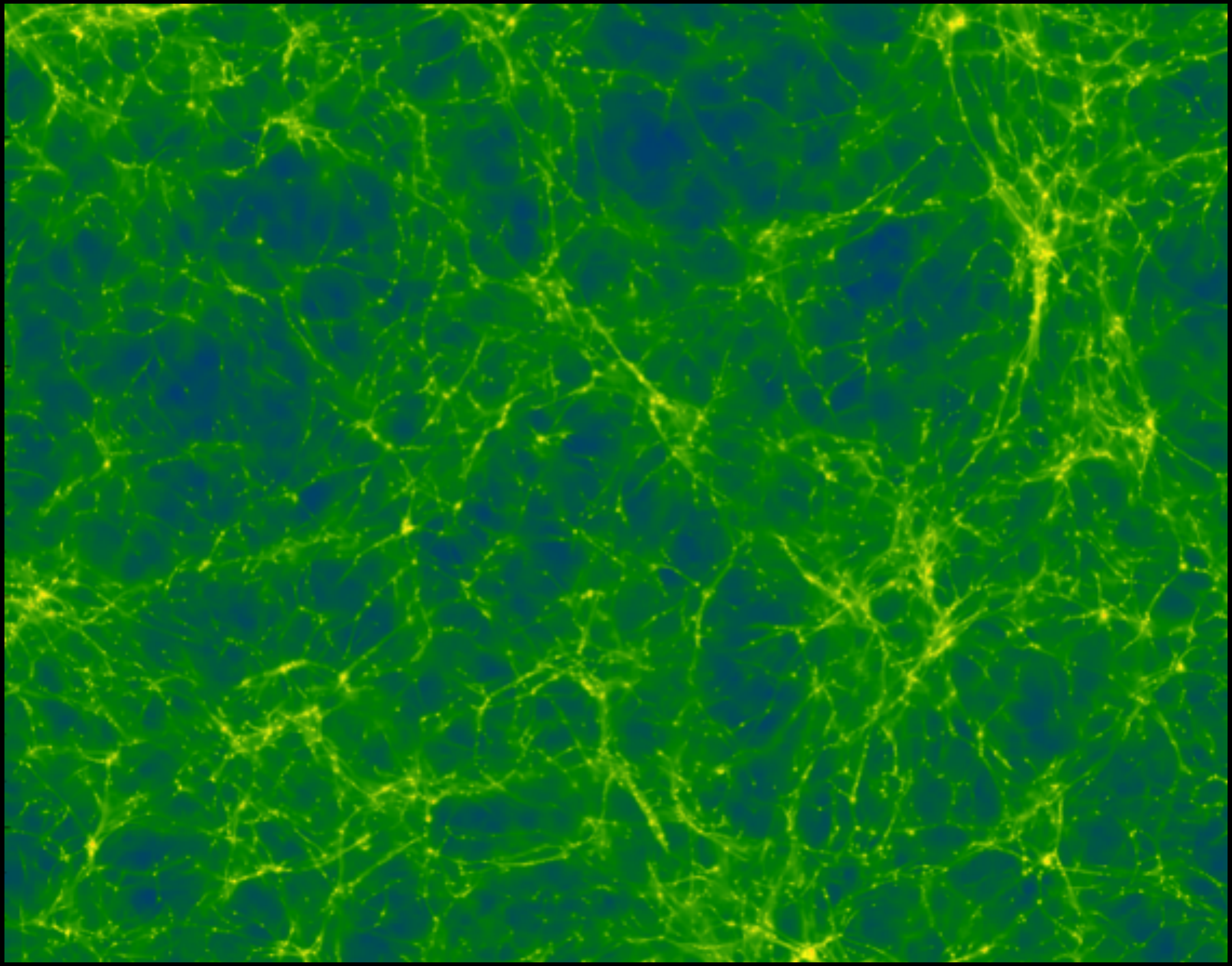
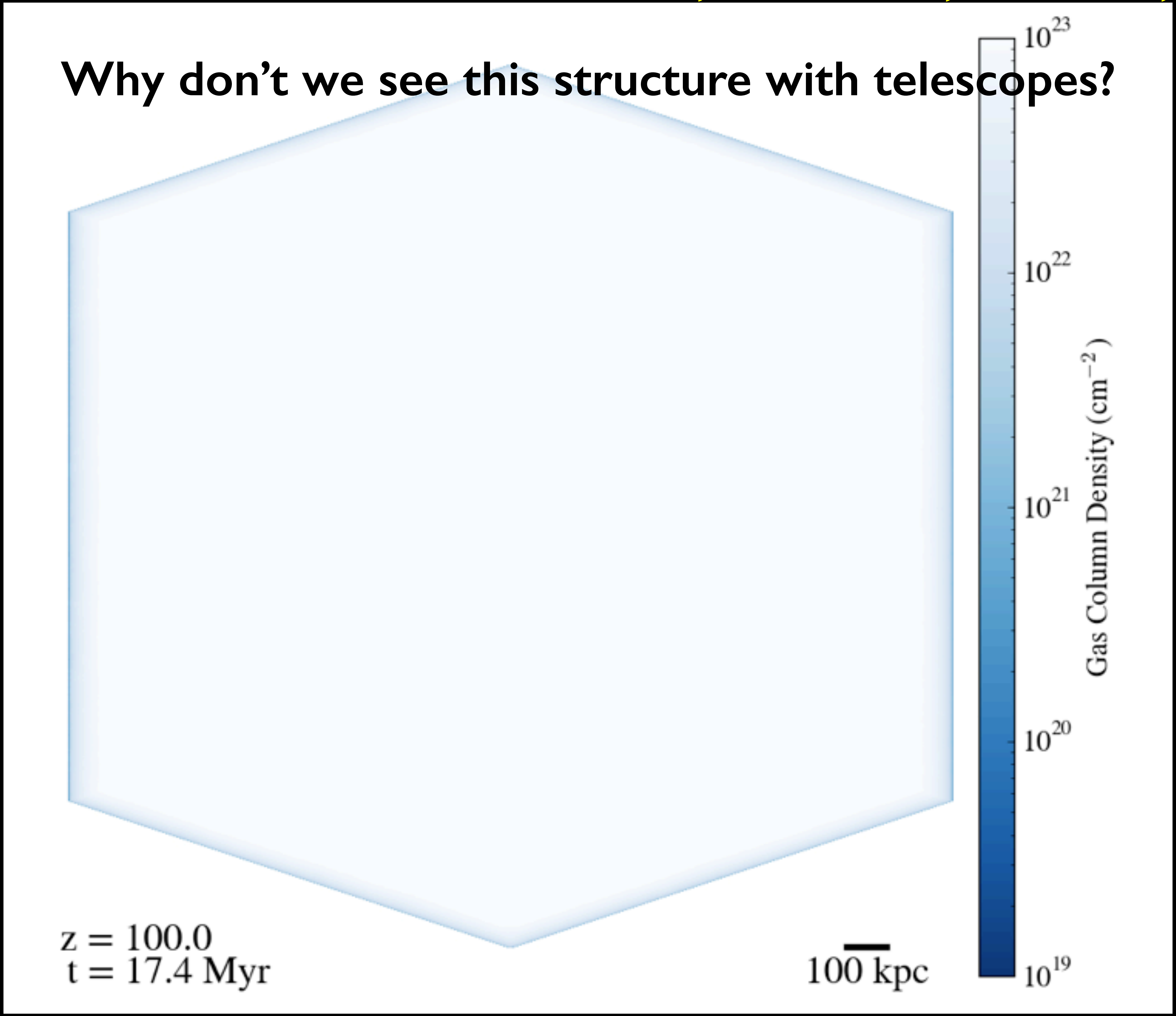
The Intergalactic Medium (IGM) and the Circumgalactic Medium (CGM)



Cameron Hummels
NSF Fellow, Caltech

The evolution of the universe: walls, filaments, clusters, voids



Hummels, in prep.

The evolution of the universe: walls, filaments, clusters, voids

We do, in the distribution of galaxies (as seen here), where the galaxies act as tracer particles in the fluid. But why can we not see the gas *itself*?

2dF survey

The evolution of the universe: walls, filaments, clusters, voids

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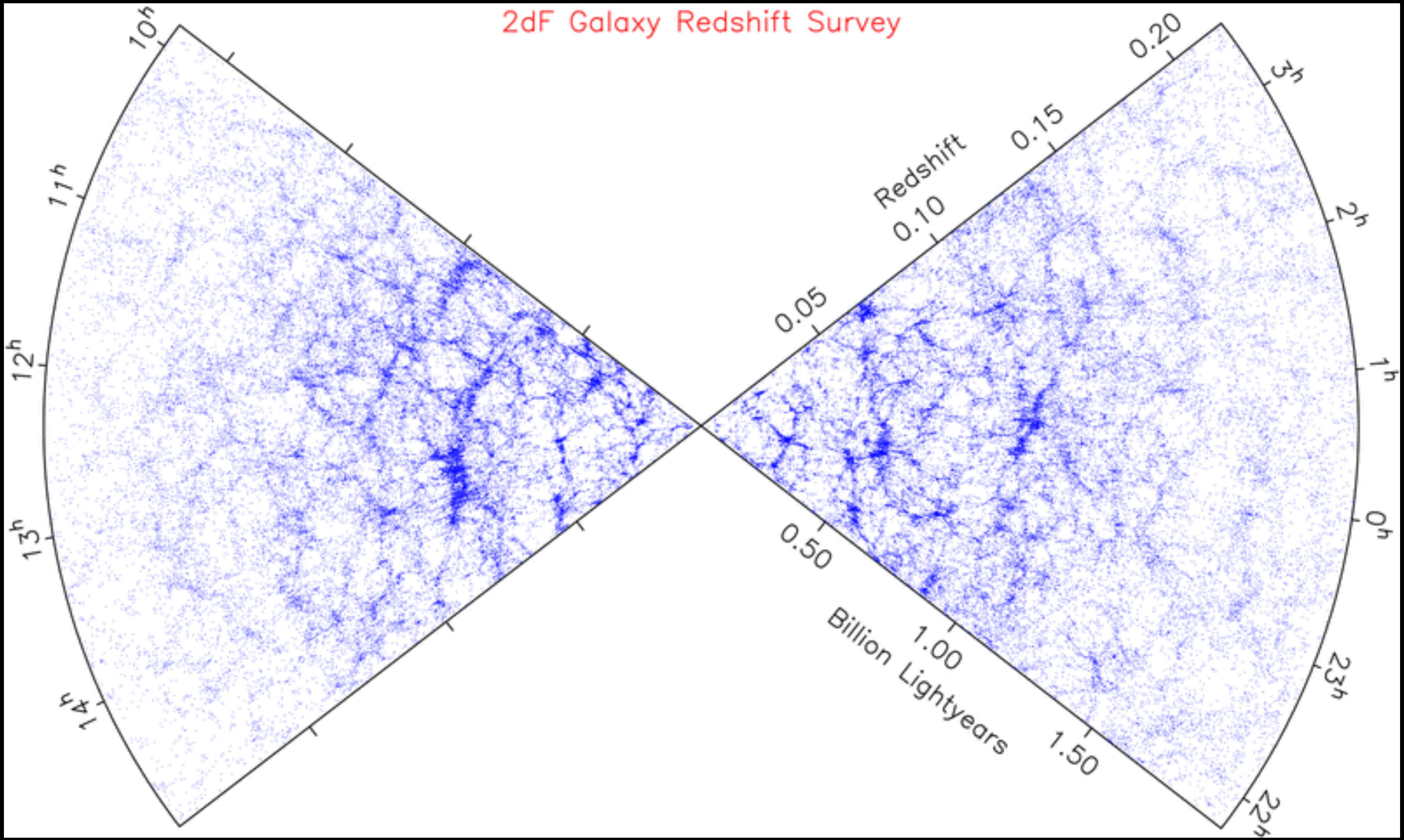
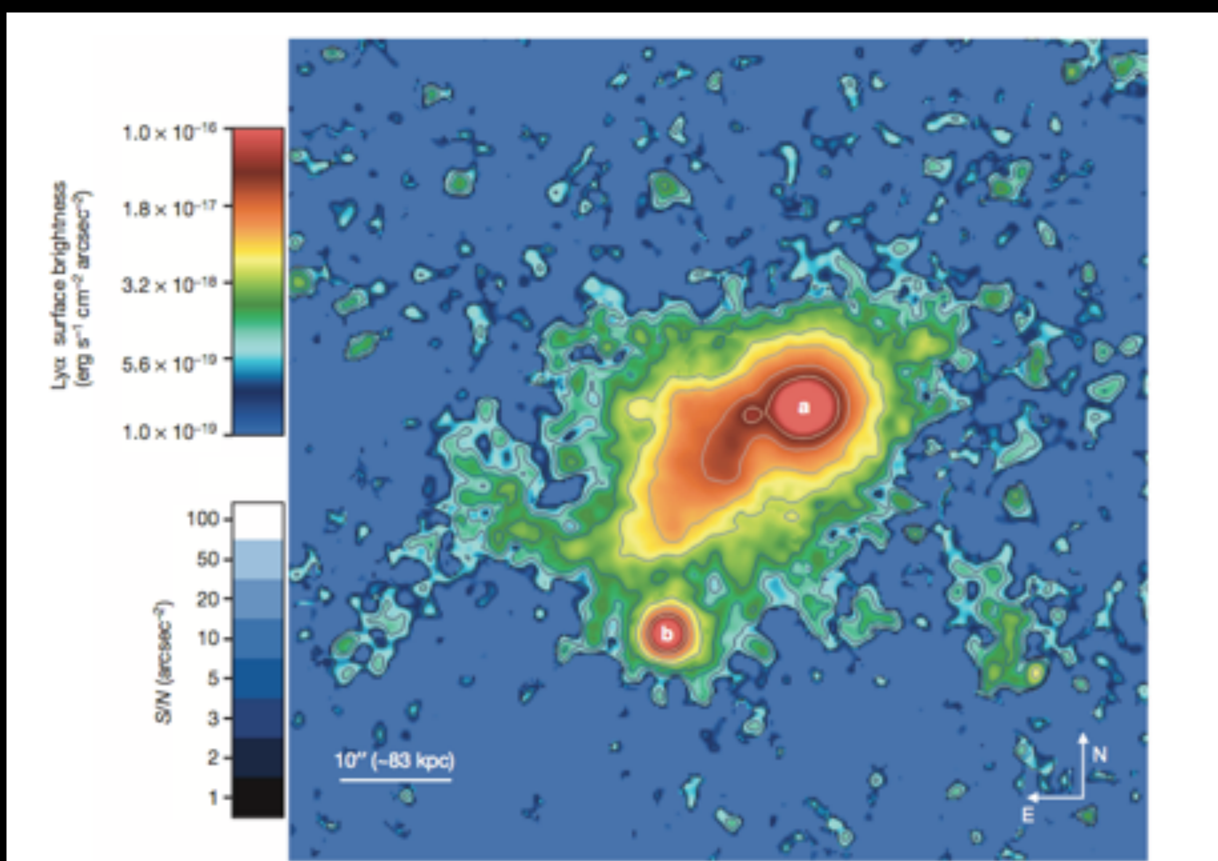


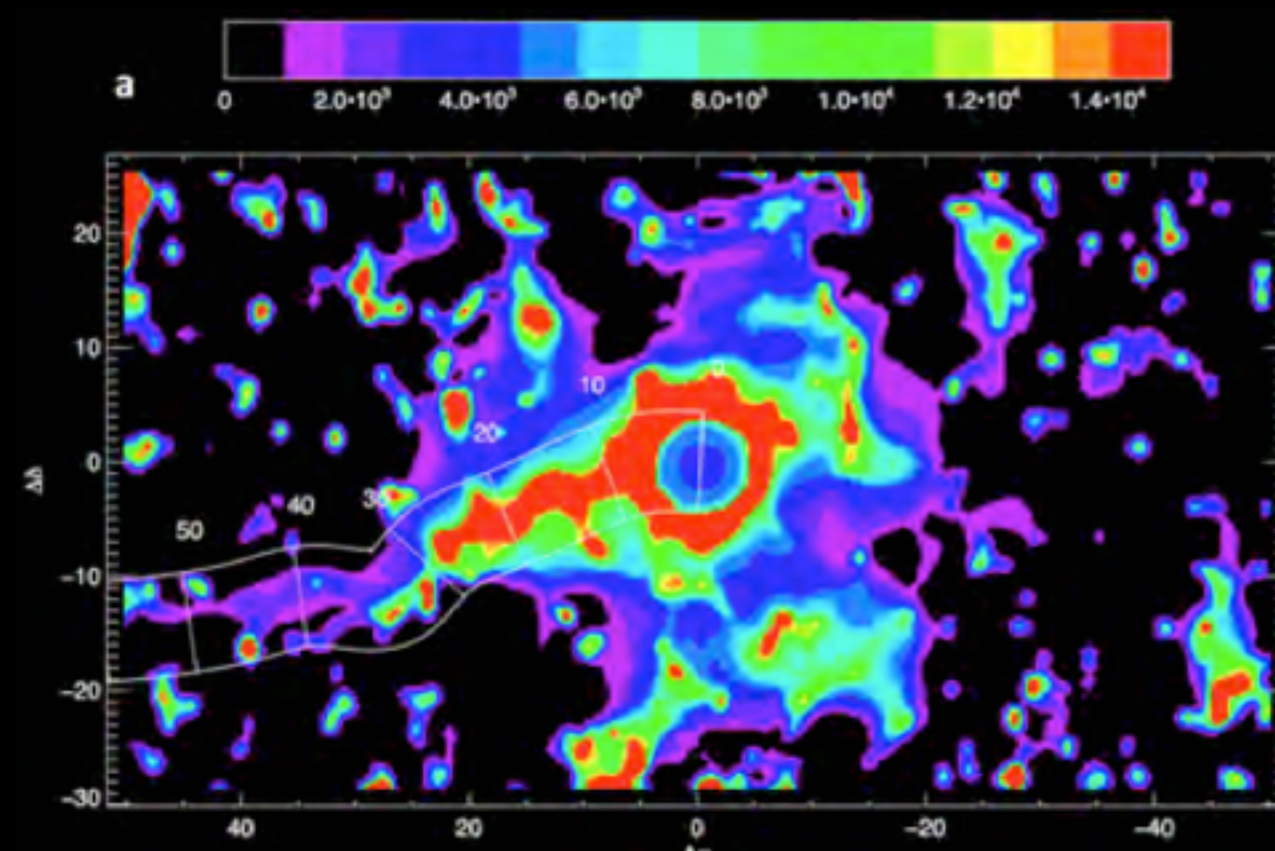
2dF survey

The evolution of the universe: walls, filaments, clusters, voids

Historically, we have not been able to see the gas in emission because it was too faint. But new research with KCWI (Caltech) and narrow-band imaging is enabling us to see this gas in emission.

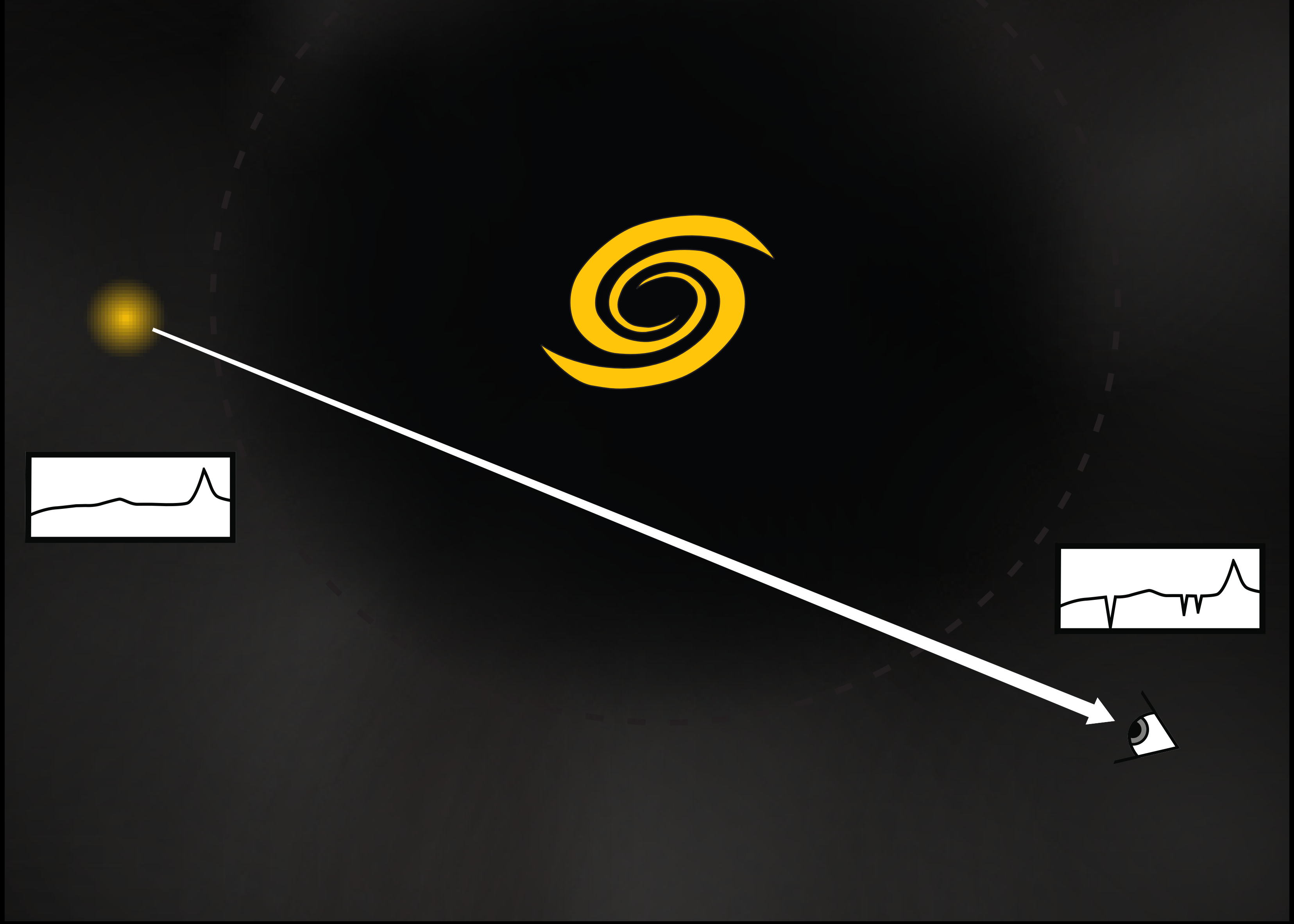


Cantalupo+ 2014



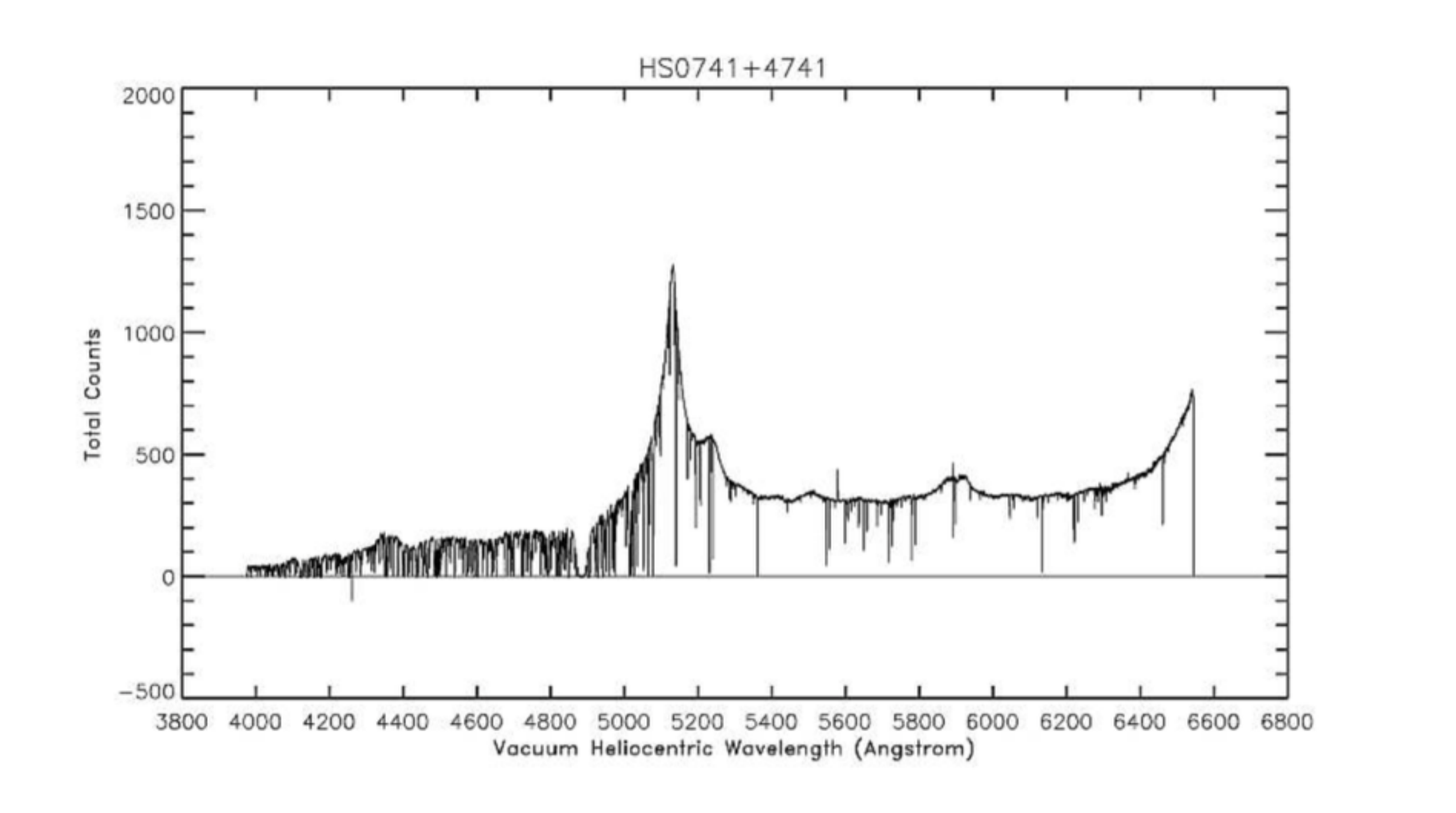
Martin+ 2014

Emissivity scales with the (gas density)^2, whereas opacity scales linearly with column density, so it's easier to see this gas in absorption. Need bright background sources like quasars to see intervening gas in absorption.



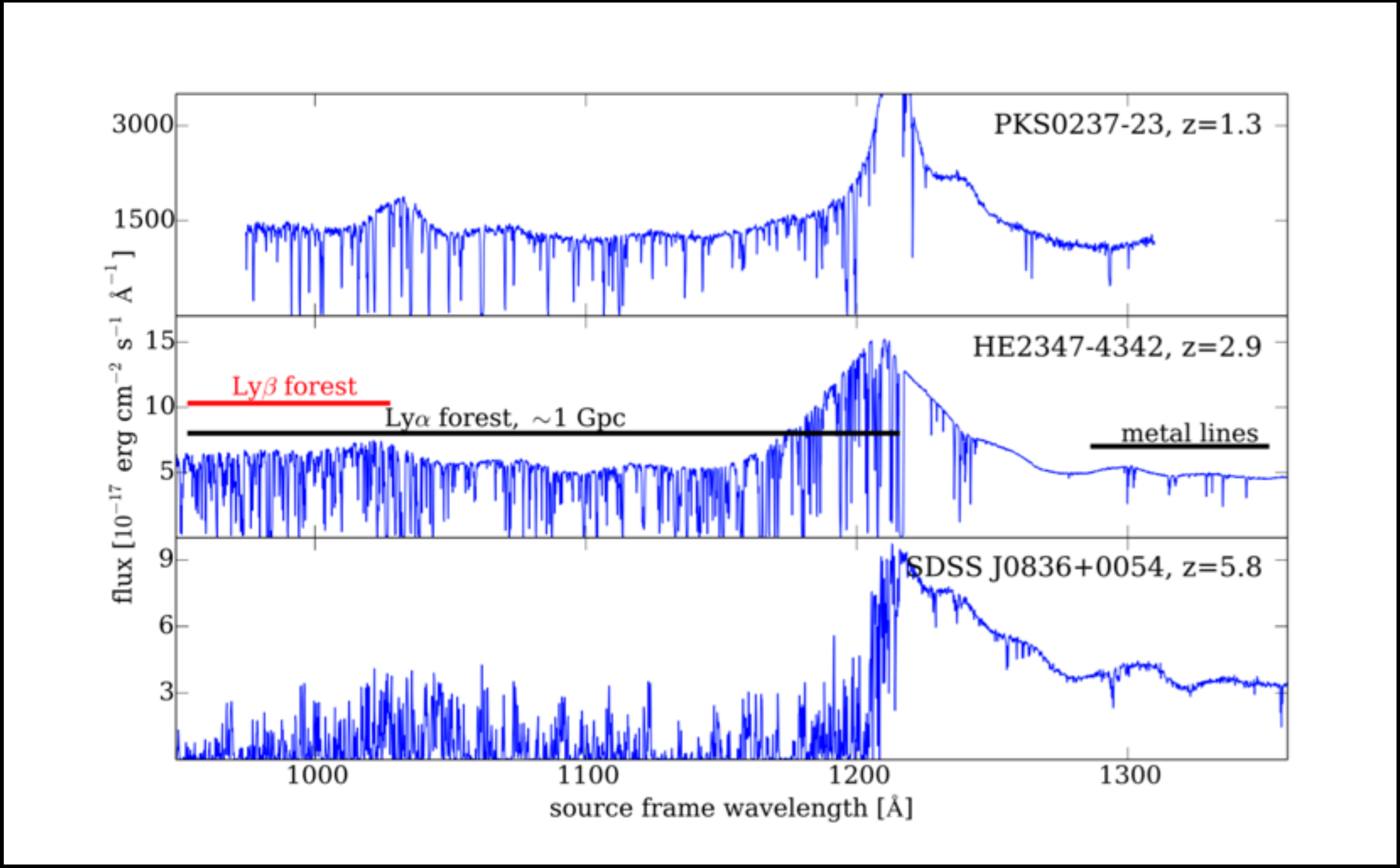
Hummels et al 2016

A quasar spectrum with absorption blueward of the lyman alpha peak from intervening neutral hydrogen between the quasar and the observer

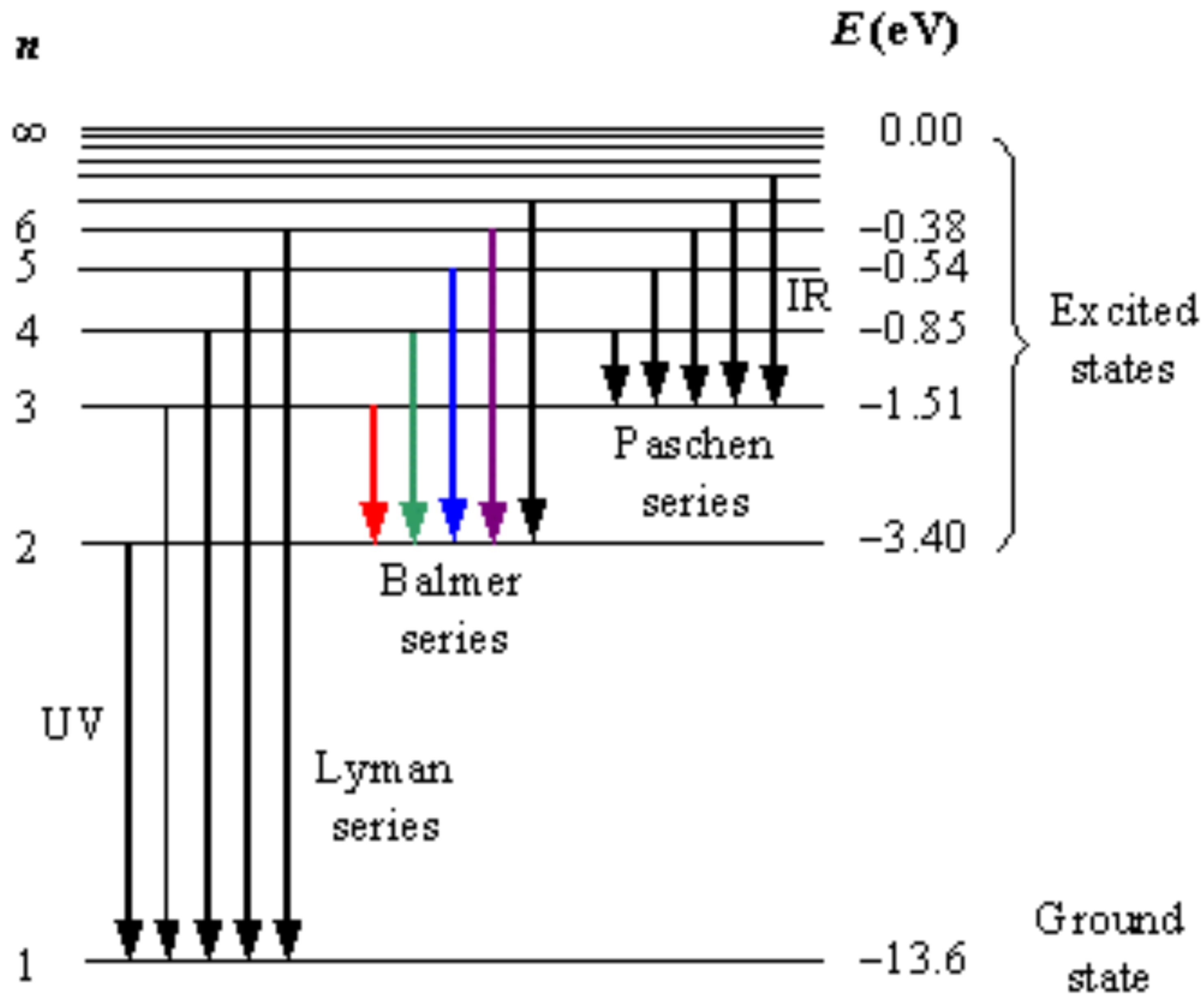


Songaila 2006

More absorption for more distant quasars. these numerous hydrogen absorbers are called the “lyman alpha forest”

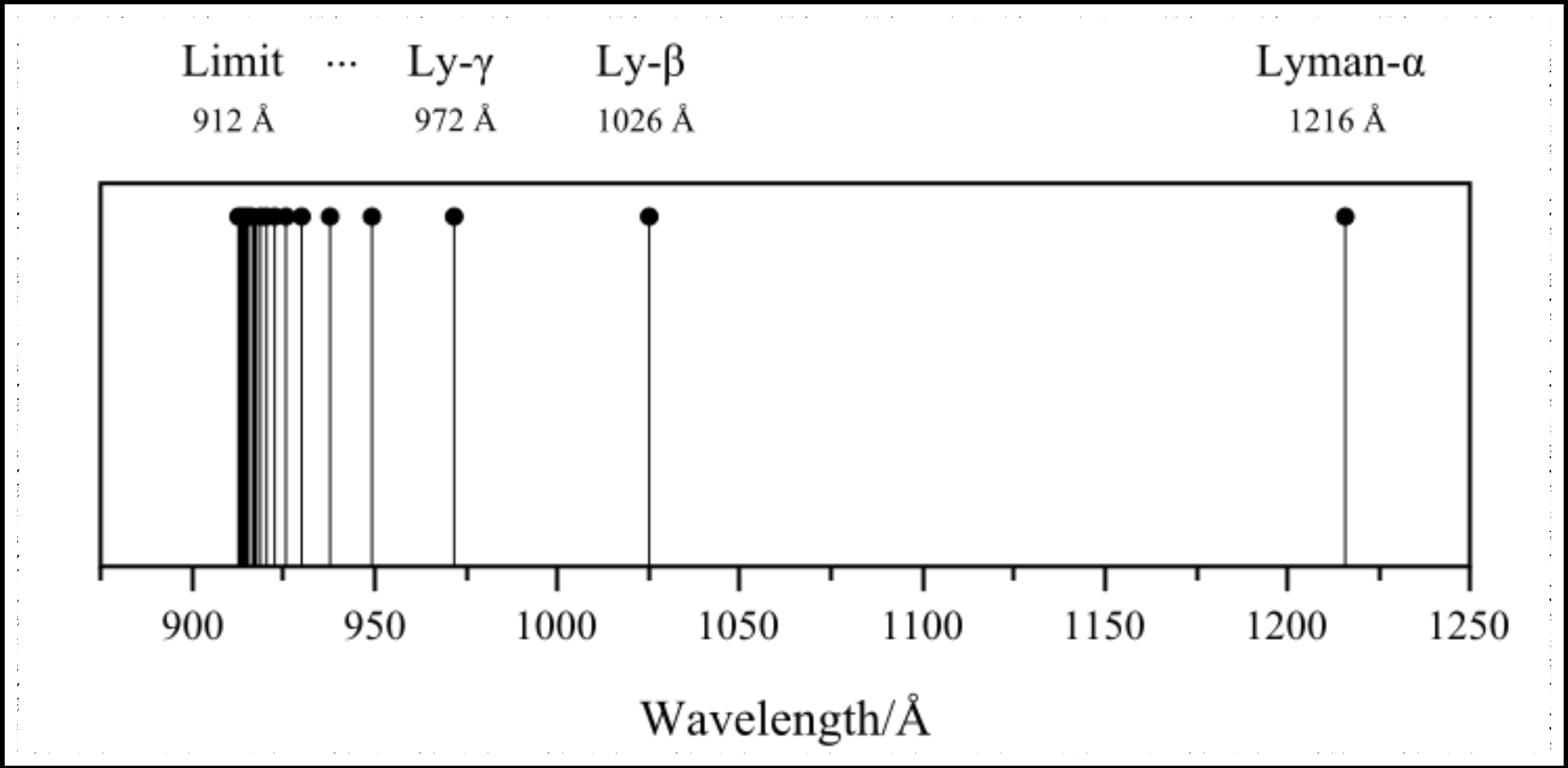


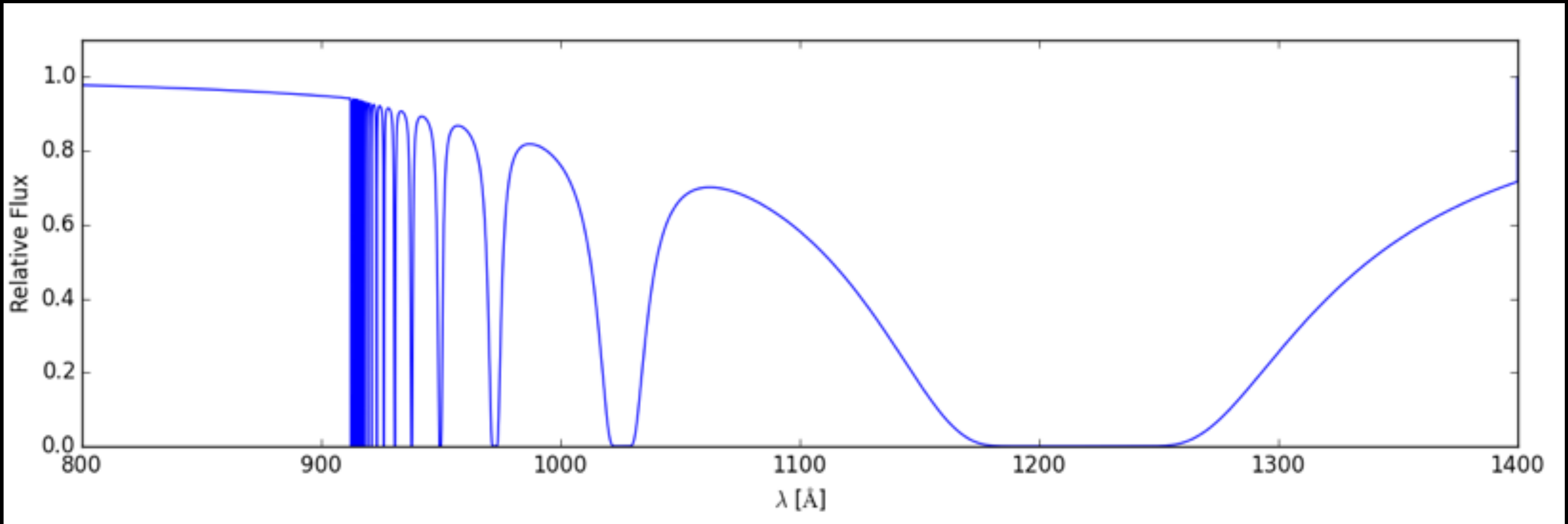
Absorption Lines are just Atomic Transitions
Most of the absorption we see is from hydrogen lyman lines because there is a lot of neutral hydrogen in the universe



Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated.

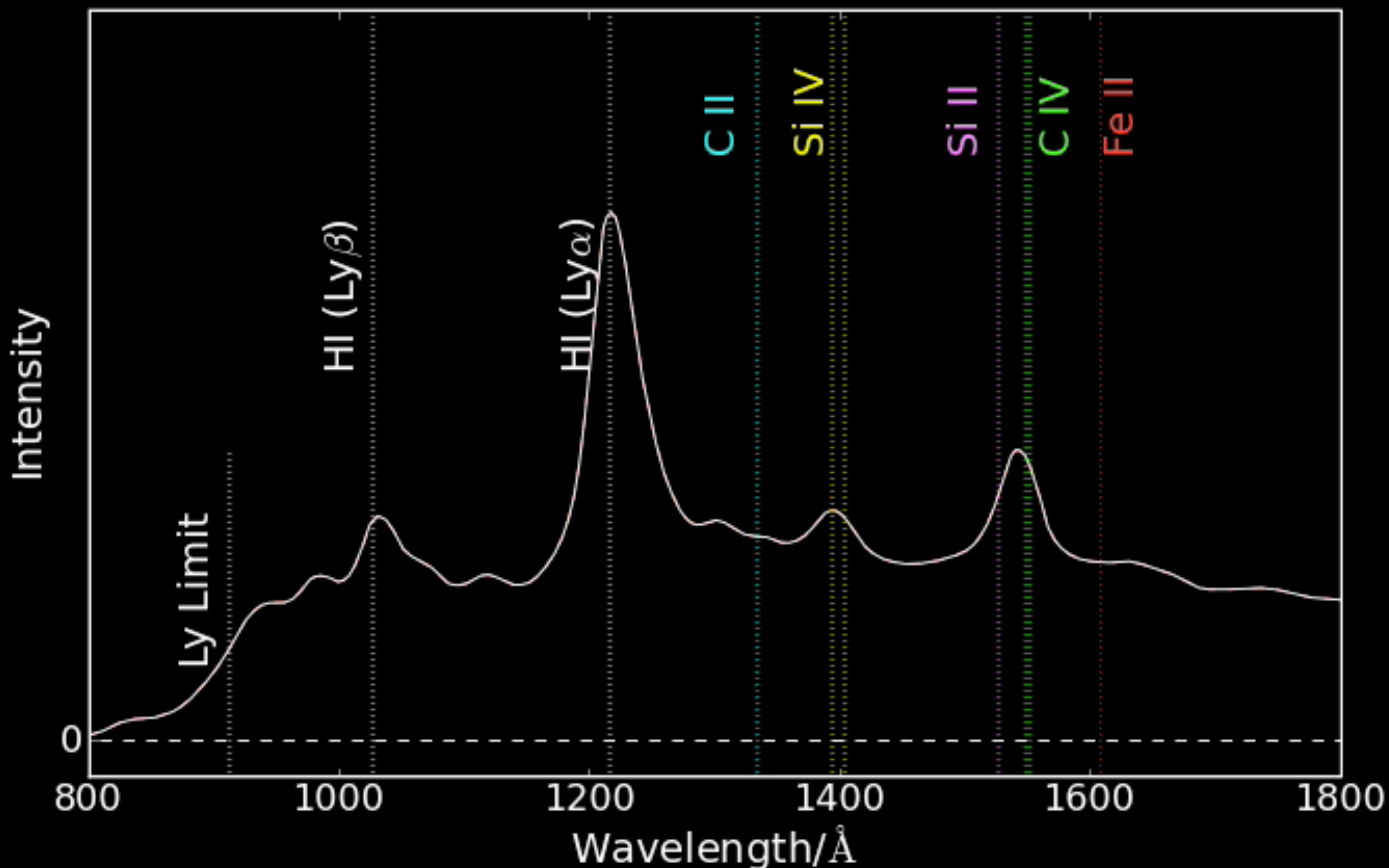
Lyman lines sit in the UV part of the spectrum





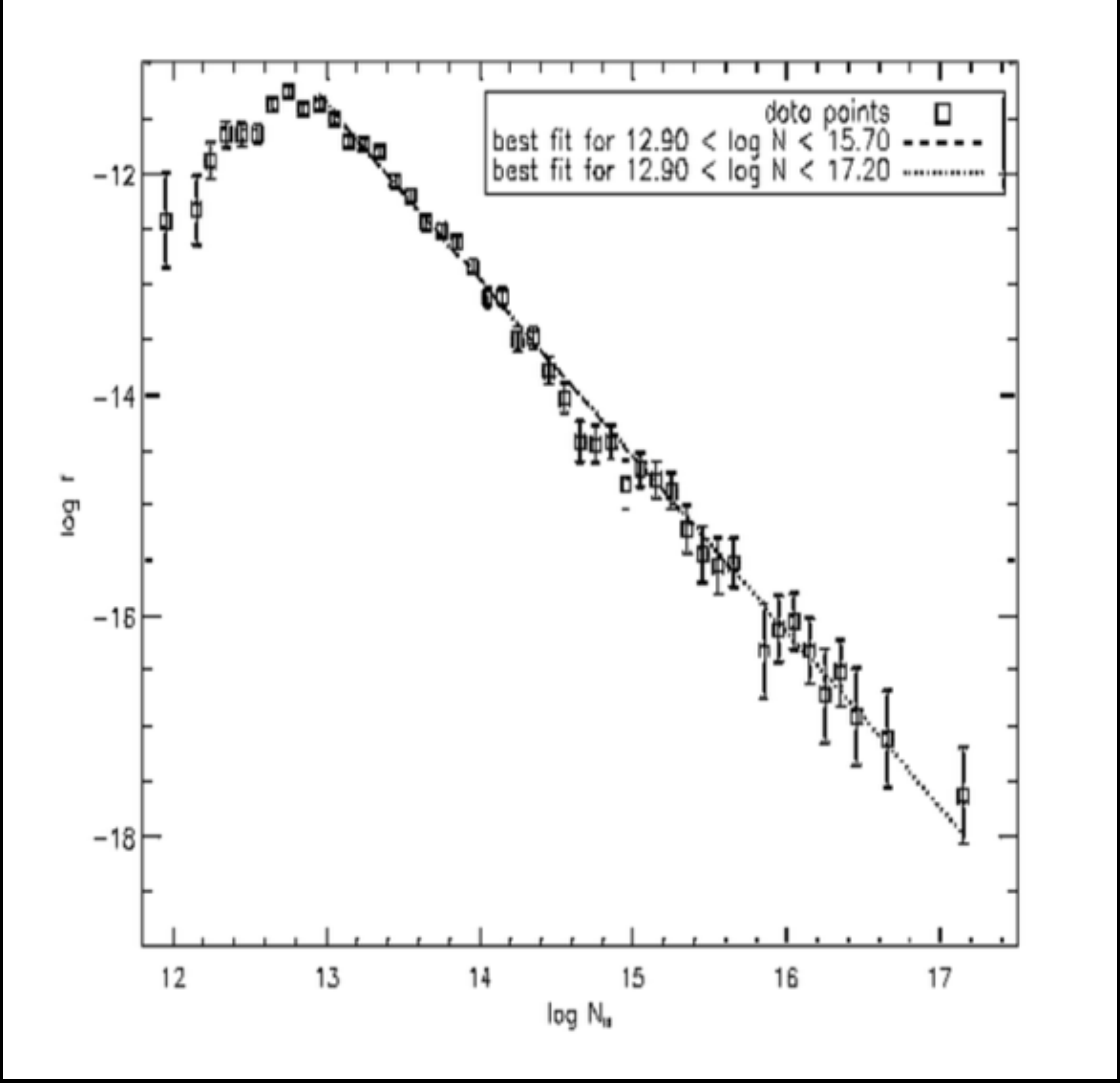
Hummels, in prep

Demonstration of how intervening gas absorbs light from a quasar emission spectrum



Andrew Pontoon

Neutral hydrogen clouds (absorbers) are a continuum of size distributions, but we break them up into 4 categories based on how they are detected



Janknecht 2006

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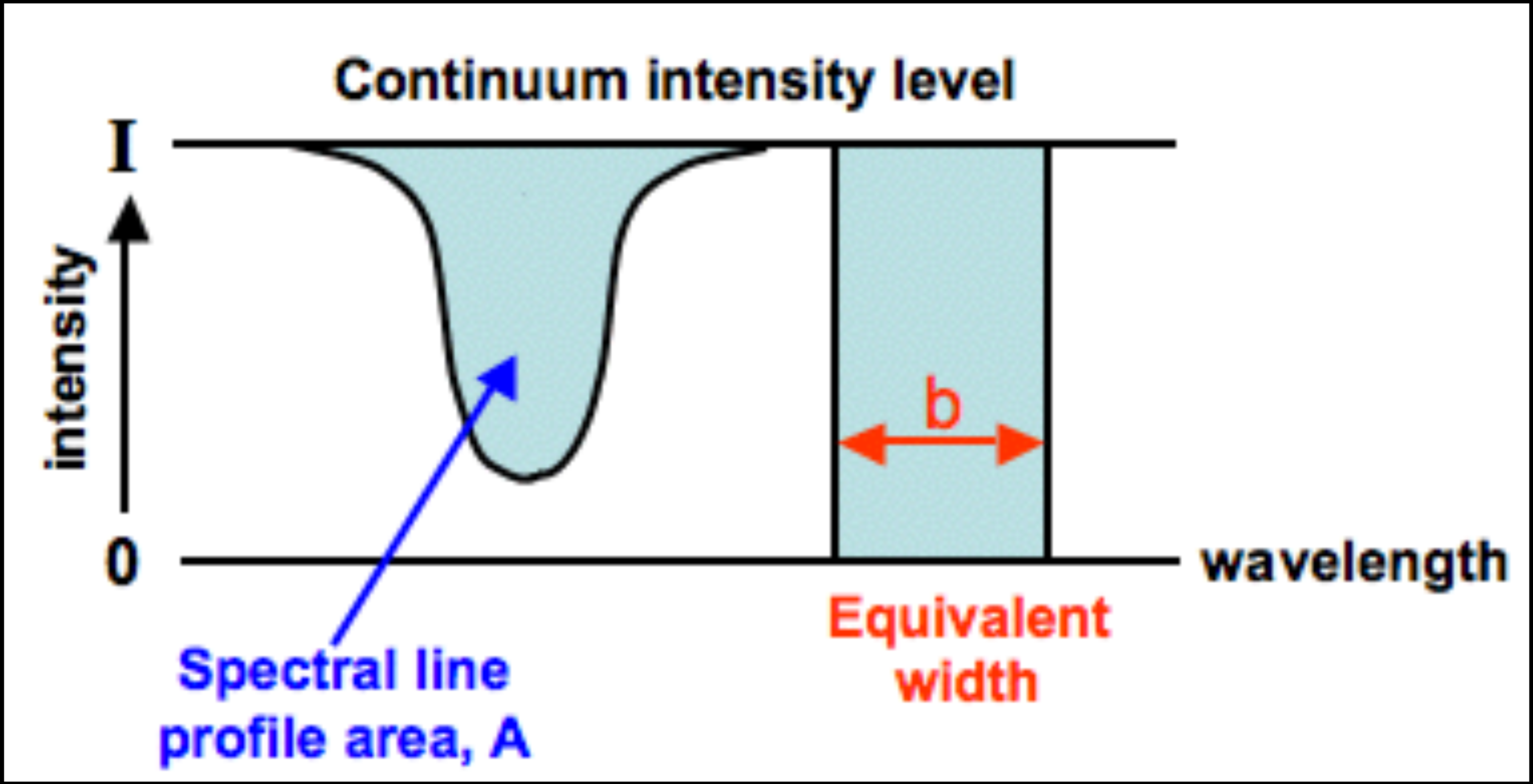
TABLE I Summary of absorption line system properties

	Line parameters		Physical characteristics				$\frac{dN^d}{dz} = N_0(1+z)^\gamma$	
Absorber class	N_{HI} (cm^{-2})	b^a (km s^{-1})	n^b (m^{-3})	T^b (K)	Size (kpc)	$[M/H]^c$	N_0	γ
Lyα forest	$\lesssim 10^{17}$	15–60	0.01 – 1000	5000 – 50000	15–1000(?)	-3.5 – -2	6.1	2.47
LLS	$10^{17} - 10^{19}$	~ 15	$\sim 10^3 - 10^4$	~ 30000	–	-3 – -2	0.3	1.50
Super LLS	$10^{19} - 2\times10^{20}$	~ 15	$\sim 10^4$	~ 10000	–	-1 – +0.6	0.03	1.50
DLA	$> 2\times10^{20}$	~ 15	$\sim 10^7; \sim 10^4$	$\sim 100; \sim 10000$	$\sim 10 - 20$(?)	-1.5 – -0.8	~ 0.03	~ 1.5

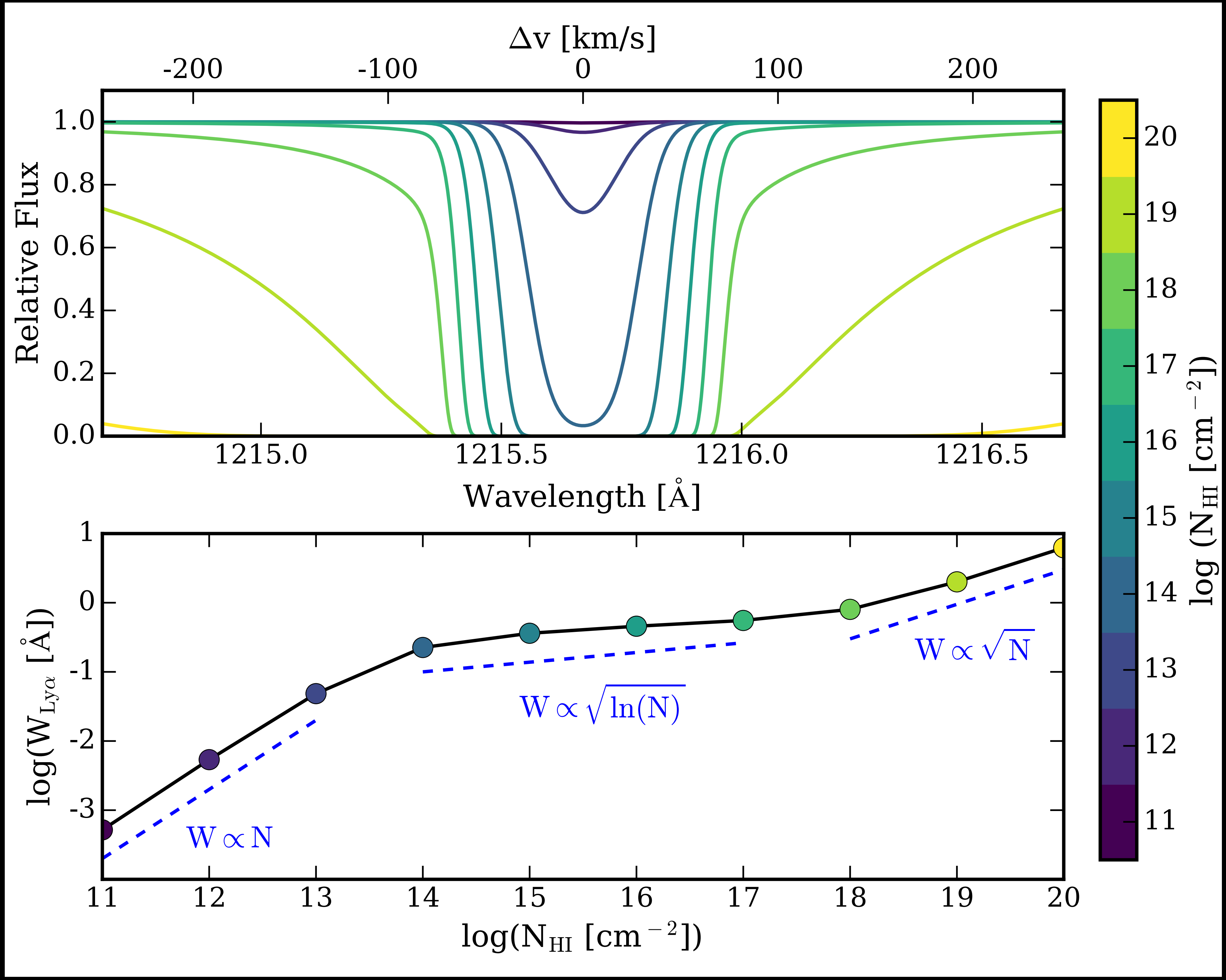
[a] Approximate ranges. Not well determined for most Lyman Limit Systems and super Lyman Limit Systems.
[b] Values not well constrained by direct observations.
[c] Approximate metallicity range, expressed as a logarithmic fraction of solar: $[M/H] = \log_{10}(M/H) - \log_{10}(M/H)_\odot$.
[d] For the following H I column density and redshift ranges. For the Lyα forest: $13.64 < \log_{10} N_{HI} < 17$ and $1.5 < z < 4$; for Lyman Limit Systems: $\log_{10} N_{HI} > 17.2$ and $0.32 < z < 4.11$. The same evolution rate is adopted for super Lyman Limit Systems. The evolution rate of Damped Lyα Absorbers over the range $2 < z < 4$ is consistent with that of Lyman Limit Systems, but poorly constrained by observations.

Lyman alpha forest are optically thin absorbers (not deep trough) with low column densities
Lyman Limit Systems exhibit a saturated lyman alpha line with higher column densities
Damped Lyman Alpha absorbers are so deep they show damped “wings”
with very high column densities

Equivalent width is a convenient way for observers to measure the strength of their absorption lines; Here the two shaded regions are equal in area



The so-called "curve of growth" showing the relationship between column density of neutral hydrogen and its corresponding absorption lines and equivalent widths



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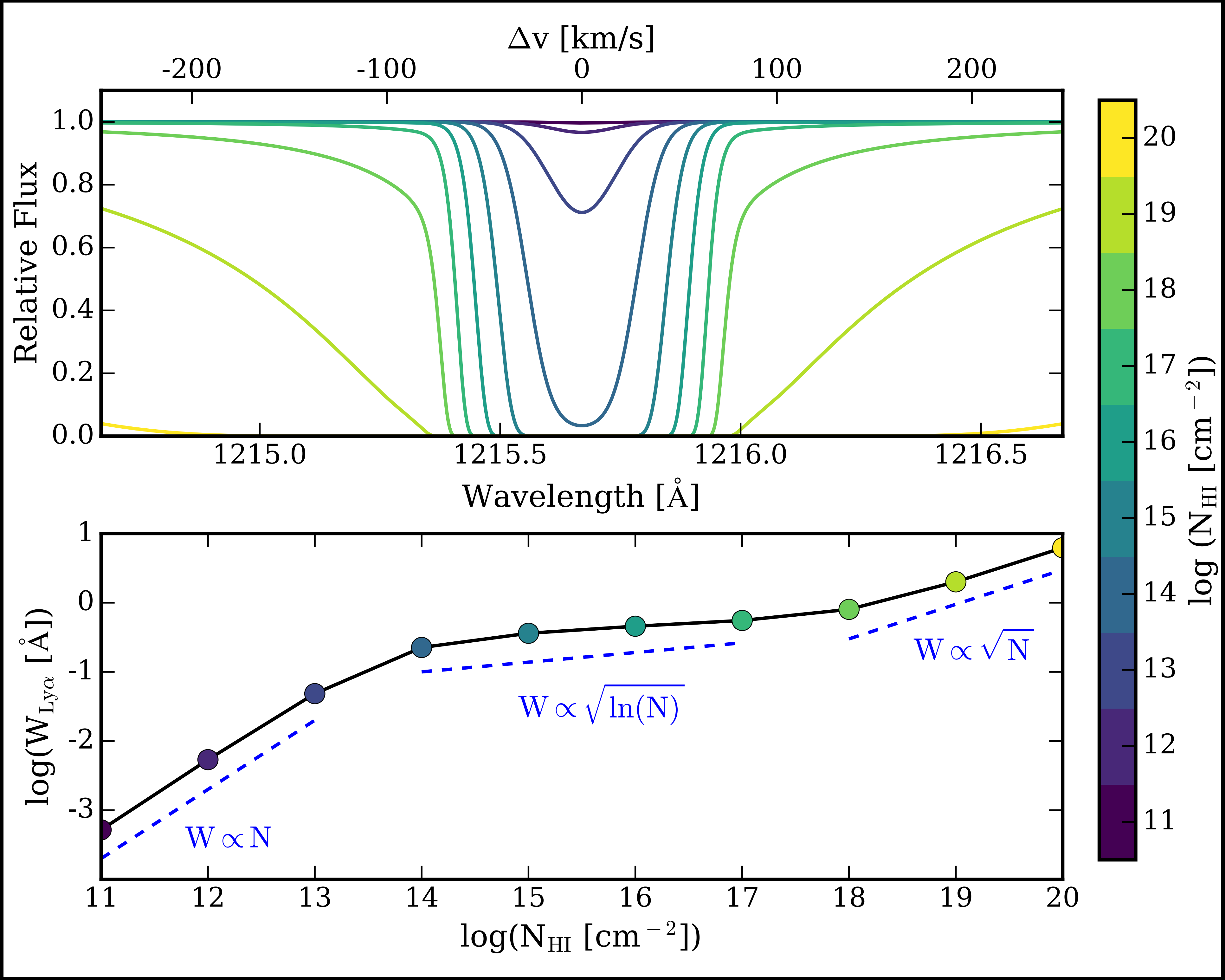
In the low column density limit (bottom left), lines are optically thin and equivalent width scales linearly with column density. In the middle column density limit (bottom center), lines are saturated and equivalent width is pretty flat wrt column density. In the highest column density limits (bottom right), lines are "damped" and equivalent width increases with the sqrt of the column density.



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Lyman alpha forest are lyman alpha absorbers in the linear regime
Lyman Limit Systems have lyman alpha in the saturated regime,
so observers observe their lyman limit lines in the linear regime
Damped Lyman Alpha absorbers are in the damped (sqrt) regime.

This is the process by which absorption features are created.

A) Sightline passing from right to observer on left through neutral hydrogen gas. Two filaments with velocity vectors overplot as arrows.

B) Points are neutral hydrogen column densities in "redshift" space from right to left, same as plot (A).

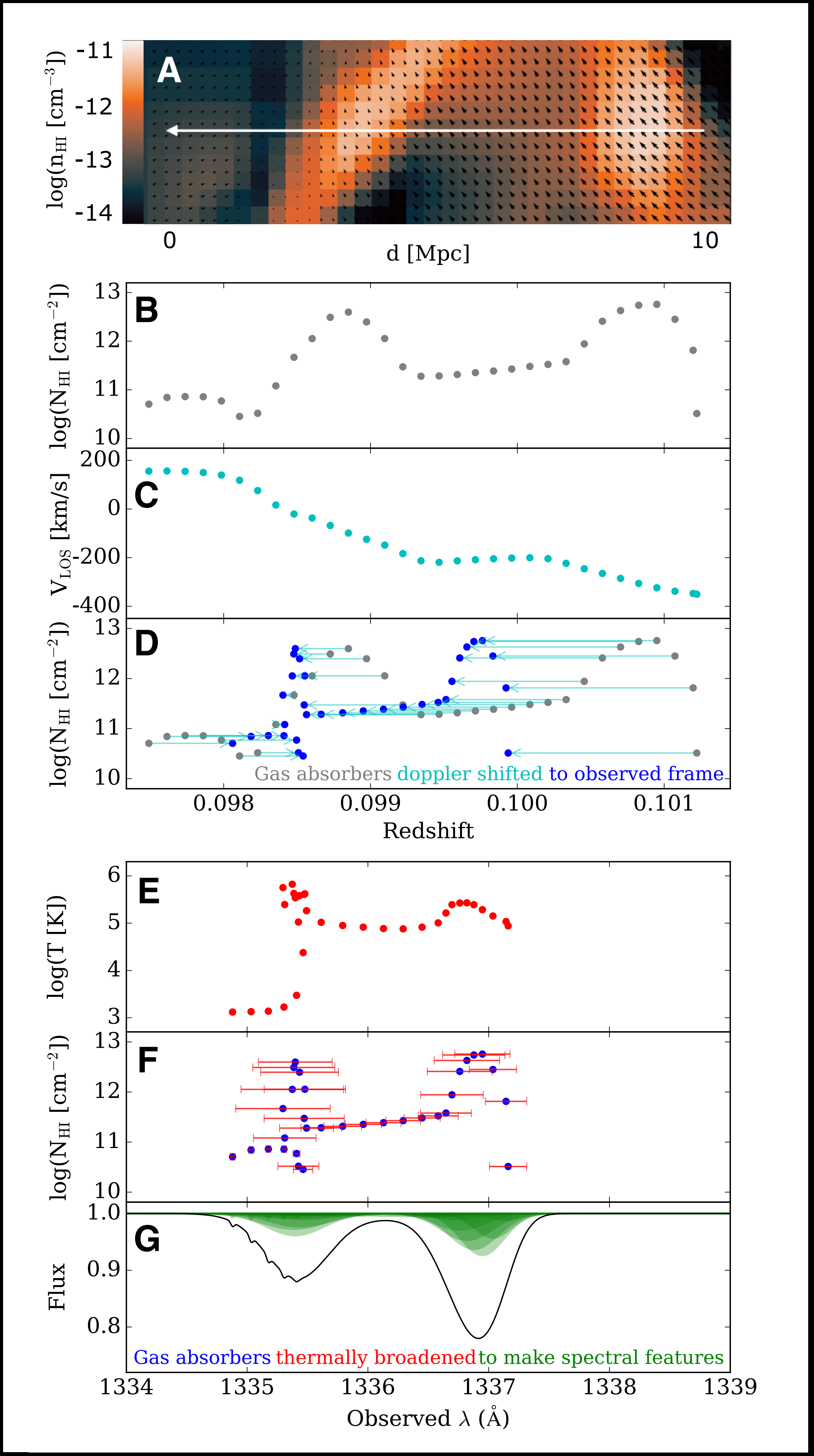
C) Line of sight velocity of gas for each HI gas parcel. High velocity is "redshift", negative velocity is "blueshift".

D) Velocity causes doppler redshift to modify cosmological redshift from gray dots to blue dots. These blue dots are what the observer sees in redshift space.

E) The temperature of each of the gas parcels dictates the thermal width of an absorption line.

F) The column densities with the thermal width in red.

G) Deposit a voigt profile for each absorber, with depth proportional to column density, and width proportional to temperature. Co-add all voigt profiles to see what observer sees.



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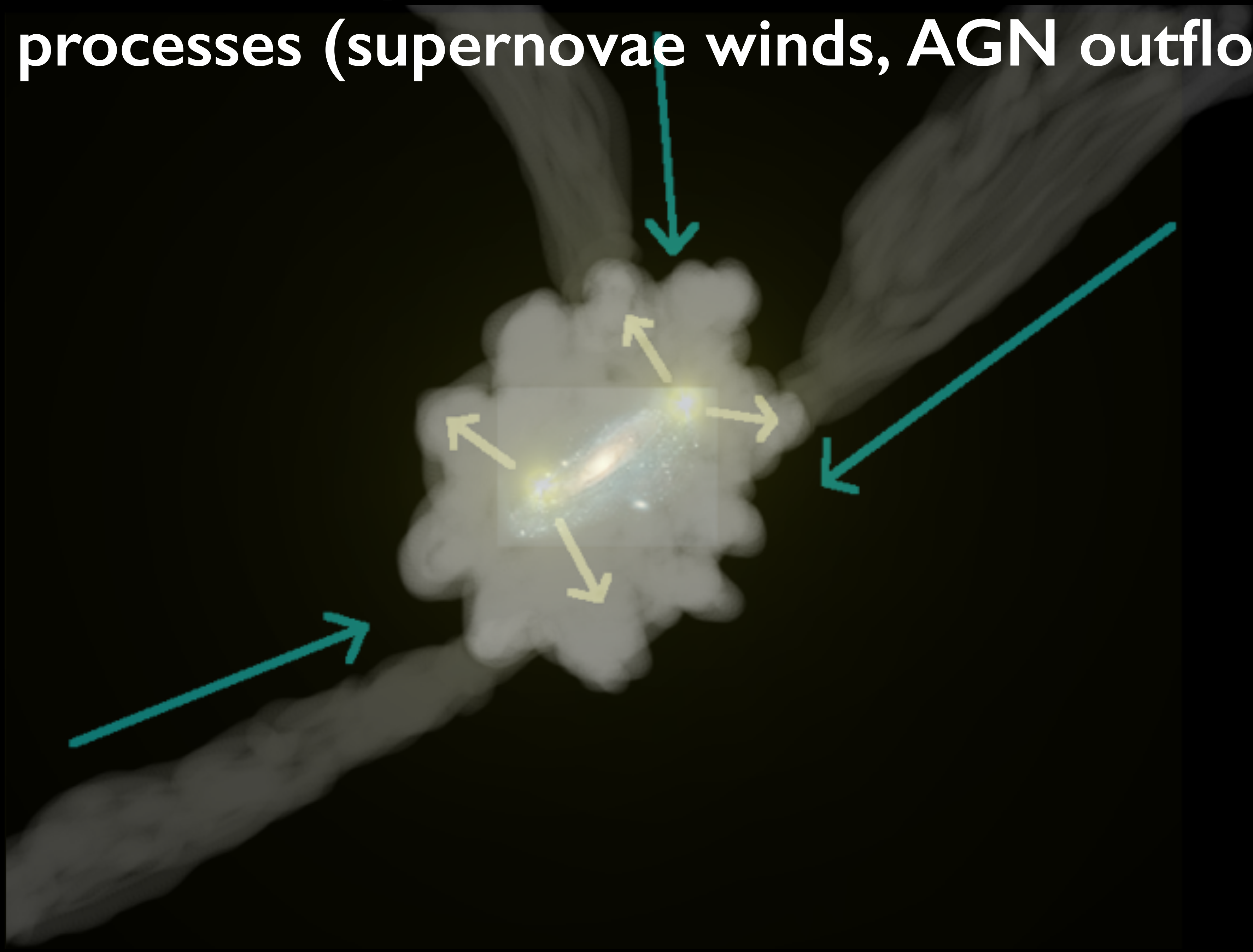
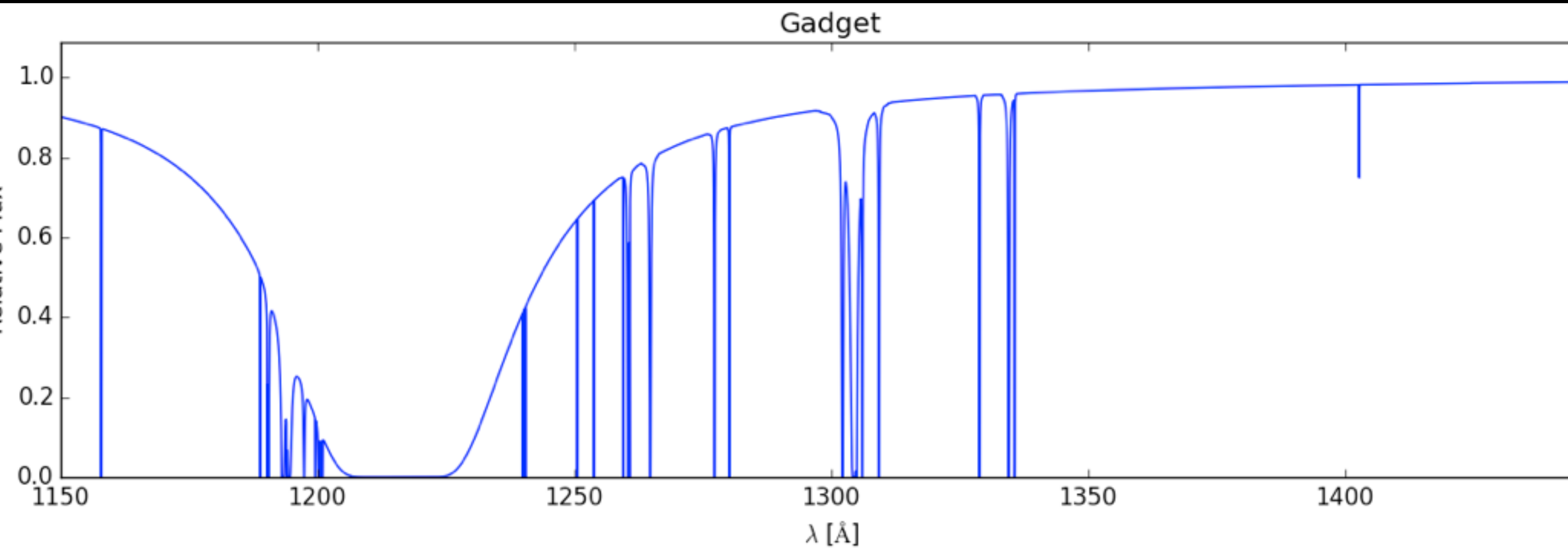
Any intervening material absorbs.
Either intergalactic medium (IGM) or circumgalactic medium (CGM). CGM created by accretion from IGM and enrichment by internal processes (supernovae winds, AGN outflows, etc.)



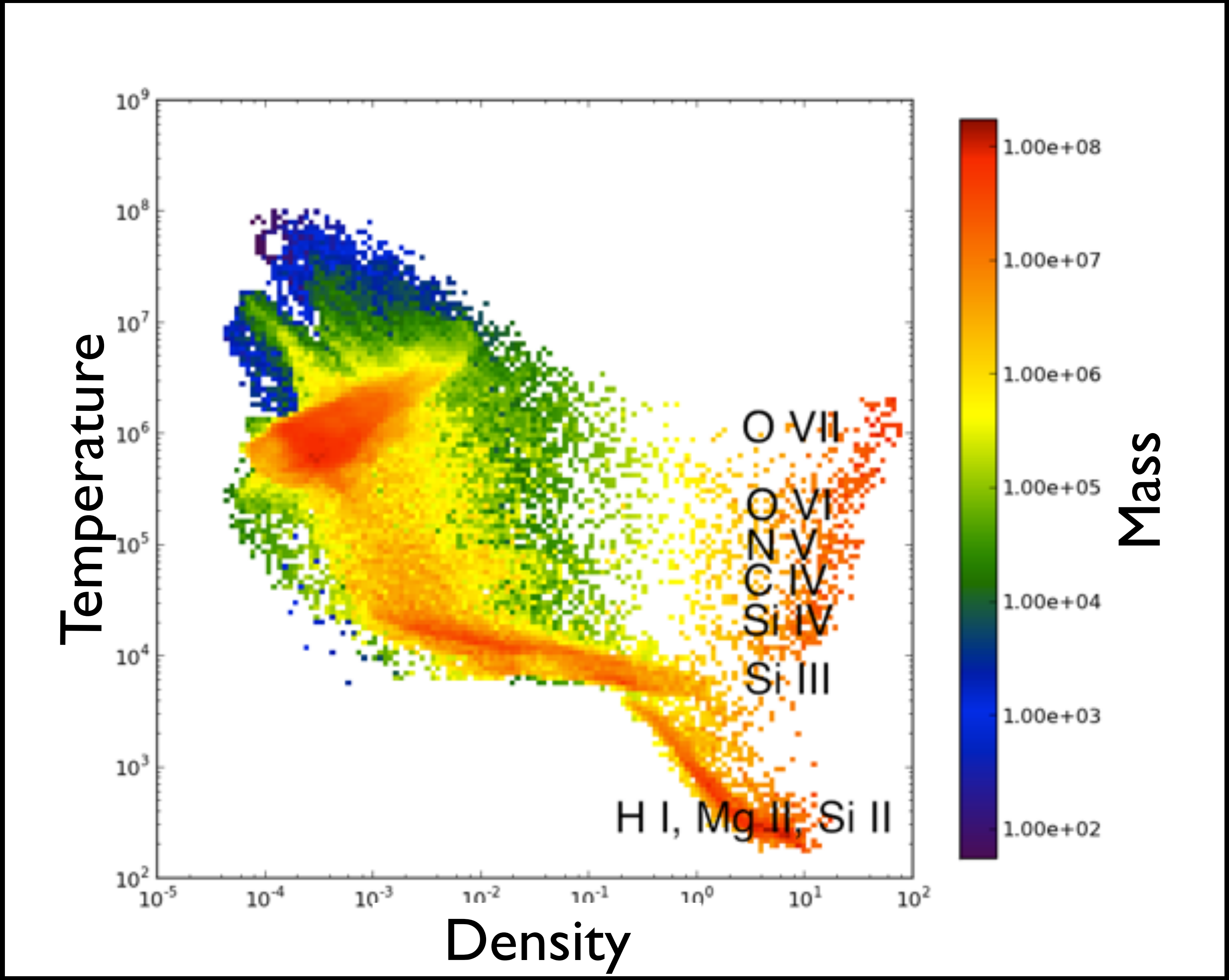
Hummels, in prep

A noiseless spectrum going through the middle of a galaxy. DLA from lots of neutral hydrogen, lots of metal lines.



Hummels, in prep

Different absorption lines probe different phases of the gas, due to different ionization potentials for each line transition. Tons of information about halo gas in these spectra!



phase(density, temperature, metallicity, radiation field)