Absorption Spectroscopy

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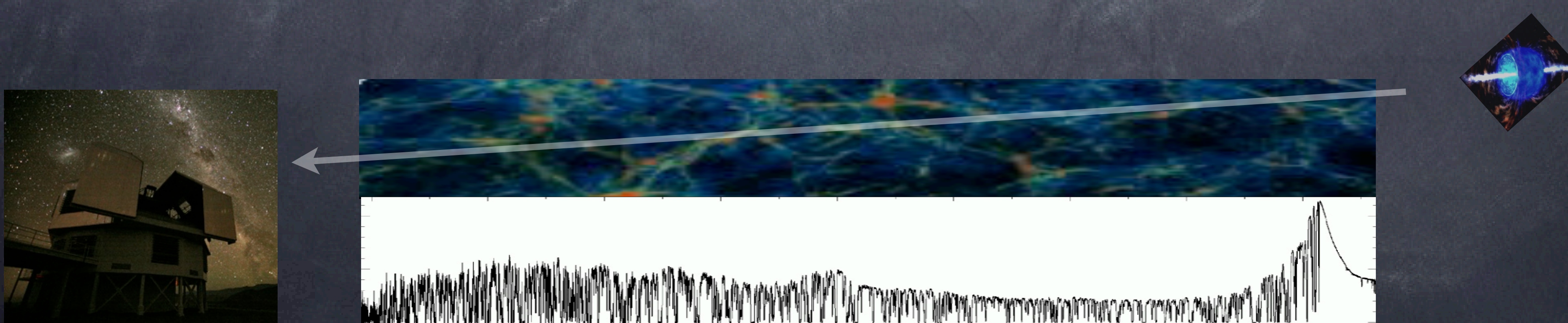
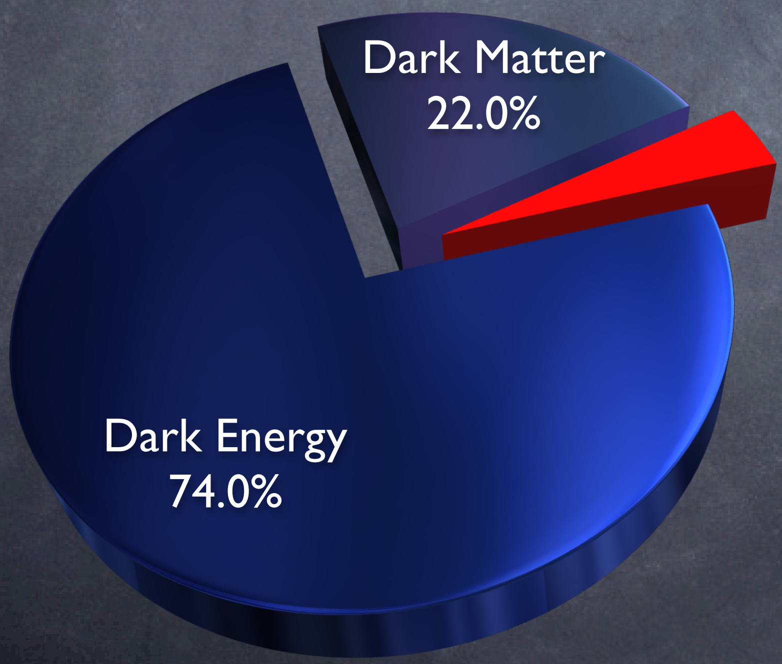


Motivation

Most baryons are not in galaxies

Cosmic Matter-Energy Density Budget



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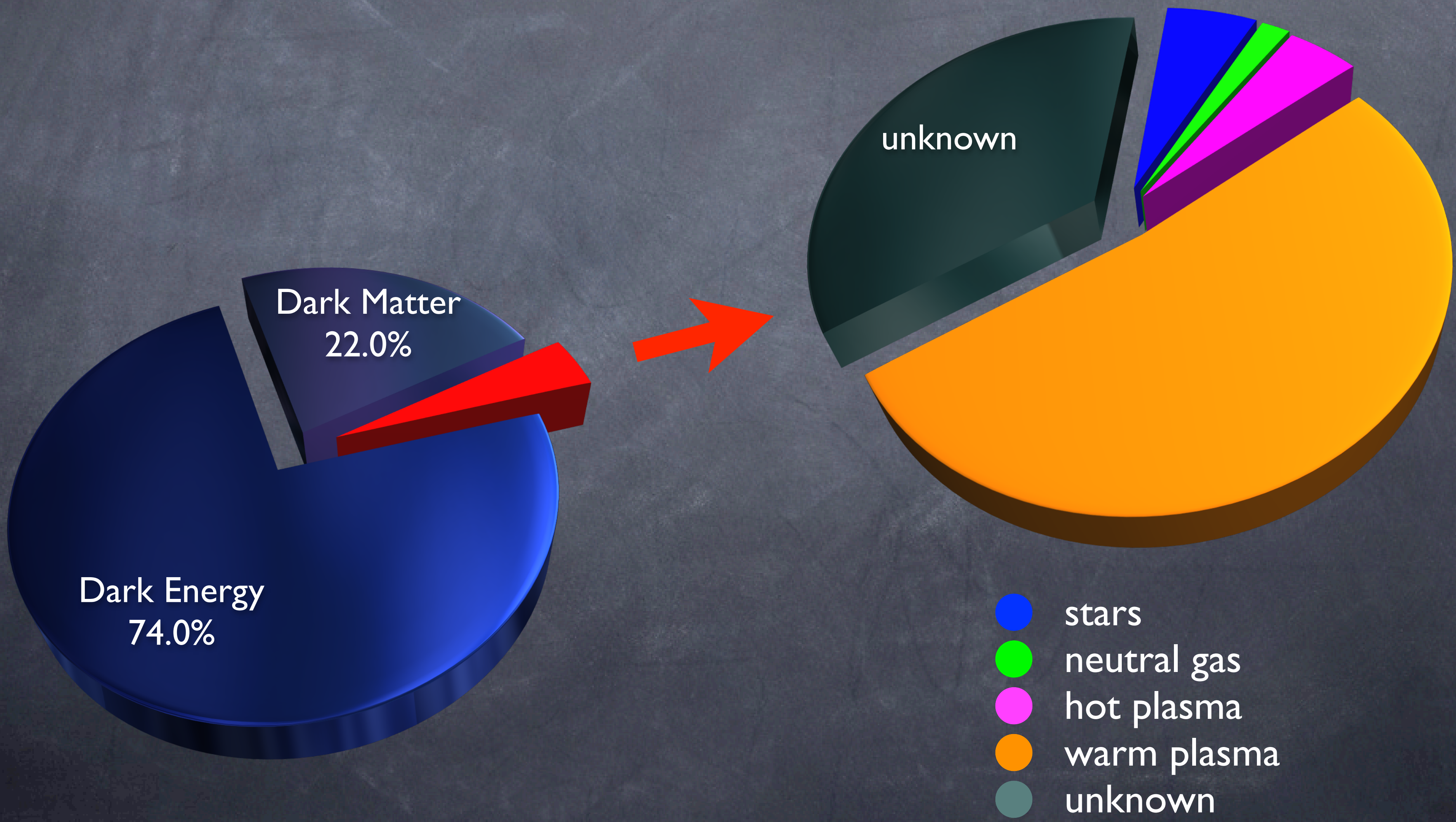

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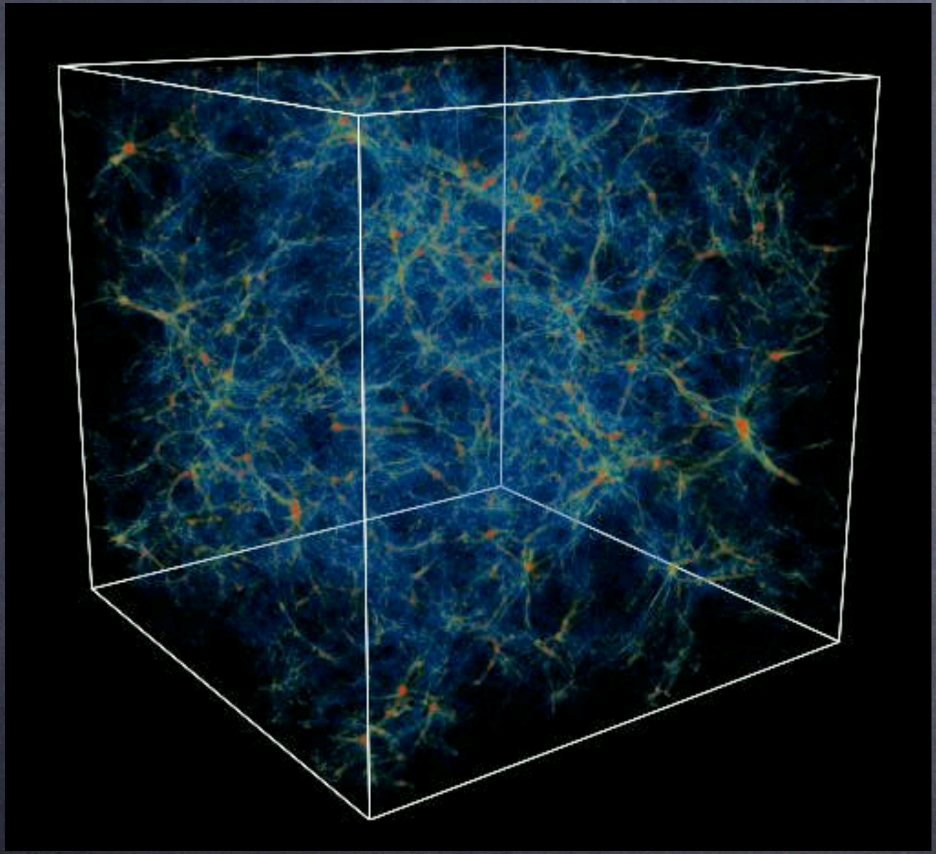

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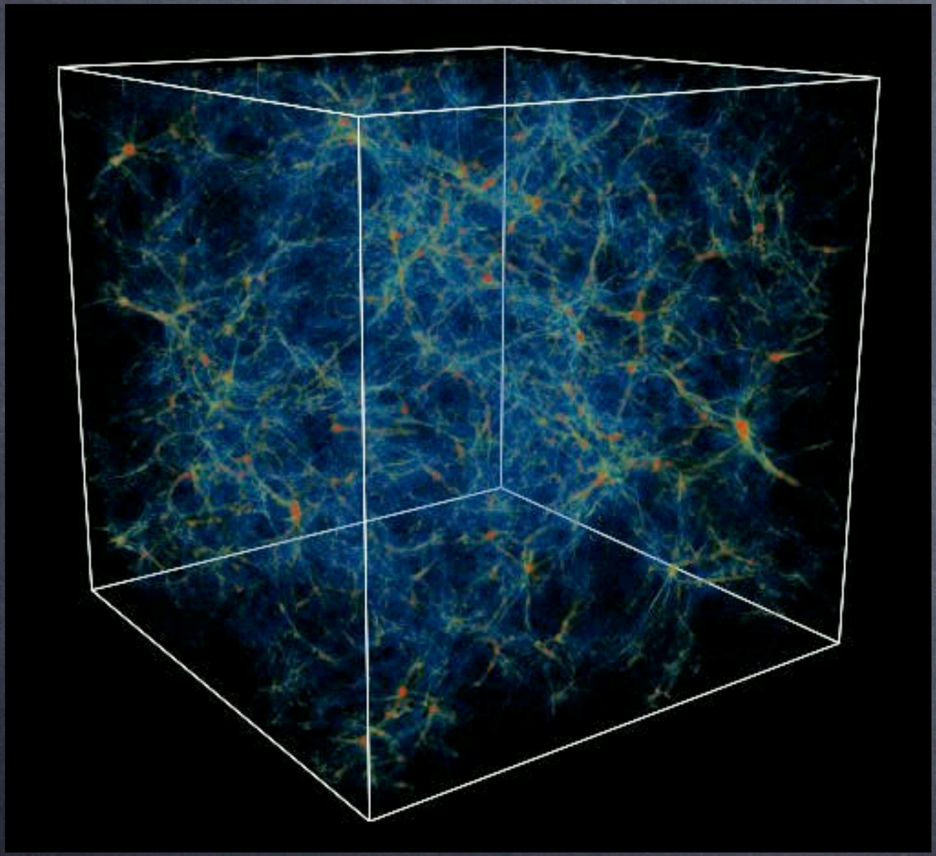

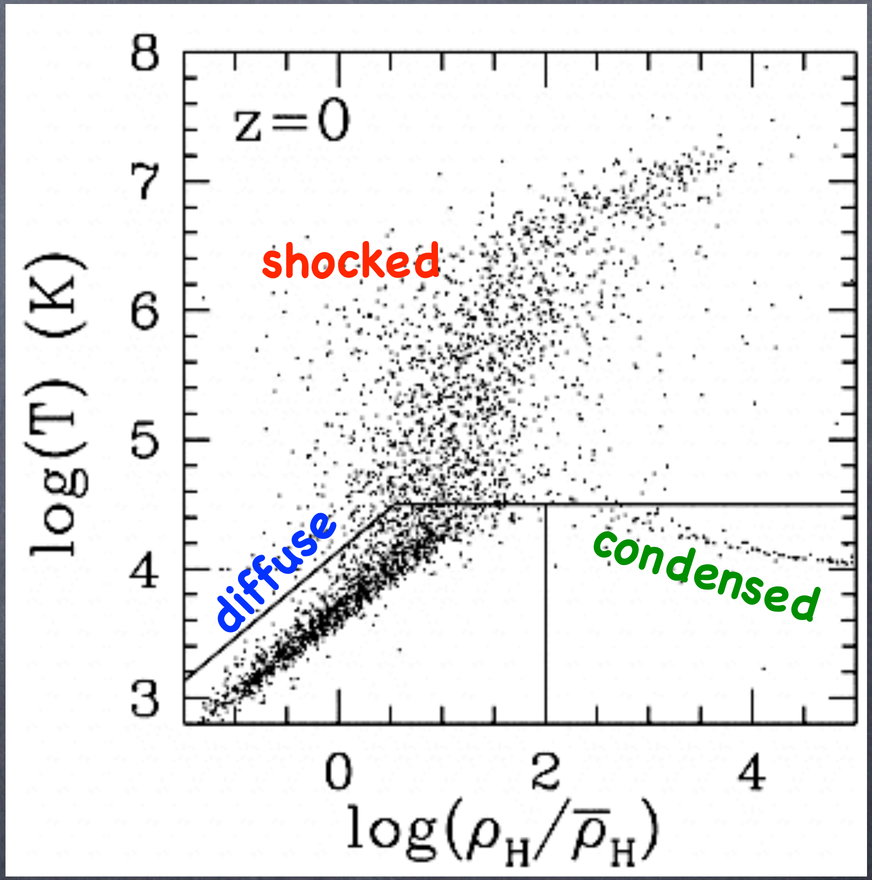

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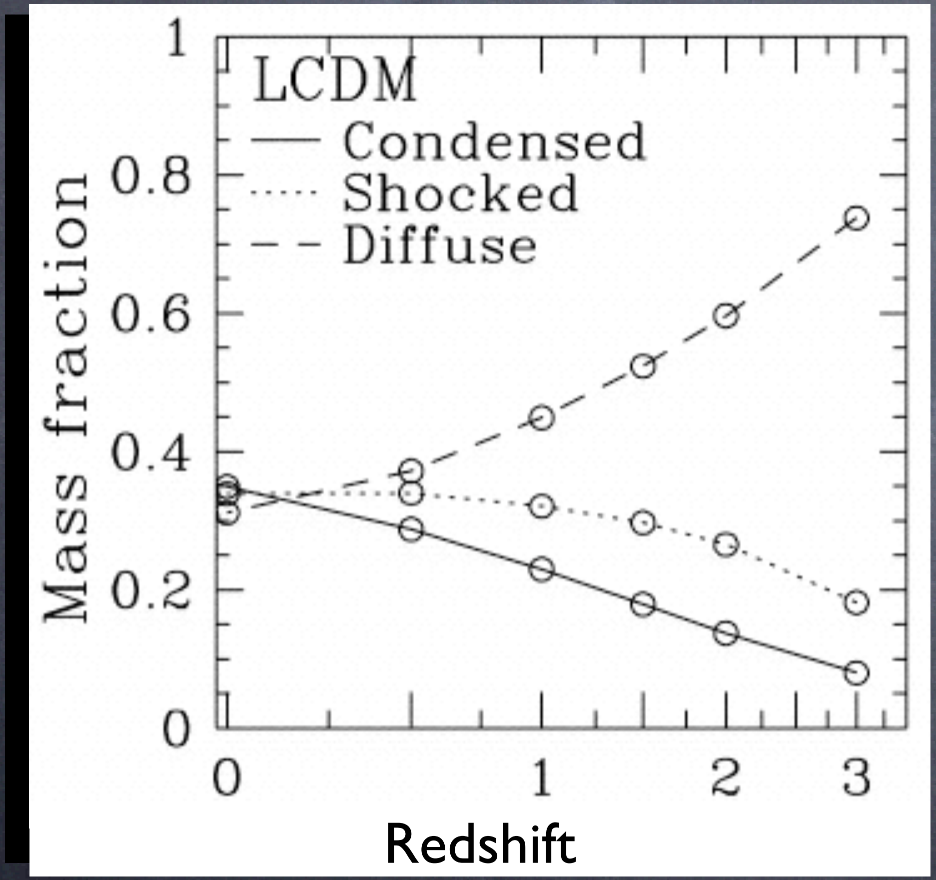

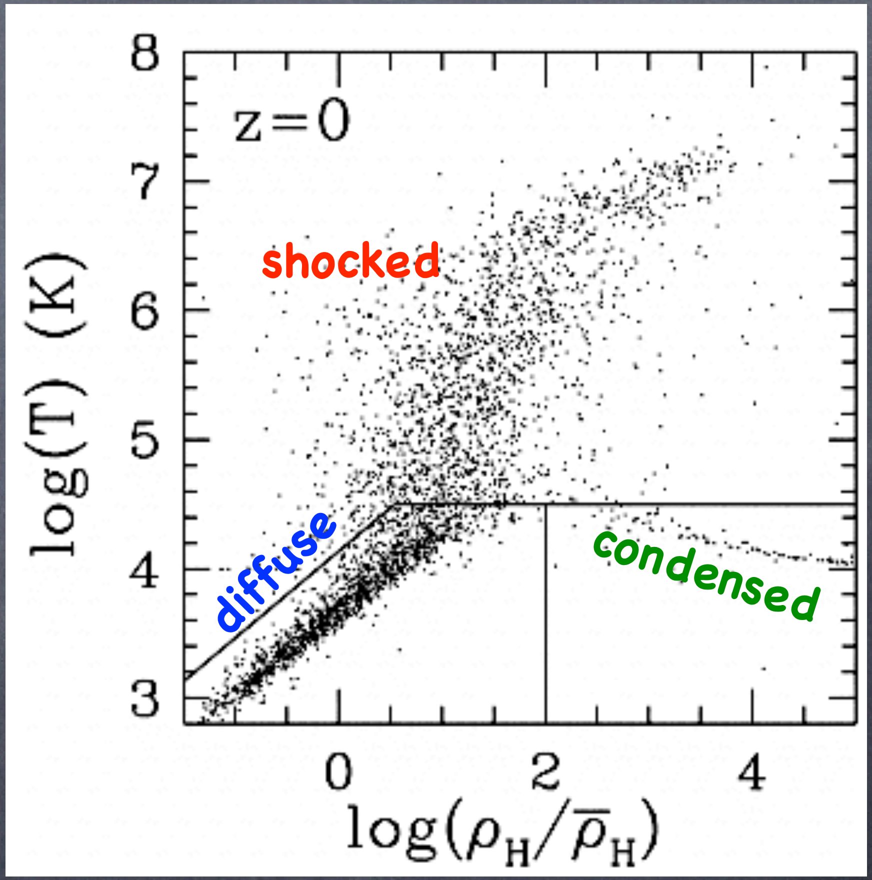

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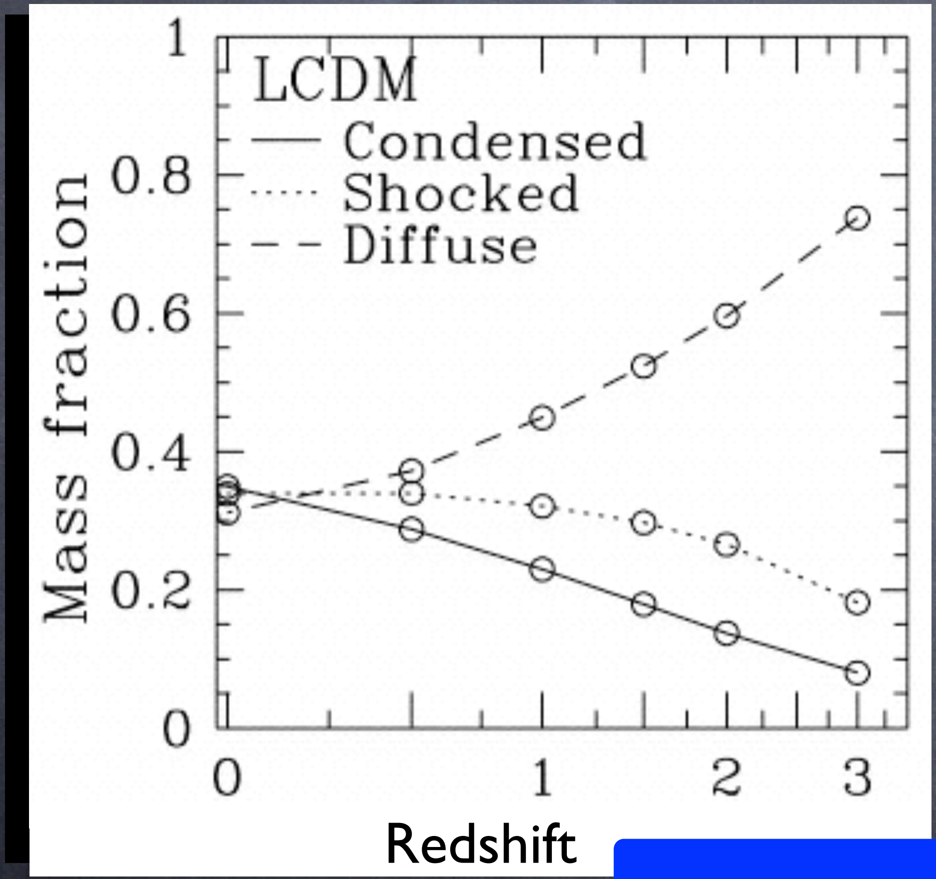
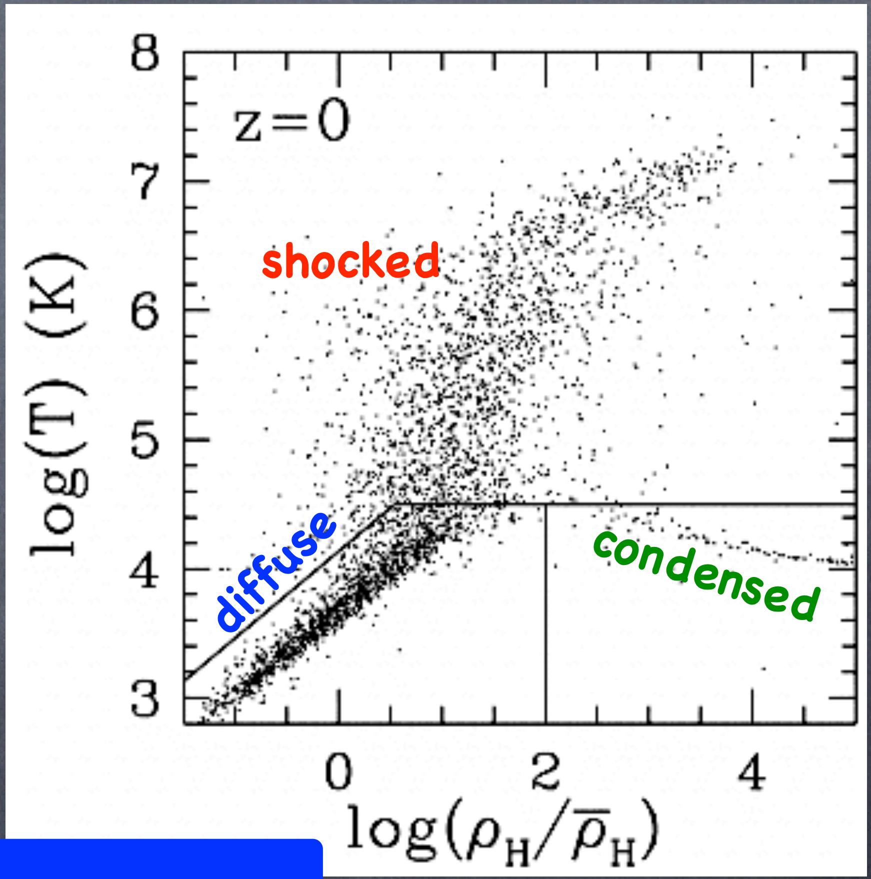
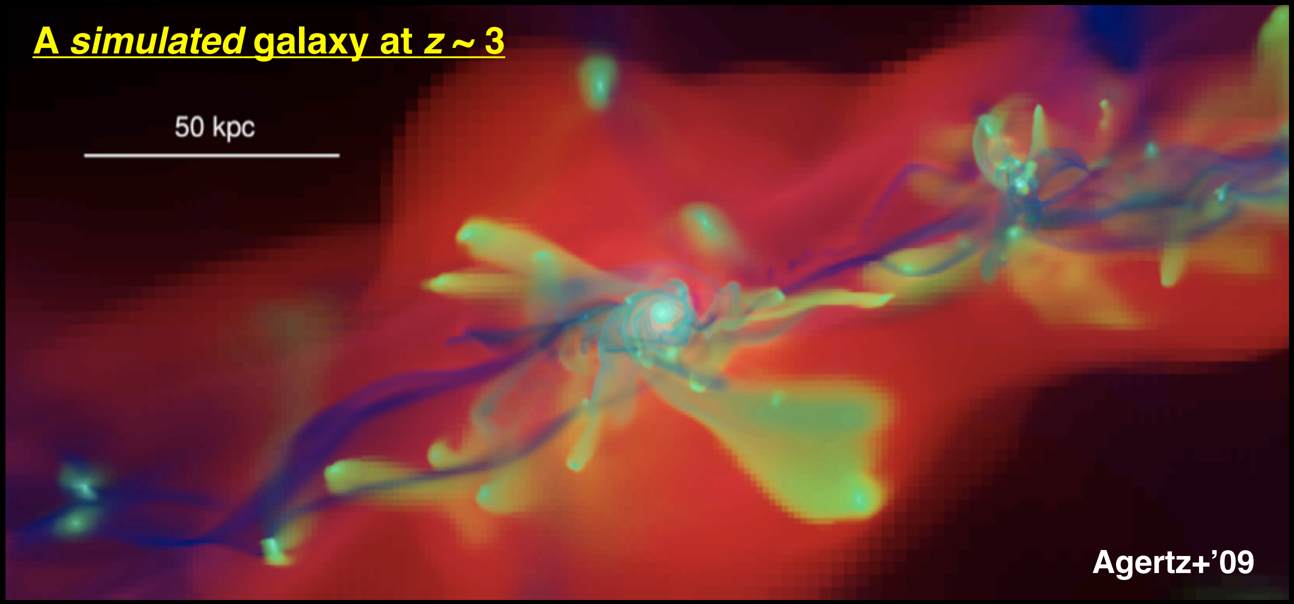




observations of galaxies provide an incomplete view of the universe

Motivation

Galaxies grow in mass by accretion/mergers



temperature

metals

density

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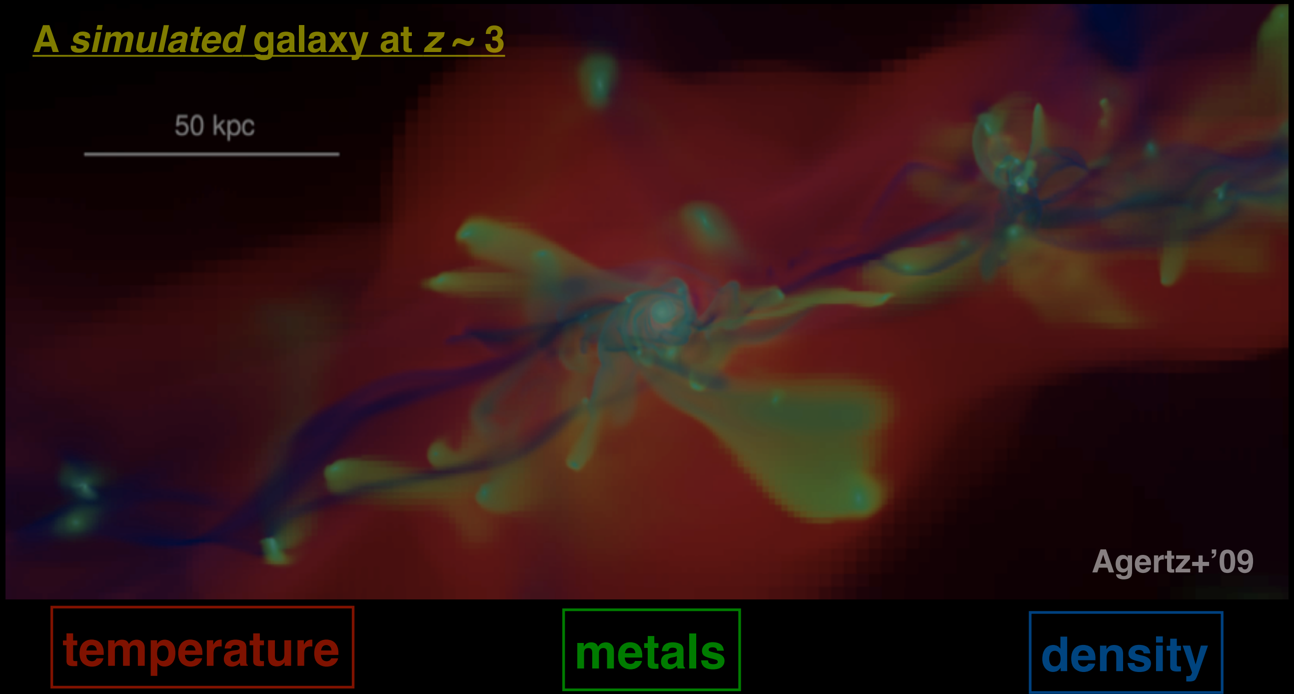
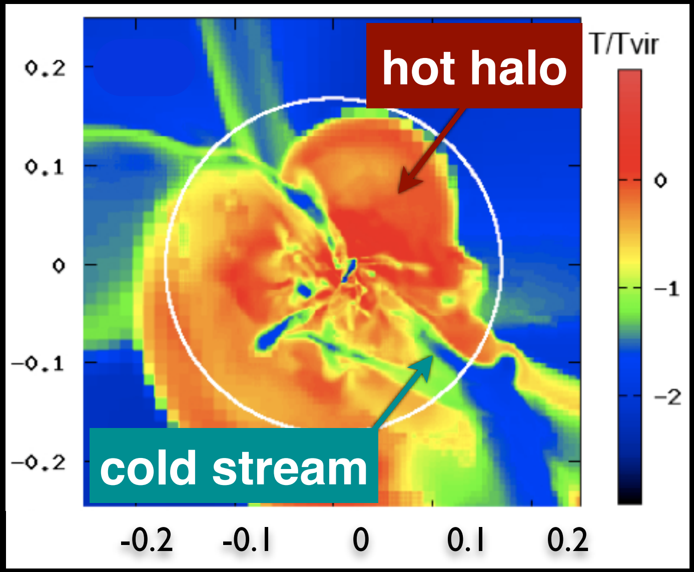
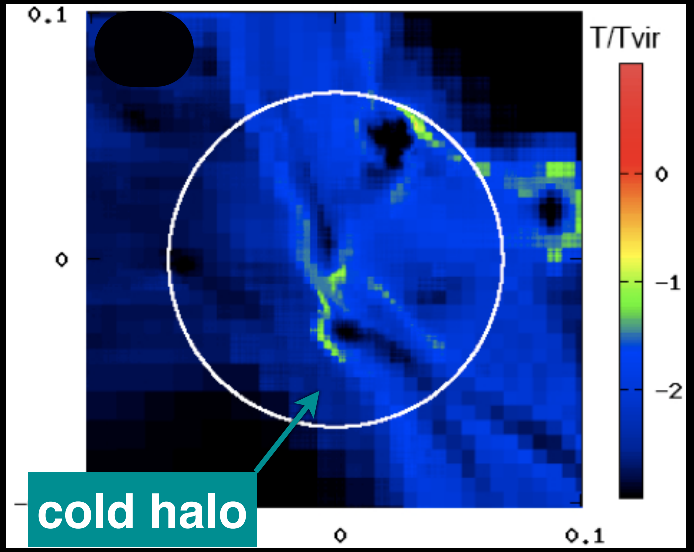


high-mass halo



low-mass halo



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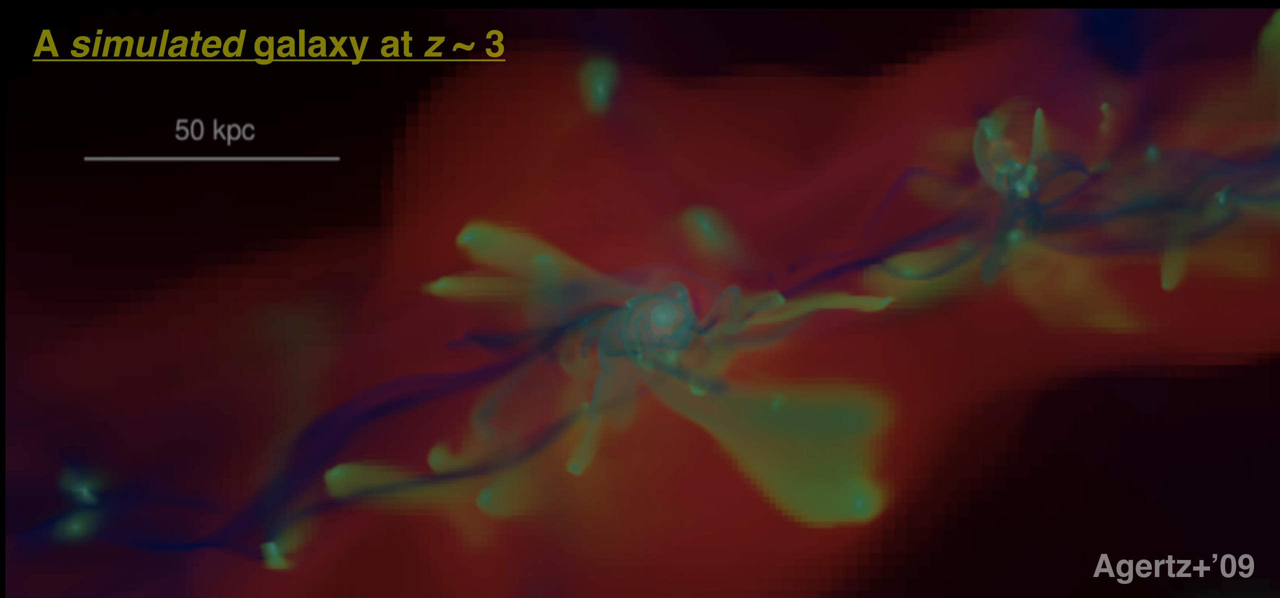
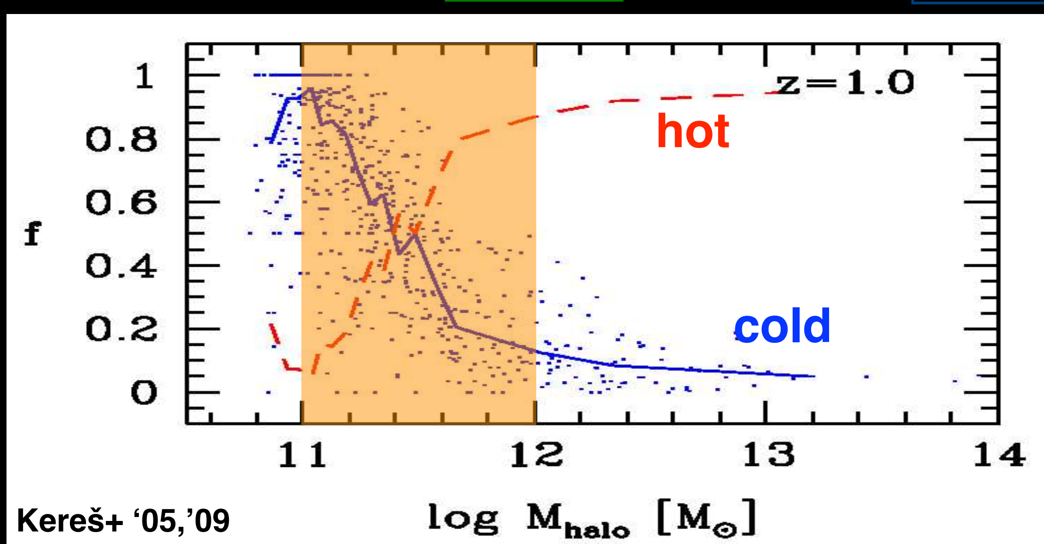


temperature metals density



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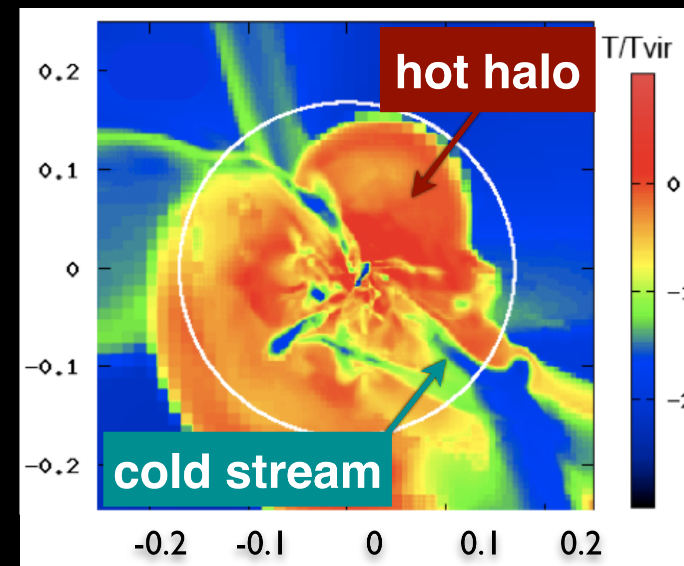

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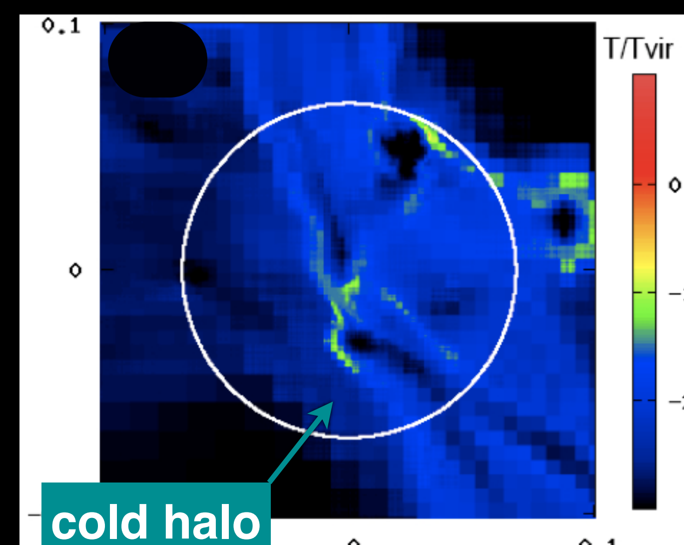
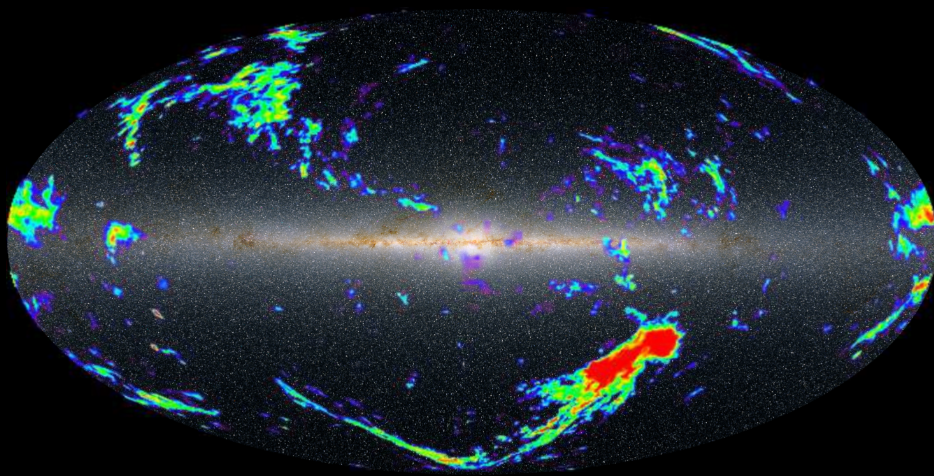


Motivation

Extended gas is directly observed around local galaxies

The Milky Way Halo



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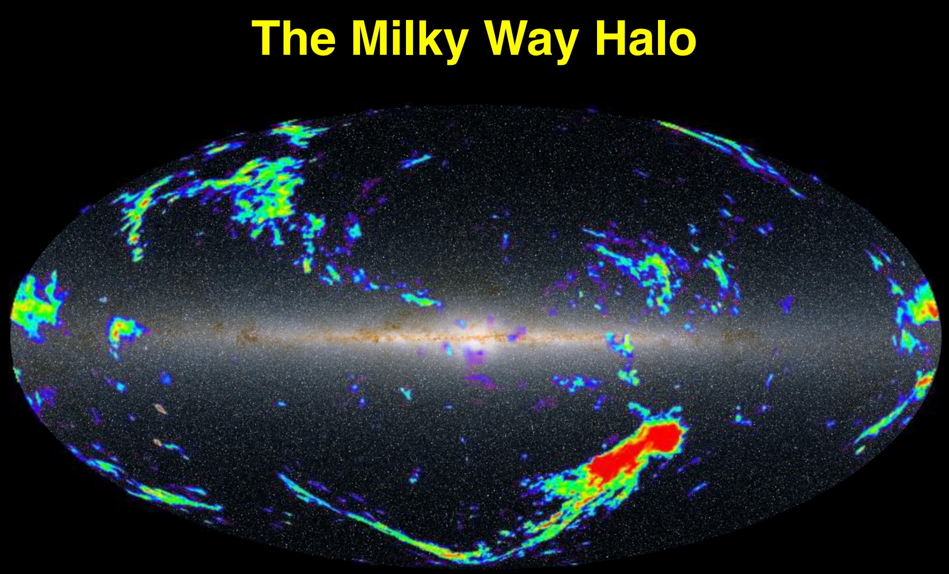

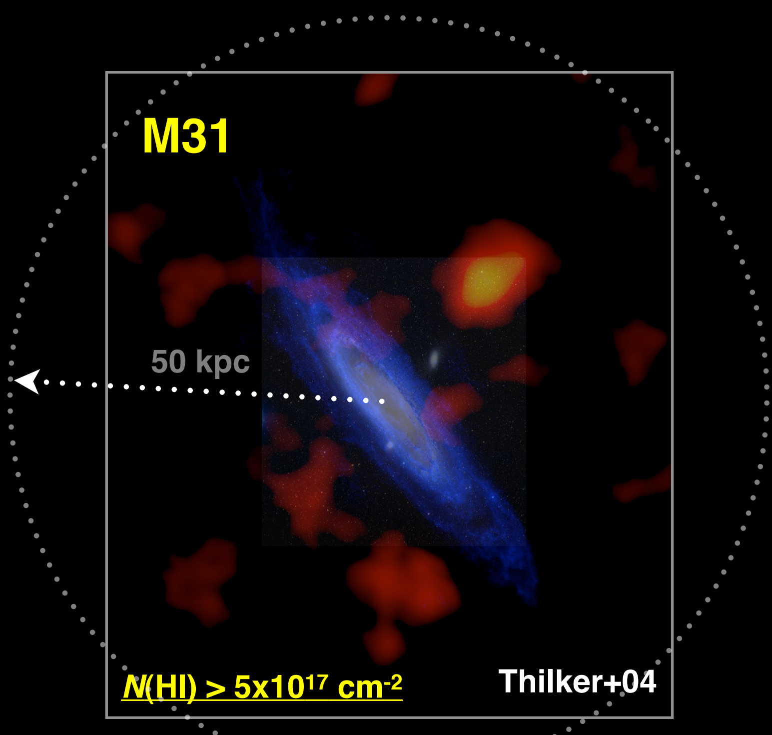

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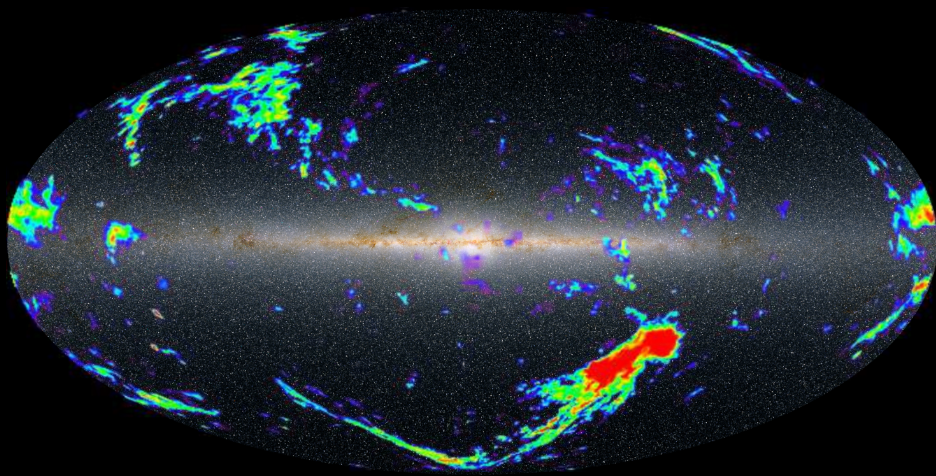
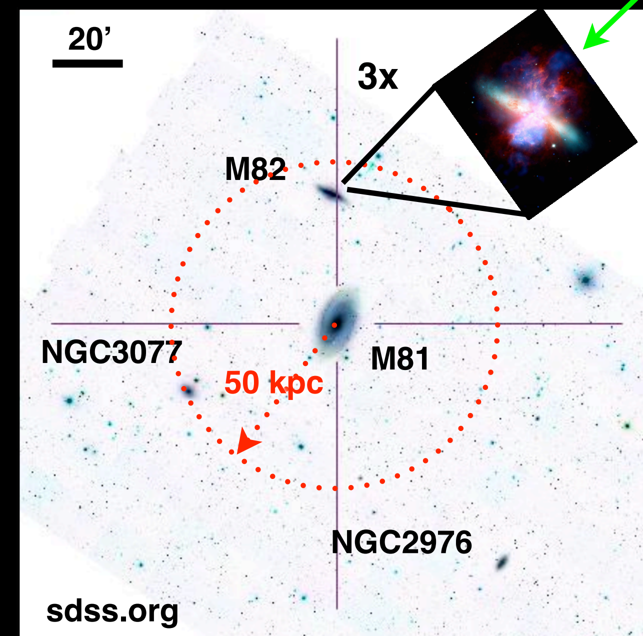
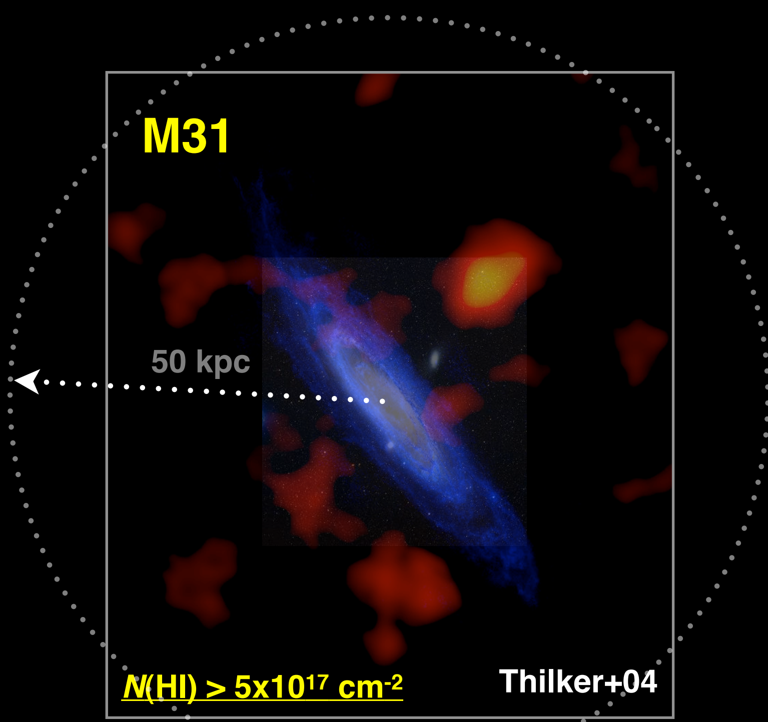
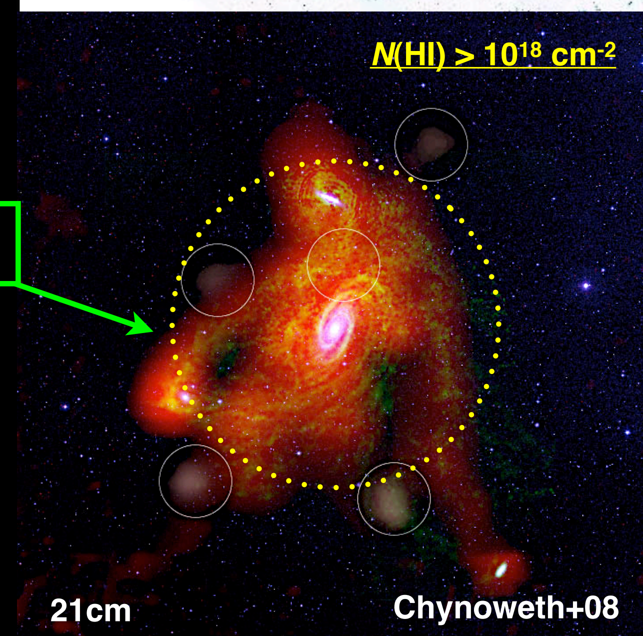


The M81 Group







Visualization of SDSS DR5

Courtesy of Mark SubbaRao

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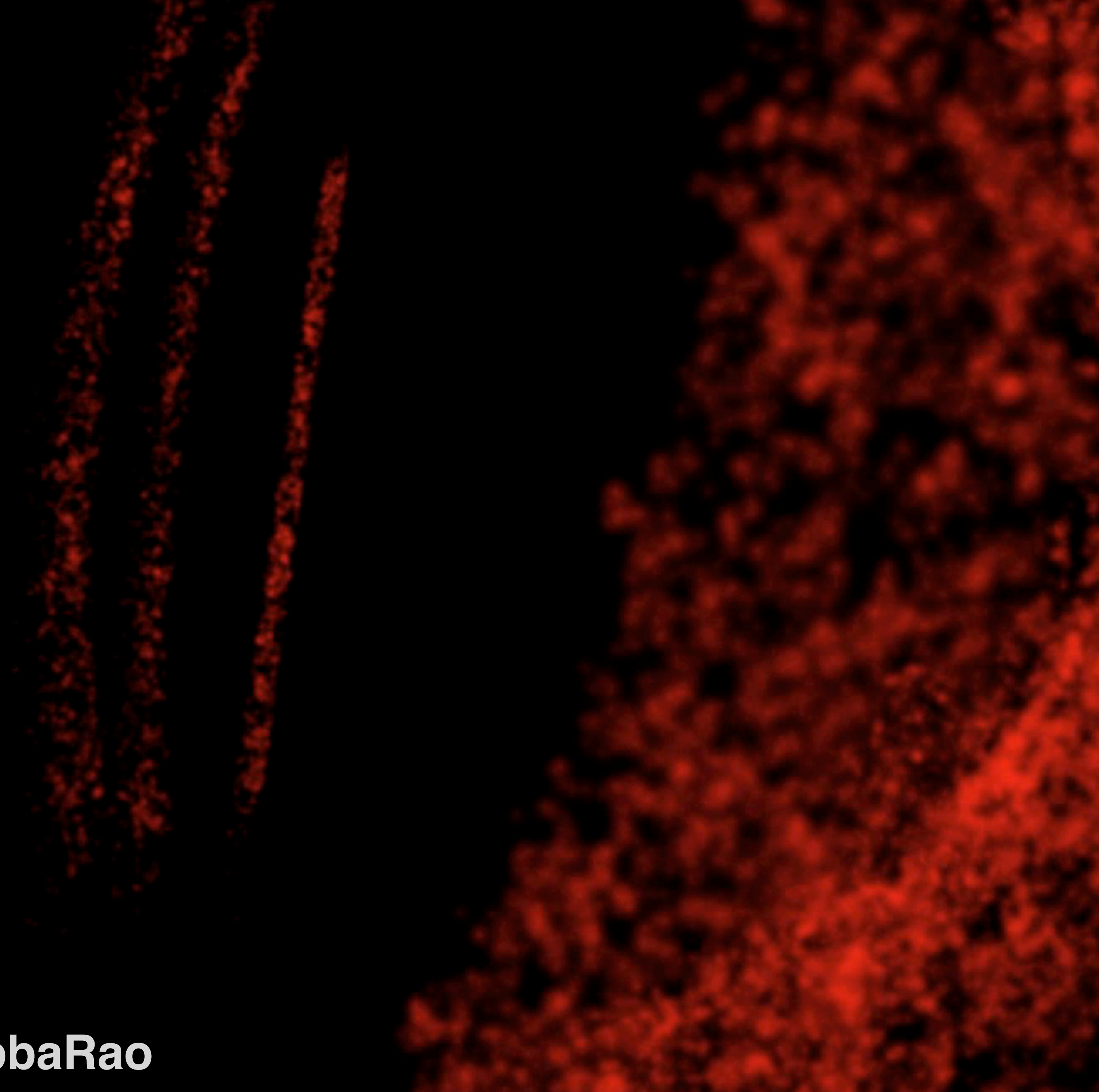

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Mapping the Dark Universe with Absorption Spectroscopy

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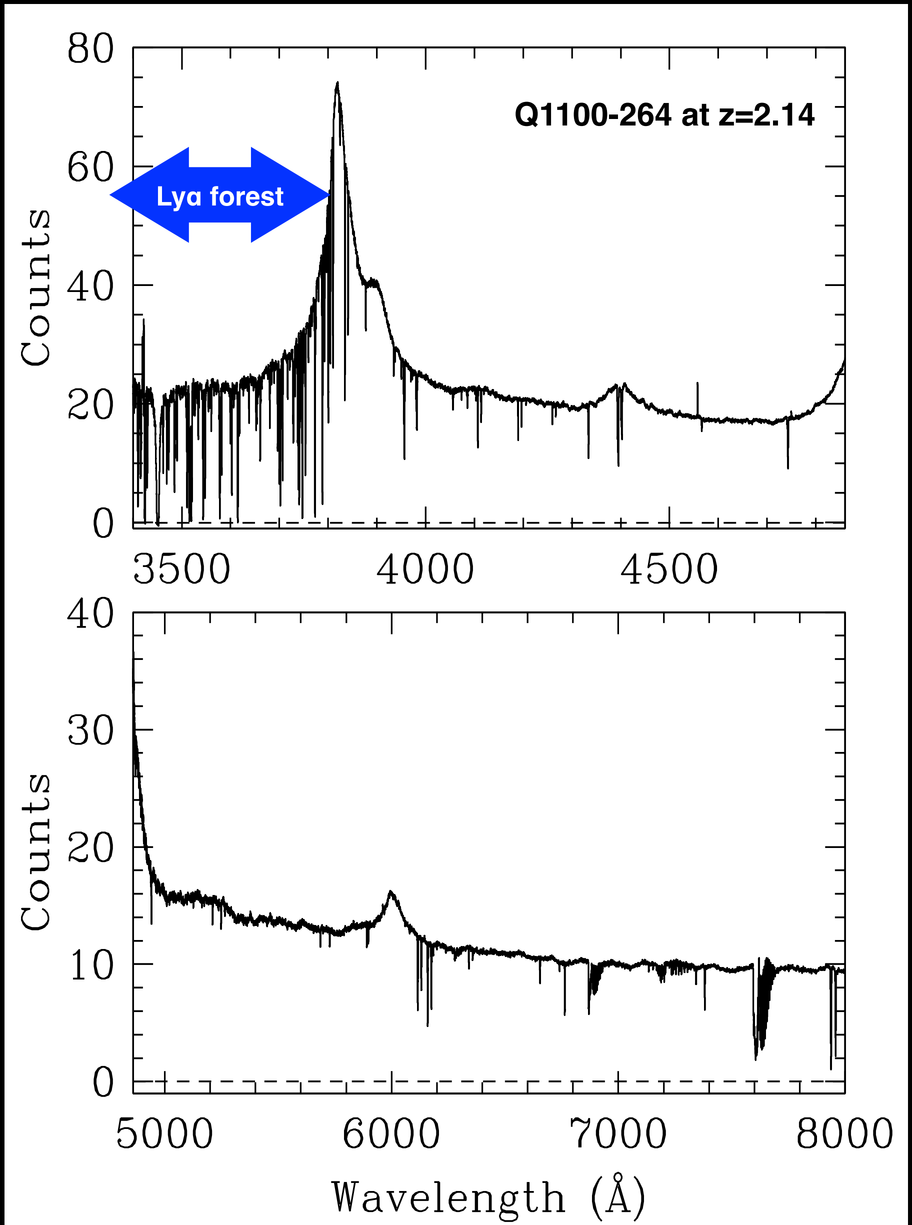
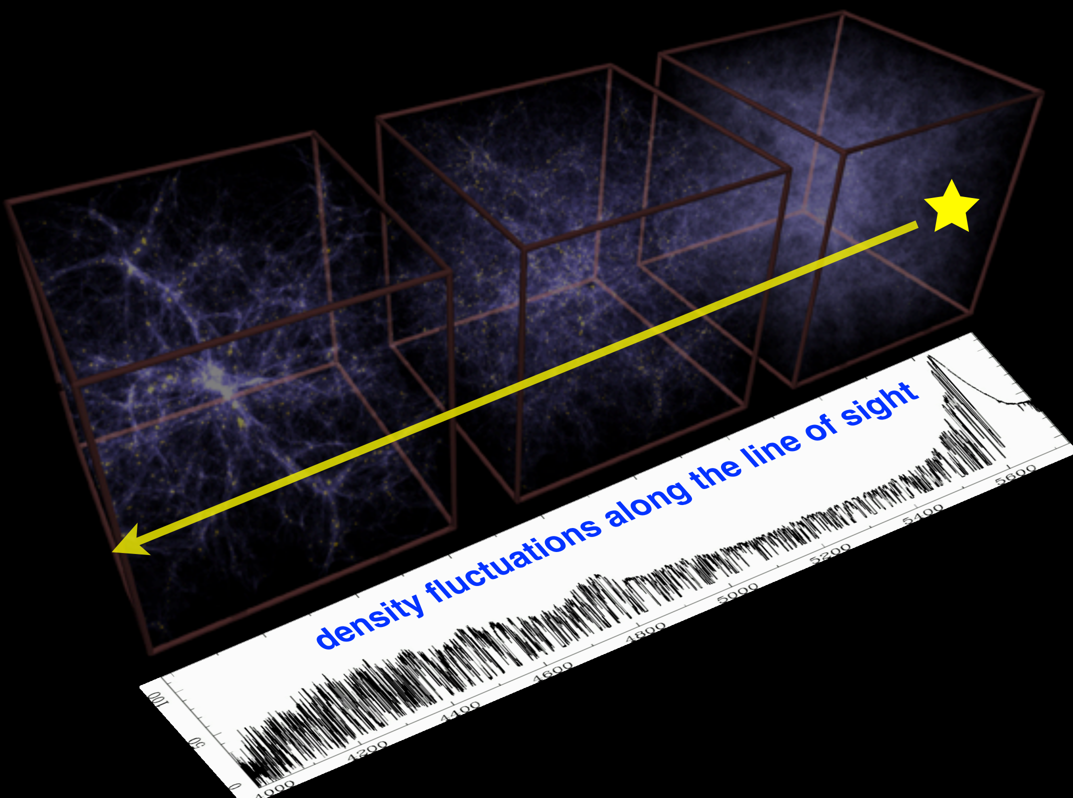
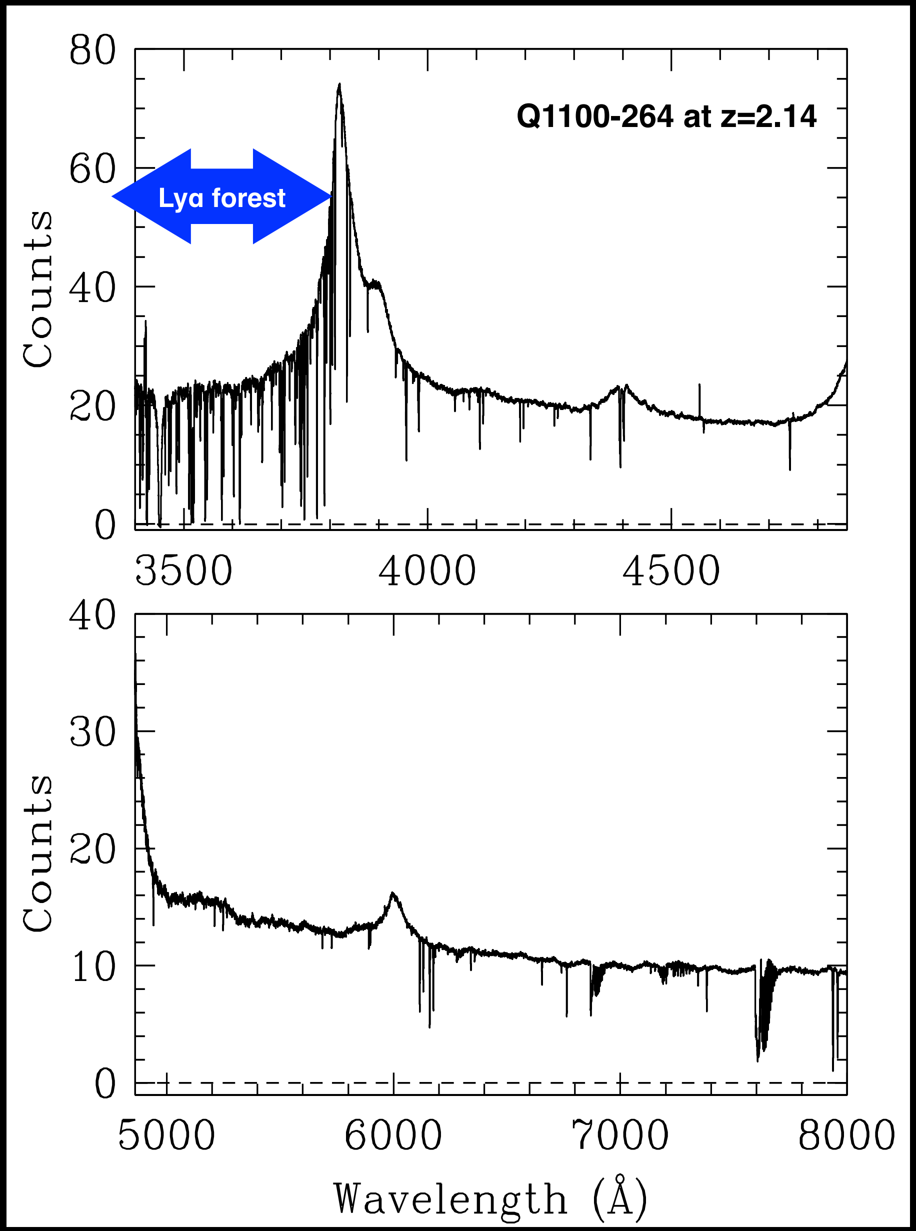


Mapping the Dark Universe with Absorption Spectroscopy

the growth of large scale structure in simulations





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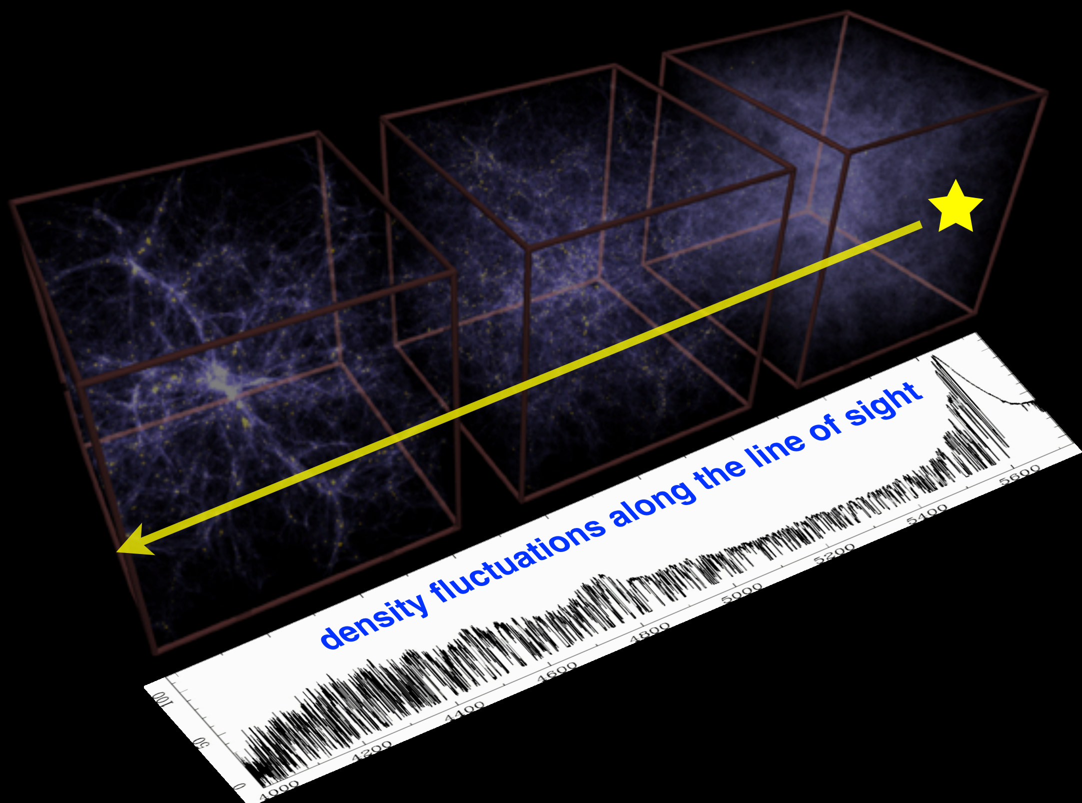

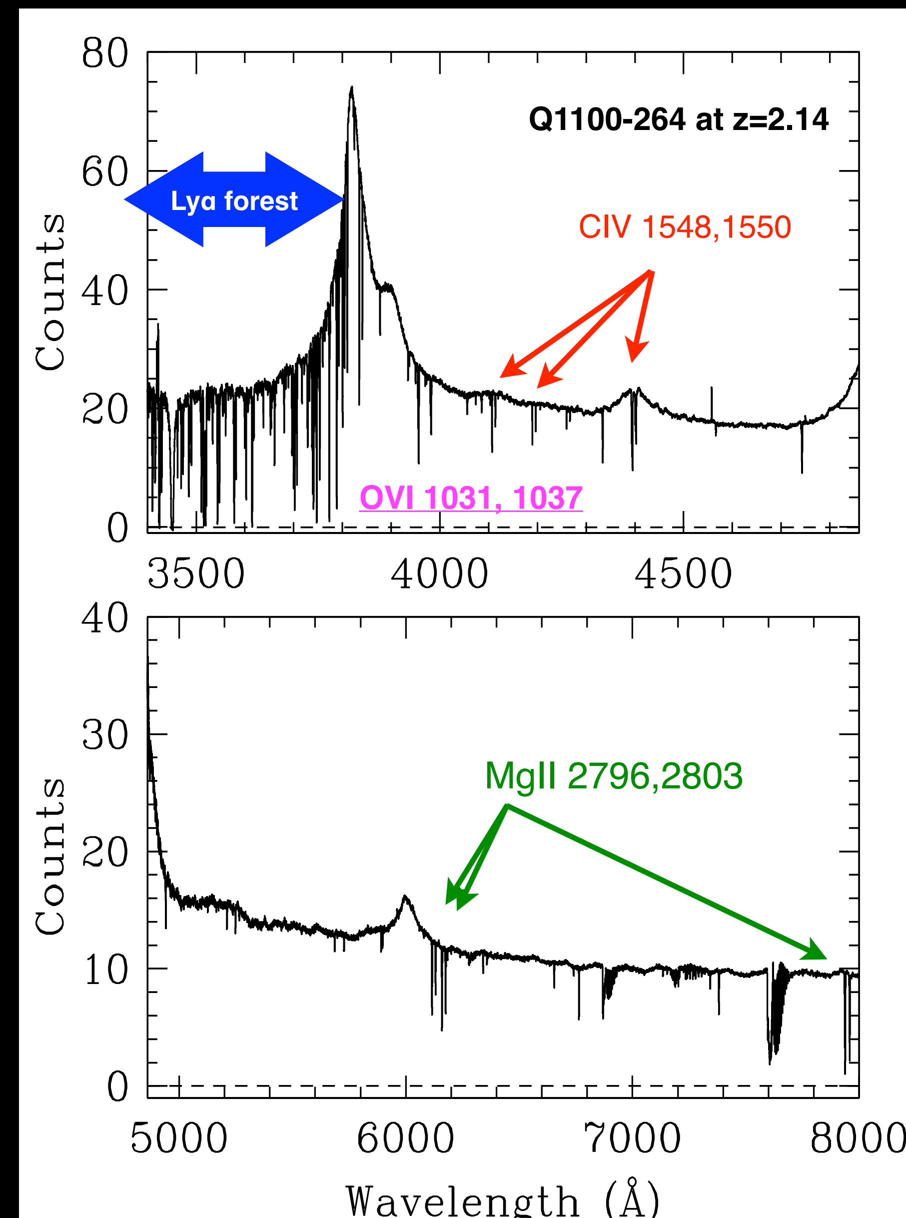

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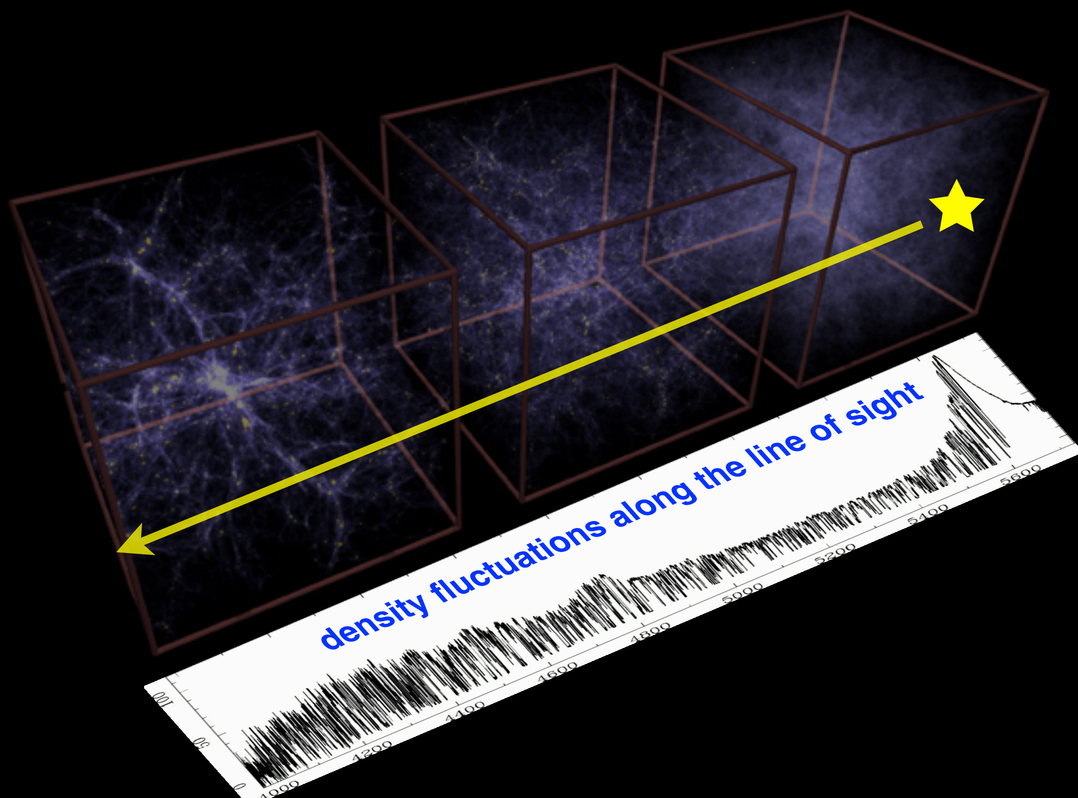
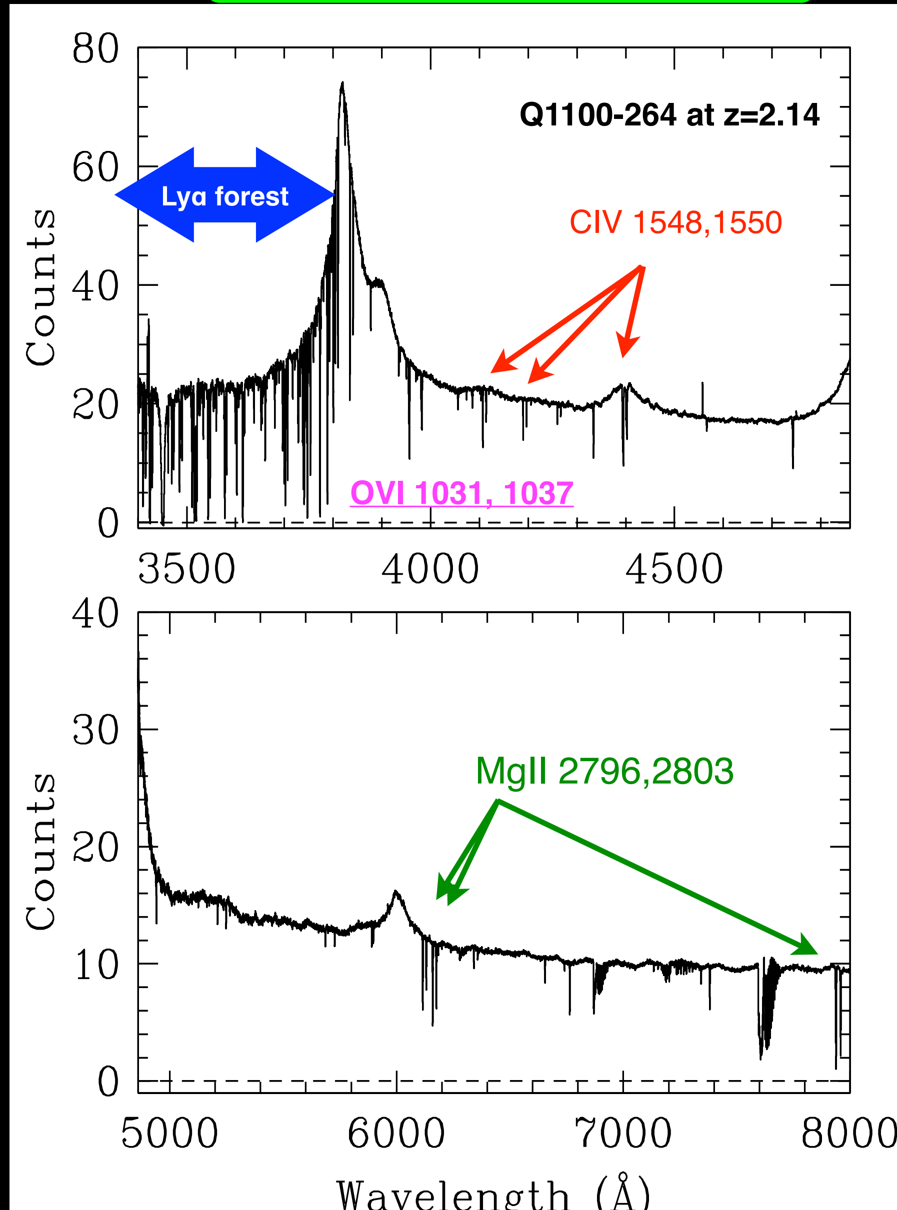
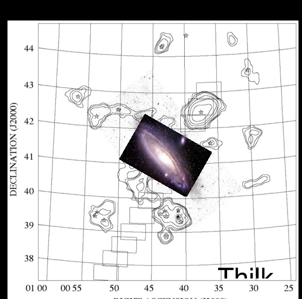


An empirical probe of the *intergalactic medium, halo gas, and ISM* in/around distant galaxies



HALO GAS



~ 10-100 kpc

ISM

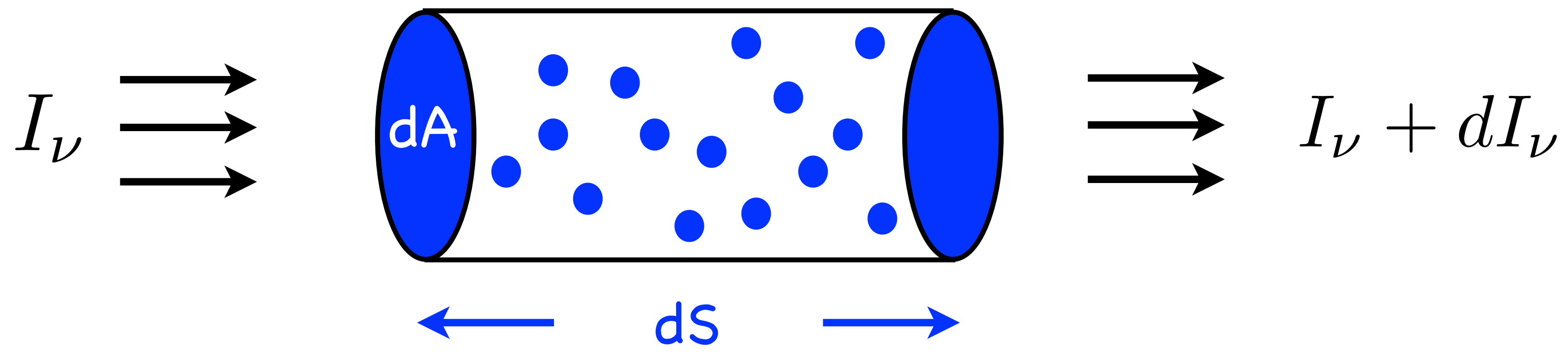
~ kpc

CSM

< 100 pc

Absorption-line Analysis

Equation of radiative transfer



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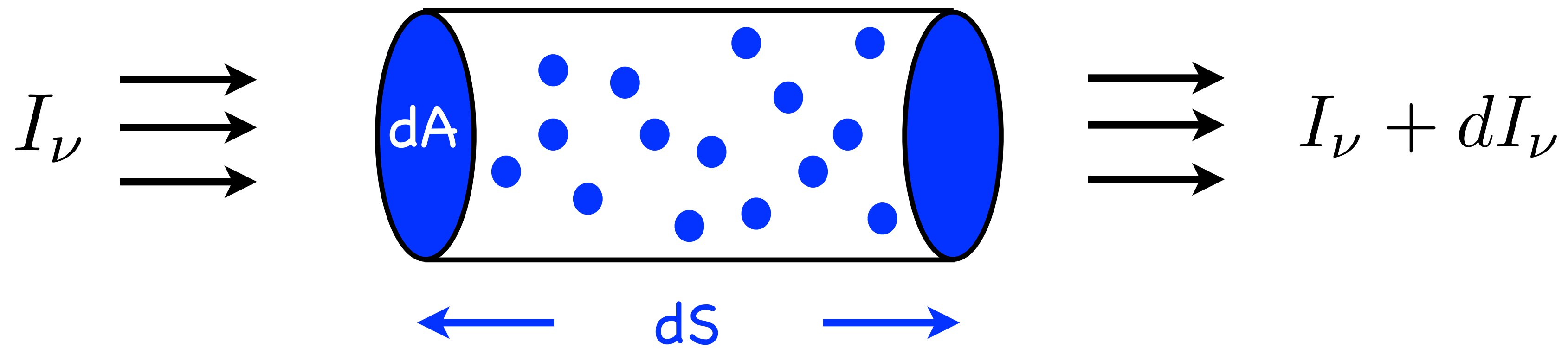

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

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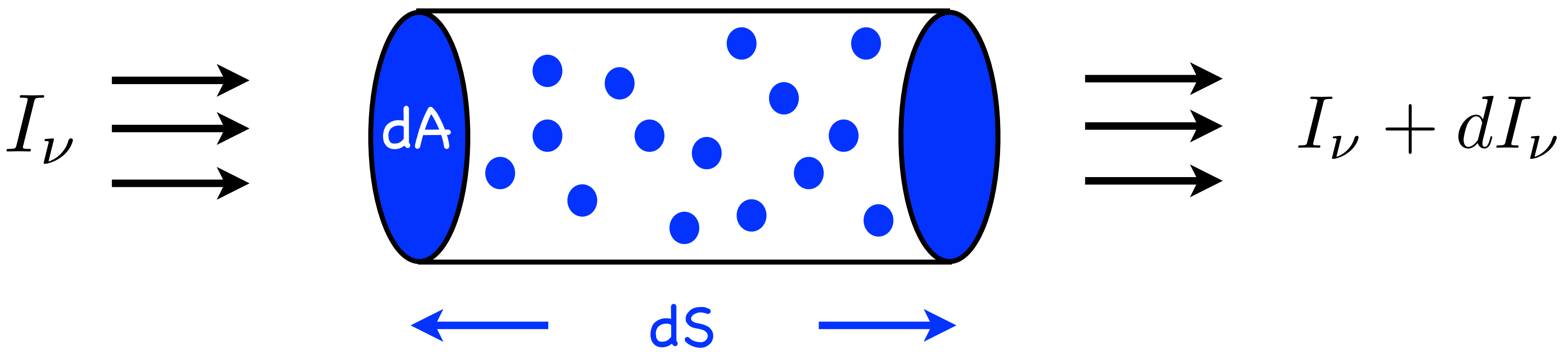

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the net change in radiation intensity

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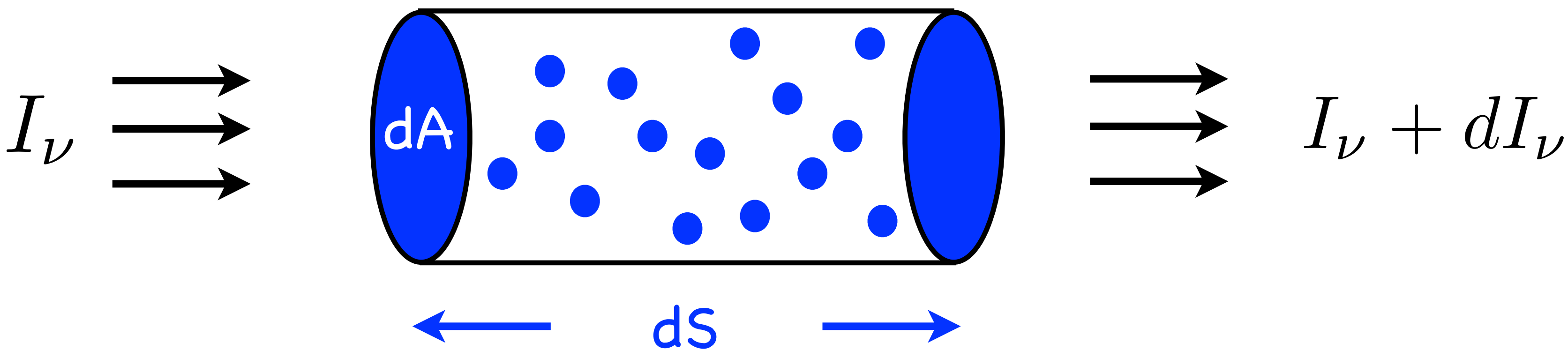

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$$\alpha_\nu = n \times \sigma_\nu$$

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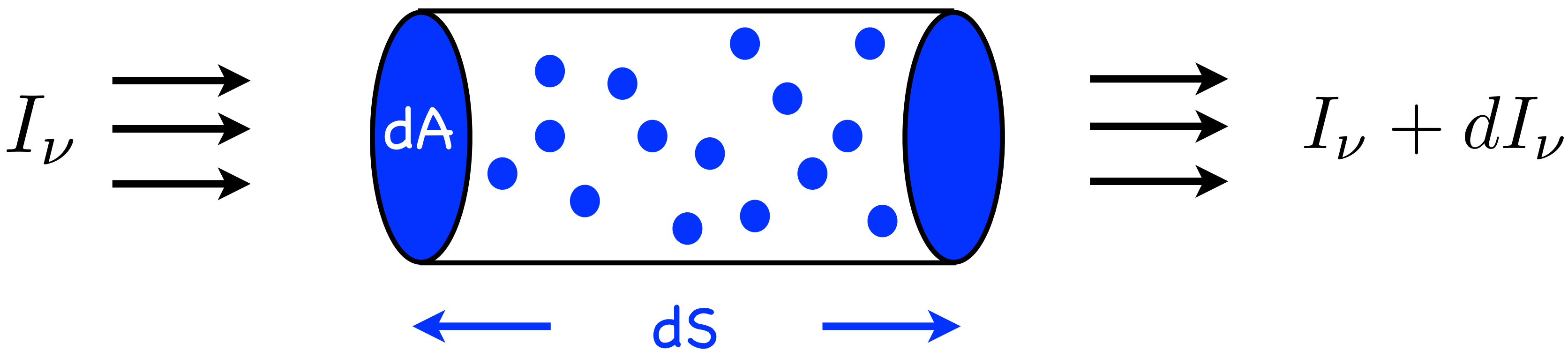

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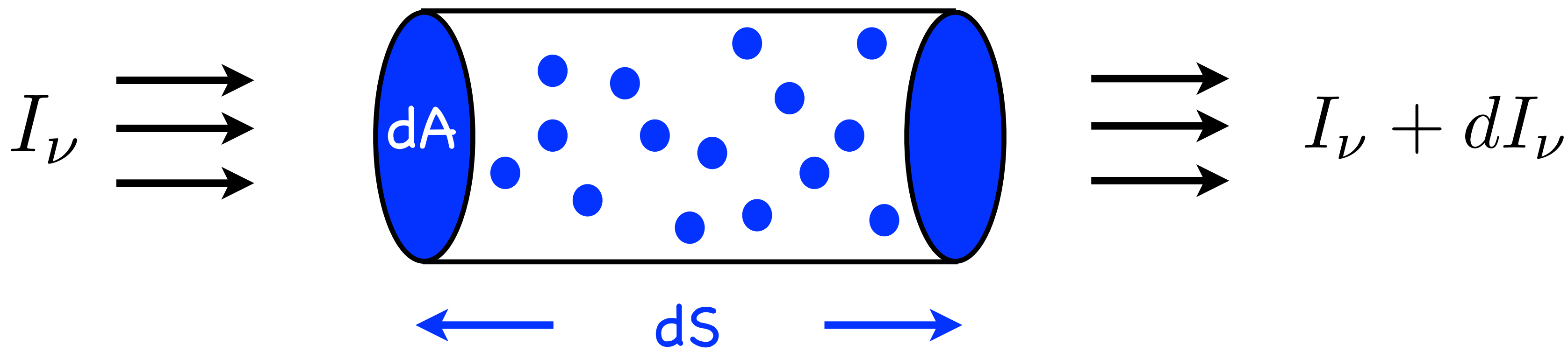

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Defining optical depth $\quad \tau_\nu(s) = \int \alpha_\nu \, ds$

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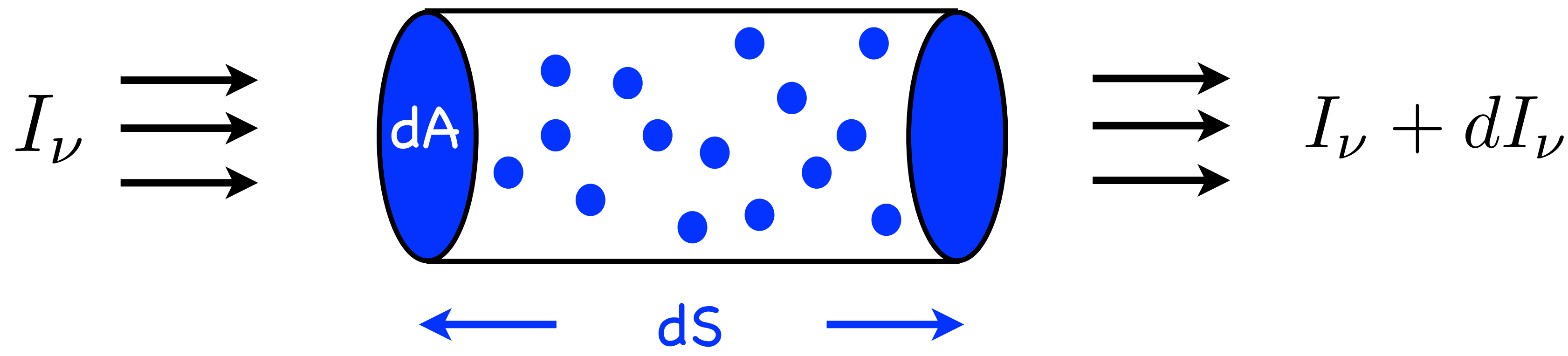

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Relation between absorption line profiles and gas properties

(gas density, ionization state, heavy element abundances, temperature, kinematics, etc.)

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Opacity: $$\tau_\nu = \int \alpha_\nu \, ds = \int n \, \sigma_\nu \, ds = \int n \, \sigma \, \Phi_\nu(\Delta\nu) \, ds$$

n = particle density

$$\sigma = \int \sigma_\nu \, d\nu = \frac{\pi e^2}{m_e c} f_{jk} = 2.654 \times 10^{-2} f_{jk} \ \mathrm{cm}^2$$

line profile function : $\int \Phi(\Delta\nu) \, d\nu = 1$ where $\Delta\nu = \nu - \nu_{jk}$

> the "effectiveness" of photons away from ν_{jk} to cause the transition

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> the "effectiveness" of photons away from ν_{jk} to cause the transition

Line broadening: $$\Phi(\Delta\nu) \neq \delta(\nu - \nu_{jk})$$

- Doppler motion
- Intrinsic line width

Line broadening --- Doppler motion

- Maxwellian distribution $\Phi(\Delta\nu) = \frac{1}{\sqrt{\pi}} \frac{\lambda_{jk}}{b} \exp\left[-\left(\frac{\Delta\nu}{\Delta\nu_D} \right)^2 \right] \propto \exp\left[-\frac{mv_z^2}{2kT} \right]$

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Doppler width: $\Delta\nu_D = b \frac{\nu_{jk}}{c} = \frac{b}{\lambda_{jk}}$

Doppler parameter: $b = \sqrt{2}\, \sigma_v$ where σ_v is the velocity dispersion

$$b = \sqrt{\frac{2kT}{m}} = 1.29 \times 10^4 \sqrt{\frac{T}{A}}\ \mathrm{cm\, s^{-1}}$$

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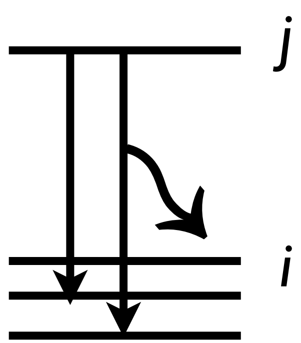
Line broadening --- Intrinsic broadening

- Lorentz profile $\Phi(\Delta\,\nu) = \frac{\Gamma/4\pi^2}{(\Delta\,\nu)^2 + (\frac{\Gamma}{4\pi})^2}$ Γ: damping coefficient



$\Gamma = \sum_{i<j} A_{ji}$ Einstein coefficient

Combined profile --- Doppler + Intrinsic

$$\Phi(\Delta\nu) = \frac{\Gamma}{4\pi^2} \int \frac{\sqrt{\frac{m}{2\pi kT}} \exp\left[-\frac{mv_z^2}{2kT}\right]}{(\Delta\nu - \frac{\nu_{jk} v_z}{c})^2 + (\frac{\Gamma}{4\pi})^2} \; d\,v_z$$

Combined profile --- Doppler + Intrinsic

an average of Lorentz profile over all velocity range.

$$\Phi(\Delta\nu) = \frac{\Gamma}{4\pi^2}\int \frac{\sqrt{\frac{m}{2\pi kT}}\exp\left[-\frac{mv_z^2}{2kT}\right]}{(\Delta\nu - \frac{\nu_{jk}v_z}{c})^2 + (\frac{\Gamma}{4\pi})^2}\; d\,v_z$$

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$$= \frac{1}{\sqrt{\pi}\Delta\nu_D} H(a,x)$$ where $$a \equiv \frac{\Gamma}{4\pi\Delta\nu_D} \text{ and } x = \frac{\Delta\nu}{\Delta\nu_D}$$

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The Voigt function $H(a,x) = \frac{a}{\pi} \int \frac{e^{-y^2}}{(x-y)^2 + (a)^2} \, d\,y$

For small *a, small x indicates* $\Phi(\Delta\nu) \propto e^{-(\Delta\nu)^2}$

large x indicates $\Phi(\Delta\nu) \propto 1/(\Delta\nu)^2$

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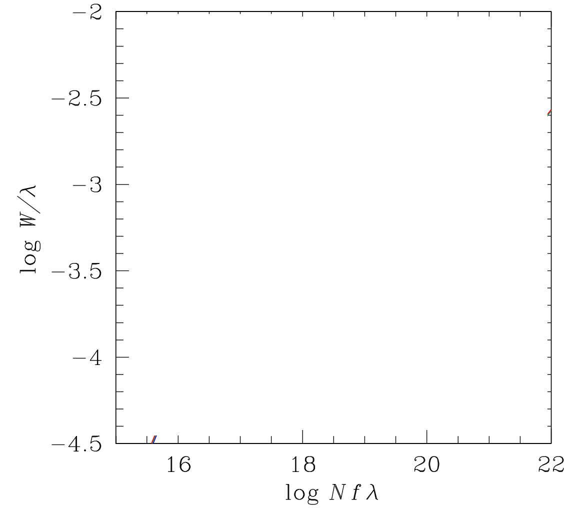
large x indicates $\Phi(\Delta\nu) \propto 1/(\Delta\nu)^2$

Optical depth

$$\tau_\nu = N\sigma\Phi(\Delta\nu) = N\frac{\pi e^2}{m_e c} f_{jk}\frac{1}{\sqrt{\pi}\Delta\nu_D} H(a,x)$$

Curve of Growth



Absorption equivalent width $W_{\rm rest} = W_{\rm obs}/(1+z)$

$$W_{\rm obs} = \int \frac{I_c - I_\nu}{I_c} d\lambda = \int (1 - e^{-\tau}) d\lambda$$

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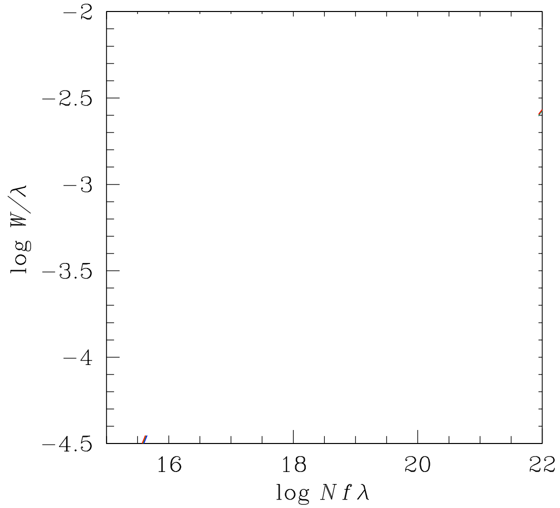

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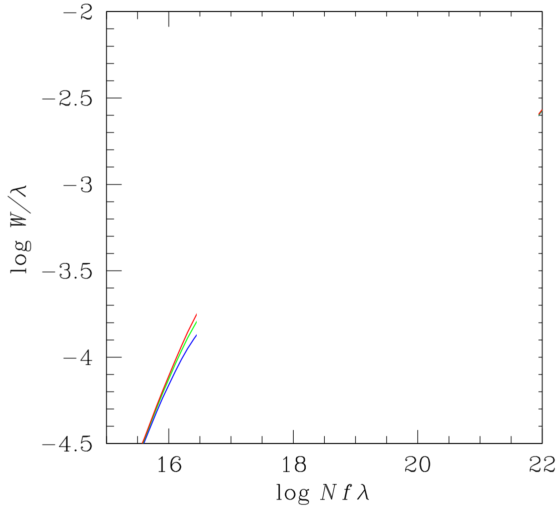
1. optically thin regime : $\tau_0 \ll 1$

$$W \approx \frac{\lambda^2}{c} \int \tau_\nu \, d\nu = \frac{\lambda^2}{c} N \frac{\pi e^2}{m_e c} f \underline{\int \Phi(\Delta\nu) \, d\nu} \quad = 1$$

Curve of Growth



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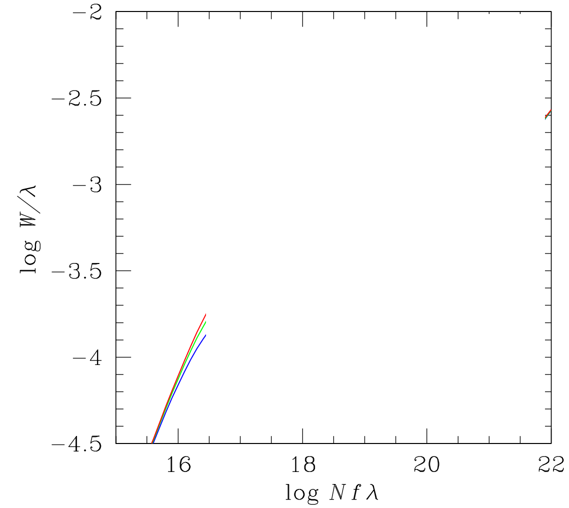
$$\frac{W}{\lambda} = \frac{\lambda}{c} \frac{\pi e^2}{m_e c} f \, N$$

W & *N* are linearly correlated, independent of *b*

Curve of Growth



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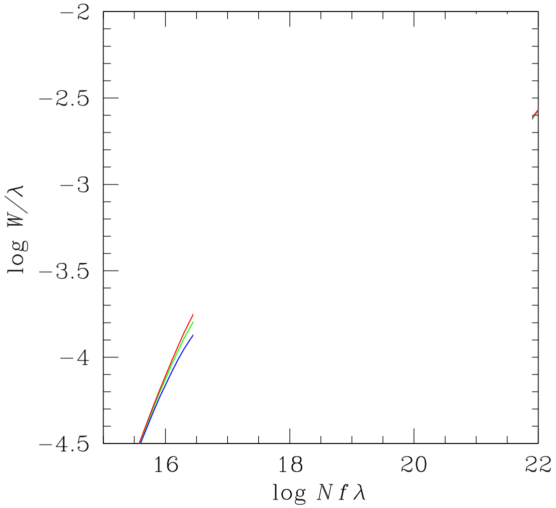
Curve of Growth



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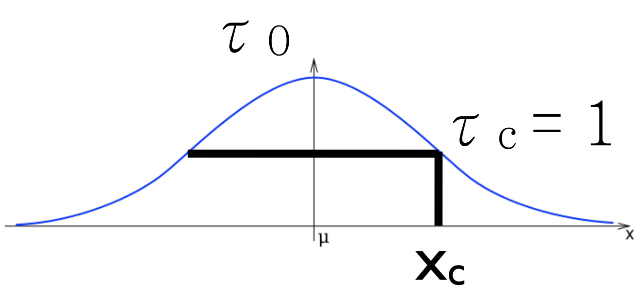

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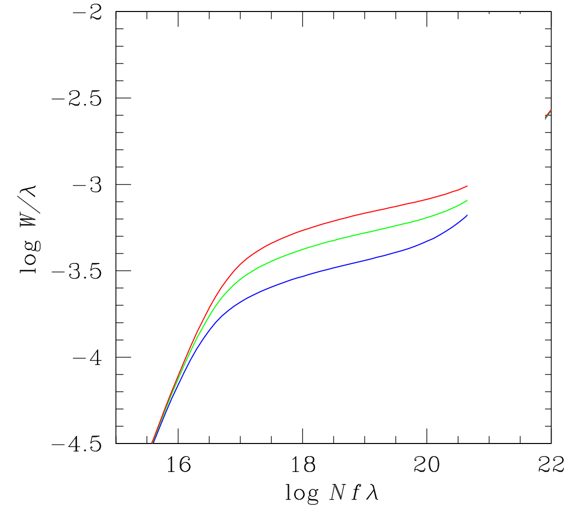
Curve of Growth



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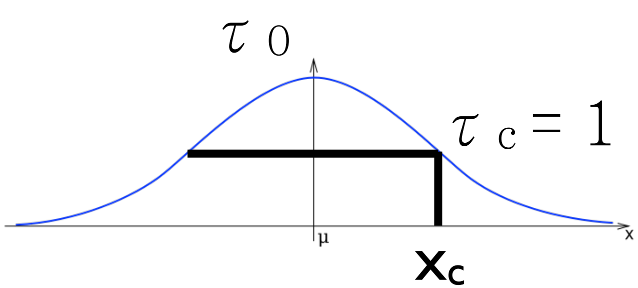
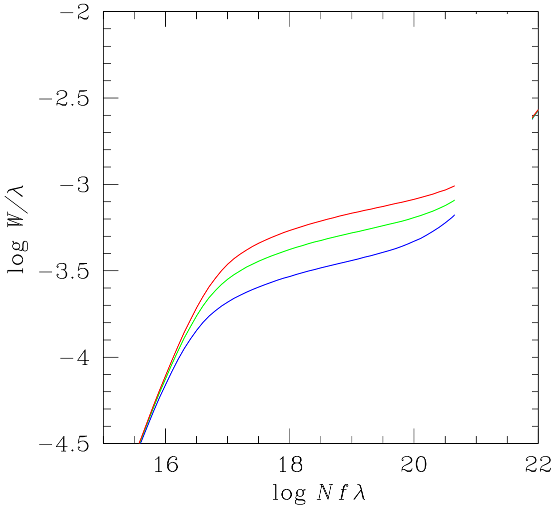


$$x_c = \sqrt{\ln \tau_0} \quad \textbf{and} \quad W \approx 2\, x_c \propto \sqrt{\ln \tau_0}$$

$$\frac{W}{\lambda} = \frac{2b}{c} \sqrt{\ln\left(\frac{\pi e^2}{m_e c} f N \frac{\lambda}{\sqrt{\pi} b}\right)}$$

When the line is saturated, W depends only weakly on N but strongly on *b*

Curve of Growth



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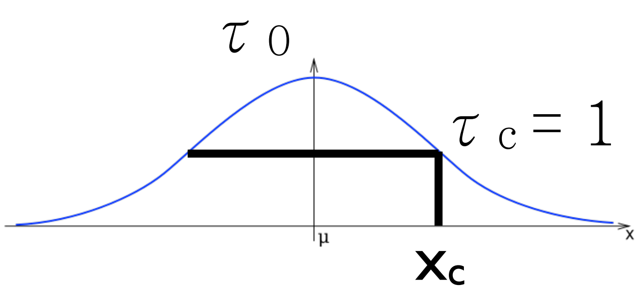
$$\tau_\nu = \tau_0 \frac{a^2}{x^2 + a^2}$$



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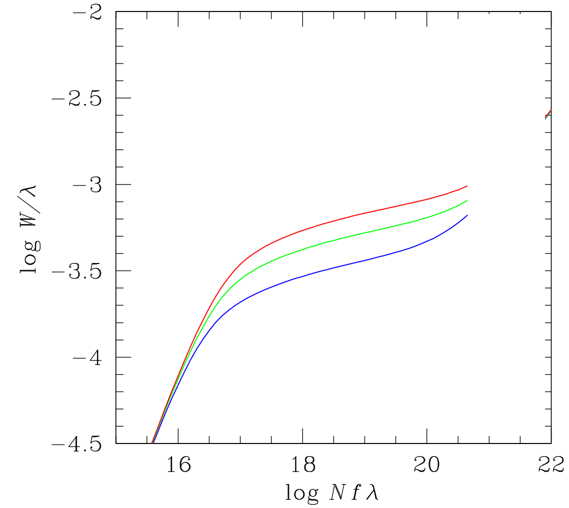

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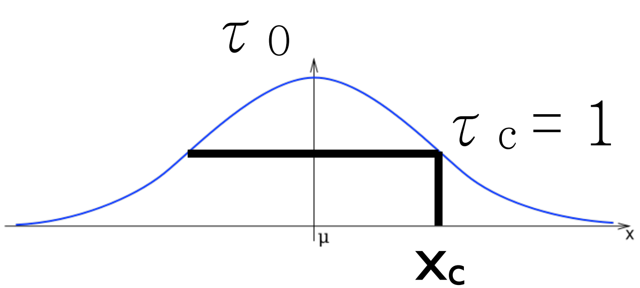

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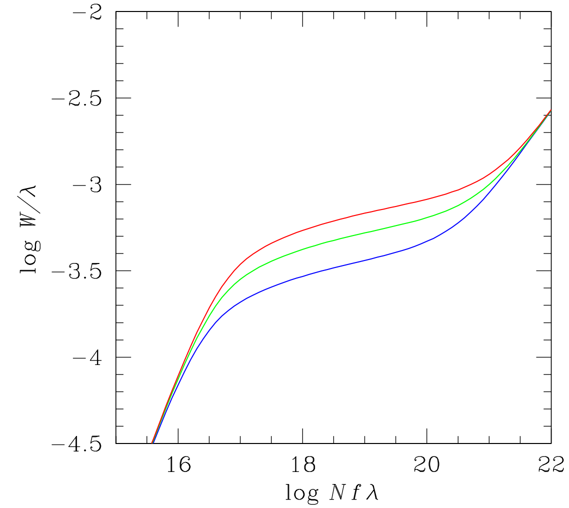

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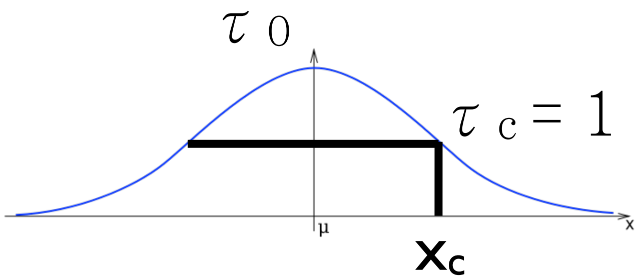

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$$W \approx 2\,x_c \propto \sqrt{\tau_0}$$

asymptotic expression $$\frac{W}{\lambda} = \frac{2}{c}\frac{1}{4\pi}\sqrt{\lambda^2 N \frac{\pi e^2}{m_e c} f\Gamma}$$

When the line is highly saturated, W increases as $N^{1/2}$, independent of b

Expected line strength $I_\nu = I_0\, e^{-\tau_\nu}$

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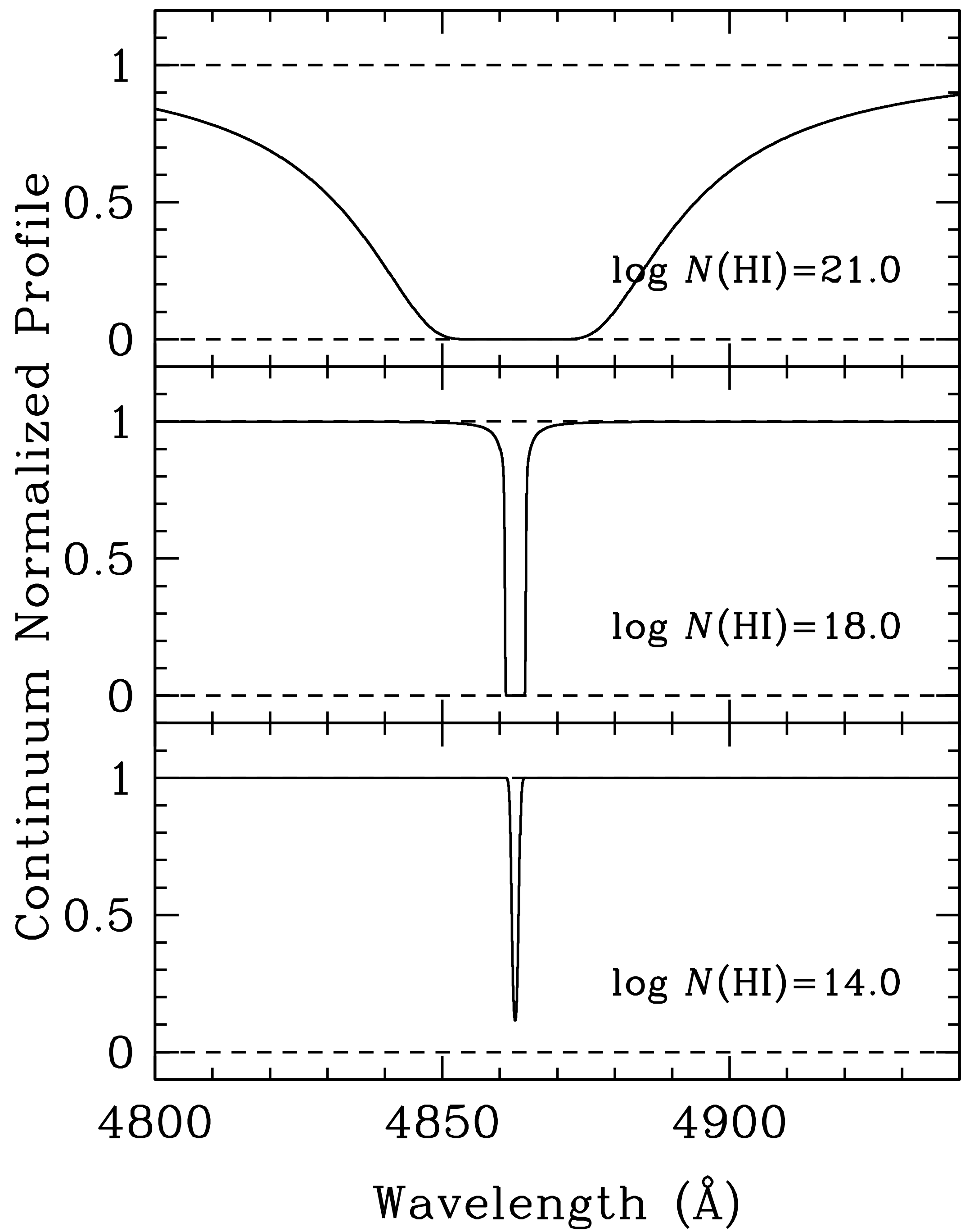
$\delta\nu$ = 5 km s^{-1}

damped absorber

optically thick absorber

optically thin absorber



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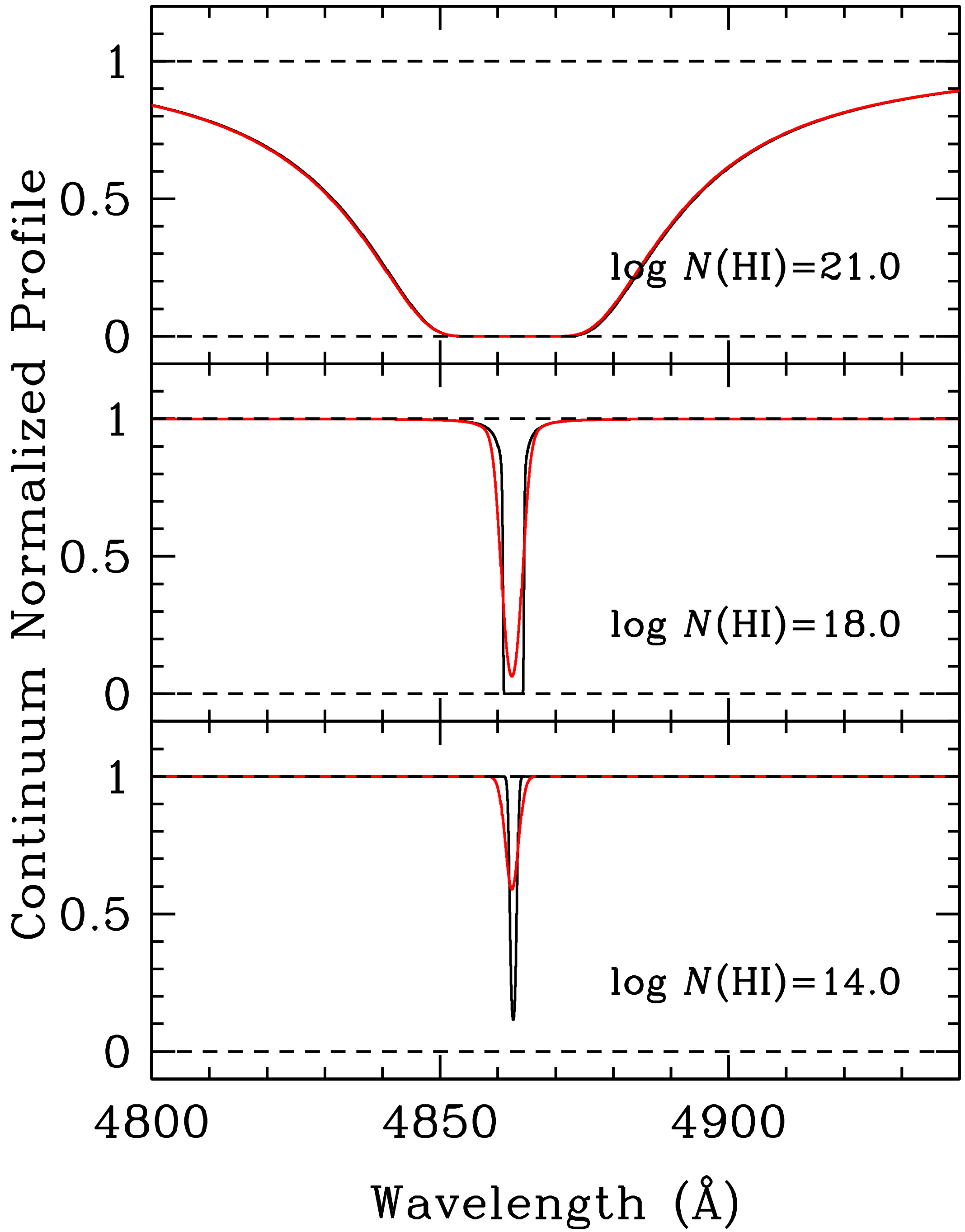

δv = 5 km s^{-1}

δv = 150 km s^{-1}

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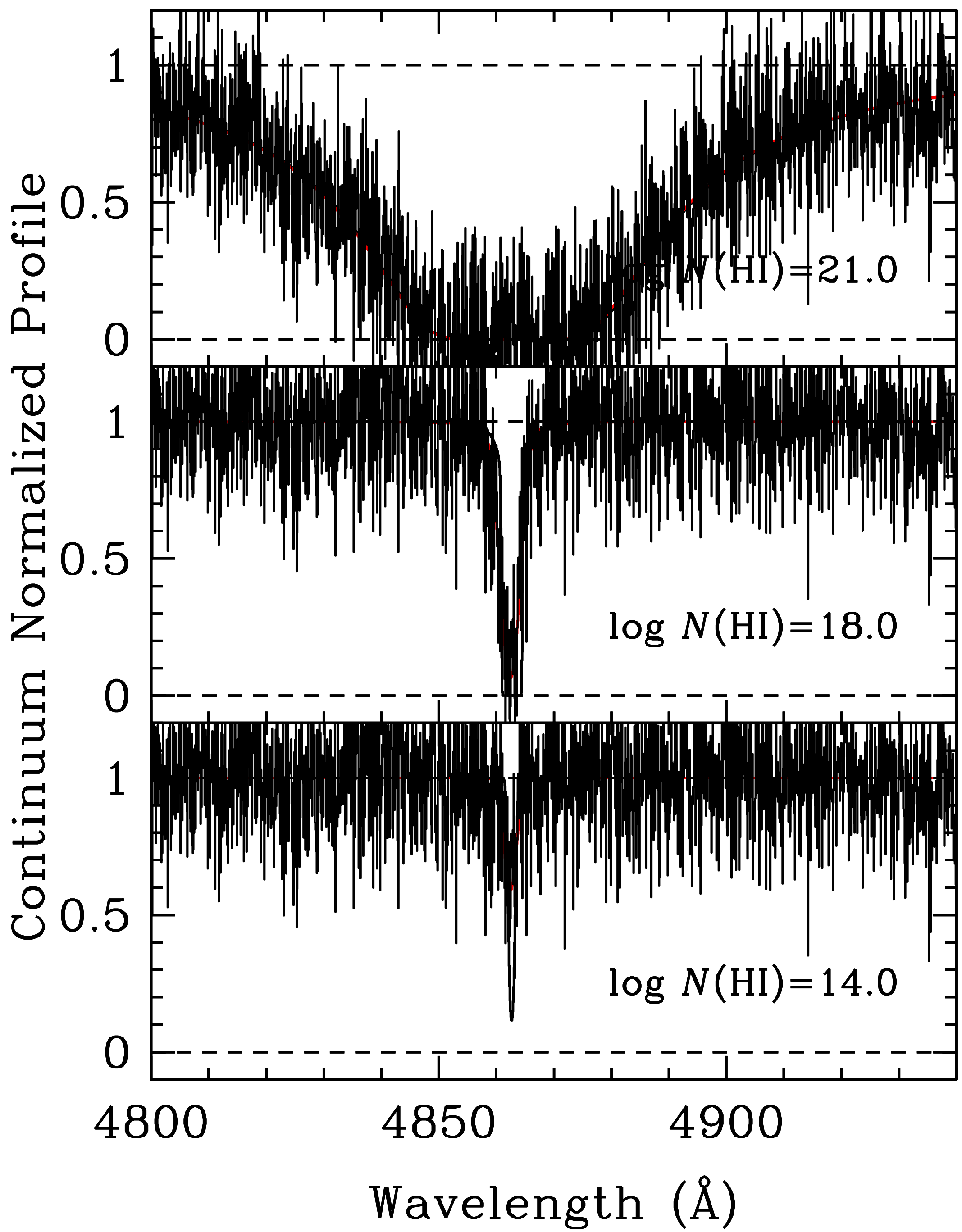

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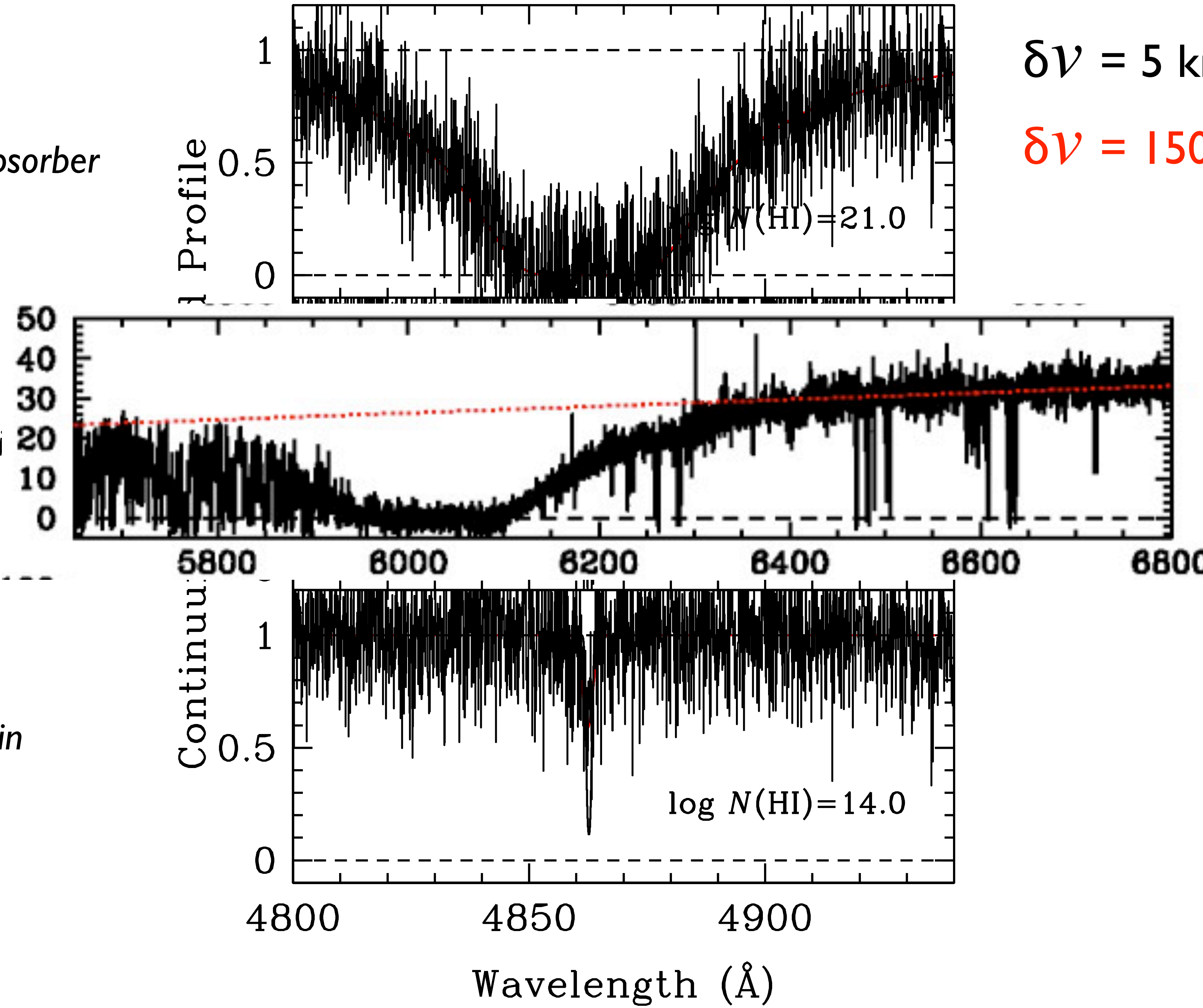

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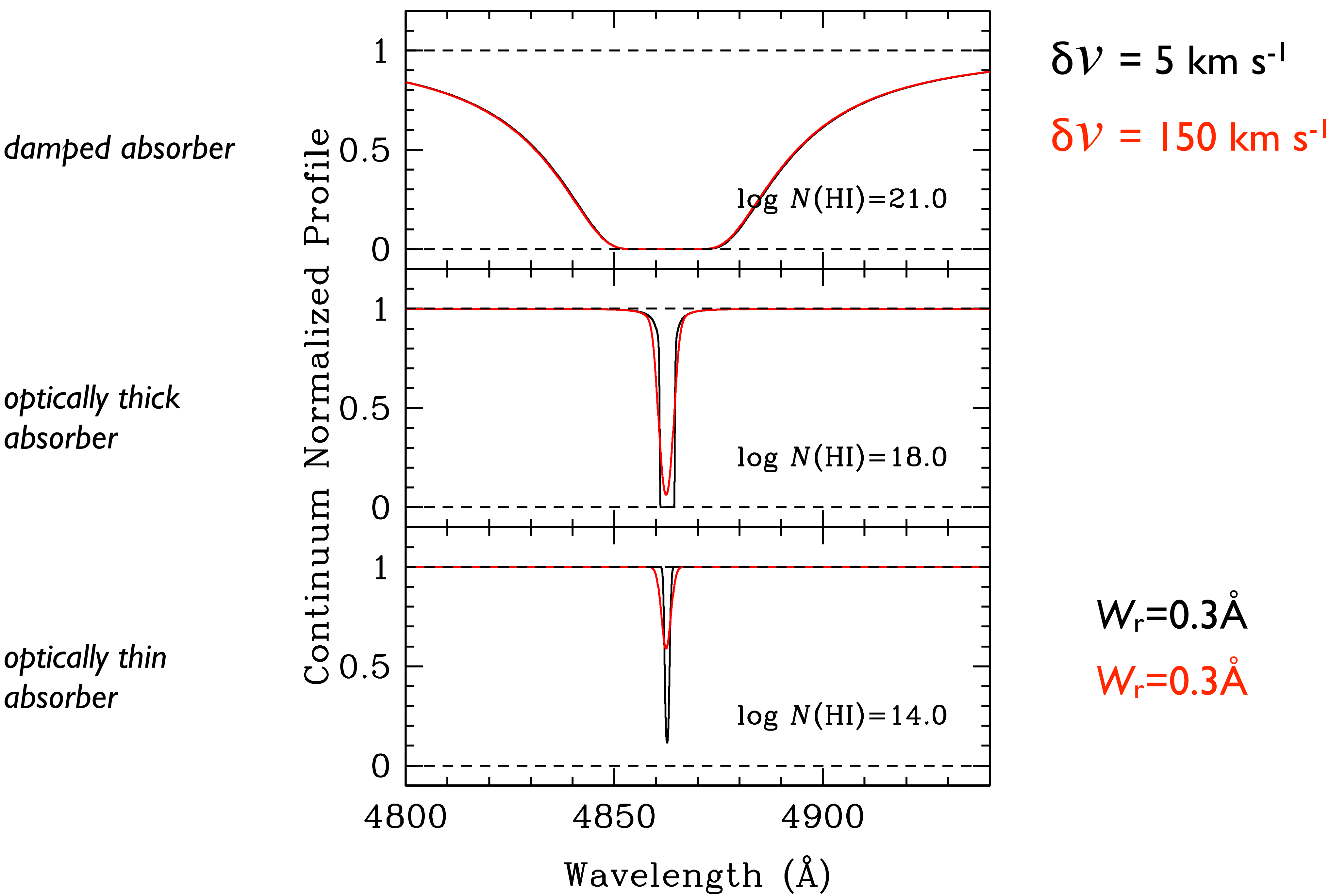
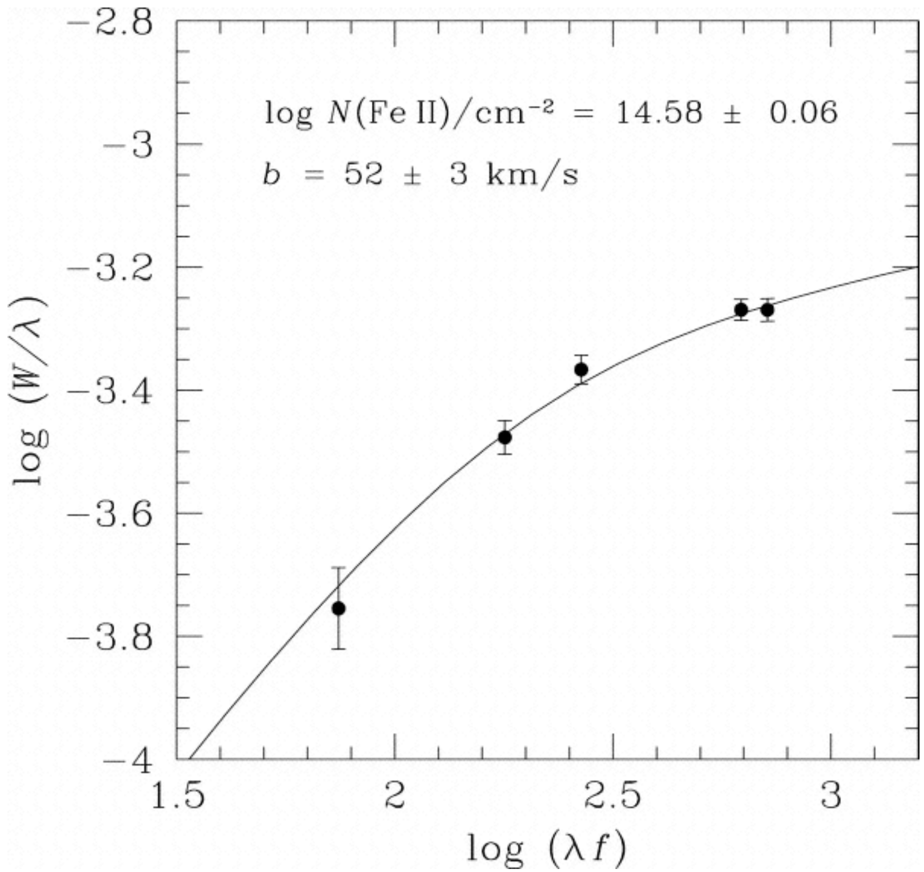


The use of curve of growth for measuring N and b

same ions



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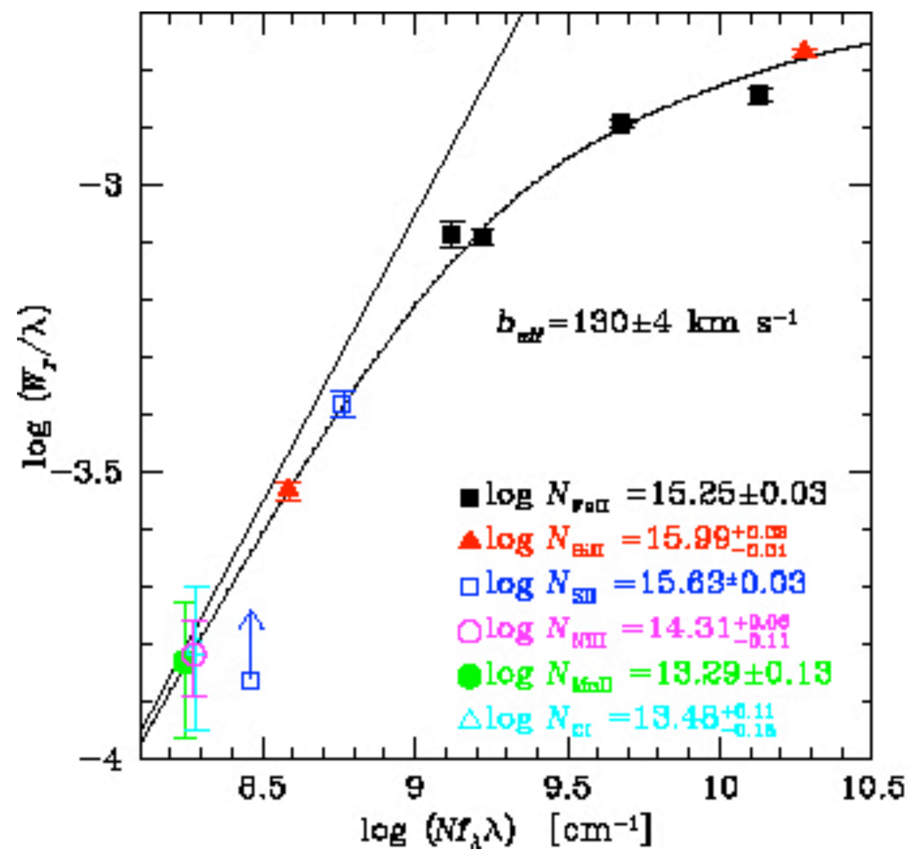

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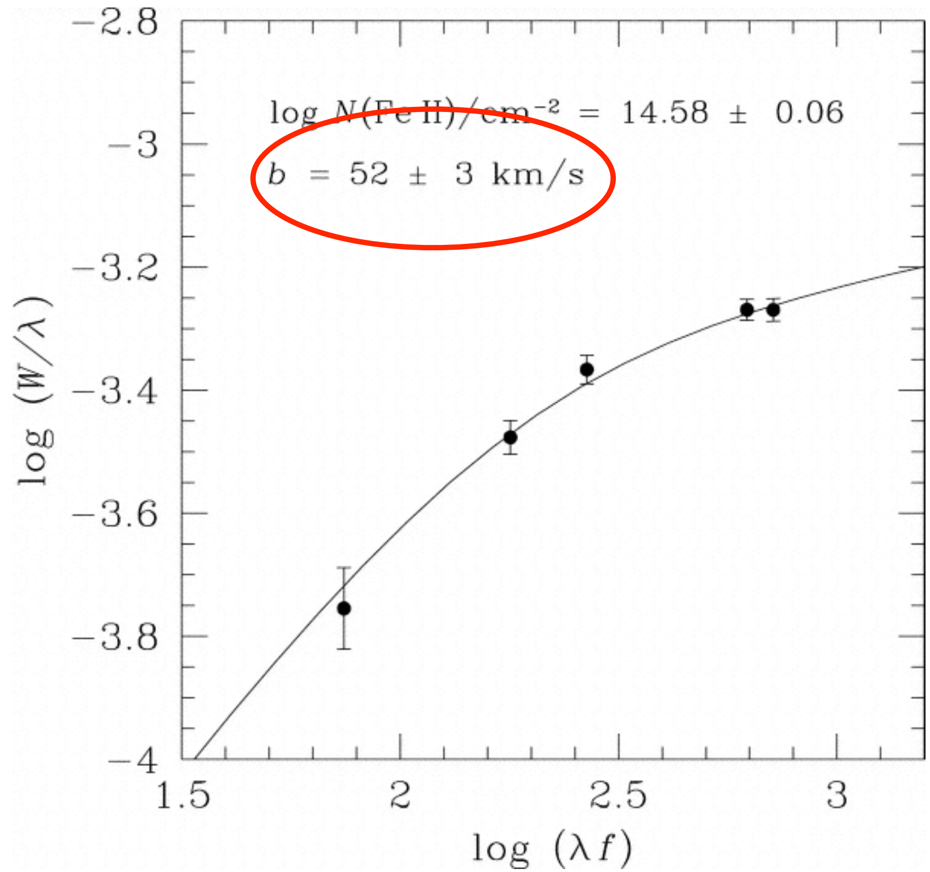

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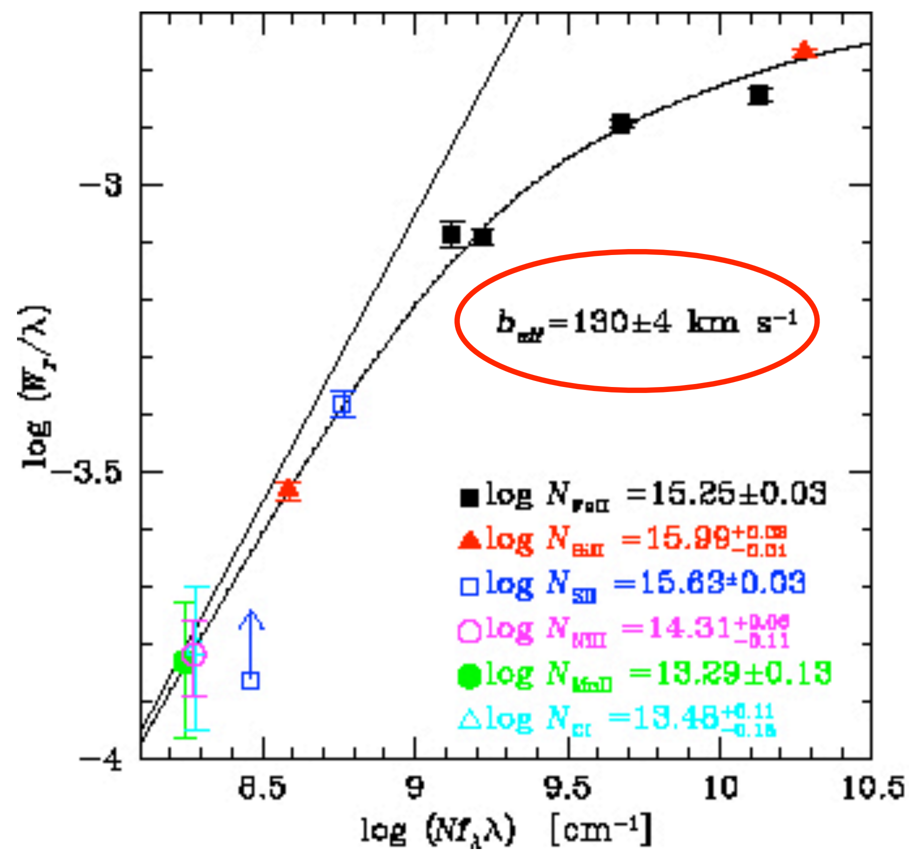
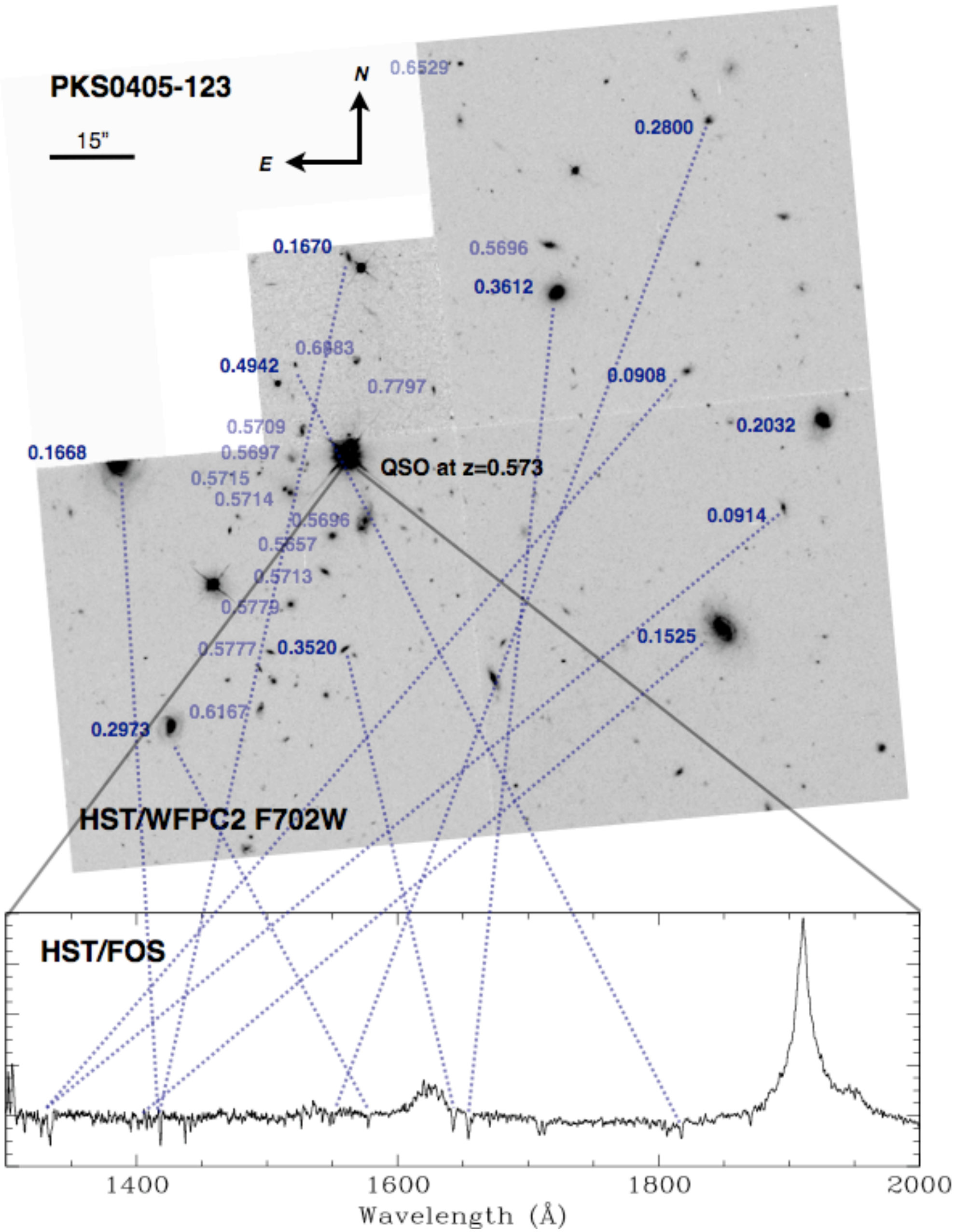


In the real world, the observed transitions are often saturated and contain multiple components

see Jenkins (1986)

Probing circumgalactic medium at high redshift

the rate of incidence



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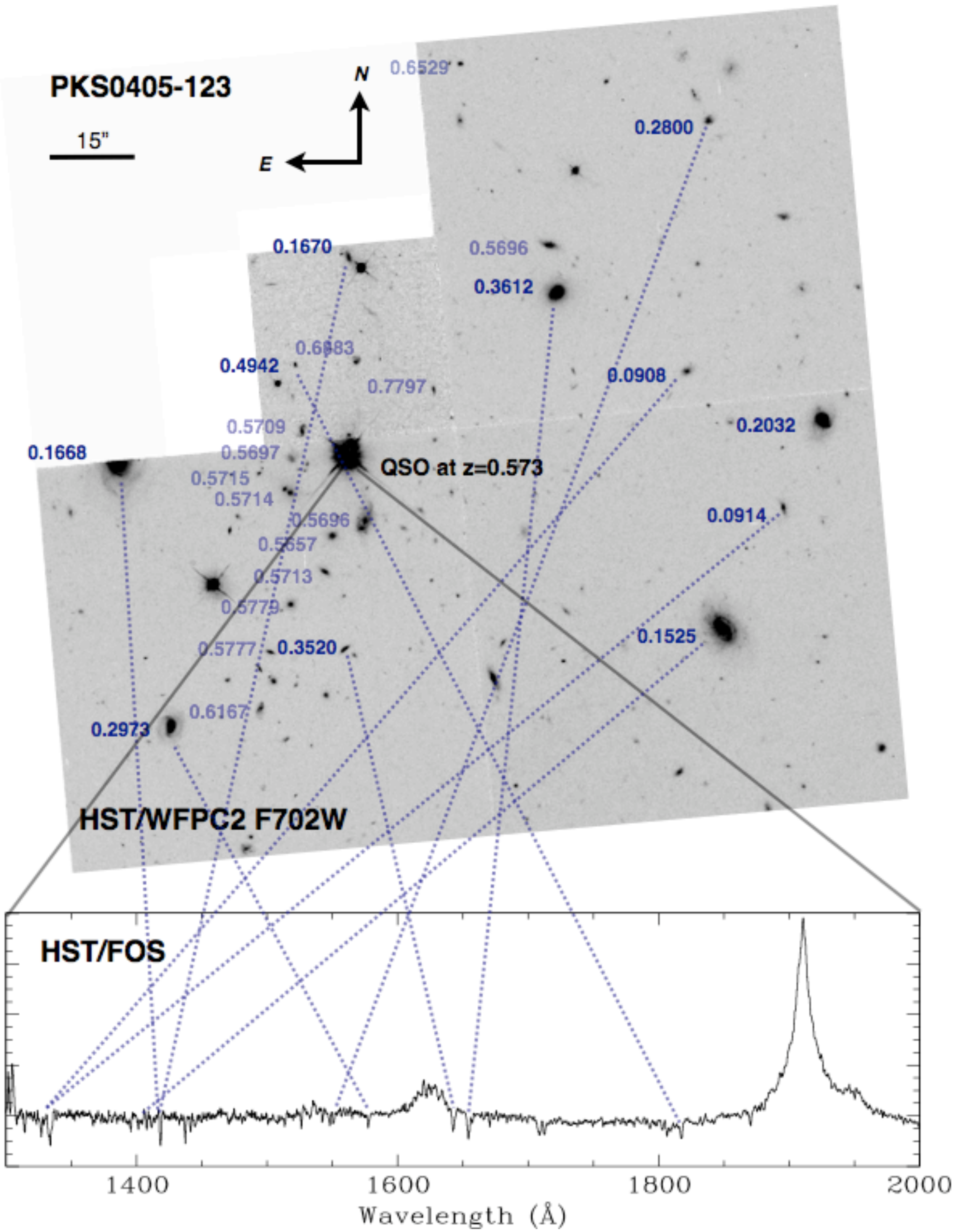

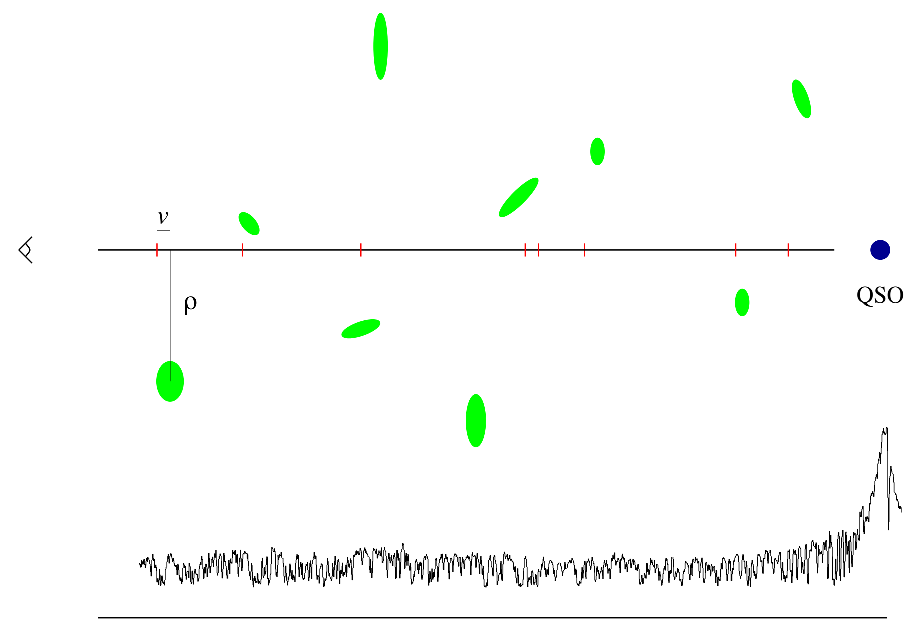

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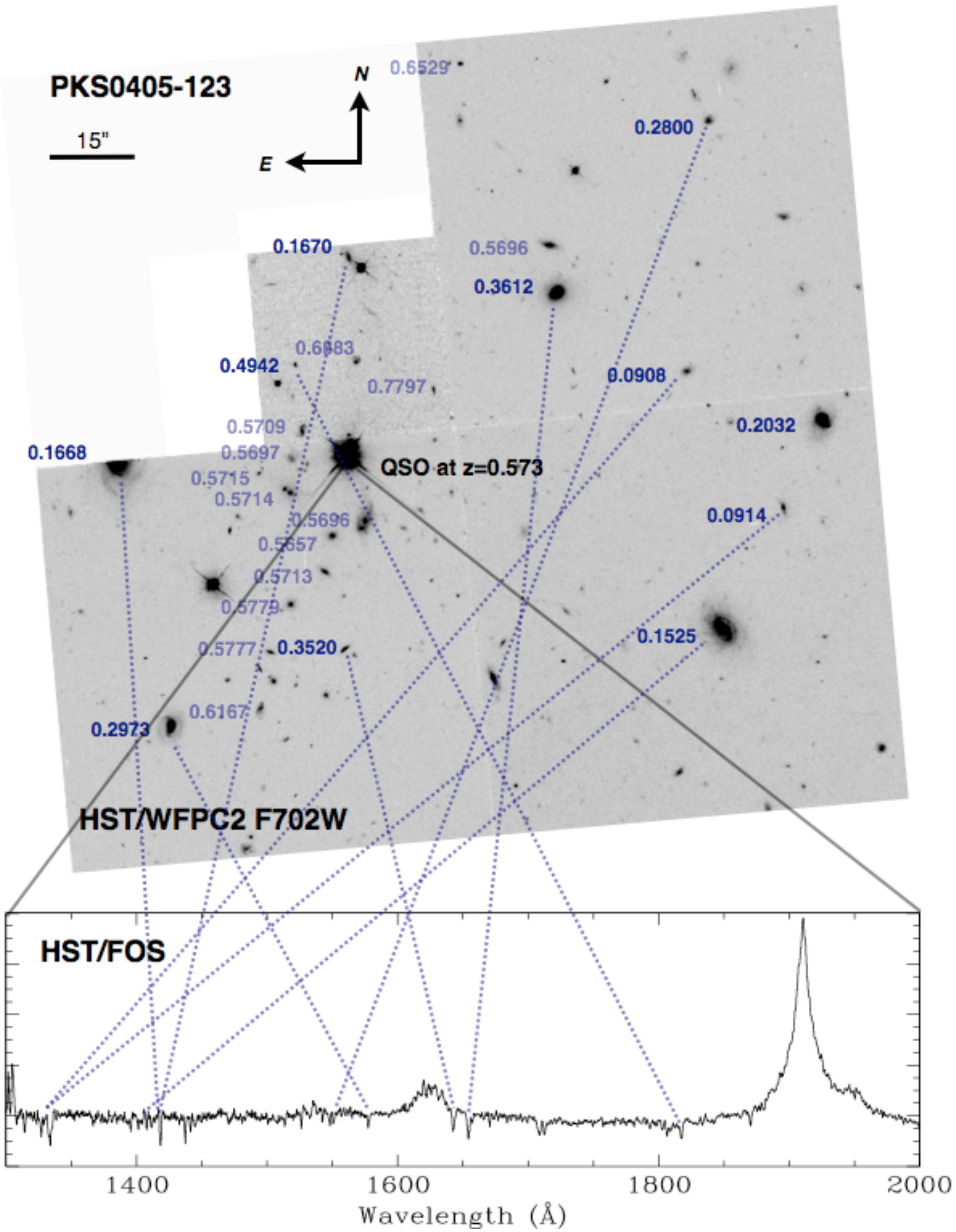

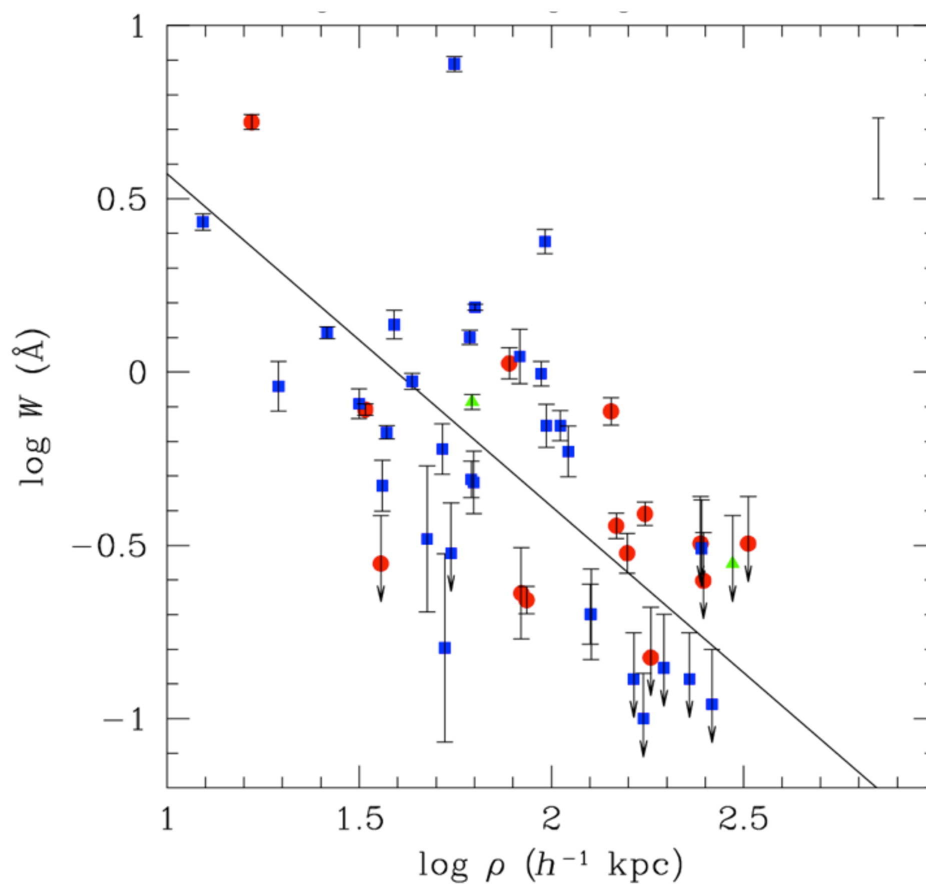

Chen et al. (1998, 2001)

Probing circumgalactic medium at high redshift

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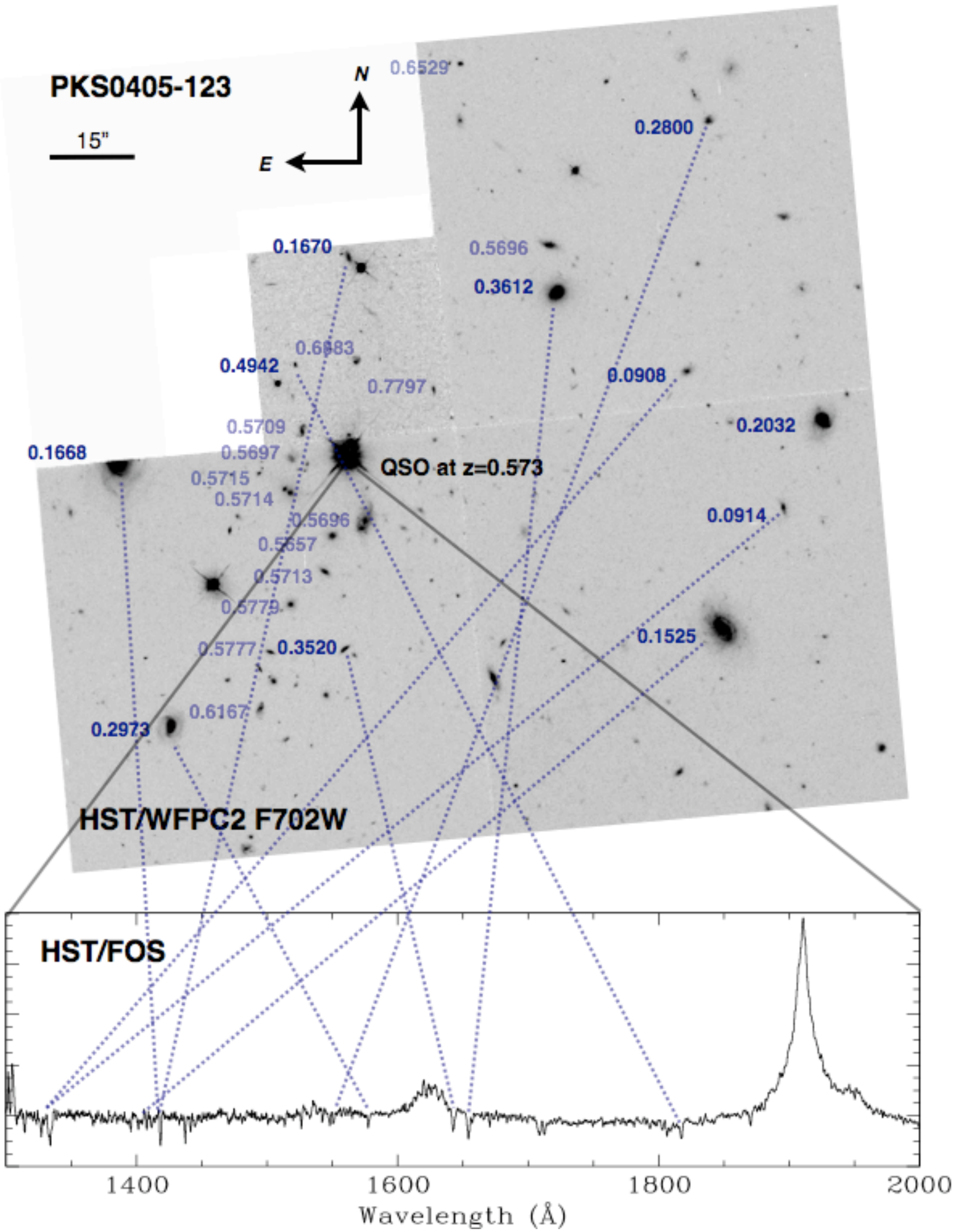

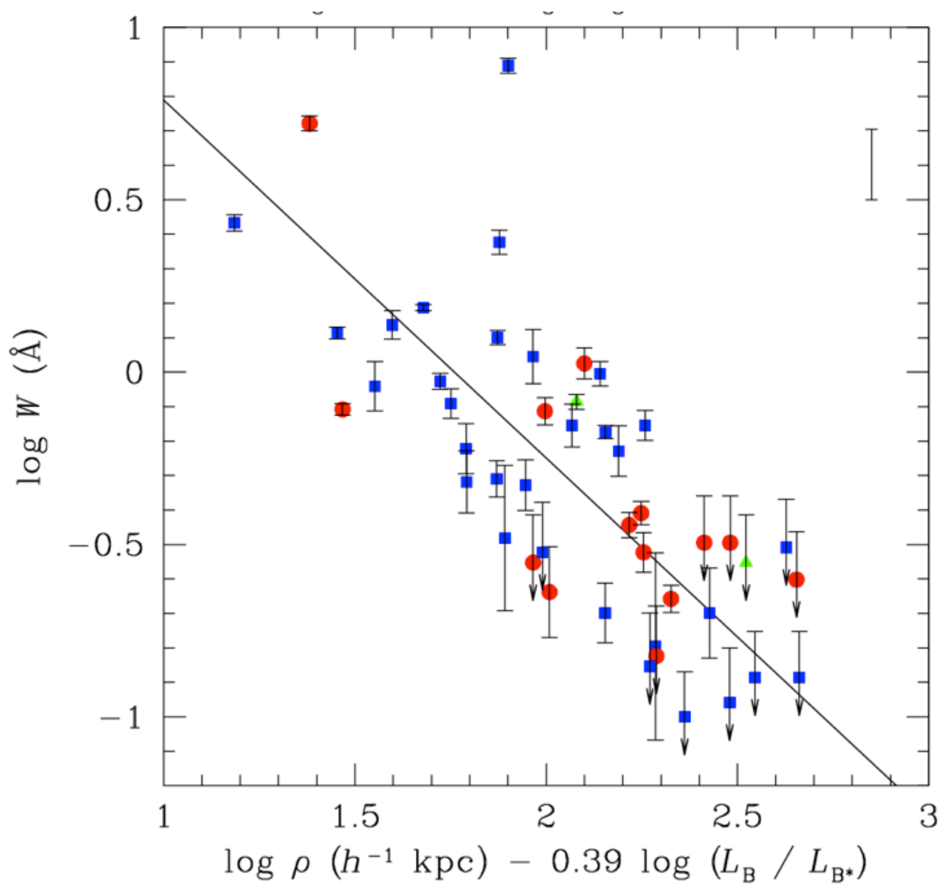

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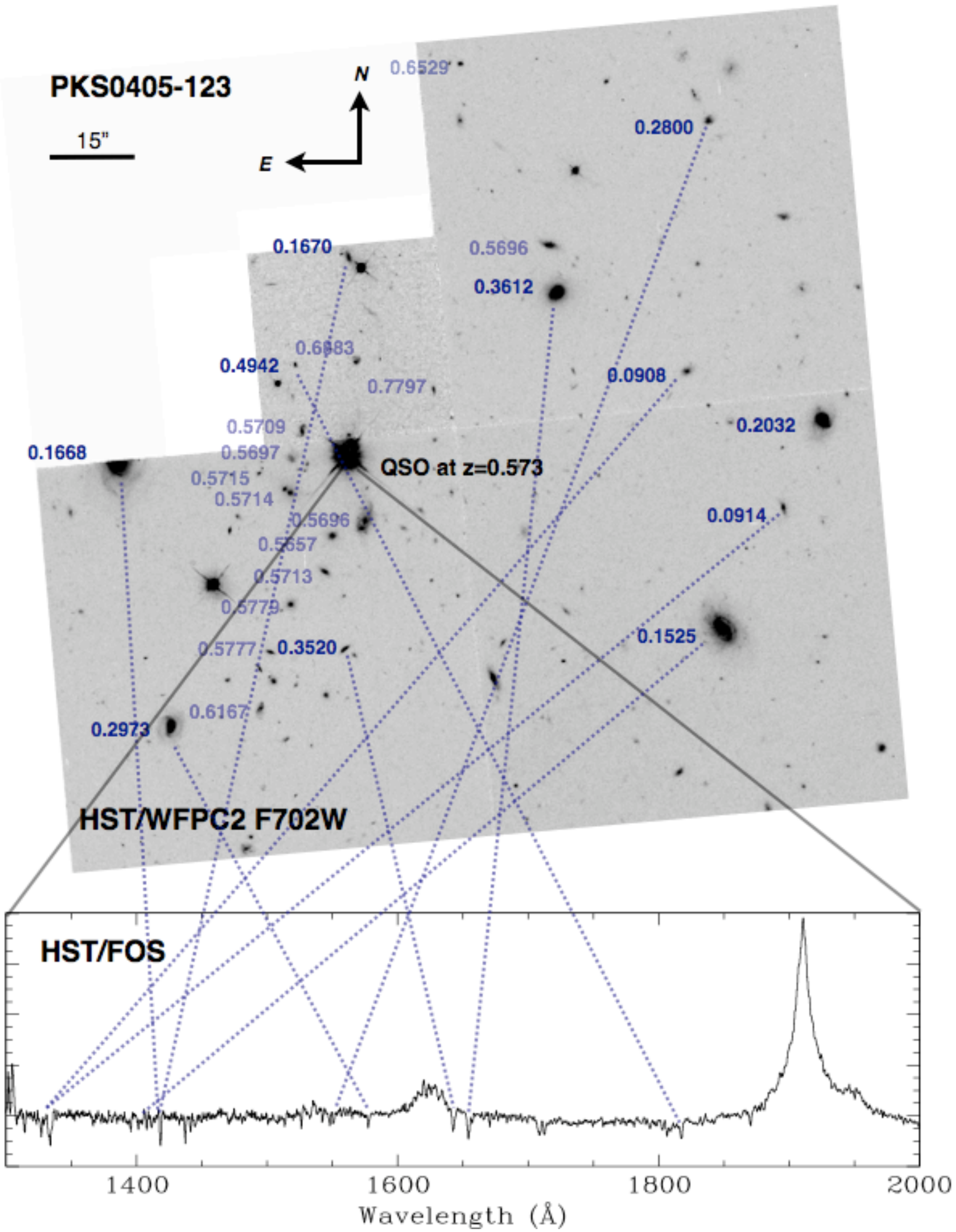

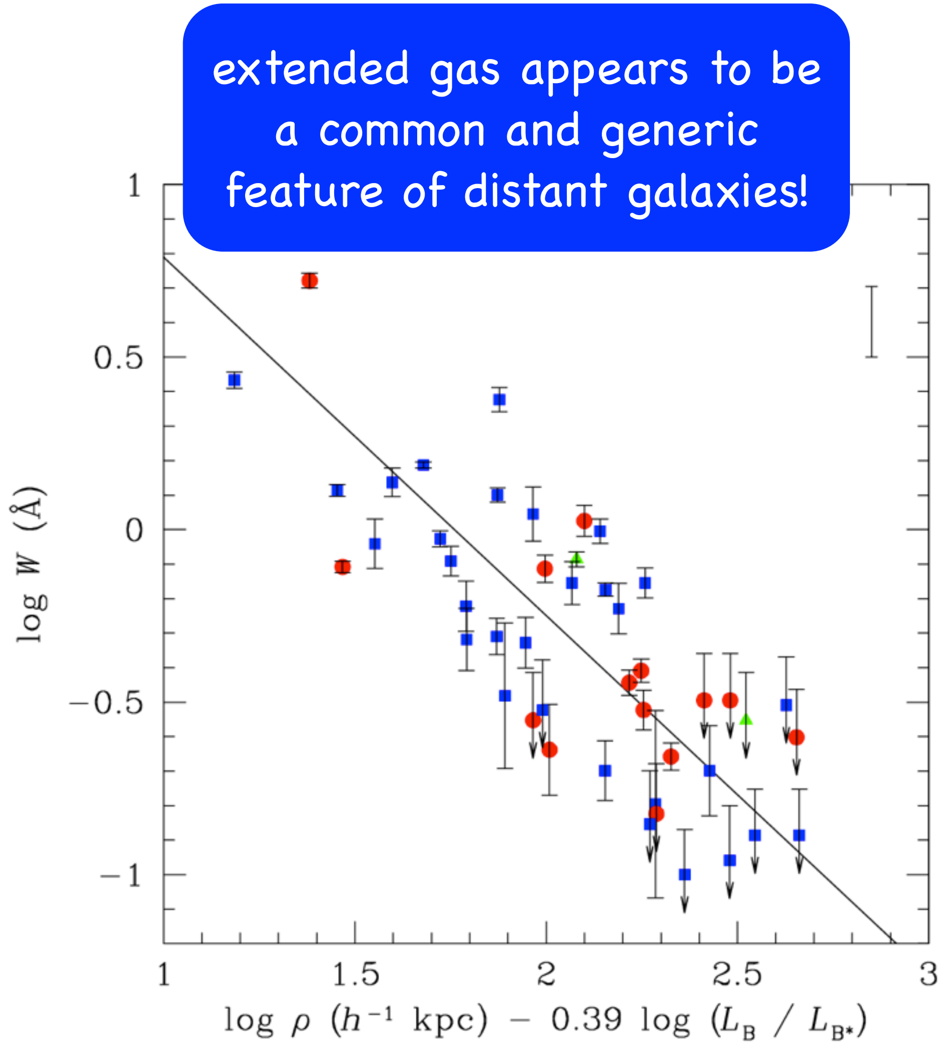

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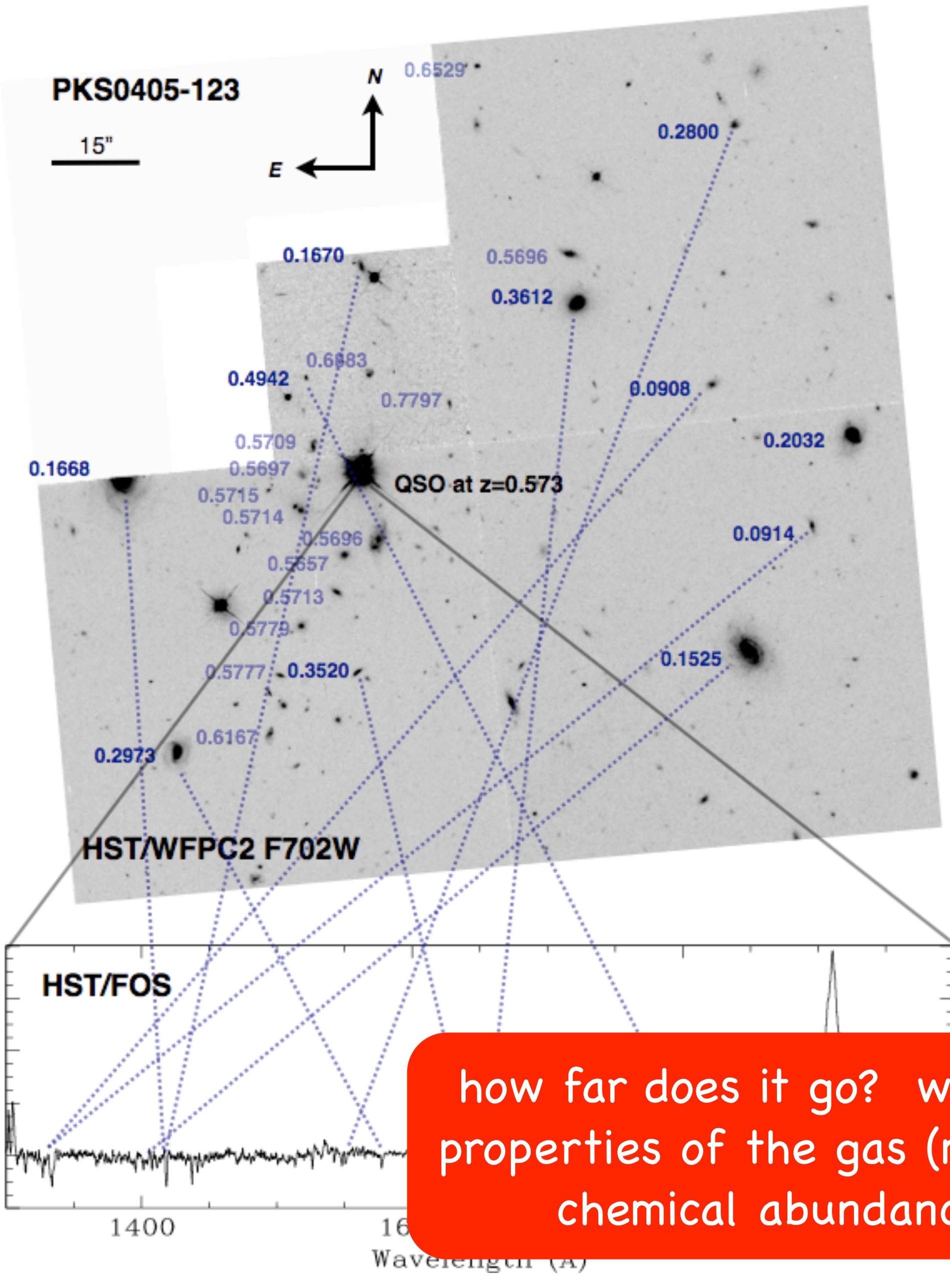
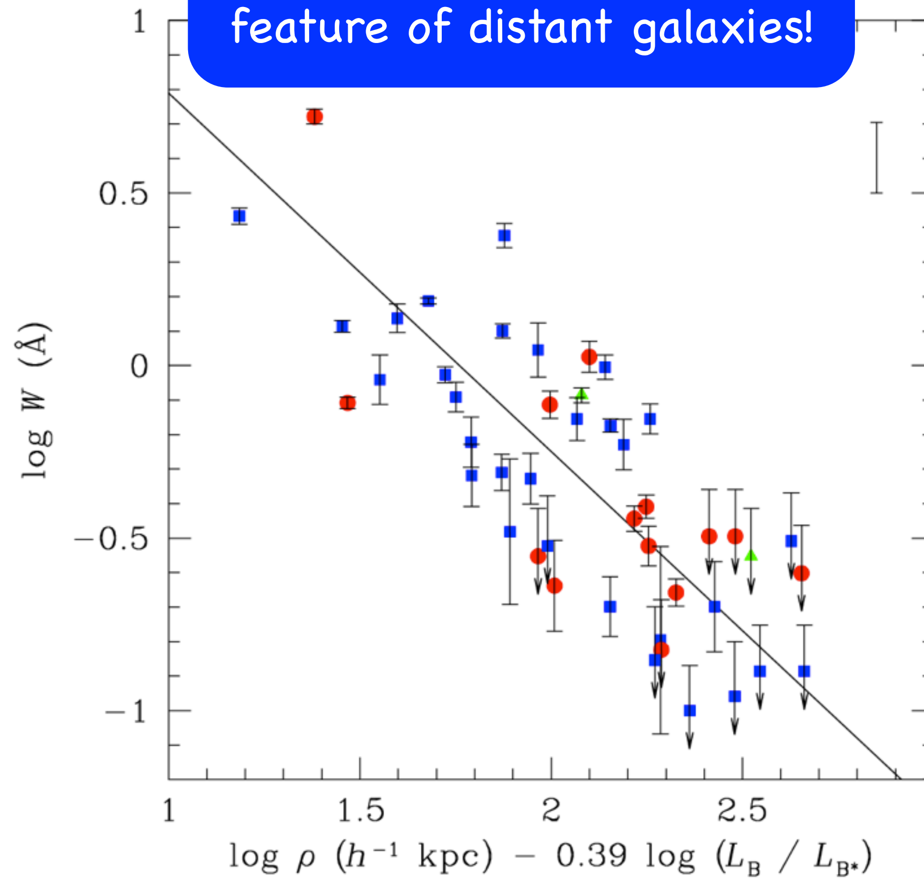


extended gas appears to be a common and generic feature of distant galaxies!



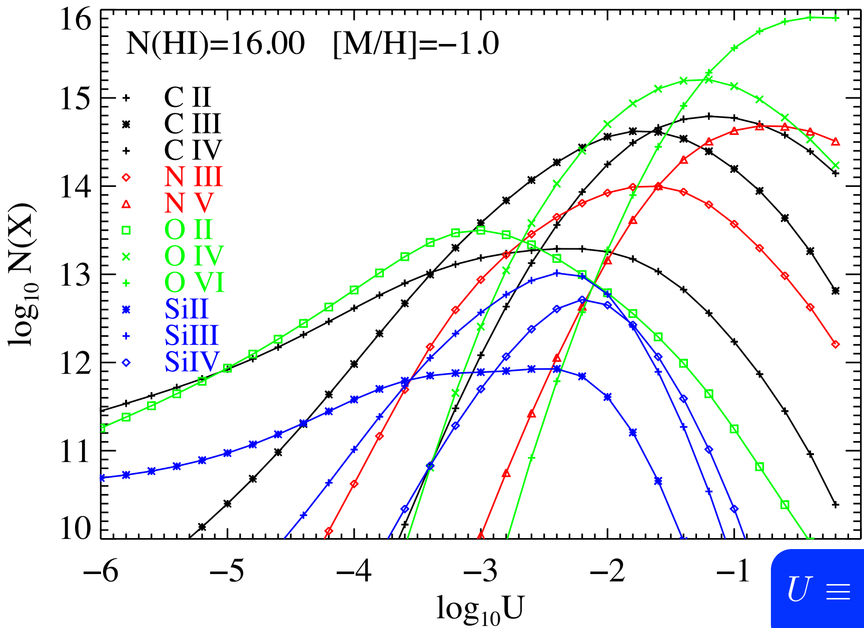
Chen et al. (1998, 2001)

how far does it go? what are the physical properties of the gas (mass, ionization state, chemical abundances, kinematics)?

Probing circumgalactic medium at high redshift

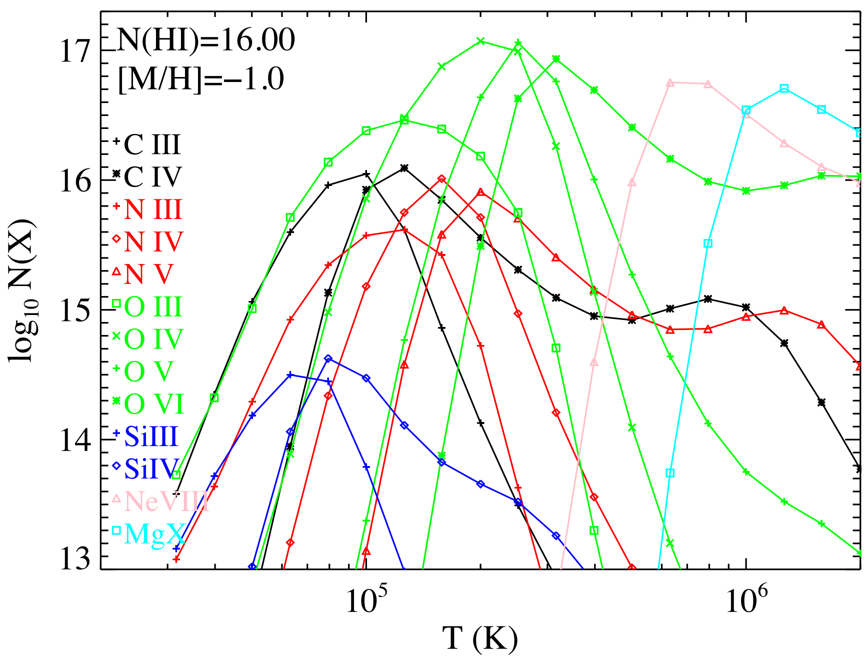
ionization state

photo-ionization



$$U \equiv \frac{\phi}{c\, n_{\mathrm{H}}}$$

collisional ionization



Probing circumgalactic medium at high redshift

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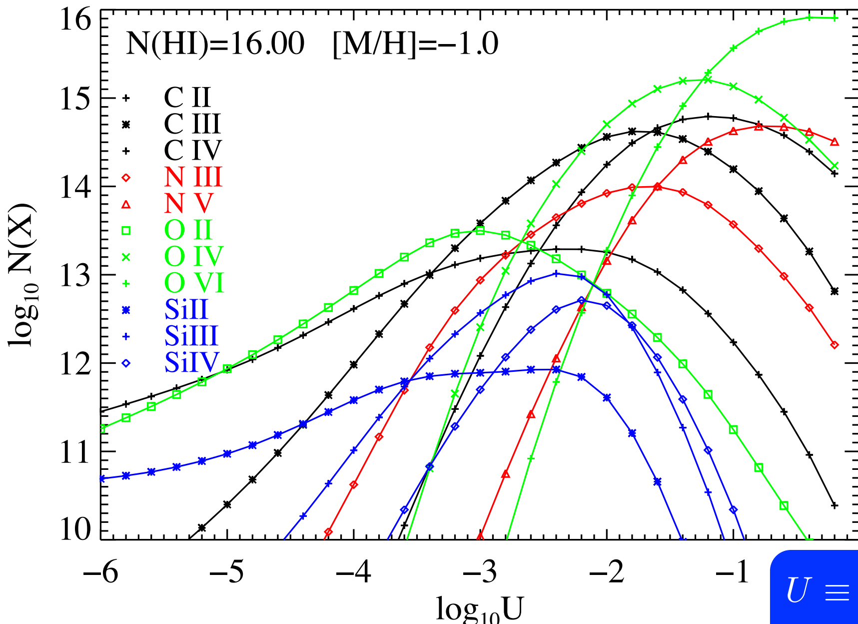

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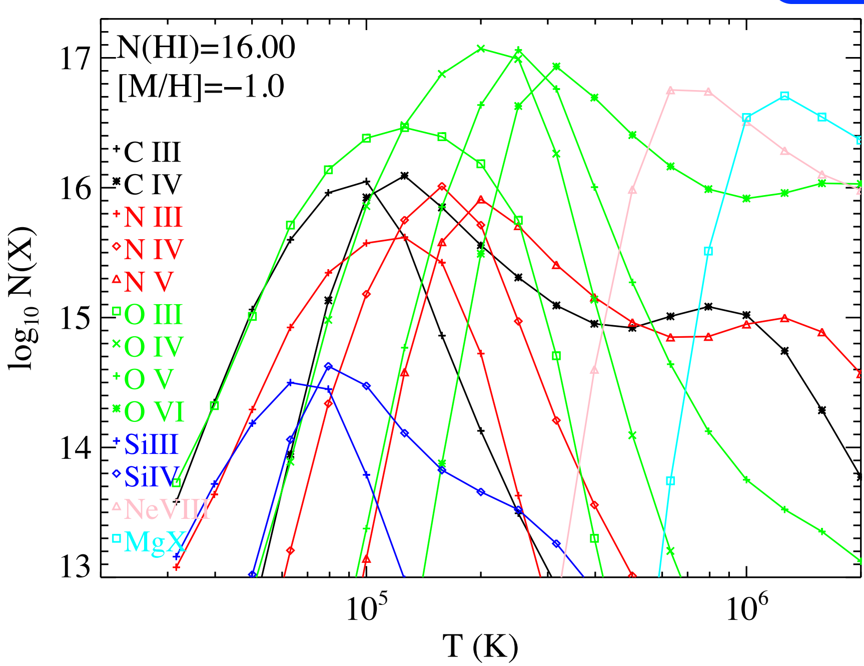
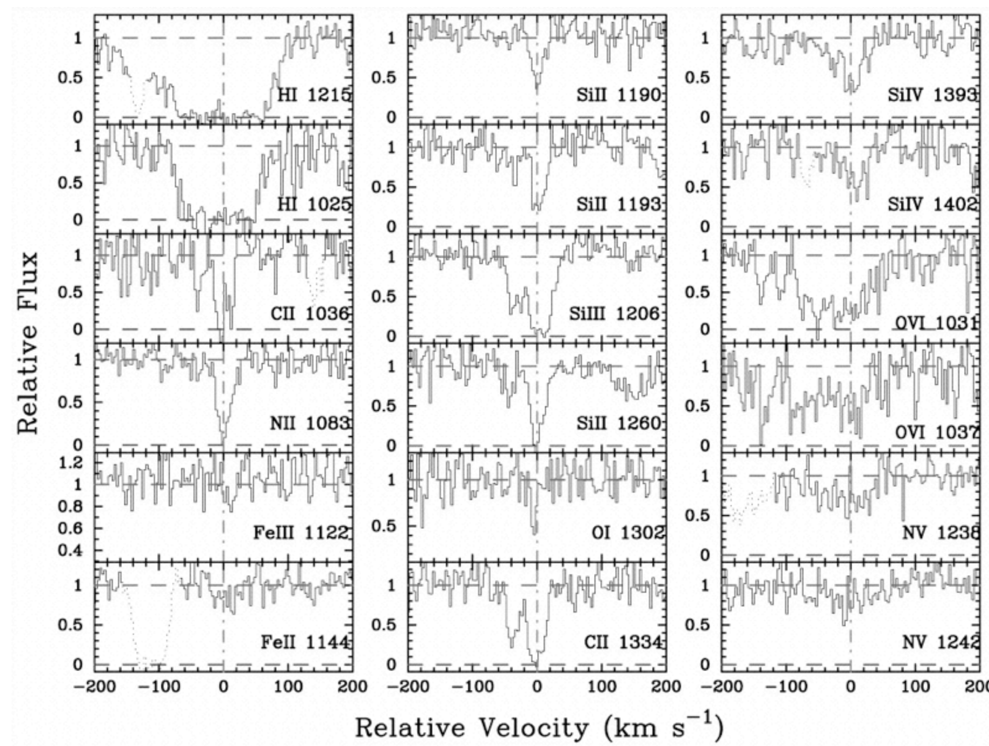


partial Lyman limit system at z=0.167



log N(HI)=16.45±0.05

Chen & Prochaska (2000)

Probing circumgalactic medium at high redshift

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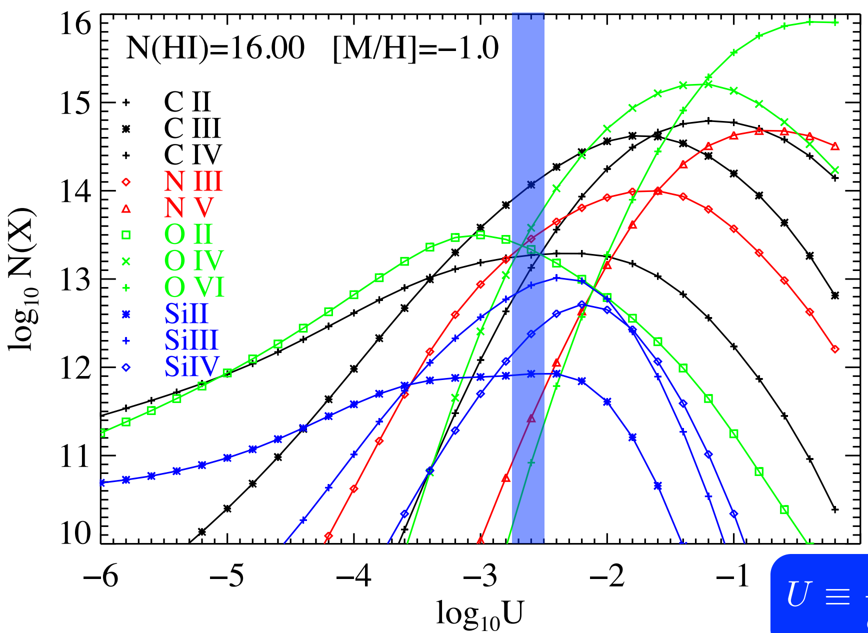

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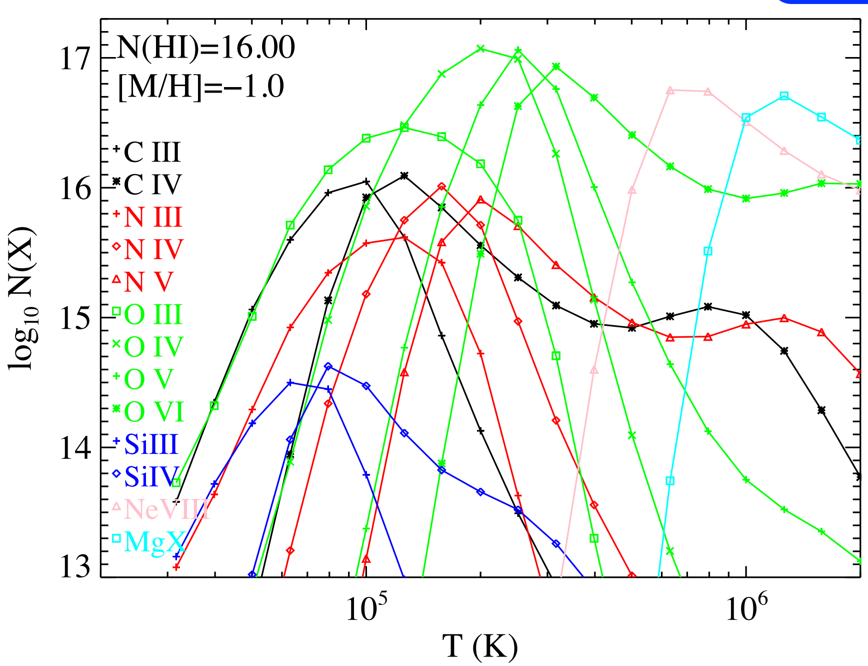

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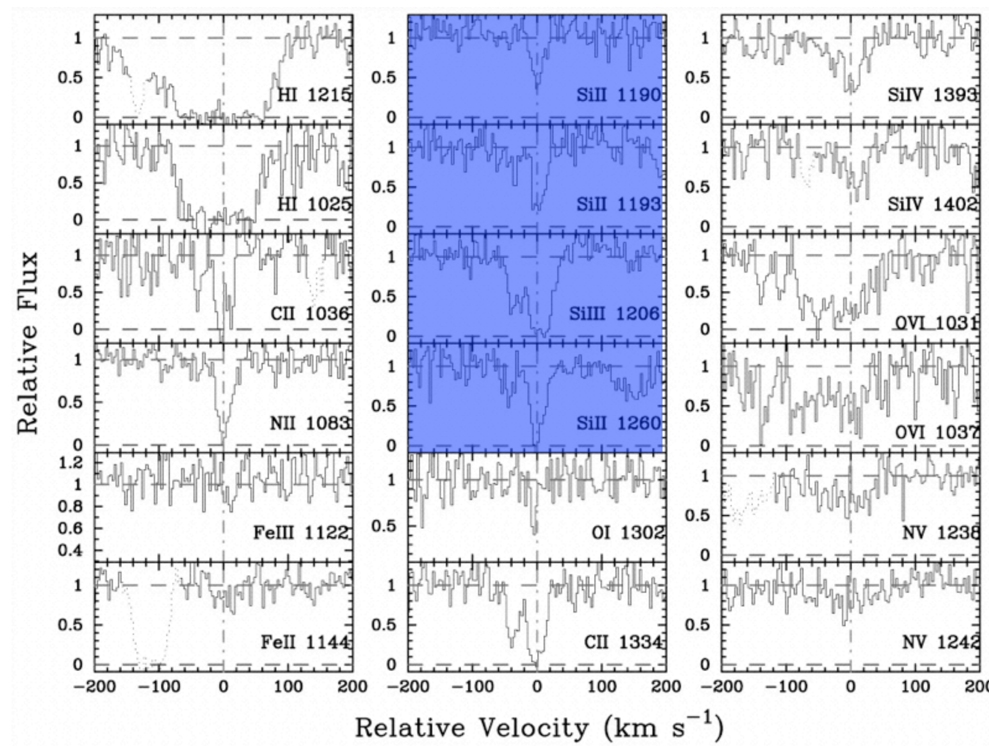

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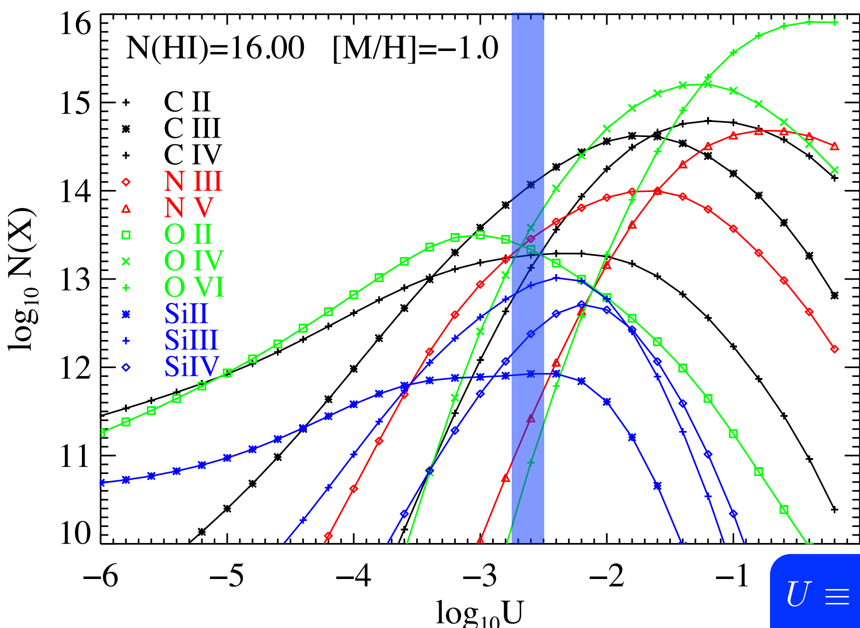

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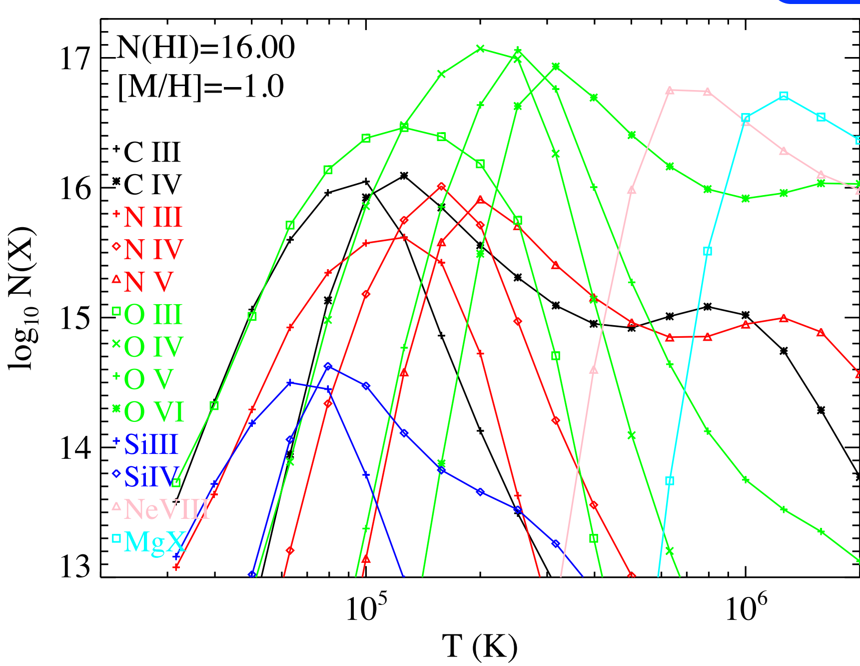

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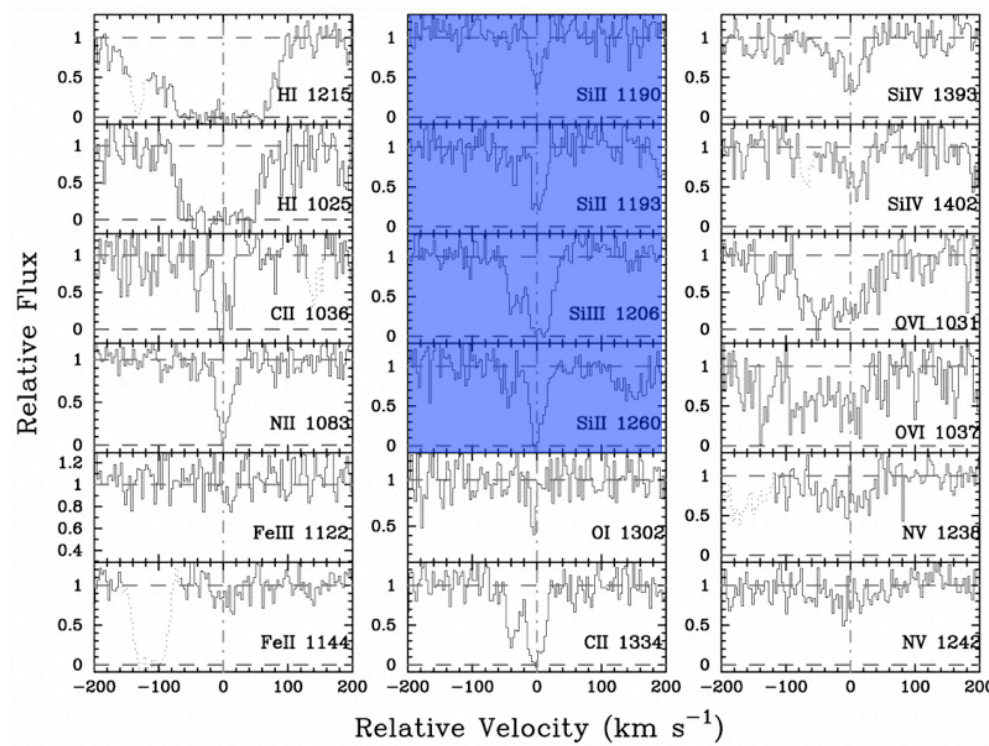

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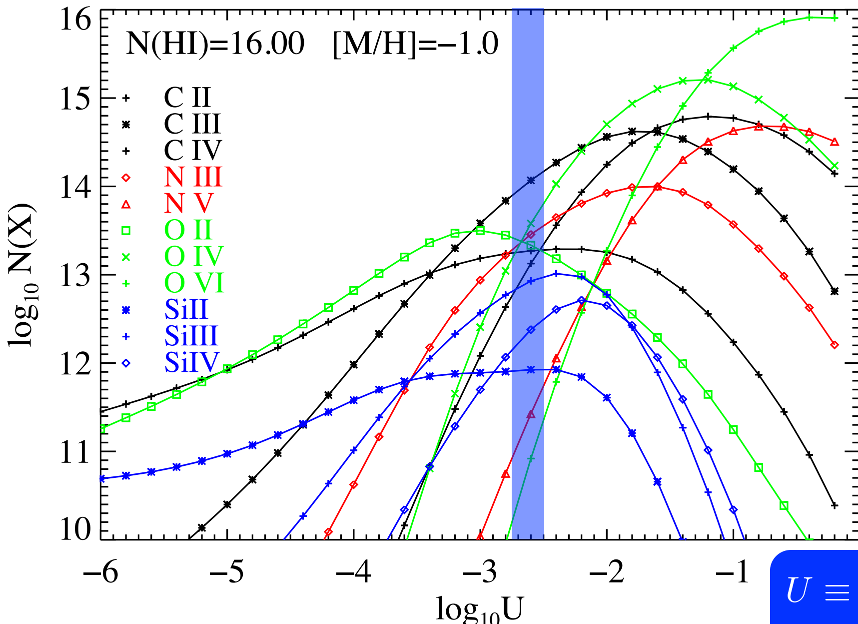
Taking $J_{912} \approx 2 \times 10^{-23}\, {\rm erg\, s^{-1}\, cm^{-2}\, Hz^{-1}\, sr^{-1}}$

$$\rightarrow n_{\rm H} \approx 6 \times 10^{-4}\, {\rm cm^{-3}}$$

Probing circumgalactic medium at high redshift

ionization state

photo-ionization



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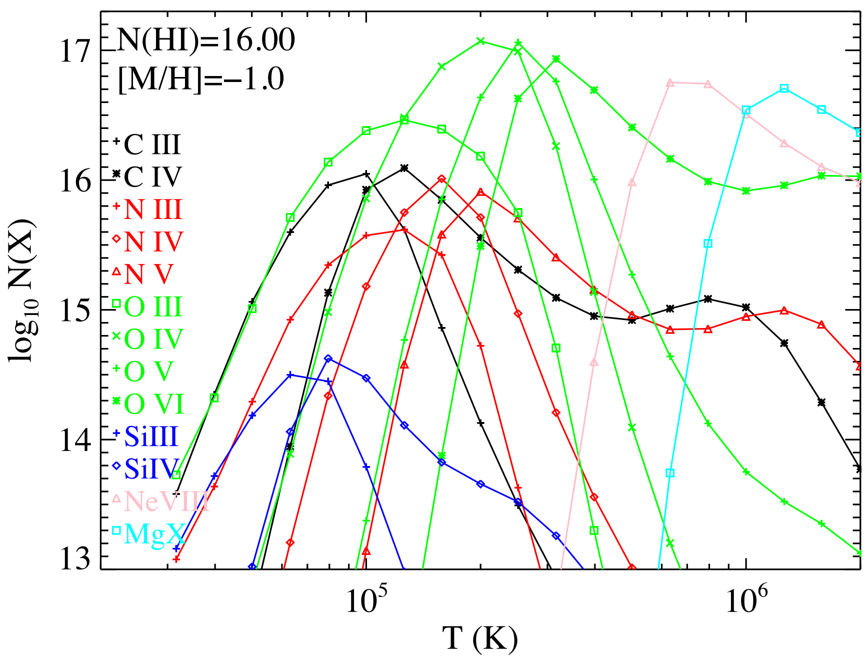

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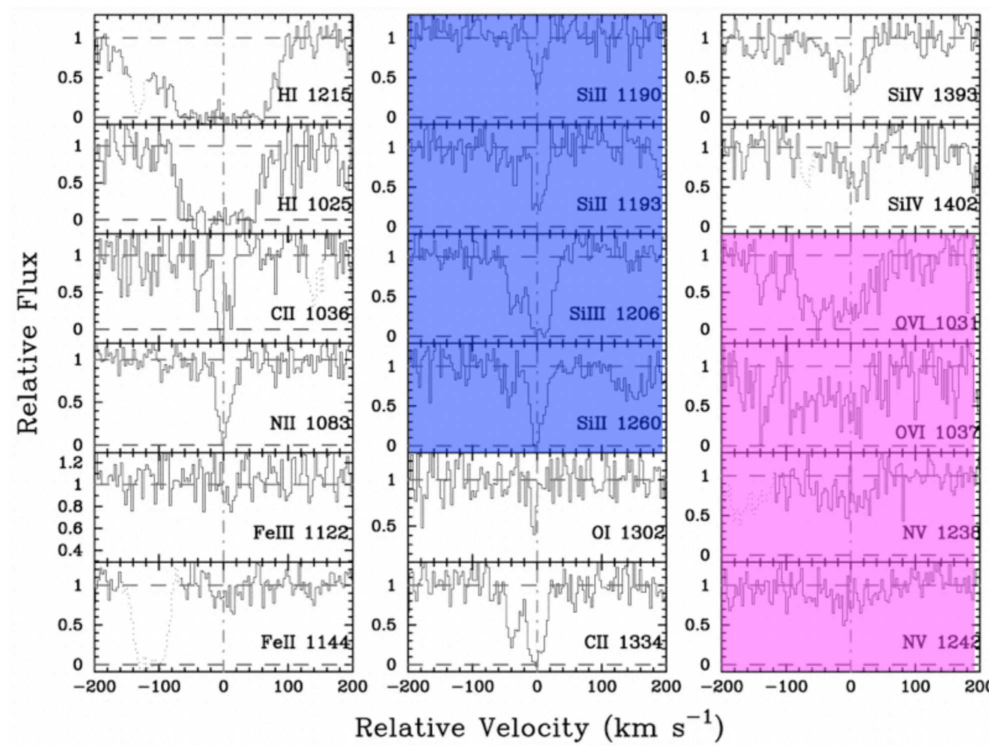

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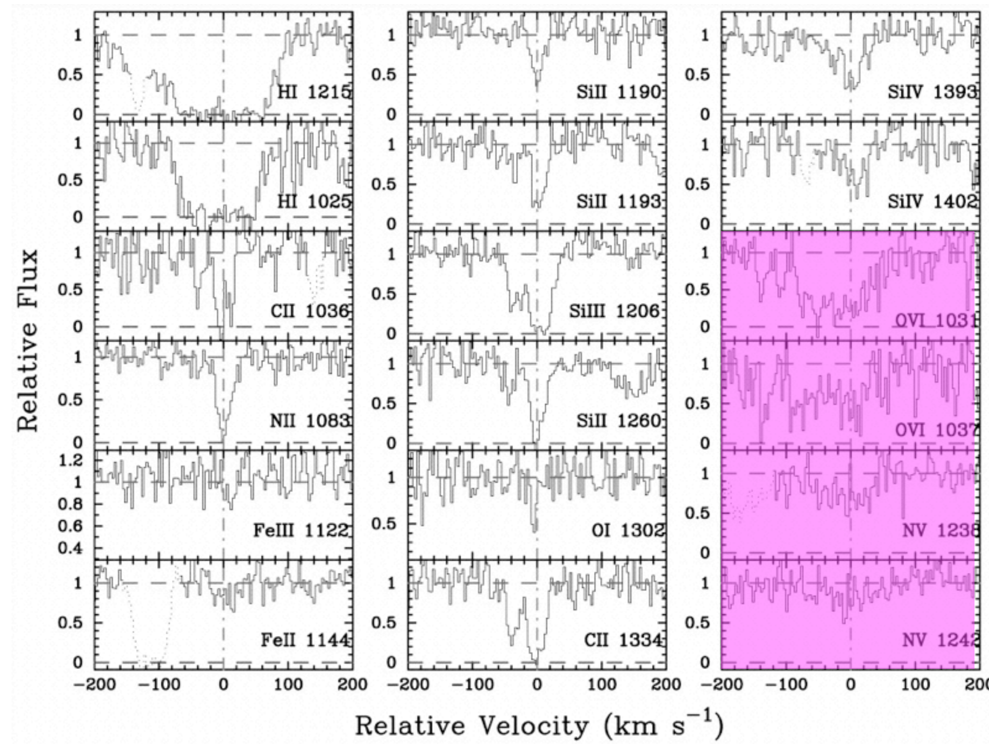
Probing circumgalactic medium at high redshift

gas temperature

partial Lyman limit system at z=0.167



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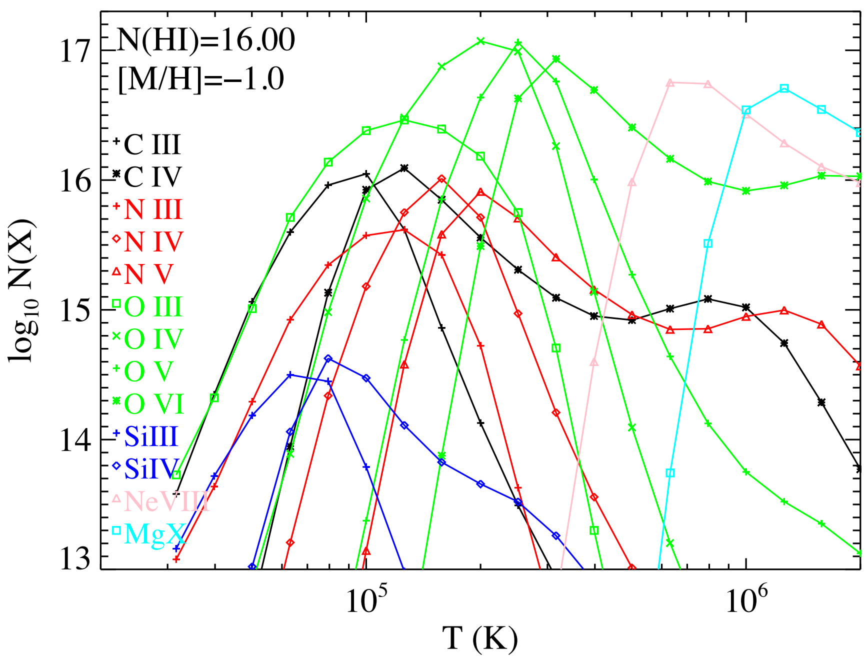

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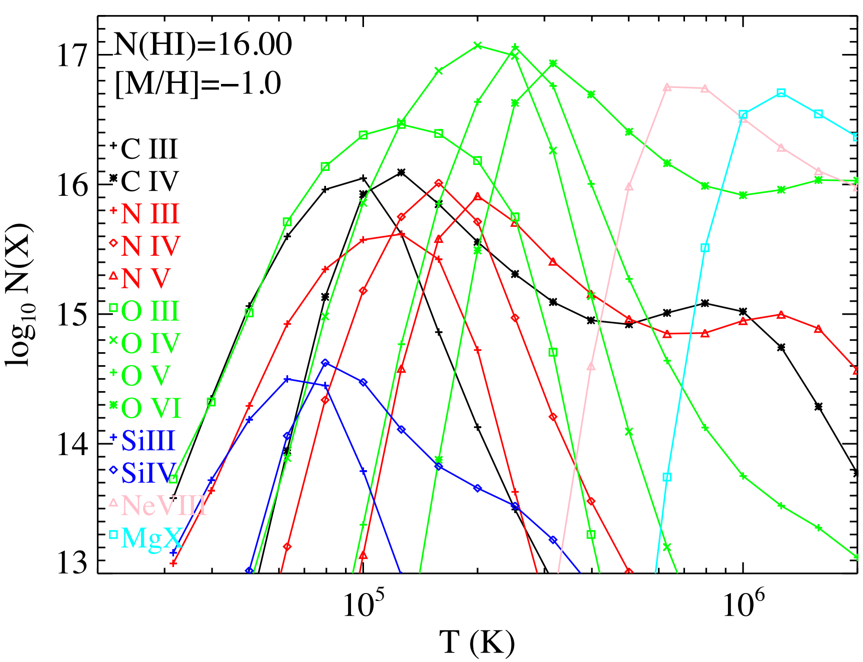
Probing circumgalactic medium at high redshift

gas temperature

$$b_{\rm obs}^2 = b_{nt}^2 + \frac{2kT}{m}$$

collisional ionization



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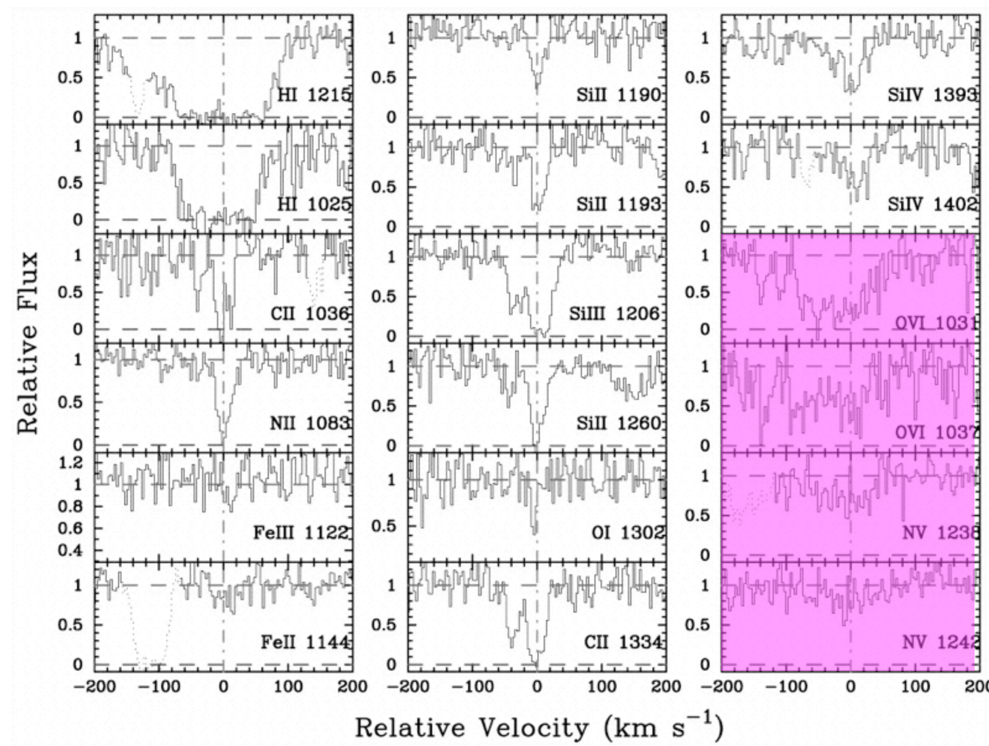

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Probing circumgalactic medium at high redshift

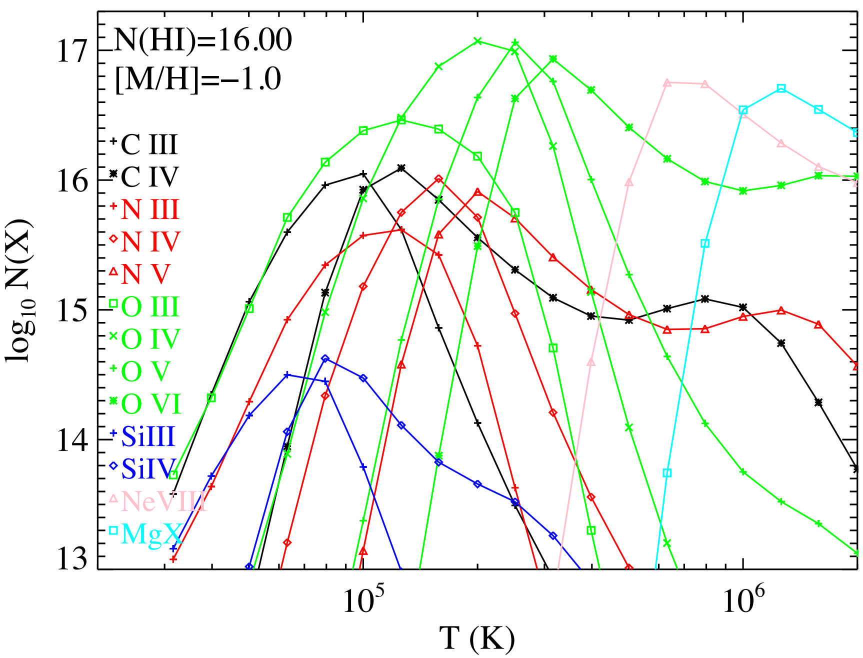
gas temperature

$$b^2_{\rm obs} = b^2_{nt} + \frac{2kT}{m}$$

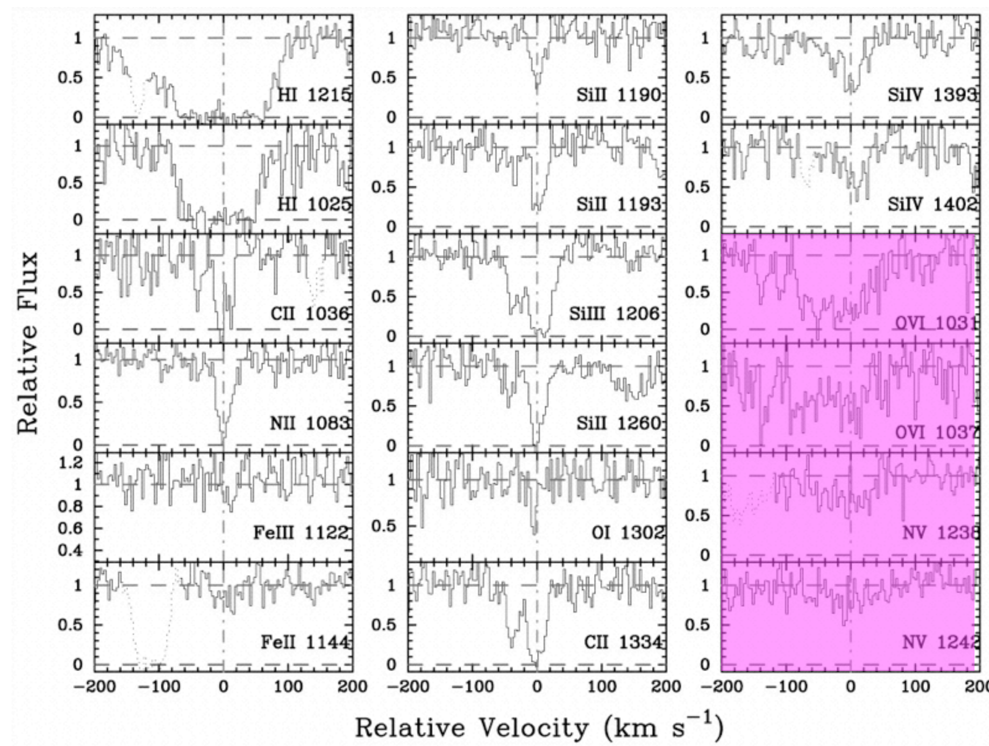
comparing b_{NV} and b_{OVI} leads to

$$T \approx 1.5 \times 10^5\,{\rm K}$$

collisional ionization



partial Lyman limit system at z=0.167



Chen & Prochaska (2000)

log N(HI)=16.45±0.05

Taking $J_{912} \approx 2 \times 10^{-23}\,{\rm erg\,s^{-1}\,cm^{-2}\,Hz^{-1}\,sr^{-1}}$

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Probing circumgalactic medium at high redshift

gas temperature

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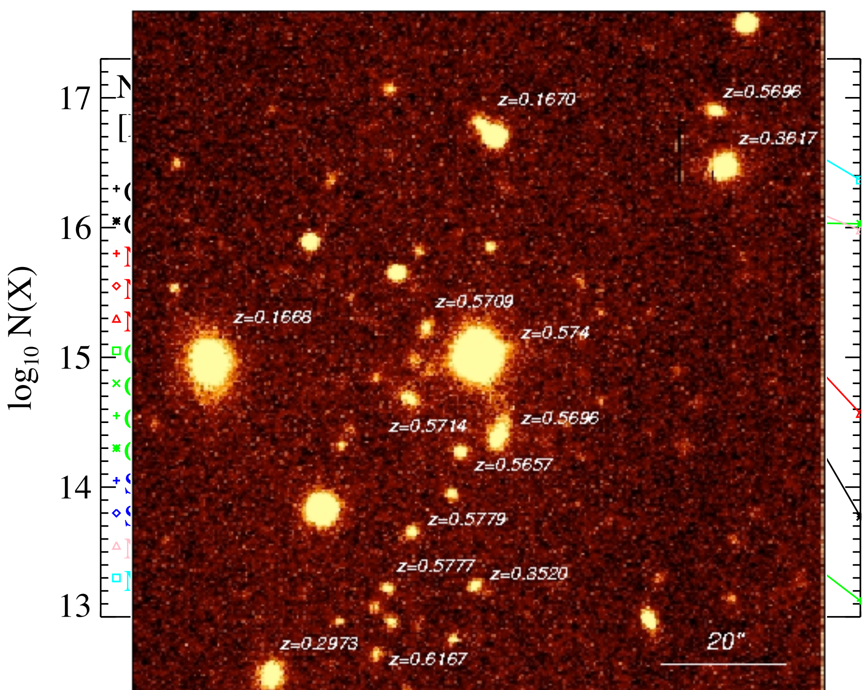

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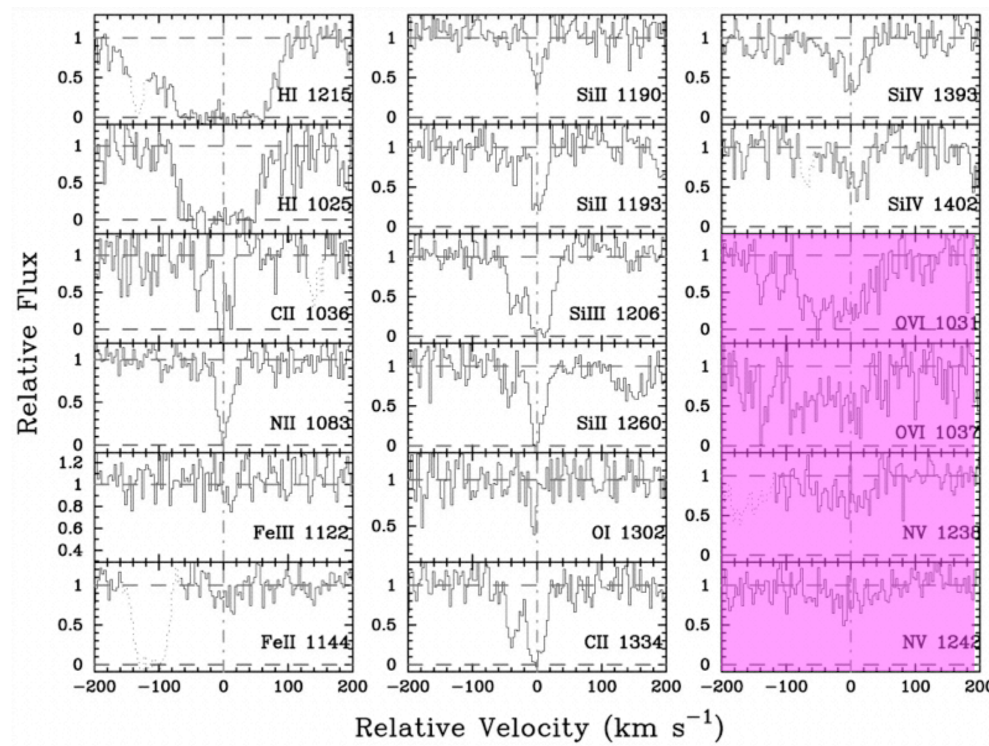

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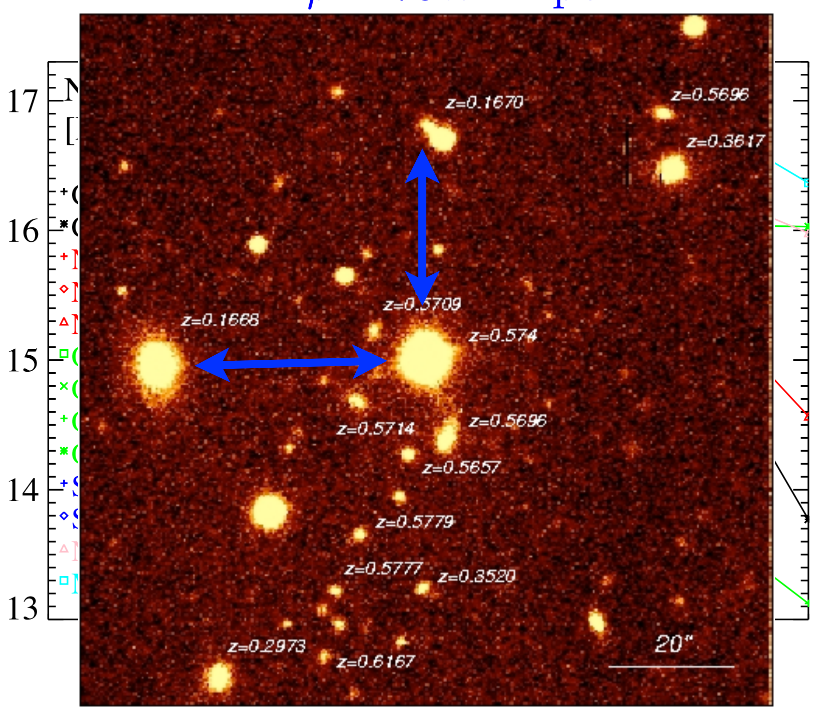

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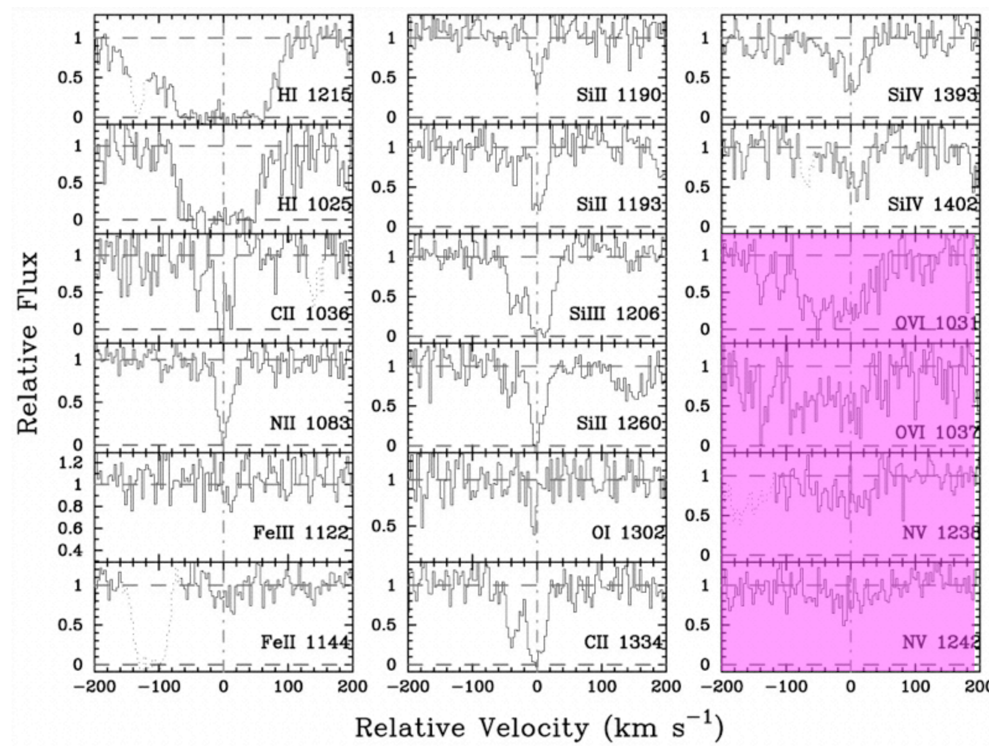

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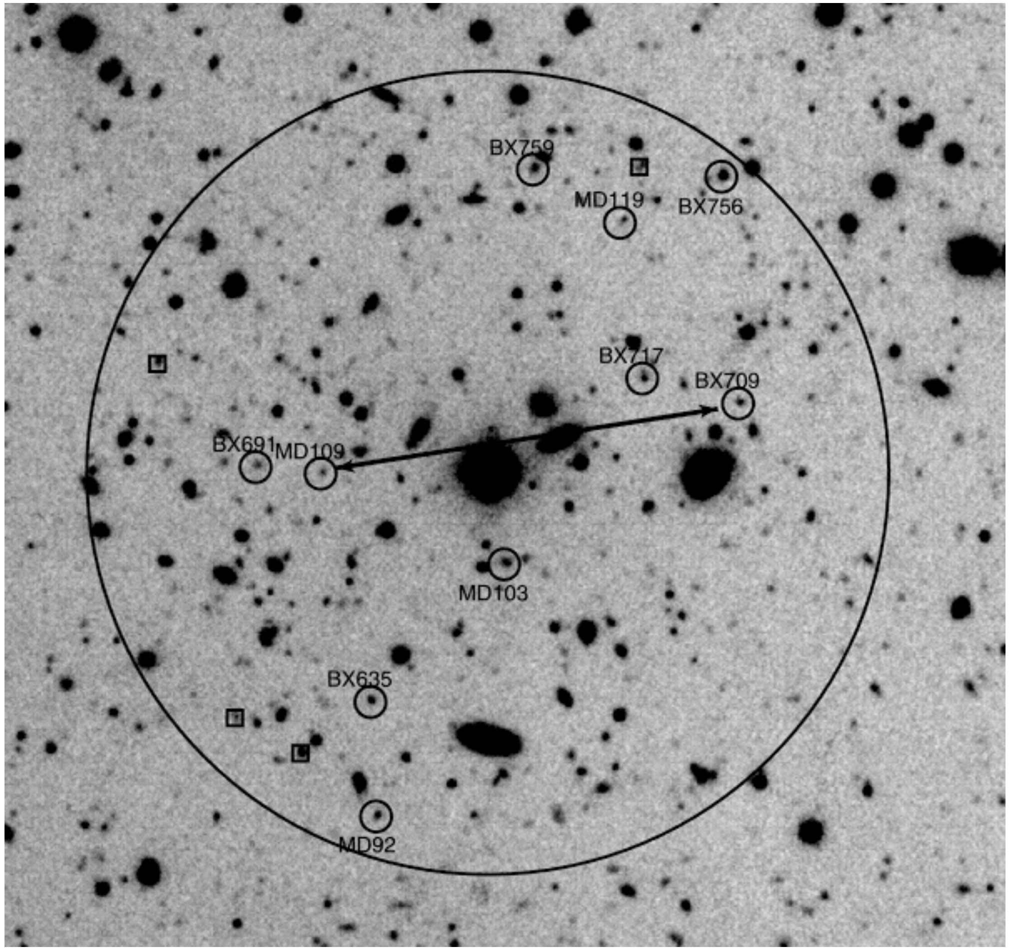

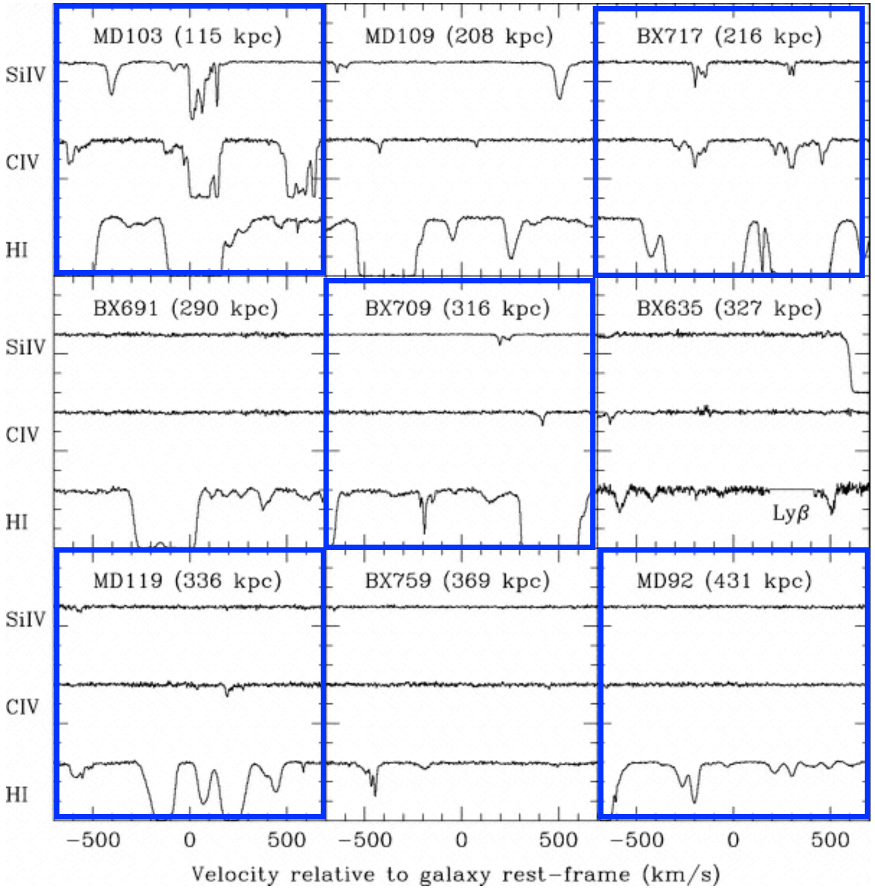

Simcoe et al. (2006)

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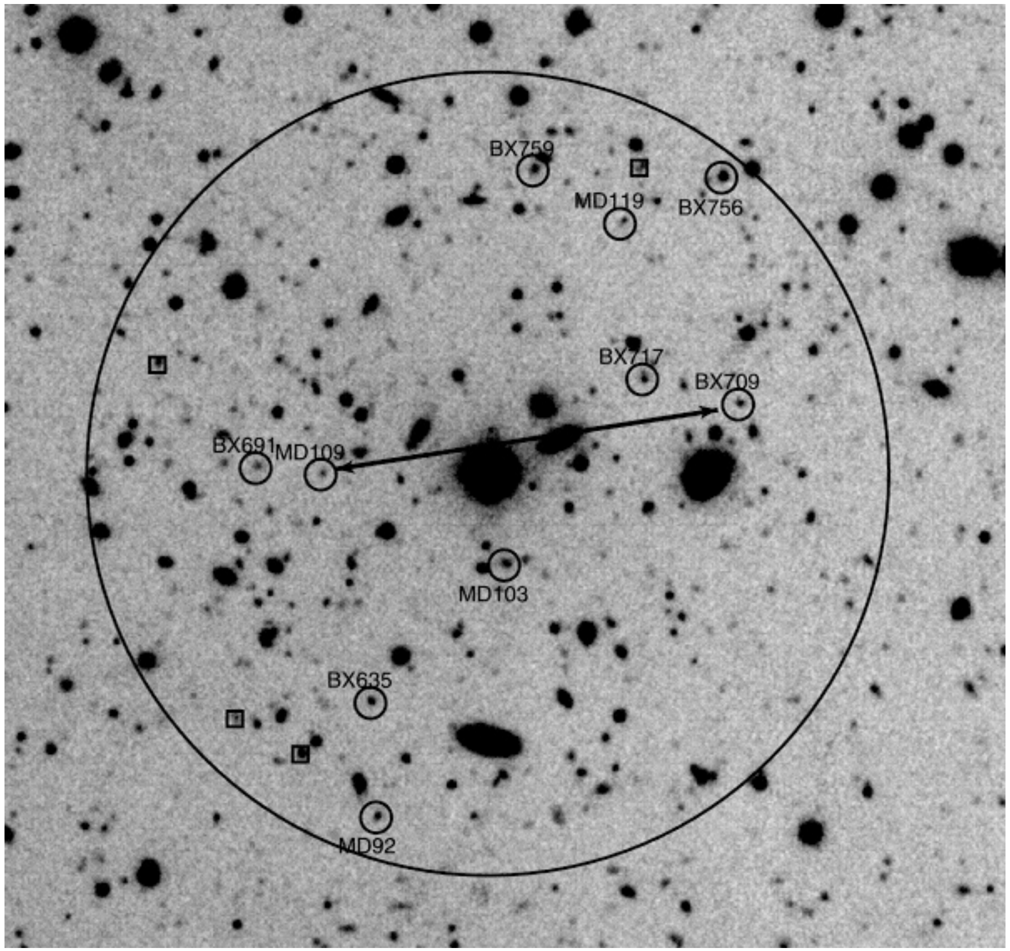

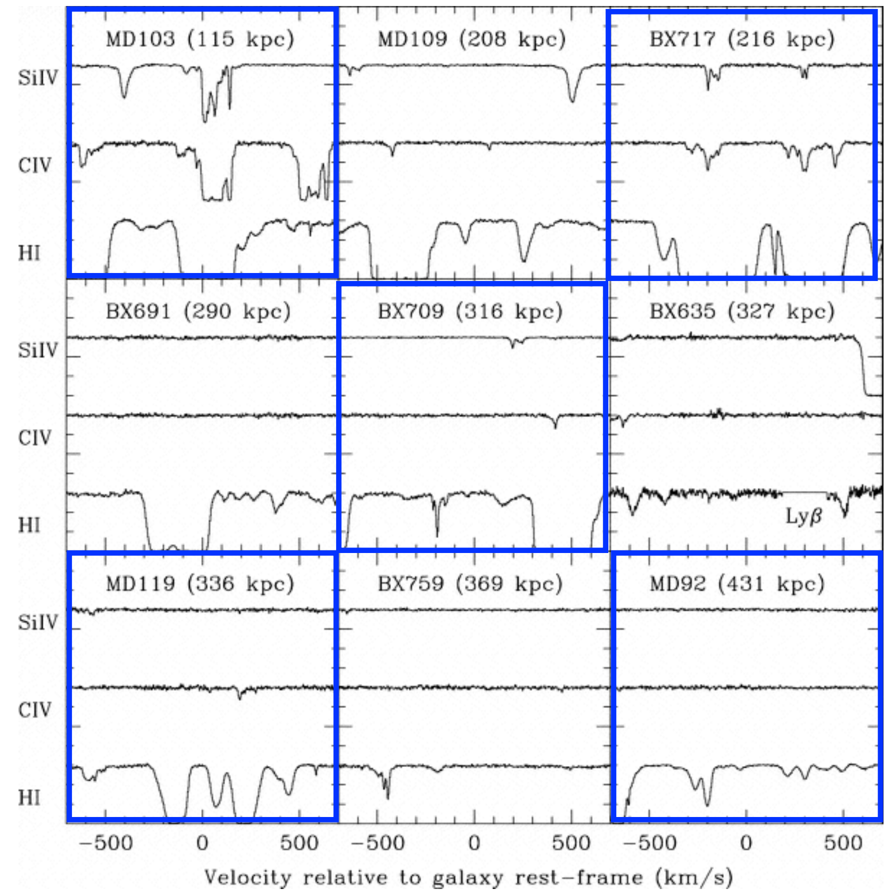

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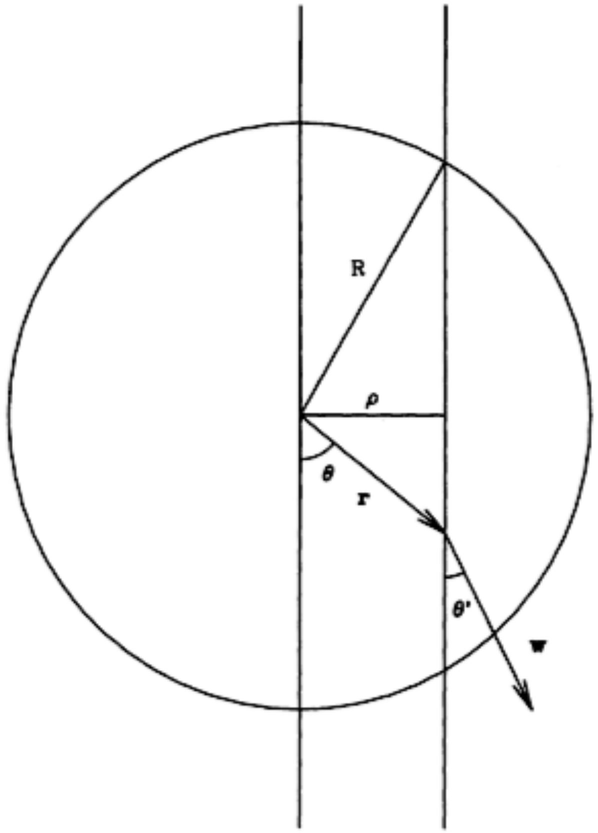
Caveat: incomplete galaxy survey, diffcult to establish a physical association

Kinematic signatures from well resolved lines

Lanzetta & Bowen 1992



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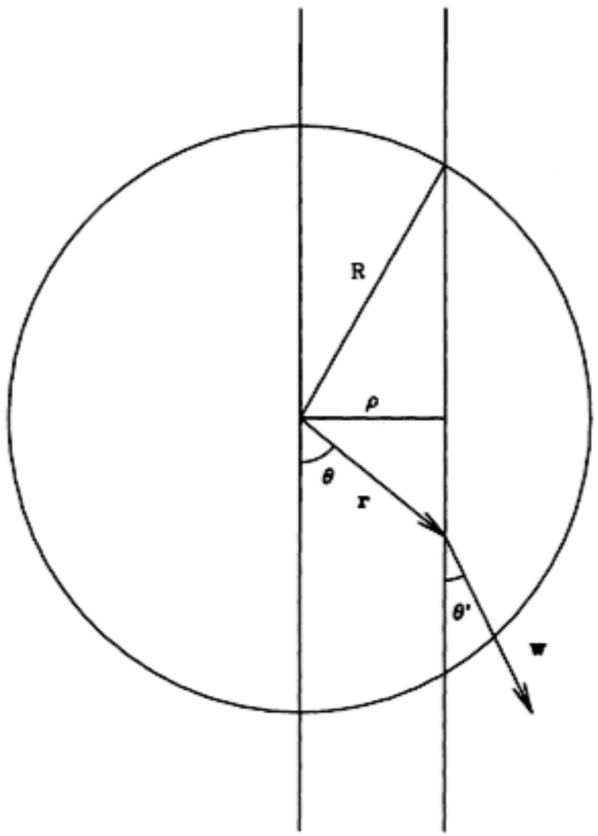

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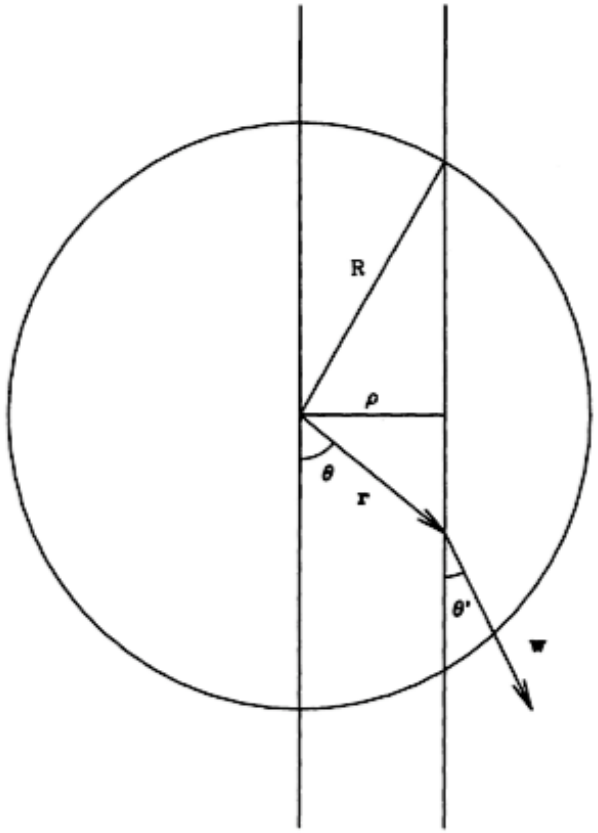

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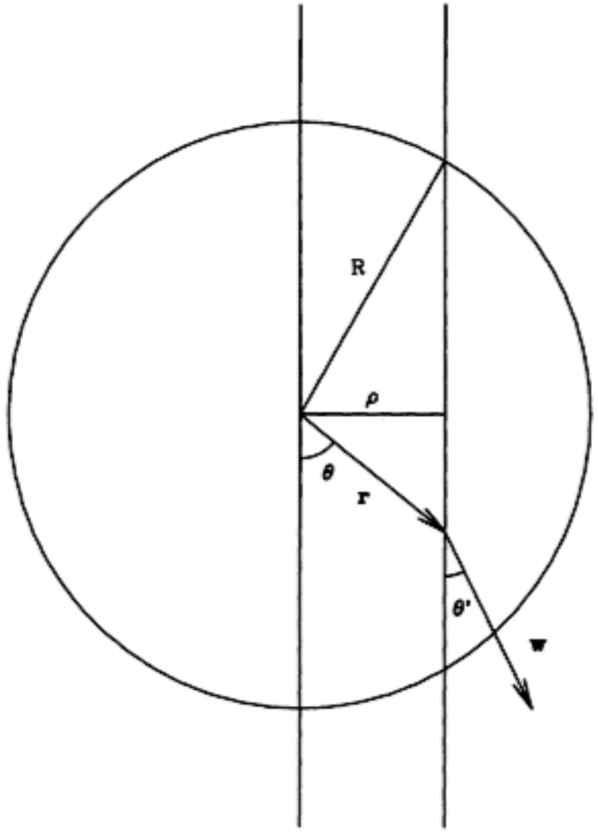

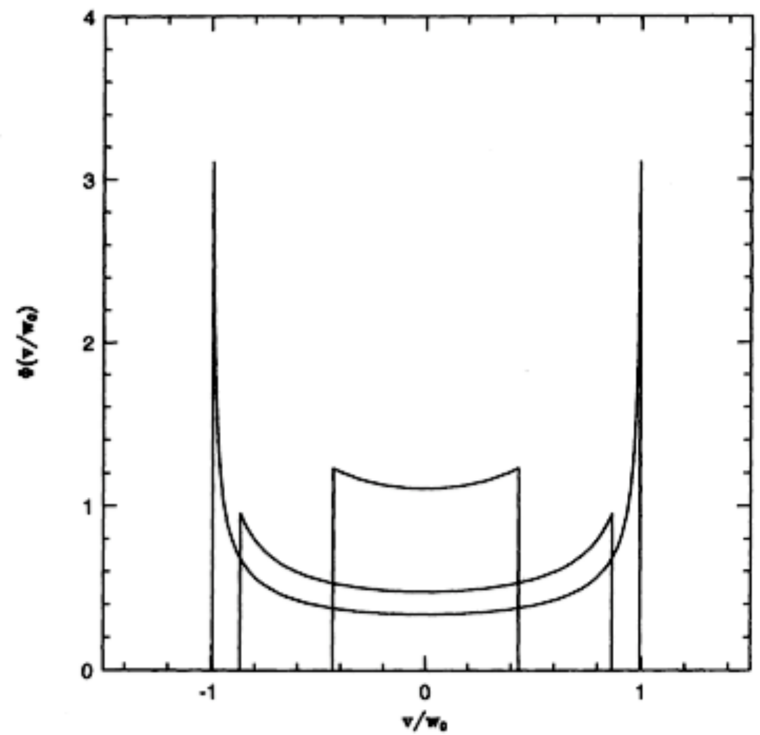

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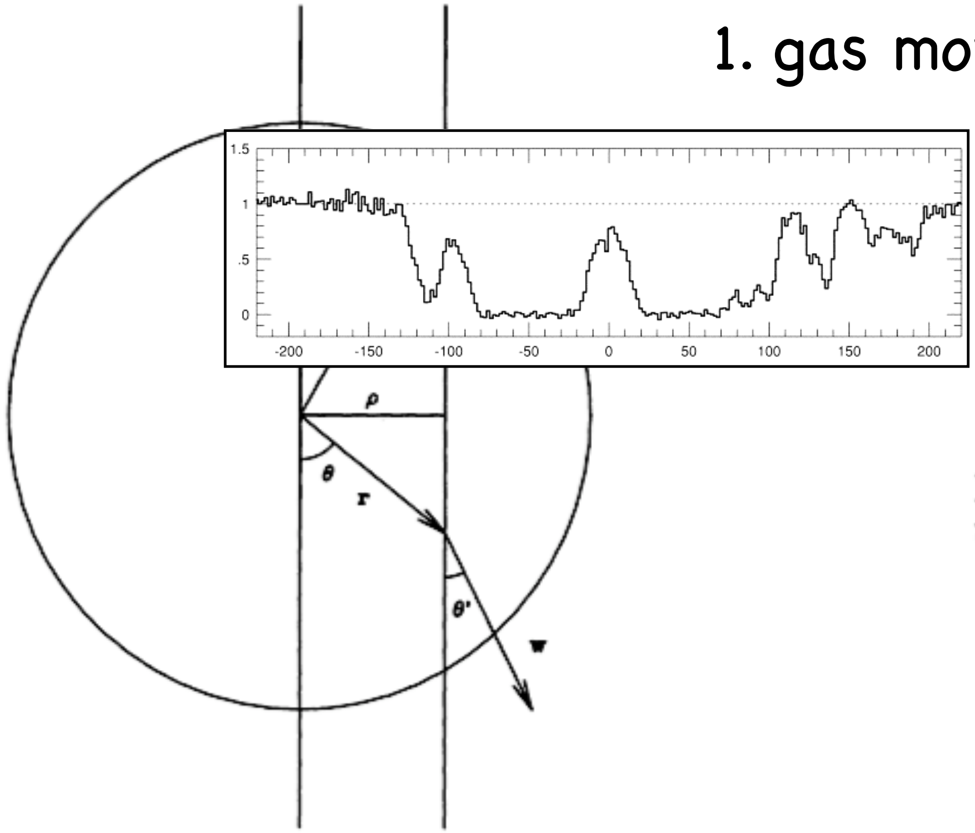

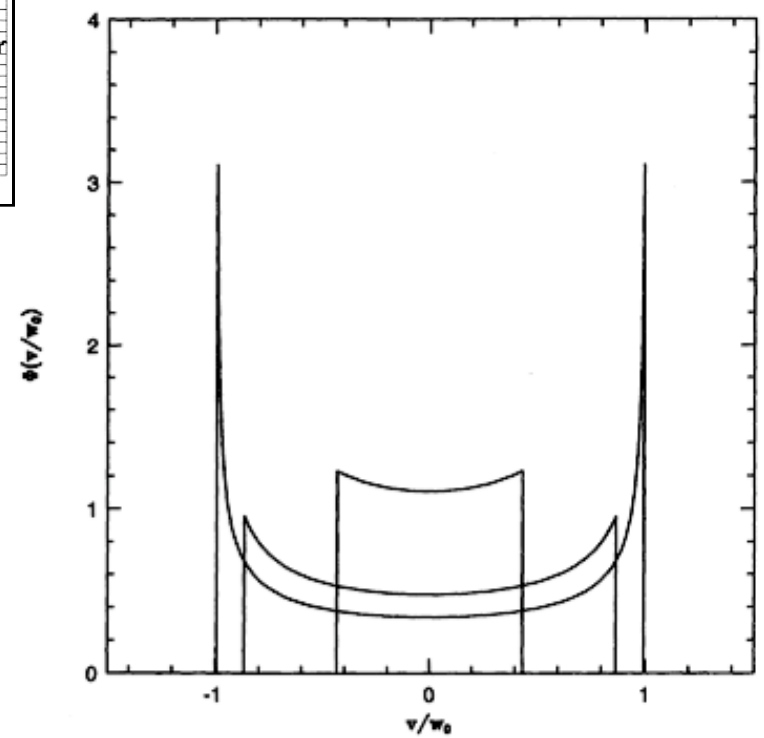

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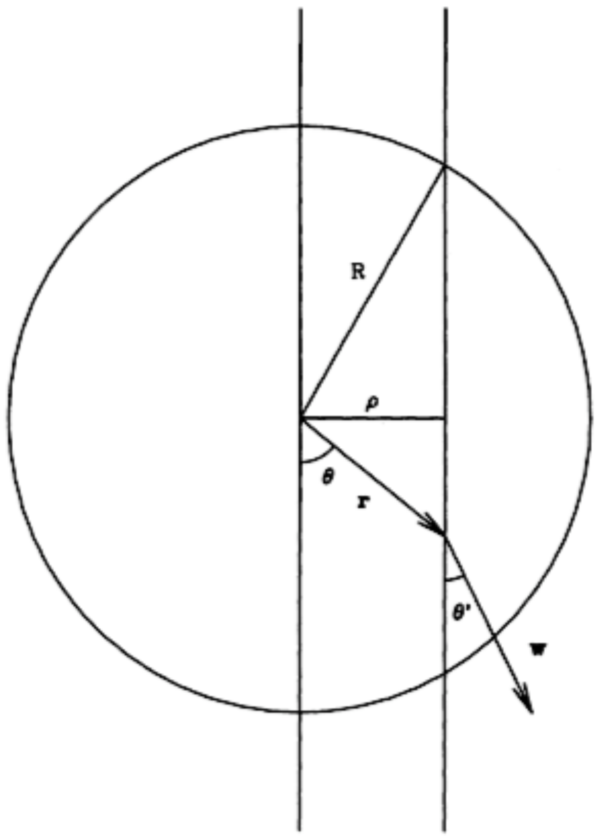

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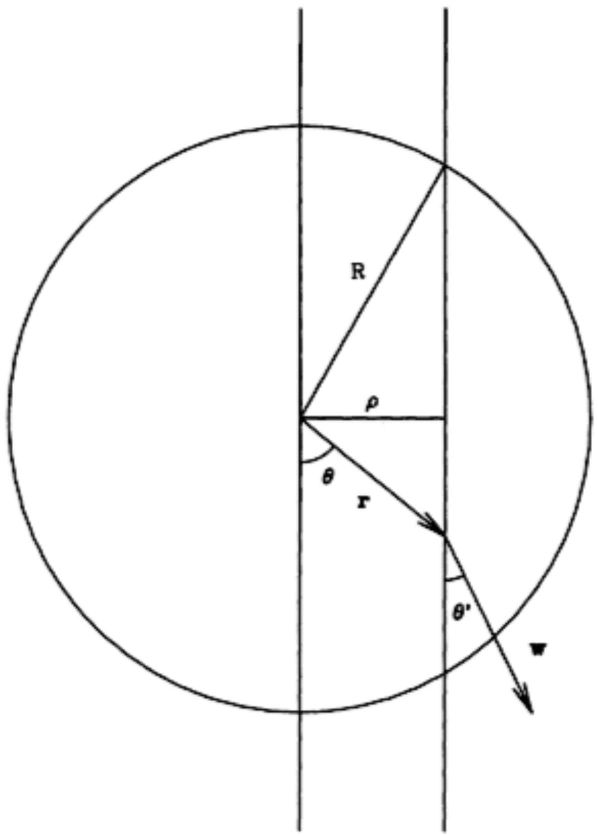

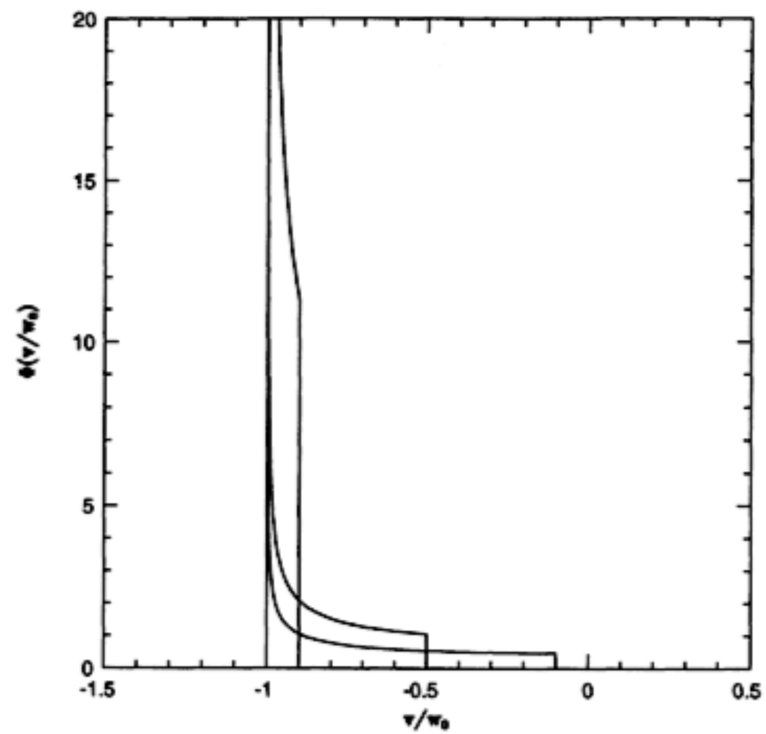

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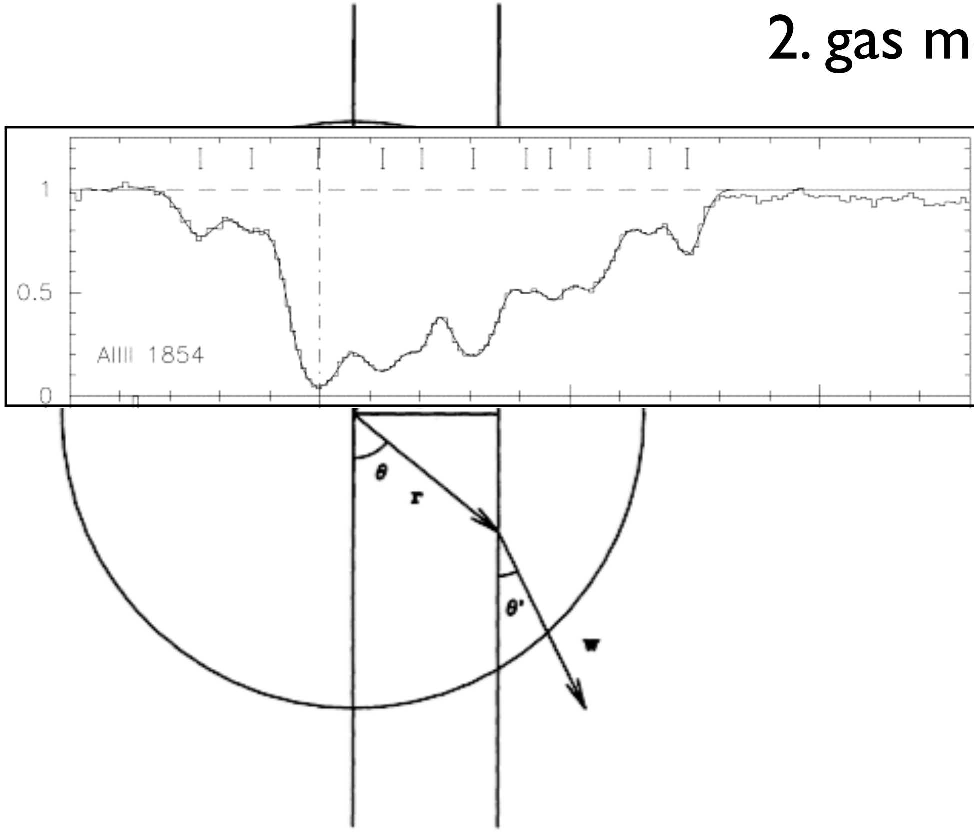

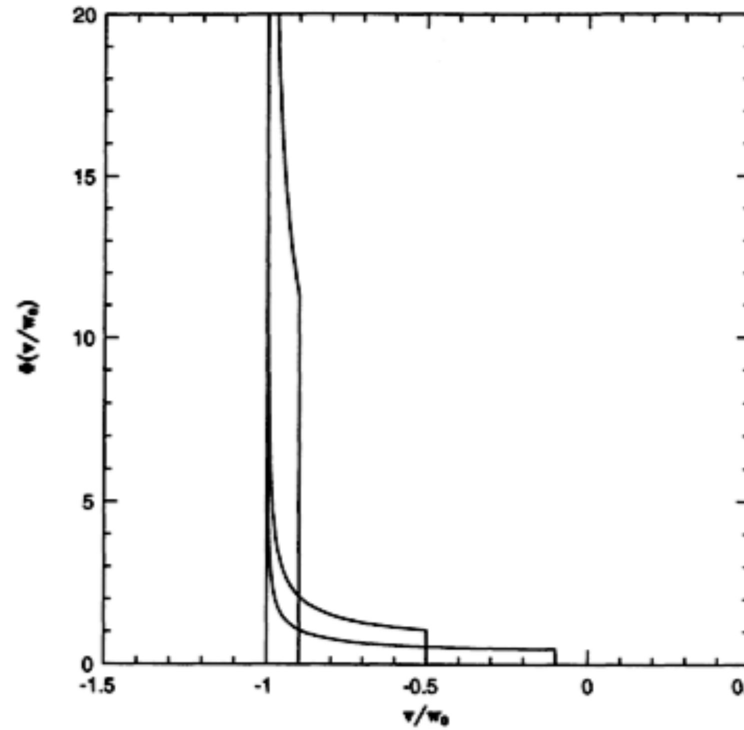

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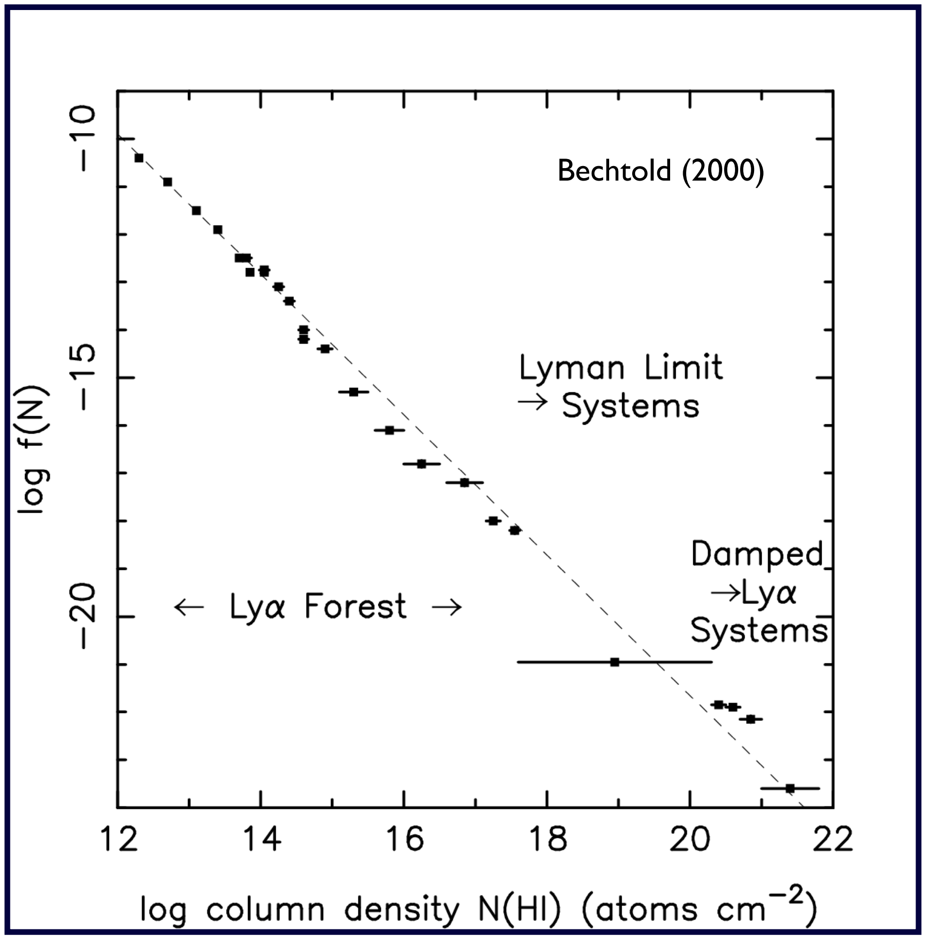
Mapping the dark universe with absorption spectroscopy

$$f(N,z) = \frac{\text{Number of Absorbers}}{\Delta N \, \Delta X} = A\,N^{-\beta}$$



10^9 x lower gas column

The Milky Way

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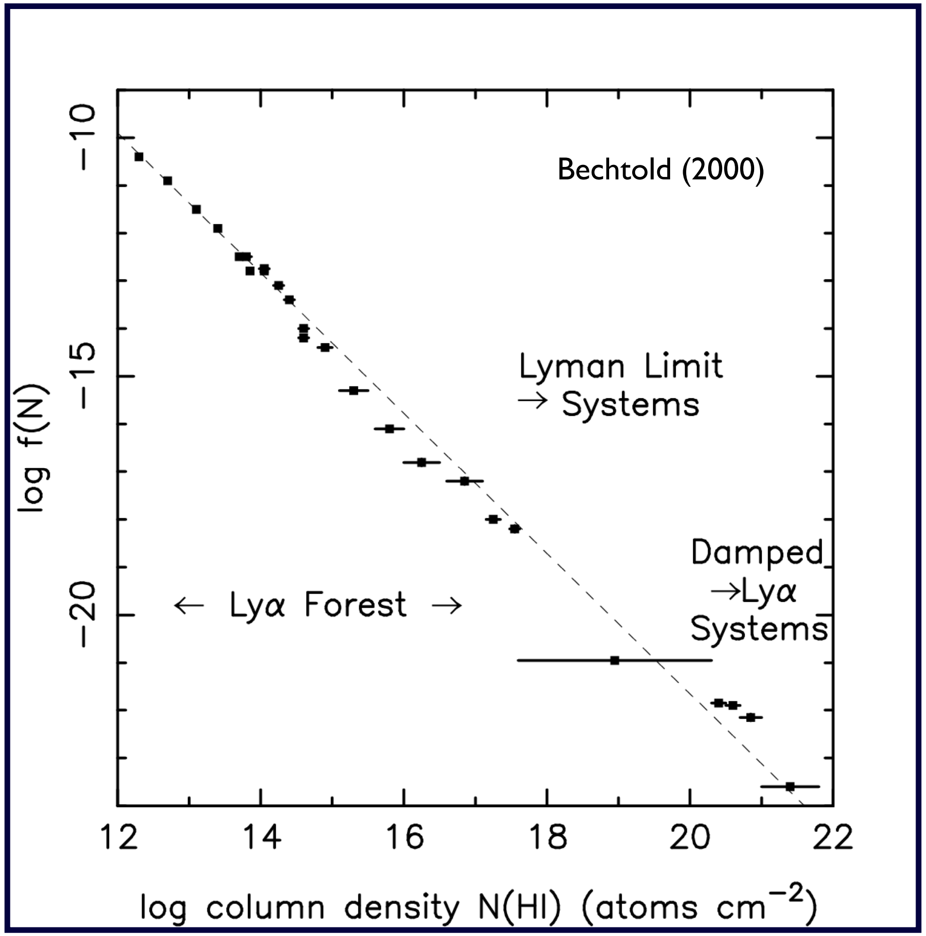

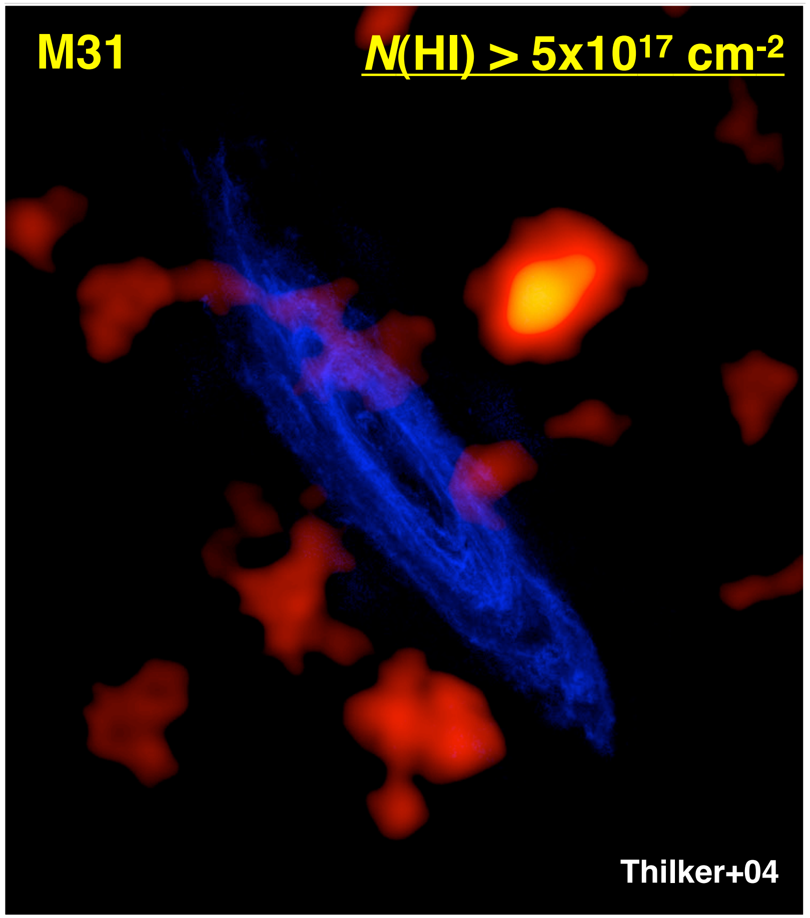

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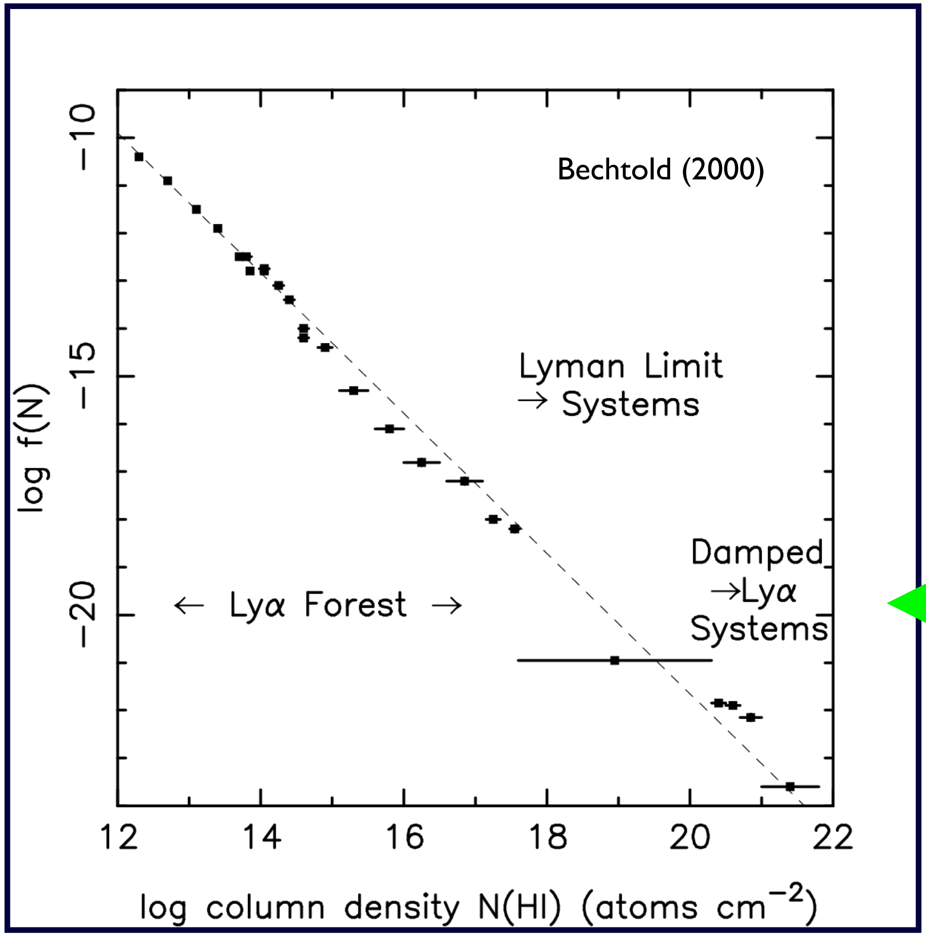

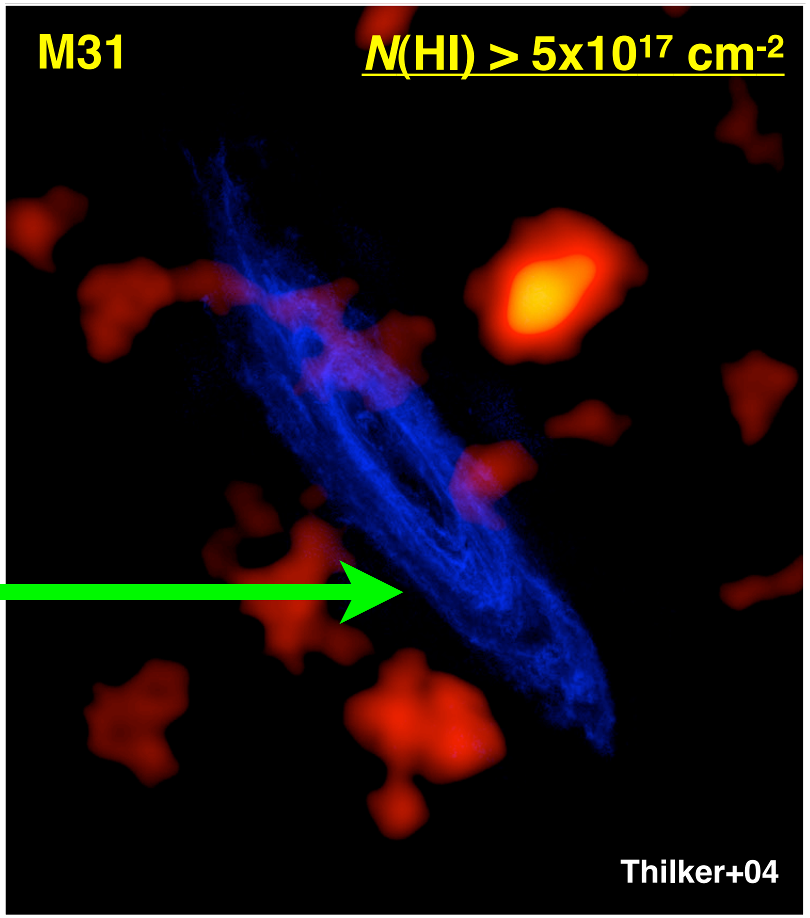

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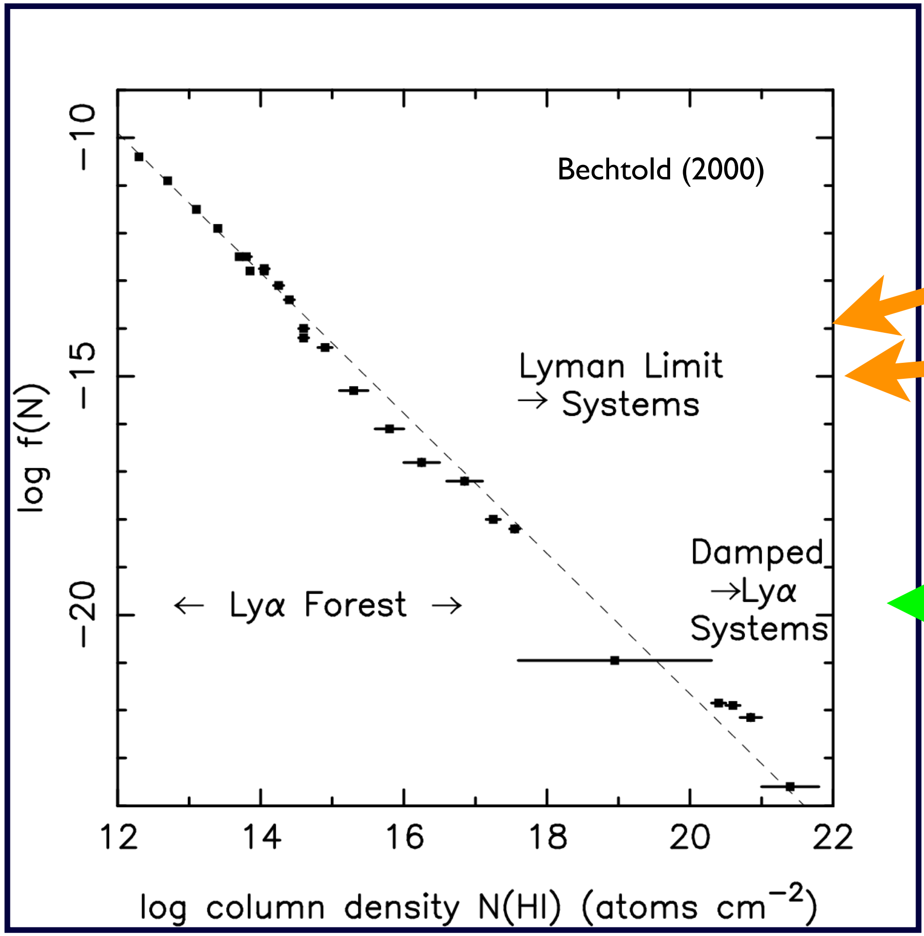

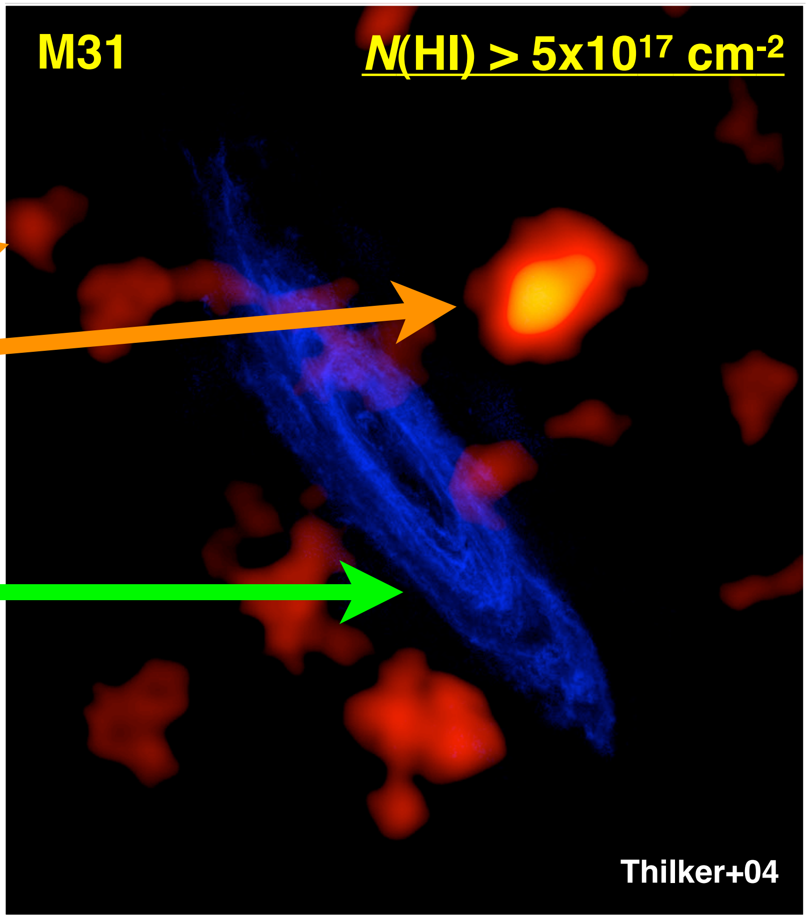

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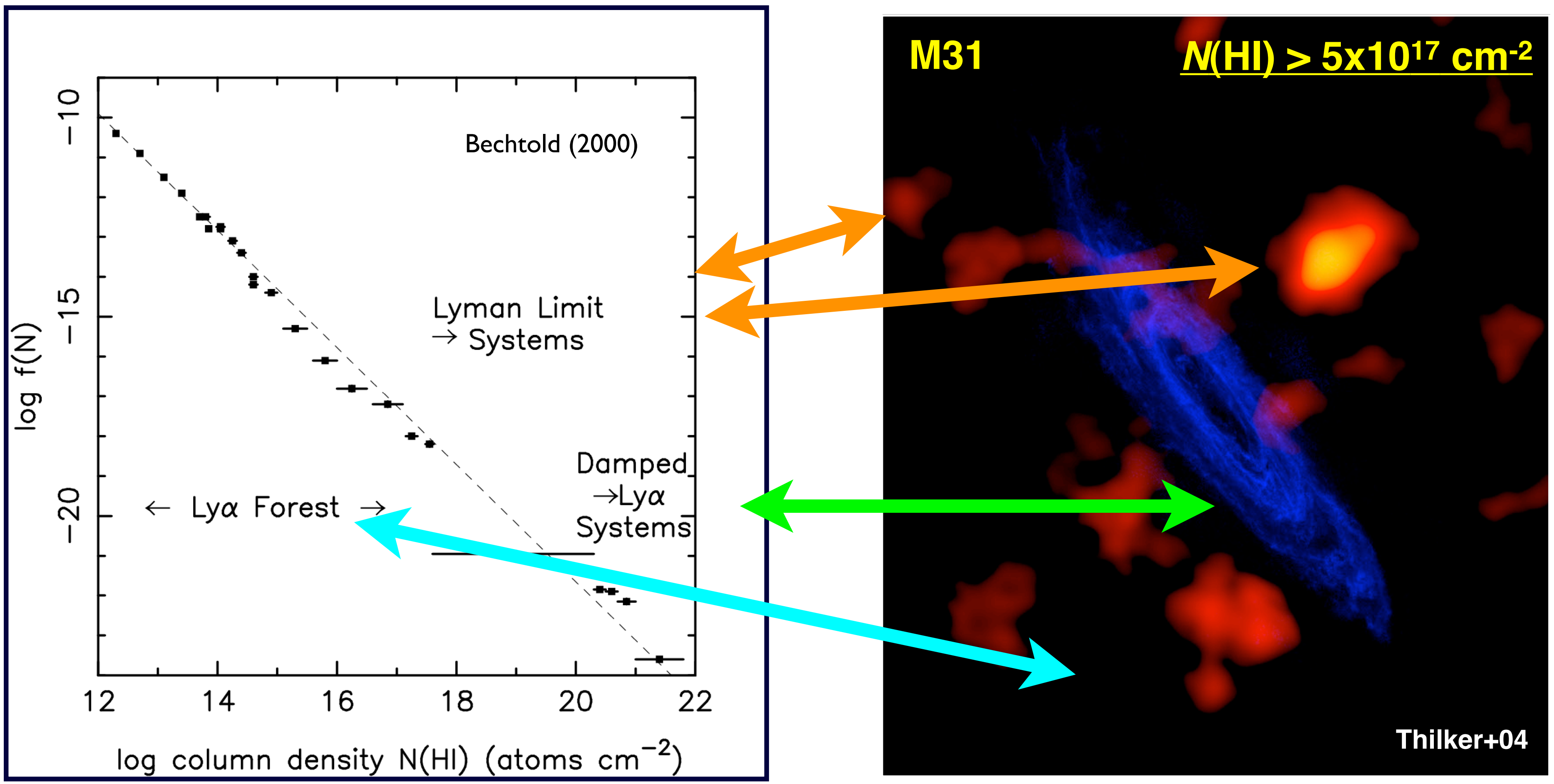

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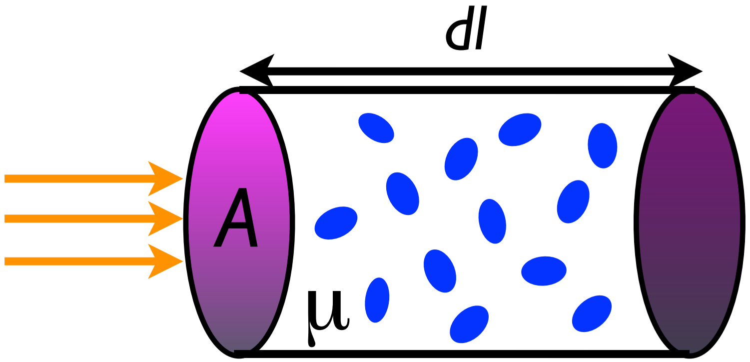

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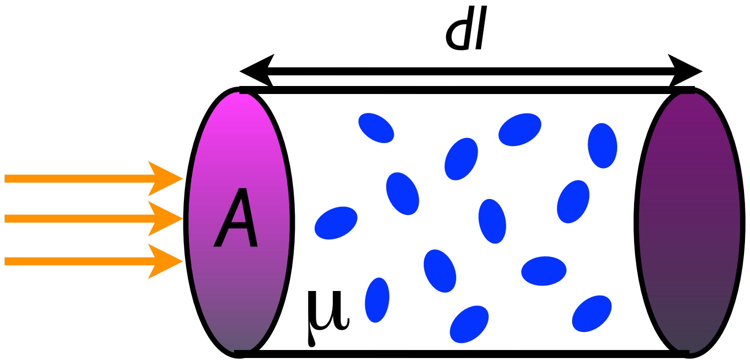

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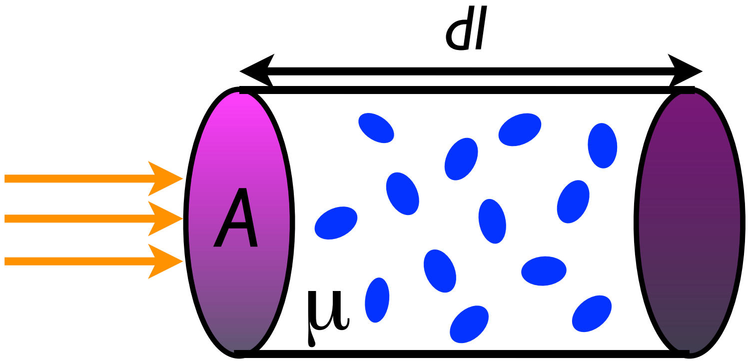

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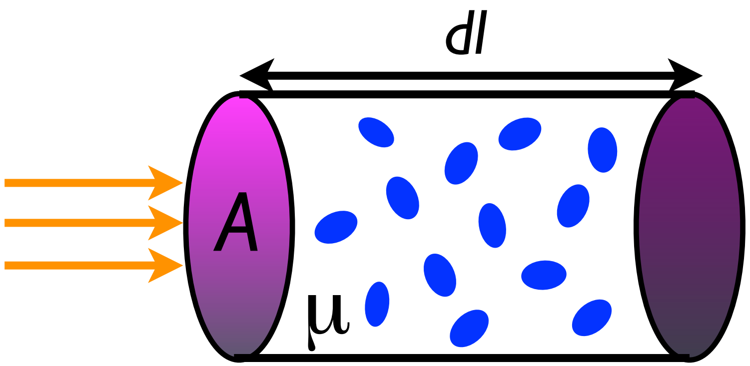

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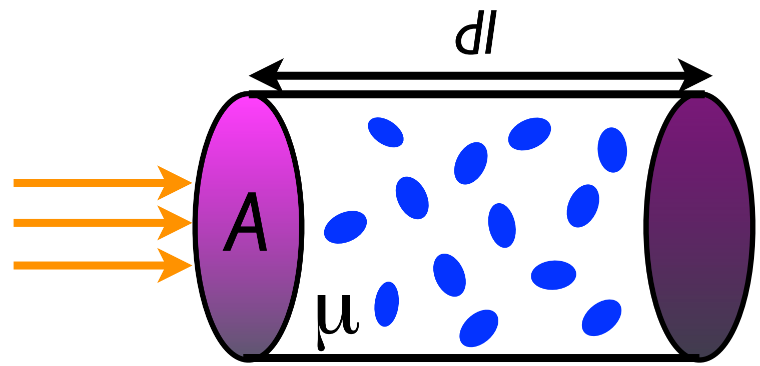

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At high redshift, $n(z) \propto (1+z)^{1/2}$

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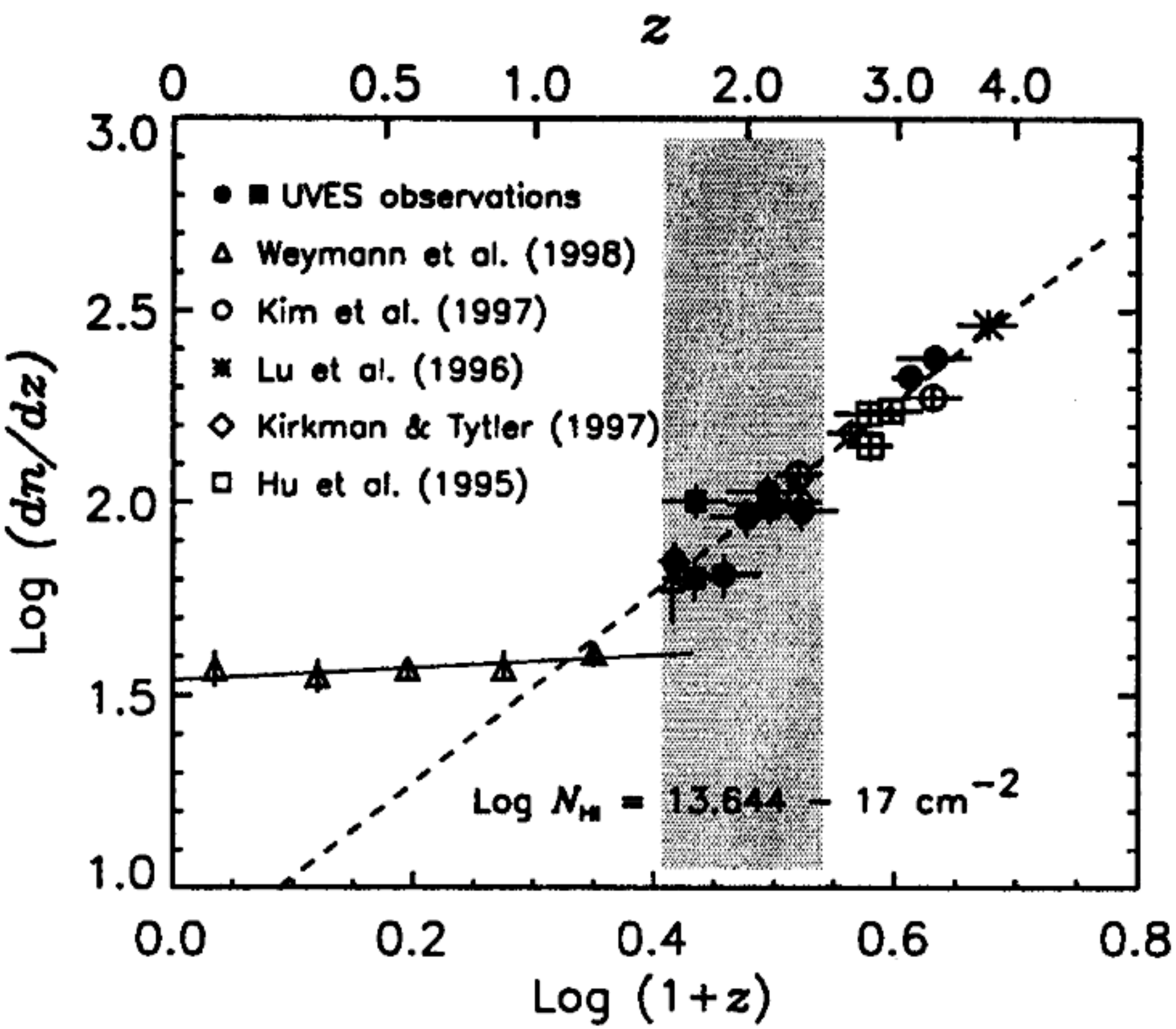

Bianchi et al. (2002)

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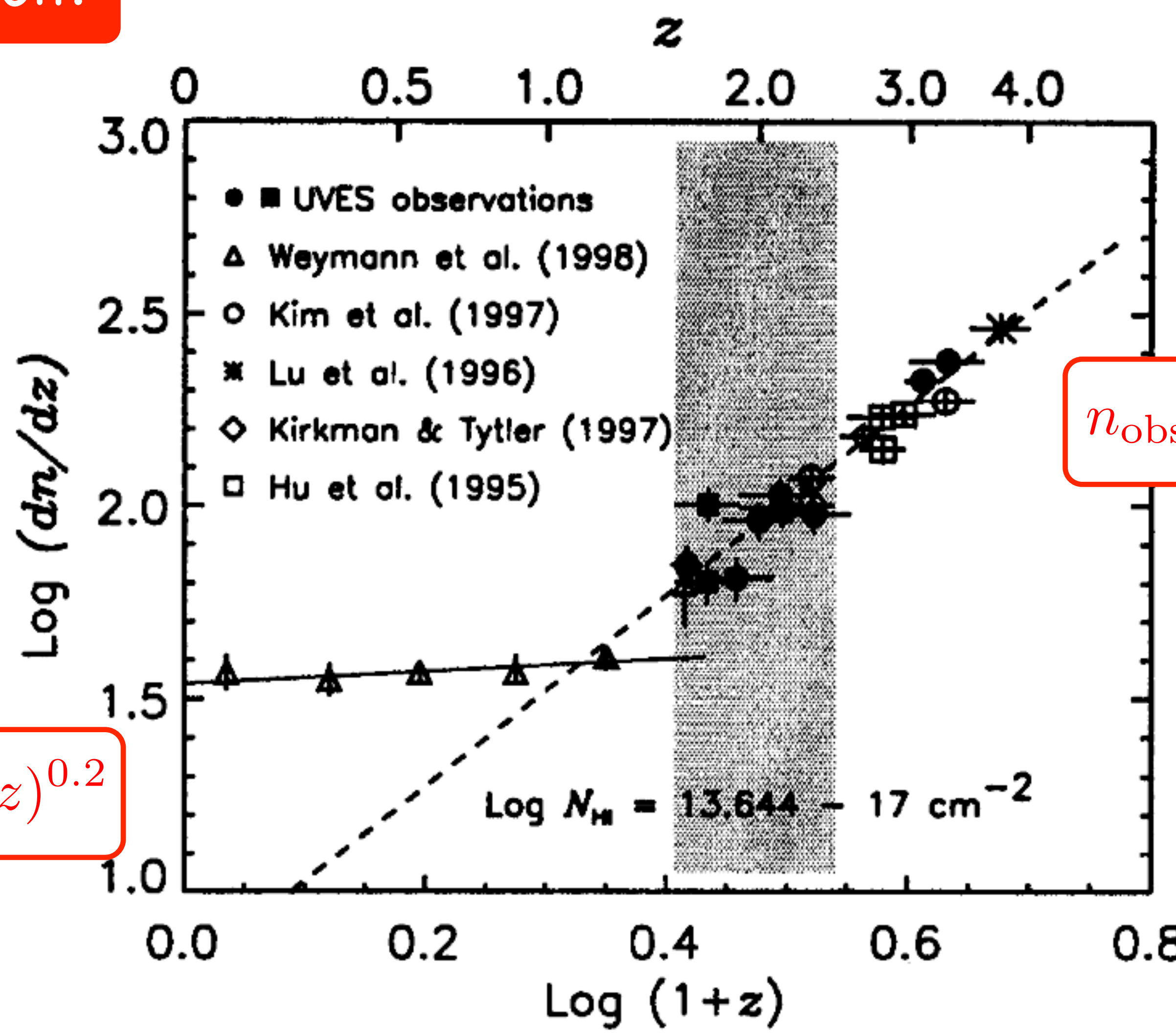
What's going on?



$n_{\rm obs}(z) \propto (1+z)^{2.5}$

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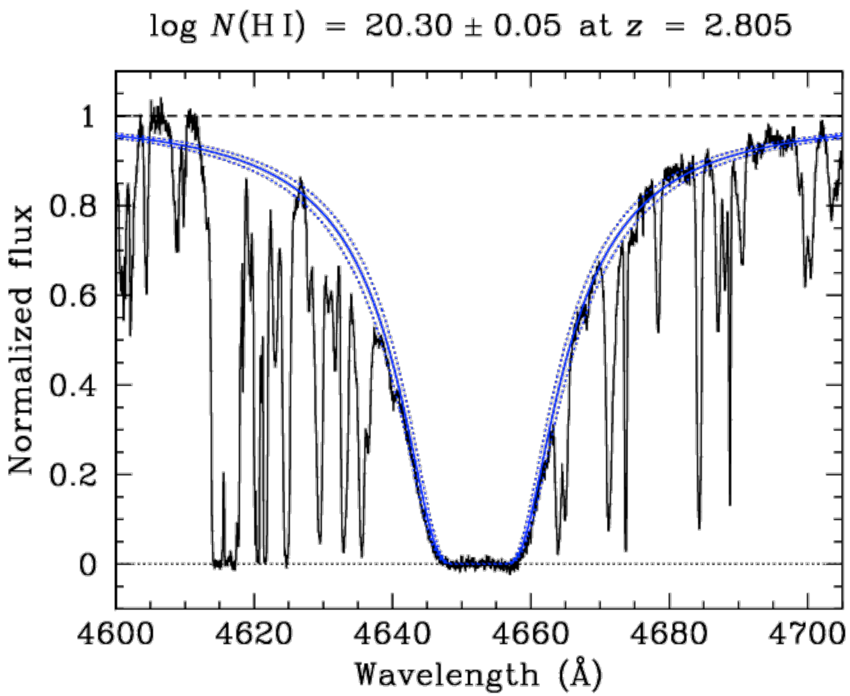
Probing distant ISM

Damped Lyα absorbers of $N(HI) \geq 2 \times 10^{20}$ cm^{-2}



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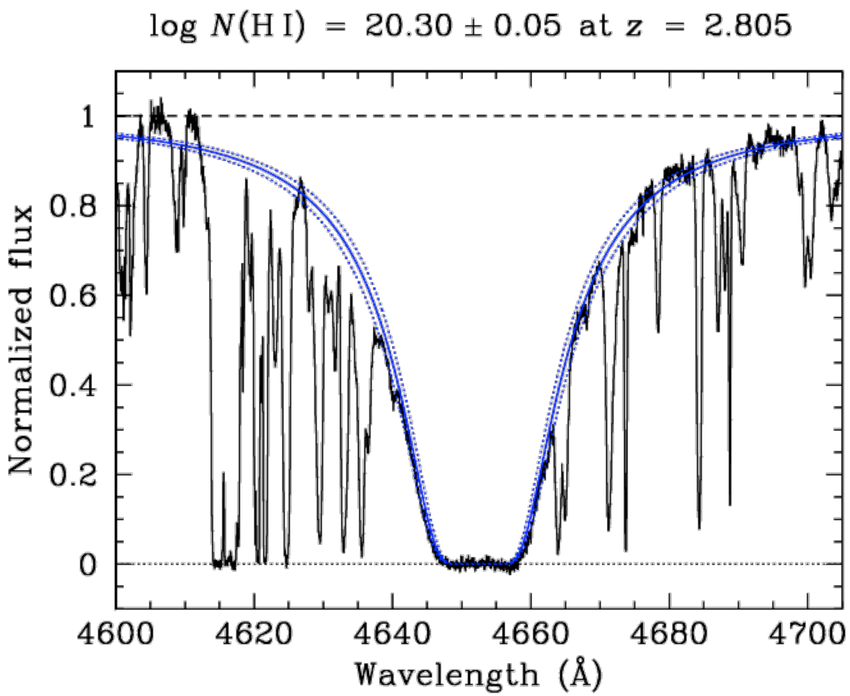
Damped Lyα absorbers of N(HI)$\geq$2x10^{20} cm^{-2} → neutral gas



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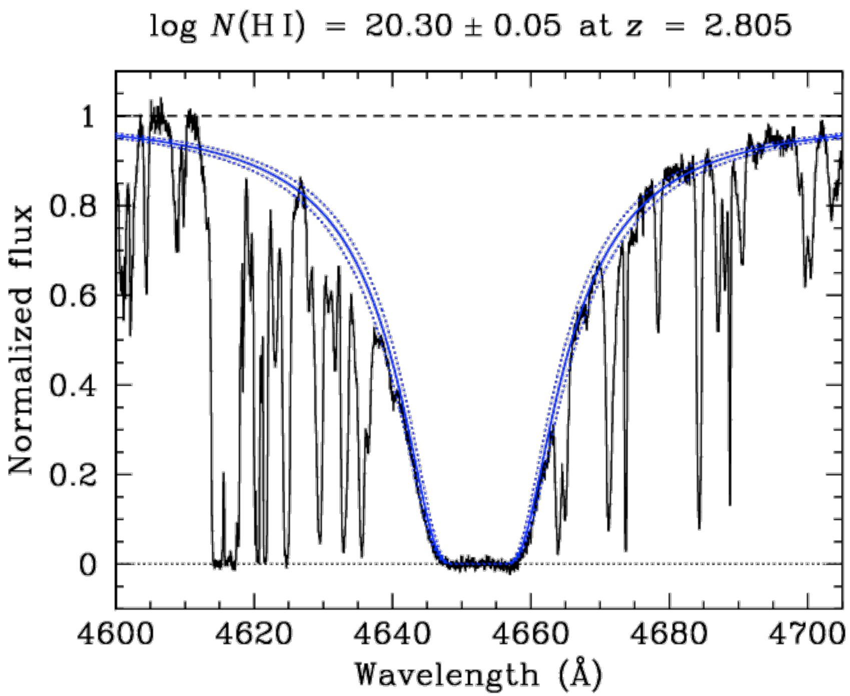

$$\Omega_{\rm gas} = \frac{H_0}{c}\frac{\mu m_{\rm H}}{\rho_{\rm crit}}\int N f(N,t)dN$$

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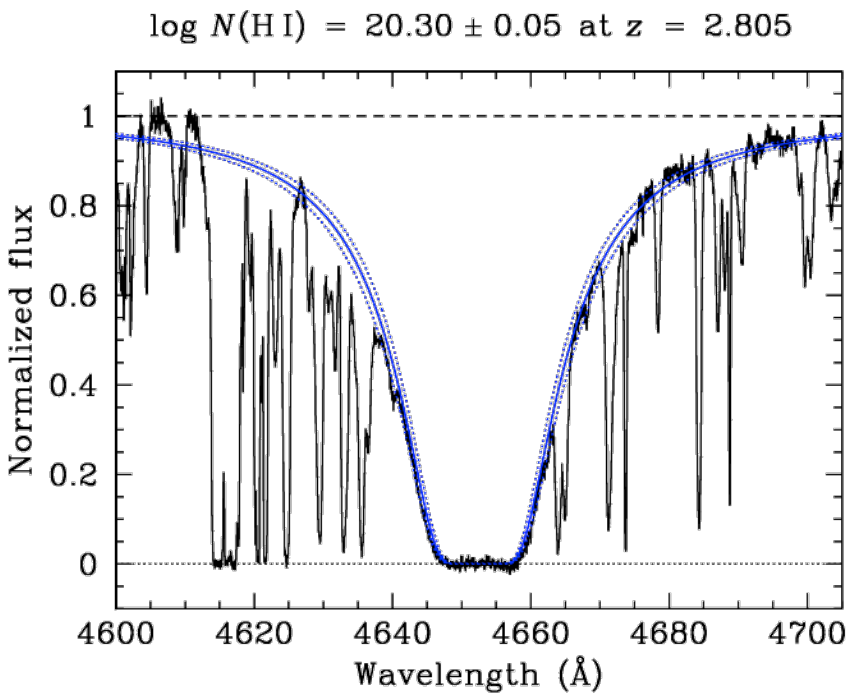

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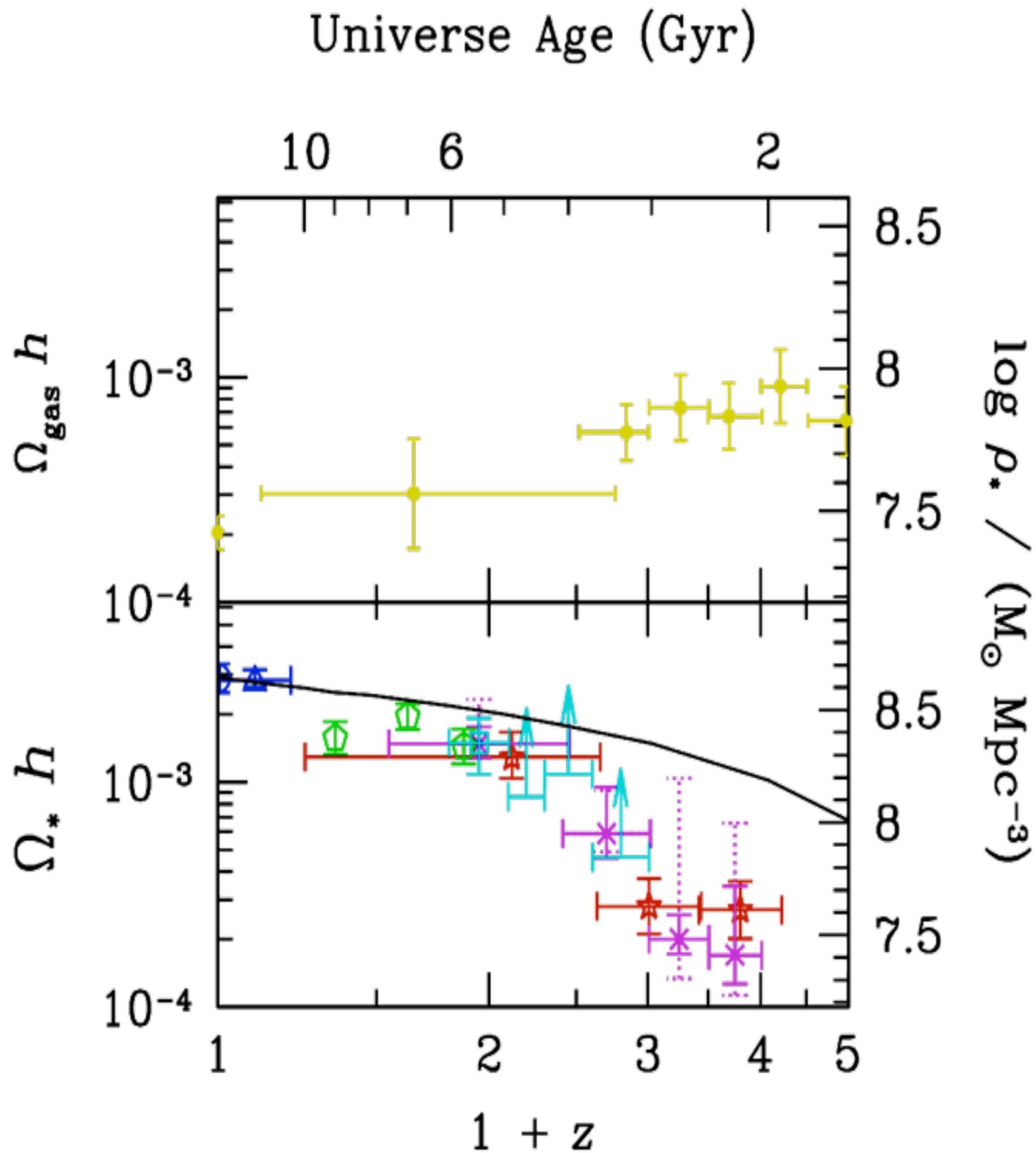
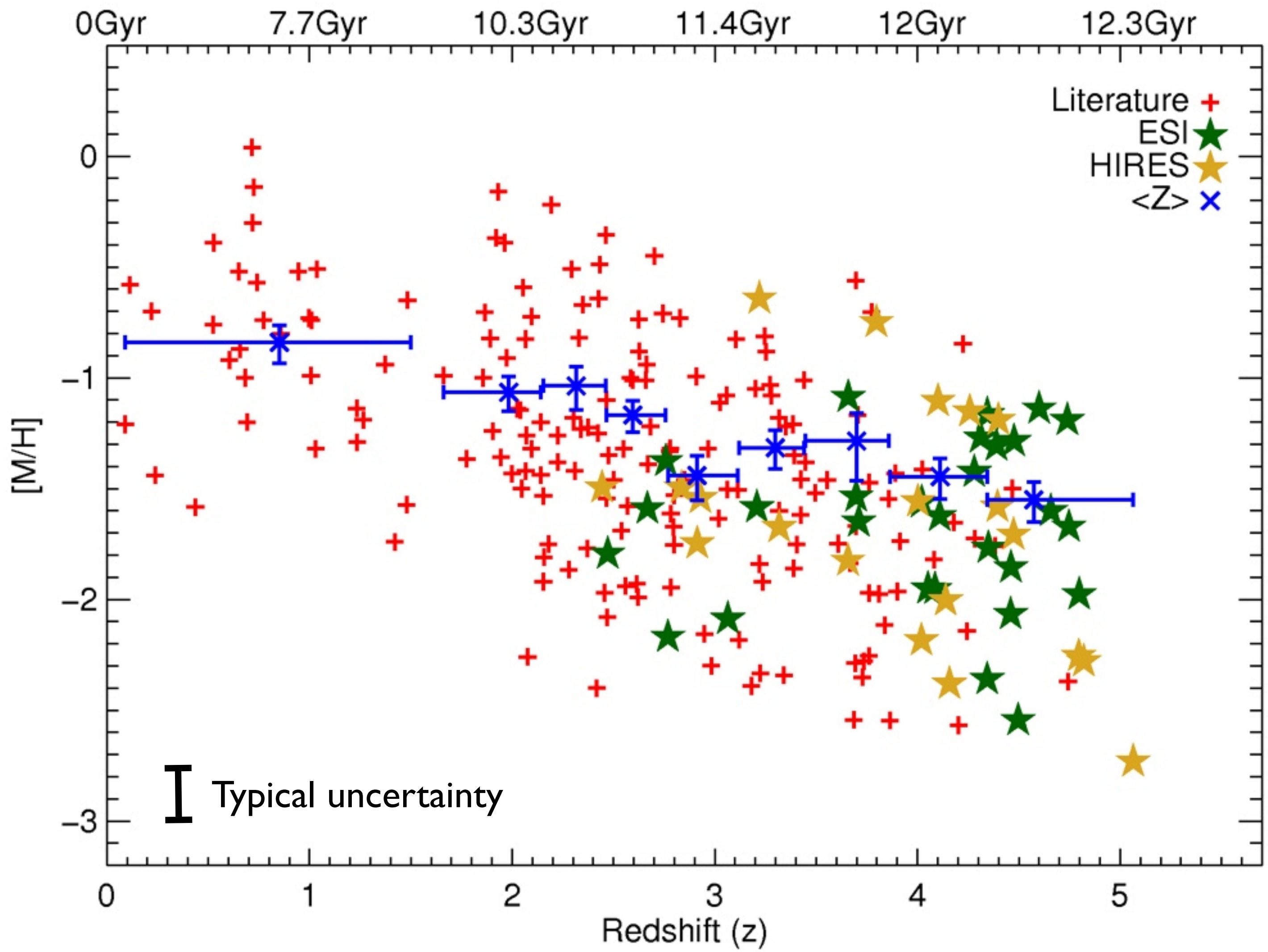


Probing distant ISM

Chemical enrichment history in neutral gas



Rafelski et al. (2012)

$$\langle Z \rangle \equiv \log \frac{\Omega_{\rm metal}}{\Omega_{gas}} - \log Z_\odot = \frac{\Sigma_i Z_i \, N_i}{\Sigma_i \, N_i}$$

Probing distant ISM

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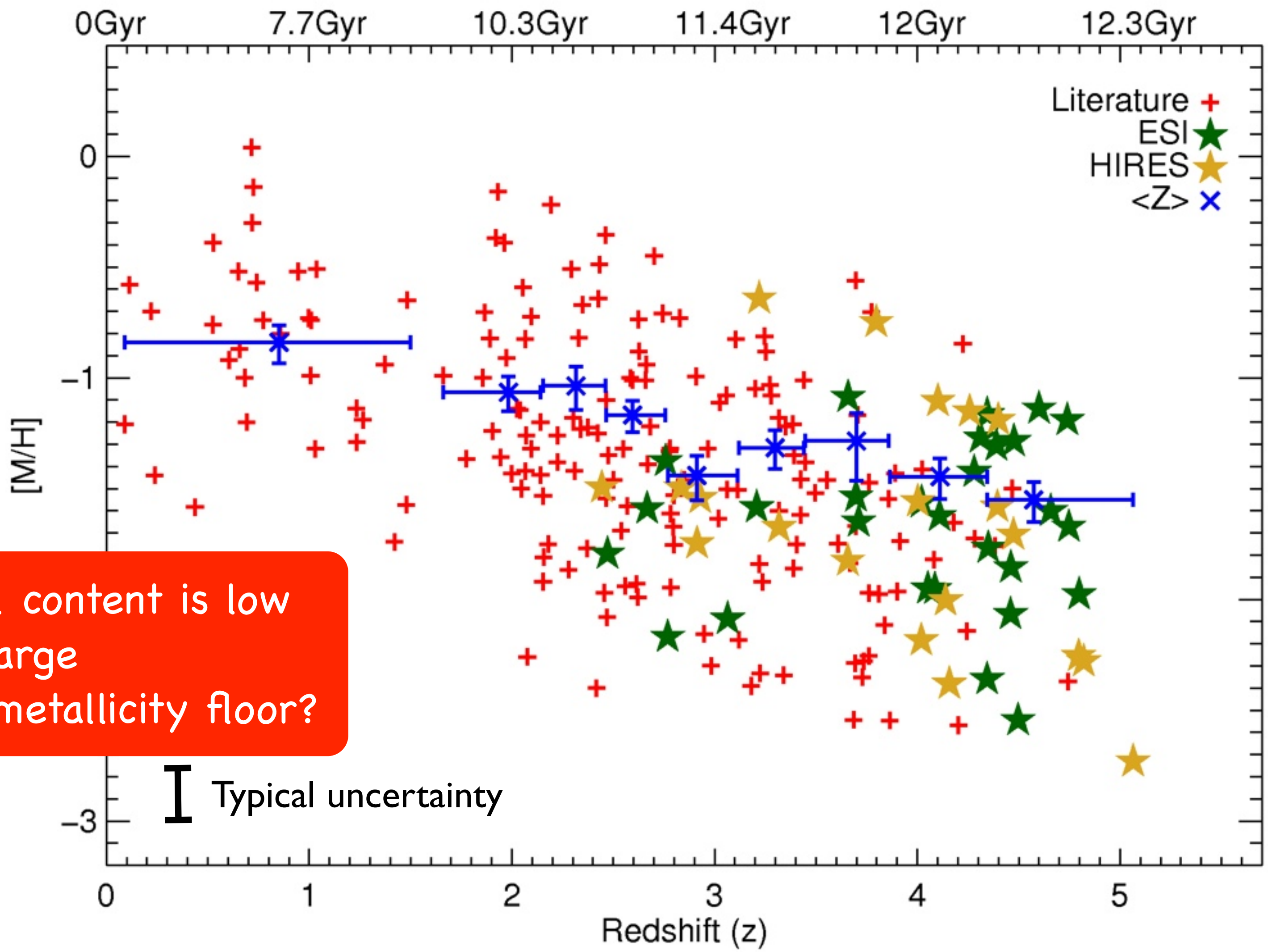

- mean metal content is low
- scatter is large
- is there a metallicity floor?

Rafelski et al. (2012)

$$\langle Z \rangle \equiv \log \frac{\Omega_{\rm metal}}{\Omega_{gas}} - \log Z_\odot = \frac{\Sigma_i Z_i\, N_i}{\Sigma_i\, N_i}$$

Absorption line profile :
constraining the thermal history of the IGM

Doppler parameter: $b = \sqrt{2}\,\sigma_v$ where σ_v is the velocity dispersion

$$b = \sqrt{\frac{2kT}{m}} = 1.29 \times 10^4 \sqrt{\frac{T}{A}}\ \mathrm{cm\,s^{-1}}$$

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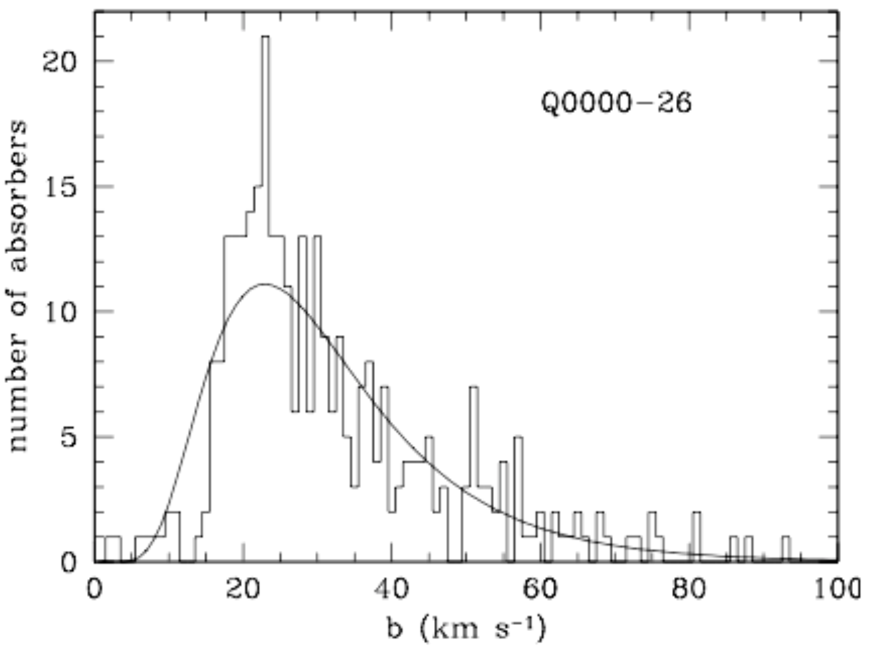
The caveat is line blending, and systematic uncertainties in profile fitting



$$f(\xi) = \exp(-0.5\xi^2)/\sqrt{2\pi},$$

where $\xi = -7.15 + 2.13\ln(b)$

Going beyond discrete lines

$$\tau \propto \frac{(\Omega_b H_0^2)^2}{\Gamma H(z)} (1+z)^6 \alpha(T) \left(\frac{\rho}{\bar{\rho}}\right)^2 \left(1 + \frac{dv_{\rm pec}}{H(z)dr}\right)^{-1}$$

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