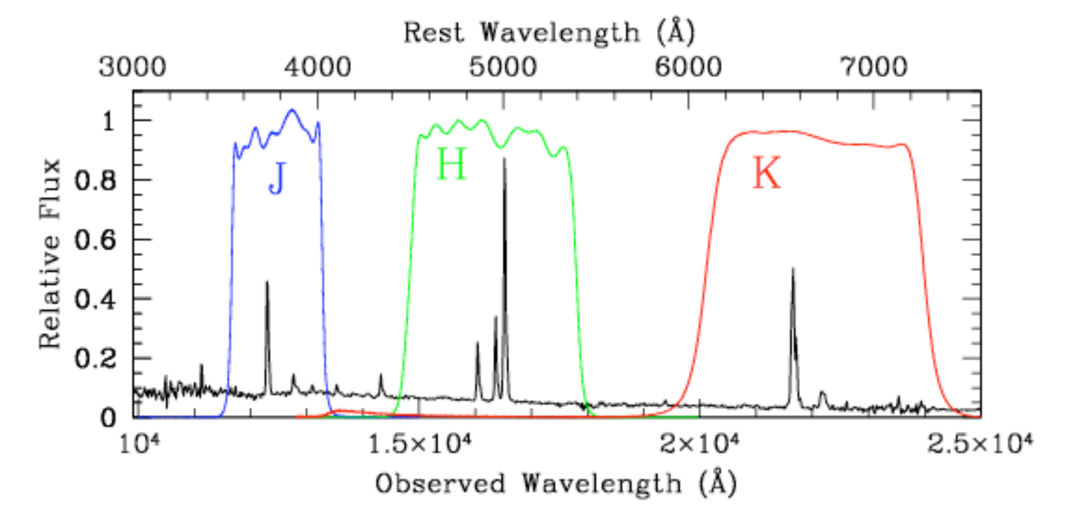
>50% of the stars in the present-day universe formed in the interval 3.5 > z > 1.5

Can watch all of the effects that shaped the present-day universe while they were happening

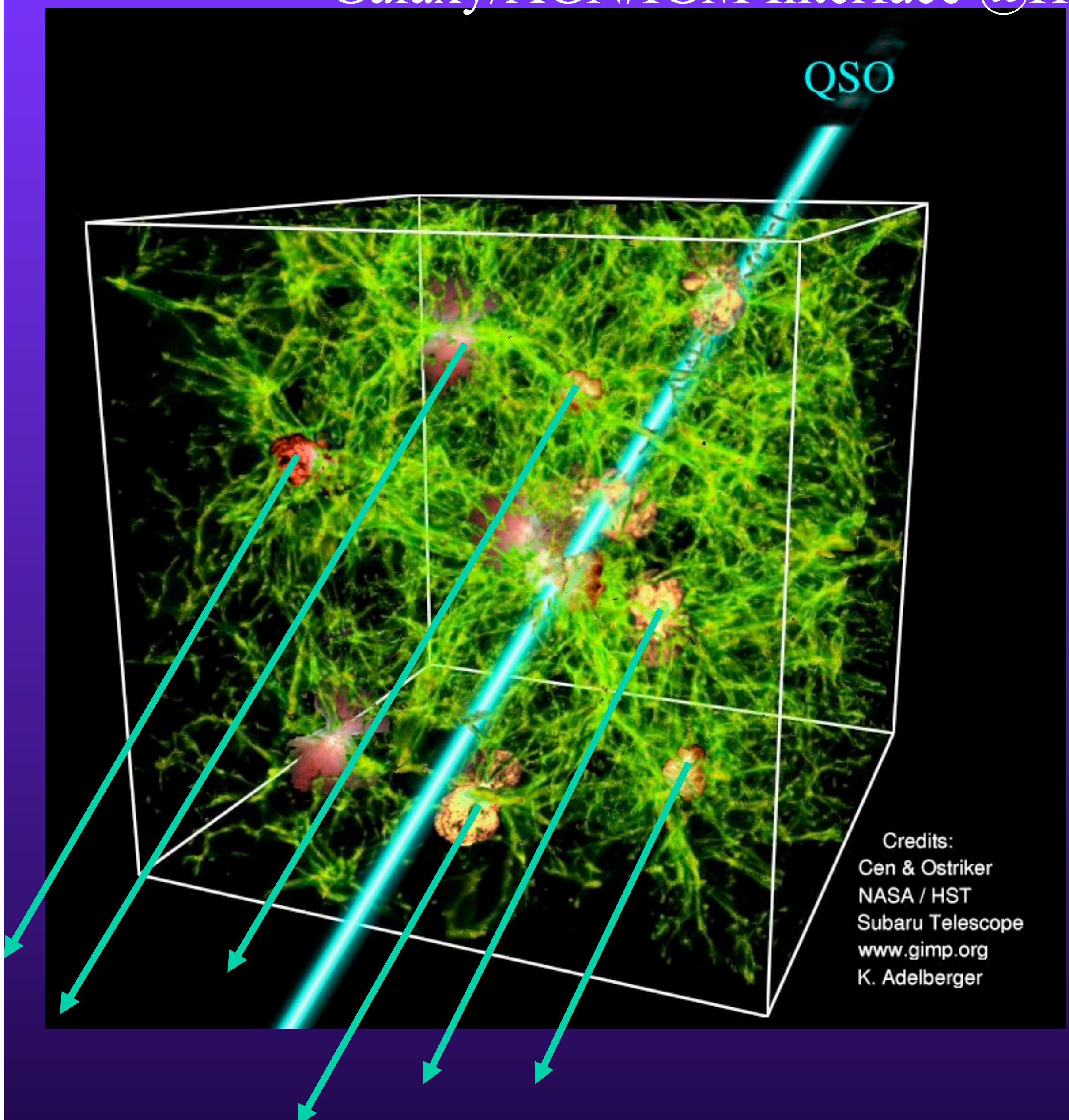
Reddy et al 2008

Why z~2-3 is interesting….

- The peak of the QSO epoch, and (apparently) of star formation in galaxies
- Allows for simultaneous study of diffuse IGM in the same cosmic volumes (and the IGM still has some dynamic range!)
- Large numbers of galaxies are bright enough for detailed spectroscopic study with 8m-class telescopes (still faint though!)
- Access to diagnostic spectroscopy in both the rest-frame far-UV and the rest-frame optical; well placed nebular lines in atmospheric windows!



Galaxy/AGN/IGM Interface @High Redshift



- Can use background QSOs, AGN, and galaxies to study gas kinematics, metallicity, etc. in outer parts of foreground galaxies

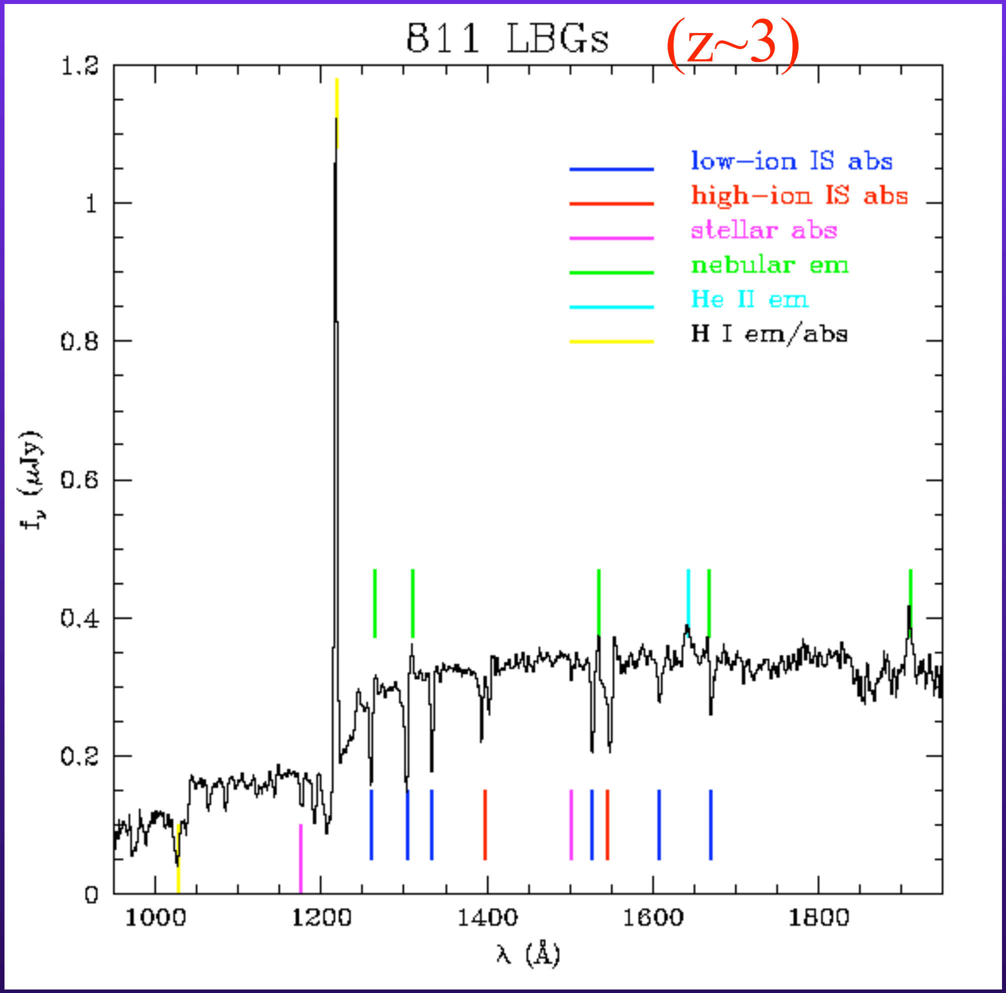
- Use the interface , or "circum-galactic medium", as a barometer for "feedback" processes

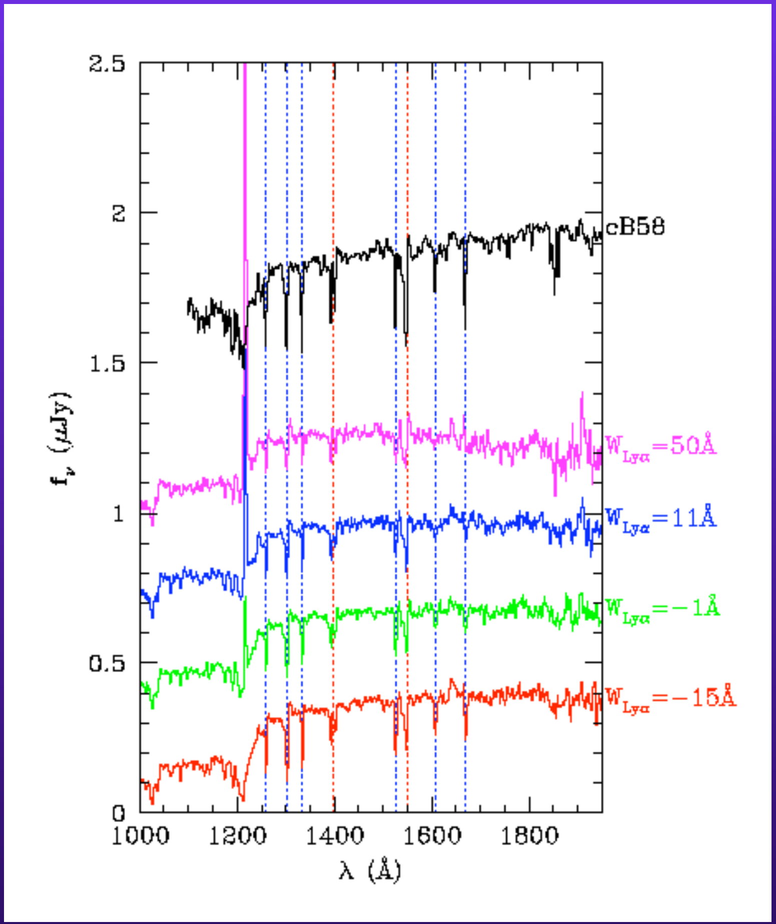
⇒true IGM "tomography" is possible now.

A “typical” star forming galaxy at z~2-3

- Lives in a dark matter halo of mass ~several x 10^{11} to 10^{12} $M_\odot$ (from clustering) (e.g., Adelberger et al 2005; Conroy et al 2008)
- Is ~half stars and ~half cold gas in inner few kpc, a few times 10^{10} $M_\odot$ of each (Hα, SEDs, kinematics)
  - Taken together, may account for >50% of total baryons associated with the halo
- Is (probably) losing more gas than it is converting into stars (e.g., Pettini et al 2000; Erb et al 2006a,b)
  - v_c~150 km/s, v_{esc} ~450 km/s
- Has R~24-25 (AB), K~23-24 (AB)- faint, but not *that* faint

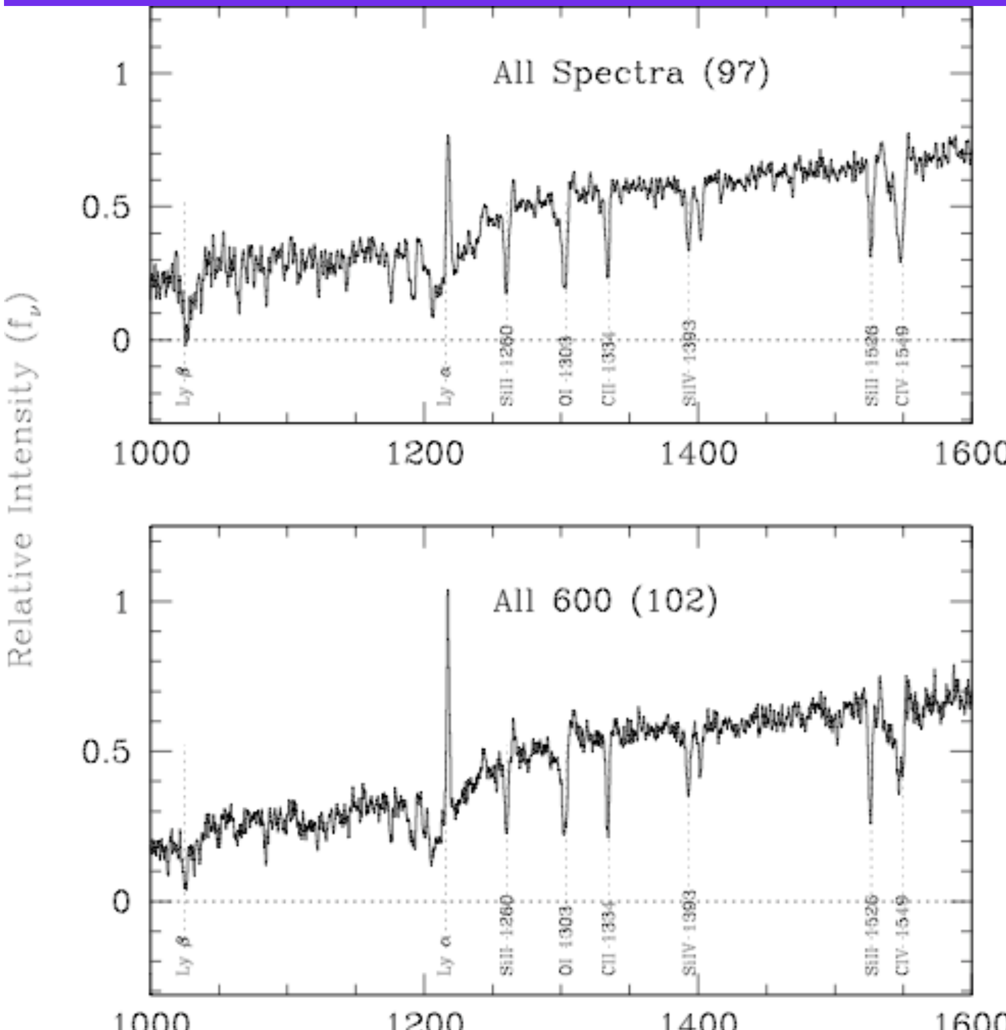
Far-UV Spectra of LBGs

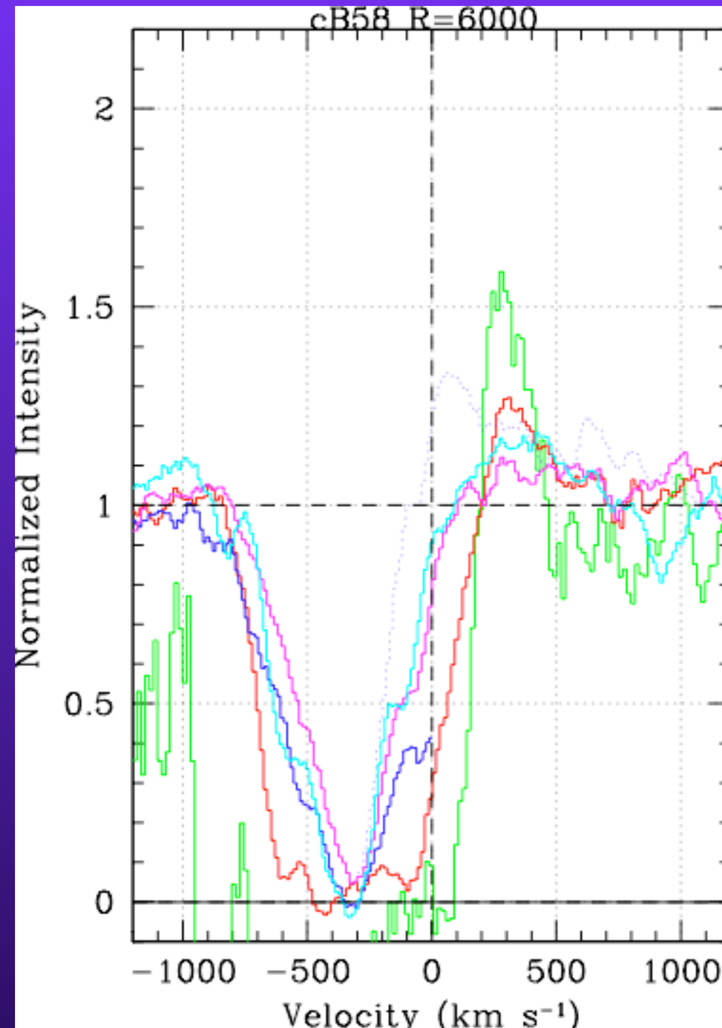




Shapley et al 2003

Far-UV Spectra: Gas Flows

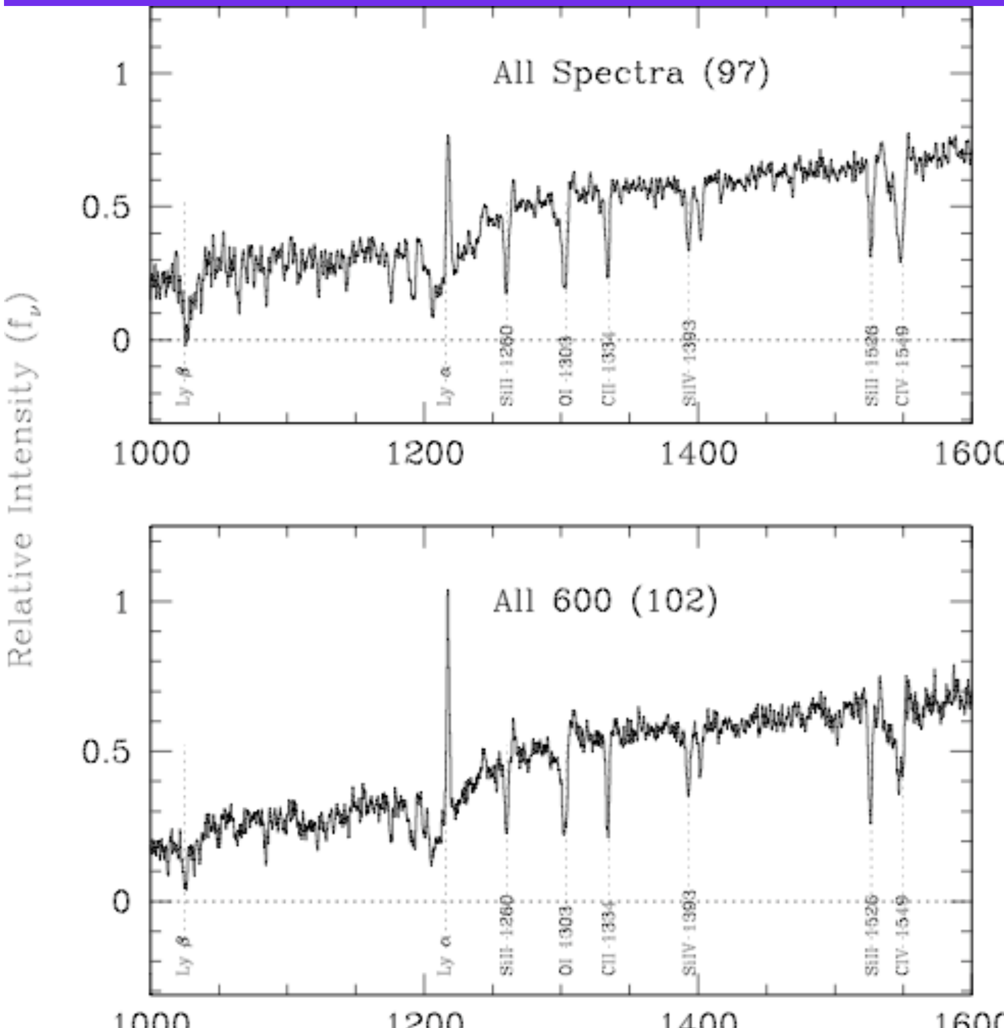


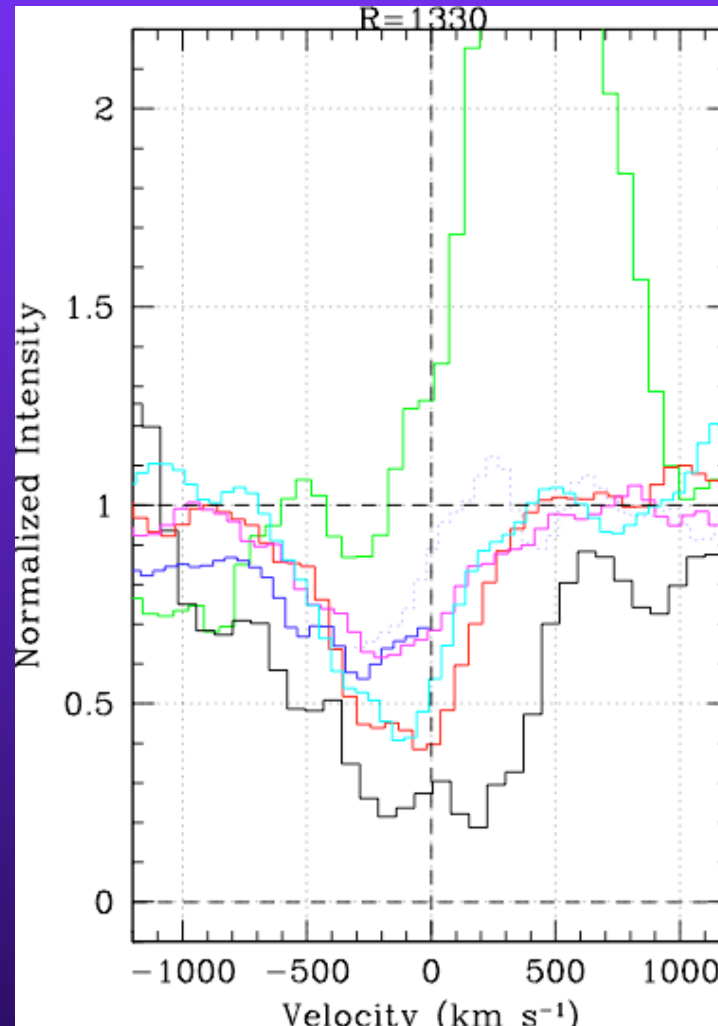


Composite spectra of z~2-2.6 UV-selected galaxies

Velocity profiles in selected transitions relative to z_{sys}

Far-UV Spectra: Gas Flows

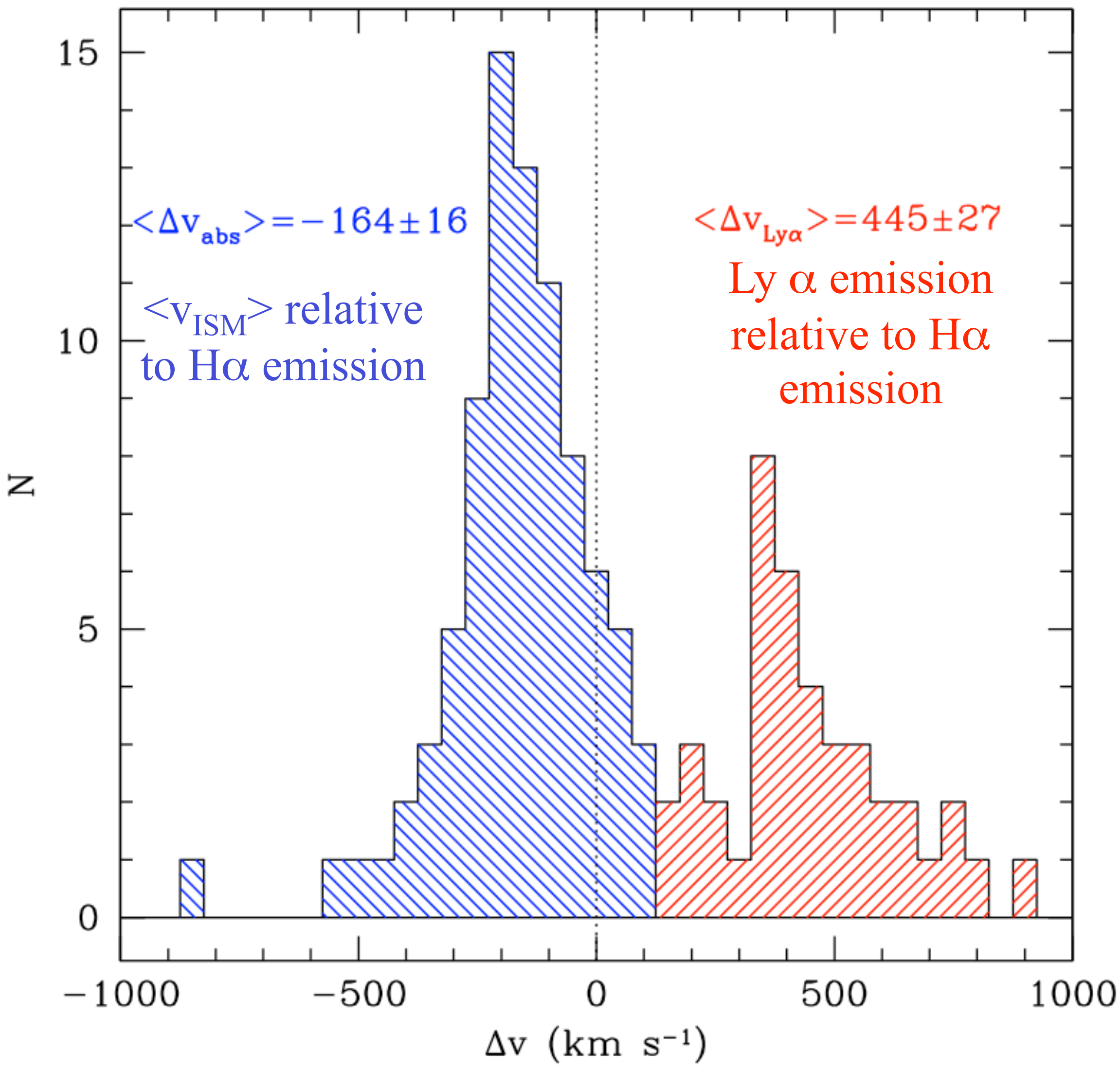




Composite spectra of z~2-2.6 UV-selected galaxies

Velocity profiles in selected transitions relative to z_{sys}

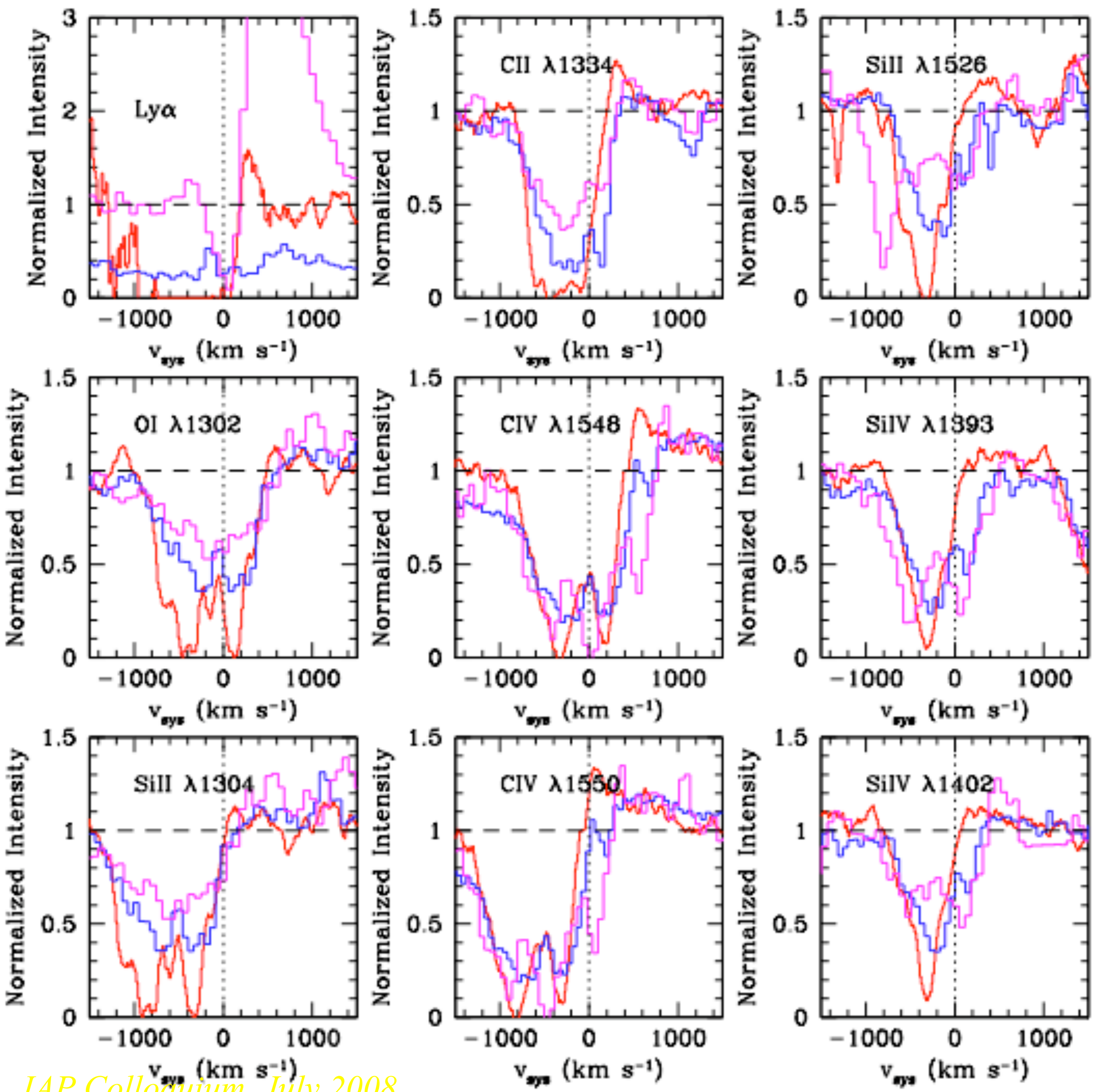
Galactic Scale Outflows are Ubiquitous @ high redshift



CS, Erb, Shapley, et al 2008

- Typical centroid velocities are ~200 km/s with respect to nebular line (systemic) redshifts
- Typical line widths are ~550 -750km/sec (FWHM)
- Close to unity covering fraction is common
- Lines of all accessible ionization stages seen (e.g., OI to OVI)

Consistency of Velocity Envelopes for Interstellar Material

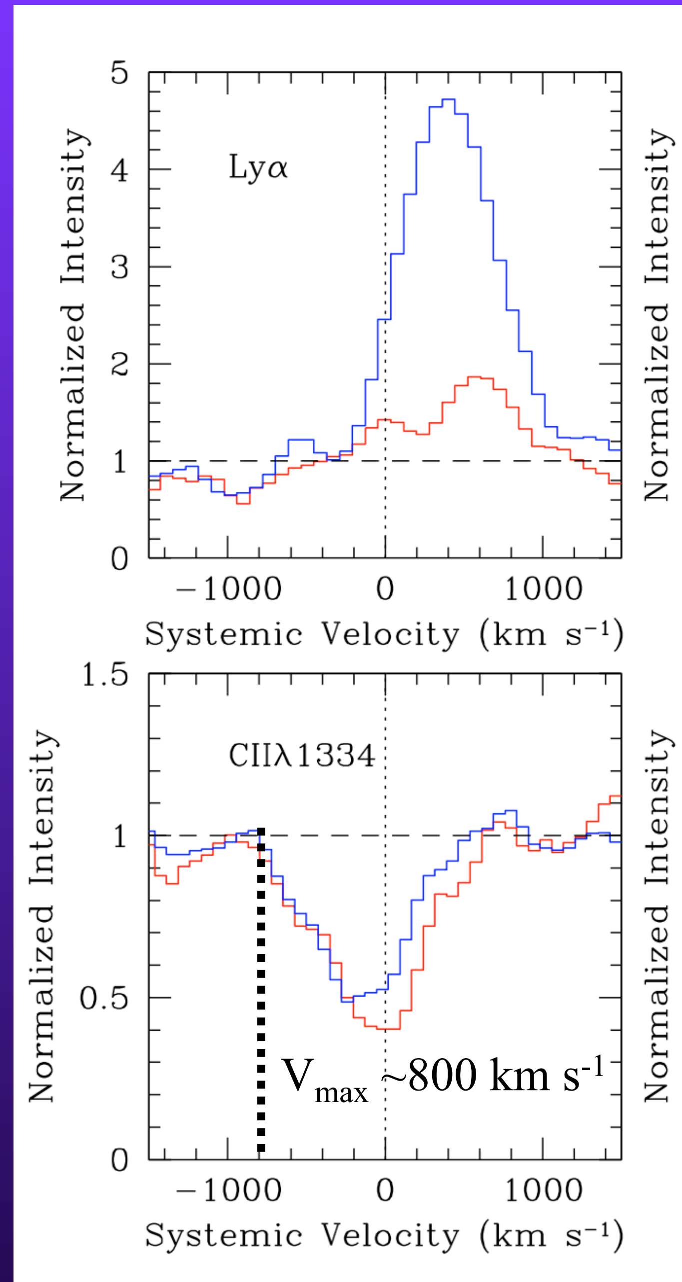


3 lensed z~2.7-3 galaxies, all R=6000 with stellar velocity zero point (red is cB58)

Sample of ~120 galaxies with accurate (Hα) systemic redshifts, good UV spectra

Correlations of Bulk Outflow Velocity and Galaxy Properties[a]

Quantity	$-\Delta v_{IS}$	$\Delta v_{Ly\alpha}$	$\Delta v_{Ly\alpha} - \Delta v_{IS}$
σ_v[b]	−2.08 (65)	+1.81 (29)	+0.74 (29)
SFR[c]	−1.52 (87)	−0.04 (42)	−0.08 (39)
Σ_{SFR}[d]	+0.95 (81)	+0.82 (37)	+0.49 (35)
M_{dyn}[e]	−2.24 (57)	+1.02 (24)	+0.14 (24)
M_{gas}[f]	−1.68 (73)	+0.71 (36)	+0.85 (34)
M_*[g]	−1.93 (73)	−0.37 (36)	−0.48 (34)
M_{bar}[h]	−2.66 (73)	−0.10 (36)	−0.10 (34)
μ[i]	+1.72 (73)	+0.64 (36)	+0.93 (34)



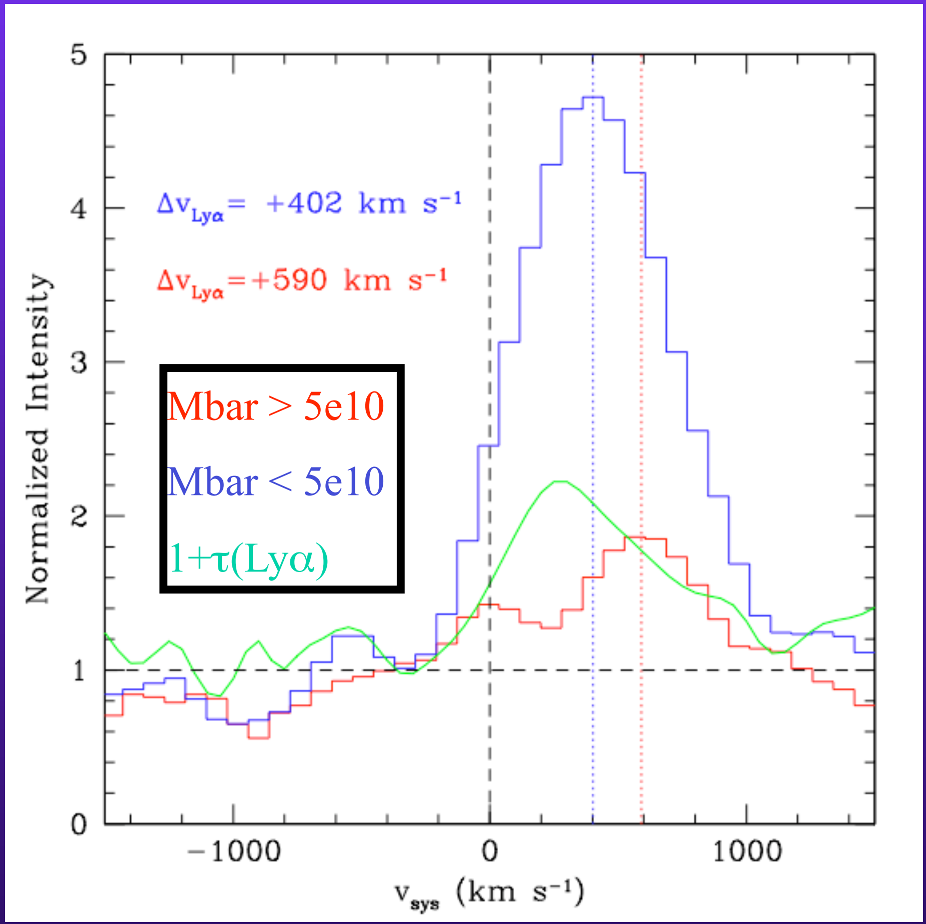
CS, Erb, Shapley, et al 2008

Blue: M_{bar}<5x10^{10} $M_\odot$

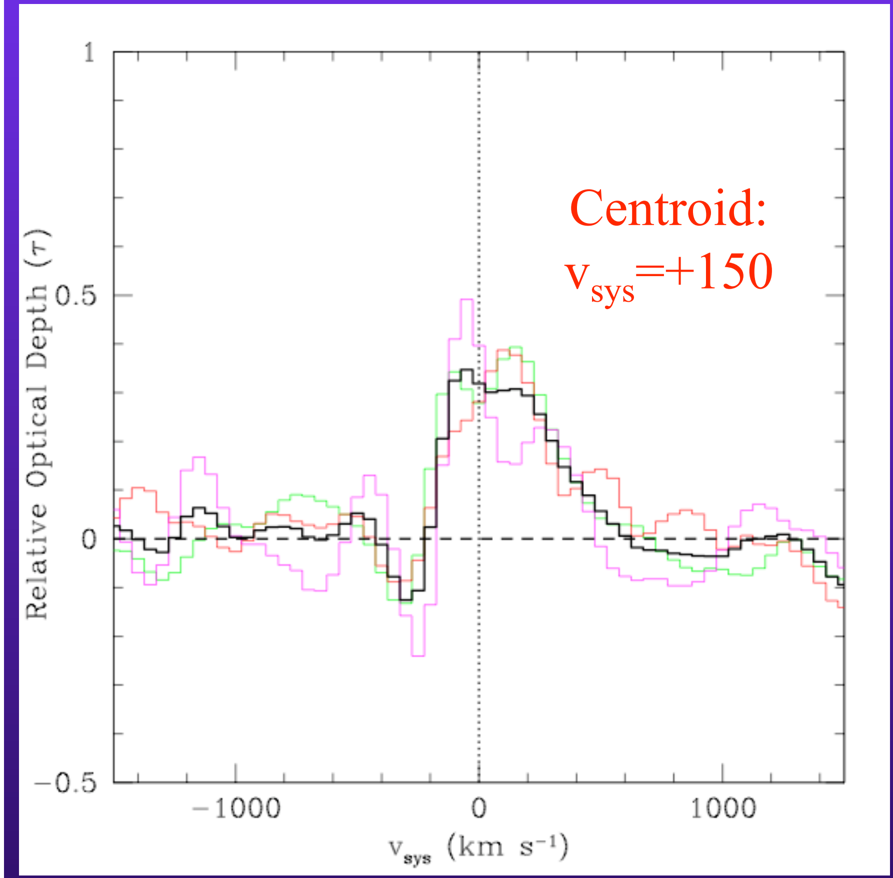
Red: M_{bar}>5x10^{10} $M_\odot$

(M_{bar}=M_*+M_{gas})

Differences in Line Profiles vs. M_{bar}: Evidence for Infall in Higher Mass Sub-sample?



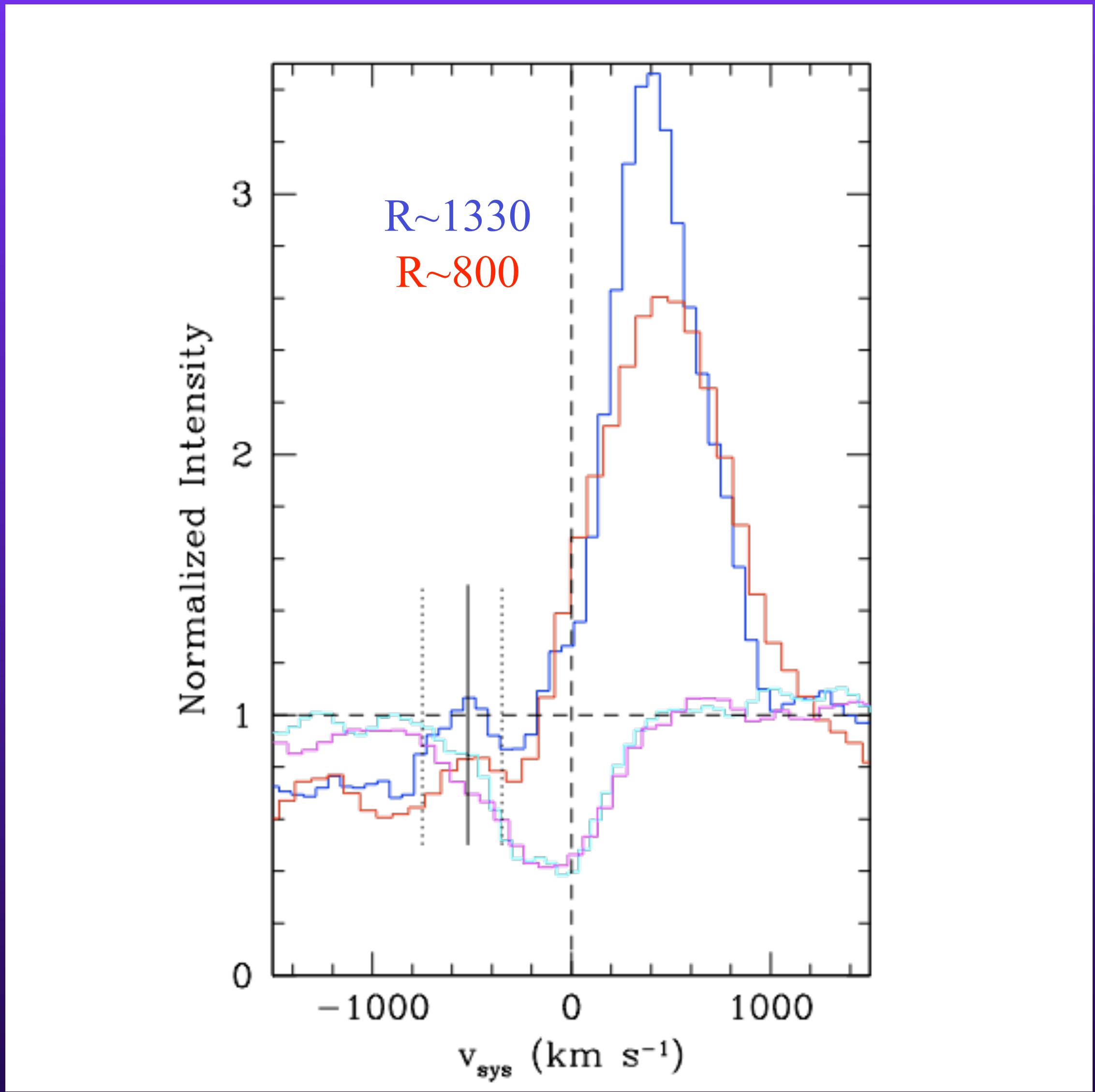
Lyα Profiles



Differential Optical Depth in Low-Ionization Lines

IAP Colloquium, July 2008

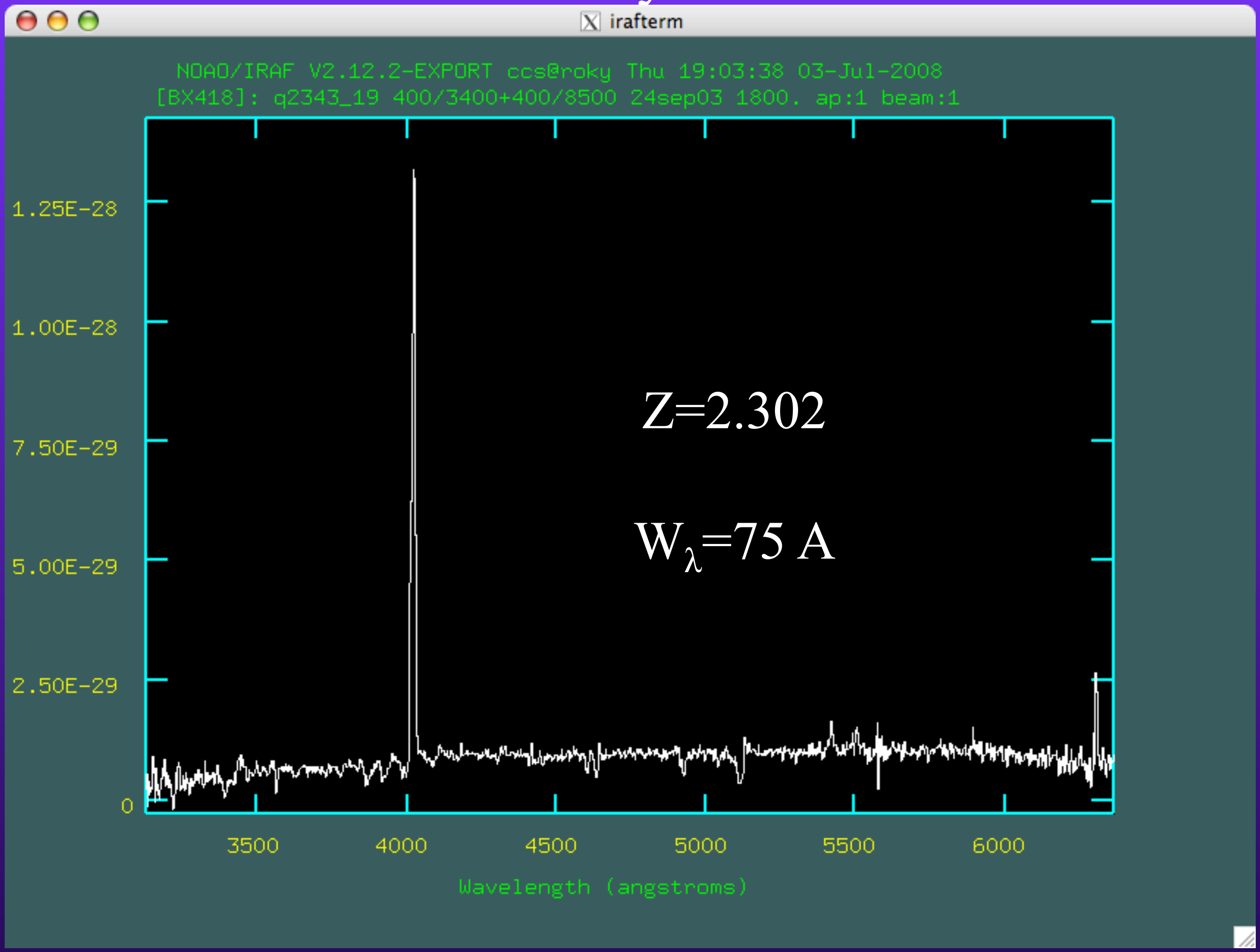
Kinematics of Lyman α Emission from Galaxies

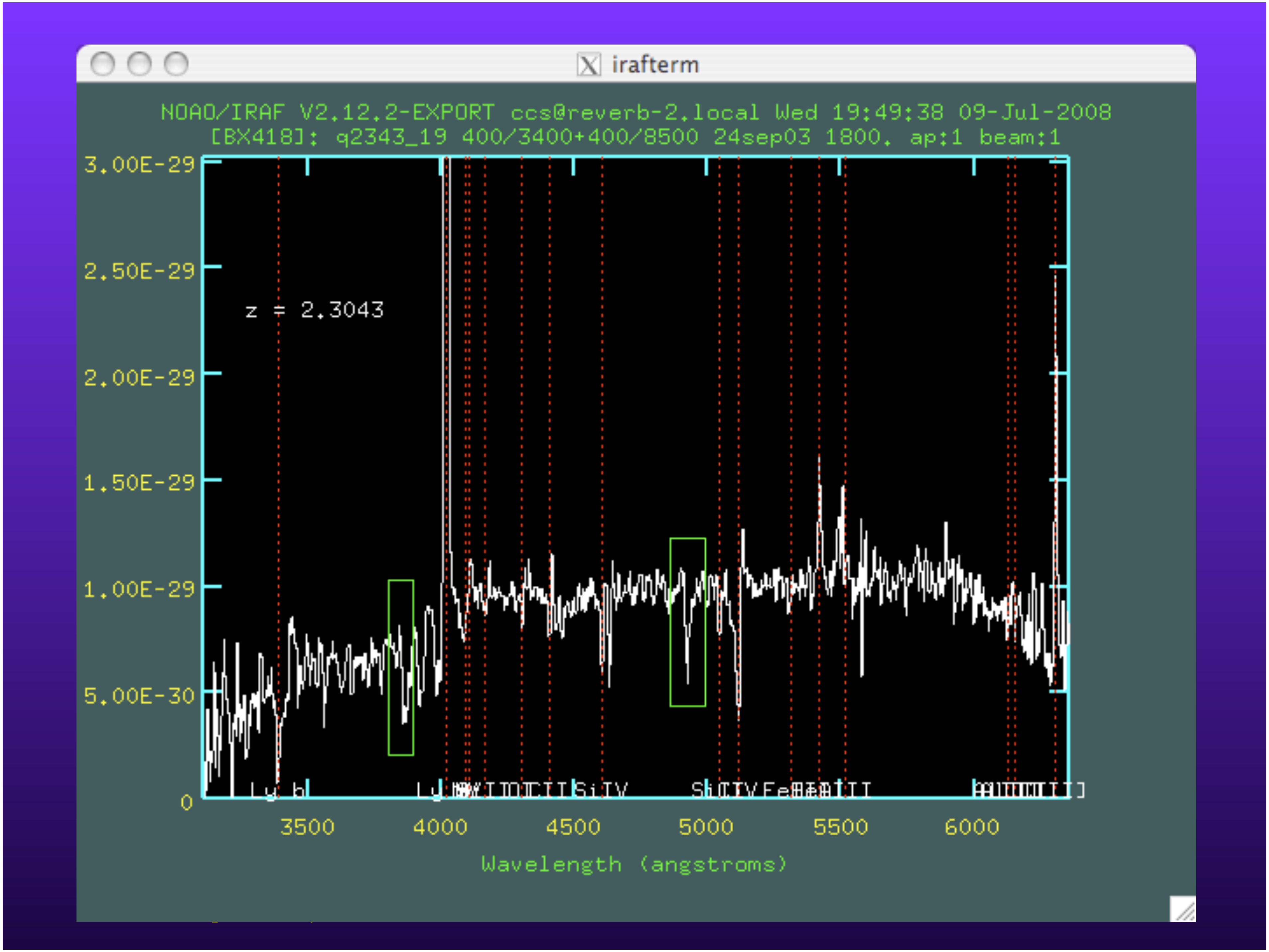


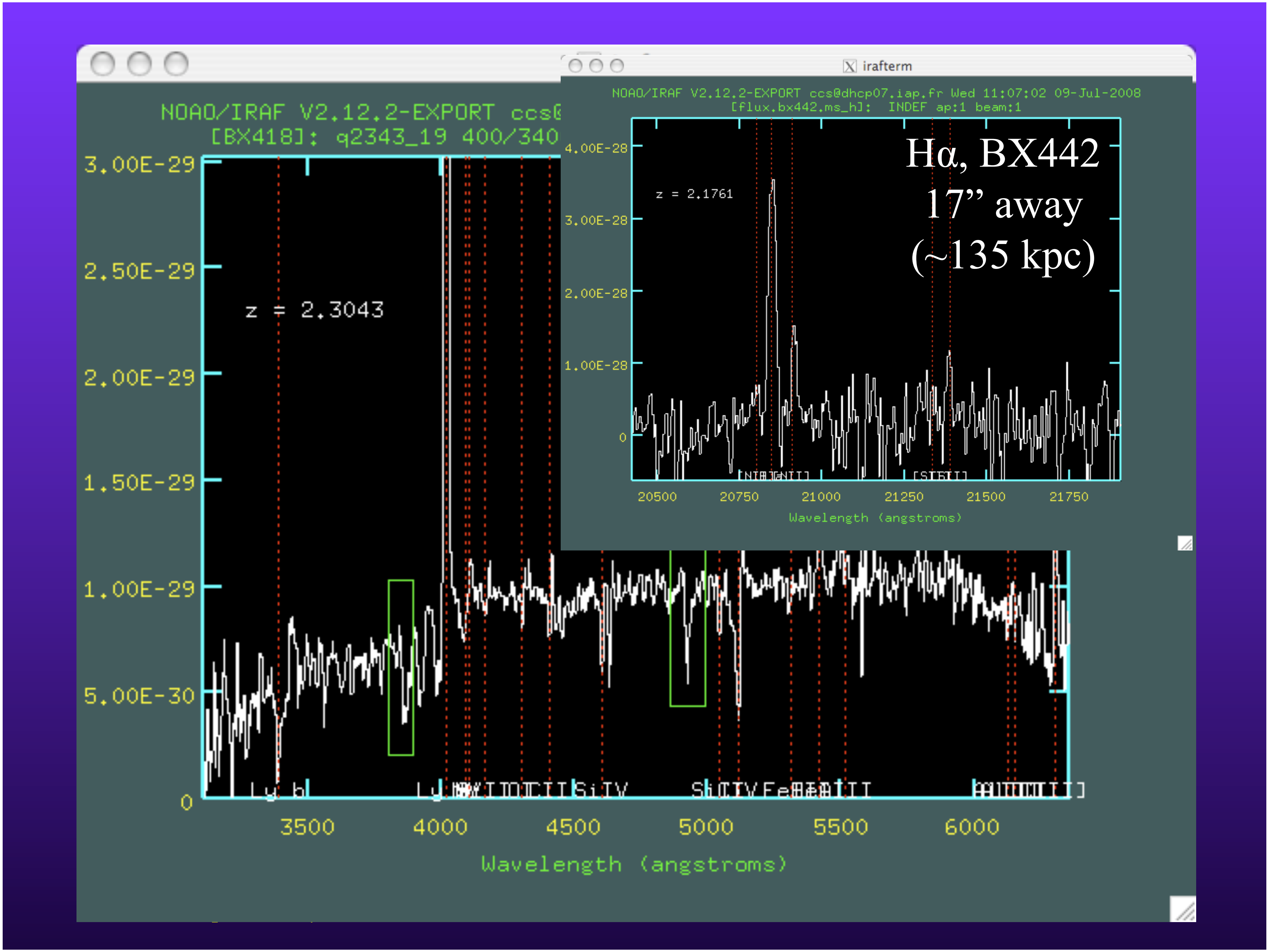
- <z>=2.3 Ly α composite (~100 spectra)

- Clear secondary blue-shifted peak at +500 km/s (very difficult to see in higher redshift samples)

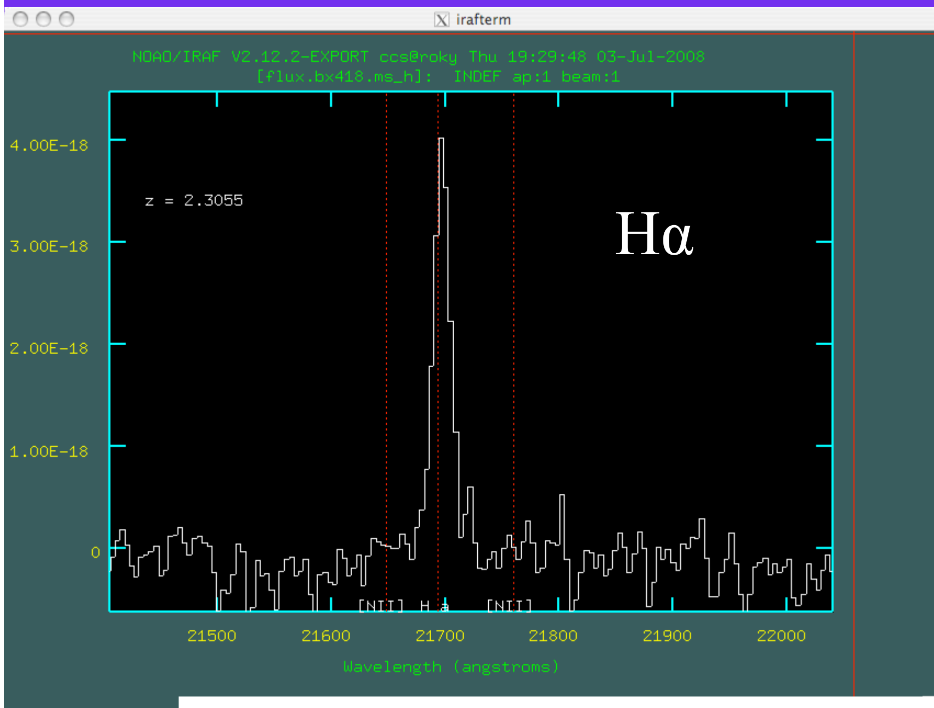
Just for fun...a "Ly α Emitter" at z=2.3

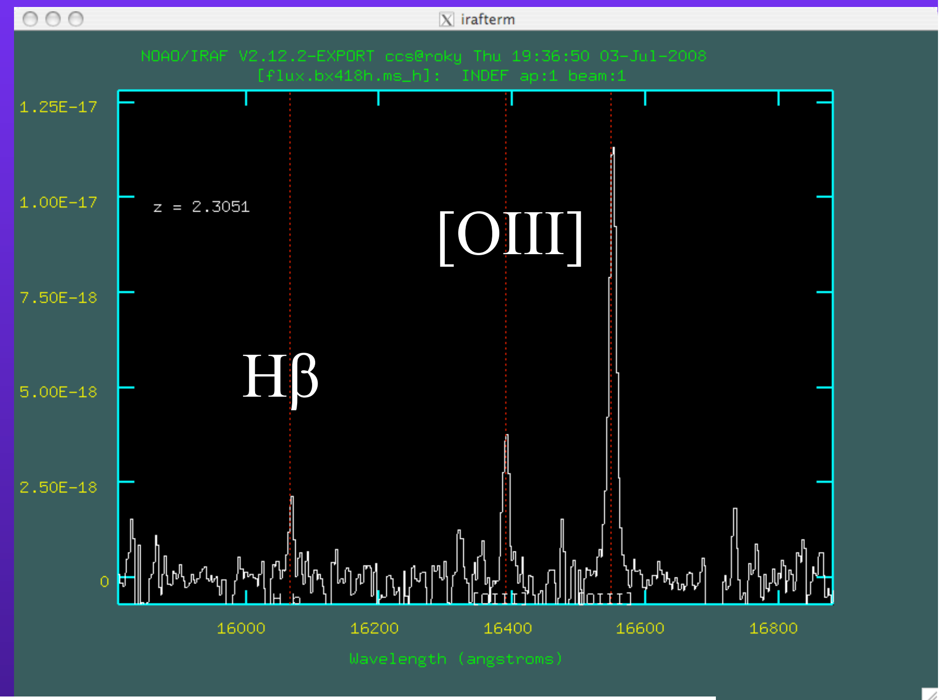


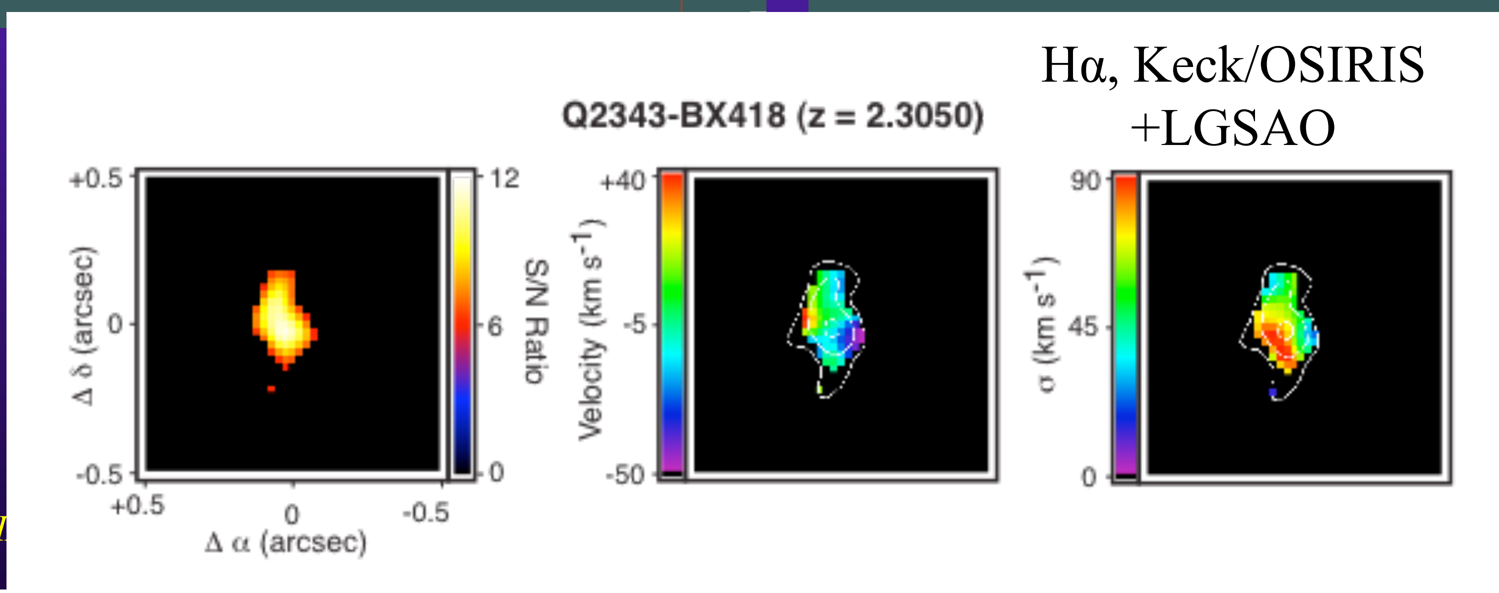

irafterm
NOAO/IRAF V2.12.2-EXPORT ccs@reverb-2.local Wed 19:49:38 09-Jul-2008
[BX418]: q2343_19 400/3400+400/8500 24sep03 1800. ap:1 beam:1
z = 2.3043
3.00E-29
2.50E-29
2.00E-29
1.50E-29
1.00E-29
5.00E-30
0
3500
4000
4500
5000
5500
6000
Wavelength (angstroms)


NOAO/IRAF V2.12.2-EXPORT ccs@
[BX418]: q2343_19 400/340
z = 2.3043
Wavelength (angstroms)
irafterm
NOAO/IRAF V2.12.2-EXPORT ccs@dhcp07.iap.fr Wed 11:07:02 09-Jul-2008
z = 2.1761
Hα, BX442
17” away
(~135 kpc)
Wavelength (angstroms)

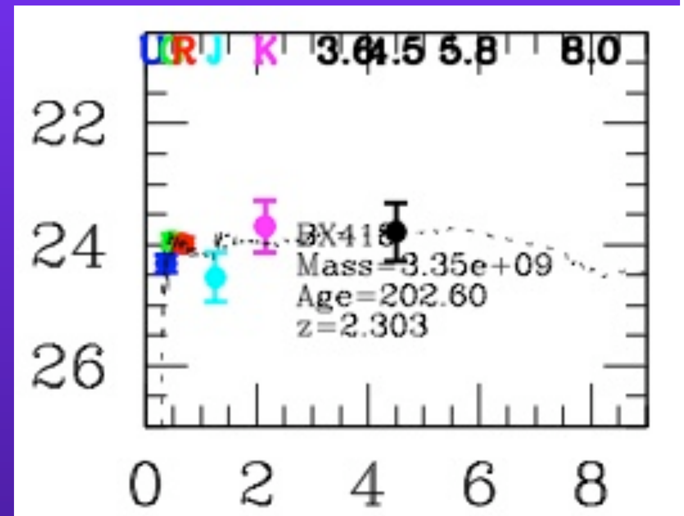
Z~2.3 Ly α emitter

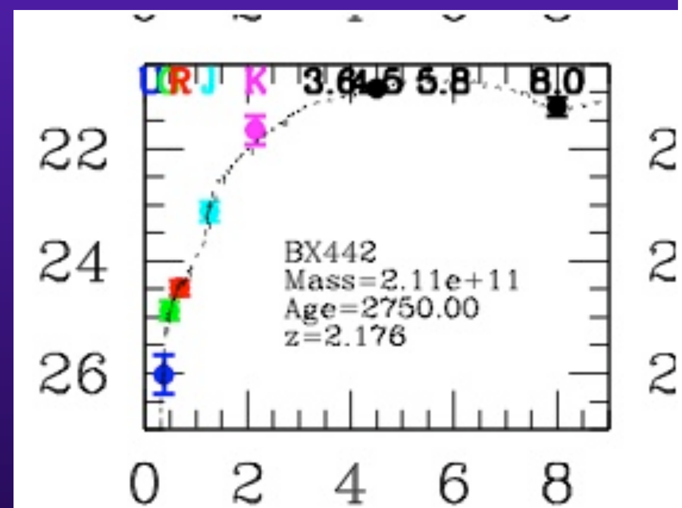




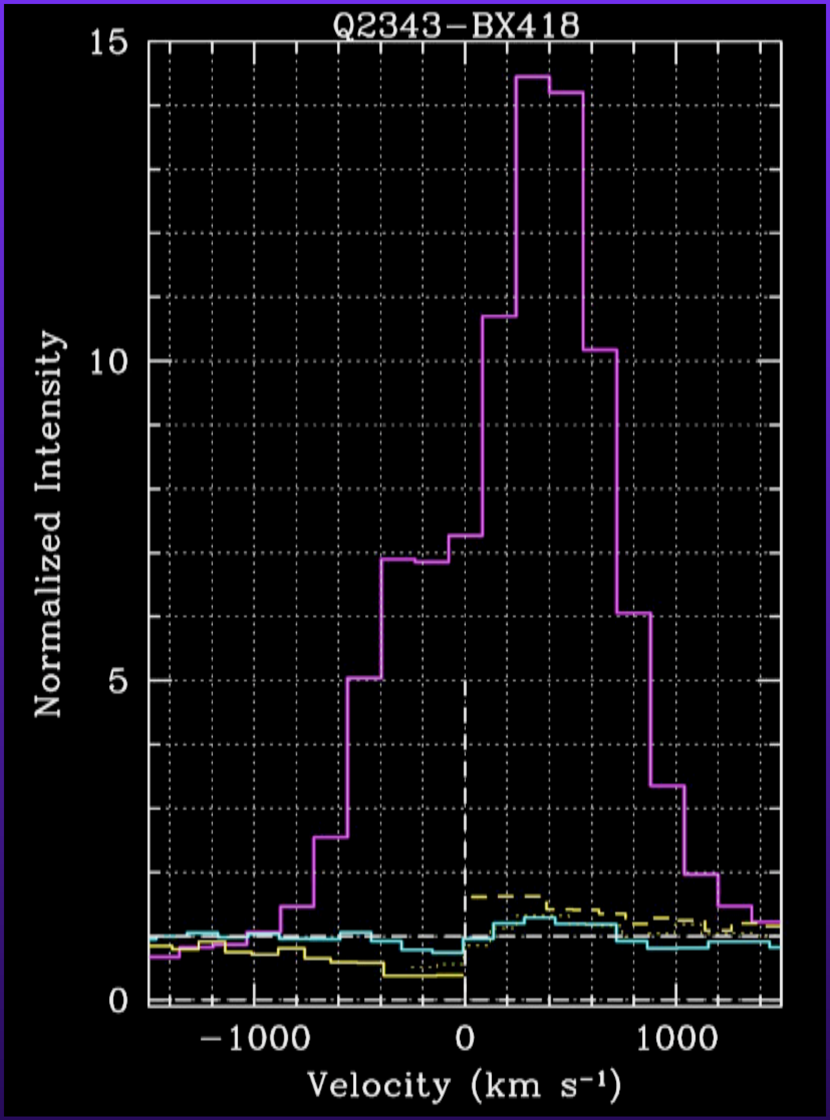


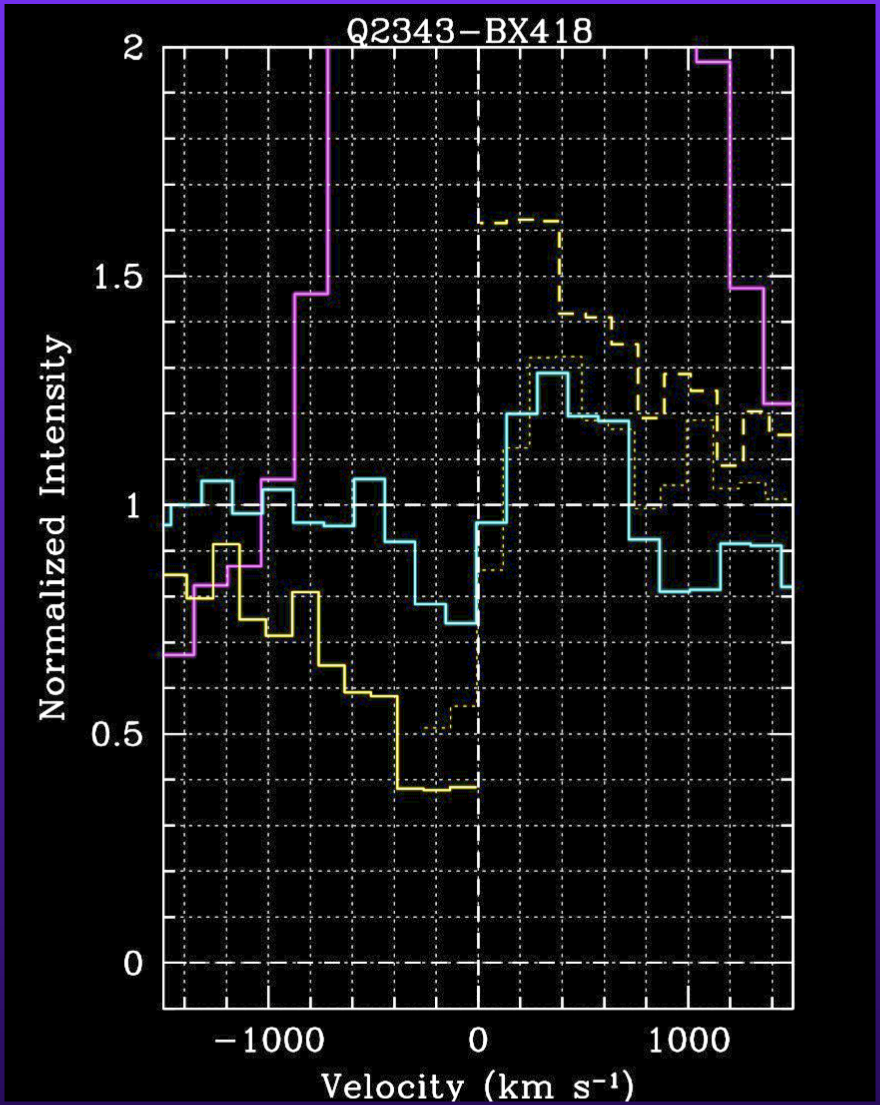
Q2343-BX418	Measured Property
[O/H]	<0.3 solar (from N2O3)
SFR ($M_\odot$/yr)	14 (UV); 22 (Hα); ~20 (Lya)
E(B-V)	0.015
L/L* (UV) L_{bol} ($L_\odot$)	1 4×10^{11}
Σ_{sfr} ($M_\odot$/yr/kpc^2)	~30
M_* ($M_\odot$)	~2×10^9
M_{dyn} ($M_\odot$)	~10^{10}
σ_v (km/s)	70 (no shear @0.08" resoln)
Size	r<~1 kpc
Age	<100 Myr





Velocity Profiles relative to Systemic

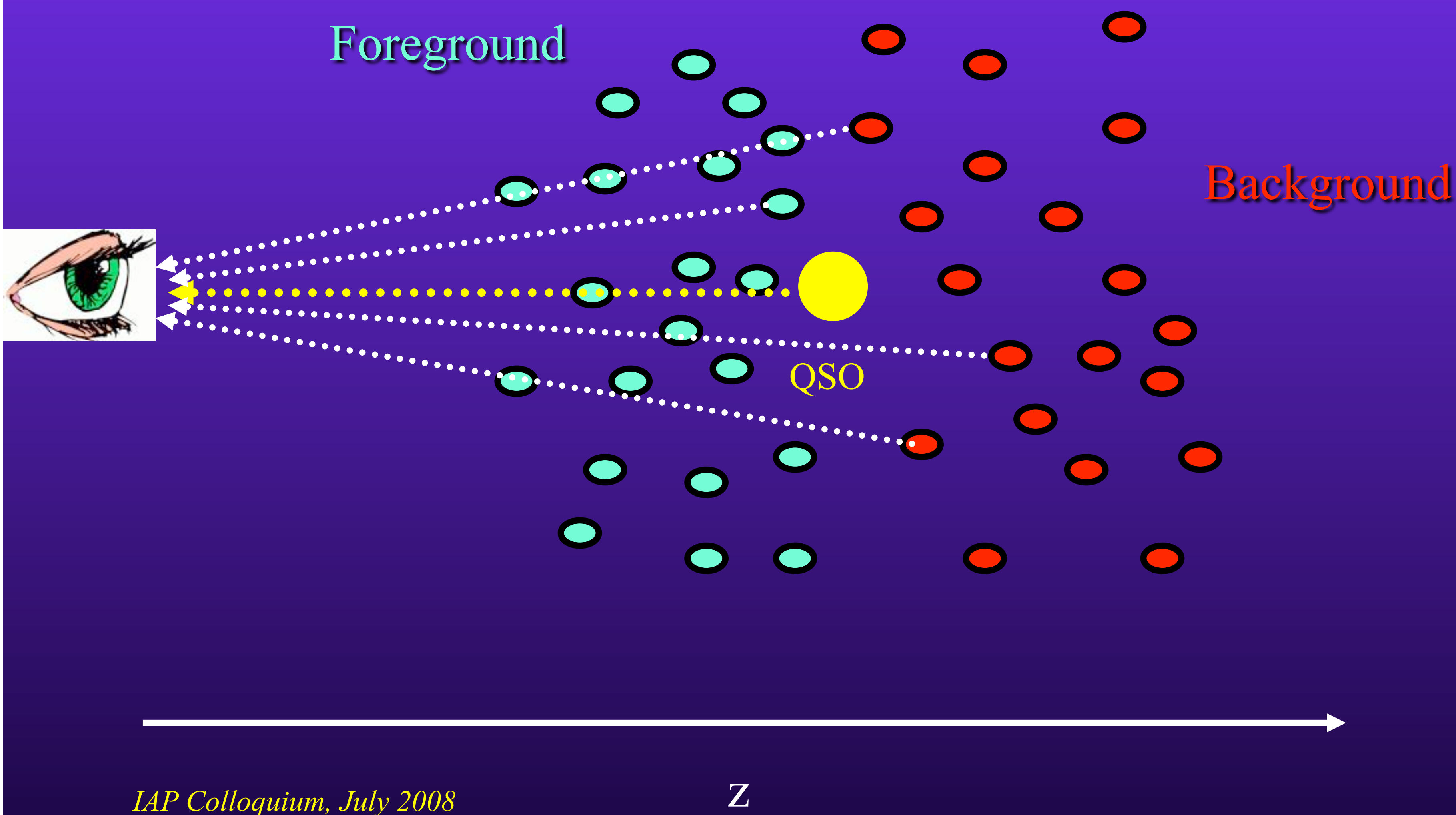




OK, So everything at high redshift has an outflow.

But where is the gas, and how far does it get?

Densely Sampling the Universe @z~1.8-3.2

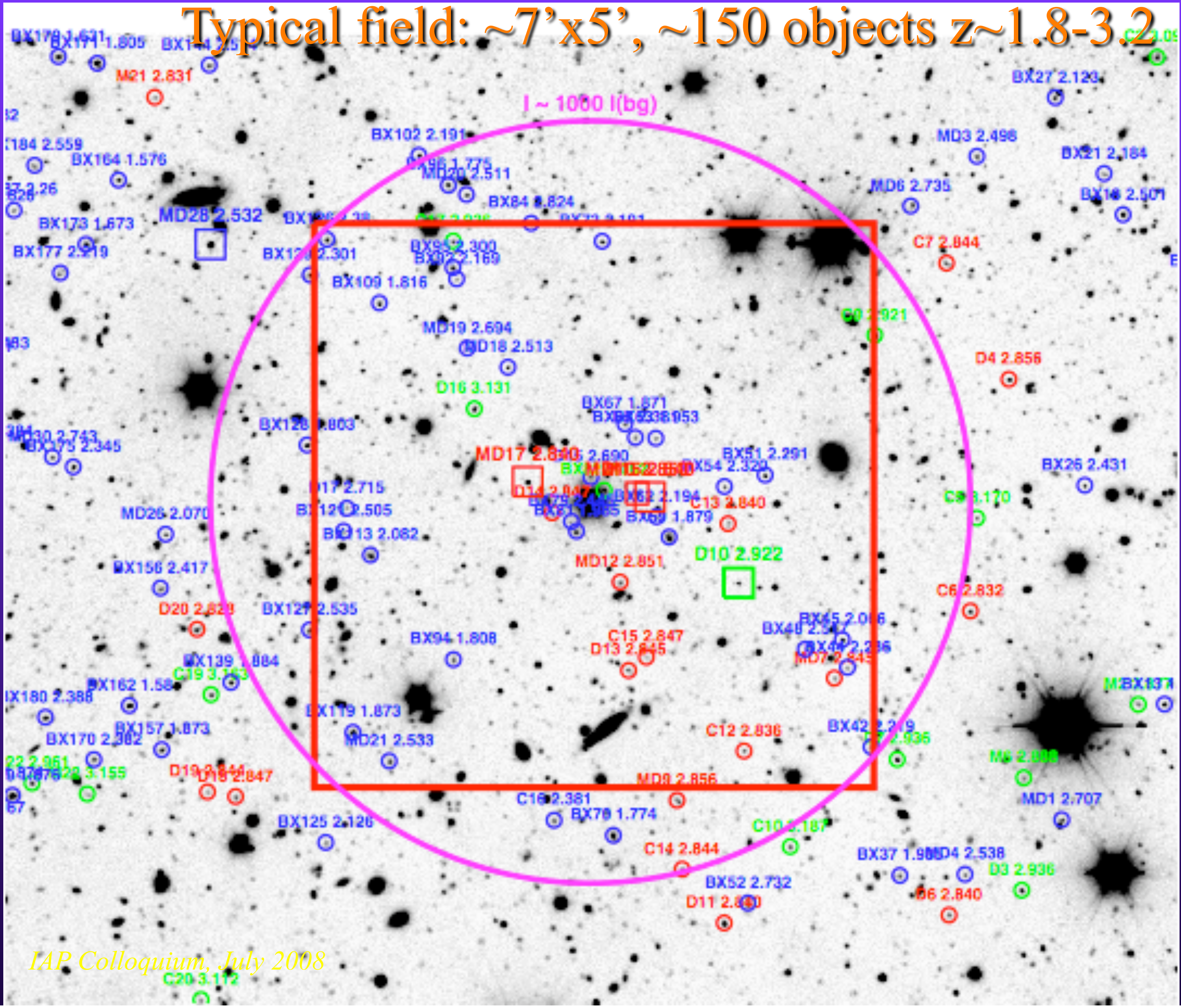


Galaxies and AGN in Bright QSO Fields: Impact on the IGM @z~2-3

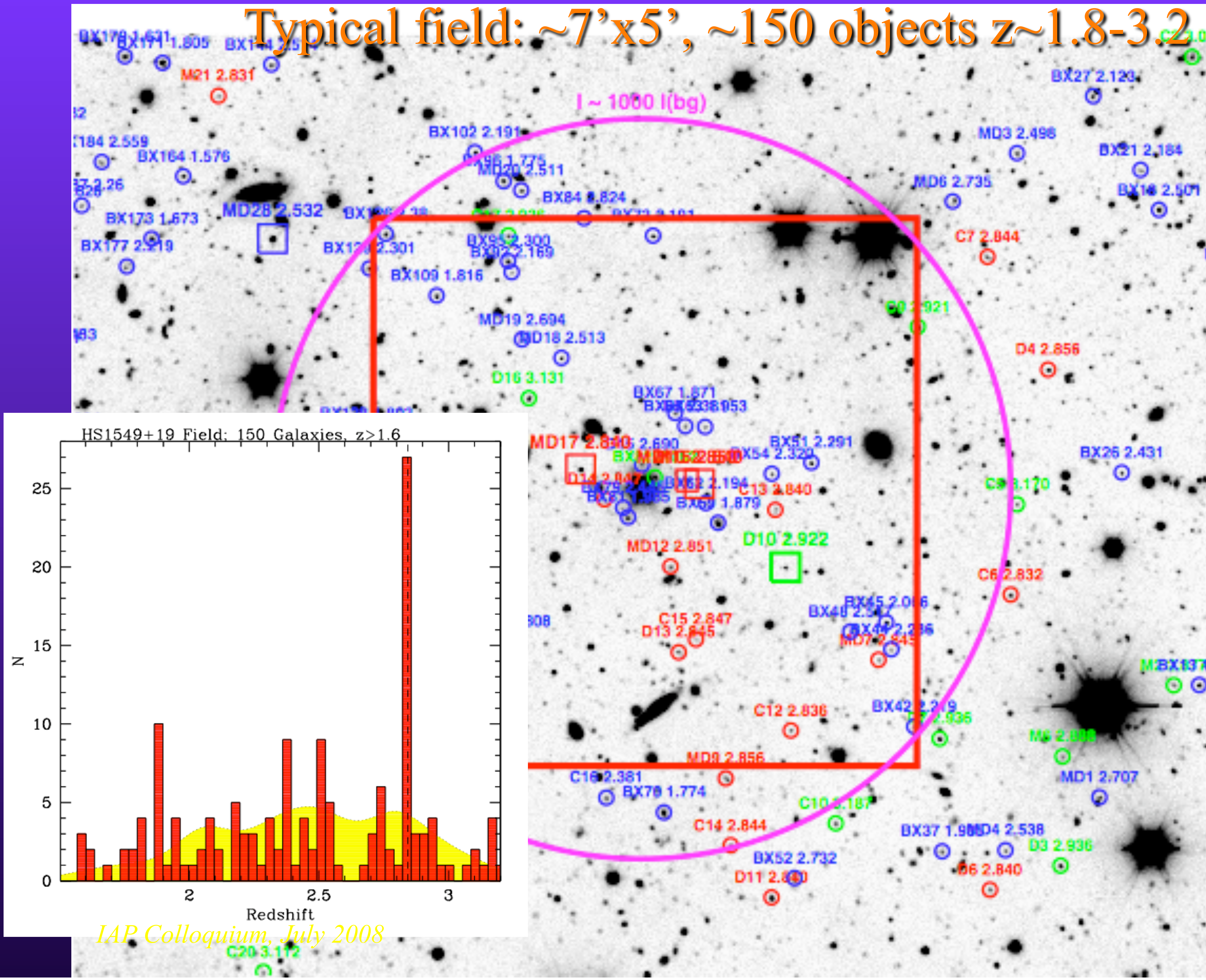
(previous work: Adelberger et al 2003,2005)

- 11 fields of brightest QSOs in the sky @ z=2.5-2.8
  - All have Keck/HIRES 3100-6000 A, S/N~50-200, R=40,000
- 1460 galaxy spectra, z=1.8-3.2, R<25.5 (Keck/LRIS-B)
  - Sampling density ~4-5 galaxies/arcmin^2
  - Allows large number of galaxy foreground/background pairs
- QSO environments
- Transverse Proximity Effect Measures
- Impact of individual galaxies on the IGM via HI, OVI, CIV, etc. transitions @very high fidelity, on a range of scales.
- Pixel Optical Depth analysis w/Joop Schaye, Olivera Rakic (Leiden)

Typical field: ~7'x5', ~150 objects z~1.8-3.2



Typical field: ~7'x5', ~150 objects z~1.8-3.2



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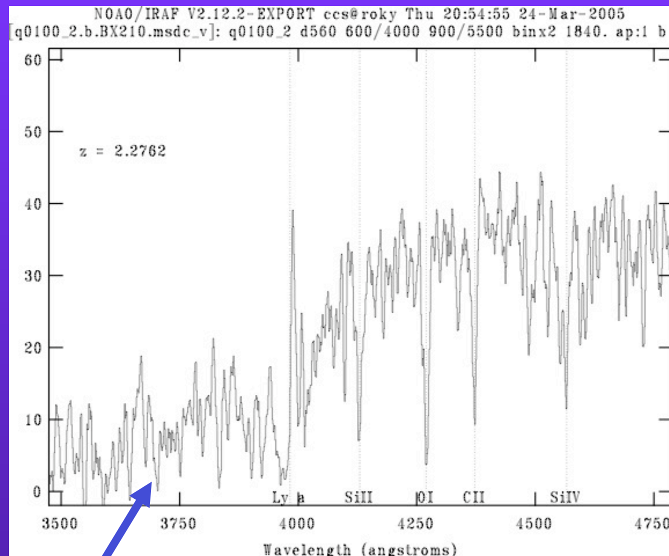
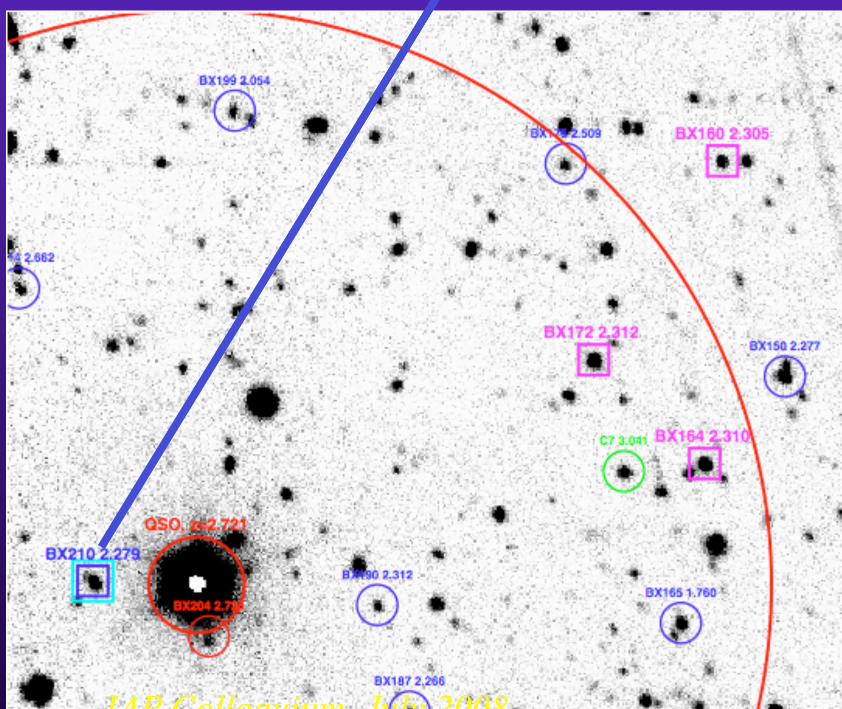
Galaxy BX210:

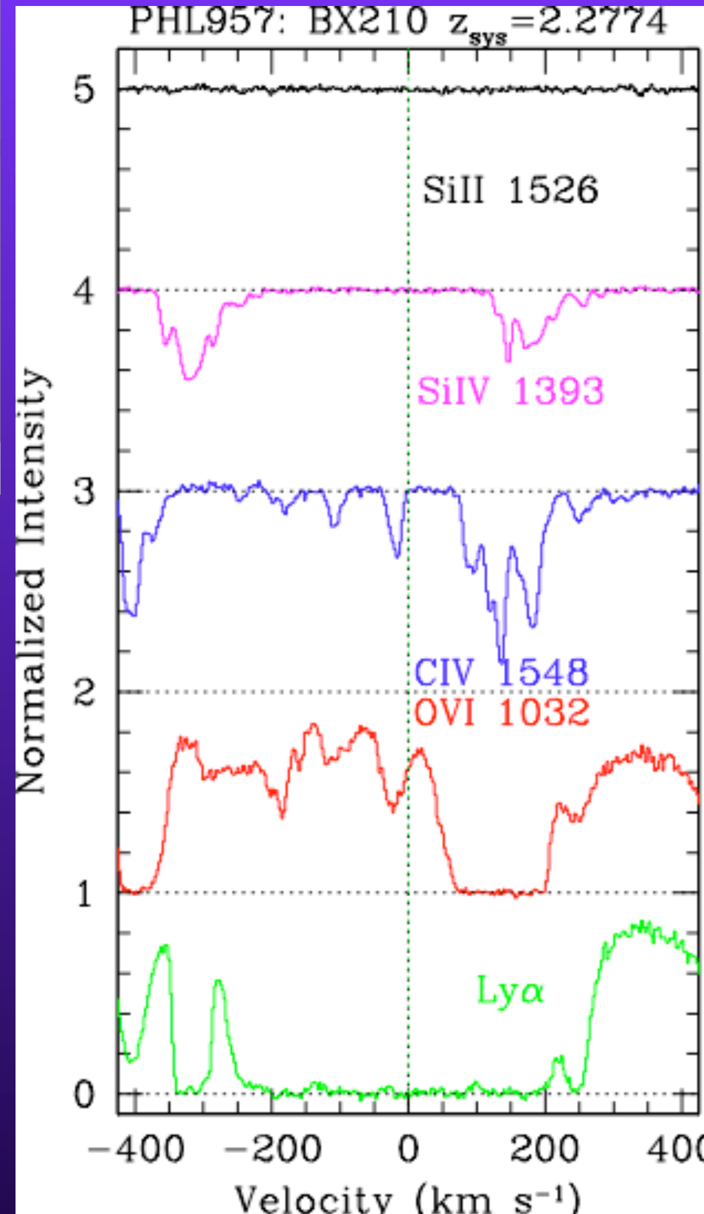
$\Delta v \sim 660$ km/sec

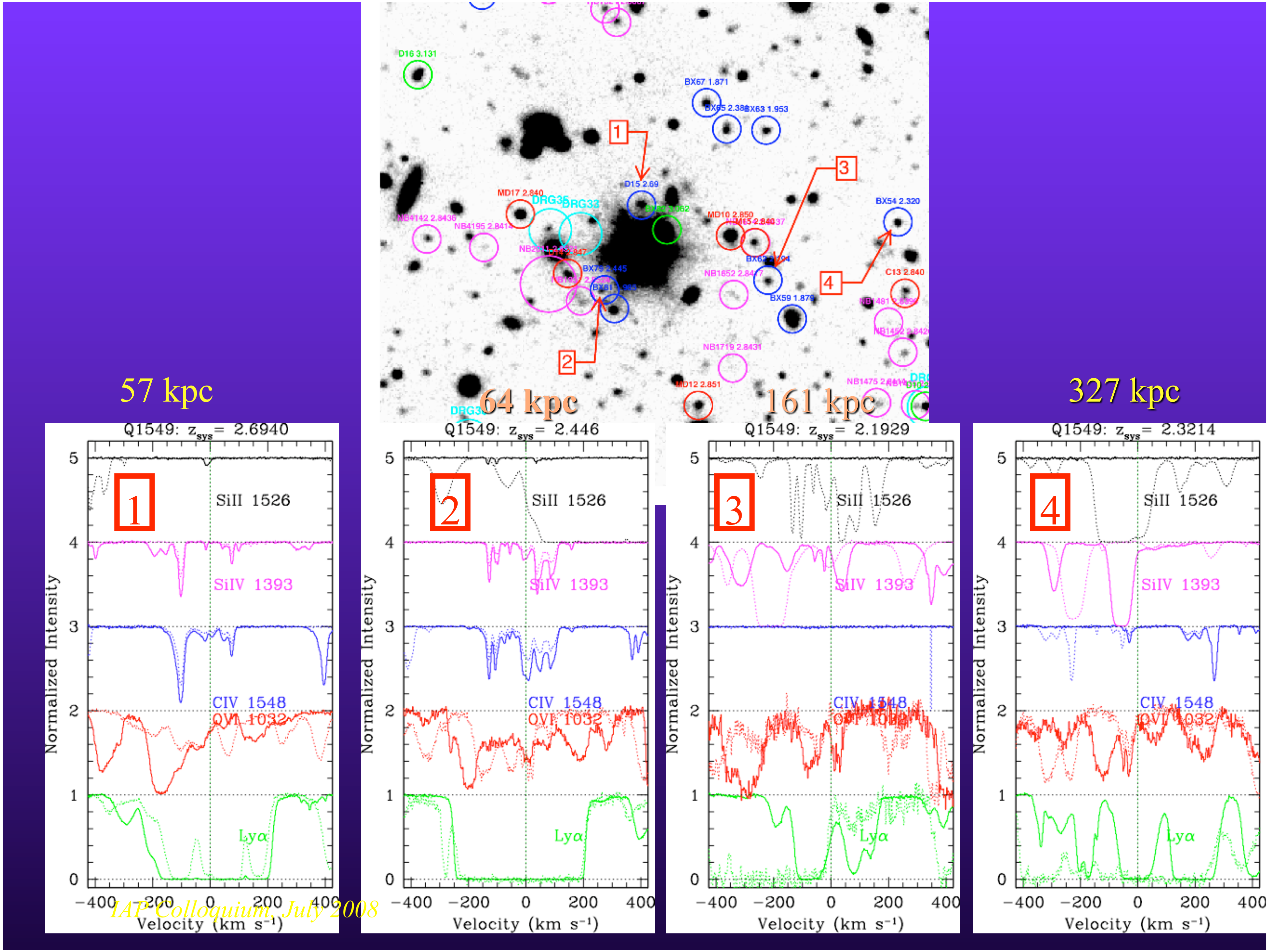
$v_{max} \sim -800$ km/sec



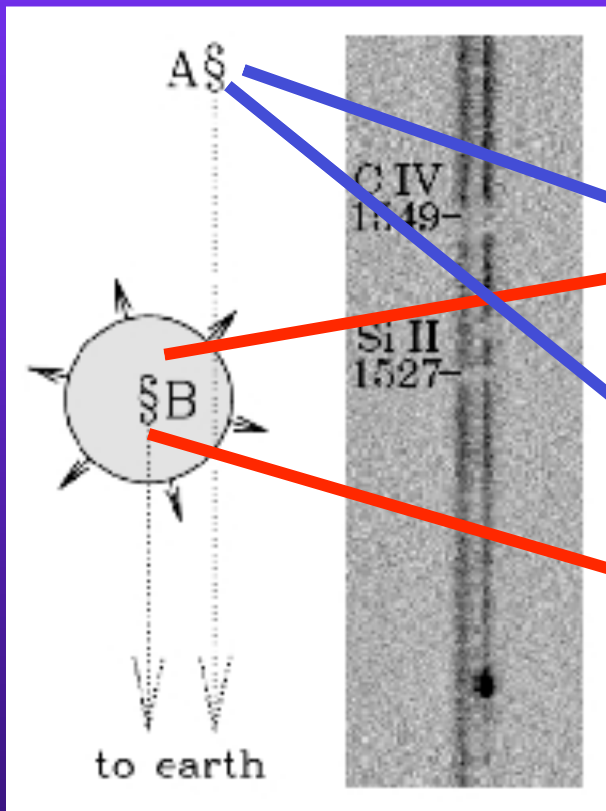


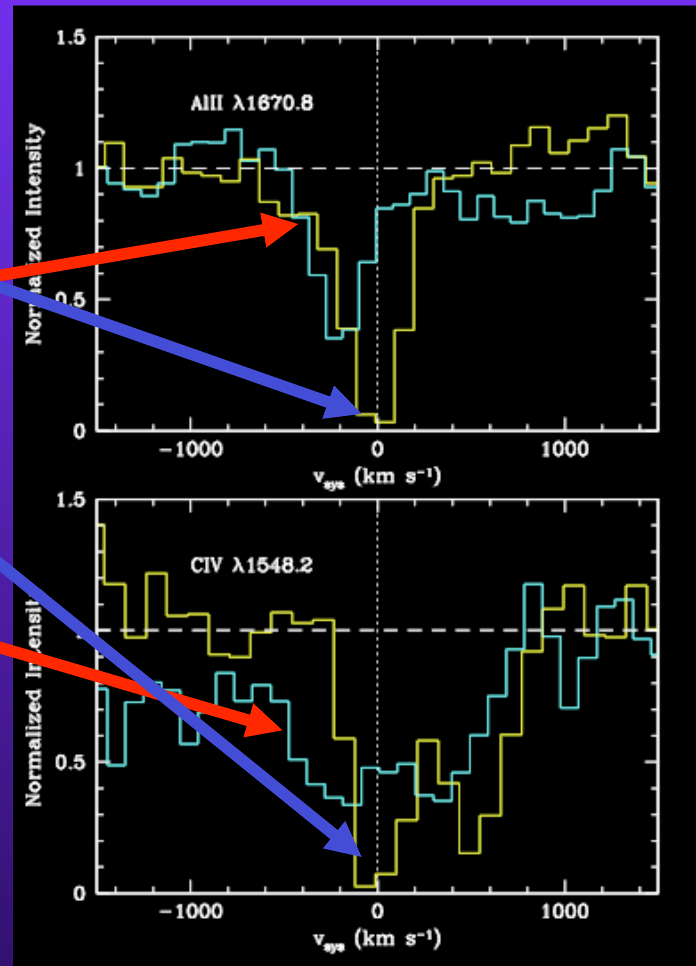
QSO sightline, 85 kpc away




57 kpc
64 kpc
161 kpc
327 kpc
1
2
3
4
Q1549: z_{sys} = 2.6940
Q1549: z_{sys} = 2.446
Q1549: z_{sys} = 2.1929
Q1549: z_{sys} = 2.3214
SiII 1526
SiIV 1393
CIV 1548
OVI 1032
Lyα
Normalized Intensity
Velocity (km s⁻¹)

Using Background Galaxies for Foreground Galaxy Superwinds



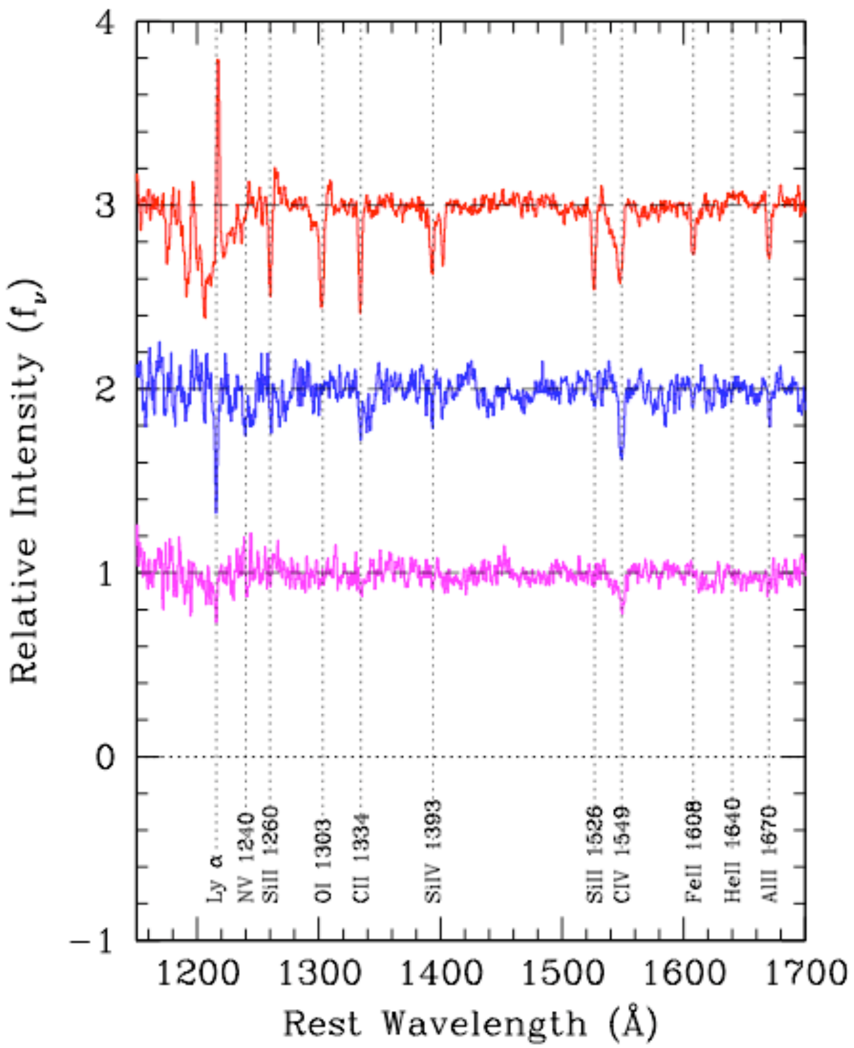


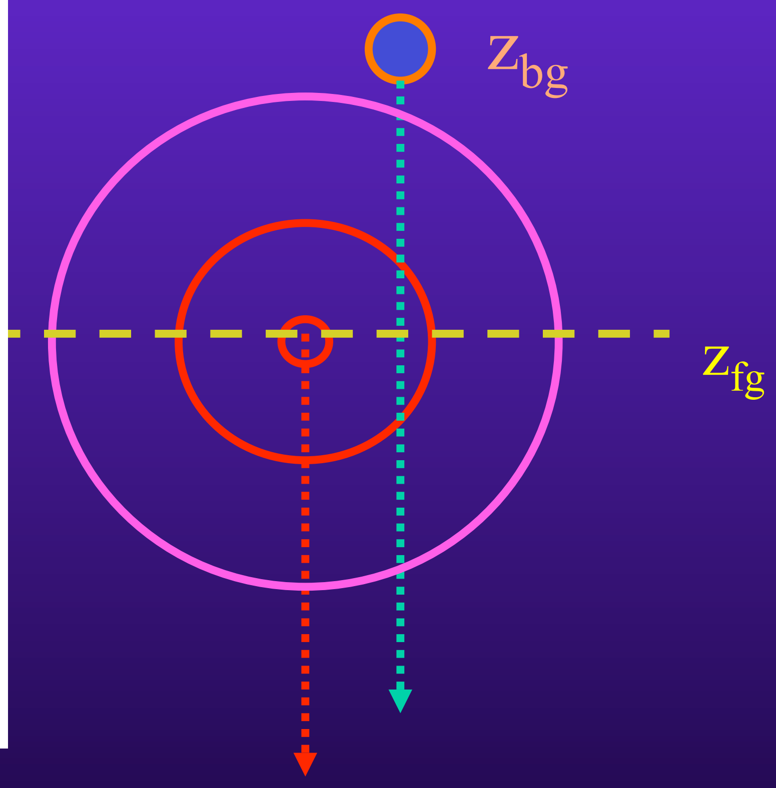
Keck/ LRIS-B spectra, R=1500, 3800-4100 A

- Higher z galaxy probes outflow of lower-z gal at ~15 kpc galactocentric distance
- Absorption @z=1.60 in spectrum of background galaxy is at rest (but with velocity width of 650 km/sec wrt foreground galaxy)

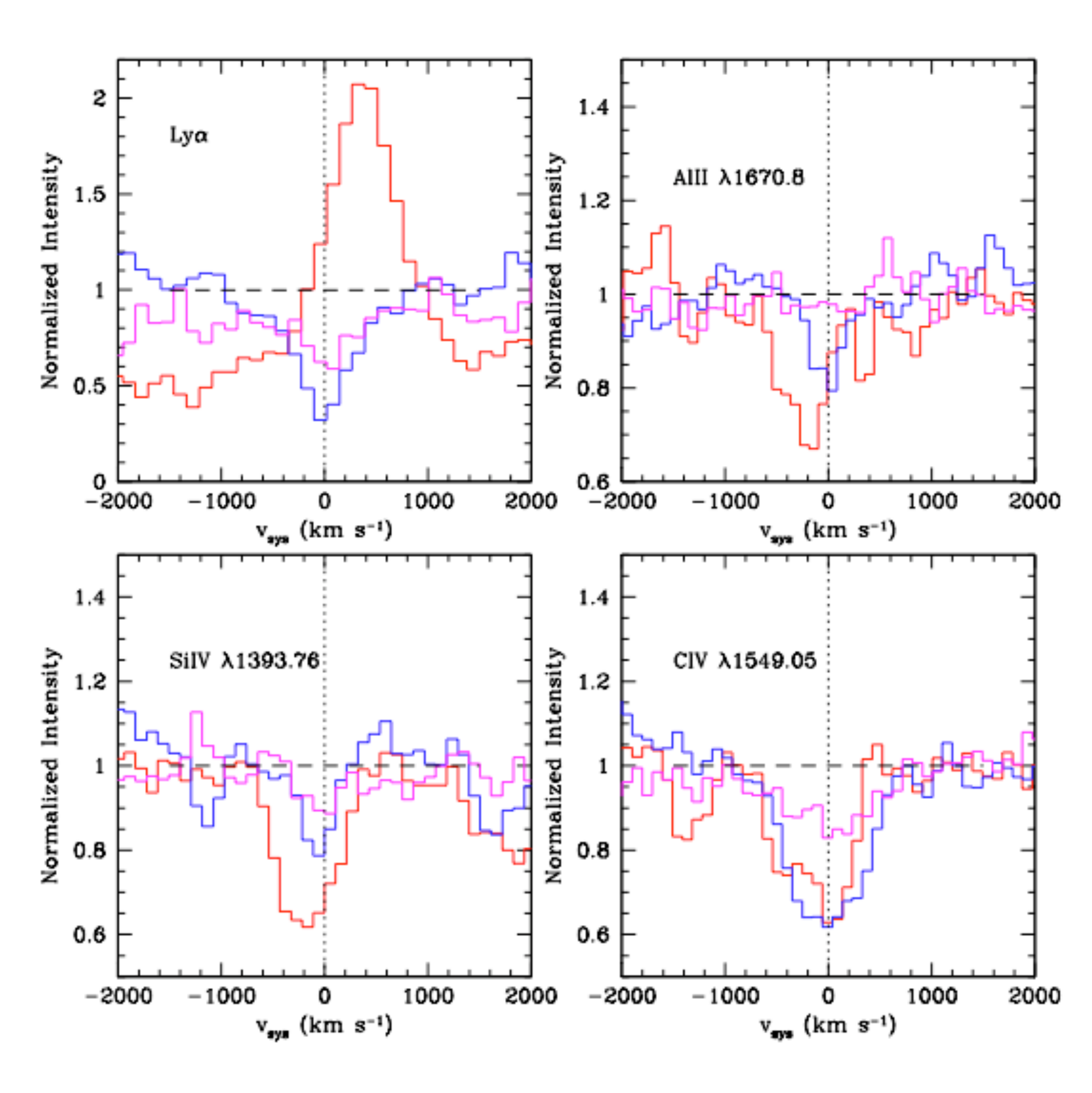
Galaxy Pair Composite Spectra

- 50 pairs 1-5” **(<d>=30 kpc)**
- 190 pairs 5-10” **(<d>=70 kpc)**





Galaxy-Galaxy Pairs: Line Strengths



Red: "Down the Barrel"

W(CII)=1.61 A

W(SiIV)=1.45 A

W(CIV)=1.61 A

1-5" (8-40 kpc)

W(Lya)=2.07 A

W(CII)=0.85 A

W(SiIV)=0.31 A

W(CIV)=1.62 A

5-10" (40-80 kpc)

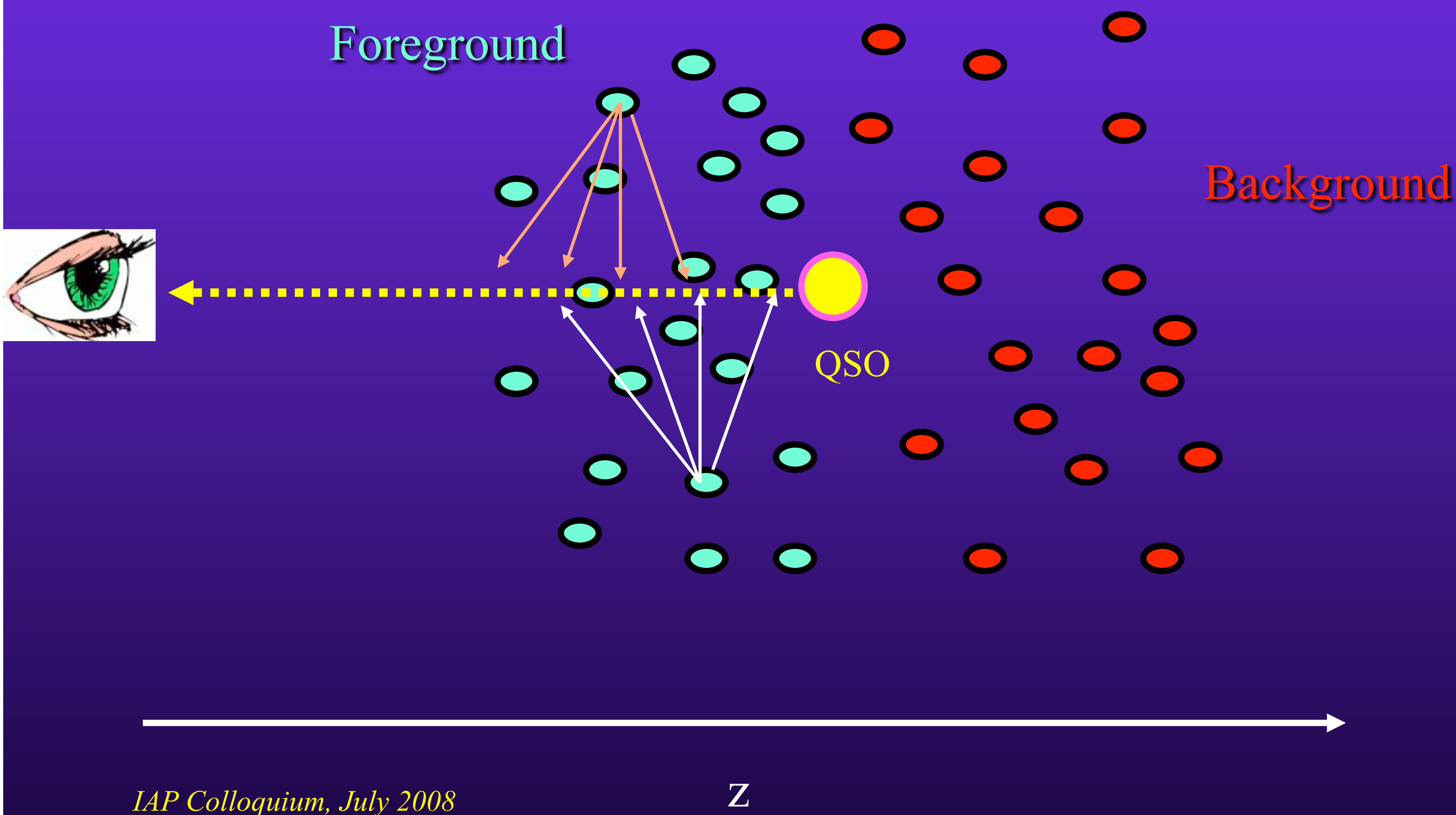
W(Lya)=1.21 A

W(CII)=0.67 A

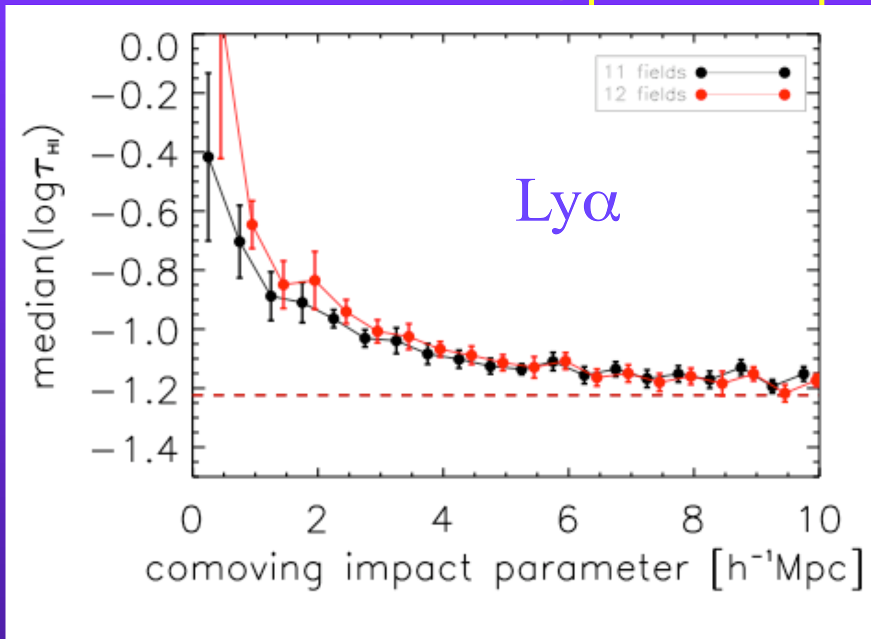
W(CIV)=0.91 A⇒

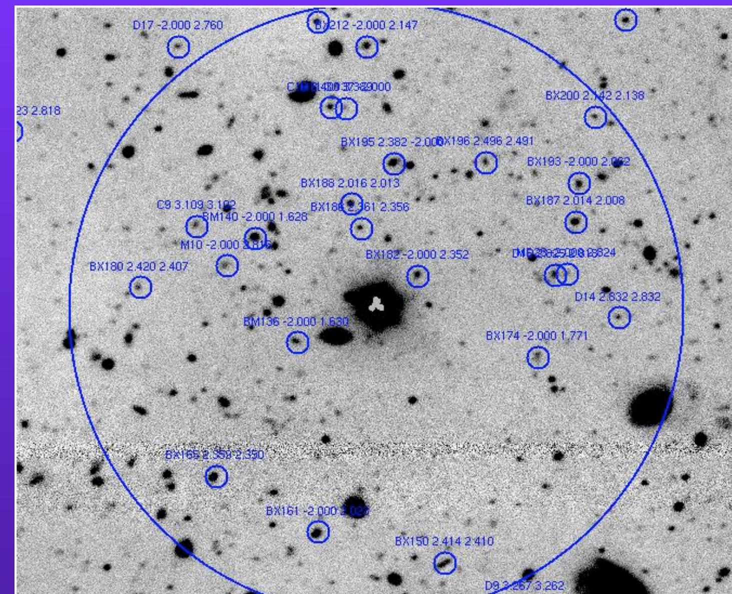
log N(CIV) ~ 14.2

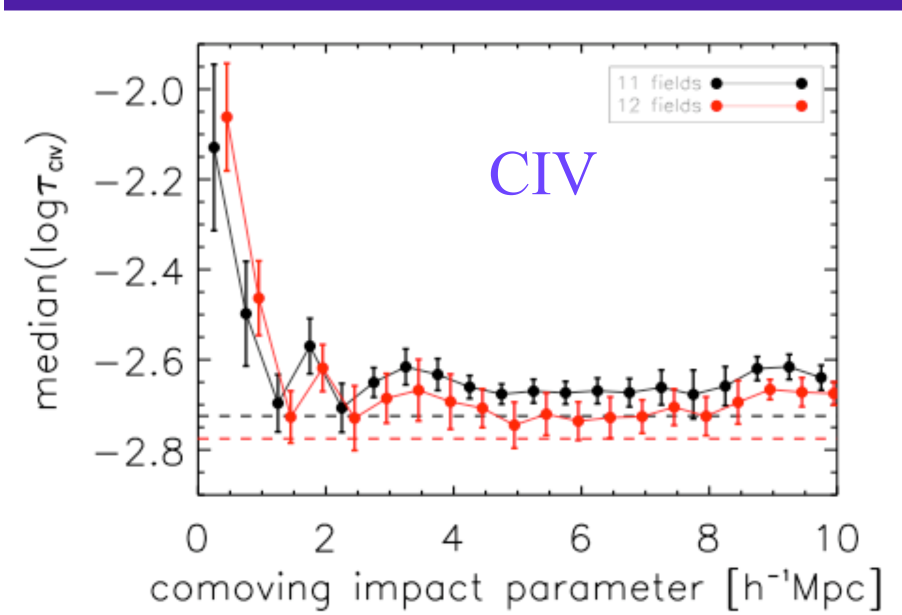
Densely Sampling the Universe @z~1.8-3.2

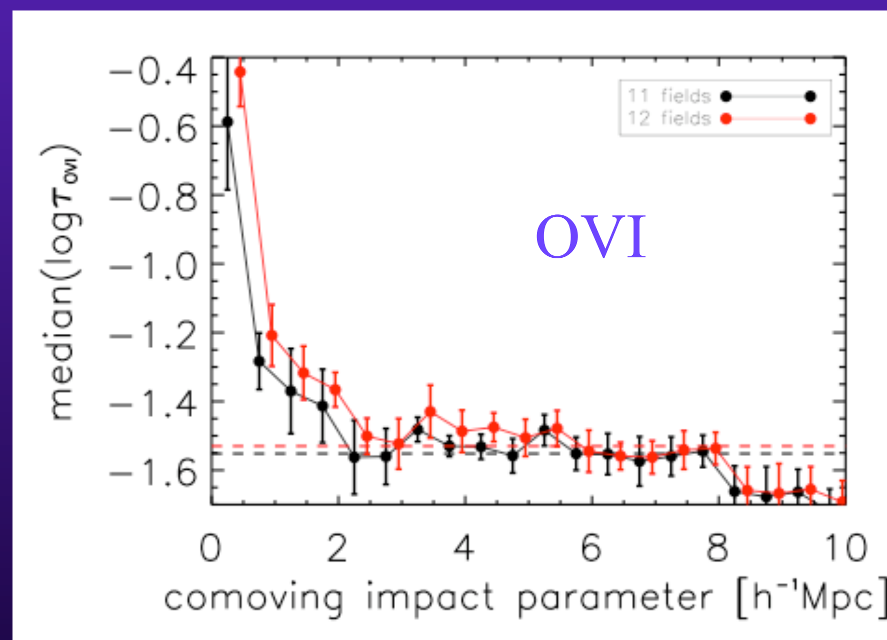


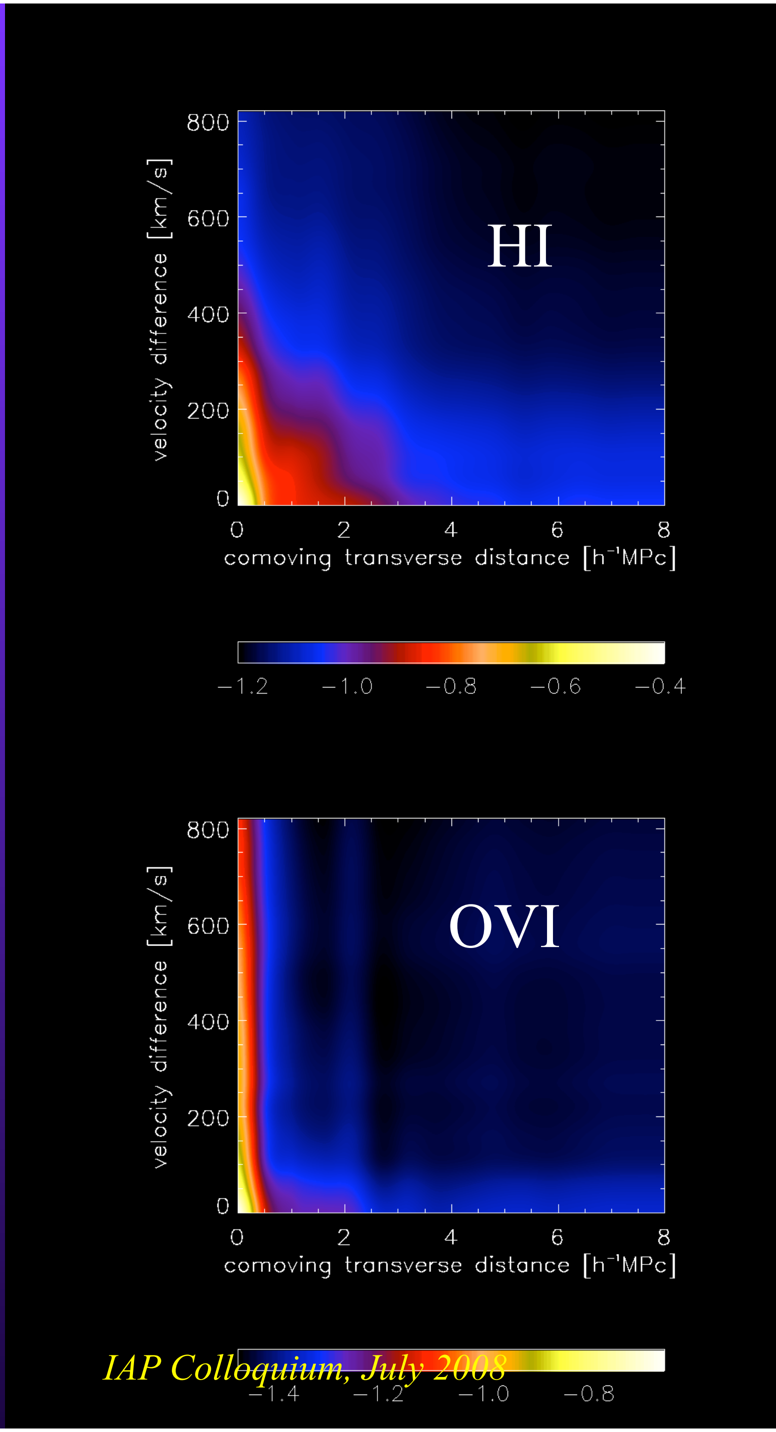
Results: Median Optical Depth vs. Distance from Galaxies

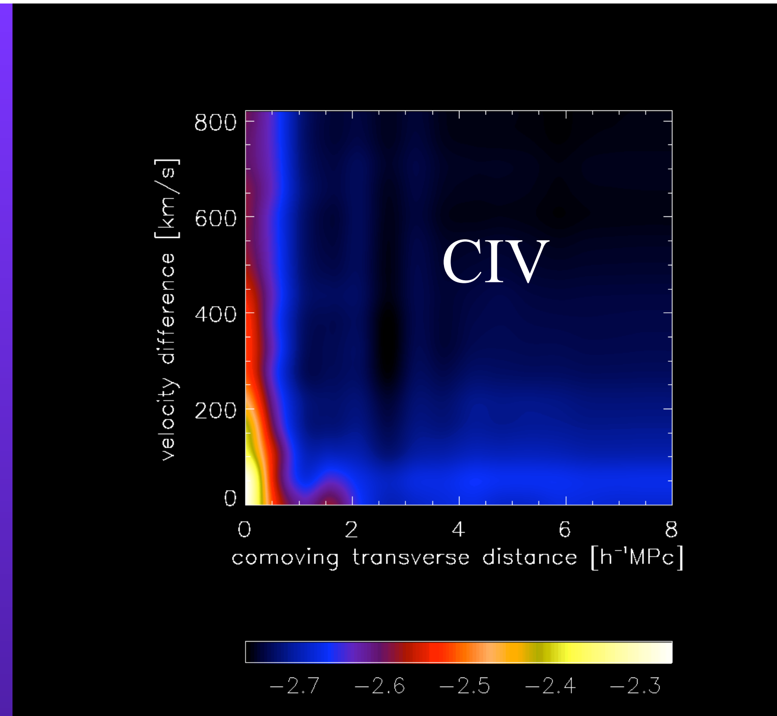




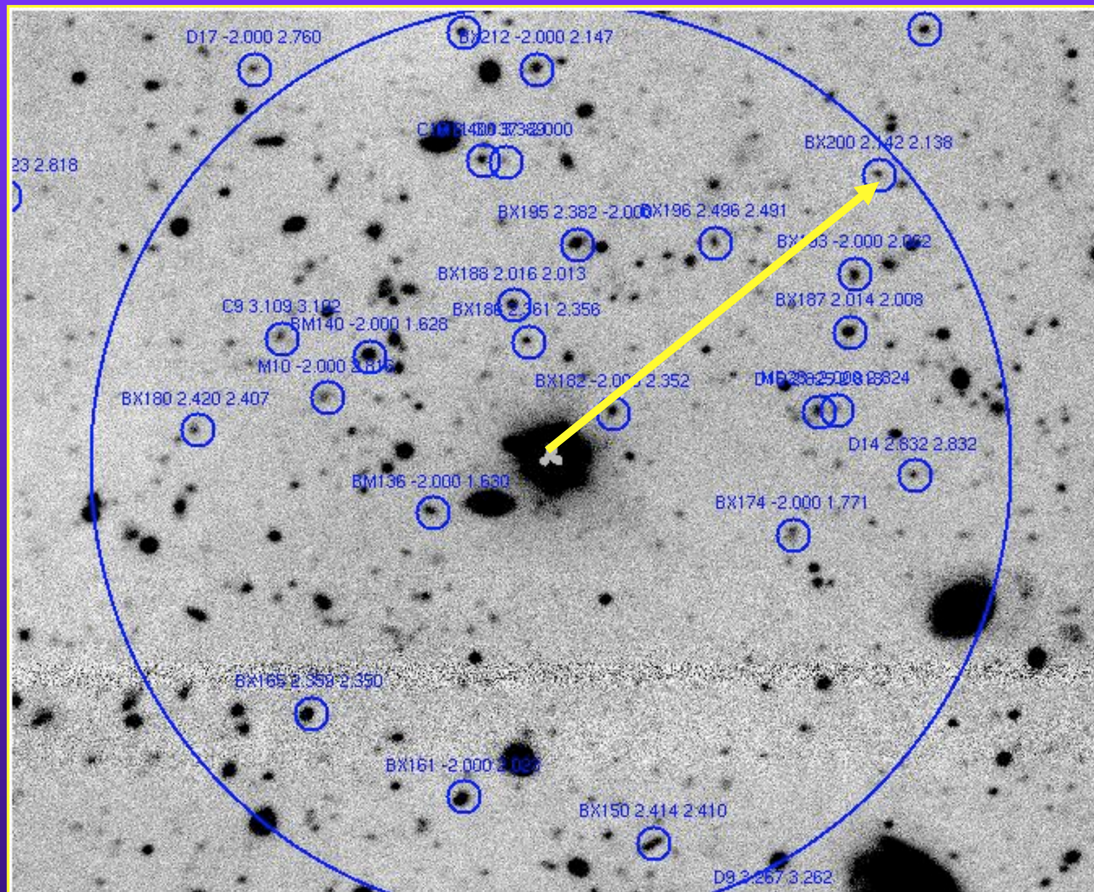








At transverse distances of <~1h^{-1} Mpc (300-400 kpc physical), CIV and especially OVI, have excess peculiar velocities of many hundred km/s



- ~50”
- ~ 400 physical kpc
- ~1.4 Mpc [co-moving]

}

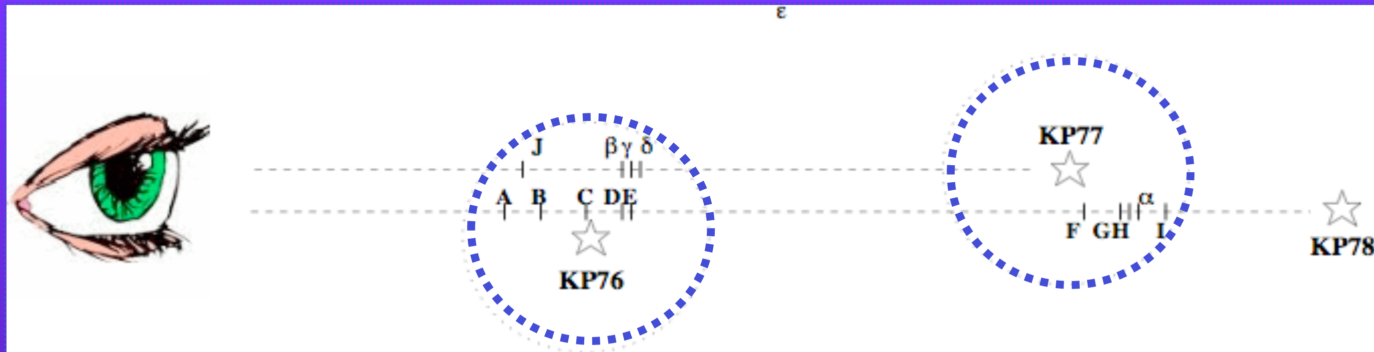
“sphere of influence” of individual galaxies on the IGM @ z~2-3

Radiative Feedback: Observable Manifestations

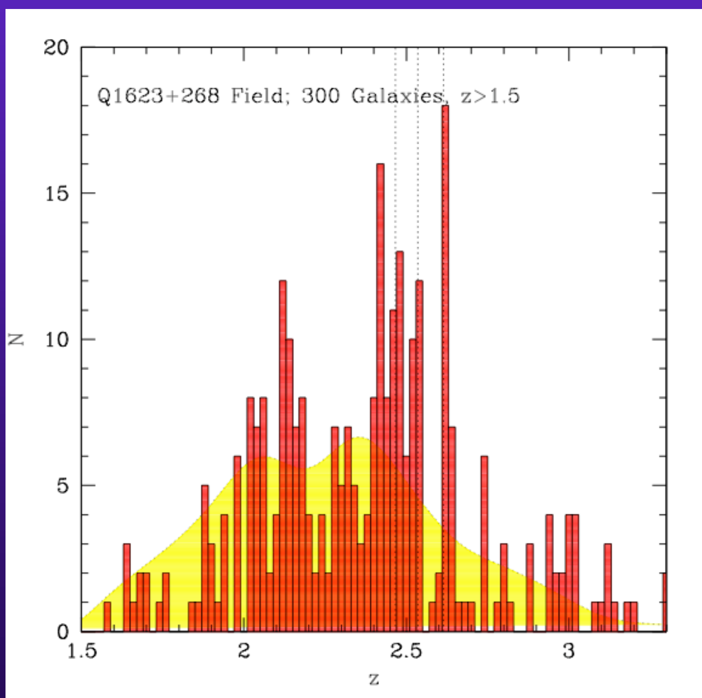
- The metagalactic ionizing background: what is the intensity, what produces it?
  - QSOs are known to contribute; galaxies strongly suspected to dominate the ionizing photon budget at $z \geq 3$
    - but, detection is difficult even at “low” redshift
    - until recently, most attempts to measure the “escape fraction” have yielded null results.
    - Recently: convincing spectroscopic (Shapley et al 2006) and NB imaging (Iwata et al 2008; Shapley et al 2008) detections at z~3. [poster, talk at this meeting]

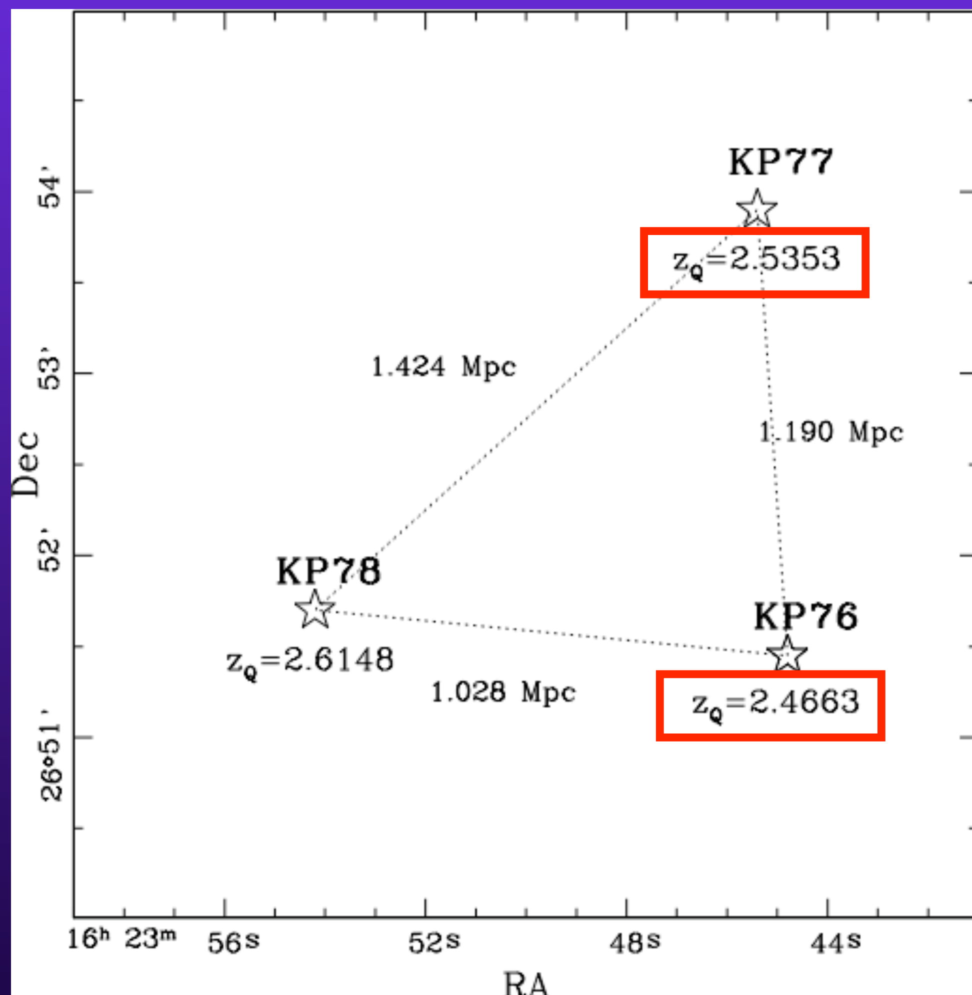
Radiative Feedback: Observable Manifestations

- (Line of Sight) Proximity Effect
  - measurements from ensembles of QSO spectra since the late 1980s; still viewed with skepticism by many due to possible systematics (new result- see Dall Aglio poster; discussion of biases in Faucher-Giguere et al 2007)
- "Transverse" Proximity Effect
  - detection of ionized regions produced by QSOs, transverse to the line of sight to a background object
  - offers, in principle, a measure of QSO radiative lifetime and isotropy of QSO radiation.
  - most searches have yielded very puzzling non-detections
    - (e.g. Hennawi et al 2006-8; Tytler et al 2008, but see Worseck et al 2006,2008; Gallerani et al 2007, Goncalves, CS,& Pettini 2008)
  - The effect can be more subtle than one might expect...
    - due to: (generally) unknown environments of QSOs, redshift uncertainties, small number statistics, insensitivity of measures.



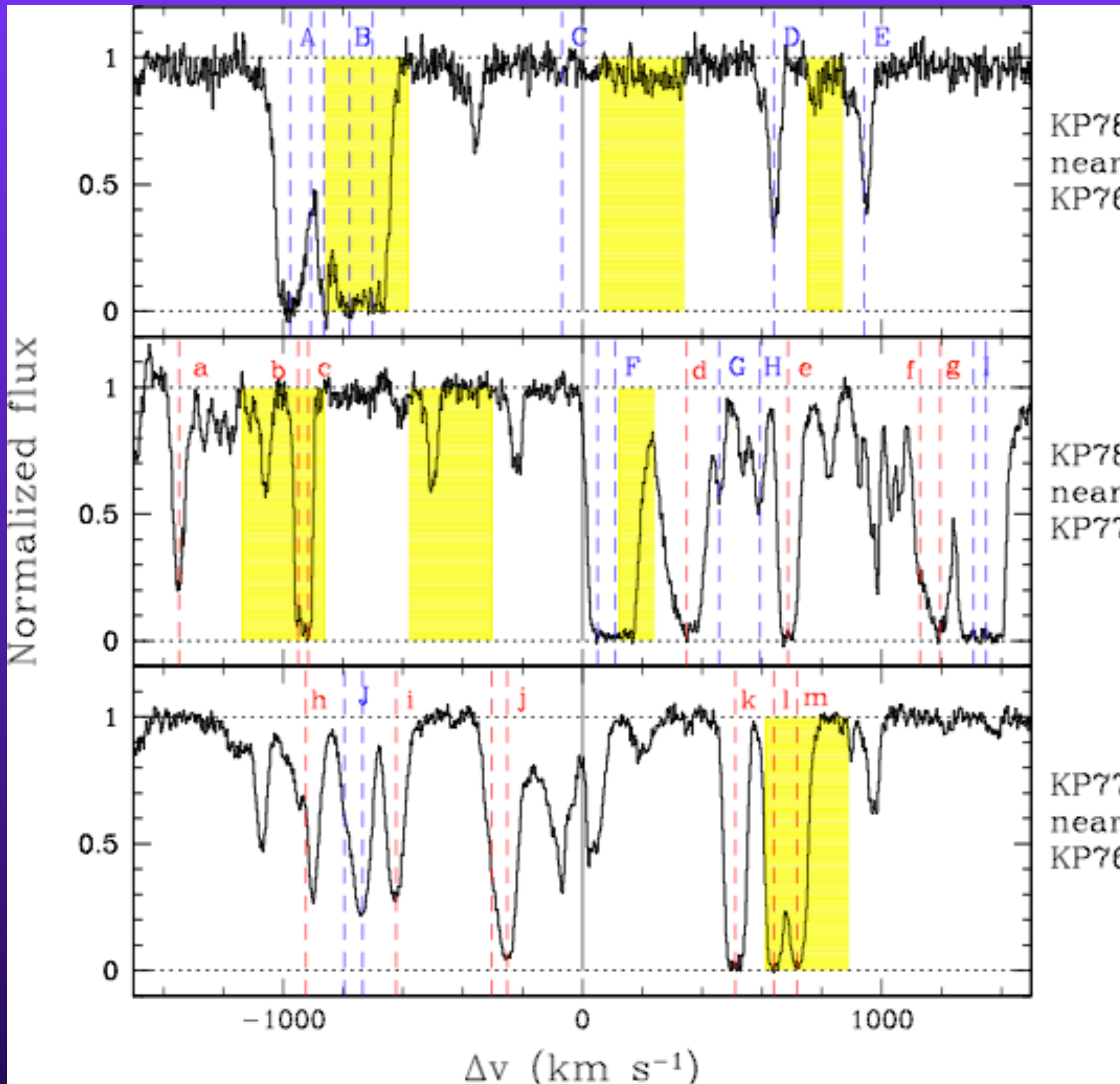
A Hard Look at the Transverse Proximity Effect





Goncalves, CS, Pettini 2008

3 “Proximity Regions” of the Lyα Forest



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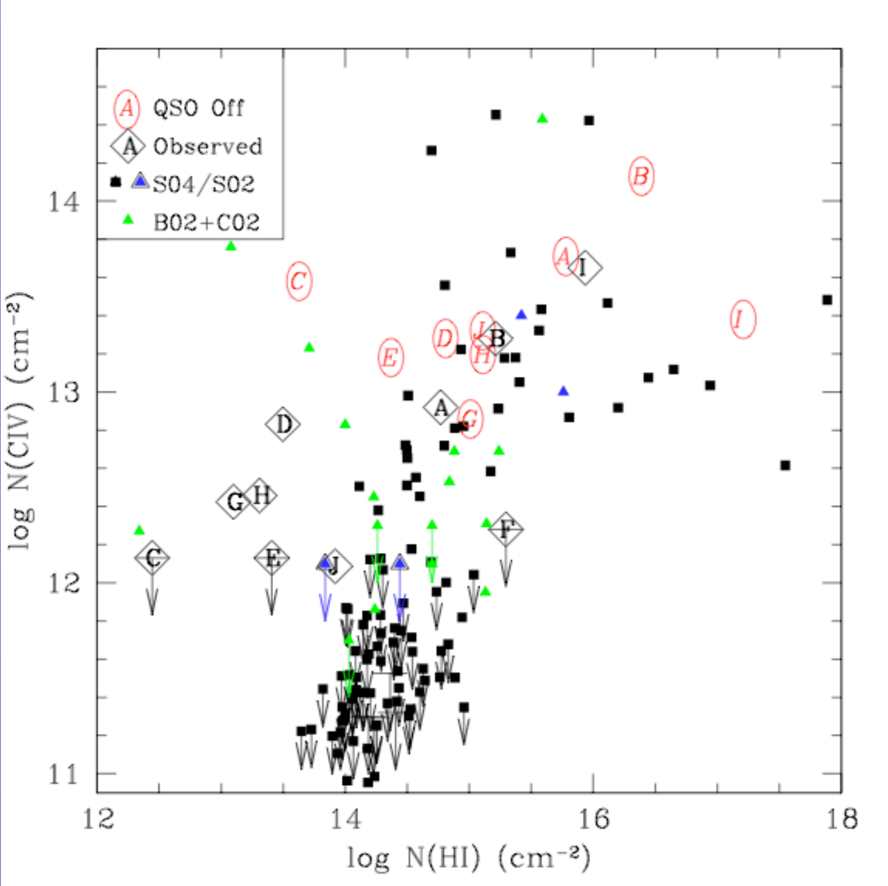
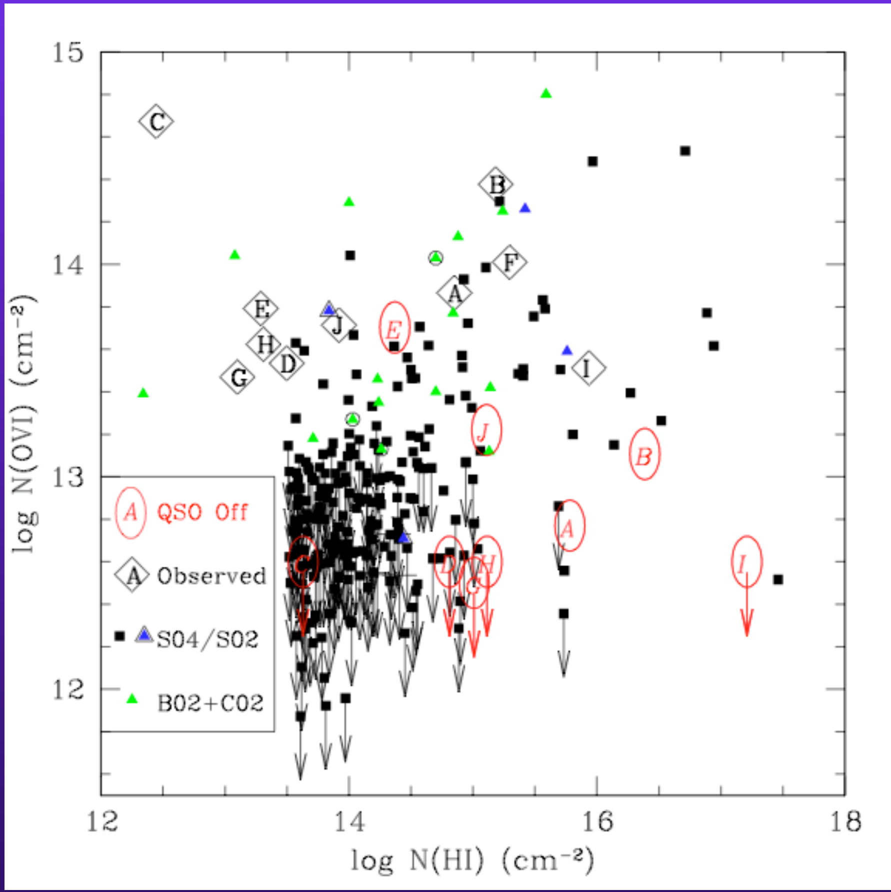
Physical State of Metal-Line Systems in Proximity Regions



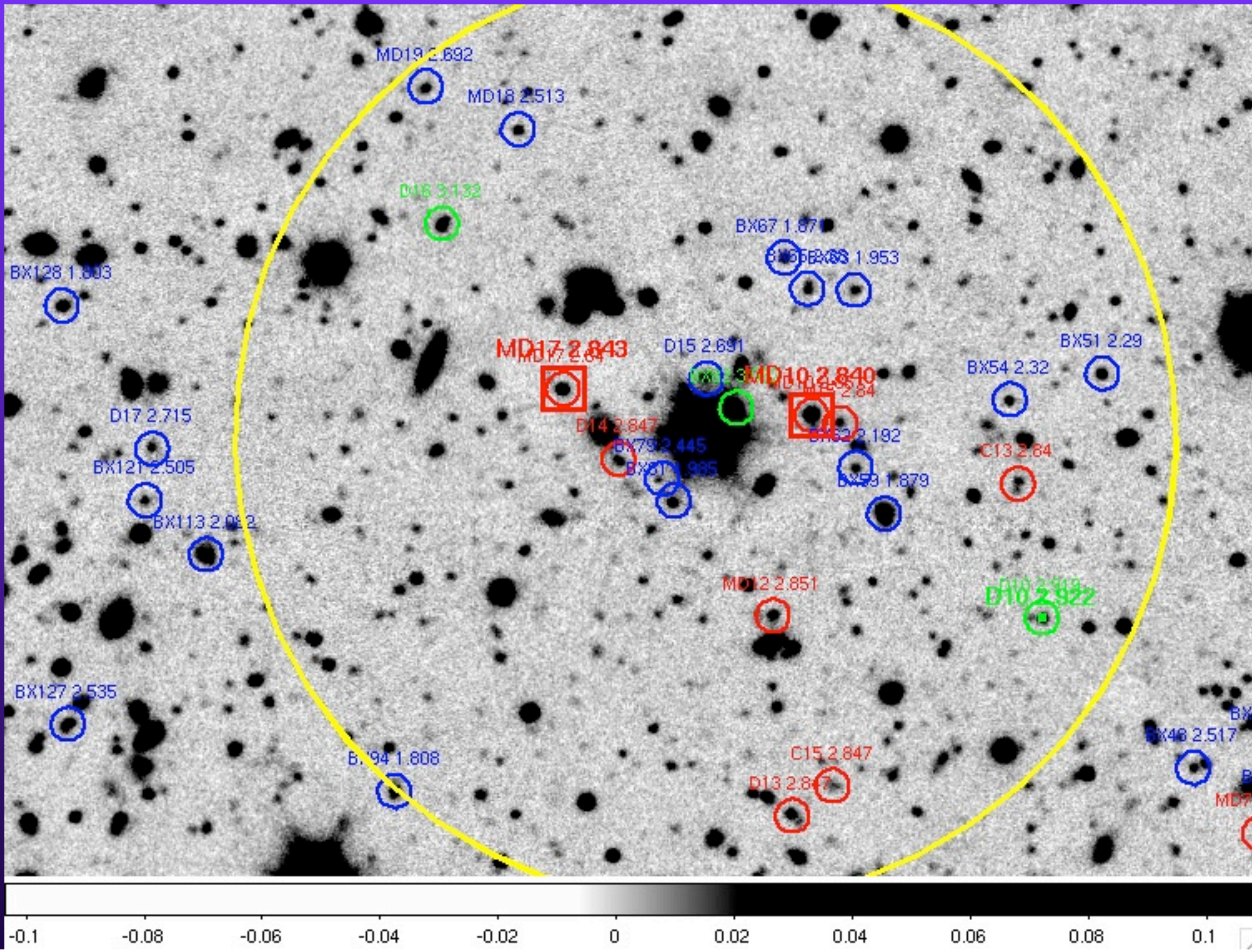


Goncalves, CS, Pettini 2008

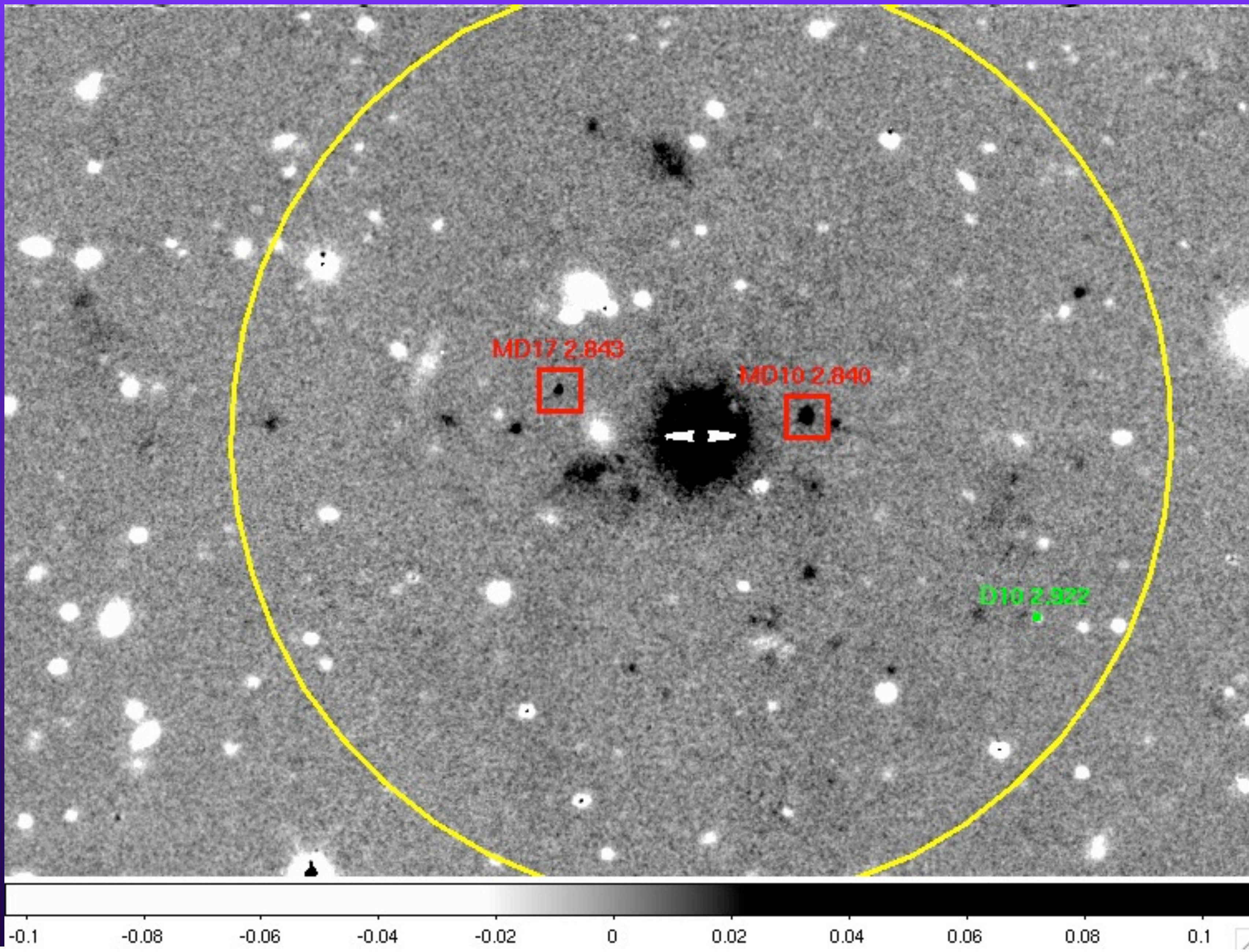
Radiative Feedback: Observable Manifestations

- Fluorescence: mapping neutral HI near strong UV sources
  - proposed originally as method to measure the metagalactic radiation field intensity (Hogan &Weymann (1986), Gould and Weinberg (1996) ; measurements attempted by many groups since. [too difficult?]
  - the inverse of the TPE- most sensitive to denser gas that remains neutral within the "HII region"
  - Possibility to "image the IGM" with a high-pass filter
  - Extremely promising as a means of examining processes akin to re-ionization: the response of the IGM material to an expanding HII region [e.g., Cantalupo et al 2005, 2007; Adelberger et al 2006]
    - Has it been observed? Somewhat controversial...

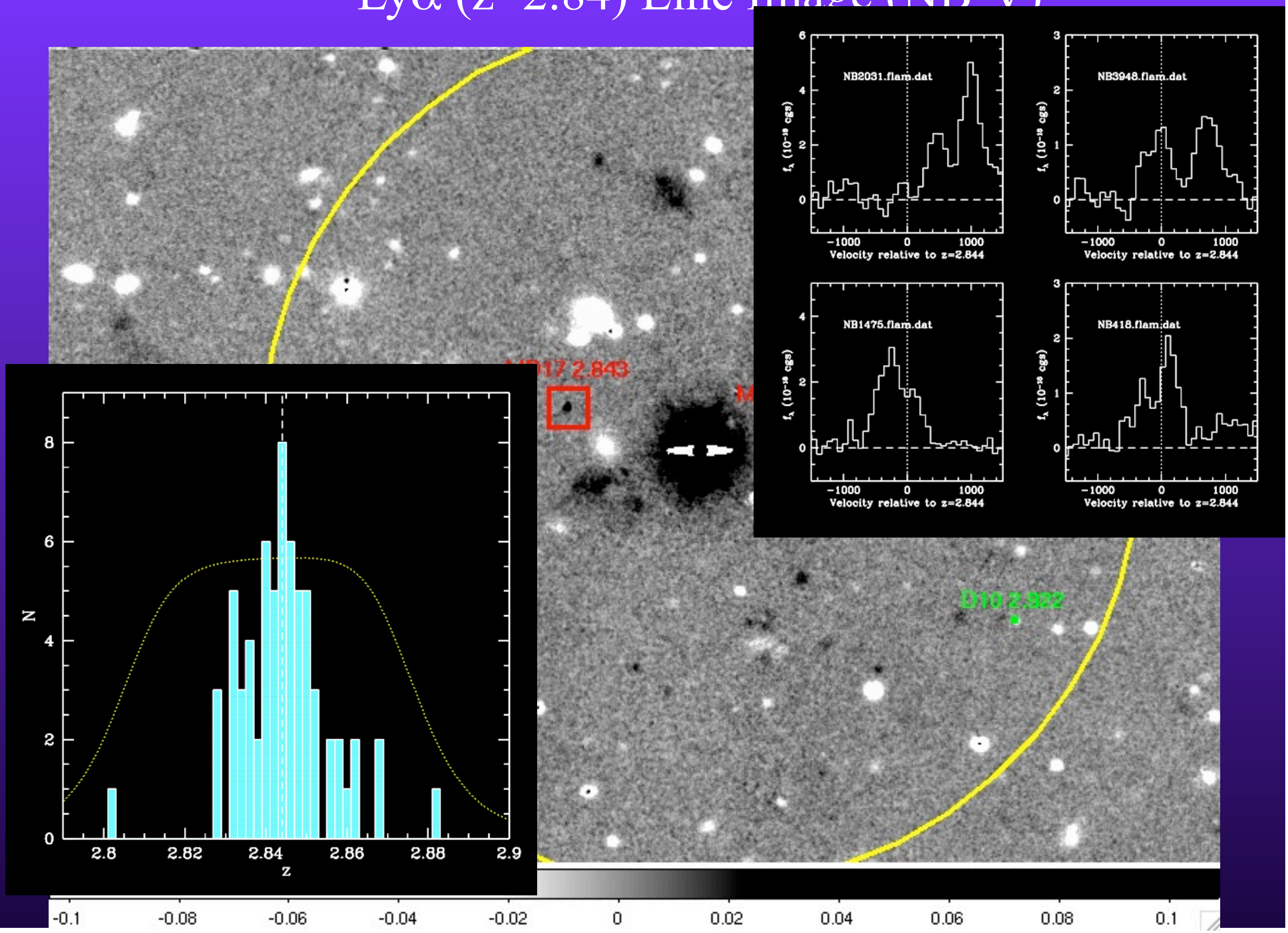
Lyα Fluorescence: tracing HI in Emission

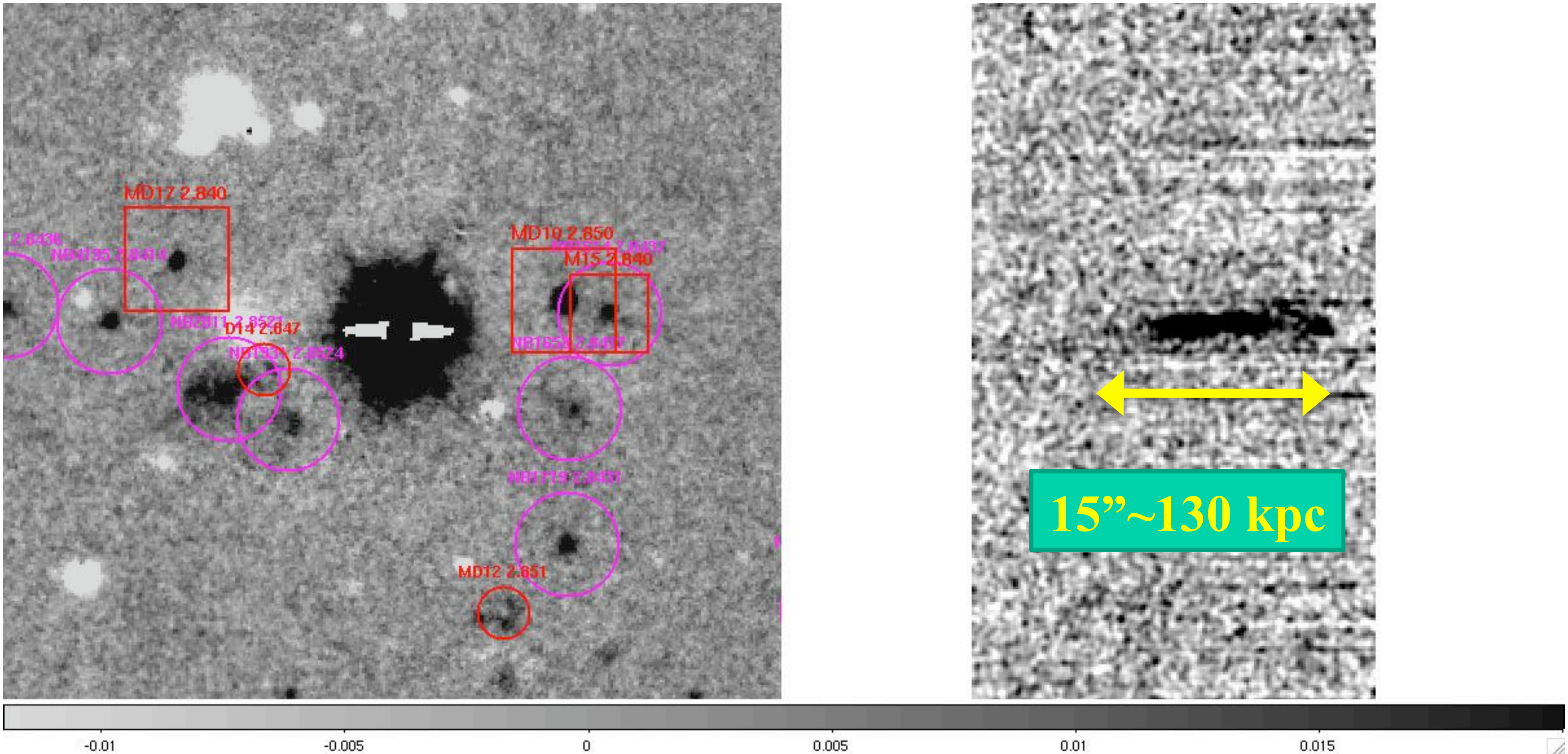


Lyα (z=2.84) Line Image (NB-V)

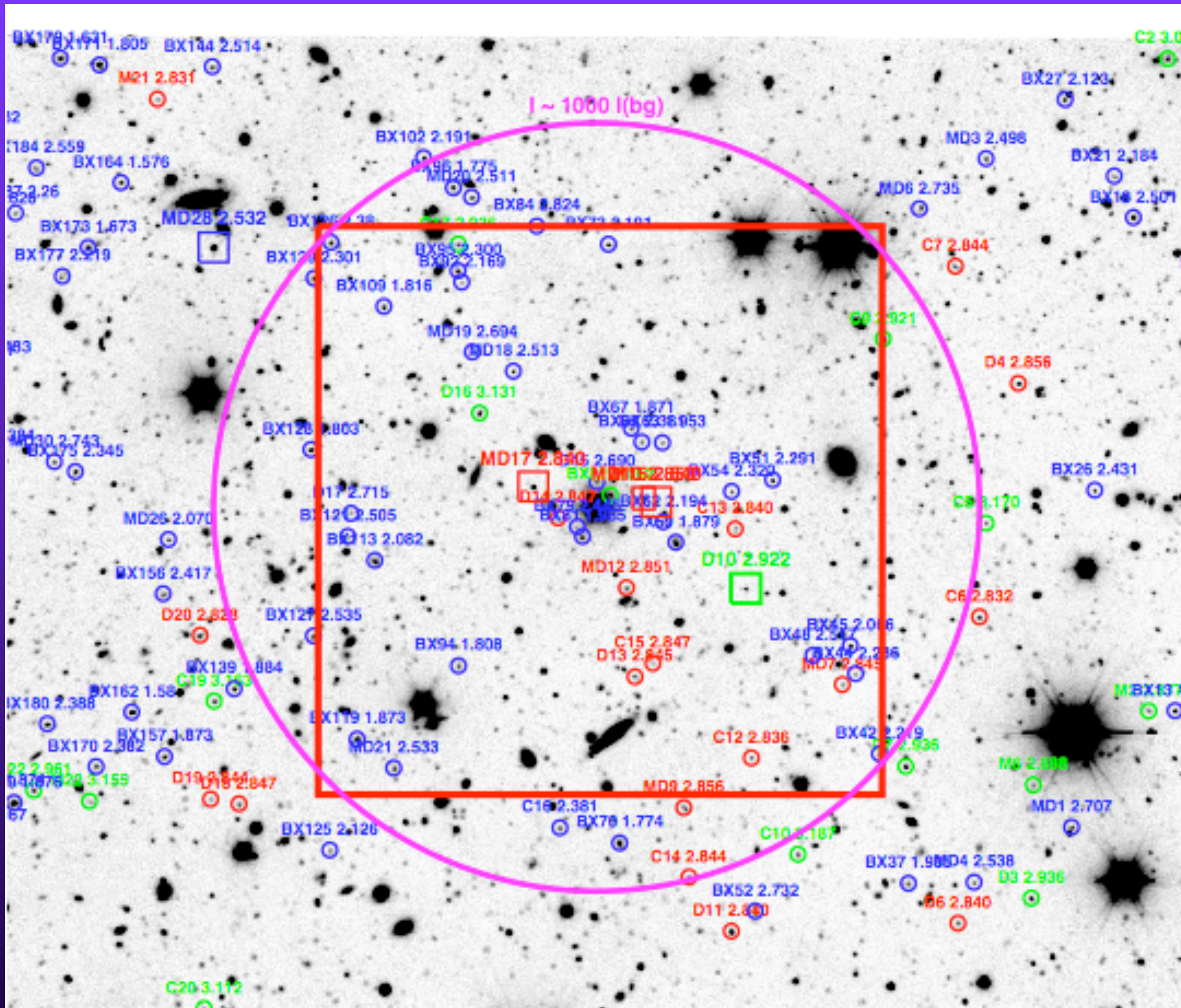


Lyα (z=2.84) Line Image (NB-V)





- •286 Ly α emitters in 5’ x 7’ field (64 have spectra, no interlopers)
- •Several giant Ly α “blobs” in same field (example above)
- •Maps structure of high-density HI, independent of star formation
- •How many are due to fluorescence??


I ~ 1000 I(bg)
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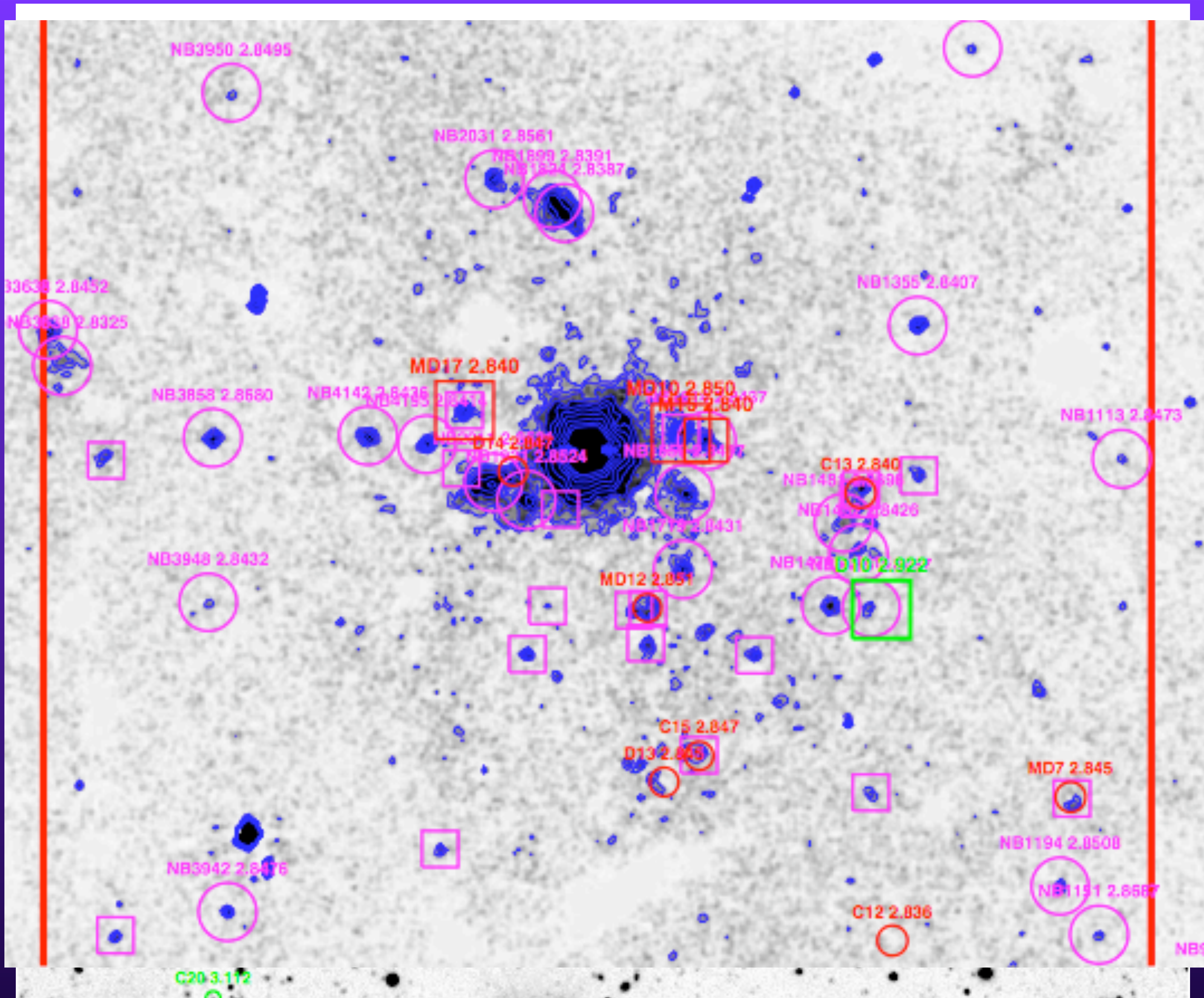
M21 2.831
BX27 2.123
MD3 2.496
BX21 2.184
BX102 2.191
BX164 1.576
MD20 2.511
MD6 2.735
MD28 2.532
BX173 1.673
BX177 2.219
C7 2.844
BX109 1.816
MD19 2.694
MD18 2.513
D4 2.856
D16 3.131
BX67 1.871
MD30 2.743
MD17 2.840
BX51 2.291
BX54 2.320
BX26 2.431
MD26 2.070
C13 2.840
D10 2.922
MD12 2.851
BX156 2.417
C6 2.832
BX94 1.808
C15 2.847
BX157 1.873
MD21 2.533
C12 2.836
MD9 2.856
BX76 1.774
MD1 2.707
BX125 2.126
C14 2.844
MD4 2.538
D3 2.936
BX52 2.732
D6 2.840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MD10 2.850
NB3858 2.8680
NB1113 2.8473
C13 2.840
NB3948 2.8432
MD12 2.851
D10 2.922
C15 2.847
MD7 2.845
NB1194 2.8508
C12 2.836
NB9

Summary

- Even fairly massive galaxies are blowing out significant gas and metals, affecting IGM regions within several hundred physical kpc at z~2-3 (~1-2 co-moving Mpc).
  - Undoubtedly this is happening at z>>3- just more difficult to observe!
  - Gas flows are easy to observe via absorption line tracers: the observable signatures are generally in one direction: OUT.
  - Possible indications of infalling gas, particularly for high mass galaxies ($M_{bar} > 5 \times 10^{10}\ M_{\odot}$)
  - Lyα emission strength and apparent redshift is strongly affected by presence of gas near $v_{sys}=0$, which is often *absent* in lower-mass objects.
- AGN feedback: is it important for moving gas/metals around, or just producing ionizing photons that illuminate the IGM?

- *One needs to observe gas, and not just galaxies, to understand the high redshift universe.*