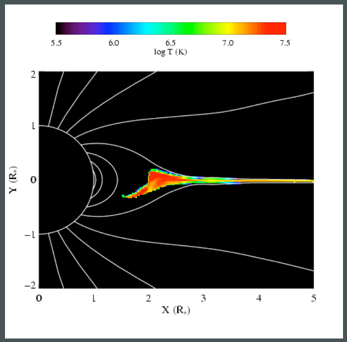
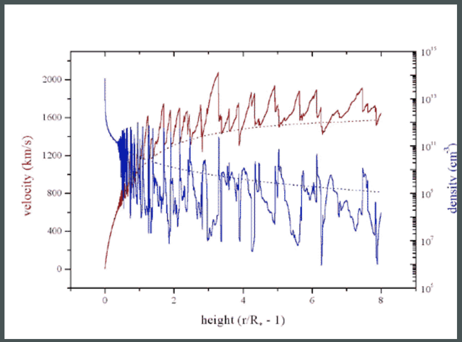
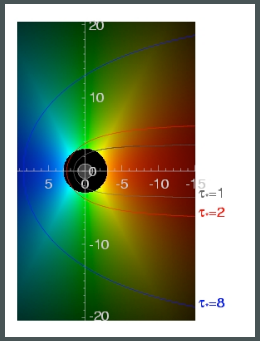
X-ray Spectroscopy of the Radiation-Driven Winds of Massive Stars:

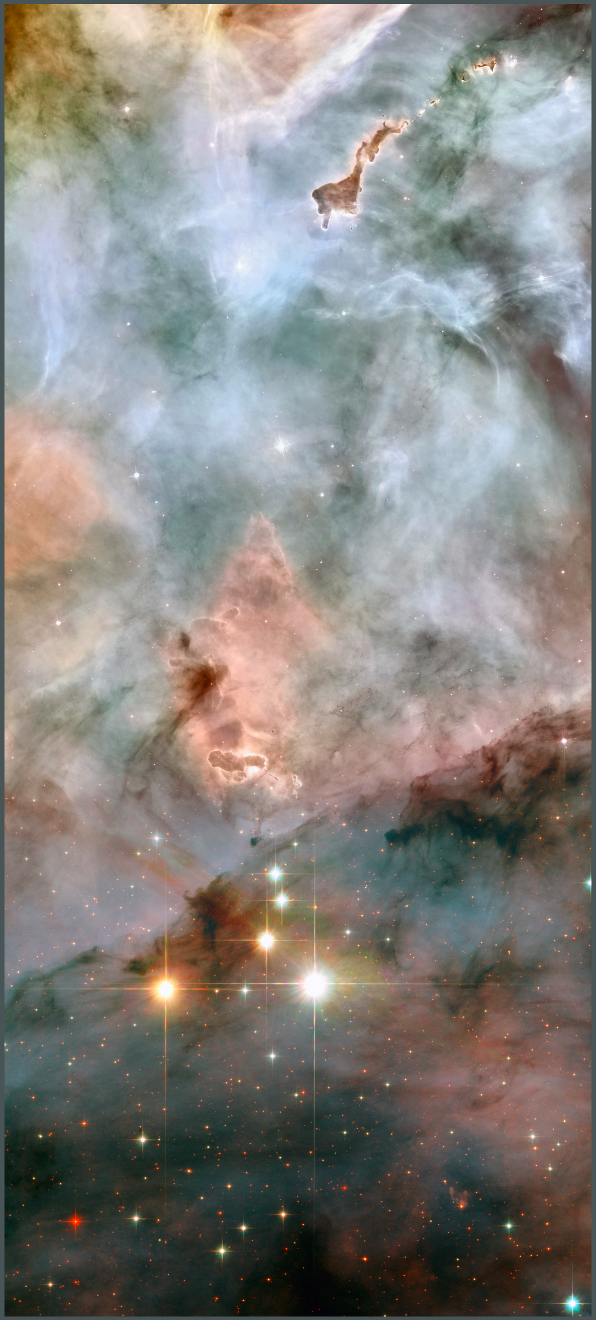
Line Profile and Line Ratio Diagnostics

David Cohen
Swarthmore College









Carina/Keyhole Nebula (HST)

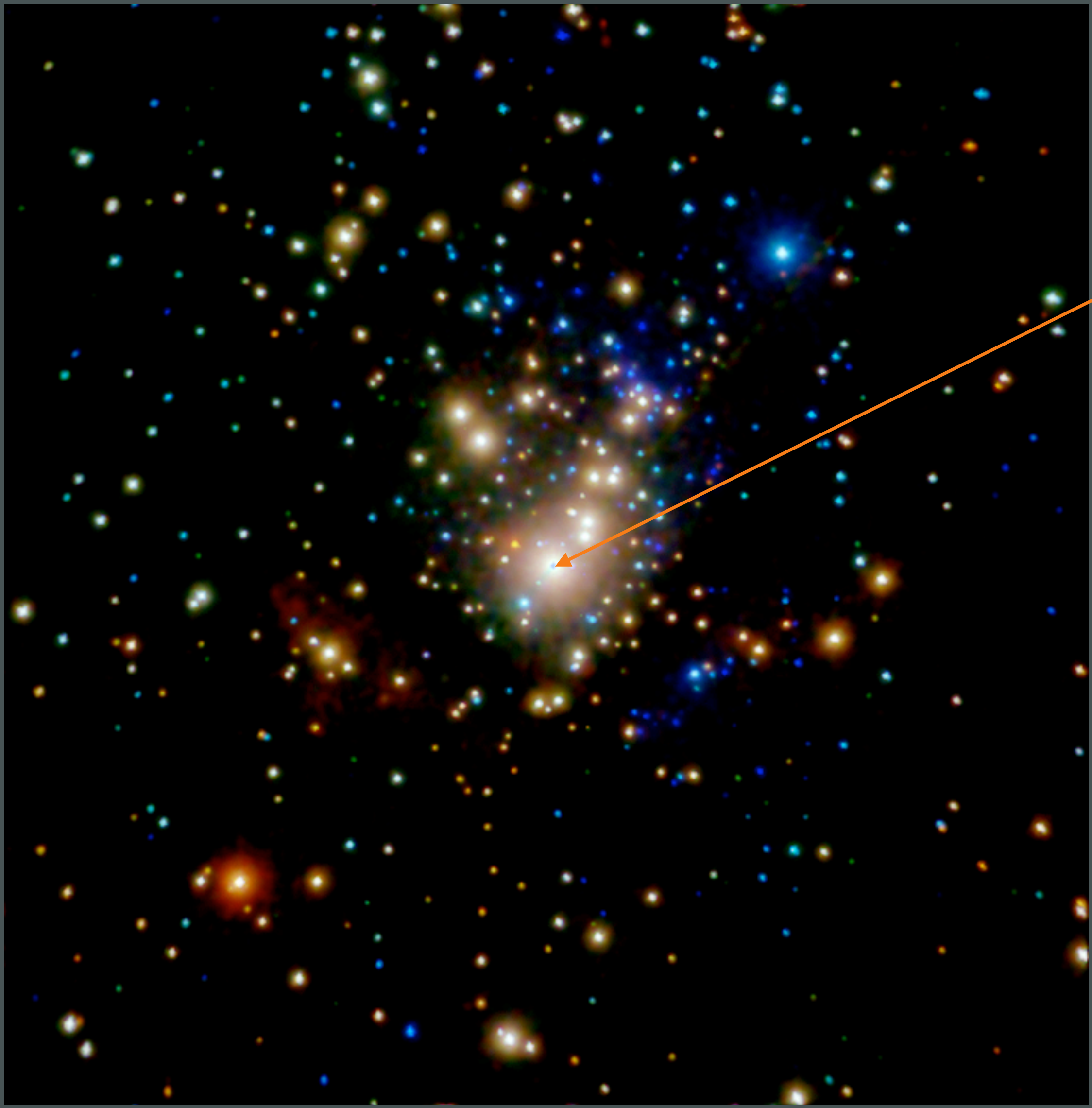
massive stars:

20 to 100 M_{sun}

10^6 L_{sun}

T ~ 50,000 K

Chandra X-ray Telescope image of the Orion Nebula Cluster



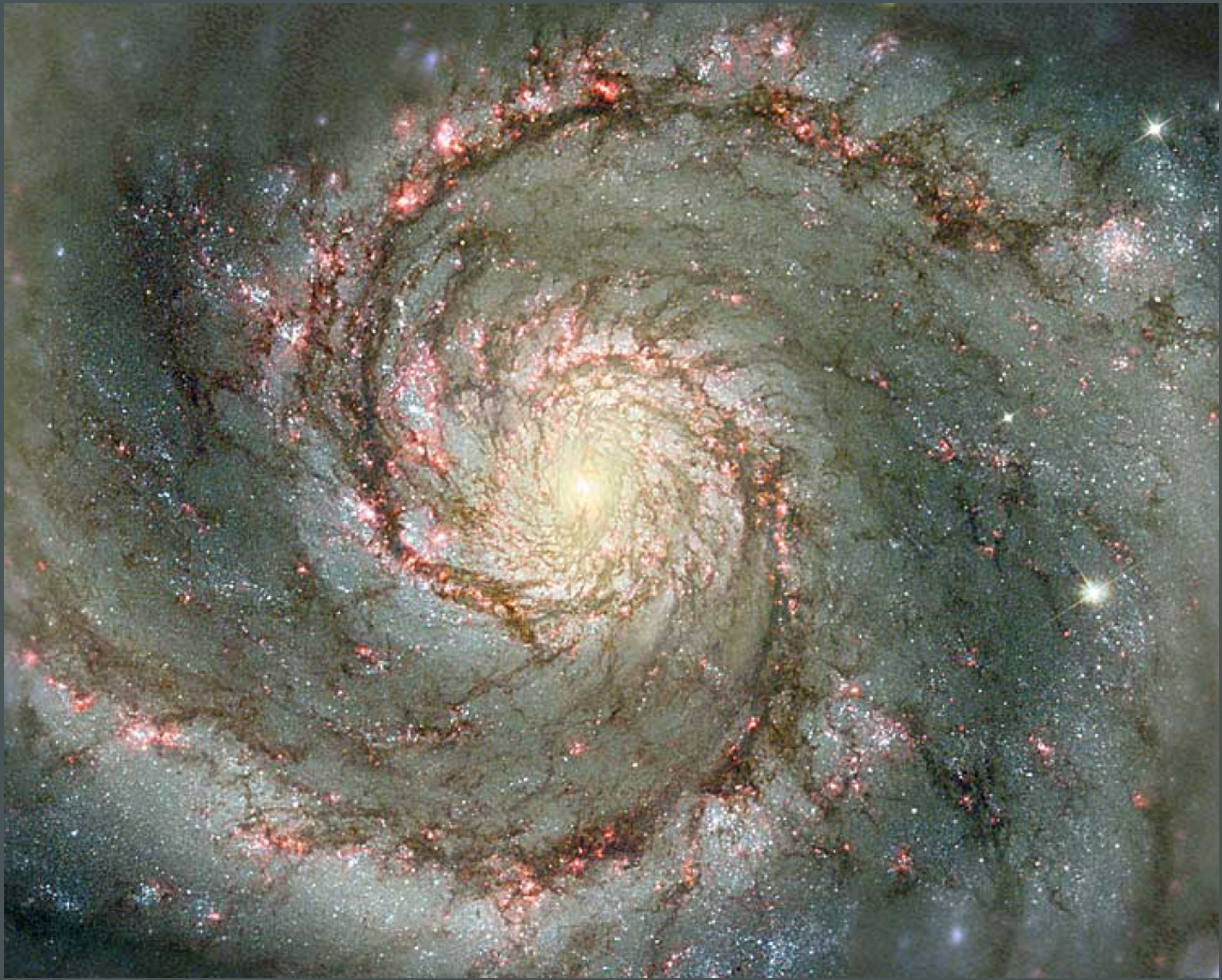
young, massive star:
θ^1 Ori C

Color coded according to photon energy (red: <1keV; green 1 to 2 keV; blue > 2 keV)

Keyhole Nebula

Hubble Heritage

NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC00-06



Whirlpool/M51 (HST)

1000 yr old supernova remnant

Crab Nebula (WIYN)

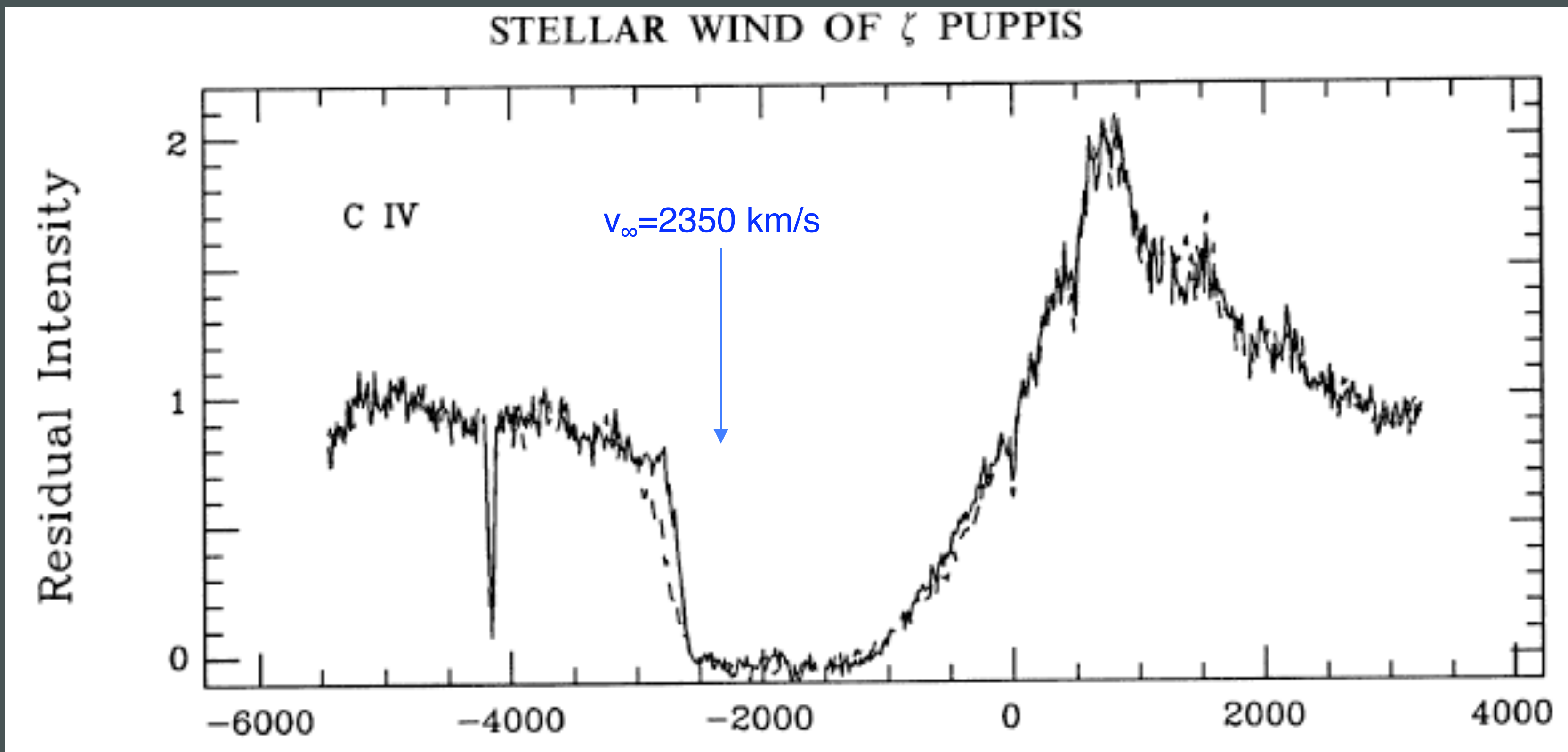
wind-blown bubble: stellar wind impact on its environment

NGC 6888 Crescent Nebula (Tony Hallas)

Radiation-driven massive star **winds**

$\dot{M} \sim 10^{-6}\ M_{sun}/yr$

UV spectrum: C IV 1548, 1551 Å



Prinja et al. 1992, ApJ, 390, 266

Velocity (km/s)

Power in these winds:

$$\tfrac{1}{2}\dot{M}v_\infty^2 \approx 3\times10^{36}\ \text{erg s}^{-1}$$
$$\approx .001L_*$$

L_{sun} = 4 x10^{33} erg s^{-1}

$L_{massive}$ ≈ 4 x10^{39}

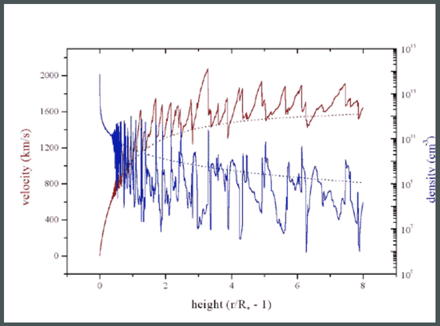
while the x-ray luminosity

$$L_X \approx 10^{-7}L_*$$

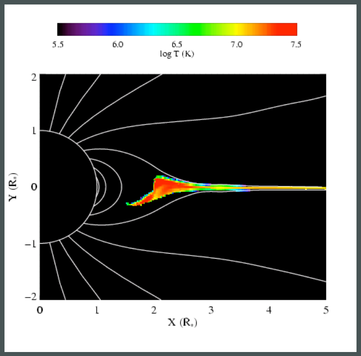
To account for the x-rays, only **one part in 10^{-4}** of the wind's mechanical power is needed to heat the wind

Three models for massive star x-ray emission

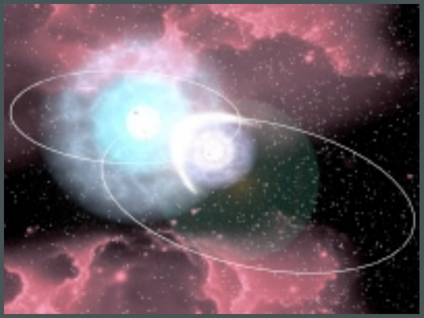
1. Instability driven shocks



2. Magnetically channeled wind shocks

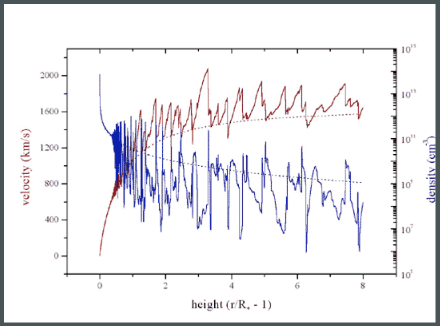


3. Wind-wind interaction in close binaries



Three models for massive star x-ray emission

1. Instability driven shocks



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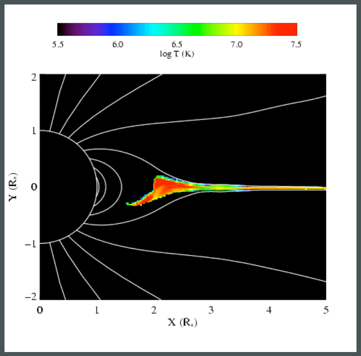


3. Wind-wind interaction in close binaries

Winds of massive stars are driven by **radiation pressure**

opacity

luminosity

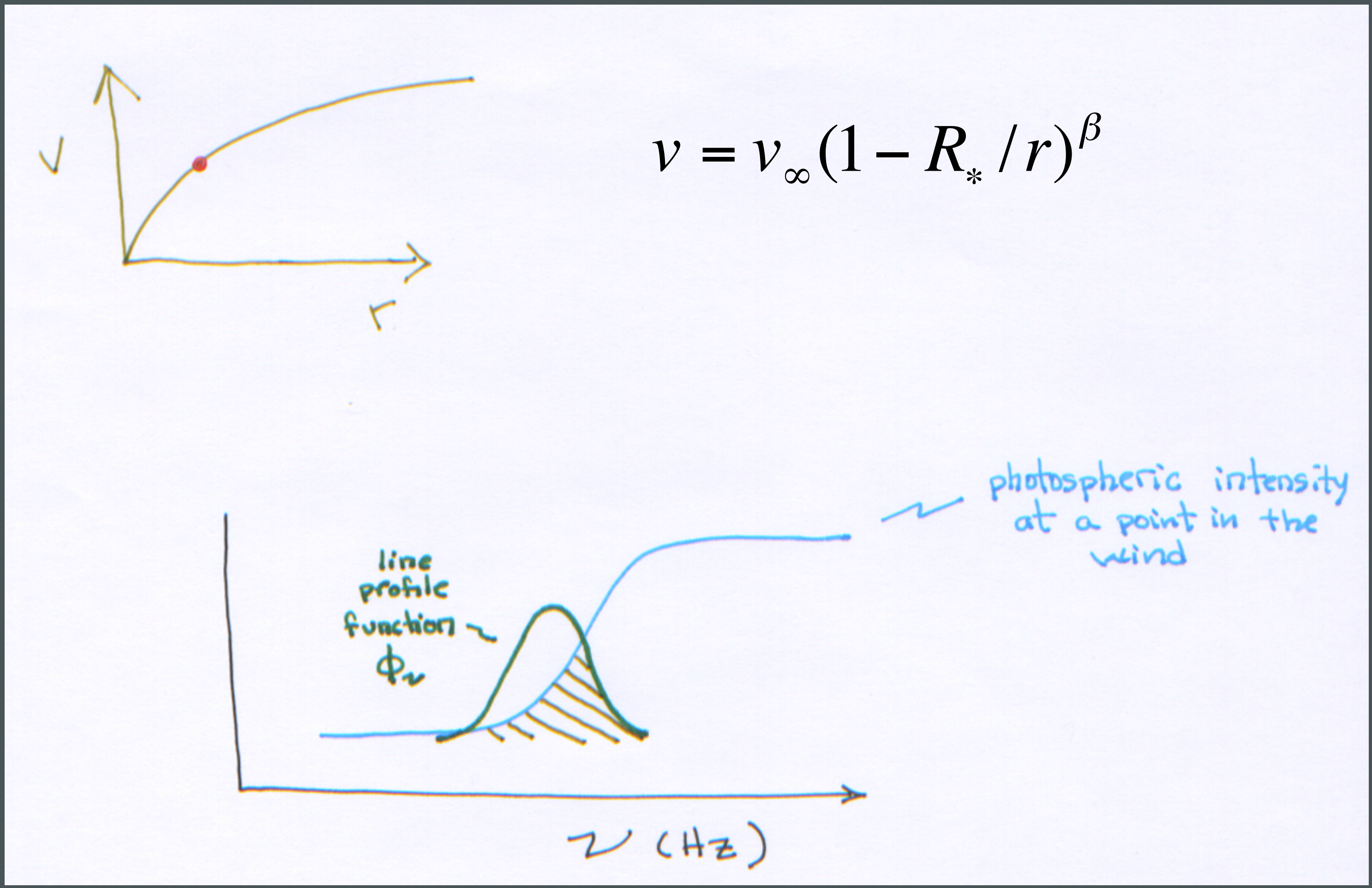
$$\Gamma_{edd} \equiv \frac{F_{rad}}{F_{grav}} = \frac{\kappa L}{4\pi c G M}$$

mass

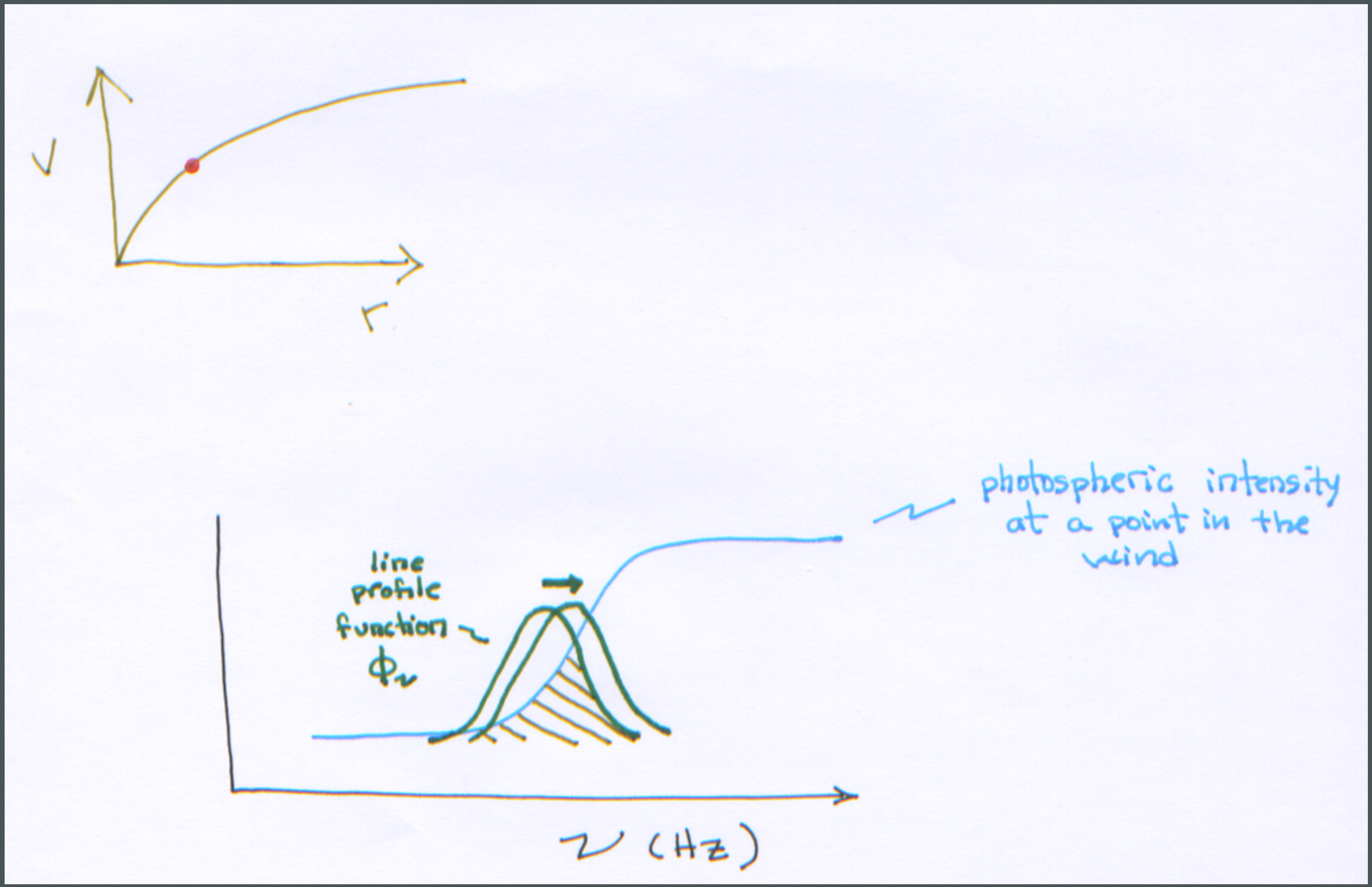
For the Sun, $\Gamma_{edd} \sim 10^{-5}$

For massive stars, Γ_{edd} approaches unity

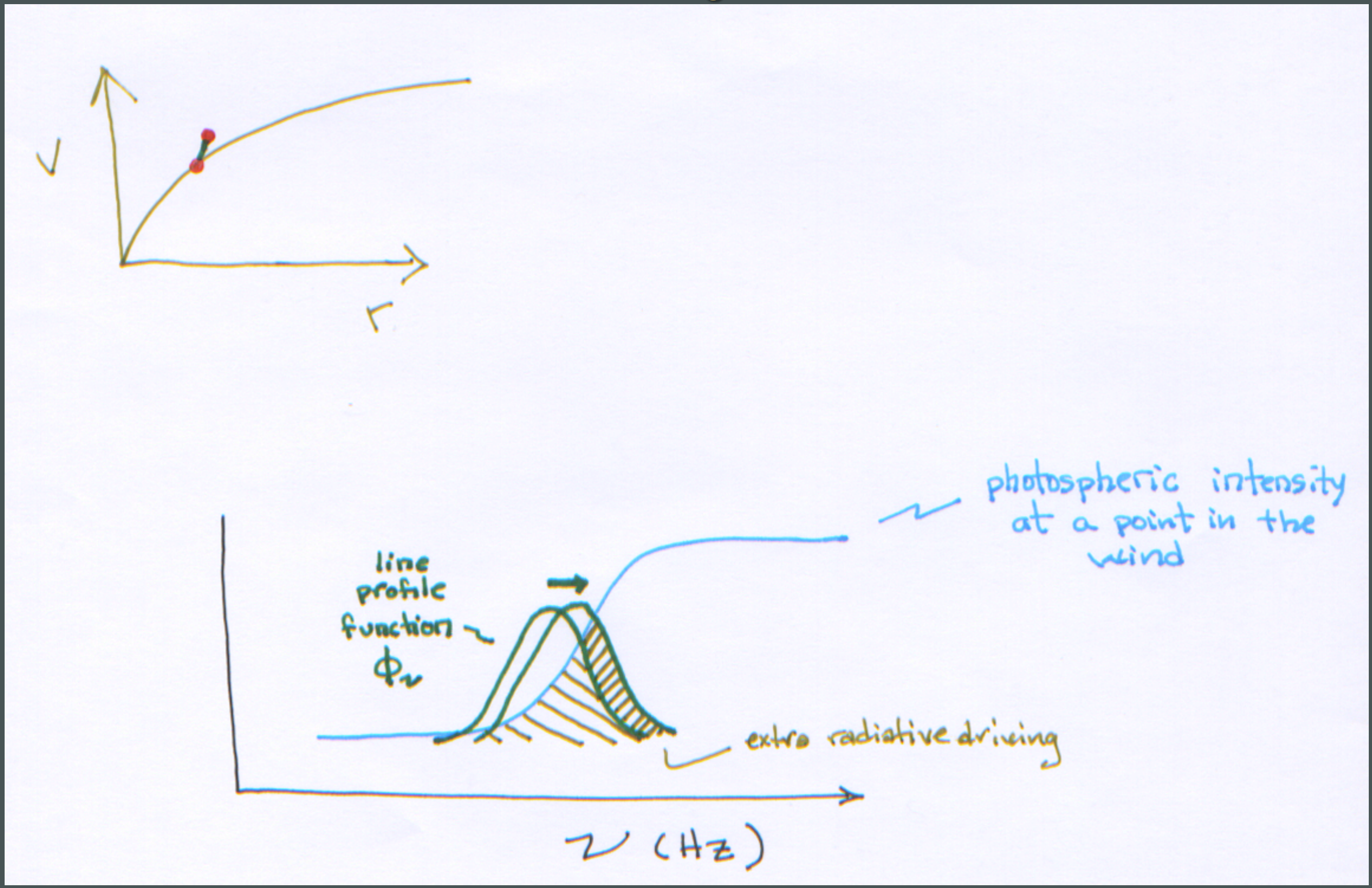
The Line-Driven Instability (LDI; Milne 1926)



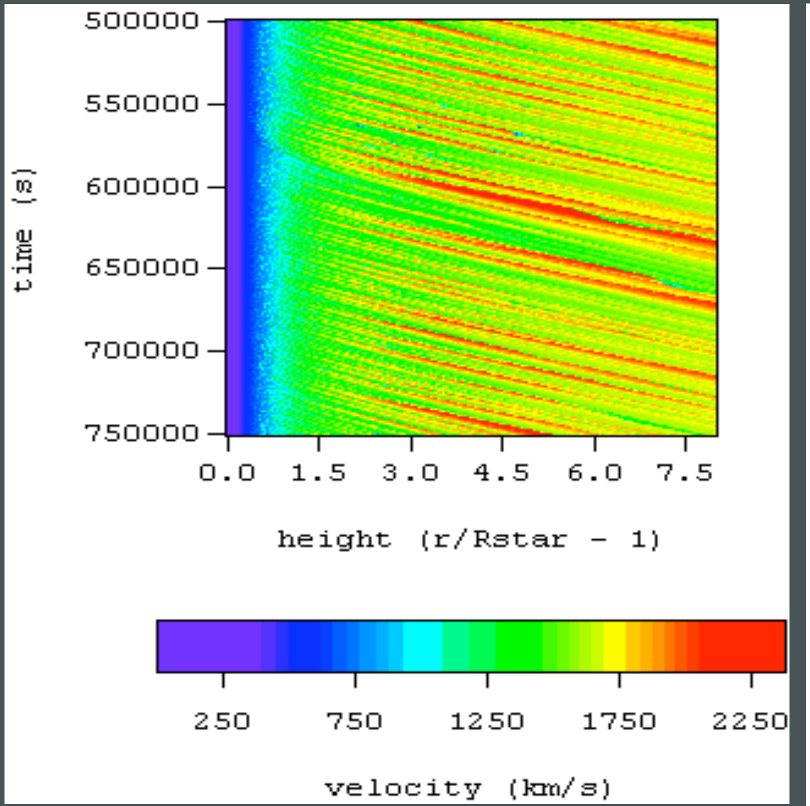
Consider a positive velocity perturbation

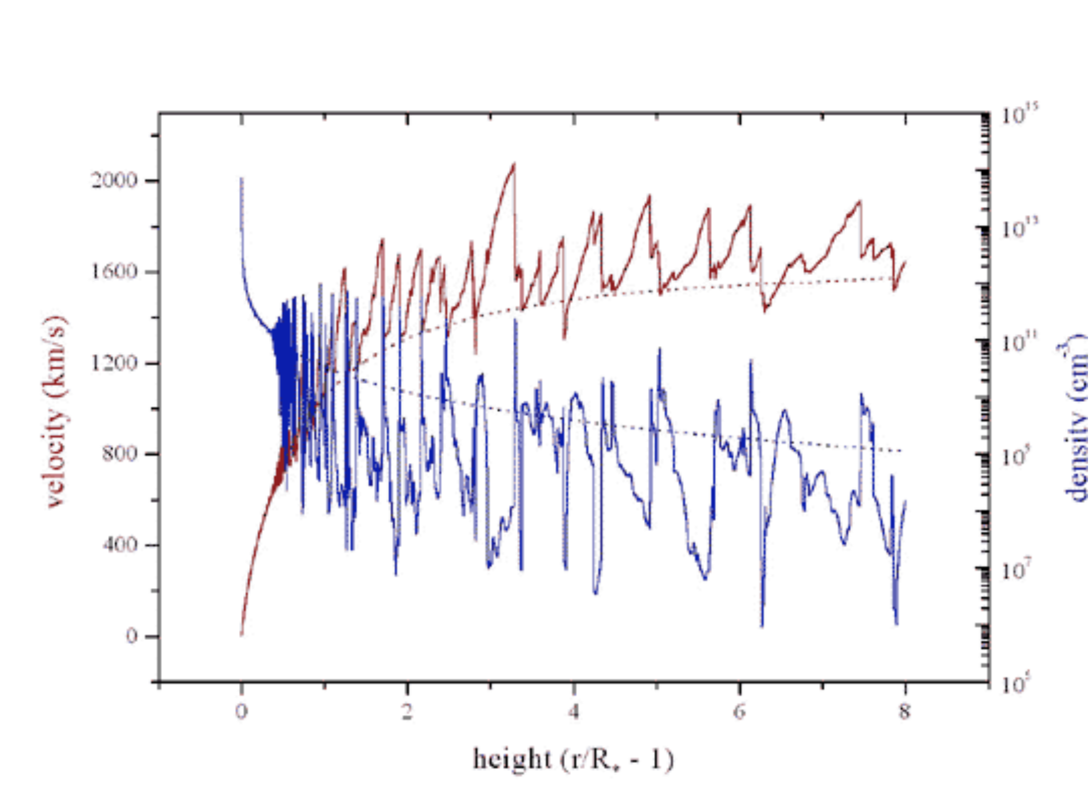


Positive feedback: ion moves out of the Doppler shadow, sees more radiation, gets accelerated…



1-D rad-hydro simulation of a massive star wind

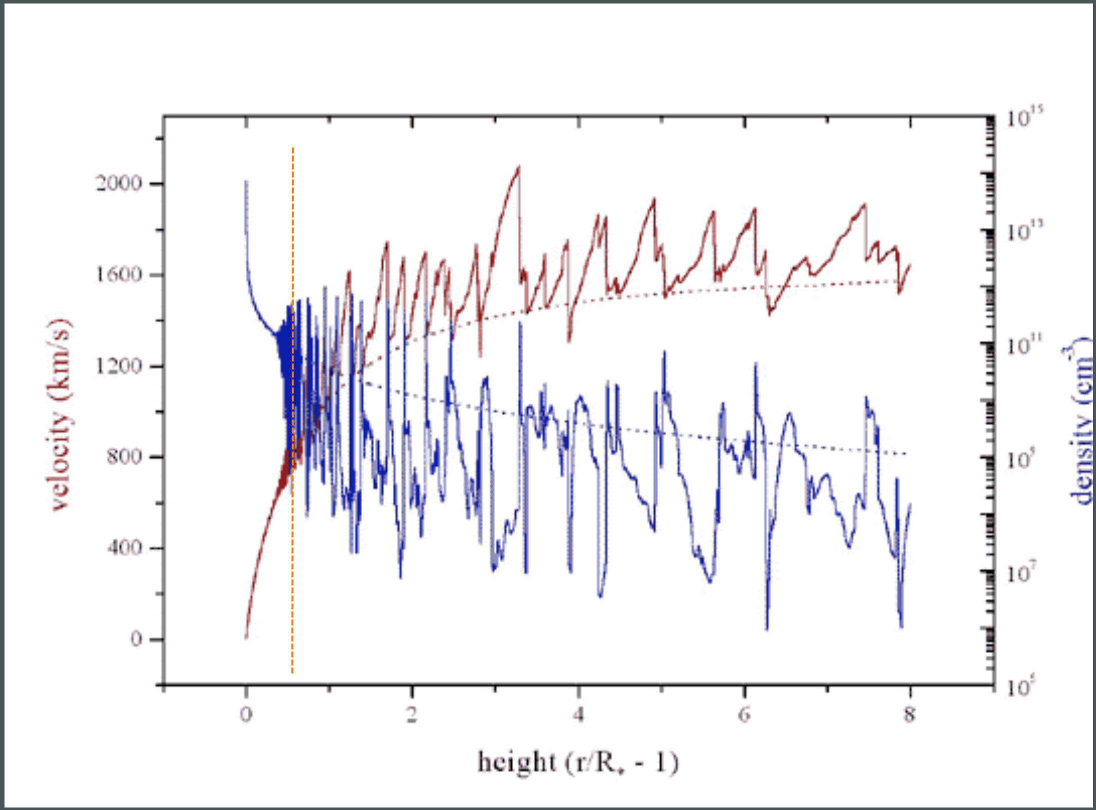




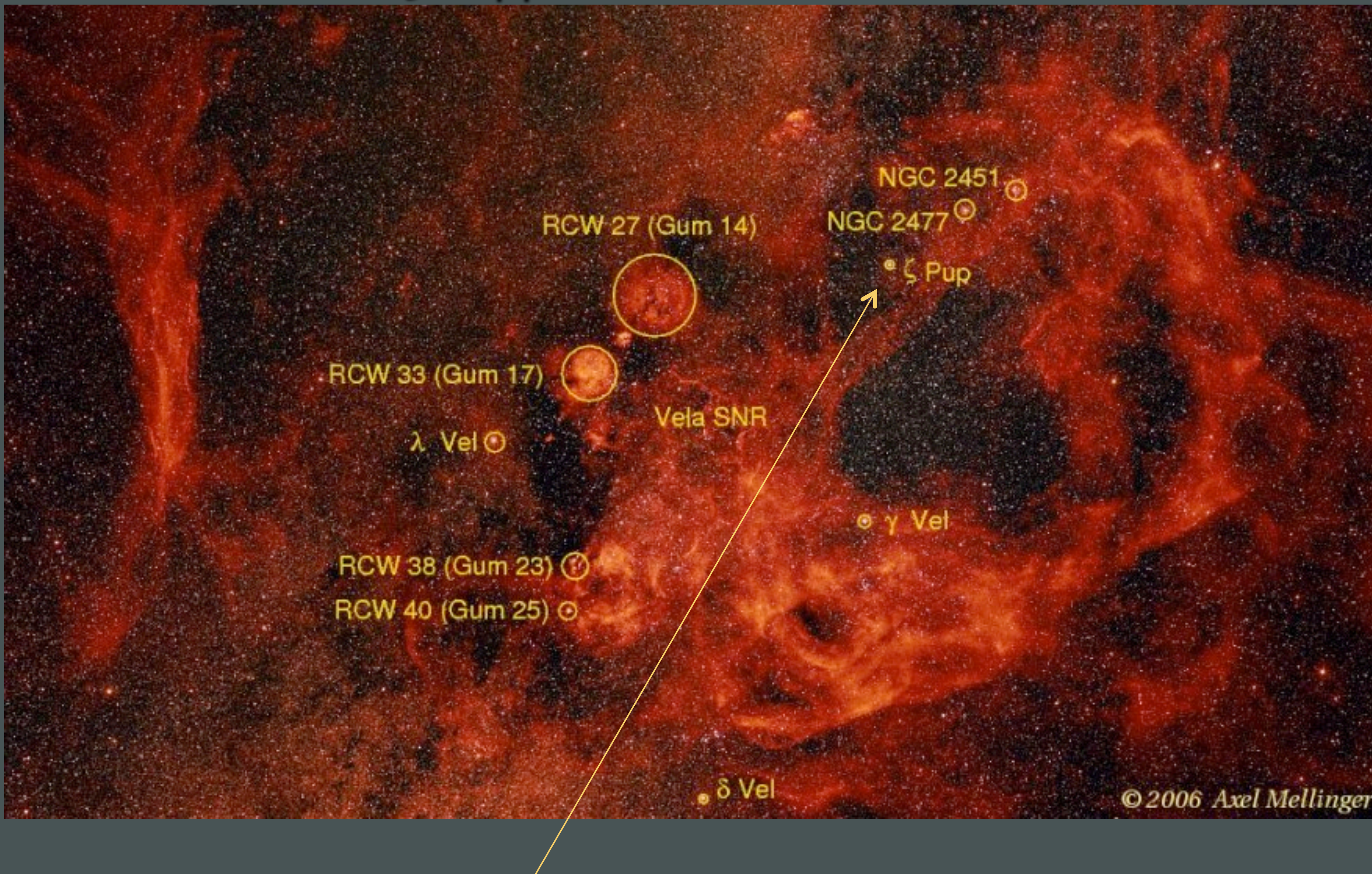
Radiation line driving is inherently unstable:
shock-heating and X-ray emission
Owocki, Castor, & Rybicki 1988

Predictions of the rad-hydro wind simulations:

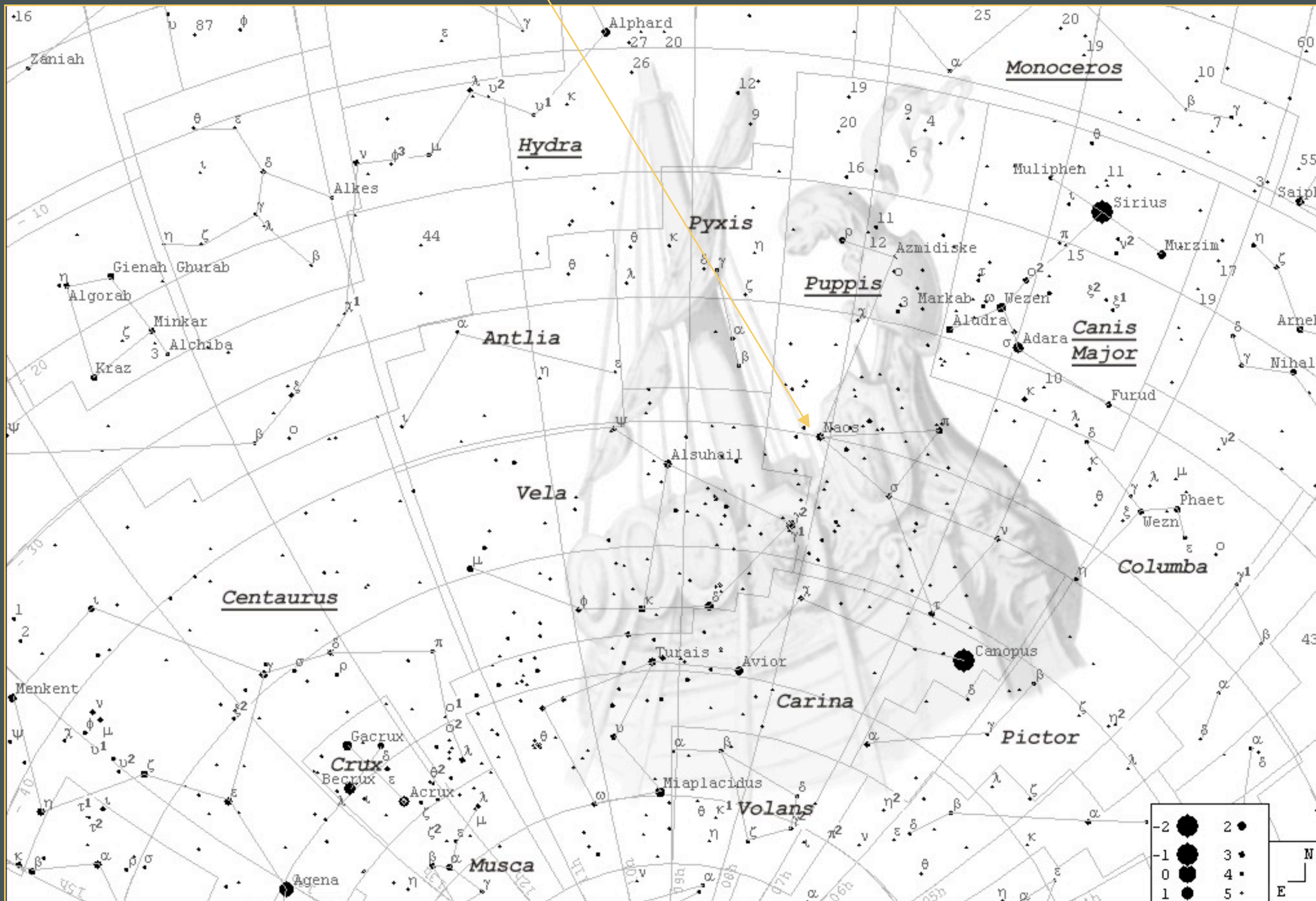
1. Significant Doppler broadening of x-ray emission lines due to bulk motion of the wind flow (1a. Shock onset several tenths R_* above the surface)
2. Bulk of the wind is cold and unshocked – source of attenuation of the X-rays.



ζ Puppis in the Gum Nebula

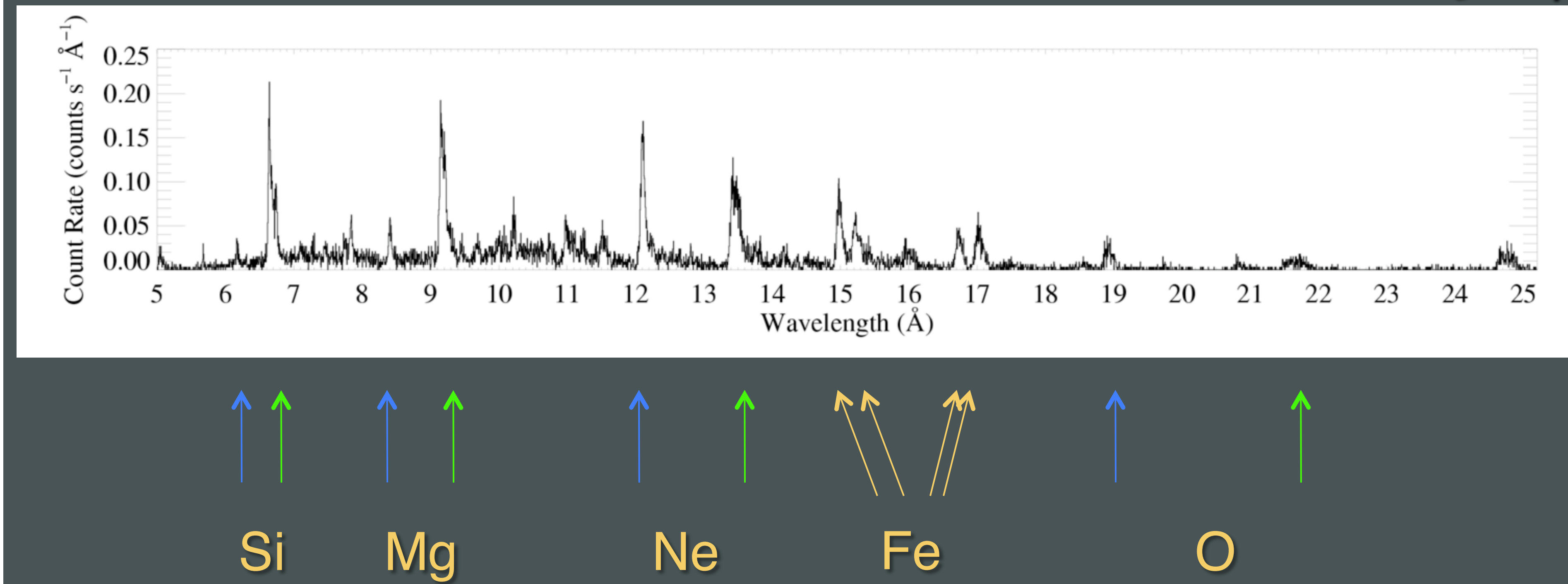


ζ Puppis: 50 M_{sun}, 10^6 L_{sun}



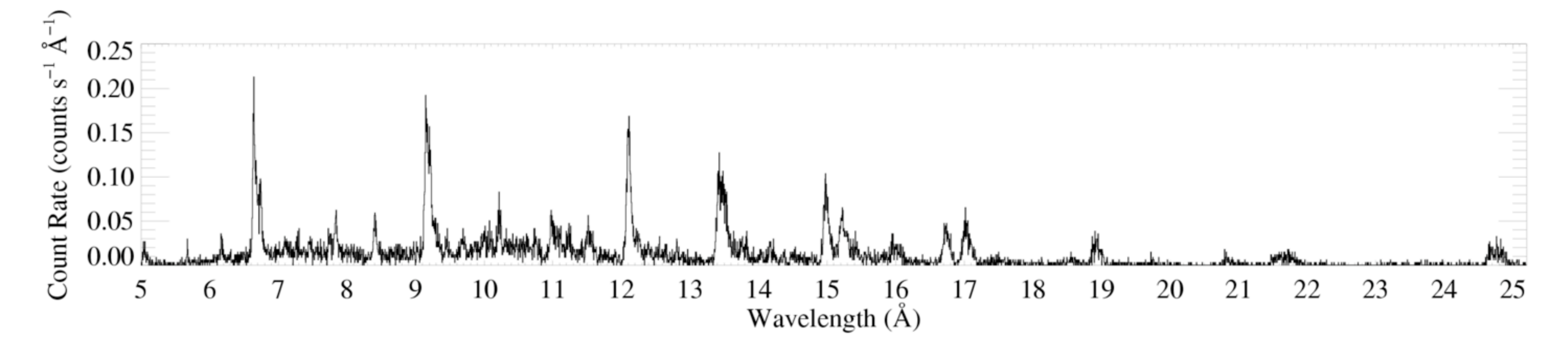
Chandra HETGS/MEG spectrum
(R ~ 1000 ~ 300 km s^{-1})

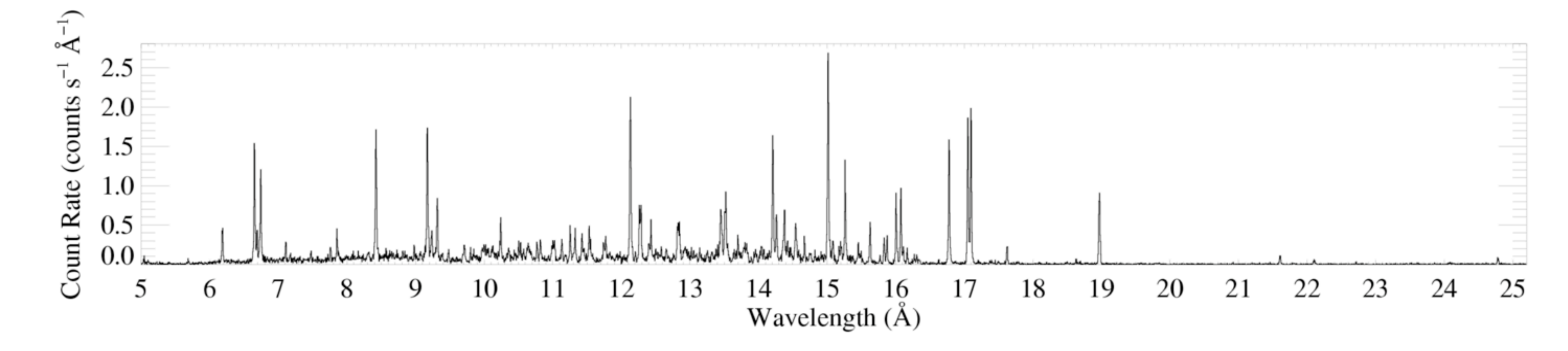
ζ Pup



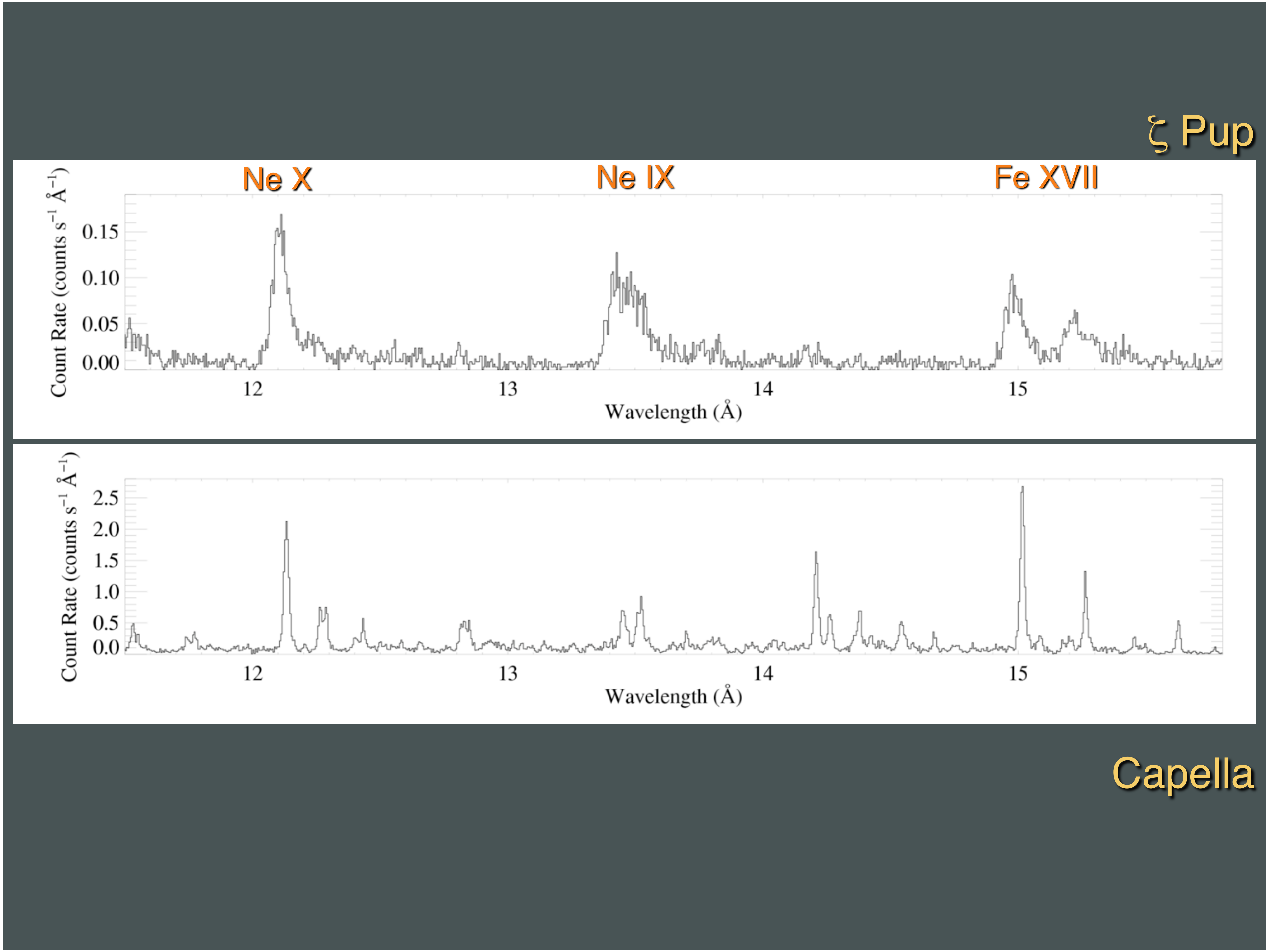
H-like
He-like

ζ Pup

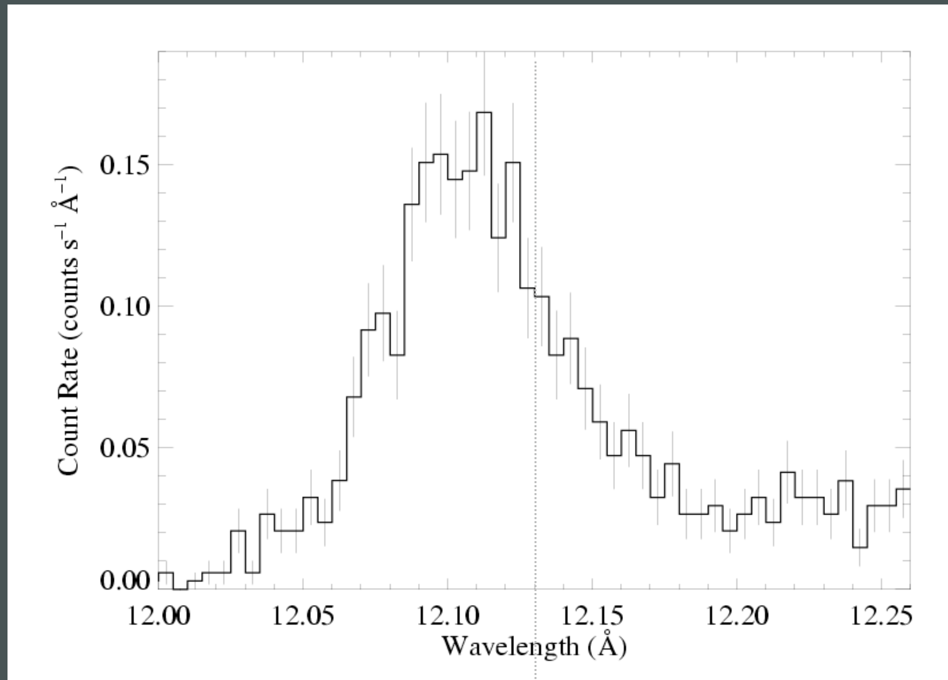




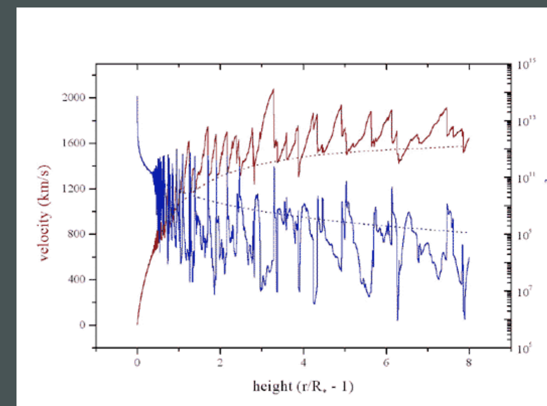
Low-mass star (Capella) for comparison

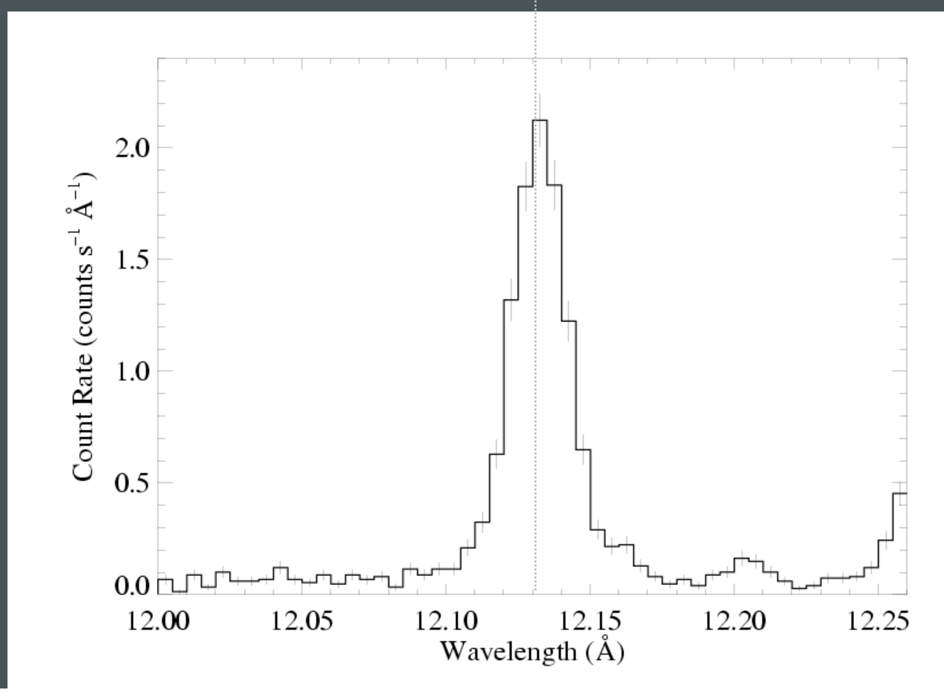


ζ Pup
Ne X
Ne IX
Fe XVII
Count Rate (counts s^{-1} Å^{-1})
0.15
0.10
0.05
0.00
12
13
14
15
Wavelength (Å)
Count Rate (counts s^{-1} Å^{-1})
2.5
2.0
1.5
1.0
0.5
0.0
12
13
14
15
Wavelength (Å)
Capella

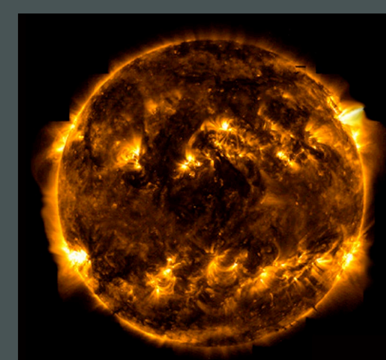


ζ Pup
massive

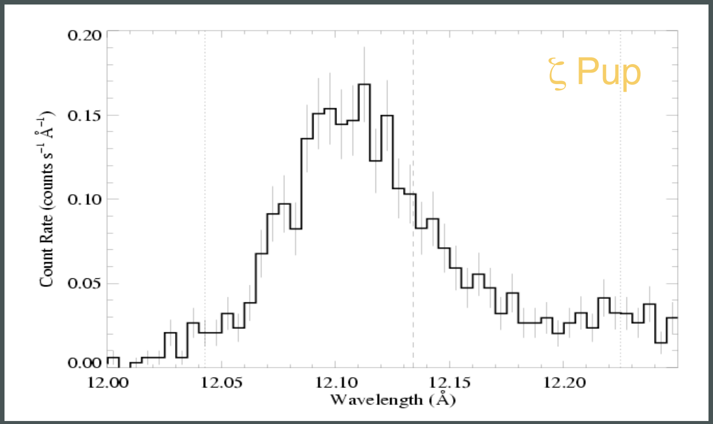




Capella
low mass

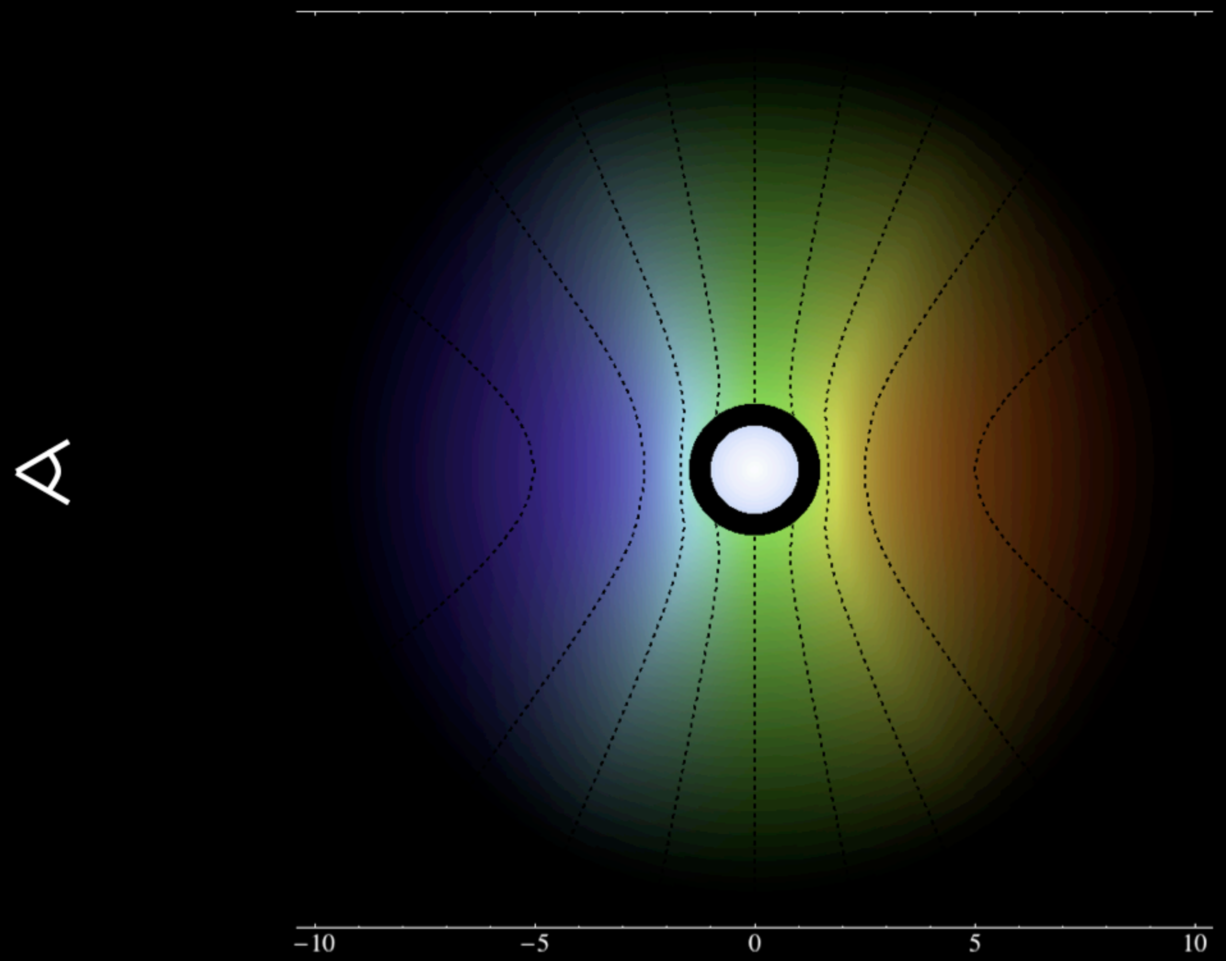


The x-ray emission lines are broad: agreement with rad hydro simulations

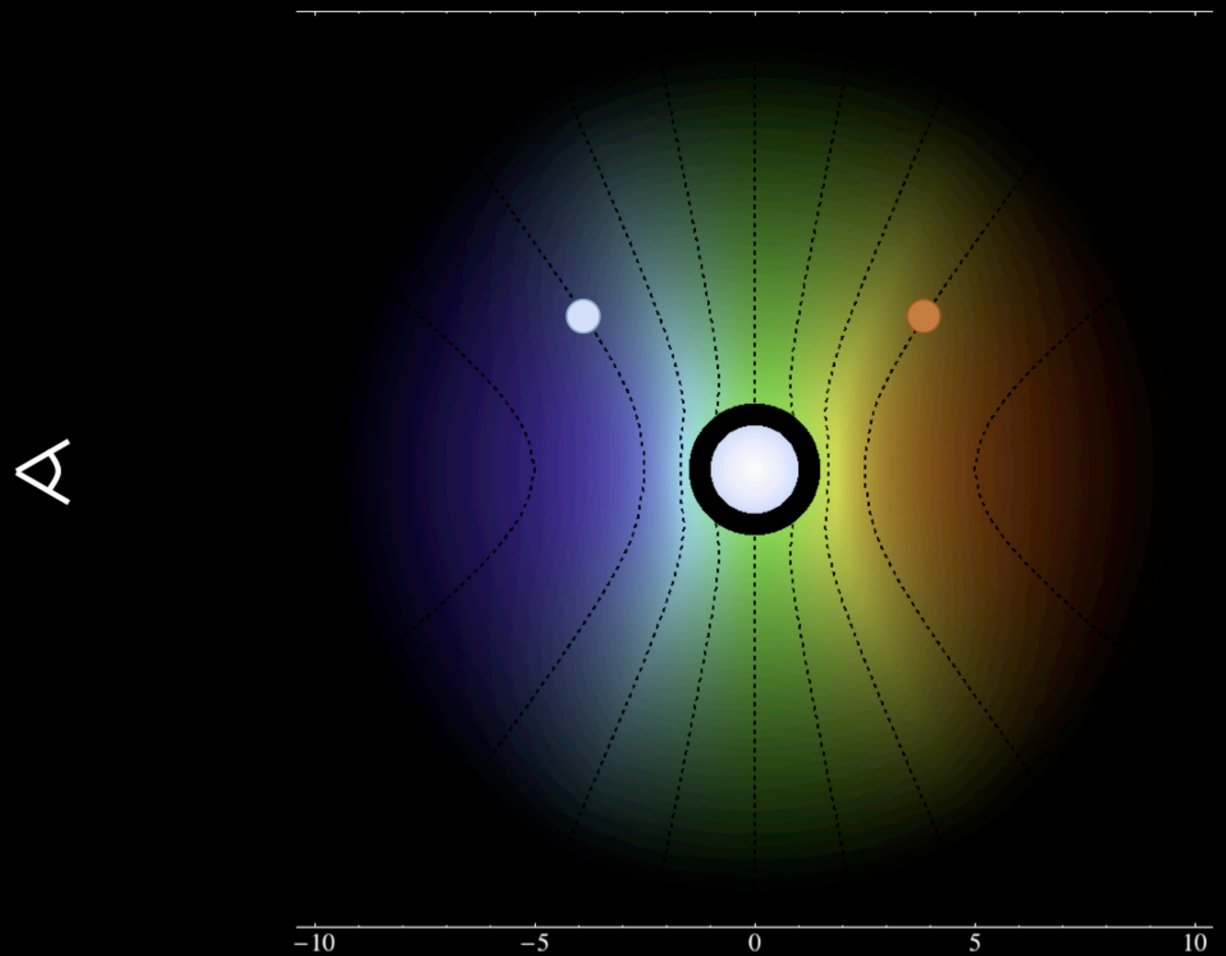


But… they're also blue shifted and asymmetric
Is this predicted by the wind shock scenario?

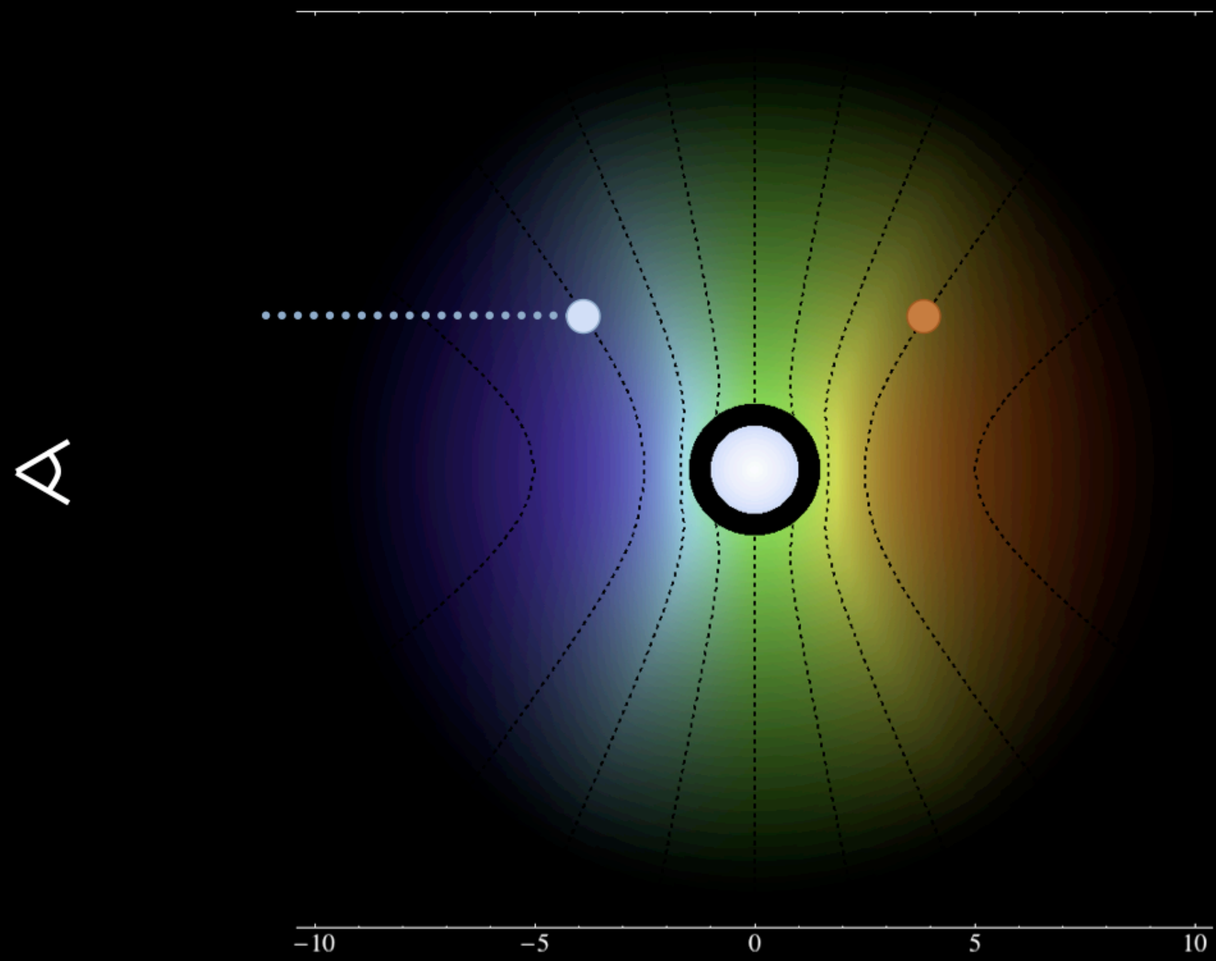
Wind Profile Model



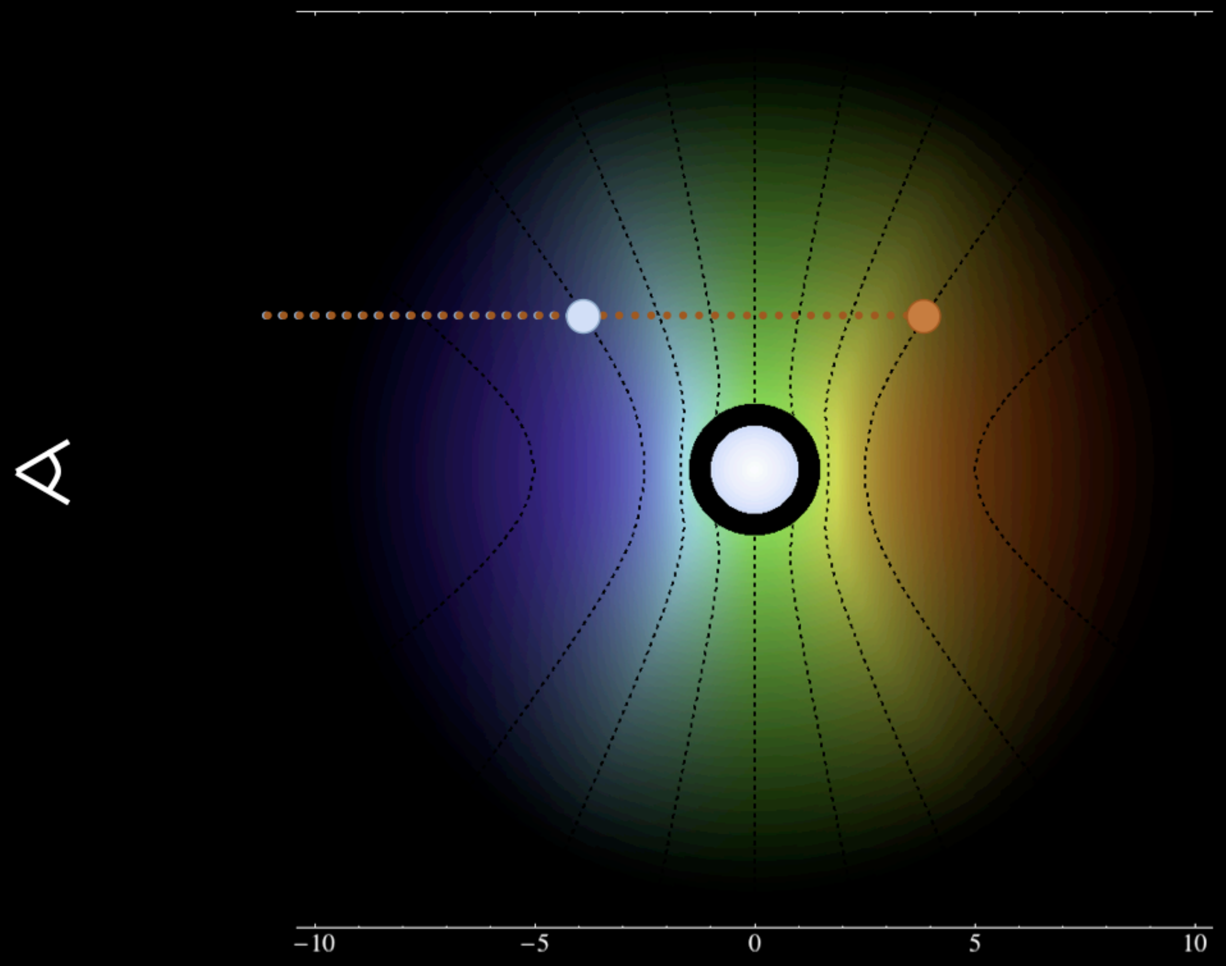
Wind Profile Model



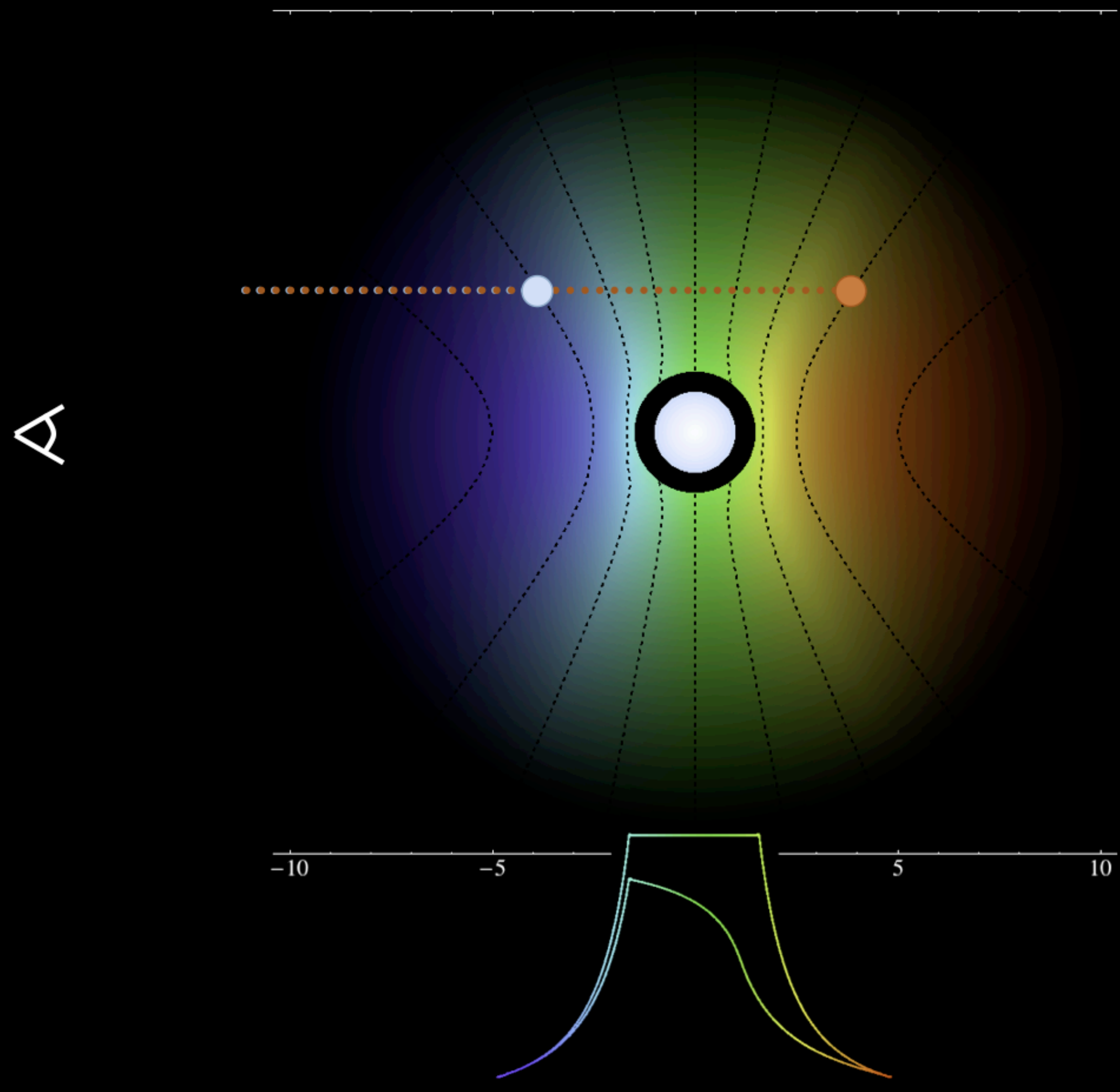
Wind Profile Model



Wind Profile Model

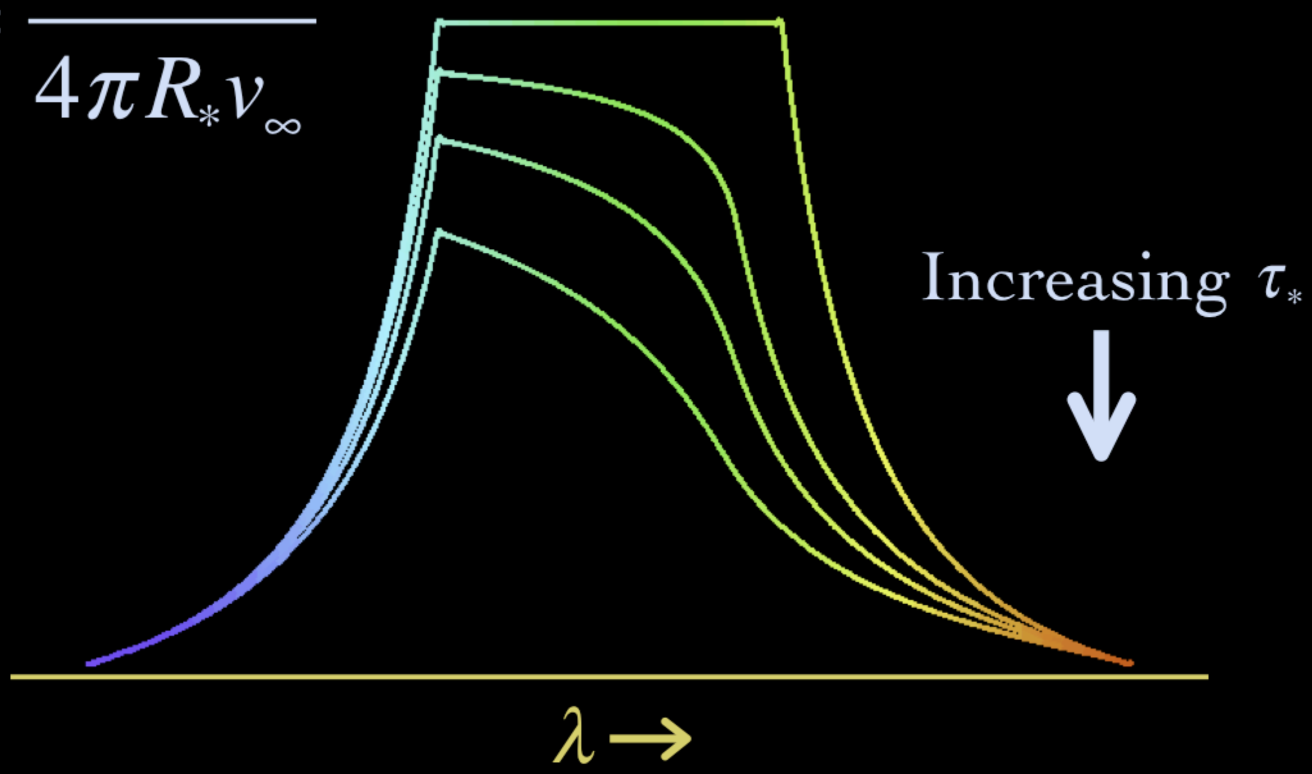


Wind Profile Model



Wind Profile Model

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



opacity of the cold wind component

wind mass-loss rate

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

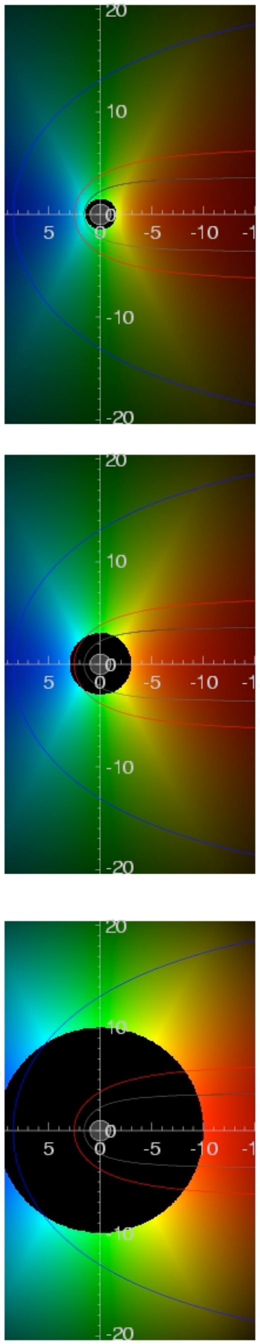
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

radius of the star

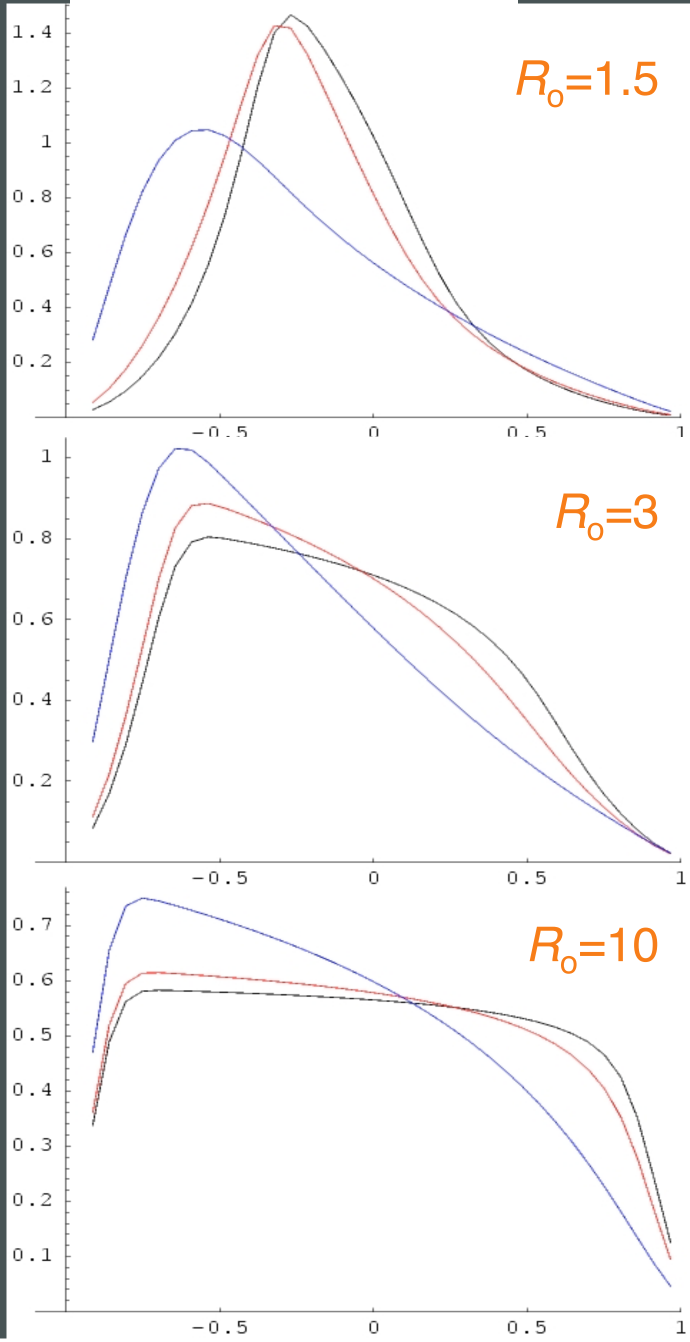
wind terminal velocity

The basic wind-profile model

τ=1 contours



$\tau_*=1,2,8$



key parameters: $\mathbf{R_o}$ & τ_*

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

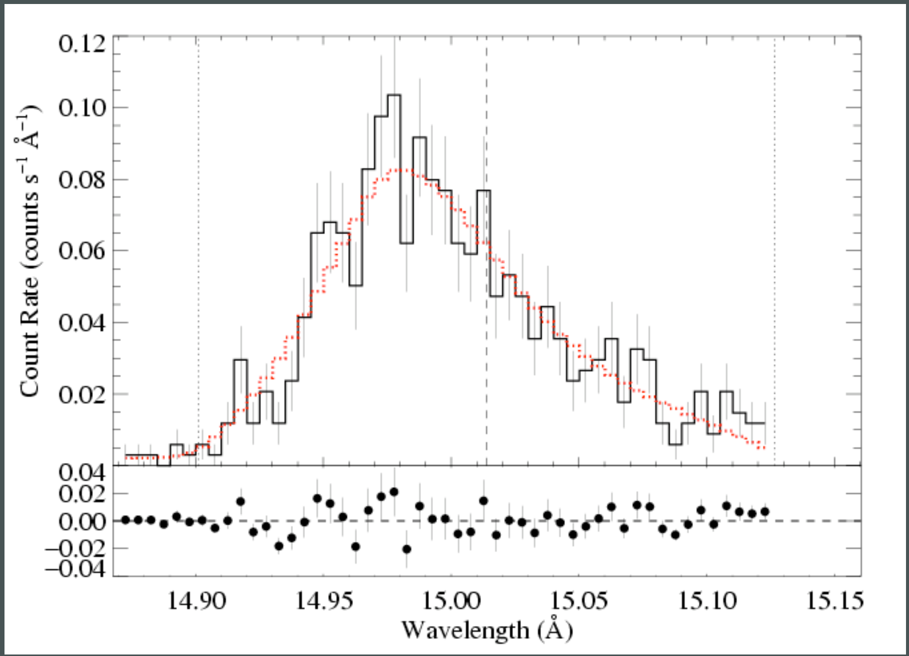
= 0 otherwise

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

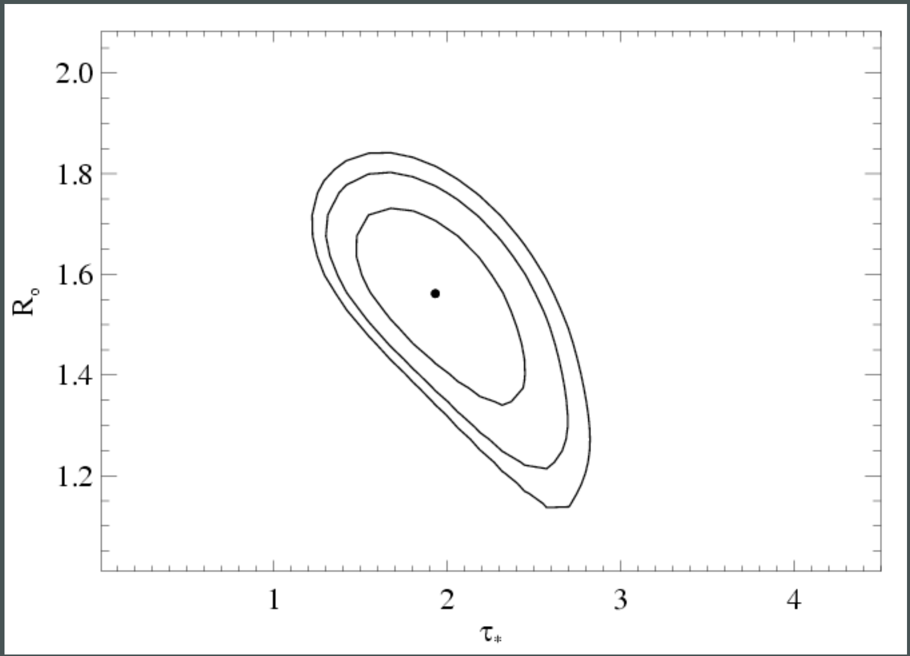
$$\tau_* \equiv \frac{\kappa \dot{M}}{4 \pi R_* v_\infty}$$

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

And find a best-fit τ_* and R_o & place confidence limits on these fitted parameter values

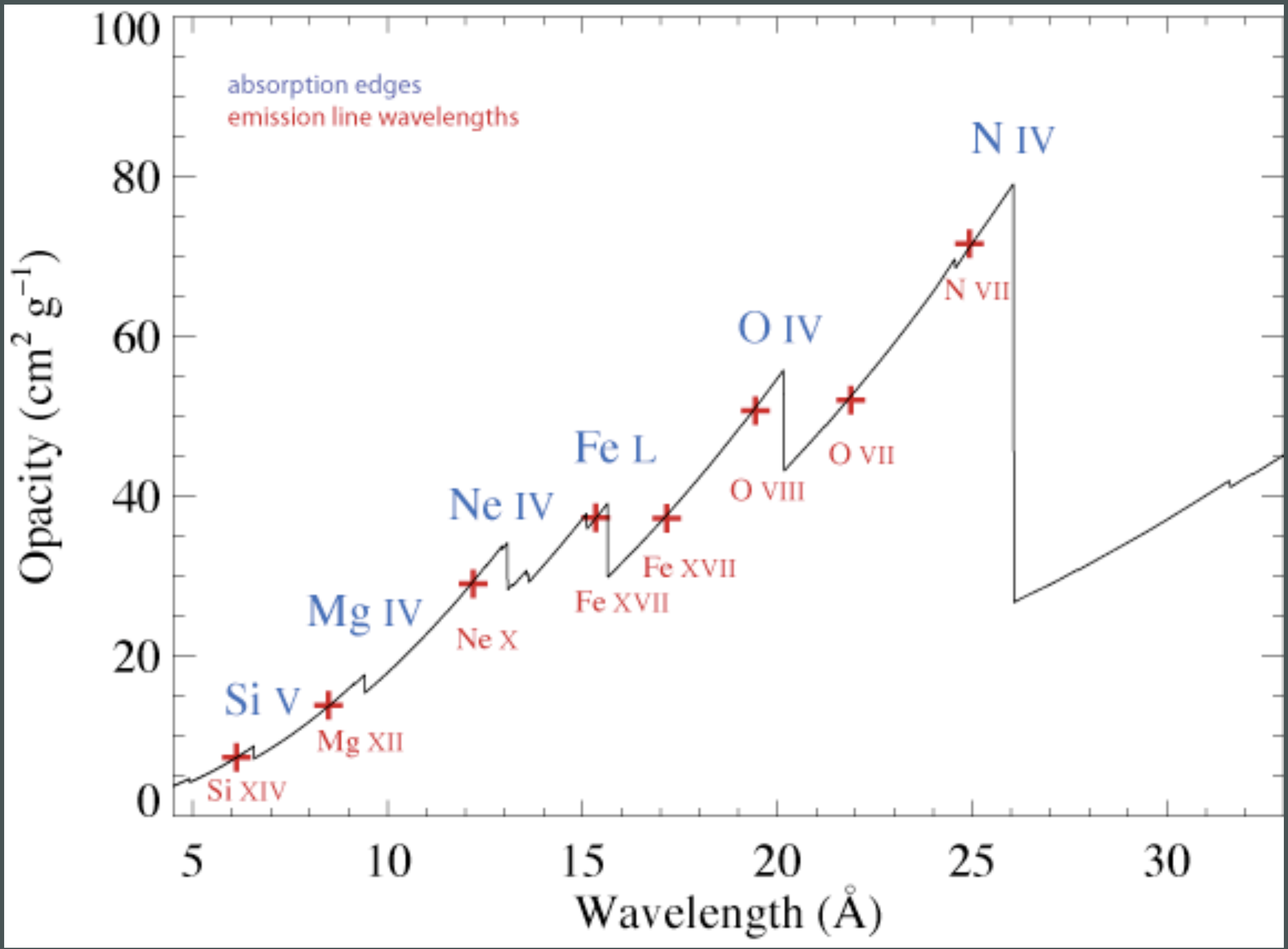


Fe XVII



68, 90, 95% confidence limits

Wind opacity: photoelectric absorption

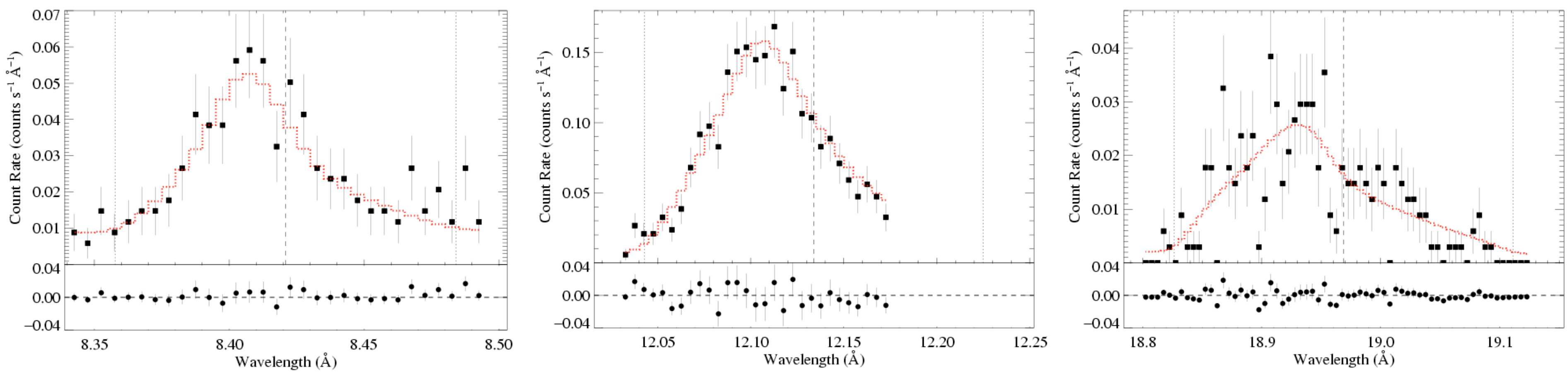


Abundances; ionization balance; atomic cross sections

Verner & Yakovlev 1996

ζ Pup: three emission lines

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

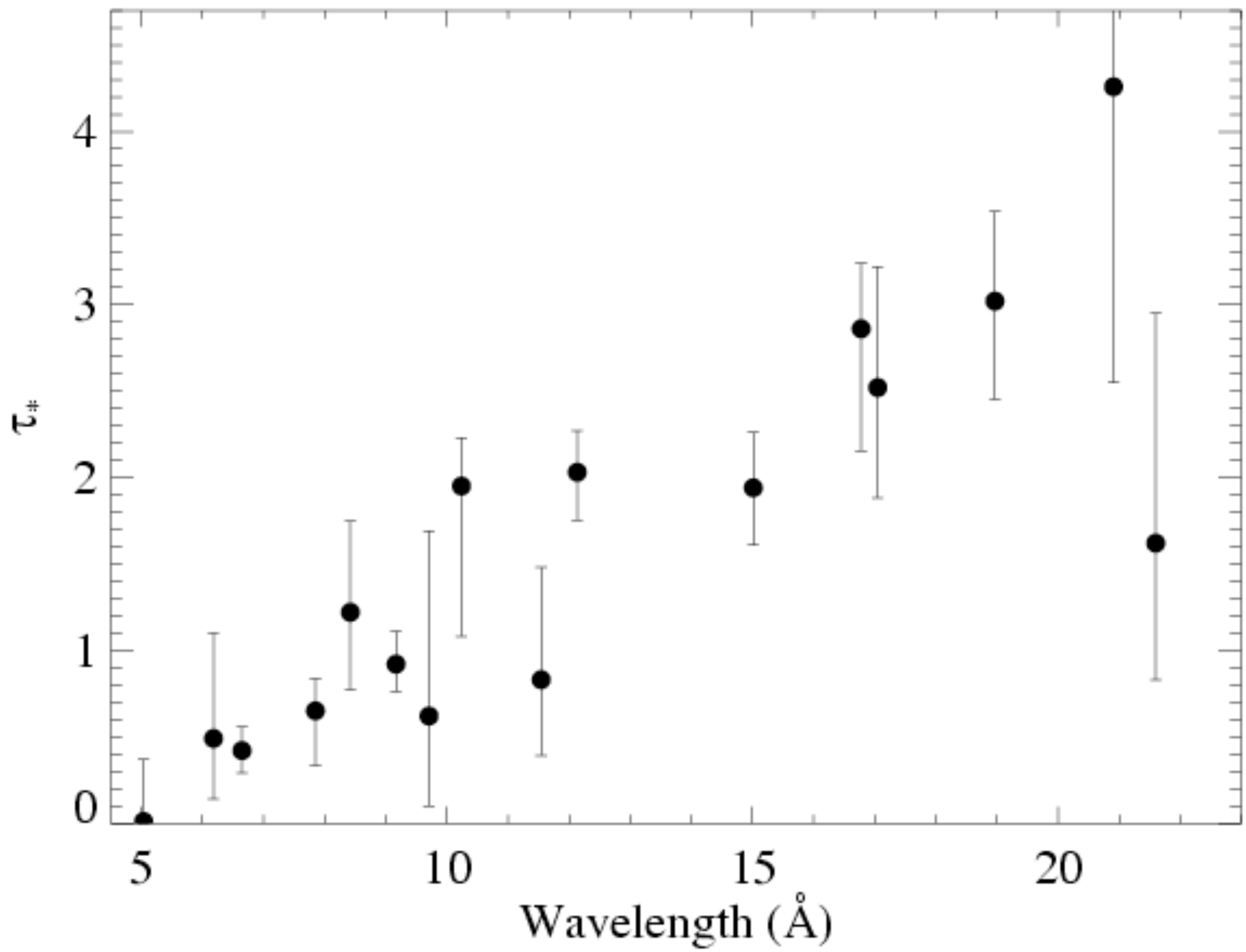


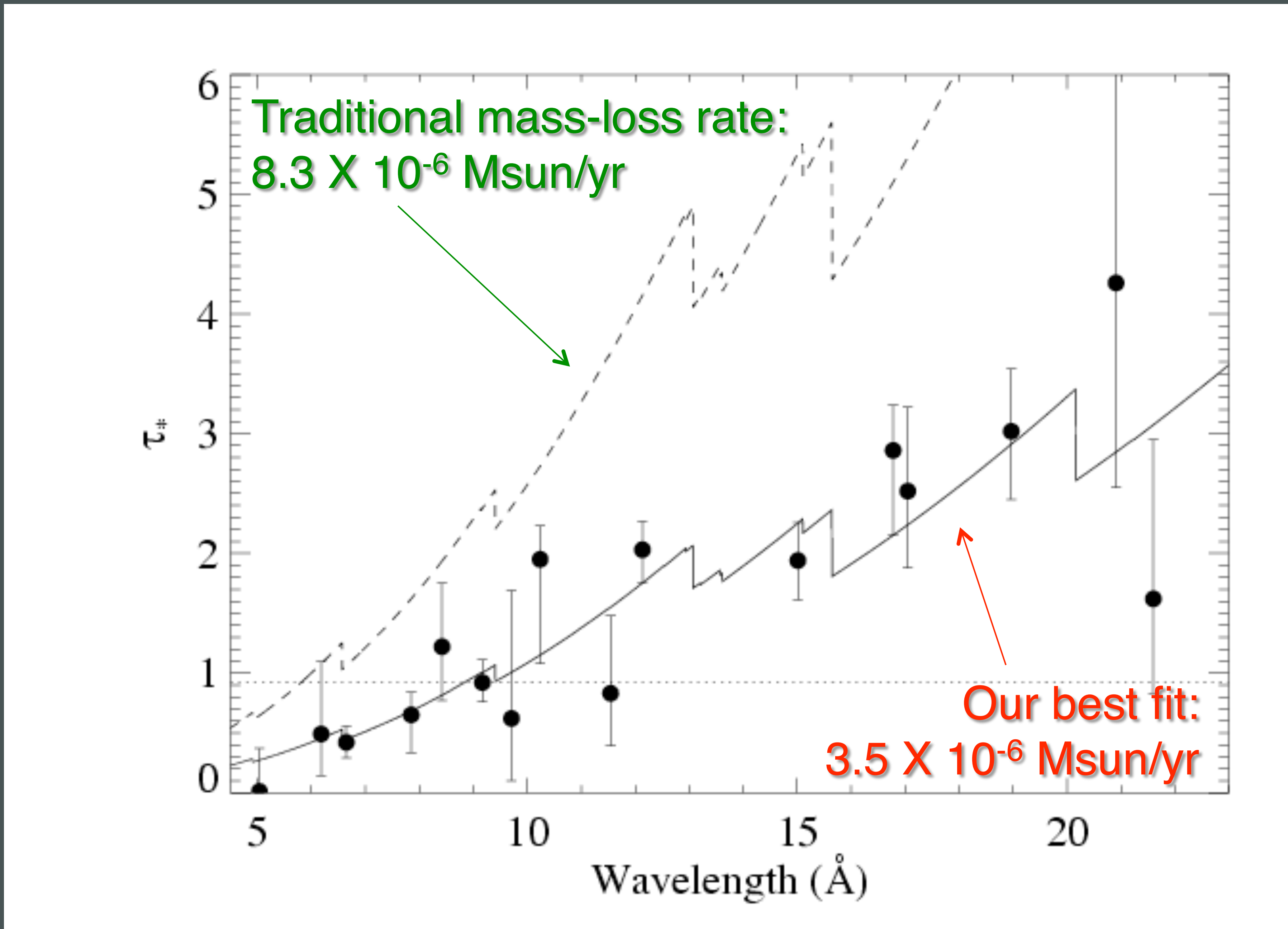
$\tau_* = 1$ | $\tau_* = 2$ | $\tau_* = 3$

Recall:

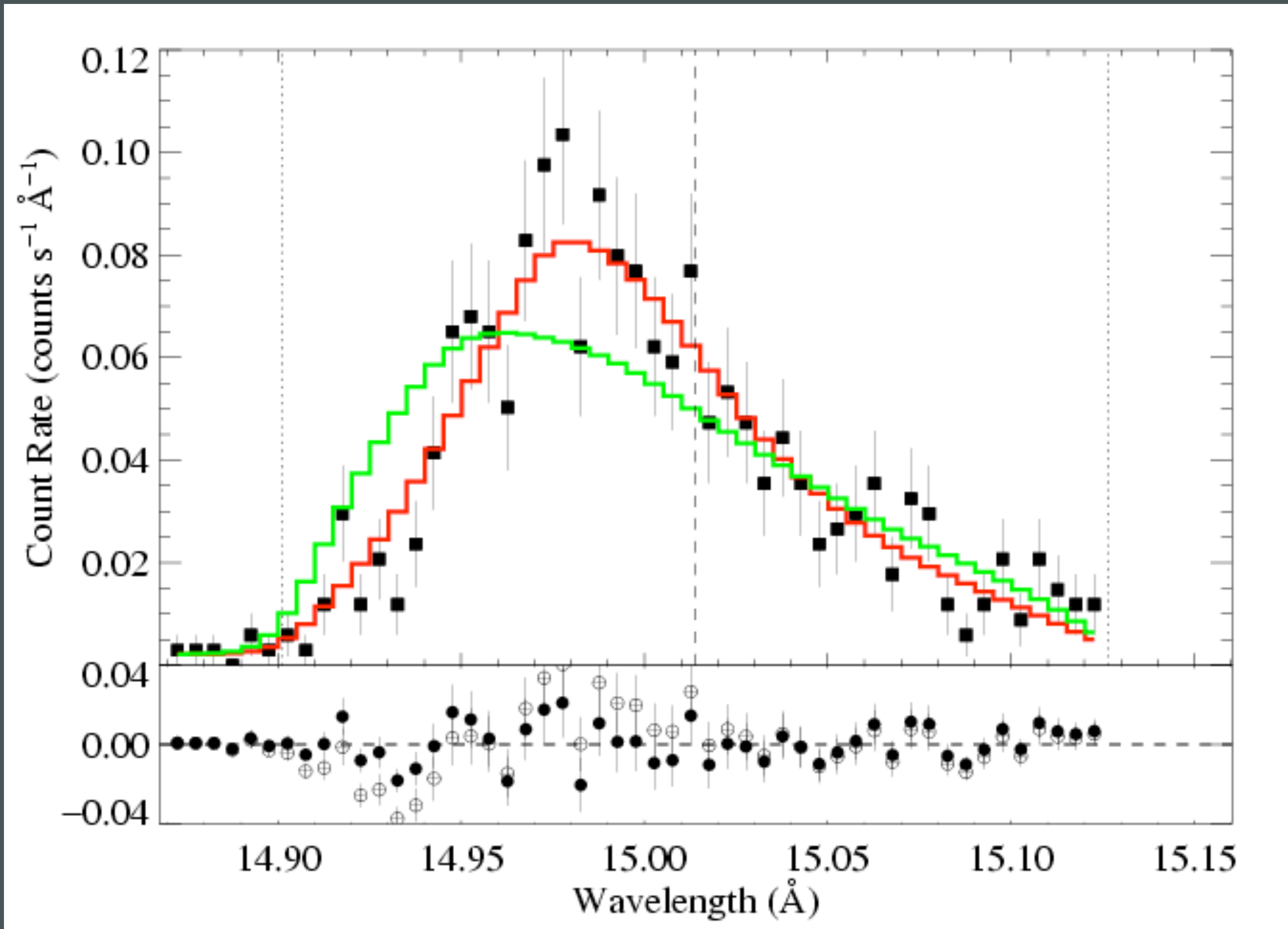
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

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



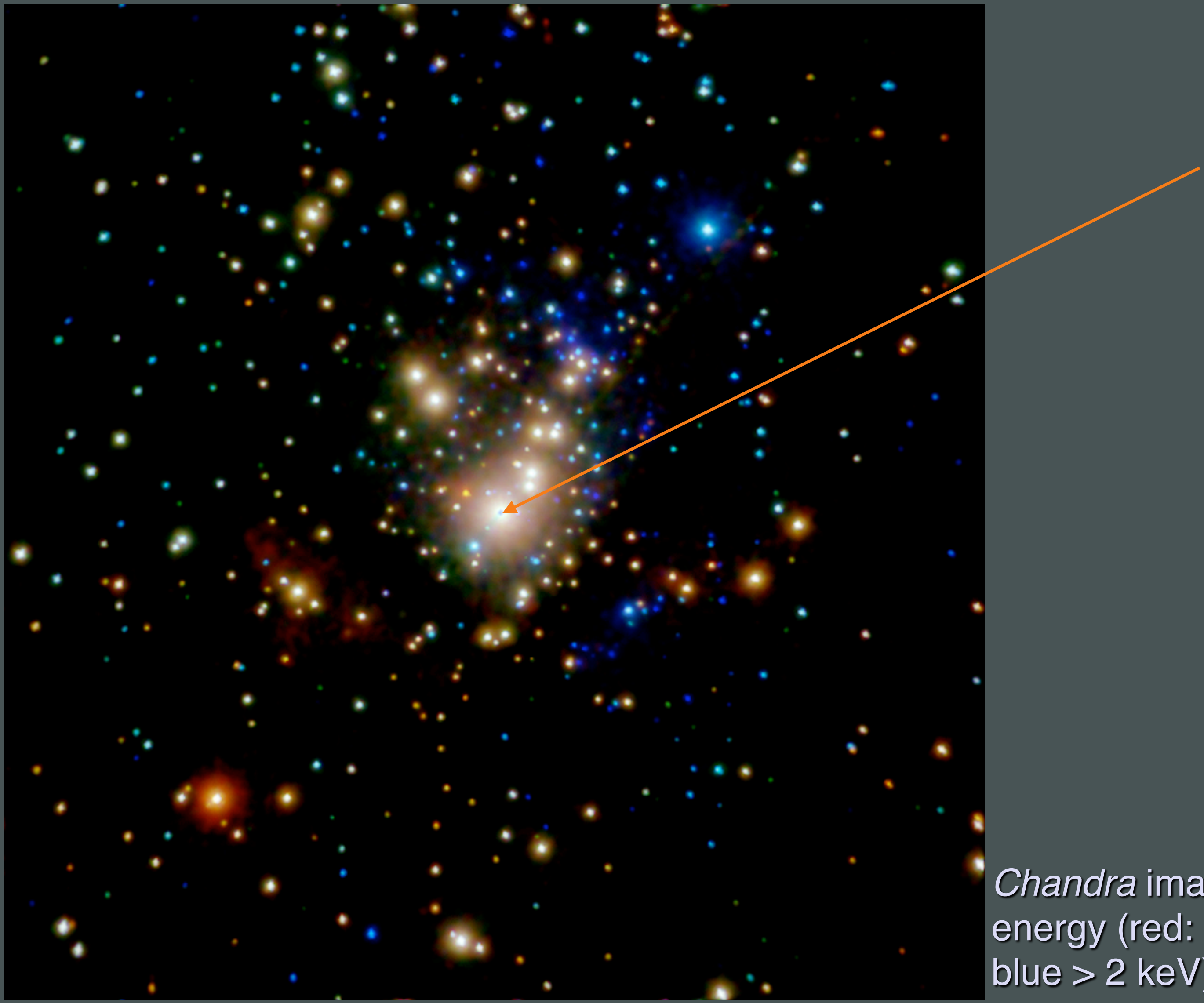


Traditional mass-loss rate:
8.3 X 10-6 Msun/yr
Our best fit:
3.5 X 10-6 Msun/yr
τ*
Wavelength (Å)
0
1
2
3
4
5
6
5
10
15
20


0.12
0.10
0.08
0.06
0.04
0.02
Count Rate (counts s^{-1} Å^{-1})
0.04
0.00
−0.04
14.90
14.95
15.00
15.05
15.10
15.15
Wavelength (Å)

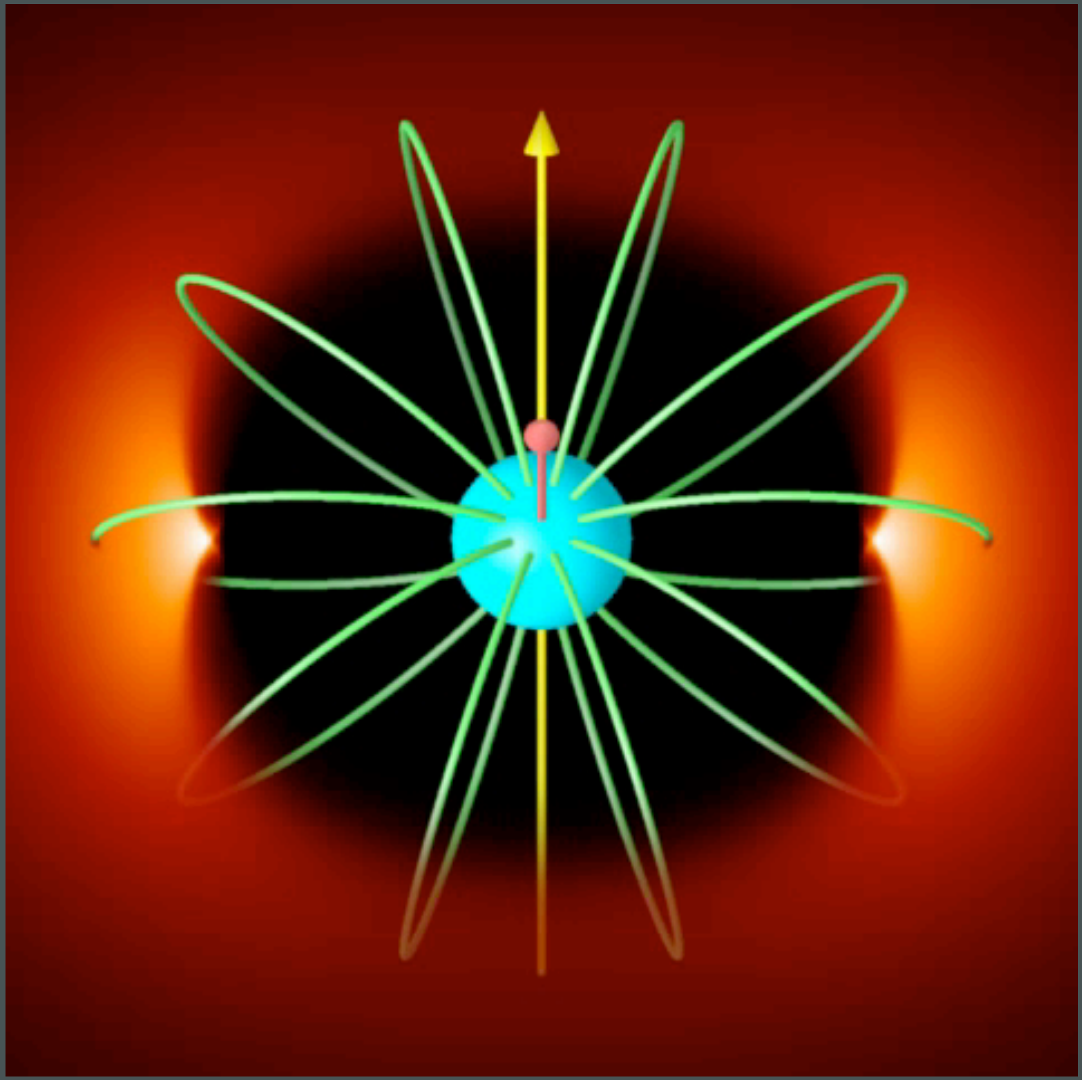
Part 2: Magnetically Channeled Winds

The central star in the Orion Nebula Cluster - θ^1 Ori C - is a source of strong and relatively hard x-rays



Chandra image: color coded by photon energy (red: <1keV; green 1 to 2 keV; blue > 2 keV)

Recently discovered dipole magnetic field of > 1 kG : Zeeman Doppler spectroscopy (Wade et al. 2006)



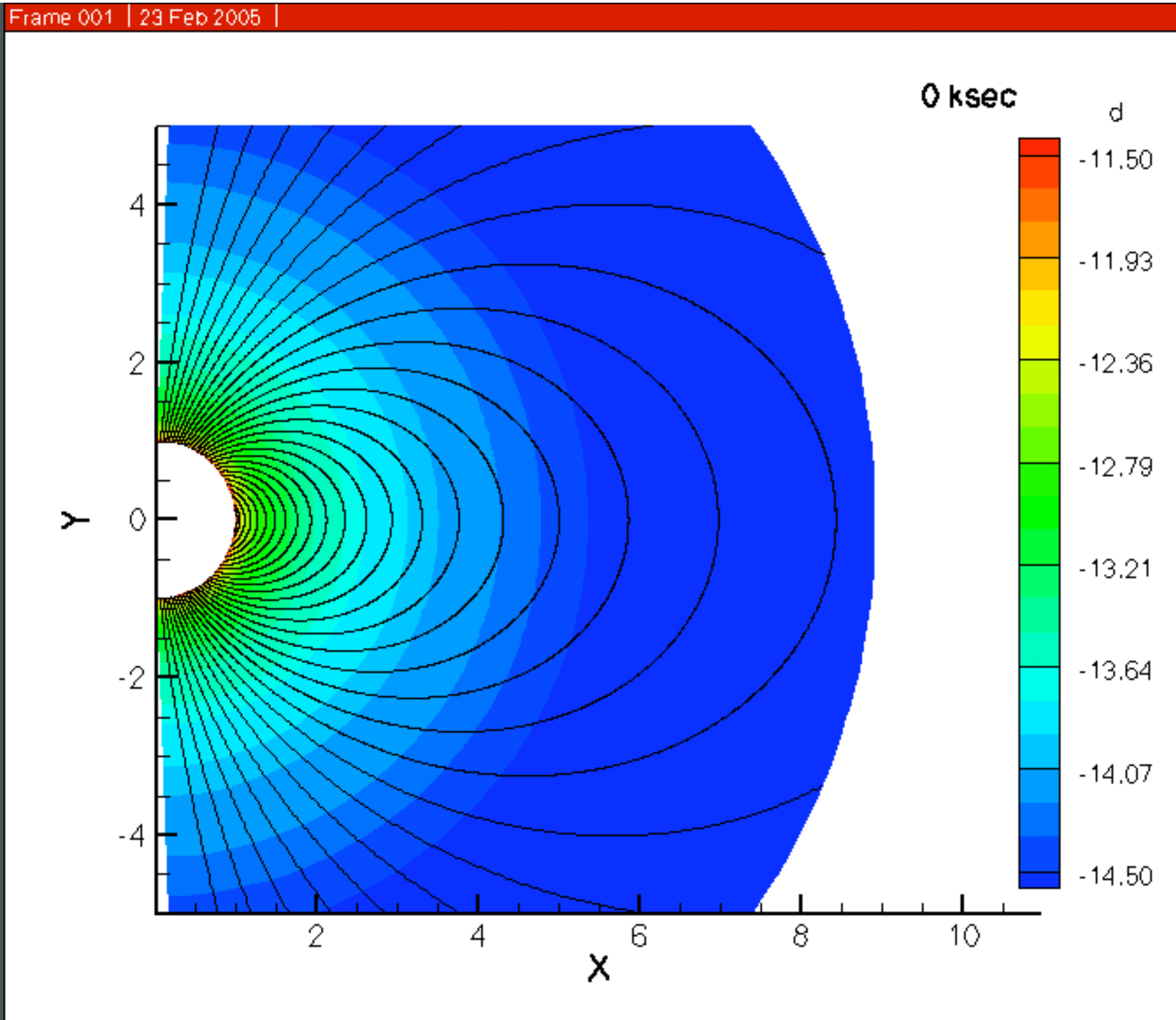
Simulation/visualization courtesy R. Townsend

Movie available at astro.swarthmore.edu/~cohen/presentations/apip09/rrm-o25-i75-b60-redt.avi

This field confines and channels the stellar wind out to several stellar radii –

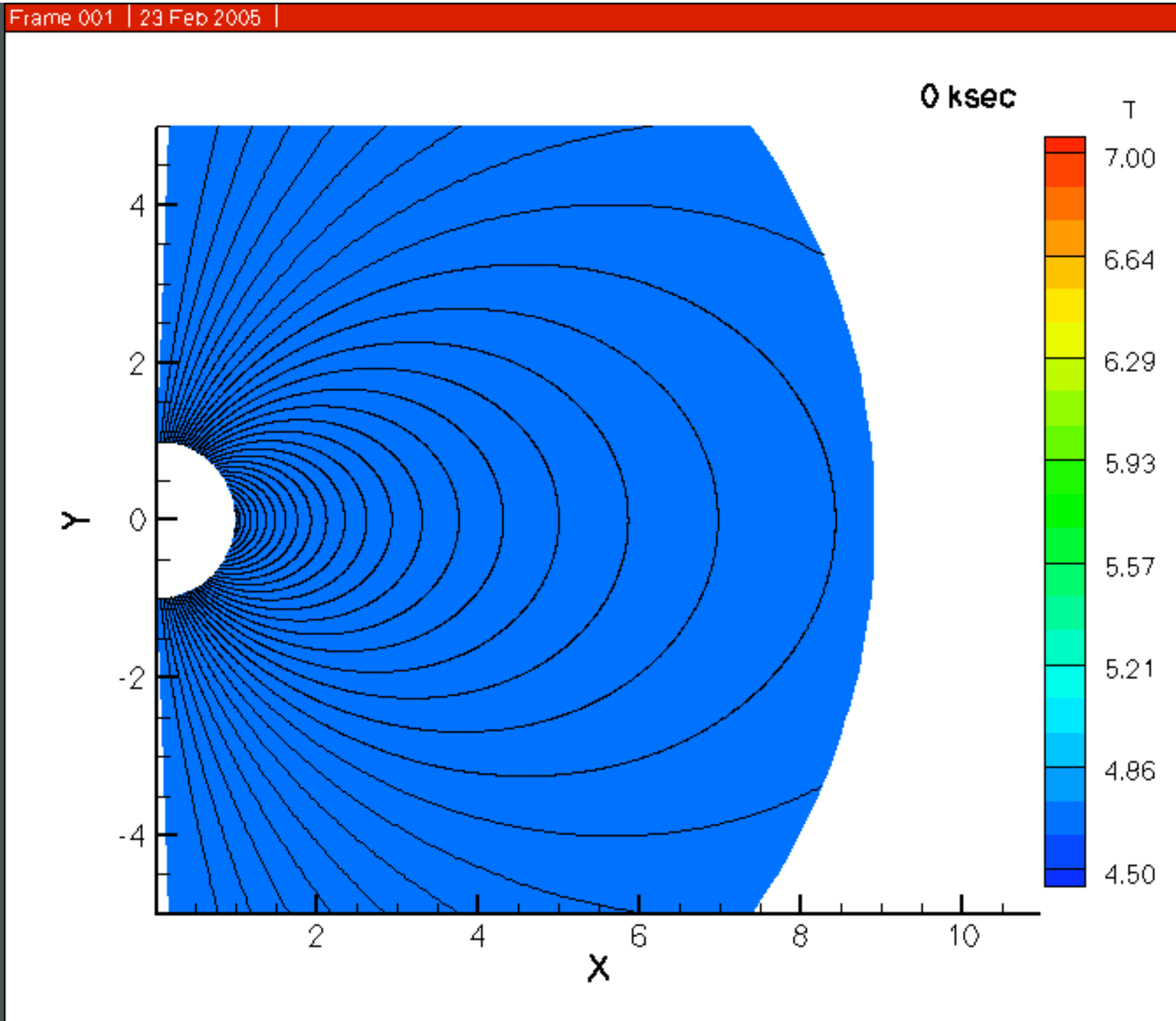
what is the effect?

…MHD simulations (ZEUS, 2-D)



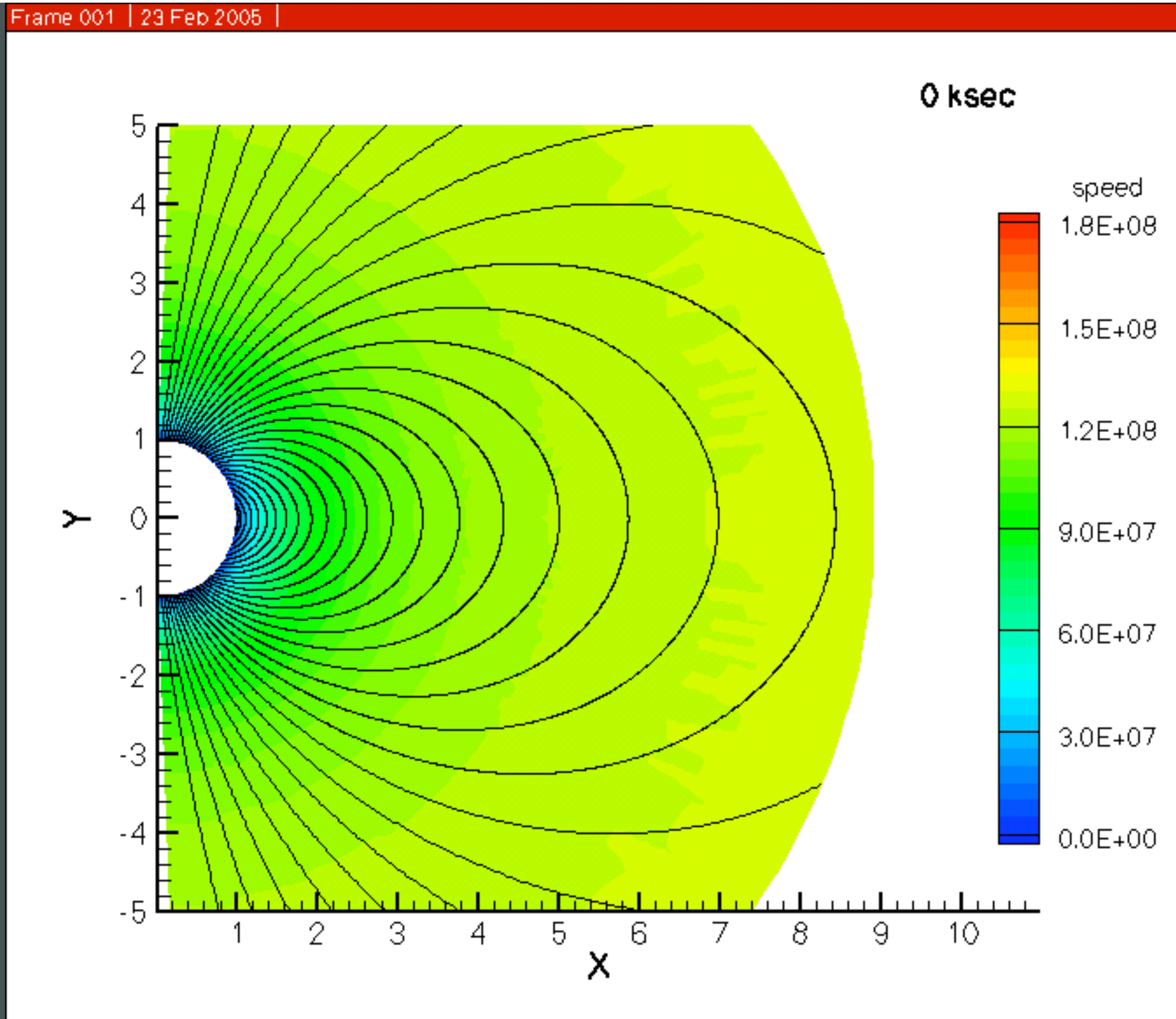
Simulation/visualization courtesy A. ud-Doula

Movie available at astro.swarthmore.edu/~cohen/presentations/apip09/t1oc-lowvinf-logd.avi



Simulation/visualization courtesy A. ud-Doula

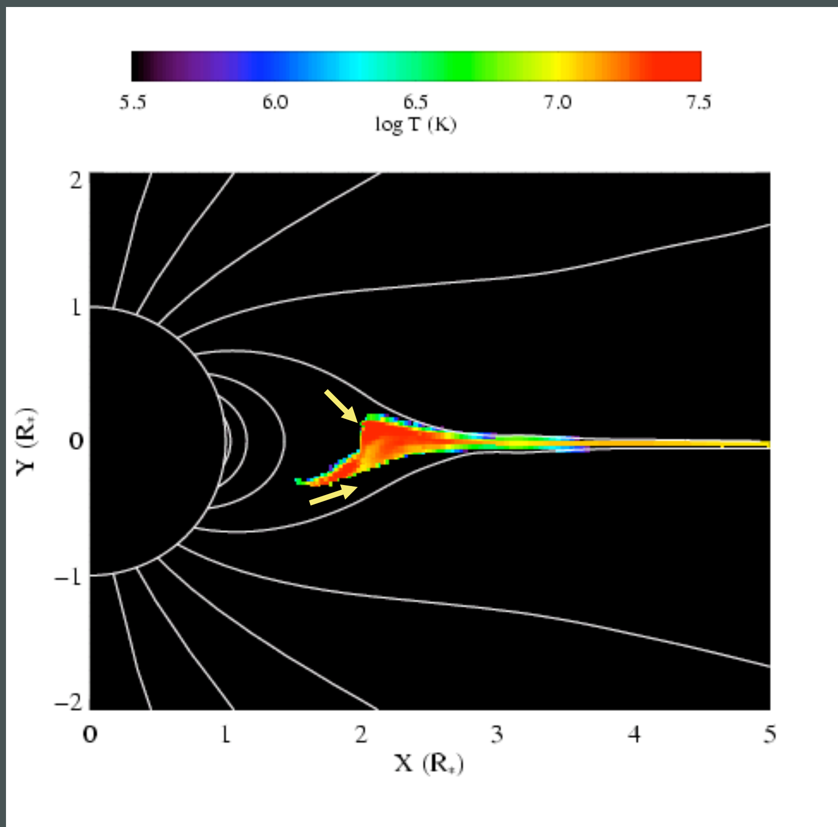
Movie available at astro.swarthmore.edu/~cohen/presentations/apip09/t1oc-lowvinf-logT.avi



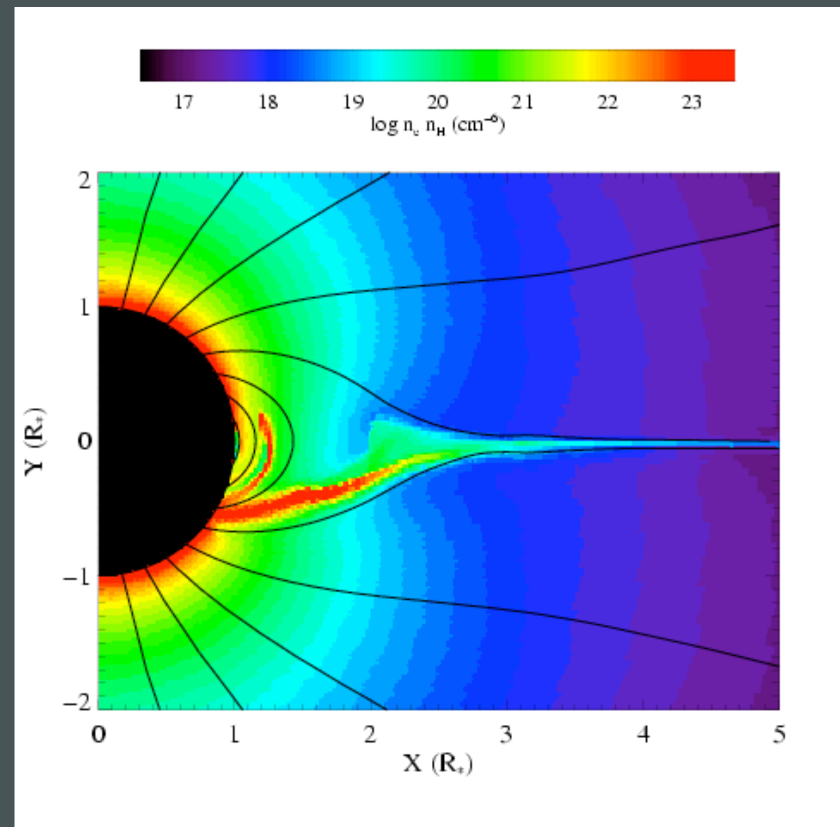
Simulation/visualization courtesy A. ud-Doula
Movie available at astro.swarthmore.edu/~cohen/presentations/apip09/t1oc-lowvinf-speed.avi

MHD simulations of magnetically channeled wind

temperature



emission measure



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

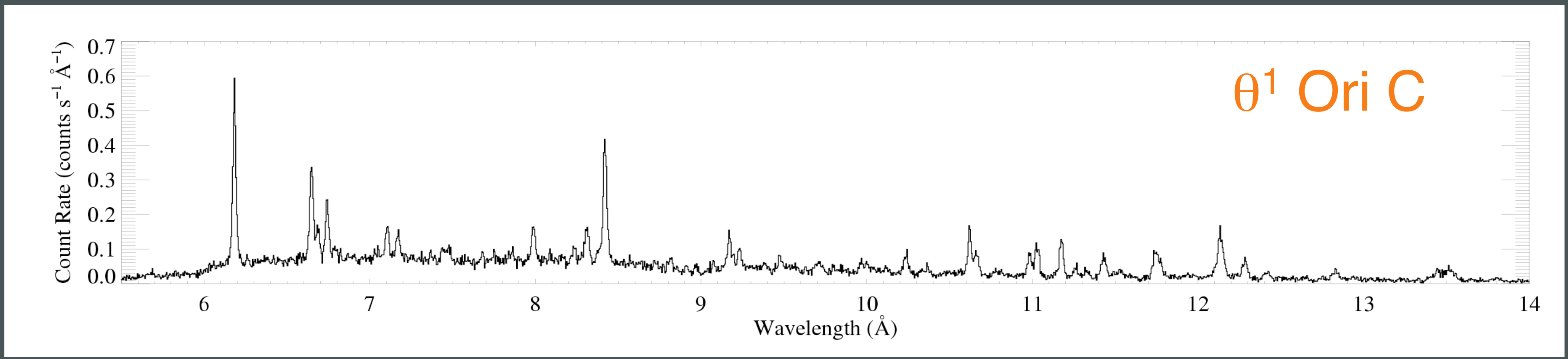
Channeled collision is close to head-on –

>1000 km s^{-1} : T > 10^7 K

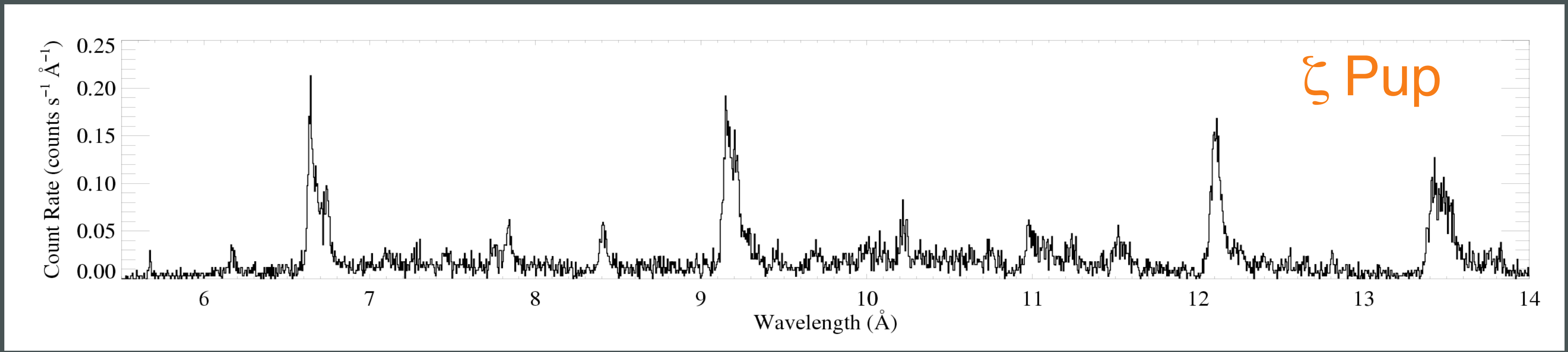
Predictions:

1. Shocks are strong – head-on – and so plasma is hotter;
2. Hot plasma is moving much slower (confinement);
3. Rotational modulation of X-ray flux;
4. Hot plasma is ~1 R_* above the surface.

Chandra grating spectra

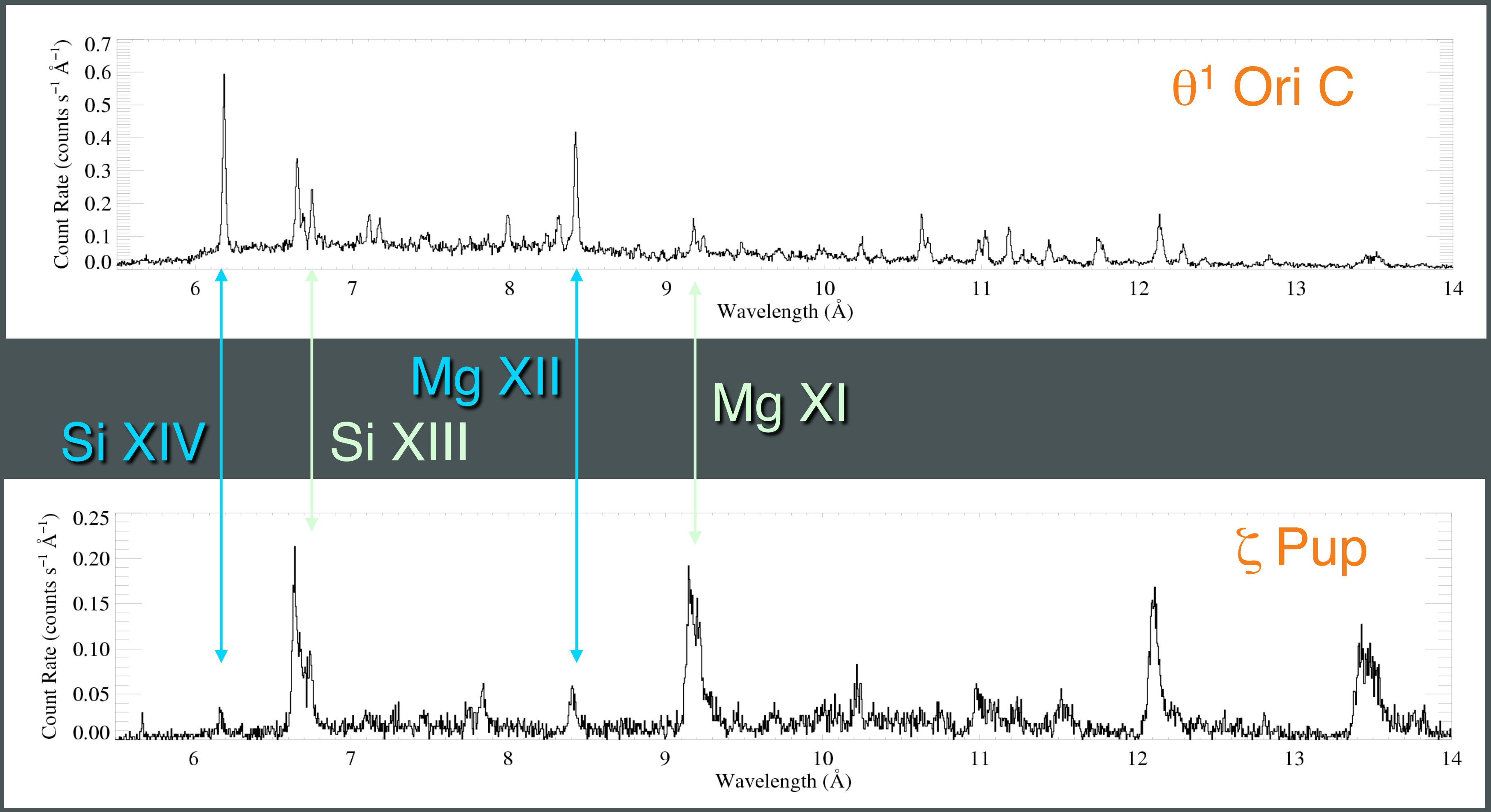


θ¹ Ori C: hotter plasma, narrower emission lines

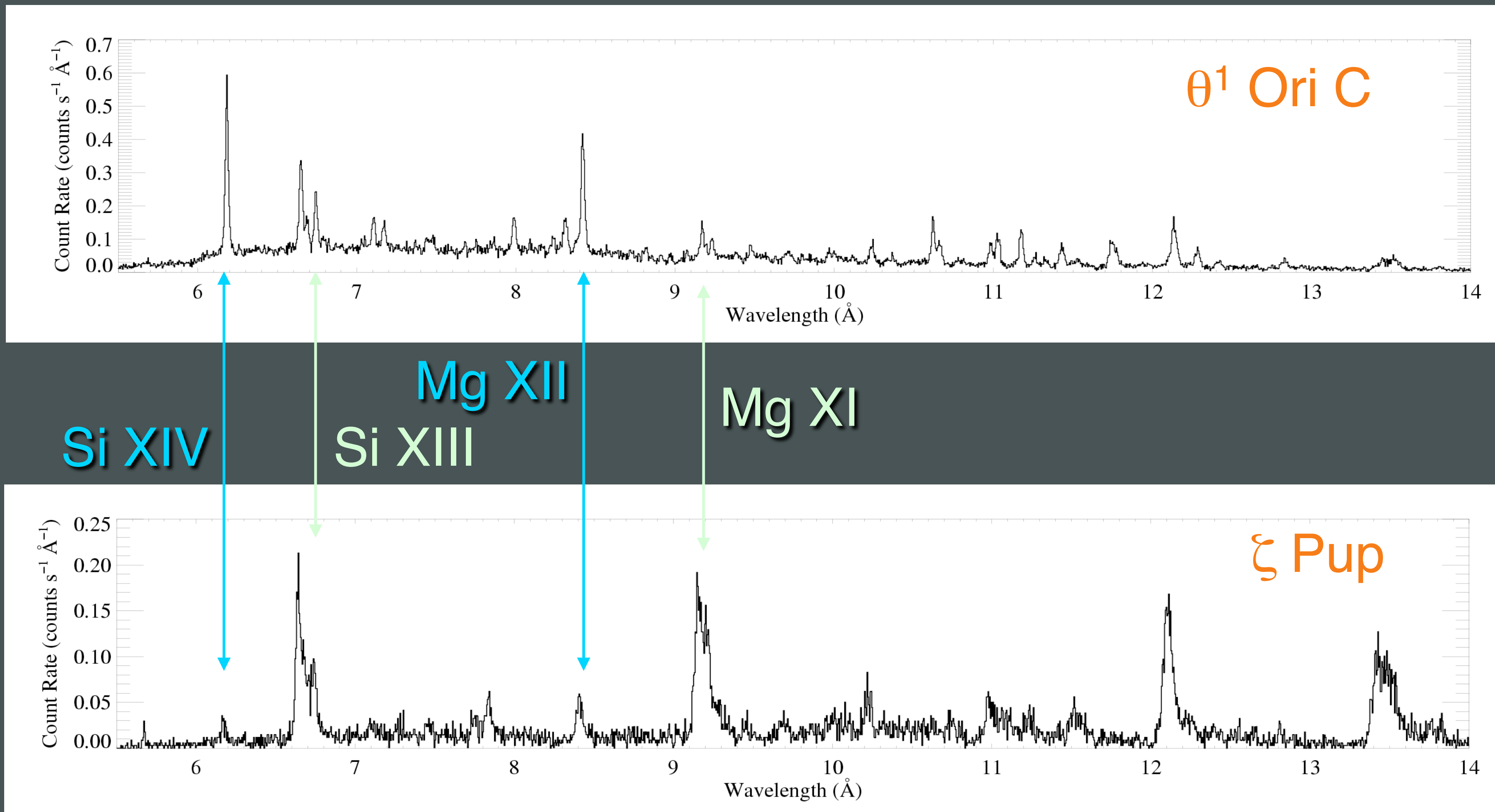


ζ Pup: cooler plasma, broad emission lines

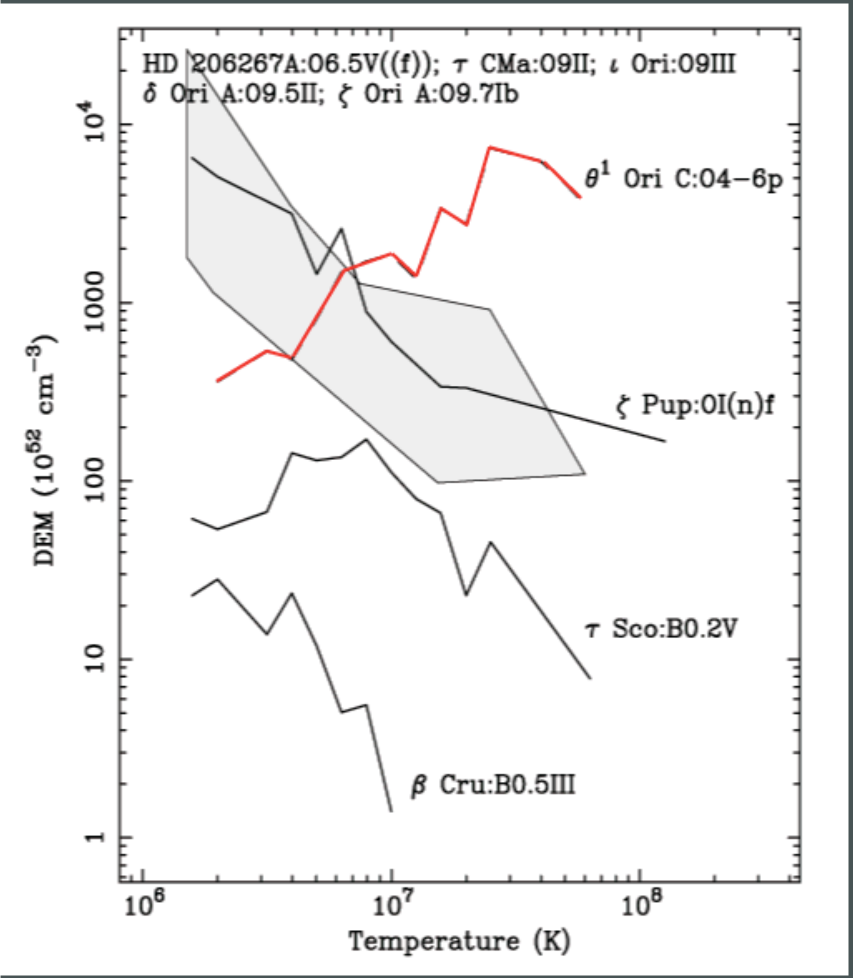
H-like/He-like ratio is temperature sensitive

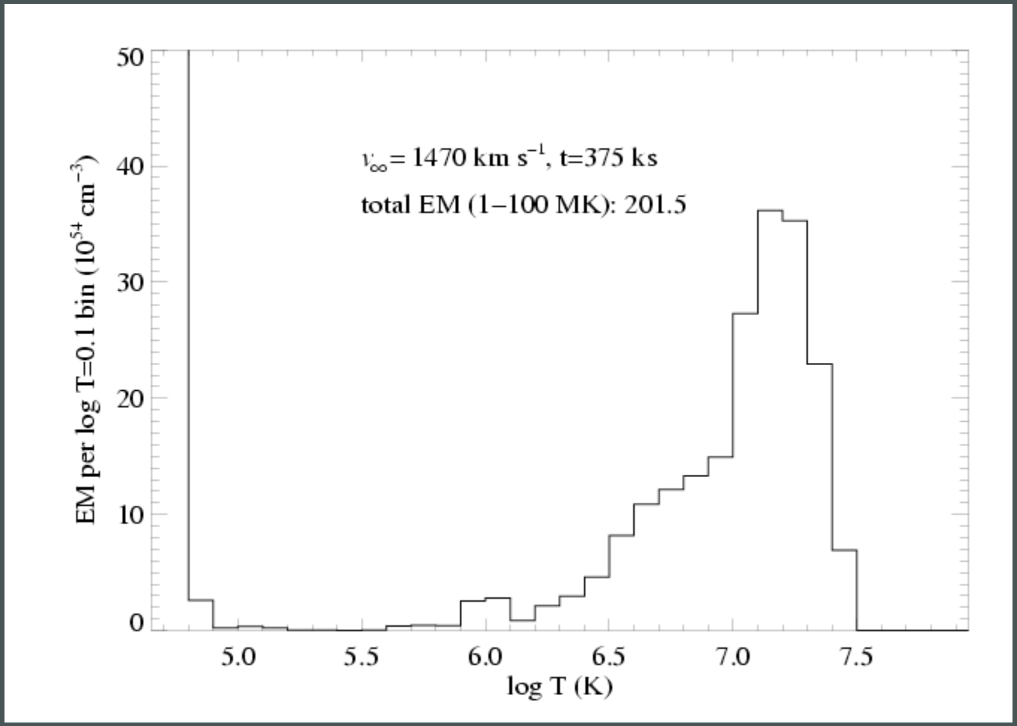


The magnetic O star – θ^1 Ori C – is hotter



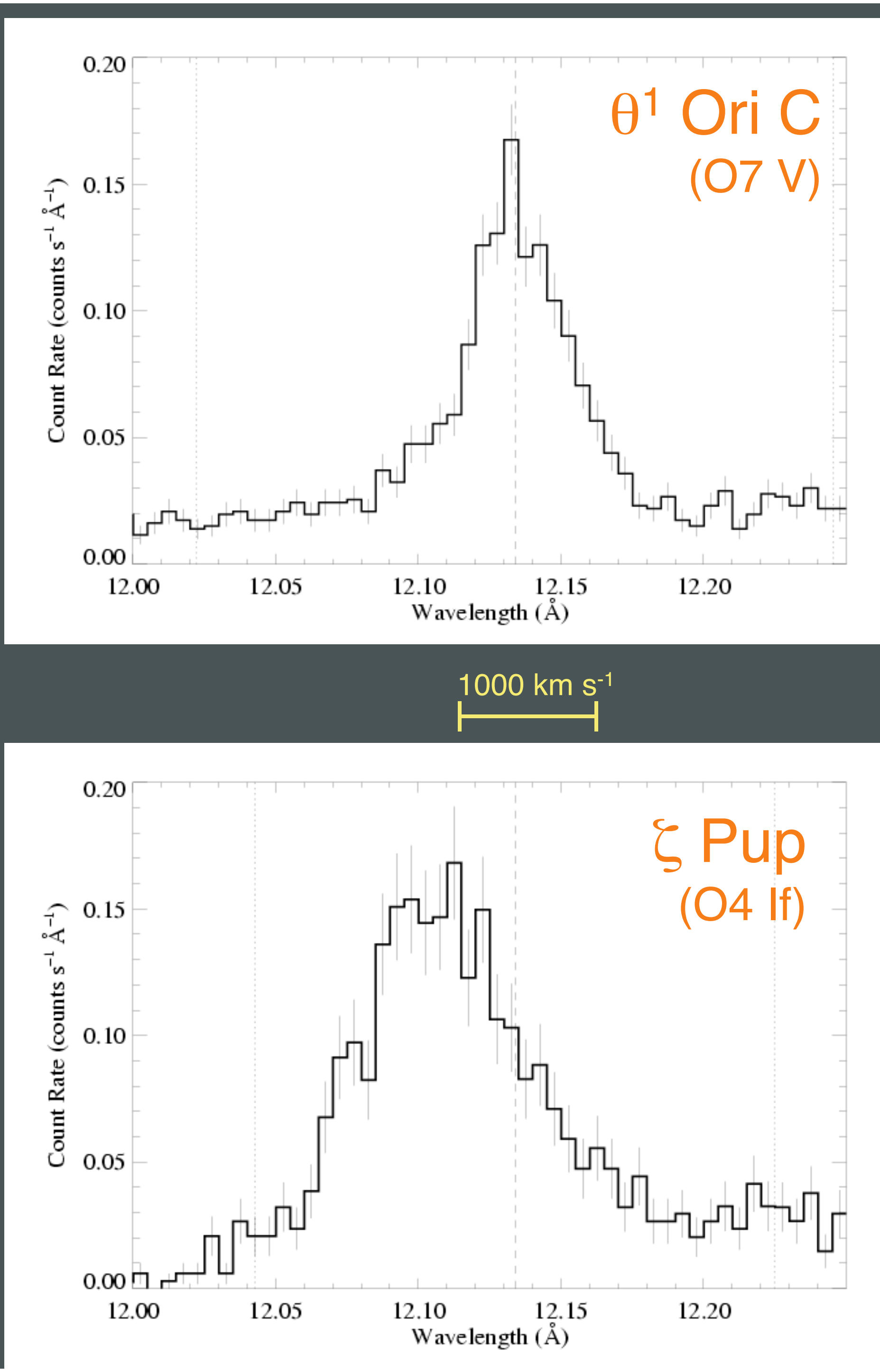
Differential emission measure
(temperature distribution)





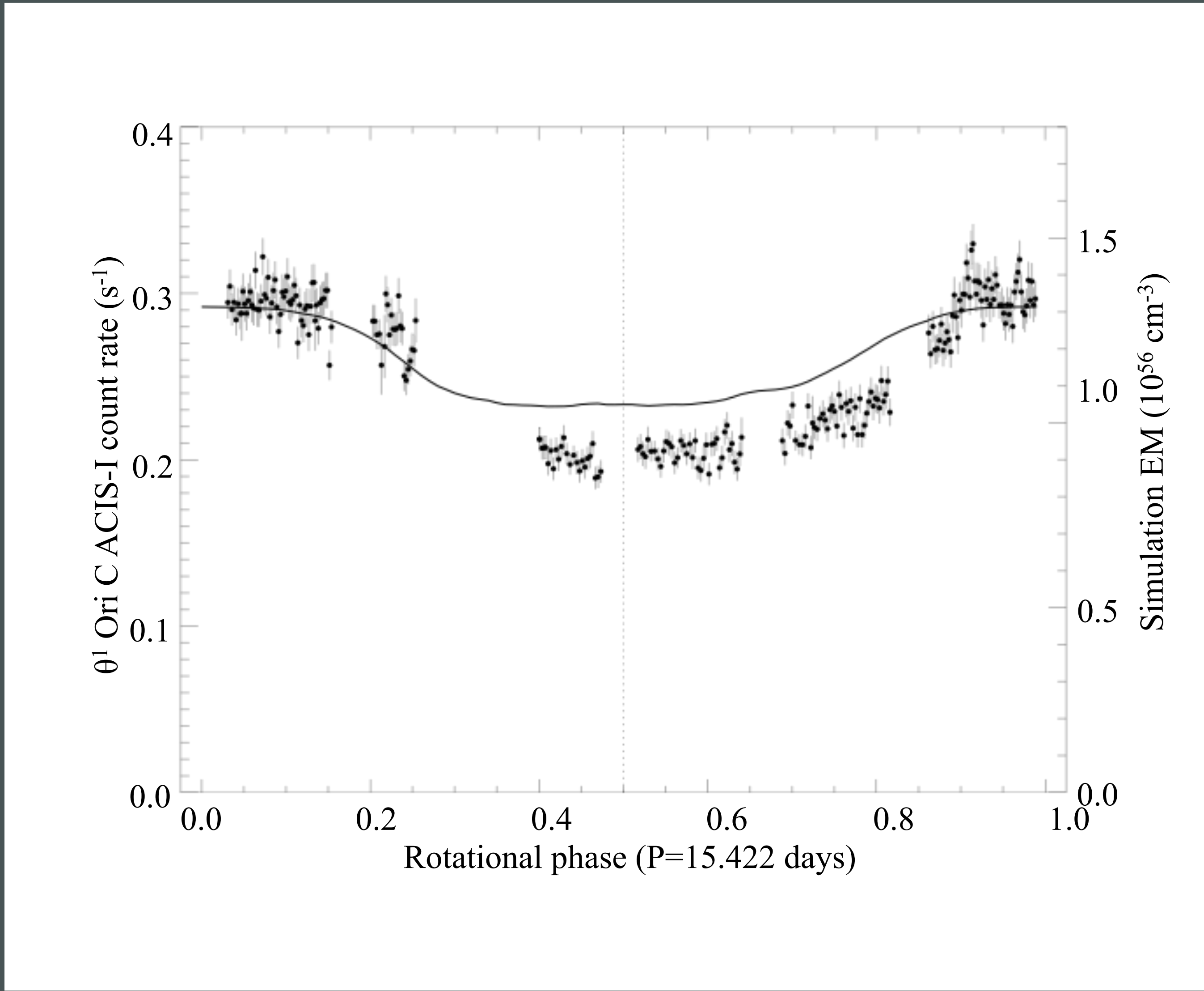
Wojdowski & Schulz (2005)

MHD simulation of θ^1 Ori C reproduces the observed differential emission measure



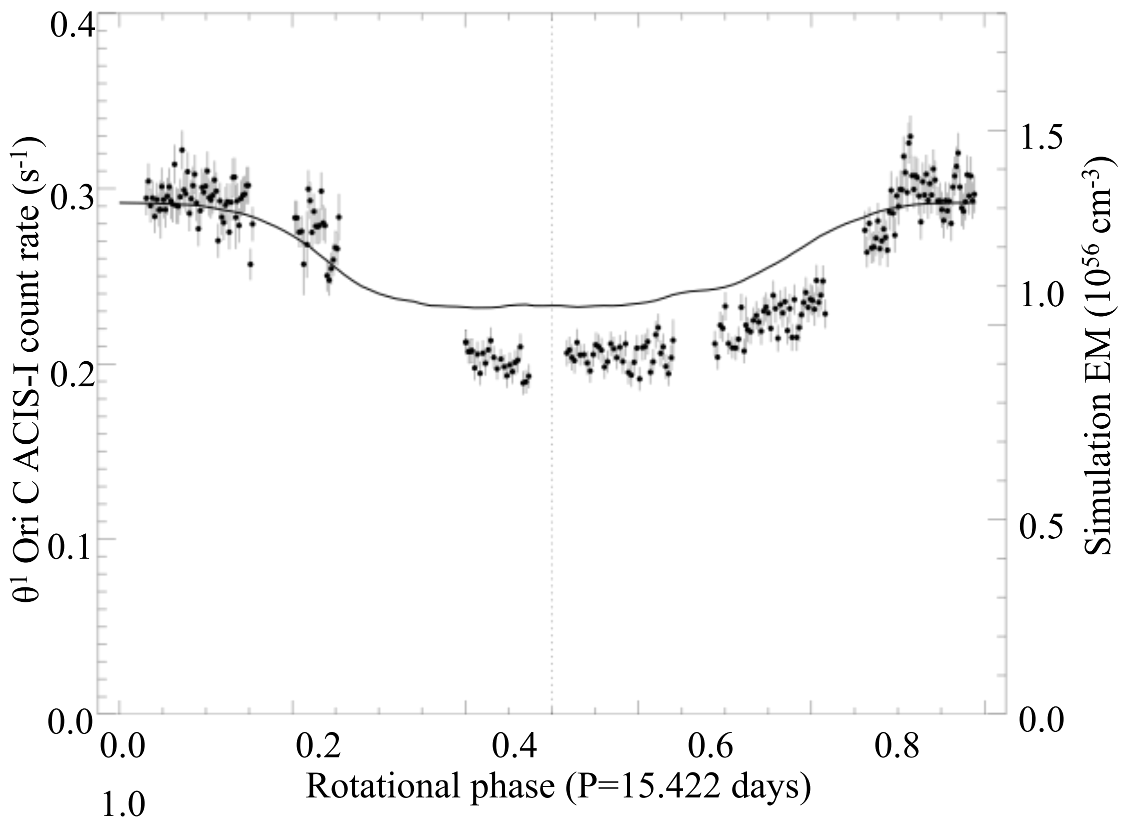
Emission lines *are* significantly narrower in the magnetic massive star's x-ray spectrum

Chandra broadband count rate vs. rotational phase



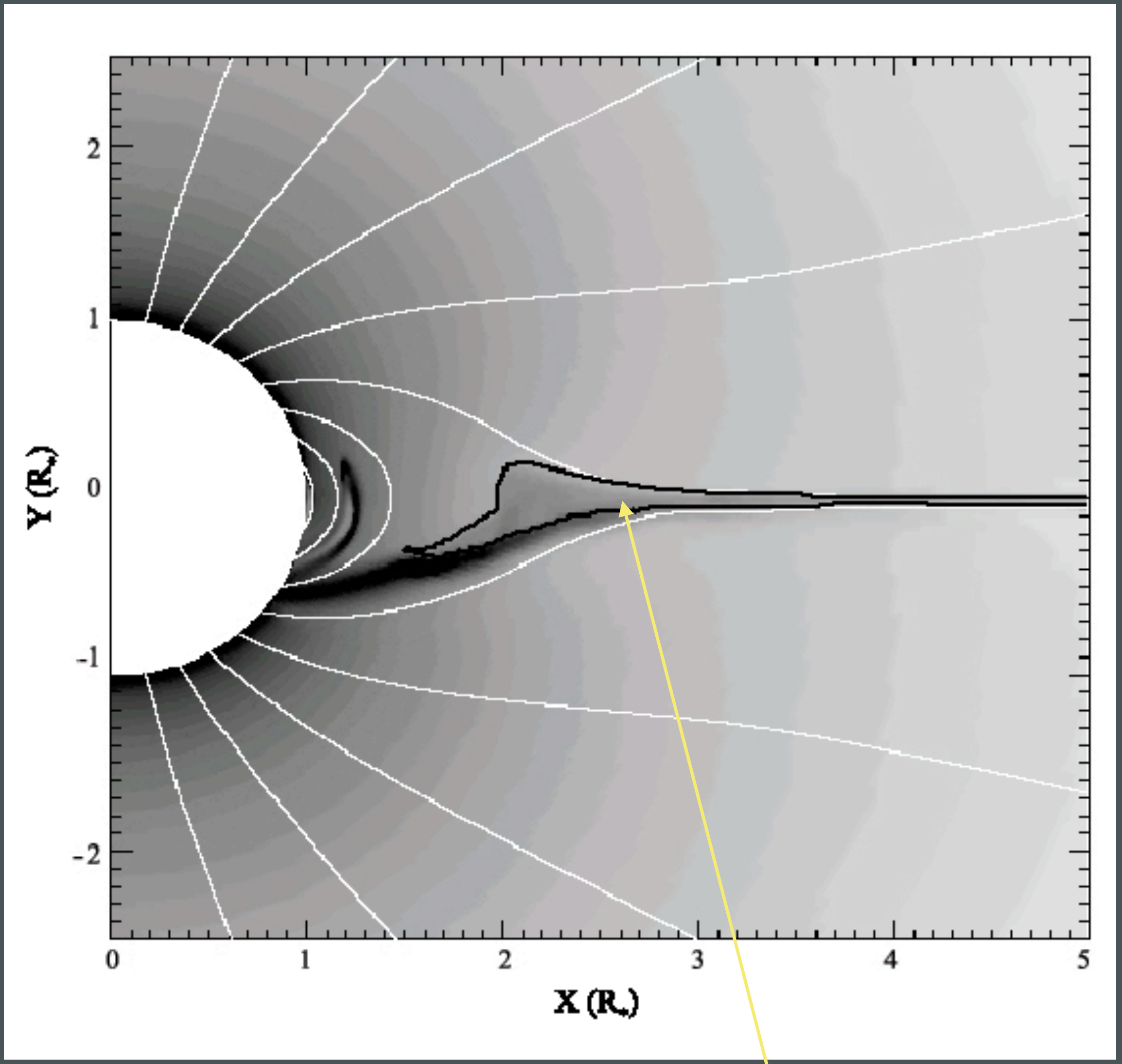
Model from MHD simulation

The star itself occults the hot plasma torus



The closer the hot plasma is to the star, the deeper the dip in the x-ray light curve

Emission measure

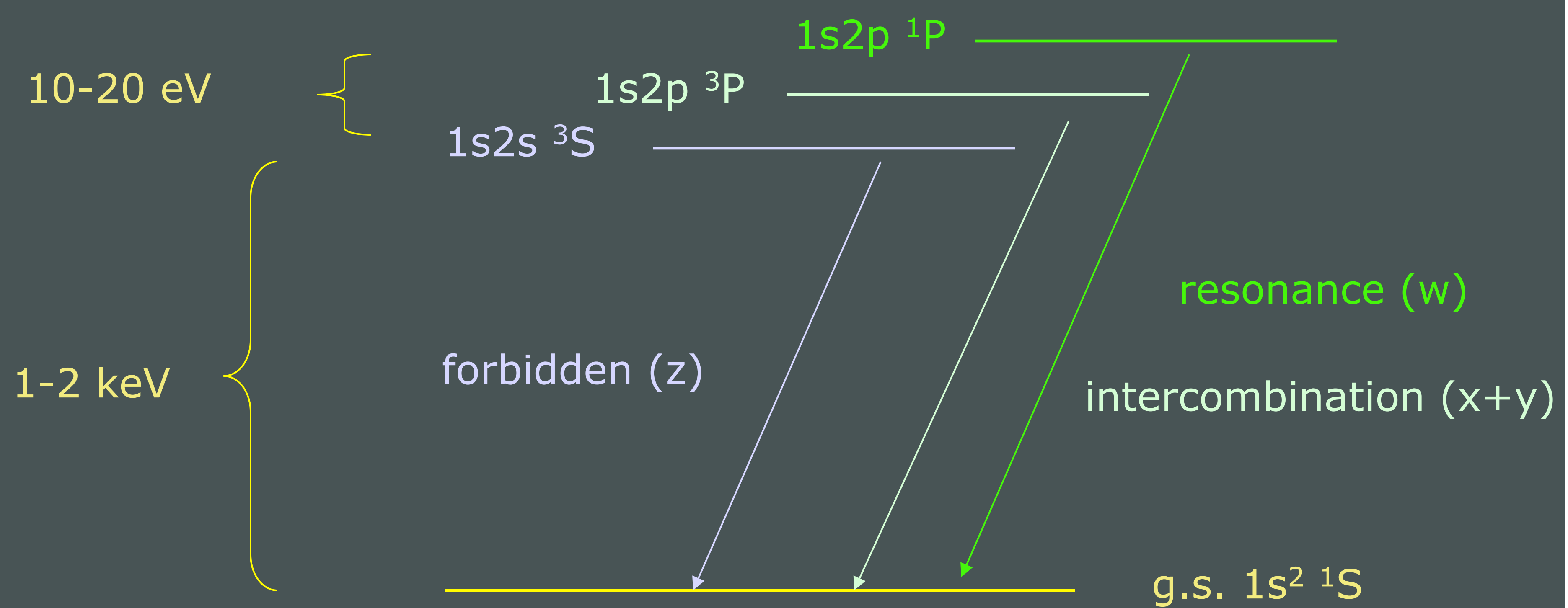


contour encloses $T > 10^6$ K

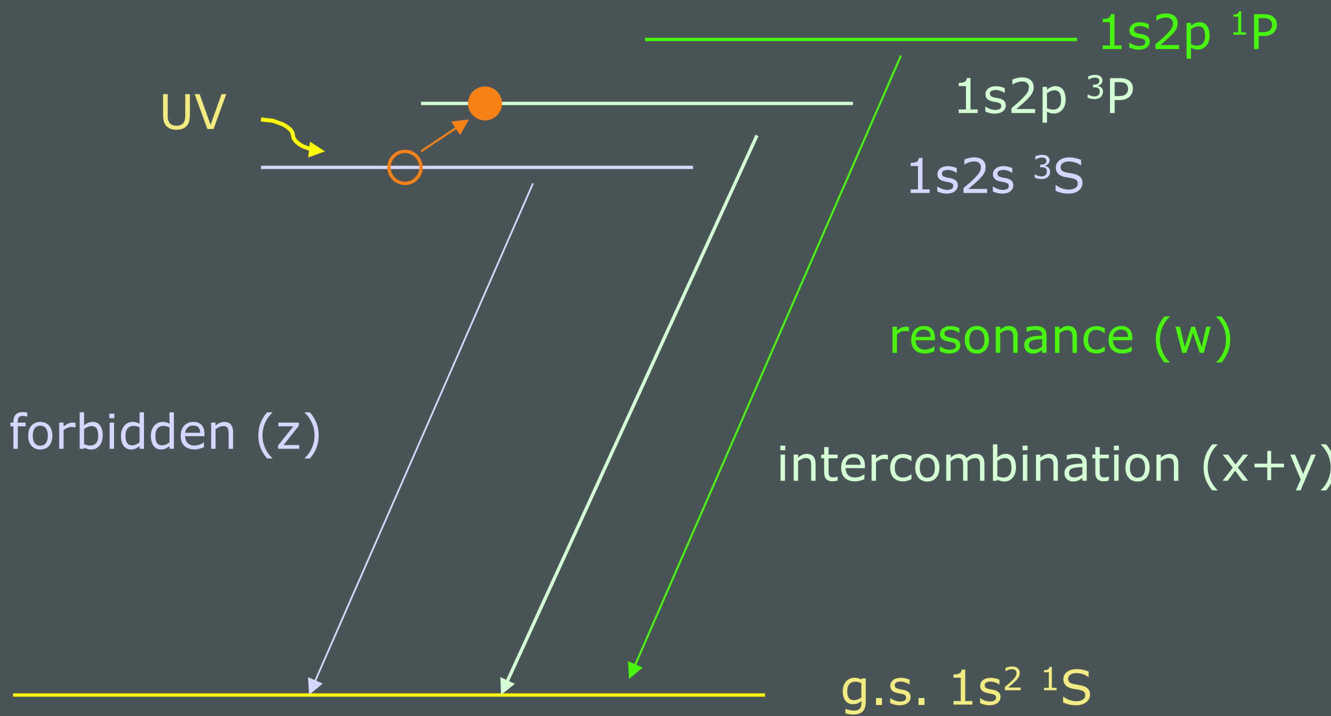
Helium-like species' forbidden-to-intercombination line ratios – $z/(x+y)$ – provide information about the *location* of the hot plasma

…not the *density*, as is usually the case.

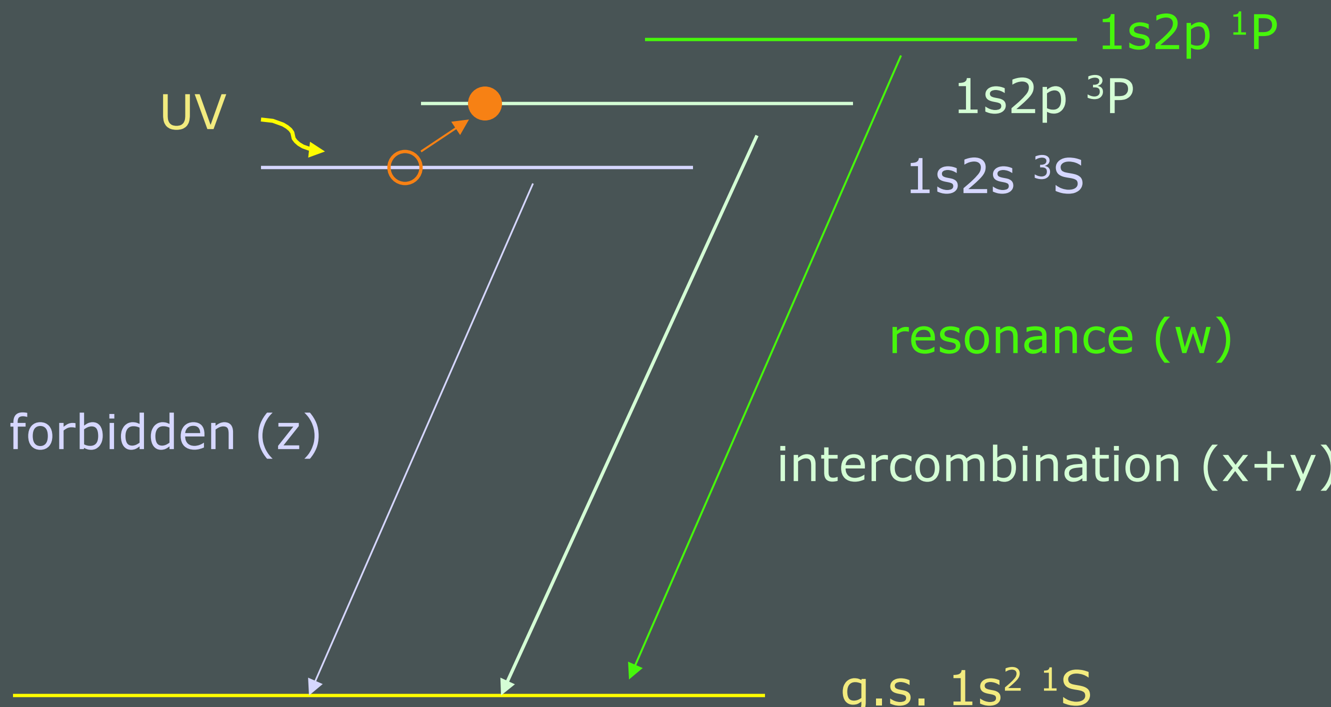
Helium-like ions (e.g. O^{+6}, Ne^{+8}, Mg^{+10}, Si^{+12}, S^{+14}) – schematic energy level diagram



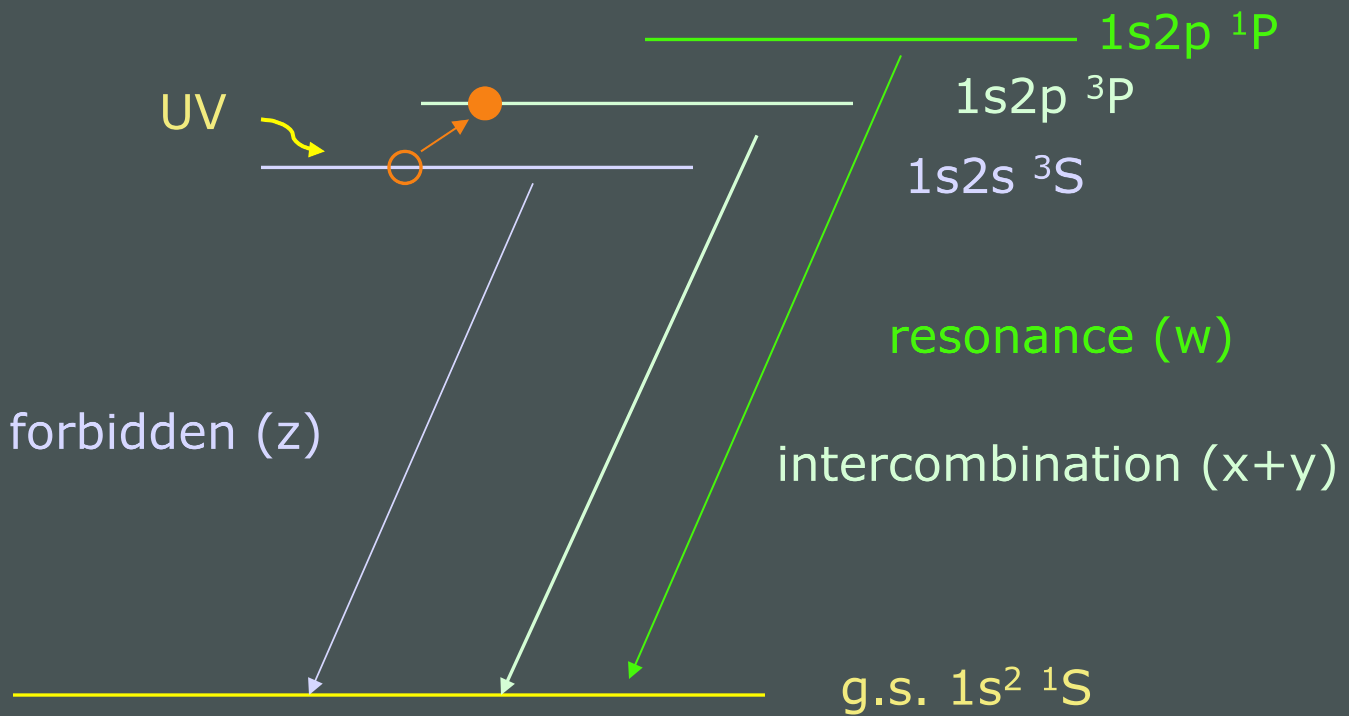
Ultraviolet light from the star's photosphere drives photoexcitation out of the ^3S level



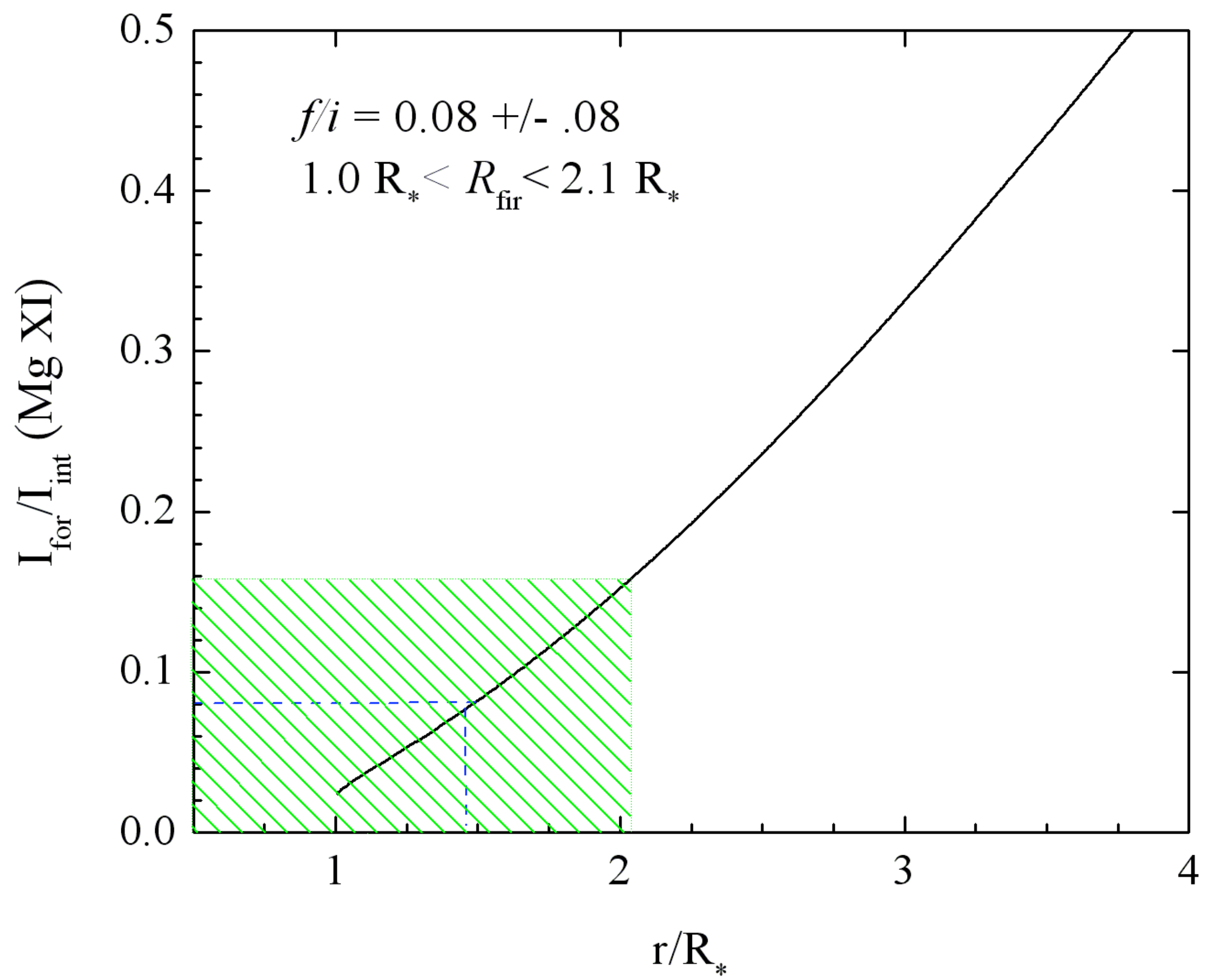
The f/i ratio is thus a diagnostic of the local UV mean intensity…

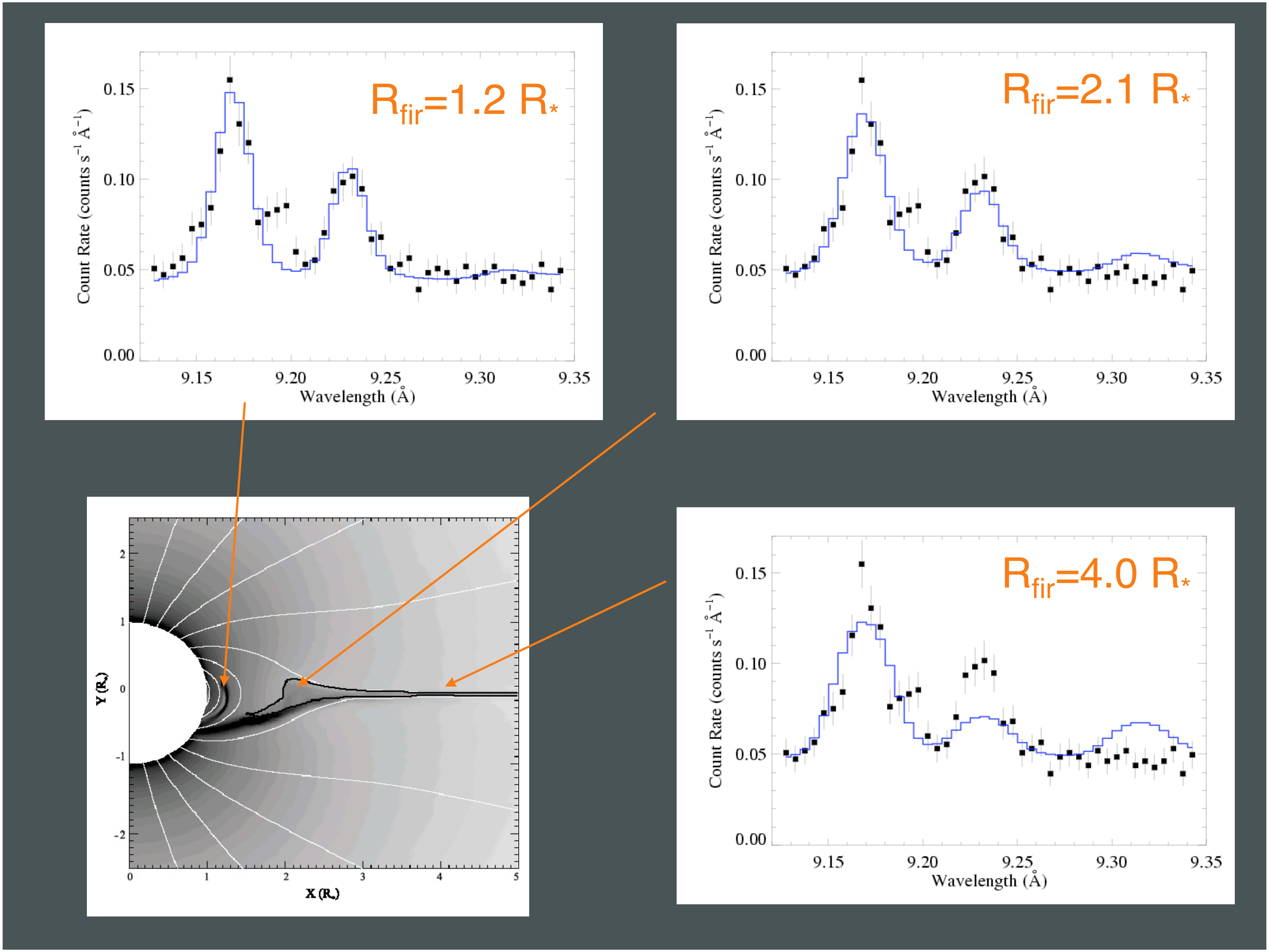


…and thus the distance of the x-ray emitting plasma from the photosphere



Model of f/i ratio dependence on dilution factor (radius)





Rfir=1.2 R*
Rfir=2.1 R*
Rfir=4.0 R*
Count Rate (counts s−1 Å−1)
Wavelength (Å)
0.00
0.05
0.10
0.15
9.15
9.20
9.25
9.30
9.35
Y (R*)
X (R*)

He-like f/i ratios and the x-ray light curve both indicate that the hot plasma is somewhat closer to the photosphere than the MHD models predict.

Conclusions

Normal massive stars have x-ray line profiles consistent with the predictions of the wind instability model.

Photoelectric absorption's effect on the profile shapes can be used as a mass-loss rate diagnostic: *mass-loss rates are lower than previously thought*.

Magnetic massive stars have harder spectra with narrower lines and rotationally modulated variability, in general agreement with MHD simulations.

Line ratio diagnostics are useful for localizing the hot plasma, and indicate that the *MHD simulations predict a location that is too far from the photosphere*.