A Preponderance of Metals in the Circumgalactic Medium

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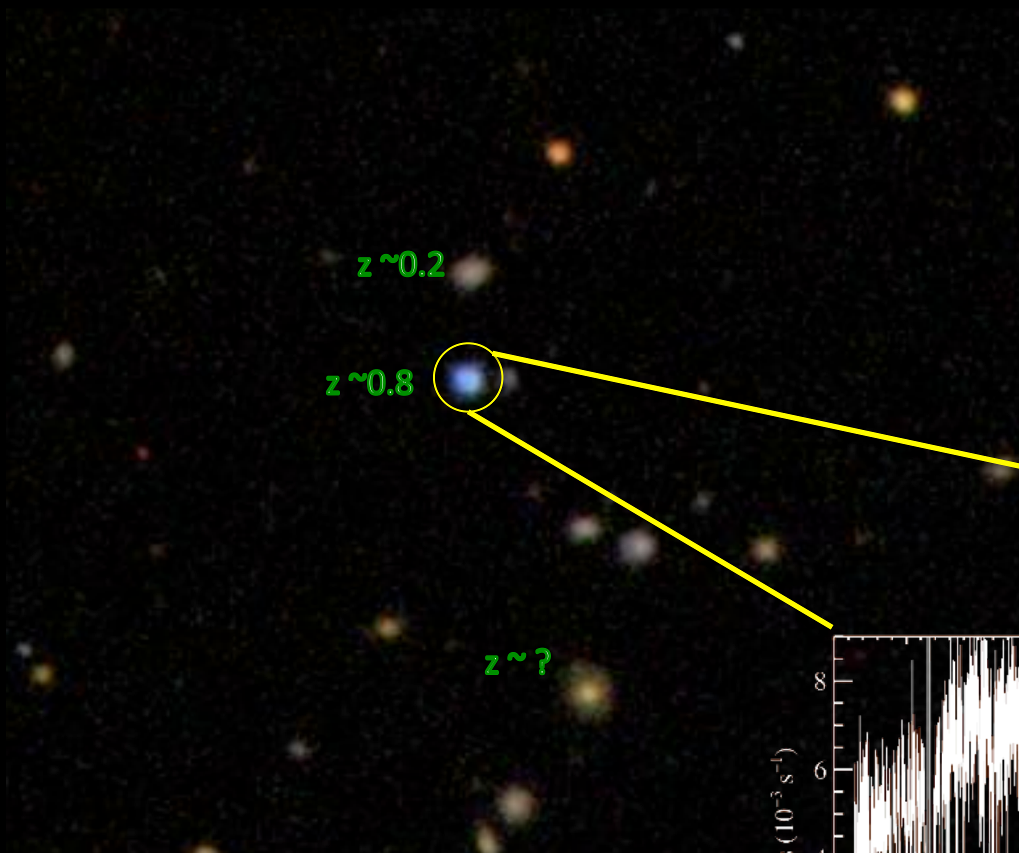
The Circumgalactic Medium (CGM)

Diffuse gas, including metals and dust, often extending to 300 kpc, and largely bound to the dark matter halo

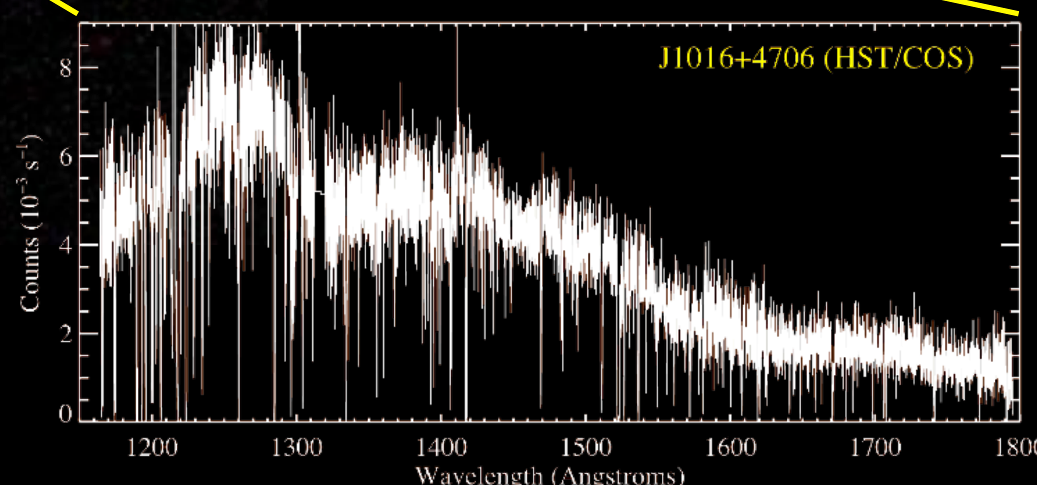
A complication: Circumgalactic galaxy halo gas is too diffuse to be studied in emission, and a random sightline through the IGM is intercepted by <1 massive galaxy halo.

Absorption Line Experiments



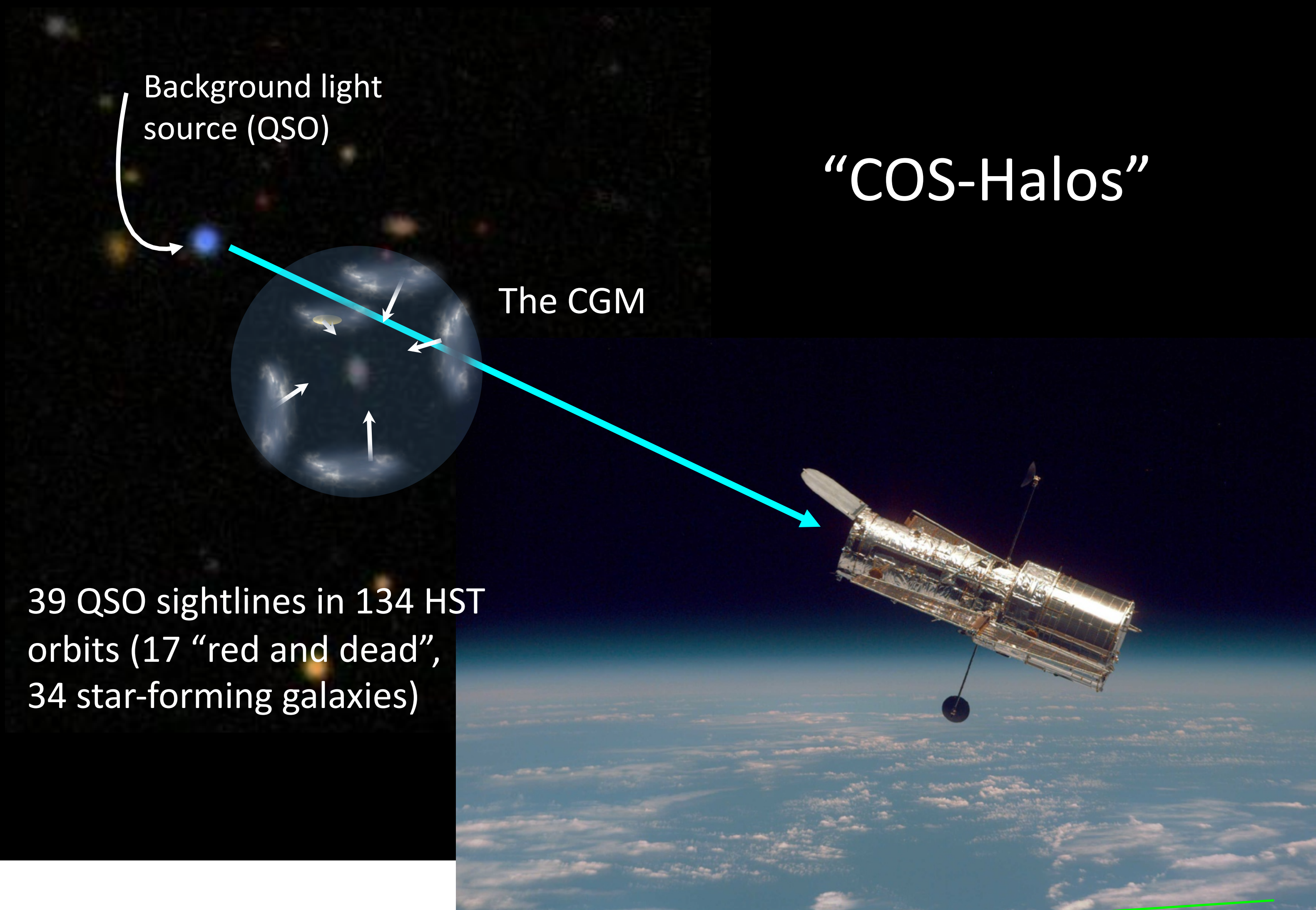
Method A: Find absorber in spectrum, go hunting for a galaxy at the proper redshift

Method B: Know redshifts of nearby galaxies in projection, go hunting for absorption in the spectrum at those redshifts

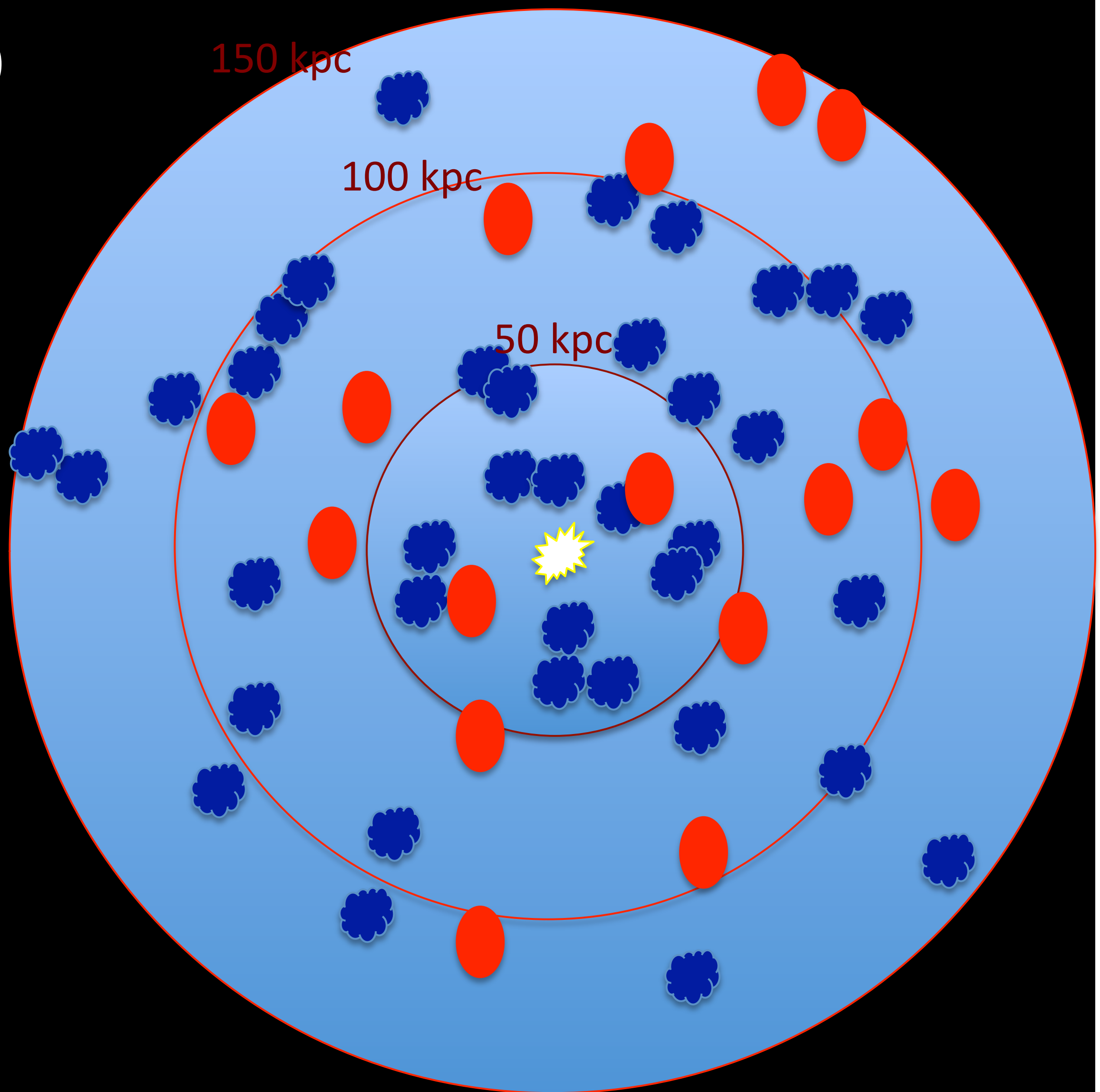


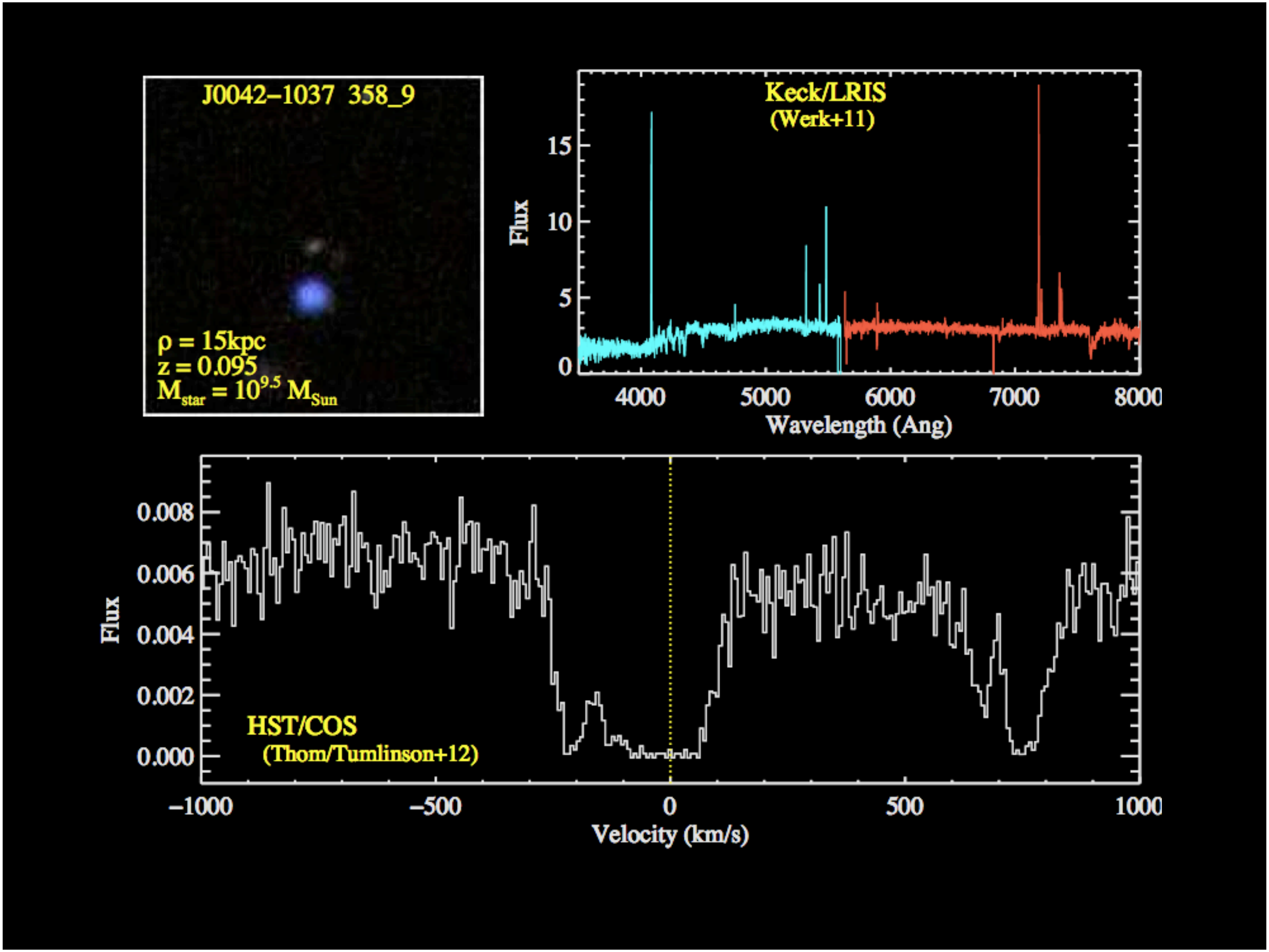
Statistically Sampling the CGM of L* Galaxies

“COS-Halos”

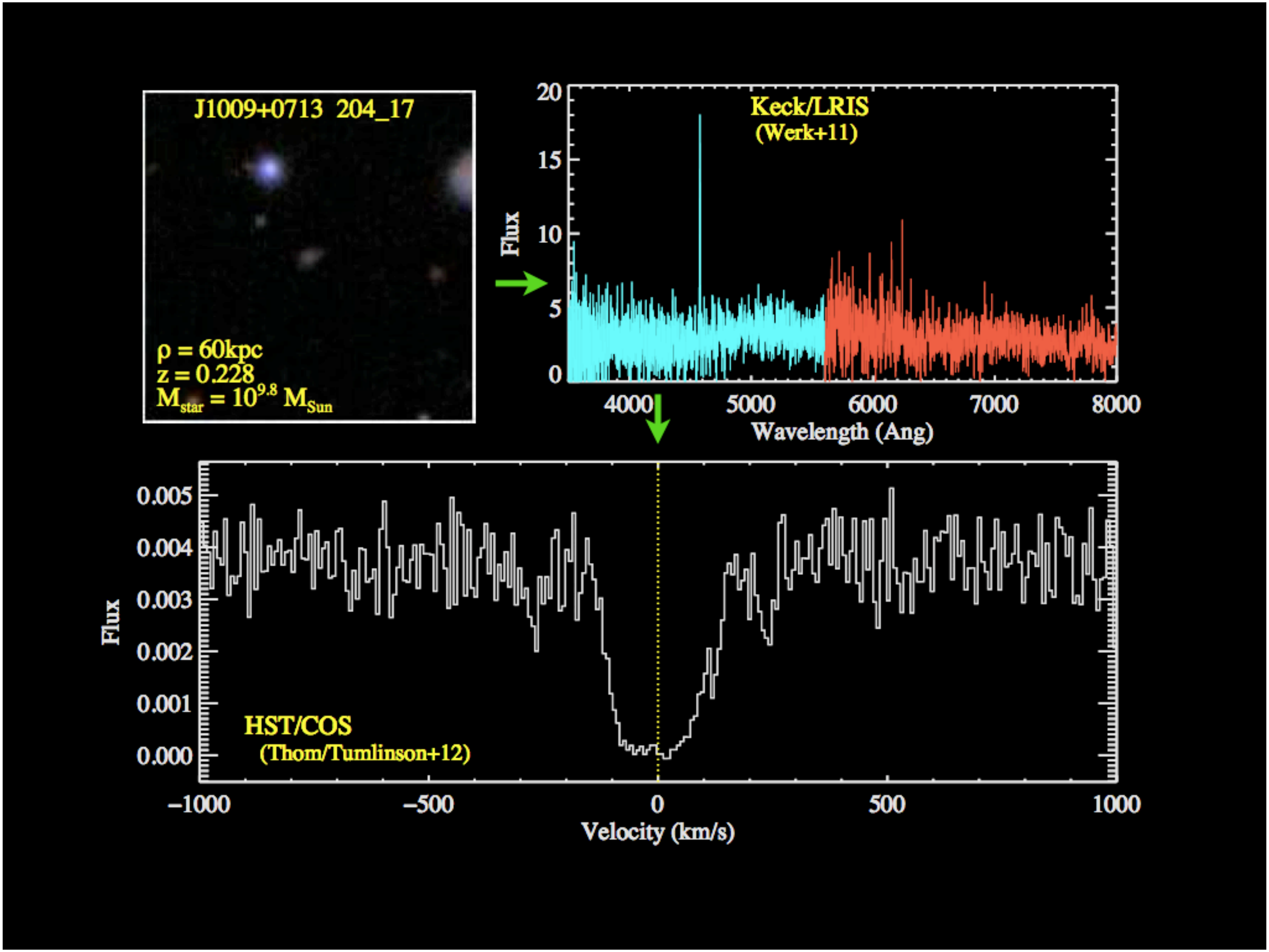


Sightline Map

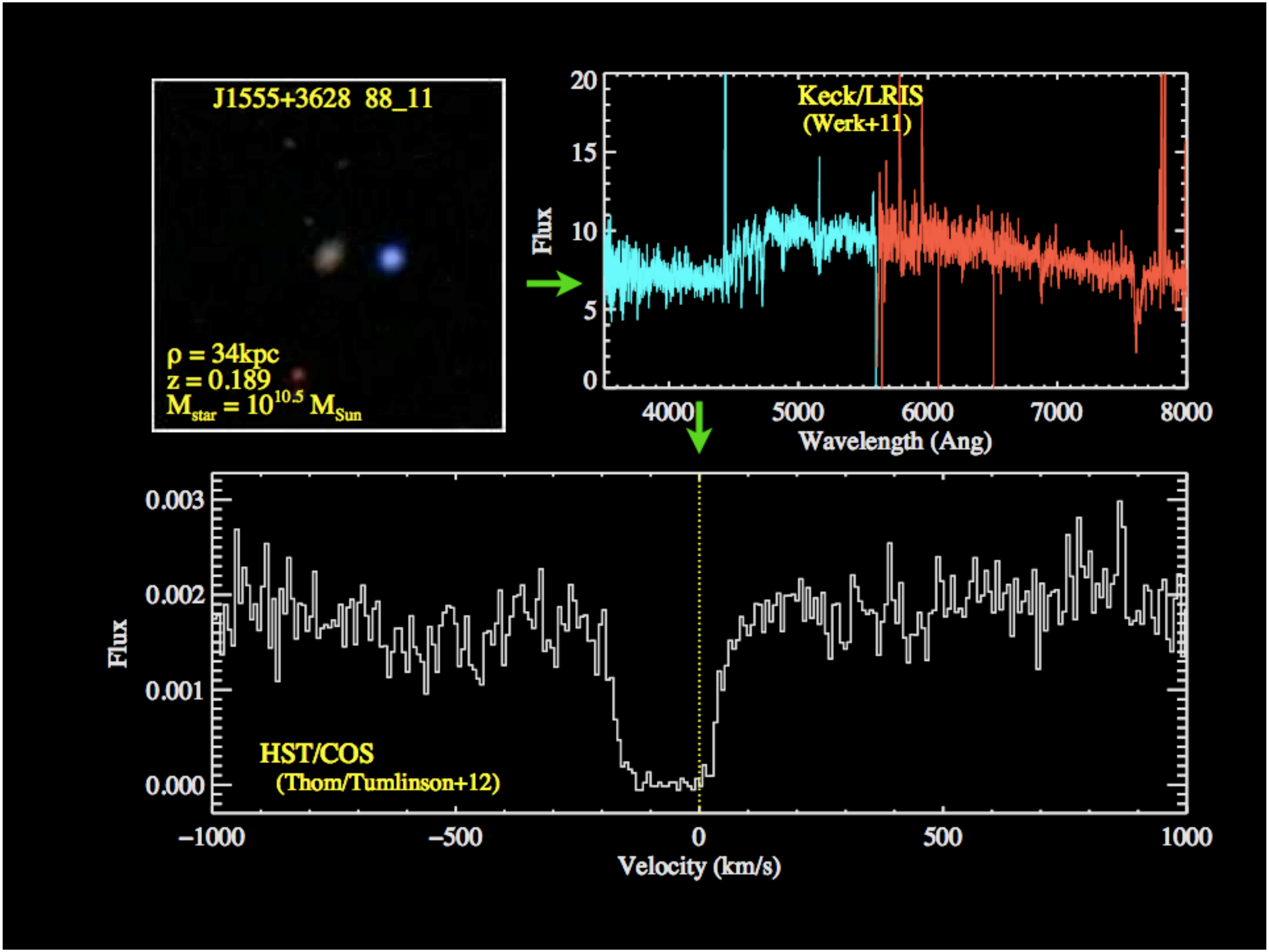




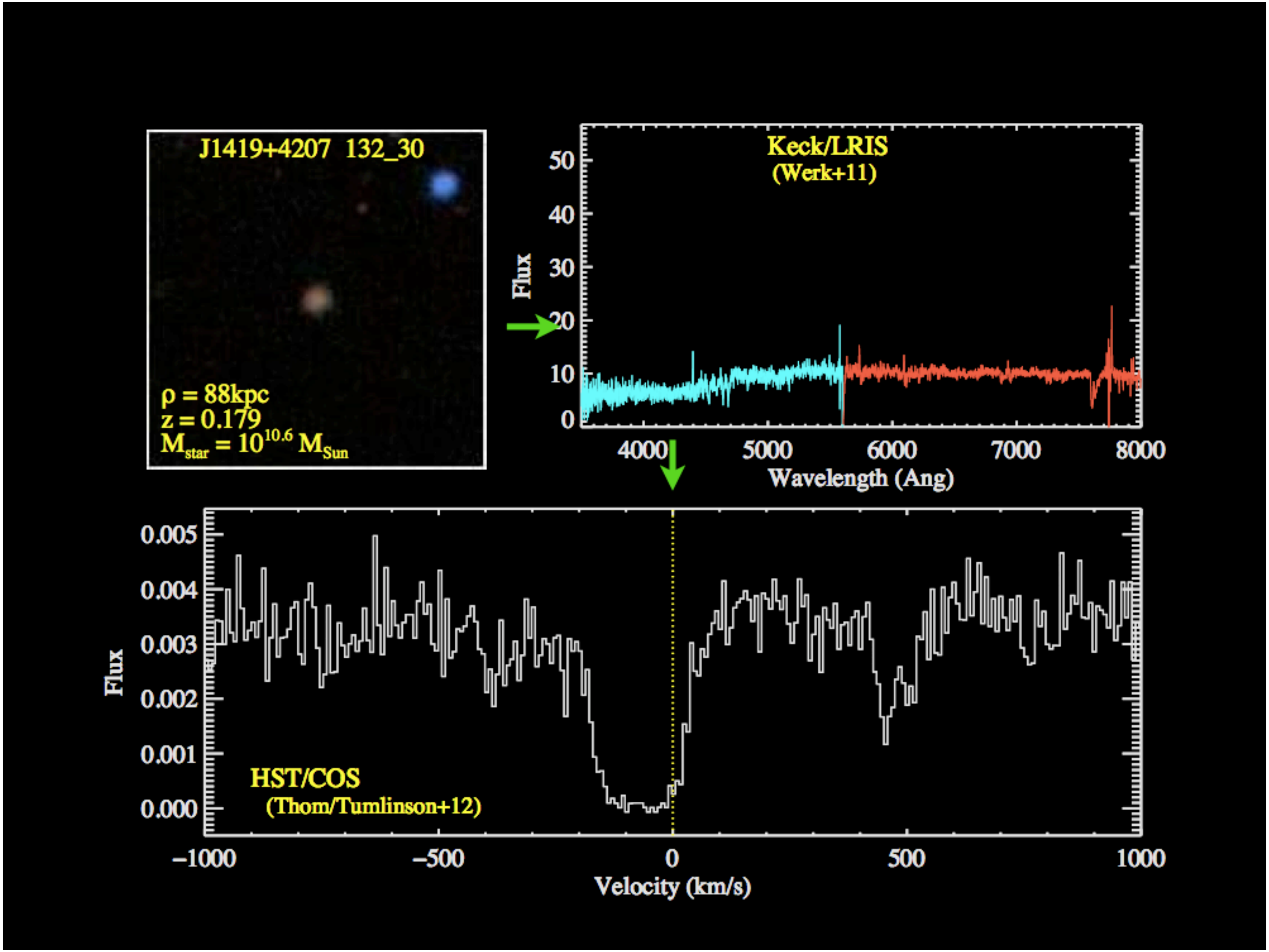
J0042–1037 358_9
ρ = 15kpc
z = 0.095
$M_{star} = 10^{9.5}\ M_{Sun}$
Keck/LRIS
(Werk+11)
Flux
15
10
5
0
4000
5000
6000
7000
8000
Wavelength (Ang)
HST/COS
(Thom/Tumlinson+12)
Flux
0.008
0.006
0.004
0.002
0.000
–1000
–500
0
500
1000
Velocity (km/s)



J1009+0713 204_17
ρ = 60kpc
z = 0.228
$M_{star} = 10^{9.8}$ M_{Sun}
Keck/LRIS
(Werk+11)
Flux
Wavelength (Ang)
HST/COS
(Thom/Tumlinson+12)
Flux
Velocity (km/s)

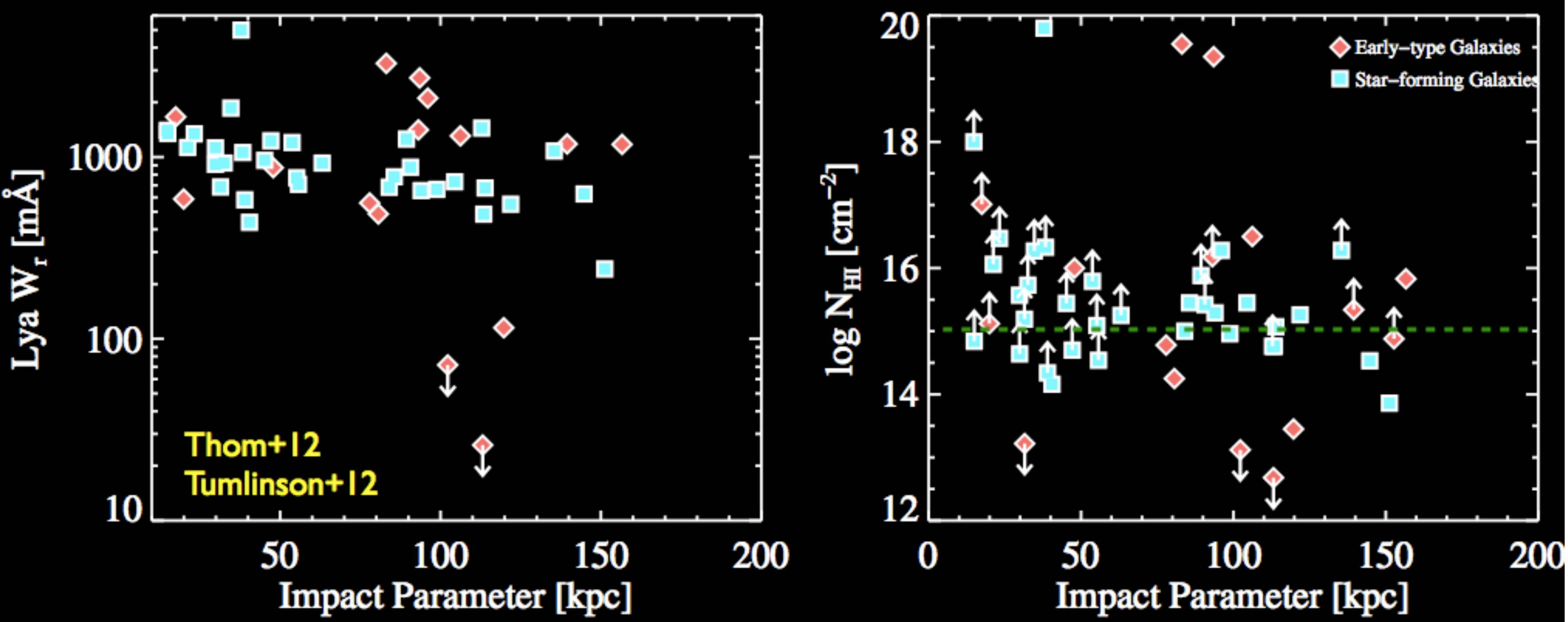


J1555+3628 88_11
ρ = 34kpc
z = 0.189
M_star = 10^10.5 M_Sun
Keck/LRIS
(Werk+11)
Flux
Wavelength (Ang)
HST/COS
(Thom/Tumlinson+12)
Flux
Velocity (km/s)



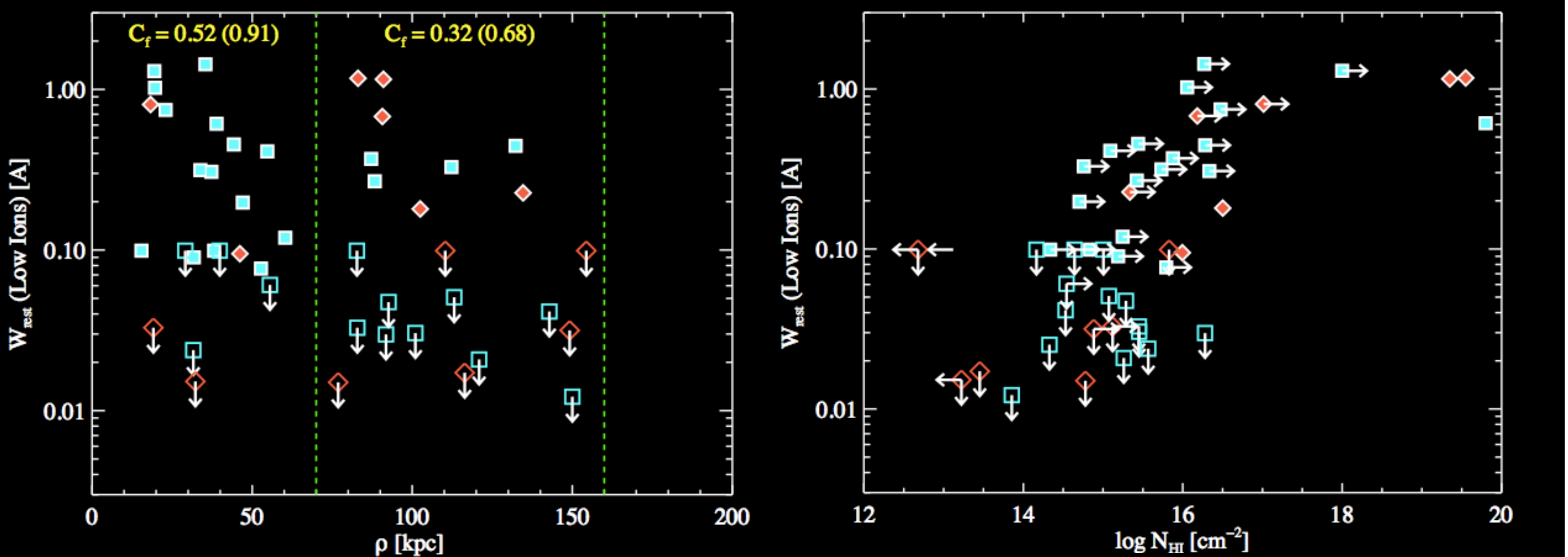
J1419+4207 132_30
ρ = 88kpc
z = 0.179
M_star = 10^10.6 M_Sun
Keck/LRIS
(Werk+11)
Flux
Wavelength (Ang)
HST/COS
(Thom/Tumlinson+12)
Velocity (km/s)

The CGM of z ~ 0, L* Galaxies: The HI Gas



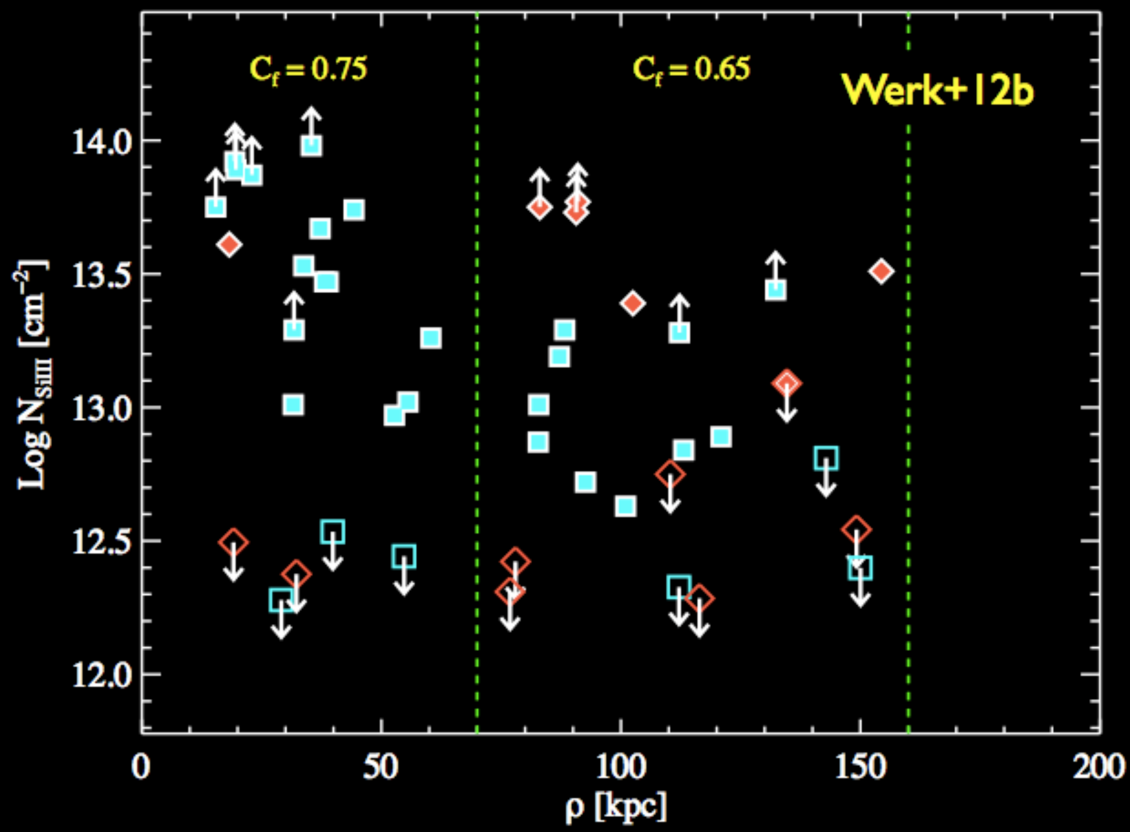
1. A cool (10^4 K) medium with high covering fraction of $N_{HI} > 10^{15}$ cm^{-2} exists around nearly every L* galaxy, even ellipticals, to 150 kpc.
2. Thus, there is no obvious suppression of “cold accretion” around massive elliptical galaxies.

The CGM of z ~ 0, L* Galaxies: The Low Ionization State Metals



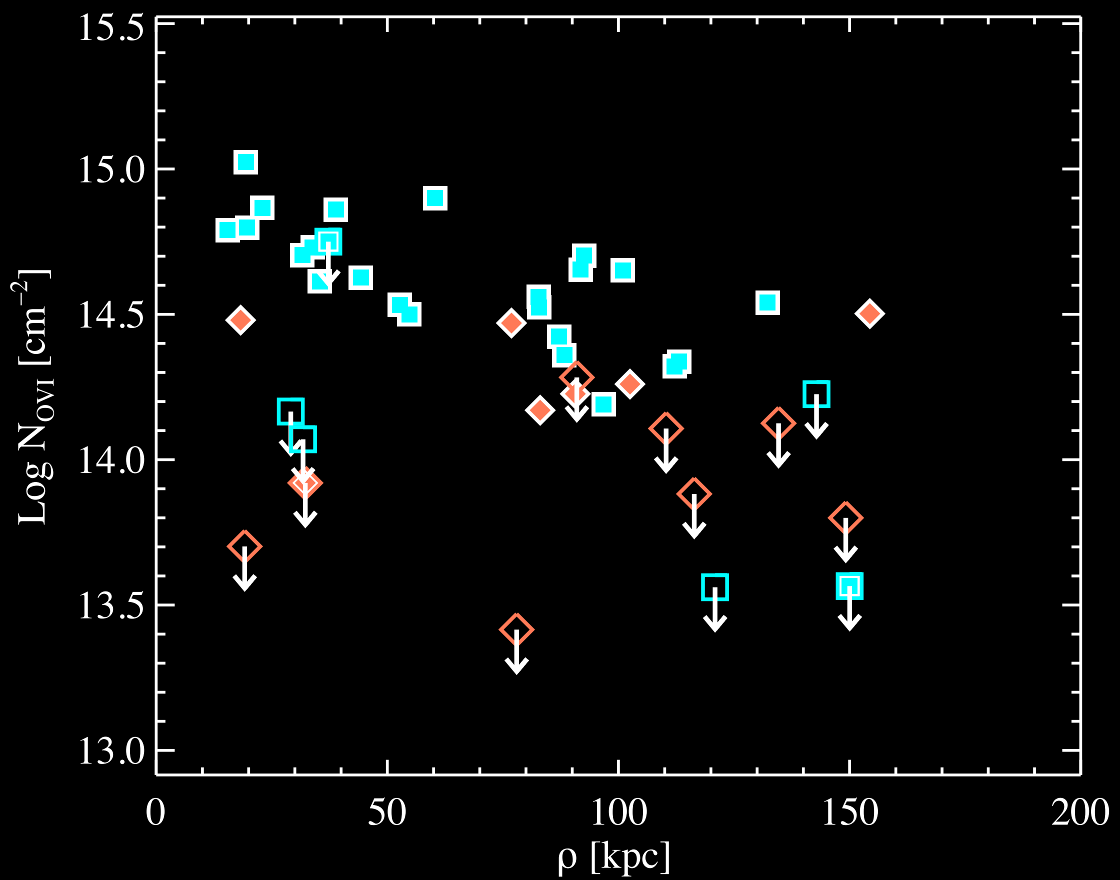
1. Low-Ion metals (Mg II) are present throughout the CGM, and have 50% covering fraction, to 70 kpc
2. There is no obvious distinction between blue and red galaxies
3. These low-ions seem to trace high N_{HI} (> 10^{16} cm^{-2})

The CGM of z ~ 0, L* Galaxies:
The Intermediate Ionization State Metals



1. Intermediate ionization state metals (SiIII, CIII) are very common throughout the CGM, and have 70% covering fraction to 150 kpc (90% for CIII).
2. There is no obvious distinction between blue and red galaxies.
3. There is a likely trend of decreasing column with impact parameter.

The CGM of z ~ 0, L* Galaxies: The Higher Ionization State Metals



1. OVI is more common around star-forming galaxies than around massive, red, ellipticals. (SF = 90%; Red = 40%)
2. There is a likely trend of decreasing column with impact parameter.

What is the origin of the CGM?

Accreting IGM gas?

Cooling Coronal Gas?

Supernovae Winds?

AGN feedback?

Galactic Fountains?

Tidal debris?

Ram-stripped material?

Cold flows?

Extended HI disks?

All of the Above!

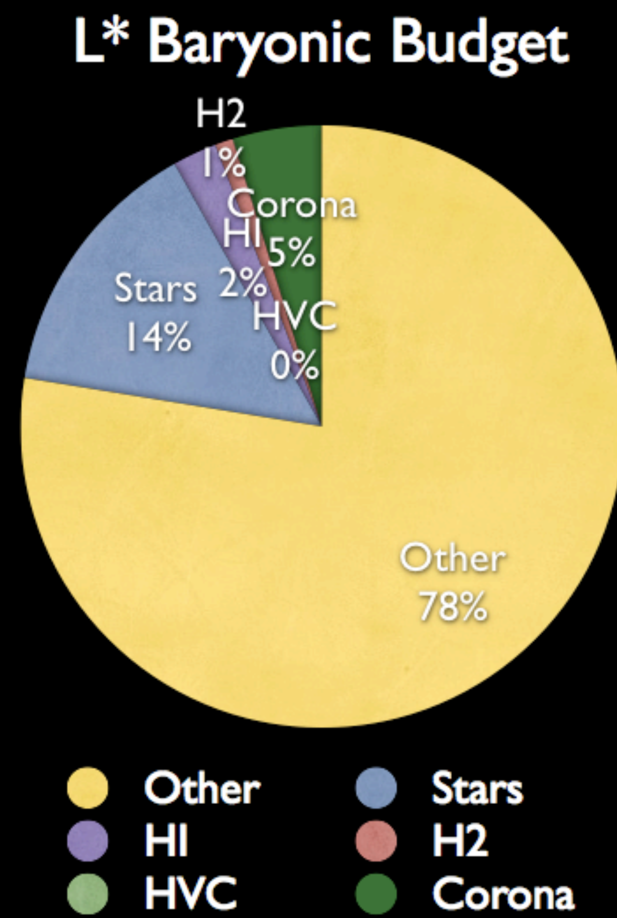
The Baryonic Content of the CGM of z~0, L* galaxies Warm and Cool Phases

The Galaxy Missing Baryon Problem

Anderson & Bregman 2010: Field spirals are observed to be missing their baryons, if you consider the content of the hot X-ray halo and the stellar content alone.

Klypin, Zhao, and Somerville 2002: Dynamical models unequivocally require that 50% of the gas within the virial radius of a galaxy must not be within the disk or the bulge.

But, perhaps they didn't fall in to begin with? Davé et al. 2009 say that most are in the WHIM, outside of galactic halos.



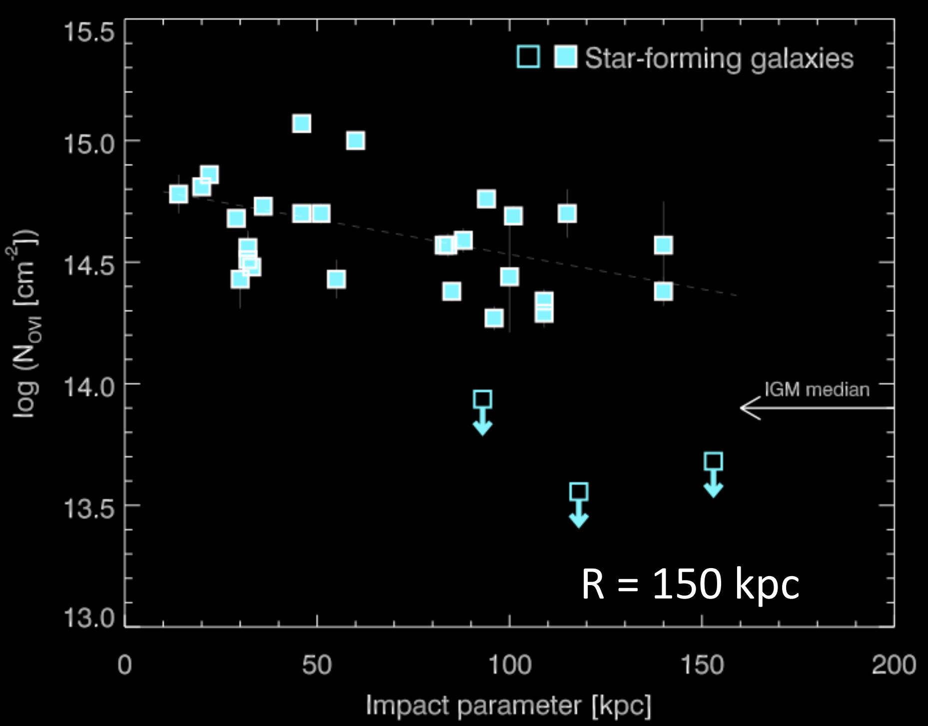
Theoretical Prediction

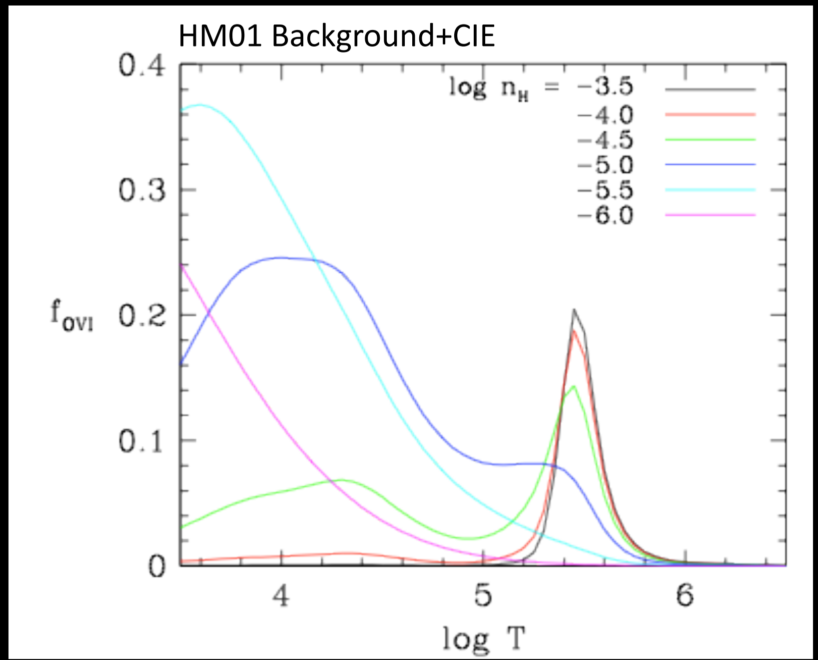
"The simulations of individual galaxies predict that the 'missing baryons' are found in the CGM of galaxies." – Stinson et al. 2011

"We further note that the HI surface densities at < 50 kpc are sufficiently large that the CGM will yield significant absorption from lower ionization states of heavy metals (e.g. MgII, SiII, SiIII). A proper estimate of the column densities for these ions, however, will require a full treatment of radiative transfer (i.e. to account for self-shielding by optically thick HI gas)."

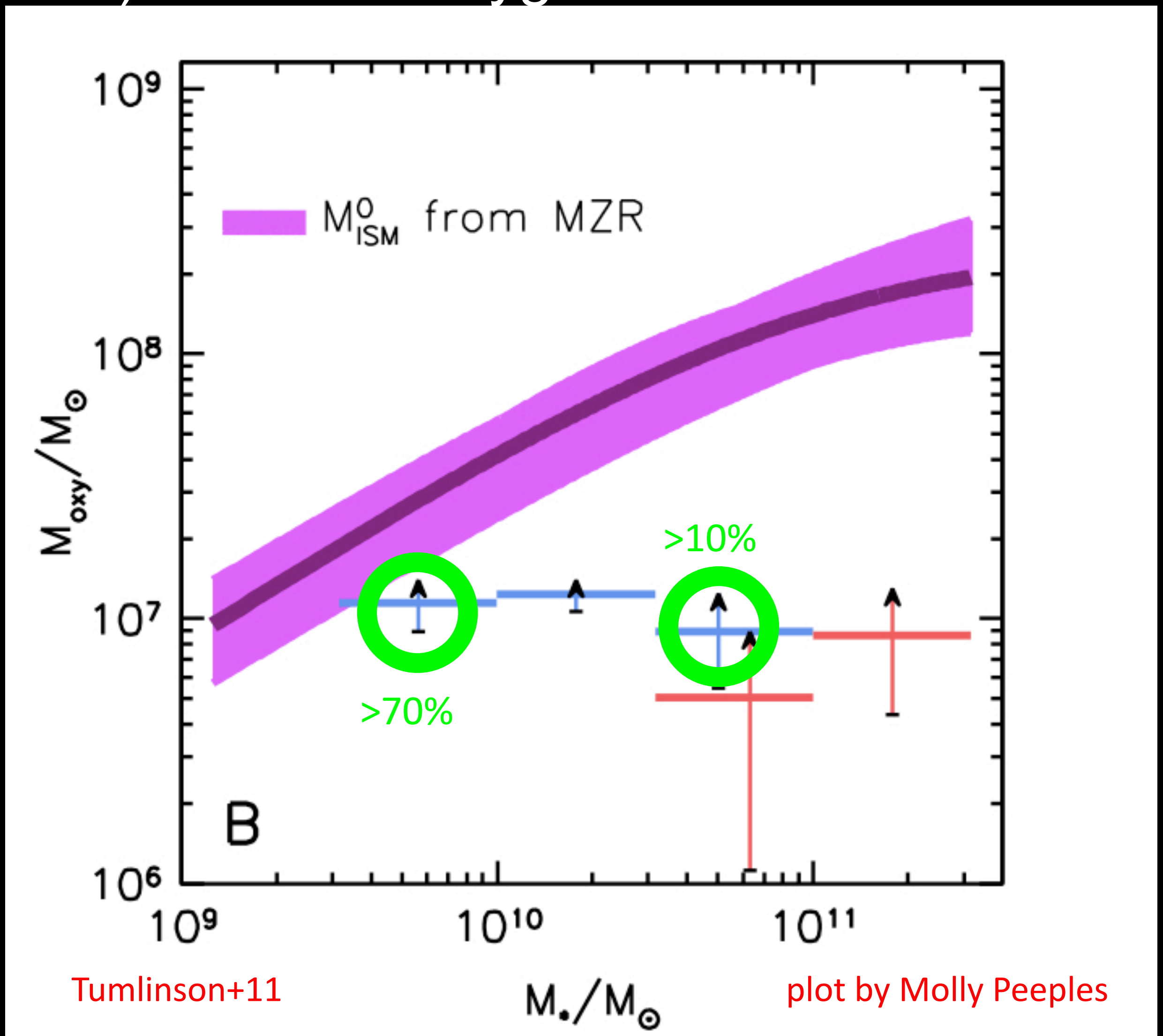
The CGM of z~0, L* Galaxies: The Highly Ionized Phase Mass Budget (Tumlinson+11)

- $M_{OVI} = \pi R^2 N_{OVI}\ 16 m_H\ M_\odot$
- . . . then apply ionization correction f_{OVI}. . .
- $M_{Oxygen} = 1.2 \times 10^7\ (0.2/f_{OVI})\ M_\odot$
- $M_{gas} = 2 \times 10^9\ (Z_\odot/Z)\ (0.2/f_{OVI})\ M_\odot$



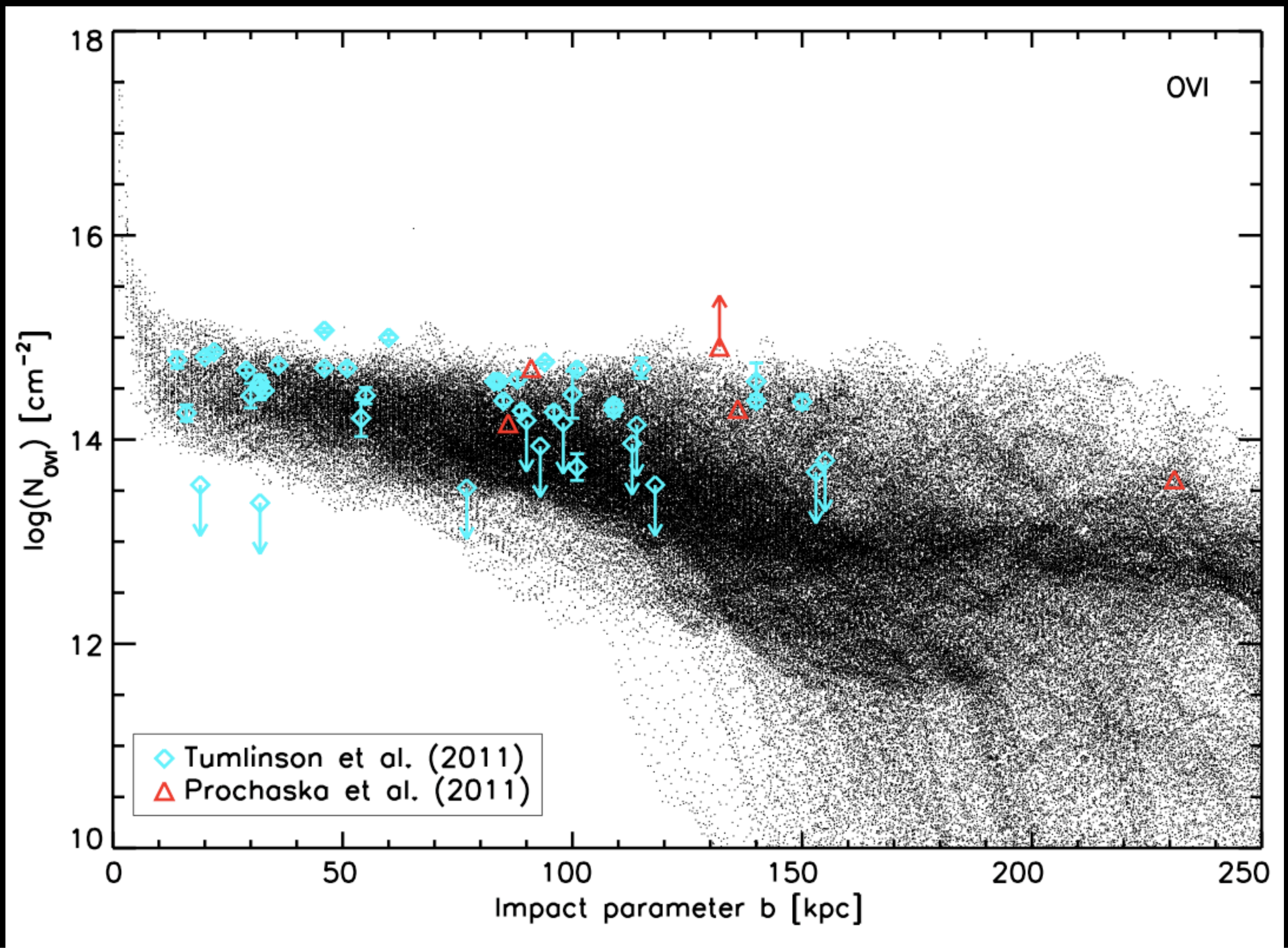


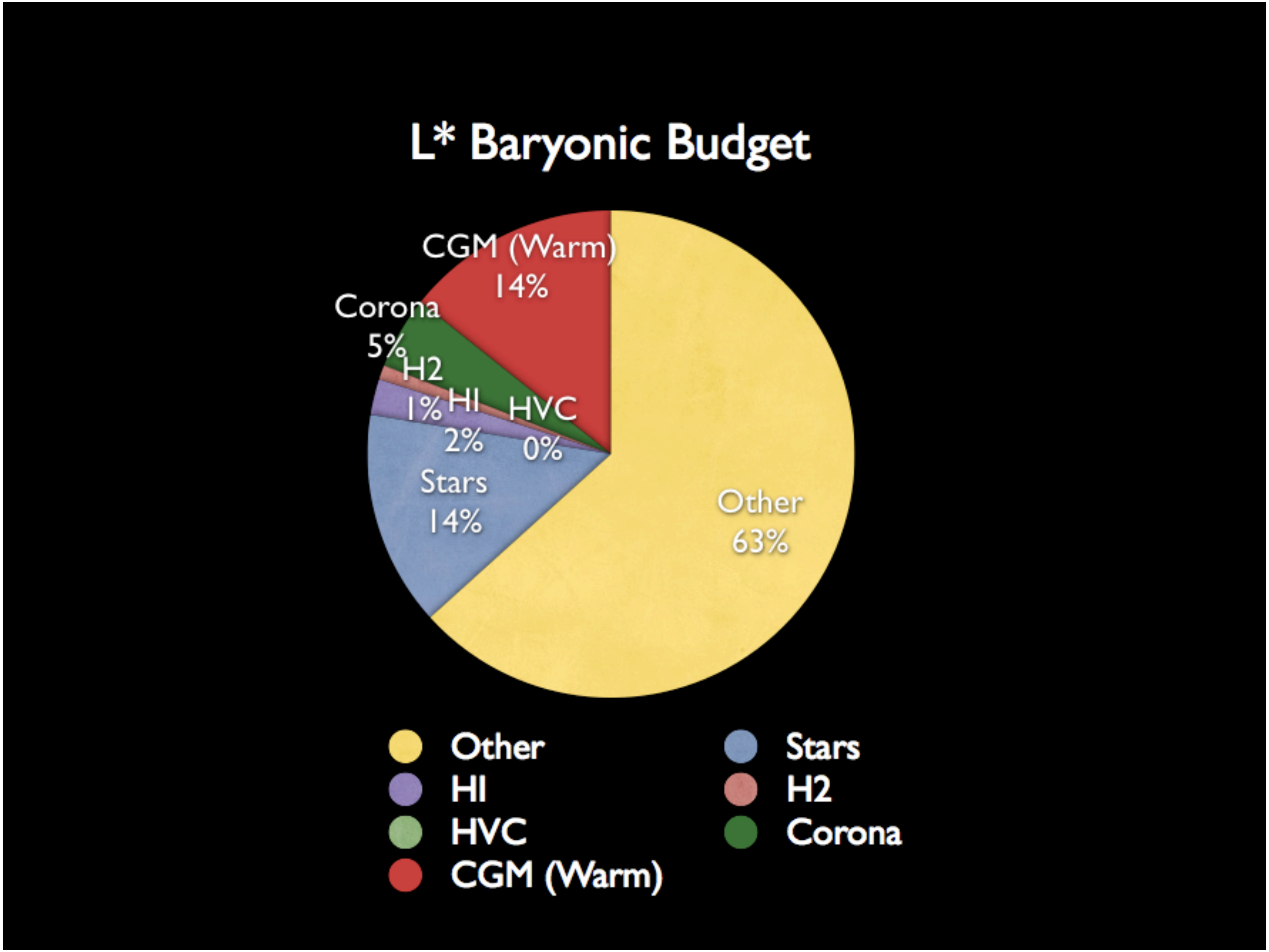
(Almost) As Much Oxygen in the CGM as in the ISM!



Does the decline in CGM to ISM oxygen mass ratio imply more efficient metal escape from low-mass galaxies? Or just some mass dependence to the ionization conditions?

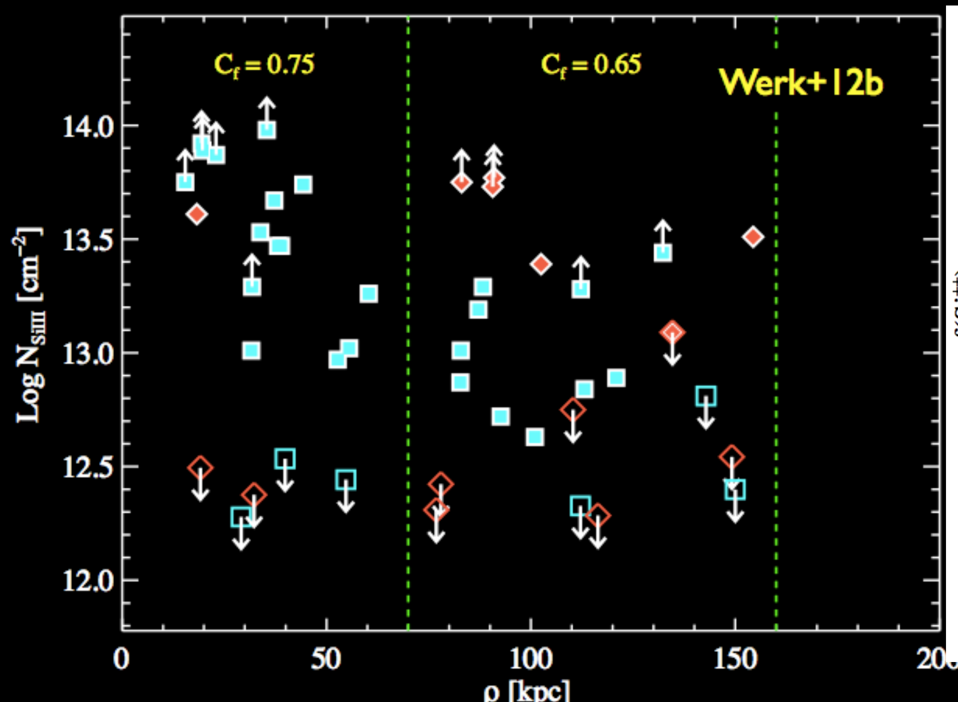
The Simulations at z ~ 2.8, Courtesy of Sijing Shen

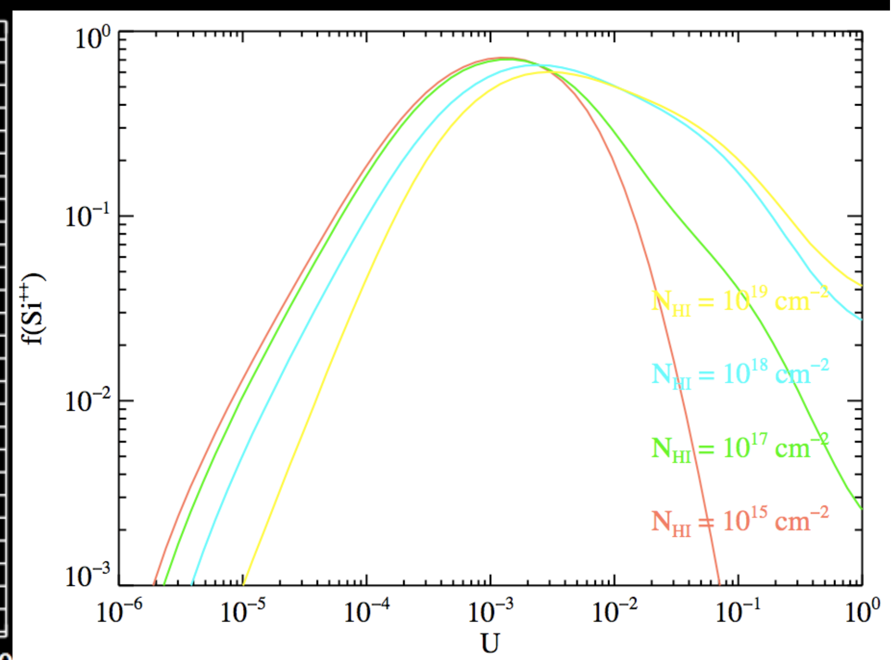



L* Baryonic Budget
CGM (Warm)
14%
Corona
5%
H2
1%
HI
2%
HVC
0%
Stars
14%
Other
63%
Other
Stars
HI
H2
HVC
Corona
CGM (Warm)

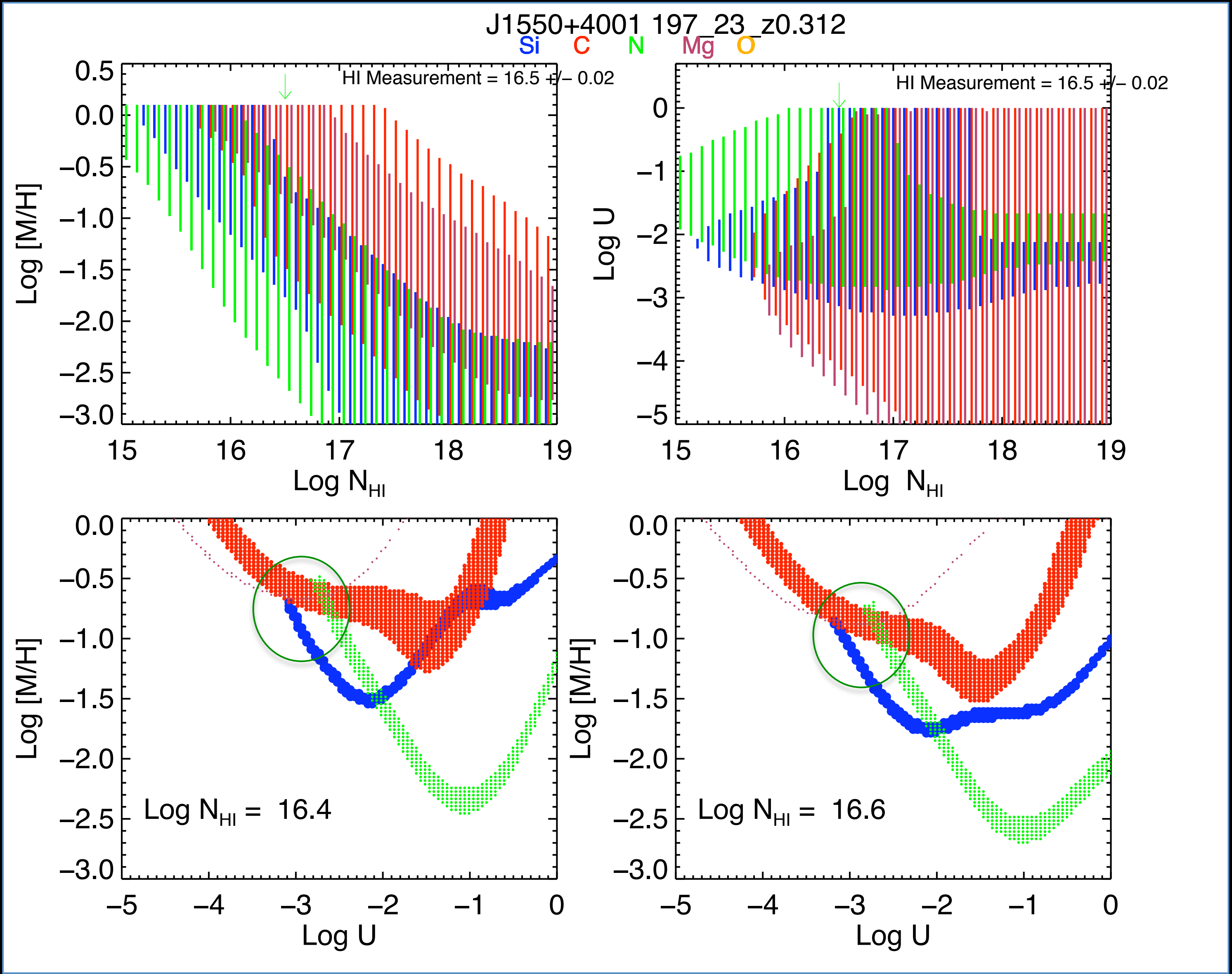
Lower Limit: Cool, Ionized CGM (10^4 K < T < 10^5 K)

- $M_{SiIII} = C_f \pi R^2 N_{SiIII}\ 28 m_H\ M_\odot$
- . . . then apply ionization correction f_{SiIII}. . .
- $M_{Silicon} = 5.5 \times 10^5\ (0.7/f_{SiIII})\ M_\odot$
- $M_{gas} > 8 \times 10^8\ (Z_\odot/Z)\ (0.7/f_{SiIII})\ M_\odot$

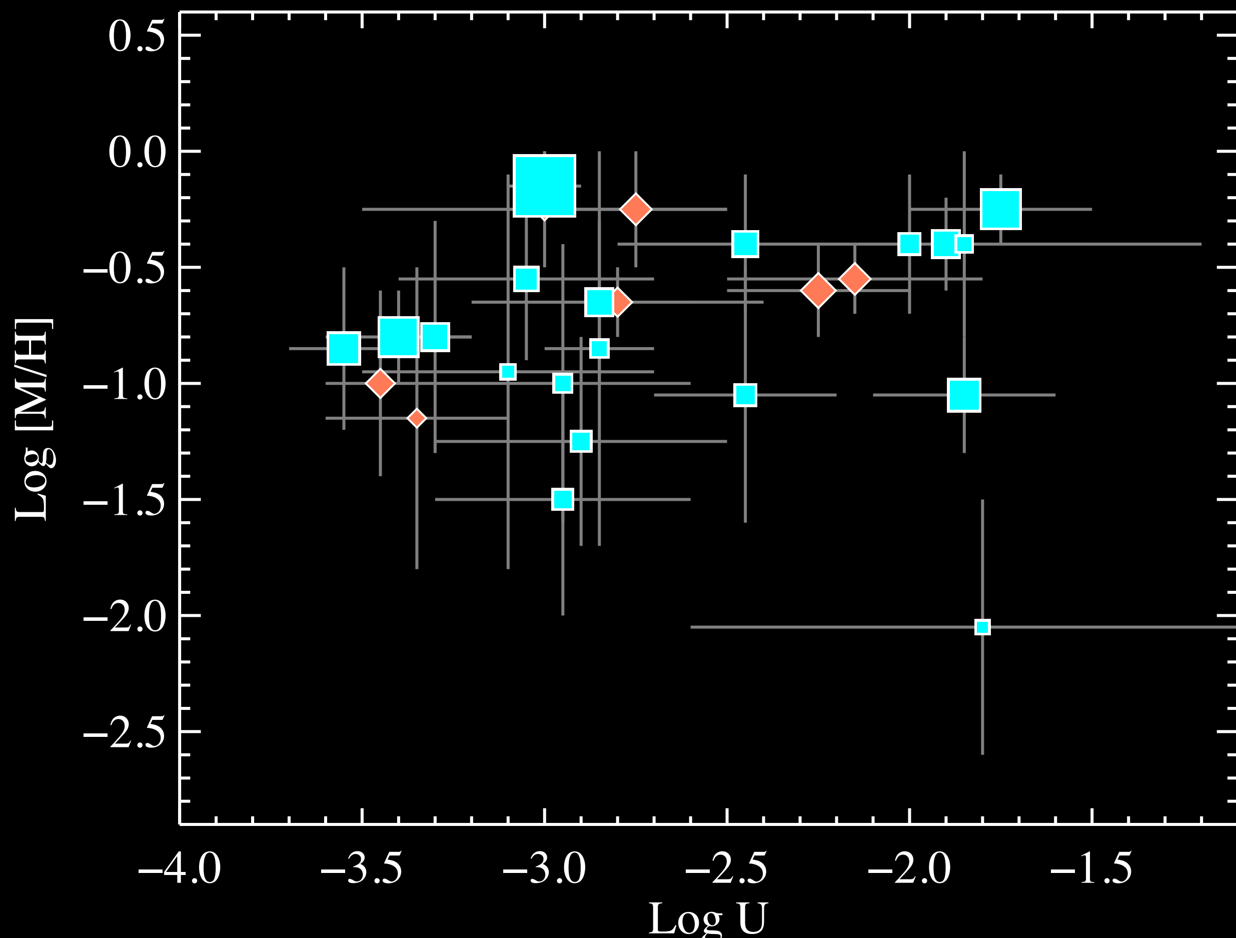




Photoionization Modeling

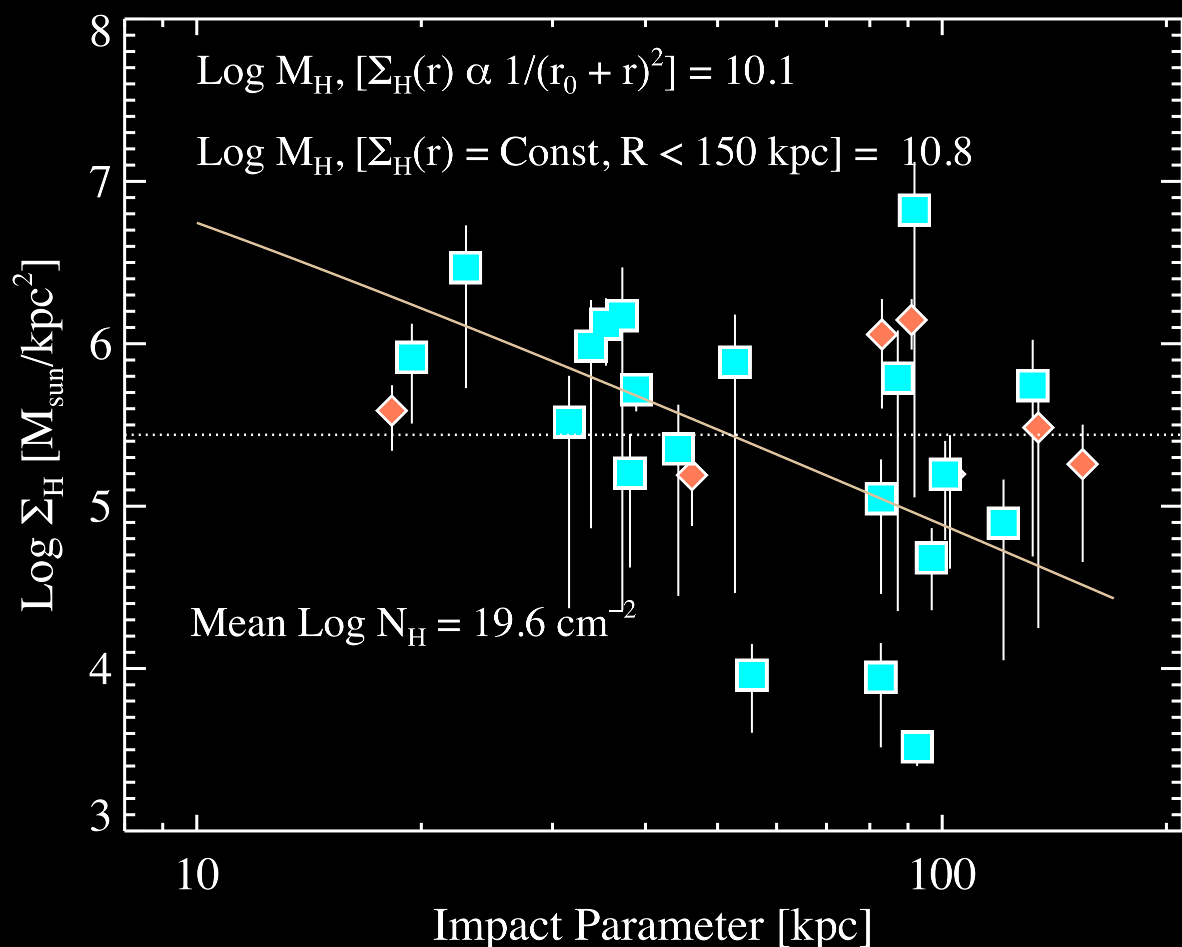


The Ionization State and Metallicity of the CGM

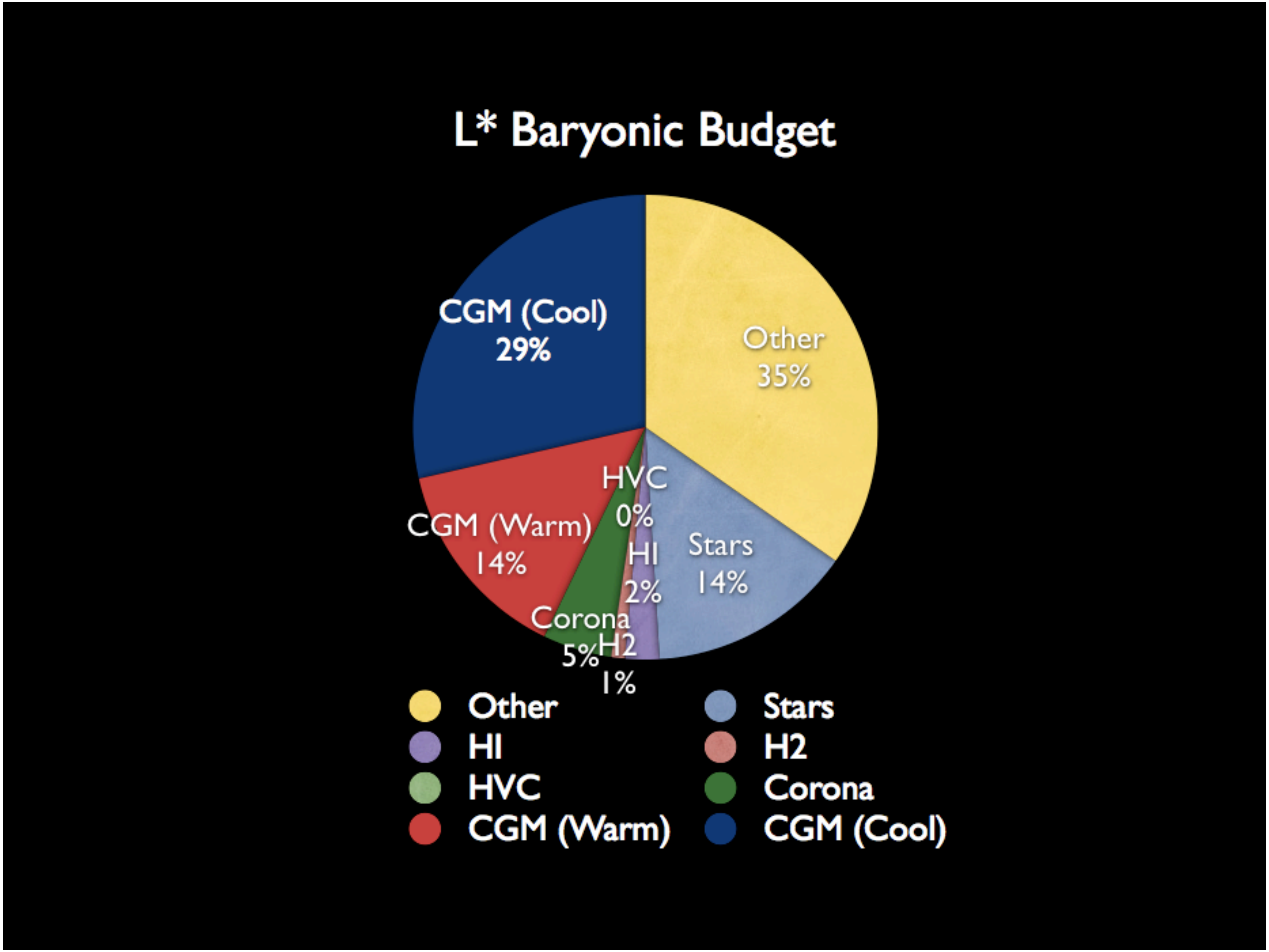


Werk+12b

The Mass Surface Density of Hydrogen



Werk+12b


L* Baryonic Budget
CGM (Cool)
29%
Other
35%
HVC
0%
CGM (Warm)
14%
HI
2%
Stars
14%
Corona
5%
H2
1%
Other
Stars
HI
H2
HVC
Corona
CGM (Warm)
CGM (Cool)

Next Steps

- Extend the analysis to a diverse set of galaxies and environments: dwarfs (PI Tumlinson, HST Cycle 18); Red galaxies, groups, clusters; Map ρ = 200 – 500 kpc (Tripp+12)
- Improve the HI measurements since they are critical for mass and metallicity determinations
- Improve imaging over what is provided by SDSS at z ~ 0.2
- Integrate kinematic information
- Direct Imaging of the CGM?

The CGM is an Important Reservoir of Baryons

And can account for much of the missing mass!

- A cool, metal-enriched CGM traced by HI and lower ionization states of metal lines (MgII, SiII, SiIII, CII, CIII) is pervasive out to 300 kpc
- A second, highly-ionized phase traced by OVI is ubiquitous around star-forming galaxies, but absent around passively evolving elliptical galaxies
- Both high and low ionization phases in the halos of star-forming galaxies contain > 10^7 $M_\odot$ of oxygen
- These metal masses are comparable to the entire ISM of the Galaxy
- Combined CGM (Warm + Cool Phases) can account for 50+% of a galaxies baryons, and may resolve the galaxy missing baryon problem