Quasars Probing Quasars: Thinking Outside the Grid

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Heidelberg
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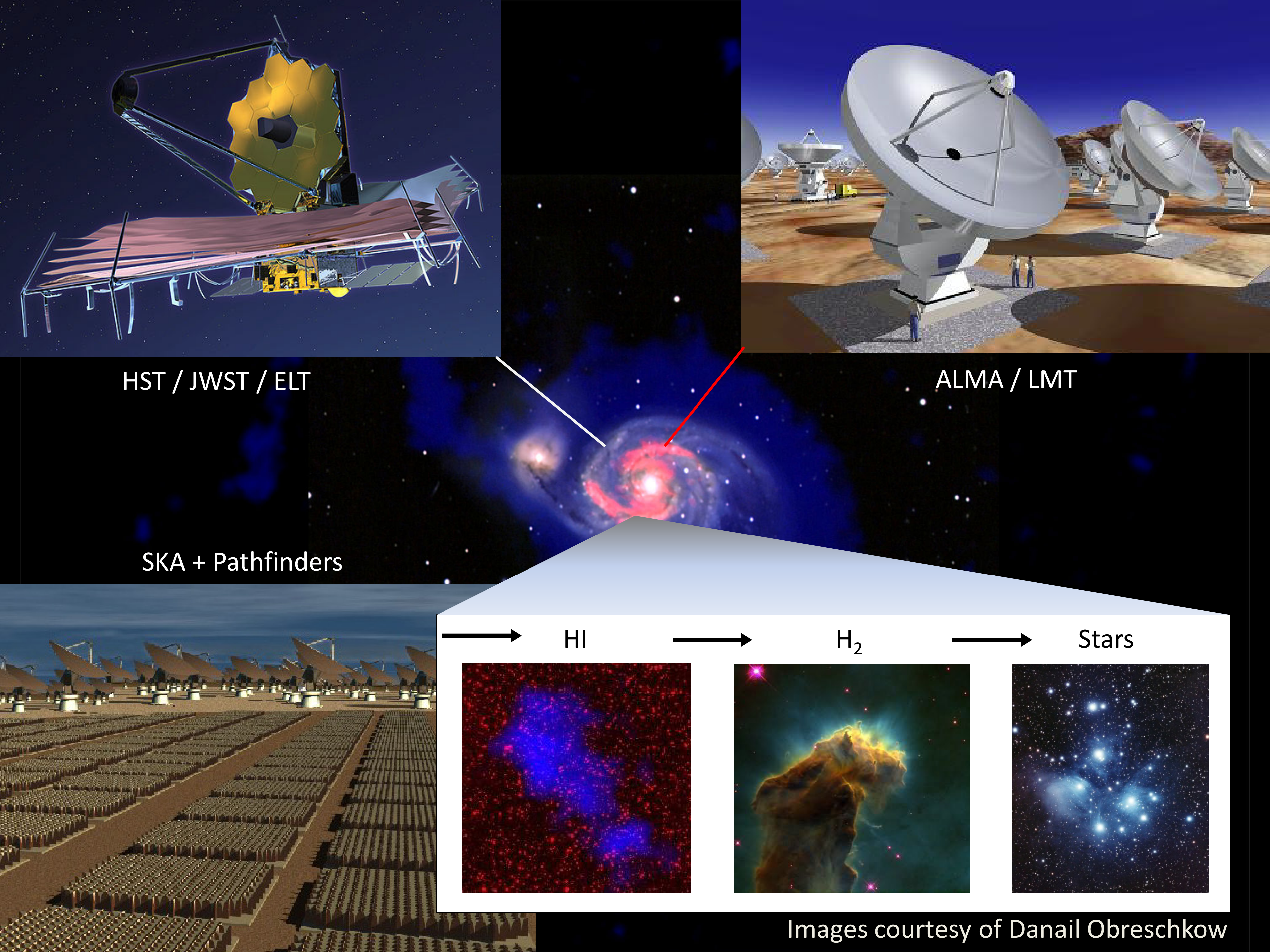
SDSS

Credits

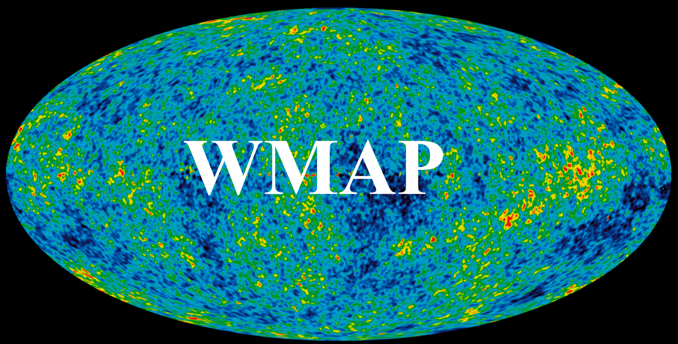
Jason Xavier Prochaska
(UCSC)


HST / JWST / ELT
ALMA / LMT
SKA + Pathfinders
HI
H_2
Stars
Images courtesy of Danail Obreschkow

Prediction: Dark Matter

versus

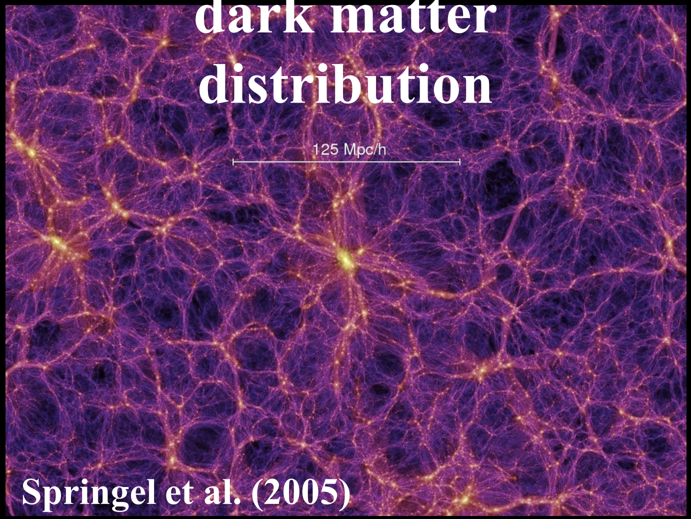
Postdiction: Baryons

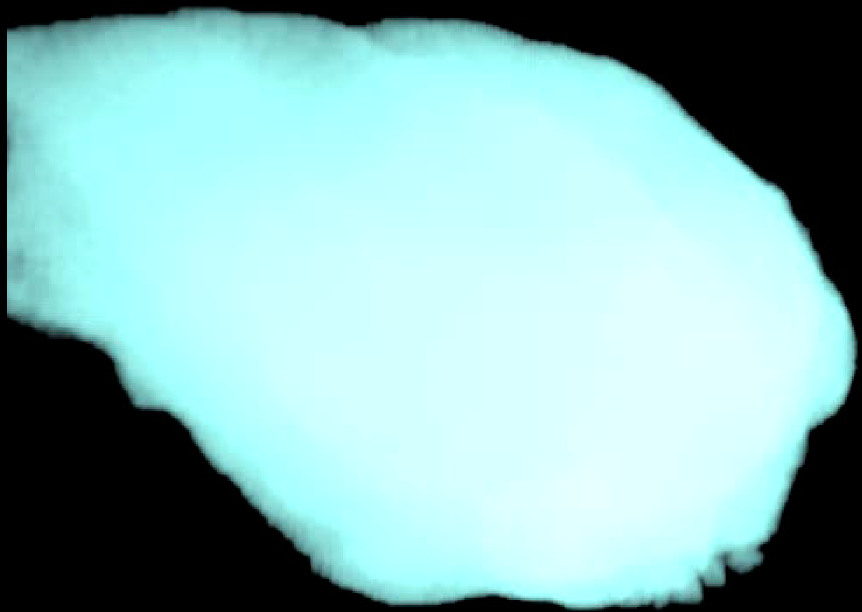


ab initio theory

sub-grid recipes

resolution: ~ 100 pc
convert gas to stars:
n ~ 0.1-1 cm^{-3}

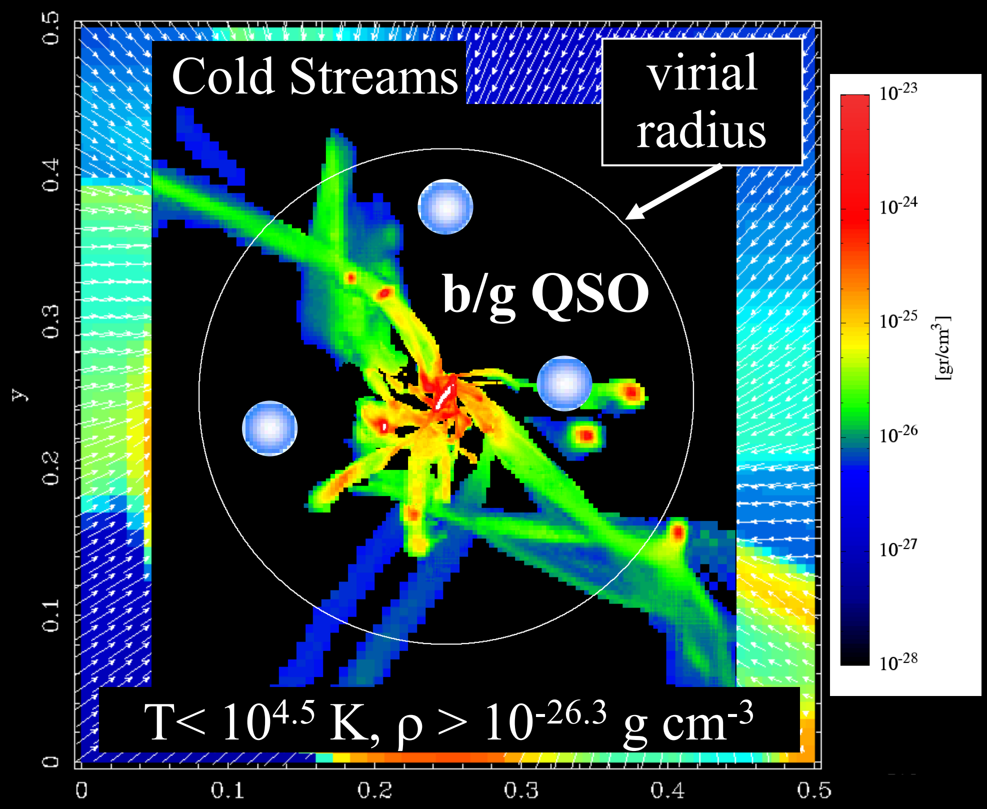




Movie Credit: Fabio Governato

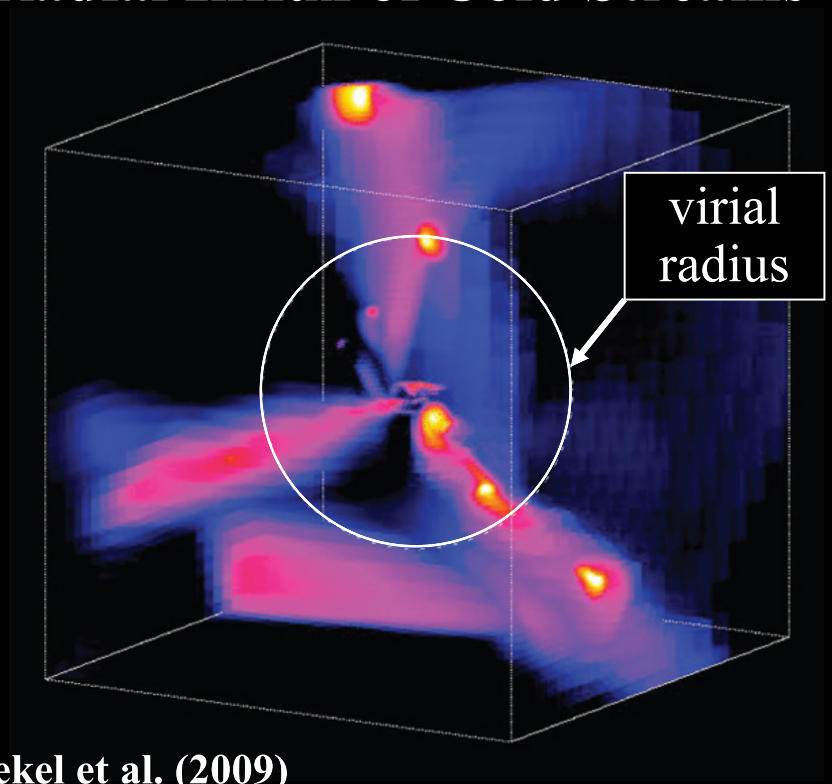
How can we test the initial conditions for galaxy formation?

The Initial Conditions for Galaxy Formation



Dekel & Bernboim (2006)

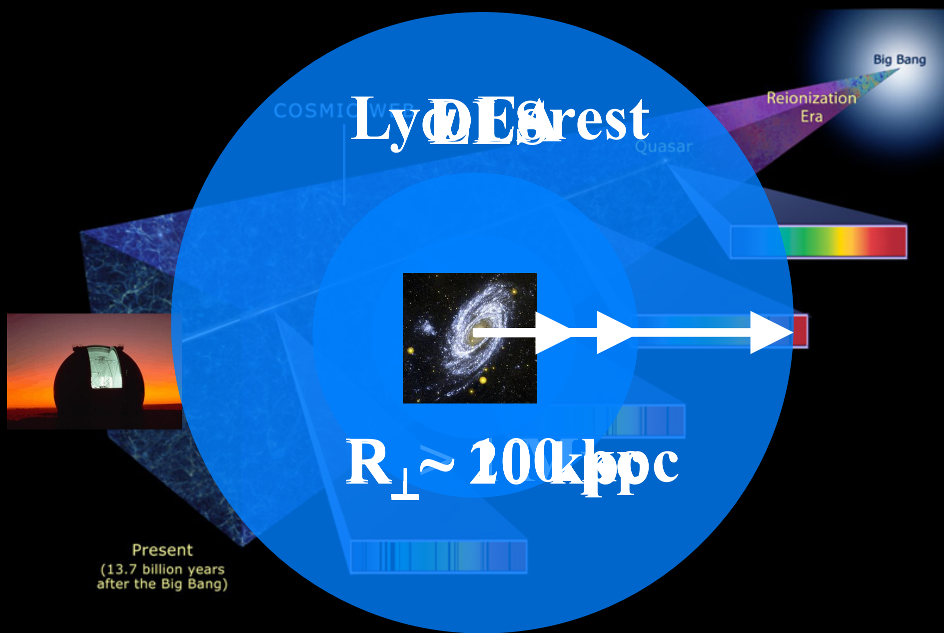
Radial Influx of Cold Streams



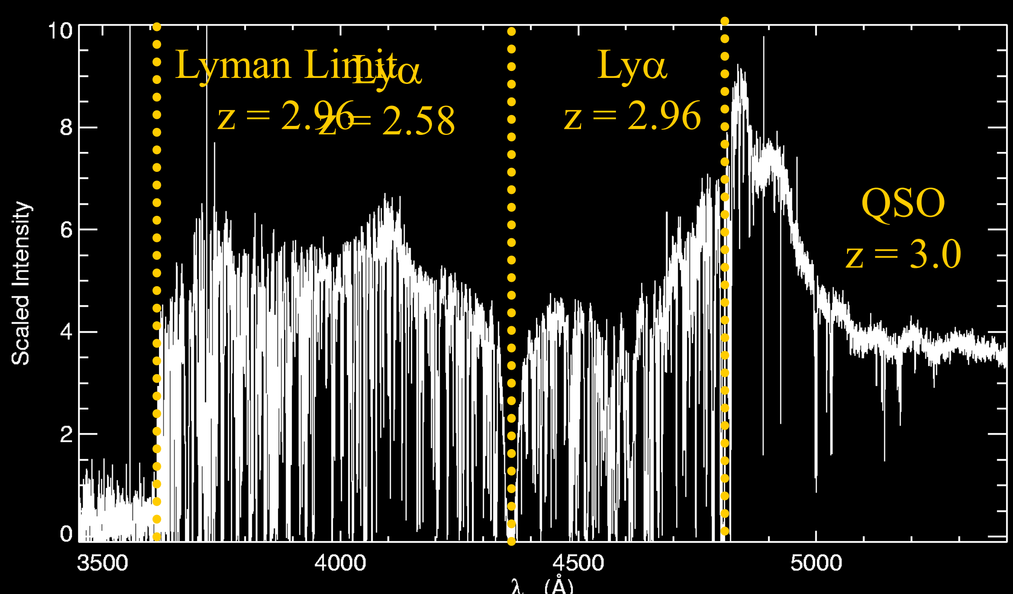
Dekel et al. (2009)

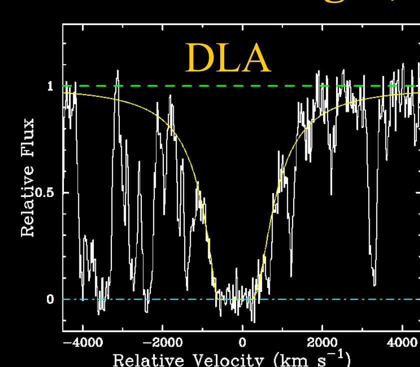
Hydro sims predict $M{\sim}10^{12}\,M_\odot$ halos have a ~ 30% covering factor of cold gas with column $N_H > 10^{20}$ cm^{-2}

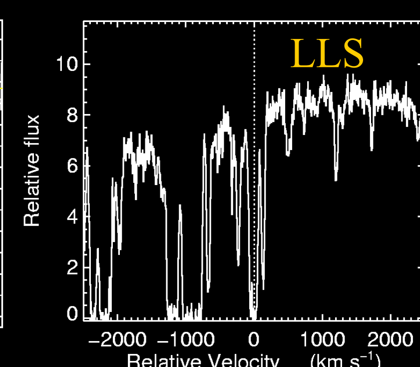
Quasar Absorption Lines



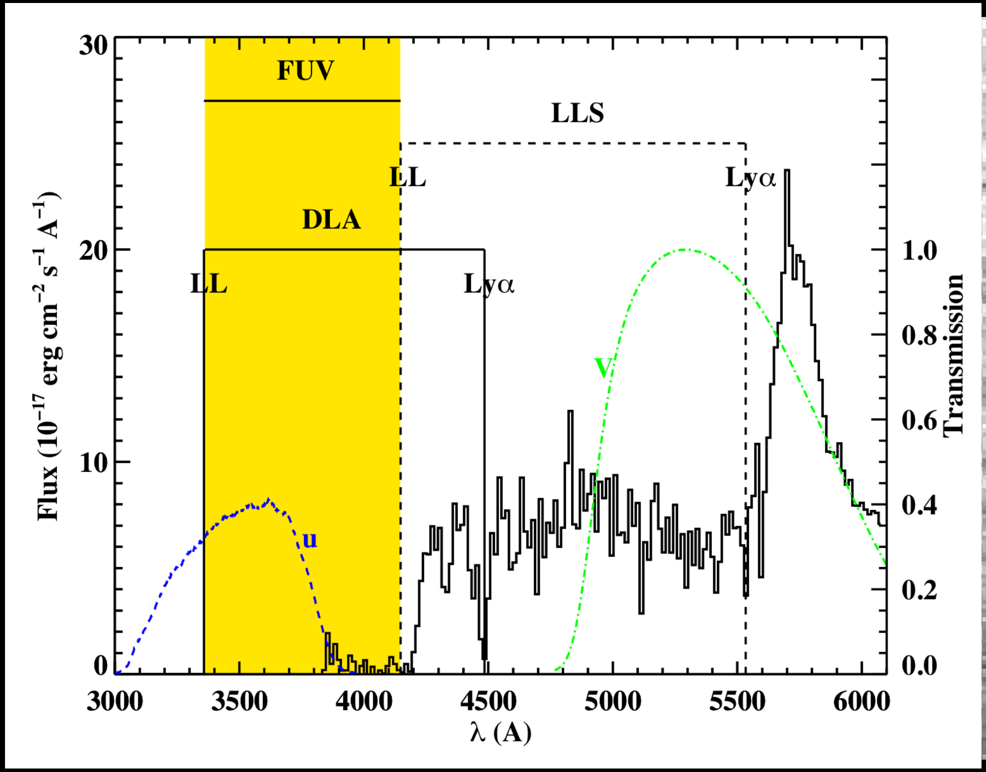
- Lyα Forest
  - Optically thin diffuse IGM
  - $\rho/\langle\rho\rangle \sim$ 1-10; $10^{14} < N_{HI} < 10^{17.2}$
  - photoionized gas $T \sim 10^4$ K
- Lyman Limit Systems (LLSs)
  - Optically thick $\tau_{912} > 1$
  - $10^{17.2} < N_{HI} < 10^{20.3}$
  - photoionized gas $T \sim 10^4$ K
- Damped Lyα Systems (DLAs)
  - $N_{HI} > 10^{20.3}$ ~ galactic disks
  - sub-L_* galaxies?
  - neutral gas, $T \sim$ 100-5000 K

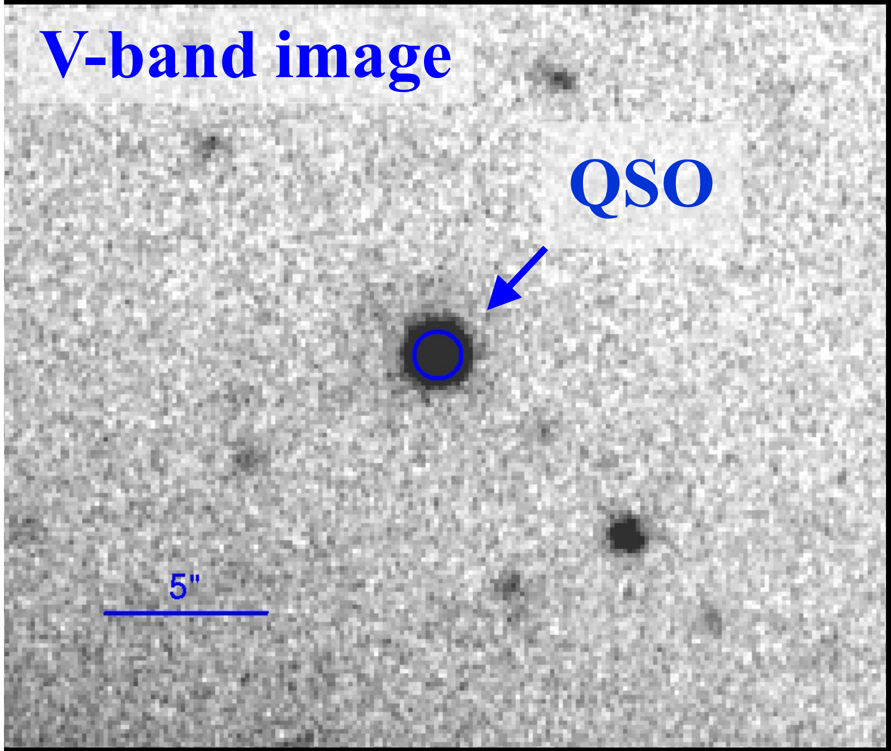






Directly Identifying Absorber Galaxies





Fumagalli et al. (2010)

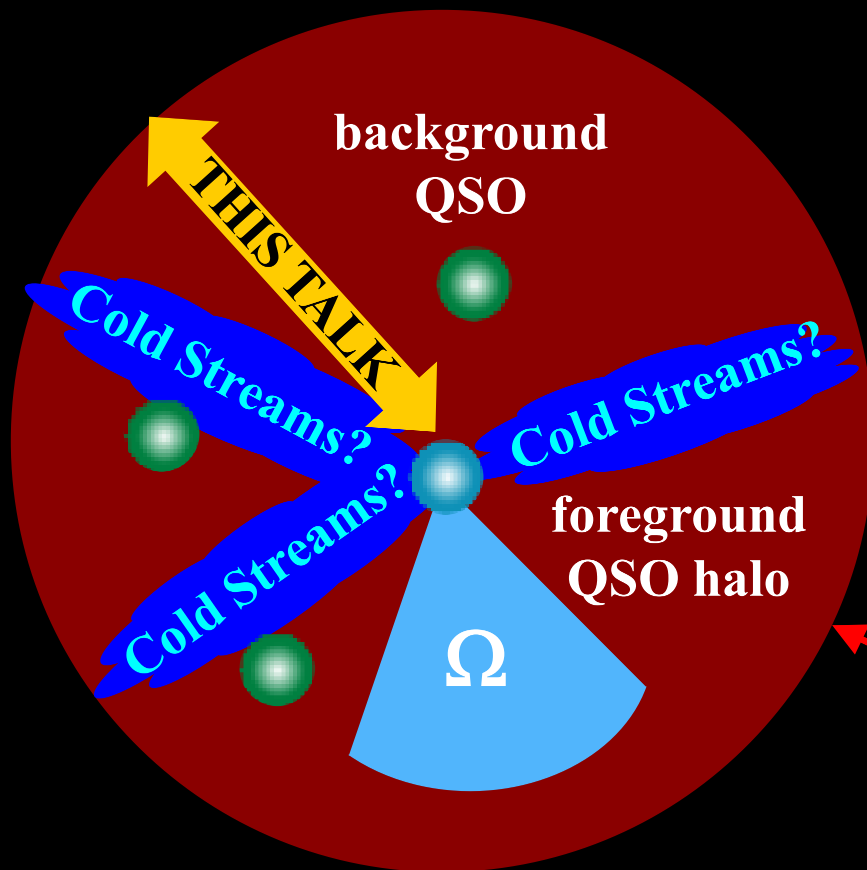
- Absorption selects by covering factor, faint end dominates
- Typical counterpart r ~ 27 (L ~ $0.1L_*$), follow-up extremely hard
- Multiple counterparts, assignment ambiguous
- No dynamic range in galaxy type and/or dark halo mass

Quasars Probing Quasars

Use absorption lines to probe diffuse gas

r ~ 30 – 200 kpc

$N_{HI} \sim 10^{12-22}$ cm^{-2} and T ~ 10^{2-6} K



r_{vir} ~ 200 kpc

Virial Radius

T ~ 10^{6-7} K virialized plasma

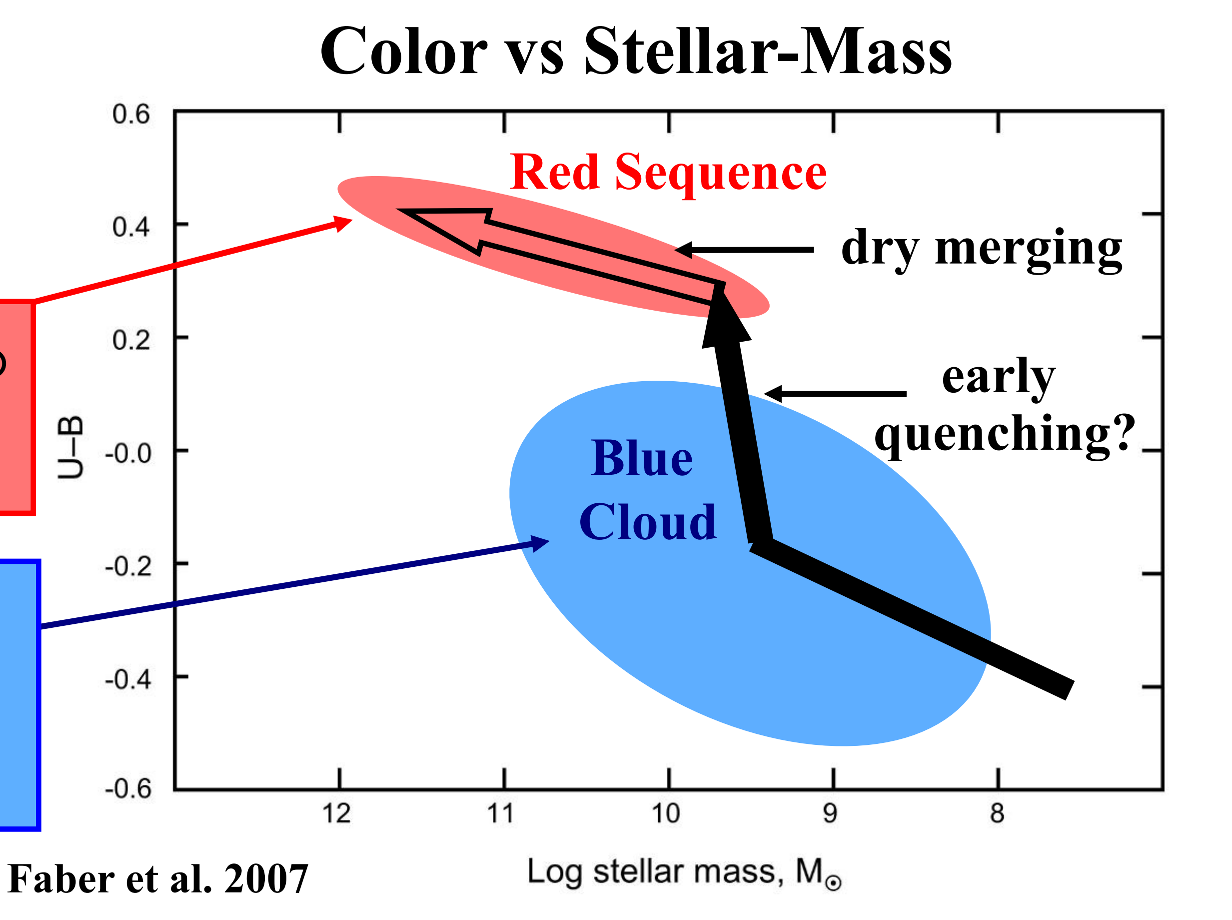
- Use foreground QSOs to trace massive galaxies at high-z
- Why use QSOs? Because we can find ~ 10^6 in SDSS
- Directly probe gas $\rho/\langle\rho\rangle \sim 10^{2-3}$ resolved by hydro grids
- Complications: ionizing radiation, are QSOs atypical?

What Quenched Star Formation?

Clustering gives dark halo mass scale z ~ 2.5

QSOs: $M \sim 10^{12.9} M_\odot$ end up here
(Shen et al. 2008)

z ~ 2-3 star-forming gals: $M \sim 10^{11.9} M_\odot$ end up here.
(Conroy et al. 2007)

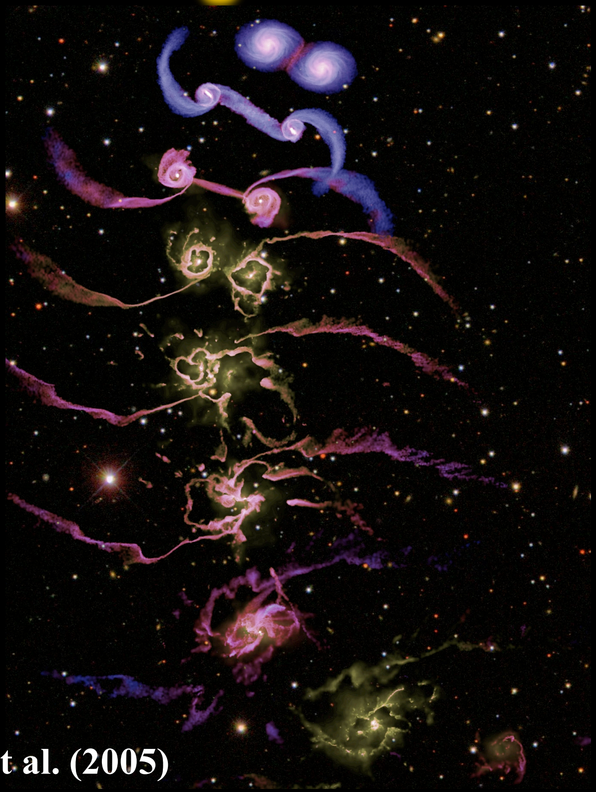


Faber et al. 2007

What physics gives rise to this bimodality? When did quenching occur? QSOs at z ~ 2-3 are the progenitors of local massive *red-and-dead* galaxies.

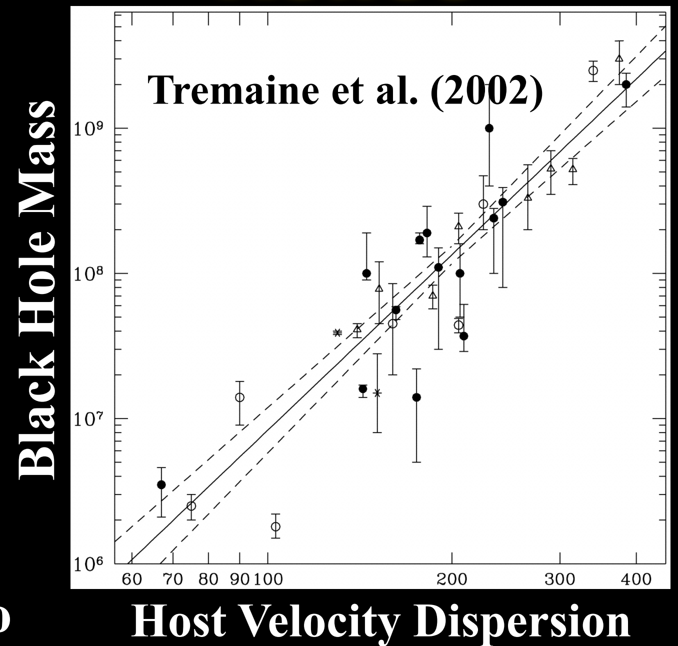
Quasar Feedback?

Progenitors



Springel et al. (2005)

Relics



5% coupling to accretion power

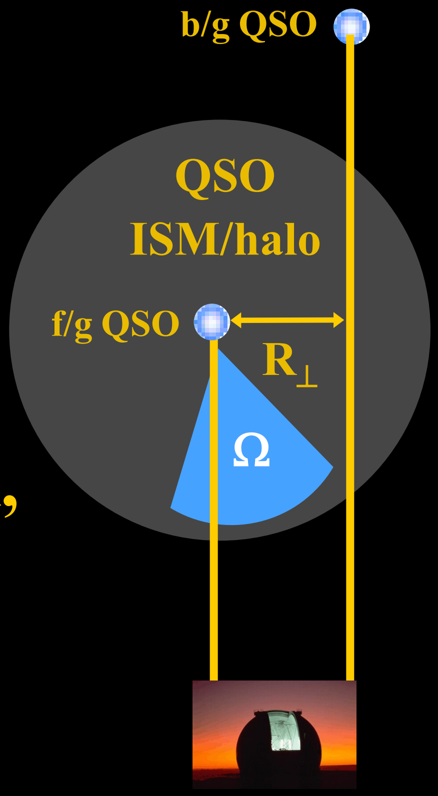
radiated energy

$$E_{\rm feedback} = \eta \epsilon_{\rm rad} M_{\rm BH} c^2 = 9 \times 10^{60} \left(\frac{\eta}{0.05}\right) \overbrace{\left(\frac{\epsilon_{\rm rad}}{0.1}\right)\left(\frac{M_{\rm BH}}{10^9\,M_\odot}\right)}^{\text{radiated energy}} \text{erg}$$

There is no observational evidence that accretion energy couples to large > 1 kpc scales in typical QSOs.

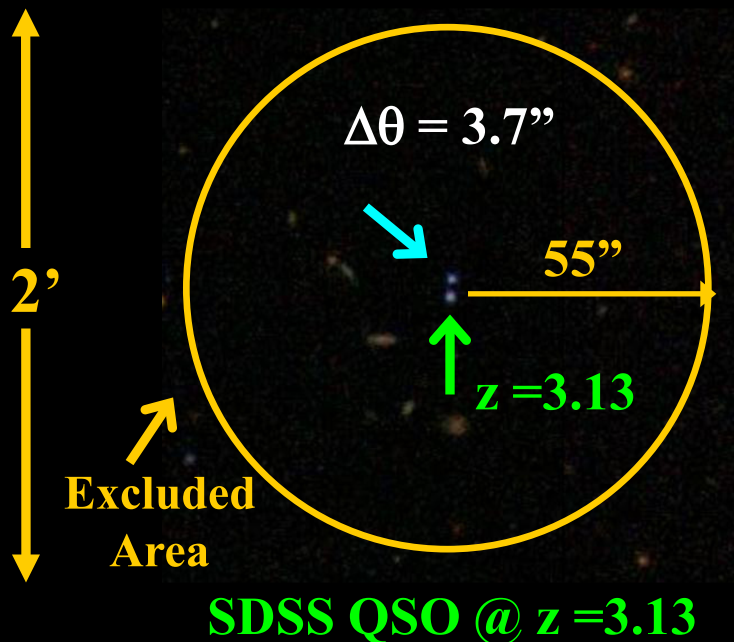
Fundamental Questions

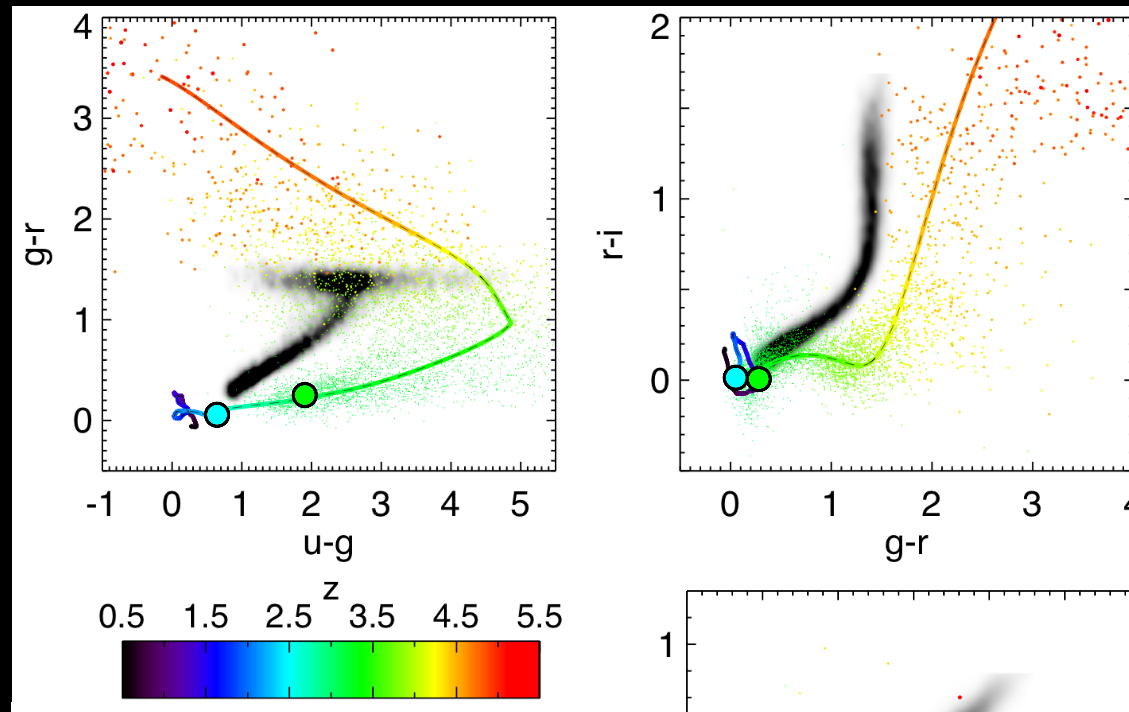
- What is the physical state of gas in the high-z progenitors of red-and-dead galaxies?
- Is there evidence for cold flows? What is the supply of $T \sim 10^4$ K gas?
- Is feedback occurring in the typical QSO?
- If so how far does feedback energy, material, metals travel in ISM/halo?
- How does feedback energy correlate with accretion power?

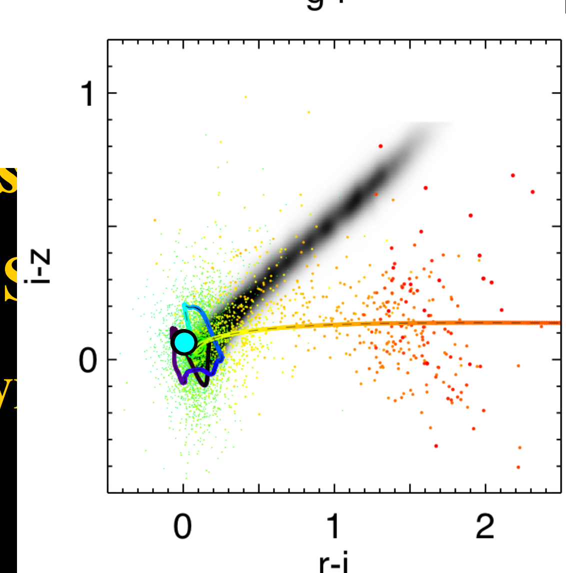


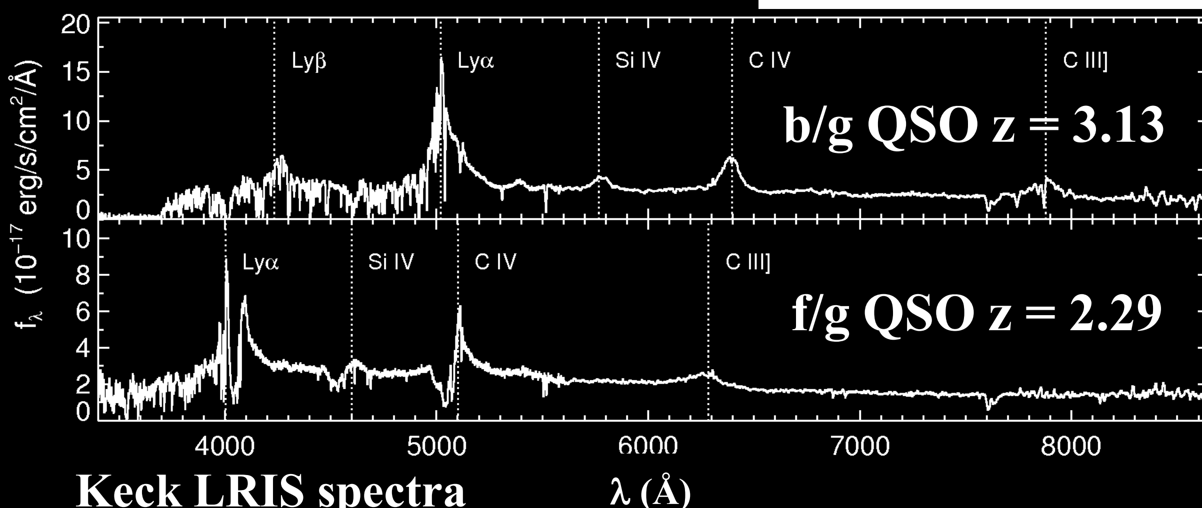
We have never studied QSOs or massive high-z DM halos $M \sim 10^{13}\ M_\odot$ in absorption before.

Finding Projected Quasar Pairs





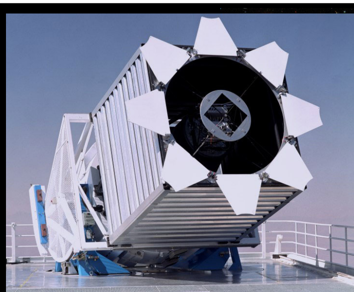


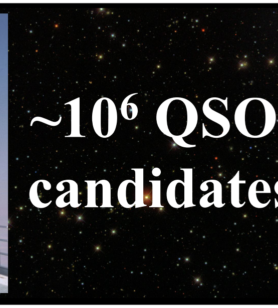


Hennawi et al. (2006,2009)

Cosmology with Quasar Pairs

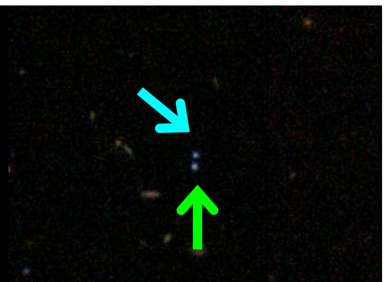
¼ Sky SDSS imaging





~10^6 QSO candidates

Pair Confirmation: 4m Telescopes



> 200 new pairs $R_{\perp}$ < 500 kpc, increase # known by factor 40

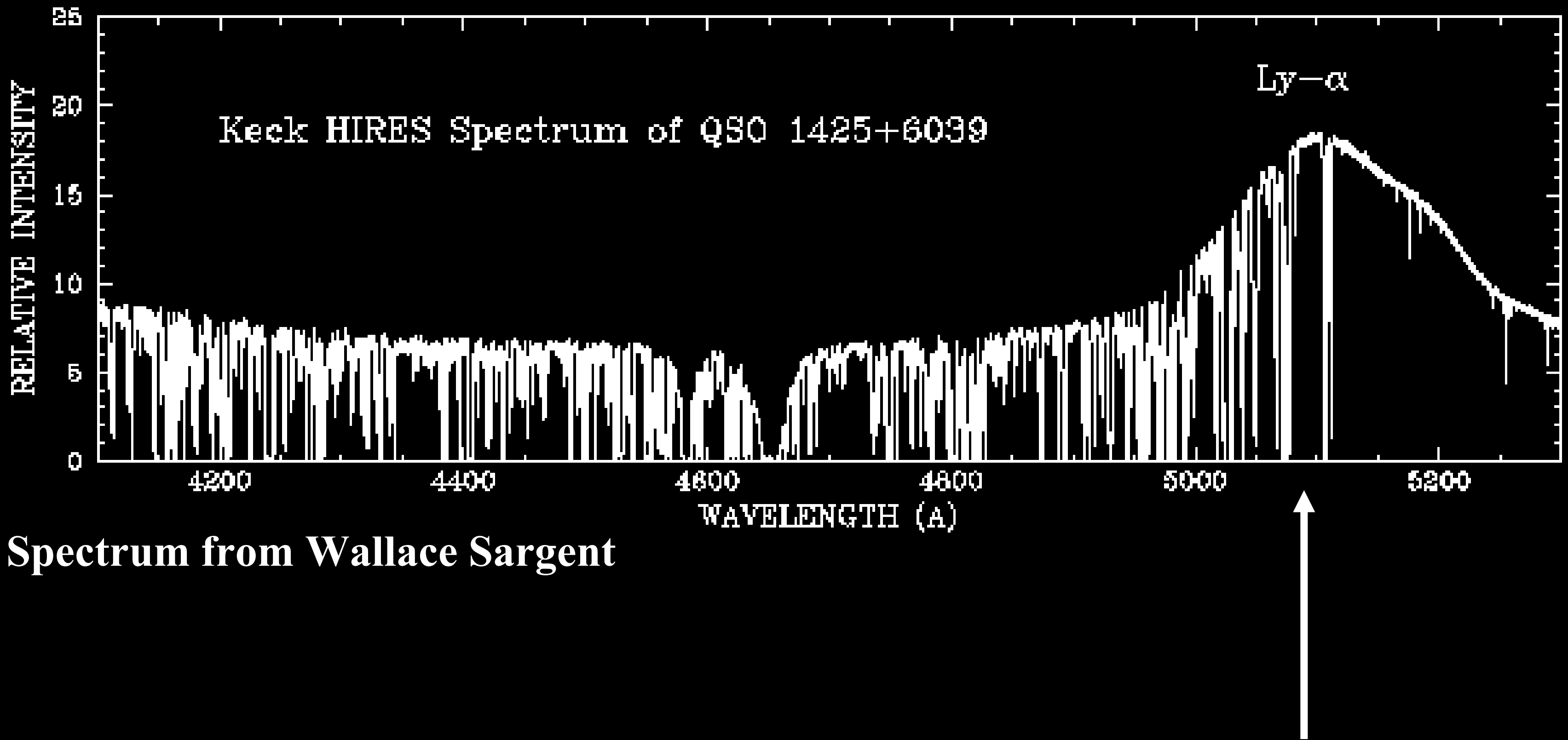
Science Spectra: 8m telescopes

Obtained > 60 nights of optical & near-IR spectroscopy

Science Goals

- Small scale QSO clustering
- Small scale Lyα forest
- Topology of metal enrichment
- Transverse proximity effect
- Study QSOs in absorption

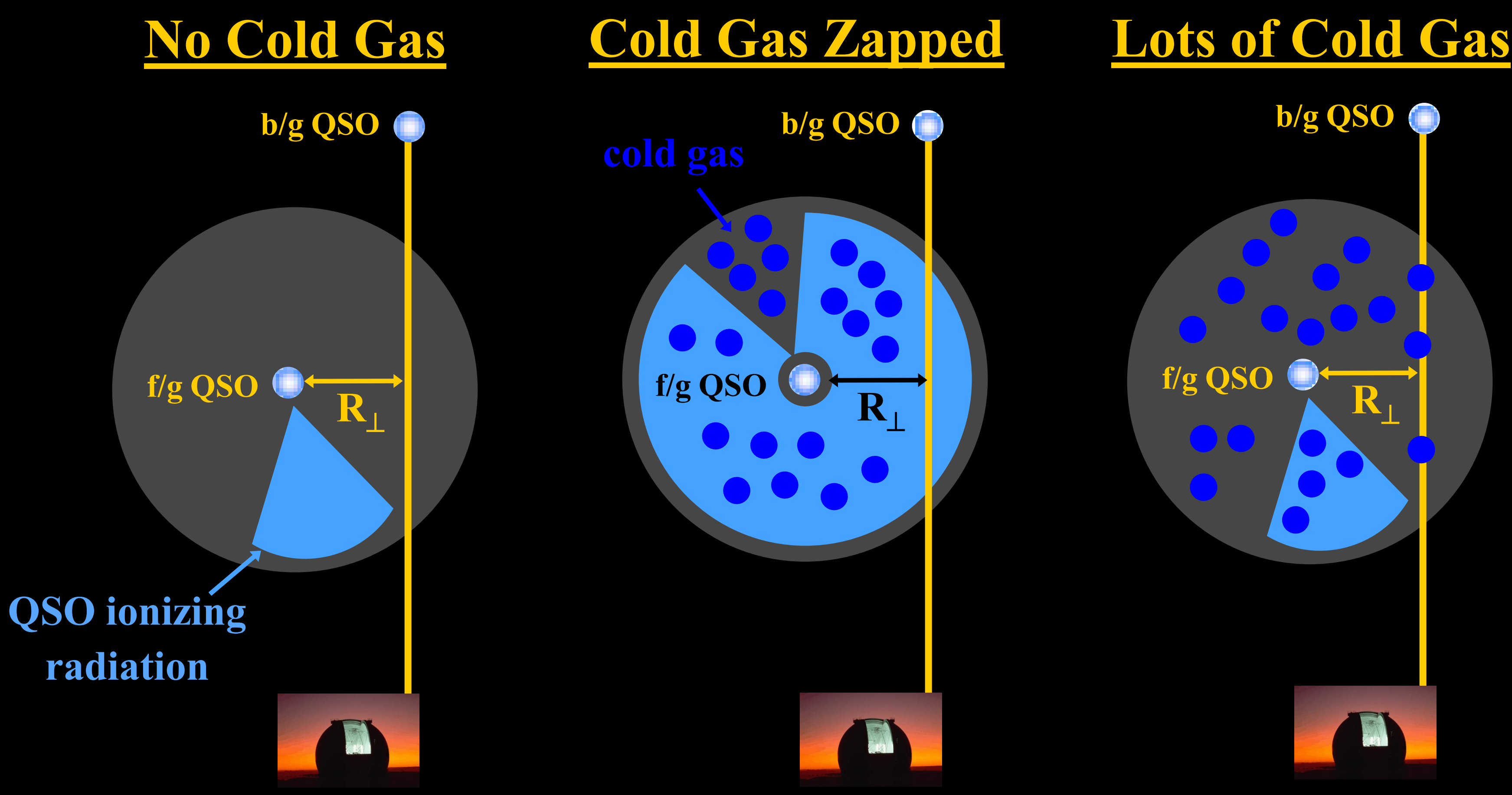
Where is the Host Galaxy?



Spectrum from Wallace Sargent

No strong Lyα absorption at QSO redshift?

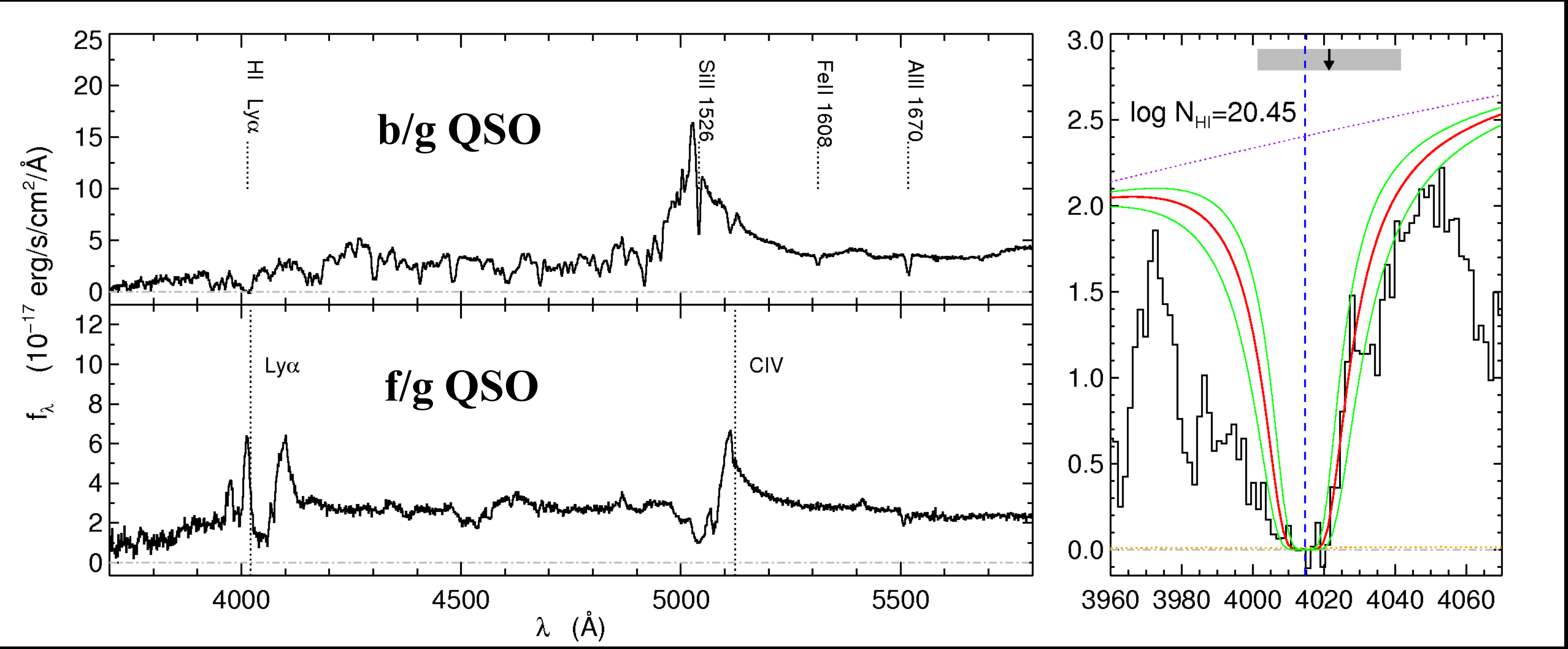
What is the Supply of Cold Gas?



Measure covering factor of cold T ~ 10^4 K gas. Large column density (optically thick) absorbers will dominate total density.

Quasars Probing Quasars

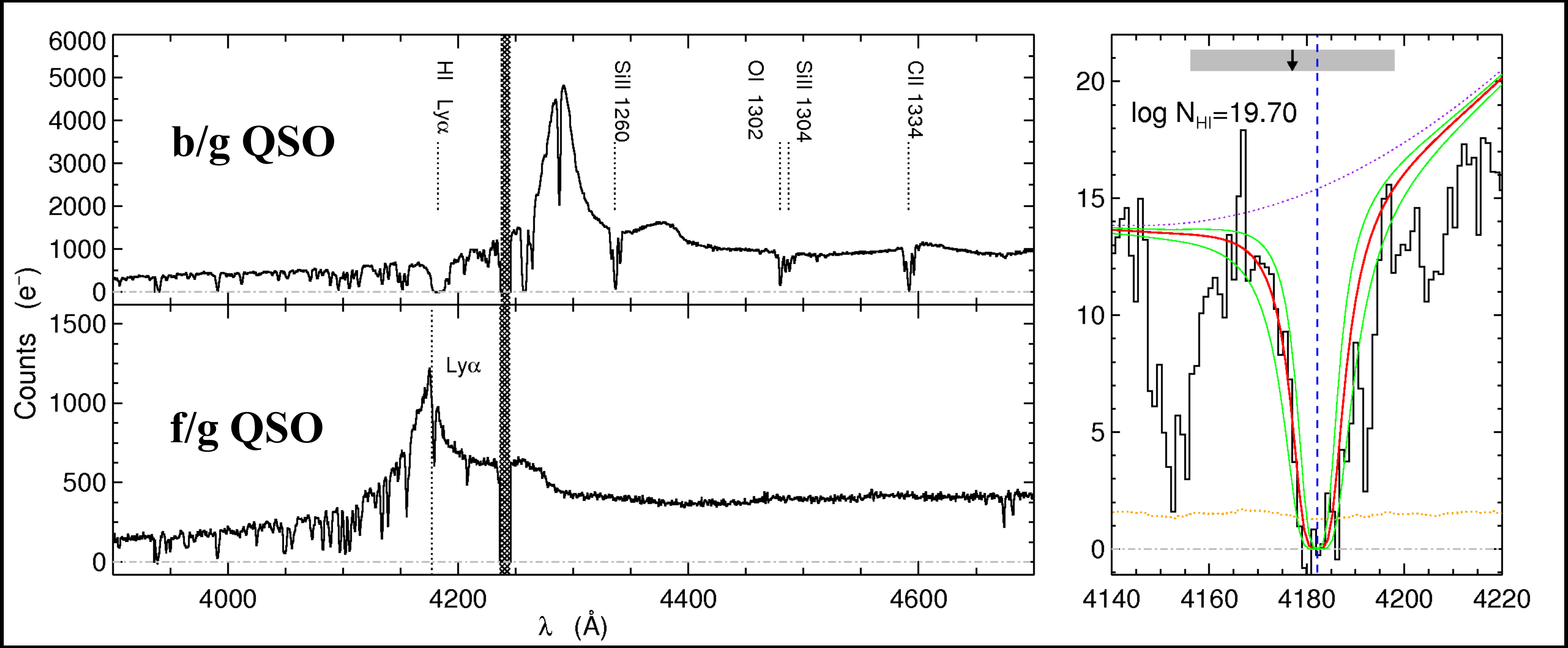
z_{bg} = 3.13; z_{fg} = 2.29; $R_\perp$ = 31 kpc; logN_{HI} = 20.5



Hennawi et al. (2007)

Quasars Probing Quasars

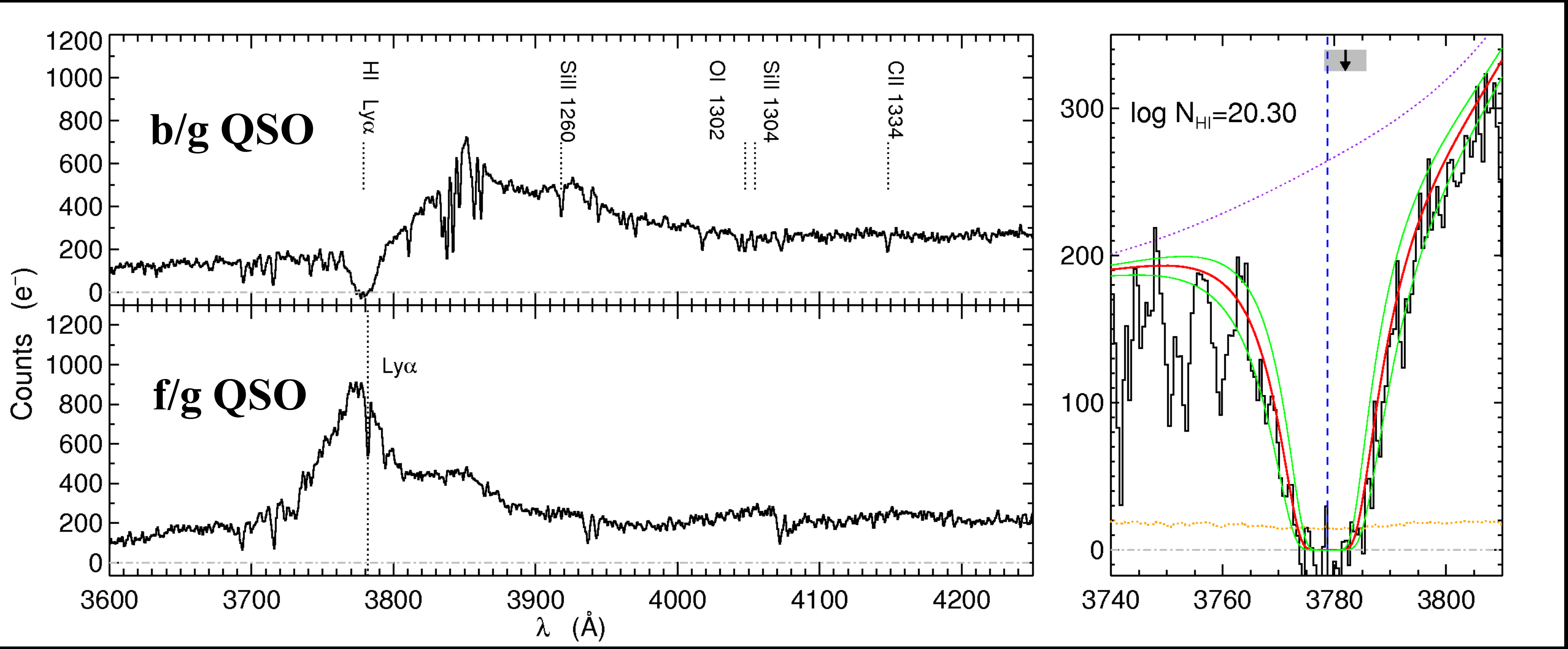
$z_{bg} = 2.53$; $z_{fg} = 2.43$; $R_{\perp} = 109$ kpc; $\log N_{HI} = 19.7$



Hennawi et al. (2007)

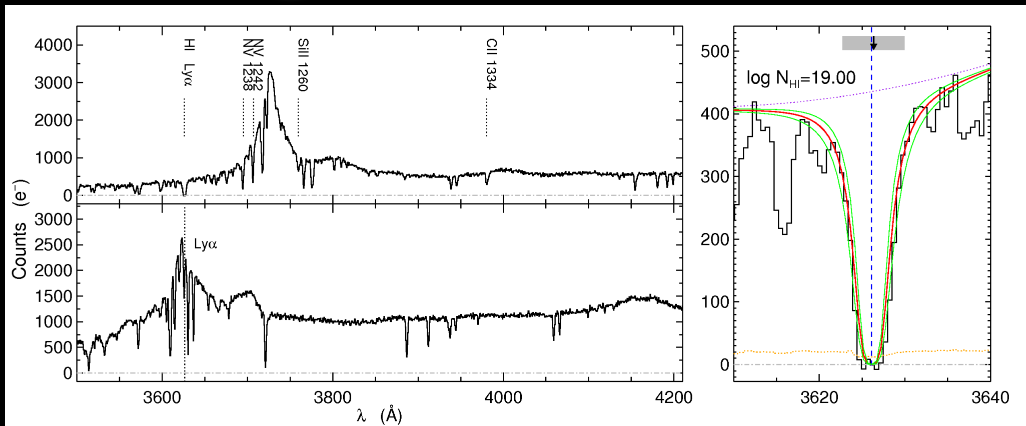
Quasars Probing Quasars

z_{bg} = 2.17; z_{fg} = 2.11; $R_{\perp}$ = 139 kpc; $\log N_{HI}$ = 20.3



Hennawi et al. (2007)

Quasars Probing Quasars

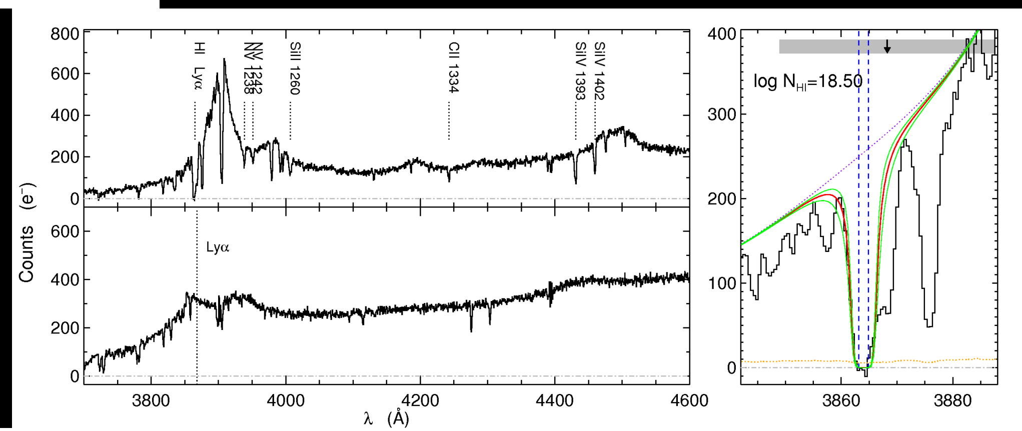


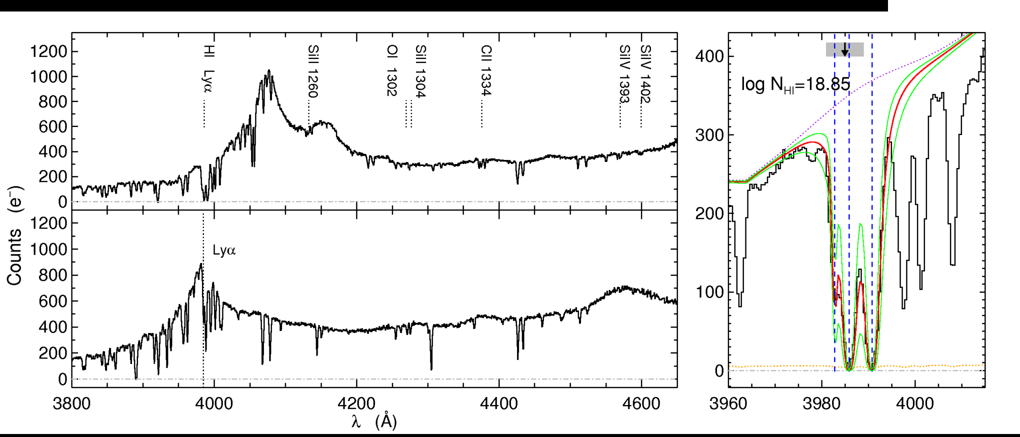
z_{bg} = 2.07; z_{fg} = 1.98

$R_\perp$ = 199 kpc; $\log N_{HI}$ = 19.0

z_{bg} = 2.35; z_{fg} = 2.28

$R_\perp$ = 53 kpc; $\log N_{HI}$ = 18.9



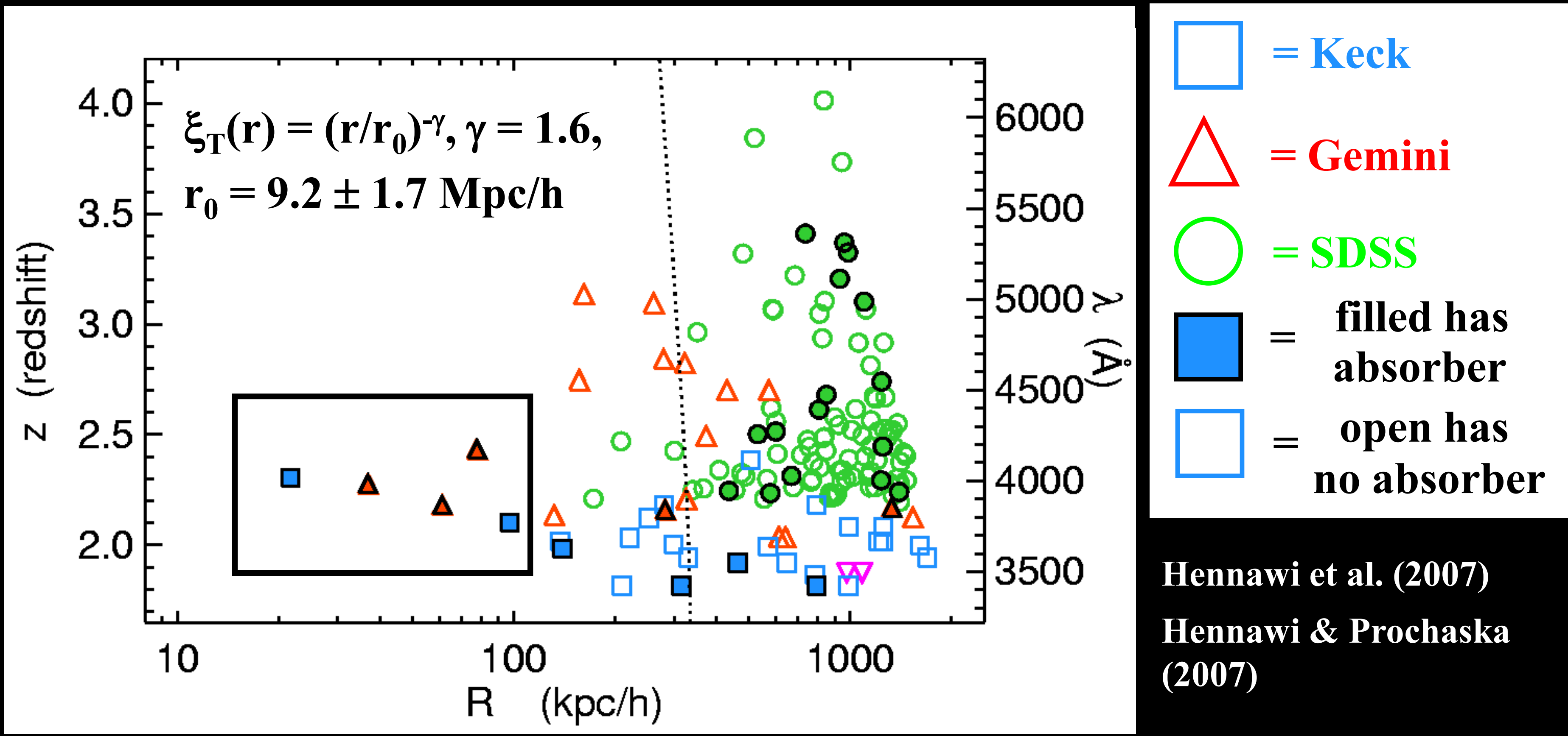


z_{bg} = 2.21; z_{fg} = 2.18

$R_\perp$ = 87 kpc; $\log N_{HI}$ = 18.5

Hennawi et al. (2007)

High Transverse Covering Factor



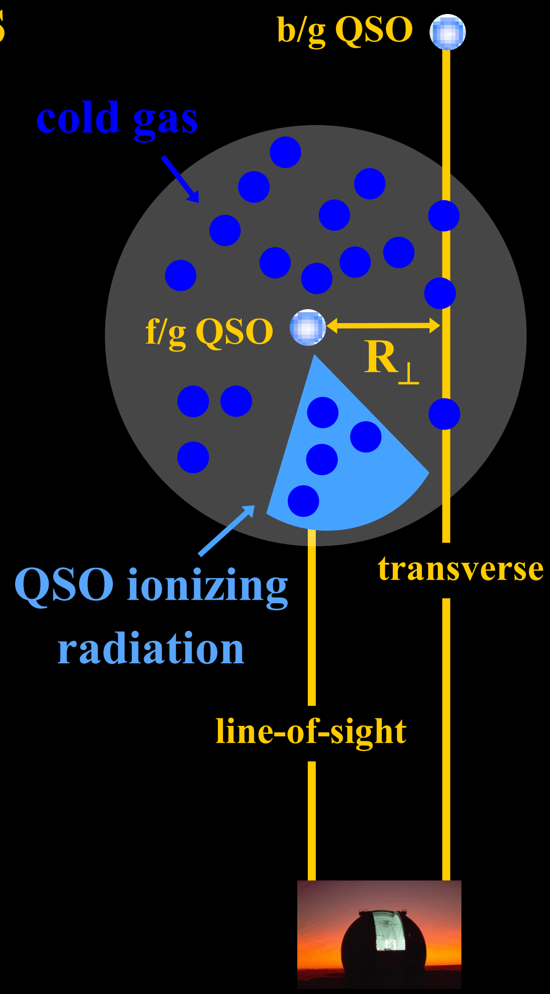
Hennawi et al. (2007)

Hennawi & Prochaska (2007)

- High covering factor for R < 100 kpc/h
- This cold gas is not seen along the line-of-sight!

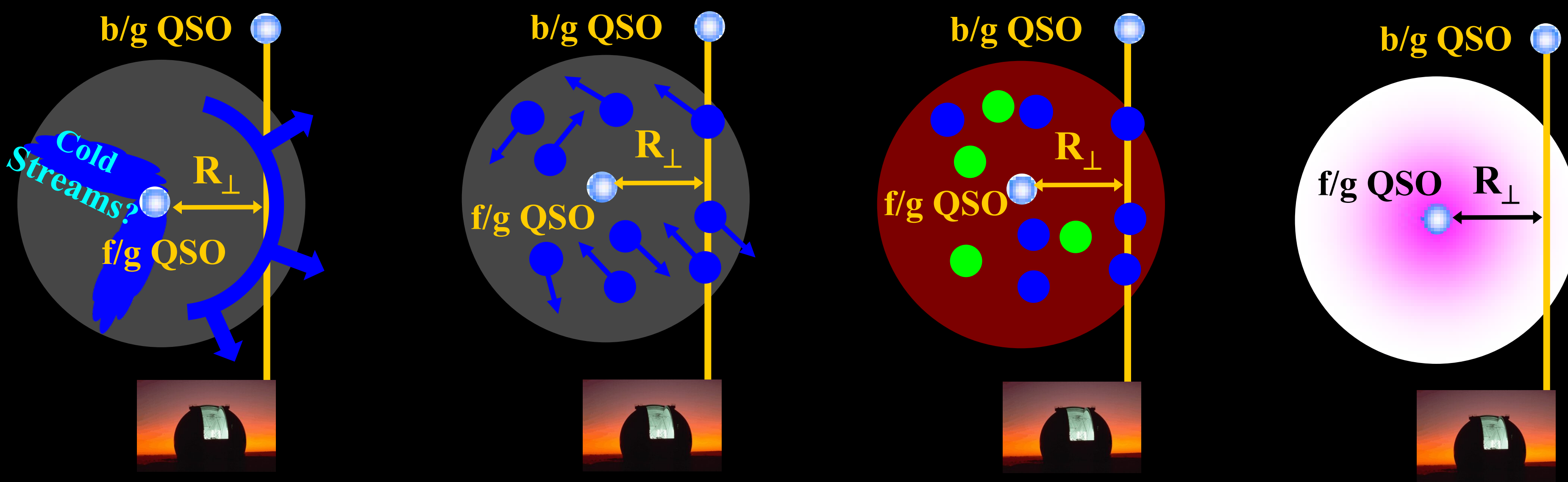
Anisotropic Covering Factor

- Clustering of absorbers around quasars is highly anisotropic.
- Anisotropic (or intermittent) emission:
  - line-of-sight material photoevaporated
  - transverse material shadowed
- Background sightlines probe ISM/halo gas *unaltered* by effects of QSO radiation



For individual systems, we can directly test for transverse illumination (stay tuned).

What is the Physical State of the Gas?



Outflow or Cold Flows?

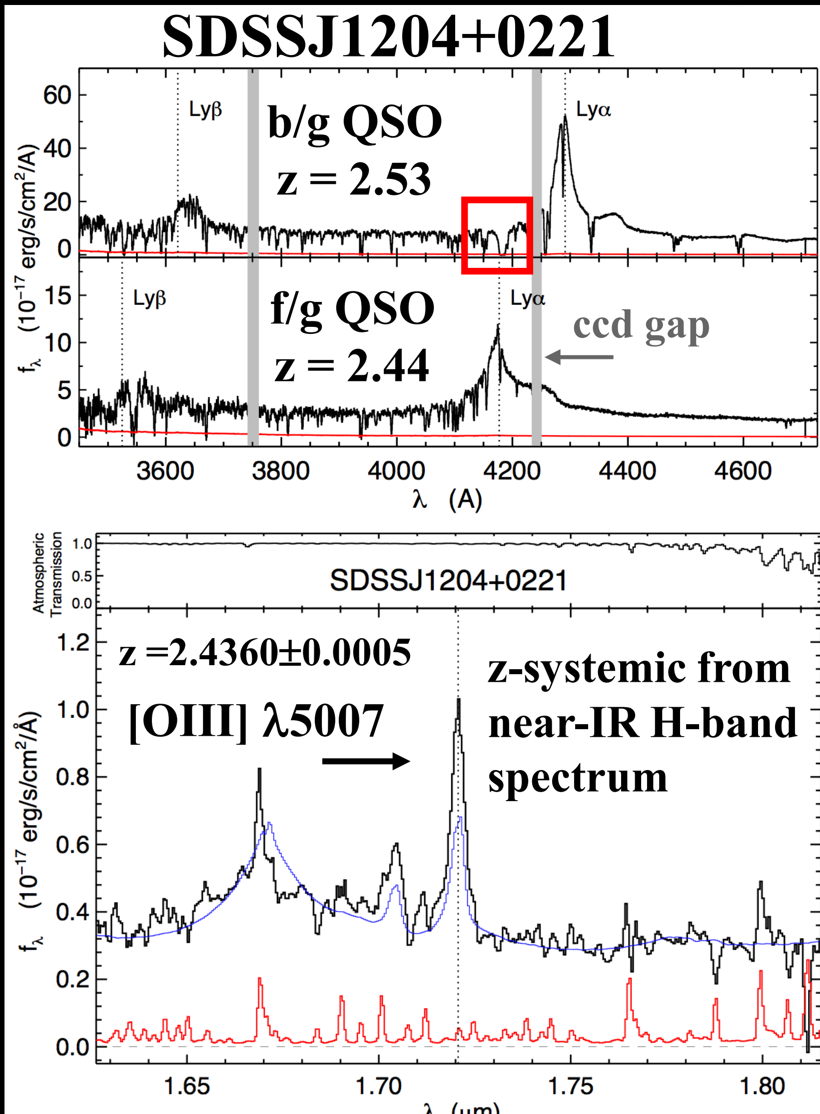
Cloud Density, Size, Pressure?

Multiphase? Cold, Warm, Hot?

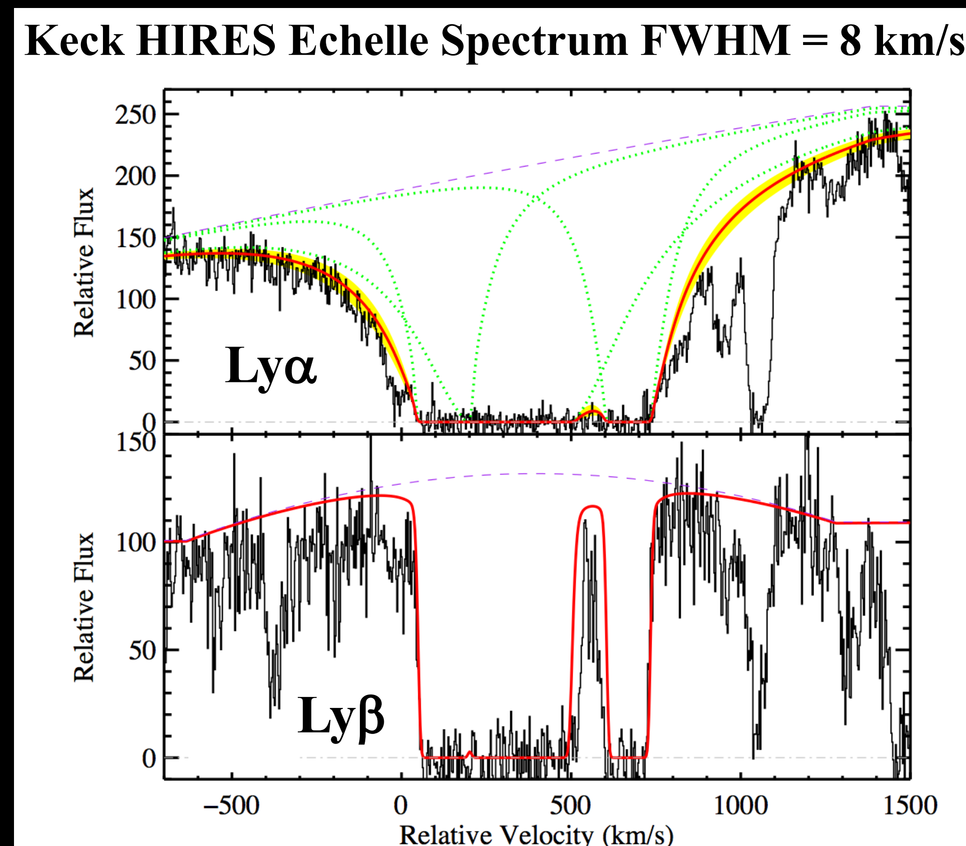
Distribution of Metals?

Use high resolution spectra to conduct detailed studies of the physical state of gas near the foreground quasar.

What is the Physical State of the Gas?

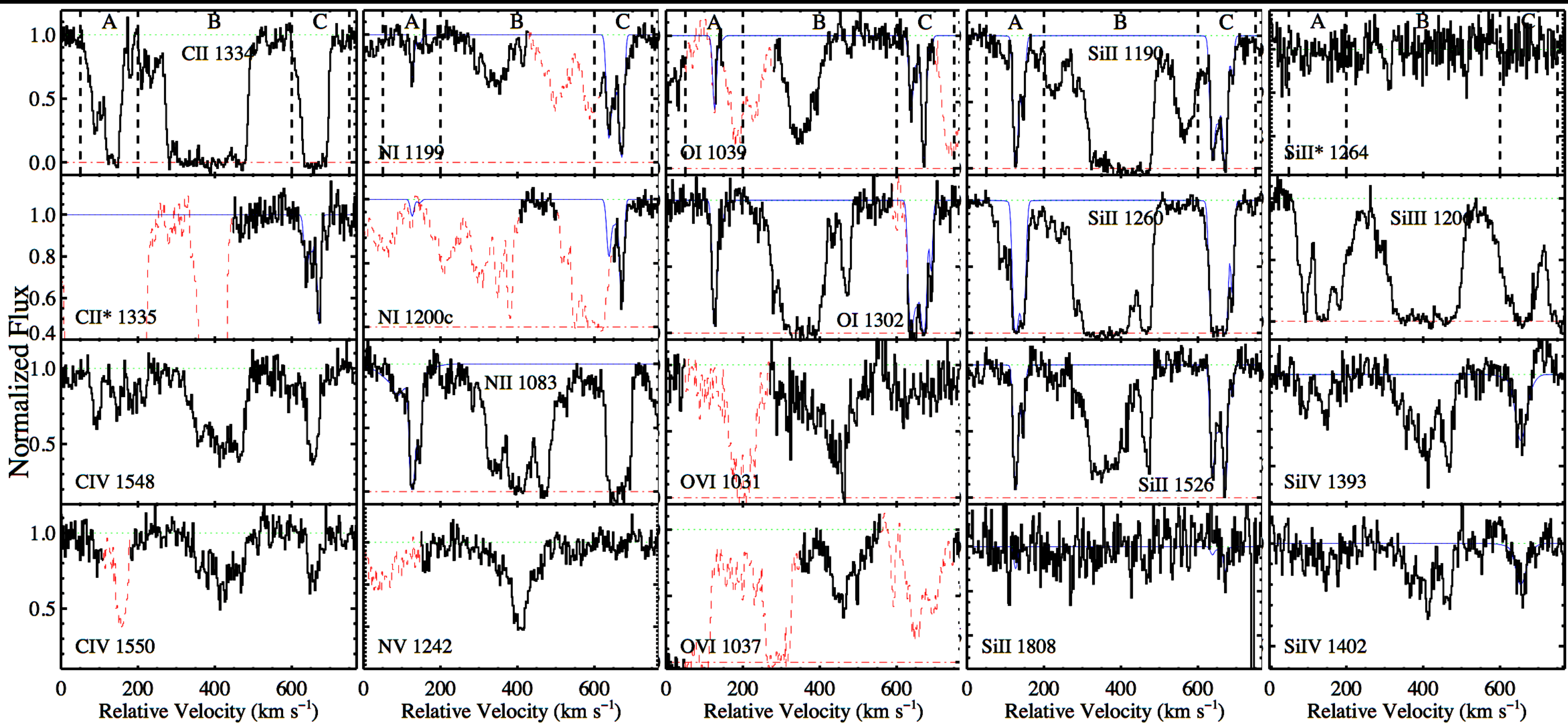


- $\Delta\theta$ = 13.3” or $R_\perp$ = 108 kpc
- Lyman limit system: log N_{HI} = 19.7



b/g QSO bright enough (r = 19.0) for Echelle Spectroscopy!

SDSSJ1204+0221: Metal Lines

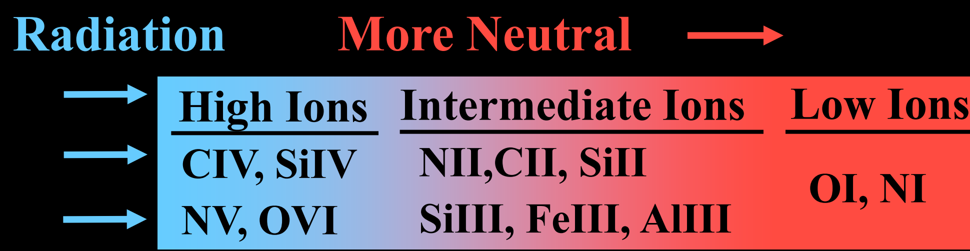


Prochaska & Hennawi (2009)

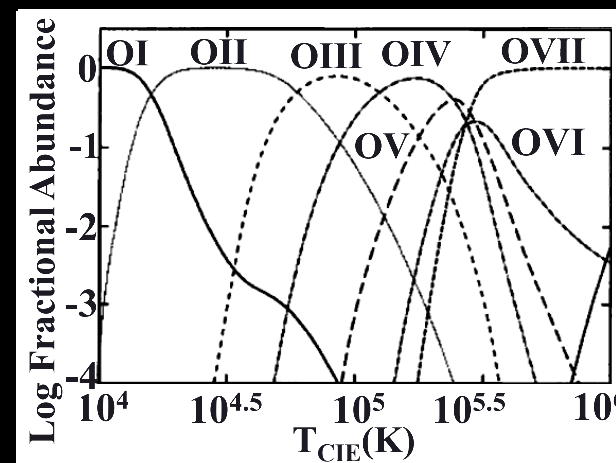
How do we interpret all of this information?

Absorption Line Physics

- **Photionization**
  Ionizing radiation sets relative strength of ionic transitions.
  Determine ionization corrections and hence total gas mass

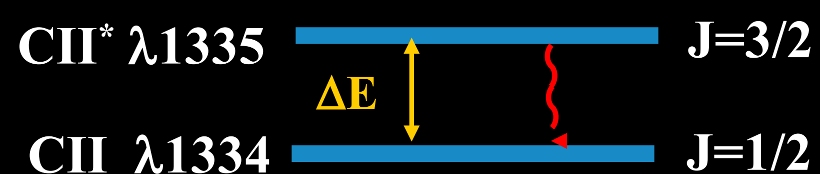


- **Collisional Ionization**
  Collisions with free electrons sets strength of high ions.
  Measure amount of gas in warm phase T ~ 10^5-10^6 K



- **Collisional Excitation**
  Collisions with free electrons excite fine structure levels.
  Measure electron density

Fine Structure of C^+ ion

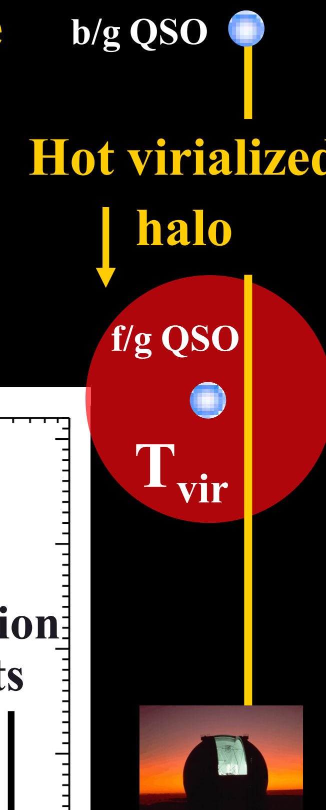


$\Delta E = 0.008$ eV, $\lambda = 158\mu m$, $T = 92$ K

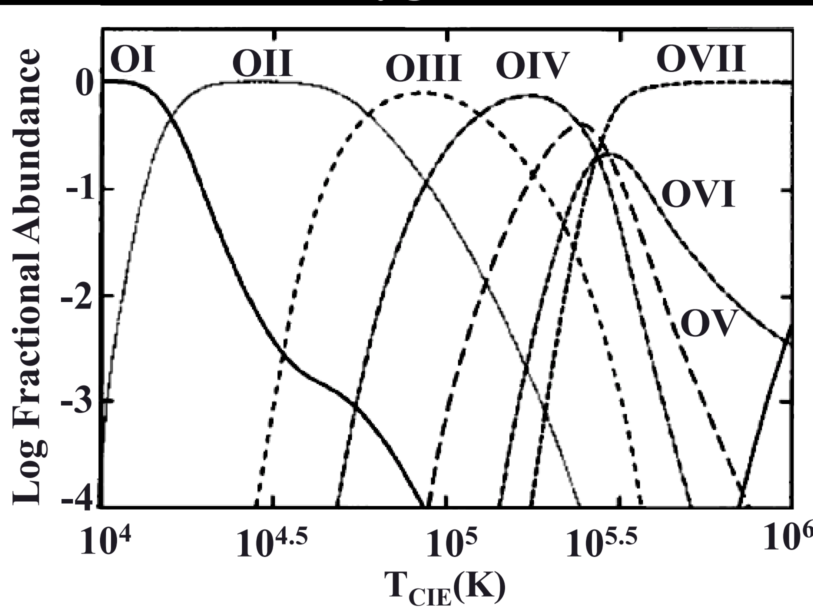
Collisional Ionization

Degree of collisional ionization set only by temperature

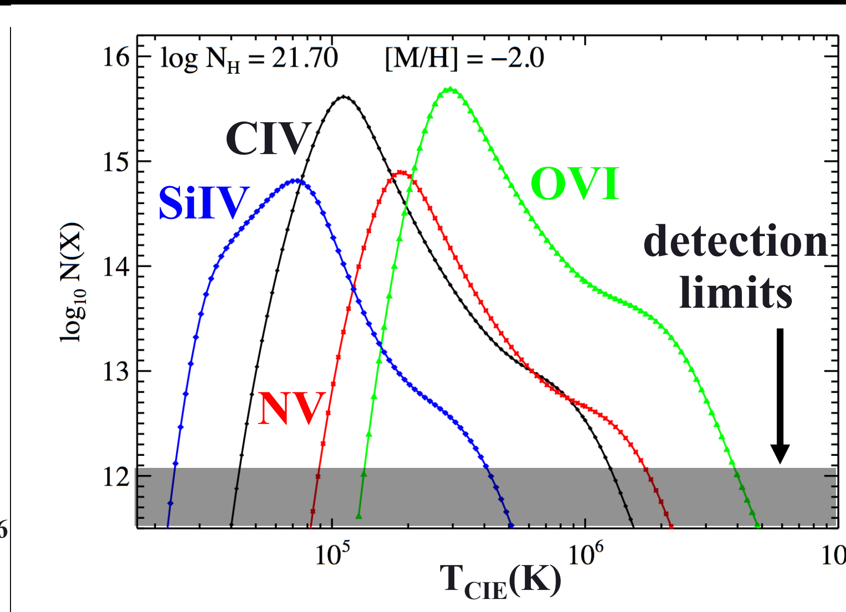
$$T_{\rm vir} = \frac{\mu m_{\rm p} V_{\rm circ}^2}{2 k_{\rm B}} = 7 \times 10^6 \left(\frac{M}{10^{12.9} M_\odot} \right)^{2/3} {\rm K}$$



Fractional Oxygen Abundance



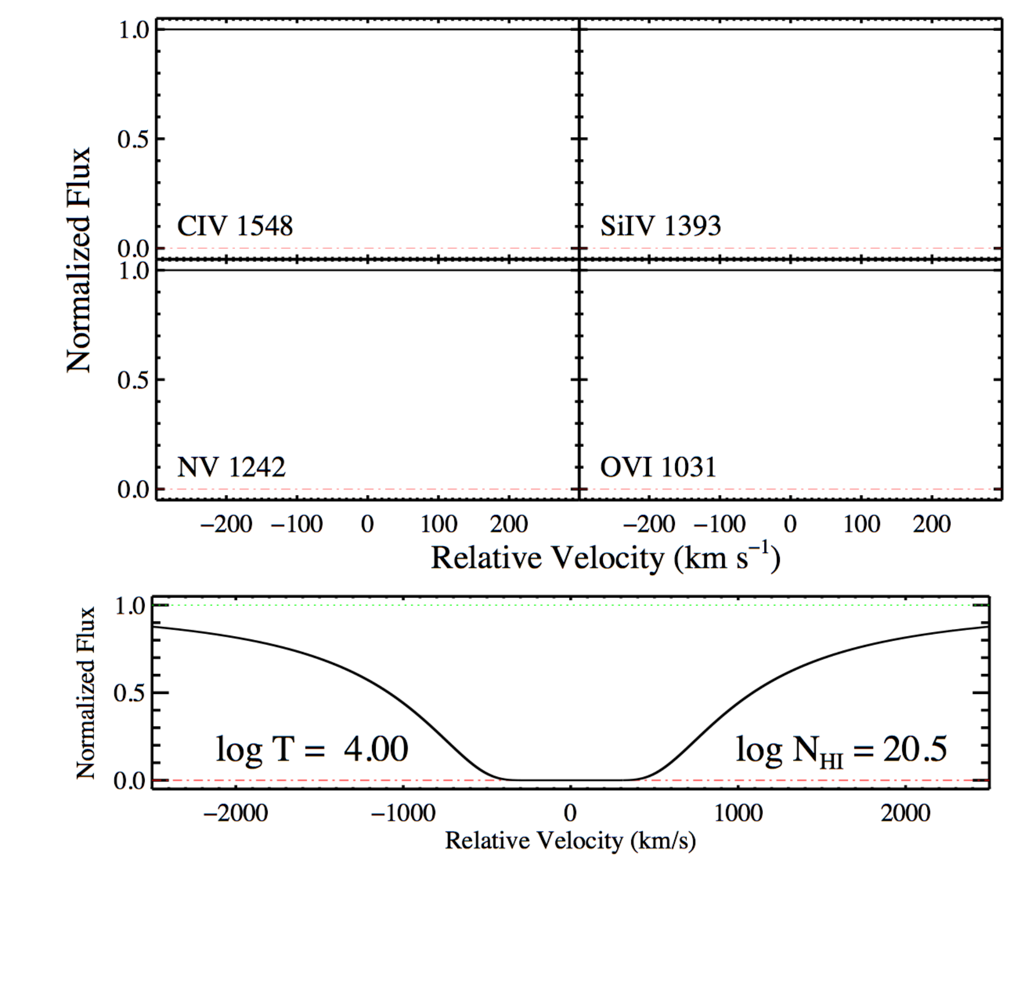
Column Densities for CIE



<u>So we can measure</u> **gas column in "warm" phase 10^5 K< T_{vir}< 10^6 K.**

Need X-ray observations to detect T_{vir} > 10^6 K.

Collisional Ionization



In this simulation we tie the bulk motion (line width) to temperature via the virial relation

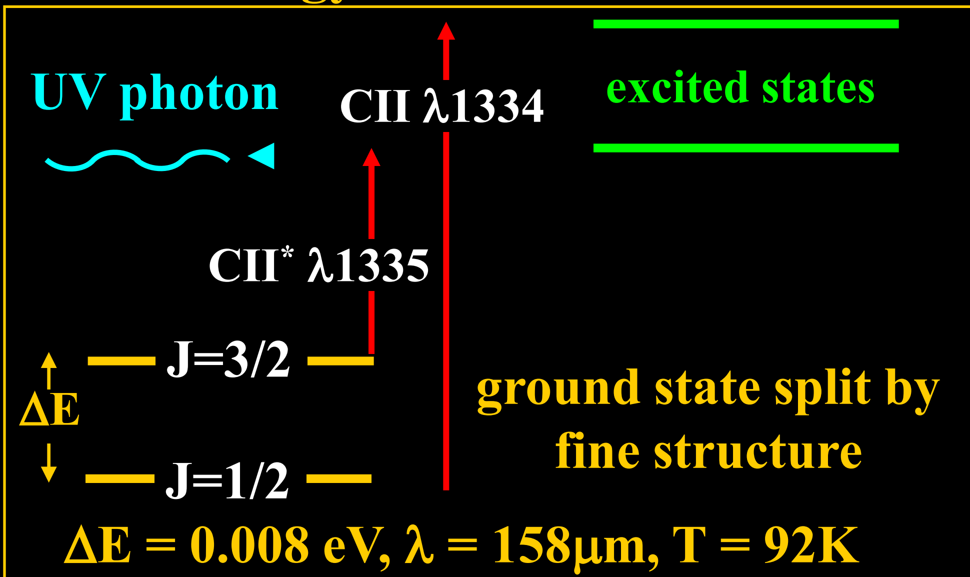
$$T_{\rm vir} = \frac{\mu m_{\rm p} V_{\rm circ}^2}{2 k_{\rm B}}$$

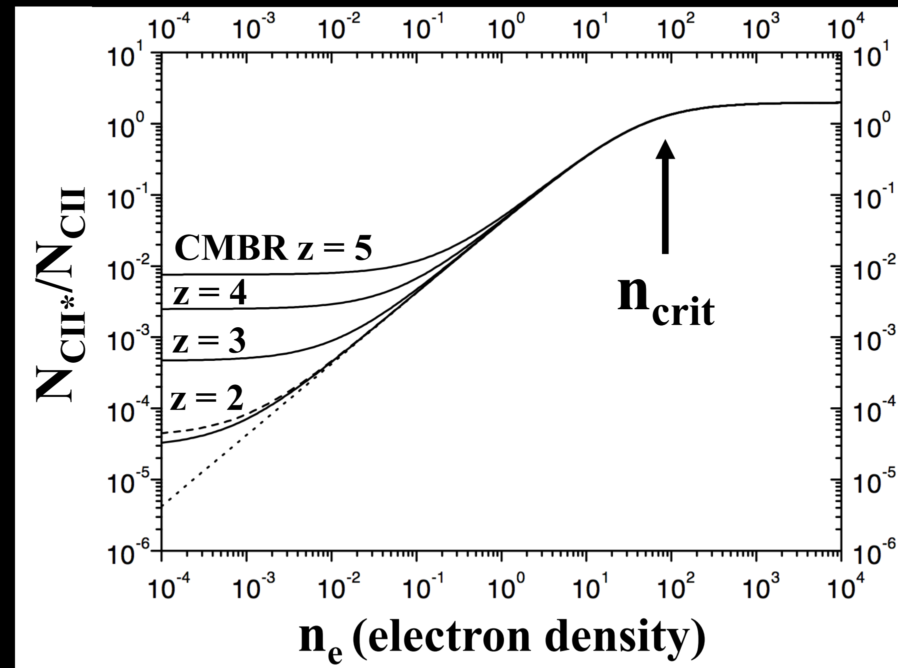
and vary virial temperature.

Virialized hot gas shows high-ion transitions with large "mechanical" broadening from bulk random motions.

Collisional Excitation

Energy Levels of CII ion





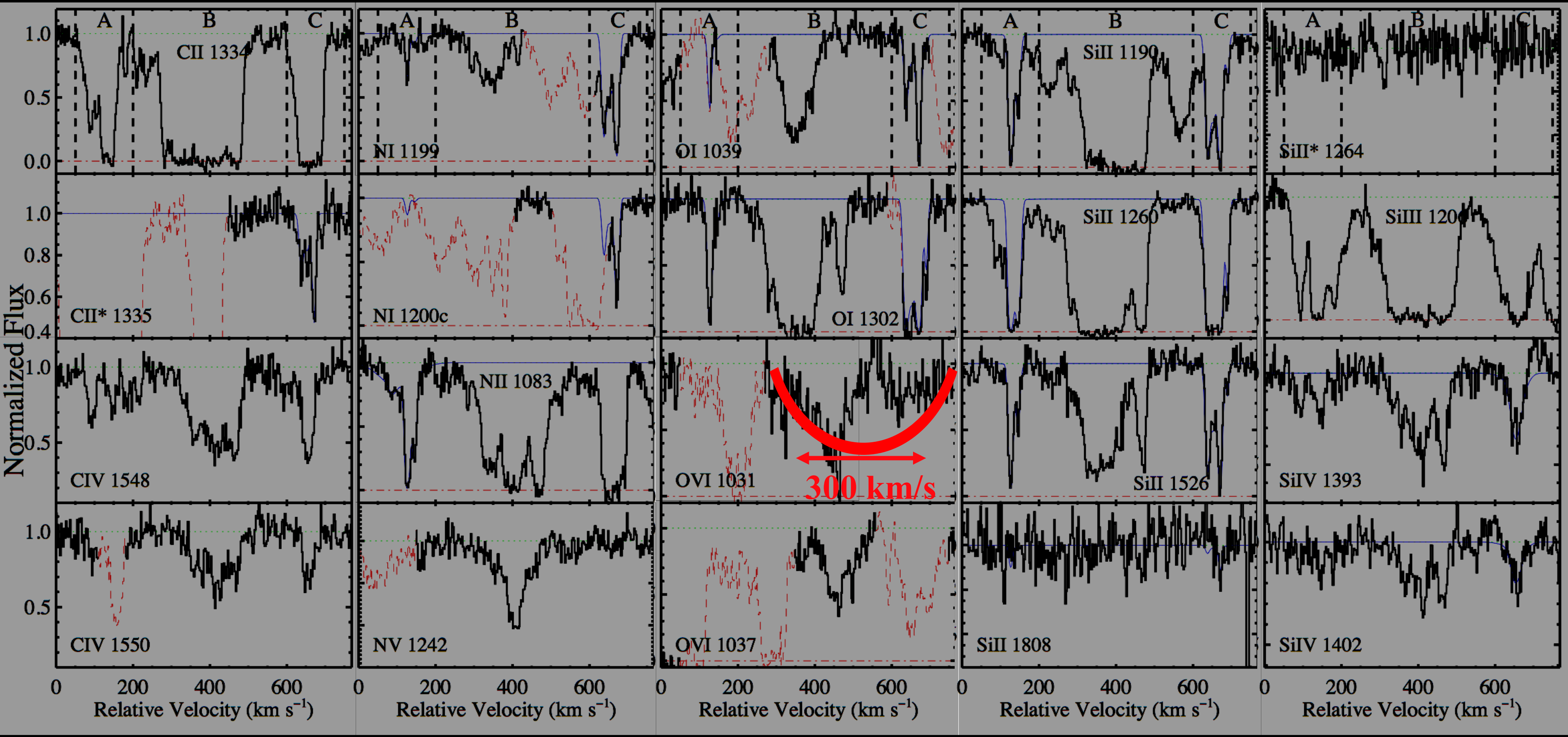
Silva & Viegas 2002

$$\underbrace{\frac{N_{\mathrm{C\,II^*}}}{N_{\mathrm{C\,II}}}}_{\text{column ratio}} = \frac{n_e}{n_{crit}}\left(1+\frac{n_e}{n_{crit}}\right)^{-1}\underbrace{\frac{g_{\mathrm{C\,II^*}}}{g_{\mathrm{C\,II}}}e^{-\frac{\Delta E}{kT}}}_{\text{thermodynamic equilibrium}} = 1$$

electron density (n_e); critical density (n_{crit})

- Populated by electron collisions, 158μm CMB photons, UV pumping
- Temperature independent! <u>So we can measure</u> electron density.
- Dynamic range from CII*, SiII*, and FeII* 10^{-2} cm^{-3} < n_e < 10^{5} cm^{-3}.

SDSSJ1204+0221: Metal Lines



- Absorption ~ 700 km/s from f/g QSO systemic ➡ extreme kinematics
- Large NII/NI ➡ gas is definitely ionized
- Weak narrow CIV and SiIV ➡ ionization level is not extreme
- Detection of fine structure line CII* 1335 ➡ we can measure n_e
- No compelling broad NV or OVI ➡ no warm gas T ~ 10^5-10^6 K

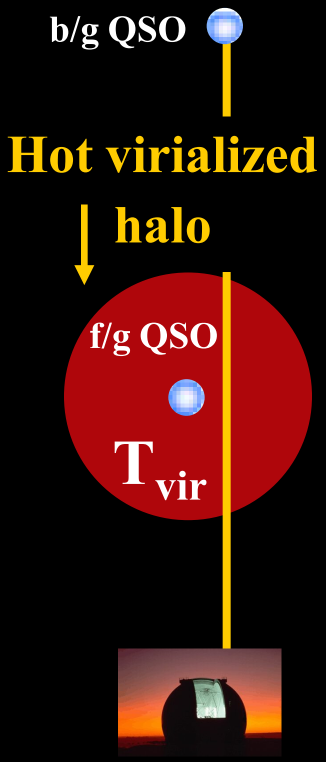
Properties of the Cold Gas

Property	Value	Anomalous for absorbers?
Neutral Column	$N_{HI} = 10^{19.65}$ cm^{-2}	Typical
Total Column	$N_H = 10^{20.6}$ cm^{-2}	Typical ($n_{HI}/n_H = 0.1$)
Total Mass	$M \sim 3\times10^{11} M_\odot$	Little is known
Velocity Field	$\Delta v = 700$ km/s	High. 99%-ile of absorbers
Metallicity	$Z = (0.25\text{-}1.6)\ Z_\odot$	High. 99%-ile of absorbers. Seen only in AGN or starburst gals
Number Density	$n_H \approx 1\text{-}5$ cm^{-3}	Little is known
Temperature	$T \approx 10{,}000$ K	Typical of ionized gas
Pressure	$nT \approx 4\times10^4$ cm^{-3} K	Little is known
Ionizing Flux	$\Phi < 10^{6.5}$ photons s^{-1} cm^{-2}	Typical. No QSO illumination!
Cloud Radius	$R \approx 10 - 100$ pc	Little is known
Covering Factor	$C \approx 0.25 - 1.0$	Little is known
Filling Factor	$C_V \approx 10^{-5} - 10^{-4}$	Little is known

Is there a Virialized Halo?

- QSO mass scale $M \approx 10^{13}\,M_{\odot}$. ΛCDM model predicts a virialized halo with

$$T_{\rm vir} = \frac{\mu m_{\rm p} V_{\rm circ}^2}{2 k_{\rm B}} = 7 \times 10^6 \left(\frac{V_{\rm circ}}{450\,{\rm km\,s^{-1}}} \right)^2 \,{\rm K}$$



- Collisional ionization strength of high-ions (NV, OVI) determined only by temperature
- Data are consistent with expectation:
  - no high ions detected ⇒ halo gas $T > 10^6$ K
  - extreme absorber kinematics $\Delta v \sim 700$ km/s consistent with $V_{circ} = 450$ km s^{-1}

Two Phase Medium

Combine statistical covering factor with photoionization model, to estimate cold gas density at r ~ 100 kpc

$$\rho_{\rm cold} \sim 3\times10^{-6}\underbrace{\left(\frac{f_{\rm C}}{0.3}\right)}_{\text{covering factor}}\underbrace{\left(\frac{N_{\rm H}}{10^{20.6}{\rm cm}^{-2}}\right)}_{\text{ionization model of SDSSJ1204}} M_\odot\,{\rm pc}^{-3}$$

Significant cold gas fraction ⇒ two-phase medium

$$\frac{\rho_{\rm cold}}{\rho_{\rm NFW}} \sim 0.08\left(\frac{f_{\rm gas}}{0.12}\right)^{-1}\left(\frac{f_{\rm C}}{0.3}\right)\left(\frac{N_{\rm H}}{10^{20.6}{\rm cm}^{-2}}\right)\left(\frac{M}{10^{12.9}M_\odot}\right)^{-0.7}$$

We measure cold phase *pressure* P = nT reasonably well:

$$P_{\rm cold} \approx 4\times10^{4}\left(\frac{n_{\rm e}}{2\,{\rm cm}^{-3}}\right)\left(\frac{T}{10^4\,{\rm K}}\right){\rm K\,cm}^{-3}$$

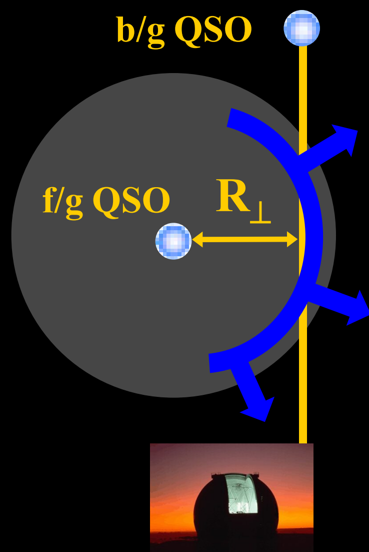
$$P_{\rm hot,NFW} \sim 2\times10^{4}\left(\frac{n_{\rm NFW}}{3\times10^{-3}\,{\rm cm}^{-3}}\right)\left(\frac{T_{\rm vir}}{7\times10^6\,{\rm K}}\right){\rm K\,cm}^{-3}$$

Pressure Equilibrium!

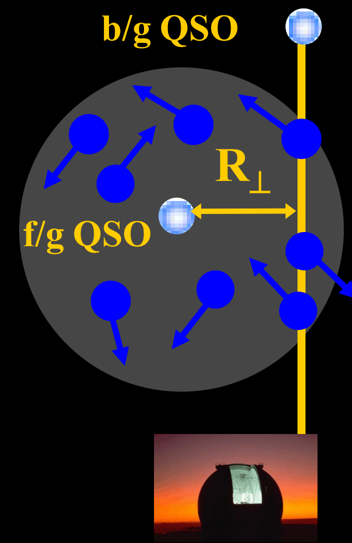
Outflow or Cold Flows?

Outflow

QSO feedback ejects or sweeps up cold material



?



Cold Flows

Gravitational motions in two phase medium

- Strongest evidence for outflow is high $Z \sim Z_\odot$ at 108 kpc.
- Outflow power $\dot{E} \sim \frac{1}{2}\Omega m_{\rm p} N_{\rm H} R_\perp \Delta v^3$

$$\dot{E}_{\rm outflow} \sim 9\times 10^{44}\left(\frac{\Omega}{2\pi}\right)\left(\frac{N_{\rm H}}{10^{20.6}\,{\rm cm}^{-2}}\right)\left(\frac{R_\perp}{108\,{\rm kpc}}\right)\left(\frac{\Delta v}{1000\,{\rm km\,s^{-1}}}\right)^3 {\rm erg\,s^{-1}}$$

kinetic luminosity

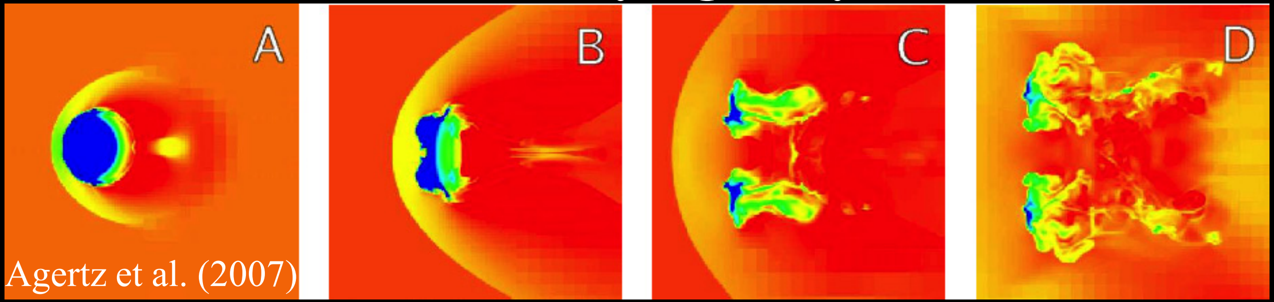
$$\eta = \frac{\dot{E}_{\rm feedback}}{L_{\rm bol}} \gtrsim \frac{\dot{E}_{\rm outflow}}{L_{\rm bol}} = 0.06$$

Significant coupling to accretion!
Are these energetics plausible?

Problems with Outflows

- Cloud size, density, velocity indicate they are short lived
  - Disruption by instabilities ~ 10^6 yr, dynamical time ~ 10^8 yr

Kelvin-Helmholtz & Rayleigh-Taylor instabilities



$$t \sim \frac{r_{\rm cloud}}{v_{\rm cloud}} \left(\frac{n_{\rm cloud}}{n_{\rm hot}} \right)^{1/2}$$

  - conductive evaporation in ~ 10^6 yr
  - cold clouds constantly forming and disrupted in outflow?

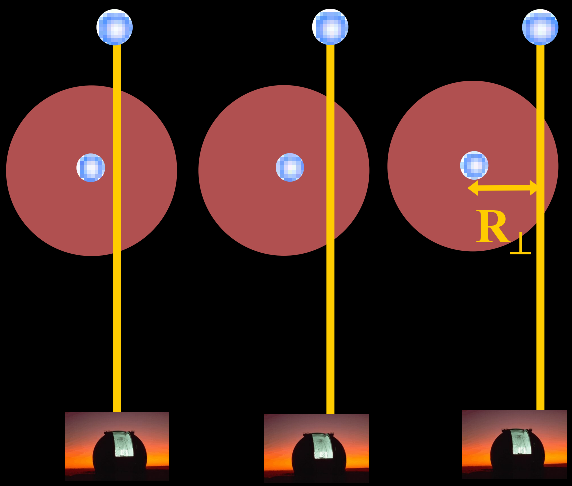
  $\Rightarrow$ must be significant gas mass in a hotter phase

- Why no significant warm phase T ~ 10^5-10^6 K?
- Our outflow power did not include hot phase or radiation
- Extreme energetics: outflow power > 6% accretion power

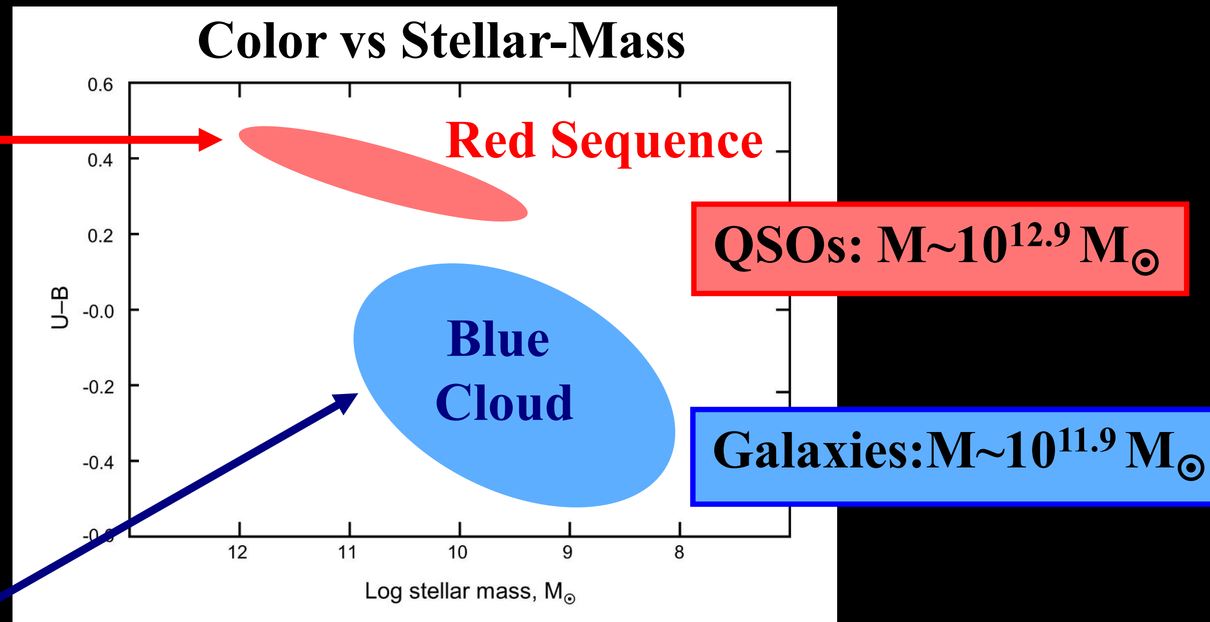
Problems with Cold Flows

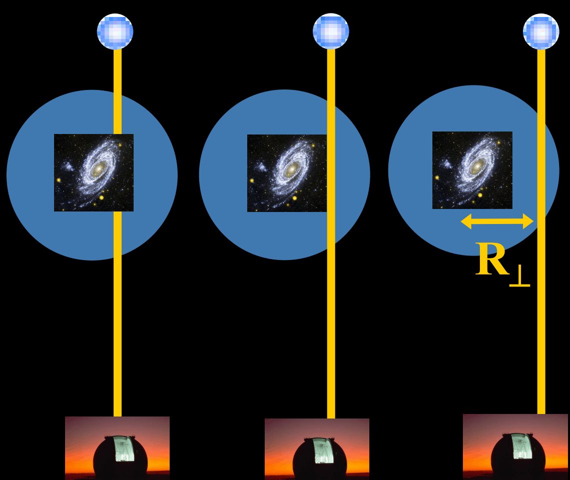
- <u>Why is the gas so metal enriched</u> $Z \sim Z_{\odot}$?
  - At z ~ 2.5 solar Z only in QSO BLRs and centers of starbursts
  - Today X-ray groups have $Z \sim 0.1Z_{\odot}$ at $R_{\perp} \sim 100$ kpc
  - Too few galaxies near QSO to produce high metal cov factor
- Observed $n \sim 1\ cm^{-3} >>$ hydro sims predict $n \sim 10^{-2}\ cm^{-3}$
- Cold cloud properties indicate they are short lived ~ 10^6 yr
  - Will not survive for dynamical time ~ 10^8 yr. No cold flows?
  - If clouds formed/disrupted then hot halo must have $Z \sim Z_{\odot}$???
- Hydro simulations predict less cold gas in massive halos

Statistical Samples



Foreground QSOs





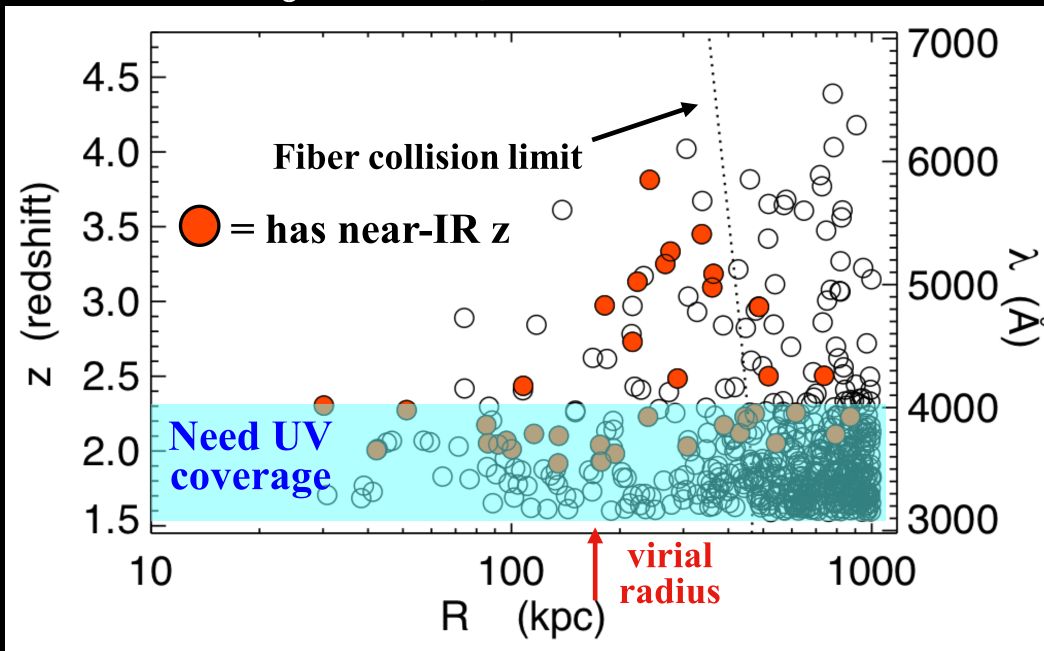
Foreground Galaxies

Map out physical properties versus impact parameter $R_\perp$ for statistical samples

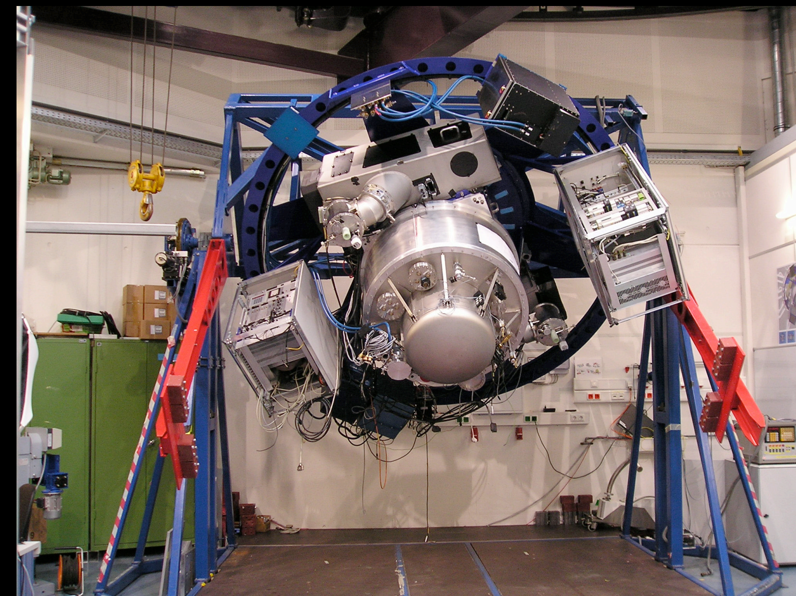
- metallicity
- kinematics
- cold (10^4 K) and warm ($10^{5\text{-}6}$ K) gas mass
- gas properties (density, pressure, size, covering factor)

The Future

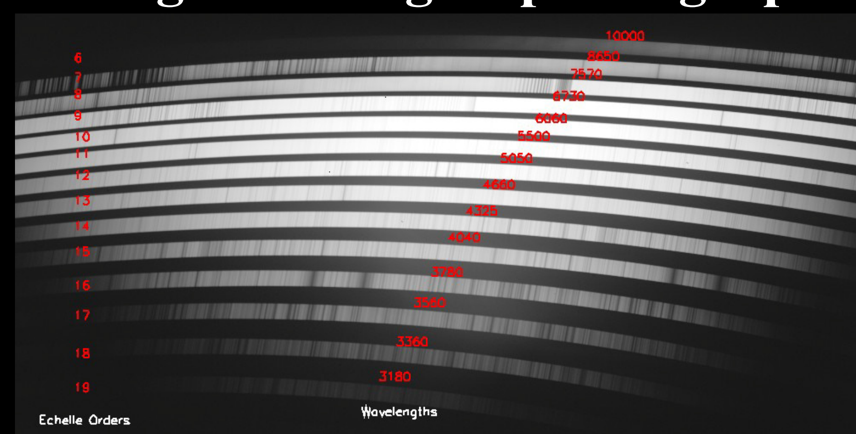
All Projected QSO Pairs Known



New VLT X-shooter Spectrograph

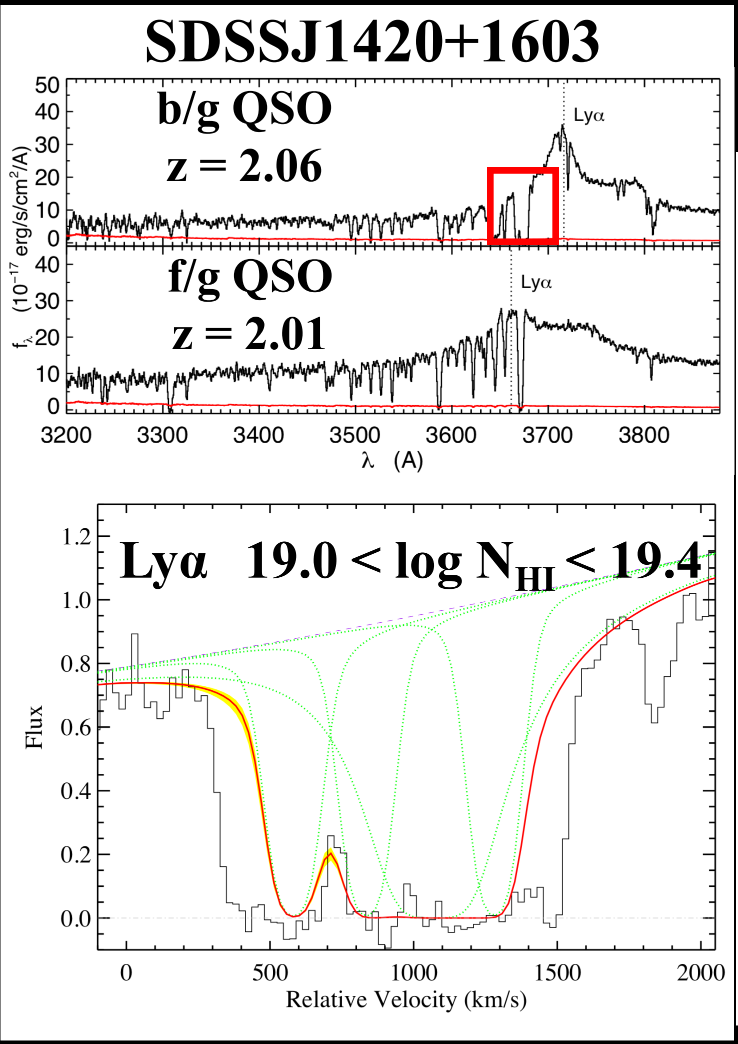


Magellan MagE Spectrograph

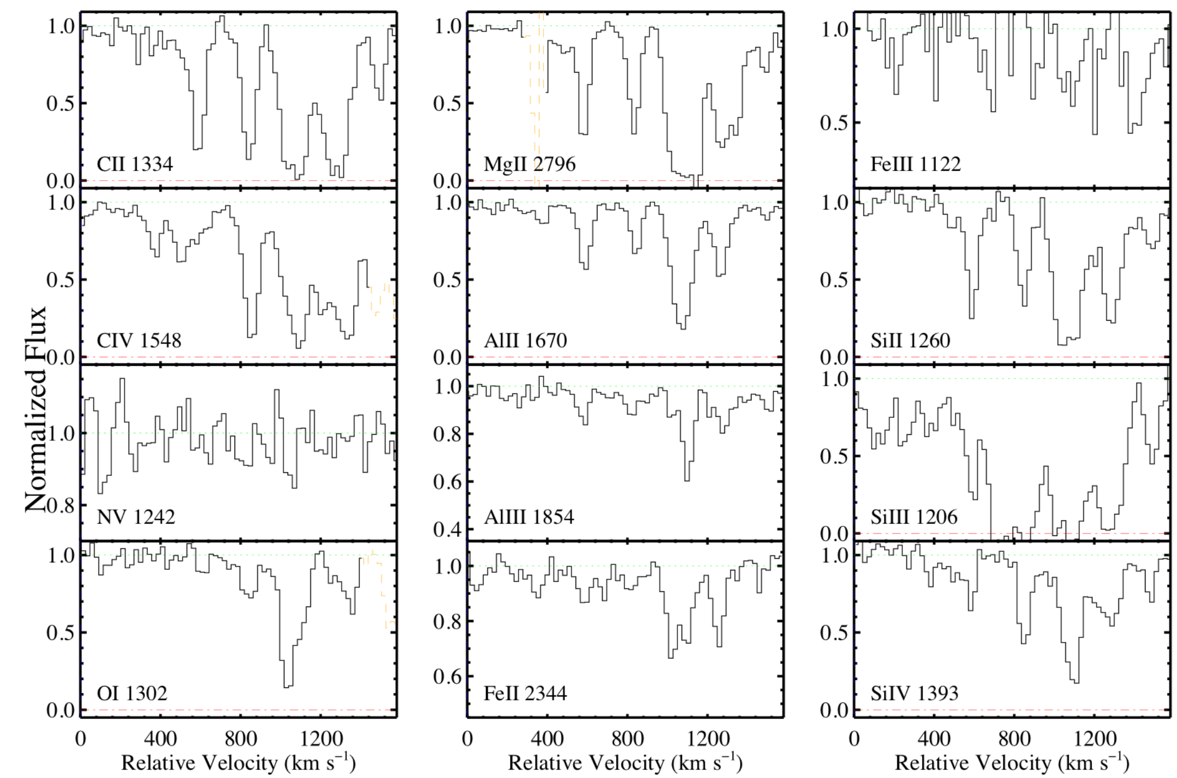


- 70 pairs with R < 200 kpc ~ r_{vir}
- Bottleneck: faint sources g ~ 21. Need UV sensitive echellette.
- MagE and X-shooter will enable statistical studies of ~ 100 QSOs.

Towards a Statistical Sample



$\Delta\theta$ = 12.0" or $R_\perp$ = 100 kpc Hennawi et al. (2011)



Magellan/MagE Echellette Spectrum, FWHM = 50 km/s

Similarly exhibits extreme kinematics $\Delta v \approx 800$ km/s and a high enrichment level $Z > 0.14\ Z_\odot$

Summary

- **What is the physical state of gas in progenitors of red and dead galaxies?**

  The gas is multiphase:

  – **Cold Phase $T \sim 10^4$ K: accounts for ~ 10% of expected density. Gas is highly eneriched $Z \sim Z_{\odot}$. Exhibits extreme kinematics ~ 700 km/s.**

  – **Warm Phase 10^5 K < T < 10^6 K: No evidence for one.**

  – **Hot Phase $T \sim 10^7$ K: impossible to detect, but should have right pressure to confine cold phase.**

- **Is there evidence for cold flows? What is the supply of $T < 10^4$ K gas?**

  Possibly. About ~ 3×10^{11} $M_{\odot}$ of cold gas or ~ 10% of expected gas mass.

Summary

- **Is feedback occurring in typical QSOs?**
  Most compelling argument is high metallicity $Z \sim Z_\odot$
- **How far does feedback energy, material, metals travel?**
  Metals travel to at least $R_\perp \sim 100$ kpc. Map this out with a statistical sample
- **How does feedback energy correlate with accretion power?**
  If we are observing feedback $dE/dt_{feedback} > 0.06\ L_{bol}$
- <u>**Theorists can predict gas MUCH MORE reliably than stars!!**</u>