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

David Cohen
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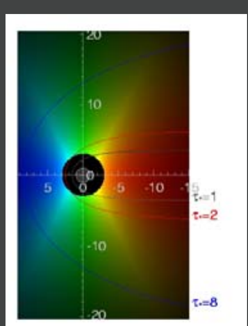
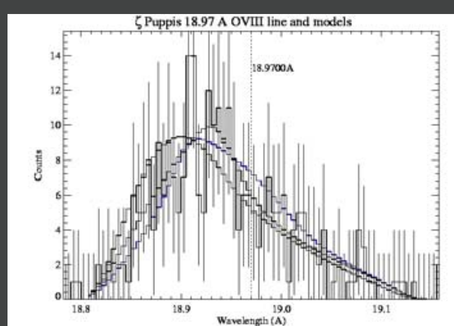
With Maurice Leutenegger, Asif ud-Doula, Rich Townsend, and Stan Owocki





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X-ray Production in Hot Stars

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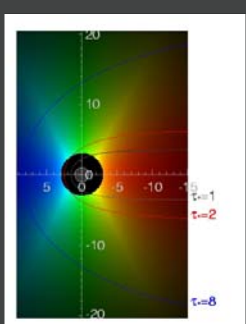

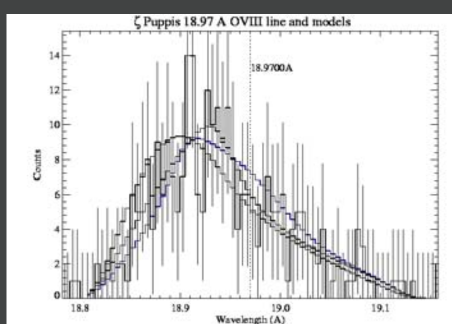

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astro.swarthmore.edu/~cohen/presentations/AMNH_2May07/

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

Profile symmetry, clumping, and mass-loss rate reduction

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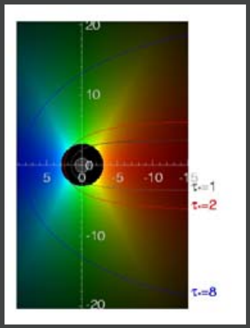

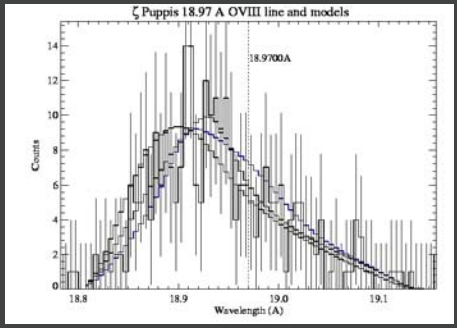

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OUTLINE

1. Hot-star X-rays in context

    -> the discovery of X-ray emission from OB stars in the late 70s came as a surprise

2. Hot-star winds

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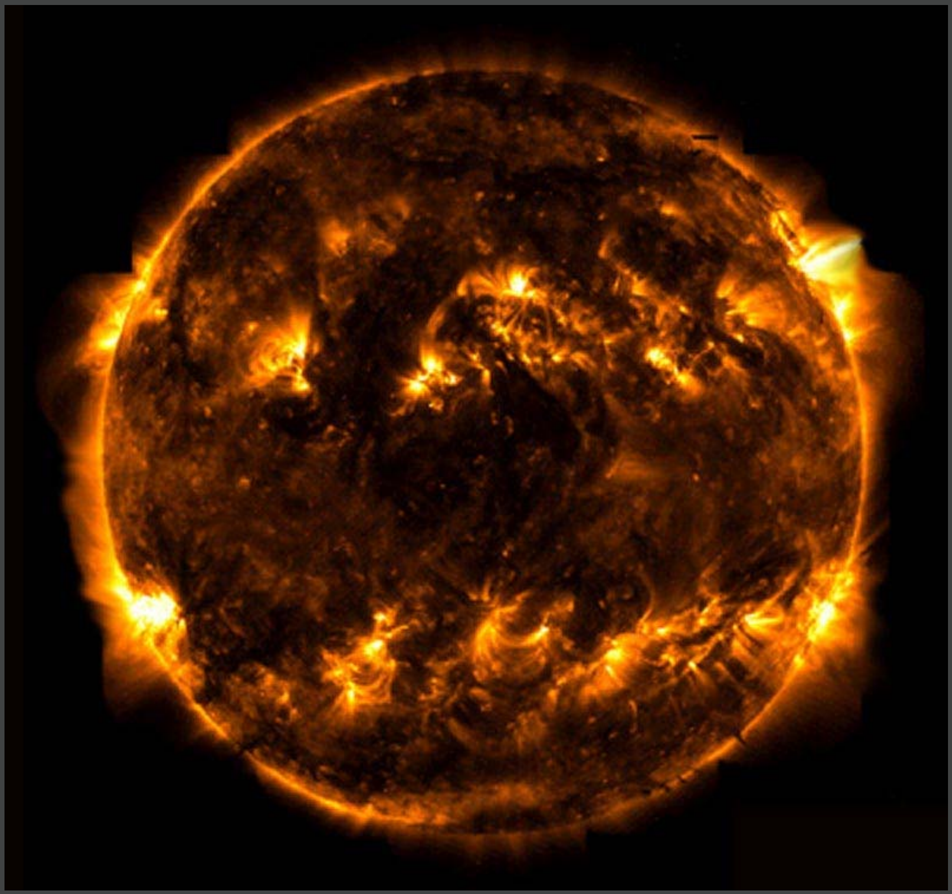
The Sun is a strong source of X-rays

$L_x \sim 10^{-5}\, L_{Bol}$
$T_x \sim$ few 10^6 K

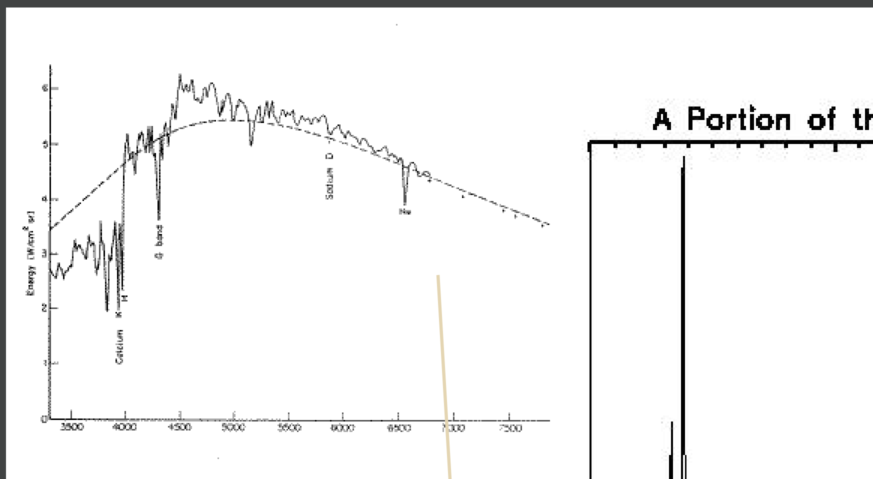
← *both are higher for active M stars & low-mass PMS stars*

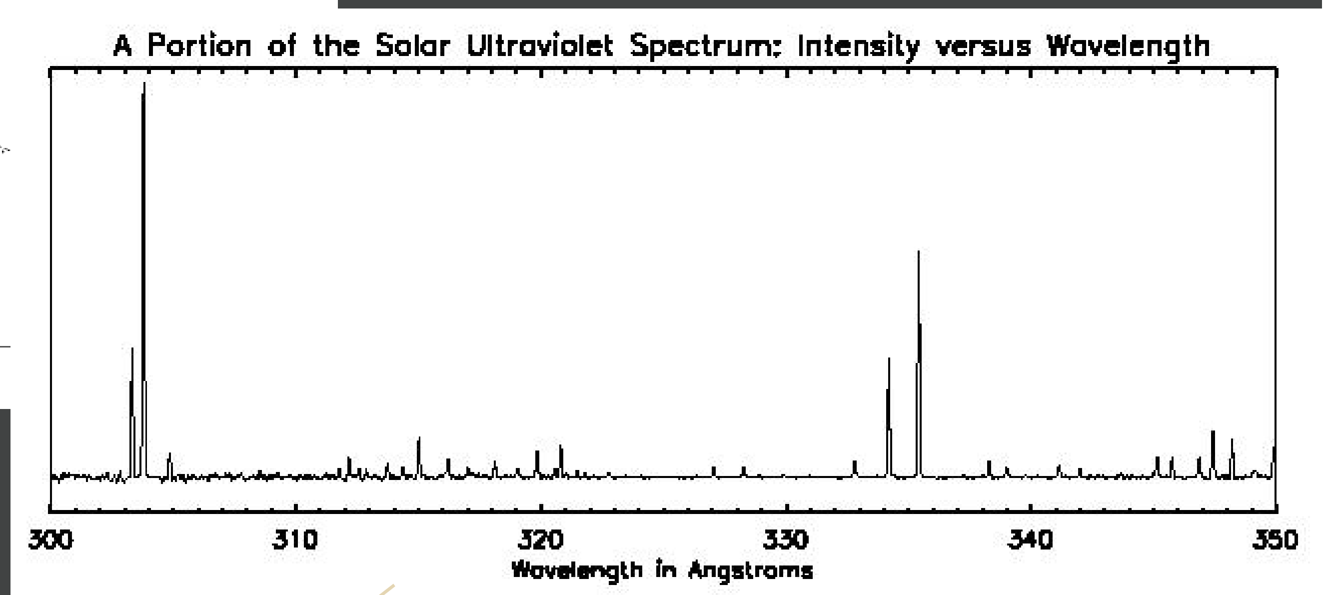


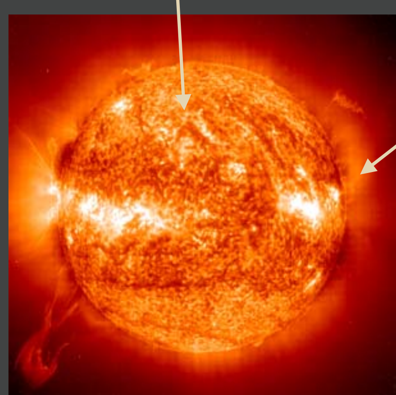
The hot plasma is generally **confined** in magnetic structures above – but near - the surface of the Sun.

Coronal Spectra

visible solar spectrum

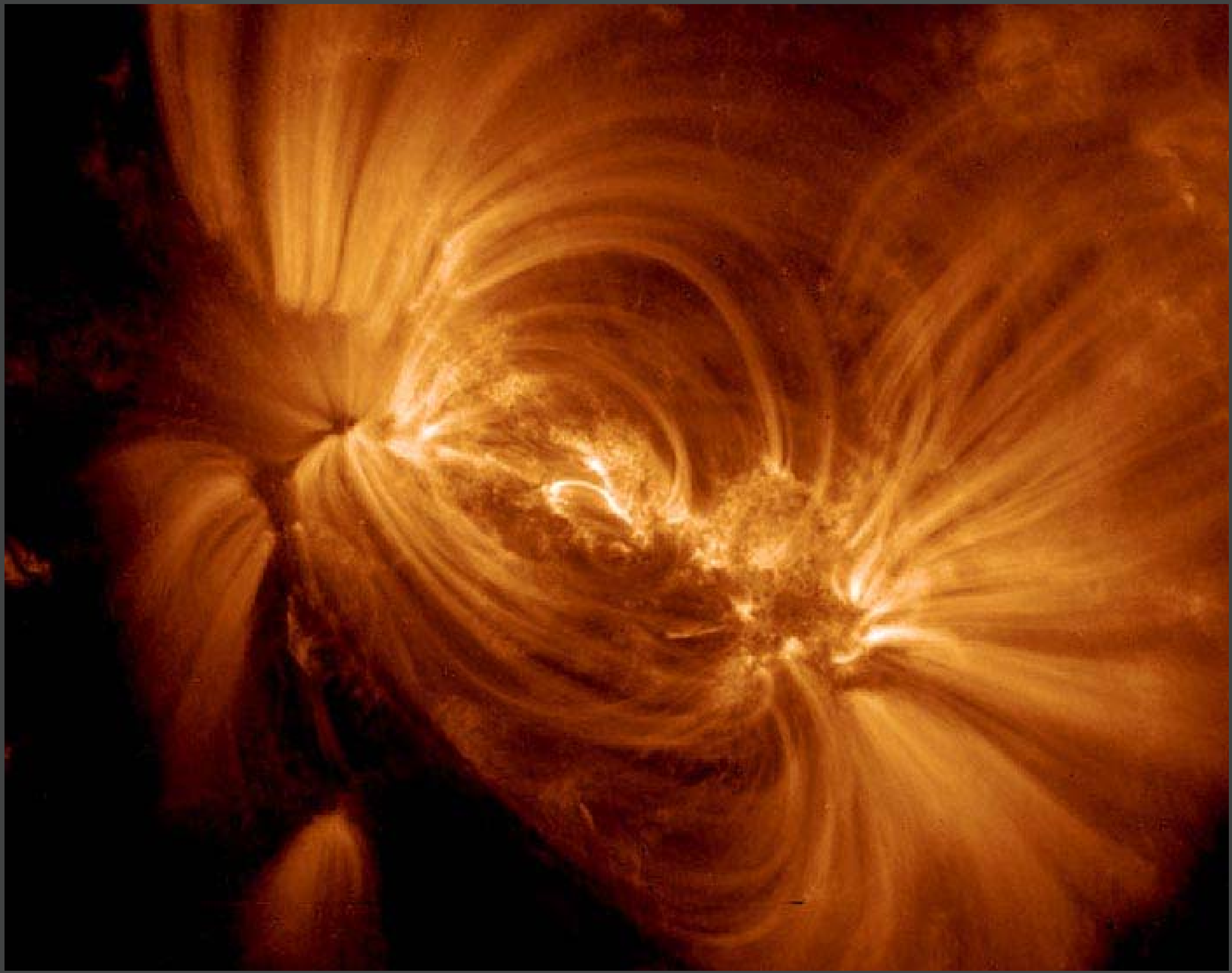




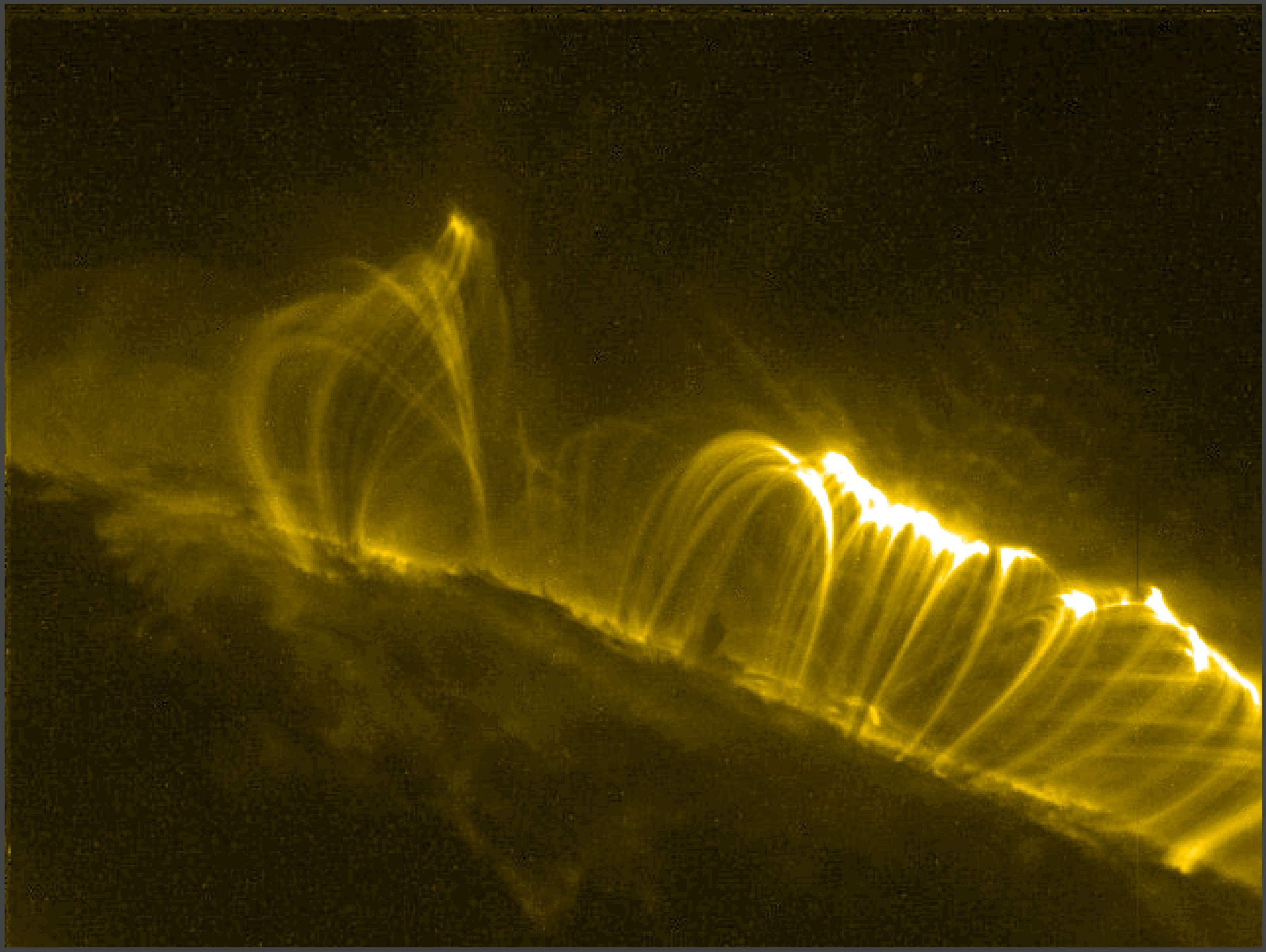


X-ray/EUV solar spectrum:
narrow emission lines from
hot, optically thin plasma

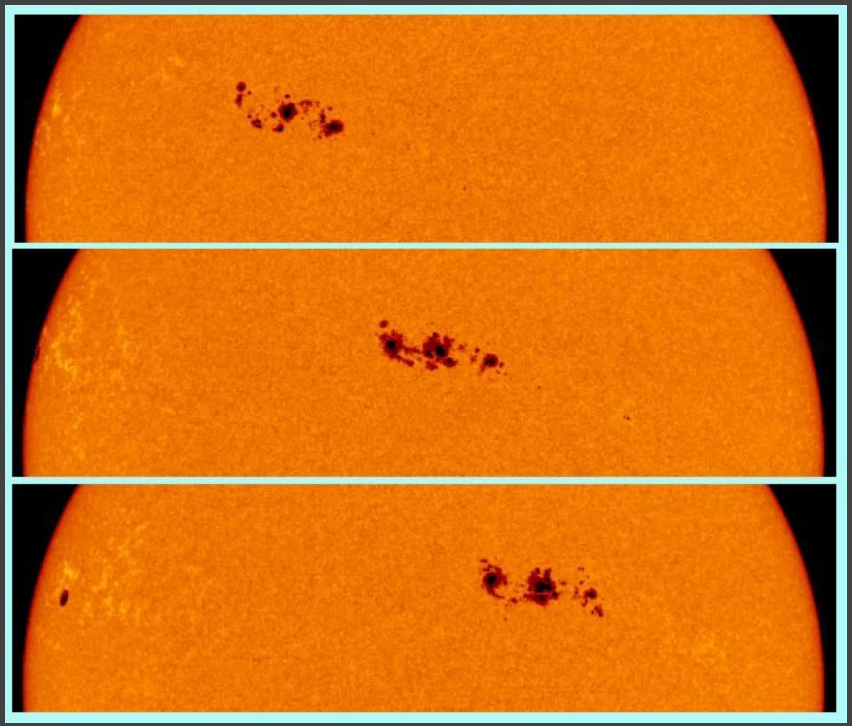
This hot plasma is related to magnetic fields on the Sun: confinement and heating; also spatial structure, conduits of energy flow



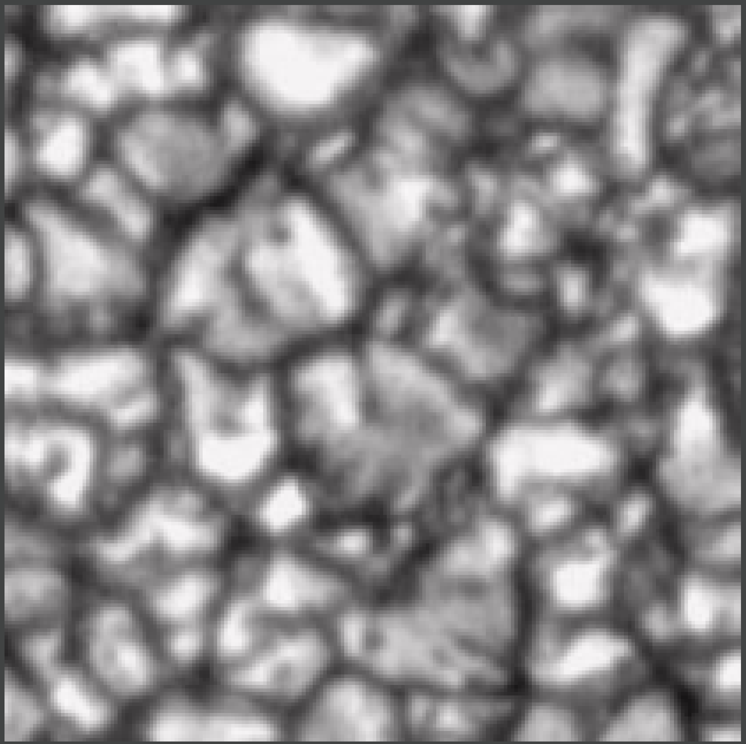
More magnetic structures on the Sun: X-ray image from *TRACE*



The Sun's magnetic dynamo requires rotation + convection to regenerate and amplify the magnetic field



Sunspots over several days: *rotation*



Note granulation, from *convection*

The **Sun** and other **cool stars** emit X-rays associated with magnetic activity, related to convection and rotation...

But what of ***hot, massive stars***?

Hot, Massive Stars

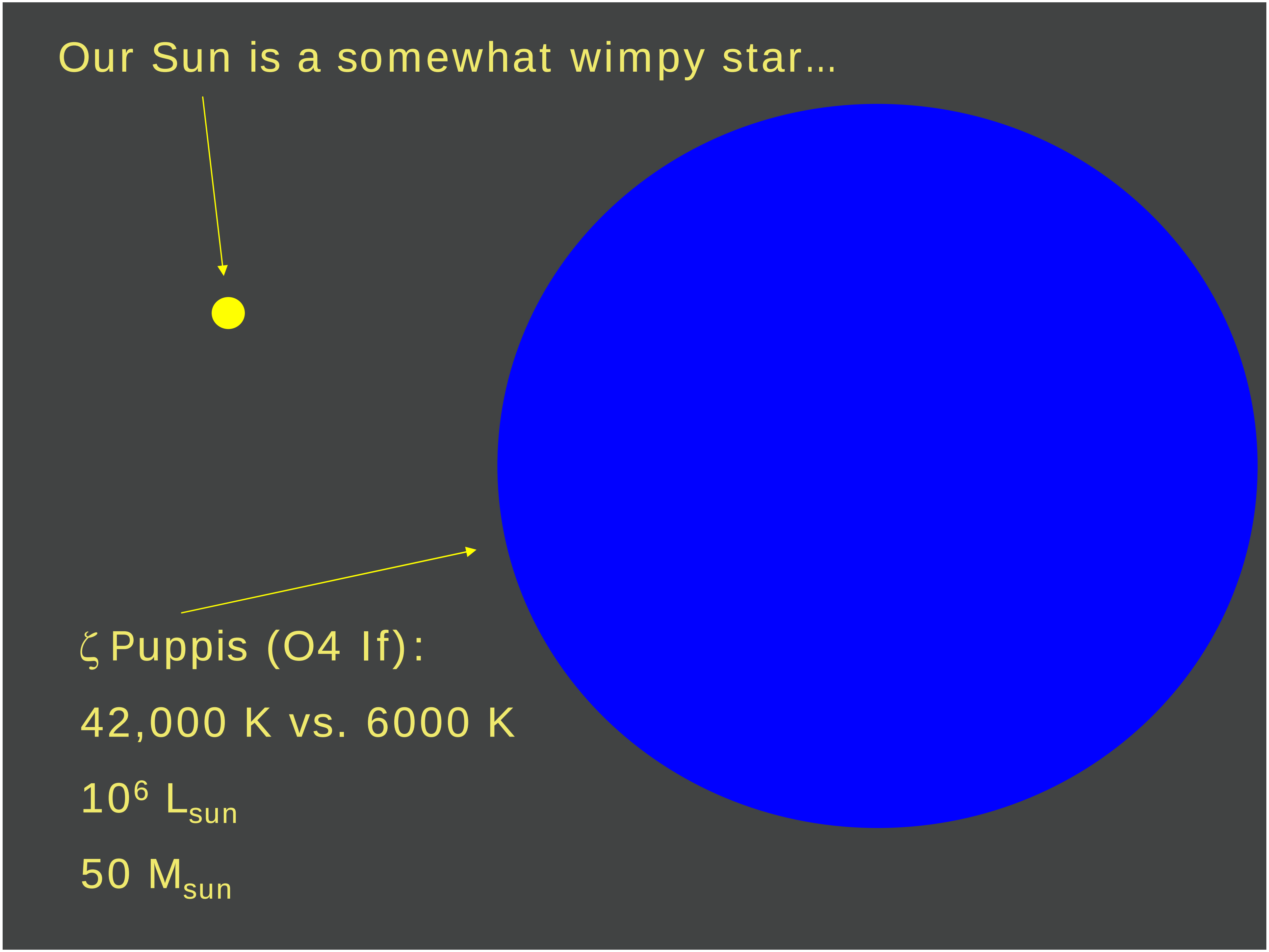
Representative properties:

B0 V: T=30,000 K, $M=20M_{sun}$, $L=10^5L_{sun}$

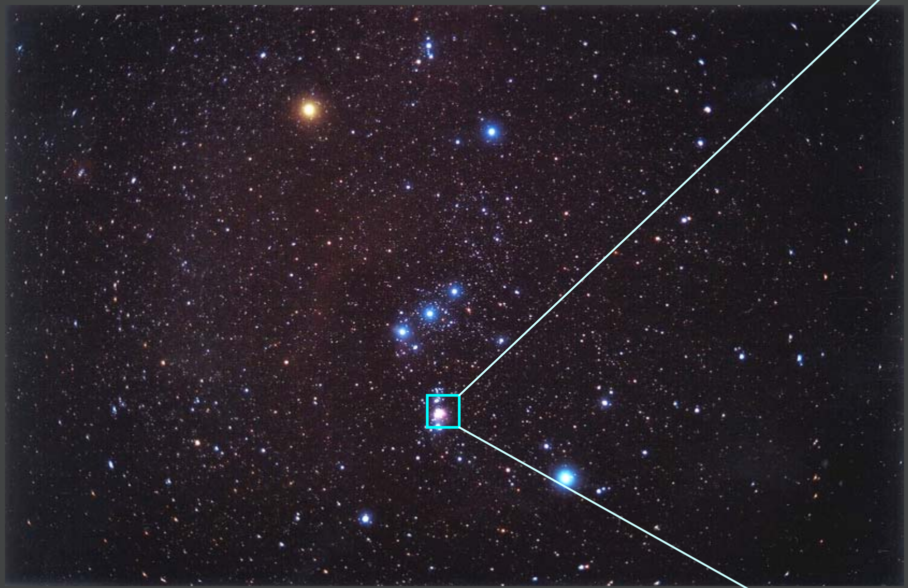
O5 I: T=40,000 K, $M=40M_{sun}$, $L=10^6L_{sun}$

Stars hotter than about 8000 K do ***not*** have convective envelopes - no convection - no dynamo - no hot corona...

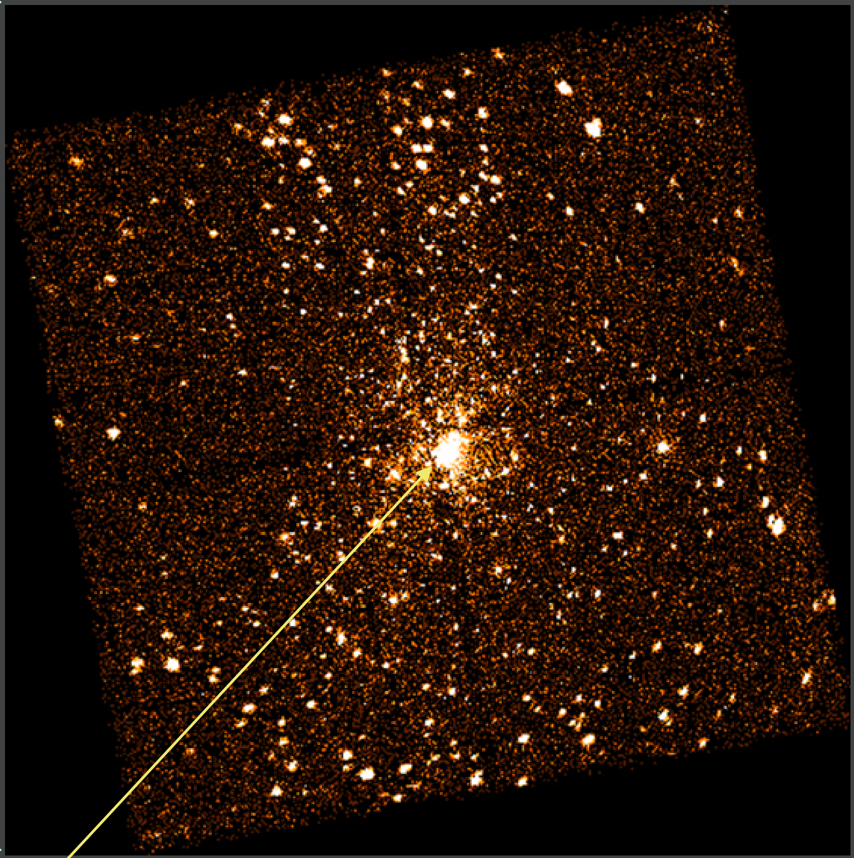
...no X-rays**?**


Our Sun is a somewhat wimpy star…
ζ Puppis (O4 If):
42,000 K vs. 6000 K
10^6 L_{sun}
50 M_{sun}

In 1979 the *Einstein Observatory* made the surprising discovery that many O stars are strong X-ray sources



Chandra X-ray image of the Orion star forming region



θ^1 Ori C: a T_{eff}=40,000 K O7 V star (very young, too)

Strong correlation between rotational velocity and x-ray luminosity in solar-type stars

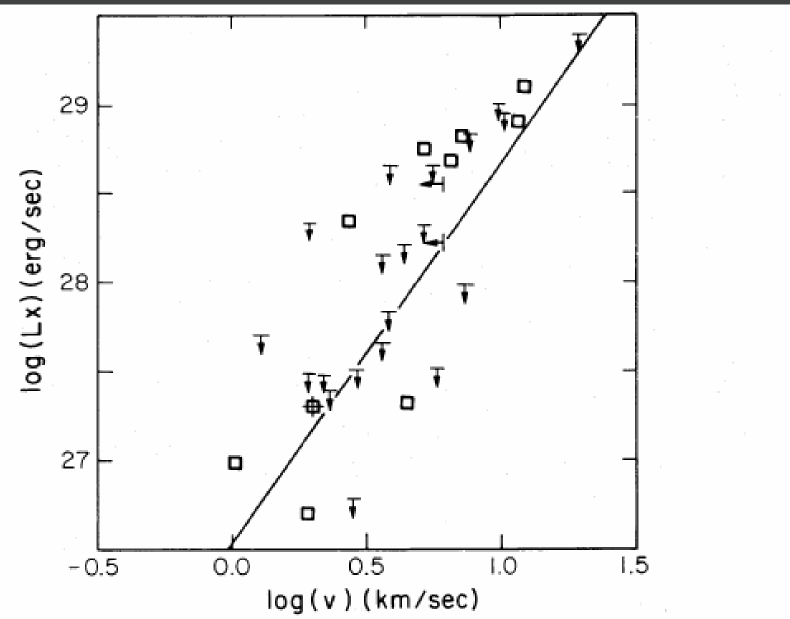


FIG. 7.—Scatter plot of X-ray luminosity vs. rotational velocity. Square, single stars. The indicated best-fit power-law relation again assumes that all the multiple stars (detected or not) are upper limits.

Maggio et al, 1987, ApJ, 315, 687

No L_x – *v*sin*i* correlation in O stars

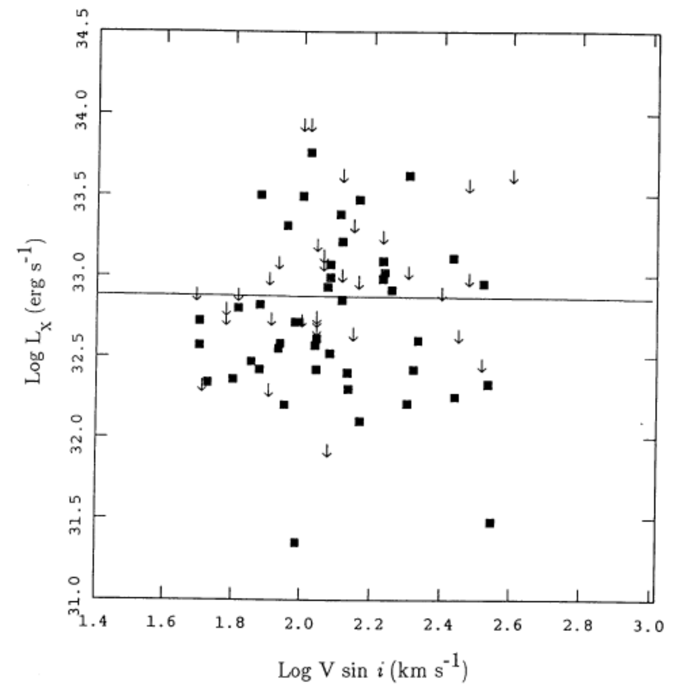


FIG. 16*f*

Sciortino et al., 1990, ApJ, 361, 621

Note higher L_x values for O stars; $L_x \sim 10^{-7}\ L_{Bol}$

So, we’ve got a **good scientific mystery**: how do massive, hot stars make X-rays?

Could we have been wrong about the lack of a magnetic dynamo - might massive star X-rays be similar to solar X-rays?

Before we address this directly, we need to know about one very important property of massive stars...

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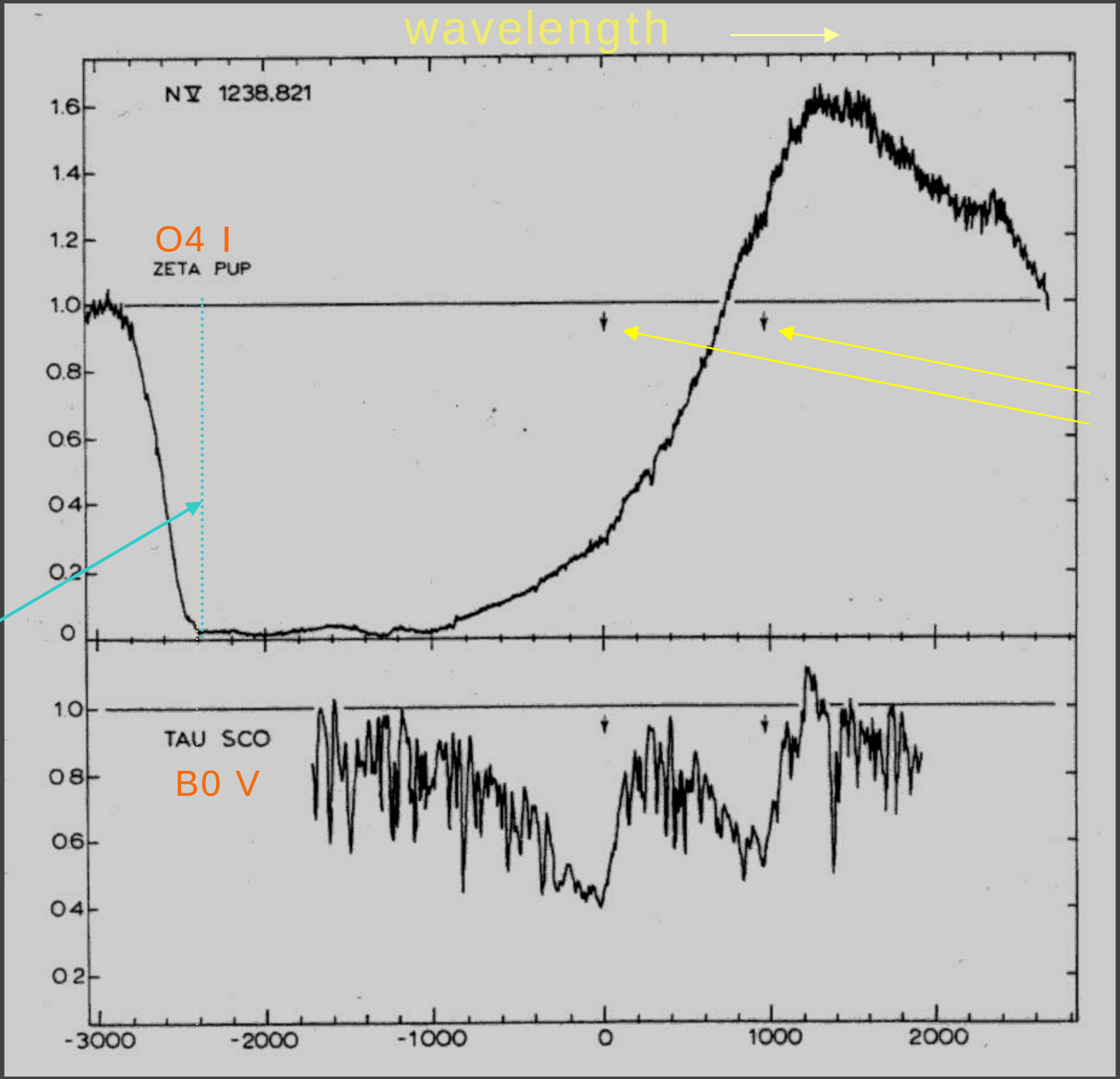
Hot star winds deposit significant amounts of (enriched) matter, momentum, and energy into the galactic environment

NGC 7635, a Wolf-Rayet star with a mass-loss rate of nearly 10^{-4} M_{sun} yr^{-1}

UV absorption lines are the most direct, quantitative means for diagnosing hot-star wind properties

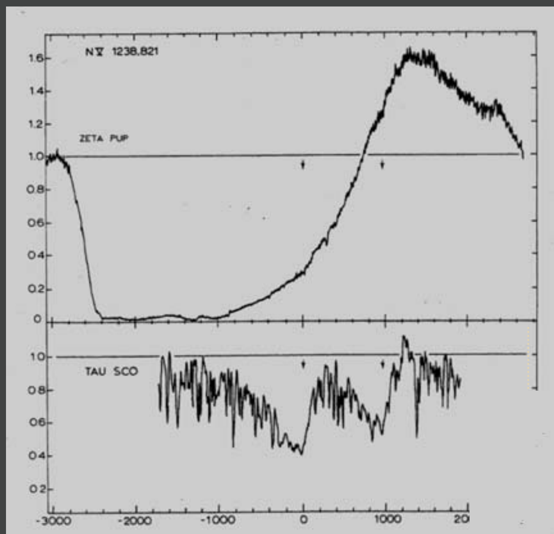


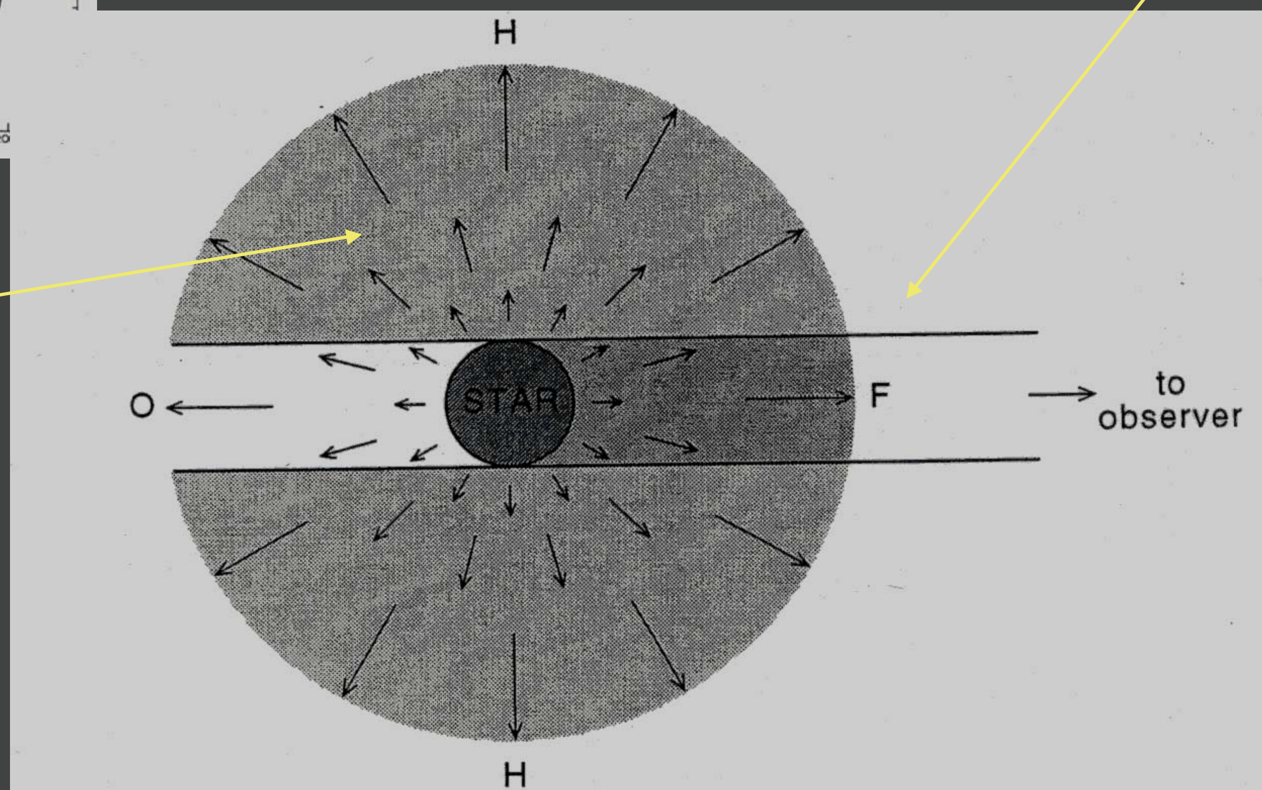
You can read the terminal velocity right off the blue edge of the absorption line

rest wavelength(s) – this N V line is a doublet

blue *velocity* (km/s) red

P Cygni line formation



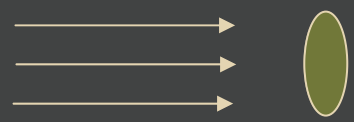


Absorption comes exclusively from region *F* - it's all blue-sifted

Red-shifted emission from scattered photospheric radiation

The steady winds of normal O stars are *radiation-driven*

The *flux* of light, *F* (ergs s^{-1} cm^{-2})



electron with cross section, σ_T (cm^2)

$$\frac{dp}{dt} = \frac{F\sigma}{c} = \frac{L\sigma_T}{4\pi c R^2}$$

The rate at which momentum is absorbed by the electron

$$a_{rad} = \frac{L\kappa_T}{4\pi c R^2}$$

radiative acceleration

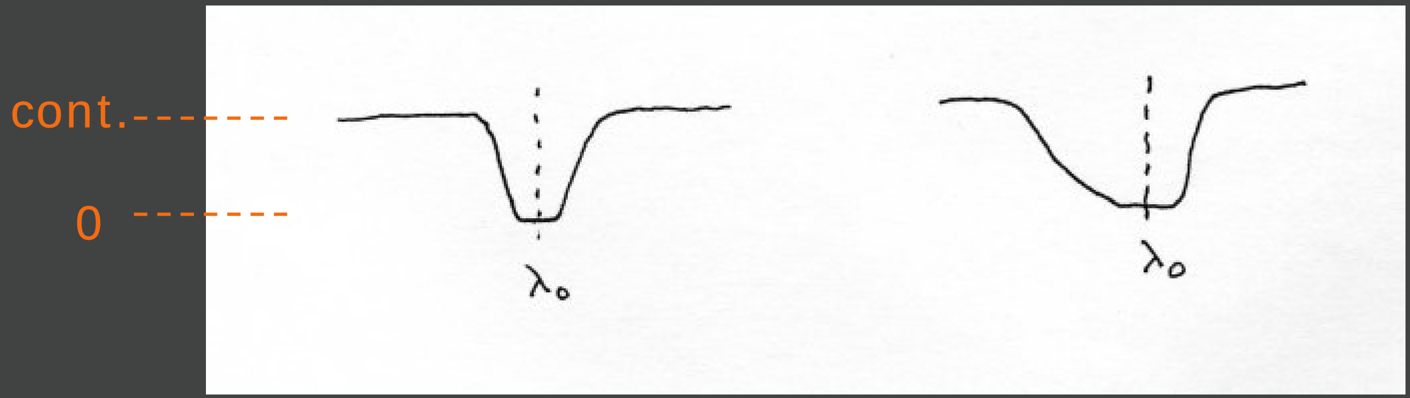
in fact, they are *line-driven*:

$\kappa = \kappa(\lambda)$

Radiation driving in spectral *lines*

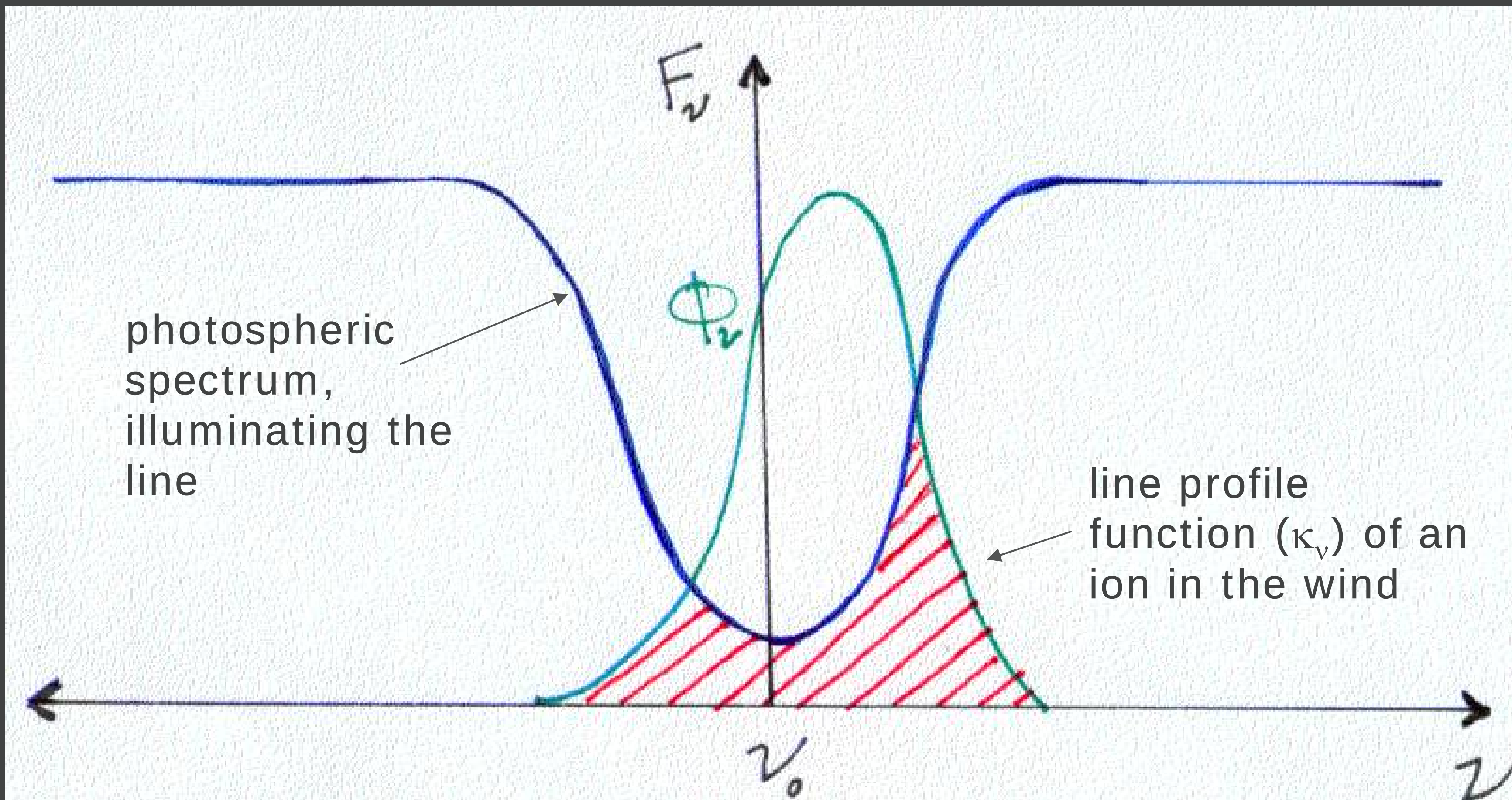
As the radiation-driven material starts to move off the surface of the star, it is Doppler-shifted, making a previously narrow line broader, and increasing its ability to absorb light.

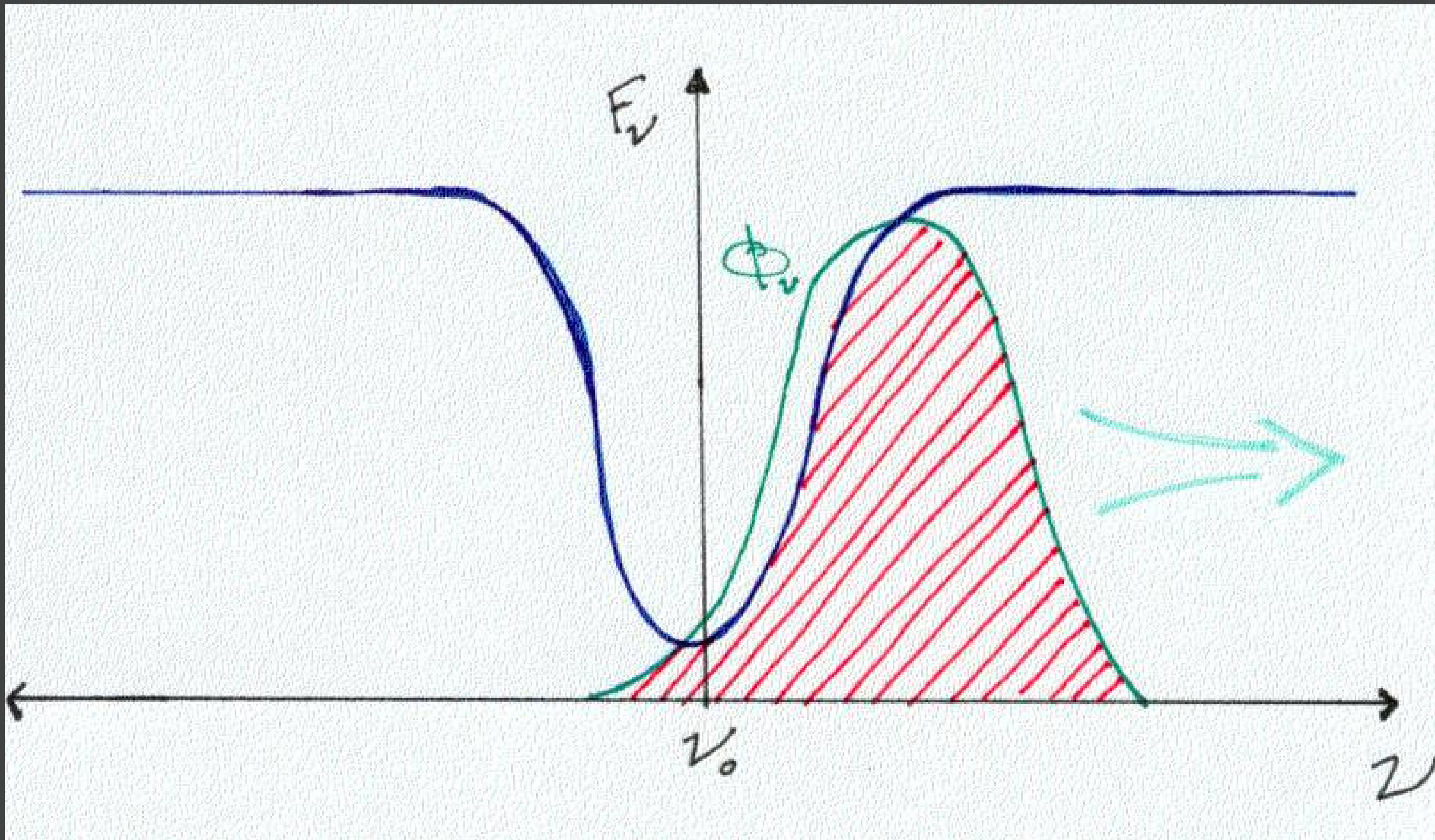
Opacity, κ – and thus the radiation force - is a function of the local acceleration (*F* -> *a* -> *F*...)



Optically thick line – from stationary plasma (left); moving plasma (right) broadens the line and *increases* the overall opacity.

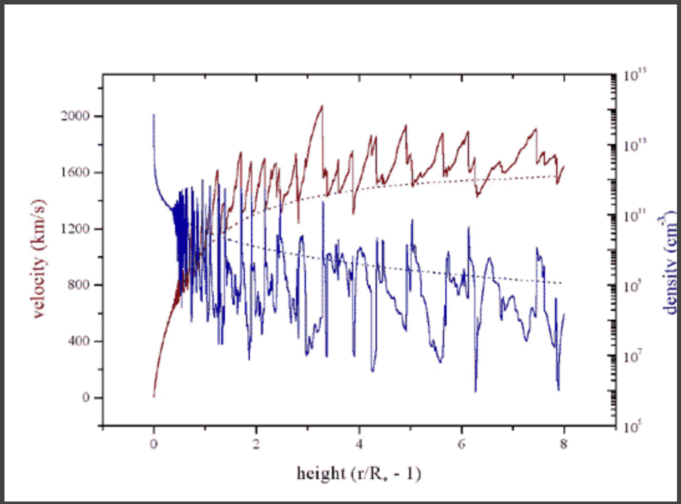
Line driving has an inherent instability

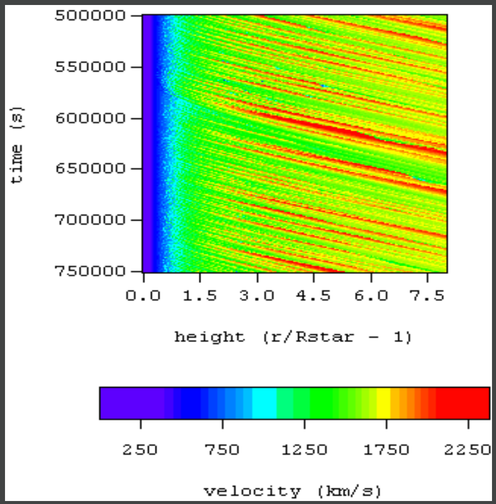




If the ion is perturbed, it moves out of the Doppler shadow, absorbs more radiation, and is further accelerated...

The Doppler desaturation that's so helpful in driving a flow via momentum transfer in spectral lines is inherently unstable

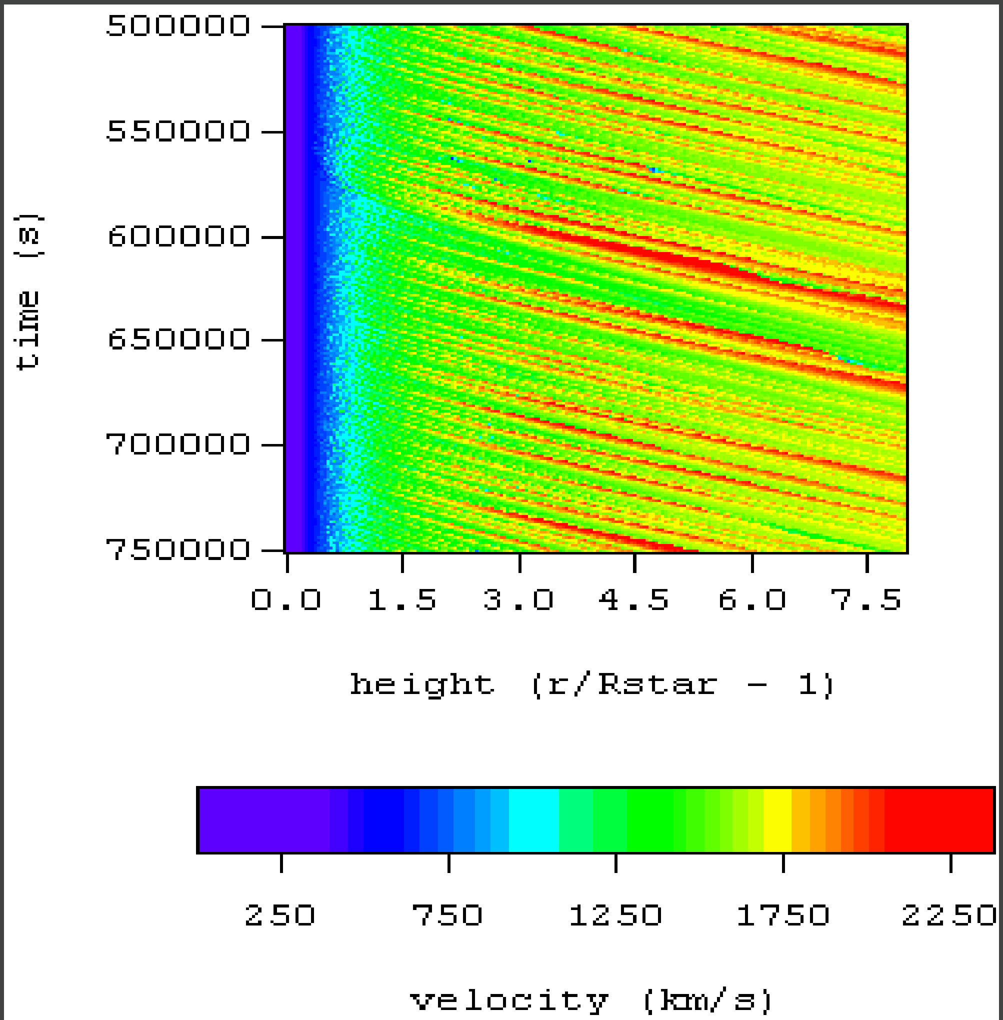




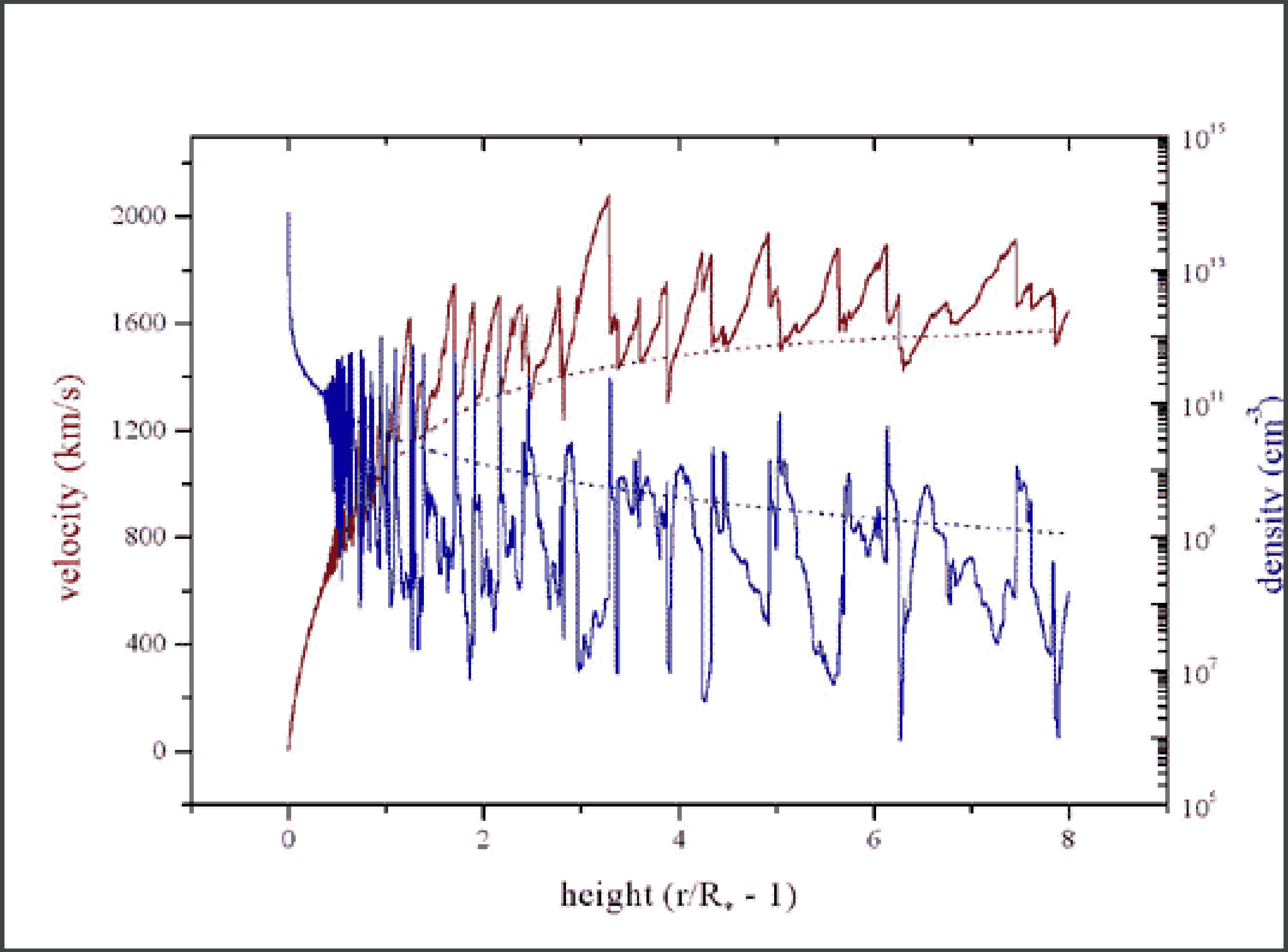
The line-driven instability (LDI) should lead to shock-heating and X-ray emission

Numerical modeling of the hydrodynamics show lots of structure: turbulence, shock waves, collisions between “clouds”

This non-linear behavior is predicted to **produce X-rays** through **shock-heating** of some small fraction of the wind.



A snapshot at a single time from the same simulation. Note the discontinuities in velocity. These are shock fronts, compressing and **heating** the wind, producing **x-rays**.



Most of the wind mass is in dense inter-shock regions, in which cold material provides a source of photoelectric absorption

Other groups find similar wind structure in their simulations

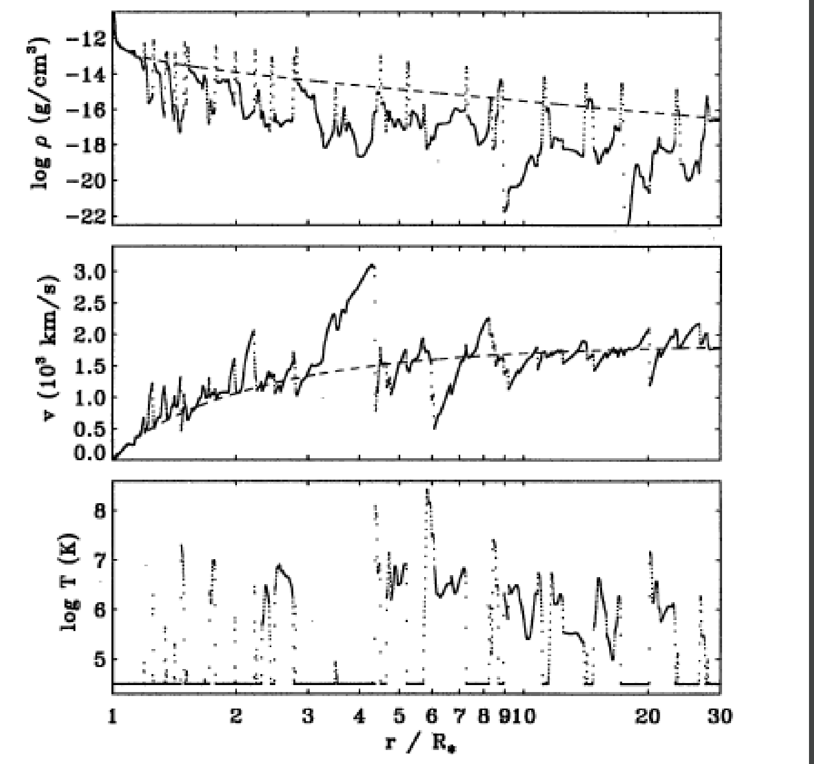
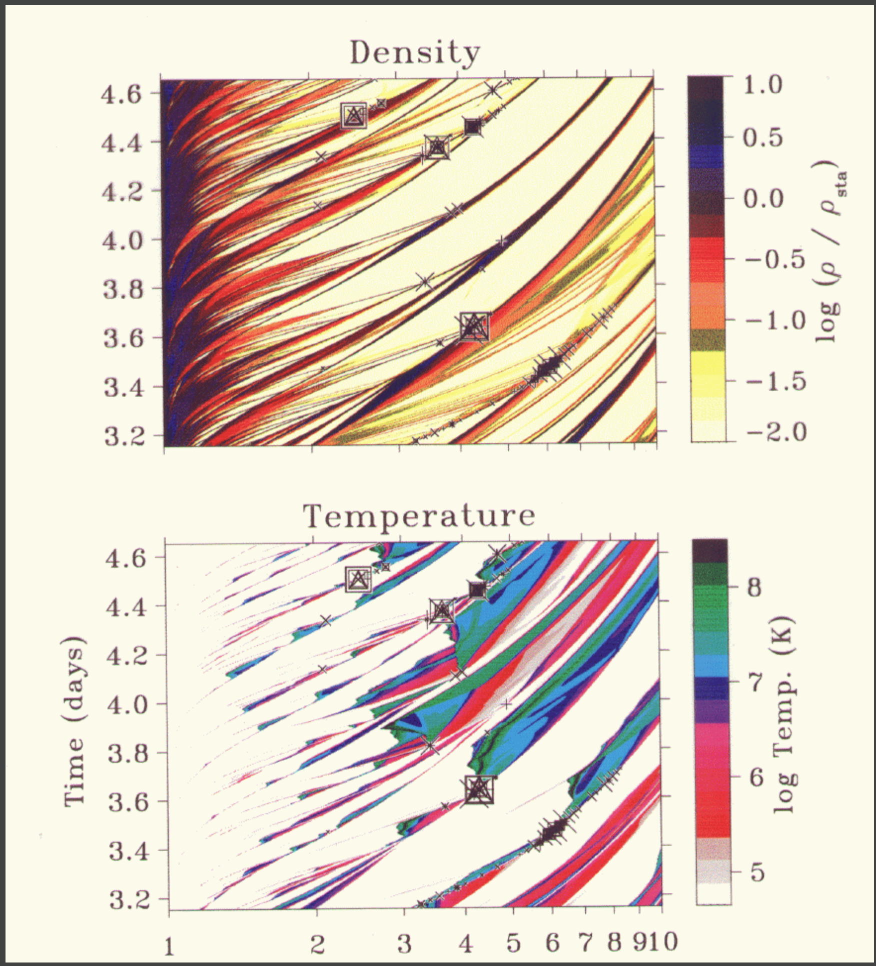


Fig. 13. Snapshot of the wind structure triggered by photospheric Langevin turbulence at three days after model start.



from Feldmeier et al., 1997, A&A, 322, 878

There's ample evidence for wind clumping

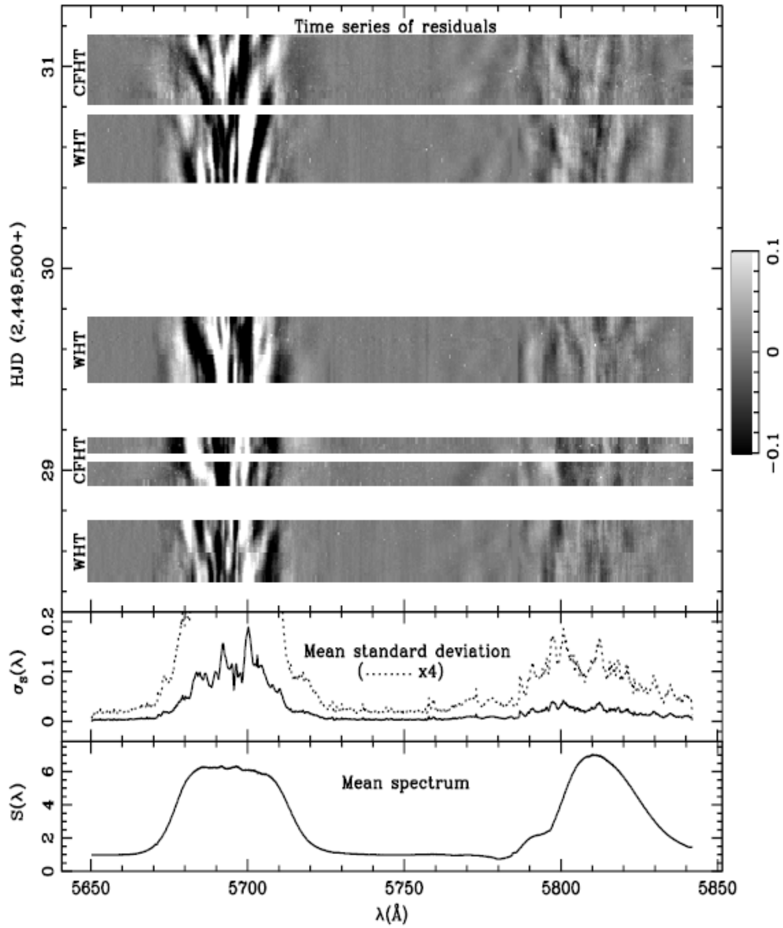
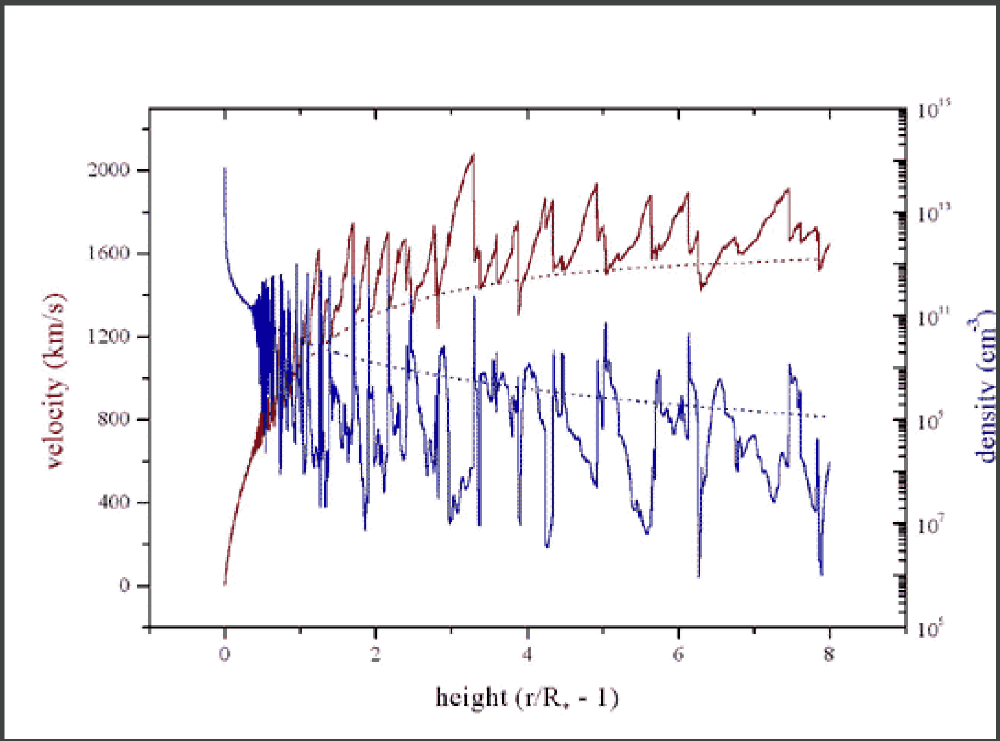
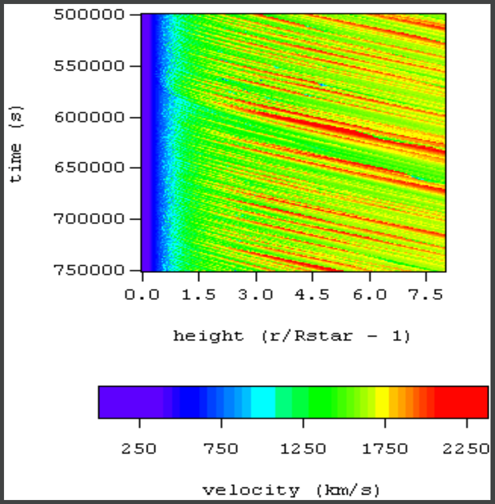


FIG. 2.—Combined CFHT and WHT spectroscopic monitoring of HD 192103. The mean profile for the whole data set is shown, along with the mean standard deviation, which indicates 4 times as much variability in the C III λ5696 emission line as in the C IV λ5808 doublet region. The gray-scale part is a time series of the residuals (obtained after subtracting off the global mean profile), detailing the variability pattern as a function of time. Note how the narrow emission features (*subpeaks*) appear to systematically move away from the line center. This pattern is consistent with the C III and C IV emission arising in a volume where the wind is clumped and accelerating away from the star.

Optical line profile variability in WR stars: from Lepine et al., 2000, ApJ, 120, 3201

Wind structure and physical properties





Highly time-dependent, but statistically quite constant

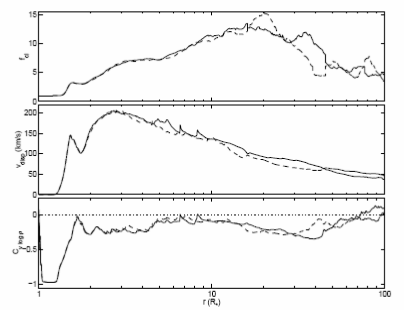


Fig. 5. Statistical properties of the reference model. The three panels, from top to bottom, show the clumping factor, the velocity dispersion, and the velocity-density correlation, all as a function of radius. The full line corresponds to averages taken between 2 and 2.5 Msec, the dashed line to averages taken between 2.5 and 3 Msec. The zero level for the correlation function is indicated by a dotted line.

Small pockets of hot plasma, embedded in a cold ($T \sim T_{eff}$) wind with a standard beta-law velocity profile

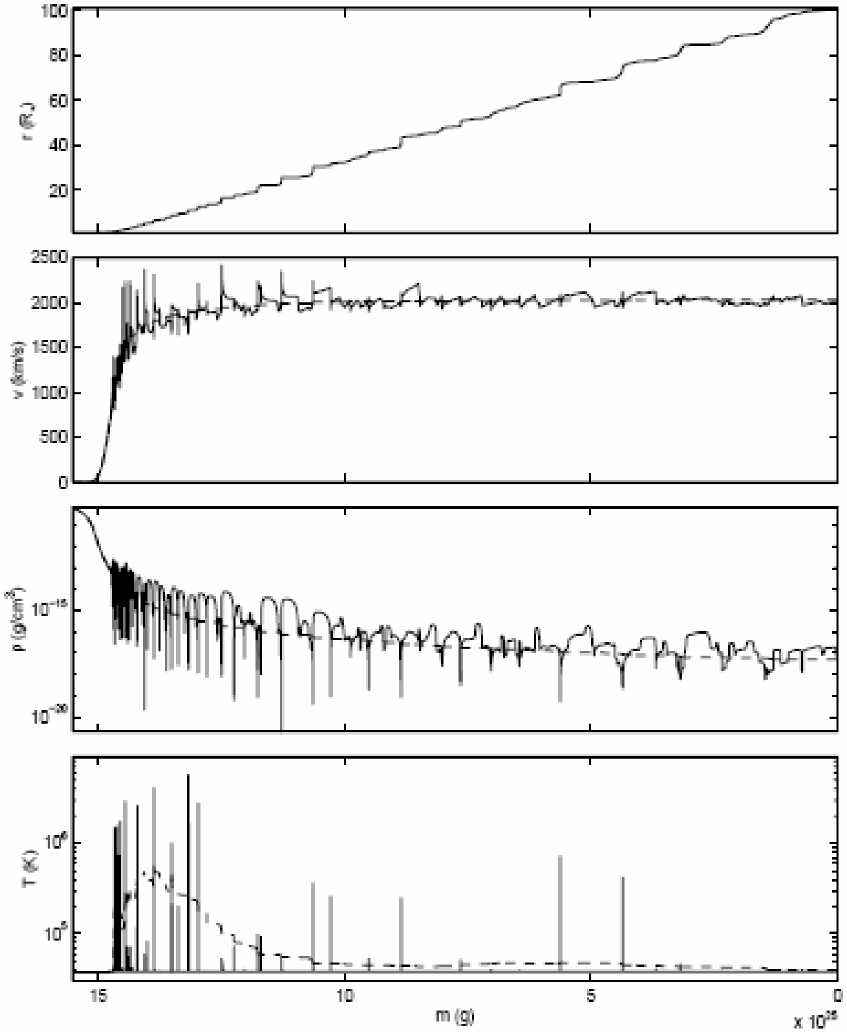


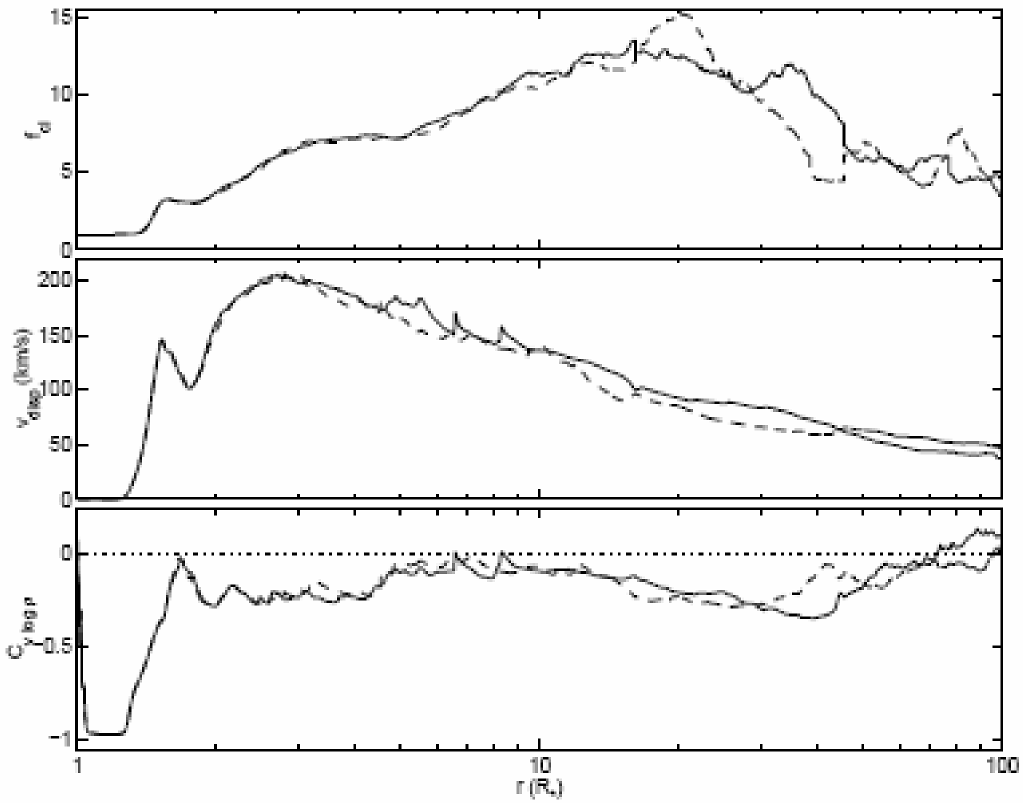
Fig. 4. Snapshot of the reference model at 2 Msec, now plotted versus the Lagrangian mass coordinate m defined in Eq. (10). The upper panel shows the Eulerian radius, while the remaining panels show the velocity, density, and temperature. The dashed lines in these lower panels show the corresponding time-averaged values.

Another rad-hydro simulation, but plotted in Lagrangian coordinates.

The shock-heated regions are a small fraction of the wind mass

Runacres & Owocki, 2002, A&A, 381, 1015

Statistics from a long rad-hydro run (vs. radius)



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clumping factor
$\rho_{clump}/<\rho>$

velocity dispersion

density-velocity correlation

Runacres & Owocki, 2002, A&A, 381, 1015

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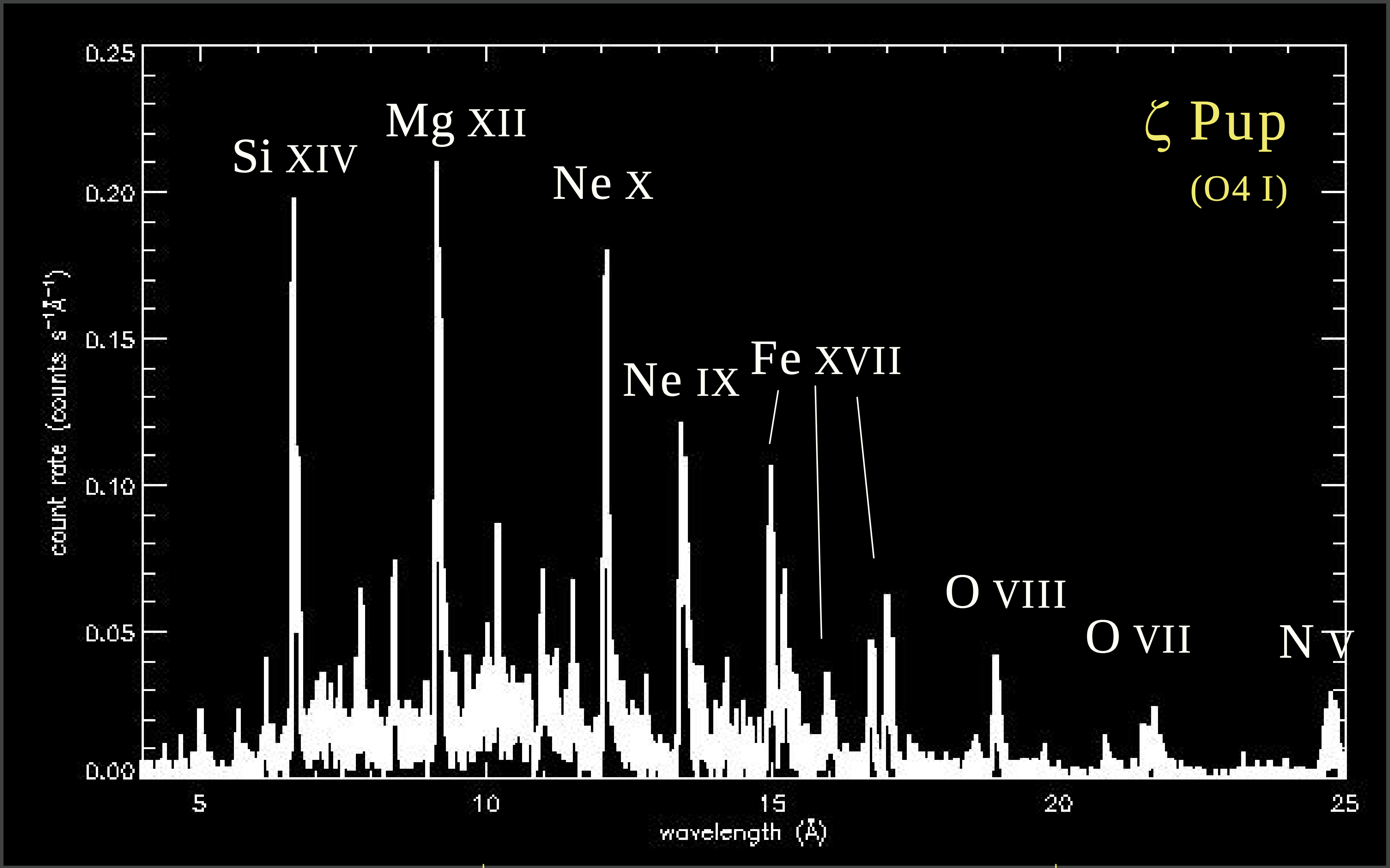
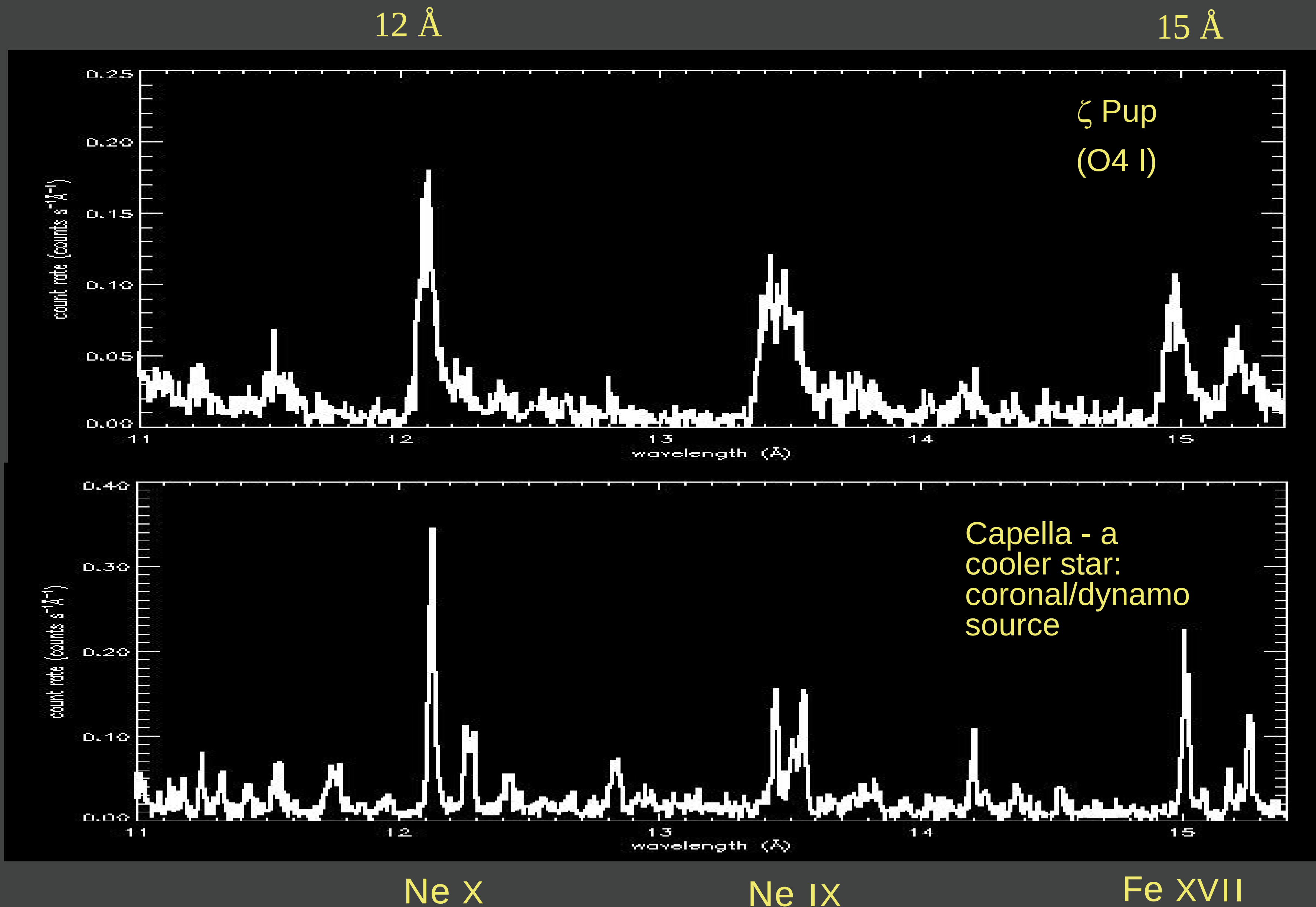
Globally, O star X-ray spectra look like coronal spectra



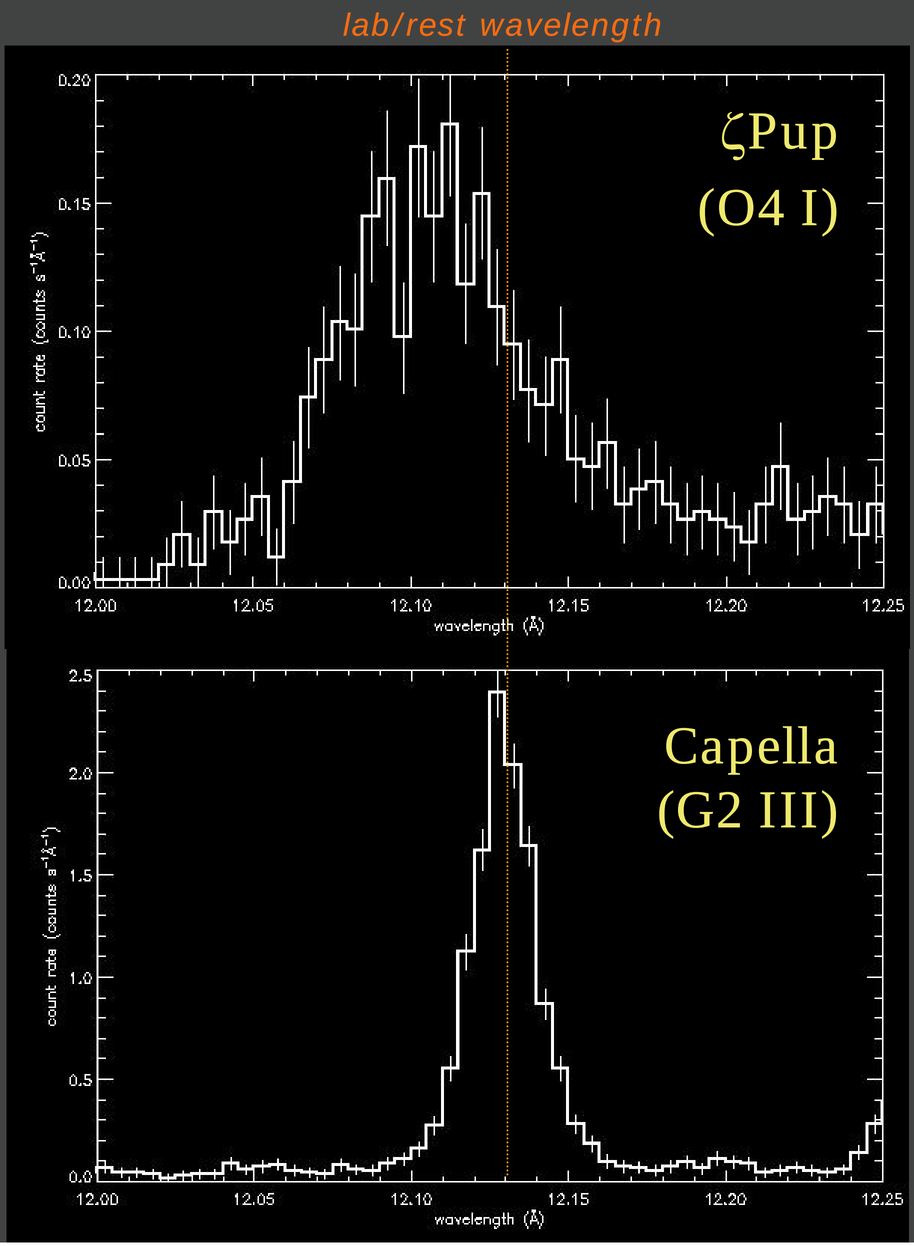
10 Å

20 Å

Focus in on a characteristic portion of the spectrum



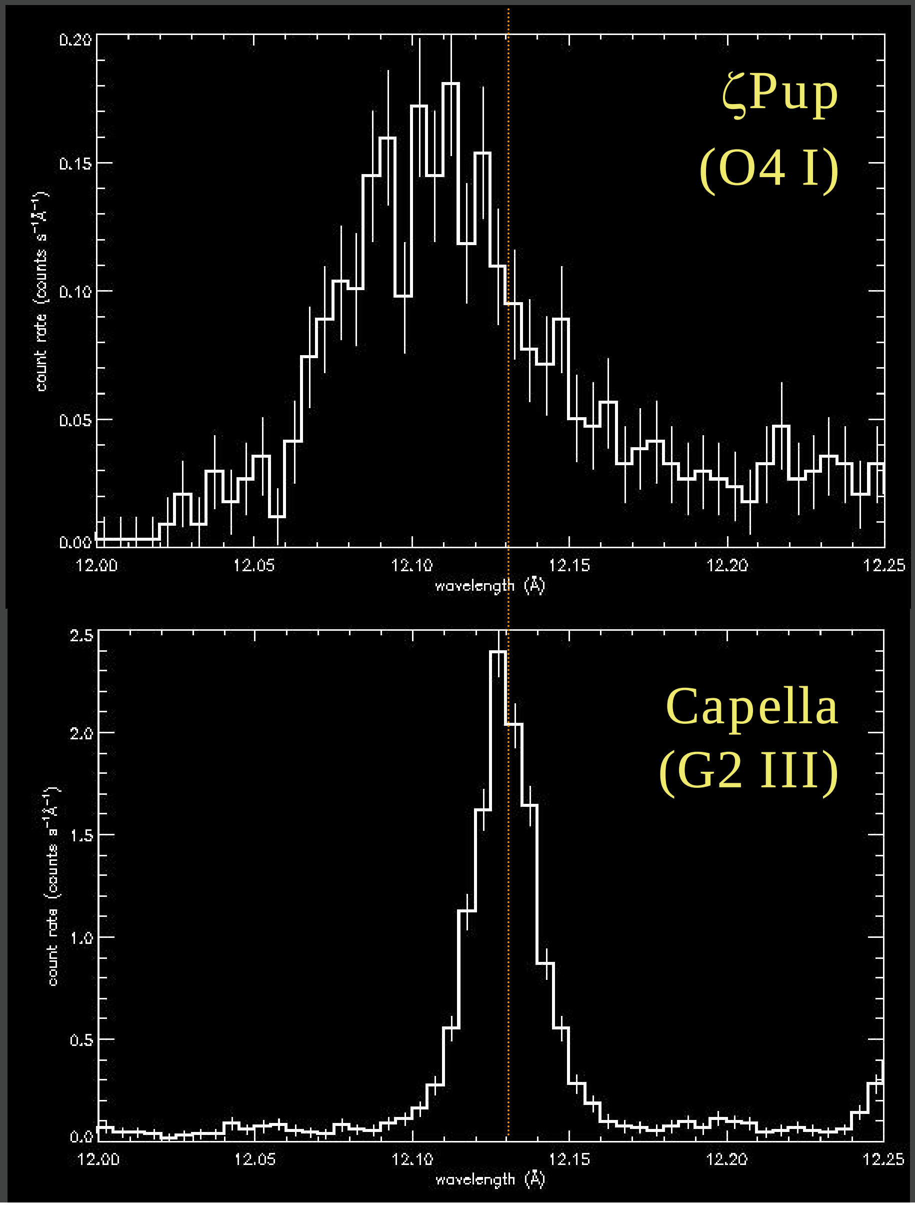
Each individual line is significantly Doppler broadened (here is Ne X Lyα at 12.13 Å)



HWHM ~ 1000 km/s

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

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**

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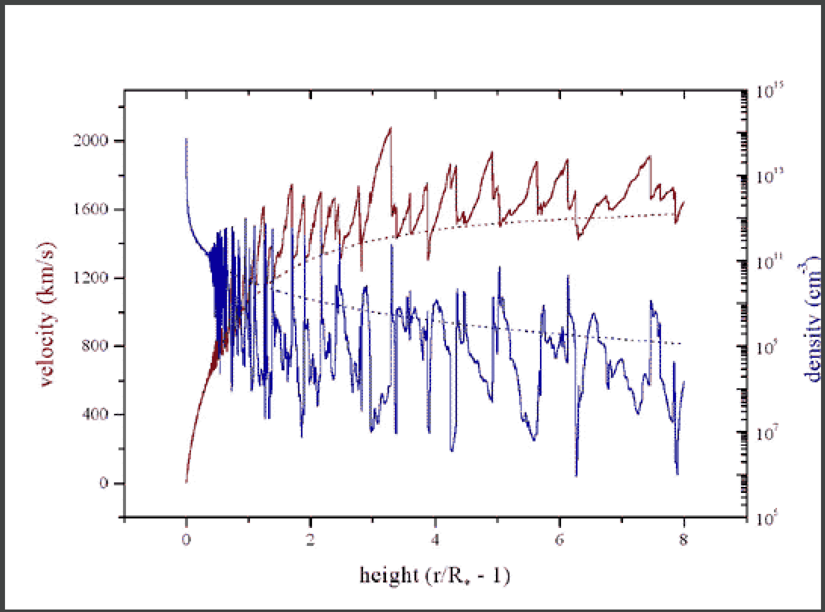
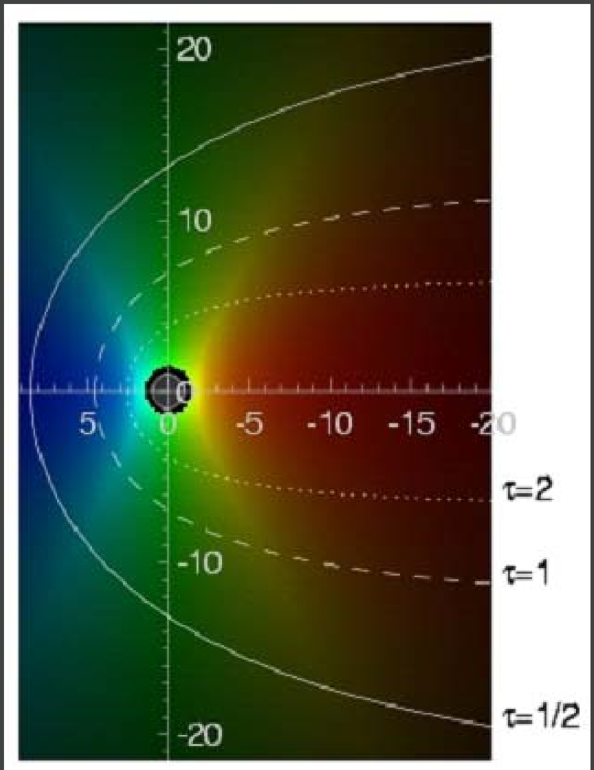
To analyze data, we need a simple, empirical model



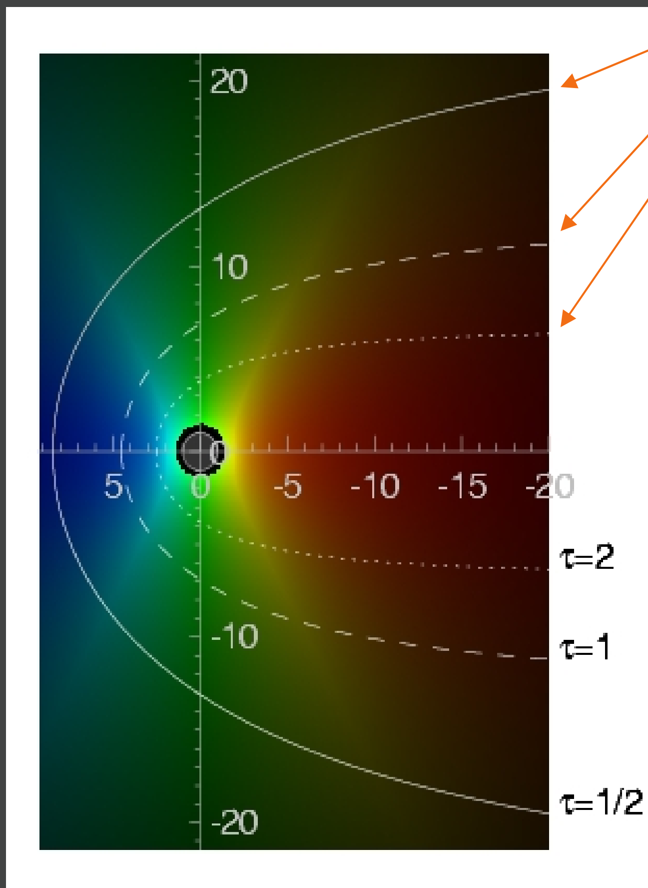
Detailed numerical model with lots of structure

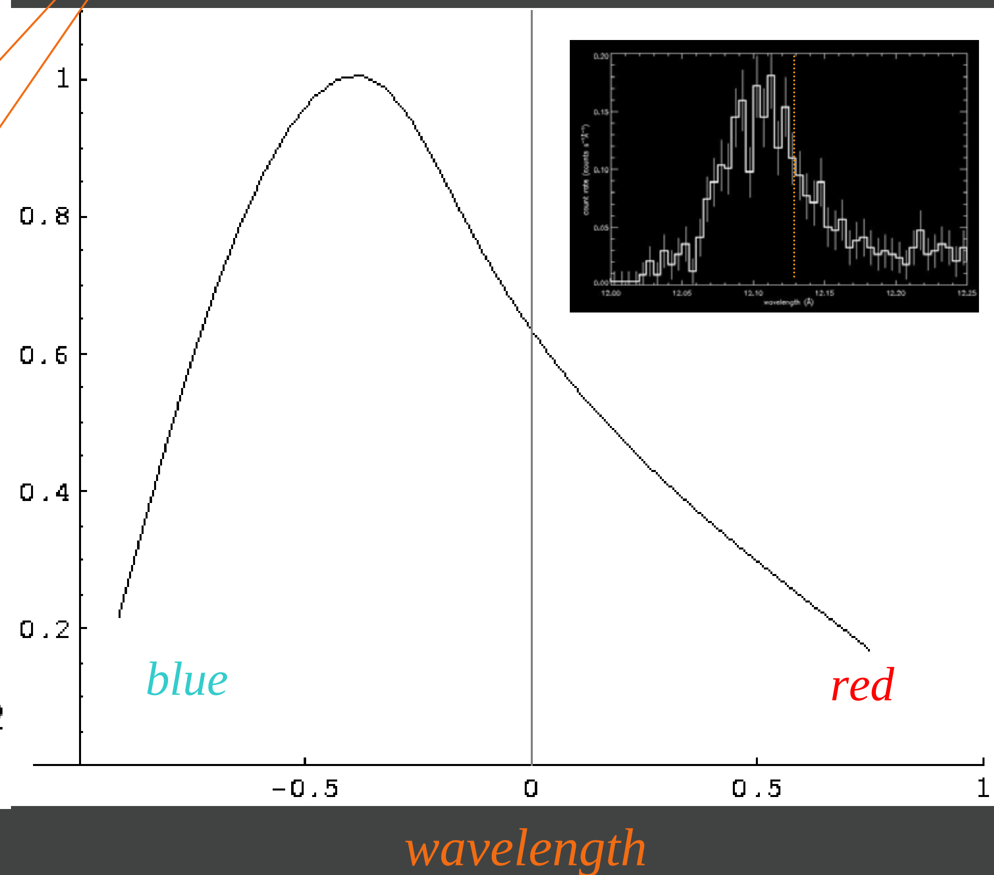


Smooth wind; two-component emission and absorption

Spherically symmetric wind; specified filling factor of hot plasma

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,

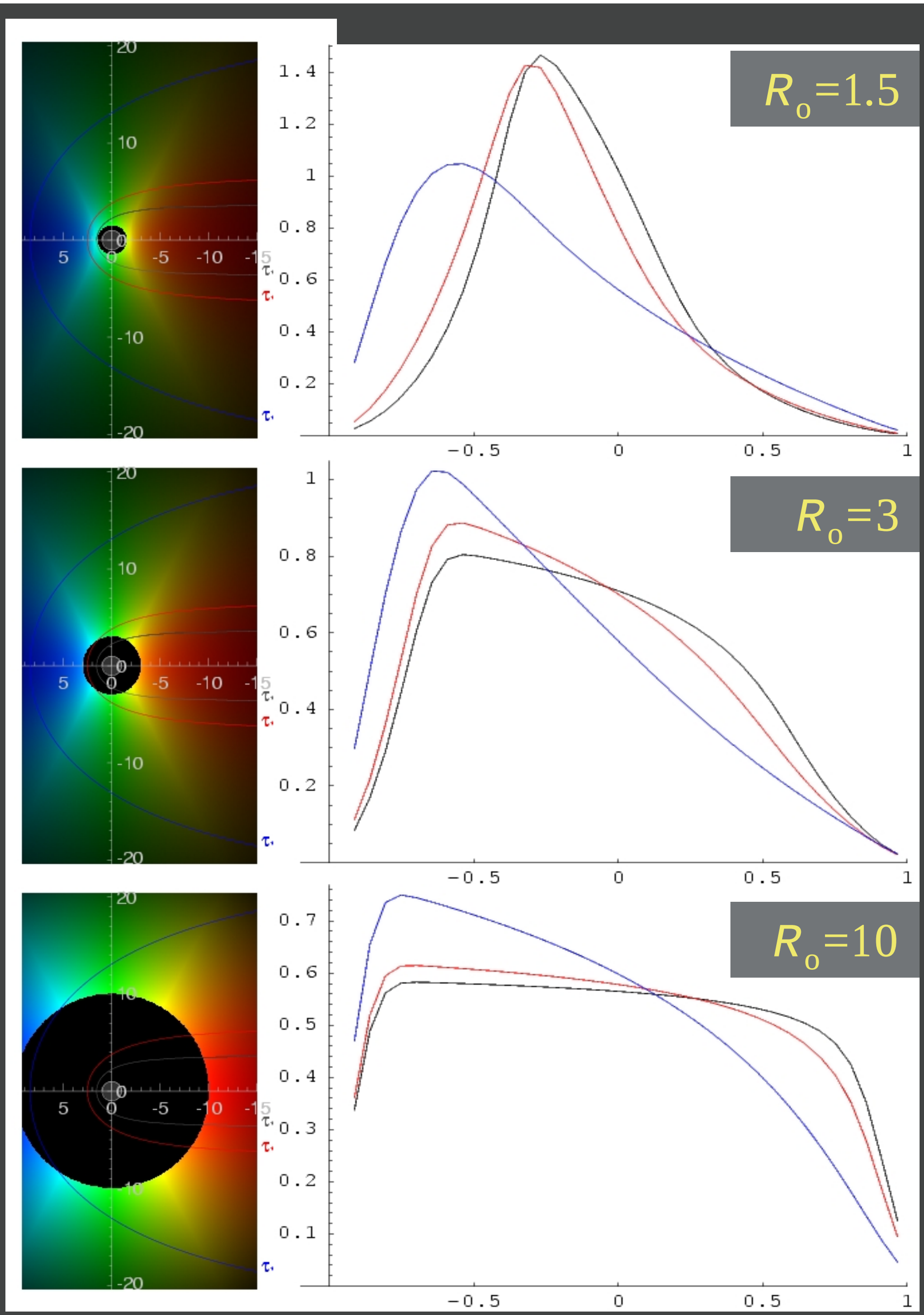
AND by the amount of **attenuation** by the cold wind, characterized by the optical depth parameter:

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

The line profile is calculated from:

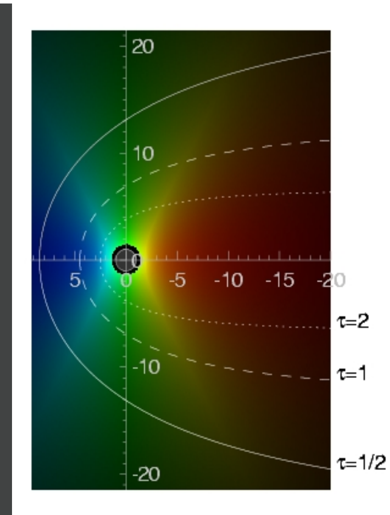
$$L_\lambda = 8\pi^2 \int_{-1}^{1}\int_{R_o}^{\infty} j e^{-\tau} r^2 dr d\mu$$

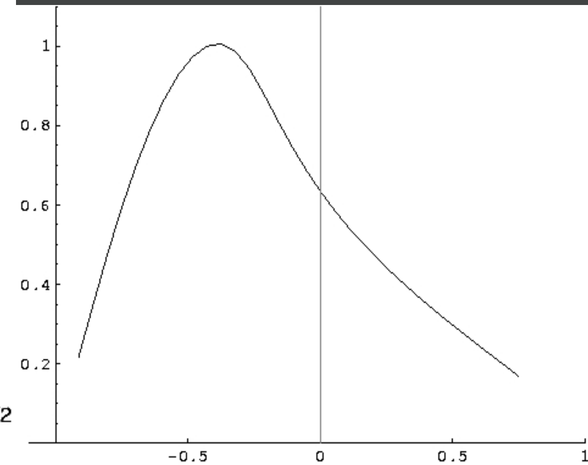
Increasing R_o makes lines broader; increasing τ_* makes them more blue shifted and skewed.



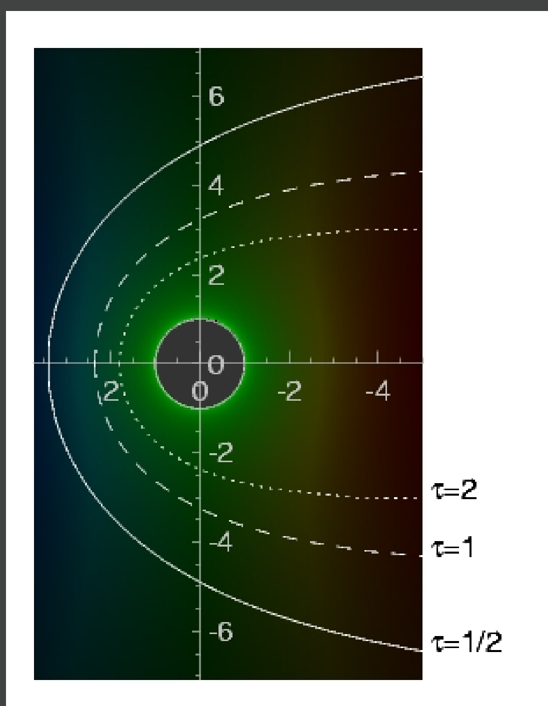
τ_*=1,2,4

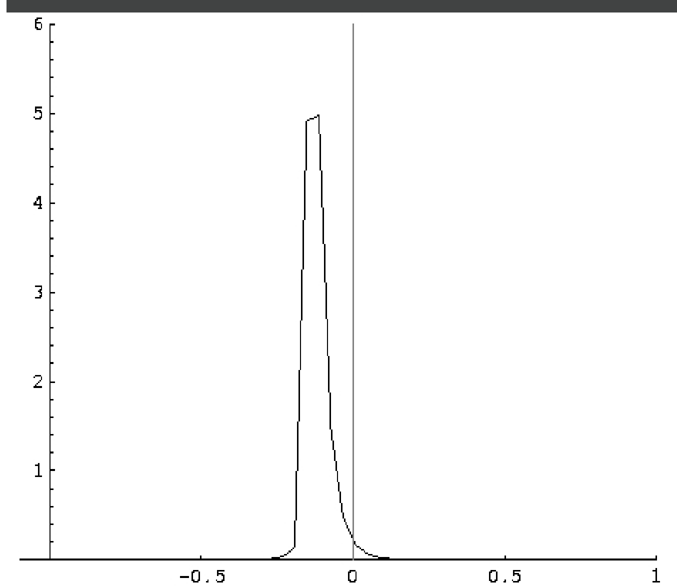
In addition to a wind-shock scenario,





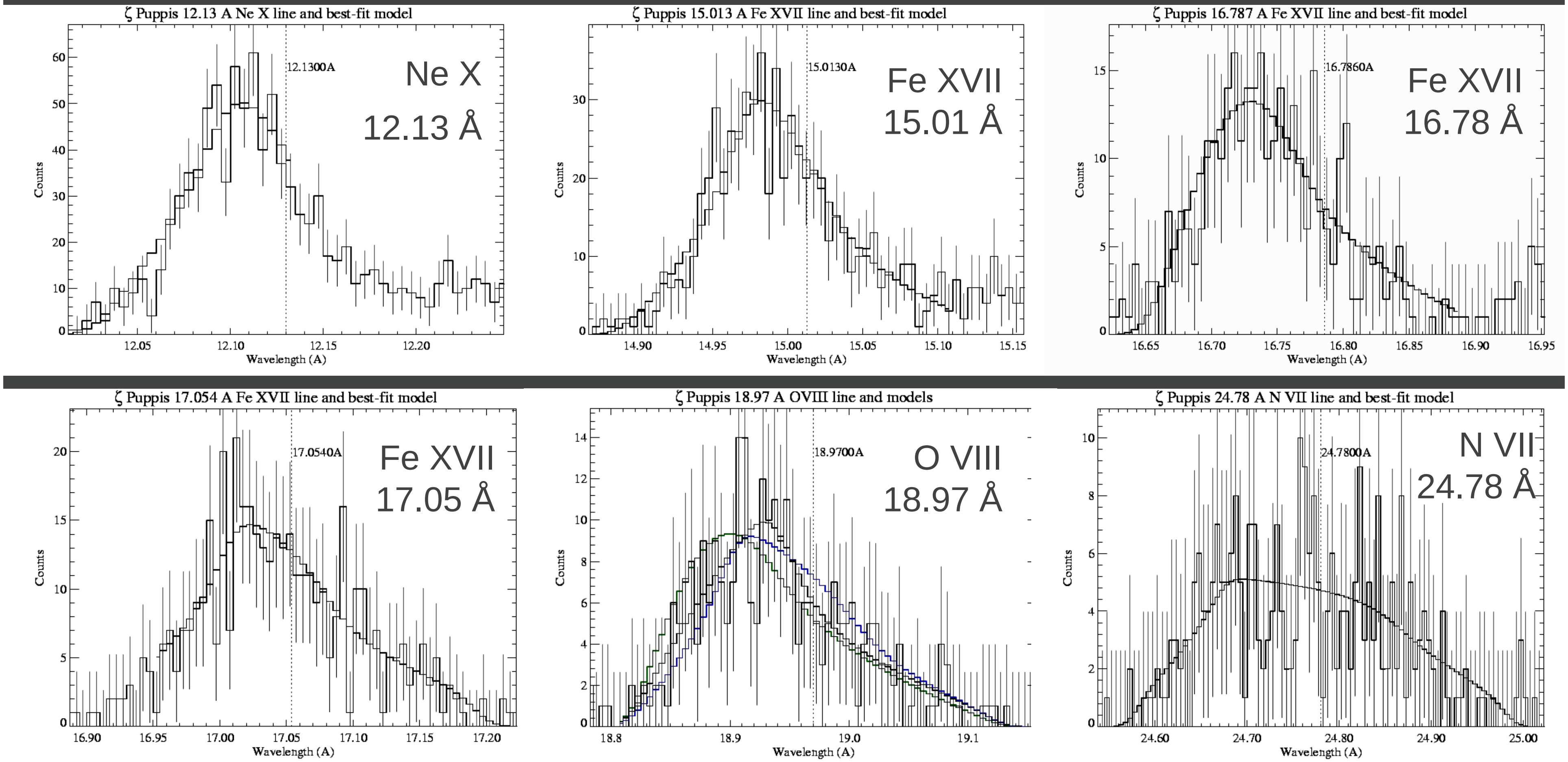
our empirical line-profile model can also describe a corona





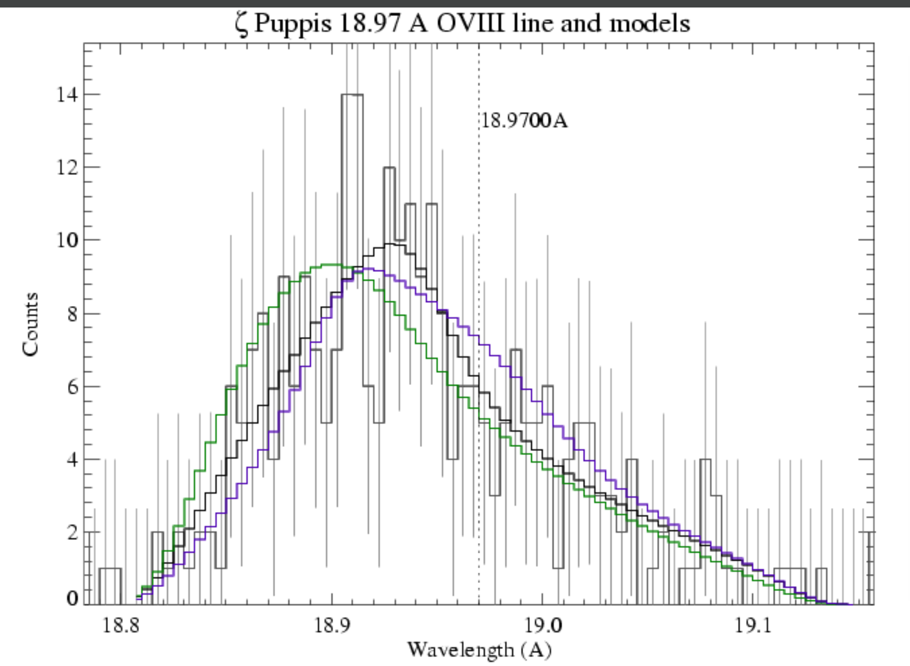
With most of the emission concentrated near the photosphere and with very little acceleration, the resulting line profiles are very narrow.

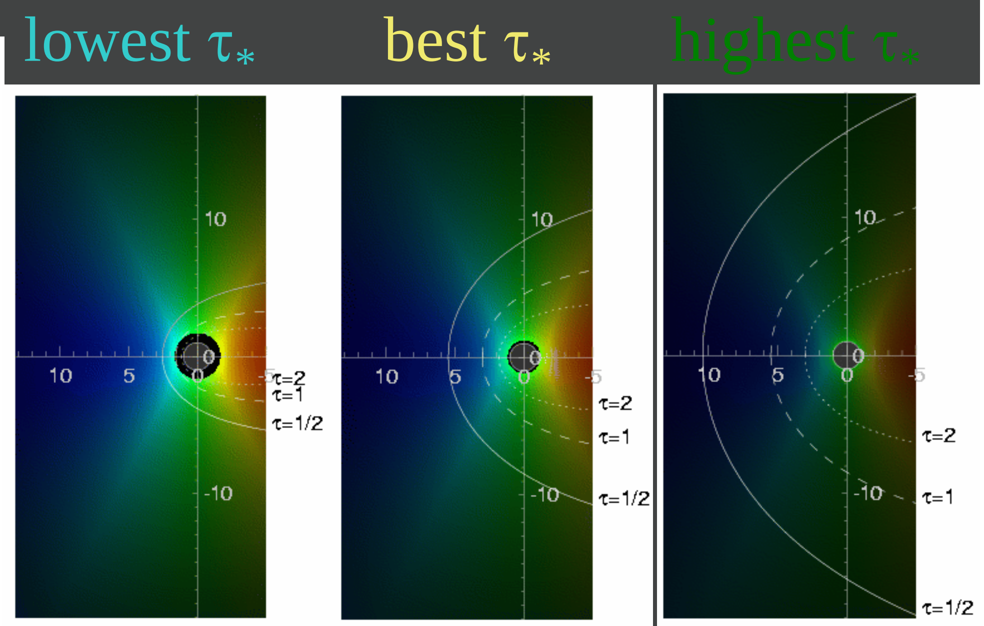
We fit all the unblended strong lines in the *Chandra* spectrum of ζ Pup: all the fits are statistically good



Kramer, Cohen, & Owocki, 2003, ApJ, 592, 532

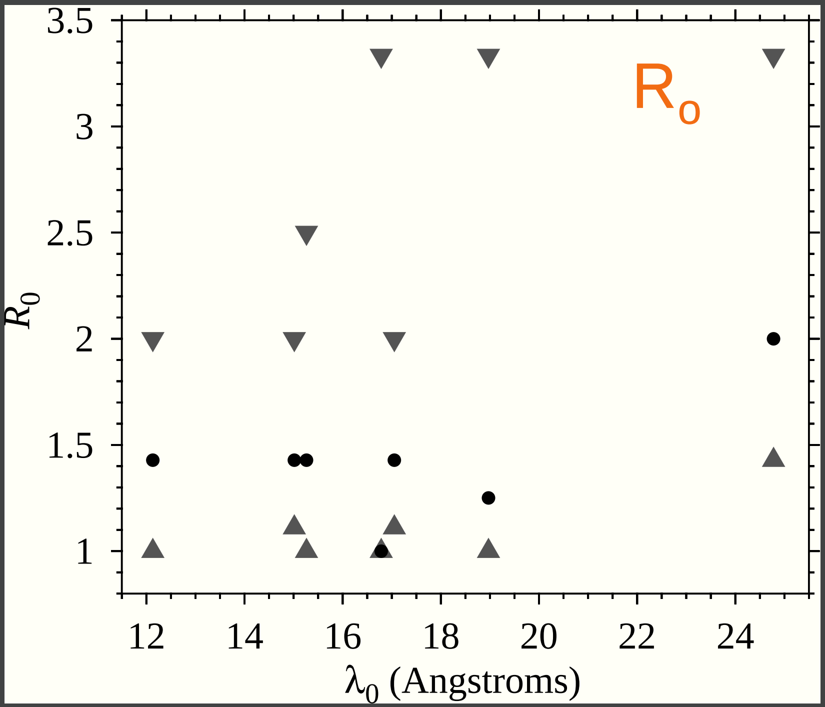
We place *uncertainties* on the derived model parameters

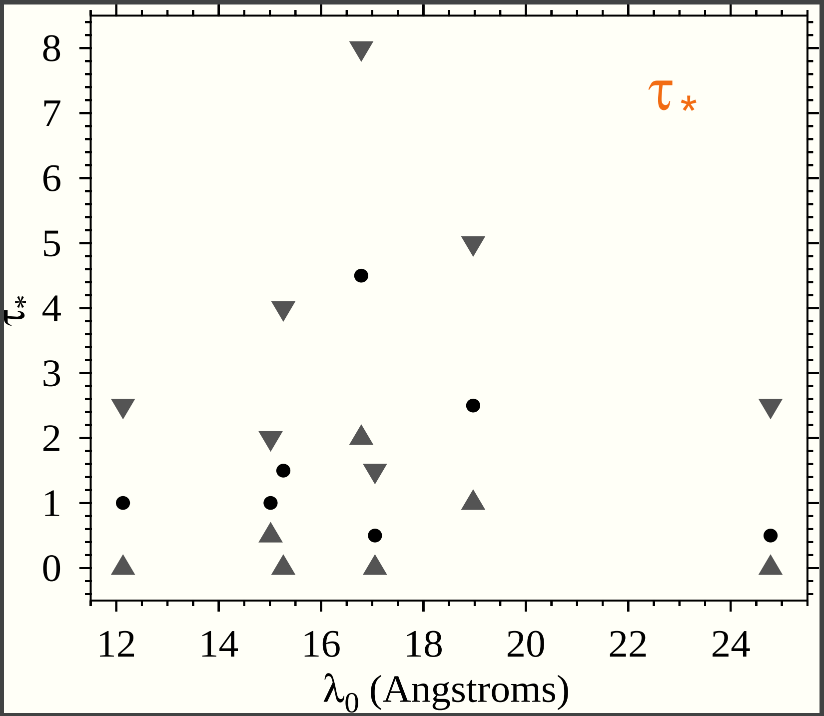




Here we show the best-fit model to the O VIII line and two models that are marginally (at the 95% limit) consistent with the data; they are the models with the highest and lowest τ_* values possible.

Summary of profile fits to ζ Pup's *Chandra* emission lines

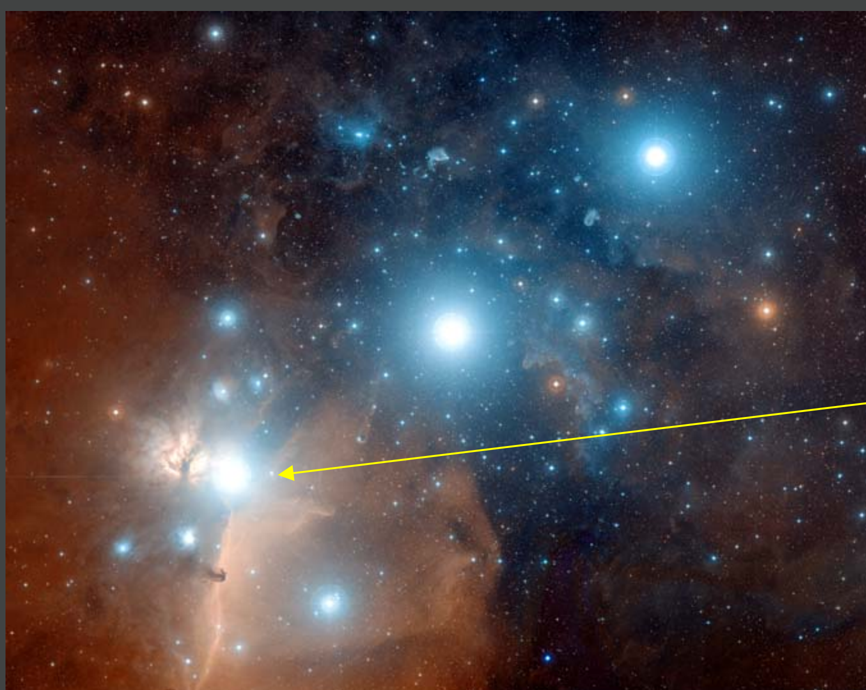




onset of X-ray emission at ~1.5 R_*

some opacity, but optical depths are low

Let's look at another normal O supergiant



ζ Ori: *Alnitak*

O9.7 I

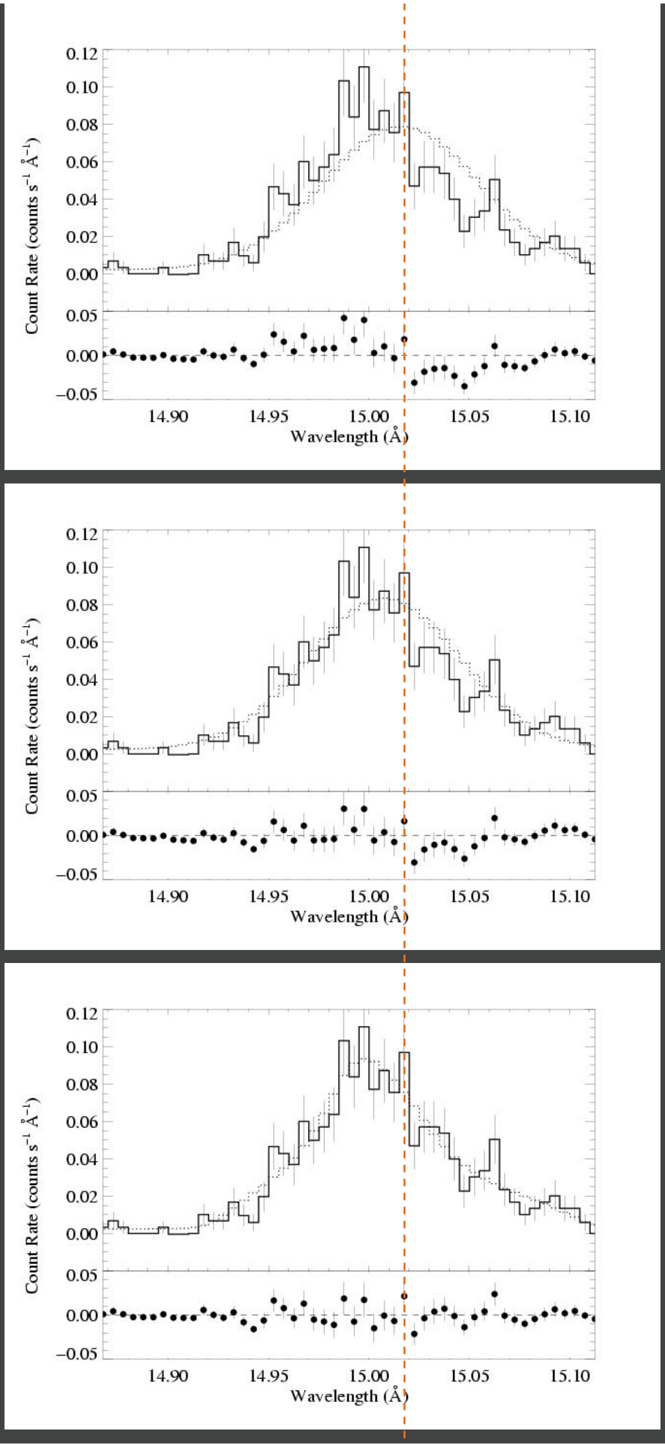
wind is less dense than ζ Pup's

ζ Ori (O9.7 I) – 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



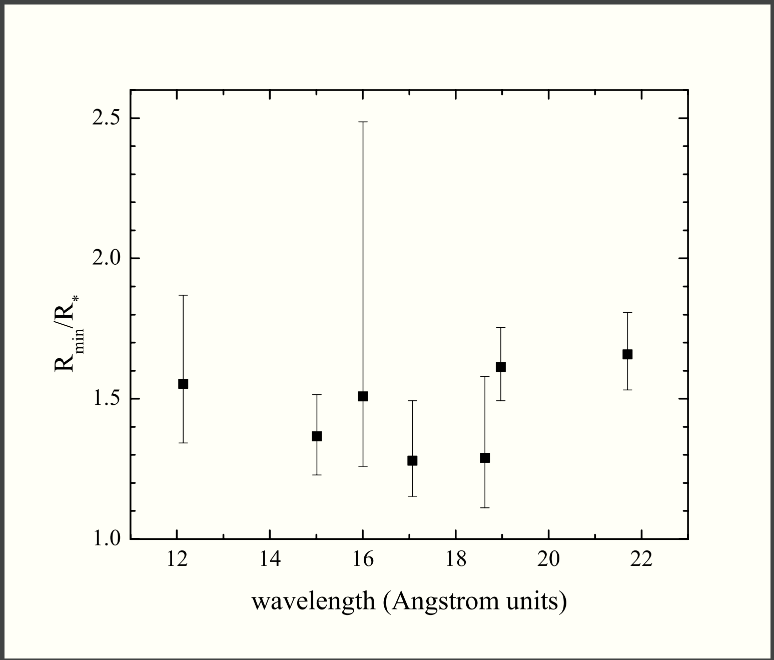
94%

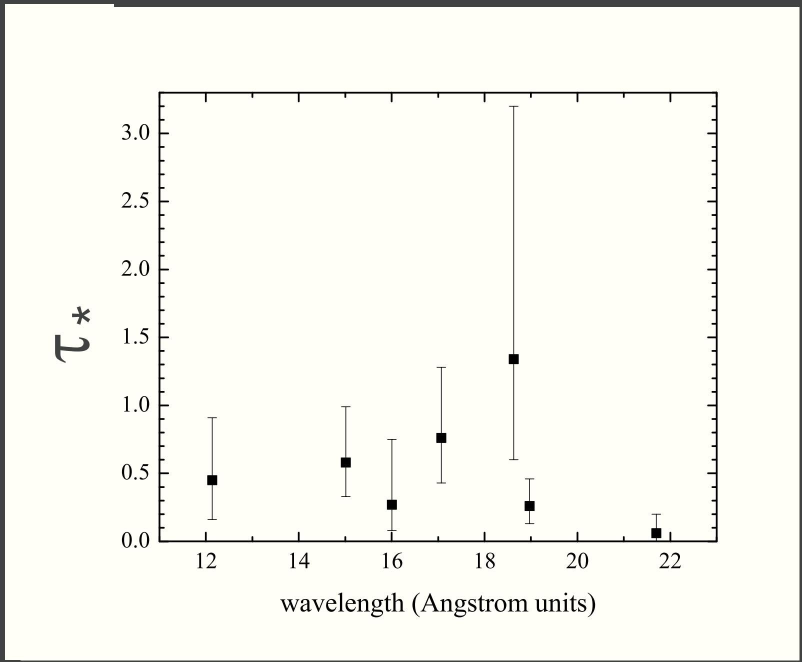
73%

54%

Rejection probabilities are shown on the right of each panel.

Fit results for ζ Ori summarized





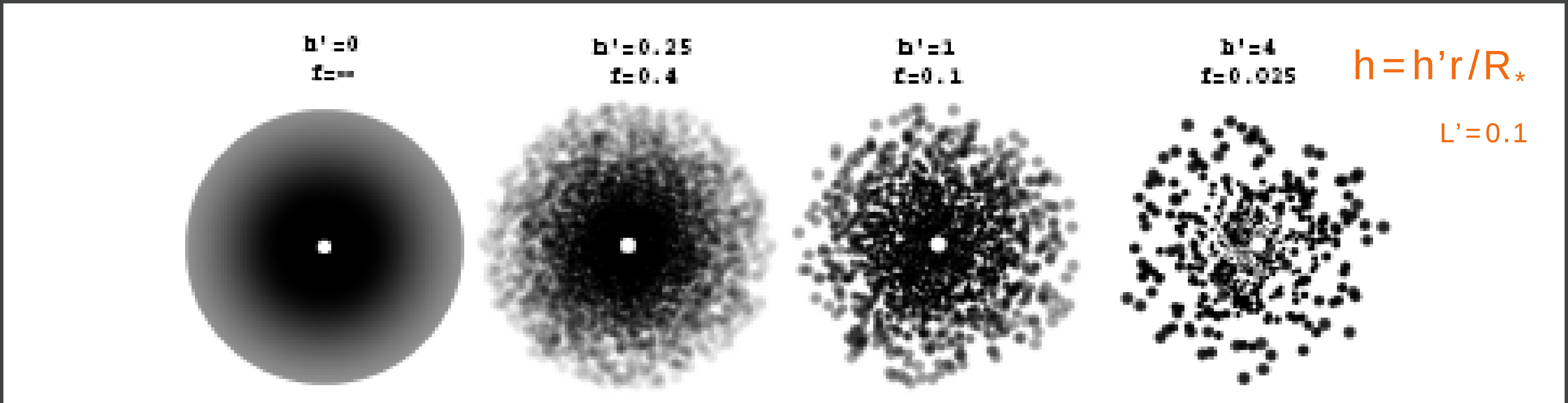
The onset radii (left) are exactly what's expected from the standard wind-shock picture. There is evidence for attenuation by the cold wind (right), but at levels **nearly 10 times lower** than expected. This is the same result that we found for ζ Pup.

Mass-loss rates of O stars may need to be revised downward

Several different lines of evidence:

- P V absorption (FUSE) [Fullerton et al. 2006]
- Density-squared emission – radially varying clumping (H-alpha and radio free-free) [Puls et al. 2006]
- Detailed atmosphere + wind UV modeling [Bouret et al. 2003]

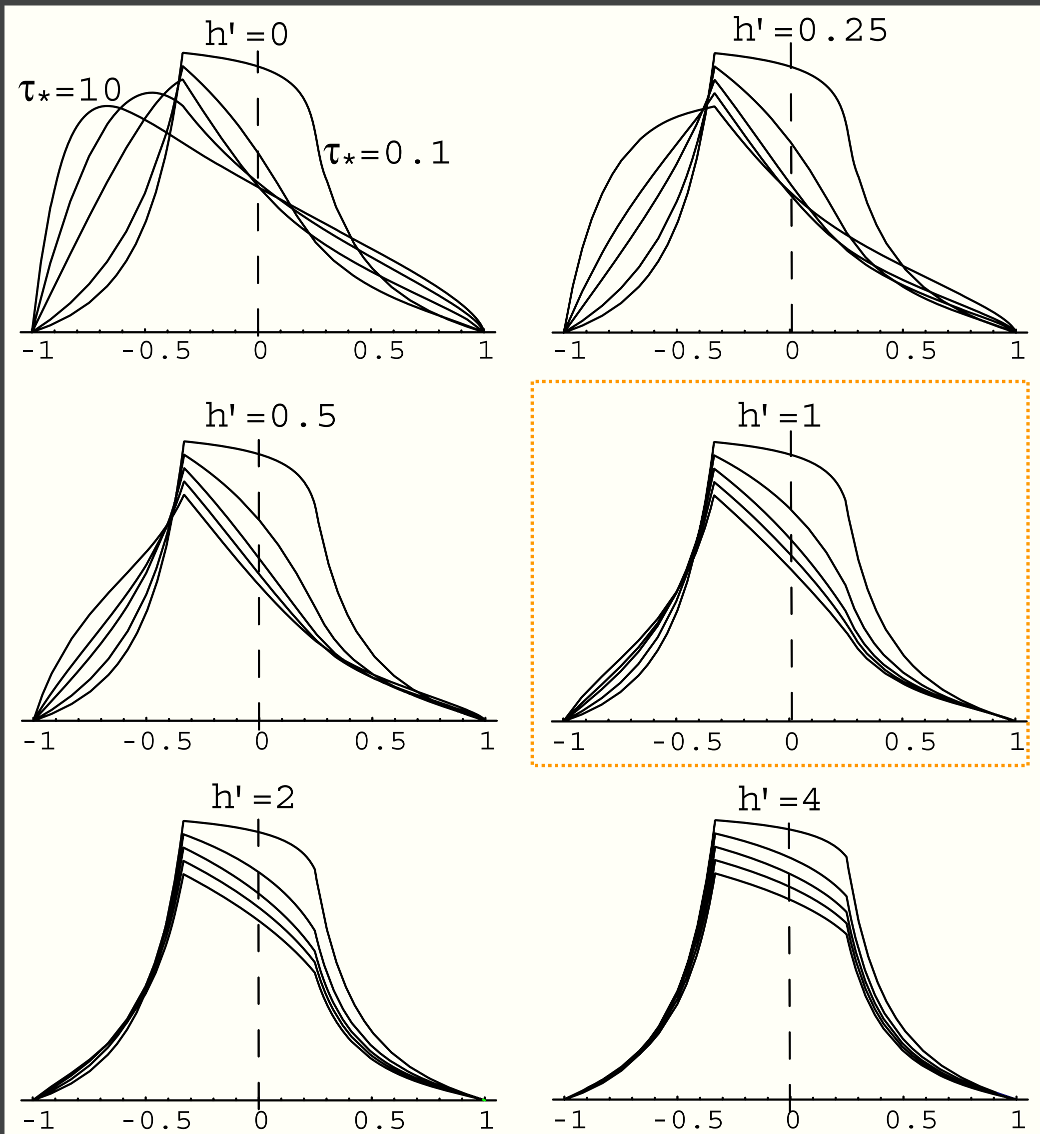
Clumping in the cold, absorbing wind can reduce the overall effective opacity: Can clumping explain the relative symmetry of the profiles?



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: $h=L/f$.

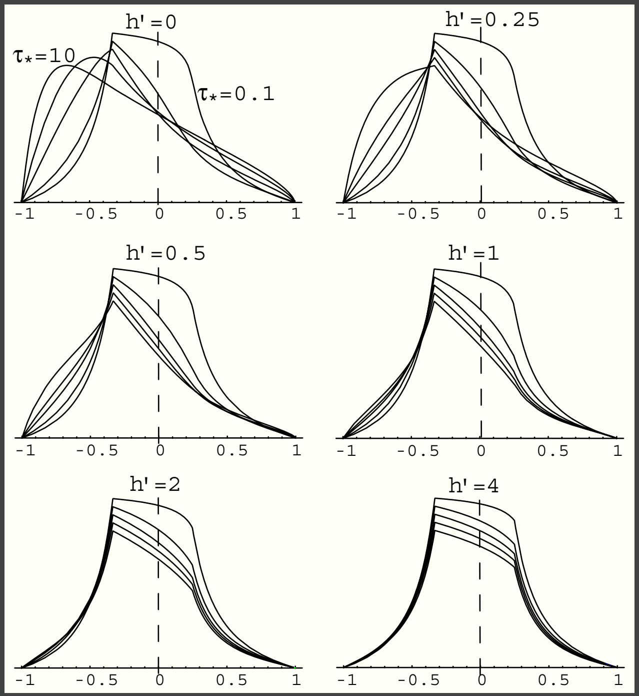
We dub this quantity the ***porosity length***, h.

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



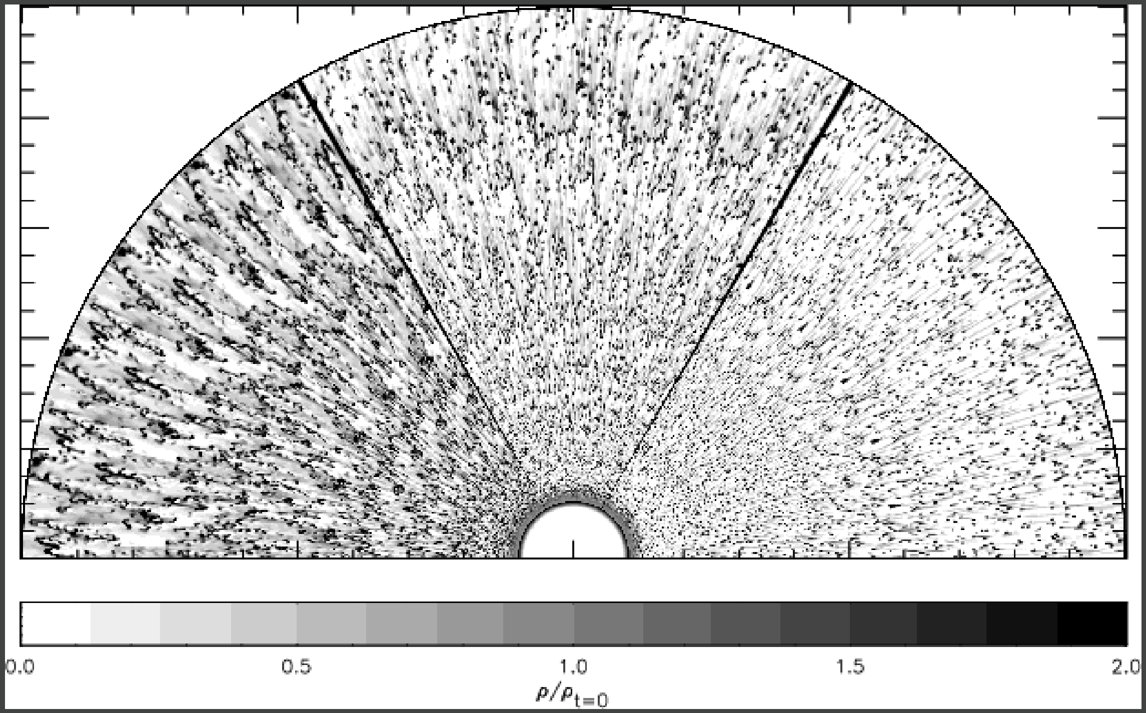
It turns out that line profiles are not significantly affected until the porosity length is **comparable to the stellar radius**

(unity, in the unitless formulation of these slides).

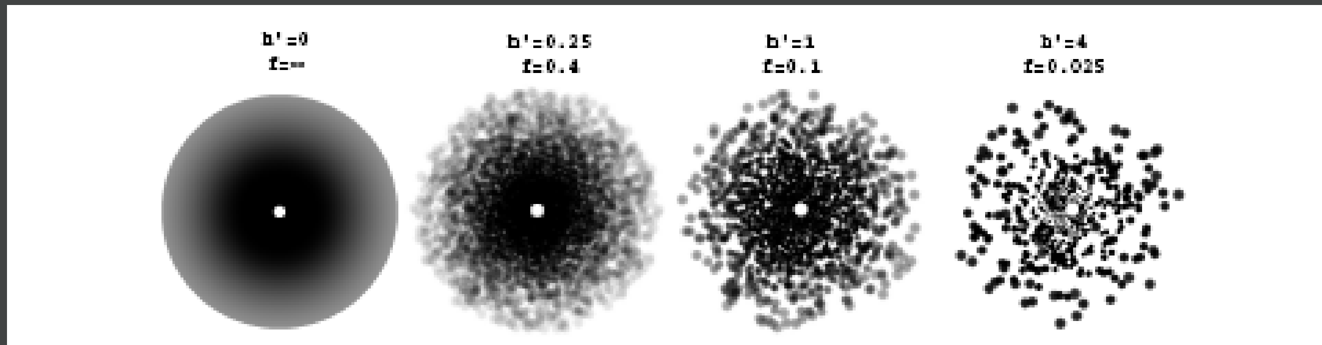


This degree of porosity is ***not*** expected from the line-driven instability.

The clumping in 2-D simulations (below) is on quite *small scales*.

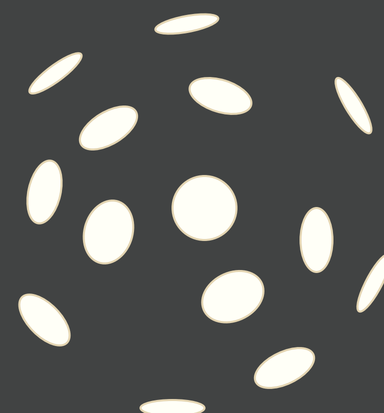


Dessart & Owocki, 2003, A&A, 406, L1



Note: these clumps are spherical

The line-driven instability might be expected to compress clumps in the radial direction: pancakes, oriented parallel to the star's surface.

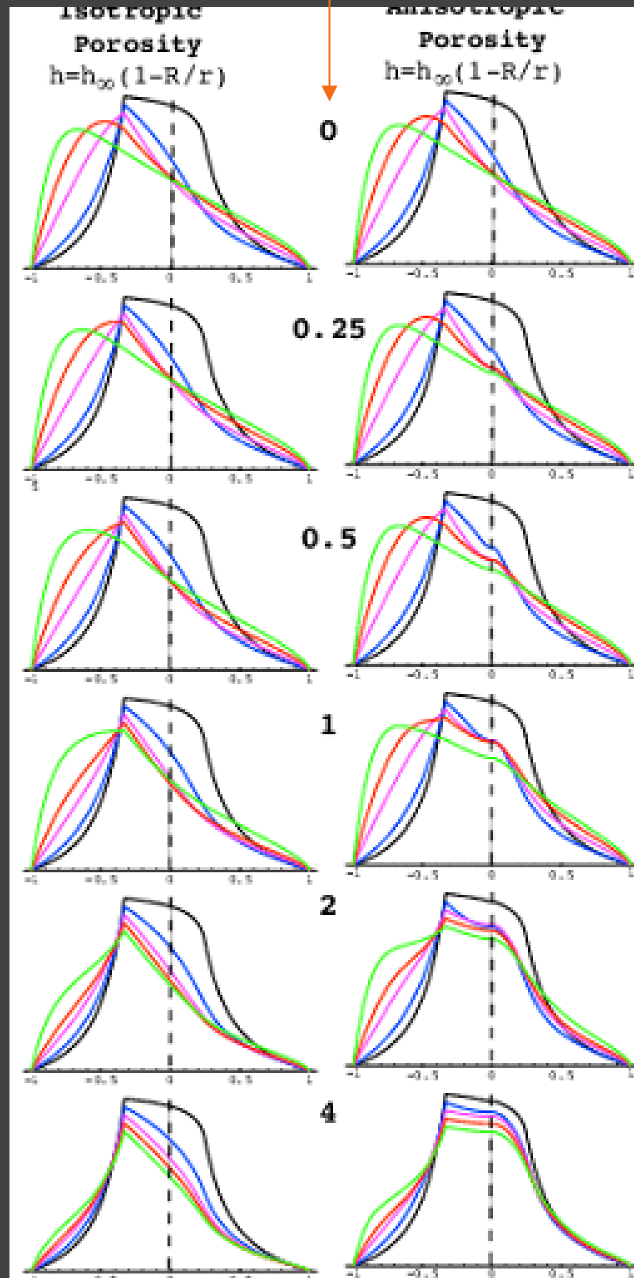


We've started working on models with non-isotropic/oblate clumps: the **Venetian-blind** model.

porosity length, h

Left column:

Isotropic porosity (i.e. spherical blobs)



Right column:

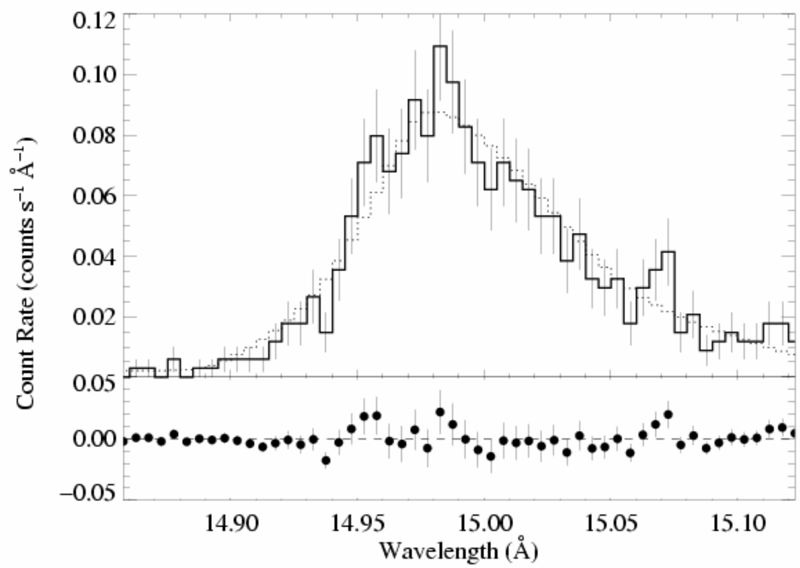
Anisotropic porosity (i.e. pancakes)

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

Best-fit model with adjustable clumping and wind opacity:

h_∞ = 0 (no clumping)

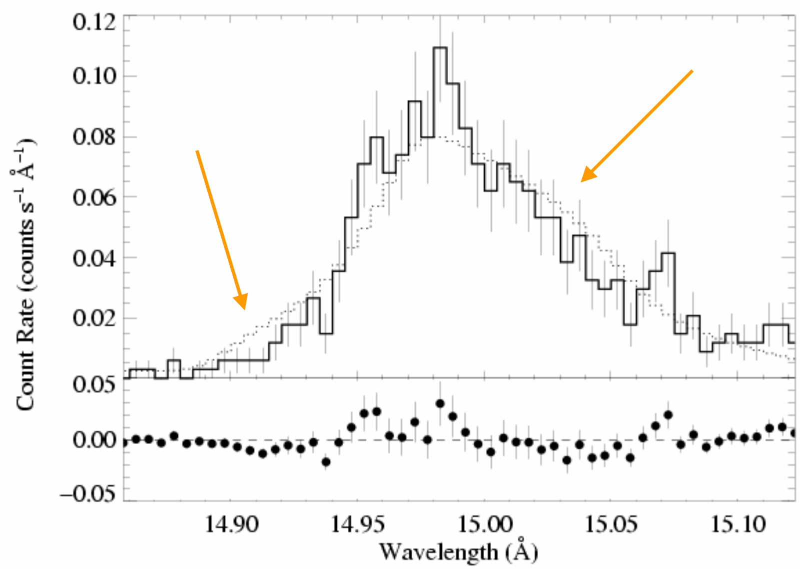
τ_* = 1.4 +/- 0.4



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

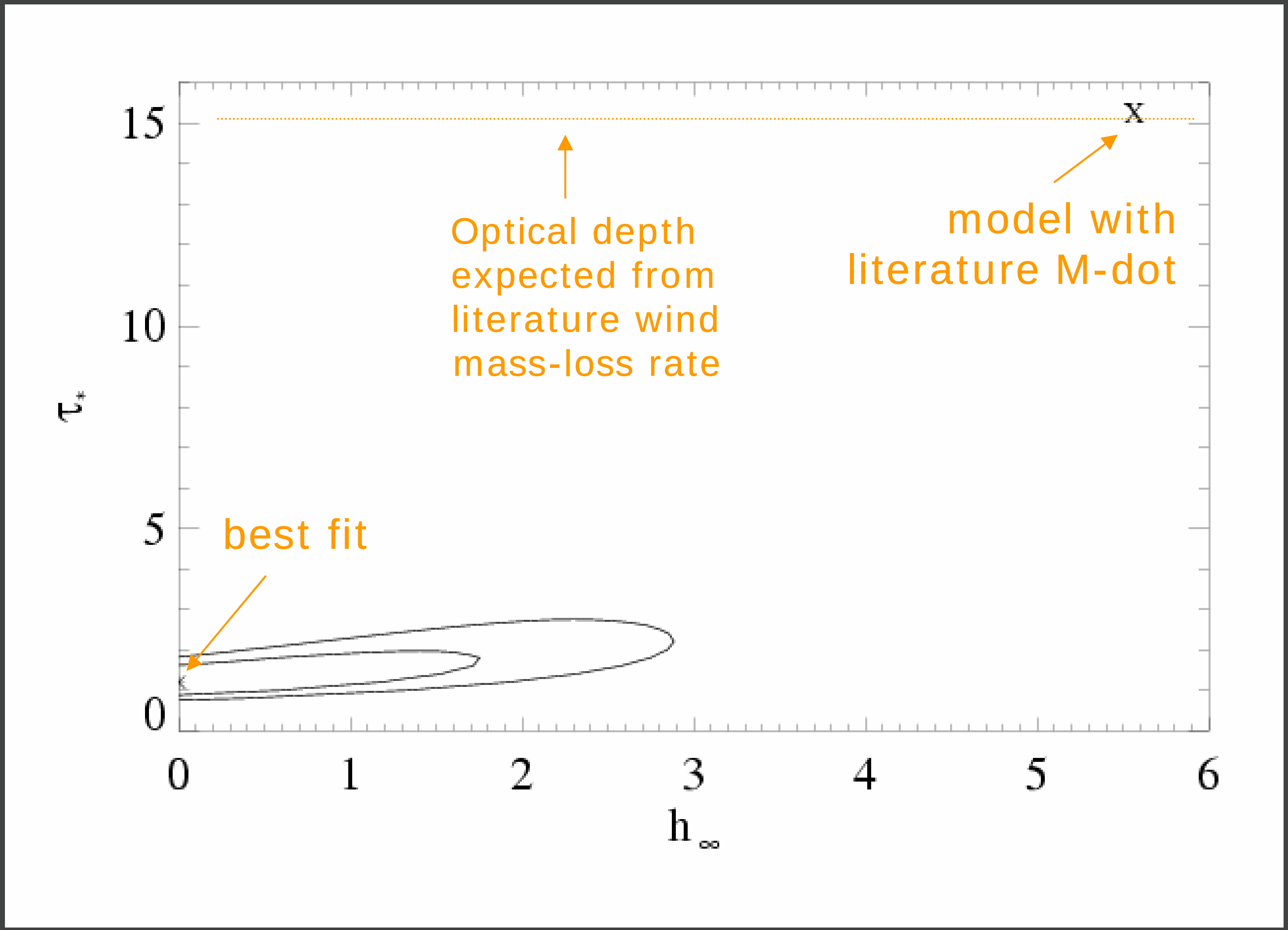
h_∞ = 6.7 +/- 1.1

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

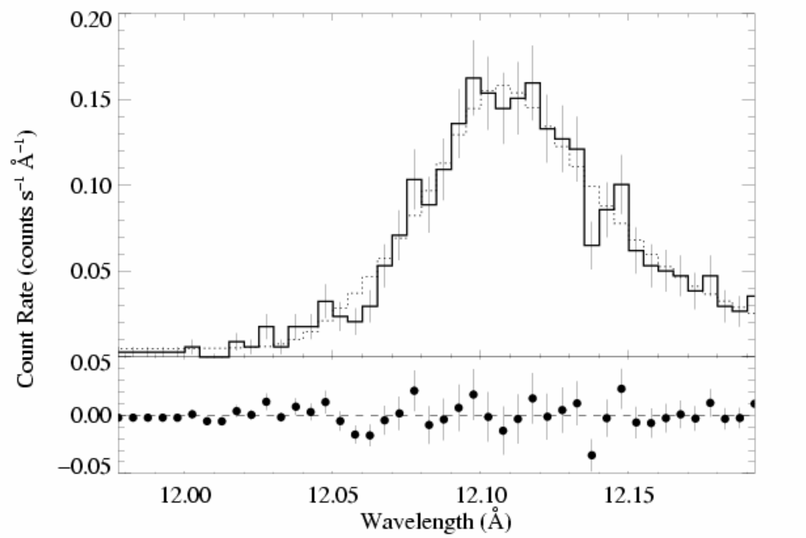


68% and 90% confidence limits for the fits to the Fe XVII 15.014 Å line in ζ Pup

optical depth



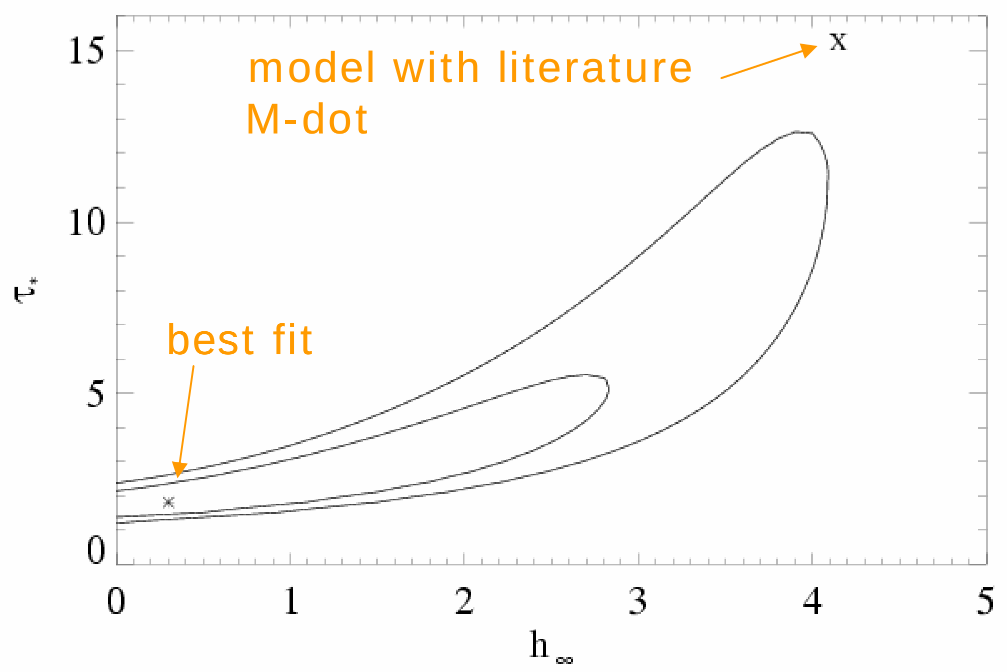
Porosity length (“clumpiness”)

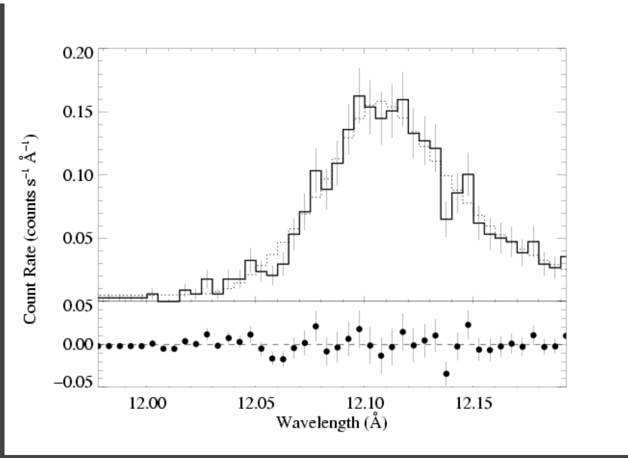


Similar fit to another line: Ne X Lyα

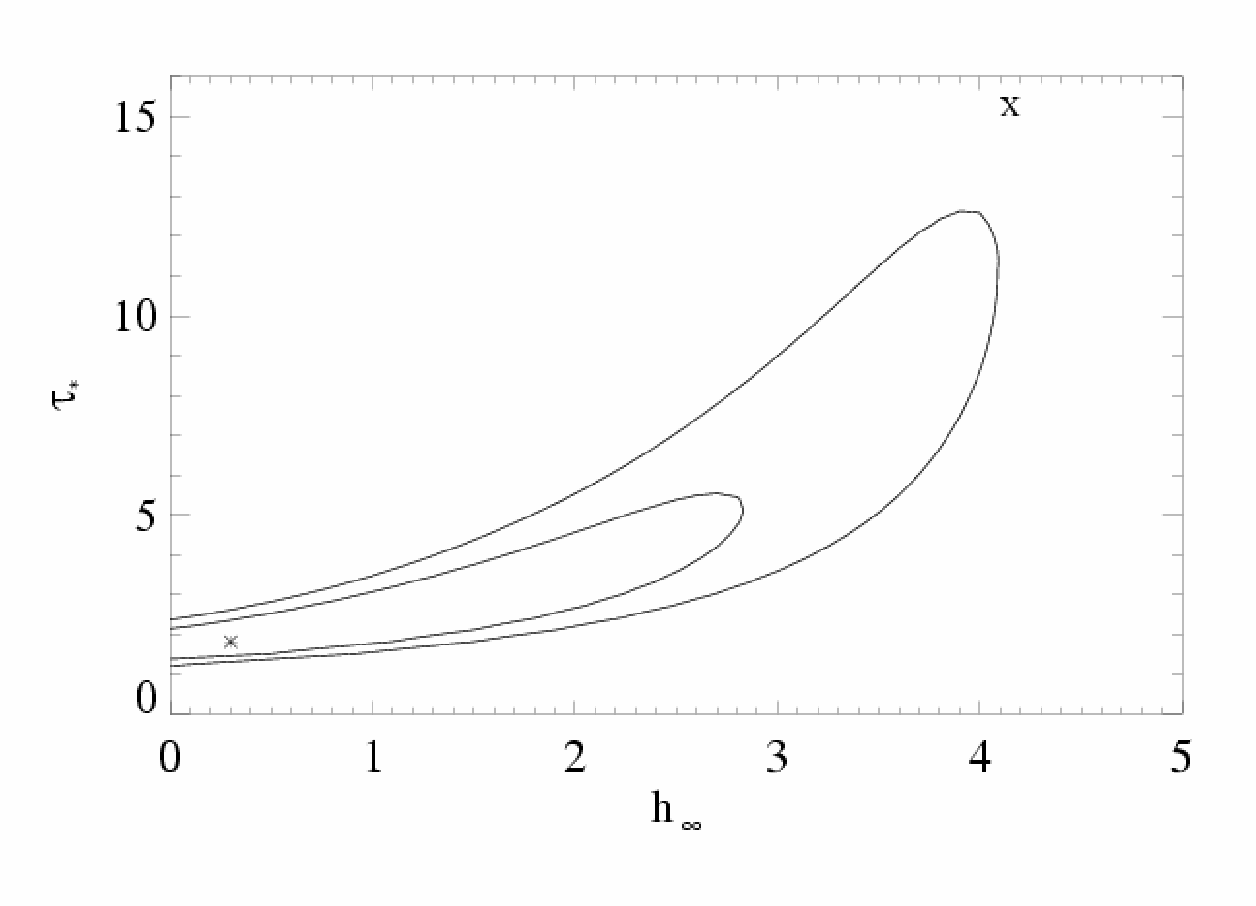
Clumpy model also ruled out here

Fits to 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$_{star}$.

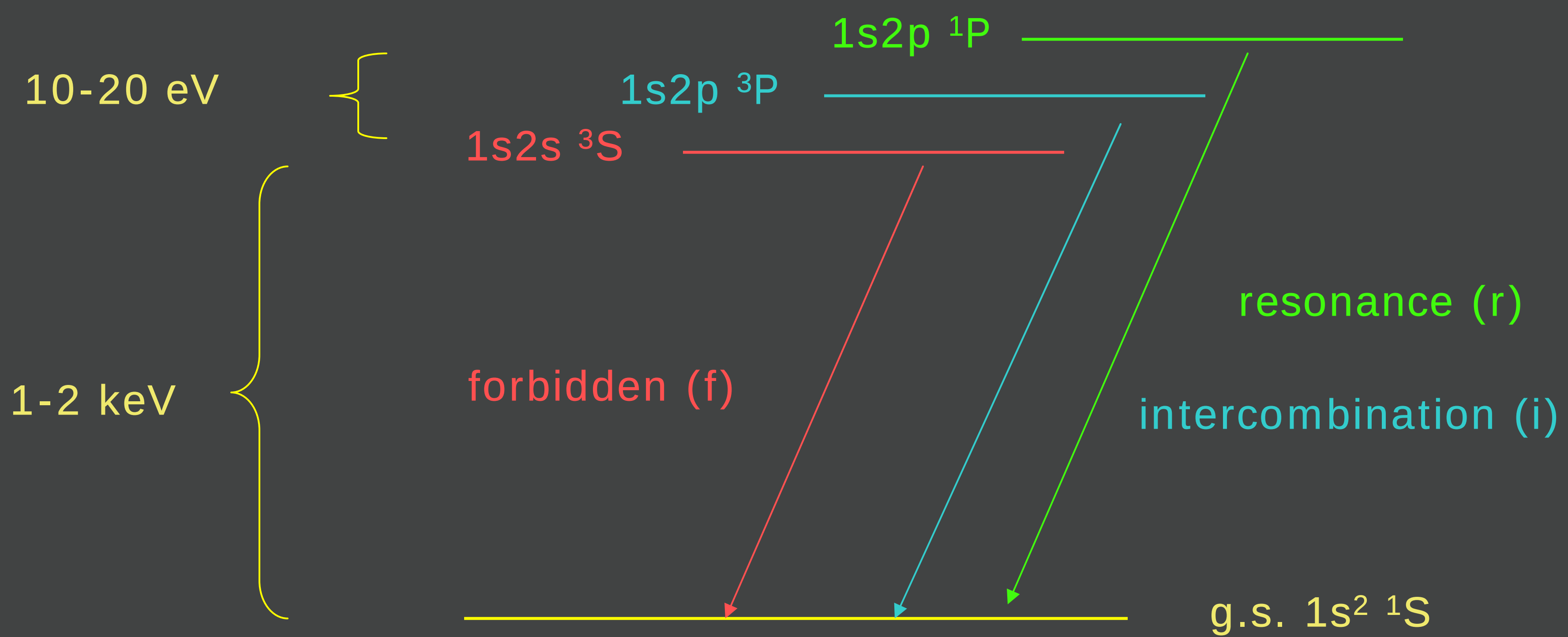


There's one more powerful x-ray spectral diagnostic that can provide useful information to test the wind-shock scenario:

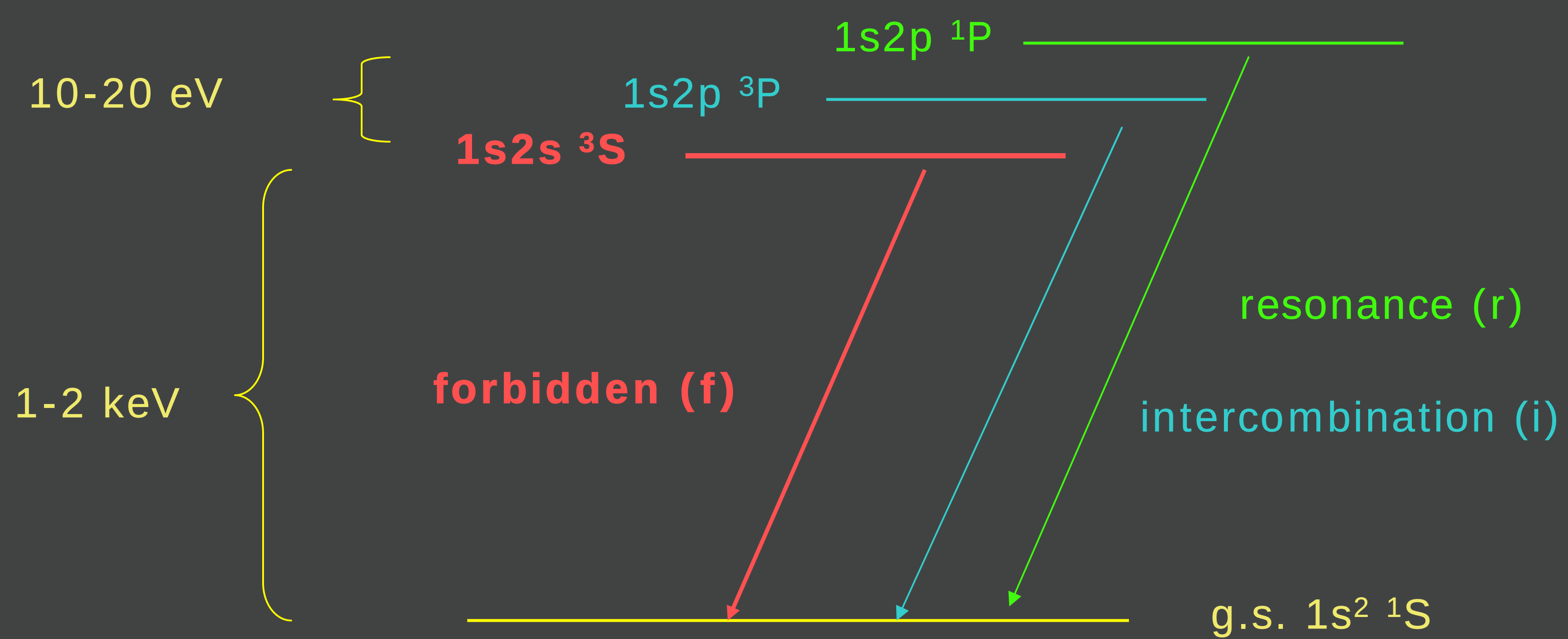
Certain x-ray **line ratios** provide information about the *location* of the x-ray emitting plasma

Distance from the star via the line ratio's sensitivity to the local UV radiation field

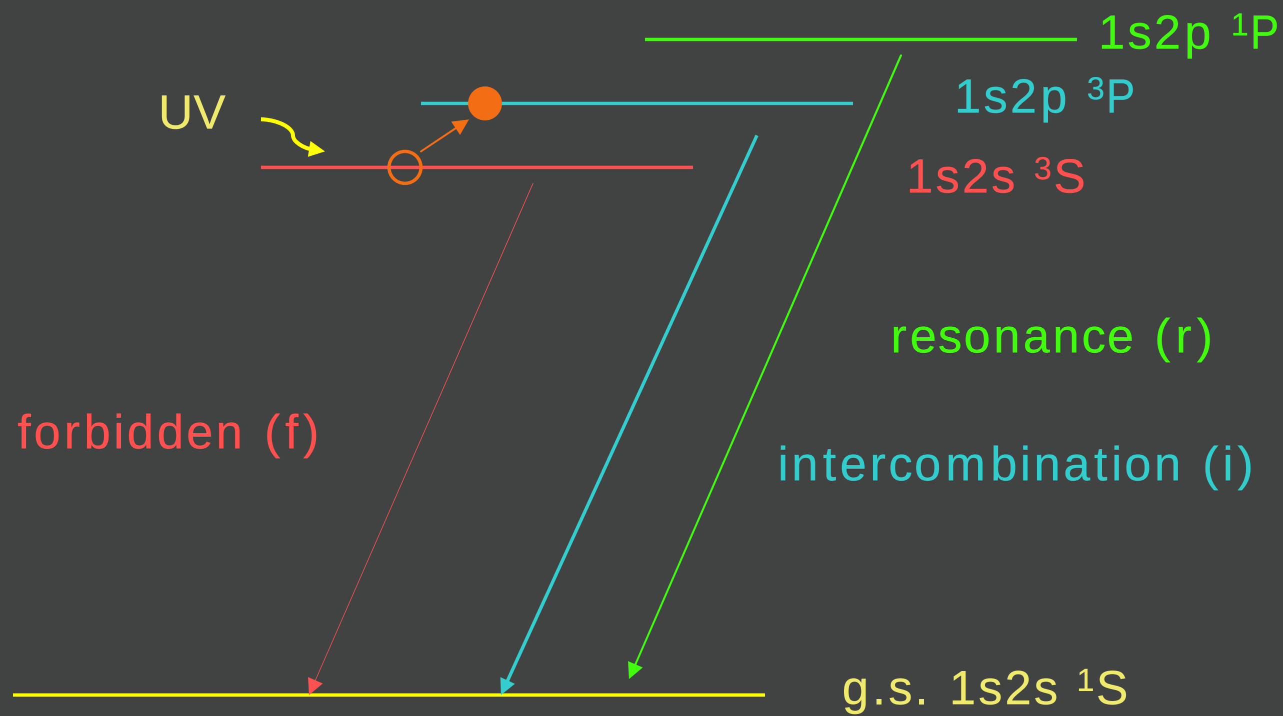
Helium-like ions (e.g. O^{+6}, Ne^{+8}, Mg^{+10}, Si^{+12}, S^{+14}) – schematic energy level diagram



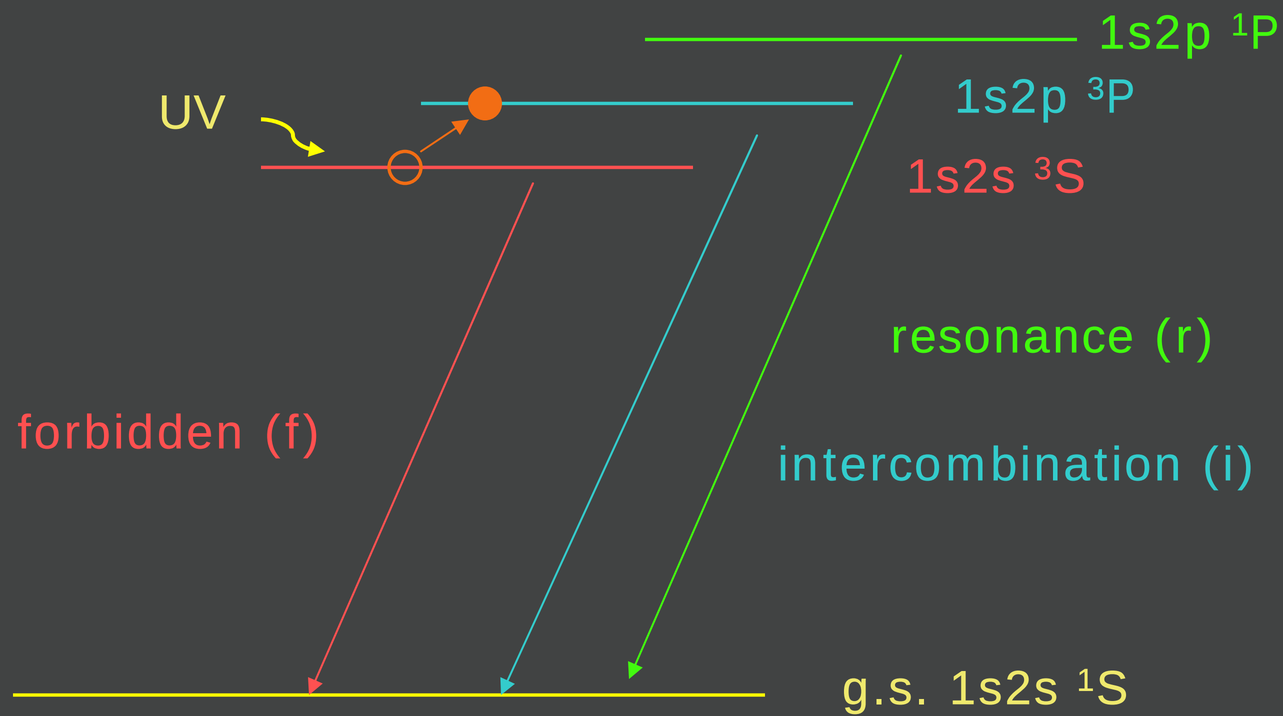
The upper level of the forbidden line is very long lived – *metastable* (the transition is dipole-forbidden)



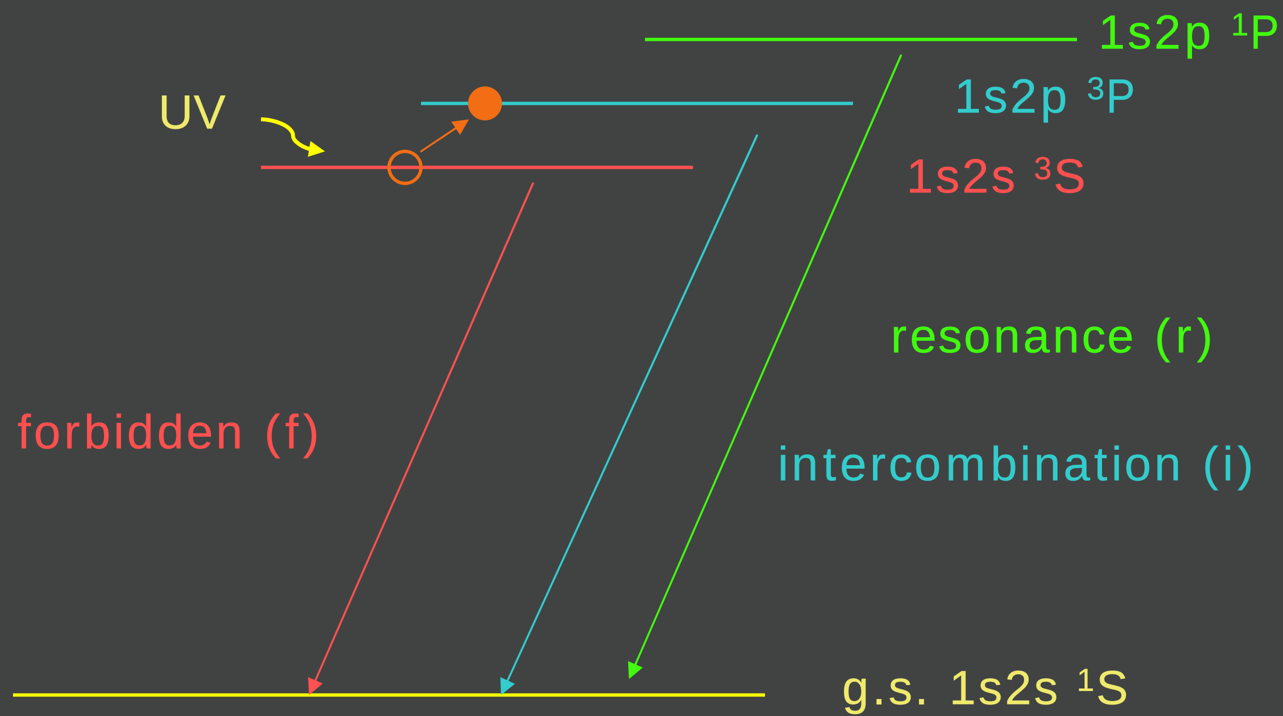
While an electron is sitting in the metastable ^3S level, an ultraviolet photon from the star's photosphere can excite it to the ^3P level – this decreases the intensity of the forbidden line and increases the intensity of the intercombination line.



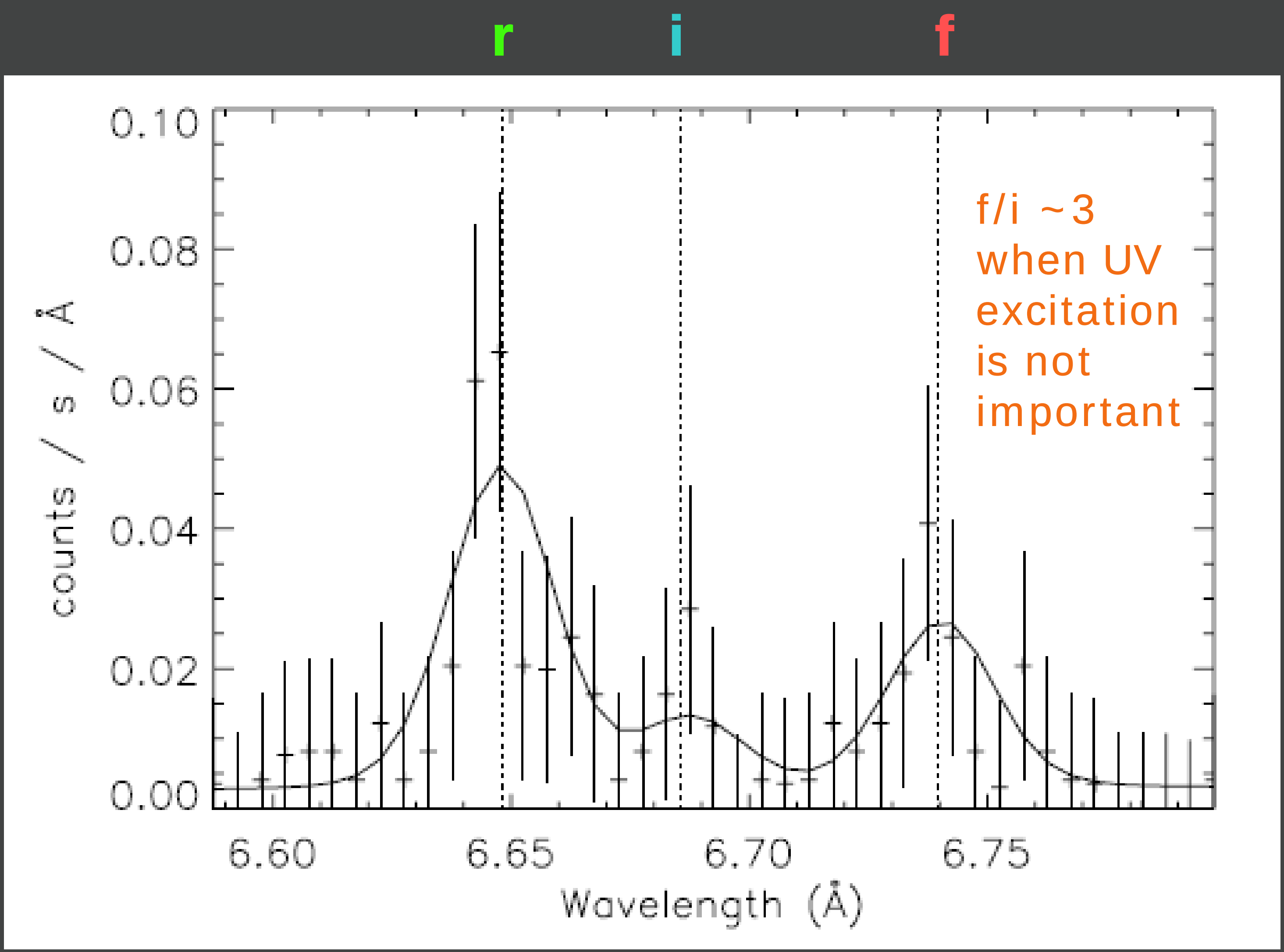
The *f*/*i* ratio is thus a diagnostic of the strength of the local UV radiation field.



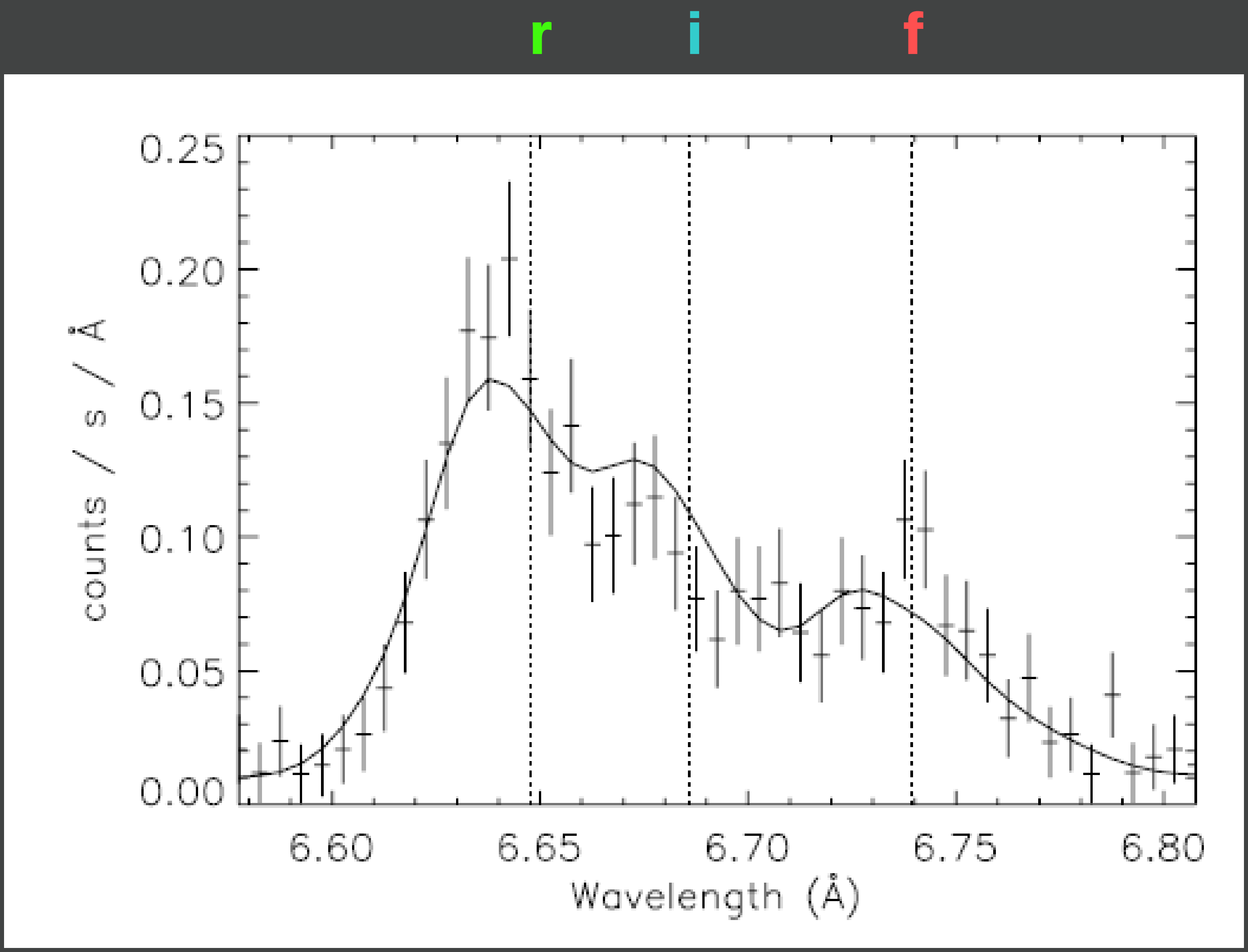
If you know the UV intensity emitted from the star's surface, it thus becomes a diagnostic of the distance that the x-ray emitting plasma is from the star's surface.



Si XIII line complex in the *Chandra* spectrum of a massive star where the local UV mean intensity is **not** strong enough to affect the forbidden-to-intercombination ratio.



Si XIII line complex in the *Chandra* spectrum of ζ Pup where the local UV mean intensity **is** strong enough to affect the forbidden-to-intercombination ratio.



Here the f/i ratio is *reduced*, due the effects of UV photoexcitation … this occurs because the x-ray emitting plasma is relatively close to the photosphere.

Leutenegger et al., 2006, ApJ, 650, 1096

We have fit line profile models *simultaneously* to the *f-i-r* complexes in four hot stars – and get consistent fits:

Hot plasma smoothly distributed throughout the wind, above roughly **1.5 R_{star}**

- The f/i line ratios are consistent with this spatial distribution
- The line profile shapes are also consistent with this distribution (as already was shown for single, unblended lines)

There is *no* O star for which the He-like f/i diagnostics require hot plasma very close to the photosphere

Conclusions

O star X-ray emission line profiles are broadened, shifted, and asymmetric as the wind-shock scenario 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 – mass-loss rate reductions of factors of several are favored

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