Three Unresolved Problems in Studies of the Circumgalactic Medium

Joseph F. Hennawi

MPIA

Starring:

F. Arrigoni-Battaia

S. Cantalupo

N. Crighton

M. Fumagalli

J. X. Prochaska

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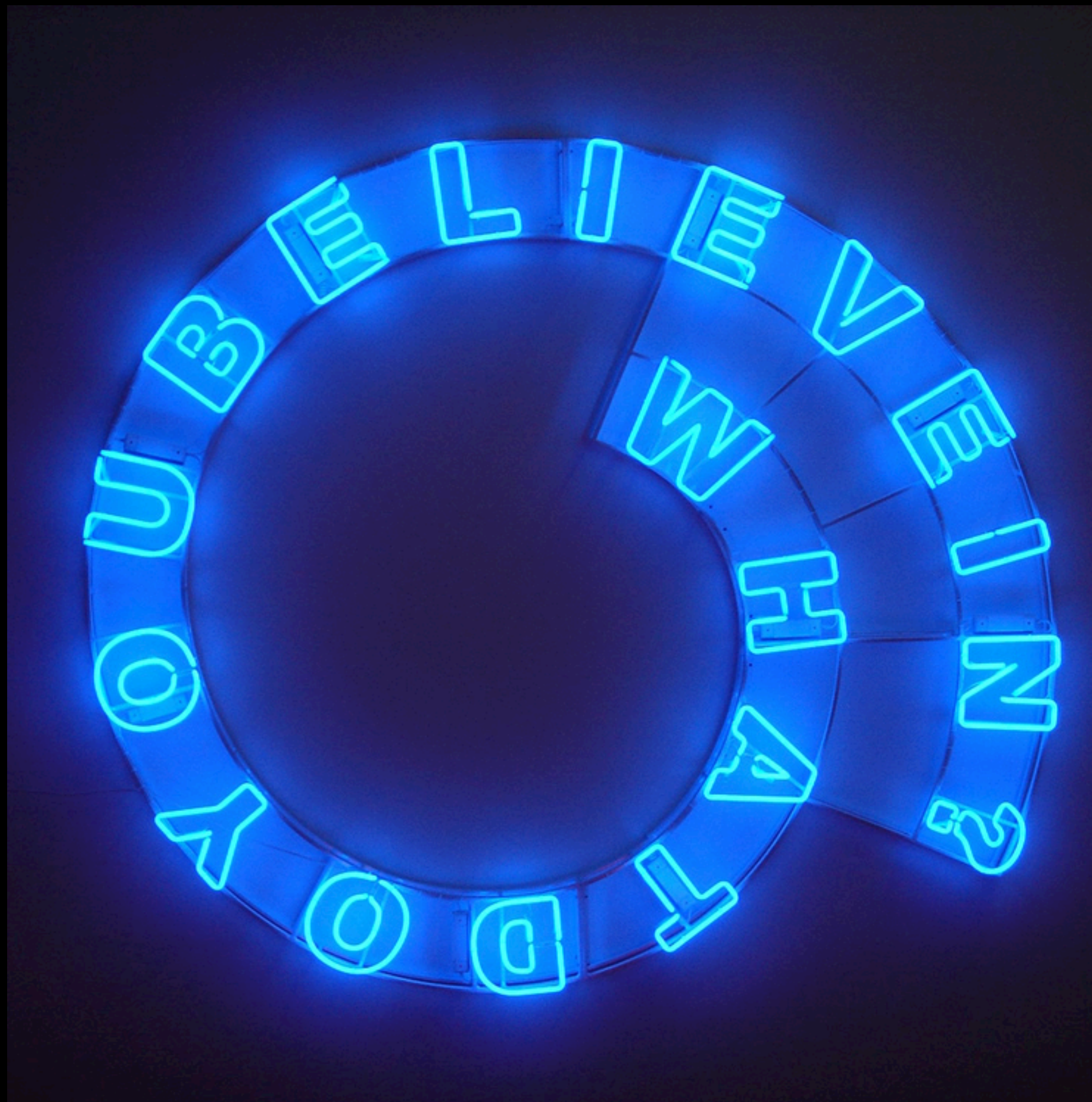
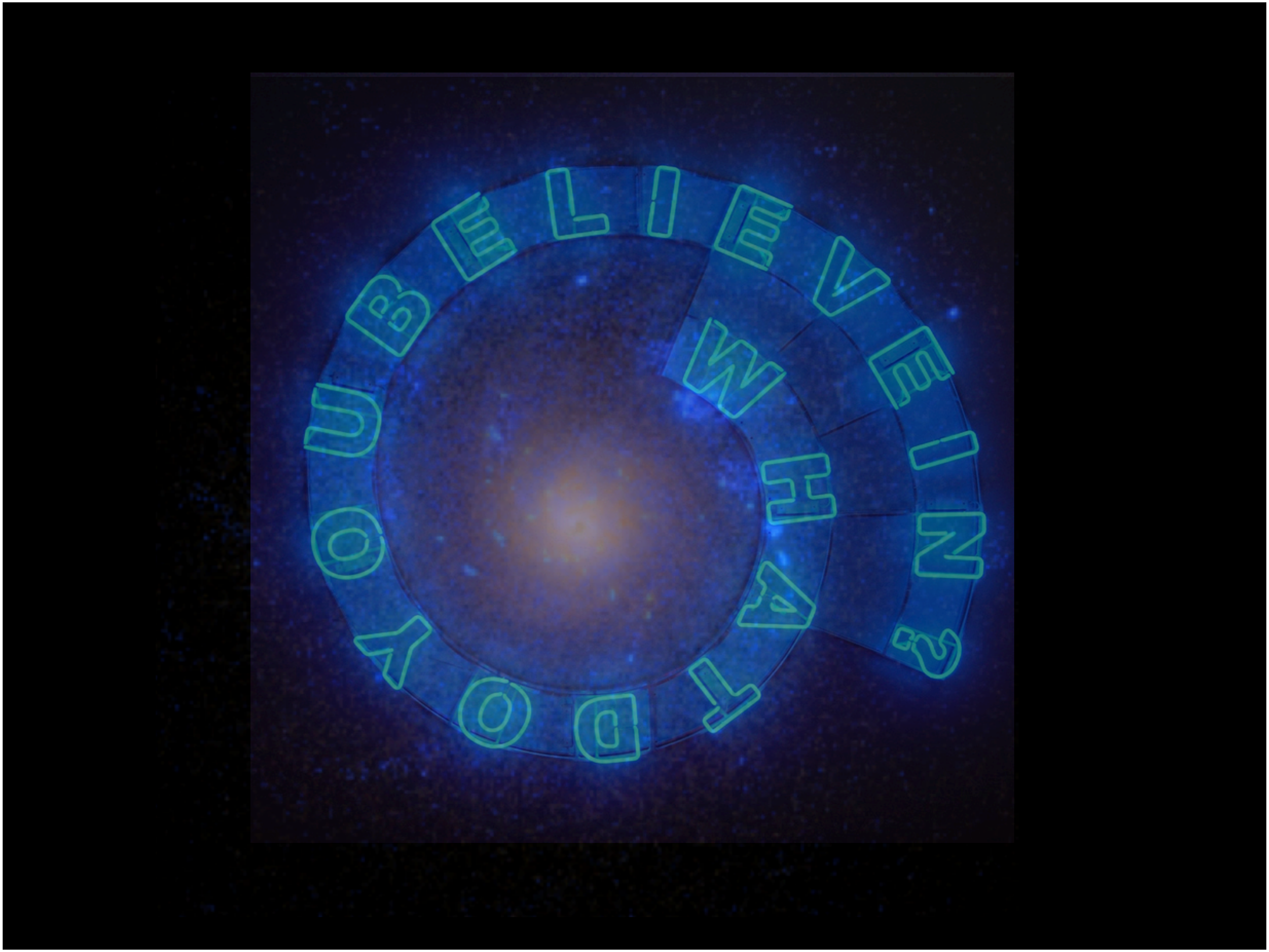
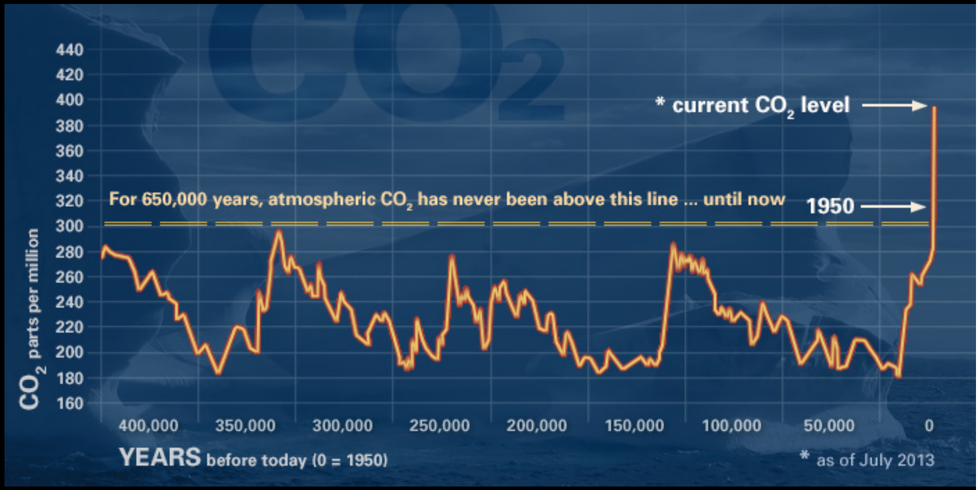

WHAT DO YOU BELIEVE IN?


WHAT DO YOU BELIEVE IN?

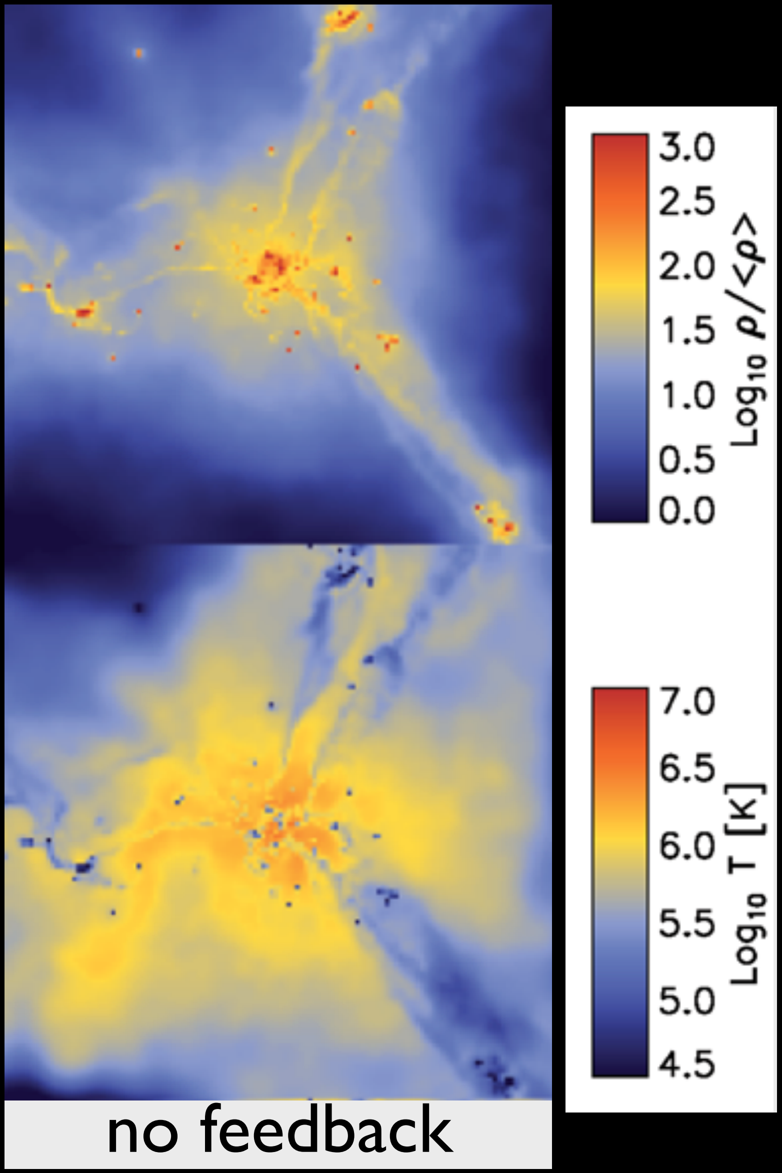
I Don't Believe in AGN Feedback

at least not as a panacea for solving problems with massive galaxy formation

I Do Believe in Climate Change

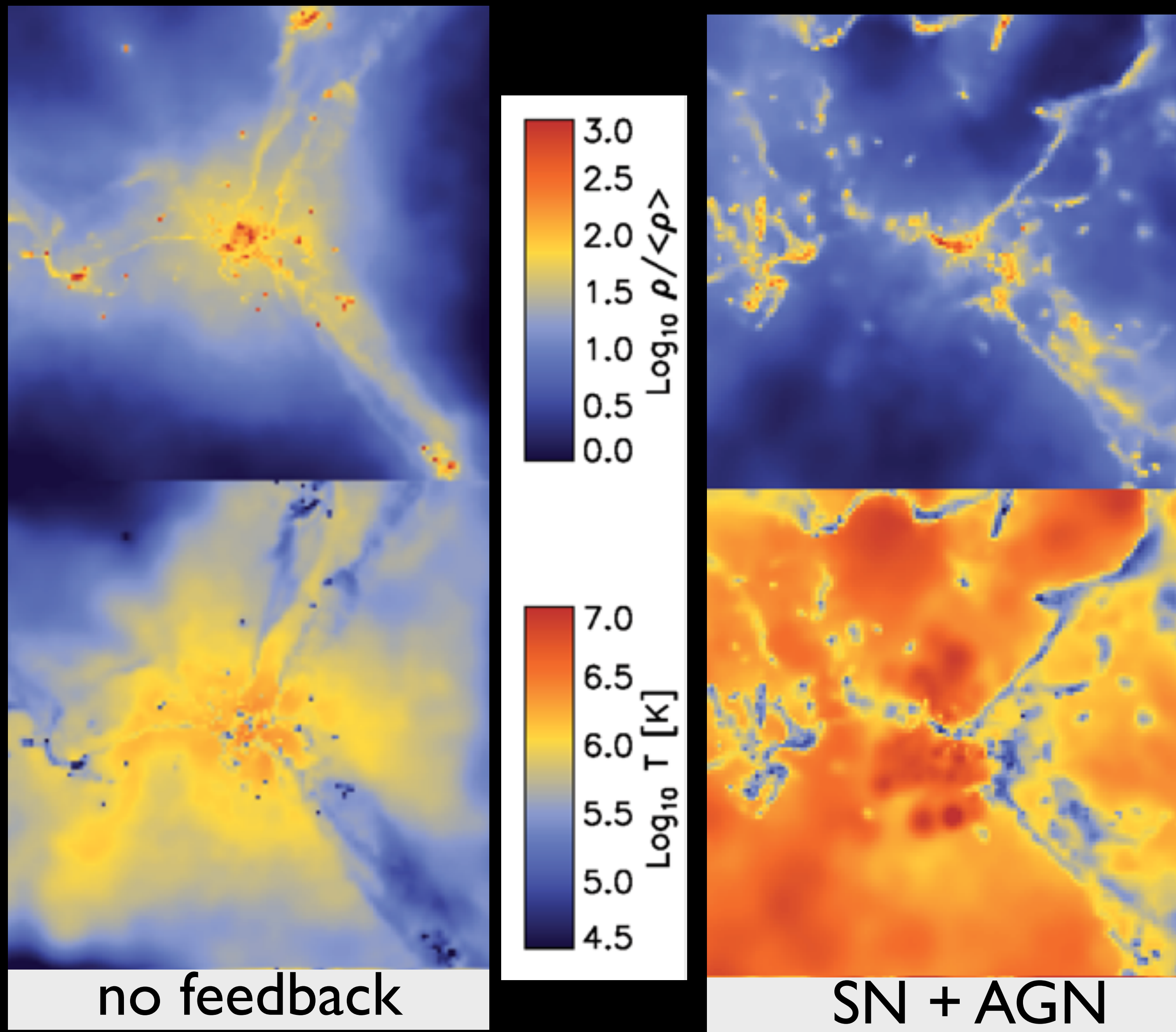


OWLS sims Freeke van de Voort's talk



The physical state of diffuse gas falling onto galaxies is assumed to be resolved and predicted *ab initio* by simulations

OWLS sims Freeke van de Voort's talk



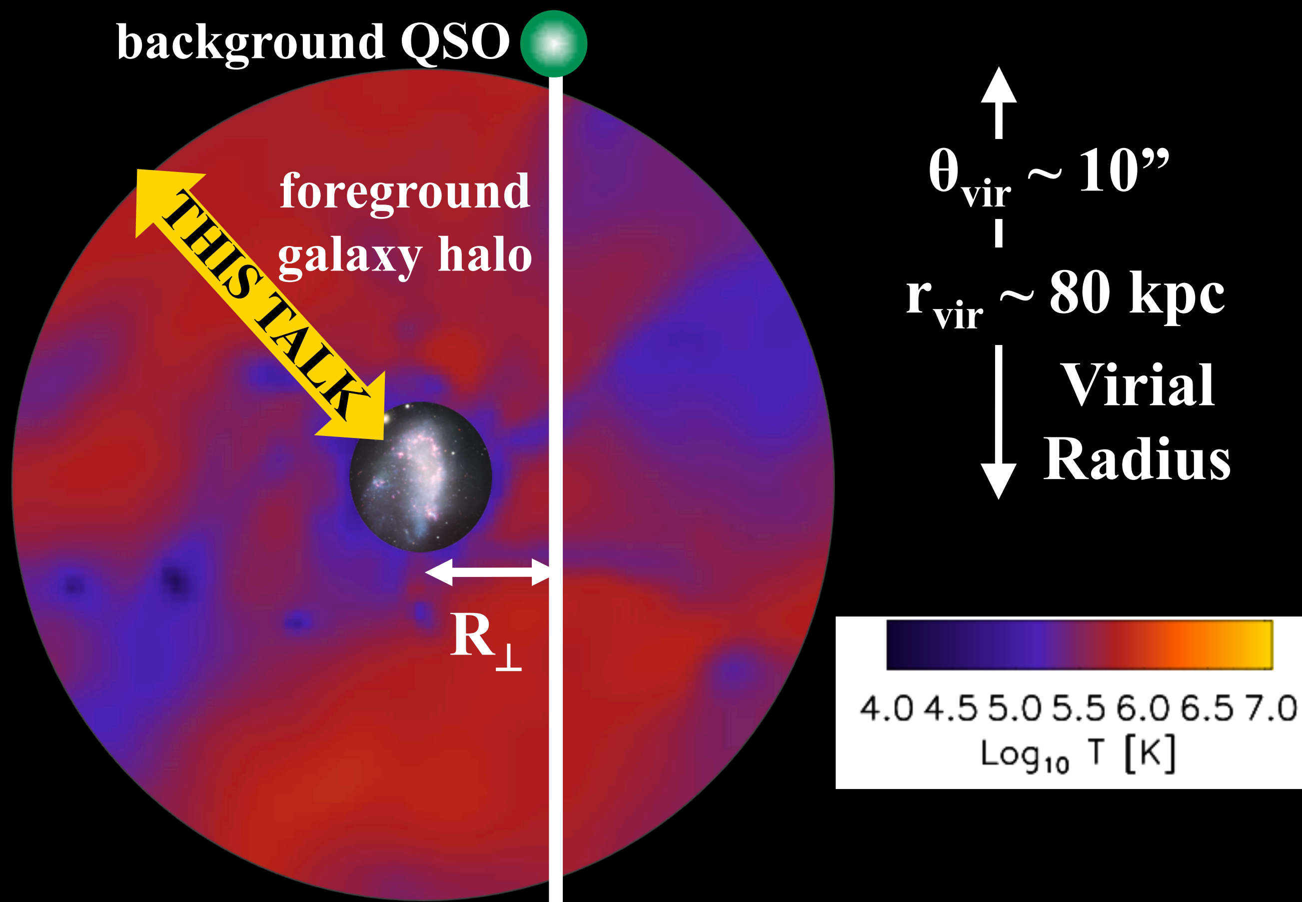
Feedback might alter the structure of the CGM. If CGM modeled incorrectly/unresolved, sims may not be believable

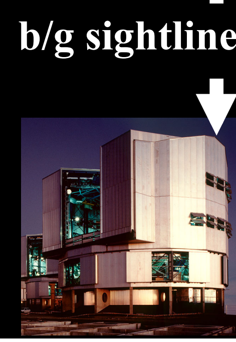
Probing the Circumgalactic Medium (CGM)

Use absorption lines to probe diffuse gas

$r \sim 30 – 200$ kpc

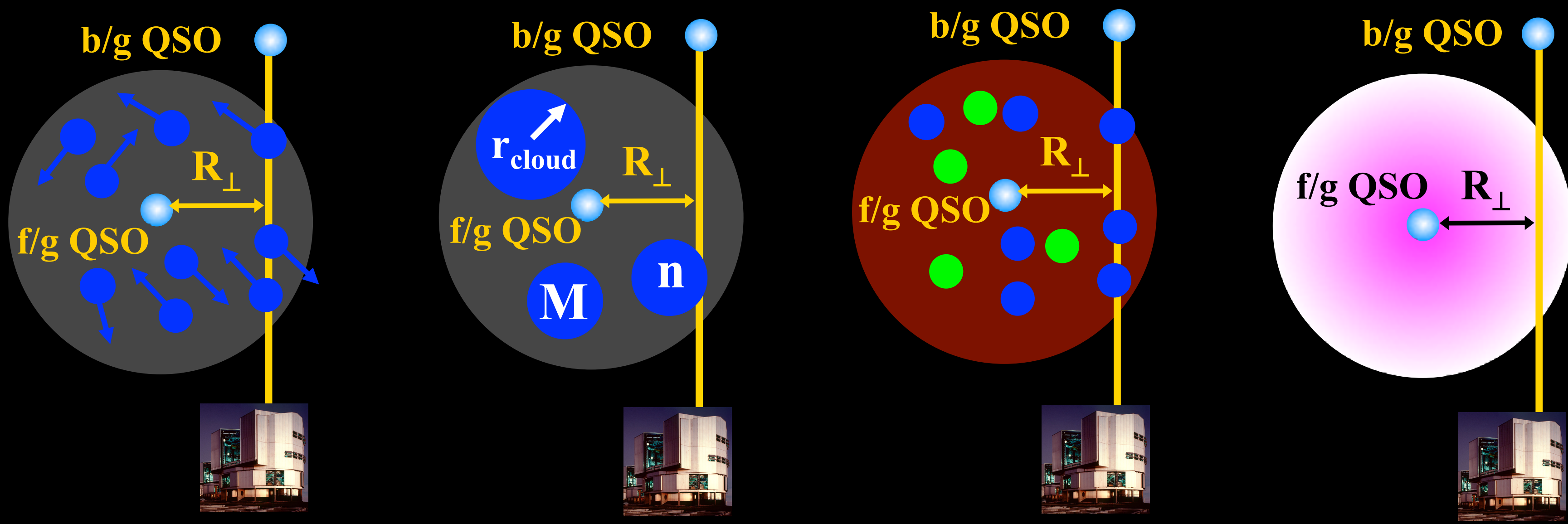
$N_{HI} \sim 10^{12-22}$ cm^{-2} and $T \sim 10^{2-6}$ K





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

What Can we Actually Measure?



Covering factor & kinematics

Gas mass, cloud density, size?

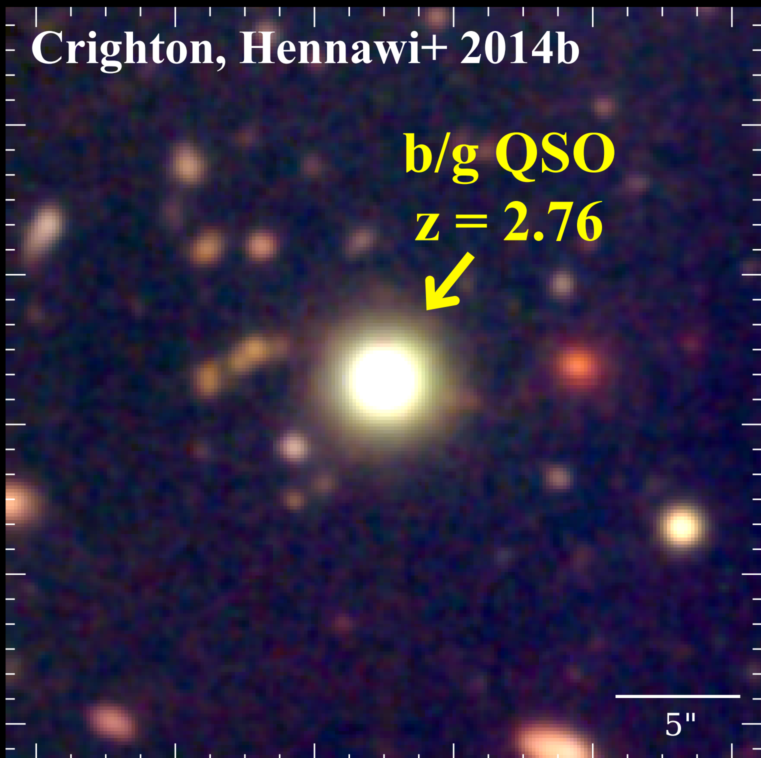
Multiphase? Cold, Warm, Hot?

Metal Enrichment?

Moderate R ~ 2000
150 km/s

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

The CGM of a Low-Mass Galaxy



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

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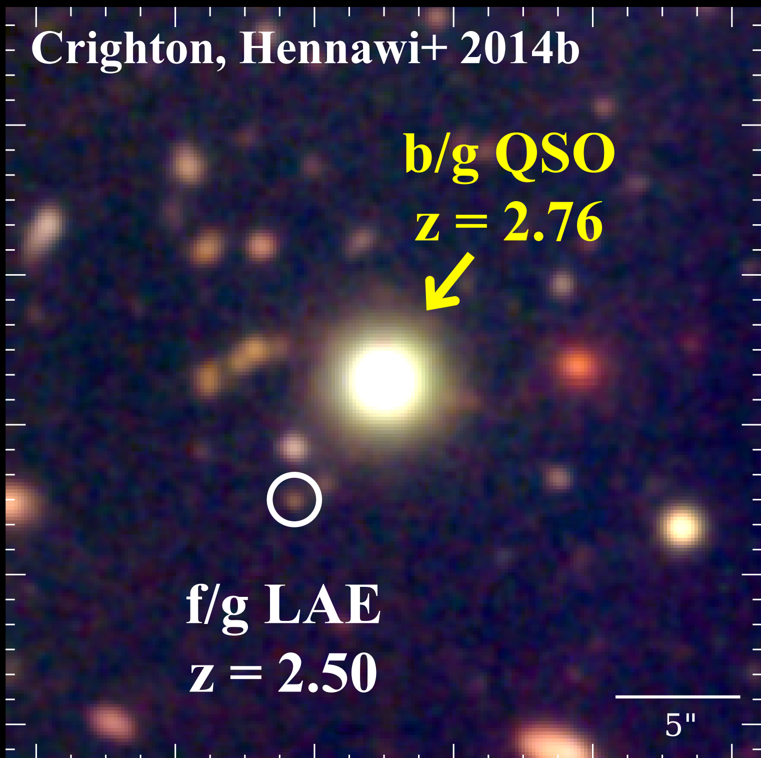

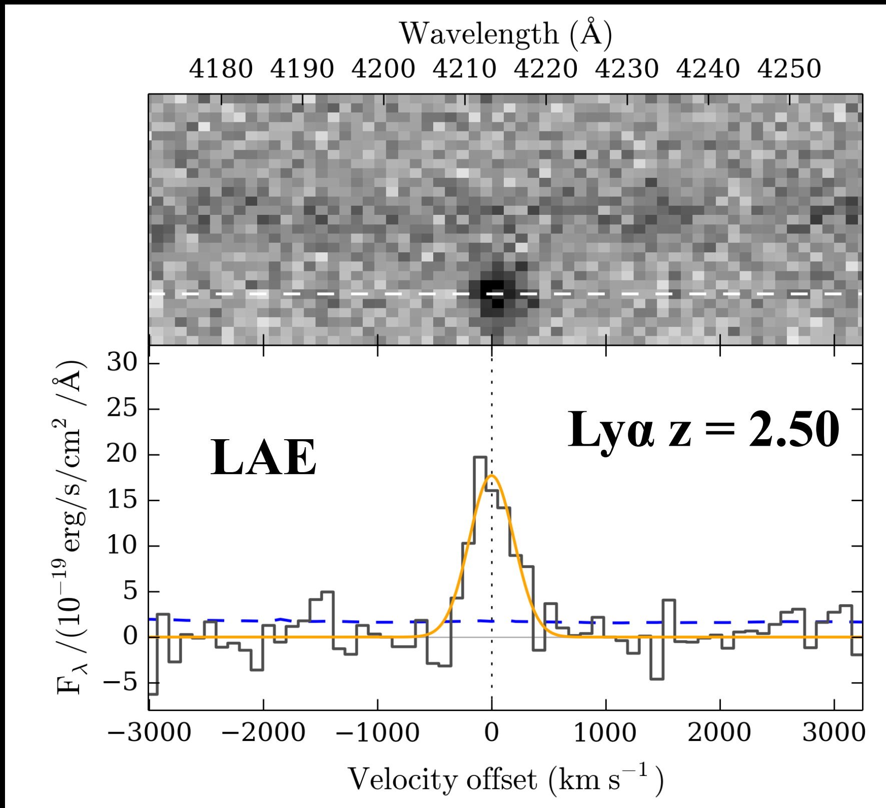

f/g Lyα-emitter @ $R_\perp$ = 50 kpc

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

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

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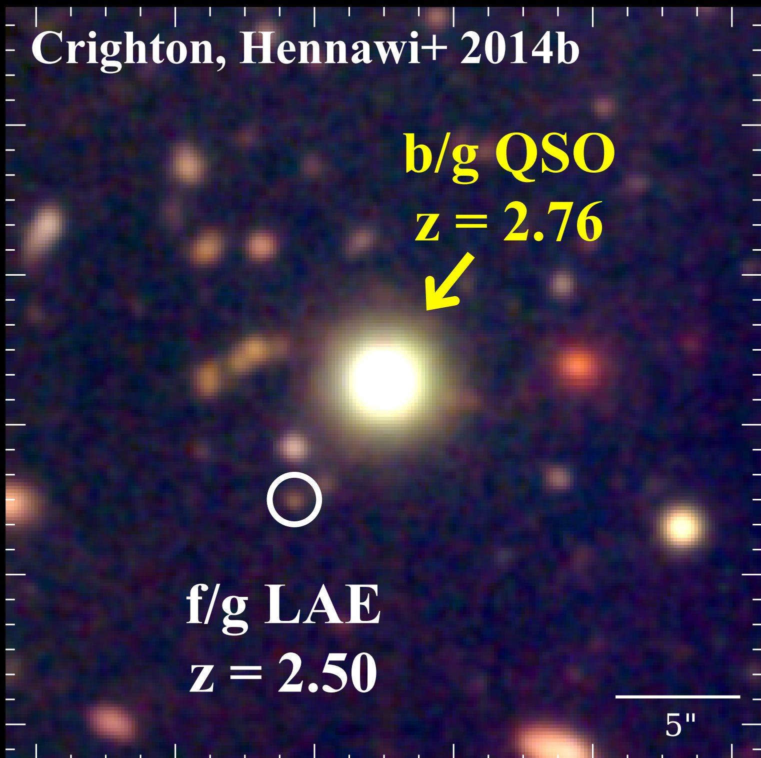

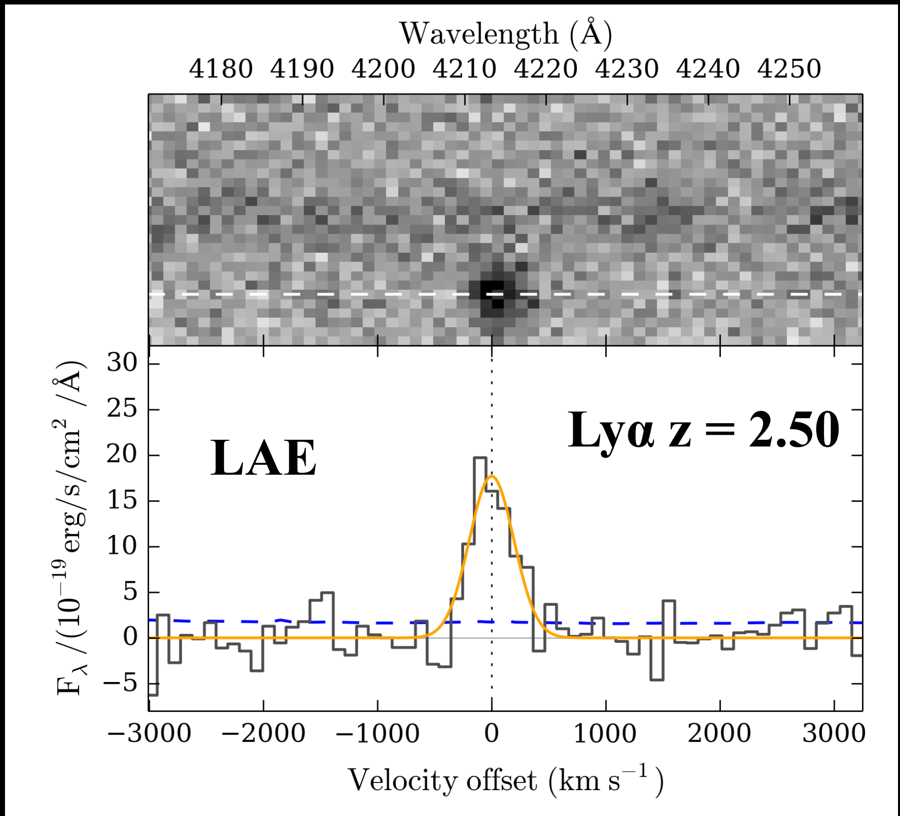

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$M_\star$ ~ $10^{9.1}$ $M_\odot$; M_h ~ $10^{11.4}$ $M_\odot$

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

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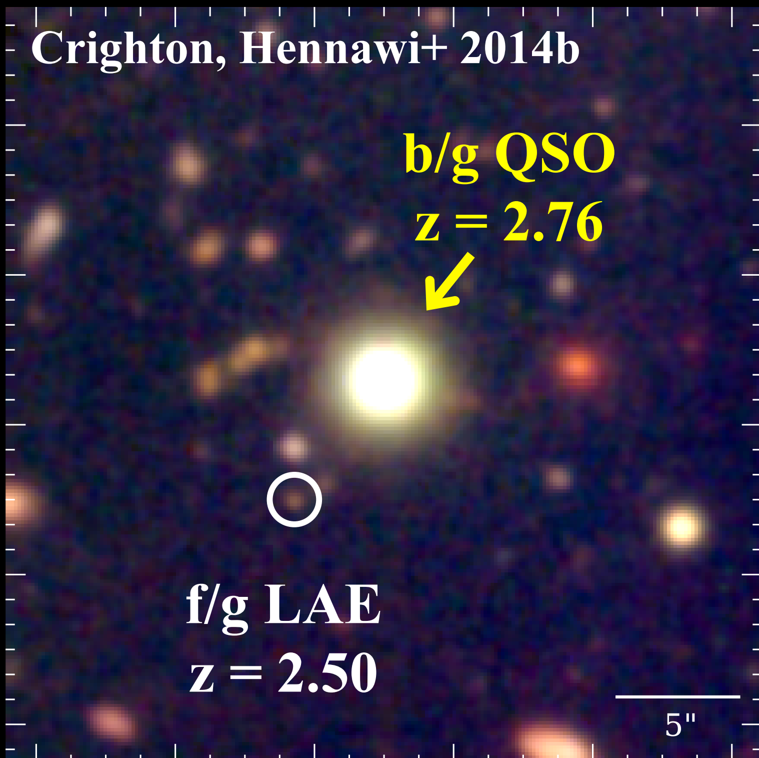

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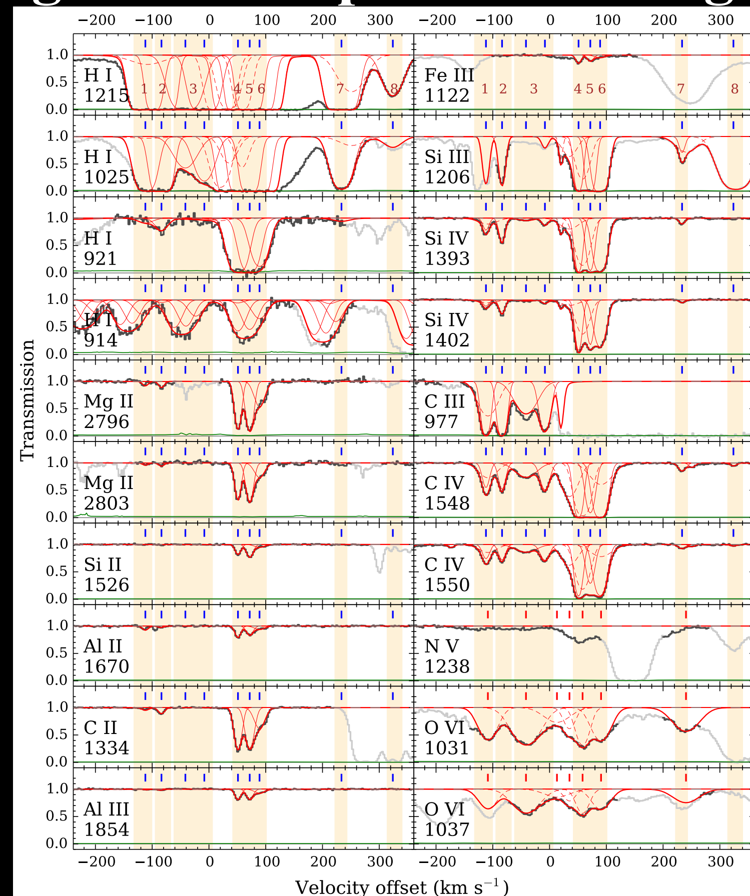
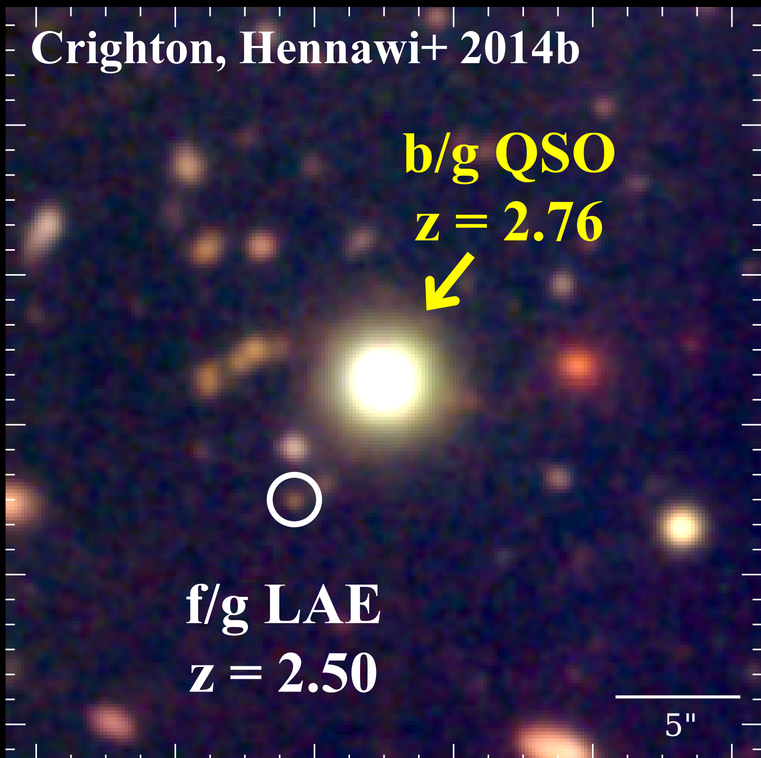
High-Resln. Spectrum of b/g QSO



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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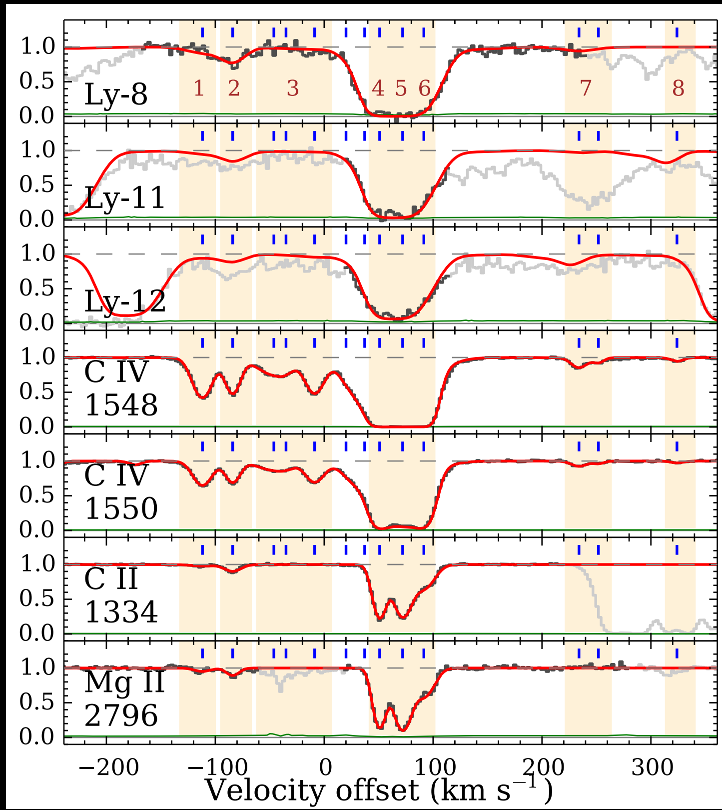
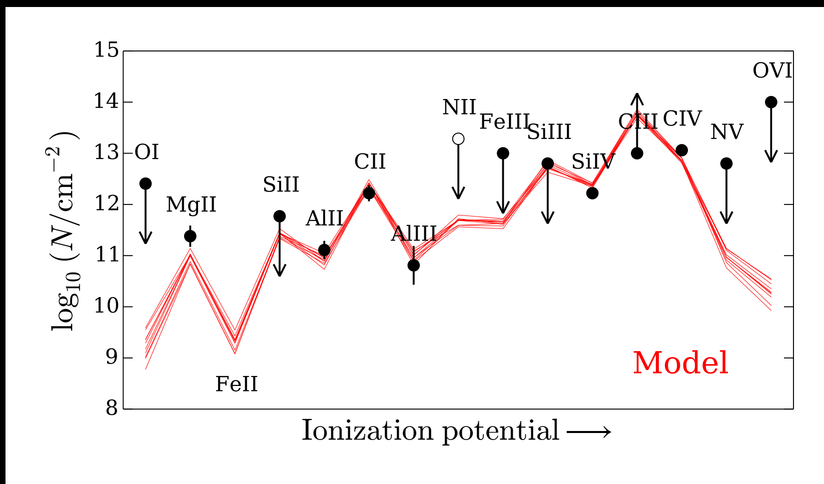
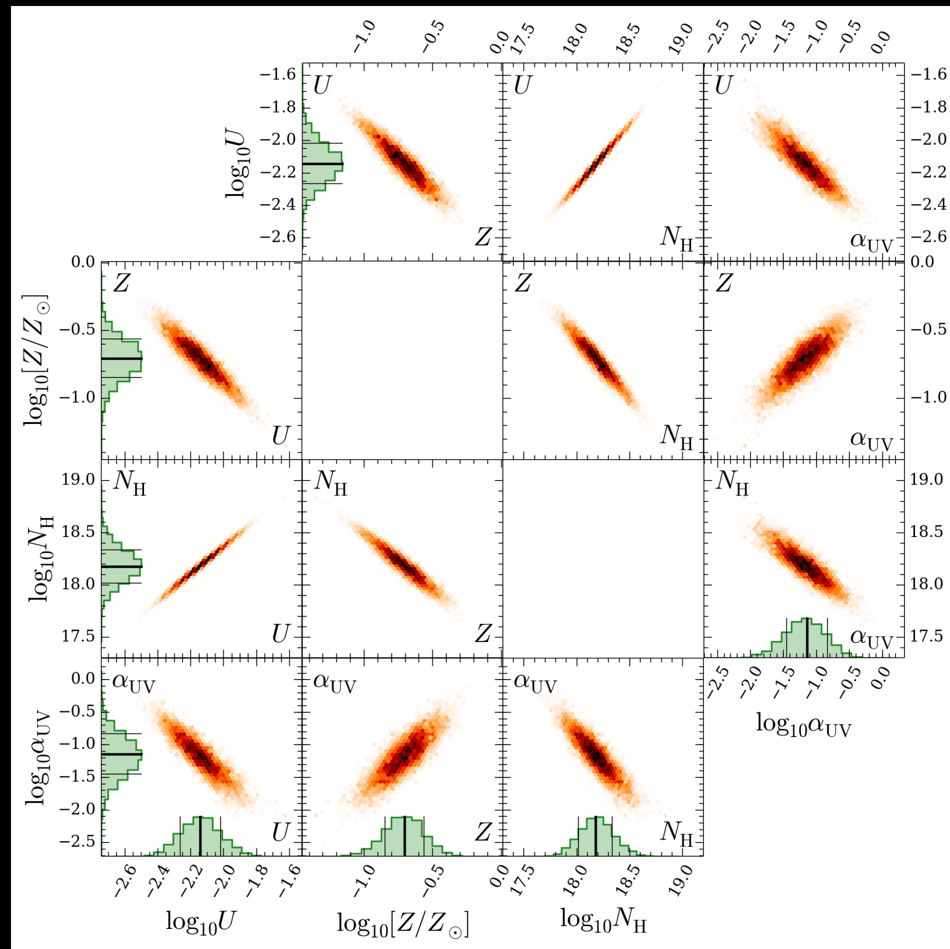


Δv = 430 km/s; MgII EW = 0.37Å

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

Precise Determination of CGM Parameters





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

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

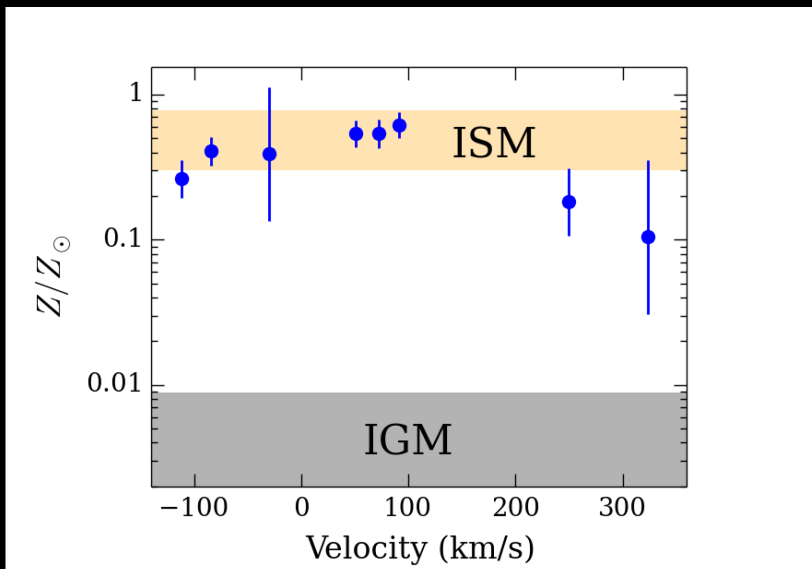
$\log N_H = 18.18 \pm 0.16$ (cm^{-2})

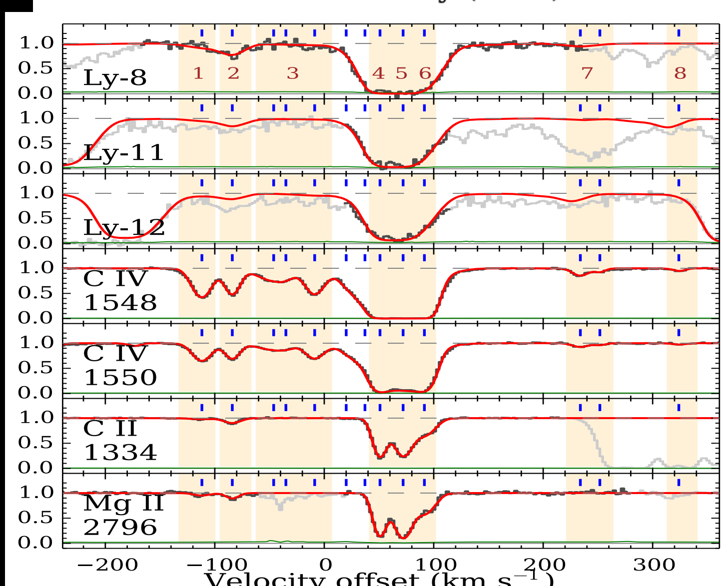
$\log r_{cloud} = -0.58 \pm 0.42$ (kpc)

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

- 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?

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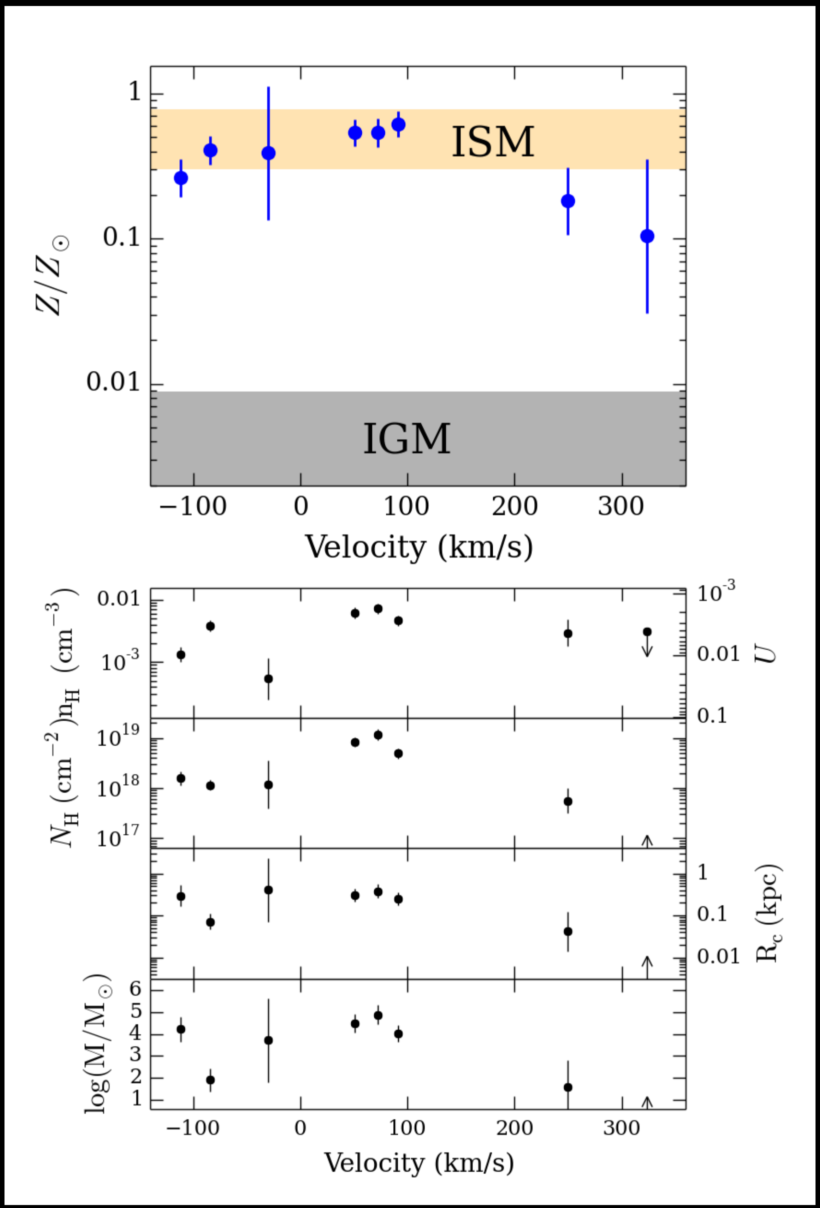


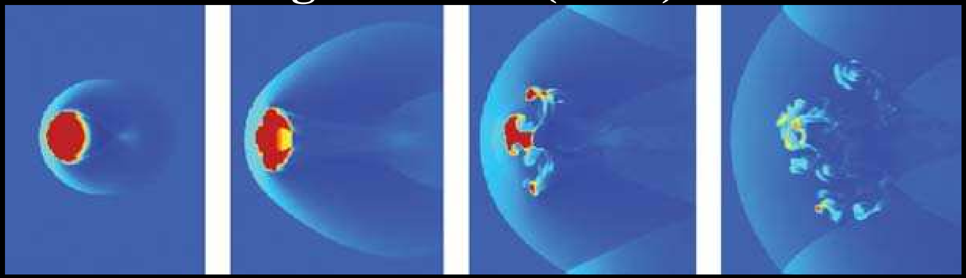
- **Enriched (0.2-0.6 $Z_\odot$) LLS (log N_{HI}=17) with 430 km/s motions ➡ outflow?**
- **Extremely small clouds!**
  r_{cloud} = 100-400 pc and cloud masses M_{cloud} = 200-5×10^4 $M_\odot$
- **Uncertain radiation field not an issue. Local sources make clouds denser and smaller**
- **Large cool gas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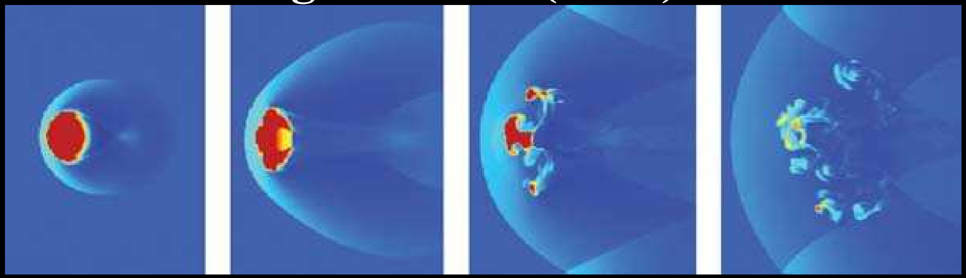

$$t_{cc} \simeq 5 \frac{r_{\rm cloud}}{v_{\rm bulk}} \left(\frac{n_{\rm cold}}{n_{\rm hot}} \right)^{1/2}$$

- **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**

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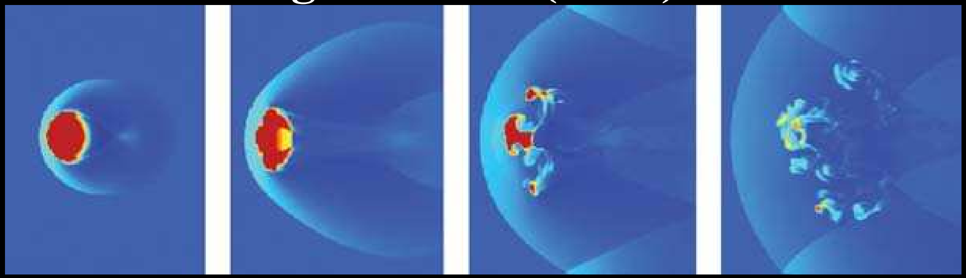

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- Do current simulations resolve this?

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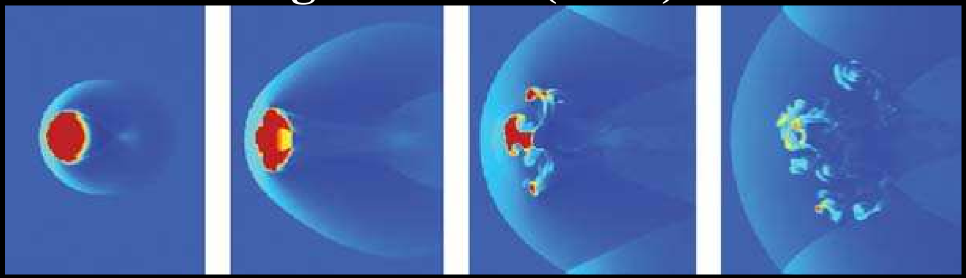

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  - v_{bulk} = 300 km/s
- **Do current simulations resolve this? Not even close**

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

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

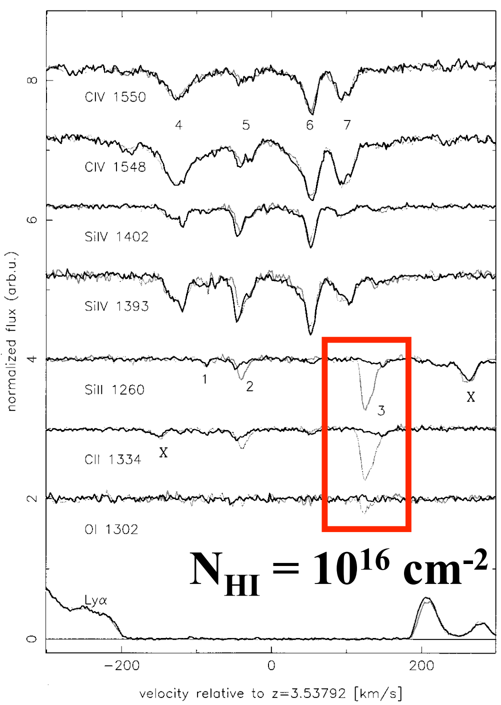
Eris2 zoom-in: $M_{gas} = 2\times10^4\ M_\odot$, FIRE: $5\times10^3\ M_\odot$

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

This has been seen before….

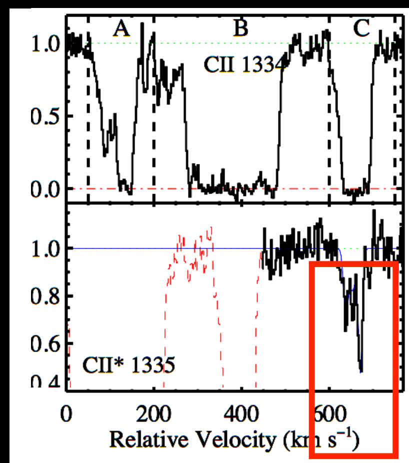
Lensed QSOs

$R_{\perp} \approx 30$ pc



Rauch et al. 1990

QSO CGM



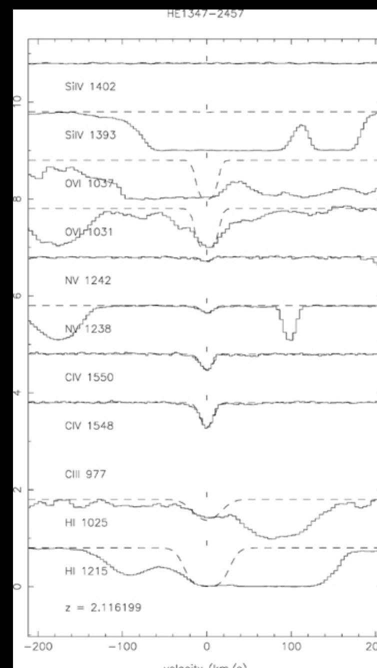
$n_H \sim 1\text{-}5$ cm^{-3}

$r \sim 10\text{-}100$ pc

Prochaska & Hennawi 2009

Absorption Line Modeling

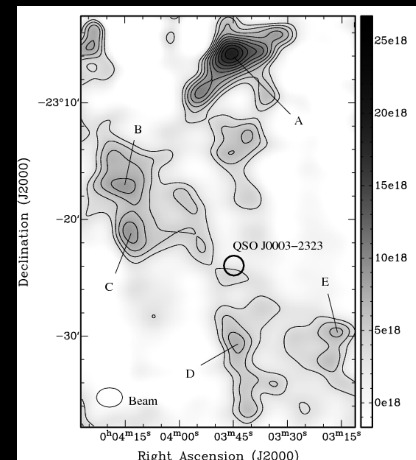
Sizes r < 100 pc



Schaye et al. 2007

HVCs

Sizes r < 50 pc



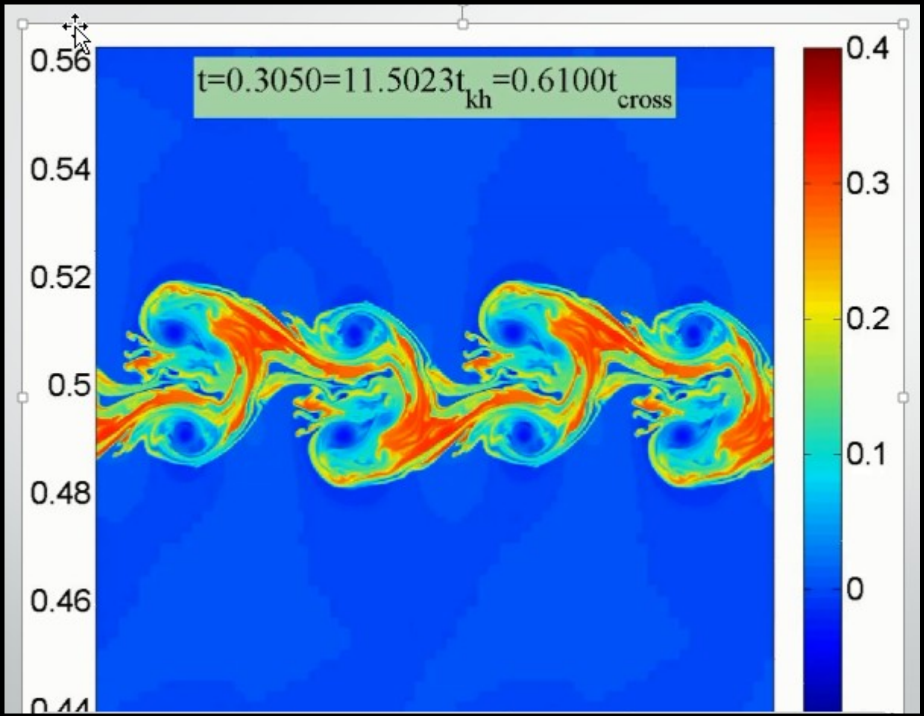
clump	r	M_{HI}	n_{HI}
	[pc]	[$M_\odot$]	[cm^{-3}]
A	45	470	0.14
B	45	280	0.06
C	49	160	0.06
D	36	150	0.06
E	32	160	0.07

Ben Bekhti et al. 2009

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

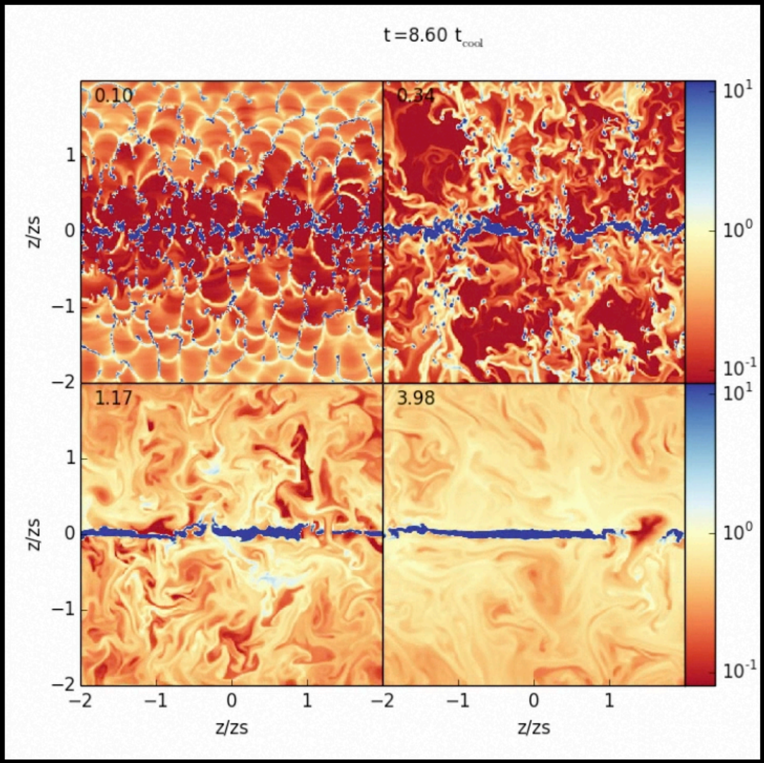
We Need a Sub-Grid Model for the CGM

Stability of Cold Streams



Yuval Birnboim's talk

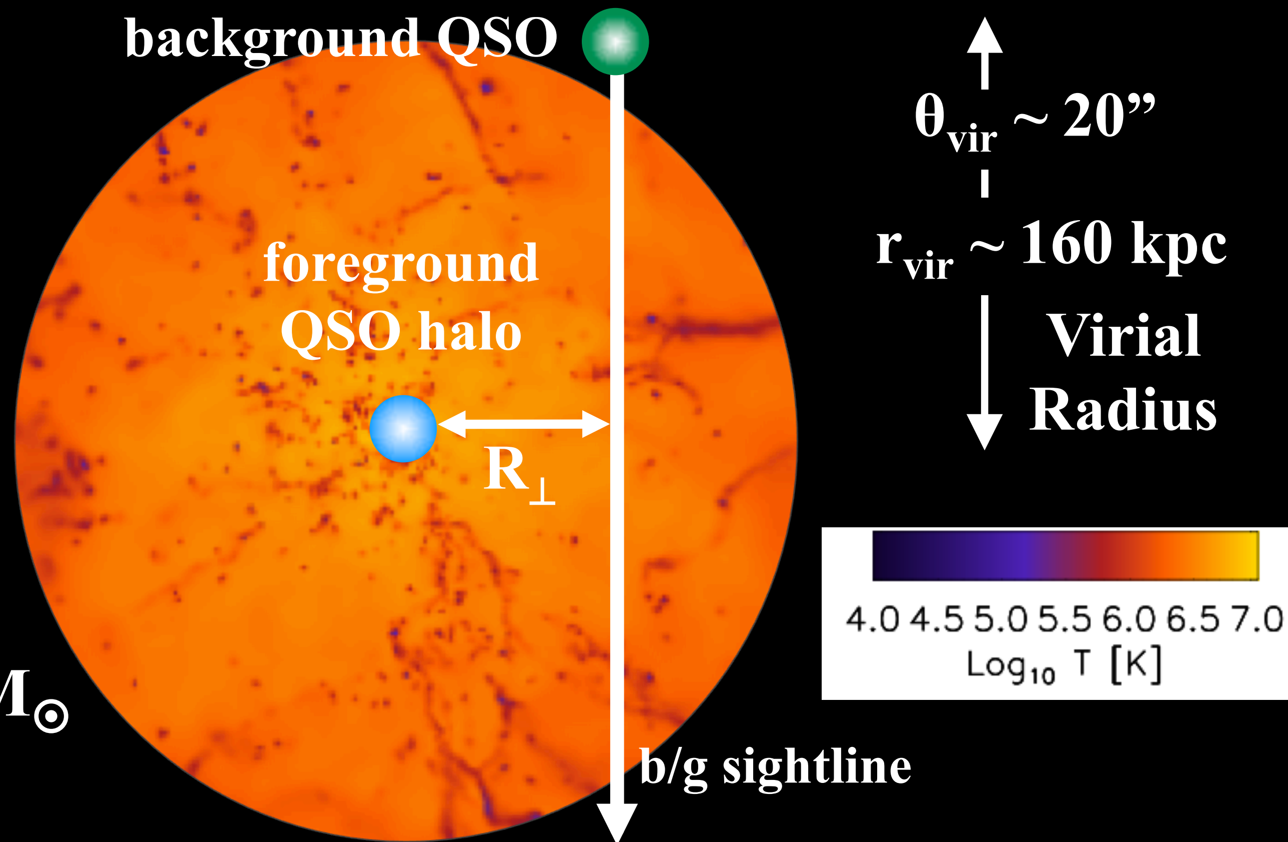
Thermal Instabilities in ICM



Brian O'Shea's talk

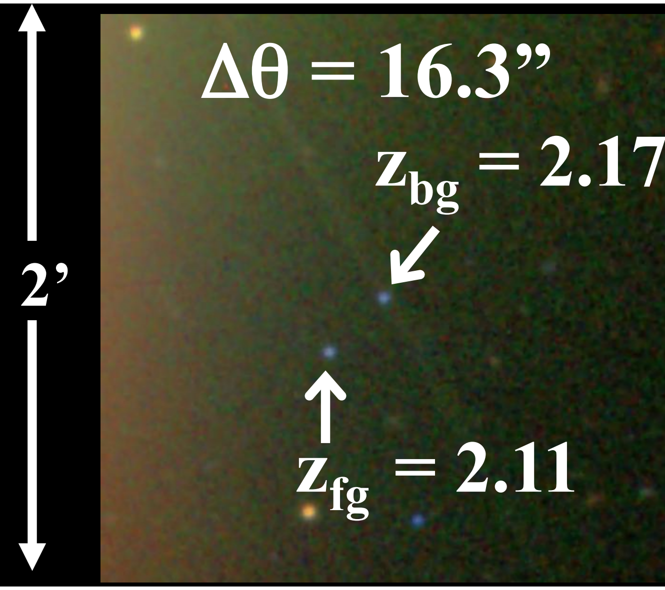
Probing the CGM of High Mass Halos

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



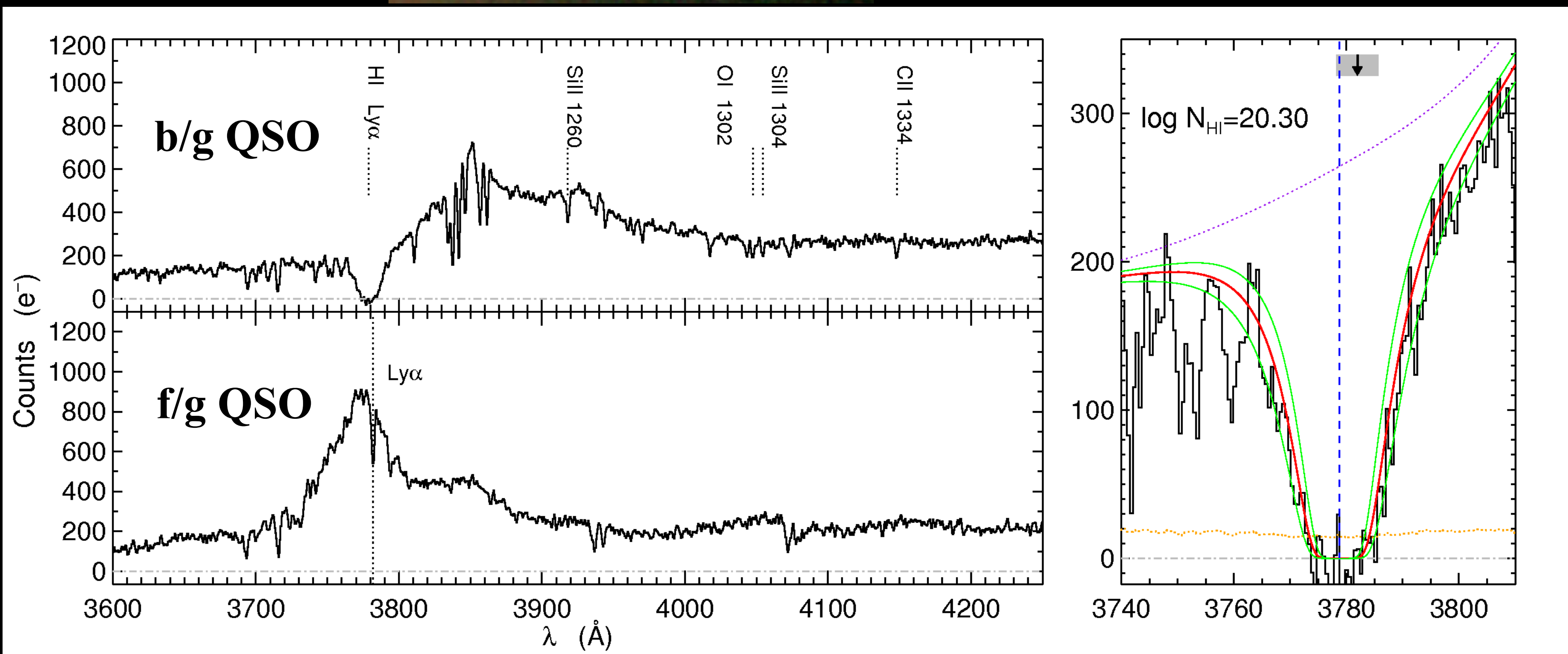
$M_{halo} = 10^{12.5} M_\odot$

- 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

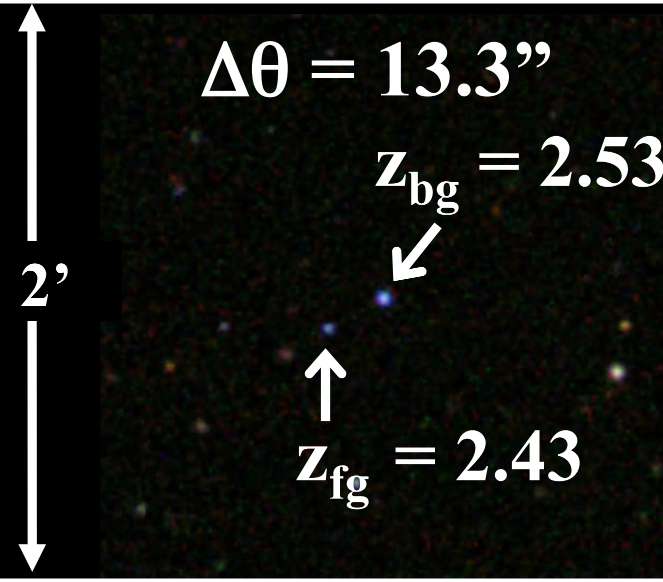


$R_\perp$ = 139 kpc

$\log N_{HI}$ = 20.3

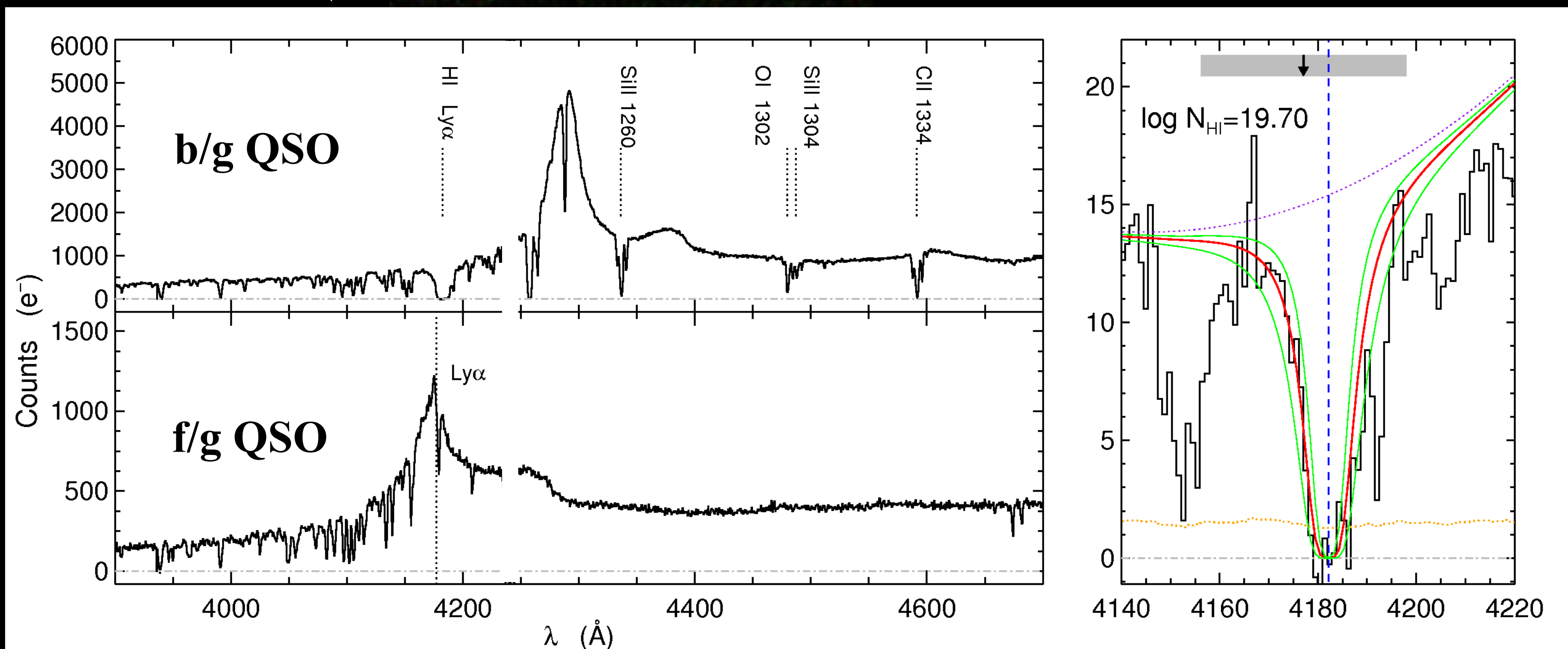


Hennawi+ 2006, 2007, 2013; Prochaska, Hennawi+ 2013



$R_{\perp} = 108$ kpc

$\log N_{HI} = 19.7$



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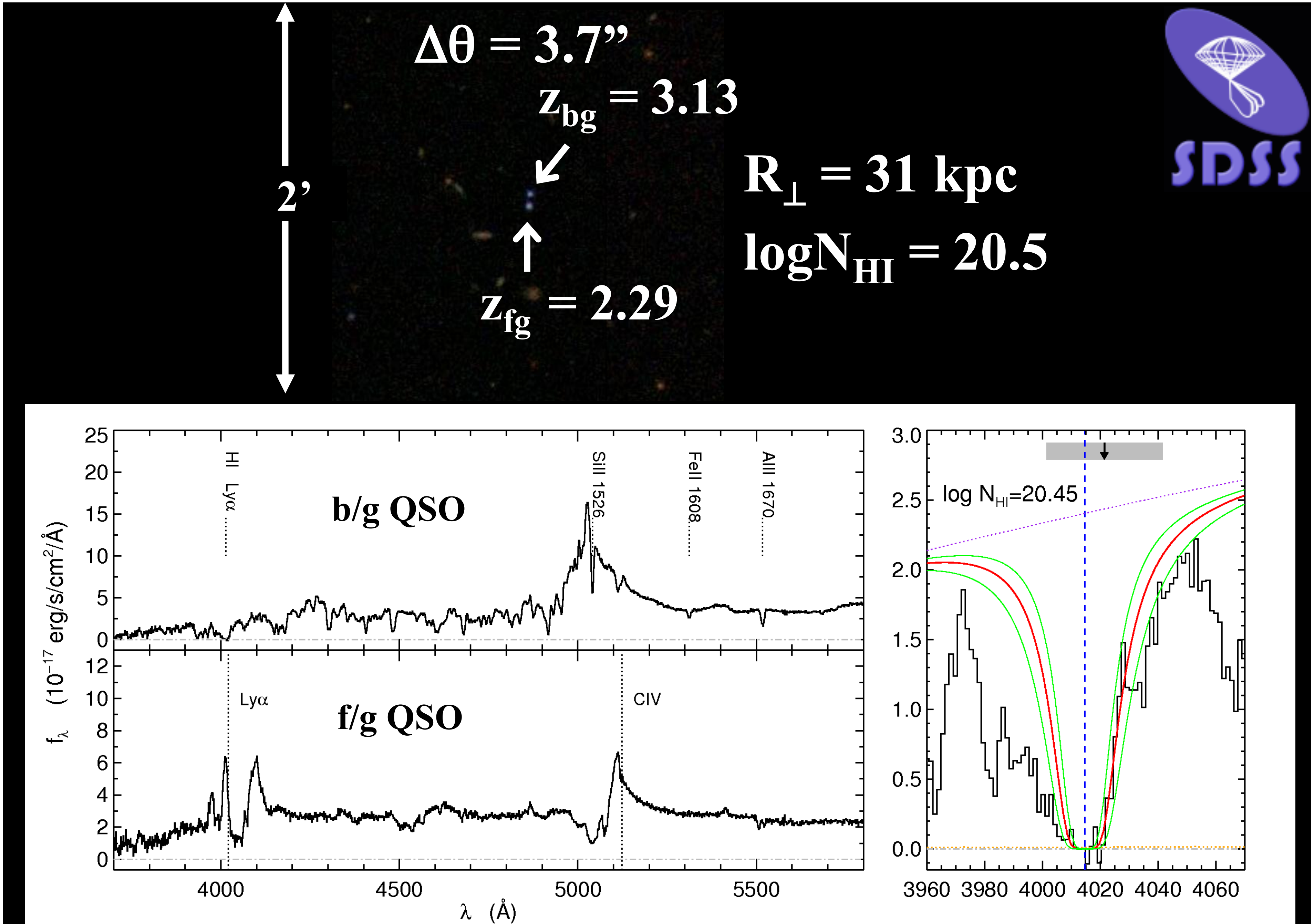

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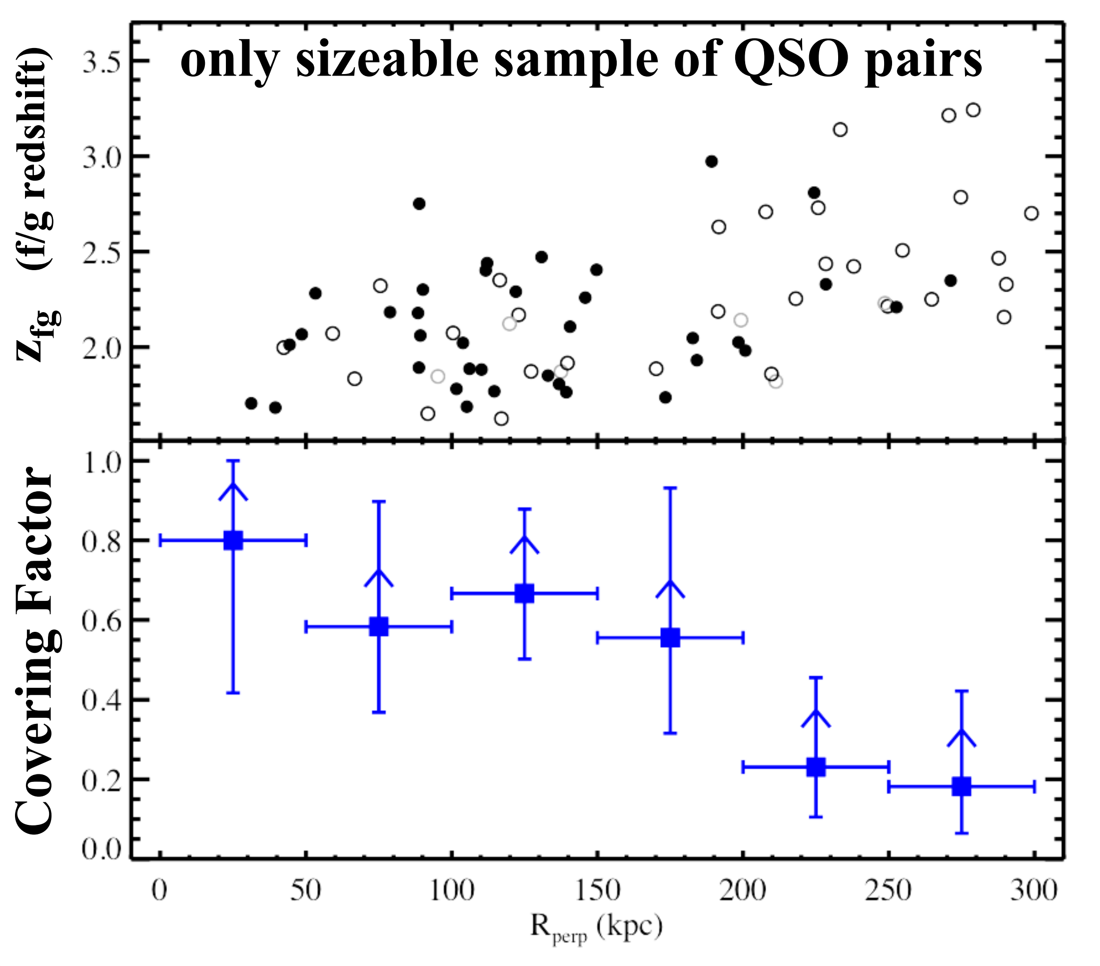
A Massive Reservoir of Cool Gas Around QSOs



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

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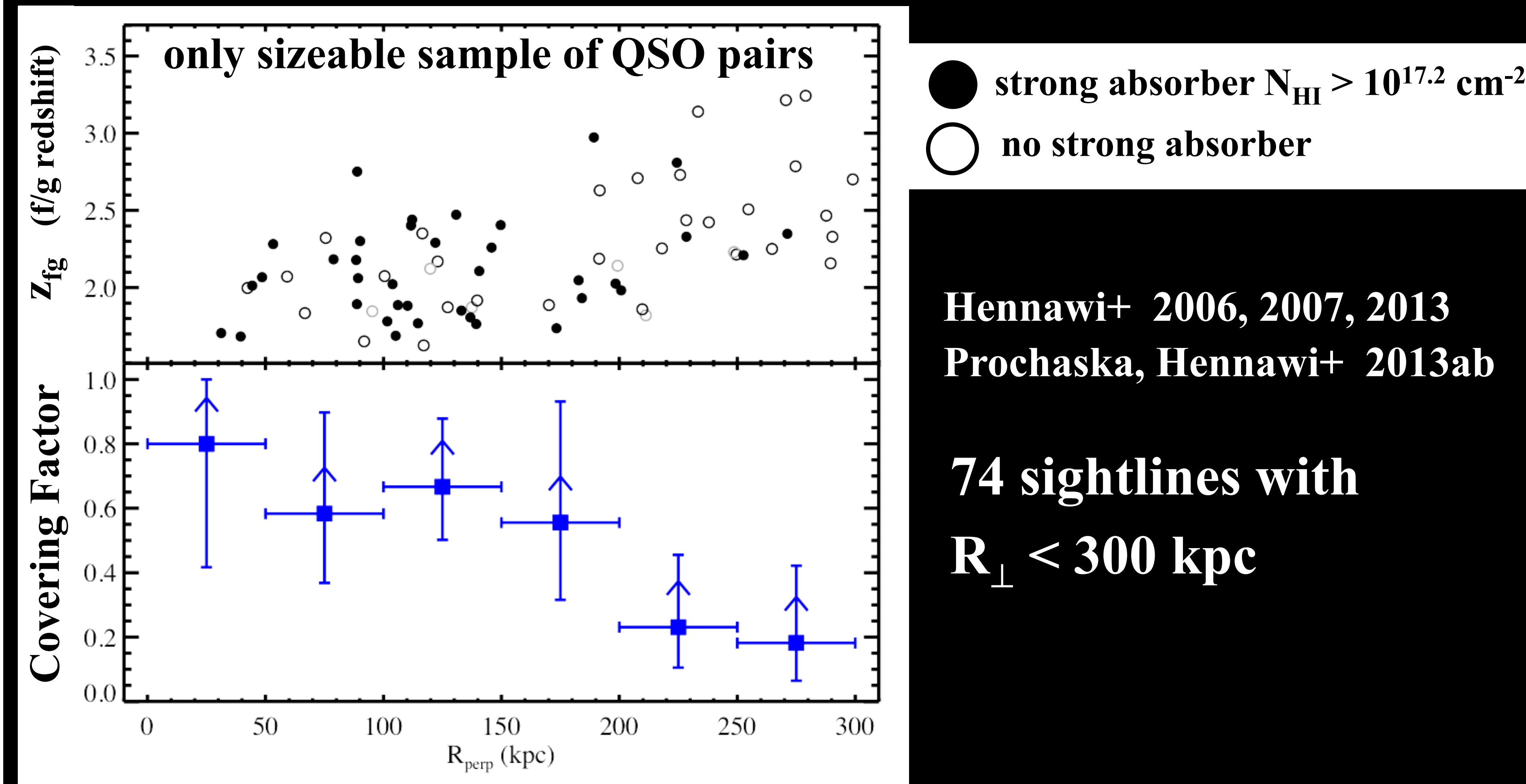

Hennawi+ 2006, 2007, 2013
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- High ~ 60% covering factor for $R < r_{vir} = 160$ kpc

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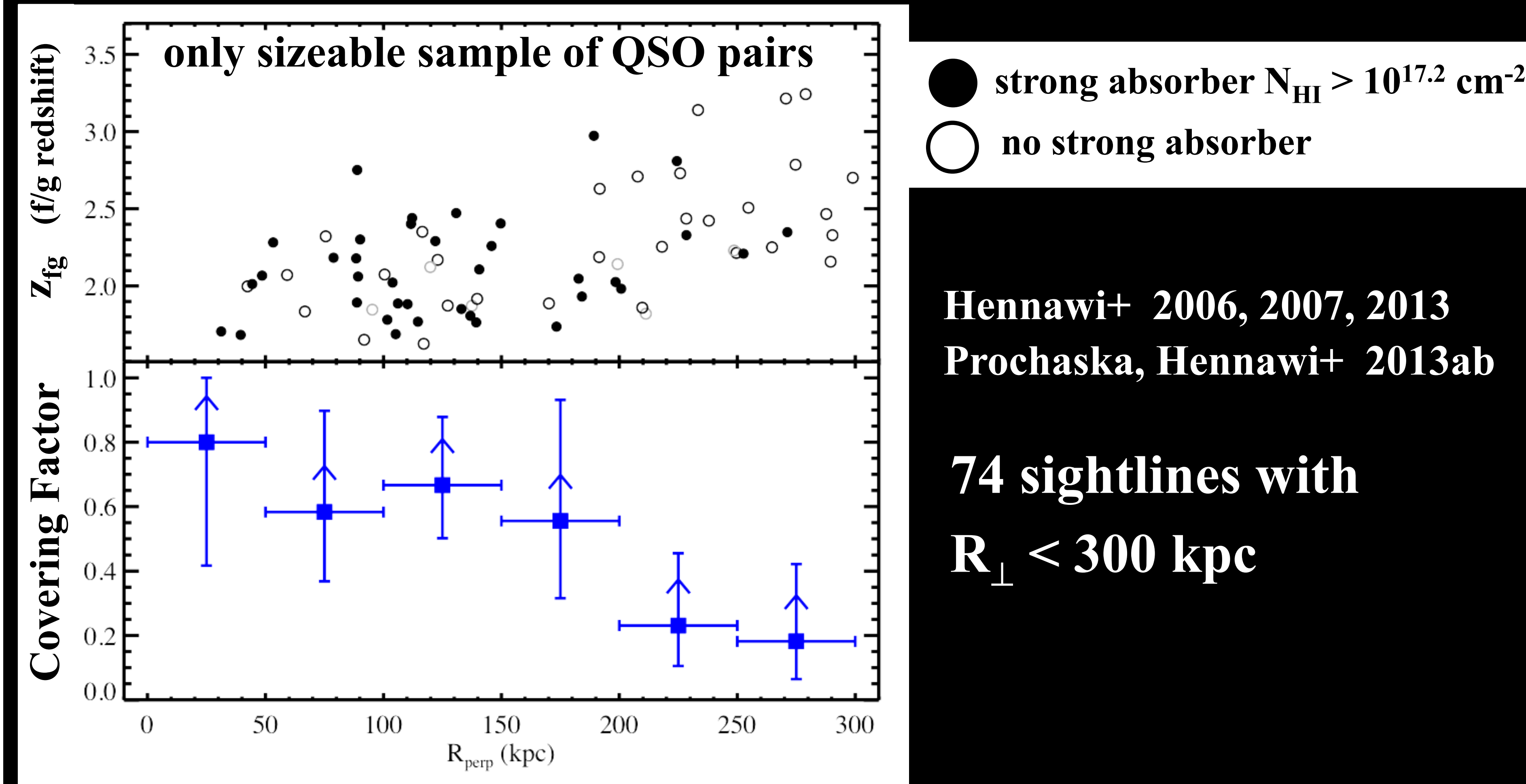


Hennawi+ 2006, 2007, 2013
Prochaska, Hennawi+ 2013ab

74 sightlines with
$R_\perp < 300$ kpc

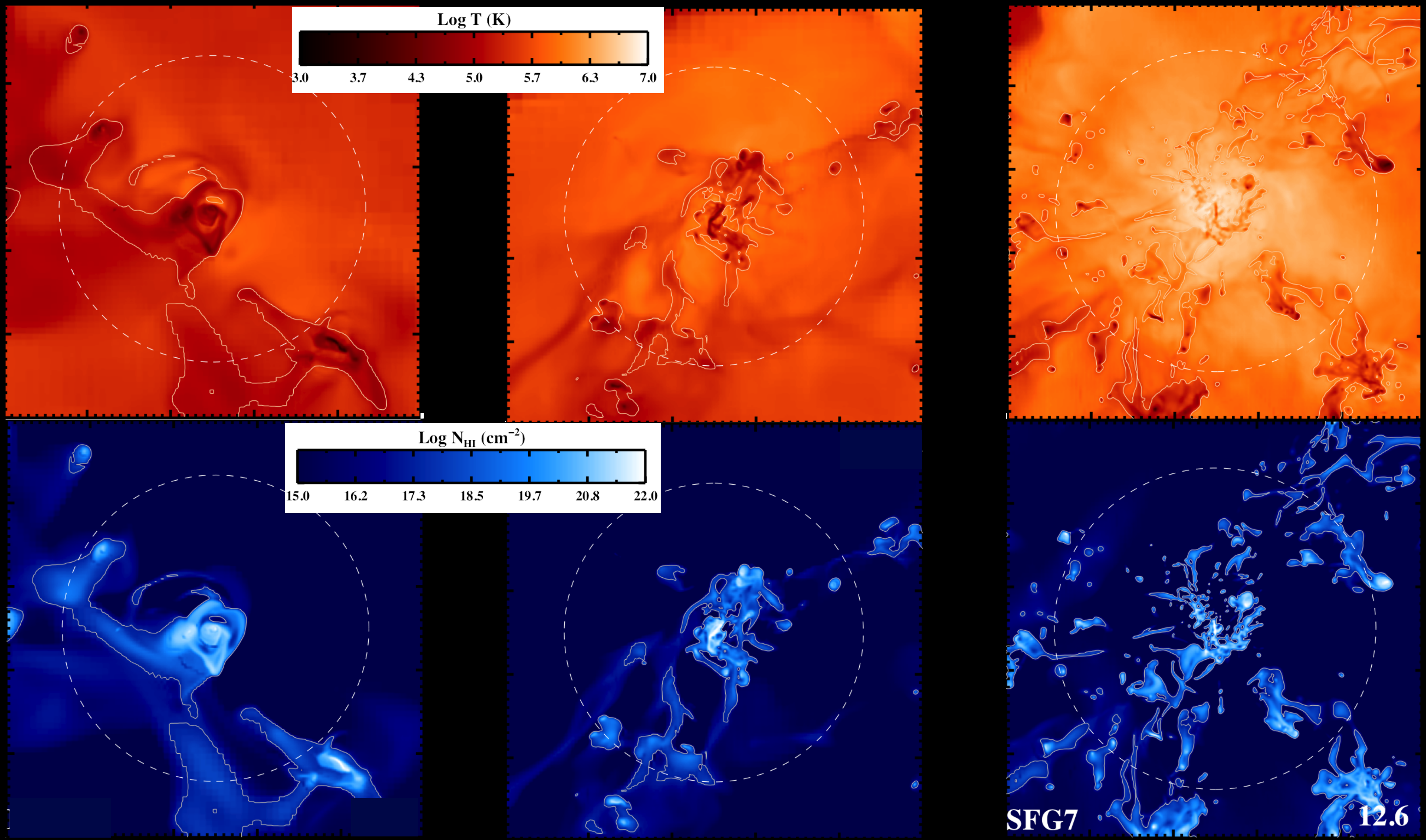
- High ~ 60% covering factor for $R < r_{vir} = 160$ kpc
- CGM is dominated by a cool ($T \sim 10^4$ K) massive ($>10^{10}\ M_\odot$) metal-enriched medium ($Z > 0.1 Z_\odot$)

Simulating CGM Observations

M = $10^{11.2}$; r_{vir} = 58 kpc

M = $10^{11.9}$; r_{vir} = 98 kpc

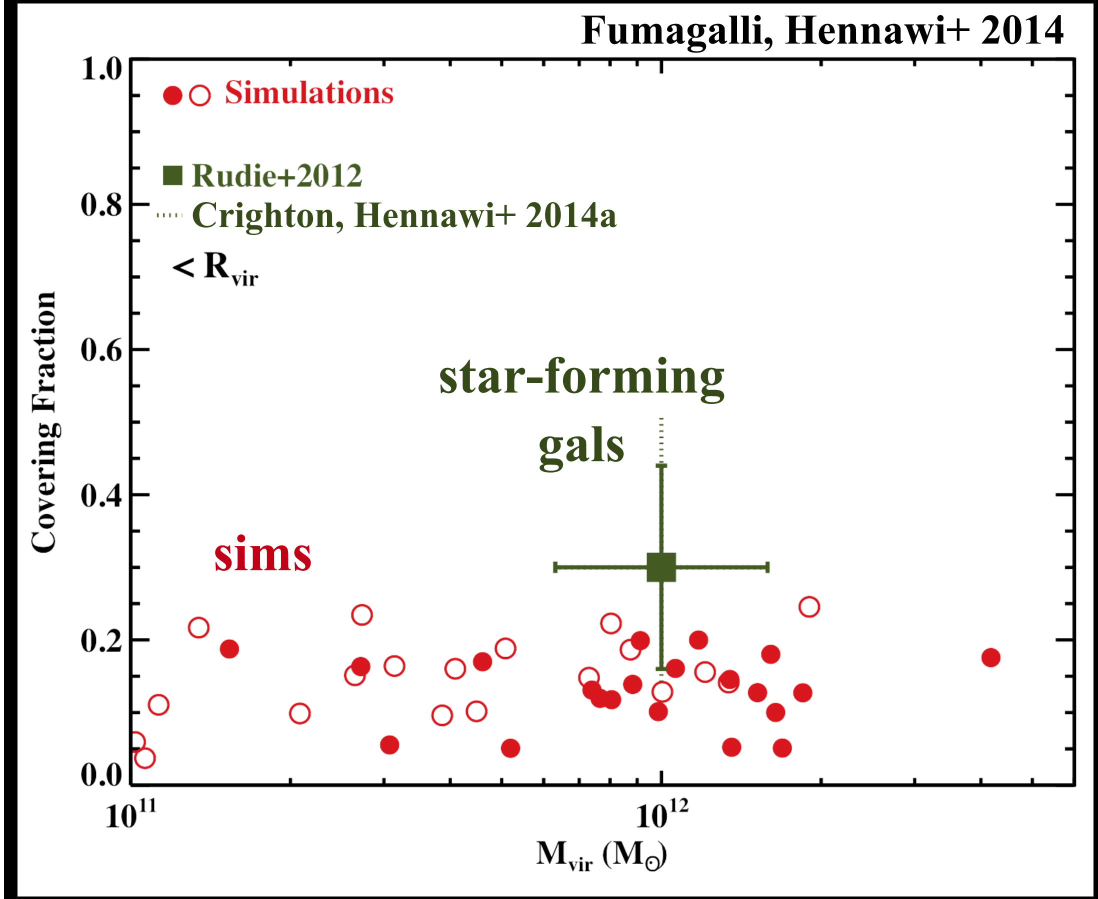
M = $10^{12.6}$; r_{vir} = 153 kpc

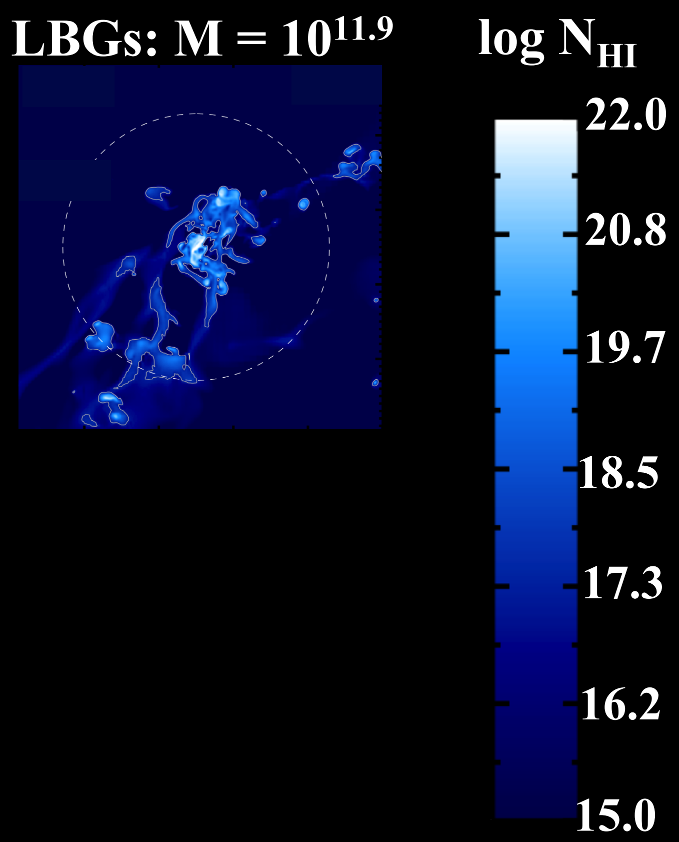


ART AMR zoom-in + ionizing rad. transfer

Fumagalli, Hennawi+ 2014
Ceverino et al. 2010

Problem #2: The Perplexing CGM of Massive Halos





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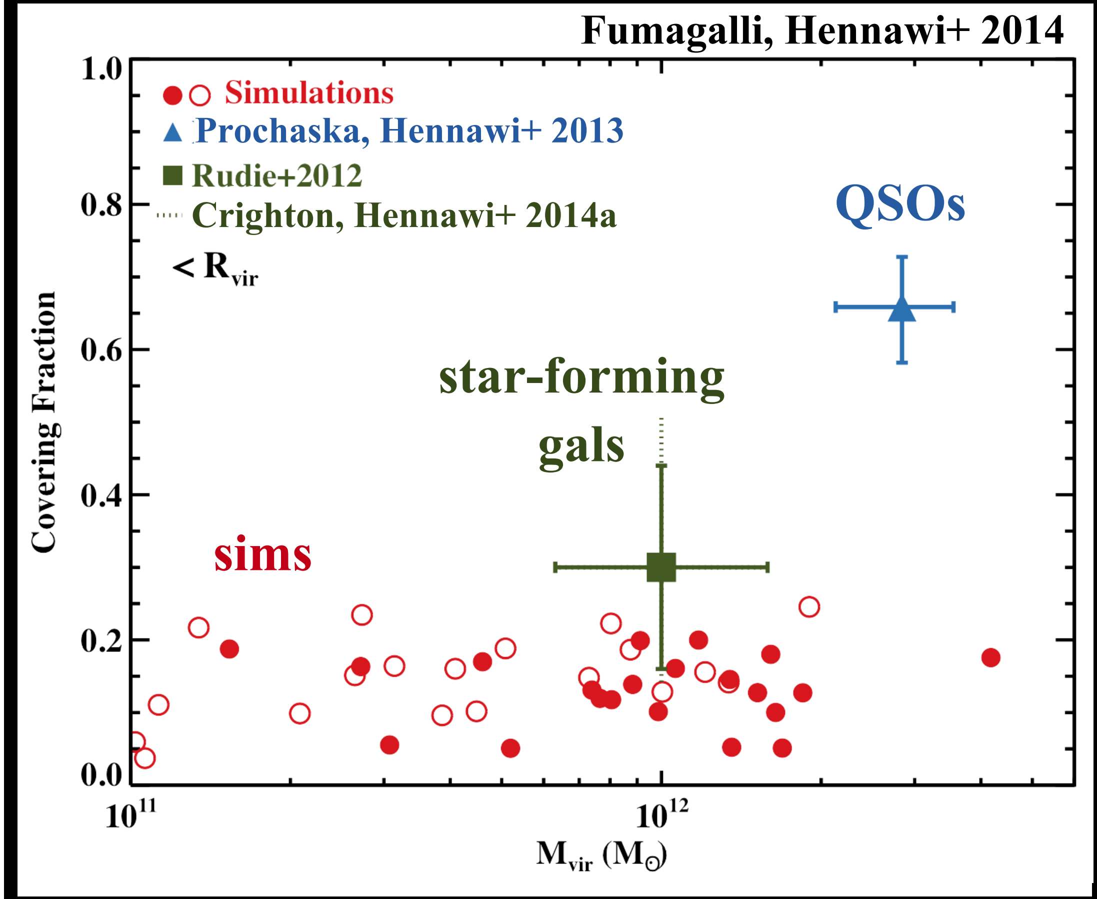

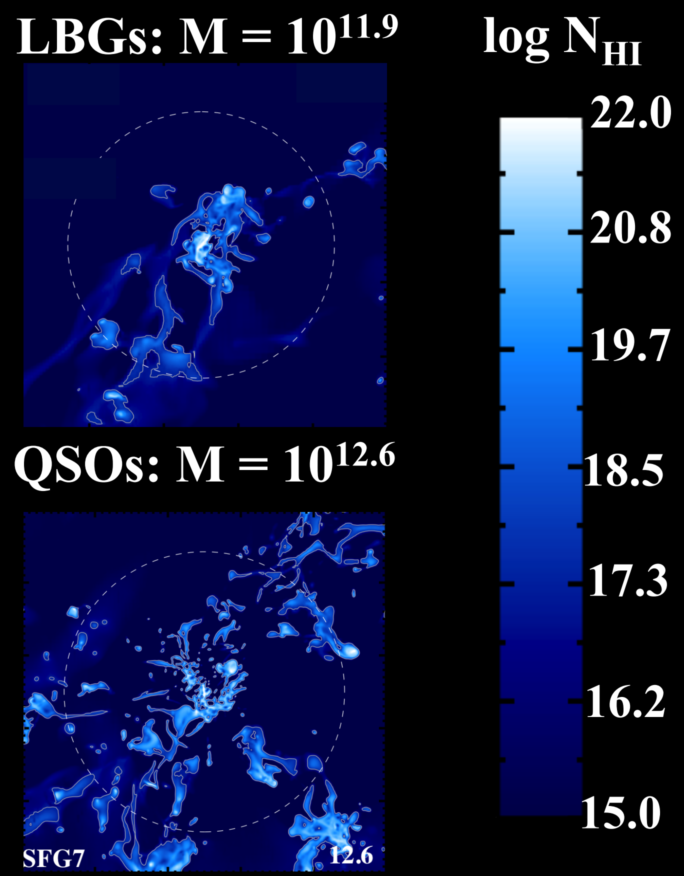

- More cold gas observed at high-mass (QSOs) than sims predict

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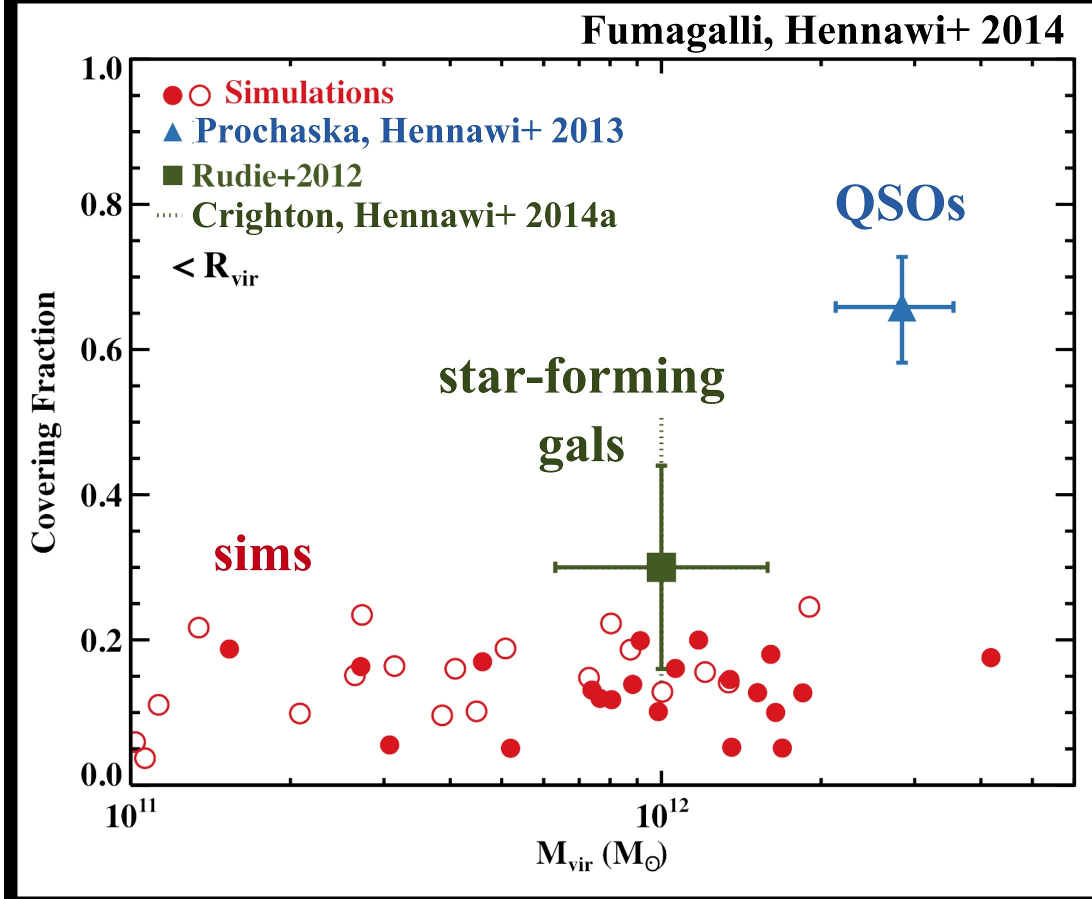
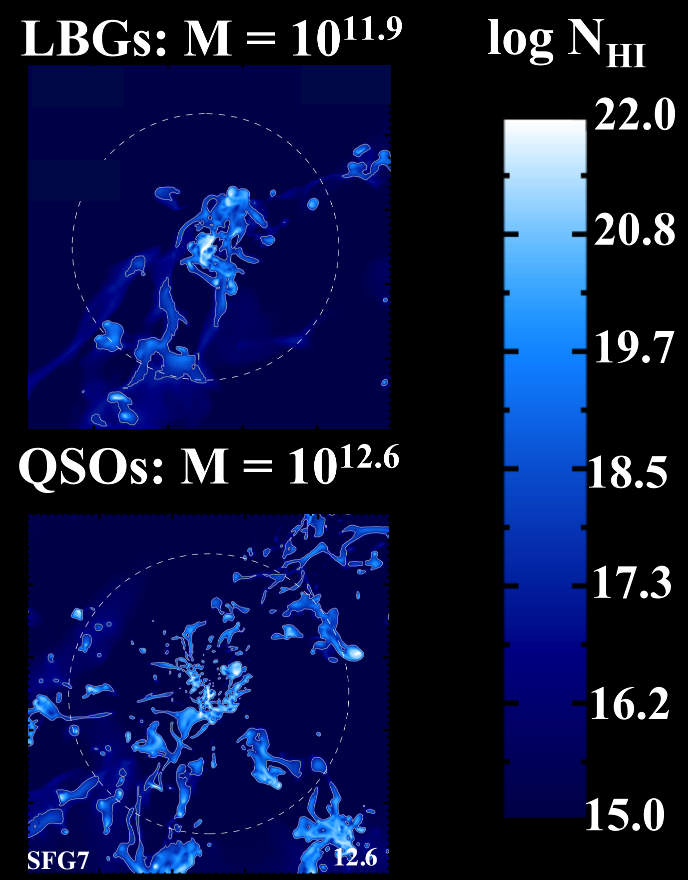
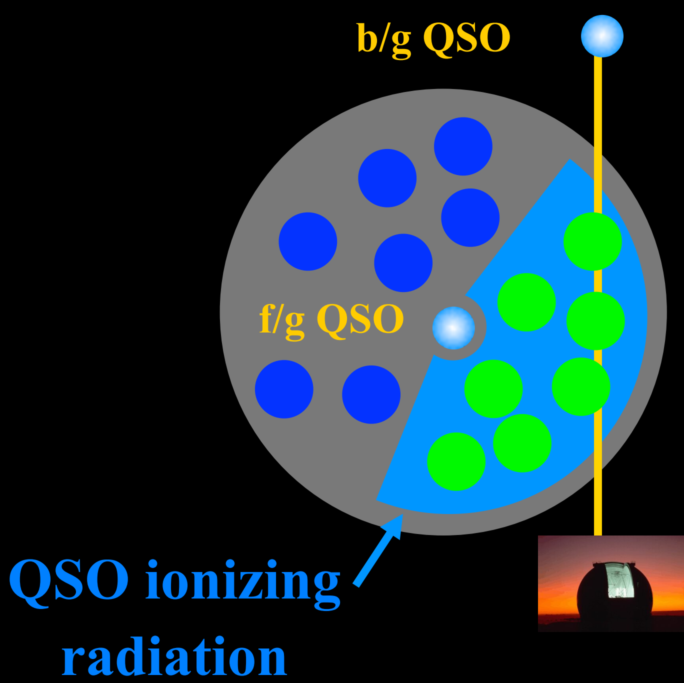




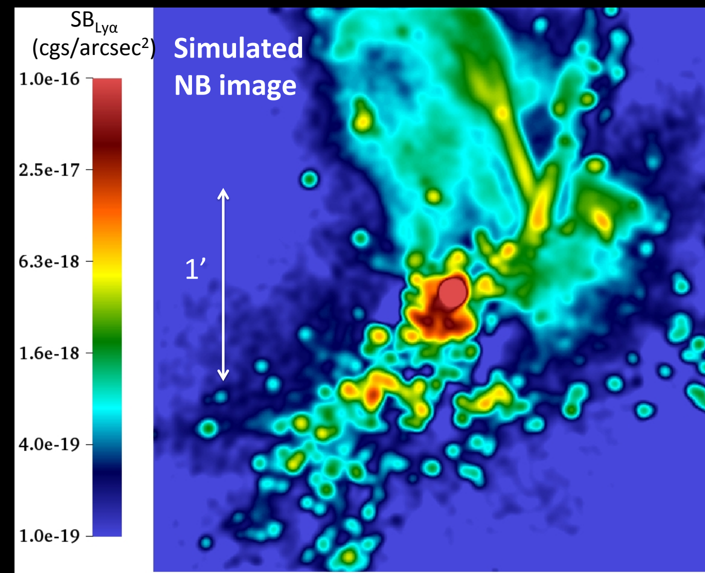
- More cold gas observed at high-mass (QSOs) than sims predict
- Solutions: QSO feedback? Is this what we want/expect it to look like ~ 10^{11} $M_\odot$ cold gas? QSOs are special (unlikely)?
- Small-scale structure unresolved in sims?

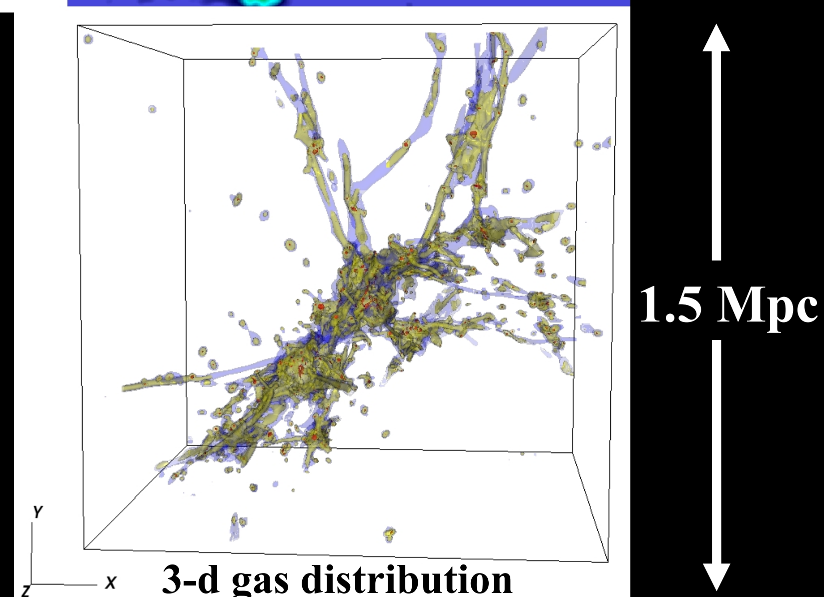
Can We Detect CGM Gas in Lyα Emission?

Photoionization/Scattering



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





Cantalupo, Arrigoni, Prochaska, Hennawi+ 2014

$R_\perp$ = 183 kpc

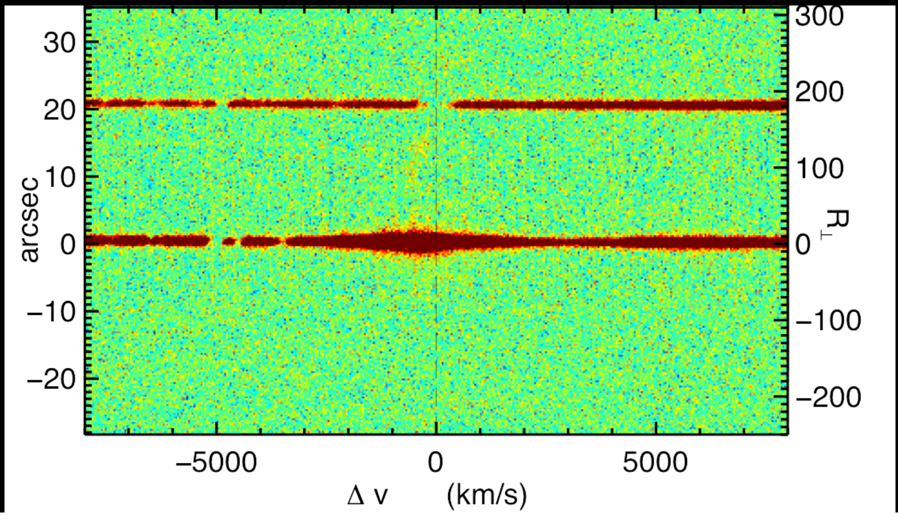
$SB_{1\sigma} = 2 \times 10^{-18}$ erg/s/cm^2/□″

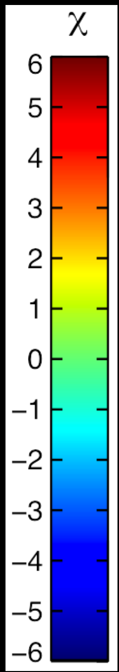
Hennawi & Prochaska (2013)

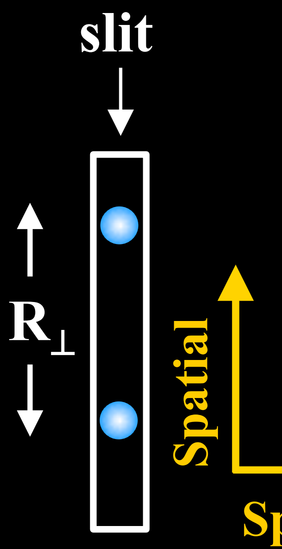
b/g QSO z = 2.21 →

f/g QSO z = 2.04 →

2-d spectrum







$R_\perp = 183$ kpc

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

Hennawi & Prochaska (2013)

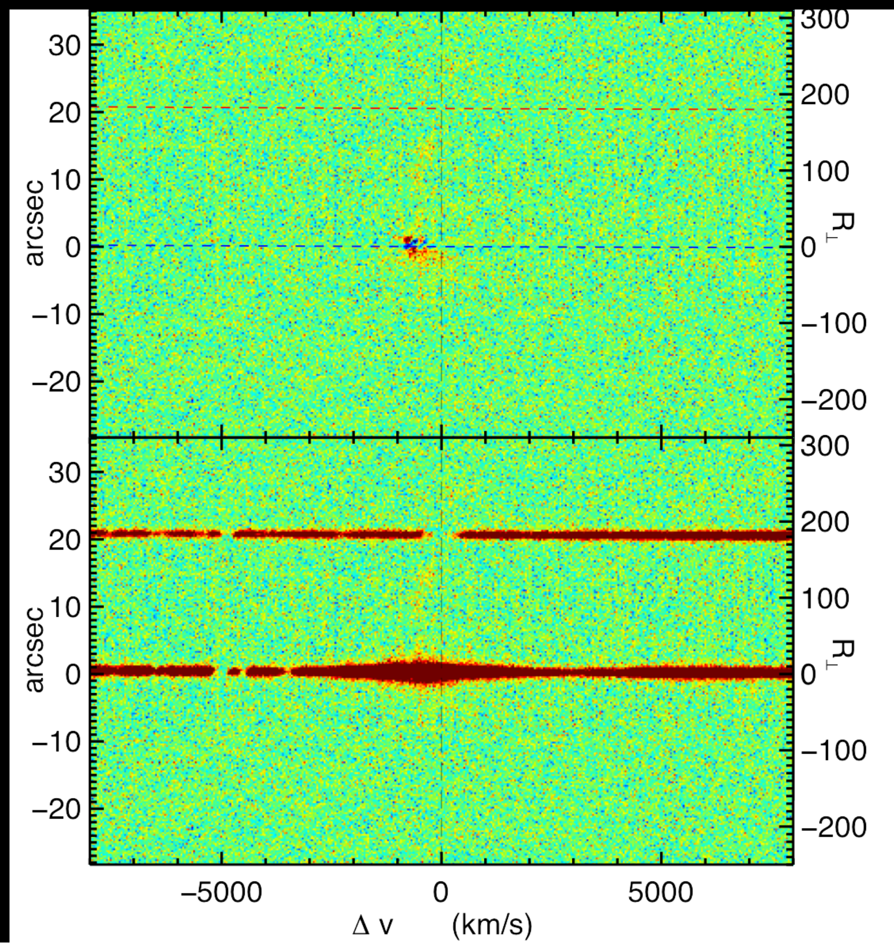
PSF subtracted 2-d spectrum

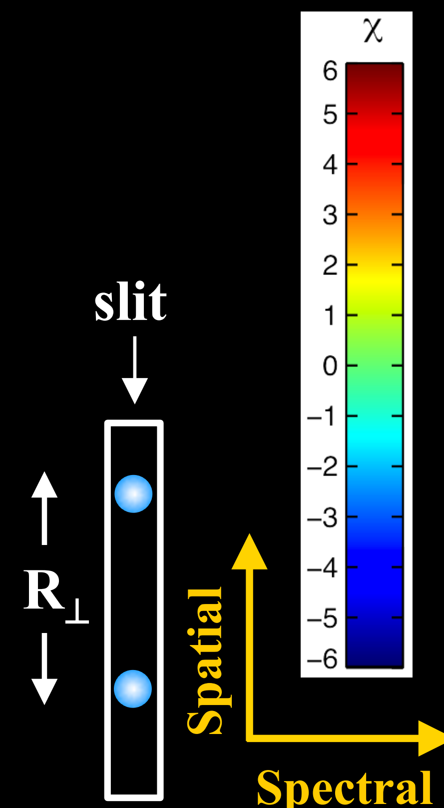
(data-model)/noise

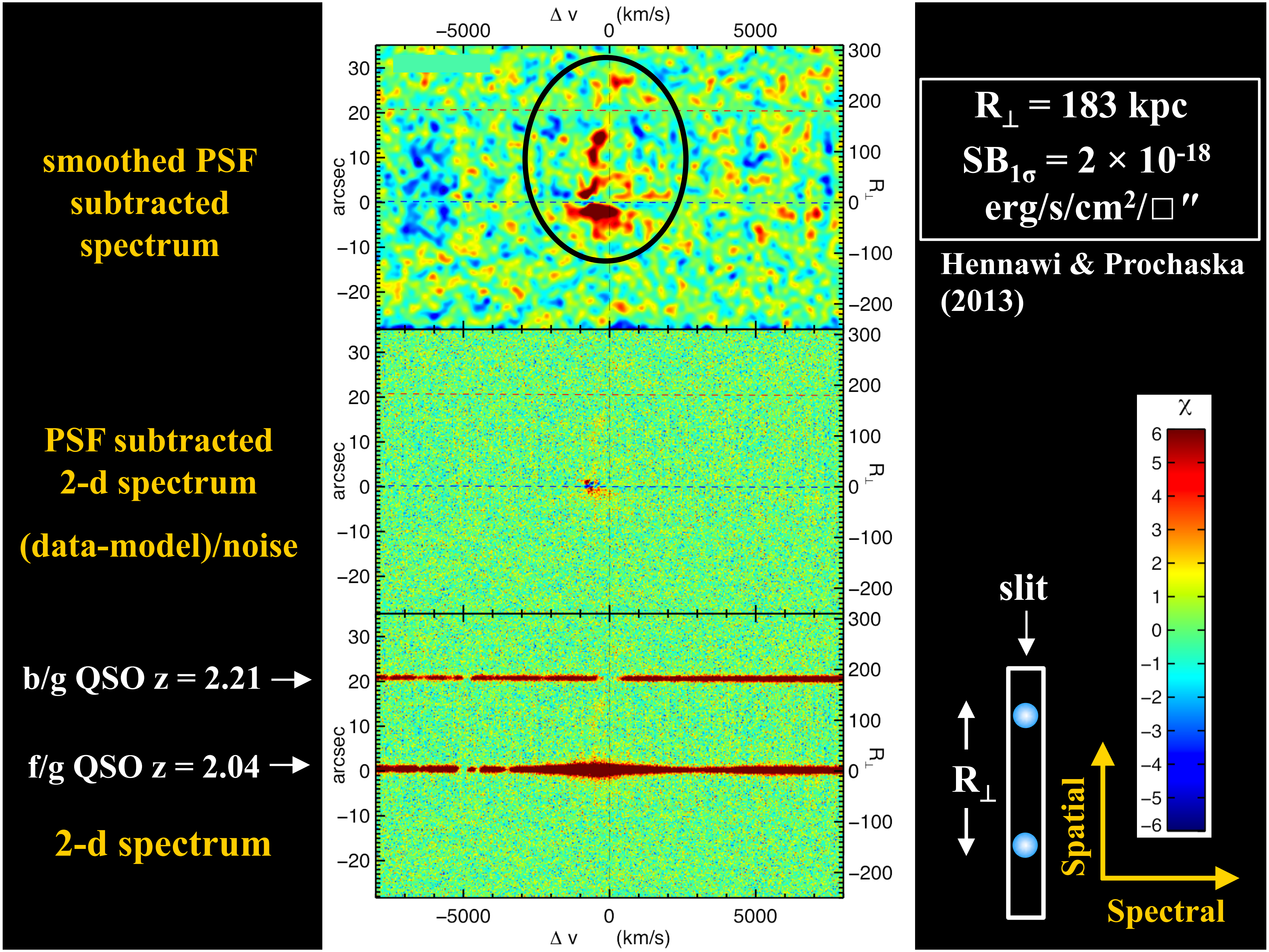
b/g QSO z = 2.21 →

f/g QSO z = 2.04 →

2-d spectrum



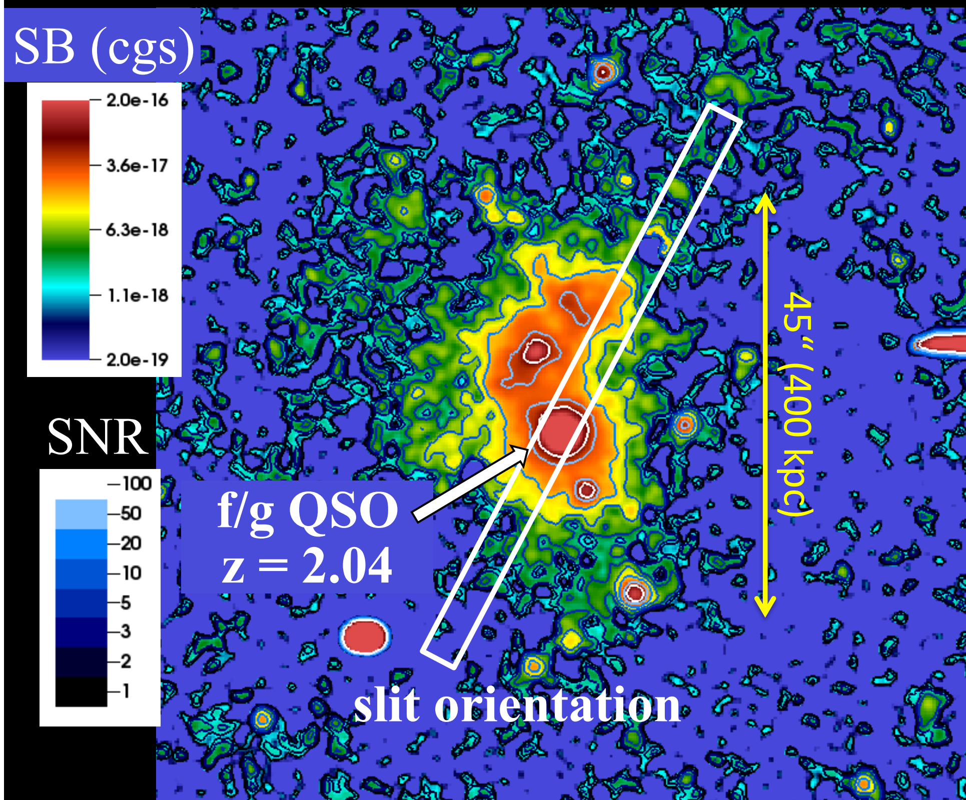




smoothed PSF subtracted spectrum
PSF subtracted 2-d spectrum
(data-model)/noise
b/g QSO z = 2.21 →
f/g QSO z = 2.04 →
2-d spectrum
Δ v (km/s)
−5000
0
5000
arcsec
30
20
10
0
−10
−20
300
200
100
−100
−200
R⊥
R⊥ = 183 kpc
SB1σ = 2 × 10-18 erg/s/cm2/□″
Hennawi & Prochaska (2013)
χ
6
5
4
3
2
1
−1
−2
−3
−4
−5
−6
slit
Spatial
Spectral

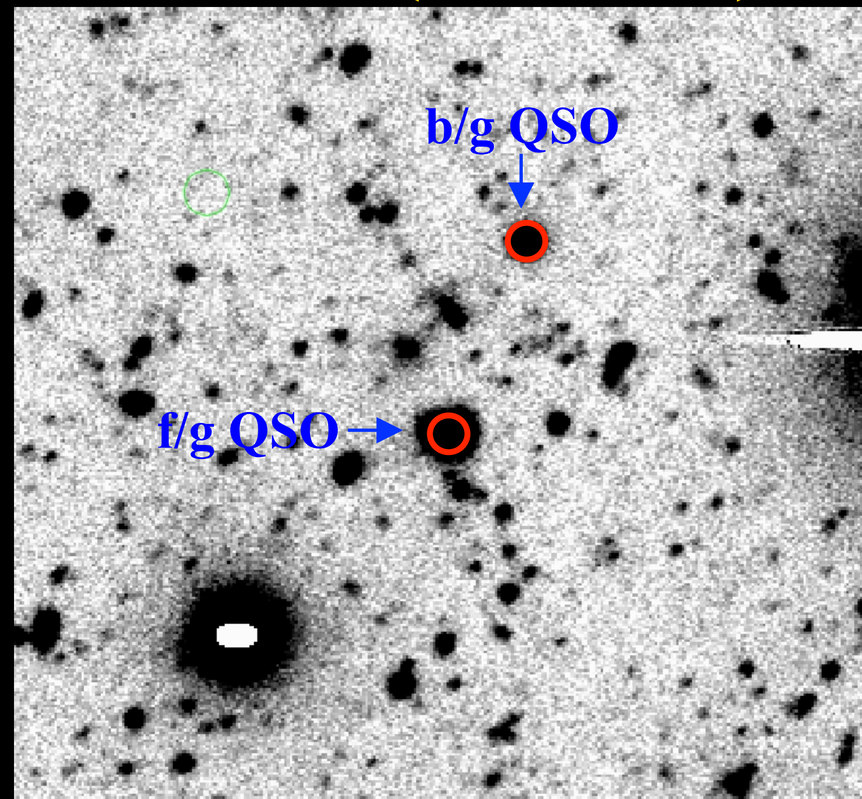
The CGM in Absorption and Emission

Narrow Band Lyα Image



Hennawi+ 2014

V-band (continuum)

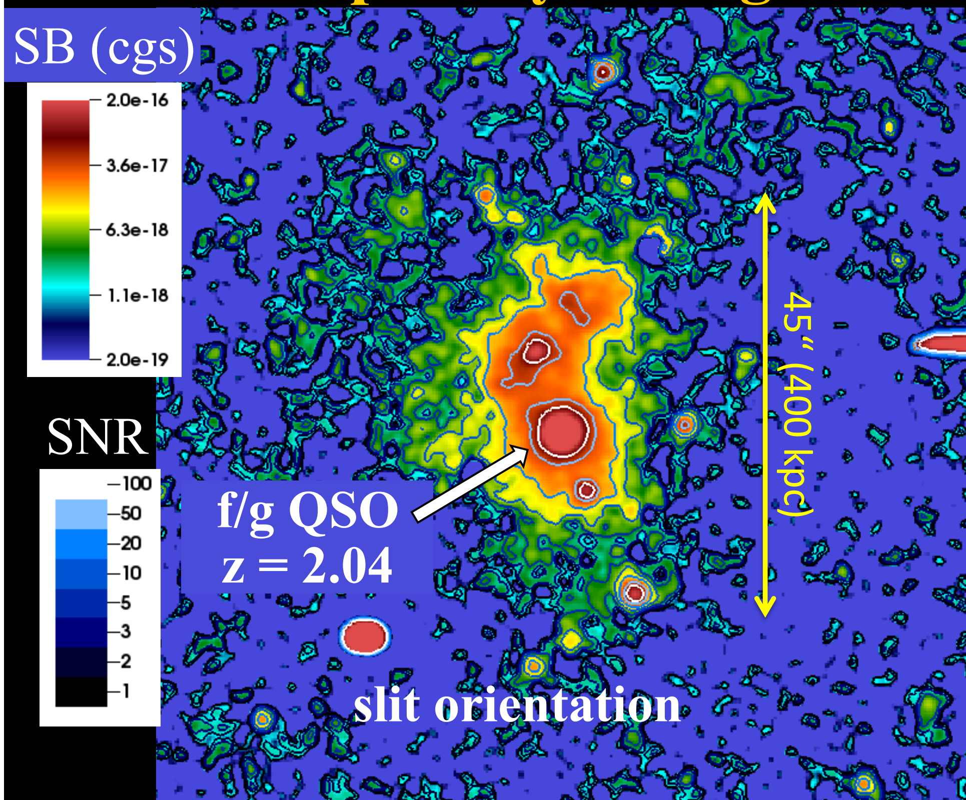


Imaging from Keck telescope

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

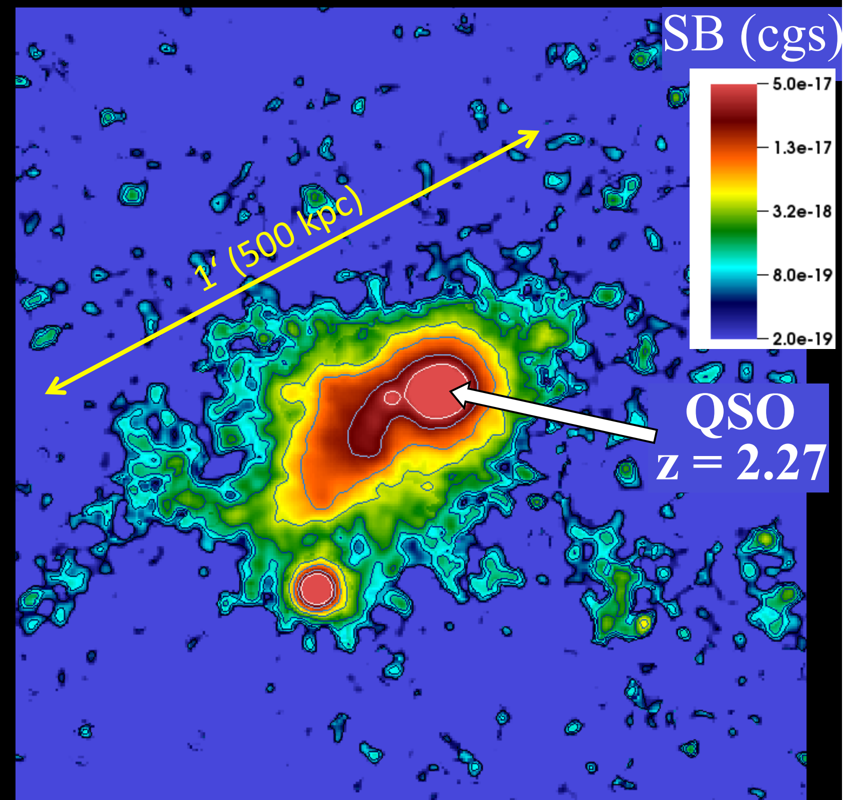
The Largest Emission Line Nebulae Known

Jackpot: Lyα Image



Hennawi+ 2014

Slug: Lyα Image

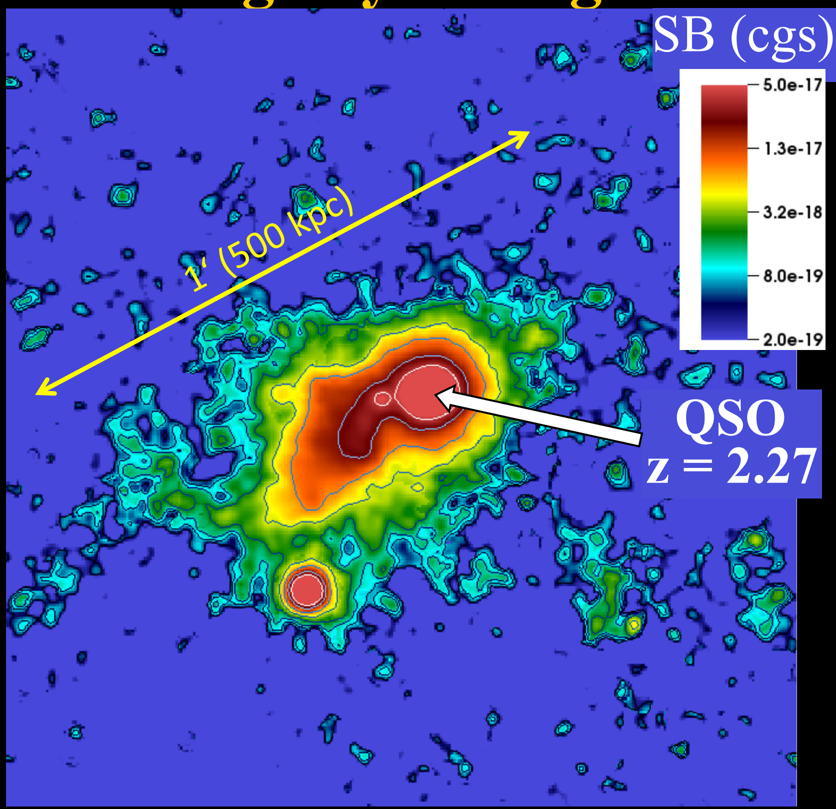


Cantalupo, Arrigoni, Prochaska, Hennawi + 2014

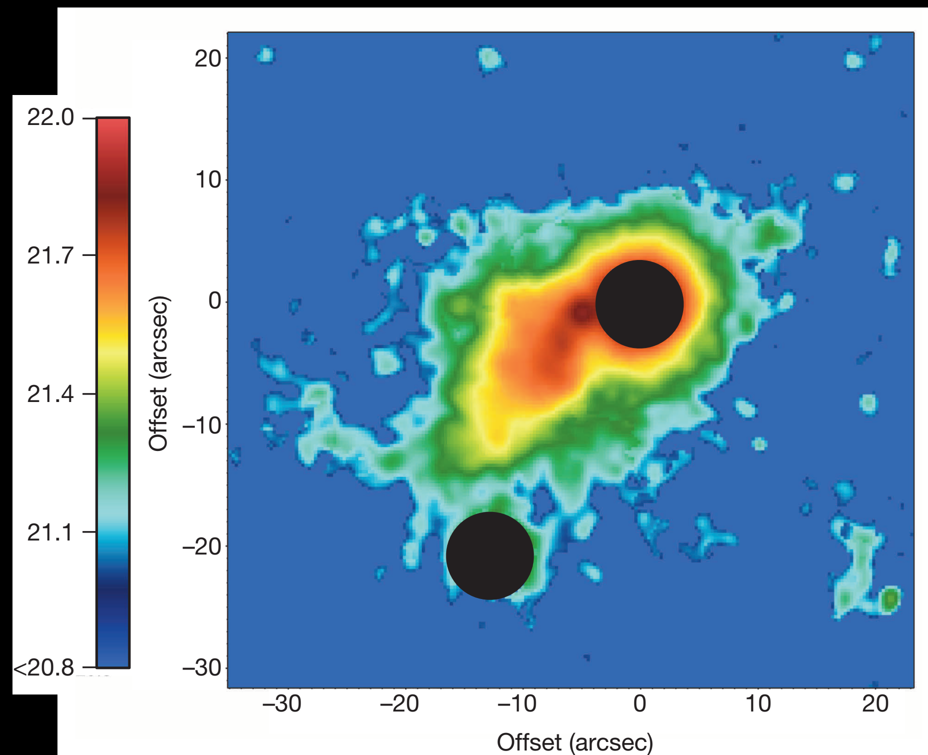
- **Limited statistics suggest ~10% of QSOs may similarly illuminate their CGM detectably**
- **Emission is likely recombination powered by the QSOs**

Problem #3: Large Densities Required to Explain Giant Nebulae

Slug: Lyα Image



Radiative Transfer Simulation



Cantalupo, Arrigoni, Prochaska, Hennawi + 2014

- Rad transfer modeling implies cool gas mass ~ $10^{12}/C^{1/2}$ $M_{\odot}$
- Reasonable cool gas masses (~ 10^{11} $M_{\odot}$) requires clumping C ~ 100 larger than present in zoom-in simulations.

Three Unresolved Problems

- **Problem # 1: CGM exhibits significant clumpiness 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. Clumping ~ 100 × higher than present in zoom-in sims seem required**