Project Goals

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measure the temperature distribution and the wind mass-loss rates of ~15 O stars with high-resolution spectra in the Chandra data archive

Method: fit combined *apec* emission and *windtabs* transfer/absorption models to Chandra grating spectra; complement this with line-ratio analysis.

One early motivation for this project was the recognition by Walborn, Nichols, & Waldron (2009, *Ap.J.*, 703, 633) that stars with early spectral suptypes have harder (higher energy photons) Chandra grating spectra than OB stars with later spectral subtypes. These authors claimed that the trend is caused by an underlying plasma temperature or ionization trend. But their neglect of wind absorption calls that claim into question.

Note: "early" vs. "late" refers to hotter/bluer vs. colder/redder spectral types of subtypes. For O stars, there's a fairly large spread in physical properties from the early (say, O4) to the late (O8 or O9).

The Data: main sequence & giants

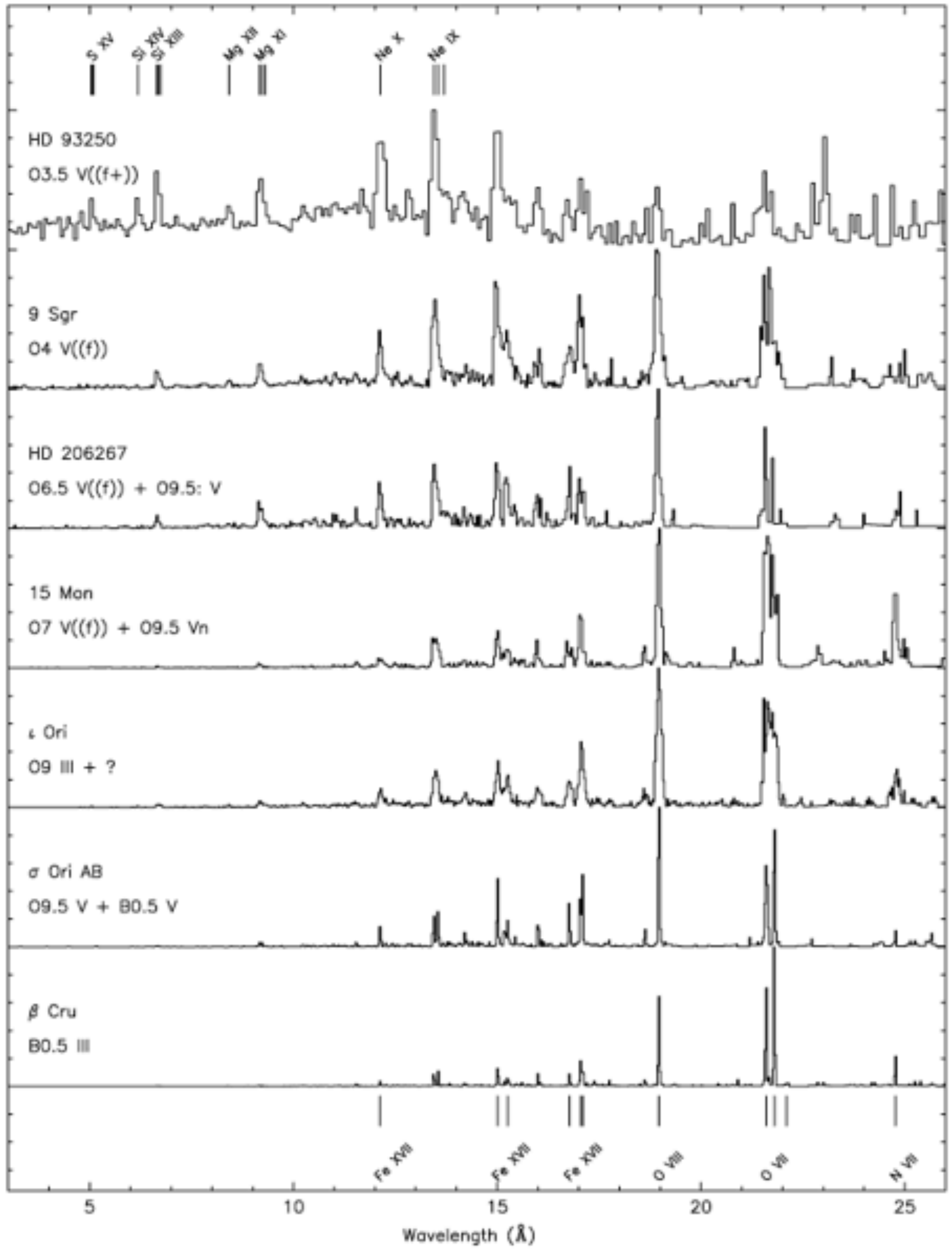


Figure 1. X-ray spectral-type sequence of normal dwarfs and giants. The ordinate units are normalized to 1.0 at the peak emission feature in each spectrum, and the corresponding factors are given in Table 1. Thus, this scale may not be intercompared among different spectrograms. The wavelengths of the identified spectral lines are given in Table 2.

Walborn, Nichols, & Waldron, 2009, Ap.J., 703, 633

The Data: supergiants

636 WALBORN, NICHOLS, & WALDRON Vol. 703

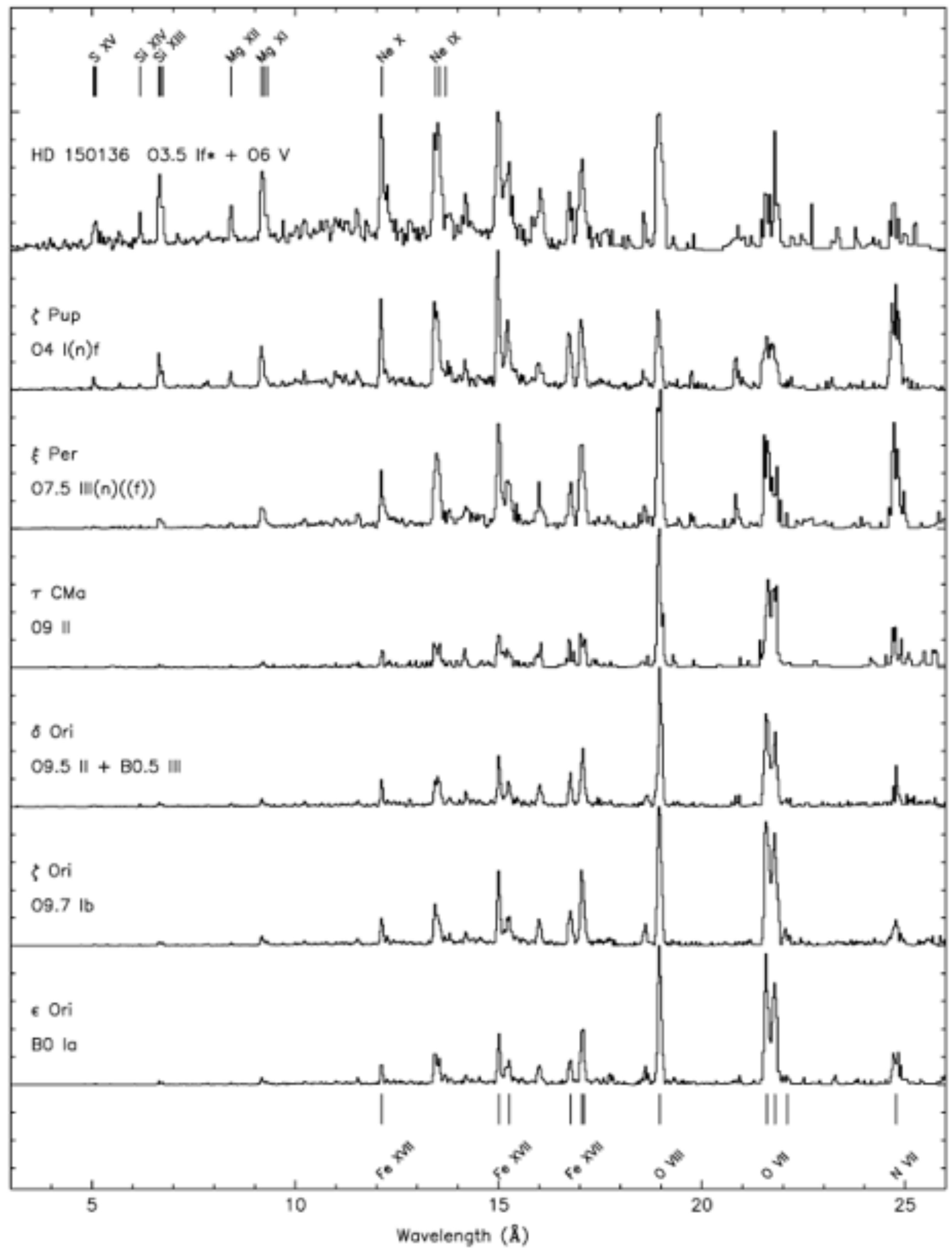


Figure 2. X-ray spectral-type sequence of normal supergiants and giants. The ordinate units and the wavelengths of the identified spectral lines are as in Figure 1.

Walborn, Nichols, & Waldron, 2009, Ap.J., 703, 633

It is certainly possible that there is a small but significant temperature/ionization* effect. But wind absorption clearly must play a role, too.

A big reason why no one else has attempted our project is that until recently, there was no good model of wind absorption available. But our group developed one a couple of years ago: Leutenegger et al., 2010, *Ap.J.*, 719, 1767.

* Waldron et al.'s interpretation of this as a plasma emission temperature trend is based almost entirely on the qualitative, morphological trend seen in the spectra, but they back this up with the measurement of one pair of lines (of neon).

The Leutenegger et al. 2010 paper and the associated *windtabs* model have two important and new ingredients that enable us to accurately model the radiation transport through the wind:

1. The atomic opacity of the wind material is accurately treated (other studies use the higher ISM opacities; they're higher because all atoms are neutral, whereas wind material is partially ionized).

2. We use a treatment of the radiation transport that accounts for the fact that the emitting material is spatially distributed within the absorbing material in the wind. This is different than the ISM case, where the light comes from a star behind the absorbing cloud (and so exp(-tau) correctly describes the transmission of the cloud).

Transmission (fraction of emitted radiation that is not absorbed) for three different models. "Windtabs" is our wind absorption model.

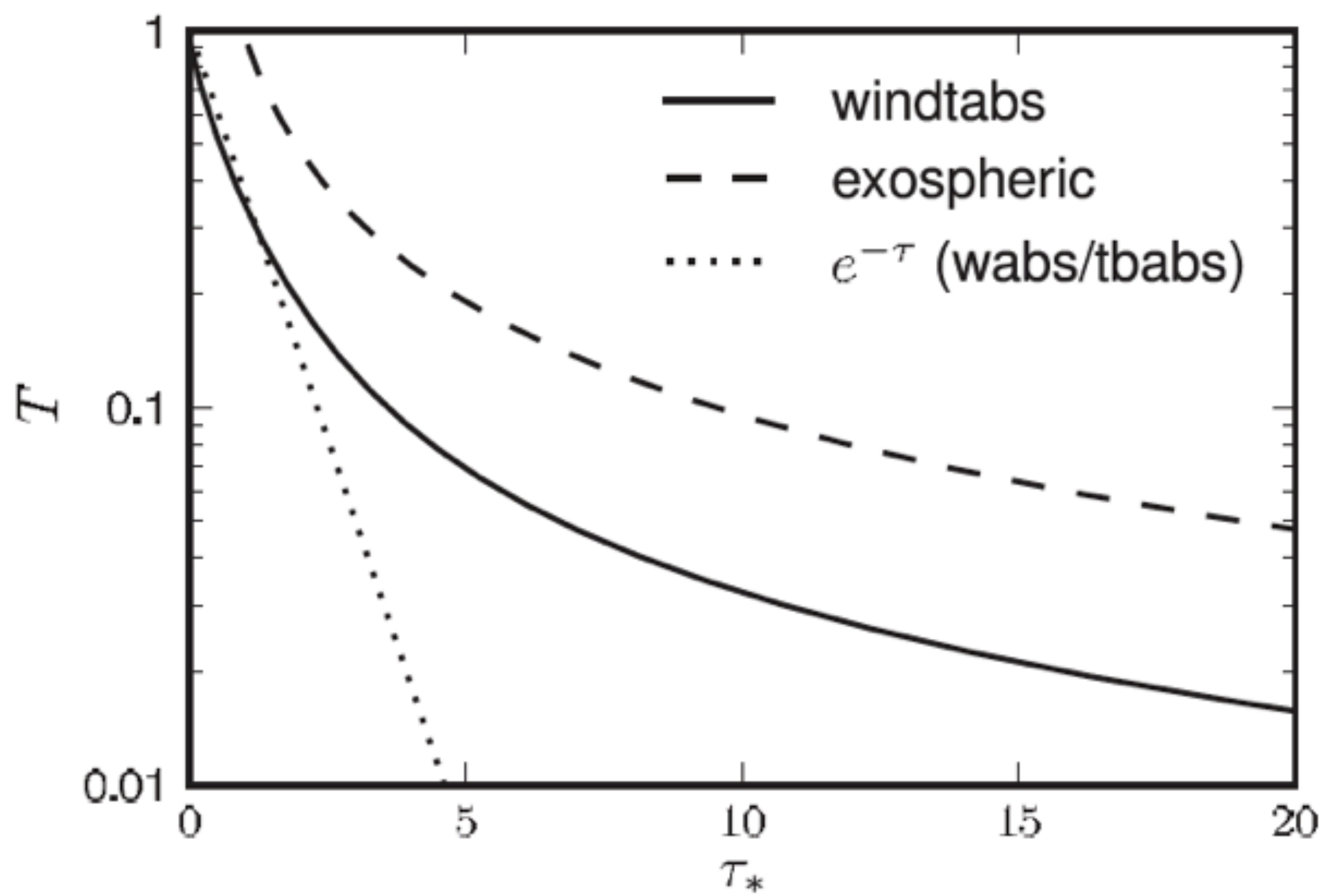


Figure 5. Comparison of transmission of three different models: coronal slab ($e^{-\tau}$), exospheric, and more realistic wind model (*windtabs*). The fixed parameters are $\beta = 1$, $R_0 = 1.5$.

The transmission of a wind is much greater than that of the ISM geometry (exp(-tau)) because no matter how optically thick the wind, some emitting plasma is near the top of the wind and so is not subject to much absorption.

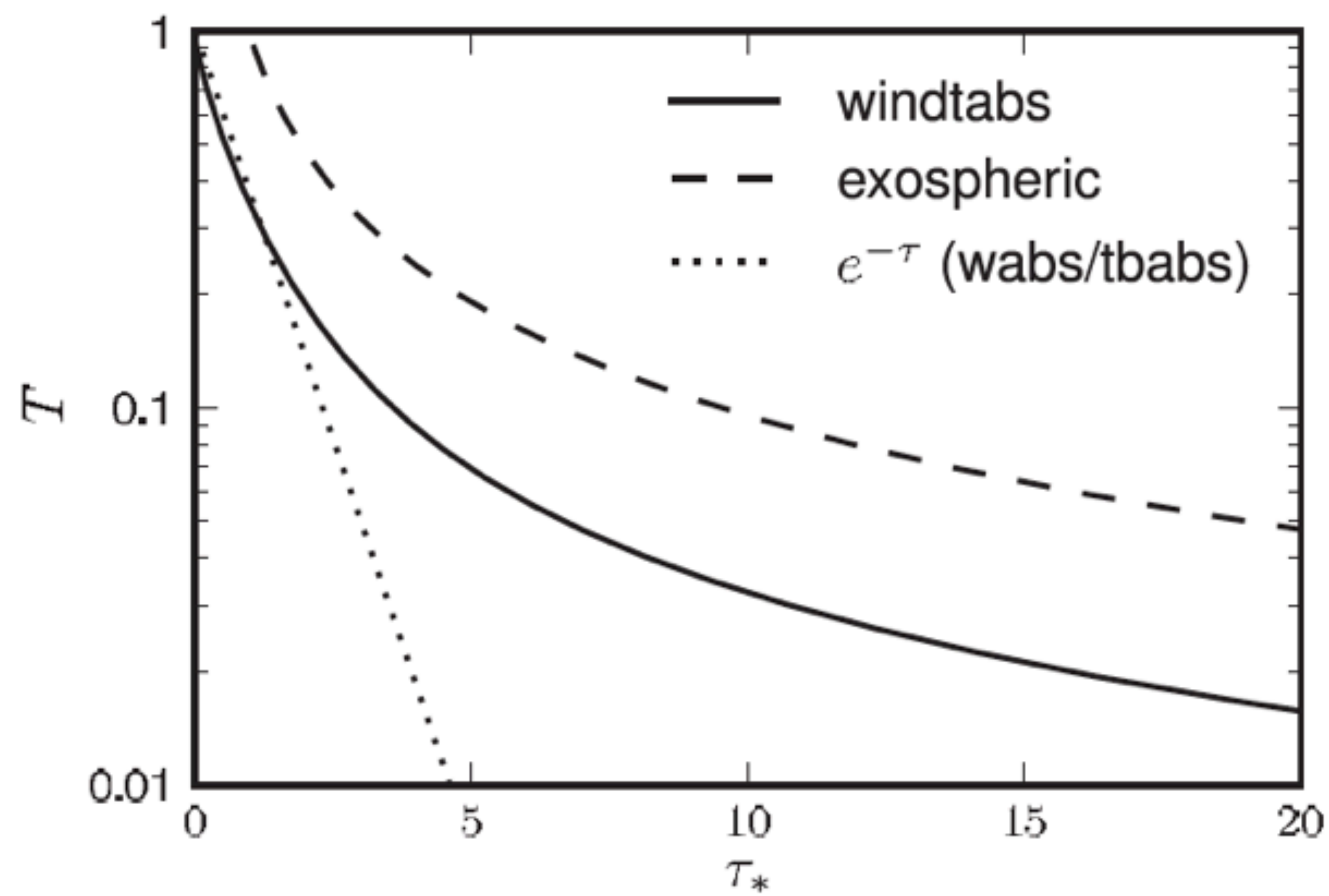
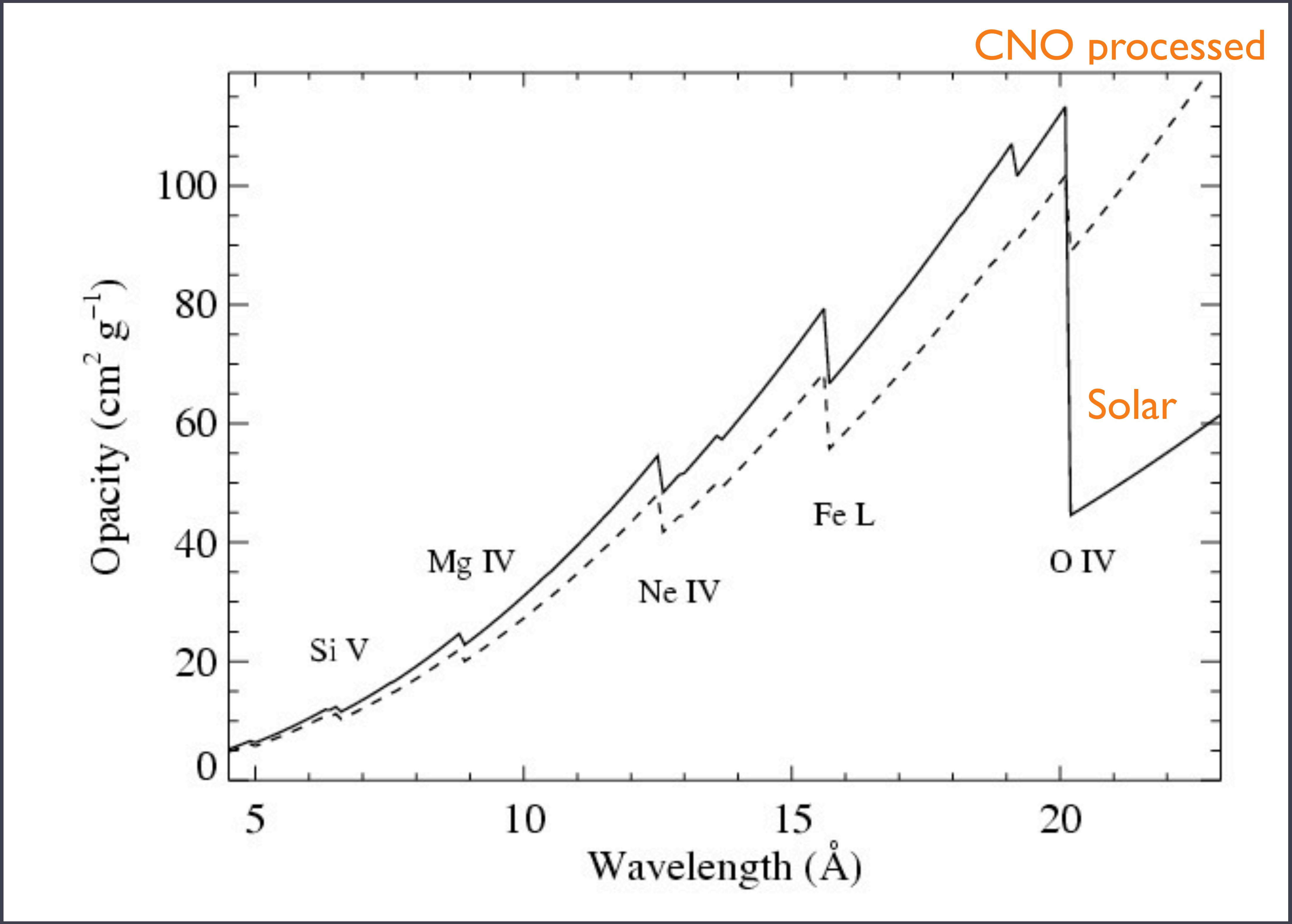


Figure 5. Comparison of transmission of three different models: coronal slab ($e^{-\tau}$), exospheric, and more realistic wind model (*windtabs*). The fixed parameters are $\beta = 1$, $R_0 = 1.5$.

More on this another time, but the tau_* parameter (x-axis) is an average optical depth parameter in the context of *windtabs*. See the Leutenegger et al. 2010 paper for details.

Here, again, is the wind opacity (two different models, each with different elemental abundances). I don't have a plot of the ISM opacity handy, but it's higher by a factor of several and also steeper. (Actually, see left panel, two slides ahead.)



Note that the wavelength dependence of the opacity implies that ignoring wind absorption will affect line ratios dervied from the data unless the two lines are at similar wavelengths.

Combining the transmission and opacity models shows that the *windtabs* transmission is generally much higher than the exponential (ISM-appropriate, "tbabs") model.

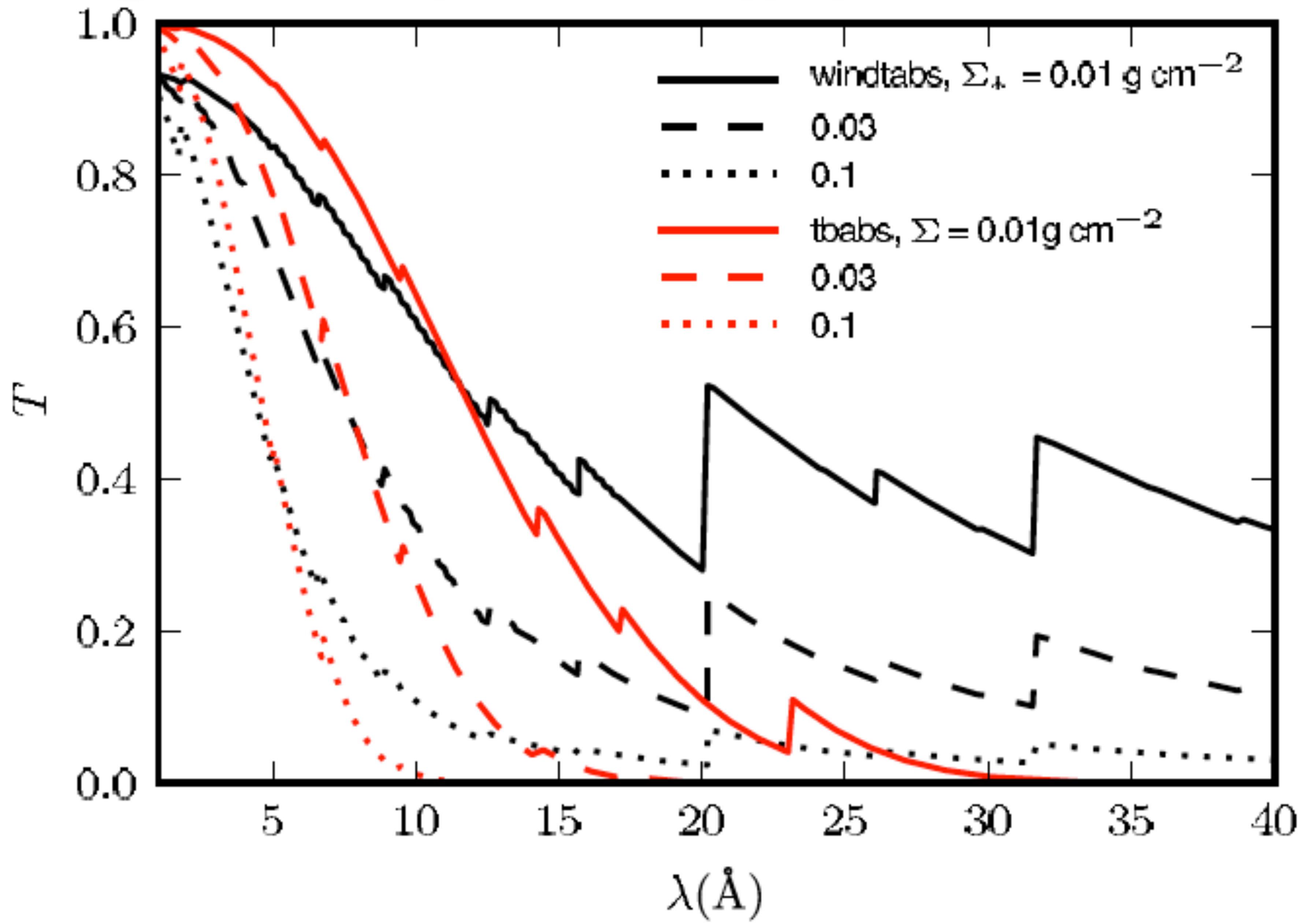


Figure 8. Transmission as a function of wavelength for ionized wind absorption model (*windtabs*, black) and for neutral slab absorption (*tbabs*, gray; red in the electronic version). Three values of absorbing column are given; for *windtabs*, the degree of absorption is specified by the characteristic mass column density Σ_*, while for *tbabs* it is given simply by the mass column Σ.

For each of the two model flavors, we show three different values of the wind mass column density, Σ, which is proportional to the wind mass-loss rate.

This is a less busy version of the preceding plots: left compares the wind and ISM opacity, center compares the windtabs vs. exponential transmission models, right combines the two effects (and for just one value of the wind mass column density)

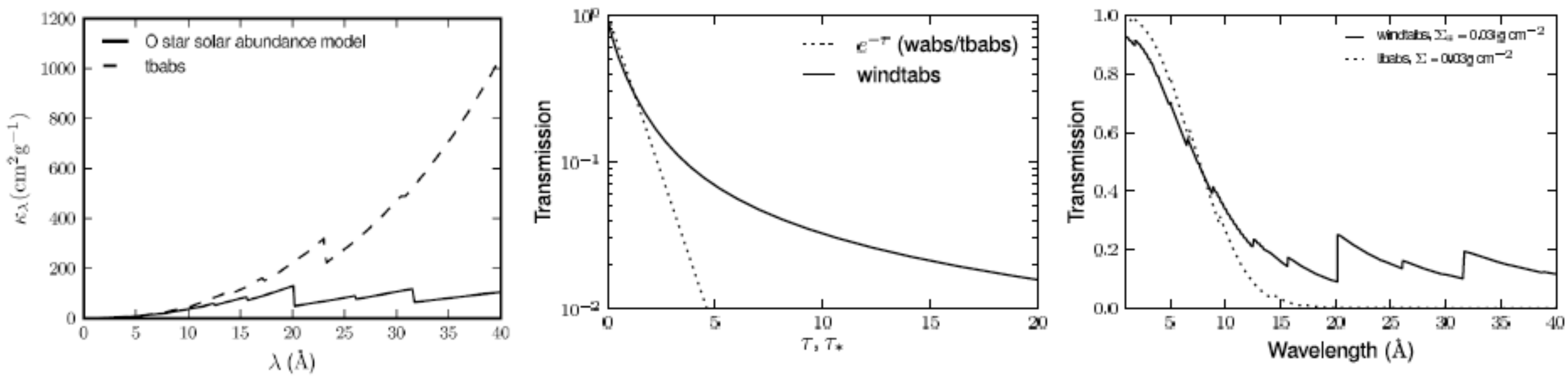
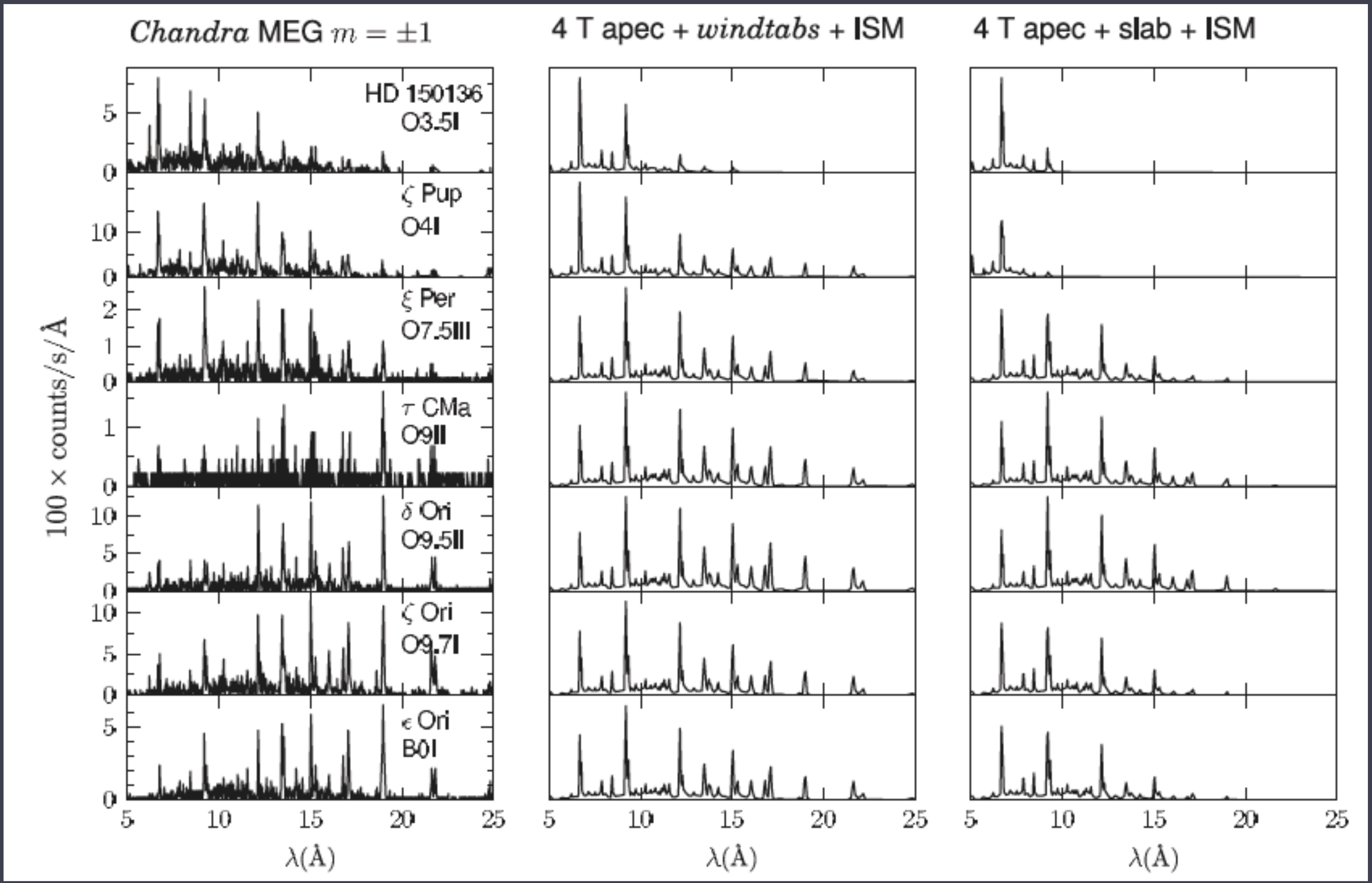


Figure 1: Three illustrations of the inapplicability of the standard ISM *tbabs* tool for modeling wind absorption. Left: the opacity in the *Chandra* bandpass of a typical O star's wind, compared to that of the neutral interstellar medium. Middle: the transmission for a source embedded in a spherically symmetric wind vs. the exponential transmission for an intervening absorber. Note how much more gradual the decline of transmission is for an optically thick embedded source compared to the exponential absorption from "slab" ISM models. Right: combining the opacity and the radiation transport model gives the wavelength-dependent transmission in the *Chandra* bandpass for a typical value of the wind column density. The excess ISM treatment is quite inaccurate.

The data trend (left) is qualitatively reproduced by the *windtabs* absorption (center) but not the exponential ("slab") ISM absorption model (right)

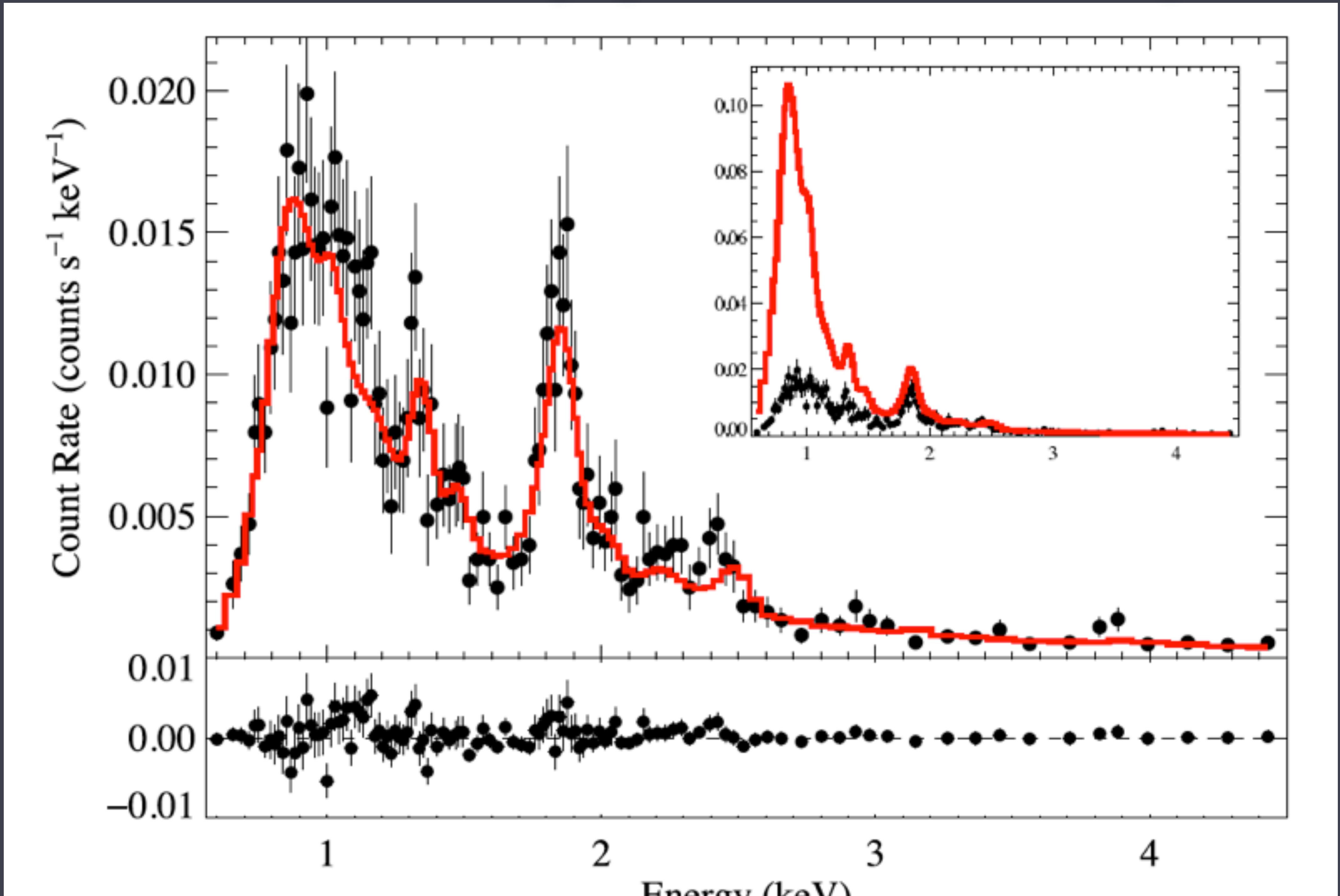


Ultimately, the temperature distribution (from the *apec* model component) and the wind mass column density, and thus the mass-loss rate (from the *windtabs* model component) are the quantities we'll derive for each star in our sample.

The plot on the previous slide (middle column) is not a *fit* to the data, but simply uses an assumed temperature distribution (same for each star) and an assumed mass-loss rate (different for each star).

Note that we will also measure the line ratios for H-like/He-like lines of Si and Mg (as well as Ne) for another handle on the temperature distribution.

We have already published one paper on fitting *apec+windtabs* to a *low*-resolution Chandra X-ray spectrum of an O star (HD 93129A)



Cohen et al. 2011, *MNRAS*, 415, 3354

Note that the x-axis is photon energy, not wavelength. The red histogram is the best-fit *apec+windtabs* model. The inset shows the same model but ignoring wind absorption, showing that ~80% of the produced X-rays are absorbed.