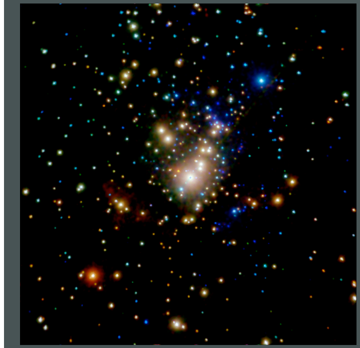
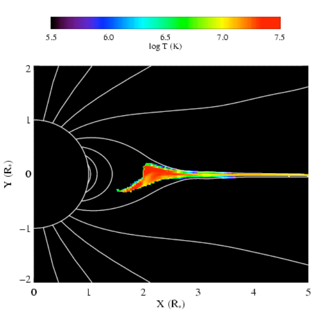
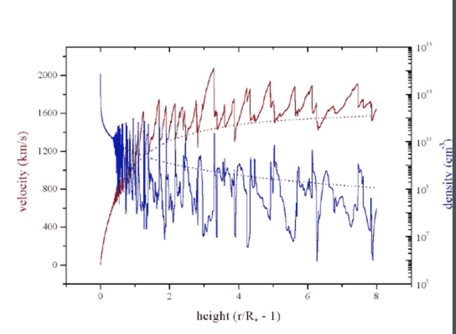
# X-ray Emission from Massive Stars:

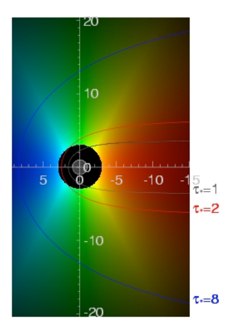
## Hydrodynamics, Wind Mass-Loss Rates, and Magnetic Fields

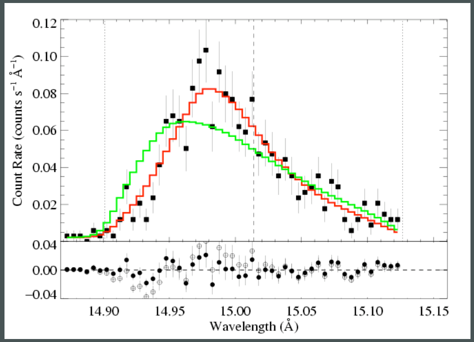
David Cohen
Swarthmore College











The Orion Nebula (Messier 42)
(MPG/ESO 2.2-m + WFI)

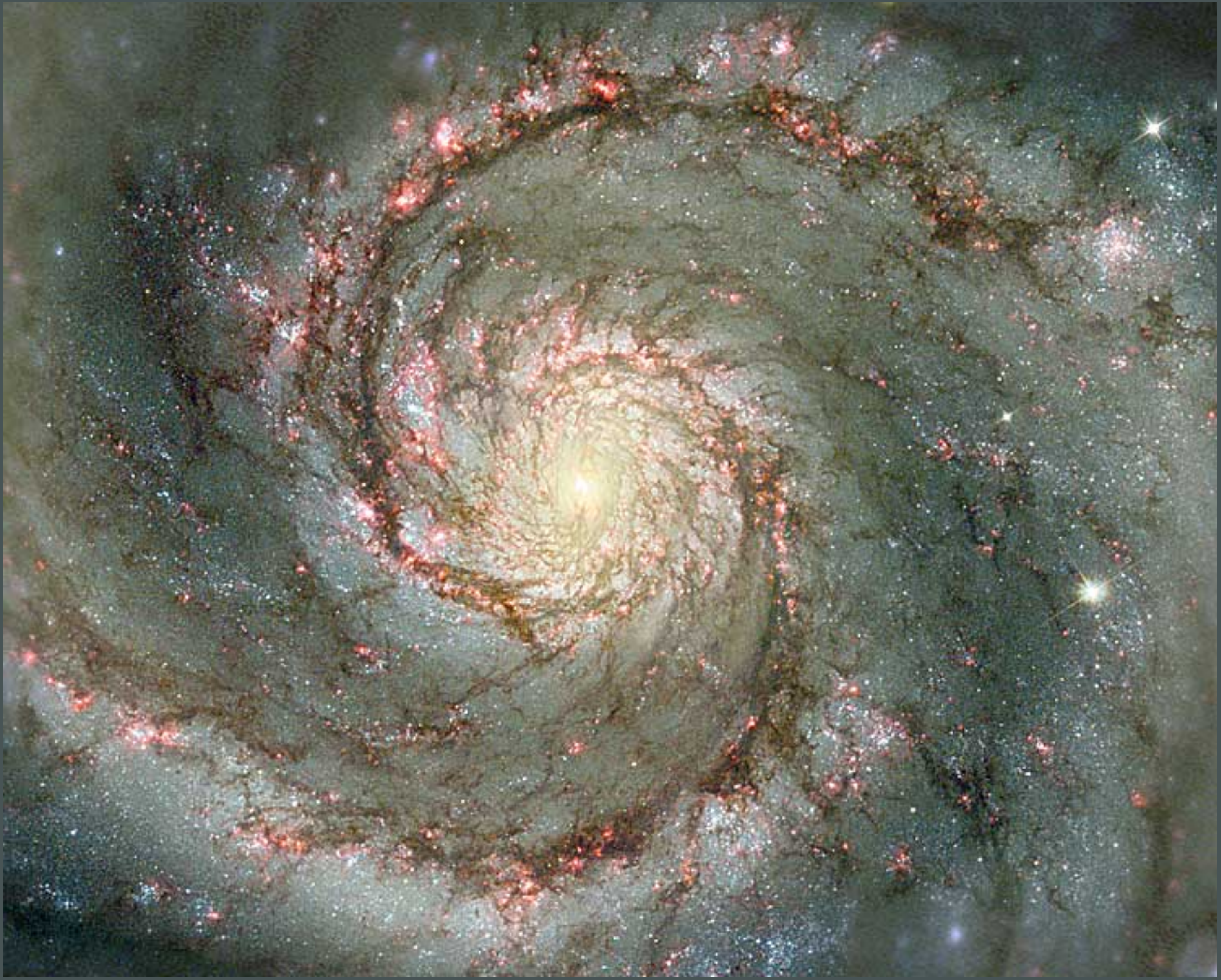
ESO PR Photo 20/04 (30 June 2004)

# massive stars:

$20$ to $100\ M_{sun}$

$10^6\ L_{sun}$

$T \sim 50{,}000$ K



Whirlpool/M51 (HST)

# 1000 yr old supernova remnant

Crab Nebula (WIYN)

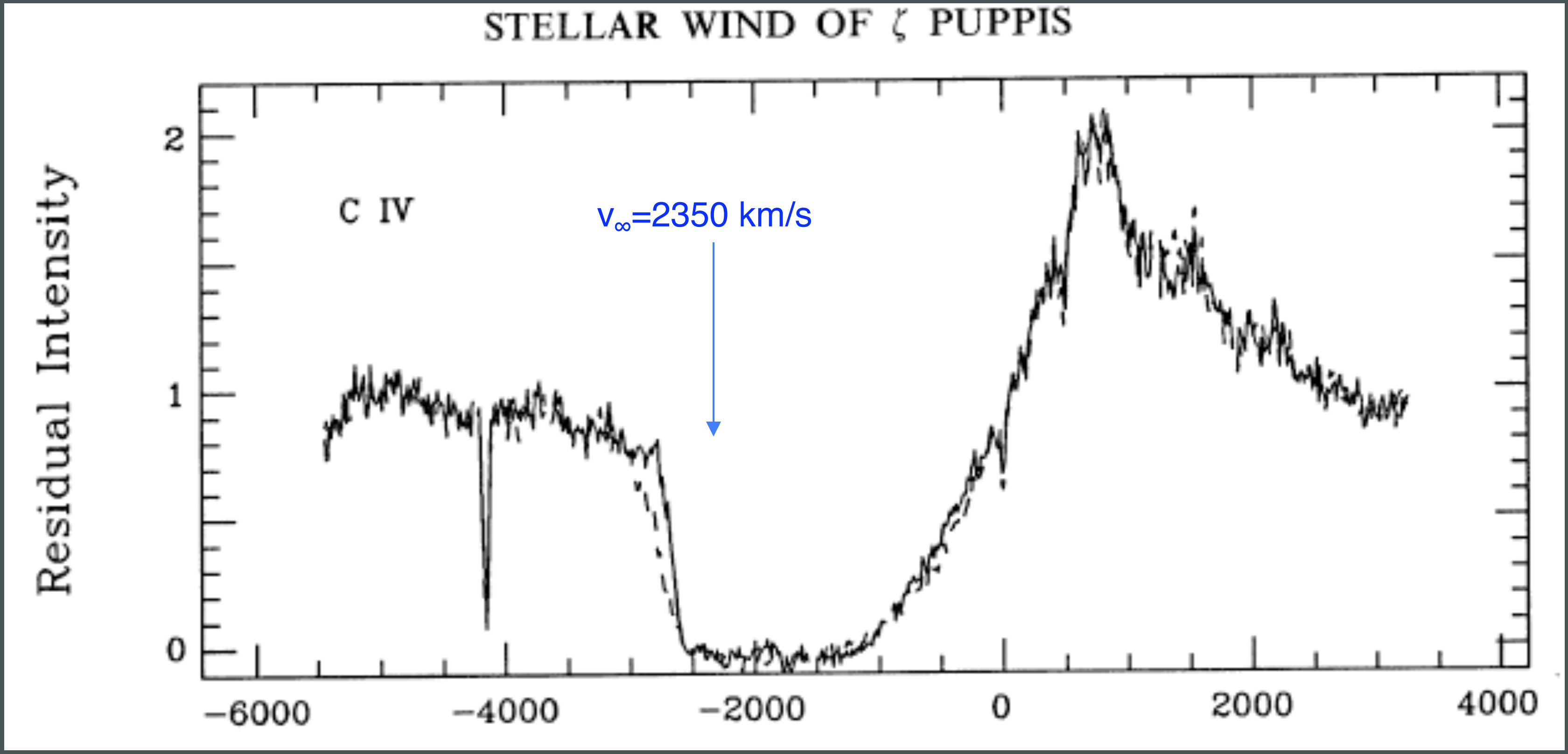
# wind-blown bubble: stellar wind impact on its environment

NGC 6888 Crescent Nebula (Tony Hallas)

# Radiation-driven massive star **winds**

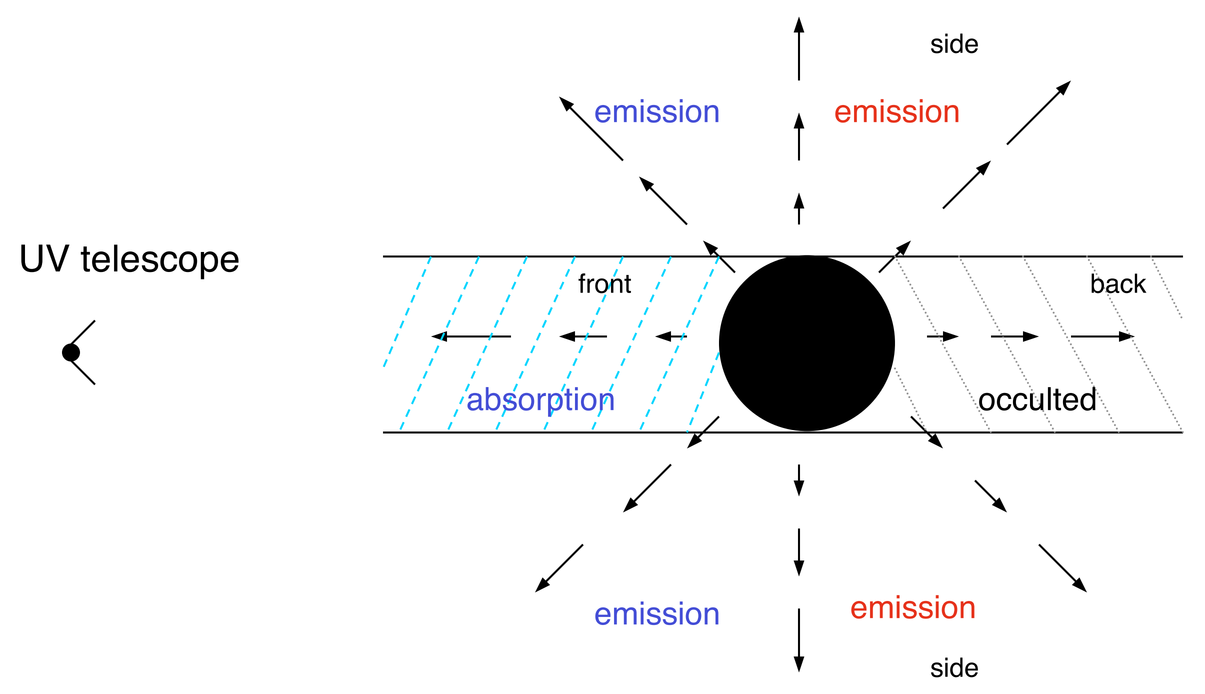
$\dot{M} \sim 10^{-6}\ M_{sun}/yr$

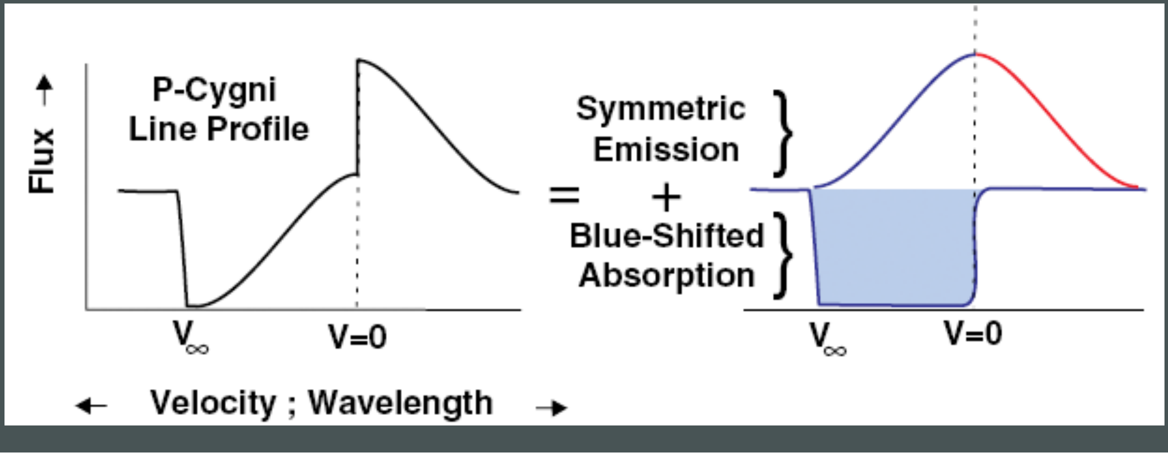
UV spectrum: C IV 1548, 1551 Å

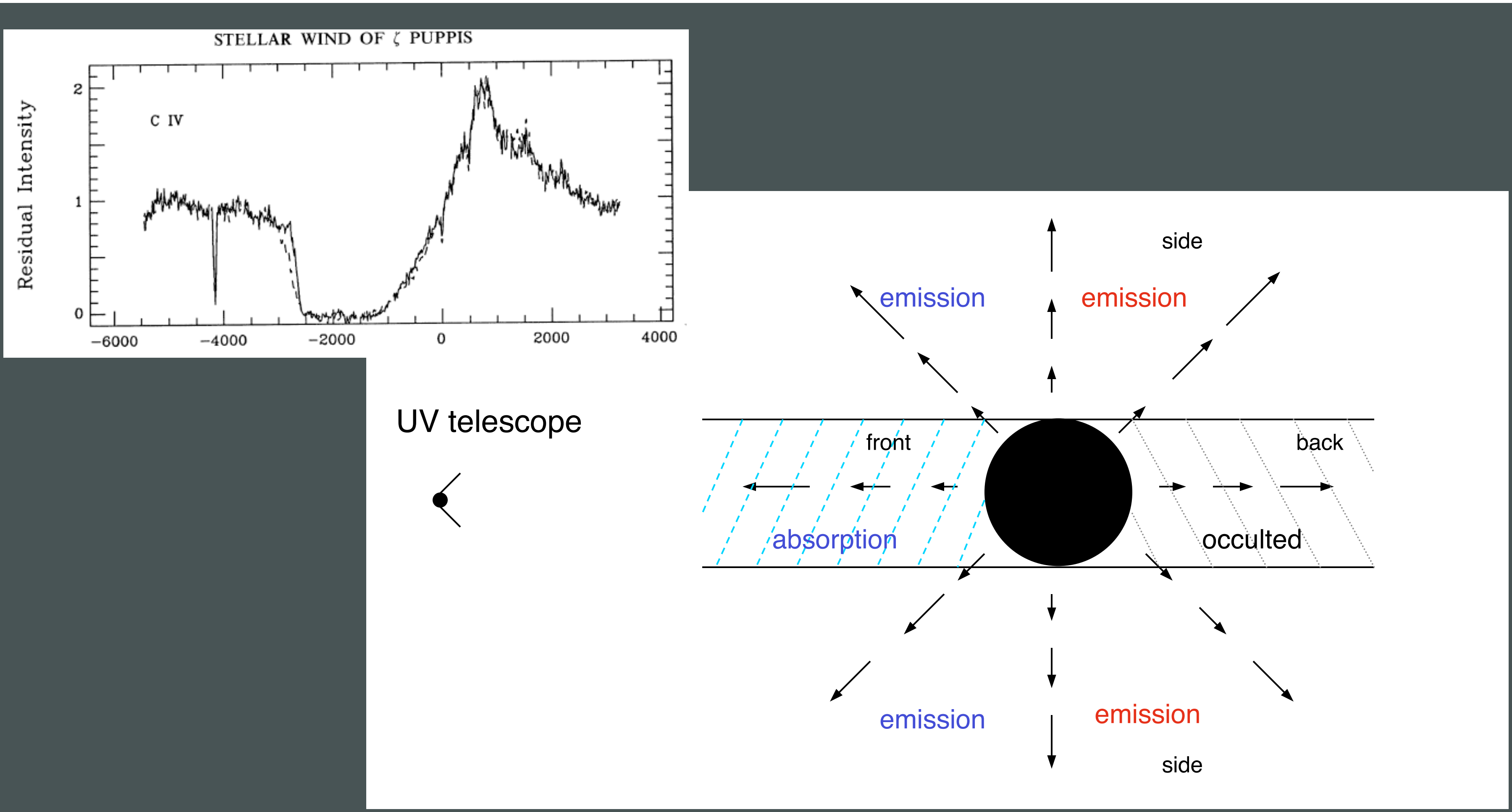


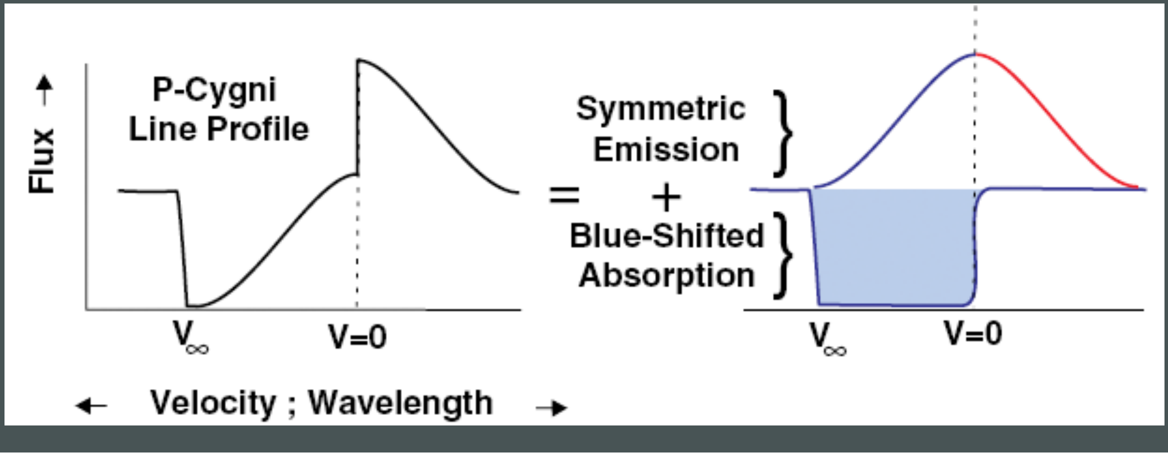
Prinja et al. 1992, ApJ, 390, 266

Velocity (km/s)


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


Flux
P-Cygni
Line Profile
$V_\infty$
V=0
Velocity ; Wavelength
=
Symmetric
Emission
+
Blue-Shifted
Absorption
$V_\infty$
V=0


STELLAR WIND OF ζ PUPPIS
Residual Intensity
C IV
0
1
2
−6000
−4000
−2000
0
2000
4000
UV telescope
side
emission
emission
front
back
absorption
occulted
emission
emission
side


Flux
P-Cygni
Line Profile
$V_\infty$
V=0
=
Symmetric
Emission
+
Blue-Shifted
Absorption
$V_\infty$
V=0
Velocity ; Wavelength

# Winds of massive stars are driven by **radiation force**

cross-section (cm$^2$)

Luminosity (ergs/s)

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

radius

# Winds of massive stars are driven by **radiation force**

opacity ($cm^2/g$)

Luminosity (ergs/s)

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

radius

# Winds of massive stars are driven by **radiation force**

opacity (cm$^2$/g)

Luminosity (ergs/s)

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

radius

# Eddington factor, $\Gamma_{edd}$: ratio of radiation force to gravity

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, $\Gamma_{edd}$ approaches unity

Mechanical **power** in these winds:

$$\frac{1}{2}\dot{M}v_{\infty}^{2} \approx 3 \times 10^{36} \quad \text{erg s}^{-1}$$

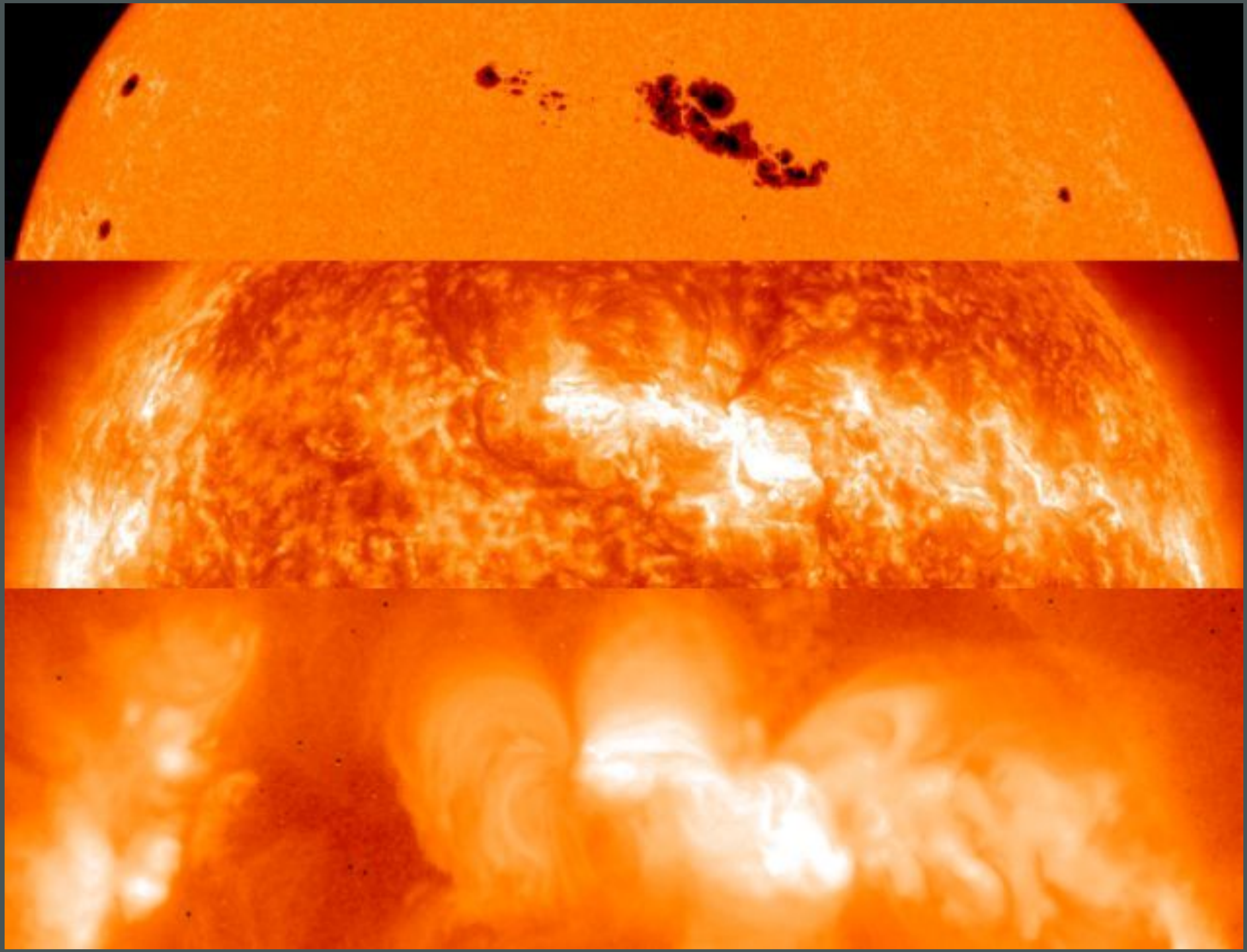
$$\approx .001L_{*}$$

$L_{sun} = 4 \times 10^{33}$ erg $s^{-1}$

**$L_{massive} \approx 4 \times 10^{39}$**

# Massive star X-rays
# vs.
# Solar-type X-rays

# The Sun at different wavelengths

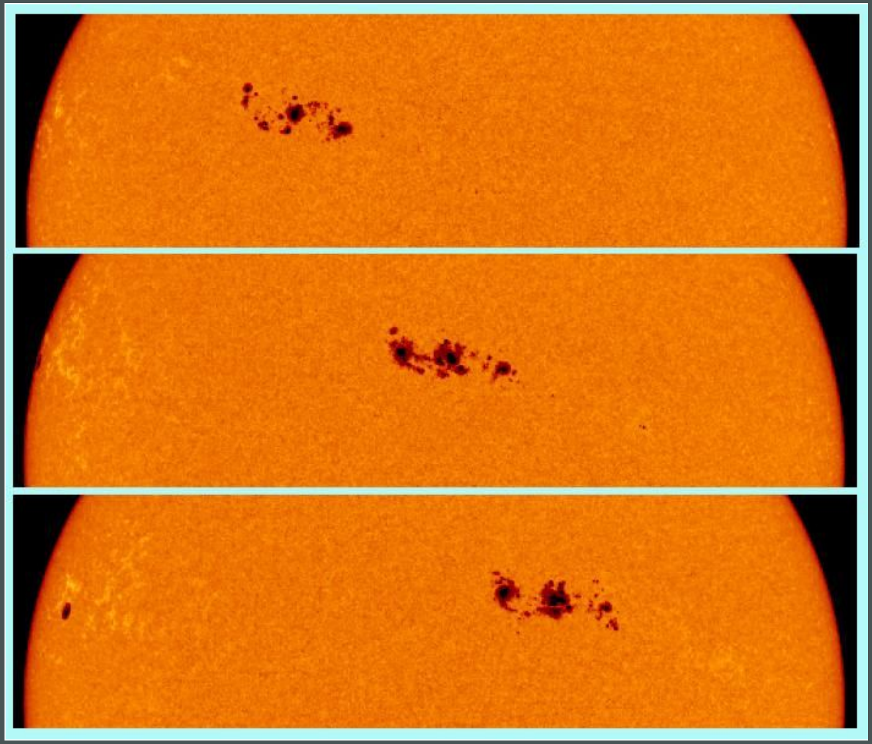


Optical
5800 K

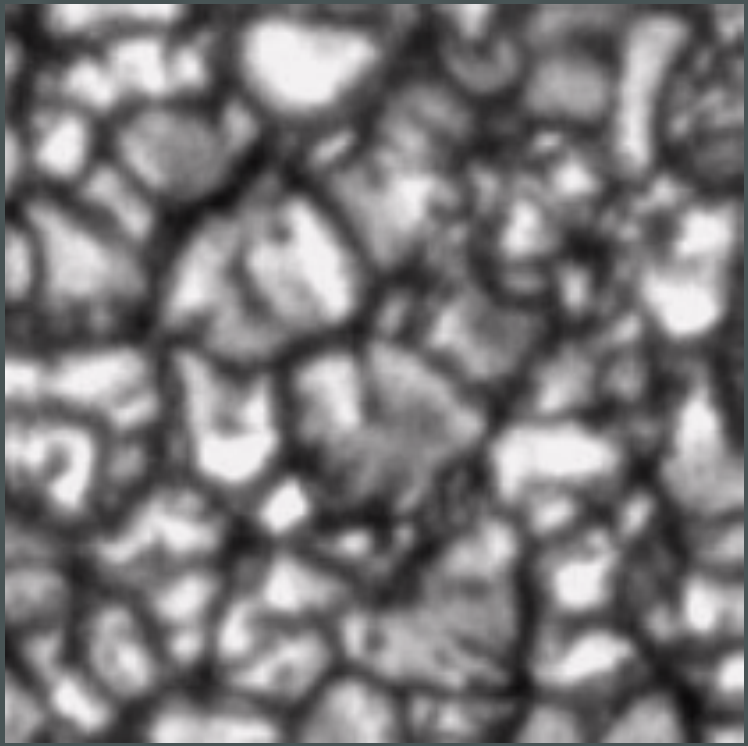
SOHO
EUV
few $10^5$ K

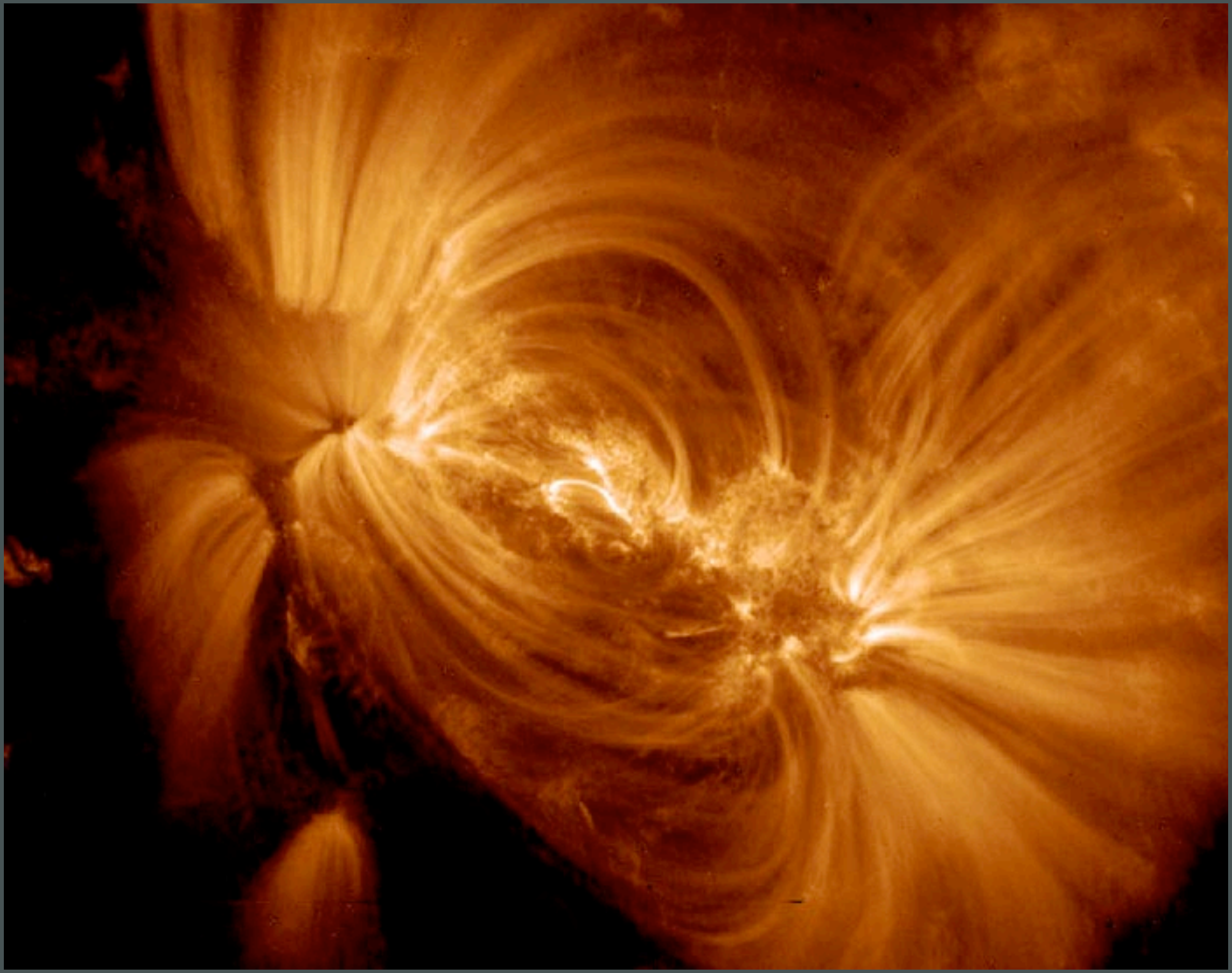
YOKOH
x-ray
few $10^6$ K

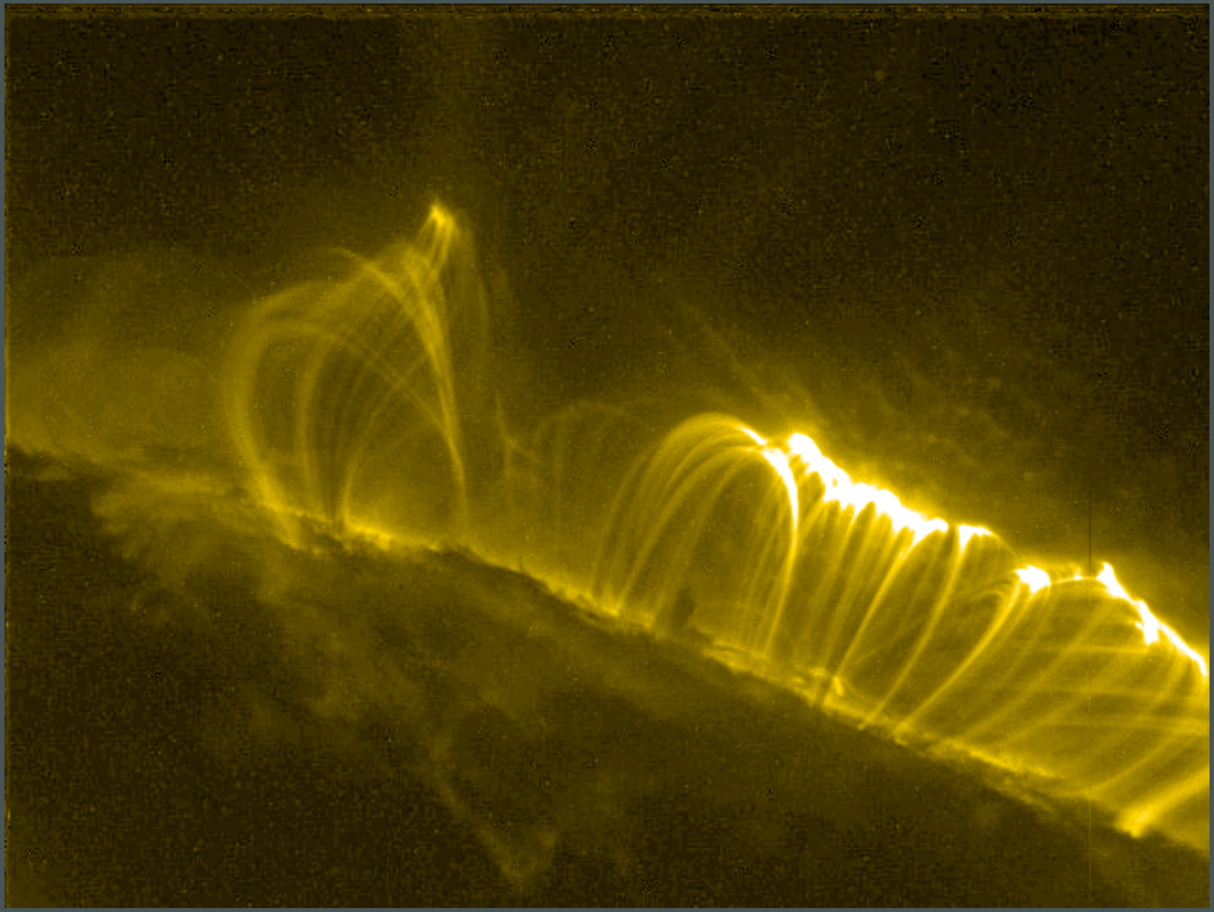
rotation

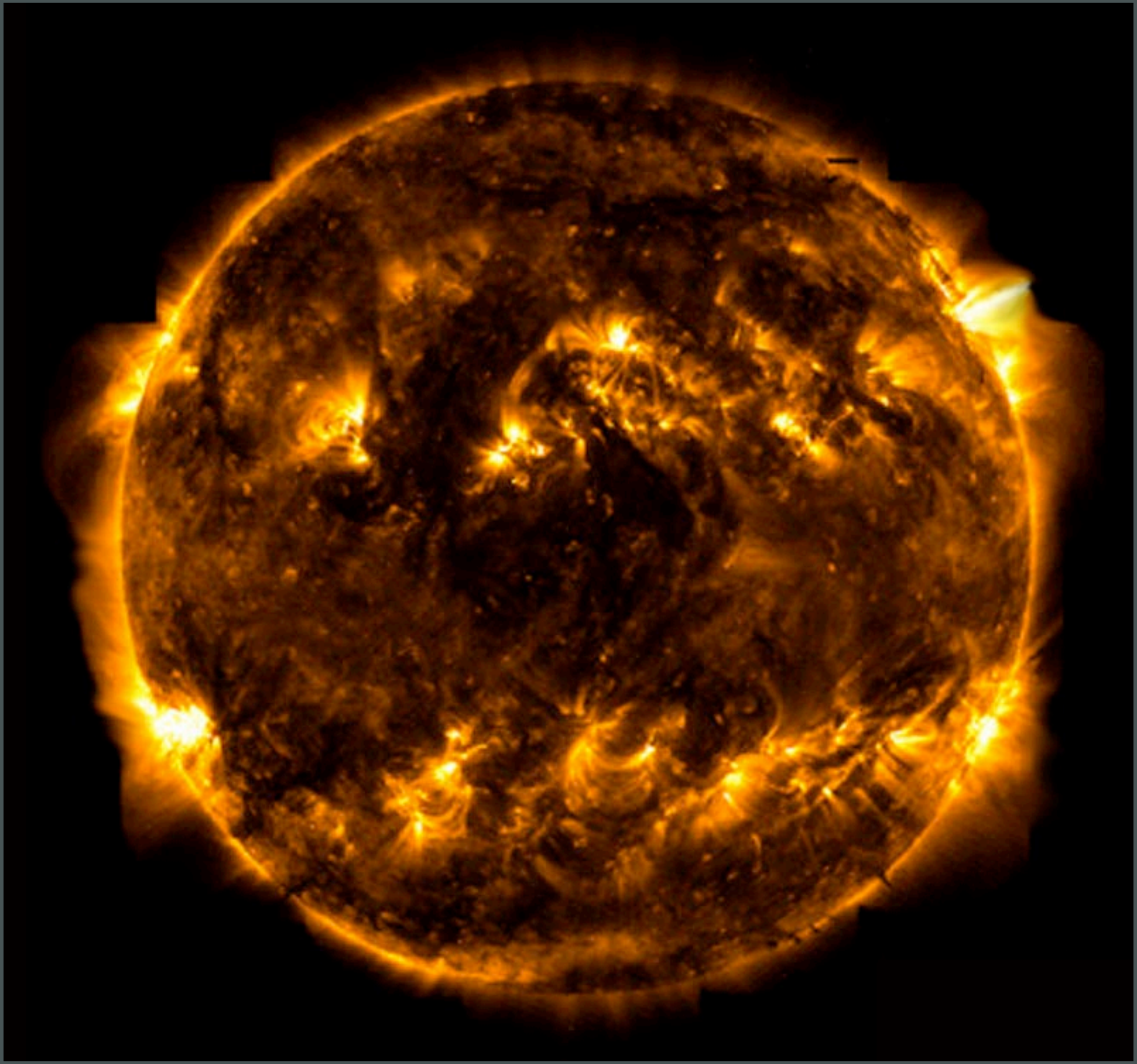


convection





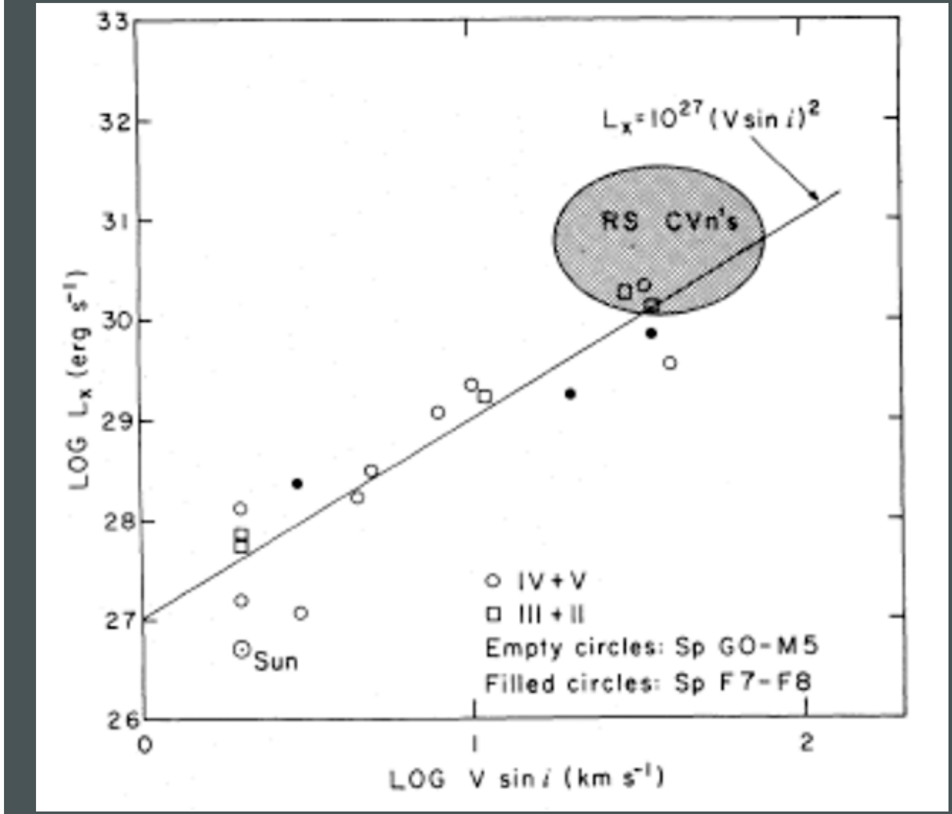




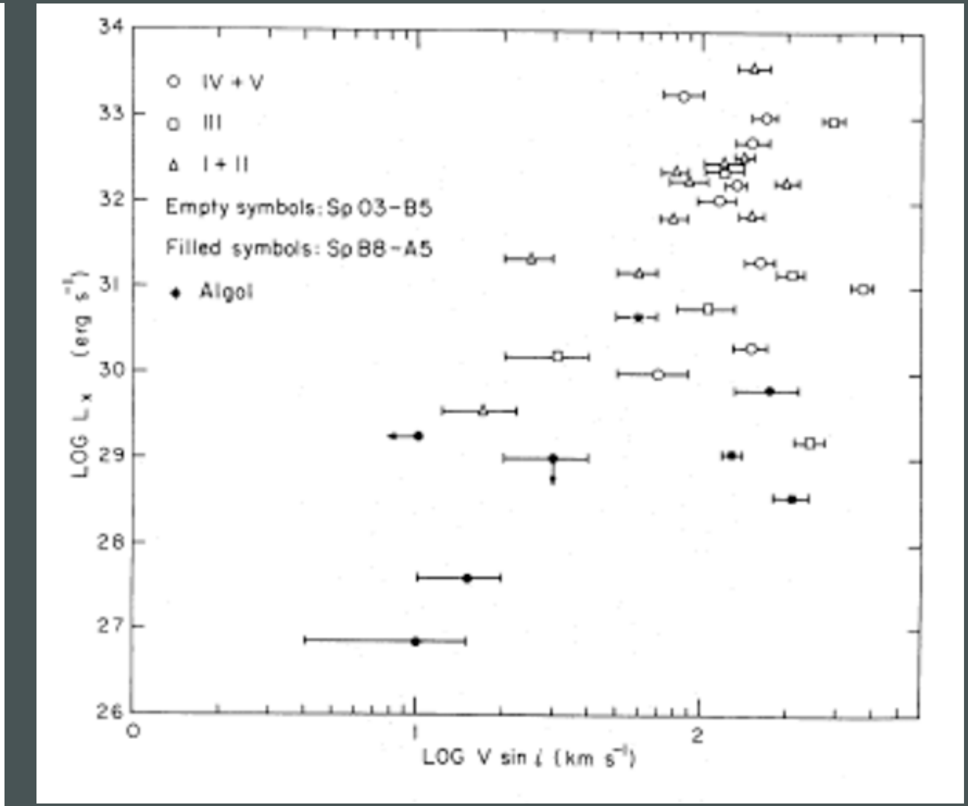
TRACE

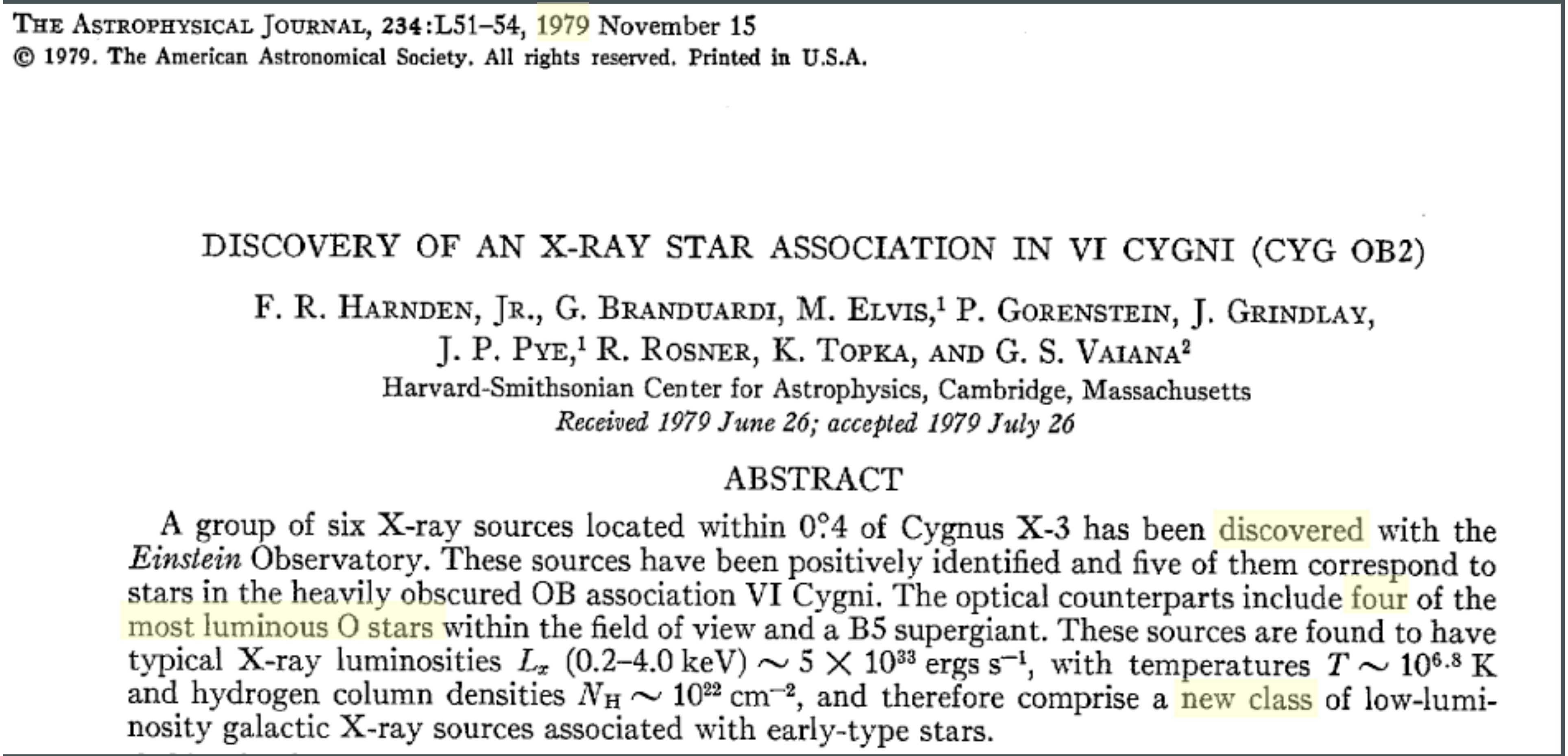
# Stellar rotation vs. X-ray luminosity

## low-mass stars



## high-mass stars





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

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

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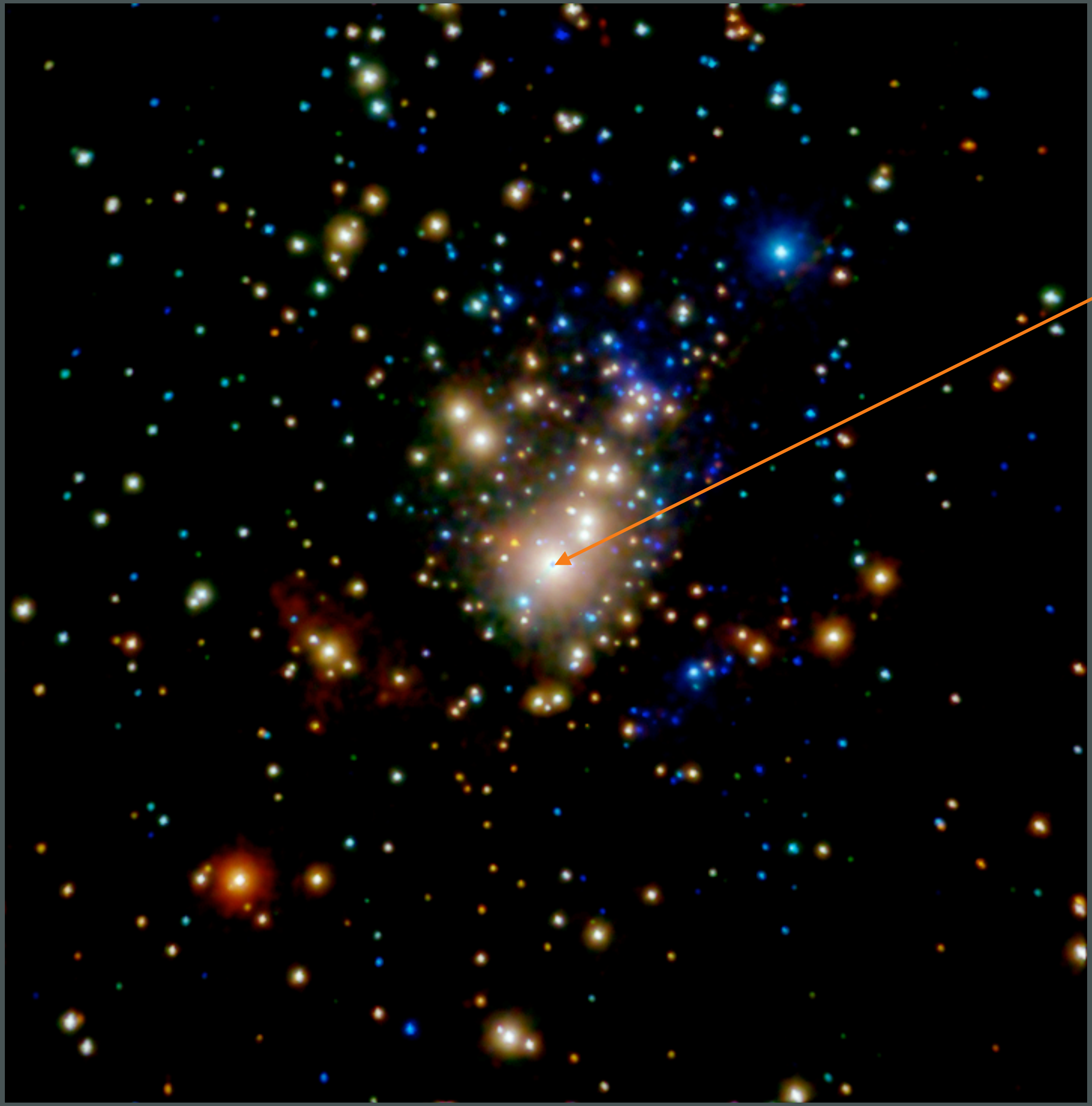
## ABSTRACT

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 $N_{\rm H} \sim 10^{22}$ cm$^{-2}$, and therefore comprise a new class of low-luminosity galactic X-ray sources associated with early-type stars.

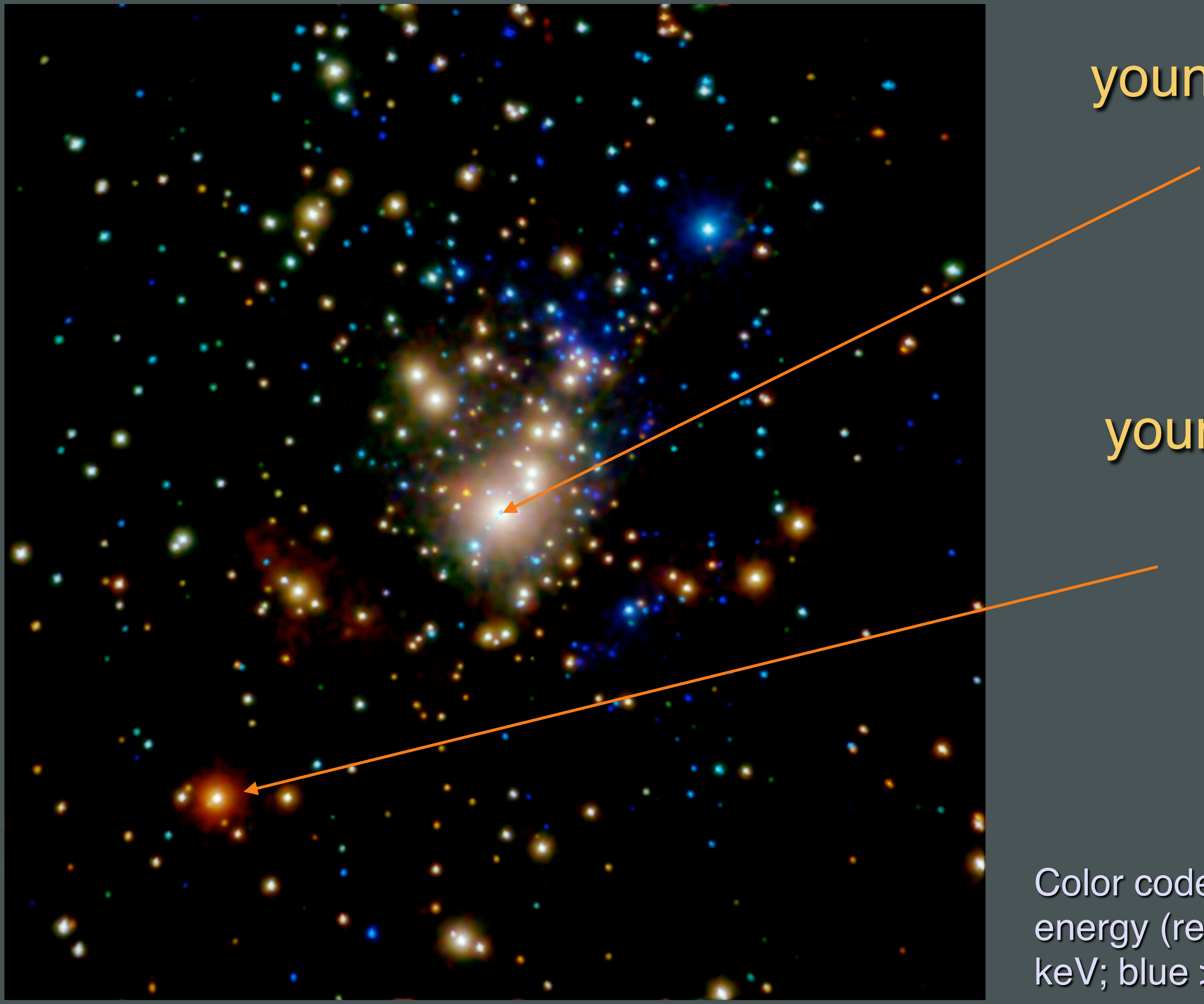
# Chandra X-ray Telescope image of the Orion Nebula Cluster



young, massive star:
$\theta^1$ Ori C

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

# Chandra X-ray Telescope image of the Orion Nebula Cluster



young, massive star:
$\theta^1$ Ori C

young, massive star:
$\theta^2$ Ori A

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

# The connection between X-rays and stellar winds in massive stars

## Power in massive star winds:

$$\tfrac{1}{2}\dot{M} v_\infty^2 \approx 3 \times 10^{36} \text{ erg s}^{-1}$$

$$\approx .001 L_*$$

$L_{sun}$ = 4 x$10^{33}$ erg $s^{-1}$

$L_{massive}$ ≈ 4 x$10^{39}$

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

# Energy Considerations and Scalings

1 keV ~ 12 × $10^6$ K ~ 12 Å

Shock heating: $\Delta v = 300$ km/s
gives $T \sim 10^6$ K (and $T \sim v^2$)

*Chandra*, *XMM* 350 eV to 10 keV

# Energy Considerations and Scalings

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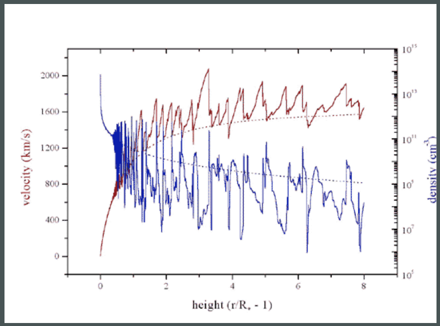
gives $T \sim 10^7$ K (and $T \sim v^2$)

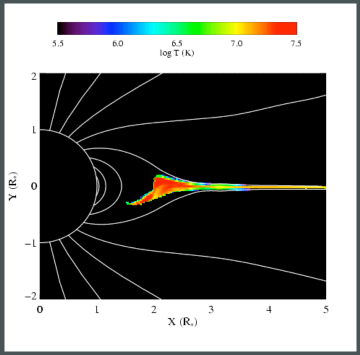
*Chandra*, *XMM* 350 eV to 10 keV

# Three models for massive star x-ray emission

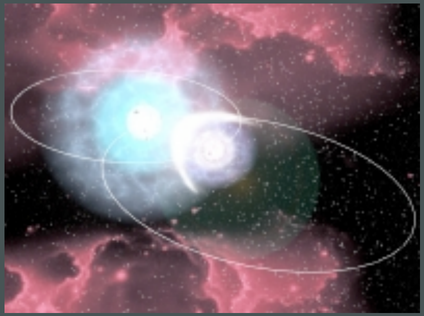
1. Instability driven shocks



2. Magnetically channeled
wind shocks

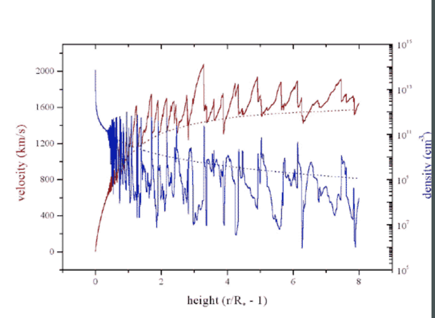


3. Wind-wind interaction in
close binaries



# Three models for massive star x-ray emission

1. Instability driven shocks



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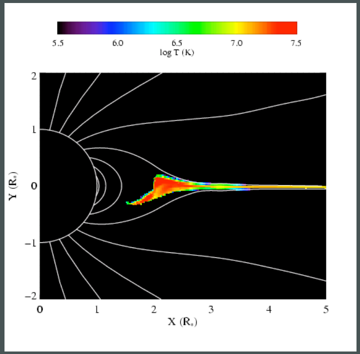
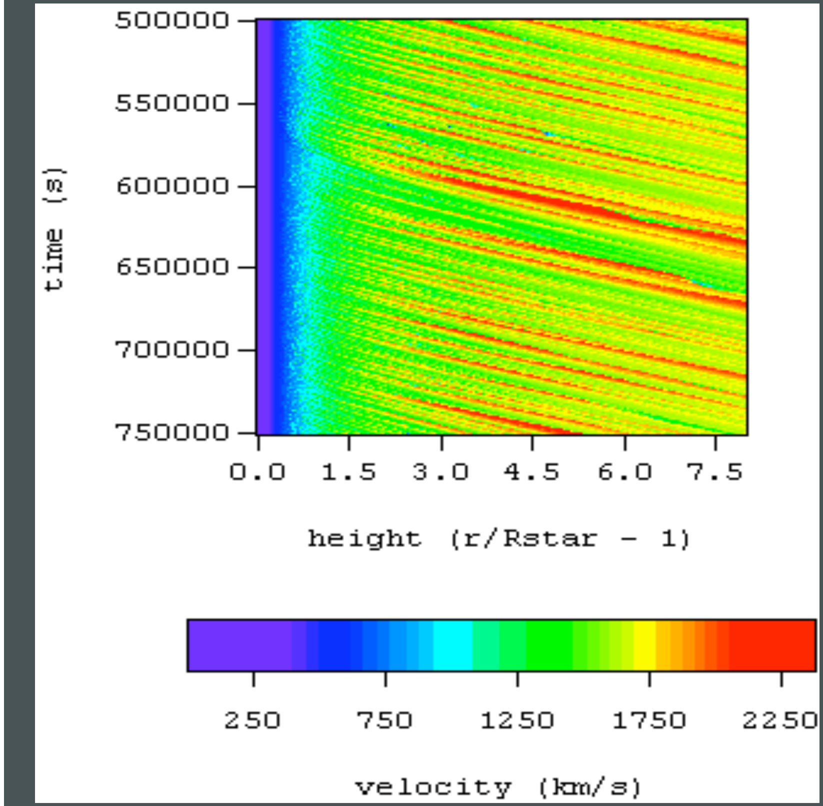
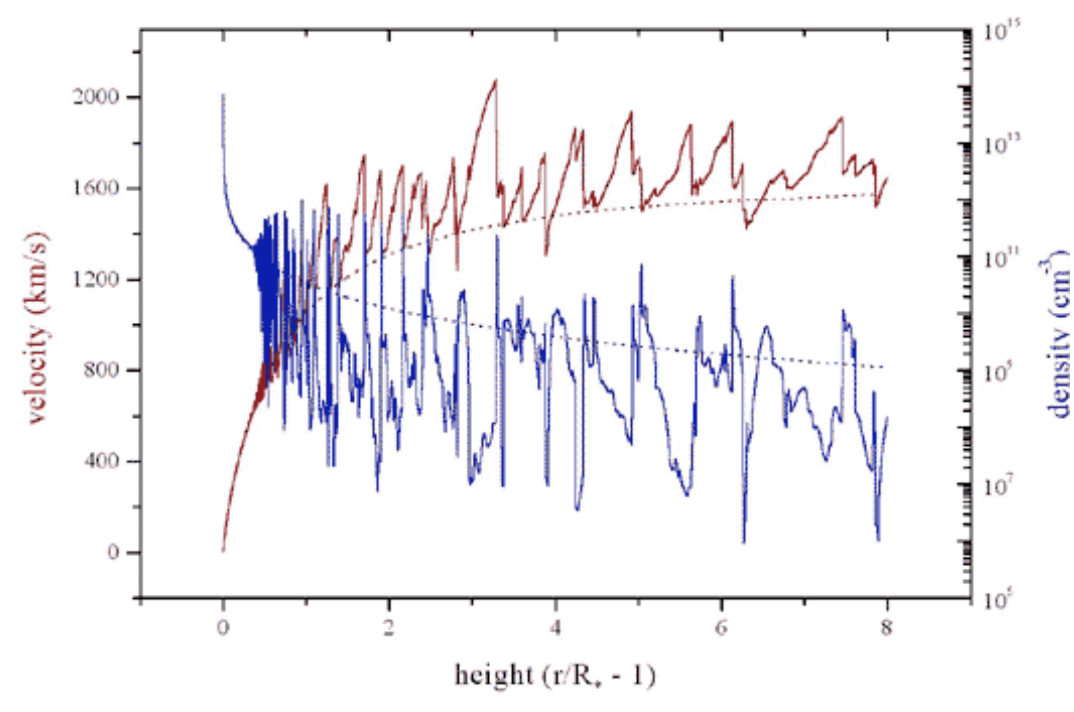


3. Wind-wind interaction in close binaries

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

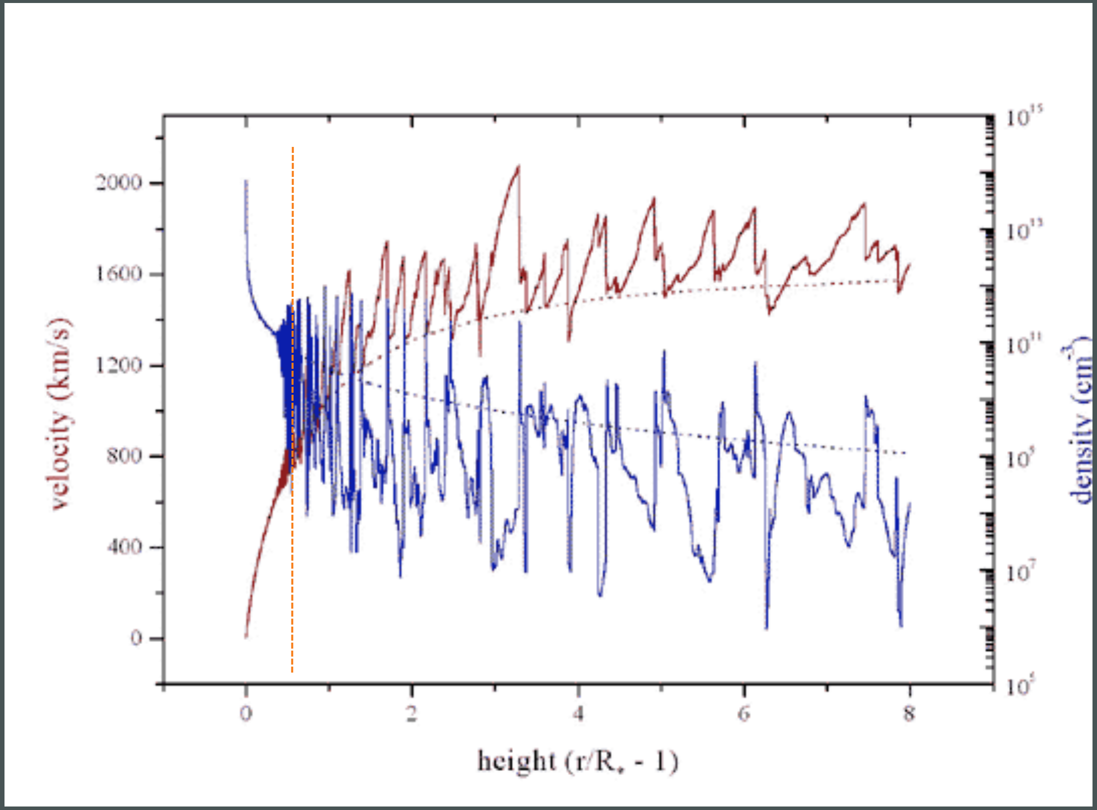




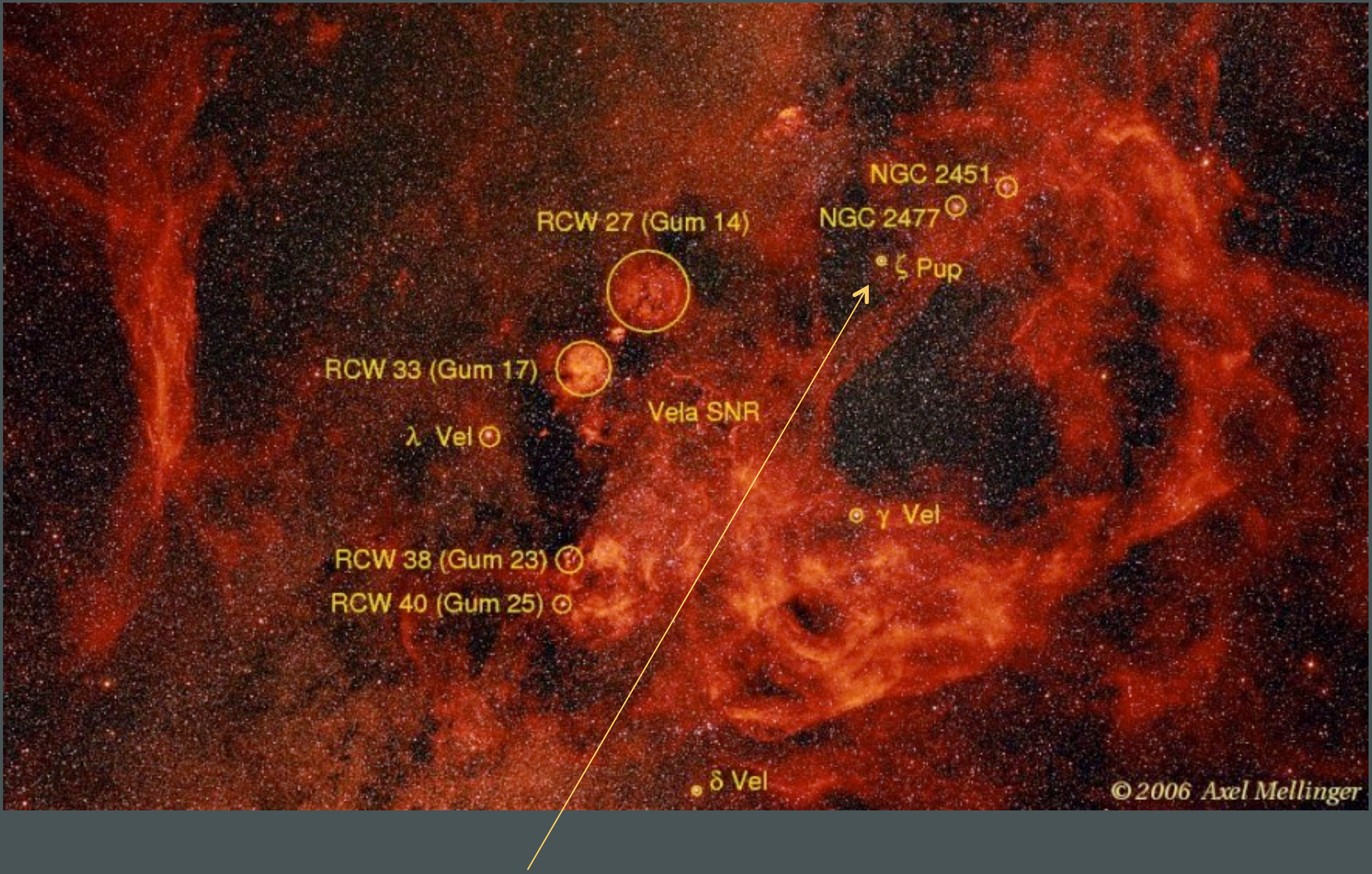
Radiation line driving is inherently unstable:
shock-heating and X-ray emission

# 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.

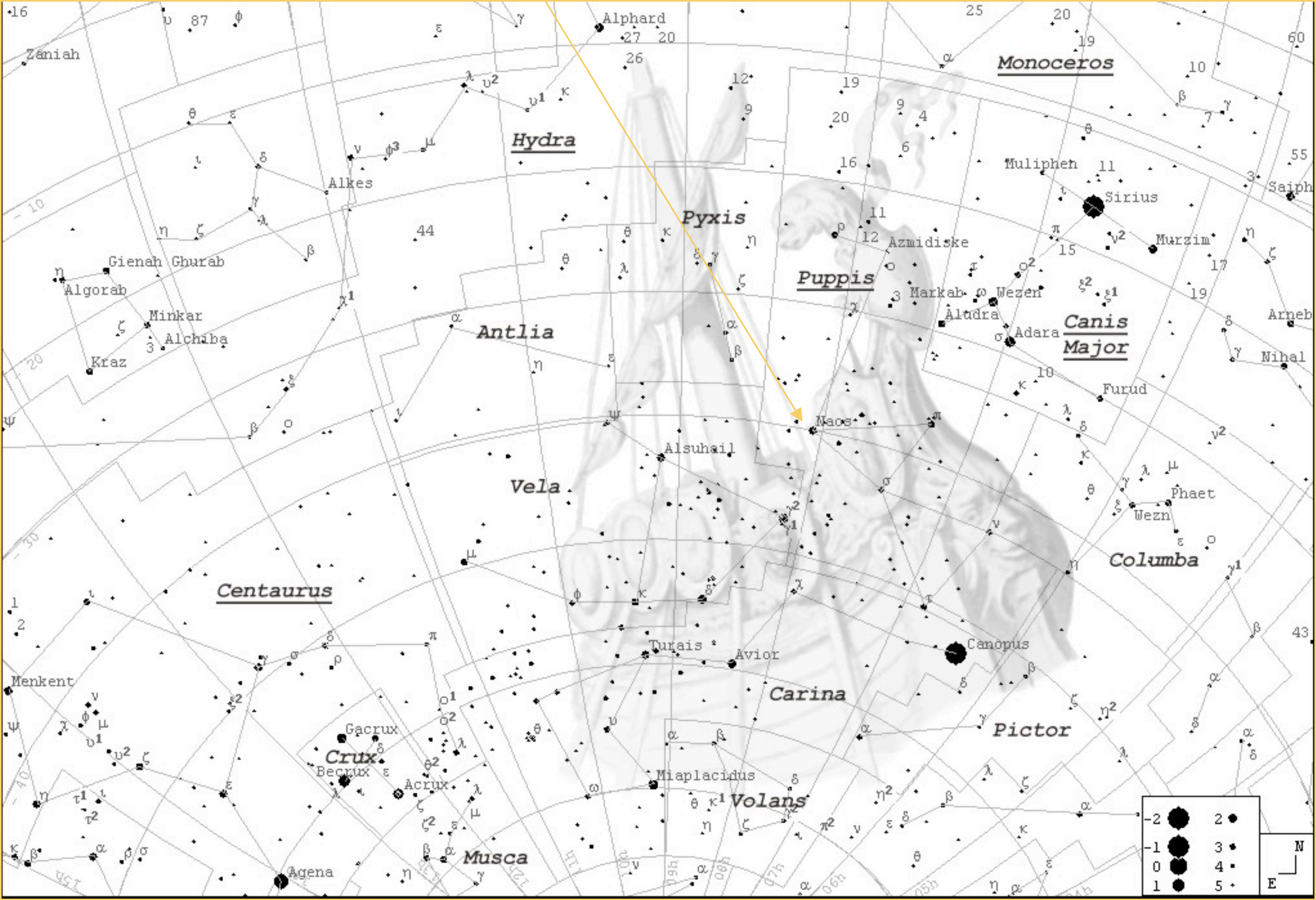


# ζ Puppis in the Gum Nebula



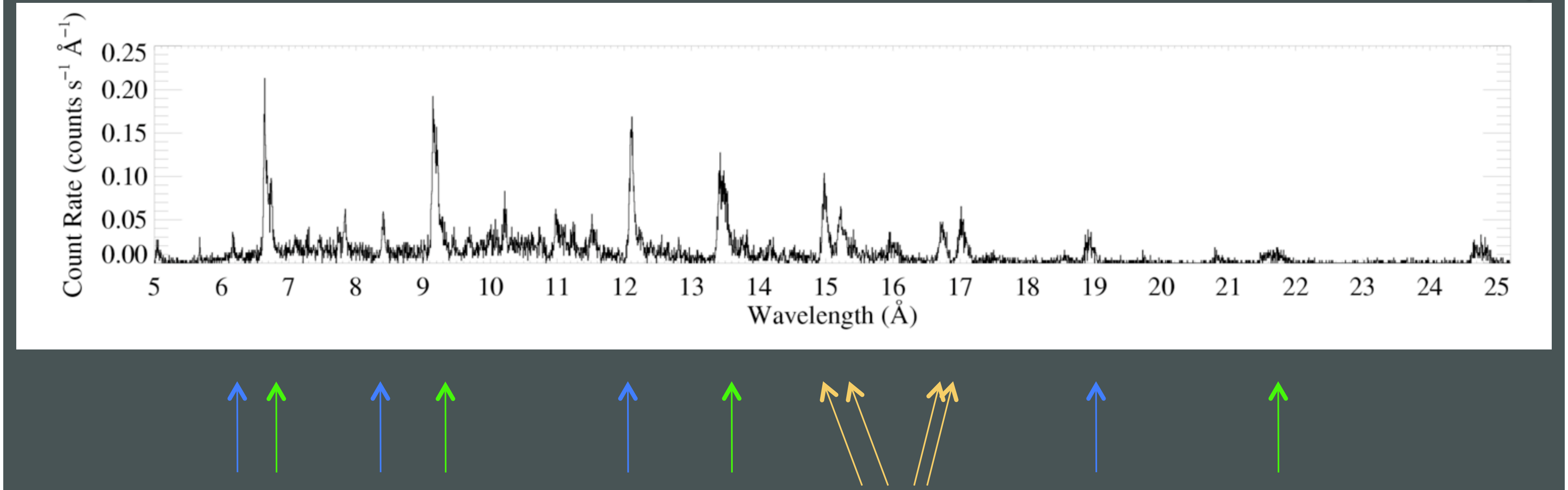
©2006 Axel Mellinger

# ζ Puppis: 50 $M_{sun}$, $10^6$ $L_{sun}$



# *Chandra* HETGS/MEG spectrum
# ($R \sim 1000 \sim 300$ km s$^{-1}$)

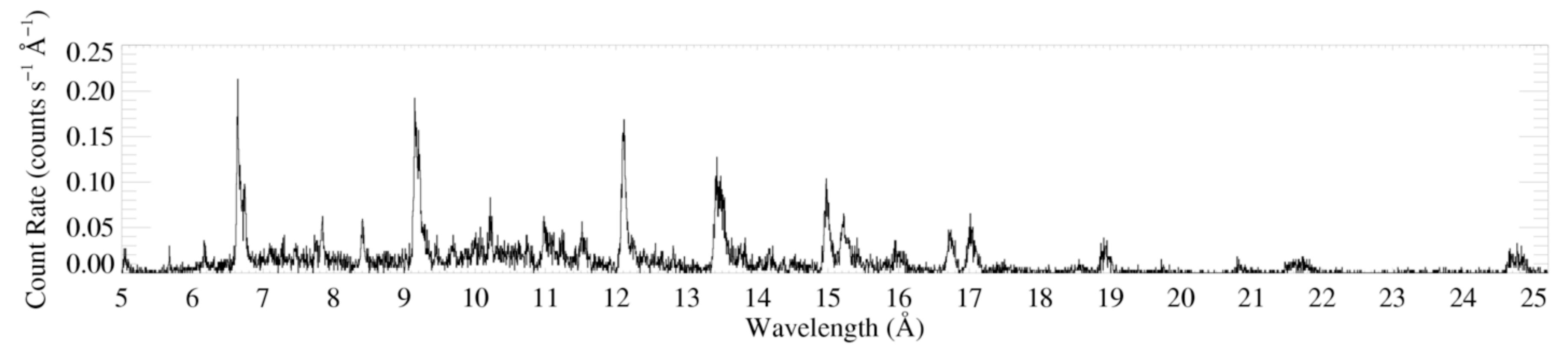
ζ Pup

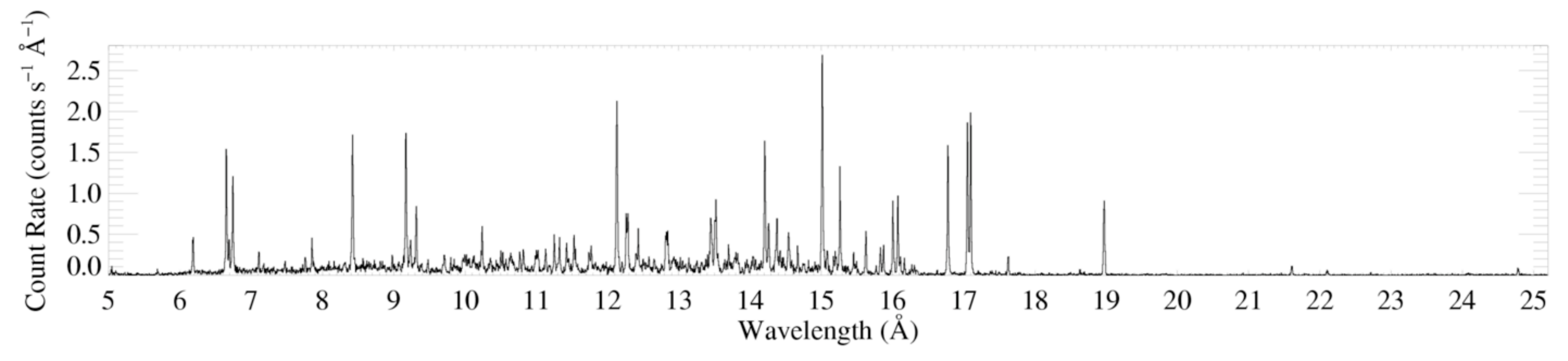


Si Mg Ne Fe O

H-like
He-like

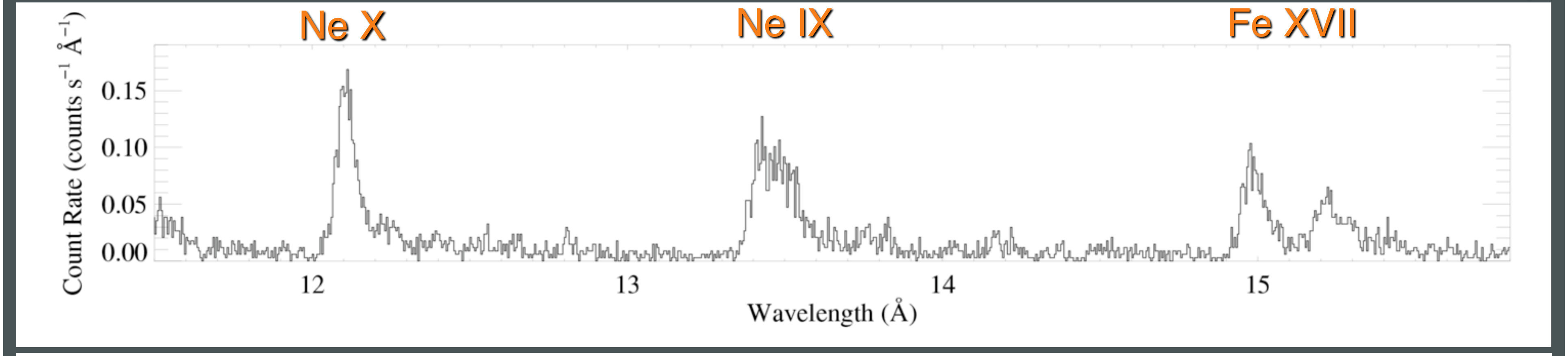
ζ Pup

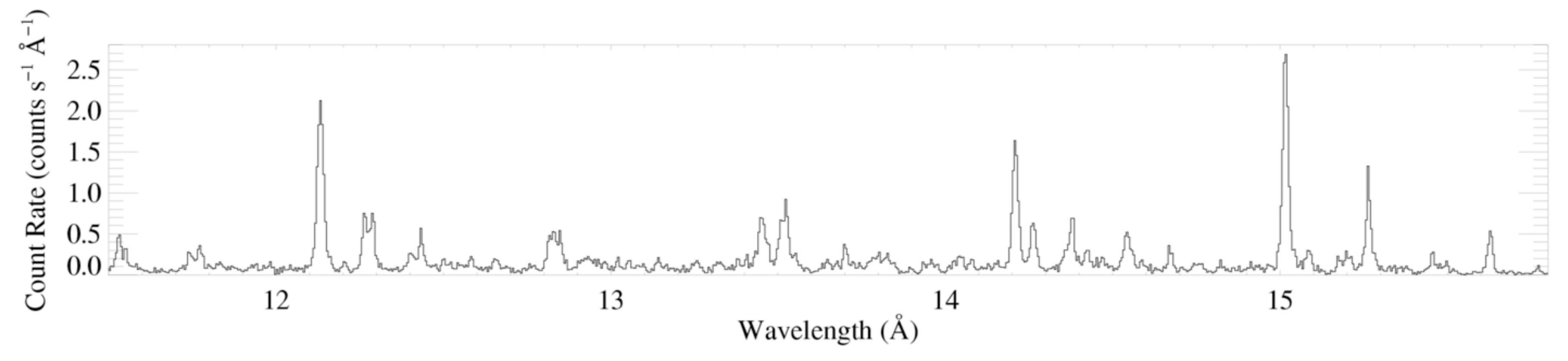




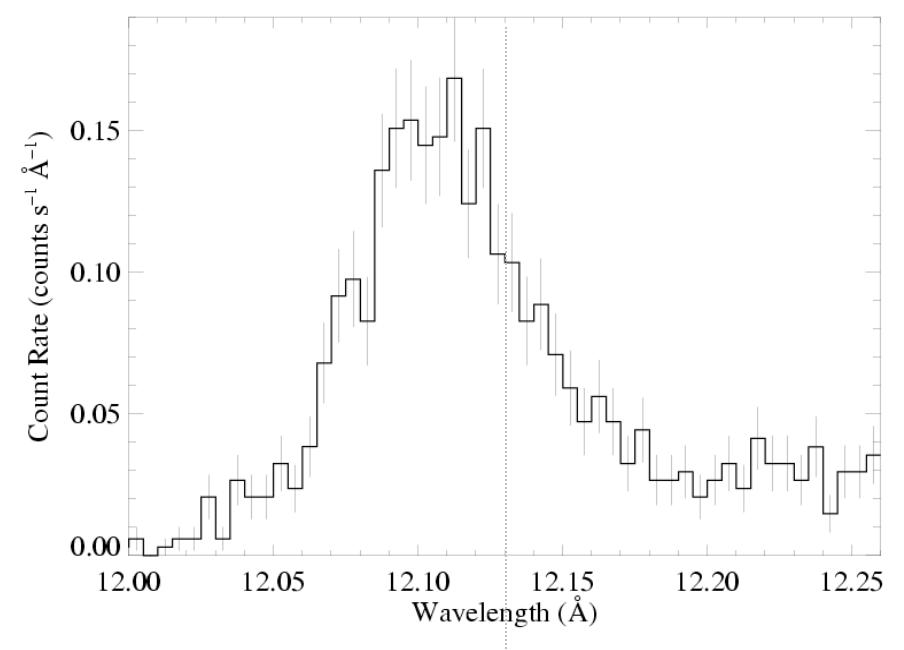
Low-mass star (Capella) for comparison

ζ Pup



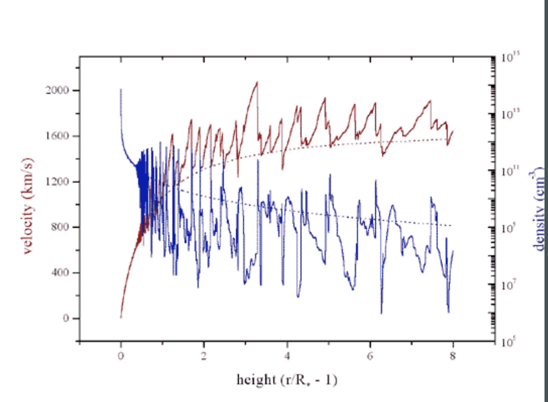


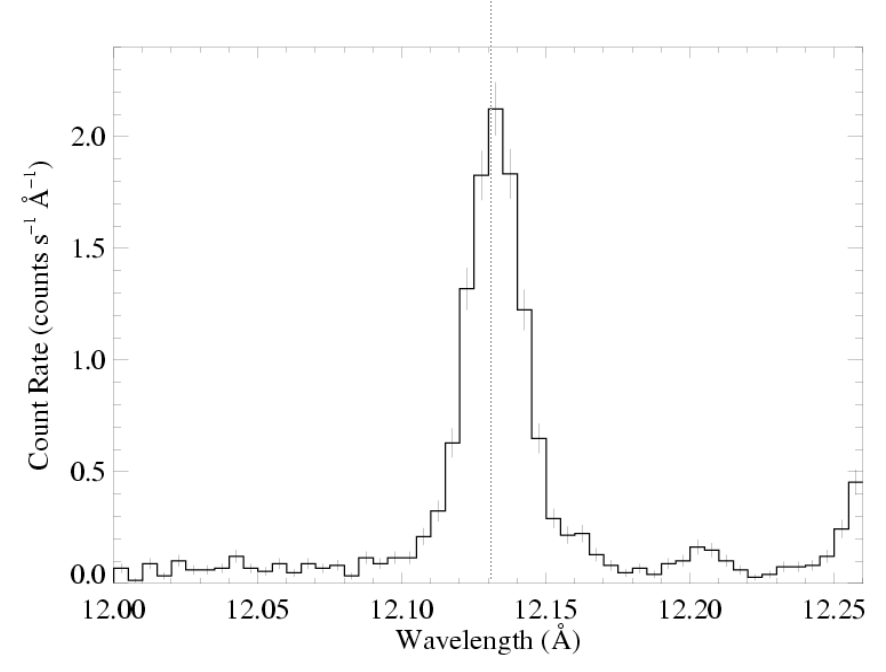
Capella



## ζ Pup

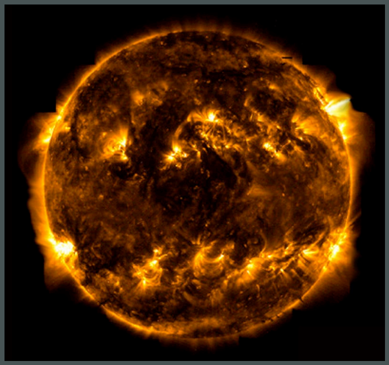
massive



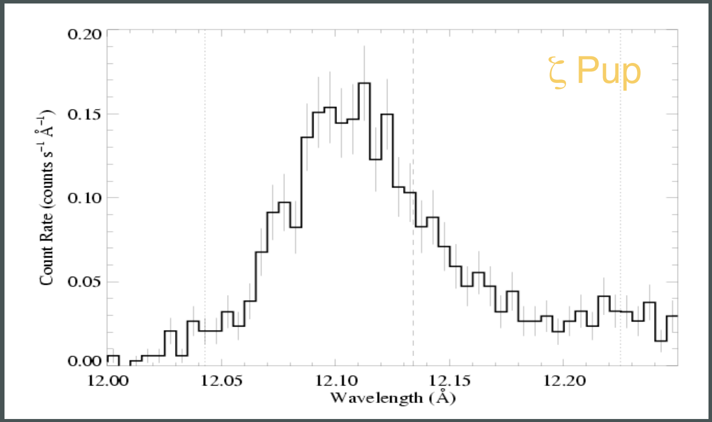


## Capella

low mass

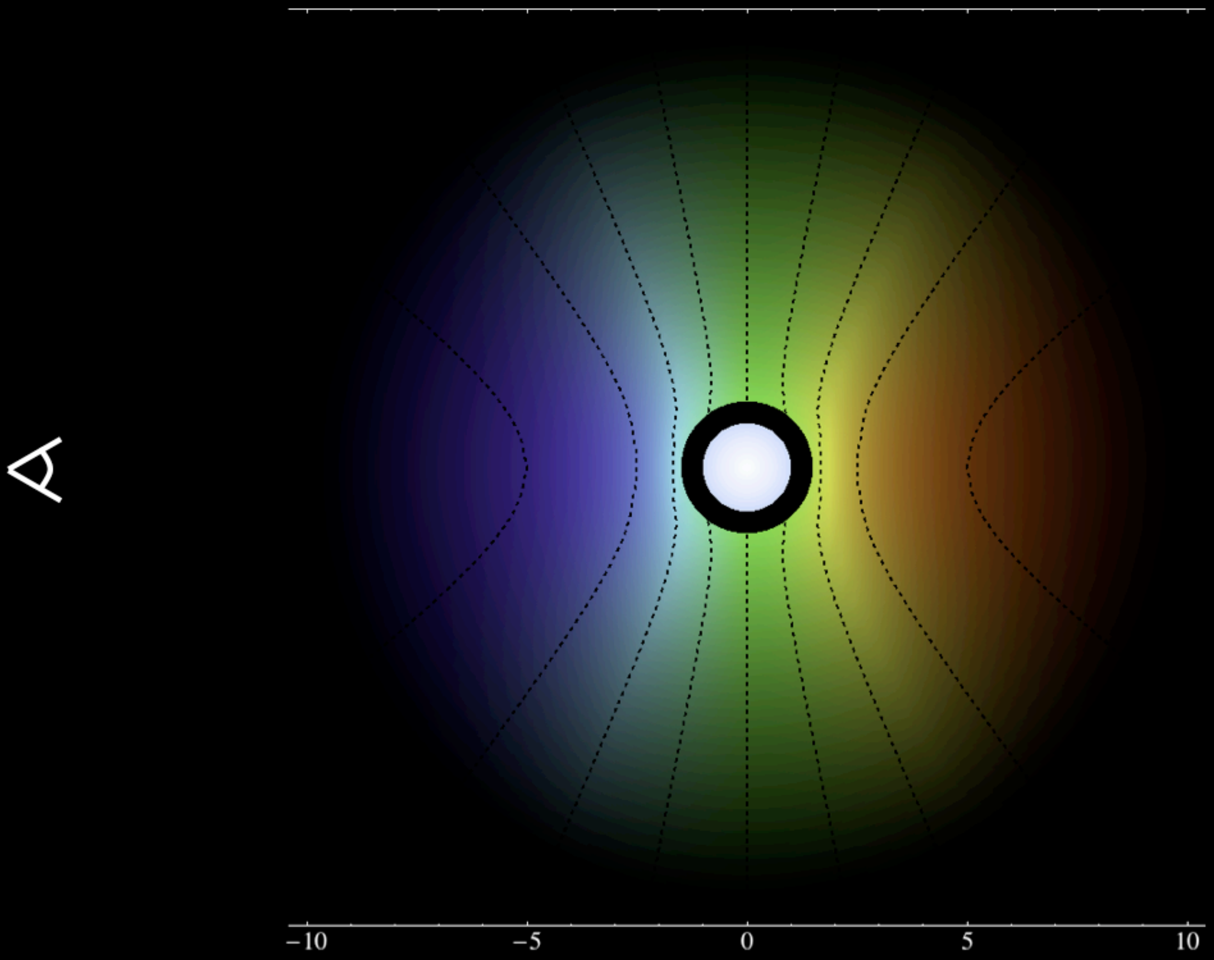


The x-ray emission lines are broad: agreement with rad hydro simulations



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

# Wind Profile Model



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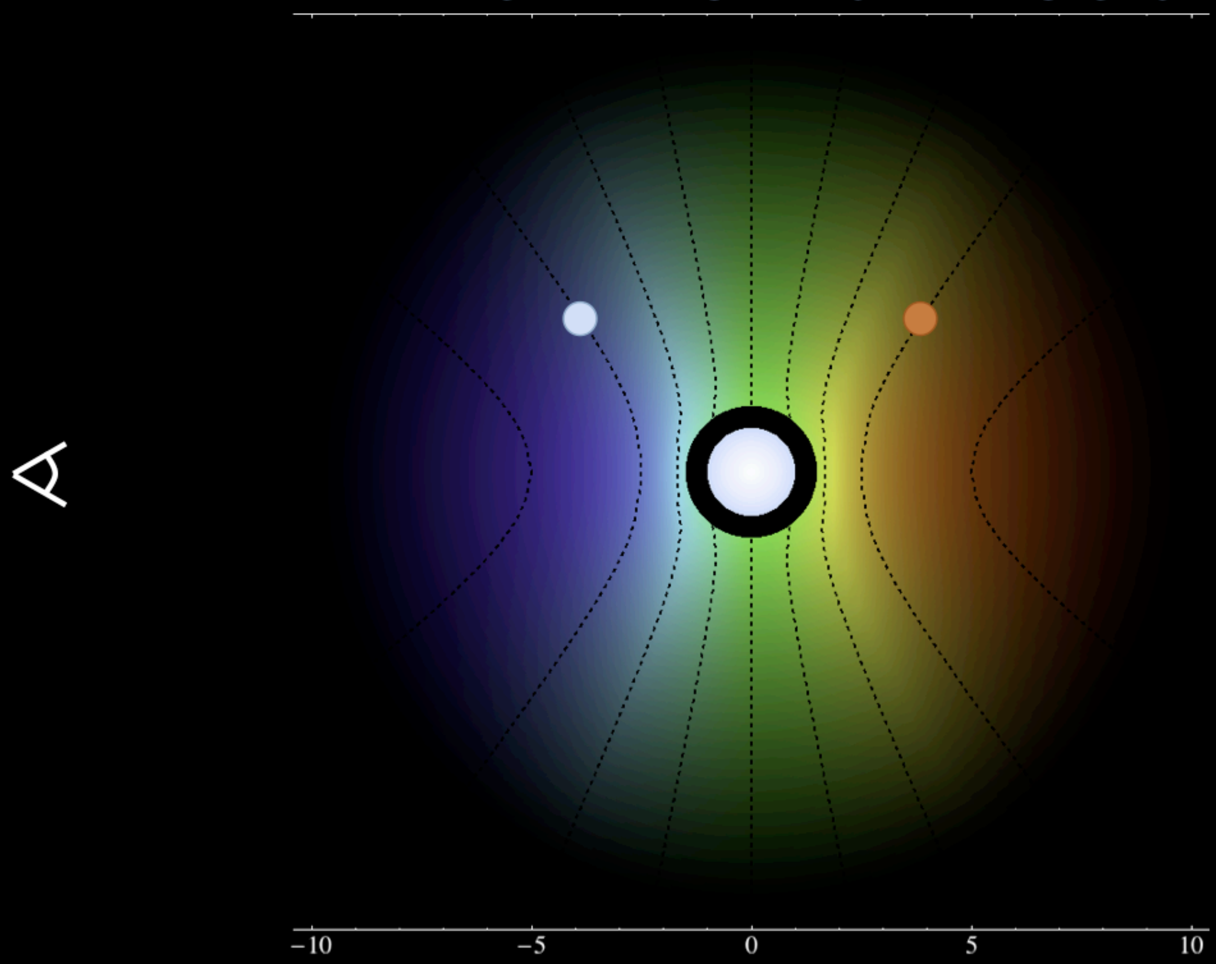

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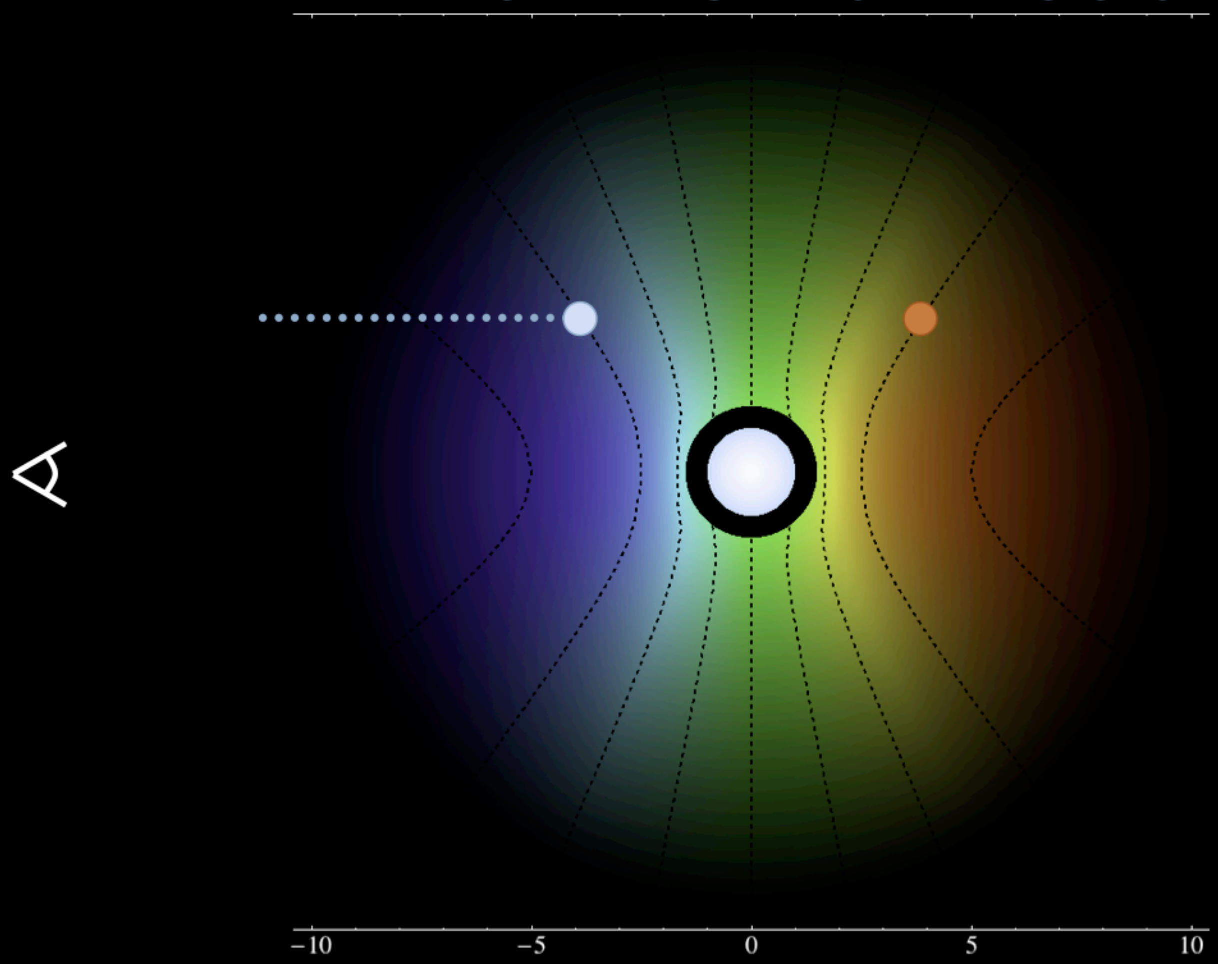

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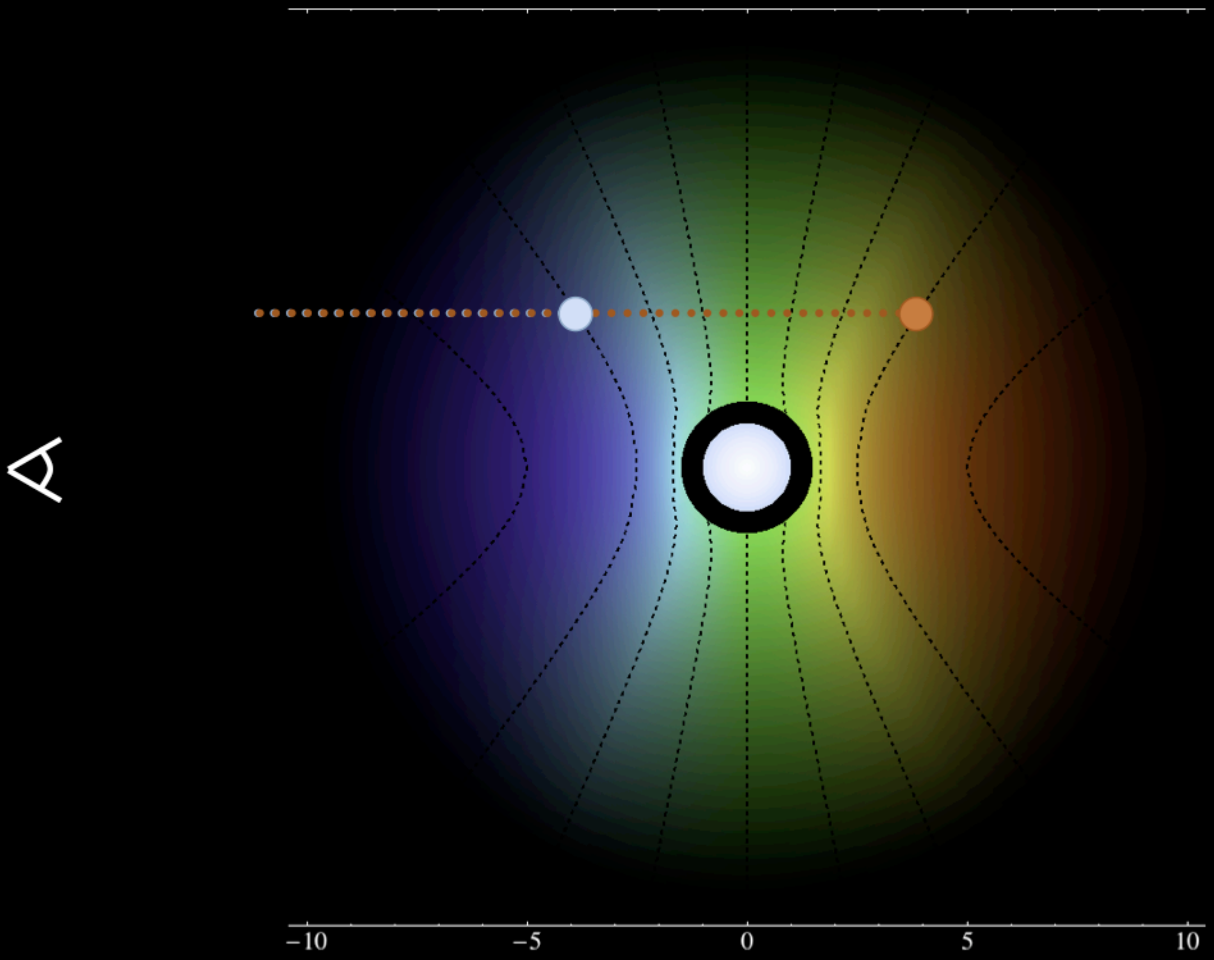

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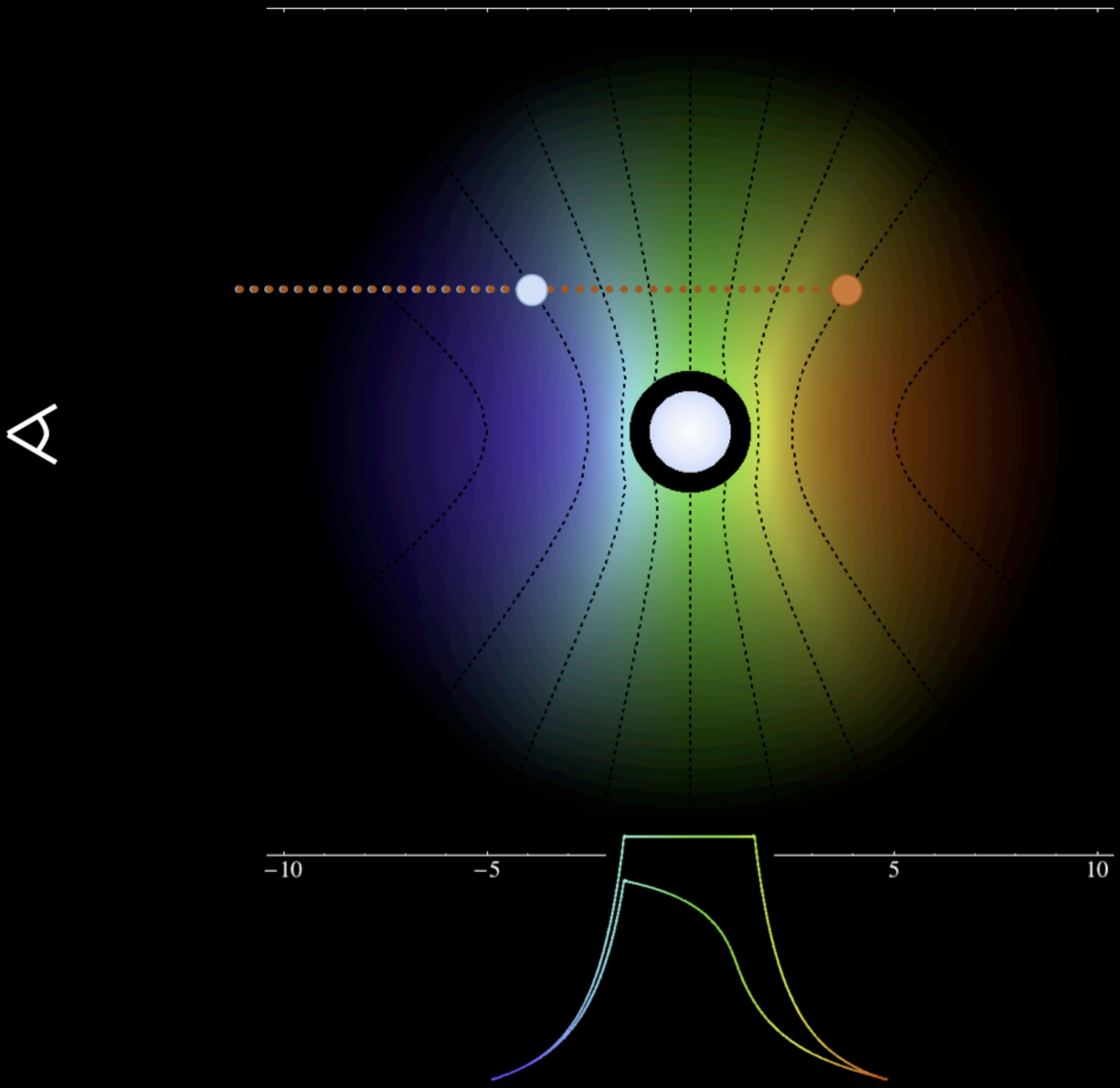
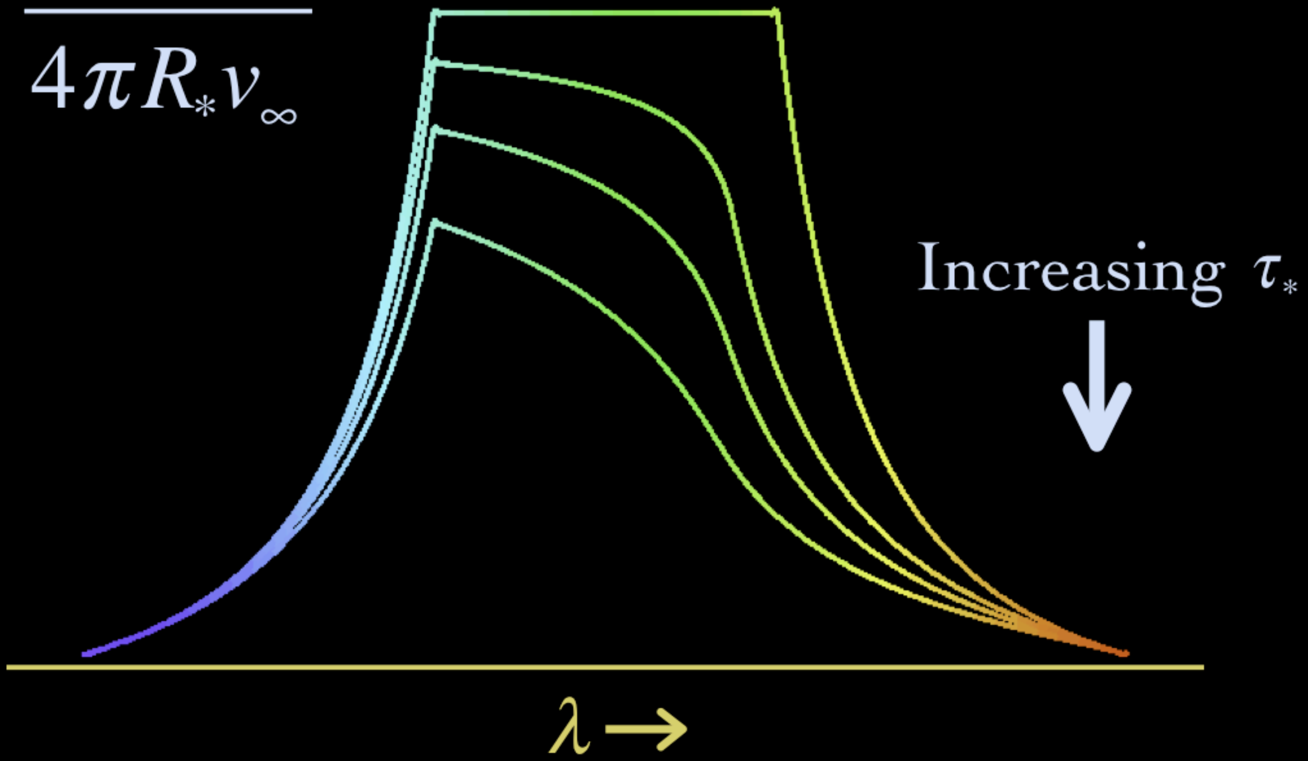


# Wind Profile Model

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



**opacity** of the cold wind component

wind mass-loss rate

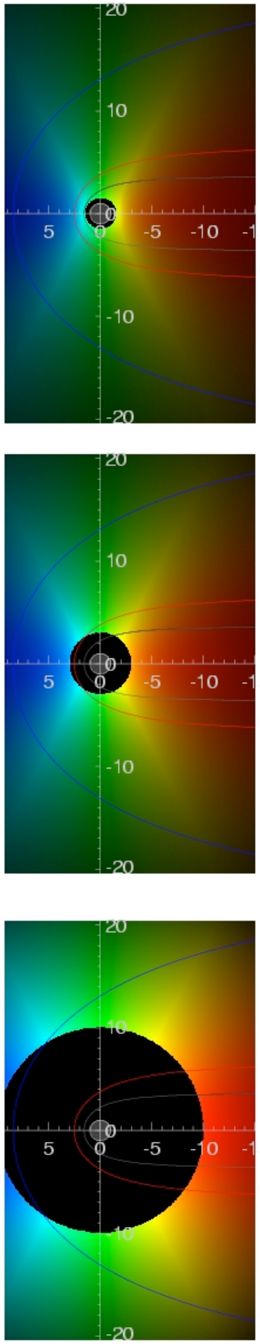
$$\dot{M} = 4\pi r^2 v\rho$$

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

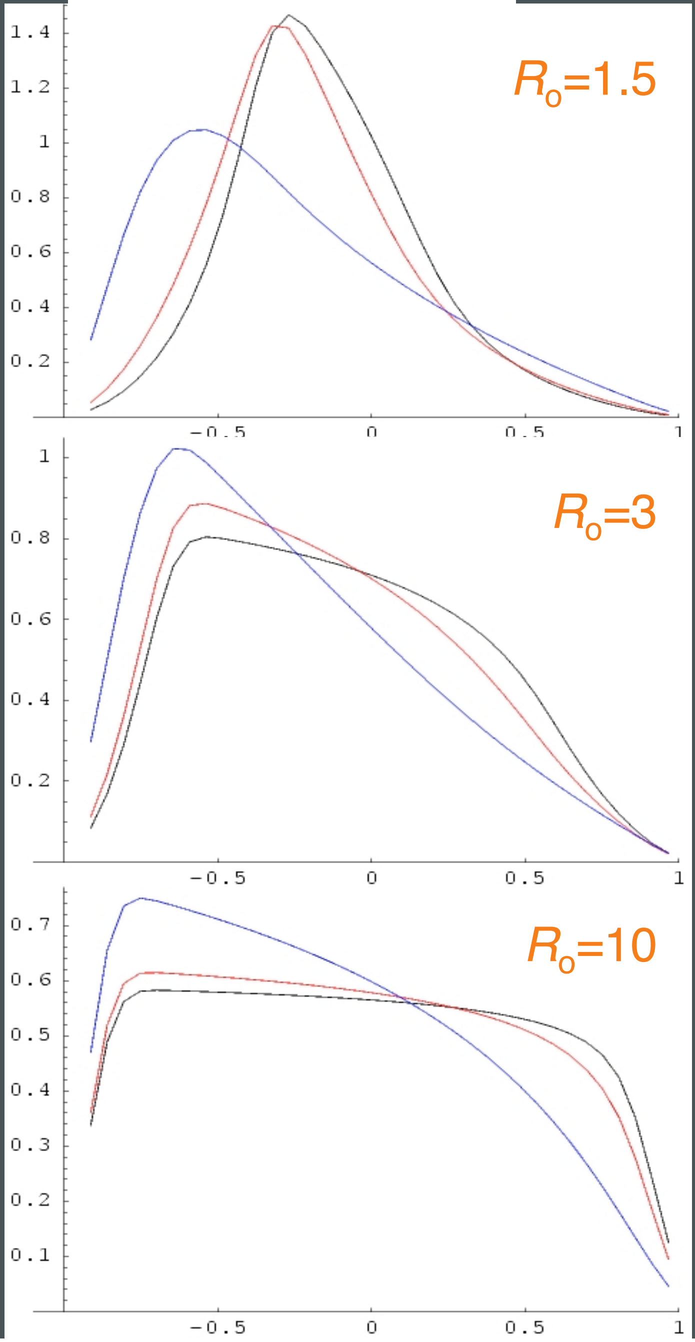
radius of the star

wind terminal velocity

$\tau$=1 contours



$\tau_*$=1,2,8



## key parameters: $R_o$ & $\tau_*$

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

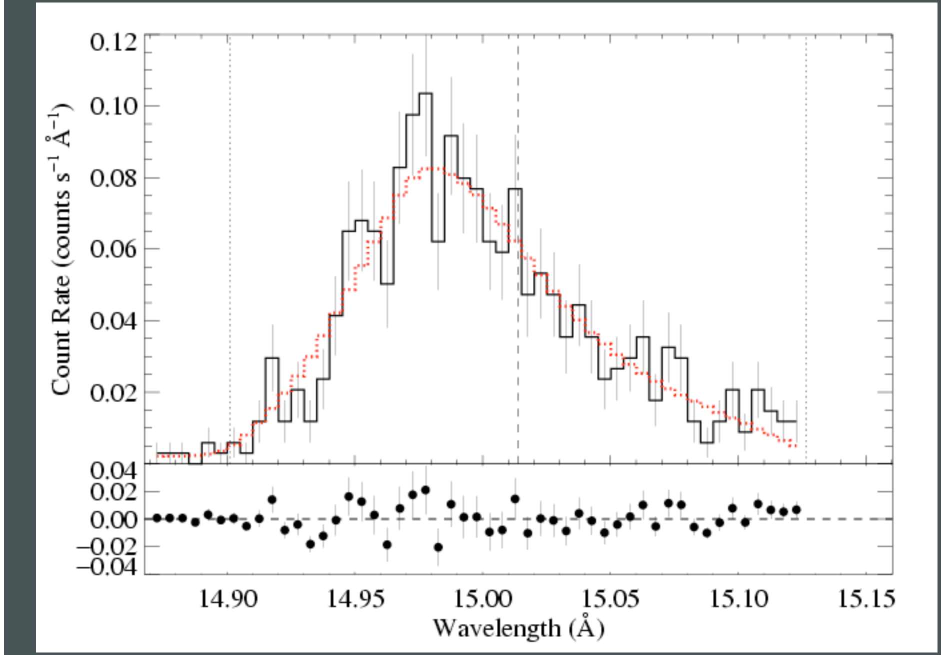
$= 0$ otherwise

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

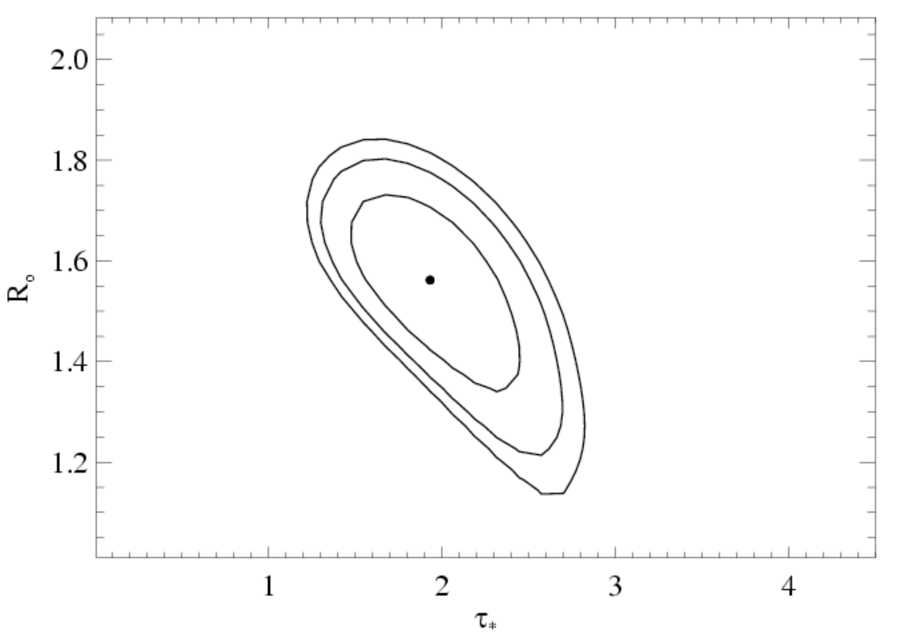
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

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

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

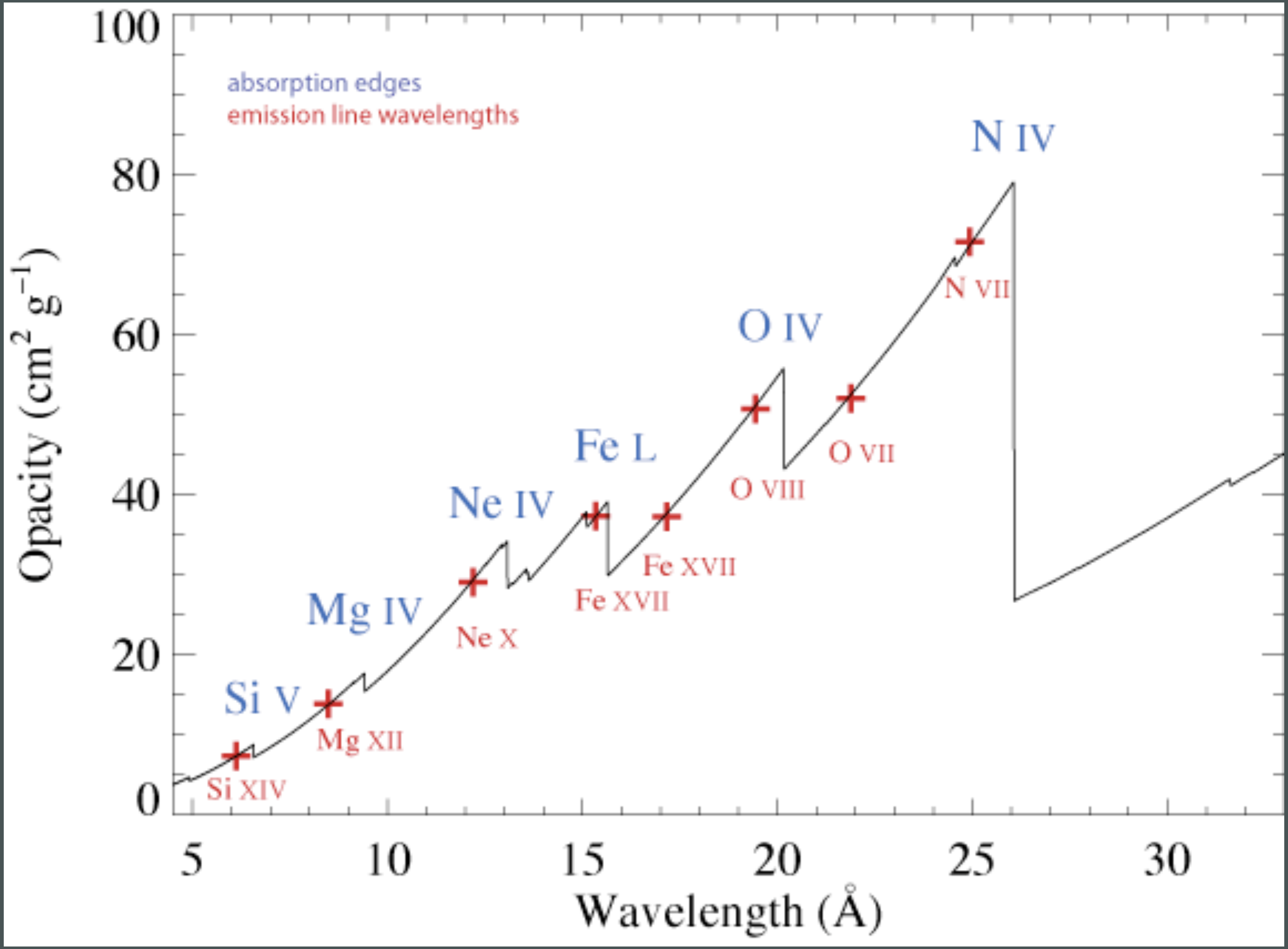


Fe XVII



68, 90, 95% confidence limits

# Wind opacity: photoelectric absorption

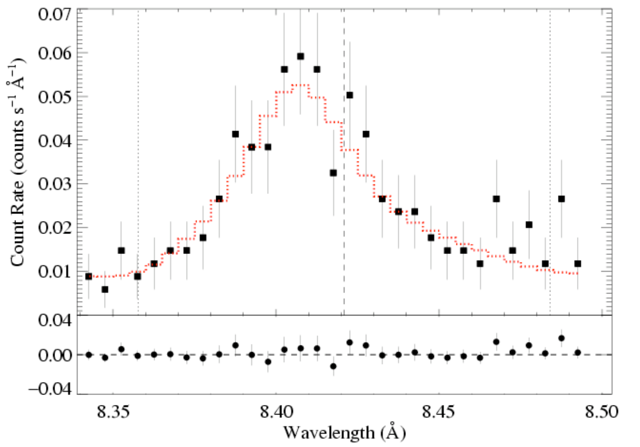


Abundances; ionization balance; atomic cross sections

Verner & Yakovlev 1996

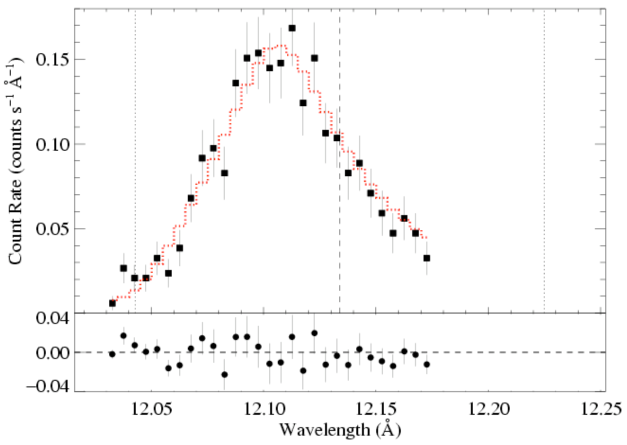
# ζ Pup: three emission lines

## Mg Lyα: 8.42 Å



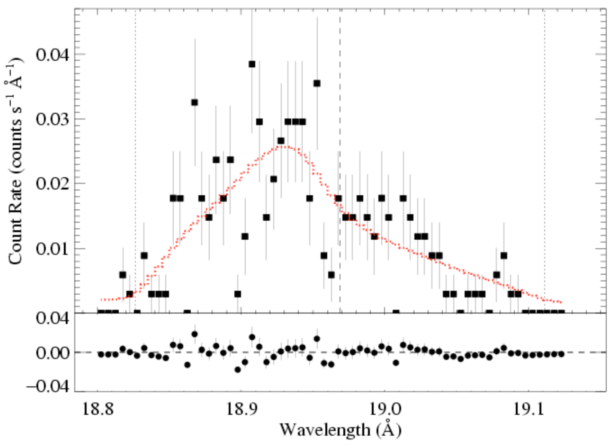
**$\tau_* = 1$**

## Ne Lyα: 12.13 Å



**$\tau_* = 2$**

## O Lyα: 18.97 Å

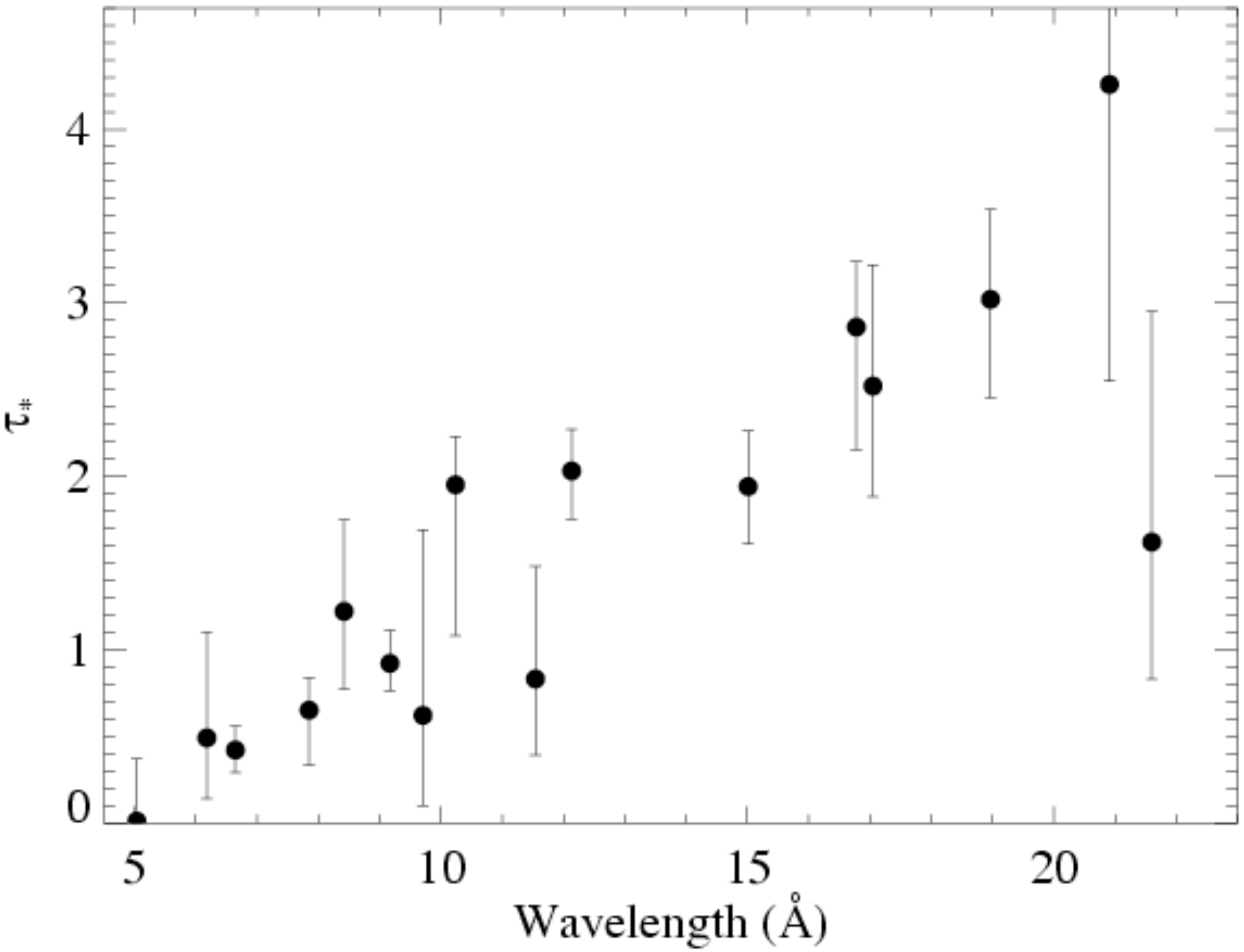


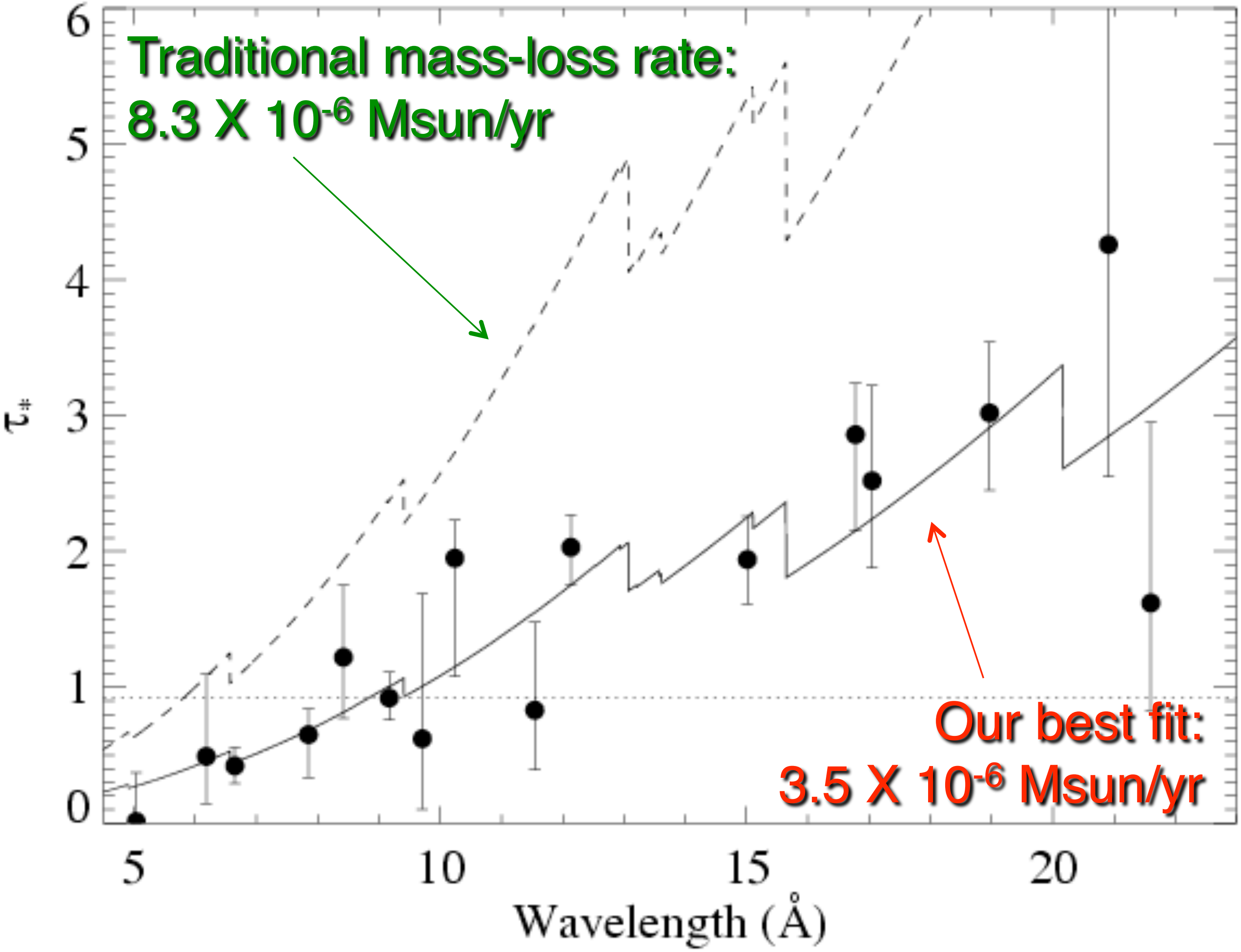
**$\tau_* = 3$**

*Recall:*

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

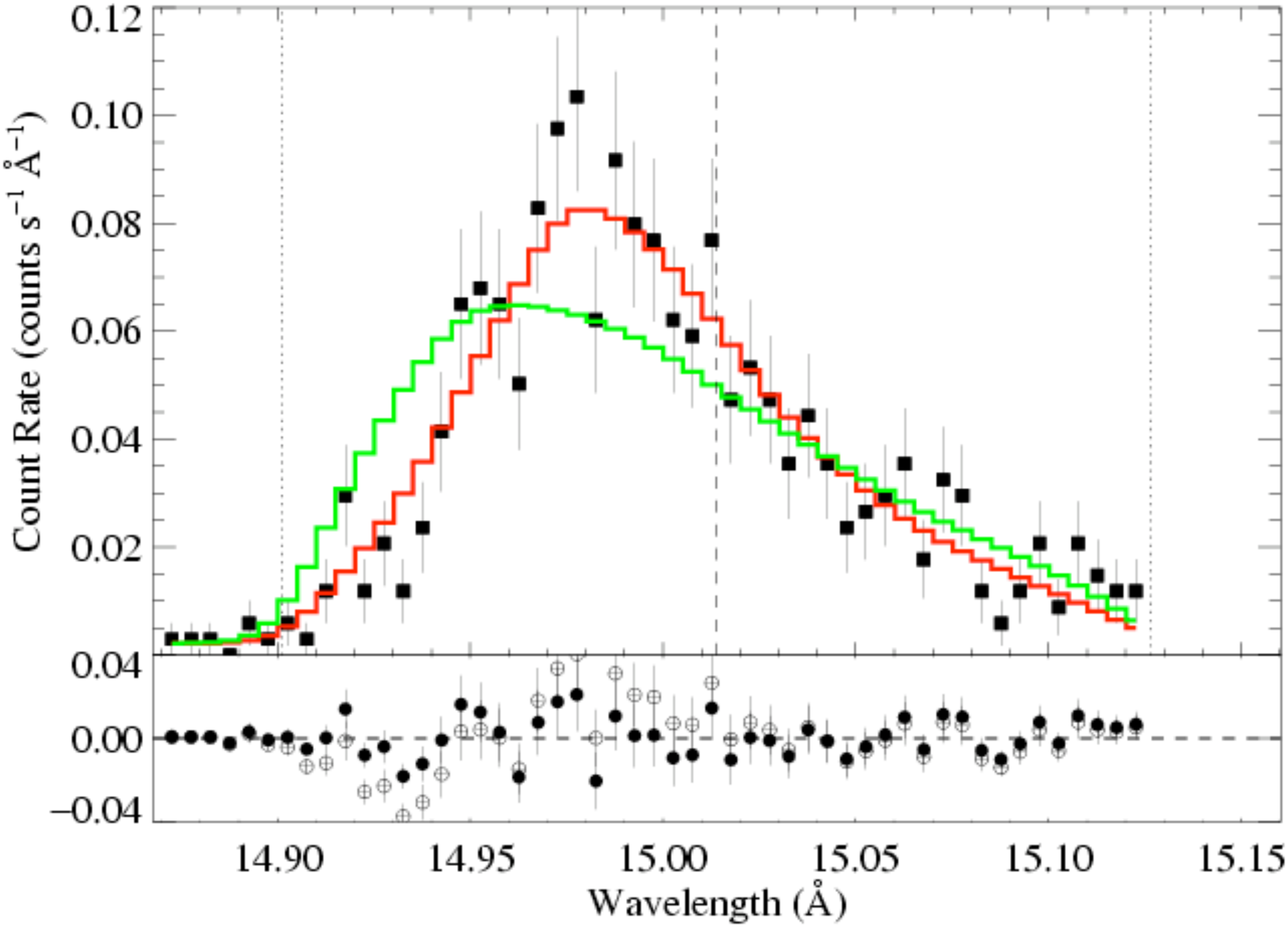
# Fits to 16 lines in the *Chandra* spectrum of ζ Pup





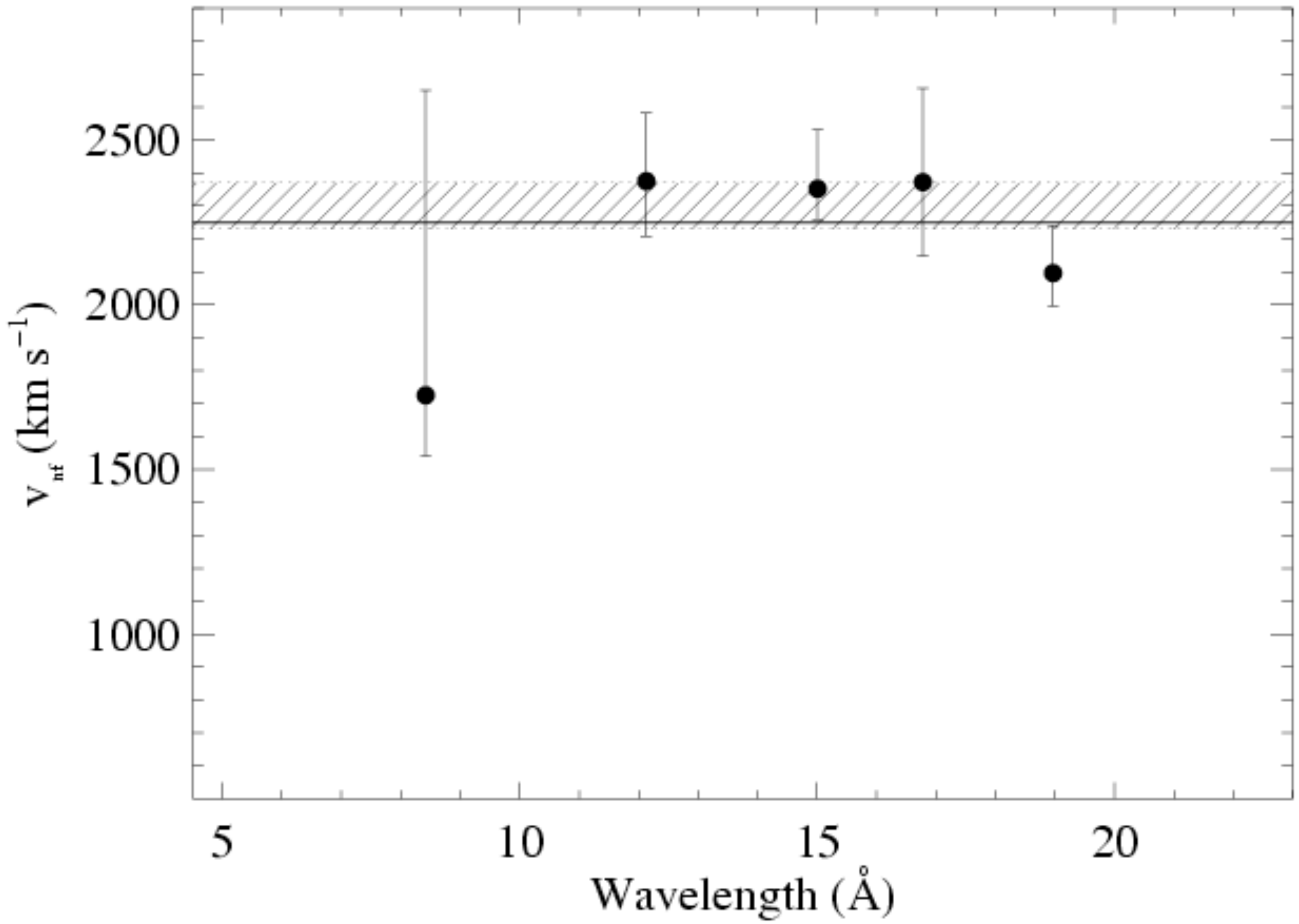
Traditional mass-loss rate:
8.3 X $10^{-6}$ Msun/yr

Our best fit:
3.5 X $10^{-6}$ Msun/yr

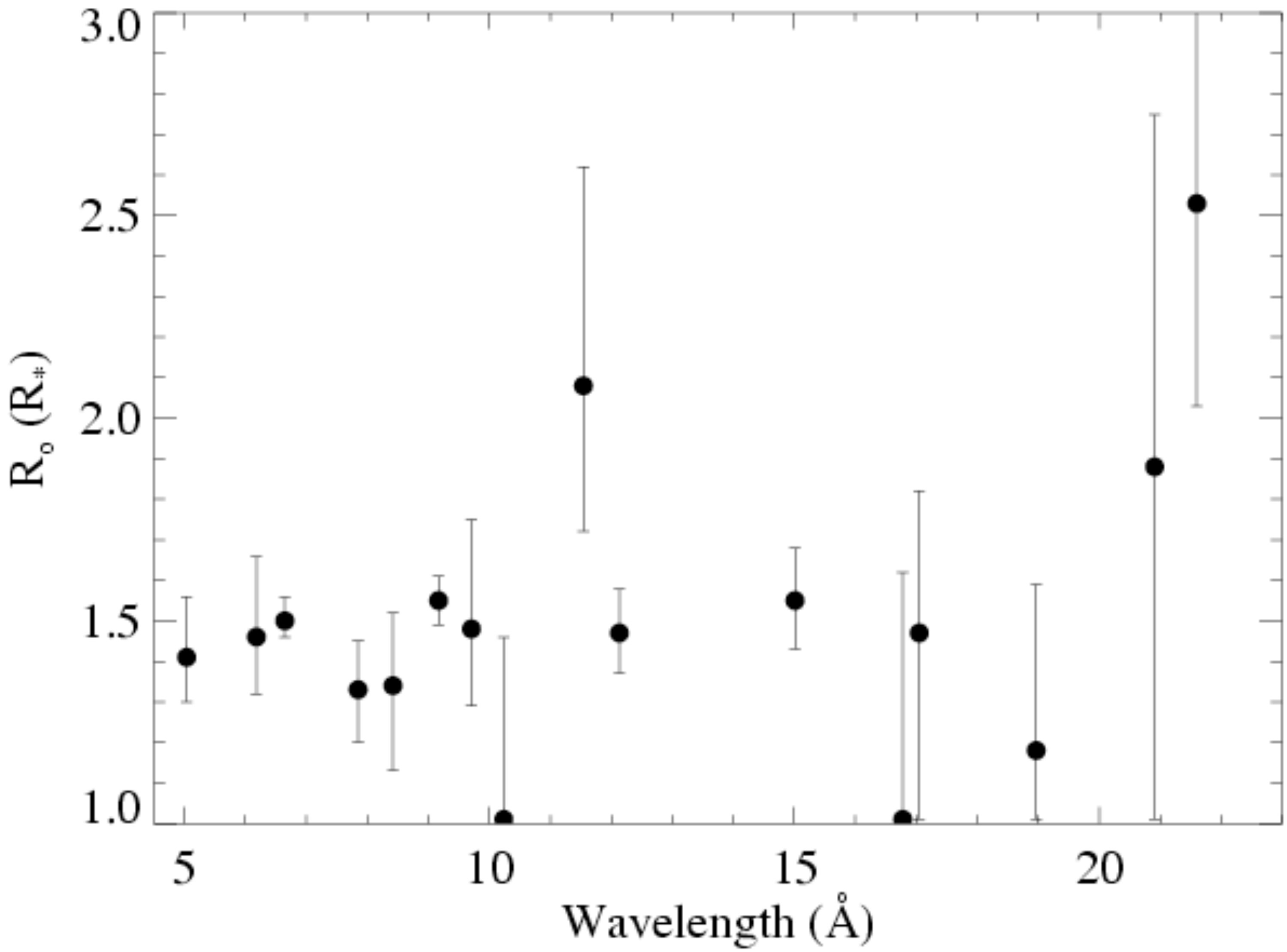


0.12
0.10
0.08
0.06
0.04
0.02
Count Rate (counts $s^{-1}$ Å$^{-1}$)
0.04
0.00
−0.04
14.90
14.95
15.00
15.05
15.10
15.15
Wavelength (Å)

# Terminal velocity of the x-ray plasma – from line fitting

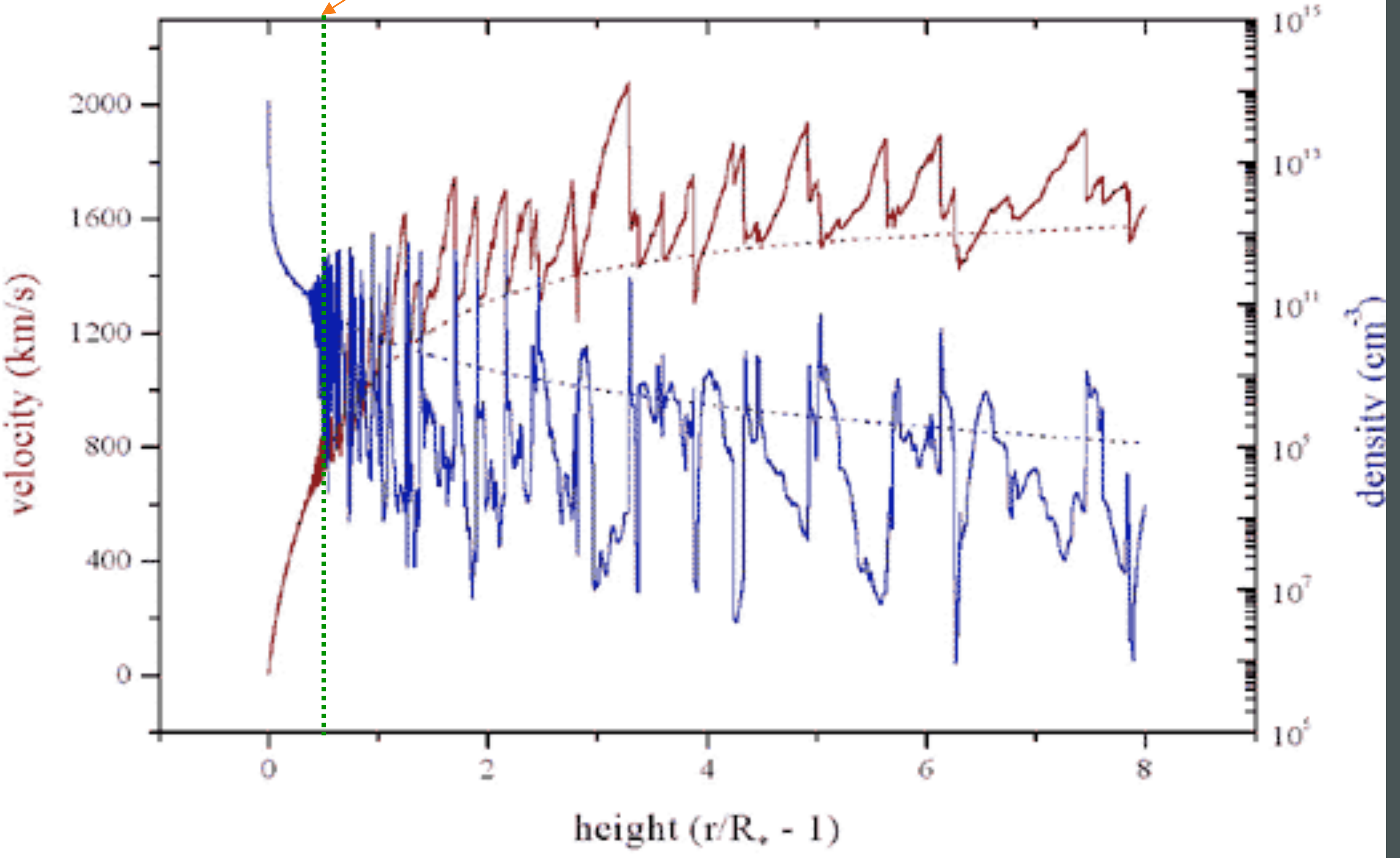


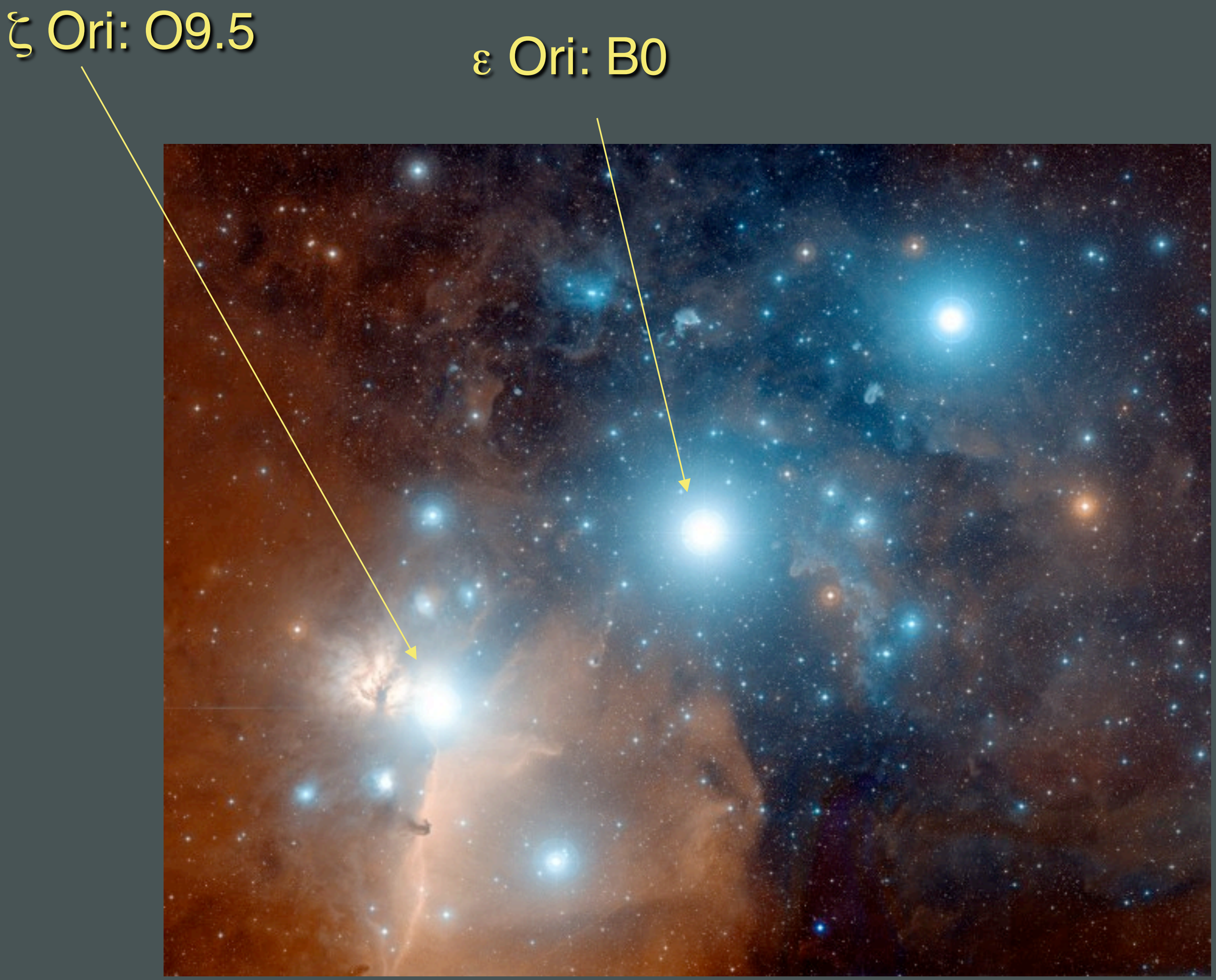
# onset radius of x-ray emission, $R_o$



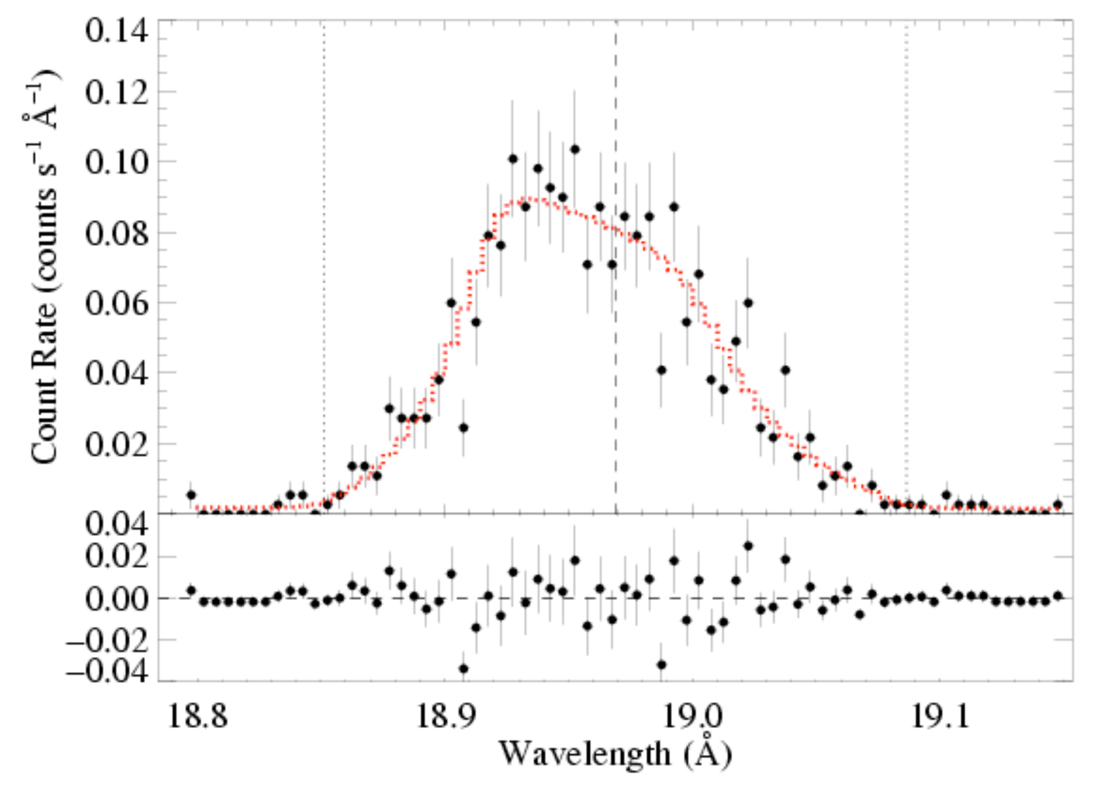
# Onset of instability-induced shock structure: $R_o \sim 1.5$

1.5 R* = height of 0.5 R*

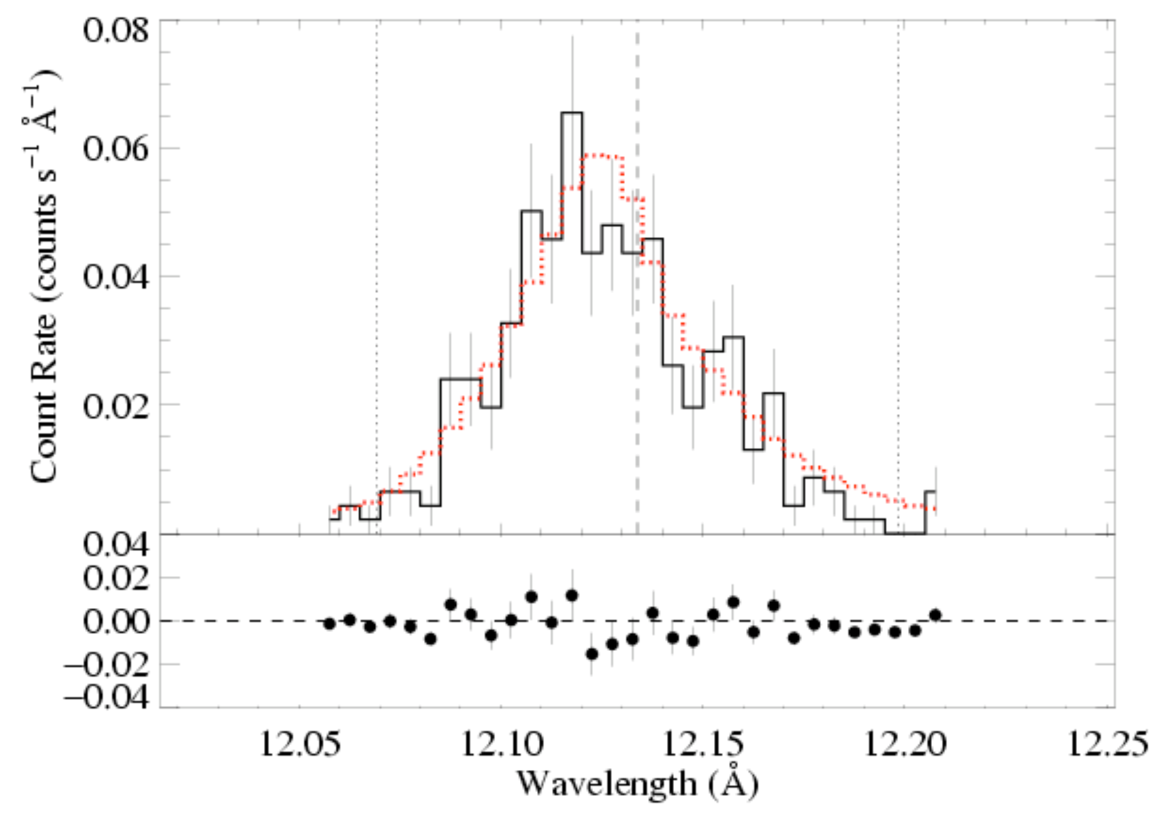



ζ Ori: O9.5
ε Ori: B0

# ζ Ori (09.7 I): O Lyα 18.97 Å



# ε Ori (B0 Ia): Ne Lyα 12.13 Å



# Conclusions

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

- Line widths are consistent with the wind velocity inferred from UV absorption lines;
- Onset radius of X-rays is $r \sim 1.5\ R_{star}$

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*.