Statistical Momentum Analysis of the Strong DLA Profiles

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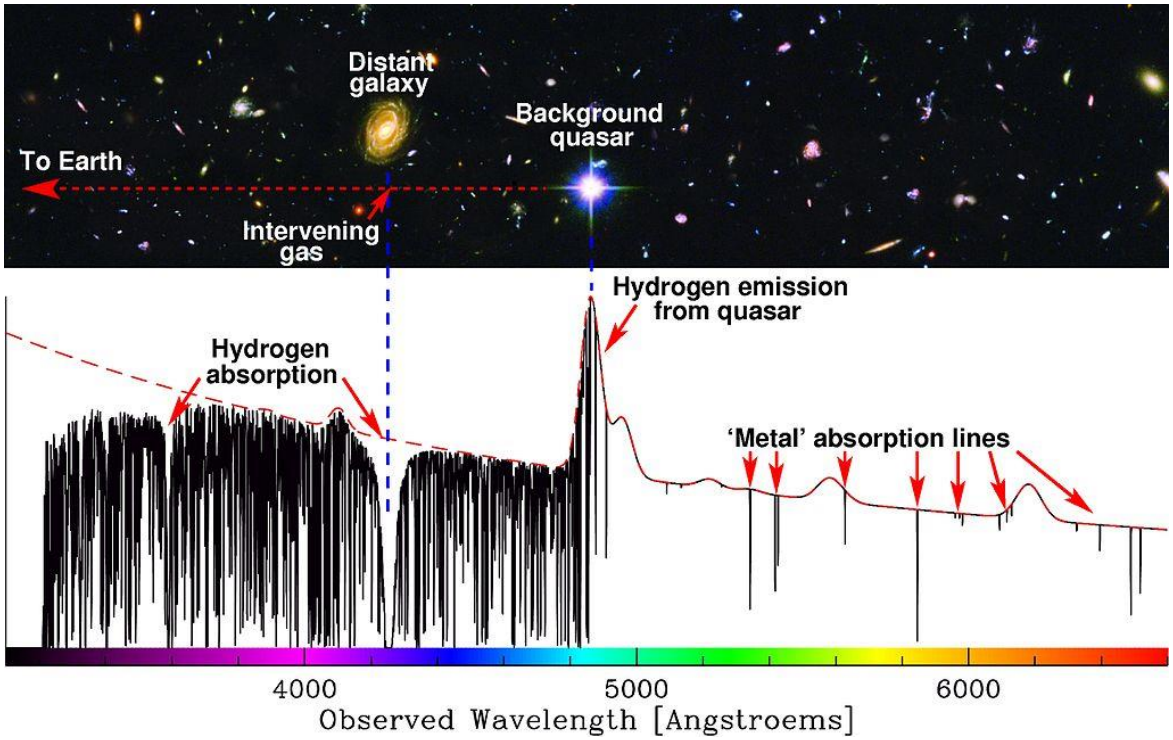
Lyα Absorption in Quasar Spectra



Lyman Alpha Forest

$N_{HI} > 10^{14} cm^{-2}$

Atomic hydrogen in the intergalactic media

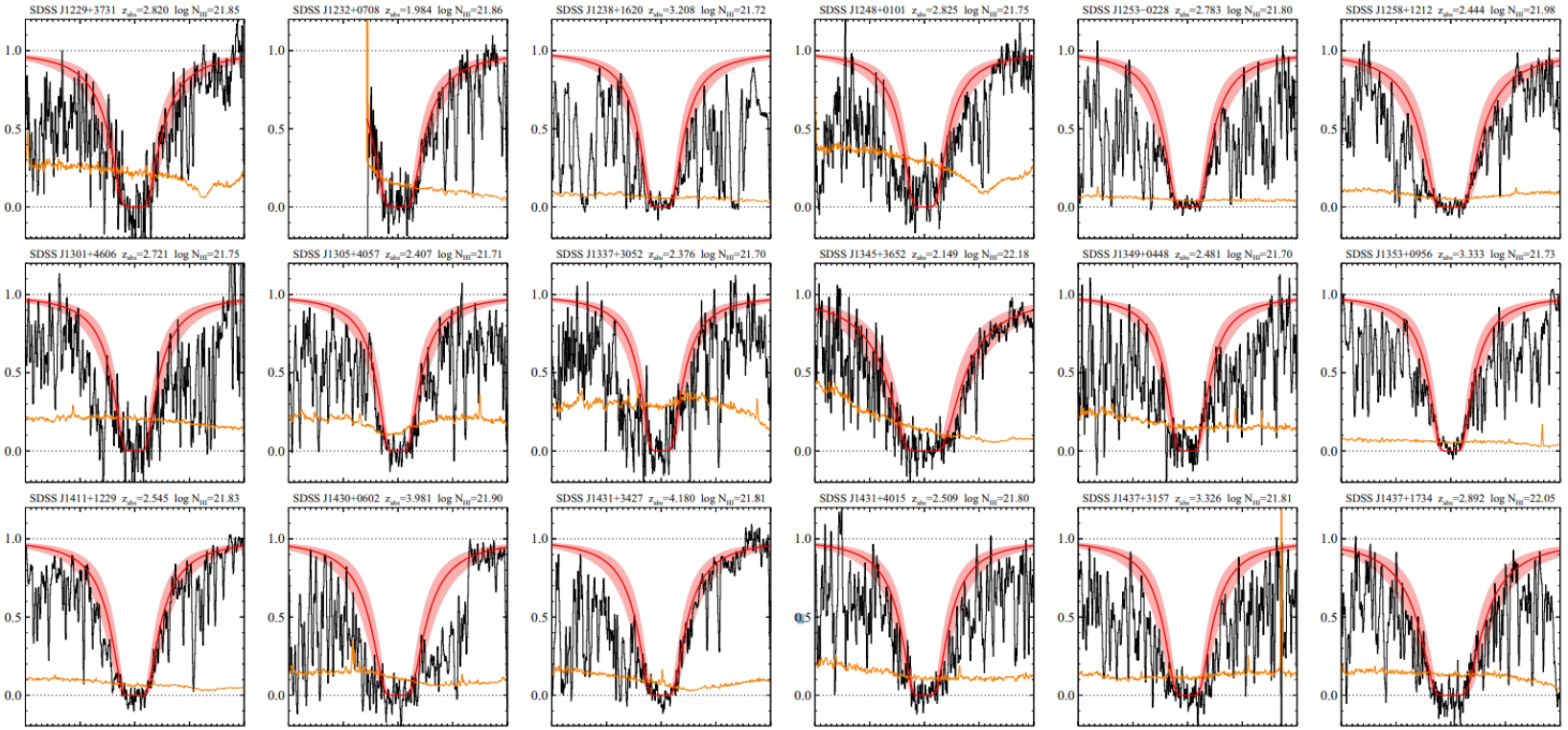
Damped Lyman Alpha System (DLA)

$N_{HI} > 2 \times 10^{20} cm^{-2}$

Distant galaxy

- Spectra of some quasars show a lot of absorption line from a hydrogen or metal.
- Lyman alpha forests exhibit in blueward of Lyman alpha emission from quasars.
- Those absorption lines are from intergalactic media or galaxies between the earth and quasar.

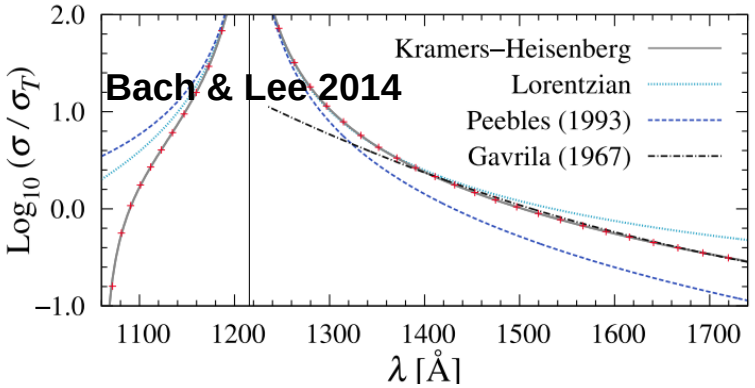
Measuring N_{HI} of DLA

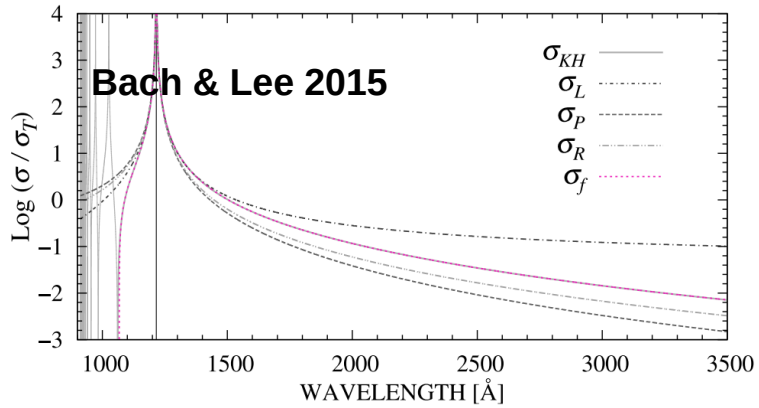


DLA in SDSS-III (Noterdaeme et al. 2014)

$$I_\lambda / I_0 = e^{-\tau_\lambda} \qquad \tau_\lambda = N_{HI}\,\sigma(\lambda)$$

The Cross Section $\sigma(\lambda)$





The comparison of various cross sections

$$\frac{d\sigma}{d\Omega}(\omega) = \frac{r_0^2}{m_e^2\hbar^2}\left|\sum_I\left[\frac{\omega(\vec{p}\cdot\hat{\epsilon}^{(\alpha')})_{AI}(\vec{p}\cdot\hat{\epsilon}^{(\alpha)})_{IA}}{\omega_{IA}(\omega_{IA}-\omega-i\Gamma_I/2)} - \frac{\omega(\vec{p}\cdot\hat{\epsilon}^{(\alpha)})_{AI}(\vec{p}\cdot\hat{\epsilon}^{(\alpha')})_{IA}}{\omega_{IA}(\omega_{IA}+\omega)}\right]\right|^2,$$

Kramers-Heisenberg (K-H) formula (Sakurai 1967)

$$\sigma_{\mathrm{P}}(\omega) = \frac{3\lambda_0^2}{8\pi}\frac{\Gamma_{2p}^2\,(\omega/\omega_0)^4}{(\omega_0-\omega)^2+\Gamma_{2p}^2\,(\omega/\omega_0)^6/4}.$$

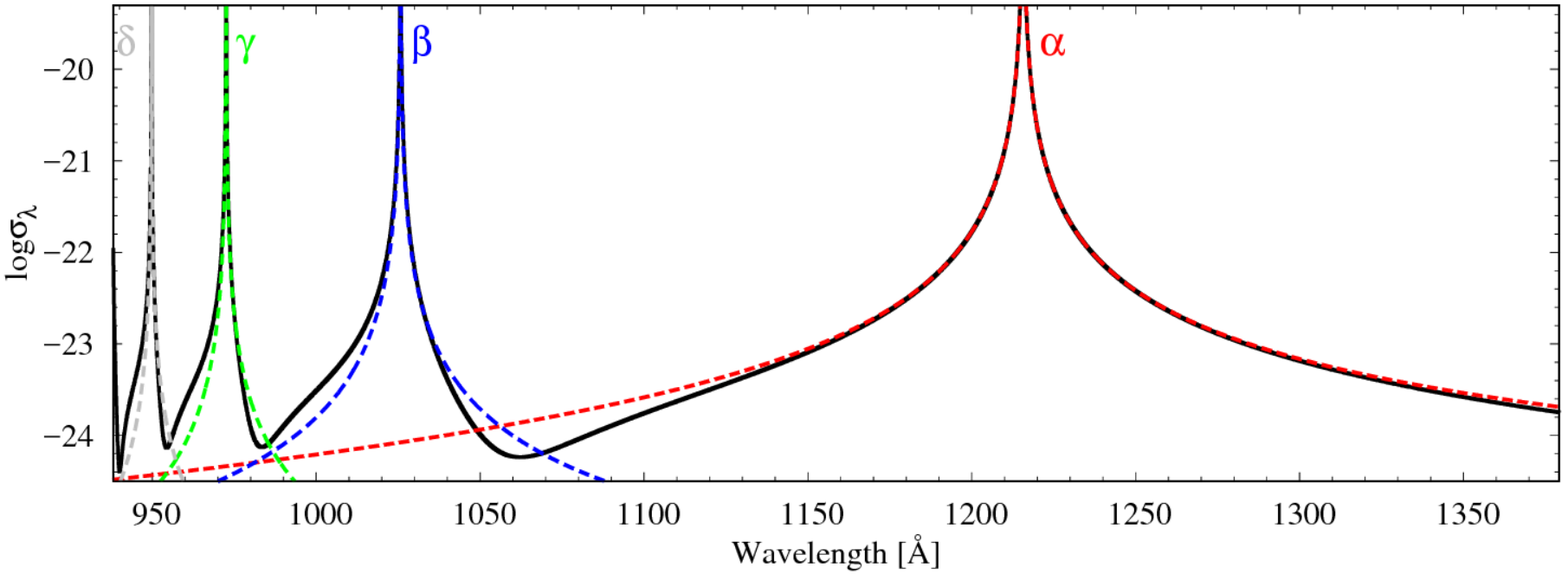
The cross section in Peebles 1993

$$\sigma_{\mathrm{L}}(\omega) = \sigma_{\mathrm{T}}\left(\frac{f_{12}}{2}\right)^2\frac{\omega_0^2}{(\omega_0-\omega)^2+\Gamma_{2p}^2/4}$$

The Lorentzian cross section

- K-H formula is from the second-order time-dependent perturbation theory.
- Damping profiles of Lyα and Lyβ using K-H show the asymmetry for the high column density. (Lee 2003, 2013, Bach & Lee 2014 and Bach 2017)

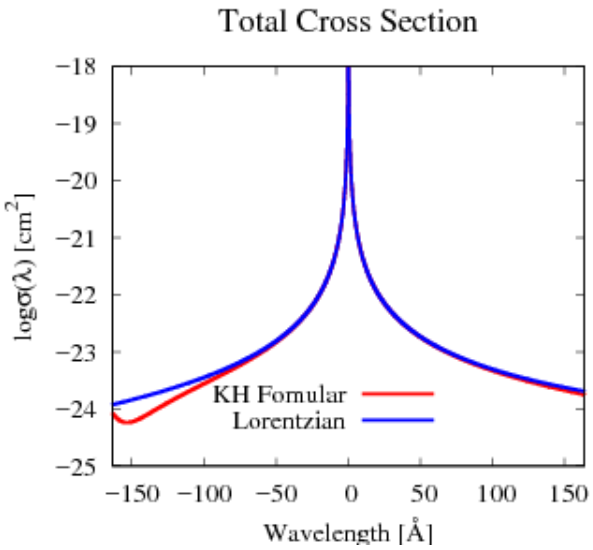
$\sigma(\lambda)$ of Lyman series

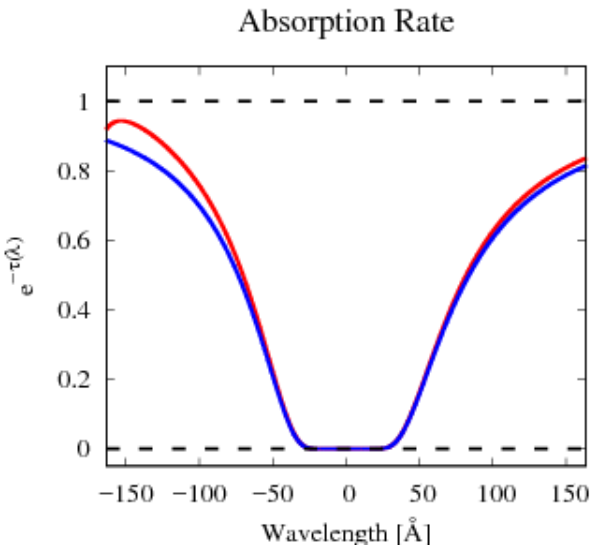


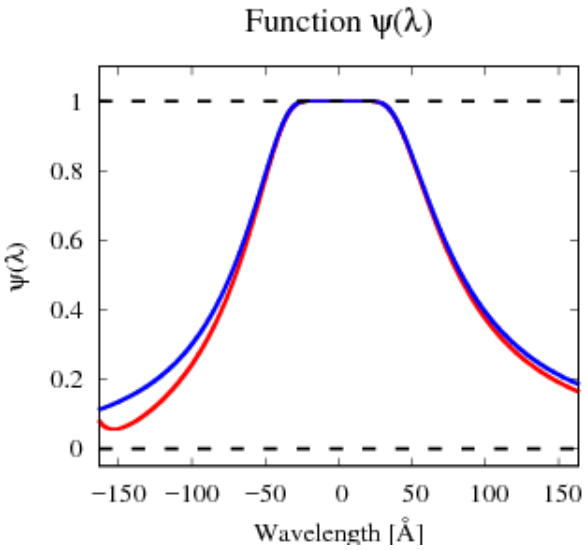
The cross section using K-H (solid line) and single Lorentzian (dashed lines).

- Lyα has more red damping wing.
- In the case of Lyβ, Lyγ and Lyδ, the blueward is stronger than the redward.
- The cross section is too small to detect the asymmetric features.

Statistical Function $\Psi(\lambda)$

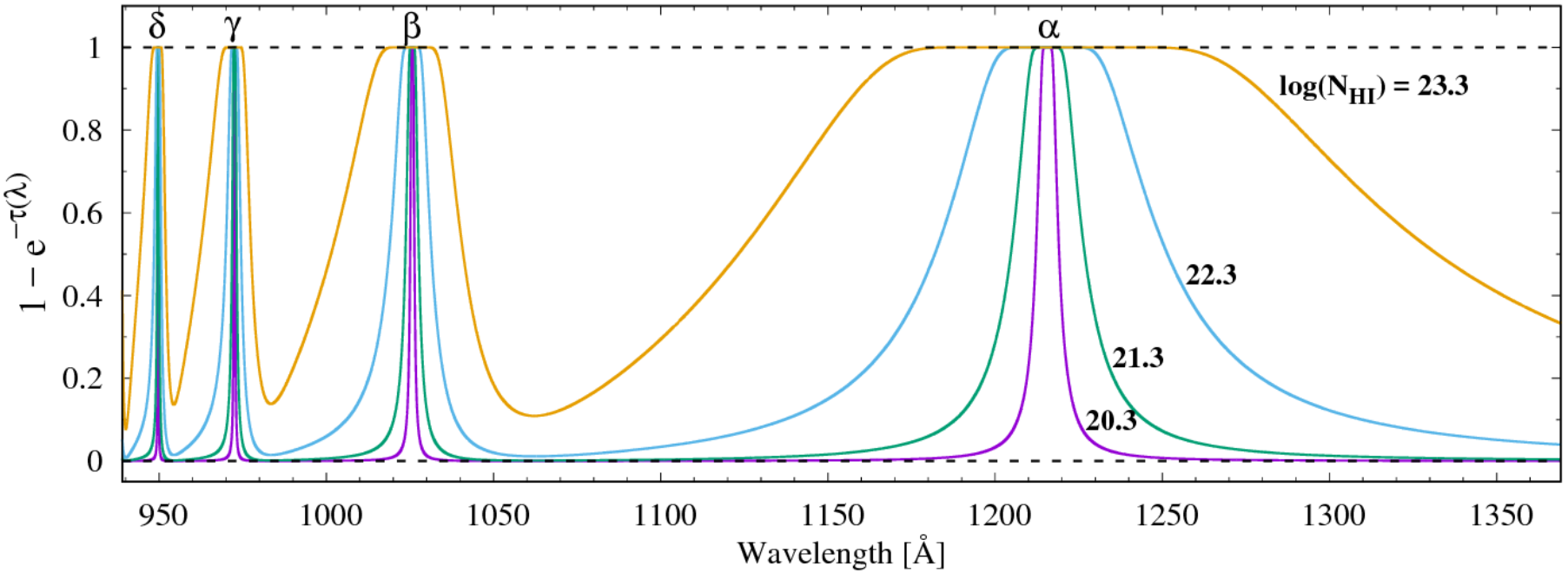






- We define statistical function $\Psi(\lambda)$ to compare the asymmetry of DLA profiles using K-H and Lorentzian
- Single Lorentzian profiles is used as $\Psi(\lambda)$ is computed by Lorentzian function.

Statistical Function $\Psi(\lambda)$



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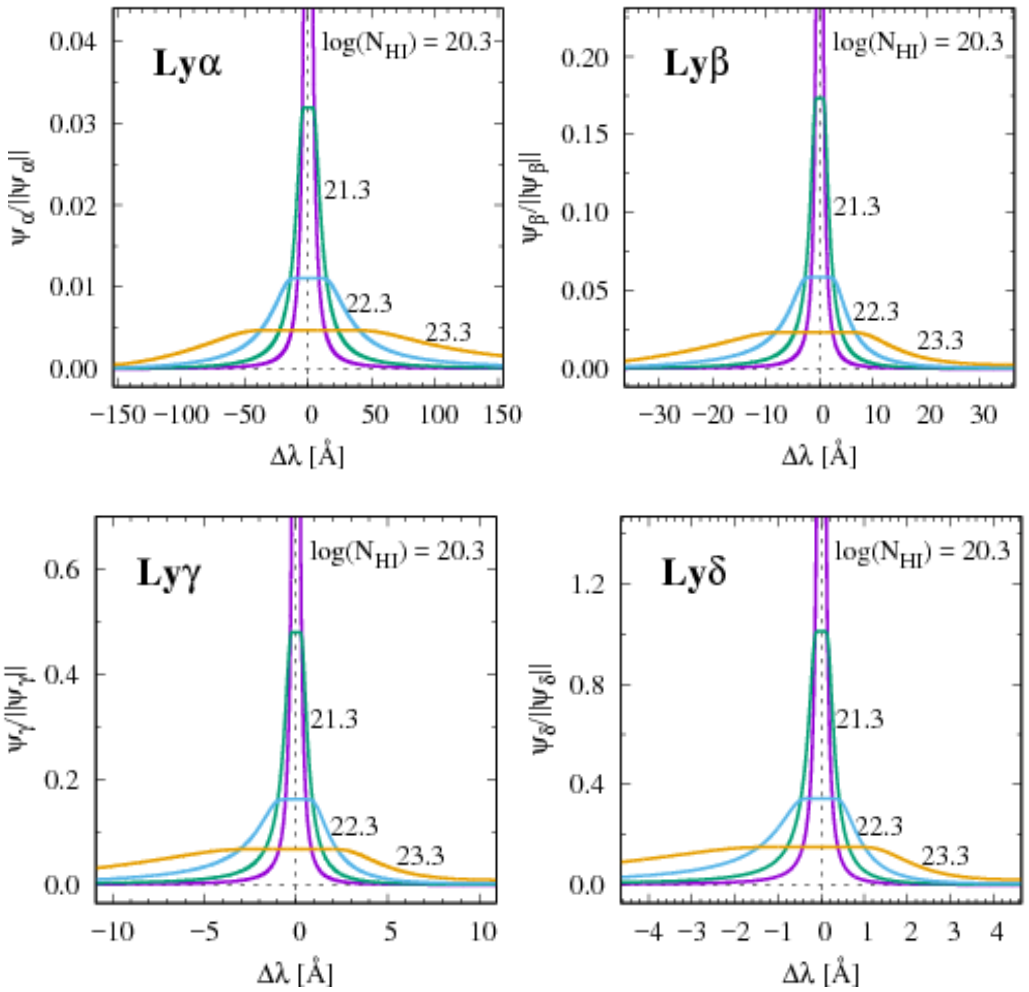
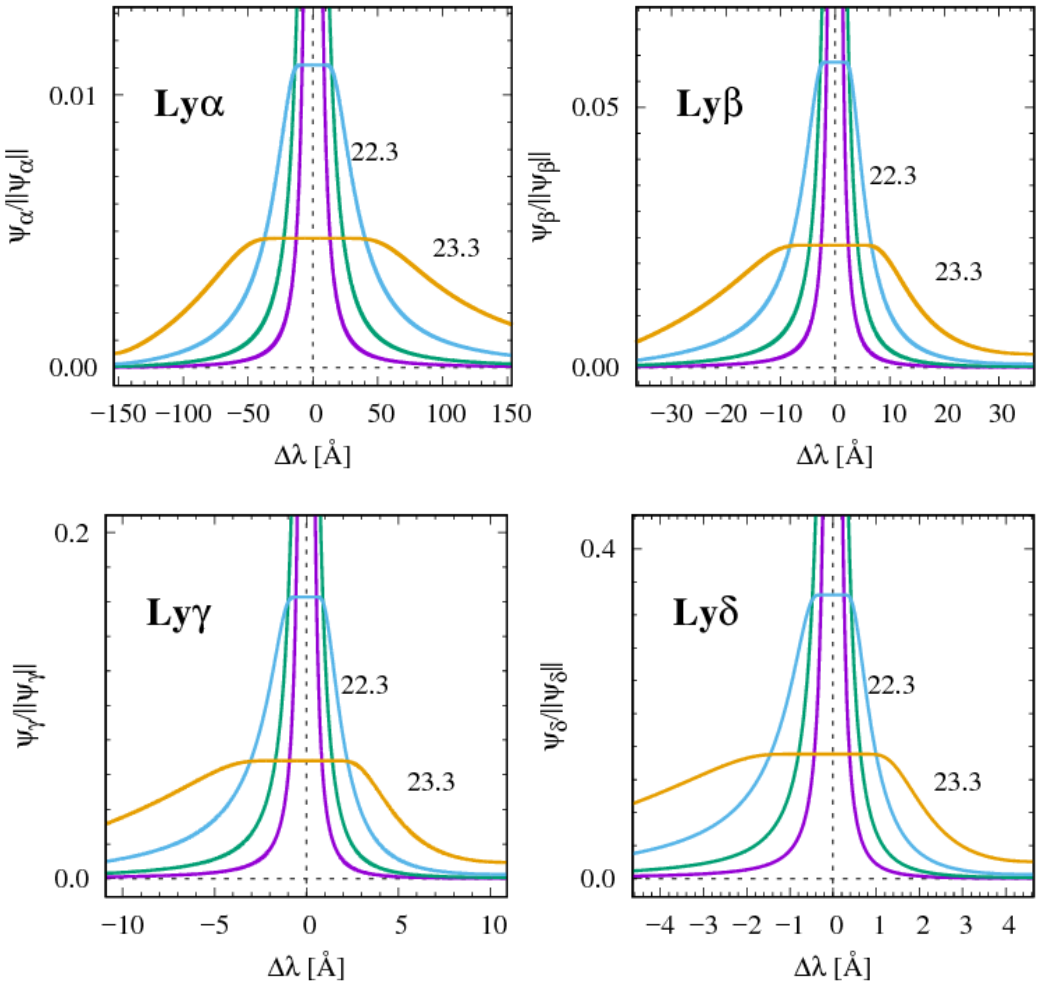
Normalized $\Psi(\lambda)$



$\Psi(\lambda)/\|\Psi(\lambda)\|$ is normalized function.

$$\left(\|\Psi(\lambda)\| = \int_{\lambda_2}^{\lambda_1} \Psi(\lambda) d\lambda\right)$$

Normalized $\Psi(\lambda)$



$\Psi(\lambda)/\|\Psi(\lambda)\|$ is normalized function.

$$\left(\|\Psi(\lambda)\| = \int_{\lambda_2}^{\lambda_1} \Psi(\lambda) d\lambda\right)$$

Statistical Moment Analysis

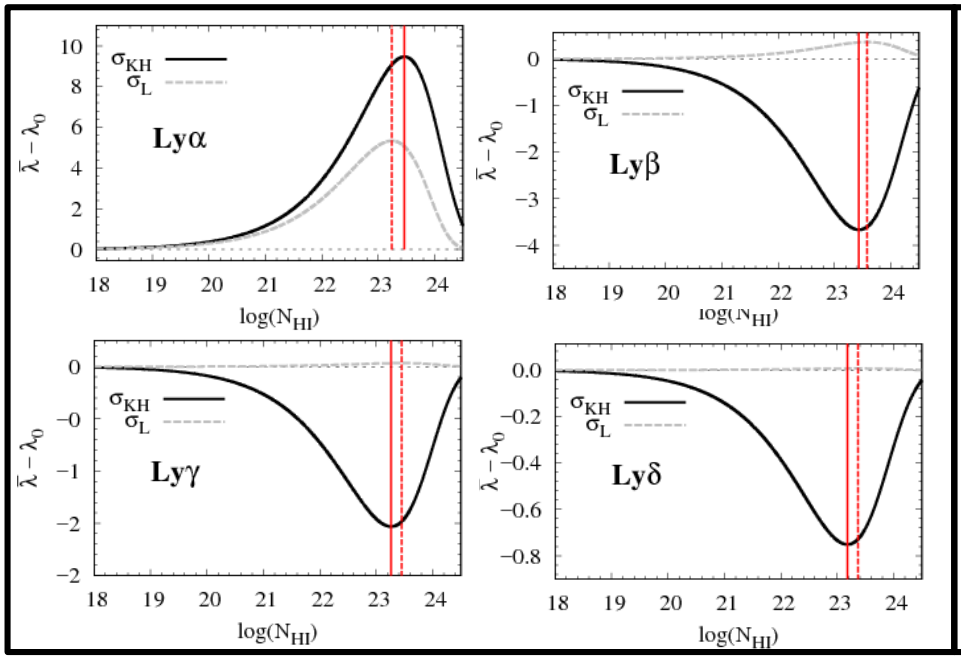
$$\bar{\lambda} = \int_{\lambda_2}^{\lambda_1} \lambda \Psi(\lambda) d\lambda \,/\, \|\Psi(\lambda)\|$$ → **Line Center**

$$\text{Std. Dev.} = \int_{\lambda_2}^{\lambda_1} (\lambda - \bar{\lambda})^2 \Psi(\lambda) d\lambda \,/\, \|\Psi(\lambda)\|$$ → **Width**

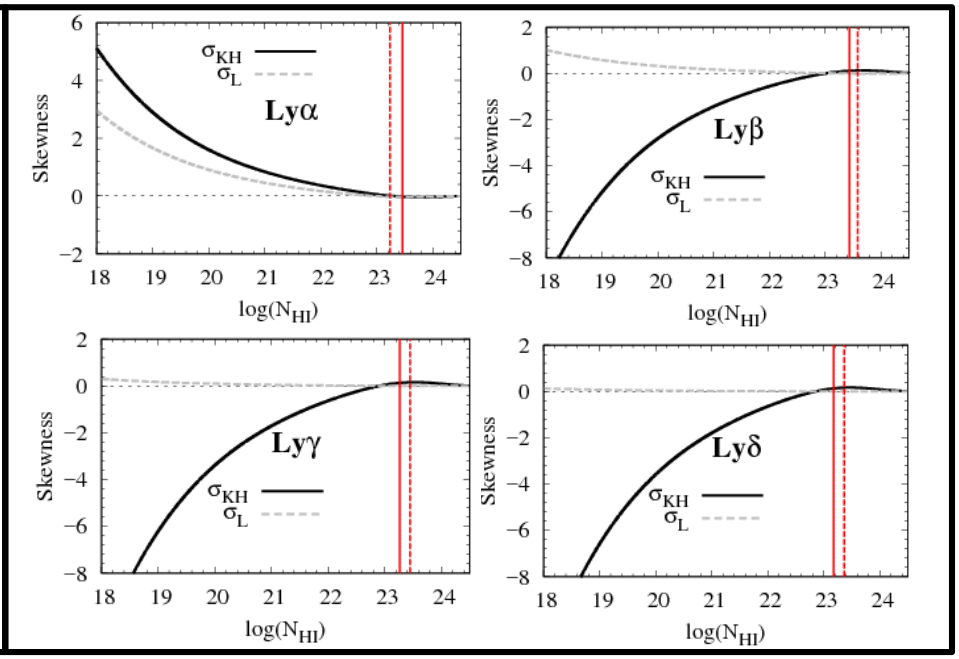
$$\text{Skewness} = \int_{\lambda_2}^{\lambda_1} (\lambda - \bar{\lambda})^3 \Psi(\lambda) d\lambda \,/\, \|\Psi(\lambda)\|$$ → **Asymmetry**

$$\text{Kurtosis.} = \int_{\lambda_2}^{\lambda_1} (\lambda - \bar{\lambda})^4 \Psi(\lambda) d\lambda \,/\, \|\Psi(\lambda)\|$$ → **Sharpness**

Statistical Moment Analysis



$\bar{\lambda} - \lambda_0$

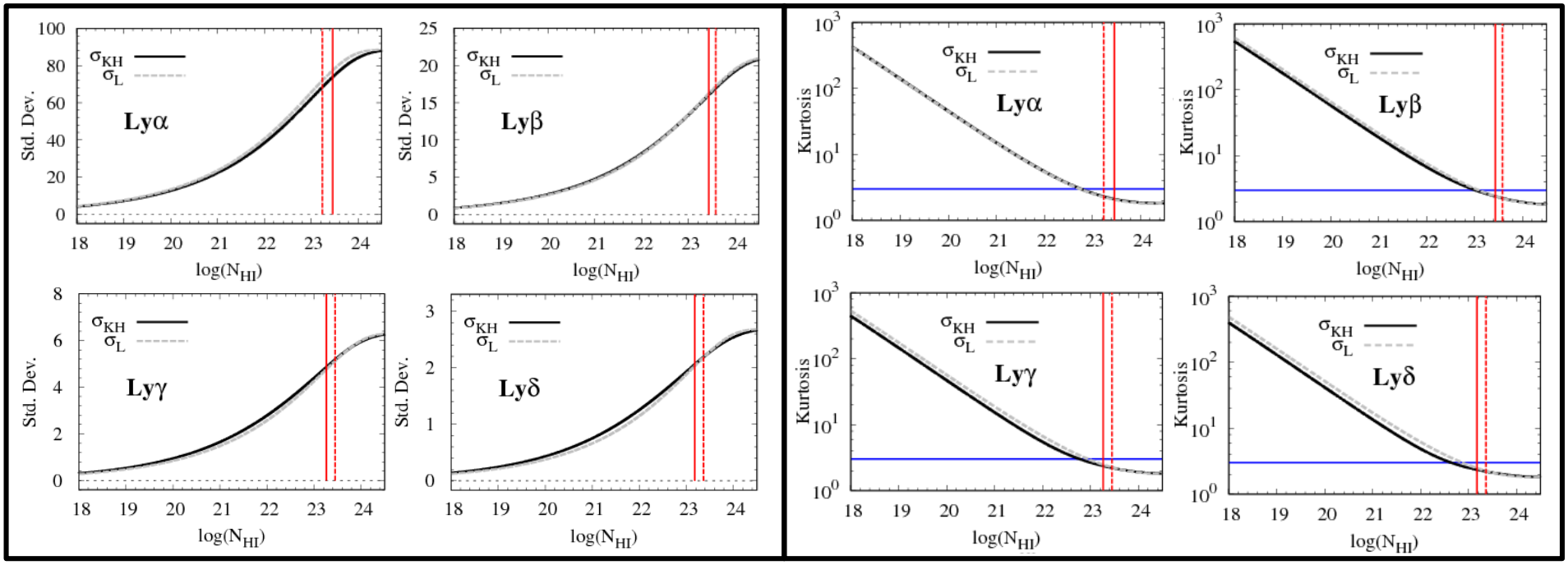


Skewness

- After the peak of $\bar{\lambda} - \lambda_0$, $\bar{\lambda} - \lambda_0$ is decreased as the profiles are saturated and are affected by Lyman lines.

- Skewness of Lyβ, Lyγ and Lyδ using K-H and Lorentzian show blue and red asymmetry.

Statistical Moment Analysis



Standard Deviation **Kurtosis**

- Standard Deviation and Kurtosis of Lyman series using two types of the cross section are similar.
- For $N_{HI} > 10^{23} cm^{-2}$, Kurtosis are smaller than 3 in all of lines.

Summary and Discussion

1. We extend the range of the total scattering cross section from K-H to Lyδ.
2. For high column density $N_{HI} > 10^{22}\ cm^{-2}$, damping wings of Lyman series is asymmetric.
3. Lorentzian σ_L has the problem in the region far from the line center.
4. The Lyα and other higher lines show the blue and red asymmetry.
5. K-H have to be considered as extremely damped DLA profiles, $N_{HI} > 10^{22}\ cm^{-2}$.

Thanks