Inter-galactic medium

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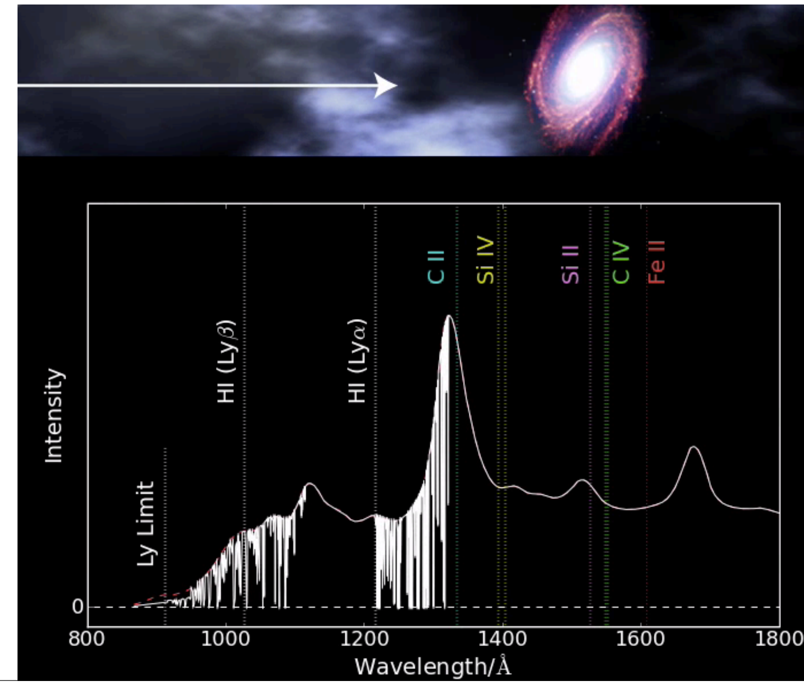


Image by A. Pontzen

The virial radius of a dark matter halo

A dark matter halo does not have a true "radius", but bound matter tends to stay within a **virial radius**, defined as that for which the mean overdensity is 200 times the critical density:

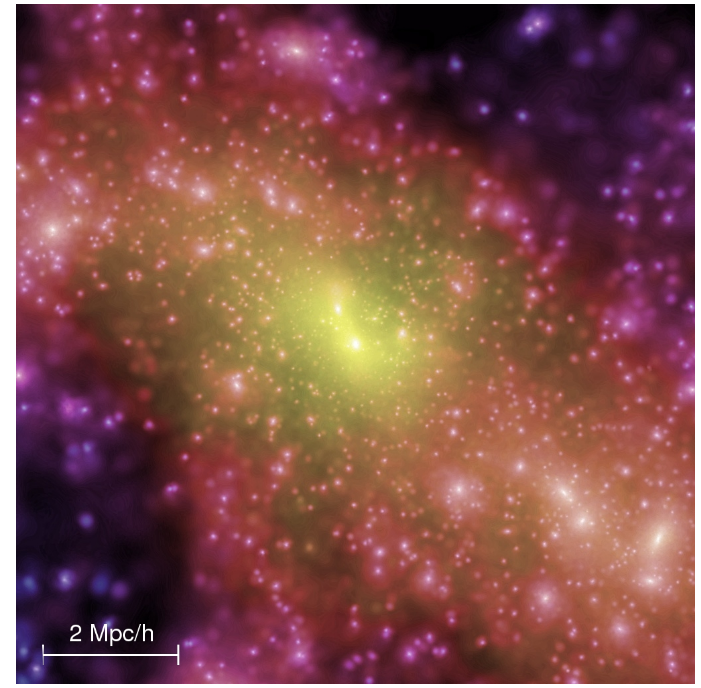
$$\bar{\rho} = \frac{3M_H}{4\pi r_H^3} = 200\,\rho_c = 200\,\frac{3H^2}{8\pi G}$$

It is customary to define the halo **circular velocity** as the velocity of a circular orbit at the virial radius:

$$V_c = \sqrt{\frac{GM}{r_H}}$$

It is easy to demonstrate that:

$$r_H = \frac{V_c}{10\,H}, \quad M = \frac{V_c^3}{10\,GH}$$



Galaxies are hosted by dark matter halos, and there is a difference between matter inside or outside halos. This slide defines the virial radius of a dark matter halo.

Baryonic matter outside galaxies

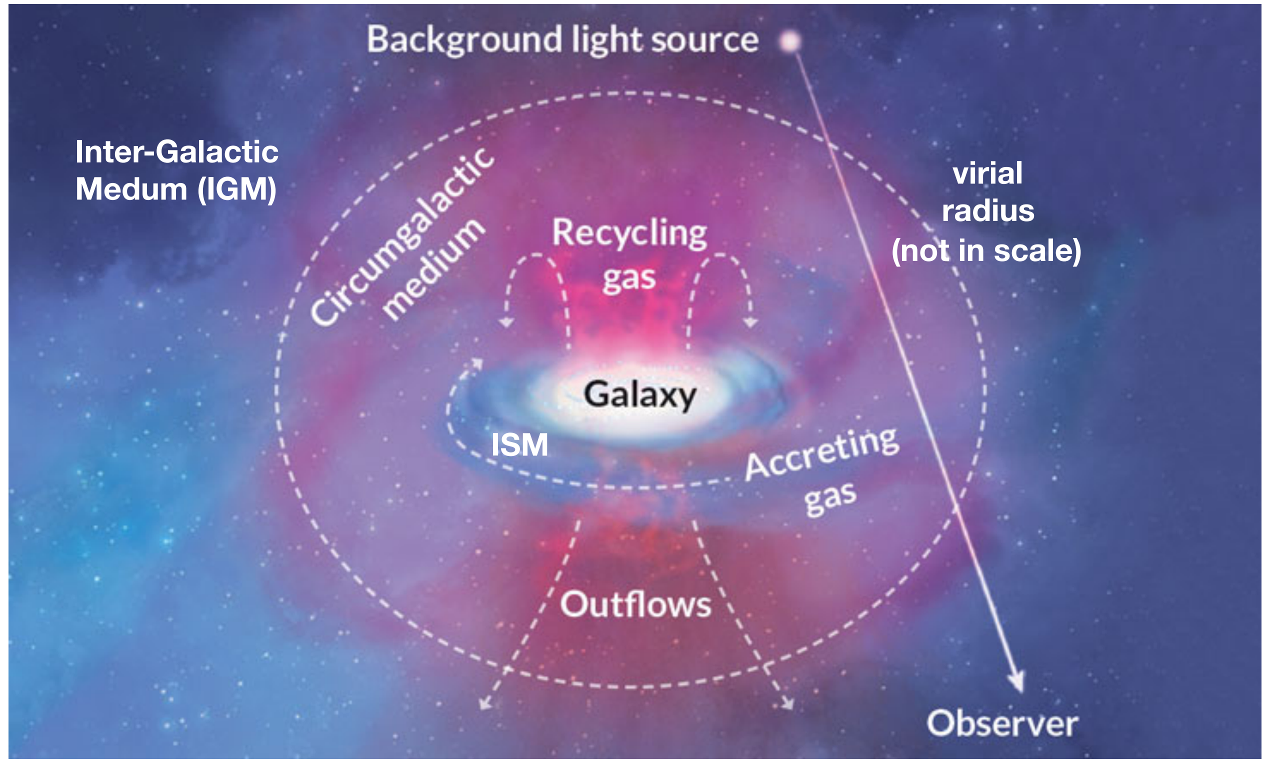
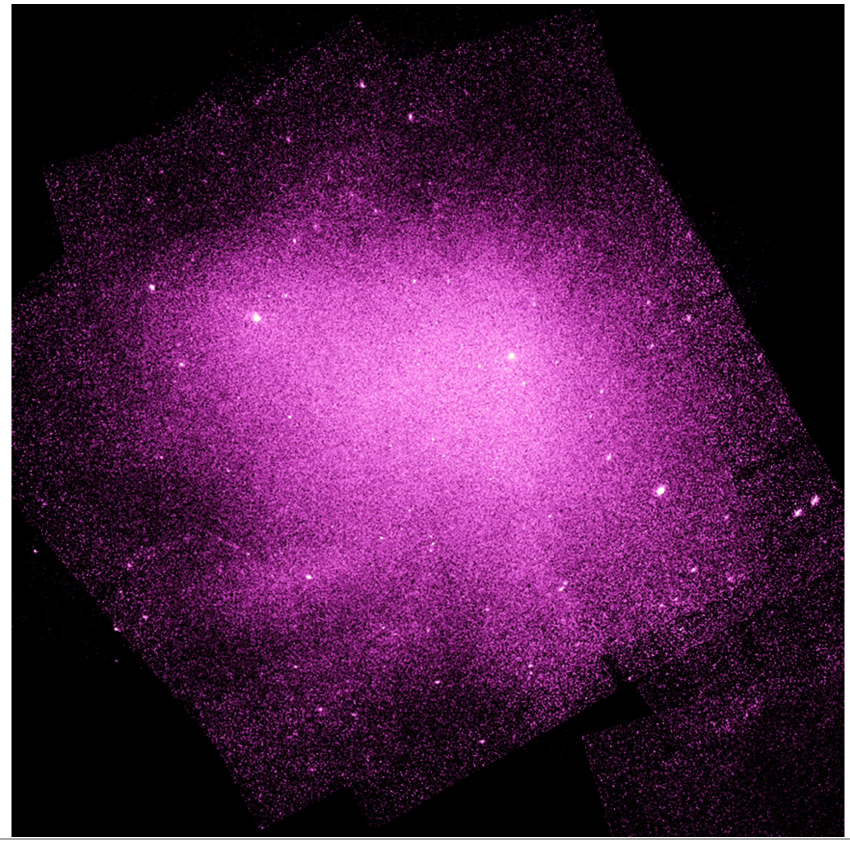


Image from sciencenews.org

This slide shows the difference between ISM, the Circum-Galactic Medium (CGM) outside the galaxy but inside the virial radius, and the Inter-Galactic Medium, outside the virial radius. The only way to observe the CGM is in absoprtion of a bright background source, as illustrated in the figure (source https://www.sciencenews.org/article/cosmic-cloak-controls-galaxy-future-coming-focus).

The Intra-Cluster Medium

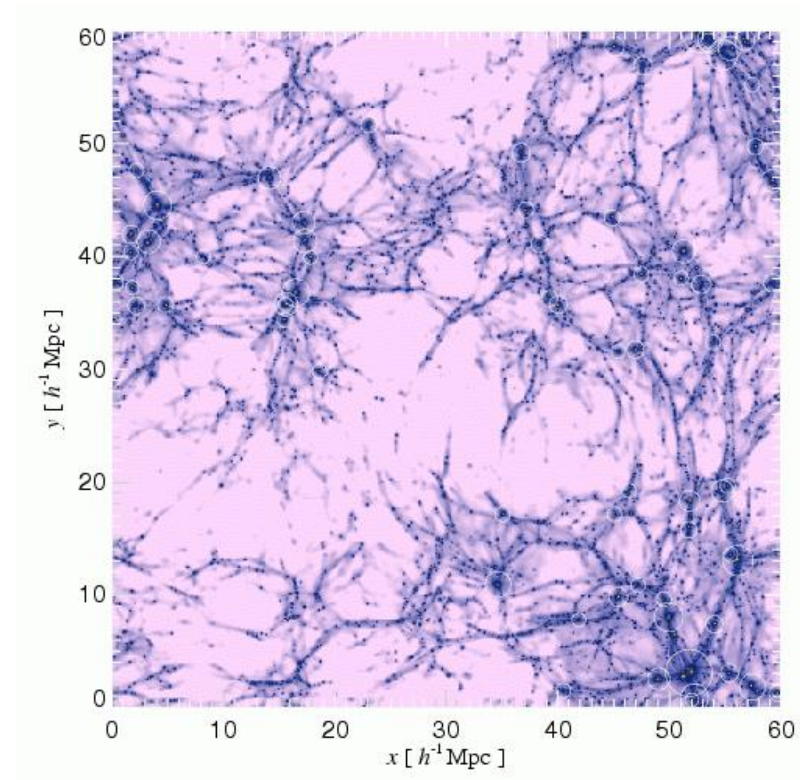


Chandra image of the Coma galaxy cluster

This is an X-ray image of the Coma galaxy cluster. It shows bremsstrahlung emission from hot ICM, plus some background AGNs.

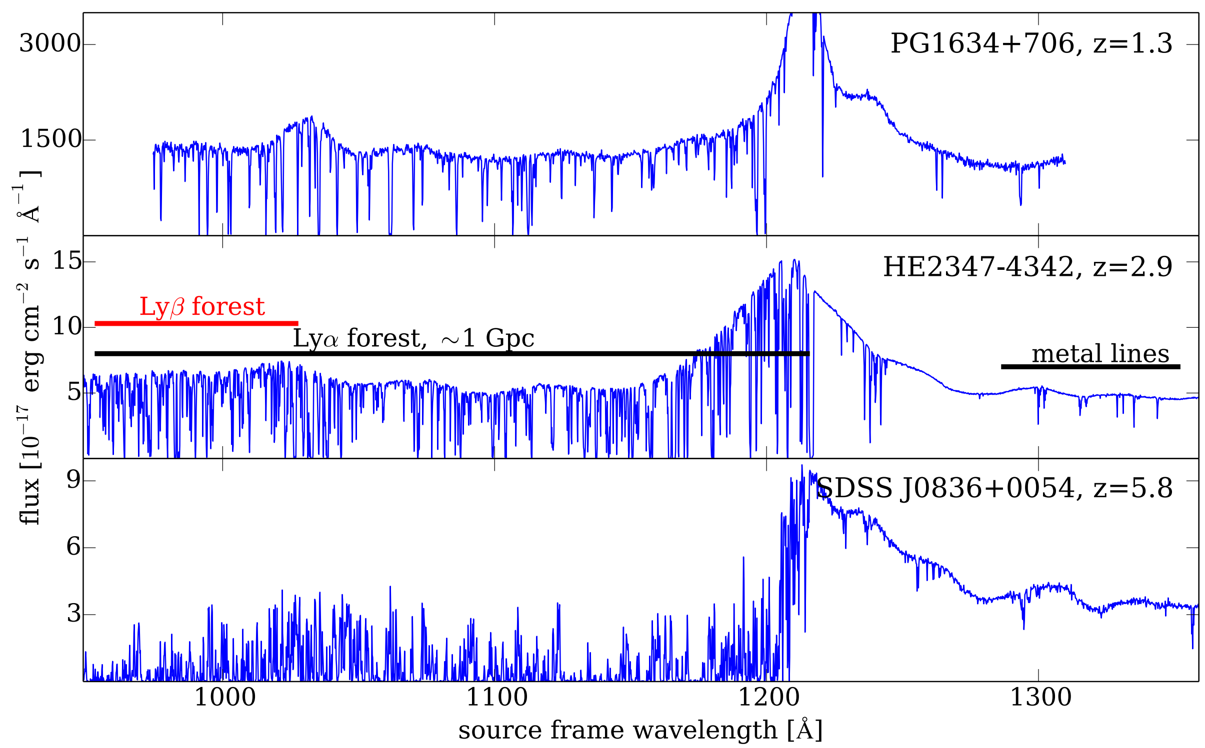
The IGM on large scales

This figure shows a simulation, by M, Viel, of the distribution of gas in the IGM at large scales. Colors track gas density.



On large scales, the IGM traces the large-scale structure, similarily to dark matter.

Absorption spectra of quasars



A large number of absorpion lines are visible blueward of the Lyman-alpha emission line. The number and absorbed flux of these lines depends on redshift, and grows toward high z.

The Gunn-Peterson effect

Observations of quasars showed, already in the '60s, significant flux bluewards of the Lyman-alpha emission line.

Photons at higher energies than Lyman alpha have a high probability of interaction when they are redshifted to the Lyman-alpha frequency.

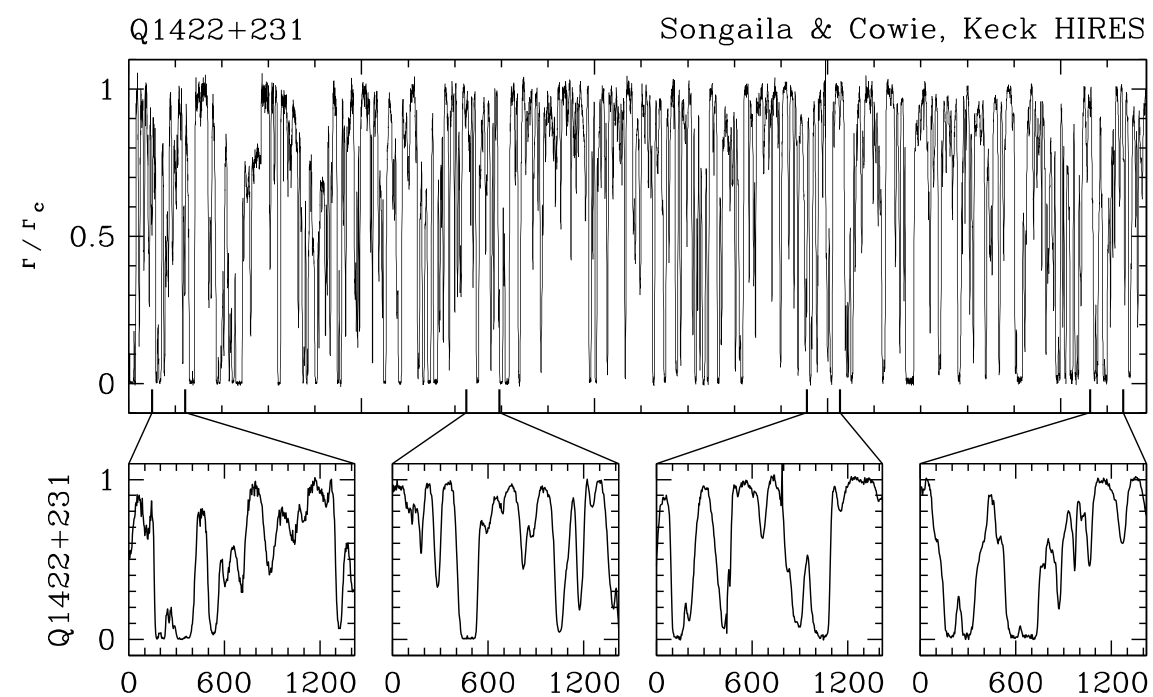
$$\tau = n_{HI}(z)\,(4.2 \times 10^{10}\ h^{-1}\ \mathrm{cm}^3)\,\frac{1}{E(z)}$$

This gives a very high opacity for these photons, if all baryons in the IGM are in neutral HI atoms at the mean density:

$$\tau \sim 10^4\, h^{-1} \left(\frac{\Omega_b h^2}{0.022}\right) \frac{(1+z)^3}{E(z)}$$

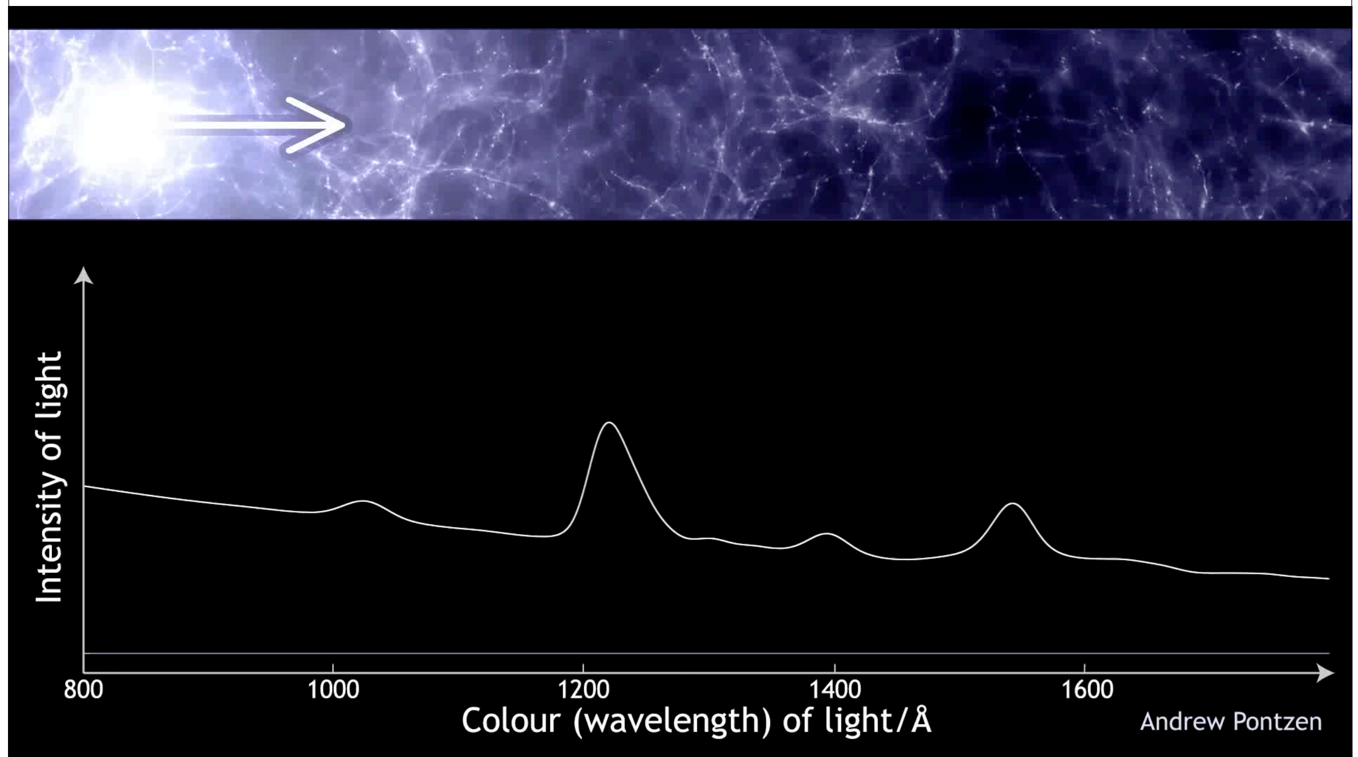
This implies that hydrogen in the IGM must be highly ionized. This calls for a **UV ionizing background**, given by the ionizing light from quasars and galaxies.

The discussion on the formulas is given in the notes.



This is a fine detail of a high-resolution spectrum of the forest, to appreciate the amount of structure present in a single quasar line of sight.

The Lyman-alpha forest



This animation shows how the Lyman-alpha forest is formed when ionising light from the quasar travels toward us.

Estimating column density for Lyman-alpha lines

These curves of growth show how the equivalent width of Lyman-alpha lines varies with the column density of neutral hydrogen atoms.
There are three regimes:

Lyman-alpha forest, corresponding to non-saturated lines:

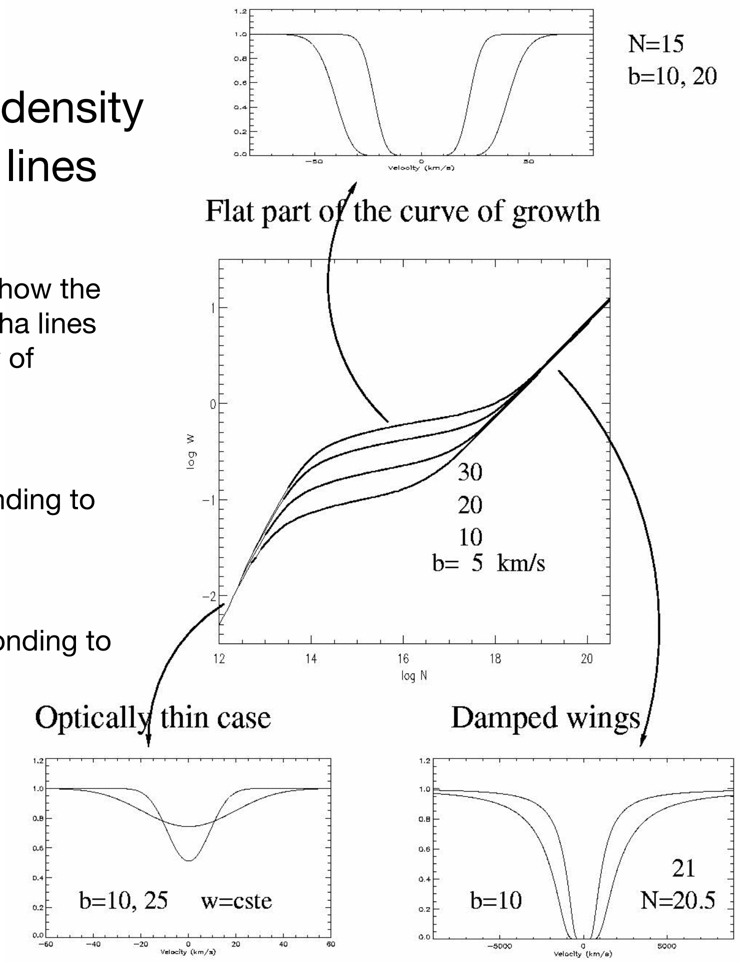
$N_H < 10^{17}\ \mathrm{cm}^{-2}$

Lyman-limit systems, corresponding to saturated lines:

$10^{17}\ \mathrm{cm}^{-2} < N_H < 10^{20}\ \mathrm{cm}^{-2}$

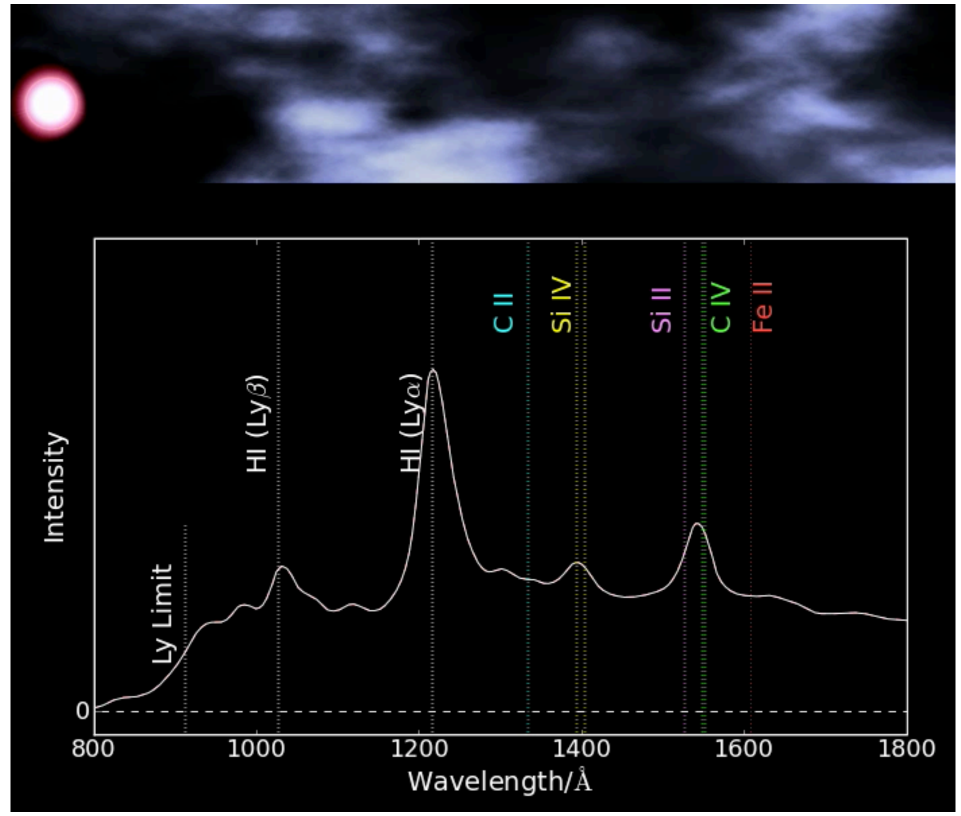
Damped systems:

$N_H > 10^{20}\ \mathrm{cm}^{-2}$



This slide shows how column density can be estimated from the measurement of line Equivalent Width. The measurement depends on the "Doppler parameter" b, that defines the line width due to gas temperature.

Damped systems



This animation illustrates how a damped system forms when the quasar line of sight crosses the external parts of a galaxy.

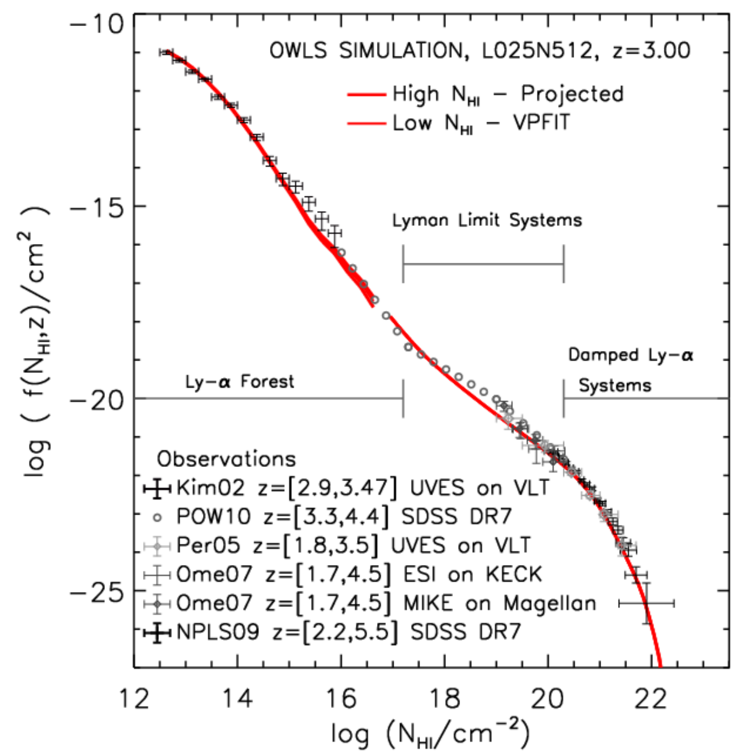
Statistics of absorbers

This figures shows the distribution of column densities of absorbers.
The quantity on the y-axis is the number of absorbers per interval of column density and per

$$dX = (1+z)^{1/2}\Omega_m(z)^{-1/2}dz$$

The most common lines are those of the forest, damped systems are much rarer.

The red line gives the result from a set of simulations of galaxy formation, and is beyond our interest.



Note: the definition of dX, used in the review by McQuinn, is given only for completeness.