X-ray Emission from the Winds of Massive Stars

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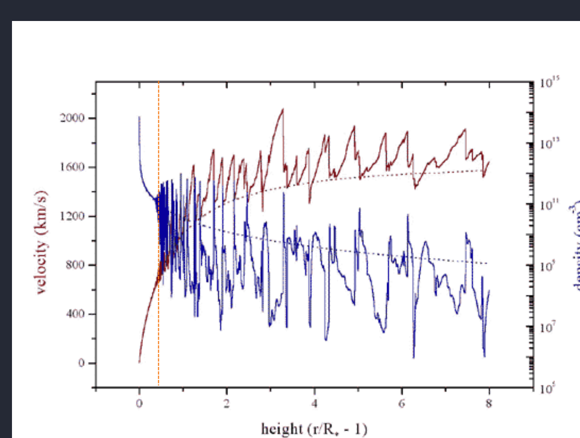
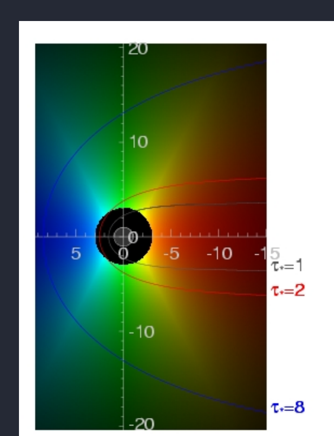
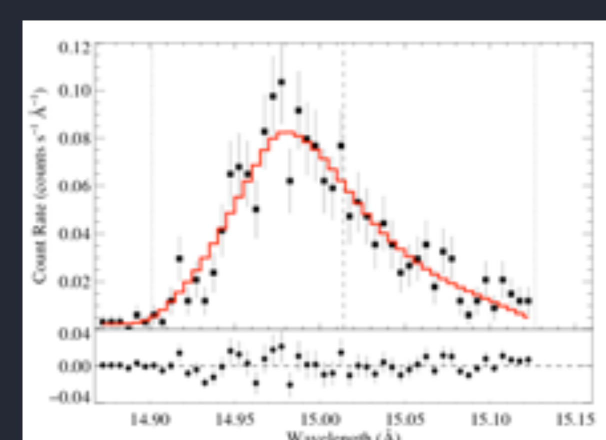
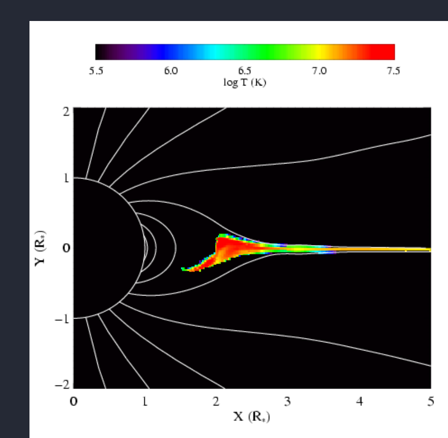






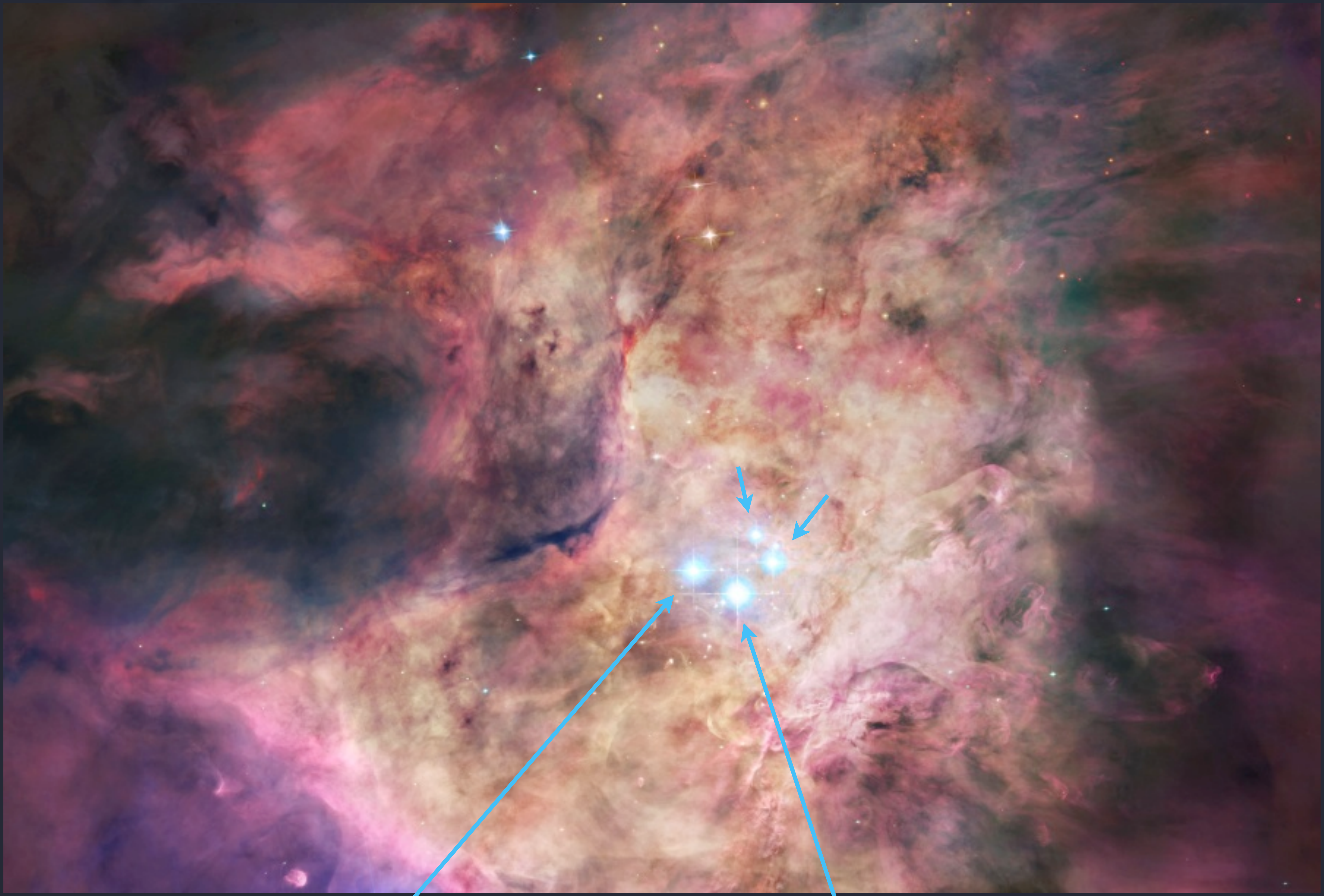


massive stars are usually hot & therefore blue

Orion

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

Basic properties of O stars

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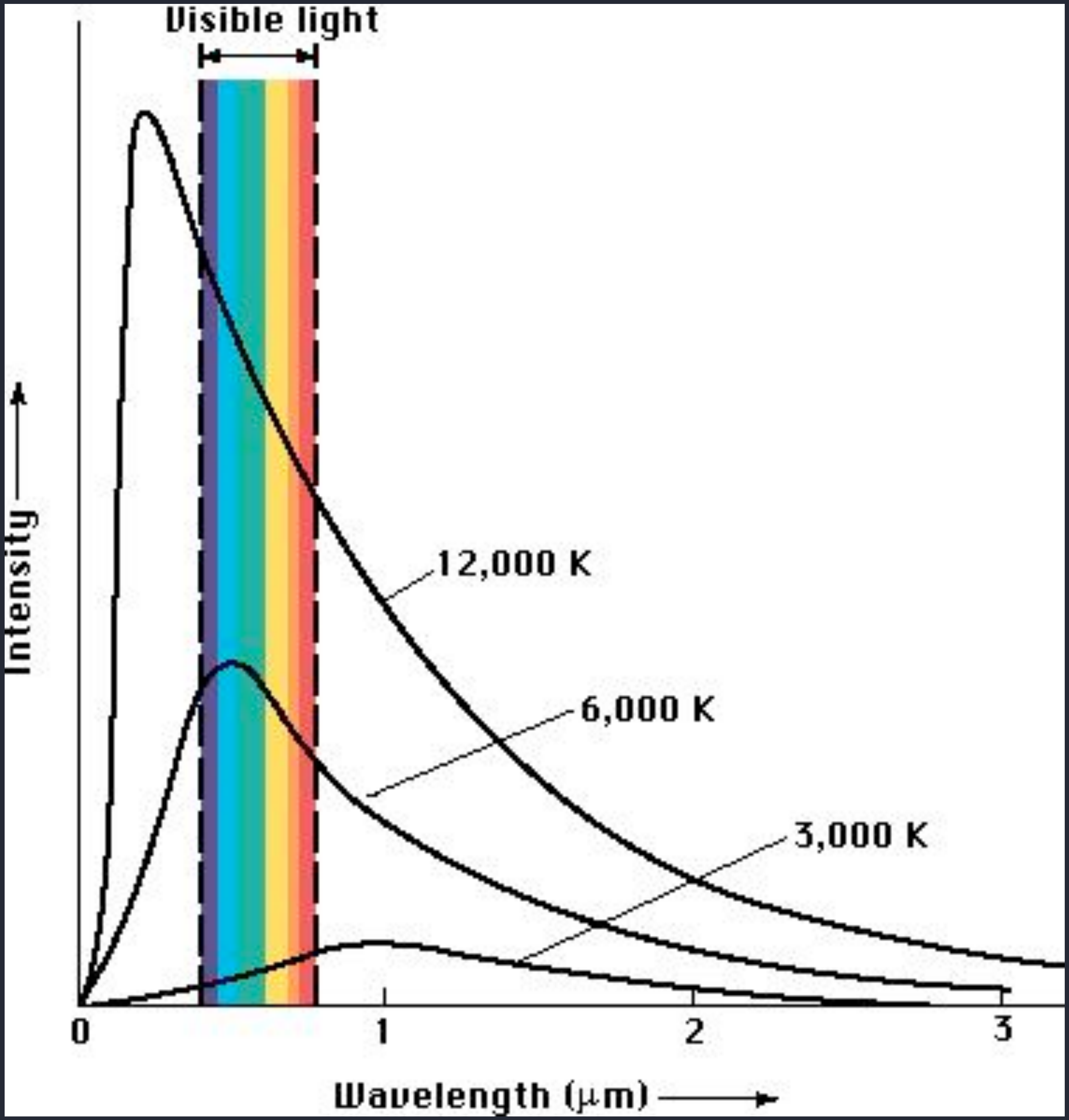
Sun and full Moon - factor of a million (10^6) in brightness

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

even so, **no X-ray** emission from the photospheres (surfaces) of even the hottest stars

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*

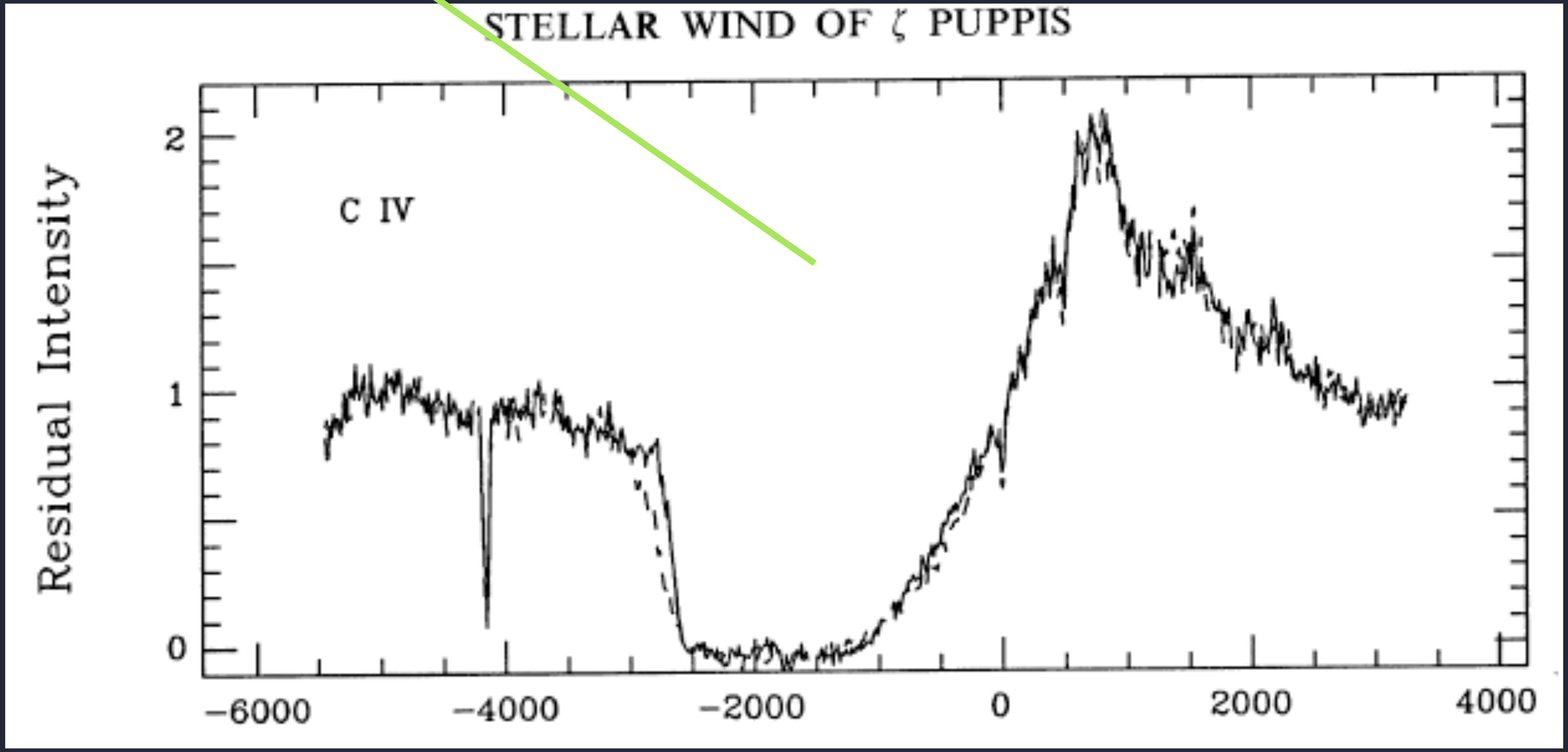
Strong, *radiation-driven* stellar winds are a characteristic of massive stars

NGC 6888 Crescent Nebula - Tony Hallas

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*



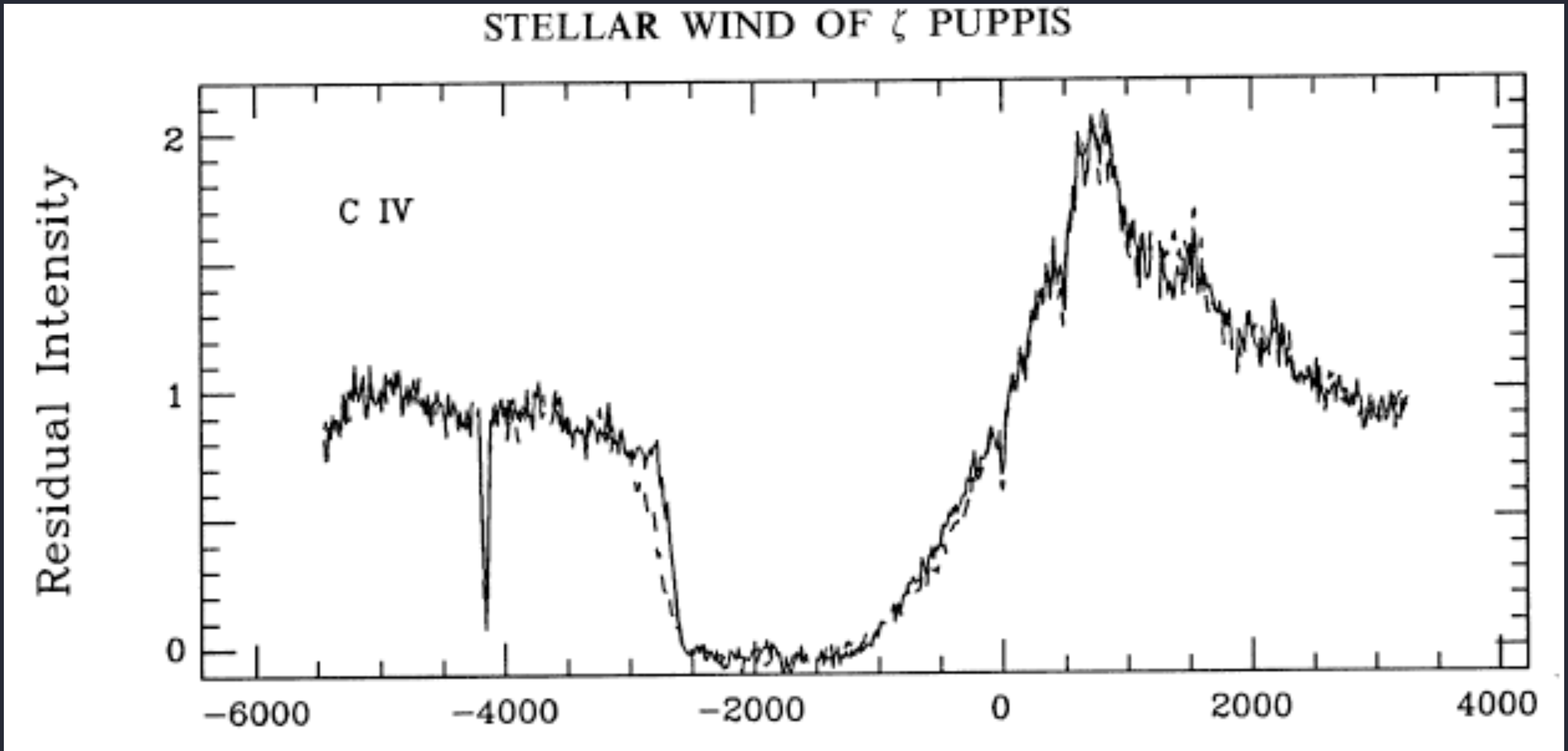
Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

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

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

UV spectrum: C IV 1548, 1551 Å



Prinja et al. 1992, ApJ, 390, 266

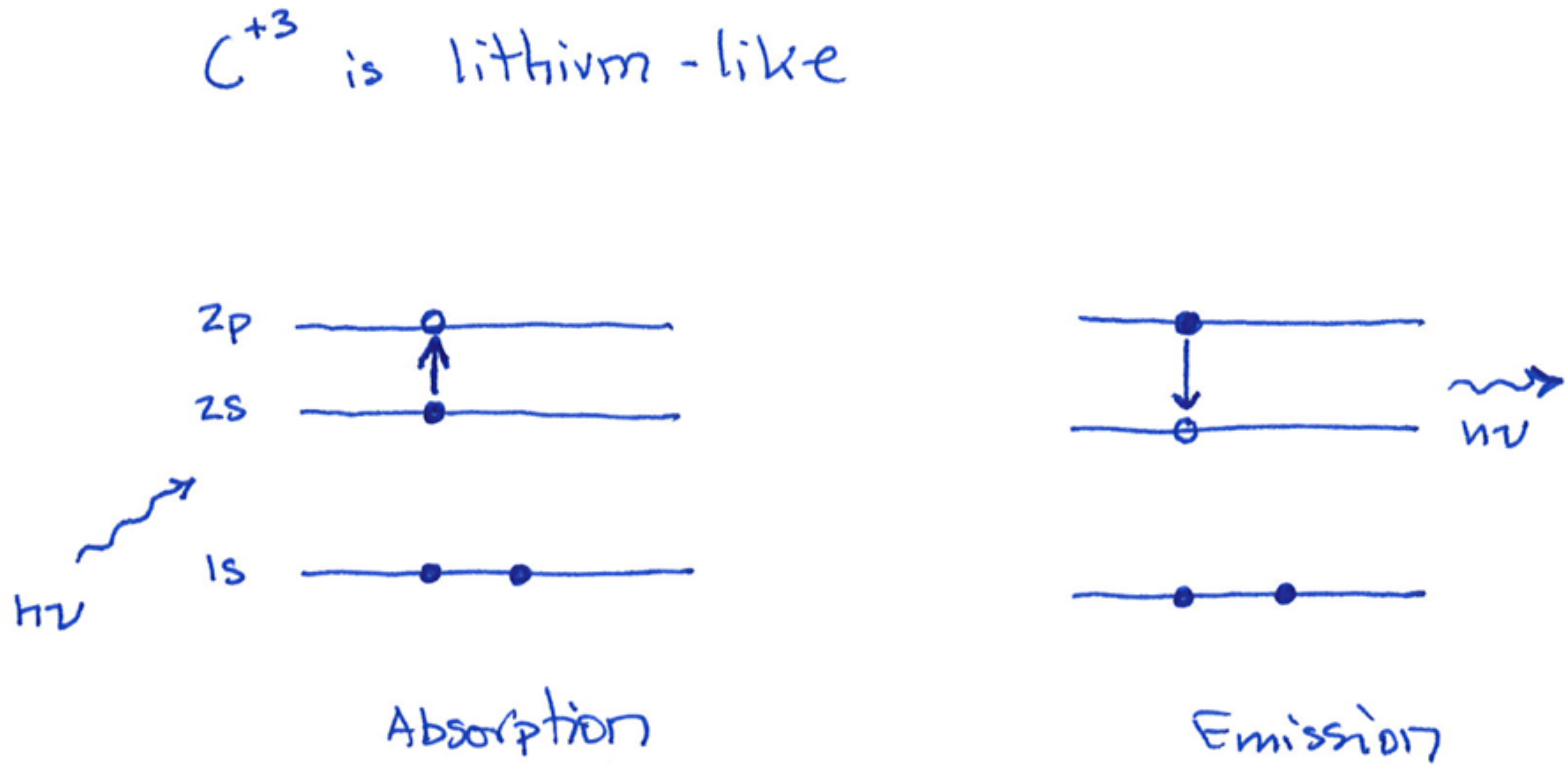
Velocity (km/s)

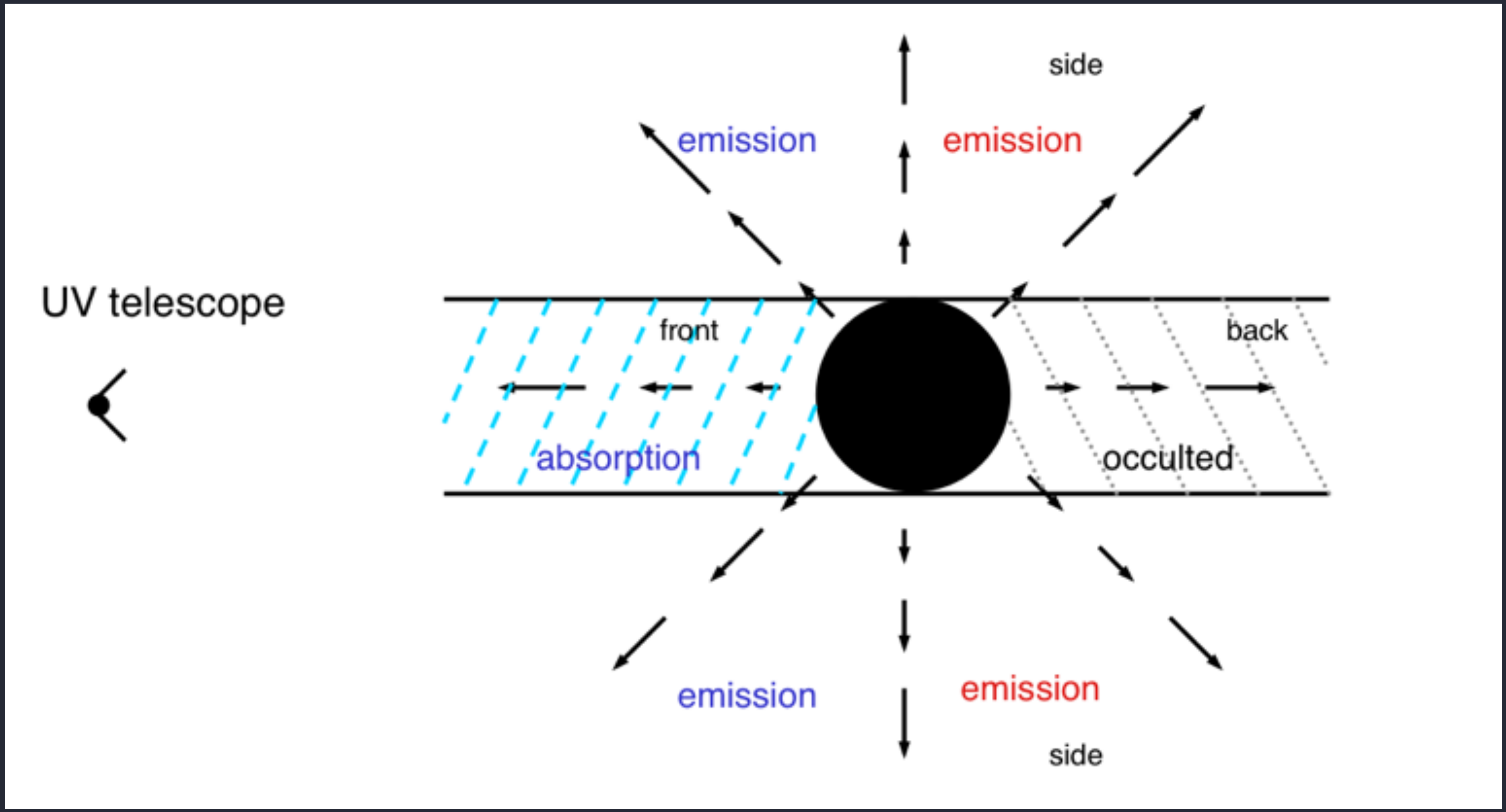
Spectral lines:

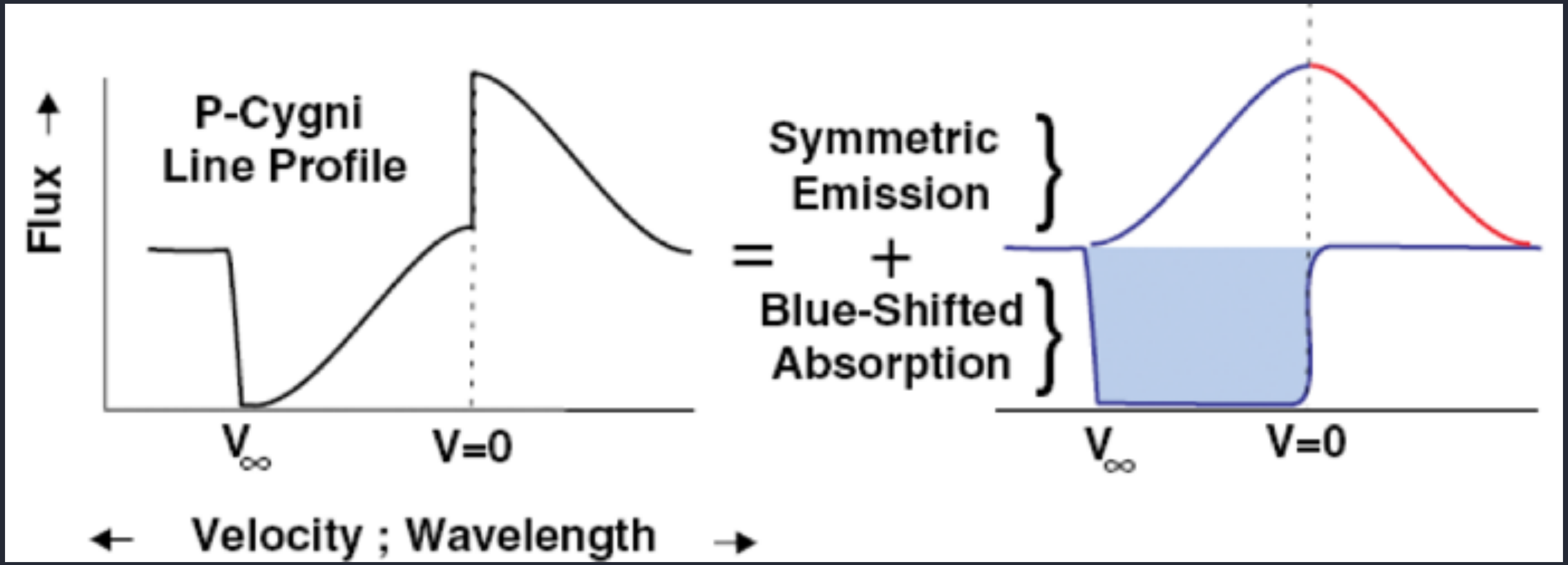
absorption line when translucent gas is between you and a hotter, opaque source of continuum photons

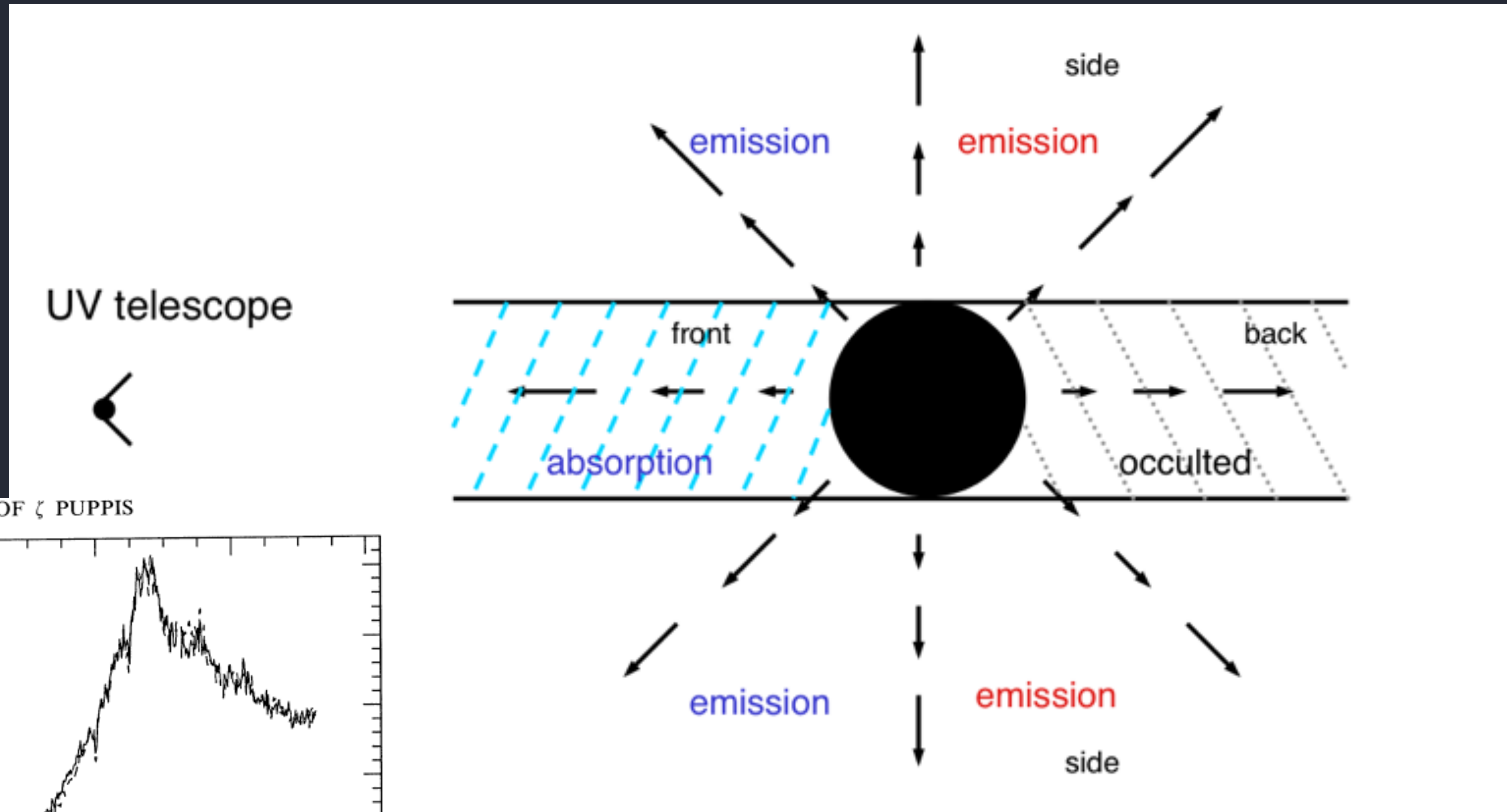
emission line when hot gas is seen against a cold background

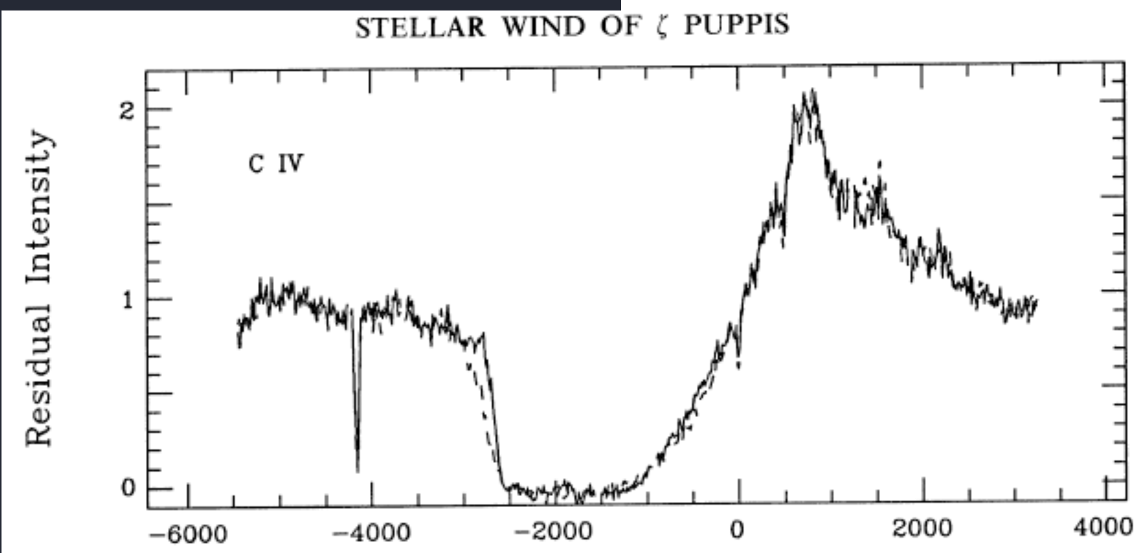
absorption and emission: atomic energy level diagrams




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


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





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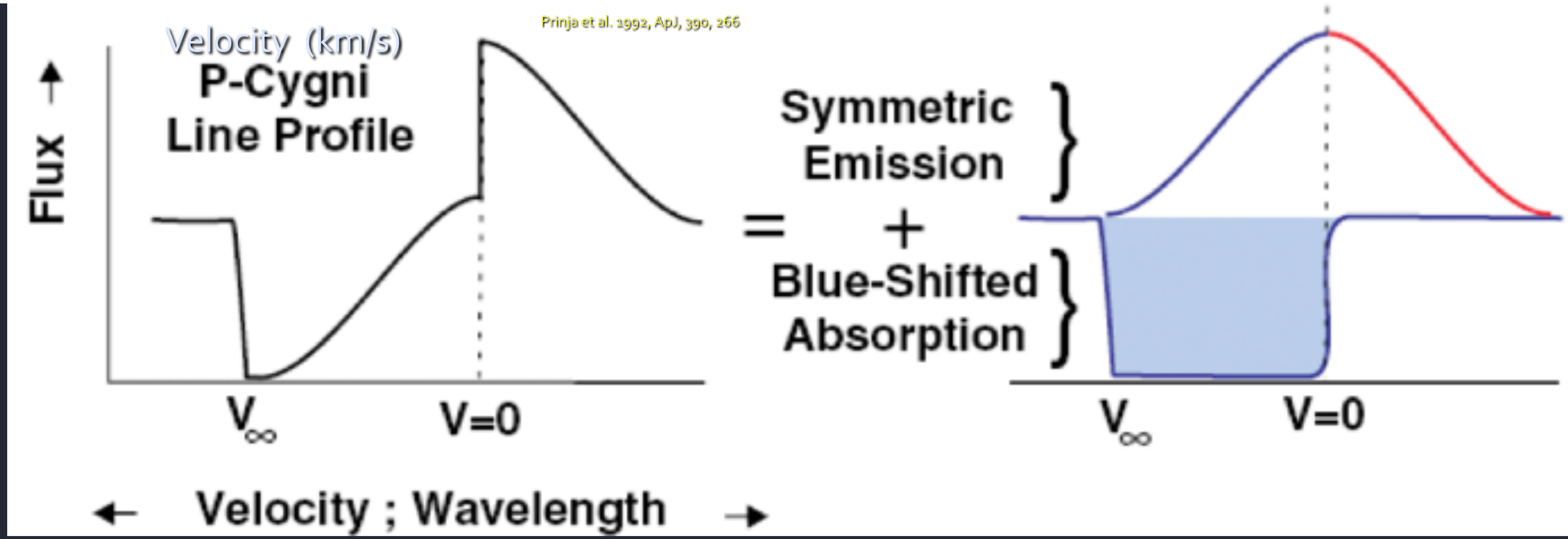

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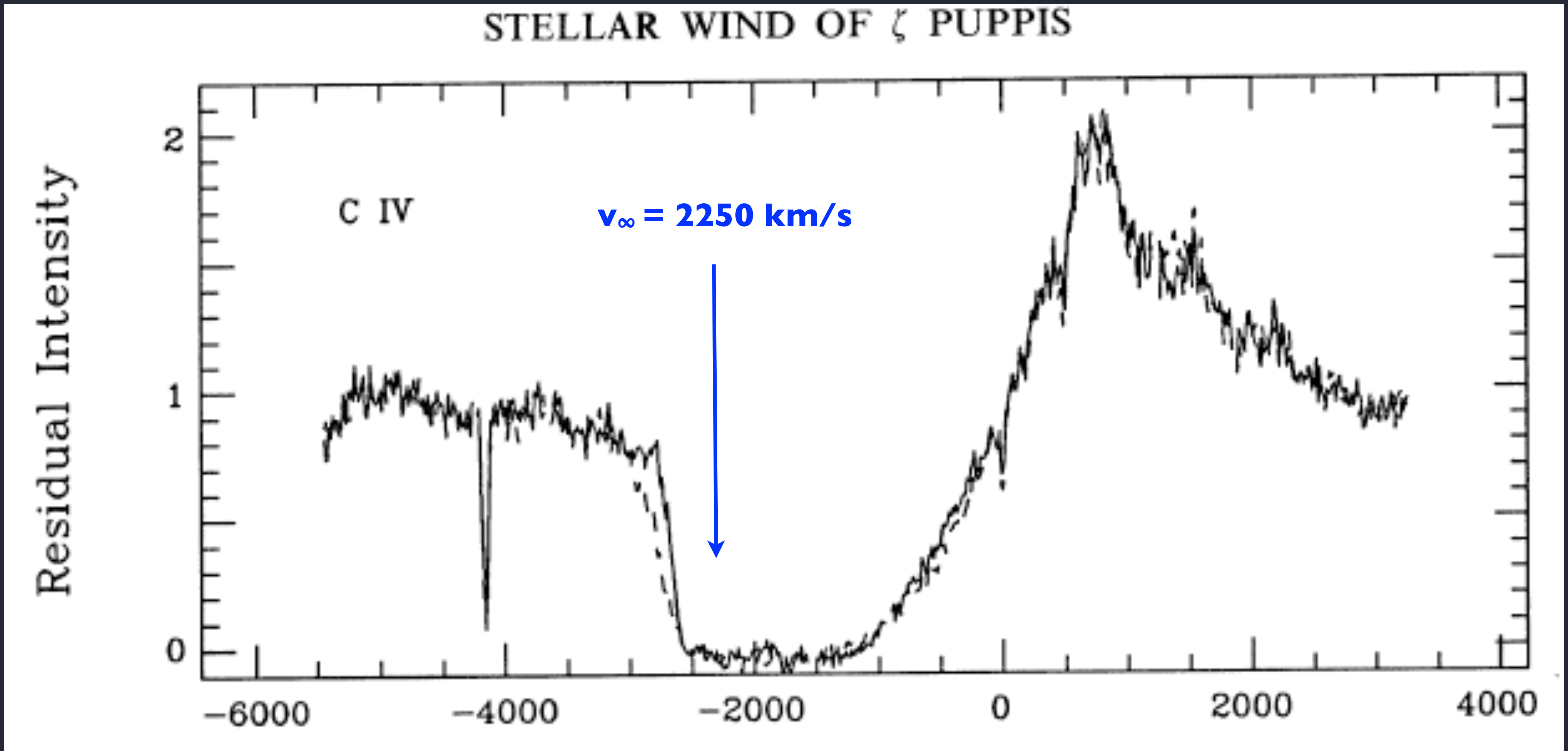

Prinja et al. 1992, ApJ, 390, 266

Velocity (km/s)

Radiation Force on an atom

$h\nu$ (energy)

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

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

luminosity, star's power output (watts)

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

absorption cross section of atom (m^2)

Radiation driving of massive star winds

$\dot{M} \sim 10^{-6}\ M_{sun}/yr$ (10^8 times the Sun's value)

kinetic power in the wind = $1/2\ \dot{M} v_\infty^2$ ($\sim 10^{-3}\ L_{bol}$)

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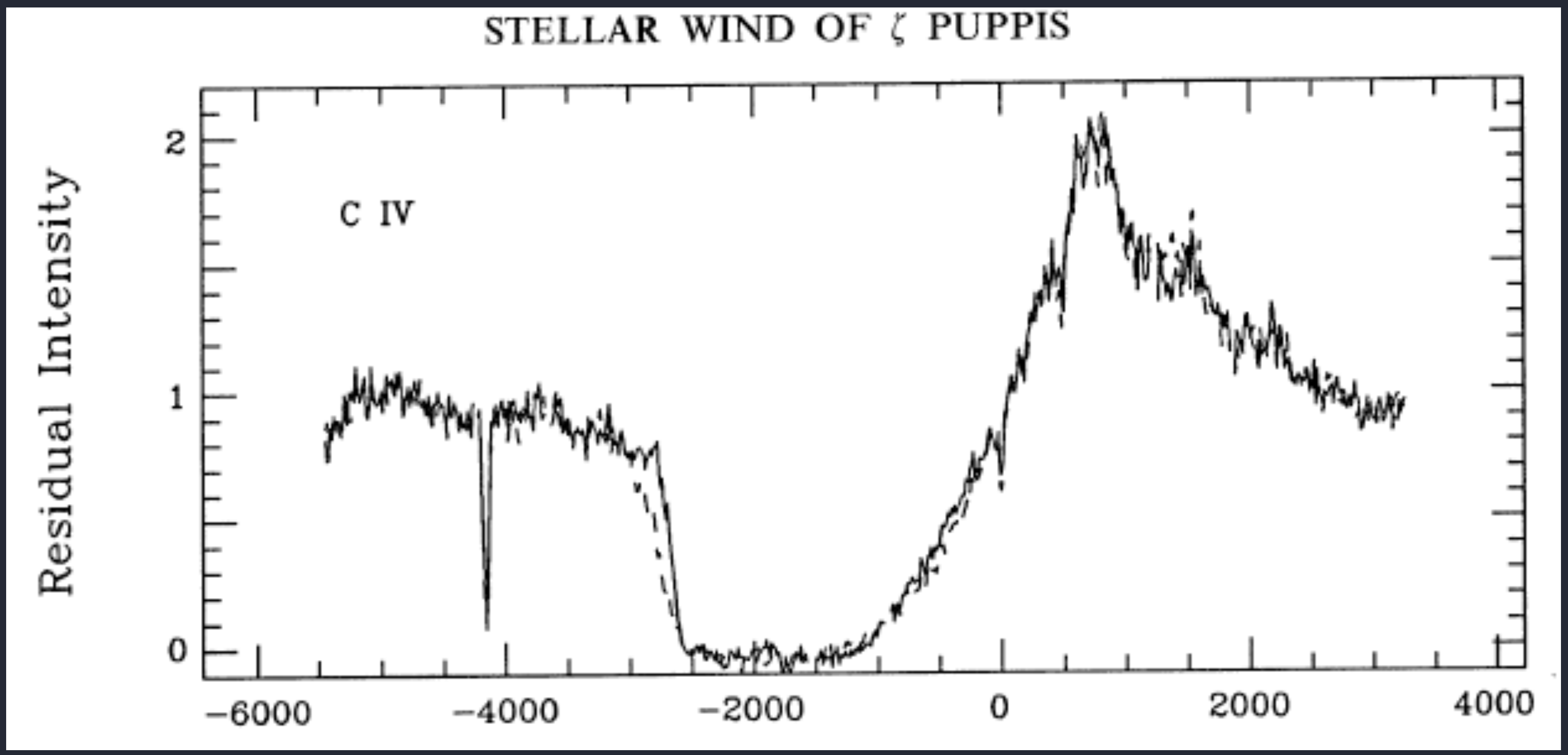


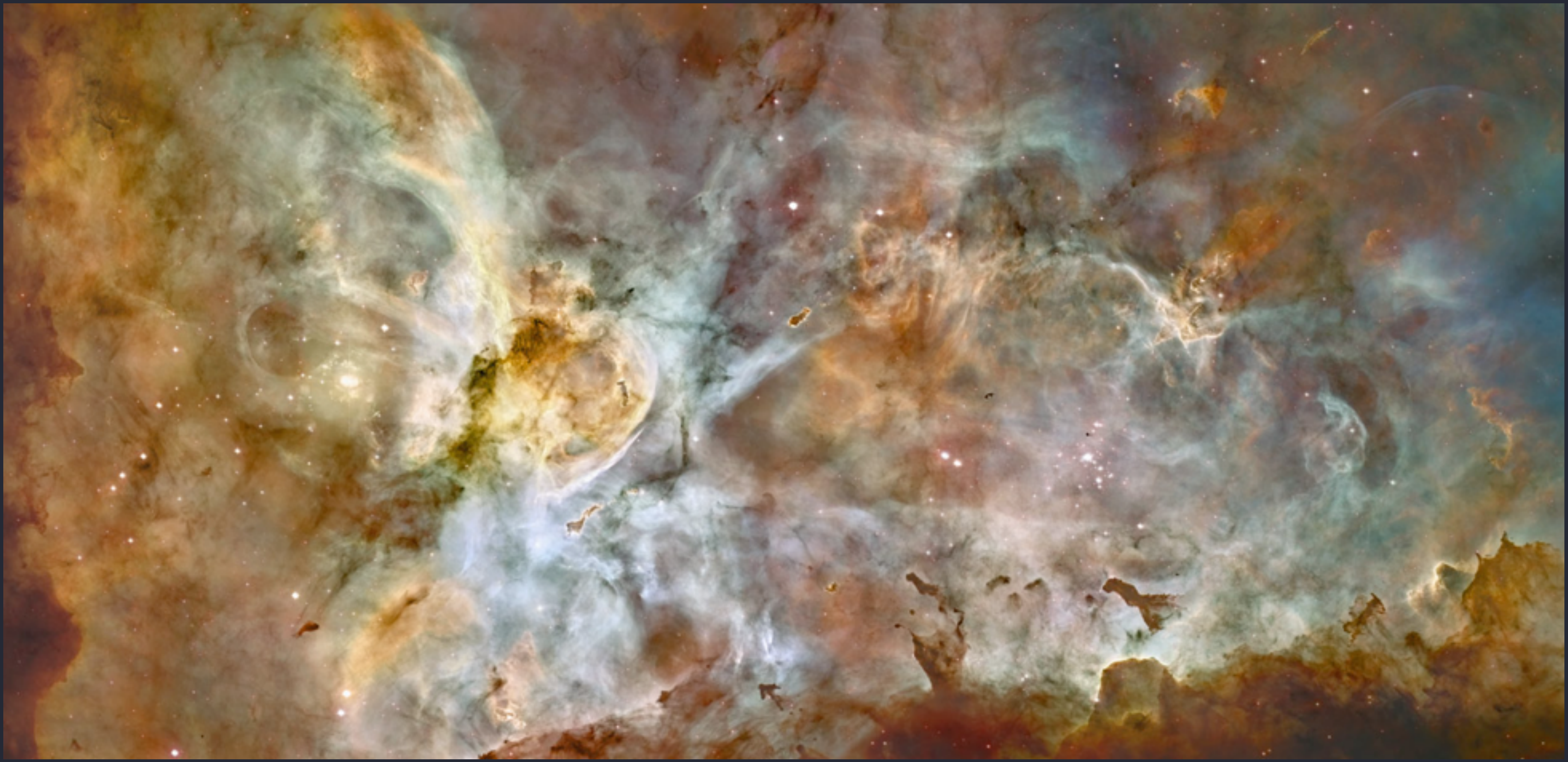
Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

Carina Nebula

massive, luminous stars drive the physics

winds, eruptive mass loss, and supernovae all contribute



Carina Nebula, *Hubble Space Telescope*

~1000 year-old core-collapse supernova remnant

Crab Nebula, *WIYN*

Scale nearest massive stars are ~1000 parsecs* away

*1 parsec = 3.26 light years

Whirlpool Galaxy, *Hubble Space Telescope*

Massive stars as drivers of Galactic physics

Tarantula, *HST*

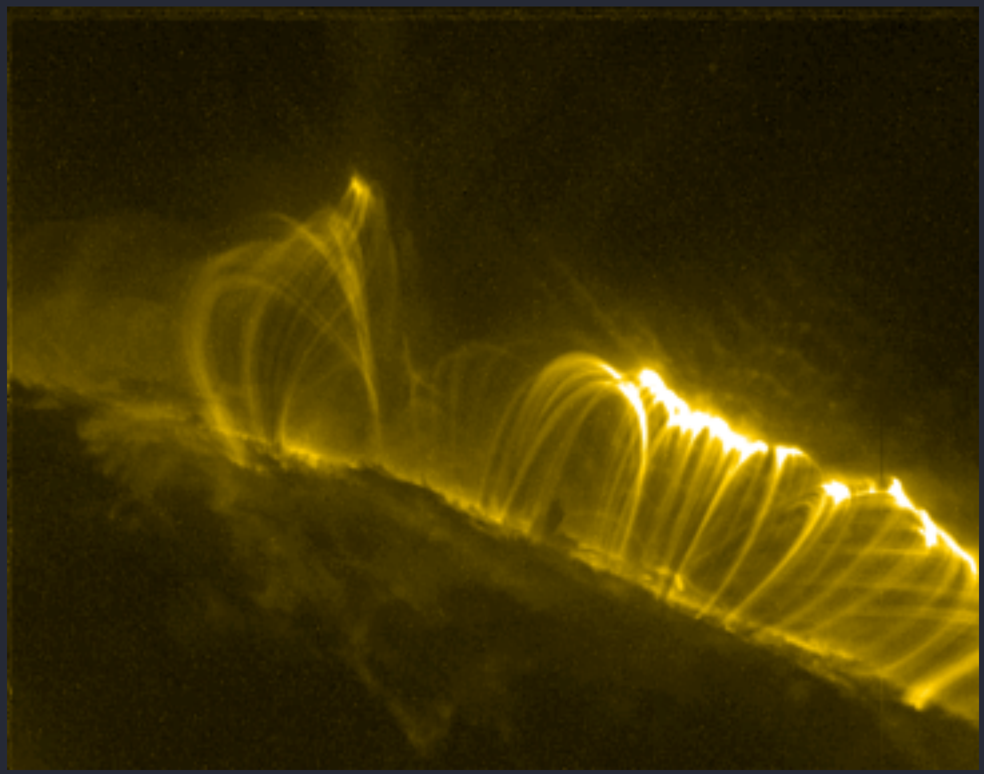
Key points so far:

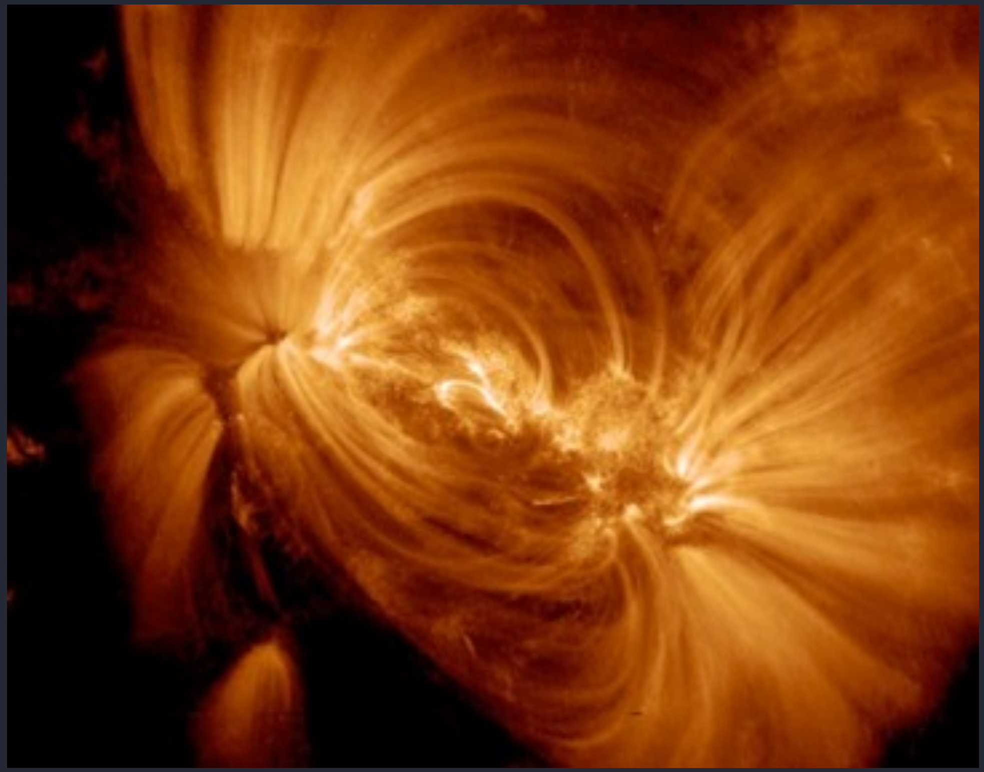
Massive stars have strong winds

Spectroscopy allows us to study structures that we can't see in images

Next: Stellar X-ray emission

The Sun - and other cool, low-mass stars - emit X-rays

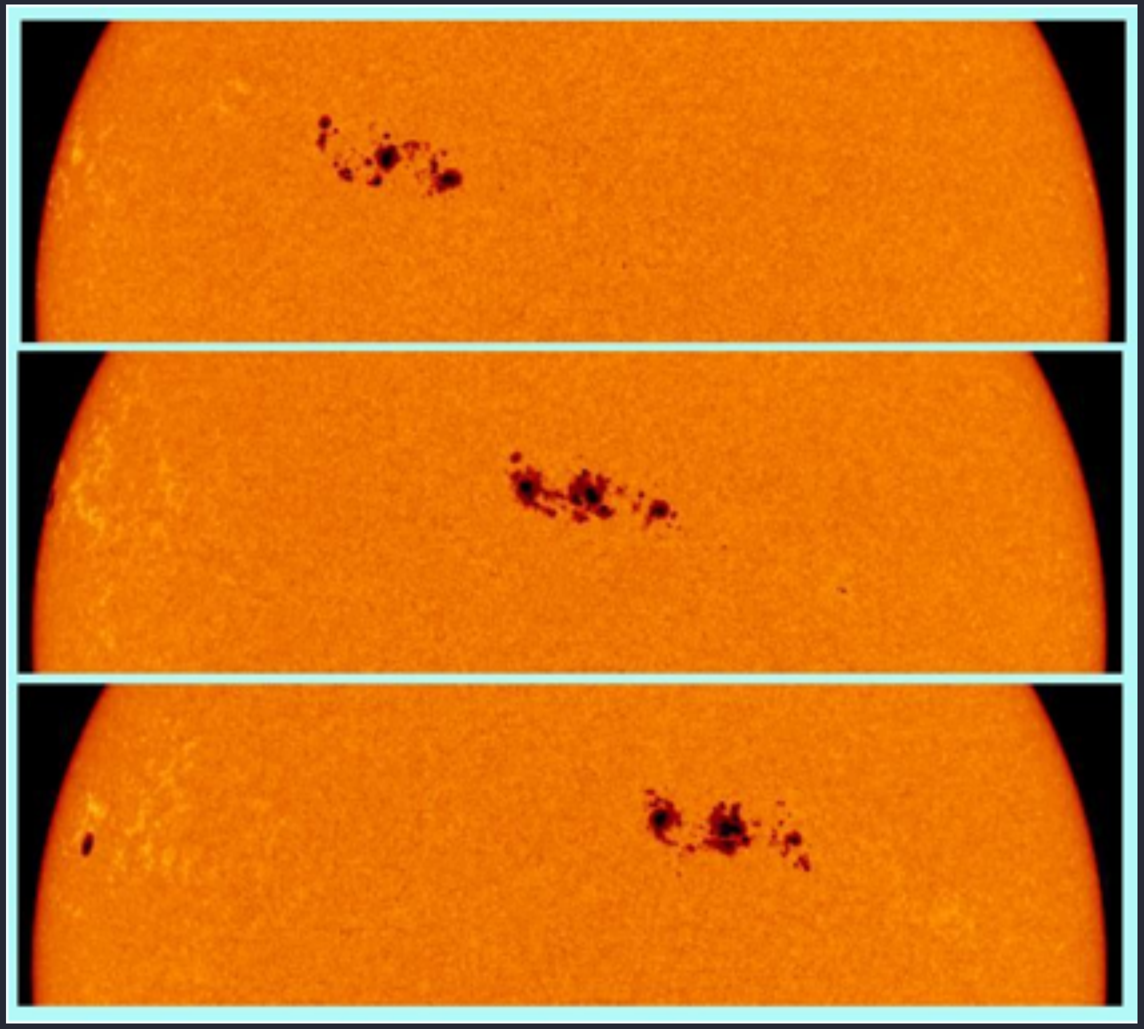




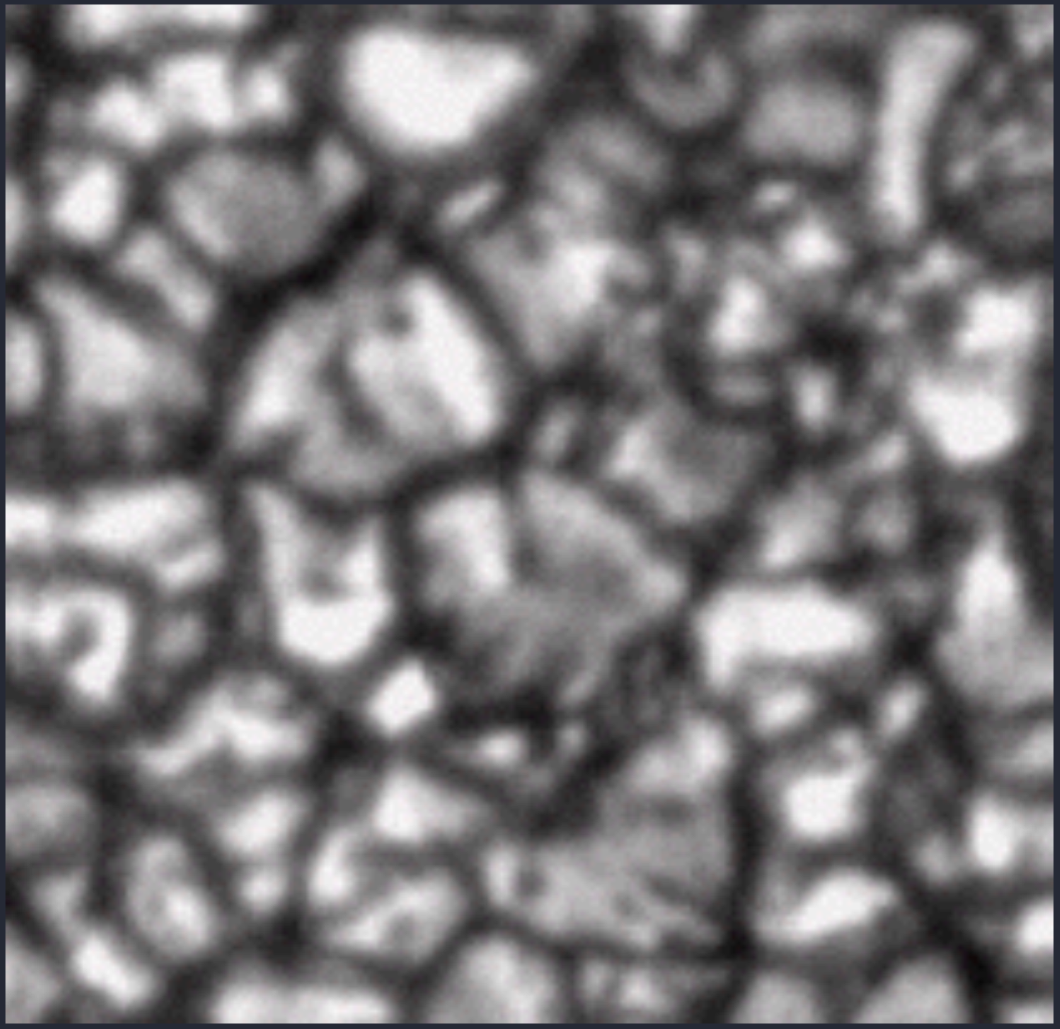
NASA: TRACE

The Sun's X-ray emission is associated with its magnetic dynamo (rotation + convection are key ingredients)

rotation



convection



cool stars vs. hot stars

starfish, *in situ*, at the Monterey, California Aquarium (photo: D. Cohen)

cool stars vs. hot stars

starfish, *in situ*, at the Monterey, California Aquarium (photo: D. Cohen)

discovery of massive star X-ray emission in 1970s

THE ASTROPHYSICAL JOURNAL, 234:L51–54, 1979 November 15

DISCOVERY OF AN X-RAY STAR ASSOCIATION IN VI CYGNI (CYG OB2)

F. R. HARNDEN, JR., G. BRANDUARDI, M. ELVIS,[1] P. GORENSTEIN, J. GRINDLAY,
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Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts
Received 1979 June 26; accepted 1979 July 26

ABSTRACT

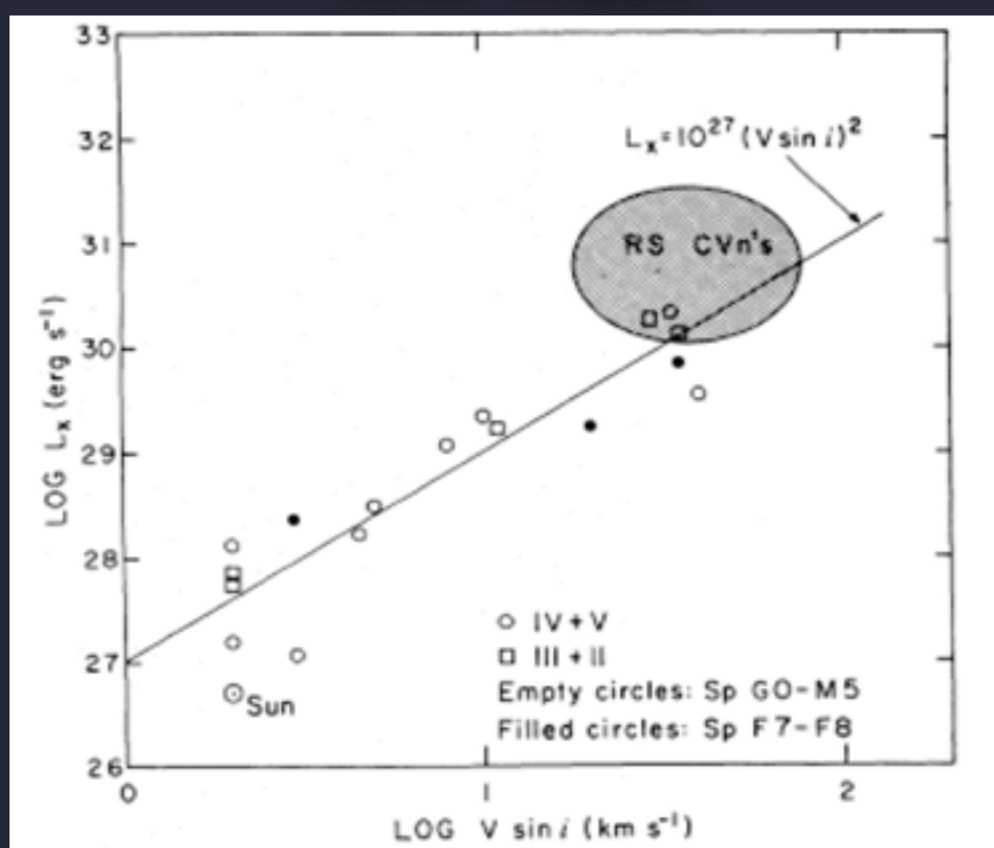
A group of six X-ray sources located within $0\overset{\circ}{.}4$ of Cygnus X-3 has been discovered with the *Einstein* Observatory. These sources have been positively identified and five of them correspond to stars in the heavily obscured OB association VI Cygni. The optical counterparts include four of the most luminous O stars within the field of view and a B5 supergiant. These sources are found to have typical X-ray luminosities L_x (0.2–4.0 keV) $\sim 5 \times 10^{33}$ ergs s^{-1}, with temperatures $T \sim 10^{6.8}$ K and hydrogen column densities $N_H \sim 10^{22}$ cm^{-2}, and therefore comprise a new class of low-luminosity galactic X-ray sources associated with early-type stars.

Massive stars have some *different* X-ray production mechanism

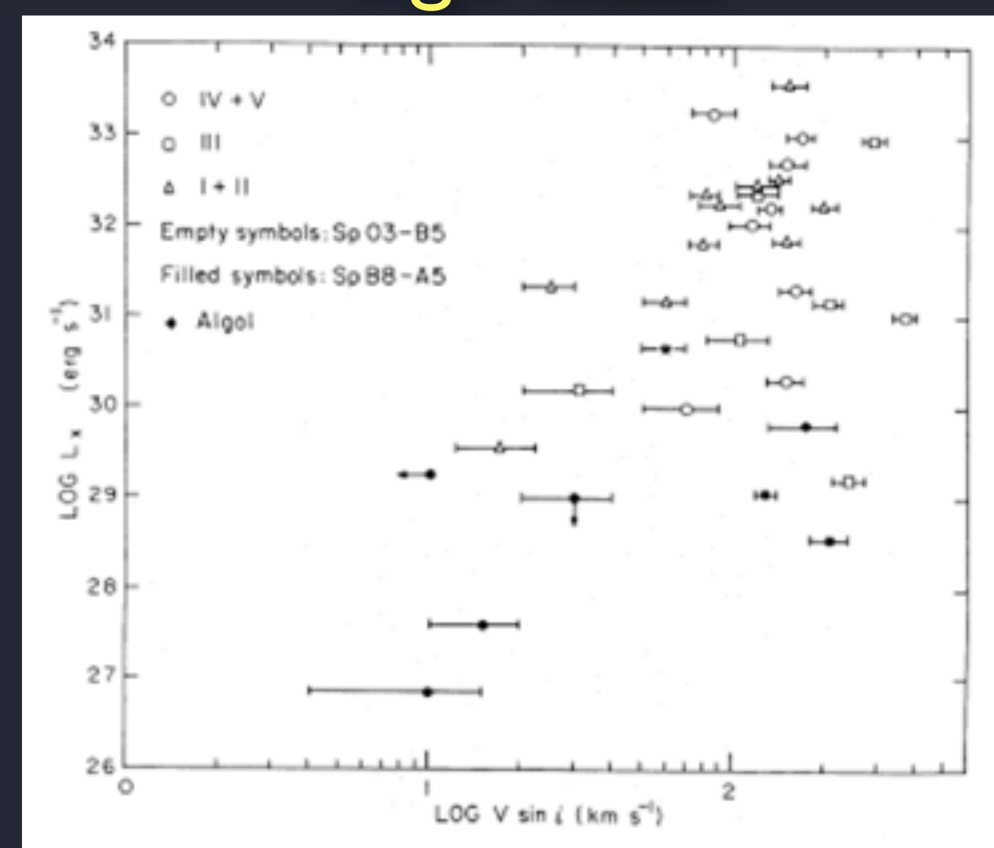
Maybe due to their powerful winds?

No observed correlation between rotation and X-ray luminosity

low mass



high mass



Astron. Astrophys. 322, 167–174 (1997)

ASTRONOMY
AND
ASTROPHYSICS

X-ray properties of bright OB-type stars detected in the ROSAT all-sky survey

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[2] Center for EUV Astrophysics, 2150 Kittredge Street, University of California, Berkeley, CA 94720, USA
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Received 17 July 1996 / Accepted 26 November 1996

Abstract. The ROSAT all-sky survey has been used to study the X-ray properties for all OB-type stars listed in the Yale Bright Star Catalogue. Here we present a detailed astrophysical discussion of our analysis of the X-ray properties of our complete sample of OB-type stars; a compilation of the X-ray data is provided in an accompanying paper (Berghöfer, Schmitt & Cassinelli 1996).

We demonstrate that the "canonical" relation between X-ray and total luminosity of $L_x/L_{Bol} \approx 10^{-7}$ valid for O-type stars extends among the early B-type stars down to a spectral type B1–B1.5; for stars of luminosity classes I and II the spectral type B1 defines a dividing line for early-type star X-ray emission.

1979, Pallavicini *et al.* 1981, Chlebowski *et al.* 1989, Sciortino *et al.* 1990). However, the scatter for values of individual stars, 2 orders of magnitude, around the mean value is quite large. The widely accepted model for the X-ray emission from O stars assumes that it is produced by shock-heated gas propagating in the strong winds of these stars. In a phenomenological model Lucy & White (1980) and Lucy (1982) postulate the existence of shocks in the radiation driven winds of hot stars which are formed as a consequence of a strong hydrodynamic instability (e.g., Lucy & Solomon 1980). Hydrodynamical calculations for hot star winds (e.g., Owocki, Castor & Rybicki 1988) provide strong support for such a model. The base corona source of X-

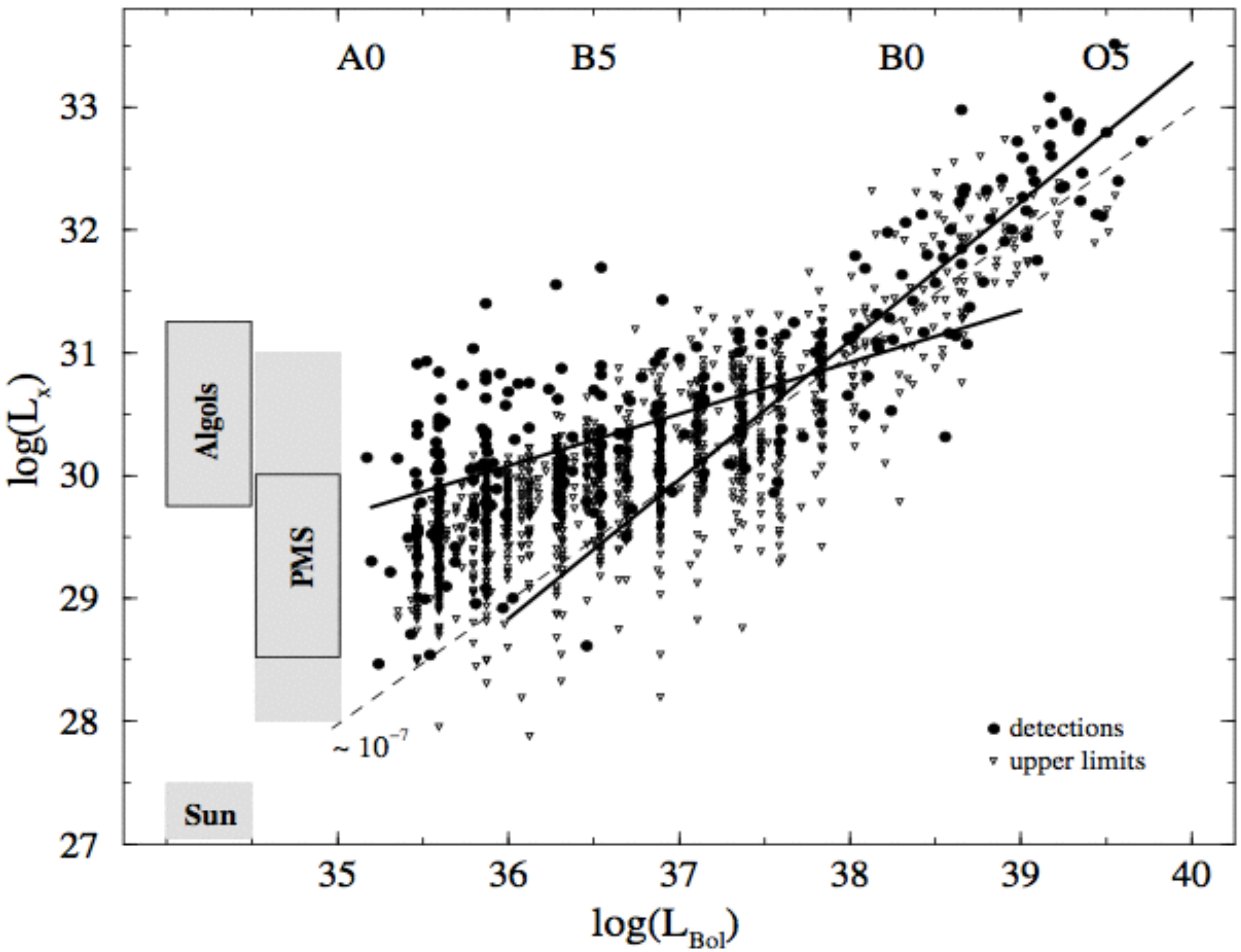


Fig. 4. X-ray luminosities L_x plotted versus bolometric luminosities L_{Bol}; solid lines represent regression lines for $L_{Bol} < 10^{38} erg\, s^{-1}$ and $L_{Bol} > 10^{38}$ erg s^{-1}, whereas the dashed line shows $L_x = 10^{-7} \times L_{Bol}$, grey bars at the left side show typical ranges for the X-ray luminosity of Algol-type systems, pre-main sequence stars (PMS), and our Sun.

The wind kinetic power is typically 10^4 times larger than the observed L_x

some process - which doesn't have to be very efficient - converts a small fraction of this kinetic power to heat

the observed X-rays are the thermal radiation from this hot stellar wind plasma

The line-deshadowing instability (LDI)

causes fast, rarefied wind plasma to slam into slower, denser wind plasma

the resulting shocks heat the plasma

the X-rays we see are the thermal emission from this hot wind plasma

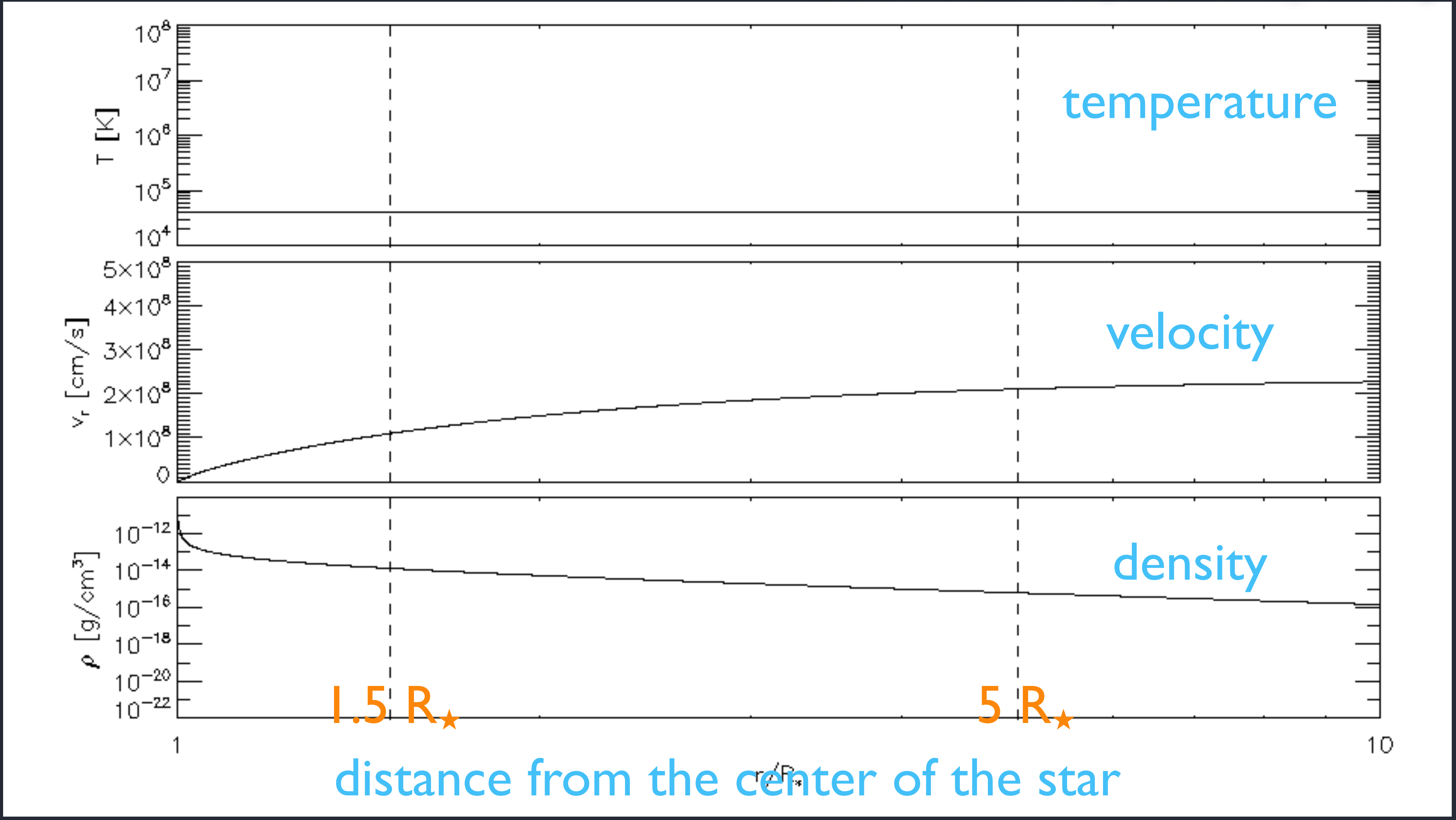
general result from shock theory:

$$T \sim 10^6(\Delta v_{shock}/300\ \mathrm{km/s})^2$$

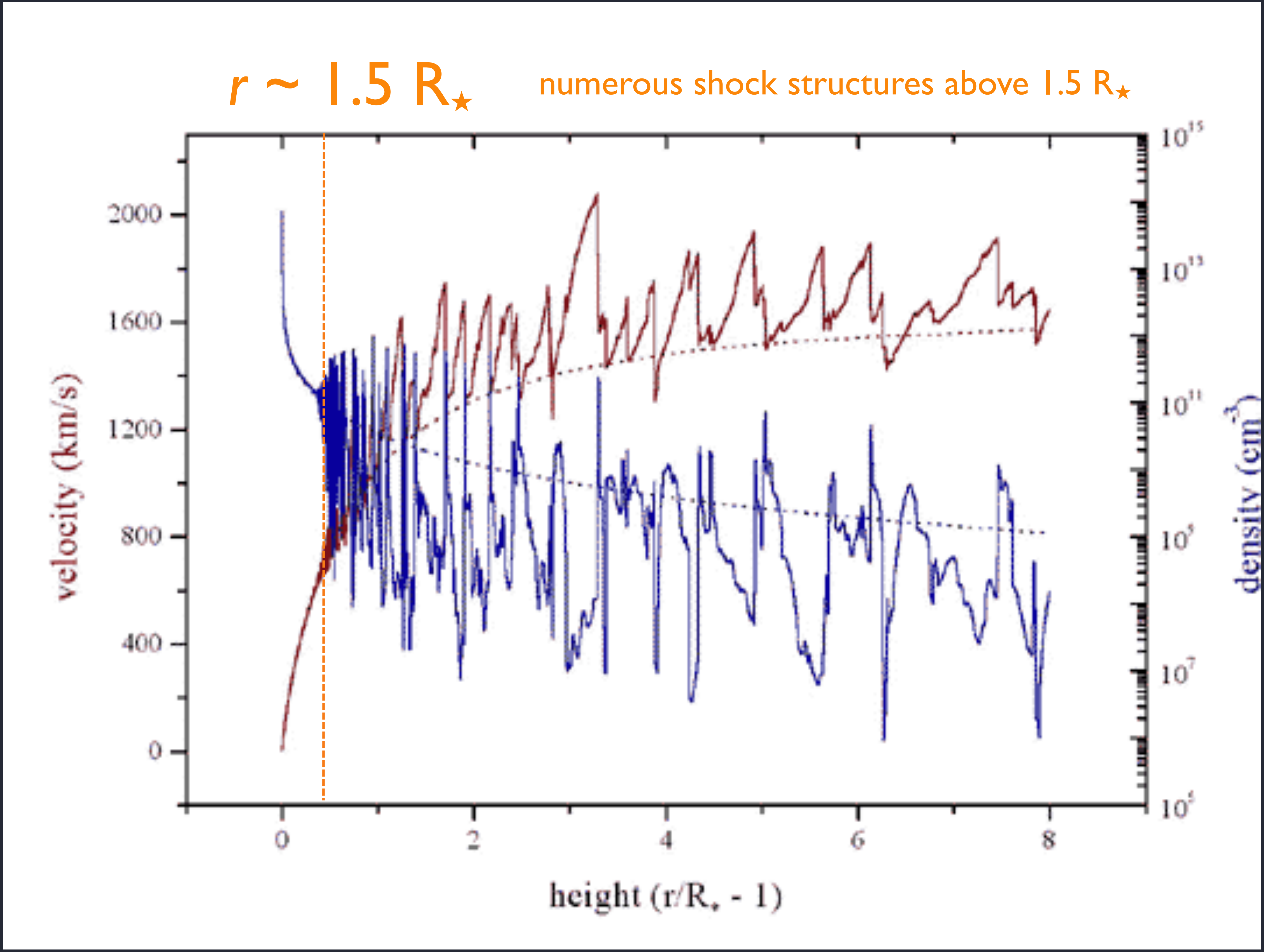
X-ray emitting plasma is embedded in the wind

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

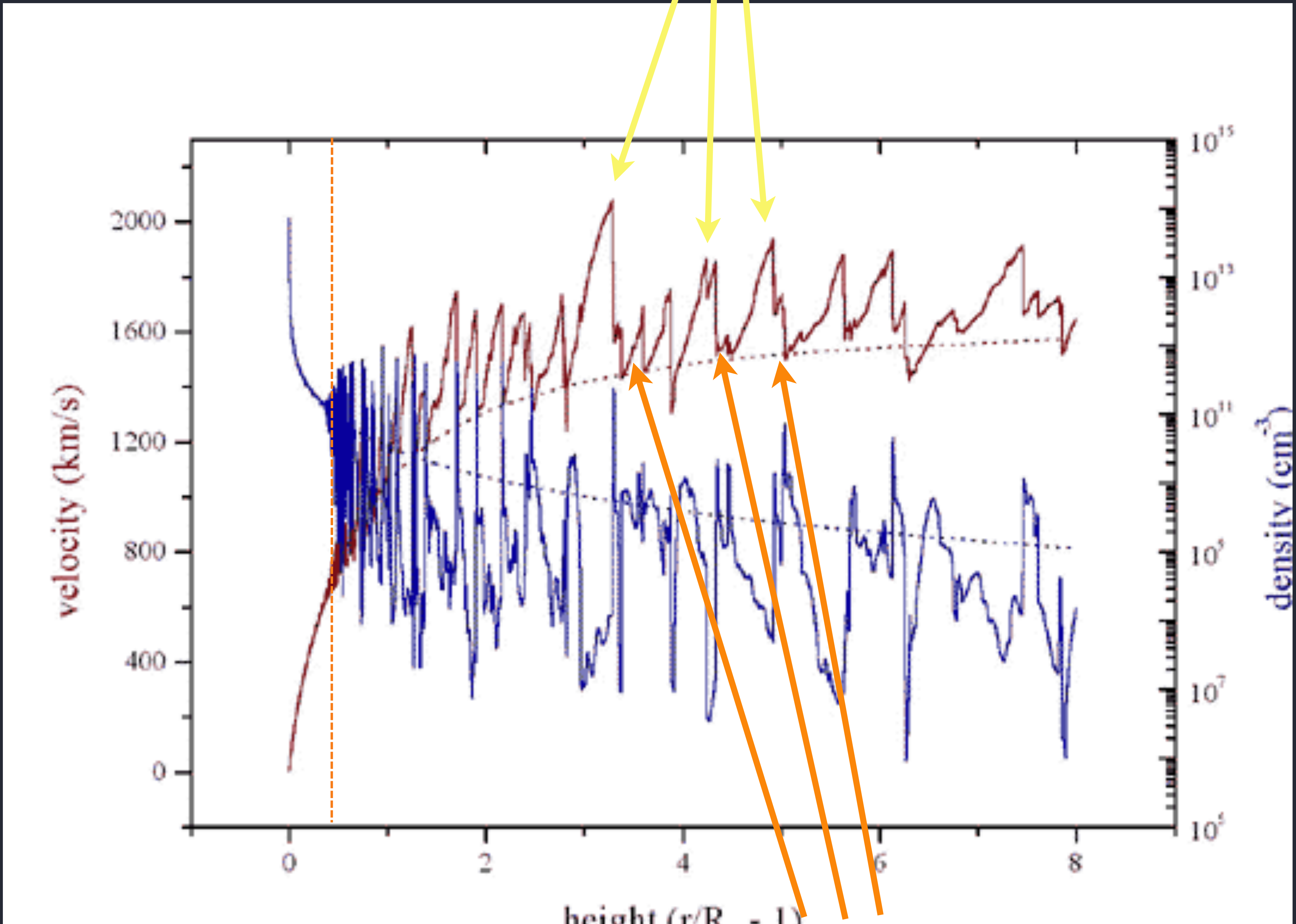
astro.swarthmore.edu/~cohen/presentations/ifrc3_xmbko1.e-2.gif



snapshot from the hydro simulation

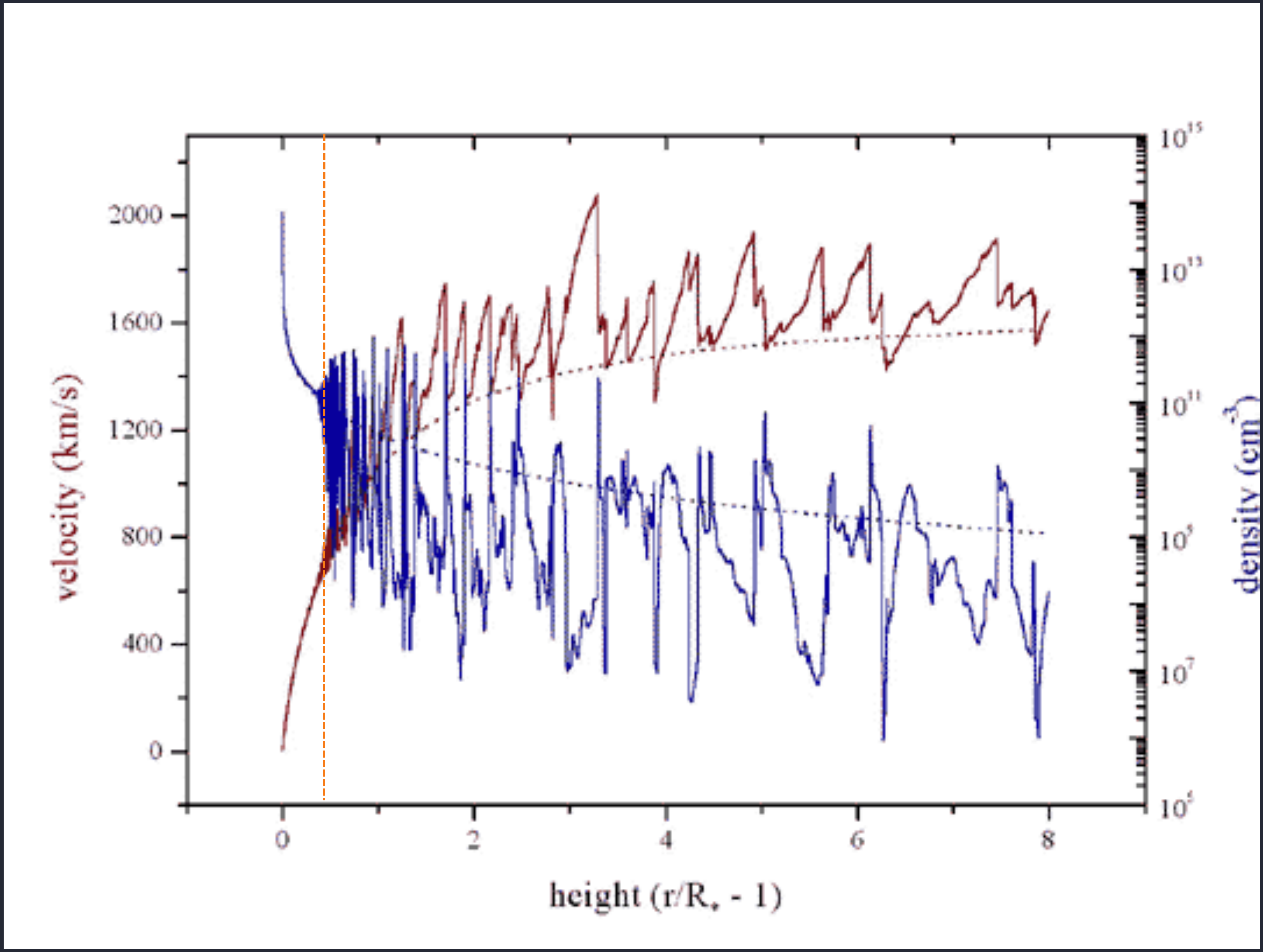


$V_{shock} \sim 300$ km/s : $T \sim 10^6$ K

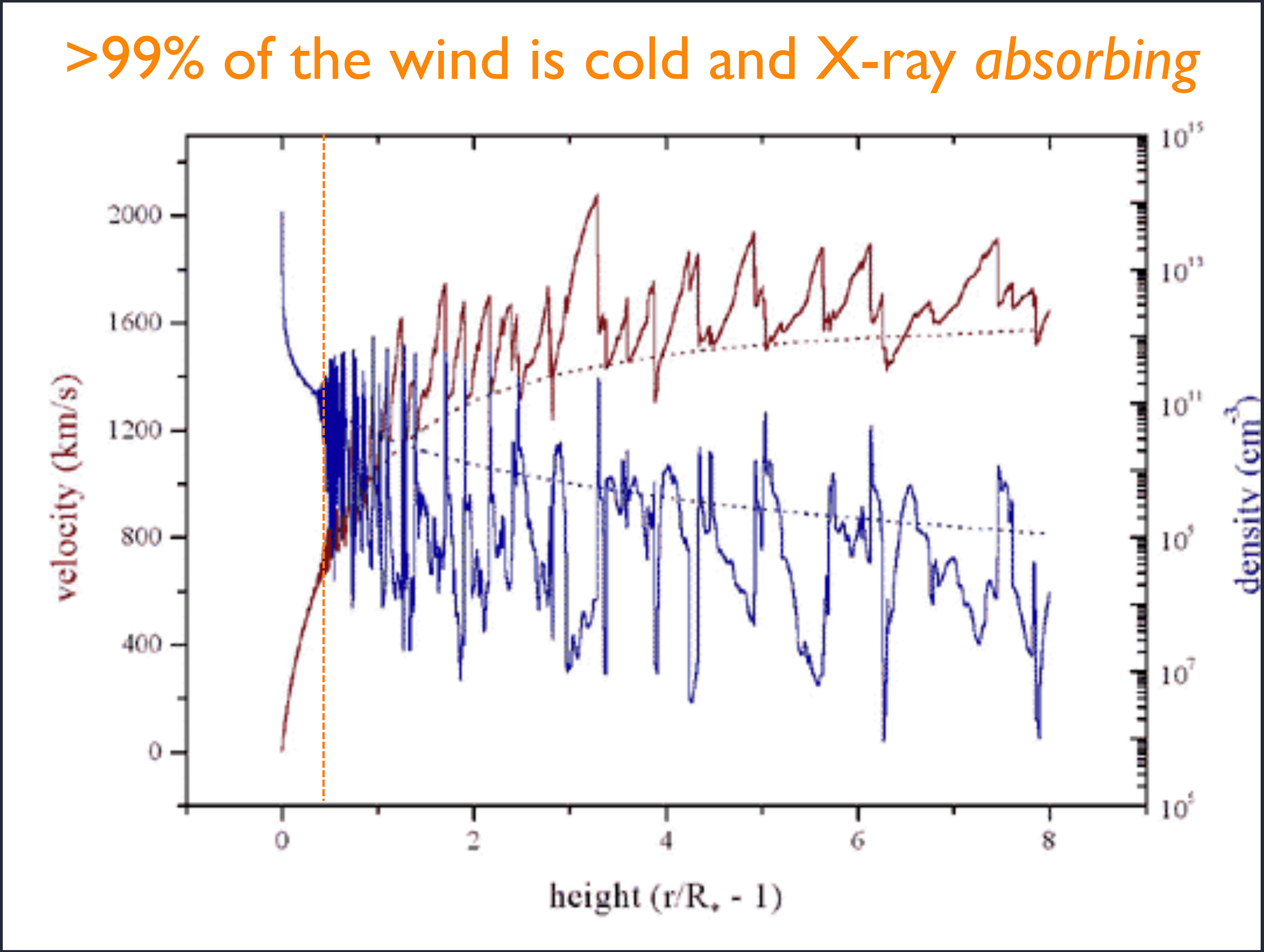


shocked wind plasma is decelerated back down to the local steady-state wind velocity

X-ray emission lines should be Doppler broadened



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



Key points so far:

Massive stars emit X-rays

Their radiation-driven winds are the site of the X-ray emission (according to theory)

Next: X-ray spectroscopy of massive stars

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
$h\nu$ ~ 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)

Spectral resolution and velocity

"spectral resolution" how close can two lines be in a spectrum and still be seen as two separate lines?

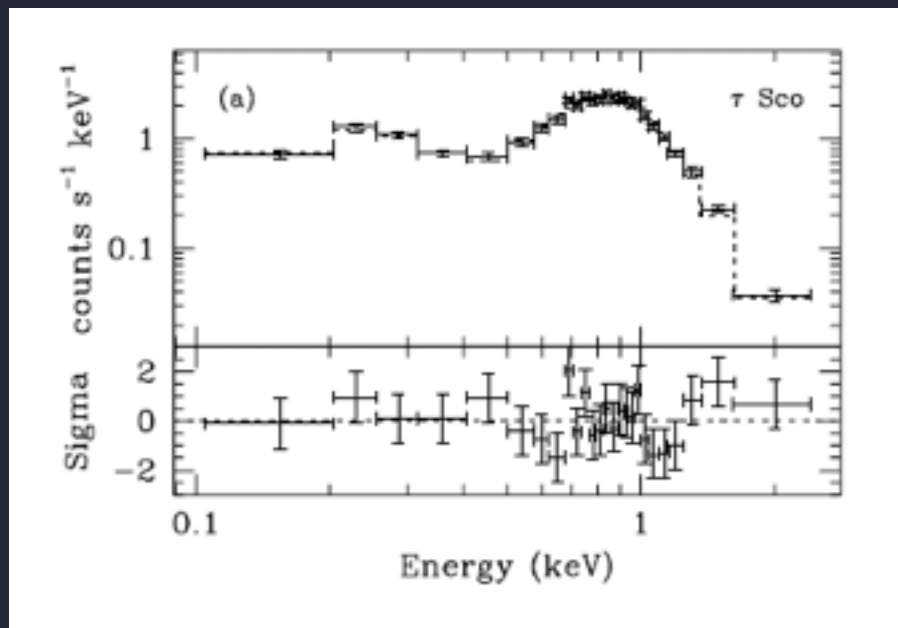
"spectral resolution" how broad does an intrinsically narrow spectral line looks in the spectrograph?

spectral resolution, $R = \lambda/\Delta\lambda$

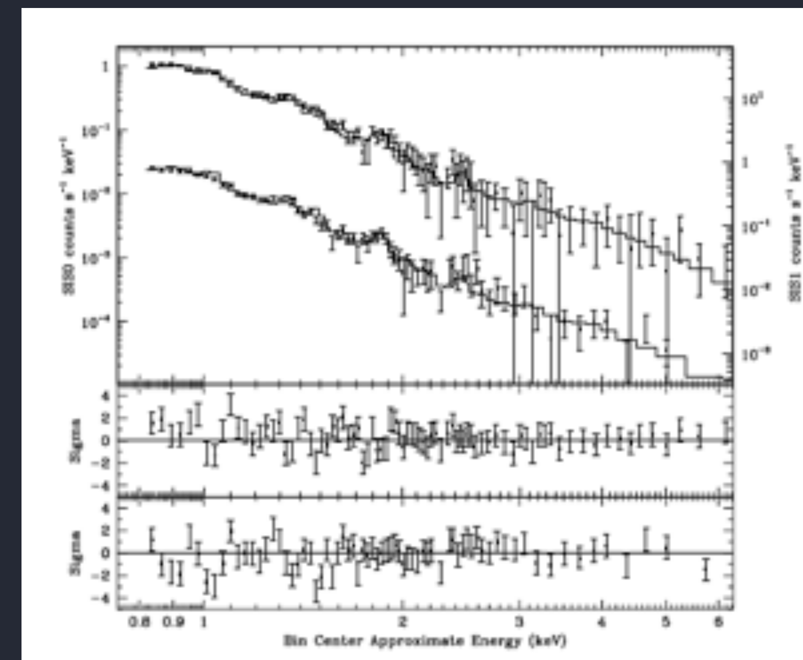
Doppler shift, $\Delta\lambda/\lambda = v/c$

now for some X-ray data... the same star (tau Sco) observed with three different X-ray telescopes

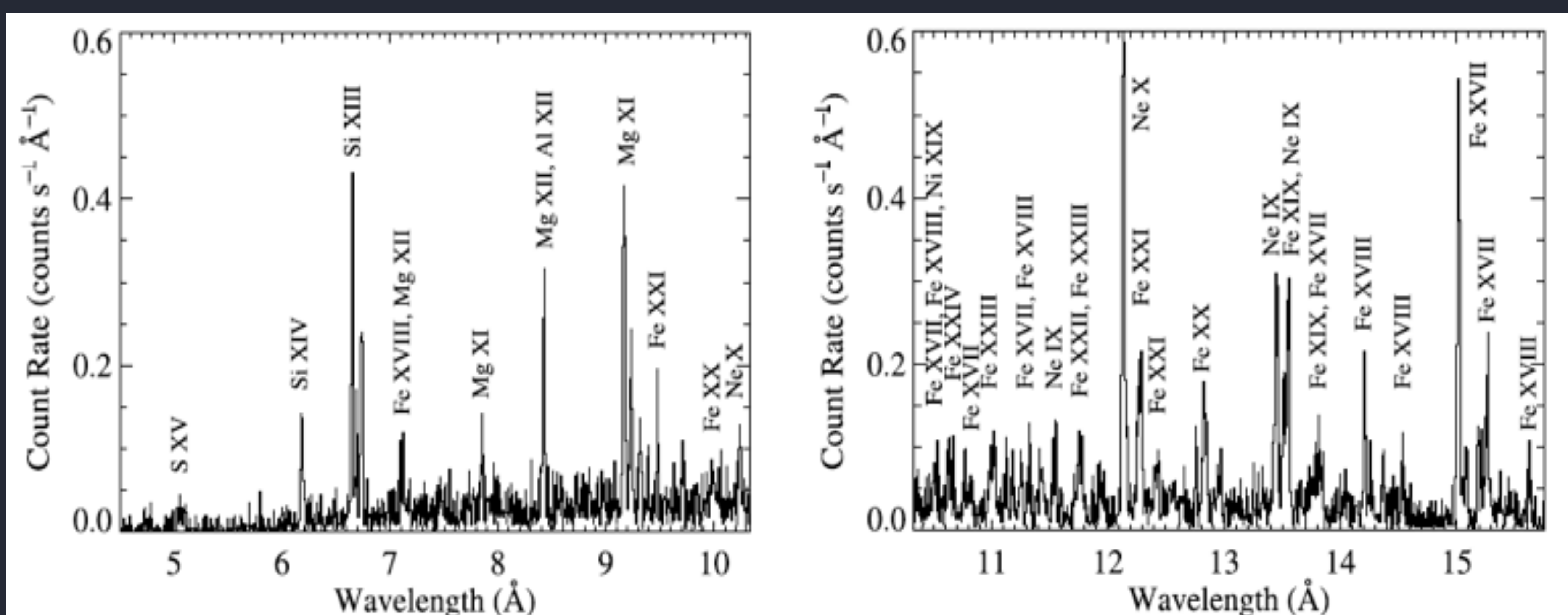
ROSAT 1991



ASCA 1994

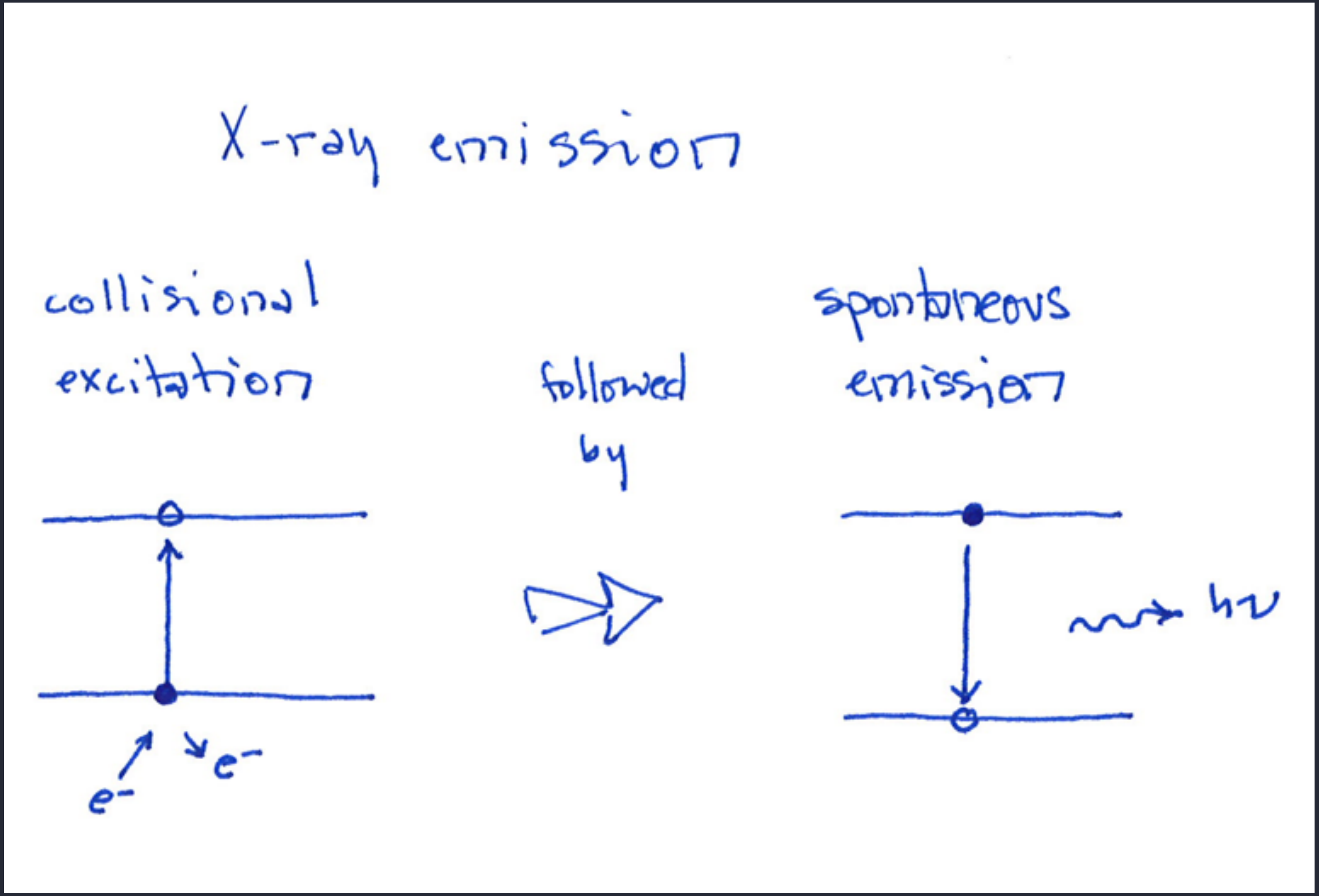


Chandra 2001



X-ray emission process

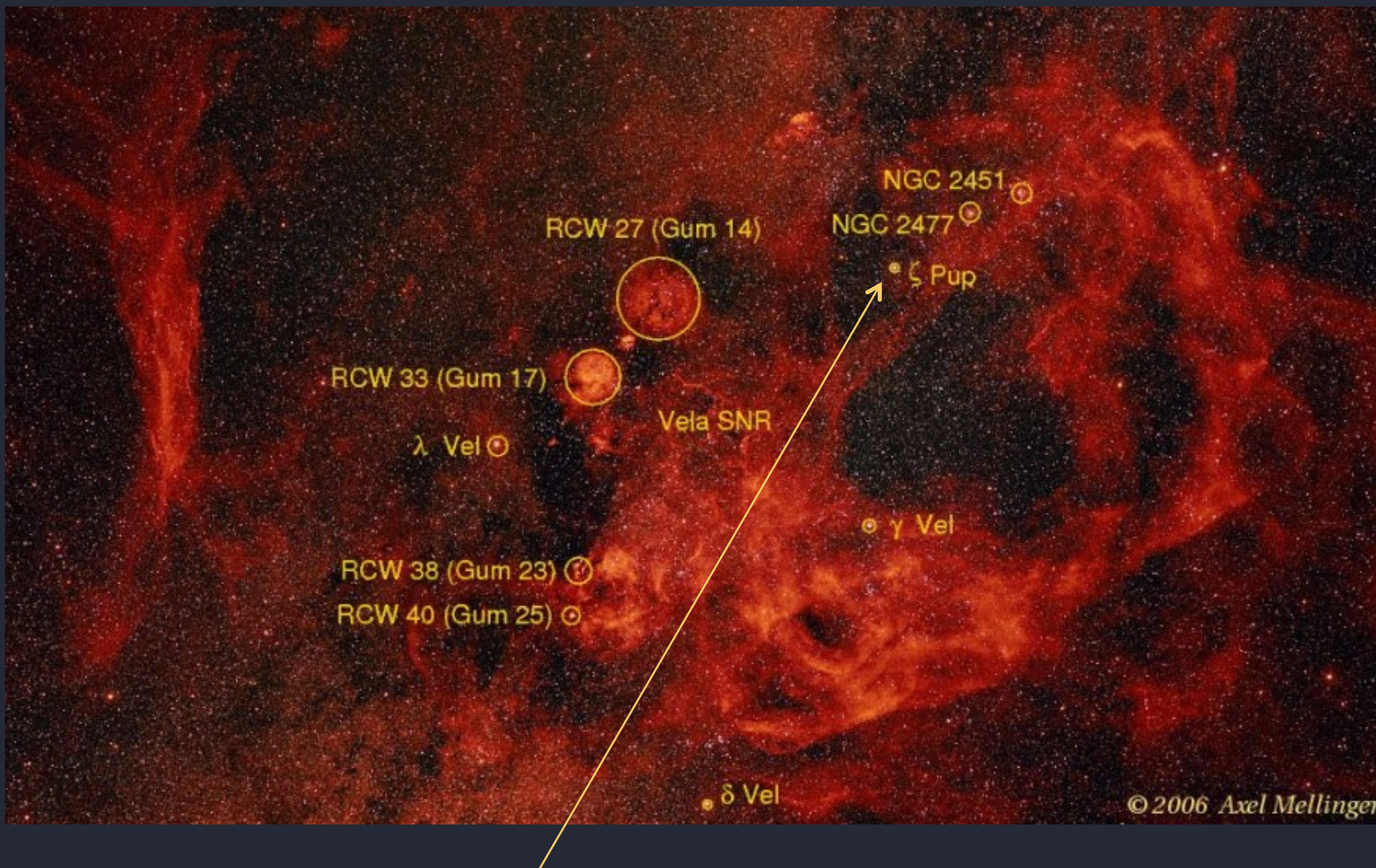
thermal emission from collisional plasma



Chandra grating spectroscopy

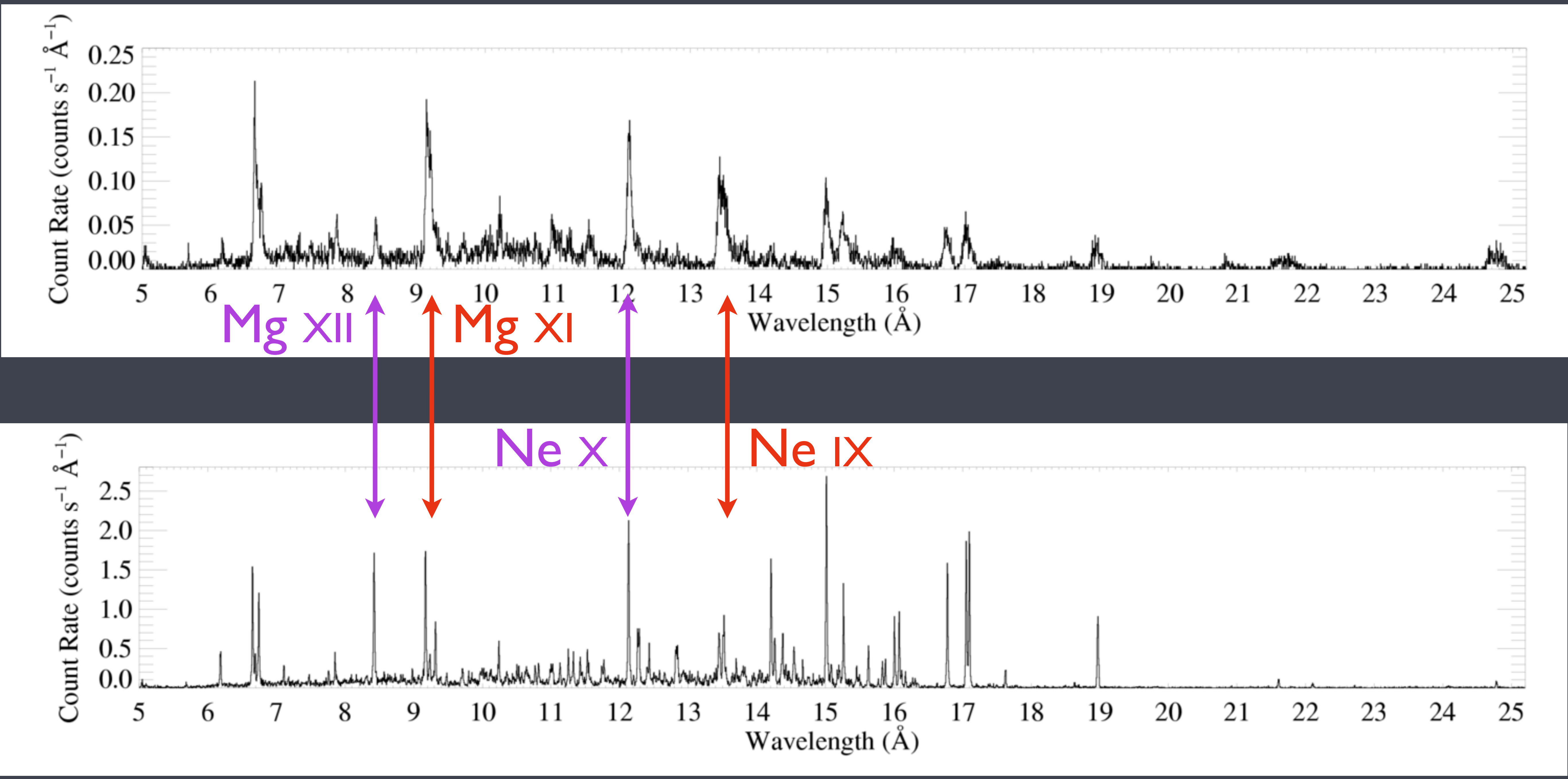
ζ Pup (O4 If)

CHANDRA
X-RAY OBSERVATORY



Chandra grating (HETGS/MEG) spectra

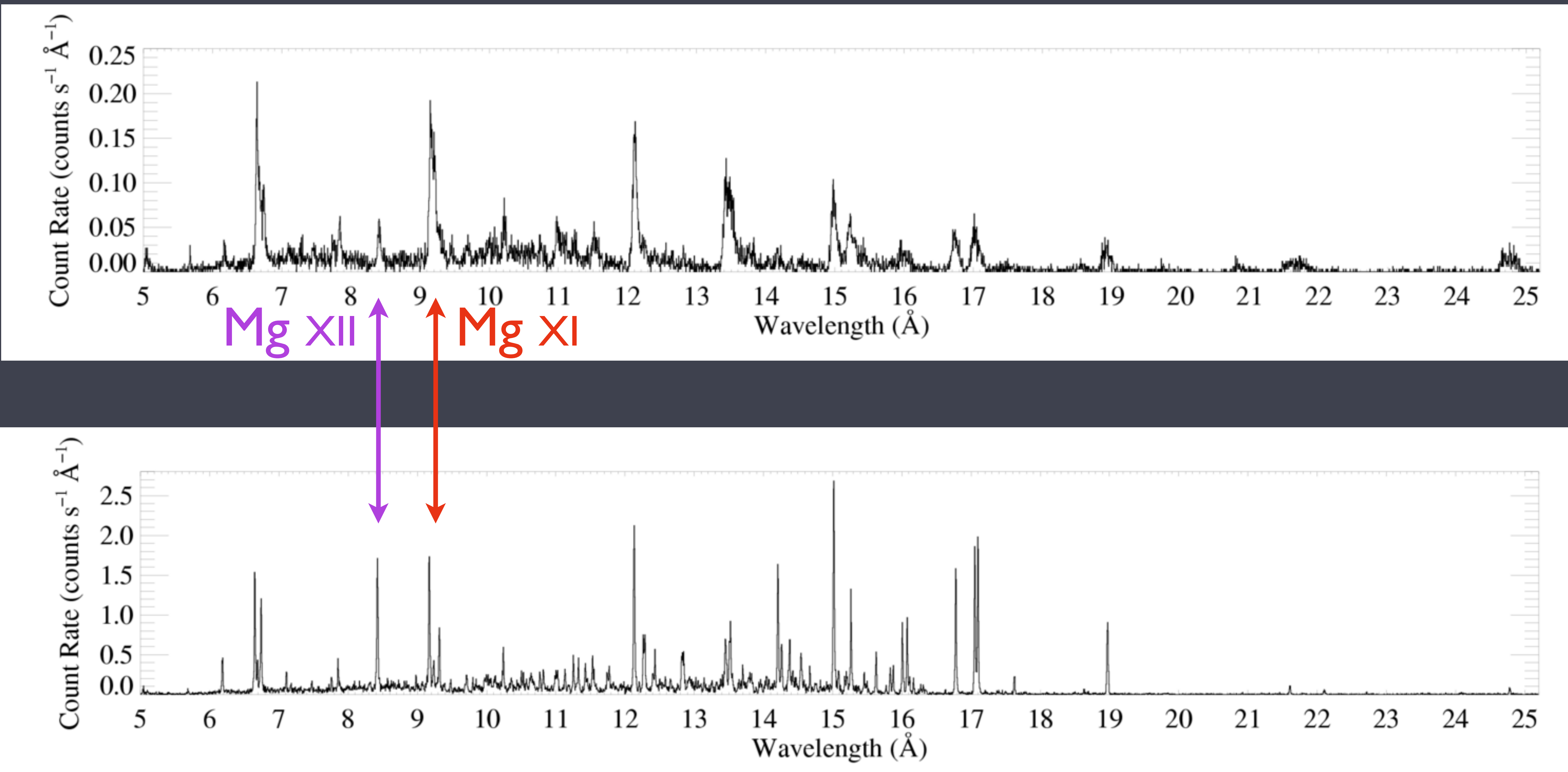
ζ Pup (O4 If)



Capella (G5 III)

typical temperatures $T \sim$ few 10^6 K
(late-type stellar coronae tend to be hotter)

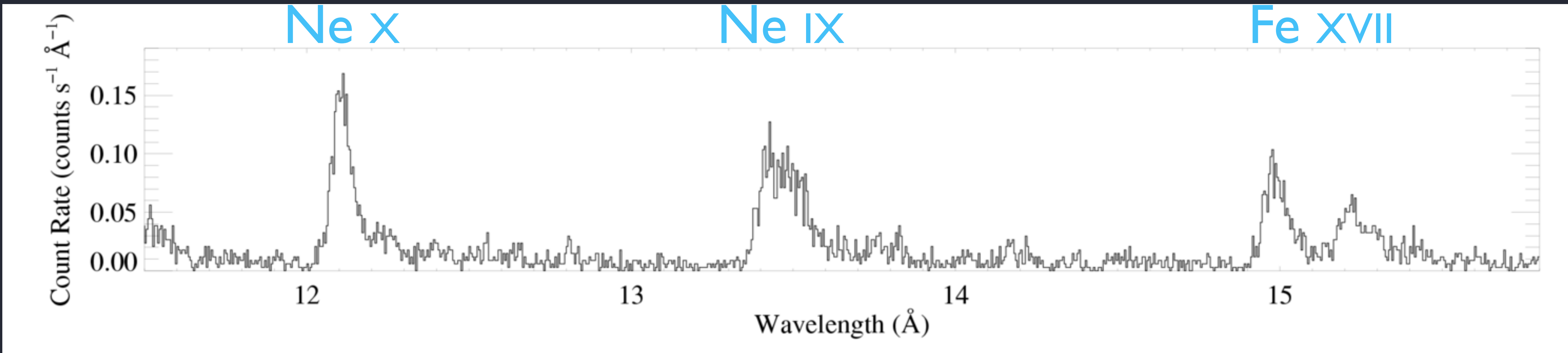
ζ Pup (O4 If)

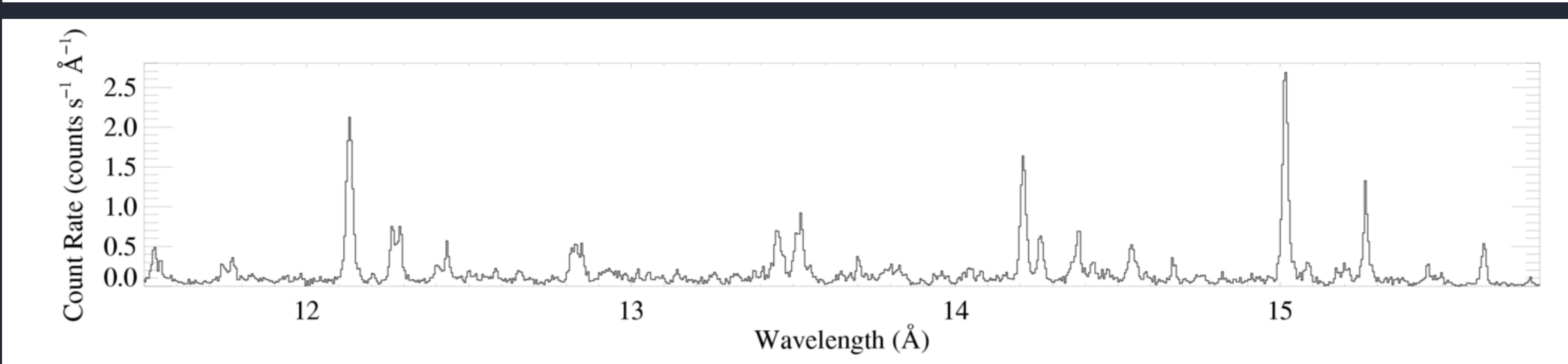


Capella (G5 III)

Zoom in

ζ Pup (O4 If)

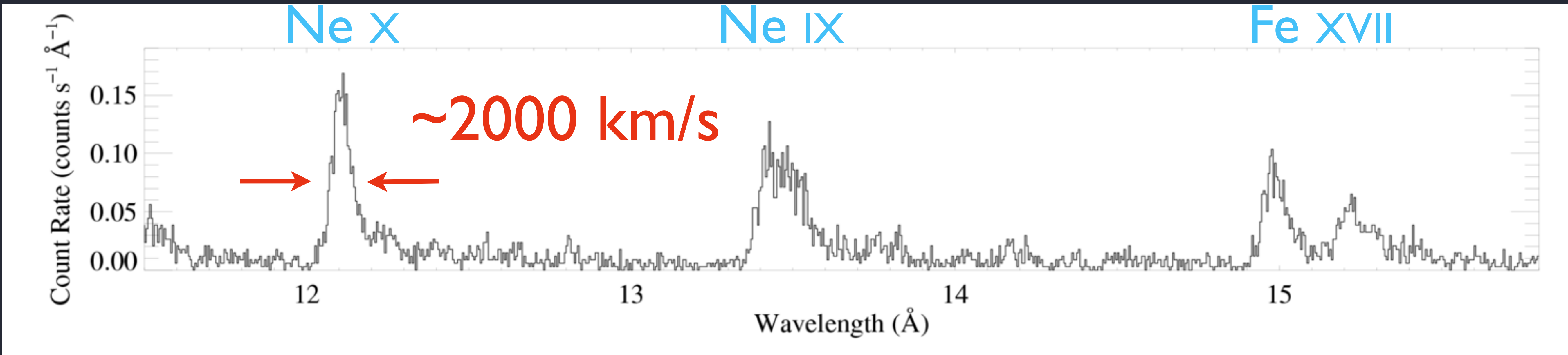


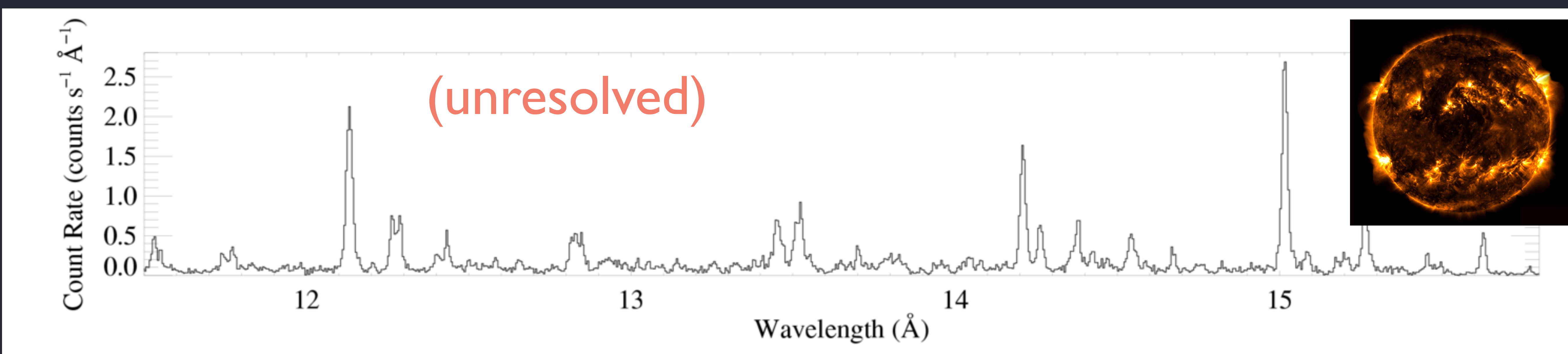


Capella (G5 III)

Zoom in

ζ Pup (O4 If)



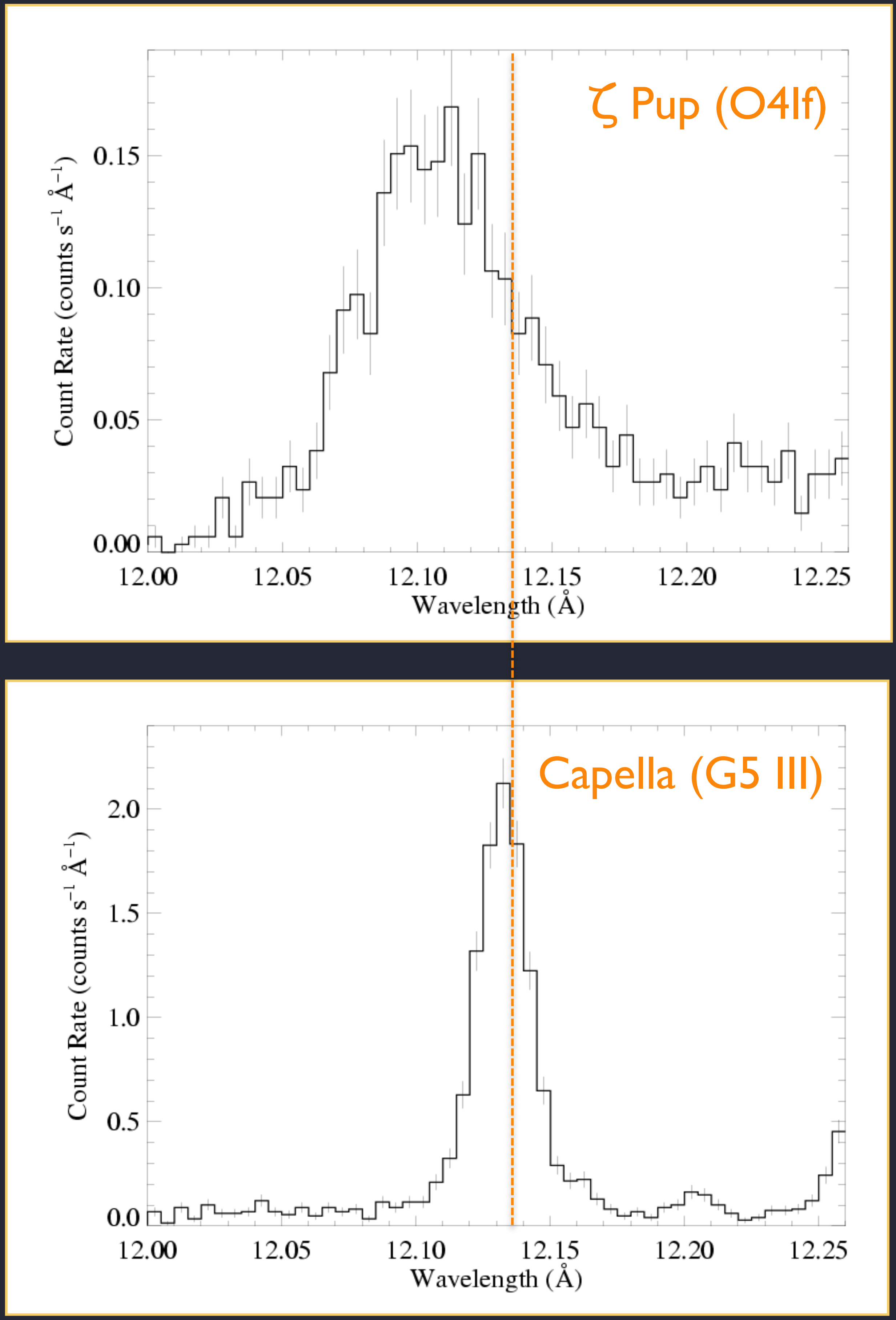


Capella (G5 III)

A careful look at the individual emission lines

characteristic *asymmetry*

blue-shifted peak
& skewness



A careful look at the individual emission lines

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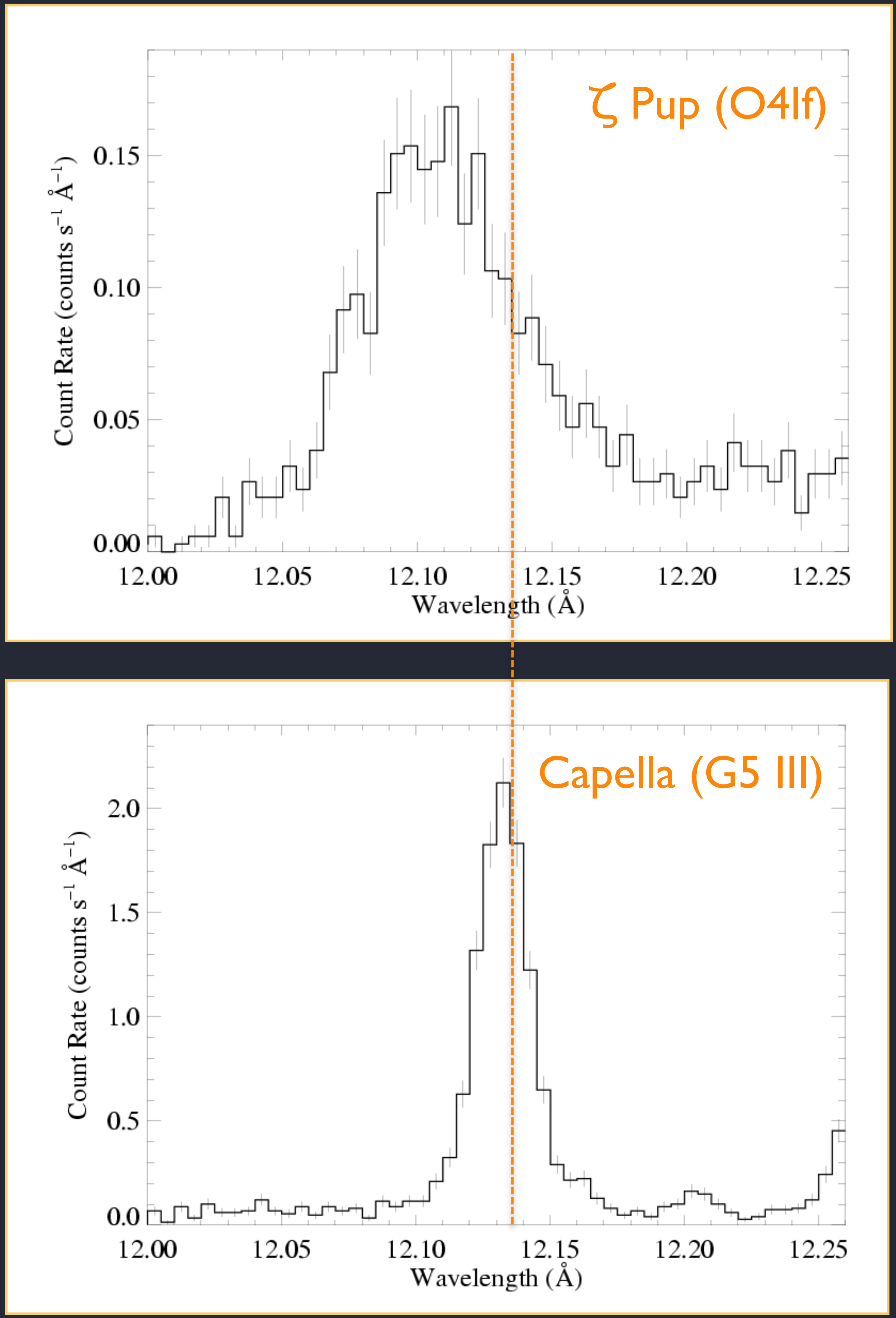
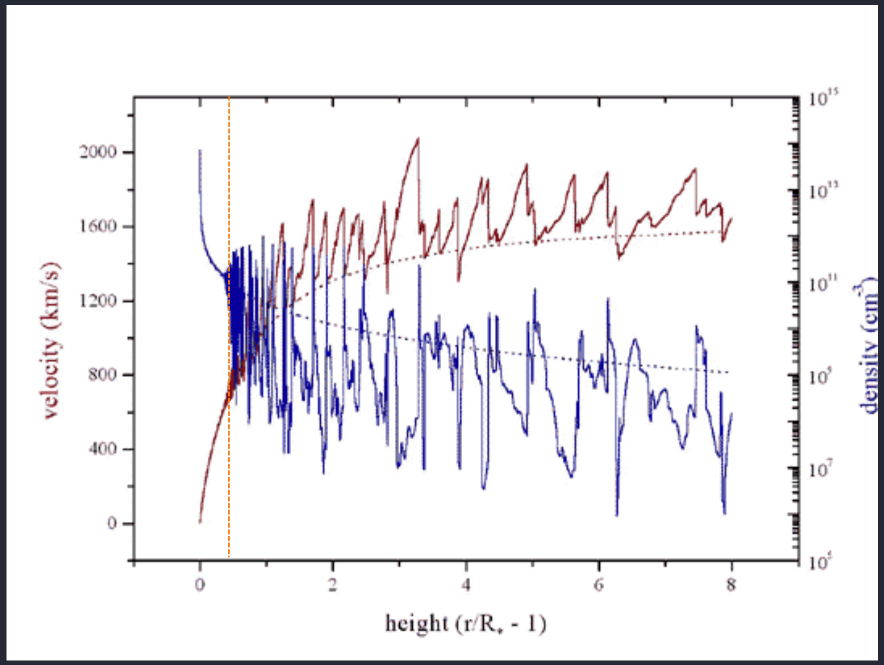


How can this be explained in the context of embedded wind shocks (EWS)?

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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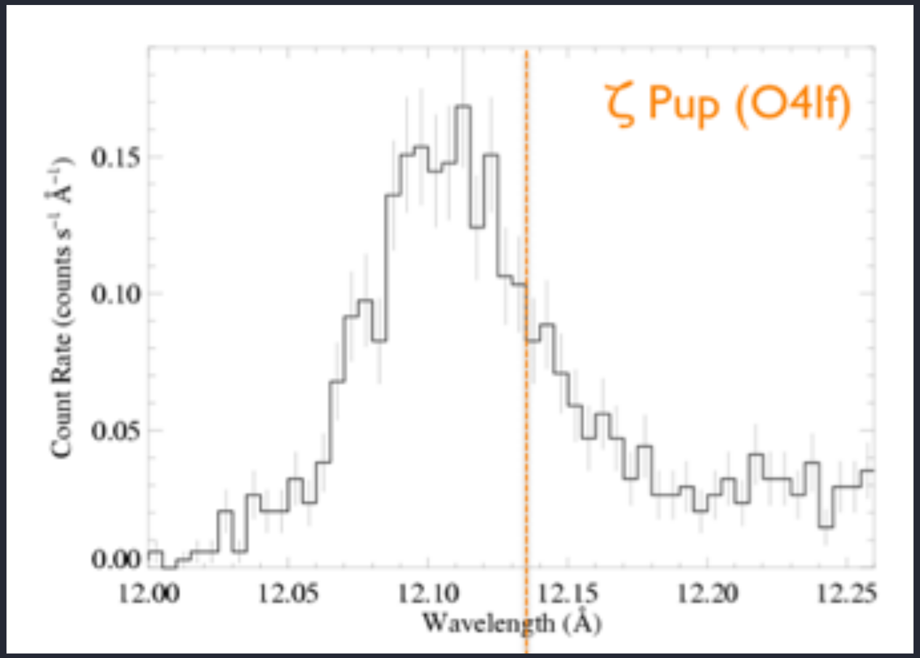
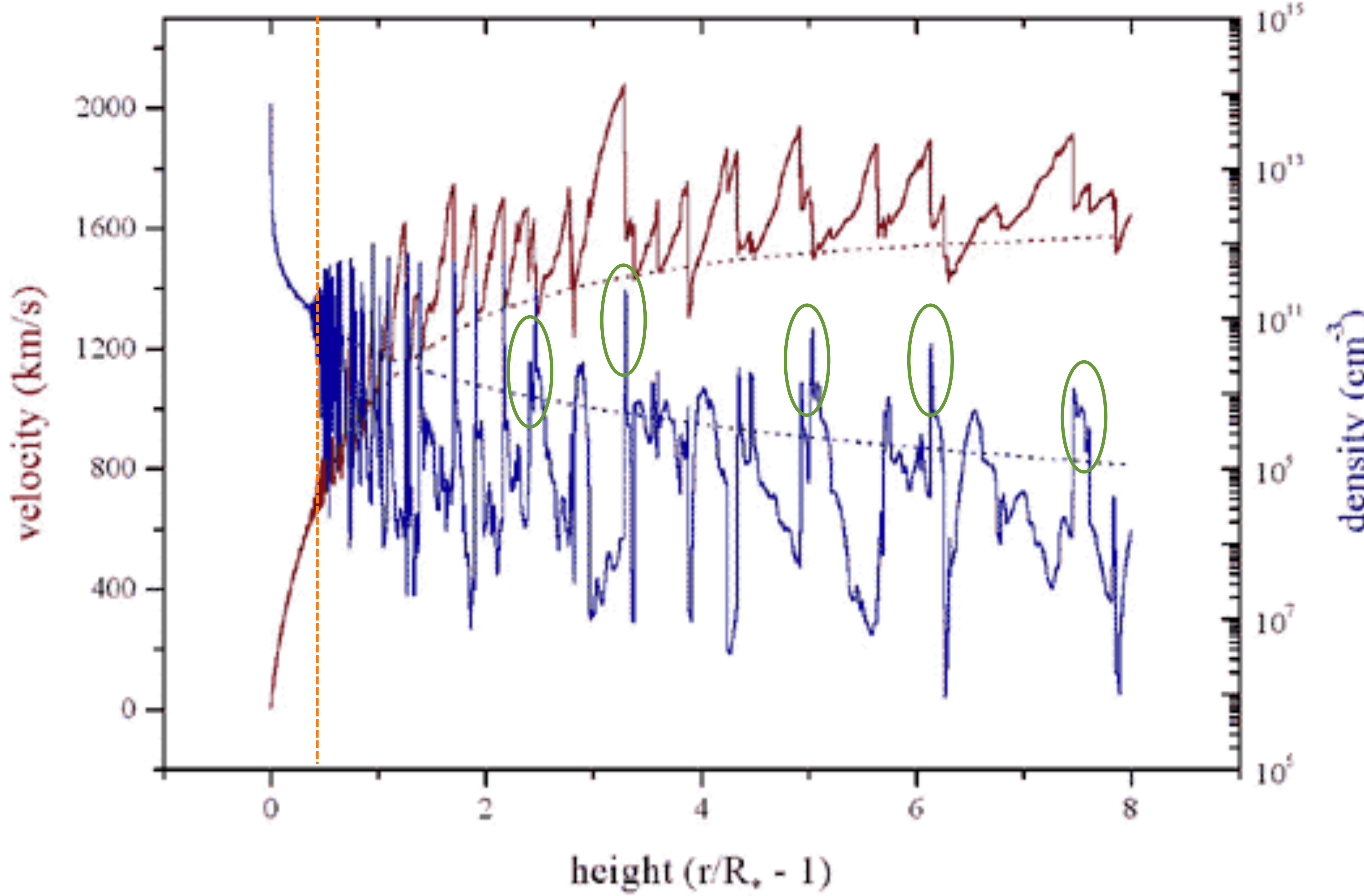
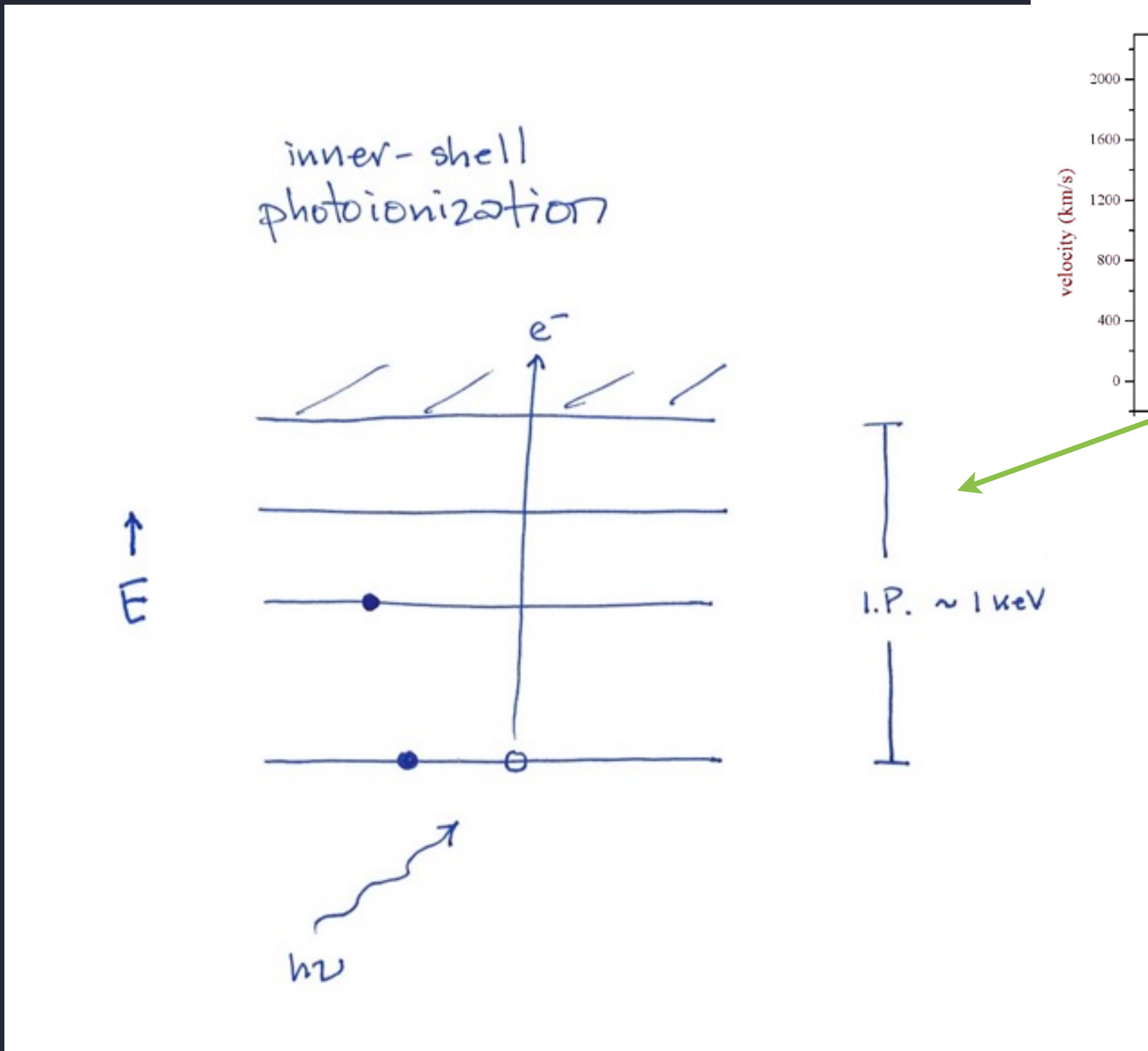


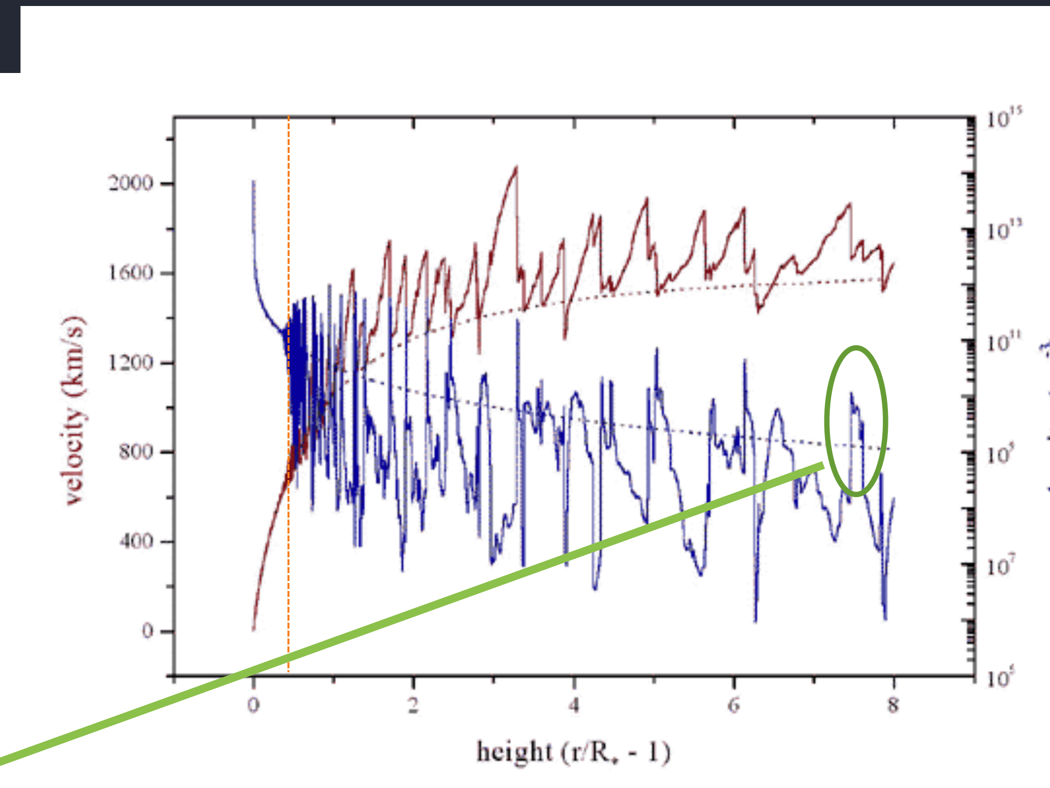
Recall that most of the wind is cold

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



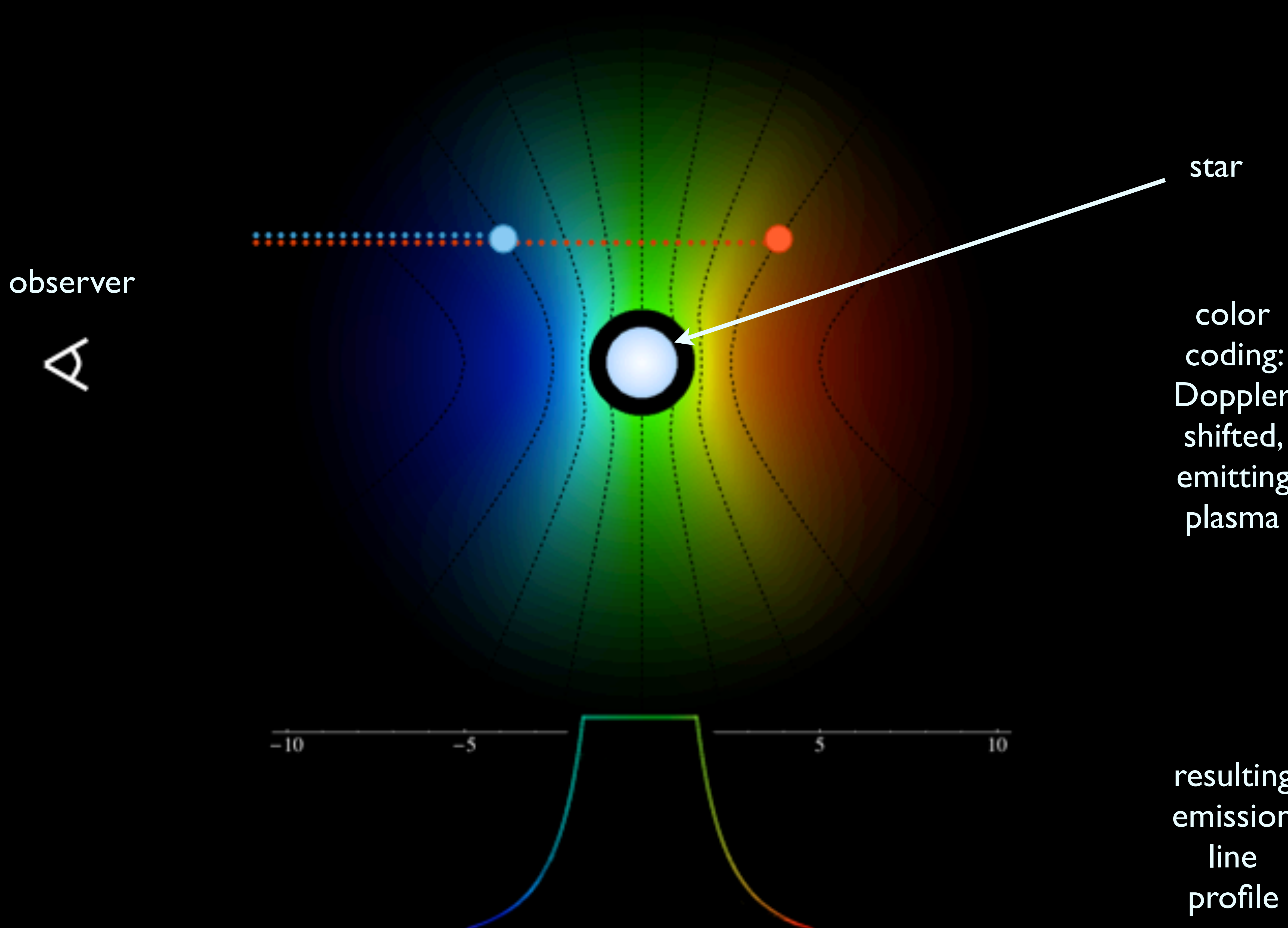
>99% of the wind is cold and X-ray *absorbing*



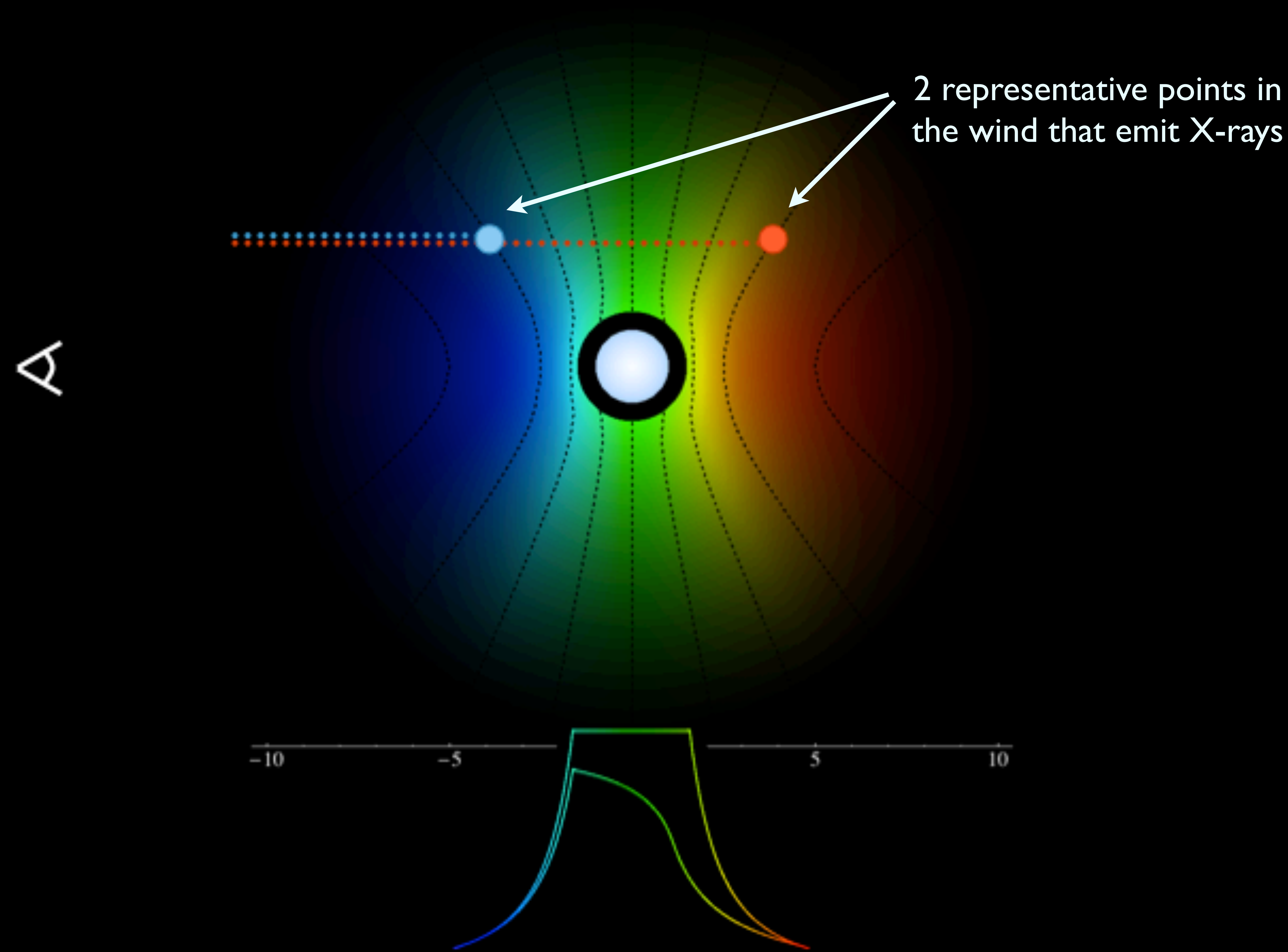


Line Asymmetry

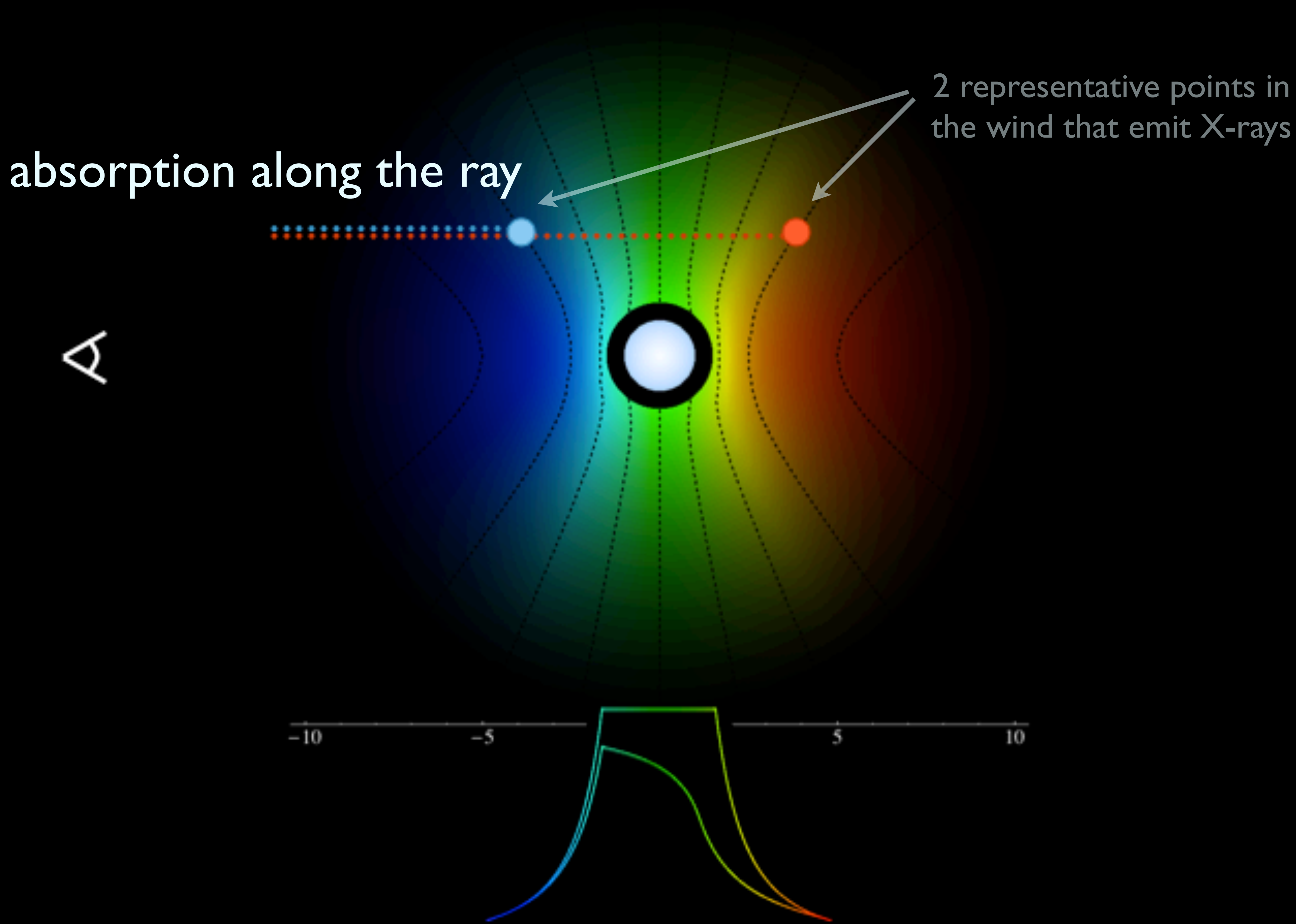
Emma Wollman ('09)
Roban Kramer ('03)



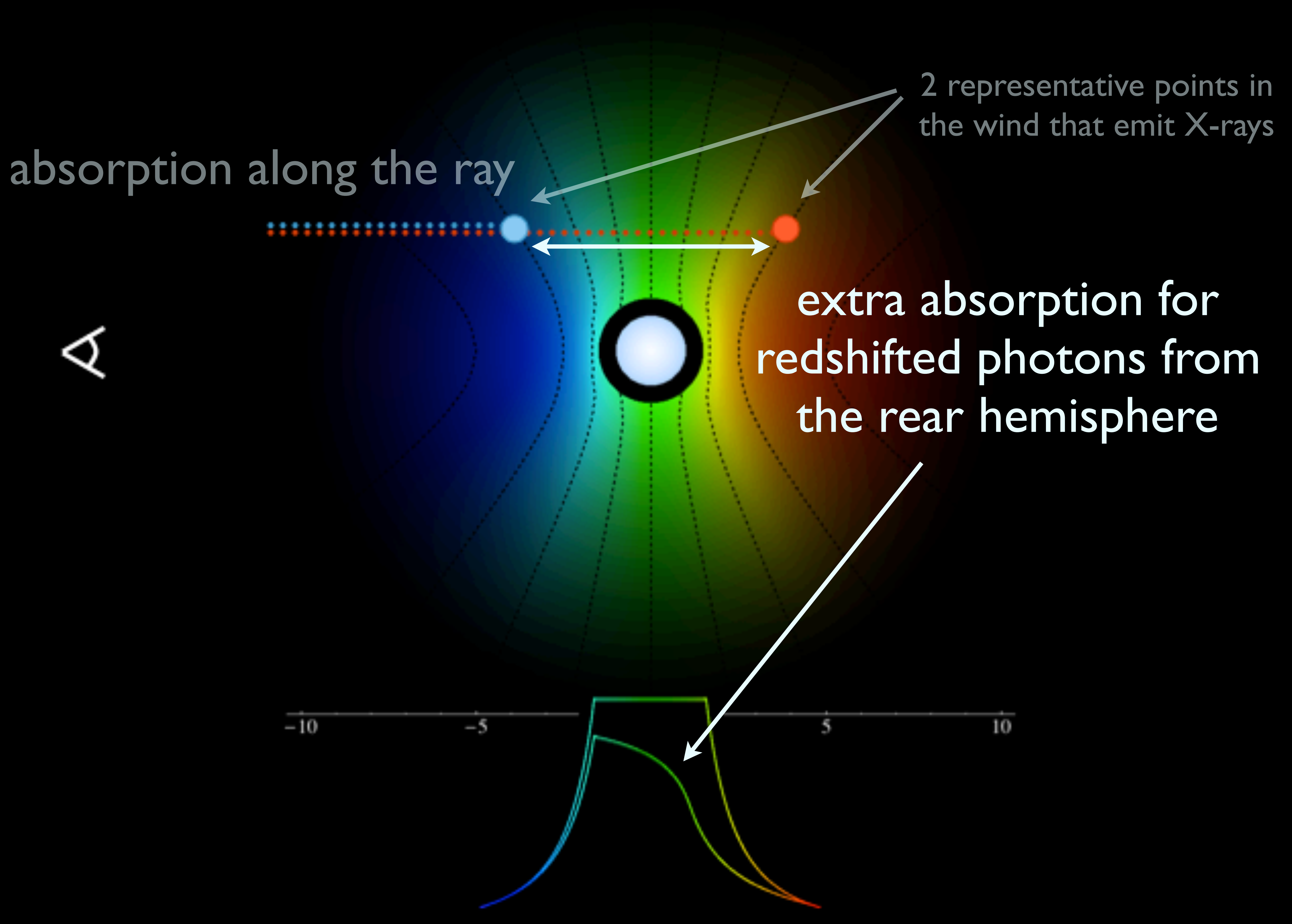
Line Asymmetry



Line Asymmetry

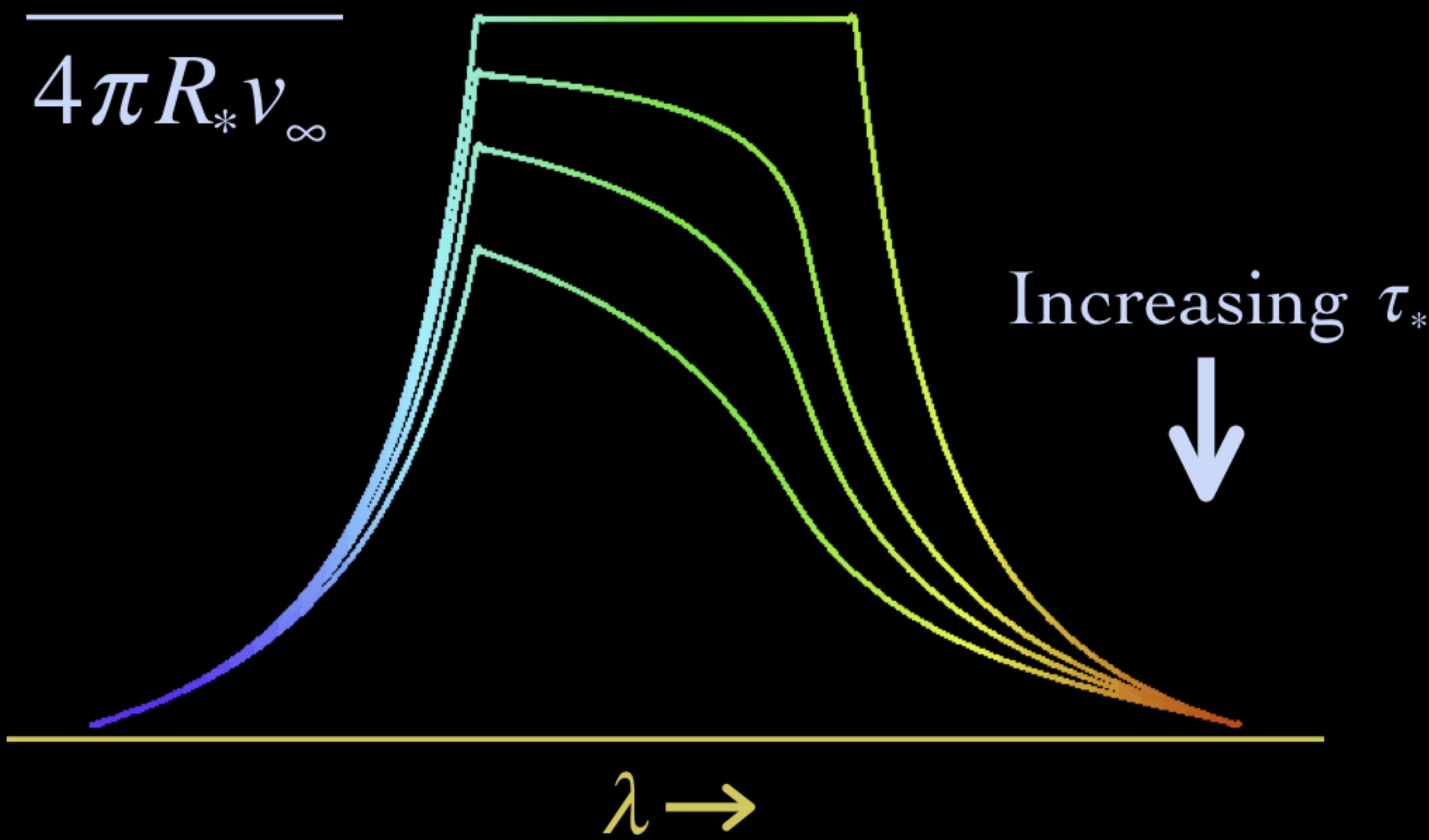


Line Asymmetry



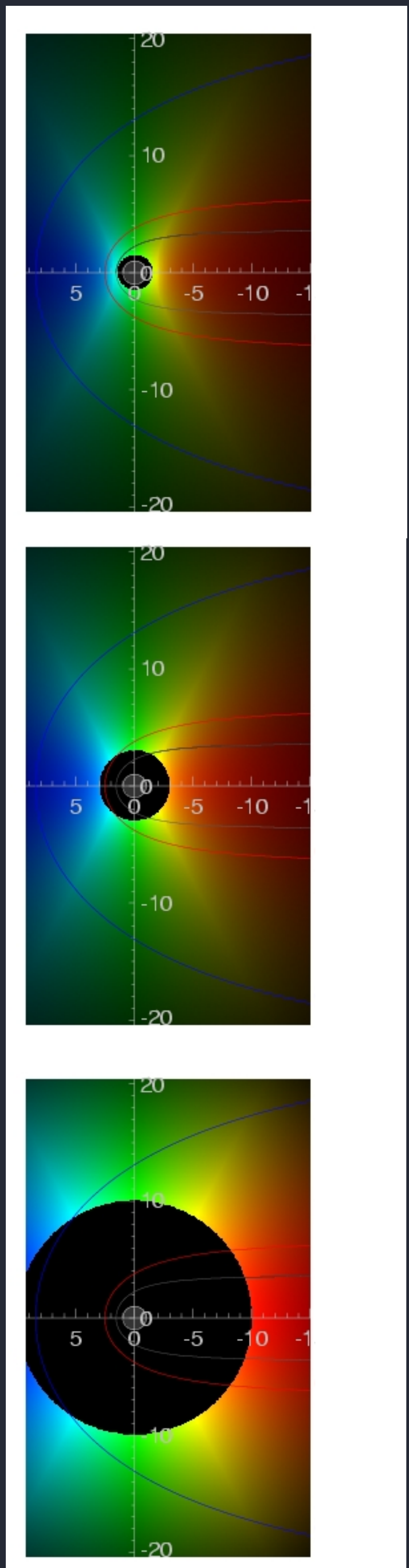
Wind Profile Model

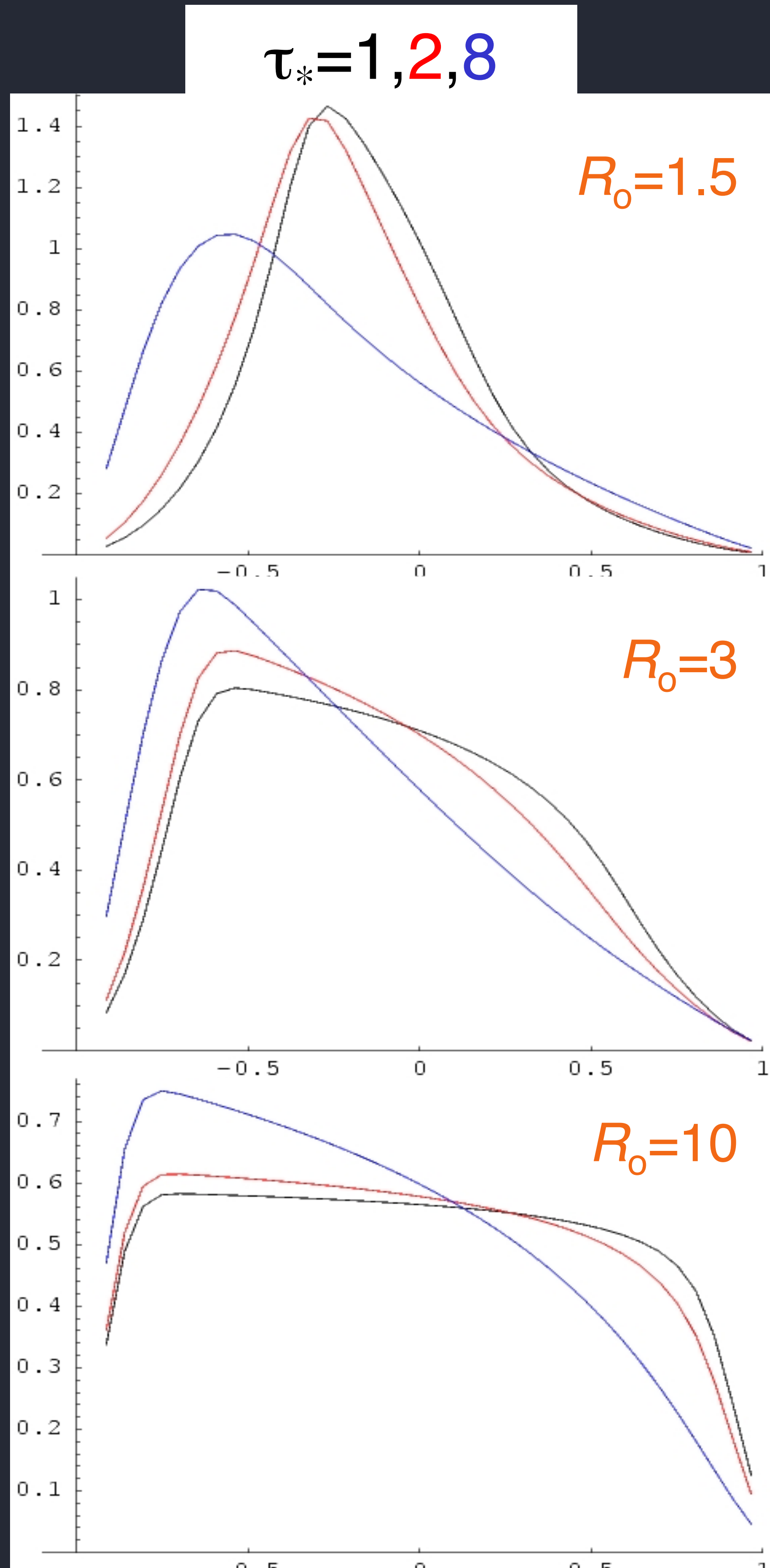
$$\tau_* = \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$



Line profile shapes

key parameters: R_o & $\tau_\star$





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

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

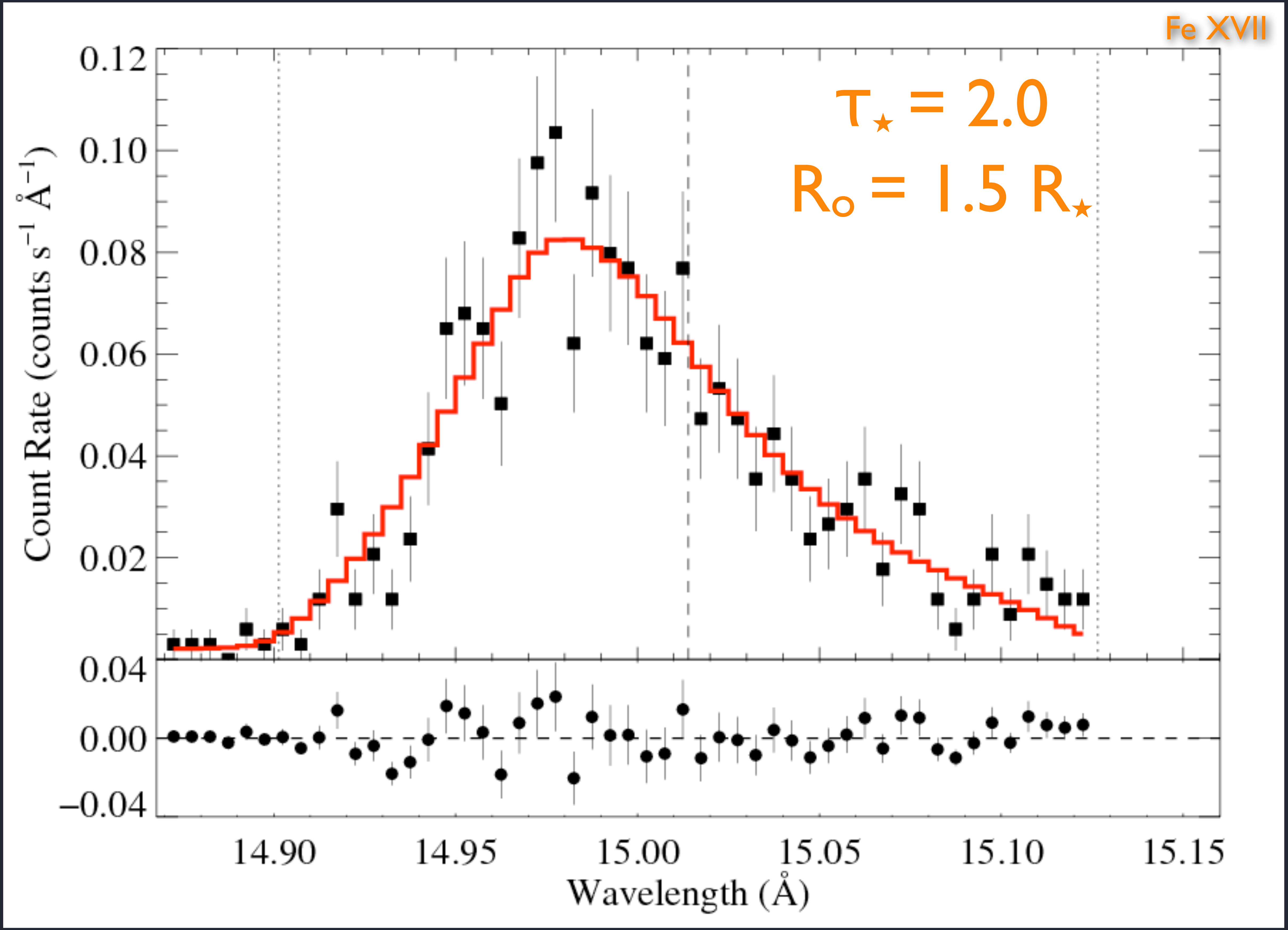
$= 0$ otherwise

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

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

Model is fit to data

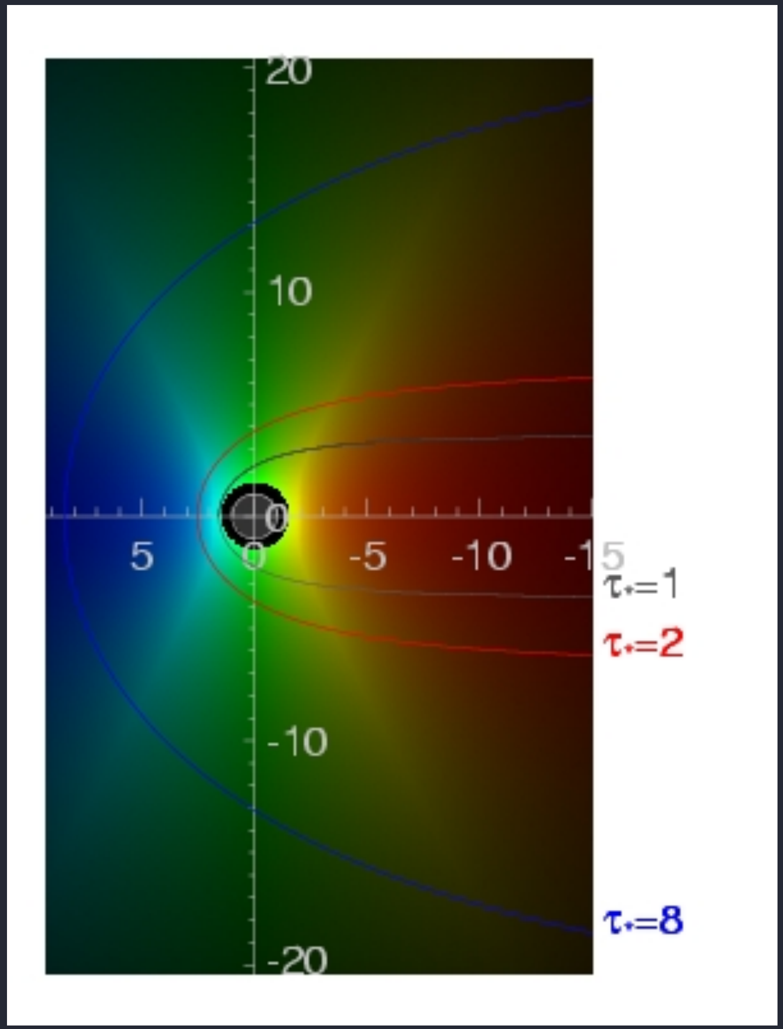
ζ Pup: *Chandra*



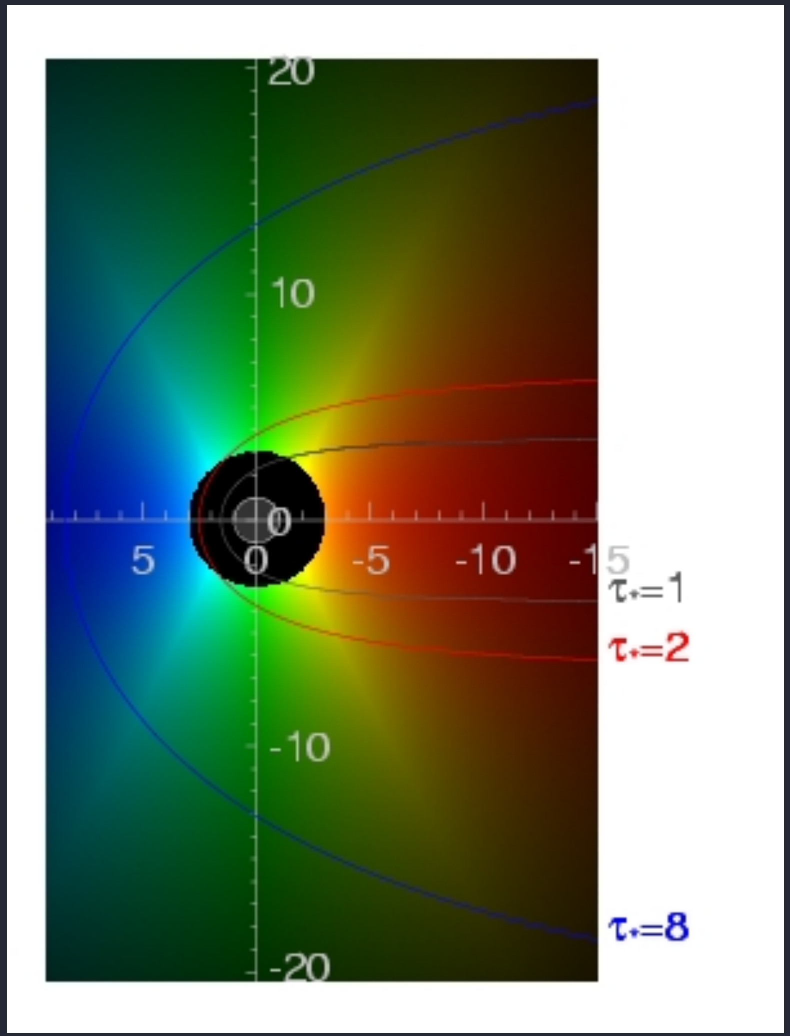
Hot plasma kinematics and location

R_o controls the line width via v(r)

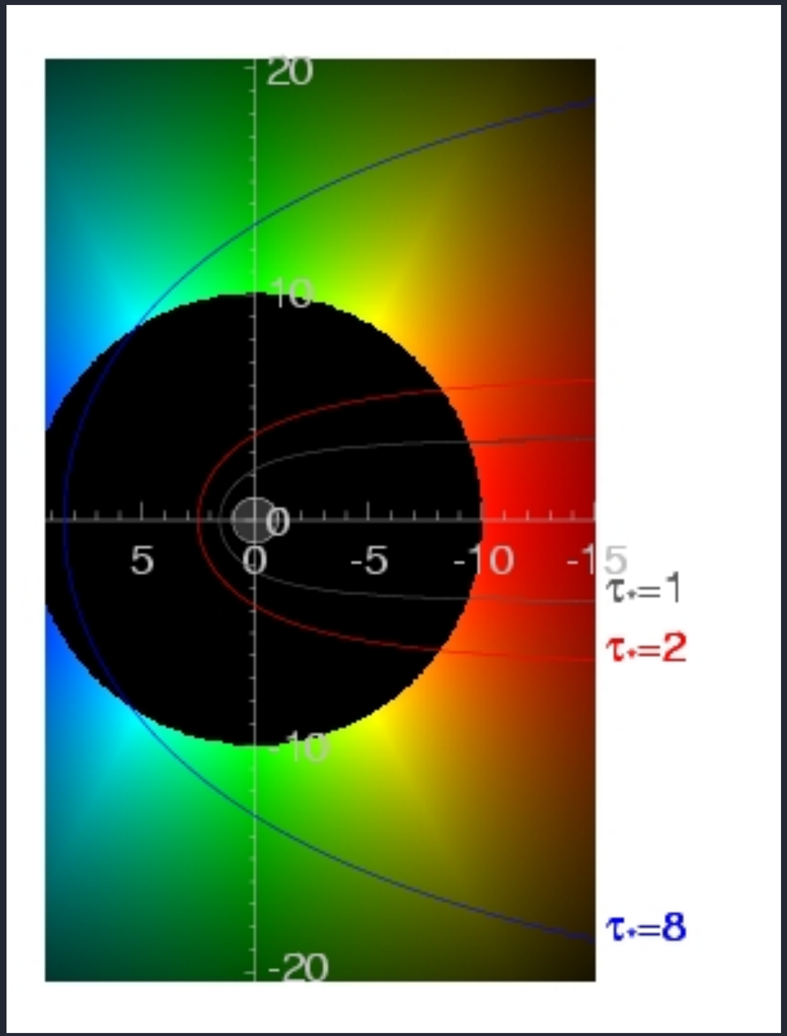
$R_o = 1.5\ R_\star$



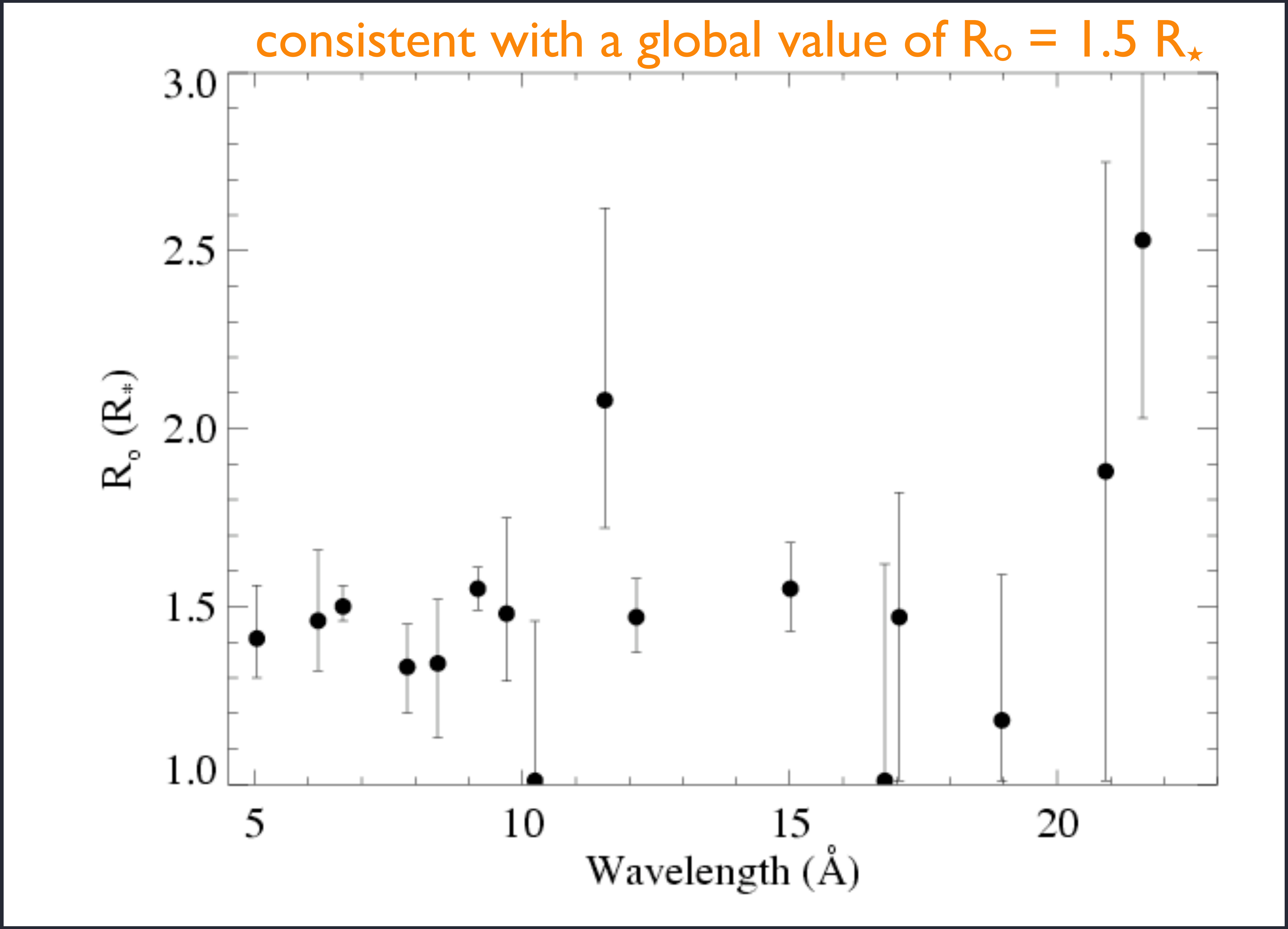
$R_o = 3\ R_\star$



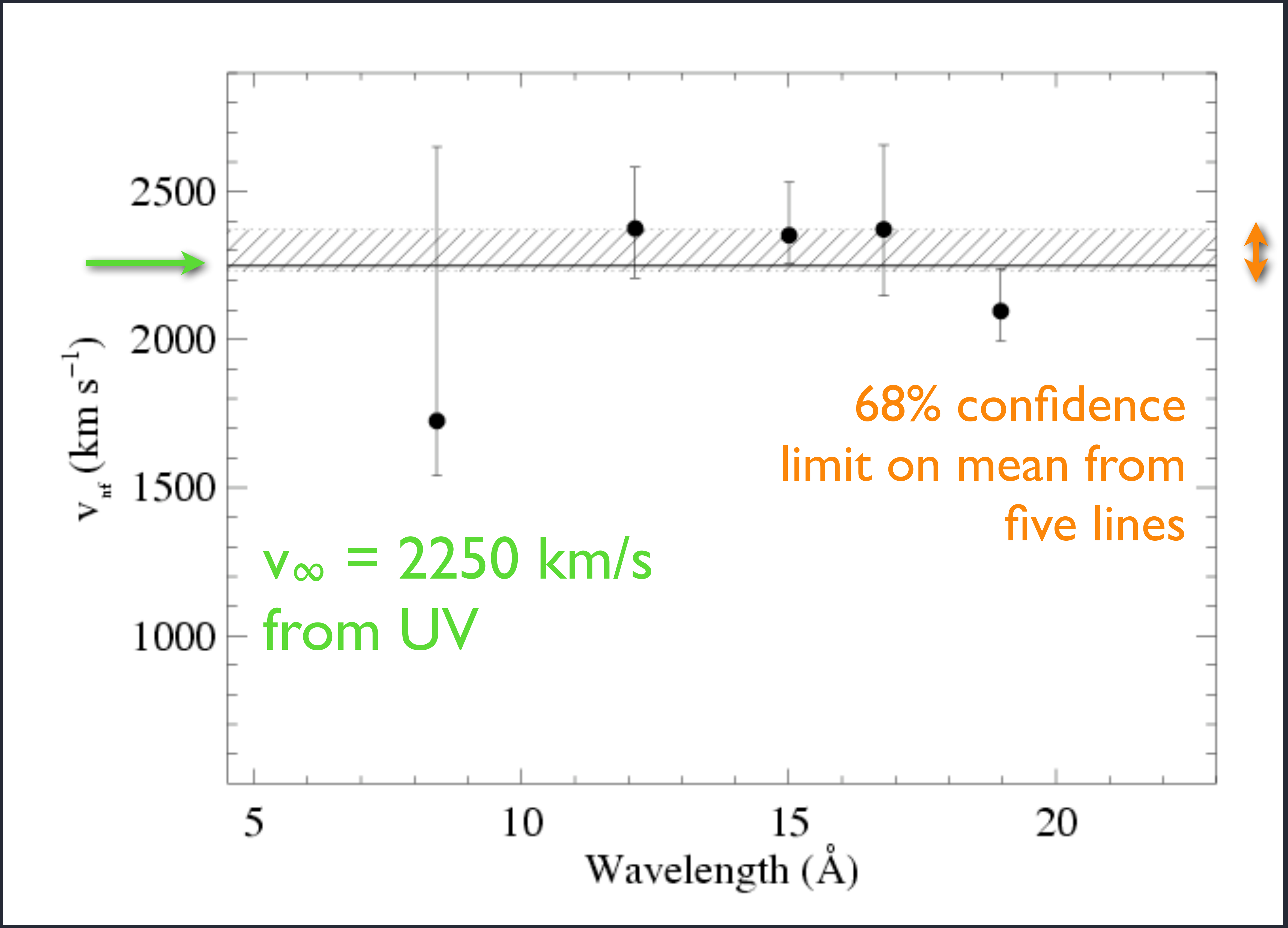
$R_o = 10\ R_\star$



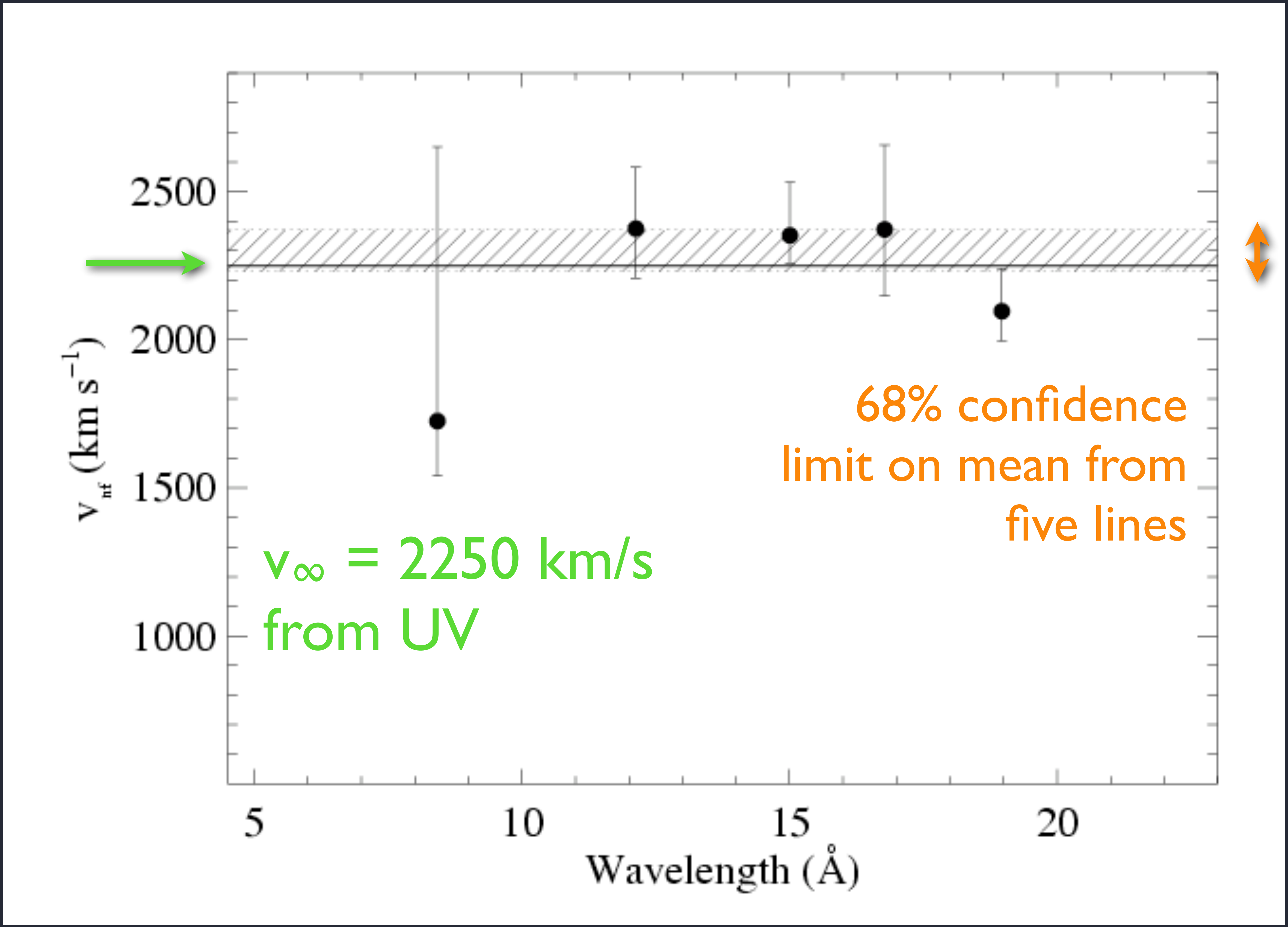
Distribution of R_o values for ζ Pup



v_∞ can be constrained by the line fitting too



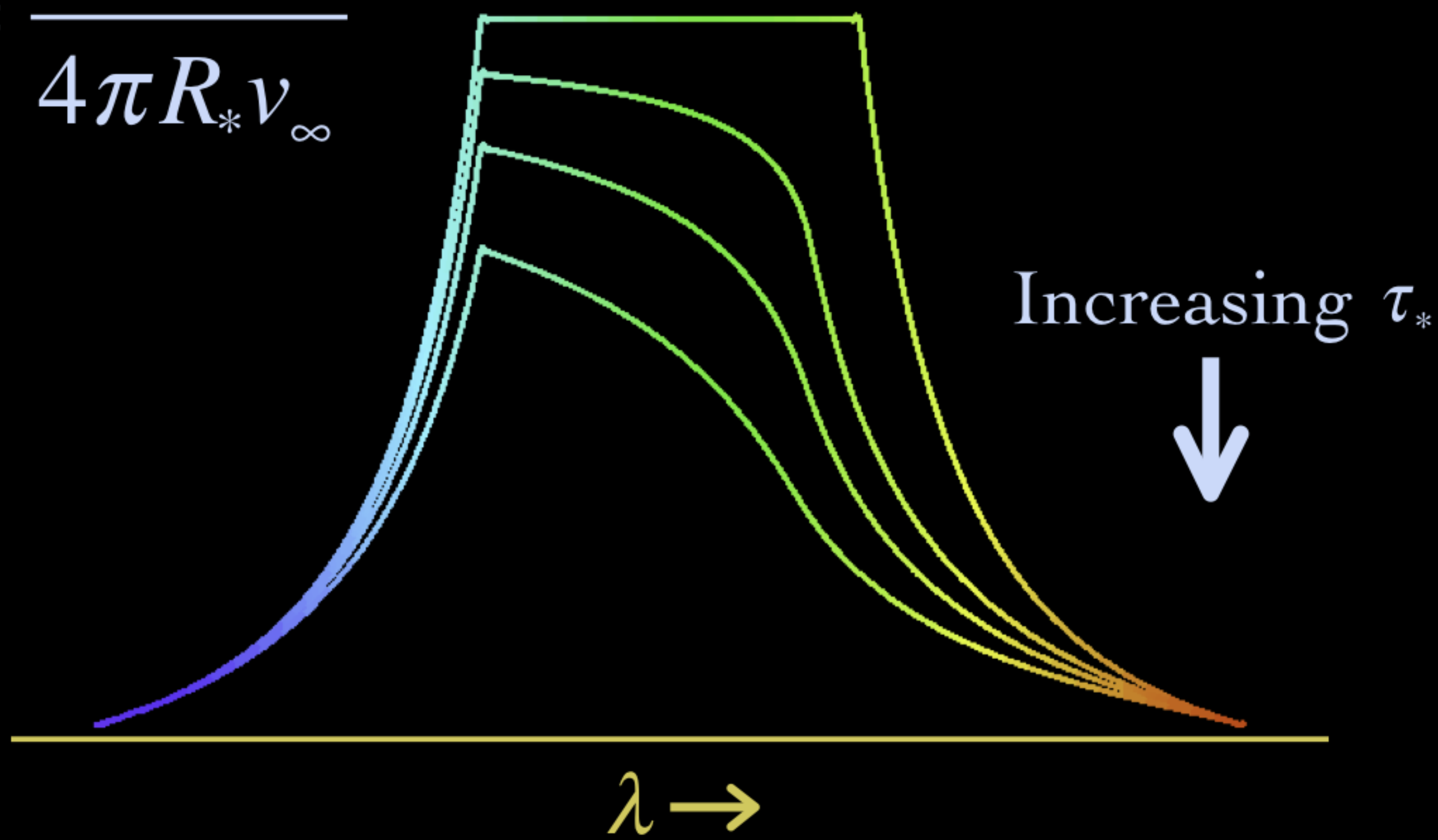
X-ray plasma and mean wind have same kinematics



The profiles also tell us about the level of wind absorption

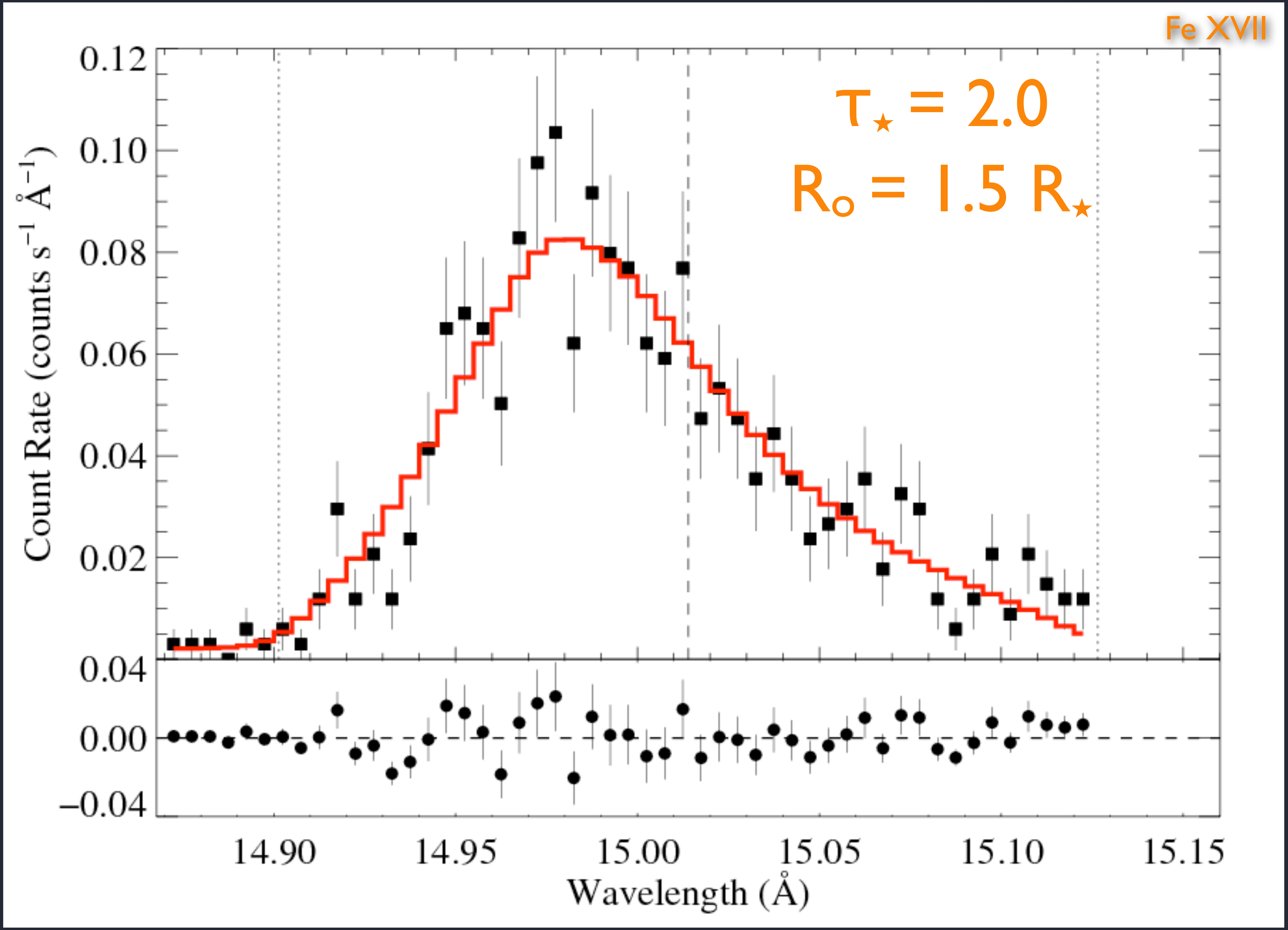
Wind Profile Model

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



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

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

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

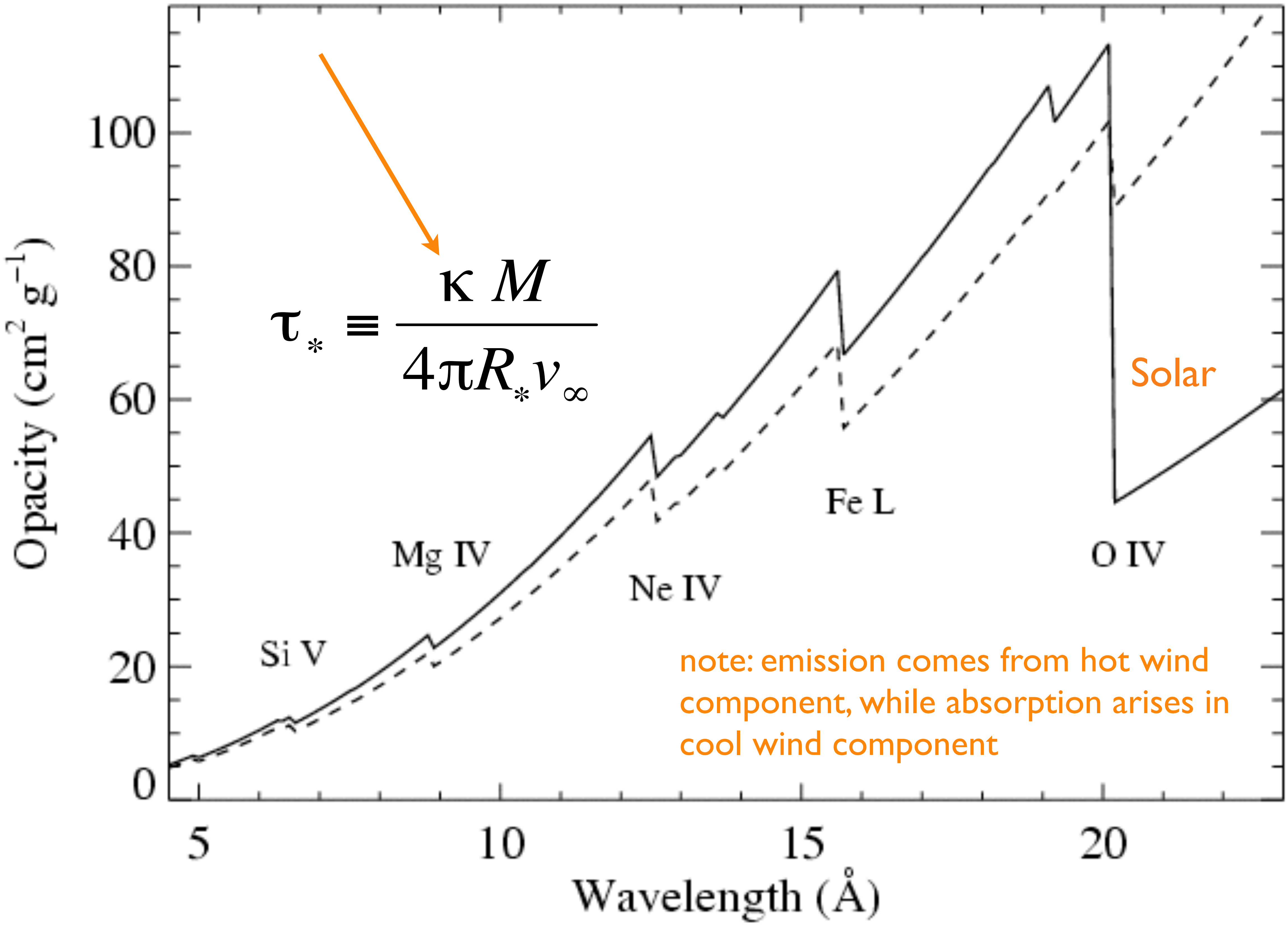
stellar radius

wind terminal velocity

soft X-ray wind opacity

CNO processed

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

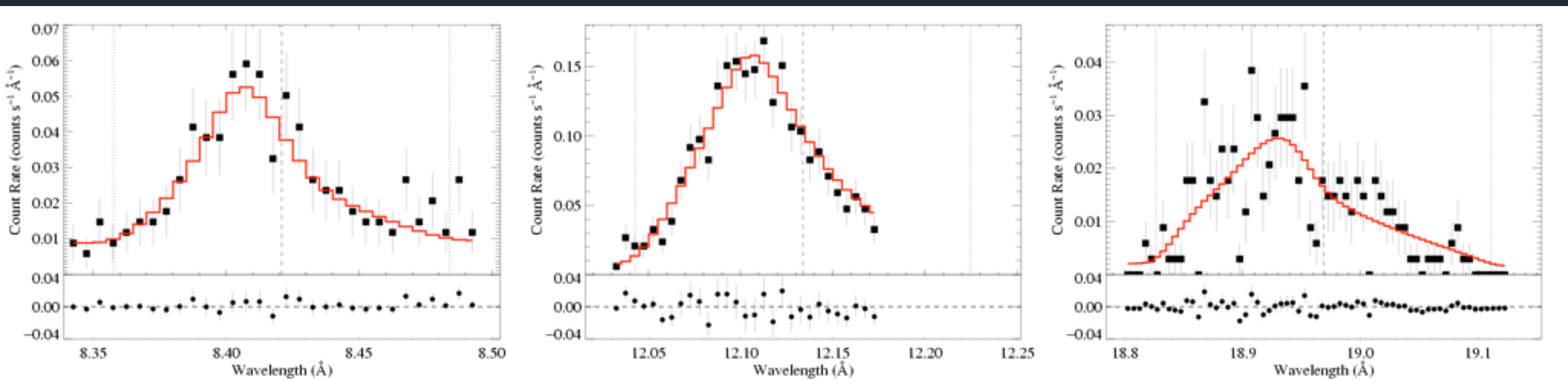


Solar

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

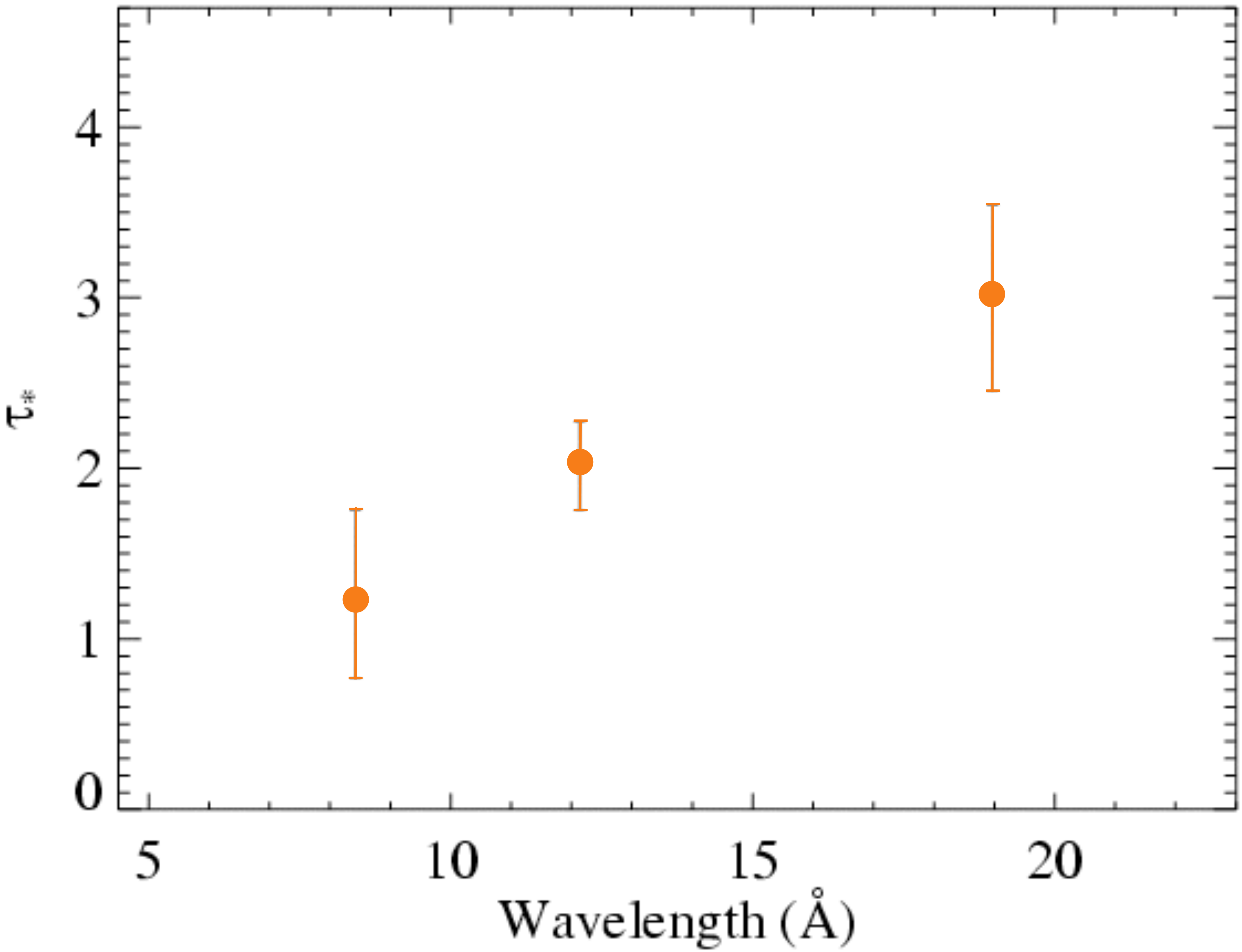


$\tau_* \sim 1$ $\tau_* \sim 2$ $\tau_* \sim 3$

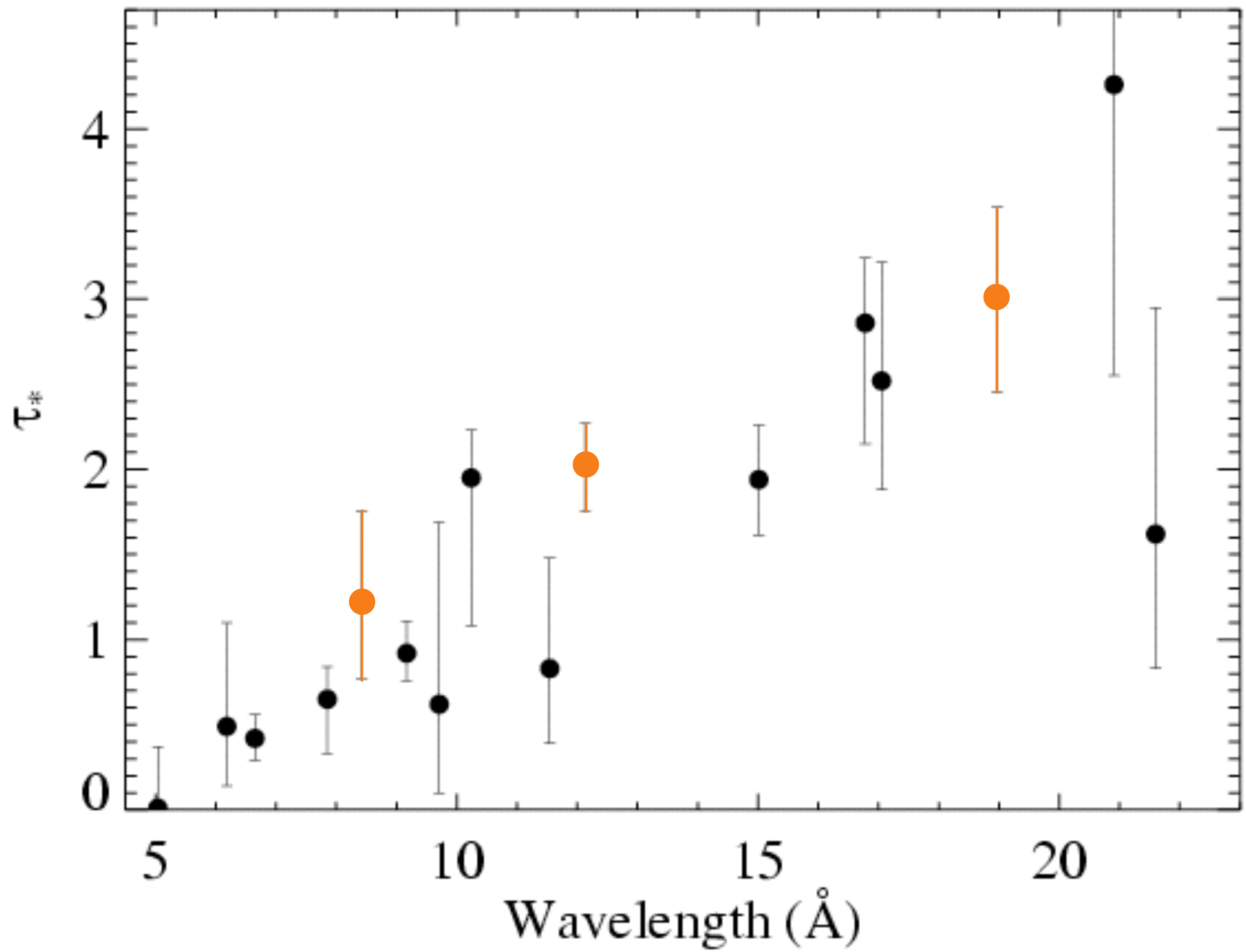
Recall:

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

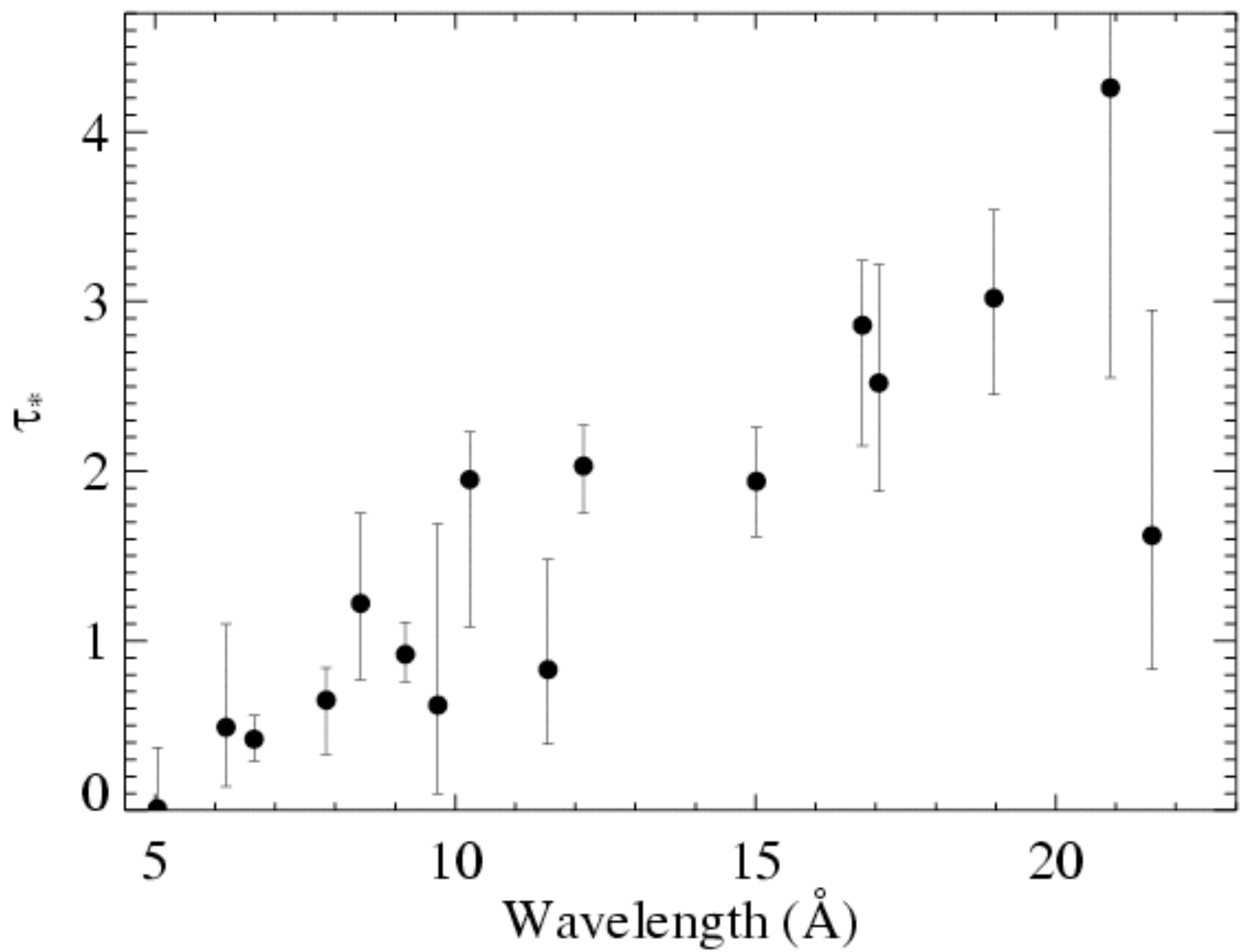
Results from the 3 line fits shown previously



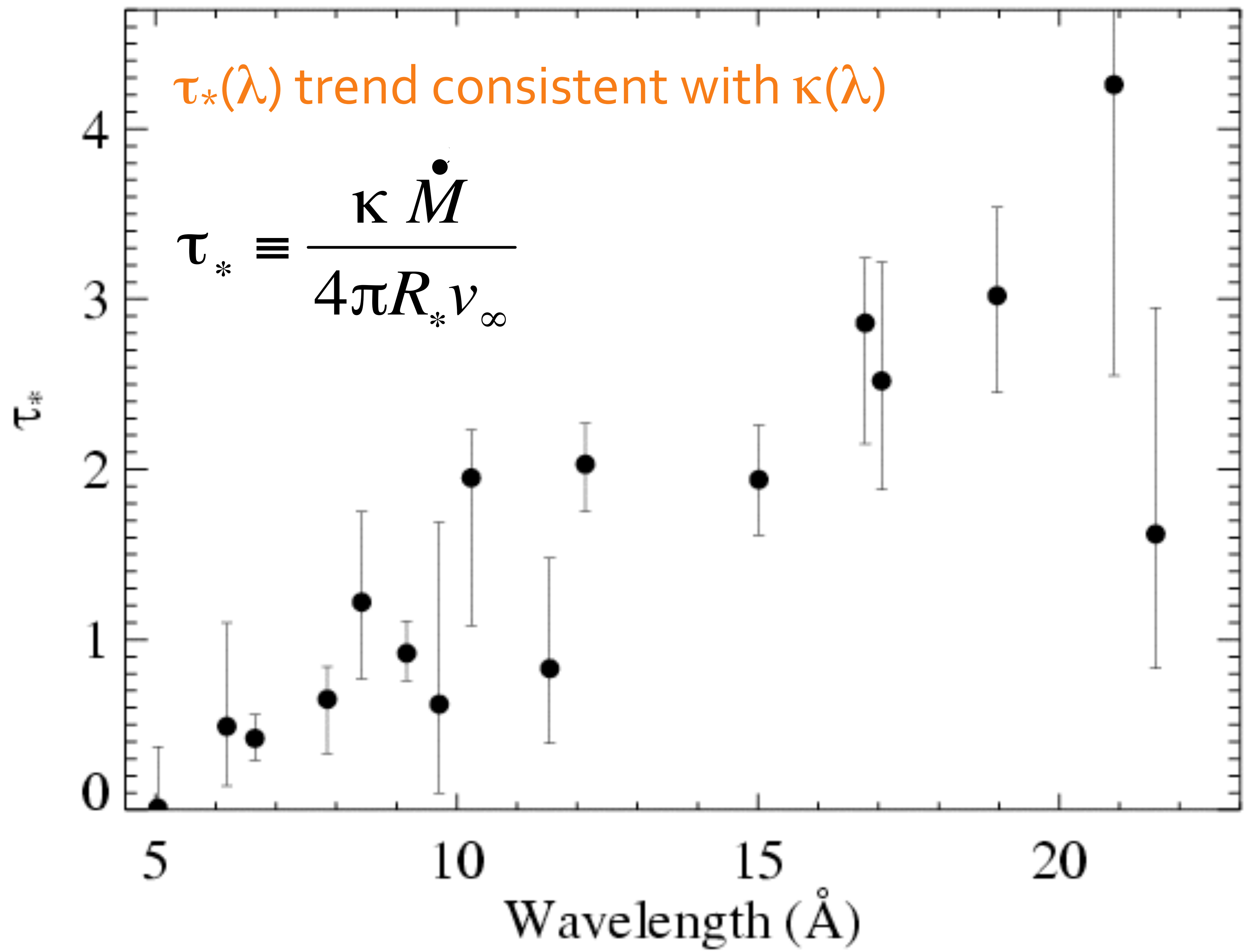
Fits to 16 lines in the *Chandra* spectrum of ζ Pup



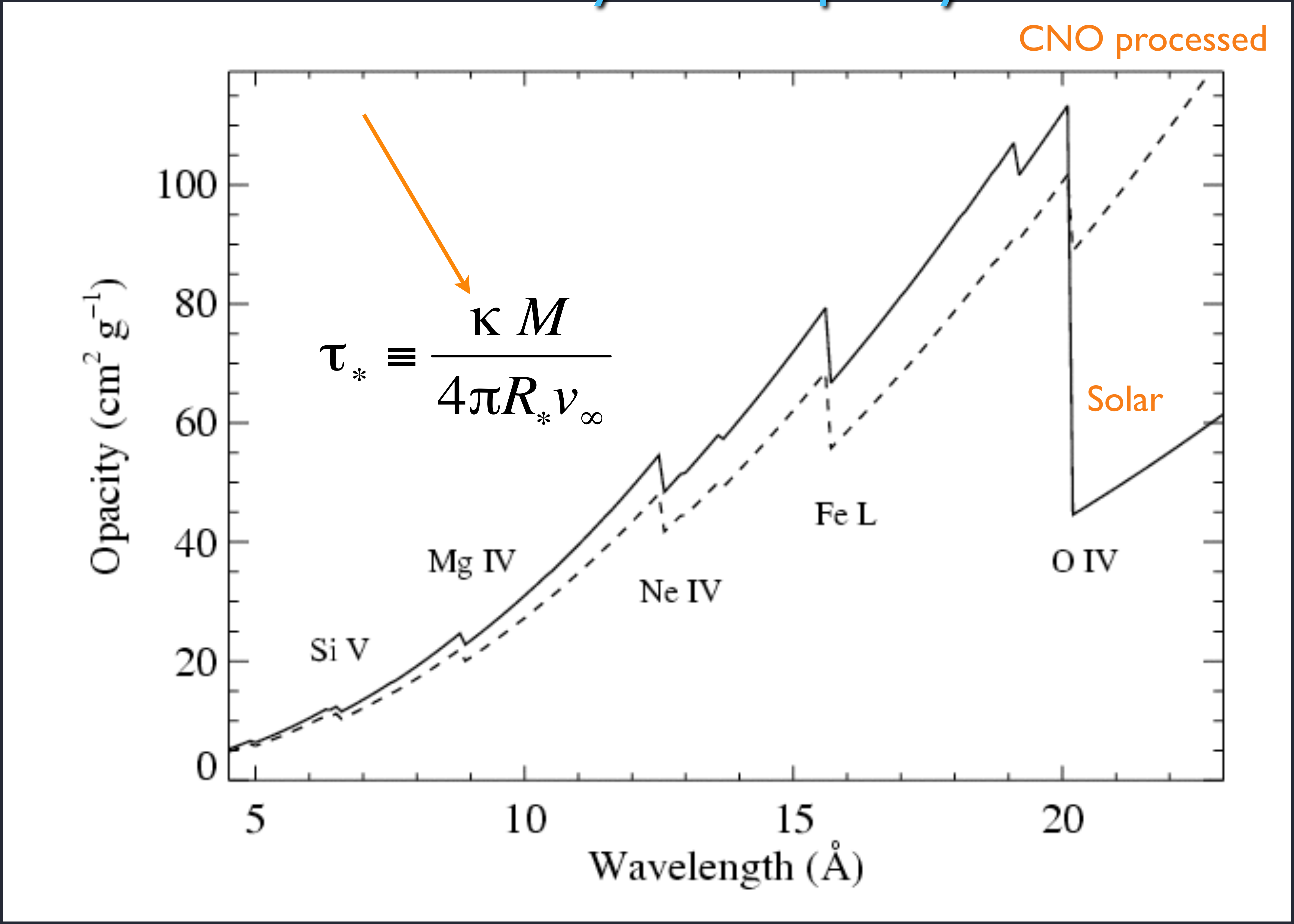
Fits to 16 lines in the *Chandra* spectrum of ζ Pup



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

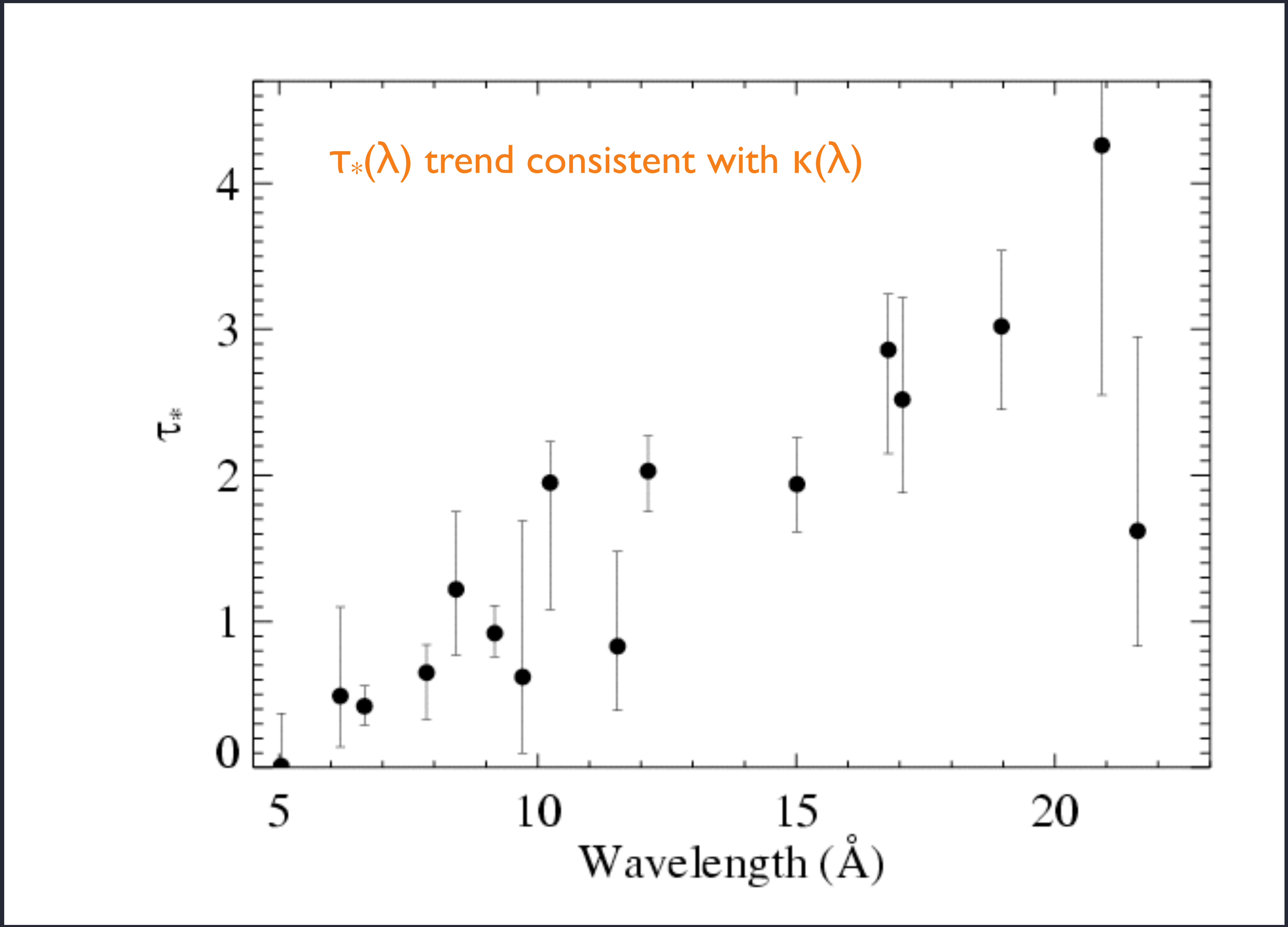


soft X-ray wind opacity



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

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



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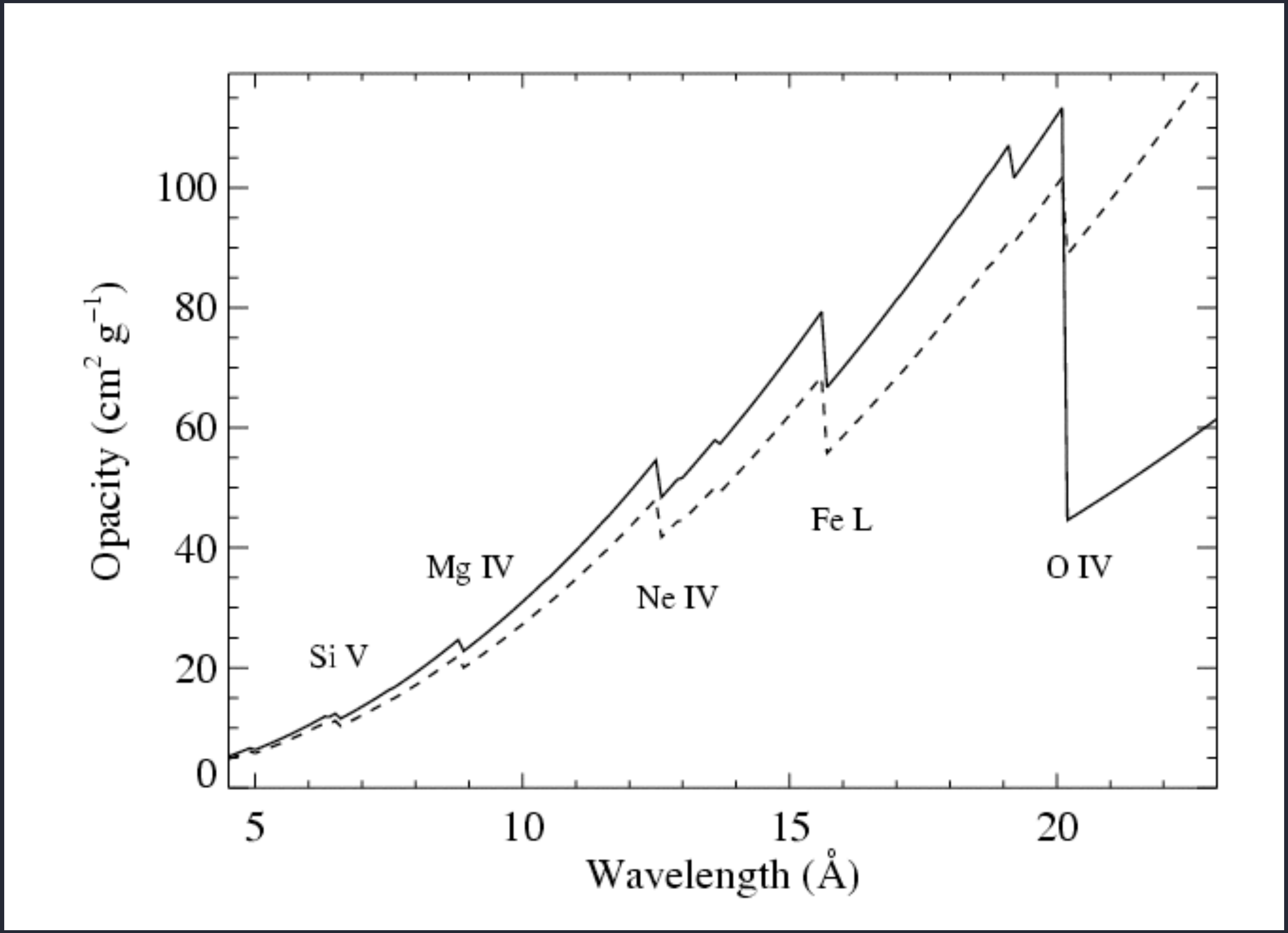
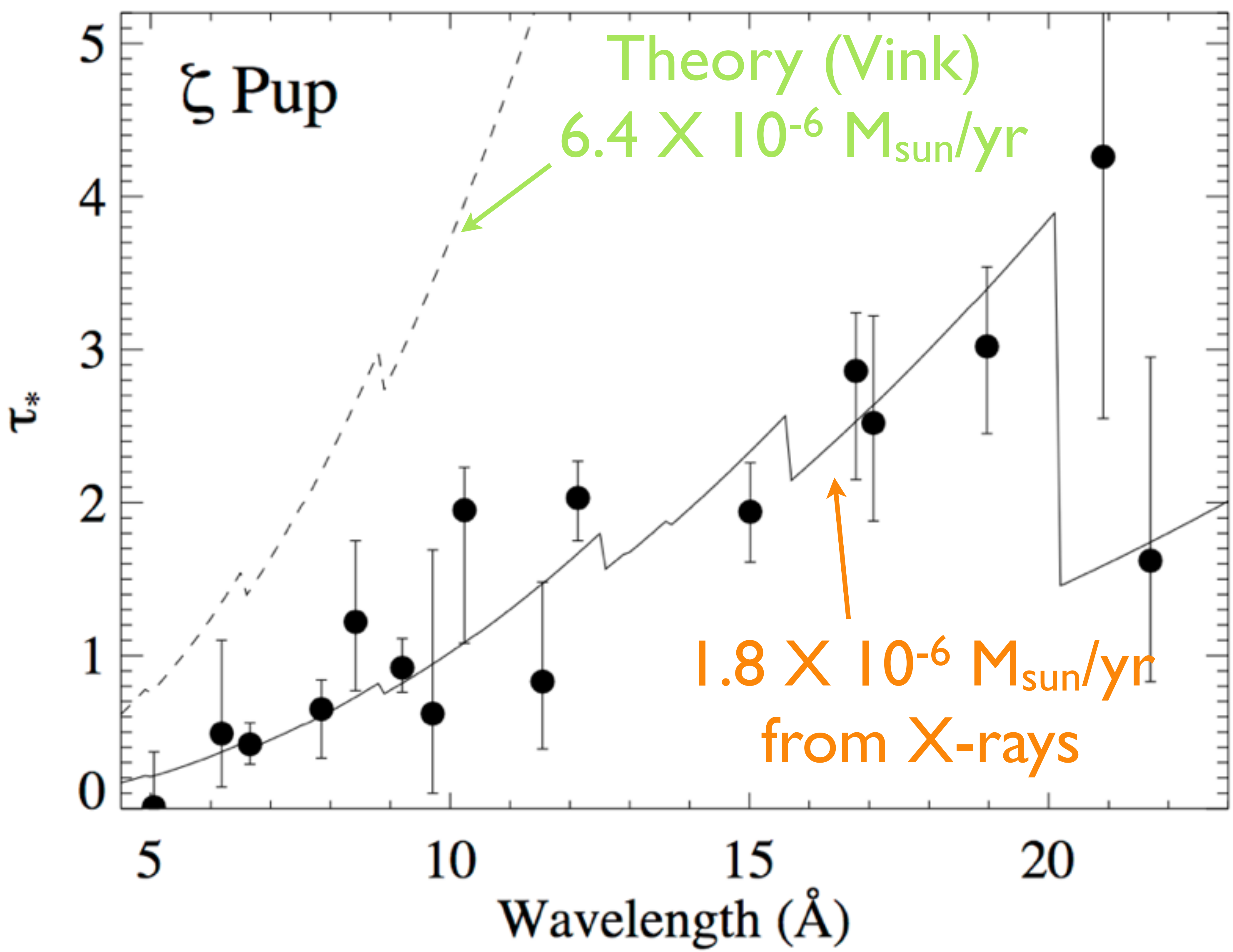
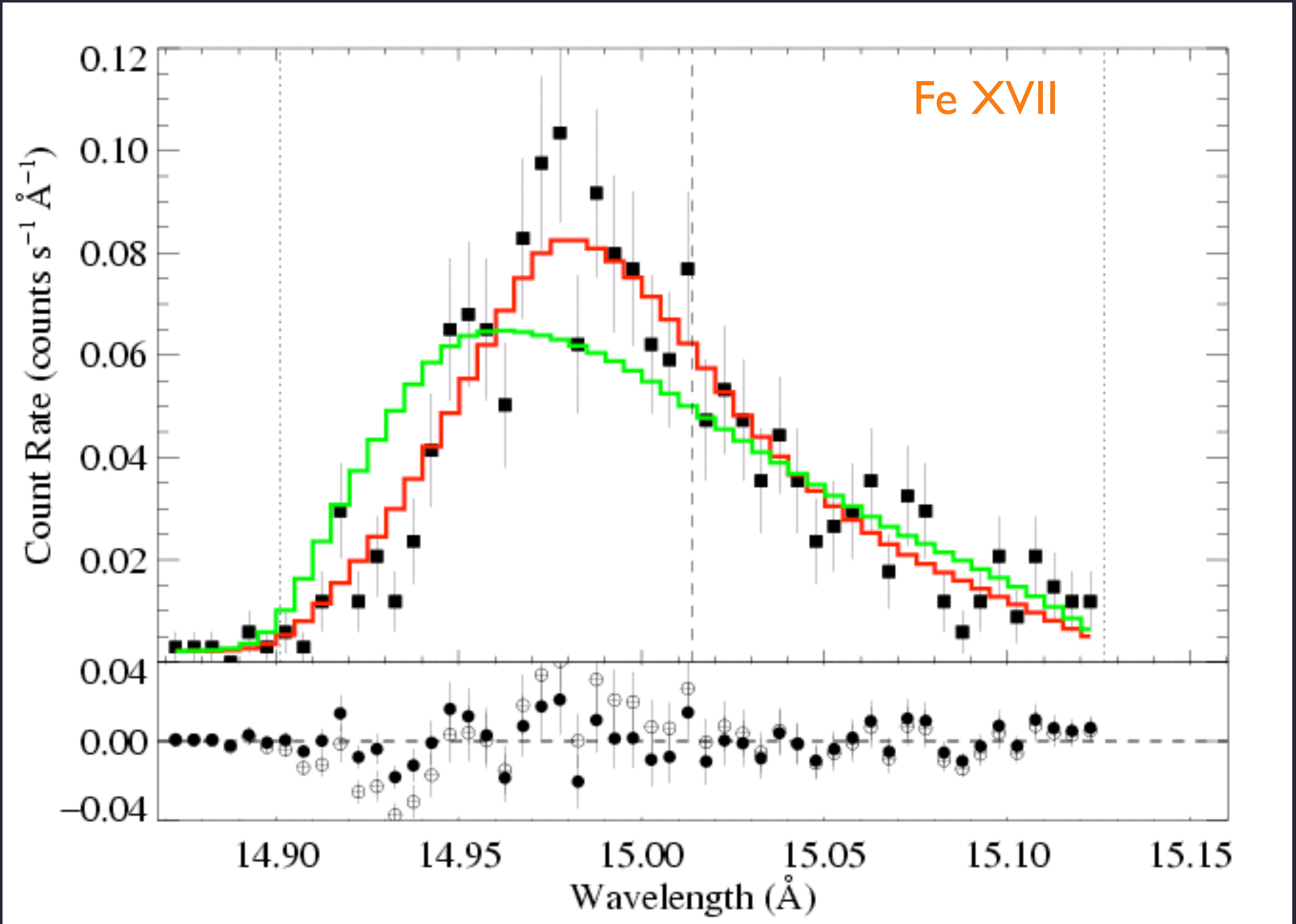




ζ Pup
Theory (Vink)
6.4 X 10-6 Msun/yr
1.8 X 10-6 Msun/yr
from X-rays
τ*
Wavelength (Å)
0
1
2
3
4
5
5
10
15
20



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

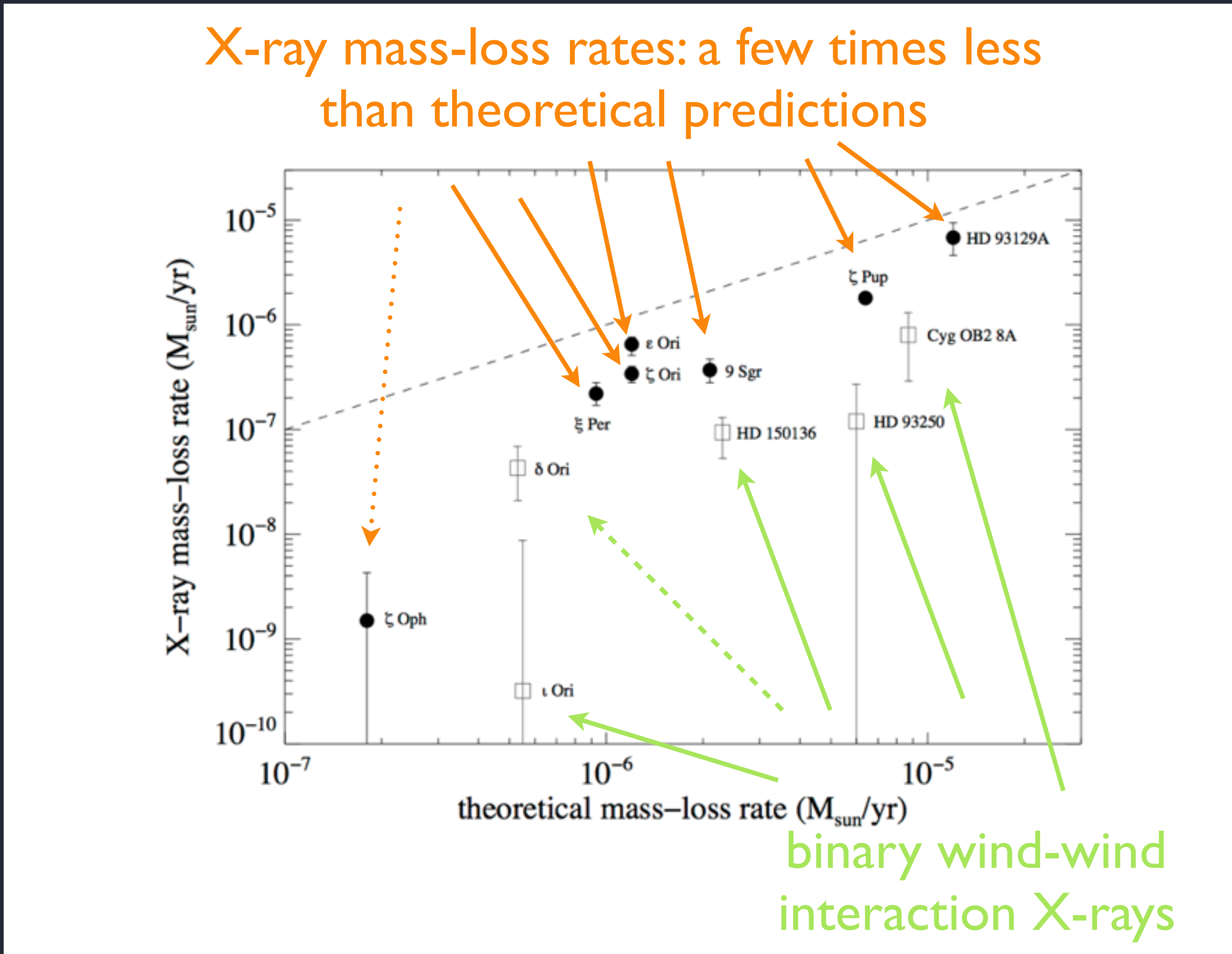
1. Doppler-broadened line profiles tell us the kinematics of the shock-heated wind plasma

consistent with hydro simulation predictions

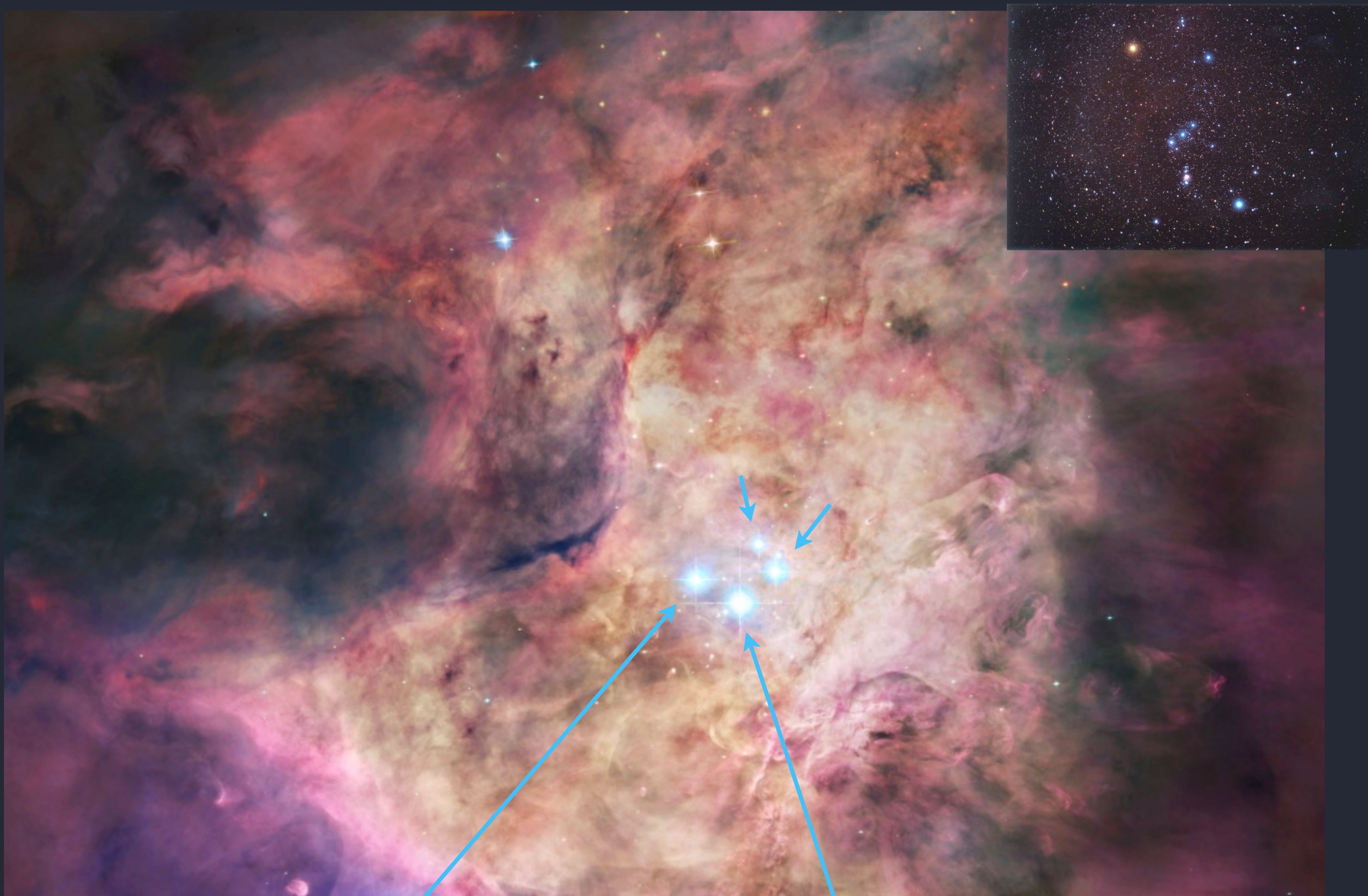
2. Line profile asymmetry tells us about the wind absorption; joint analysis of an ensemble of lines tells us the mass-loss rate of the wind

mass-loss rate factor ~3 lower than theoretically expected value

Survey of a dozen O stars



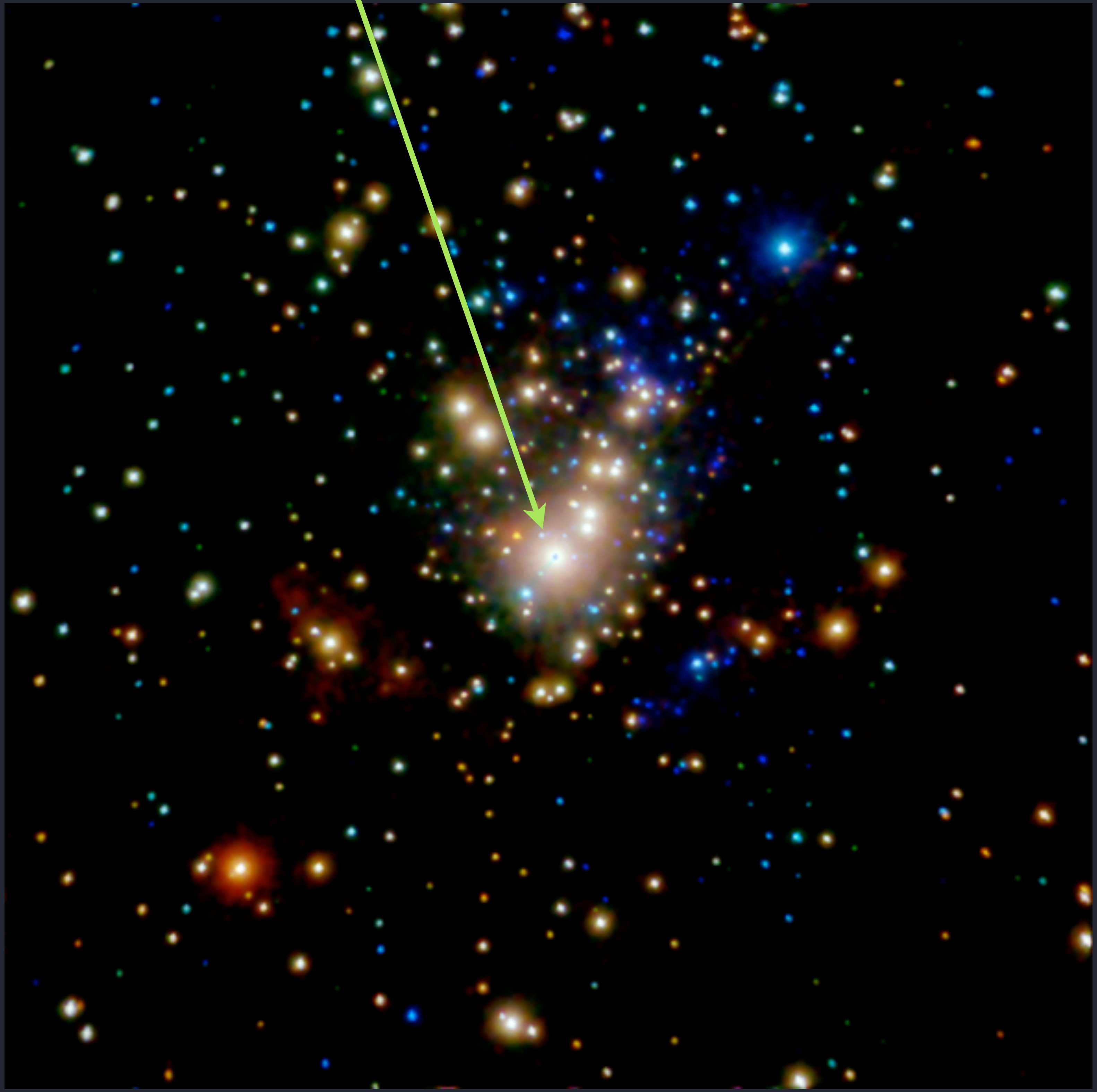
Recall the O star that ionizes the Orion Nebula



θ^1 Ori C: only O star here

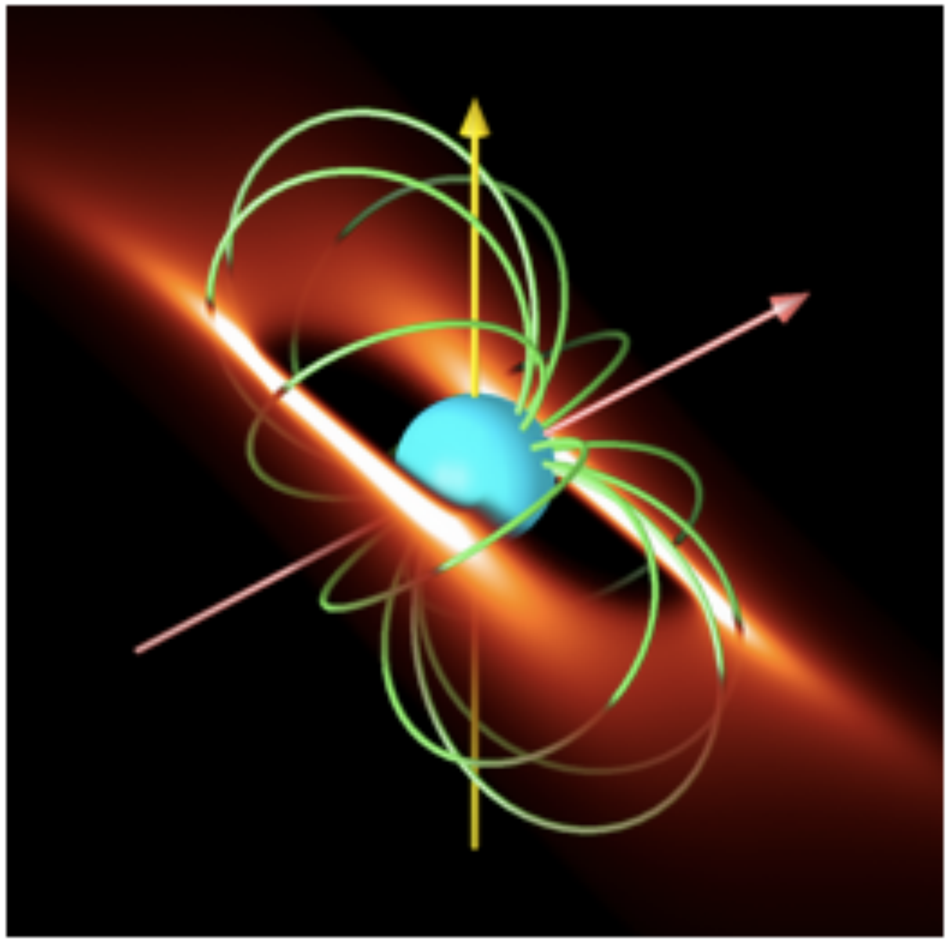
Chandra X-ray image of the Orion Nebula Cluster

θ^1 Ori C: very X-ray bright



~10% of massive stars are magnetic!

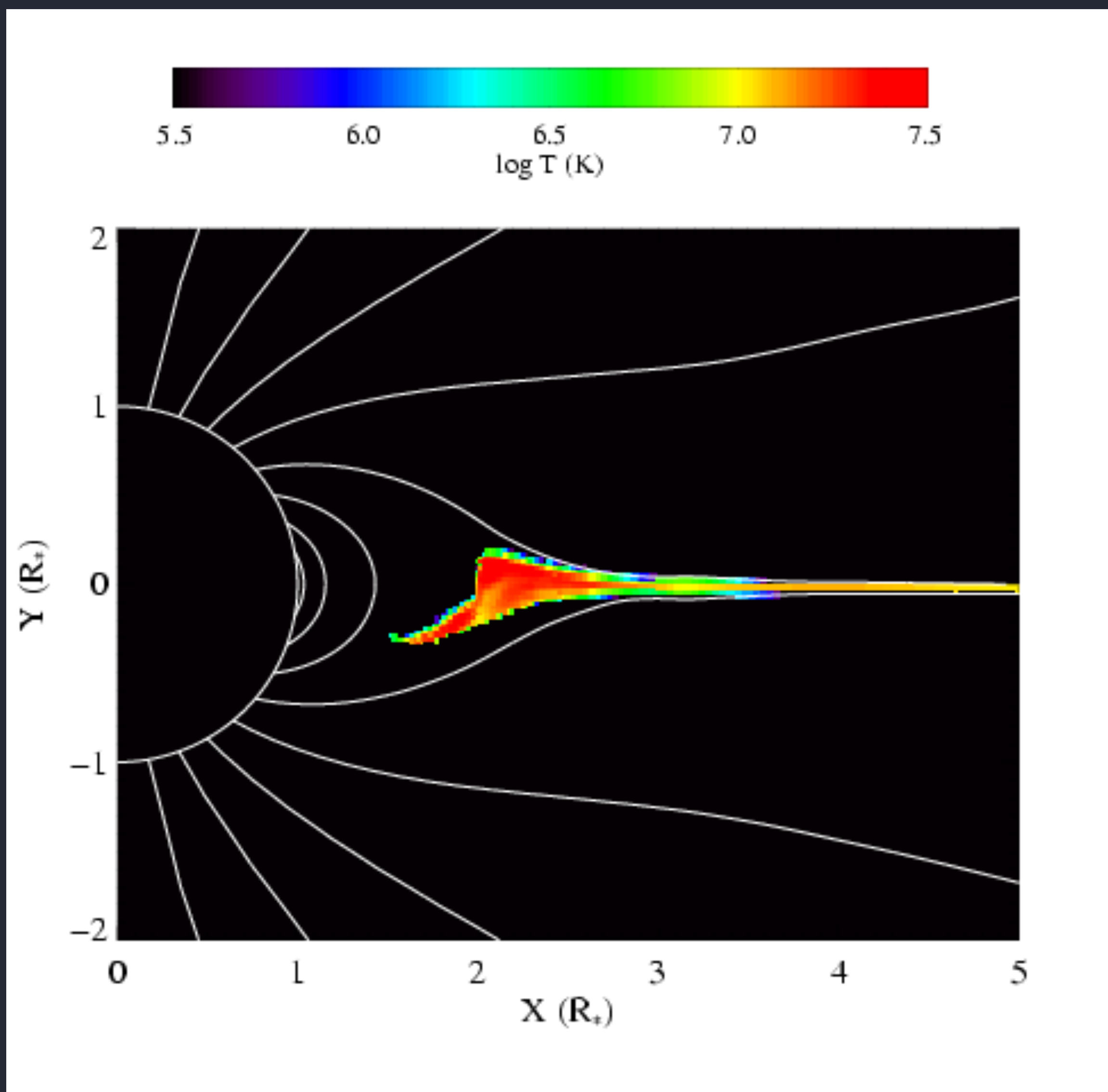
unlike solar type magnetism, though:
time-constant, not dynamo generated, often large-scale dipole



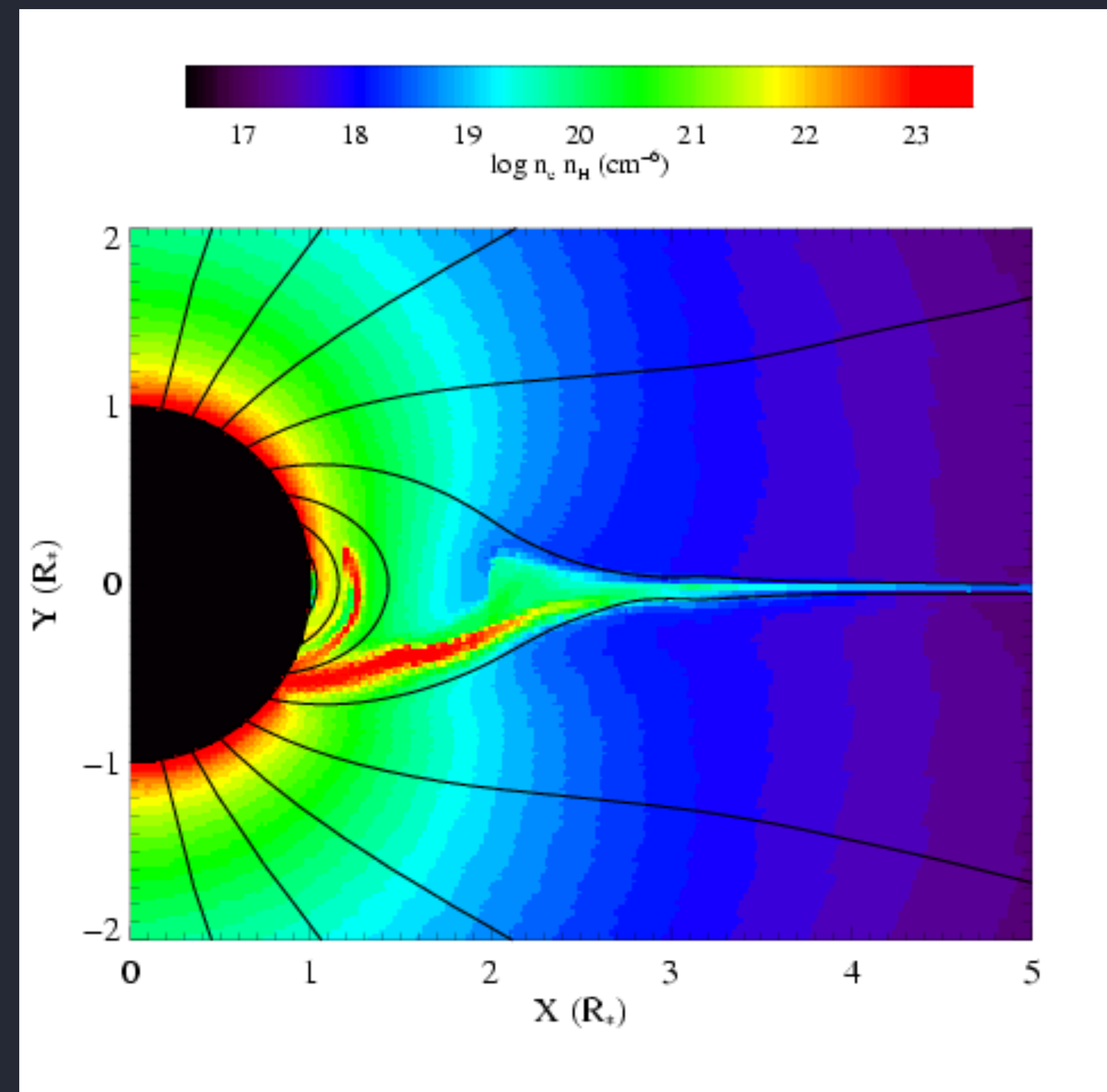
A simulation of the circumstellar matter distribution of σ Ori E, as predicted by the Rigidly Rotating Magnetosphere mode

θ¹ Ori C: prototype magnetic O star

temperature



emission measure



simulations by A. ud-Doula; Gagné et al. (2005)

The line-deshadowing instability (LDI)

causes fast, rarefied wind plasma to slam into slower, denser wind plasma

the resulting shocks heat the plasma

the X-rays we see are the thermal emission from this hot wind plasma

general result from shock theory:

$$T \sim 10^6(\Delta v_{shock}/300\ \mathrm{km/s})^2$$

Magnetically Channeled Wind Shock model

magnetic channeling causes wind flows from opposite hemispheres to collide in the magnetic equator

the resulting shocks heat the plasma

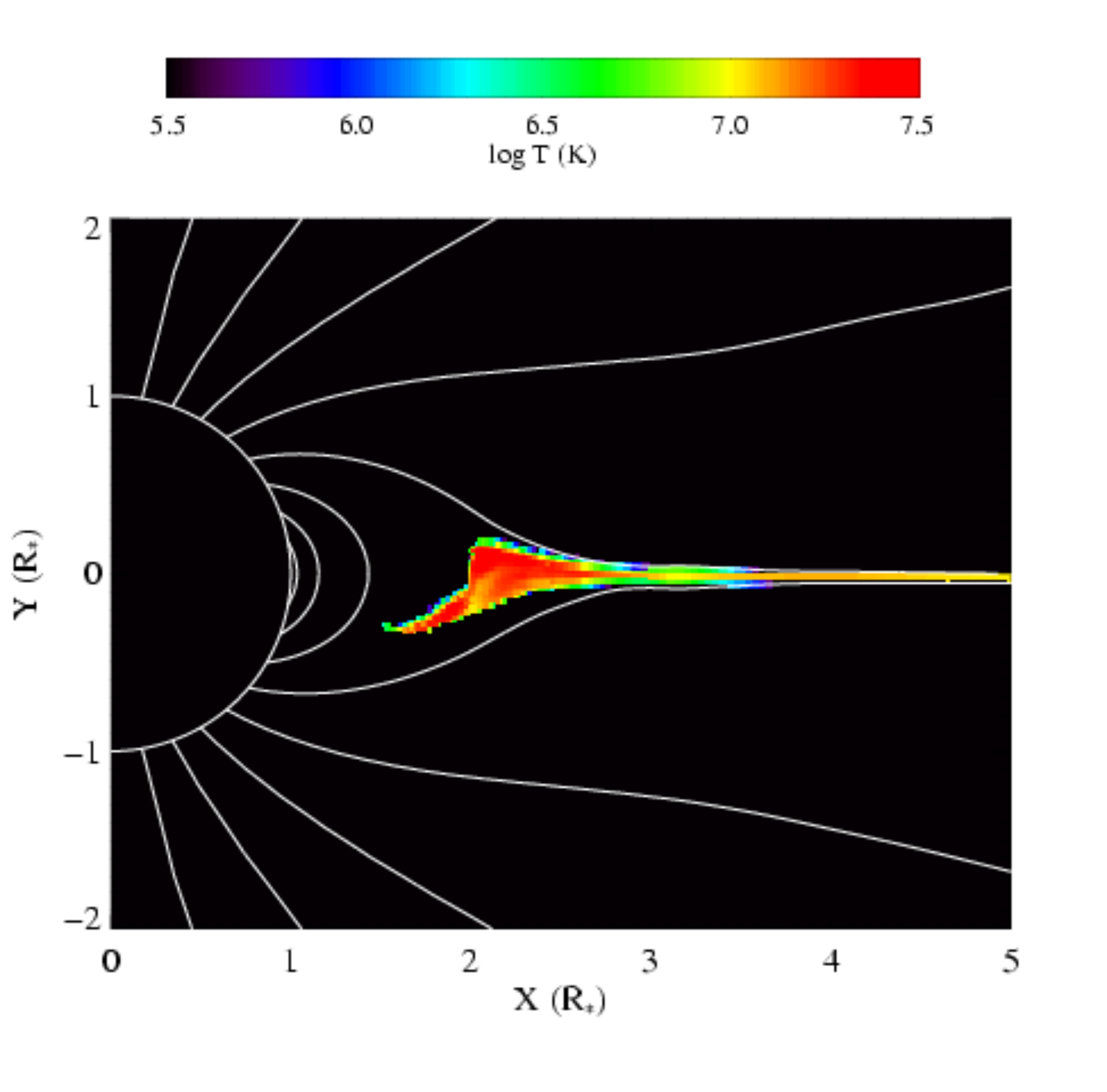
the X-rays we see are the thermal emission from this hot wind plasma

general result from shock theory:

$$T \sim 10^6 (\Delta v_{shock} / 300 \text{ km/s})^2$$

θ^1 Ori C: prototype magnetic O star

temperature



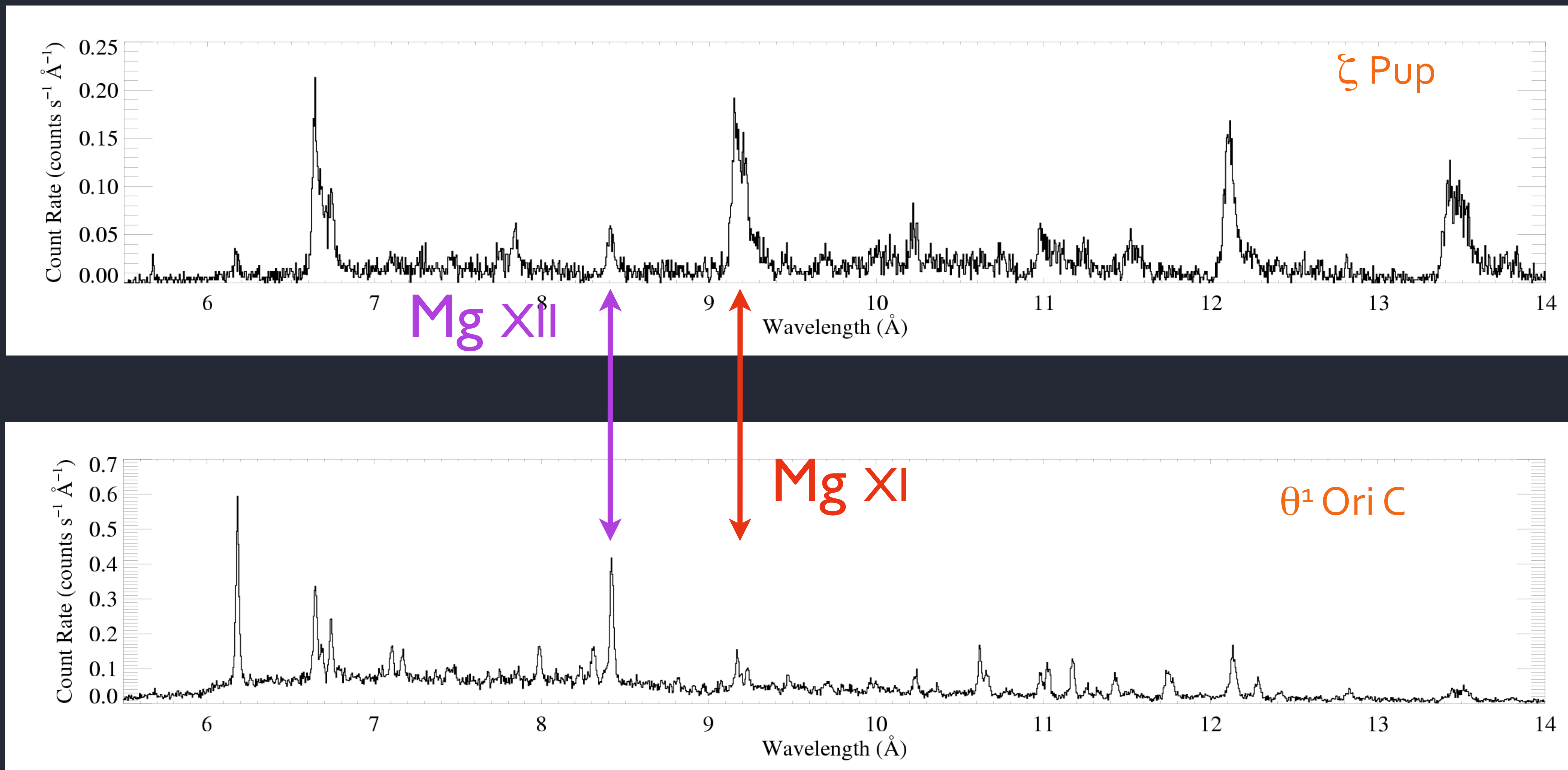
simulations by A. ud-Doula; Gagné et al. (2005)

magnetic channeling : strong shocks = hotter plasma

magnetic confinement : low post-shock velocity = narrower lines

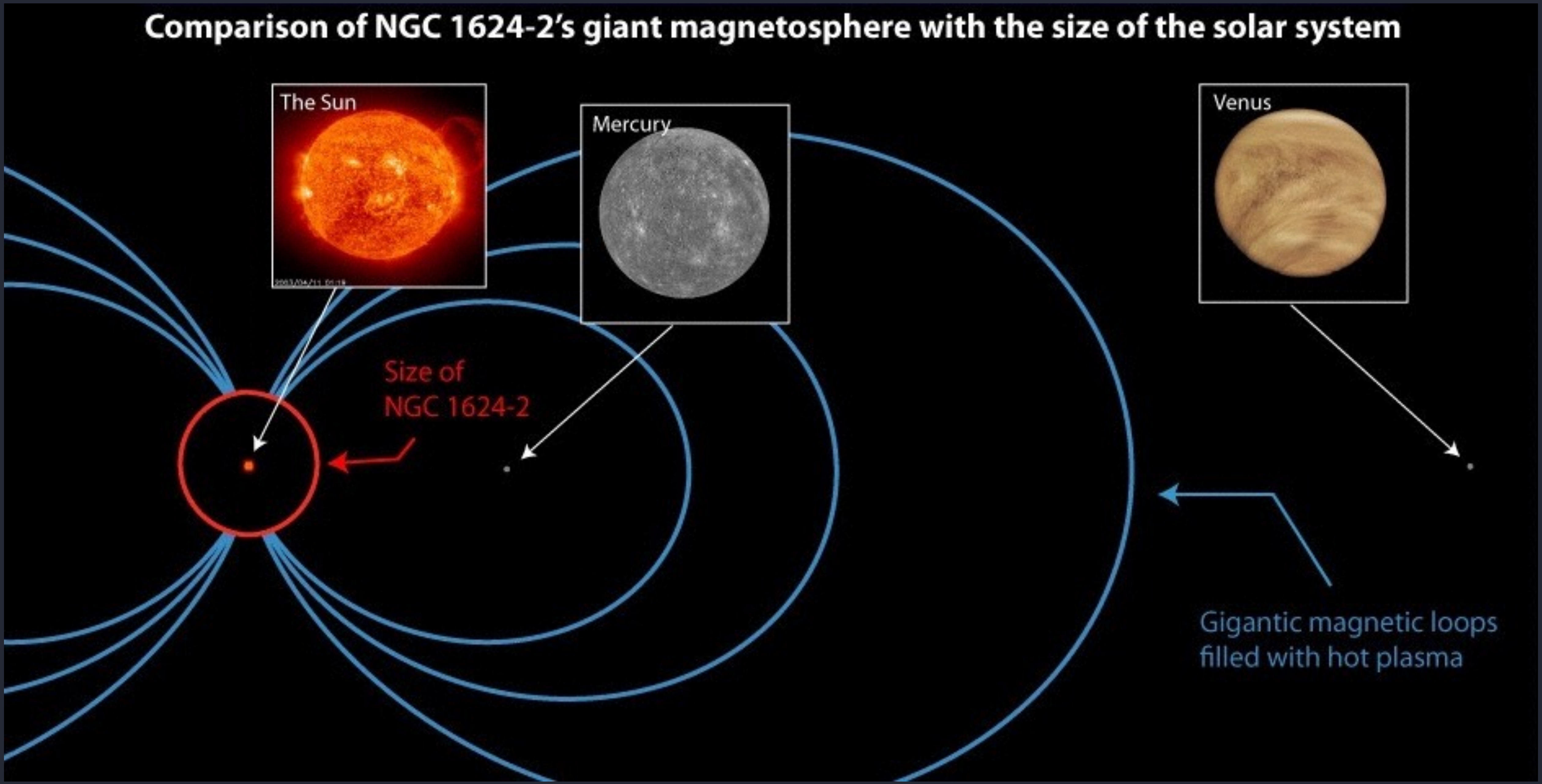
θ^1 Ori C: hotter plasma, narrower lines

Mg XII / Mg XI is proportional to temperature



recently discovered largest O star magnetosphere

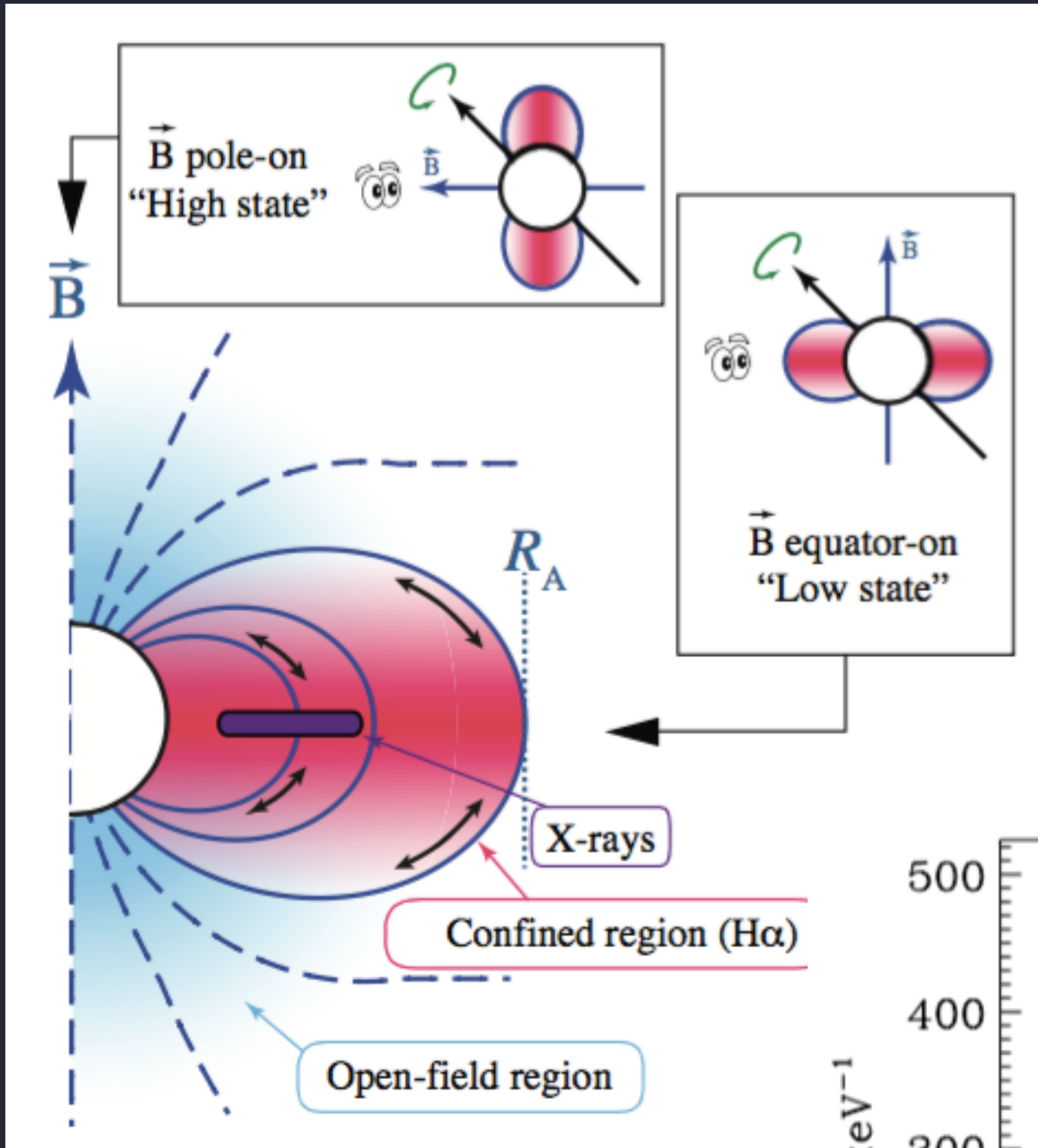
(team includes Prof. V. Petit)

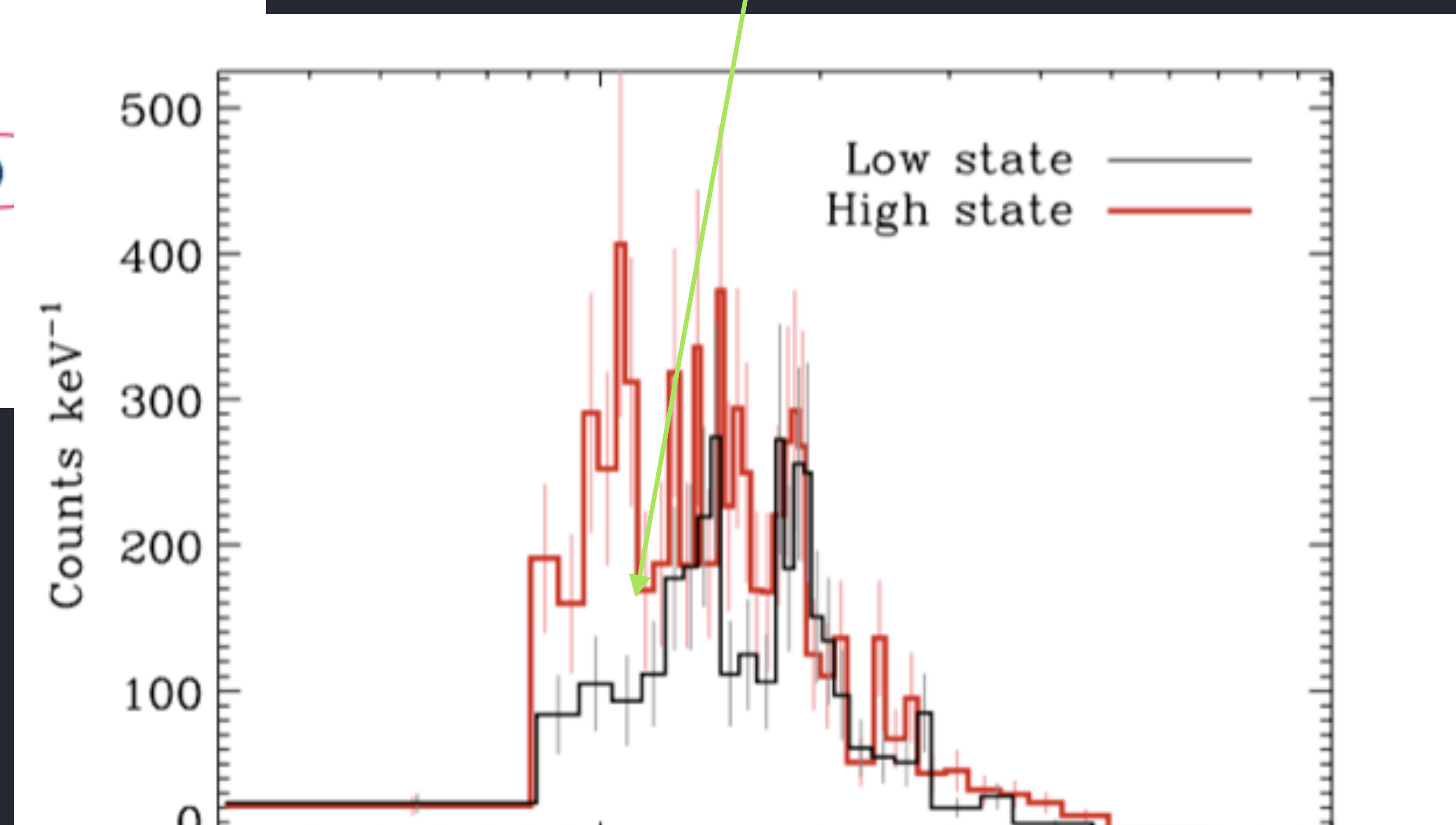


Petit et al. 2015, MNRAS, 453, 3288

Chandra observations at two phases

more absorption when viewed edge-on





photon energy

Preliminary Conclusions

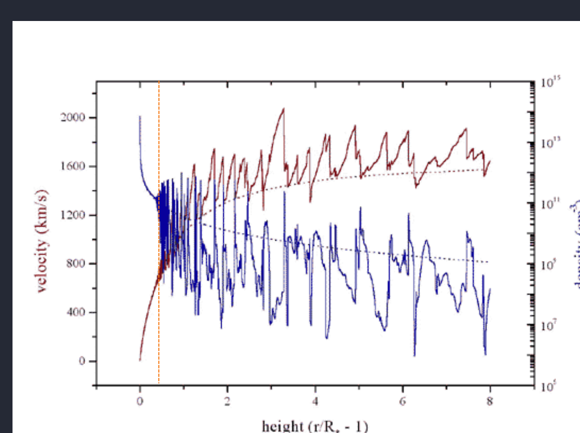
1. Magnetic massive stars produce X-rays via wind shocks in their magnetospheres

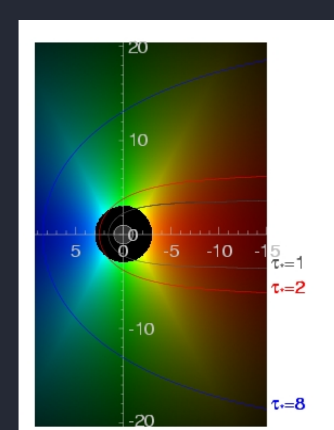
2. X-ray observations show that this process is more efficient than LDI-generated embedded wind shocks in non-magnetic O stars

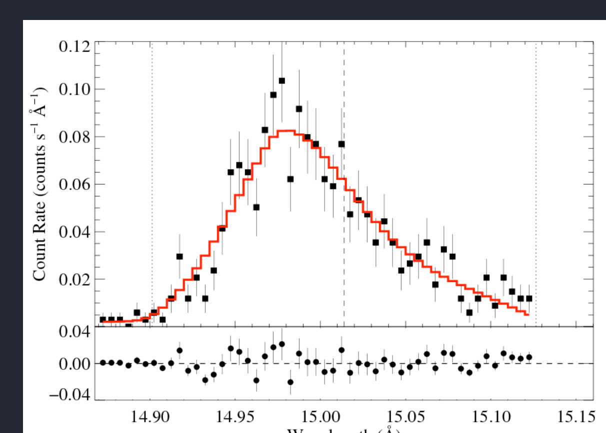
Overall Conclusions

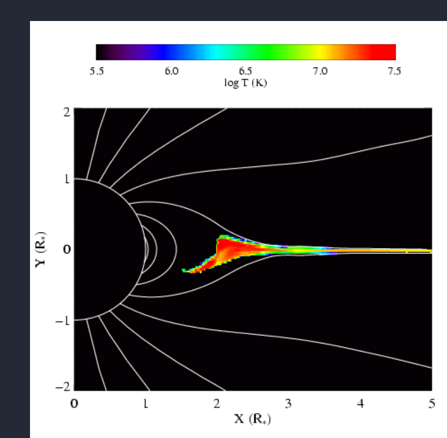
1. Shock heating extracts kinetic energy from radiation-driven winds, producing the X-rays

2. X-ray spectroscopy provides diagnostic information about plasma temperatures, velocities, and absorption



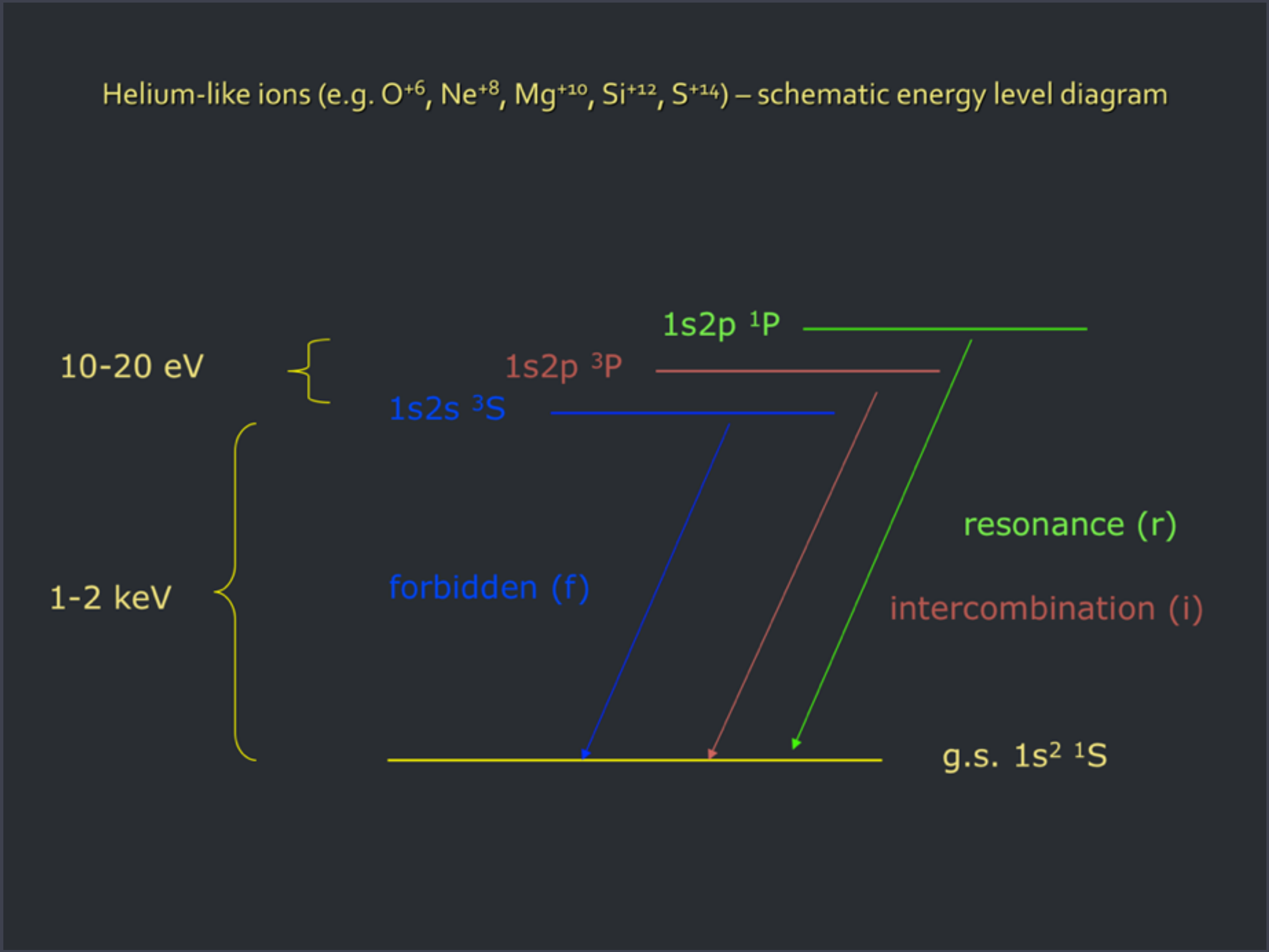




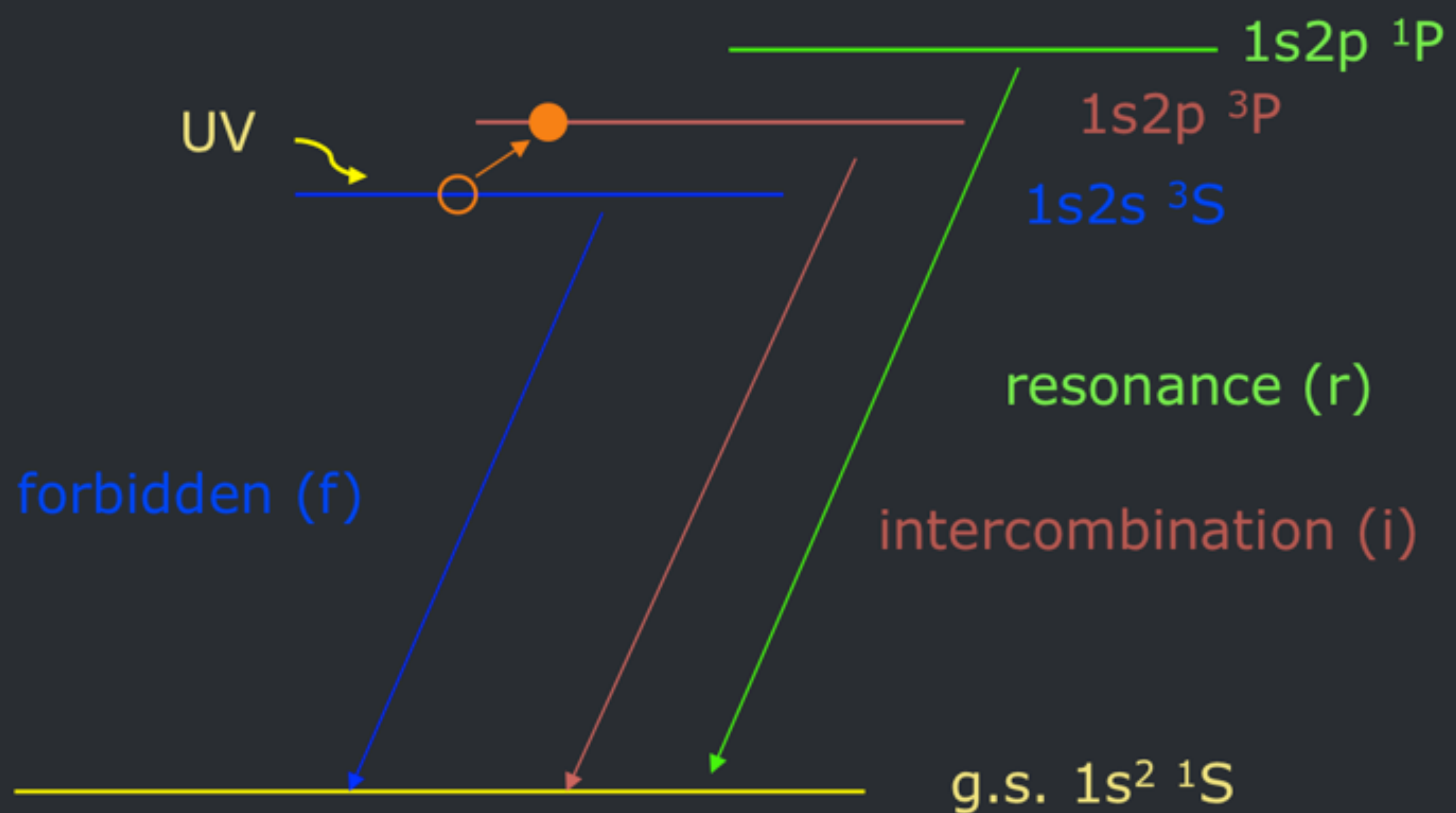


Extra Slides

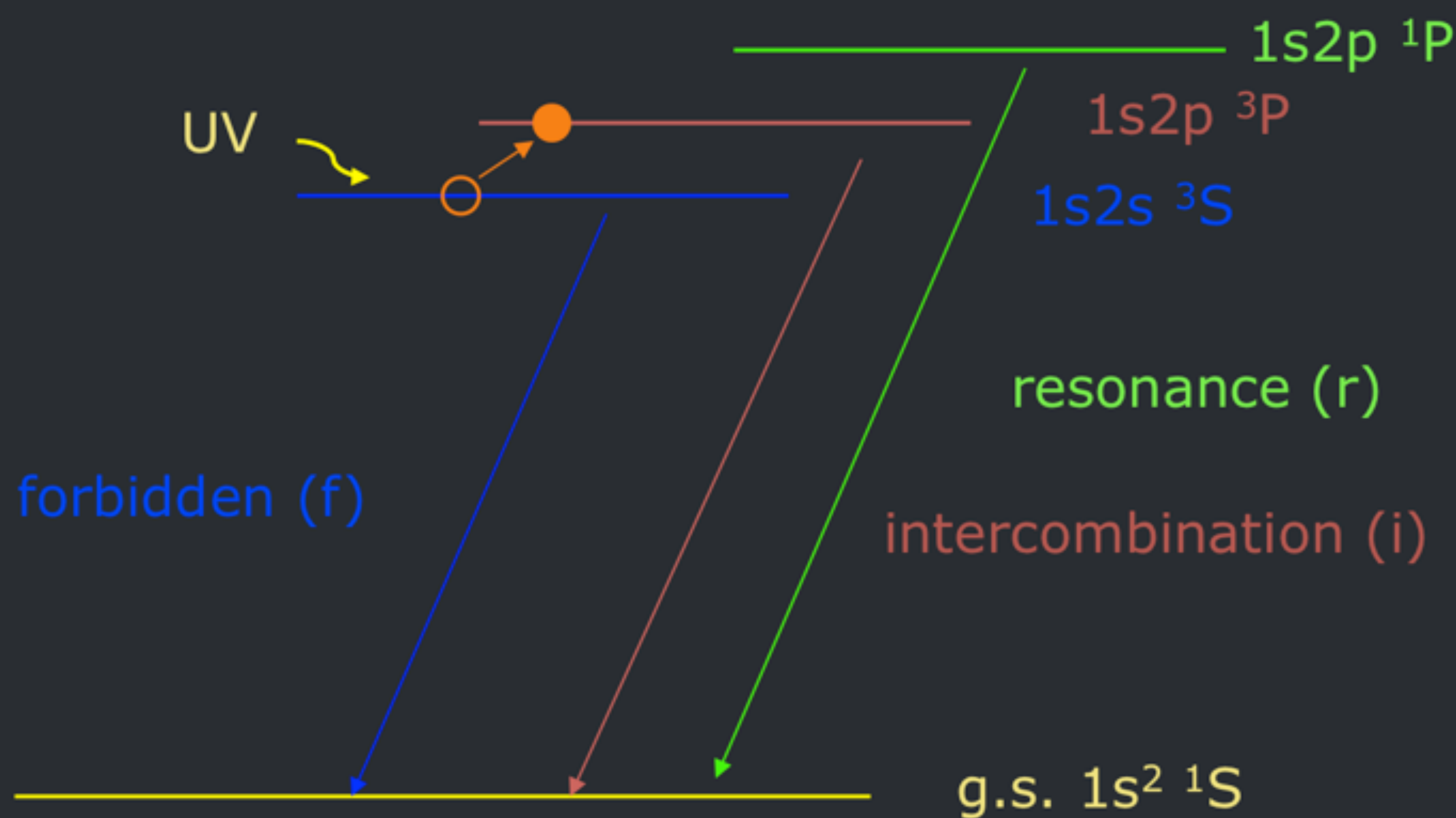
f/*i* ratios for diagnosing location of the hot plasma



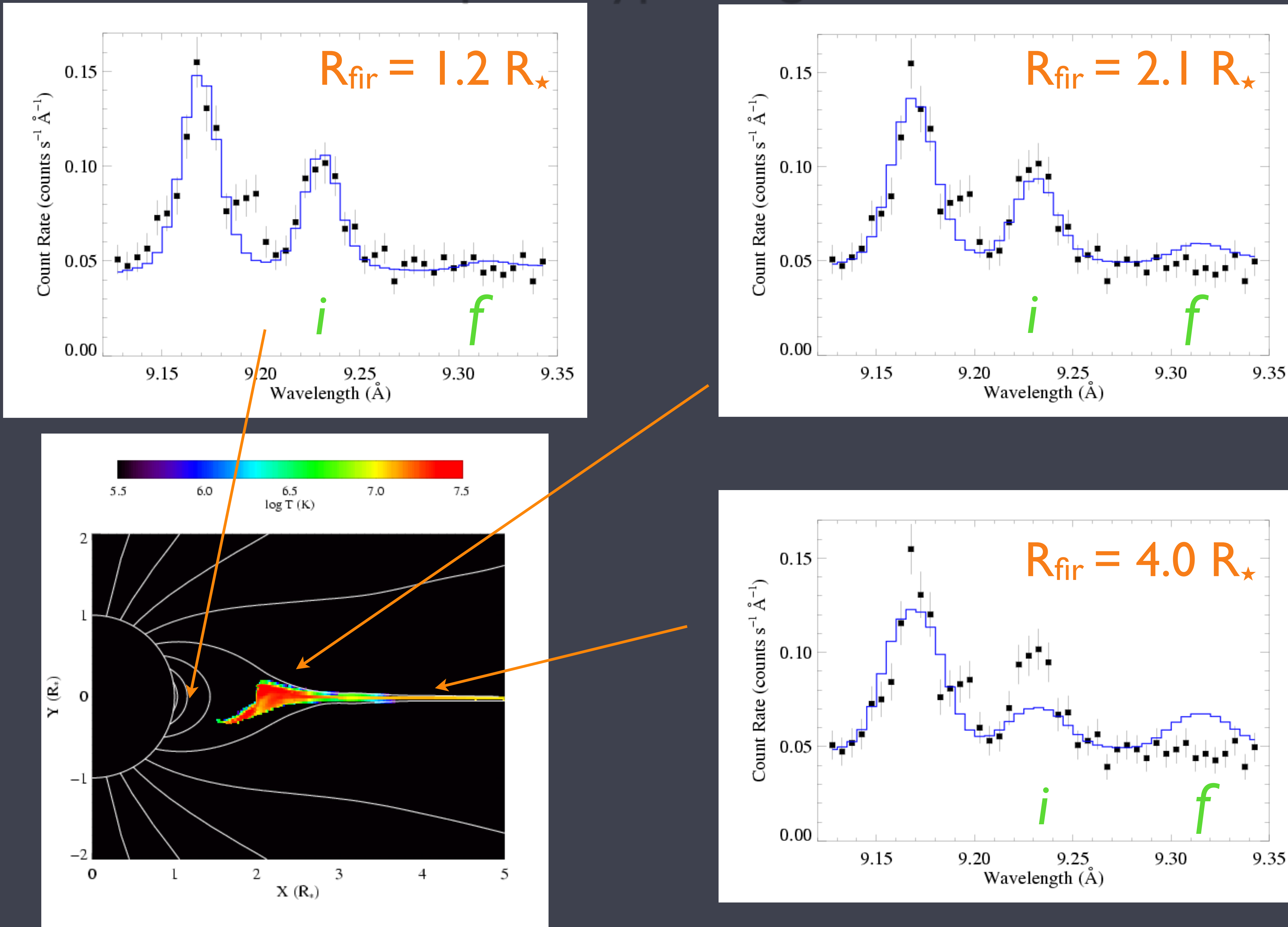
The *f*/*i* ratio is thus a diagnostic of the strength of the local UV radiation field.



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.

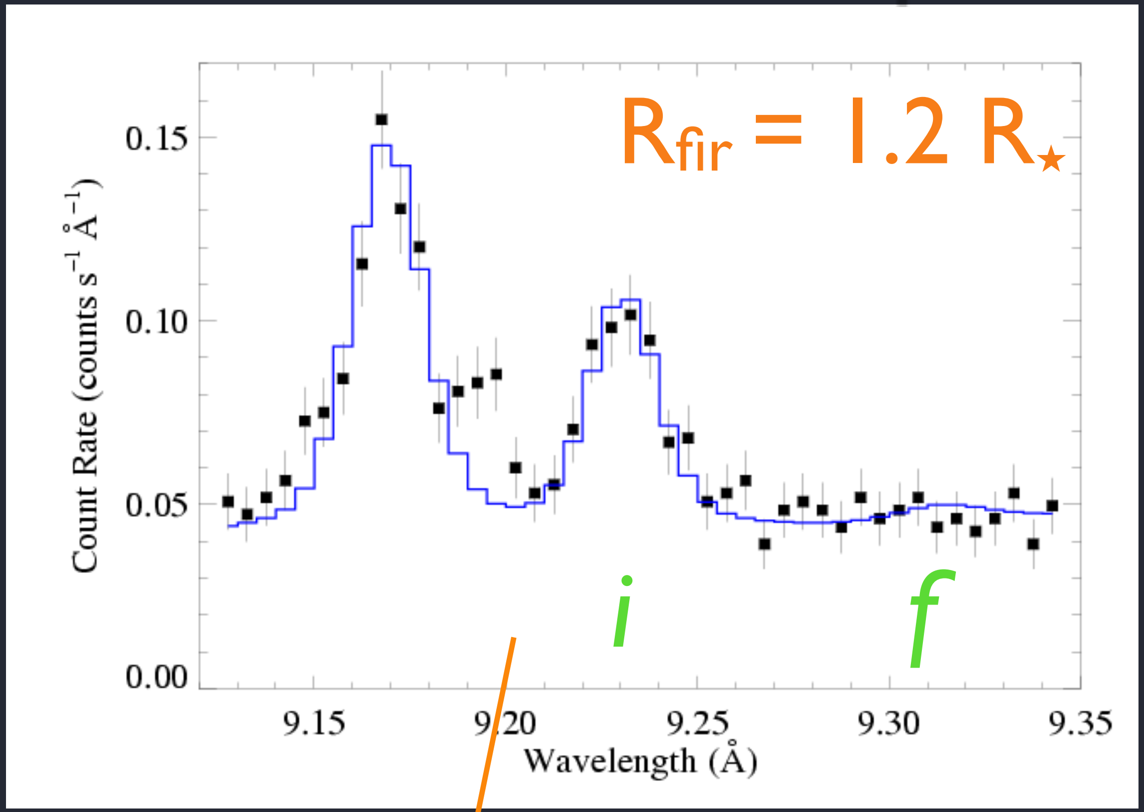


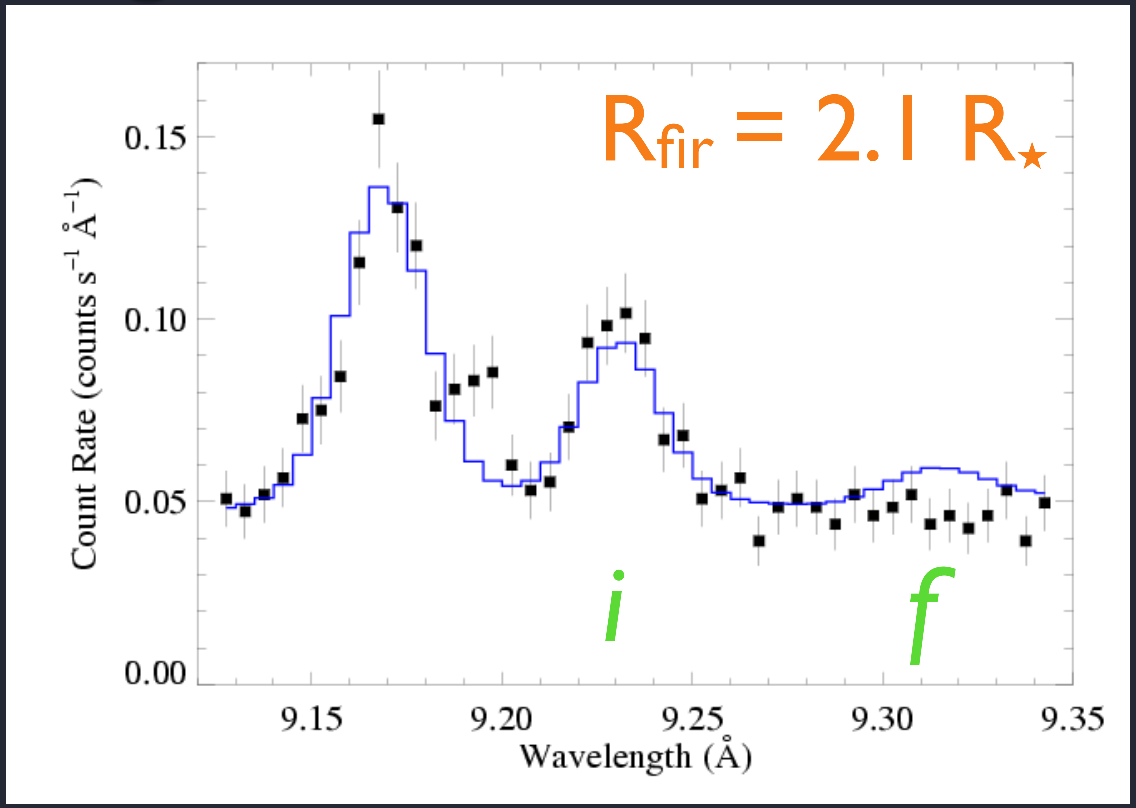
θ¹ Ori C: prototype magnetic O star

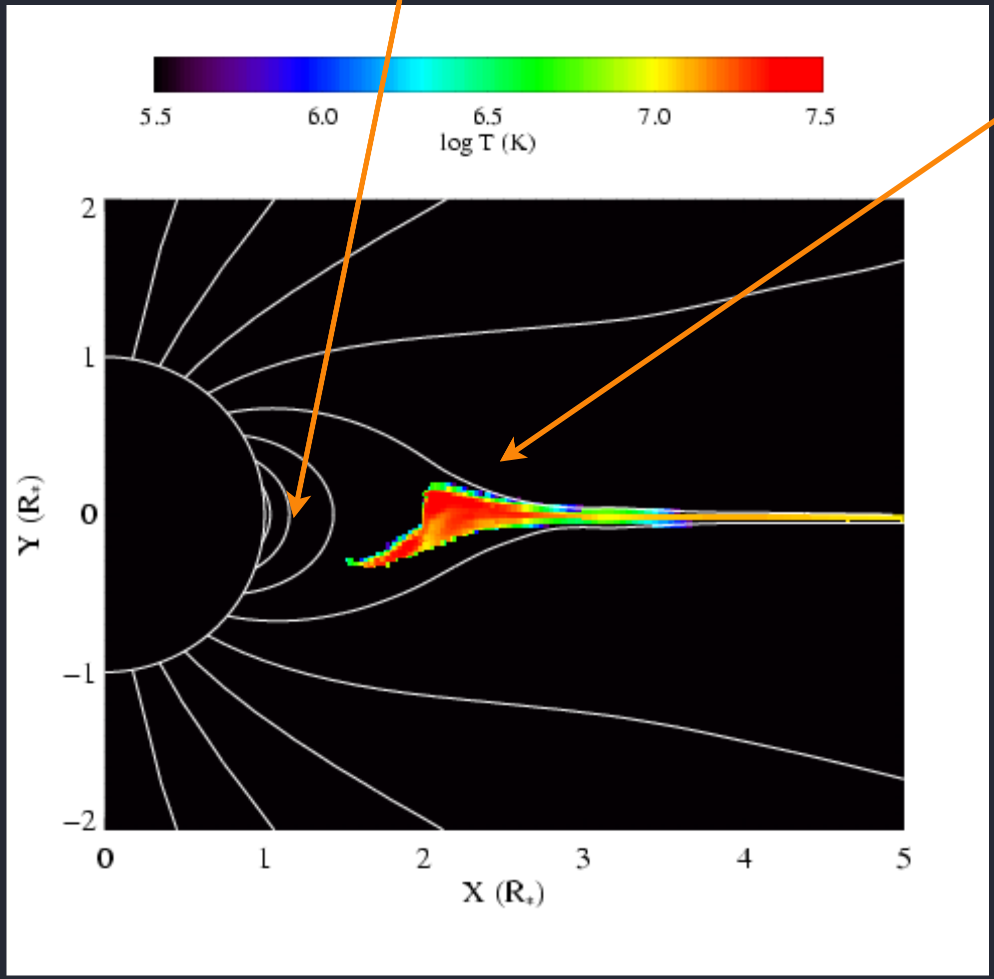


A. ud-Doula

θ¹ Ori C: prototype magnetic O star







A. ud-Doula

MDH simulations are only marginally consistent with *f*/*i* constraints

data say hot plasma is closer to the photosphere

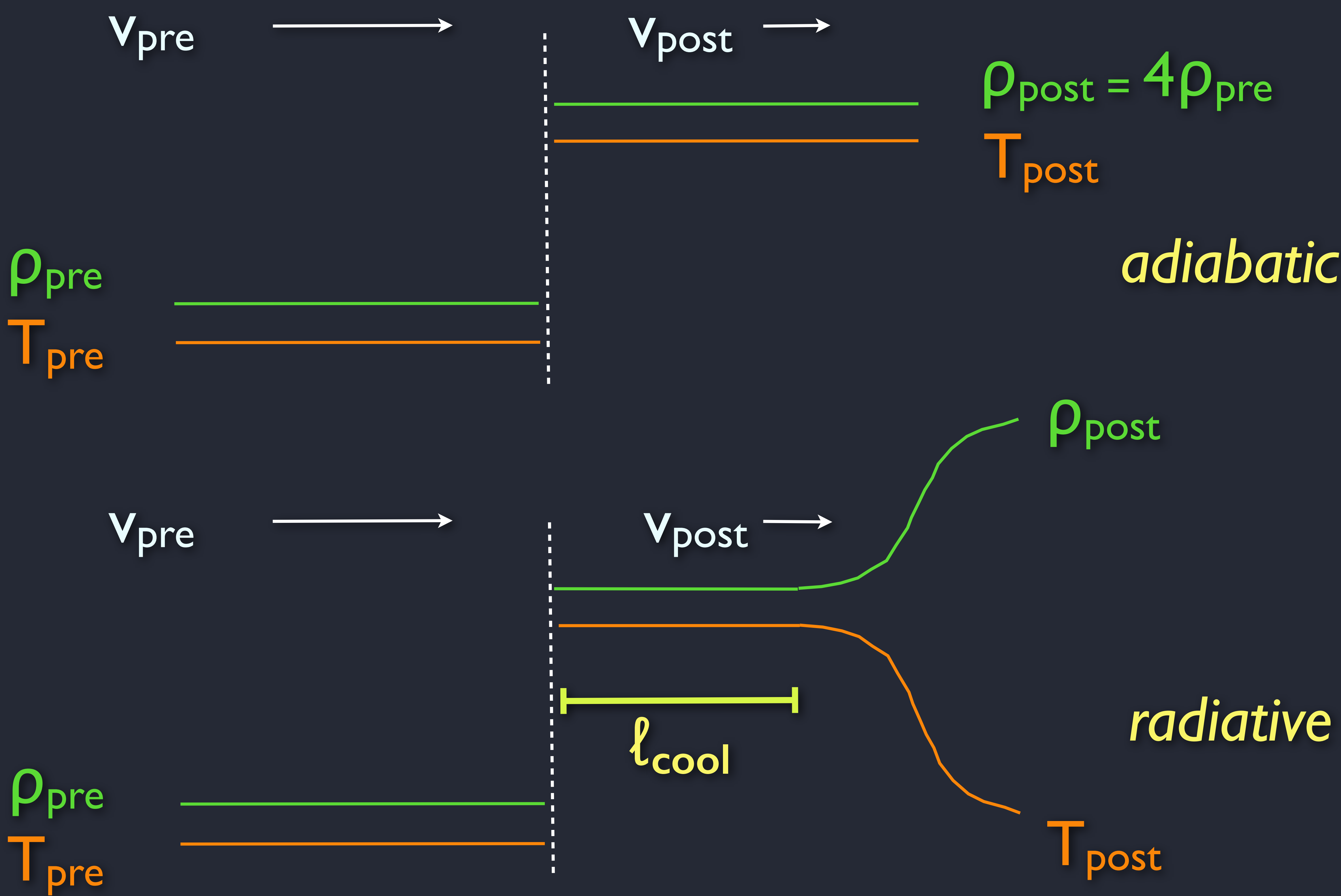
What produces the hot, X-ray emitting plasma in massive stars?

plasma with $T > 10^6$ K radiates X-rays ($h\nu > 100$ eV)

shocks heat plasma to $T \sim 10^6$ K
if $\Delta V_{shock} \sim 300$ km/s
and $T \sim (\Delta V_{shock})^2$

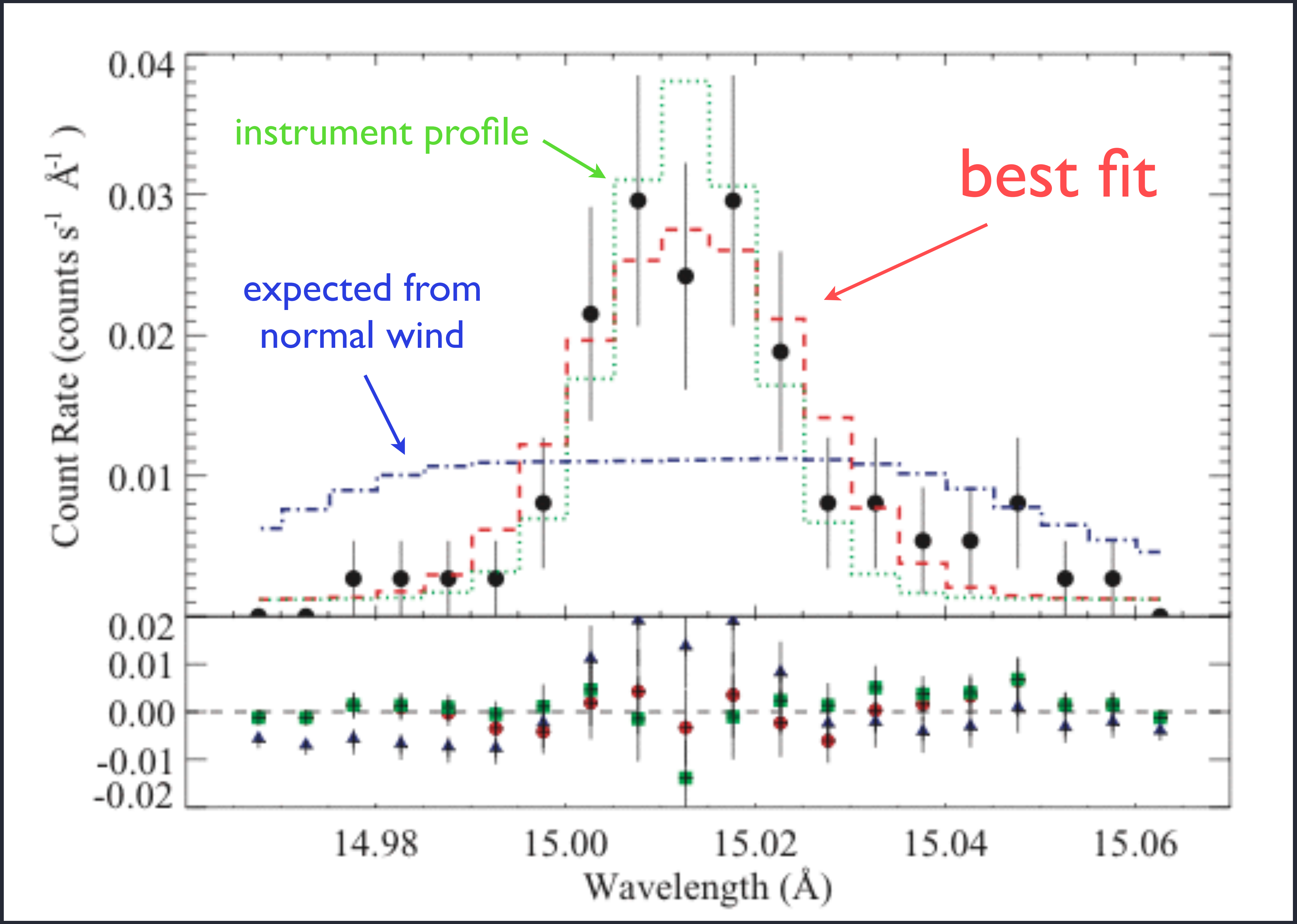
shocks are *radiative* in dense O star winds, but *adiabatic* in lower-density early B star winds

$$\Delta v_{shock} = v_{pre} - v_{post}$$

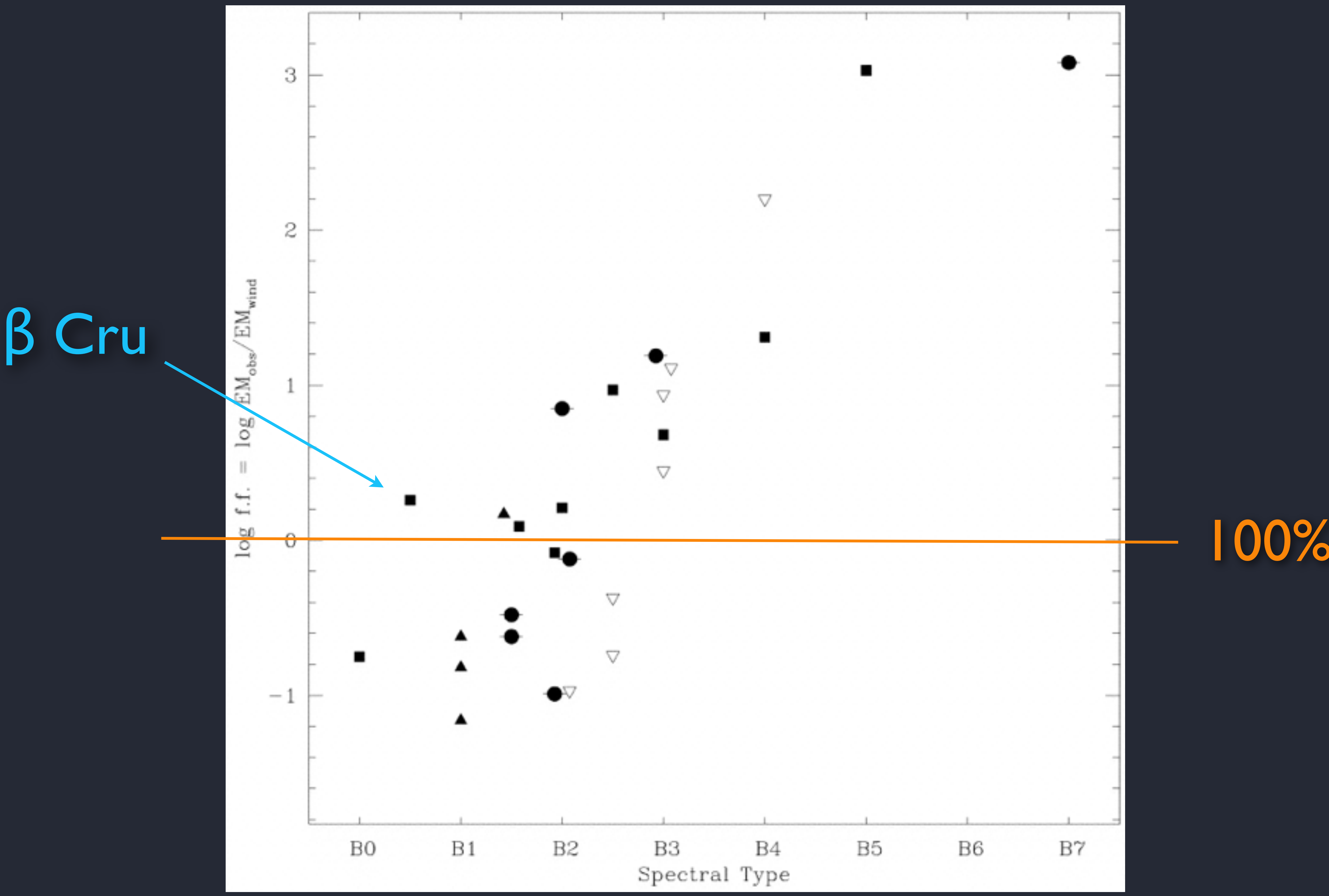


β Cru (B0.5 III)

Fe XVII line in the *Chandra* grating spectrum of β Cru (B0.5 III)



X-ray filling factors of B stars



B0 B1 B2 B3

Cohen et al. 1997

B star winds have low density, shocks are *adiabatic*

once the wind is shocked (at ~ 1.5 $R_\star$) it essentially *never* cools $\Rightarrow$ outer wind is (nearly completely) filled with hot (few 10^6 K) plasma that is no longer radiatively driven

hence, narrow-ish X-ray lines