# Quasars Probing Quasars VII & VIII. The Pinnacle of Cool CGM at $z \sim 2$ and the Physics of Massive Galaxy Formation

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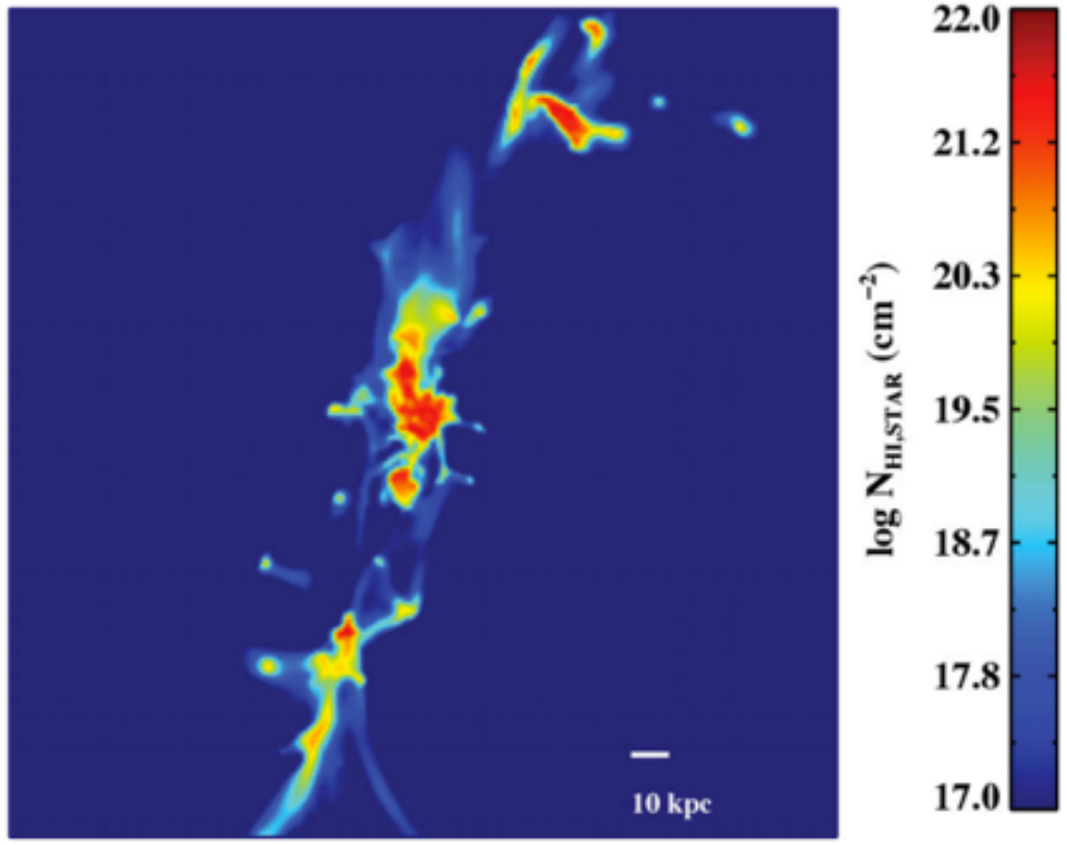
# The Circumgalactic Medium (CGM)

- Diffuse gas, metals and dust
- $T = 10^4 — 10^6$ K
- $\Delta R = 10 — 300$ kpc
- Bound to the dark matter halo?
- Supply fuel to star formation
- May be driven by SF feedback
- CGM is too diffuse to study in emission
- A random sightline is intercepted by < 1 massive halo

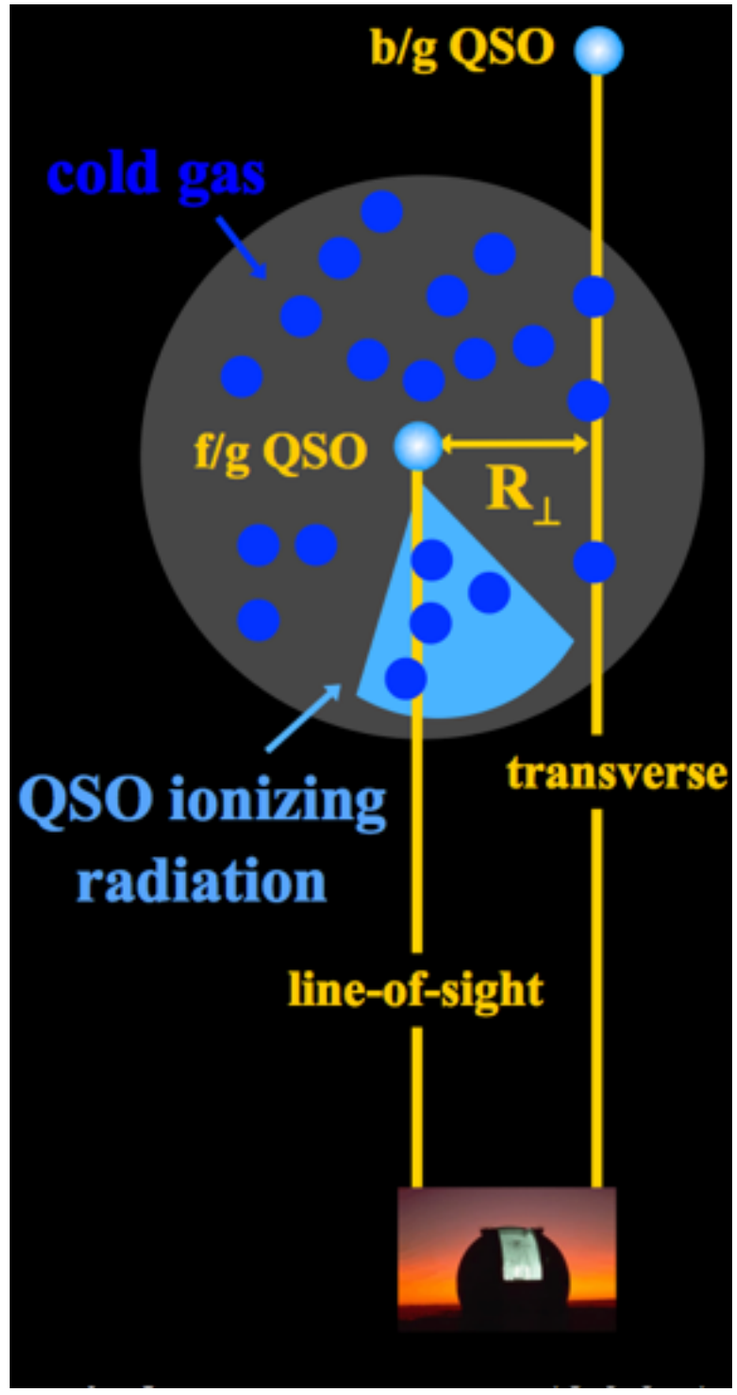



Simulated $z \sim 3$ massive galaxy CGM, AMR code ART, radiative transfer post processing, Fumagalli+11

# The Quasars Probing Quasars (QPQ) Experiment

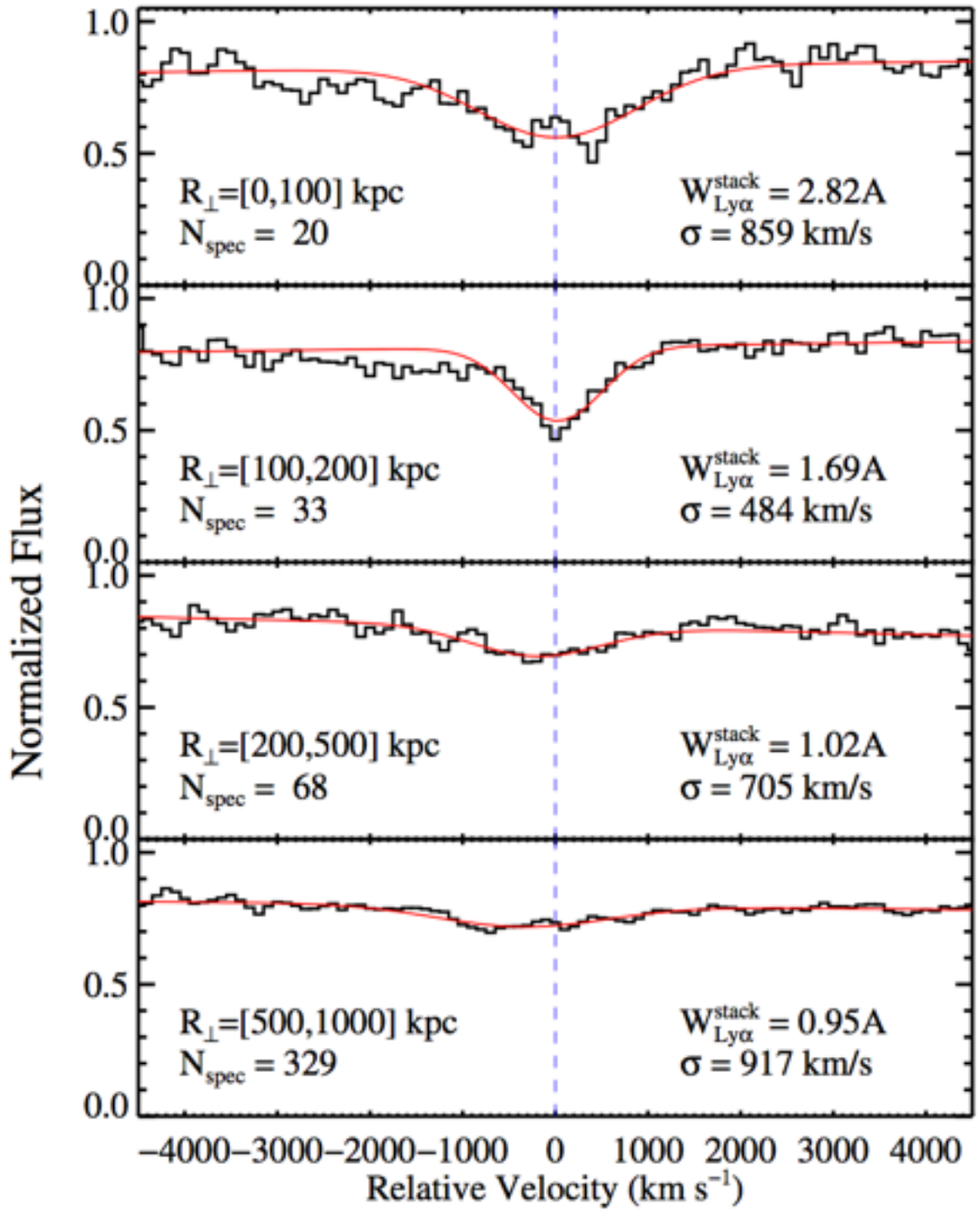
- ~ $10^6$ quasars in SDSS
- Assume correlation takes the form $\xi_{QQ} = (r/r_0)^{-\gamma}$ , clustering amplitude $r_0 \sim 8\ h^{-1}$ Mpc at $z \sim 2$ implies

  $M_{halo} \sim 10^{12.5}\ M_\odot$ (White+12)
- Quasar hosts are predicted to evolve into present day massive galaxies
- Follow up spectroscopy on closely projected quasar pair candidates
- To date our QPQ survey has ~ 700 pairs to within 1 Mpc separation (QPQ6)



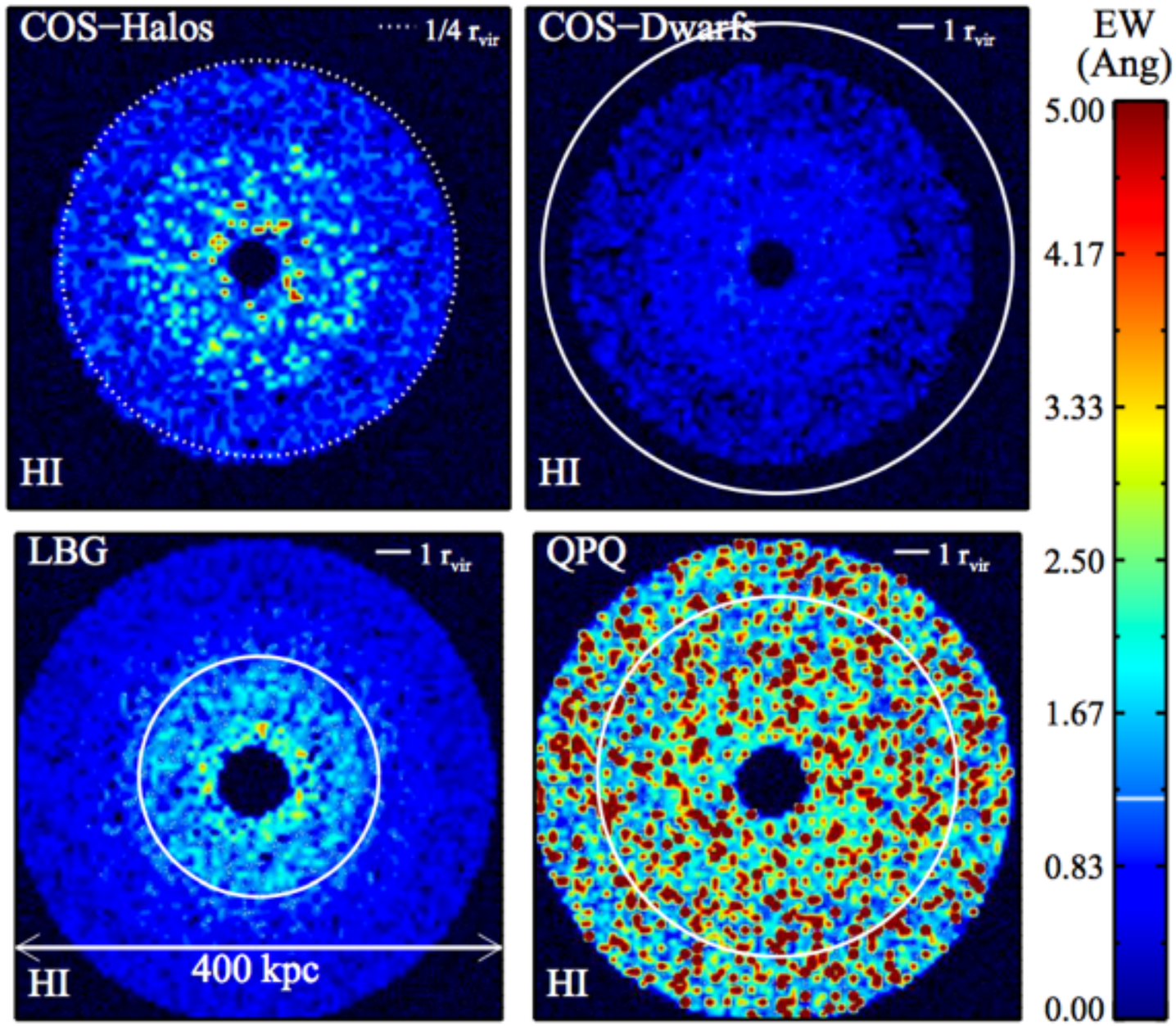
# Optically Thick Absorbers around *z* ~ 2 Quasars

- Extending to ~ 1 Mpc (QPQ1, QPQ5, QPQ6)
- Line-of-sight proximity effect: a quasar's spectrum doesn't show absorption by its own gaseous halo (QPQ2)
- No evidence of transverse proximity effect (QPQ4, QPQ6)

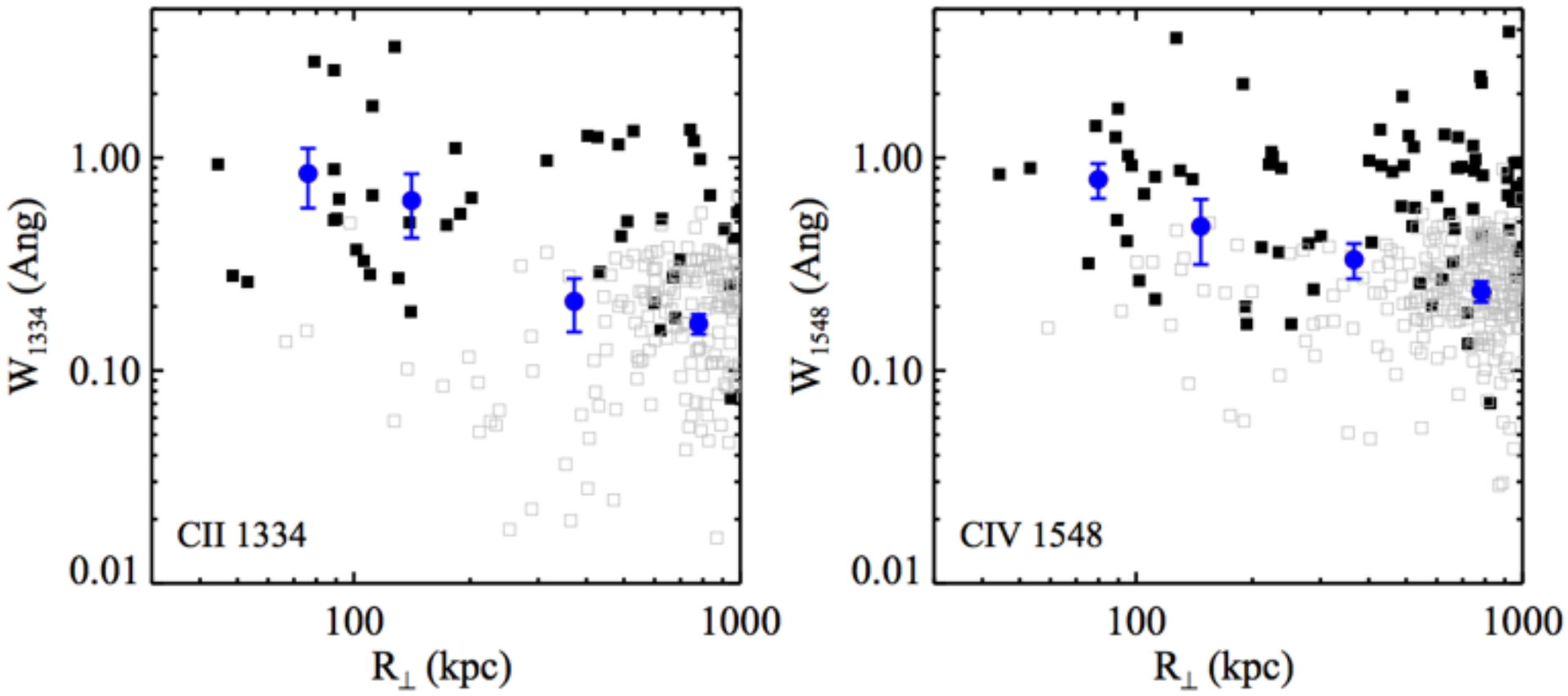


# Optically Thick Absorbers around *z* ~ 2 Quasars

- A high incidence of large HI Ly*α* EWs along the QPQ sightlines (QPQ1, QPQ2, QPQ6)
- Simulations underpredict the covering fractions (Fumagalli+14)



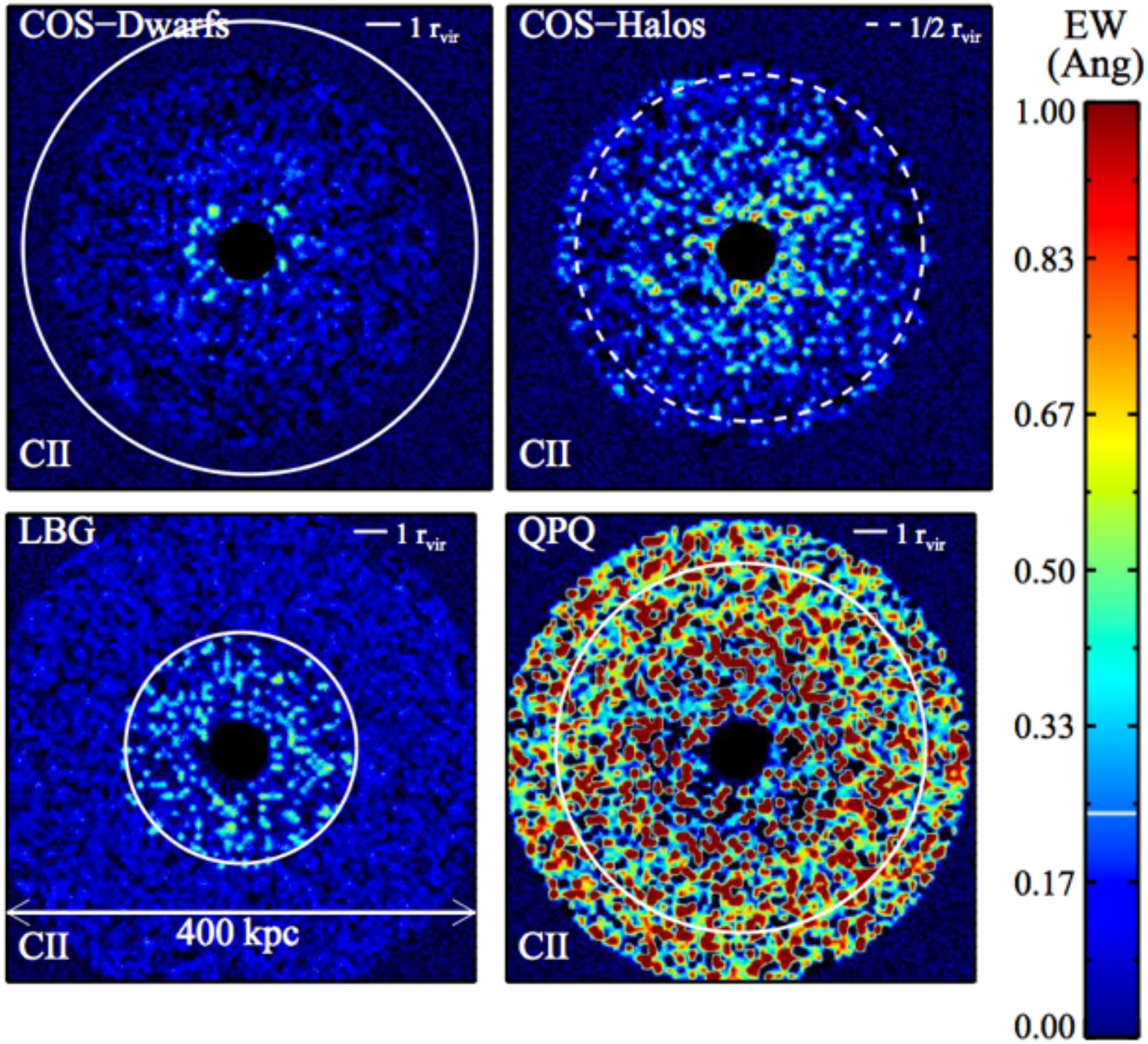
# QPQ7: Highly Enriched Cool CGM of $z \sim 2$ Quasars




- Large EWs, ~ 1 Å
- Strong CII absorption at $R_\perp < 200$ kpc and weak beyond
- Excess incidence of strong CIV absorption to 1 Mpc

# QPQ7: Highly Enriched Cool CGM of *z* ~ 2 Quasars

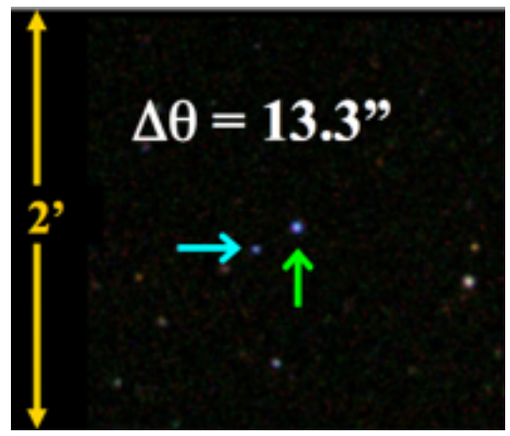
- Pinnacle of cool, enriched gas among all galaxy populations
- Quasar feedback unlikely the main driver of cool, highly enriched CGM
- Host halos more massive than coeval LBG halos
    - May be driven by halo mass?



# QPQ8: From Quantitative to Qualitative Assessment

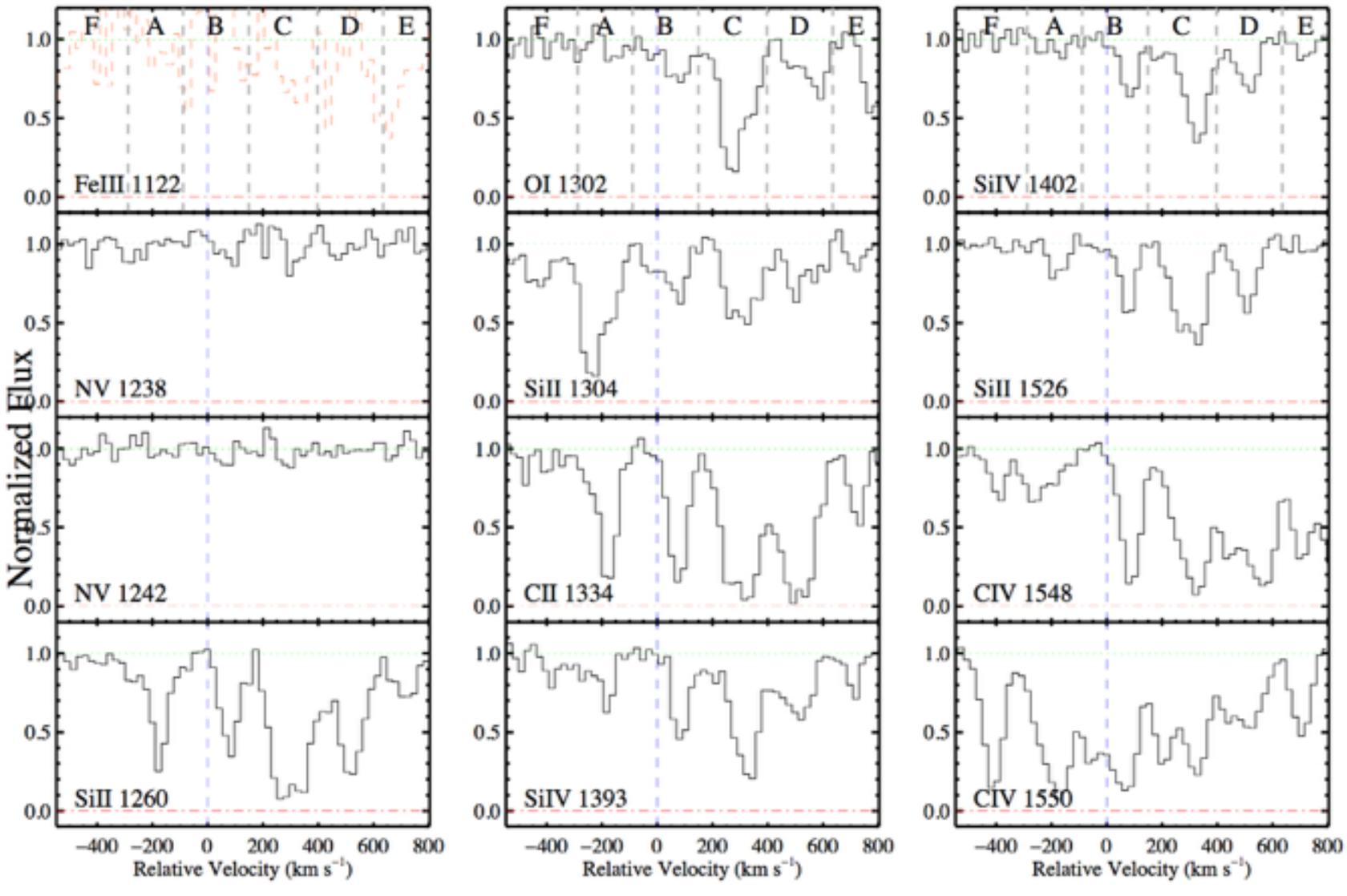
- QPQ1 — QPQ7 measured covering fractions and EWs from low dispersion data
- To construct a detailed model for the physical state of the gas, we require:
  - Echellette resolution
  - Closely projected, $R_\perp < 300$ kpc
  - Physically unassociated, $\Delta v \gtrsim 4000$ km s$^{-1}$
- The prototype QPQ3: is it typical?
  - Construct a statistical sample of 11 quasar pairs

J1204+0221

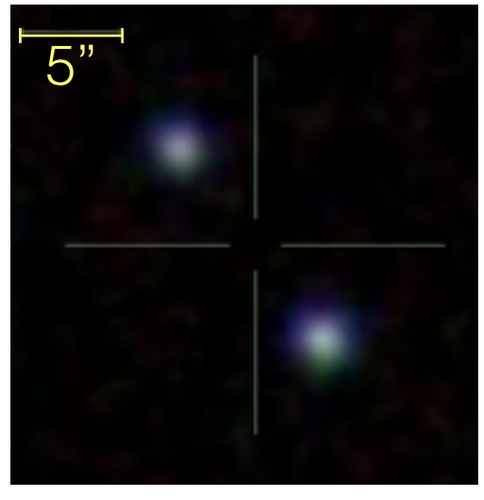


# QPQ8: Multiple Ionization States of Metals

- ± 2000 km s$^{-1}$ search window around $z_{fg}$ for absorption lines
- Absorptions at unrelated redshifts can be identified

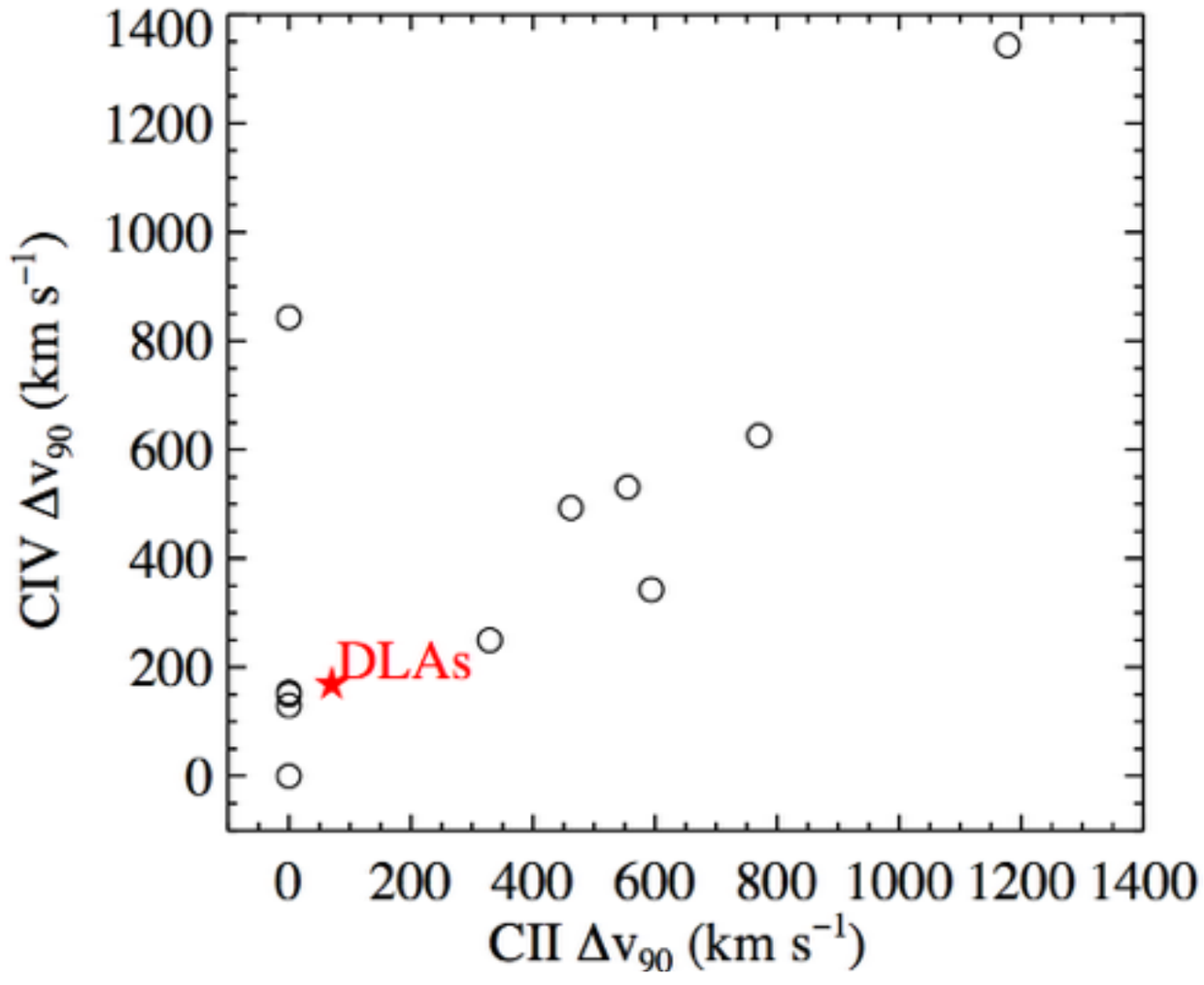



J1420+1603BG
$z_{bg}$ = 2.06
$z_{fg}$ = 2.02
$R_\perp$ = 108 kpc

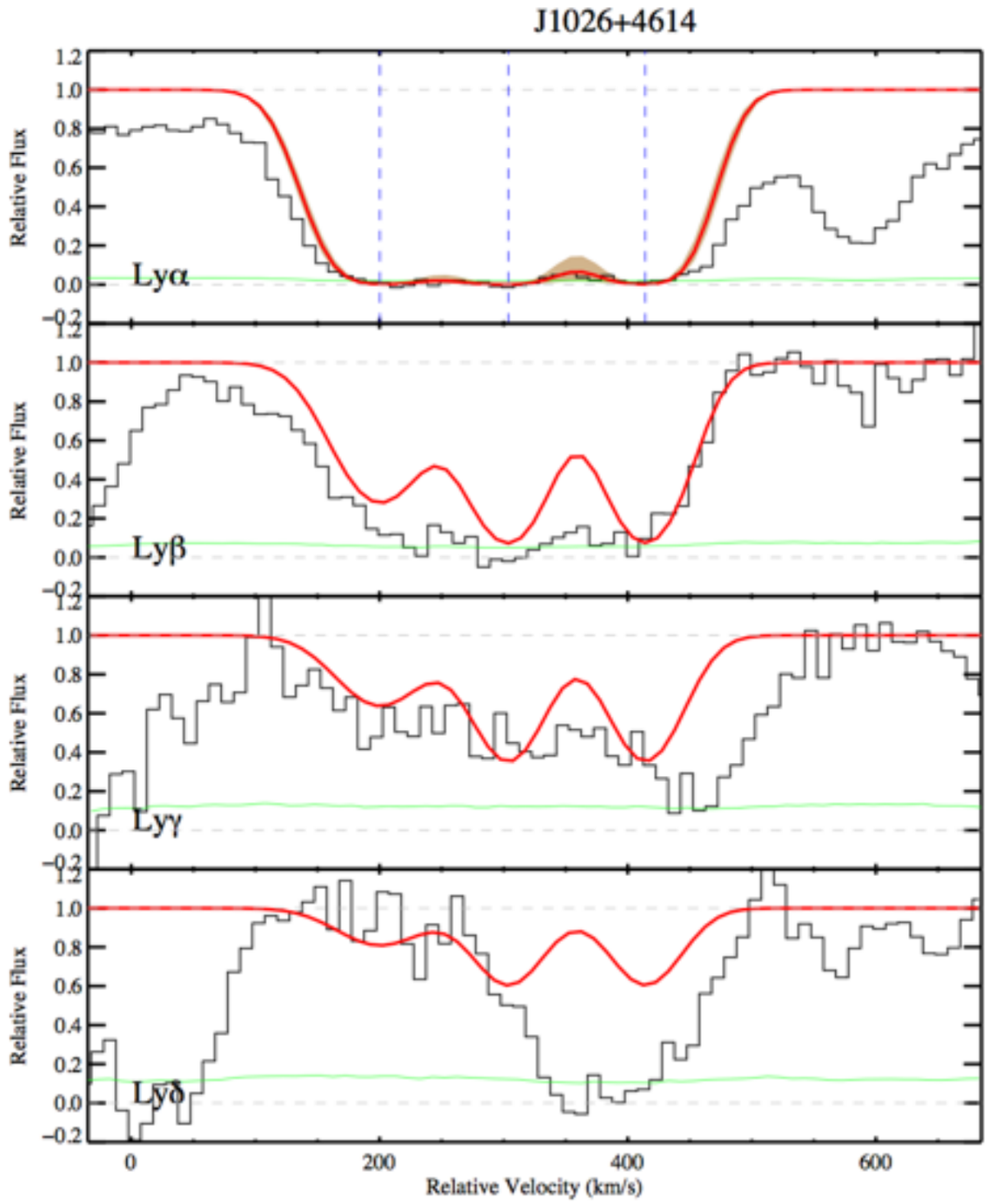


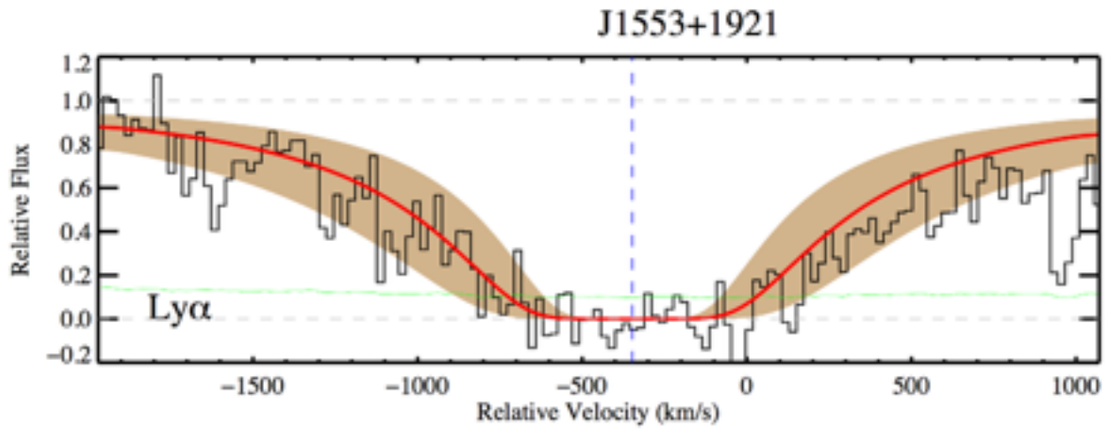
# QPQ8: Velocity Span of Low and High Ions

- $\Delta v_{90}$: velocity width enclosing 90% of the optical depth
- Low ions, when detected, show velocity width similar to that of high ions
- Impressive kinematics ≫ $v_{\rm circ}$ of host DM halo ~ 300 km s$^{-1}$ (White+12)
- $\Delta v_{90}$ of QPQ ≫ $\Delta v_{90}$ of other galaxy populations (Neeleman+13)



# QPQ8: Modeling $N_{HI}$ with Voigt Profiles

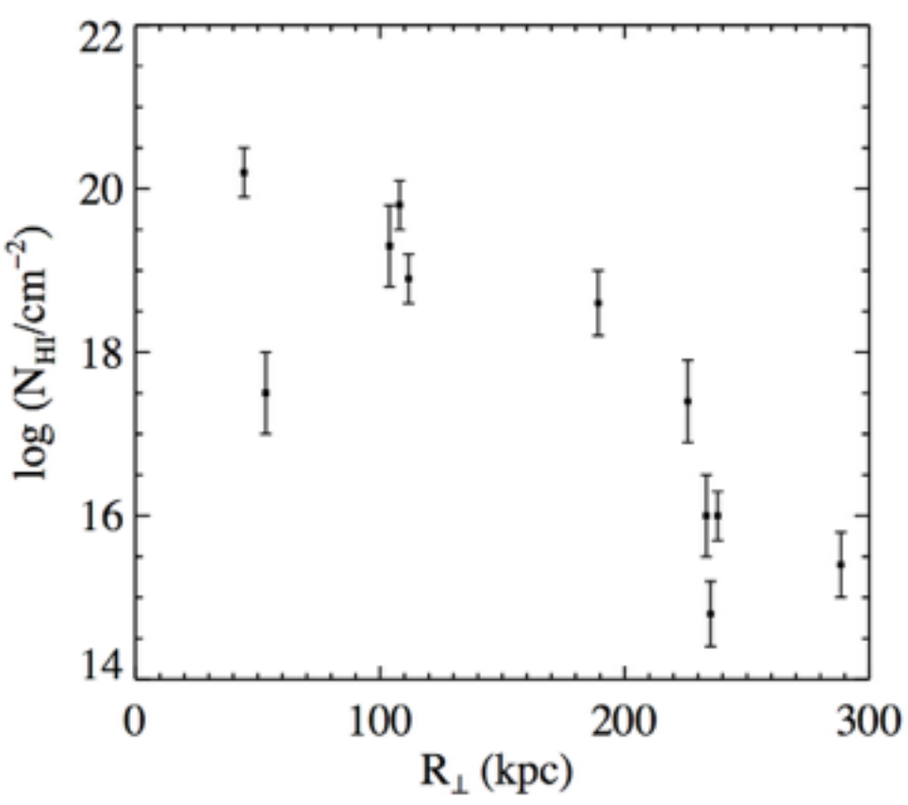


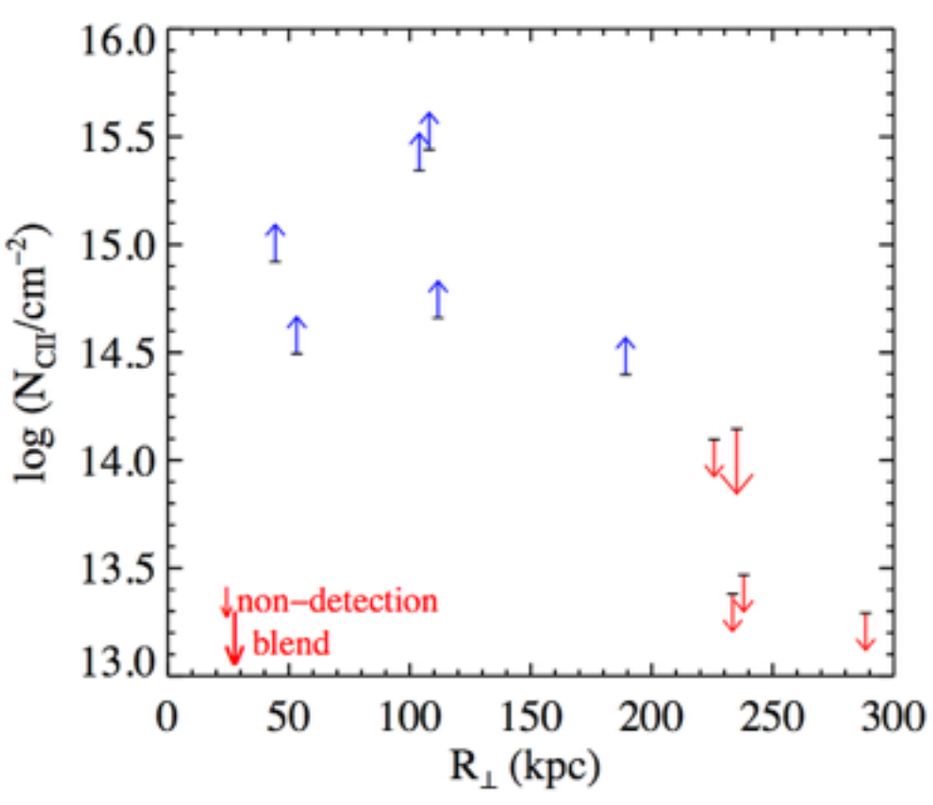




- Diverse measurement precision
  - With damping wings
  - Full series of Ly*α*, *β*, *γ*, *δ*,…
  - Ly*α* only
- $\chi^2$ best fit with ALIS (Cooke, private communication)

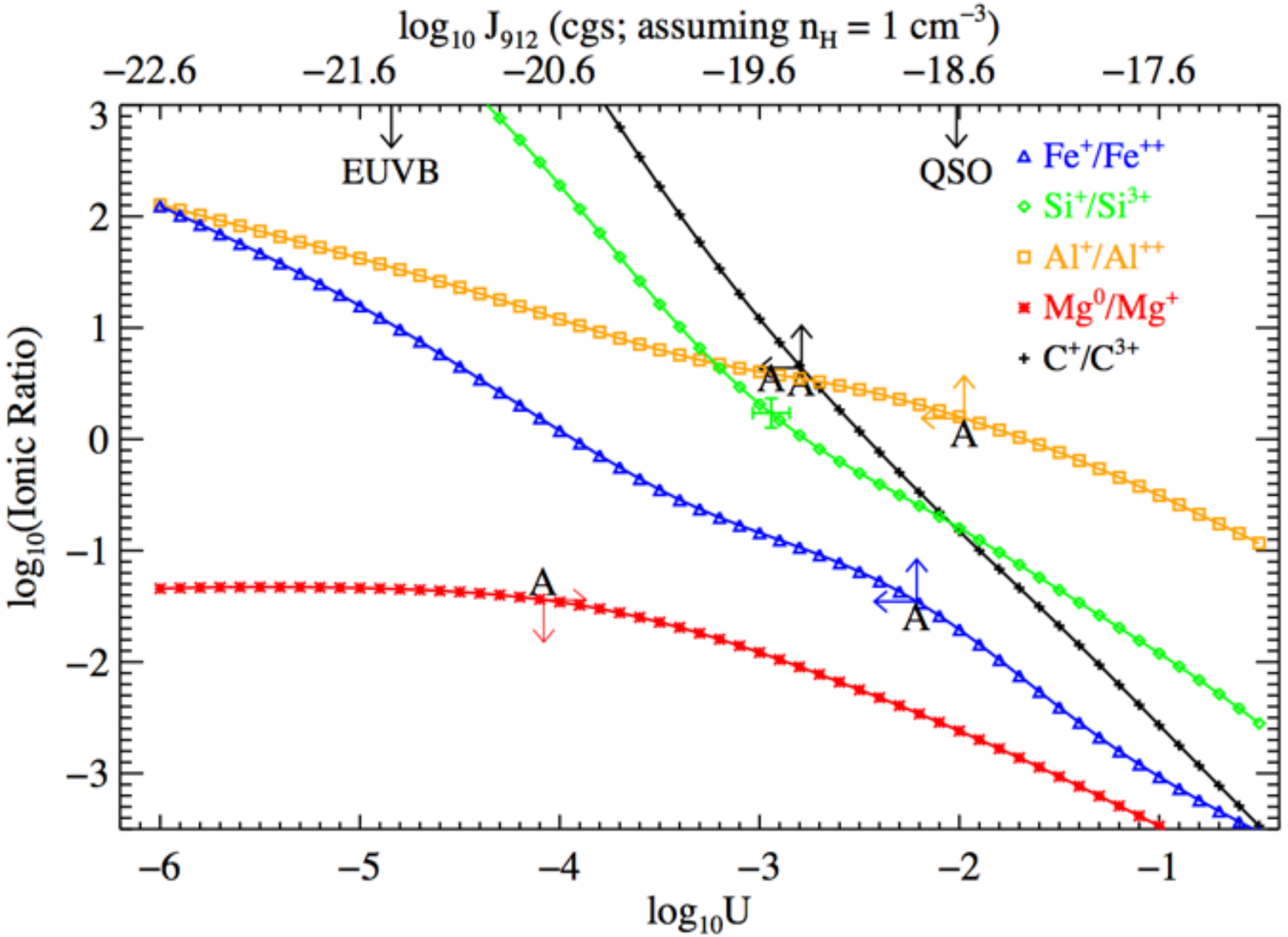
# QPQ8: Low Ion Surface Density Profiles

- Measure column densities with the apparent optical depth method
- HI and low ions' surface density decreases with $R_\perp$
- Total $M_{HI} \approx 2 \times 10^9\ M_\odot$ within $r_{vir} \approx 160$ kpc
- Large $N_{CII}$ values, substantial metal mass



# QPQ8: The Ionization Parameter $U = \Phi_{ionizing} / n_H c$

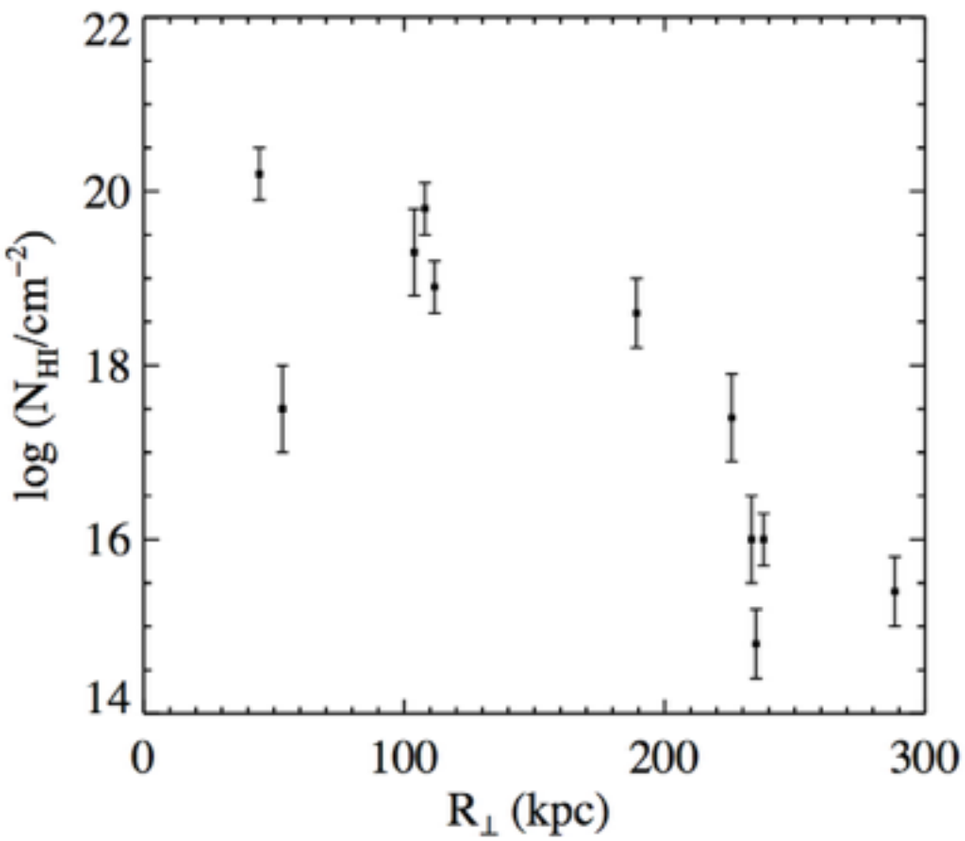


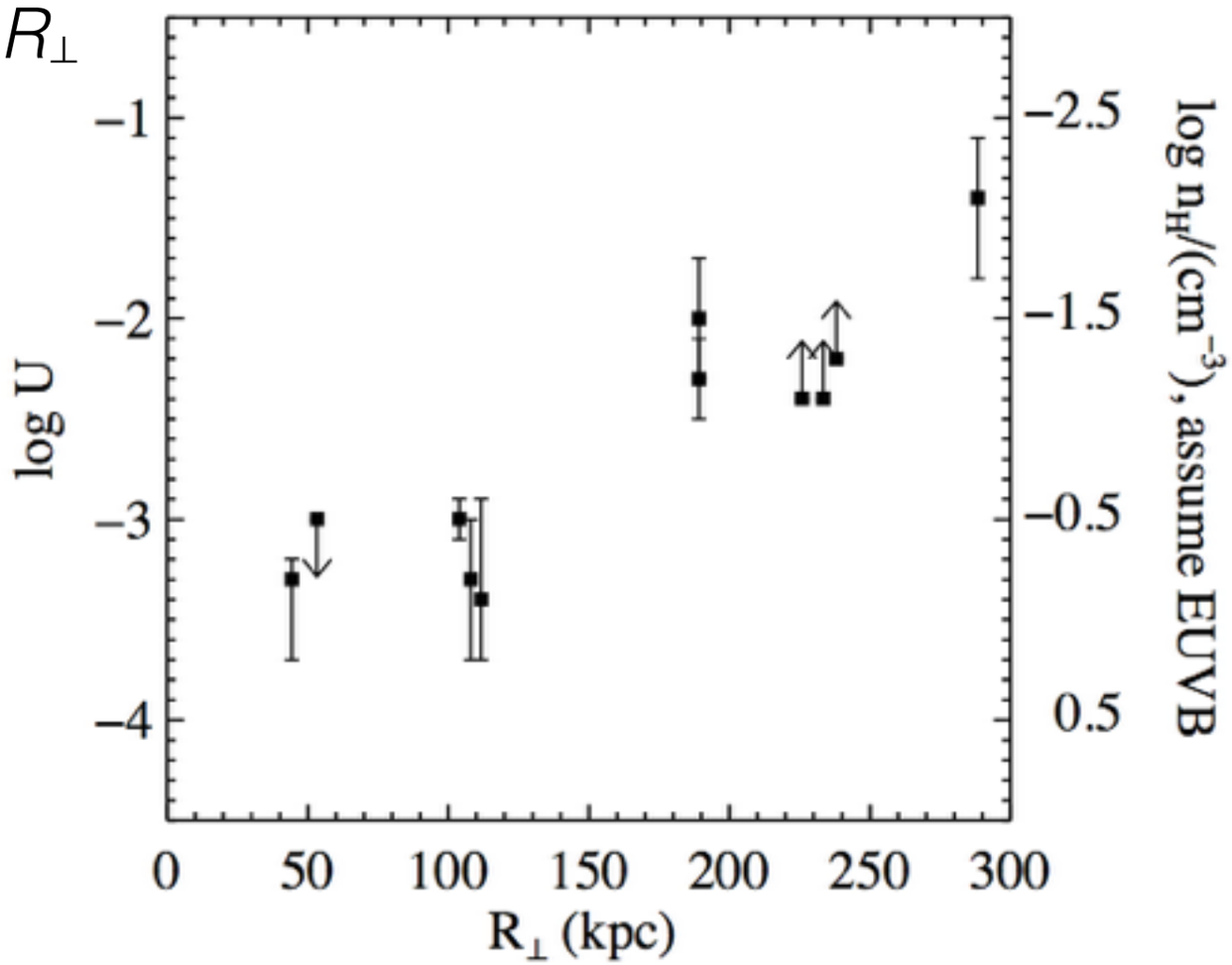

- Photo-ionization modeling using Cloudy
- Ionic ratios constraint *U*
- *U* smaller than that expected for isotropic radiation of quasar

J1420+1603FG subsystem A

# QPQ8: Mapping the Ionization States of the CGM

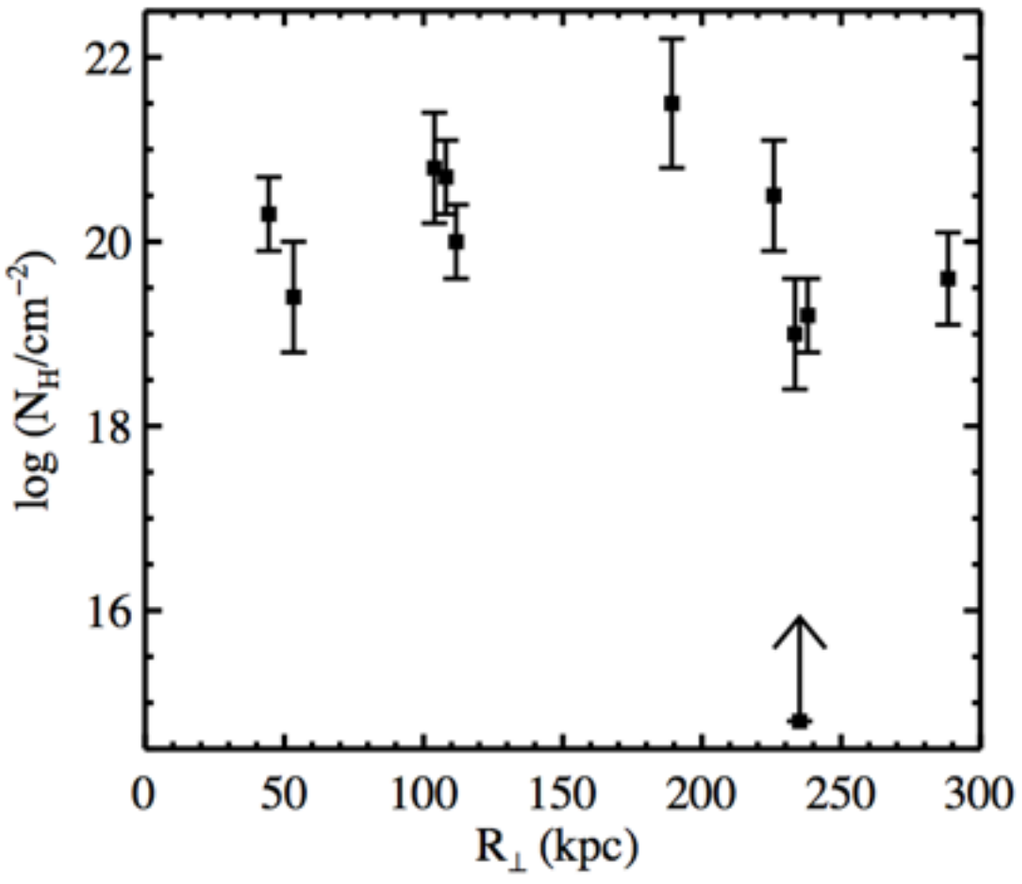
- *U* positively correlates with $R_\perp$ (and anticorrelates with $N_{HI}$)
- This dependence runs contrary to expectation if the quasar dominates
  - Implies $n_H$ decreases with $R_\perp$

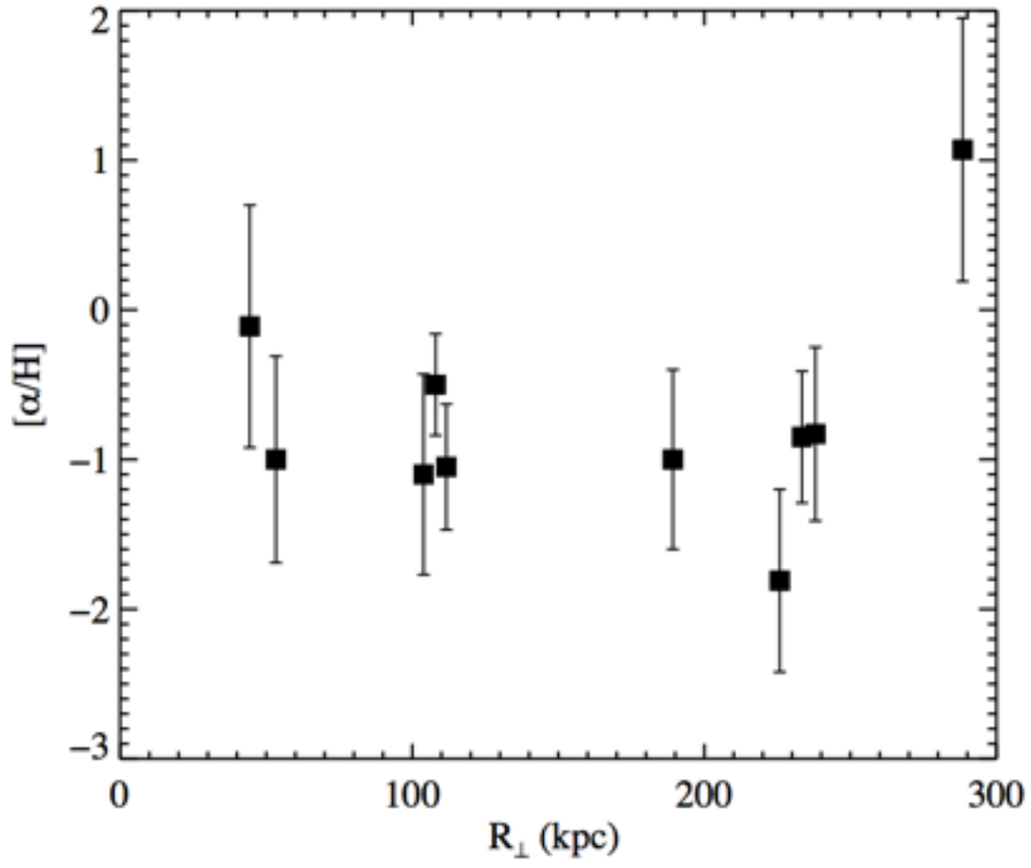


# QPQ8: Total Cool Gas Mass and Metallicity

- Modeling $N_H$ and [M/H] involves large uncertainties propagated from $N_{HI}$ measurement, ionization parameter $U$, Cloudy, …
- Using the median log $N_H \approx 19.6$, within $r_{vir}$ total $M_{cool} \approx 3 \times 10^{10}\ M_\odot$
- Typical metallicity 1/10 solar to solar



# QPQ7 & QPQ8: Summary and Speculations

- CGM of massive $z \sim 2$ galaxies is the pinnacle of cool, enriched gas
  - Progenitors of present day massive galaxies
  - Quasars unlikely the main driver
- Substantial kinematics traced by low and high ions » 300 km $s^{-1}$
  - Is the gas outflow or cold accretion?
- Within $r_{vir}$, total $M_{HI} \approx 2 \times 10^9\ M_\odot$ and total $M_{cool} \approx 3 \times 10^{10}\ M_\odot$
- Metallicity ~ 1/10 solar
- $U$ increases with $R_\perp \Longrightarrow$ quasar feedback unimportant