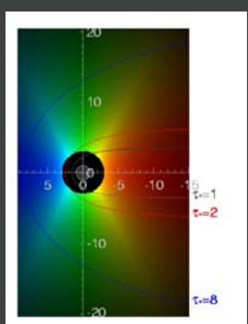
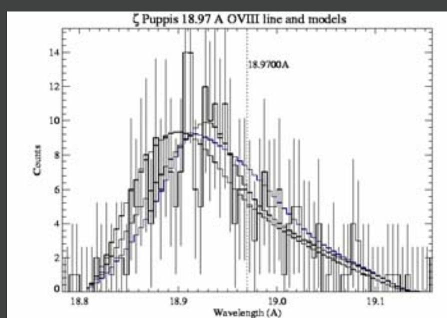
Quantitative Analysis of Resolved X-ray Emission Line Profiles of O Stars:

Profile Symmetry: Clumping and Mass-Loss Rate Reduction

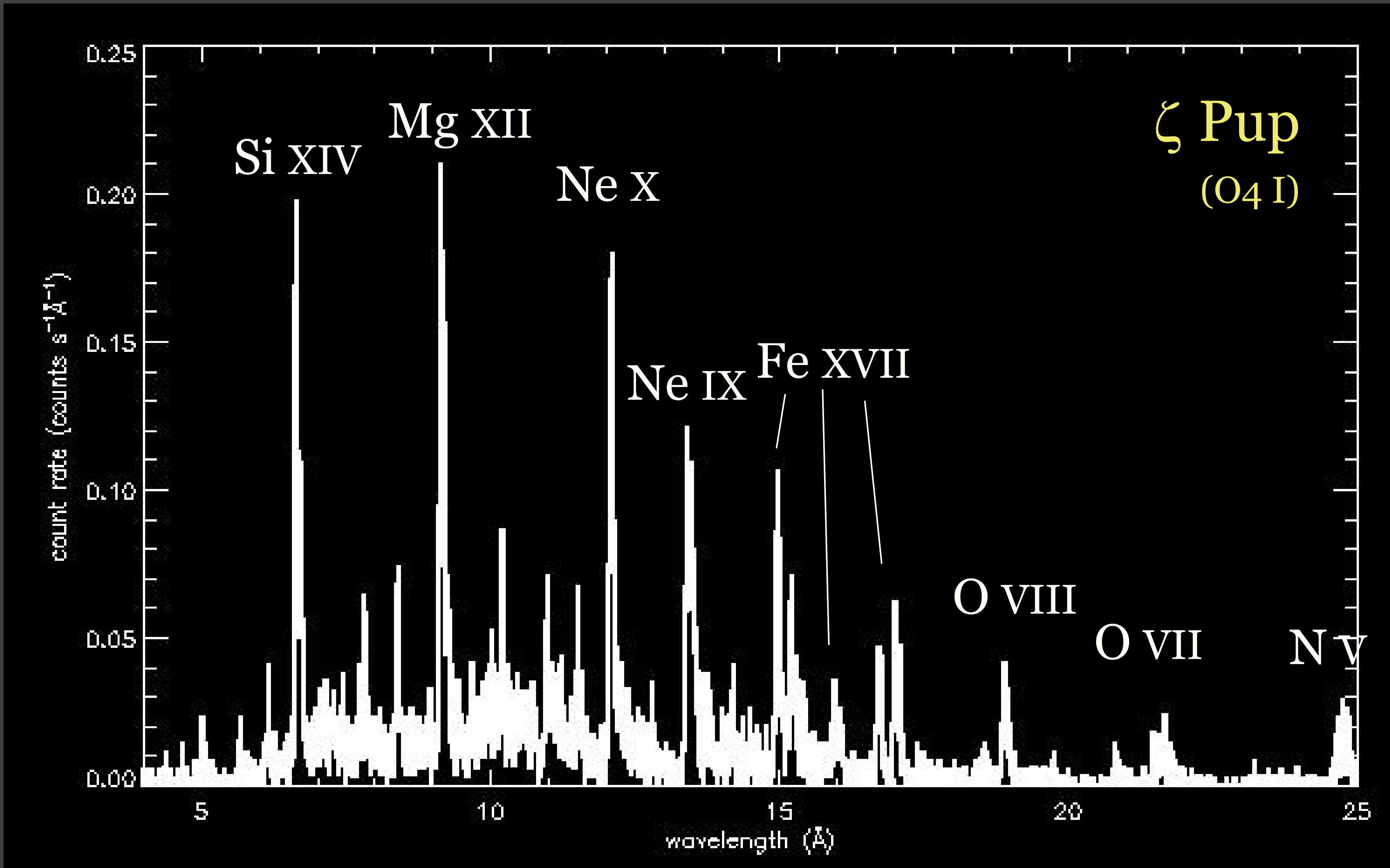
David Cohen
Department of Physics & Astronomy
Swarthmore College

With Maurice Leutenegger, Asif ud-Doula, and Stan Owocki





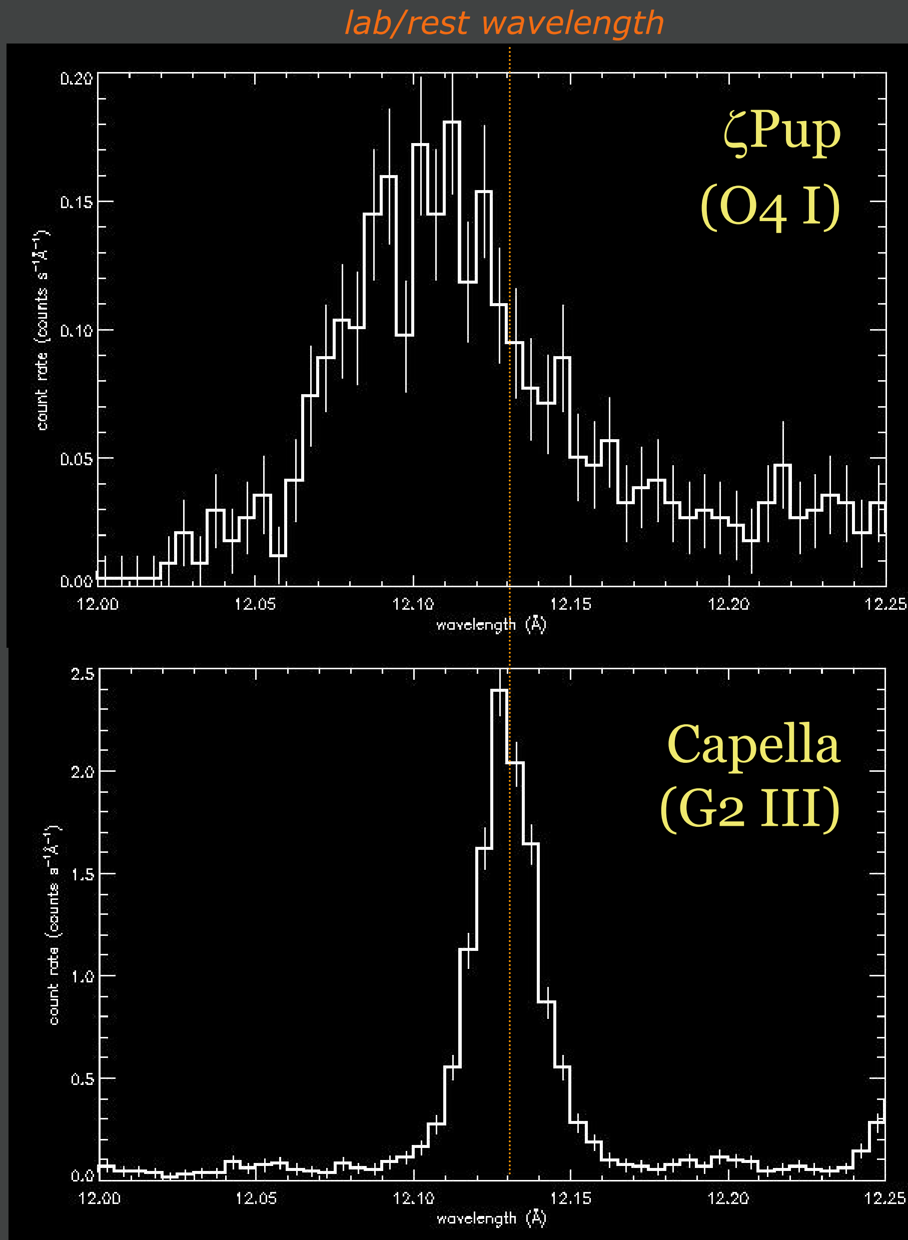
Globally, O star X-ray spectra look like coronal spectra



10 Å

20 Å

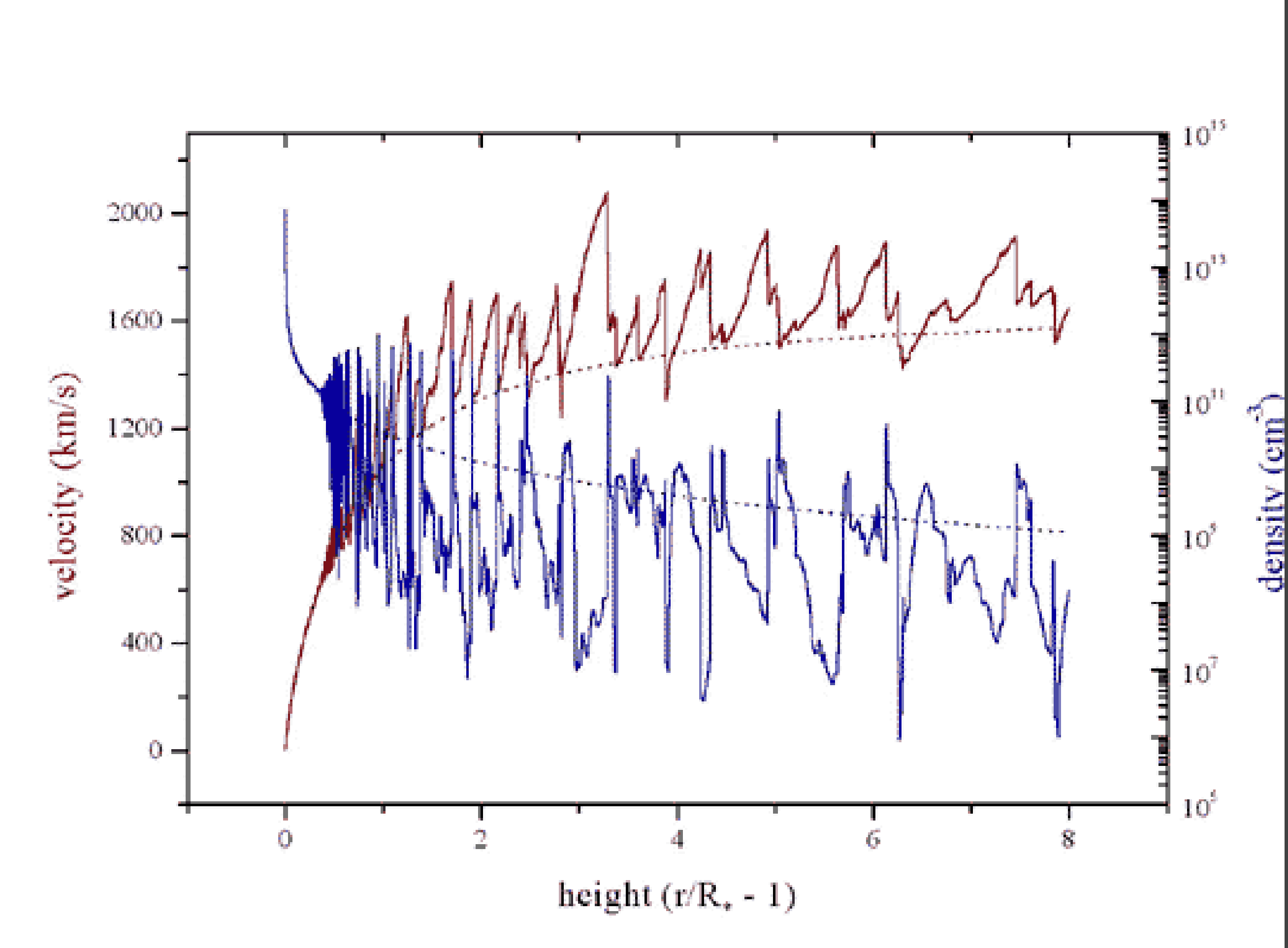
But each individual line is significantly Doppler broadened (here is Ne X Lyα at 12.13 Å)



HWHM ~ 1000 km/s

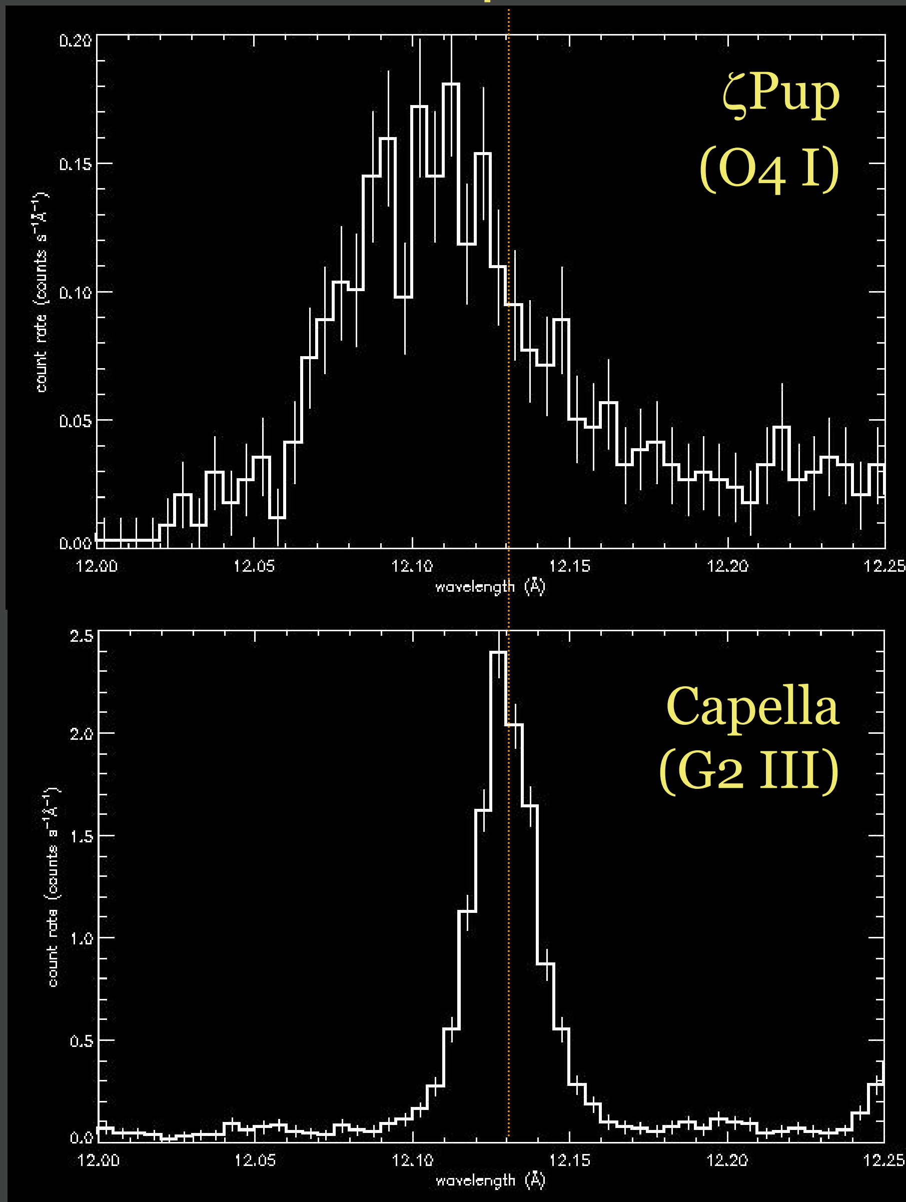
An unresolved line in a solar-like coronal source, for comparison

A snapshot from a 1-D rad-hydro simulation of an O star wind. Note the discontinuities in velocity. These are shock fronts, compressing and heating the wind, producing x-rays.



There are dense inter-shock regions, containing most of the wind mass, in which cold material provides a source of photoelectric absorption

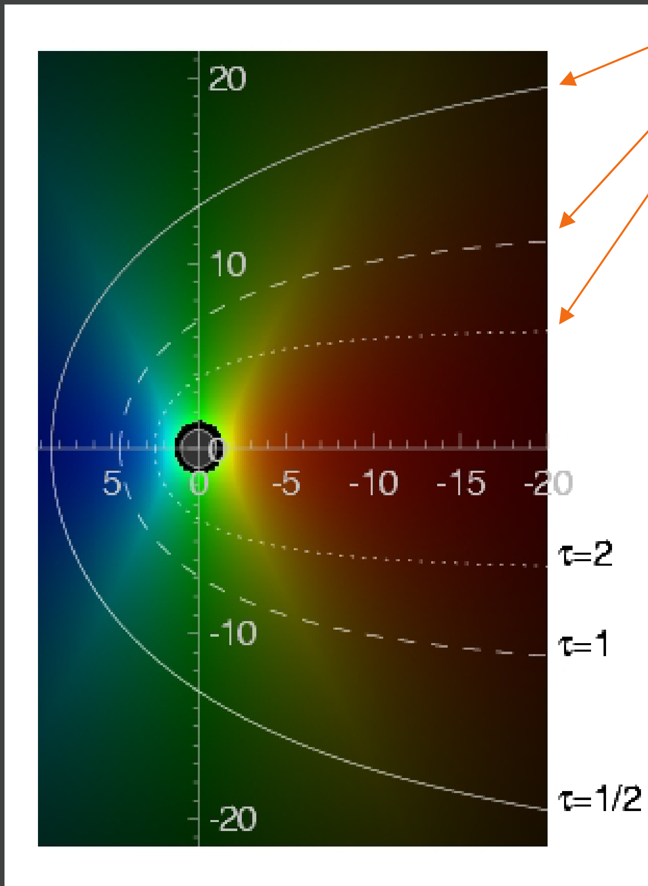
The **line shapes** in O star x-ray spectra provide information about the kinematics of the hot plasma in their winds

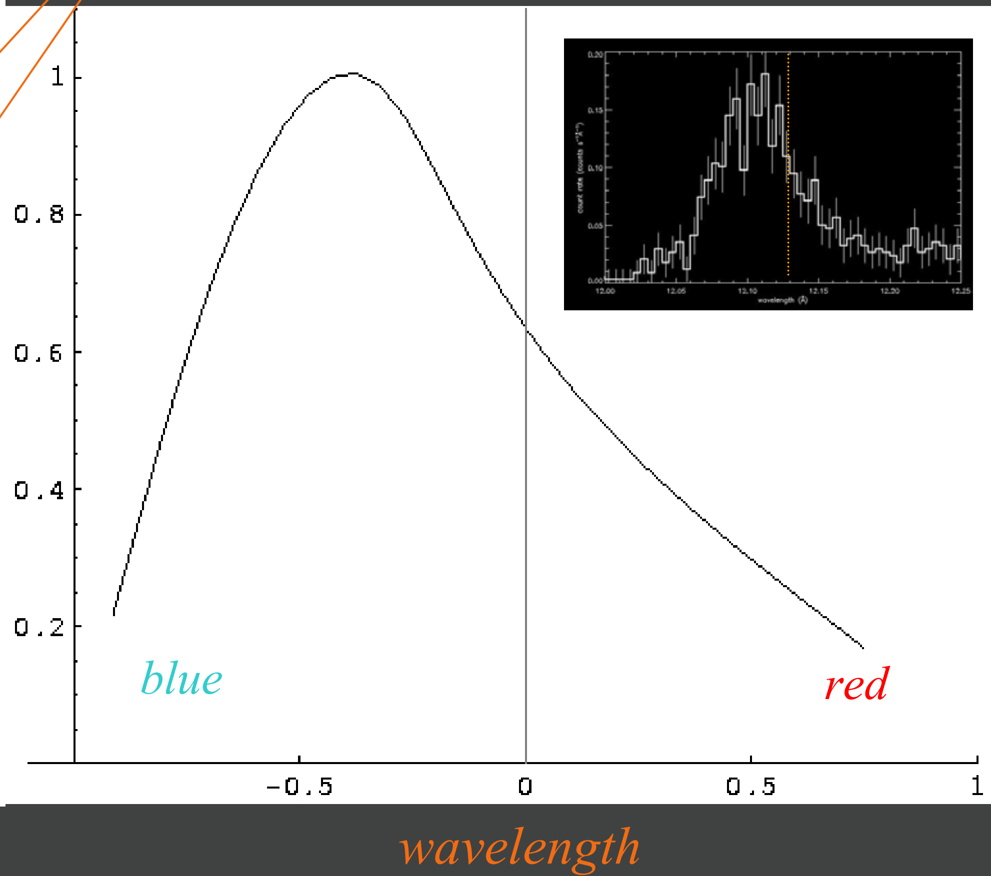


Note: the line isn't just broad, it's also **blue shifted** and **asymmetric**

Simplified model for data fitting

Contours of constant optical depth (observer is on the left)





continuum absorption in the bulk wind preferentially absorbs red shifted photons from the far side of the wind

The profile shapes are affected by the spatial and kinematic distribution of the hot plasma,

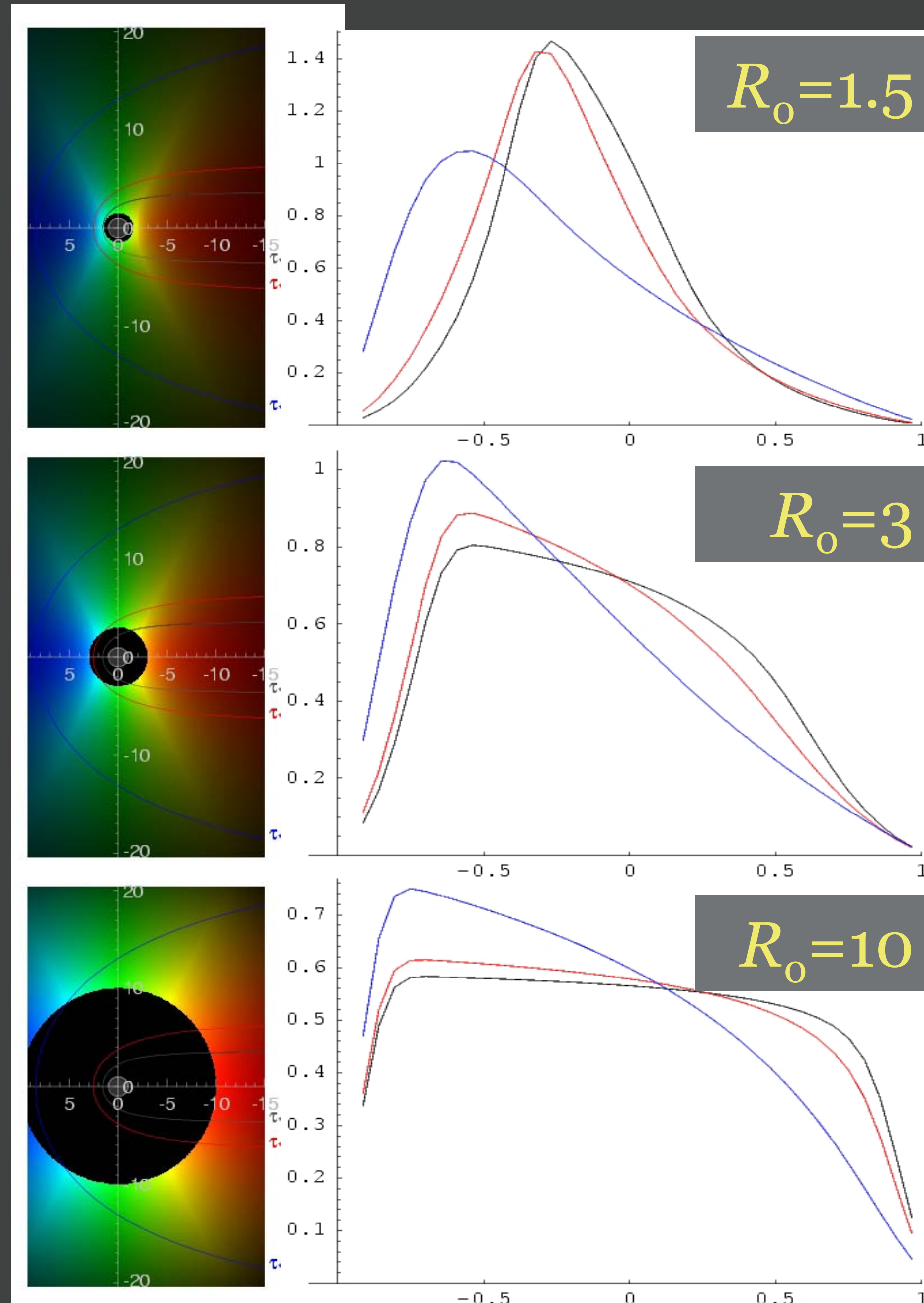
AND by the amount of **attenuation** by the cold wind, characterized by the optical depth parameter:

$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

The line profile is calculated from:

$$L_\lambda = 8\pi^2 \int_{-1}^{1} \int_{R_*}^{\infty} j e^{-\tau} r^2 \, dr \, d\mu$$

Increasing R_o makes lines broader; increasing τ_* makes them more blue shifted and skewed.



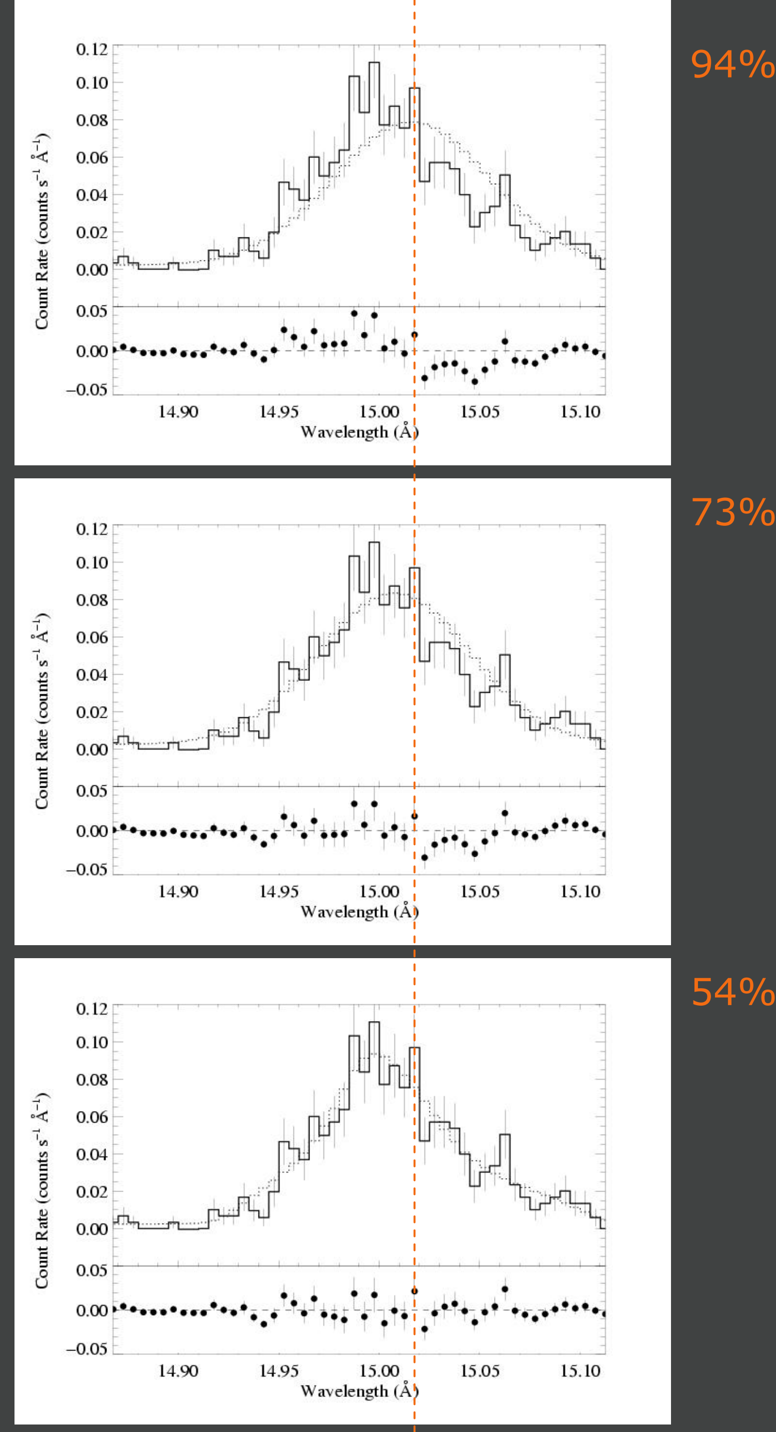
τ_*=1,2,4

Here's ζ Ori (O9.7 I) – with a weaker wind than ζ Pup, but still the lines are broad, shifted, and asymmetric.

An unshifted Gaussian doesn't fit

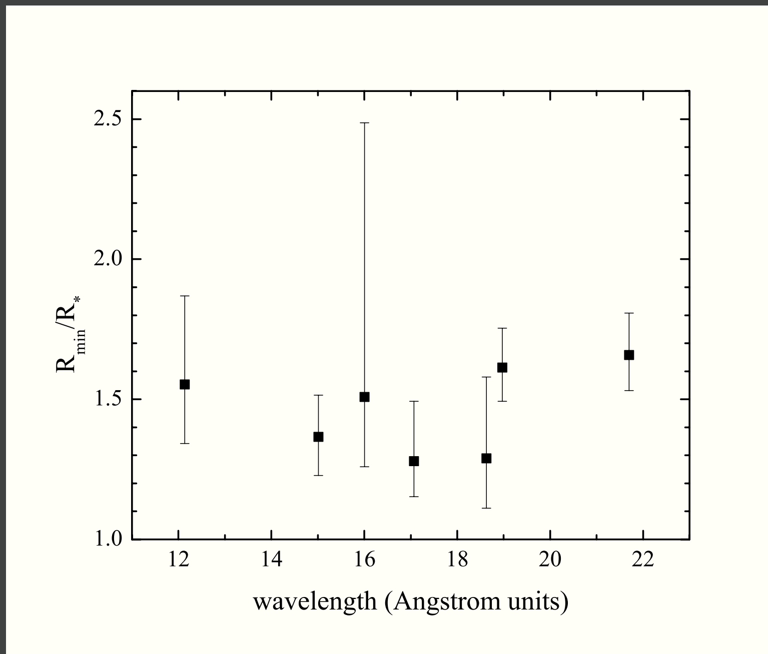
A shifted Gaussian fits OK

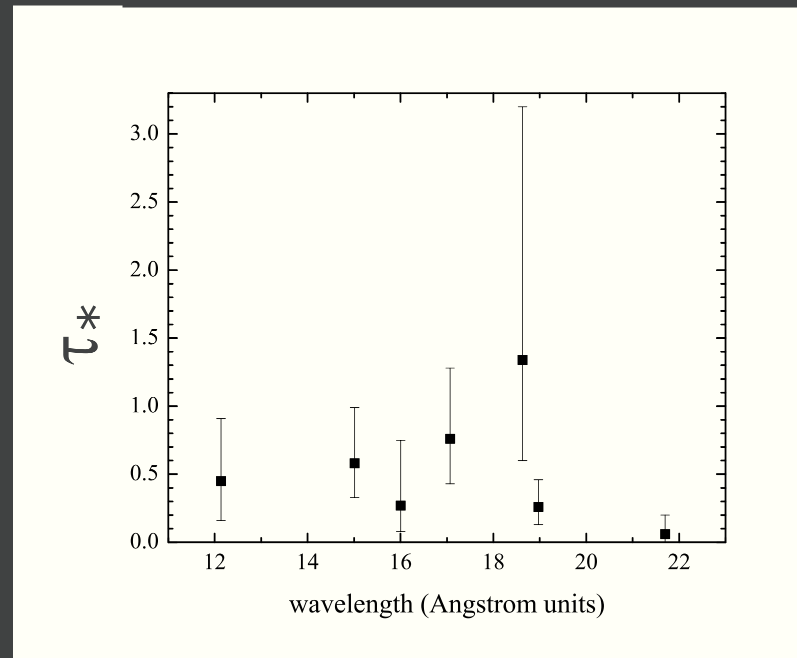
A kinematic model with absorption fits better



Rejection probabilities are shown on the right of each panel.

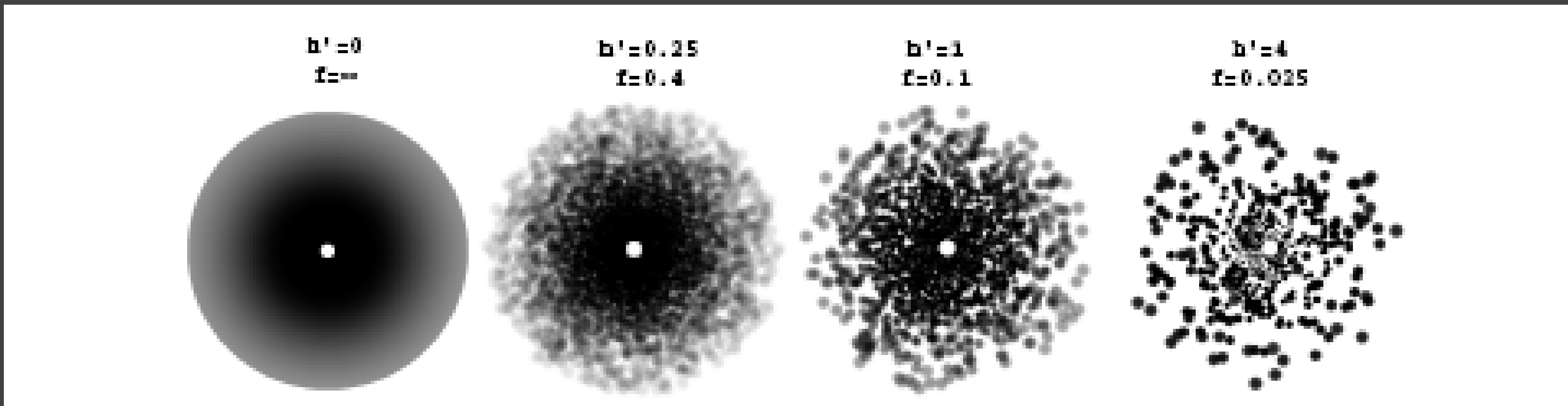
Fit results for ζ Ori summarized





The onset radii (left) are exactly what's expected from the standard wind-shock picture. There is evidence for attenuation by the cold wind (right), but at levels **nearly 10 times lower** than expected. This is the same result that we found for ζ Pup.

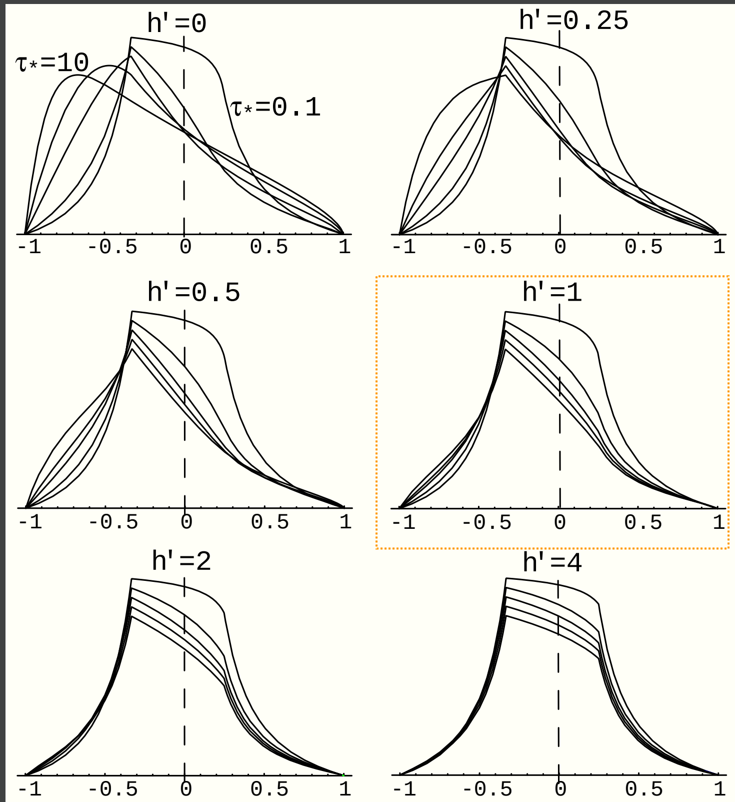
Clumping in the cold, absorbing wind can reduce the overall effective opacity: Can clumping explain the relative symmetry of the profiles?



The key parameter for describing the reduction in effective opacity due to porosity is the ratio of the clump size scale to the volume filling factor: $h=L/f$.

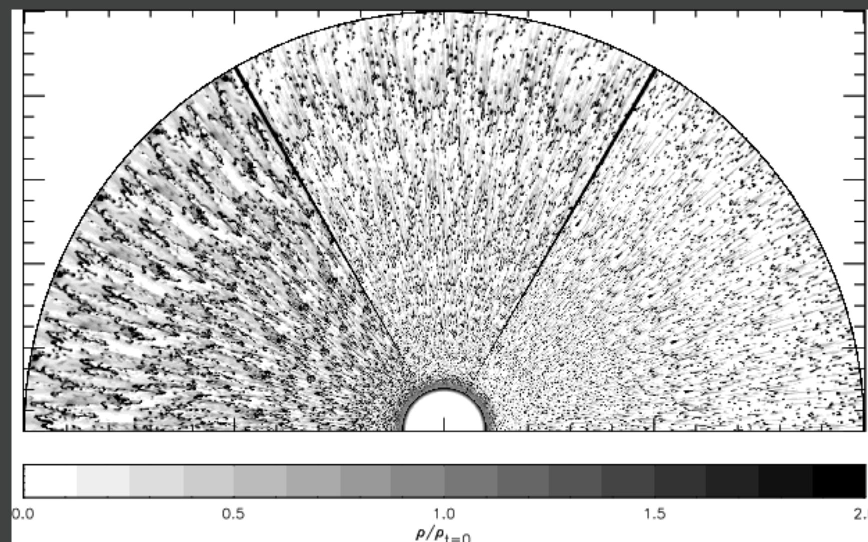
We dub this quantity the ***porosity length***, h.

Density contrast matters, but so does inter-clump spacing.



It turns out that line profiles (left) are not significantly affected until the porosity length is **comparable to the stellar radius** (unity, in the unitless formulation of these slides).

This degree of porosity is ***not*** expected from the line-driven instability. The clumping in 2-D simulations (right) is on quite *small scales*.



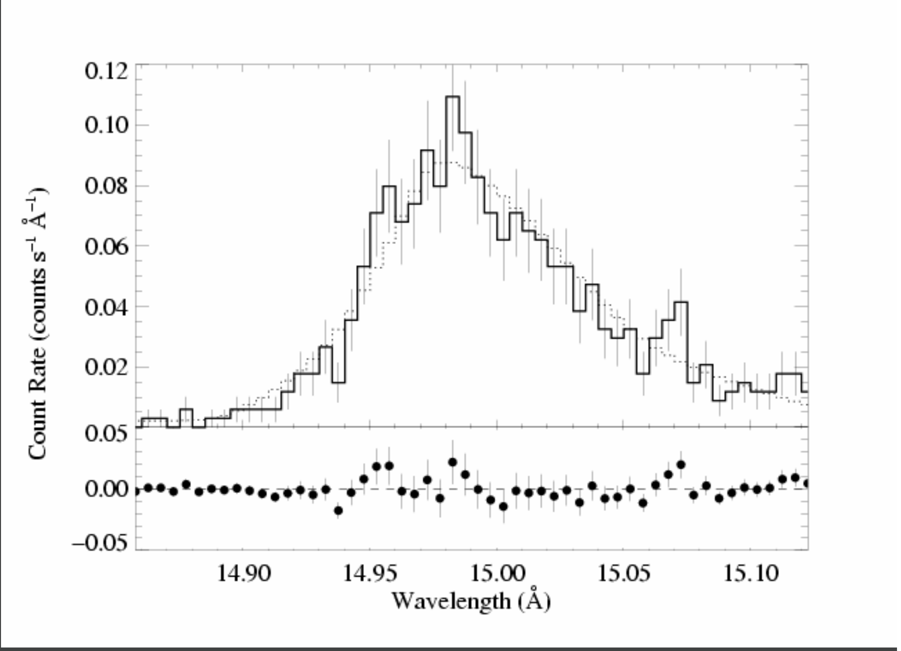
Dessart & Owocki, 2003

Fitting kinematic models with **absorption and clumping** to ζ Pup

Best-fit model with adjustable clumping and wind opacity:

h_∞ = 0 (no clumping)

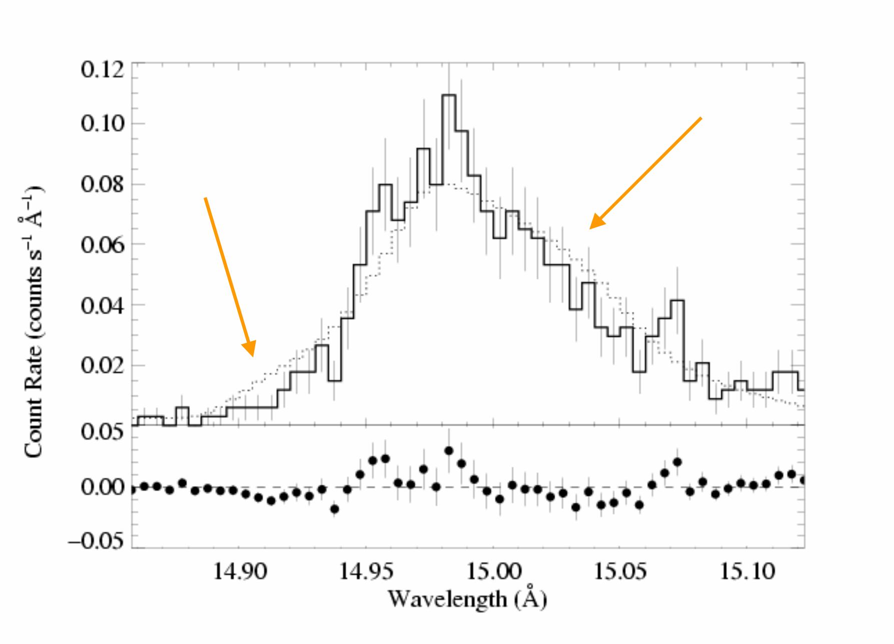
τ_* = 1.4 +/- 0.4



Best fit model with τ_* fixed at τ_*=15

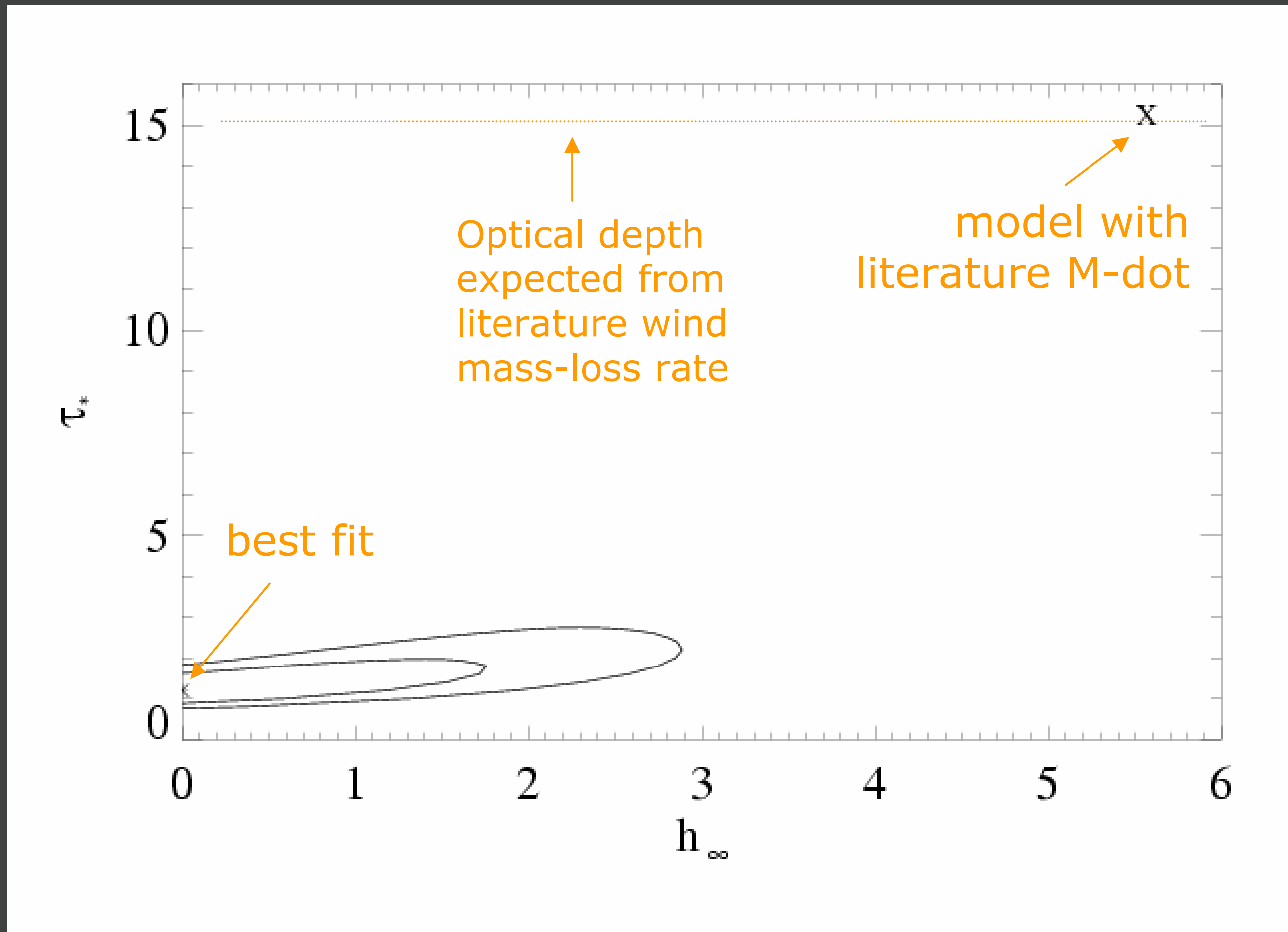
h_∞ = 6.7 +/- 1.1

h_∞ is unrealistically high…and the fit's not even that good



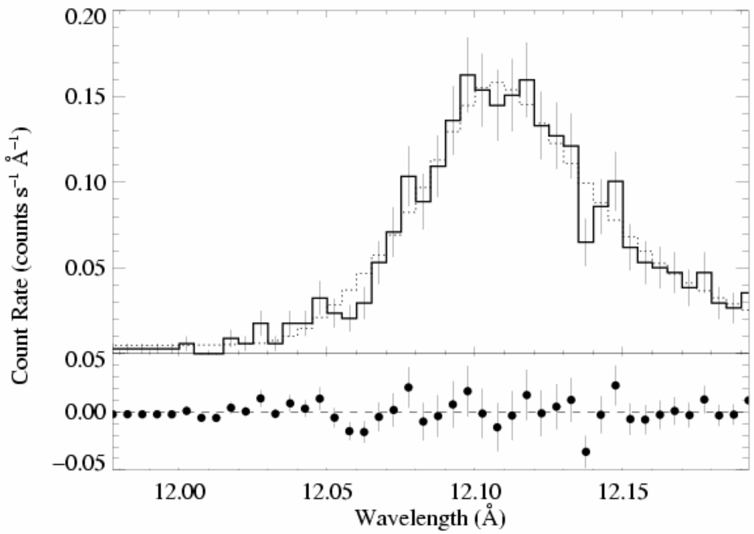
68% and 90% confidence limits for the fits to the Fe XVII 15.014 Å line in ζ Pup

optical depth



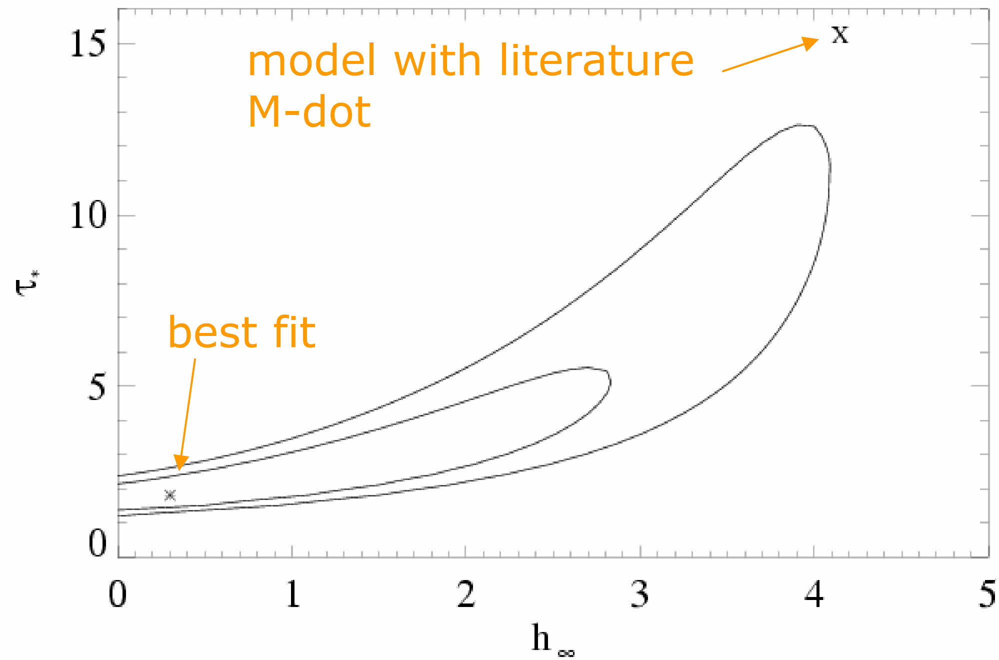
Porosity length (“clumpiness”)

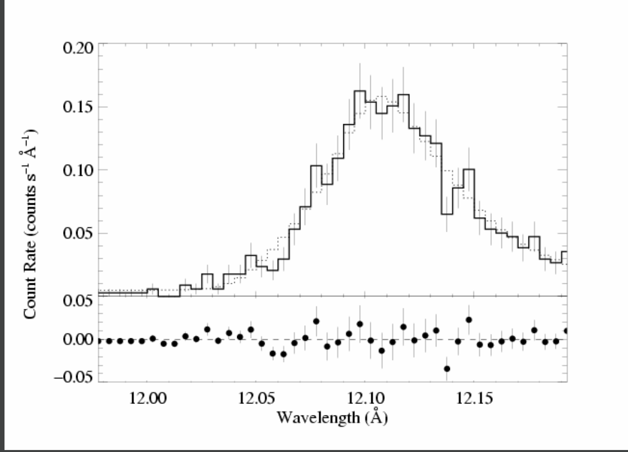
Similar fit to another line: Ne X Lyα



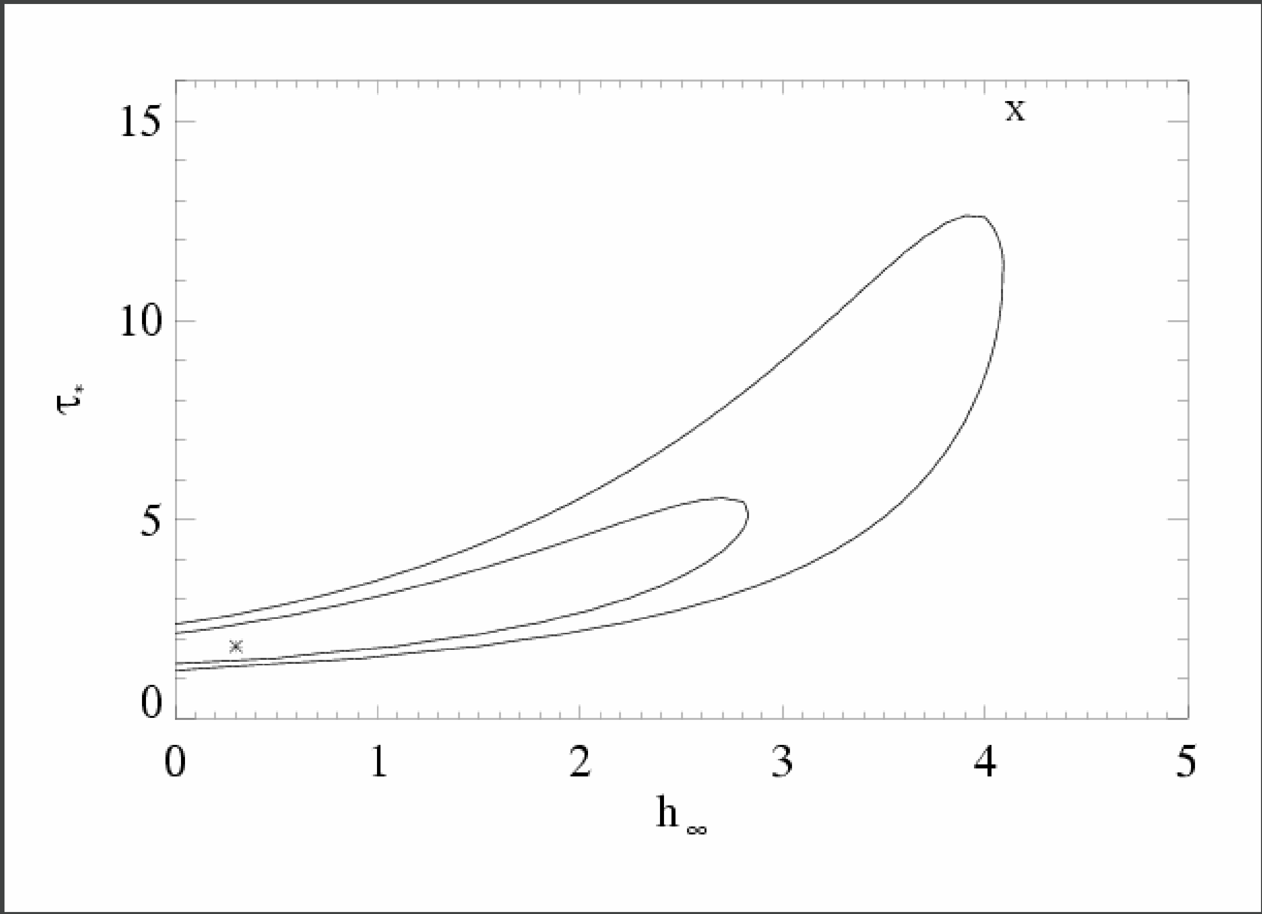
Clumpy model also ruled out here

Fits to real data show that reduced mass-loss rate models are preferred over clumpy models.





And furthermore, clumping only has an effect when the clump spacing is >1R_{star}.



Conclusions

O star X-ray emission line profiles are broadened, shifted, and asymmetric as the wind-shock model predicts

But the degree of asymmetry requires significantly lower wind optical depths than are expected in these stars

Clumping and the associated porosity can, in principle, alleviate this problem, but only if the degree of clumping is unrealistically high

The wind-shock scenario explains the data, but O star mass-loss rates are lower than have been supposed!