Metals in the Circumgalactic Medium of Lyman Break Galaxies at $z \sim 2.5$

Neil Crighton, Joe Hennawi, J. Xavier Prochaska, Rich Bielby, Tom Shanks, Rob Simcoe, ...

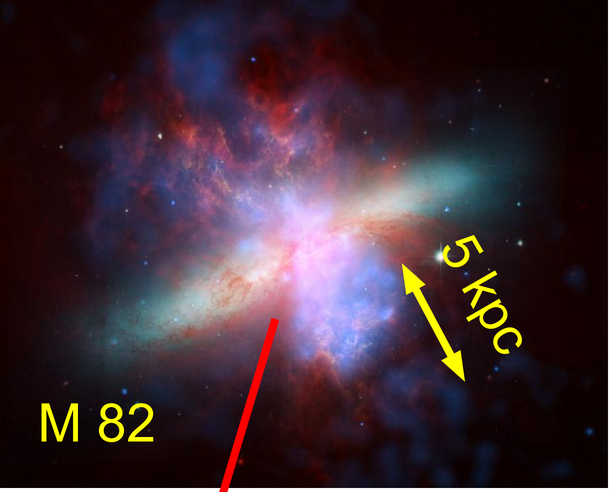
Open Questions in Galaxy Formation

- What mechanism fuels the high star formation rates seen in most galaxies at $z \sim 2 - 3$?
- What is the nature of star-formation driven outflows in these same galaxies?

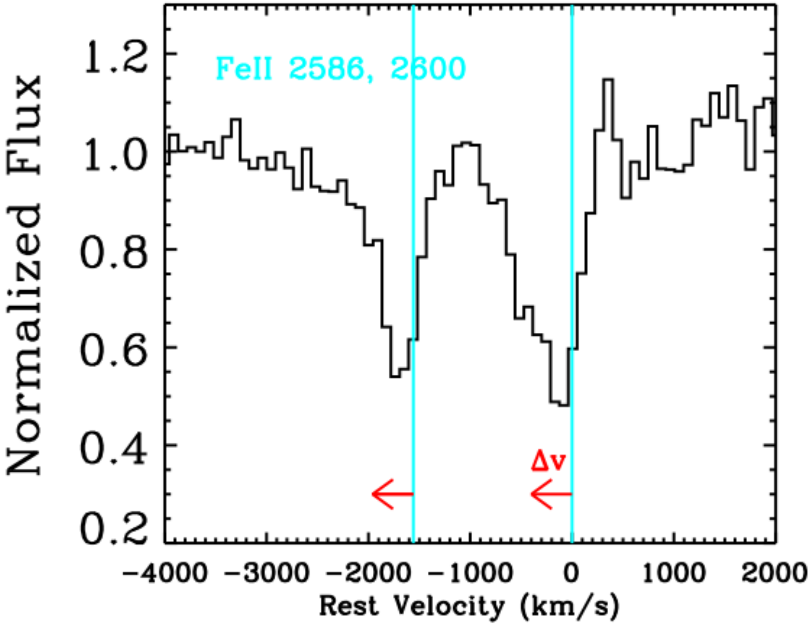
Stinson+ in preparation

Supernovae-driven Winds

How far do they extend?
What is their mass outflow rate?

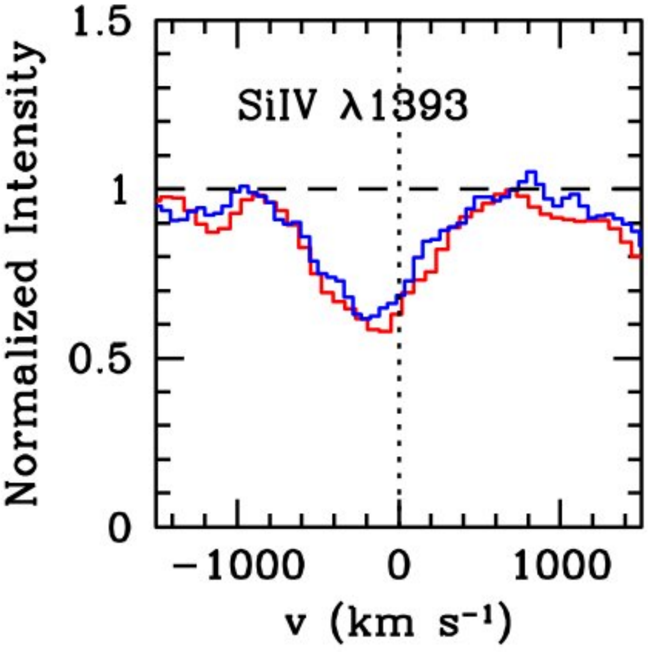


z ~ 0.8



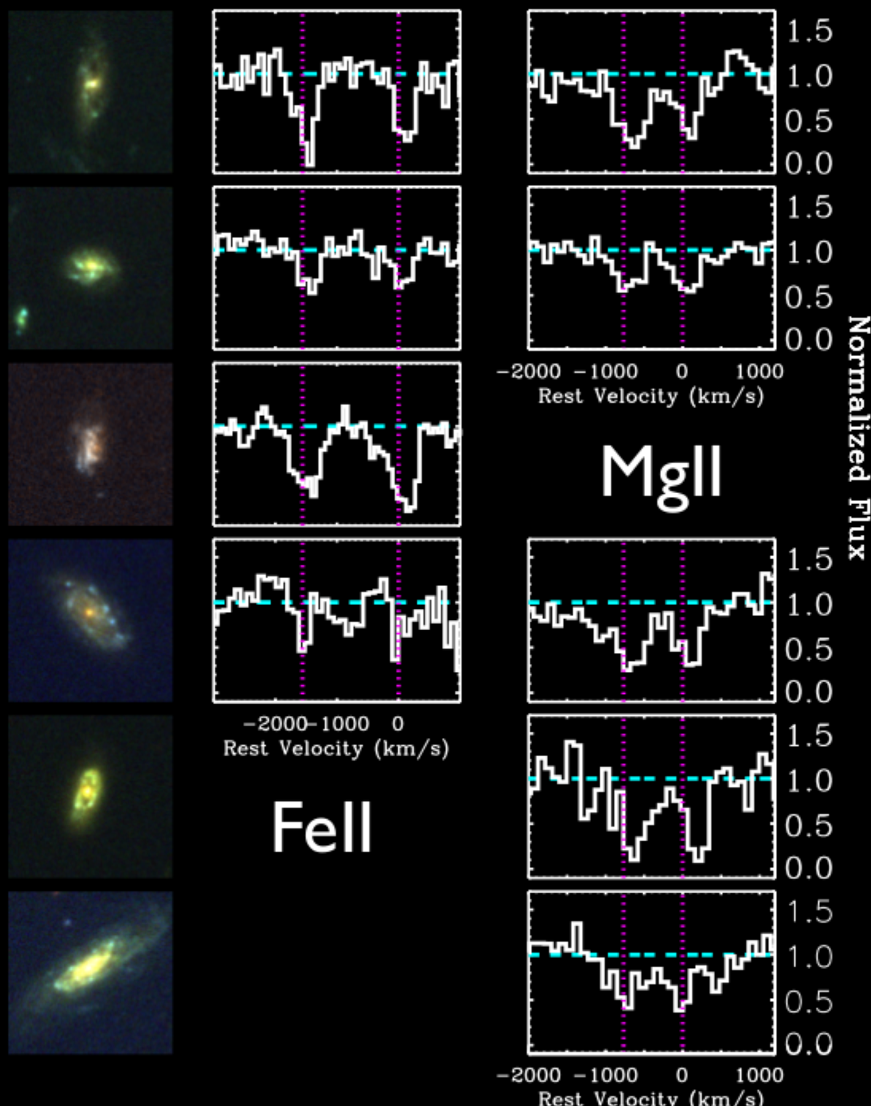
Rubin+ submitted, Martin+ 2012,
Weiner+ 2009 z ~ 1.4

z ~ 2.4



Steidel+ 2010

Inflows



Metal enriched inflows – galactic fountains?

Easiest to detect when galaxy seen edge on: aligned with disk?

But metal-poor inflows cannot be detected...

Rubin, Prochaska, Koo & Phillips 2012

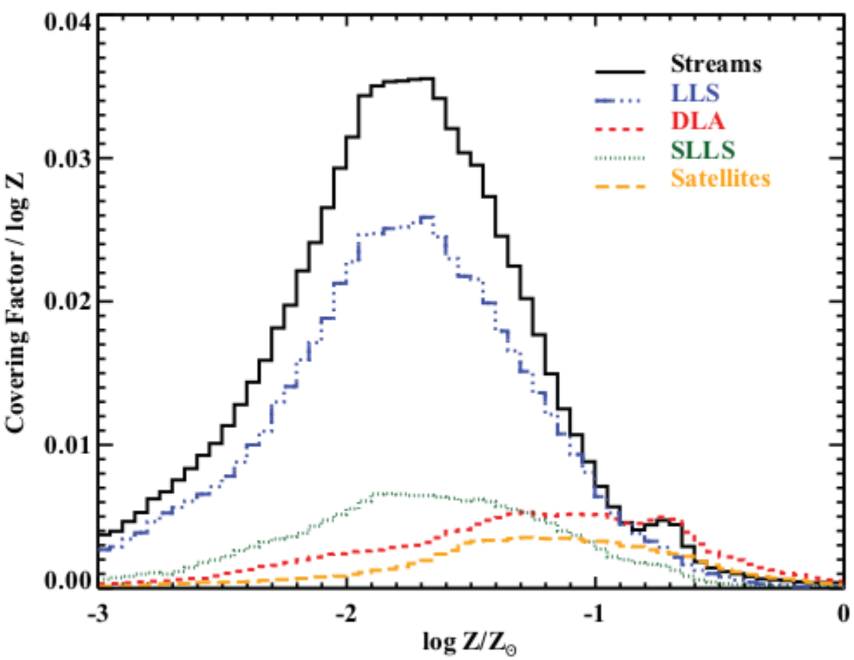
Also Martin+ 2012

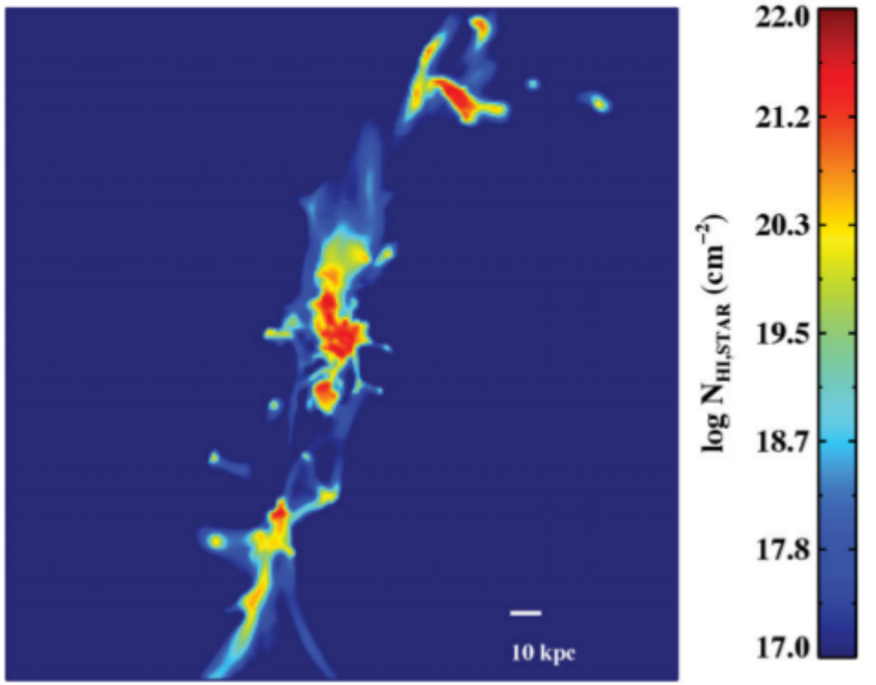
Measuring Metallicity is the Key to Observing Cool Accretion

Fumagalli+ 2011, van de Voort+ 2012, Stewart+ 2011, Shen+ 2013

Inflowing streams:

Cool ($T<10^5$ K) High-N_{HI} Low metallicity





Fumagalli+ 2011

How can we measure the metallicity?

$$[\mathrm{X}/\mathrm{H}] \equiv \log_{10} \frac{(N_{\mathrm{X}}/N_{\mathrm{H}})_{\mathrm{obs}}}{(N_{\mathrm{X}}/N_{\mathrm{H}})_{\odot}}$$

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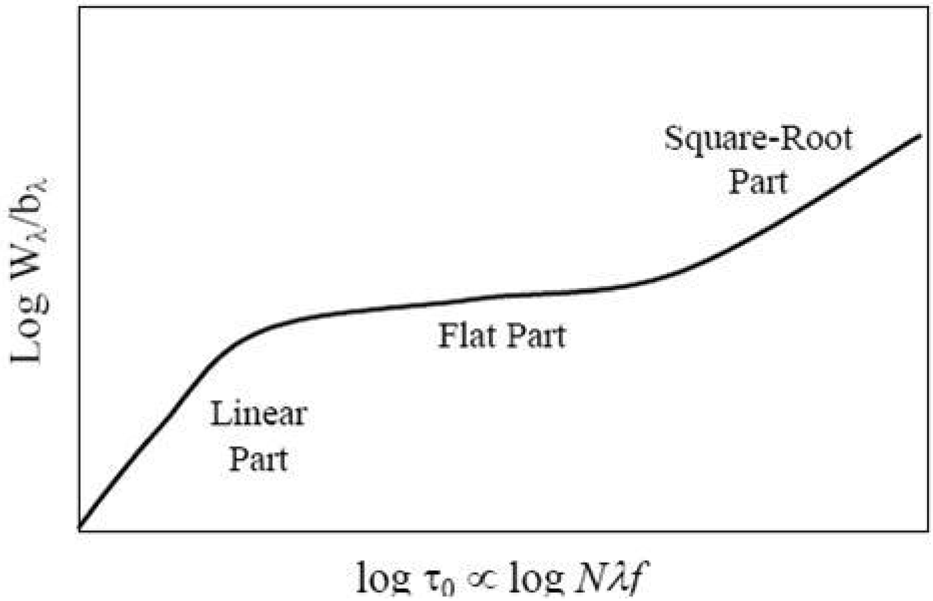
$N(C^+)$: $N(C)$?

How can we measure the metallicity?

$$[X/H] \equiv \log_{10} \frac{(N_X/N_H)_{obs}}{(N_X/N_H)_\odot}$$

Ly-α at
$N(H^0) = 10^{14}$ cm^{-2}
looks the same as Ly-α at
$N(H^0) = 10^{17}$ cm^{-2}



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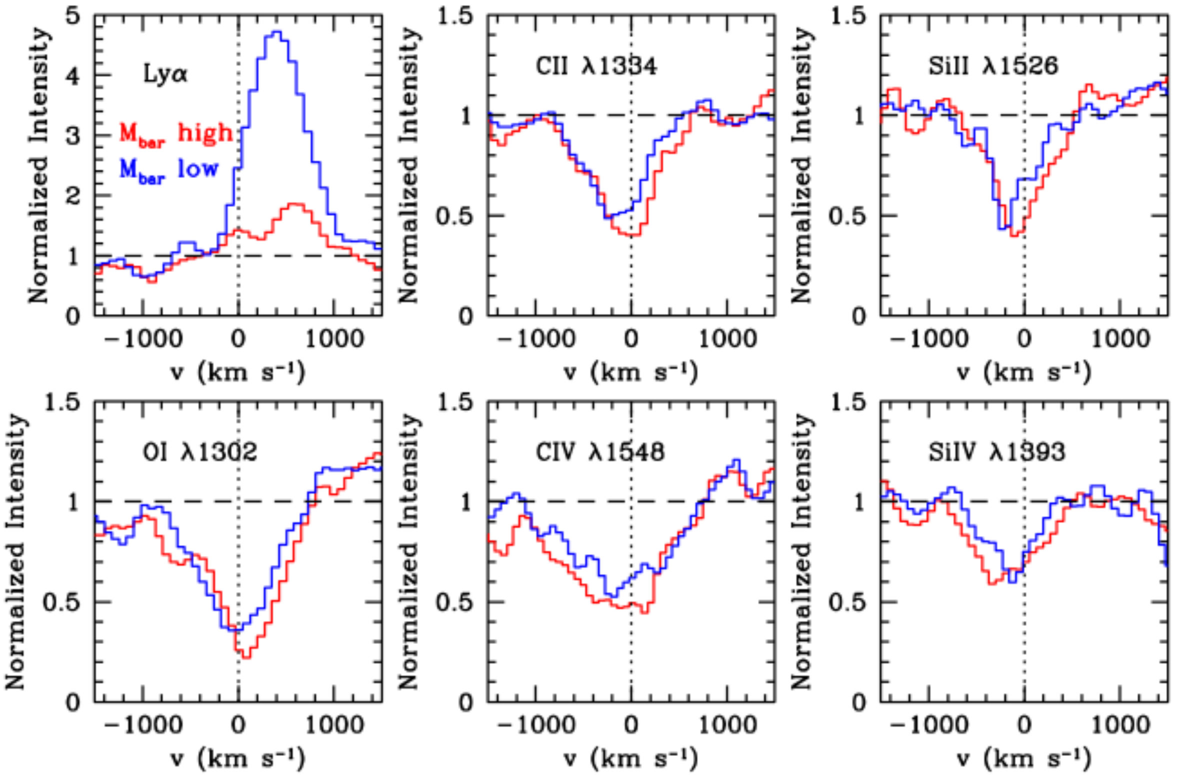

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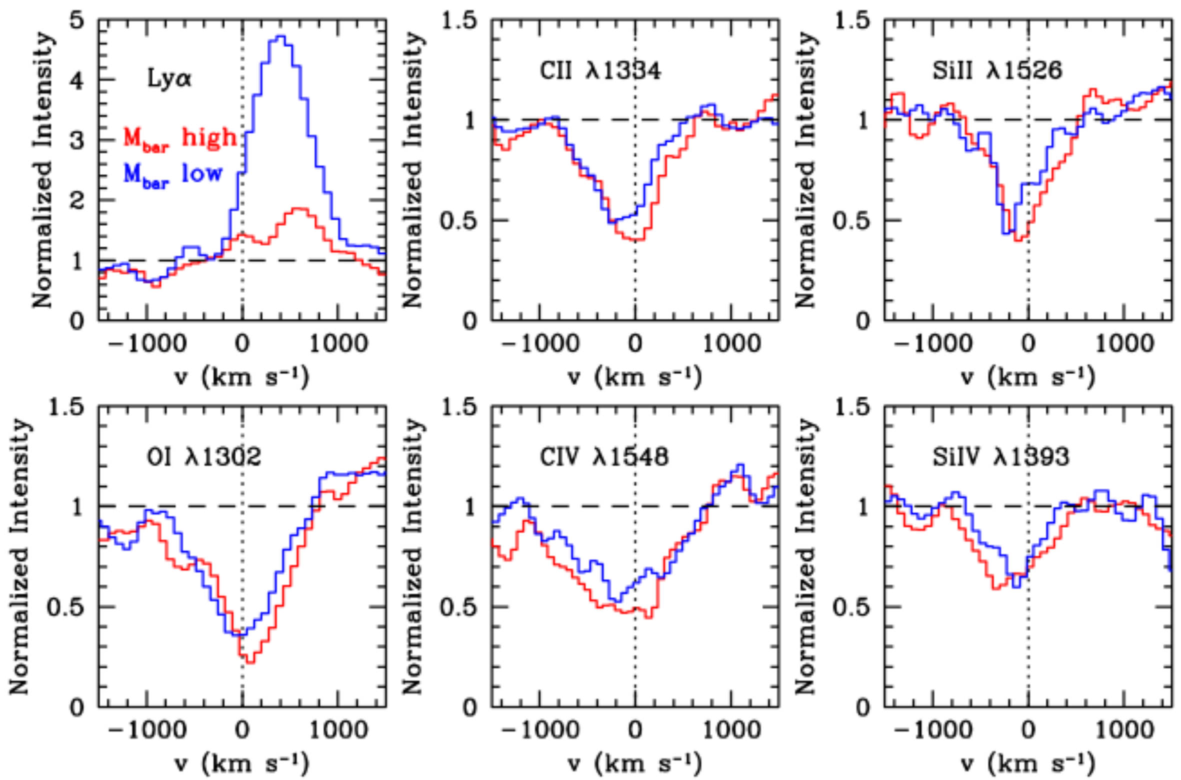
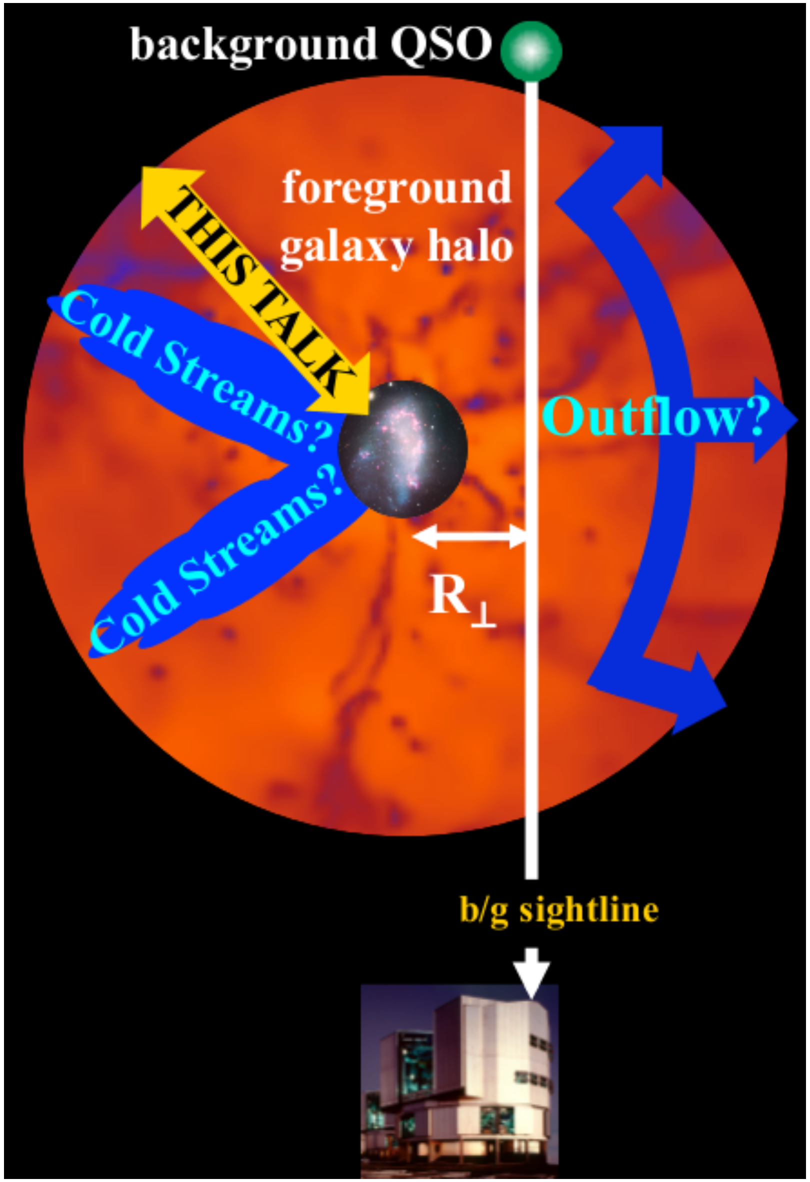
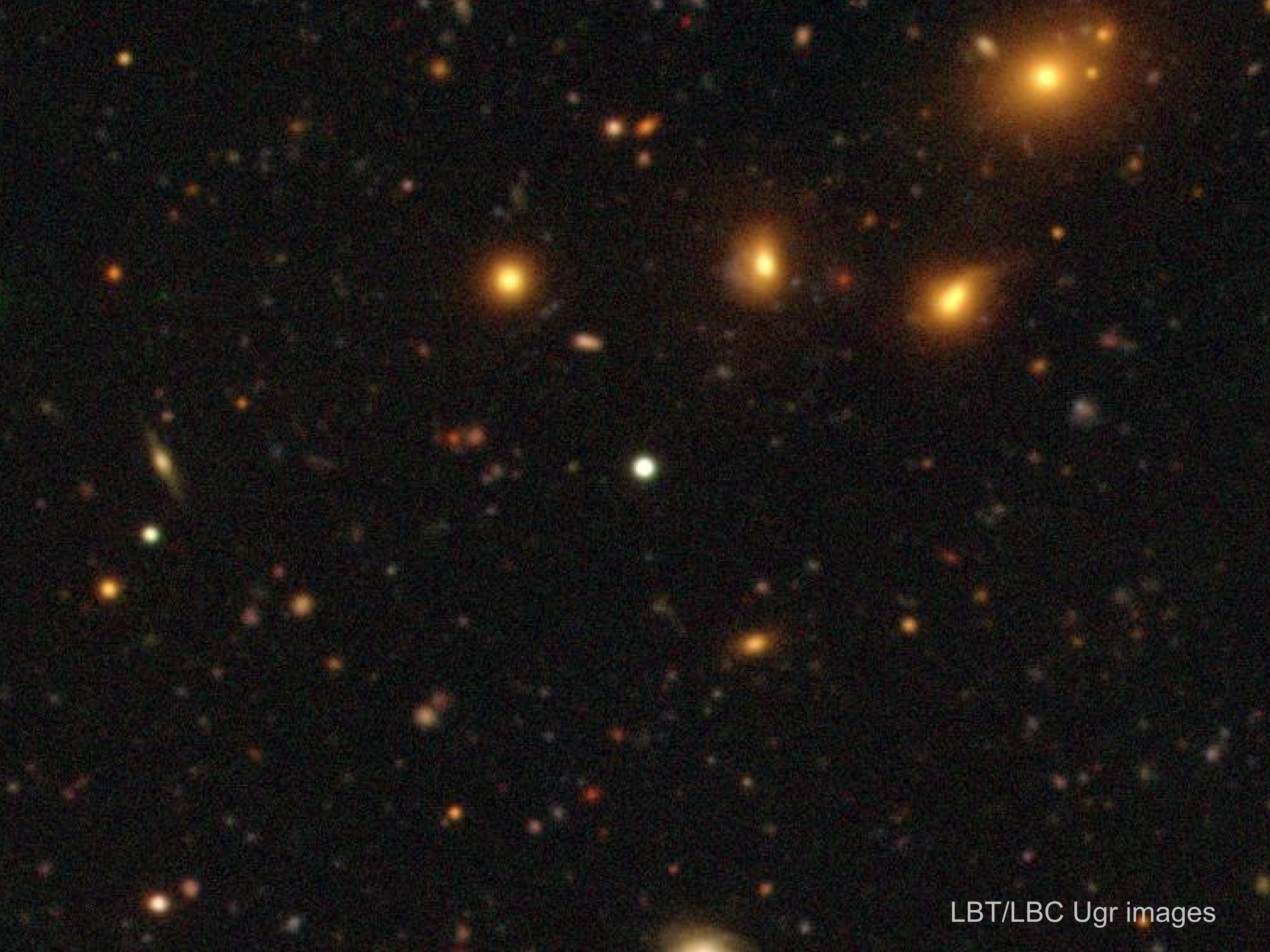


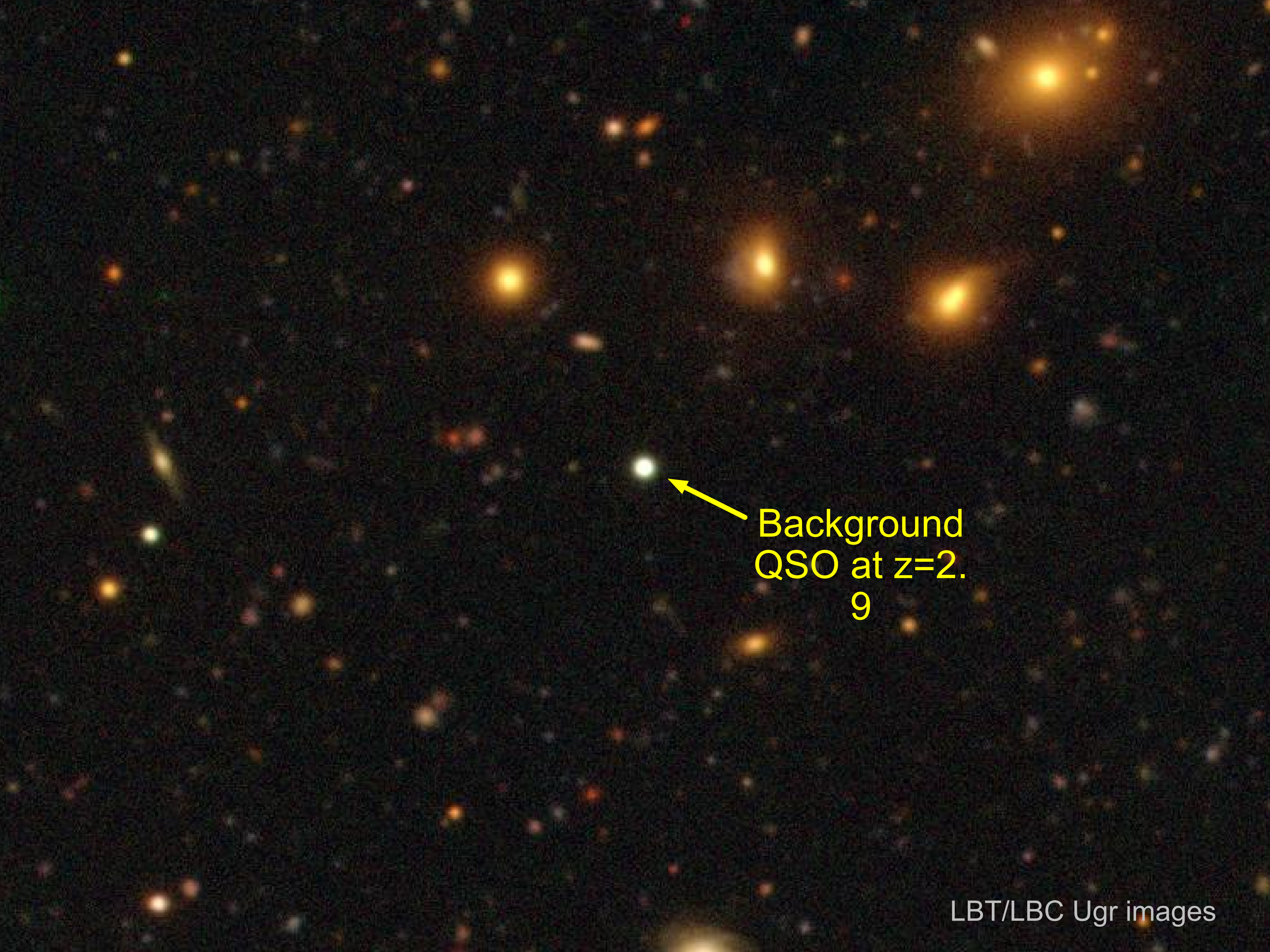
?

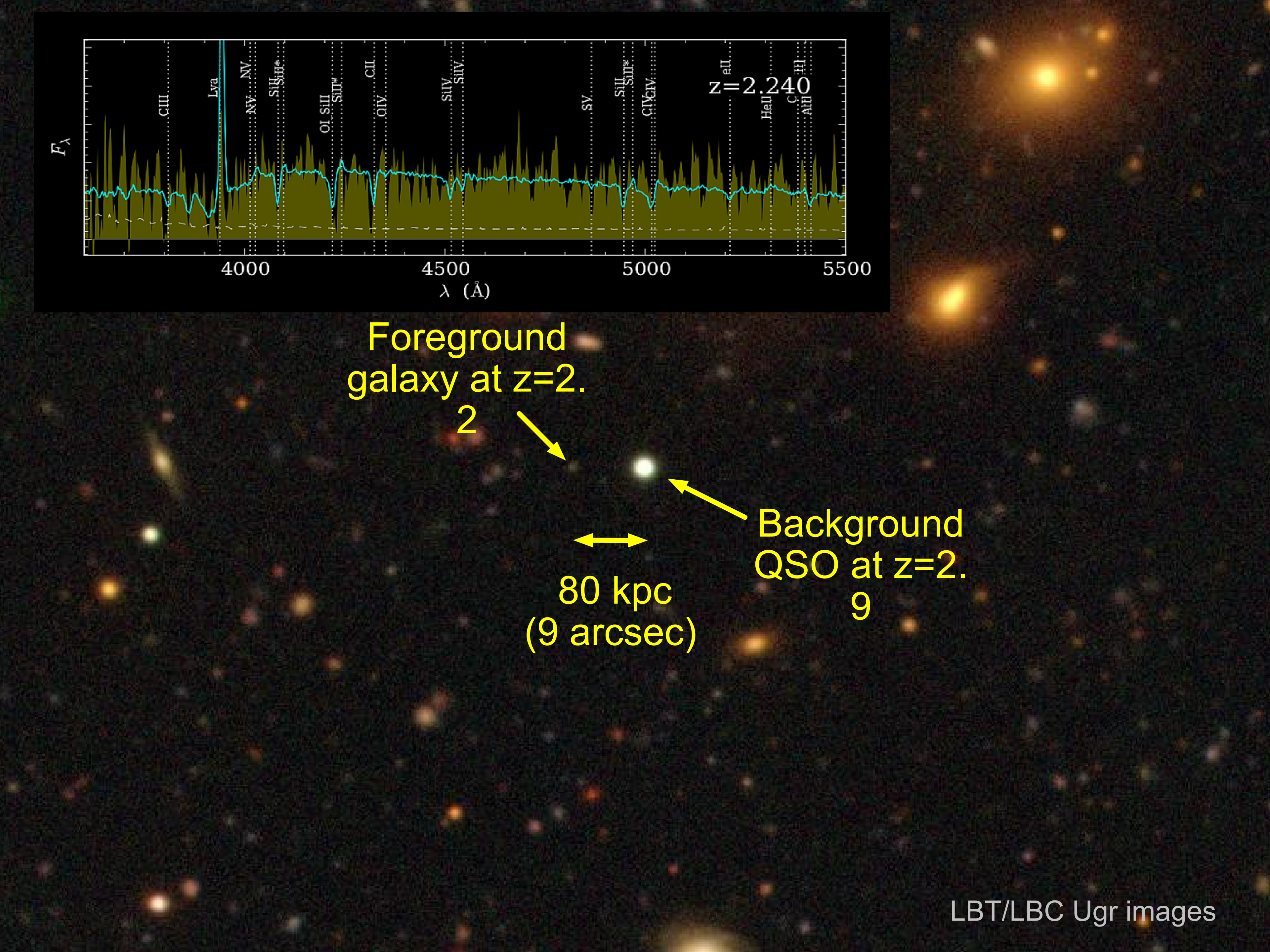
Absorption using background QSOs

- Diffuse T ~10^4-10^5 K gas, $N_{HI} > 10^{13}$ cm^{-2}
- Many rest-frame UV metal transitions & HI, modelling possible.
- Directly measure projected distance.
- High-quality, high S/N spectra are needed!




LBT/LBC Ugr images

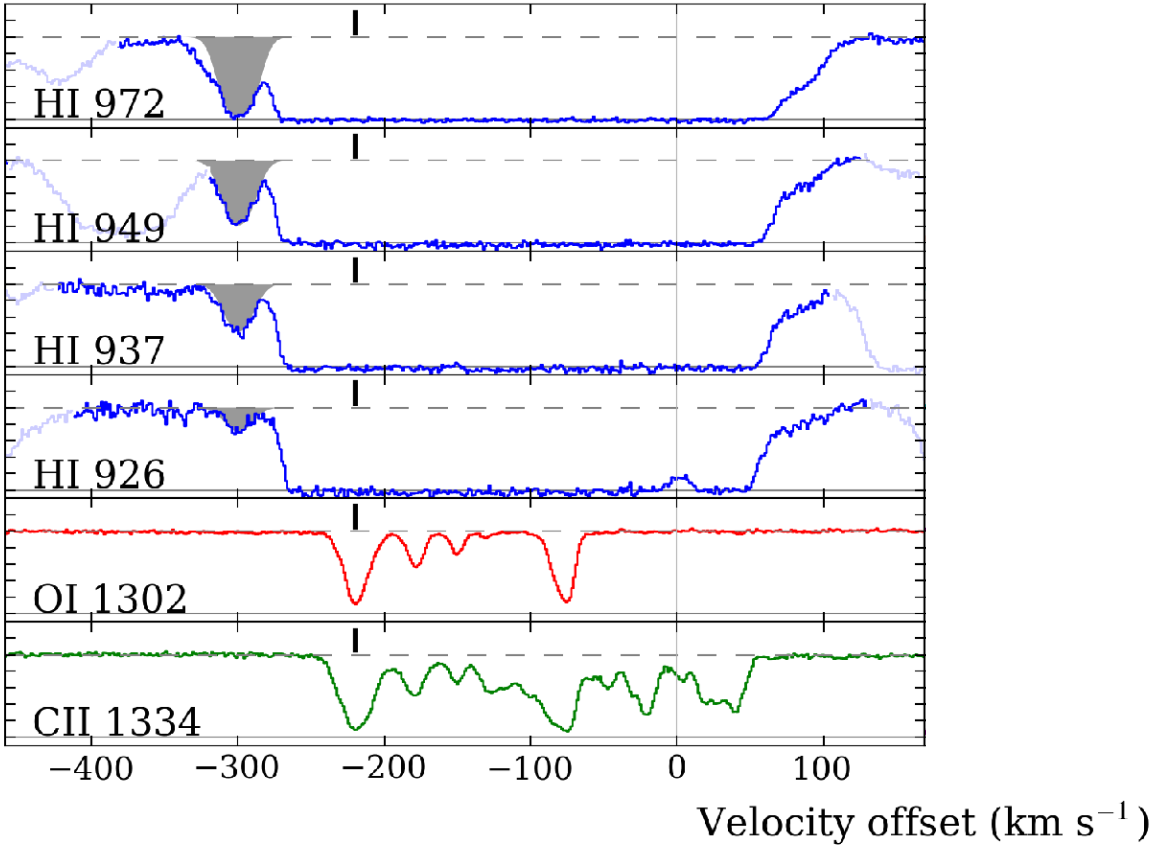

Background
QSO at z=2.
9
LBT/LBC Ugr images



z=2.240
Lyα
CIII
NV
SiII
SiII*
OI SiII
CII
OIV
SiIV
SV
CIV
HeII
AlII
F_λ
4000
4500
5000
5500
λ (Å)
Foreground galaxy at z=2.2
Background QSO at z=2.9
80 kpc (9 arcsec)
LBT/LBC Ugr images

A deuterium absorber in the CGM

Strong HI absorber at $R_{\perp}$ = 58 kpc from a foreground z = 2.44 galaxy. sub-DLA with N_{HI}= $10^{19.85}$ cm^{-2}

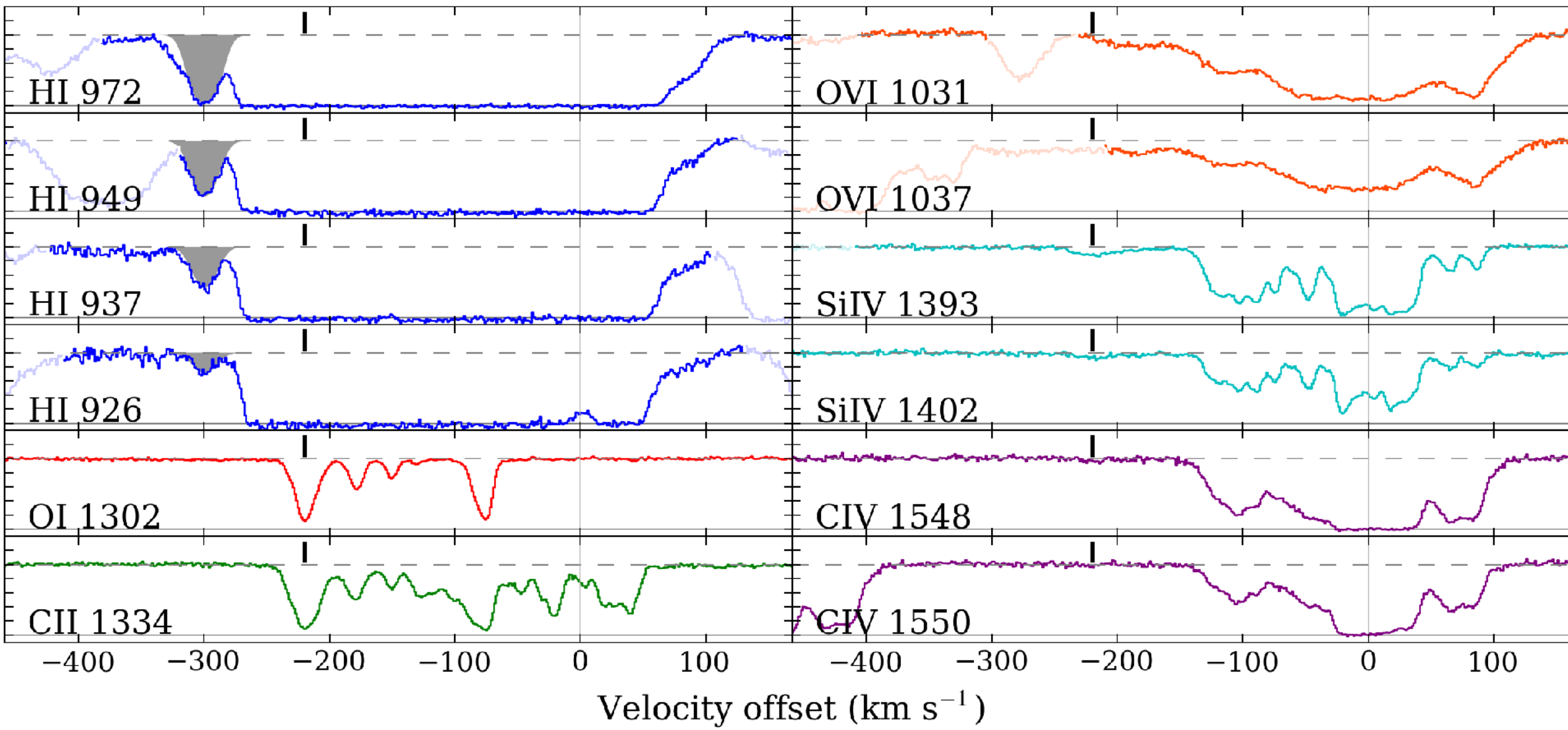


Crighton, Hennawi & Prochaska, submitted.

Pair discovered by Rudie+ 2012

A D absorber in the Circumgalactic medium

Strong HI absorber at $R_{\perp}$ = 58 kpc from a foreground z = 2.44 galaxy. sub-DLA with N_{HI}= $10^{19.85}$ cm^{-2}



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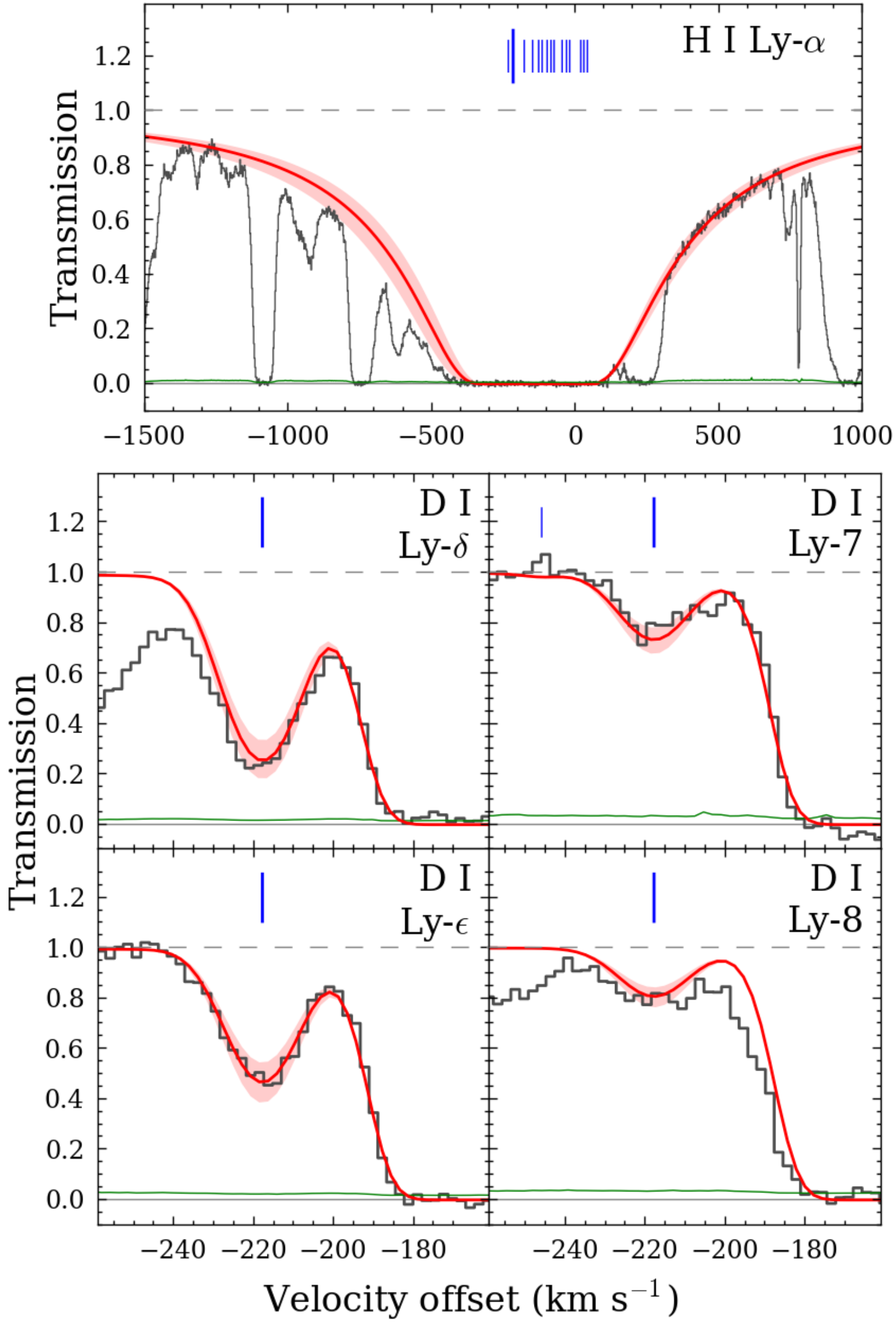
Pair discovered by Rudie+ 2012

Background QSO
J1444535+291905

- z_{qso}= 2.66

Foreground galaxy:

- z_{gal}= 2.439
- SFR ~30 Msun/yr
- R = 58 kpc
- M_{halo}~ $10^{11.7}$ $M_{\odot}$



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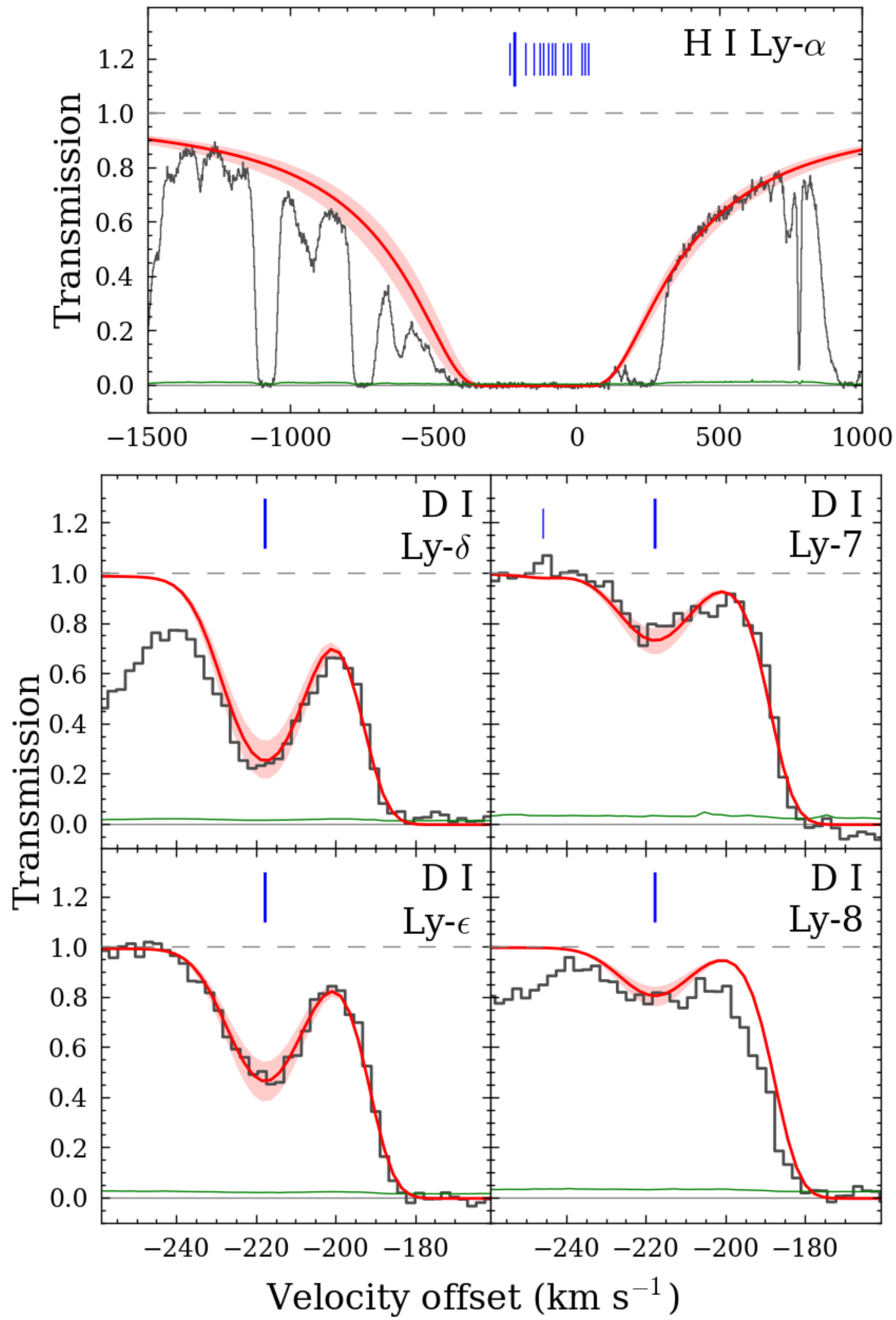
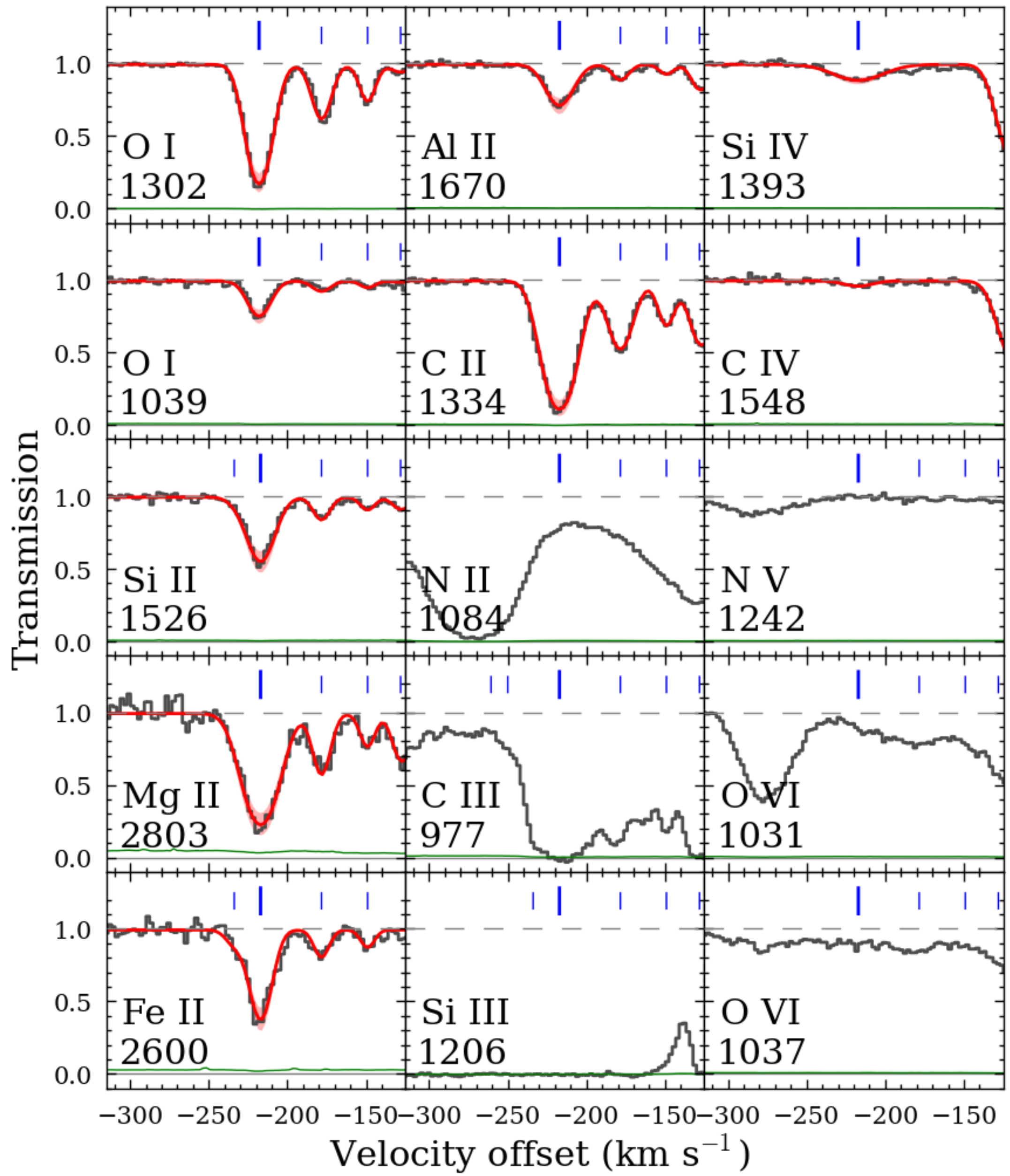
$N(H^0)$ precisely determined from $N(D^0)$ absorption, as D/H is known from big bang nucleosynthesis.

log N(HI) = 19.50 +/- 0.16



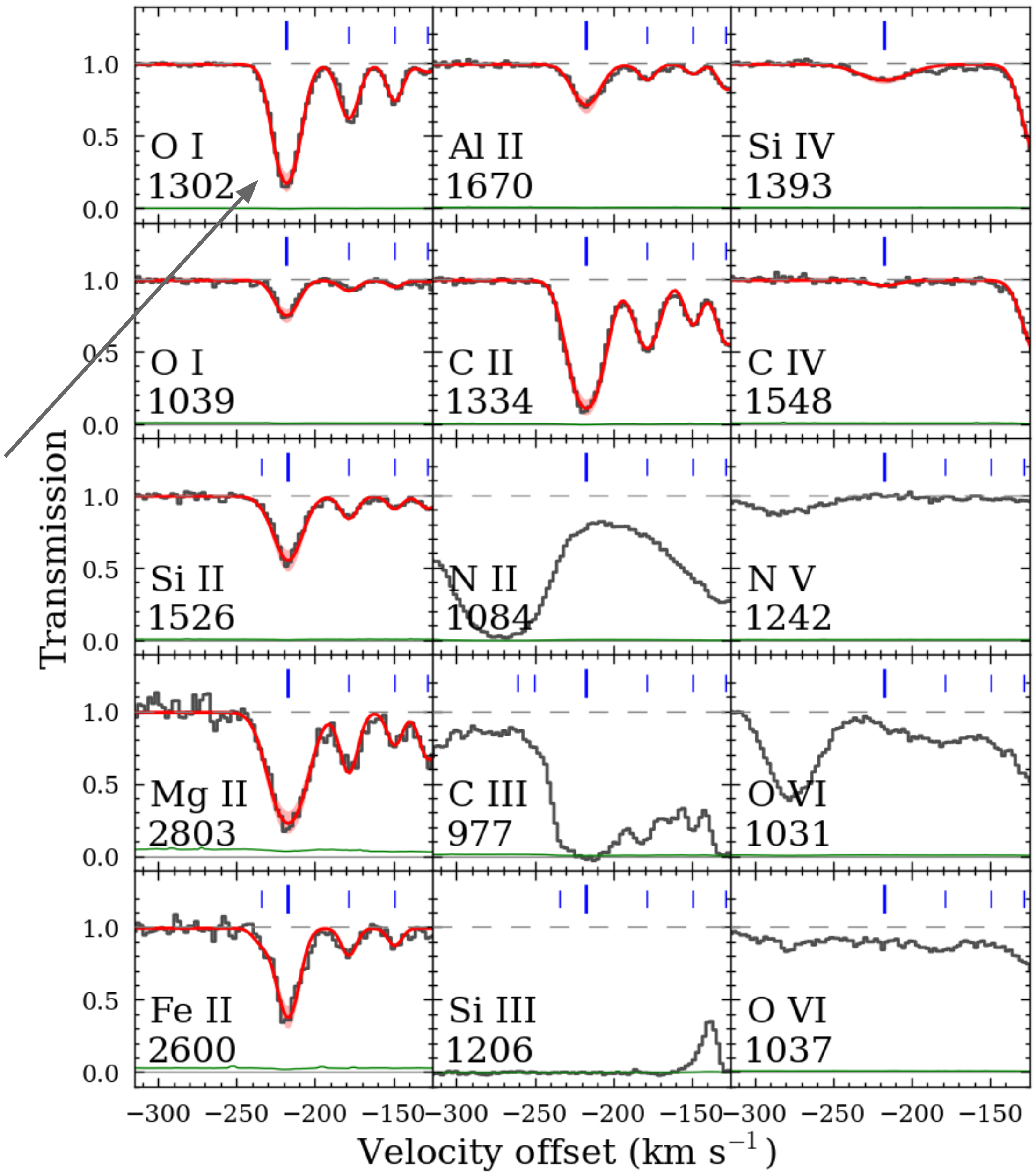


O I
1302
Al II
1670
Si IV
1393
O I
1039
C II
1334
C IV
1548
Si II
1526
N II
1084
N V
1242
Mg II
2803
C III
977
O VI
1031
Fe II
2600
Si III
1206
O VI
1037
Transmission
Velocity offset (km s^{-1})

OI and HI have similar ionization energies and exchange electrons, which allows a robust, model-independent metallicity measurement:

[O/H] = -2.0 +/- 0.17

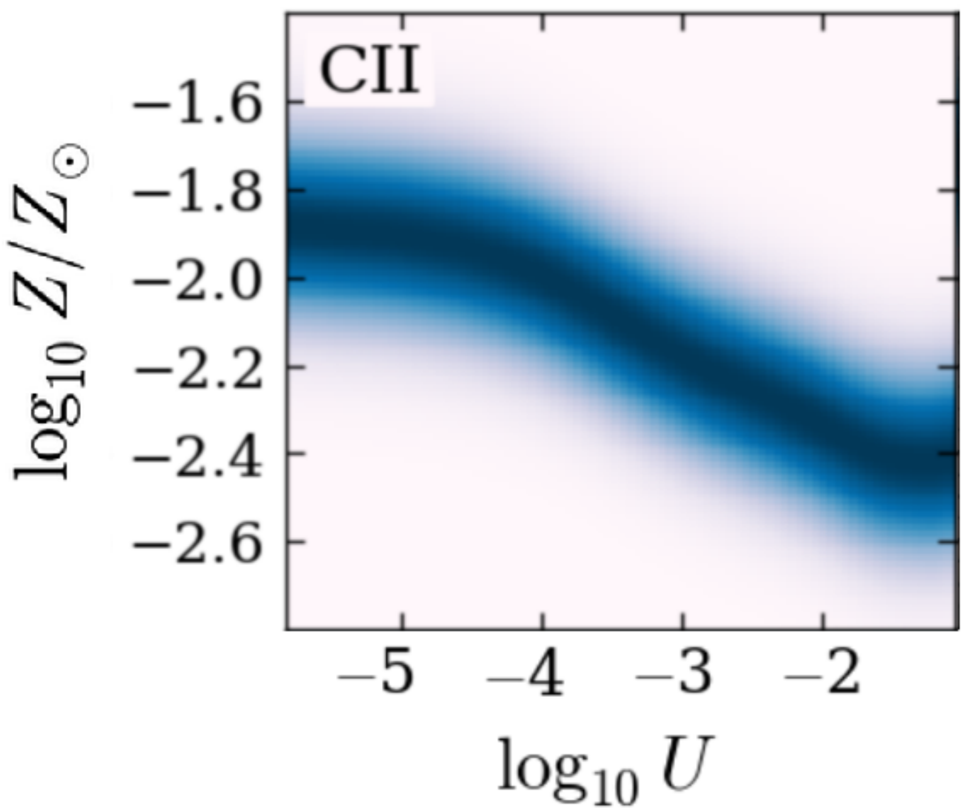
(~ 0.01 times solar metallicity)



Cloudy & Associates

Photoionization Simulations for the Discriminating Astrophysicist Since 1978

(Ferland et al.)



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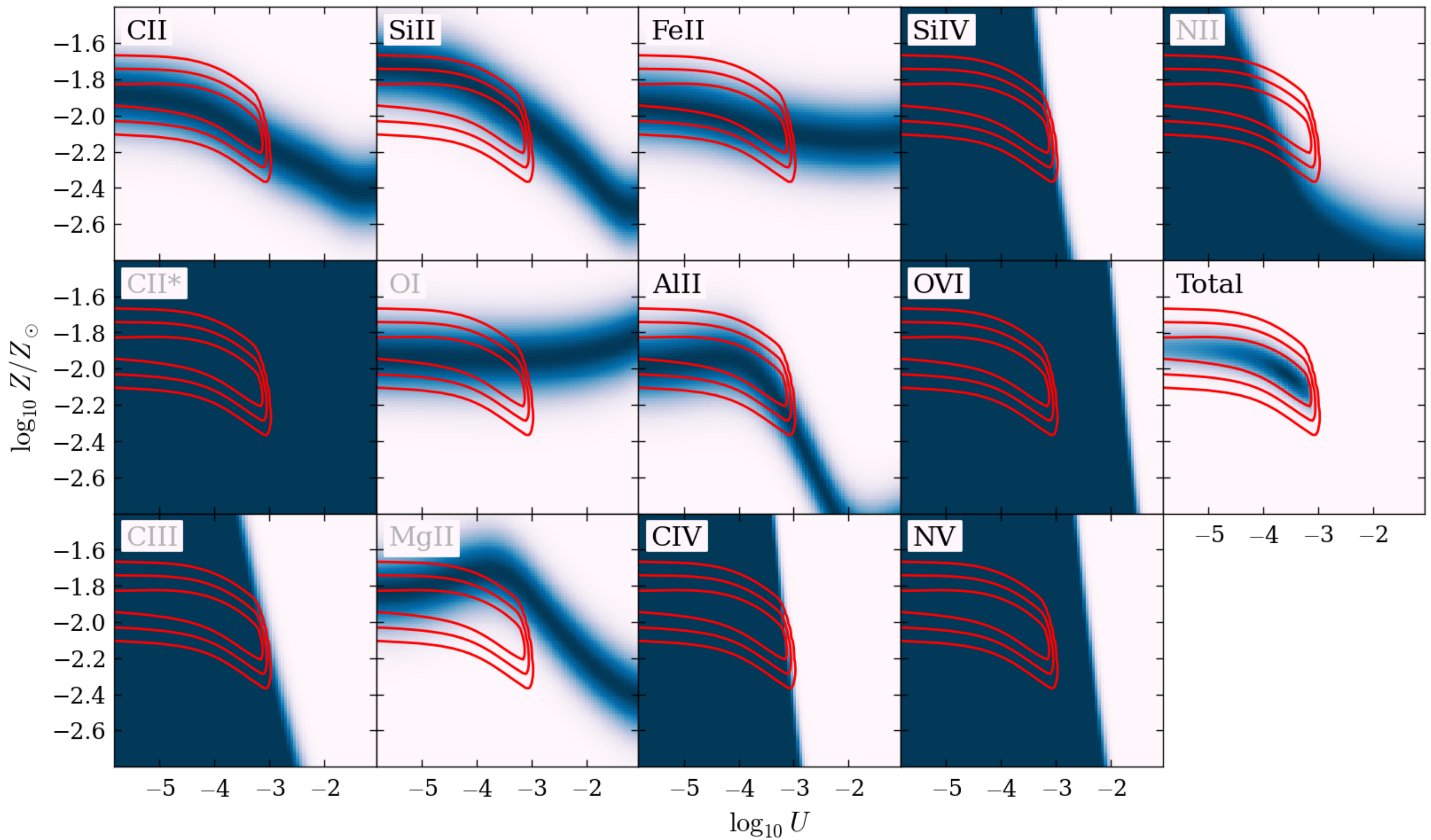

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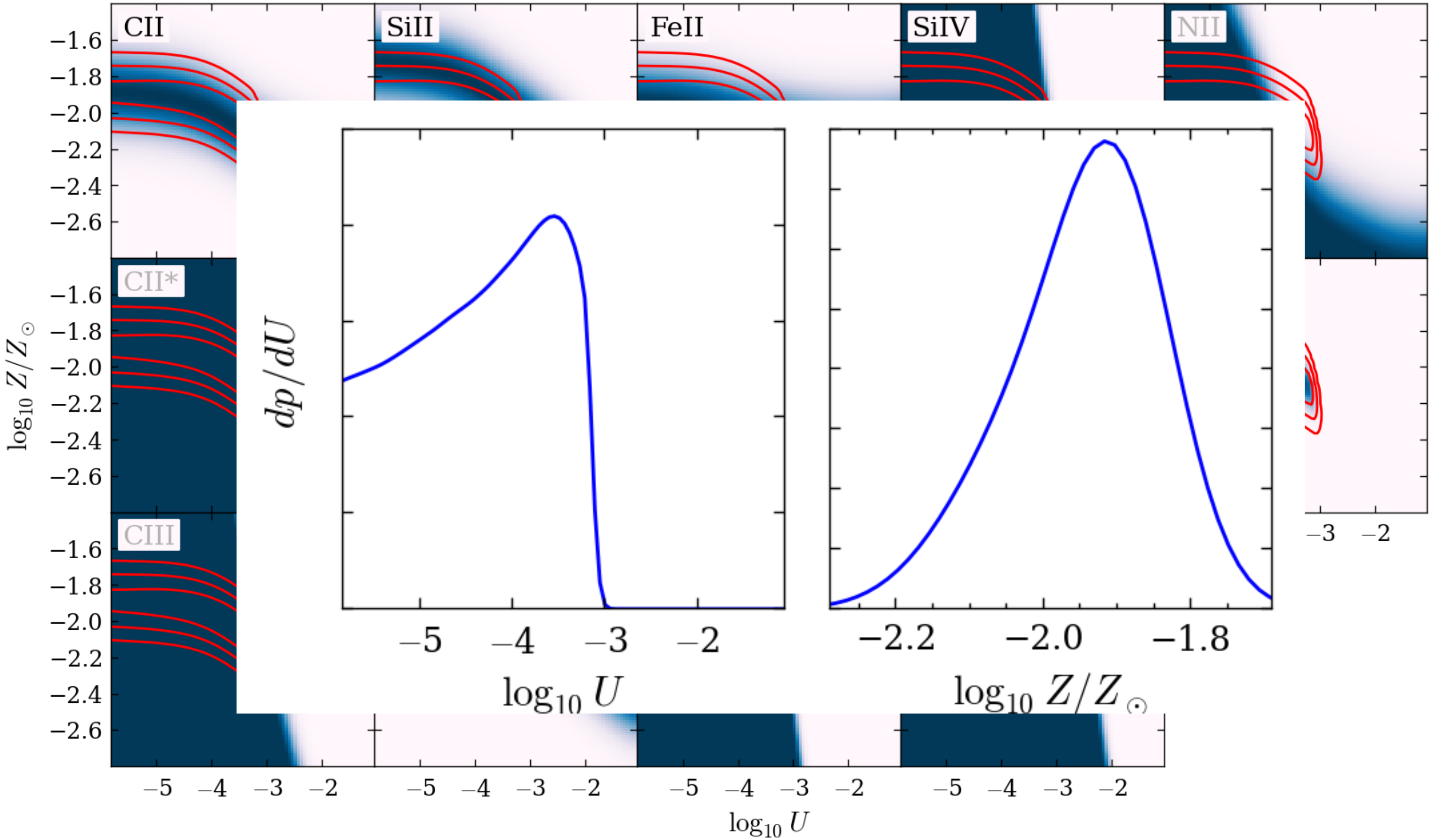

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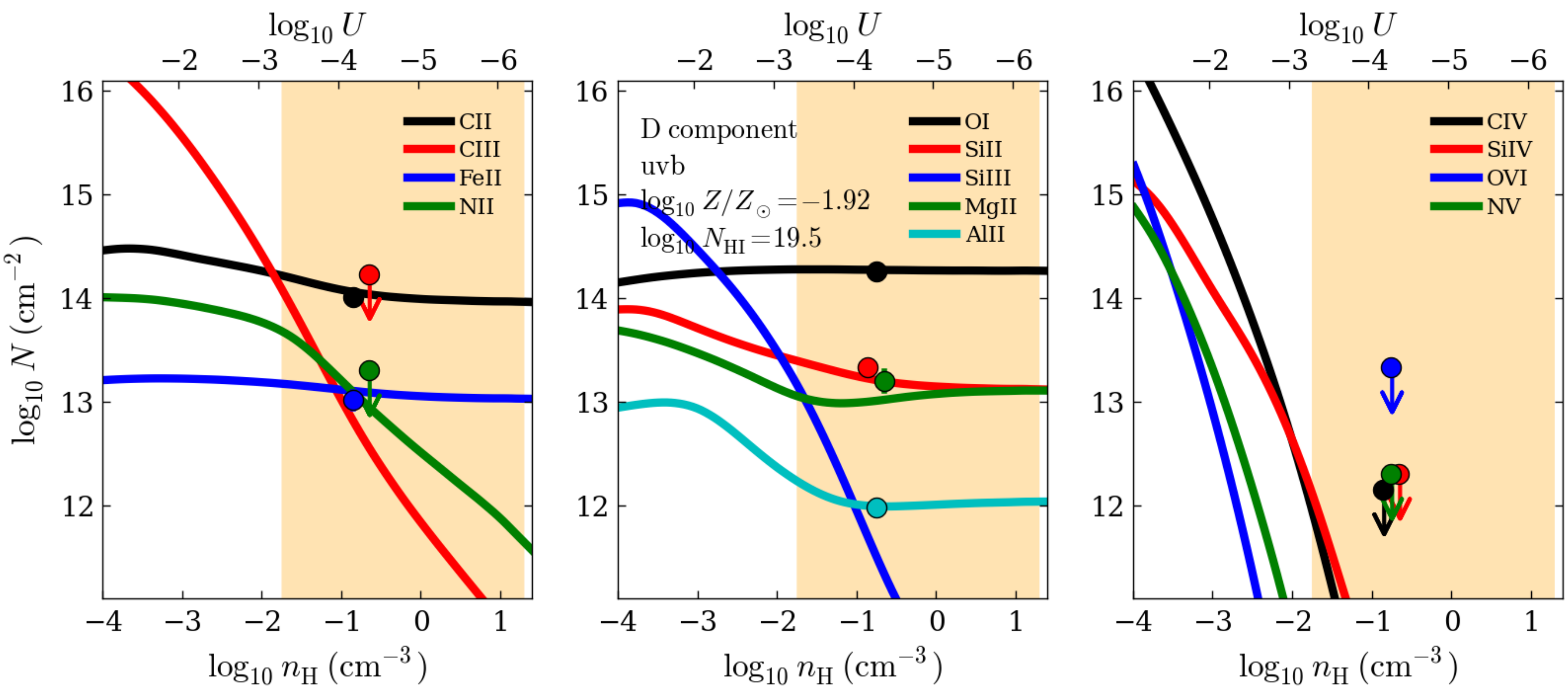

Have we detected cool accretion?

Predicted:

- $10^{17} < N(HI)/cm^{-2} < 10^{20}$
- $T \sim 10^4$ K
- $-2.5 < \log Z < -1.5$
- dv < ~250 km/s
- At the virial radius
- Stream thickness ~kpc

Observed:

- $N(HI) \sim 10^{19.85}\ cm^{-2}$
- T < 20,000K
- log Z = -2.0, no dust
- dv = 140 km/s
- $R_{\perp} = 58$ kpc $< \sim R_{vir}$
- Thickness < ~3 kpc

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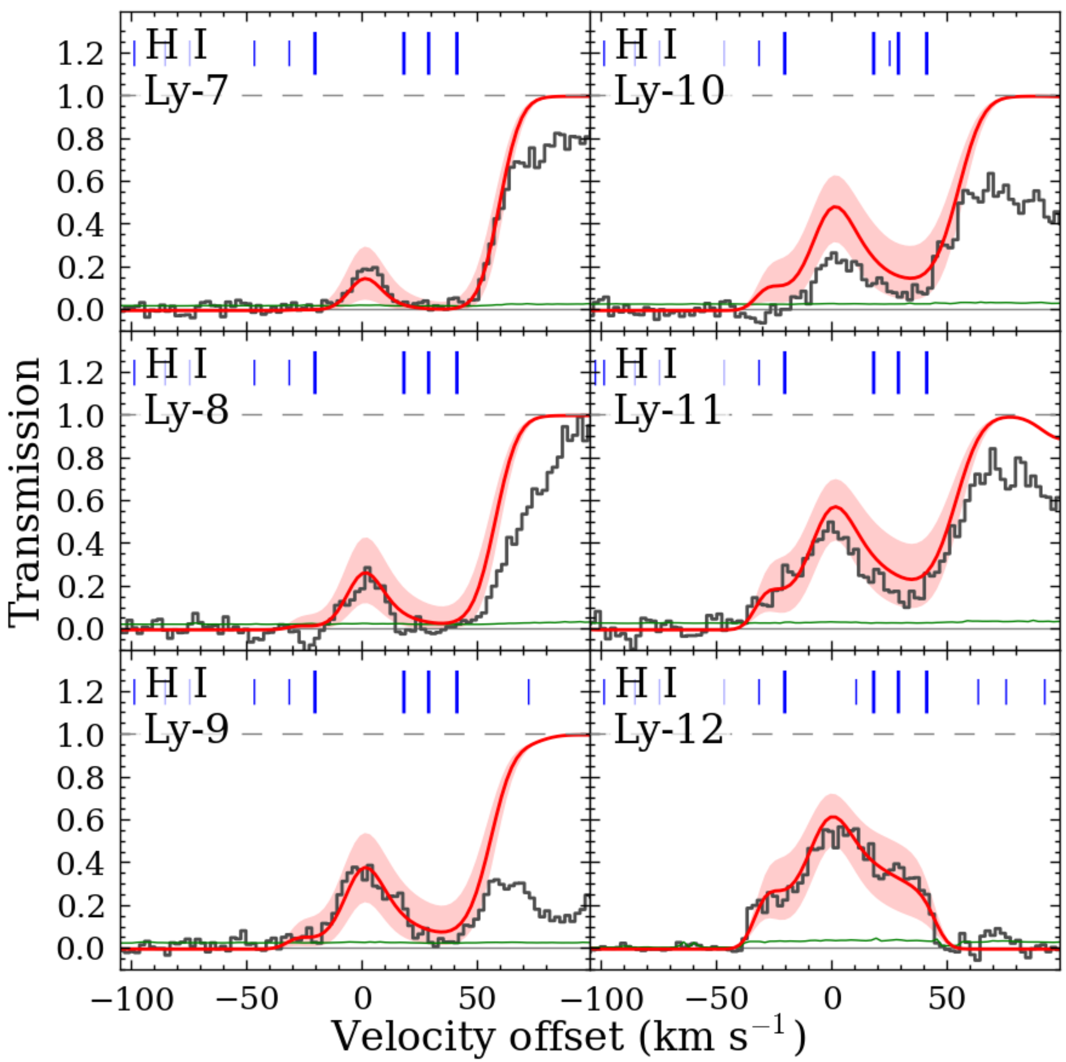
We believe that the best explanation for this system is a cool accretion stream.

Highly ionized, high metallicity components in the same CGM



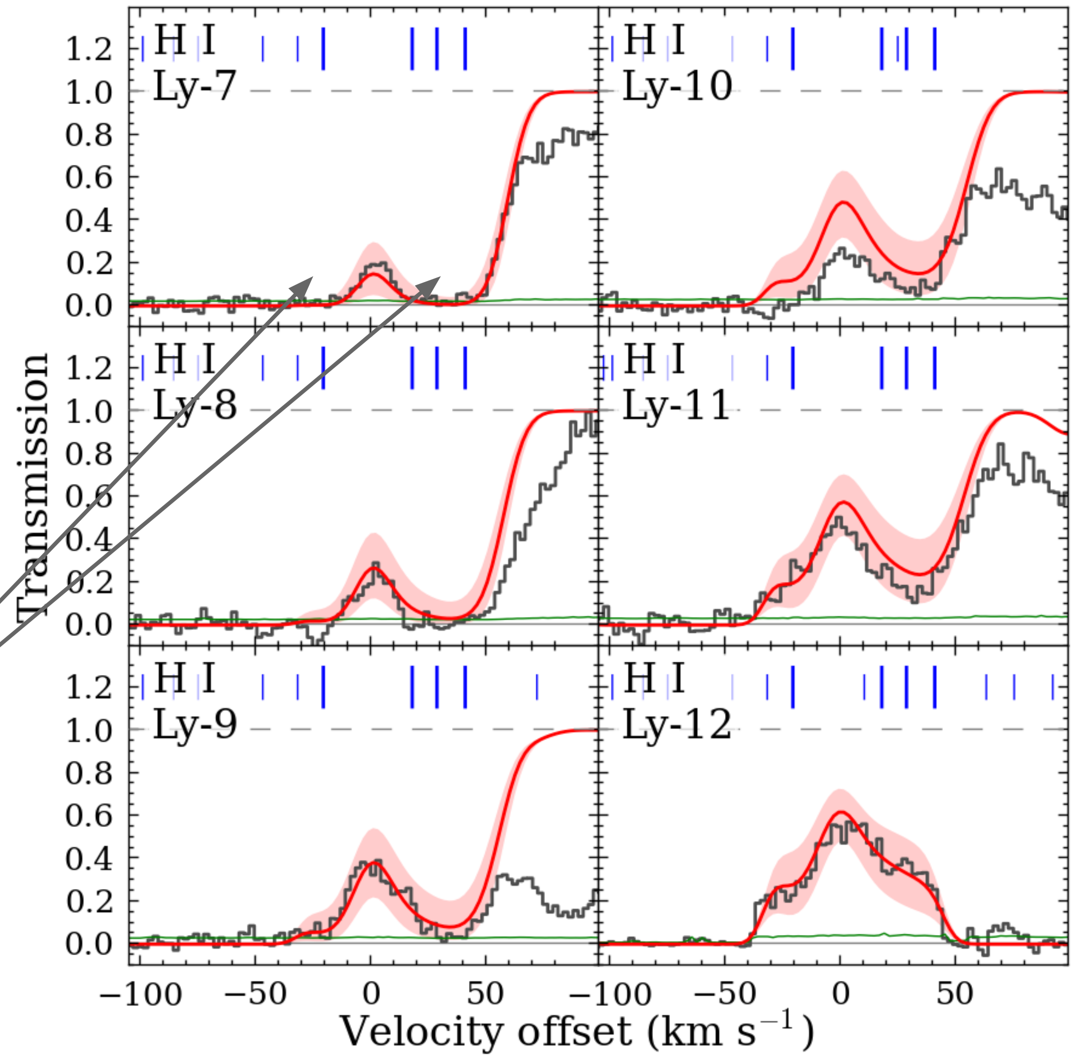
Highly ionized, high metallicity components in the same CGM

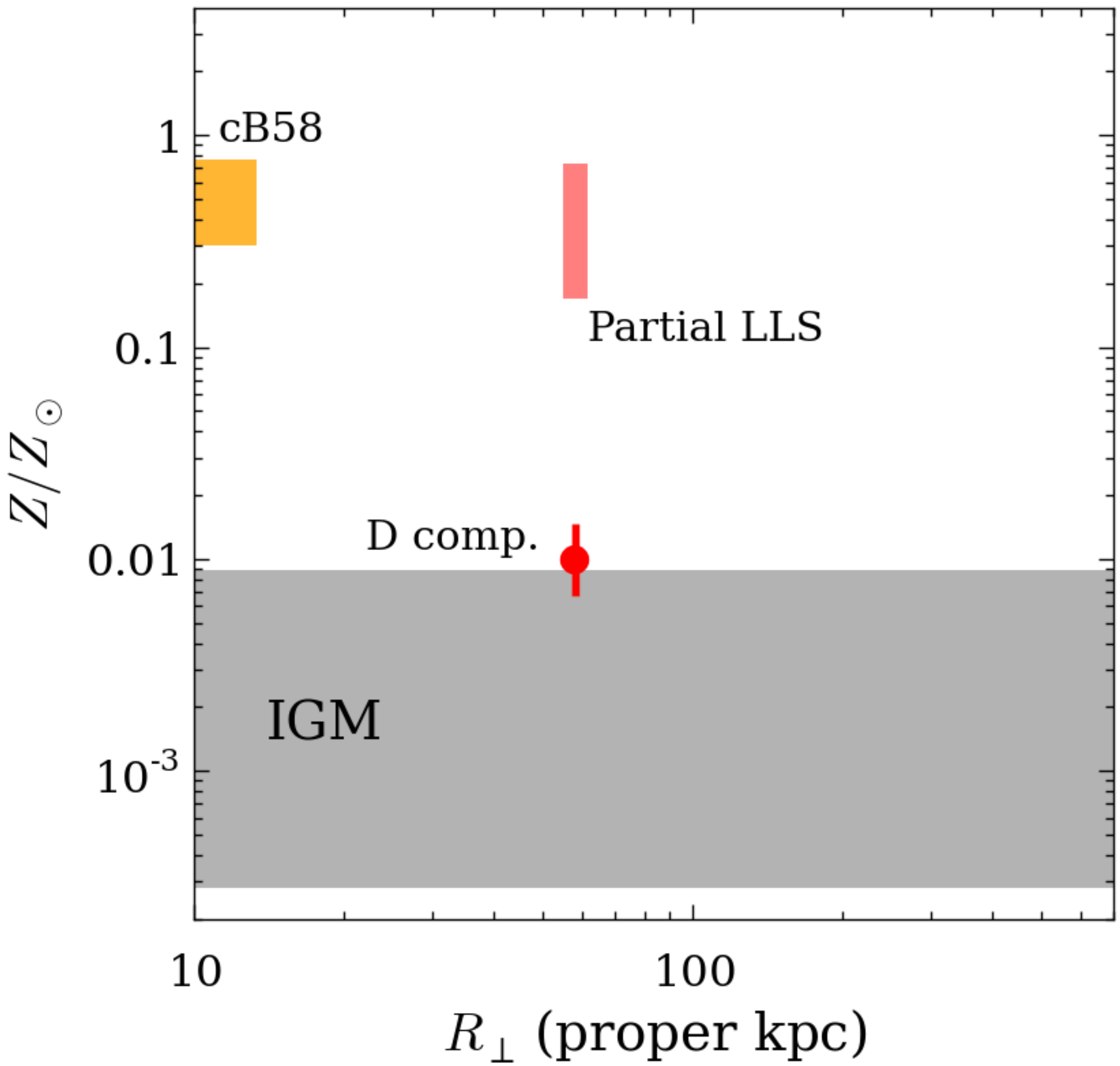
'Partial
Lyman limit'
H I components

log N(HI) ~
16.2 - 16.5

From Cloudy modelling: neutral fraction < 0.01, and log Z = -0.4 +/- 0.3

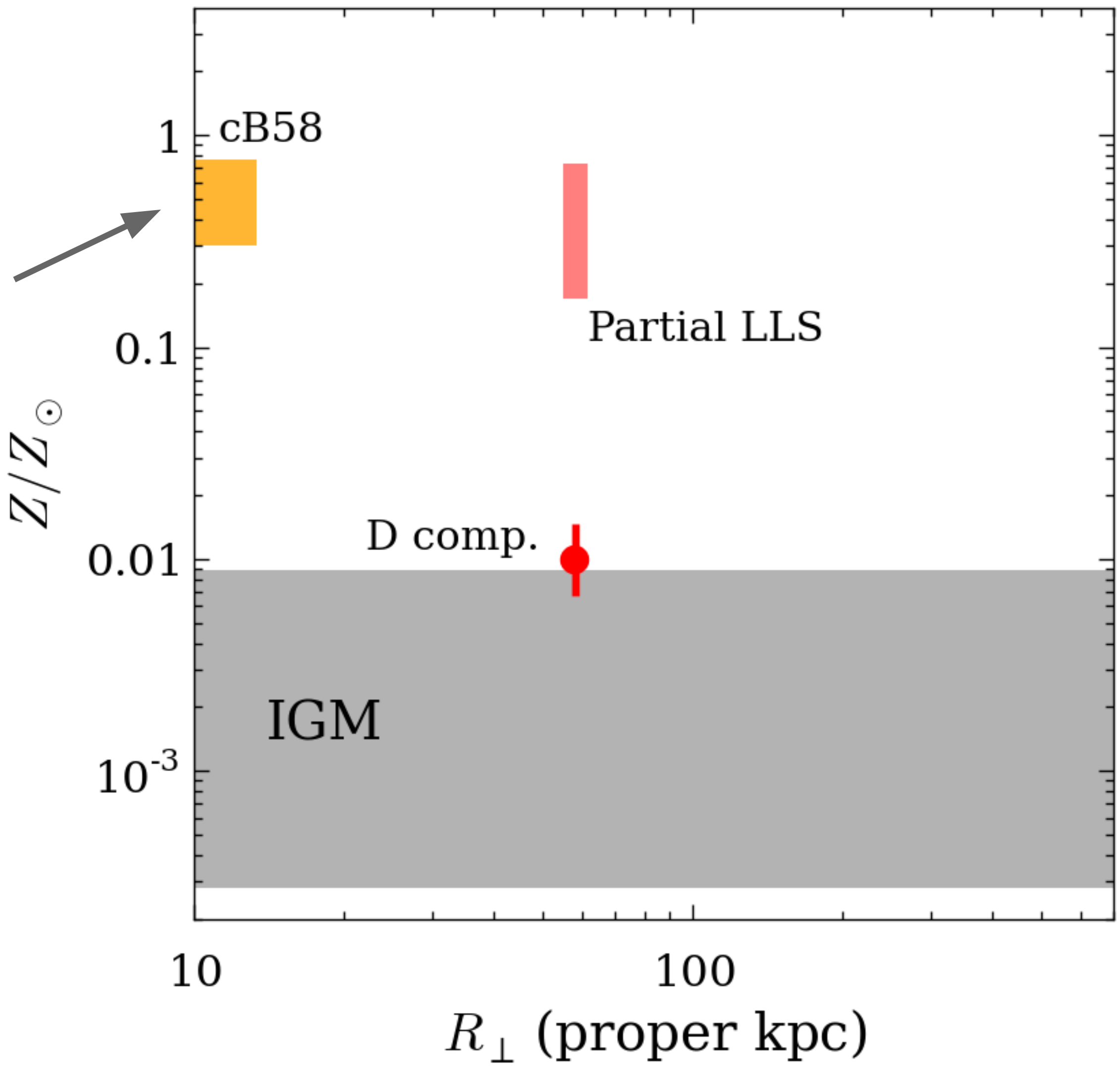
or 0.2 - 0.7 solar metallicity

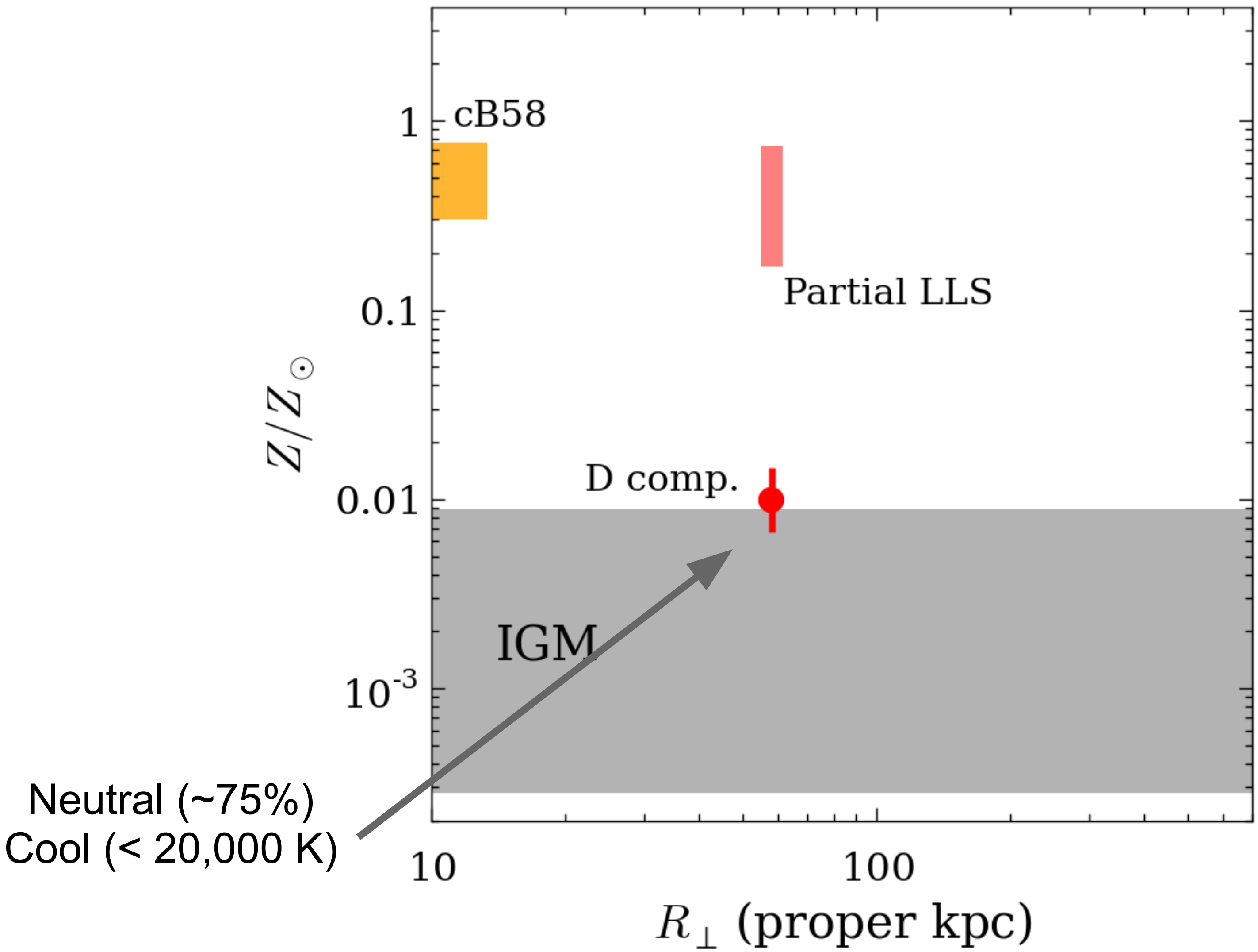




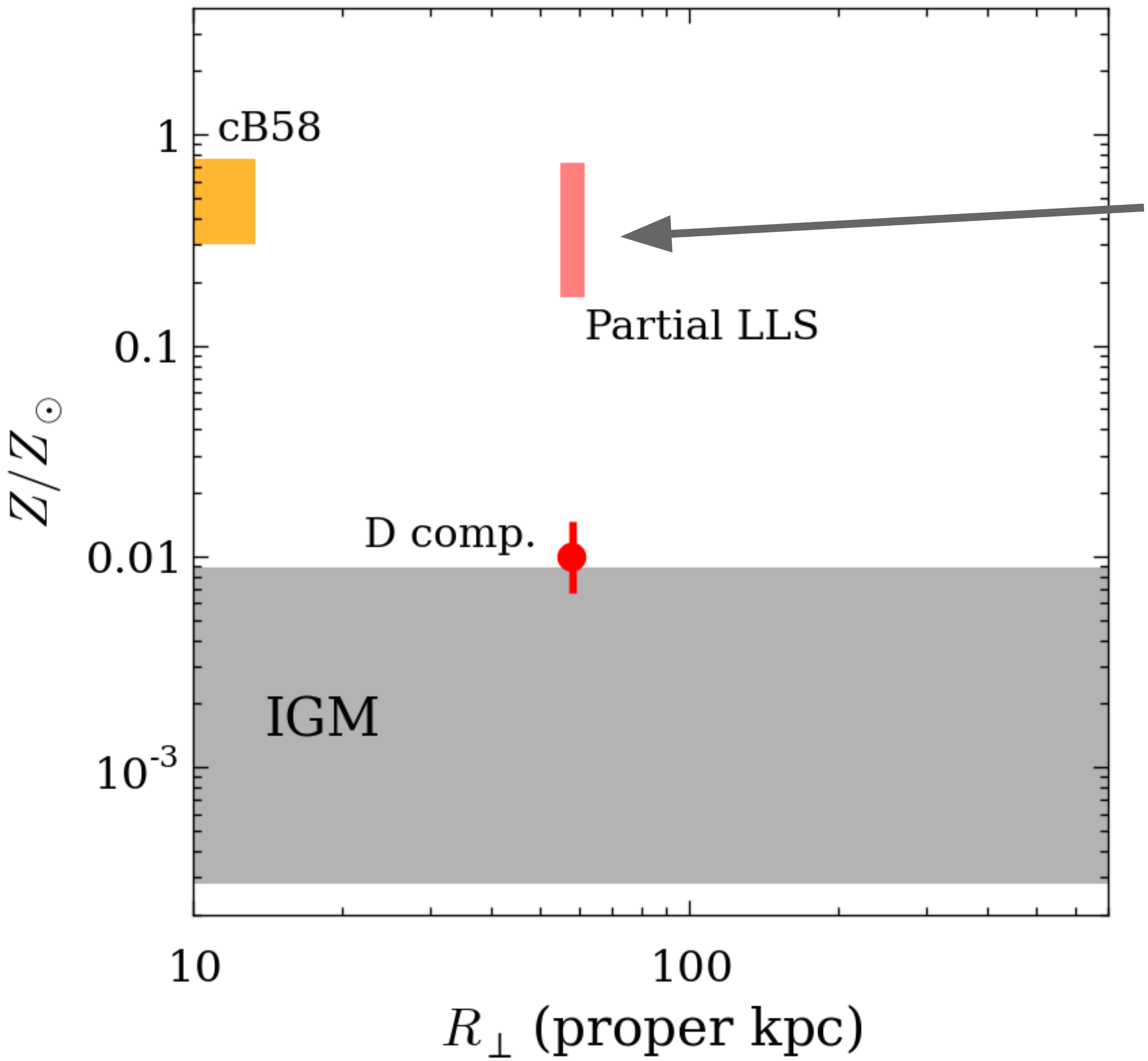
cB58
Partial LLS
D comp.
IGM
1
0.1
0.01
10^-3
Z/Z⊙
10
100
R⊥ (proper kpc)

'Down the barrel' direct ISM metallicity using a lensed LBG (Pettini+ 2002)





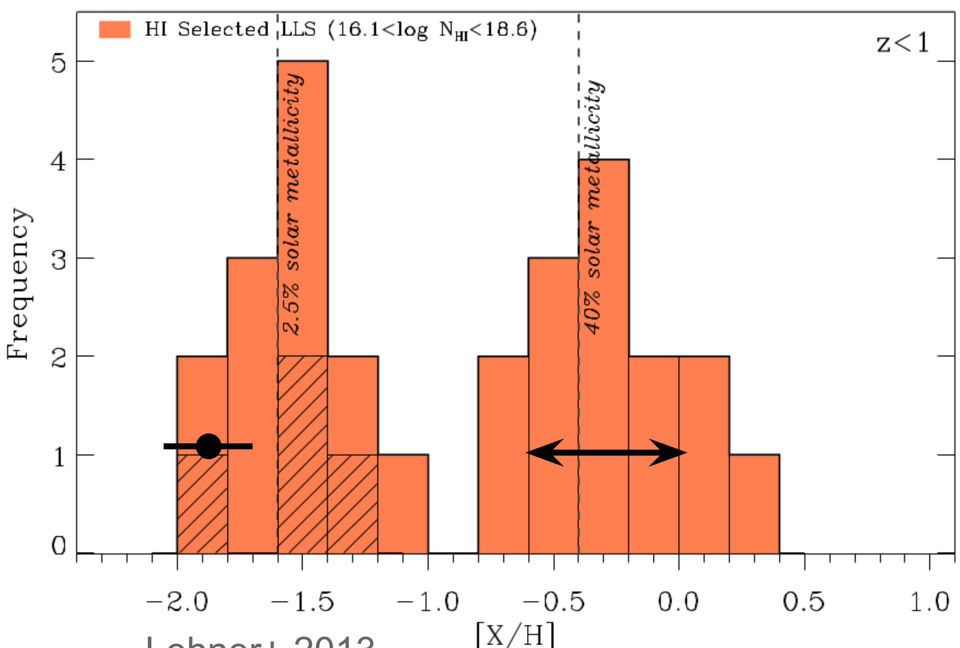
cB58
Partial LLS
D comp.
IGM
Neutral (~75%)
Cool (< 20,000 K)
1
0.1
0.01
10^{-3}
$Z/Z_\odot$
10
100
$R_\perp$ (proper kpc)



Highly ionized (<1% neutral), associated with broad O VI absorption that may indicate hot (shocked?) gas.

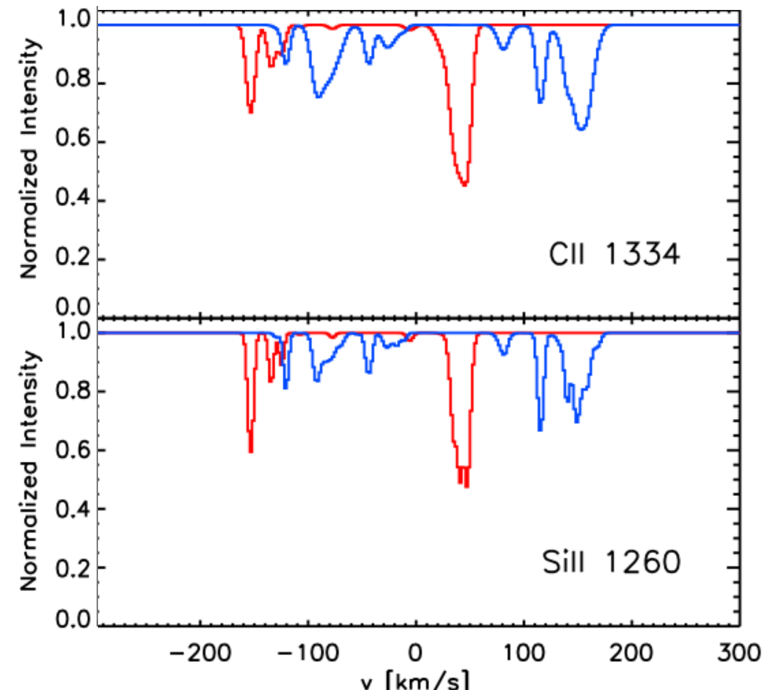
Simcoe et al. 2002, Fox et al. 2007.

An Inhomogeneous CGM



Lehner+ 2013

(also Prochter+ 2011, Schaye+ 2007)



Shen+ 2013

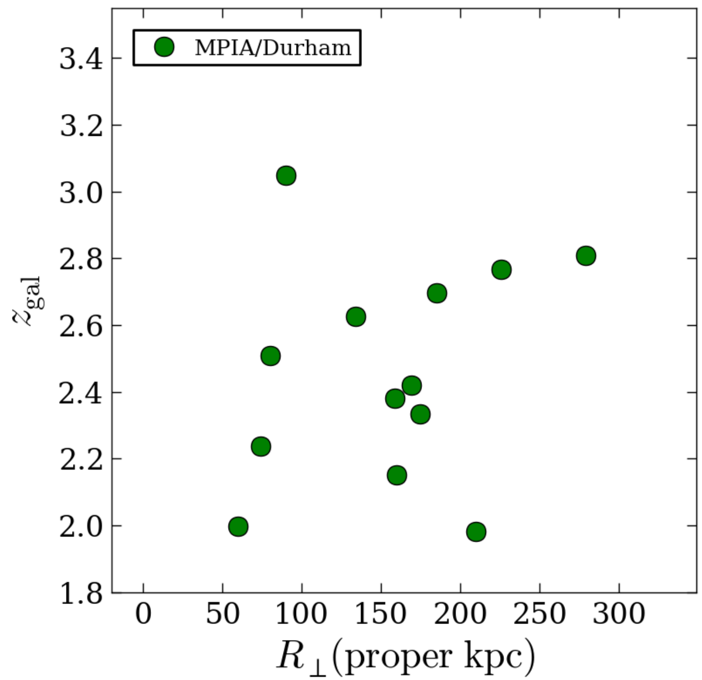
(Simulations)

- Low resolution and composite spectra cannot measure this bimodality.
- High quality, high resolution spectra & photoionization modelling are required.

Building a Statistical Sample

LBGs at 2 < z < 3.2

23 < r < 25.5



Building a Statistical Sample

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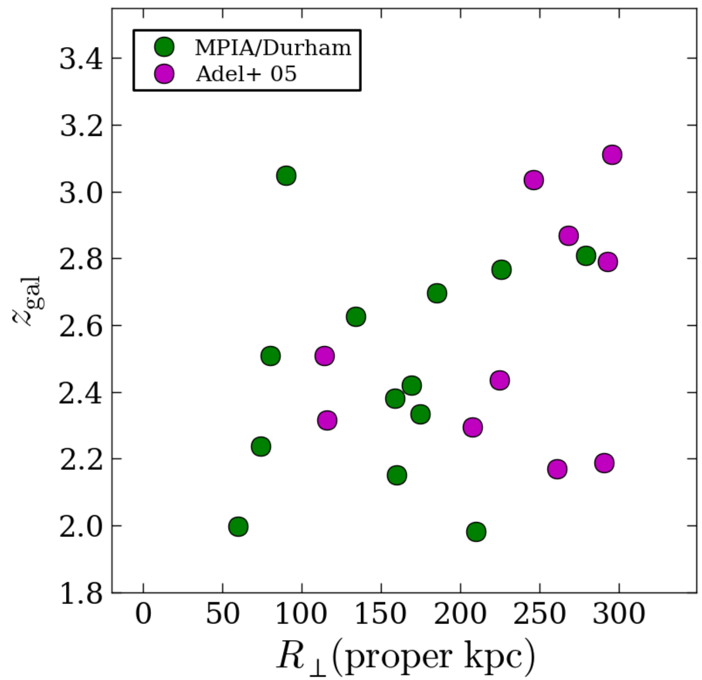


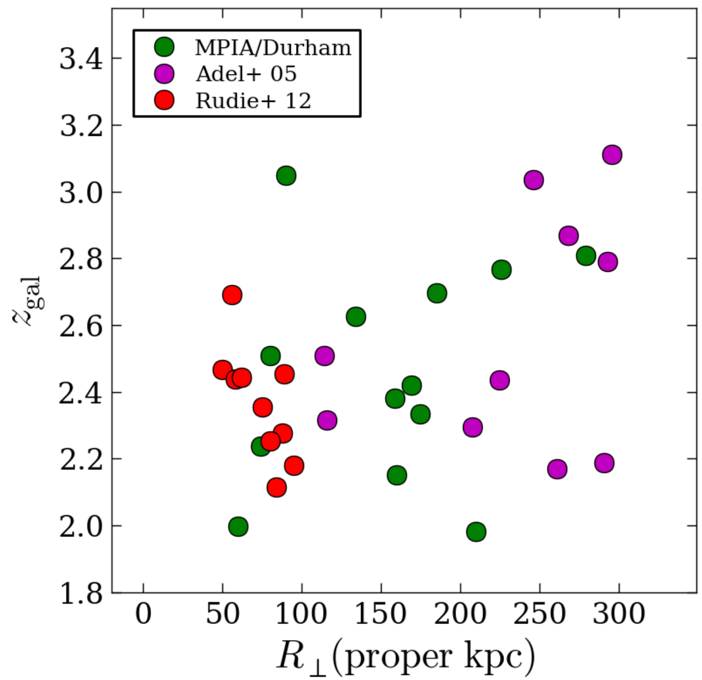
Building a Statistical Sample

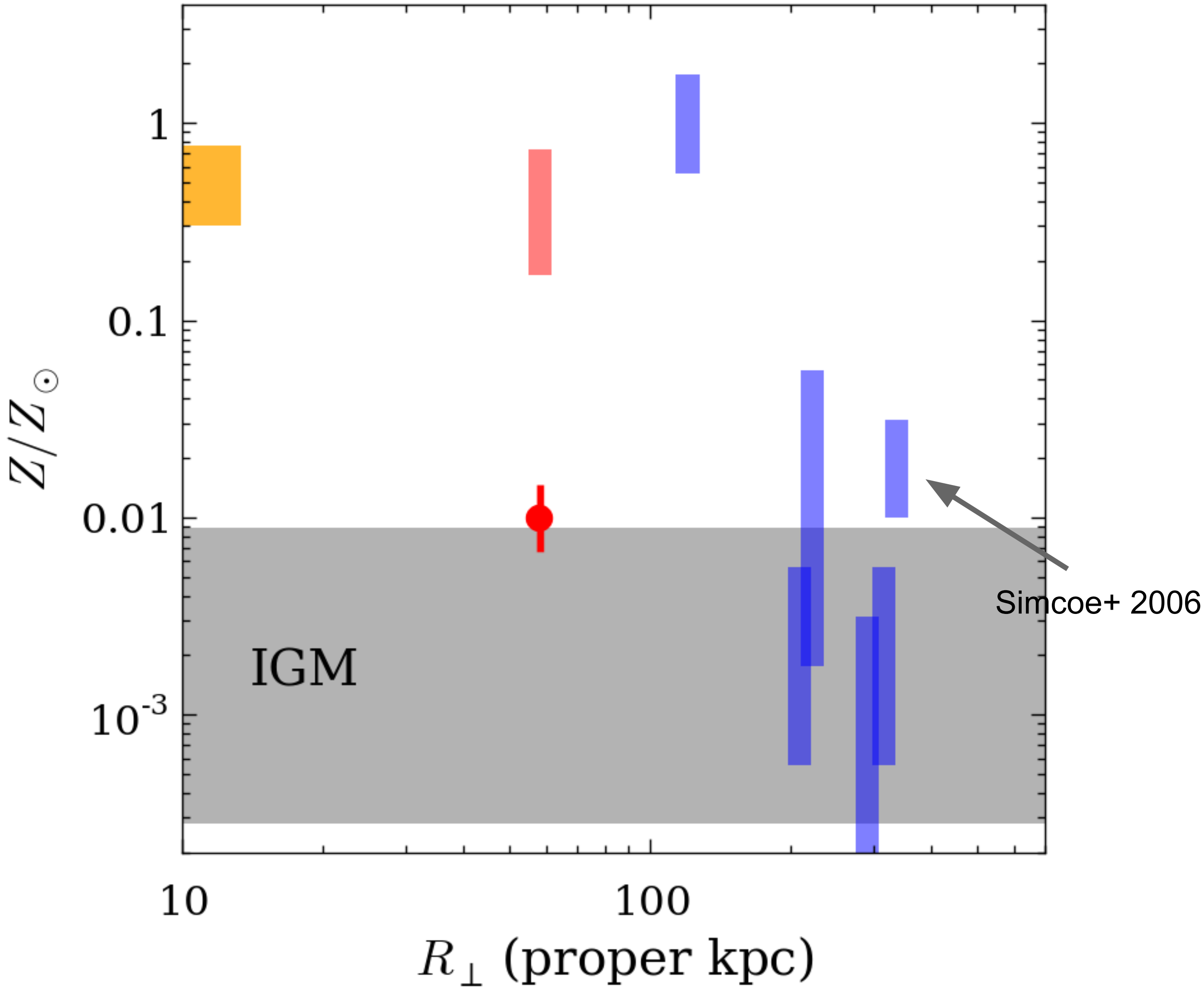
LBGs at $2 < z < 3.2$

$23 < r < 25.5$

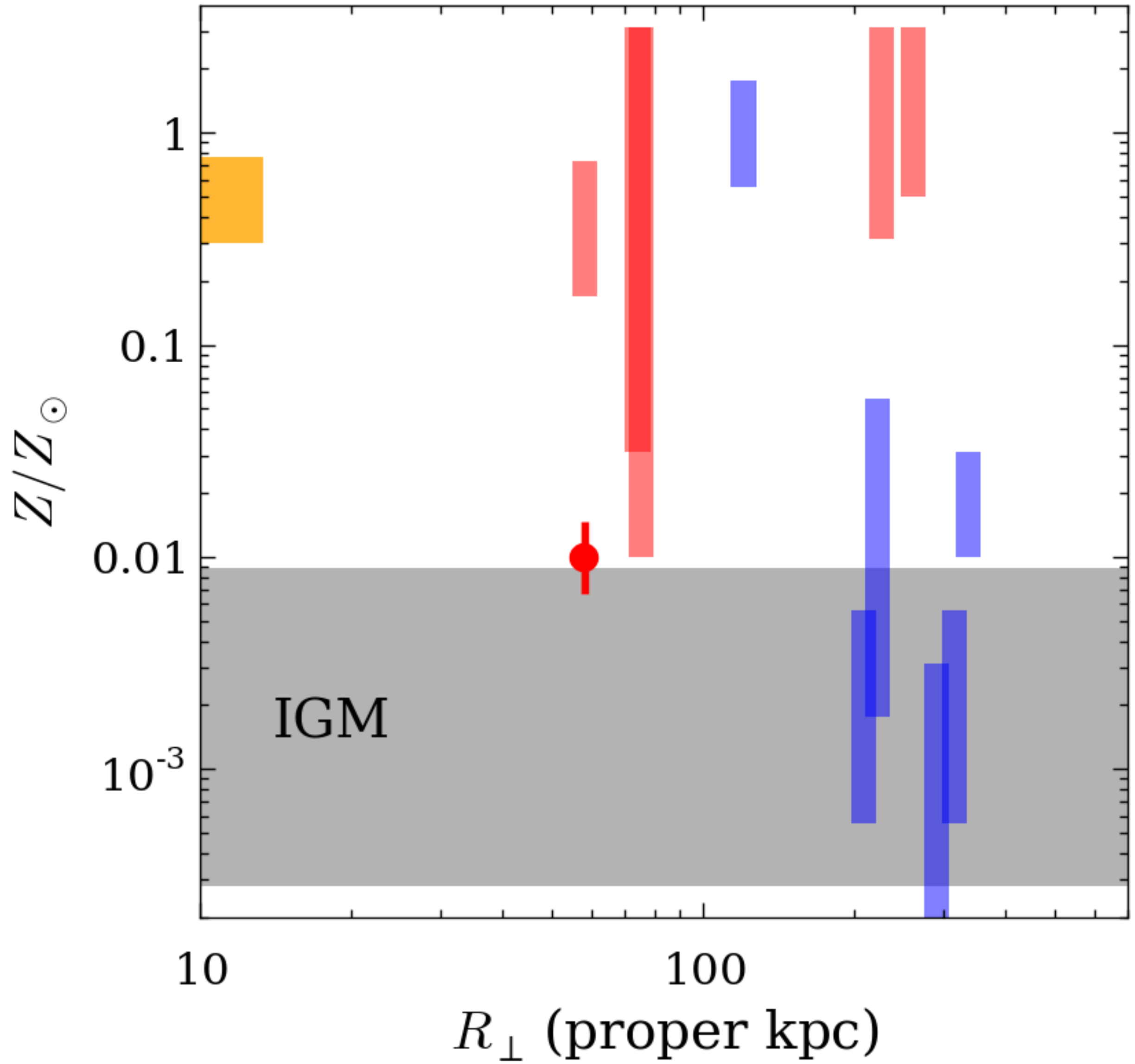
17 pairs with
$R_\perp < 150$ kpc

33 pairs with
$R_\perp < 300$ kpc

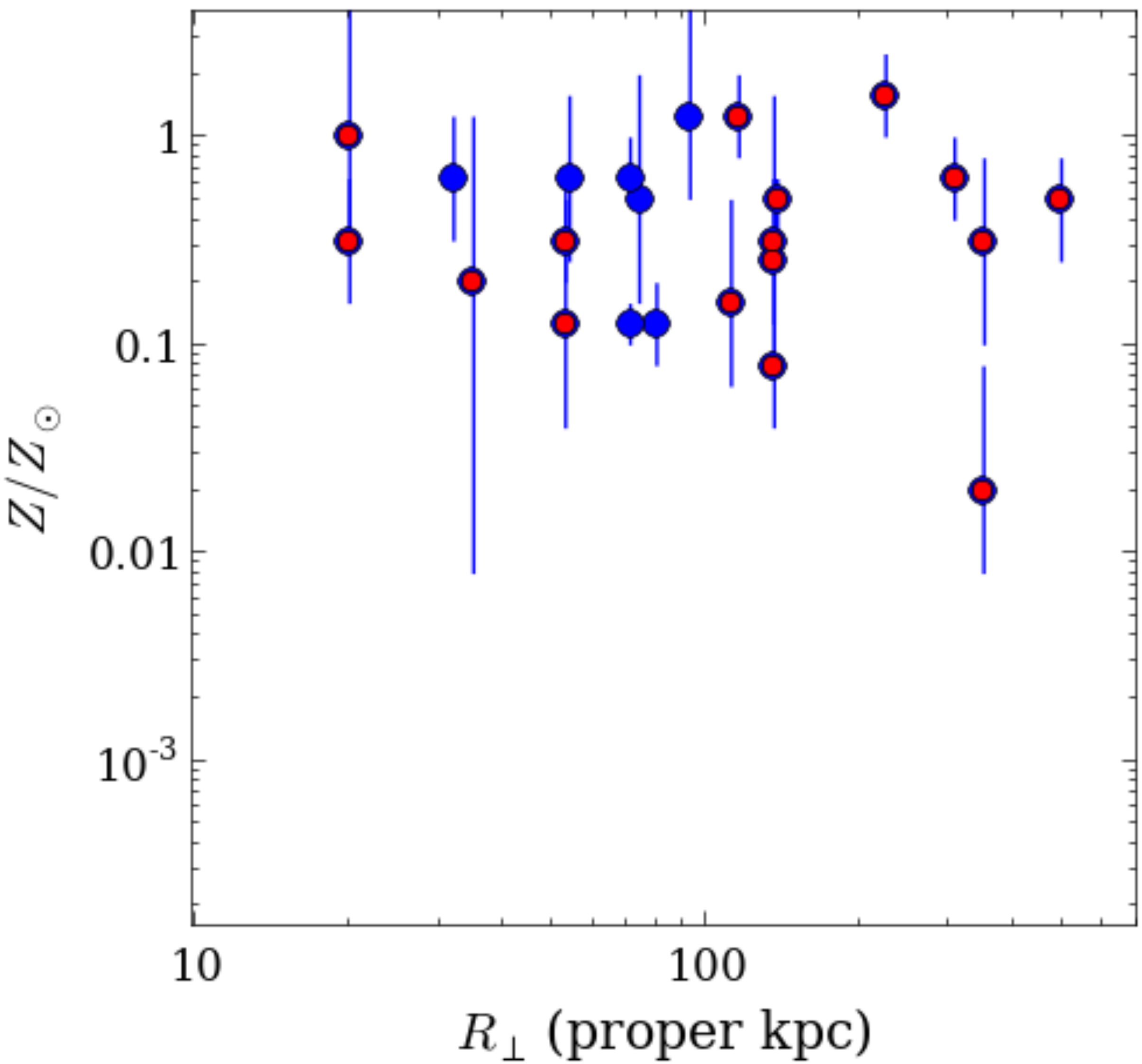




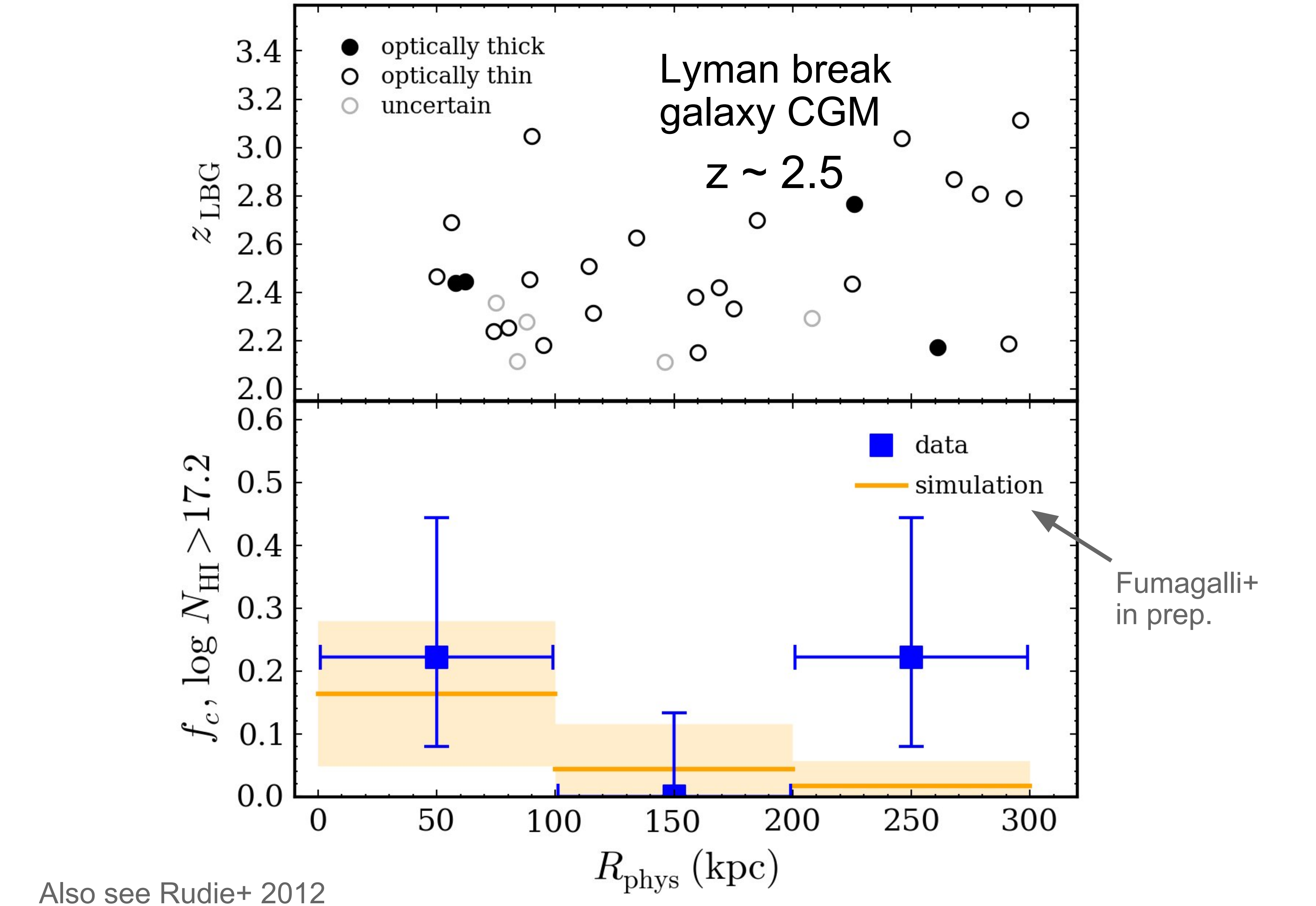
1
0.1
0.01
10^{-3}
$Z/Z_\odot$
10
100
$R_\perp$ (proper kpc)
IGM
Simcoe+ 2006



1
0.1
0.01
10^{-3}
$Z/Z_{\odot}$
IGM
10
100
$R_{\perp}$ (proper kpc)



Stocke 2012


optically thick
optically thin
uncertain
Lyman break galaxy CGM
z ~ 2.5
$z_{\rm LBG}$
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
data
simulation
f_c, log $N_{\rm HI} > 17.2$
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
200
250
300
$R_{\rm phys}$ (kpc)
Fumagalli+ in prep.
Also see Rudie+ 2012

Summary

- We have detected high N(HI), metal poor (0.01 solar), $T < 20{,}000$ K, dust-free gas near the virial radius of a $z=2.44$ star-forming galaxy. It shows the characteristics expected for a cool accretion stream.

- The halo gas metallicity and ionization state are highly inhomogeneous.

- High S/N, high-resolution observations and photoionization modelling are essential to measure these metallicities and other physical properties.

- The observed covering fraction of optically thick systems agrees with simulations, but uncertainties are currently large.