X-ray Spectral Measurements of the Most Massive Stars:
Stellar Wind Mass-Loss Rates and Shock Physics

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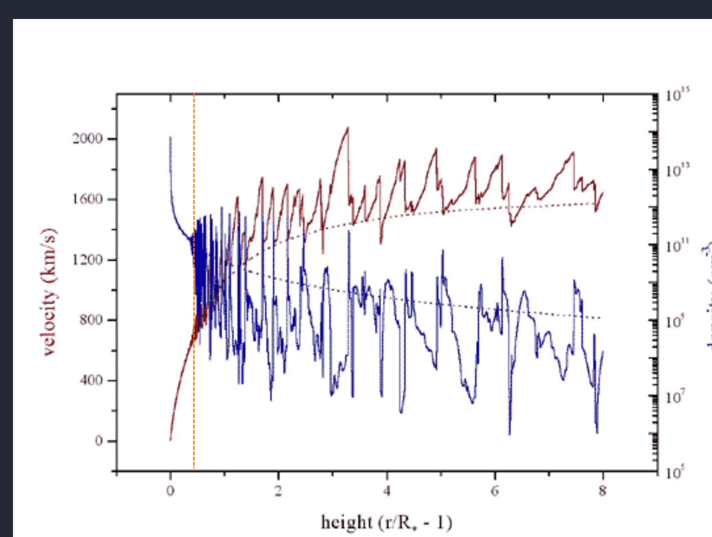
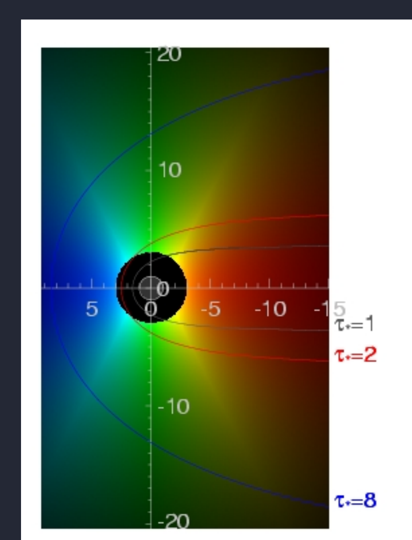
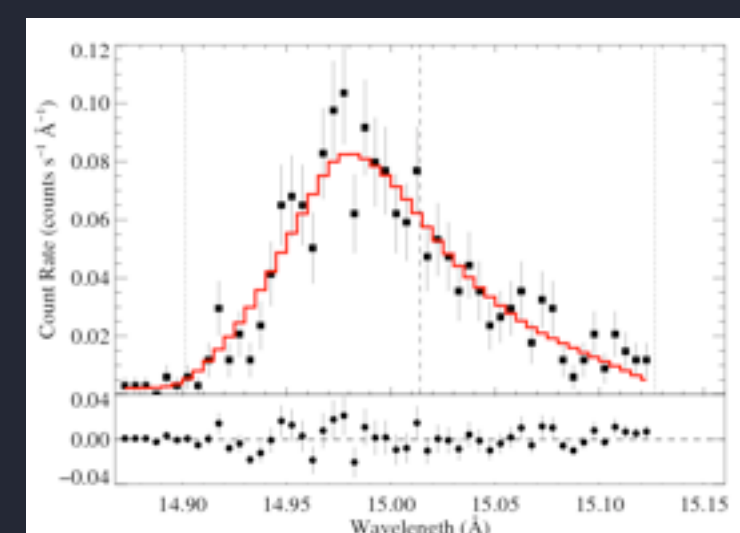






Background/Themes:

Significant technological advances in X-ray astronomy have driven discovery over the last few decades.

New spectroscopy capabilities (post-1999) allow us to infer spatial information on smaller scales than we can see in images.

I work at the intersection of observation and theory; it is a very fruitful place to work.

The priorities at Swarthmore have allowed me to do careful work on the small number of X-ray spectral datasets; and the work with students fosters a careful, pedagogical approach that can lead to discoveries that might otherwise be missed.

My research for nearly 20 years has focused on massive stars, their X-ray emission, and their winds (the site of X-ray production). From the basic question of how the X-rays are produced, I have branched out to questions of wind structure and wind mass-loss rates that the X-ray observations can address.

Orion

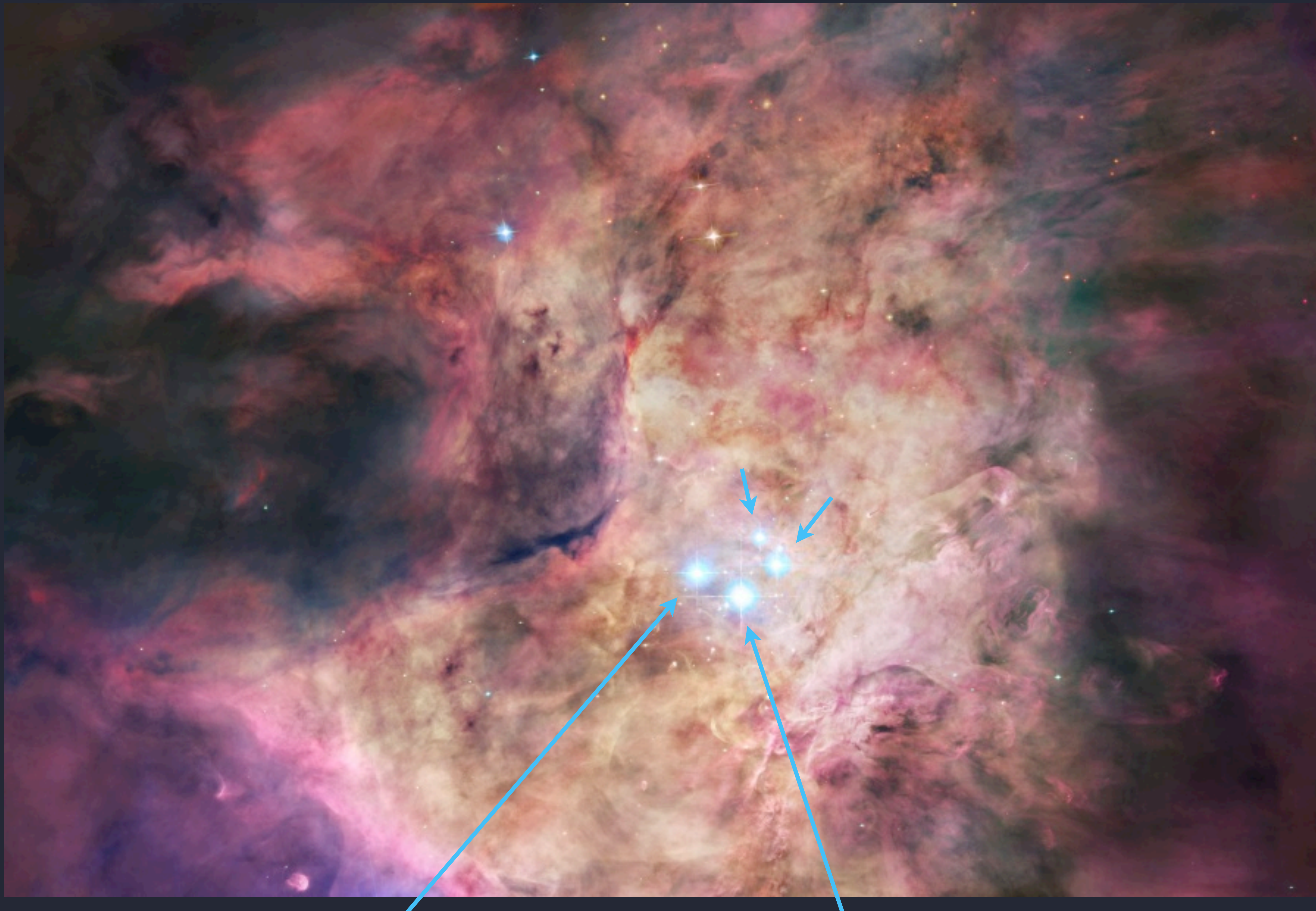
massive stars are usually hot & therefore blue

Scale nearest massive stars are ~1000 parsecs away

Whirlpool Galaxy, *Hubble Space Telescope*

Orion Nebula, *Hubble Space Telescope*

"O-type star" is the hottest stellar spectral classification



θ[1] Ori C: only O star here

Basic properties of O stars

mass ~ 50 M_{sun}
luminosity ~ 10^6 L_{sun}
surface temperature ~ 45,000 K

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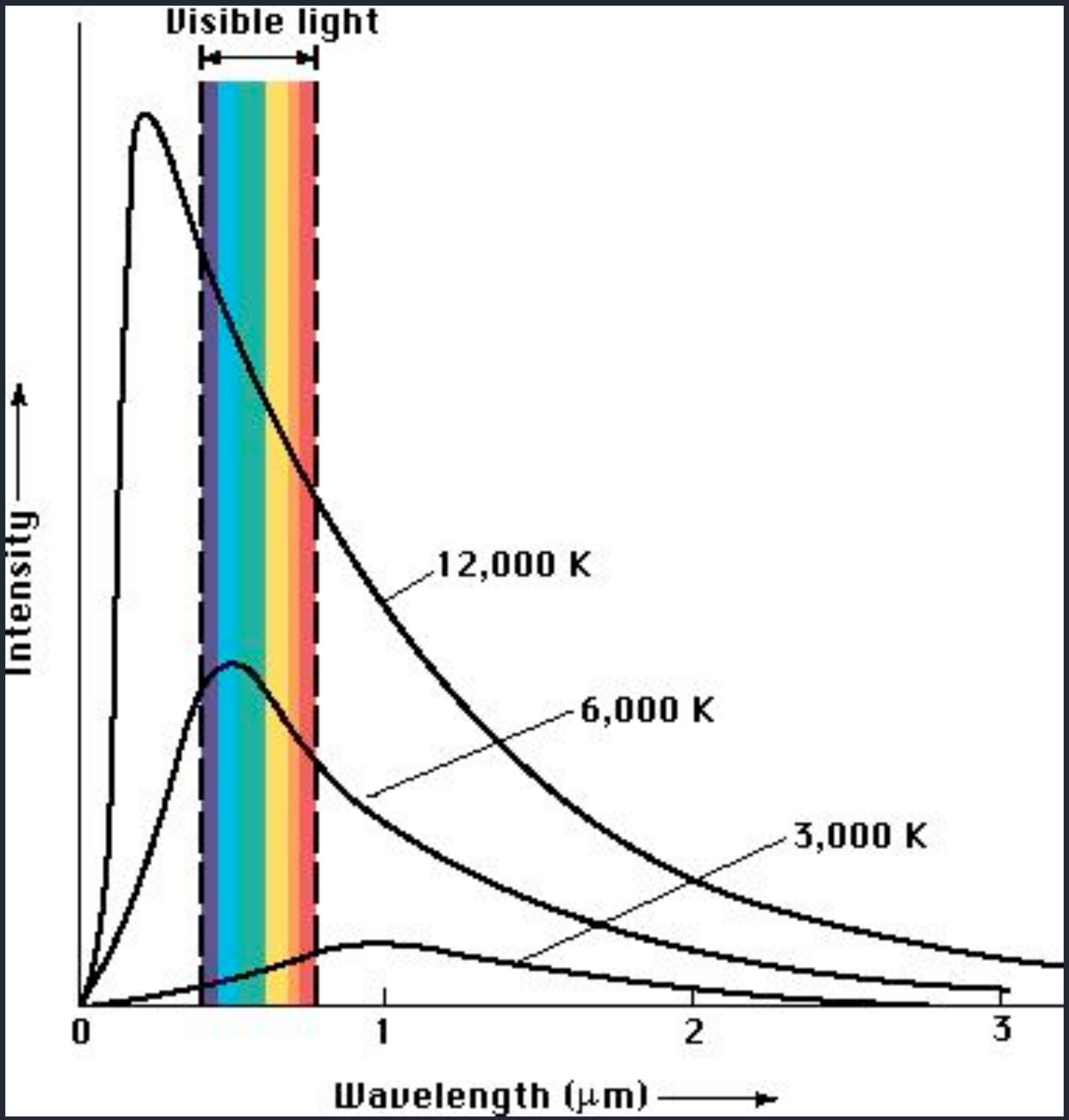
Blackbody spectra



above T ~ 10,000 K
most of a star's
emission is in the UV

O stars are even more
extreme: T > 30,000 K

Basic properties of O stars

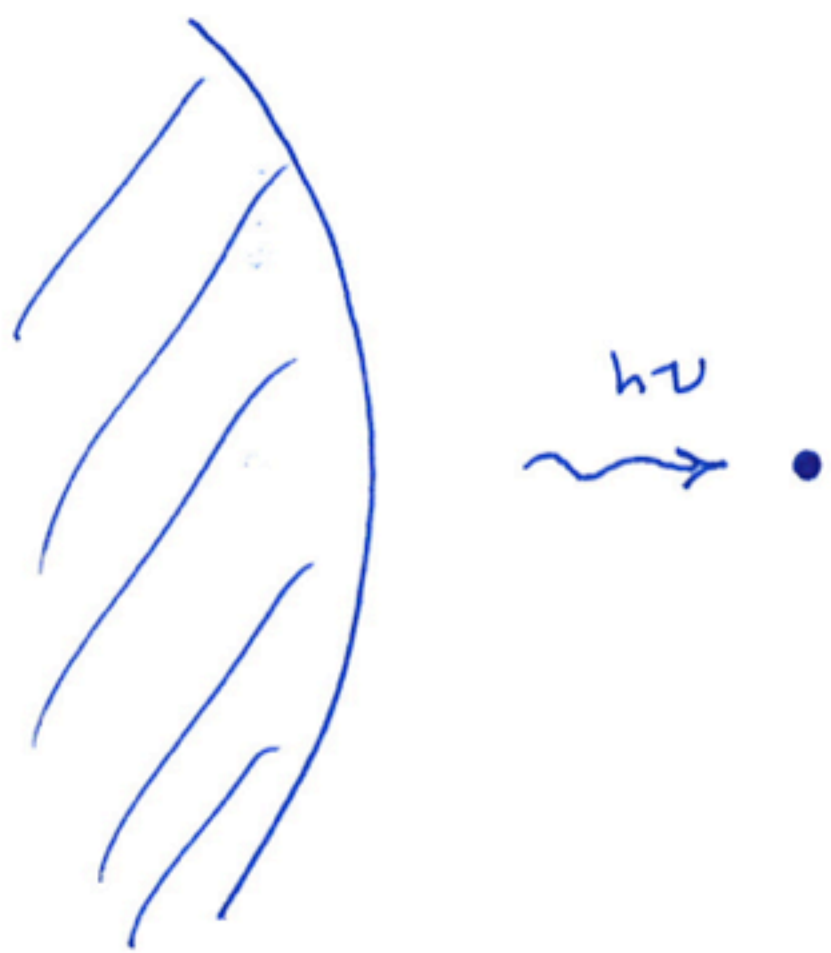
mass ~ 50 M_{sun}
luminosity ~ 10^6 L_{sun}
surface temperature ~ 45,000 K

*significant **momentum** in the photospheric radiation field*

Strong, *radiation-driven* stellar winds are a characteristic of massive stars

NGC 6888 Crescent Nebula - Tony Hallas

Radiation Force on an atom



$h\nu$ (energy)

$\frac{h\nu}{c}$ (momentum, p)

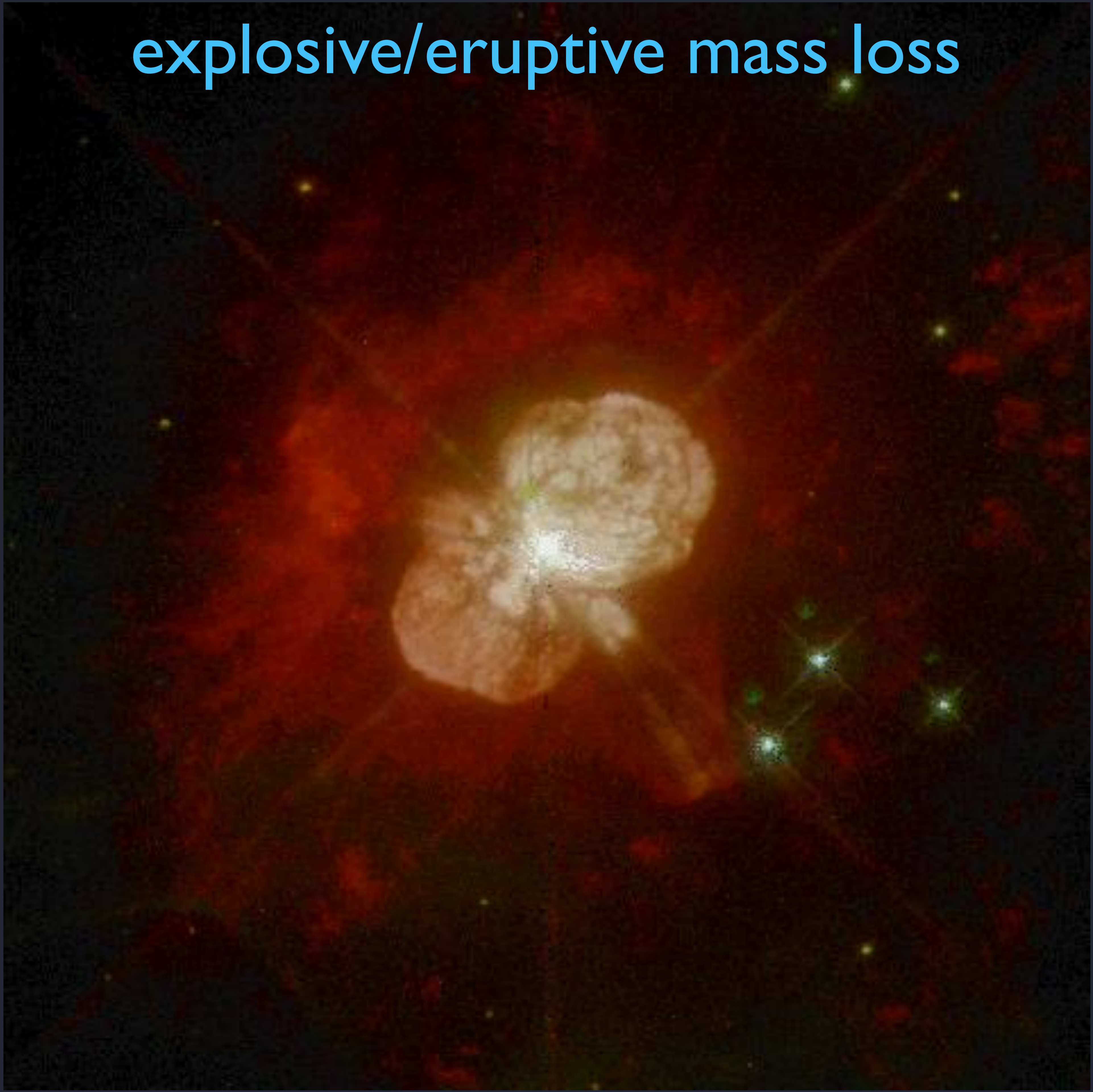
rate at which atom absorbs momentum $\frac{dp}{dt} = F_{rad}$

$$F_{rad} = \frac{L\sigma}{4\pi r^2 c}$$

L: luminosity, star's power output (watts)

σ: absorption cross section of atom (m^2)

explosive/eruptive mass loss



eta Carinae: Hubble Space Telescope

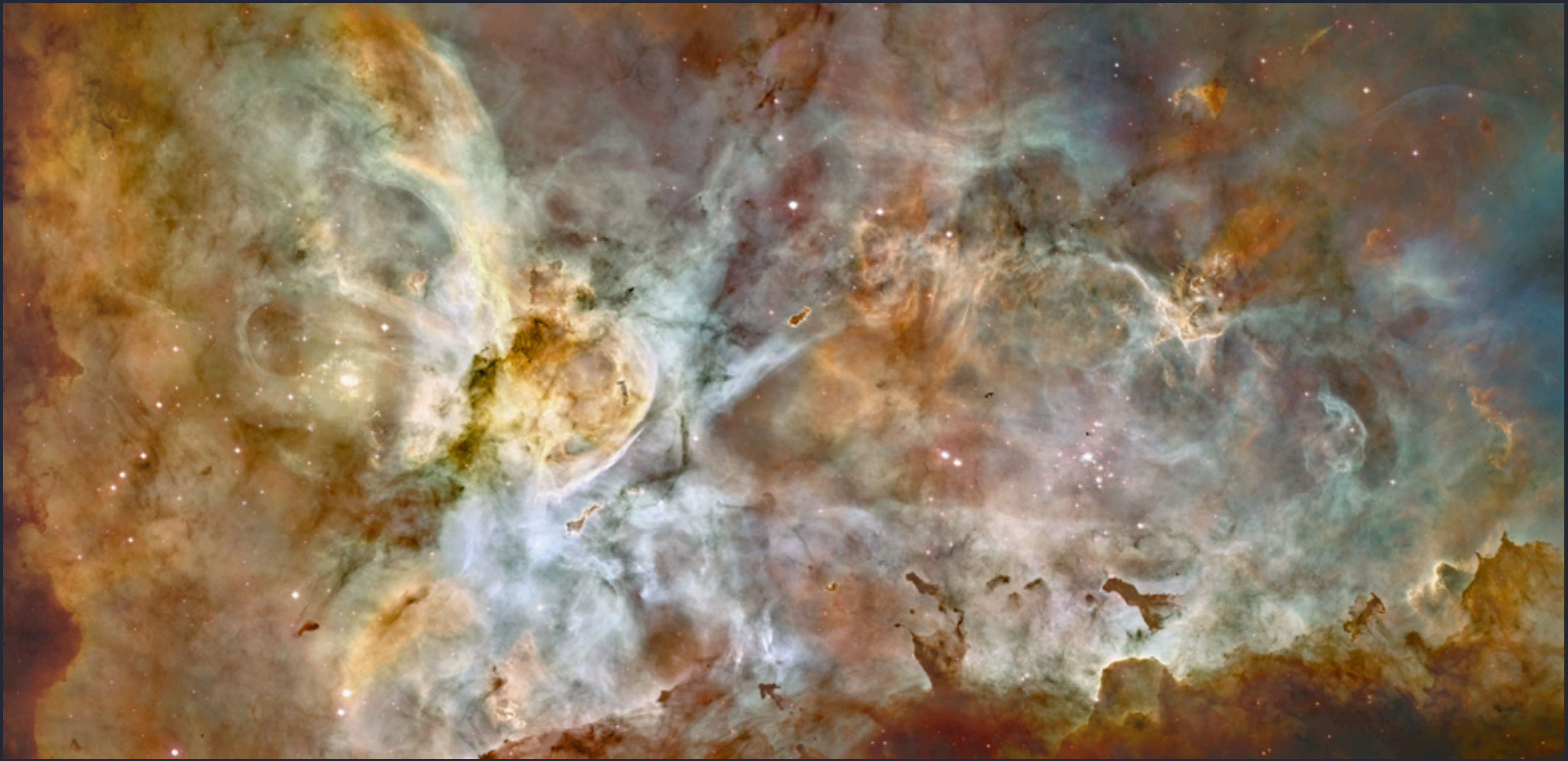
~1000 year-old core-collapse supernova remnant

Crab Nebula, *WIYN*

Carina Nebula

massive, luminous stars drive the process

winds, eruptive mass loss, and supernovae all contribute



Carina Nebula, *Hubble Space Telescope*

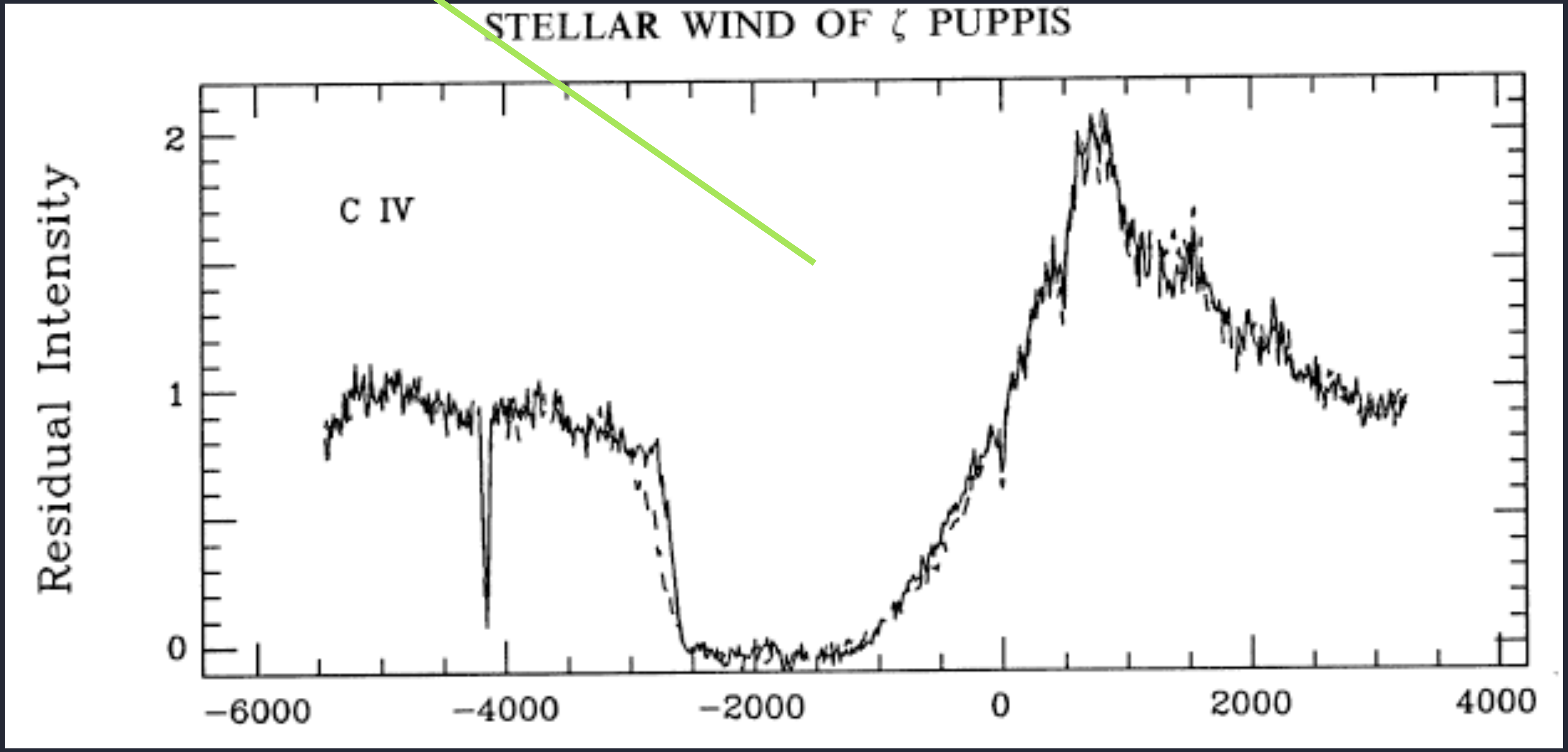
I study the steady mass-loss of young and middle-aged O stars

NGC 6888 Crescent Nebula - Tony Hallas

O star - source of wind bubble:
~1 arc second instrumental resolution;
star's angular size is 10^4 times smaller

NGC 6888 Crescent Nebula - Tony Hallas

small spatial scales can be studied using *spectroscopy*



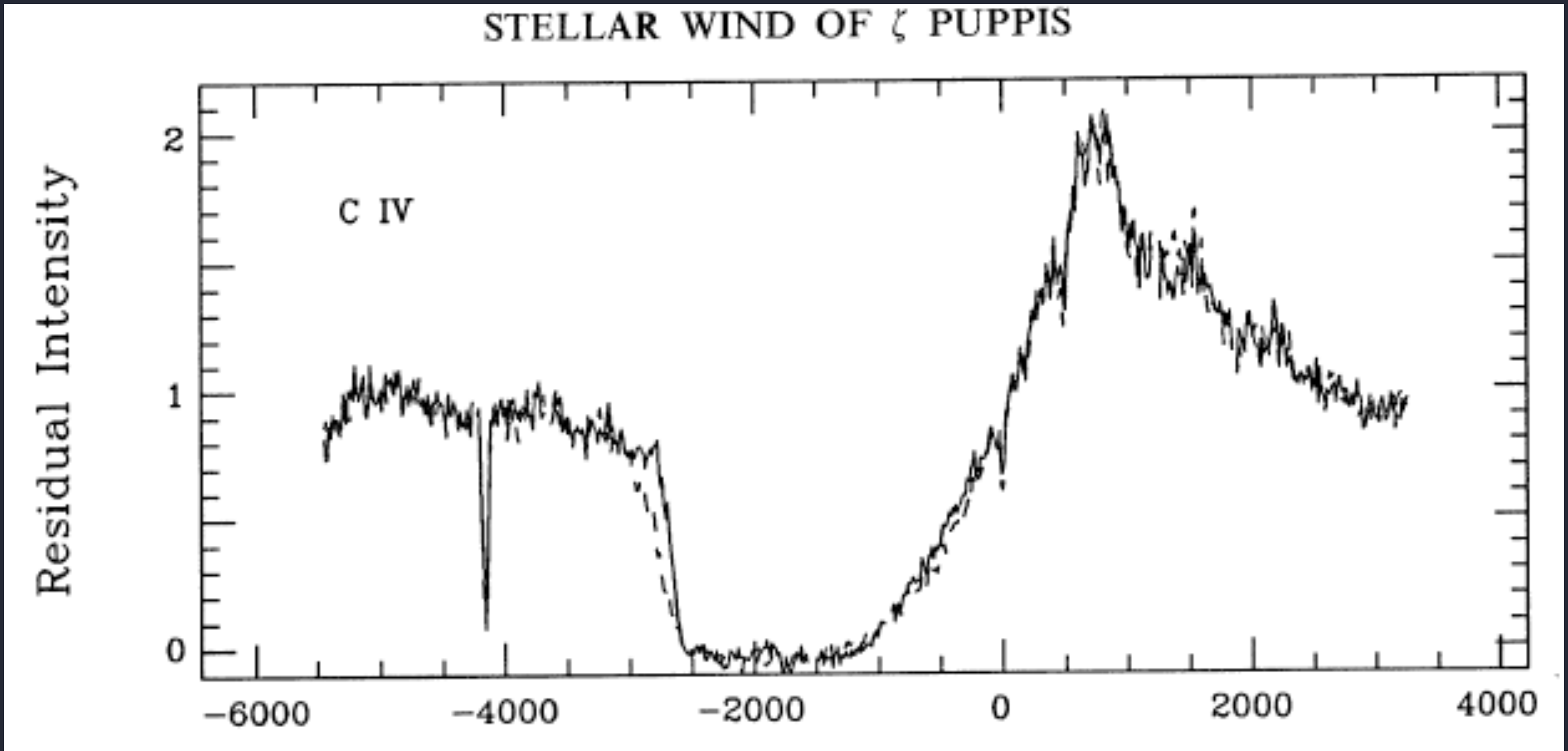
Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

Ultraviolet spectrum showing wind feature from C^{+3}

ζ Pup (O4 supergiant): $\dot{M}$ ~ few 10^{-6} M_{sun}/yr

UV spectrum: C IV 1548, 1551 Å



Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

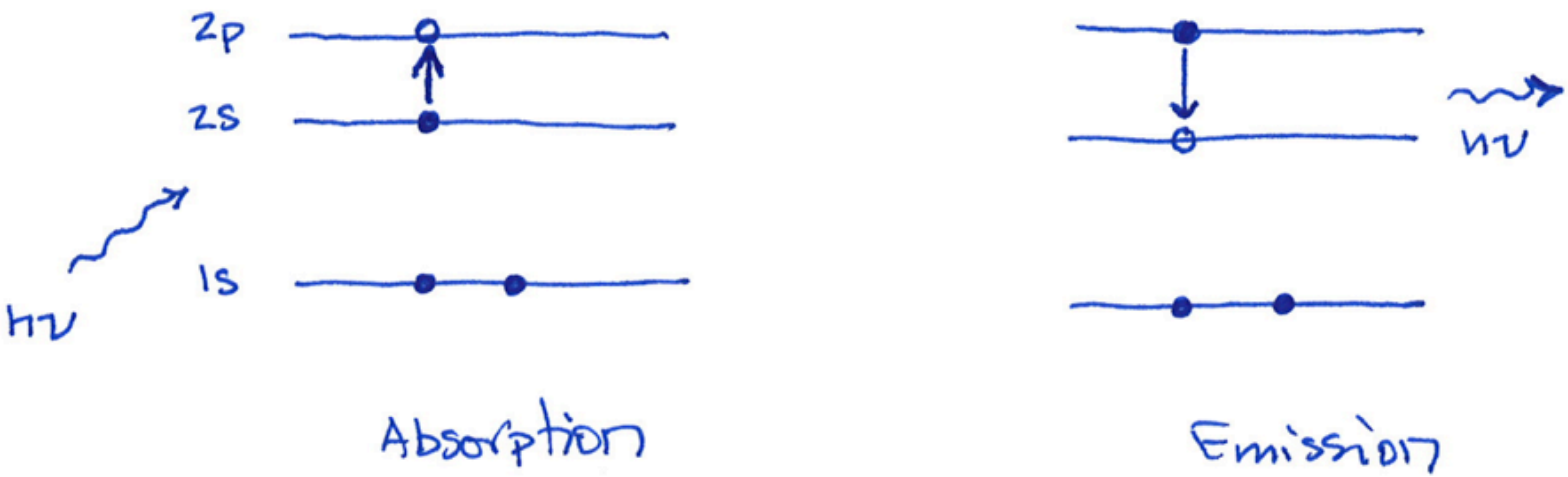
Spectral lines:

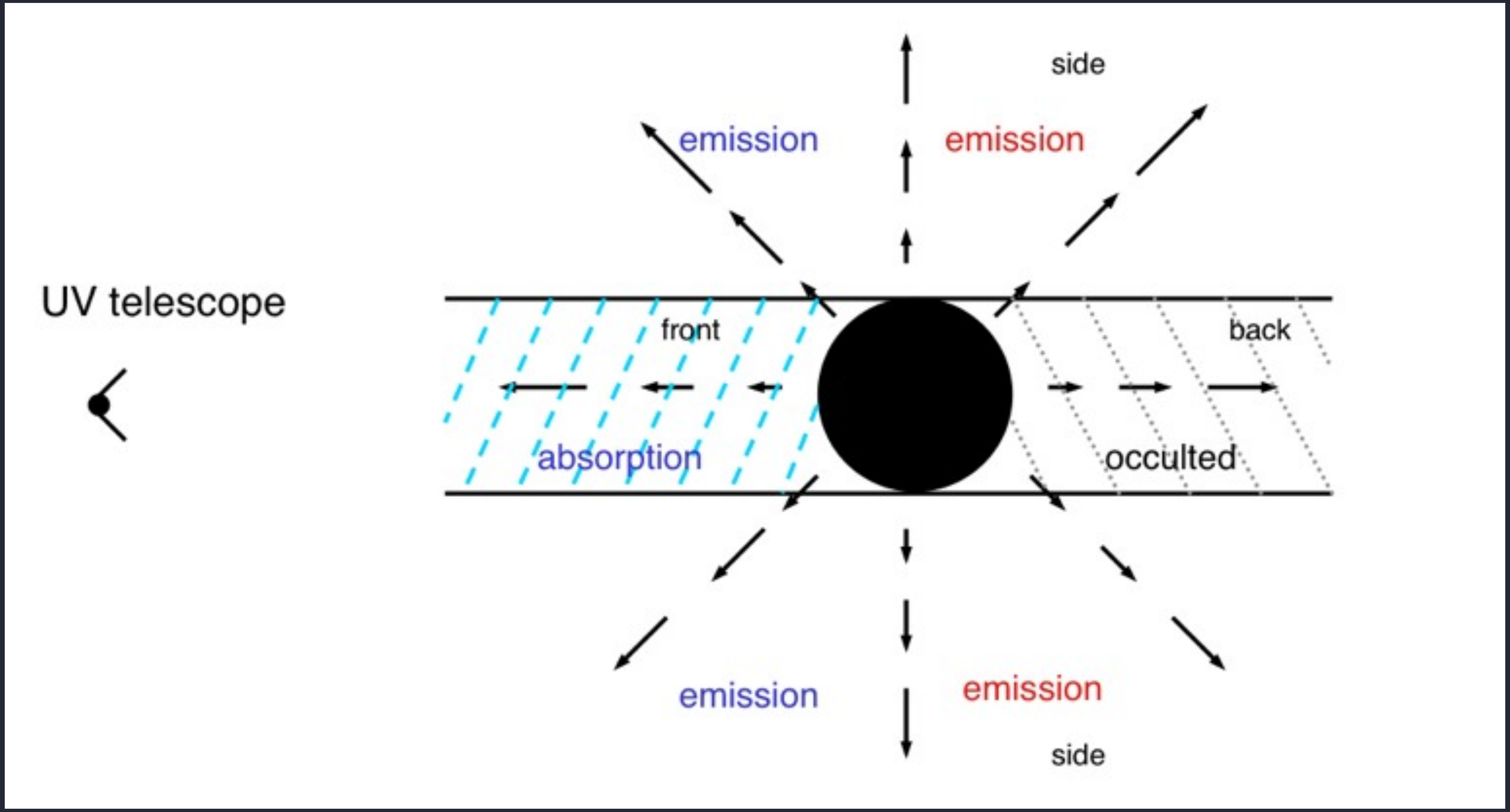
absorption line when translucent gas is between you and a hotter, opaque source of continuum photons

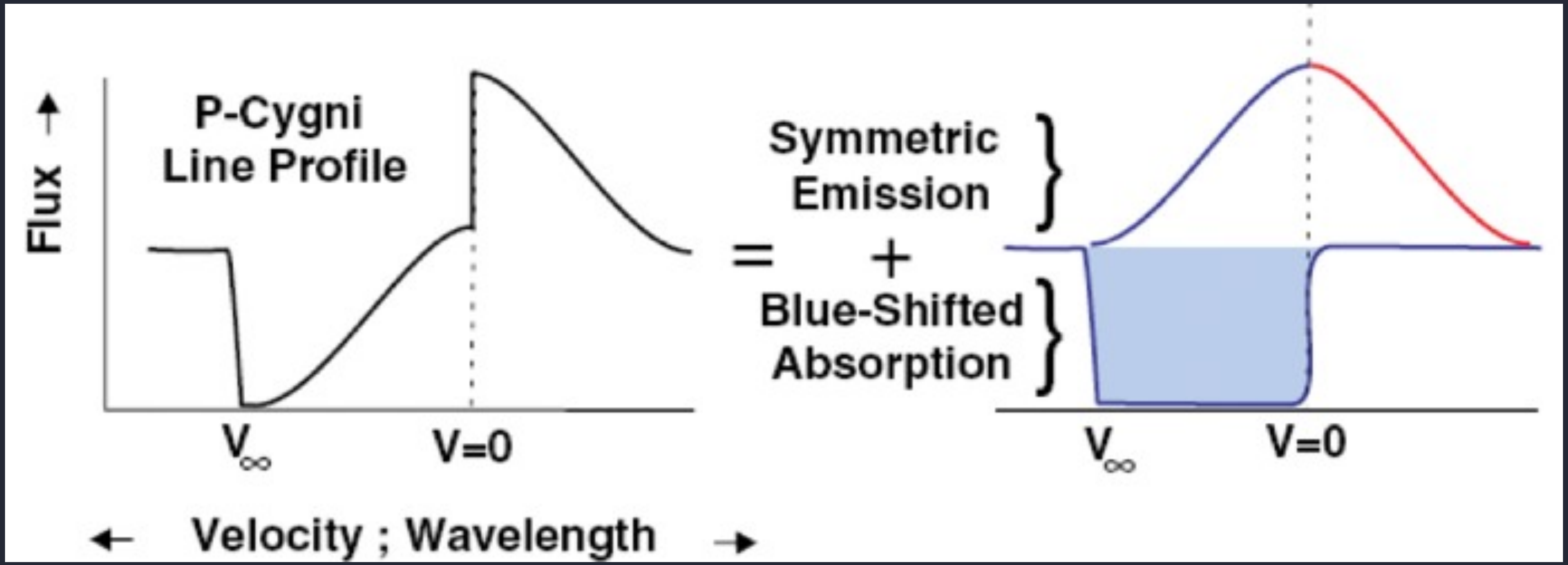
emission line when hot gas is seen against a cold background

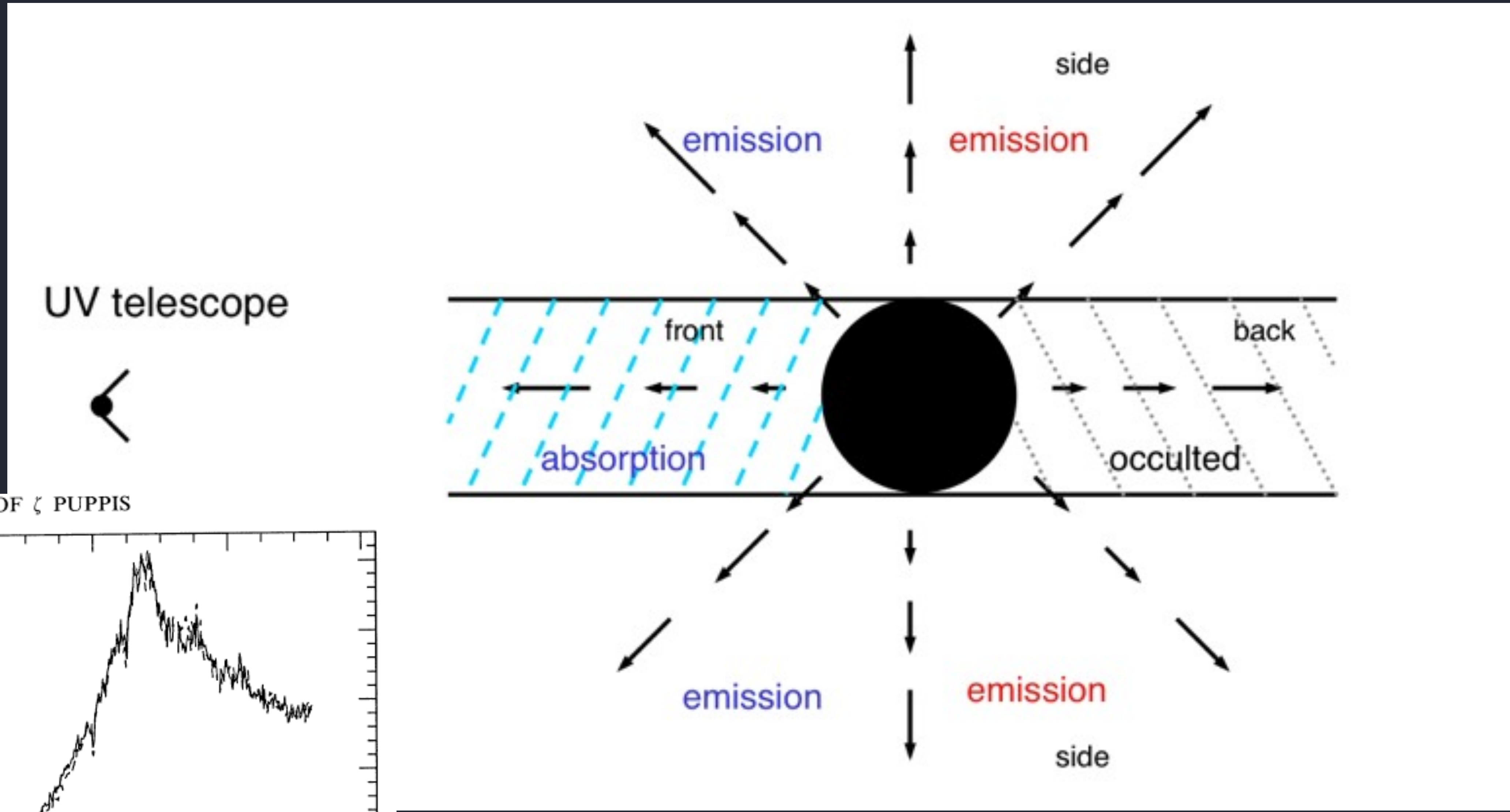
absorption and emission: atomic energy level diagrams

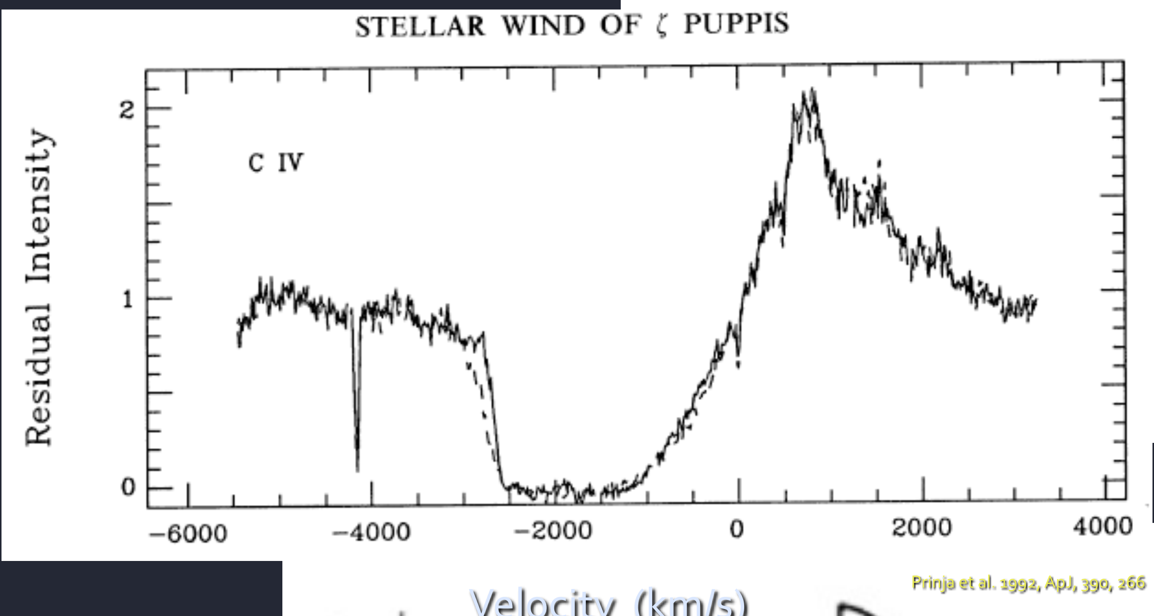
C^{+3} is lithium-like




side
emission
emission
UV telescope
front
back
absorption
occulted
emission
emission
side


Flux
P-Cygni
Line Profile
Symmetric
Emission
=
+
Blue-Shifted
Absorption
V∞
V=0
V∞
V=0
Velocity ; Wavelength





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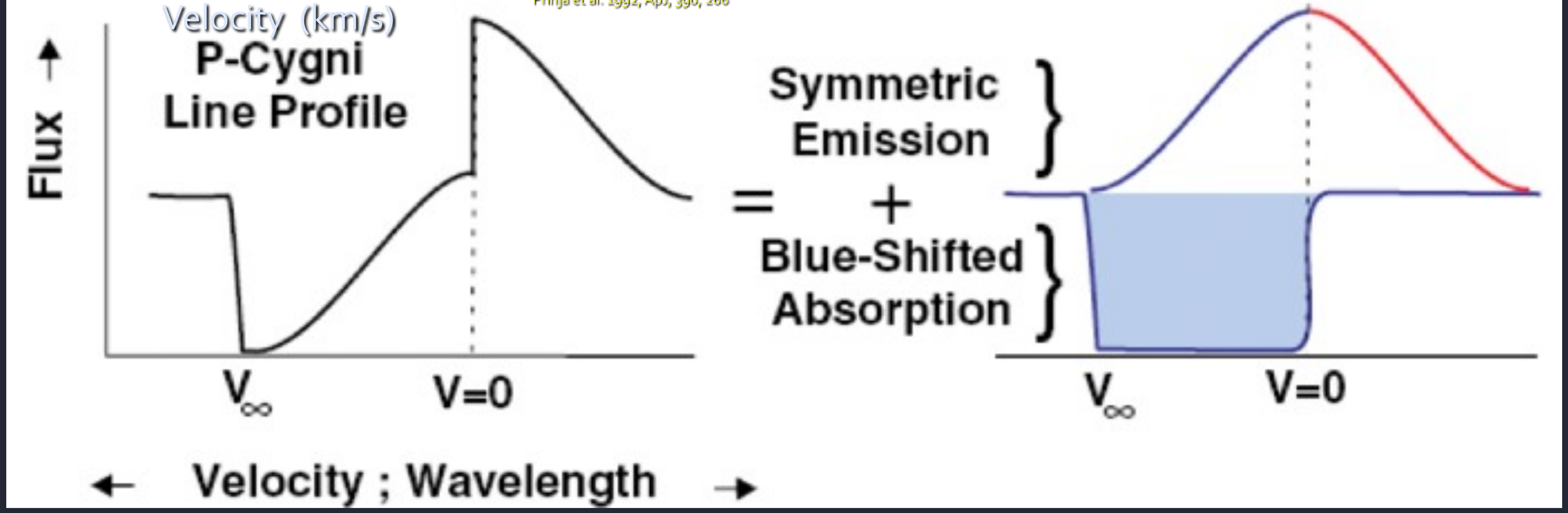

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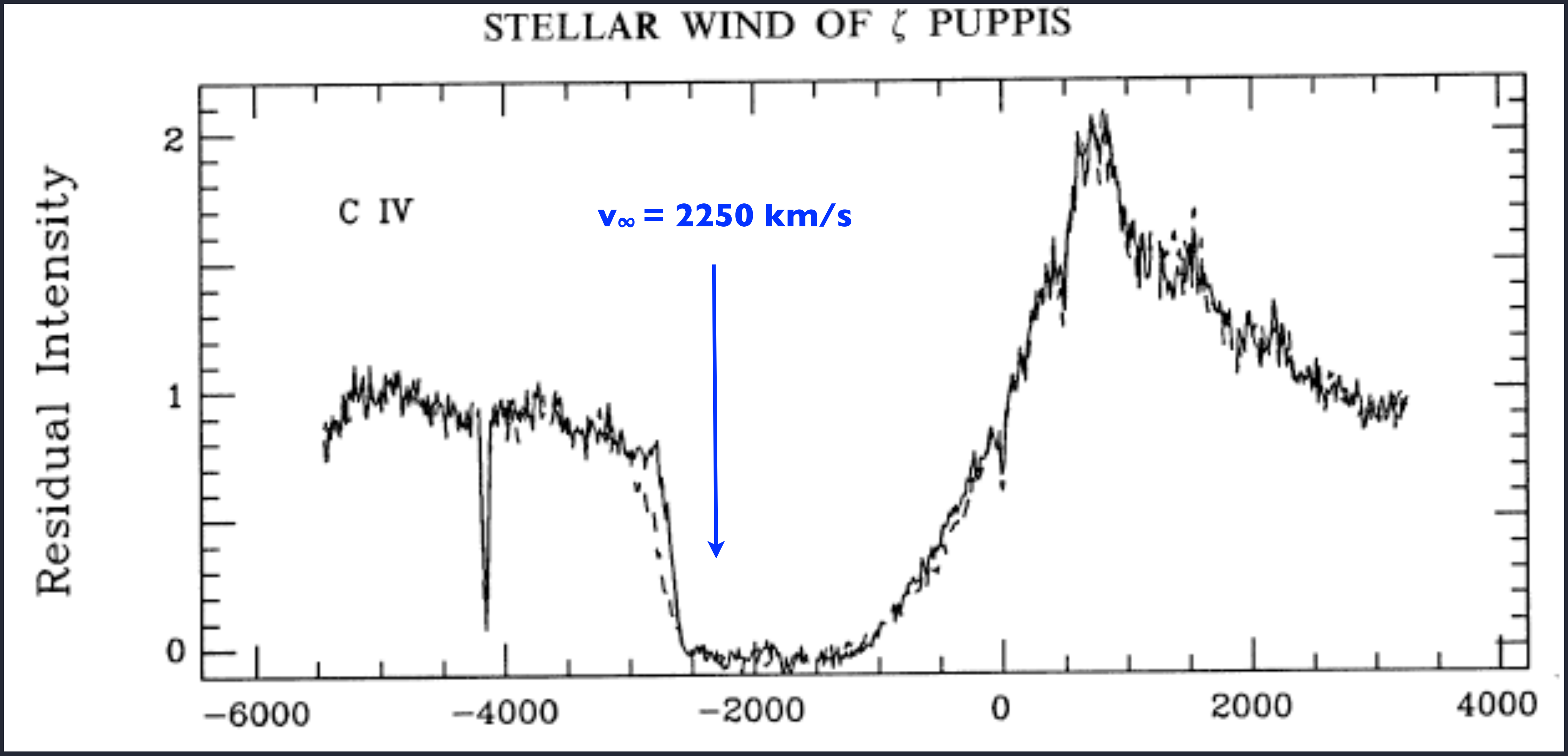
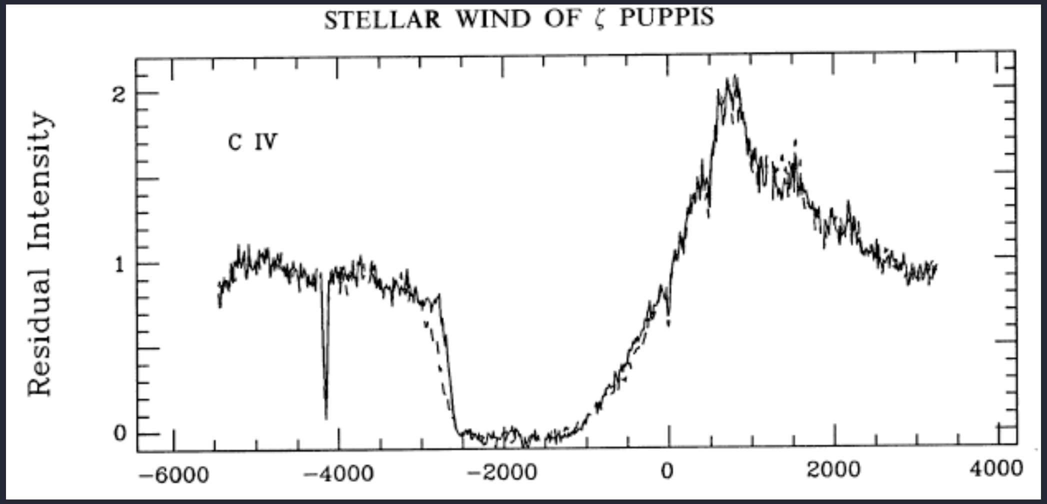


Prinja et al. 1992, ApJ, 390, 266

Velocity (km/s)

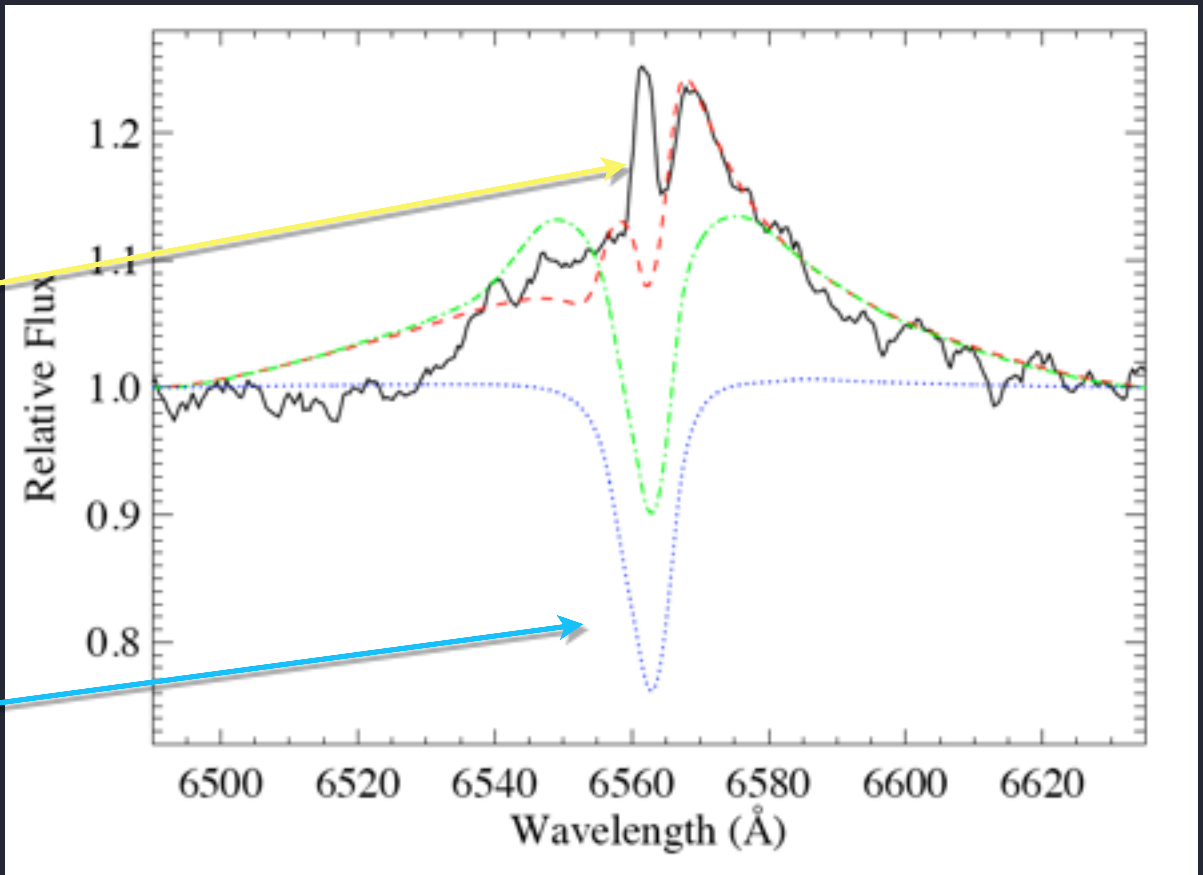
Wind mass-loss rates ($\dot{M}$) can be inferred from the strength of the absorption component



Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

but, more reliable are recombination emission lines such as Hα



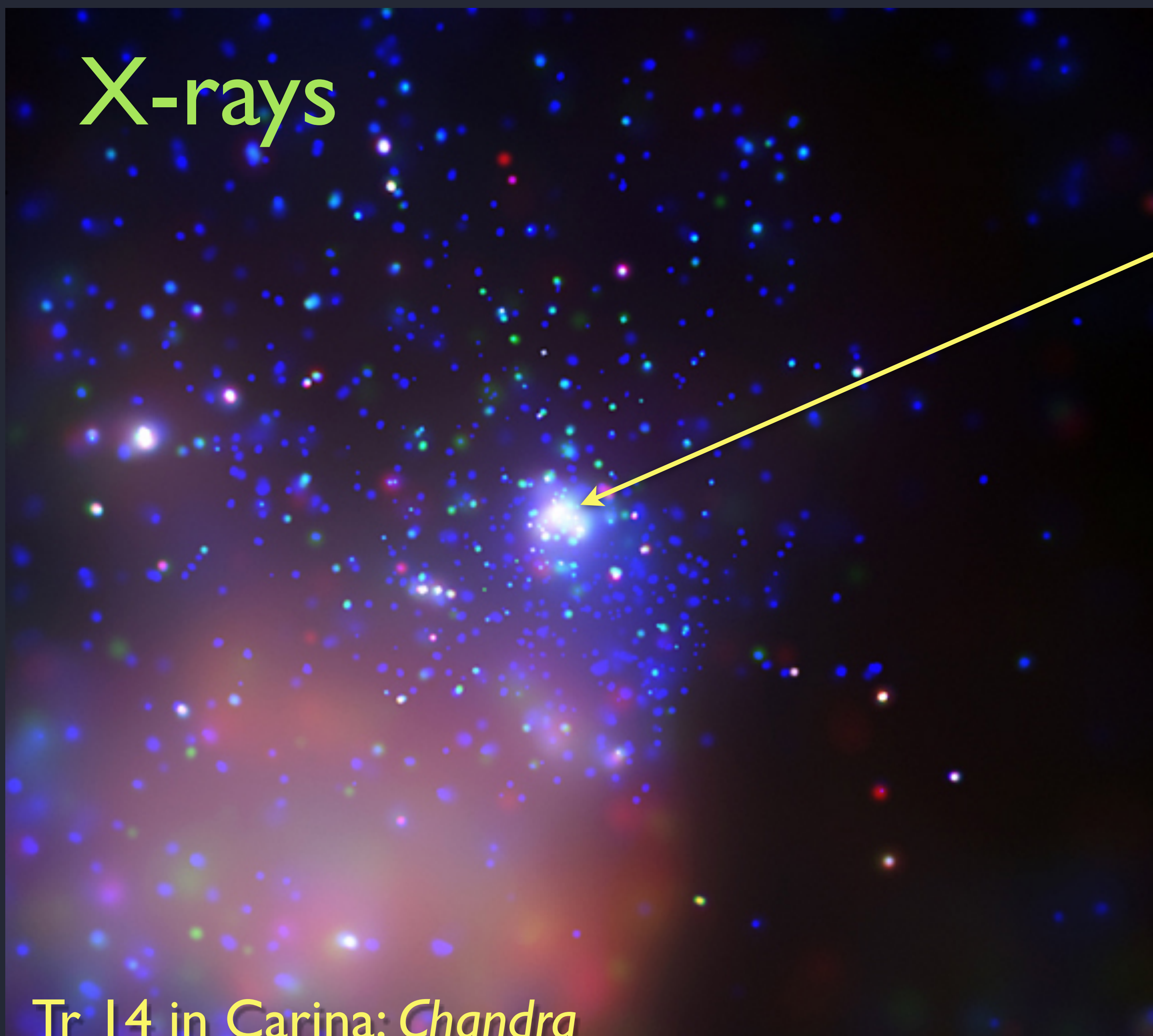
emission from the wind

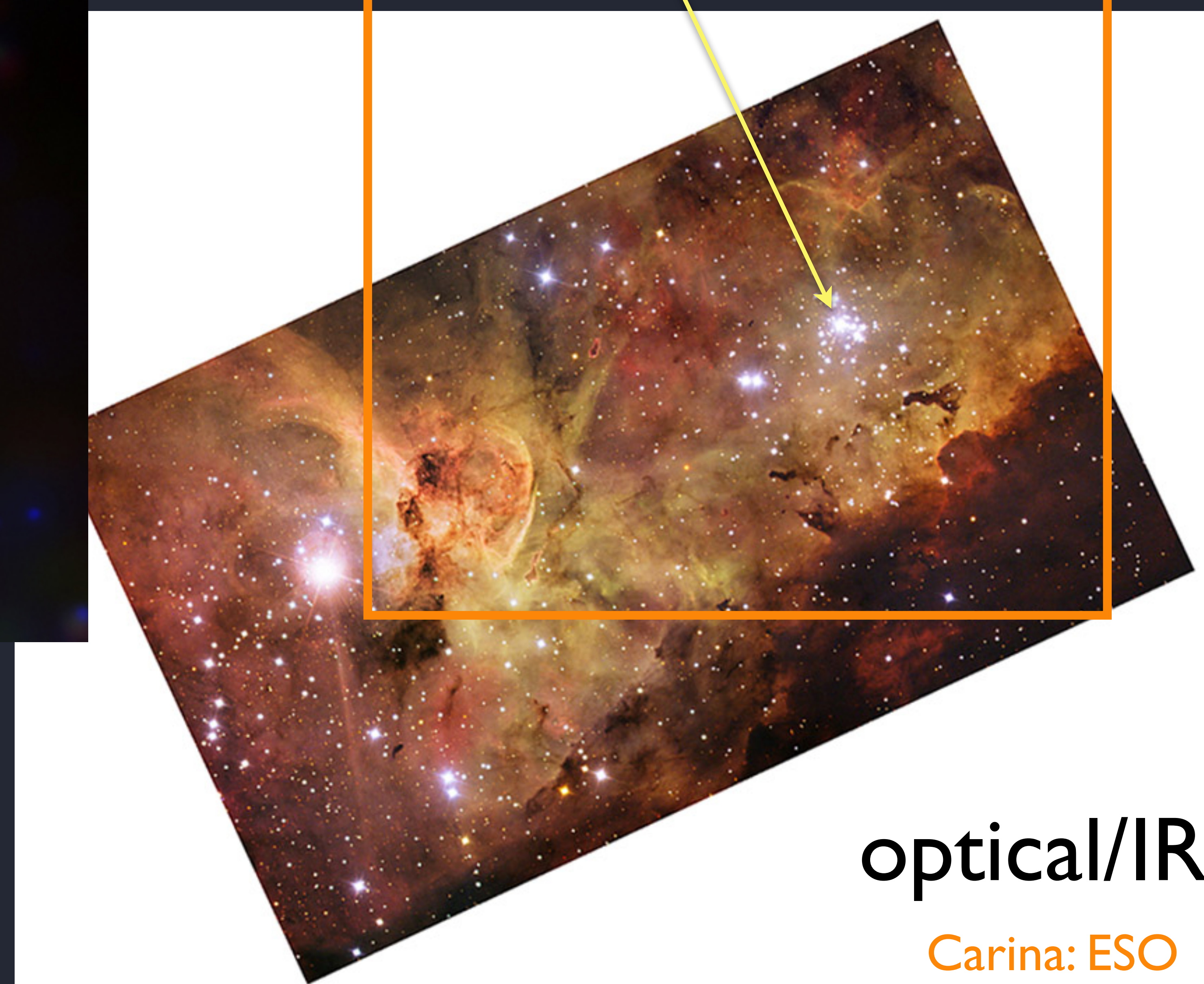
photosphere only (absorption), no wind

O stars are strong sources of X-ray emission

thermal emission from hot ($T > 10^6$ K) plasma

HD 93129A (O2 supergiant)





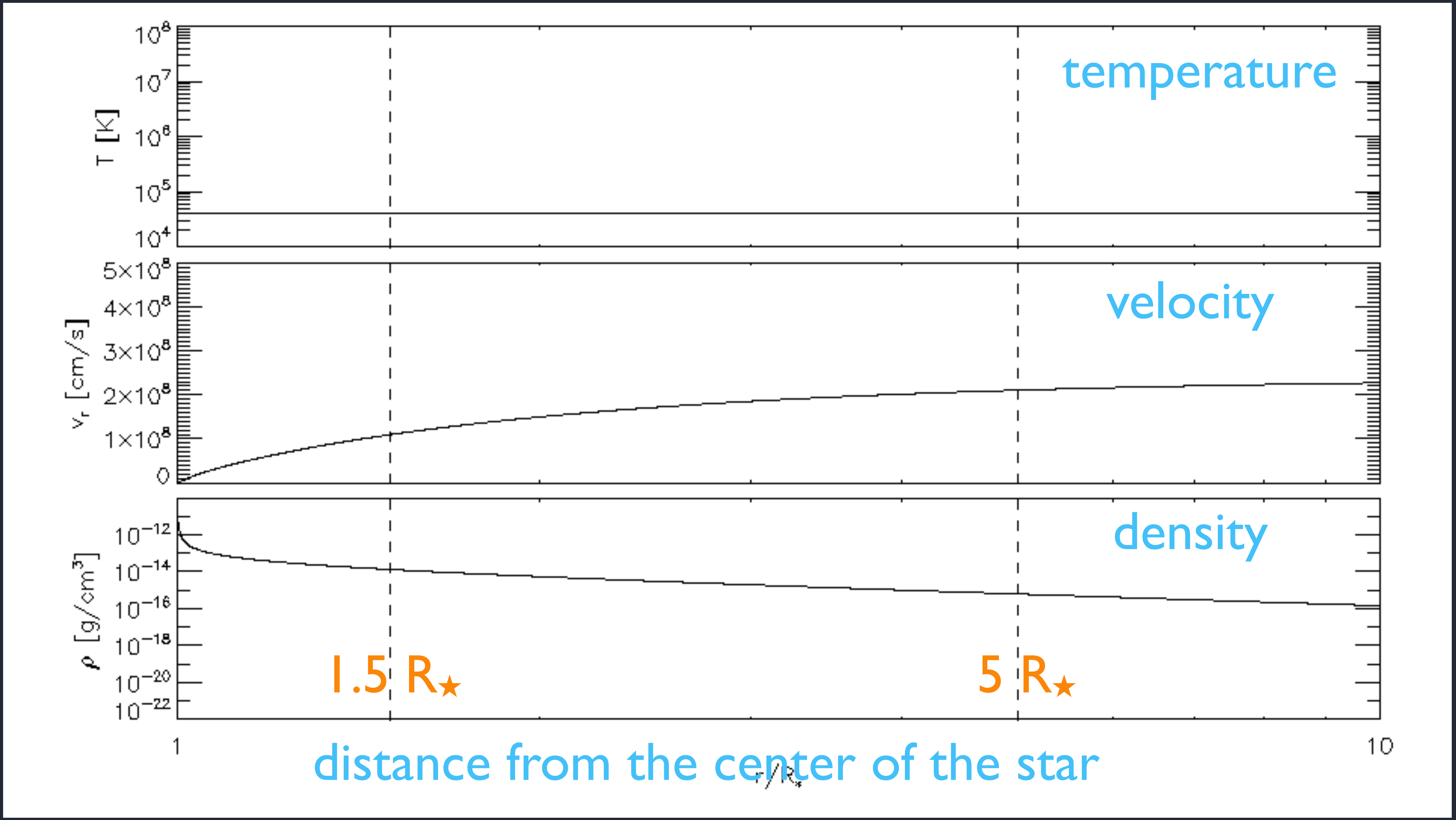
HD 93129A is the brightest X-ray source in this cluster

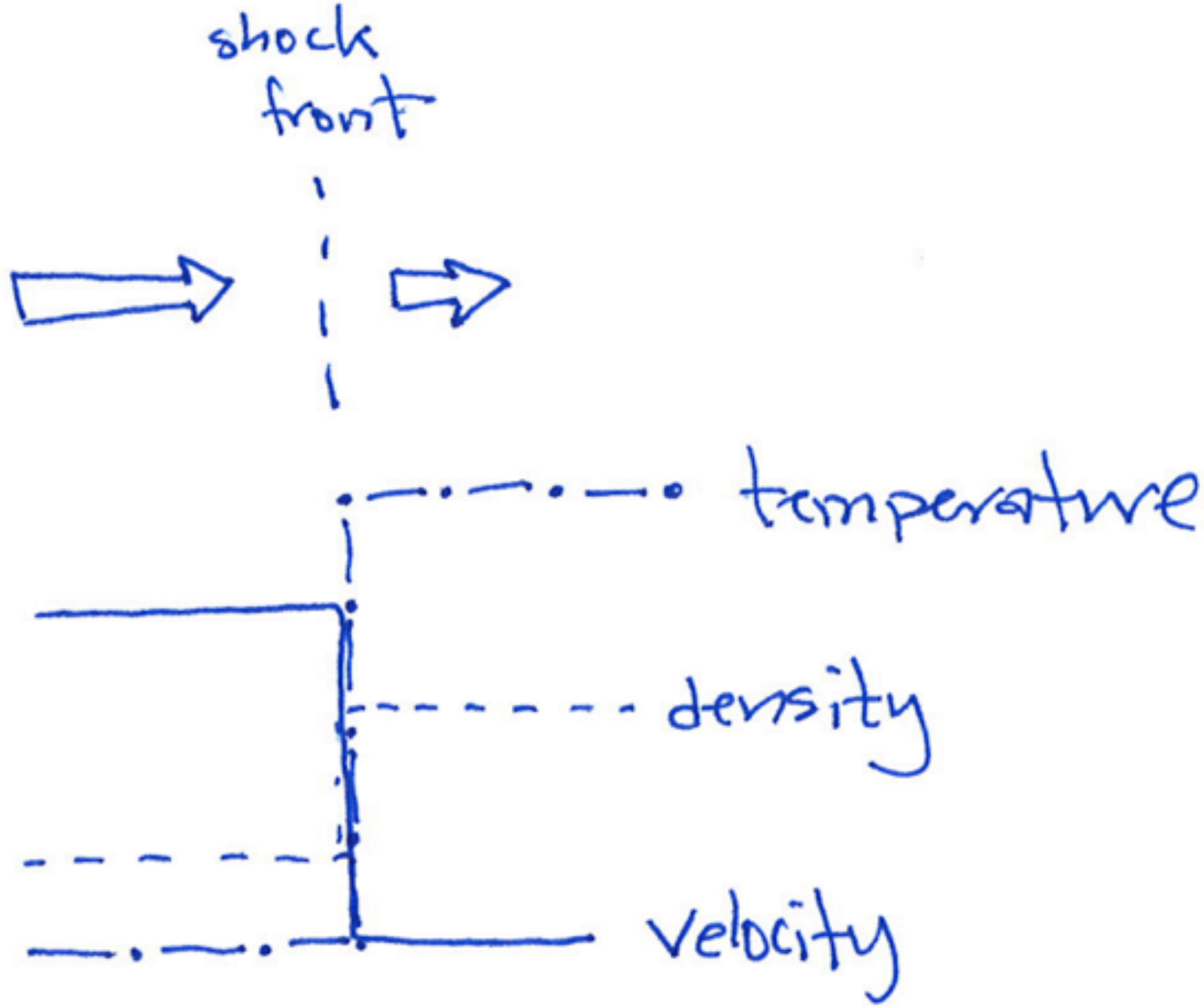
red < 1 keV, green 1 - 2 keV, blue > 2 keV

Tr 14 in Carina: *Chandra*

X-ray emitting plasma is embedded in the wind

intrinsic instability of radiative driving, Line Deshadowing Instability (LDI), leads to shock-heating of the wind

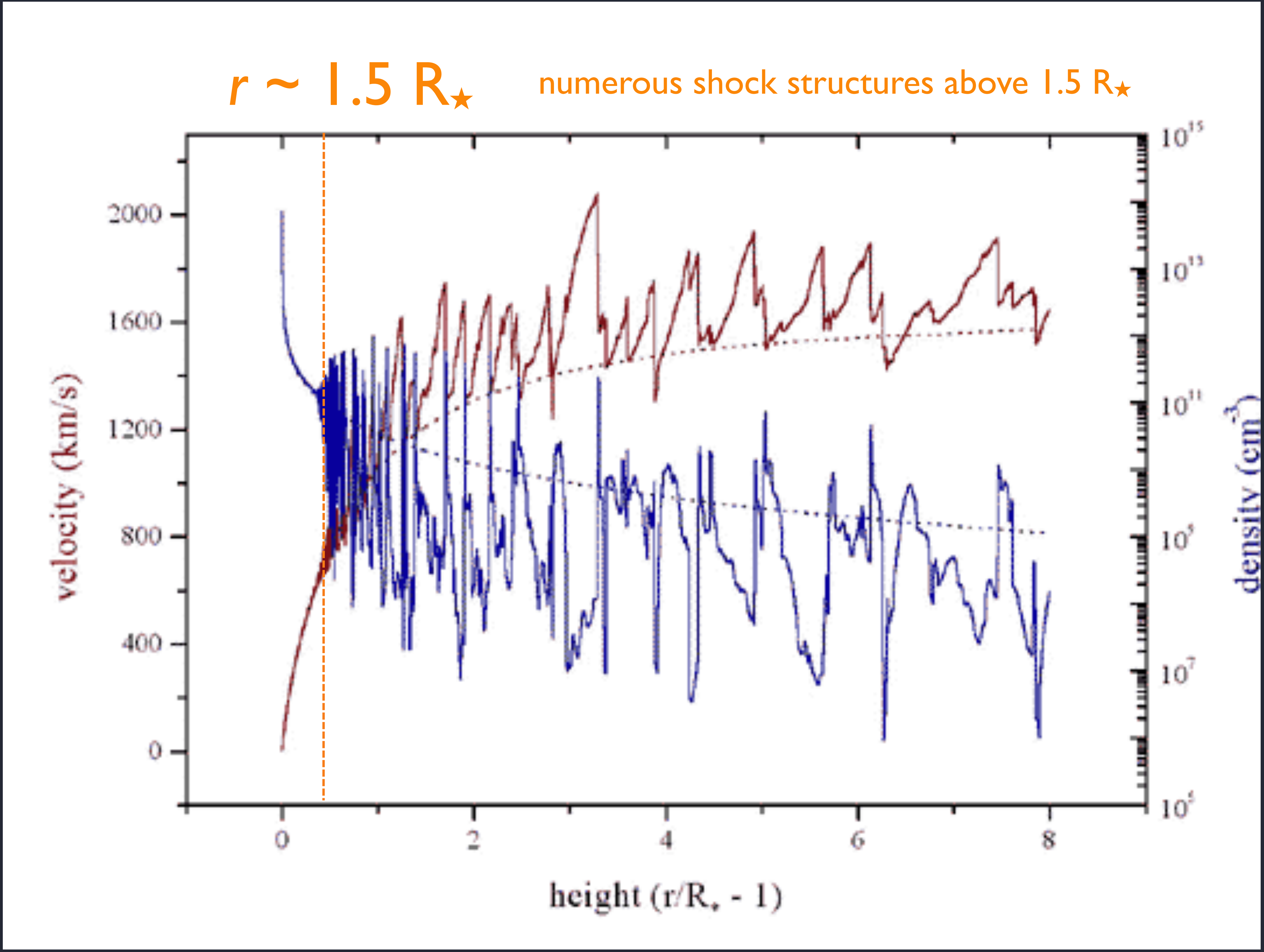


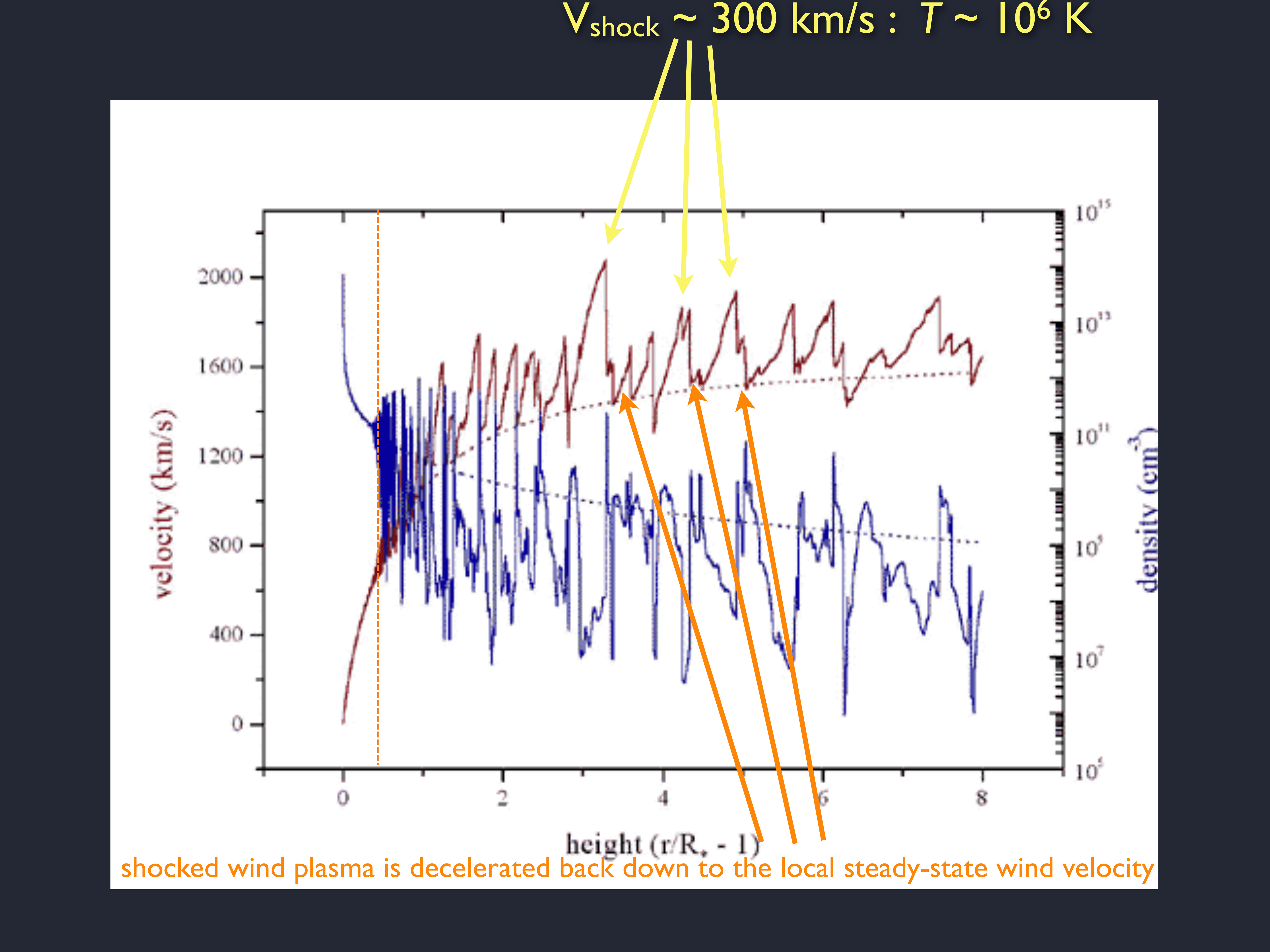


kinetic energy → heat at shock front

$$T \approx 10^6 \left(\frac{V_{shock}}{300\ km/s} \right)^2$$

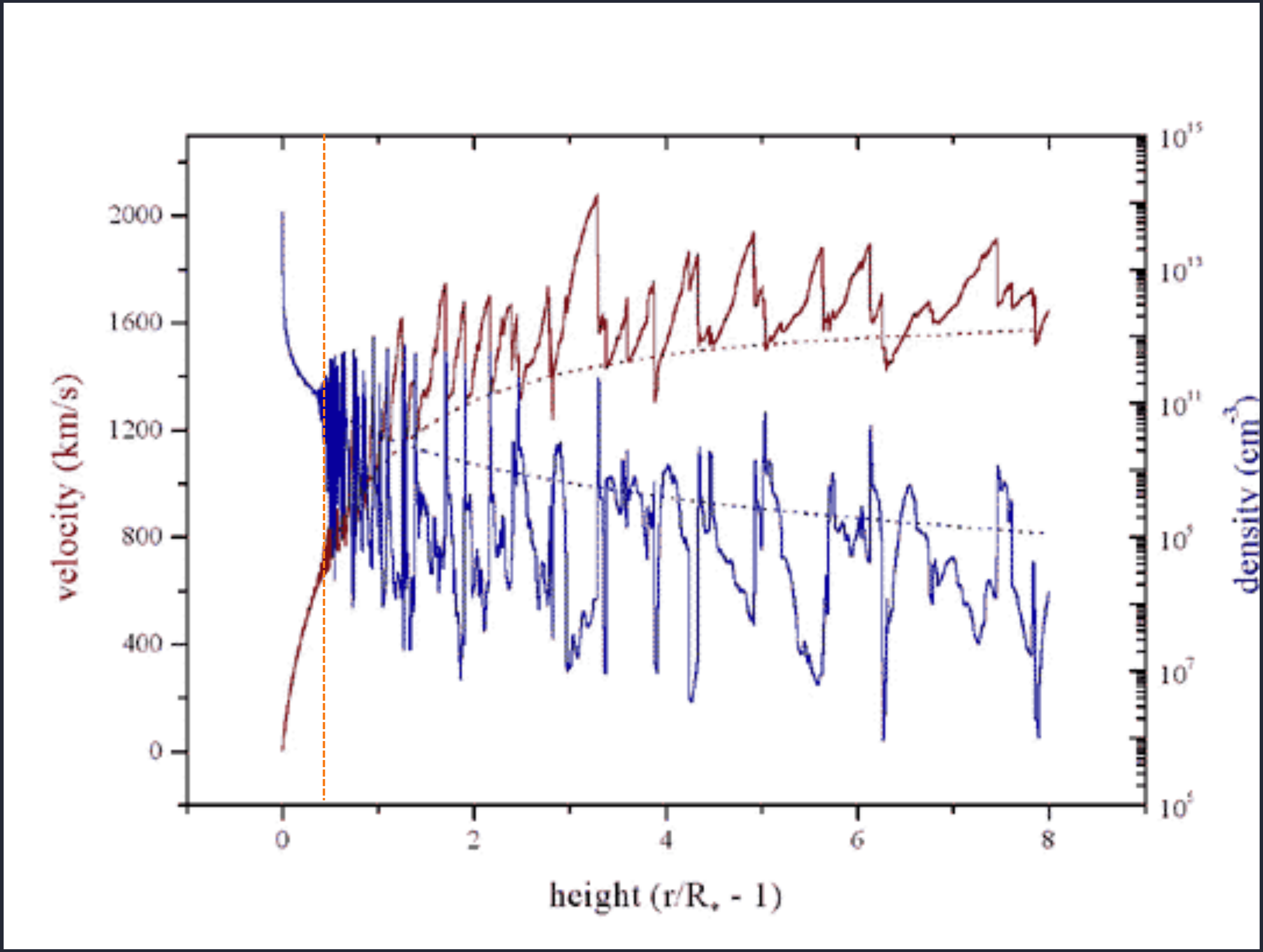
snapshot from the hydro simulation





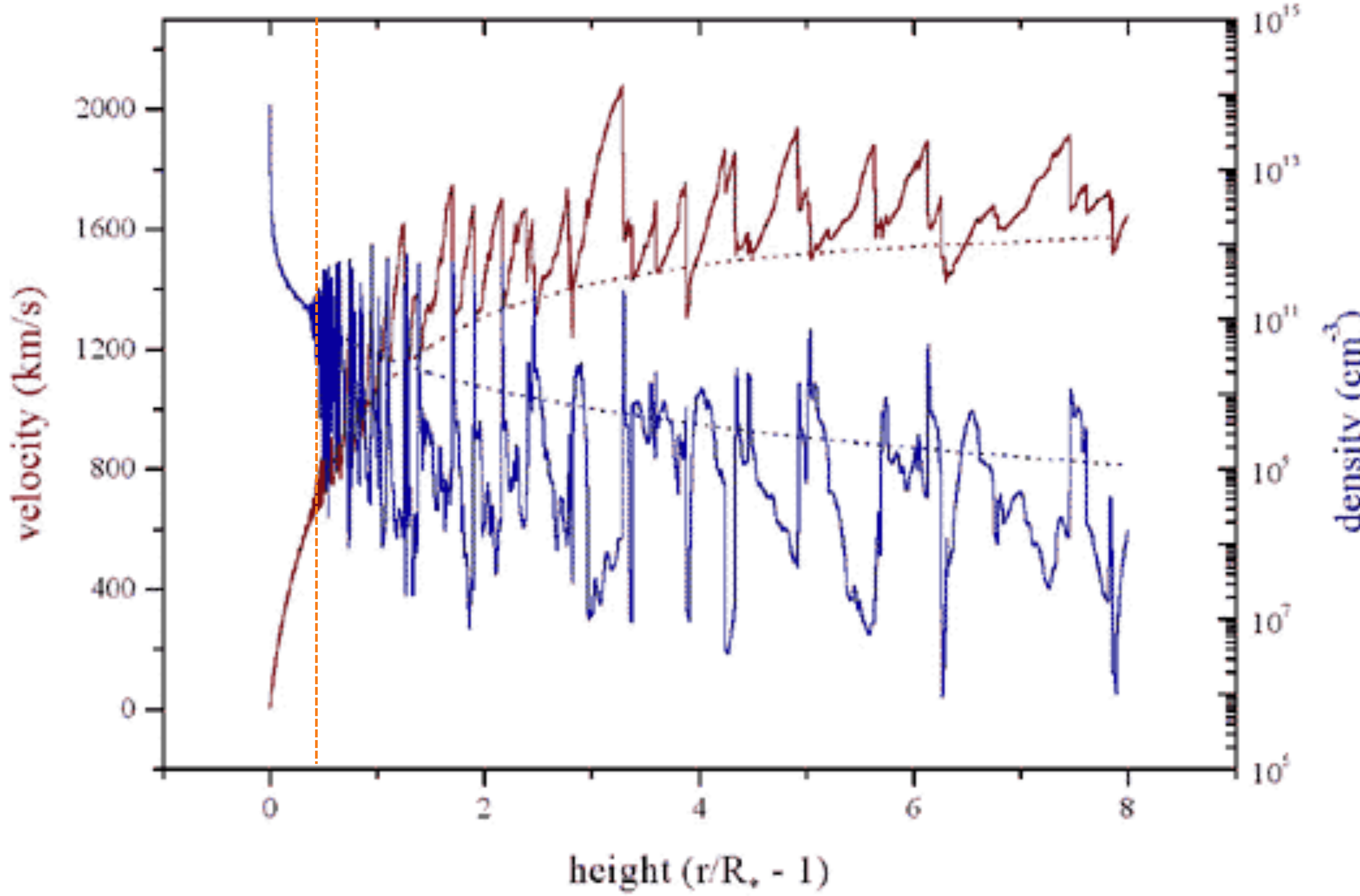
Vshock ~ 300 km/s : T ~ 10⁶ K
velocity (km/s)
2000
1600
1200
800
400
0
0
2
4
6
8
height (r/R* - 1)
density (cm⁻³)
shocked wind plasma is decelerated back down to the local steady-state wind velocity

X-ray emission lines should be **Doppler broadened**



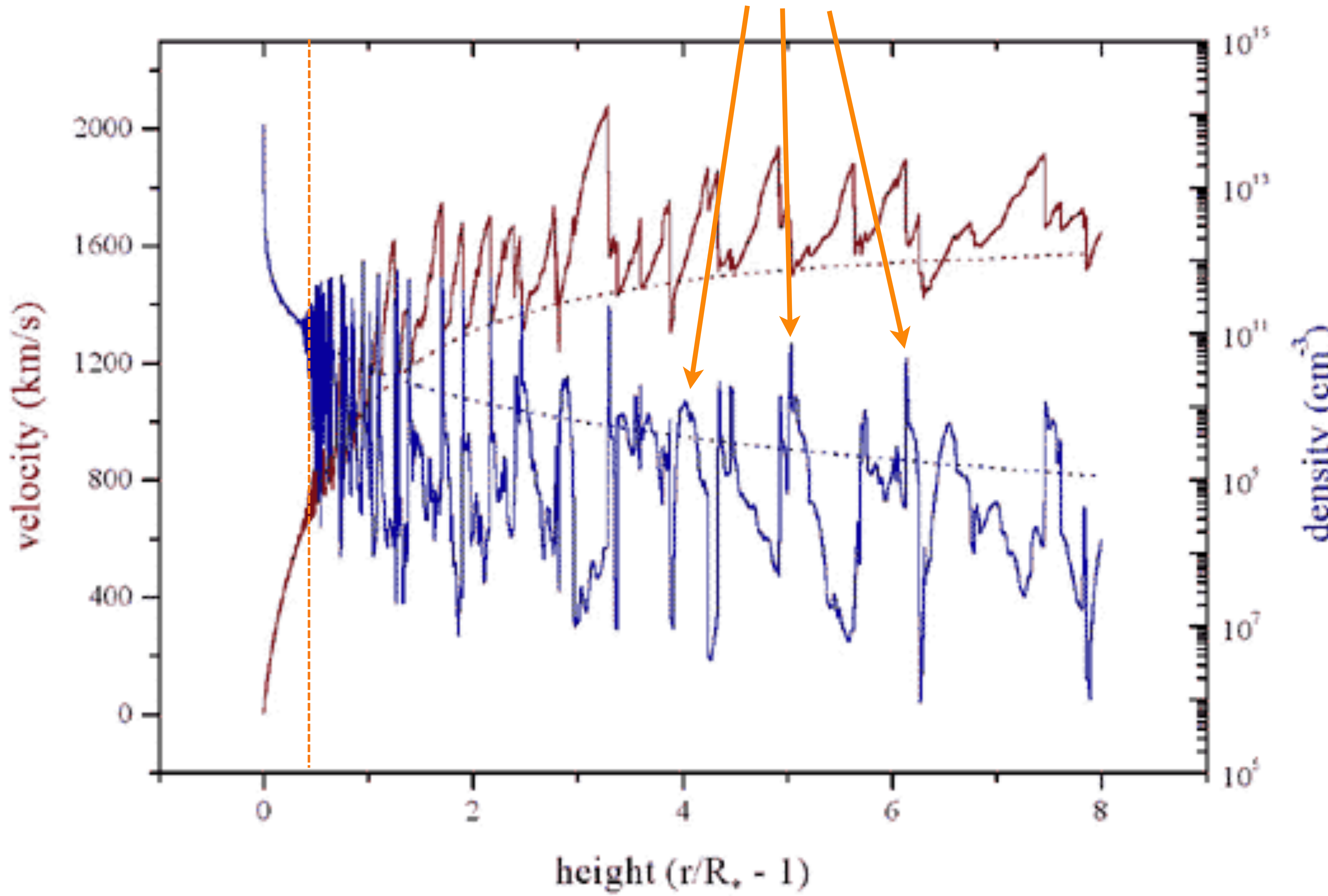
Less than 1% of the mass of the wind is emitting X-rays

>99% of the wind is cold and X-ray *absorbing*



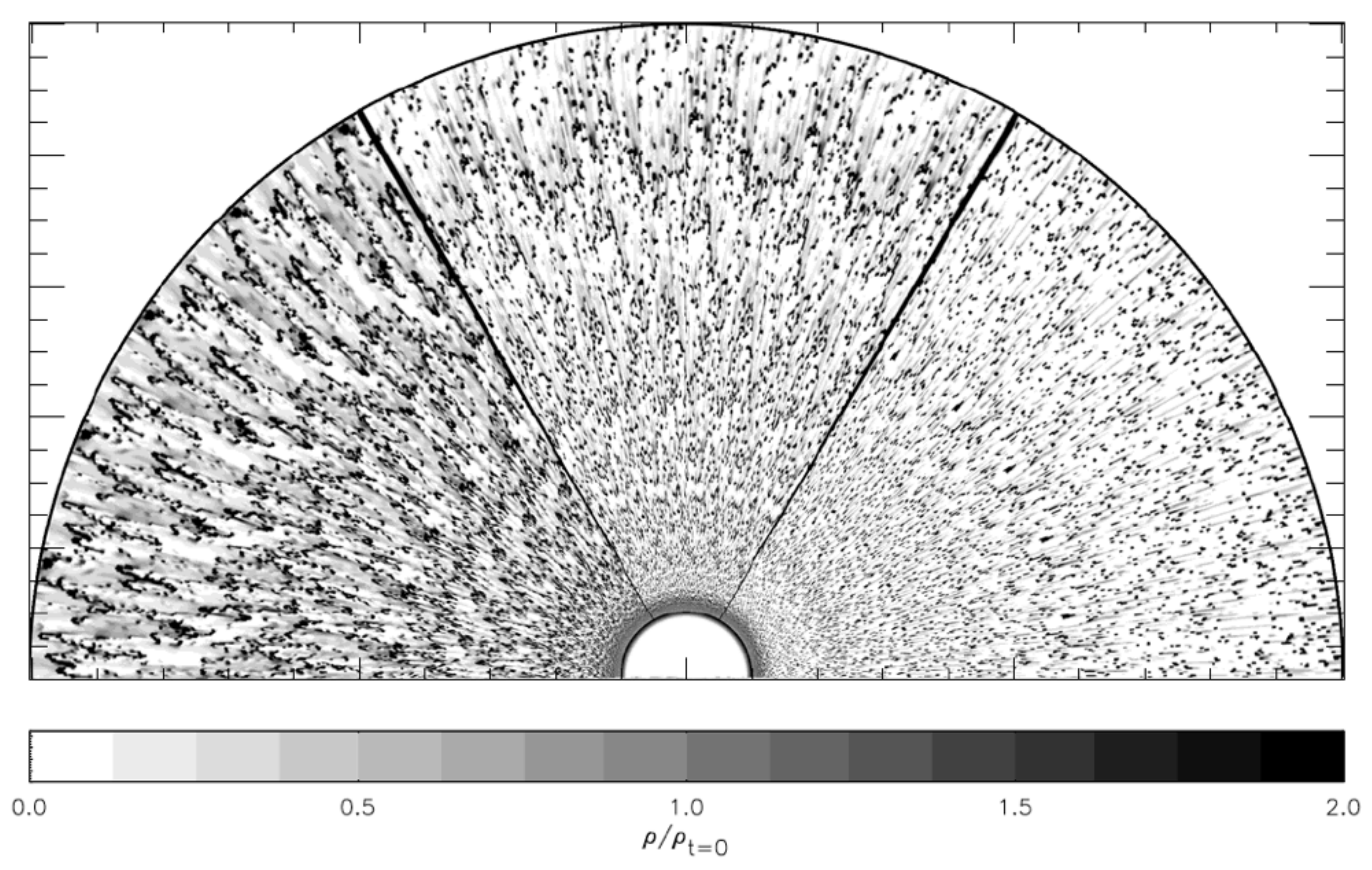
Wind is *clumpy*

a **clump** is a dynamically coherent, over-dense region



2-D radiation-hydro simulations

clumps break up to the grid scale



Dessart & Owocki 2003

X-ray spectroscopy confirms the general scenario

embedded wind shocks (EWS)

Chandra launched in 1999 -
first high-resolution X-ray spectrograph

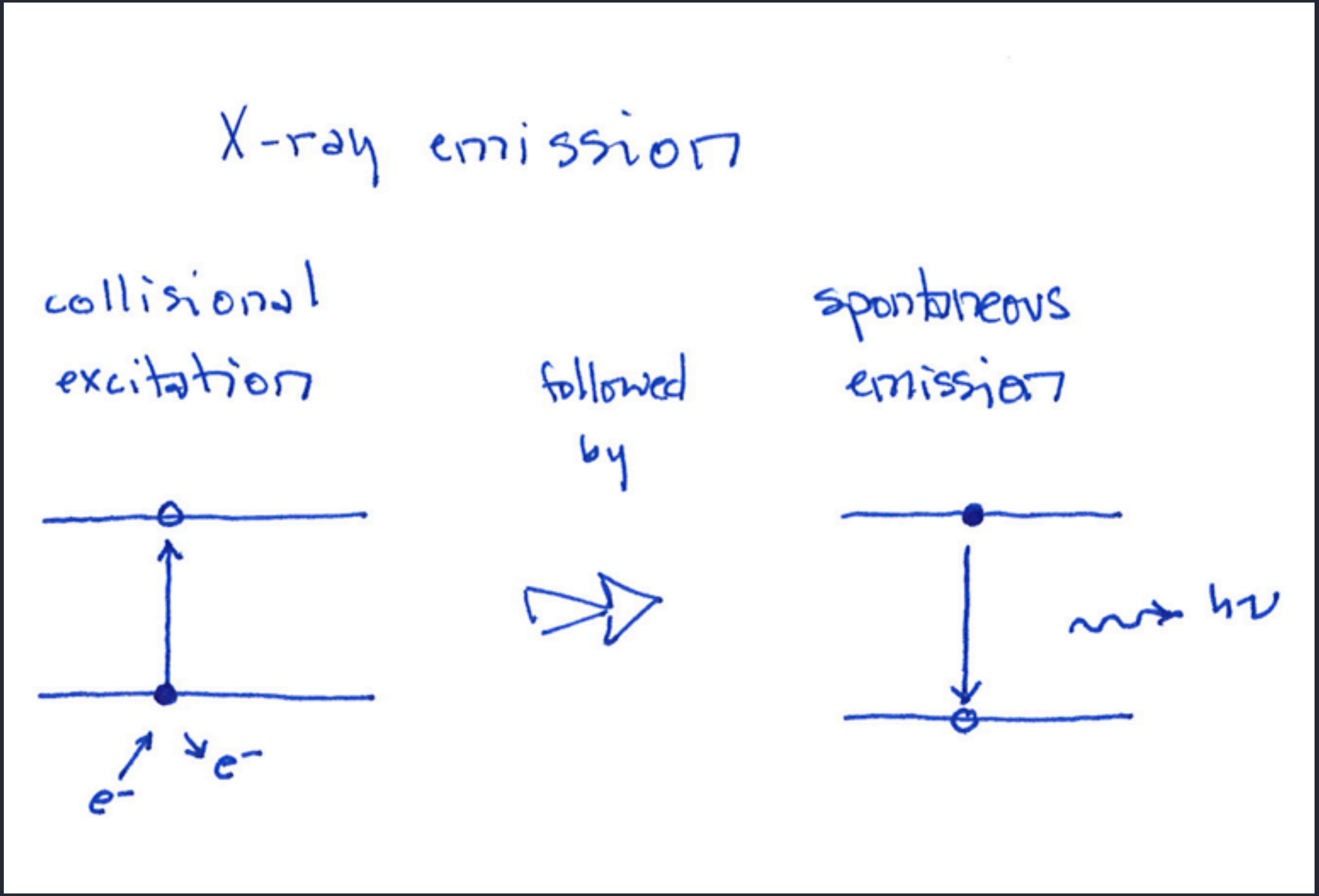
response to photons with
$h\nu \sim 0.5$ keV up to a few
keV (corresp. ~5Å to 24Å)

X-ray imaging? > 0.5 arc sec, at best (100s of AU)

spectroscopy ($\lambda/\Delta\lambda < 1000$ corresp. v > 300 km/s)

X-ray emission process

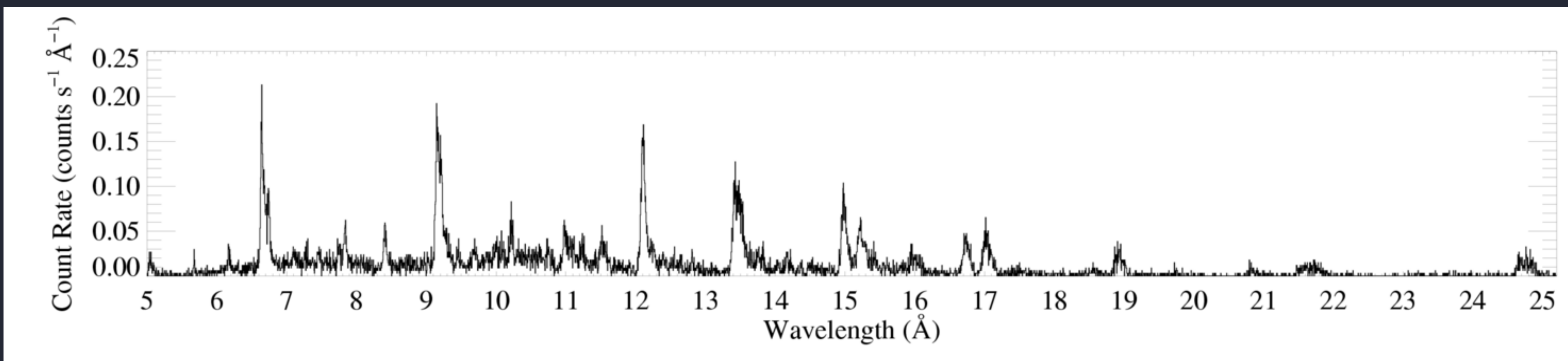
thermal emission from collisional plasma



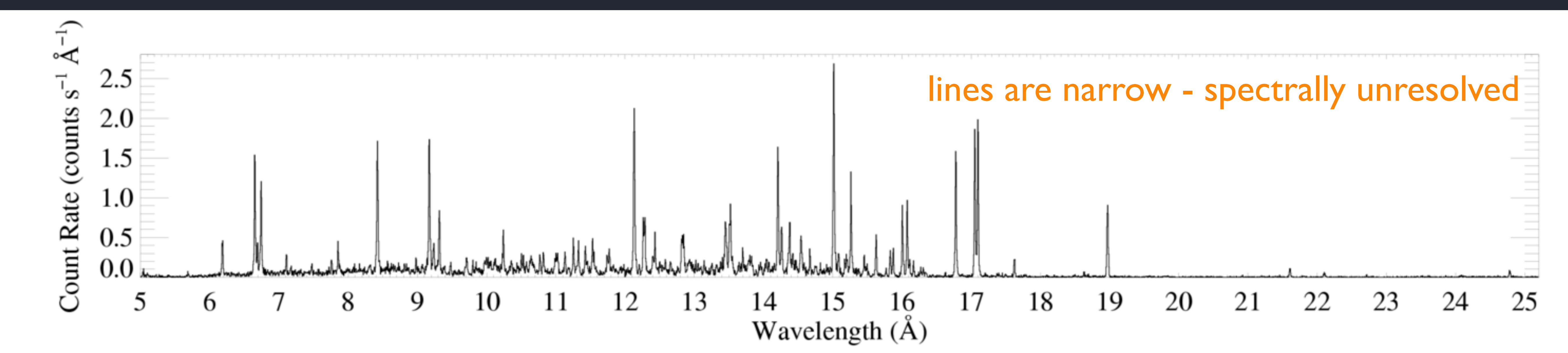
X-ray spectroscopy confirms the general scenario

embedded wind shocks (EWS)

ζ Pup (O4 If)



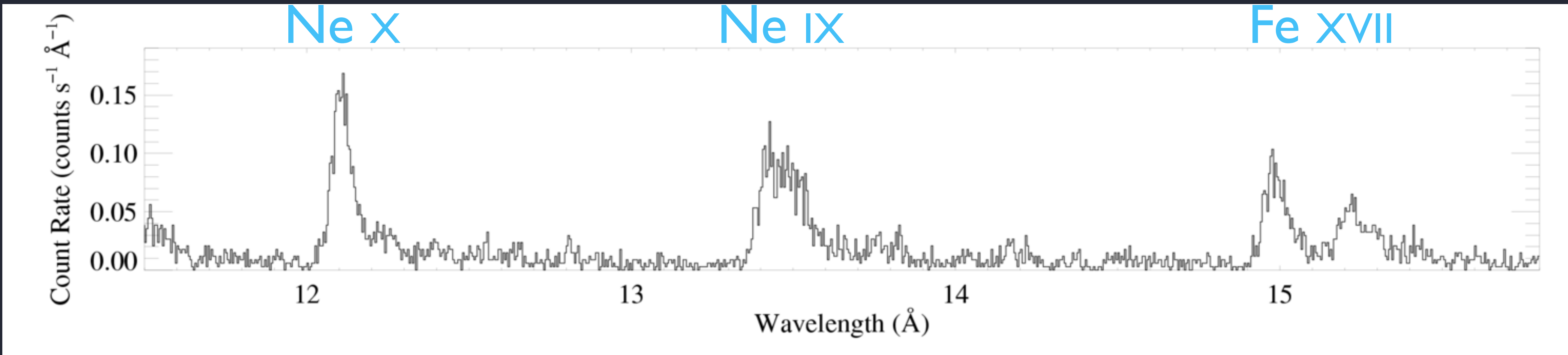
5Å 15Å 25Å

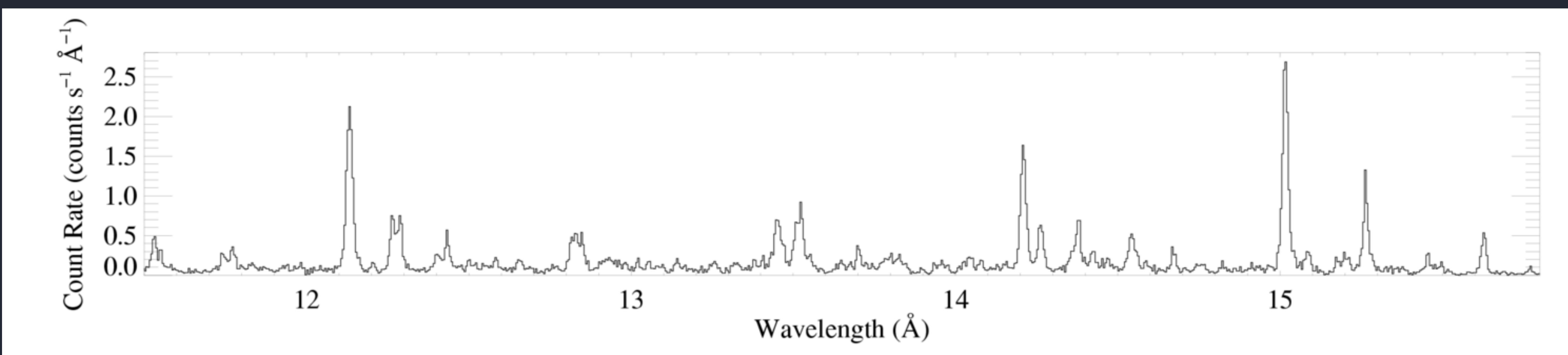


Capella (G5 III)

Zoom in

ζ Pup (O4 If)





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Zoom in

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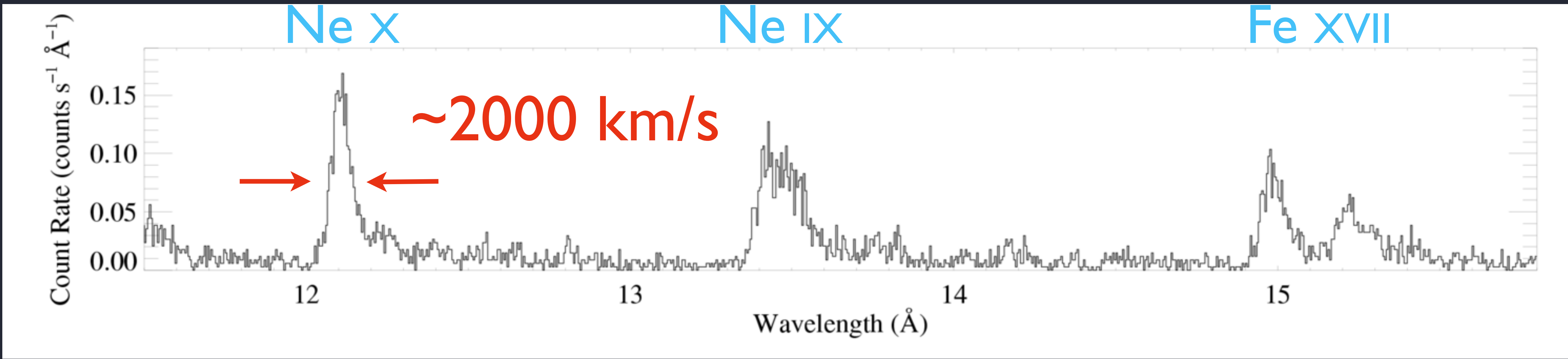
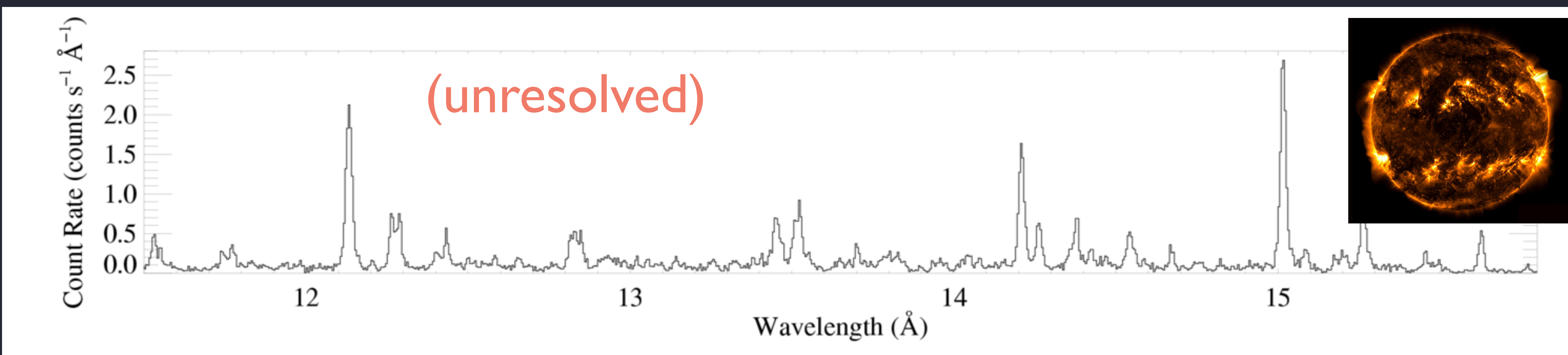


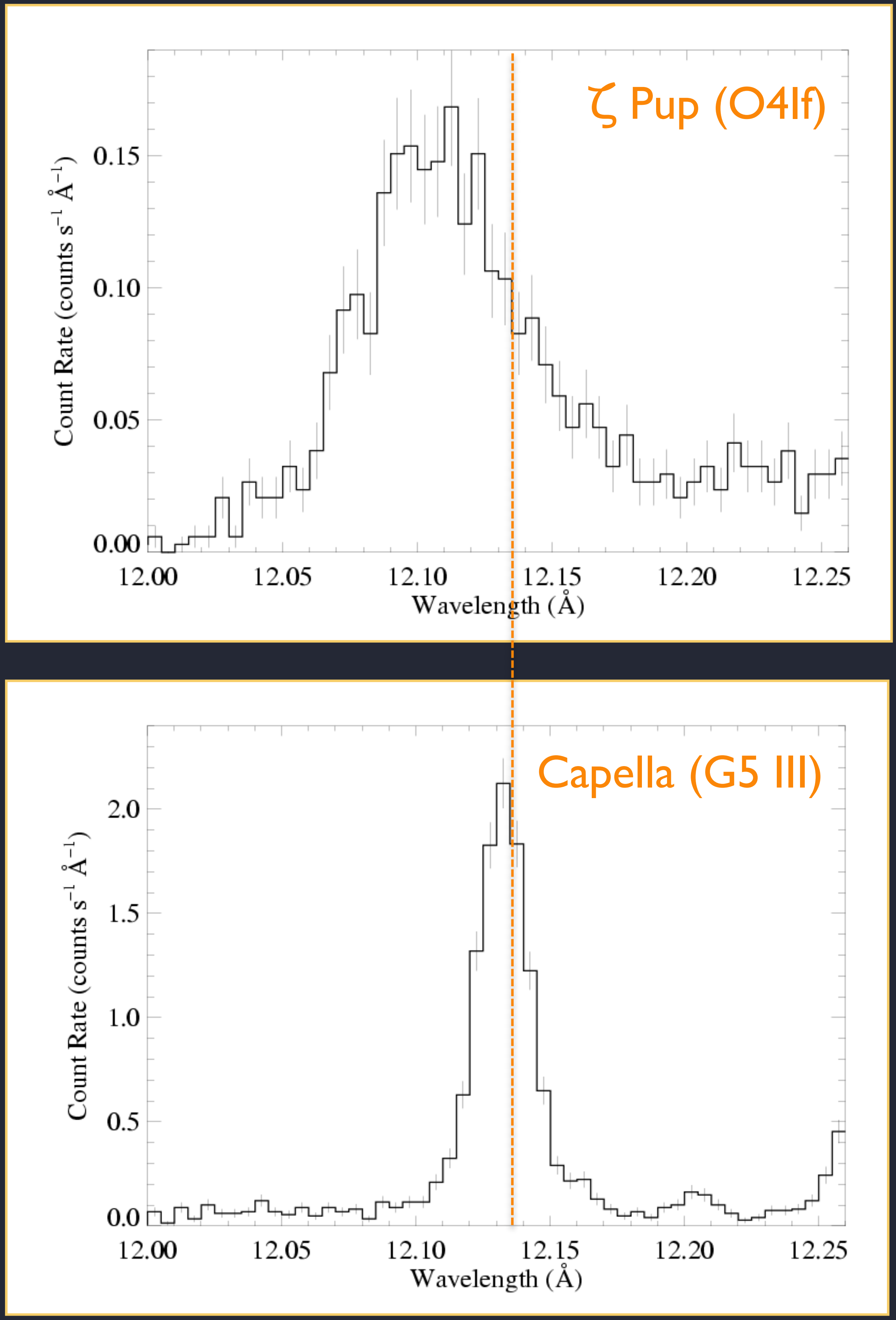


Capella (G5 III)

A careful look at the individual emission lines

characteristic *asymmetry*

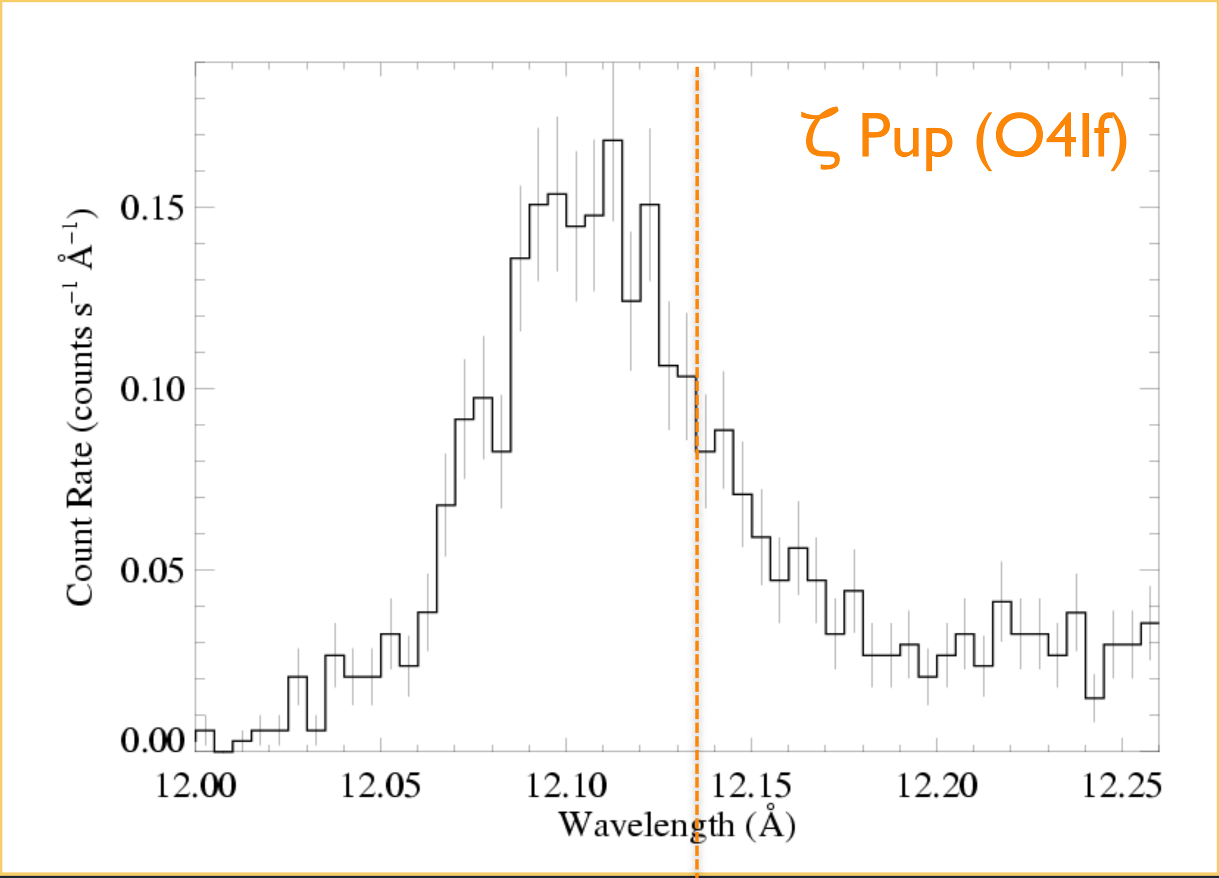
blue-shifted peak
& skewness

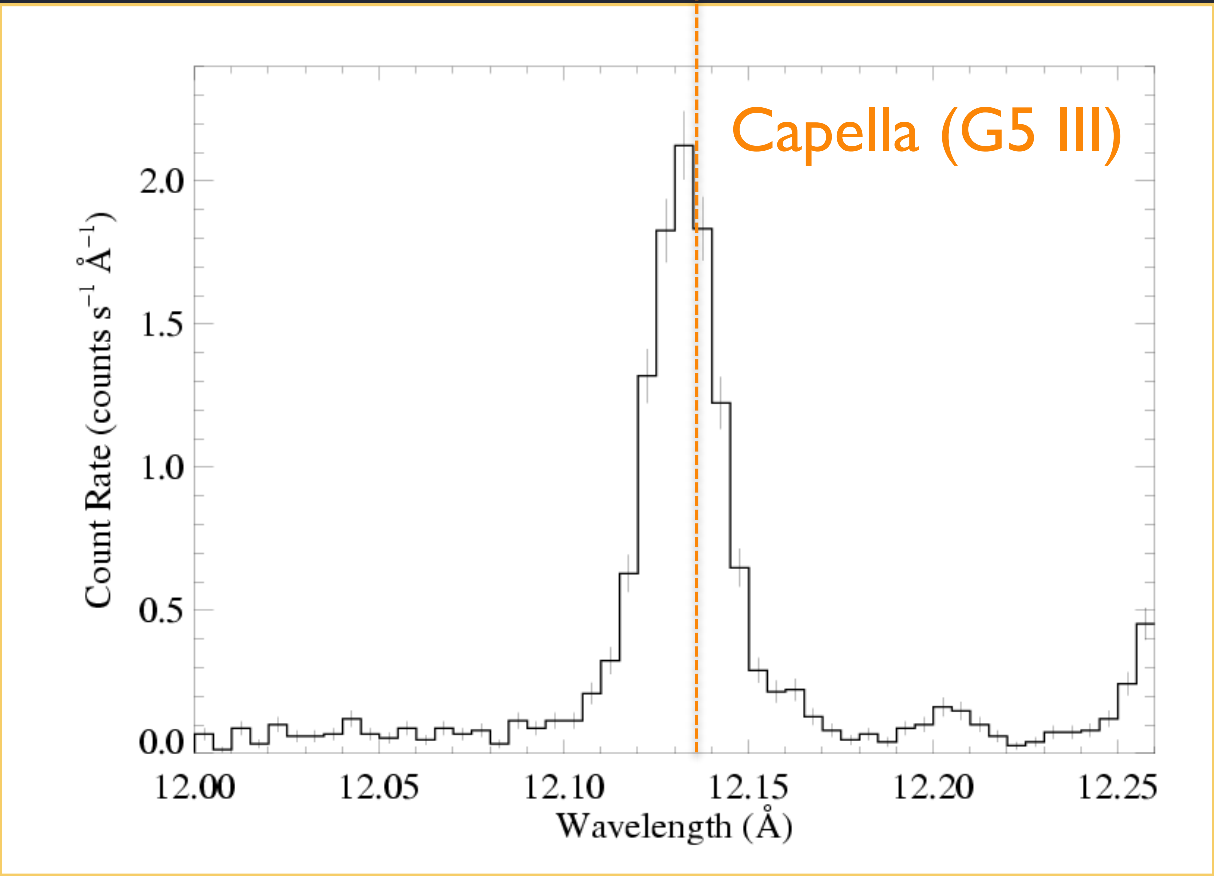


A careful look at the individual emission lines

characteristic *asymmetry*

How can this be explained in the context of embedded wind shocks (EWS)?

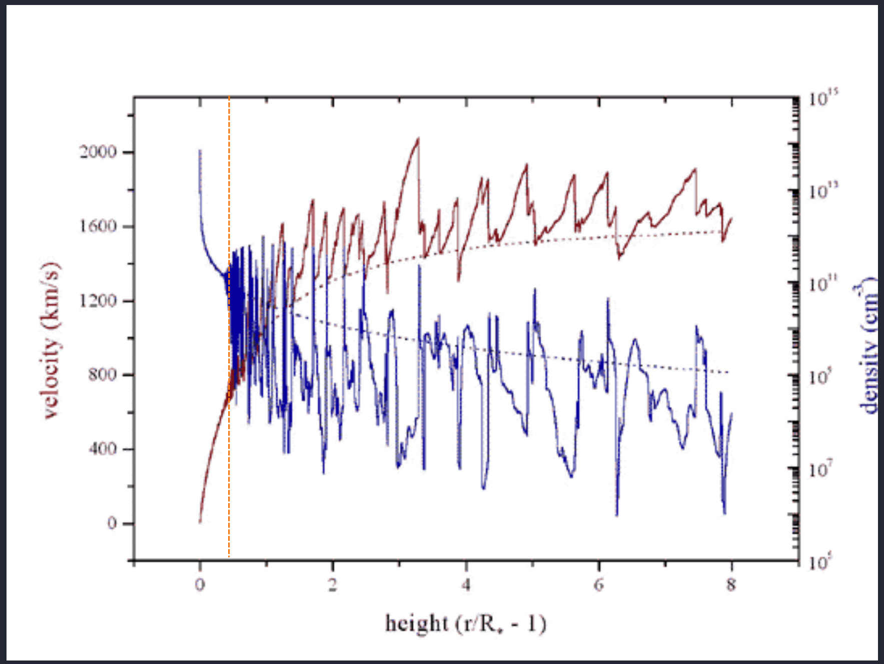




We need a model that...

captures the basic physical properties of the hydro simulations of the LDI

but is simple enough to parameterize and fit to data



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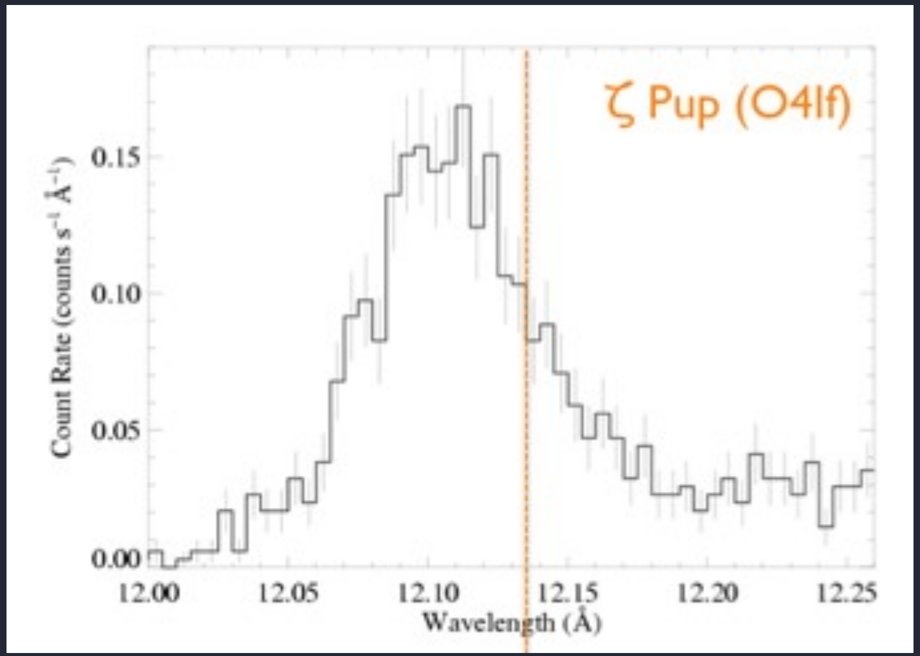
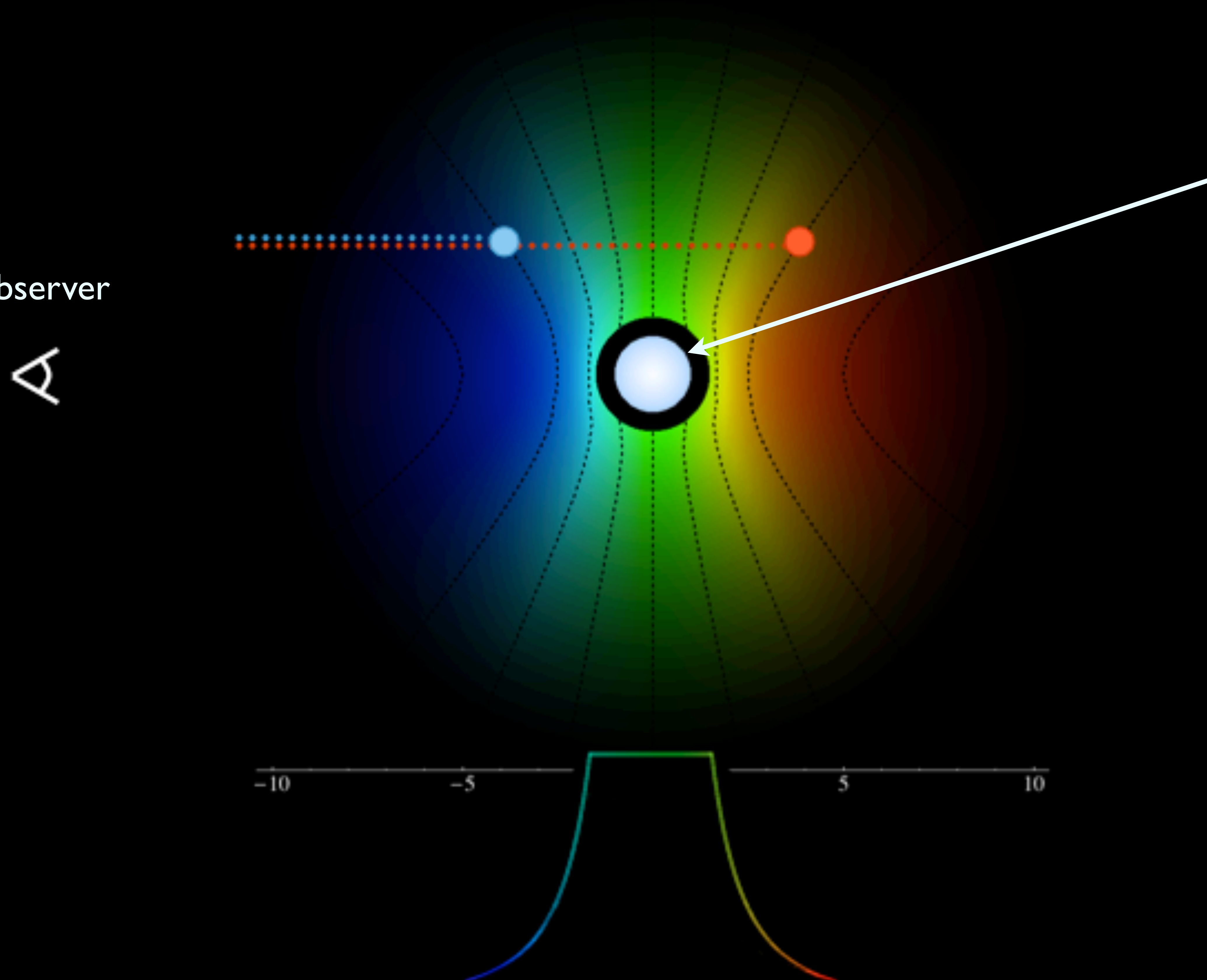
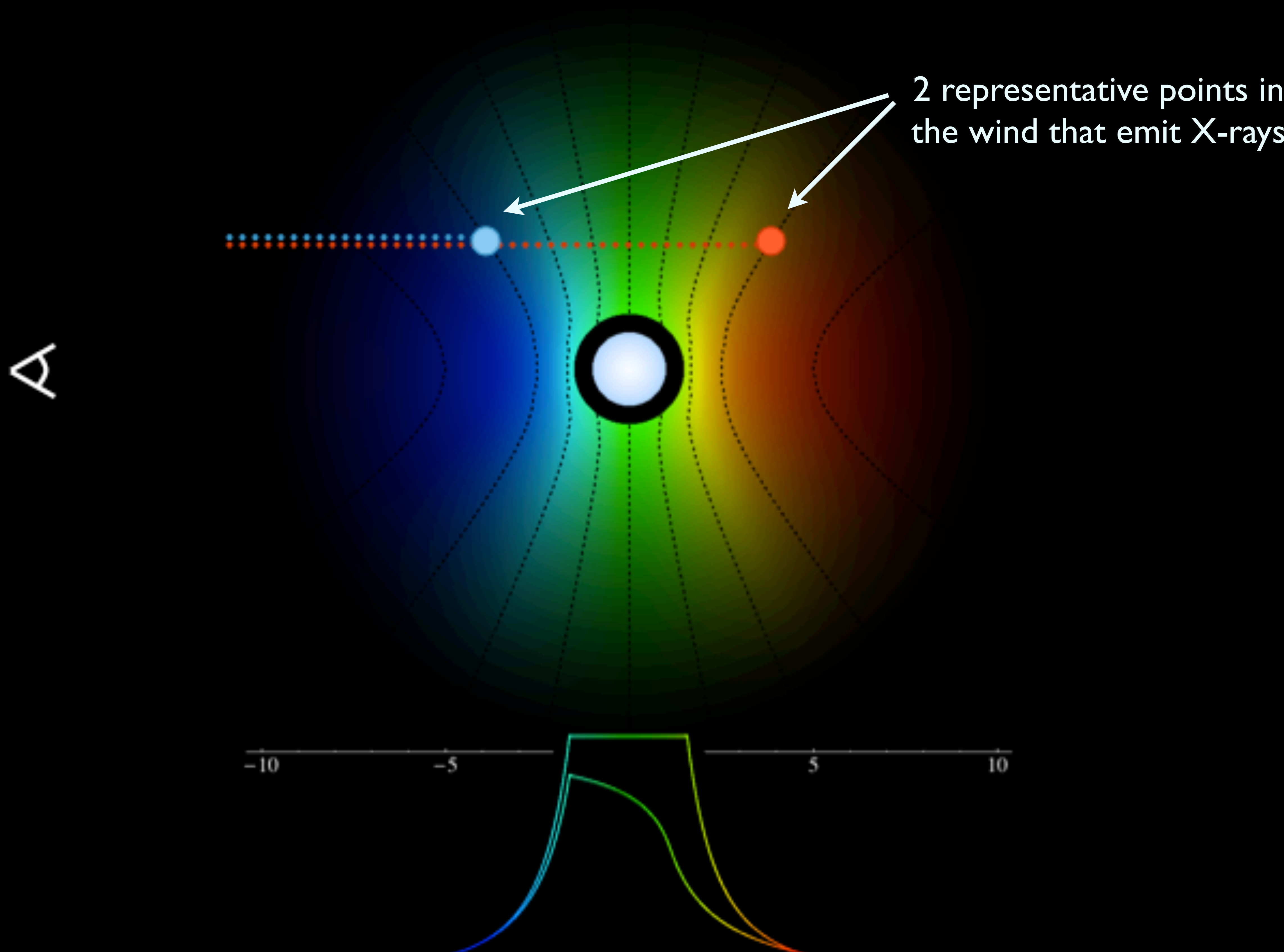


Line Asymmetry

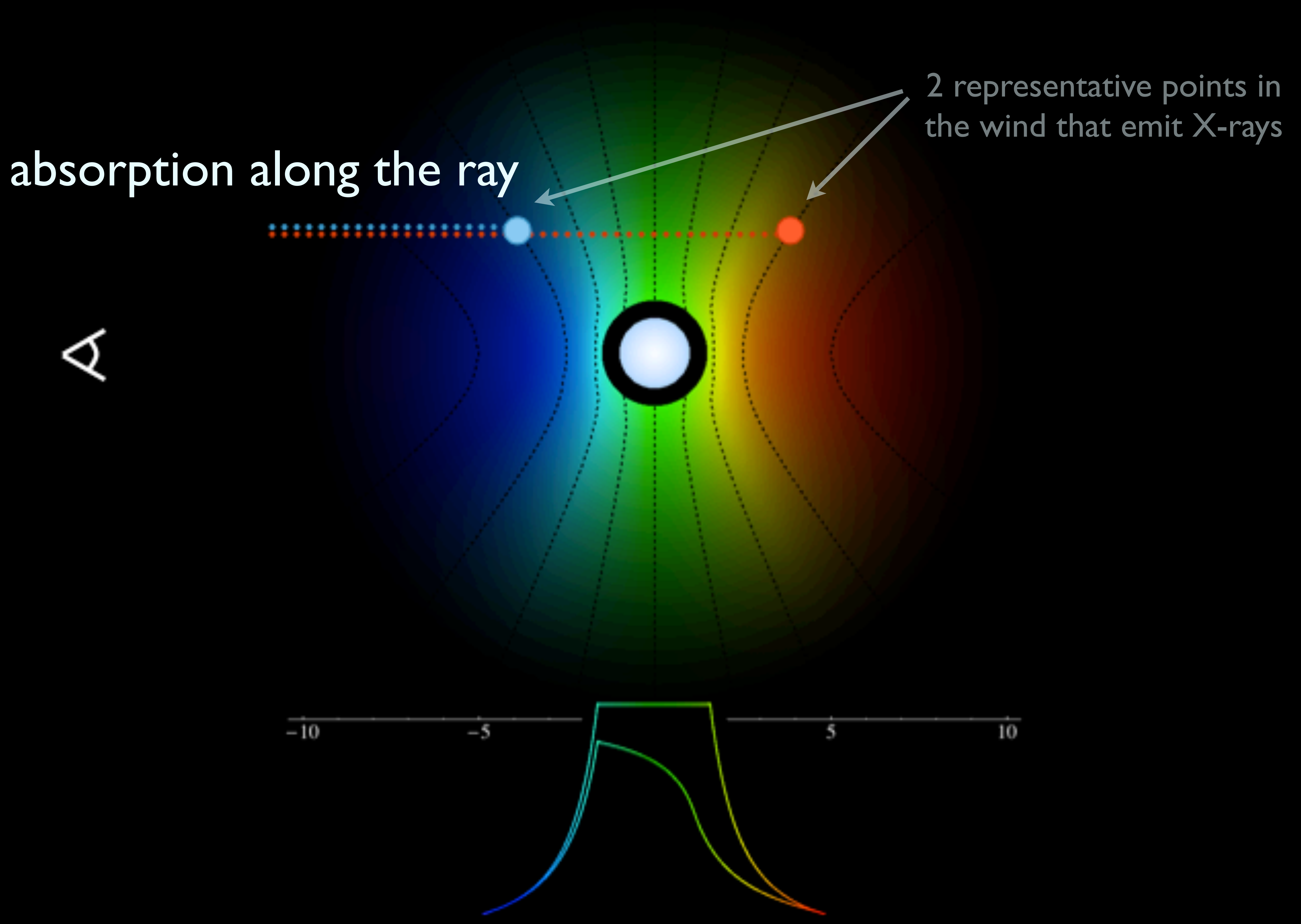
Emma Wollman ('09)
Roban Kramer ('03)



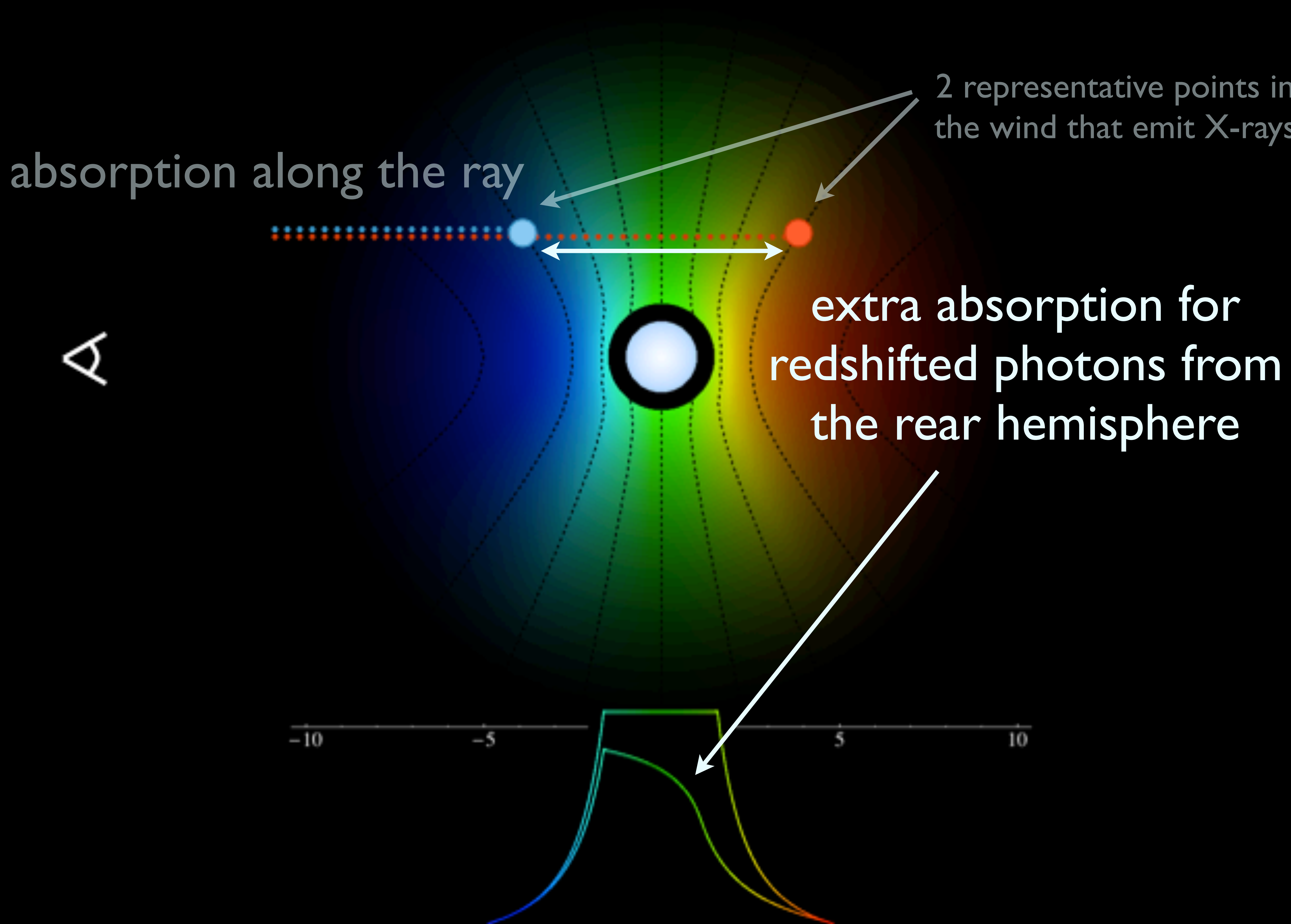
Line Asymmetry



Line Asymmetry

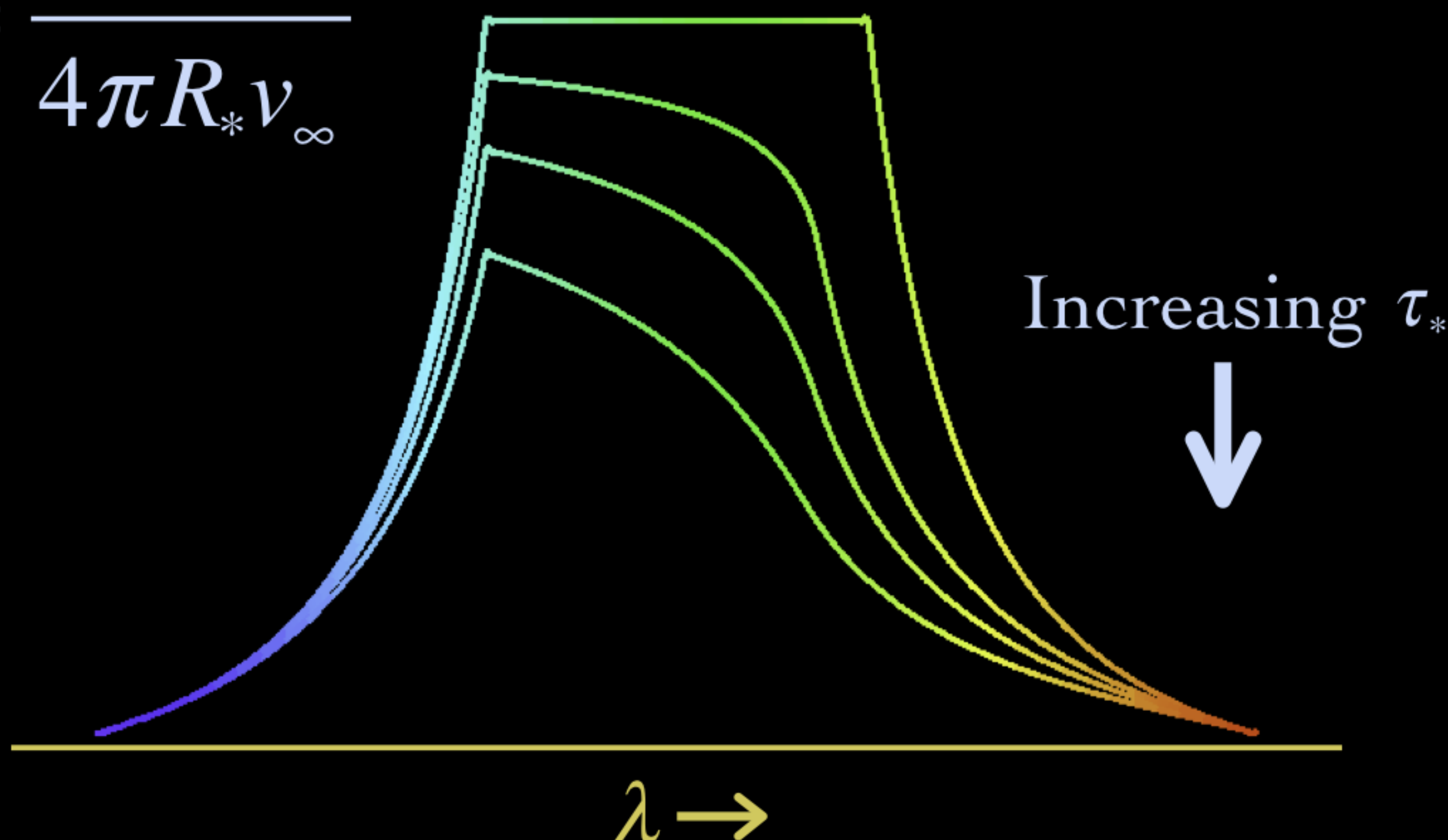


Line Asymmetry

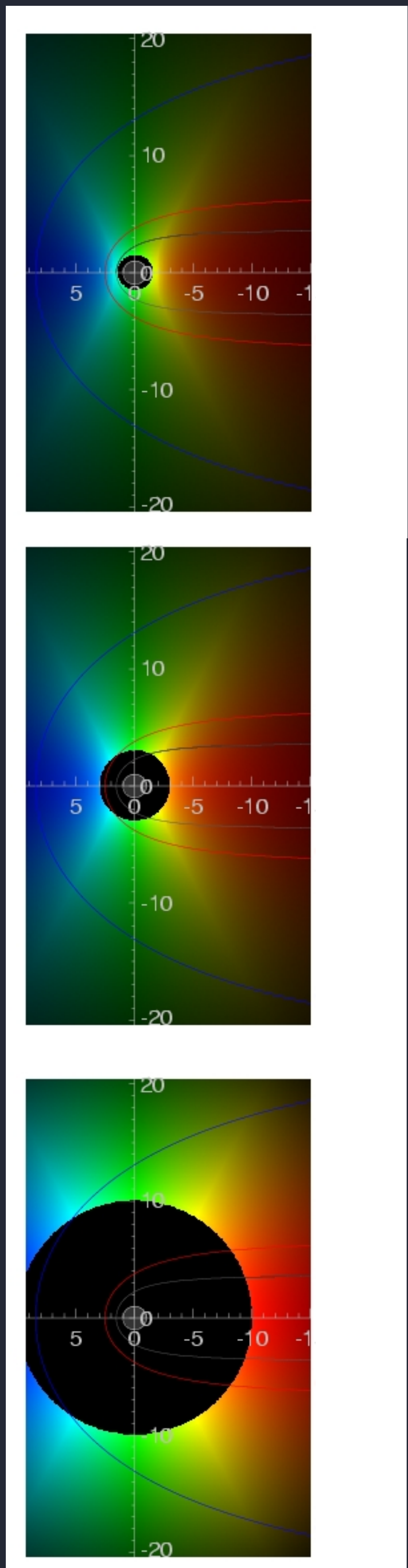


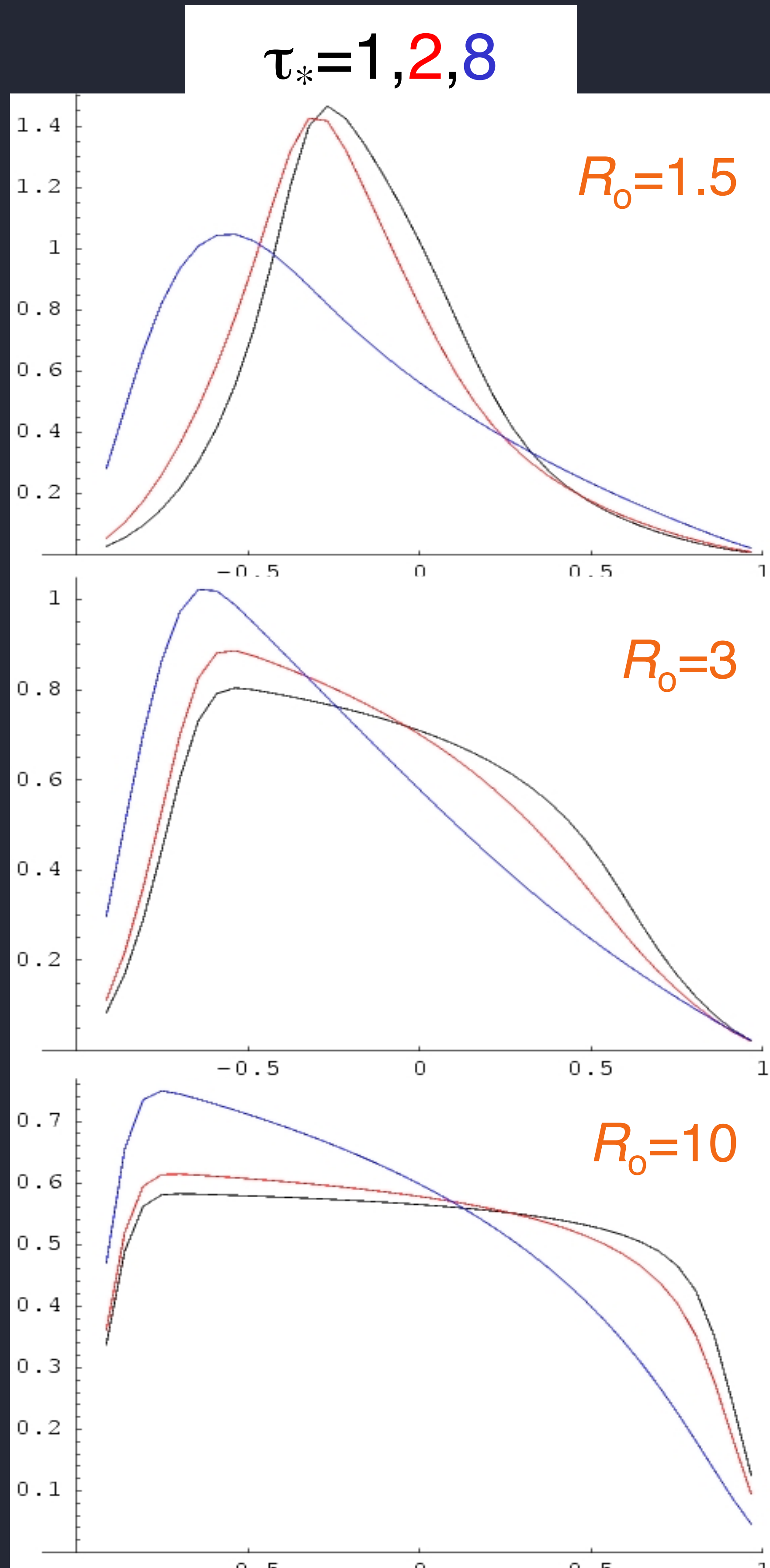
Wind Profile Model

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



Line profile shapes





key parameters: R_o & $\tau_\star$

$$v = v_\infty (1 - r/R_\star)^\beta$$

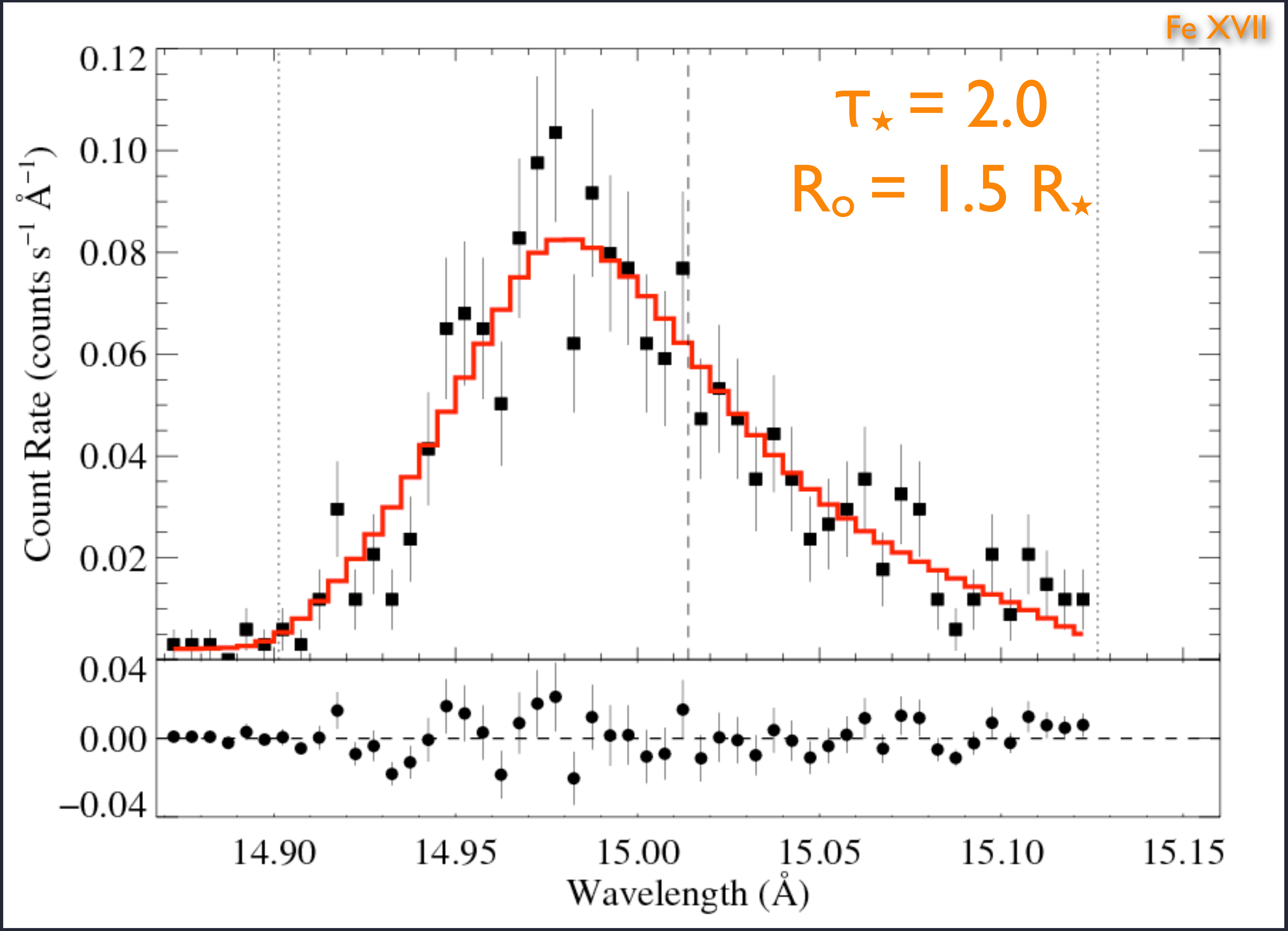
$$j \sim \rho^2 \text{ for } r/R_* > R_o, \quad = 0 \text{ otherwise}$$

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

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

Model is fit to data

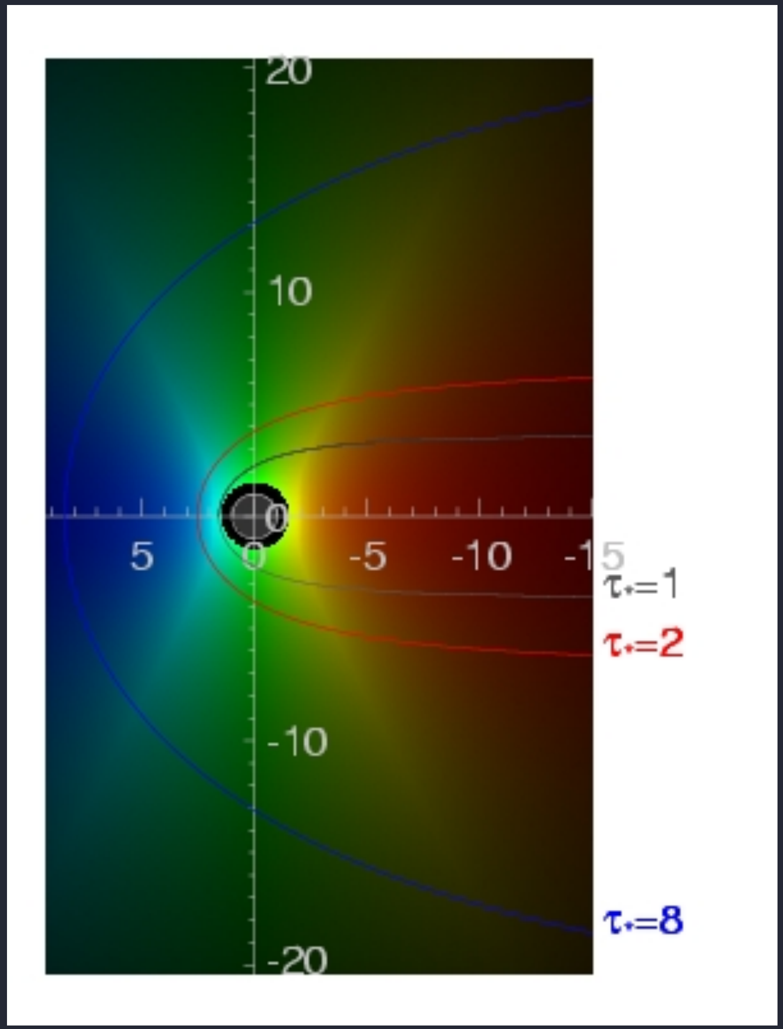
ζ Pup: *Chandra*



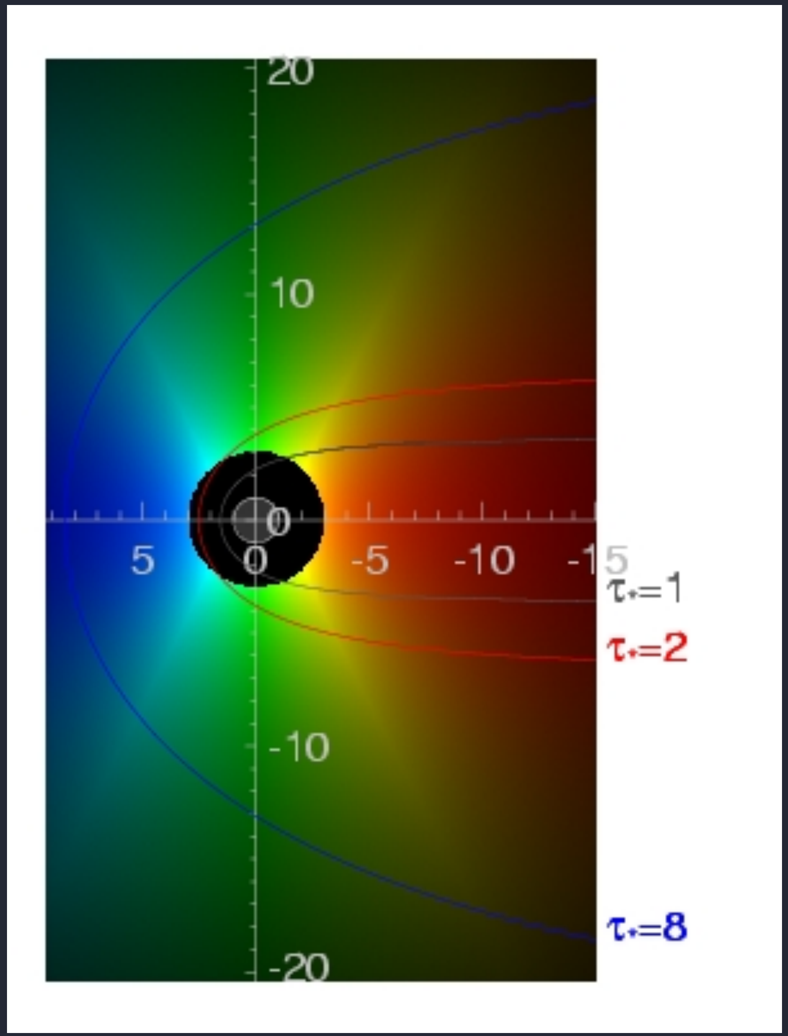
Hot plasma kinematics and location

R_o controls the line width via v(r)

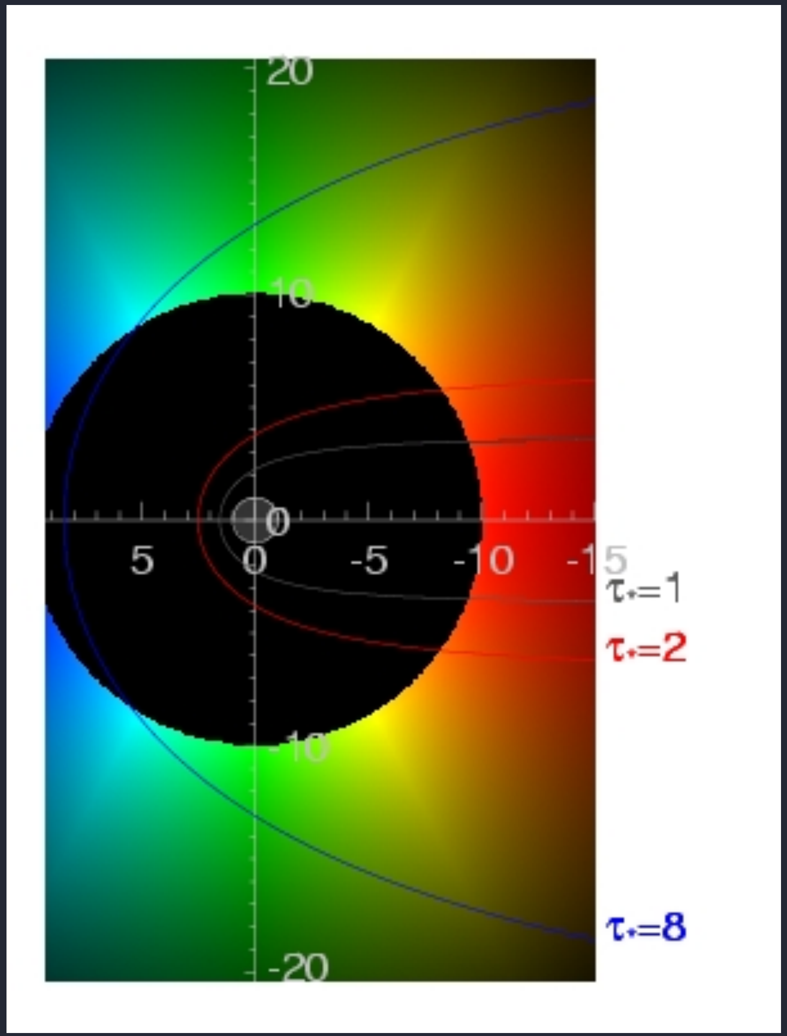
$R_o = 1.5 R_\star$



$R_o = 3 R_\star$

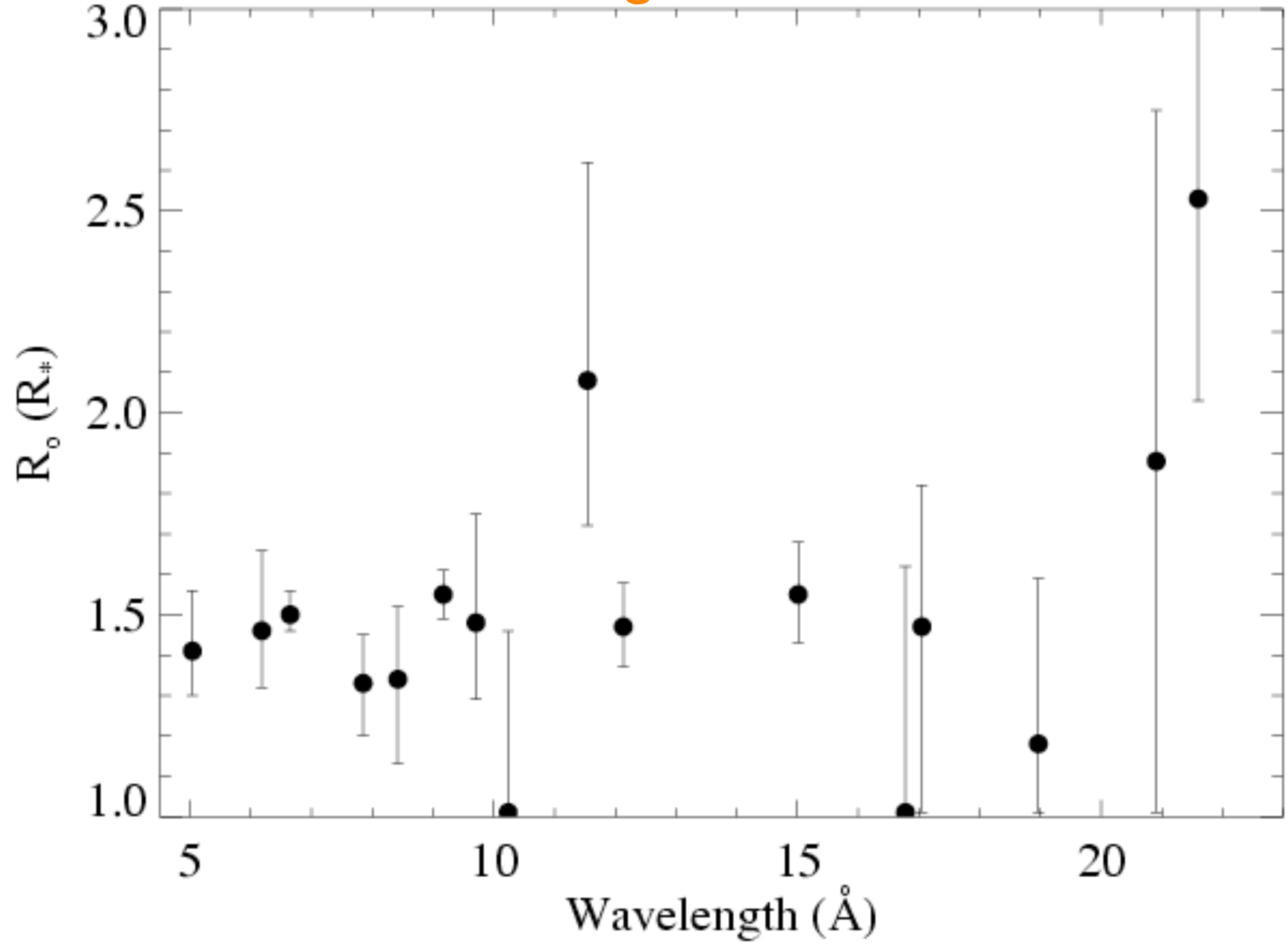


$R_o = 10 R_\star$

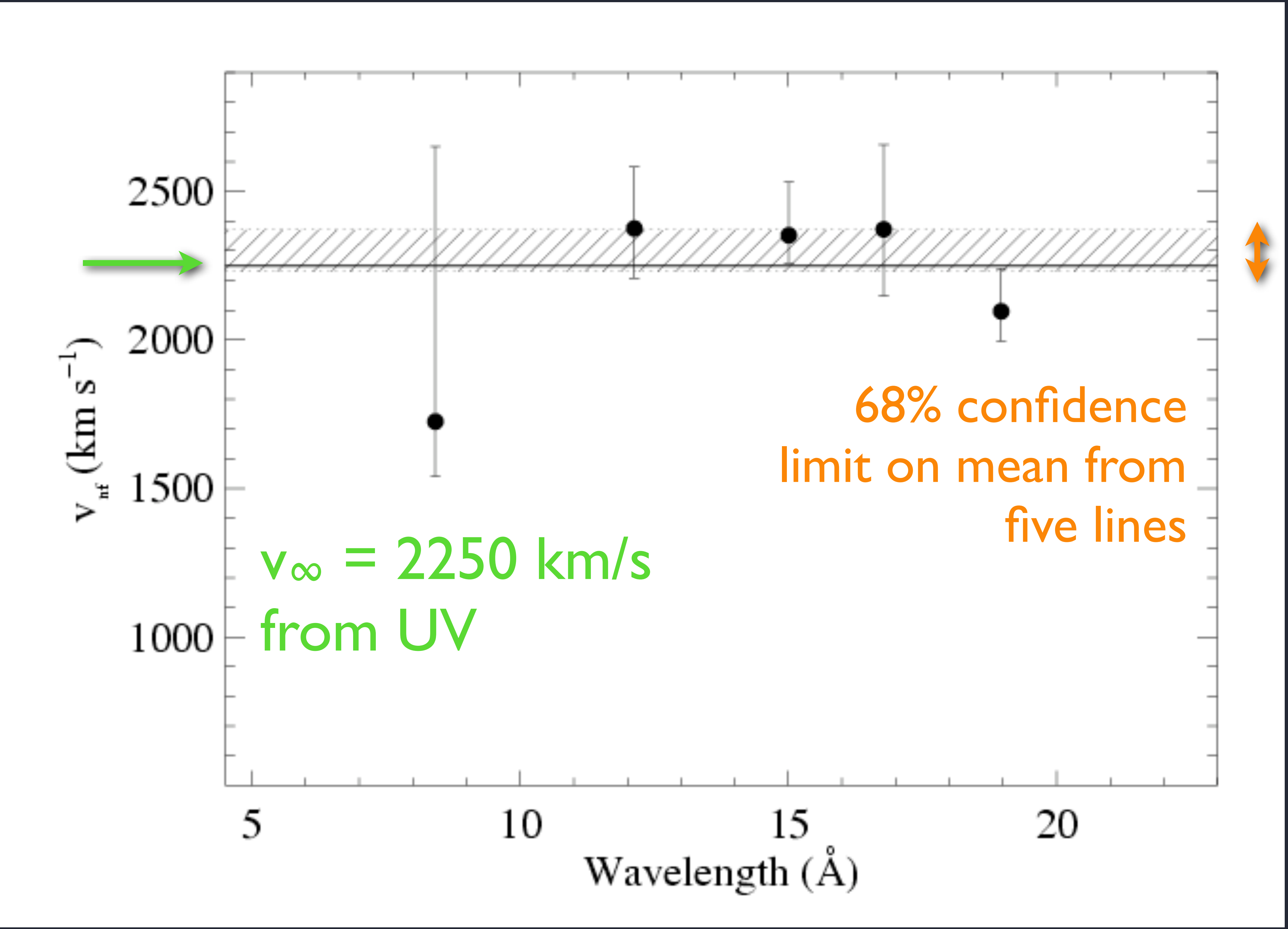


Distribution of R_o values for ζ Pup

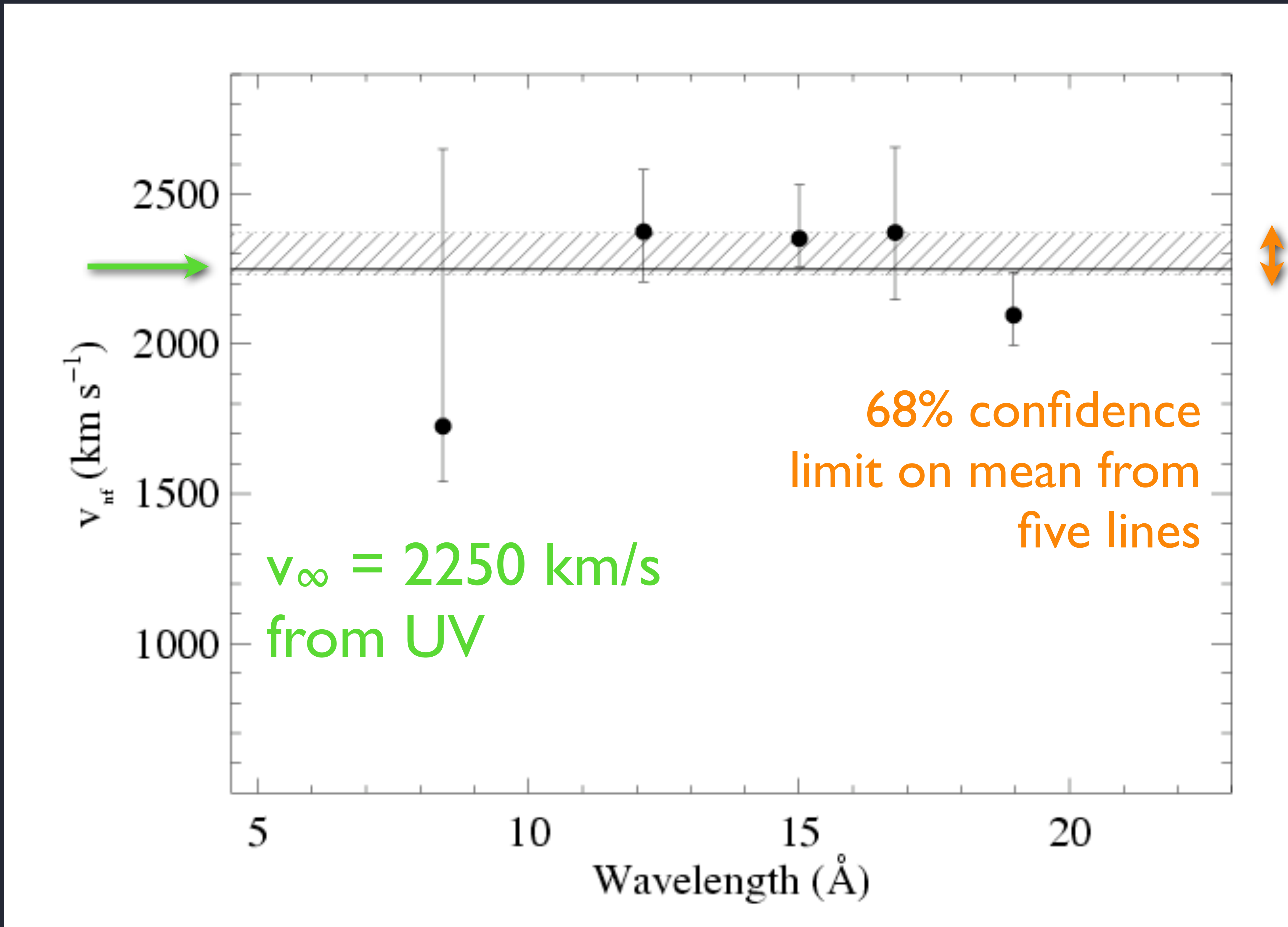
consistent with a global value of $R_o = 1.5\ R_\star$



v∞ can be constrained by the line fitting too



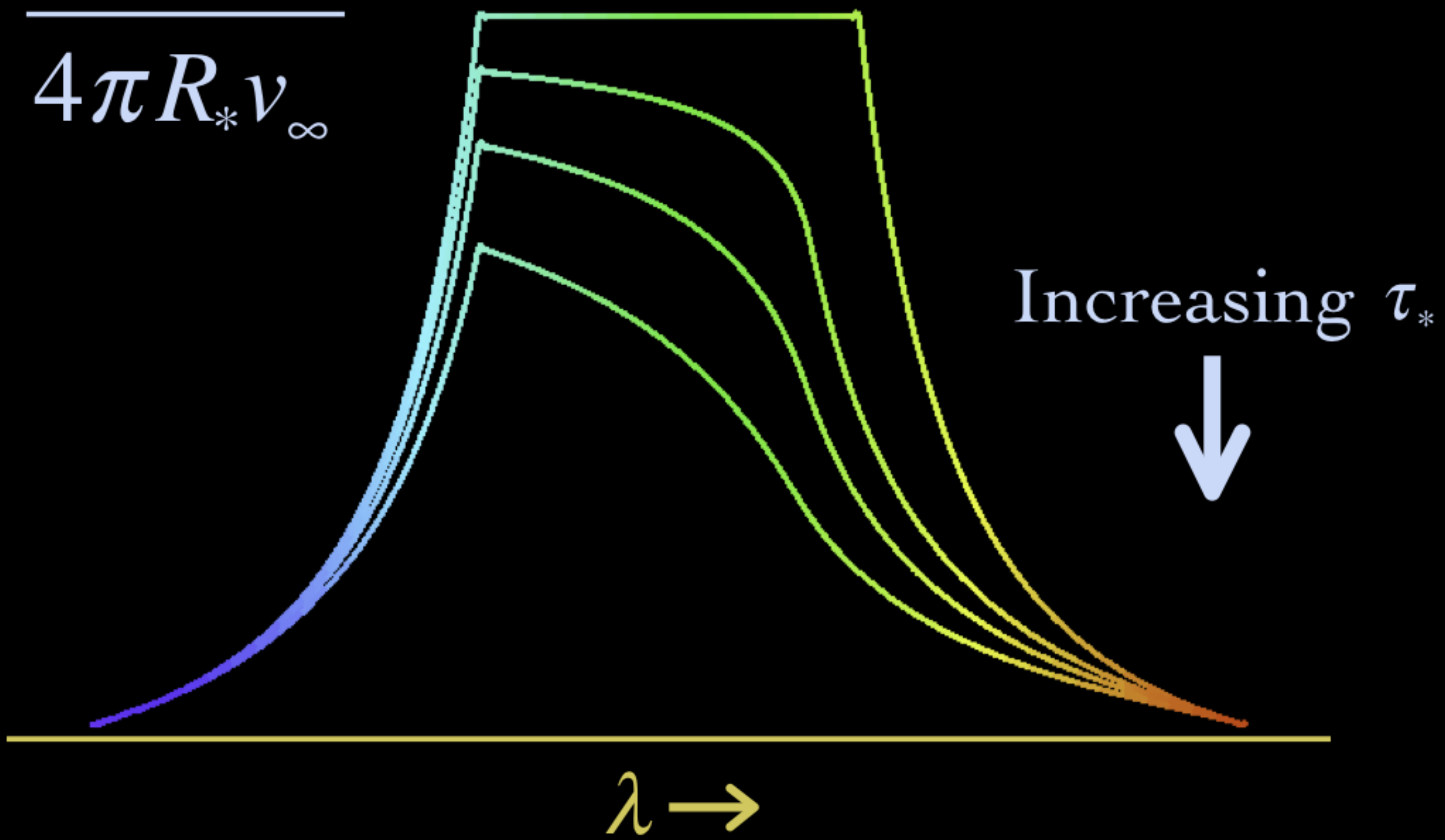
X-ray plasma and mean wind have same kinematics



The profiles also tell us about the level of wind absorption

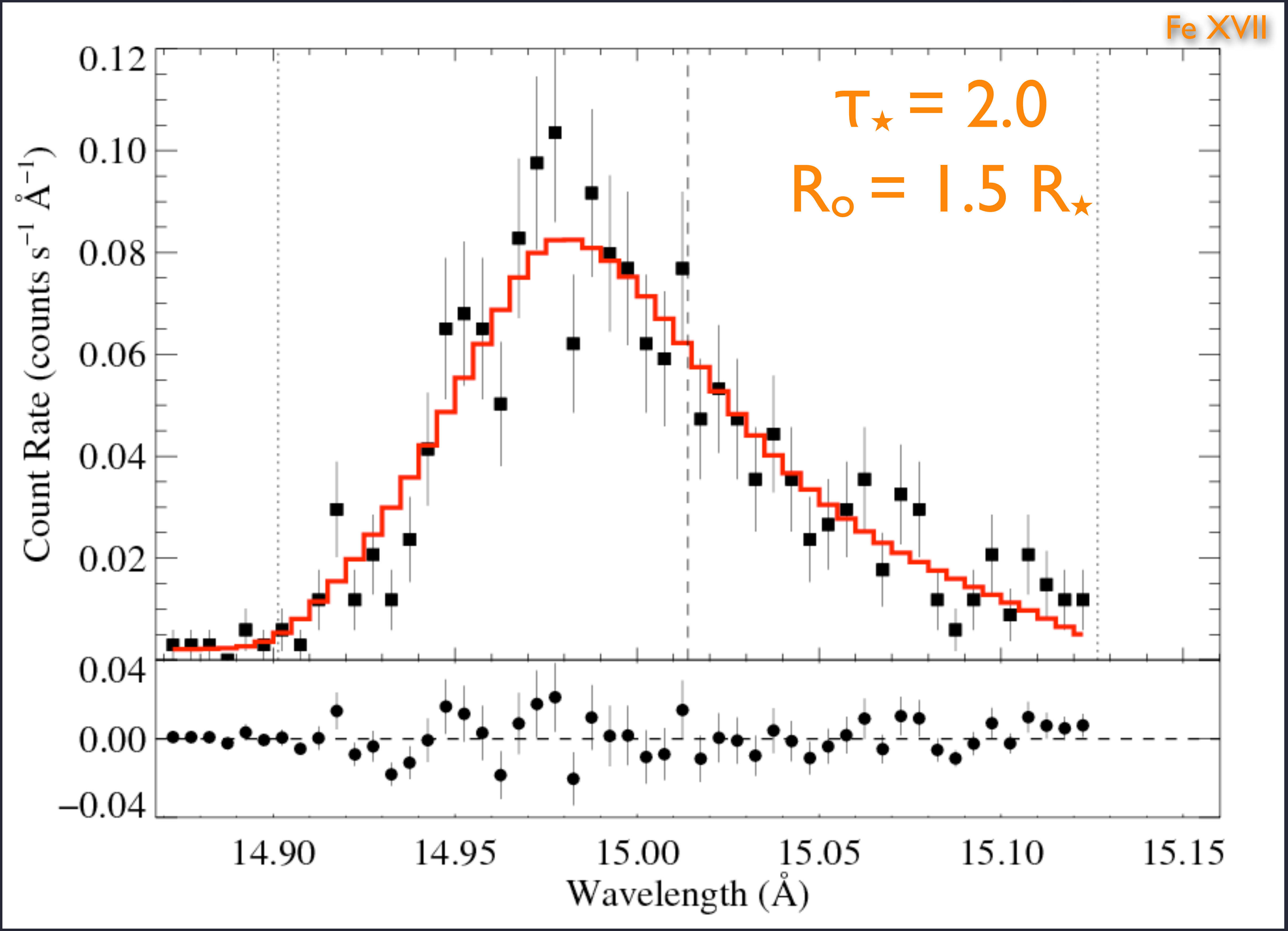
Wind Profile Model

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



Model is fit to data

ζ Pup: *Chandra*



Quantifying the wind optical depth

opacity of the cold wind component (due to bound-free transitions in C, N, O, Ne, Fe)

wind mass-loss rate

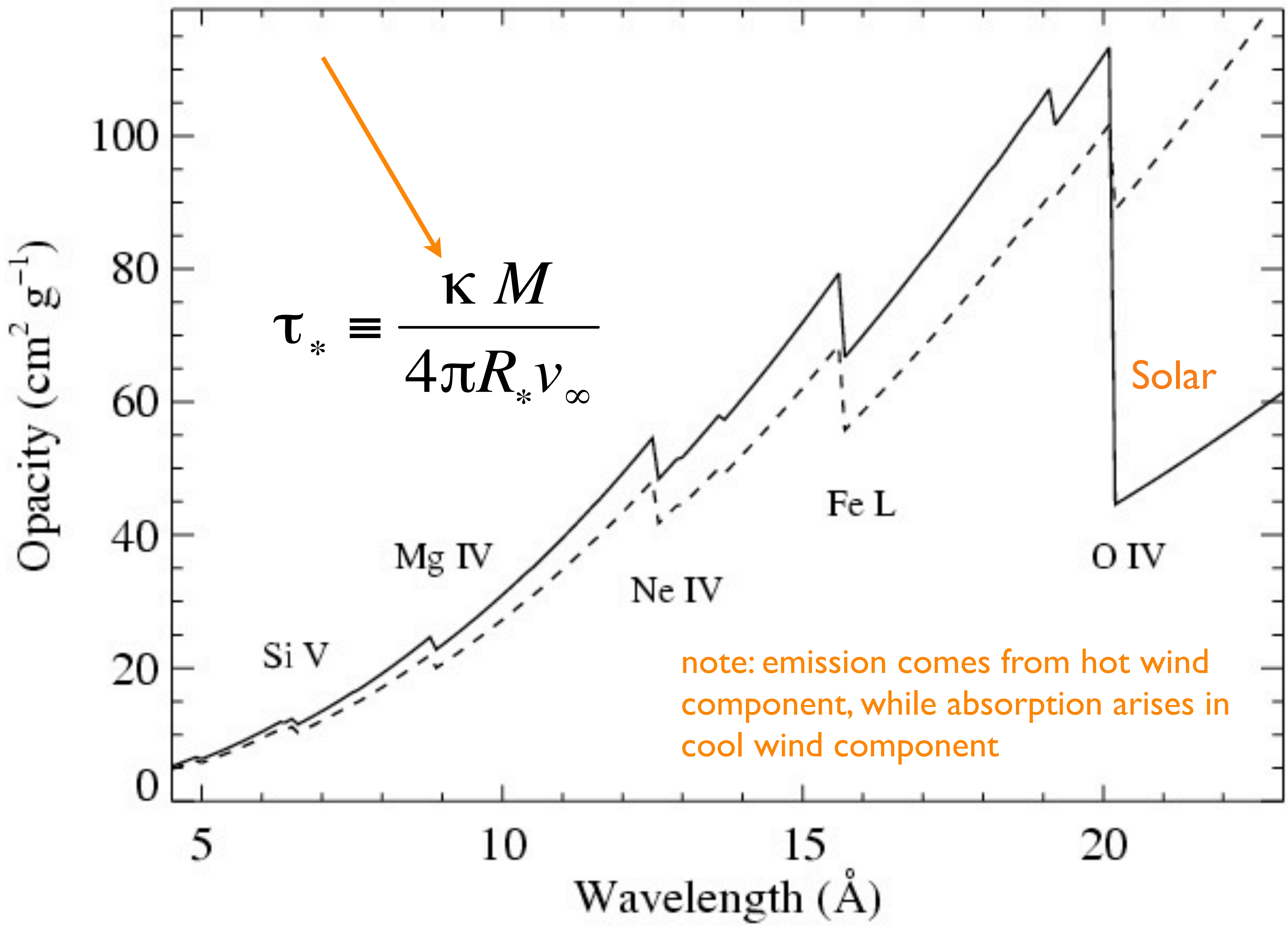
$$\dot{M} = 4\pi r^2 v \rho$$

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

stellar radius

wind terminal velocity

soft X-ray wind opacity

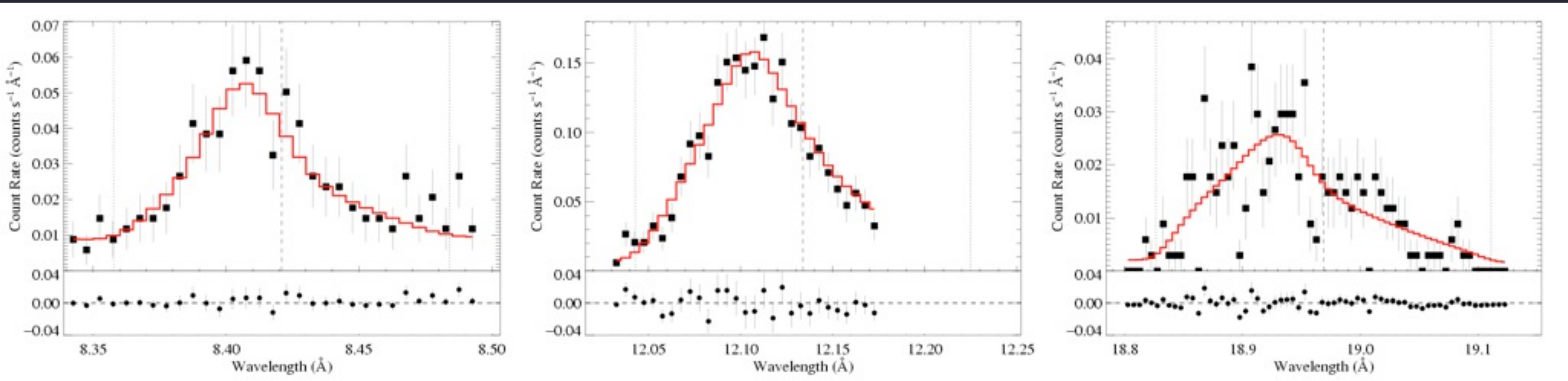


$$\tau_* \equiv \frac{\kappa M}{4\pi R_* v_\infty}$$

note: emission comes from hot wind component, while absorption arises in cool wind component

ζ Pup *Chandra*: three emission lines

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

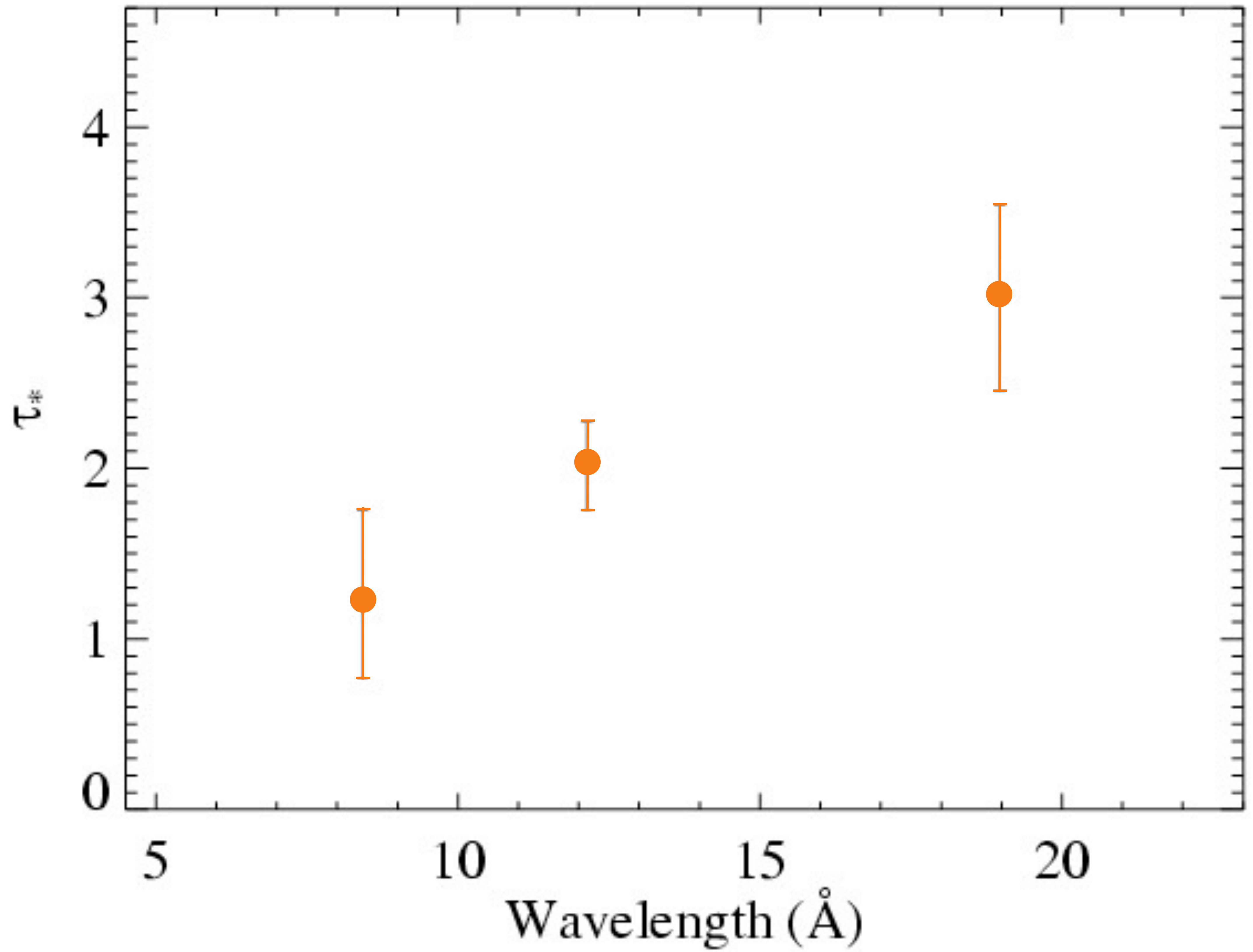


$\tau_* \sim 1$ $\tau_* \sim 2$ $\tau_* \sim 3$

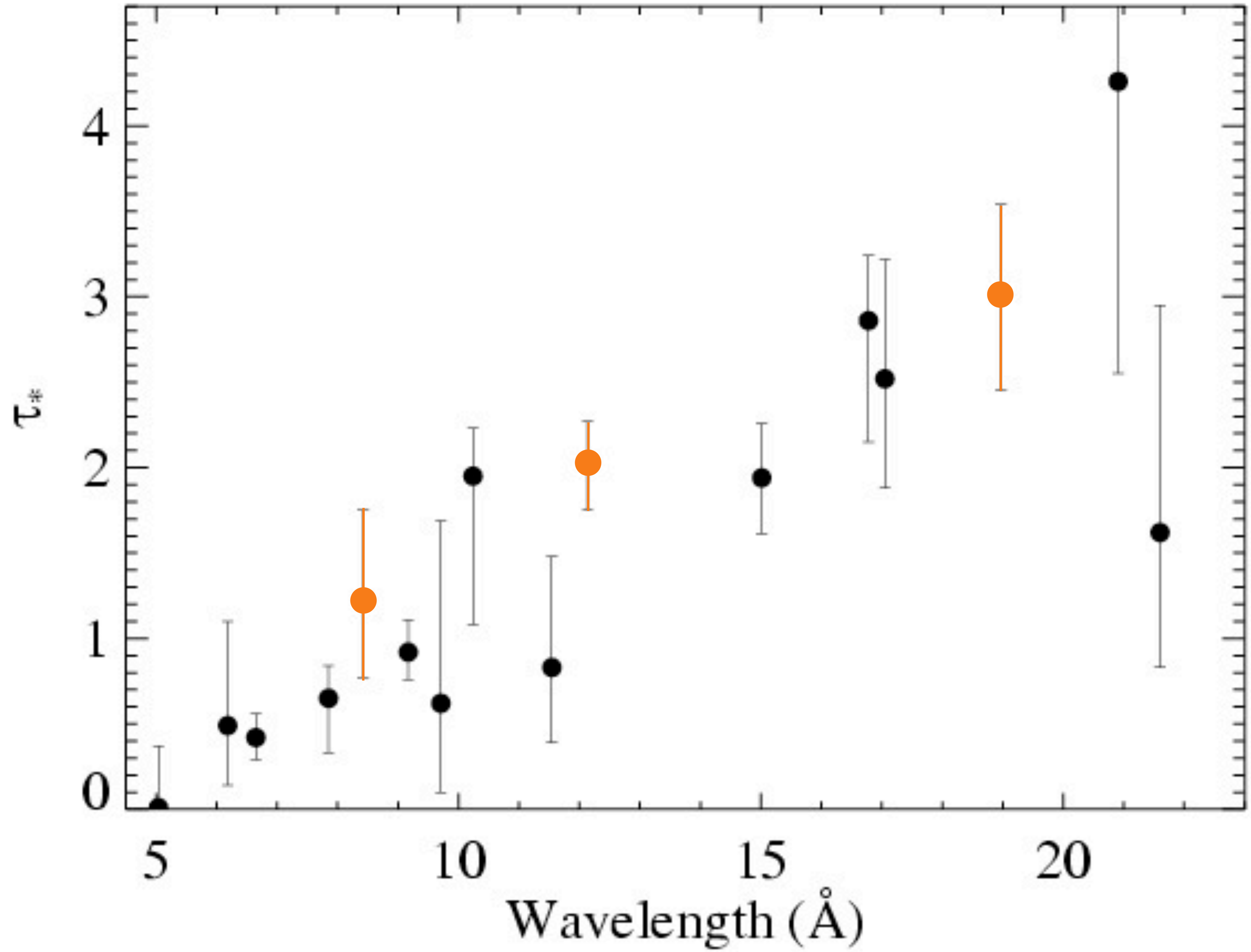
Recall:

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

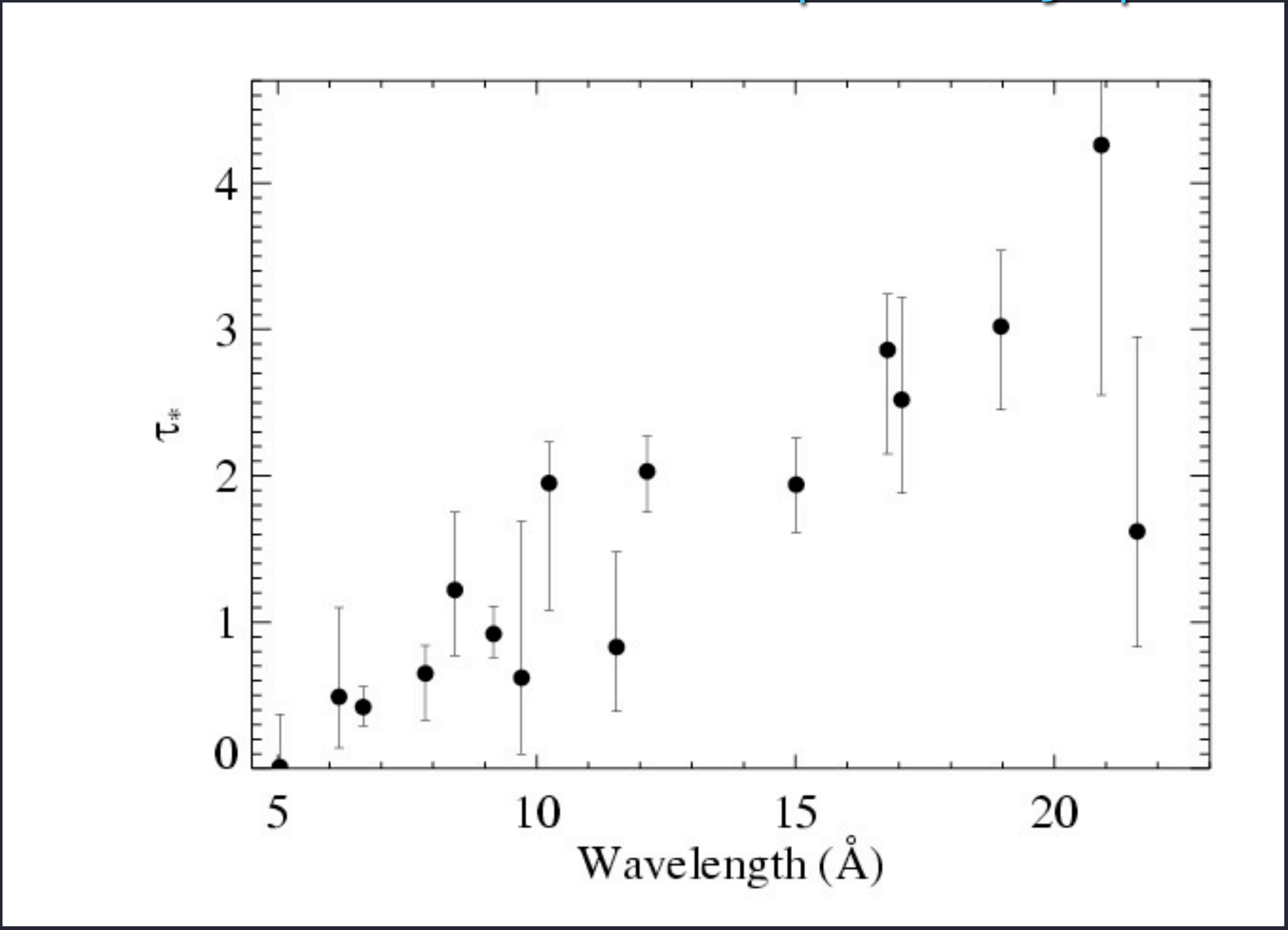
Results from the 3 line fits shown previously



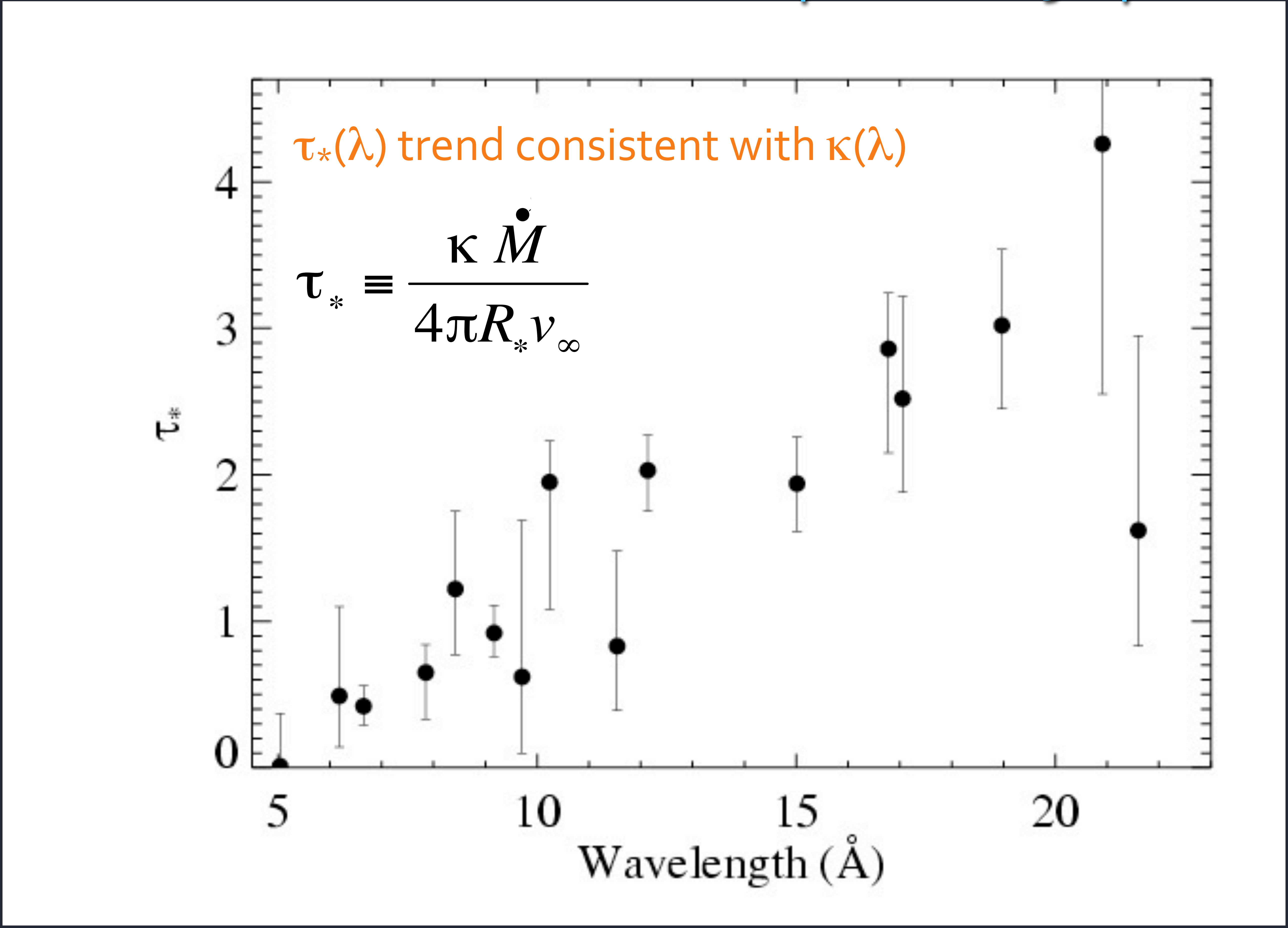
Fits to 16 lines in the *Chandra* spectrum of ζ Pup



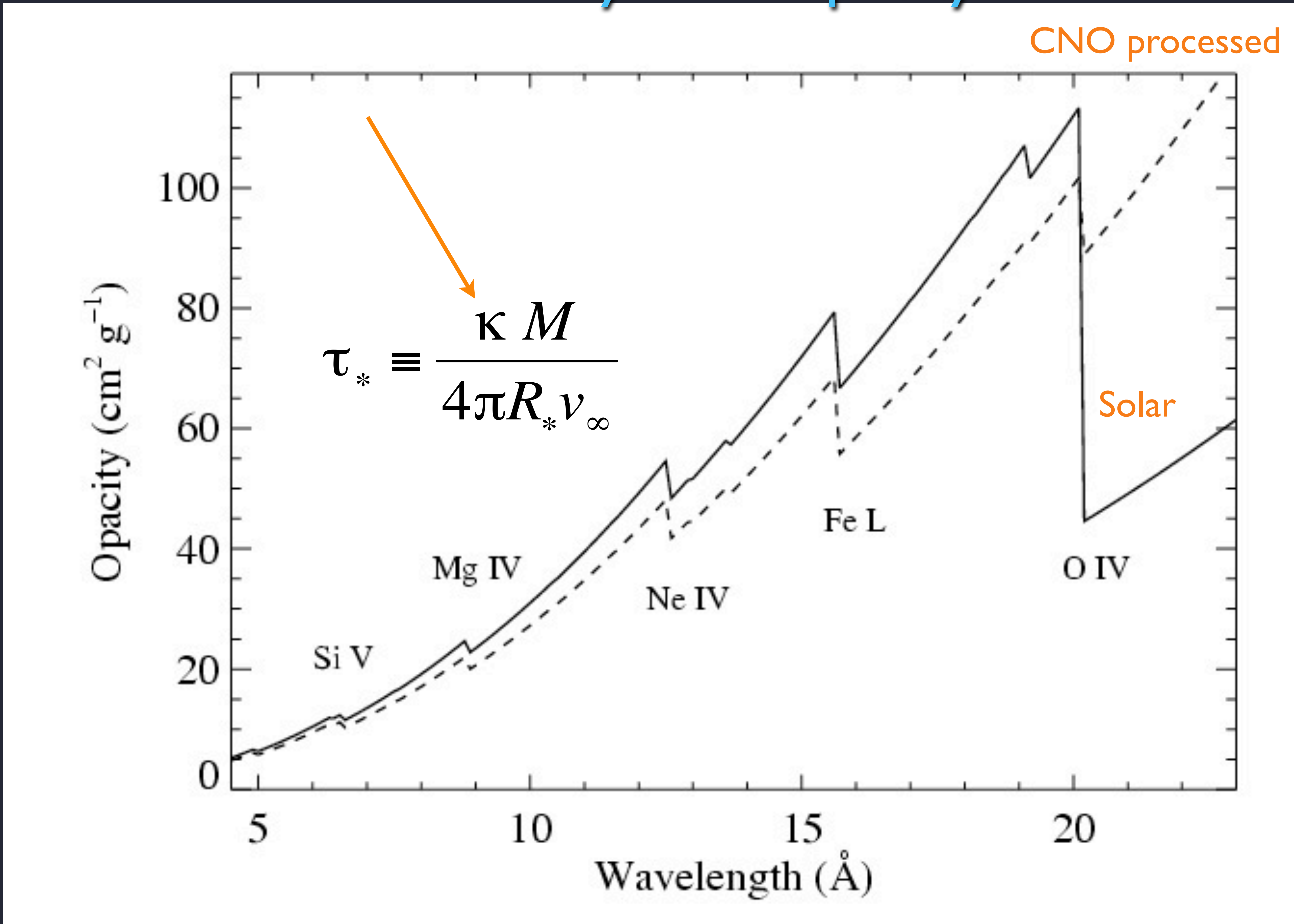
Fits to 16 lines in the *Chandra* spectrum of ζ Pup



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

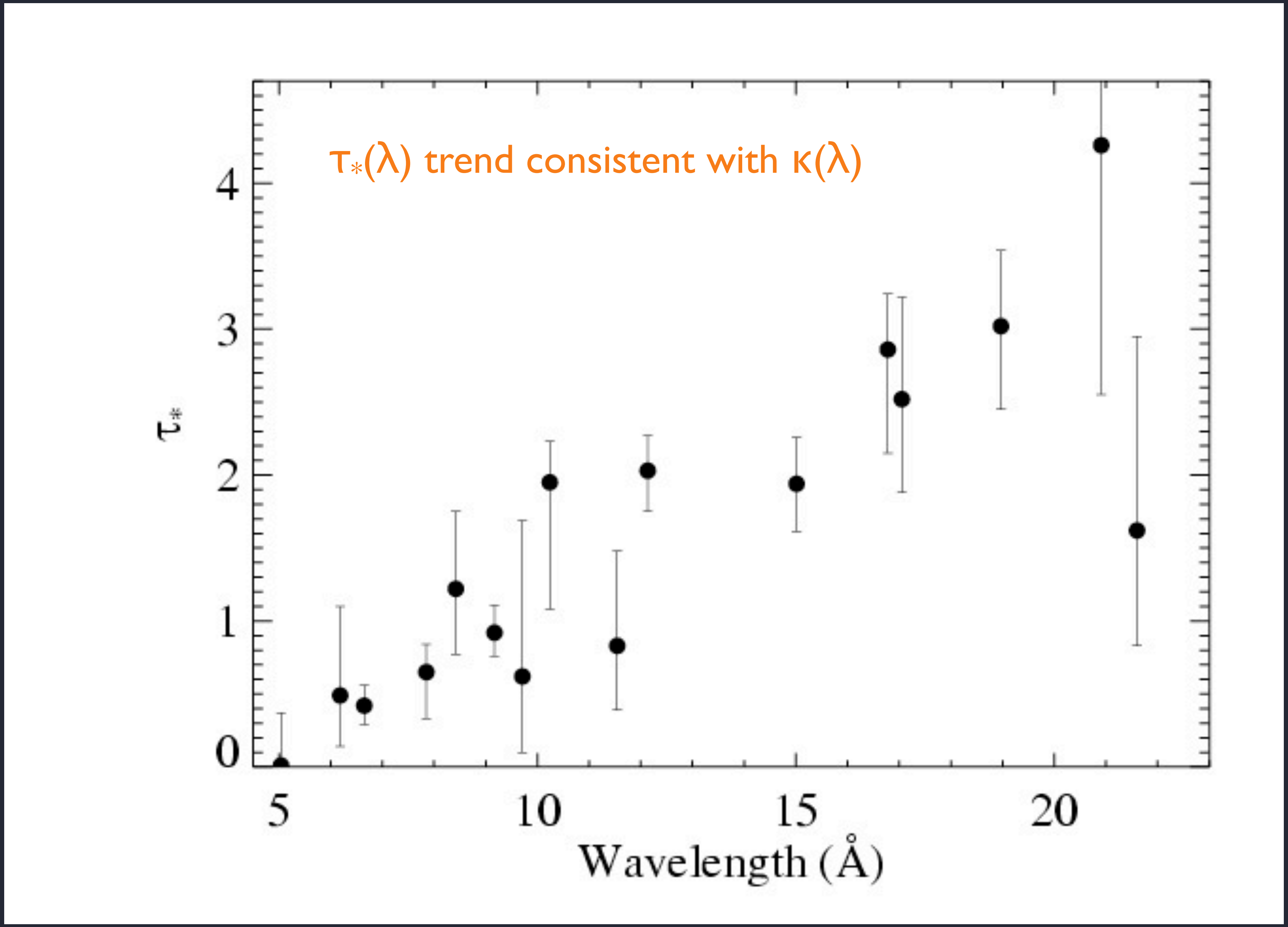


soft X-ray wind opacity



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

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



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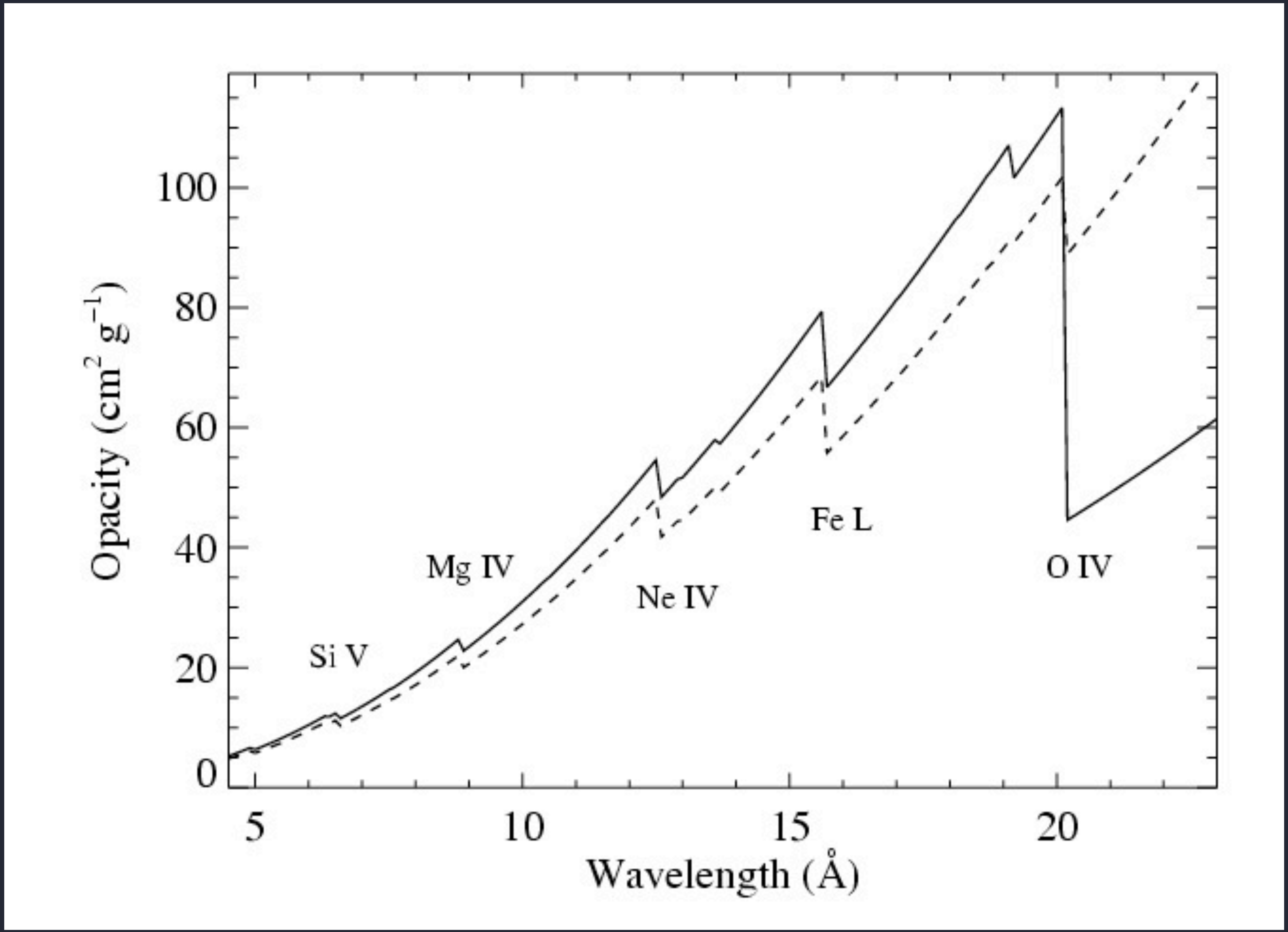
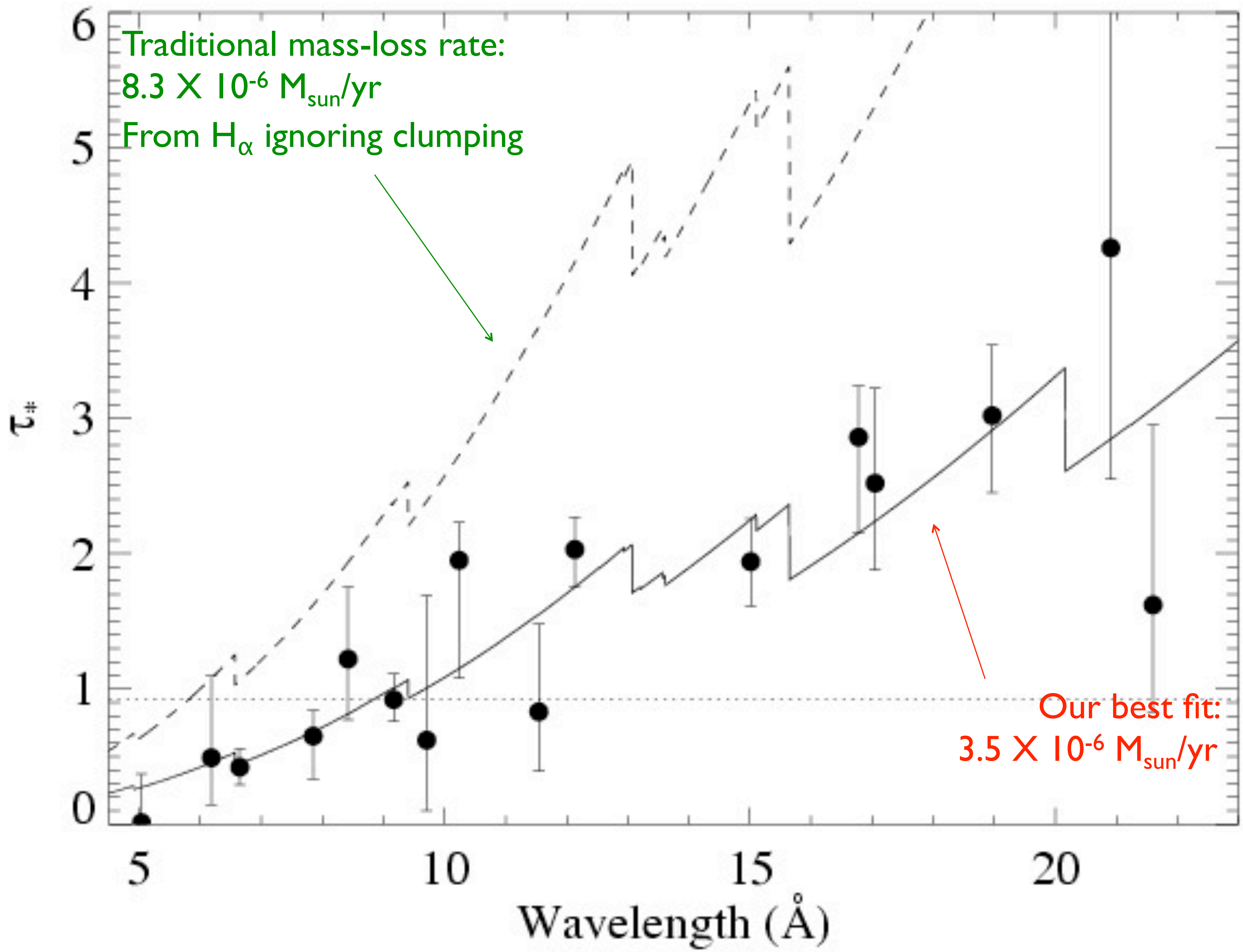
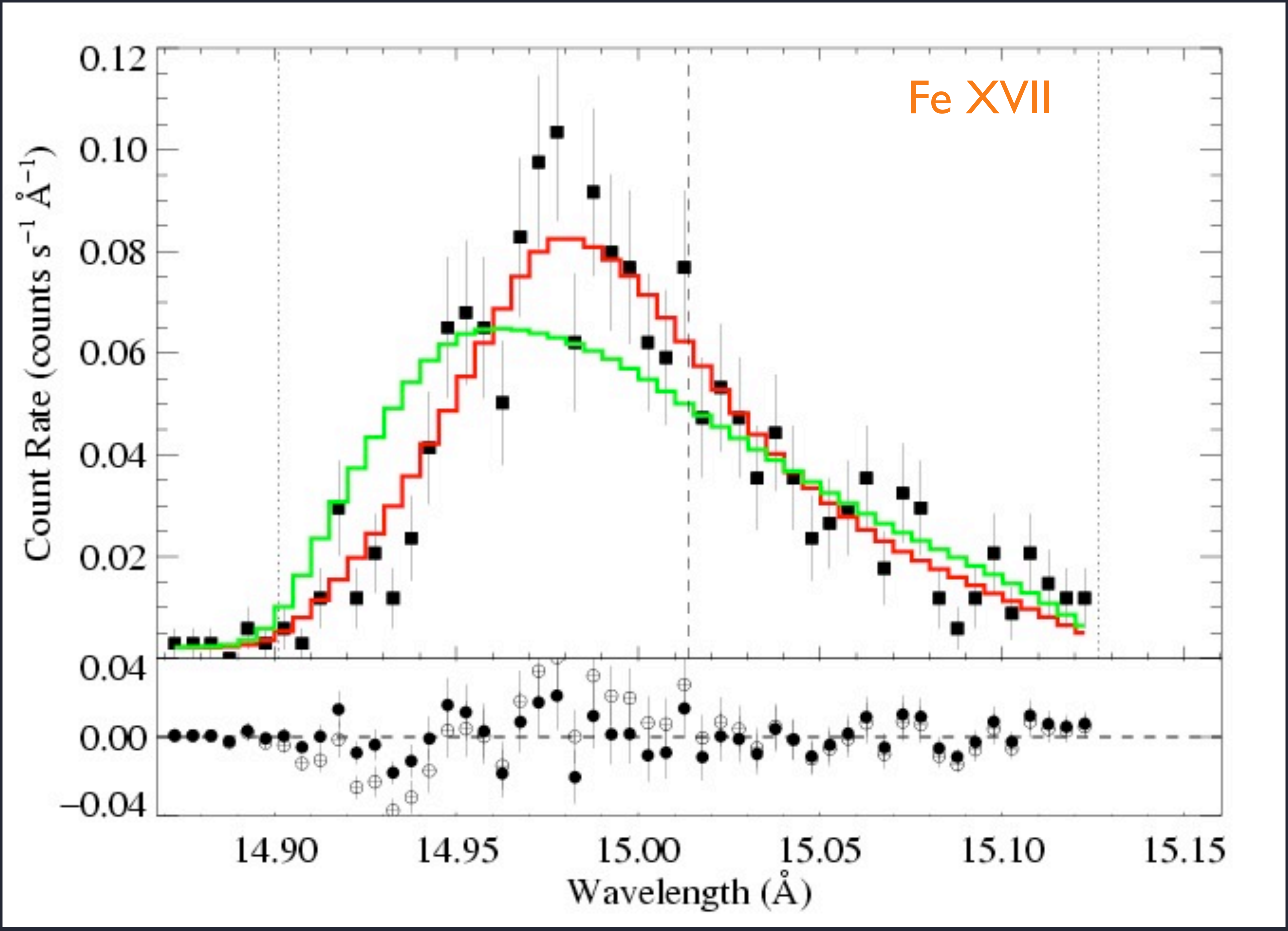



Traditional mass-loss rate:
8.3 X 10^{-6} M_{sun}/yr
From H_α ignoring clumping
Our best fit:
3.5 X 10^{-6} M_{sun}/yr
τ_*
6
5
4
3
2
1
0
5
10
15
20
Wavelength (Å)


Fe XVII
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)

Preliminary Conclusions

1. Doppler-broadened line profiles tell us the kinematics of the shock-heated wind plasma

2. Line profile asymmetry tells us about the wind absorption; joint analysis of an ensemble of lines tells us the mass-loss rate of the wind

Preliminary Conclusions

1. Doppler-broadened line profiles tell us the kinematics of the shock-heated wind plasma

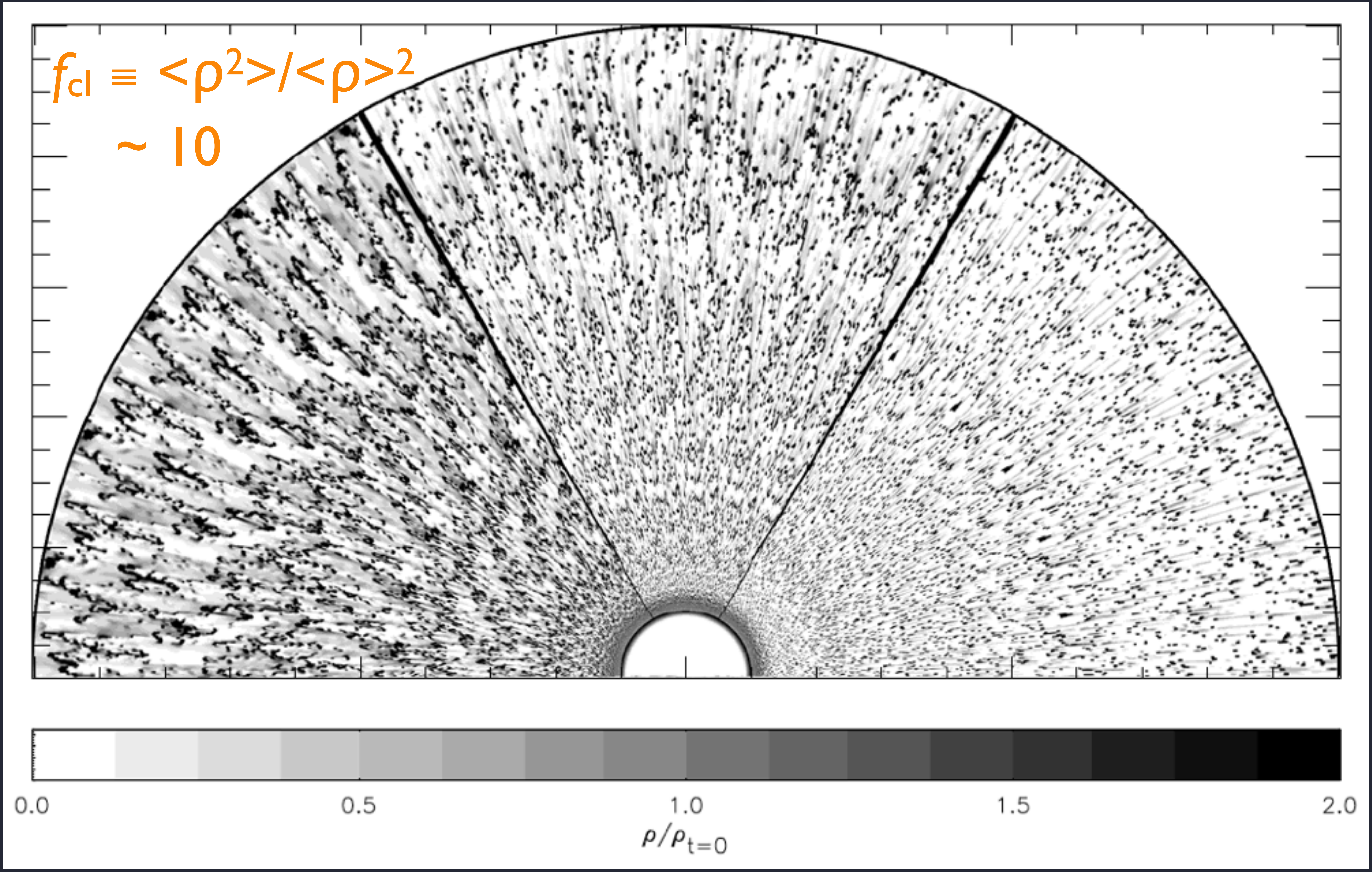
consistent with hydro simulation predictions

2. Line profile asymmetry tells us about the wind absorption; joint analysis of an ensemble of lines tells us the mass-loss rate of the wind

mass-loss rate factor ~3 lower than traditional value from Hα diagnostics (but consistent with new determinations that account for wind clumping)

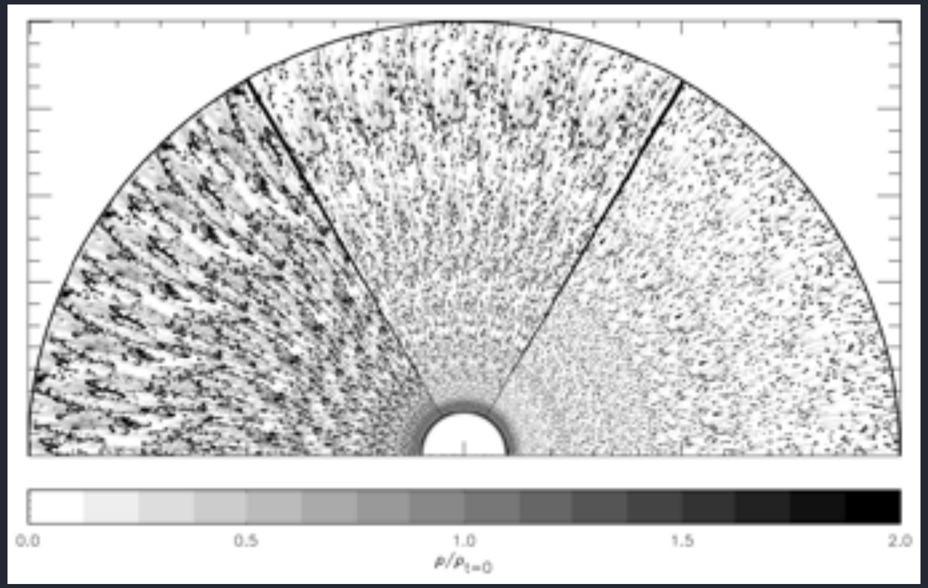
2-D radiation-hydro simulations

clumping



Dessart & Owocki 2003

X-ray line profile based mass-loss rate: implications for clumping

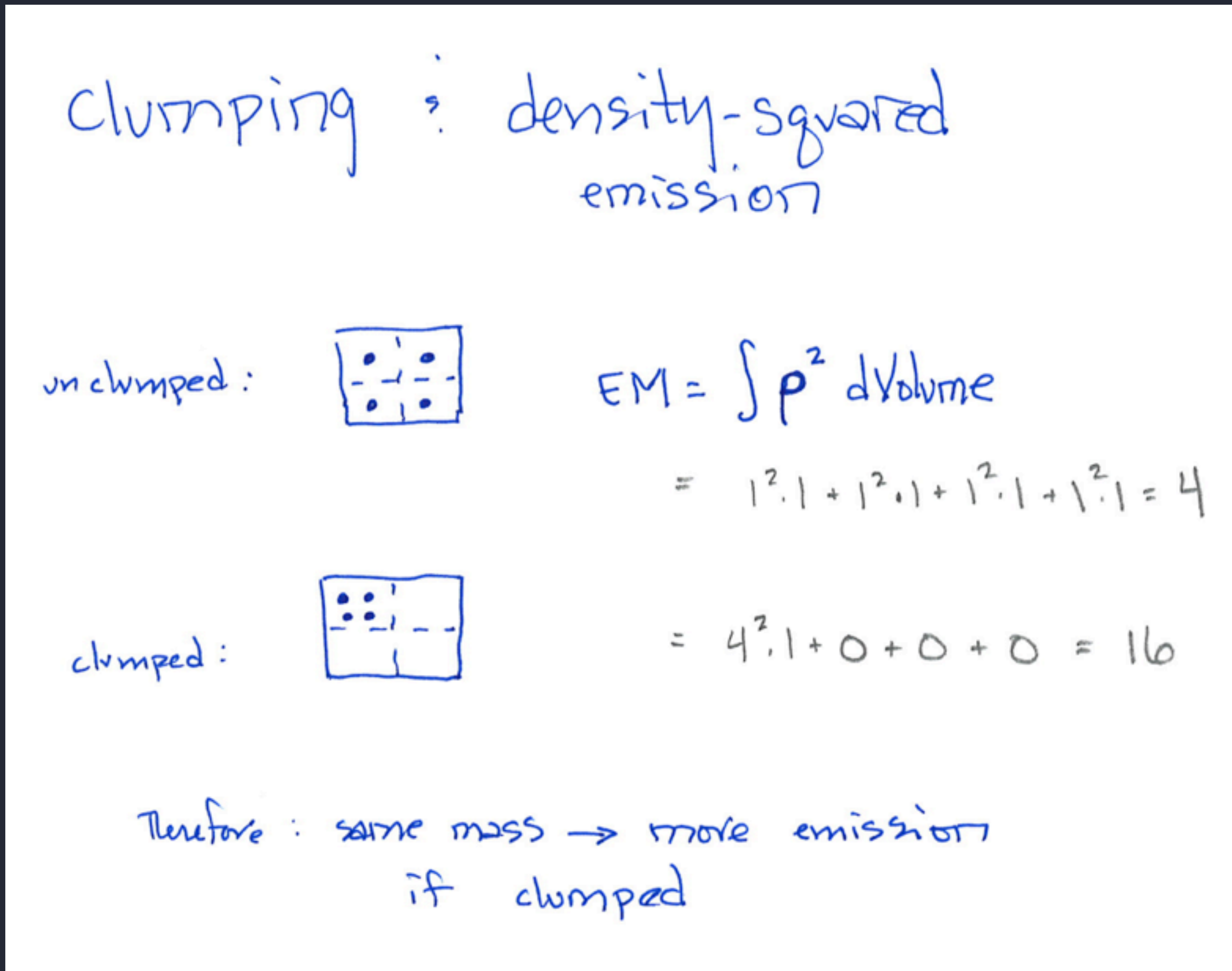


basic definition: $f_{cl} \equiv \langle\rho^2\rangle/\langle\rho\rangle^2$

clumping factor

ignoring clumping will cause you to *overestimate* the mass-loss rate

ignoring clumping will cause you to *overestimate* the mass-loss rate



X-ray line profile based mass-loss rate: implications for clumping

basic definition: $f_{cl} \equiv \langle\rho^2\rangle/\langle\rho\rangle^2$

clumping factor

from (column) density diagnostic like $\tau_\star$ from X-ray profiles

from density-squared diagnostics like Hα, IR & radio free-free

ζ Pup mass-loss rate $< 4.2 \times 10^{-6}\ M_{sun}$/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 $r < 3 \ldots 5\, R_\star$. 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.

trade-off/degeneracy between clumping factor and mass-loss rate

$$\dot{M}_{cl} \equiv \dot{M}_{smooth} / f_{cl}^{0.5}$$

Puls et al. (2006) : relative clumping (vs. radius), but free scale factor

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

X-ray mass-loss rate breaks degeneracy and sets the scale factor

ζ Pup: radially varying clumping

for $\dot{M} = 3.5 \times 10^{-6}\ M_{sun}/yr$

$f_{cl} \equiv \langle\rho^2\rangle / \langle\rho\rangle^2$

$\dot{M}_{cl} \equiv \dot{M}_{smooth} / f_{cl}^{0.5}$

$f_{cl} = 1.3$ @ $r < 1.12\ R_*$ Hα

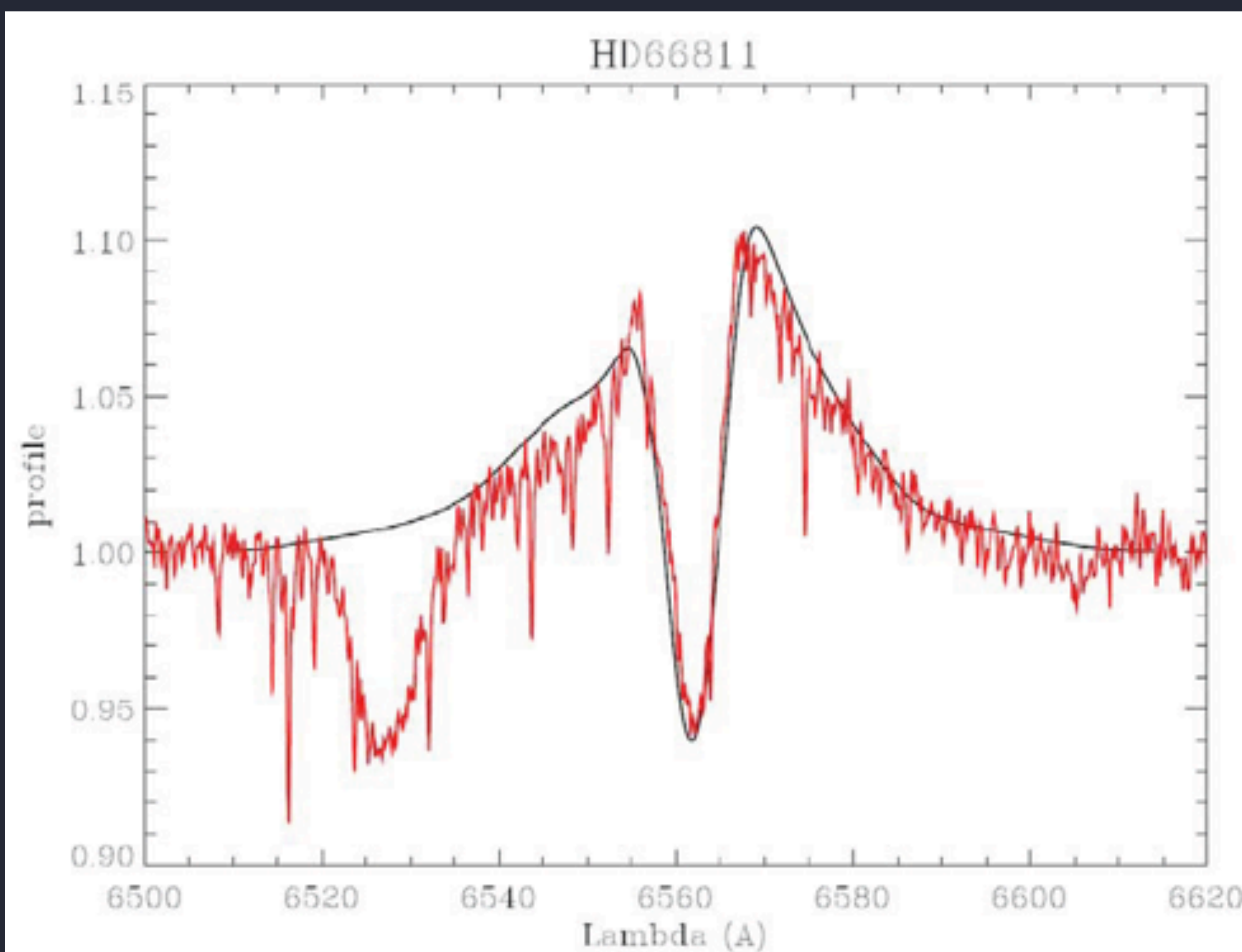
$f_{cl} = 6.0$ @ $1.12 < r < 1.5\ R_*$ Hα

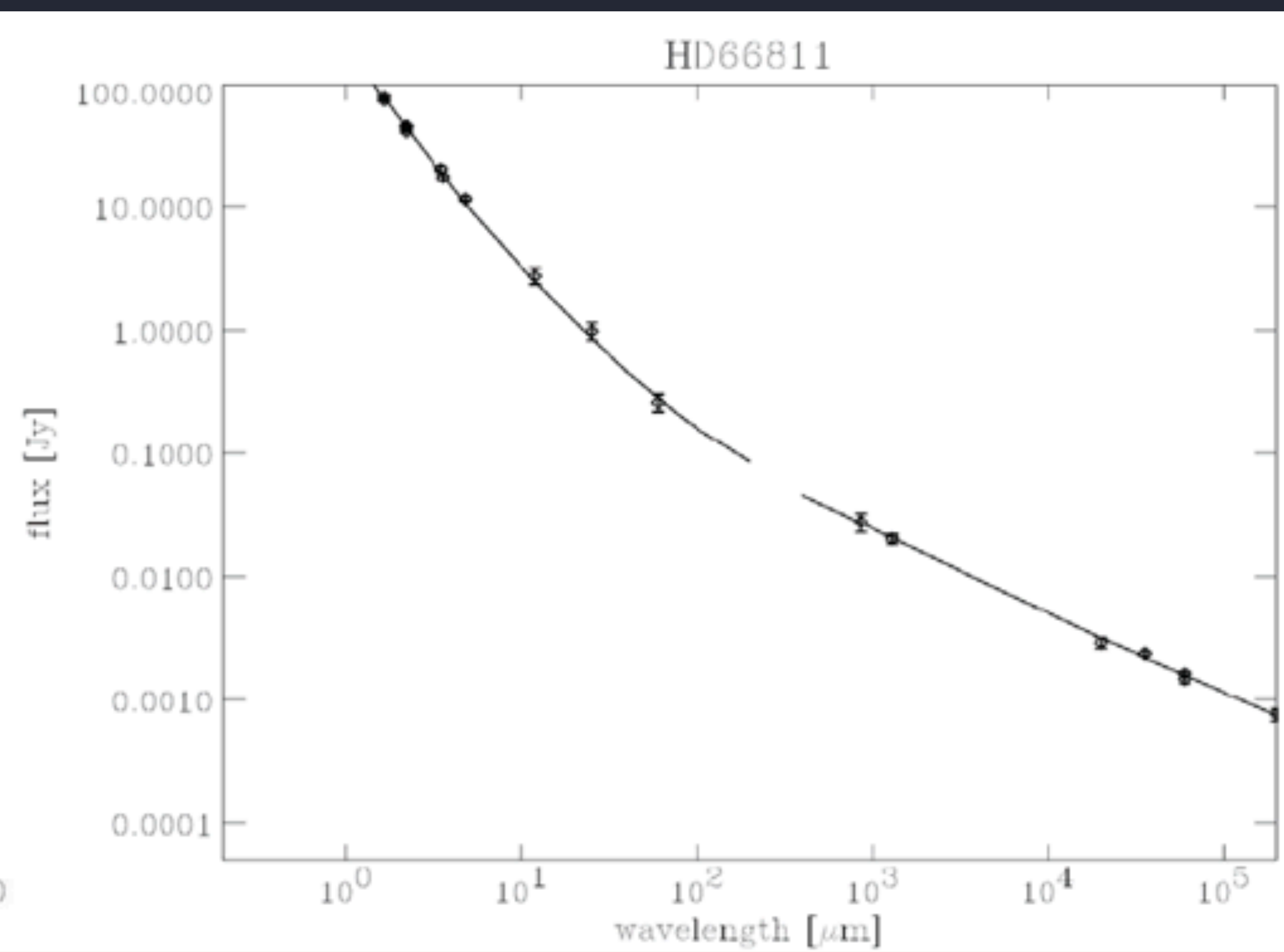
$f_{cl} = 3.7$ @ $1.5 < r < 2\ R_*$ Hα

$f_{cl} = 2.6$ @ $2 < r < 15\ R_*$ IR

$f_{cl} = 1.3$ @ $r > 15\ R_*$ radio

Hα IR radio





base of the wind ($r < 1.5\ R_\star$)

is clumped

...but...

$f_{cl} = 1.3$ @ $r < 1.12\ R_*$ Hα

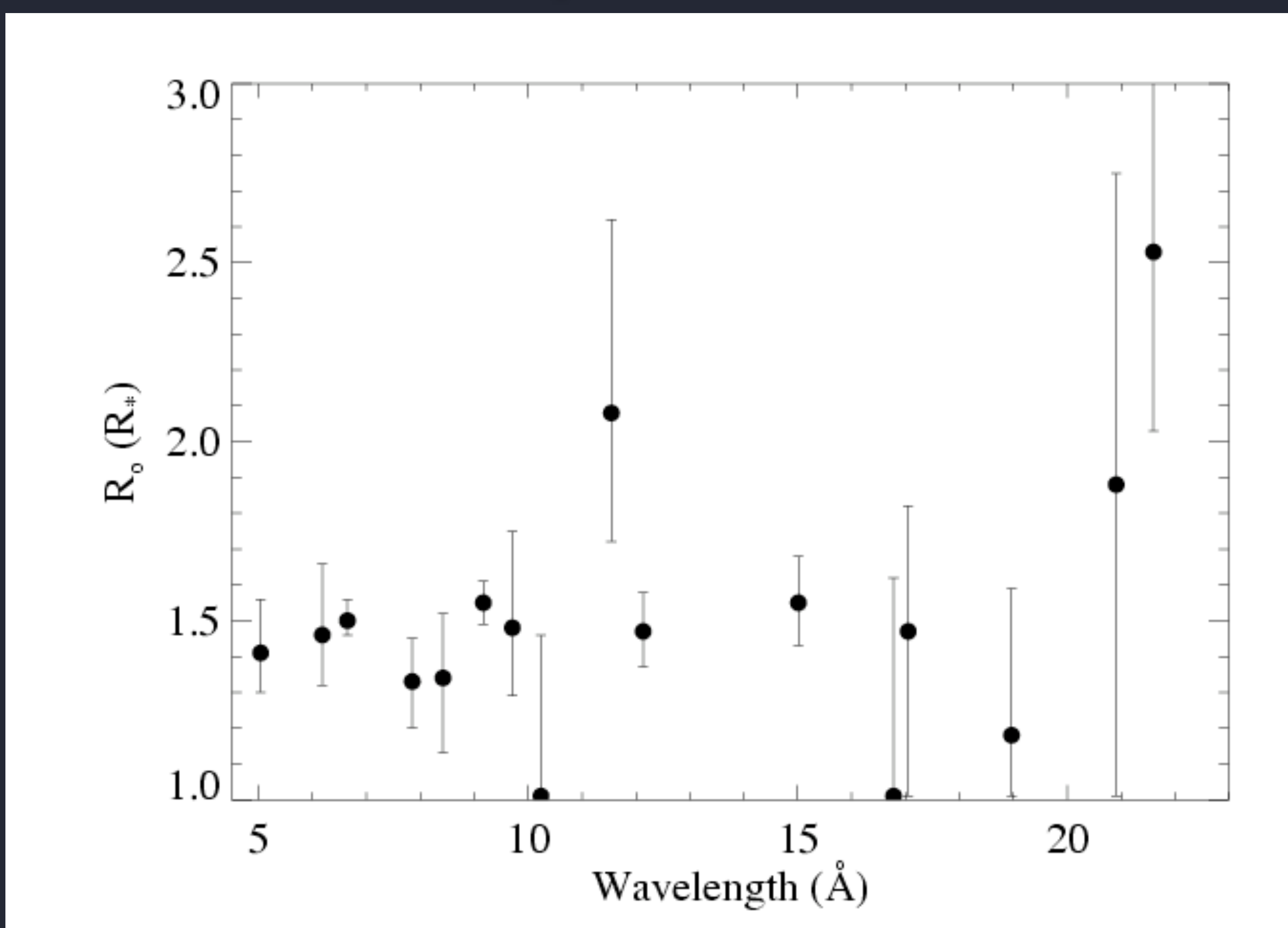
$f_{cl} = 6.0$ @ $1.12 < r < 1.5\ R_*$ Hα

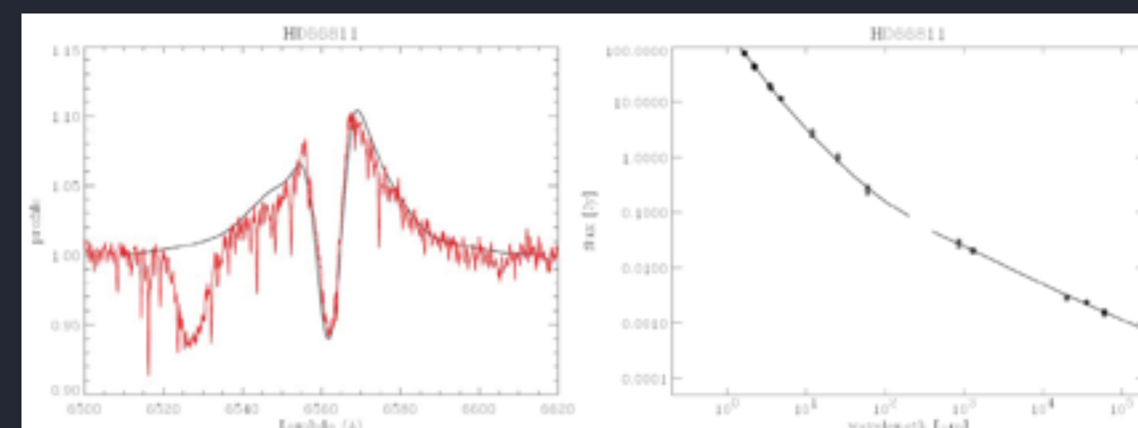
$f_{cl} = 3.7$ @ $1.5 < r < 2\ R_*$ Hα

$f_{cl} = 2.6$ @ $2 < r < 15\ R_*$ IR

$f_{cl} = 1.3$ @ $r > 15\ R_*$ radio

recall: X-ray $R_o = 1.5\ R_\star$

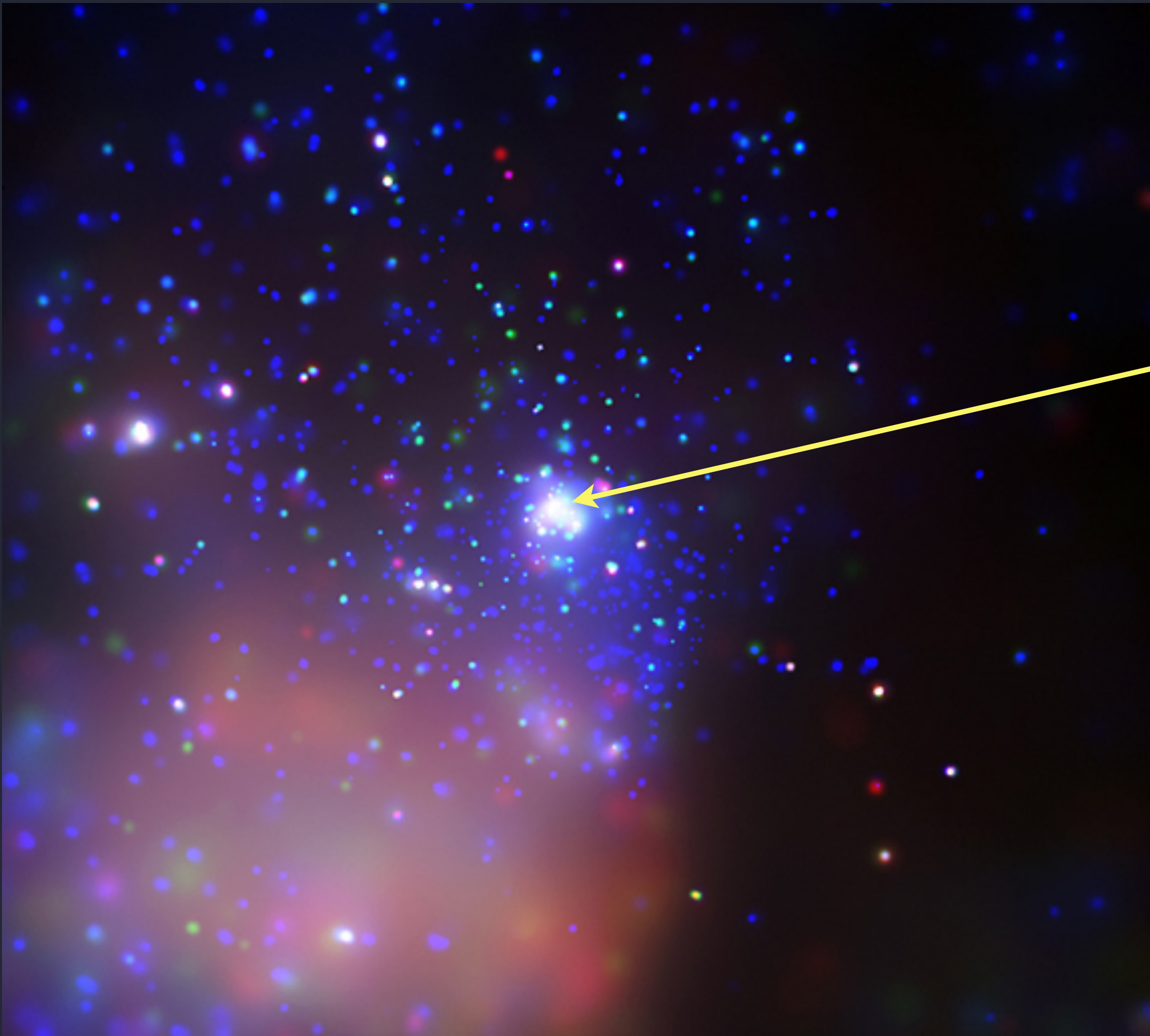




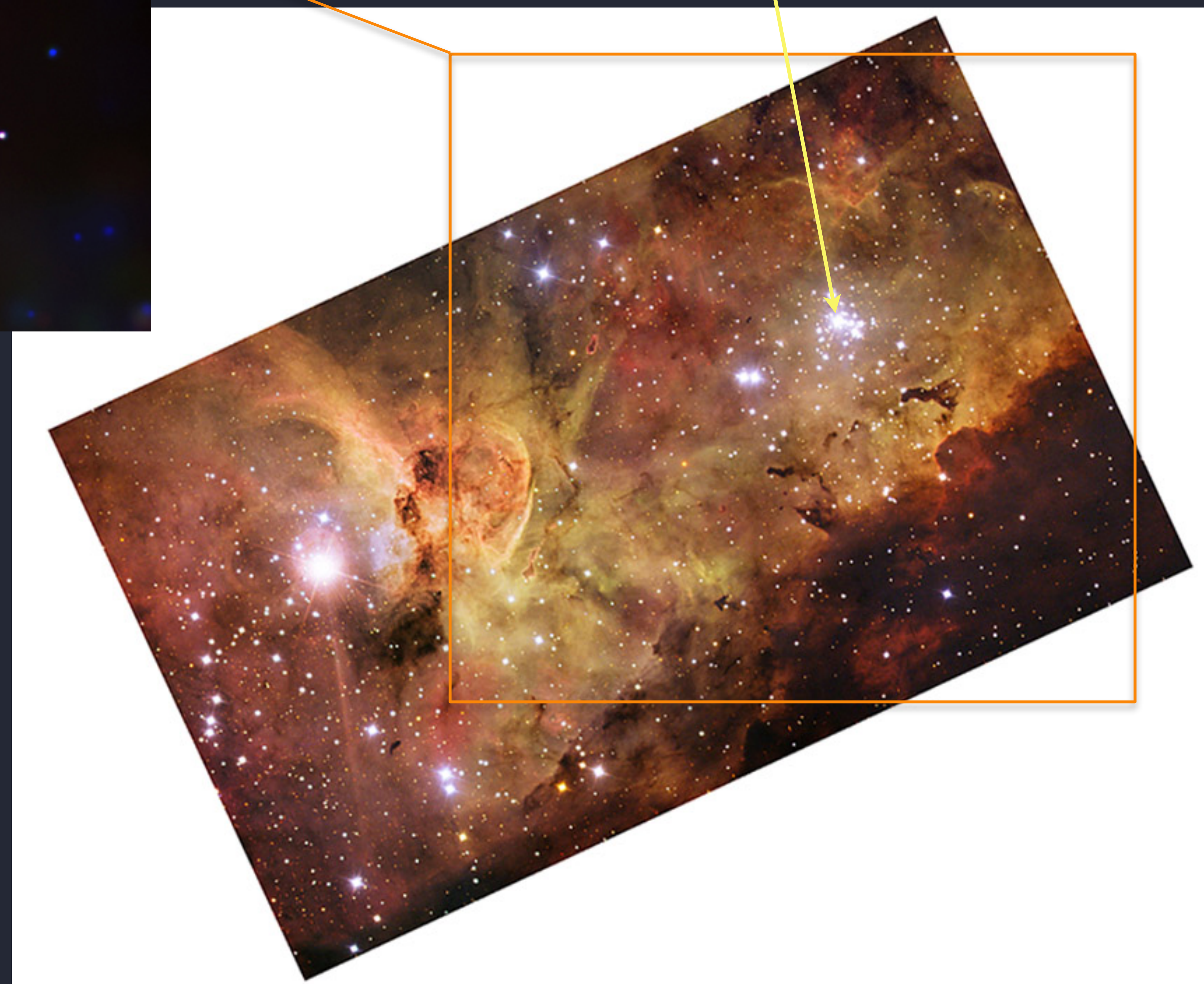
wind clumping starts very close to the star's surface, but the X-ray emission doesn't "turn on" until ~0.5 stellar radii above the surface

Other Stars?

HD 93129A



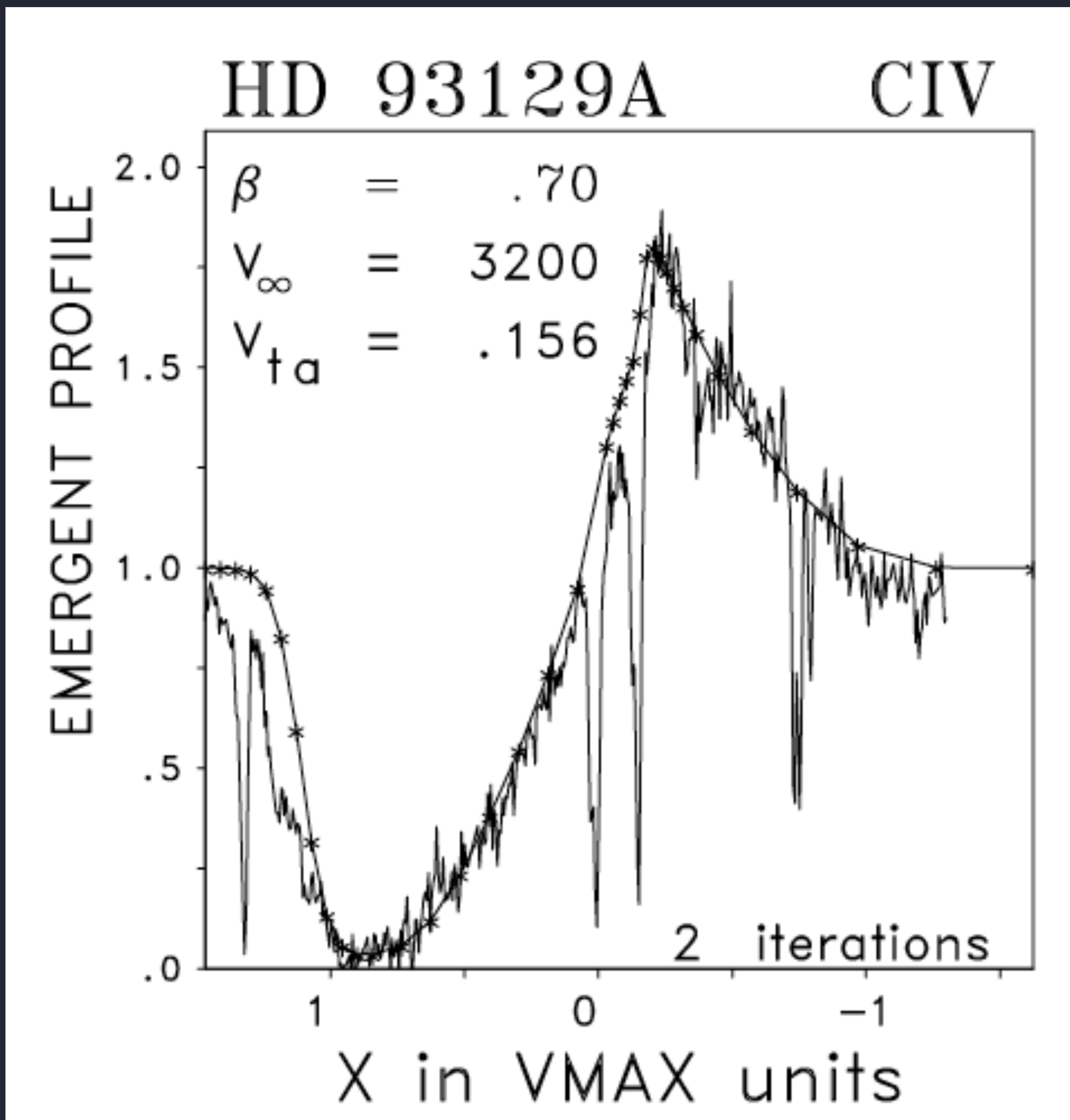
Tr 14: *Chandra*



Carina: ESO

Strong stellar wind: traditional diagnostics

UV



Taresch et al. (1997)

$\dot{M} = 2 \times 10^{-5}\ M_{sun}/yr$

$v_\infty = 3200$ km/s

Hα

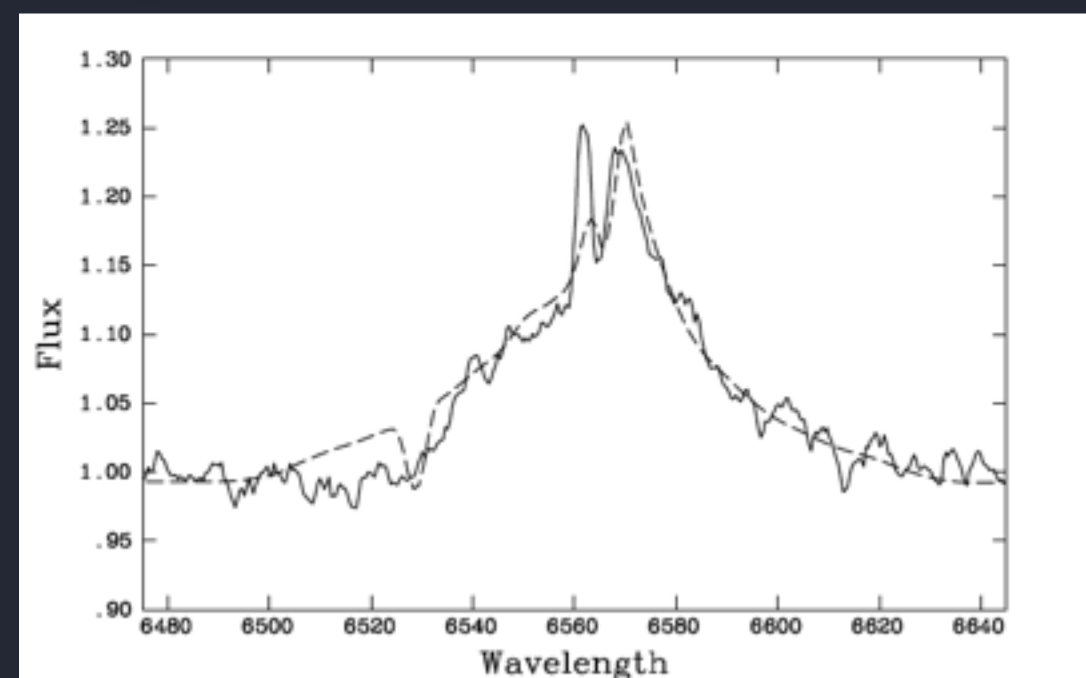


Fig. 13. Observed Hα profile (**solid**) compared with the calculation assuming a mass loss of $18 \times 10^{-6}\ M_\odot$/yr (dashed). Note that the blue narrow emission peak originates from the H II-region emission.

HD 93129A: strongest wind measured in an O star

Hα

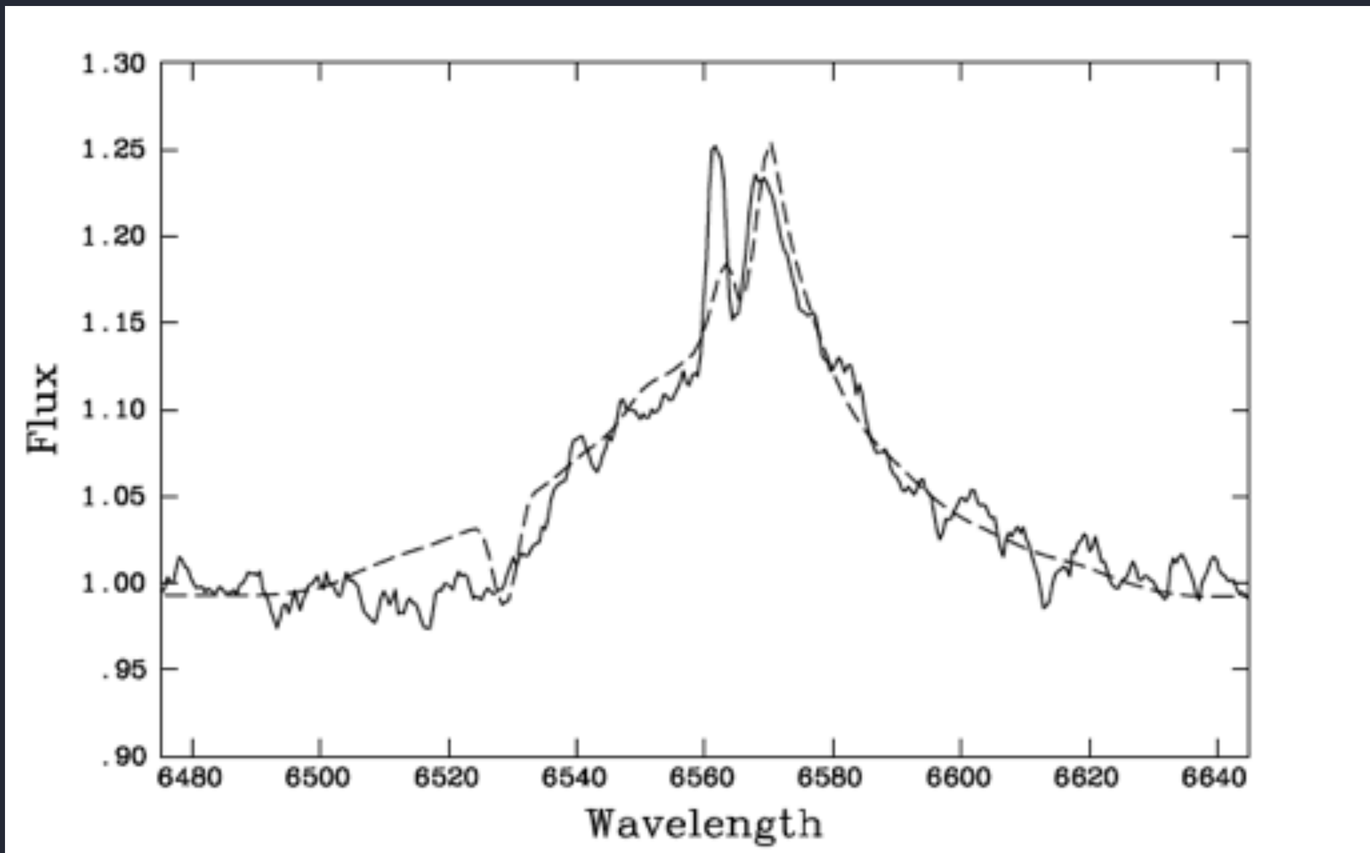


Fig. 13. Observed Hα profile (**solid**) compared with the calculation assuming a mass loss of 18×10^{-6} $M_\odot$/yr (dashed). Note that the blue narrow emission peak originates from the H II-region emission.

Taresch et al. (1997)

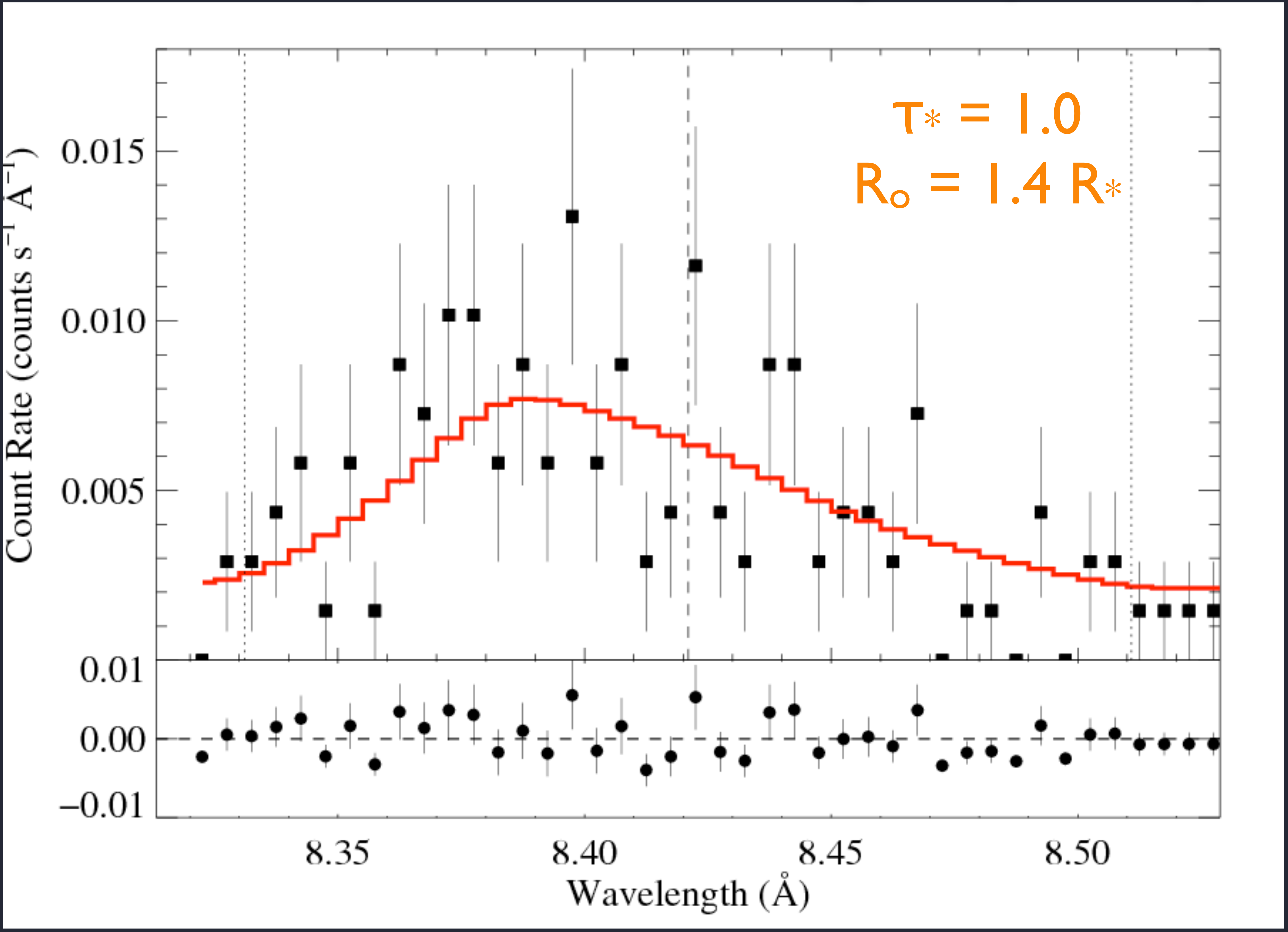
$\dot{M} = 2 \times 10^{-5}\ M_{sun}$/yr

assuming a *smooth* wind

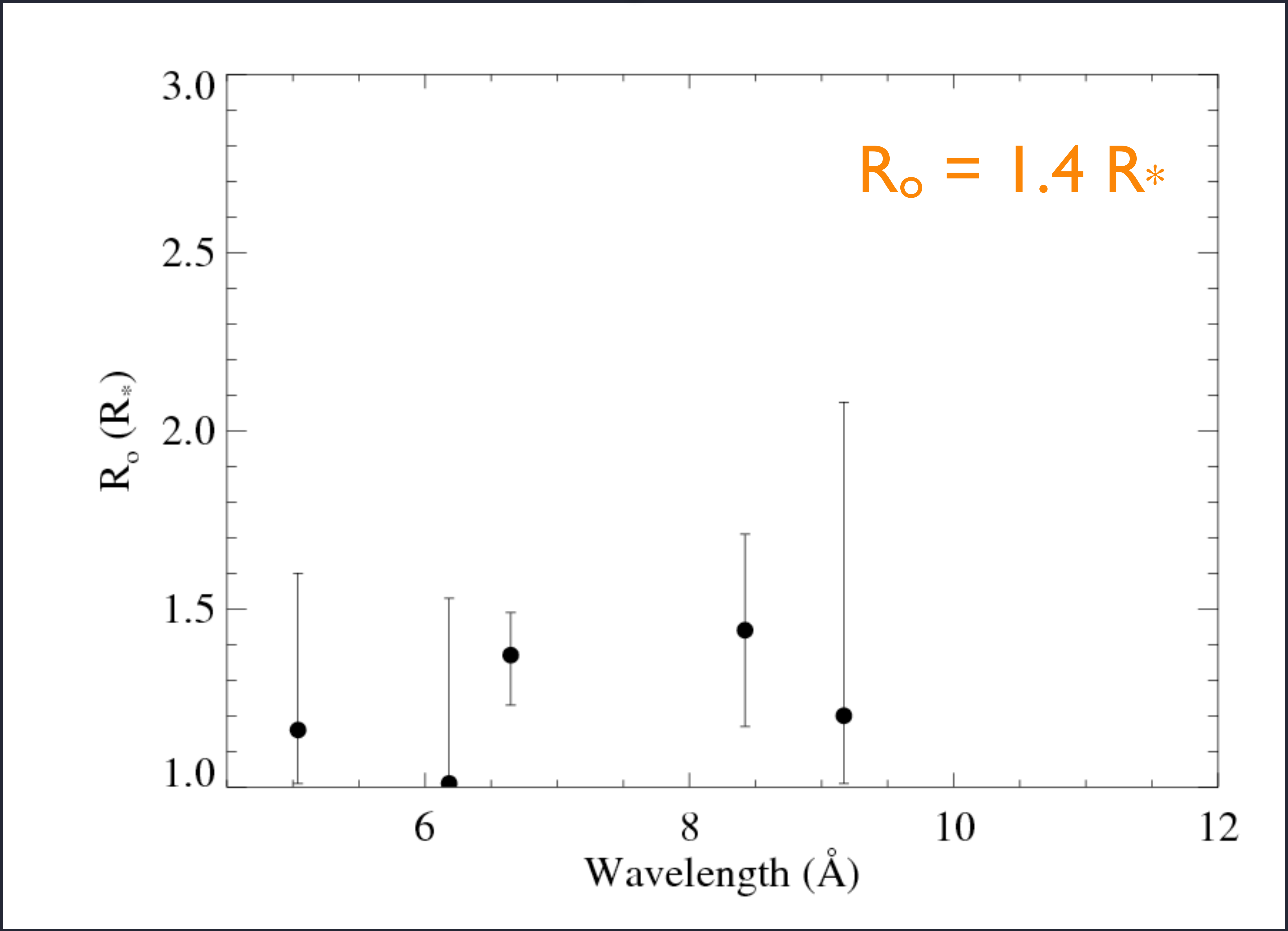
i.e. no clumping

HD 93129A

Mg XII Lyman-alpha

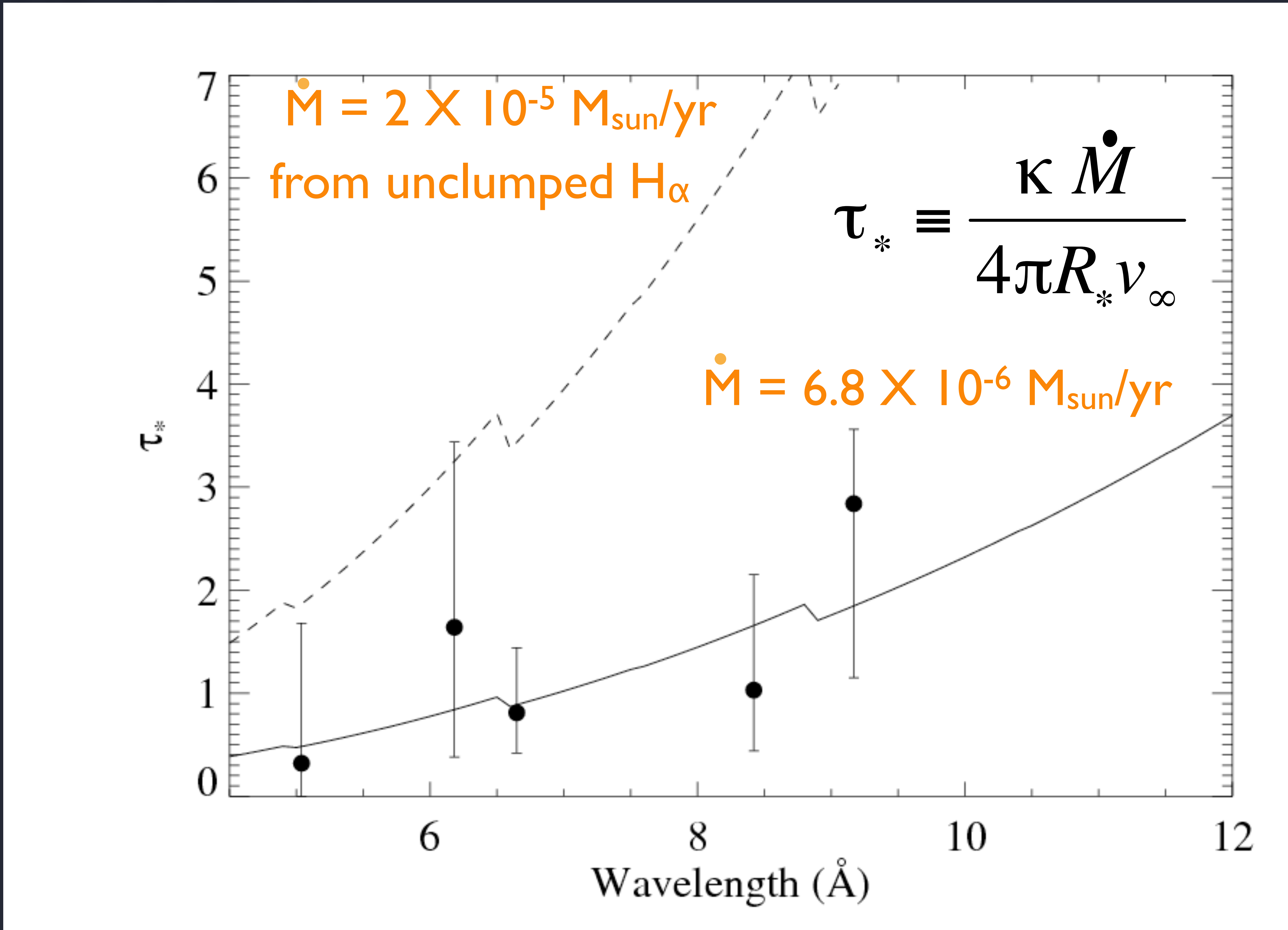


R_o = onset radius of X-ray emission



HD 93129A

τ_* from five emission lines

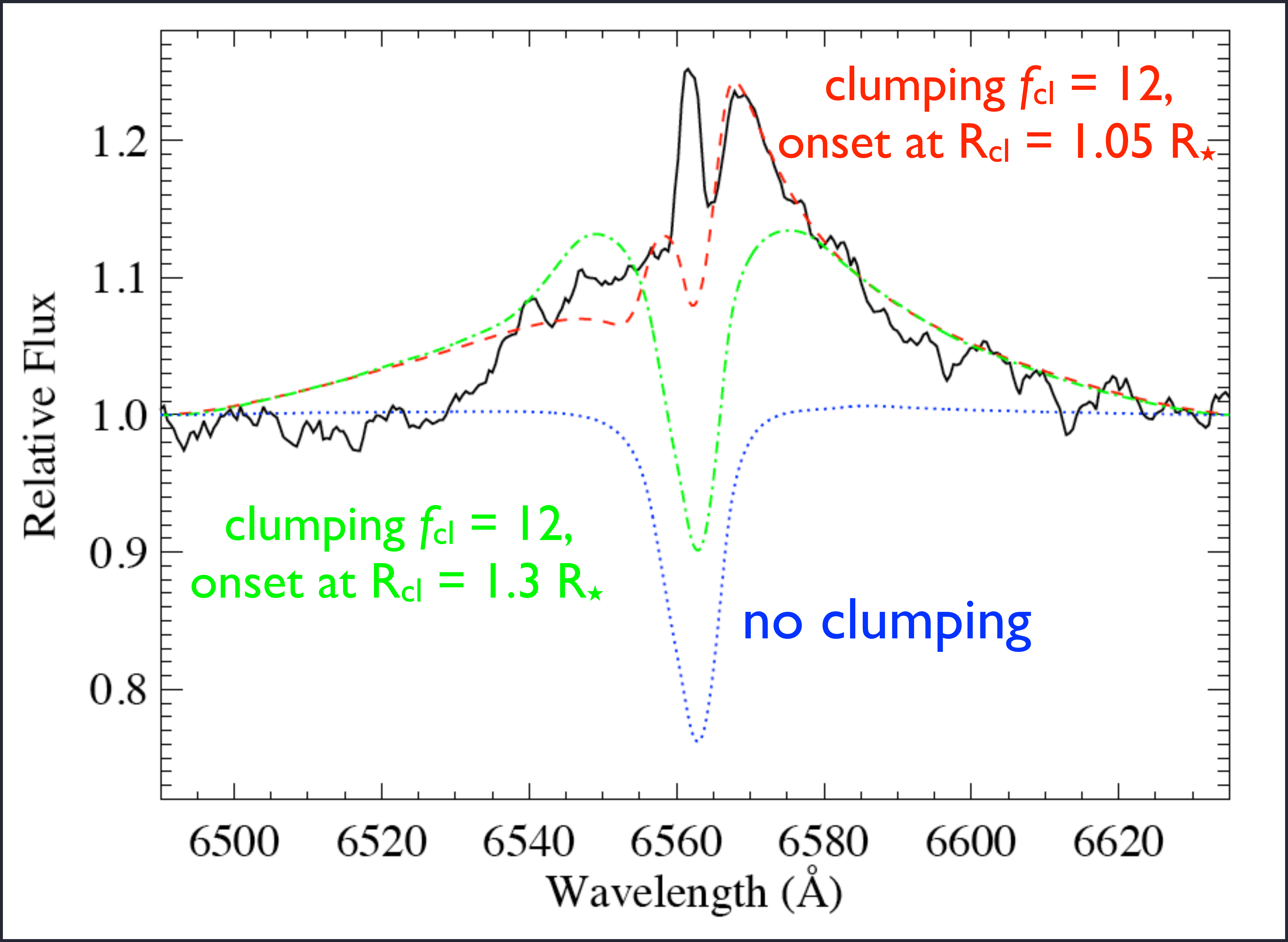


Lower mass-loss rate: consistent with Hα?

Lower mass-loss rate: consistent with Hα?

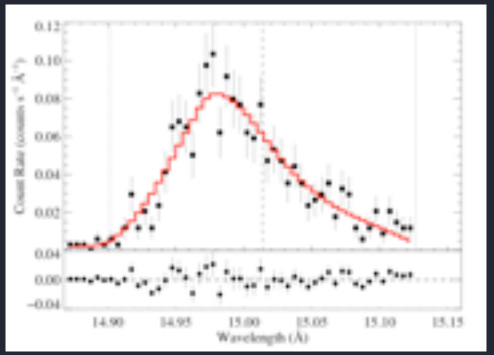
Yes! With clumping factor of $f_{cl} = 12$

$\dot{M} = 7 \times 10^{-6}\ M_{sun}/yr$

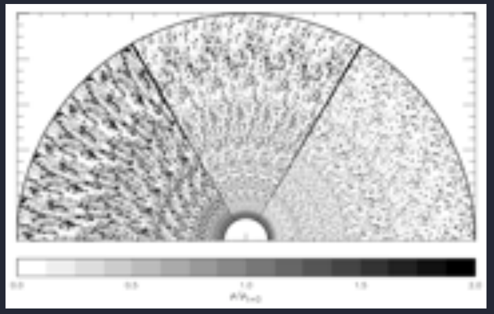


Conclusions

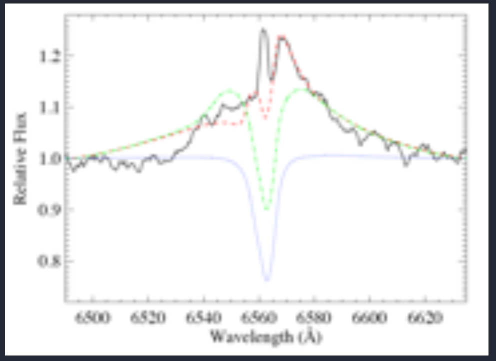
1. Embedded Wind Shock scenario - inspired by hydro simulations of the LDI - is consistent with X-ray emission properties



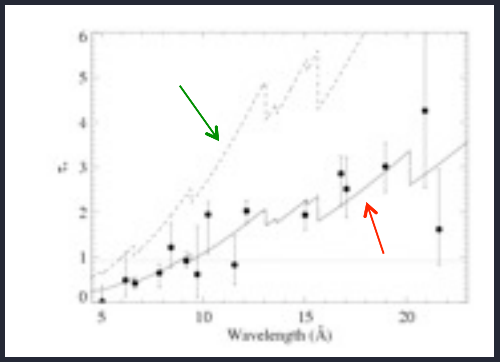
2. Clumping factors of order 10 are consistent with optical and X-ray diagnostics



3. Clumping starts at the base of the wind, lower than the onset of X-ray emission



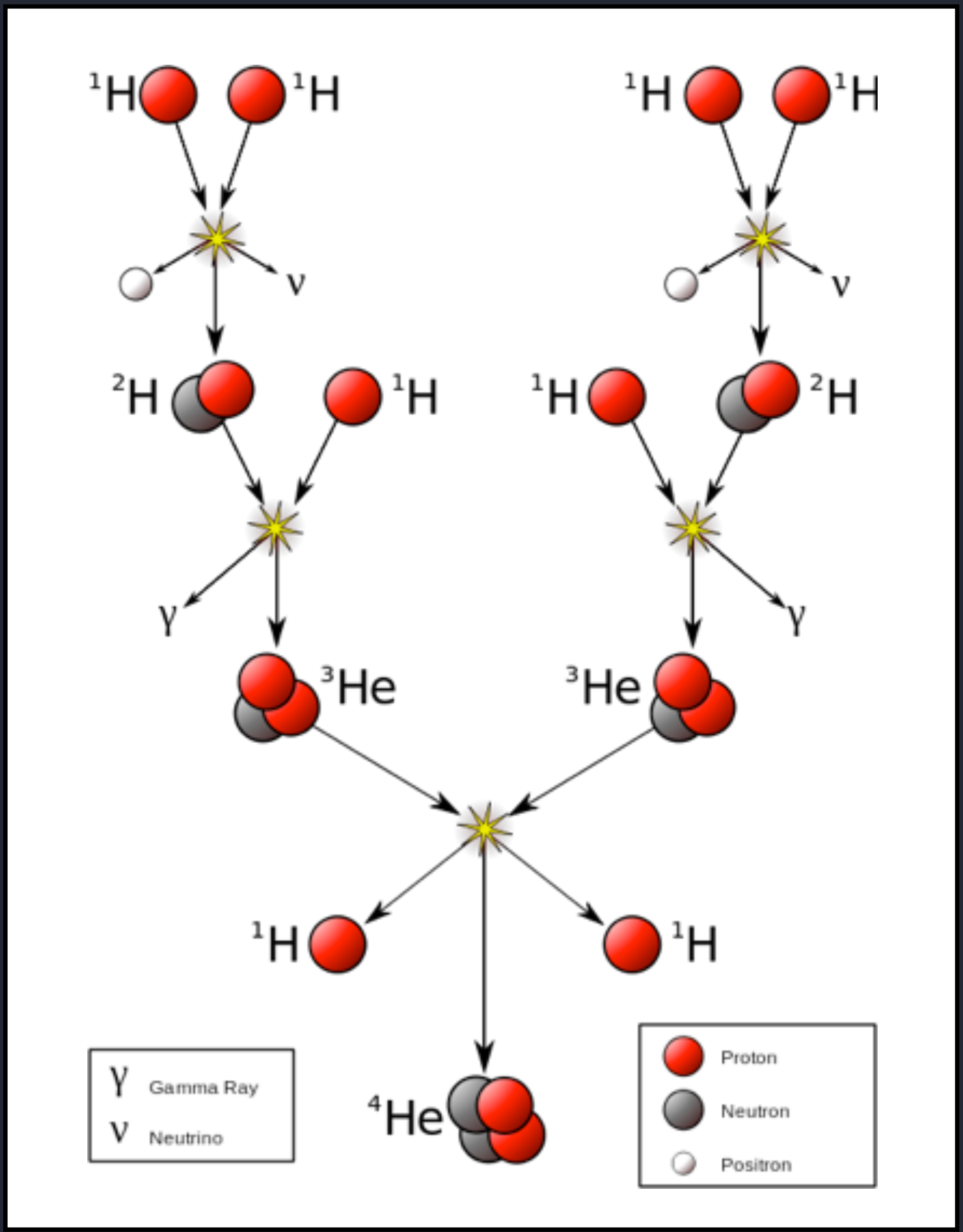
4. Mass-loss rates are lowered by roughly a factor of three



X-ray line profile spectroscopy is a good, clumping-independent mass-loss rate estimator

Extra Slides

Nucleosynthesis



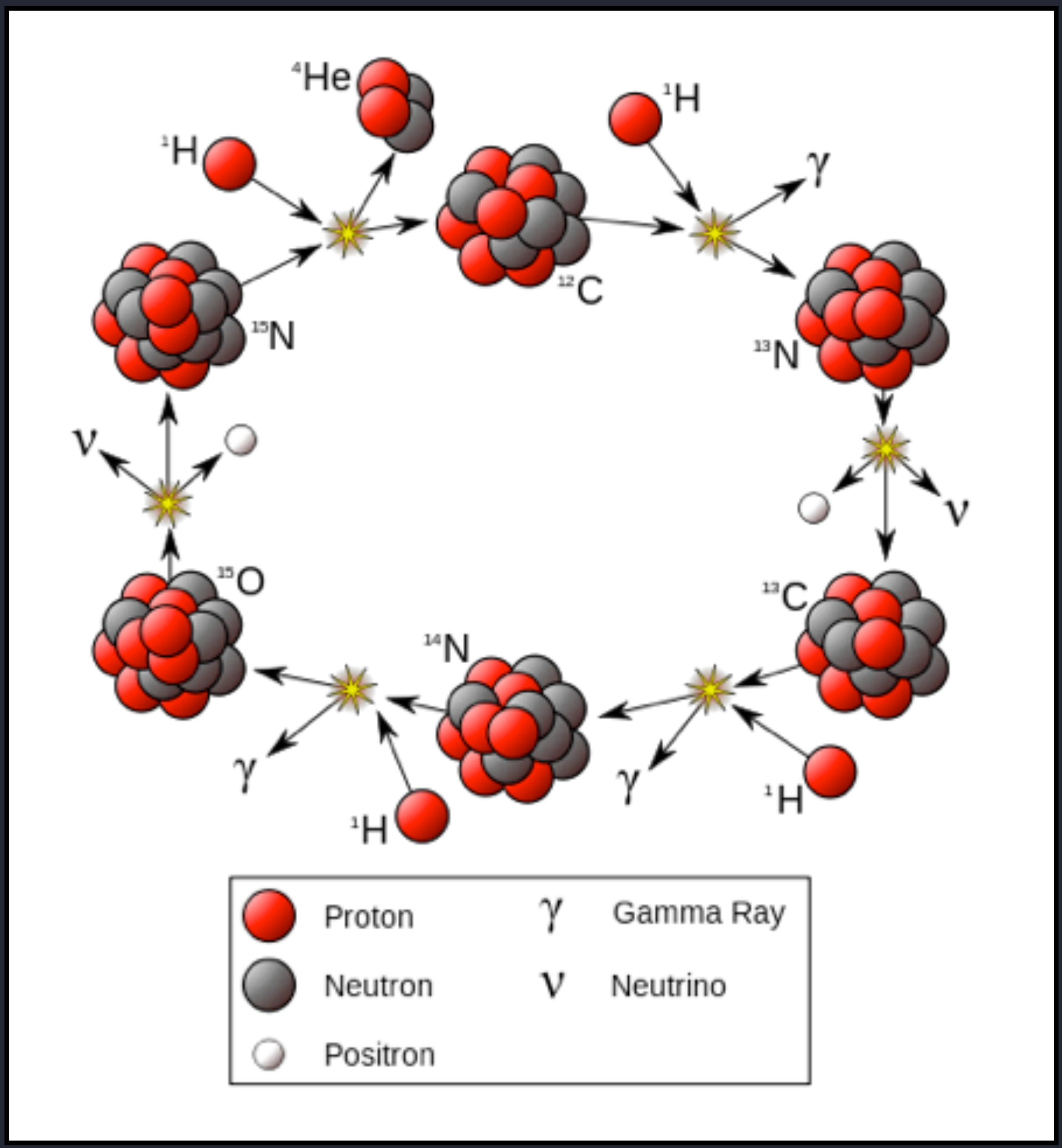
proton-proton chain

source of energy in the Sun
4 H to 1 He

nuclear binding energy is ~10^7 times higher than chemical (electron) binding energy

tens of MeV per reaction

Nucleosynthesis

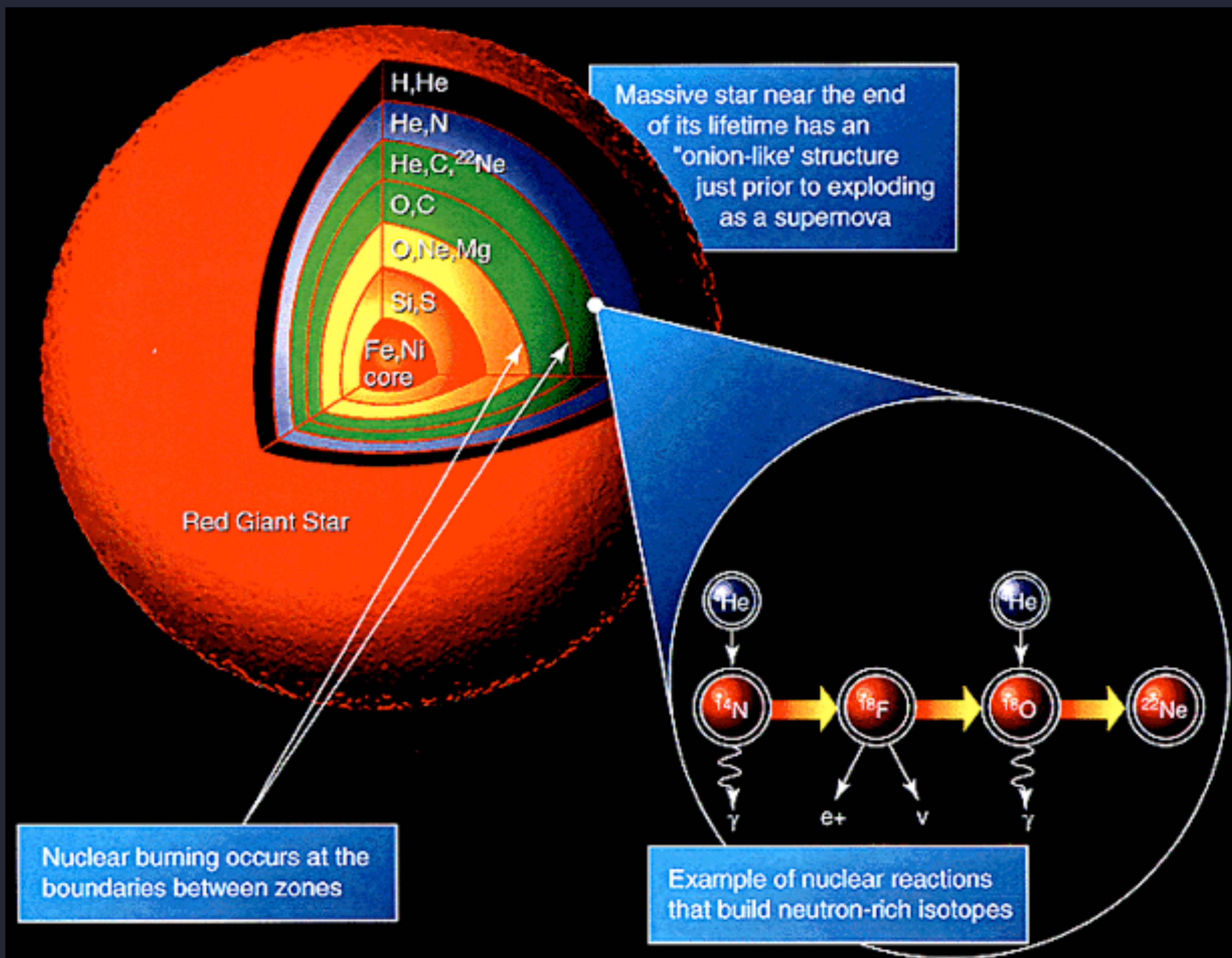


CNO cycle

source of energy in massive stars
also 4 H to 1 He
but C, N, and O are catalysts

Nucleosynthesis

massive stars: hotter cores: nucleosynthesis of heavier elements



late in their lives, no more H, so fusion of 3 He to C; C + He to O...