Quasars Probing Quasars: Circumgalactic Gas in Absorption and Emission

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Credits

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SDSS

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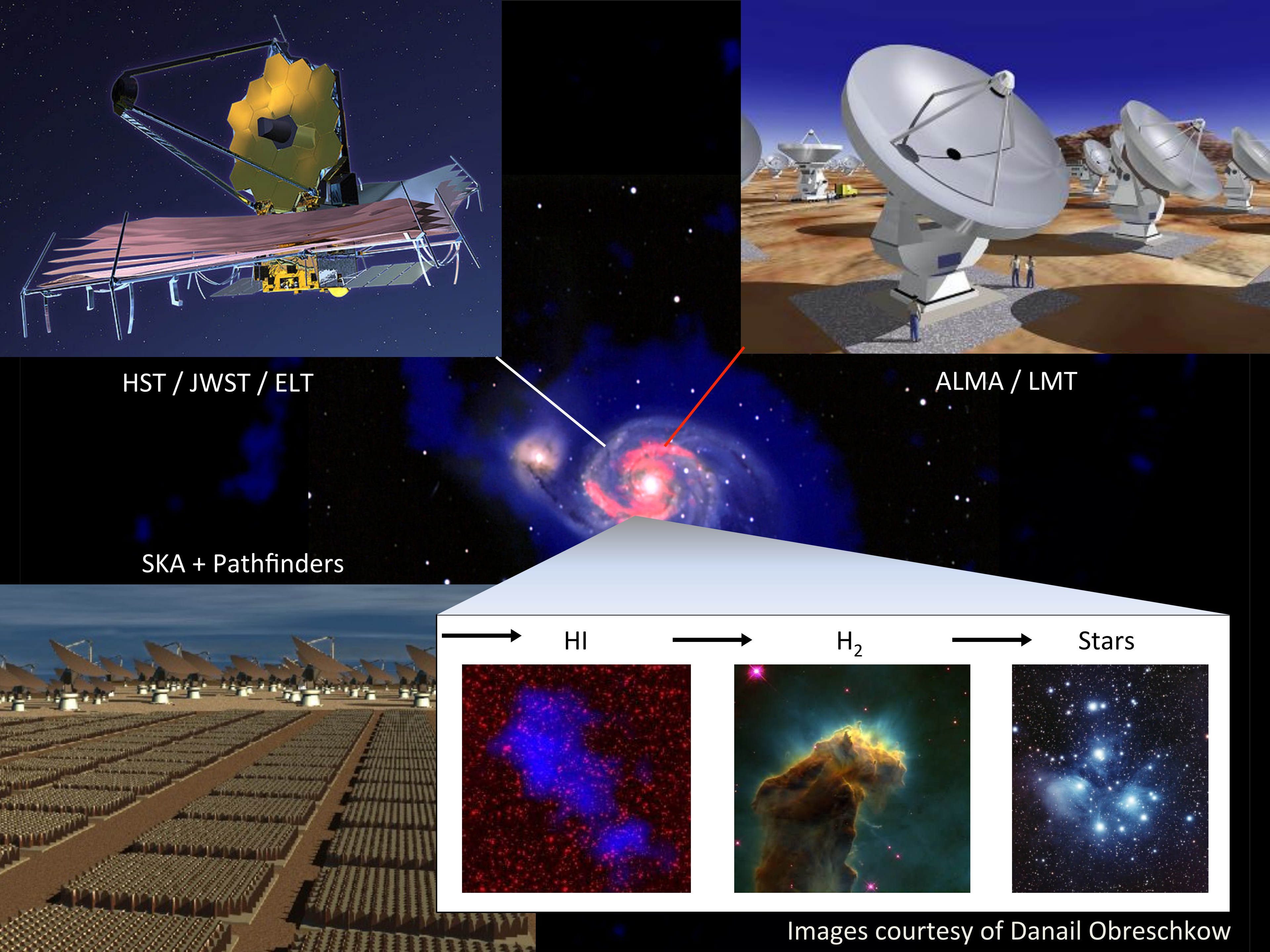
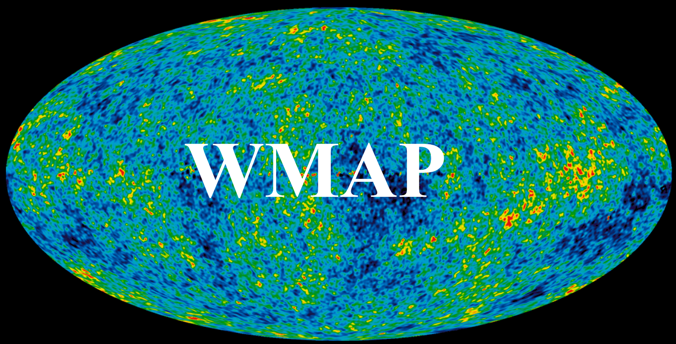


HST / JWST / ELT
ALMA / LMT
SKA + Pathfinders
HI
H_2
Stars
Images courtesy of Danail Obreschkow

Prediction: Dark Matter

versus

Postdiction: Baryons

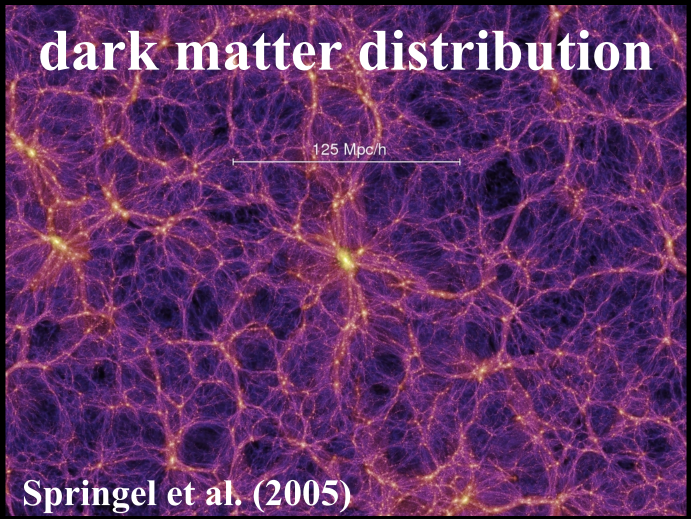


sub-grid

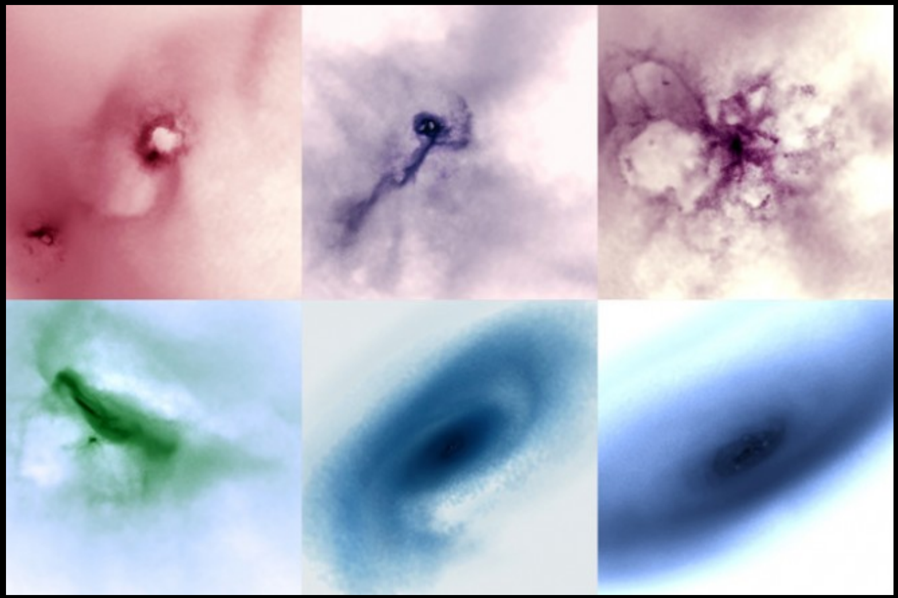
recipes

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

ab initio theory



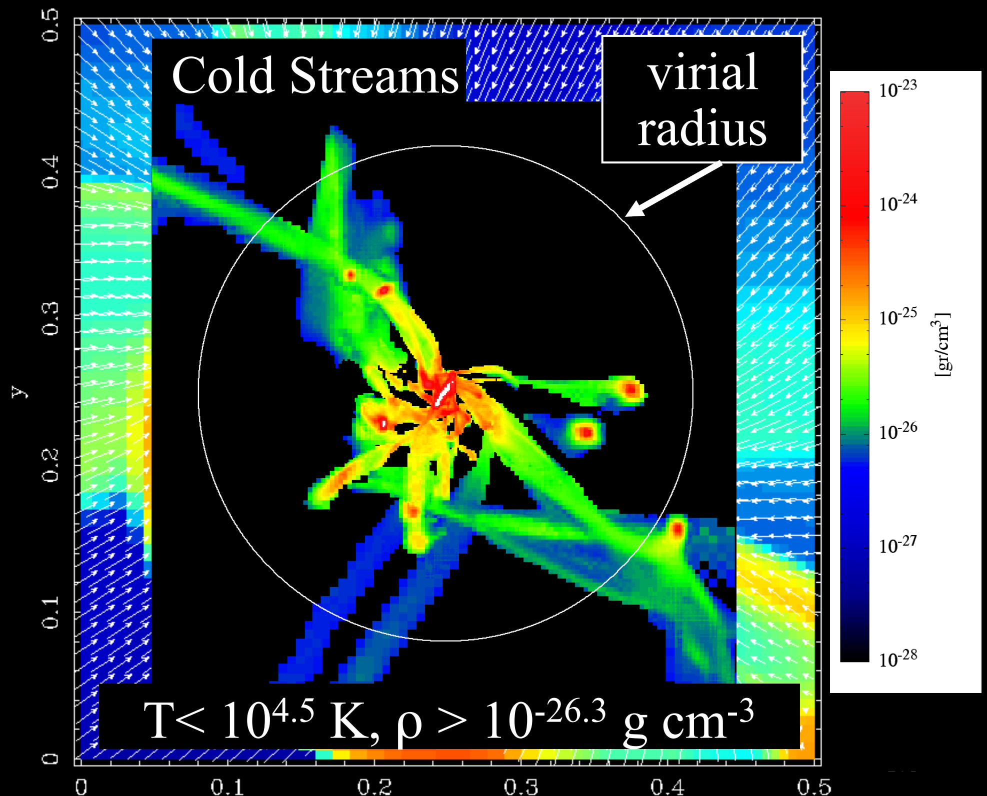
Springel et al. (2005)



Simulated Galaxies: Fabio Governato

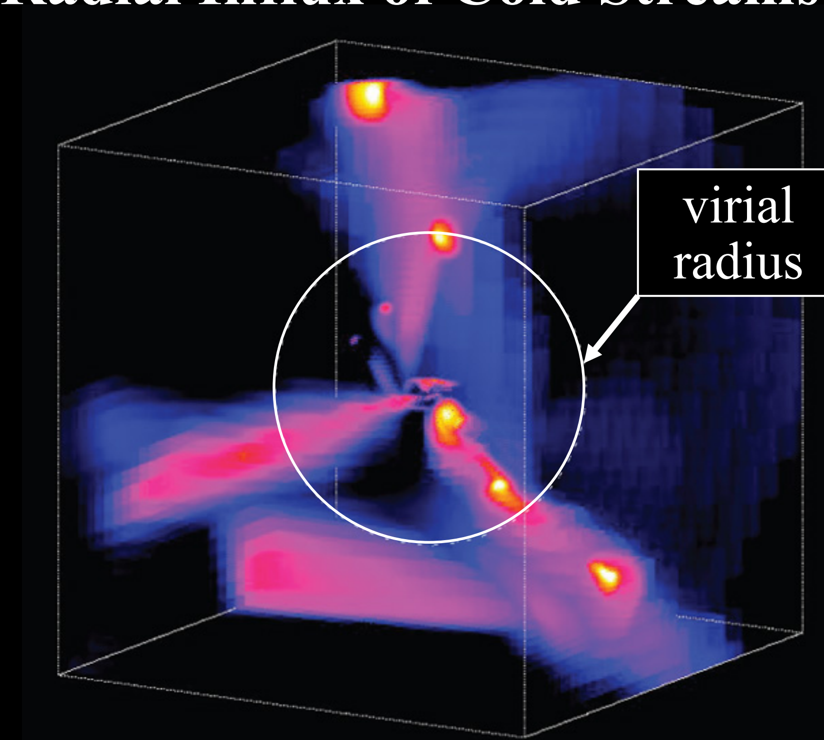
What are the initial conditions for galaxy formation?

The Initial Conditions for Galaxy Formation



Dekel & Bernboim (2006)

Radial Influx of Cold Streams



Dekel et al. (2009)

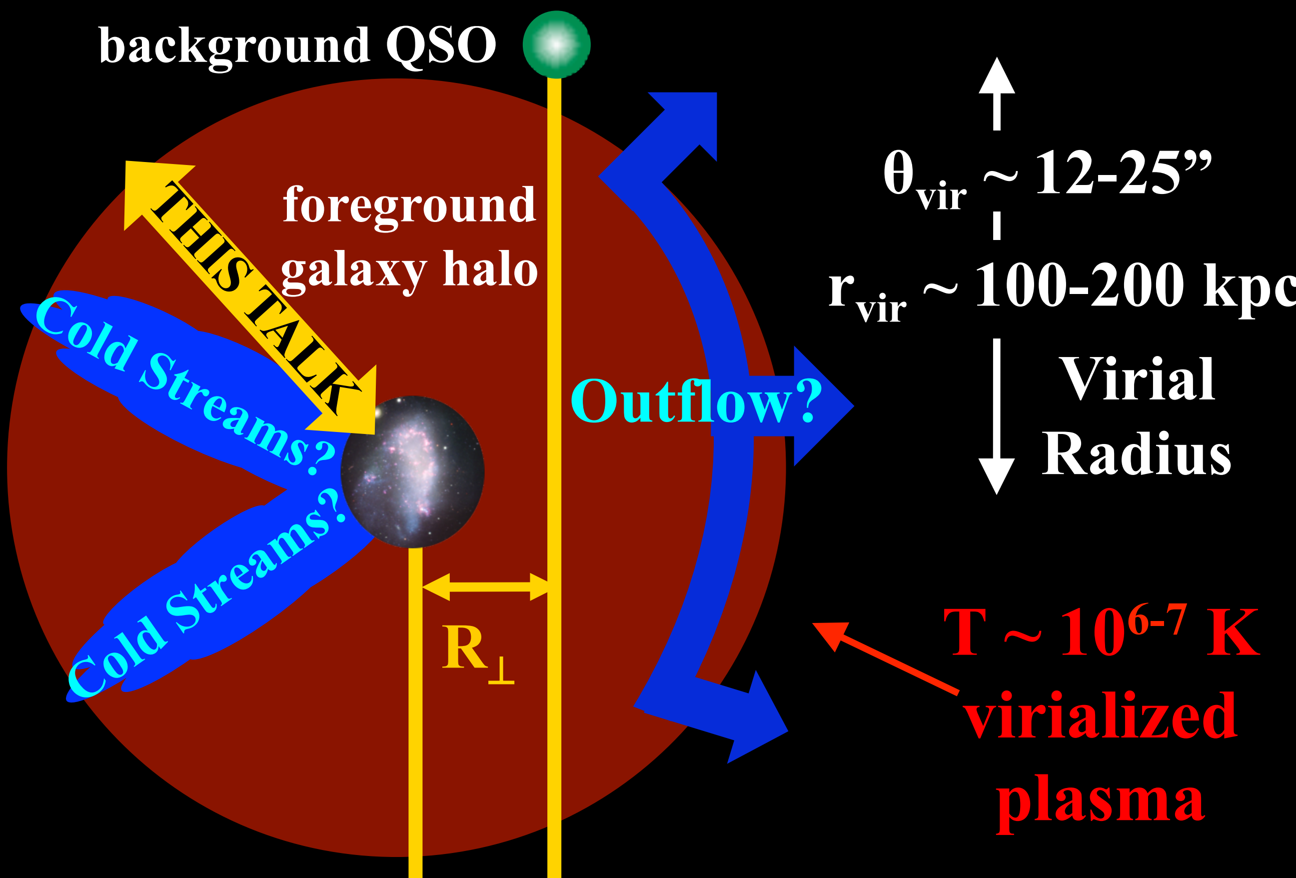
Hydro sims predict that the circumgalactic medium (CGM) of $M \sim 10^{12}\ M_\odot$ halos have ~ 20% covering factor of cold gas with $N_{HI} > 10^{17.2}$ cm^{-2}

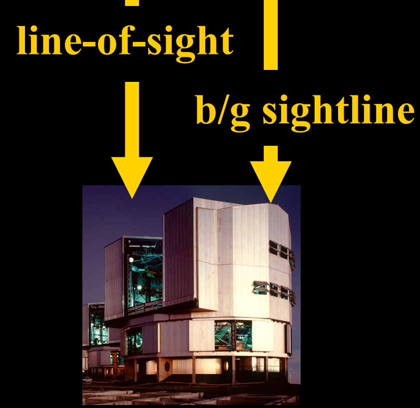
Probing the Circumgalactic Medium (CGM)

Use absorption lines to probe diffuse gas

r ~ 30 – 200 kpc

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





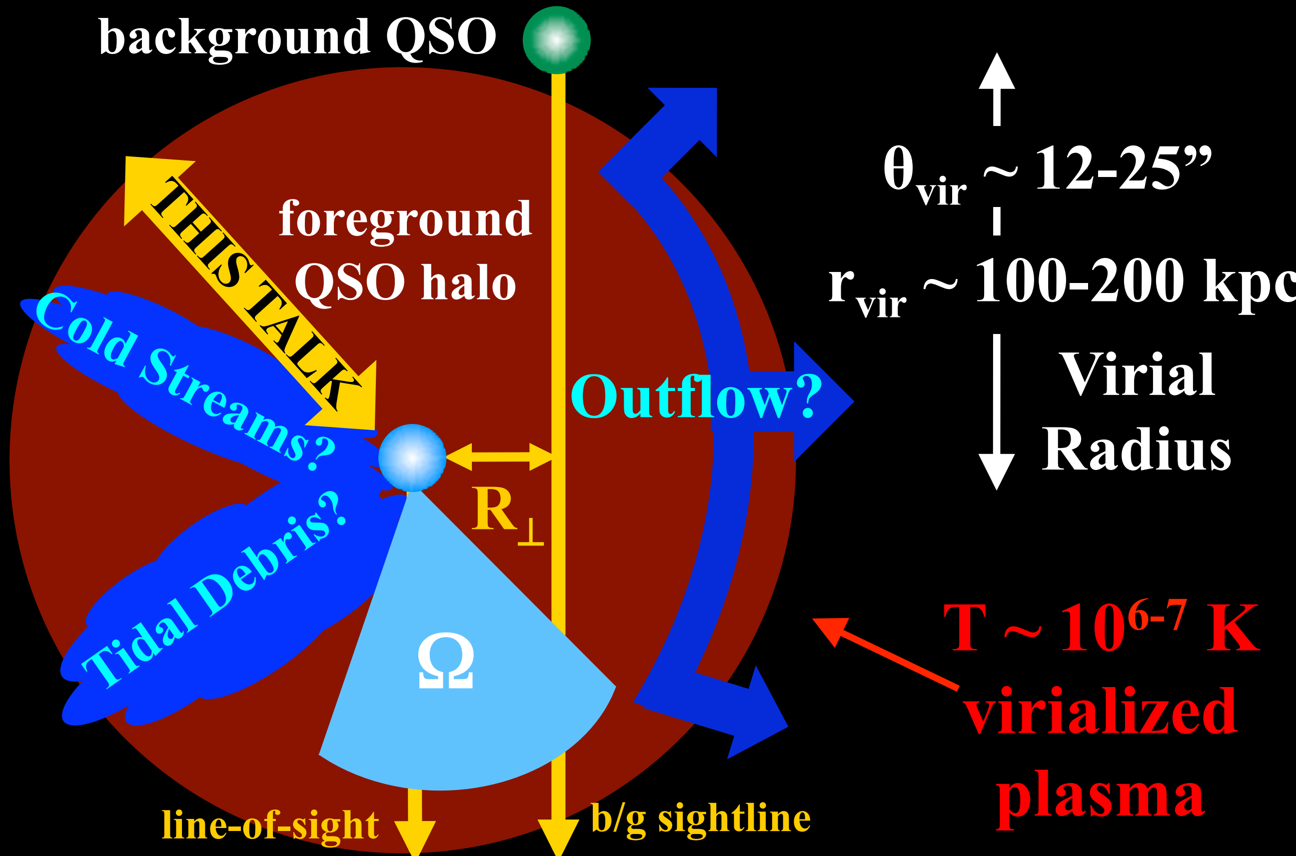
Observational Challenge: find bright b/g QSO at small impact parameter to distant galaxies

Probing the CGM of Quasars

Use absorption lines to probe diffuse gas

$r \sim 30 - 200$ kpc

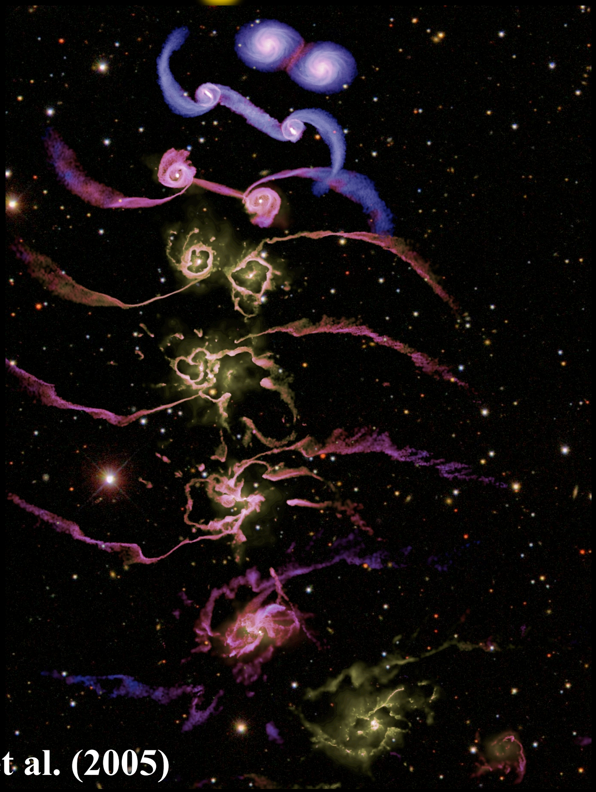
$N_{HI} \sim 10^{12\text{-}22}$ cm^{-2} and $T \sim 10^{2\text{-}6}$ K



- QSOs trace massive $M_{halo} \sim 10^{12.5} M_\odot$ galaxies at high-z
- Why use QSOs? Because we can find $\sim 10^6$ in SDSS
- Directly probe gas $\rho/\langle\rho\rangle \sim 10^{2\text{-}3}$ resolved by hydro grids
- Complications: ionizing radiation, are QSOs atypical?

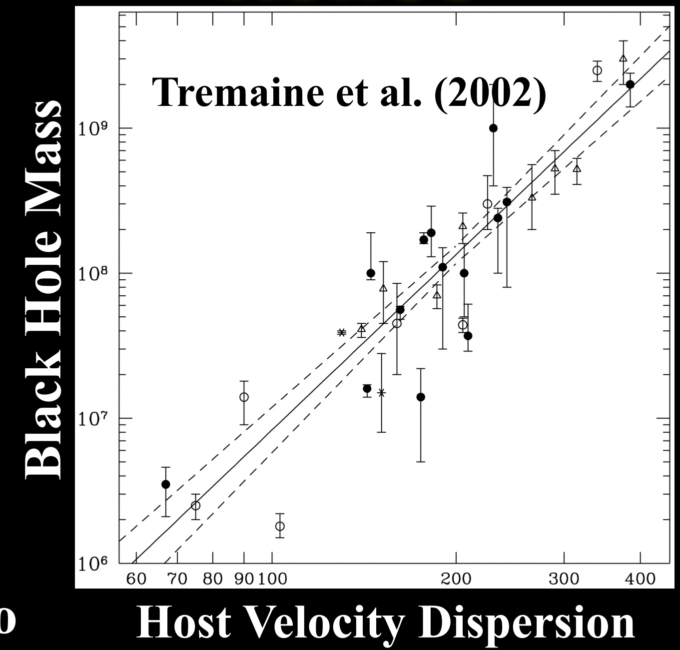
Quasar Feedback?

Progenitors



Springel et al. (2005)

Relics



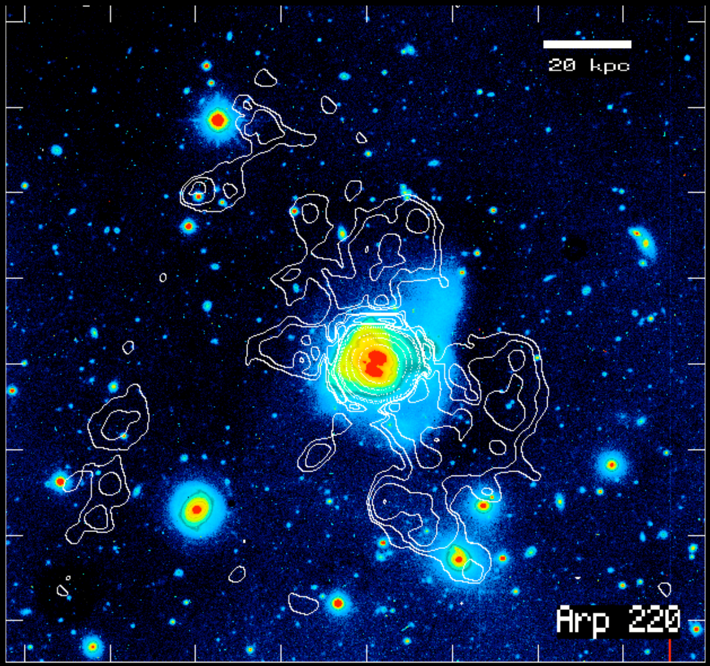
5% coupling to accretion power

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

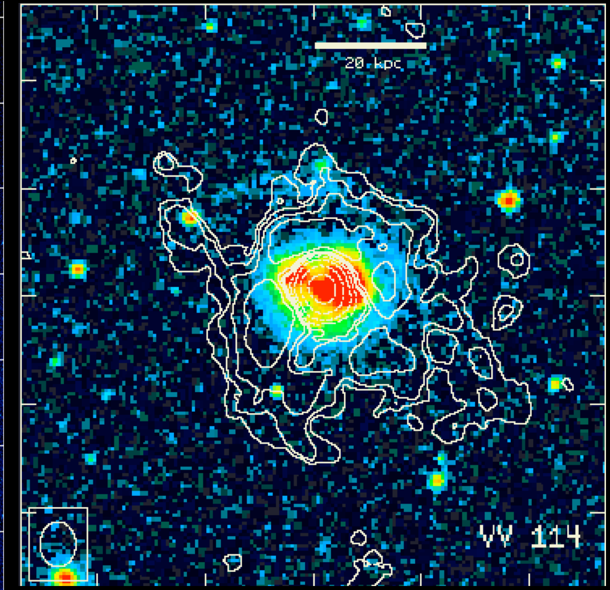
It remains unclear whether accretion energy can couple to large > 1 kpc scales in <u>typical</u> QSOs

The CGM of Mergers: Tidal Debris

Arp 220

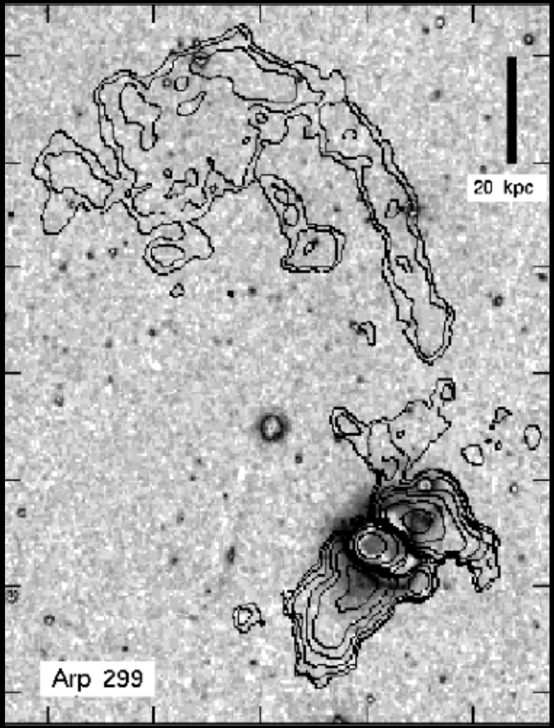


VV 114



from Hibbard & Yun (1996)

Arp 299



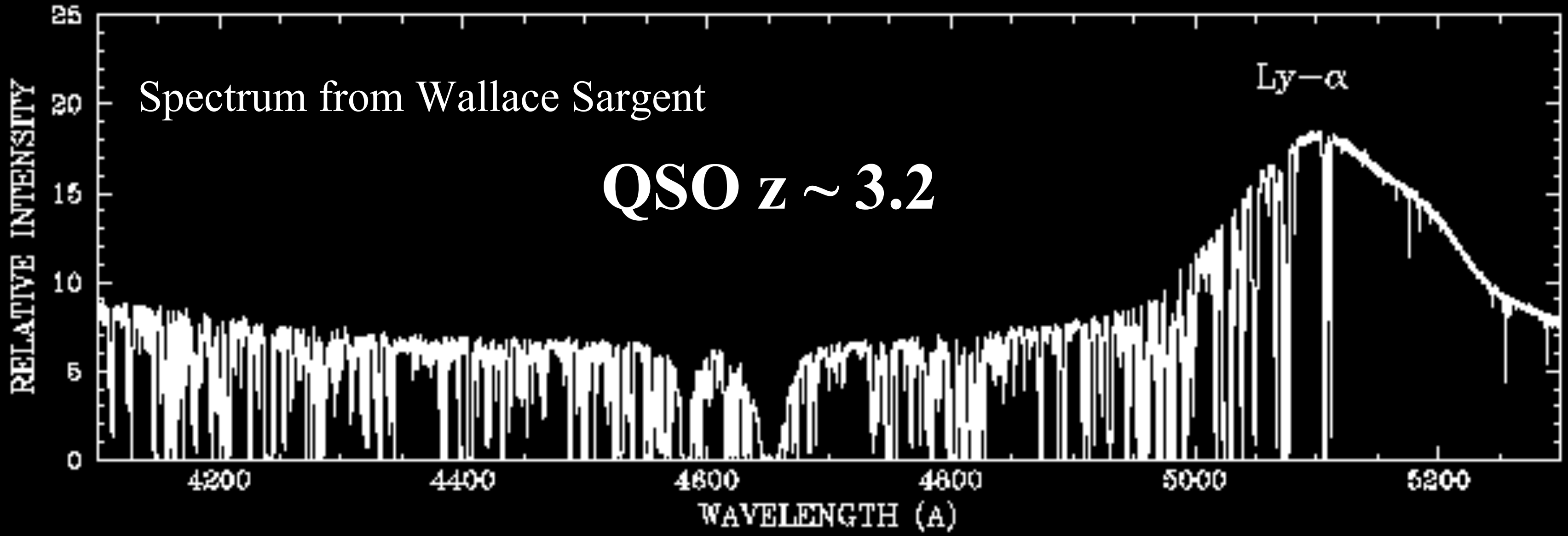
Contours: HI 21cm emission; lowest level $N_{HI} = 5 \times 10^{19}$ cm^{-2}

The circumgalactic media of LIRGs/ULIRGs show dramatic evidence for tidally stripped ISM out to large radii ~ 50-100 kpc

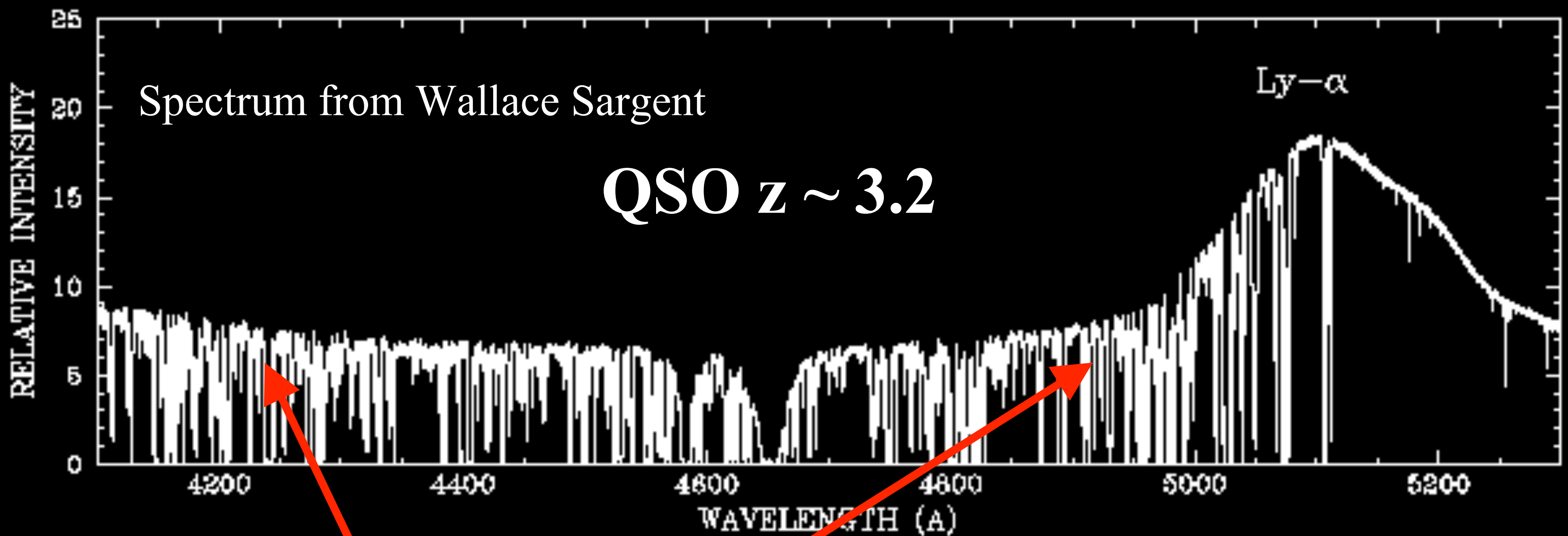
Outline

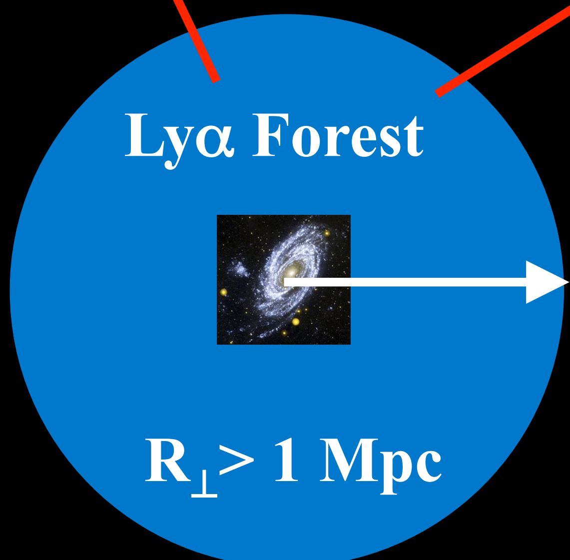
- Quasars absorption lines
- What is the supply of cold gas?
- What is the physical state of the gas?
- Can we detect cold gas in emission?

Quasar Absorption Lines



Quasar Absorption Lines

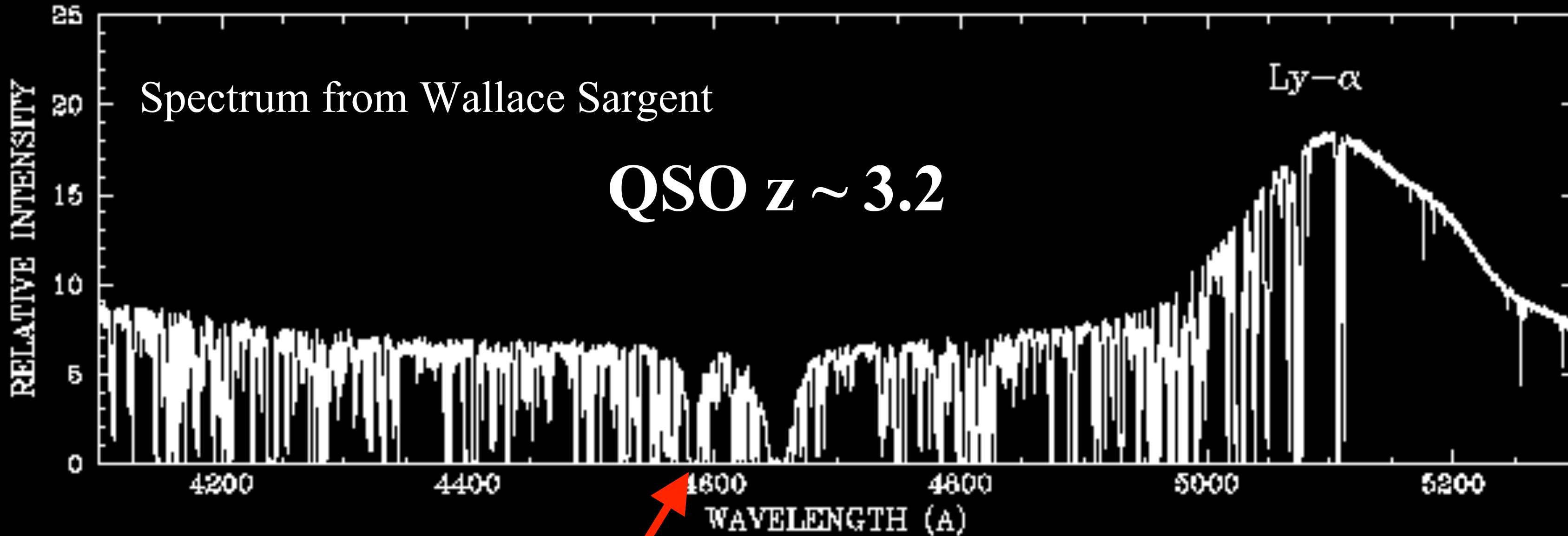


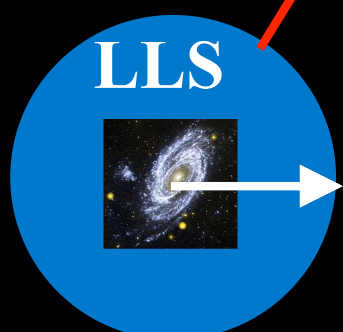


Lyα Forest

- 10^{12} cm^2 < N_{HI} < $10^{17.2}$ cm^2
- cosmic web

Quasar Absorption Lines



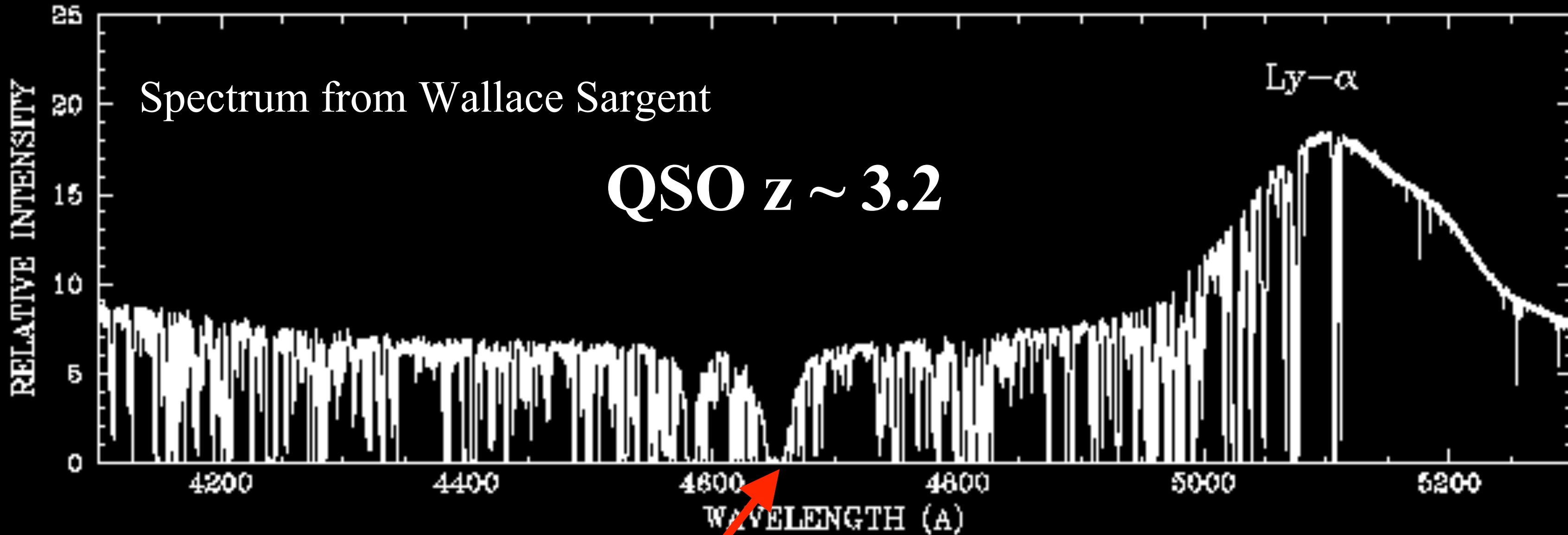


$R_{\perp} \sim 100$ kpc

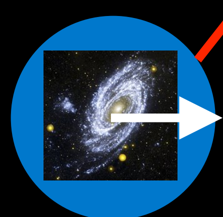
Lyman Limit System (LLS)

- $10^{17.2}$ cm^2 < N_{HI} < $10^{20.3}$ cm^2
- halos of galaxies

Quasar Absorption Lines



DLA

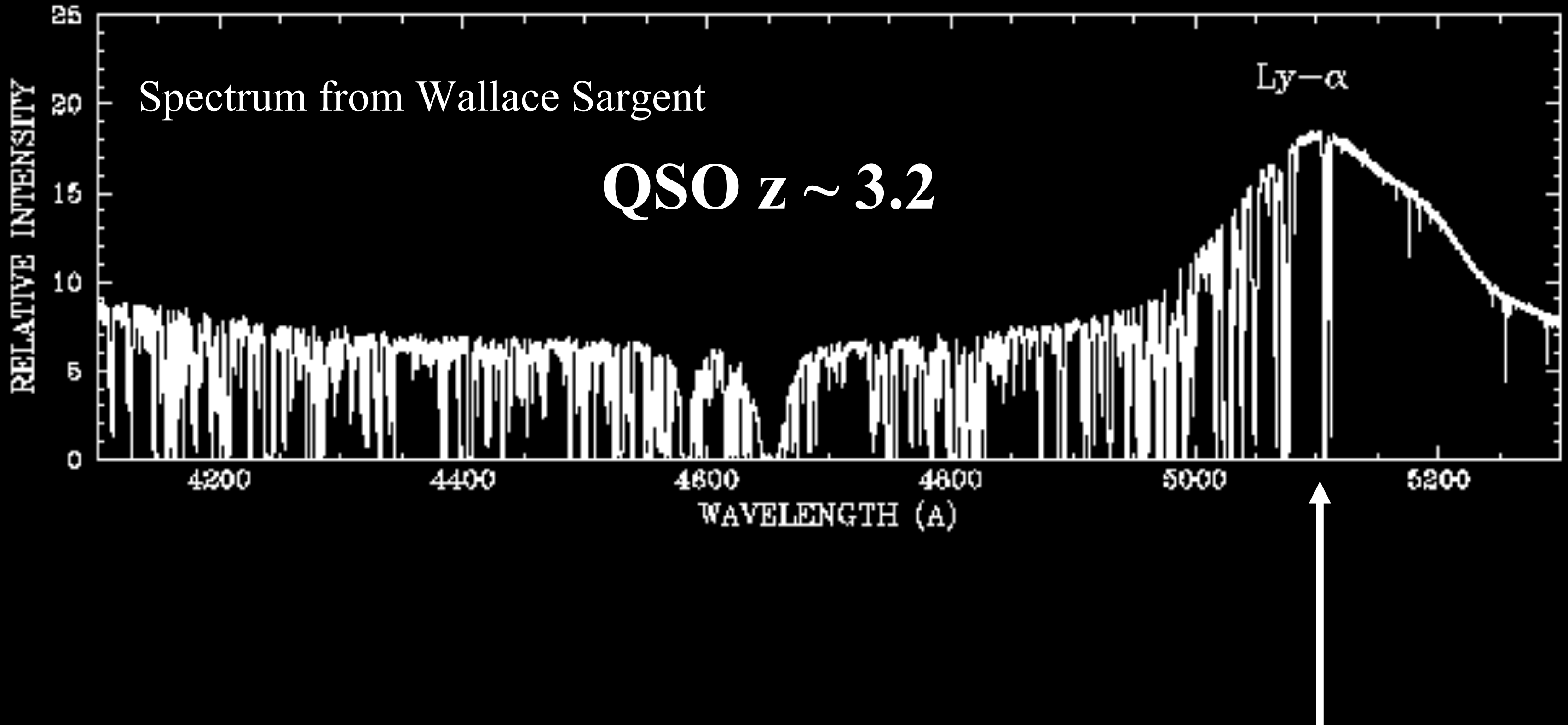


$R_\perp \sim 20$ kpc

__Damped Lyα System (DLA)__

- $N_{HI} > 10^{20.3}$ cm^2
- galactic disk

Quasar Absorption Lines

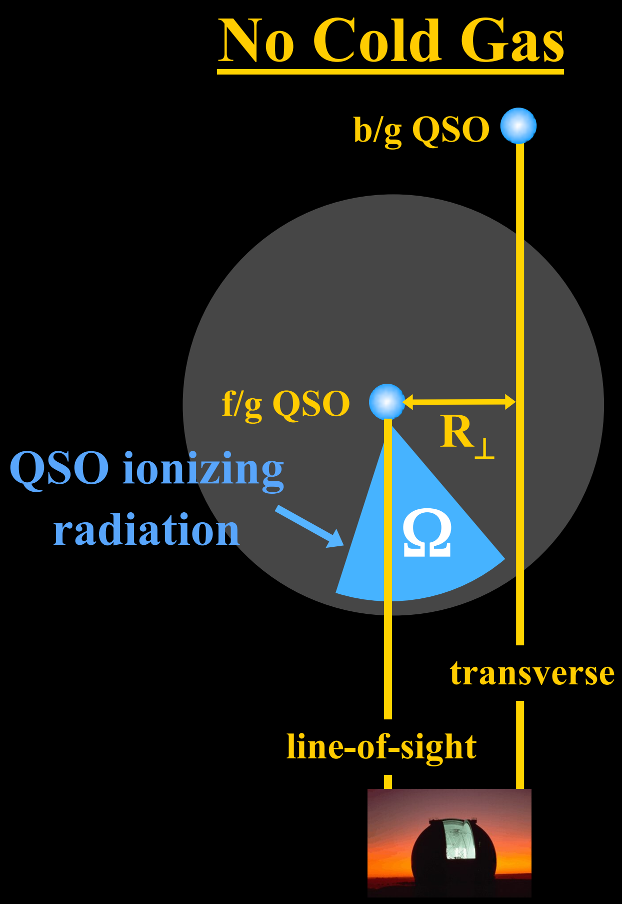


No strong Lyα absorption at QSO redshift?

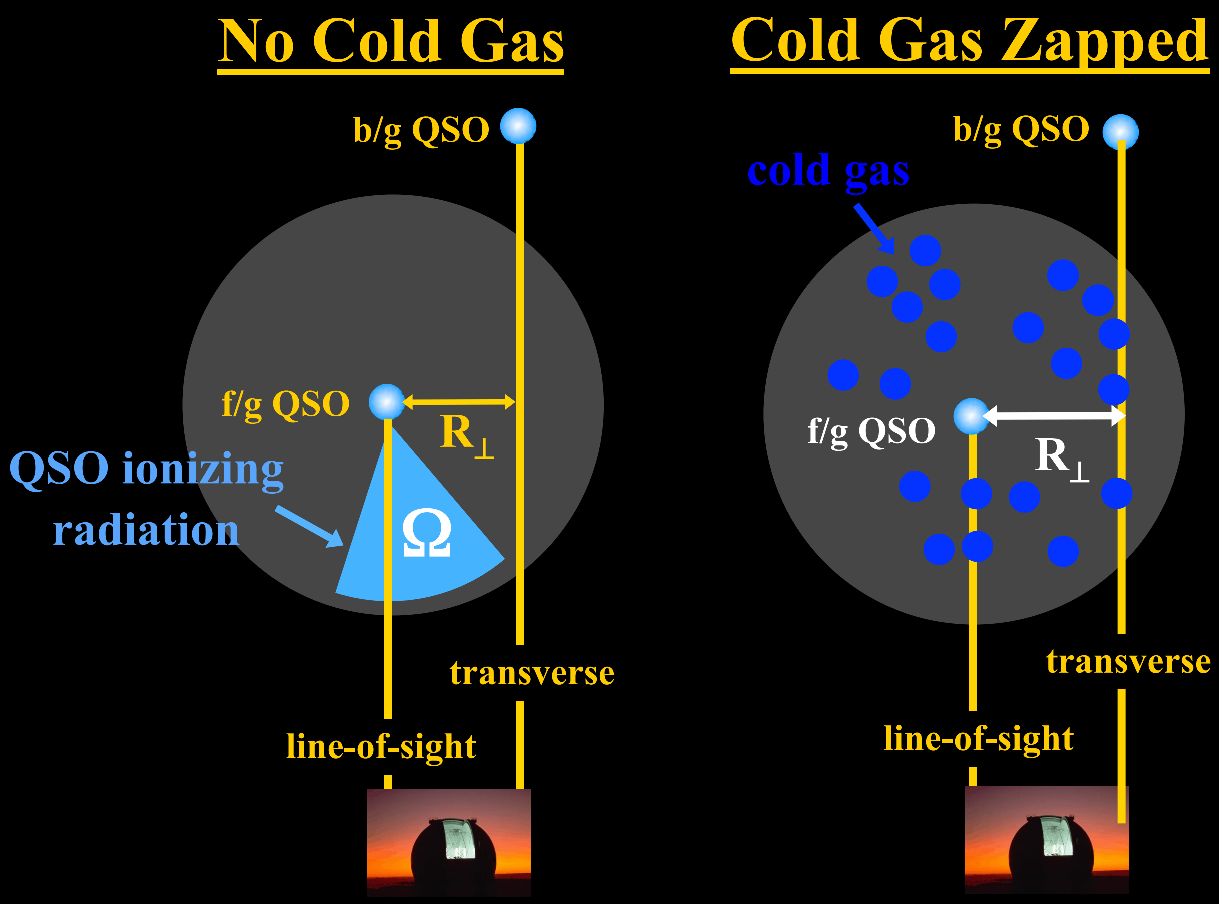
Outline

- Quasars absorption lines
- **What is the supply of cold gas?**
- What is the physical state of the gas?
- Can we detect cold gas in emission?

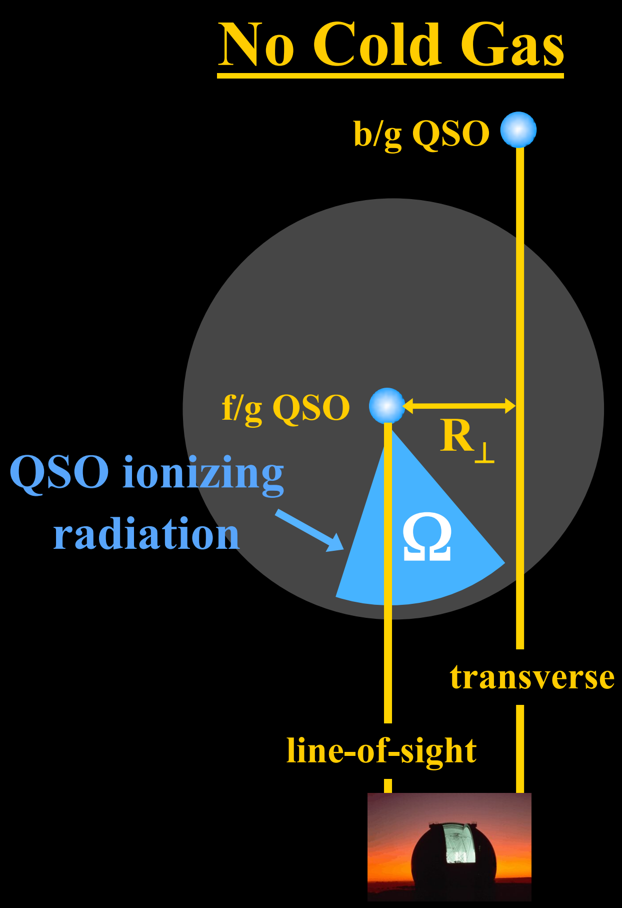
What is the Supply of Cold Gas?

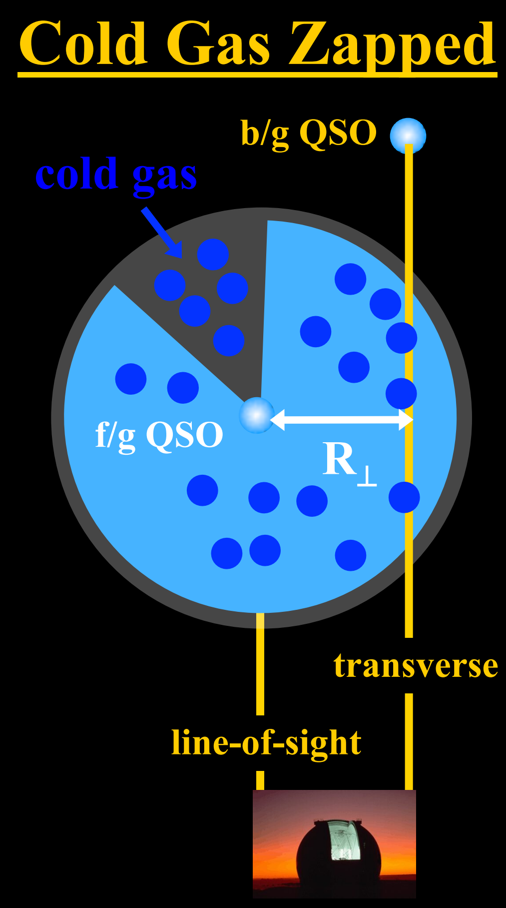


What is the Supply of Cold Gas?



What is the Supply of Cold Gas?





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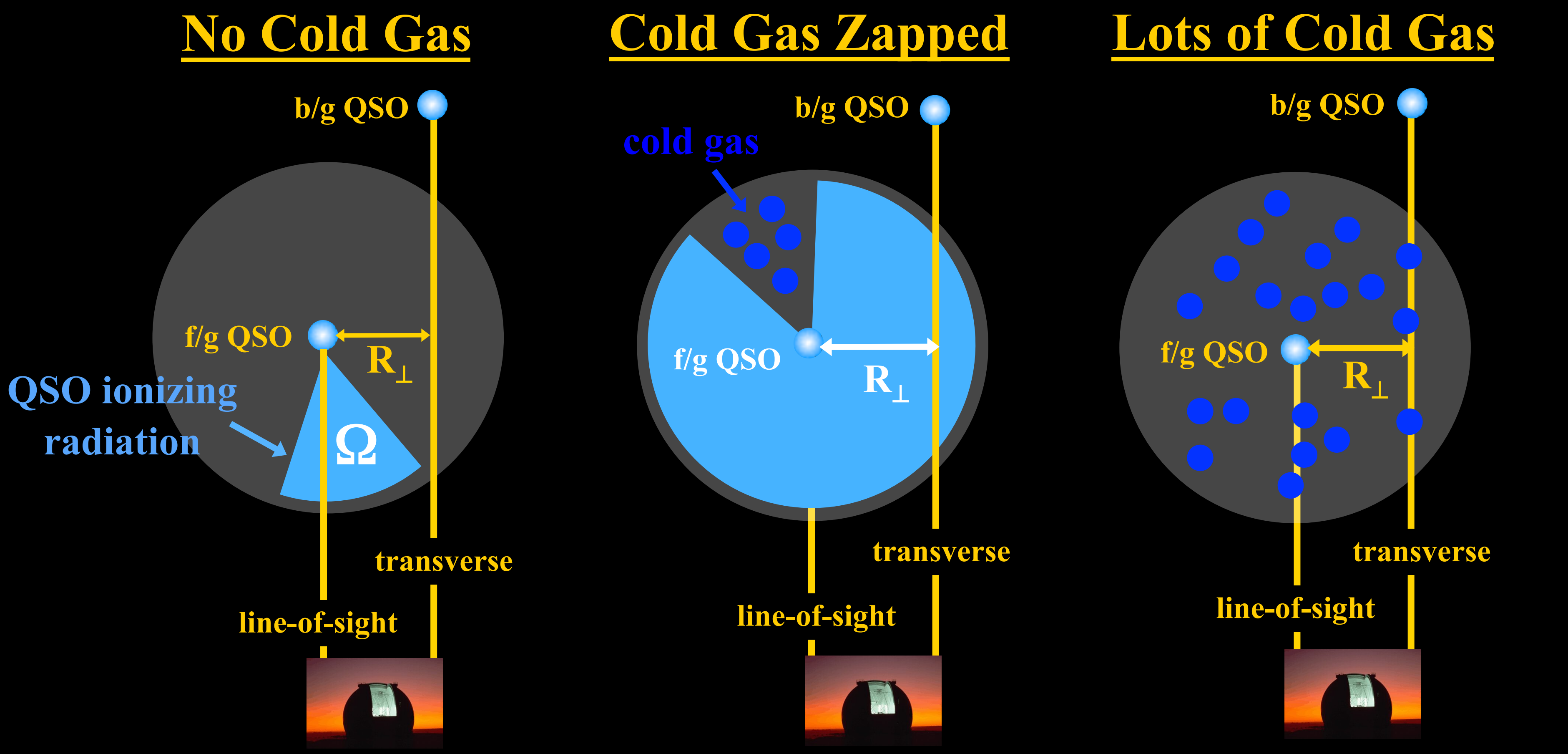

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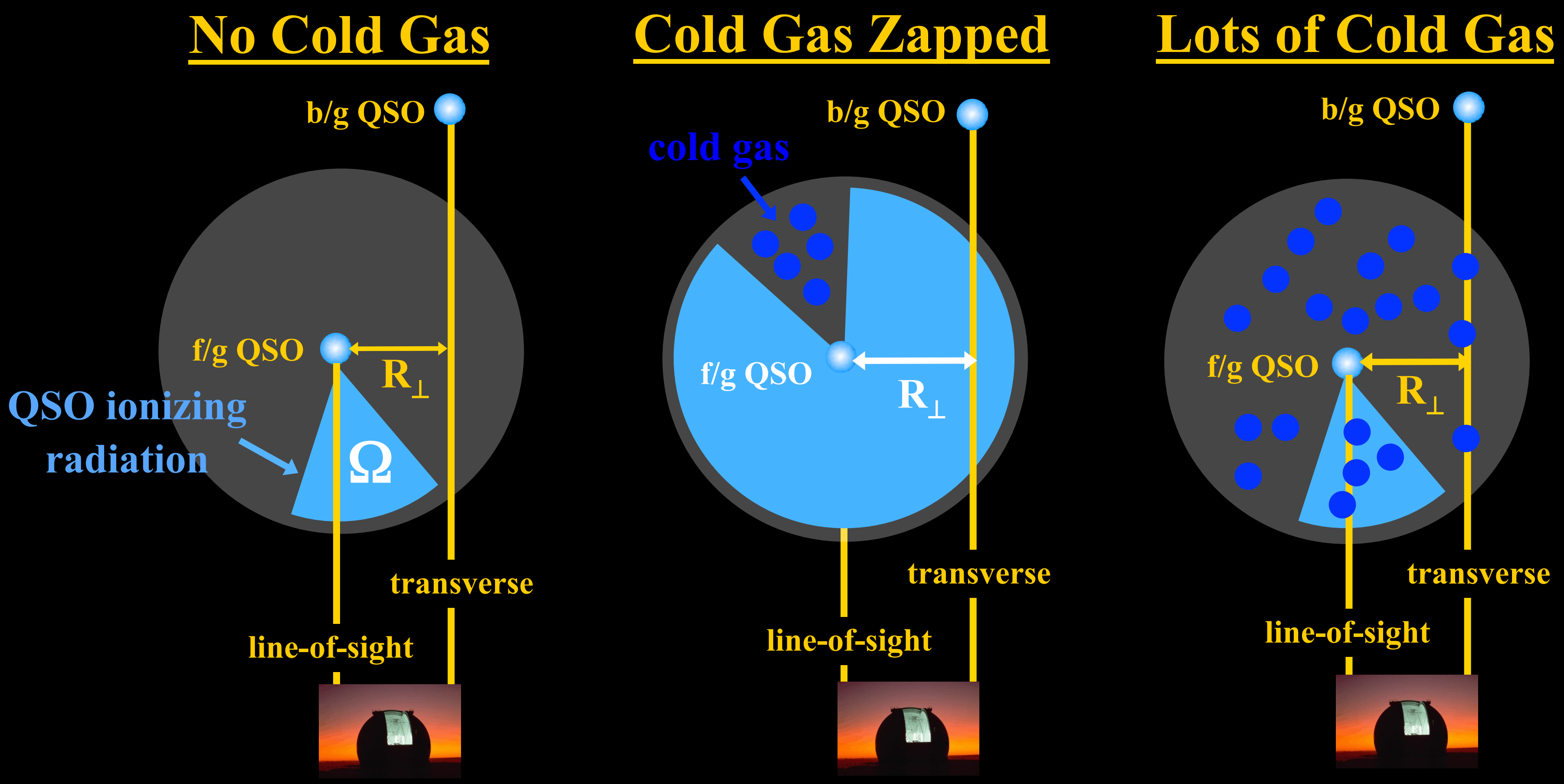
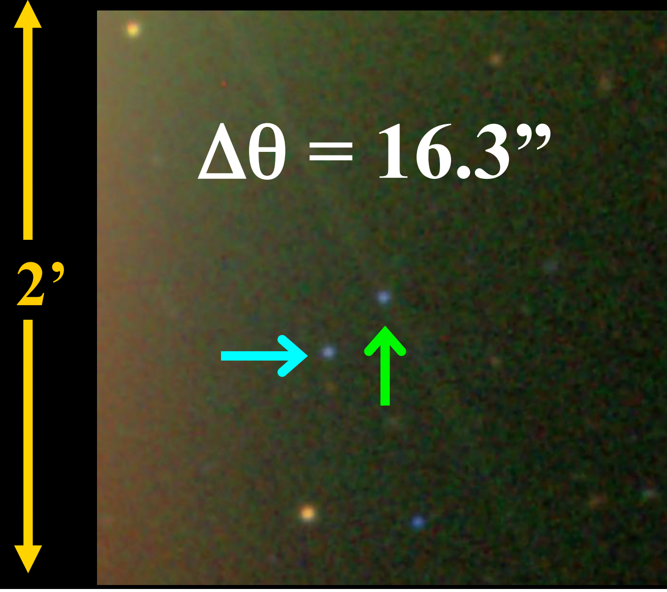


Measure covering factor of cold T ~ 10^4 K gas. Large column density (LLSs and DLAs) absorbers will dominate total mass.

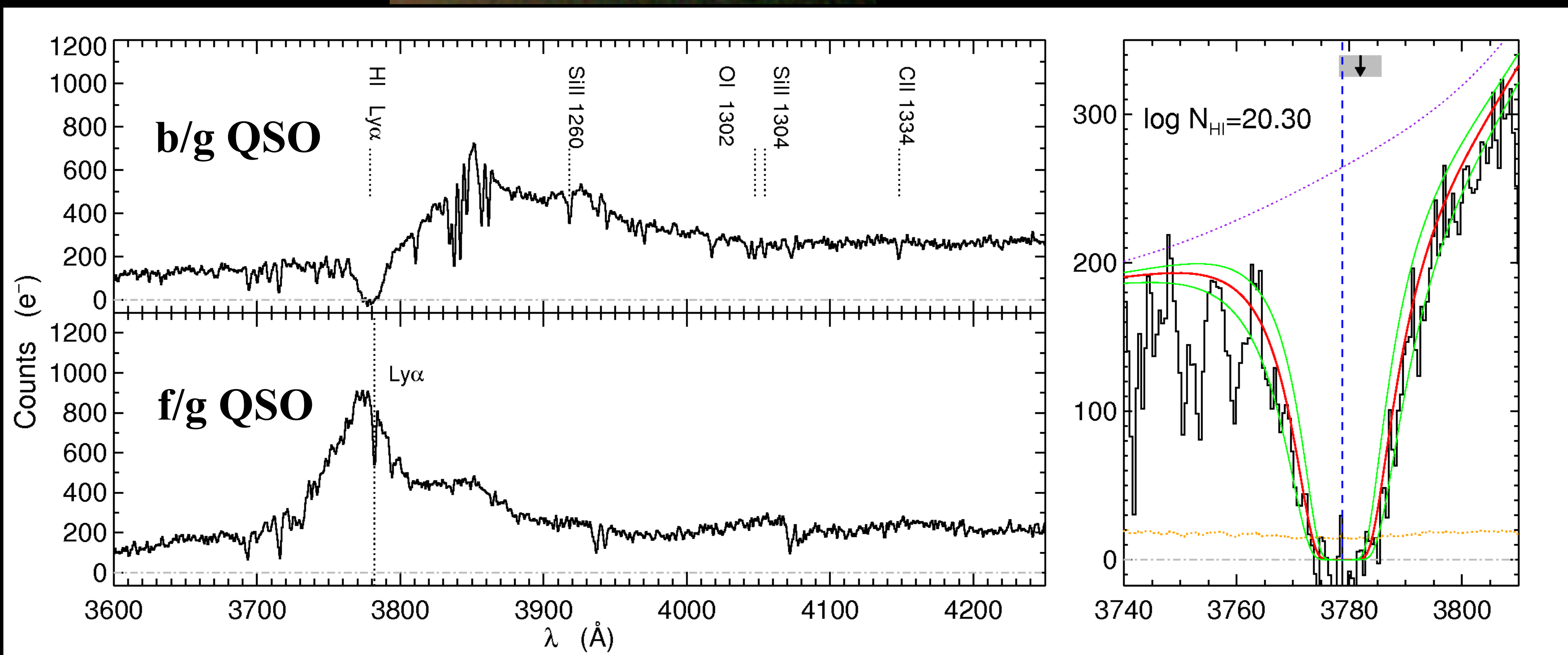


$z_{bg} = 2.17$

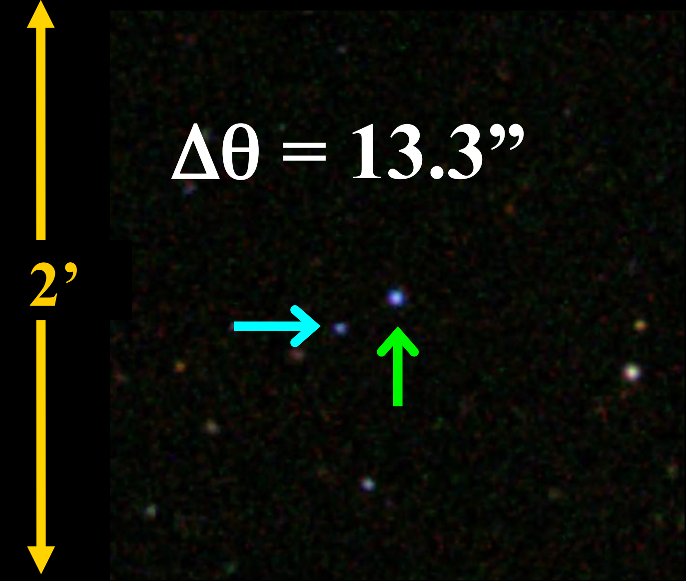
$z_{fg} = 2.11$

$R_{\perp} = 139$ kpc

$\log N_{HI} = 20.3$



Hennawi et al. (2007)

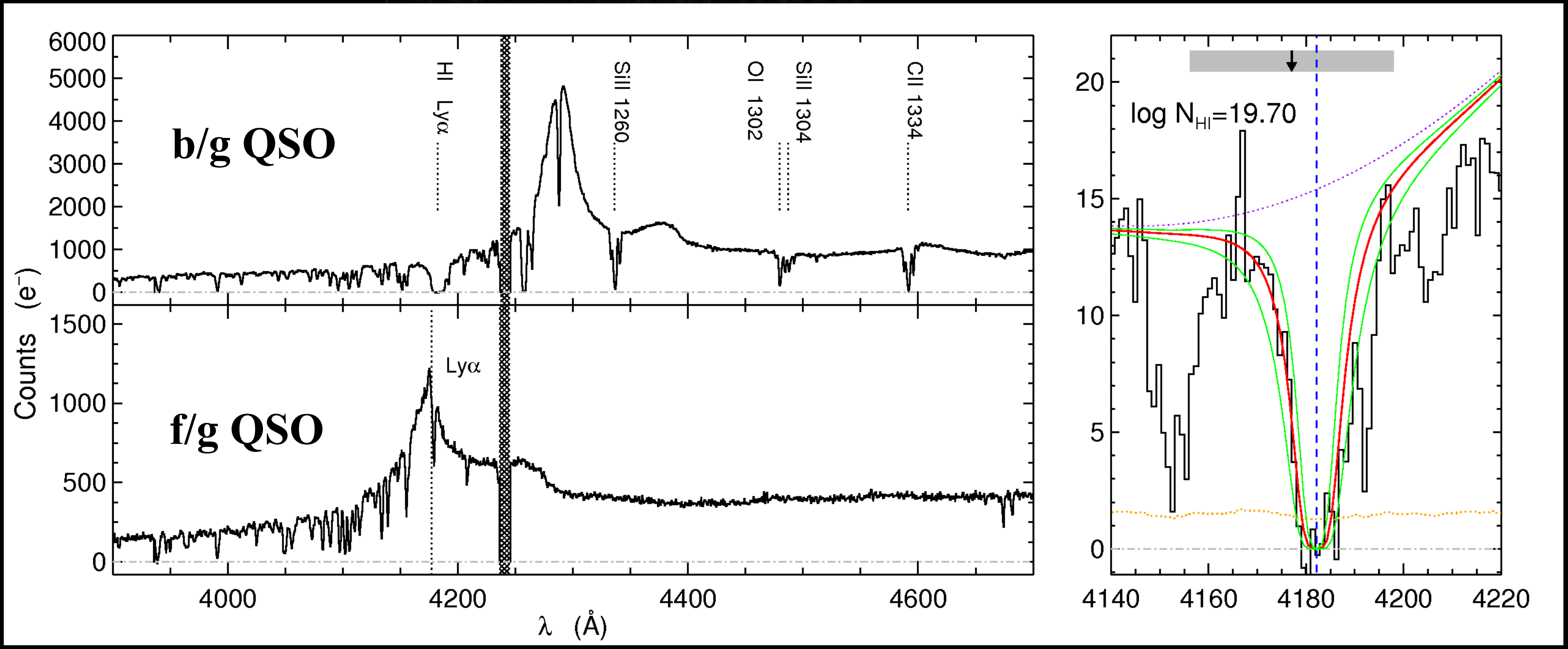


$z_{bg} = 2.53$

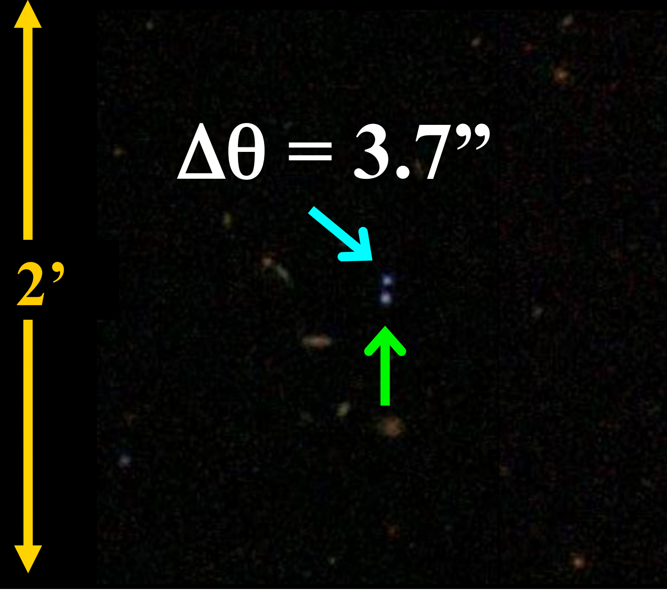
$z_{fg} = 2.43$

$R_{\perp} = 108$ kpc

$\log N_{HI} = 19.7$



Hennawi et al. (2007)

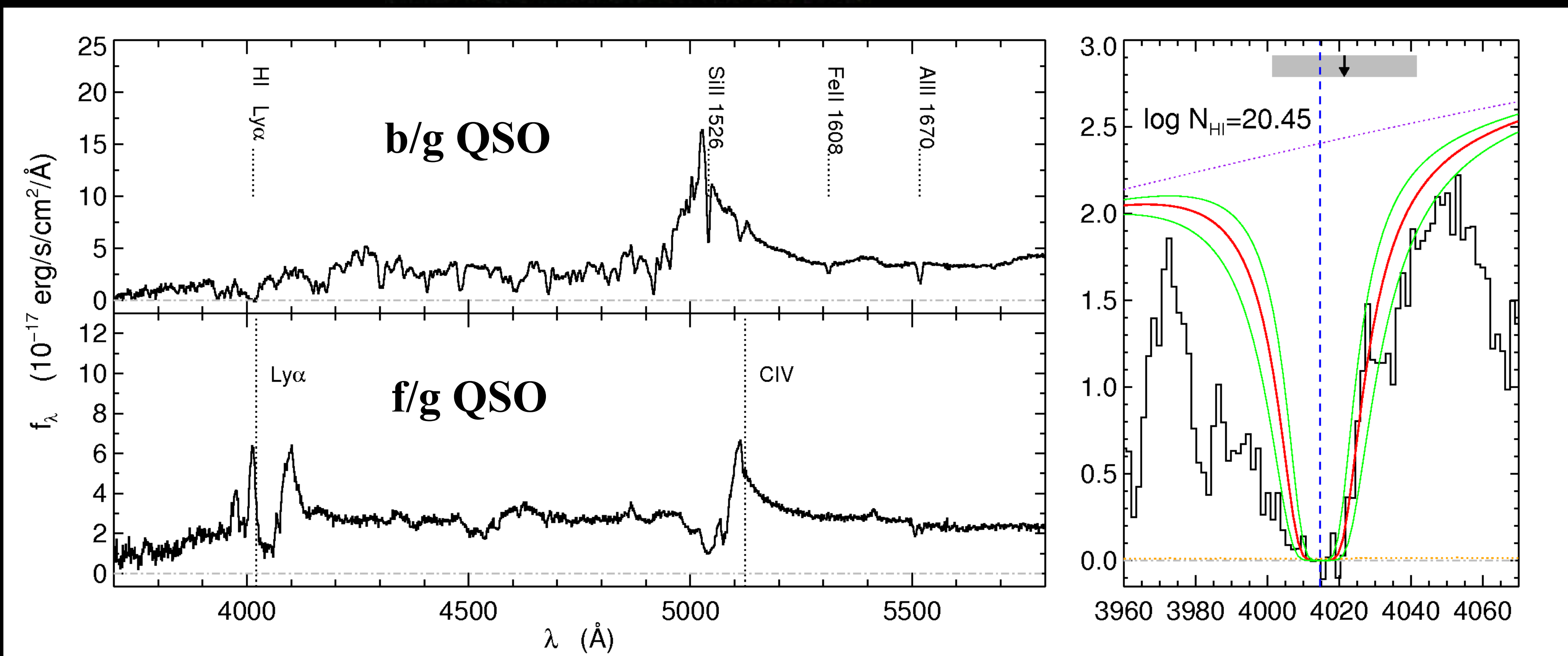


z_{bg} = 3.13

z_{fg} = 2.29

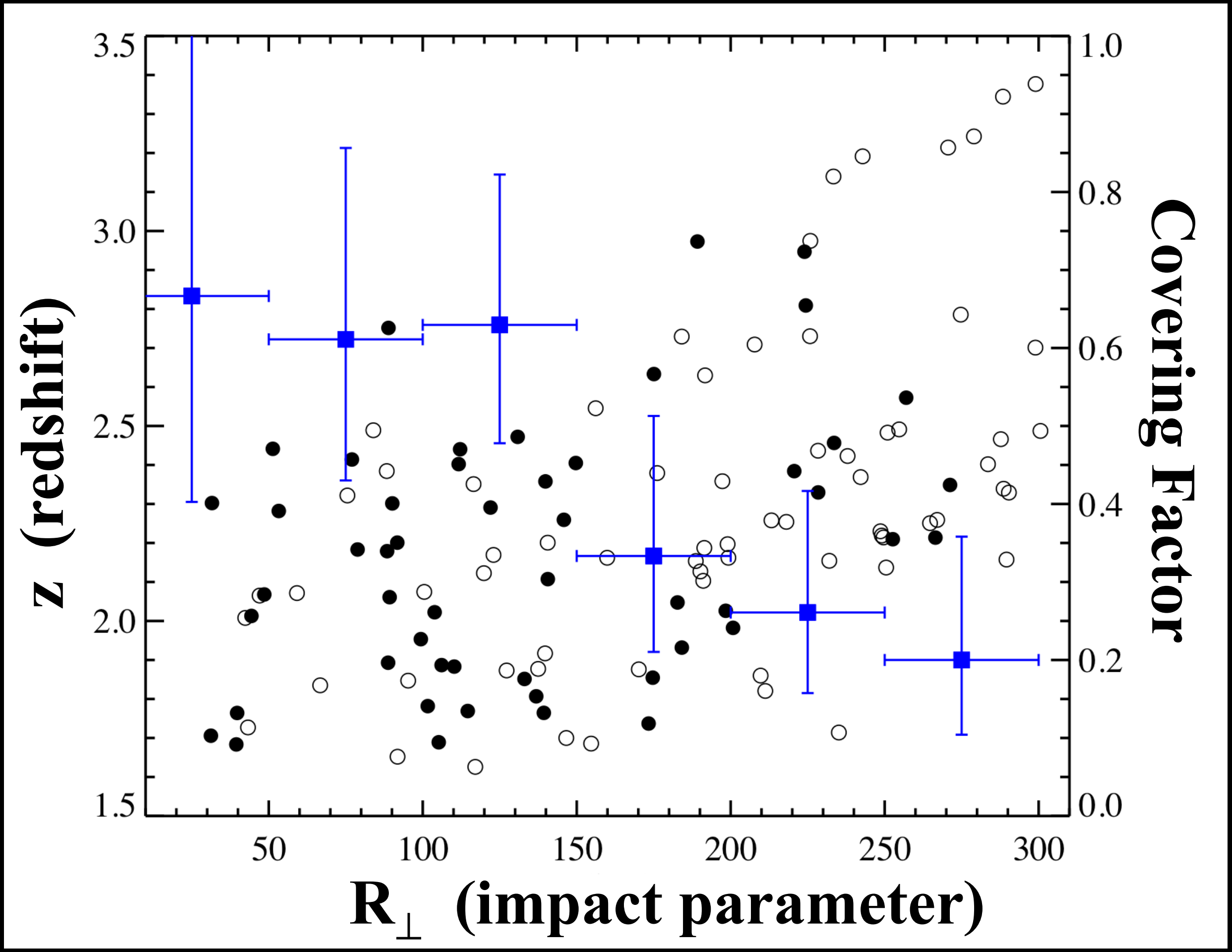
$R_{\perp}$ = 31 kpc

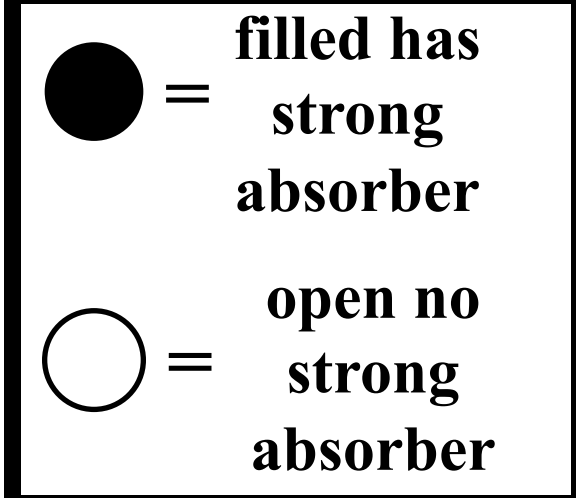
$\log N_{HI}$ = 20.5



Hennawi et al. (2007)

High Transverse Covering Factor





(Preliminary!!)

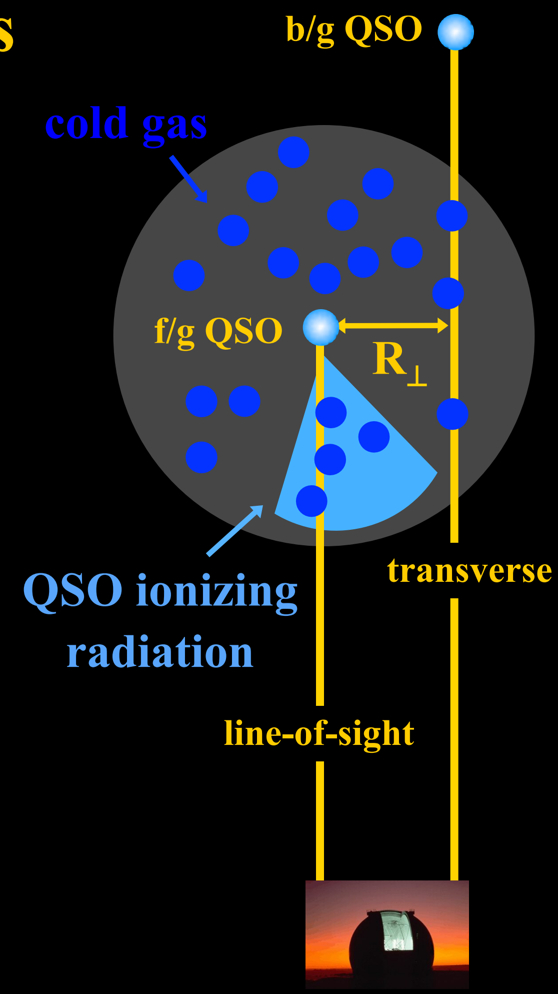
Prochaska, Hennawi et al. 2012

193 sightlines with $R_\perp < 300$ kpc

- High ~ 60% covering factor for R < 150 kpc
- 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).

The Halo Mass Dependence of the CGM

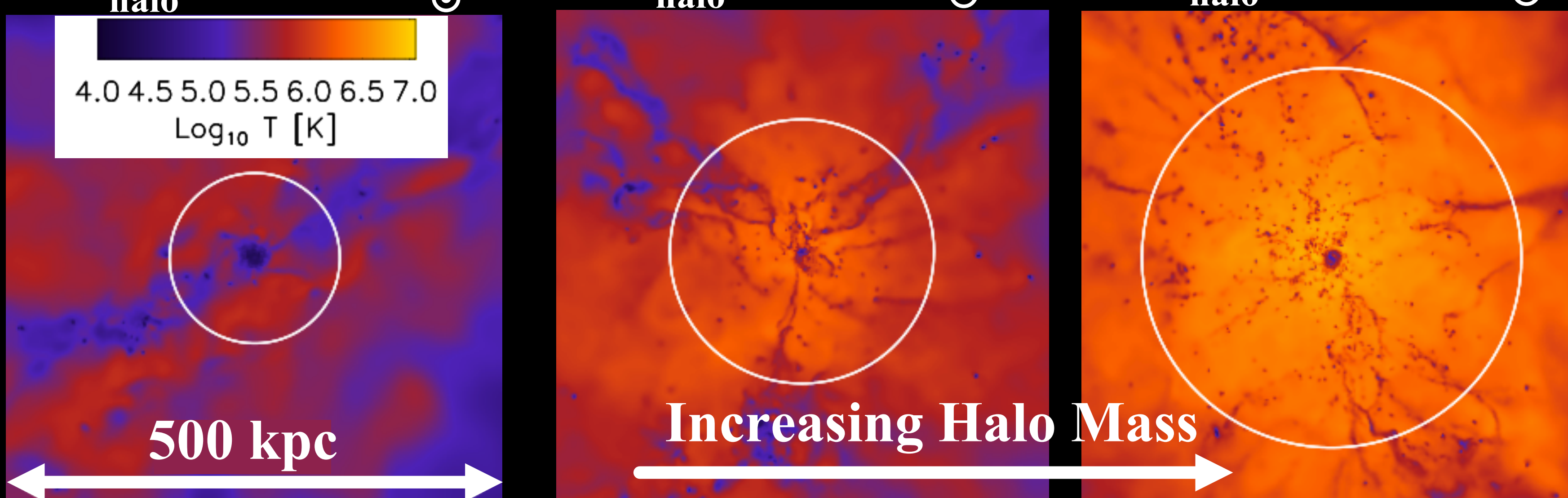
$$t_{\rm cool} = \frac{\frac{3}{2} k_{\rm B} T}{n^2 \Lambda(T)} \qquad t_{\rm dyn} = \pi \sqrt{\frac{R^3}{GM}}$$

Rees & Ostriker 1977

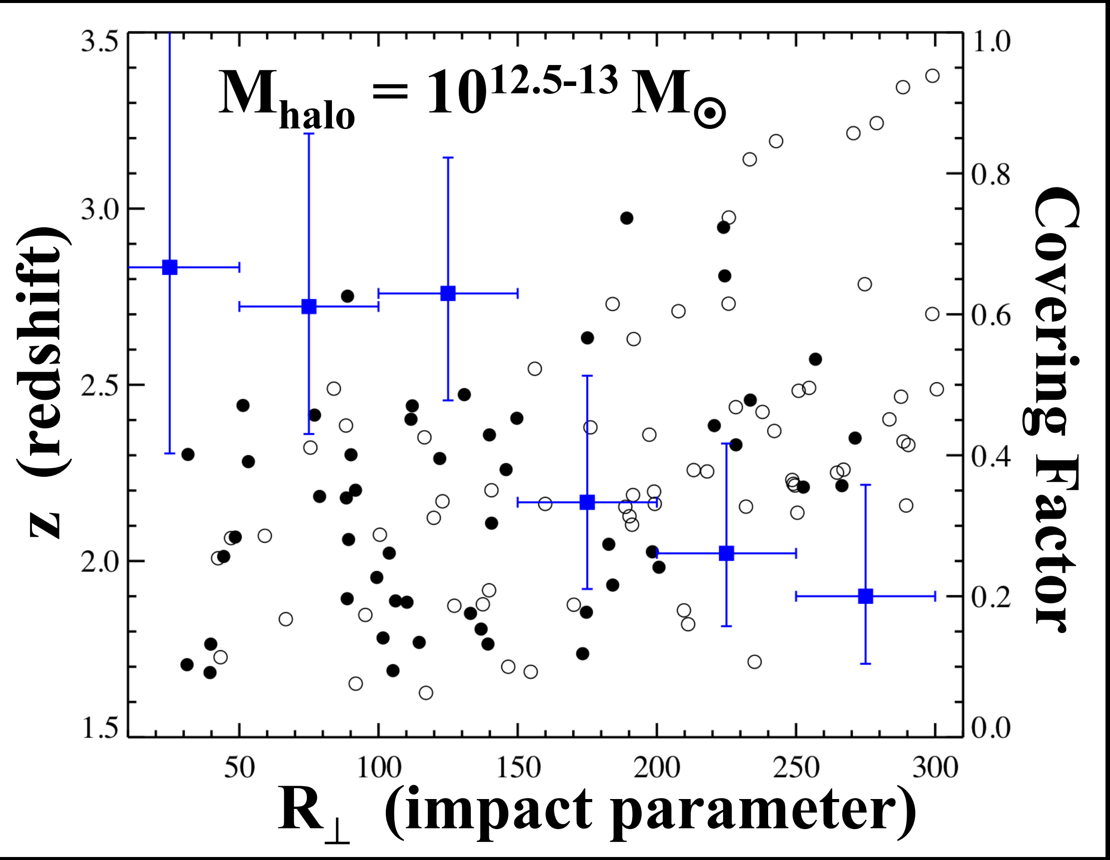
- Low masses: $t_{cool} < t_{dyn}$, Cools too fast that galaxy formation is limited only by free-fall.
- High masses: $t_{cool} > t_{dyn}$, Cools too slow, hot pressure supported halo forms in quasi-static equilibrium.

$M_{halo} = 10^{11.5}\ M_\odot$ $M_{halo} = 10^{12}\ M_\odot$ $M_{halo} = 10^{12.5}\ M_\odot$

van de Voort+ 11



Is Large Cold Gas Mass around QSOs at Odds with Cold Accretion?



- QSOs are active SMBHs – are they special? Mergers?
- Are we seeing outflows from QSO feedback?

Outline

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- What is the physical state of the gas?
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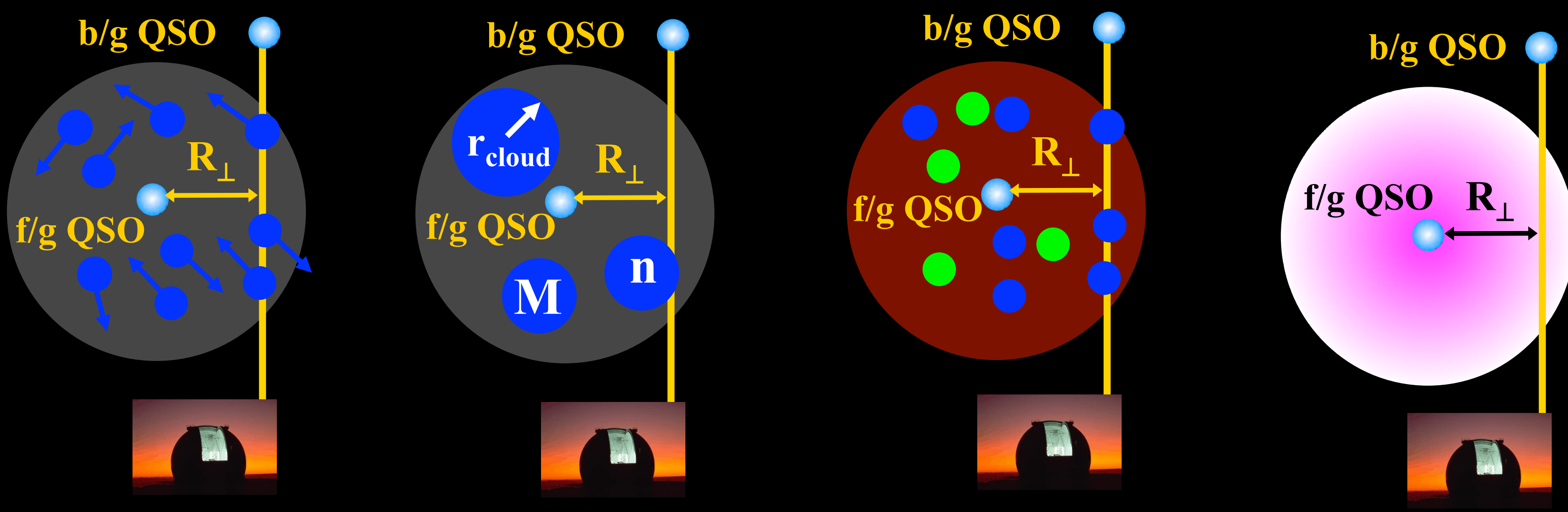
What is the Physical State of the Gas?



Kinematics?

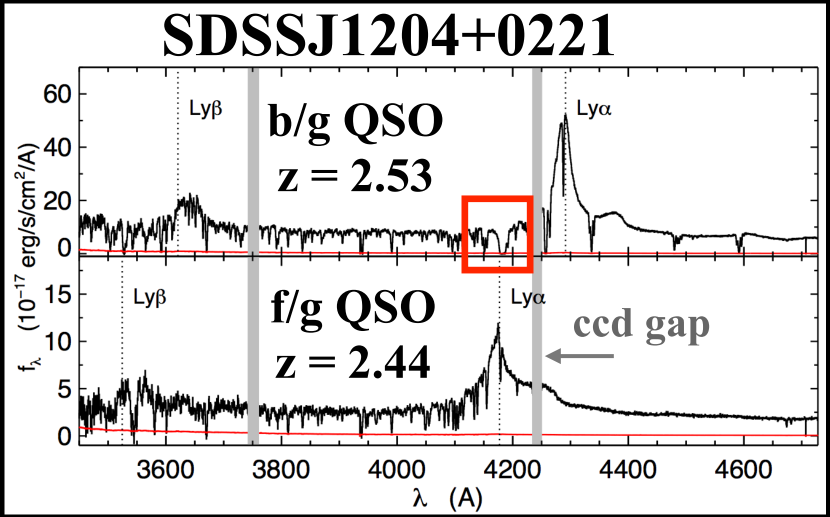
Gas mass, cloud density, size?

Multiphase? Cold, Warm, Hot?

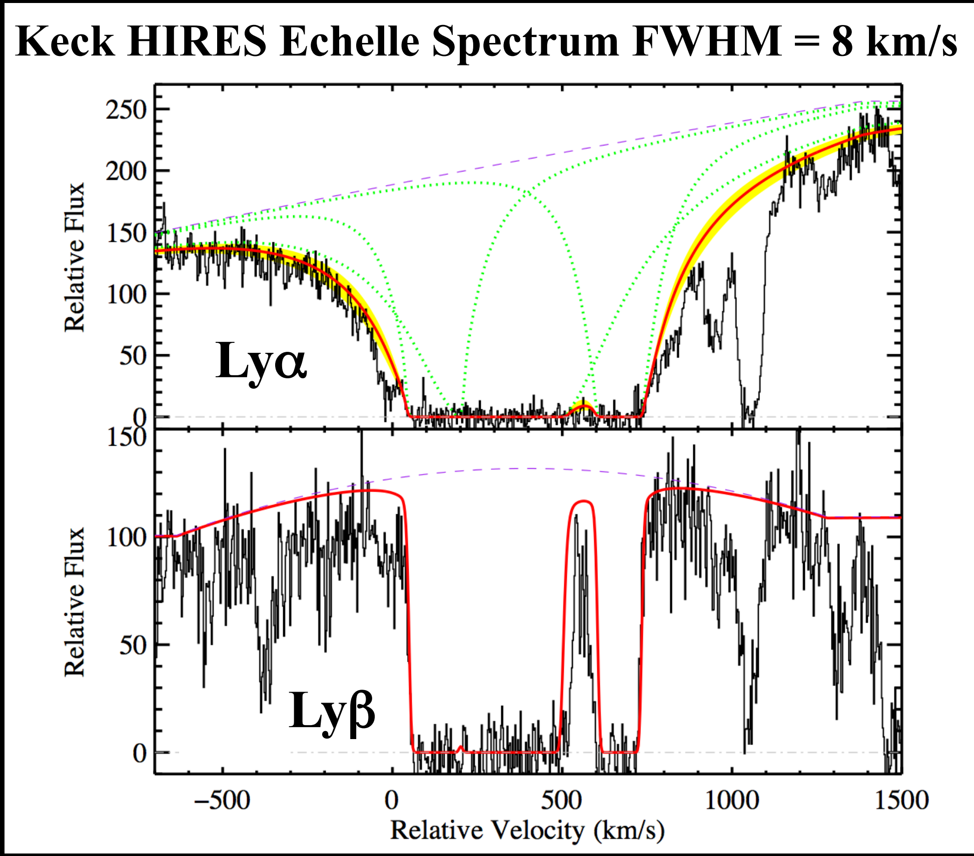
Metal Enrichment?

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

The Poster Child: SDSS1204+0221



- $\Delta\theta$ = 13.3" or $R_\perp$ = 108 kpc
- Lyman limit sys: $N_{HI} = 10^{19.7}$ cm^{-2}

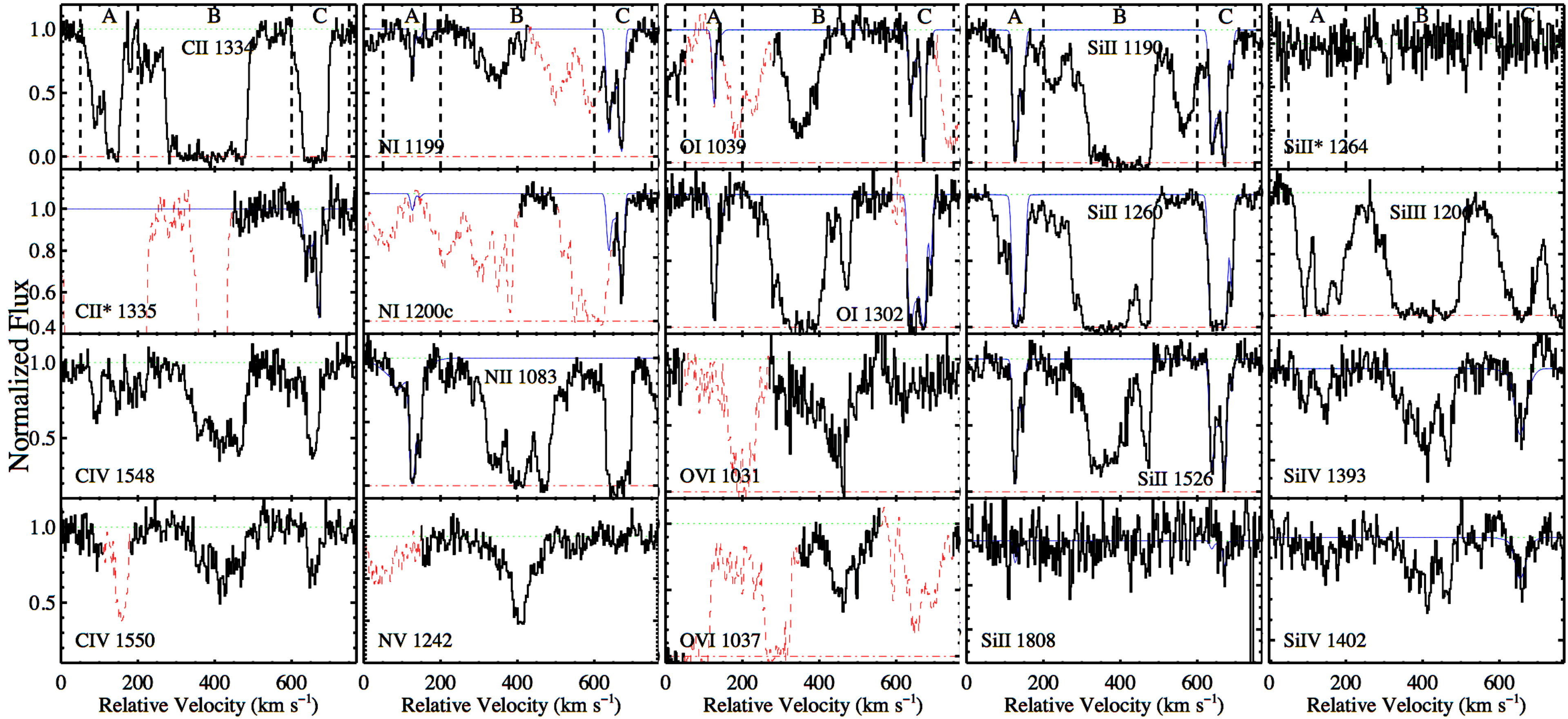


Typical foreground QSO

- i = 20.5 (mag)
- $L_{bol} = 10^{46}$ erg/s
- $M_{BH} = 10^9 M_\odot$ (f_{edd} = 0.1)

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

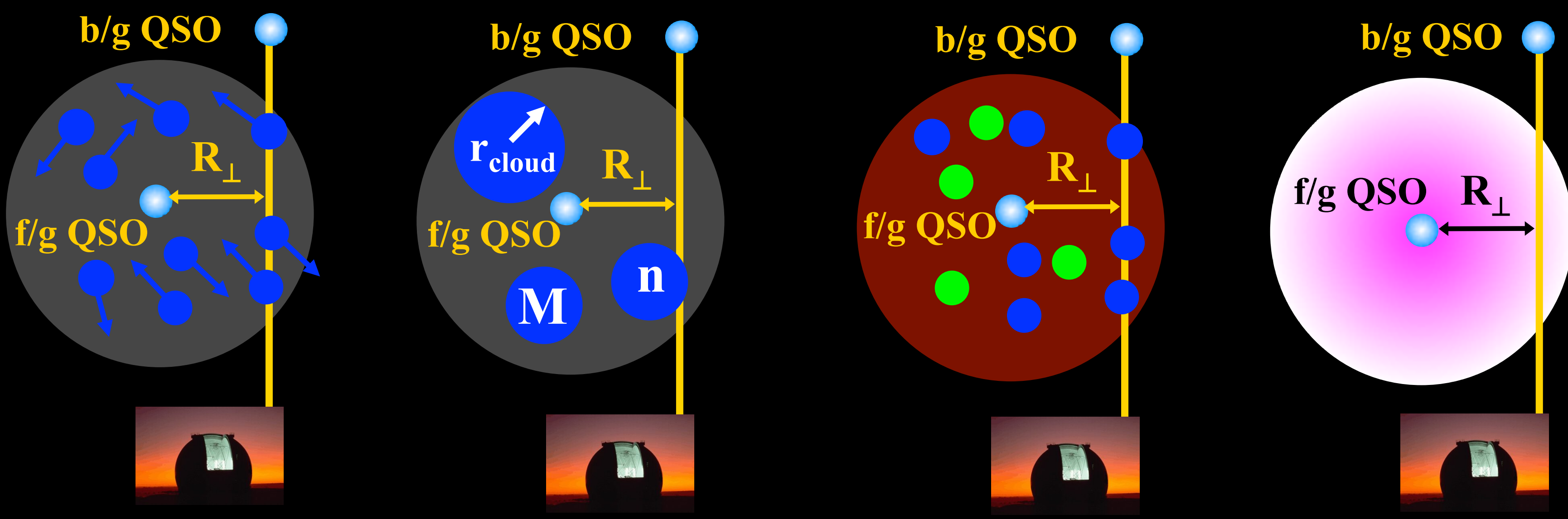
SDSSJ1204+0221: Metal Lines



Prochaska & Hennawi (2009)

Use metal lines to construct a detailed model for the physical state of gas (ionization, density, metallicity, etc.)

What is the Physical State of the Gas?



kinematics:
Δv = 700 km/s
Extreme!

mass: ~ $10^{11.5}$ $M_\odot$
density: $n_H \sim 1$ cm^{-3}
size: ~ 10-100 pc

Multiphase:
No warm gas
10^{5-6} K

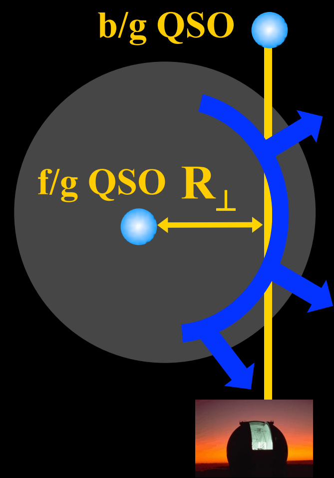
Metallicity:
$Z = (0.25\text{-}1.6)\ Z_\odot$
Extreme!

Prochaska & Hennawi (2009)

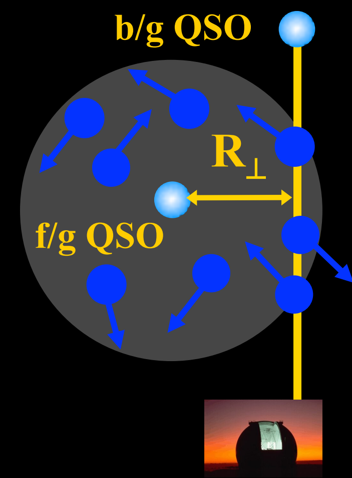
Outflow or Cold Accretion?

Outflow

QSO feedback ejects or sweeps up cold material



?



Cold Accretion

Gravitational infall in two phase medium

- Cold gas ~ 10% of total gas mass with right pressure to be confined by T ~ 10^7 K virialized plasma
- Strongest evidence for outflow is high Z ~ $Z_\odot$ at 108 kpc
- Outflow power $\dot{E} \sim \frac{1}{2}\Omega m_{\rm p} N_{\rm H} R_\perp \Delta v^3$

$$\dot{E}_{\rm outflow} \sim 9\times10^{44}\left(\frac{\Omega}{2\pi}\right)\left(\frac{N_{\rm H}}{10^{20.6}\,{\rm cm^{-2}}}\right)\left(\frac{R_\perp}{108\,{\rm kpc}}\right)\left(\frac{\Delta v}{1000\,{\rm km\,s^{-1}}}\right)^3 {\rm erg\,s^{-1}}$$

kinetic luminosity

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

Is this power plausible?

What is the Bottom Line?

Problems with an outflow:

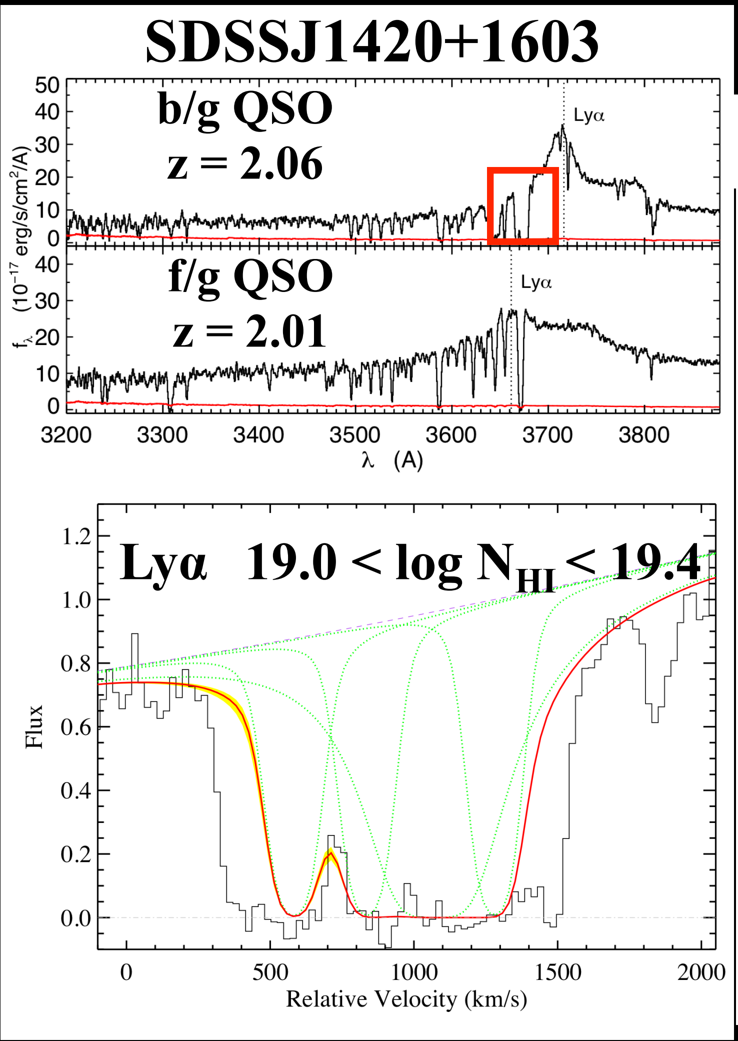
- Extreme energetics: outflow power > 6% accretion power, and more energy expected in a hot wind
- Lack of significant warm phase $T \sim 10^{5\text{-}6}$ K unphysical?
- Clouds disrupted by hydro instabilities in ~ 1 kpc, can't travel to 100 kpc?

Problems with cosmological cold accretion:

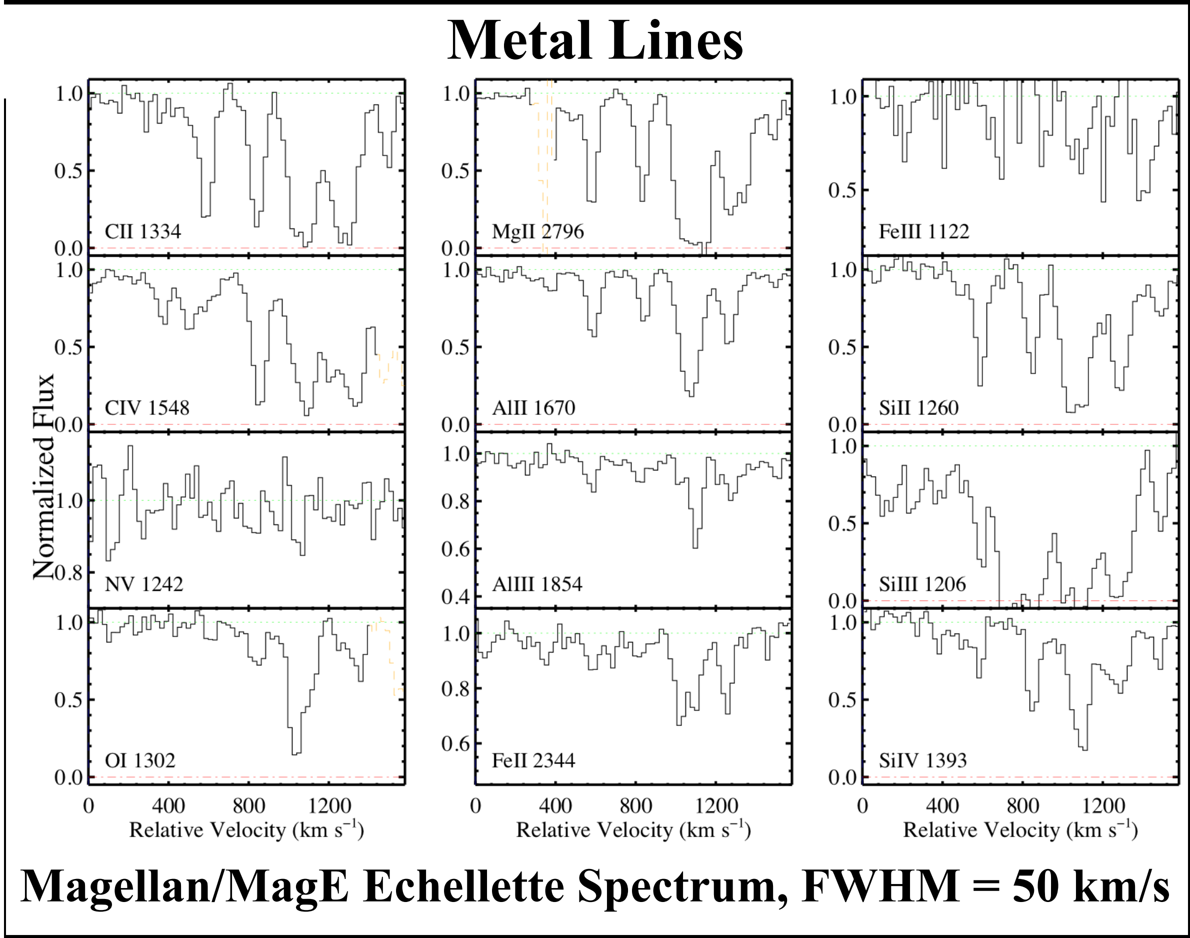
- Why is the gas so metal enriched $Z \sim Z_{\odot}$?
- Density too high: $n \sim 1\ cm^{-3} \gg$ hydro sims $n \sim 10^{-2}\ cm^{-3}$
- Clouds too small: $r_{cloud} \sim 10\text{-}100$ pc, sims predict ~ 1-3 kpc
- Simulations predict less cold gas in such massive halos

Must study statistical samples!

Towards a Statistical Sample: z ~ 2



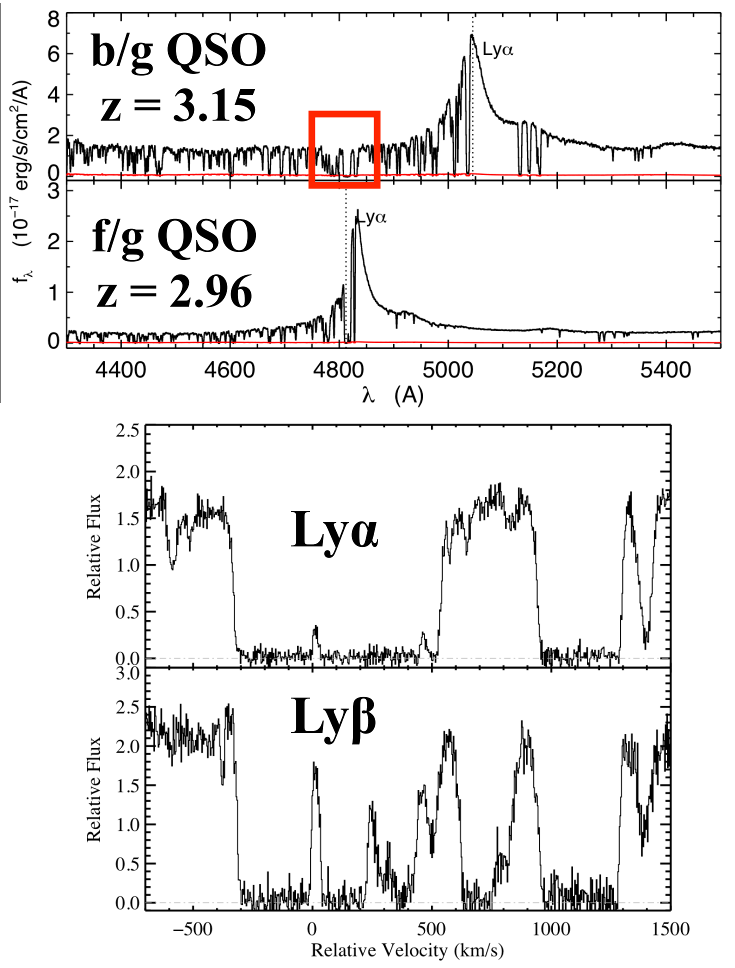
$\Delta\theta = 12.0''$ or $R_\perp = 100$ kpc



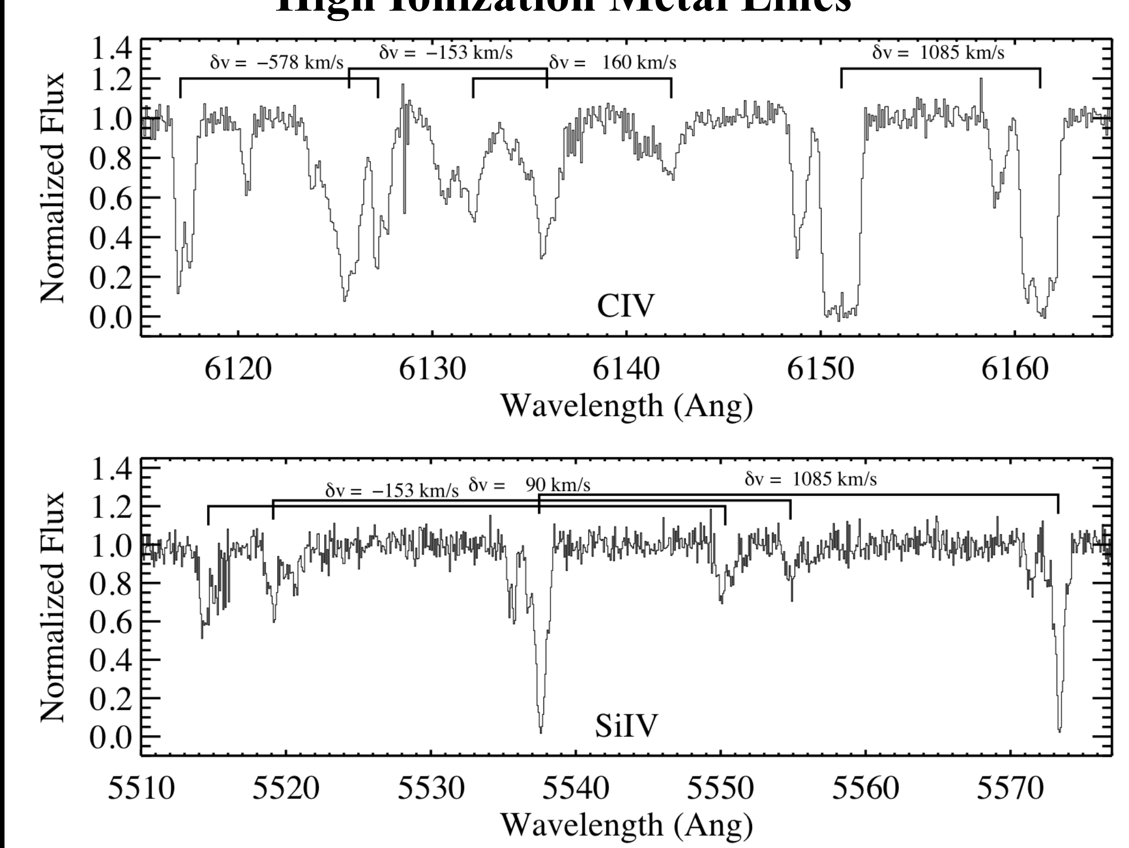
Extreme kinematics $\Delta v \approx 800$ km/s and high enrichment level $Z > 0.14\ Z_\odot$

Towards a Statistical Sample: z ~ 3

SDSSJ1144+0959



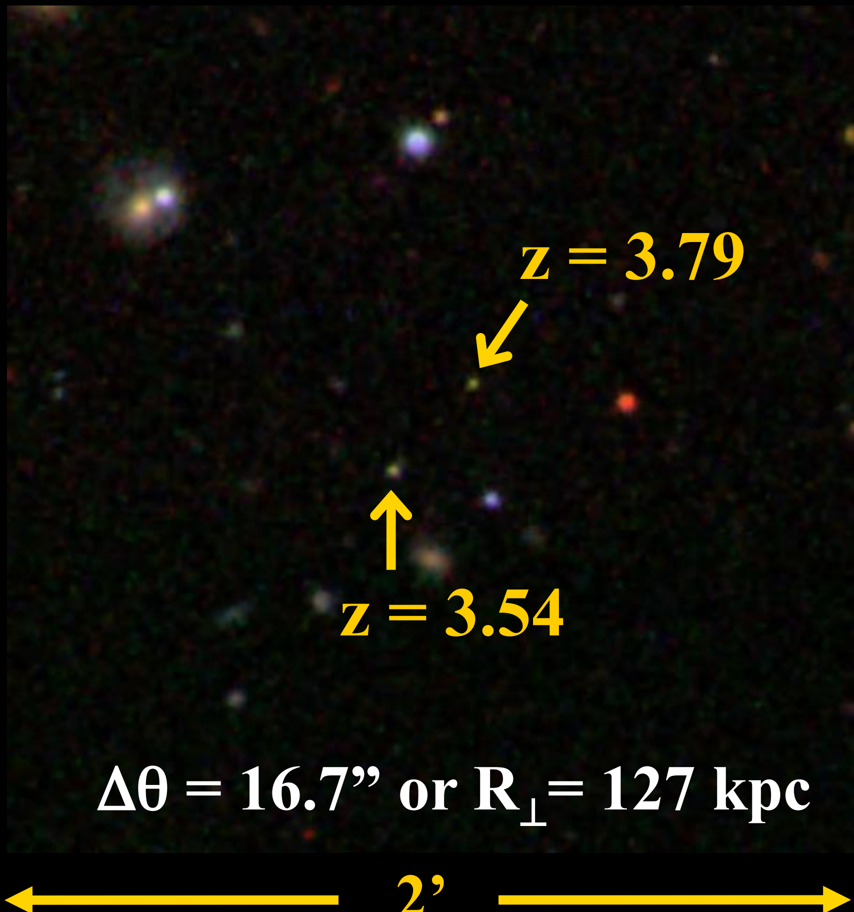
$\Delta\theta = 23.5''$ or $R_\perp = 181$ kpc

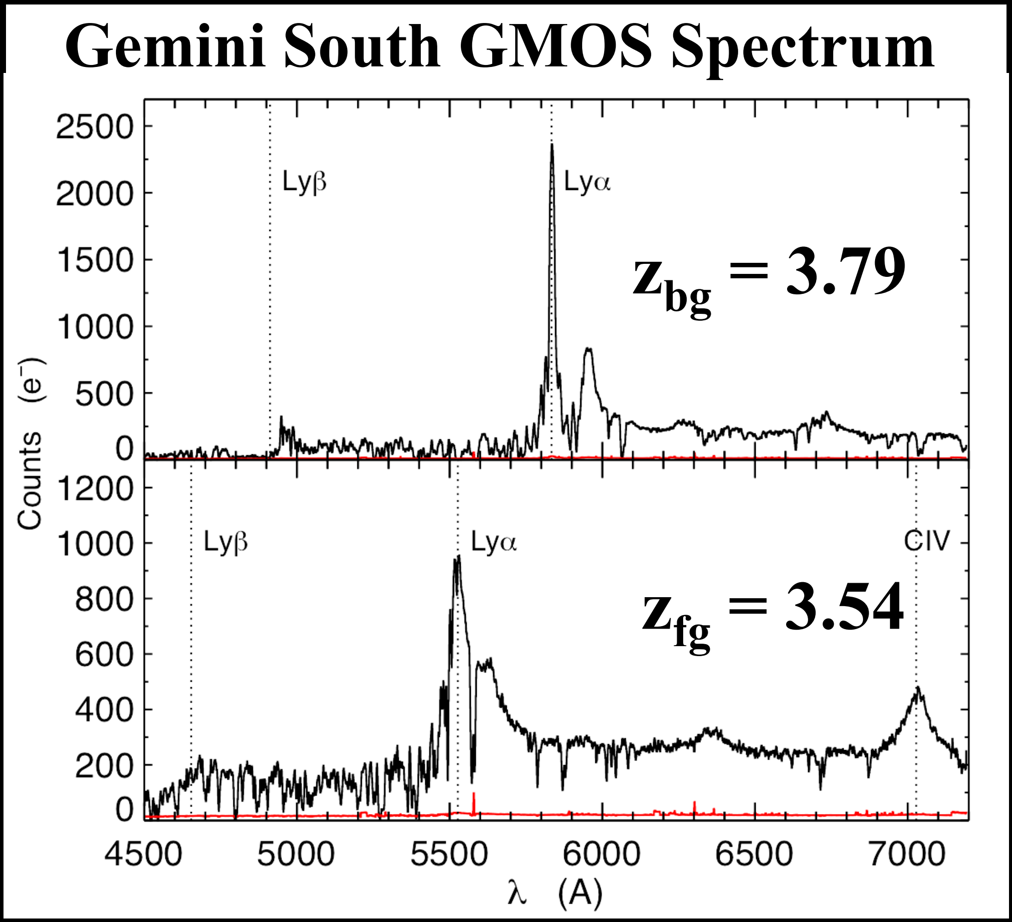


Magellan/MIKE Echelle Spectrum, FWHM = 10 km/s

Extreme kinematics $\Delta v \approx 1600$ km/s and a high enrichment level $Z = (0.1\text{-}1)Z_\odot$

Towards a Statistical Sample: z ~ 4

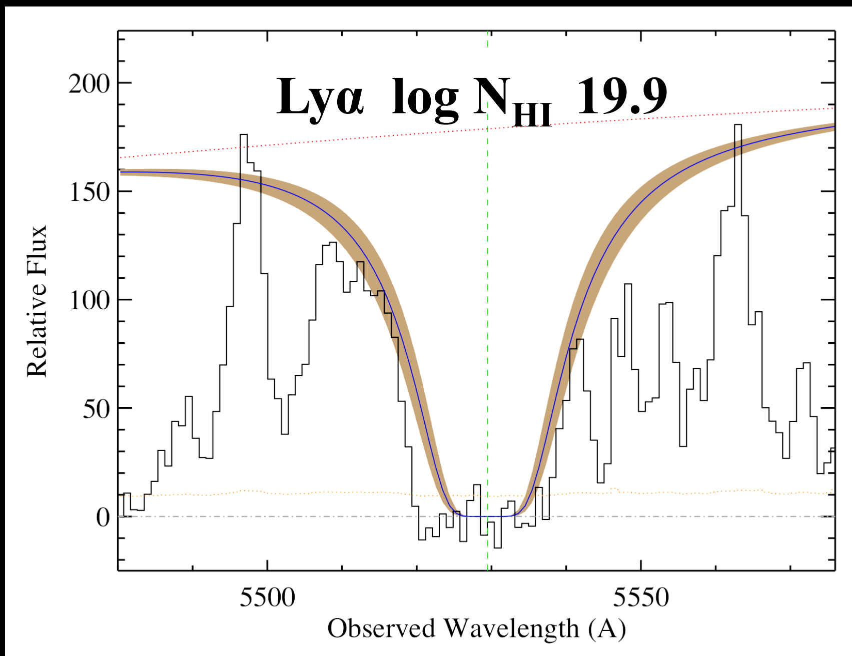


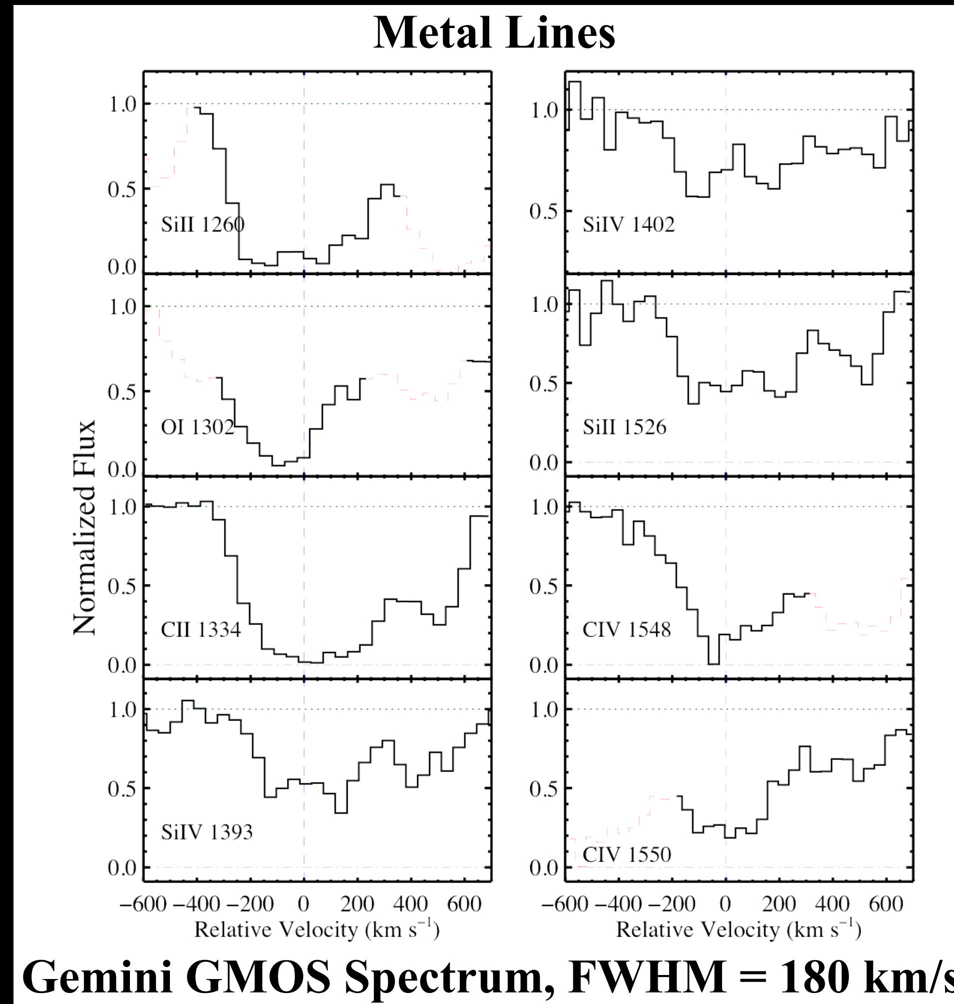


Newly discovered close projected pair of QSOs at z ~ 4

Towards a Statistical Sample: z ~ 4

$\Delta\theta$ = 16.7" or $R_\perp$ = 127 kpc





Extreme kinematics $\Delta v \approx 800$ km/s and high enrichment level $Z \approx 0.4\ Z_\odot$

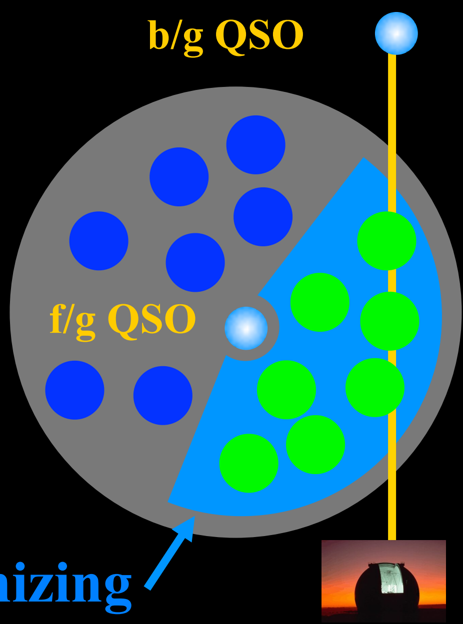
Outline

- Quasars pairs and absorption lines
- What is the supply of cold gas?
- What is the physical state of the gas?
- Can we detect cold gas in emission?

Preliminary

Can We Detect the Cold Gas in Emission?

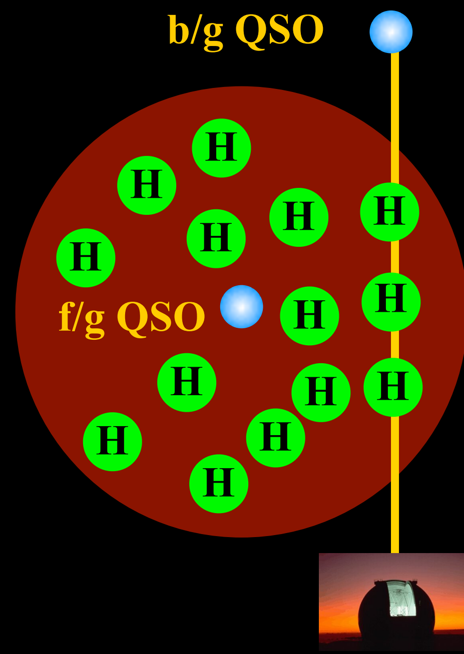
Photoionization



QSO ionizing radiation

- Recombinations from optically thick gas
- Directly test if gas is illuminated by QSO

Cooling Radiation



heating rate per H atom

H [erg/s/H]

cooling surface brightness

covering factor

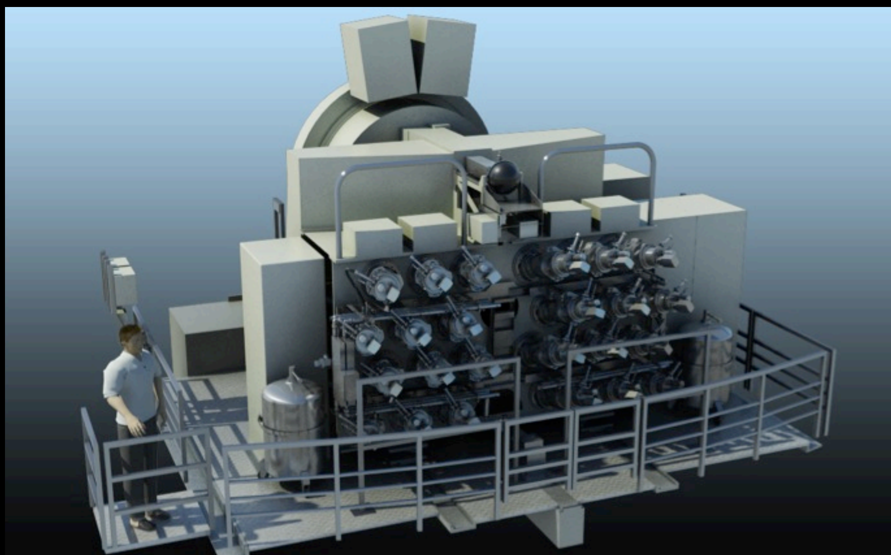
hydrogen column

heating rate

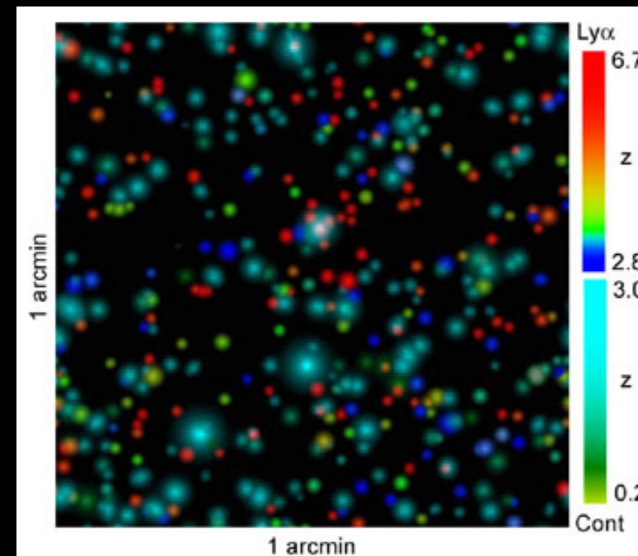
$$\mathrm{SB} = \frac{f_{\rm cov} N_{\rm H} H}{4\pi(1+z)^4} \quad [\mathrm{erg/s/cm^2/\square''}]$$

Future Deep 3-D Spectroscopy

MUSE: The Multi-Unit Spectroscopic Explorer



3-D Image Slicing IFU



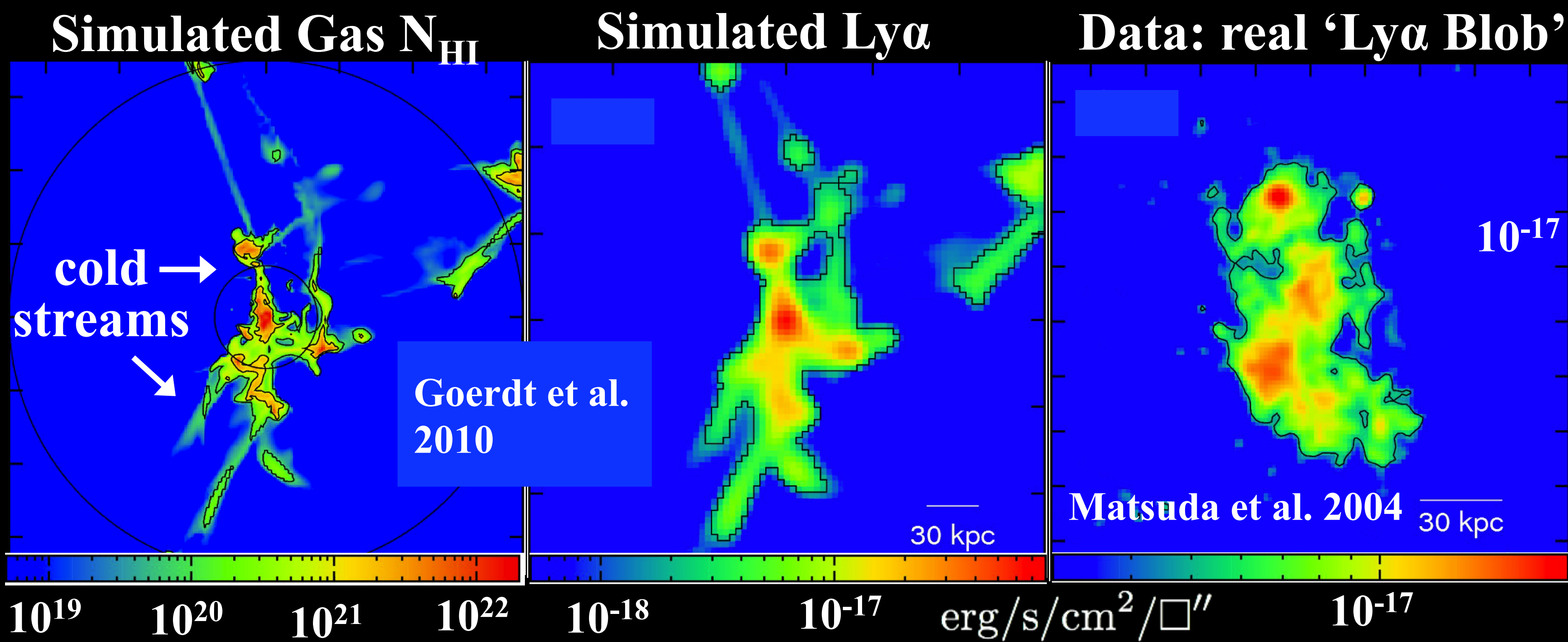
MUSE: FOV = 1’×1’, λ = 500-930nm, 2013

Keck Cosmic Web Imager: FOV = 20”×34”, λ = 350nm-1μ, 2014

Unprecedented combination: Multiplexing + Sensitivity

SB ~ 5×10^{-19} erg/s/cm^2/□” in 50 hour integrations

Cooling Radiation

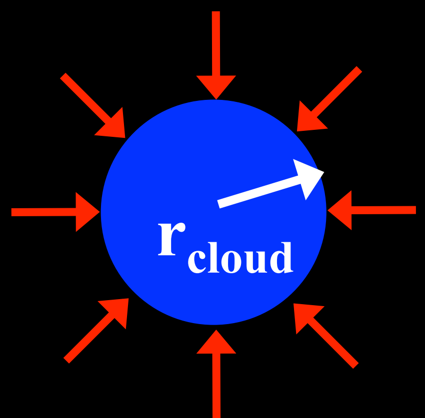


- For low metallicity T ~ 10^4 K gas, 60% of cooling through collisional excitation of Lyα
- Exponentially sensitivity to T $q_{1s\rightarrow 2p} \propto e^{-h\nu_{\mathrm{Ly}\alpha}/k_B T}$

$$SB_{\mathrm{Ly}\alpha} = 5\times 10^{-17} \boxed{\left(\frac{f_{\mathrm{cov}}}{0.3}\right)\left(\frac{n_e}{1\,\mathrm{cm}^{-3}}\right)\left(\frac{N_{\mathrm{HI}}}{10^{19}\,\mathrm{cm}^{-2}}\right)} q_{1s\rightarrow 2p}(T=10^{4.3}\,\mathrm{K})$$

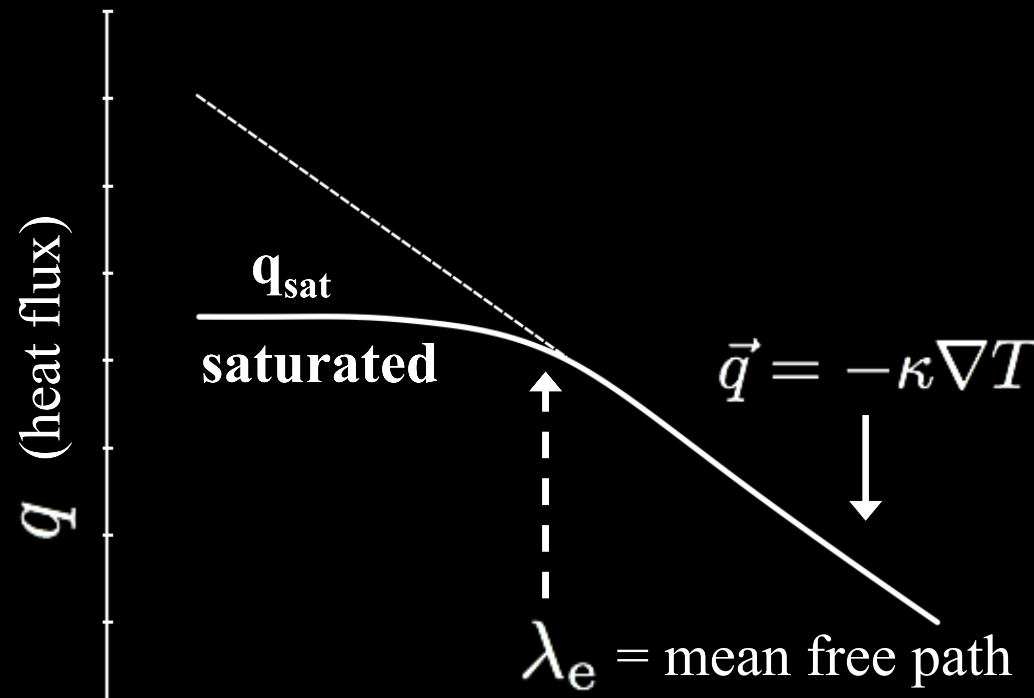
Thermal Conduction

Spitzer formula $\vec{q} = -\kappa \nabla T$



$r_{\text{cloud}} \sim T/\nabla T$

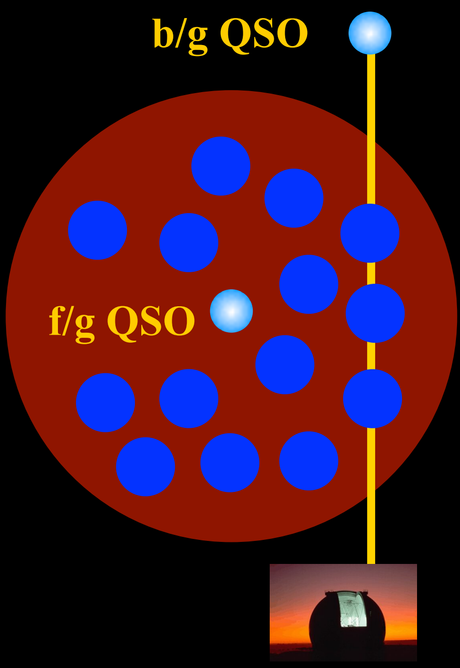
gradient scale length ↑



$$q_{\text{sat}} = 0.4 n_{\text{e}} k T \left(\frac{2kT}{\pi m_{\text{e}}} \right)^{1/2} \propto \rho_{\text{hot}} c_{\text{s}}^3$$

- **If (cloud size) ≤ (electron mean free path) then conduction is ‘saturated’ and heat flux ~ energy flux of hot electrons**

Cooling Radiation: Conduction



$$\lambda_e = 40 \left(\frac{T}{10^7\,\mathrm{K}}\right)^2 \left(\frac{n_{\rm hot}}{10^{-2}\,\mathrm{cm}^{-3}}\right)^{-1} \mathrm{pc}$$

measured cloud size for SDSS1204 → $r_{\rm cloud} \simeq 10\,\mathrm{pc} < \lambda_e$

(cloud size) ≤ (mean free path)

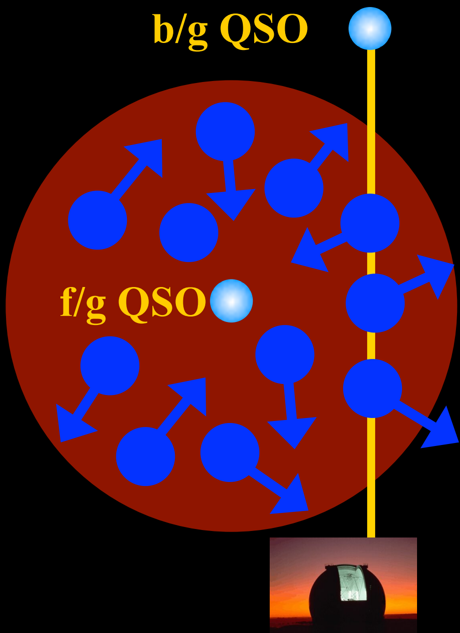
⇒ conduction saturated

$$\Rightarrow \quad q_{\rm sat} \propto n_{\rm hot} T^{3/2}$$

Hennawi & Prochaska (2012a)

$$\mathrm{SB}_{\mathrm{Ly}\alpha} = 8 \times 10^{-17} \left(\frac{f_{\rm cov}}{1.0}\right) \left(\frac{n_{\rm hot}}{10^{-2}\,\mathrm{cm}^{-3}}\right) \left(\frac{T}{10^7\,\mathrm{K}}\right)^{3/2} \mathrm{erg/s/cm^2/}\square''$$

Cooling Radiation: Ram Pressure



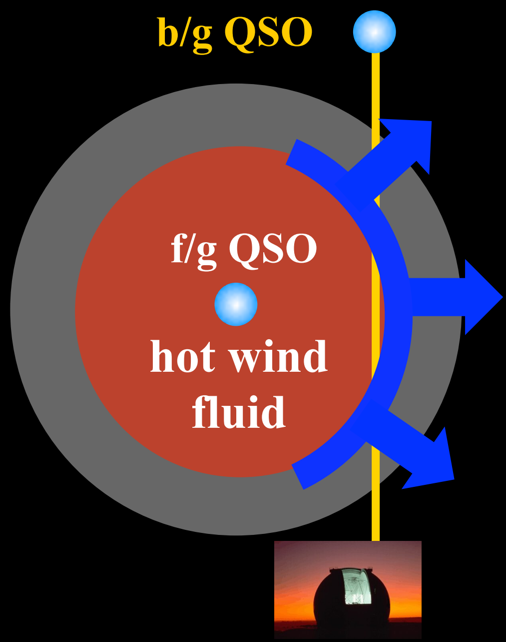
ram pressure heat flux → $q_{\rm ram} = f_{\rm cold}\rho_{\rm hot}v^3$

$f_{\rm cold} \equiv$ fraction of ram pressure work heating cold phase

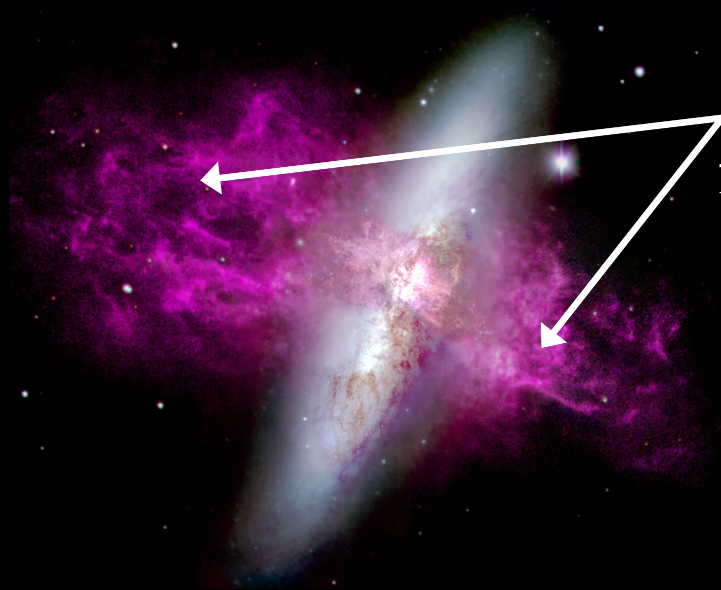
Hennawi & Prochaska (2012a)

$$\mathrm{SB}_{\mathrm{Ly}\alpha} = 2\times 10^{-17}\left(\frac{f_{\rm cold}}{0.50}\right)\left(\frac{f_{\rm cov}}{1.0}\right)\left(\frac{n_{\rm hot}}{10^{-2}\,{\rm cm}^{-3}}\right)\left(\frac{v}{700\,{\rm km\,s^{-1}}}\right)^3 \;{\rm erg/s/cm^2/\square''}$$

Cooling Radiation: Outflow



Hennawi & Prochaska (2012a)



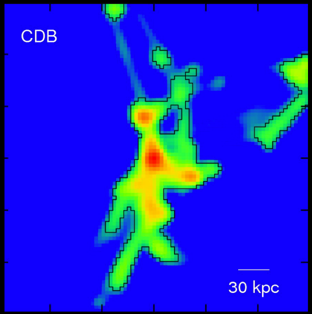
$f_{\rm cold} \equiv$ fraction of kinetic luminosity thermalized in cold phase

$$\mathrm{SB}_{\mathrm{Ly}\alpha} = 10^{-17}\left(\frac{f_{\rm cold}}{0.50}\right)\left(\frac{\dot{E}_{\rm outflow}}{10^{45}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{R}{100\,\mathrm{kpc}}\right)^{-2}\ \mathrm{erg/s/cm^2/\square''}$$

Other processes (e.g. turbulent mixing) can similarly heat the cold gas resulting in comparable emission

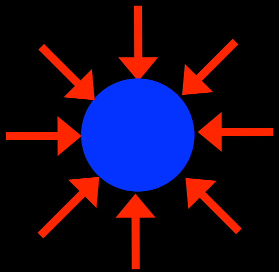
Heating Mechanisms

Hennawi & Prochaska (2012a)



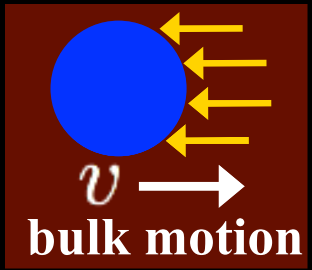
Gravitational

$$\mathrm{SB}_{\mathrm{Ly}\alpha} = 10^{-17}\left(\frac{f_{\mathrm{cold}}}{0.50}\right)\left(\frac{f_{\mathrm{cov}}}{1.0}\right)\left(\frac{N_{\mathrm{H}}}{10^{21}\,\mathrm{cm}^{-2}}\right)\left(\frac{M}{10^{13}\,M_{\odot}}\right)^{2/3}$$



Thermal Conduction

$$\mathrm{SB}_{\mathrm{Ly}\alpha} = 8\times 10^{-17}\left(\frac{f_{\mathrm{cov}}}{1.0}\right)\left(\frac{n_{\mathrm{hot}}}{10^{-2}\,\mathrm{cm}^{-3}}\right)\left(\frac{T}{10^{7}\,\mathrm{K}}\right)^{3/2}$$



Ram Pressure

$$\mathrm{SB}_{\mathrm{Ly}\alpha} = 2\times 10^{-17}\left(\frac{f_{\mathrm{cold}}}{0.50}\right)\left(\frac{f_{\mathrm{cov}}}{1.0}\right)\left(\frac{n_{\mathrm{hot}}}{10^{-2}\,\mathrm{cm}^{-3}}\right)\left(\frac{v}{700\,\mathrm{km\,s}^{-1}}\right)^{3}$$

Thermalized Superwind

$$\mathrm{SB}_{\mathrm{Ly}\alpha} = 10^{-17}\left(\frac{f_{\mathrm{cold}}}{0.50}\right)\left(\frac{\dot{E}_{\mathrm{outflow}}}{10^{45}\,\mathrm{erg\,s}^{-1}}\right)\left(\frac{R}{100\,\mathrm{kpc}}\right)^{-2}$$

Hennawi & Prochaska (2012b)

SDSSJ1204+0221

$R_\perp$ = 108 kpc

log N_{HI} = 19.7

smoothed PSF subtracted spectrum

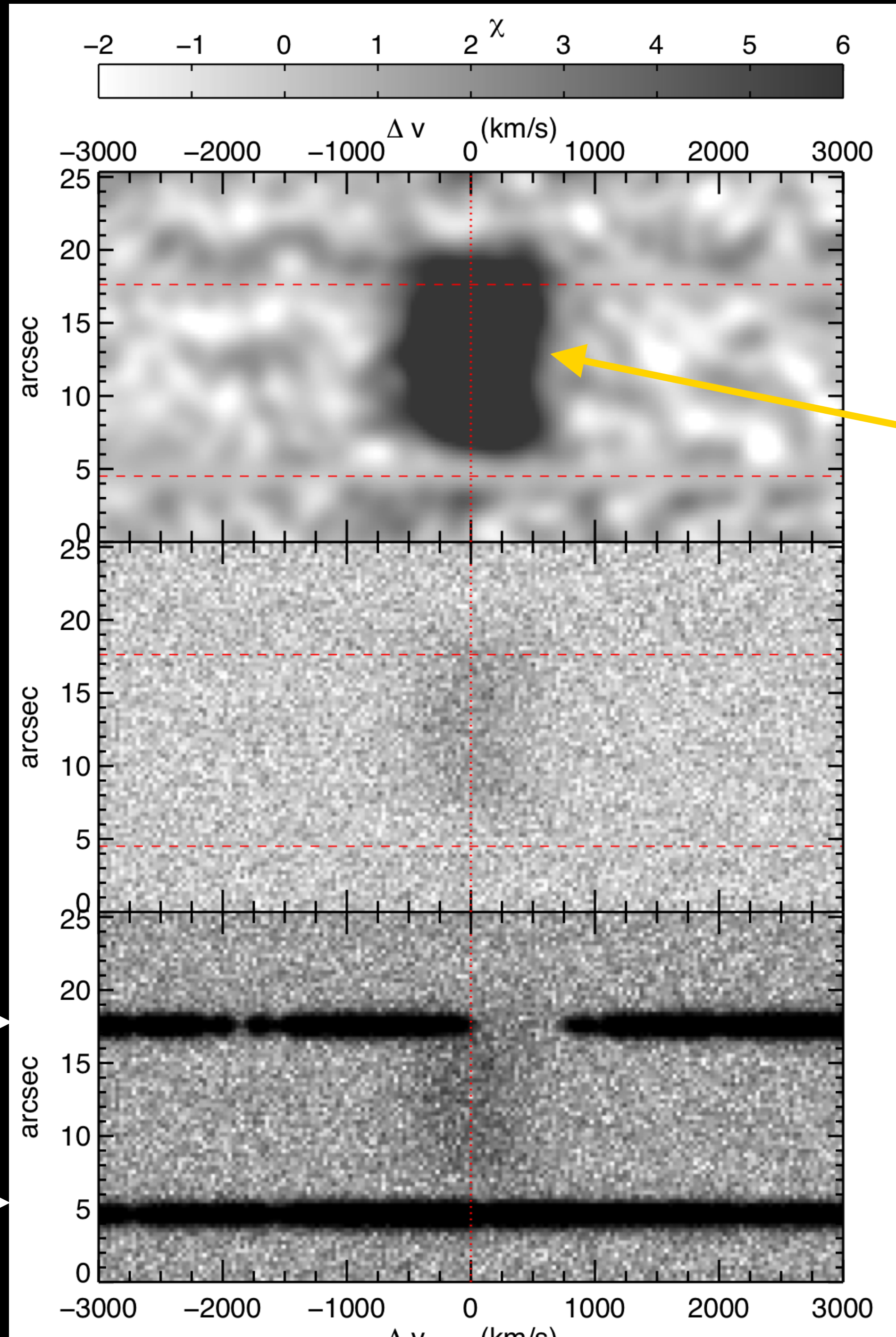
PSF subtracted 2-d spectrum

(data-model)/noise

b/g QSO z = 2.53 →

2-d spectrum

f/g QSO z = 2.44 →



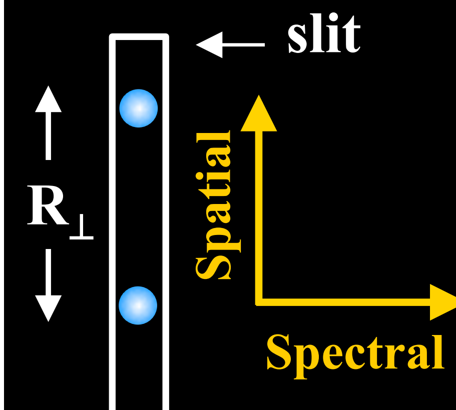
fake source

$\mathrm{SB} = 5\times10^{-17}$

5σ surface brightness limit

$\mathrm{SB}_{5\sigma} = 10^{-17}$

$\mathrm{erg/s/cm^2/\square''}$



Hennawi & Prochaska (2012b)

SDSSJ1427-0121

$R_\perp$ = 53 kpc

log N_{HI} = 18.9

smoothed PSF subtracted spectrum

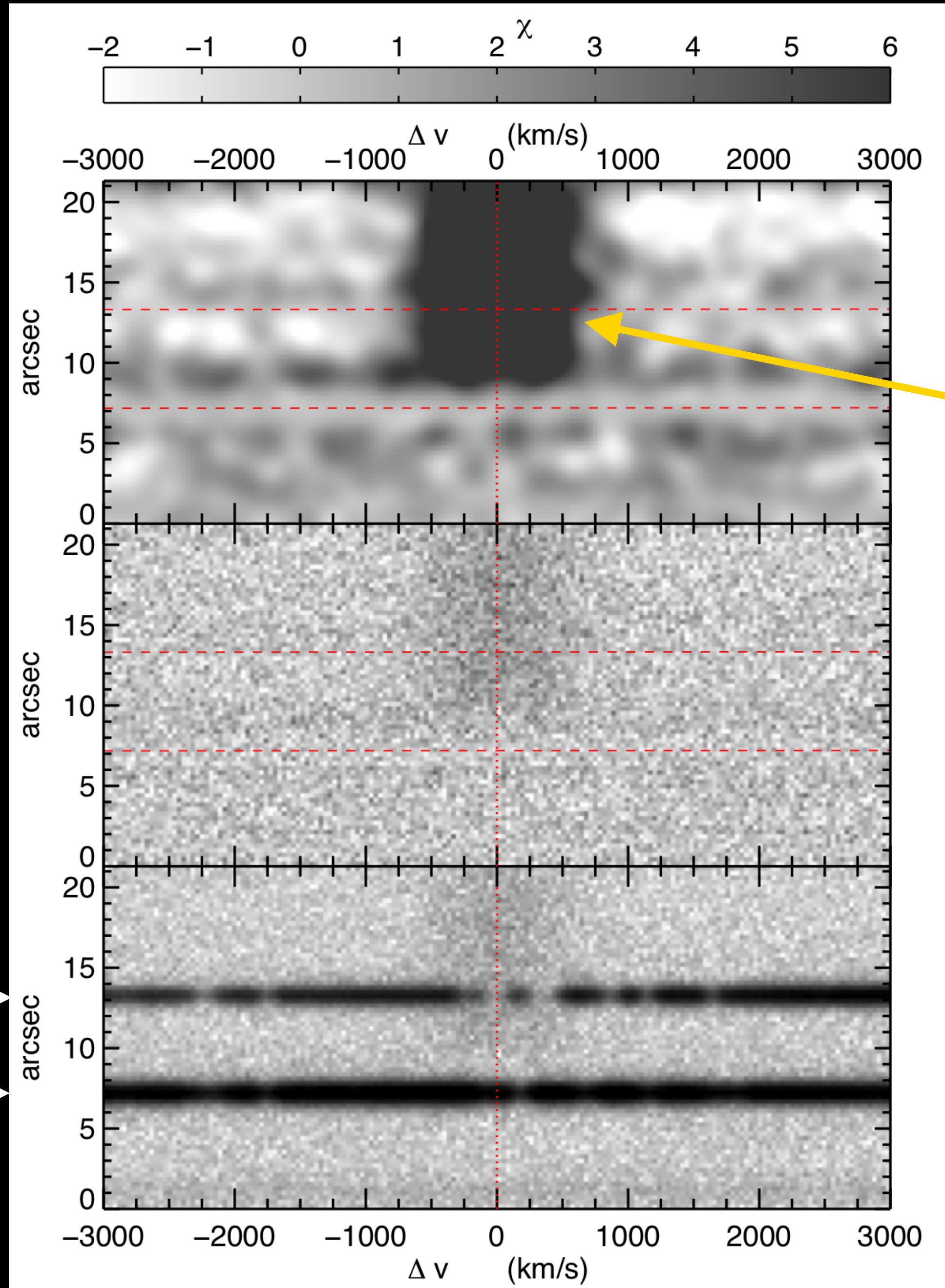
PSF subtracted 2-d spectrum

(data-model)/noise

b/g QSO z = 2.35 →

f/g QSO z = 2.28 →

2-d spectrum

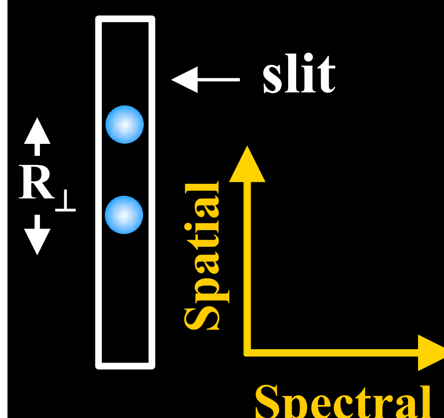


fake source

$\mathrm{SB} = 5 \times 10^{-17}$

5σ surface brightness limit

$\mathrm{SB}_{5\sigma} = 10^{-17}$ $\mathrm{erg/s/cm^2/\square''}$



Hennawi & Prochaska (2012b)

smoothed PSF subtracted spectrum

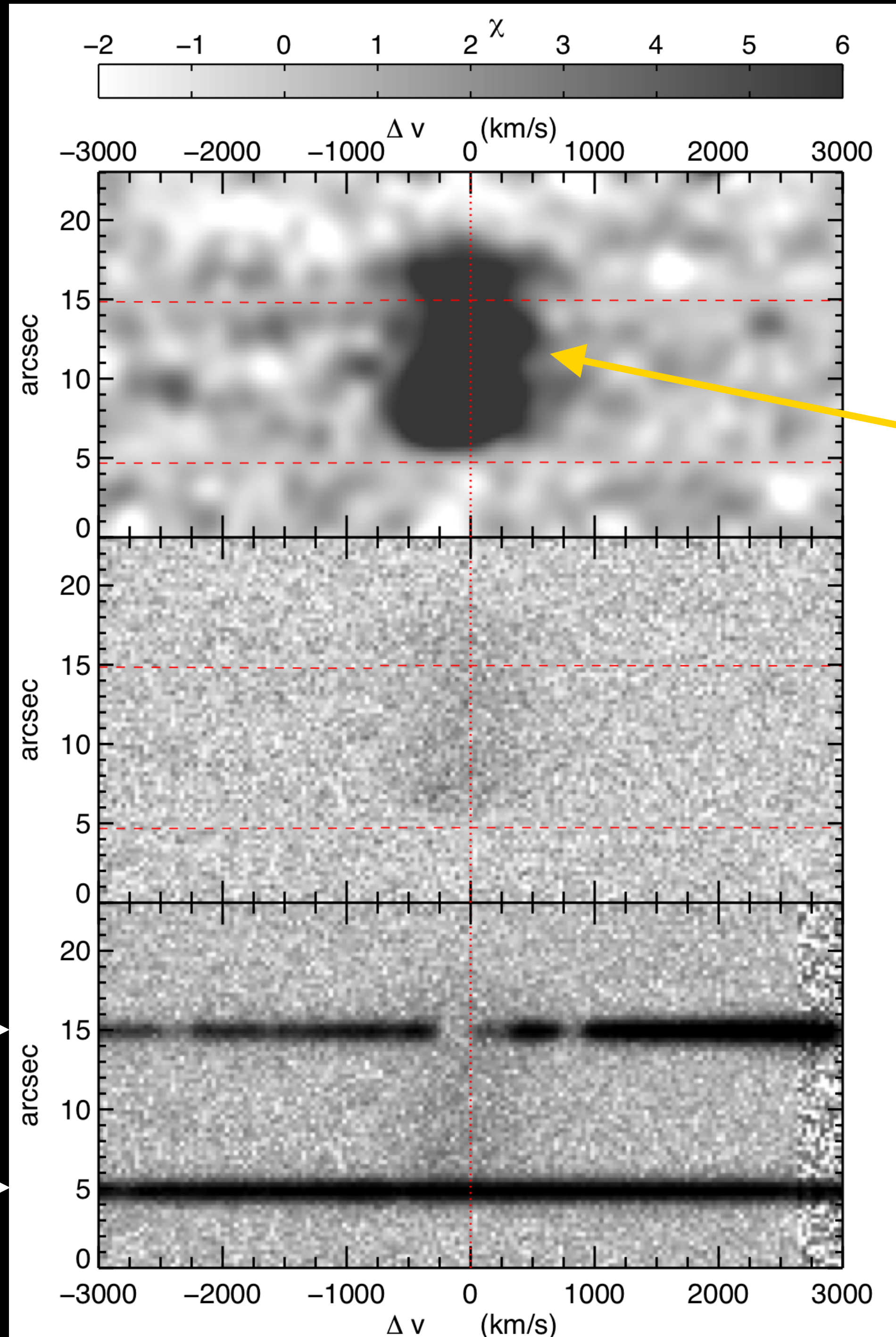
PSF subtracted 2-d spectrum

(data-model)/noise

b/g QSO z = 2.21 →

2-d spectrum

f/g QSO z = 2.18 →



SDSSJ0814+3250

$R_\perp$ = 87 kpc

log N_{HI} = 18.5

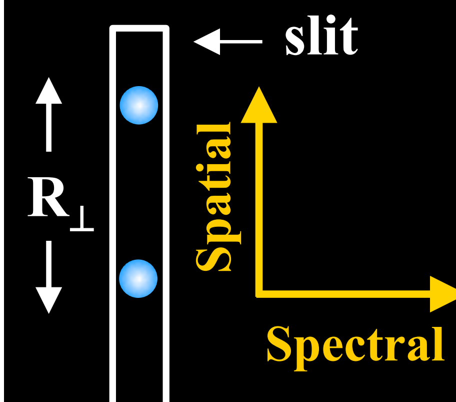
fake source

$SB = 5 \times 10^{-17}$

5σ surface brightness limit

$SB_{5\sigma} = 2 \times 10^{-17}$

$\mathrm{erg/s/cm^2/\square''}$



Why No Lyα Emission?

- Dust can only reduce Lyα emission by a factor ~ 2
- No recombination emission (fluorescence) ⇒ confirms gas is not illuminated by QSO radiation
- Large cold gas mass & high heating rates imply large cooling SB ~ 10^{-17} erg/s/cm^2/□", none detected
- Did we overestimate heating rates? Hot phase has different properties than we assumed?
- Cooling radiation (emission) + physical properties of gas (absorption) can place interesting constraints on heating rates

Summary

- **High covering factor** of optically thick gas ($N_{HI} > 10^{17.2}$) around QSOs, which trace massive halos $M_{halo} \approx 10^{12.5}\ M_{\odot}$
- **Detailed analysis of single system**: extreme kinematics (700 km s^{-1}), high enrichment (solar), high n_H (~ 1 cm^{-3}), large gas mass ($\sim 10^{11.5}\ M_{\odot}$)
- **Interpretation unclear**
  - Outflow: energetics too extreme
  - Cold Accretion: gas properties disagree with sims
- Large cold gas mass & high heating rates imply **cooling radiation should be extremely bright**, none detected.
- Combining absorption line with cooling emission constraints is a powerful new technique for studying the CGM.