

Interstellar Medium (ISM)

Lecture 14
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Intergalactic Medium 2

- Ly α Forest
- Warm-Hot Intergalactic Medium

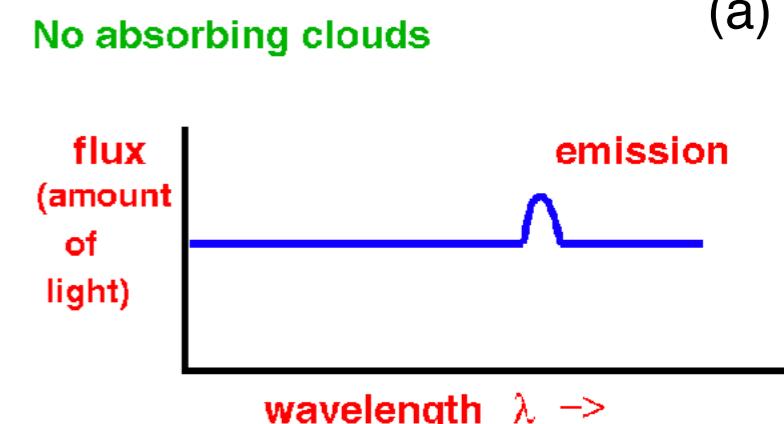
Ly α Forest

- 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 Ly α 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 Ly α emission line of the quasar.
 - ▶ Lynds concluded that most of the absorption lines that he saw were Ly α 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.

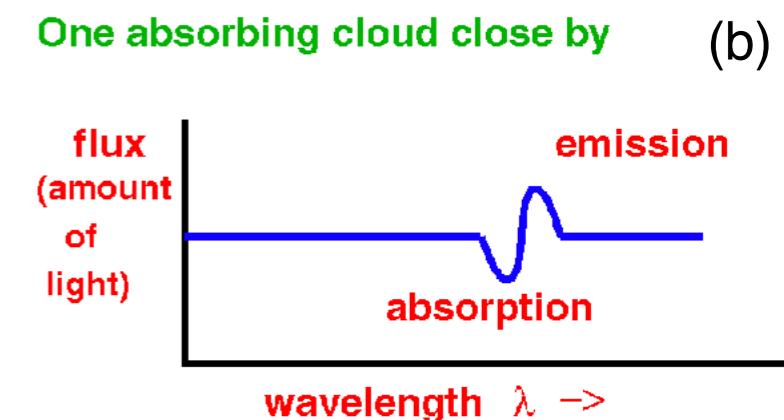
Ly α Forest

- 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.

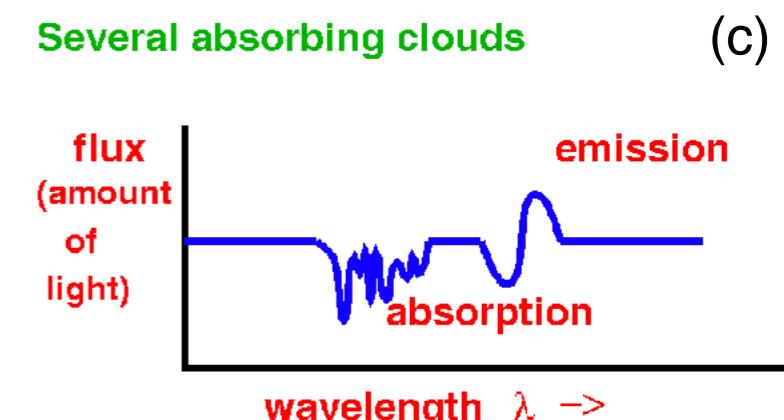
- The quasar continuum is relatively flat. Broad emission features are produced by the quasar itself (near the black hole and its accretion disk).



- In some cases, gas near the quasar central engine also produces “intrinsic” absorption lines, most notably Ly α , 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 its Ly α emission line redshifted from the UV into the red, and the Ly α 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 $\lambda_{\text{obs}} = \lambda_{\text{rest}}(1 + z_{\text{gas}})$, where z_{gas} is the redshift of the absorbing gas and $\lambda_{\text{rest}} = 1216\text{\AA}$ is the rest wavelength of the Ly α transition. Since $z_{\text{gas}} < z_{\text{quasar}}$, the redshift of the quasar, these Ly α absorption lines form a “forest” at wavelengths blueward of the Ly α emission of the quasar.
- The region redward of the Ly α emission will be populated only by absorption through other chemical transitions with longer $\lambda_{\text{Ly}\alpha}$.

Definition of redshift:

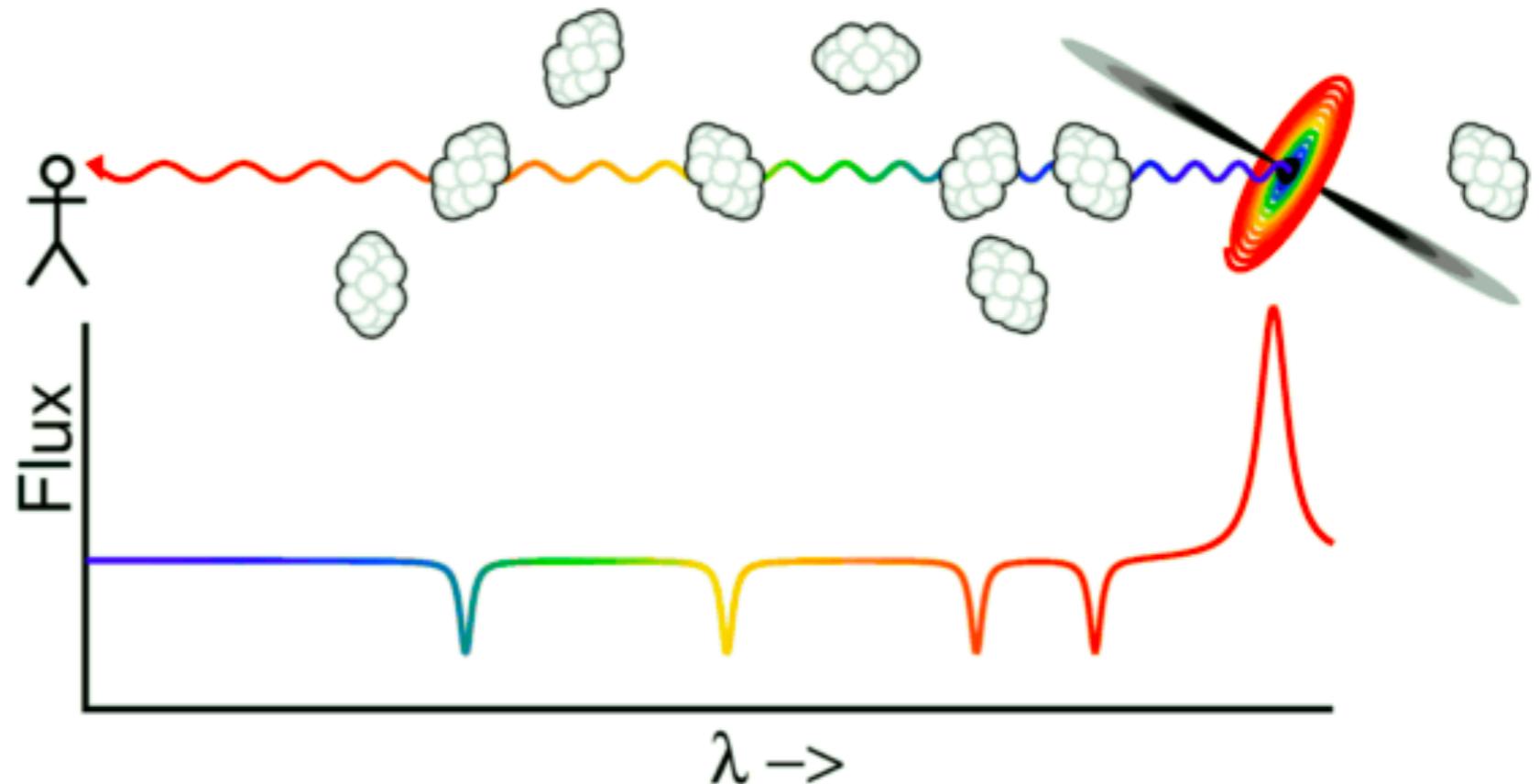
$$z \equiv \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}$$

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

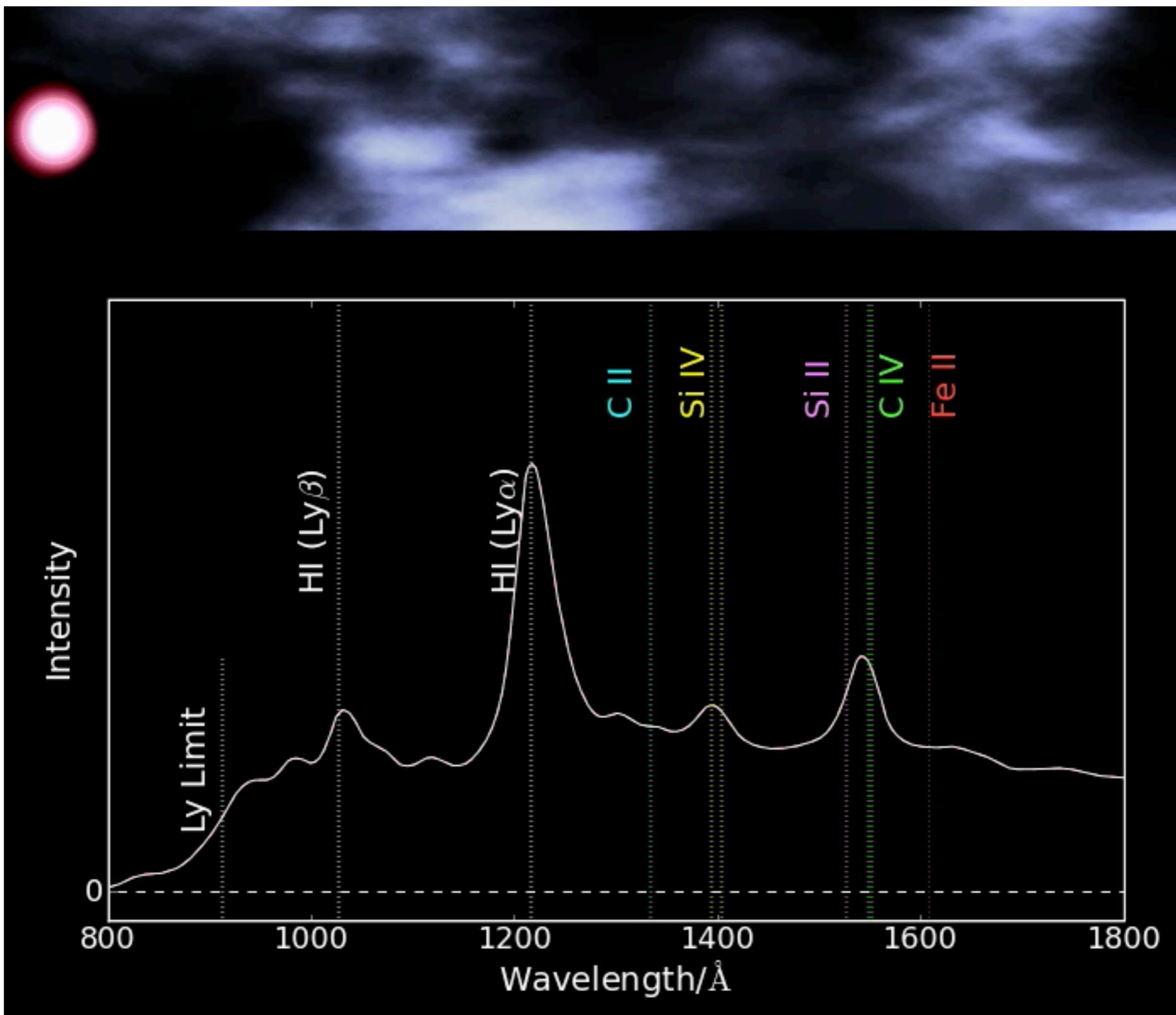
$$\lambda_{\text{obs}}^{\text{gas}} = \lambda_{\text{rest}}(1 + z_{\text{gas}})$$

$$\lambda_{\text{obs}}^{\text{quasar}} = \lambda_{\text{rest}}(1 + z_{\text{quasar}})$$

$$\therefore \lambda_{\text{obs}}^{\text{gas}} < \lambda_{\text{obs}}^{\text{quasar}}$$



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

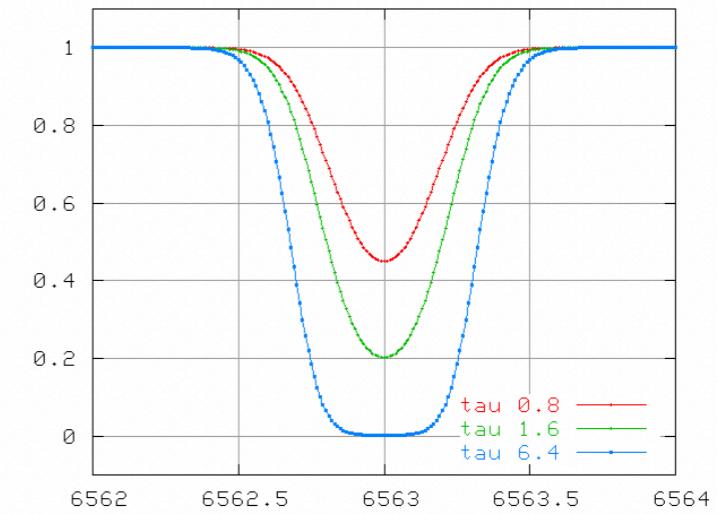


Ly α Absorption System

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

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

$N(\text{H I}) < 10^{12} \text{ cm}^{-2}$	Currently not observable
$10^{12} < N(\text{H I}) < 10^{17} \text{ cm}^{-2}$	Ly α forest
$10^{17} < N(\text{H I}) < 2 \times 10^{20} \text{ cm}^{-2}$	Lyman limit systems
$2 \times 10^{20} < N(\text{H I})$	Damped Ly α systems



As $N(\text{HI})$ increases, the absorption line depth and width increase.

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

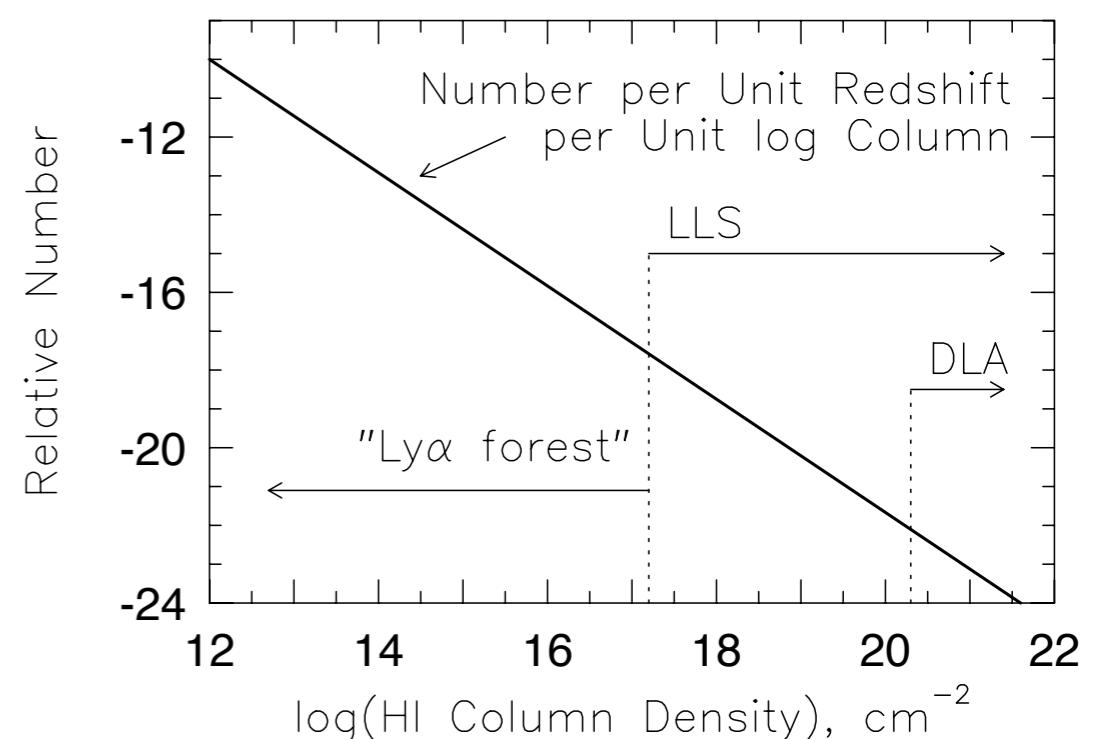
$$\tau_0 \approx 1.9 \left(\frac{b}{40 \text{ km s}^{-1}} \right)^{-1} \left(\frac{N_{\text{HI}}}{10^{14} \text{ cm}^{-2}} \right)$$

- The name “**Lyman limit system**” is given because at these column densities, **clouds become optically thick to photons with $\lambda < 912\text{\AA}$** , 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.

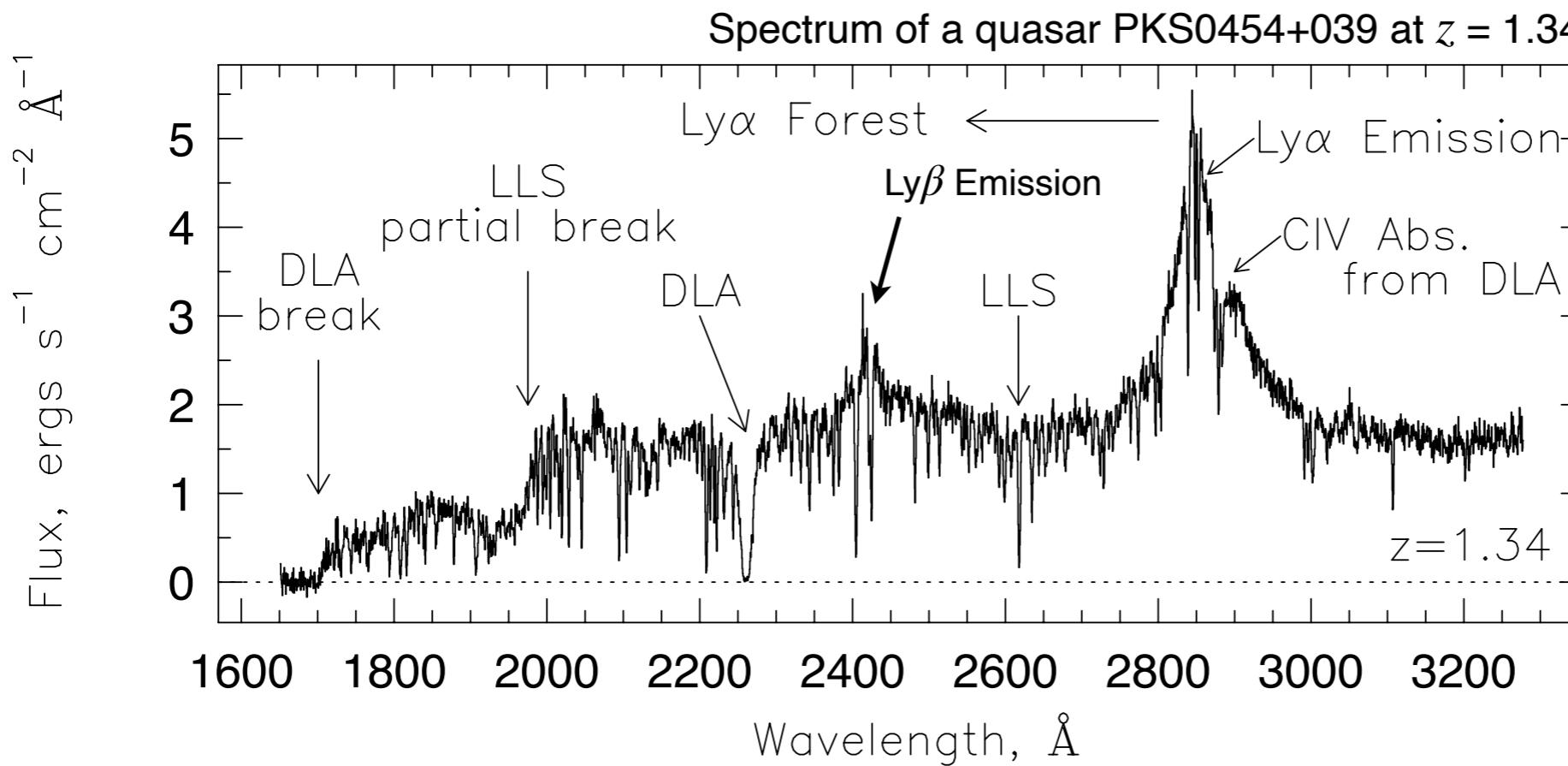
What are the Ly α absorption systems?

- Metallicity
 - The metallicity of DLAs is typically in the range $Z \approx 0.01 - 0.3Z_{\odot}$.
 - The Lyman alpha forests has a lower metallicity of $Z \approx 0.001 - 0.01Z_{\odot}$.
- 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, virialized 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, **Lyman alpha forests 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

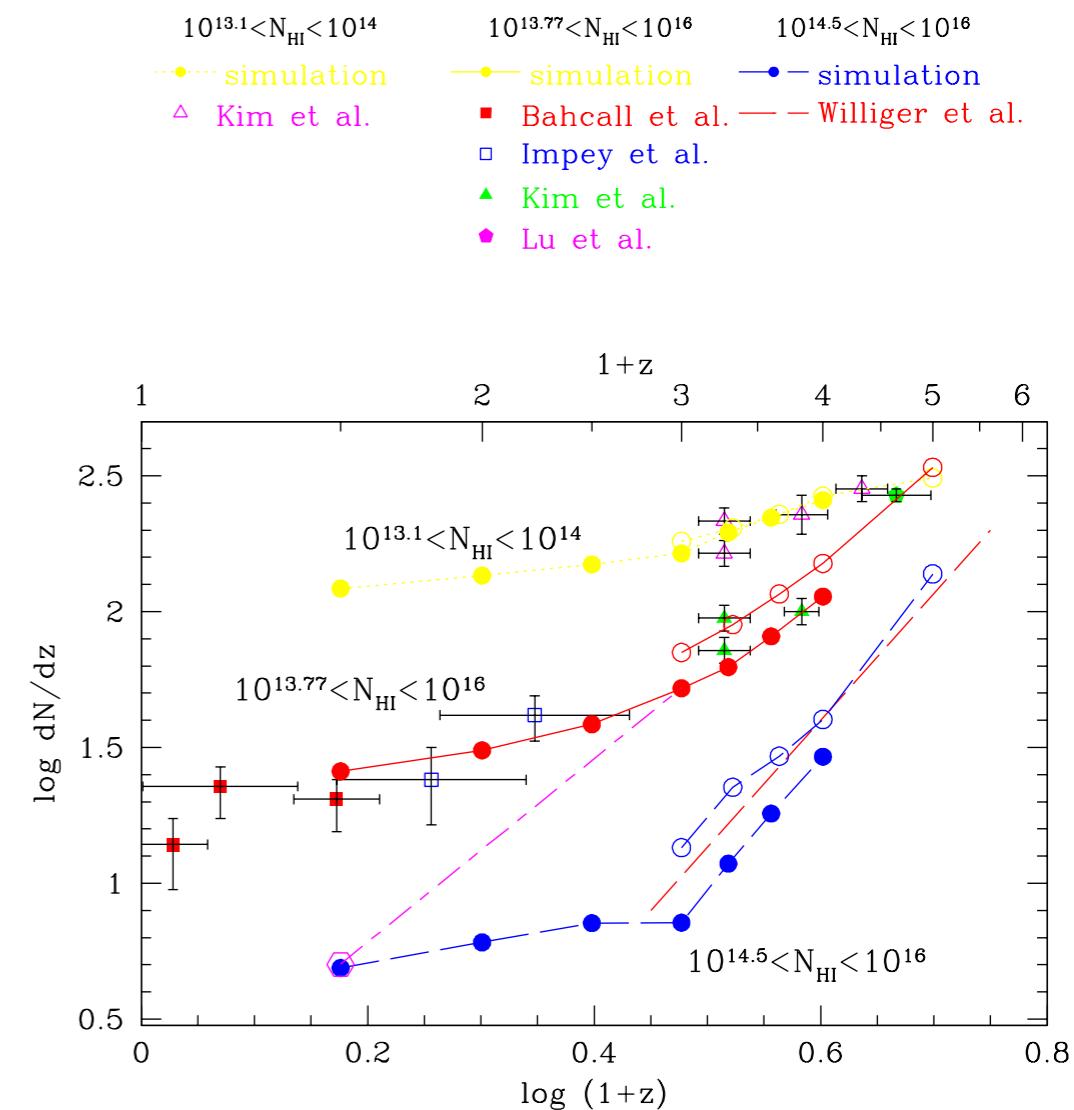


$$\begin{aligned}\lambda_{\text{rest}}^{\text{Ly}\alpha} &= 1216 \text{\AA} \\ \lambda_{\text{rest}}^{\text{Ly}\beta} &= 1026 \text{\AA} \\ \lambda_{\text{rest}}^{\text{Lyman break}} &= 912 \text{\AA}\end{aligned}$$

- 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 Ly α forest, absorption produced by various intergalactic clouds, is apparent at wavelengths blueward of the Ly α emission line.
 - The two strongest absorbers, due to galaxies, are a damped Ly α absorber at $z = 0.86$ ($(1 + 0.86) \times 1216 = 2262 \text{\AA}$) and a Lyman limit system at $z = 1.15$ ($(1 + 1.15) \times 1216 = 2614 \text{\AA}$).
 - The damped Ly α absorber produces a Lyman limit break at $\sim 1700 \text{\AA}$ ($(1 + 0.86) \times 912 = 1696 \text{\AA}$).
 - The Lyman limit system: a partial Lyman limit break at $\sim 1960 \text{\AA}$ ($(1 + 1.15) \times 912 = 1961 \text{\AA}$) since the neutral Hydrogen column density is not large enough for it to absorb all ionizing photons.

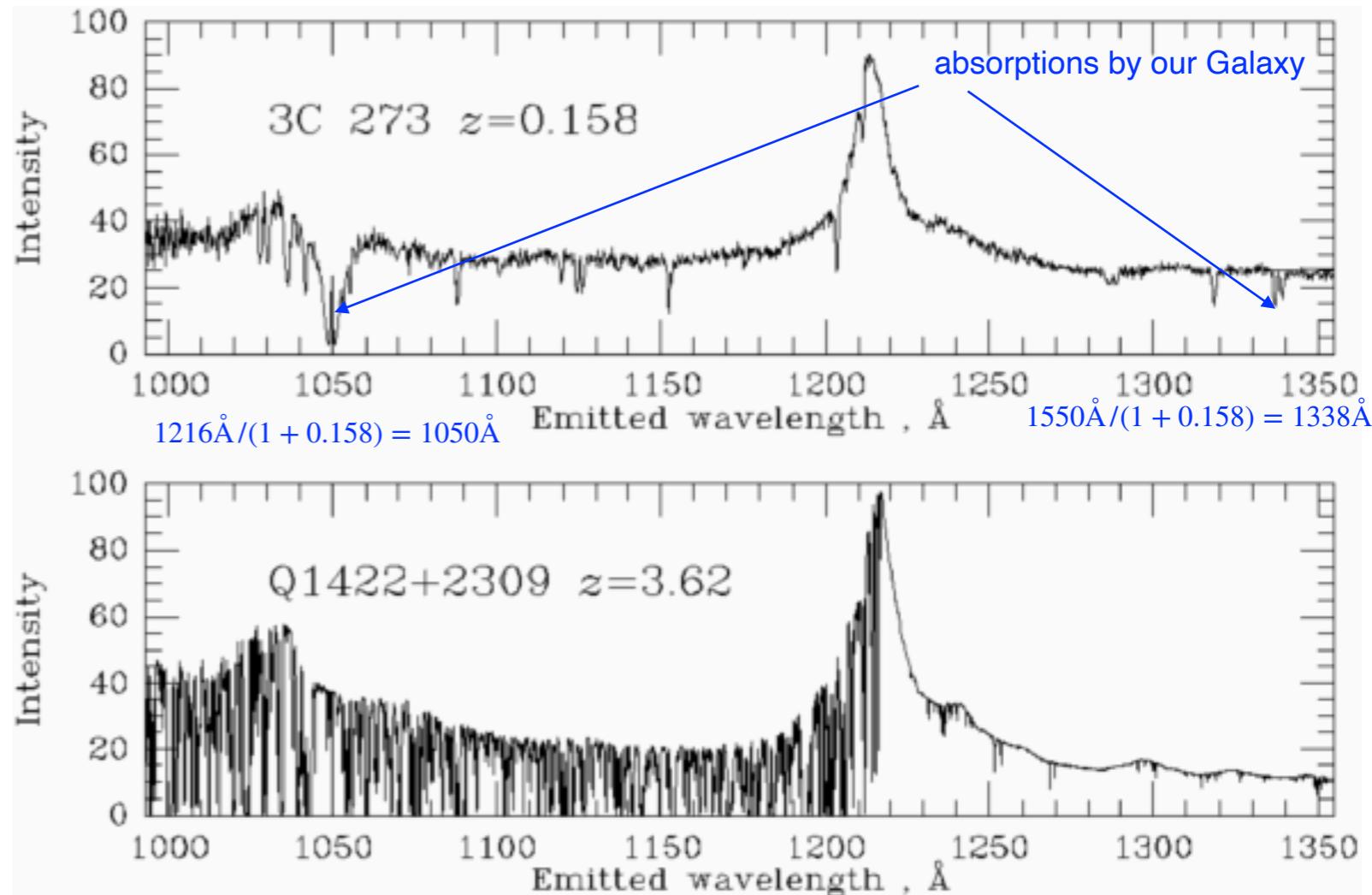
Evolution of Ly α Absorption Systems

- The Ly α 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 Ly α 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 Ly α 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.***

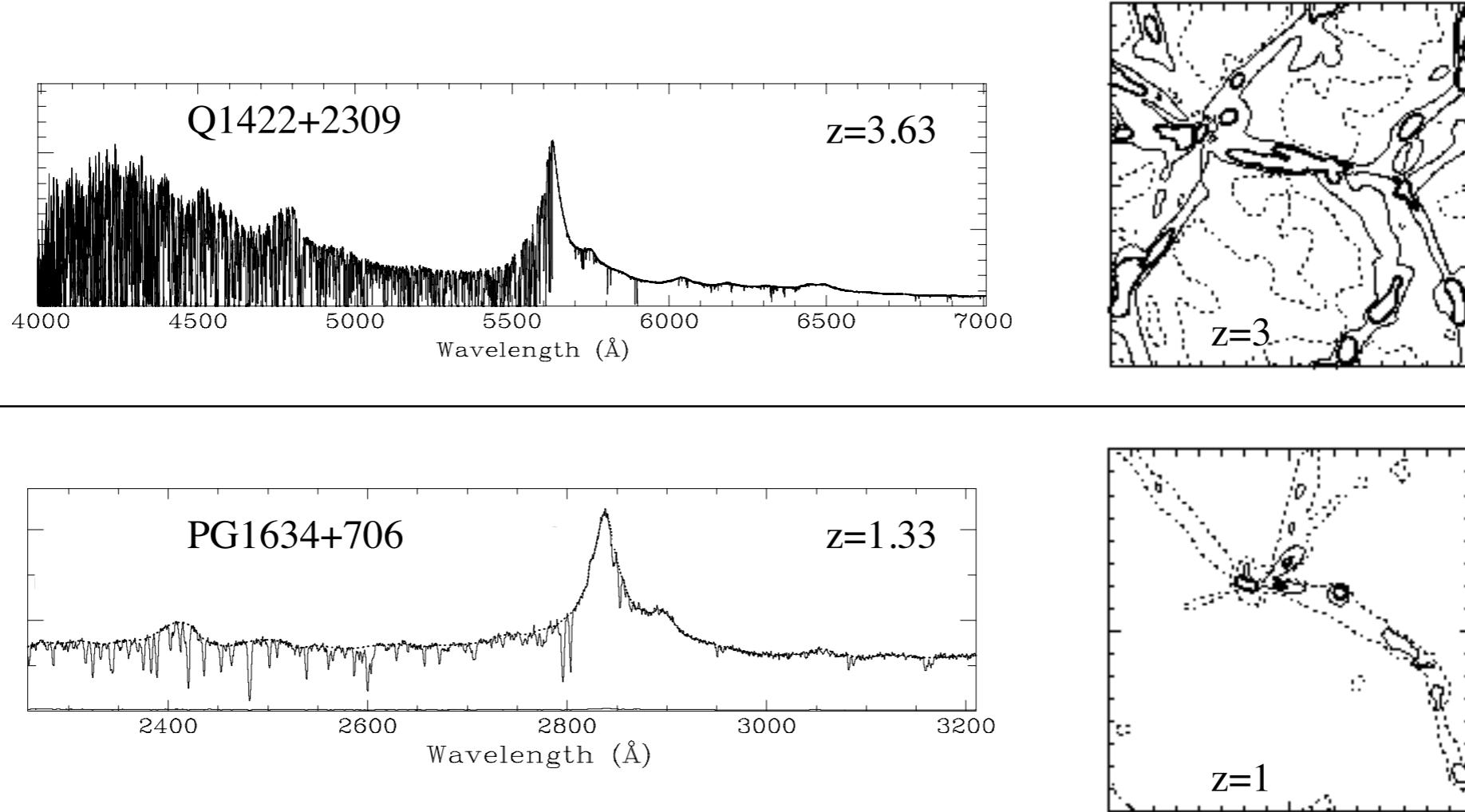


Evolution of the number of lines within a given range of column density obtained from numerical simulations and observations (Efstathiou et al.)

- 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 Ly α 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 Ly α , which is almost chopped in half by the onset of the Ly α forest in the high-redshift quasar.
- ***This is a very general feature showing how the density of Ly α 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 Ly α 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} cm^{-2} (dotted lines), 10^{12} cm^{-2} (solid lines) and 10^{13} 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:

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

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

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

$\langle E \rangle$ = 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 Ly α 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:

$$\mathcal{L}_{\text{adi}} = -\frac{d\mathcal{E}}{dt} = \gamma \frac{\mathcal{E}}{V} \frac{dV}{dt} = \left(\gamma \frac{\mathcal{E}}{V} \right) 3 \frac{V}{a} \frac{da}{dt}$$

$$V \propto a(t)^3$$

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

$$H(t) \equiv \frac{\dot{a}}{a}$$

► Energy Balance:

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

We then obtain

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

$$T = T_0 \left(\frac{n_{\text{H}}}{\bar{n}_{\text{bary}}} \right)^{0.58}$$

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

• **Optical Depth versus Density** in the intergalactic gas

- The balance equation between the photoionization and radiative recombination is given by

$$\begin{aligned} \zeta_{\text{pi}} n_{\text{H}^0} &= n_e n_p \alpha_{\text{A,H}} \\ \zeta_{\text{pi}} (1-x) n_{\text{H}} &= x^2 n_{\text{H}}^2 \alpha_{\text{A,H}} \end{aligned} \quad \xleftarrow{\text{fractional ionization}} \quad x \equiv n_e / n_{\text{H}}, \quad n_e = n_p$$

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

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

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

-
- Then, the number density of neutral hydrogen atoms is

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

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

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

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

$$\tau \propto n_{\text{H}^0} \propto n_{\text{H}}^2 T^{-0.72} \zeta_{\text{pi}}^{-1} \propto n_{\text{H}}^{1.6} \zeta_{\text{pi}}^{-1} \quad \leftarrow \begin{array}{l} \text{using the density-temperature correlation} \\ T \propto n_{\text{H}}^{0.58} \end{array}$$

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

$$\tau = \bar{\tau} \left(\frac{n}{\bar{n}_{\text{bary}}} \right)^{1.6} \quad \leftarrow \quad n \propto n_{\text{H}}$$

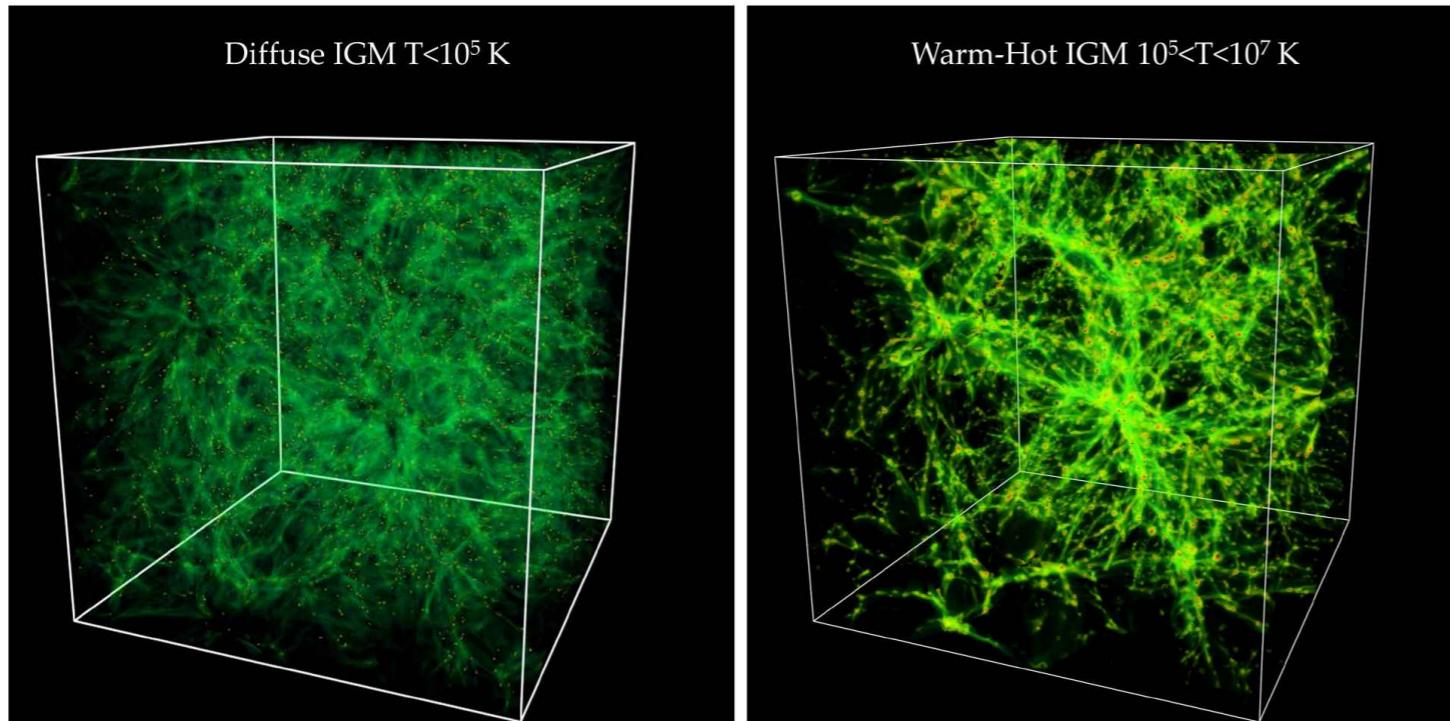
- The constant $\bar{\tau}$ depends on the assumed cosmology as well as on the amount of ionizing radiation present.
- The above equation is referred to as the ***fluctuating Gunn-Peterson approximation***.

Warm-Hot Intergalactic Medium

- The Warm-Hot Intergalactic Medium (WHIM)
 - The WHIM is at temperature $10^5 \text{ K} < T < 10^7 \text{ K}$,
and has a density in the range $5 \times 10^{-7} \text{ cm}^{-3} < n < 5 \times 10^{-5} \text{ cm}^{-3}$ ($n \approx (2 - 200) \times \bar{n}_{\text{bary},0}$)
 - 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 $\sim 0.1 \bar{n}_{\text{bary},0}$.
 - 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 $\delta \equiv n/\bar{n} - 1$ and temperature T .
 - ▶ **Diffuse IGM:** $\delta < 1000$, $T < 10^5$ K. Photoionized intergalactic gas that gives rise to Lyman alpha absorption.
 - ▶ **Condensed:** $\delta > 1000$, $T < 10^5$ K. Stars and cool galactic gas.
 - ▶ **Hot intracluster medium:** $T > 10^7$ K . Gas in galaxy clusters and large groups.
 - ▶ **Warm-Hot:** $10^5 < T < 10^7$ K. The “warm-hot intergalactic medium.”



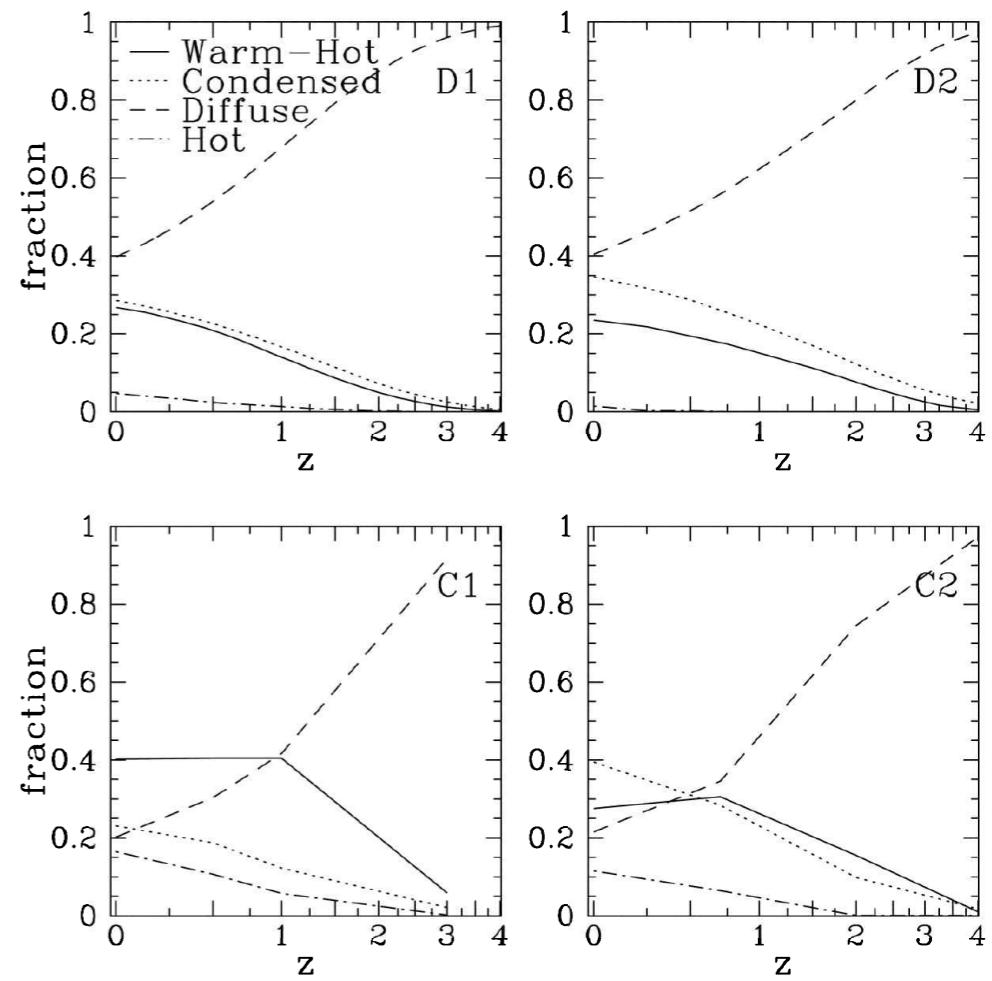
(Left) Distribution of diffuse intergalactic gas at $z = 0$. (Right) Distribution of warm-hot intergalactic gas at $z = 0$.

green : $n = 10 \bar{n}_{\text{bary},0}$

red: $n = 10^4 \bar{n}_{\text{bary},0}$

[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 photo-ionized 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.

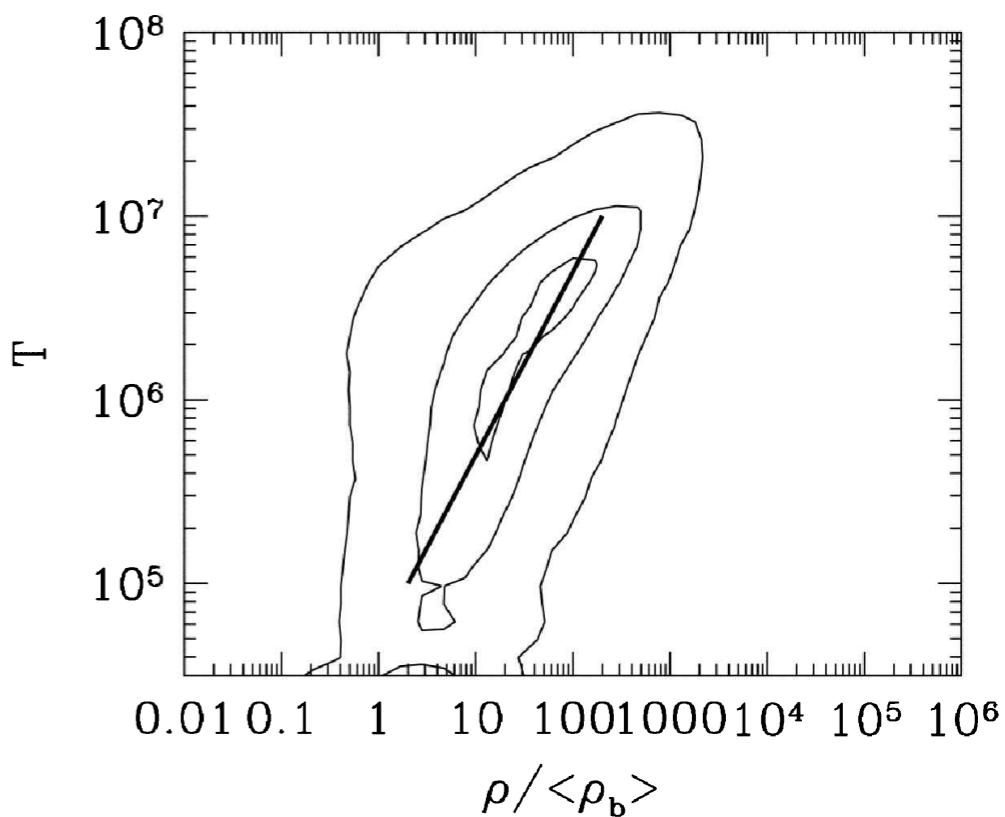
[Fig 10.2, Ryden; Dave et al. 2001]

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

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

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

- 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 $T \sim 10^6 \text{ K}$.
 - 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 ($n_{\text{HIM}} \sim 4 \times 10^{-3} \text{ cm}^{-3}$).



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

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

- 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.
 - ▶ $T < 3 \times 10^5 \text{ K}$: O V and O VI become important.
 - ▶ $3 \times 10^5 \text{ K} < T < 2 \times 10^6 \text{ K}$: The dominant ionization state of oxygen is helium-like O VII.
 - ▶ $T > 2 \times 10^6 \text{ K}$: O VIII and fully ionized O IX become important.

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

$$n_{\text{H}} \sim 6 \bar{n}_{\text{bary},0} \sim 1.5 \times 10^{-6} \text{ cm}^{-3} \quad \text{at} \quad T \sim 3 \times 10^6 \text{ K} \quad (\text{from the density-temperature relation})$$

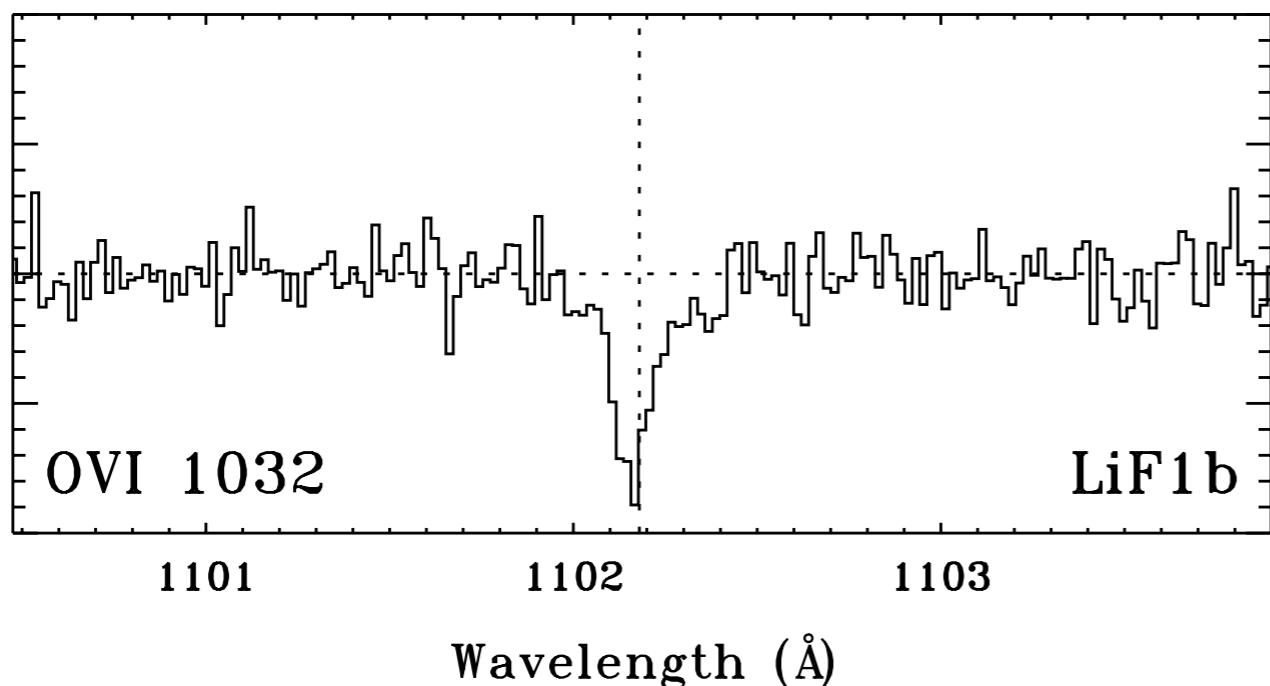
$$\frac{n}{20 \bar{n}_{\text{bary},0}} = \frac{T}{10^6 \text{ K}}$$
 - ▶ For the metallicity $Z \sim 0.01 Z_{\odot}$, the abundance ratio is $n_{\text{O}}/n_{\text{H}} \sim 5 \times 10^{-6}$. This leads to a number density of oxygen:

$$n_{\text{O}} \sim 8 \times 10^{-12} \text{ cm}^{-3}$$
 - ▶ Even at its maximum relative abundance, at $T \sim 3 \times 10^6$ K, O VI accounts for only 25% of all the oxygen:

$$n_{\text{OVI}} \sim 2 \times 10^{-12} \text{ cm}^{-3}$$
 - ▶ 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:

$$N_{\text{OVI}} \sim n_{\text{OVI}} \ell \sim 5 \times 10^{12} \text{ cm}^{-2} \left(\frac{\ell}{1 \text{ Mpc}} \right)$$
 - ▶ Measuring a emission line from column density $N_{\text{OVI}} < 10^{13} \text{ cm}^{-2}$ is difficult.

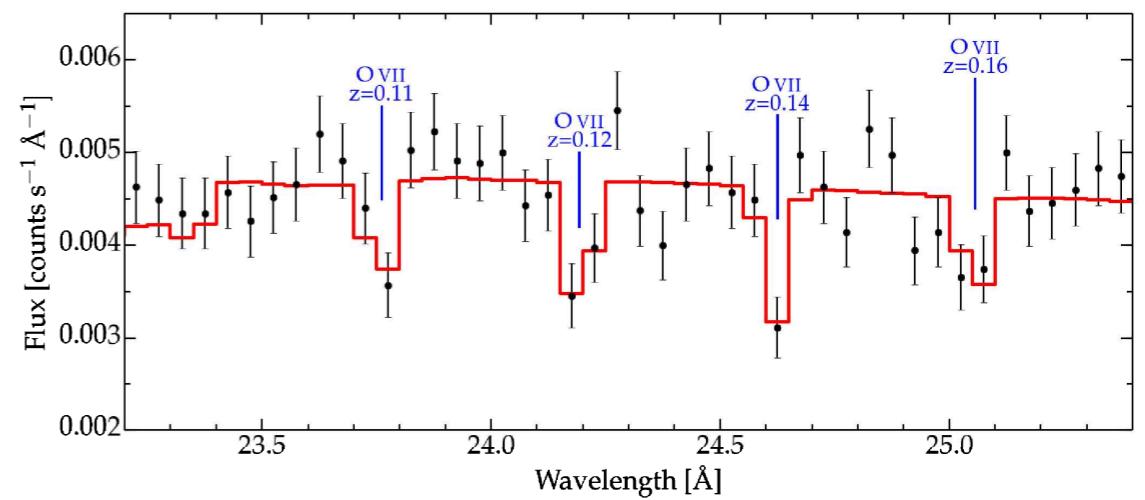
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- **O VI absorption line:**
 - ▶ Danforth & Shull (2008), in the study of UV absorption lines (HST and FUSE) toward bright AGNs, found O VI absorption systems with column densities:
- $$N_{\text{OVI}} \sim 8 \times 10^{12} - 5 \times 10^{14} \text{ cm}^{-2}$$
- ▶ The strongest absorption systems, with $N_{\text{OVI}} > 10^{14} \text{ cm}^{-2}$ had an average Doppler broadening parameter $b \sim 40 \text{ km s}^{-1}$, corresponding to $T \sim 10^6 \text{ K}$.
 - ▶ They concluded that the WHIM in the temperature range of $10^5 \text{ K} < T < 10^6 \text{ K}$, where O VI absorption is strongest, provides $\sim 10\%$ 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 $10^6 \text{ K} < T < 10^7 \text{ K}$ is more difficult.
 - ▶ The ion O VII has an X-ray line at $\lambda = 21.6\text{\AA}$ (0.57 keV). However, this is not a strong 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.
 - ▶ 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.



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

[Fig 10.5, Ryden]

Final Exams (Take-Home)

Due Date:

23:59PM, July 09 (Thurs.), 2020

Q1 (Lecture 5)

Suppose the HI gas to be in a plane-parallel slab geometry, with full thickness $6 \times 10^{20} \text{ cm}^{-2}$, and take the velocity distribution be Gaussian with a one-dimensional velocity dispersion $\sigma_V = 10 \text{ km s}^{-1}$. Neglect the effects of Galactic rotation.

- (a) If the spin temperature is $T_{\text{spin}} = 100 \text{ K}$, for what galactic latitudes is the line-center optical depth $\tau < 0.5$, as seen from a point in the mid-plane?
- (b) If the full-thickness of the HI disk is 300 pc, out to what radius (in the plane) can it be observed with line-center optical depth $\tau < 0.5$?
- (c) What is the maximum $N(\text{HI})$ that can be observed with $\tau < 0.5$ at all radial velocities?

Q2 (Lecture 6)

Consider a runaway O star, of spectral type O8V, traveling through a diffuse region with $n_{\text{H}} \approx 0.2 \text{ cm}^{-3}$.

- (a) What is the Strömgren radius R_{S0} if the photoionized gas has $T = 10^4 \text{ K}$?
- (b) If the star is traveling at $v_* = 100 \text{ km s}^{-1}$, compare the time required for the star to travel a distance equal to the Strömgren radius to the recombination time.
- (c) Very briefly discuss the implications of the comparison in item (b).

Q3 (Lecture 9)

Suppose that dust produced extinction $A(\lambda)$ directly proportional to the frequency of the light. What would be the value of R_V ?

If the extinction were to vary as a power law, $A \propto \nu^\beta$, what power-law index β would give $R_V = 3.1$?

Q4 (Lecture 11)

Both H_2 and HD have similar internuclear separation $r_0 \approx 0.741 \text{ \AA}$. Assume that the molecules can be approximated as rigid rotors.

- (a) Calculate $[E(v=0, J) - E(v=0, J=0)]/k$ for H_2 for $J=1$, $J=2$, and $J=3$.
- (b) Calculate $[E(v=0, J) - E(v=0, J=0)]/k$ for HD for $J=1$, $J=2$, and $J=3$.
- (c) Because H_2 has no electric dipole moment, $\Delta J = \pm 1$ transitions are forbidden, and instead the only radiative transitions are electric quadrupole transitions with $\Delta J = 0, \pm 2$. Calculate the wavelengths of the $J=2 \rightarrow 0$ and $J=3 \rightarrow 1$ transitions of H_2
- (d) Because HD has a (small) electric dipole moment, it has (weak) electric dipole transitions. What is the longest-wavelength spontaneous decay for HD in the $v = 0$ vibrational level?

Q6 (Lecture 12)

The mass distribution of GMCs in the Galaxy is given by [eq. (32.1) in the textbook]:

$$\frac{dN_{\text{GMC}}}{d \ln M_{\text{GMC}}} \approx N_u \left(\frac{M_{\text{GMC}}}{M_u} \right)^{-\alpha} \quad 10^3 M_\odot \lesssim M_{\text{GMC}} < M_u$$

with $M_u \approx 6 \times 10^6 M_\odot$, $N_u \approx 63$, and $\alpha \approx 0.6$ (Williams & McKee 1997, *Astrophys. J.* 476, 166).

- (a) Calculate the total mass in GMCs in the Galaxy.
- (b) Calculate the number of GMCs in the Galaxy with $M > 10^6 M_\odot$.

Q7 (Lecture 12)

Consider a spherical cloud with a total mass M and a radius R . Assume that the cloud has a radial density profile of $\rho = \rho_0(r/R)^{-\beta}$. The gravitational potential energy can be expressed as follows:

$$U = -\alpha \frac{GM^2}{R}$$

- (a) For the above equation to be satisfied, what is the condition for β ?
- (b) Express α in terms of β .
- (c) What is the virial mass? Express the mass in terms of the cloud radius R .

Q8 (Lecture 13 & Lecture 5)

An absorption line is observed in the spectrum of a quasar at an observed wavelength $\lambda = 5000$ Å. The absorption is produced by an intergalactic cloud of gas somewhere between us and the quasar. The observer measures an equivalent width $W_\lambda = 1.0 \times 10^{-2}$ Å. The absorption line is resolved, with an observed FWHM $_\lambda = 0.50$ Å.

The line is assumed to be HI Lyman α , with rest wavelength $\lambda_0 = 1215.7$ Å and oscillator strength $f_{\ell u} = 0.4164$.

- (a) What is the redshift z of the absorber?
- (b) What is the column density of HI in the absorbing cloud?
- (c) In the rest frame of the cloud, the HI has a one-dimensional velocity distribution $\propto e^{-(\Delta v/b)^2}$. What is the value of b for this cloud?