Line Shapes in Hot Stars:

Hydrodynamics & Wind Mass-Loss Rates

David Cohen

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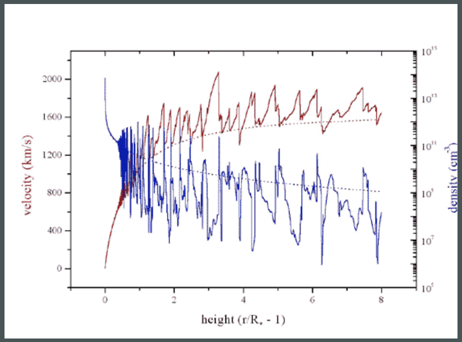
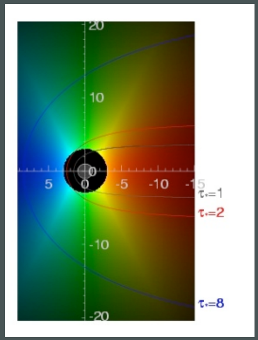
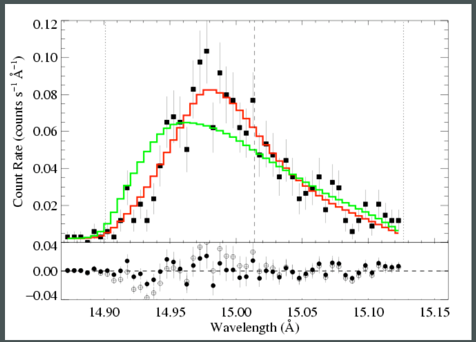
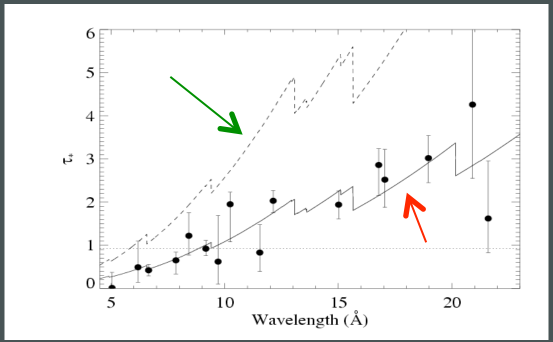
with Maurice Leutenegger, Stan Owocki, Rich Townsend,
Emma Wollman ('09), James MacArthur ('11)

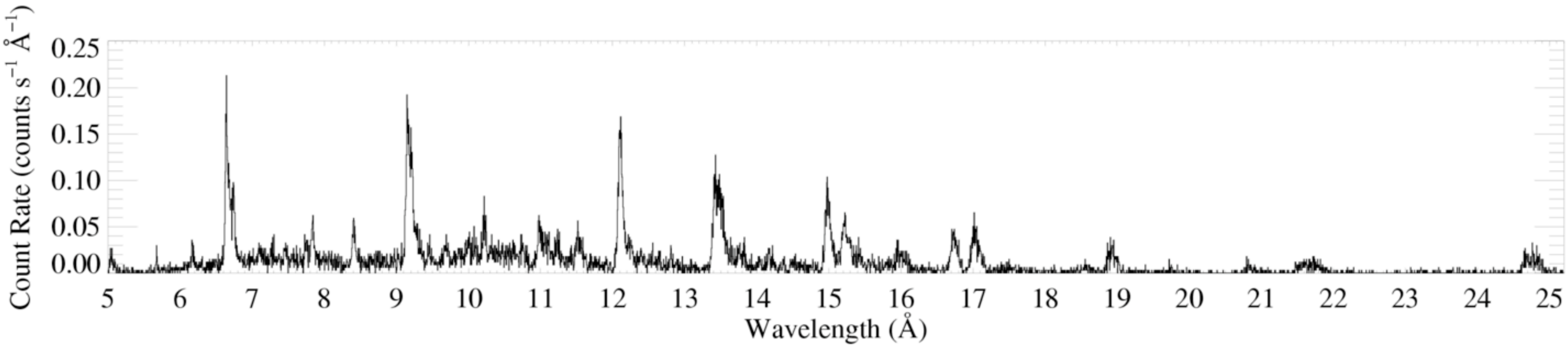


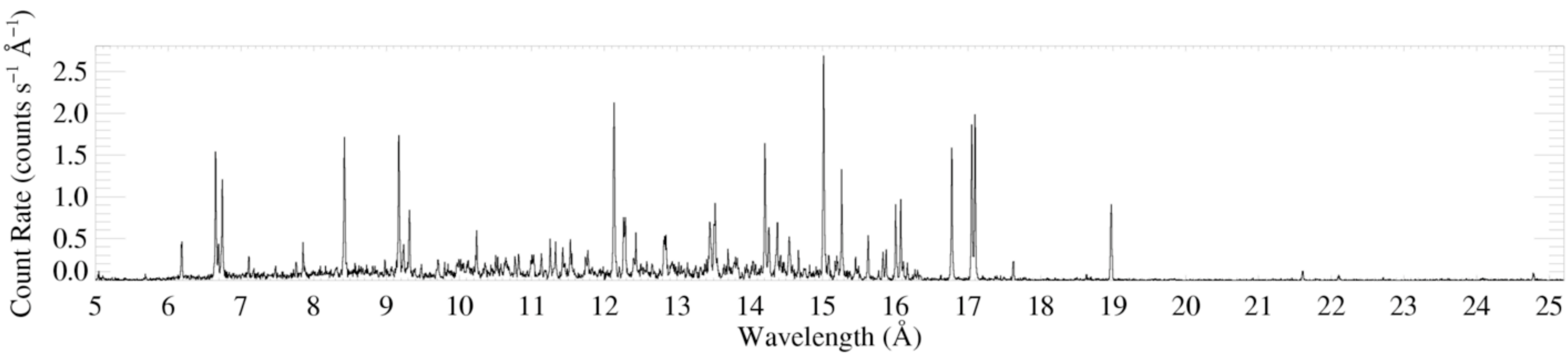






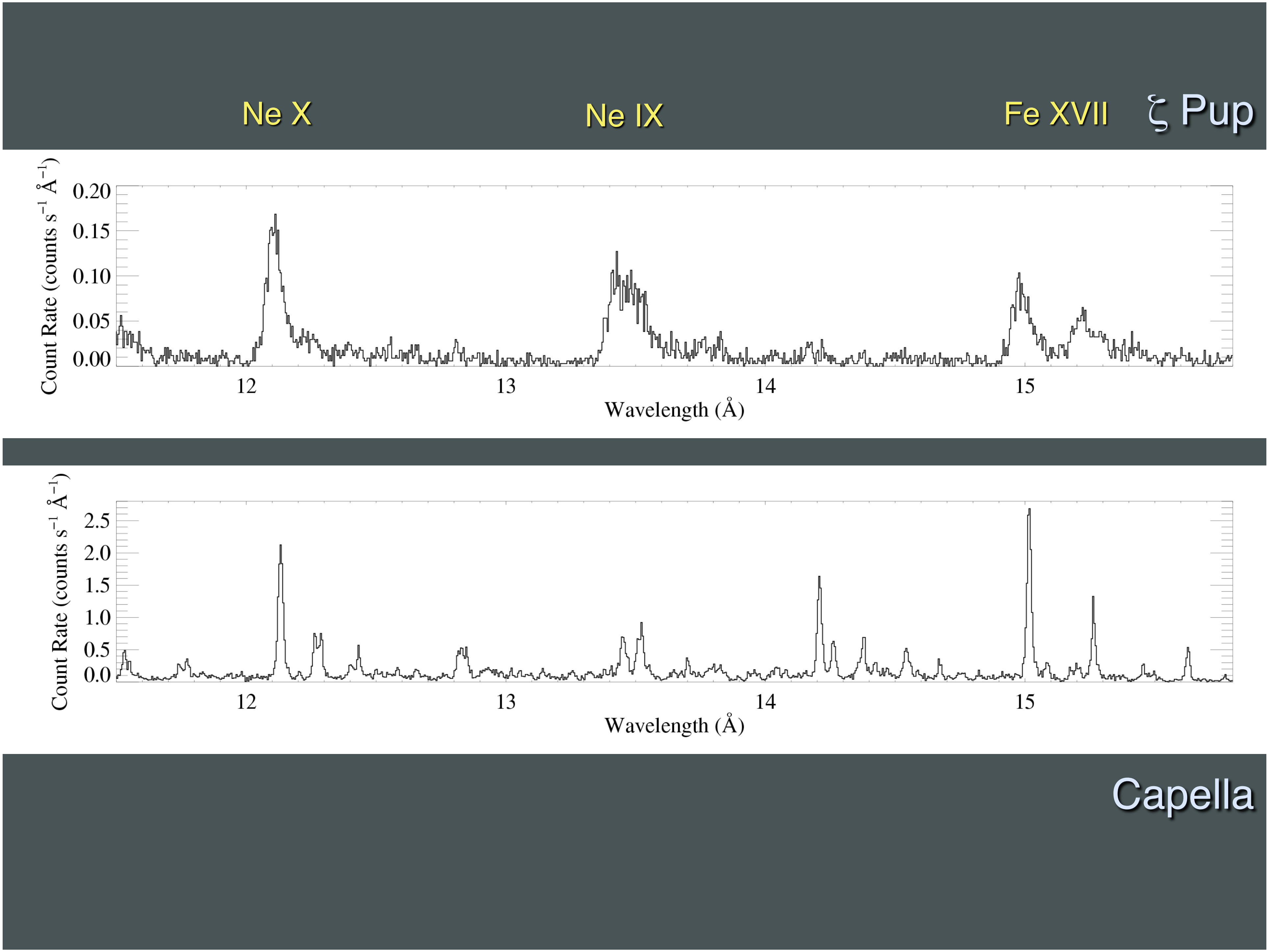
ζ Pup (O4 If)

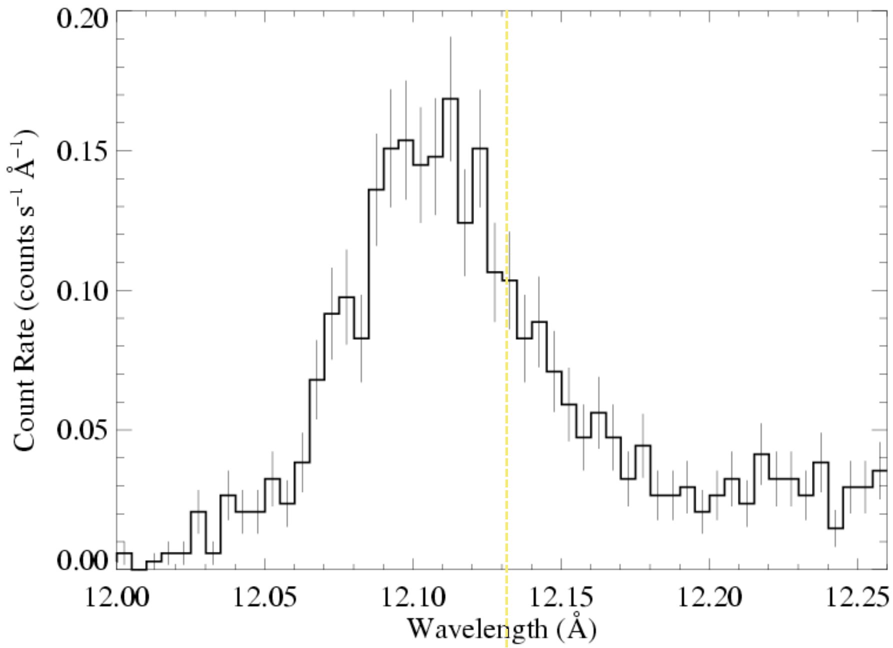




Capella (G5 III) – coronal source

– for comparison


Ne X
Ne IX
Fe XVII
ζ Pup
Count Rate (counts s^-1 Å^-1)
0.20
0.15
0.10
0.05
0.00
12
13
14
15
Wavelength (Å)
Count Rate (counts s^-1 Å^-1)
2.5
2.0
1.5
1.0
0.5
0.0
12
13
14
15
Wavelength (Å)
Capella



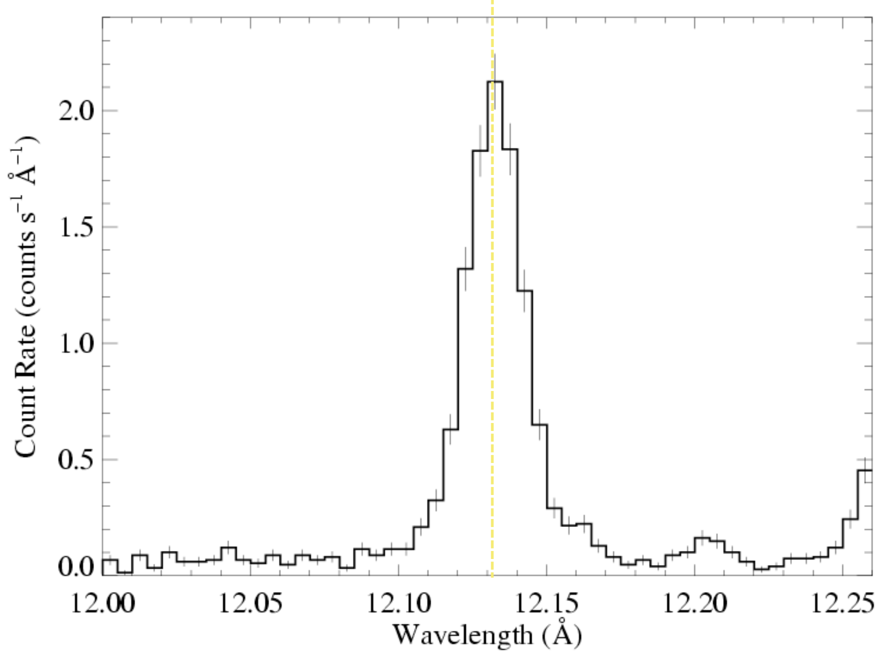
ζ Pup

massive

broad,

skewed,

blue shifted

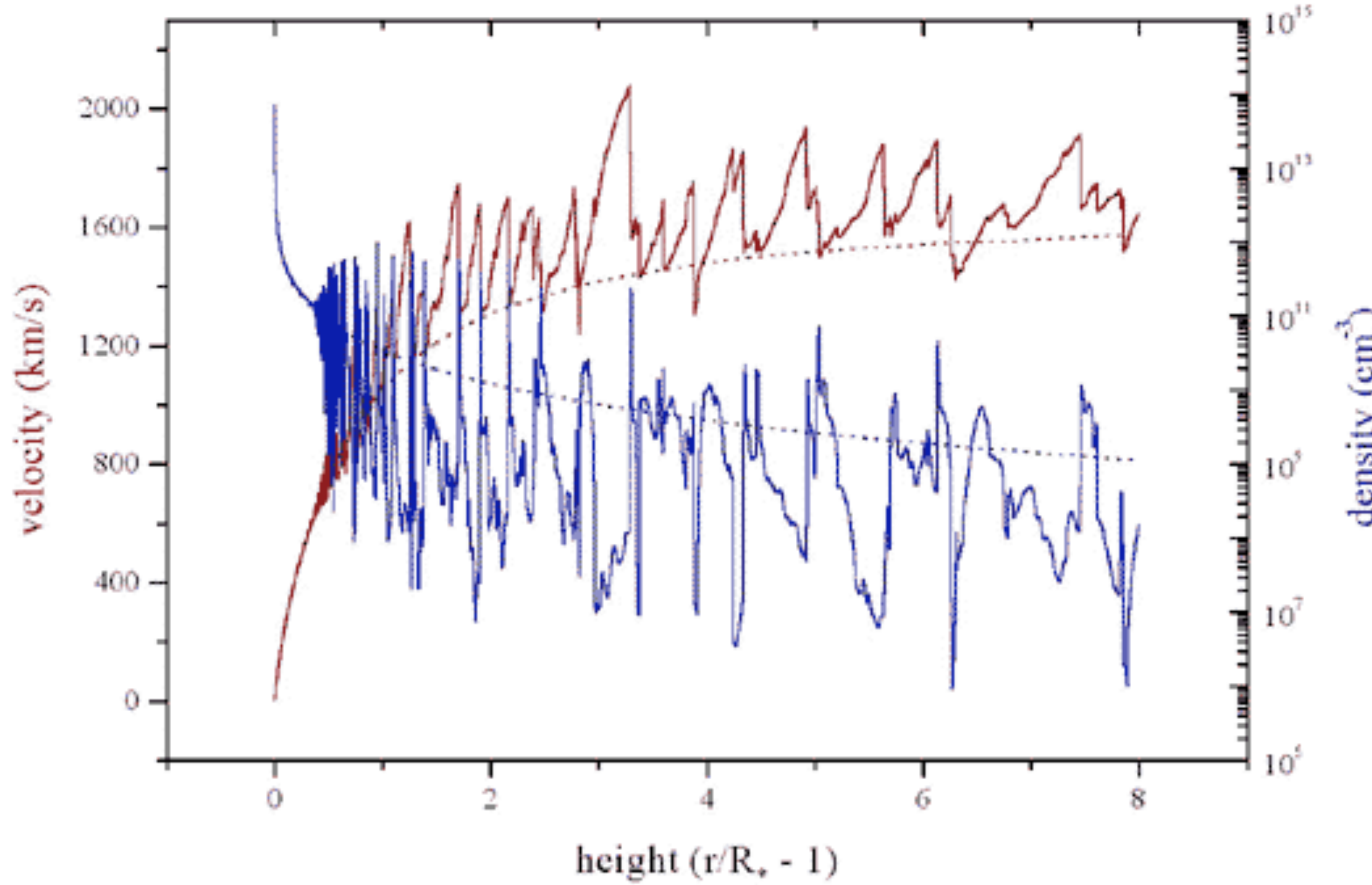


Capella

low mass

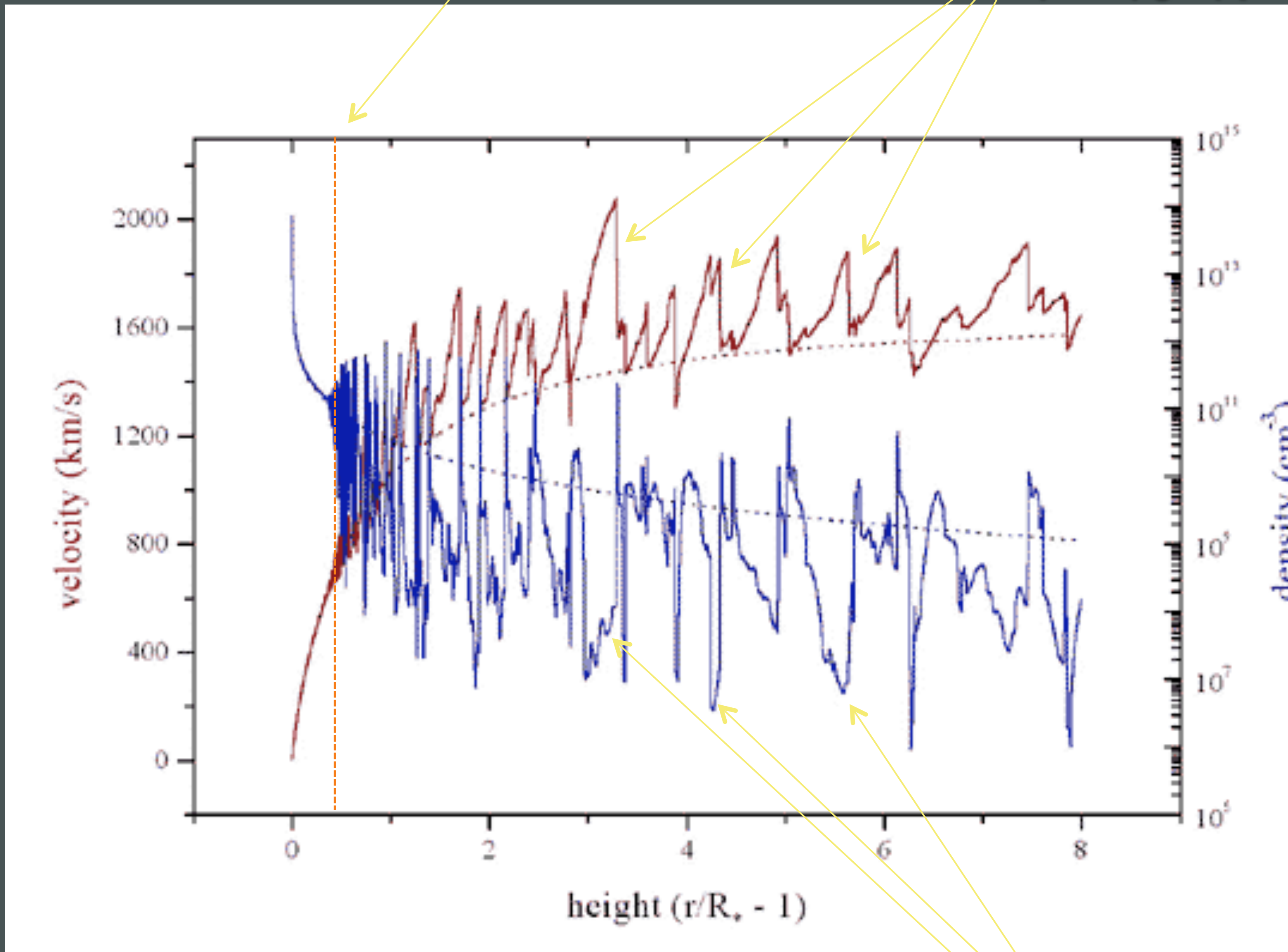
unresolved

rad-hydro wind simulations: line-driving instability



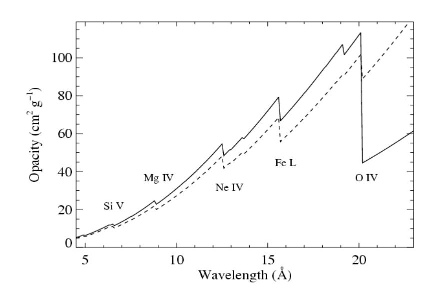
shock onset at r ~ 1.5 R_{star}

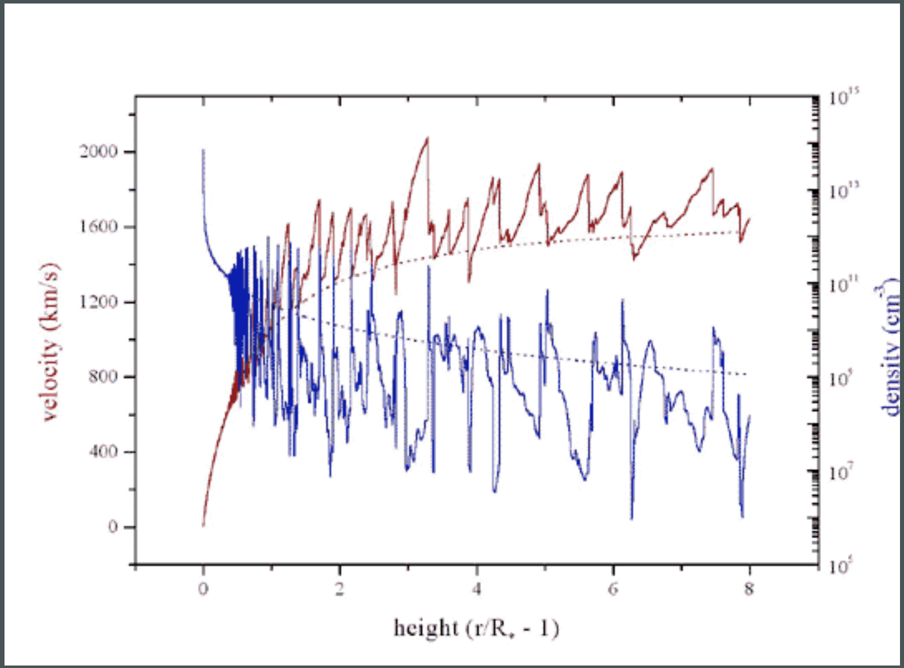
V_{shock} ~ 300 km/s : T ~ 10^6 K



hot plasma has low density

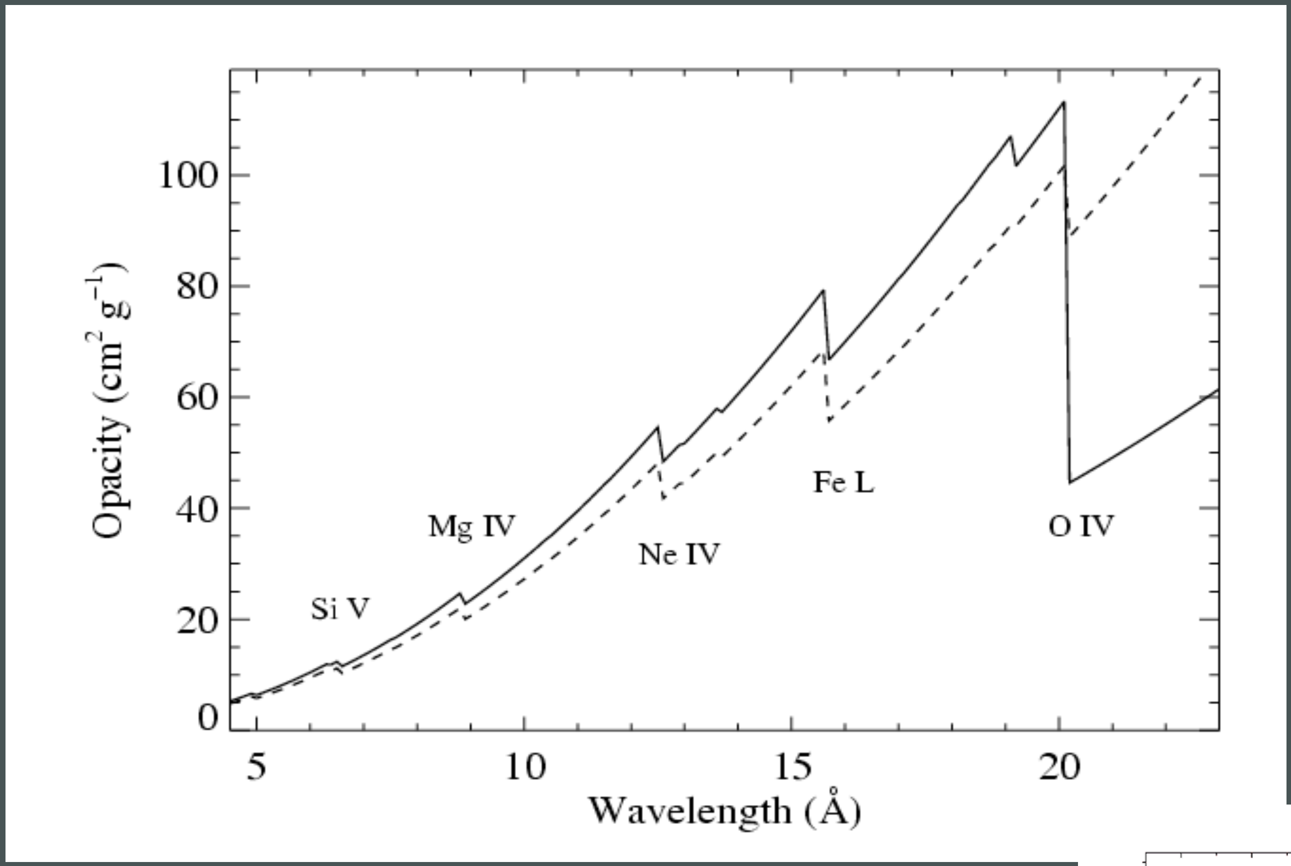
99% of the wind mass is cold*, partially ionized… x-ray **absorbing**





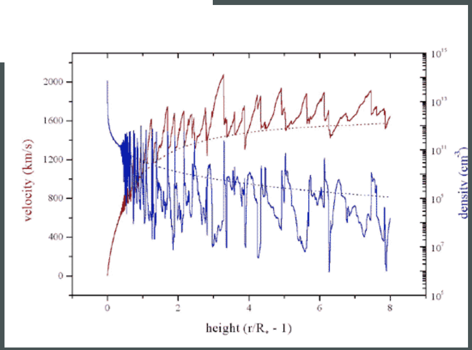
*typically 20,000 – 30,000 K; maybe better described as “warm”

photoelectric absorption: continuum opacity in the cold wind component

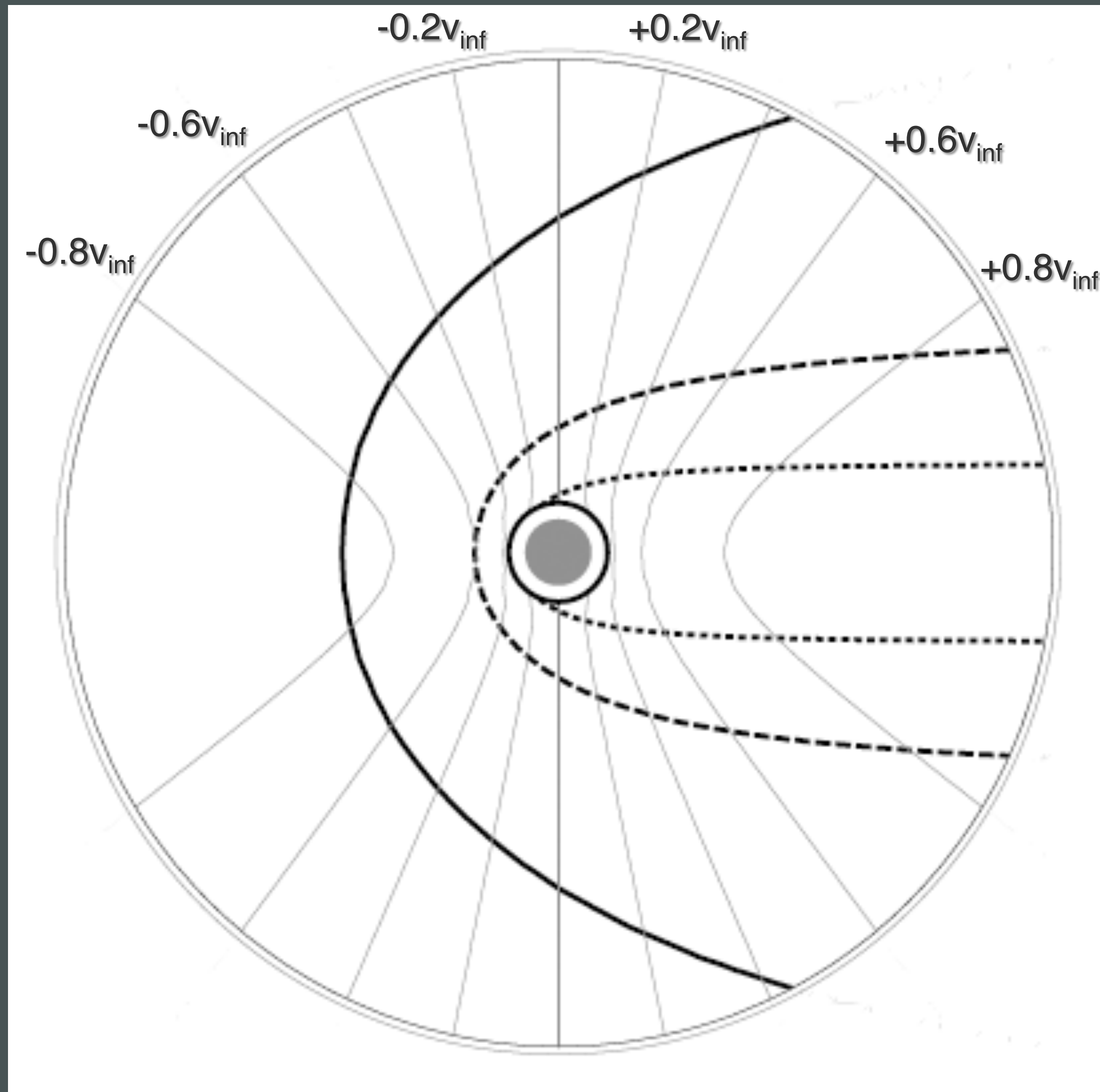


CNO processed

solar abundance



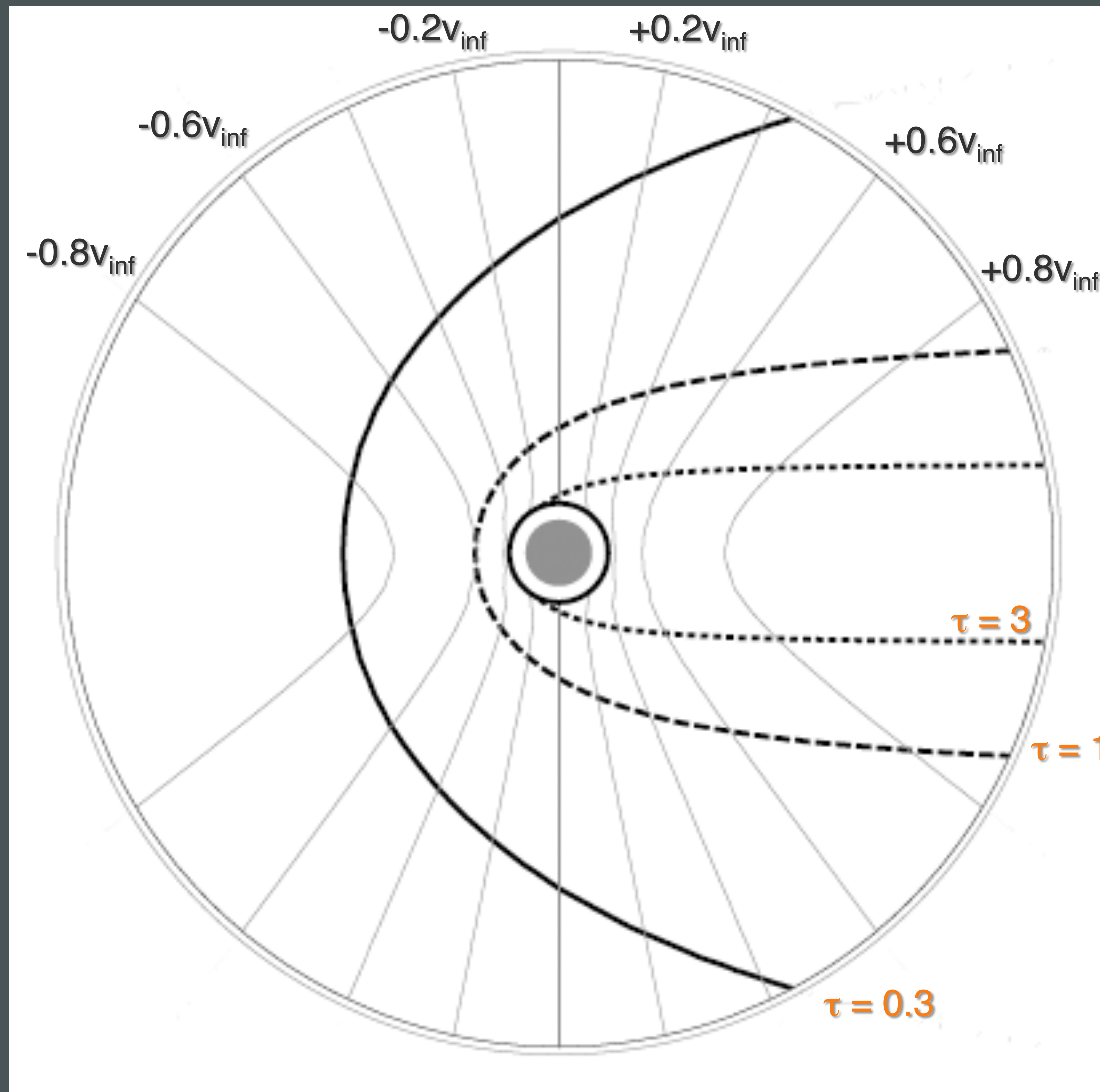
isovelocity contours



observer
on left

isovelocity contours

observer
on left



optical
depth
contours

opacity of the **cold wind** component

wind mass-loss rate

$$\dot{M} = 4\pi r^2 v \rho$$

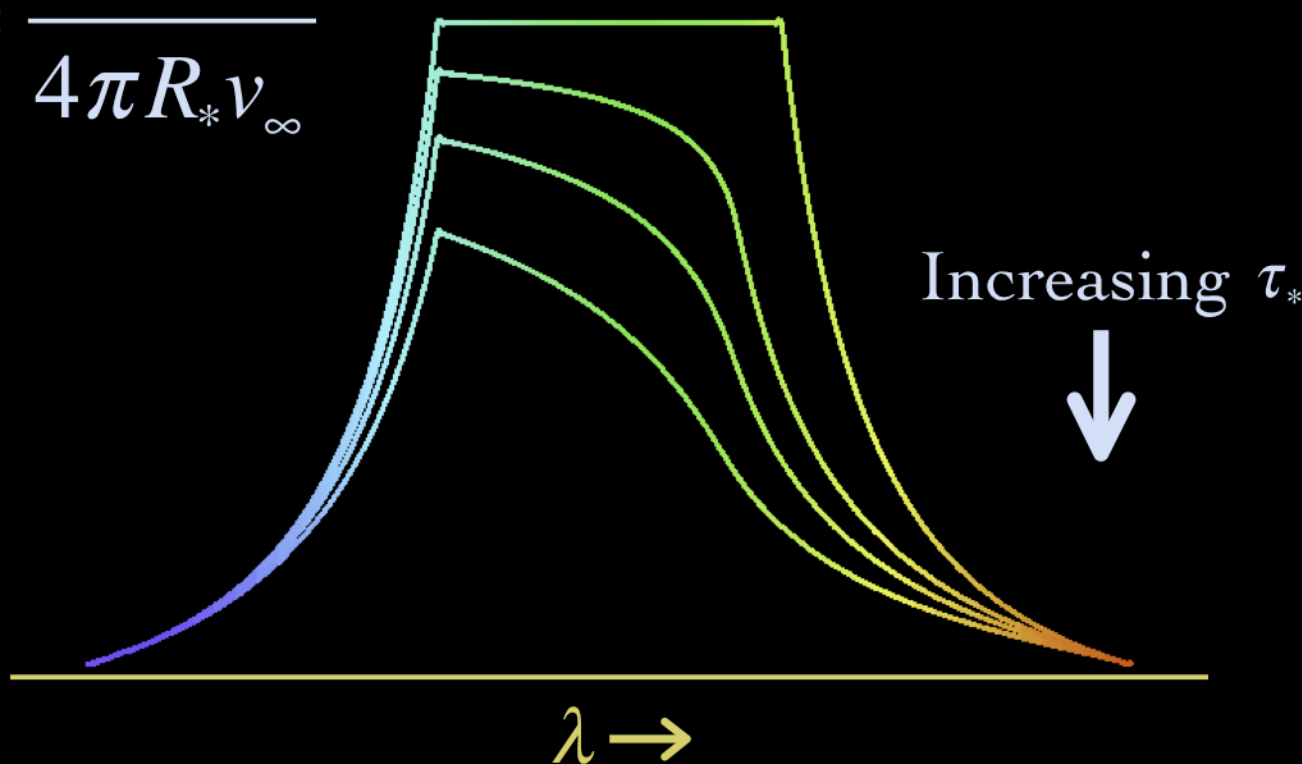
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

radius of the star

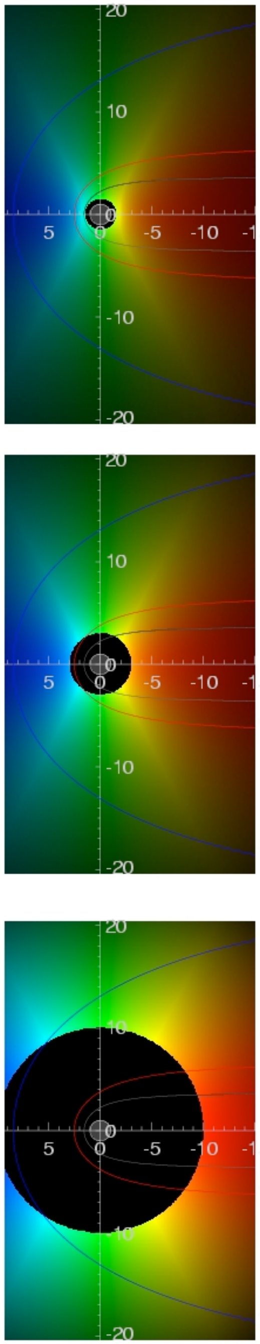
wind terminal velocity

Wind Profile Model

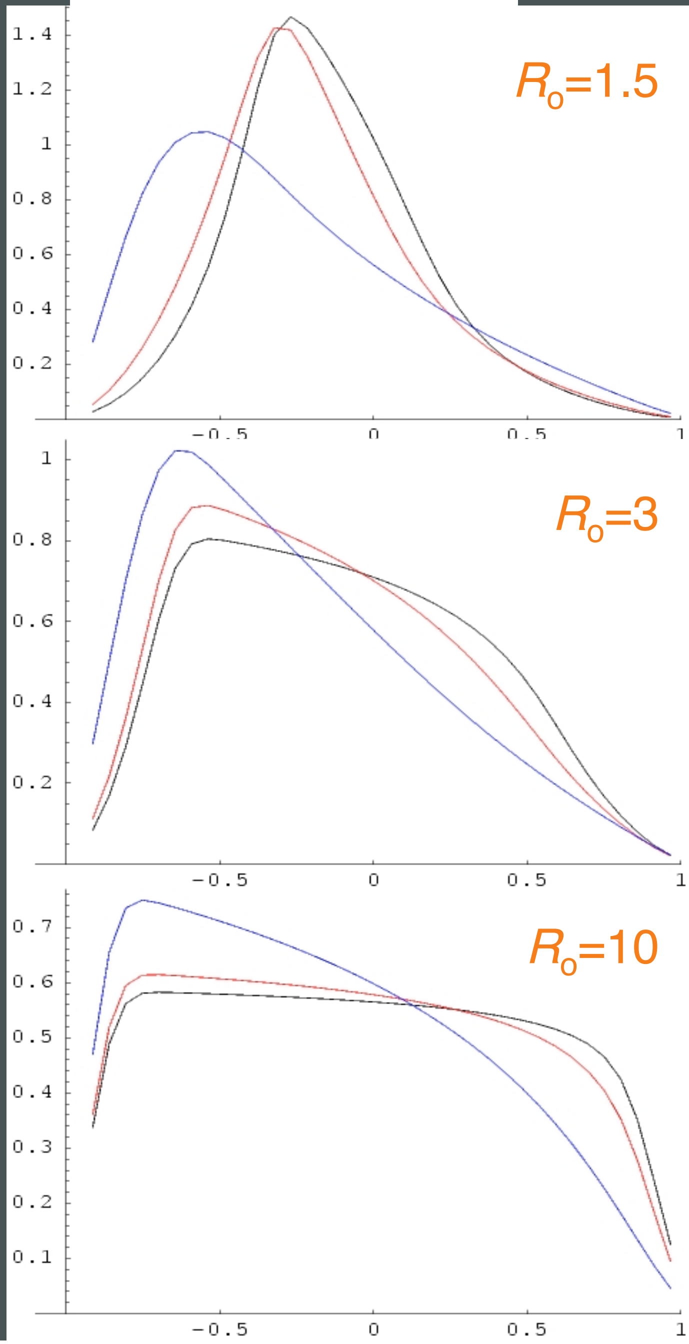
$$\tau_* = \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$



τ=1 contours



$\tau_* = 1, 2, 8$



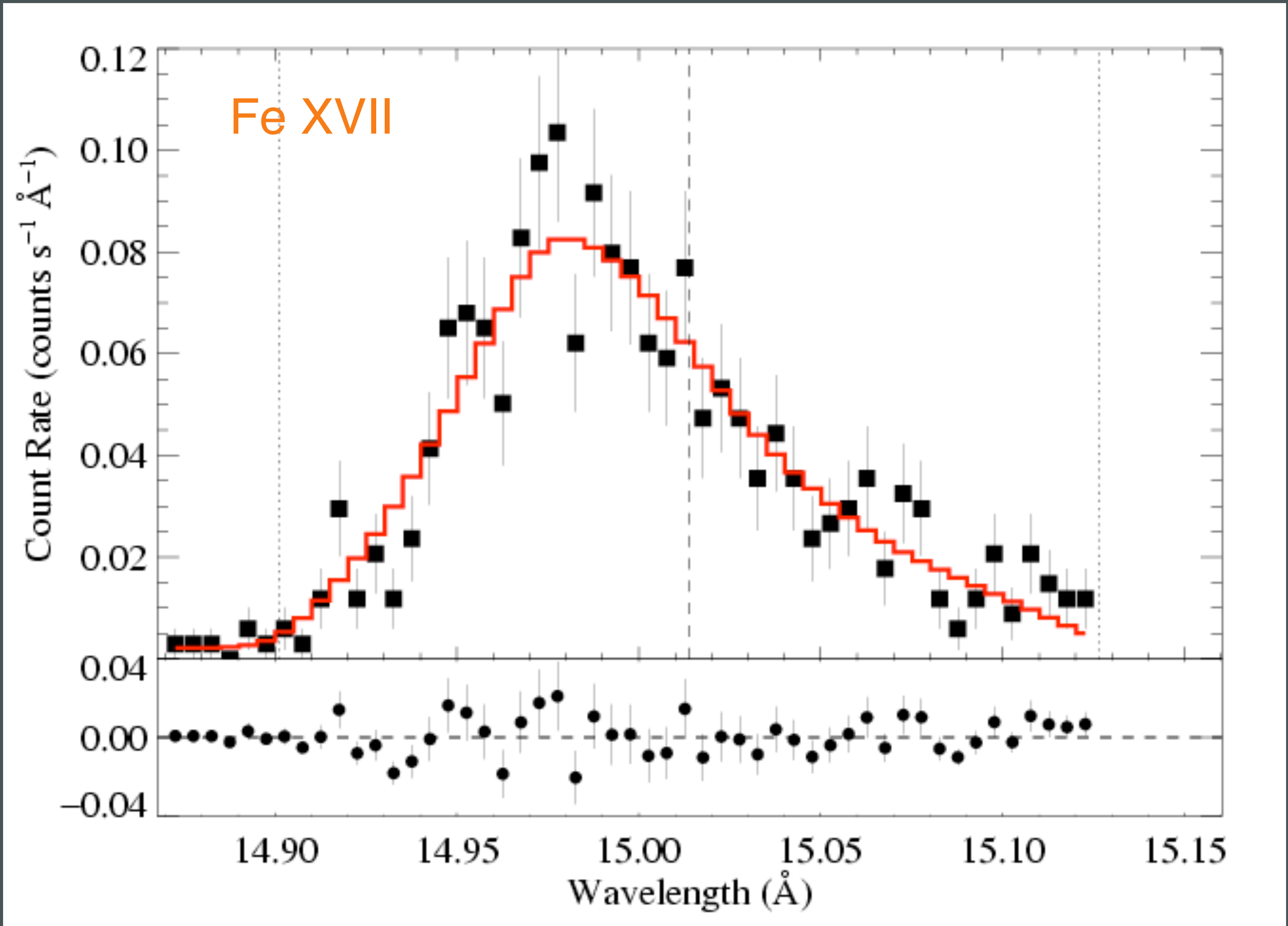
key parameters: R_o & τ_*

$j \sim \rho^2$ for $r/R_* > R_o$,
$= 0$ otherwise

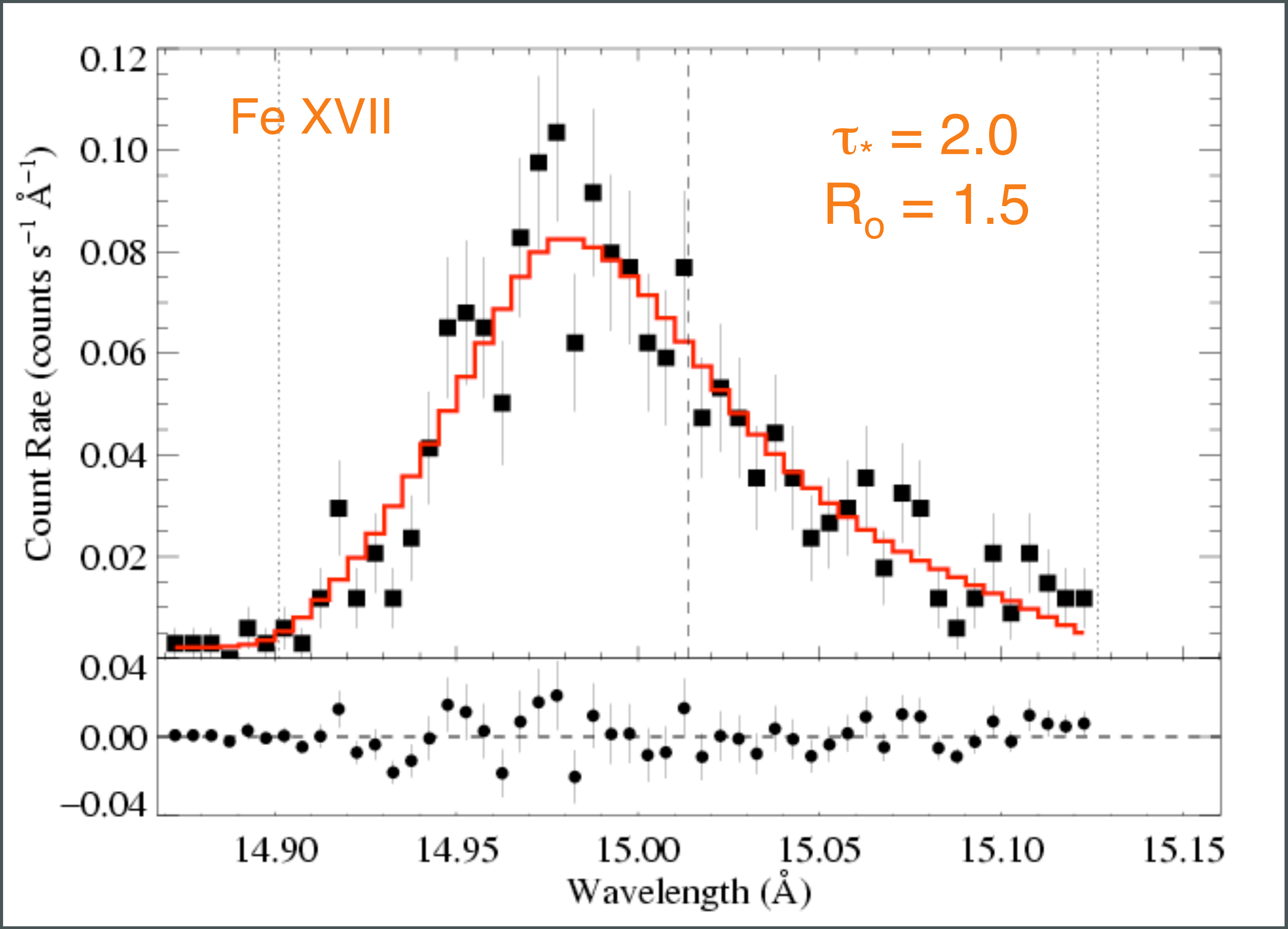
$$\tau = \tau_* \int_z^\infty \frac{R_* \, dz'}{r'^2 \left(1 - {R_*}/{r'}\right)^\beta}$$

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

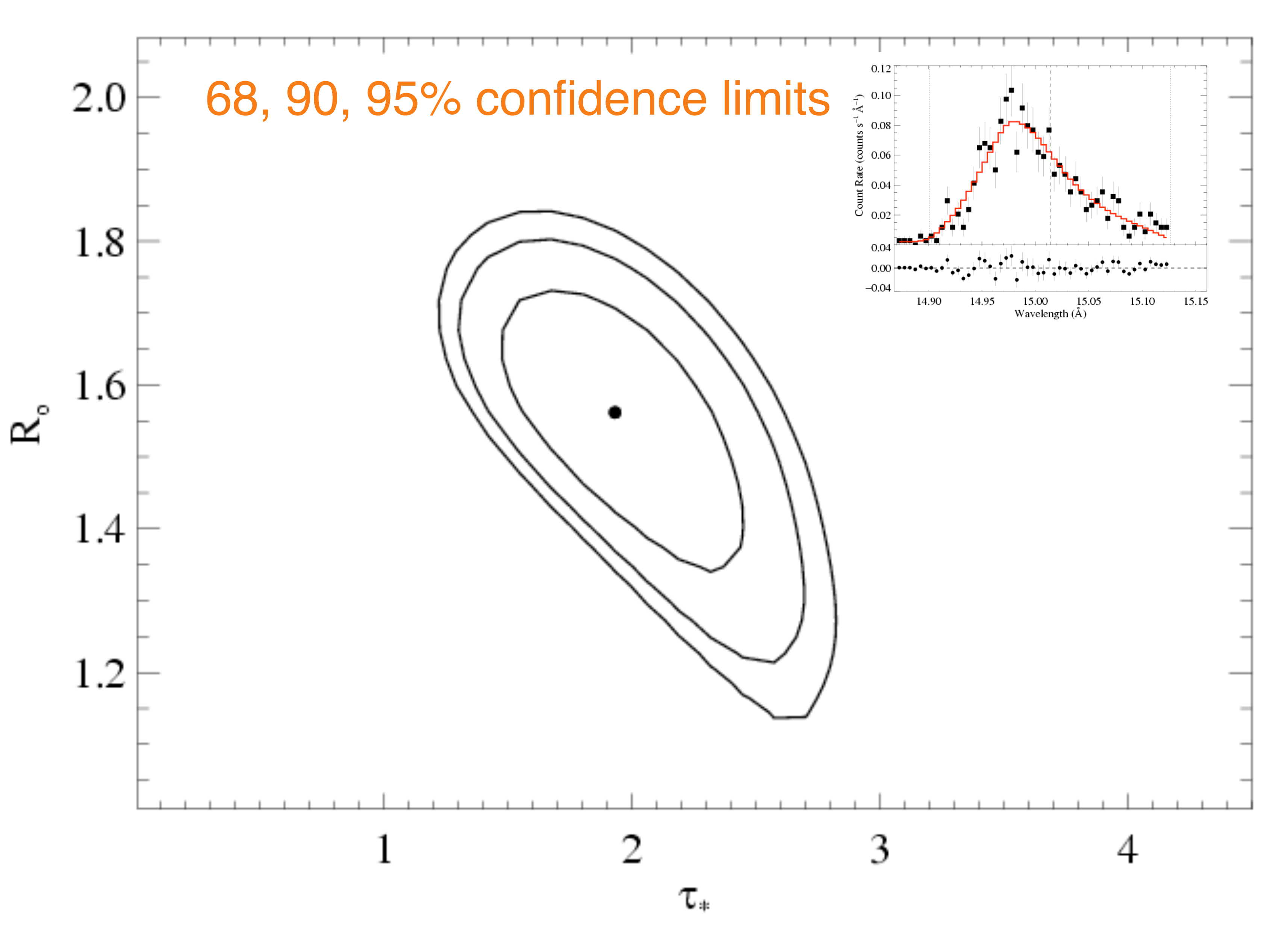
We fit these x-ray line profile models to each line in the *Chandra* data



And find a best-fit τ_* and R_o…

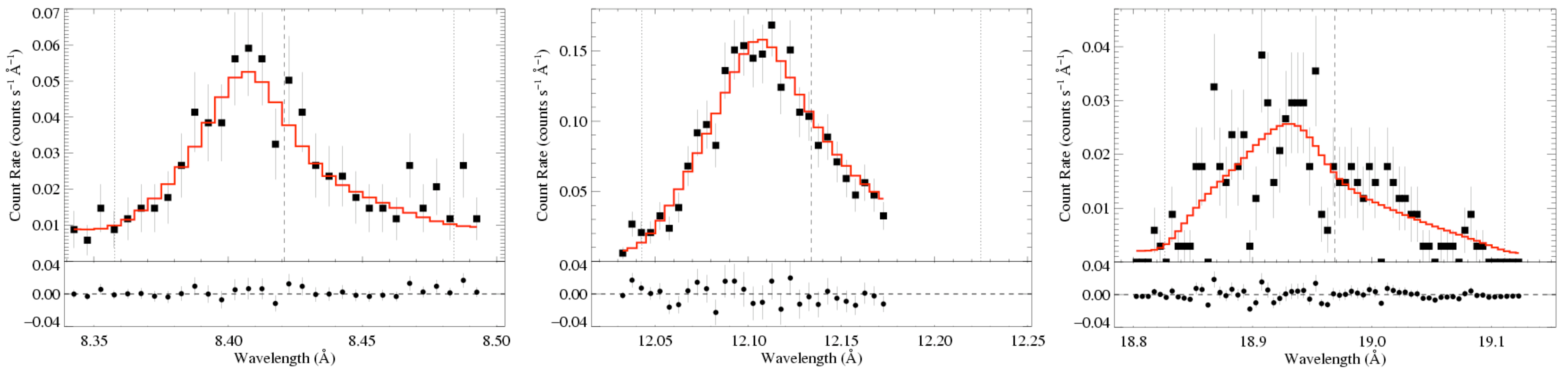


…and place confidence limits on these fitted parameter values



ζ Pup: three emission lines

Mg Lyα: 8.42 Å | Ne Lyα: 12.13 Å | O Lyα: 18.97 Å

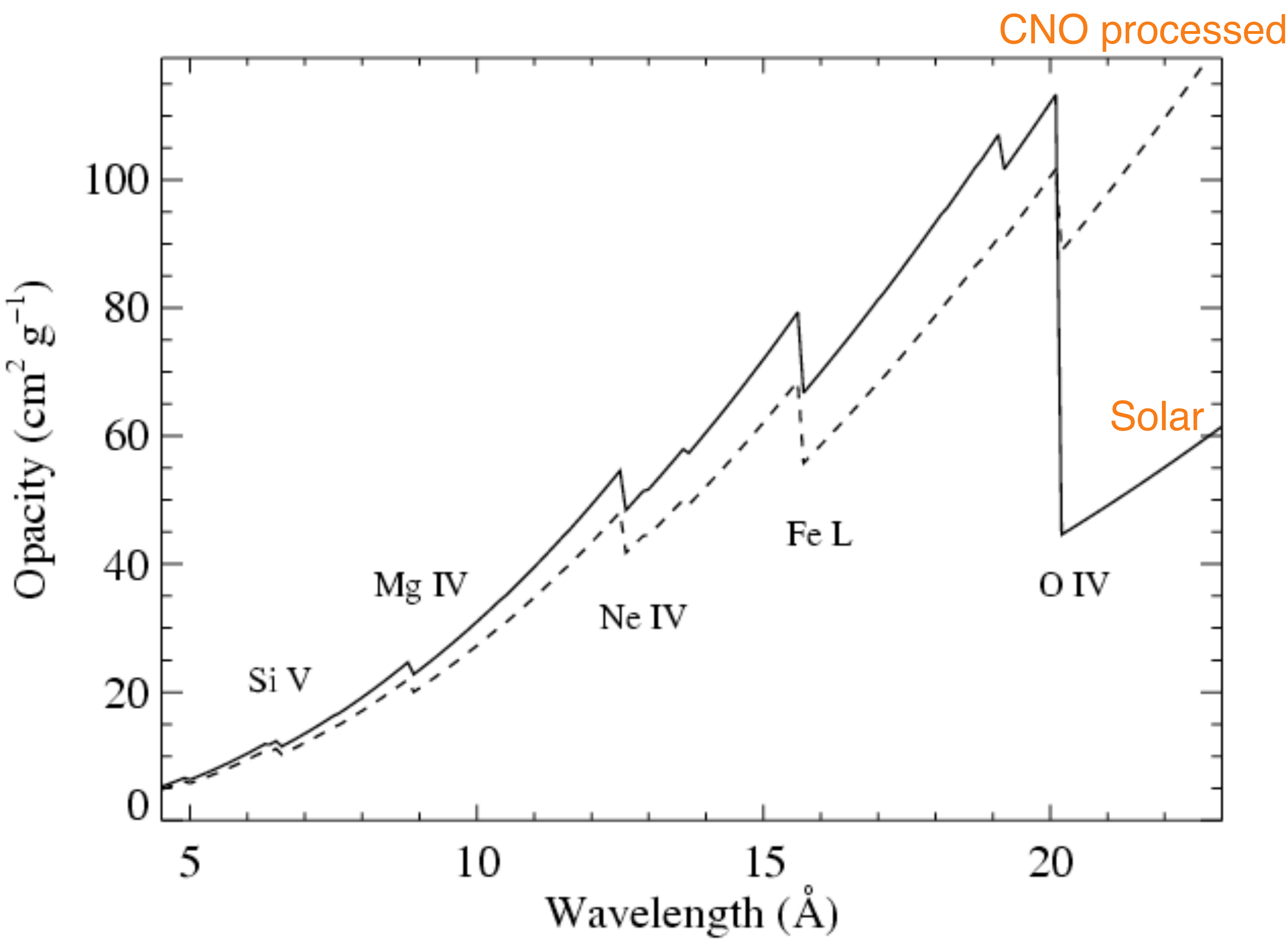


$\tau_* = 1$ | $\tau_* = 2$ | $\tau_* = 3$

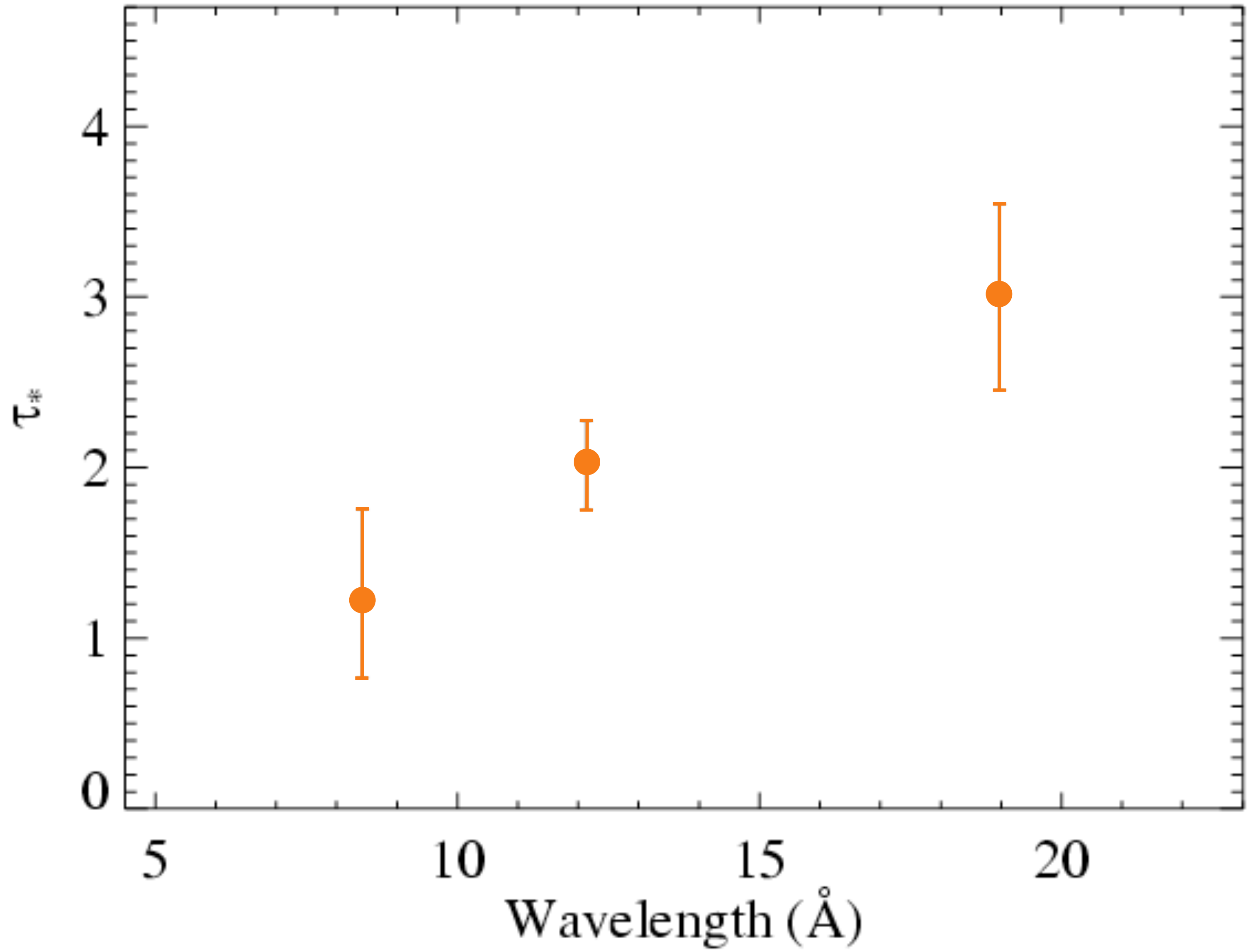
Recall:

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

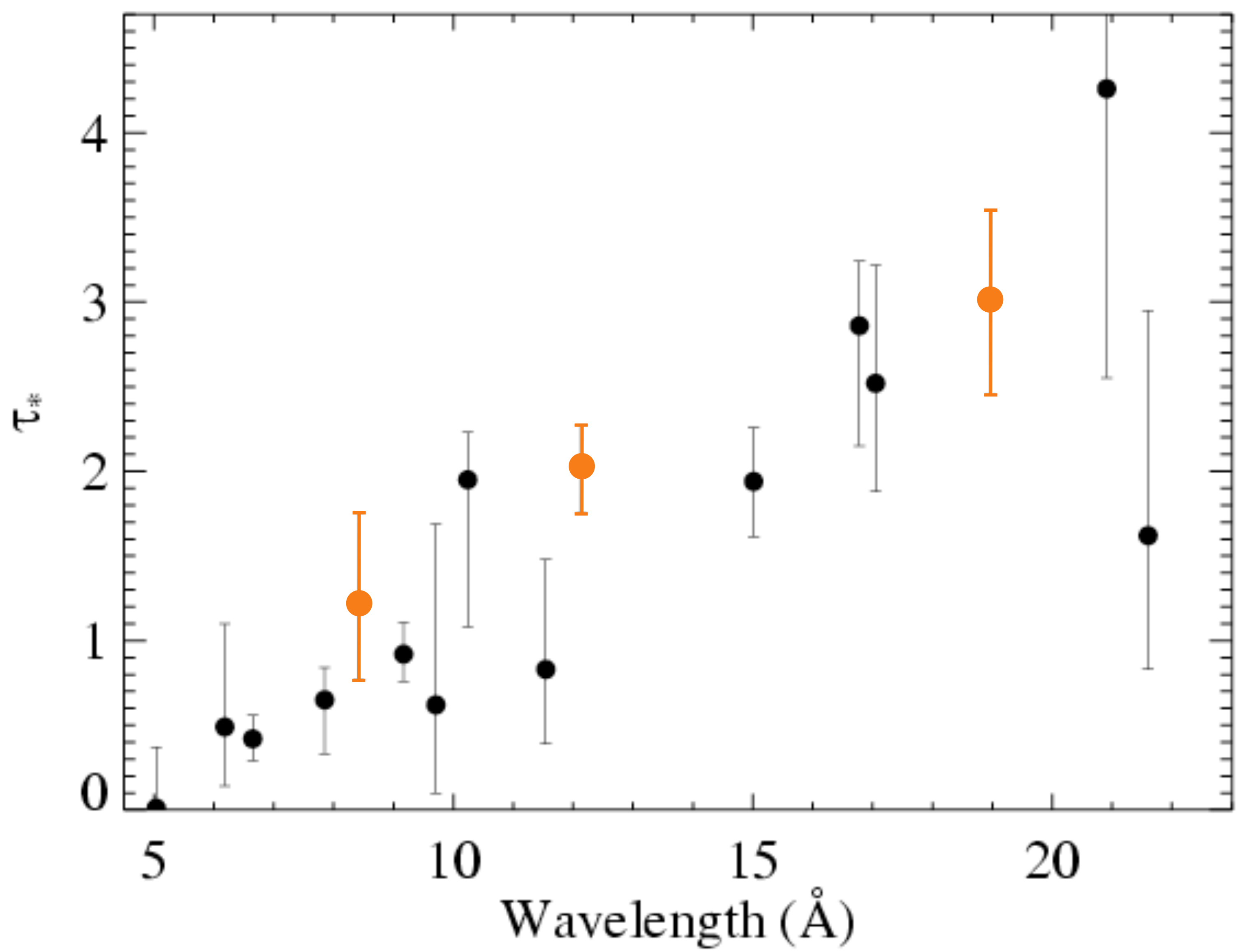
atomic opacity of the wind



Results from the 3 line fits shown previously



Fits to 16 lines in the *Chandra* spectrum of ζ Pup



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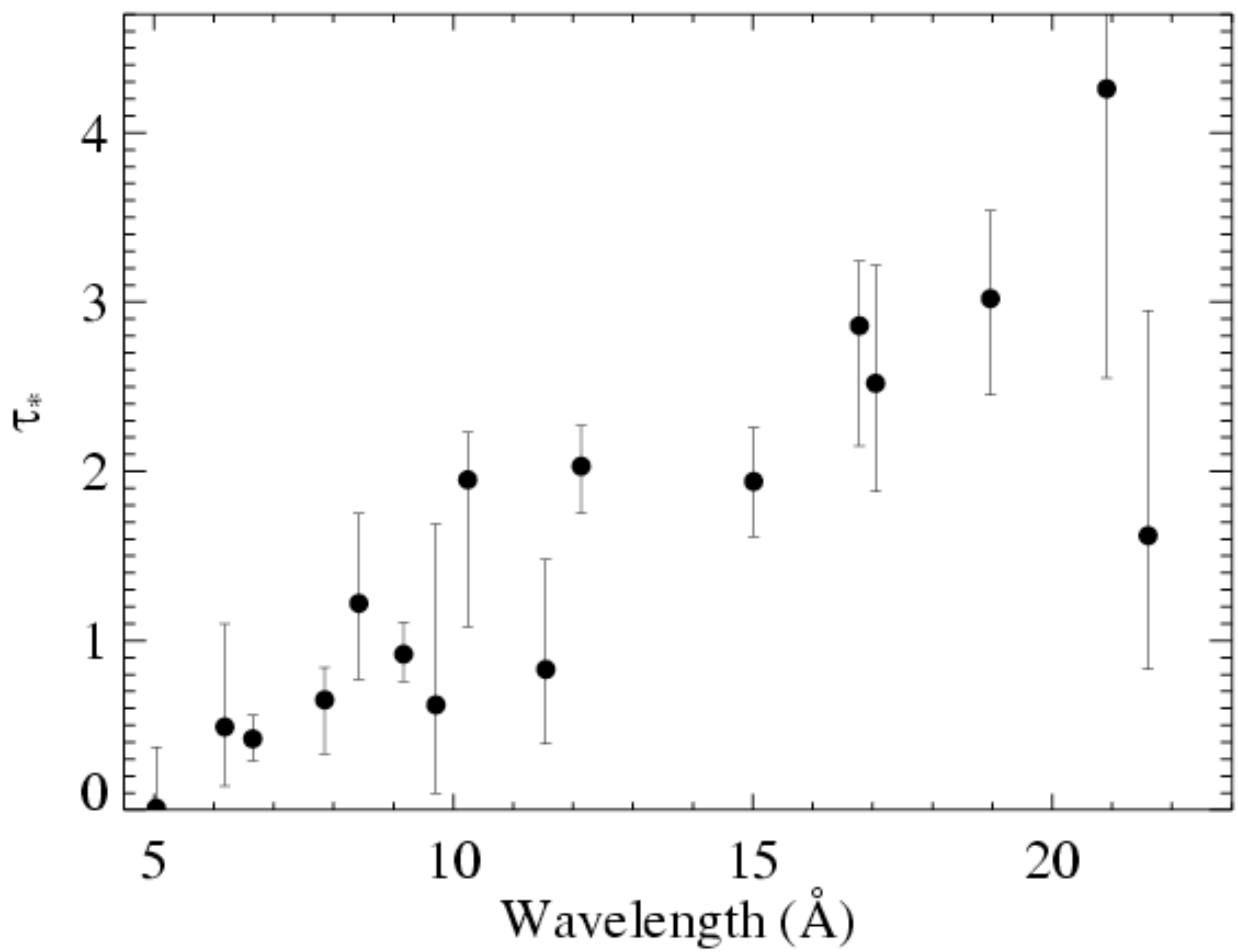
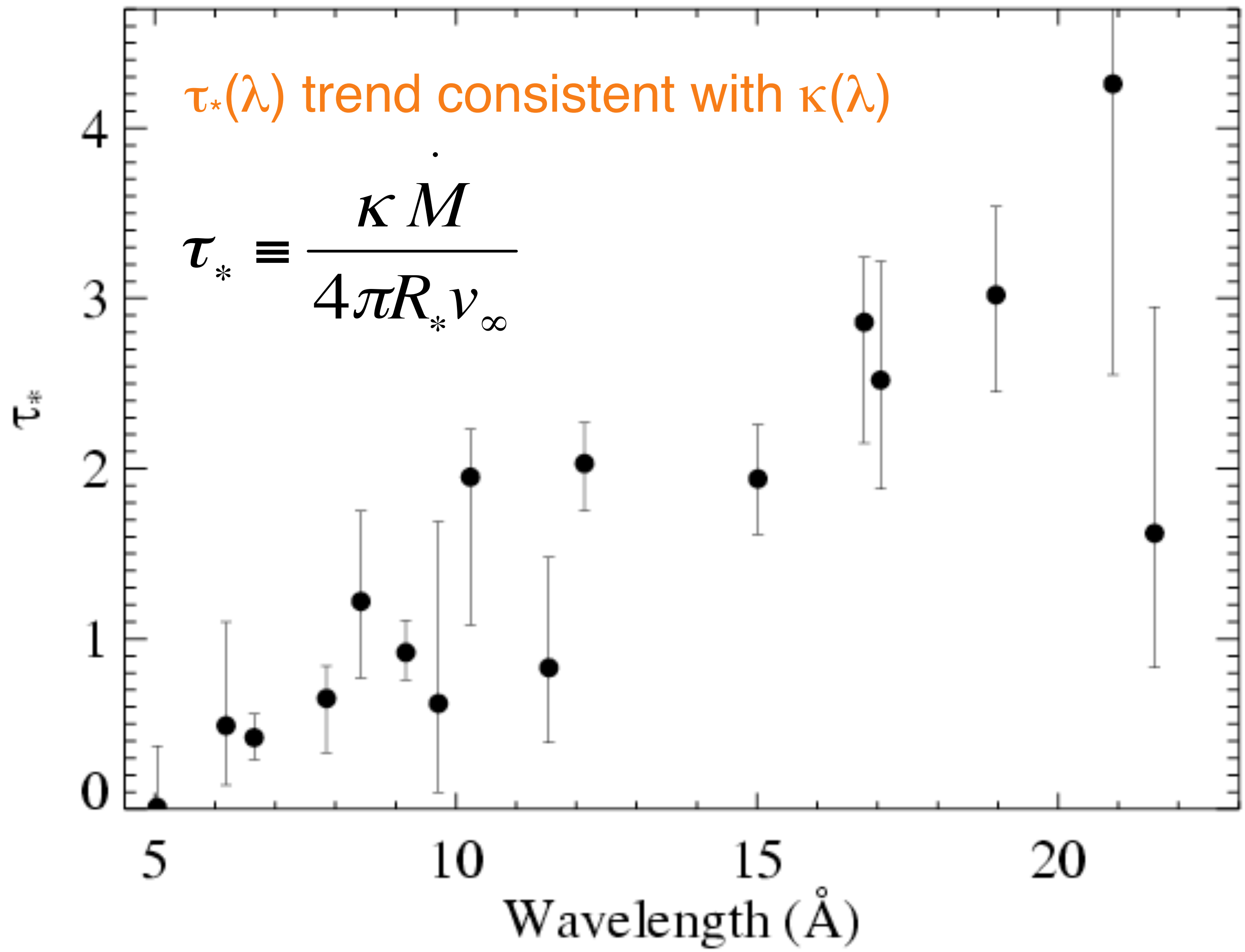
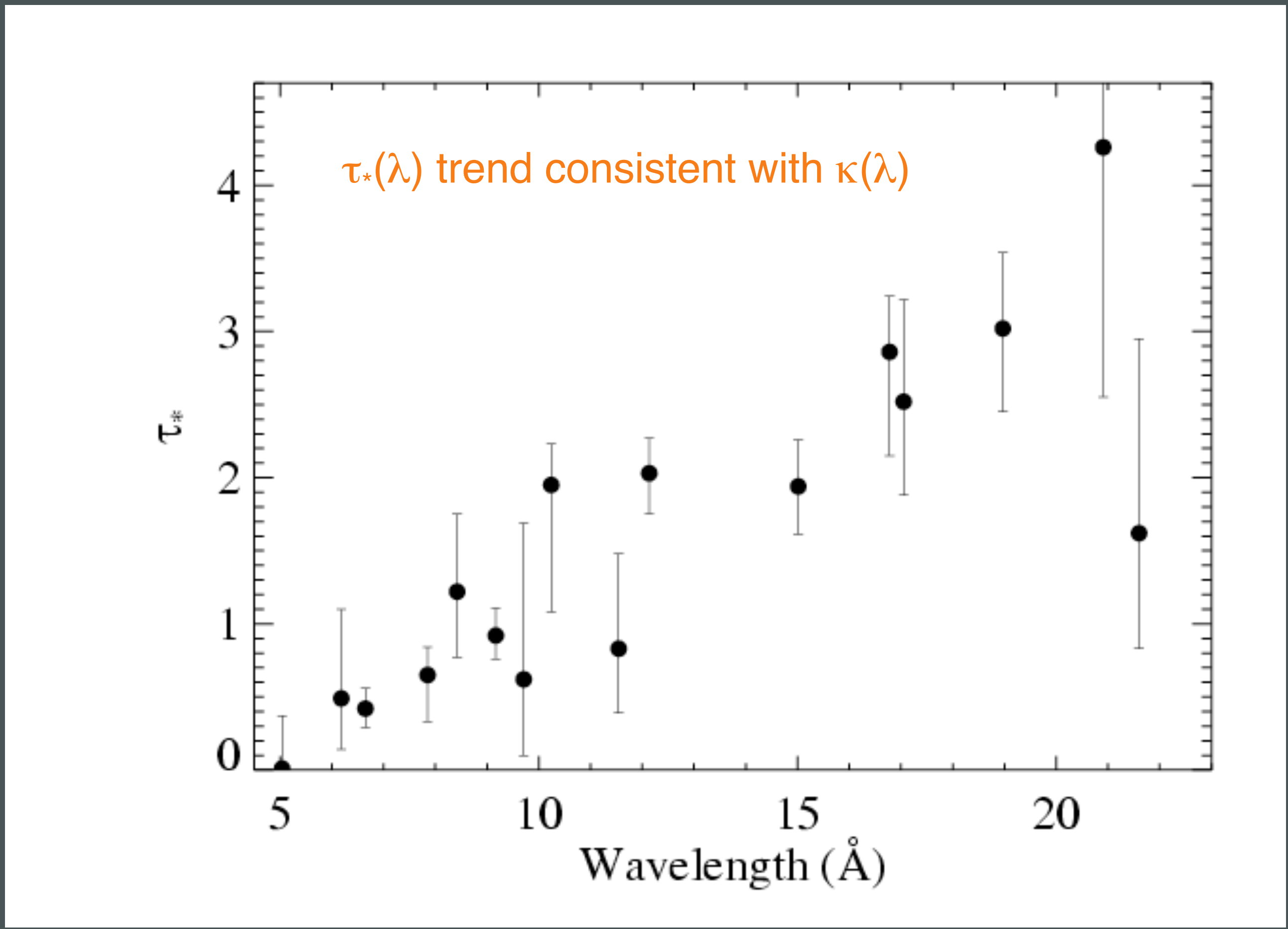


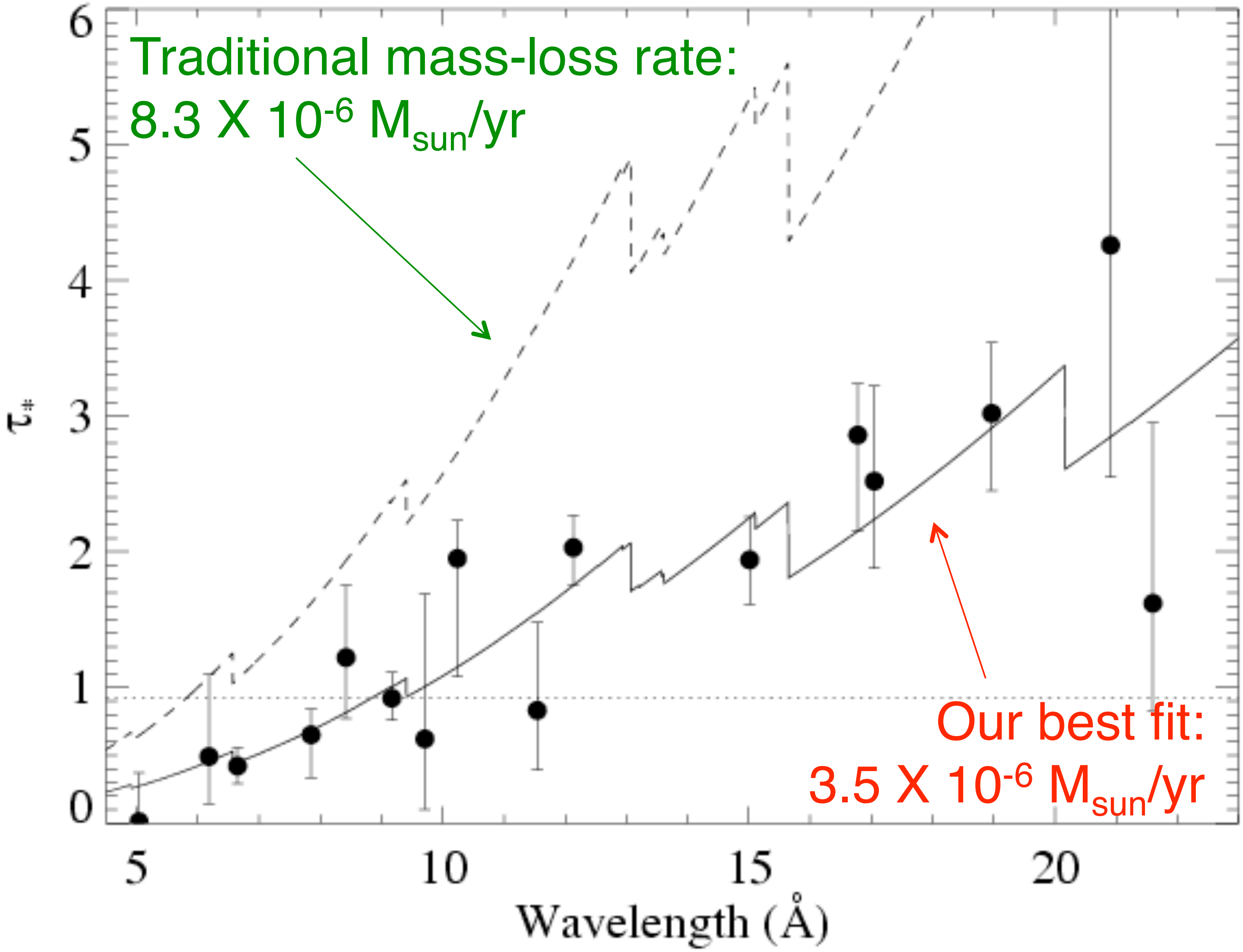
Fits to 16 lines in the *Chandra* spectrum of ζ Pup



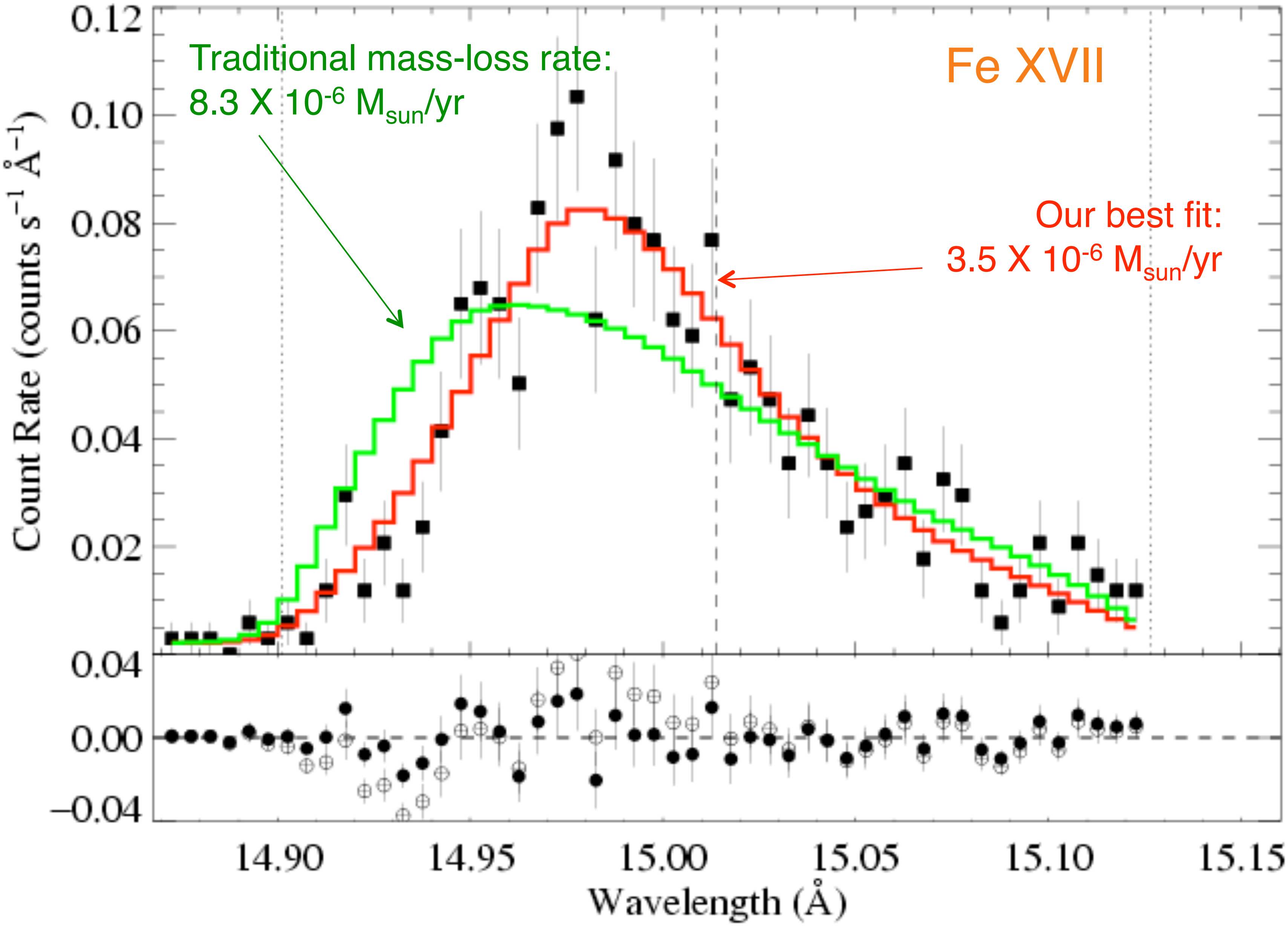
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

$\dot{M}$ becomes the free parameter of the fit to the $\tau_*(\lambda)$ trend

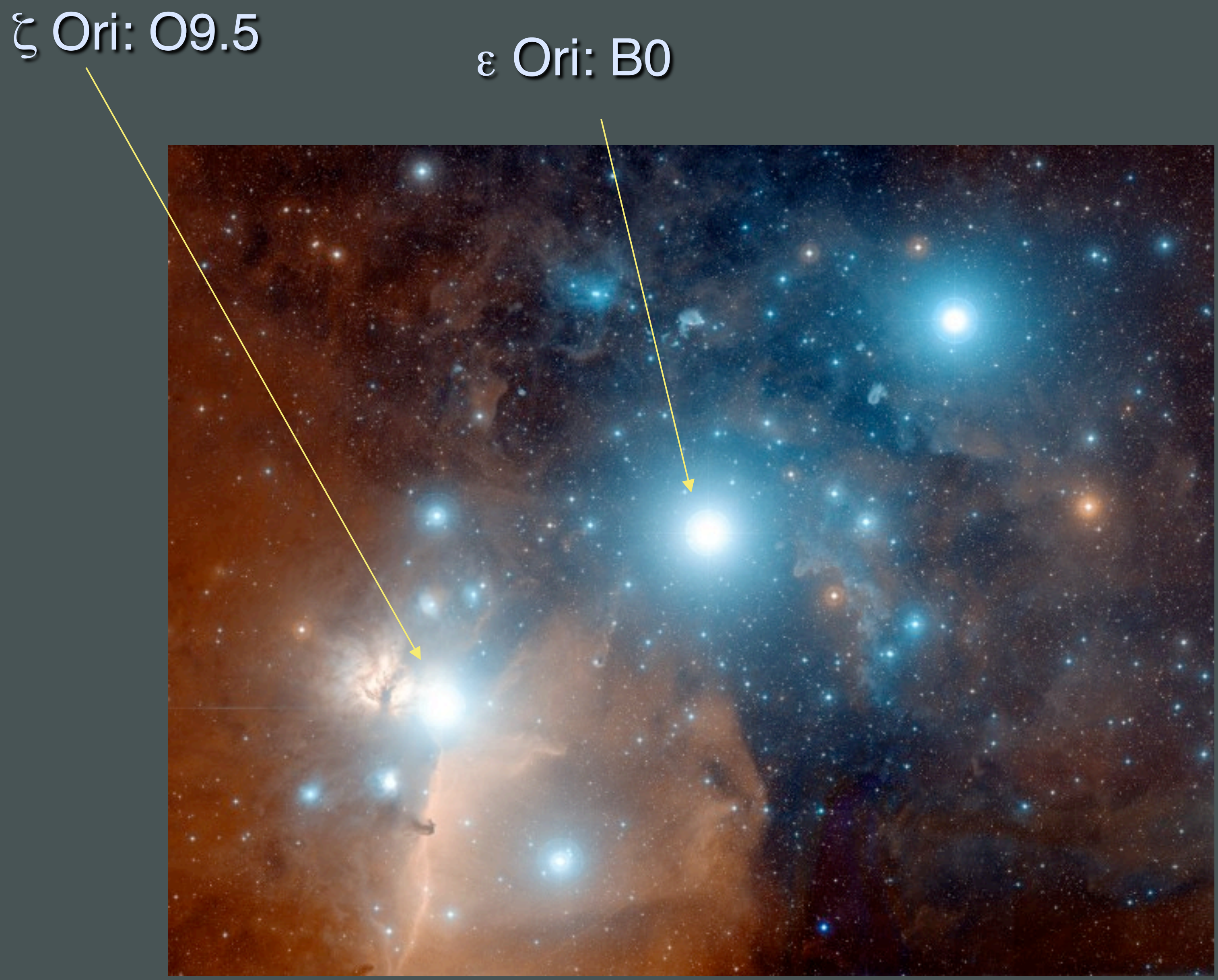




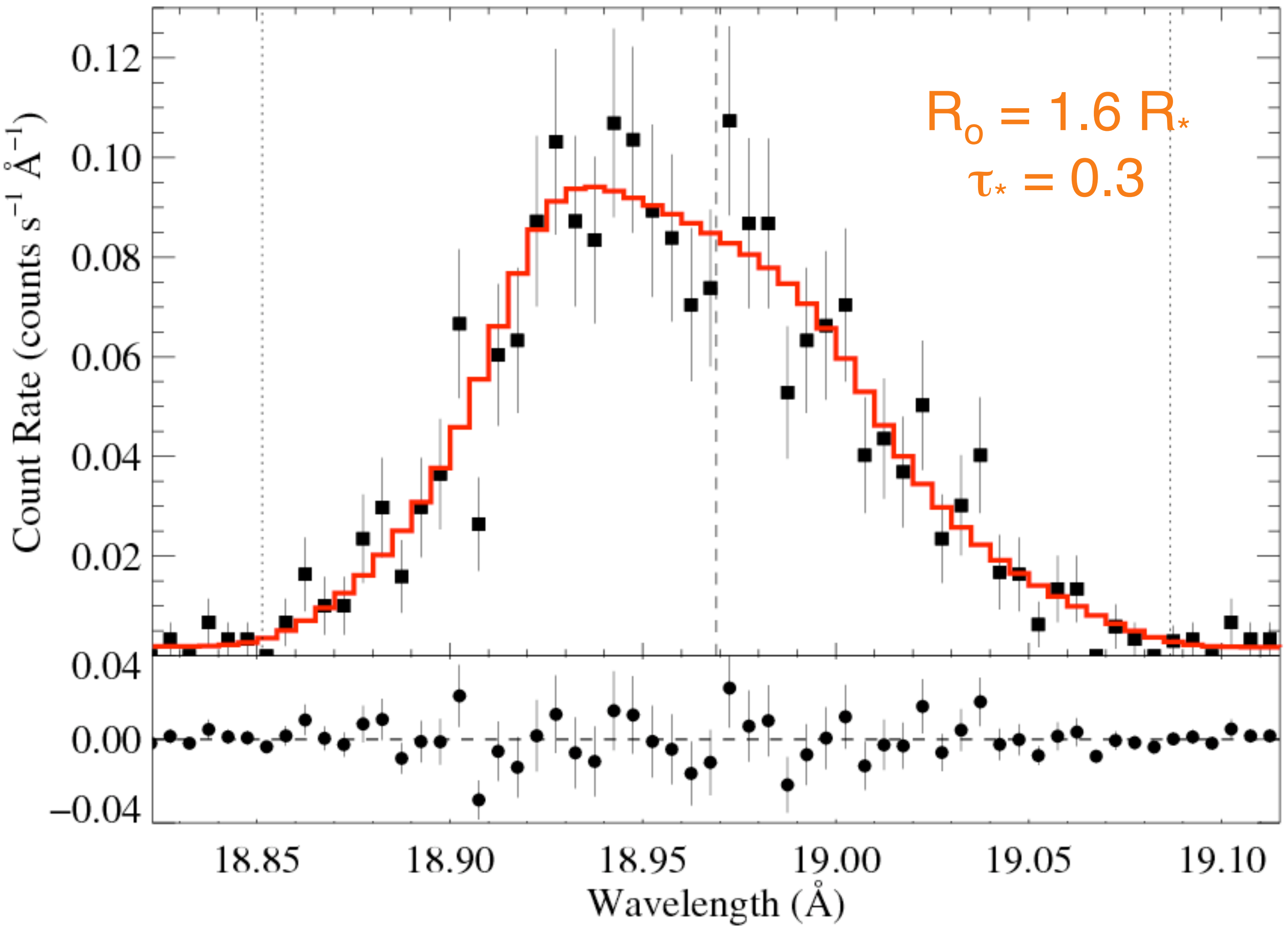
Traditional mass-loss rate:
8.3 X 10-6 Msun/yr
Our best fit:
3.5 X 10-6 Msun/yr
τ*
Wavelength (Å)
0
1
2
3
4
5
6
5
10
15
20



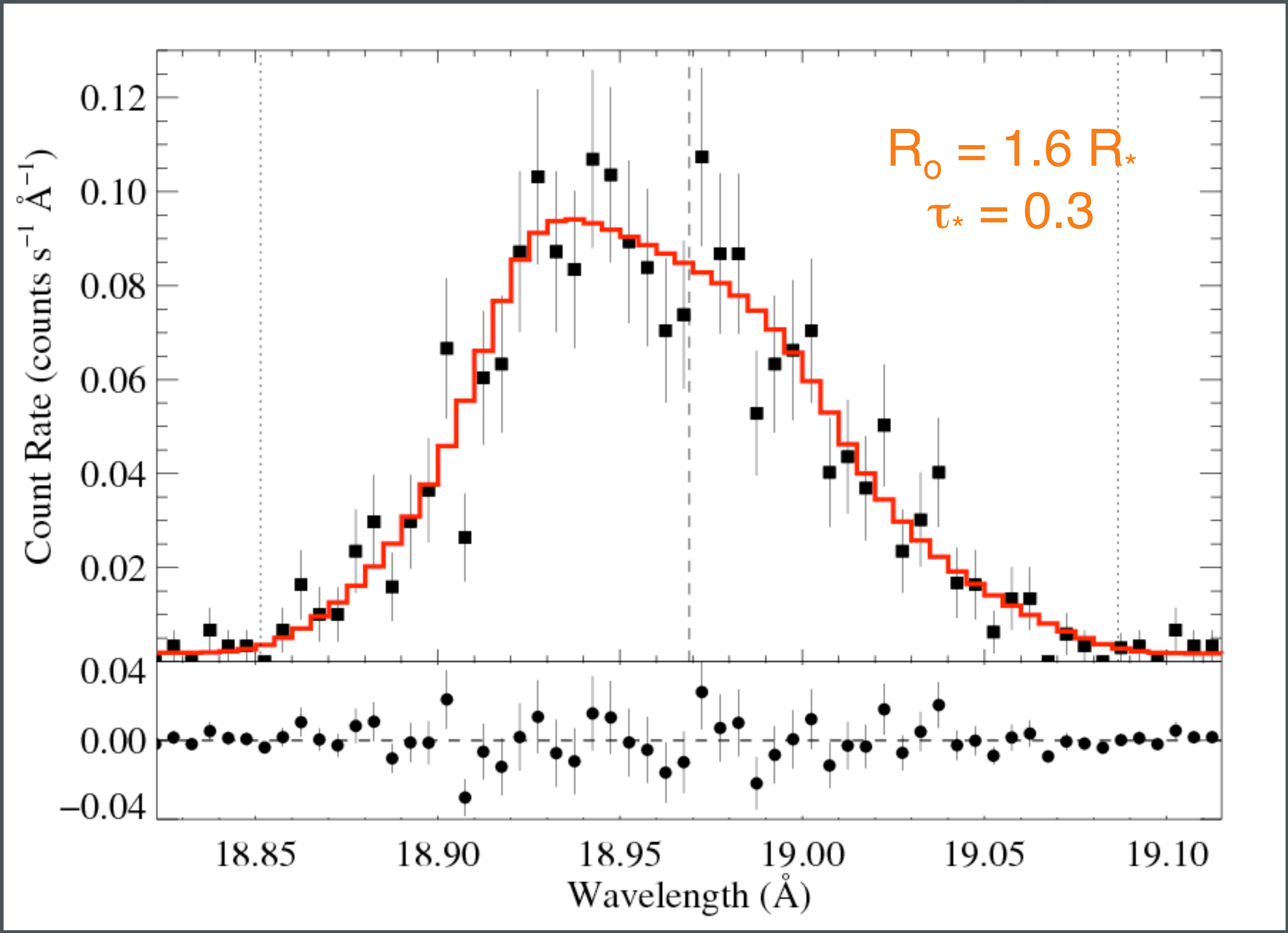
Traditional mass-loss rate:
8.3 X 10-6 Msun/yr
Fe XVII
Our best fit:
3.5 X 10-6 Msun/yr
Count Rate (counts s−1 Å−1)
0.12
0.10
0.08
0.06
0.04
0.02
0.04
0.00
−0.04
14.90
14.95
15.00
15.05
15.10
15.15
Wavelength (Å)


ζ Ori: O9.5
ε Ori: B0

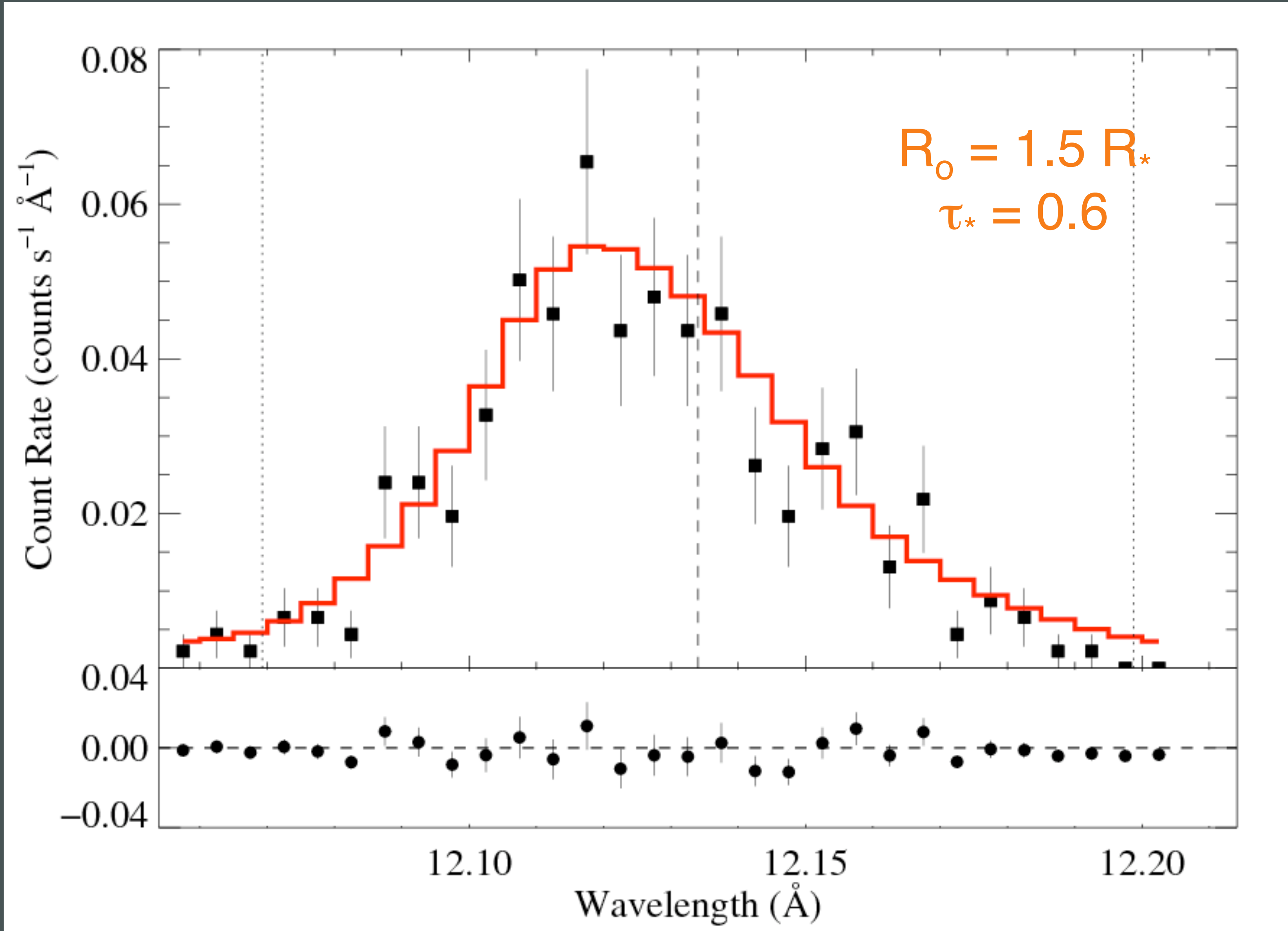
ζ Ori (O9.7 I): O Lyα 18.97 Å



τ* quite low: is resonance scattering affecting this line? - Next talk, by M. Leutenegger



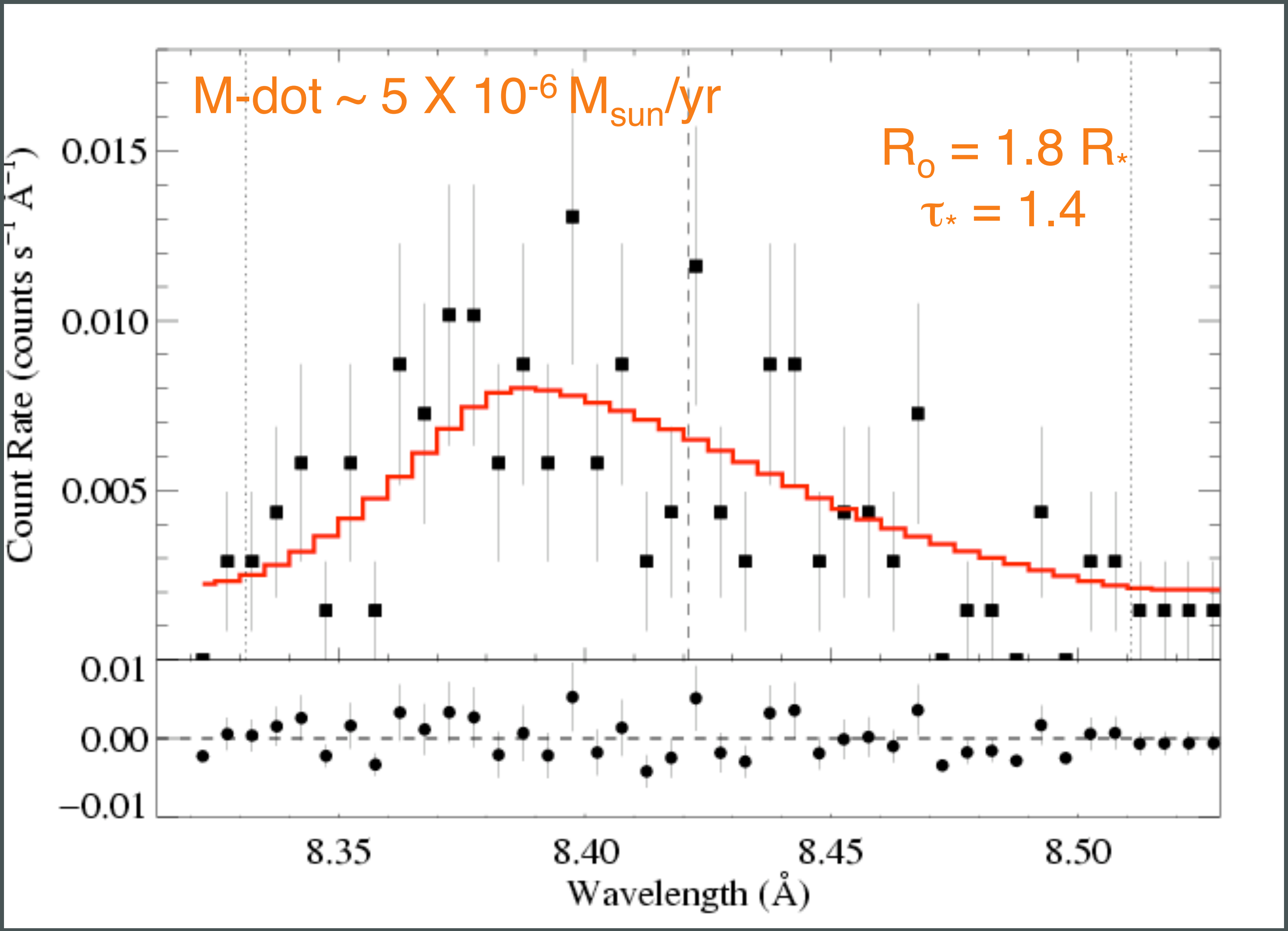
ε Ori (B0 Ia): Ne Lyα 12.13 Å



M-dot ~ 2 X 10^{-5} M_{sun}/yr

HD 93129Aab (O2.5): Mg XII Lyα 8.42 Å

V_{inf} ~ 3200 km/s



Multi-wavelength evidence for lower mass-loss rates is emerging

The Astrophysical Journal, 637:1025–1039, 2006 February 1

THE DISCORDANCE OF MASS-LOSS ESTIMATES FOR GALACTIC O-TYPE STARS

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ABSTRACT

We have determined accurate values of the product of the mass-loss rate and the ion fraction of P^{+4}, $\dot{M}q(P^{+4})$, for a sample of 40 Galactic O-type stars by fitting stellar wind profiles to observations of the P v resonance doublet obtained with *FUSE*, *ORFEUS* BEFS, and *Copernicus*. When P^{+4} is the dominant ion in the wind [i.e., $0.5 \lesssim q(P^{+4}) \leq 1$], $\dot{M}q(P^{+4})$ approximates the mass-loss rate to within a factor of $\lesssim 2$. Theory predicts that P^{+4} is the dominant ion in the winds of O7–O9.7 stars, although an empirical estimator suggests that the range O4–O7 may be more appropriate. However, we find that the mass-loss rates obtained from P v wind profiles are systematically smaller than those obtained from fits to Hα emission profiles or radio free-free emission by median factors of $\sim$130 (if P^{+4} is dominant between O7 and O9.7) or $\sim$20 (if P^{+4} is dominant between O4 and O7). These discordant measurements can be reconciled if the winds of O stars in the relevant temperature range are strongly clumped on small spatial scales. We use a simplified two-component model to investigate the volume filling factors of the denser regions. This clumping implies that mass-loss rates determined from "ρ^2" diagnostics have been systematically overestimated by factors of 10 or more, at least for a subset of O stars. Reductions in the mass-loss rates of this size have important implications for the evolution of massive stars and quantitative estimates of the feedback that hot-star winds provide to their interstellar environments.

Subject headings: stars: early-type — stars: mass loss — stars: winds, outflows

ζ Pup mass-loss rate < 4.2 X 10^{-6} M_{sun}/yr

Bright OB stars in the Galaxy

III. Constraints on the radial stratification of the clumping factor in hot star winds from a combined H_α, IR and radio analysis*

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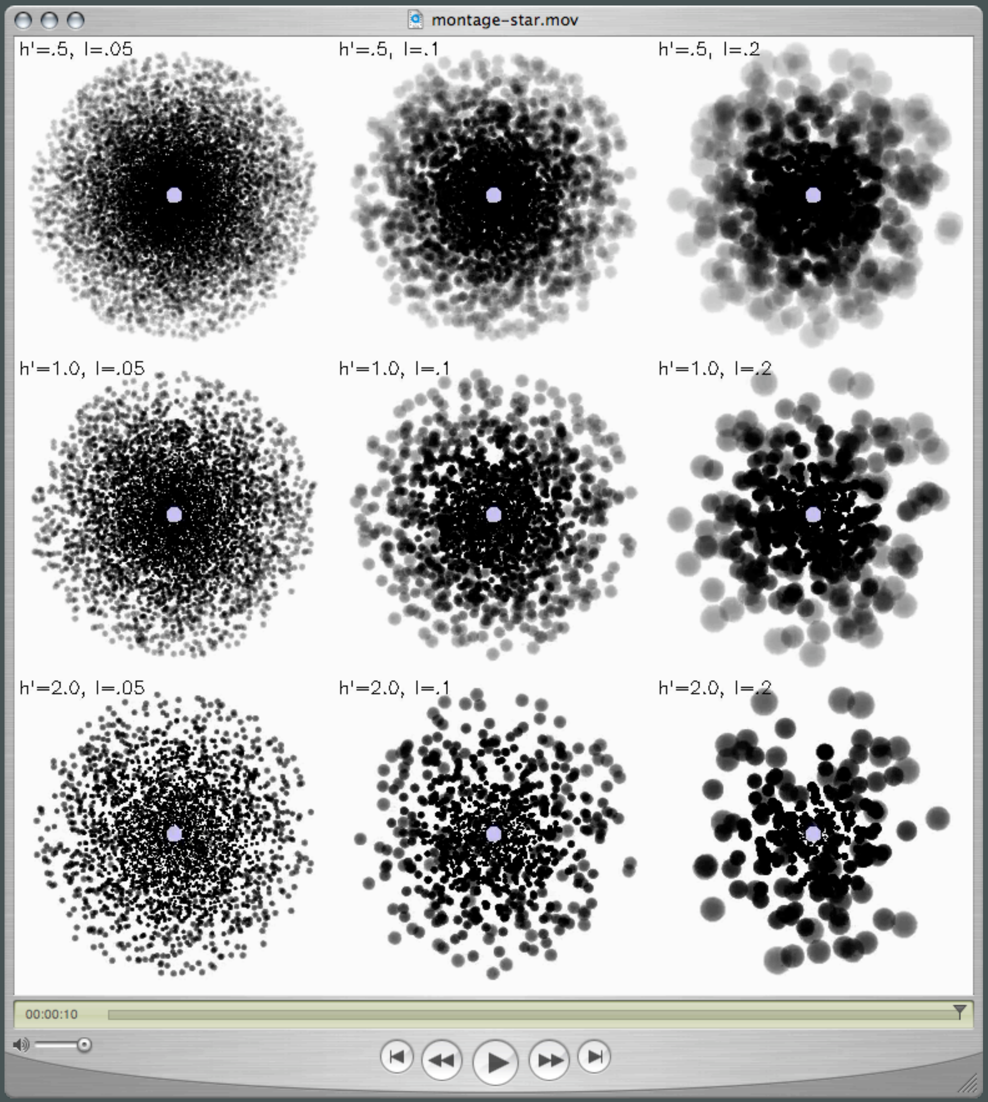
Received; accepted

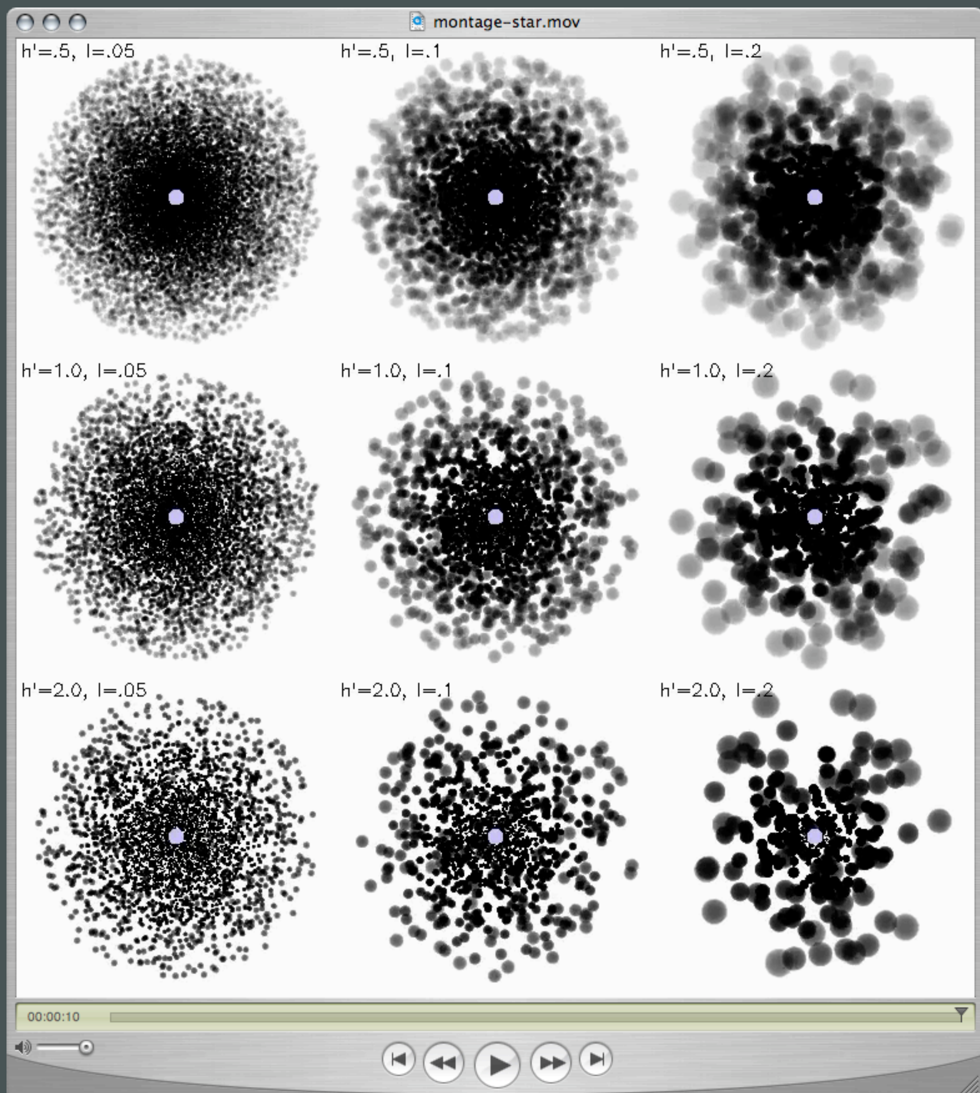
Abstract. Recent results strongly challenge the canonical picture of massive star winds: various evidence indicates that currently accepted mass-loss rates, $\dot{M}$, may need to be revised downwards, by factors extending to one magnitude or even more. This is because the most commonly used mass-loss diagnostics are affected by "clumping" (small-scale density inhomogeneities), influencing our interpretation of observed spectra and fluxes.
Such downward revisions would have dramatic consequences for the evolution of, and feedback from, massive stars, and thus robust determinations of the clumping properties and mass-loss rates are urgently needed. We present a first attempt concerning this objective, by means of constraining the radial stratification of the so-called clumping factor.
To this end, we have analyzed a sample of 19 Galactic O-type supergiants/giants, by combining our own and archival data for H_α, IR, mm and radio fluxes, and using approximate methods, calibrated to more sophisticated models. Clumping has been included into our analysis in the "conventional" way, by assuming the inter-clump matter to be void. Because (almost) all our diagnostics depends on the square of density, we cannot derive absolute clumping factors, but only factors normalized to a certain minimum.
This minimum was usually found to be located in the outermost, radio-emitting region, i.e., the radio mass-loss rates are the lowest ones, compared to $\dot{M}$ derived from H_α and the IR. The radio rates agree well with those predicted by theory, but are only upper limits, due to unknown clumping in the outer wind. H_α turned out to be a useful tool to derive the clumping properties inside $r < 3\ldots5\,R_\star$. Our most important result concerns a (physical) difference between denser and thinner winds: for denser winds, the innermost region is more strongly clumped than the outermost one (with a normalized clumping factor of 4.1 ± 1.4), whereas thinner winds have similar clumping properties in the inner and outer regions.
Our findings are compared with theoretical predictions, and the implications are discussed in detail, by assuming different scenarios regarding the still unknown clumping properties of the outer wind.

“Clumping” – or micro-clumping: affects density-squared diagnostics; independent of clump size, just depends on clump density contrast (or filling factor, *f*)



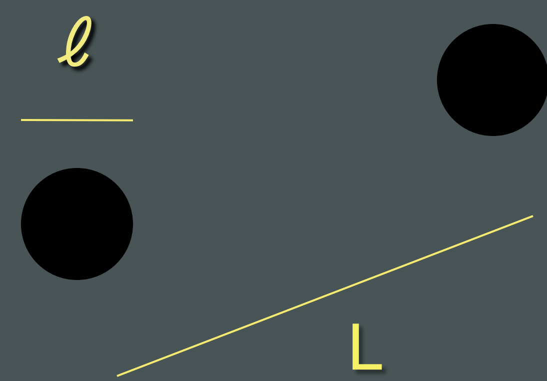
visualization: R. Townsend

But **porosity** is associated with optically thick clumps, it acts to reduce the effective opacity of the wind; it *does* depend on the size scale of the clumps



The key parameter is the **porosity length**,

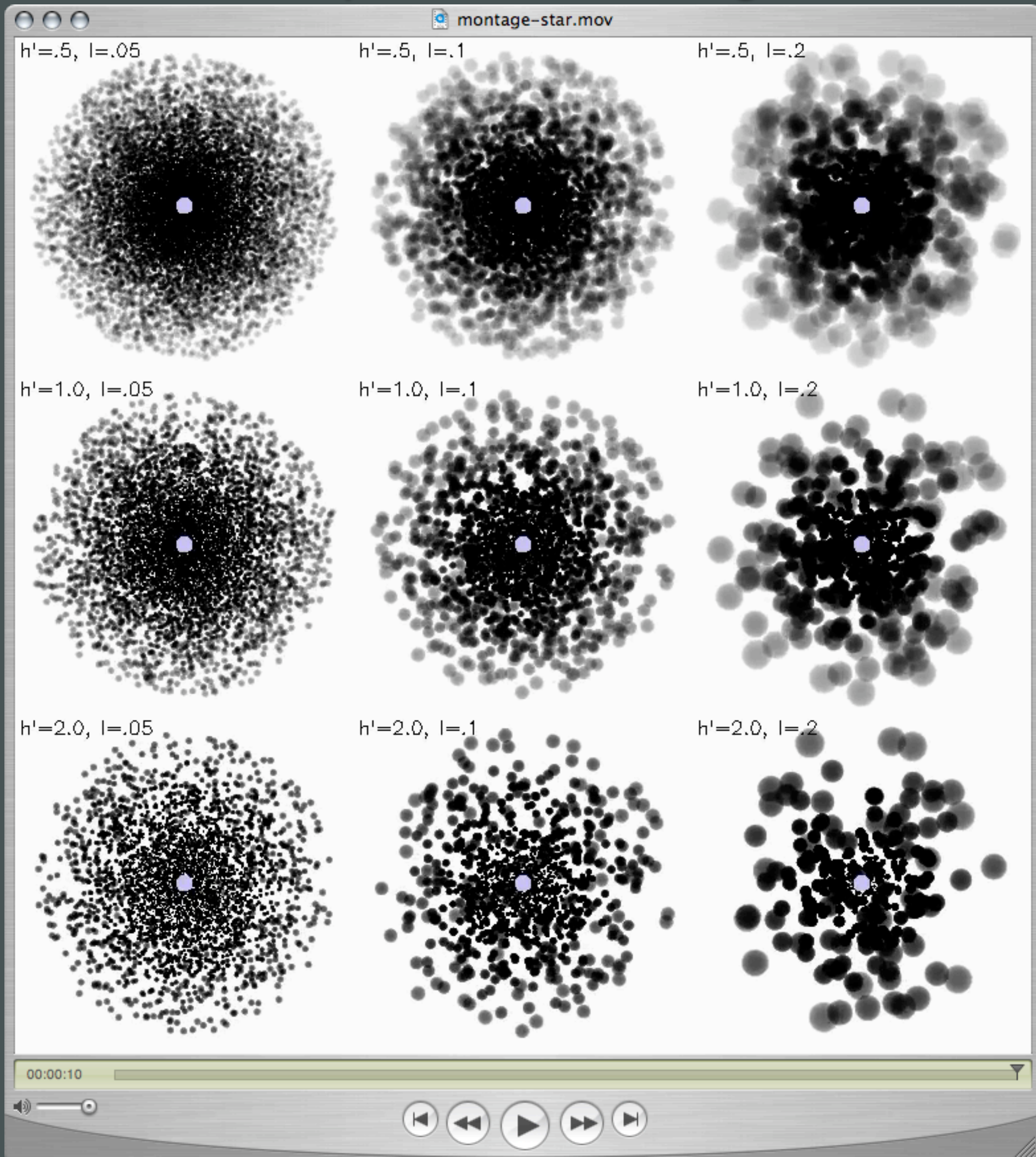
$h = (L^3/\ell^2) = \ell / f$



$f = \ell^3/L^3$

Clump size increasing →

The porosity length, *h*:



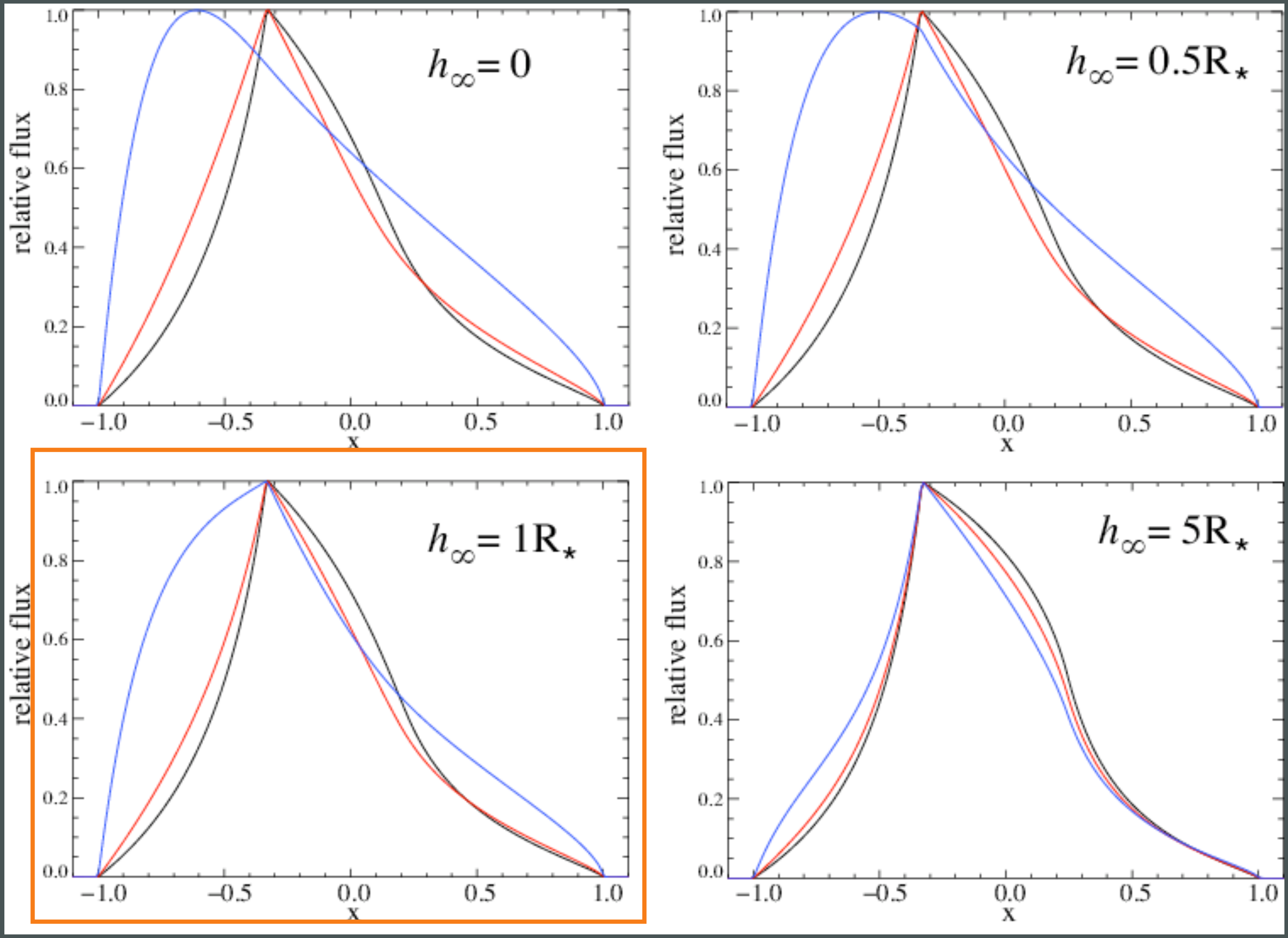
Porosity length increasing ↓

clump size

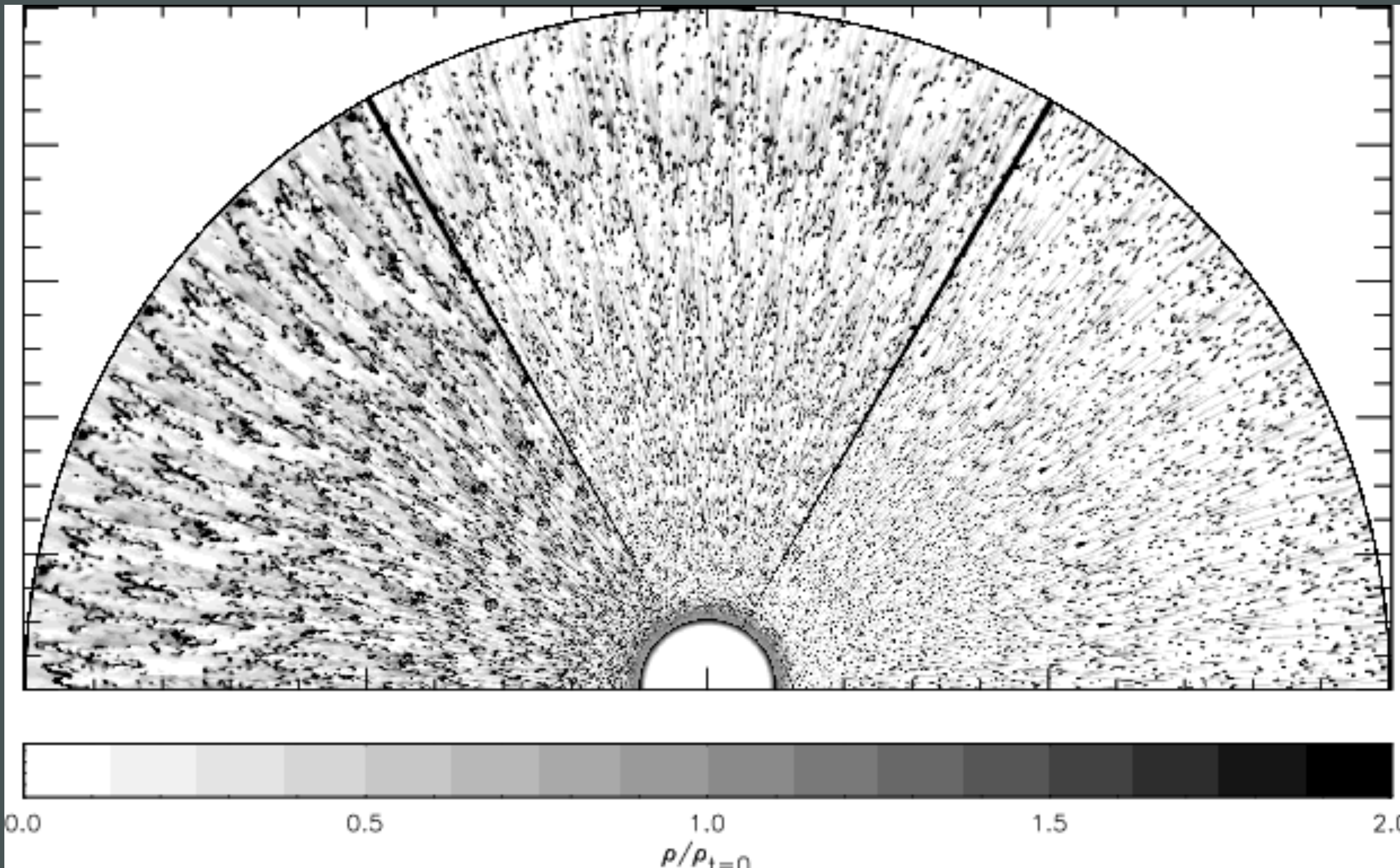
$$h = \ell / f$$

clump filling factor (<1)

Porosity only affects line profiles if the porosity length (*h*) exceeds the stellar radius



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



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

No expectation of porosity from simulations

Natural explanation of line profiles without invoking porosity

Finally, to have porosity, you need clumping in the first place, and once you have clumping…you have your factor ~3 reduction in the mass-loss rate

No expectation of porosity from simulations

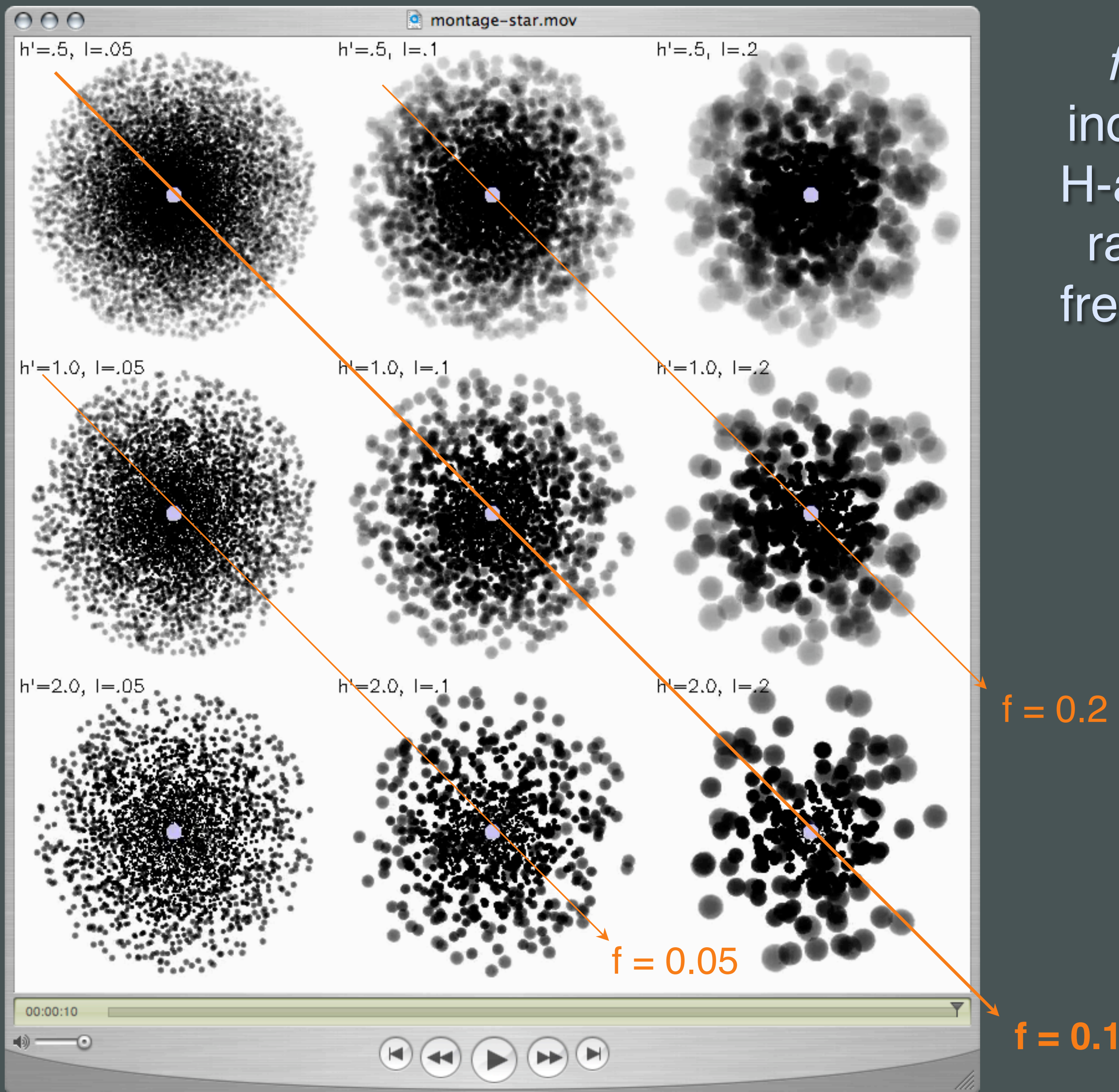
Natural explanation of line profiles without invoking porosity

Finally, to have porosity, you need clumping in the first place, and once you have clumping…you have your factor ~3 reduction in the mass-loss rate

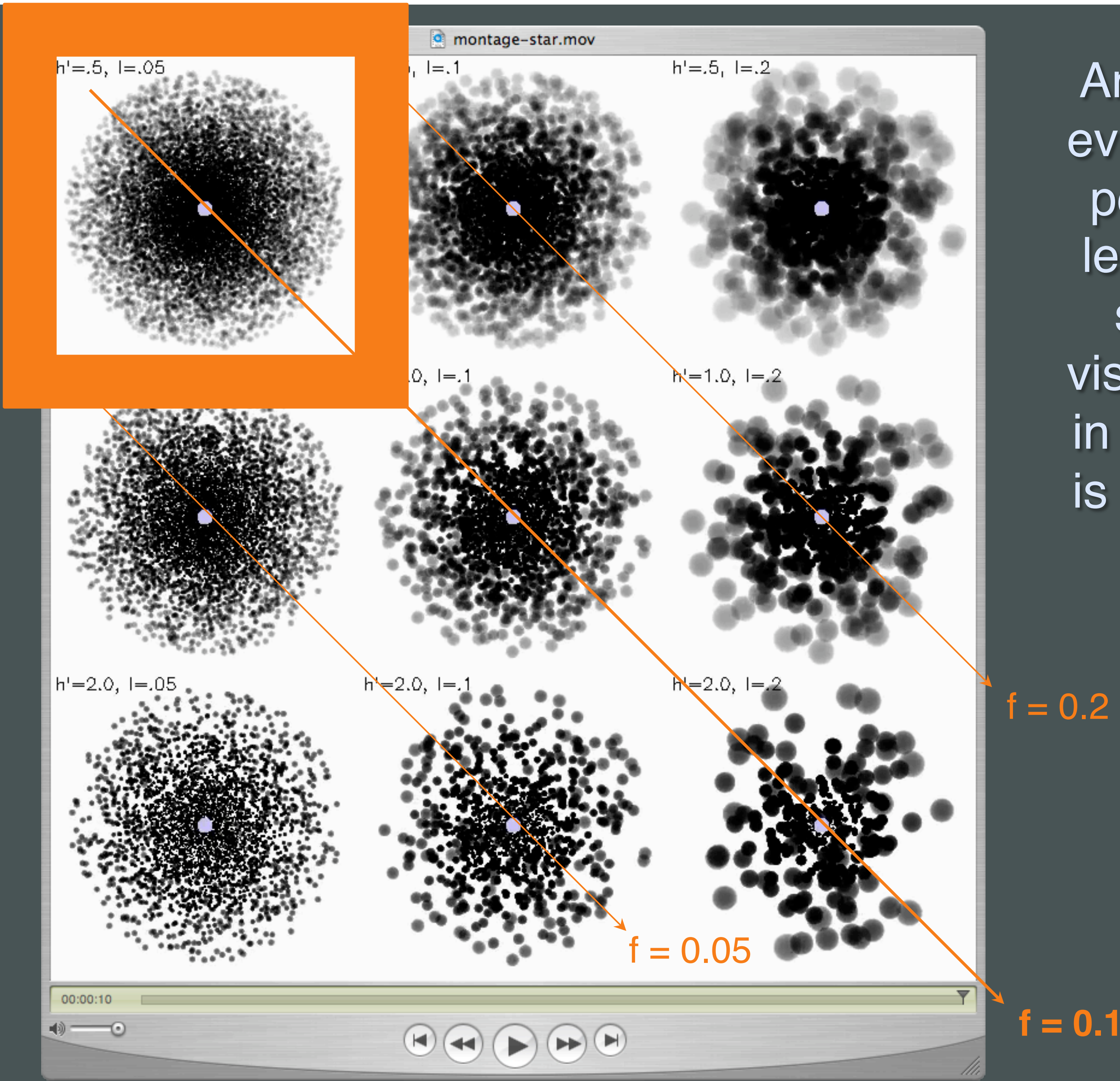
No expectation of porosity from simulations

Natural explanation of line profiles without invoking porosity

Finally, to have porosity, you need clumping in the first place, and once you have clumping…you have your factor ~3 reduction in the mass-loss rate (for ζ Pup, anyway)



f ~ 0.1 is indicated by H-alpha, UV, radio free-free analysis



And lack of evidence for porosity… leads us to suggest visualization in upper left is closest to reality

conclusions

Line widths consistent with embedded wind shocks

Skewed line shapes consistent with photoelectric absorption; magnitude and wavelength trend enable a mass-loss rate measurement

Consistent explanation for zeta Pup – $\dot{M}$ down by factor of 3, no need to invoke porosity

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Line widths consistent with embedded wind shocks

Skewed line shapes consistent with photoelectric absorption; magnitude and wavelength trend enable a mass-loss rate measurement

Consistent explanation for zeta Pup – $\dot{M}$ down by factor of 3, no need to invoke porosity