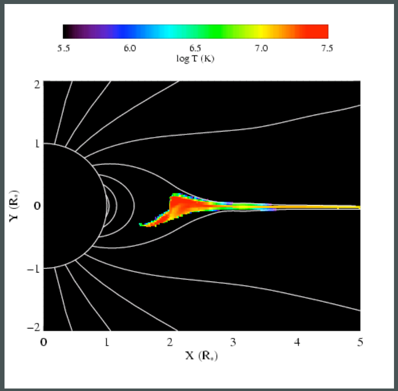
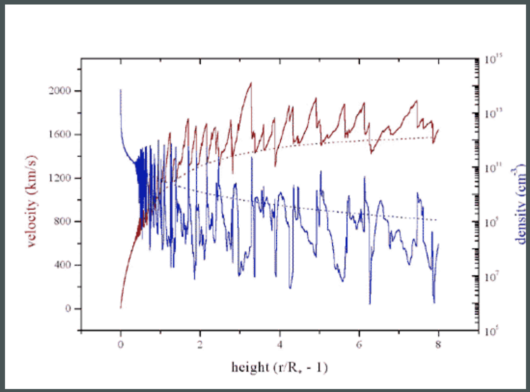
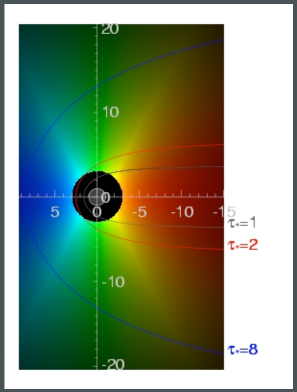
High-Resolution X-ray Spectroscopy of the Winds of Massive Stars

David Cohen
Swarthmore College





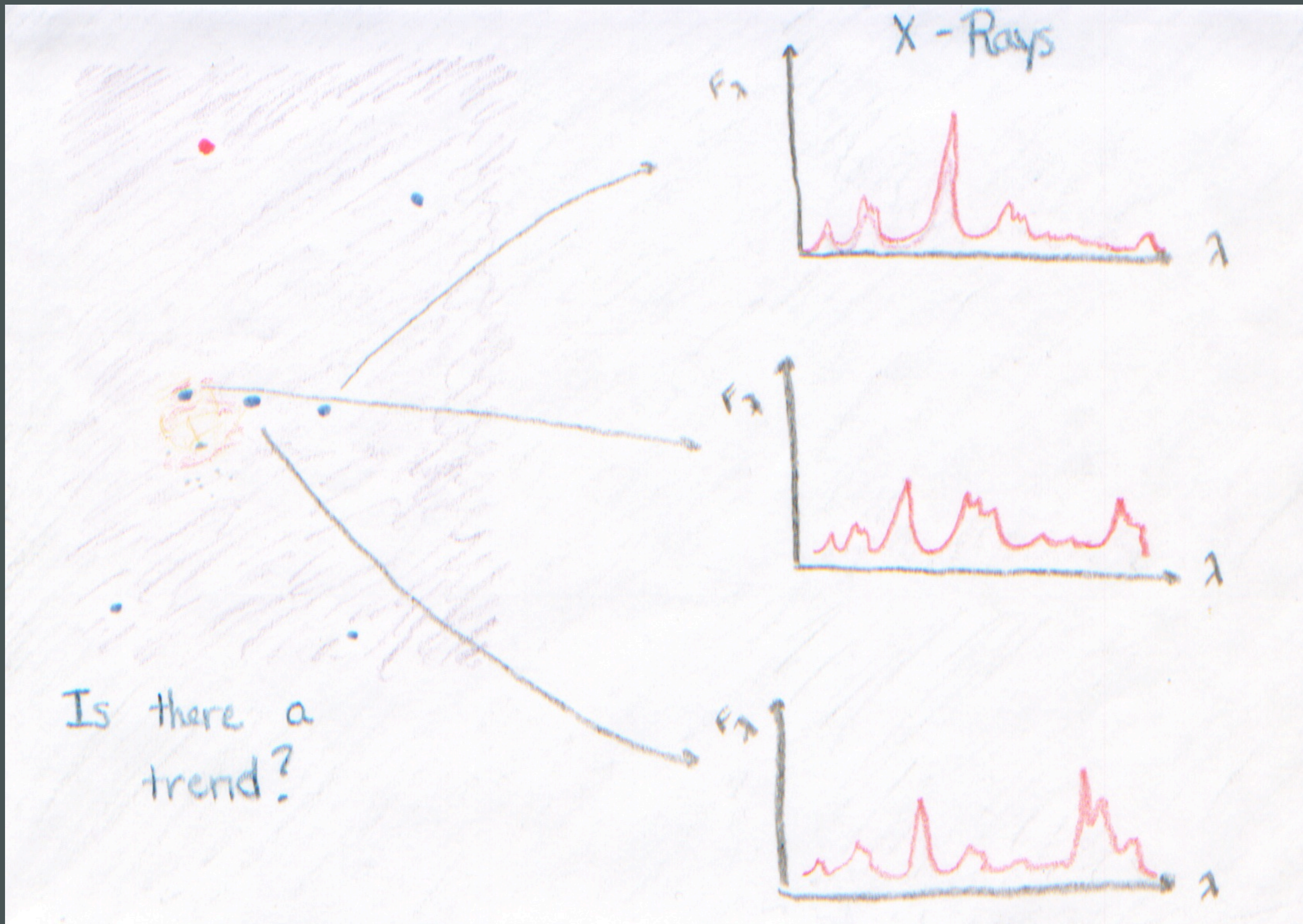



Dennis di Cicco/Sean Walker

Orion

Orion’s belt stars

De Martin/Digitized Sky Survey



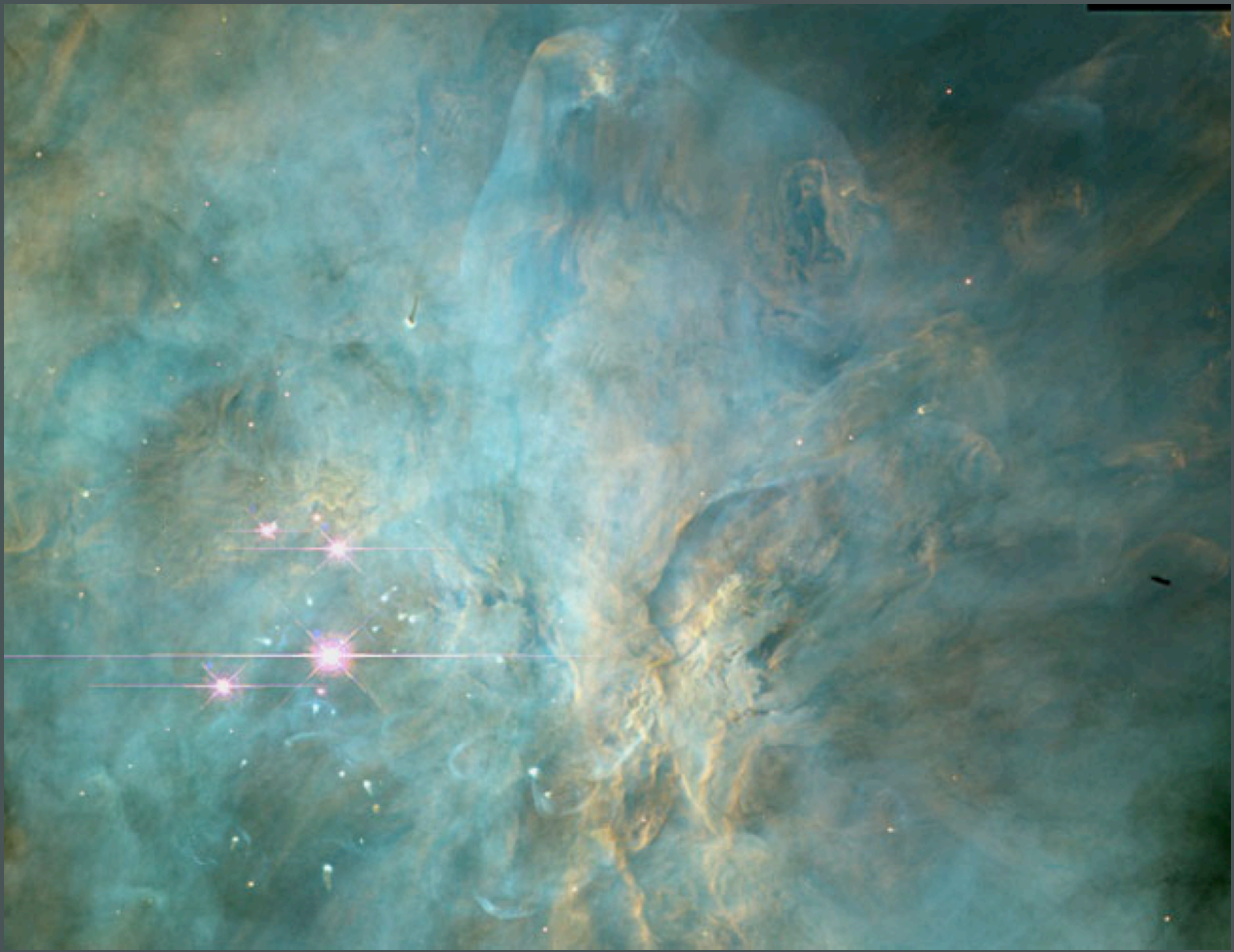
Erin Martell

Great Nebula of Orion

Robberto/HST

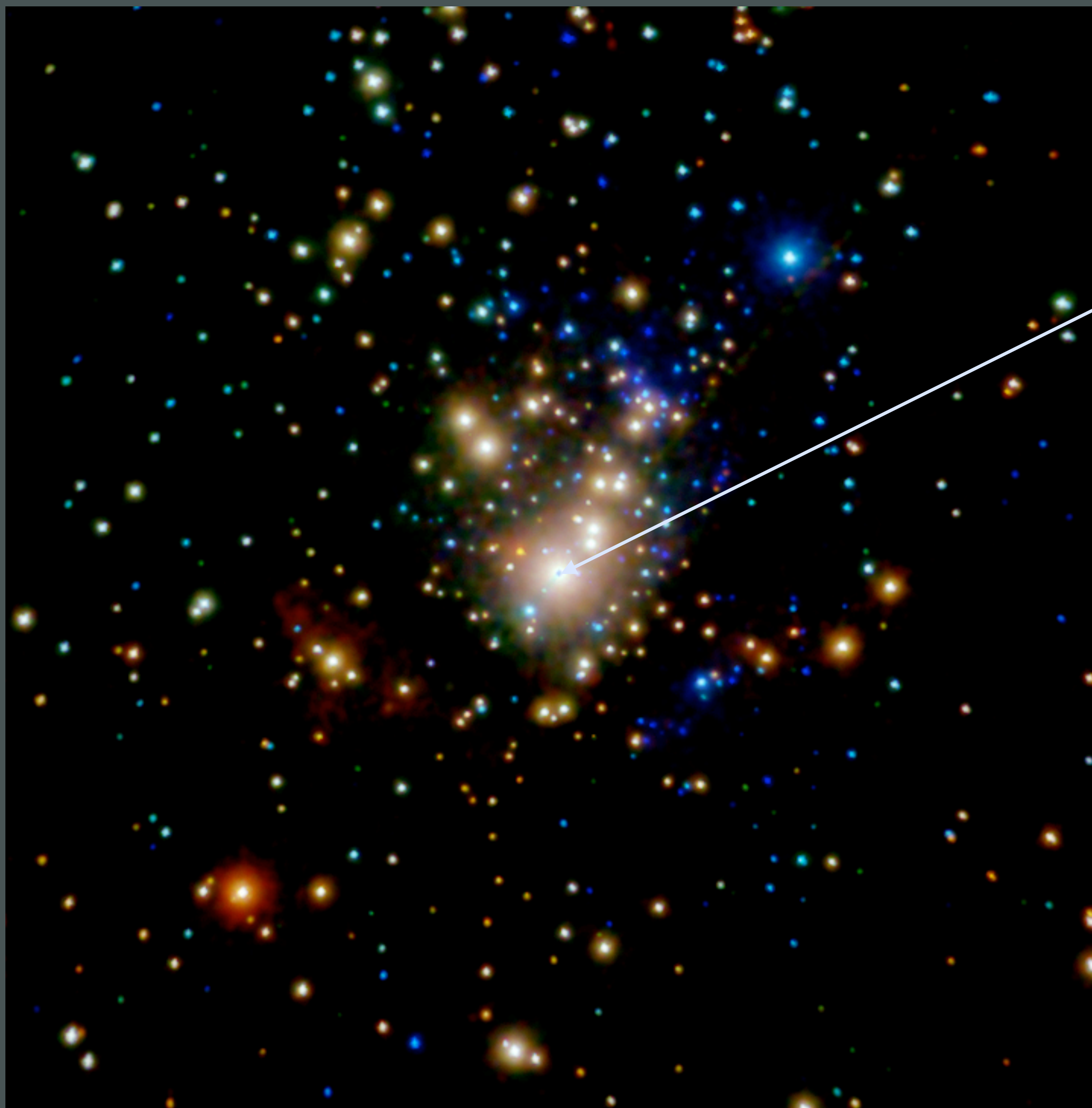
Megeath/Spitzer

Trapezium: massive, luminous stars at the center of the nebula



Bally/HST

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)


Dennis di Cicco/Sean Walker

Carina/Keyhole Nebula (HST)

massive stars:

20 to 100 M_{sun}

10^6 L_{sun}

T ~ 50,000 K

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)

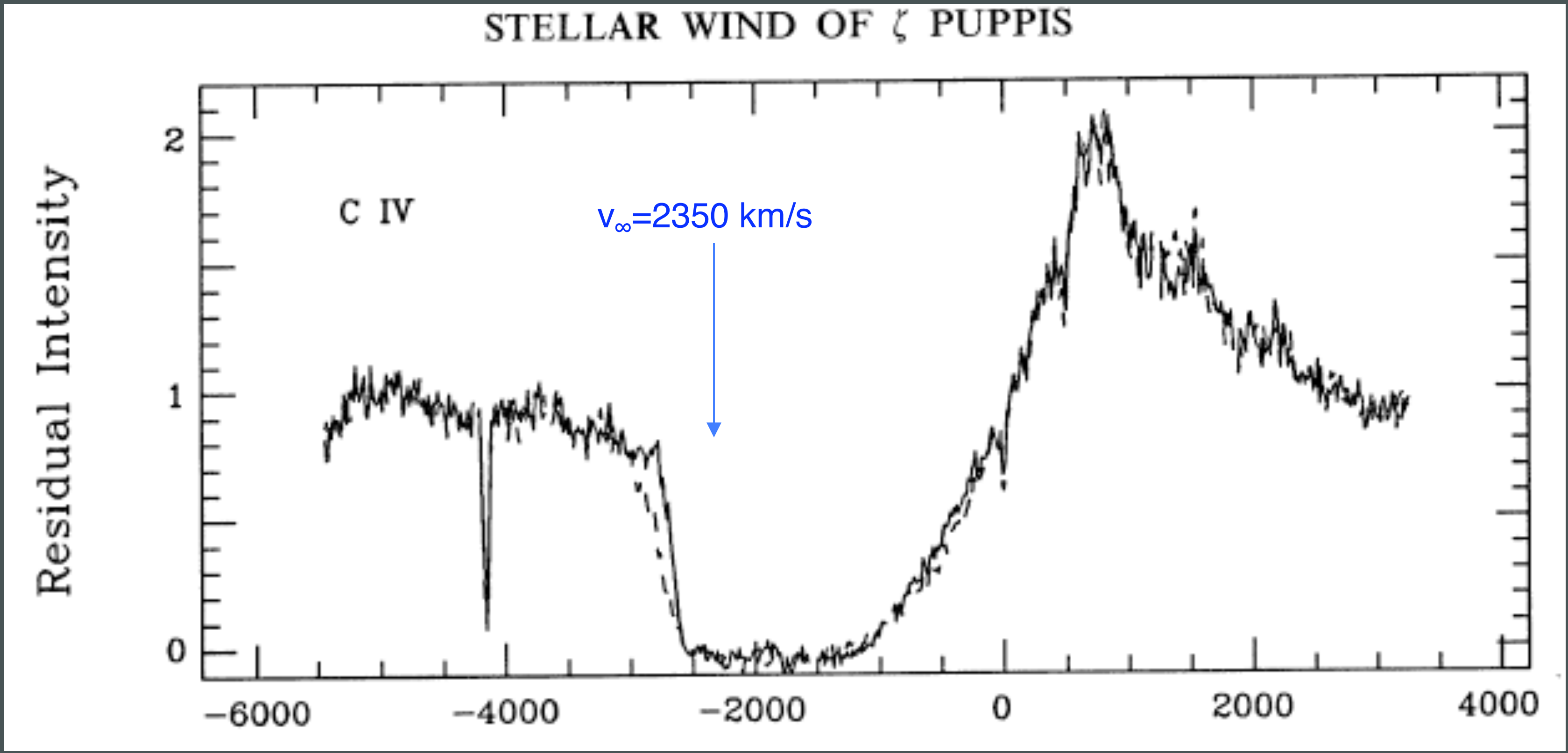
wind-blown bubble: stellar wind impact on its environment

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}

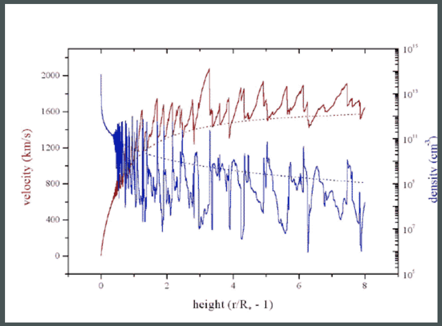
while the x-ray luminosity

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

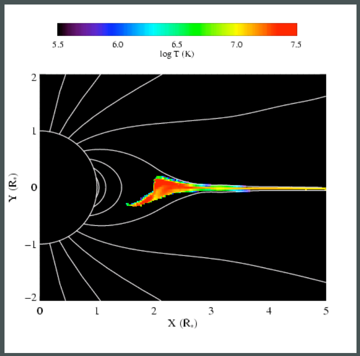
To account for the x-rays, only **one part in 10^{-4}** of the wind's mechanical power is needed to heat the wind

Three models for massive star x-ray emission

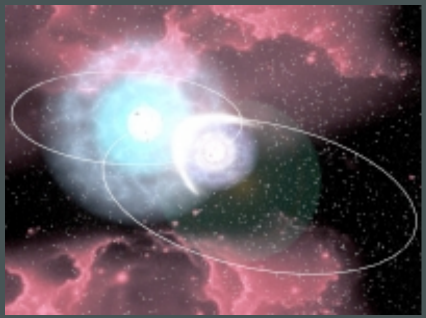
1. Instability driven shocks



2. Magnetically channeled wind shocks

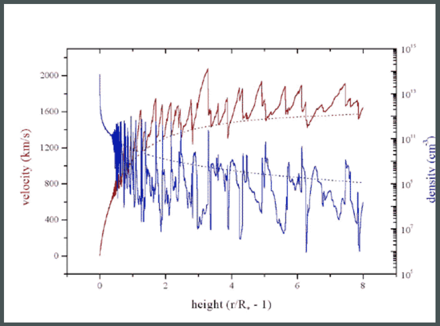


3. Wind-wind interaction in close binaries



Three models for massive star x-ray emission

1. Instability driven shocks



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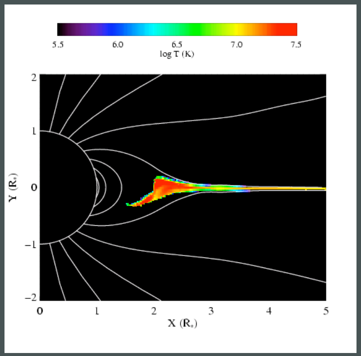


3. Wind-wind interaction in close binaries

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

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

opacity

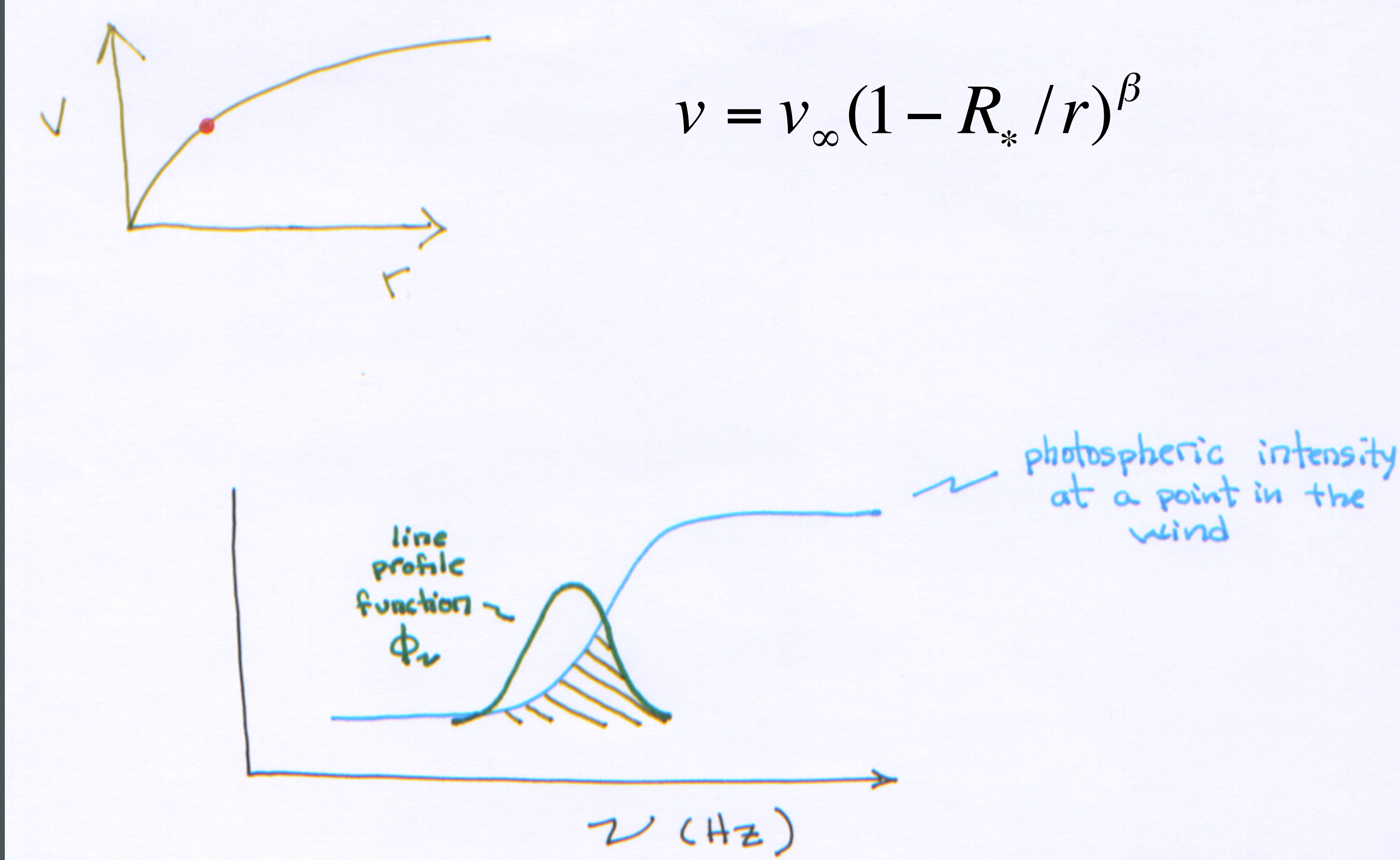
luminosity

mass

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

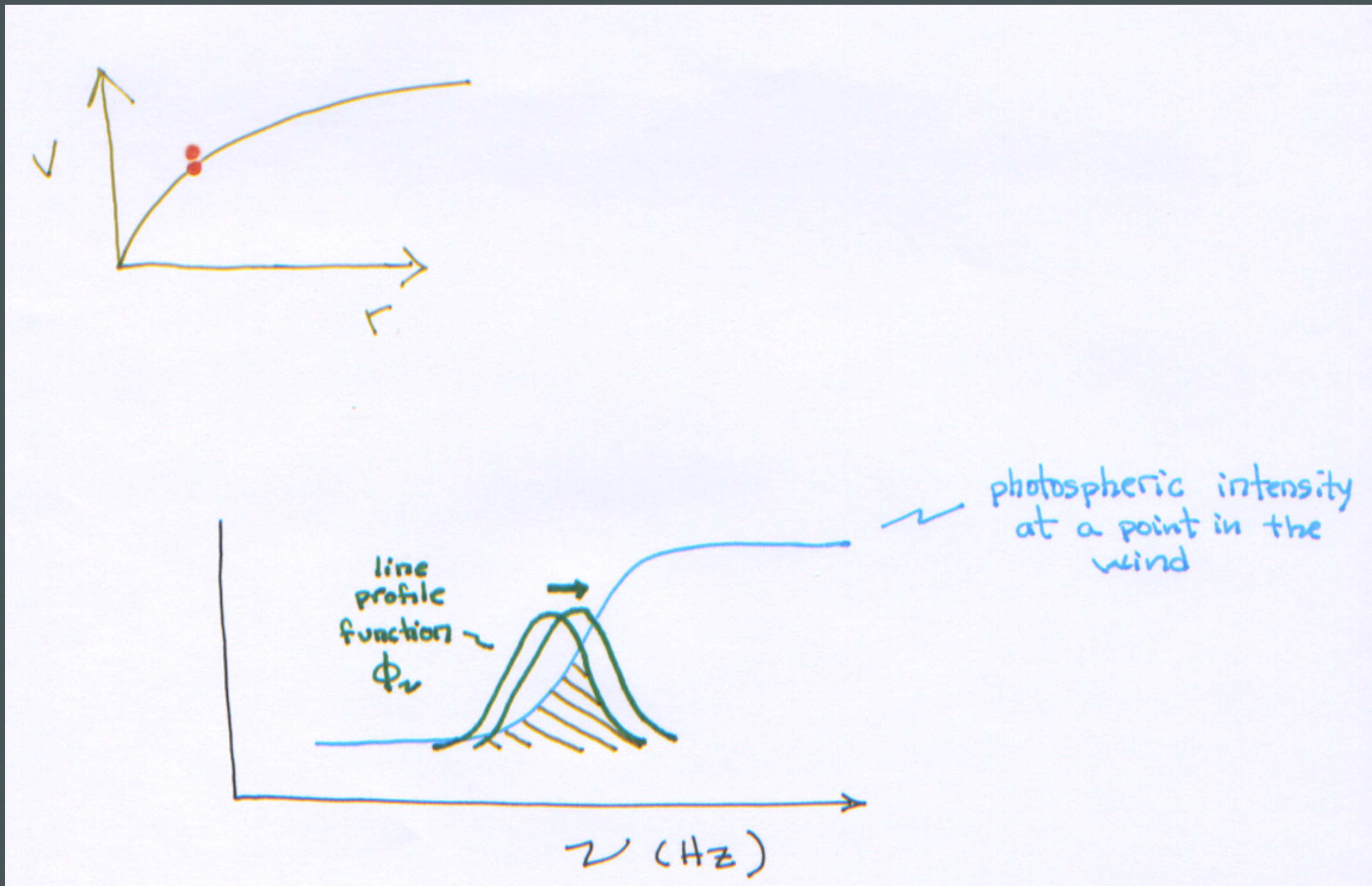
For massive stars, Γ_{edd} approaches unity

The Line-Driven Instability (LDI; Milne 1926)

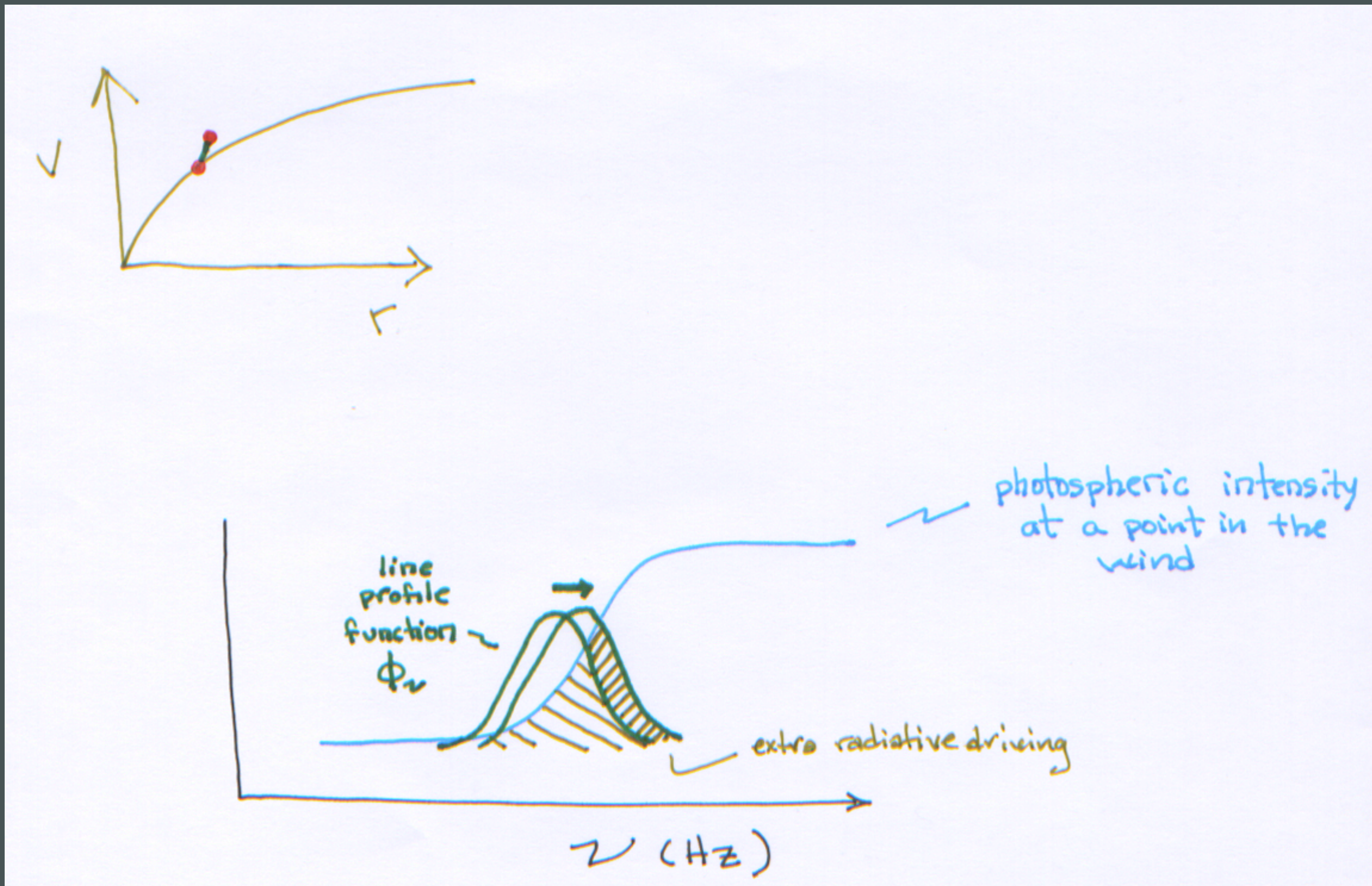


$$v = v_\infty (1 - R_* / r)^\beta$$

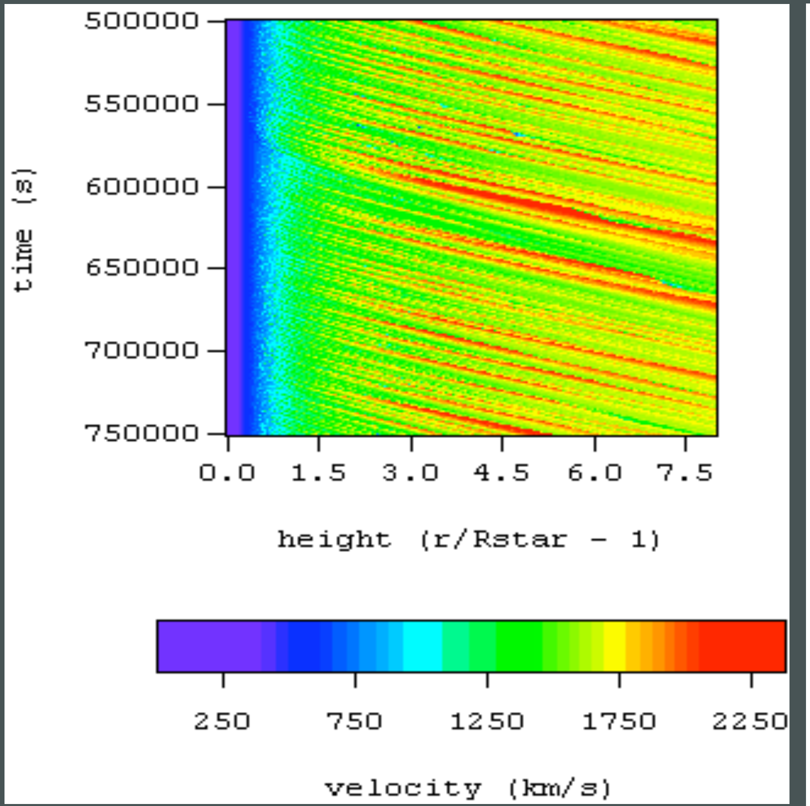
Consider a positive velocity perturbation

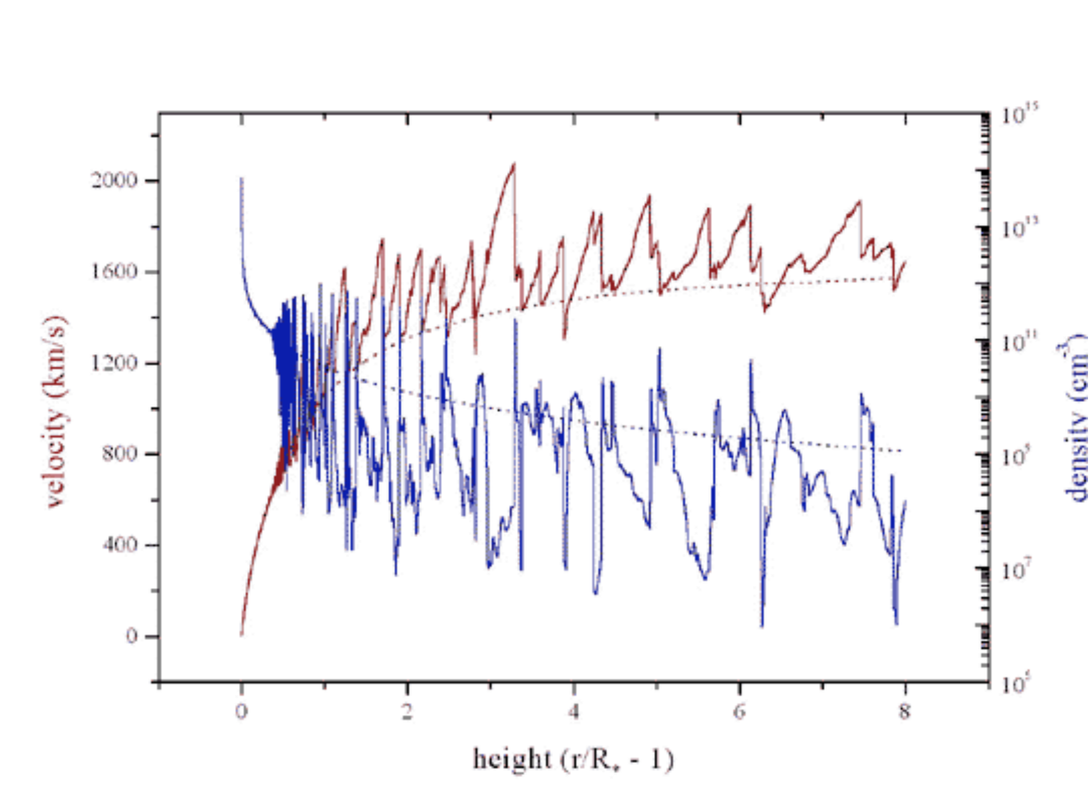


Positive feedback: ion moves out of the Doppler shadow, sees more radiation, gets accelerated…



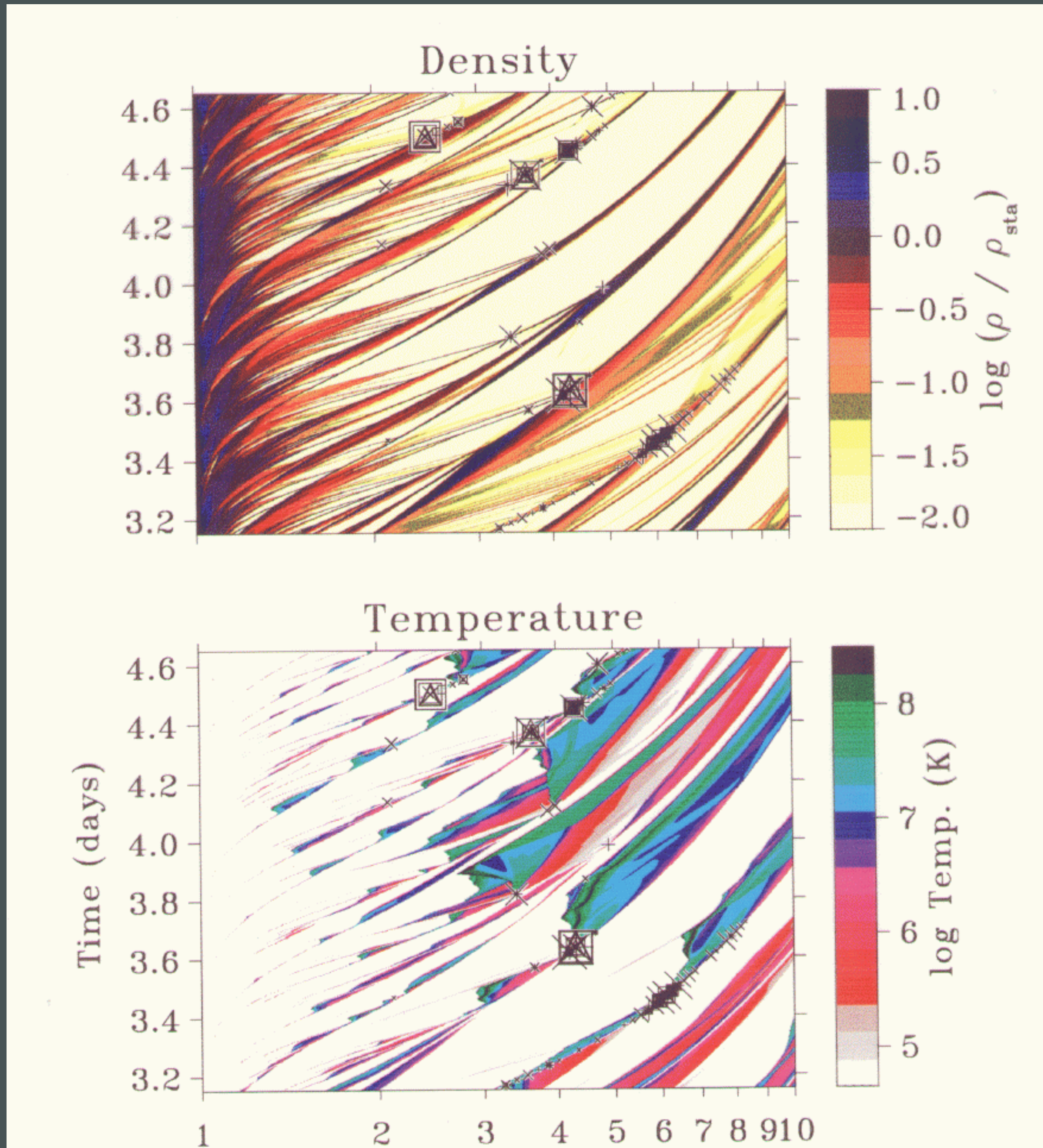
1-D rad-hydro simulation of a massive star wind





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

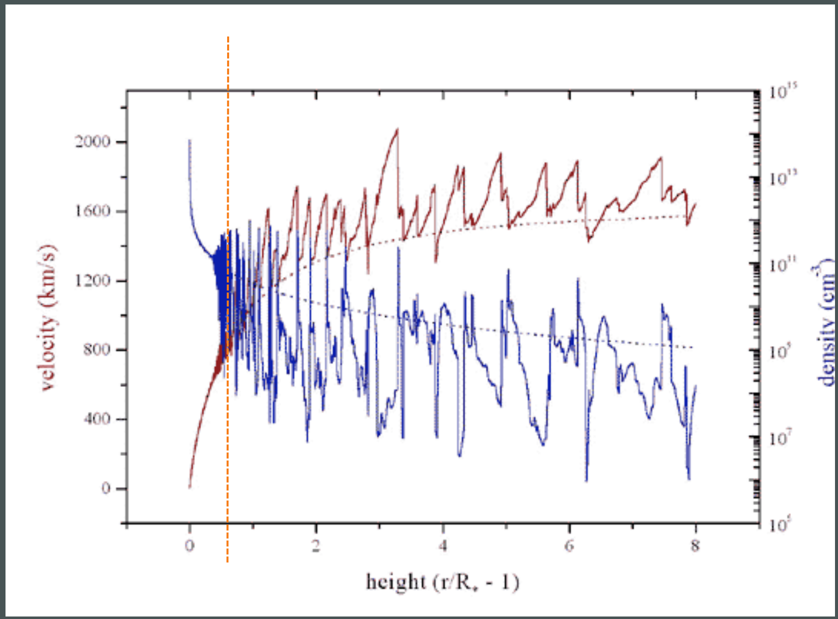
Shell-shell collisions induced by turbulence at the base of the wind flow



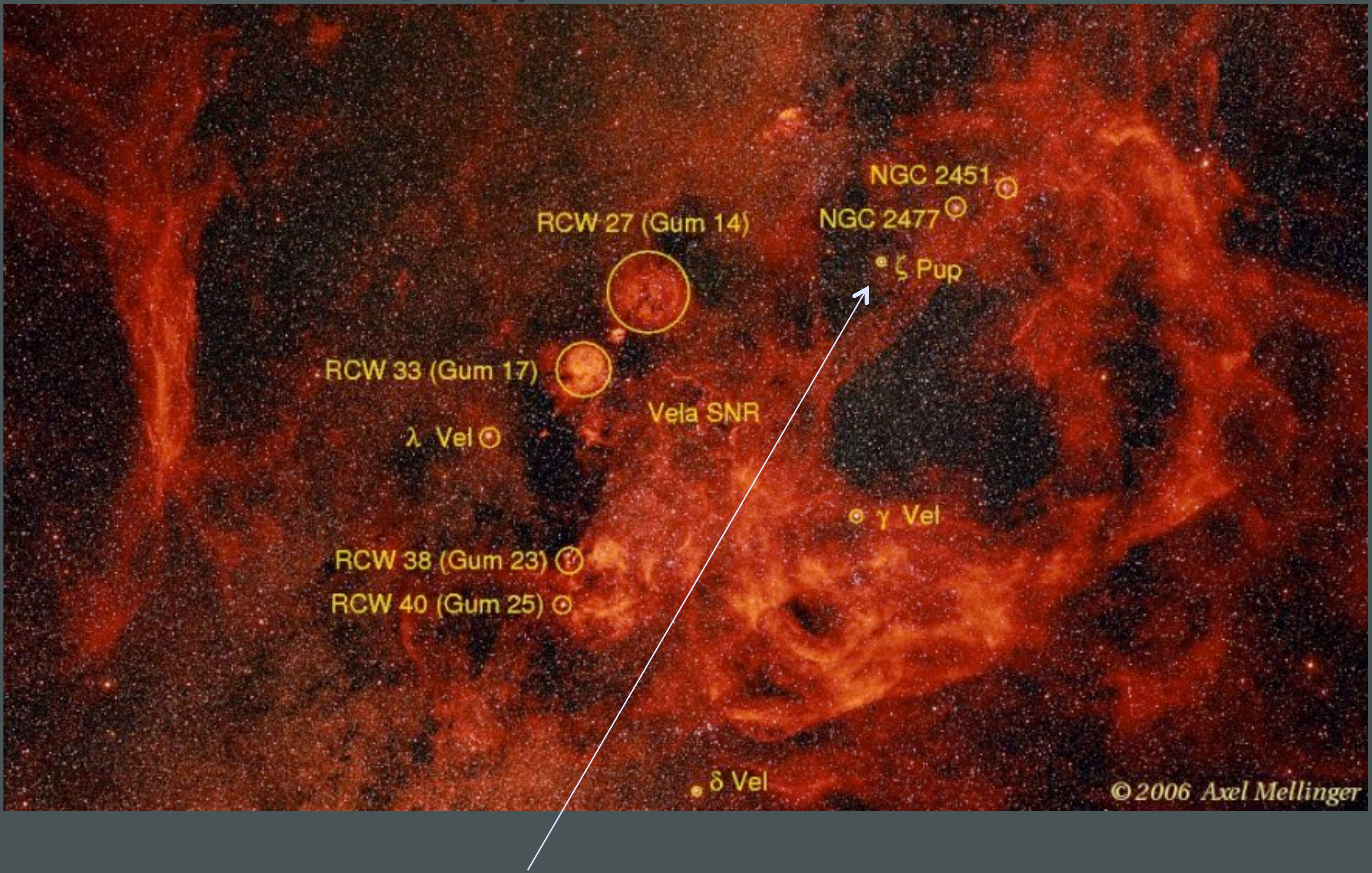
Feldmeier, et al. 1997

Predictions of the rad-hydro wind simulations:

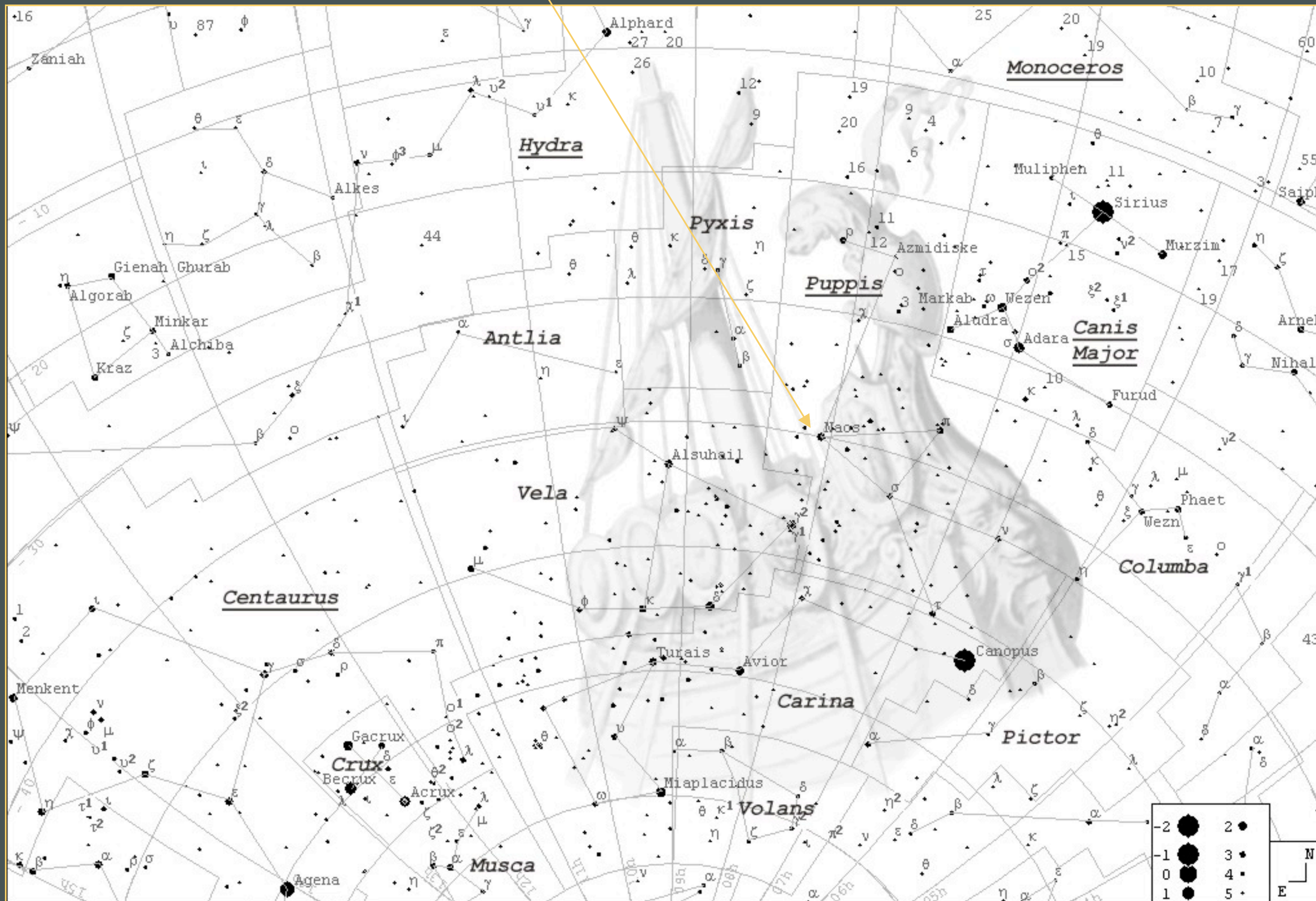
1. Significant **Doppler broadening** of x-ray emission lines due to bulk motion of the wind flow (1a. Shock onset several tenths R_* above the surface)
2. Bulk of the wind is cold and unshocked – source of **attenuation** of the X-rays.



ζ Puppis in the Gum Nebula

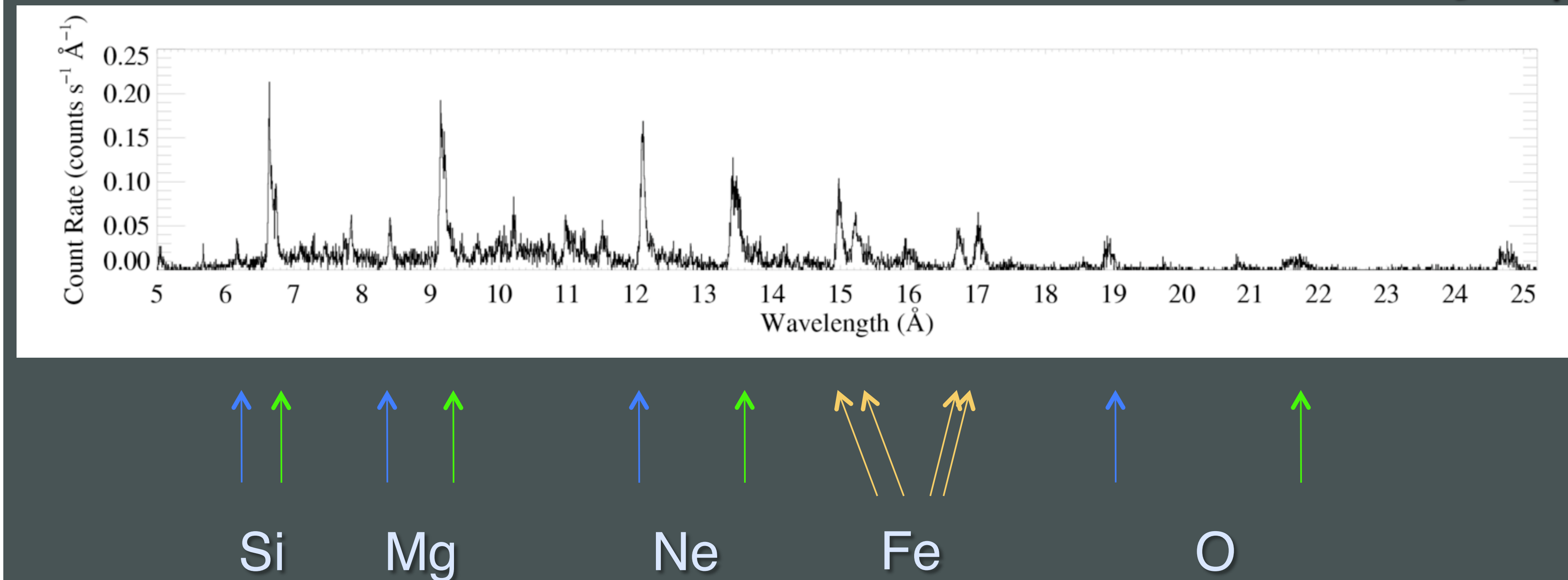


ζ Puppis: 50 M_{sun}, 10^6 L_{sun}



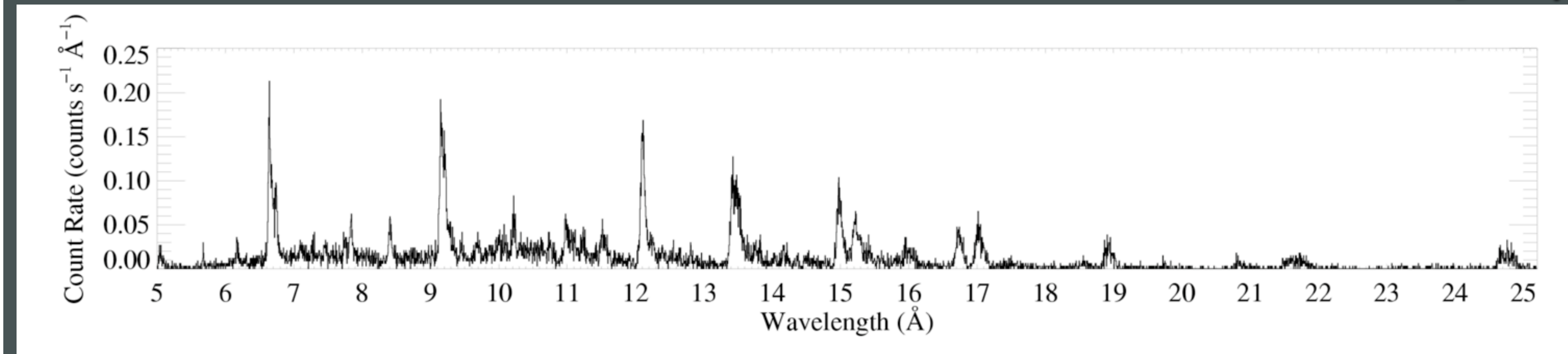
Chandra HETGS/MEG spectrum
($R \sim 1000 \sim 300$ km s^{-1})

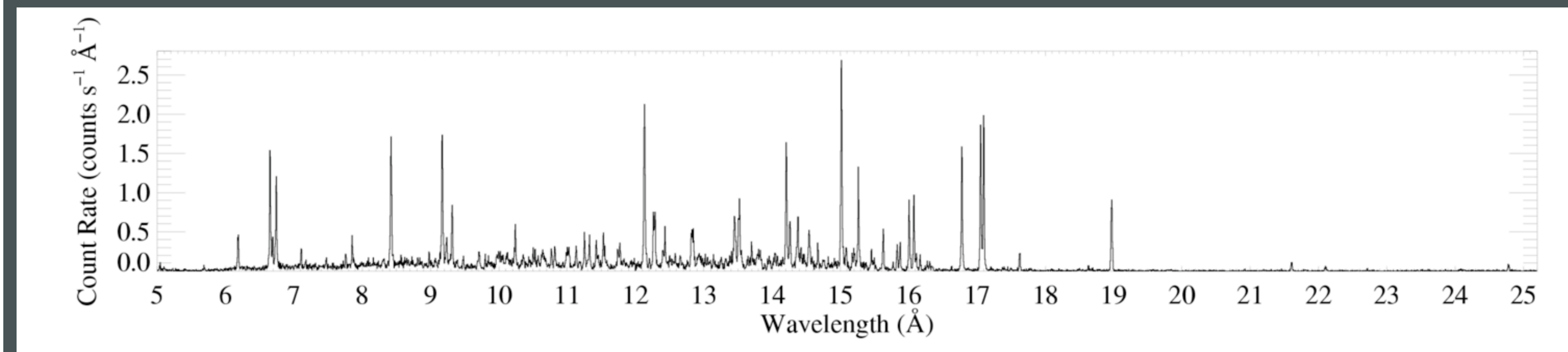
ζ Pup



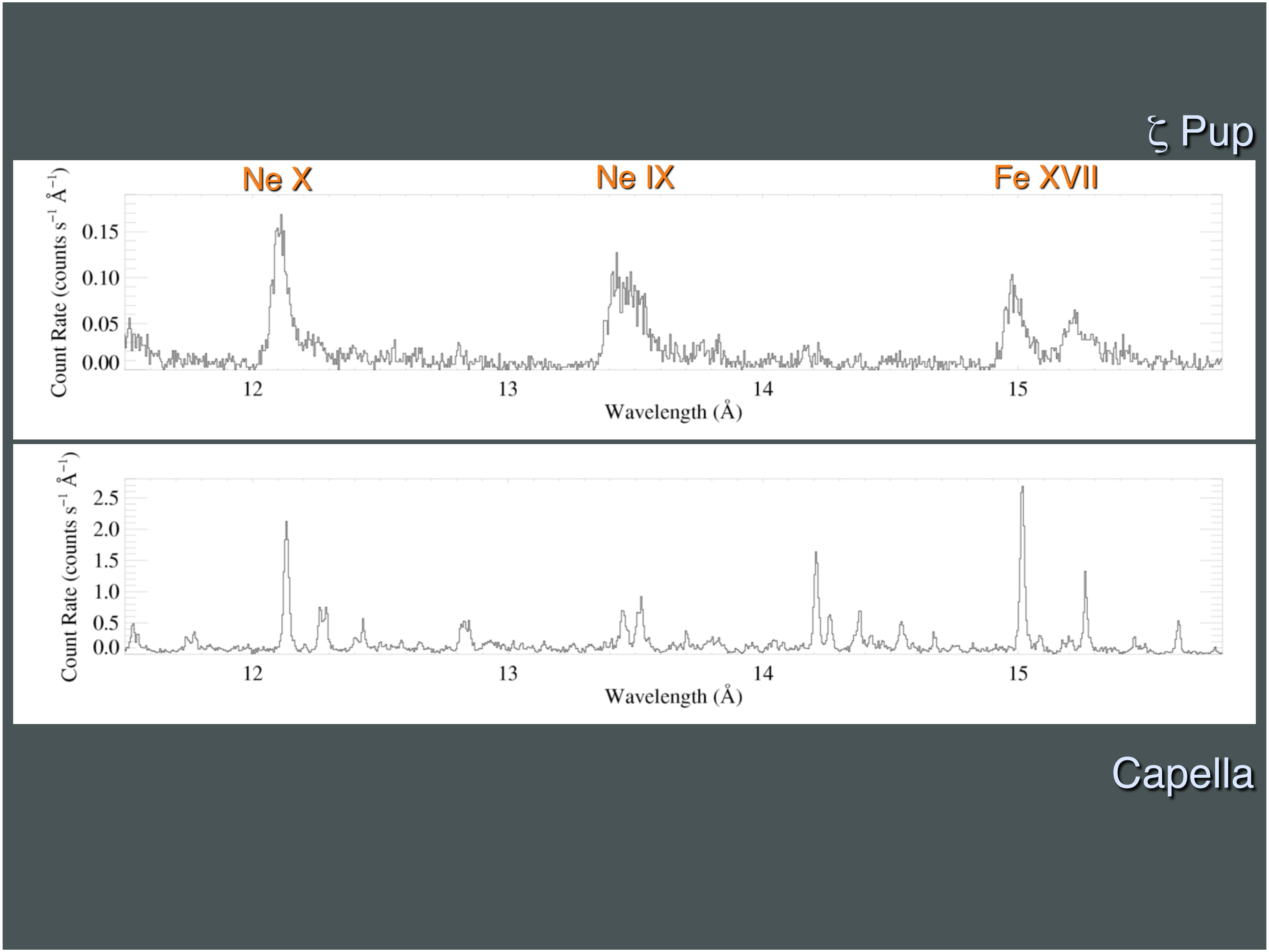
H-like
He-like

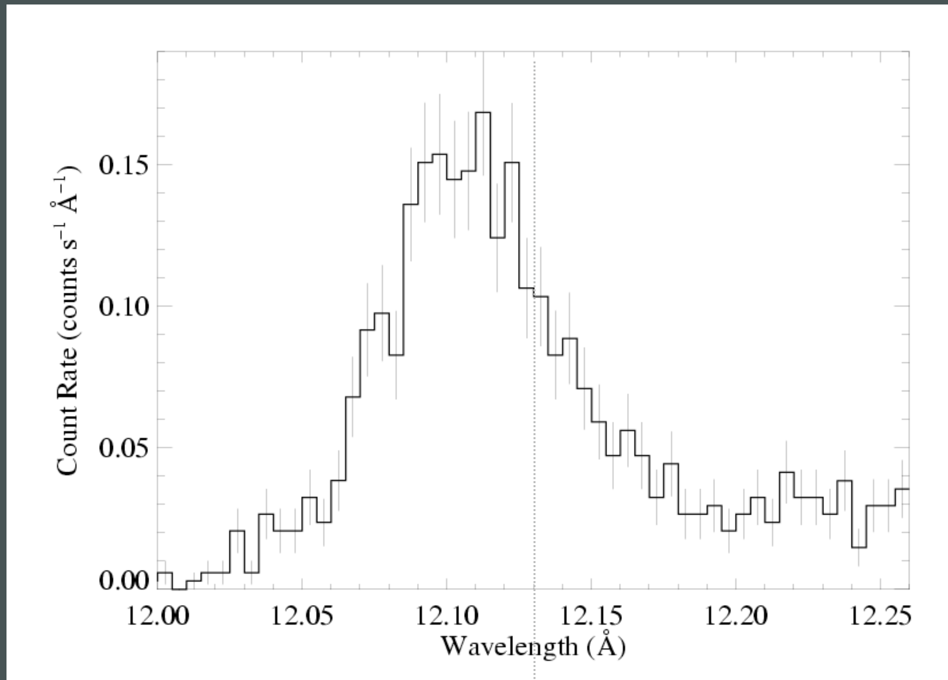
ζ Pup



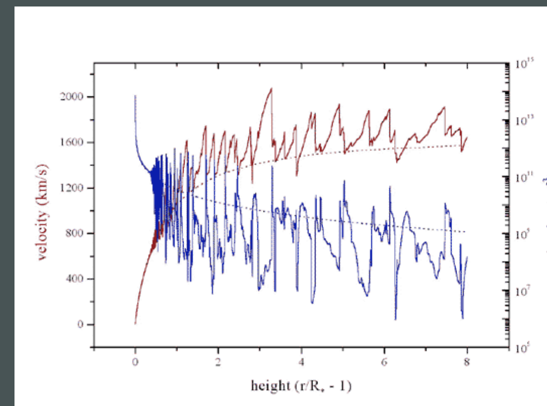


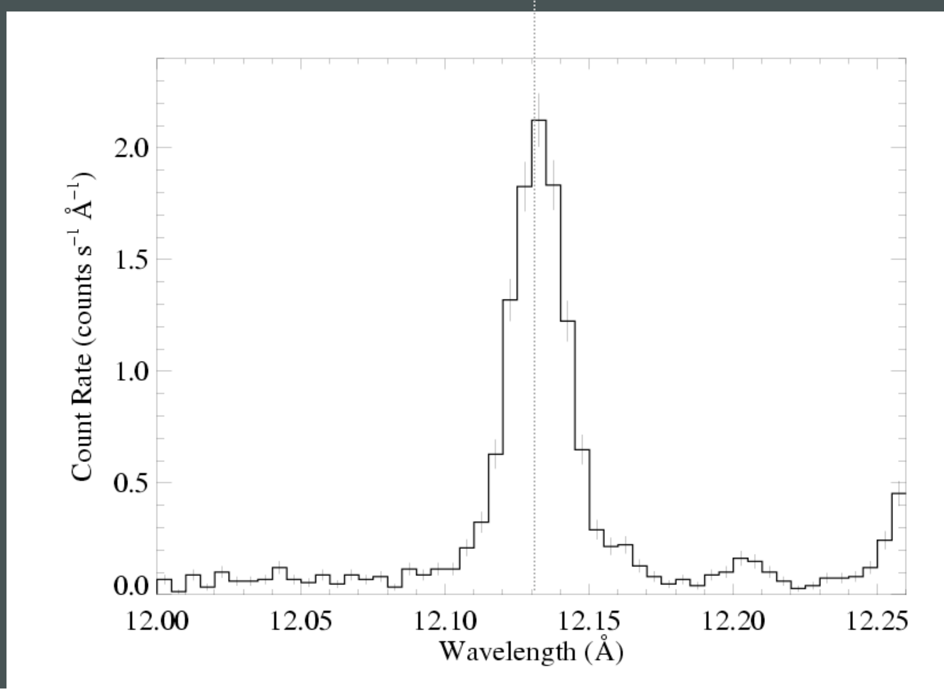
Low-mass star (Capella) for comparison


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

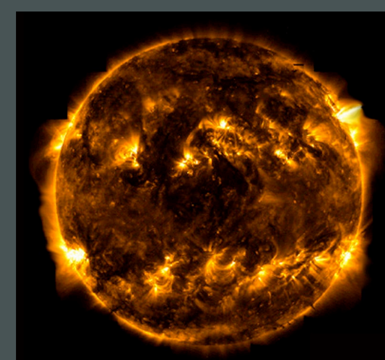


ζ Pup
massive

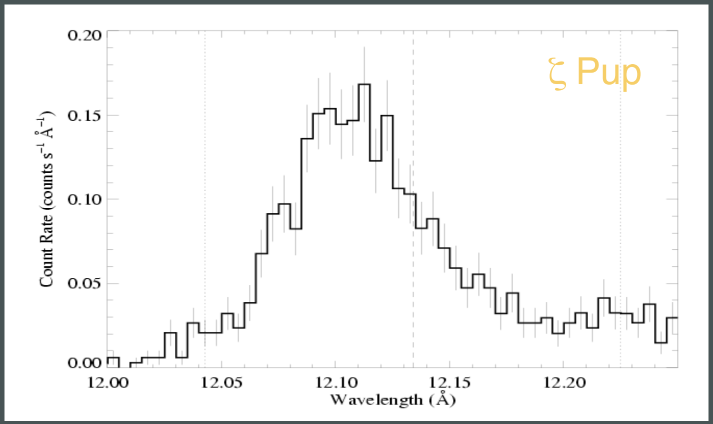




Capella
low mass

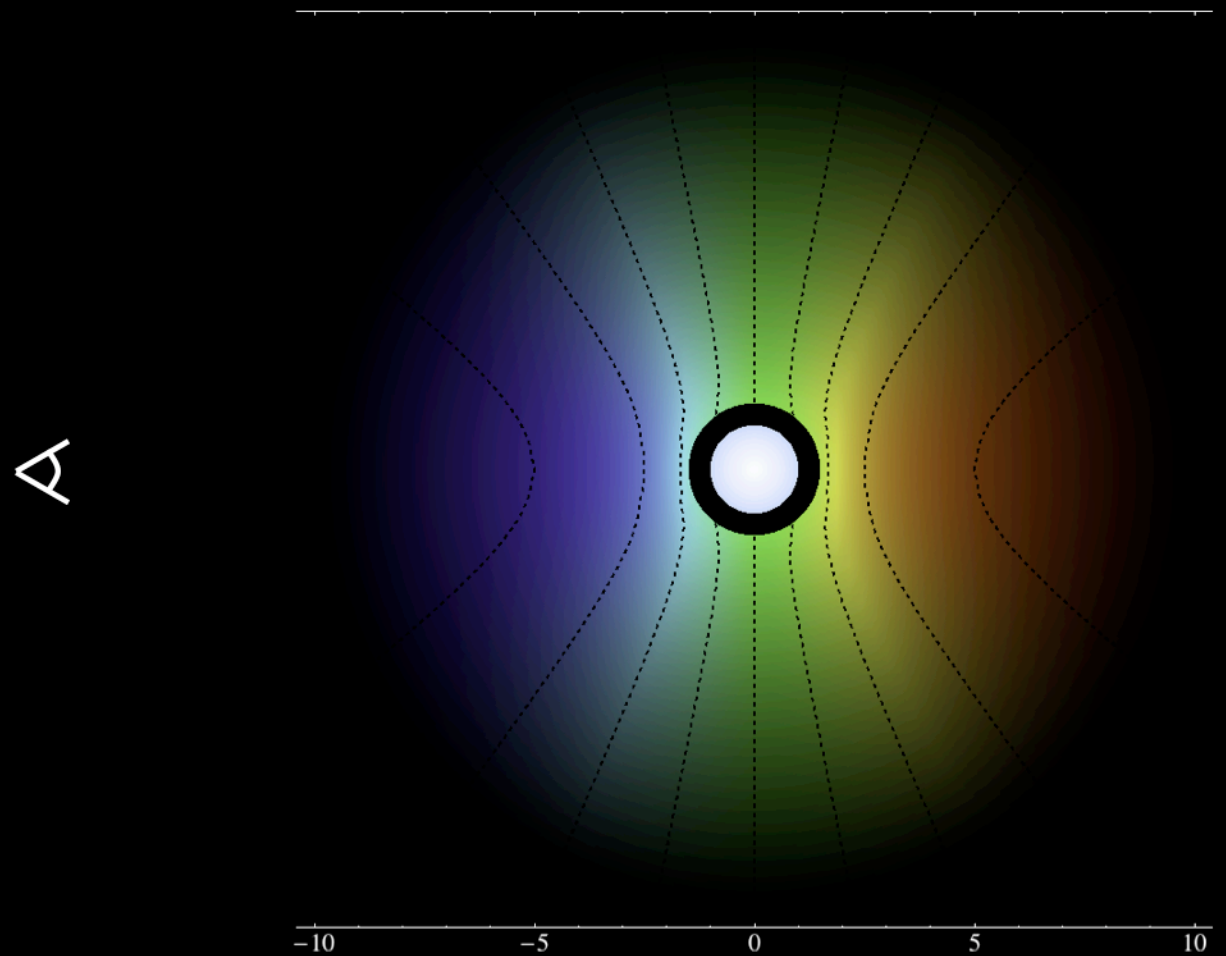


The x-ray emission lines are broad: agreement with rad hydro simulations

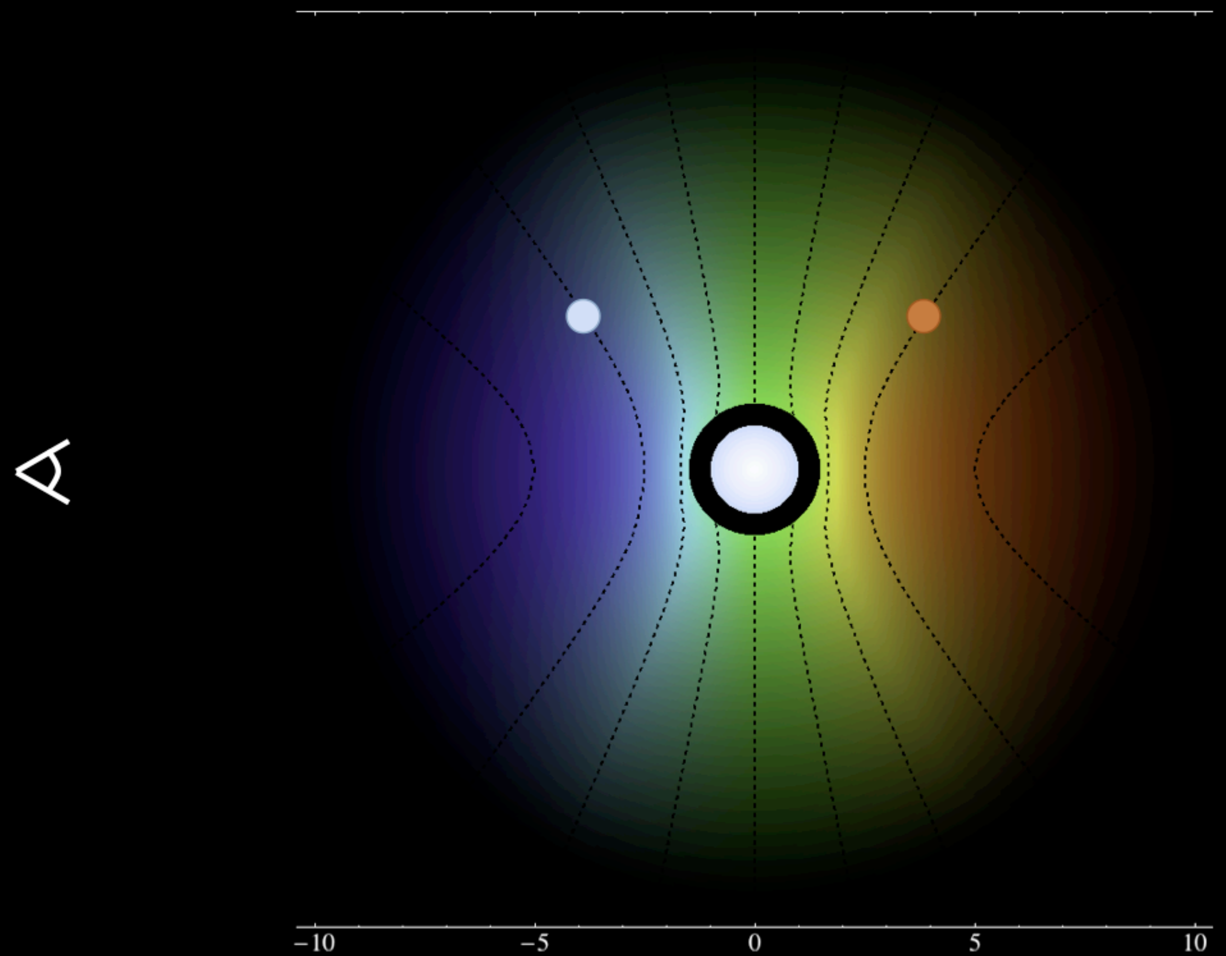


But… they're also blue shifted and asymmetric
Is this predicted by the wind shock scenario?

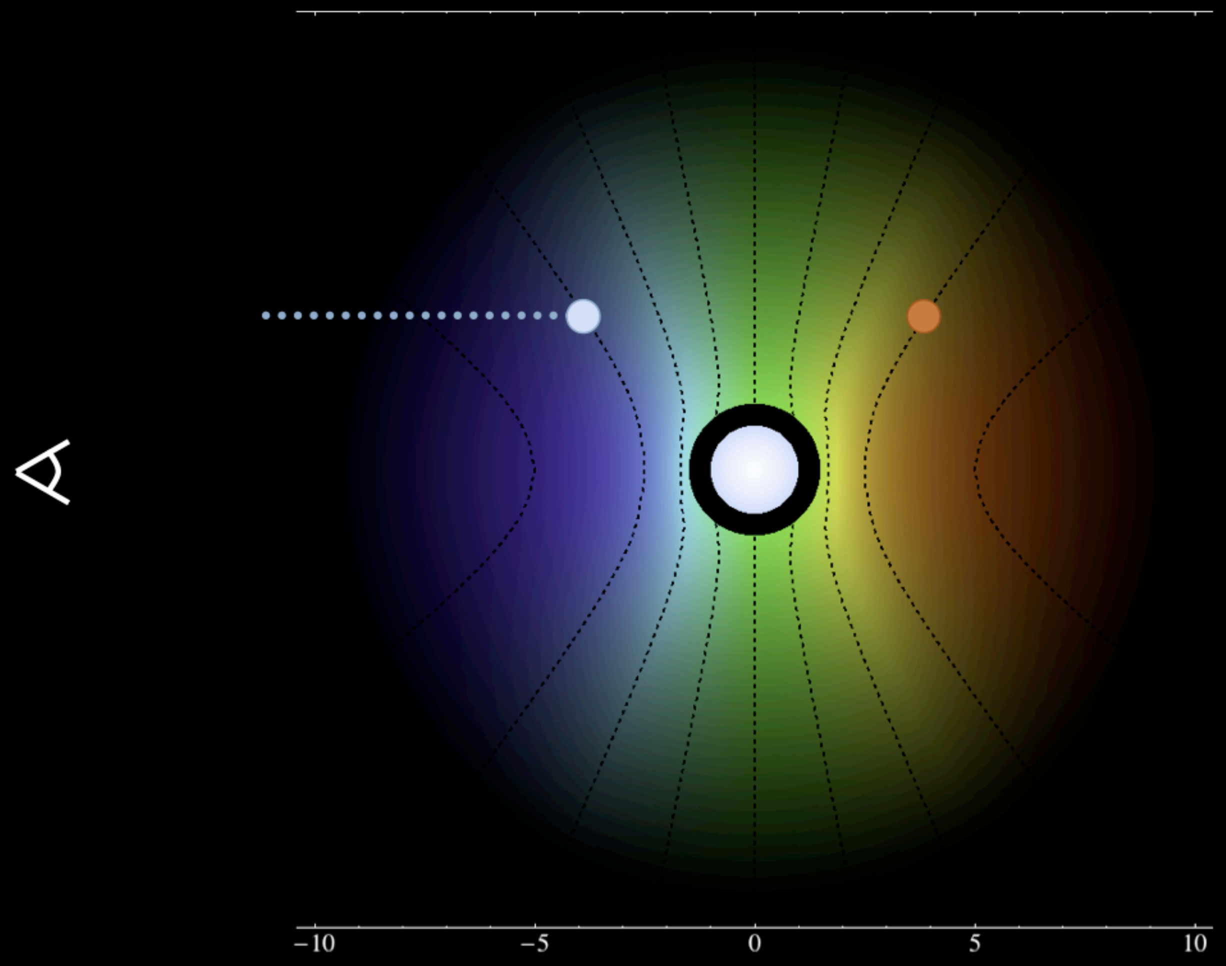
Wind Profile Model



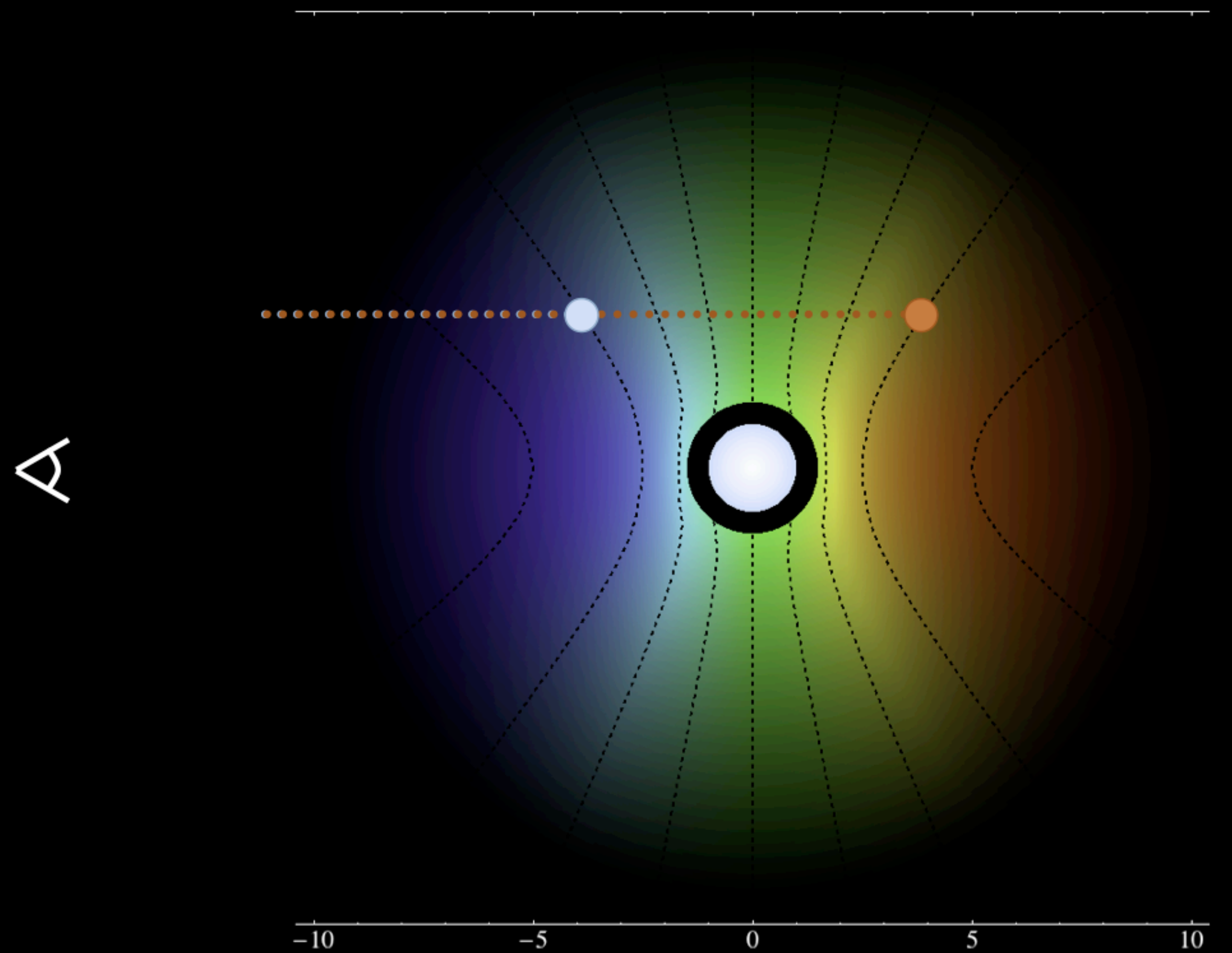
Wind Profile Model



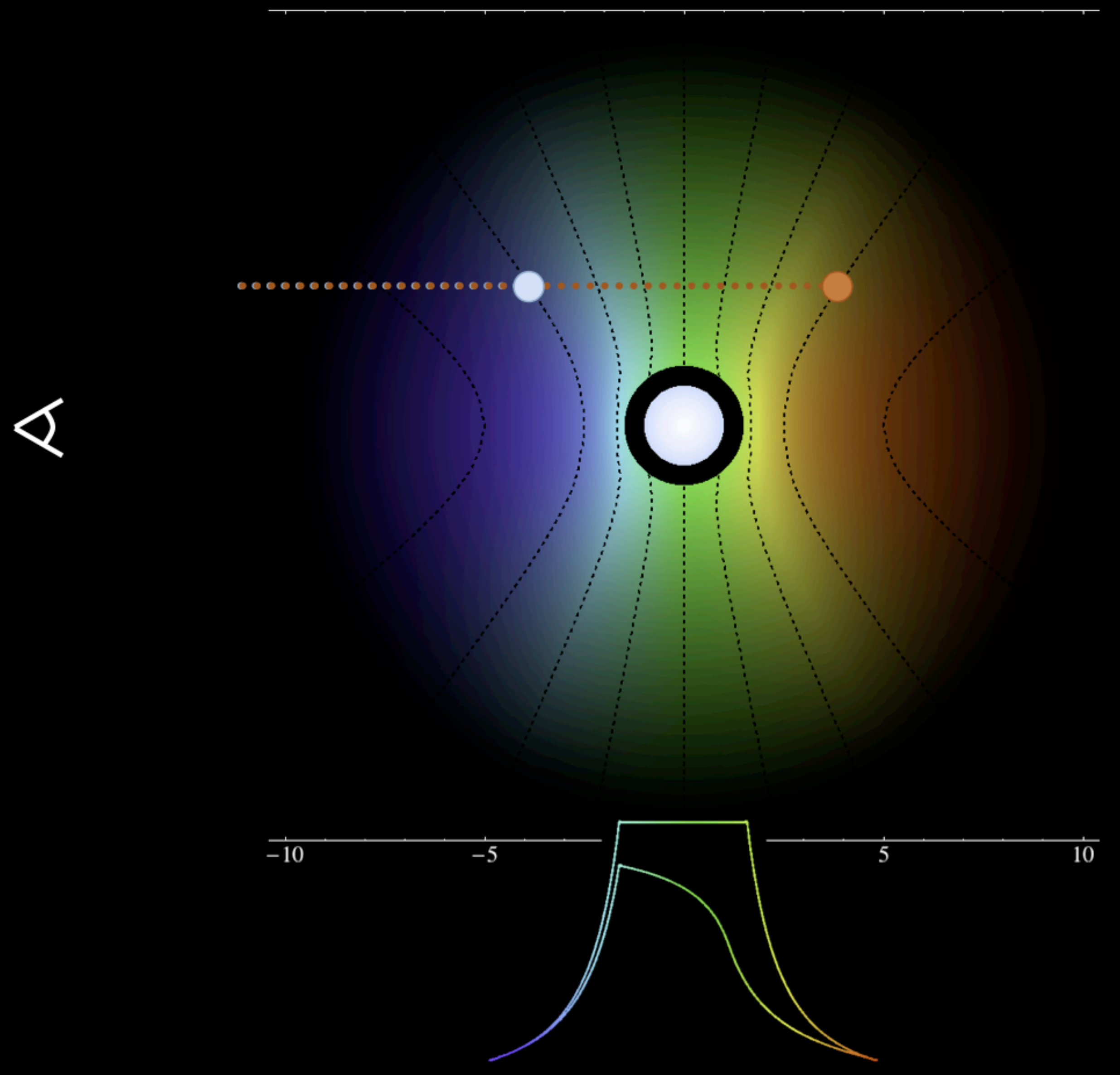
Wind Profile Model



Wind Profile Model

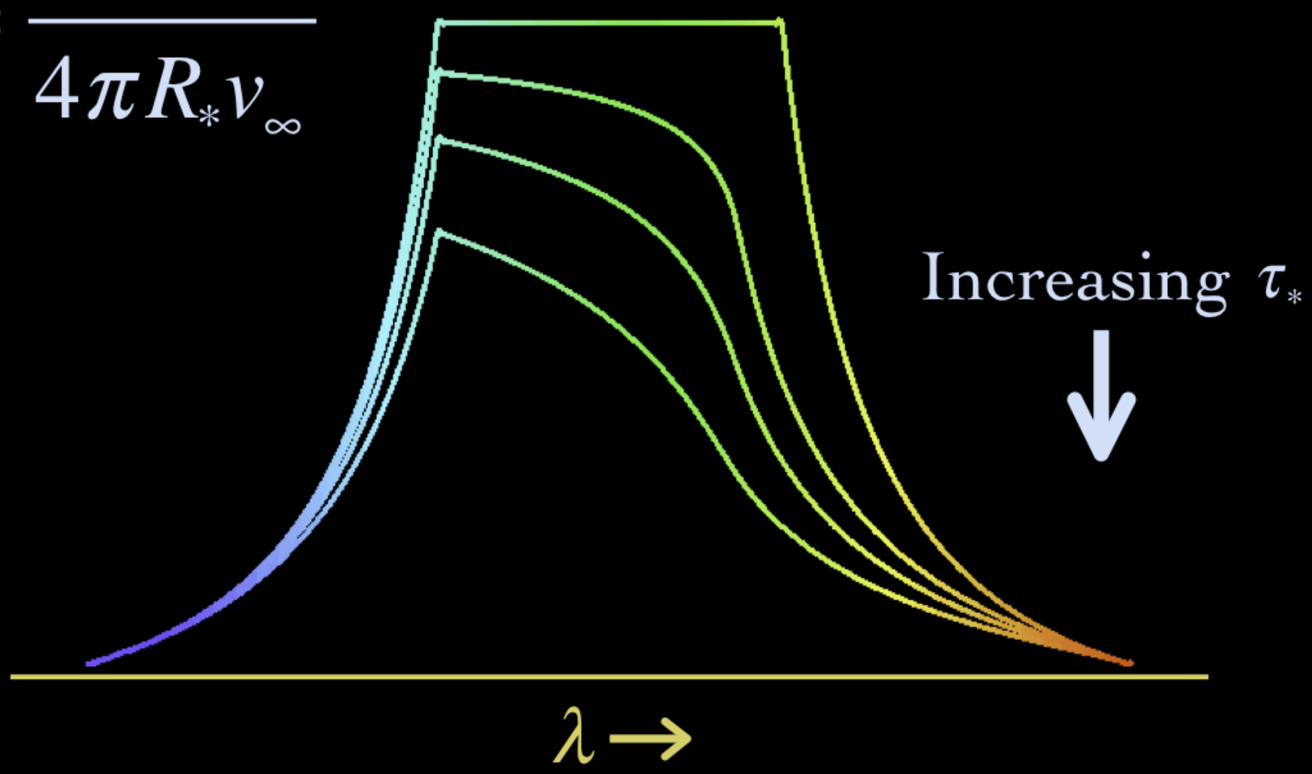


Wind Profile Model



Wind Profile Model

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



opacity of the cold wind component

wind mass-loss rate

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

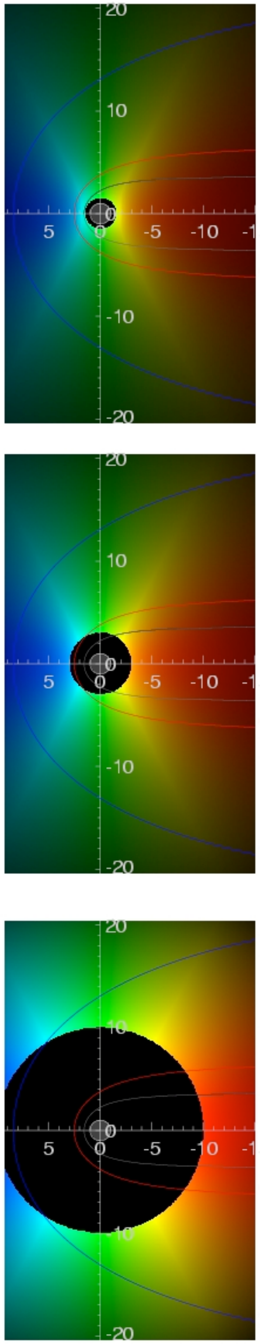
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

radius of the star

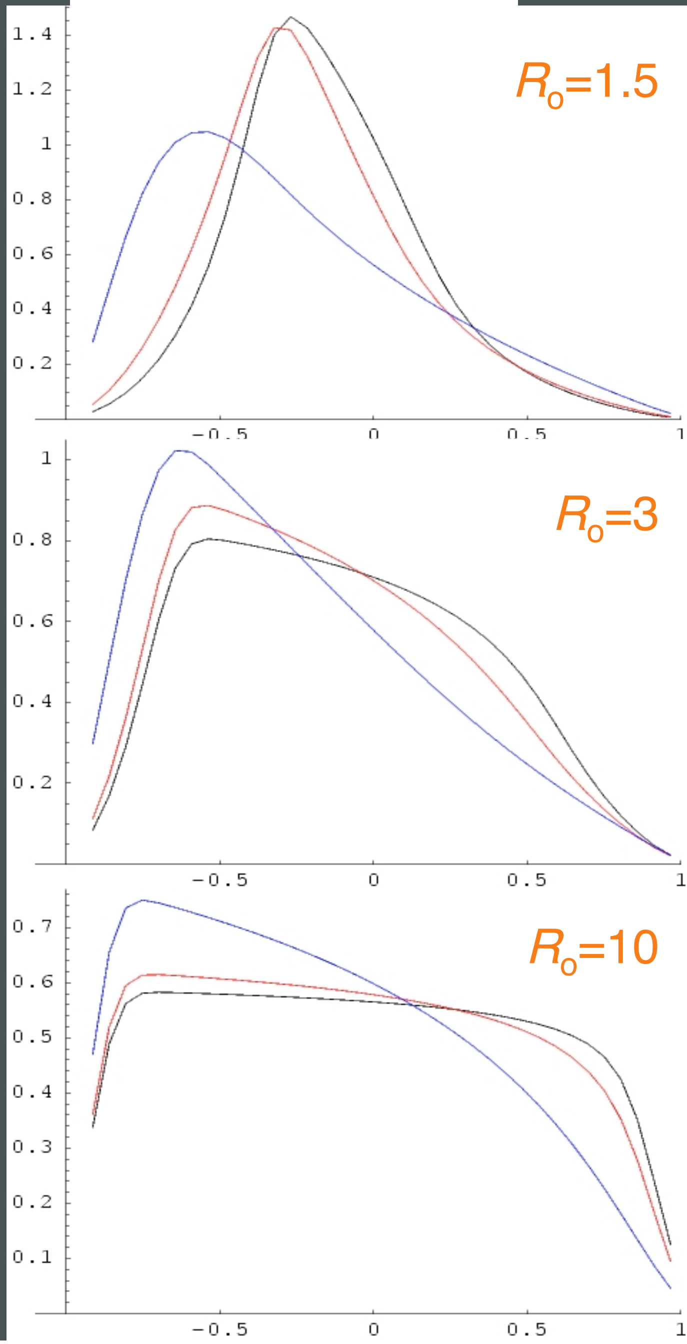
wind terminal velocity

The basic wind-profile model

τ=1 contours



τ_*=1,2,8



key parameters: $\mathbf{R_o}$ & τ_*

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

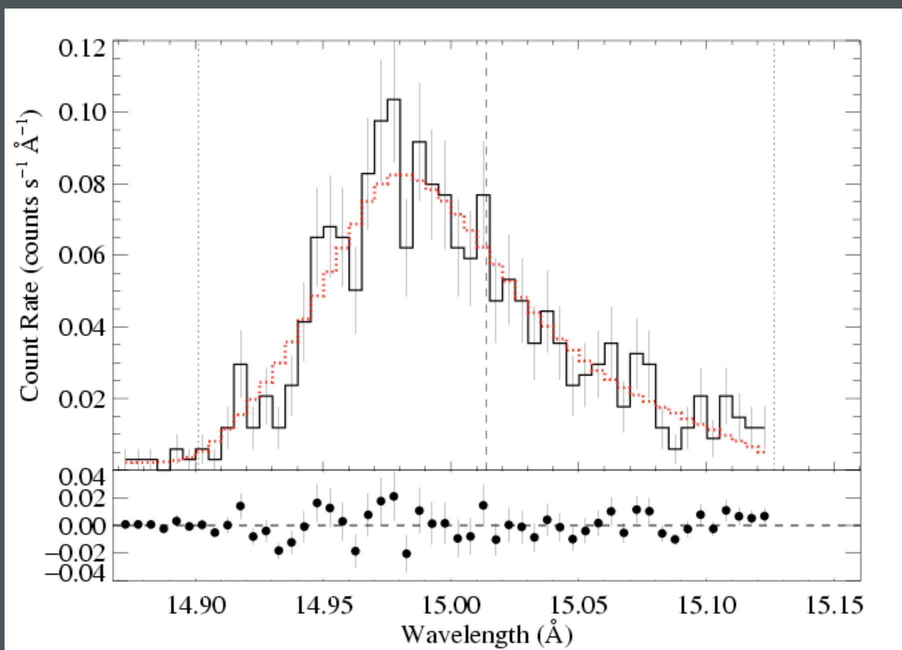
= 0 otherwise

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

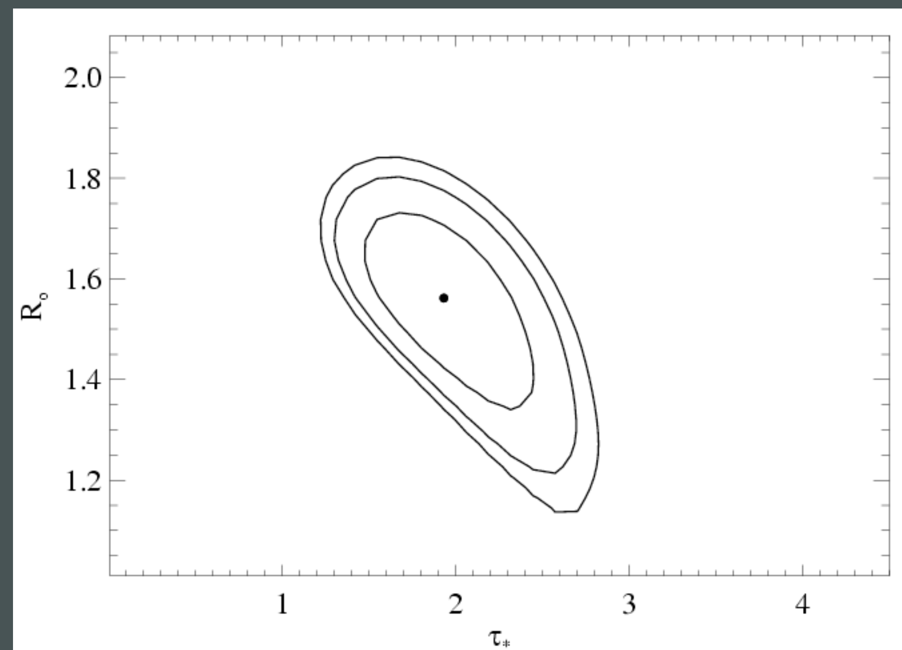
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

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

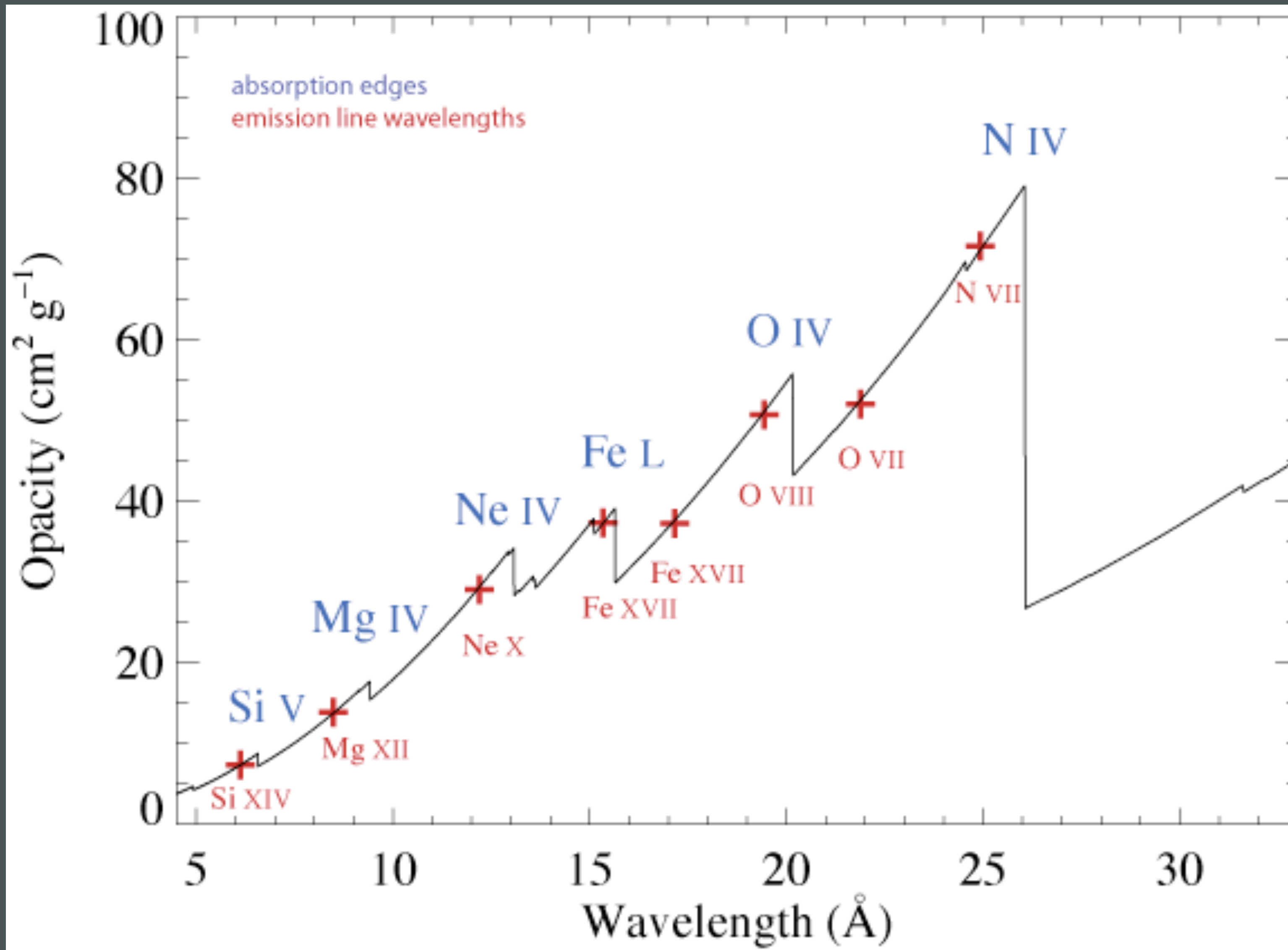


Fe XVII



68, 90, 95% confidence limits

Wind opacity: photoelectric absorption

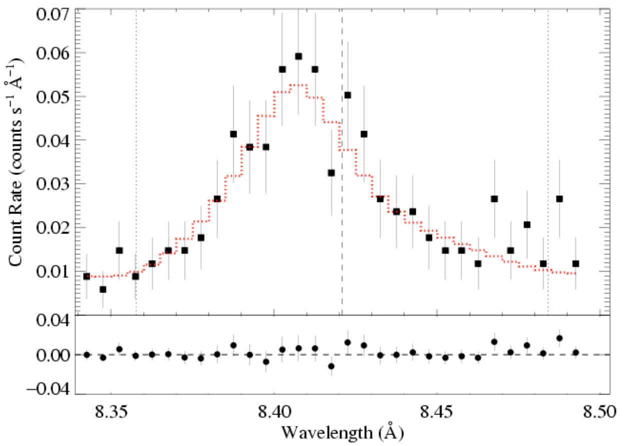


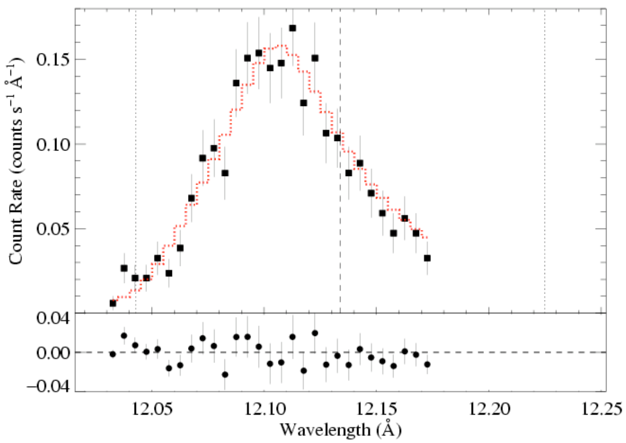
Abundances; ionization balance; atomic cross sections

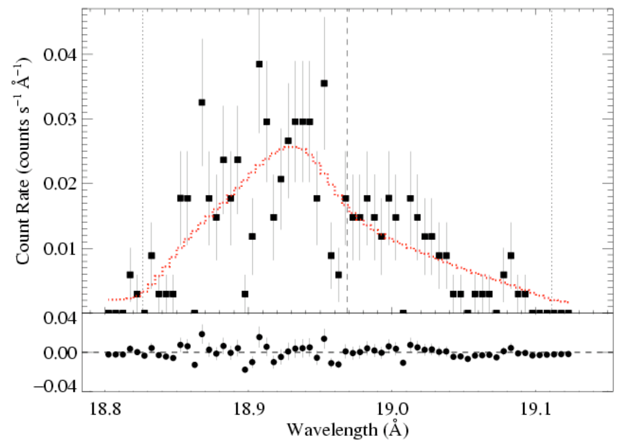
Verner & Yakovlev 1996

ζ Pup: three emission lines

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





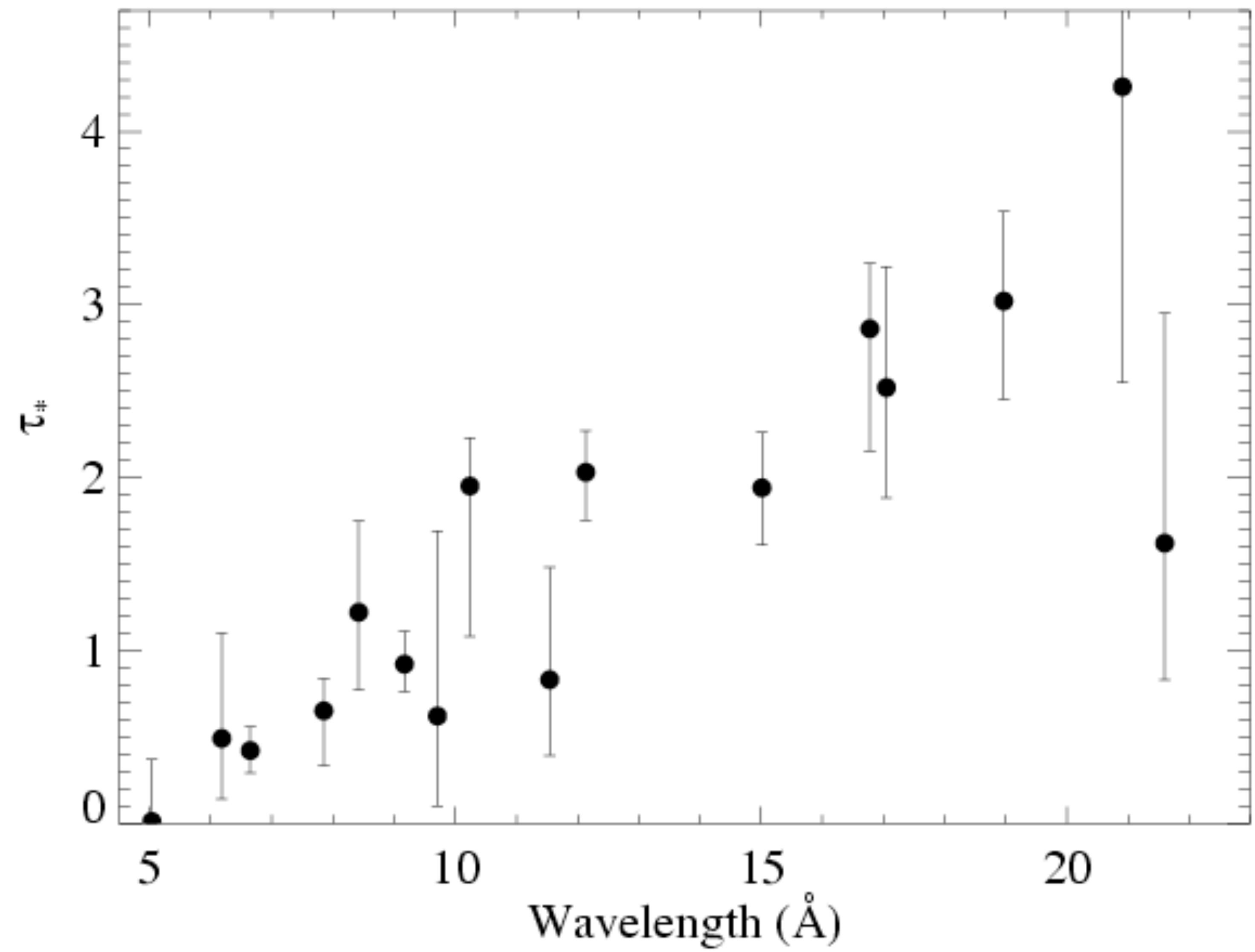


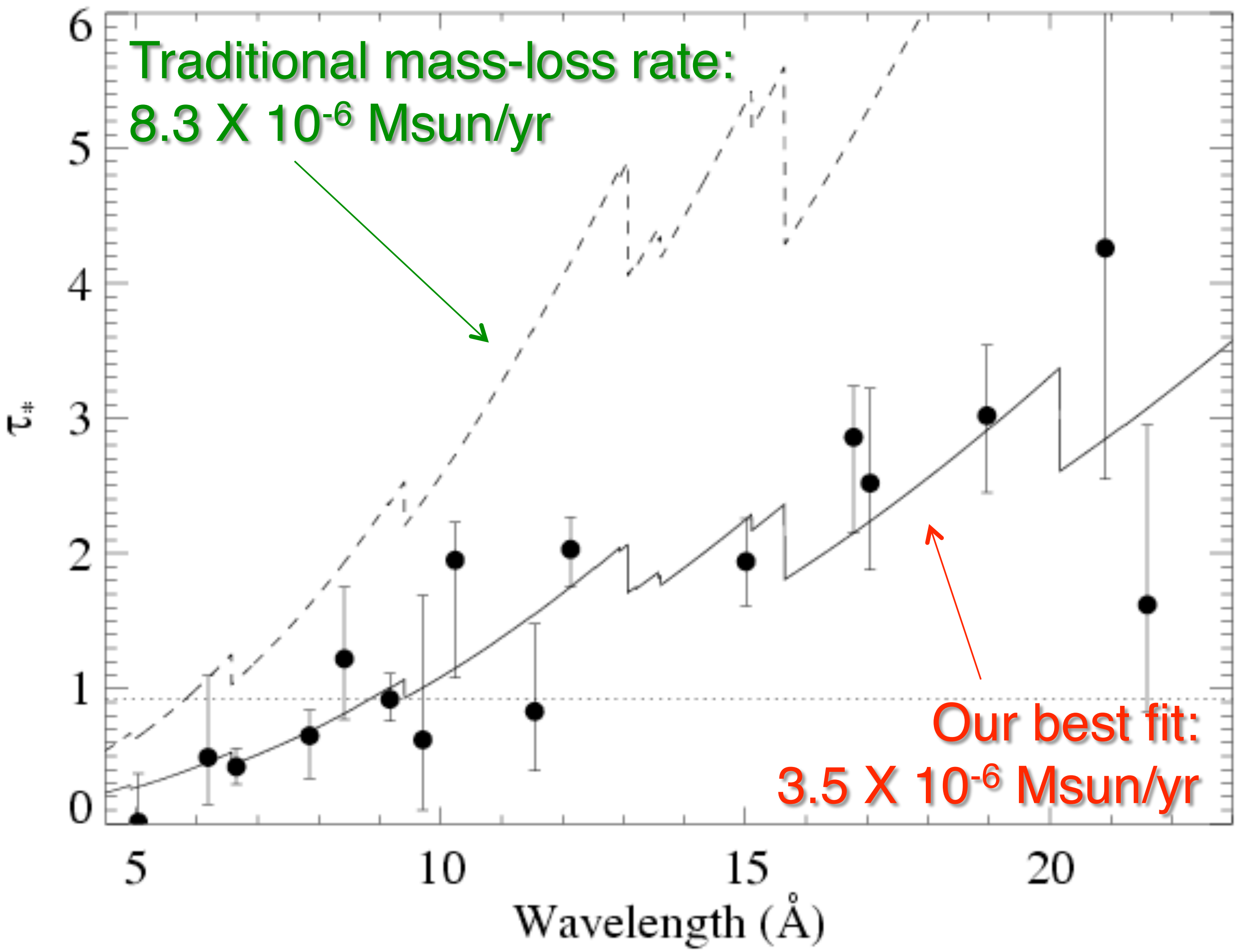
$\tau_* = 1$ | $\tau_* = 2$ | $\tau_* = 3$

Recall:

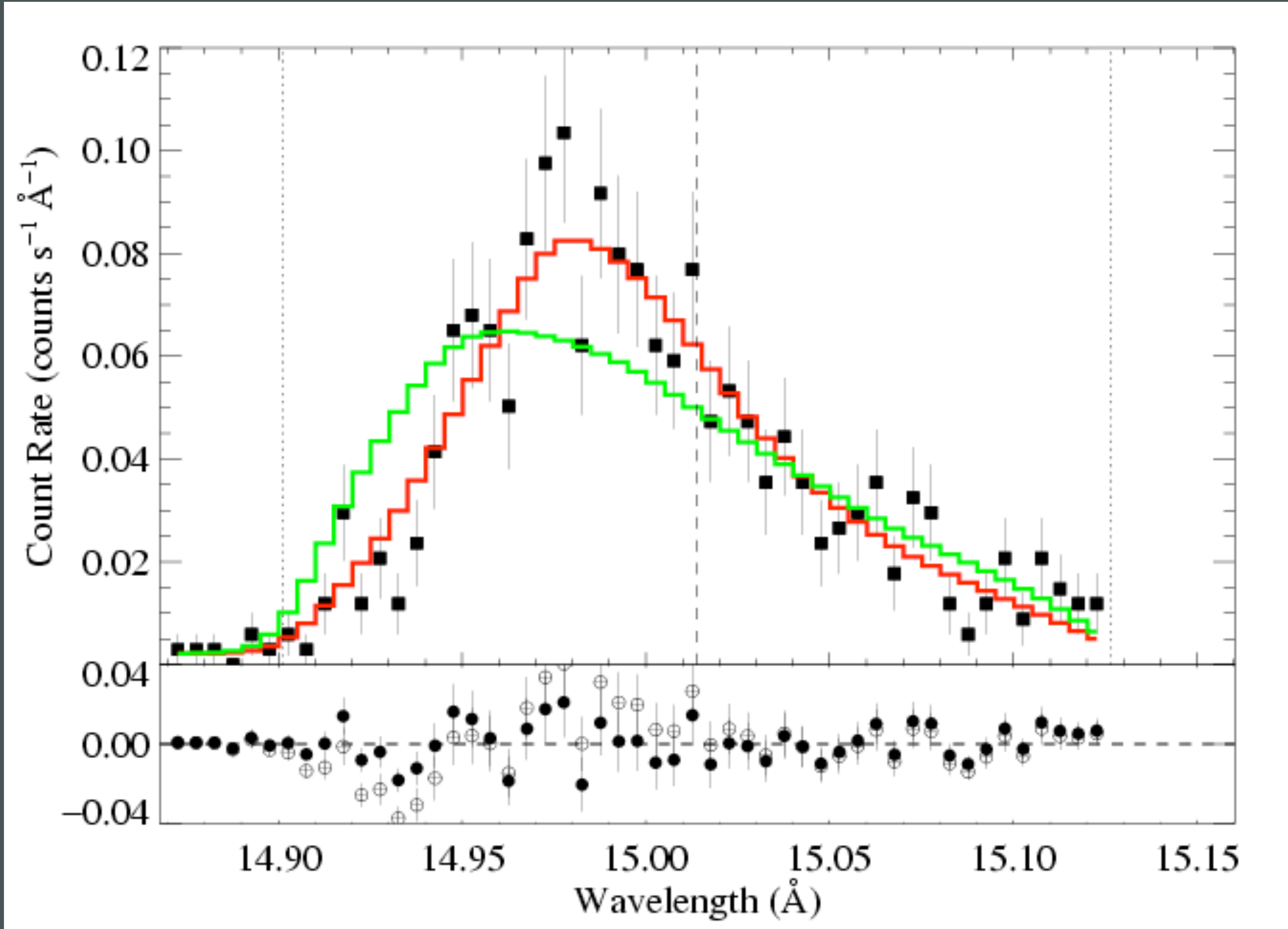
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

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

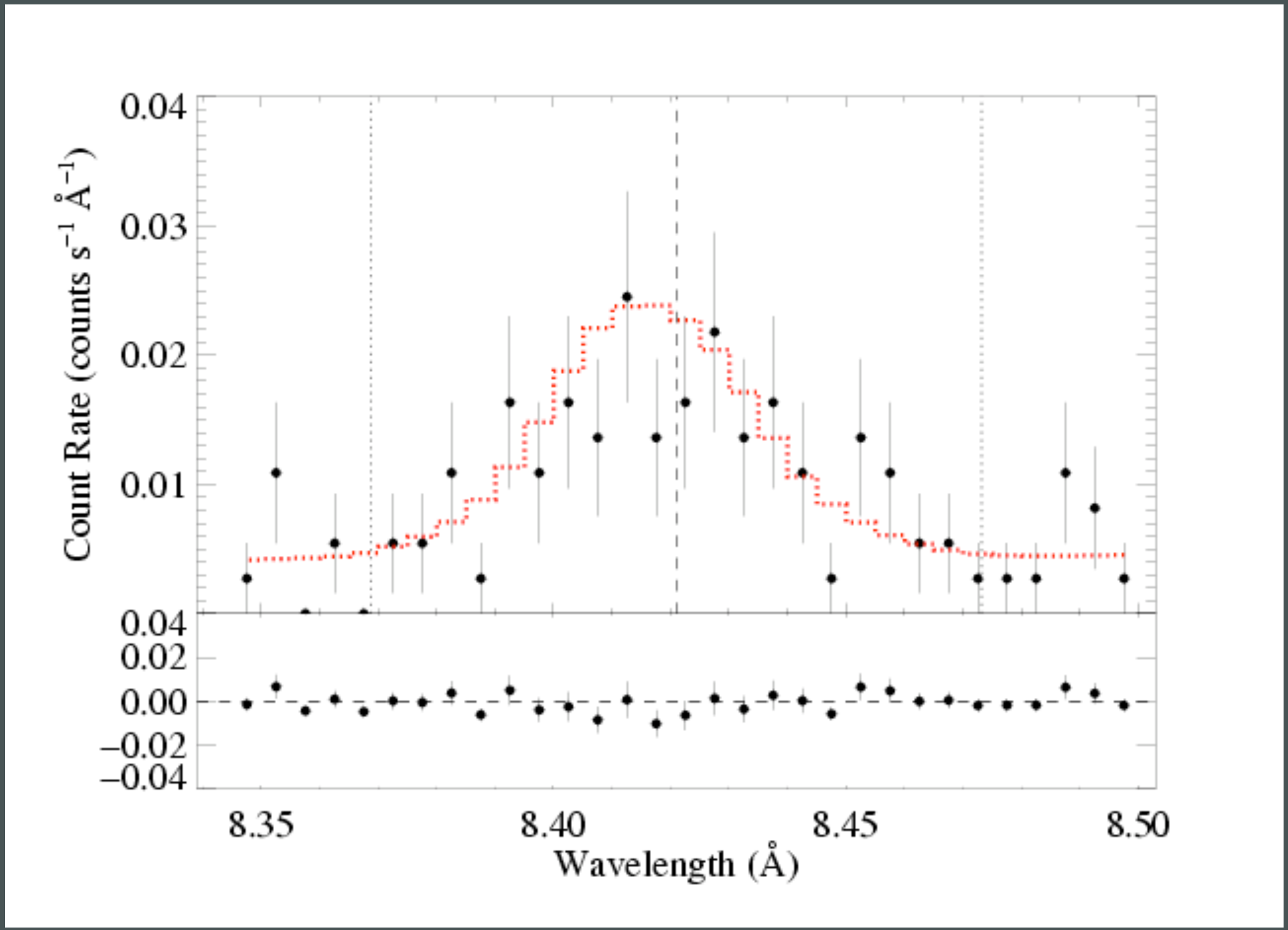


0.12
0.10
0.08
0.06
0.04
0.02
Count Rate (counts s^{-1} Å^{-1})
0.04
0.00
−0.04
14.90
14.95
15.00
15.05
15.10
15.15
Wavelength (Å)

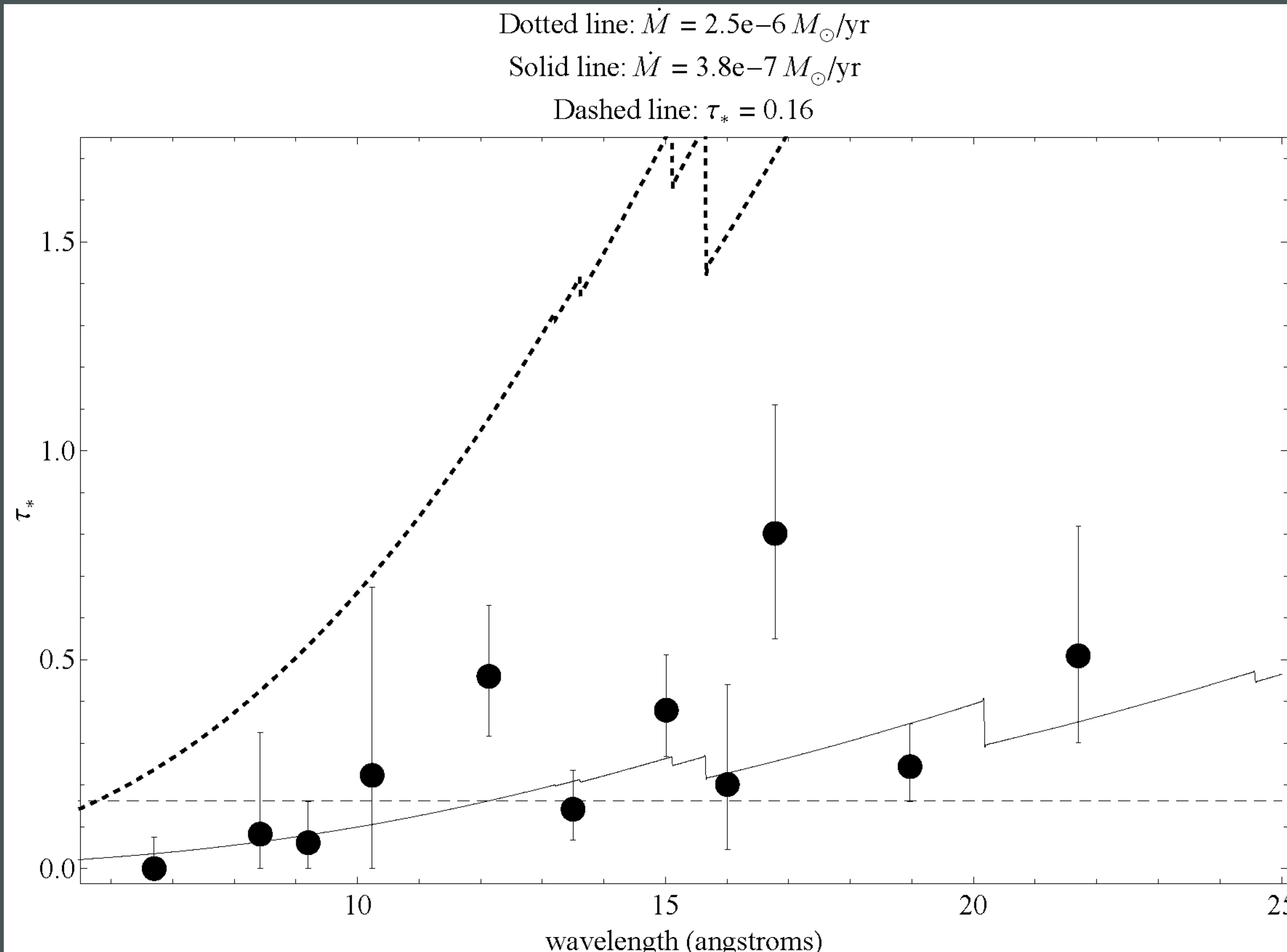
What about other massive stars?

ζ Ori: O9.5

ζ Ori: O9.5 - less massive



Mg XII Lyman-α: $\tau_* = 0.1$


Dotted line: $\dot{M}$ = 2.5e−6 $M_\odot$/yr
Solid line: $\dot{M}$ = 3.8e−7 $M_\odot$/yr
Dashed line: τ_* = 0.16
1.5
1.0
0.5
0.0
τ_*
10
15
20
25
wavelength (angstroms)

Wind shock scenario: consistent with X-ray line profiles…

…but mass-loss rates must be revised downward!

A&A 438, 301–316 (2005)
DOI: 10.1051/0004-6361:20042531

Astronomy & Astrophysics

Lower mass loss rates in O-type stars: Spectral signatures of dense clumps in the wind of two Galactic O4 stars*

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

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

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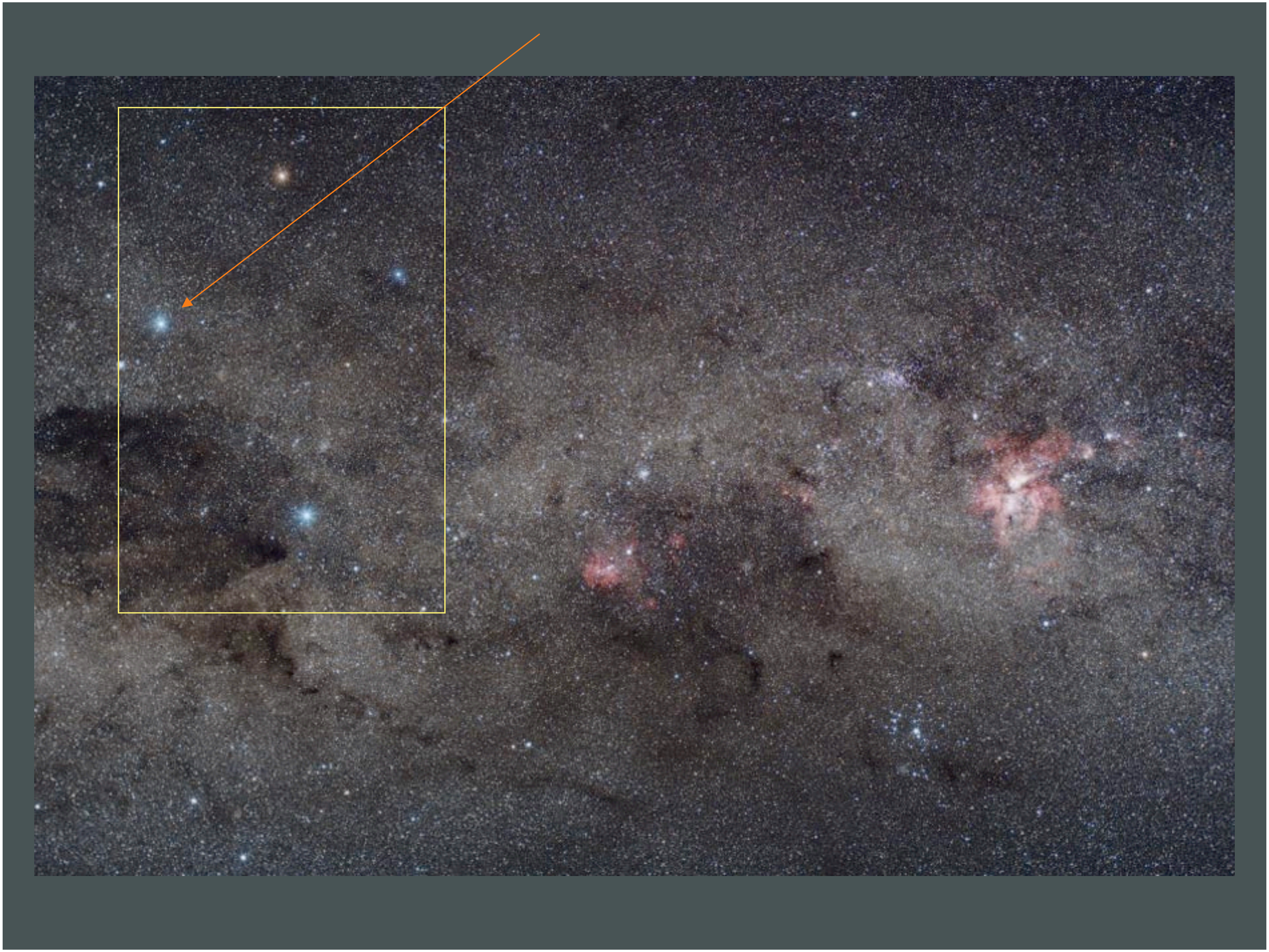
Received 2005 June 10; accepted 2005 October 4

Are there massive stars that do not fit this paradigm?

Yuri Beletsky (ESO)



β Crucis

aliases:

Mimosa

HD 111123

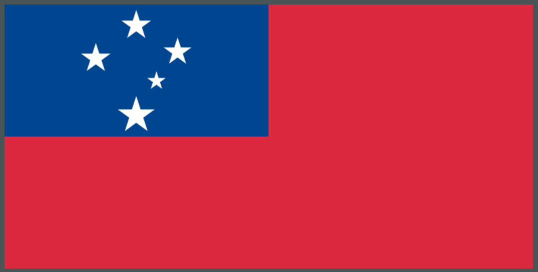
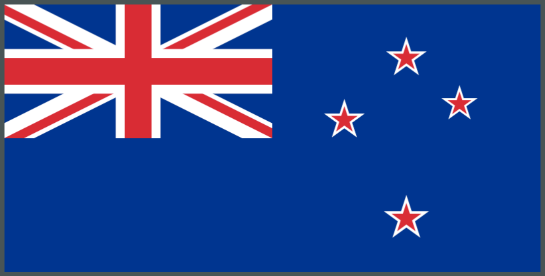
a massive (16 M_{sun}), luminous (34,000 L_{sun}), hot (30,000 K) star

…but not quite as hot, massive, and luminous as an O star: a B0.5 III star

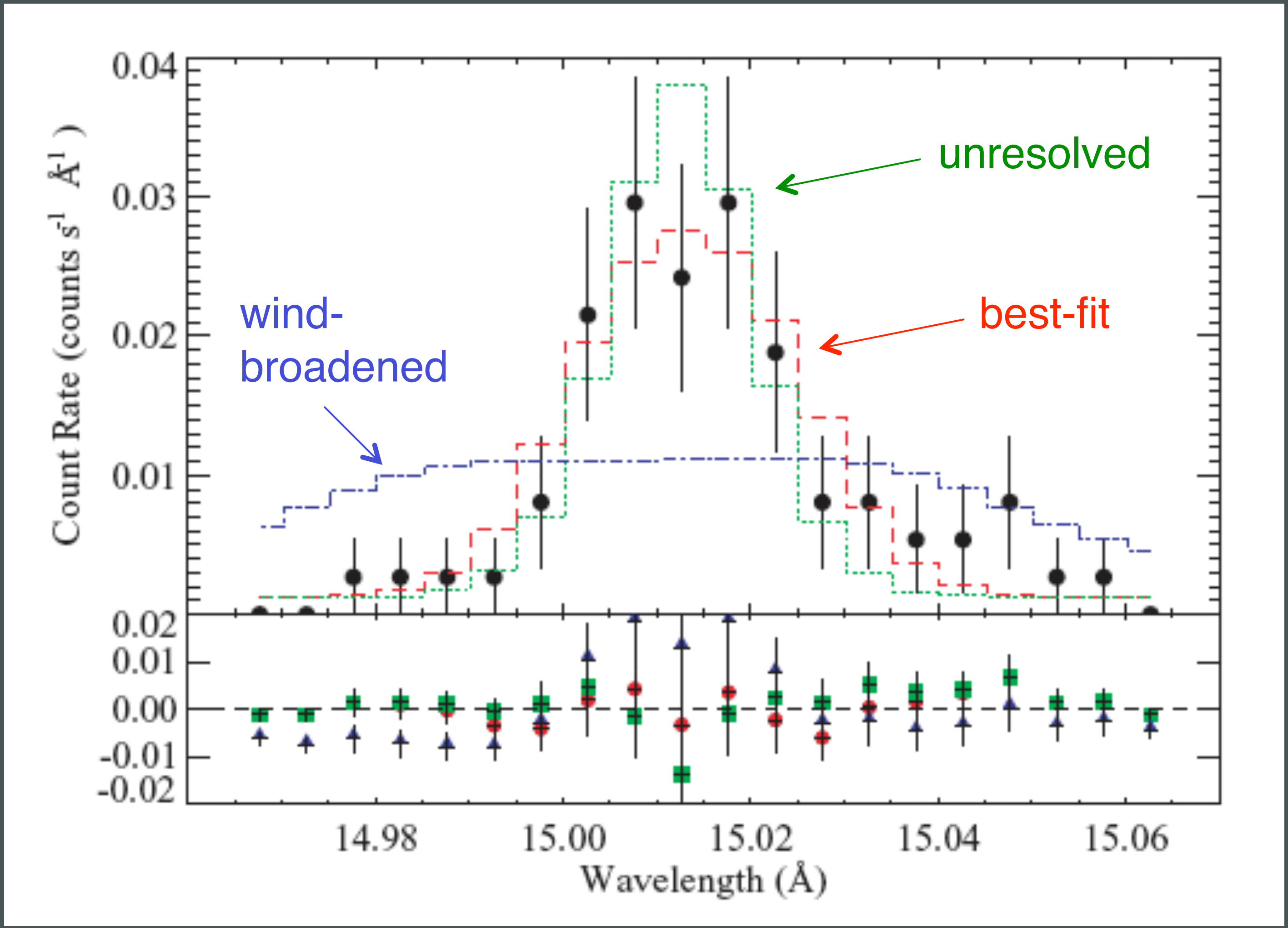
Microscopium
INDUS
PAVO
GRUS
Sagittar
Ara
Norma
Lupus
TRIANGUL. AUSTRALE
CIRCINUS
LIBELLA
INDICA
APIS
Centaurus
PHŒNIX
TOUCAN
HYDRUS
CHAMÆLEON
PISCIS VOLANS
ERIDANUS
HOROLOGIUM
PENDULUM
ARGO
NAVIS
Antlia
Pneumatica

Microscopium
INDUS
PAVO
GRUS
PHOENIX
TOUCAN
HYDRUS
ERIDANUS
HOROLOGIUM
PENDULUM
RETICULUS
NUBECULA MAJOR
NUBECULA MINOR
MONS MENSÆ
PISCIS VOLANS
CHAMÆLEON
CRUX
Centaurus
CIRCINUS
Norma
Regula
Ara
Lupus
TRIANGUL. AUSTRALE
LIBELLA
APIS
APUS
AVIS INDICA
ROBUR CAROLI II
ARGO
NAVIS
Antlia Pneumatica
Pixis Nautica
PLUTEUS
PICTORIS


ORDEM E PROGRESSO

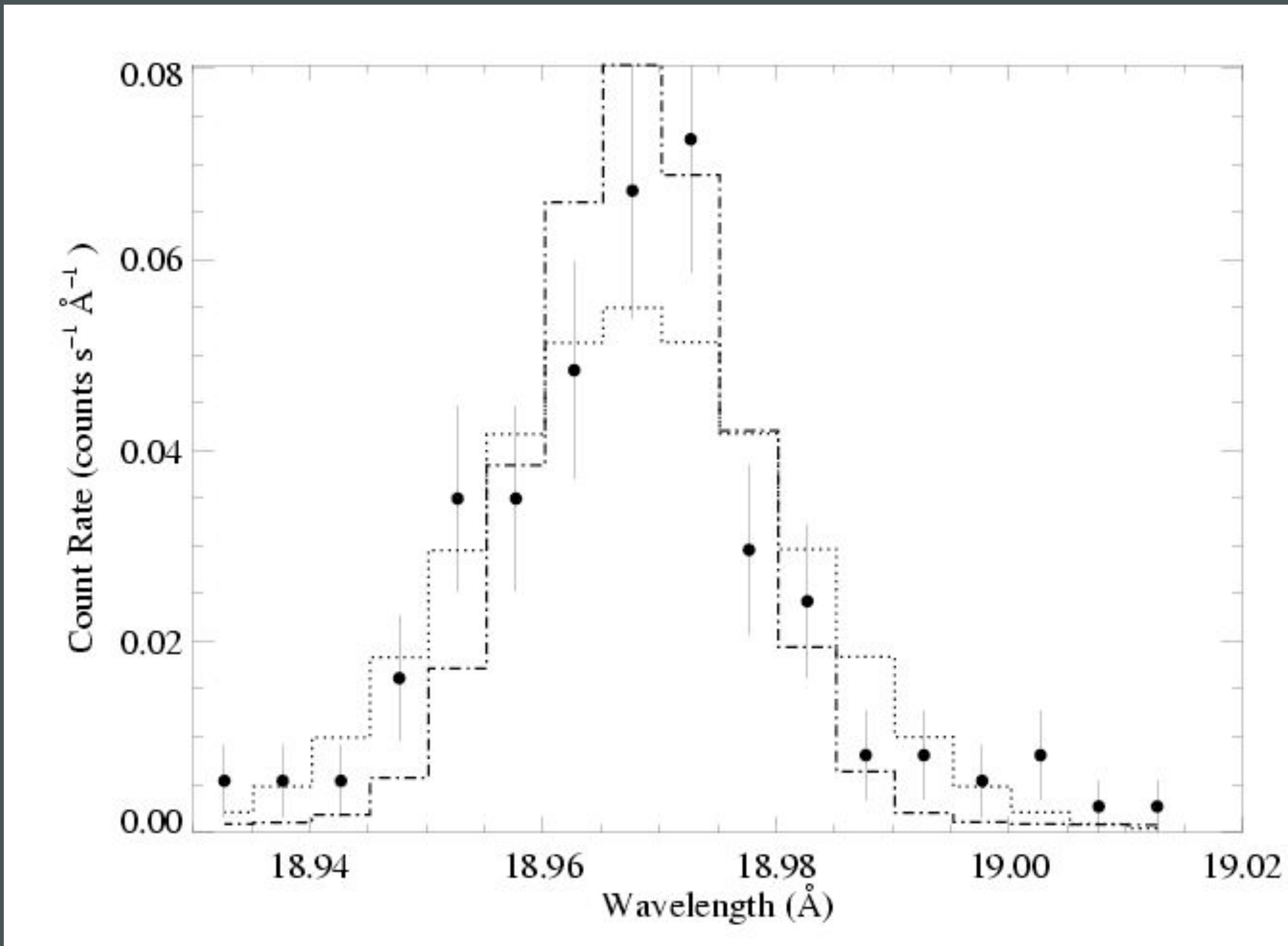



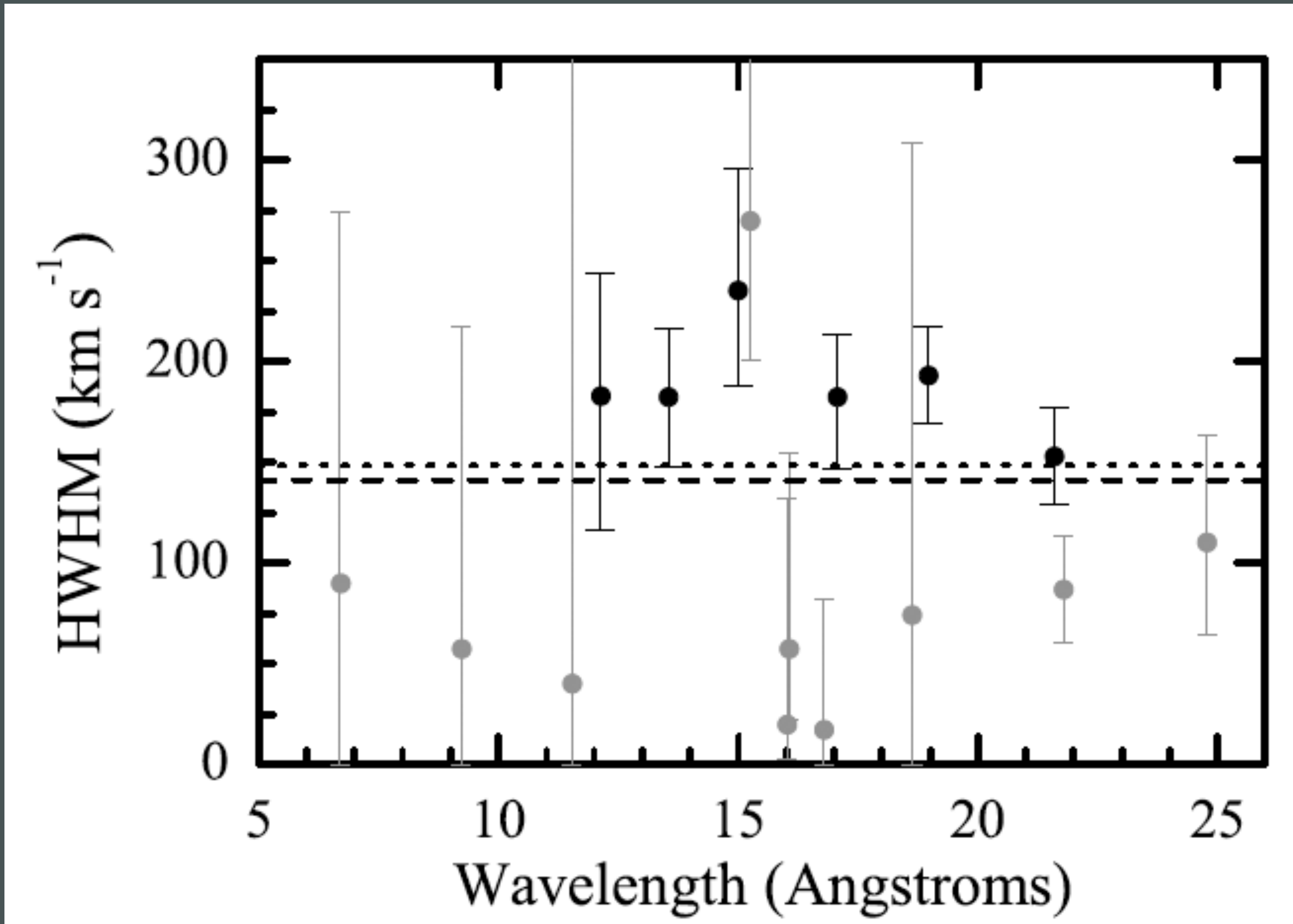

β Crucis (B0.5 V): lines are narrow!



Fe XVII line

β Cru: O VIII Ly-α line





HWHM (km s^{-1})
300
200
100
0
5
10
15
20
25
Wavelength (Angstroms)

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*.

Later-type massive stars have X-rays that are harder to understand, though…their emission lines are quite narrow.