Three Unresolved Problems in Studies of the Circumgalactic Medium

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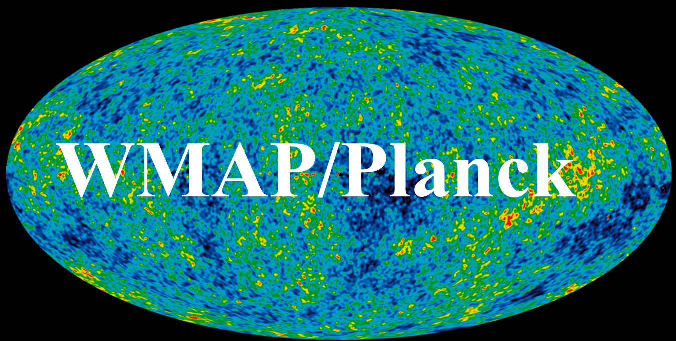
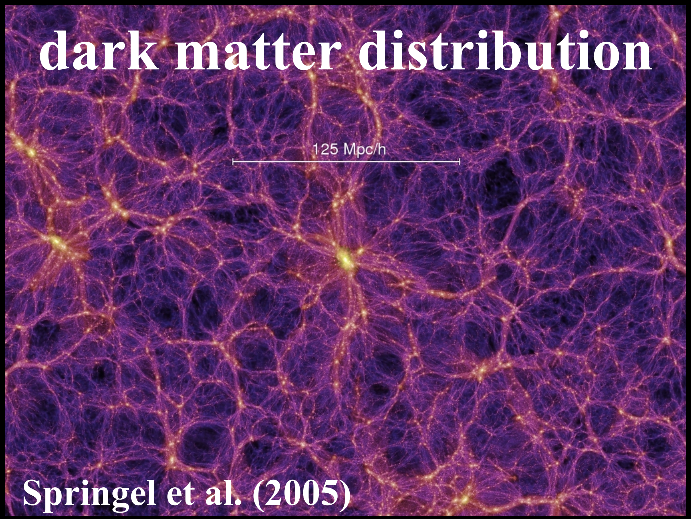
Prediction: Dark Matter

versus

Postdiction: Baryons



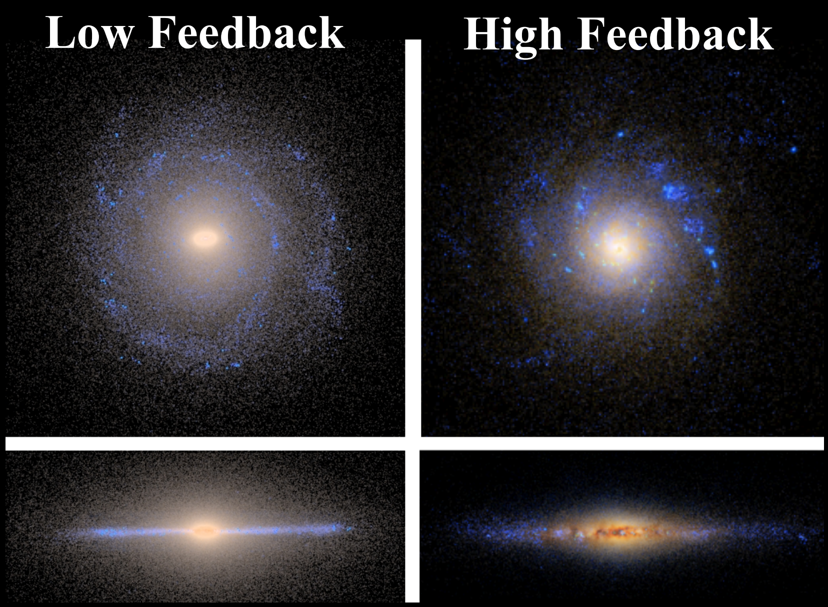
ab initio theory



sub-grid recipes

resolution: ~ 300 pc
convert gas to stars:
n ~ 1-10 cm^{-3}

MaGICC Project Sims of Milky Way

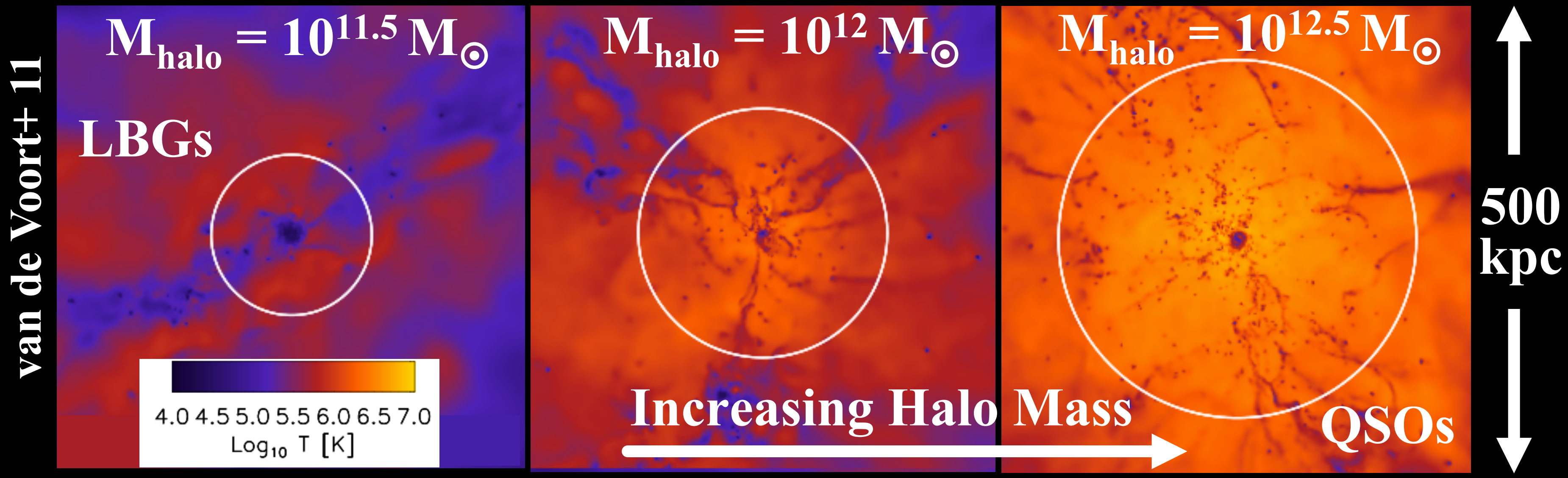


Stinson+ 2013

What initial conditions fuel star-formation in galaxies?

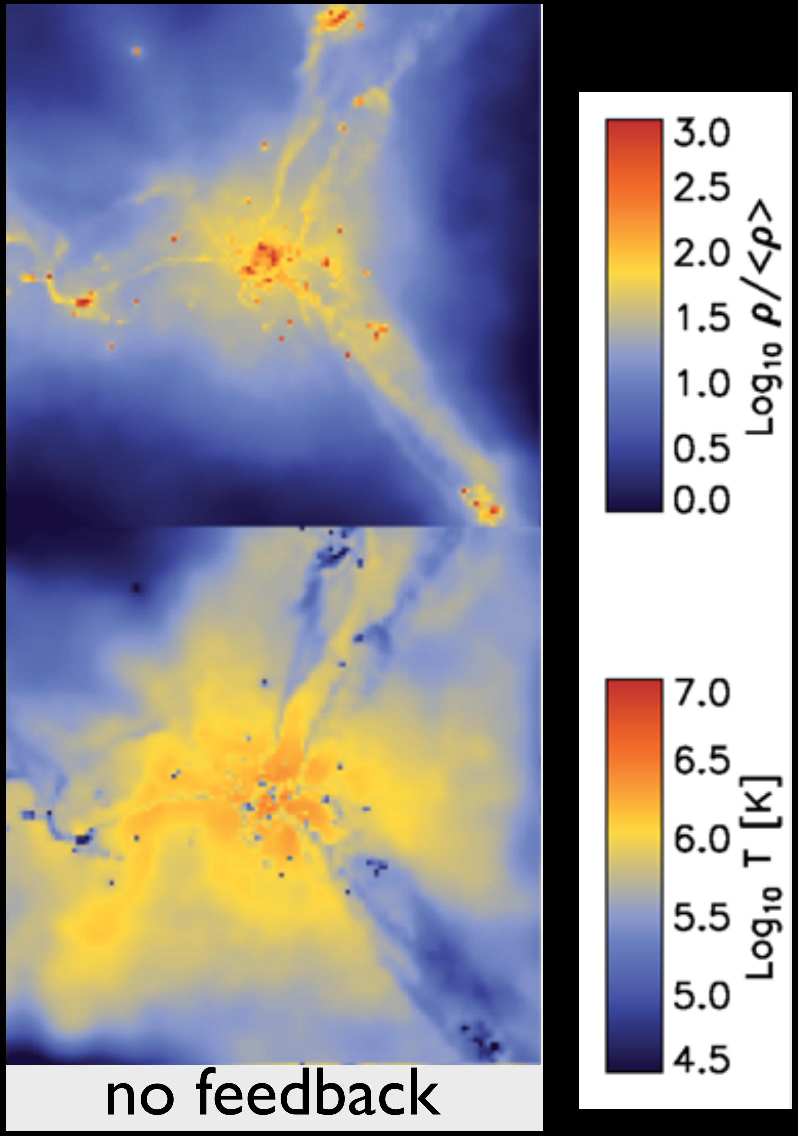
How Do Galaxies Get their Gas?

- Cosmological hydro simulations resolve the circumgalactic medium (CGM) and predict its structure



- Sims predict less cold gas in more massive halos

OWLS sims credit: F. van de Voort



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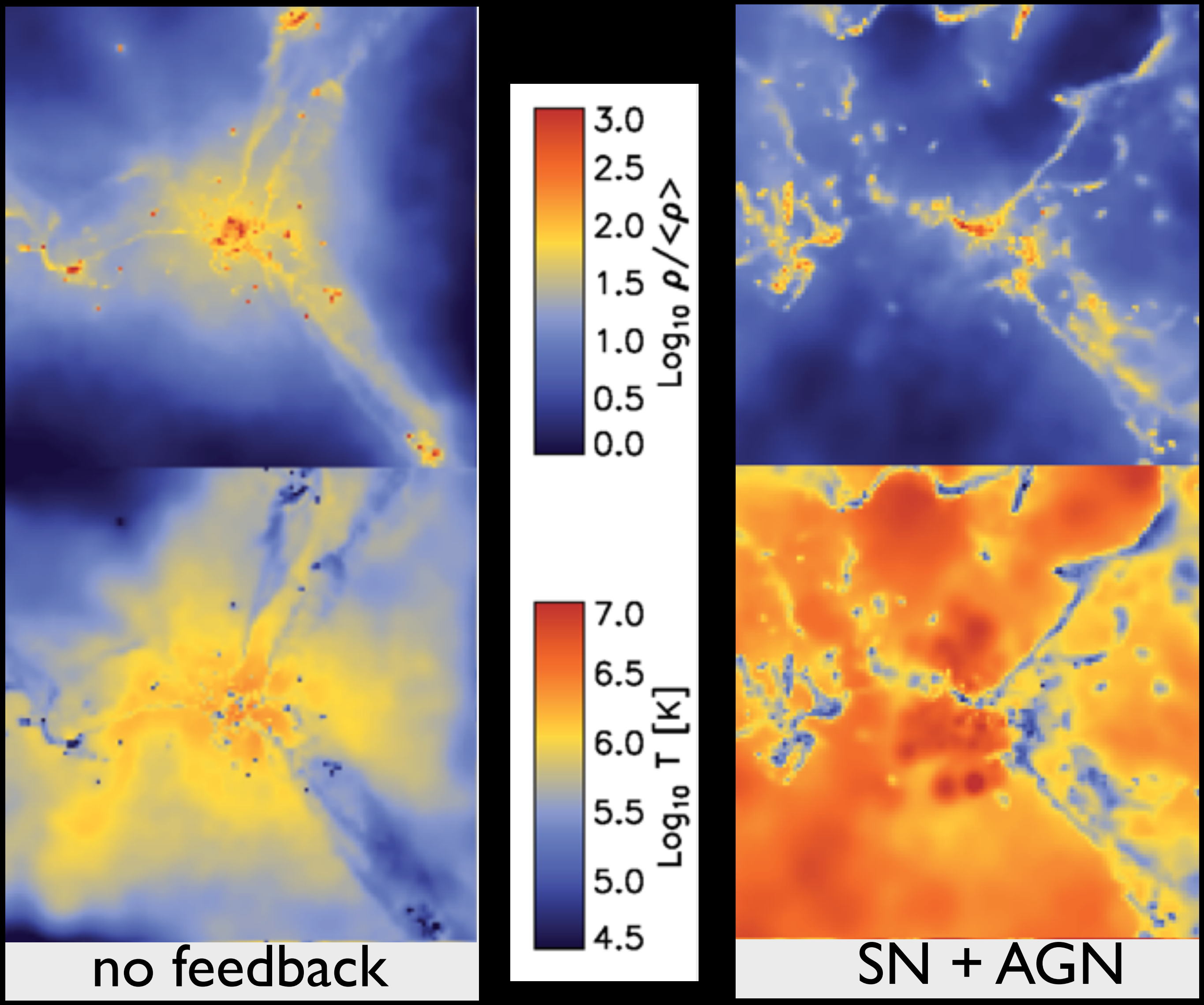
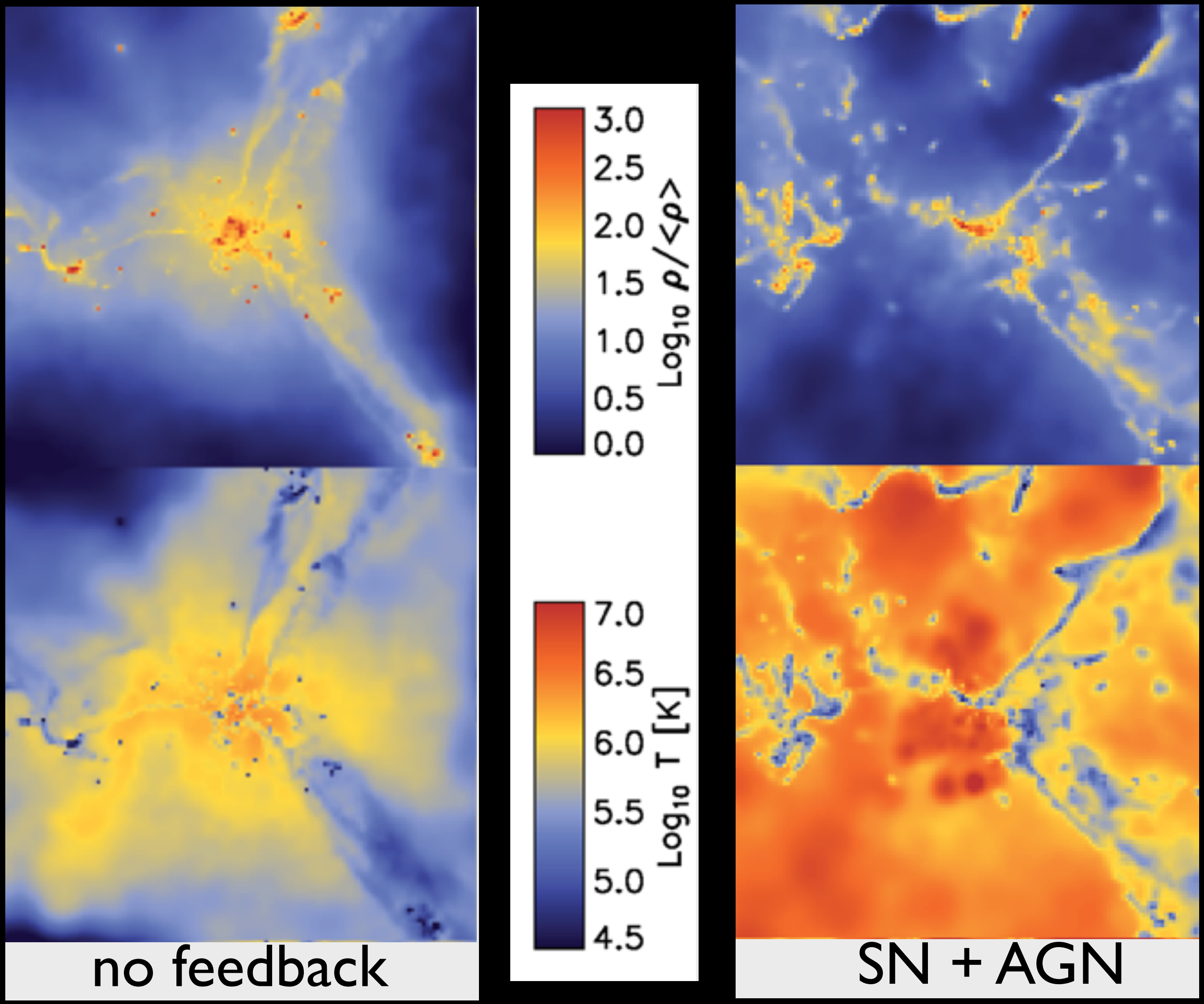


Feedback may alter the structure of the CGM. If so predicting the CGM depends on uncertain sub-grid feedback prescriptions.

OWLS sims
credit: F. van de Voort



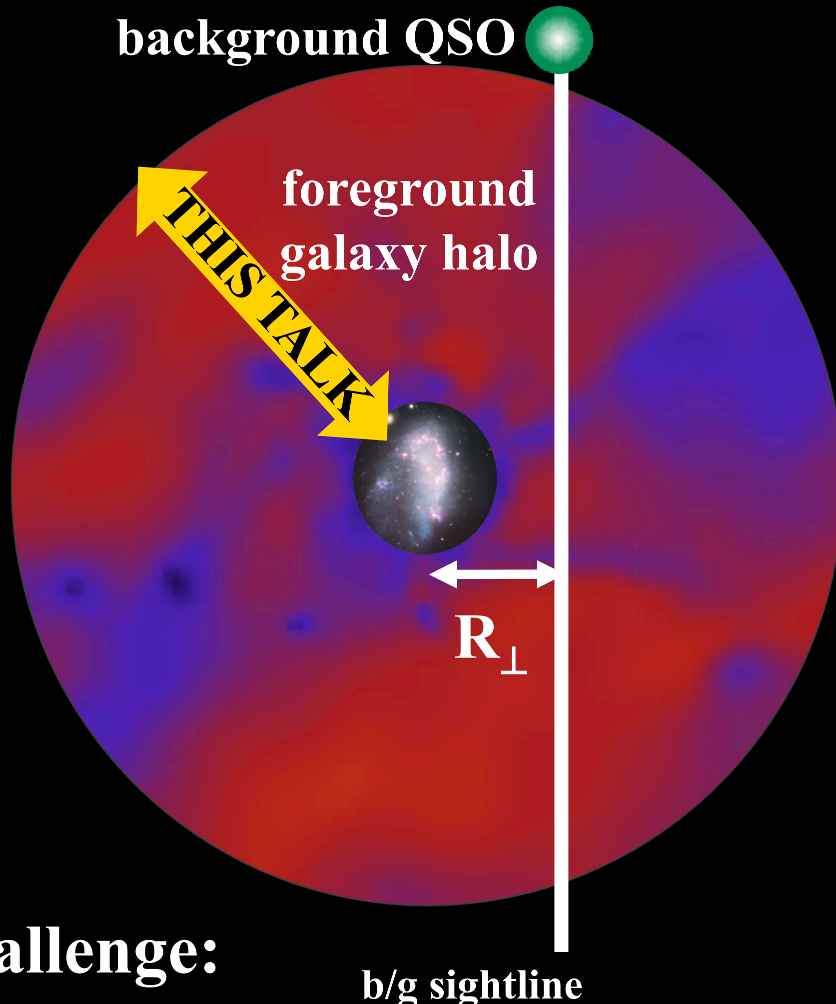
- <u>**Observational goals of CGM studies:**</u>
  - **directly test 'cold accretion' picture**
  - **characterize outflows: prevalence, physical state of gas**

Probing the Circumgalactic Medium (CGM)

Use absorption lines to probe diffuse gas

$r \sim 30 - 200$ kpc

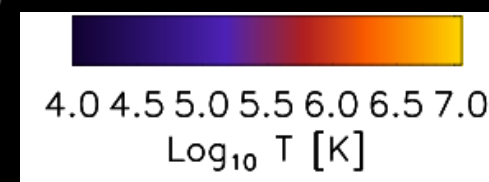
$N_{HI} \sim 10^{12-22}$ cm^{-2} and $T \sim 10^{2-6}$ K



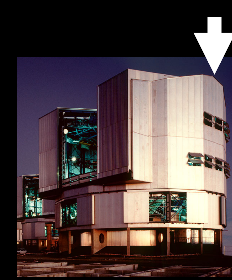
$\theta_{vir} \sim 10''$

$r_{vir} \sim 80$ kpc

Virial Radius



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



Why Study the Circumgalactic Medium at z ~ 2

Practical

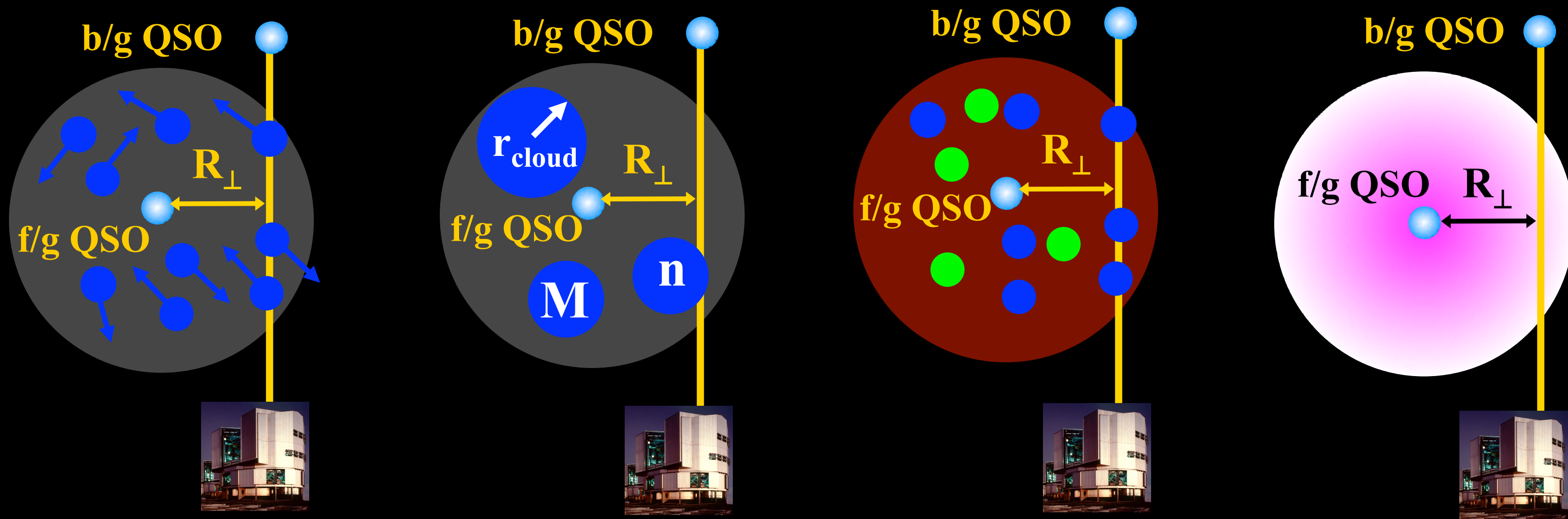
- Relevant UV absorption lines are redshifted into optical and not too blended with Lyα forest
- Spectroscopy of star-forming gals doable on 8m telescope

Conceptual

- Theory predicts more cold gas accretion at z ~ 2
- Peak of cosmic star-formation rate. If star-formation powers strong outflows, z ~ 2 is best time to find them

See also complementary work on z ~ 0 CGM with HST/COS

What Can we Actually Measure?



Covering factor & kinematics

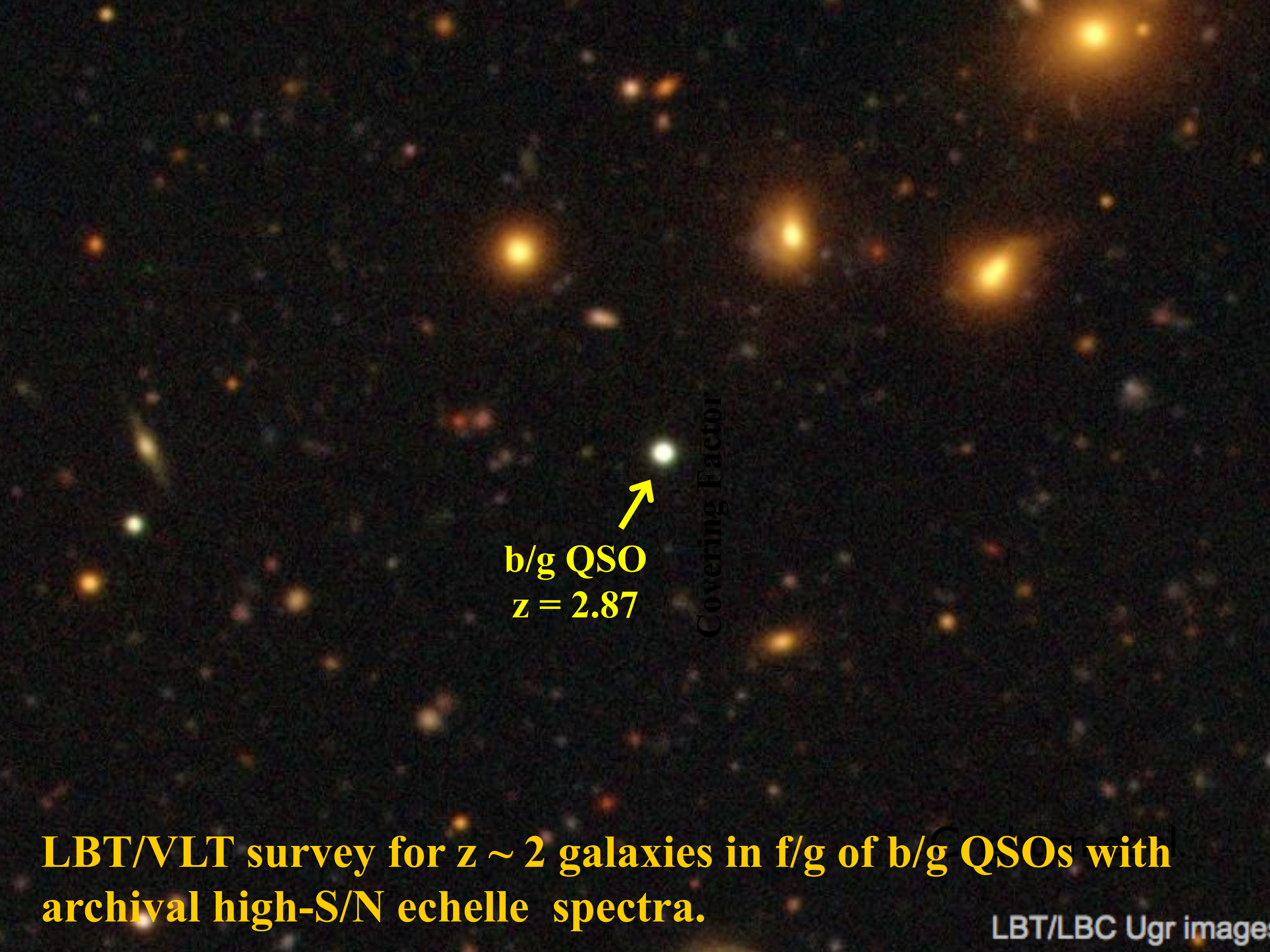
Gas mass, cloud density, size?

Multiphase? Cold, Warm, Hot?

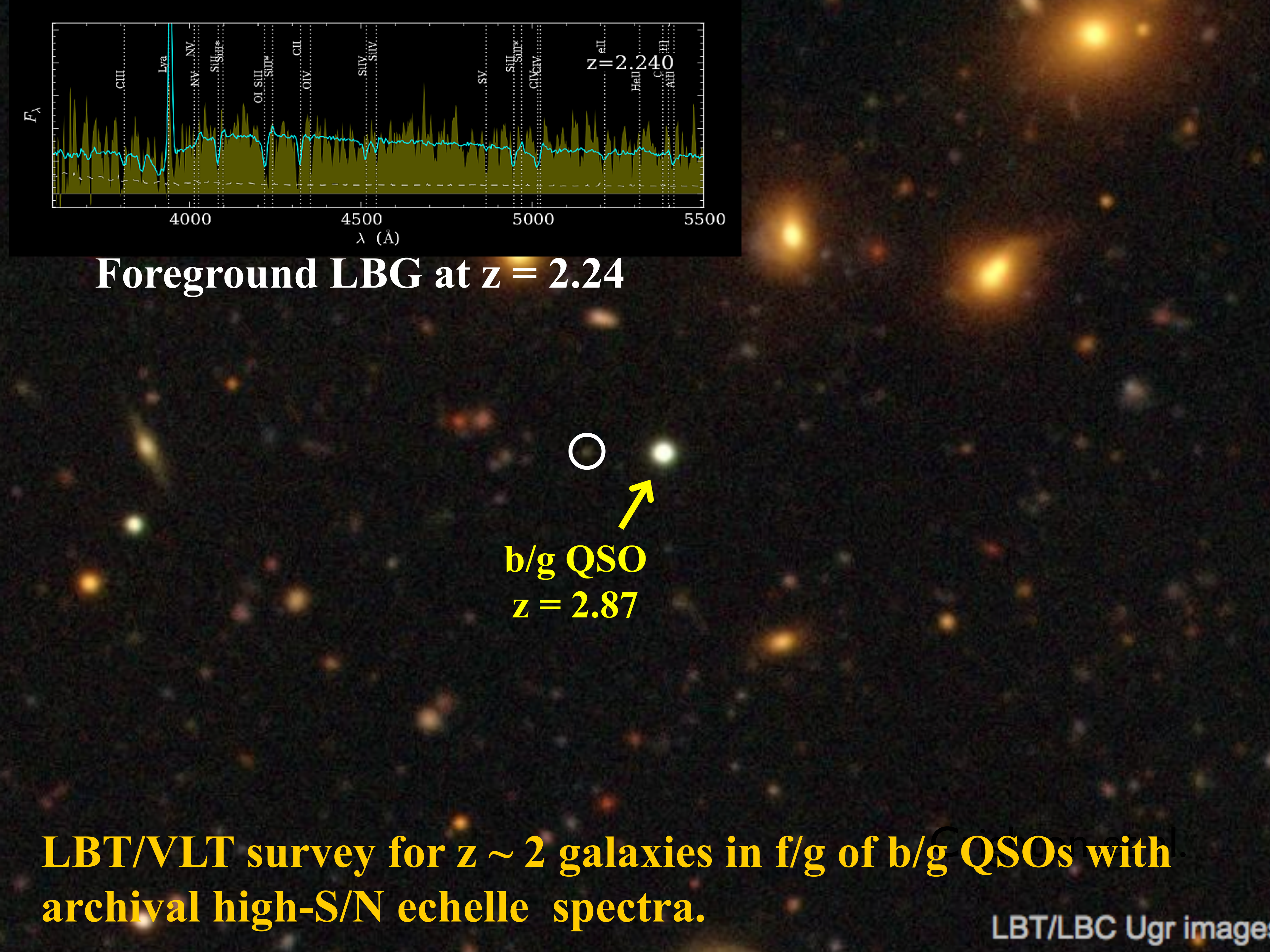
Metal Enrichment?

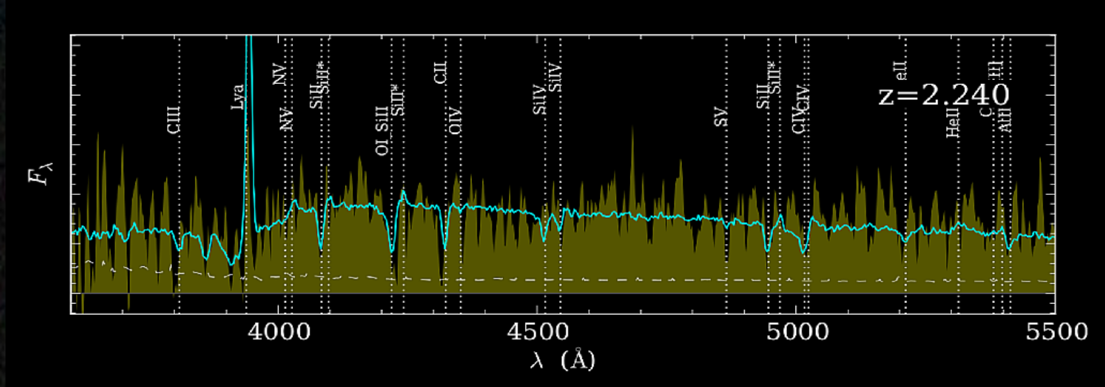
Moderate R ~ 2000
150 km/s

Echelle R ~ 5000-50,000, 6-60 km/s



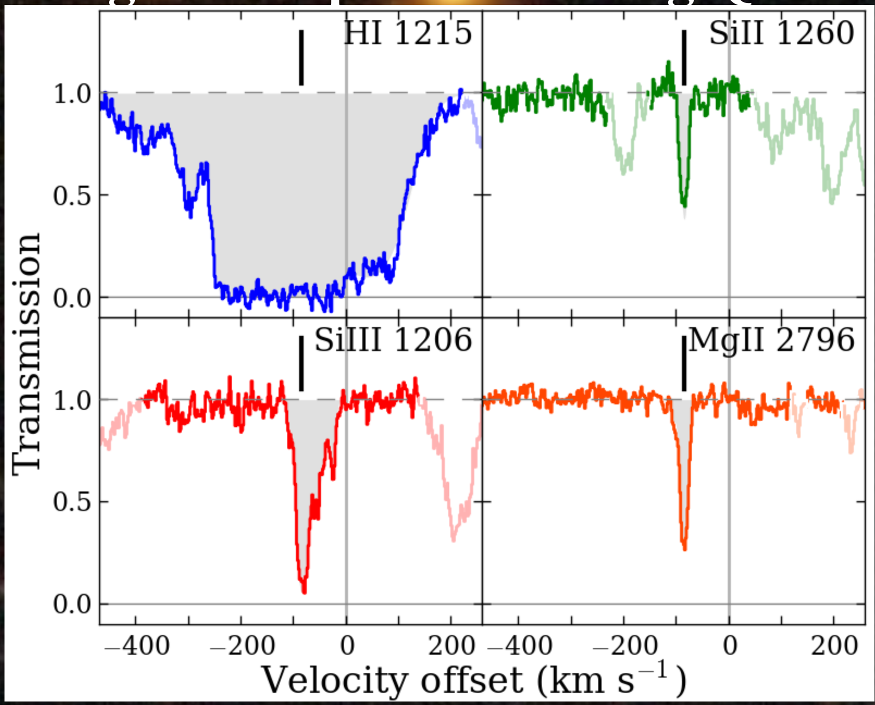
LBT/VLT survey for z ~ 2 galaxies in f/g of b/g QSOs with archival high-S/N echelle spectra.


z=2.240
CIII
Lyα
NV
SiII
OI SiII
CII
OIV
SiIV
SV
CIV
HeII
AlII
4000
4500
5000
5500
λ (Å)
F_λ
Foreground LBG at z = 2.24
b/g QSO
z = 2.87
LBT/VLT survey for z ~ 2 galaxies in f/g of b/g QSOs with archival high-S/N echelle spectra.
LBT/LBC Ugr image



Foreground LBG at z = 2.24

High-Res Spectrum of b/g QSO

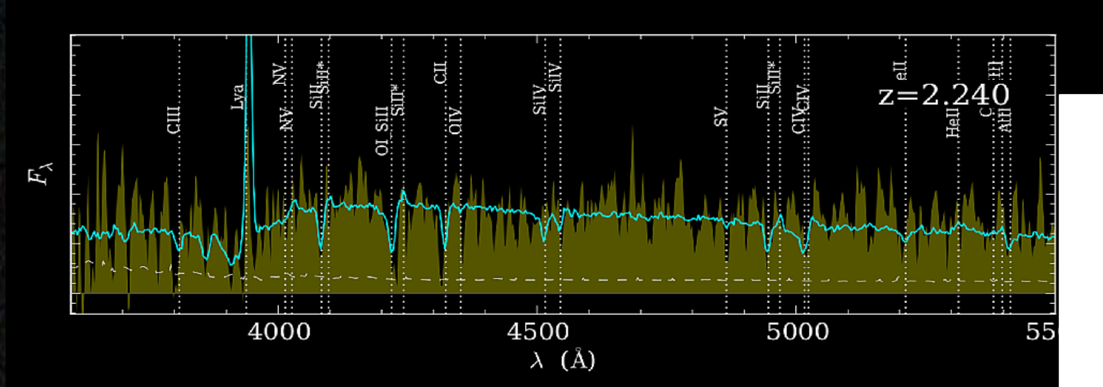


b/g QSO
z = 2.87

absorber at $R_\perp$ = 77 kpc, N_{HI} < 17.2

LBT/VLT survey for z ~ 2 galaxies in f/g of b/g QSOs with archival high-S/N echelle spectra.

LBT/LBC Ugr image



Foreground LBG at z = 2.24

b/g QSO
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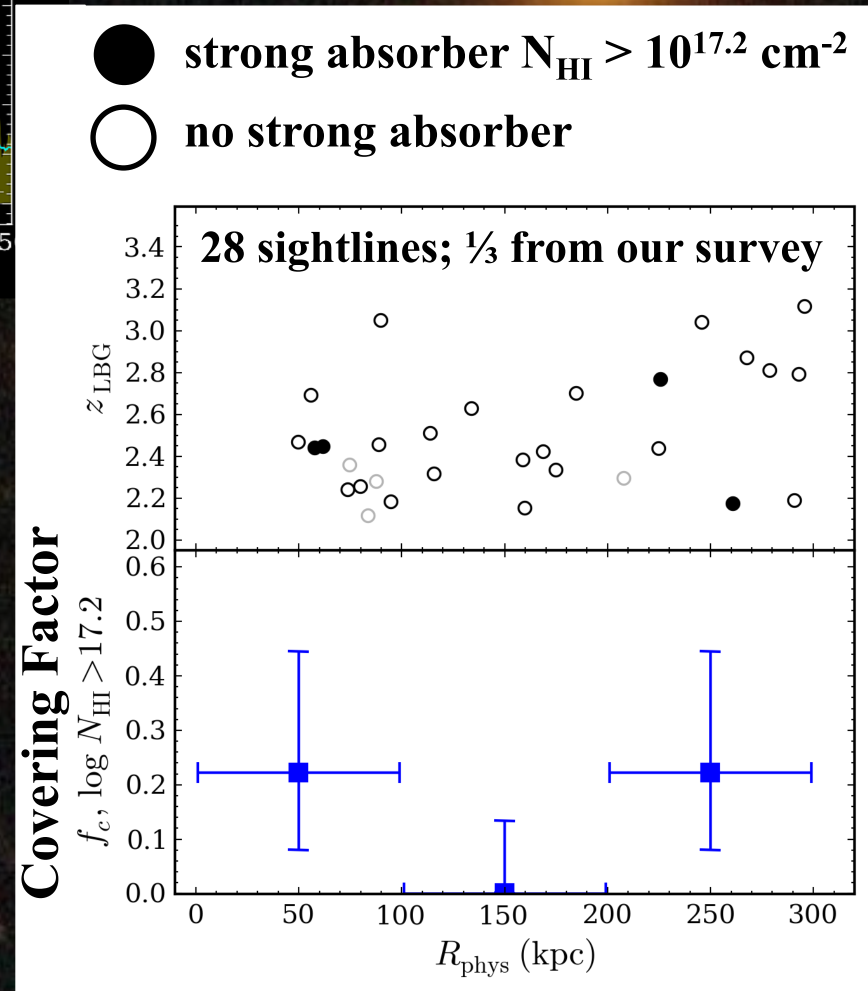
LBT/LBC Ugr image



Rudie+ 2011; Crighton, Hennawi+ 2014a

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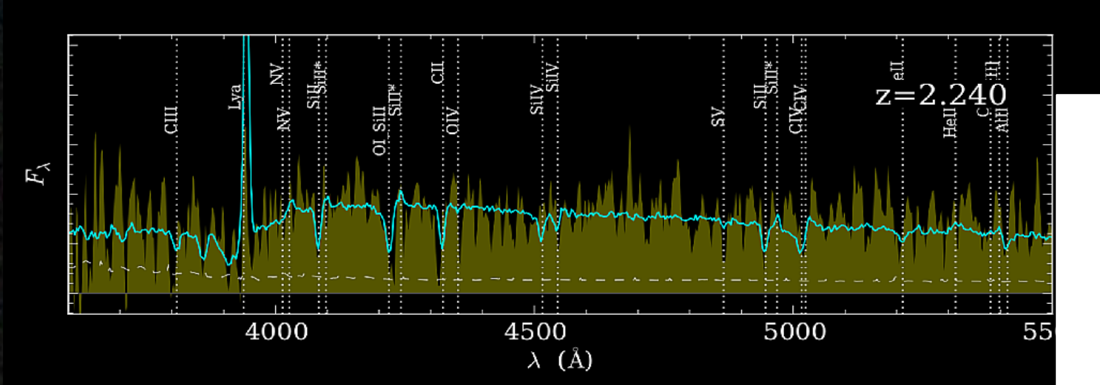
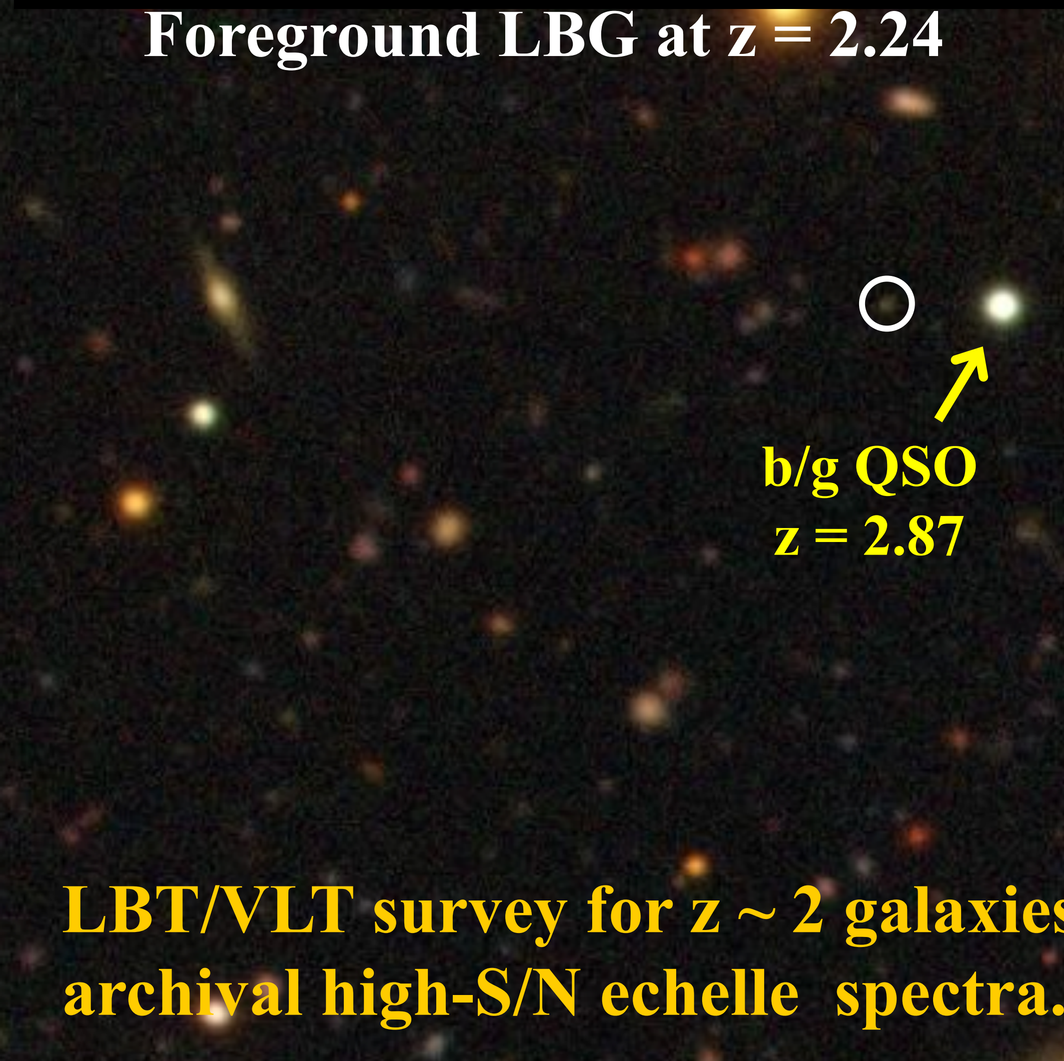
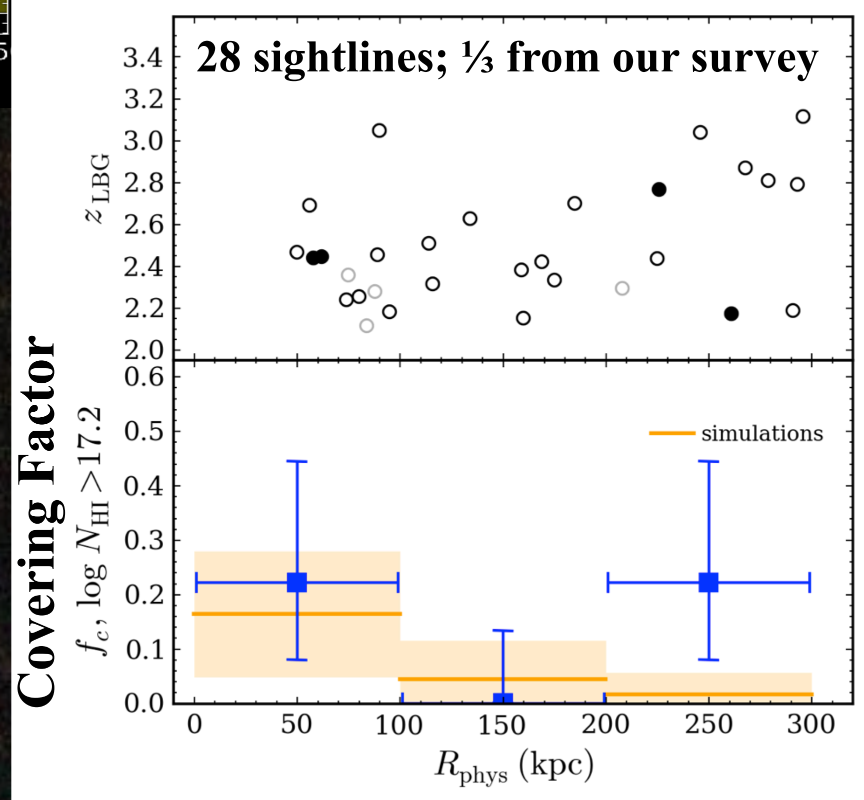


Foreground LBG at z = 2.24

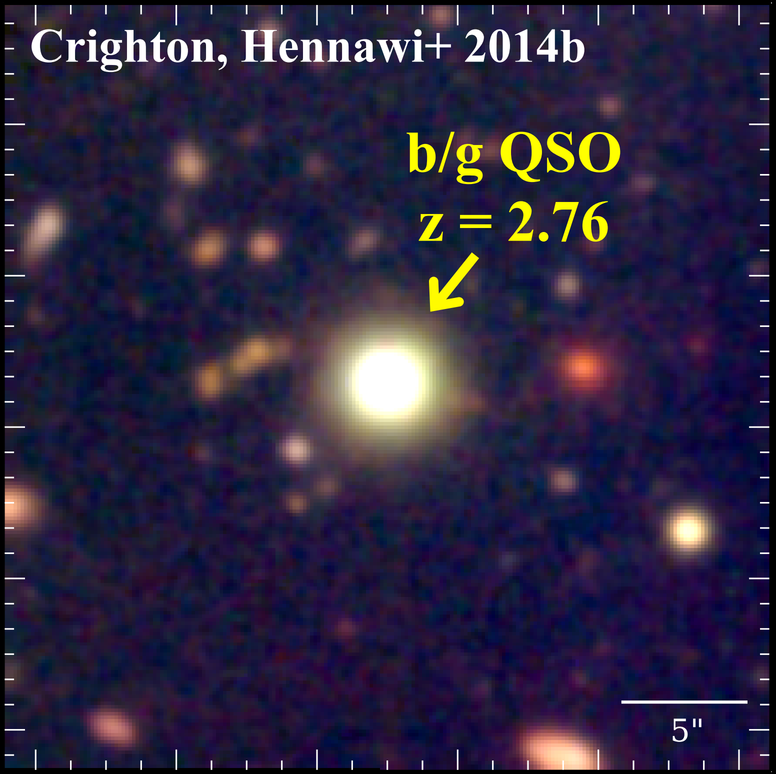




Rudie+ 2011; Crighton, Hennawi+ 2014a
Fumagalli, Hennawi+ 2014

LBT/VLT survey for z ~ 2 galaxies in f/g of b/g QSOs with archival high-S/N echelle spectra.

The CGM of a Low-Mass Galaxy



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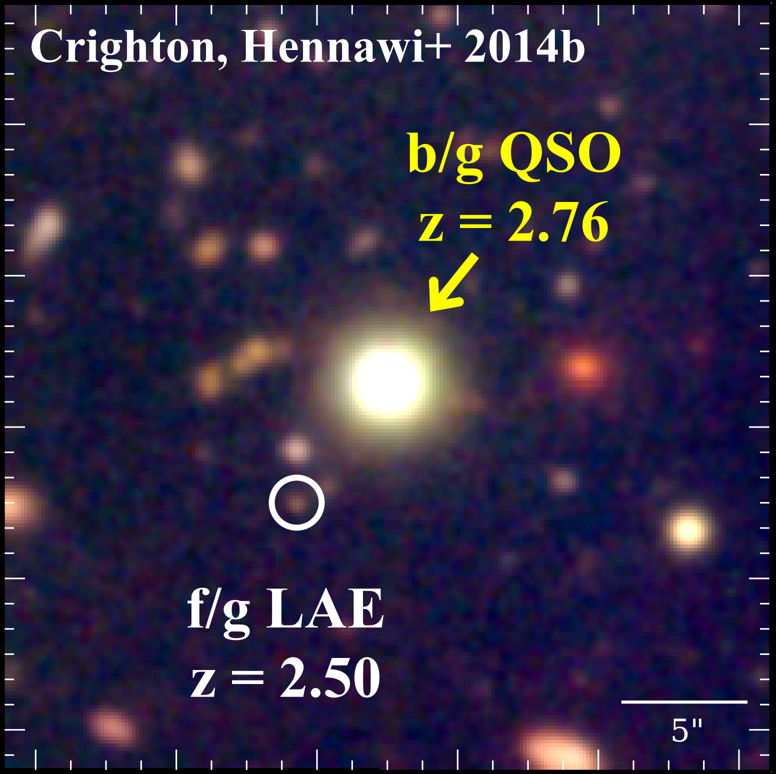
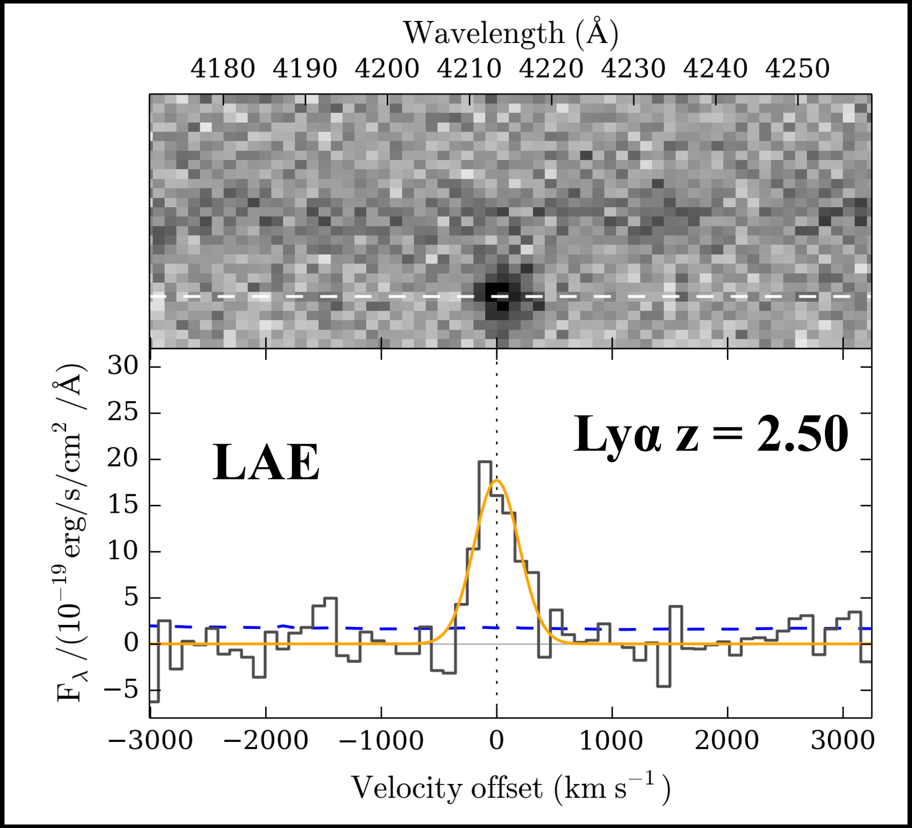


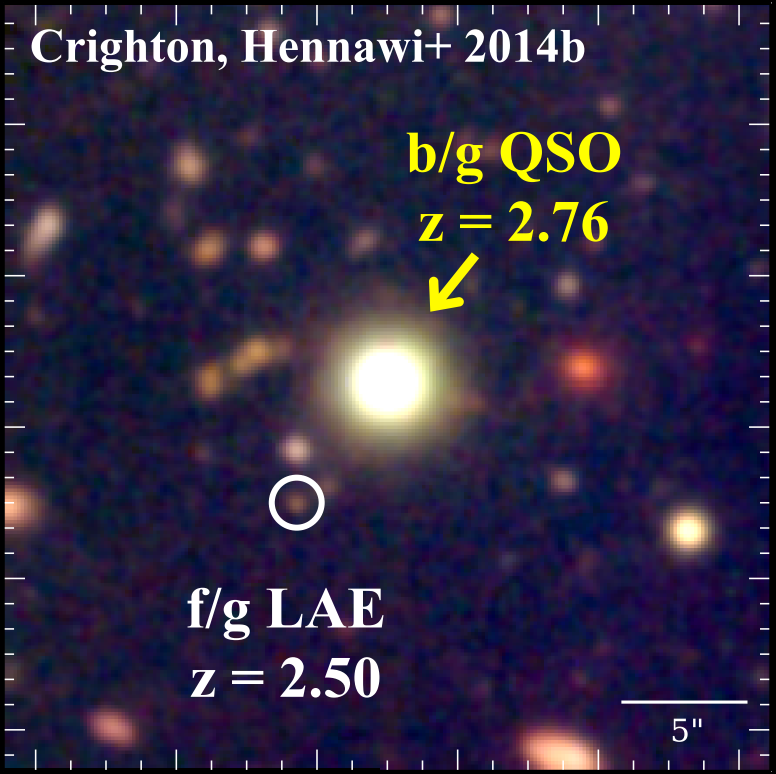


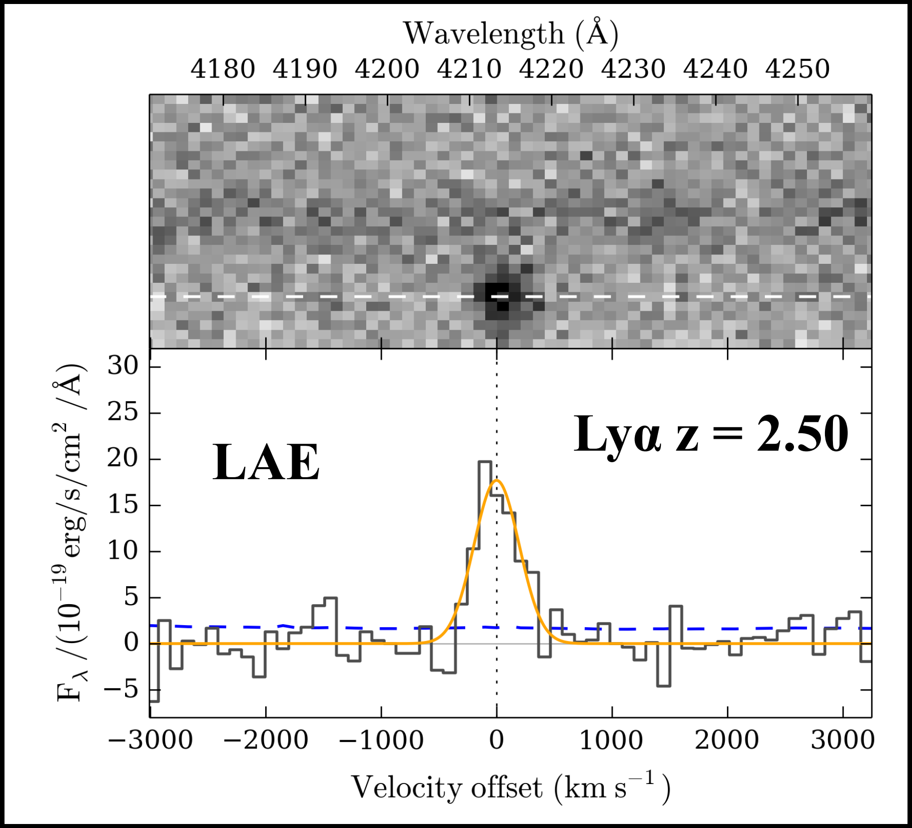
f/g Lyα-emitter @ $R_\perp$= 50 kpc

L = 0.2L* ; SFR ~ 1.5 $M_\odot$/yr

$M_\star \sim 10^{9.1}\ M_\odot$; $M_h \sim 10^{11.4}\ M_\odot$

The CGM of a Low-Mass Galaxy





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Background QSO observed for 50 hours on UVES, S/N ~ 70

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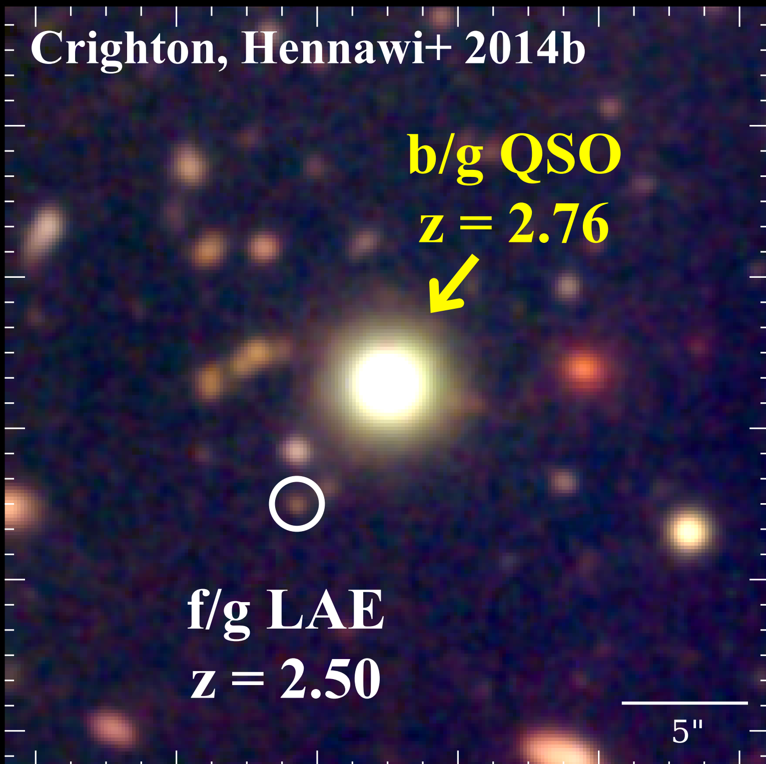
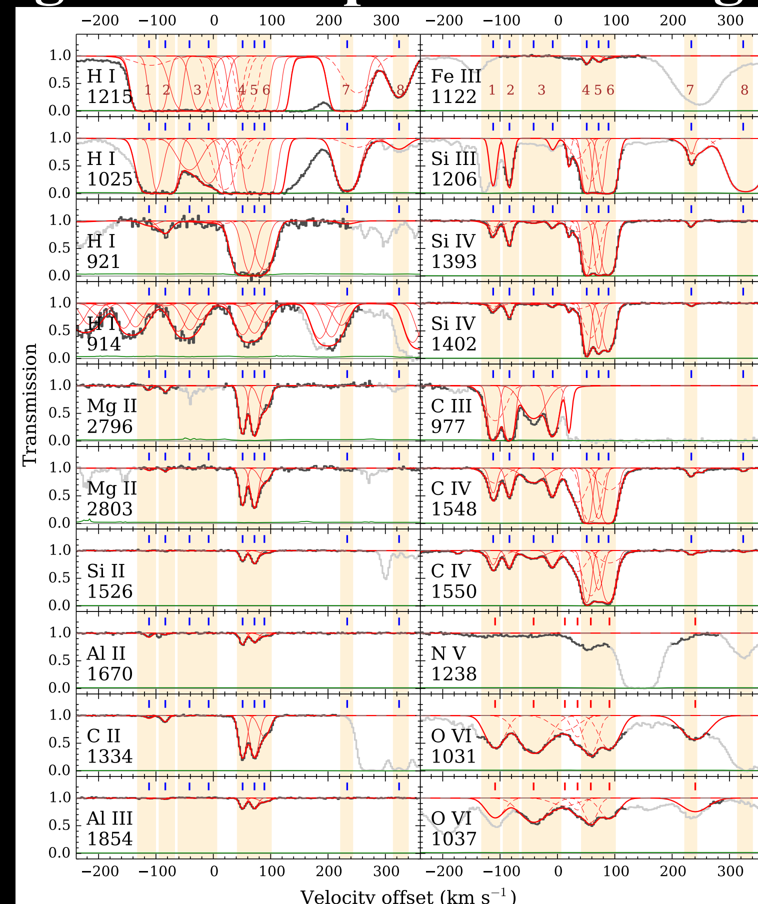


High-Resln. Spectrum of b/g QSO



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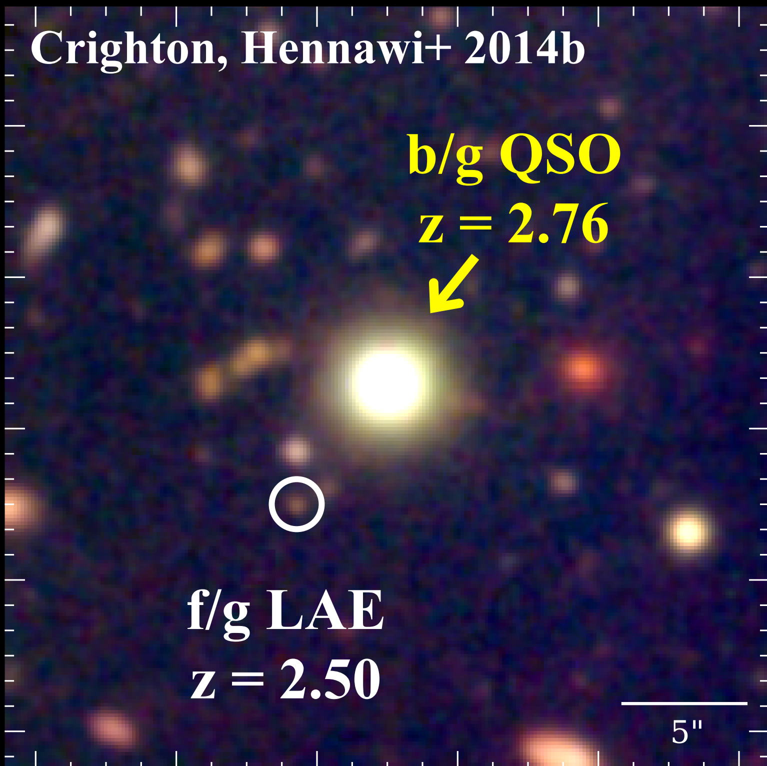
LLS $\log N_{HI} = 10^{16.94 \pm 0.1}$ @ $R_\perp$ = 50 kpc

- **Sensitive column densities for 13 ionic metal states**
- **Full Lyman series analysis gives HI for each component**

The CGM of a Low-Mass Galaxy



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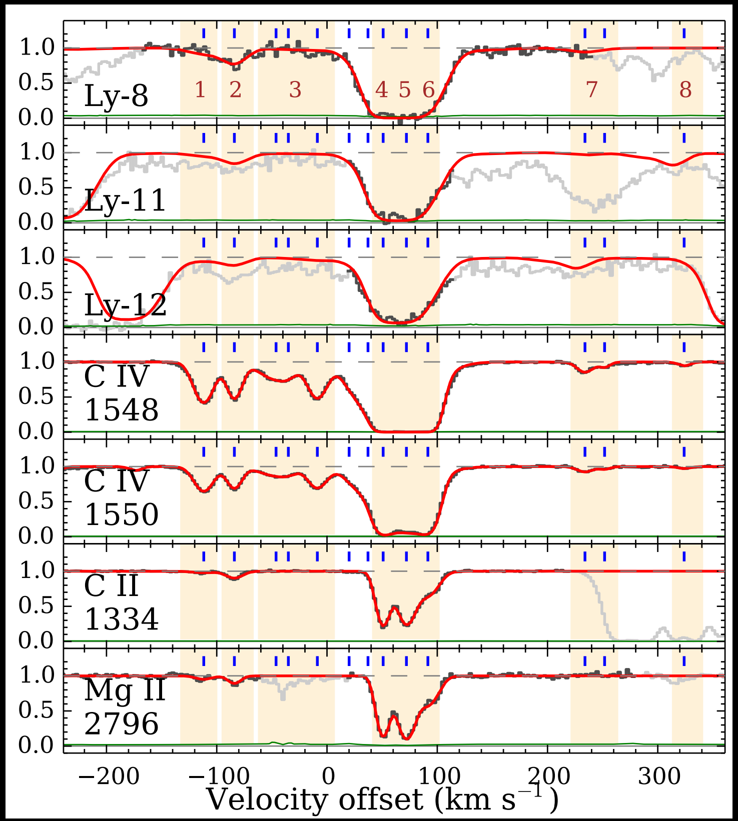
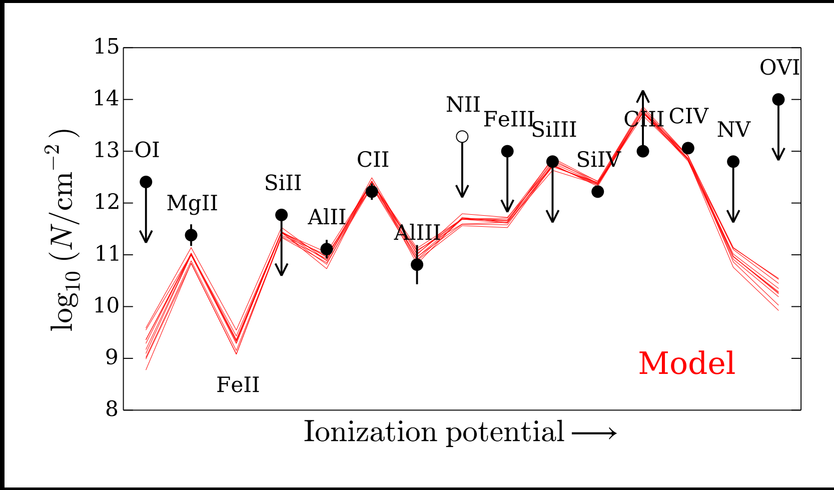
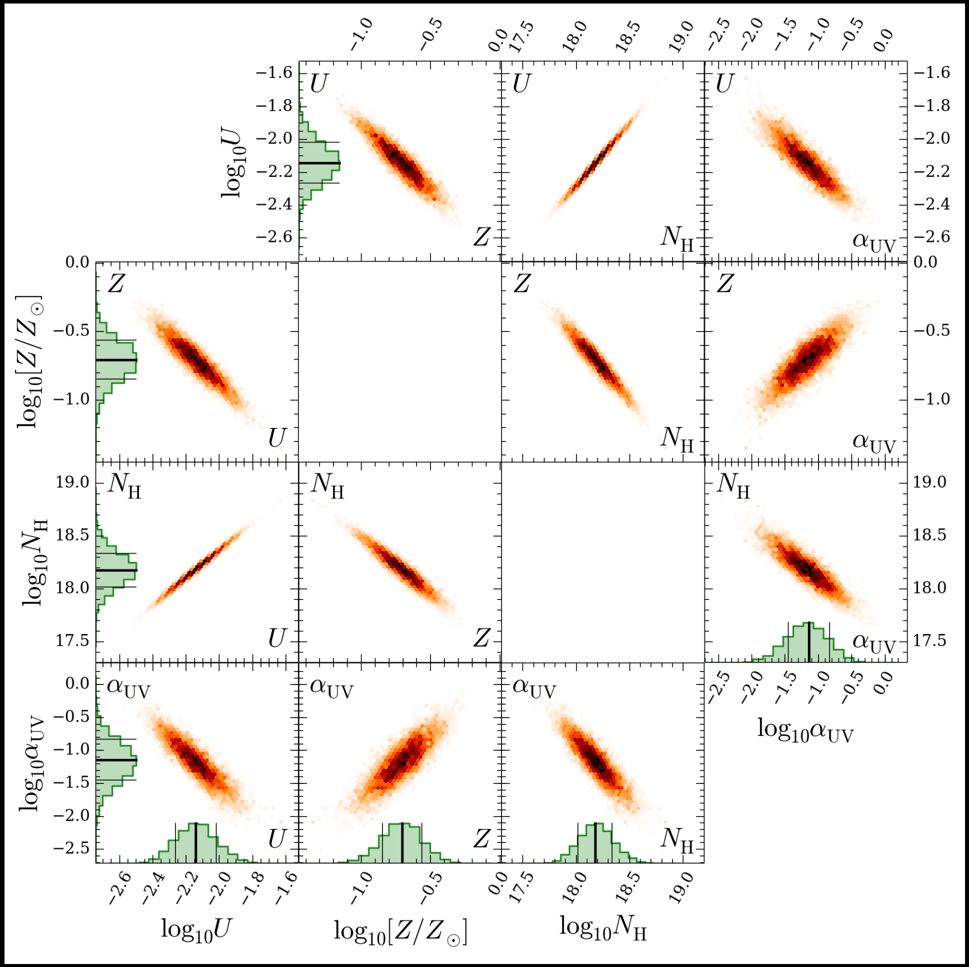


Δv = 430 km/s; MgII EW = 0.37Å

- **Perfect alignment between metal and HI kinematics ➡ gas well mixed. HI smoother because of thermal broadening**

Precise Determination of CGM Parameters





$\log n_H = -2.85 \pm 0.33\ (\mathrm{cm}^{-3})$

$\log Z = -0.70 \pm 0.14\ (Z_\odot)$

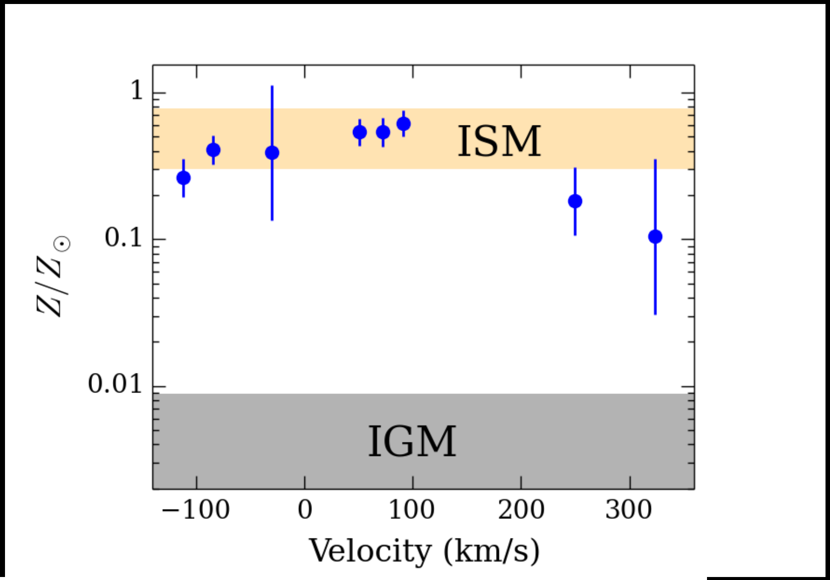
$\log N_H = 18.18 \pm 0.16\ (\mathrm{cm}^{-2})$

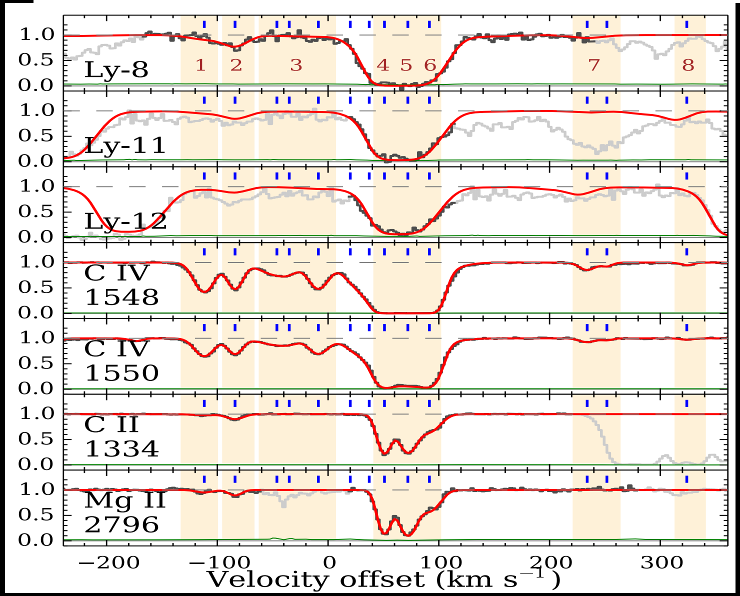
$\log r_{cloud} = -0.58 \pm 0.42\ (\mathrm{kpc})$

$x_{HI} = -3.30 \pm 0.16$

- Photoionization models provide excellent fit to the data
- Bayesian MCMC modeling gives robust errors fully accounting for parameter degeneracies

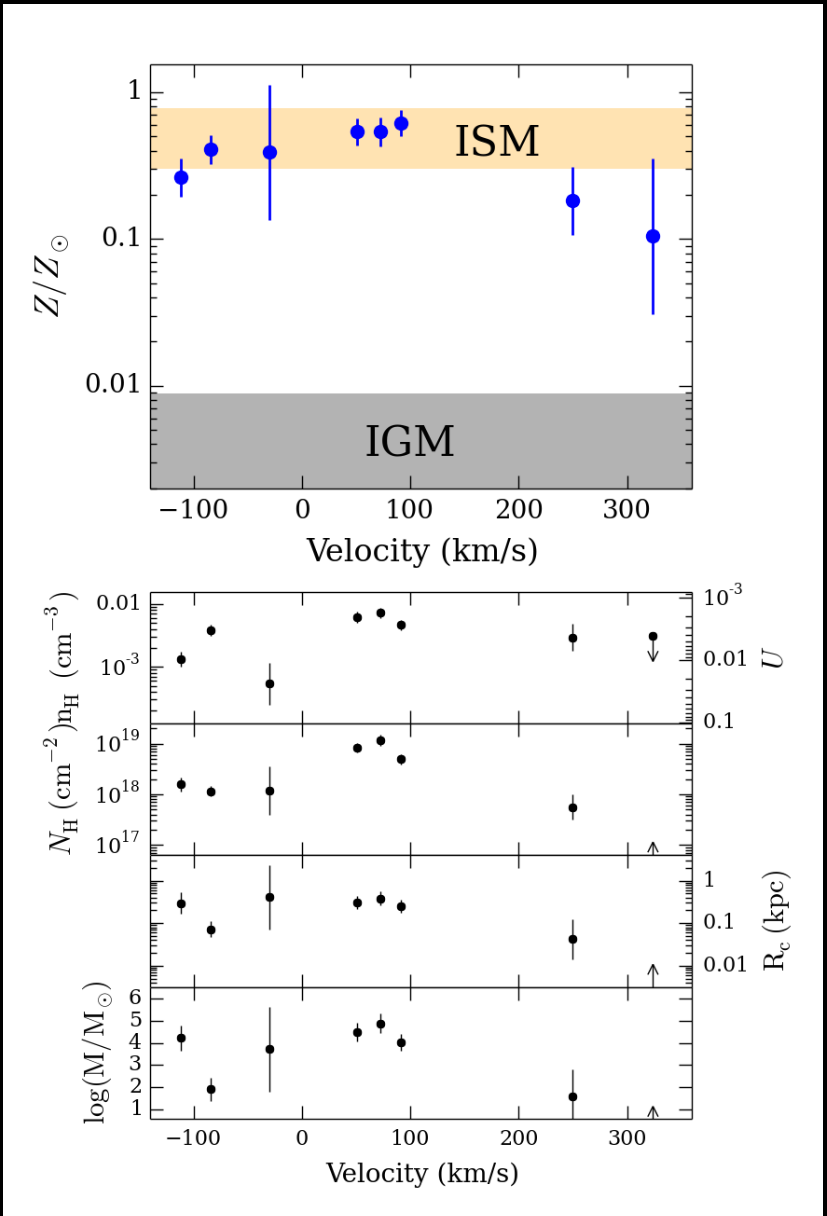
Precise Determination of CGM Parameters





- Enriched (0.2-0.6 $Z_\odot$) LLS (log N_{HI}=17) with 430 km/s motions ➡ outflow?

Precise Determination of CGM Parameters



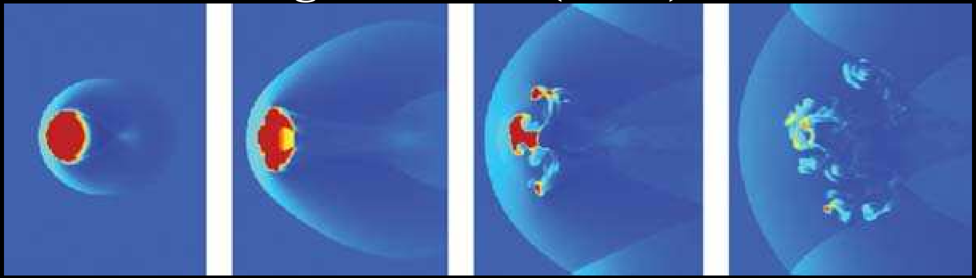
- **Enriched (0.2-0.6 $Z_\odot$) LLS (log N_{HI}=17) with 430 km/s motions ➡ outflow?**
- **Extremely small clouds!**
  r_{cloud} = 100-400 pc and cloud masses M_{cloud} = 200-5×10^4 $M_\odot$
- **Uncertain radiation field not an issue. Local sources make clouds denser and smaller**
- **Large cool gas mass implied**

$$M_{\rm cool} = \pi R^2 N_{\rm H} f_{\rm cov}$$

$$M_{\rm cool} \simeq 4 \times 10^8 M_\odot \sim 0.6 M_\star$$

The Small Scale Structure of the CGM

Blob Test: Agertz et al. (2007)



$$t_{\rm cc} \simeq 5 \frac{r_{\rm cloud}}{v_{\rm bulk}} \left(\frac{n_{\rm cold}}{n_{\rm hot}} \right)^{1/2}$$

The Small Scale Structure of the CGM

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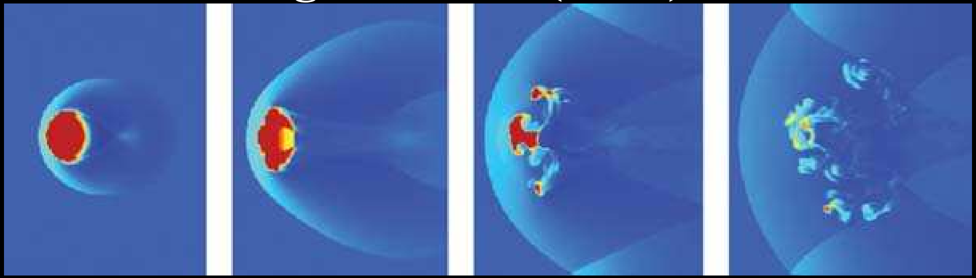

$$t_{cc} \simeq 5 \frac{r_{\rm cloud}}{v_{\rm bulk}} \left(\frac{n_{\rm cold}}{n_{\rm hot}} \right)^{1/2}$$

- **Clouds ablated in 10^7 yr << dynamical time ~ 10^8 yr, assuming:**
  - **r_{cloud} = 300 pc**
  - **$M_{cloud} = 2\times10^4\ M_\odot$**
  - **$n_{cold} = 5\times10^{-3}\ cm^{-3}$**
  - **$n_{hot} = 6\times10^{-4}\ cm^{-3}$**
  - **v_{bulk} = 300 km/s**

The Small Scale Structure of the CGM

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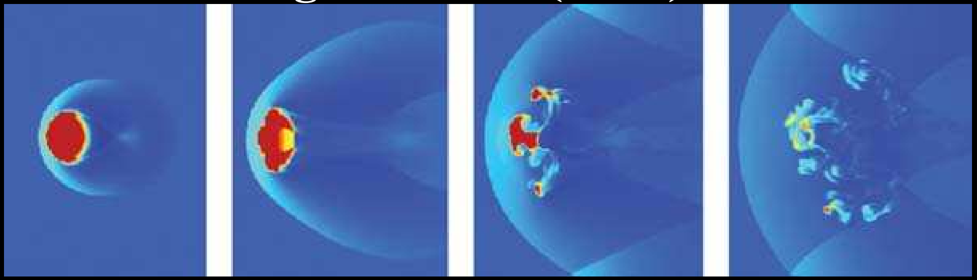

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  - **v_{bulk} = 300 km/s**
- **Do current simulations resolve this?**

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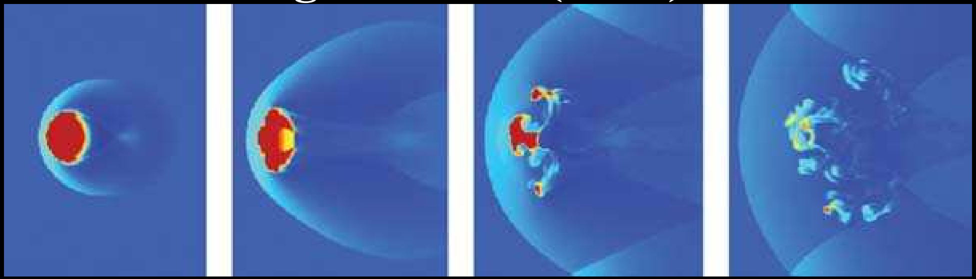

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  - **$n_{hot} = 6\times10^{-4}$ cm^{-3}**
  - **v_{bulk} = 300 km/s**
- **Do current simulations resolve this? Not even close**

Requiring ~ 3 resolution elements per r_{cloud} implies:

- **Grid hydro: grid cells ~ 100 pc**
- **SPH: ~ 7000 particles per cloud, or $M_{gas} \sim 3\ M_\odot$**

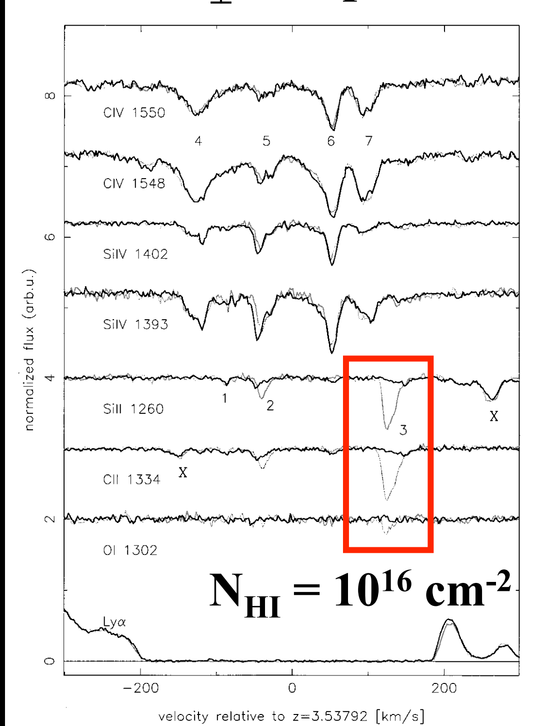
Eris2 zoom-in: $M_{gas} = 2\times10^4\ M_\odot$, FIRE: $5\times10^3\ M_\odot$

Problem #1: The Small Scale Structure of the CGM is Likely Unresolved by Current Models

This has been seen before….

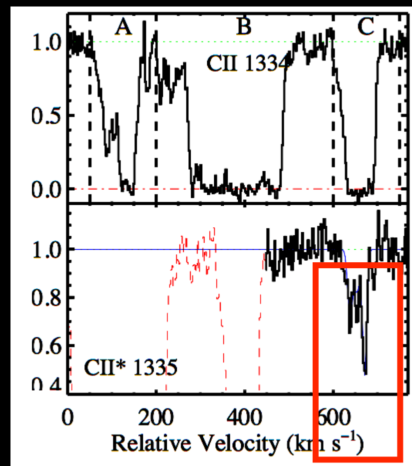
Lensed QSOs

$R_{\perp} \approx 30$ pc



Rauch et al. 1990

QSO CGM



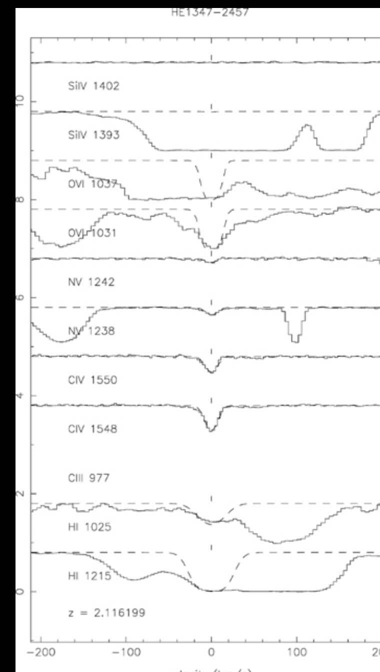
$n_H \sim$ 1-5 cm^{-3}

r ~ 10-100 pc

Prochaska & Hennawi 2009

Absorption Line Modeling

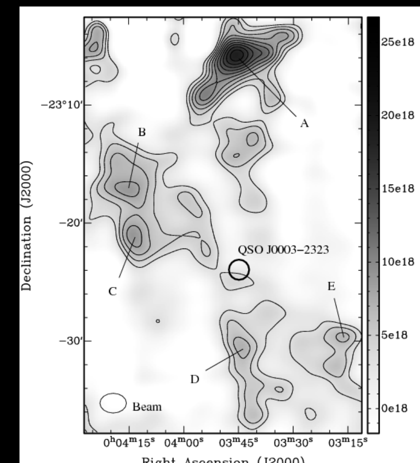
Sizes r < 100 pc



Schaye et al. 2007

HVCs

Sizes r < 50 pc



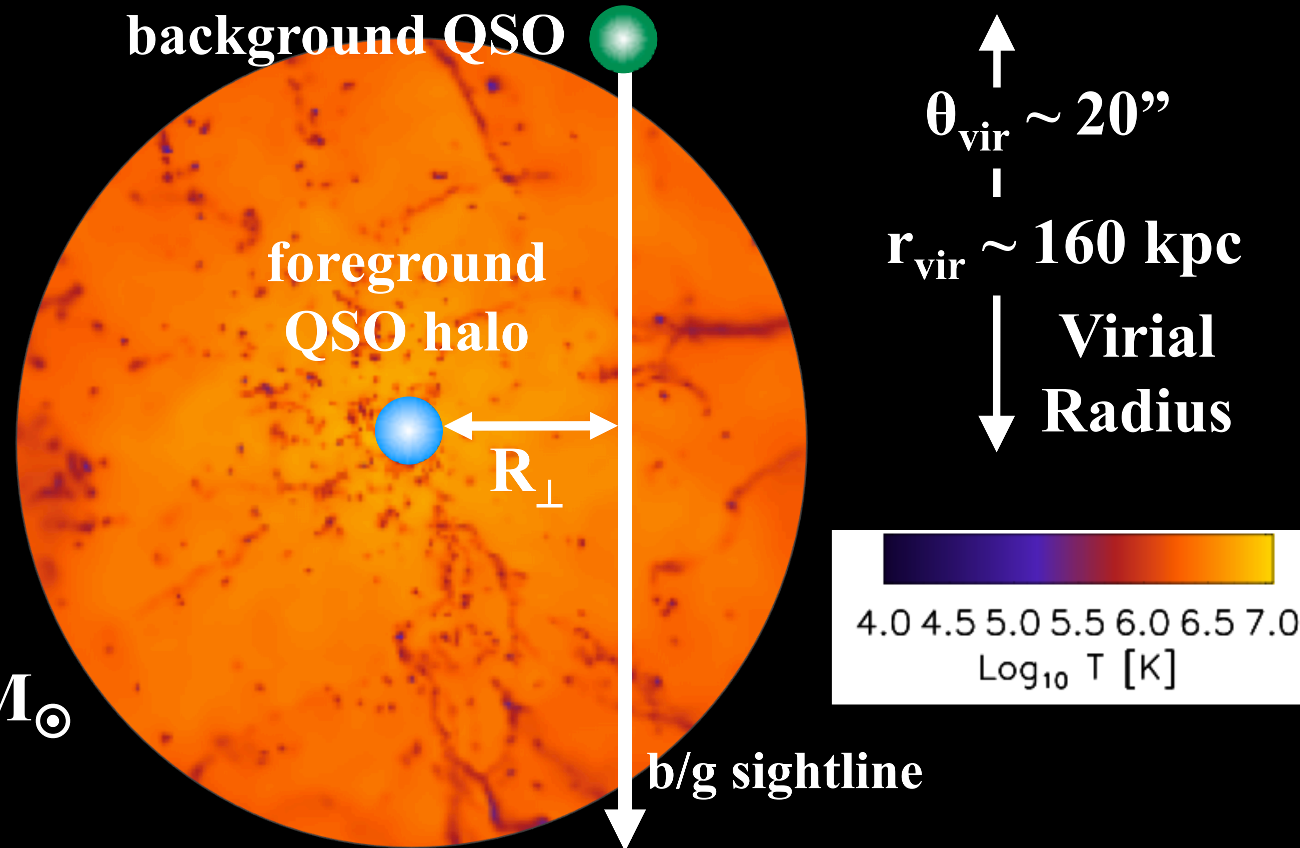
clump	r	M_{HI}	n_{HI}
	[pc]	[$M_{\odot}$]	[cm^{-3}]
A	45	470	0.14
B	45	280	0.06
C	49	160	0.06
D	36	150	0.06
E	32	160	0.07

Ben Bekhti et al. 2009

The entire CGM could be in $r_{cloud} \sim$ 300 pc clumps

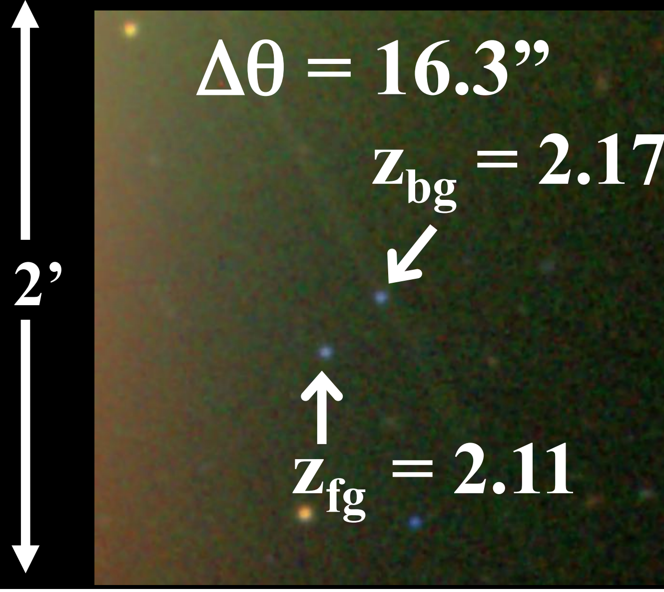
Probing the CGM of High Mass Halos

In rare projected pairs, a b/g QSO probes a f/g QSO in absorption



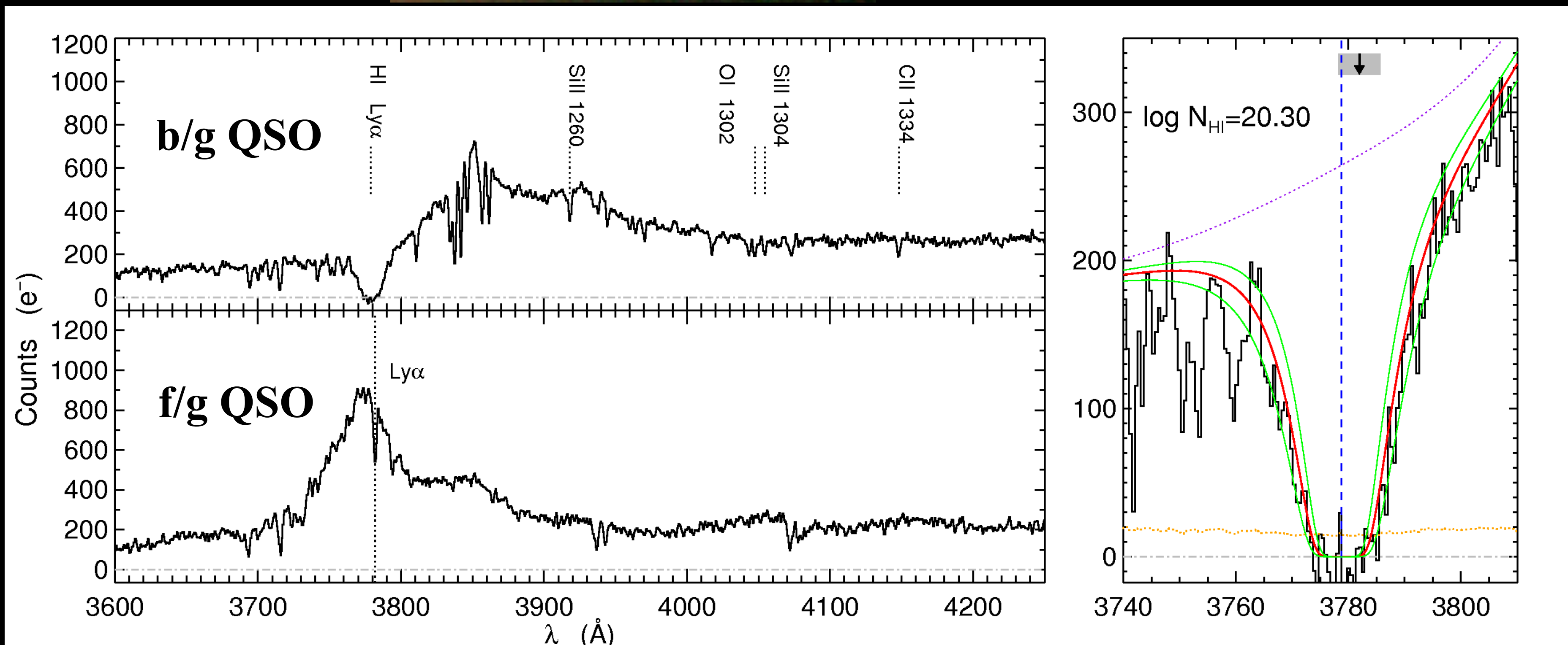
$M_{halo} = 10^{12.5}\, M_\odot$

- QSOs trace massive halos $M_{halo} \sim 10^{12.5}\, M_\odot$ at $z \sim 2$, 6 × larger than LBGs. Progenitors of local quenched galaxies
- Why QSOs? Because we can find 10^6 in digital sky surveys (SDSS)
- Herschel studies indicate QSOs lie on star-forming main sequence (Rosario et al. 2013; Knud Jahnke's talk) and represent unbiased tracers

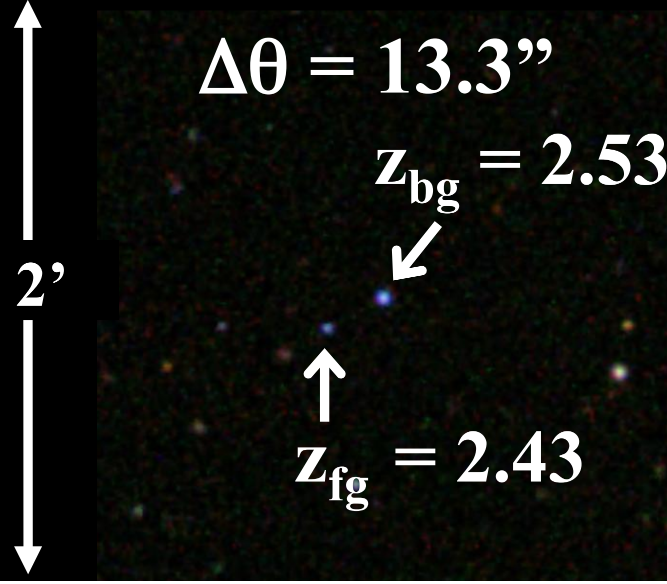


$R_\perp$ = 139 kpc

$\log N_{HI}$ = 20.3

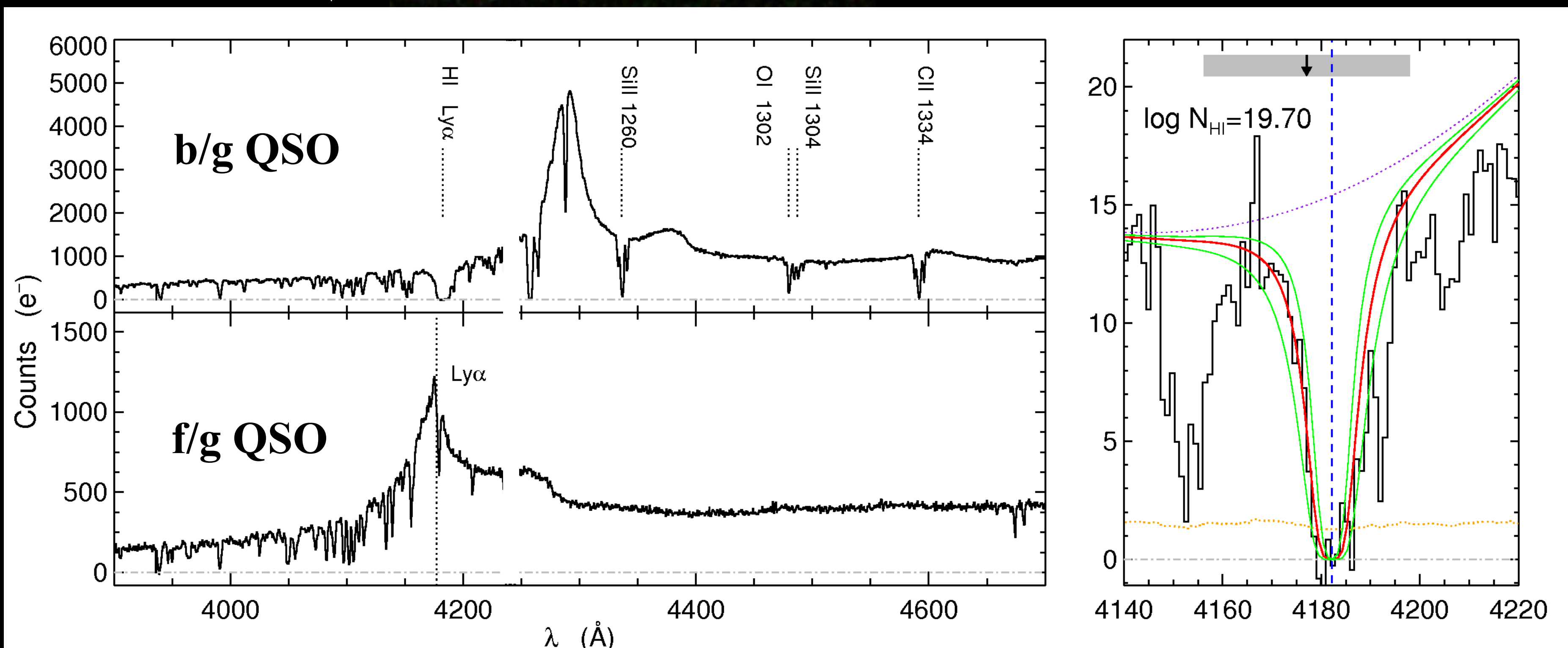


Hennawi+ 2006, 2007, 2013; Prochaska, Hennawi+ 2013



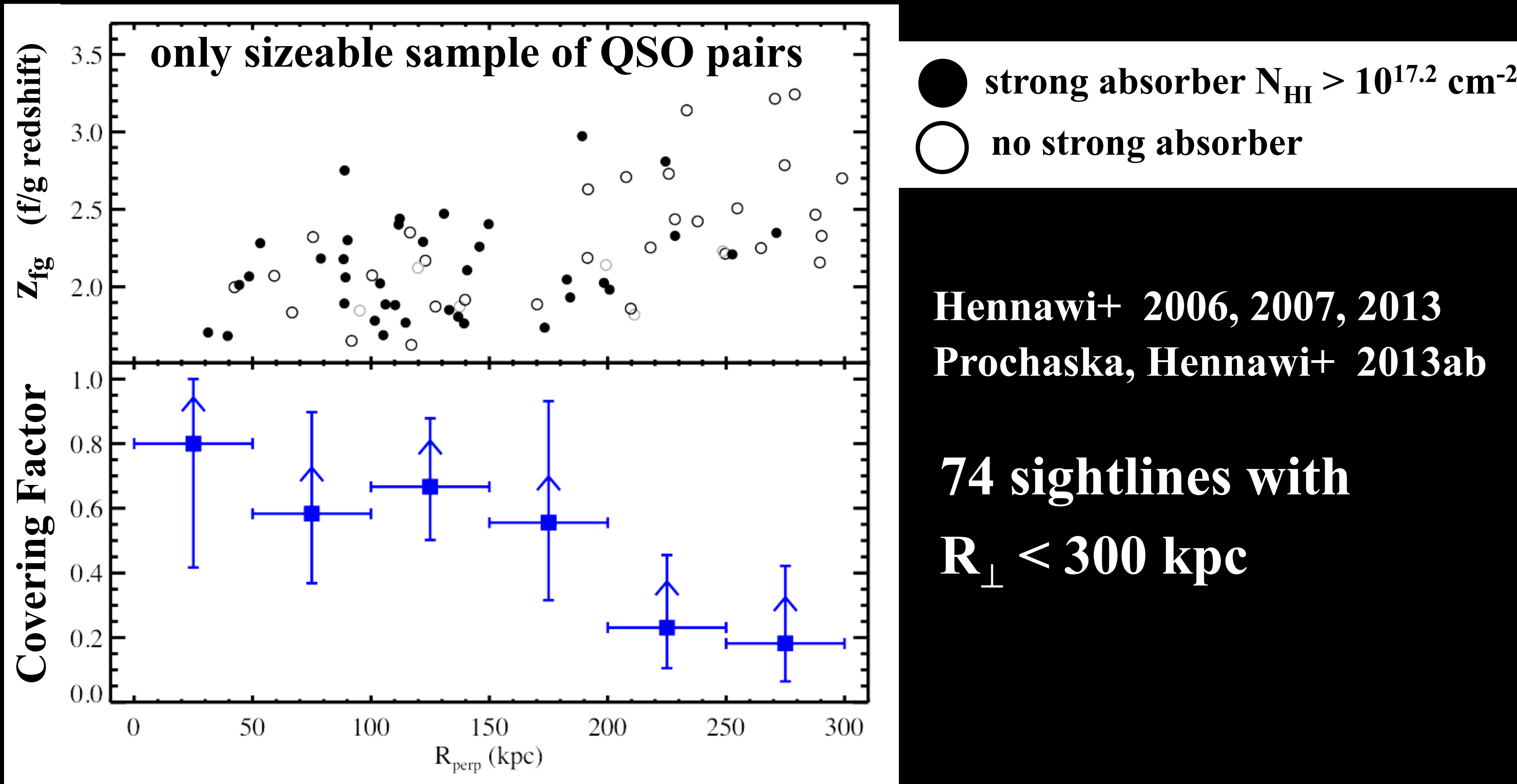
$R_\perp = 108$ kpc

$\log N_{HI} = 19.7$



Hennawi+ 2006, 2007, 2013; Prochaska, Hennawi+ 2013

A Massive Reservoir of Cool Gas Around QSOs



Hennawi+ 2006, 2007, 2013
Prochaska, Hennawi+ 2013ab

74 sightlines with $R_{\perp} < 300$ kpc

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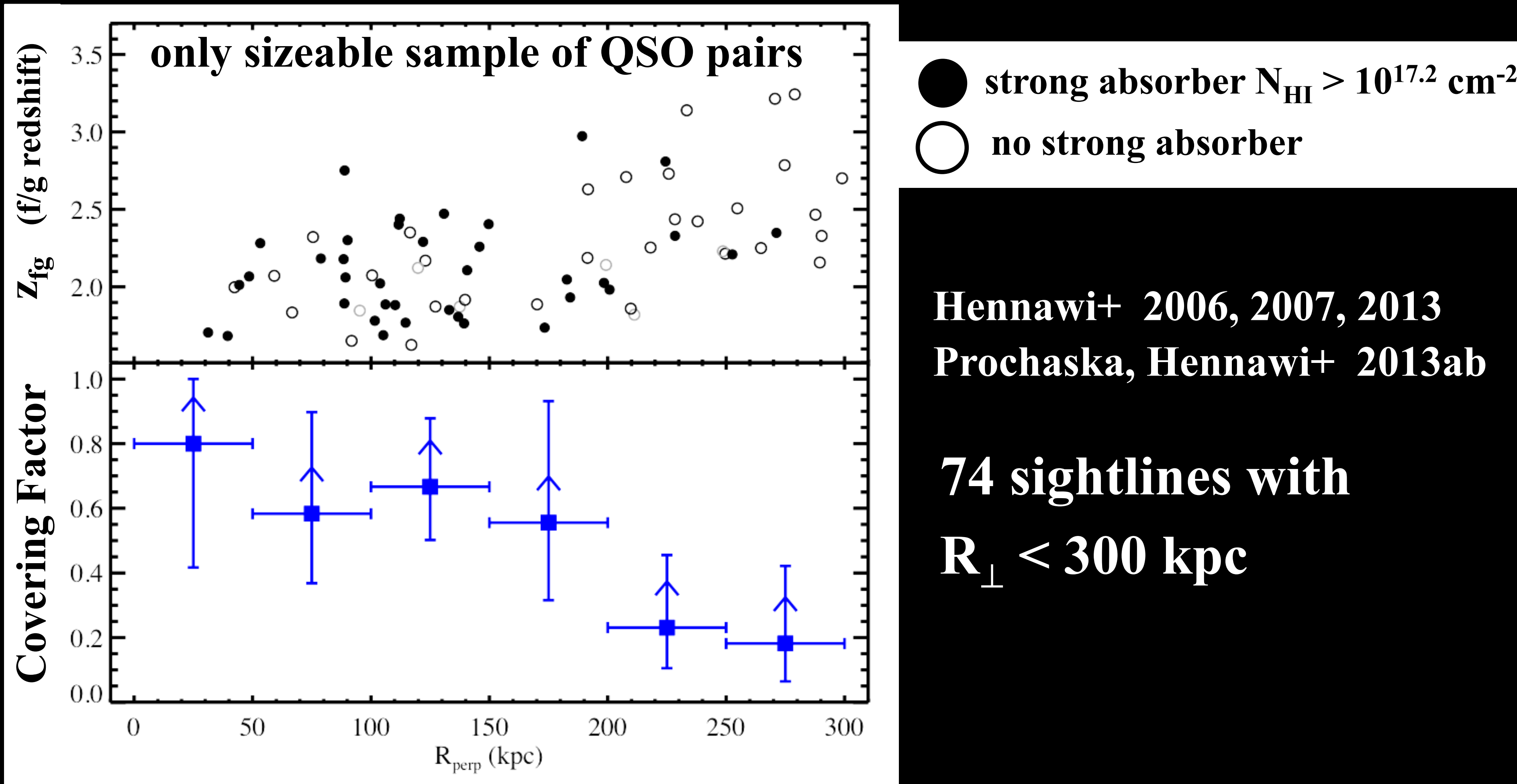

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- High ~ 60% covering factor for $R < r_{vir} = 160$ kpc

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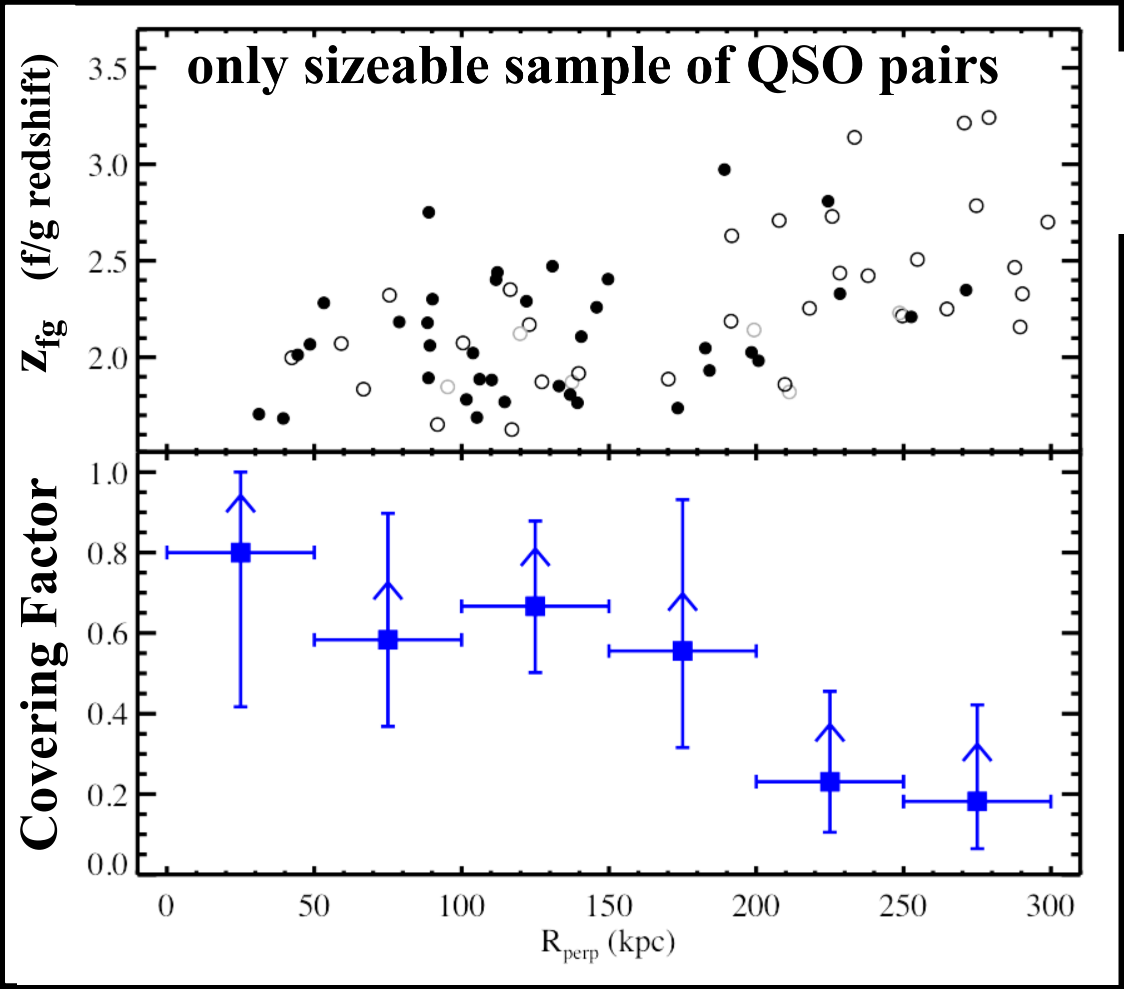


strong absorber $N_{HI} > 10^{17.2}$ cm^{-2}

no strong absorber

Hennawi+ 2006, 2007, 2013

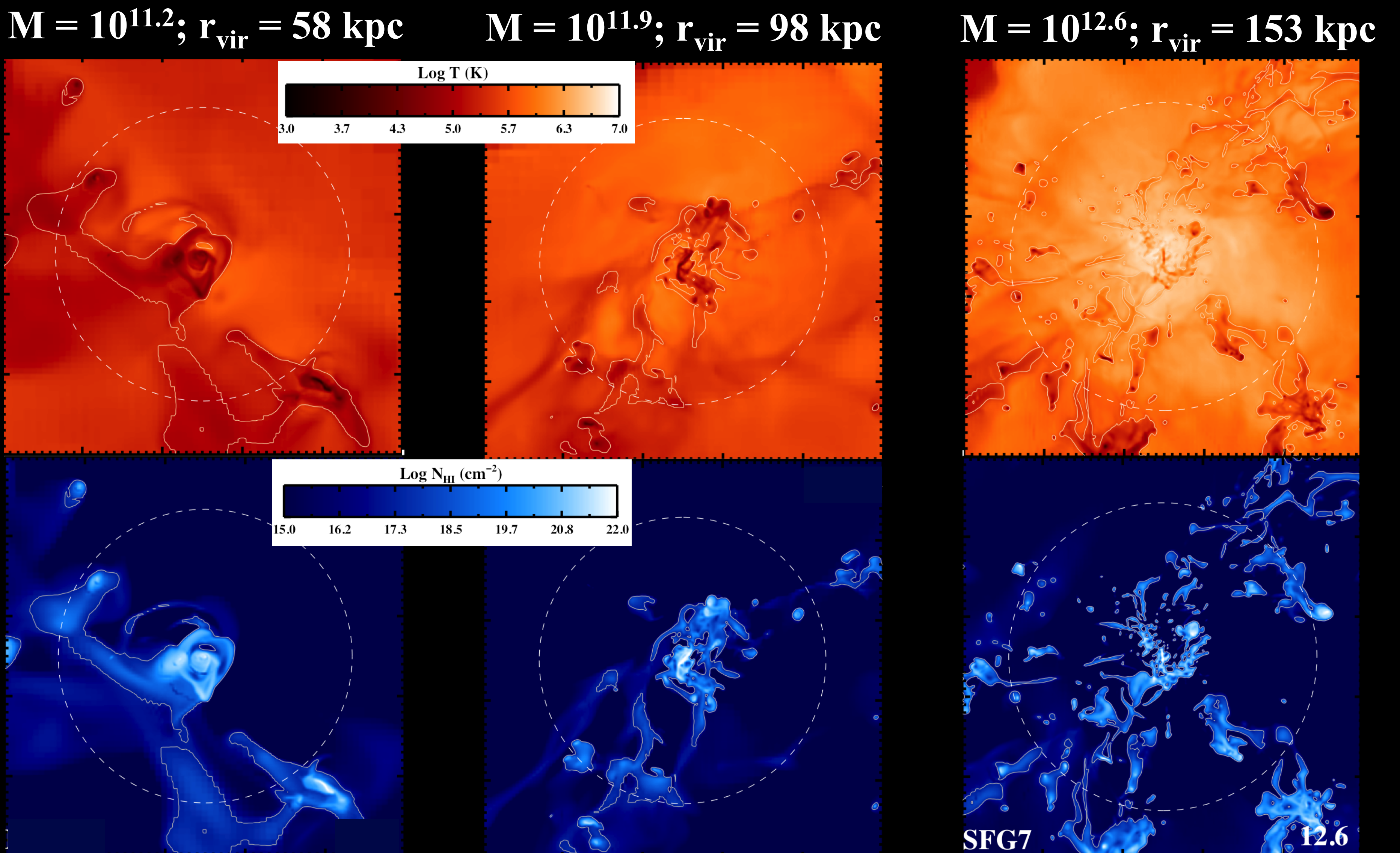
Prochaska, Hennawi+ 2013ab

74 sightlines with

$R_{\perp} < 300$ kpc

- High ~ 60% covering factor for $R < r_{vir} = 160$ kpc
- CGM is dominated by a cool ($T \sim 10^4$ K) massive ($>10^{10}\ M_{\odot}$) metal-enriched medium ($Z > 0.1 Z_{\odot}$)

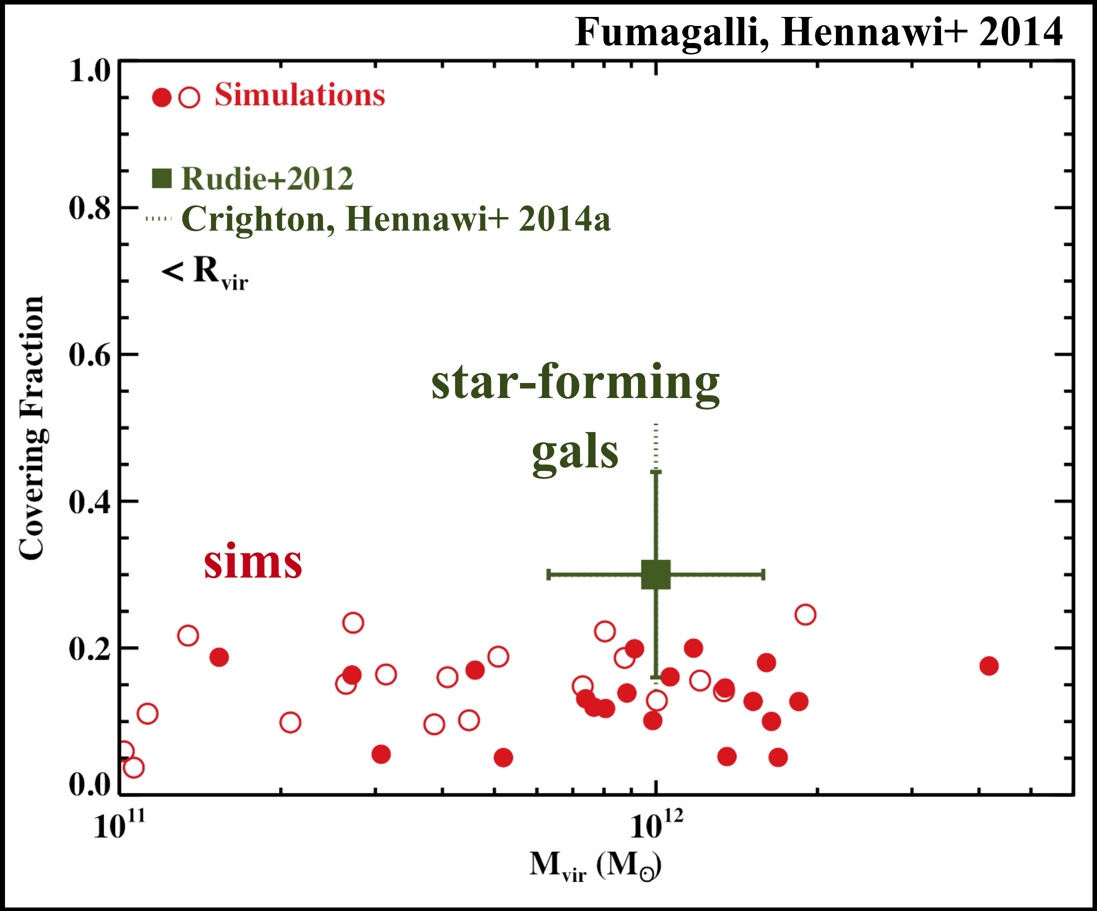
Simulating CGM Observations

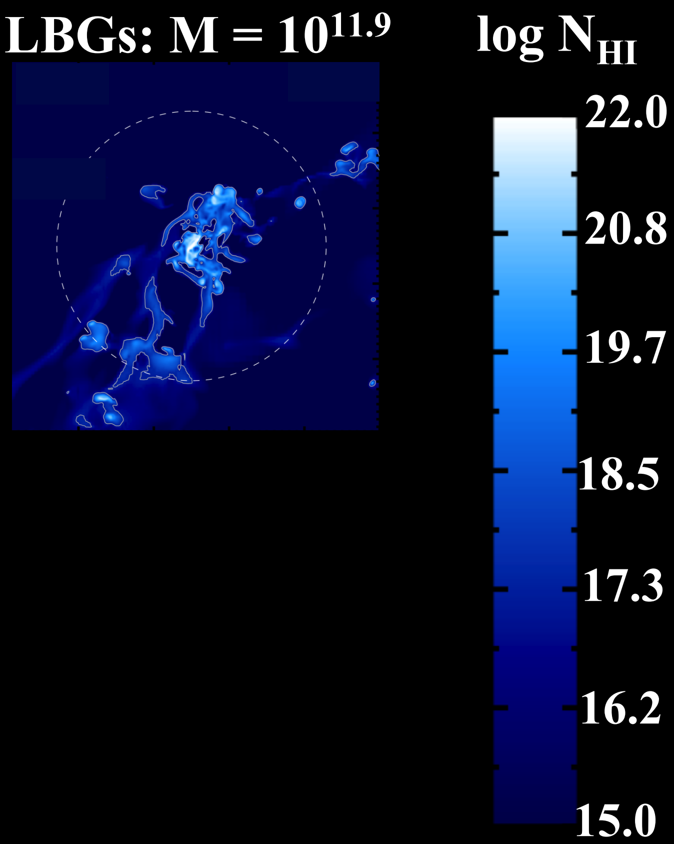


ART AMR zoom-in + ionizing rad. transfer

Fumagalli, Hennawi+ 2014
Ceverino et al. 2010

The Perplexing CGM of Massive Halos





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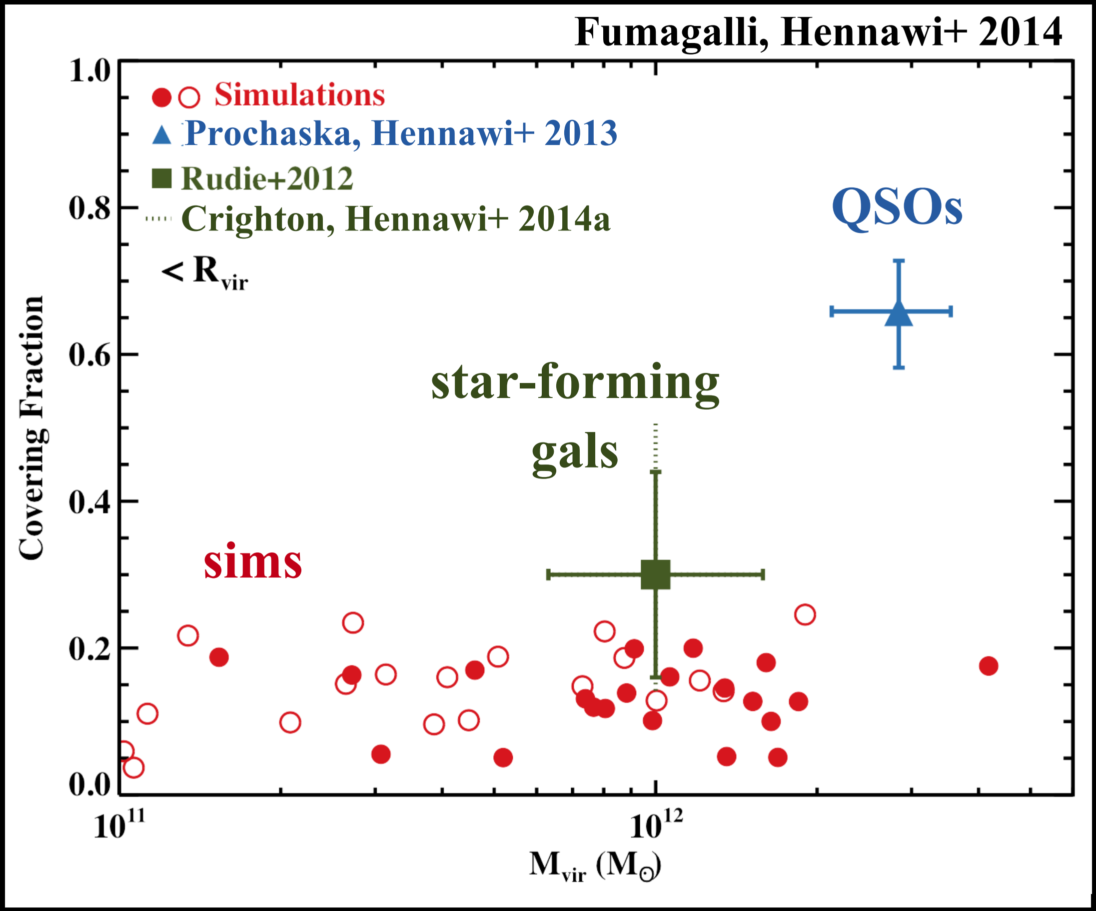
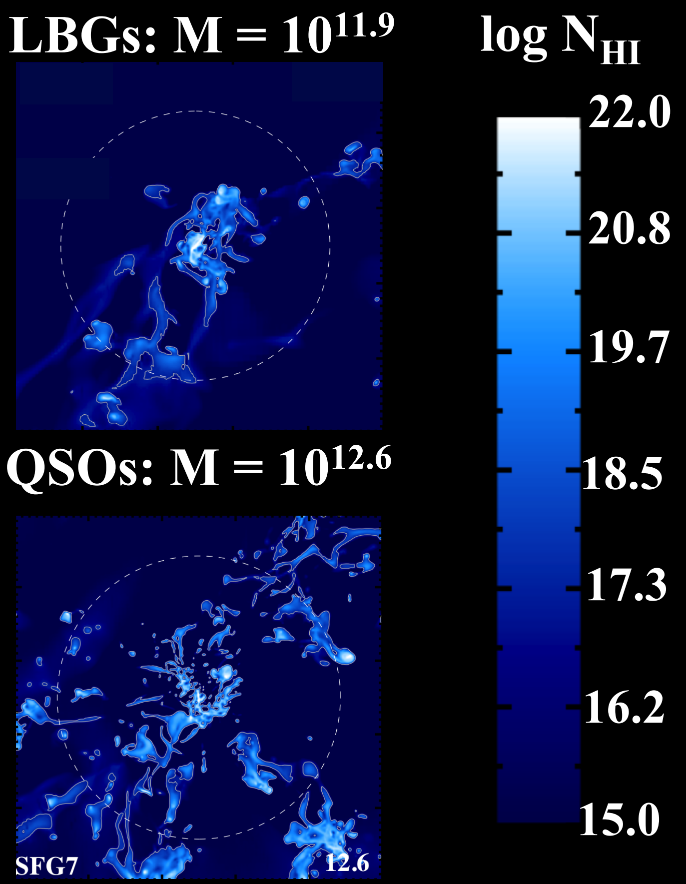
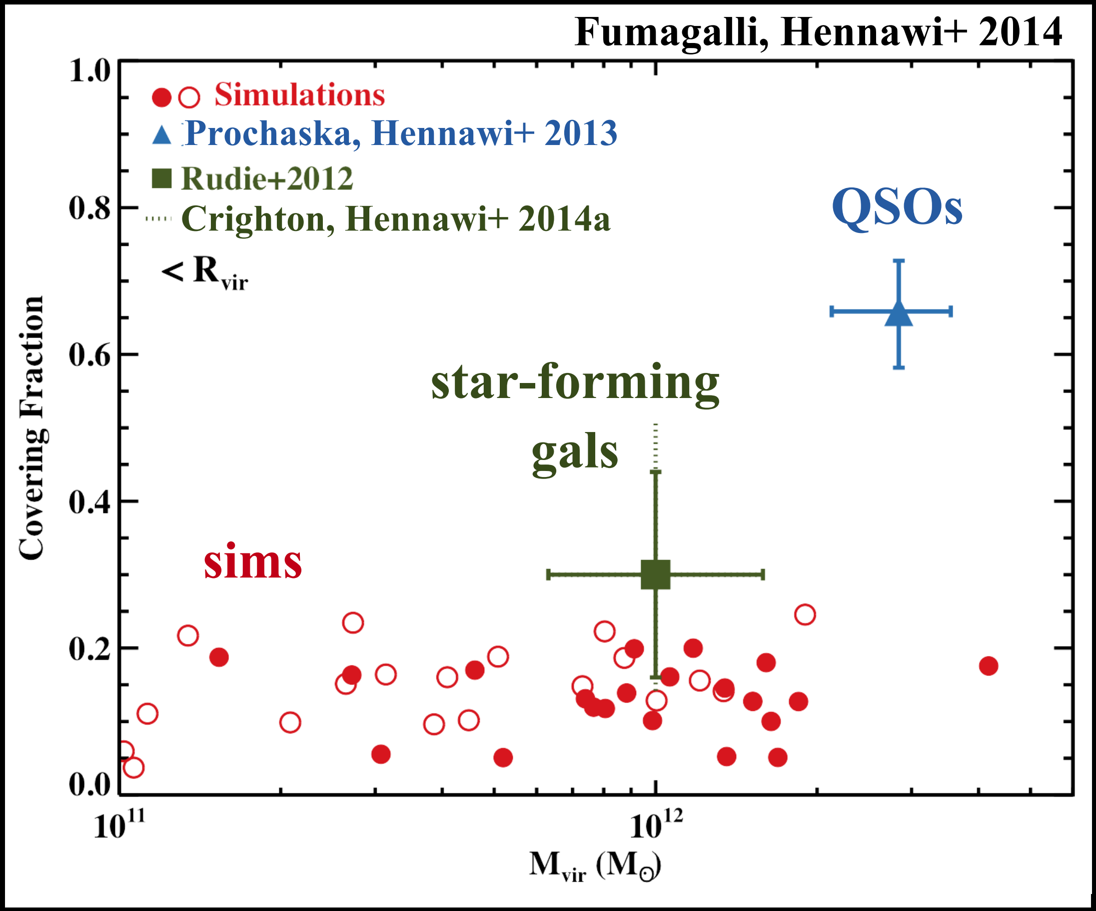
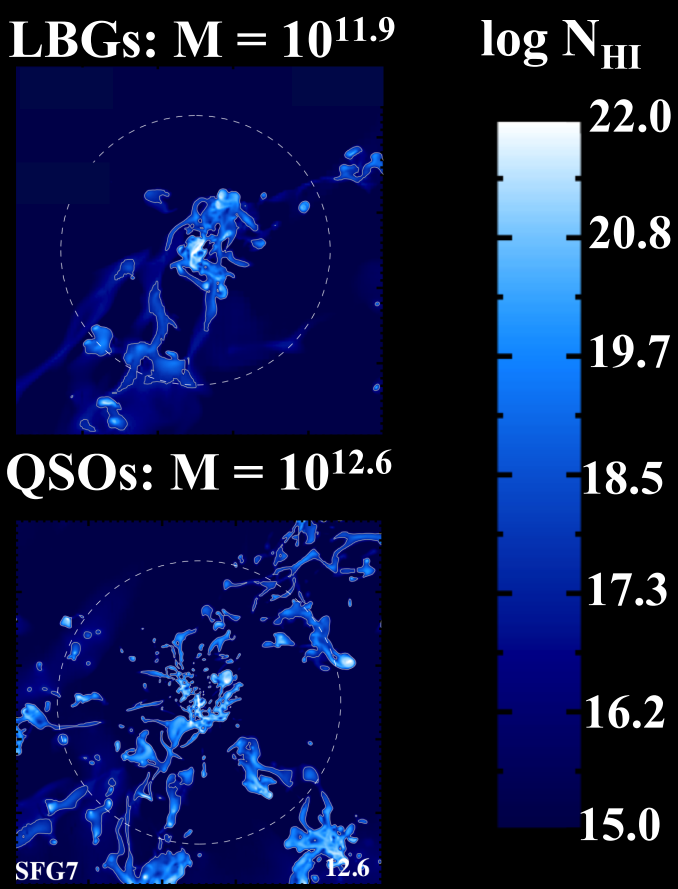




- More cold gas observed at high-mass (QSOs) than sims predict

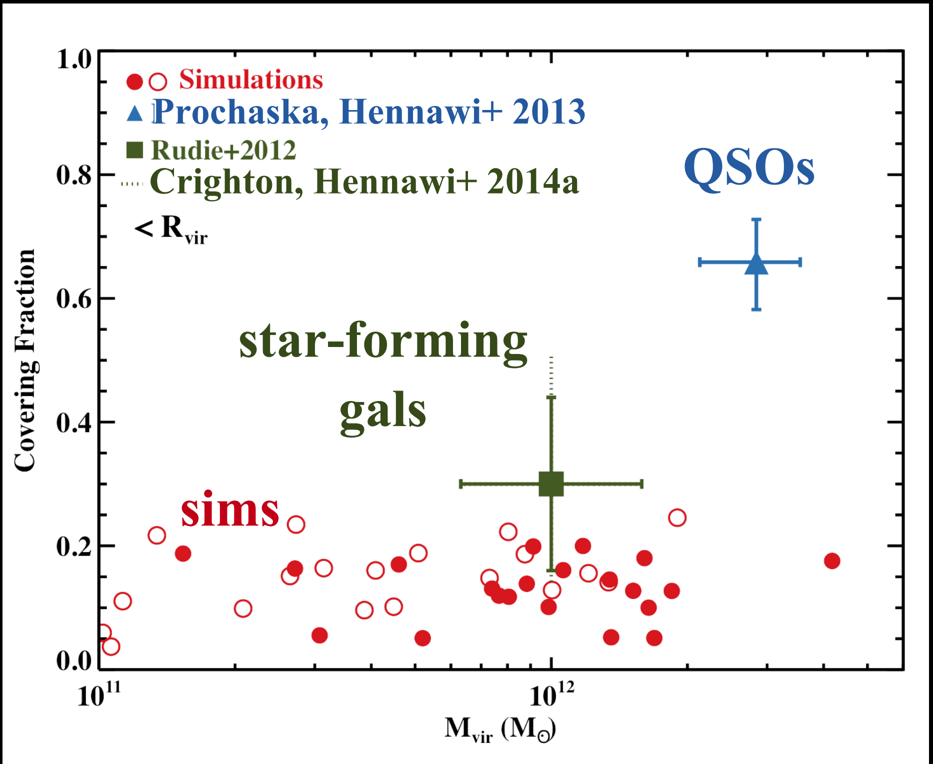
The Perplexing CGM of Massive Halos



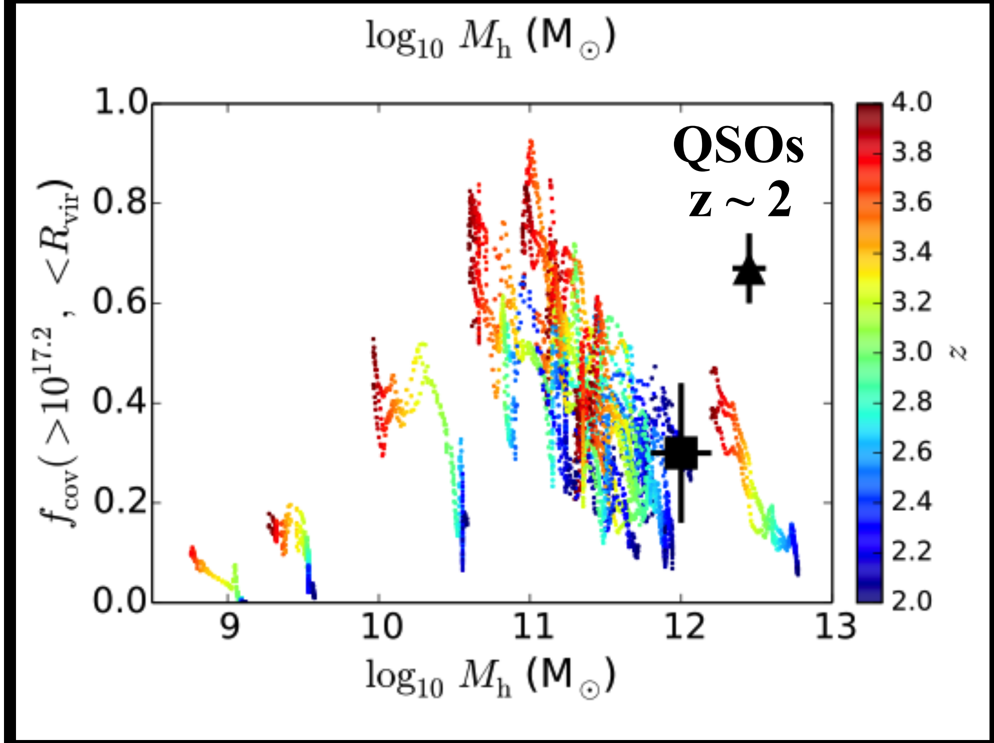


- More cold gas observed at high-mass (QSOs) than sims predict
- Solutions: QSO feedback? Is this what we want/expect it to look like ~ 10^{11} $M_\odot$ cold gas? QSOs are special (unlikely)?
- Small-scale structure unresolved in sims?

Problem #2: The Perplexing CGM of Massive Halos



Fumagalli, Hennawi+ 2014



Faucher-Giguere+ 2014

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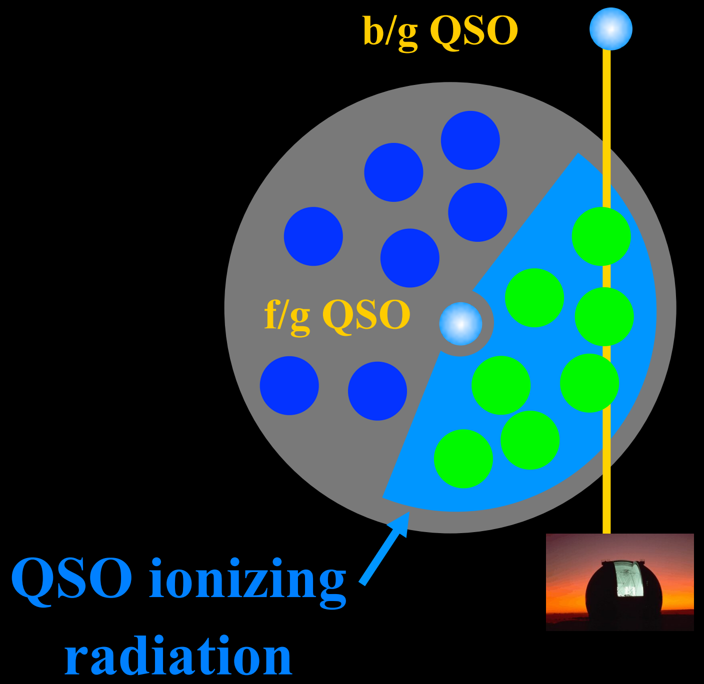
Can We Detect CGM Gas in Lyα Emission?

Photoionization/Scattering



- QSO acts as a flashlight illuminating CGM/IGM
- Recombinations/scattering from neutral gas

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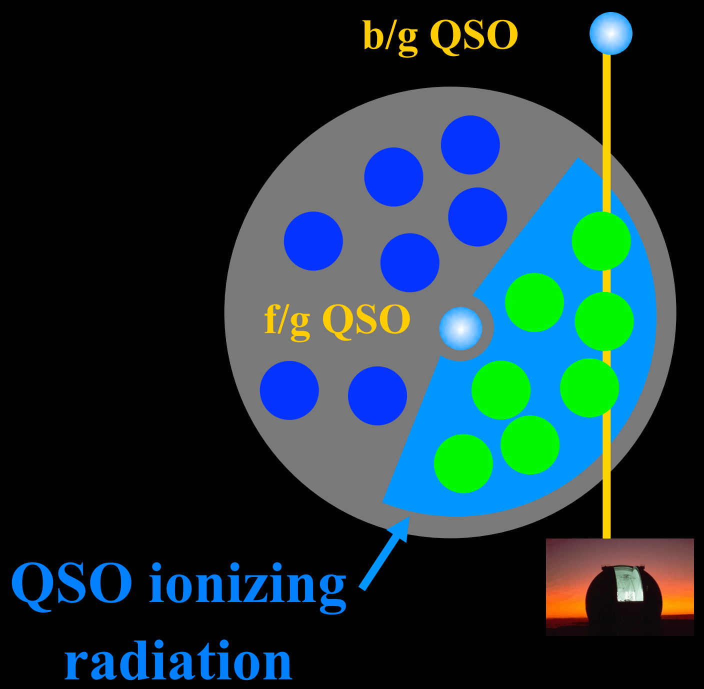

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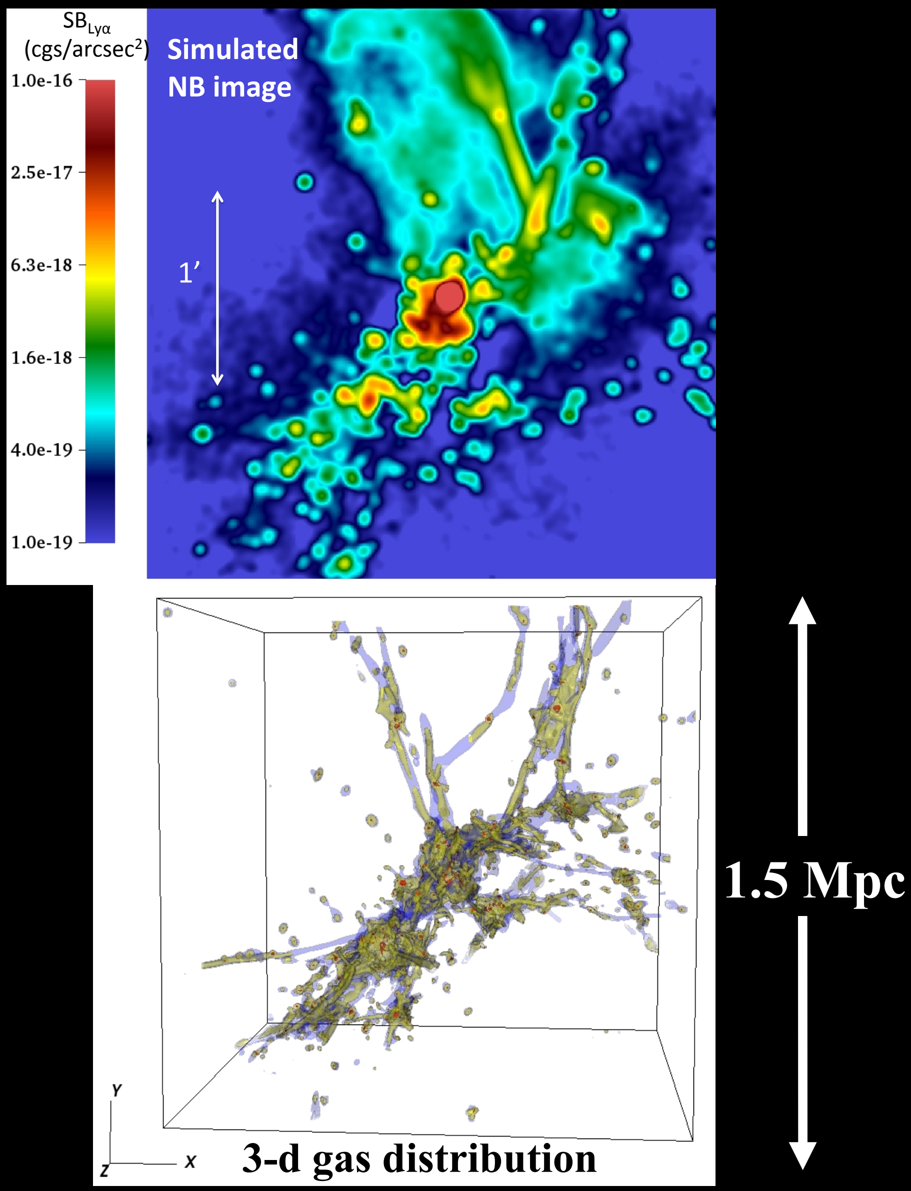


Cantalupo, Arrigoni, Prochaska, Hennawi+ 2014

$R_\perp$ = 183 kpc

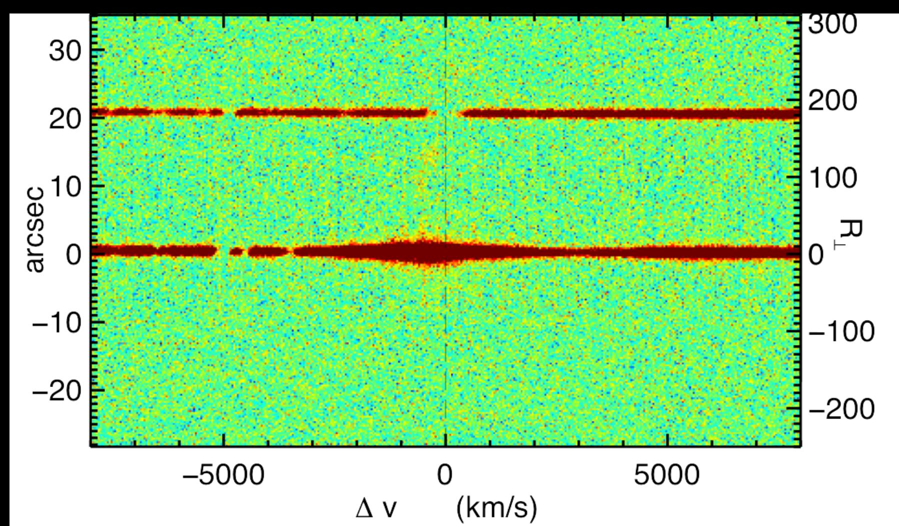
$SB_{1\sigma} = 2 \times 10^{-18}$ erg/s/cm^2/□″

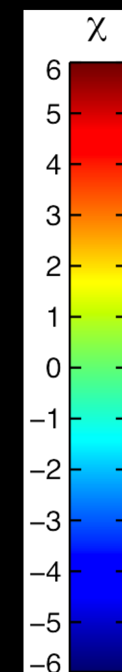
Hennawi & Prochaska (2013)

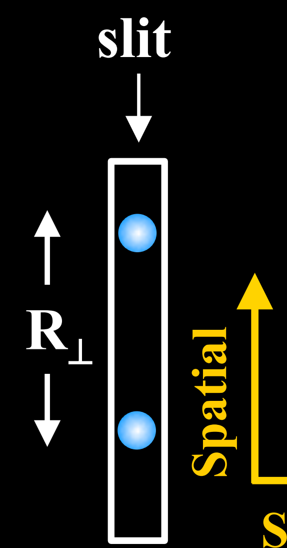
b/g QSO z = 2.21 →

f/g QSO z = 2.04 →

2-d spectrum







$R_\perp$ = 183 kpc

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$erg/s/cm^2/\square''$

Hennawi & Prochaska (2013)

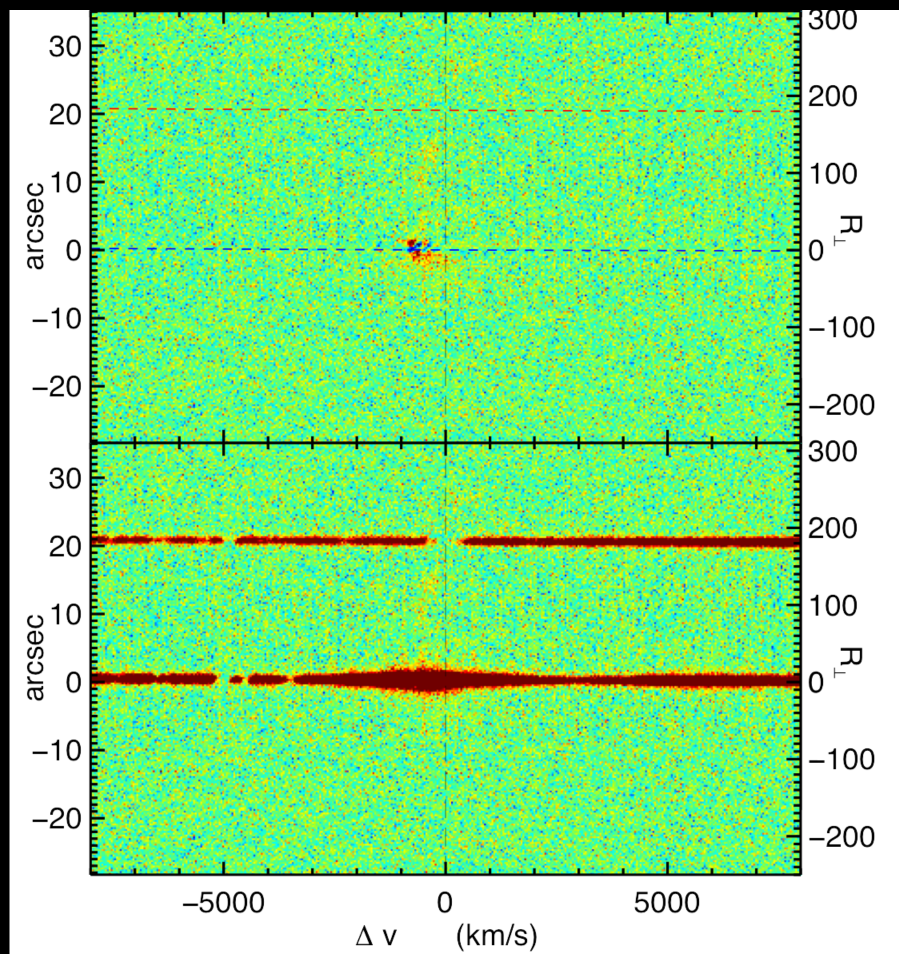
PSF subtracted 2-d spectrum

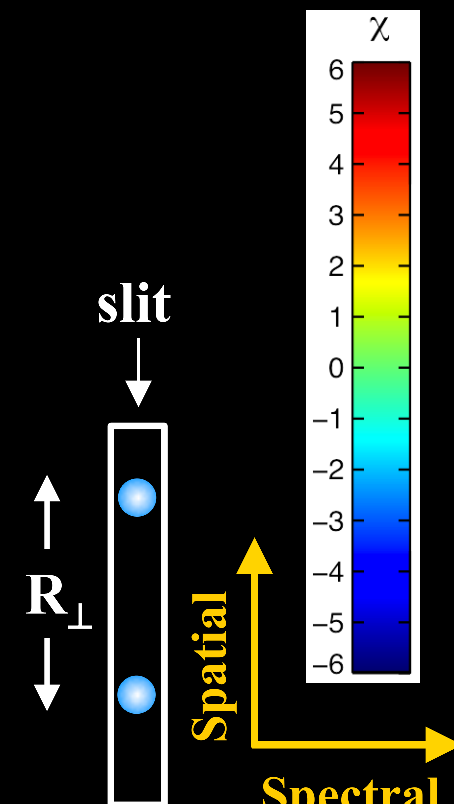
(data-model)/noise

b/g QSO z = 2.21 →

f/g QSO z = 2.04 →

2-d spectrum





smoothed PSF subtracted spectrum

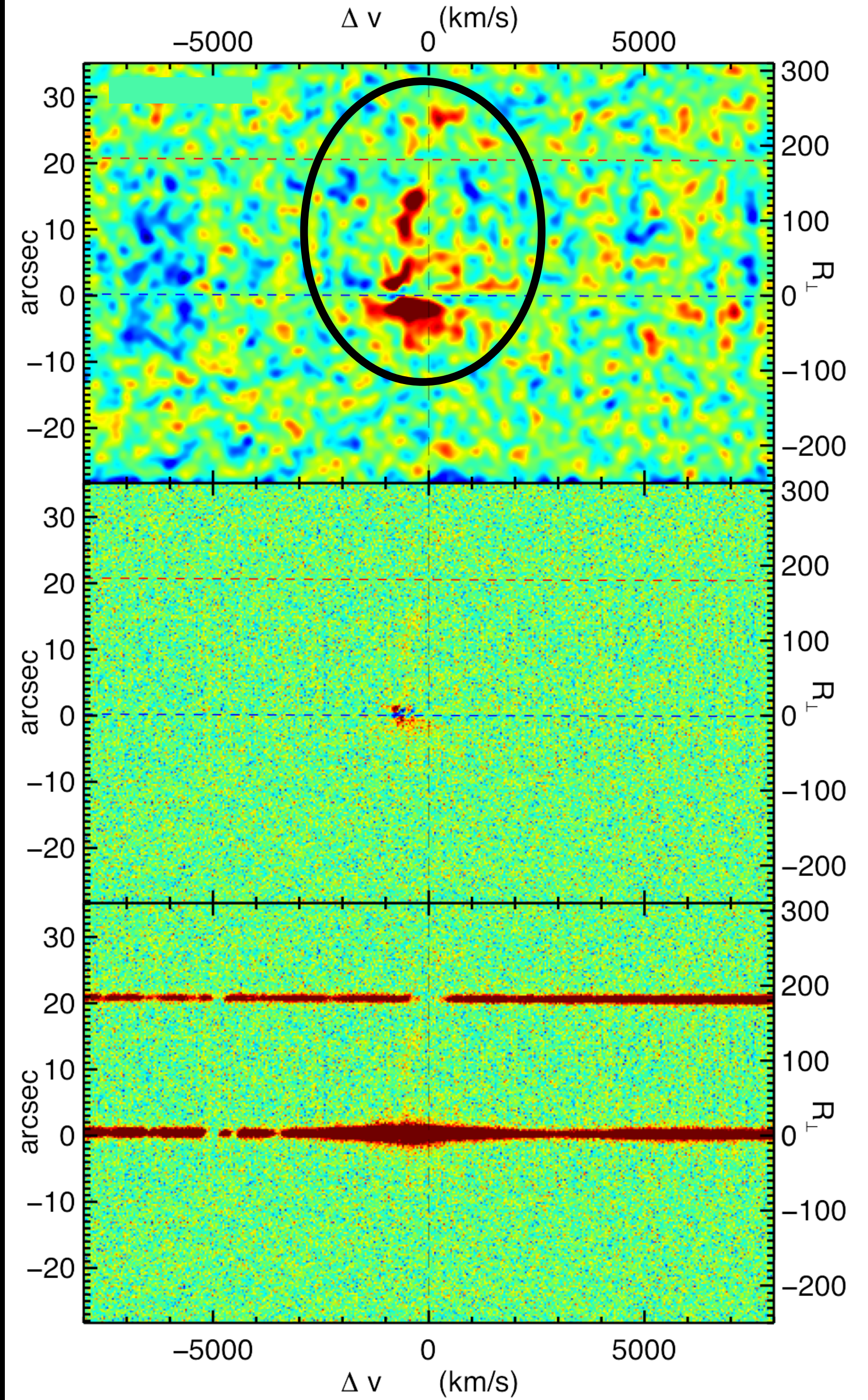
PSF subtracted 2-d spectrum

(data-model)/noise

b/g QSO z = 2.21 →

f/g QSO z = 2.04 →

2-d spectrum



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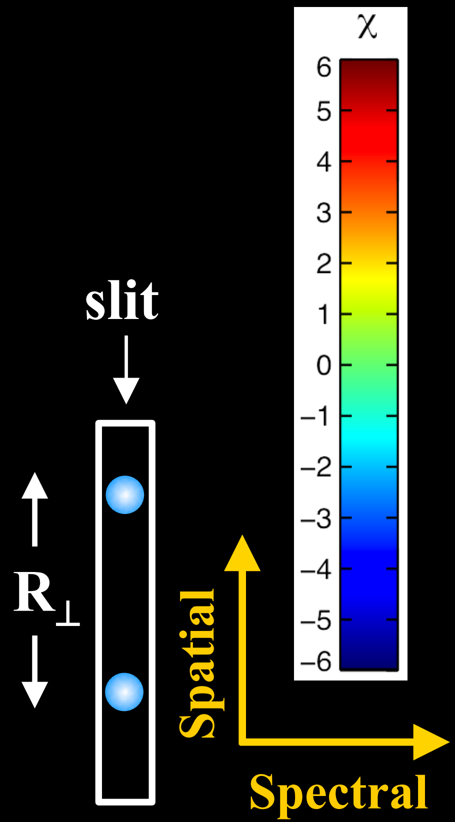
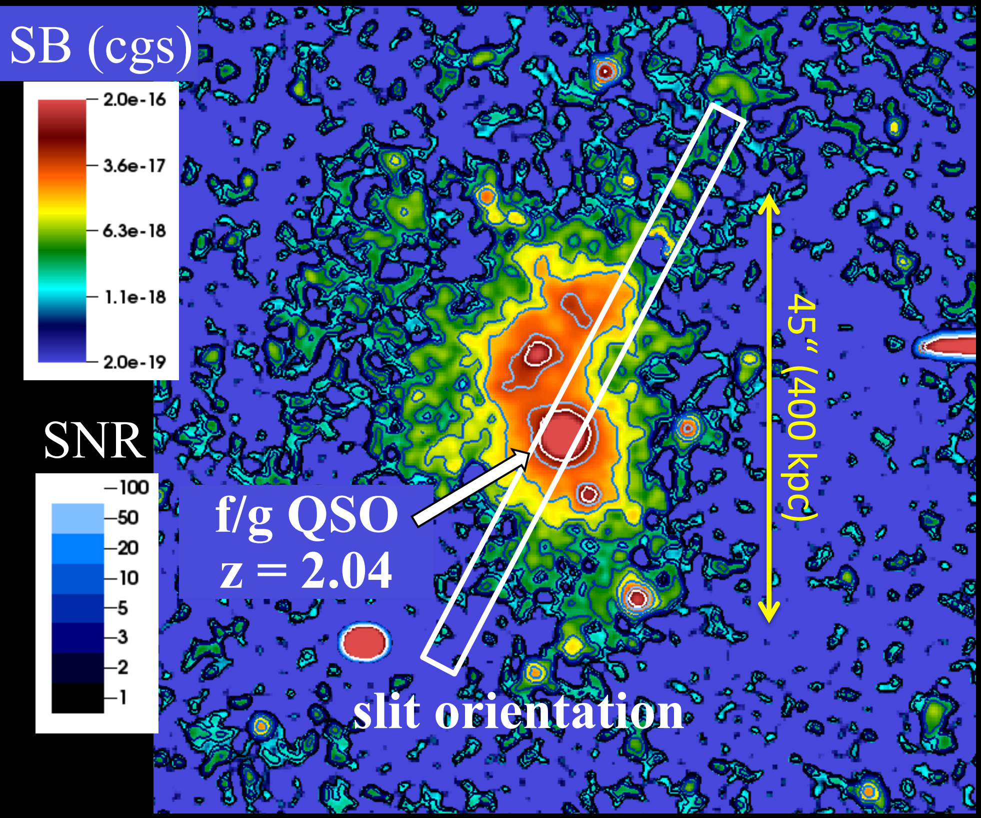


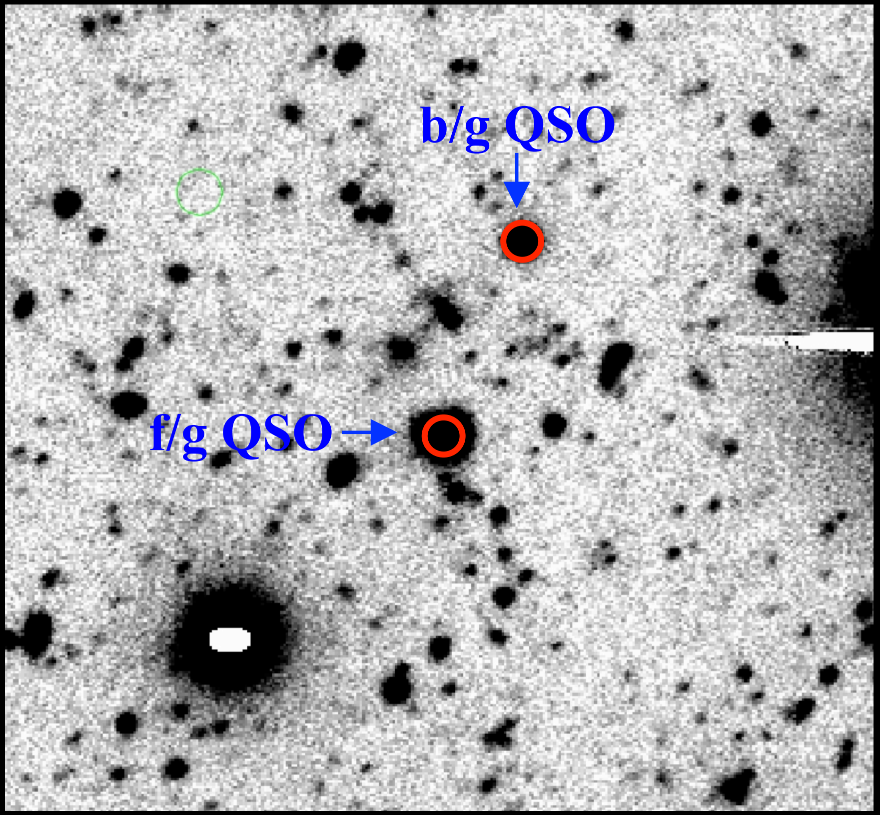
The CGM in Absorption and Emission

Narrow Band Lyα Image



Hennawi+ 2014

V-band (continuum)

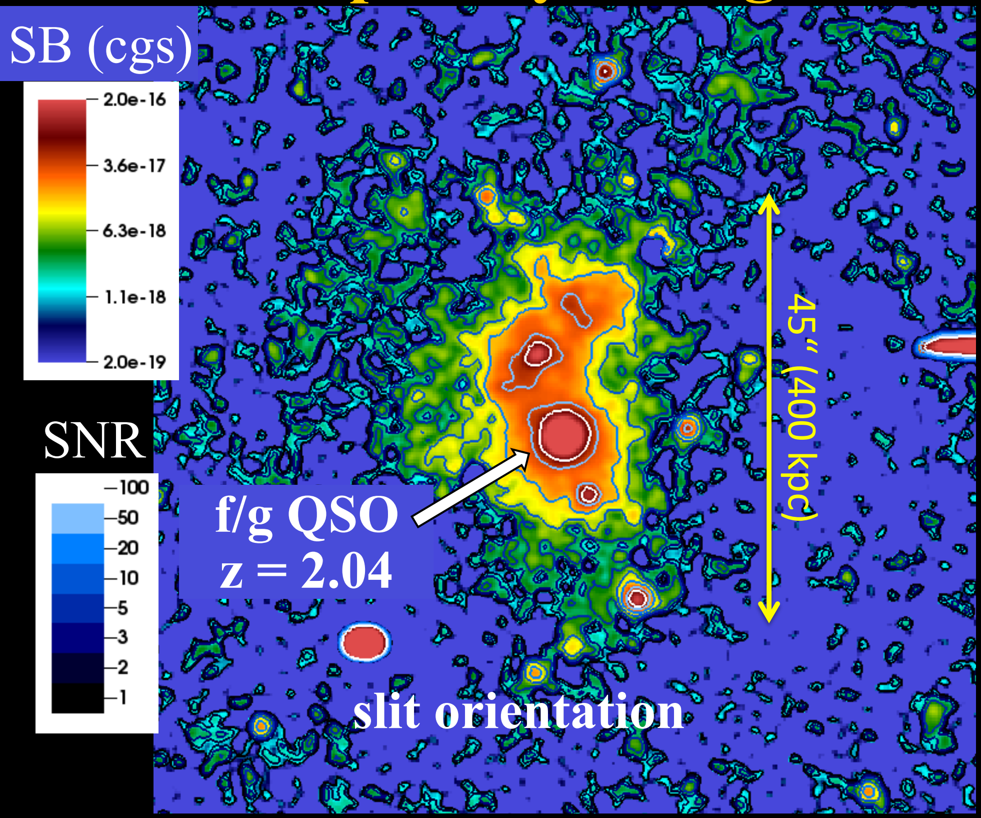


Imaging from Keck telescope

- Slit-spectroscopic survey for extended Lyα emission
- Large scale nebulosity discovered extending ~ 400 kpc

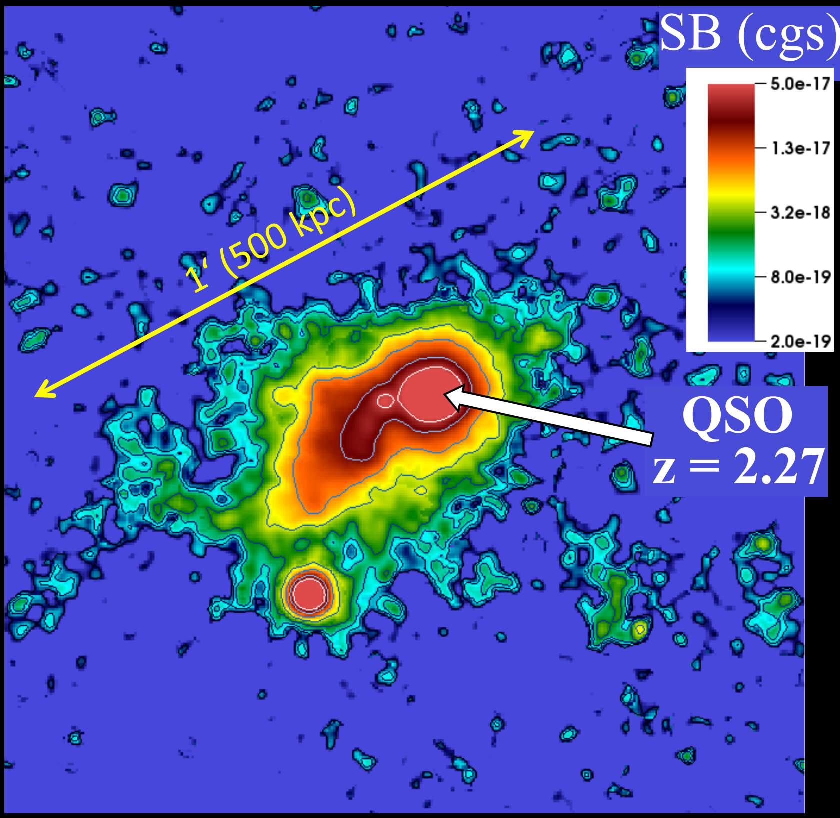
The Largest Emission Line Nebulae Known

Jackpot: Lyα Image



Hennawi+ 2014

Slug: Lyα Image



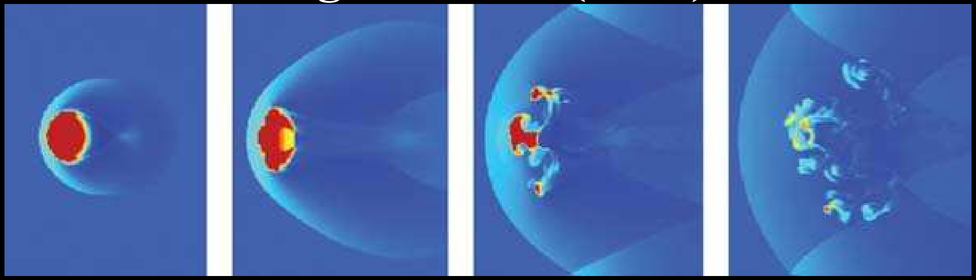
Cantalupo, Arrigoni, Prochaska, Hennawi + 2014

- **Limited statistics suggest ~10% of QSOs may similarly illuminate their CGM detectably**
- **Emission is likely recombination powered by the QSOs**

What is the Origin of this Dense Cool Gas?

- **Absorption line analysis reveals high enrichment $Z > 0.1Z_\odot$, suggesting a merger or outflow origin**
- **But such small clouds cannot survive in hot halo**

Blob Test: Agertz et al. (2007)



$$t_{cc} \simeq 5 \frac{r_{\rm cloud}}{v_{\rm bulk}} \left(\frac{n_{\rm cold}}{n_{\rm hot}} \right)^{1/2}$$

Clouds ablated in 7×10^6 yr or after traveling only 4 kpc!

- **$r_{cloud} = 30$ pc**
- **$M_{cloud} = 2\times10^4\ M_\odot$**
- **$n_{cold} = 1\ cm^{-3}$**
- **$n_{hot} = 2\times10^{-3}\ cm^{-3}$**
- **$v_{bulk} = 500$ km/s**

- **Cool dense enriched gas must form *in situ* from hot halo**

Three Unresolved Problems

- **Problem # 1: CGM is clumpy on ~ 100 pc scales, which is not resolved by current simulations**

- **Problem # 2: Covering factor of LLSs in massive (QSO) halos conflicts with predictions of existing simulations**

- **Problem # 3: CGM detected in Lyα emission all the way out to IGM in ~ 10% of QSOs. Extreme ISM like densities in tiny clumpa ~ 30 pc required to explain emission**