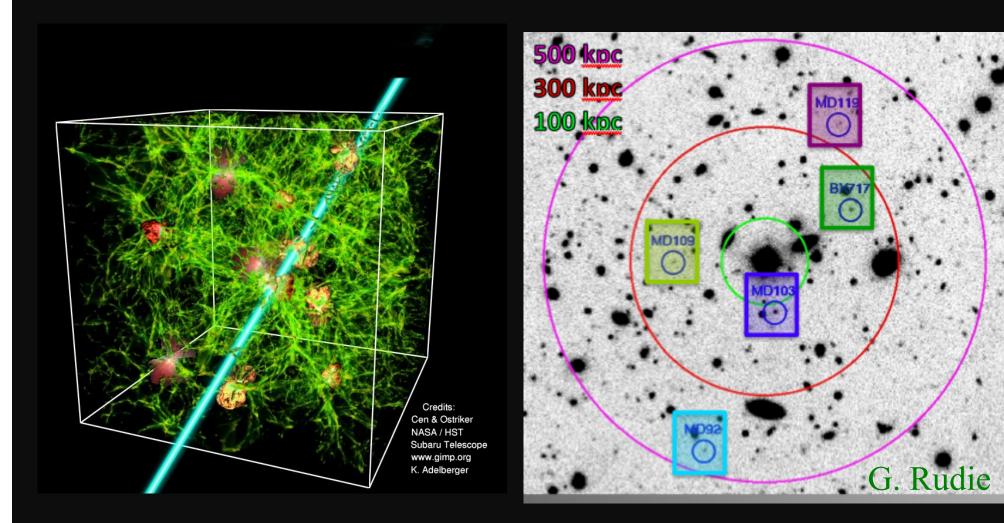
Gas-Phase Outflows and Accretion at the Peak of the Galaxy Formation Era (z~2-3)

C. Steidel, Caltech



Exchange of Baryons Between Galaxies and the IGM: **Battle Between Two Fierce Competitors**

Get down & dirty in the

Accretion:

- Fundament paradigm (
- Galaxy gro what about
- HVCs in th
- Efficient fu formation 1
- "Cold flow
 - present i and quite
 - yet, no "cosmic

floor ake both the nd of the LF tion (only s) nore or their

formation

observed ission and

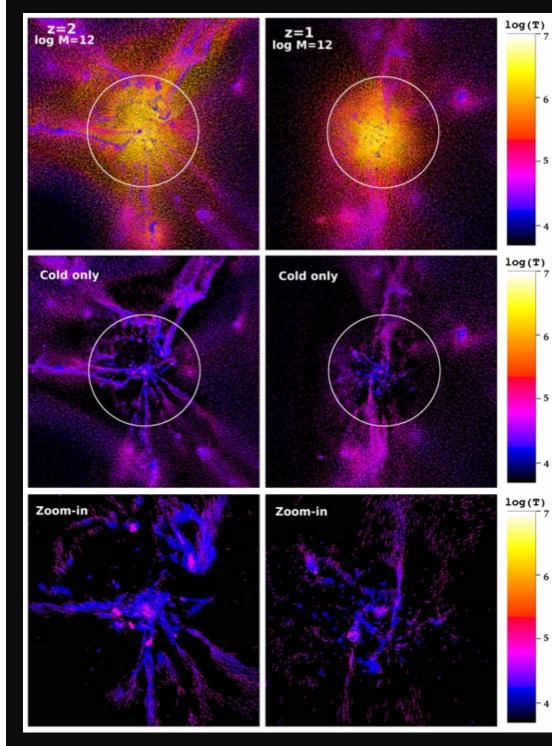
- Nature is not inconsistent with "cold streams" (they are shy creatures, wary of telescopes)

absorption reatures

Chemical enrichment of the IGM

Battlefield: the "Circum-Galactic Medium"

- Gas flows (Galaxies ←→IGM) in high redshift galaxies are crucial to allowing for, and limiting, the very high star formation rates (and accompanying metal production) during the peak epoch of galaxy formation.
- Observations of both galaxies and the IGM in the same volumes allows deeper understanding of how baryonic processes work
- Cannot understand galaxy formation without a good handle on the IGM



•Far-UV transitions (both emission and absorption) of HI and abundant metallic species are sensitive to column densities as low as $N\sim10^{12-13}$ cm⁻² and as high as $N>10^{22}$

•Trace essentially all gas at temperatures $T\sim 10^{4-6}$ K, inside or outside of galaxies

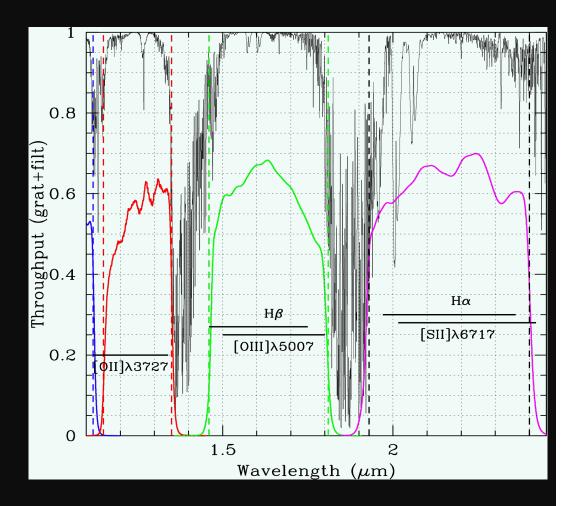
•especially effective for photoionized gas $(T\sim10^4)$ and for gas cooling from high temperature (e.g. OVI)

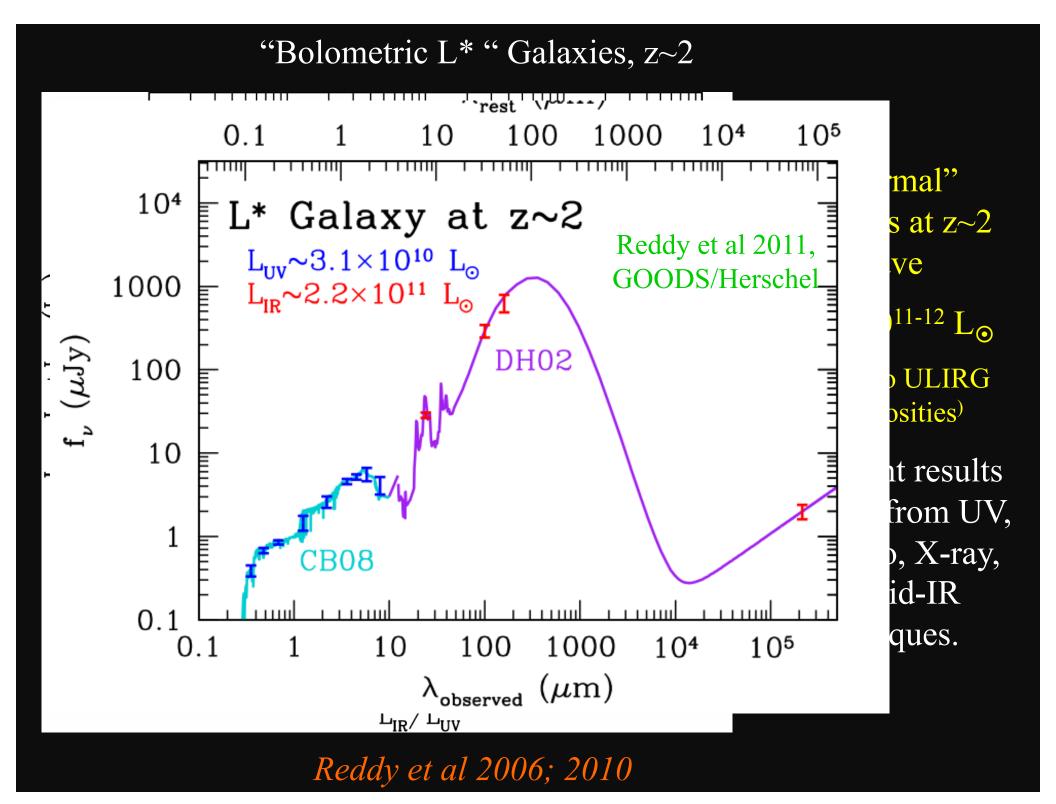
•Define CGM as region within <u>~300 kpc</u> (physical), or ~1 Mpc (co-moving) at <u>z~2-3</u>



Why z~2-3 is especially 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 current 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!





WFC3 F160W images of 300+ spectroscopically confirmed z~2-3 galaxies; (3" boxes)

Q2206-BM54	Q1549-BX113	Q1009-BX177	Q2206-BX92	Q0100-BX212	Q1217-BX146	Q2343-BX480	Q1700-BX632	Q1623-BX511	Q2343-BX587	Q1623-MD93	Q0100-BX209
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Q1623-BX412	Q1009-BX218	Q2343-BX435	Q1623-BX472	Q2343-BX551	Q1623-BX431	Q0449-BX89	Q0100-BX187	Q1009-BX146	Q1623-BX528	Q0100-BX210	Q1623-BX520
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Q1217-MD15	Q0142-BX200	Q1009-BX171	Q1623-BX338	Q1009-BX155	Q1623-BX484	Q1549-BX51	Q1623-BX506	Q0100-MD32	Q1700-MD109	Q1549-BX95	Q2343-BM168
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Q1623-BX447	Q1623-BX502	Q2343-BX389	Q2343-BX530	Q1623-BX536	Q2343-BX660	Q2343-BX418	Q0449-BX73	Q0100-BX190	Q1700-MD103	Q0142-BX212	Q1217-BX57
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Q2343-BX391	Q2343-BX429	Q2343-MD62	Q0449-MD11	Q2343-BX442	Q2206-BX88	Q1549-BX54	Q0449-BX115	Q0449-BX110	Q2343-BX537	Q0449-BX94	Q1700-BX772
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Q1623-BX432	Q1623-BX453	Q2343-D25	Q2343-BX484	Q0449-BX117	Q1700-BX691	Q0142-BX165	Q0142-BX182	Q0142-BX186	Q2206-BX64	Q2343-BX601	Q1623-BX341
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Law+ 2011

An " L_{bol} *" star forming galaxy at z~2-3:

- Lives in a dark matter halo of average mass <M_h>~10¹² M_☉ (from clustering; e.g.*CS*+1998; *Baugh*+1998; *Governato*+1998 *Adelberger* +2005; *Conroy* +2008; *Trainor* +2011)
- Space density: $\varphi * = 2.75 \pm 0.54 \times 10^{-3} \text{ Mpc}^{-3}$, $\alpha = -1.73 \pm 0.07$ (CS+1999, Adelberger+2000, Reddy & CS 2009)
- Has $L_{bol} \sim 10^{11} 10^{12} L_{\odot}$, r~1-2 kpc
 - i.e., LIRG-ULIRG; SFR~10-100 M_{\odot}/yr (=BzK, BX, LBG)

- most are compact and have high SF surface density

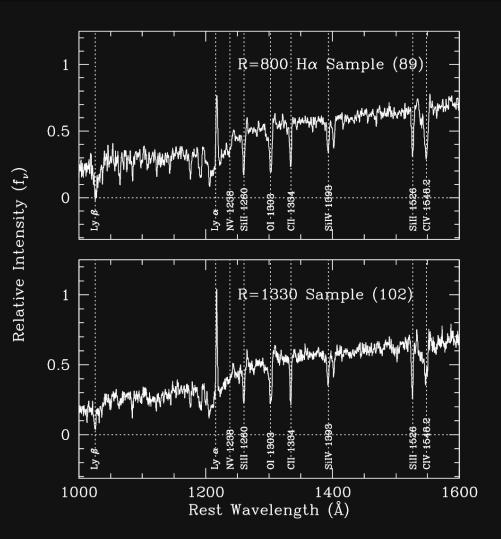
- Is ~half stars and ~half gas (by mass) in inner few kpc, a few times 10¹⁰ M_☉ of each. (e.g., Erb+06, Tacconi+10)
- Has ISM metallicity ~0.5 solar (range ~0.1-1.0) and exhibits a stellar mass-metallicity relation *(e.g. Erb+06; Maiolino+2010)*
- Has $v_c \sim 150 \text{ km/s} \Rightarrow v_{esc} \sim 450 \text{ km/s}$ at virial radius of ~90 kpc

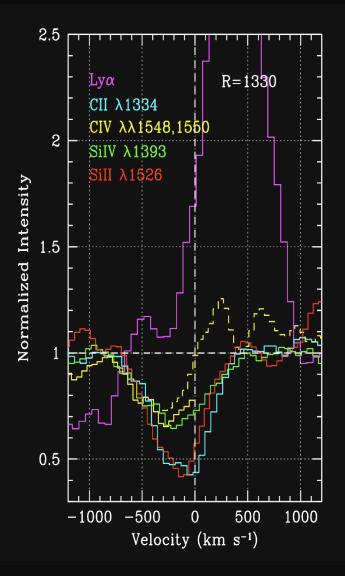
What are the expected gas flow rates?

• For typical galaxy (z=2.5) with a dark matter halo mass of ${\sim}10^{12}$ M_{\odot} :

 $(dM/dt)_{in} \sim 120 M_{\odot}/yr$ (baryonic accretion rate) $\langle SFR \rangle \sim 30 M_{\odot}/yr$ $(dM/dt)_{out} \sim 90 M_{\odot}/yr$ (for "equilibrium") \rightarrow "mass loading" $\eta = (dM/dt)_{out}/SFR \sim 3$

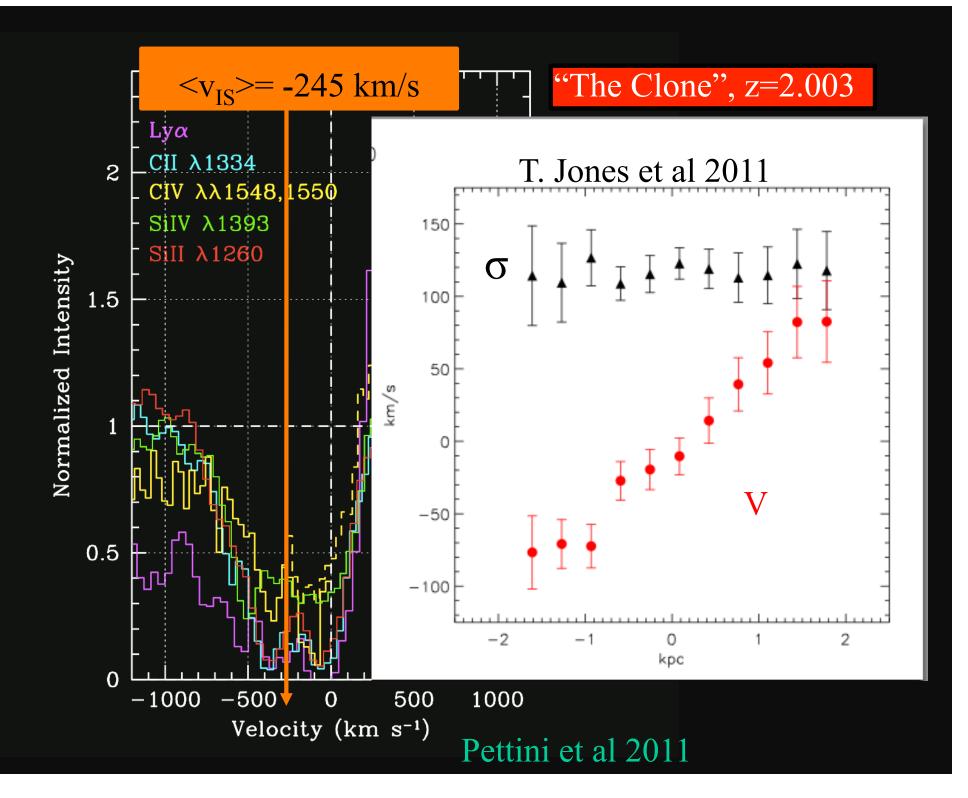
Far-UV Spectra: Gas Flows



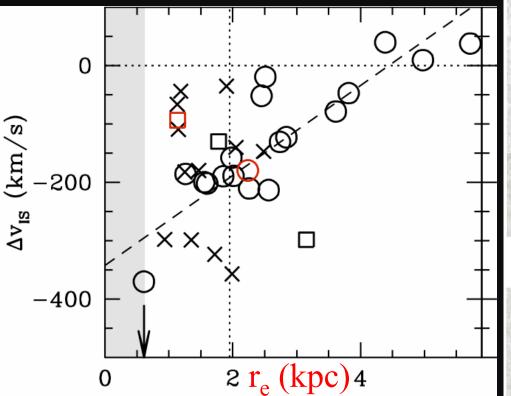


Velocity profiles in selected transitions relative to z_{sys}

Composite spectra of z~2-2.6 UVselected galaxies



Galaxy Size vs. Centroid of Absorption Lines WFC3-IR F160W



Law, CS, et al 2011

Q2343-BX587 Q1623-BX453 Q1217-BX95 Q1623-BX502 Q1623-BX543 Q1700-MD109 z=2.243 z=2.182 z=2.4244 z=2.1557 z=2.5211 z=2.2942 Q1623-BX376 Q1549-BX51 Q2343-BX480 Q2343-BX435 Q2343-BX660 Q2343-BX418 z=2.4085 z=2.29 z=2.2313 z=2.1119 z=2.1739 z=2.3053 Q1623-BX528 Q2343-BX537 Q2343-BX390 Q0449-BX93 Q1623-BX455 z=2.2682 z=2.3396 z=2.2313 z=2.0067 z=2.4074 r > 1.95 kpc Q1623-BX449 Q1217-BX102 Q1009-BX215 Q2343-BX391 Q1623-BX516 Q1623-BX366 z=2.4188 z=2.1925 z=2.174 z=2.4236 z=2.5061 z=2.4204 Q1623-BX522 Q1623-BX452 Q1623-BX472 Q2343-BX601 Q2206-BX102 Q1623-BX458 z=2.2104 z=2.4757 z=2.0595 z=2.1142 z=2.3769 z=2.4194 Q1623-BX429 Q1623-BX428 Q2343-MD62 Q2343-MD59 Q2343-BX442 Q2343-BX389 z=2.016 z=2.0538 z=2.1752 z=2.0116 z=2.176 z=2.1716

r < 1.95 kpc

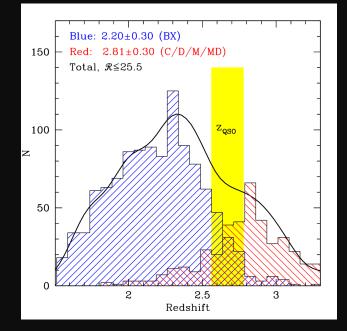
OK, So (almost) everything at high redshift has an outflow.

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

Need IGM "tomography", especially near

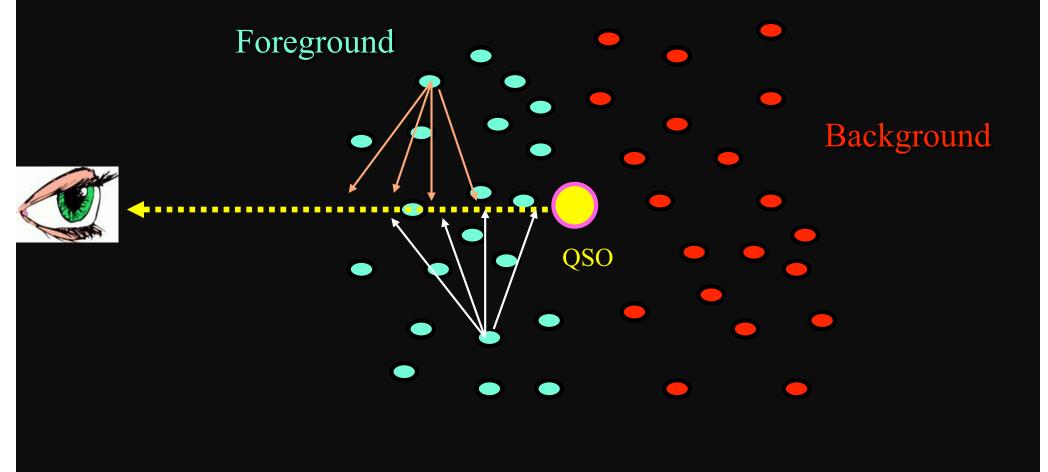
Contraction of the second seco

galaxies.



Densely Sampling the Universe @z~1.8-3.2

(previous work: Adelberger+03,05; see also Bielby+11, Crighton+11)

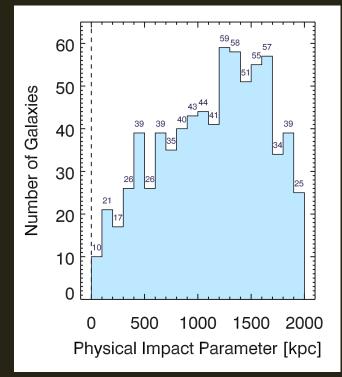


 15 fields with the brightest QSOs in the sky 2.5 < z < 2.9 at the Peak of Cosmic SF

Keck HIRES QSO spectra 17.5 > G_{AB} > 15.9

Gwen Redie relaxing at her second home, in Hawaii

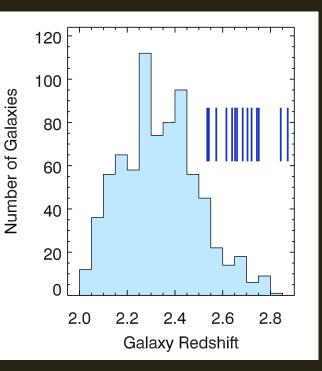
Talk this afternoon!



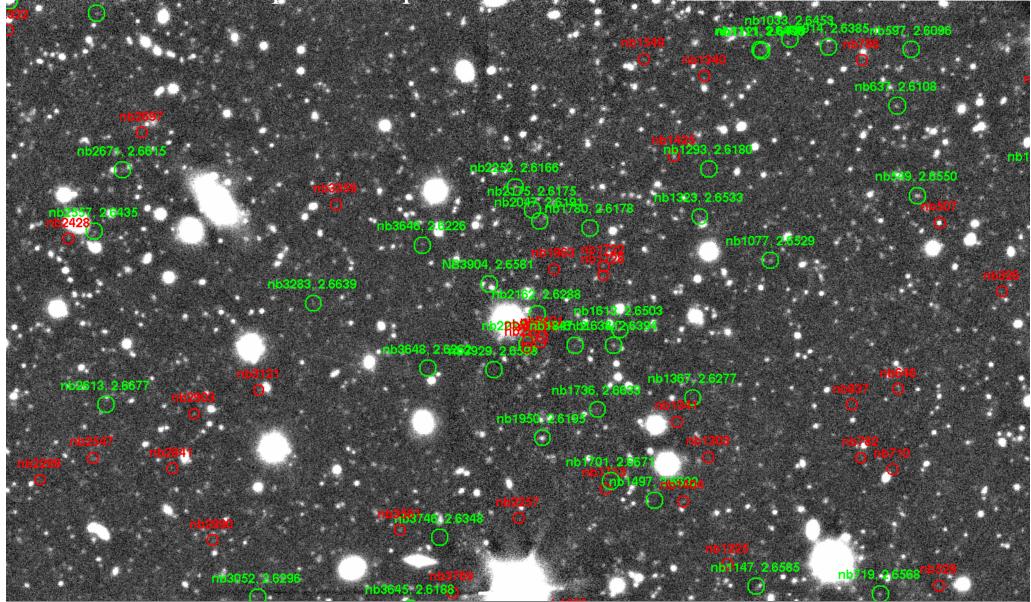
ixy sample

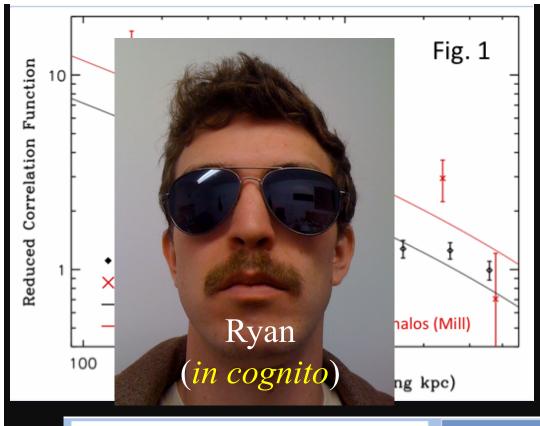
orming galaxies

h Lyβ and OVI ical (Keck/ n/s RMS) s



Typical Field, 5' x 7', ~150 spectroscopic redshifts 1.8-3.2



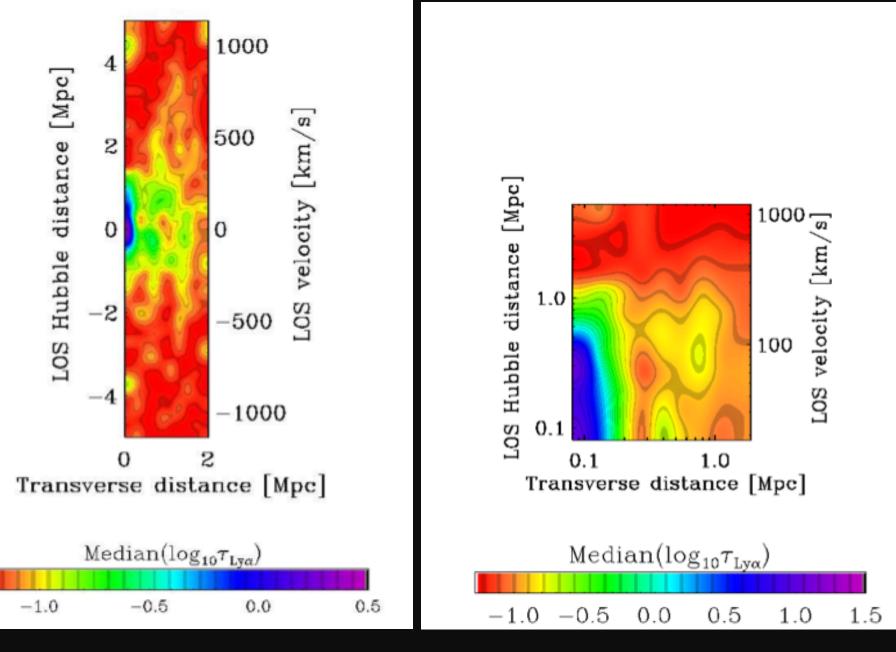


Ryan Trainor's Poster:

Hyper-luminous QSO (~ 10^{14} L_{sun}) environments at z~2.75 Brightest QSOs in the universe live in "modest", group-sized halos, log M_h~12.7, 200 kpc scales (~25" on the sky)

40 Selection Function Fig. 2		Gal-Gal ACF	Gal-QSO XCF
30 (s/up) 00 20 X	r ₀ (h ⁻¹ comoving Mpc)	5.5 ± 0.3	7.7 ± 0.9
	γ (fixed)	1.5	1.5
	$\langle z \rangle \pm \sigma_z$	2.34 ± 0.44	2.67 ± 0.10
	M _{min} (M _☉)	11.75	12.5
0 -4000 -2000 0 2000 4000 Velocity Difference (km/s)	$M_{ave}(M_{\odot})$	12.0	12.7

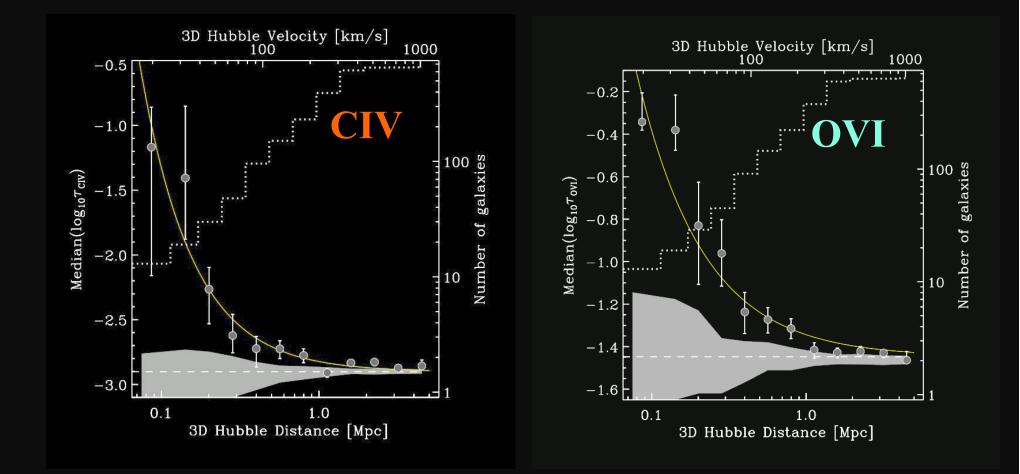
The IGM from a Galaxy-centric Perspective



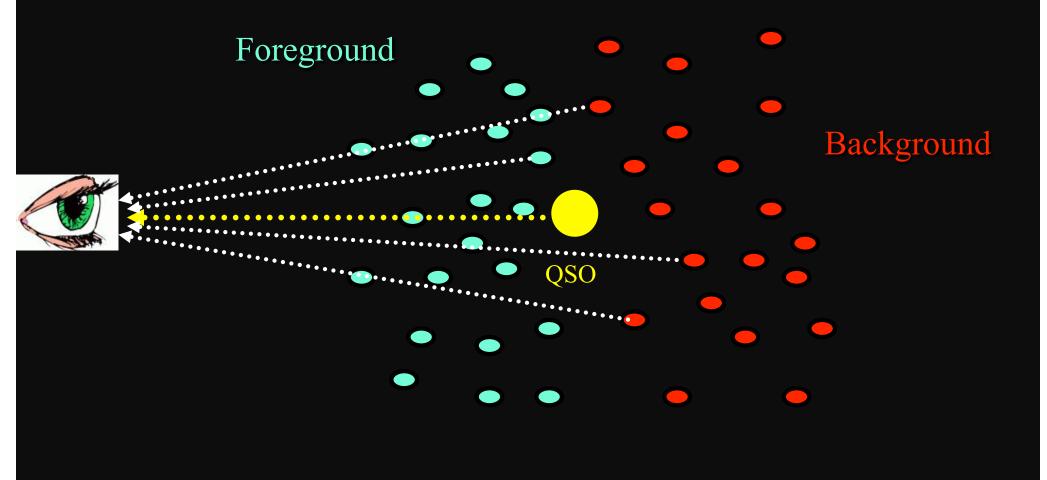
O. Rakic, CS, Schaye, Rudie+ 2011

Where are the Metals?Pixel Optical Depth vs. physical distance from a galaxy @z=2.5

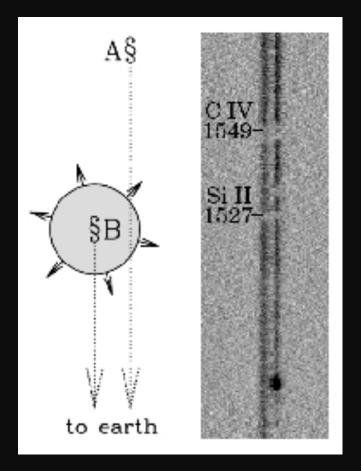
O. Rakic, CS, Schaye, Rudie+ 2011

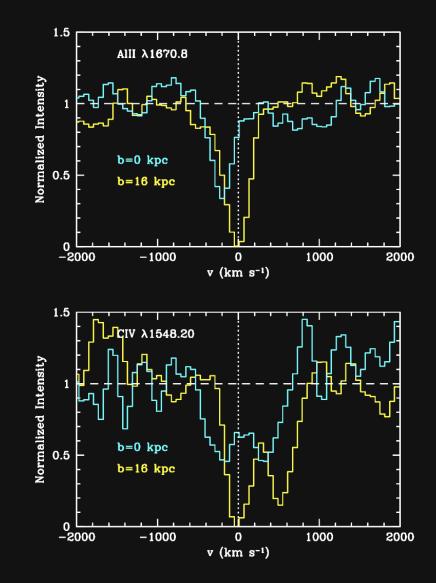


Densely Sampling the Universe @z~1.8-3.2



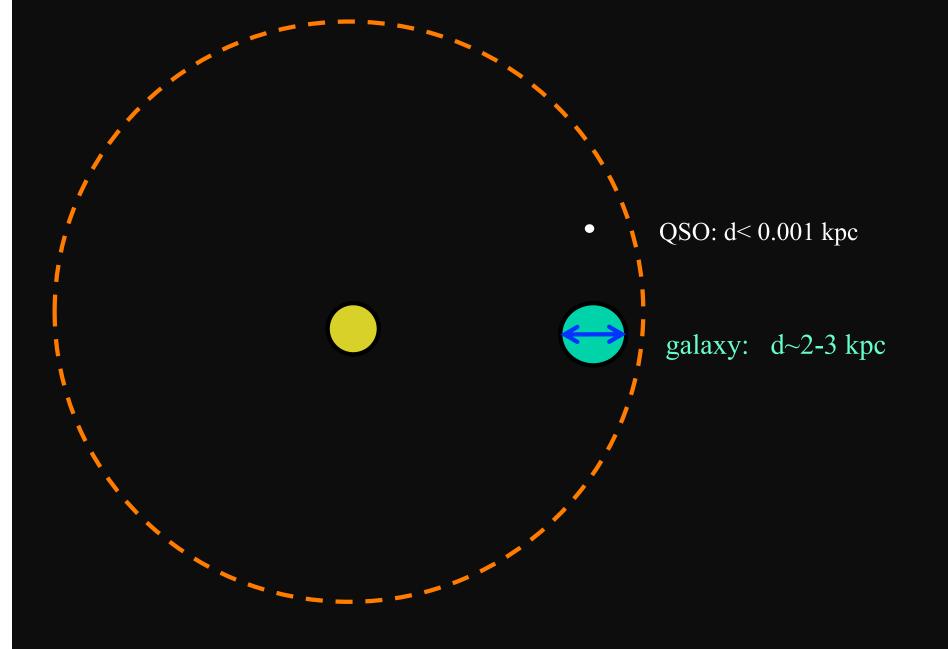
Using Background Galaxies to Probe Foreground Galaxy Flows

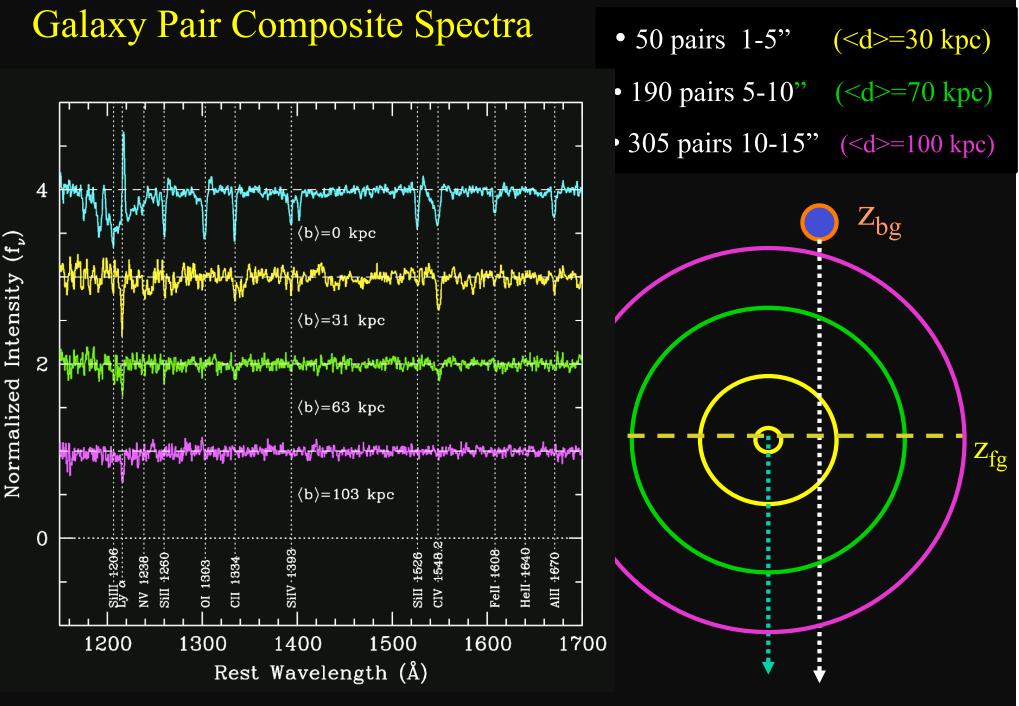




Keck/LRIS-B spectra, R=1500, 3800-4100 A

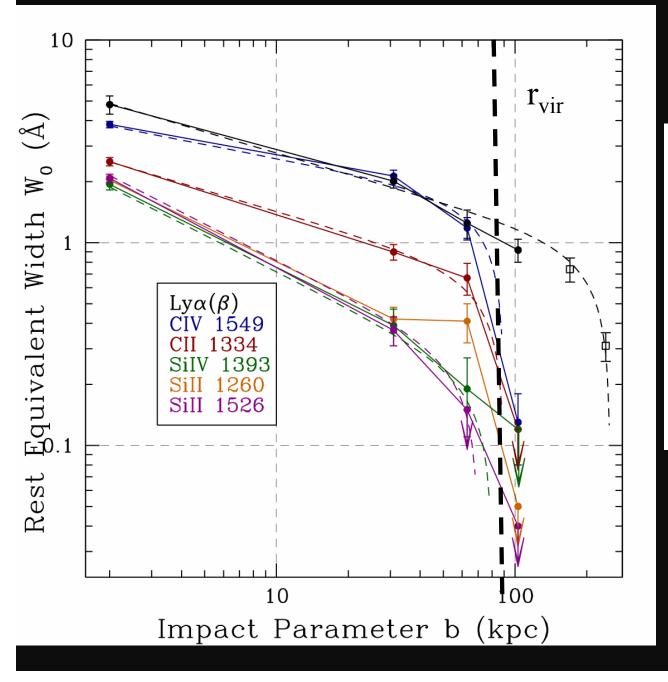
Galaxies vs. Point Sources as Probes of CGM





 $CS+2\overline{010}$

W₀ vs. Galaxy Impact Parameter, z~2-3 LBGs



Models:

TABLE 5 W0 VS. b MODEL PARAMETERS^a

Line	γ^{b}	R _{eff} (kpc)	vout	$f_{c,max}^{c}$
Lya(1216)	0.37	250	820	0.80
CIV(1549)	0.23	80	800	0.35/0.25 ^d
CII(1334)	0.35	90	650	0.52
Si II(1526)	0.60	70	750	0.40
Si IV(1393)	0.60	80	820	0.33

^a Parameters used to produce the model curves shown in Fig. 20

^b Power law exponent in the expression $f_c(r) = f_{c,max}r^{-\gamma}$

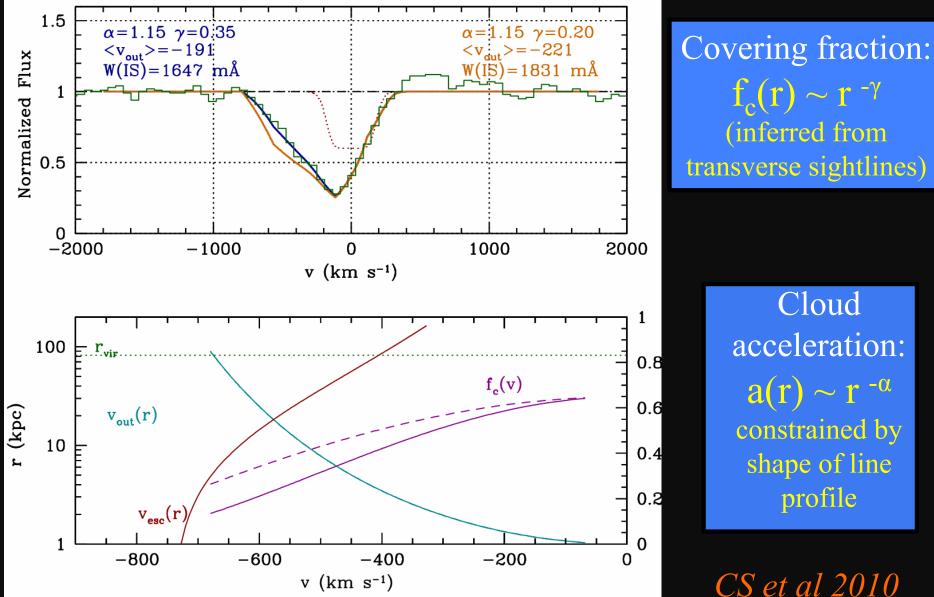
^c Maximum value of the covering fraction for each transition, measured from the composite spectrum (see Fig. 7)

 d Includes contributions from C IV $\lambda1548$ and C IV $\lambda1550$ of 0.35 and 0.25, respectively.

$$f_c(r) \sim r^{-\gamma}$$

CS et al 2010

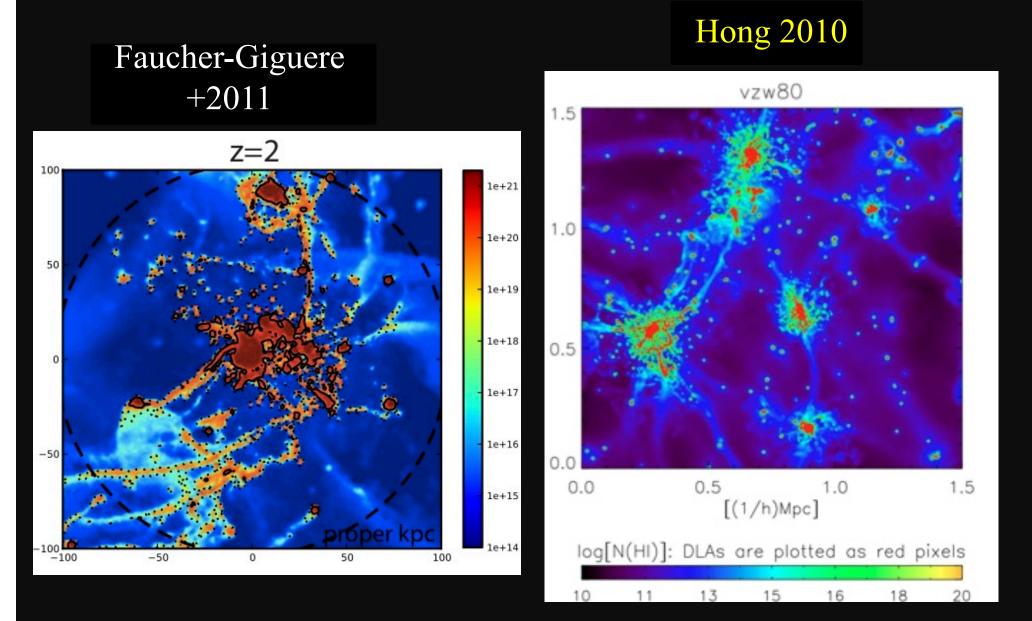
"Typical" Absorption Line Profiles, matched with a simple flow model



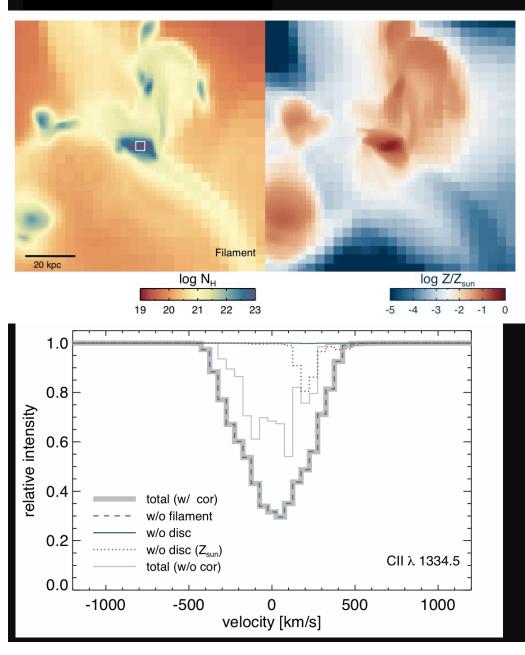
Cloud acceleration: $a(r) \sim r^{-\alpha}$ constrained by shape of line profile

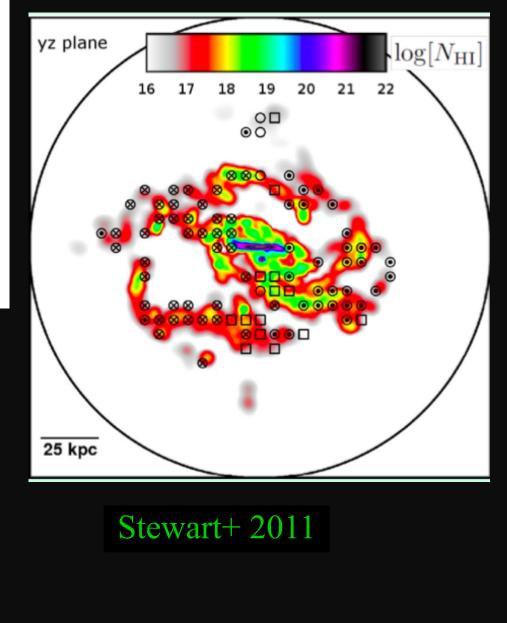
CS et al 2010

Cool Gas Accretion in Simulations



Cool Gas Accretion in Simulations Kimm+ 2010





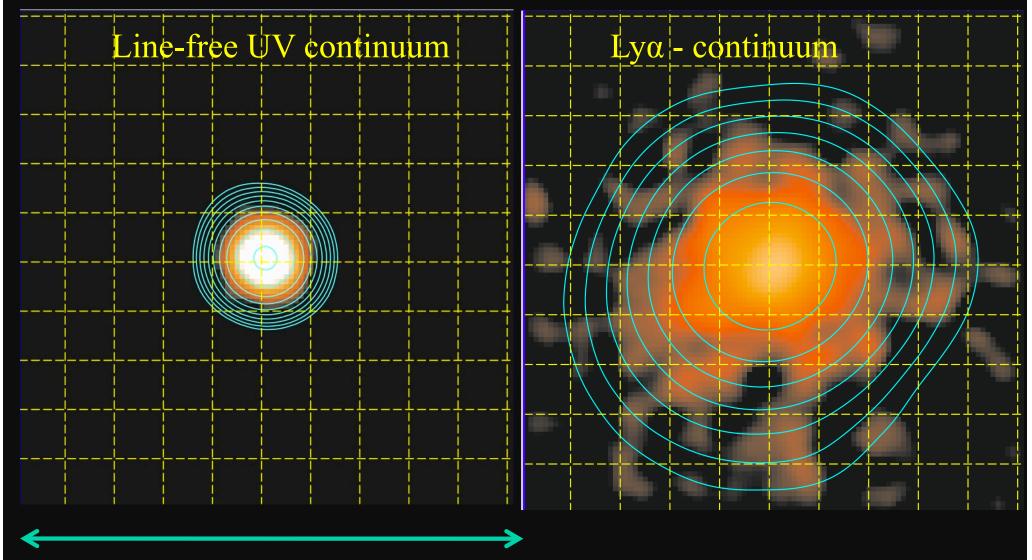
Using Ly-α *Emission* To Trace the CGM/IGM

• HI /HII gas can be a source of Ly- α emission

- collisional processes followed by radiative de-excitation
- (e.g., Keres+08, Goerdt+10, Dijkstra+09, Faucher-G+10, Kollmeier+10)
- HI gas can scatter Ly- α photons originating elsewhere
 - can *appear* to be the source, to observer
 - Lyα emission provides information on gas distribution, kinematics (e.g., Zheng+2010, Laursen+10, Verhamme+08, CS+2011; Kulas+2011)
- HI gas can shine in Ly-α via ``fluorescence''
 - i.e., external ionizing photons converted to Ly- α
 - (e.g., Gould & Weinberg 1996; Rauch+08, Adelberger+06, Cantalupo +07, Hennawi+09, Kollmeier+10)

<u>AND, Matsuda+11 (poster at this meeting), Zheng+11 poster up TODAY. M.</u> <u>Haehnelt, M. Prescott talks this afternoon!</u>

Average Ly α Emission from ~100 UV-continuum selected galaxies (0.3-3L*_{UV}), <z>~2.65

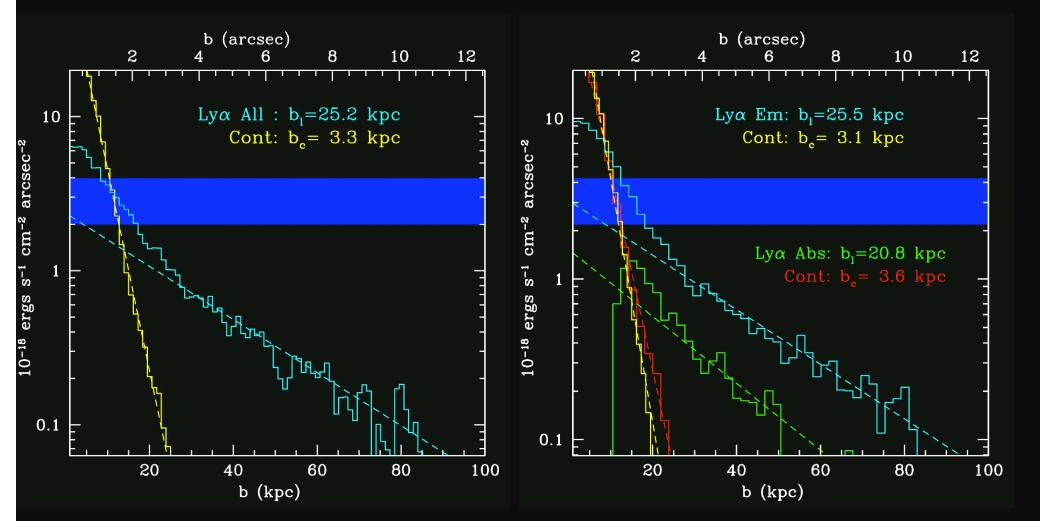


20" ~ 160 kpc (physical)

CS et al 2011; see also Hayashino et al 2004

Average, All Galaxies

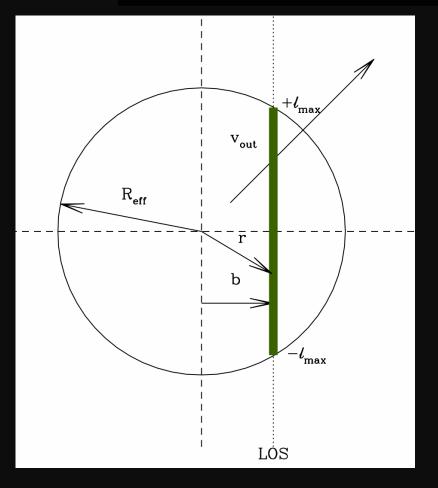
Separated by Spectral Morphology



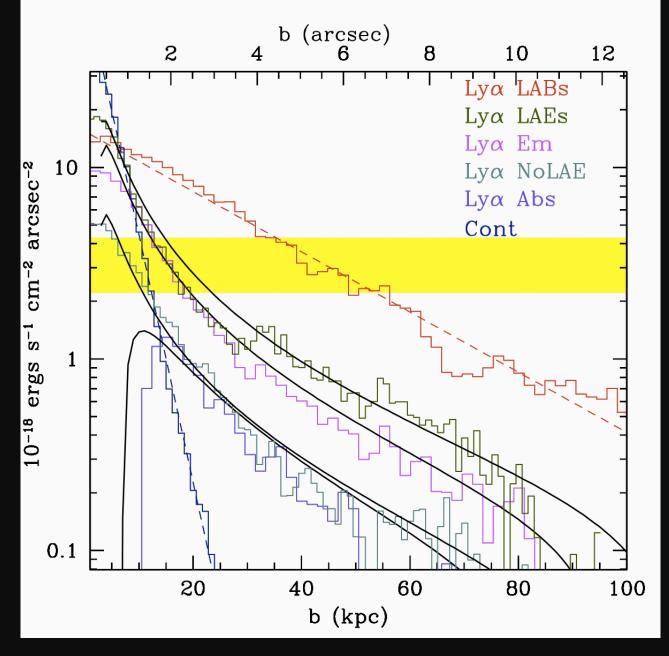
Fits are SB(b) ~ $\exp(-b/b_1)$

Lya Scattering Model for Diffuse Halos

$$S_{\text{Ly}\alpha}(b) \propto S_0 \int_{-l_{max}}^{+l_{max}} \frac{f_c(r,v)[1-f_c(r,v)]}{r^2} dl$$



•All Ly α photons produced in HII regions •Photon dilution ~ 1/r² •Scattering in observer's direction depends on HI covering factor f_c(r) • Subsequently depends on low optical depth in observer's direction, ~[1-f_c(r)]

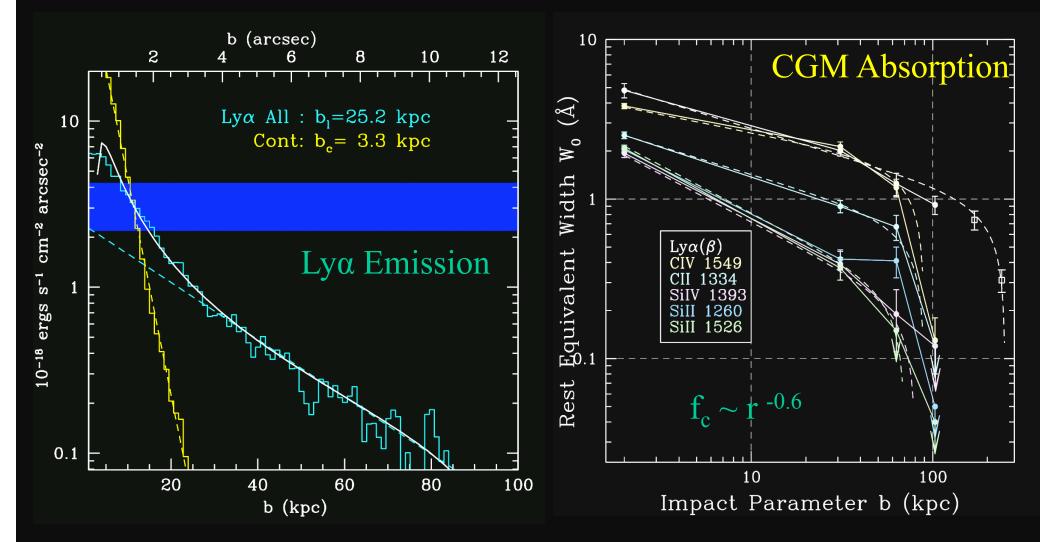


Diffuse Lyα Halos for galaxy subsets, fit with simple scattering models, same:

> • $f_c(r)$ • $R\sim 90 \text{ kpc}$



Lya Scattering and CGM Absorption Strength



model: $f_c \sim r^{-0.6}$ $R_{eff}=90 \text{ kpc}$

CS et al 2010,2011

Where are the galactic baryons?

- For typical galaxy at z=2.5 with a dark matter halo mass of ${\sim}10^{12}\,M_{\odot}$:

$$\begin{split} M_b(\text{cosmic}) &\sim 1.6 \text{ x } 10^{11} \text{ M}_{\odot} \\ M_* + M_{\text{cold}} &\sim 0.4 \text{ x } 10^{11} \text{ M}_{\odot} \\ M_{\text{CGM}} &> 0.5 \text{ x } 10^{11} \text{ (t}_{\text{sf}} \text{/}500 \text{ Myr}) \text{ M}_{\odot} \end{split}$$

Last Slide

- At the peak epoch of galaxy formation, bolometric L*, "main sequence" galaxies (aka "LBGs", BX, BzK) are driving outflows which appear to influence regions of ~300-500 kpc (physical) ~ 1-1.5 Mpc (co-moving) (*Rudie talk this afternoon*)
 - this "feedback" is distributing metals to the IGM, controlling the rate at which star formation, chemical enrichment proceeds
 - removes preferentially the low angular momentum, low entropy gas (*McCarthy talk yesterday*).
 - this gas will be "recycled" in many/most cases (Dave, Oppenheimer talks today)
 - This process began at much higher redshift
- The signature of baryonic *accretion* via cold streams is not ruled out by observations
 - generally masked by the strength of outflow signatures in both absorption and emission
 - Ways forward: Lya emission morphology? Co-rotating halo gas as often seen at lower redshift (*Kaczprak*)? Low metallicity LLSs? (*Lehner*)