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Interstellar Medium (ISM)

Lecture 14

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Intergalactic Medium 2

- Lyα Forest
- Warm-Hot Intergalactic Medium

Absorption Lines as a Probe of the IGM

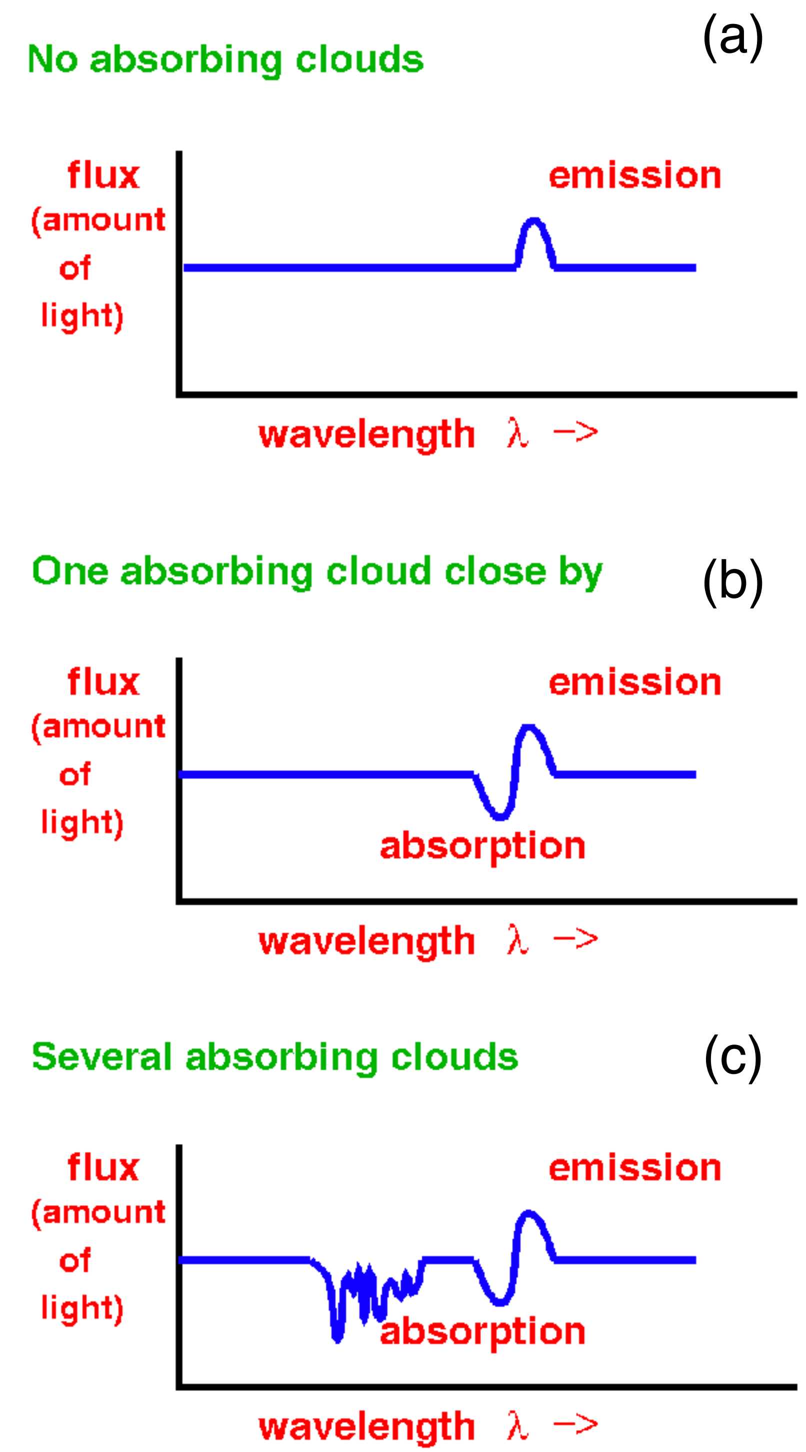
- Every parcel of gas along the line of sight to a distant quasar will selectively absorb certain wavelengths of continuum light of the quasar due to the presence of the various chemical elements in the gas.
- Through the analysis of these quasar absorption lines we can study the spatial distributions, motions, chemical enrichment, and ionization histories of gaseous structures from redshift $z \sim 7$ until the present.
- This structure includes the gas in galaxies of all morphological types as well as the diffuse gas in the IGM.

Lyα Forest

- History
  - A uniformly dark Gunn-Peterson trough is only seen at redshifts $z > 6$.
  - However, at lower redshifts, there exists a “Lyman alpha forest” of absorption lines.
  - The Lyα forest was first discovered by Roger Lynds in 1971.
    - Lynds found many absorption lines in the spectrum of 4C 05.34 (with $z = 2.877$, the largest redshift then known for any quasar), most of which were at wavelengths shorter than the Lyα emission line of the quasar.
    - Lynds concluded that most of the absorption lines that he saw were Lyα lines from hydrogen along the line of sight to the quasar; the other absorption lines were from relatively common heavier elements (such as O, C, N, and Si) at the same redshifts as the absorbing hydrogen.
    - As similar distributions of short-wavelength absorption lines began to be seen in the spectra of additional quasars, astronomers began using the metaphor of a Lyman alpha “forrest” of absorption lines.

Lyα Forest

- Figure (a) shows a cartoon of how a quasar spectrum might look like if there were no intervening neutral hydrogen between the quasar and us.
    - The quasar continuum is relatively flat. Broad emission features are produced by the quasar itself (near the black hole and its accretion disk).
- In some cases, gas near the quasar central engine also produces "intrinsic" absorption lines, most notably Lyα, and relatively high ionization metal transitions such as C IV, N V, and O VI.
- However, the vast majority of absorption lines in a typical quasar spectrum are "intervening", produced by gas unrelated to the quasar that is located along the line of sight between the quasar and the Earth.
- Its wavelength is stretched by the expansion of the Universe from what it was initially at the quasar, and, if it had continued to travel to us, it would have been stretched some more from the 1216Å wavelength it had at the absorber.



- The cartoon below shows a quasar with it Lyα emission line redshifted from the UV into the red, and the Lyα absorption lines from four intervening clouds appearing as orange, yellow and green-blue.
- Each structure will produce an absorption line in the quasar spectrum at a wavelength of $\lambda_{\rm obs} = \lambda_{\rm rest}(1+z_{\rm gas})$, where $z_{\rm gas}$ is the redshift of the absorbing gas and $\lambda_{\rm rest} = 1216\text{Å}$ is the rest wavelength of the Lyα transition. Since $z_{\rm gas} < z_{\rm quasar}$, the redshift of the quasar, these Lyα absorption lines form a "forest" at wavelengths blueward of the Lyα emission of the quasar.
- The region redward of the Lyα emission will be populated only by absorption through other chemical transitions with longer $\lambda_{Ly\alpha}$.

Definition of redshift:

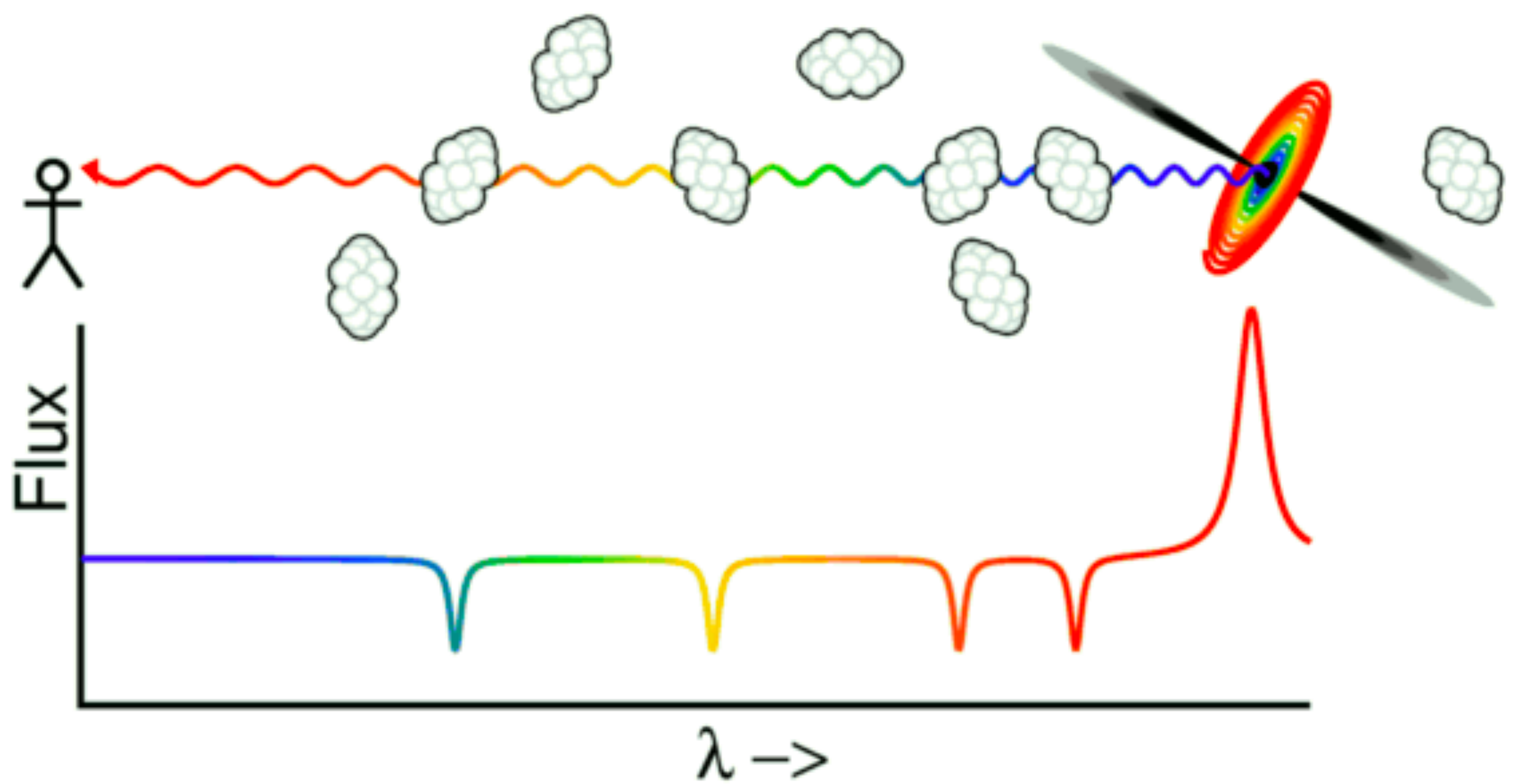
$$z \equiv \frac{\lambda_{\rm obs} - \lambda_{\rm emit}}{\lambda_{\rm emit}}$$

$$\lambda_{\rm obs} = \lambda_{\rm emit}(1+z)$$

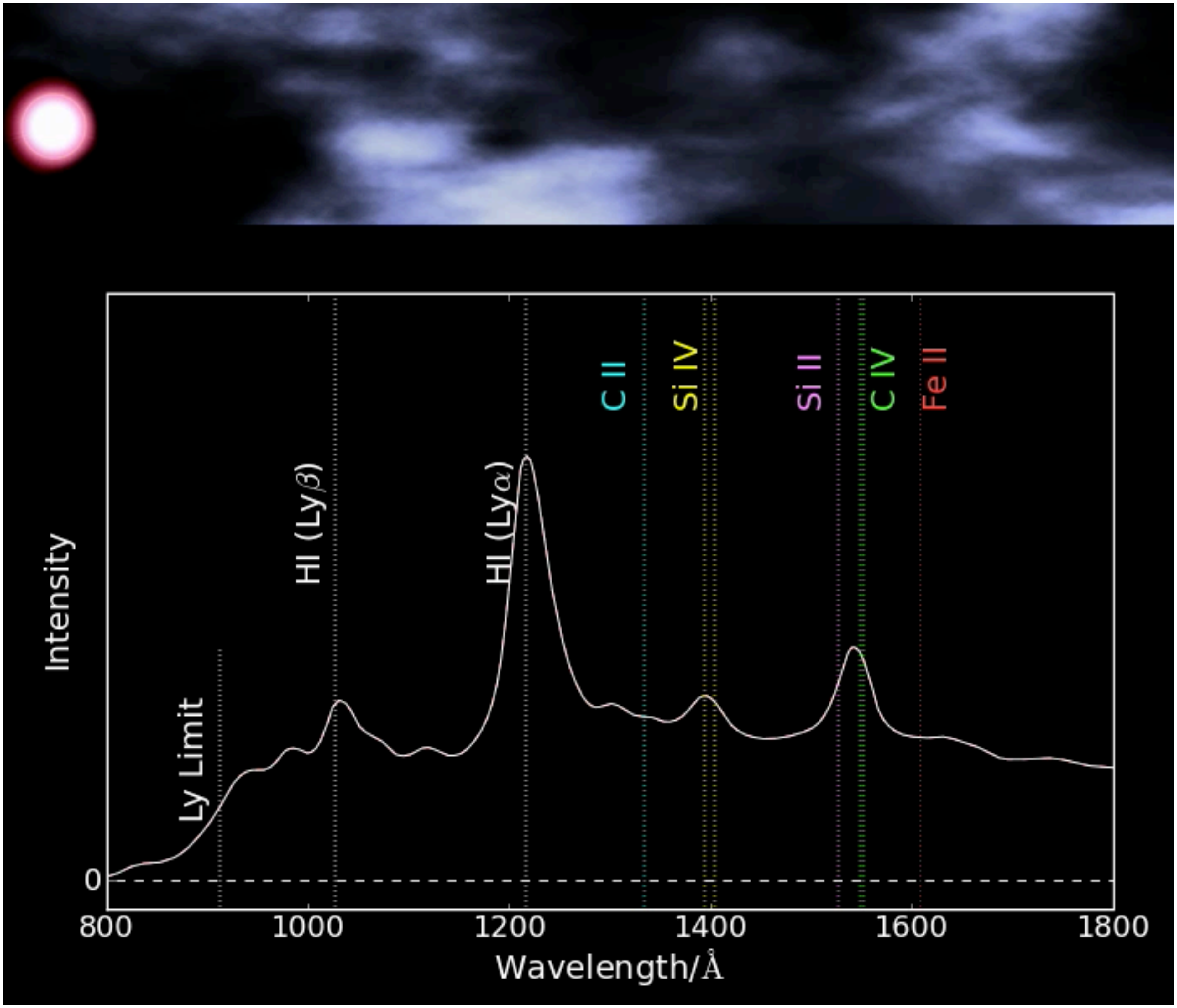
$$\lambda^{\rm gas}_{\rm obs} = \lambda_{\rm rest}(1+z_{\rm gas})$$

$$\lambda^{\rm quasar}_{\rm obs} = \lambda_{\rm rest}(1+z_{\rm quasar})$$

$$\therefore \lambda^{\rm gas}_{\rm obs} < \lambda^{\rm quasar}_{\rm obs}$$



A very nice visualization that shows how different systems absorb Lyman-alpha, made by Andrew Pontzen.
To see this movie, please download from http://www.cosmocrunch.co.uk/media/dla_credited.mov

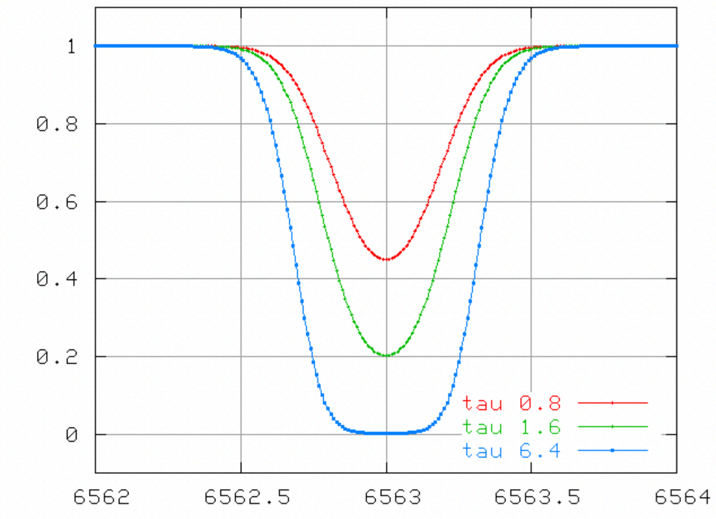


Lyα Absorption System

- A structure along the line of sight to the quasar can be described by its neutral Hydrogen column density *N*(H I), the produce of the density of the material and the path length along the line of sight through the gas.
- Classification

$$N(\mathrm{HI}) = n_H L$$

N (H I) < 10^{12} cm^{-2}	Currently not observable
10^{12} < N (H I) < 10^{17} cm^{-2}	Lyα forest
10^{17} < N (H I) < 2x10^{20} cm^{-2}	Lyman limit systems
2x10^{20} < N (H I)	Dampled Lyα systems



As N (HI) increases, the absorption line depth and width increase.

- A typical temperature of the diffuse IGM is $T \sim 10^5$ K (corresponding to a thermal broadening b ~ 40 km s^{-1} in Lyα line). The optical depth at line center is then

$$\tau_0 \approx 1.9 \left(\frac{b}{40\,\mathrm{km\,s^{-1}}}\right)^{-1} \left(\frac{N_{\mathrm{HI}}}{10^{14}\,\mathrm{cm^{-2}}}\right)$$

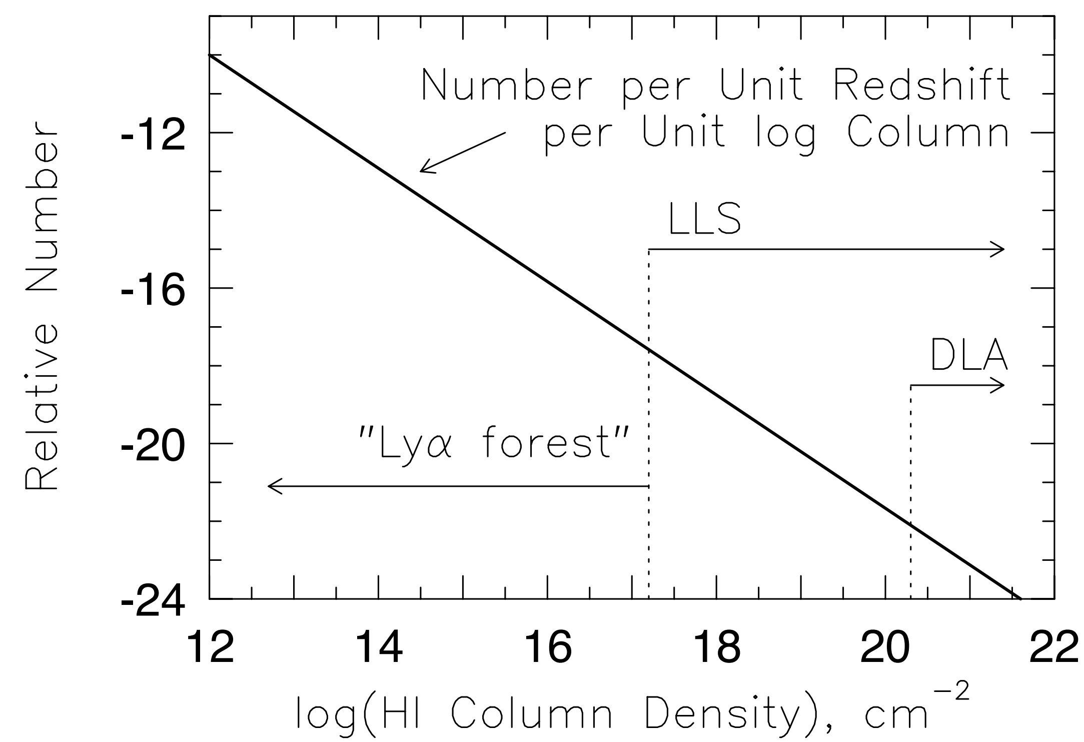
- The name ***"Lyman limit system"*** is given because at these column densities, clouds become optically thick to photons with λ < 912Å, at the Lyman limit. As a consequence, Lyman limit systems are self-shielded from outside ionizing photons.
- ***Damped Lyman alpha systems*** (DLAs) have column densities of neutral hydrogen comparable to a large galaxy like our own.

What are the Lyα absorption systems?

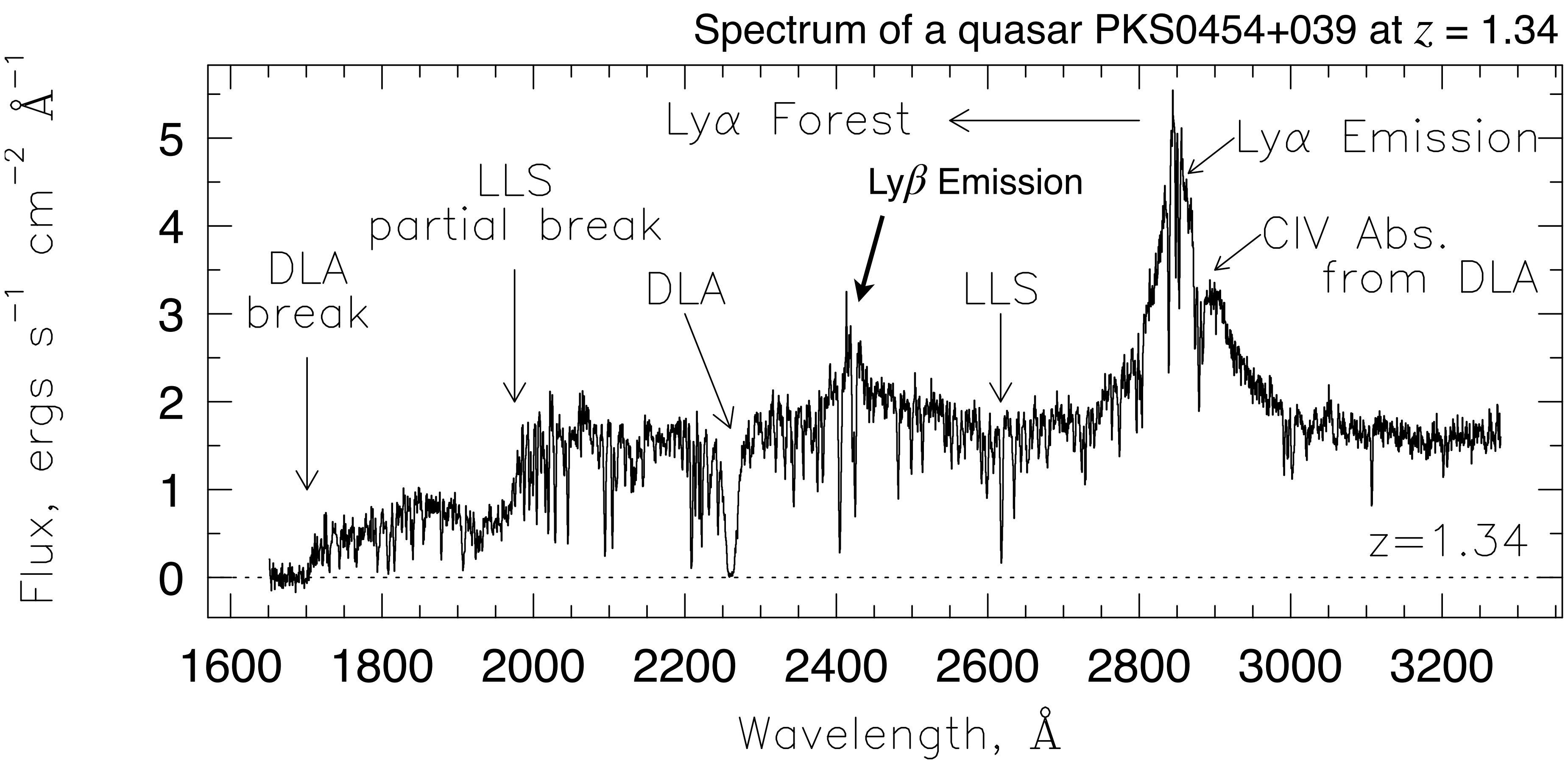
- Metallicity
  - The metallicity of DLAs is typically in the rage $Z \approx 0.01 - 0.3 Z_\odot$.
  - The Lyman alpha forests has a lower metallicity of $Z \approx 0.001 - 0.01 Z_\odot$.
- What are they?
  - ***DLAs can be thought of as gravitationally bound protogalaxies***, containing gas (and associated dark matter), but which haven't yet been effective at converting gas into stars.
  - However, the lower column density absorption lines in the Lyman alpha forest, which are vastly more numerous than the DLAs, cannot be associated with individual gravitationally bound gas clouds.
    - Densities in the Lyman alpha forests are simply not dense enough to represent gravitationally collapsed, virtualized systems with a high neutral fraction of hydrogen.
    - Instead, the absorption lines of the Lyman alpha forests are likely produced from highly ionized regions of gas that are broadened primarily by the Hubble flow.
  - The Lyman alpha forest shouldn't be thought as resulting from discrete clouds along the line of sight to a quasar.
    - Instead, ***they are more likely to be caused by a smoothly fluctuating density field*** along the line of sight.

- The Lyman alpha absorption systems are generally associated with galaxies, but not always.
  - For instance, 3C 273 lies behind the Virgo cluster of galaxies, and has a couple of absorbers in the cluster's redshift range, but they cannot be clearly identified in position and redshift with specific galaxies in the Virgo cluster.
  - At low redshift, many of the galaxies that are responsible for the DLA absorbers can be directly identified.
    - These galaxies are a heterogeneous population. They are not just the most luminous galaxies, but include dwarf and low surface brightness galaxies.
    - There are even cases where no galaxy has been identified to sensitivity limits.

- ***Column density distribution***
  - There are many more weak lines than strong lines.
  - The column density distribution roughly follows a power-law.



Typical spectrum of a quasar



$\lambda_{\text{rest}}^{\text{Ly}\alpha} = 1216\text{Å}$

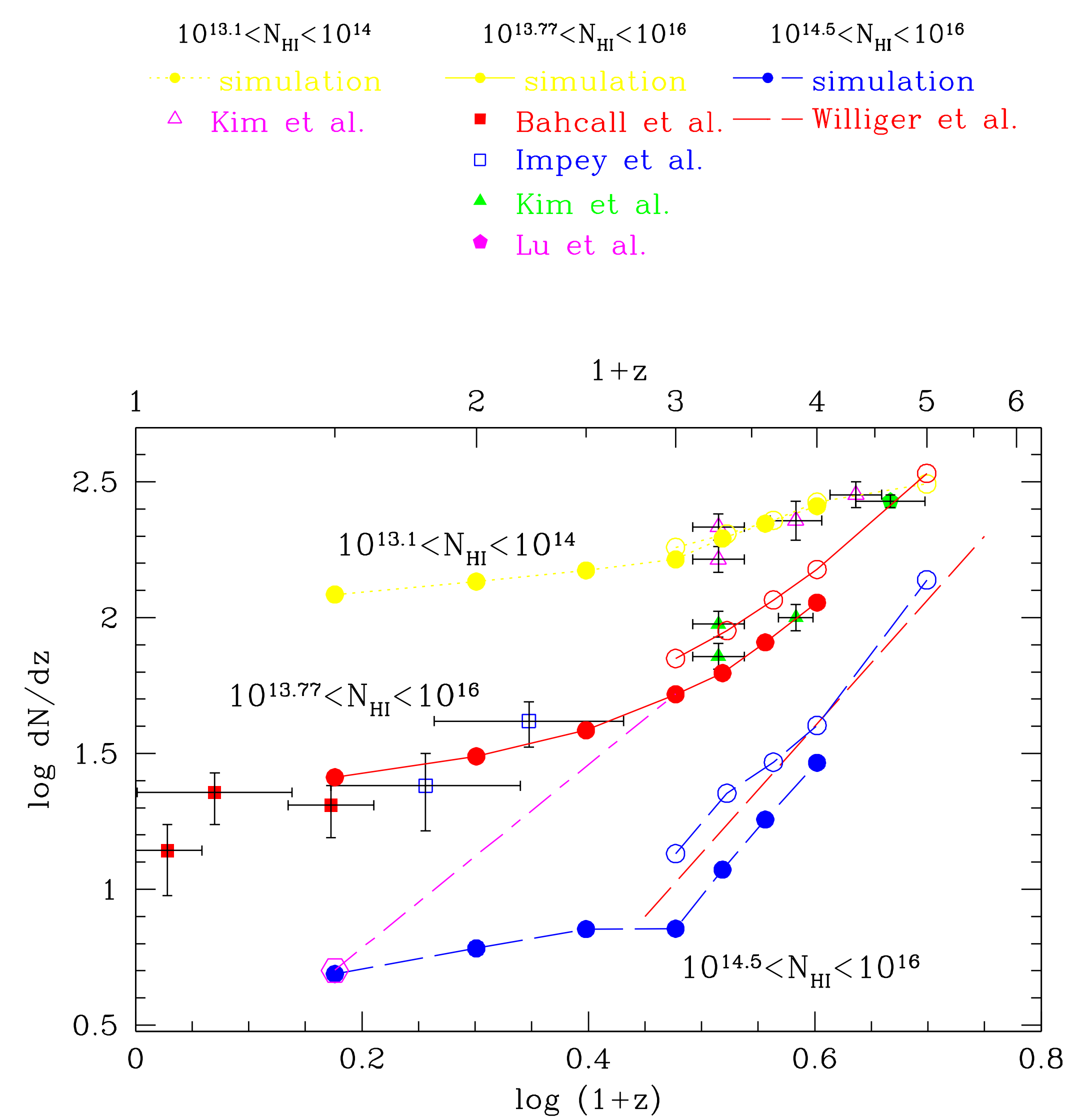
$\lambda_{\text{rest}}^{\text{Ly}\beta} = 1026\text{Å}$

$\lambda_{\text{rest}}^{\text{Lyman break}} = 912\text{Å}$

- Typical spectrum of a quasar, showing the quasar continuum and emission lines, and the absorption lines produced by galaxies and IGM that lie between the quasar and the observer.
  - The Lyα forest, absorption produced by various intergalactic clouds, is apparent at wavelengths blueward of the Lyα emission line.
  - The two strongest absorbers, due to galaxies, are a damped Lyα absorber at z = 0.86 ($(1+0.86)\times 1216 = 2262\text{Å}$) and a Lyman limit system at z = 1.15 ($(1+1.15)\times 1216 = 2614\text{Å}$).
  - The damped Lyα absorber produces a Lyman limit break at ~ 1700Å ($(1+0.86)\times 912 = 1696\text{Å}$).
  - The Lyman limit system a partial Lyman limit break at ~ 1960Å ($(1+1.15)\times 912 = 1961\text{Å}$) since the neutral Hydrogen column density is not large enough for it to absorb all ionizing photons.

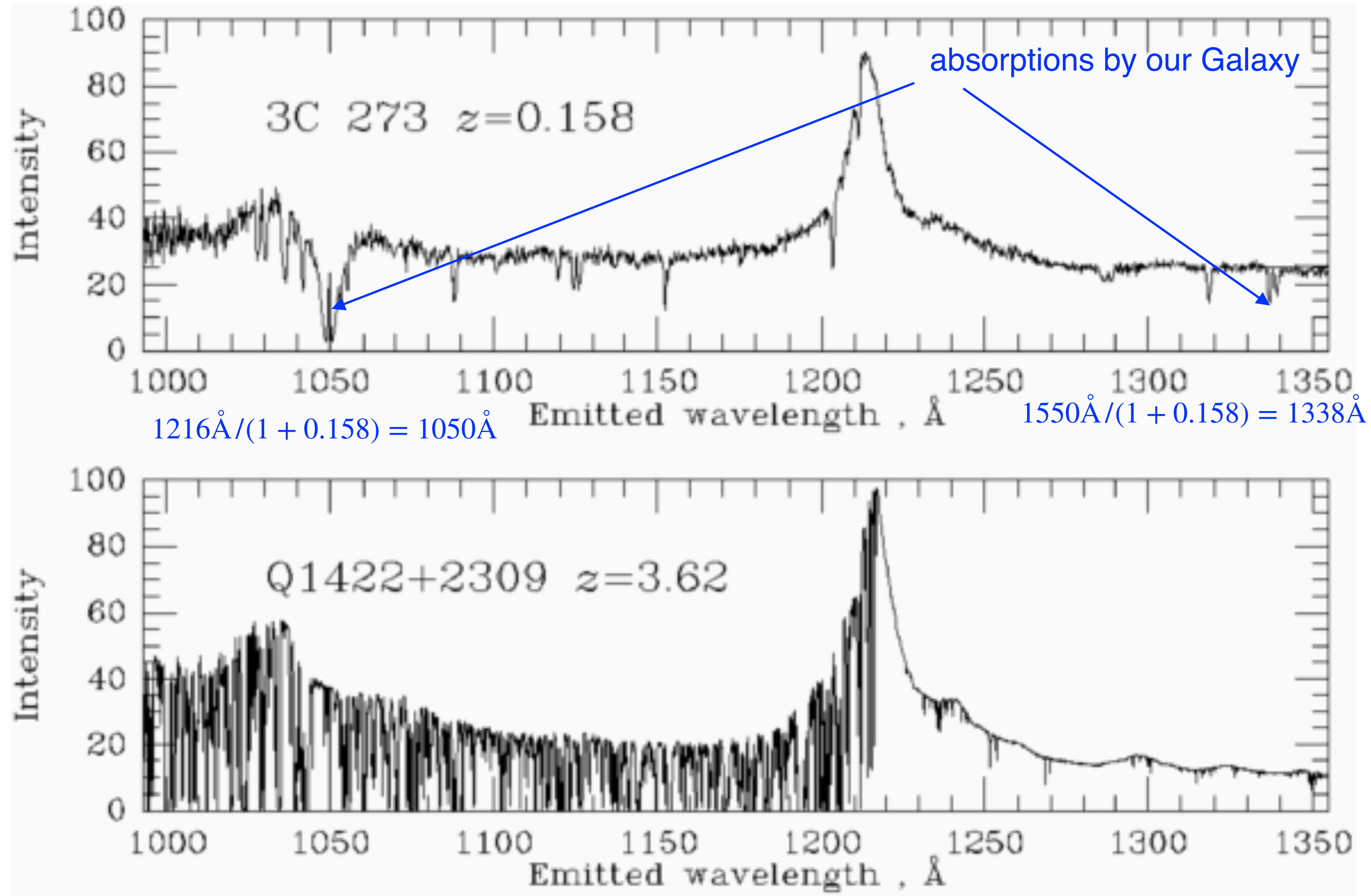
Evolution of Lyα Absorption Systems

- The Lyα absorption component evolves strongly with cosmic time.
  - We see dramatically ***more absorbers toward higher redshifts***.
  - However, they have not completely disappeared at low redshifts. When the launch of HST provided the first capability of measuring Lyα at low redshifts to the required accuracy, it was found that a few of these absorbers remain in the local Universe.
- The evolution of the Lyα forest may be intimately connected with the history of galaxy formation.
- This dramatic ***evolution in the number of forest clouds is mostly due to the expansion of the Universe, with a modest contribution from the cosmic structure growth.***

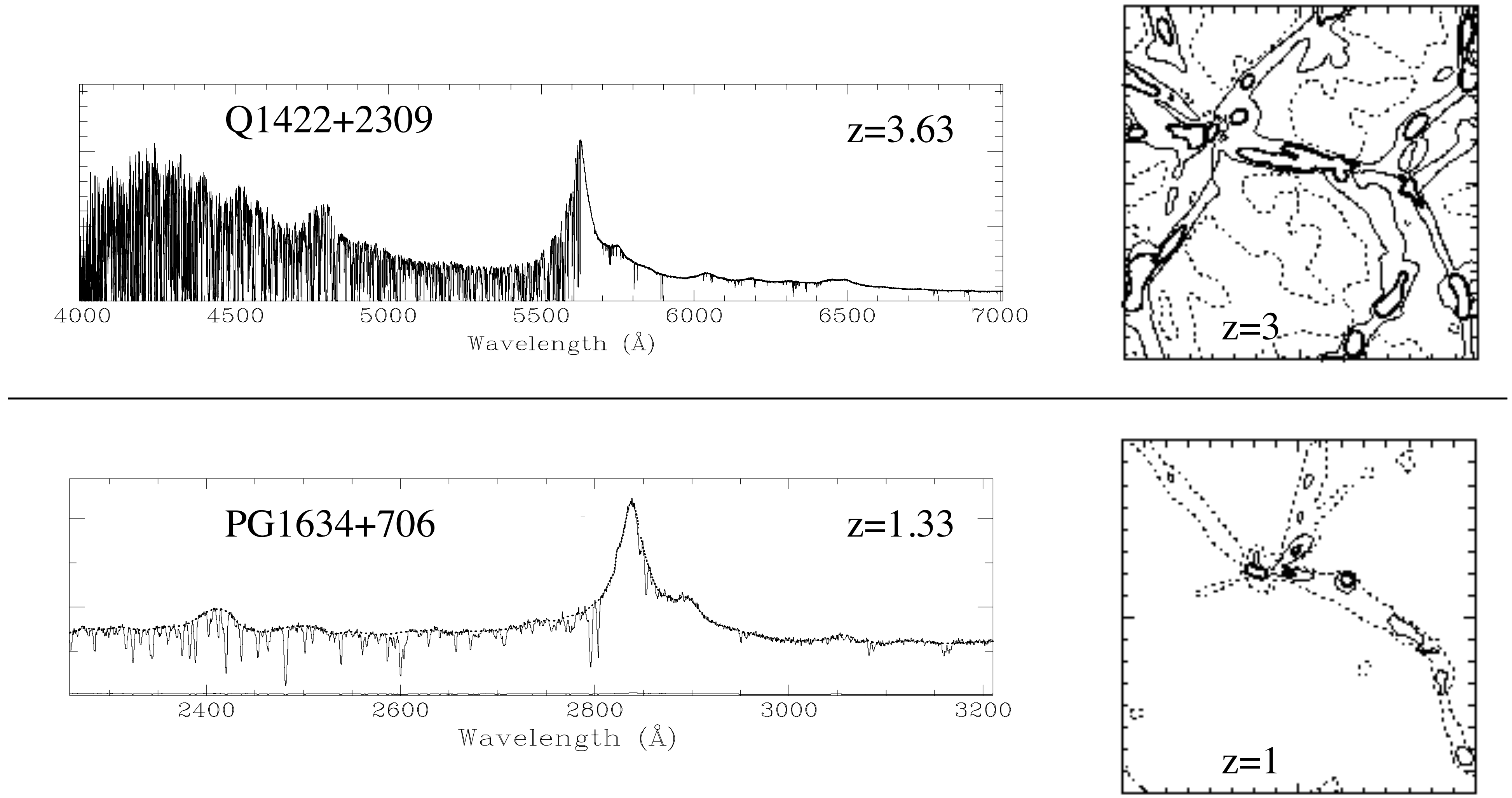


Evolution of the number of lines within a given range of column density obtained from numerical simulations and observations (Efstathiou et al.)

- This figure compares two quasars at very different redshifts, 3C 273 at z = 0.158 and 1422+2309 at z= 3.62.
- The spectra were shifted to a common scale in emitted wavelength.



- At low redshift, 3C 273 shows only a handful Lyα absorbers, including the strong and broad absorption from its light intercepting the disk of a foreground spiral galaxy (ours). Our galaxy also produces absorption in the C IV lines around 1550 Å, which appear at 1337 Å in the quasar's emitted frame.
- Hundreds of lines can be identified in the spectrum of 1422+2309, with the densest concentration near the quasar redshift. The strong and broad emission peak is Lyα, which is almost chopped in half by the onset of the Lyα forest in the high-redshift quasar.
- ***This is a very general feature showing how the density of Lyα absorbers decreases with cosmic time (lower z).***



- Illustration of structure evolution of intergalactic gas from high to low redshift.
    - Higher redshift quasars show a much thicker forest of Lyα lines.
- The right-hand panels show slices through N-body/hydrodynamic simulation results at two epochs z = 3 and z = 1.
    - Three contour levels are shown : $10^{11}\ \mathrm{cm}^{-2}$ (dotted lines), $10^{12}\ \mathrm{cm}^{-2}$ (solid lines) and $10^{13}\ \mathrm{cm}^{-2}$ (thick solid lines).
    - Evolution proceeds so that the voids become more empty and even lower column density material is found in filamentary structures at low redshifts.

Correlation between Density and Temperature

- **Density versus Temperature** in the intergalactic gas
  - In simulations of the evolution of intergalactic gas, it is found that there is **a tight correlation between density and temperature at $T < 10^5$ K**.
    - The origin of this correlation lies in the *balance between heating and cooling (adiabatic cooling* due to the expansion of the universe)
    - ***Heating***: With only hydrogen present, heating is done by the electrons ejected during the photoionization of hydrogen. The volumetric heating rate is:

$$\mathcal{G}_{\rm pi} = n_{\rm H^0}\zeta_{\rm pi}\langle E\rangle = n_e n_p \alpha_{\rm A,H}\langle E\rangle$$

$n_e = n_p \approx n_{\rm H}$ in a highly ionized hydrogen gas

$$\boxed{\mathcal{G}_{\rm pi} \approx n_{\rm H}^2 \alpha_{\rm A,H}\langle E\rangle}$$

$\langle E\rangle$ = the average kinetic energy of an ejected electron. We need to use the Case A recombination rate coefficient in a highly ionized hydrogen gas, responsible to the Lyman alpha forests.

    - ***Cooling***: The regions that give rise to low column density Lyα lines will cool mainly through adiabatic cooling as the universe expands. During adiabatic expansion, the thermal energy density has the dependence $\mathcal{E} \propto V^{-\gamma}$ (*V* = volume of a gas element). The volumetric cooling rate is then:

$$\mathcal{L}_{\rm adi} = -\frac{d\mathcal{E}}{dt} = \gamma\frac{\mathcal{E}}{V}\underbrace{\frac{dV}{dt}}_{V \propto a(t)^3} = \left(\gamma\frac{\mathcal{E}}{V}\right)3\frac{V}{a}\underbrace{\frac{da}{dt}}_{H(t)\equiv\frac{\dot{a}}{a}}$$

$$\boxed{\mathcal{L}_{\rm adi} = 3\gamma\mathcal{E}(t)H(t)}$$

- Energy Balance:

$$\alpha_{\mathrm{A,H}} \propto T^{-0.72} \quad \text{near } T \sim 10^4\,\mathrm{K}$$

$$n_{\mathrm{H}}^2 \alpha_{\mathrm{A,H}} \langle E \rangle = 3\gamma \left(\frac{3}{2} n_{\mathrm{H}} k T \right) H(t) \longrightarrow n_{\mathrm{H}} = \frac{9}{2} \frac{\gamma k T}{\alpha_{\mathrm{A,H}} \langle E \rangle} H(t) \rightarrow n_{\mathrm{H}} \propto \frac{T}{T^{-0.72}}$$

We then obtain

$$n_{\mathrm{H}} \propto T^{1.72} \quad \rightarrow \quad T \propto n_{\mathrm{H}}^{0.58}$$

$$\boxed{T = T_0 \left(\frac{n_{\mathrm{H}}}{\overline{n}_{\mathrm{bary}}} \right)^{0.58}}$$

Here, T_0 is the temperature when $n_{\mathrm{H}} = \overline{n}_{\mathrm{bary}}$

- **Optical Depth versus Density** in the intergalactic gas
  - The balance equation between the photoionization and radiative recombination is given by

$$\zeta_{\mathrm{pi}} n_{\mathrm{H}^0} = n_e n_p \alpha_{\mathrm{A,H}}$$
$$\zeta_{\mathrm{pi}} (1 - x) n_{\mathrm{H}} = x^2 n_{\mathrm{H}}^2 \alpha_{\mathrm{A,H}}$$

$\longleftarrow$ fractional ionization $x \equiv n_e / n_{\mathrm{H}}, \; n_e = n_p$

$$\boxed{1 - x = x^2 \frac{n_{\mathrm{H}} \alpha_{\mathrm{A,H}}}{\zeta_{\mathrm{pi}}}}$$

- After the epoch of reionization z ~ 8, the neutral fraction $f_{\mathrm{n}} = 1 - x$ will be smaller than one. In this limit, the solution for the neutral fraction is

$$f_{\mathrm{n}} \approx \frac{n_{\mathrm{H}} \alpha_{\mathrm{A,H}}(T)}{\zeta_{\mathrm{pi}}}$$

- Then, the number density of neutral hydrogen atoms is

$$n_{\mathrm{H}^0} = f_{\mathrm{n}} n_{\mathrm{H}} \approx \frac{n_{\mathrm{H}}^2 \alpha_{\mathrm{A,H}}(T)}{\zeta_{\mathrm{pi}}}$$

Using the Case A recombination rate coefficient, $\alpha_{\mathrm{A,H}} \approx 4.2 \times 10^{-13}\,\mathrm{cm}^3\,\mathrm{s}^{-1} \left(\frac{T}{10^4\,\mathrm{L}}\right)^{-0.72}$, we find that

$$n_{\mathrm{H}^0} \propto n_{\mathrm{H}}^2 T^{-0.72} \zeta_{\mathrm{pi}}^{-1}$$

- The optical depth for Lyα absorption at a given redshift is proportional to the number density of neutral hydrogen.

$$\tau \propto n_{\mathrm{H}^0} \propto n_{\mathrm{H}}^2 T^{-0.72} \zeta_{\mathrm{pi}}^{-1} \propto n_{\mathrm{H}}^{1.6} \zeta_{\mathrm{pi}}^{-1} \longleftarrow$$

using the density-temperature correlation $T \propto n_{\mathrm{H}}^{0.58}$

- Properly normalizing, we obtain the relation between the density and optical depth:

$$\tau = \overline{\tau} \left(\frac{n}{\overline{n}_{\mathrm{bary}}}\right)^{1.6} \longleftarrow n \propto n_{\mathrm{H}}$$

- The constant $\overline{\tau}$ depends on the assumed cosmology as well as on the amount of ionizing radiation present.
- The above equation is referred to as the ***fluctuating Gunn-Peterson approximation***.

Lyman-Alpha Emission from High-redshift galaxies?

- We have studied about the Lyα absorption features. How about the Lyα emission?
- History
  - It was first suggested by Patridge & Peebles (1967) that the Lyα emission line could be used to find distant galaxies, as it should be strong in star-forming systems.
  - It soon became clear that their assumptions were not realistic; for example, they assumed distant galaxies to have the same size as our Milky Way but with an average surface brightness equal to that of intense star formation. Even with more realistic assumptions taken into account, early surveys targeting the Lyα line ended up in failure (e.g., Pritchet 1994).
  - Meier & Terlevich (1981) found that only one metal-poor galaxy of the nearby, three galaxies showed any Lyα emission. The first detection of high-redshift Lyα emission was made in 1998 in Cowie & Hu (1998).
  - Now, thanks to new and improved technologies, the sample of known Lyα emitters at redshifts between z = 2-7 is growing rapidly.
  - ***What could be the causes of such difficulties in detecting Lyα emitting galaxies?***

- The Lyα photons are resonantly trapped.
  - The Lyα is a resonance line and thus becomes optically thick even at modest column densities.
  - Lyα photons are scattered “endlessly” in neutral hydrogen, which greatly increases the path length for these photons. The increase in path-length enhances the chance of absorption by dust grains, so that even a small amount of dust can be enough to absorb the Lyα radiation.
  - However, the dust alone is not the decisive factor that makes interpretation difficult.
  - Lyα escape depends sensitively on the kinematics of neutral gas. Lyα scatters coherently in the rest frame of the hydrogen atom, and at scattering events is shifted in frequency by the velocity of the scattering medium. The frequency shift can cause Lyα escape from galaxies.
  - ***Therefore, understanding the radiative transfer mechanism of Lyα is crucial.***
    - The sensitive dependence of Lyα transfer to the gas density distribution and kinematics complicates interpretations of Lyα observations.
    - On the other hand, the kinetic structure of the atomic gas becomes imprinted onto the line. The close interaction of the Lyα radiation and gaseous flows in and around galaxies implies that the Lyα line contains information on the scattering medium, and may thus present an opportunity to learn more about atomic hydrogen in gaseous flows in and around galaxies.

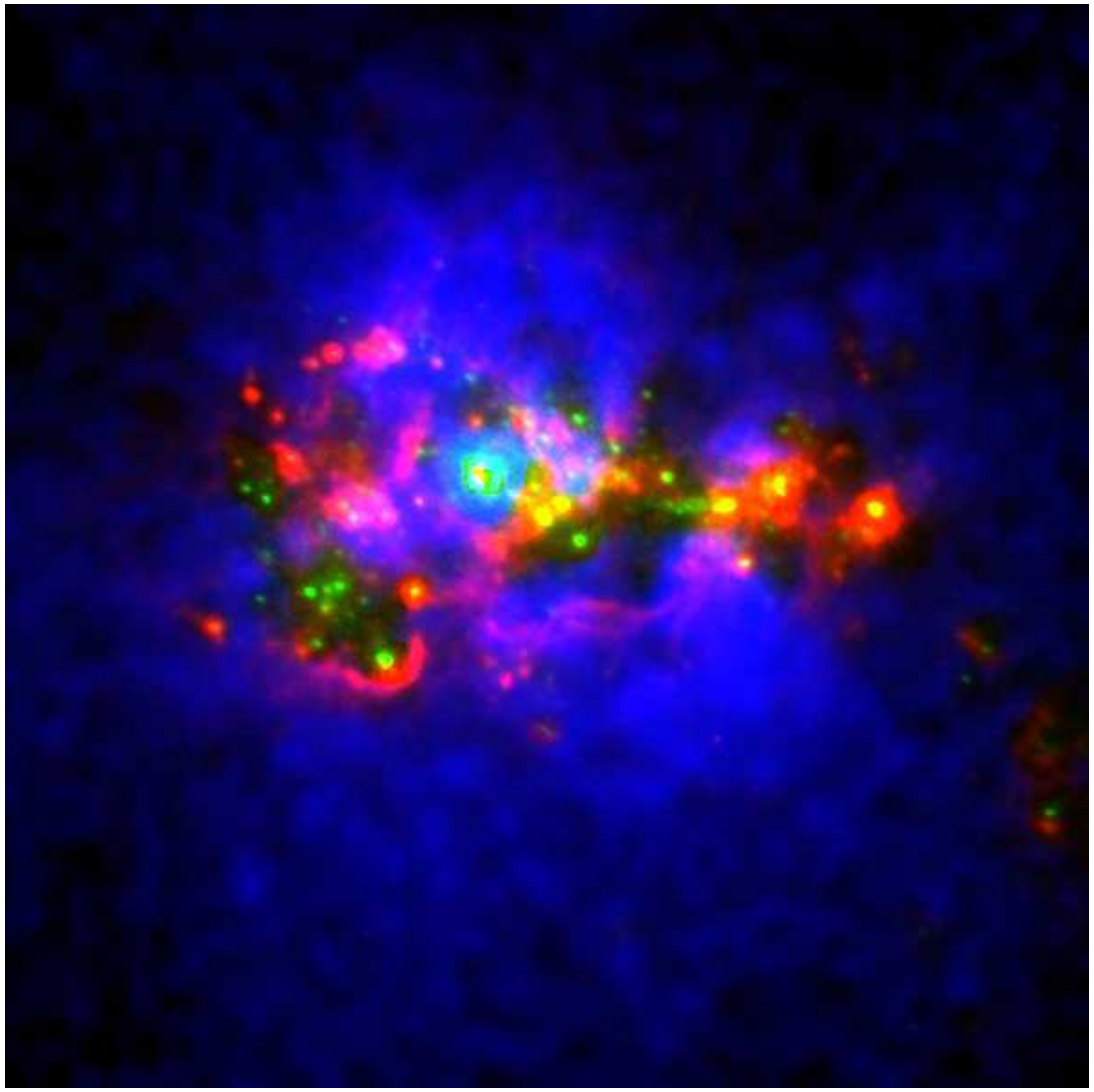
LAEs

- A Lyman-alpha emitter (LAE) is a type of actively star-forming galaxy that emits Lyα radiation and often found to have a relatively low mass.
  - The Lyα line in most LAEs is thought to be caused by recombination of interstellar hydrogen that is ionized by an ongoing burst of star-formation.
  - There are many methods available to find galaxies at high redshift. One method which is getting increasingly popular is that of targeting the Lyα emission of young, star-forming galaxies.

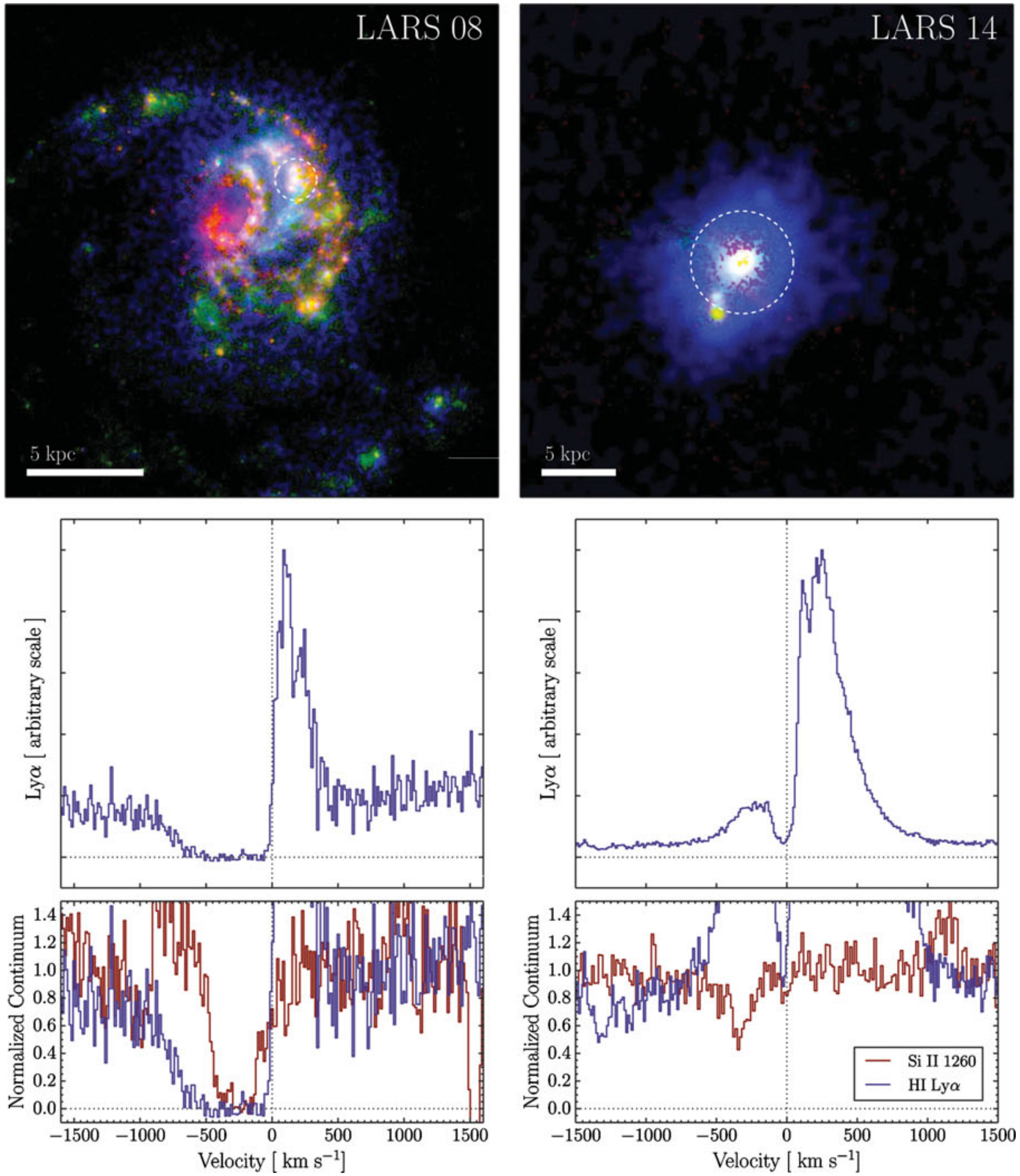
- The right image shows a LAE from “Lyman Alpha Reference Sample (LARS)”, a project in which 14 nearby galaxies and their Lyα emission are studied in detail using the Hubble Space Telescope.

- RGB composite of Hα (red), UV-continuum (green) and Lyα (blue) of the 38 Mpc distant, metal-poor, dwarf starburst galaxy ESO 338-04. The size of the image is 20x20 arcsec, or 3.5x3.5 kpc.

- ***Lyα emission is not dominated by the bright super star clusters (traced by Hα) that dominate the production of ionizing photons.*** Towards most of them, Lyα is rather seen in absorption.
- ***Most of the escaping Lyα emission comes from a diffuse extended component*** where Lyα/Hα >> 10, that can only be produced by resonant scattering (Ostlin et al. 2009)



Hα (red) is the most efficient tracer of bright stars. Notice no clear correlation between Hα and Lyα.



- More example images and Lyα spectra of local galaxies.
  - Upper panels show color composite images, encoding Hα in red, FUV continuum in green, and Lyα in blue.
  - Dotted white lines indicate the size and position of the HST/COS aperture.
  - Lower panels show the corresponding spectra around Lyα (dark blue) and SI II 1260Å (red).
  - The redshifted Lyα spectra are common in LAEs. The feature is believed to be caused by outflowing gas around the galaxies.

Lyα Emission Mechanisms

- ***Collisional excitation***: The 'collision' between an electron and a hydrogen atom can leave the atoms in an excited state, at the expense of kinetic energy of the free electron. Then, the hydrogen atom emits Lyα and decays to the ground state. This process is often referred to as Lyα production via ***'cooling'*** radiation.

- ***Recombination***: Recombination of a free proton and a free electron can leave the electron in any quantum state $(n,\ l)$. Radiative cascades to the ground state can then produce a Lyα photon.

Astrophysical Lyα Sources

- ***Interstellar H II regions***
  - Interstellar H II regions are the most prominent sources of Lyα emission in the Universe. Hot, (mostly) massive and young stars produce ionizing photons (Lyman continuum; $E > 13.6$, $\lambda < 912\text{Å}$) in their atmospheres. These ionizing photons are efficiently absorbed in the interstellar medium, and thus create ionized H II regions.
  - Recombining protons and electrons give rise to Lyα, Hα, etc lines. These lines are called 'nebular' lines.

- ***The Circumgalactic / Intergalactic Medium (CGM/IGM)***
  - Detailed analysis of the Lyα forest imply that the IGM is highly ionized. The CGM/IGM is known to be photo-ionized by the Universal "ionizing background" that permeates the entire Universe. The ionizing background is generated by adding the contribution from all ionizing sources.
  - Collisional excitation mechanism in the shock-heated warm ($T \sim 10^4$ K) or hot ($T \sim 10^6$ K) gas can also produce the cooling Lyα radiation.

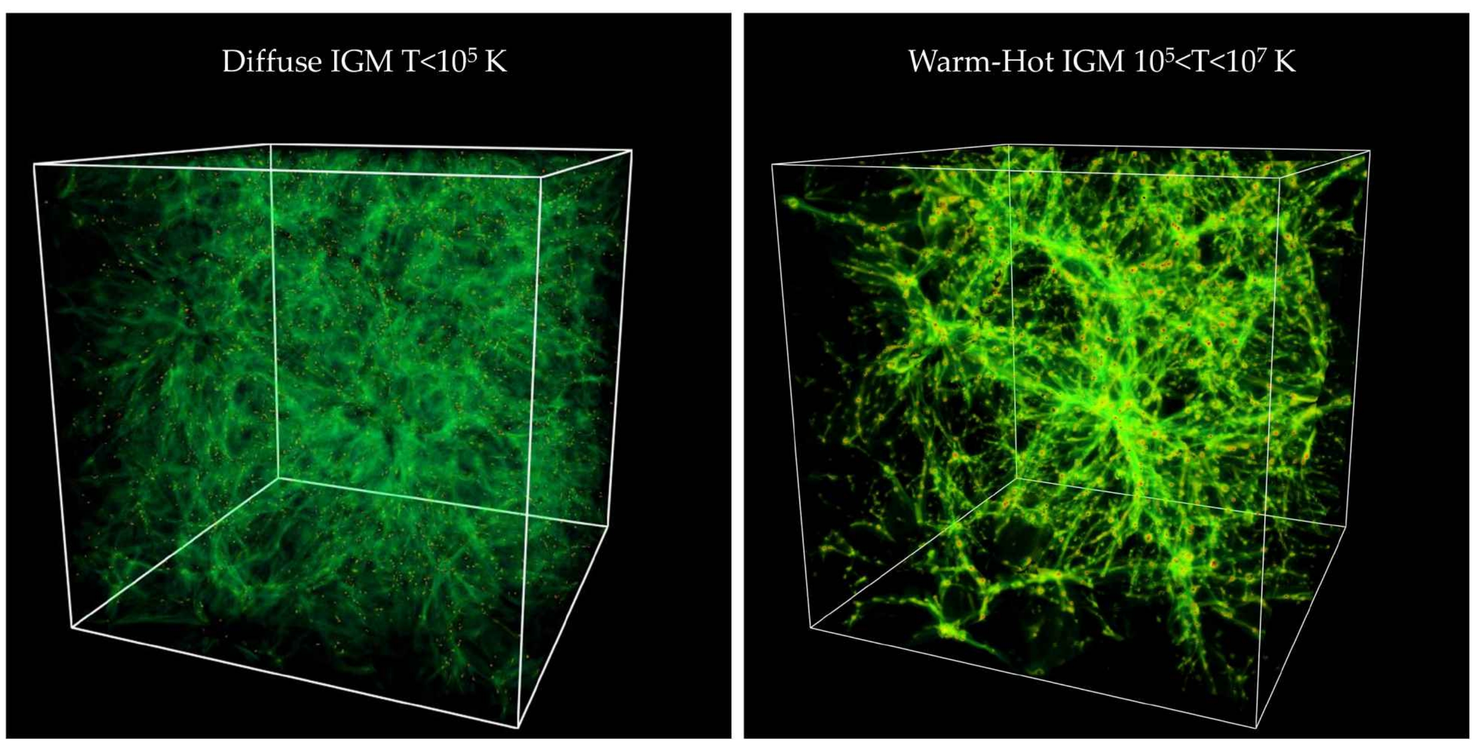
Warm-Hot Intergalactic Medium

- The Warm-Hot Intergalactic Medium (WHIM)
  - The WHIM is at temperature $10^5\,\mathrm{K} < T < 10^7\,\mathrm{K}$,

    and has a density in the range $5 \times 10^{-7}\,\mathrm{cm}^{-3} < n < 5 \times 10^{-5}\,\mathrm{cm}^{-3} \quad (n \approx (2 - 200) \times \overline{n}_{\mathrm{bary},0})$
  - These low densities and relatively high temperatures account for the difficulty of observing the WHIM.
- **Missing baryon problem**
  - The baryonic density has been fairly well known from Big Bang Nucleosynthesis and from early observations of the CMB by the COBE satellite.
  - However, the density in easily detected baryons — stars, interstellar gas, and X-ray emitting gas in clusters — was only $\sim 0.1\,\overline{n}_{\mathrm{bary},0}$.
  - It is believed that the unobserved baryons are in a low-density gas spread through intergalactic space.

Simulations of the WHIM

- Much of what we know about the WHIM comes from numerical cosmological simulations that include gas dynamics.
  - Davé et al. (2001, ApJ, 552, 473) have performed, for the first time, simulations of the intergalactic medium, and found that baryons in the universe reside in four broad phases, defined by their over density $\delta \equiv n/\overline{n} - 1$ and temperature T.
    - Diffuse IGM: $\delta < 1000,\ T < 10^5\,\mathrm{K}$. Photoionized intergalactic gas that gives rise to Lyman alpha absorption.
    - Condensed: $\delta > 1000,\ T < 10^5\,\mathrm{K}$. Stars and cool galactic gas.
    - Hot intracluster medium: $T > 10^7\,\mathrm{K}$. Gas in galaxy clusters and large groups.
    - Warm-Hot: $10^5 < T < 10^7\,\mathrm{K}$. The “warm-hot intergalactic medium.”

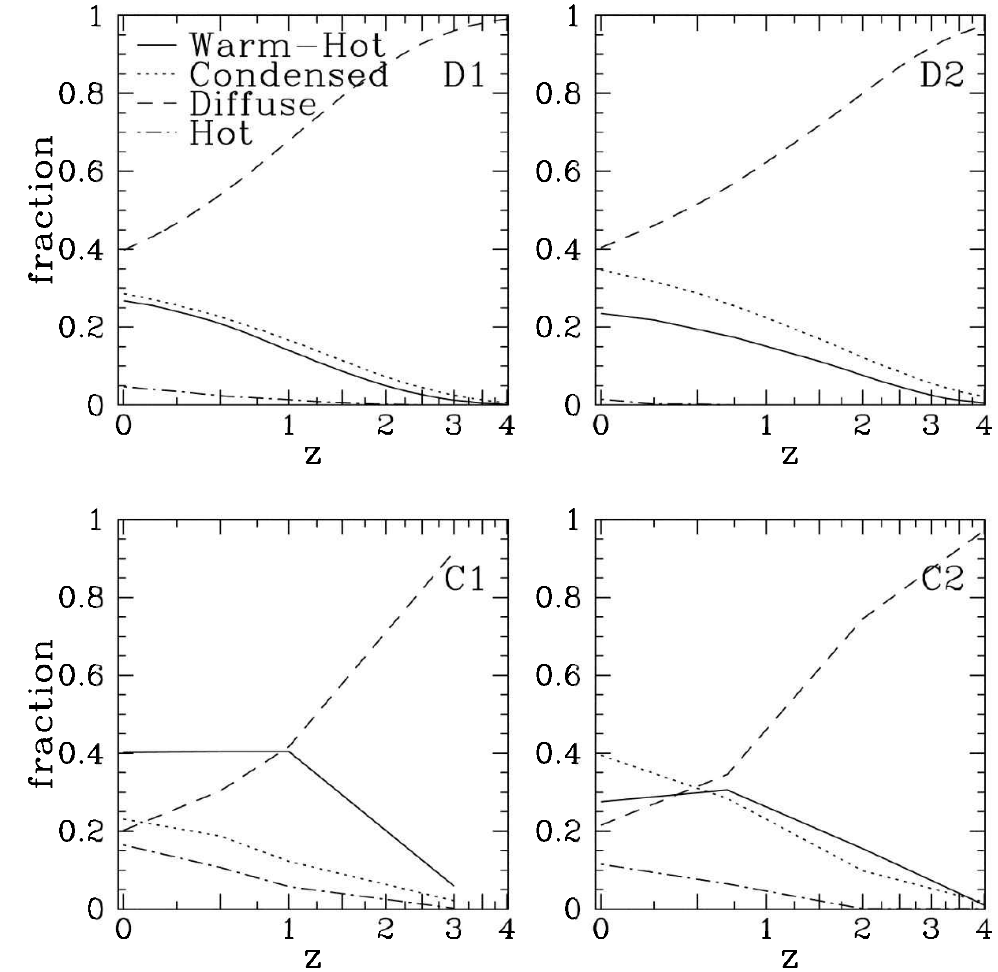


(Left) Distribution of diffuse intergalactic gas at z = 0. (Right) Distribution of warm-hot intergalactic gas at z = 0.

green : $n = 10\,\overline{n}_{\mathrm{bary},0}$
red: $n = 10^4\,\overline{n}_{\mathrm{bary},0}$

[Fig 10.1, Ryden; Renyue Cen]

- Summary:
  - At z = 4, shortly after reionization is complete, nearly all the baryonic gas was in the form of photo ionized gas with $T < 10^5$ K.
  - As structure went nonlinear and collapsed, more and more of the baryonic gas became shock-heated to temperatures $10^5 \text{ K} < T < 10^7 \text{ K}$ (WHIM).
  - The WHIM grew steadily with time until it composed 30-40% of the baryonic matter today.
  - "Condensed" gas represents galaxies containing stars, interstellar gas, and circumgalactic gas.
  - "Hot" gas is the intracluster gas at $T > 10^7$ K.
- Difference between the DIM & WHIM
  - The diffuse intergalactic medium (DIM) is smoothly distributed.
  - The WHIM is found primarily in long filaments. As it flows along filaments to the clusters, the WHIM is shocked and heated to higher temperatures than the photoionized DIM.



Evolution of the fraction of baryonic matter in each of four components. Four simulation results are shown, with different gas physics and different spatial resolutions.

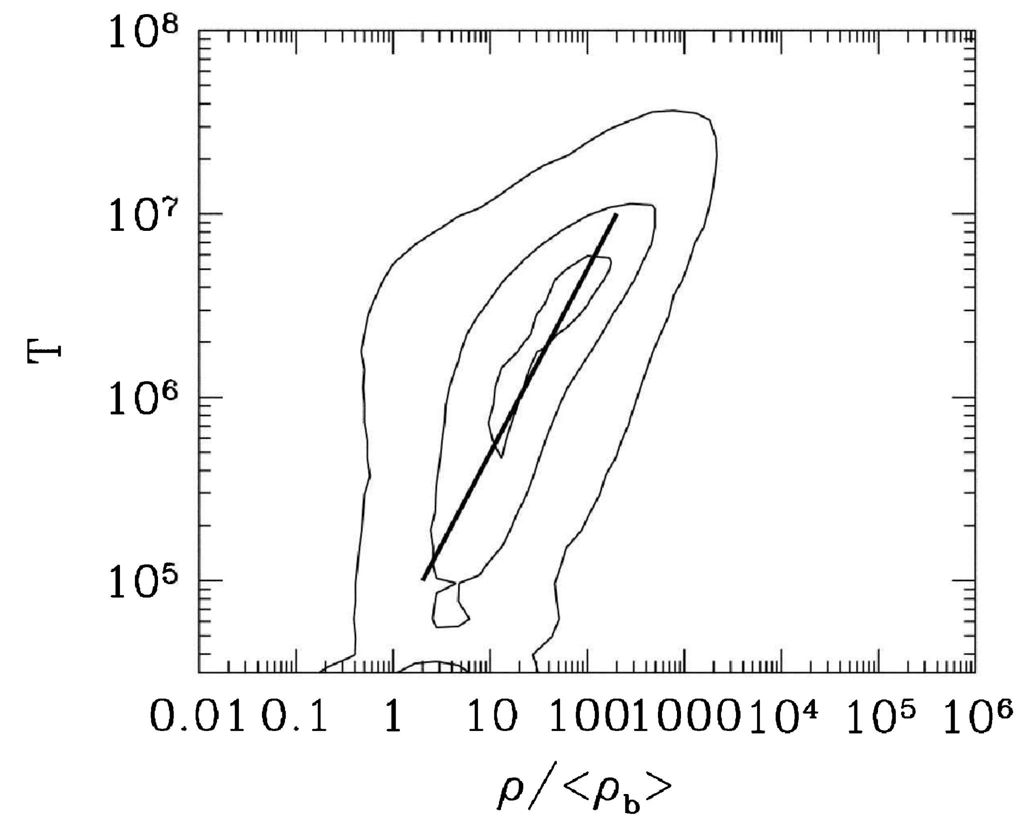
[Fig 10.2, Ryden; Dave et al. 2001]

- Density-Temperature of the WHIM
  - The density is positively correlated with temperature (so there is no pressure equilibrium).

$$\frac{n}{20\,\overline{n}_{\mathrm{bary},0}} = \frac{T}{10^6\,\mathrm{K}}$$

$$20\,\overline{n}_{\mathrm{bary},0} \approx 5 \times 10^{-6}\,\mathrm{cm}^{-3}$$

- Metallicity
  - The metallicity of intergalactic gas reaches $Z > 0.3 Z_\odot$ primarily in dense virialized clusters, contaminated with gas ejected by supernovae.
  - Along the WHIM filaments, a metallicity $Z \sim 10^{-3} Z_\odot$ is more typical.
  - At the low metallicity of the WHIM, bremsstrahlung dominates the cooling down to a temperature as low as T ~ 10^6 K.
  - The WHIM has a temperature that is typical of the hot interstellar medium of our Galaxy. However, the WHIM has densities that are smaller by 3 orders of magnitude than the HIM ($n_{\mathrm{HIM}} \sim 4 \times 10^{-3}\,\mathrm{cm}^{-3}$).



The distribution of WHIM in the density-temperature plane at z = 0. The contours contain 90%, 50%, and 10% of the baryons, from the outermost contour inward.

[Fig 10.3, Ryden; Dave et al. 2001]

Observations

- **Bremsstrahlung**
  - Observing bremsstrahlung emission from the WHIM is “challenging” (impossible).

cooling rate for ICM: $\mathcal{L}_{\rm ff} \approx 1.77 \times 10^{-29}\,{\rm erg\,cm^{-3}\,s^{-1}} \left(\frac{kT}{10\,{\rm keV}}\right)^{1/2} \left(\frac{n_{\rm H}}{10^{-3}\,{\rm cm^{-2}}}\right)^{2}$

cooling rate for WHIM: $\mathcal{L}_{\rm ff} \approx 5.4 \times 10^{-35}\,{\rm erg\,cm^{-3}\,s^{-1}} \left(\frac{kT}{0.1\,{\rm keV}}\right)^{1/2} \left(\frac{n_{\rm H}}{5 \times 10^{-6}\,{\rm cm^{-2}}}\right)^{2}$

  - Note that, in our Galaxy, seeing bremsstrahlung emission from hot bubbles other than the Local Bubble is impossible.

- **Lines from highly ionized heavy elements**.
  - Consider oxygen, for instance, the most abundance element heavier than helium.
    - $T < 3 \times 10^5\,{\rm K}$: O V and O VI become important.
    - $3 \times 10^5\,{\rm K} < T < 2 \times 10^6\,{\rm K}$: The dominant ionization state of oxygen is helium-like O VII.
    - $T > 2 \times 10^6\,{\rm K}$: O VIII and fully ionized O IX become important.

- **O VI emission line**:
  - The WHIM at $T \sim 3\text{x}10^6$ K has a low hydrogen number density:

$$n_{\rm H} \sim 6\,\overline{n}_{\rm bary,0} \sim 1.5 \times 10^{-6}\,{\rm cm}^{-3} \quad \text{at} \quad T \times 3 \times 10^6\,{\rm K}$$

(from the density-temperature relation)

$$\frac{n}{20\,\overline{n}_{\rm bary,0}} = \frac{T}{10^6\,{\rm K}}$$

  - For the metallicity $Z \sim 0.01 Z_\odot$, the abundance ratio is $n_{\rm O}/n_{\rm H} \sim 5 \times 10^{-6}$. This leads to a number density of oxygen:

$$n_{\rm O} \sim 8 \times 10^{-12}\,{\rm cm}^{-3}$$

  - Even at its maximum relative abundance, at $T \sim 3\text{x}10^6$ K, O VI accounts for only 25% of all the oxygen:

$$n_{\rm OVI} \sim 2 \times 10^{-12}\,{\rm cm}^{-3}$$

  - Since the WHIM is concentrated along filaments of the cosmic web, a line of sight passing through a single filament, whose thickness is ~ 1 Mpc, will contribute a column density:

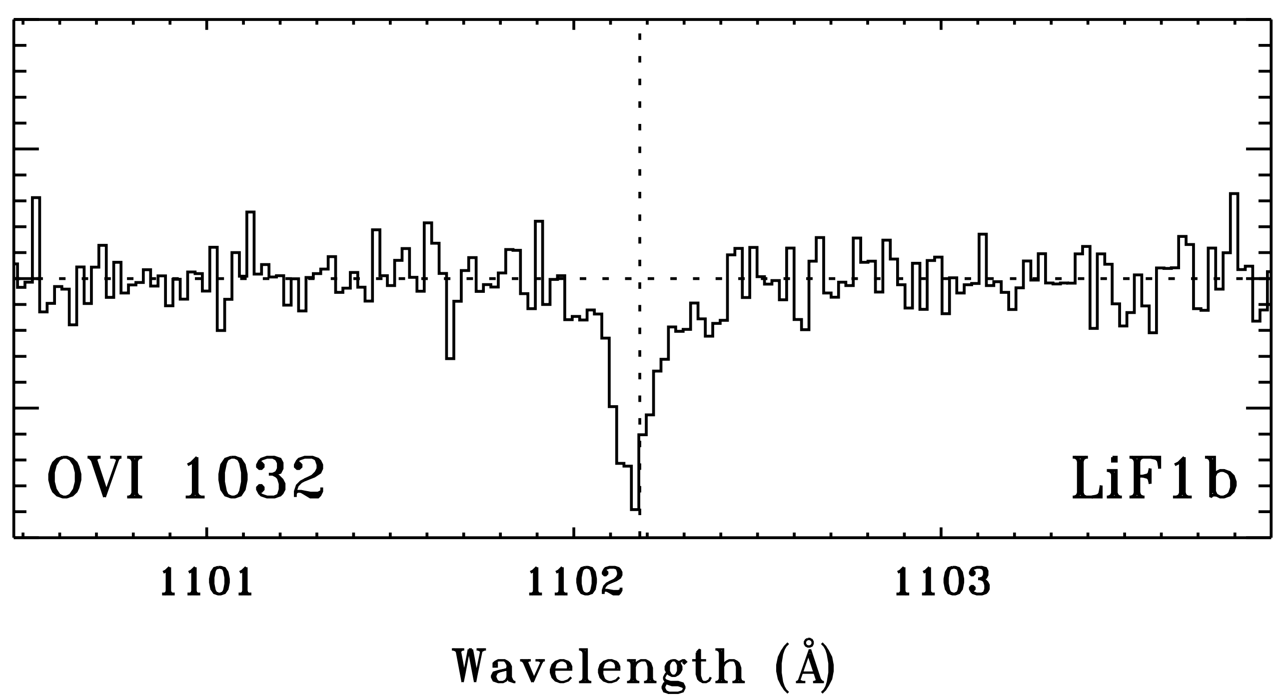
$$N_{\rm OVI} \sim n_{\rm OVI}\ell \sim 5 \times 10^{12}\,{\rm cm}^{-2} \left(\frac{\ell}{1\,{\rm Mpc}}\right)$$

  - Measuring column density $N_{\rm OVI} < 10^{13}\,{\rm cm}^{-2}$ is difficult.

- **O VI absorption line**:
  - Danforth & Shull (2008), in the study of UV absorption lines (HST and FUSE) toward bright AGNs, found O VI absorption systems with column densities:

$$N_{\rm OVI} \sim 8 \times 10^{12} - 5 \times 10^{14}\,{\rm cm}^{-2}$$

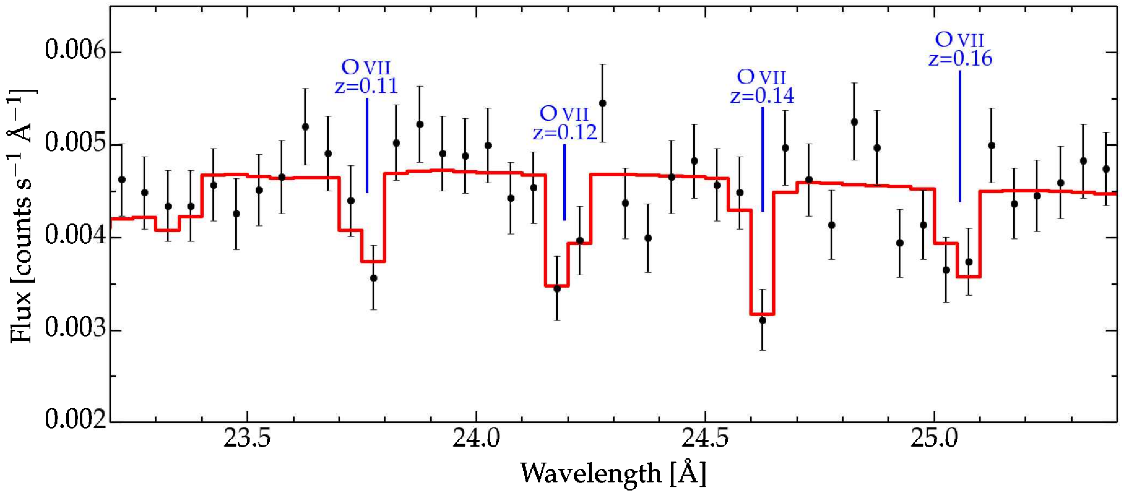
  - The strongest absorption systems, with $N_{\rm OVI} > 10^{14}\,{\rm cm}^{-2}$ had an average Doppler broadening parameter $b \sim 40\,{\rm km\,s}^{-1}$, corresponding to $T \sim 10^6\,{\rm K}$.
  - They concluded that the WHIM in the temperature range of $10^5\,{\rm K} < T < 10^6\,{\rm K}$, where O VI absorption is strongest, provides ~ 10% of the baryonic material in the universe.
  - This still leaves a large amount of “missing” baryons in the IGM.



An example spectrum of O VI absorption line in the z = 0.06808 absorber toward PG 0953+414.

Fig 1, Danforth & Shull (2008, ApJ, 679, 194)

- The ***hotter WHIM*** in the range $10^6\,\mathrm{K} < T < 10^7\,\mathrm{K}$ is more difficult.
    - The ion O VII has an X-ray line at λ = 21.6Å (0.57 keV). However, this is not a song line, and has been found only at a relatively low significance level along a few lines of sight.
    - The right figure shows a simulation of intervening O VII absorption lines at four redshifts along the line of sight to an X-ray bright AGN for a 700 ksec observation (~ 8.1 days) with the Chandra transmission grating instrument.



Simulated 700 ksec Chandra LETG/HRC spectrum of B2 1721+34 showing predicted WHIM O VII Kα absorption at redshifts of 0.11, 0.12, 0.14, and 0.16.

[Fig 10.5, Ryden]

- Observations have been very challenging and the results are controversial.

- The “missing” baryons aren’t missing: they just need high-throughput X-ray spectrographs with high energy resolution to get their message across to us.