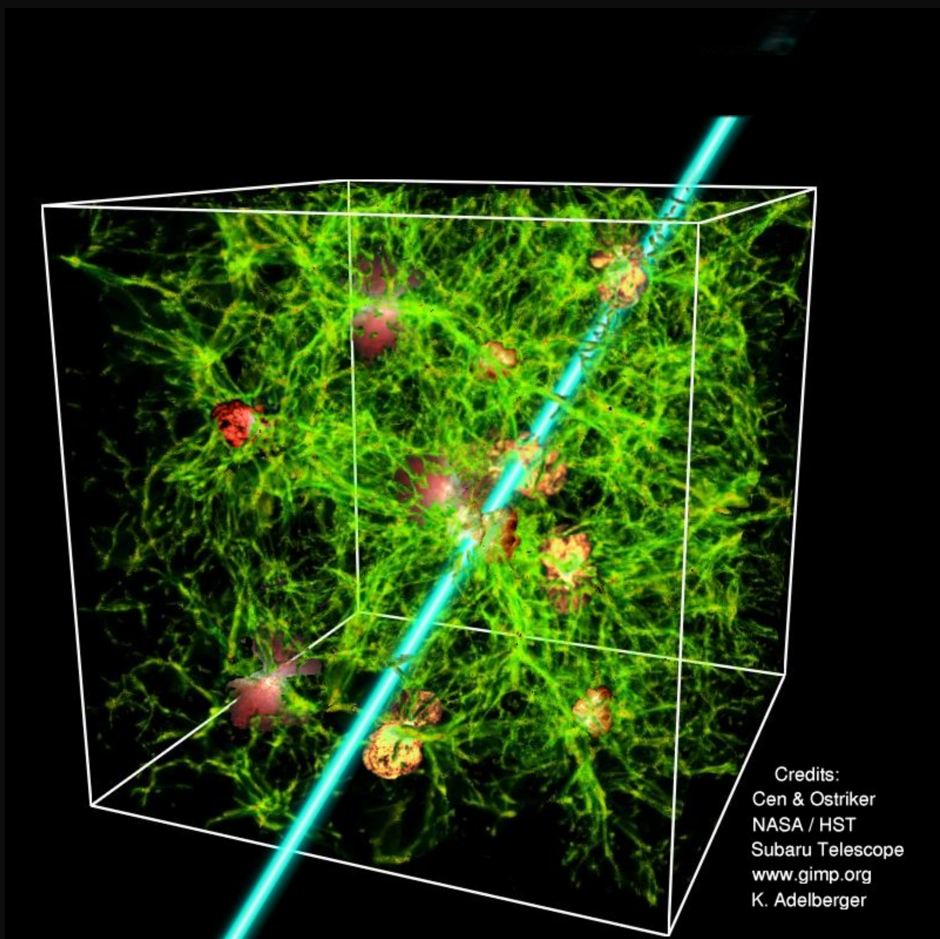
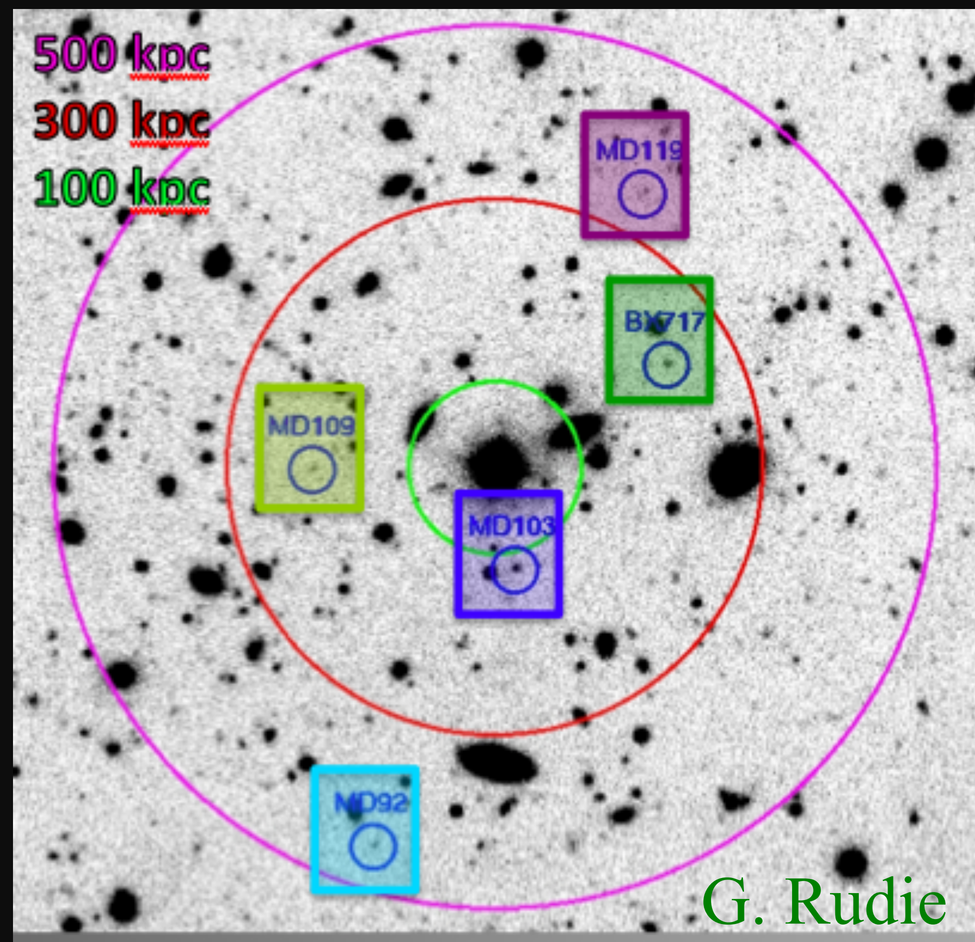
Gas-Phase Outflows and Accretion at the Peak of the Galaxy Formation Era (z~2-3)

C. Steidel, Caltech





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

Accretion:

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

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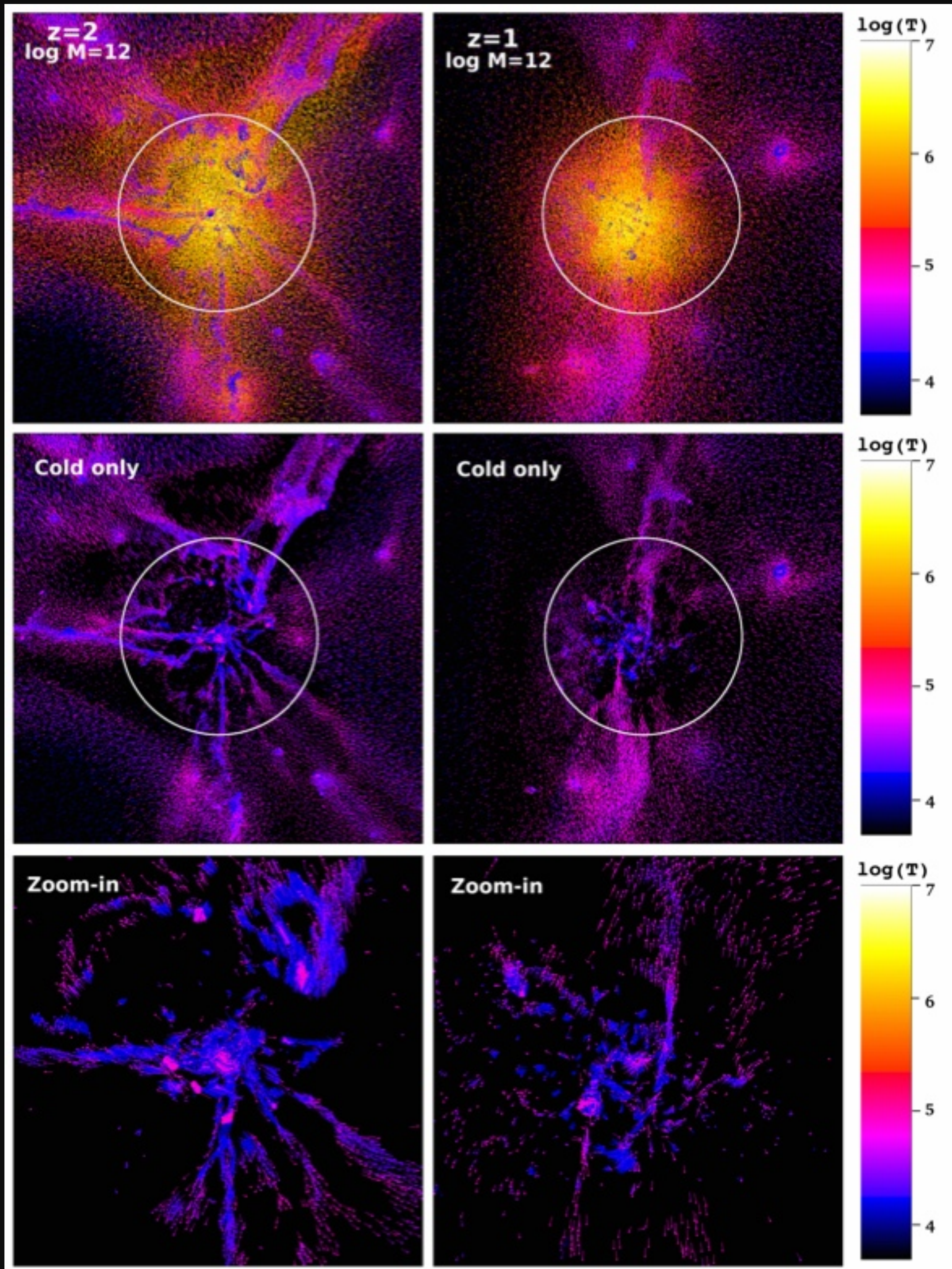
- Chemical enrichment of the IGM

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

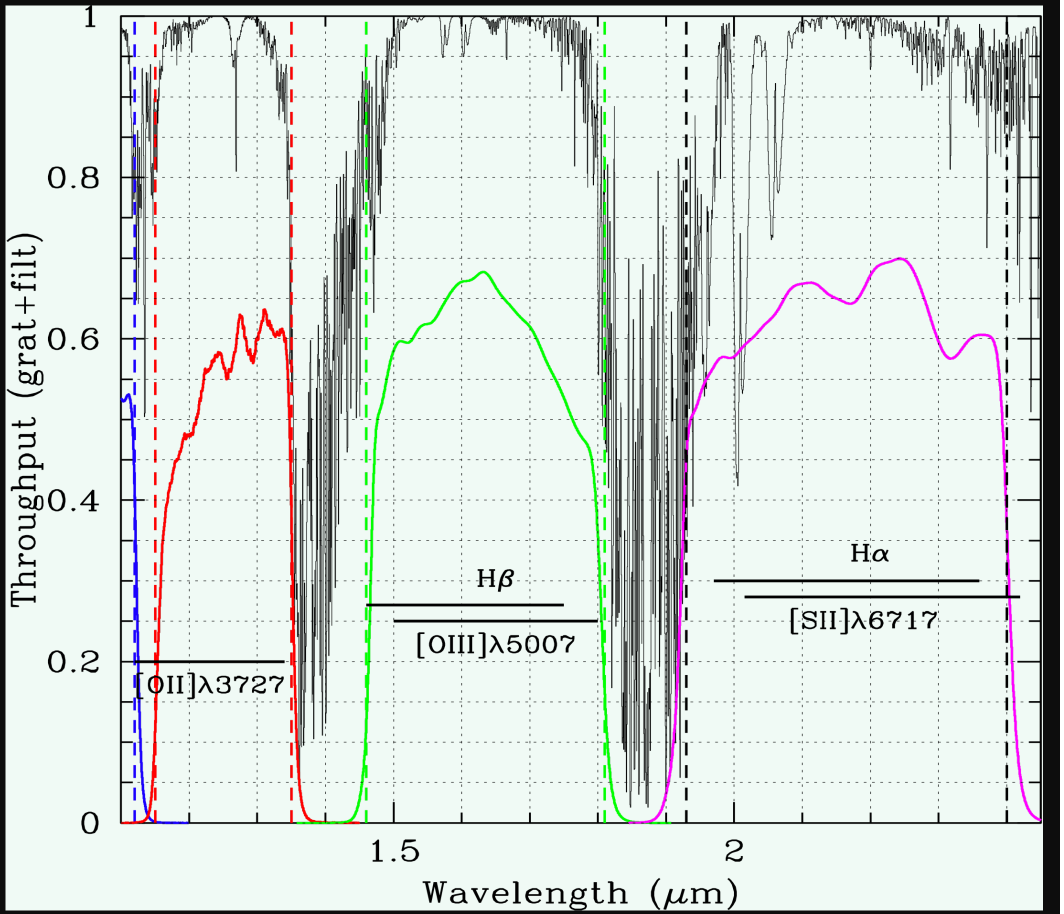


- Far-UV transitions (both emission and absorption) of HI and abundant metallic species are sensitive to column densities as low as $N \sim 10^{12-13} cm^{-2}$ and as high as $N > 10^{22}$
- Trace essentially all gas at temperatures $T \sim 10^{4-6}$ K, inside or outside of galaxies
- especially effective for photoionized gas ($T \sim 10^4$) and for gas cooling from high temperature (e.g. OVI)
- Define CGM as region within *~300 kpc (physical), or ~1 Mpc (co-moving) at z~2-3*

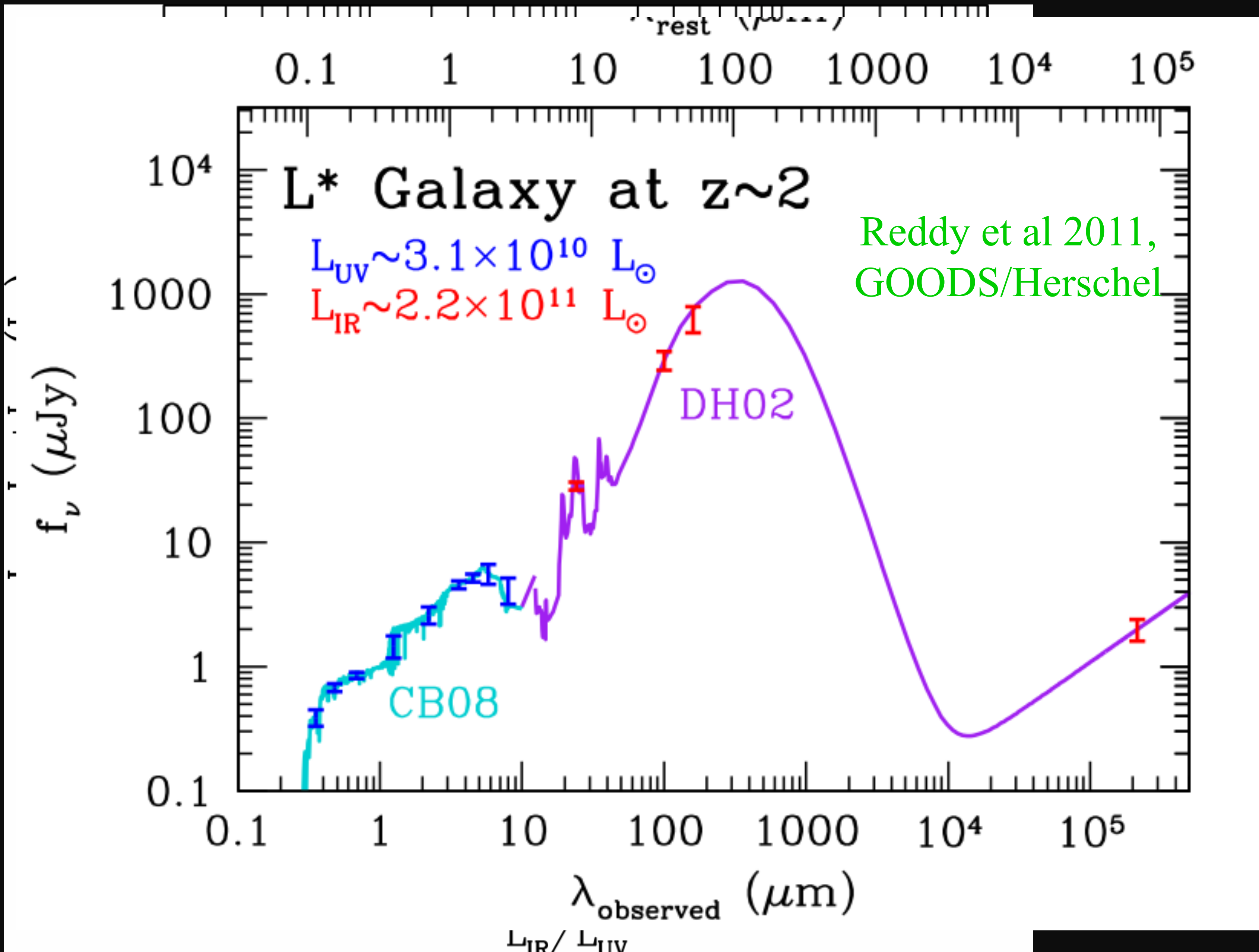
Keres +2008

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!



“Bolometric L* “ Galaxies, z~2



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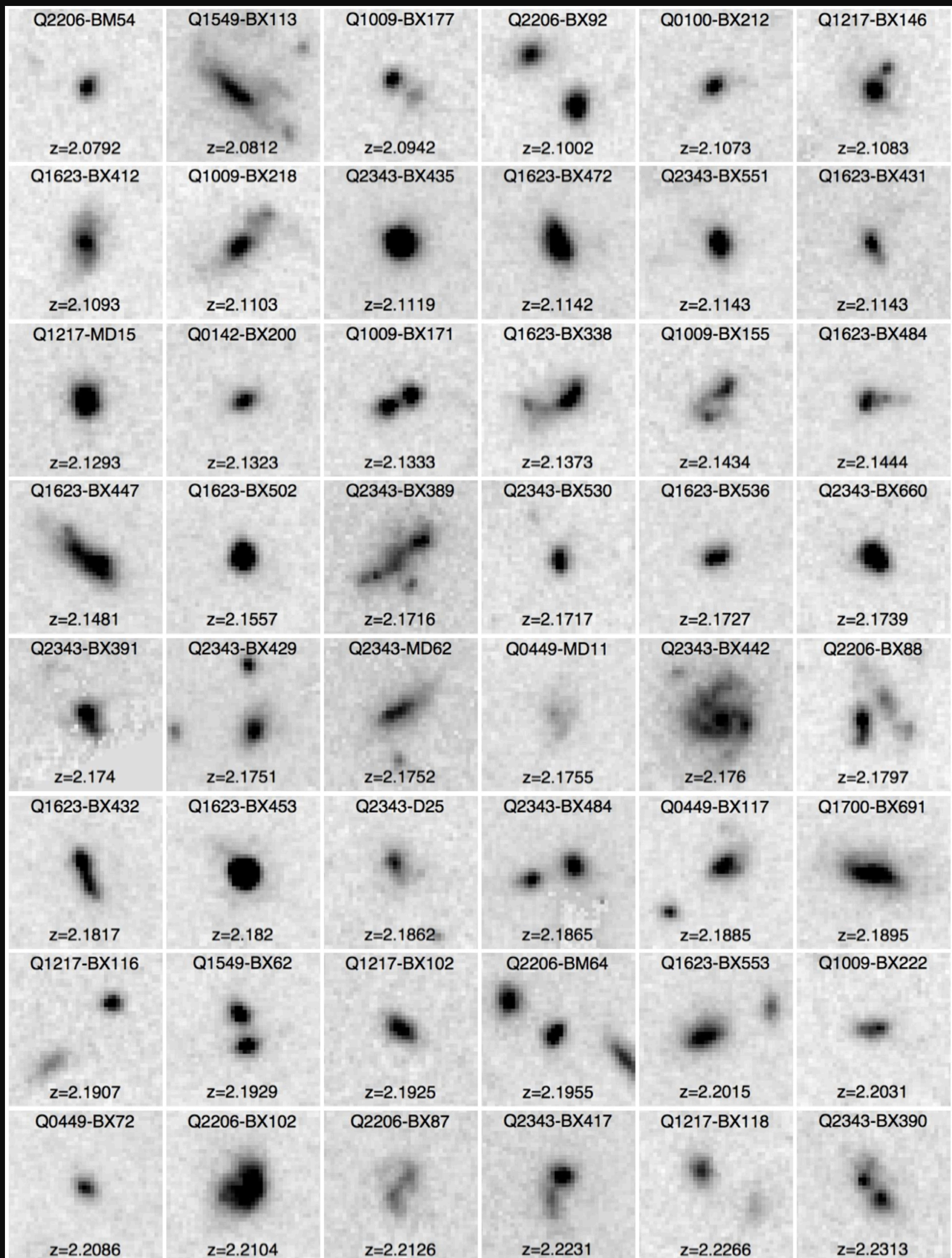
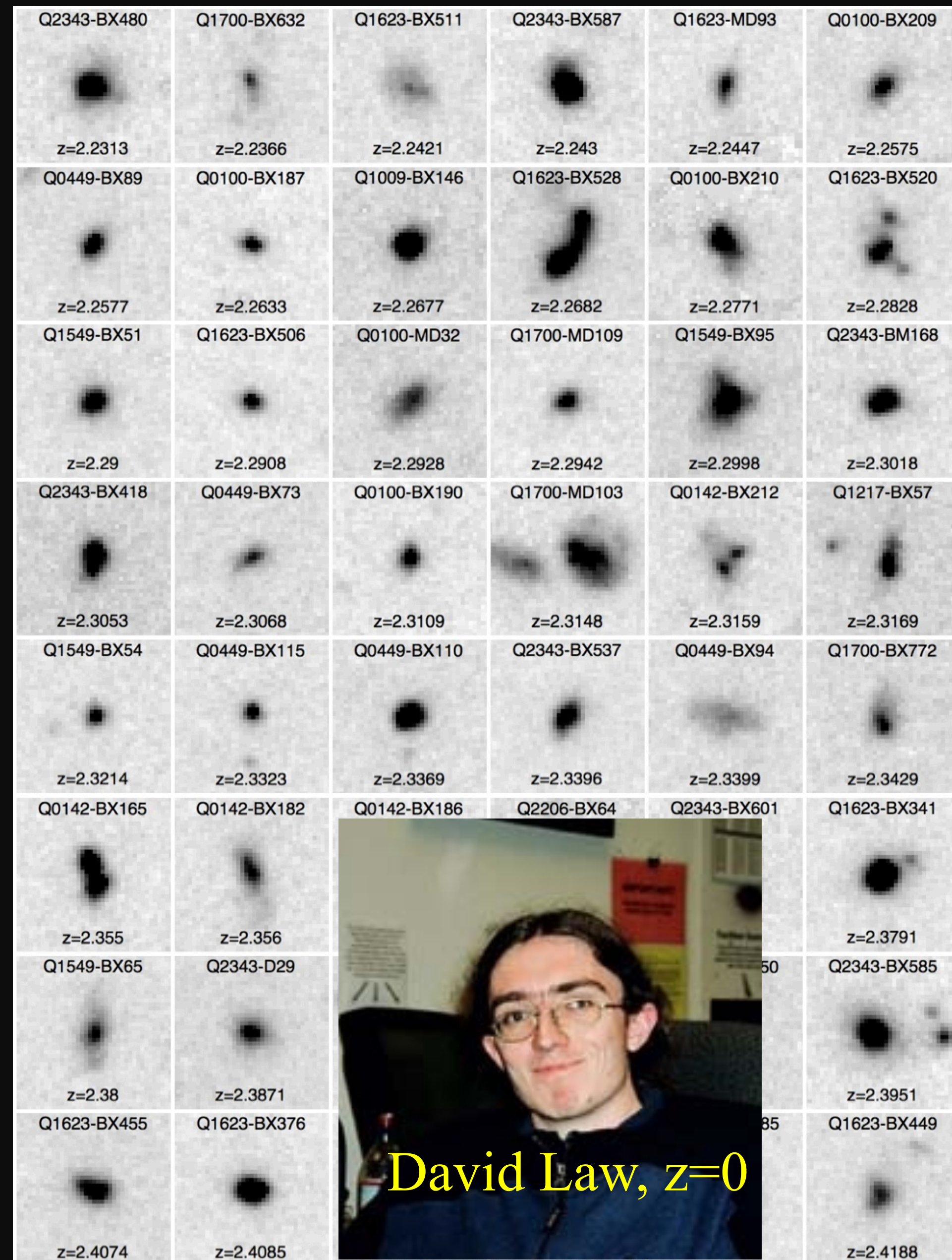
Reddy et al 2006; 2010

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





Law+ 2011

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

- Lives in a dark matter halo of average mass $\langle M_h \rangle \sim 10^{12}\,M_\odot$ (from clustering; e.g.*CS+1998; Baugh+1998;Governato+1998 Adelberger +2005; Conroy +2008; Trainor +2011*)
- Space density: $\varphi^* = 2.75 \pm 0.54 \times 10^{-3}$ 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 $10^{10}\,M_\odot$ 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~150 km/s ➔ v_{esc} ~ 450 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 $\sim 10^{12}$ $M_\odot$:

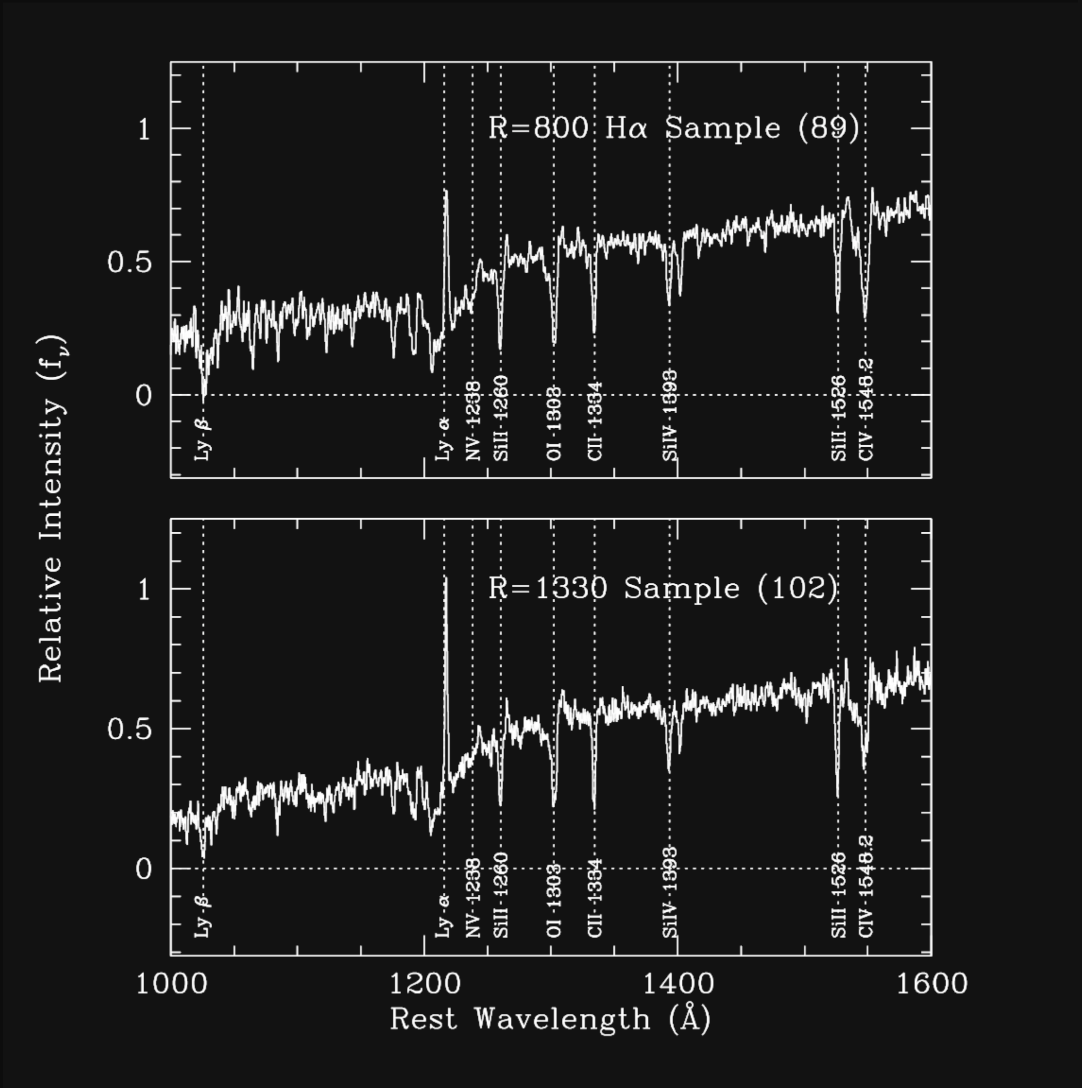
$(dM/dt)_{in} \sim$ 120 $M_\odot$/yr (baryonic accretion rate)

<SFR> ~ 30 $M_\odot$/yr

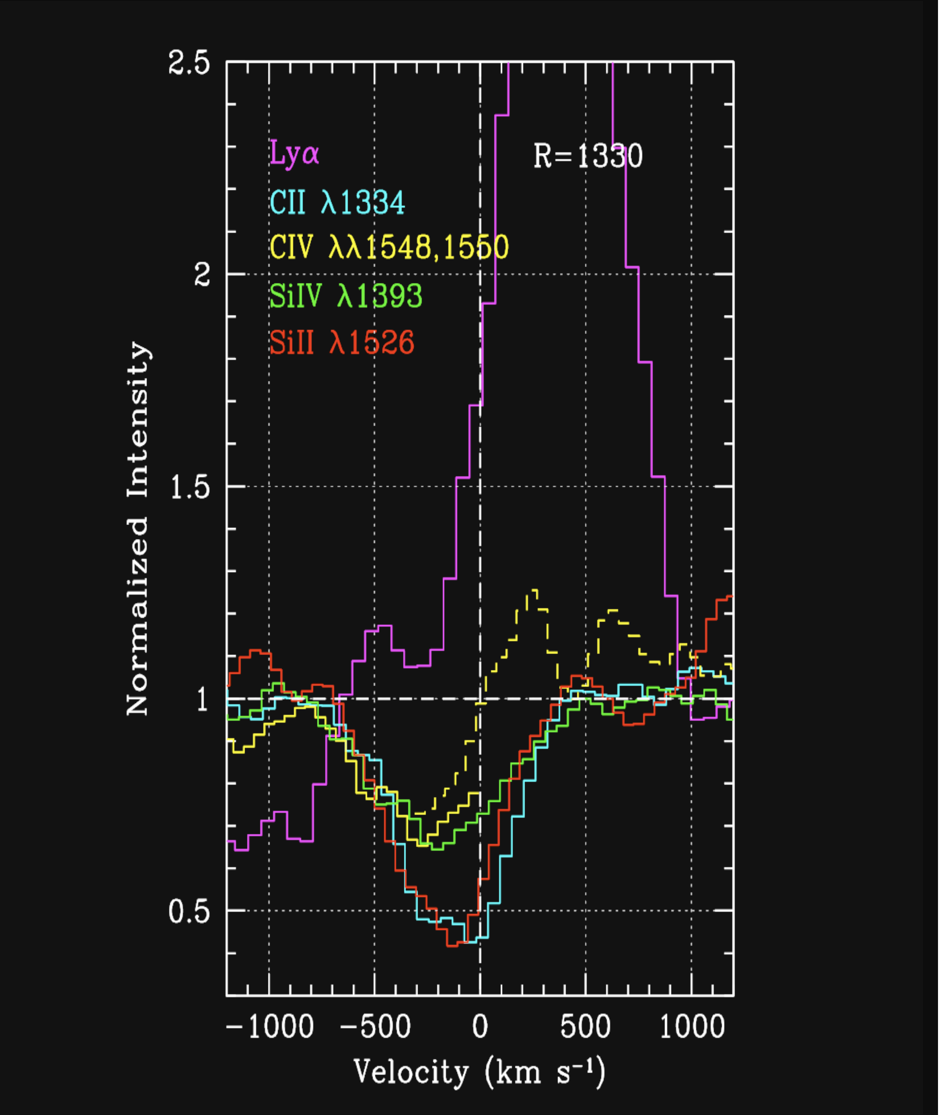
$(dM/dt)_{out} \sim$ 90 $M_\odot$/yr (for "equilibrium")

➔ "mass loading" $\eta = (dM/dt)_{out} / SFR \sim 3$

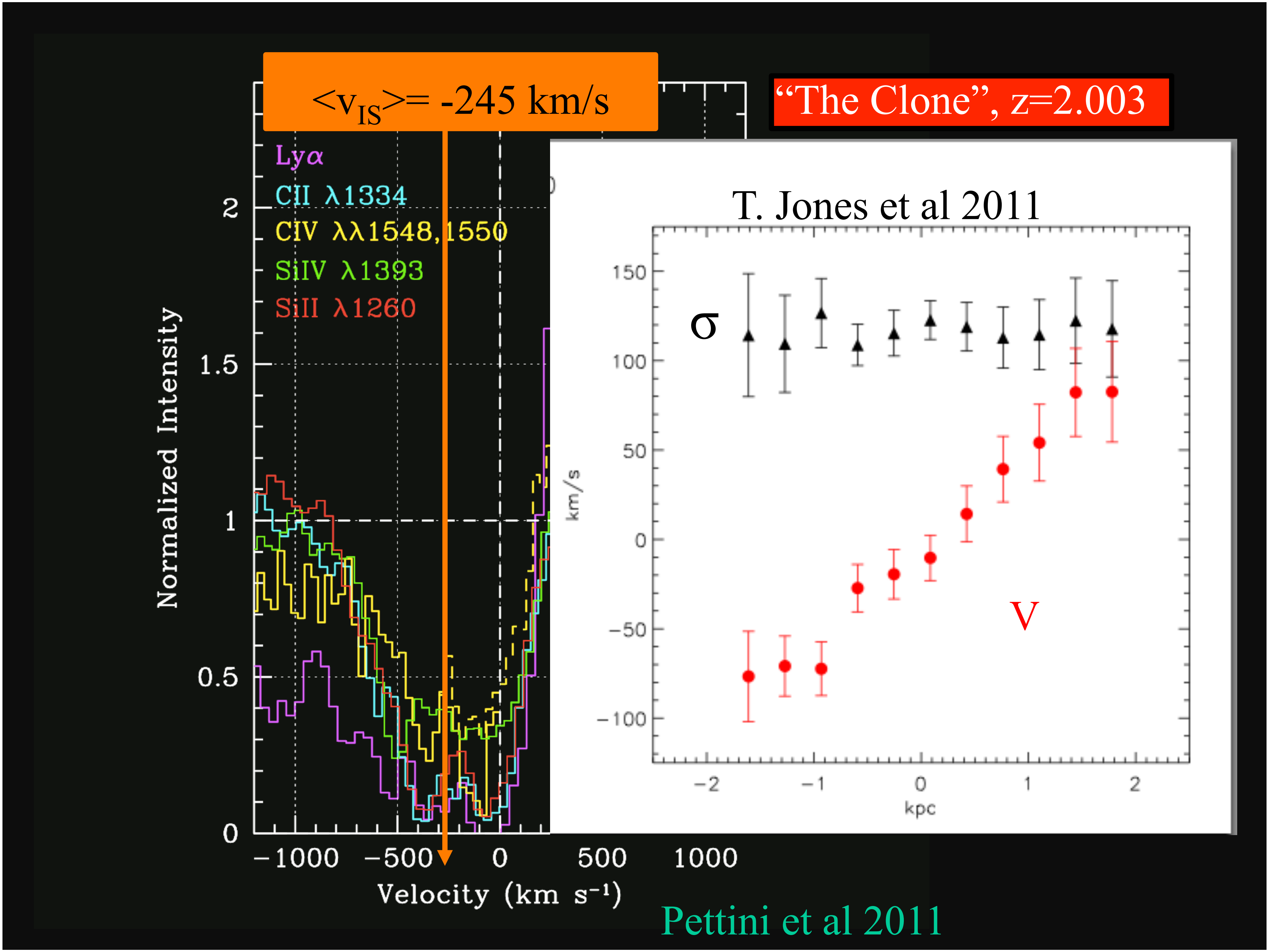
Far-UV Spectra: Gas Flows



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

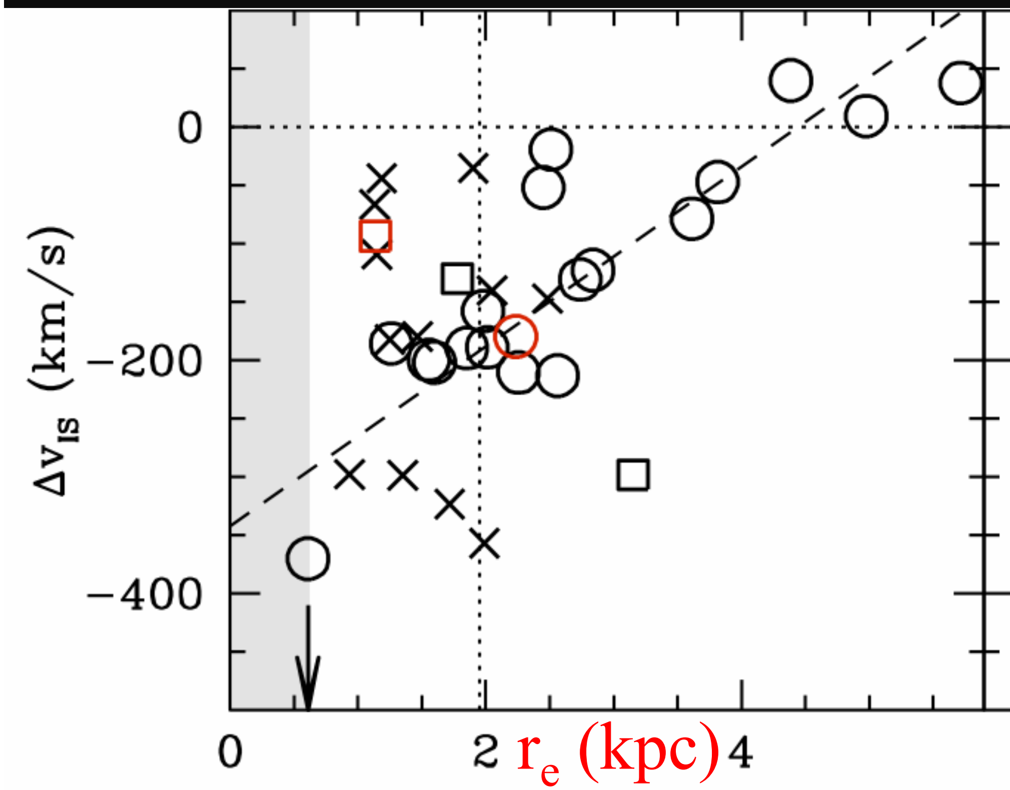


Velocity profiles in selected transitions relative to z_{sys}

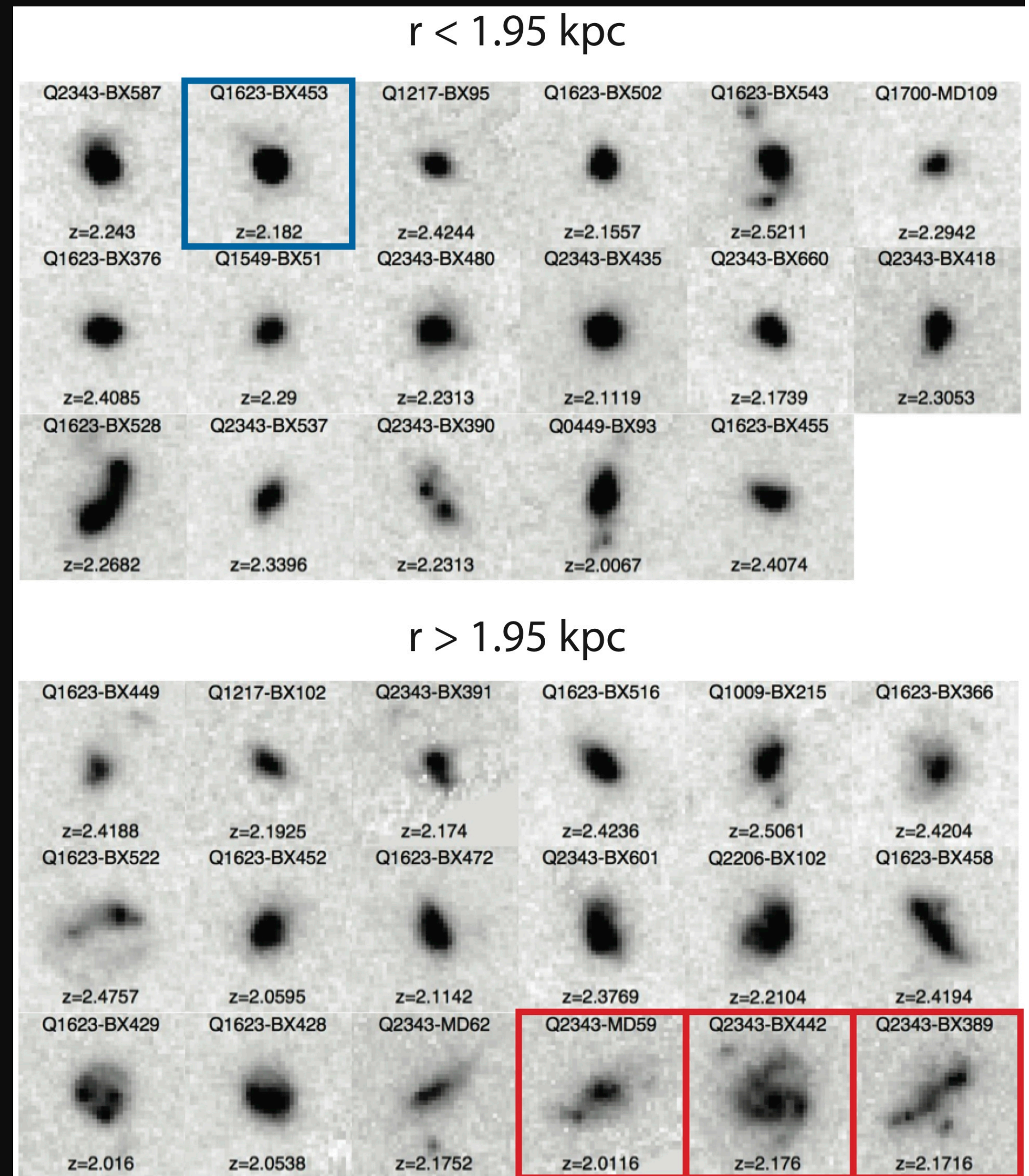


<v_IS>= -245 km/s
"The Clone", z=2.003
Lyα
CII λ1334
CIV λλ1548,1550
SiIV λ1393
SiII λ1260
Normalized Intensity
Velocity (km s⁻¹)
T. Jones et al 2011
σ
V
km/s
kpc
Pettini et al 2011

Galaxy Size vs. Centroid of Absorption Lines



WFC3-IR F160W

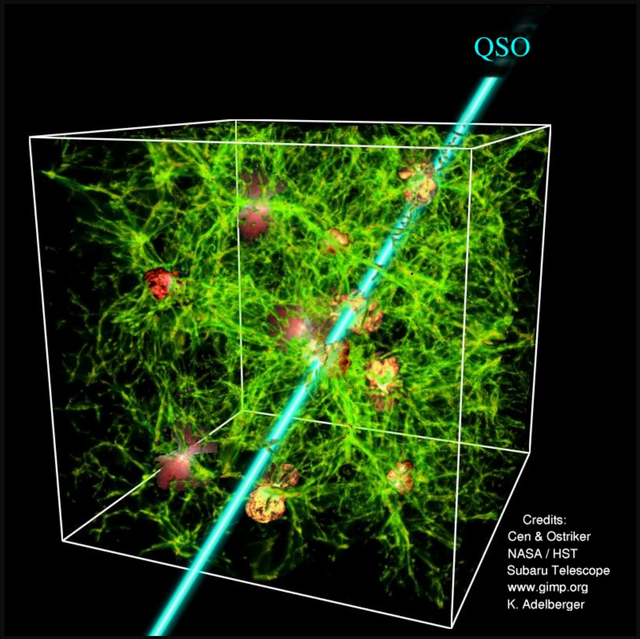


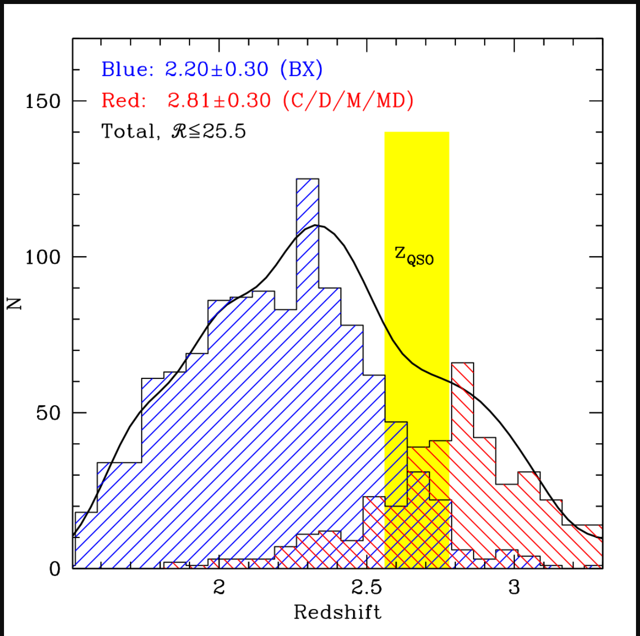
Law, CS, et al 2011

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

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

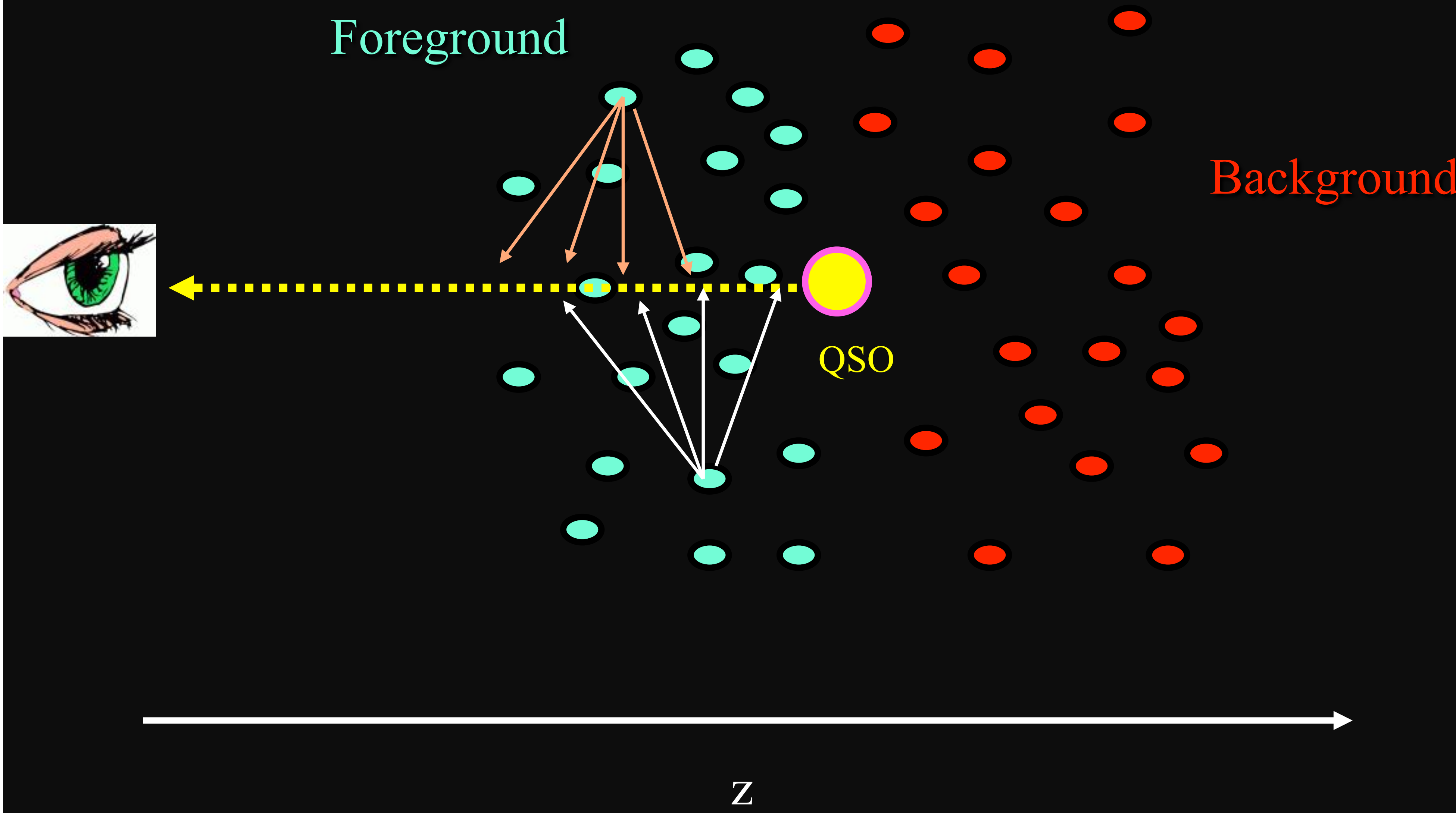
Need IGM "tomography", especially near galaxies.





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

- …axy sample

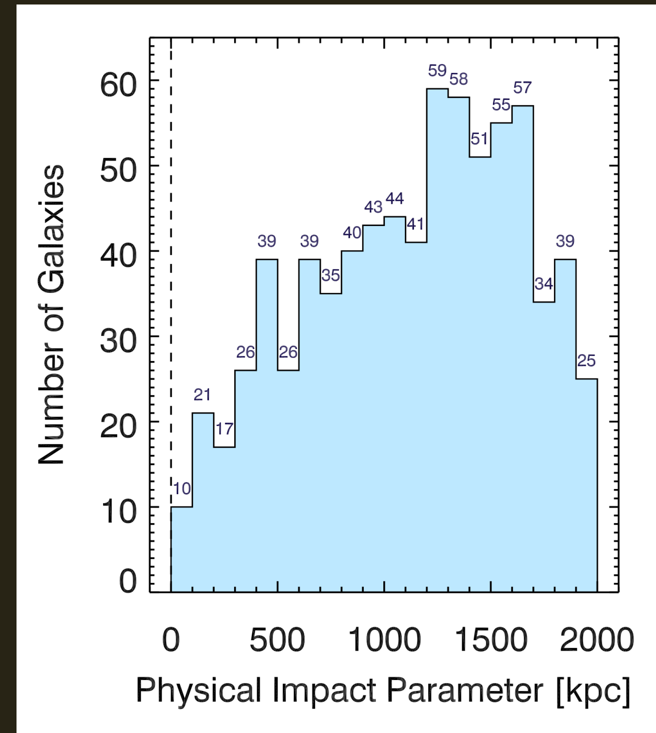
…orming galaxies

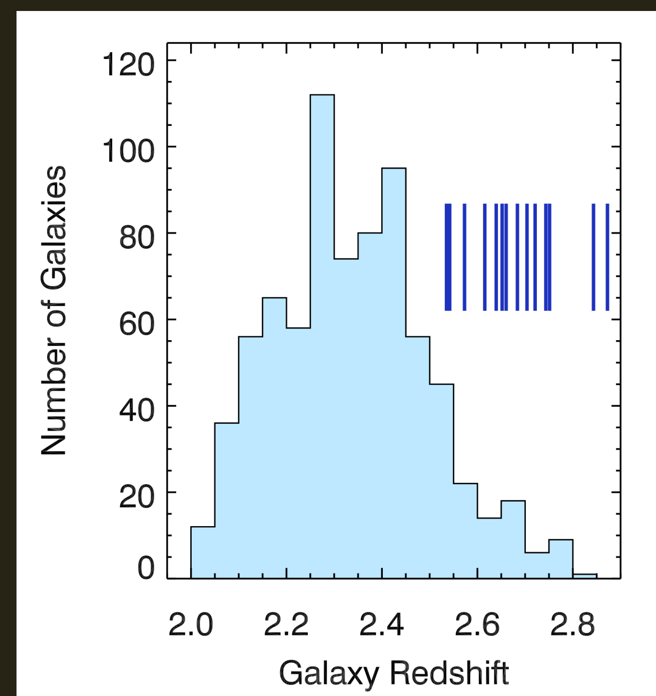
…h Lyβ and OVI

…ical (Keck/

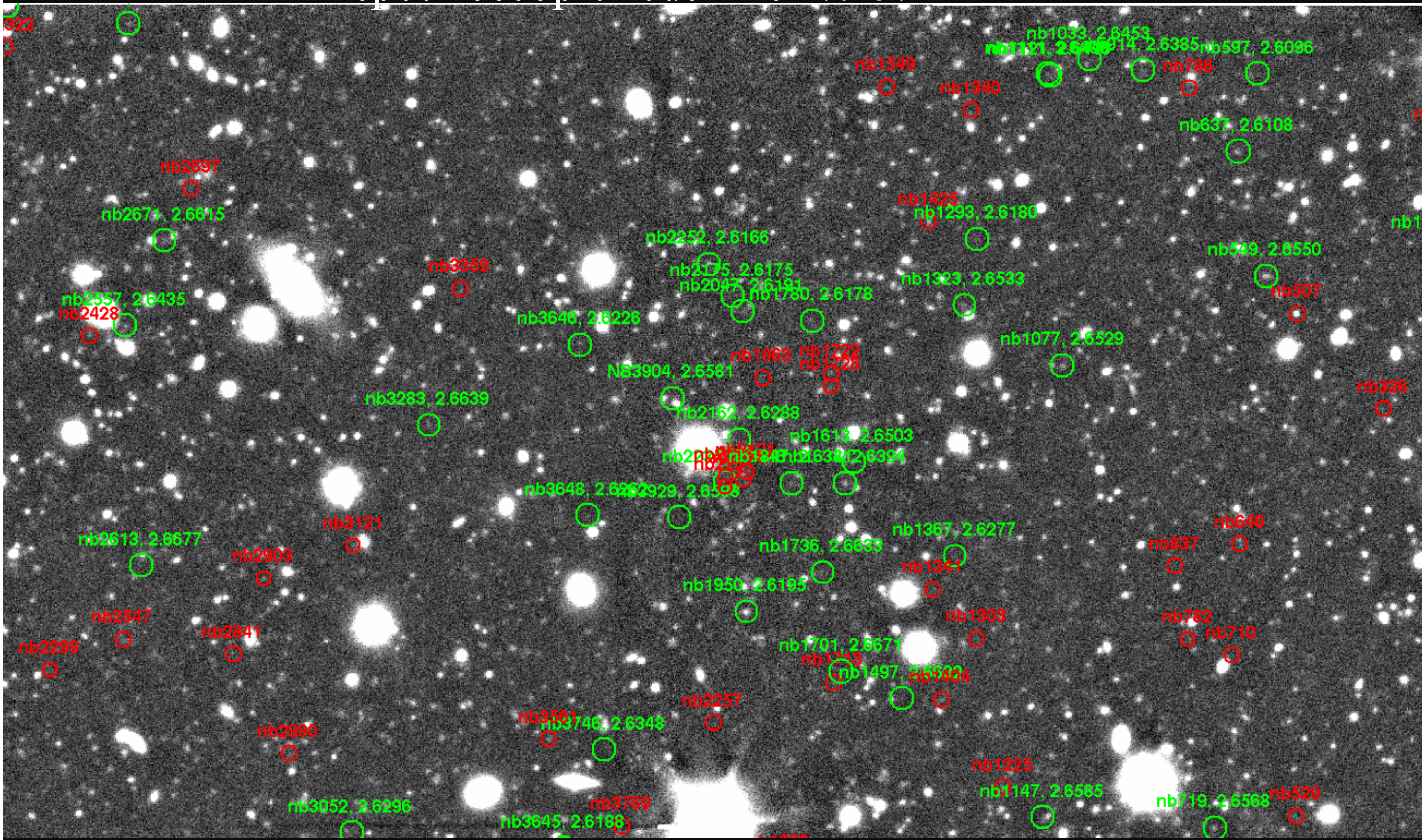
…n/s RMS)

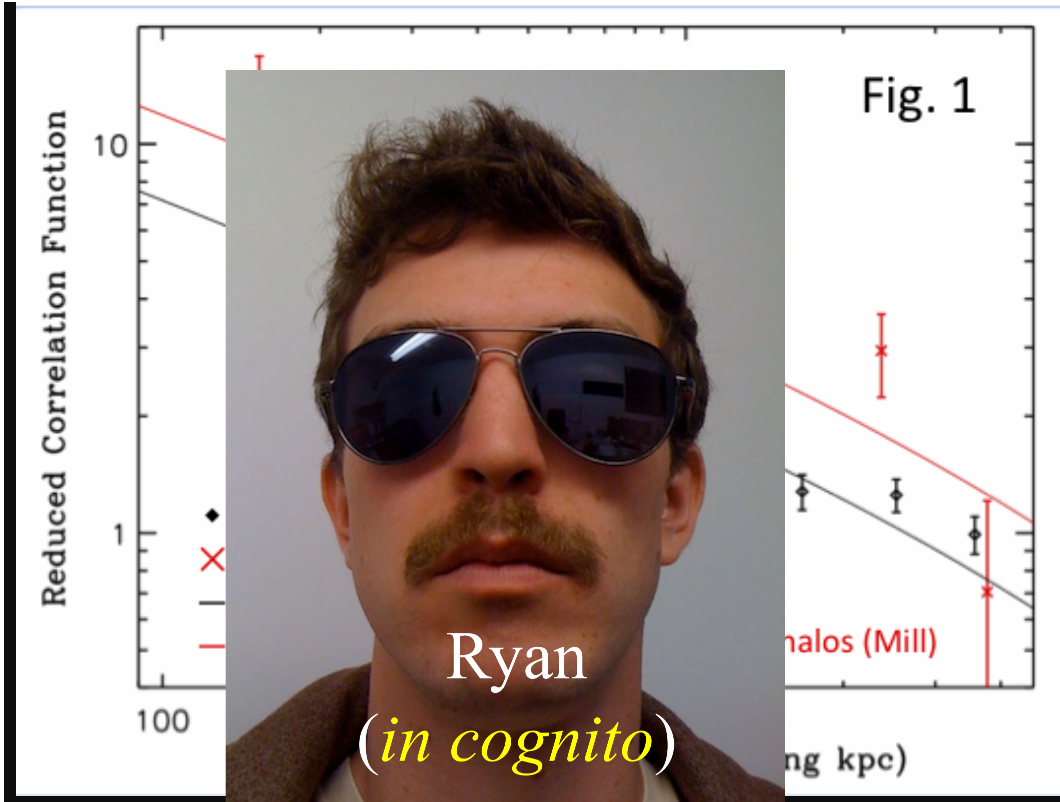
…s





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

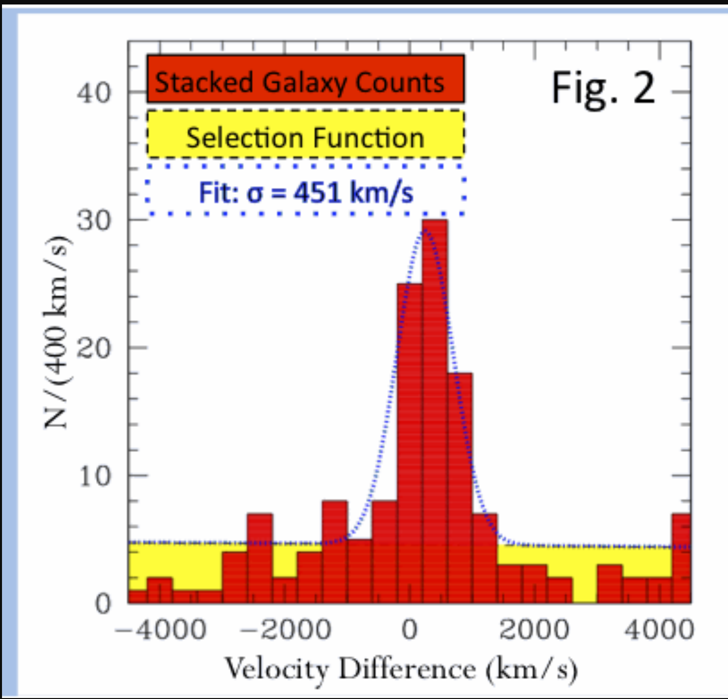




Ryan Trainor's Poster:

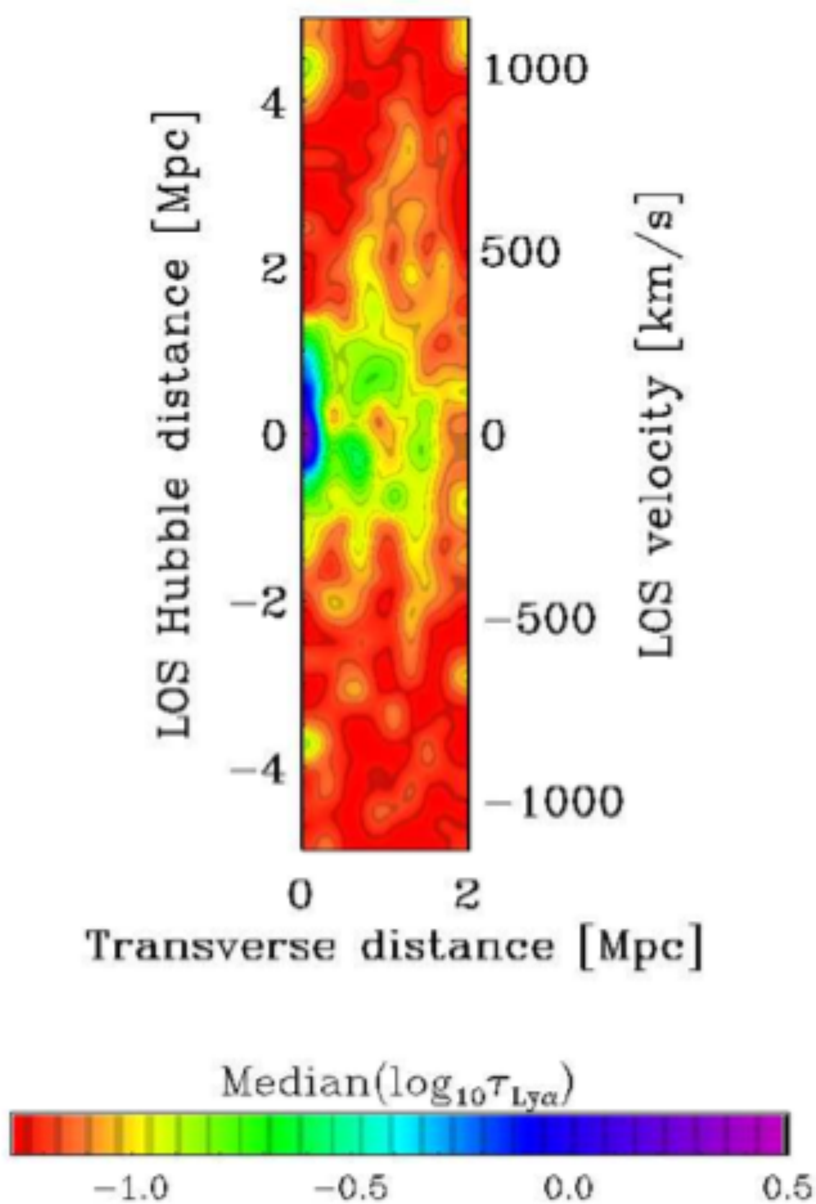
Hyper-luminous QSO ($\sim10^{14}$ L_{sun}) environments at z~2.75

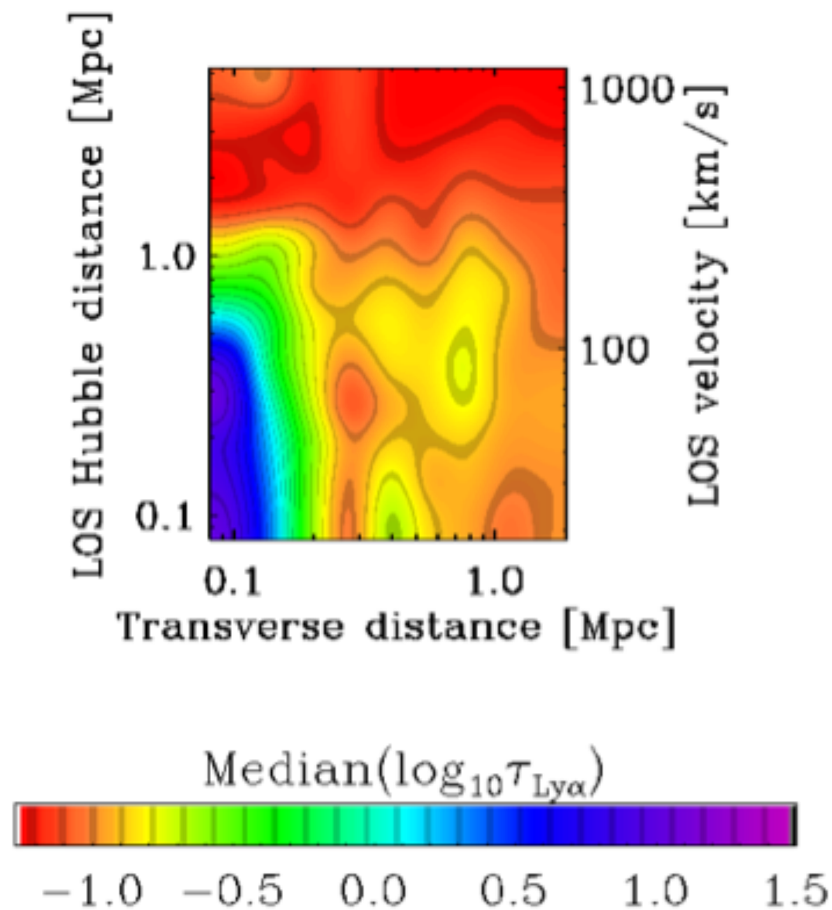
Brightest QSOs in the universe live in "modest", group-sized halos, log $M_h\sim12.7$, 200 kpc scales (~25" on the sky)



	Gal-Gal ACF	Gal-QSO XCF
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} ($M_\odot$)	11.75	12.5
M_{ave} ($M_\odot$)	12.0	12.7

The IGM from a Galaxy-centric Perspective



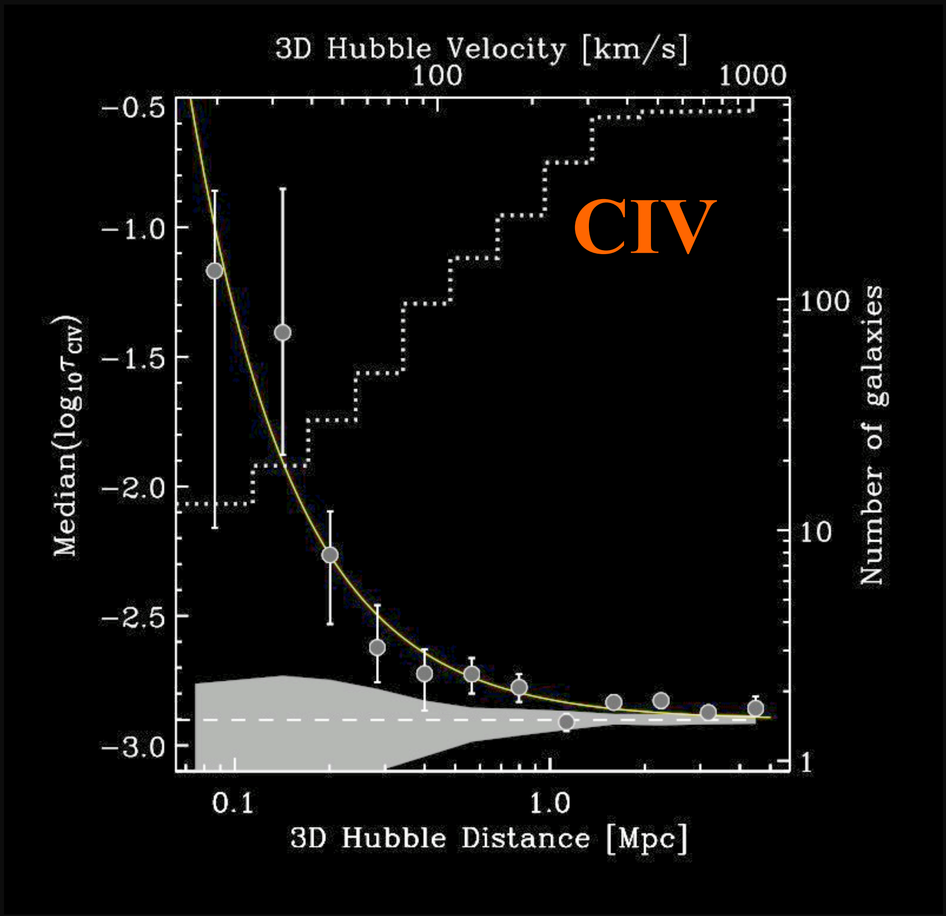


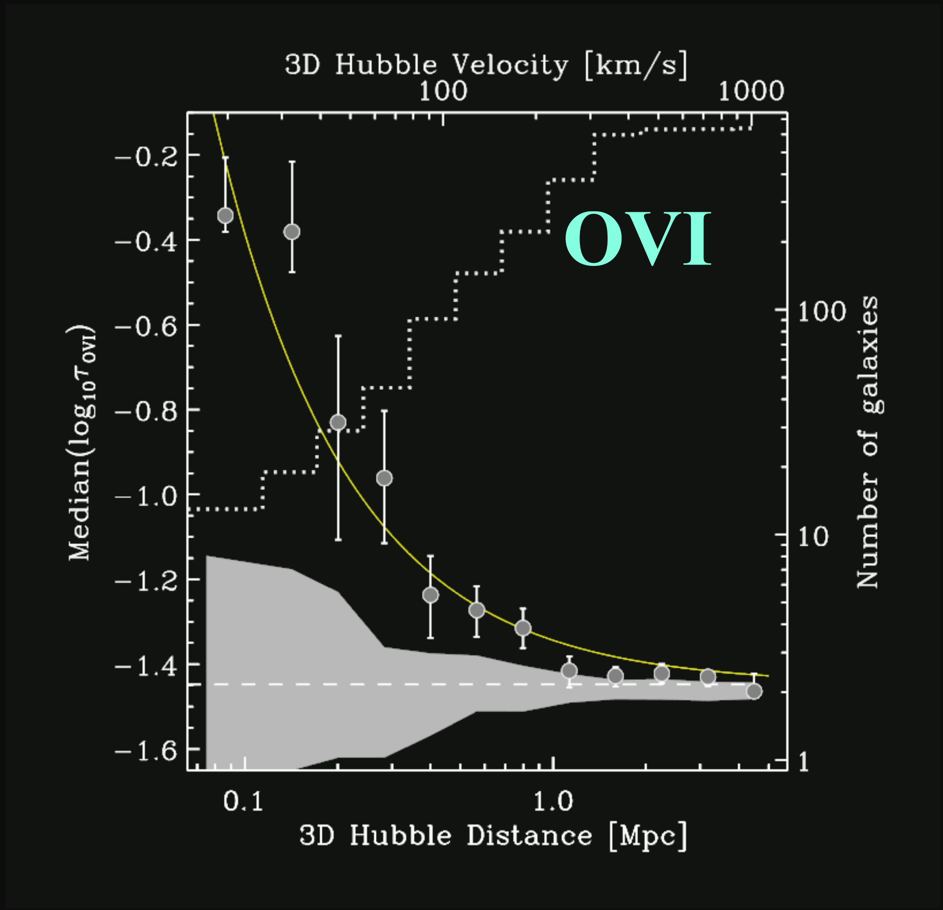
O. Rakic, CS, Schaye, Rudie+ 2011

Where are the Metals?

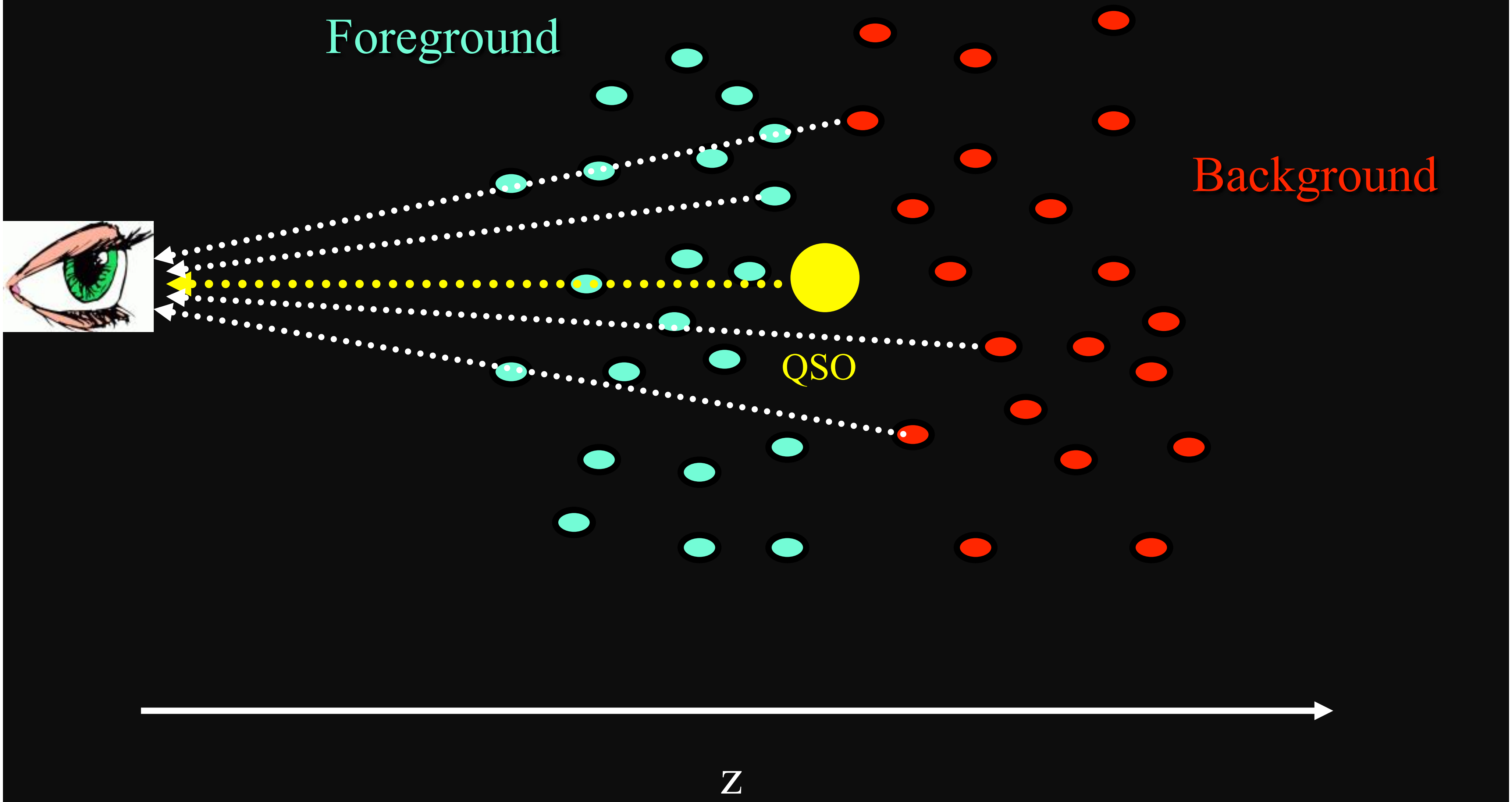
Pixel Optical Depth vs. physical distance from a galaxy @z=2.5

O. Rakic, CS, Schaye, Rudie+ 2011

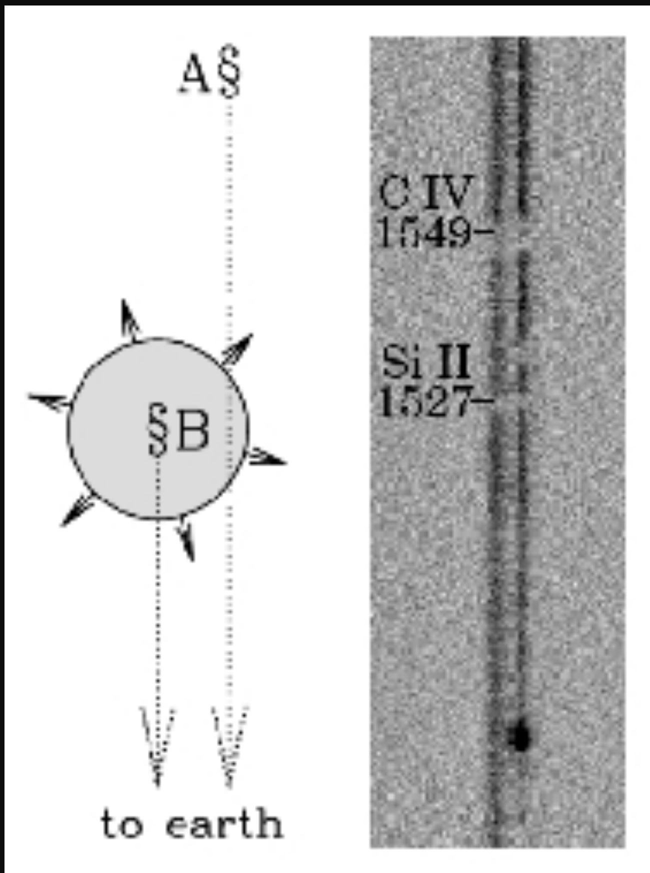


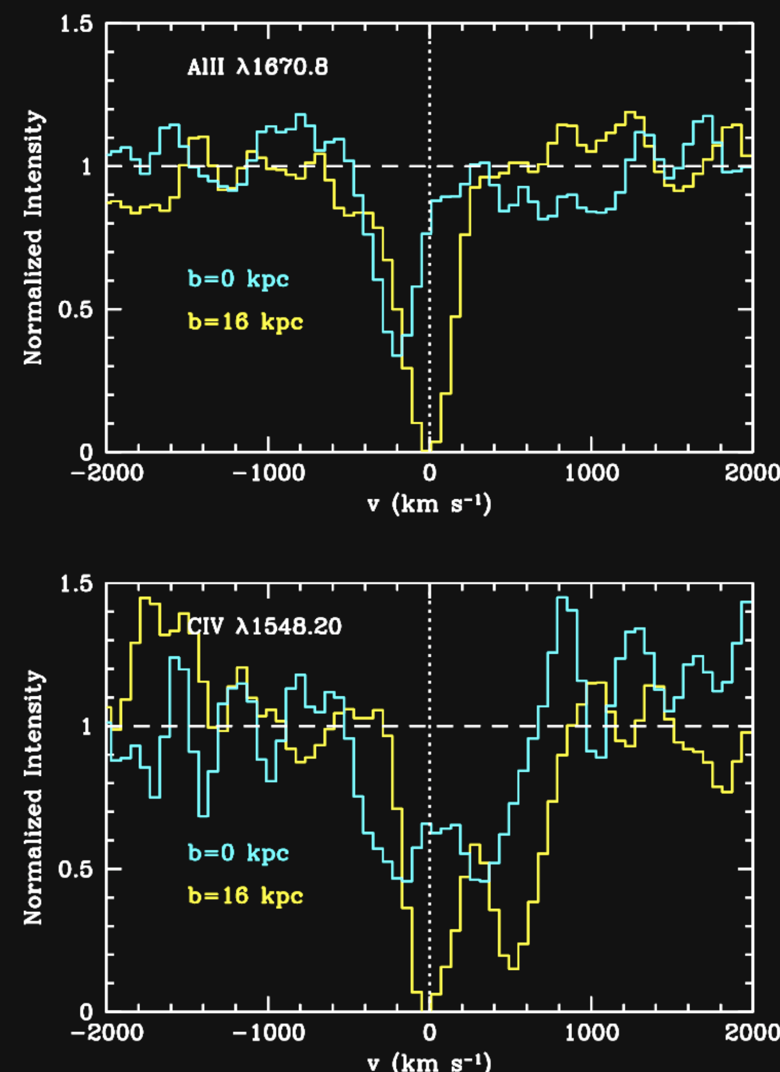


Densely Sampling the Universe @z~1.8-3.2



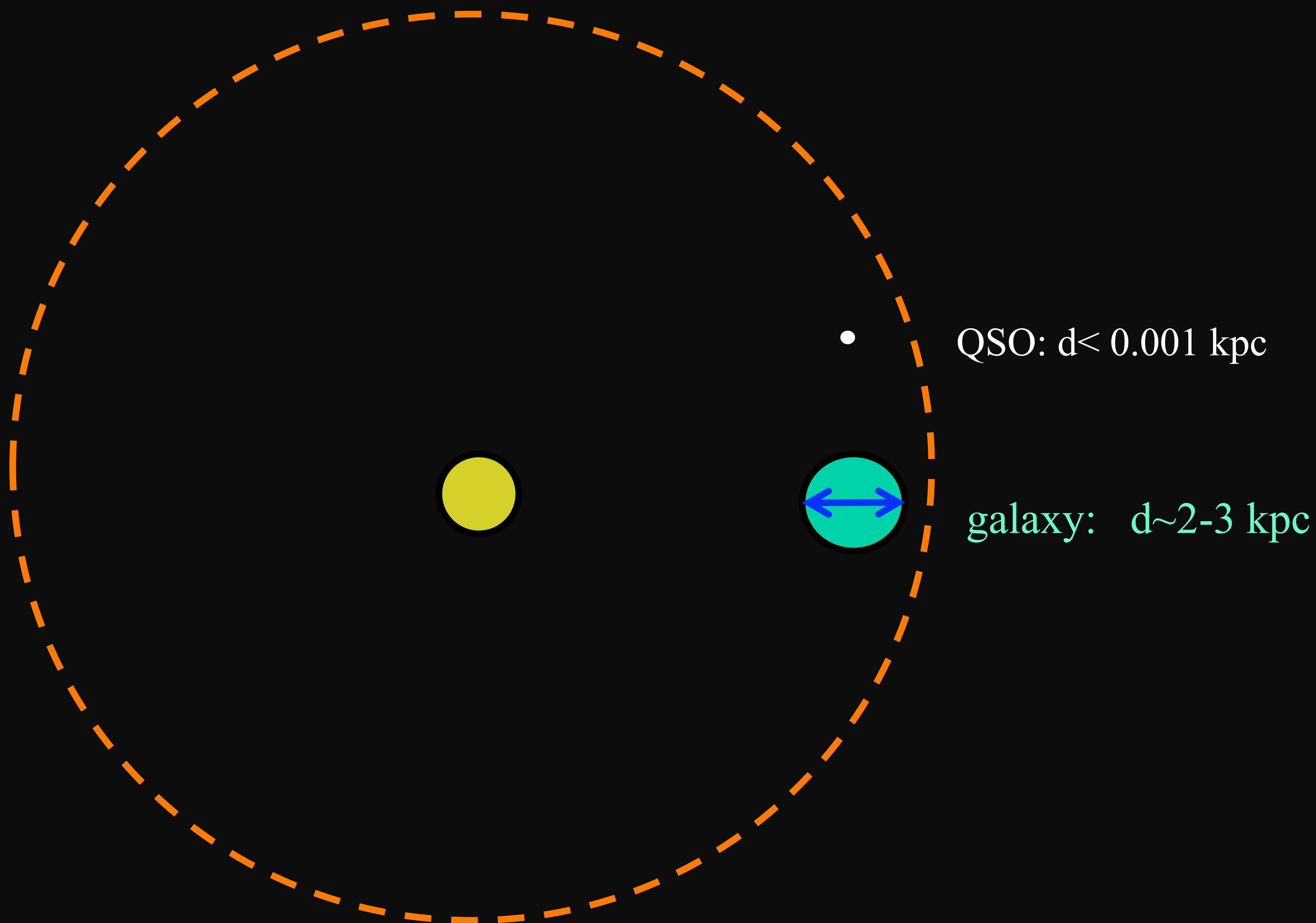
Using Background Galaxies to Probe Foreground Galaxy Flows





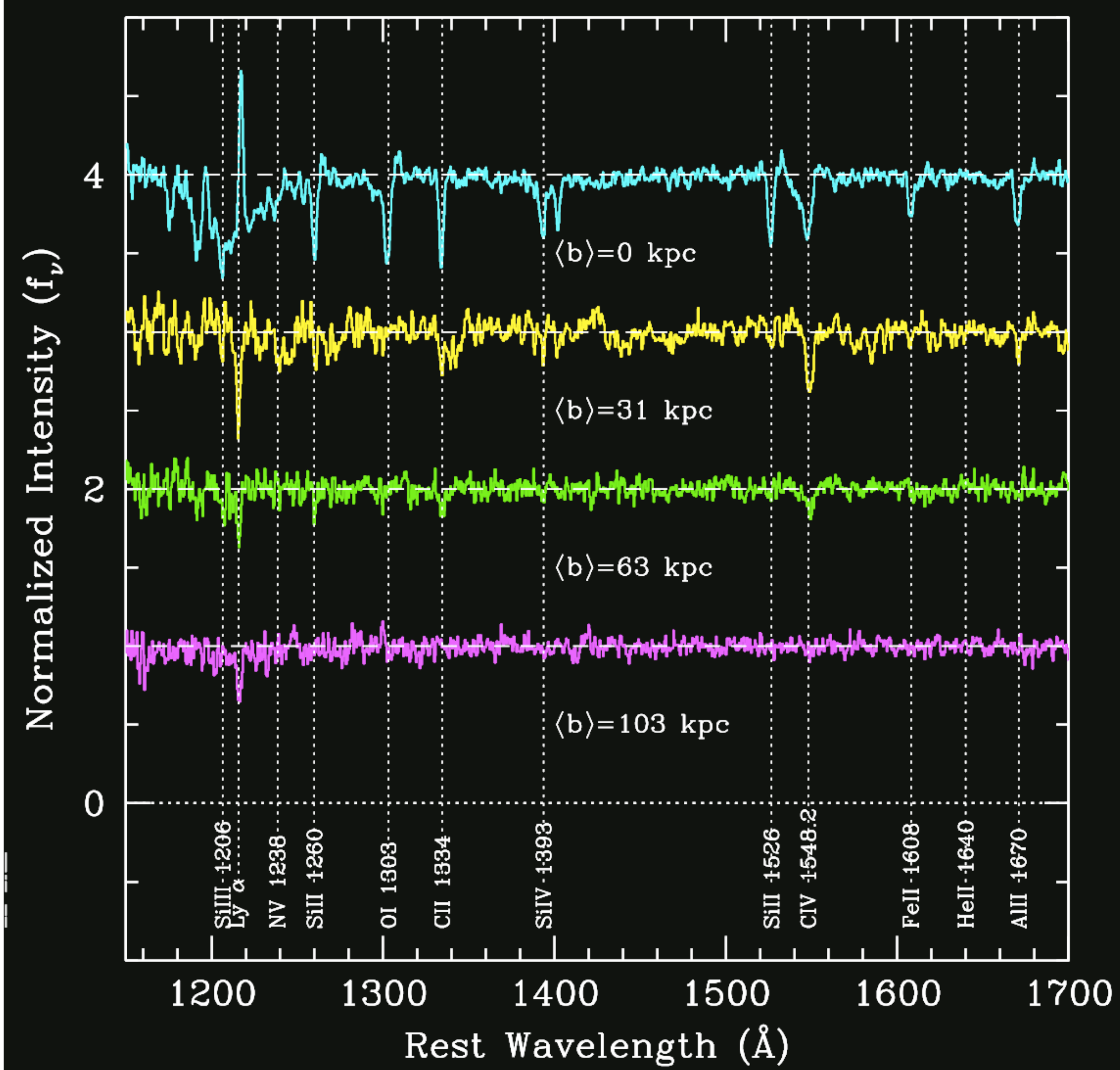
Keck/LRIS-B spectra,
R=1500, 3800-4100 A

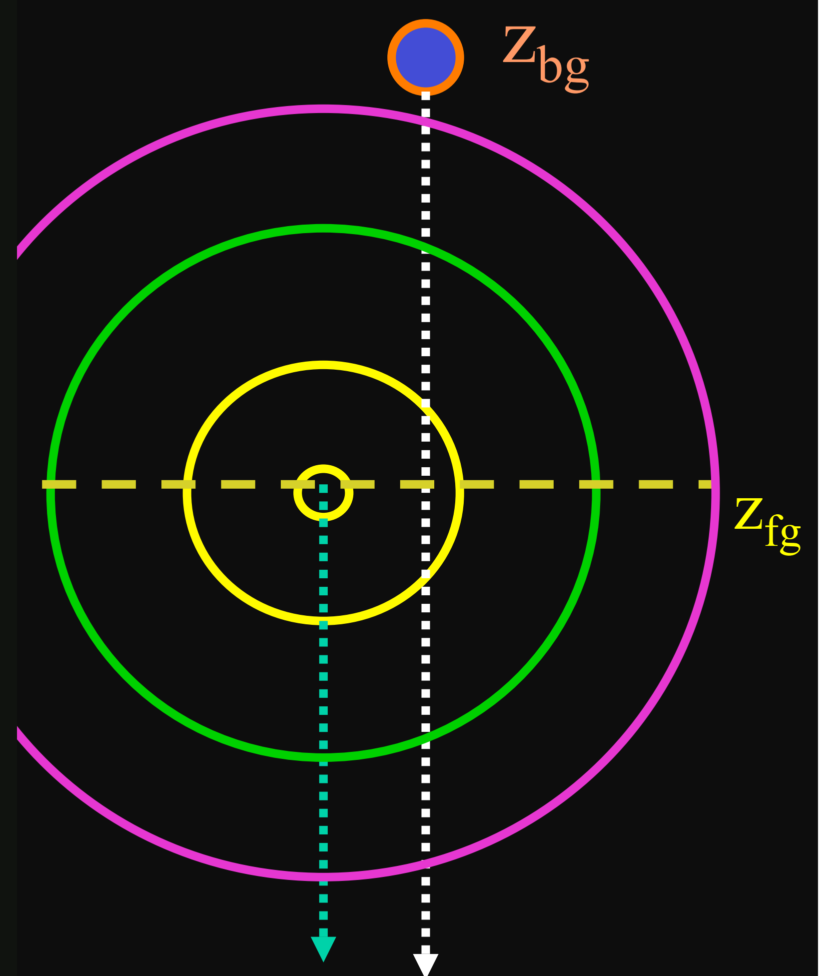
Galaxies vs. Point Sources as Probes of CGM



Galaxy Pair Composite Spectra

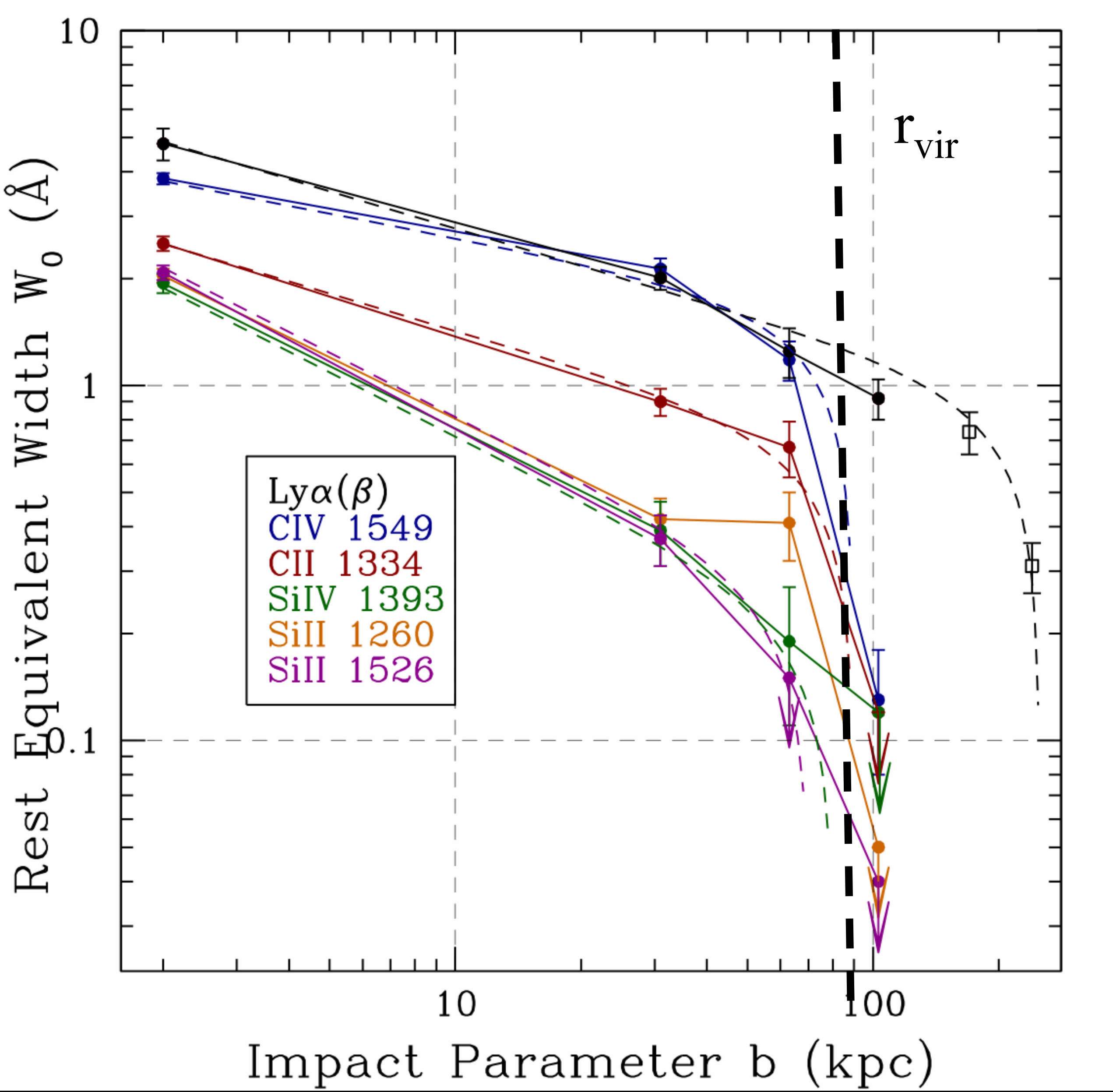
- 50 pairs 1-5” (<d>=30 kpc)
- 190 pairs 5-10” (<d>=70 kpc)
- 305 pairs 10-15” (<d>=100 kpc)





CS+2010

W_0 vs. Galaxy Impact Parameter, z~2-3 LBGs



Models:

TABLE 5
W_0 VS. b MODEL PARAMETERS[a]

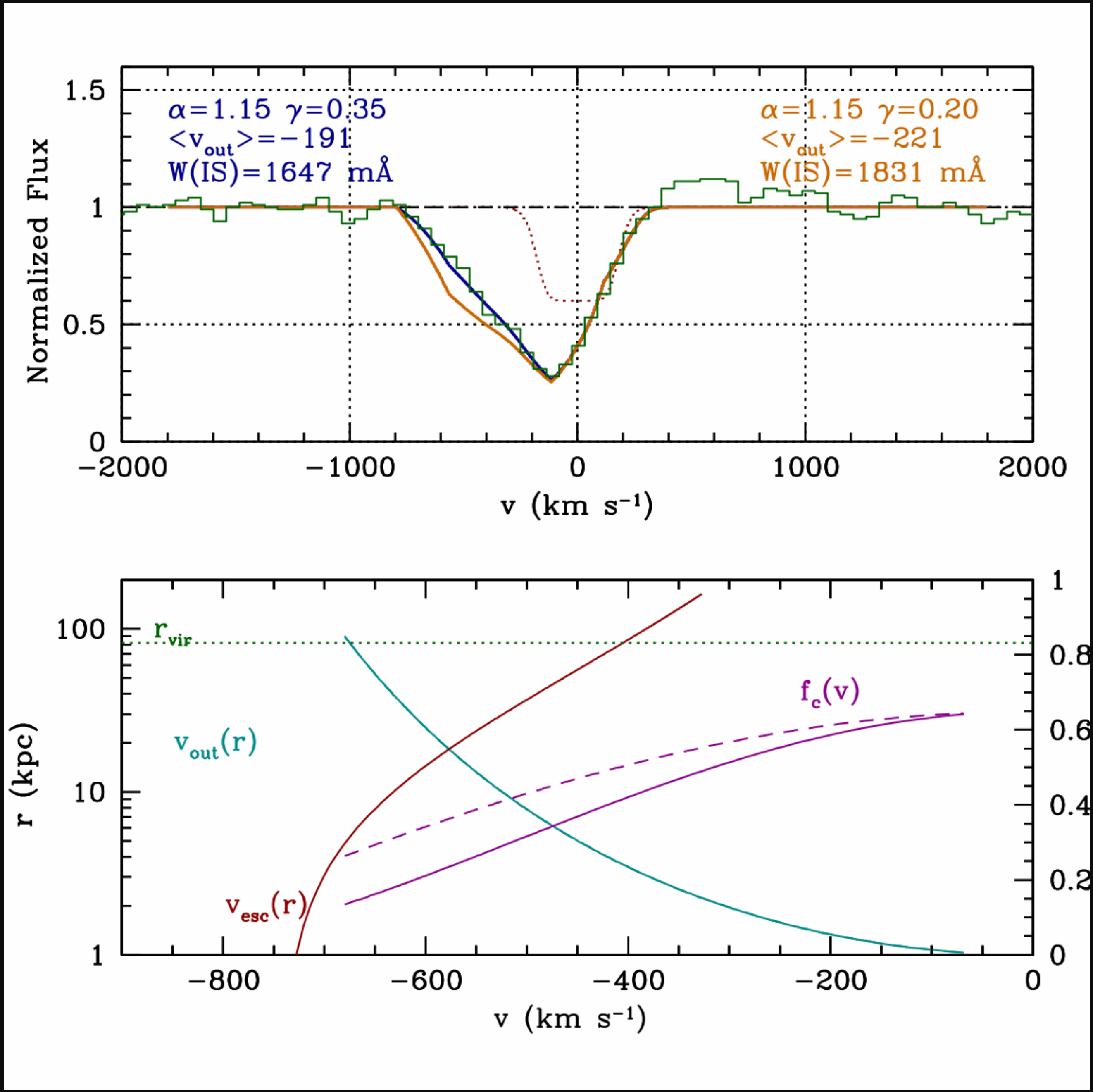
Line	γ[b]	R_{eff} (kpc)	v_{out}	$f_{c,max}$[c]
Lyα(1216)	0.37	250	820	0.80
C IV(1549)	0.23	80	800	0.35/0.25[d]
C II(1334)	0.35	90	650	0.52
Si II(1526)	0.60	70	750	0.40
Si IV(1393)	0.60	80	820	0.33

[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 λ1548 and C IV λ1550 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



Covering fraction:

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

(inferred from transverse sightlines)

Cloud acceleration:

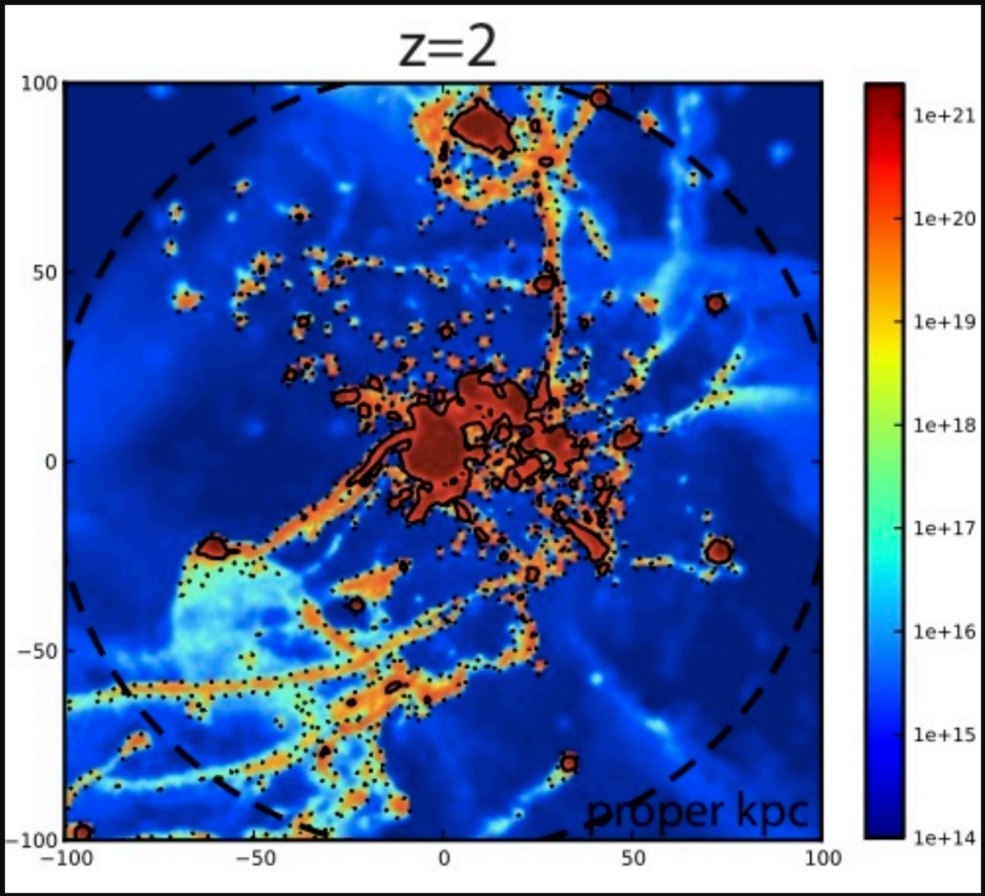
$a(r) \sim r^{-\alpha}$

constrained by shape of line profile

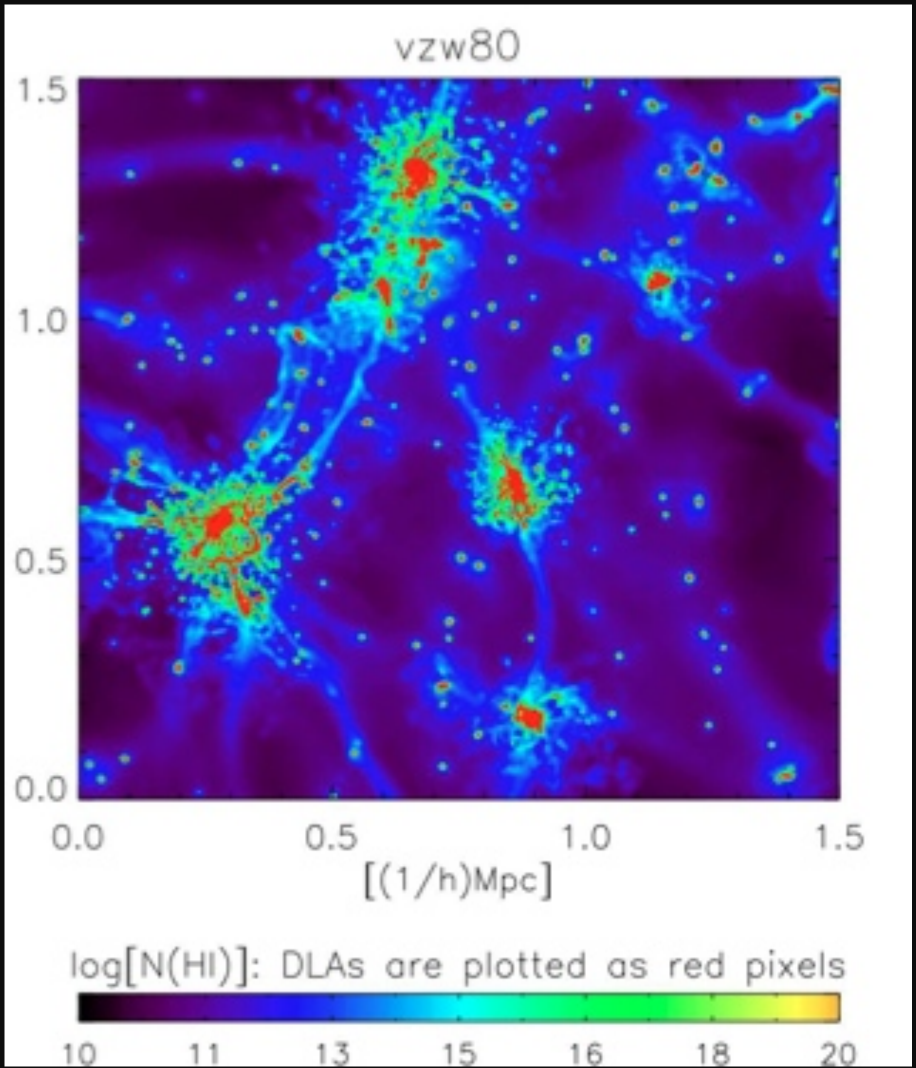
CS et al 2010

Cool Gas Accretion in Simulations

Faucher-Giguere +2011

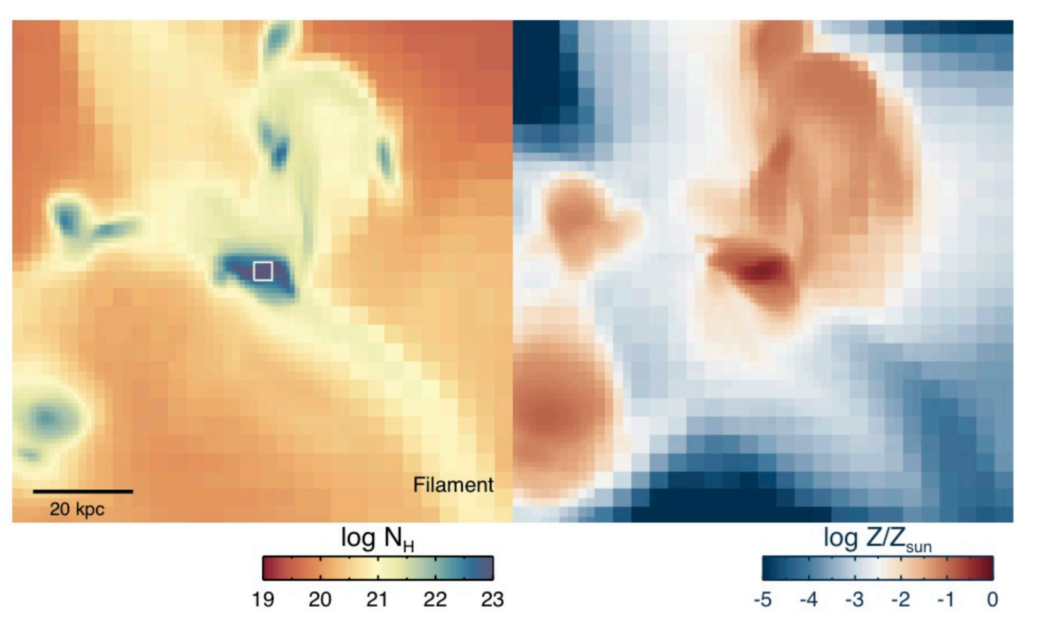


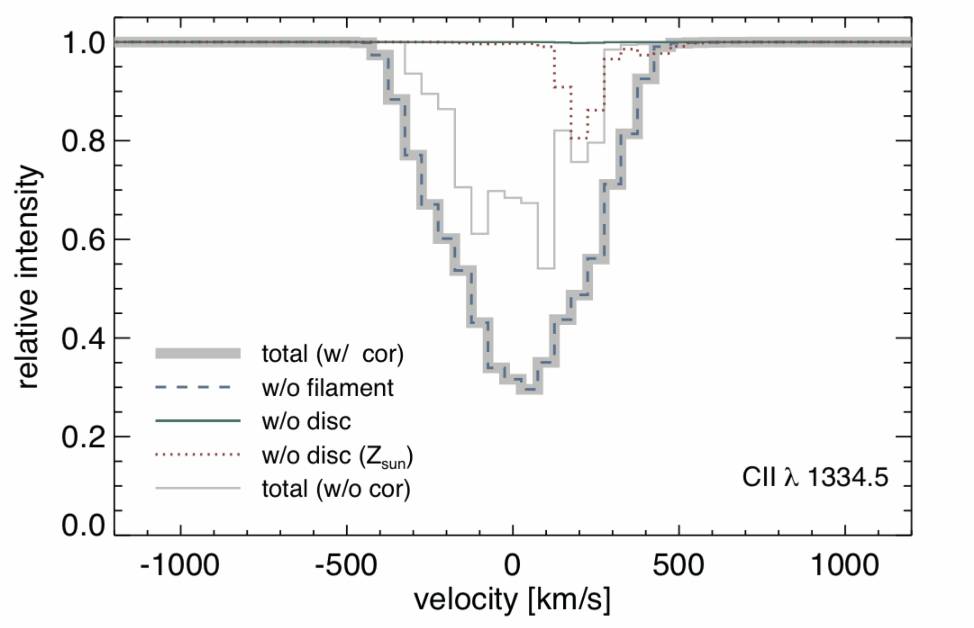
Hong 2010

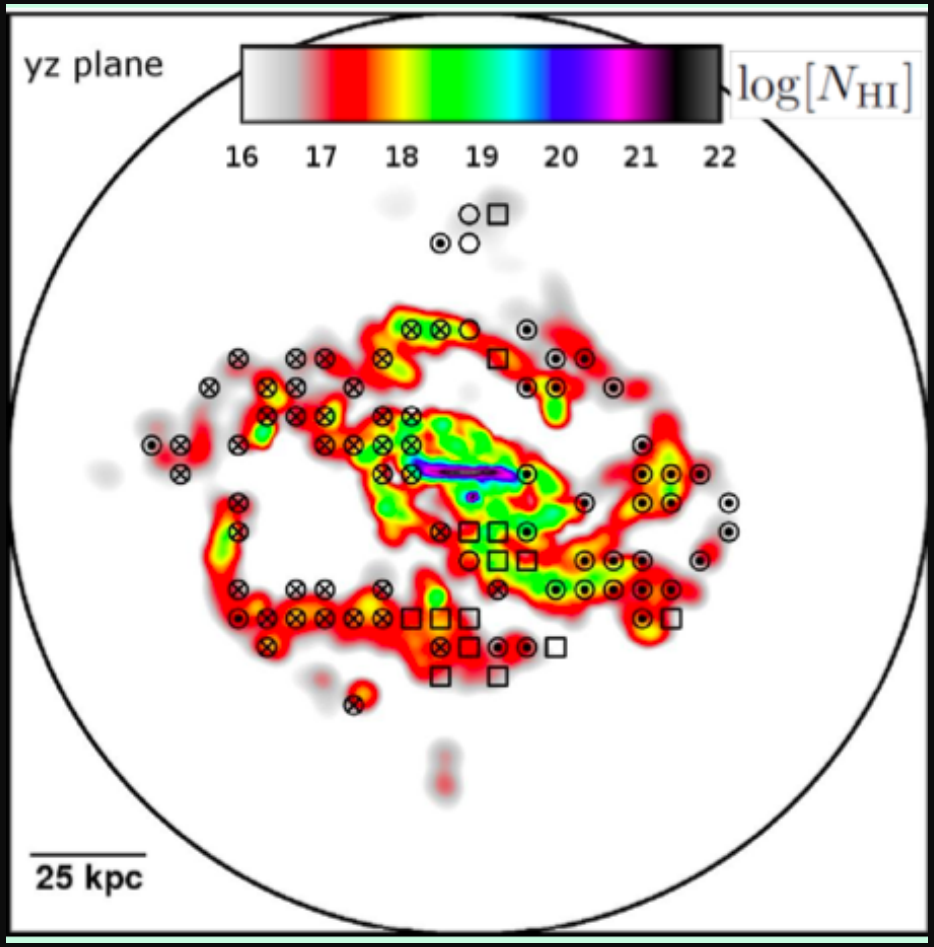


Cool Gas Accretion in Simulations

Kimm+ 2010







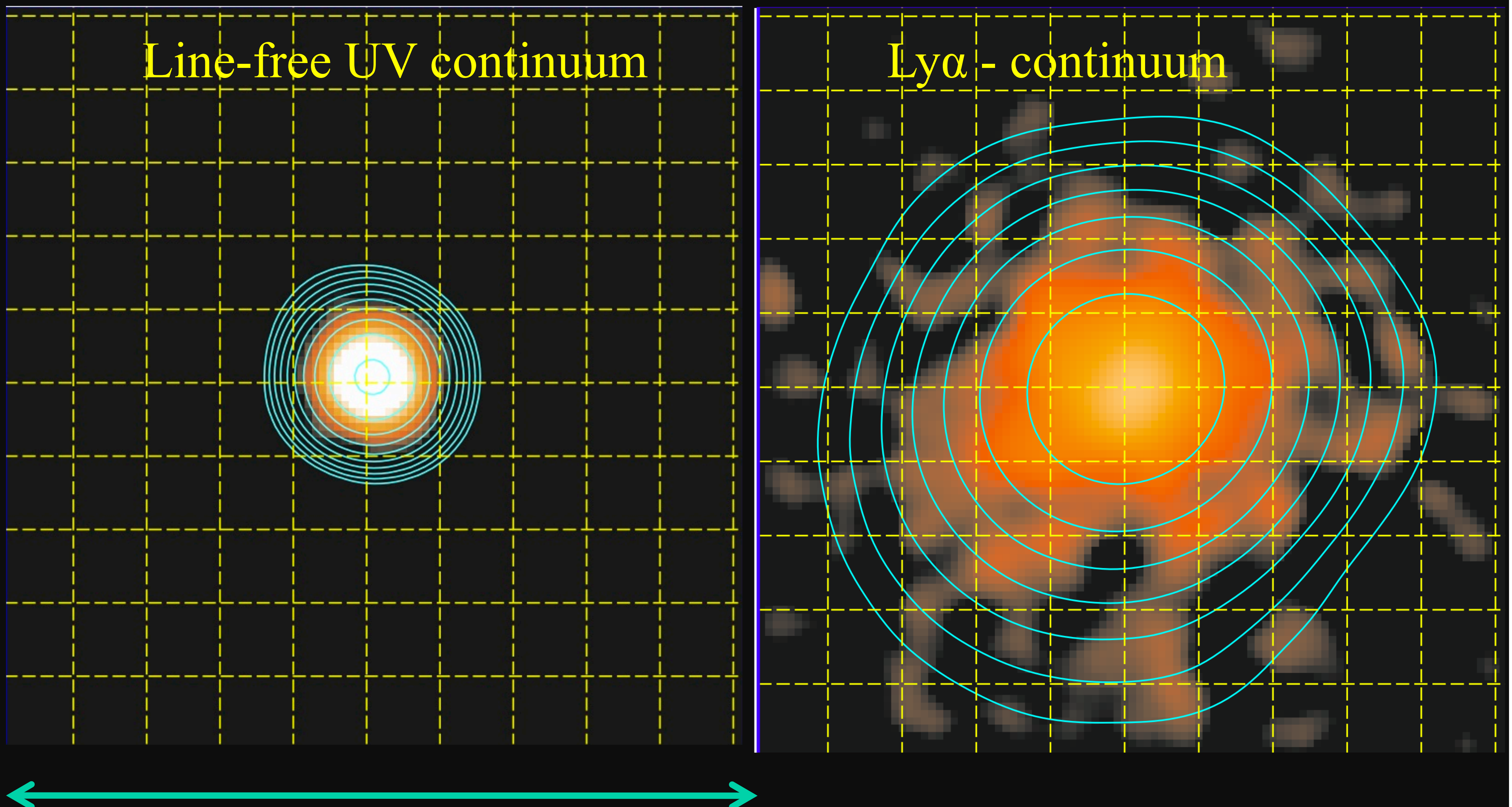
Stewart+ 2011

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)

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

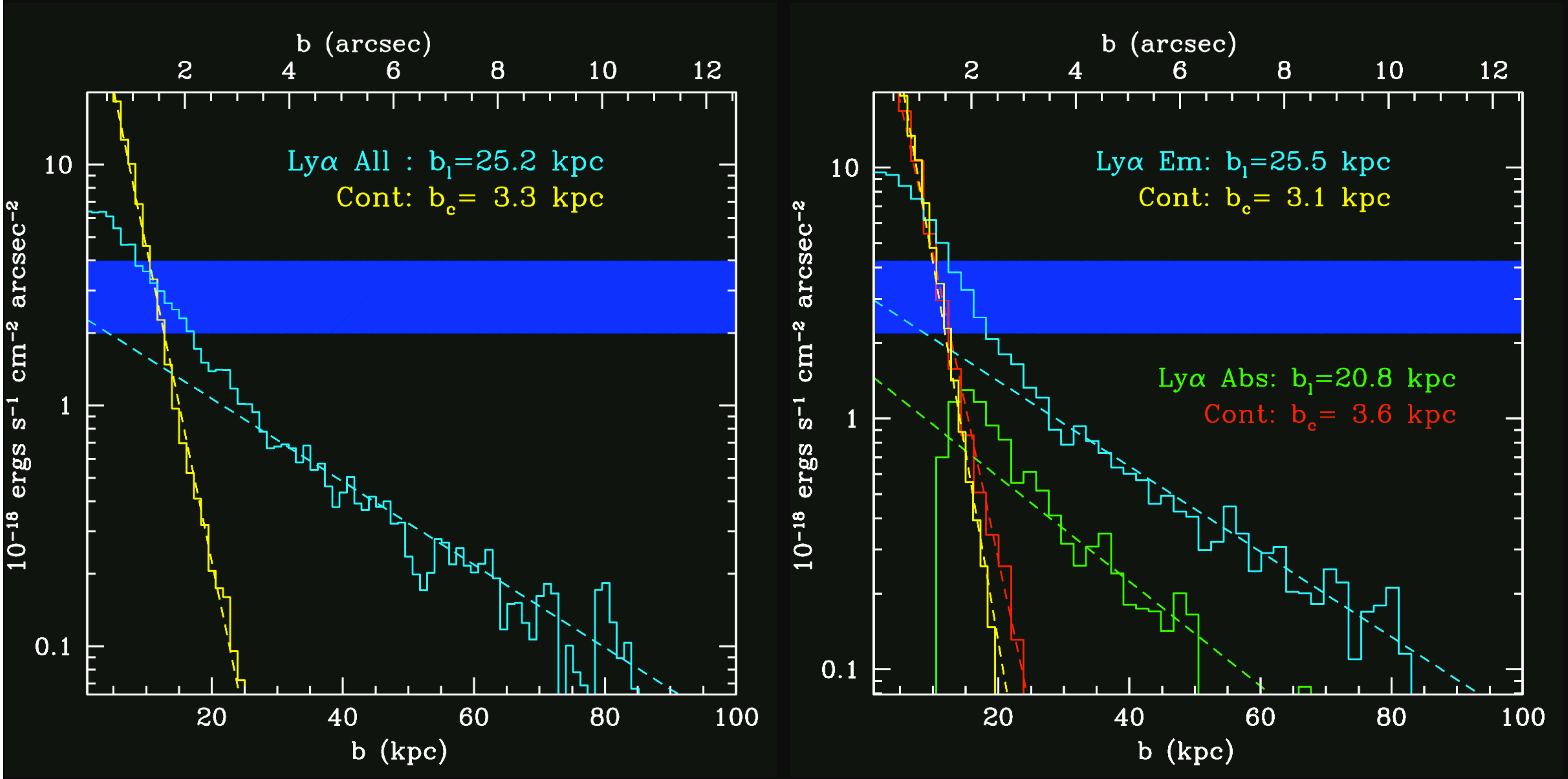
Average Lyα Emission from ~100 UV-continuum selected galaxies (0.3-$3L^*_{UV}$), $\langle z \rangle \sim 2.65$



20” ~ 160 kpc (physical)

CS et al 2011; see also Hayashino et al 2004

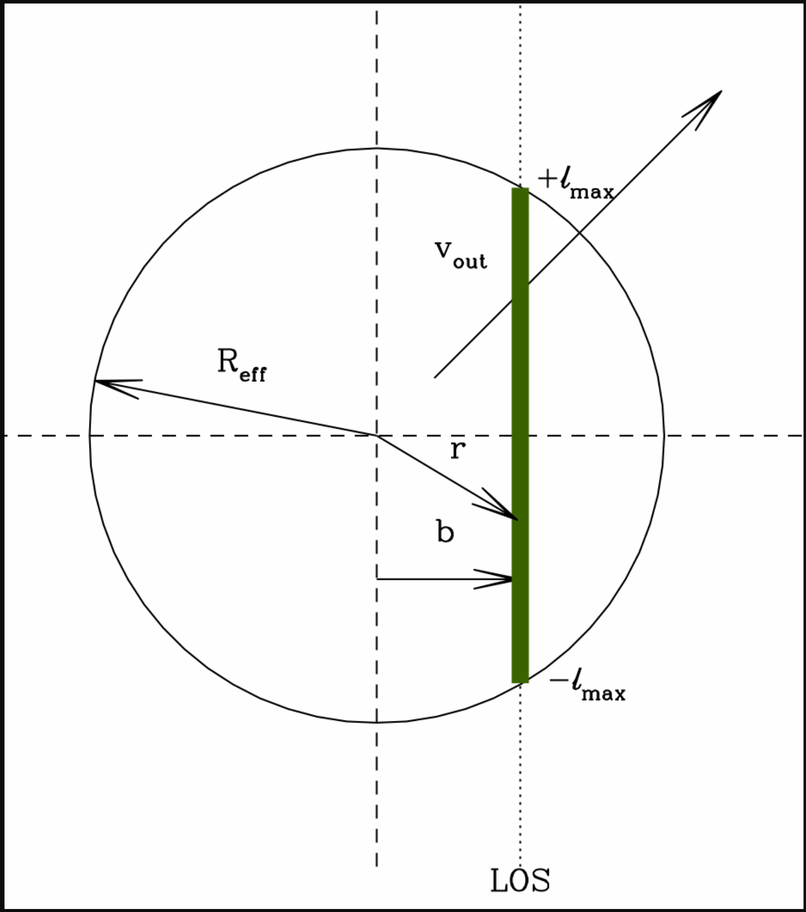
Average, All Galaxies　　Separated by Spectral Morphology



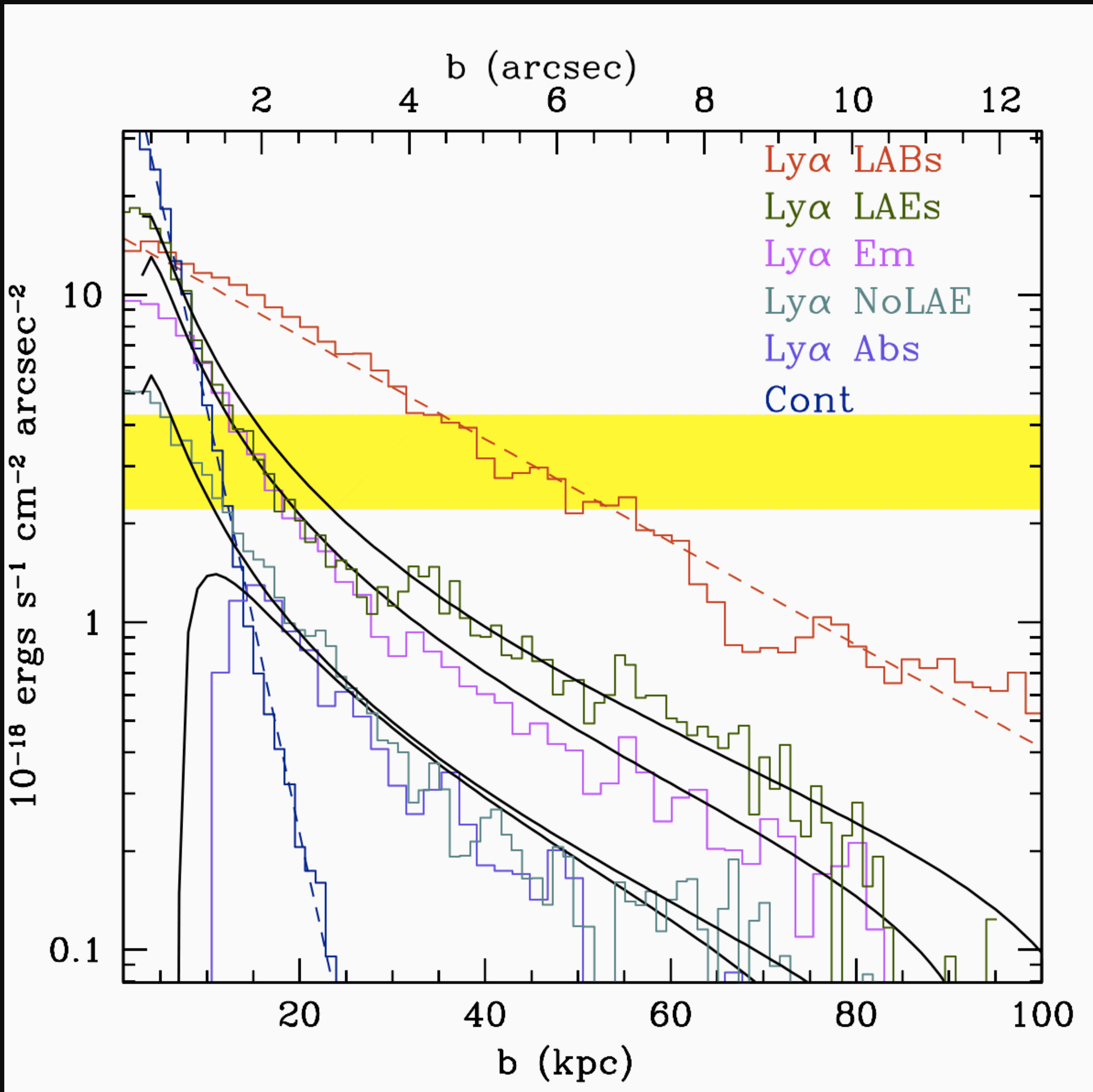
Fits are $SB(b) \sim \exp(-b/b_l)$

Lyα Scattering Model for Diffuse Halos

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



- All Lyα photons produced in HII regions
- Photon dilution ~ $1/r^2$
- Scattering in observer's direction depends on HI covering factor $f_c(r)$
- Subsequently depends on low optical depth in observer's direction, ~$[1-f_c(r)]$

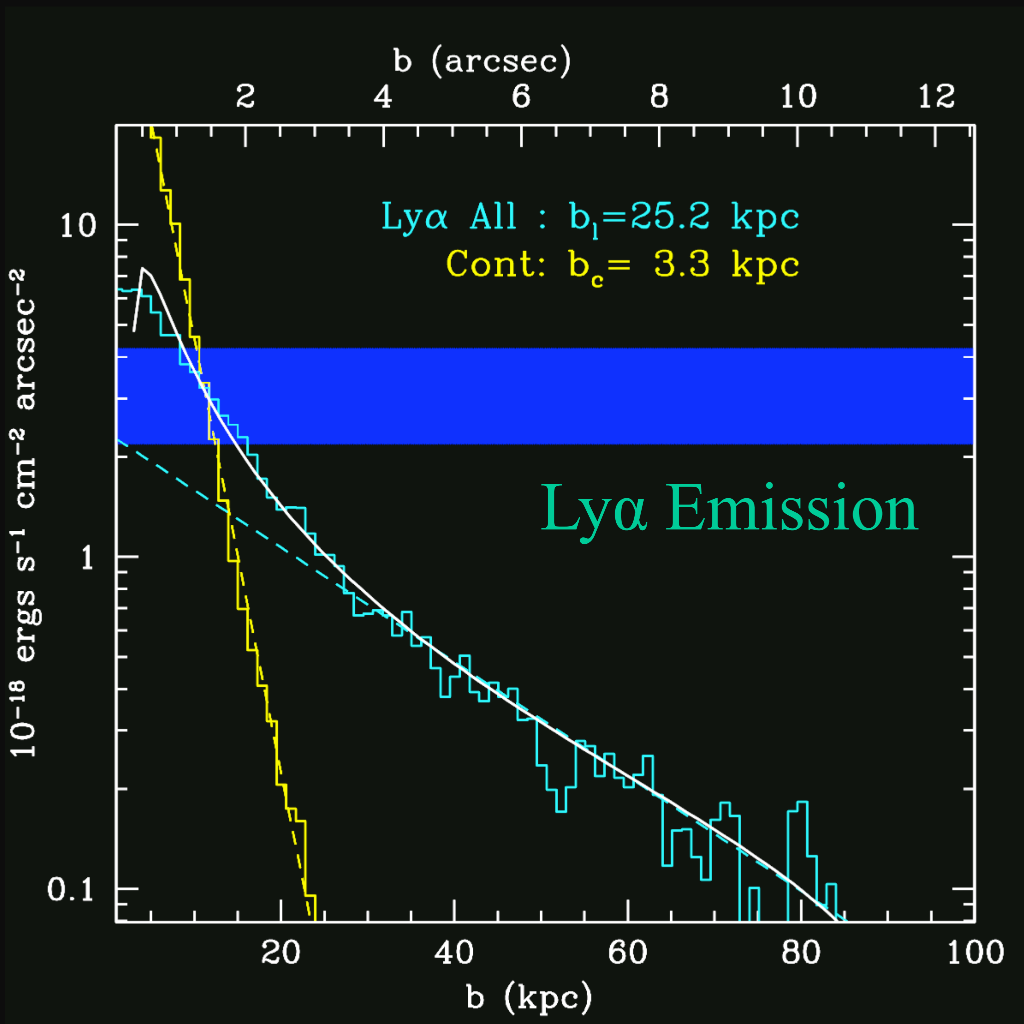


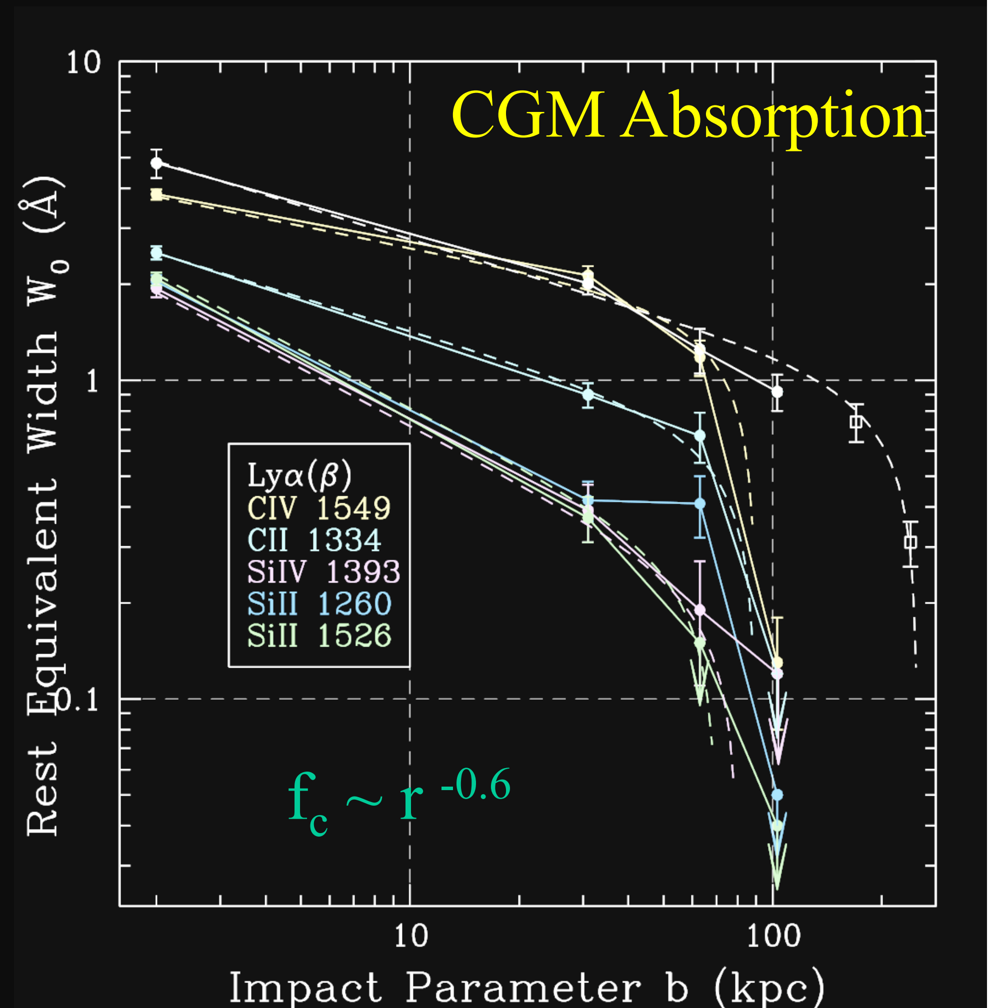
Diffuse Lyα Halos for galaxy subsets, fit with simple scattering models, same:

- $f_c(r)$
- R~90 kpc

CS et al 2011

Lyα Scattering and CGM Absorption Strength





model: $f_c \sim r^{-0.6}$

R_{eff}=90 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 $\sim 10^{12}\ M_\odot$:

$M_b(\text{cosmic}) \sim 1.6 \times 10^{11}\ M_\odot$

$M_* + M_{cold} \sim 0.4 \times 10^{11}\ M_\odot$

$M_{CGM} > 0.5 \times 10^{11}\ (t_{sf}/500\ \text{Myr})\ M_\odot$

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)*