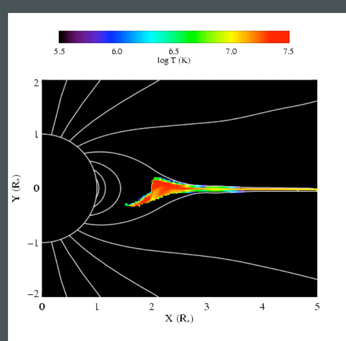
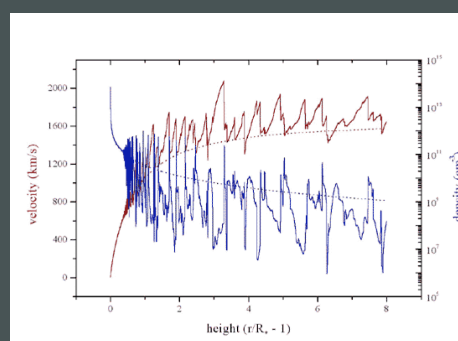
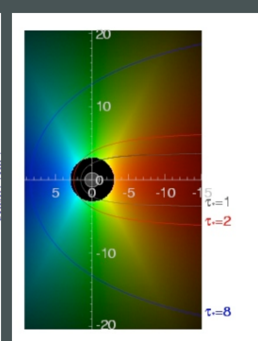
X-ray Emission from Massive Stars:
Hydrodynamics, Wind Mass-Loss Rates, and Magnetic Fields

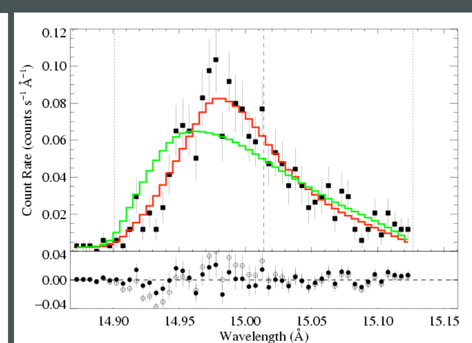
David Cohen
Swarthmore College

with Emma Wollman ('09), Maurice Leutenegger (GSFC), Stan Owocki (U. Delaware), M. Gagné (West Chester Univ.), Asif ud-Doula (Morrisville State)









Massive stars dominate their environments

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}

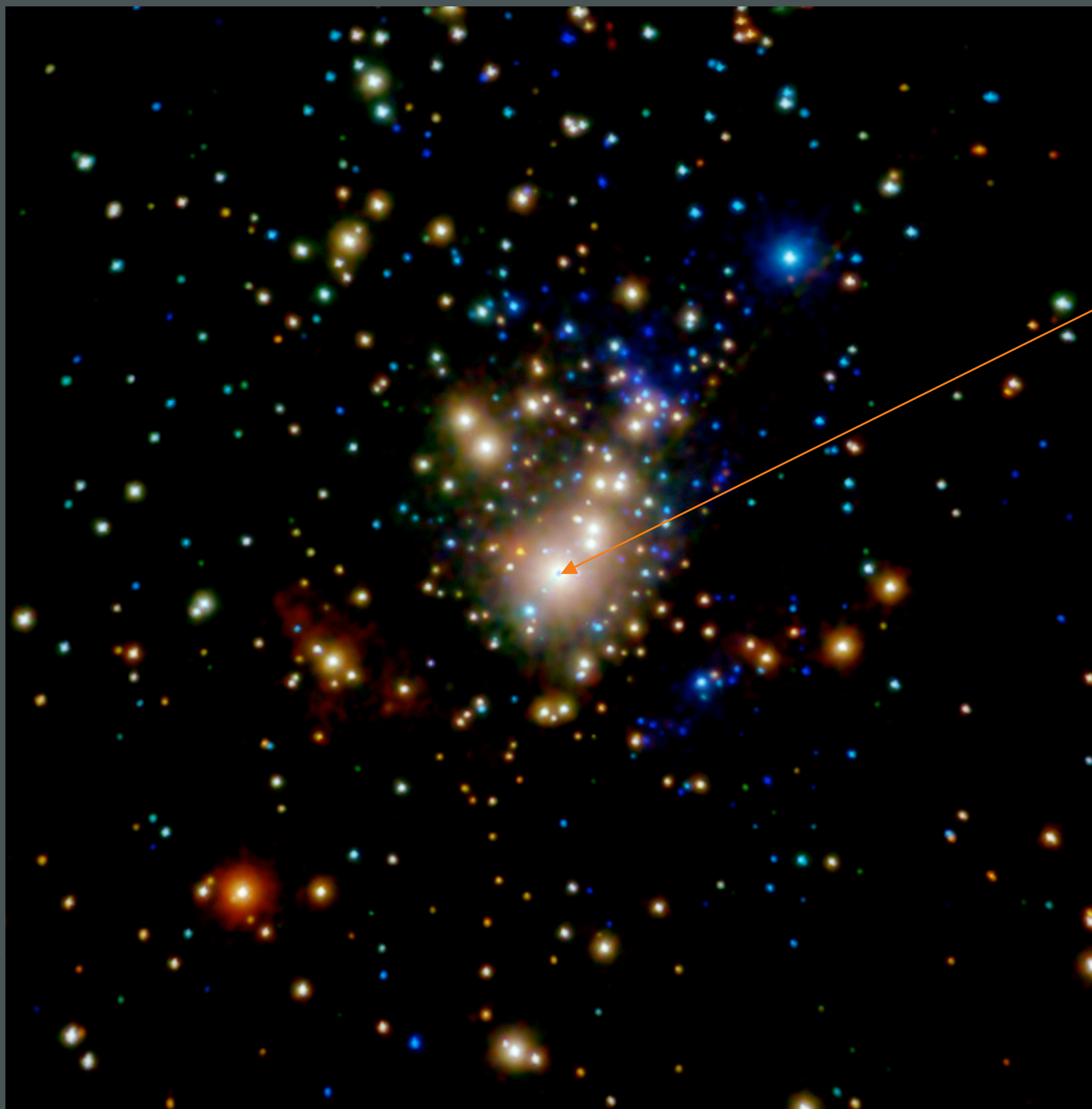
T ~ 50,000 K

The Orion Nebula and Trapezium Cluster
(VLT ANTU + ISAAC)

ESO PR Photo 03a/01 (15 January 2001)

http://astro.swarthmore.edu/~cohen/movies/COUP_optical_xray_m3.mov

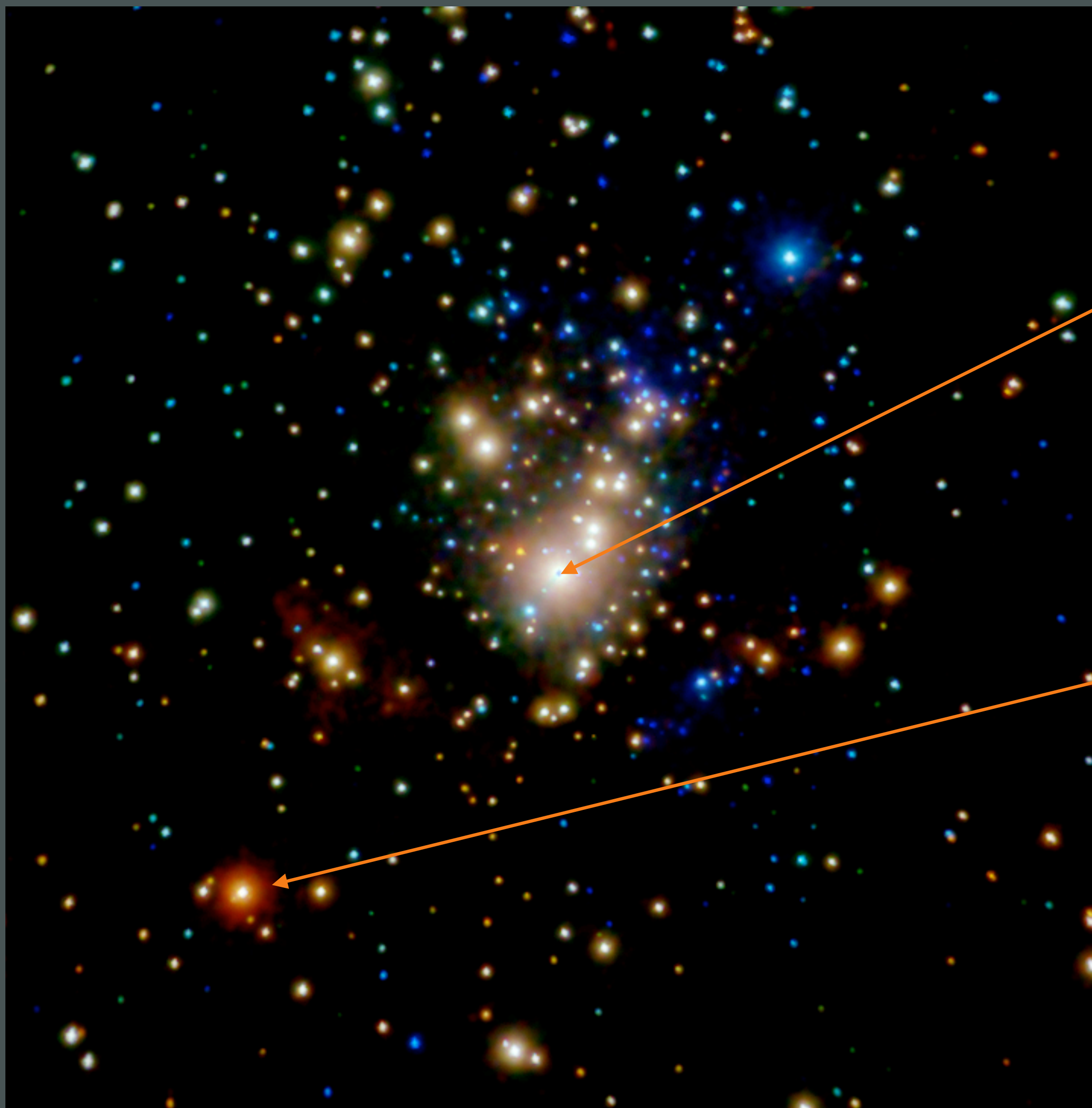
Chandra X-ray Telescope image of the Orion Nebula Cluster



young, massive star:
θ^1 Ori C

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

Chandra X-ray Telescope image of the Orion Nebula Cluster

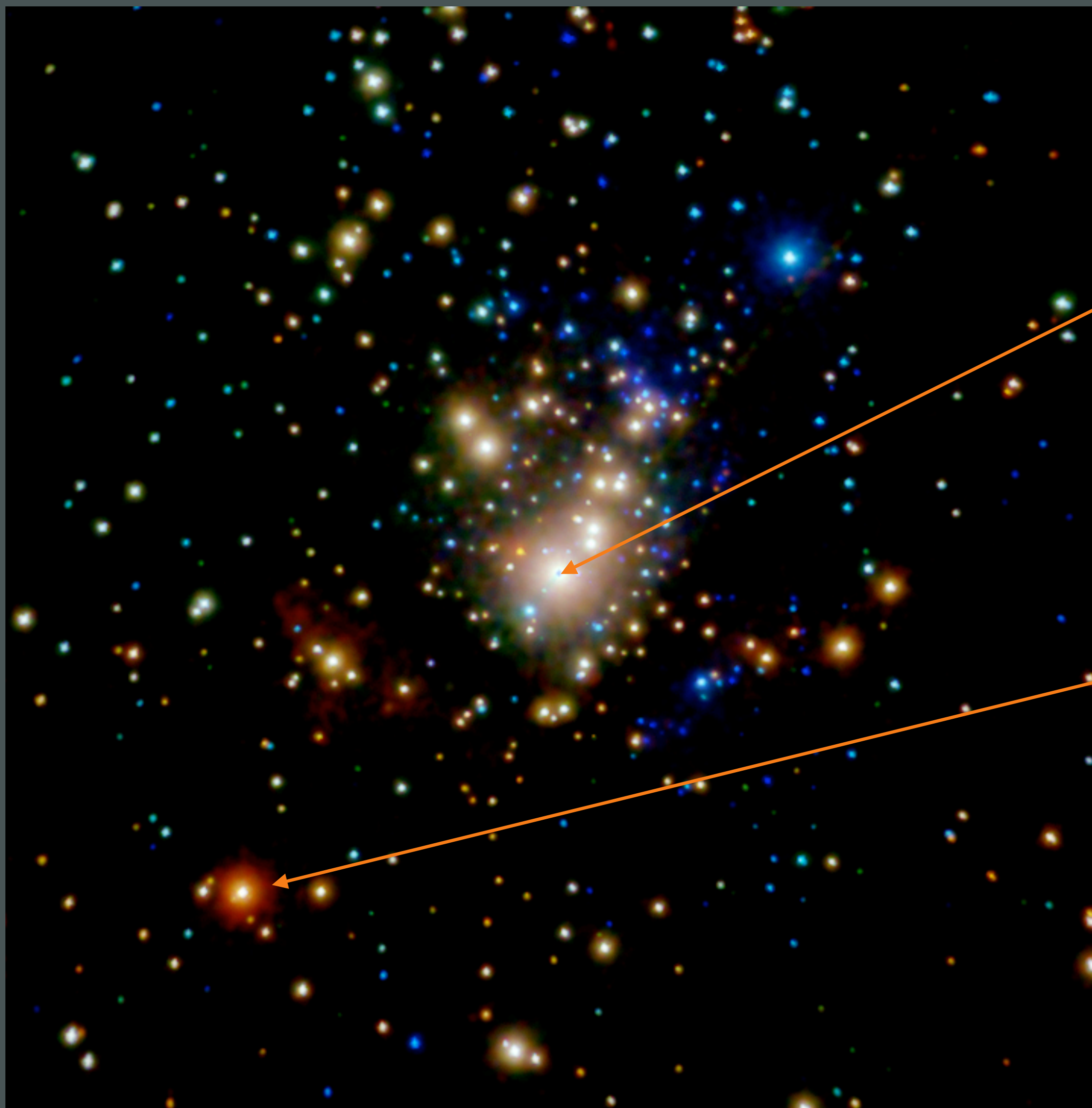


young, massive star:
θ^1 Ori C

young, massive star:
θ^2 Ori A

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

Two different paradigms for (1) non-magnetic OB stars and for (2) magnetic OB stars

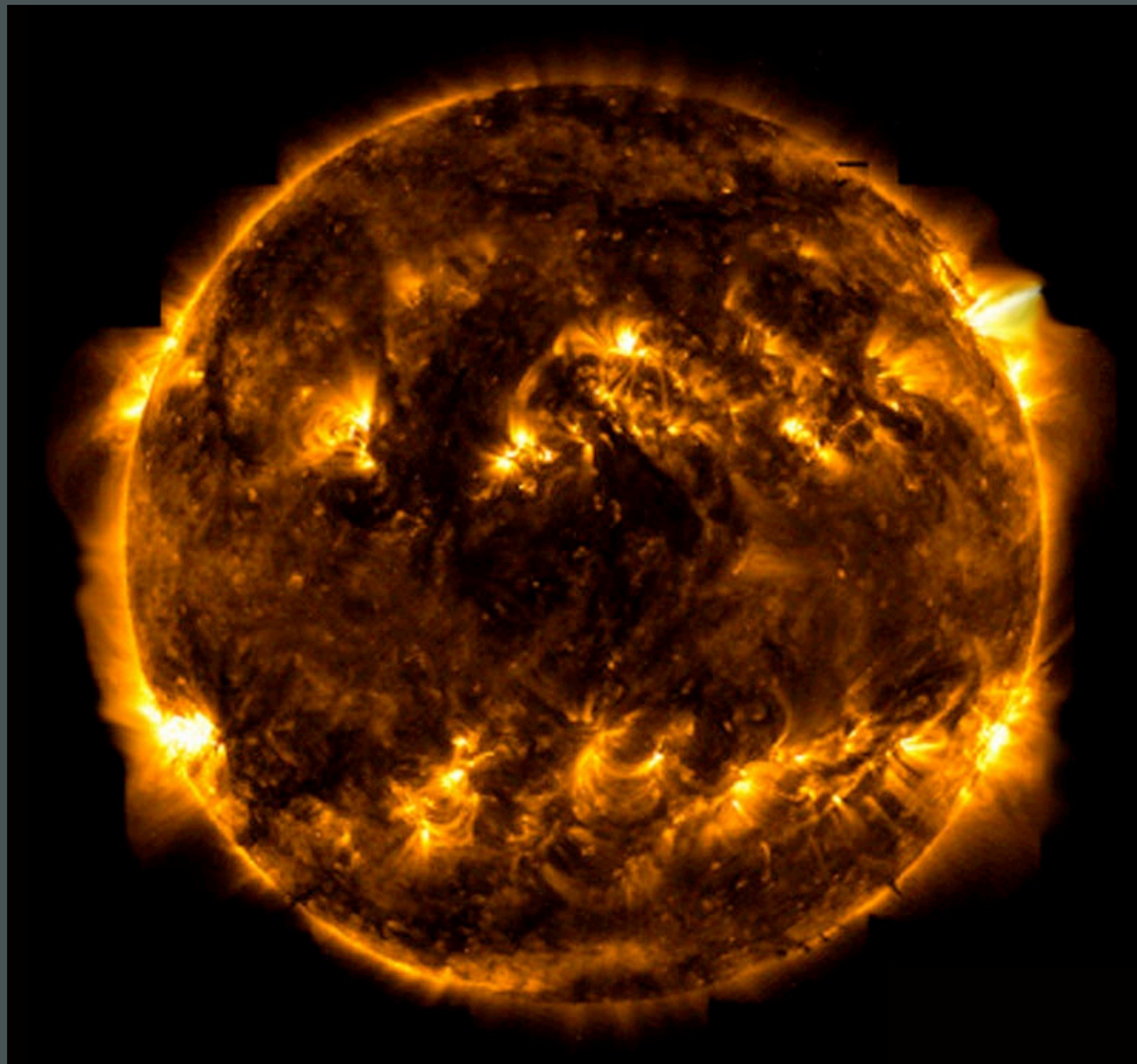


magnetic:
θ^1 Ori C

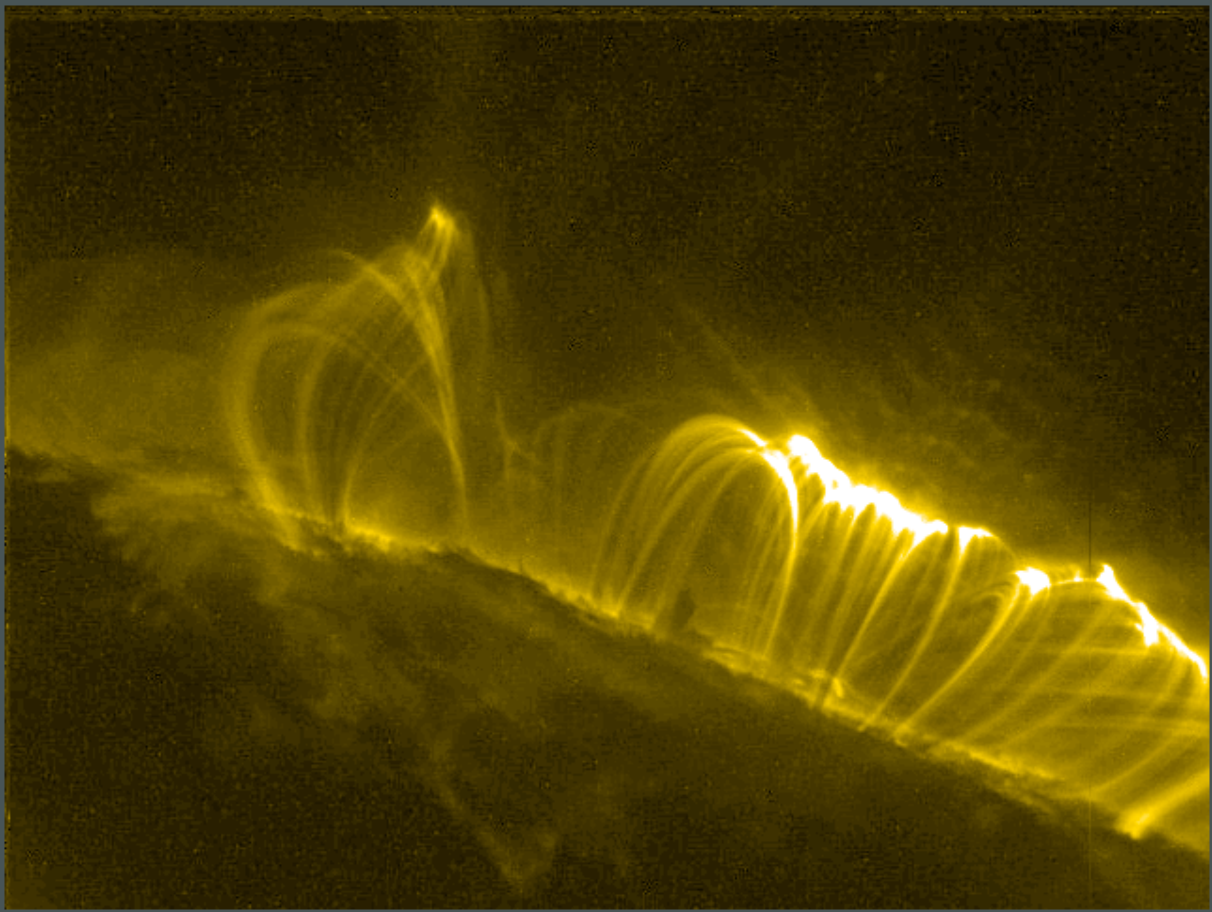
non-magnetic:
θ^2 Ori A

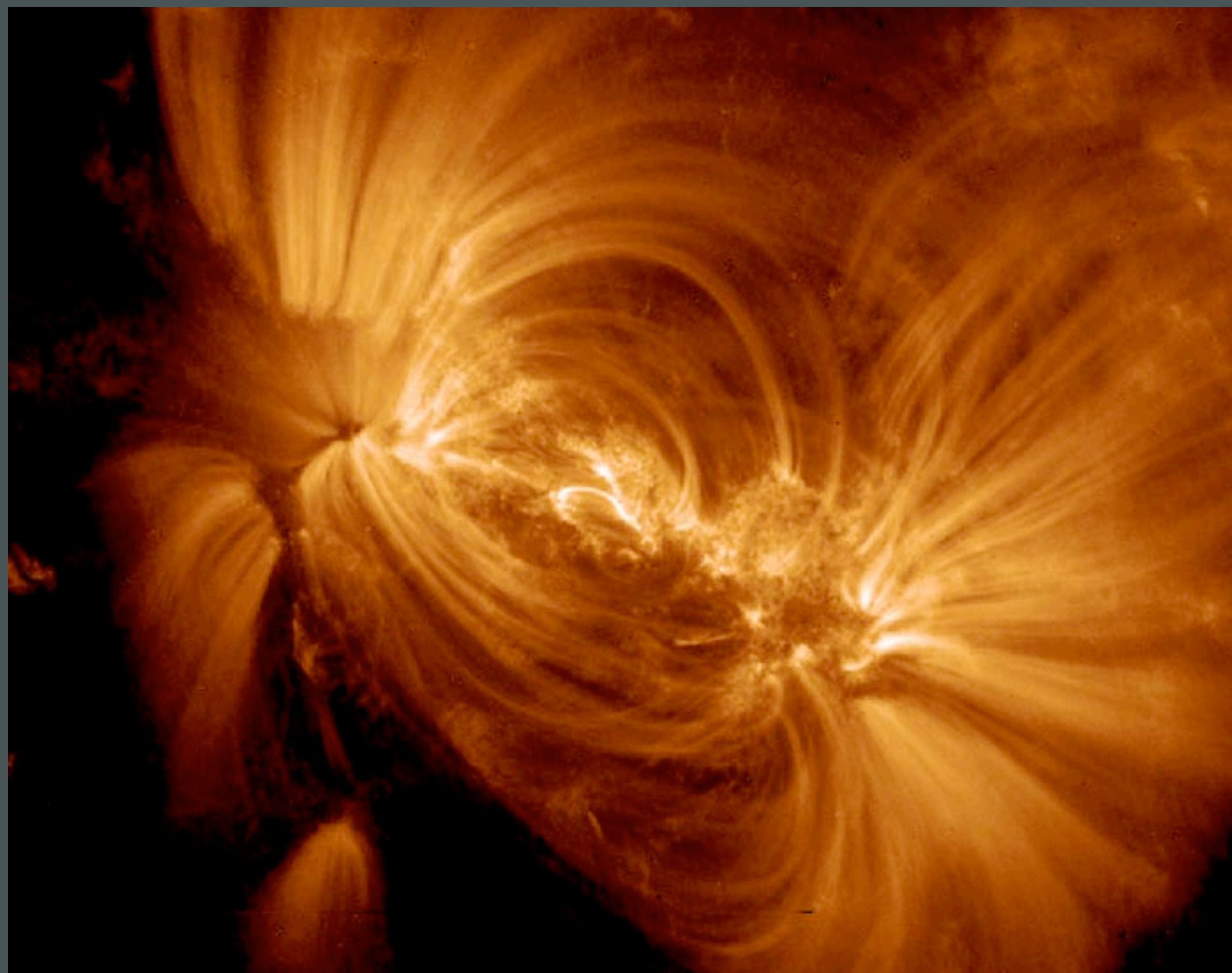
Color coded according to photon energy (red: <1keV; green 1 to 2 keV; blue > 2 keV)

Massive star X-rays are *not* Solar-type X-rays

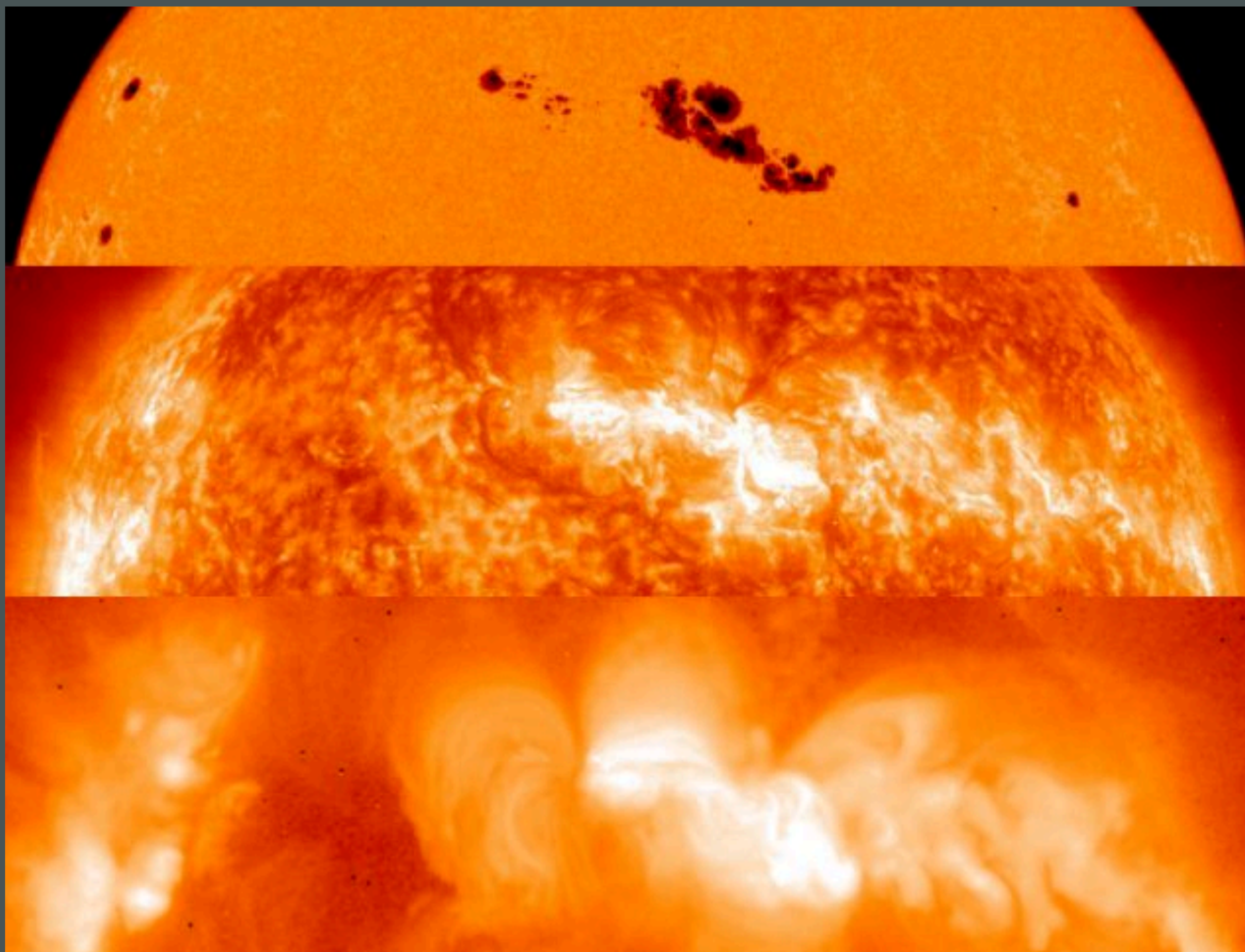


TRACE





The Sun at different wavelengths

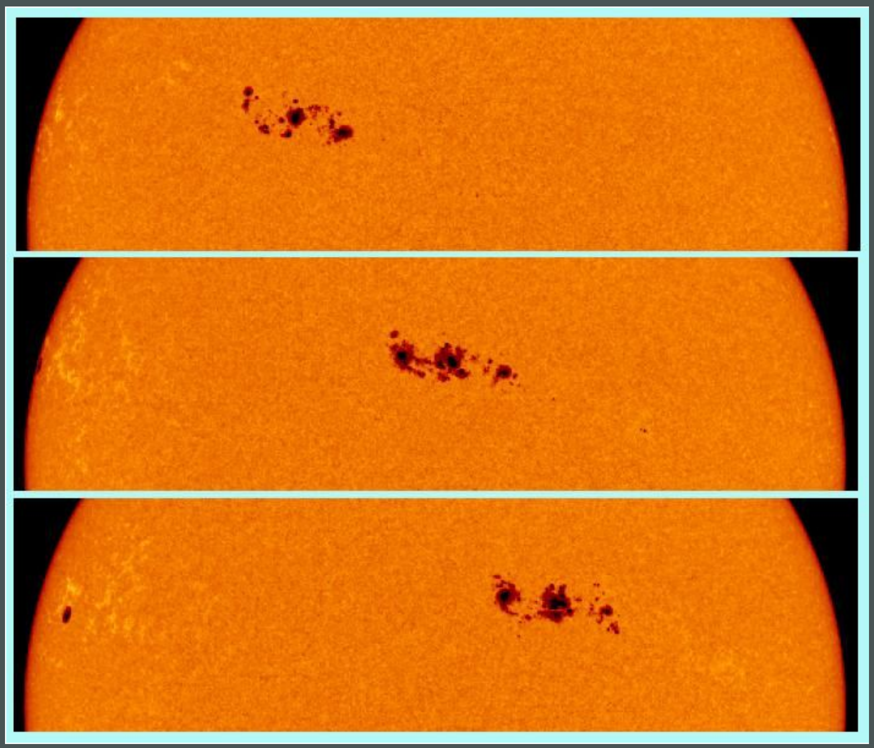


Optical
5800 K

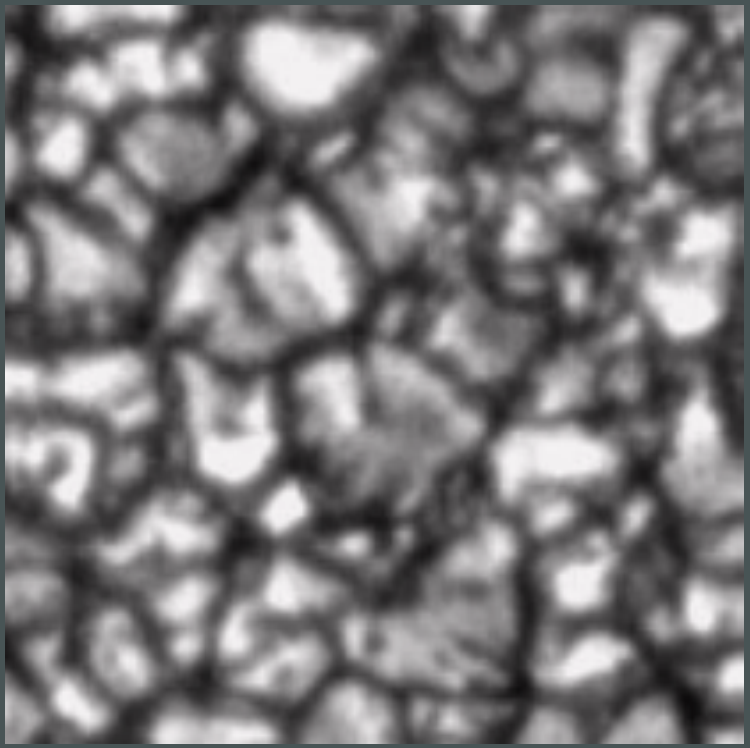
SOHO
EUV
few 10^5 K

YOKOH
x-ray
few 10^6 K

rotation



convection



massive stars are not supposed to have a dynamo – no corona…no x-rays?

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

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

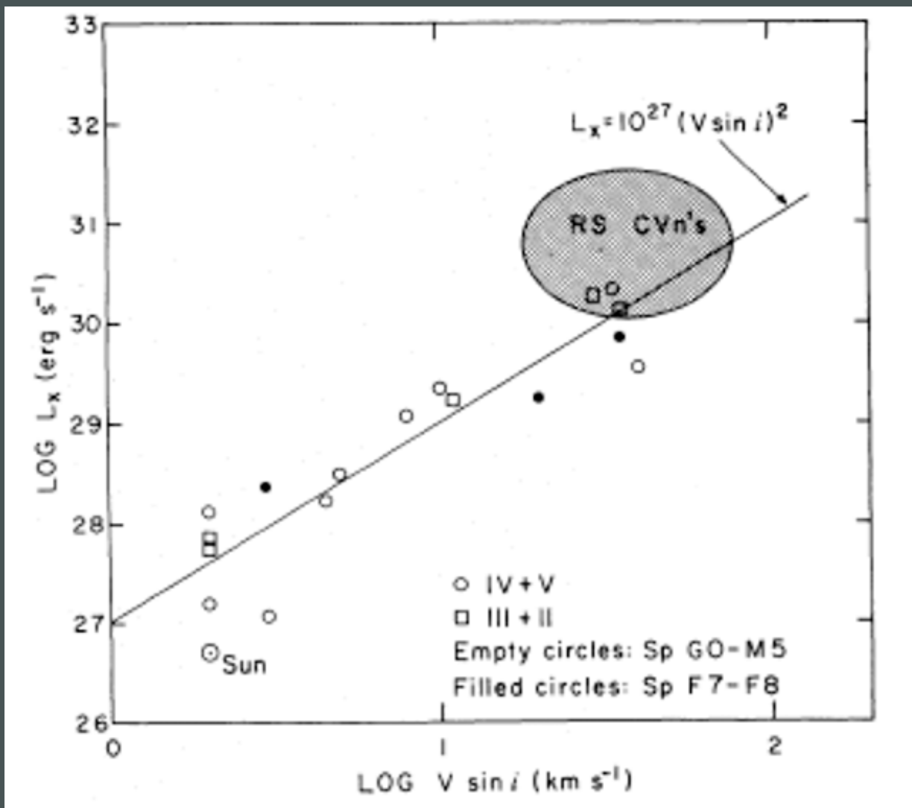
F. R. HARNDEN, JR., G. BRANDUARDI, M. ELVIS,[1] P. GORENSTEIN, J. GRINDLAY,
J. P. PYE,[1] R. ROSNER, K. TOPKA, AND G. S. VAIANA[2]
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts
Received 1979 June 26; accepted 1979 July 26

ABSTRACT

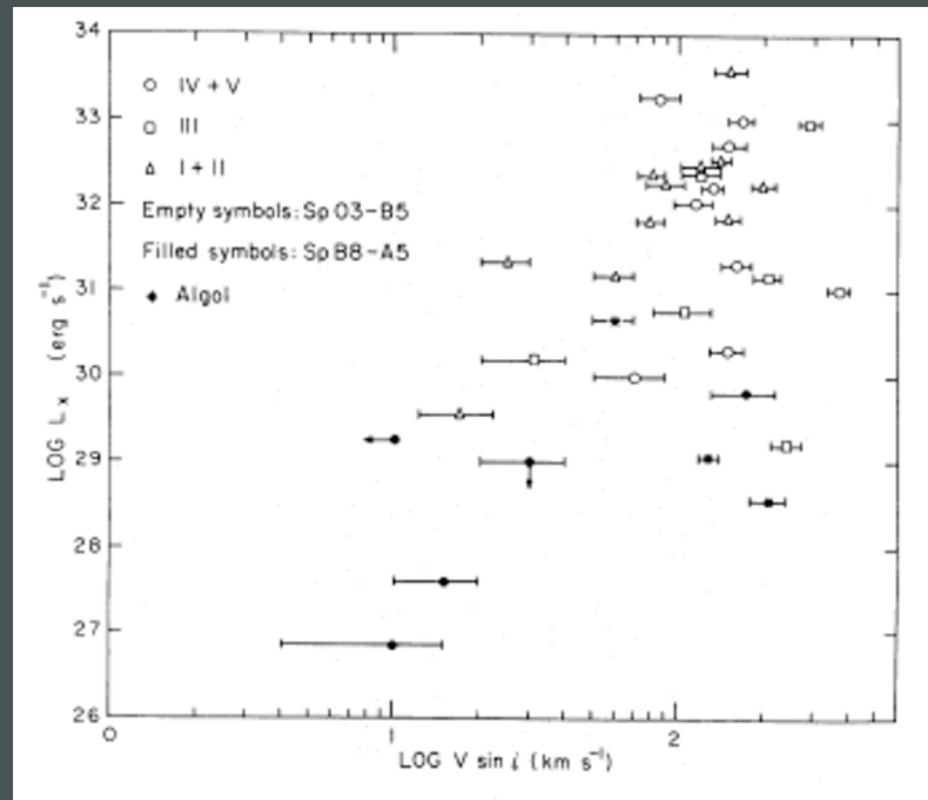
A group of six X-ray sources located within 0°.4 of Cygnus X-3 has been discovered with the *Einstein* Observatory. These sources have been positively identified and five of them correspond to stars in the heavily obscured OB association VI Cygni. The optical counterparts include four of the most luminous 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.

Stellar rotation vs. X-ray luminosity

low-mass stars



high-mass stars



Stellar rotation vs. X-ray luminosity

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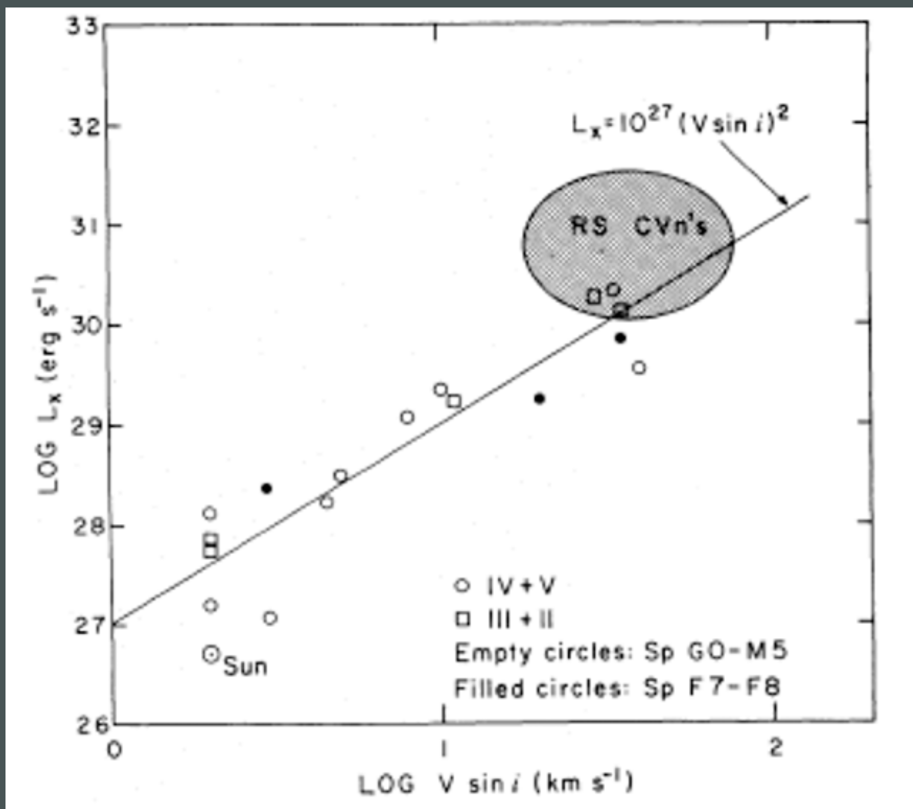
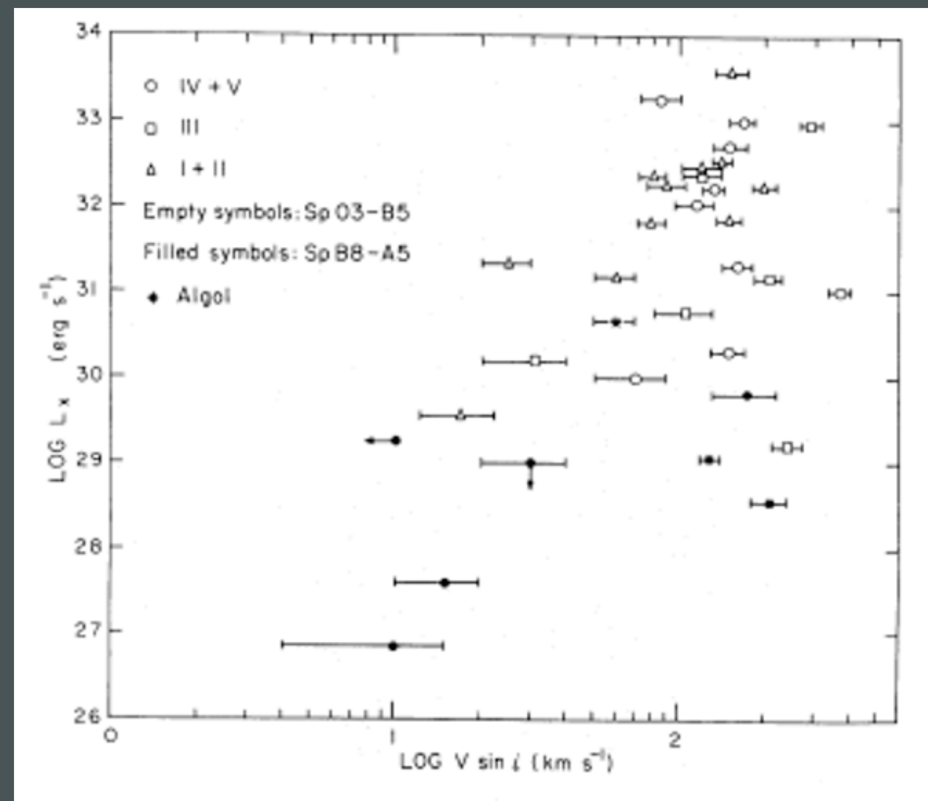


Activity-rotation correlation
= dynamo, corona

high-mass stars



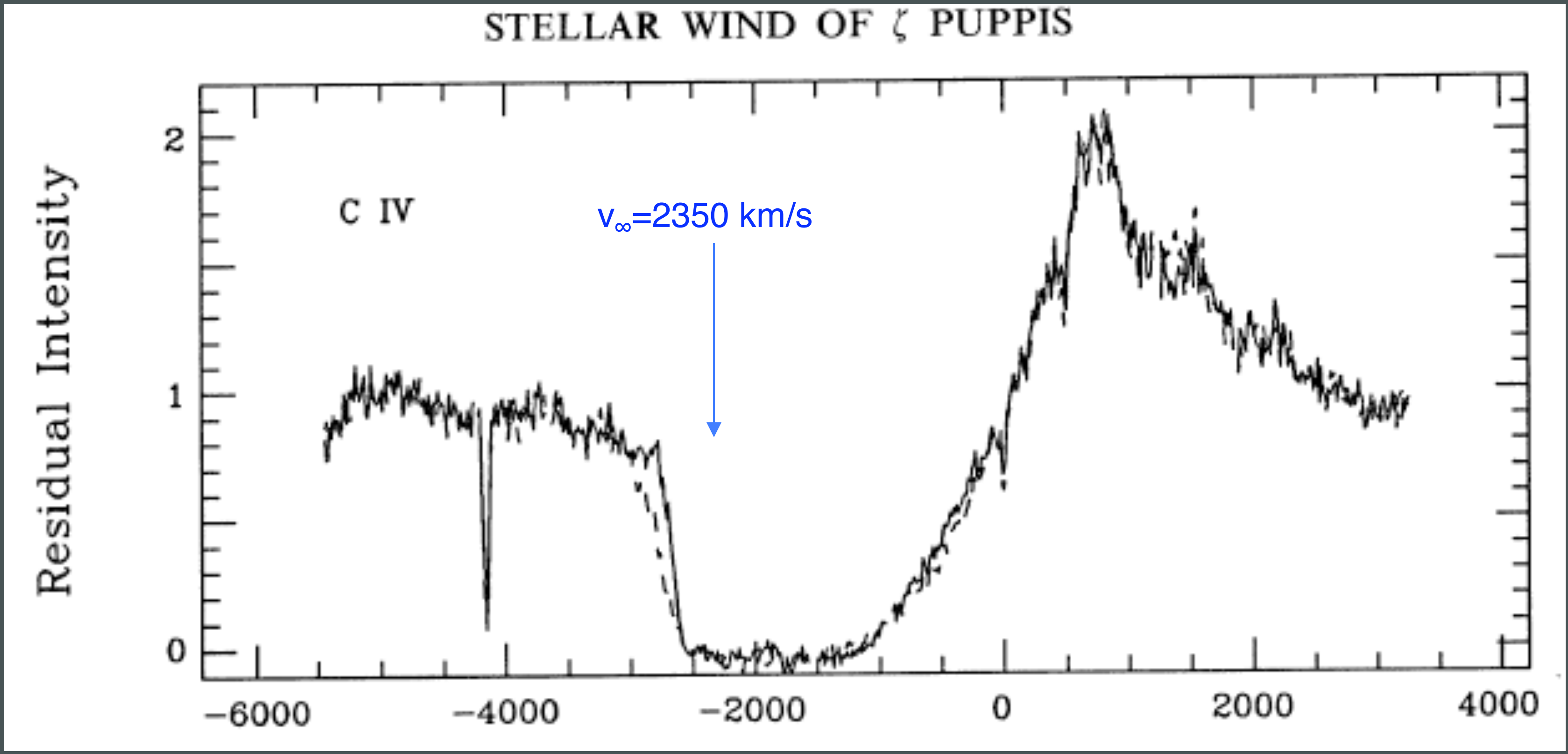
NO correlation = some *other* x-ray production mechanism radiation-driven **winds** of massive stars

wind-blown bubble: stellar wind impact on its environment

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)

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

Eddington factor, Γ_{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

Assuming electron scattering (Thompson) opacity only

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

For massive stars, Γ_{edd} approaches unity

Mechanical **power** in these winds:

$$\frac{1}{2}\dot{M}v_\infty^2 \approx 3\times10^{36} \text{ erg s}^{-1}$$

$$\approx .001L_*$$

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

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

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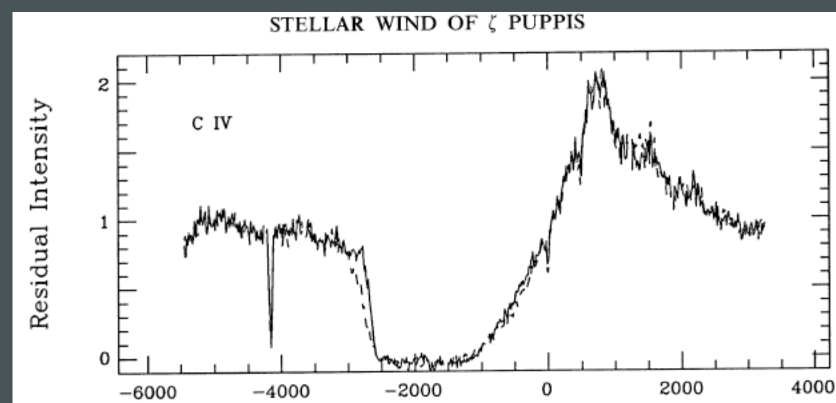
$L_{massive}$ ≈ 4 x 10^{39}



Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

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

Power in massive star winds:

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

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

Hydrodynamic shocks extract kinetic energy from a supersonic flow and convert it to thermal energy

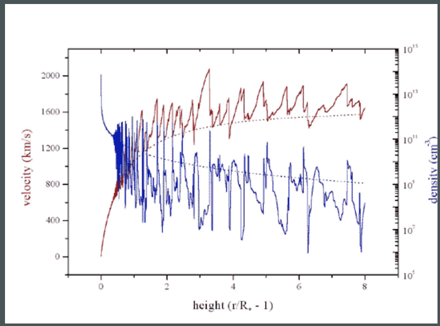
$\Delta v_{shock} = 300$ km/s gives

$T \sim 10^6$ K

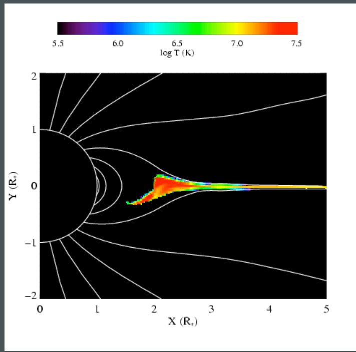
(and $T \sim v^2$)

Three models for massive star x-ray emission

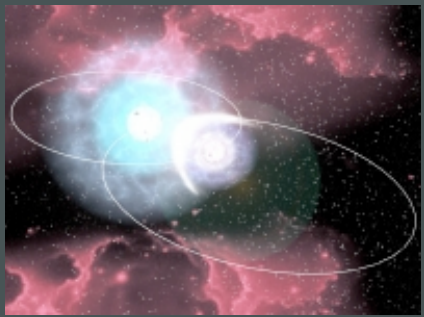
1. Instability driven shocks



2. Magnetically channeled
wind shocks

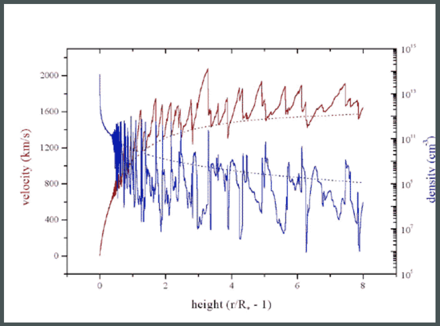


3. Wind-wind interaction in
close binaries



Three models for massive star x-ray emission

1. Instability driven shocks



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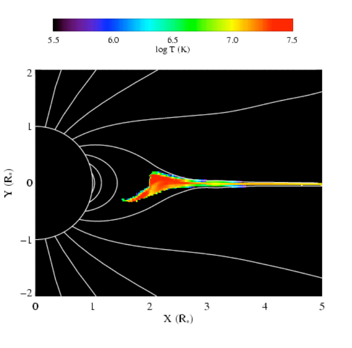

3. Wind-wind interaction in
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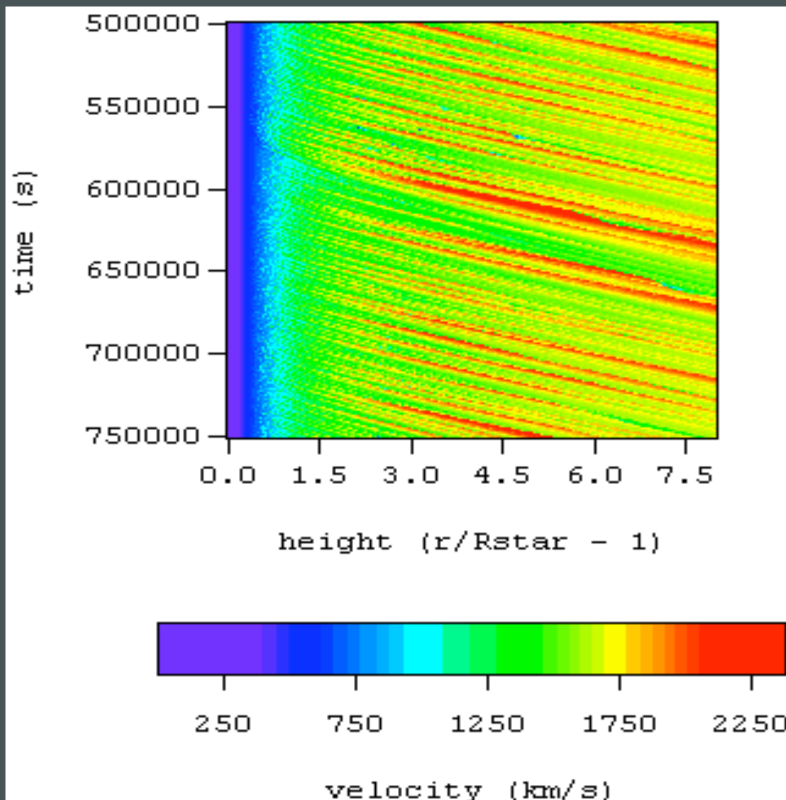
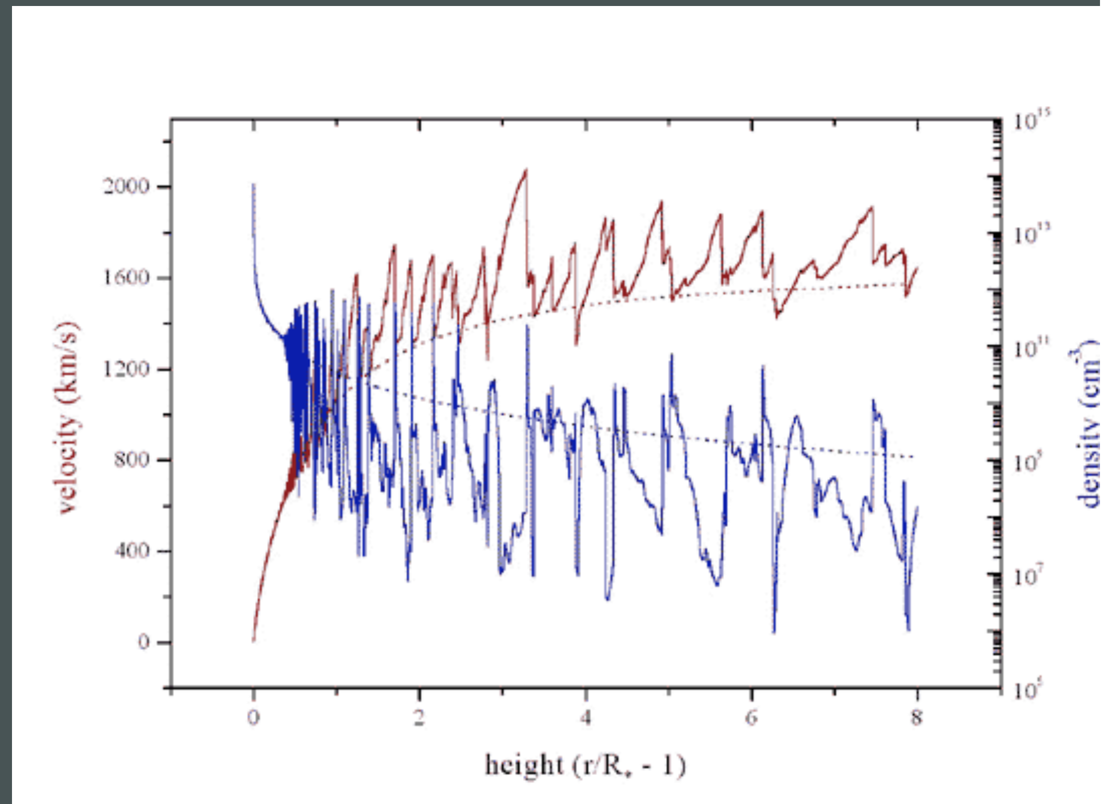
1-D rad-hydro simulation of a massive star wind

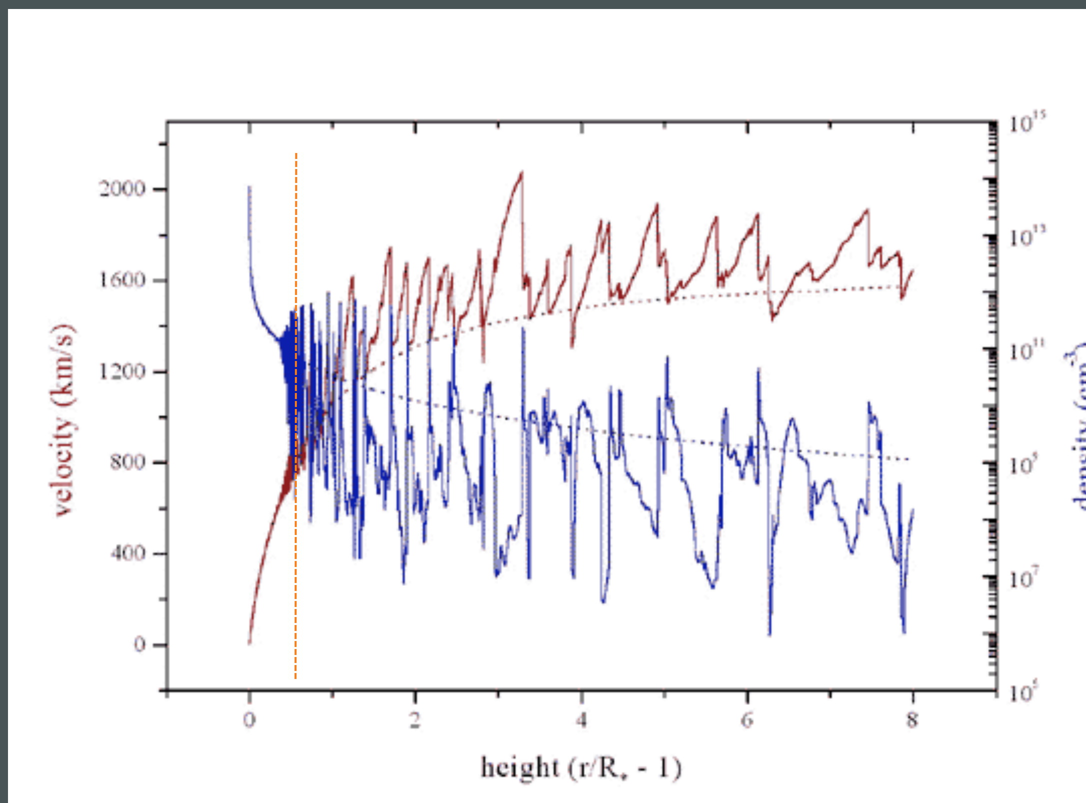




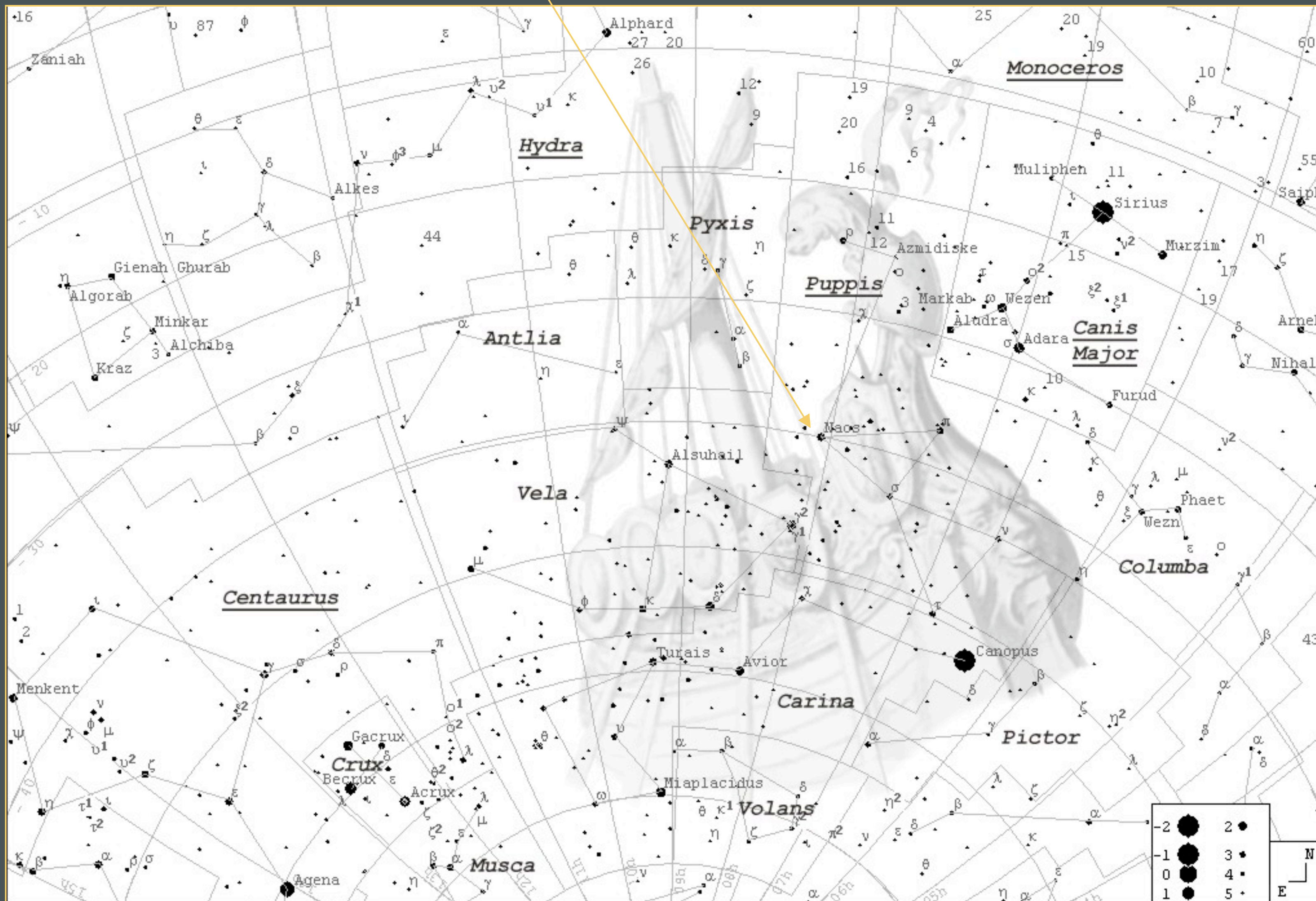
Radiation line driving is inherently unstable:
shock-heating and X-ray emission

Predictions of the rad-hydro wind simulations:

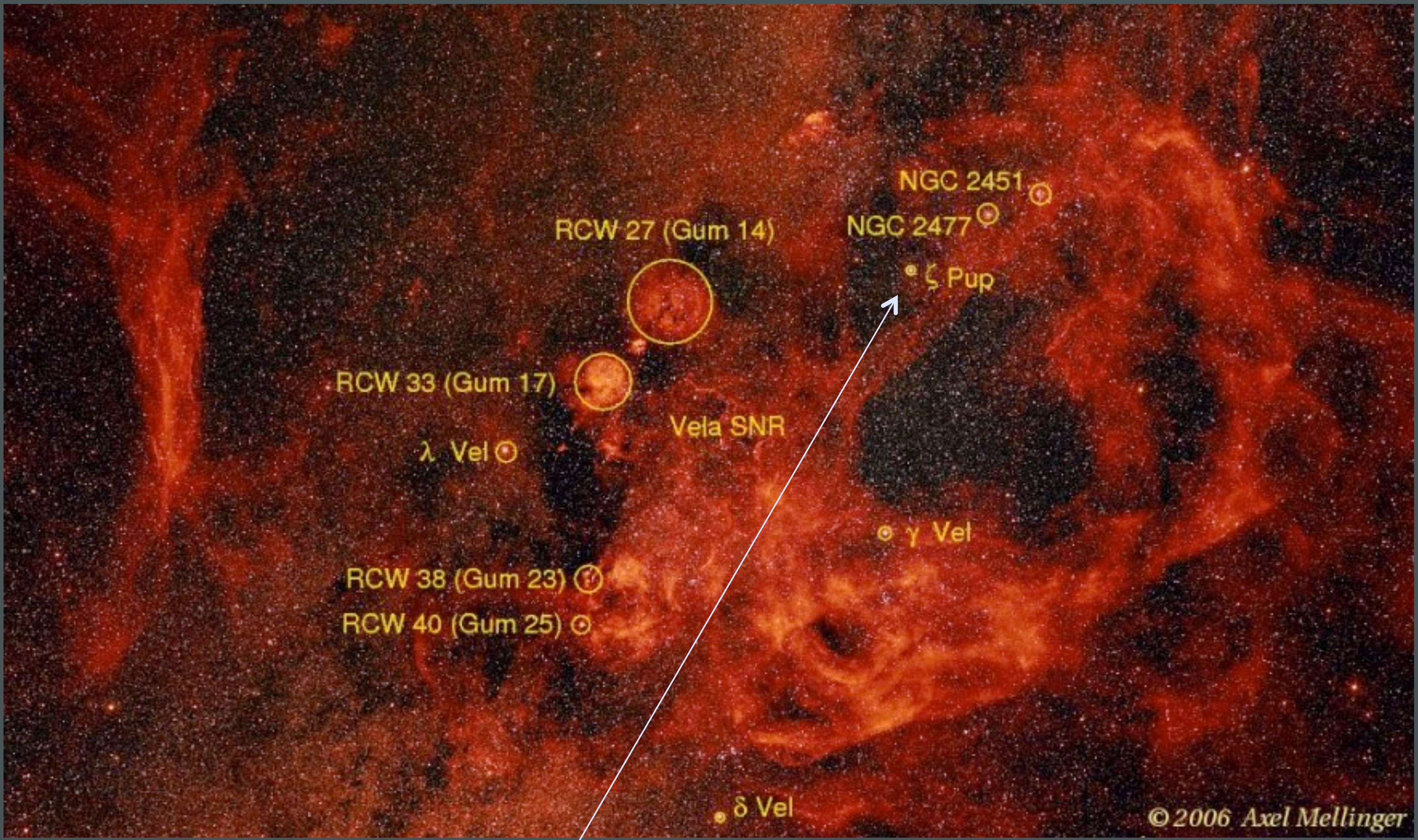
1. Significant Doppler broadening of x-ray emission lines due to bulk motion of the wind flow (1a. Shock onset several tenths R_* above the surface)
2. Bulk of the wind is cold and unshocked – source of attenuation of the X-rays.



ζ Puppis: 50 M_{sun}, 10^6 L_{sun}



ζ Puppis in context



In front of the Gum Nebula, it is one of the very closest O stars to the Earth

Chandra – launched in 1999

Energy Considerations and Scalings

1 keV ~ 12 × 10^6 K ~ 12 Å

Shock heating: Δv = 300 km/s
gives T ~ 10^6 K (and T ~ v^2)

Chandra, *XMM* 350 eV to 10 keV

Energy Considerations and Scalings

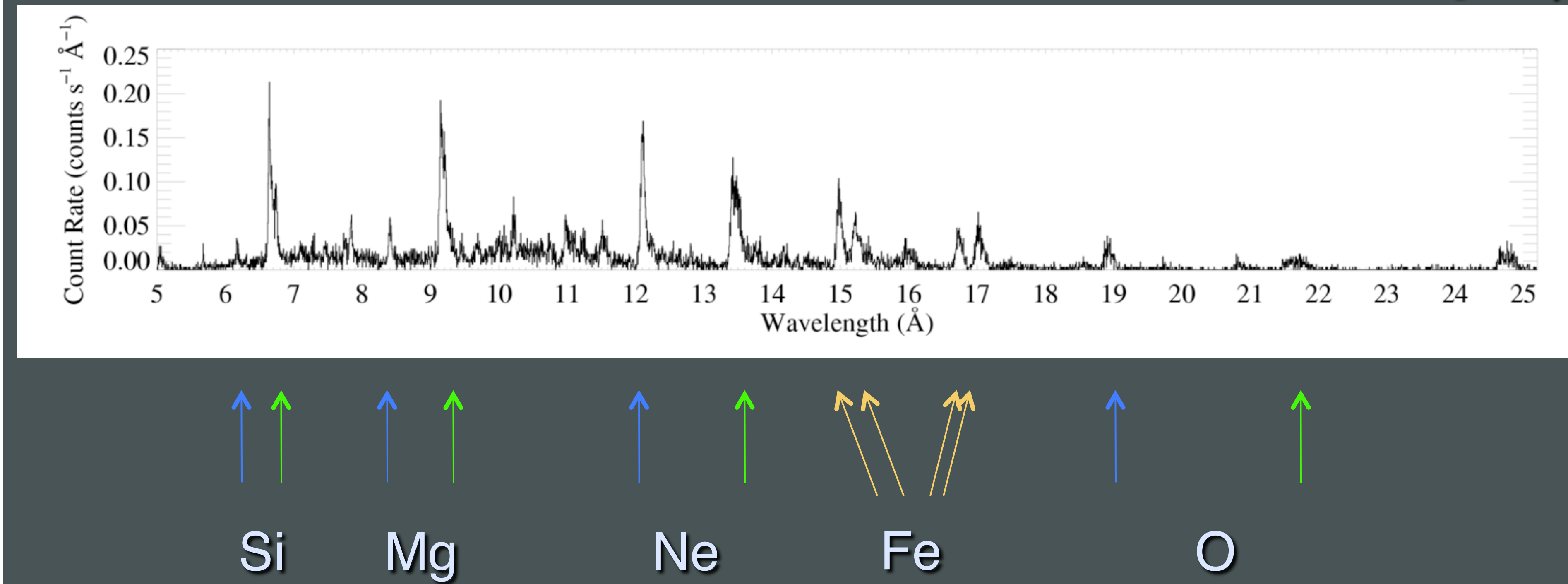
1 keV ~ 12 × 10^6 K ~ 12 Å

Shock heating: Δv = 1000 km/s
gives T ~ 10^7 K (and T ~ v^2)

Chandra, *XMM* 350 eV to 10 keV

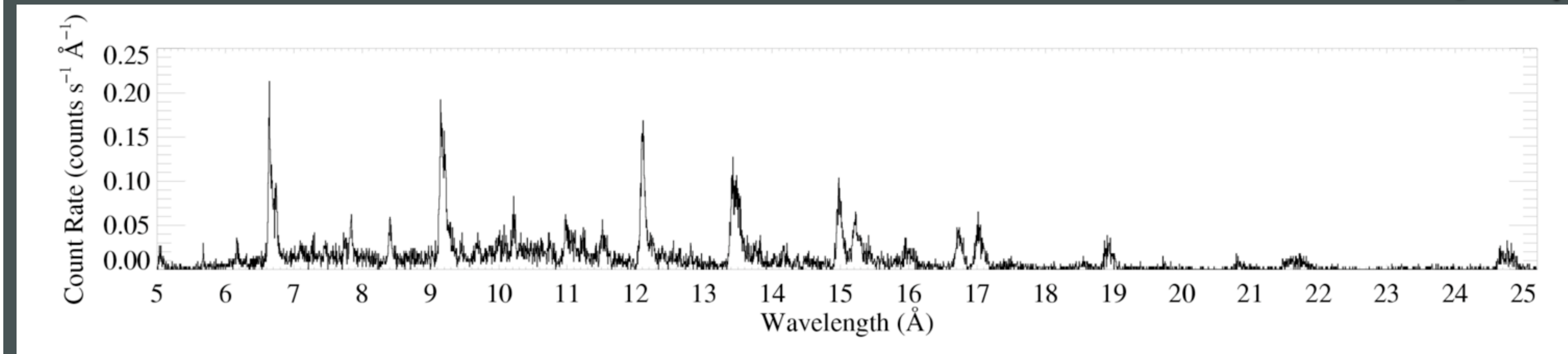
Chandra HETGS/MEG spectrum
($R \sim 1000$ corresponding to 300 km s^{-1})

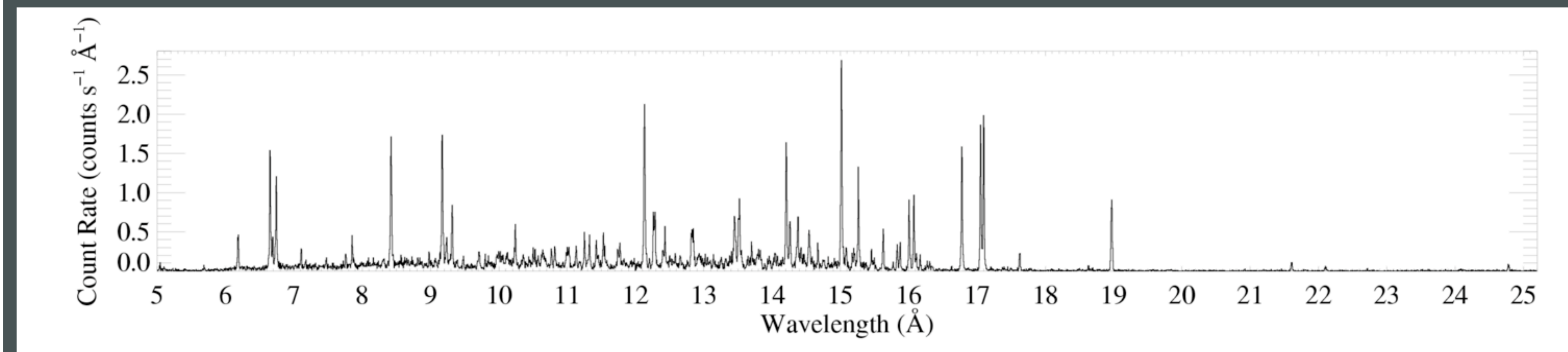
ζ Pup



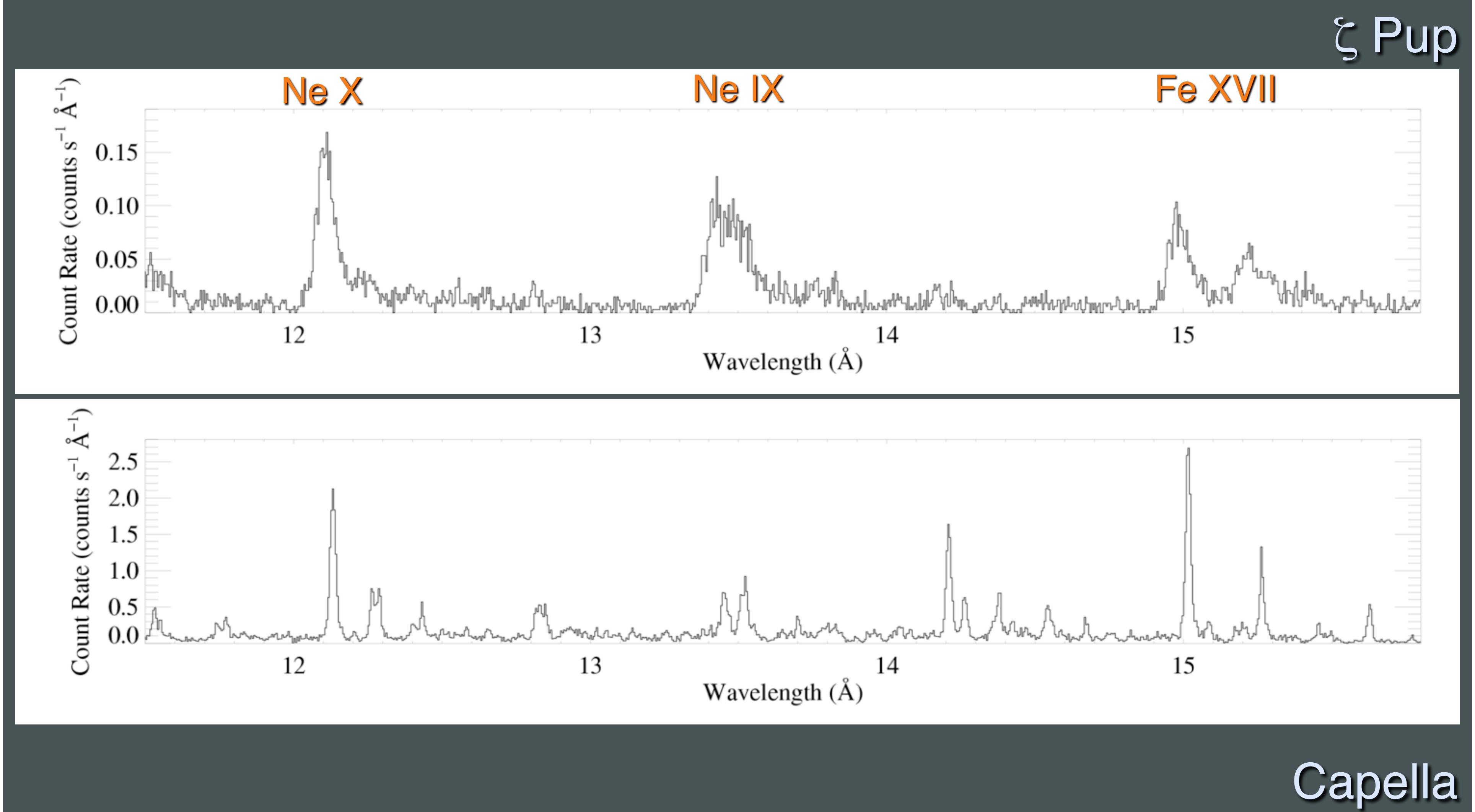
H-like
He-like

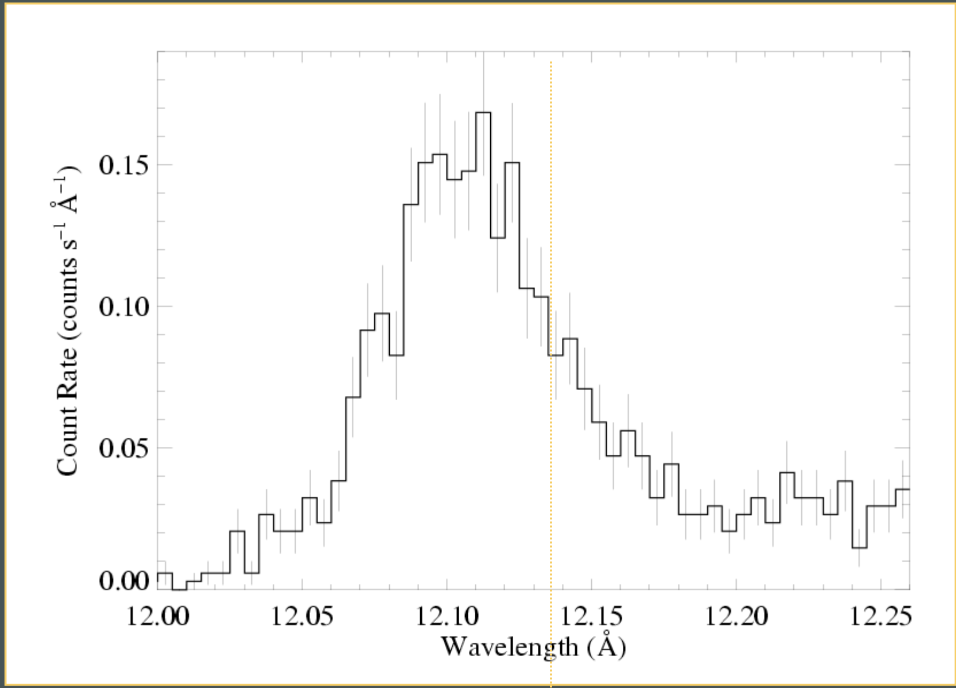
ζ Pup



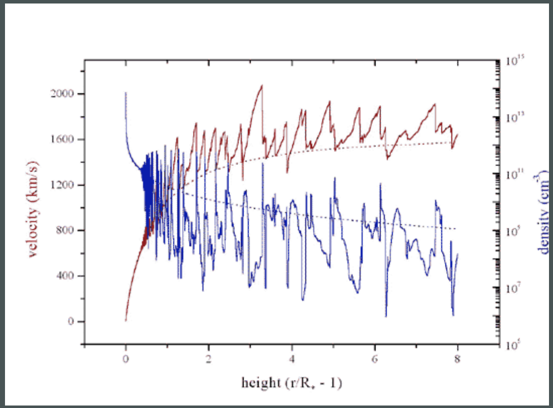


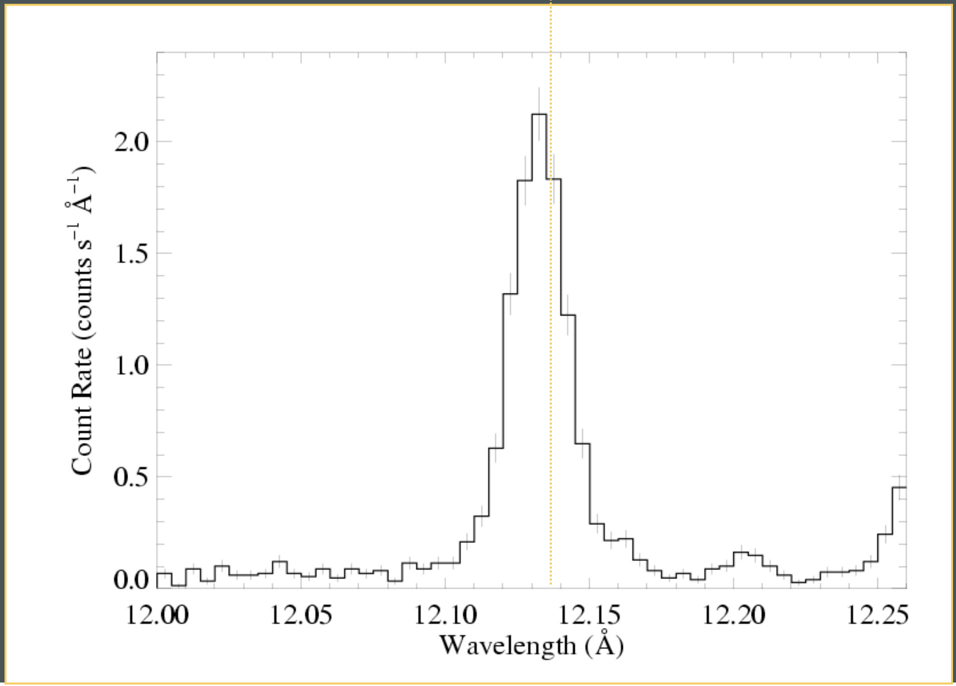
Low-mass star (Capella) for comparison


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

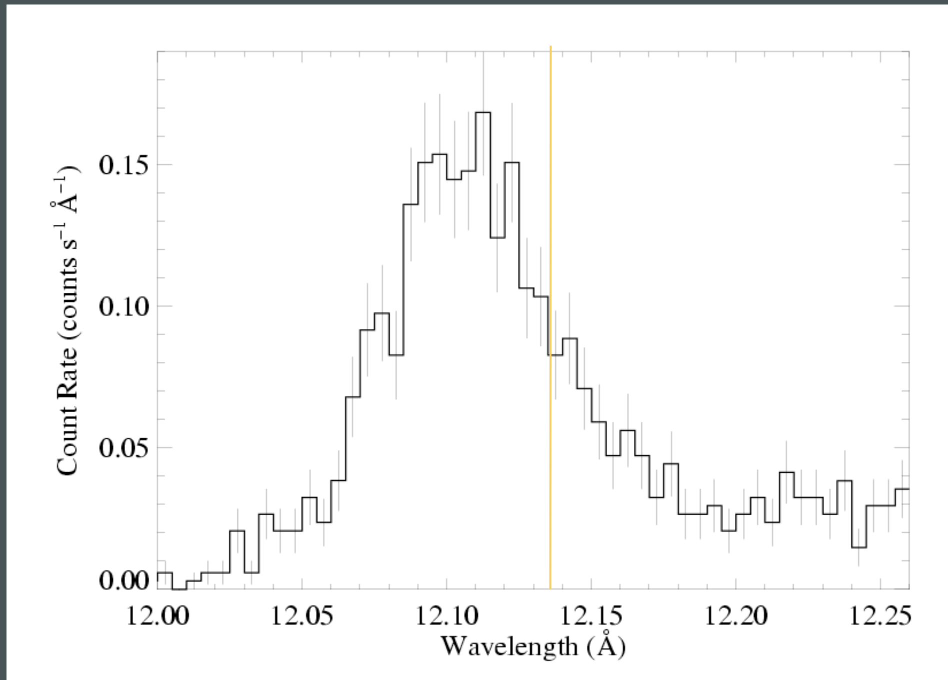


ζ Pup
massive

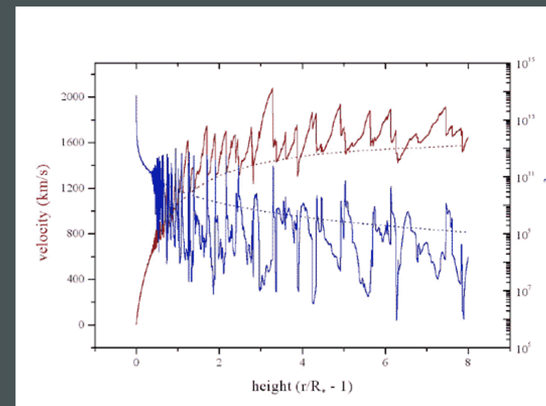




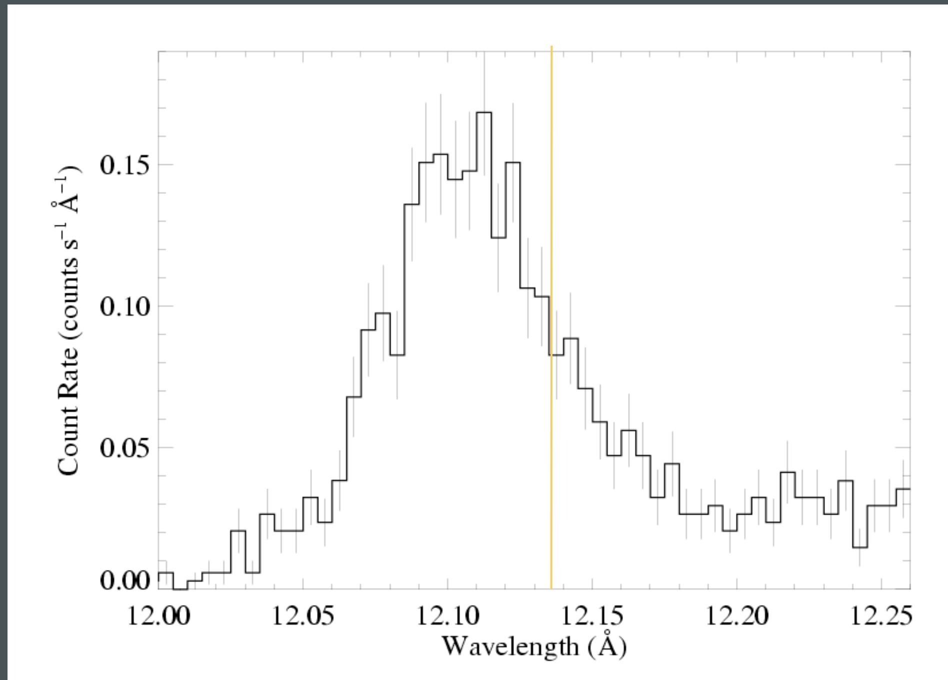
Capella
low mass



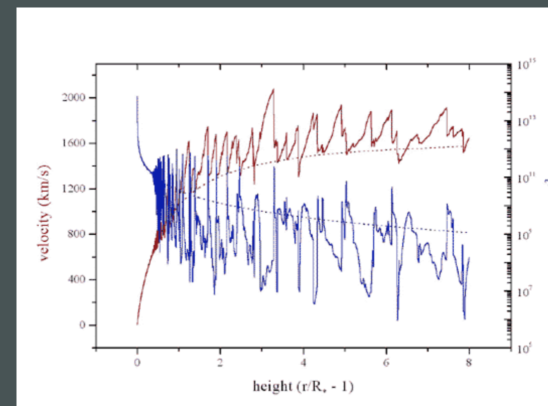
ζ Pup
massive



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



ζ Pup
massive

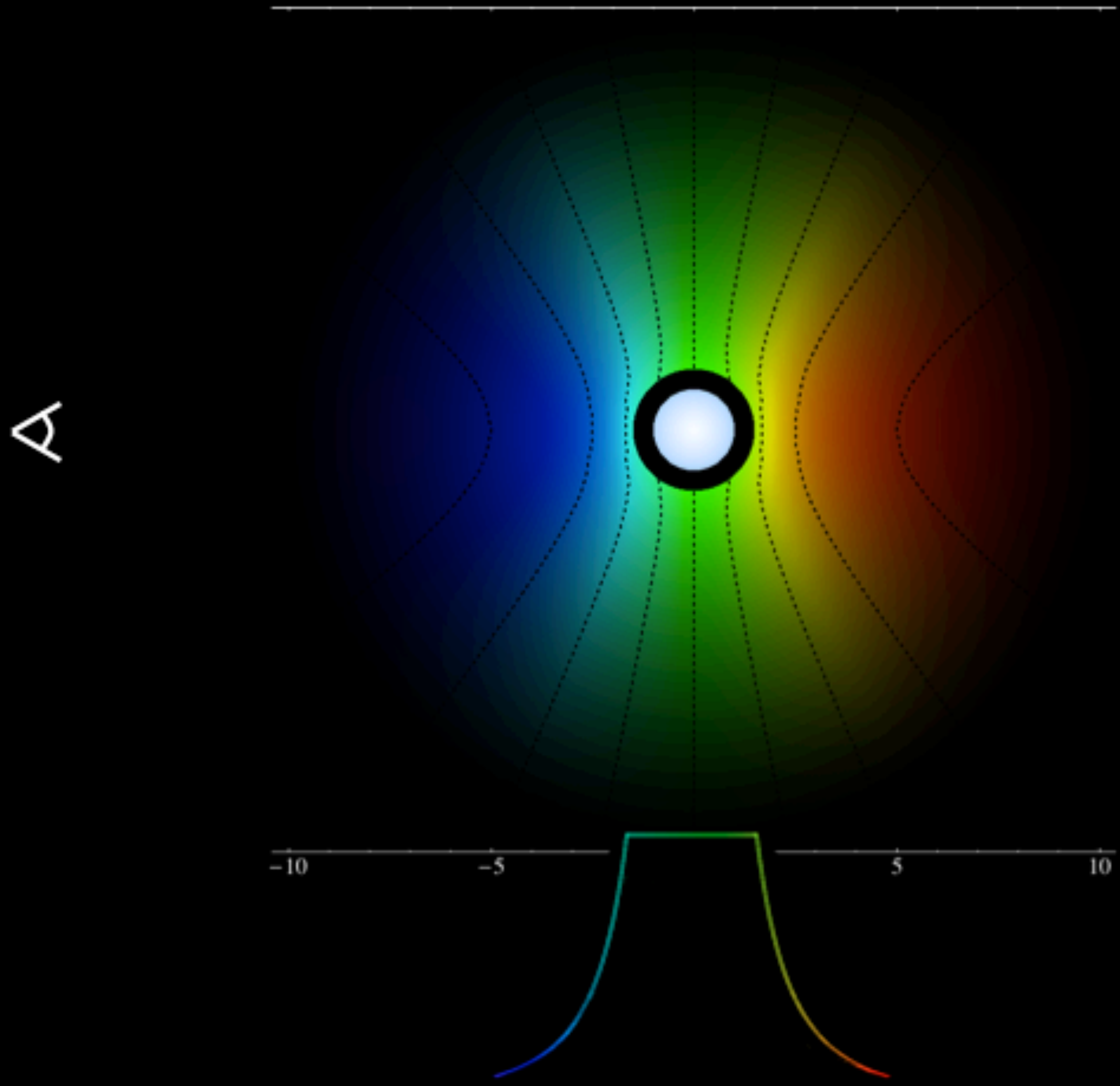


The x-ray emission lines are broad: agreement with rad-hydro simulations

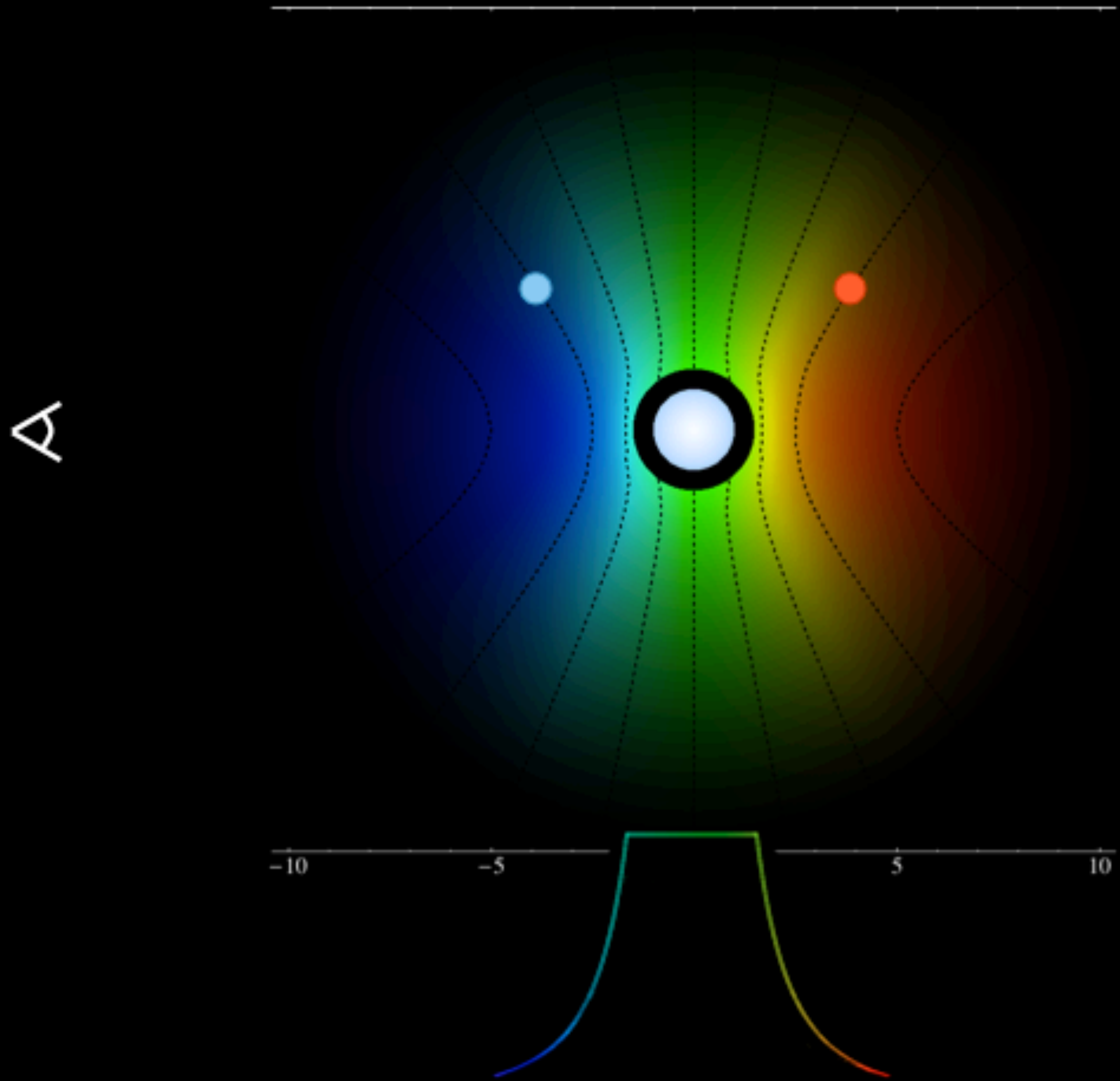
But… they're also blue shifted and asymmetric

Is this predicted by the wind shock scenario?

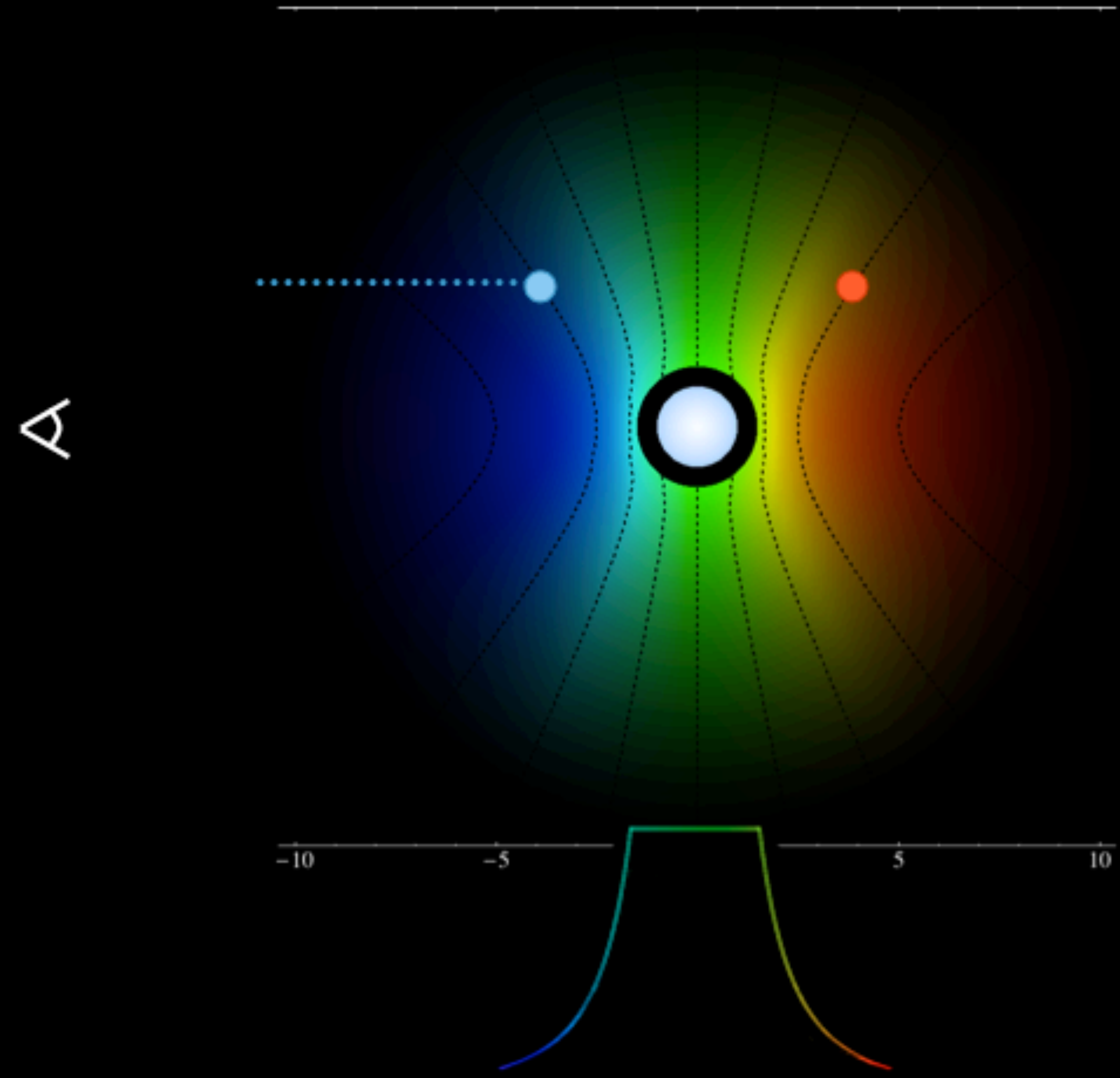
Line Asymmetry



Line Asymmetry



Line Asymmetry



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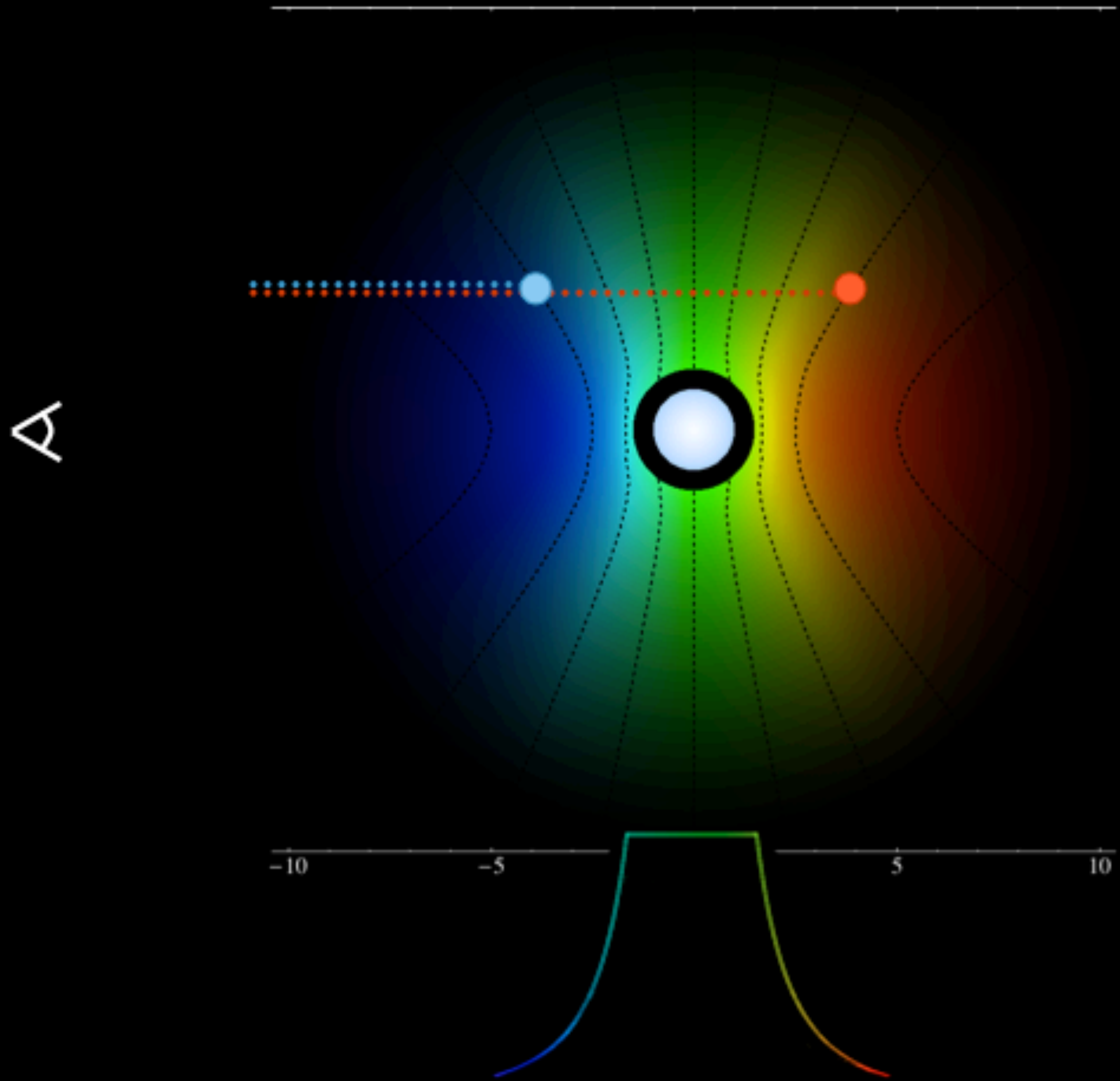
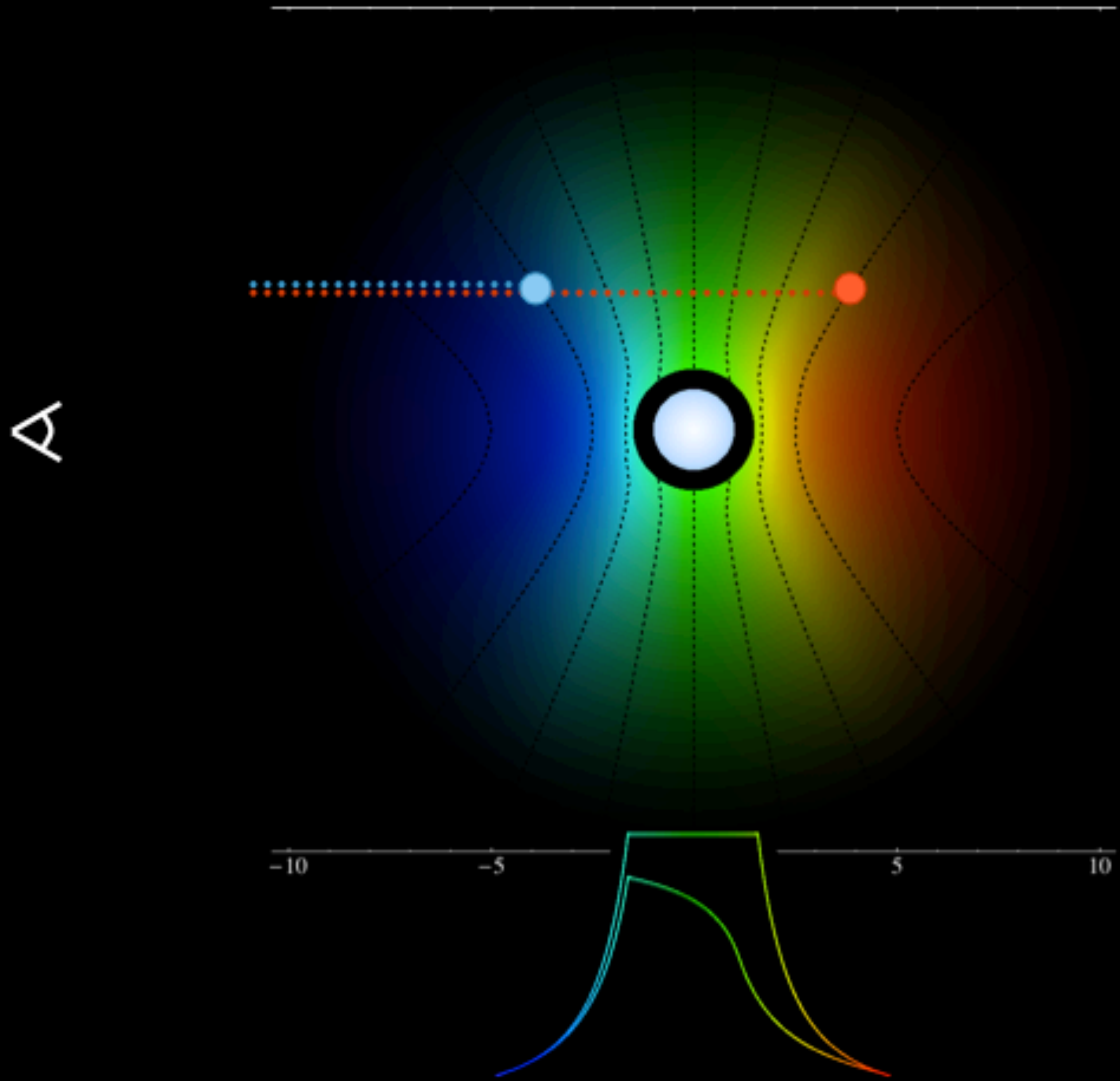
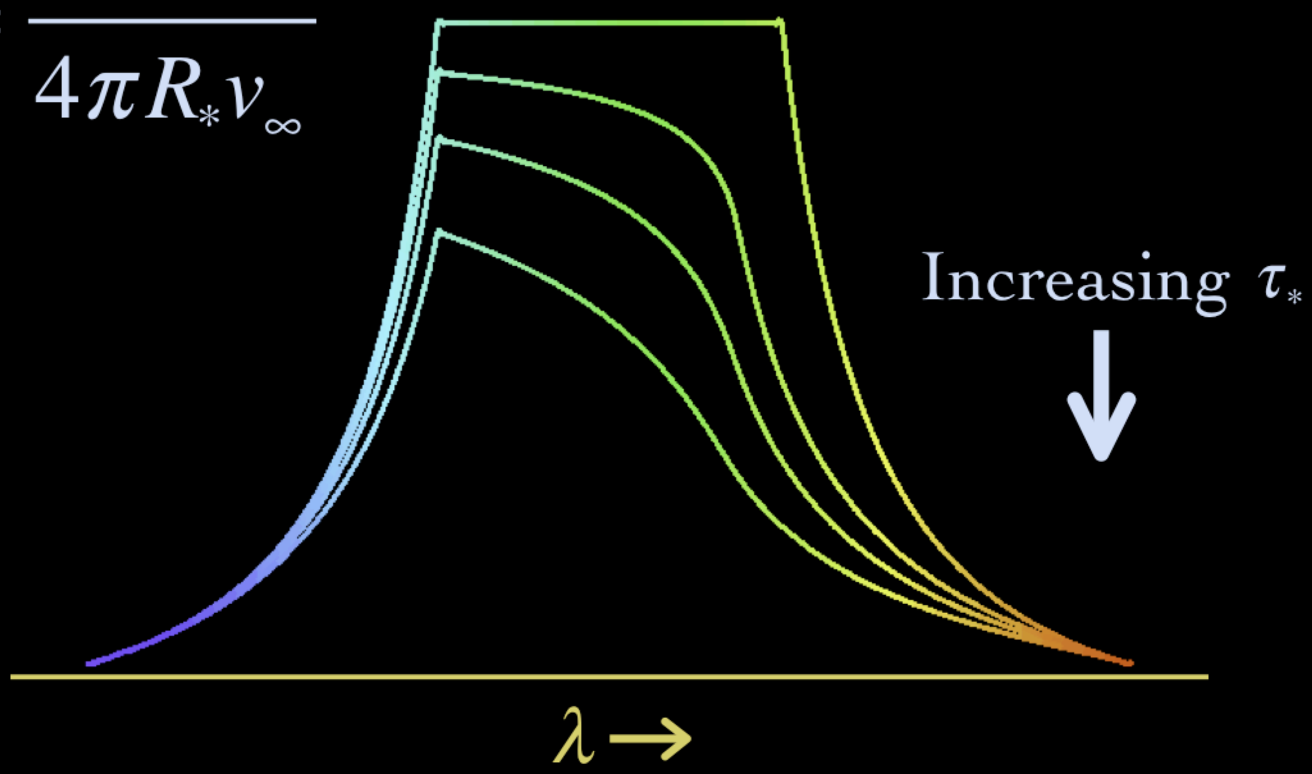


Line Asymmetry



Wind Profile Model

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



opacity of the **cold wind** component

wind mass-loss rate

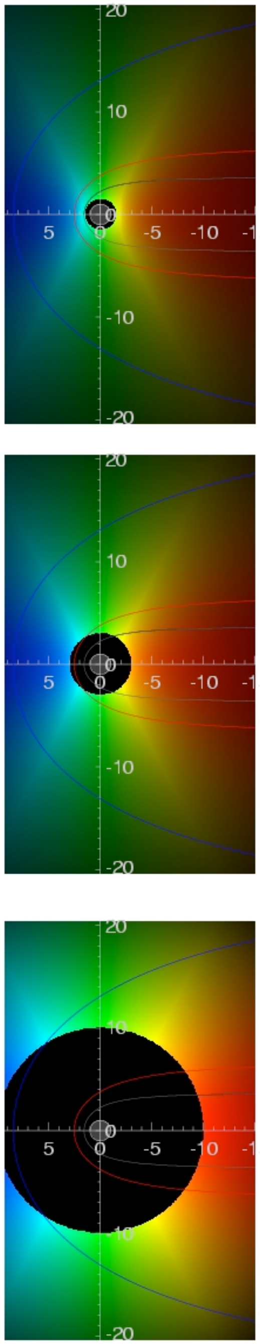
$$\dot{M} = 4\pi r^2 v \rho$$

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

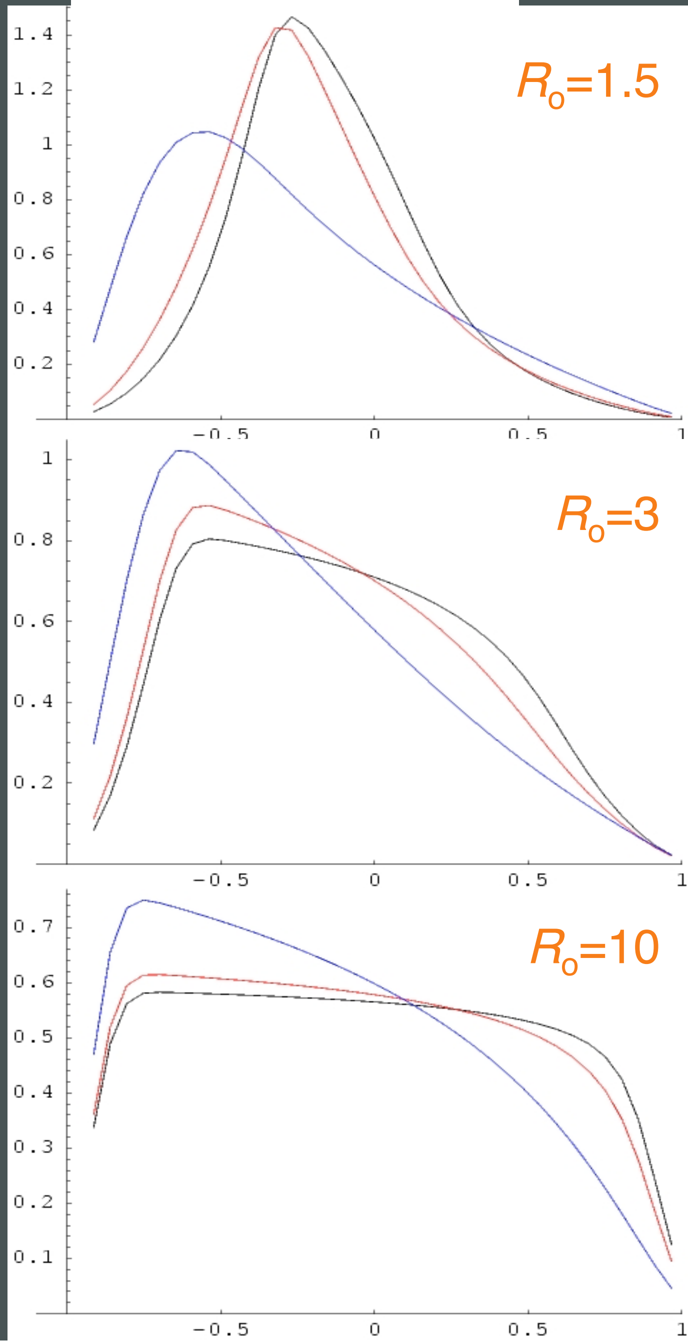
radius of the star

wind terminal velocity

τ=1 contours



τ_*=1,2,8



key parameters: $\mathbf{R_o}$ & τ_*

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

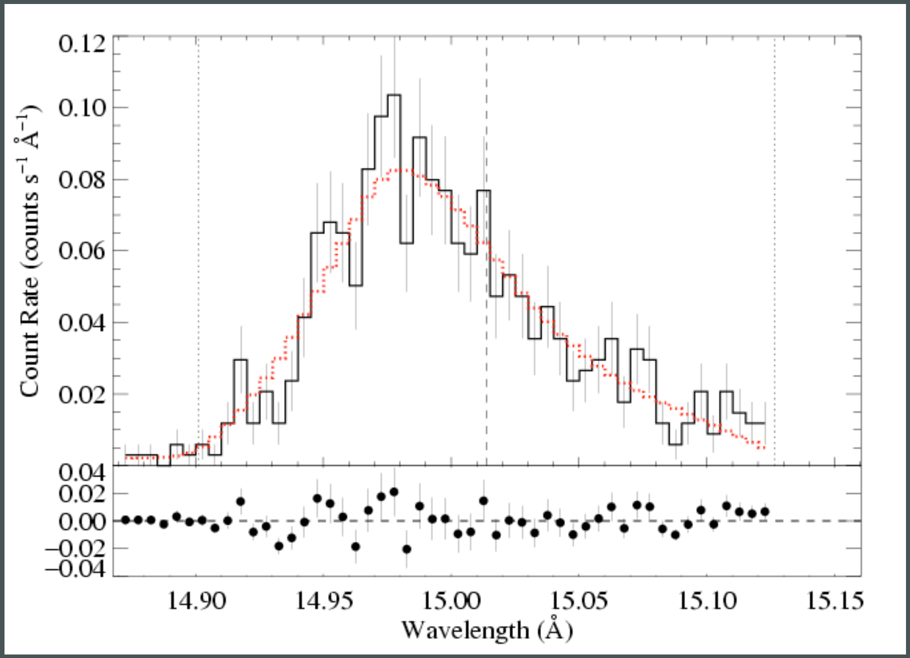
$= 0$ otherwise

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

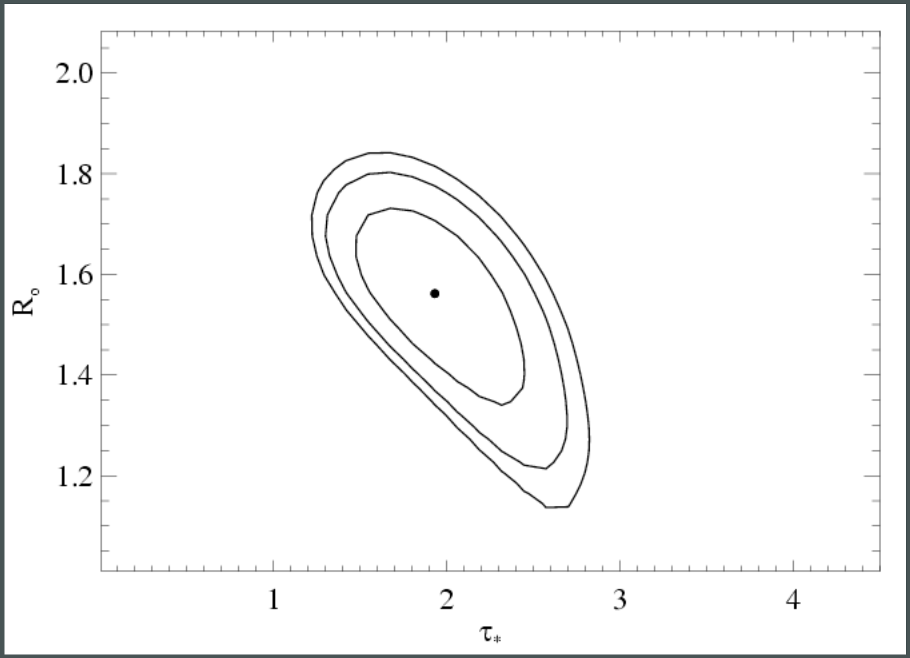
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

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

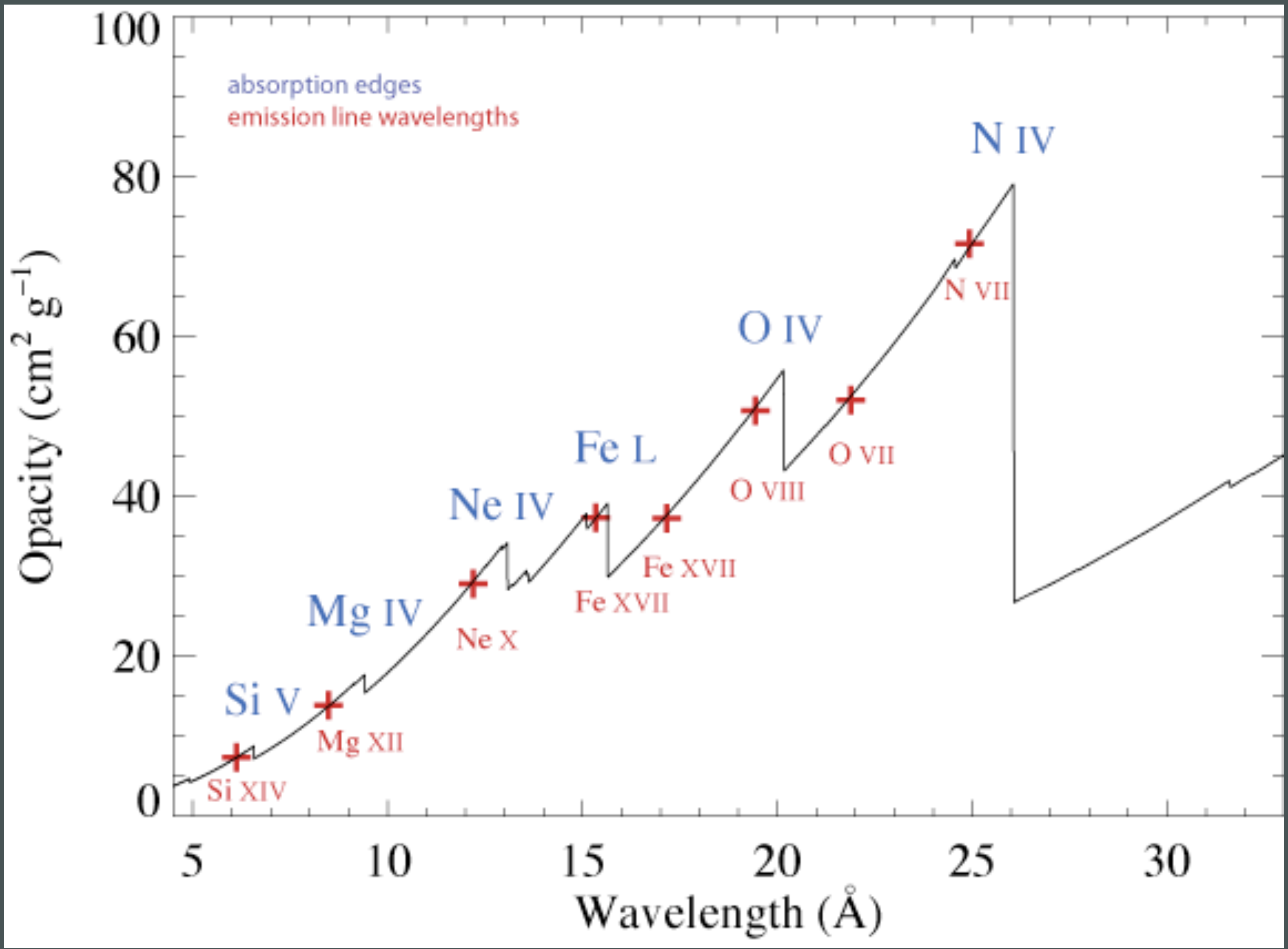


Fe XVII



68, 90, 95% confidence limits

Wind opacity: photoelectric absorption

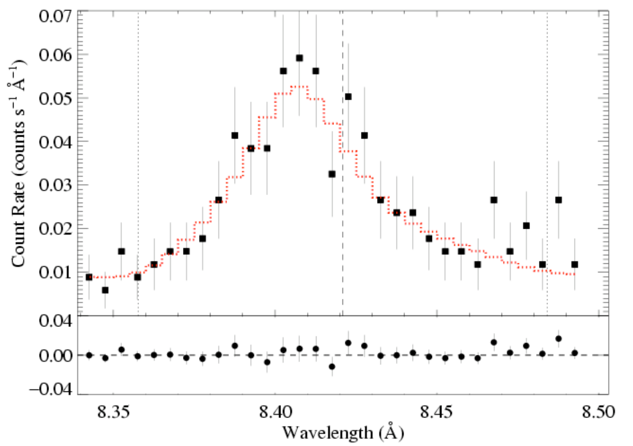


Abundances; ionization balance; atomic cross sections

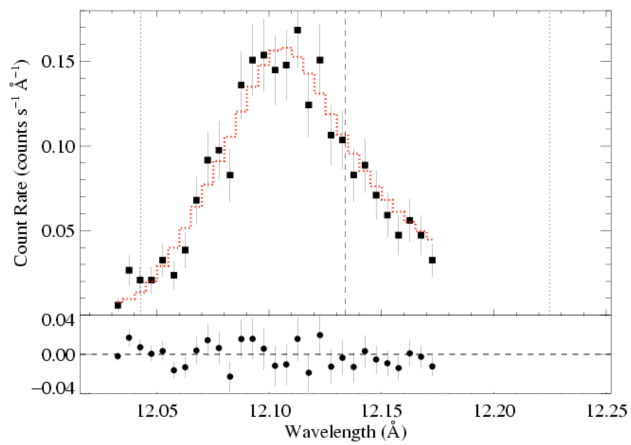
Verner & Yakovlev 1996

ζ Pup: three emission lines

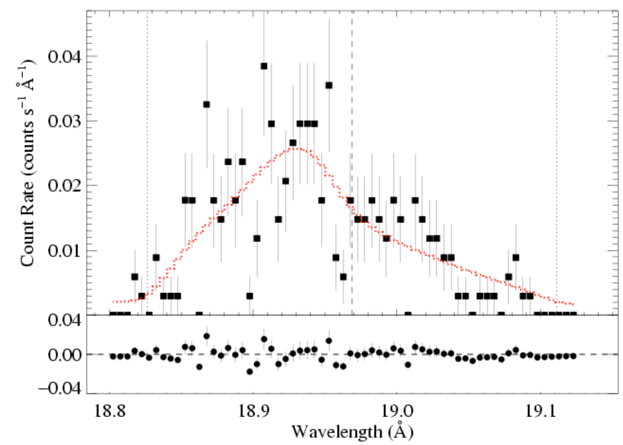
Mg Lyα: 8.42 Å



Ne Lyα: 12.13 Å



O Lyα: 18.97 Å



$\tau_* = 1$

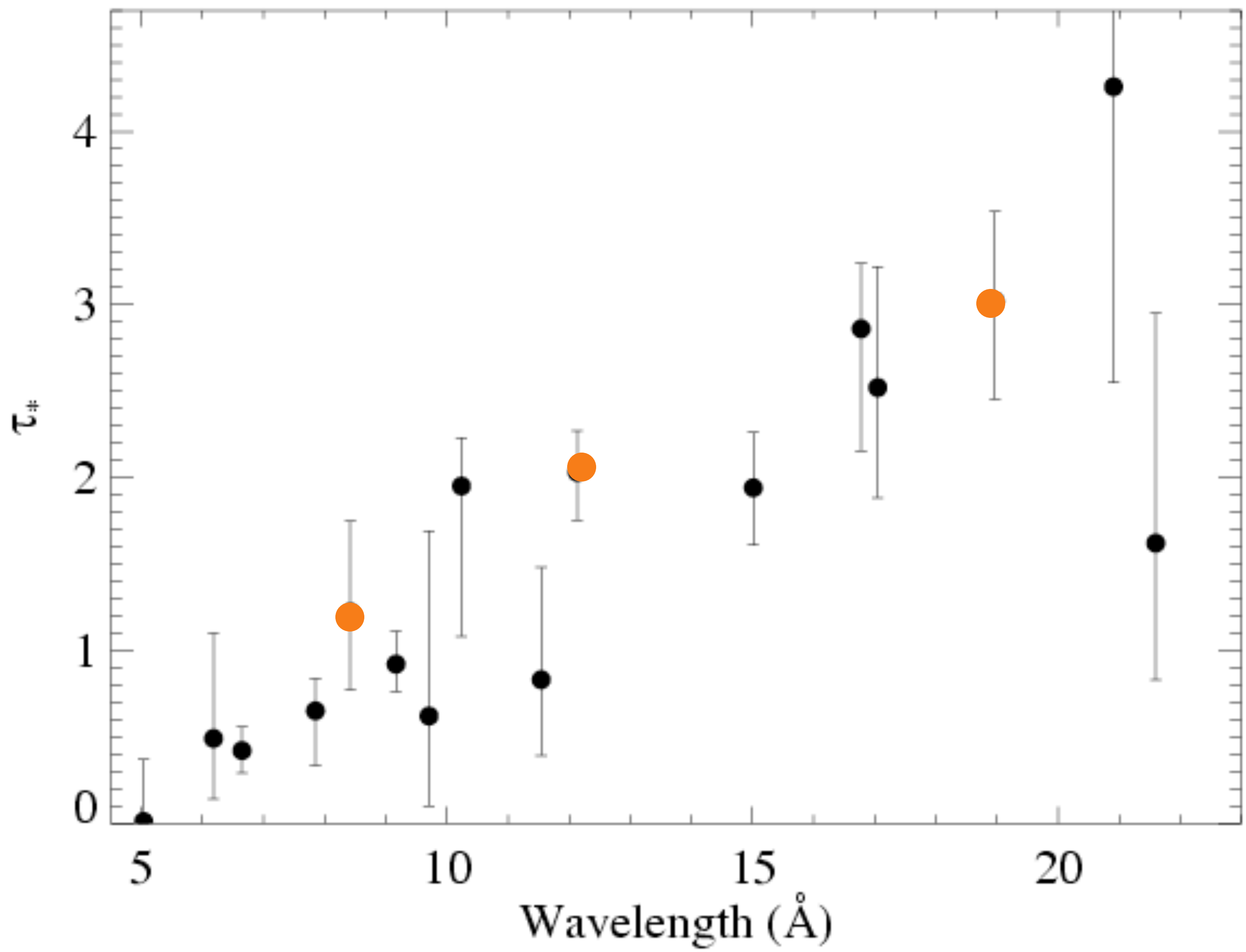
$\tau_* = 2$

$\tau_* = 3$

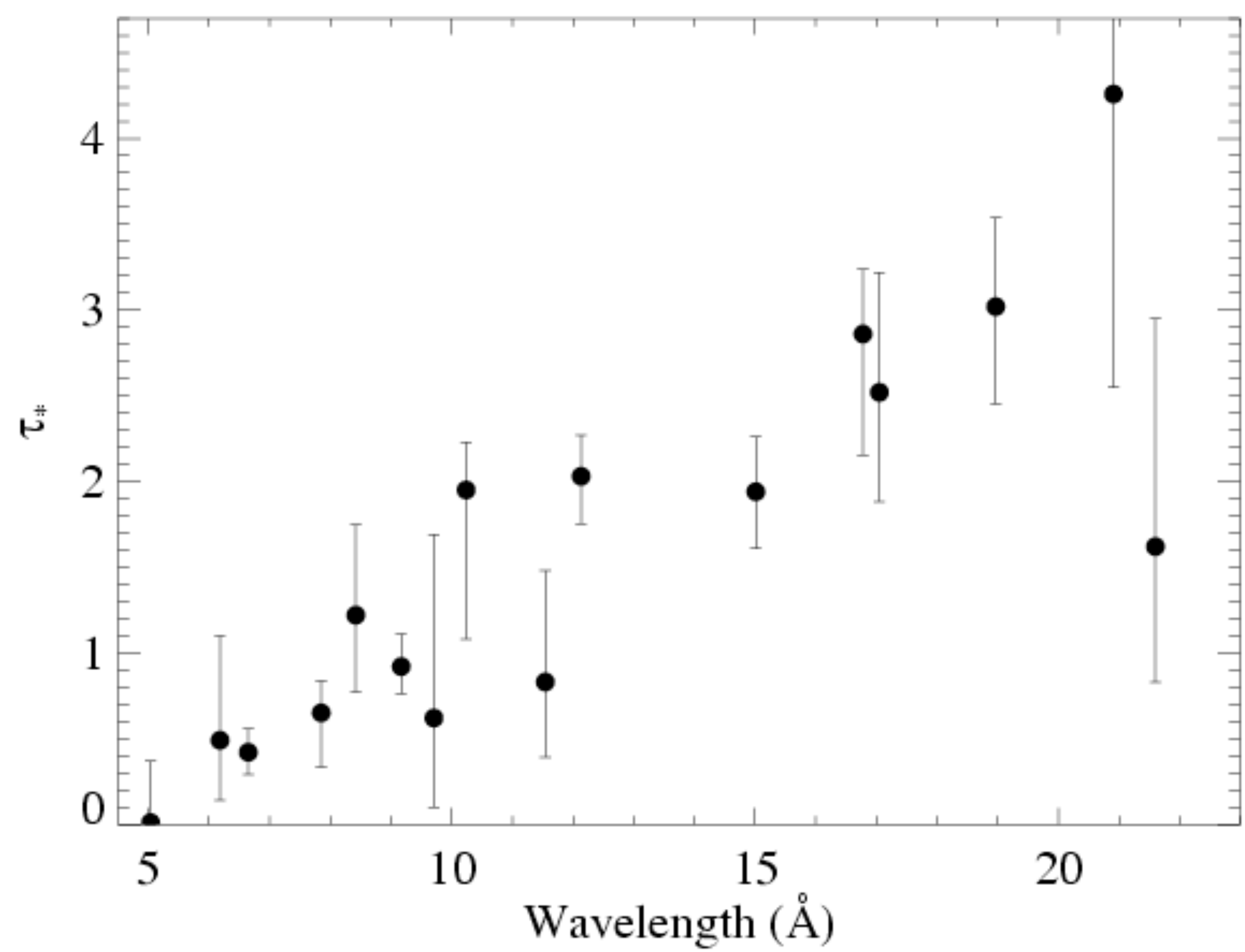
Recall:

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

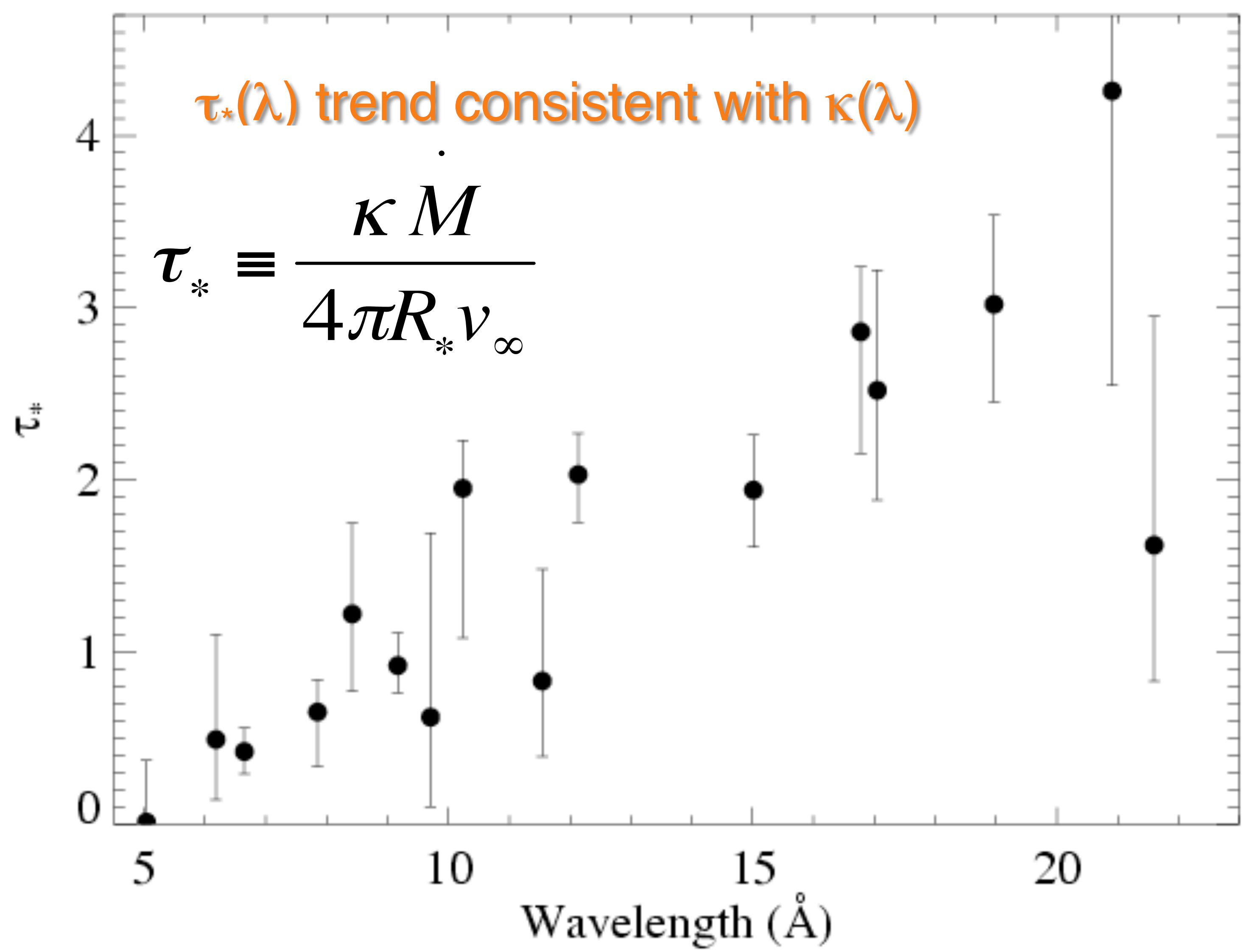
Fits to 16 lines in the *Chandra* spectrum of ζ Pup

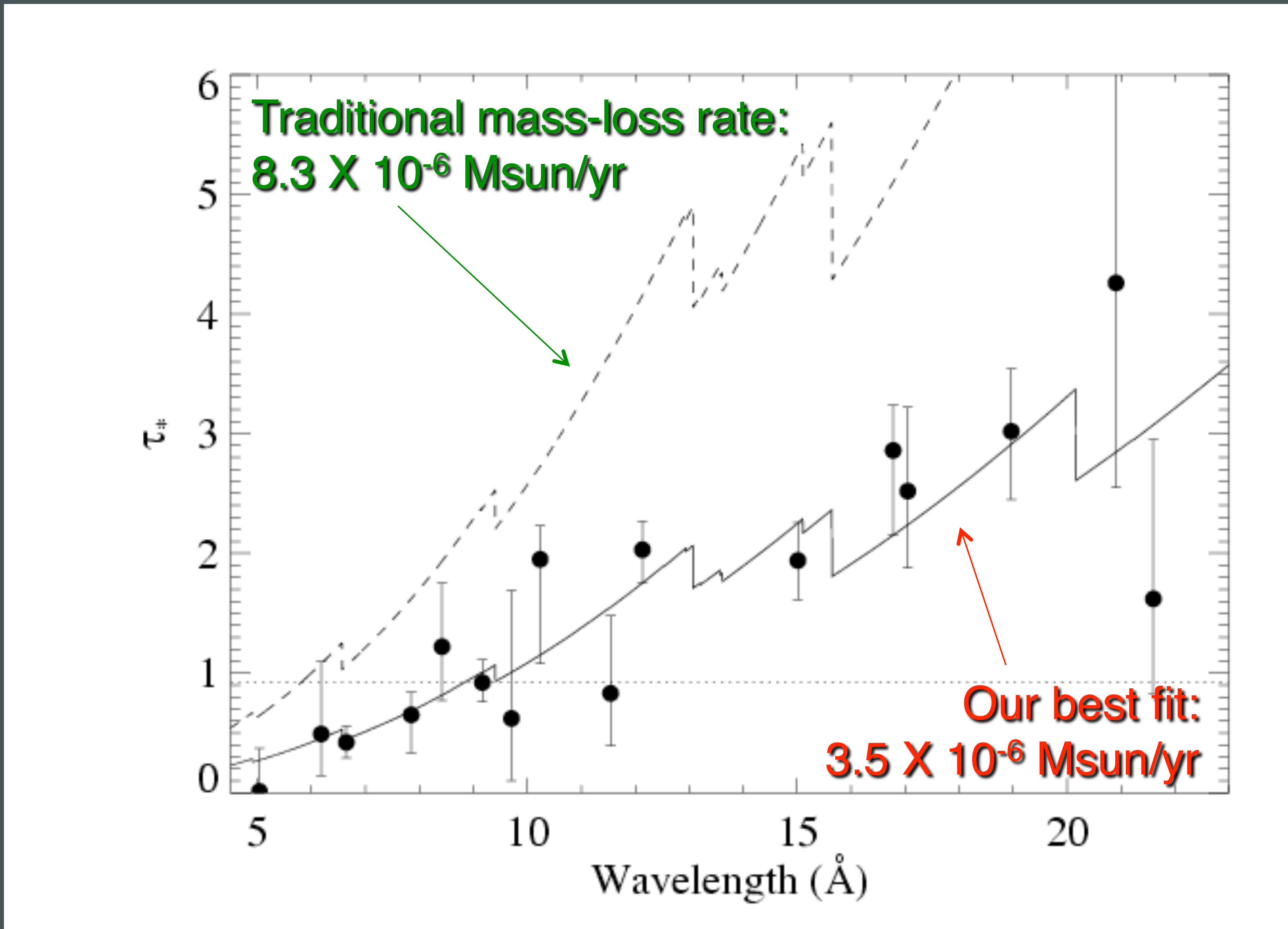


Fits to 16 lines in the *Chandra* spectrum of ζ Pup

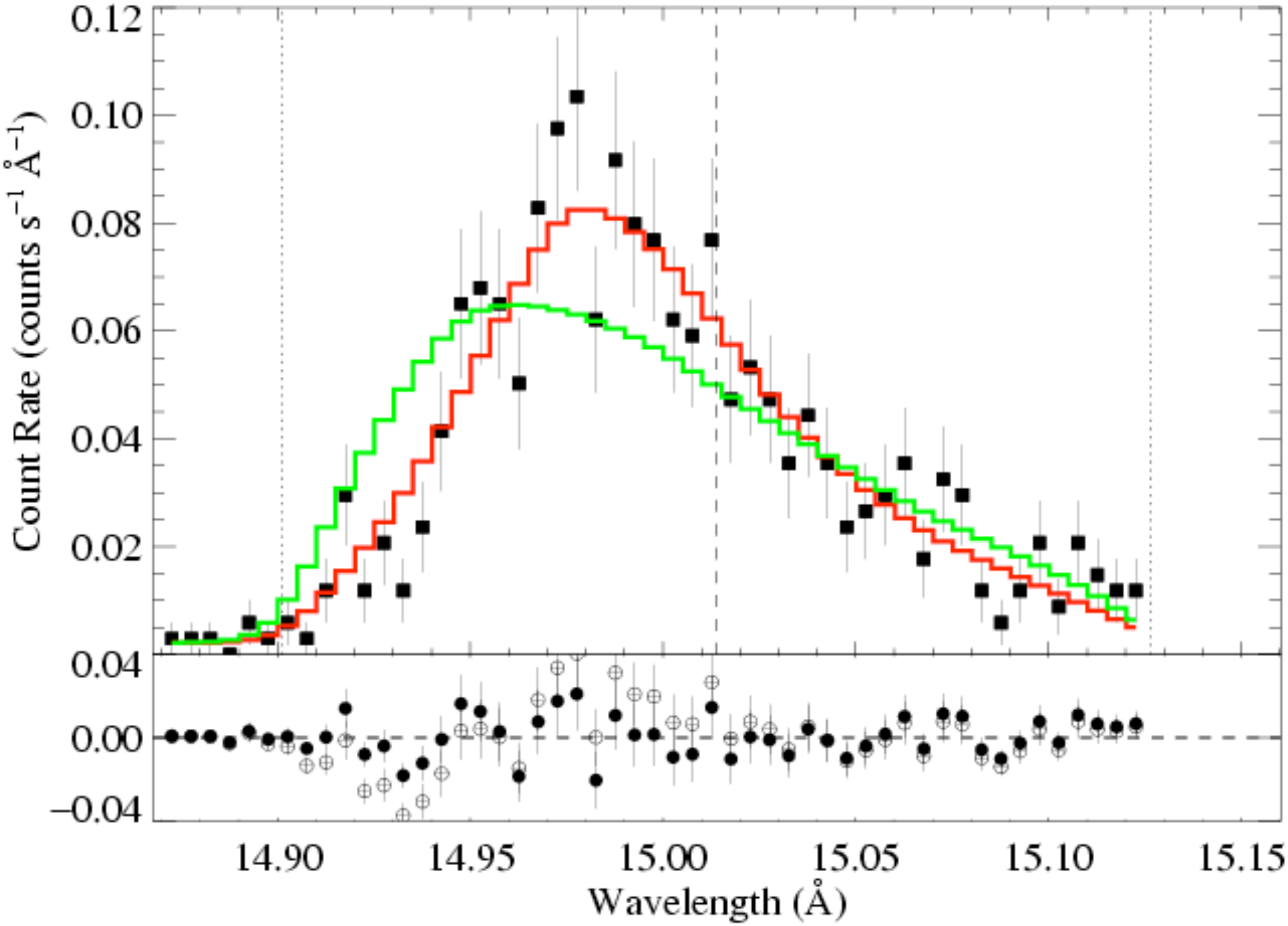


Fits to 16 lines in the *Chandra* spectrum of ζ Pup



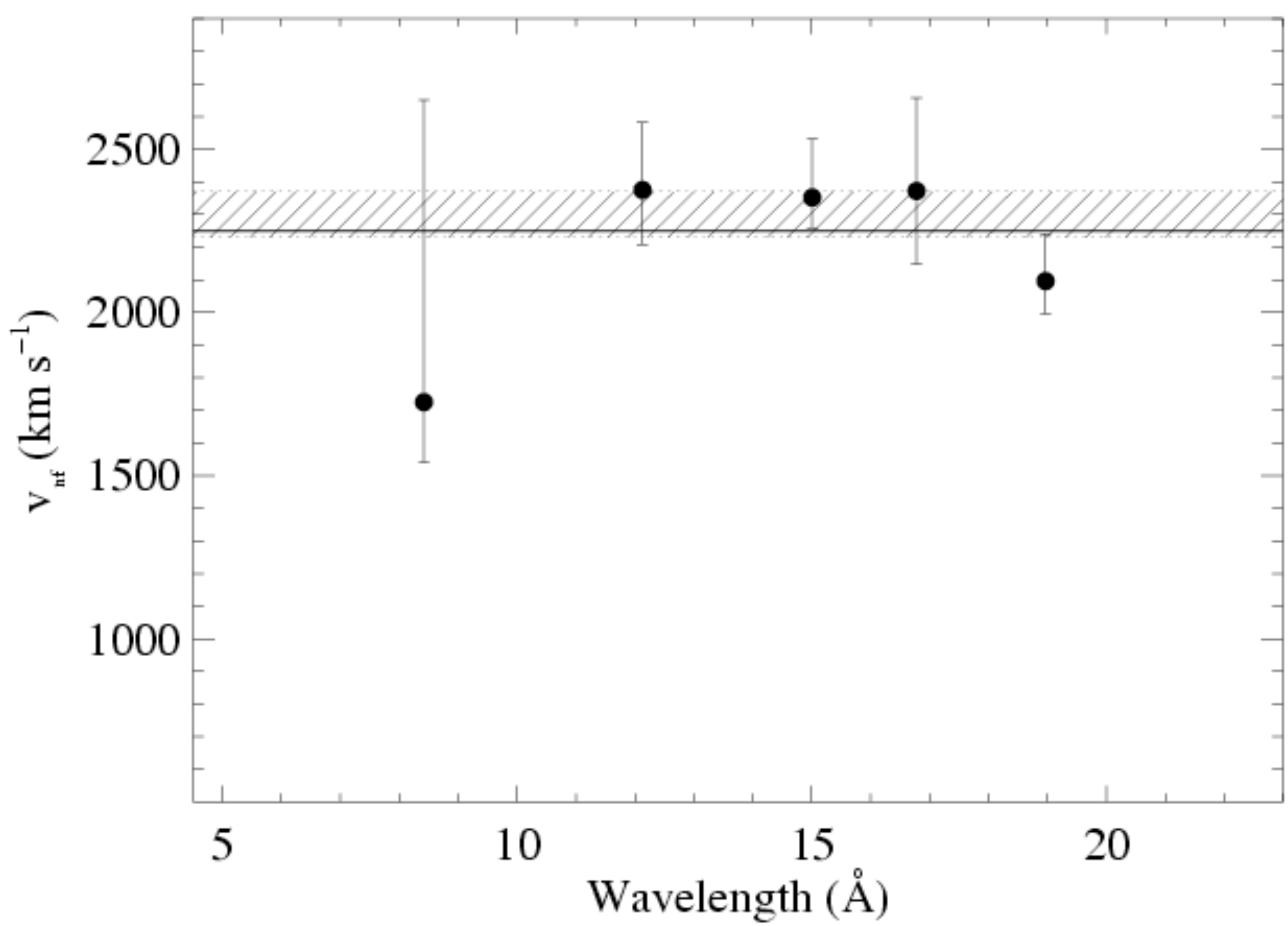


Traditional mass-loss rate:
8.3 X 10-6 Msun/yr
Our best fit:
3.5 X 10-6 Msun/yr
τ*
Wavelength (Å)
0
1
2
3
4
5
6
5
10
15
20

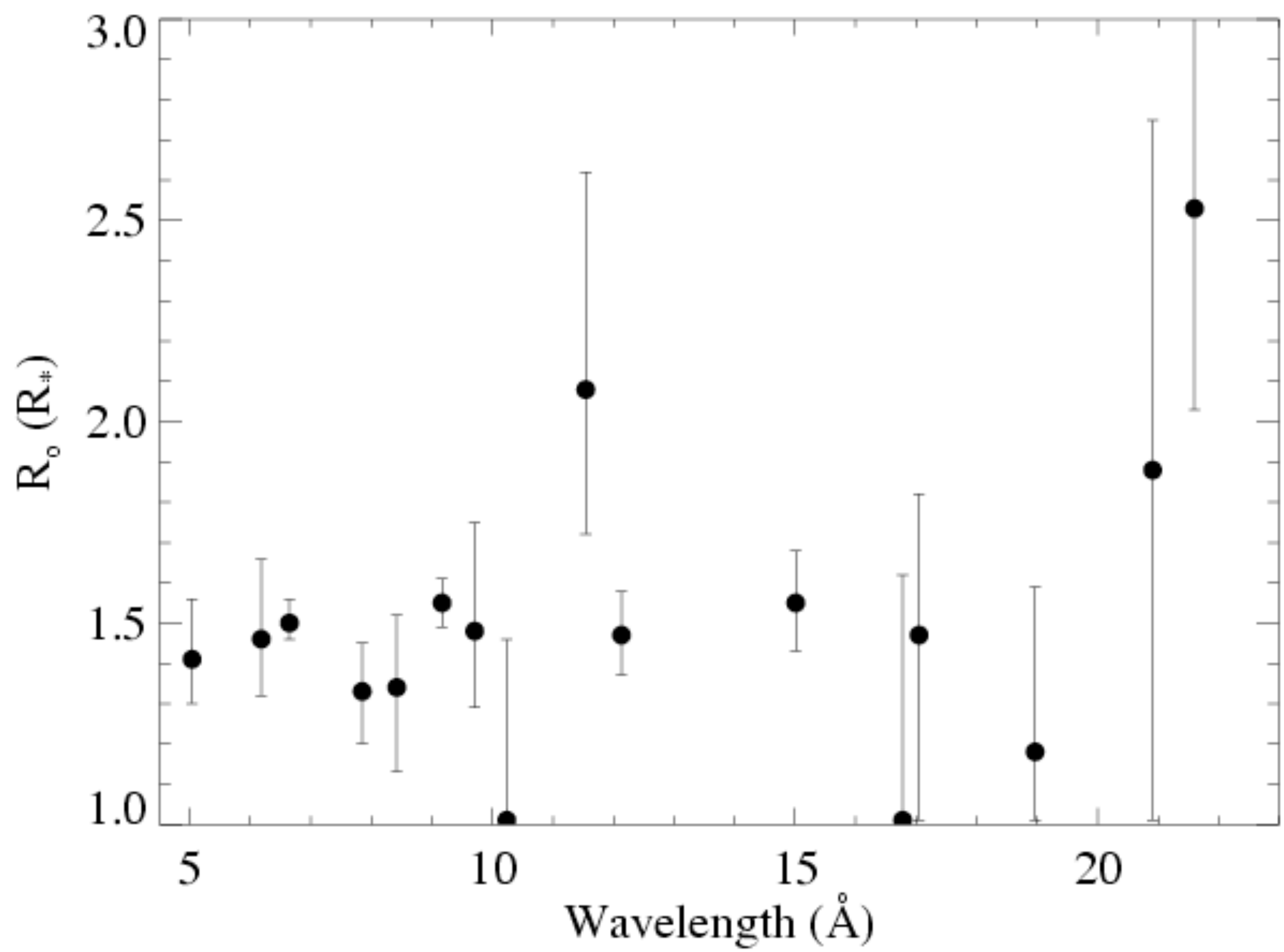


Count Rate (counts s^{-1} Å^{-1})
0.12
0.10
0.08
0.06
0.04
0.02
0.04
0.00
−0.04
14.90
14.95
15.00
15.05
15.10
15.15
Wavelength (Å)

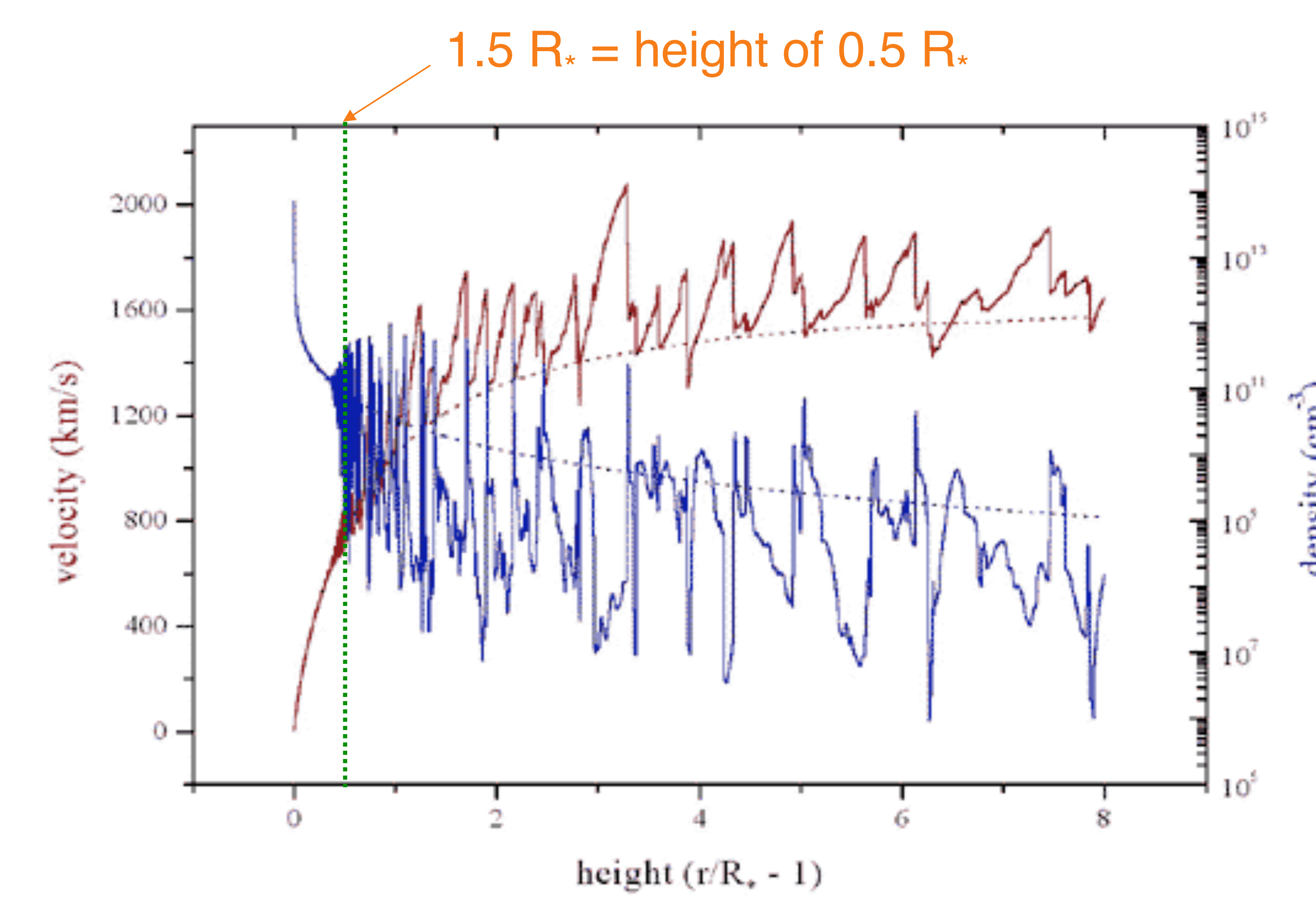
Terminal velocity of the x-ray plasma – from line fitting

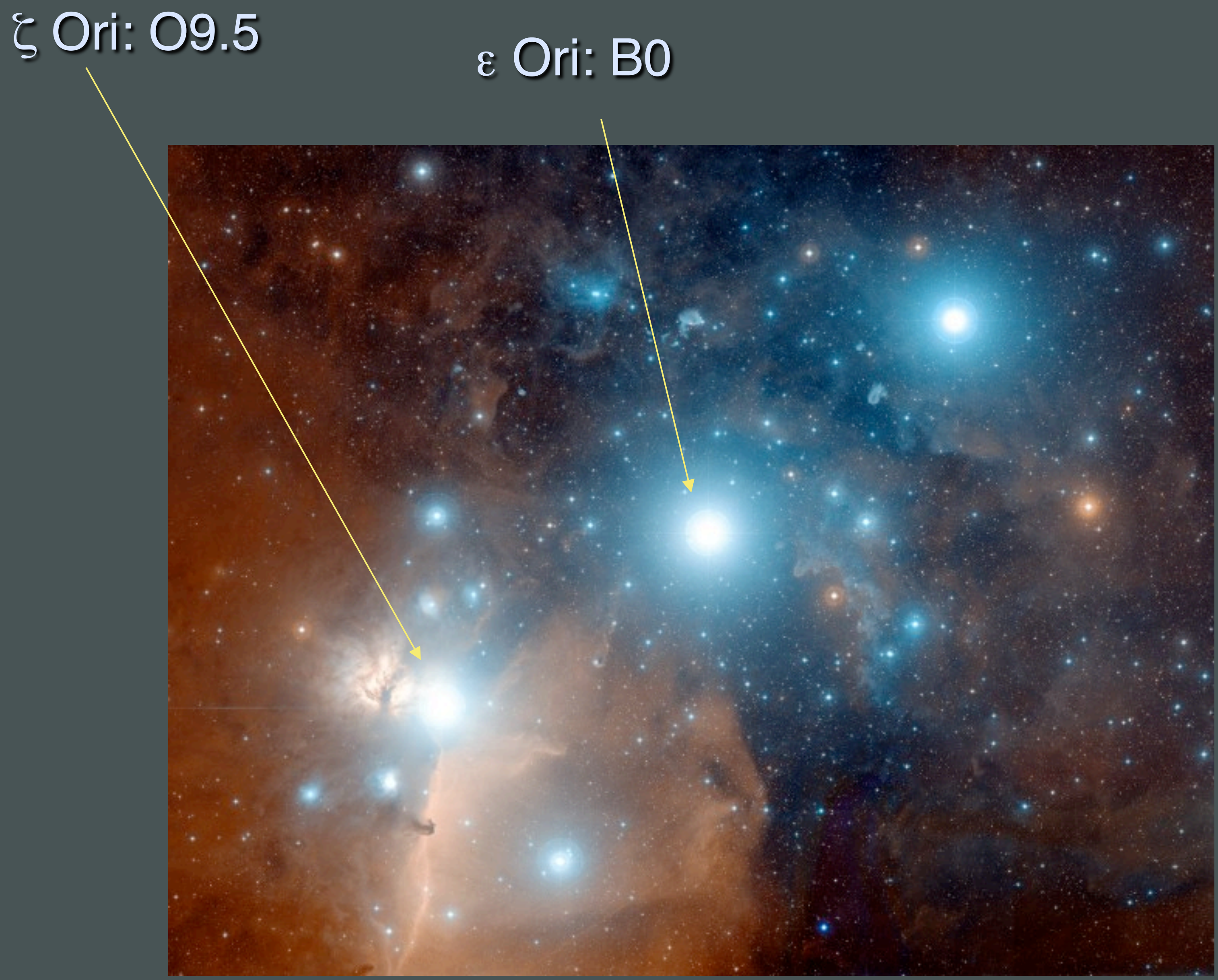


onset radius of x-ray emission, R_o

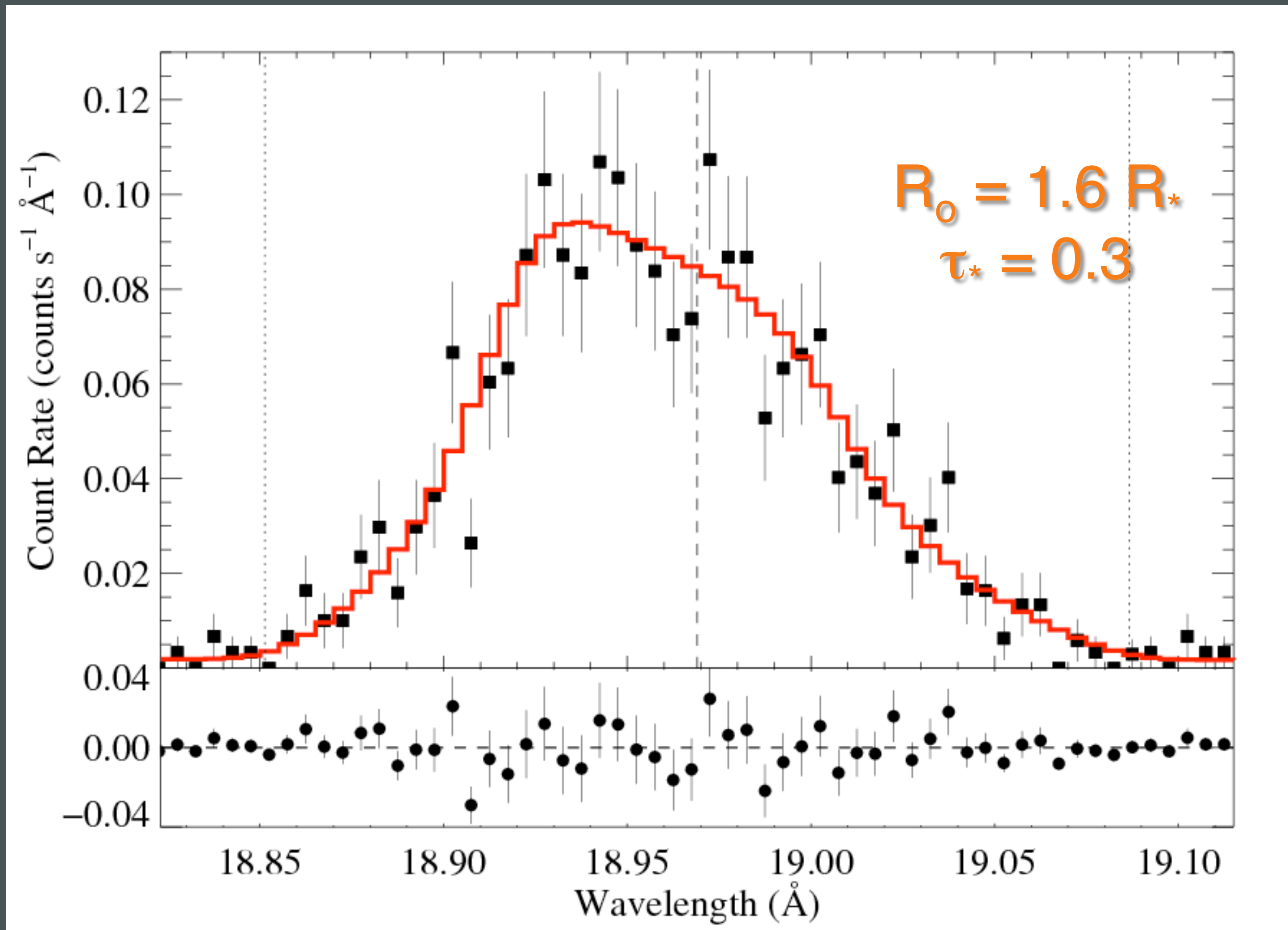


Onset of instability-induced shock structure: $R_o \sim 1.5$

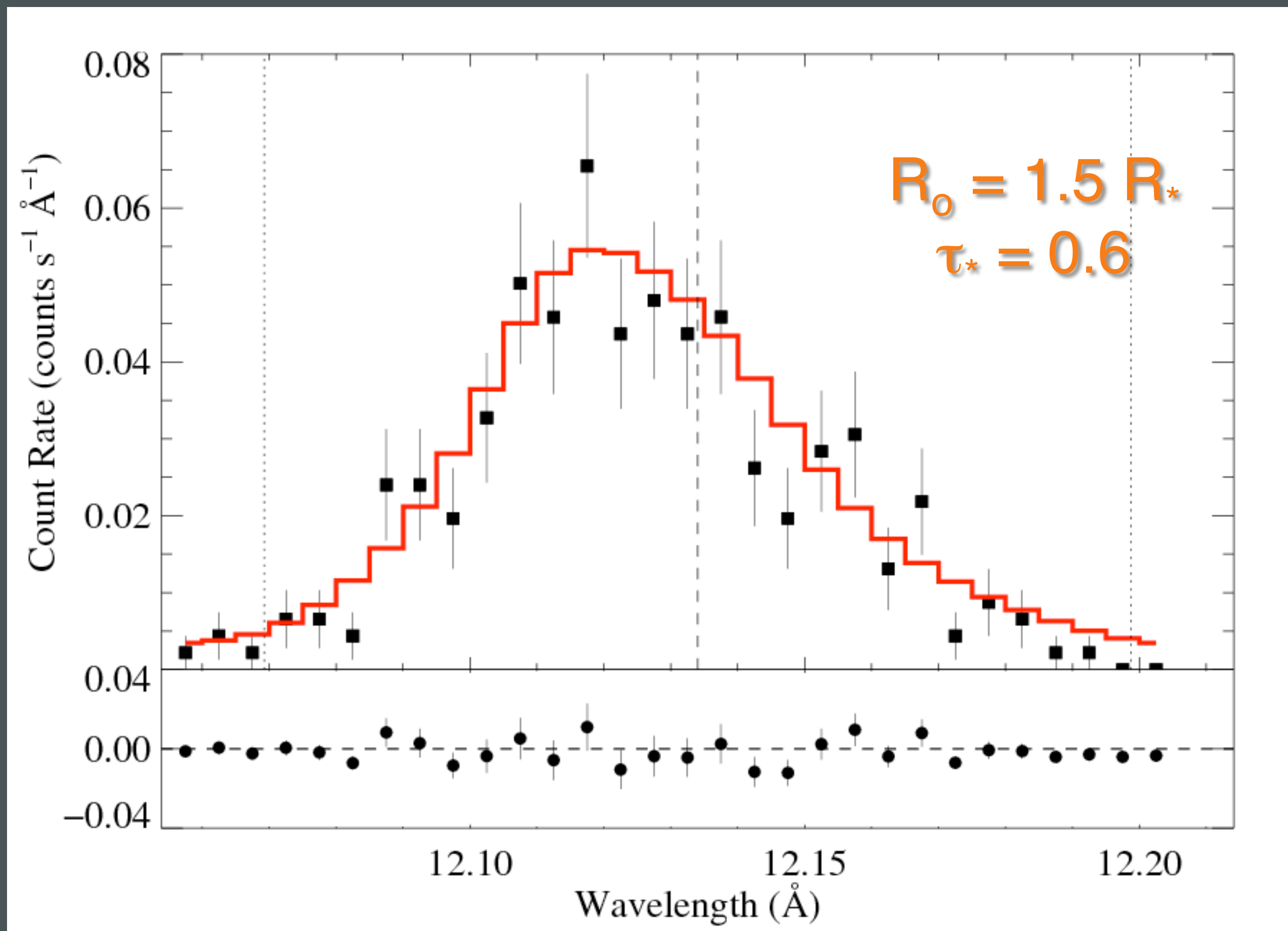



ζ Ori: O9.5
ε Ori: B0

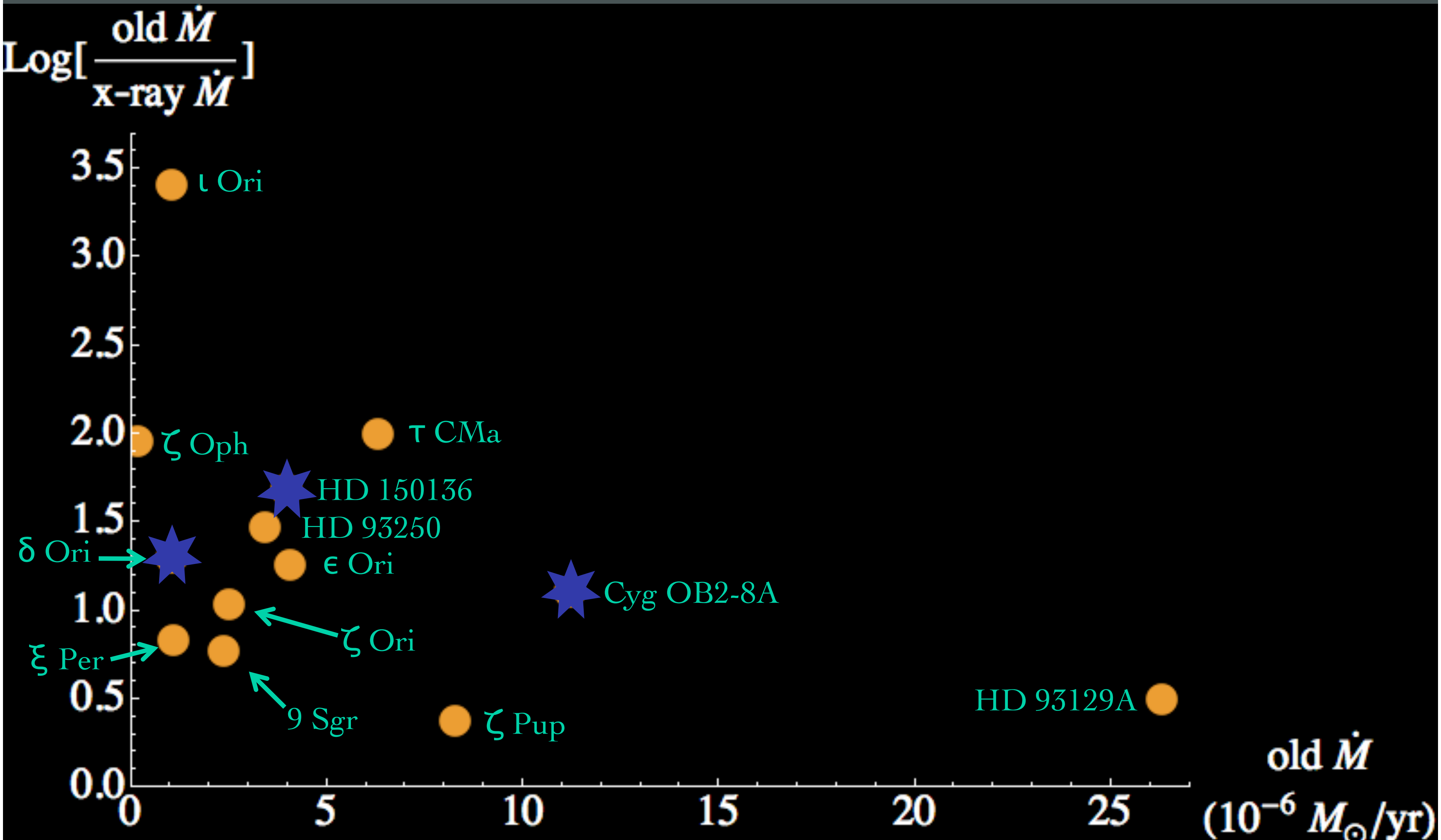
ζ Ori (09.7 I): O Lyα 18.97 Å



ε Ori (B0 Ia): Ne Lyα 12.13 Å



Mass-loss Rate Results



Multi-wavelength evidence for lower mass-loss rates is emerging

THE ASTROPHYSICAL JOURNAL, 637:1025–1039, 2006 February 1

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

A. W. FULLERTON[1]
Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC V8W 3P6, Canada; awf@pha.jhu.edu

D. L. MASSA
SGT, Inc., NASA Goddard Space Flight Center, Code 681.0, Greenbelt, MD 20771; massa@taotaomona.gsfc.nasa.gov

AND

R. K. PRINJA
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK; rkp@star.ucl.ac.uk
Received 2005 June 10; accepted 2005 October 4

ABSTRACT

We have determined accurate values of the product of the mass-loss rate and the ion fraction of P^{+4}, $\dot{M}q(P^{+4})$, for a sample of 40 Galactic O-type stars by fitting stellar wind profiles to observations of the P v resonance doublet obtained with *FUSE*, *ORFEUS* BEFS, and *Copernicus*. When P^{+4} is the dominant ion in the wind [i.e., $0.5 \lesssim q(P^{+4}) \leq 1$], $\dot{M}q(P^{+4})$ approximates the mass-loss rate to within a factor of $\lesssim 2$. Theory predicts that P^{+4} is the dominant ion in the winds of O7–O9.7 stars, although an empirical estimator suggests that the range O4–O7 may be more appropriate. However, we find that the mass-loss rates obtained from P v wind profiles are systematically smaller than those obtained from fits to Hα emission profiles or radio free-free emission by median factors of $\sim$130 (if P^{+4} is dominant between O7 and O9.7) or $\sim$20 (if P^{+4} is dominant between O4 and O7). These discordant measurements can be reconciled if the winds of O stars in the relevant temperature range are strongly clumped on small spatial scales. We use a simplified two-component model to investigate the volume filling factors of the denser regions. This clumping implies that mass-loss rates determined from "ρ^2" diagnostics have been systematically overestimated by factors of 10 or more, at least for a subset of O stars. Reductions in the mass-loss rates of this size have important implications for the evolution of massive stars and quantitative estimates of the feedback that hot-star winds provide to their interstellar environments.

Subject headings: stars: early-type — stars: mass loss — stars: winds, outflows

A&A 454, 625–651 (2006)
DOI: 10.1051/0004-6361:20065073

Astronomy & Astrophysics

Bright OB stars in the Galaxy

III. Constraints on the radial stratification of the clumping factor in hot star winds from a combined H_α, IR and radio analysis⋆,⋆⋆

J. Puls[1], N. Markova[2], S. Scuderi[3], C. Stanghellini[4], O. G. Taranova[5], A. W. Burnley[6], and I. D. Howarth[6]

[1] Universitäts-Sternwarte München, Scheinerstr. 1, 81679 München, Germany
e-mail: uh101aw@usm.uni-muenchen.de
[2] Institute of Astronomy, Bulgarian National Astronomical Observatory, PO Box 136, 4700 Smoljan, Bulgaria
e-mail: nmarkova@astro.bas.bg
[3] INAF – Osservatorio Astrofisico di Catania, via S. Sofia 78, 95123 Catania, Italy
e-mail: scuderi@oact.inaf.it
[4] INAF – Istituto di Radioastronomia, via P. Gobetti 101, 40129 Bologna, Italy
e-mail: c.stanghellini@ira.inaf.it
[5] Sternberg Astronomical Institute, Universitetski PR. 13, Moscow 119992, Russia
e-mail: taranova@sai.msu.ru
[6] Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK
e-mail: [awxb;idh]@star.ucl.ac.uk

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ABSTRACT

Context. Recent results strongly challenge the canonical picture of massive star winds: various evidence indicates that currently accepted mass-loss rates, $\dot{M}$, may need to be revised downwards, by factors extending to one magnitude or even more. This is because the most commonly used mass-loss diagnostics are affected by "clumping" (small-scale density inhomogeneities), influencing our interpretation of observed spectra and fluxes.
Aims. Such downward revisions would have dramatic consequences for the evolution of, and feedback from, massive stars, and thus robust determinations of the clumping properties and mass-loss rates are urgently needed. We present a first attempt concerning this objective, by means of constraining the radial stratification of the so-called clumping factor.
Methods. To this end, we have analyzed a sample of 19 Galactic O-type supergiants/giants, by combining our own and archival data for H_α, IR, mm and radio fluxes, and using approximate methods, calibrated to more sophisticated models. Clumping has been included into our analysis in the "conventional" way, by assuming the inter-clump matter to be void. Because (almost) all our diagnostics depends on the square of density, we cannot derive absolute clumping factors, but only factors normalized to a certain minimum.
Results. This minimum was usually found to be located in the outermost, radio-emitting region, i.e., the radio mass-loss rates are the lowest ones, compared to $\dot{M}$ derived from H_α and the IR. The radio rates agree well with those predicted by theory, but are only upper limits, due to unknown clumping in the outer wind. H_α turned out to be a useful tool to derive the clumping properties inside $r < 3\ldots5\,R_\star$. Our most important result concerns a (physical) difference between denser and thinner winds: for denser winds, the innermost region is more strongly clumped than the outermost one (with a normalized clumping factor of 4.1 ± 1.4), whereas thinner winds have similar clumping properties in the inner and outer regions.
Conclusions. Our findings are compared with theoretical predictions, and the implications are discussed in detail, by assuming different scenarios regarding the still unknown clumping properties of the outer wind.

Key words. infrared: stars – radio continuum: stars – stars: early-type – stars: winds, outflows – stars: mass-loss

Part 2: Magnetically Channeled Winds

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

ESO PR Photo 20/04 (30 June 2004)

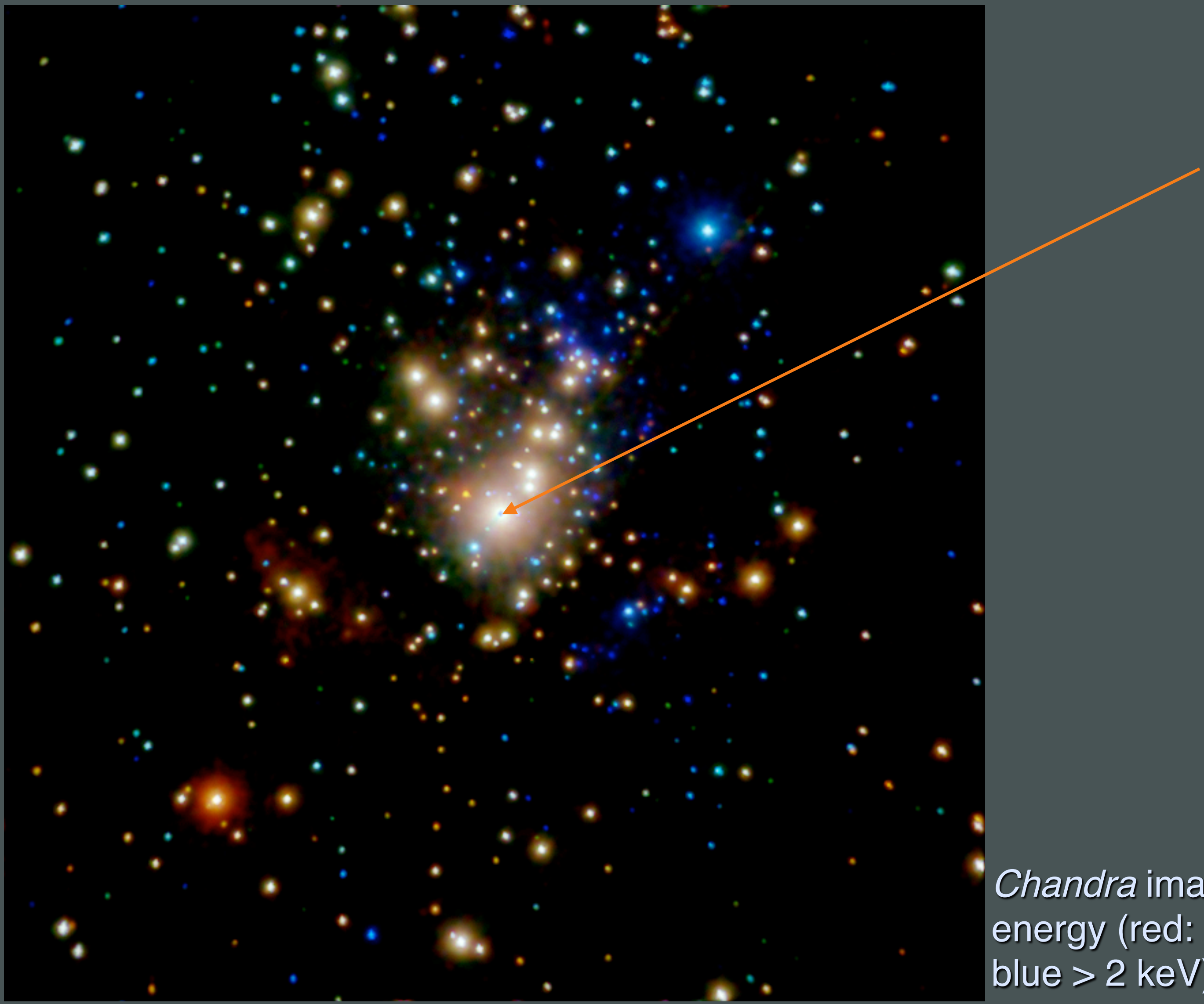
θ^1 Ori C:

$50\ M_{sun}$

$10^6\ L_{sun}$

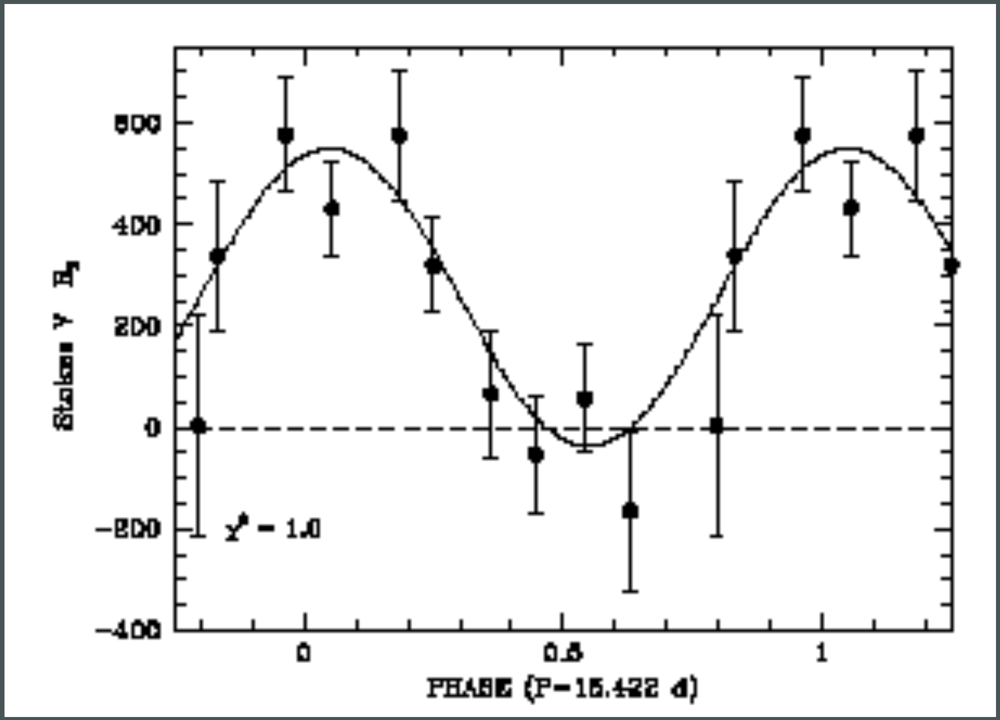
T ~ 45,000 K

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

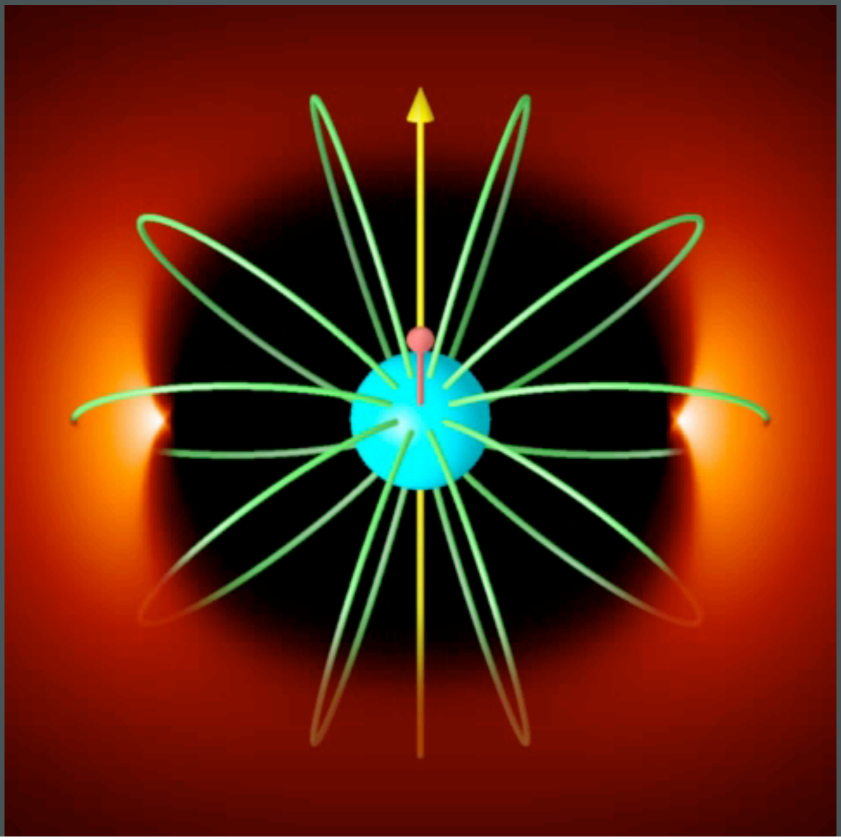


Chandra image: color coded by photon energy (red: <1keV; green 1 to 2 keV; blue > 2 keV)

Recently discovered dipole magnetic field of ~ 1.5 kG



Wade et al. (2006)



Magnetic field obliquity, $\beta \sim 45^o$

http://astro.swarthmore.edu/~cohen/movies/rrm-o25-i75-b60-redt.avi
(R. Townsend)

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

what is the effect?

…MHD simulations (ZEUS, 2-D)

Astron. Astrophys. 323, 121–138 (1997)

ASTRONOMY
AND
ASTROPHYSICS

X-ray emission from Ap-Bp stars: a magnetically confined wind-shock model for IQ Aur*

J. Babel[1] **and T. Montmerle**[2]

[1] Institut für Astronomie und Astrophysik, Universität Kiel, Germany (babel@astrophysik.uni-kiel.de)
[2] CEA, Service d'Astrophysique, Centre d'Etudes de Saclay, France (montmerle@sapvxg.saclay.cea.fr)

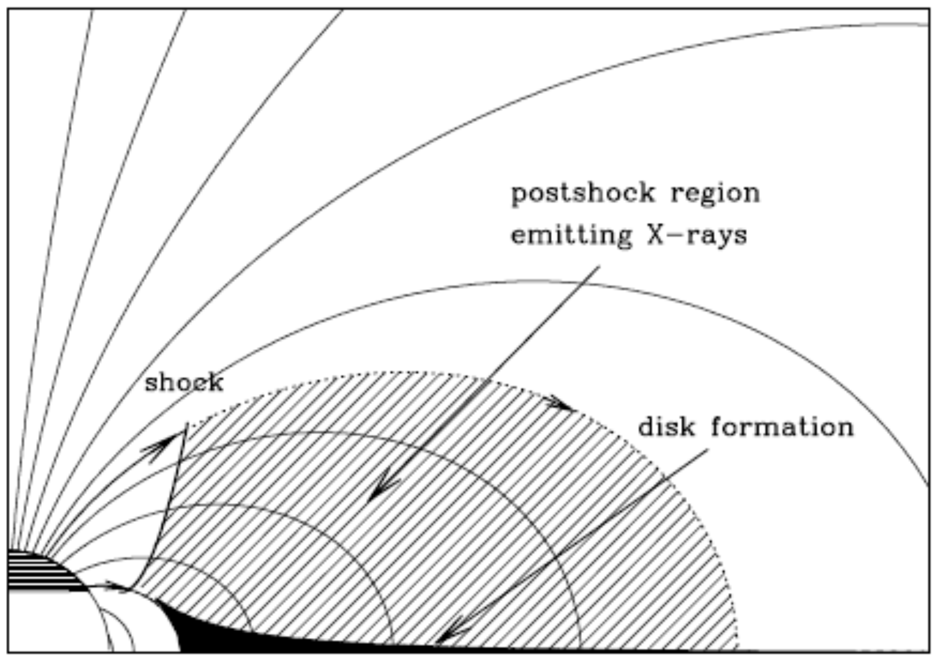
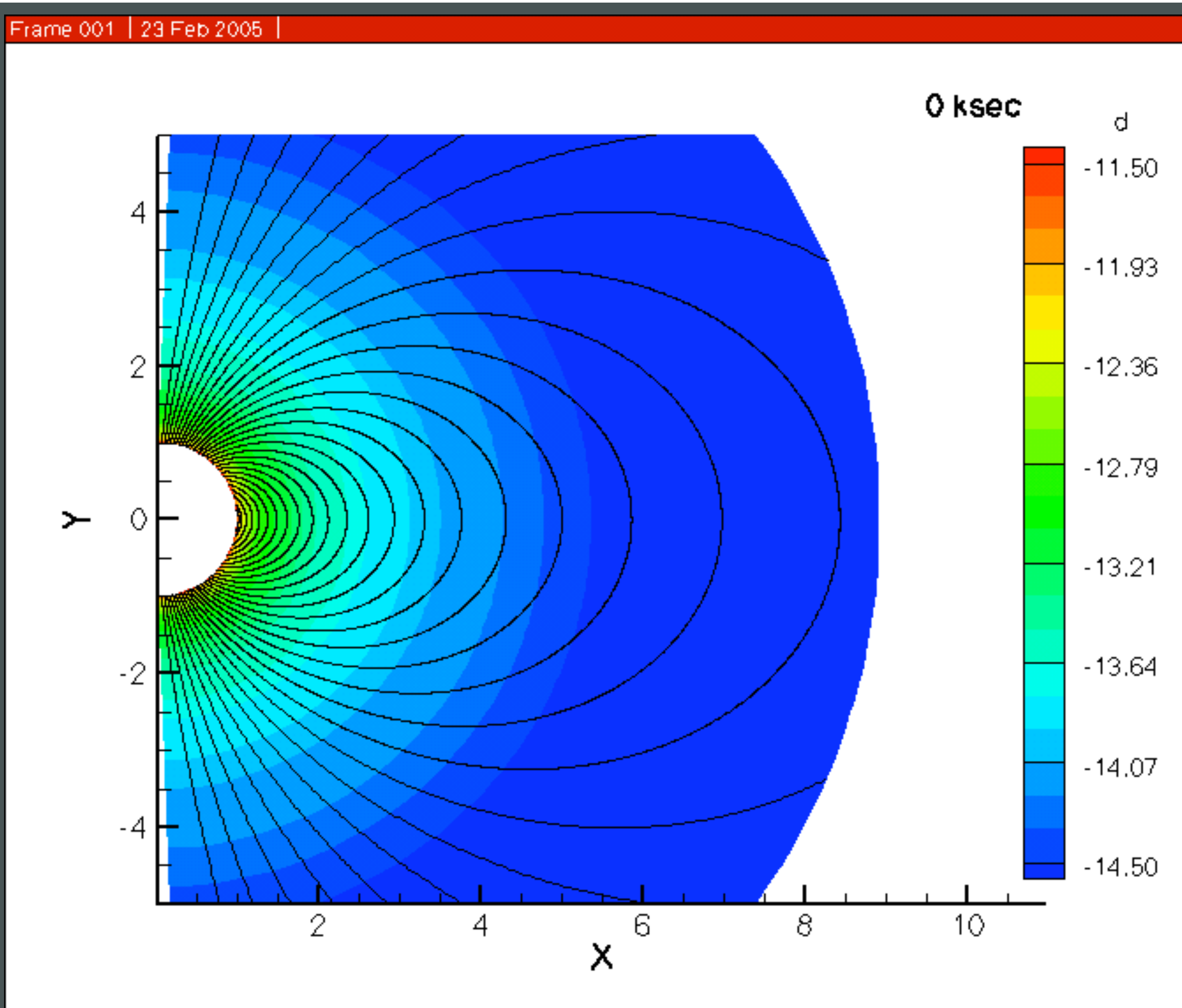
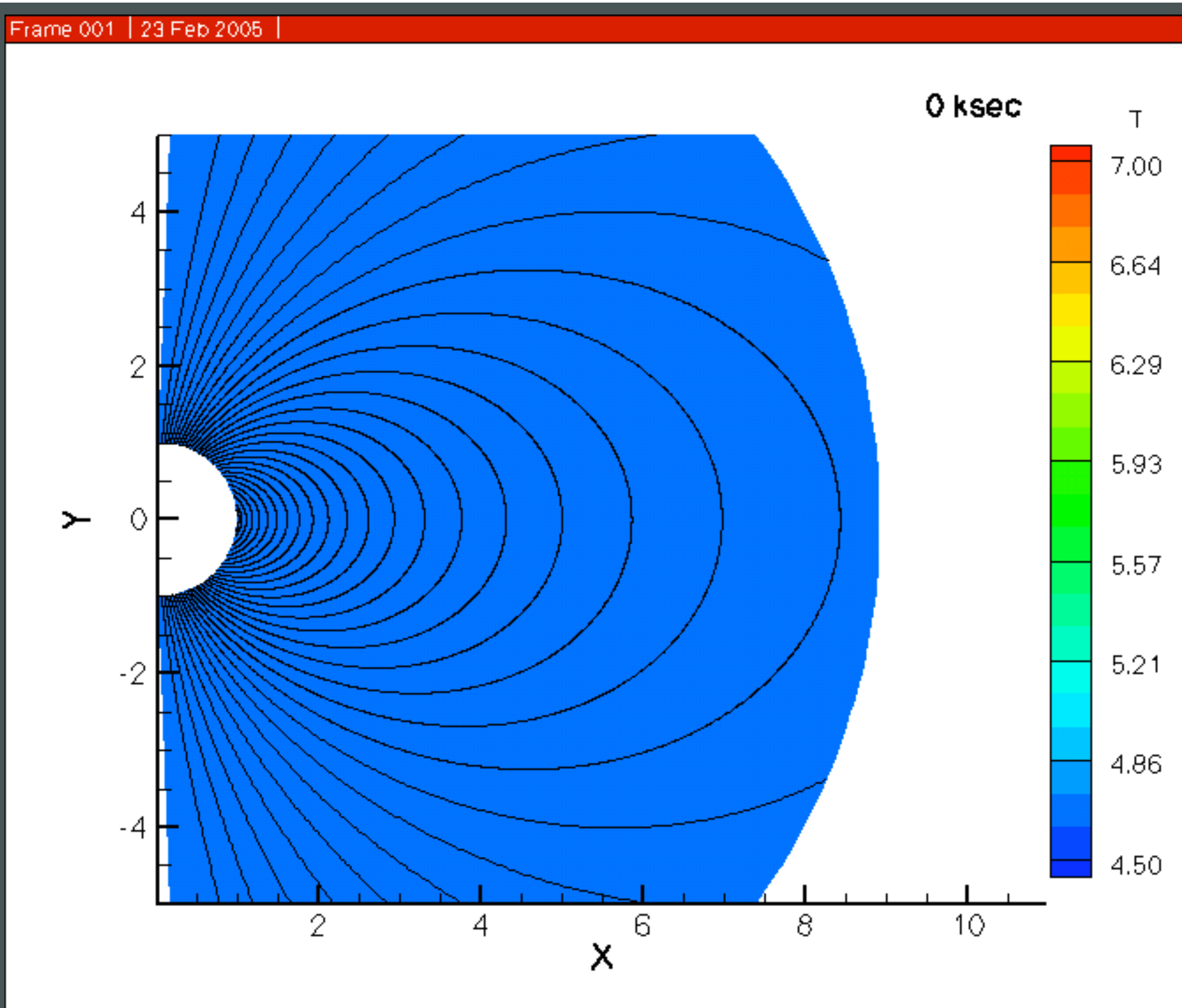


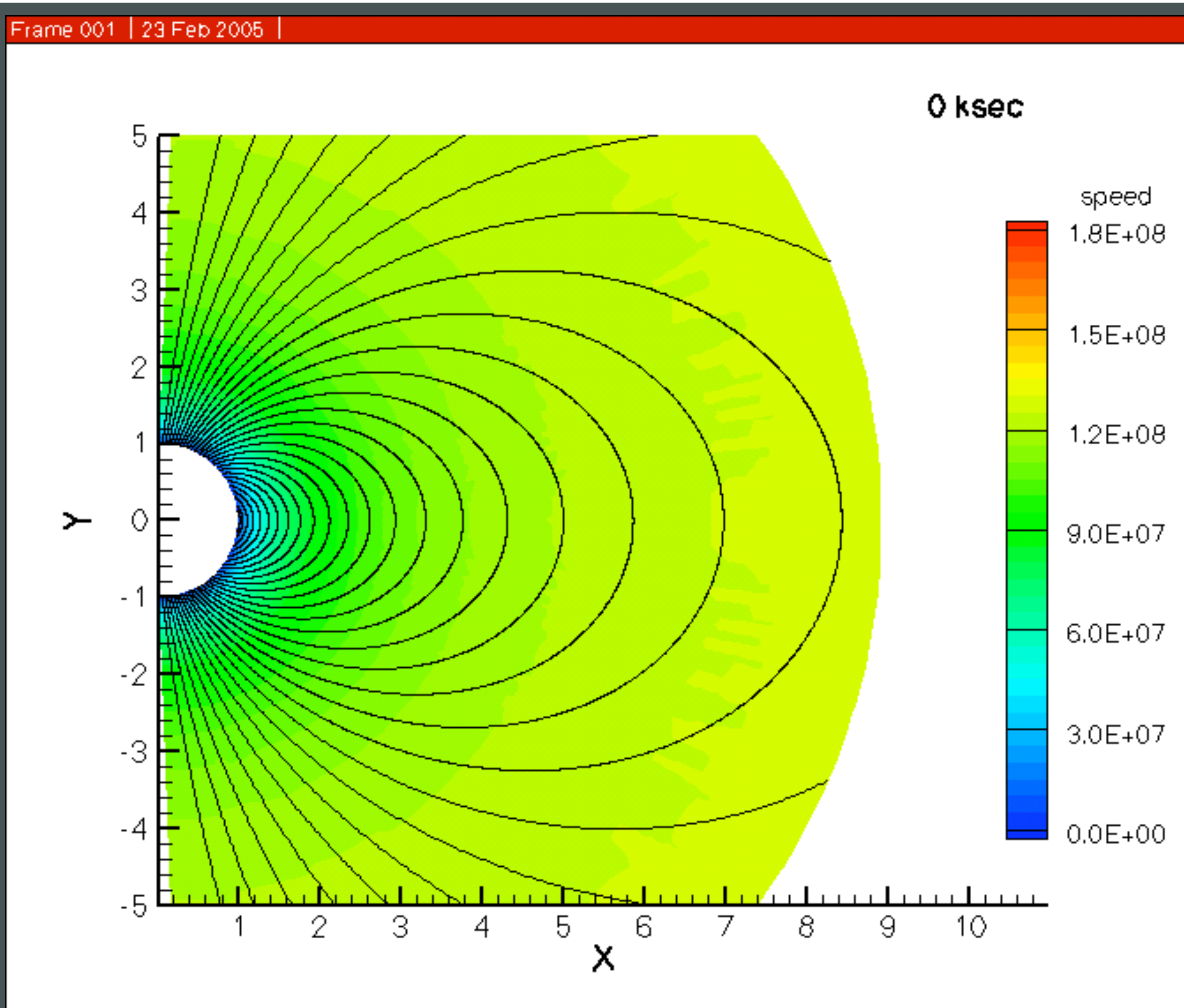
Fig. 7. Schematic view of the model proposed for the X-ray emission from IQ Aur (see text).



http://astro.swarthmore.edu/~cohen/movies/t1oc-lowvinf-logd_new.mov (Asif ud-Doula)



http://astro.swarthmore.edu/~cohen/movies/t1oc-lowvinf-logT_new.mov (Asif ud-Doula)



http://astro.swarthmore.edu/~cohen/movies/t1oc-lowvinf-speed_new.mov (Asif ud-Doula)

Predictions:

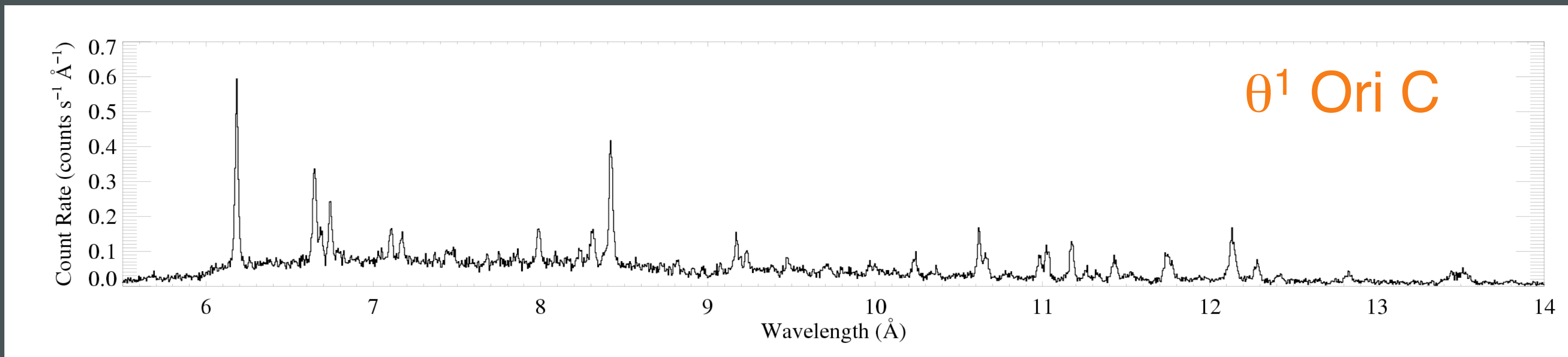
1. Shocks are strong – head-on – and so plasma is hotter;

2. Hot plasma is moving much slower (confinement);

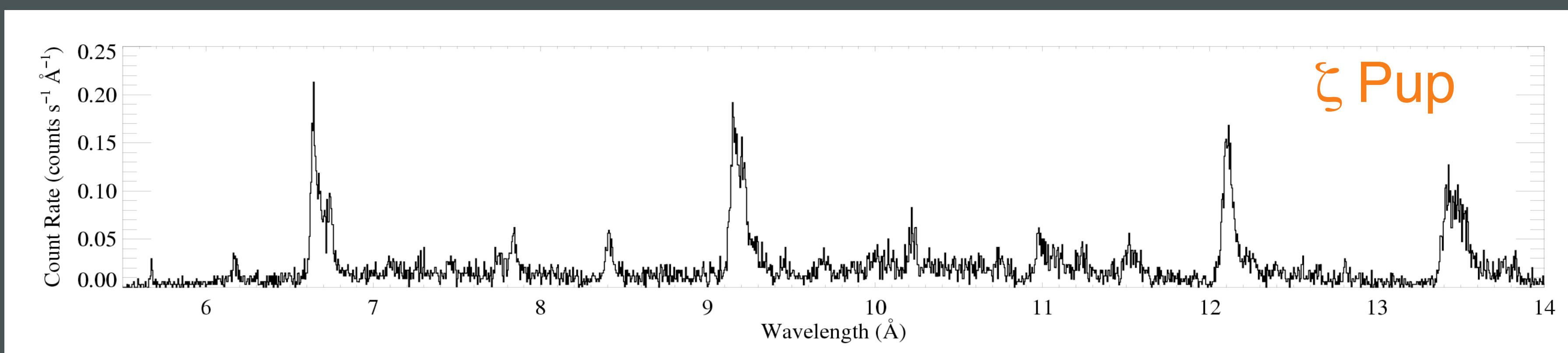
3. Rotational modulation of X-ray flux;

4. Hot plasma is ~1 R_* above the surface.

Chandra grating spectra

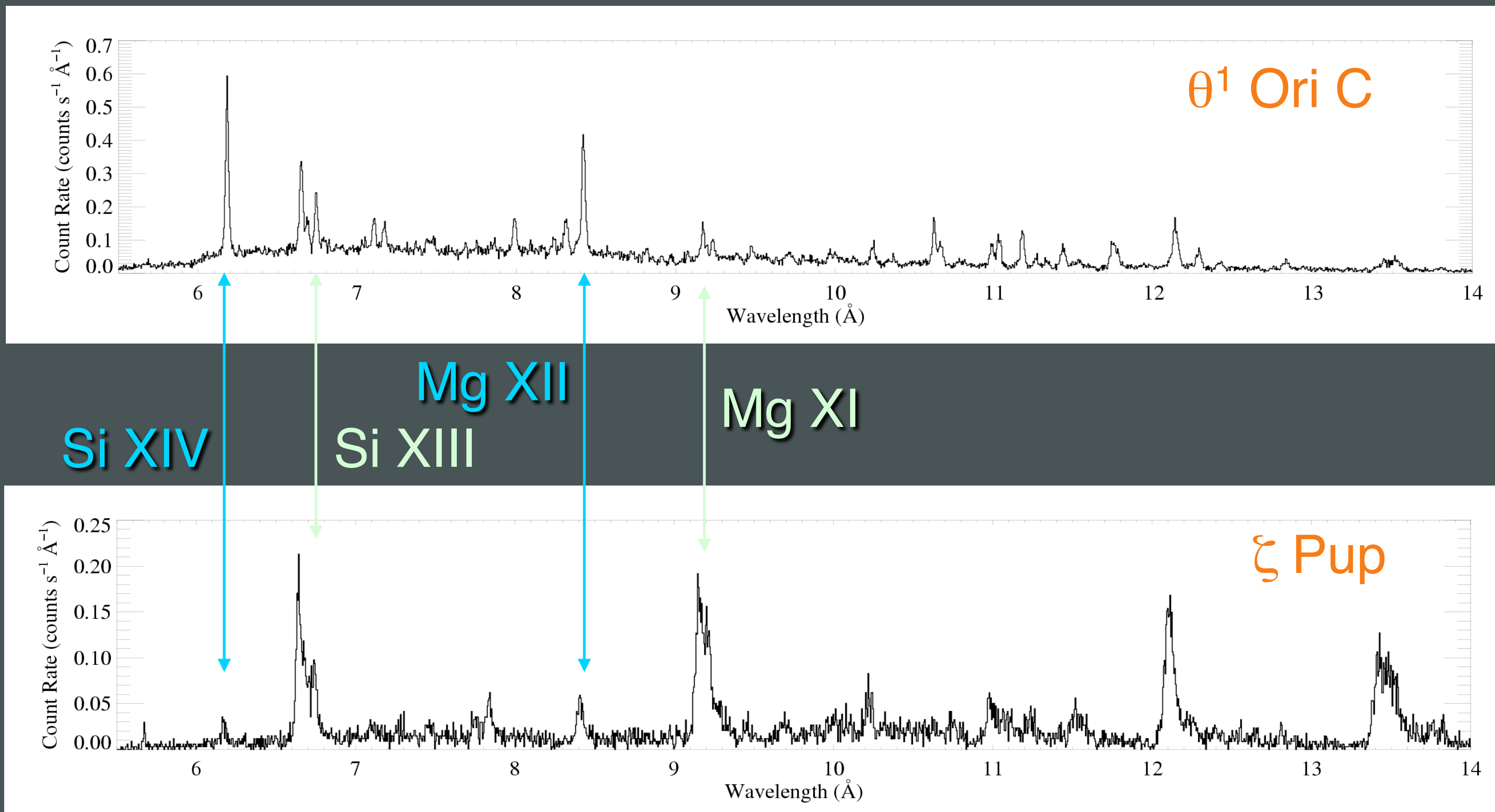


θ^1 Ori C: hotter plasma, narrower emission lines

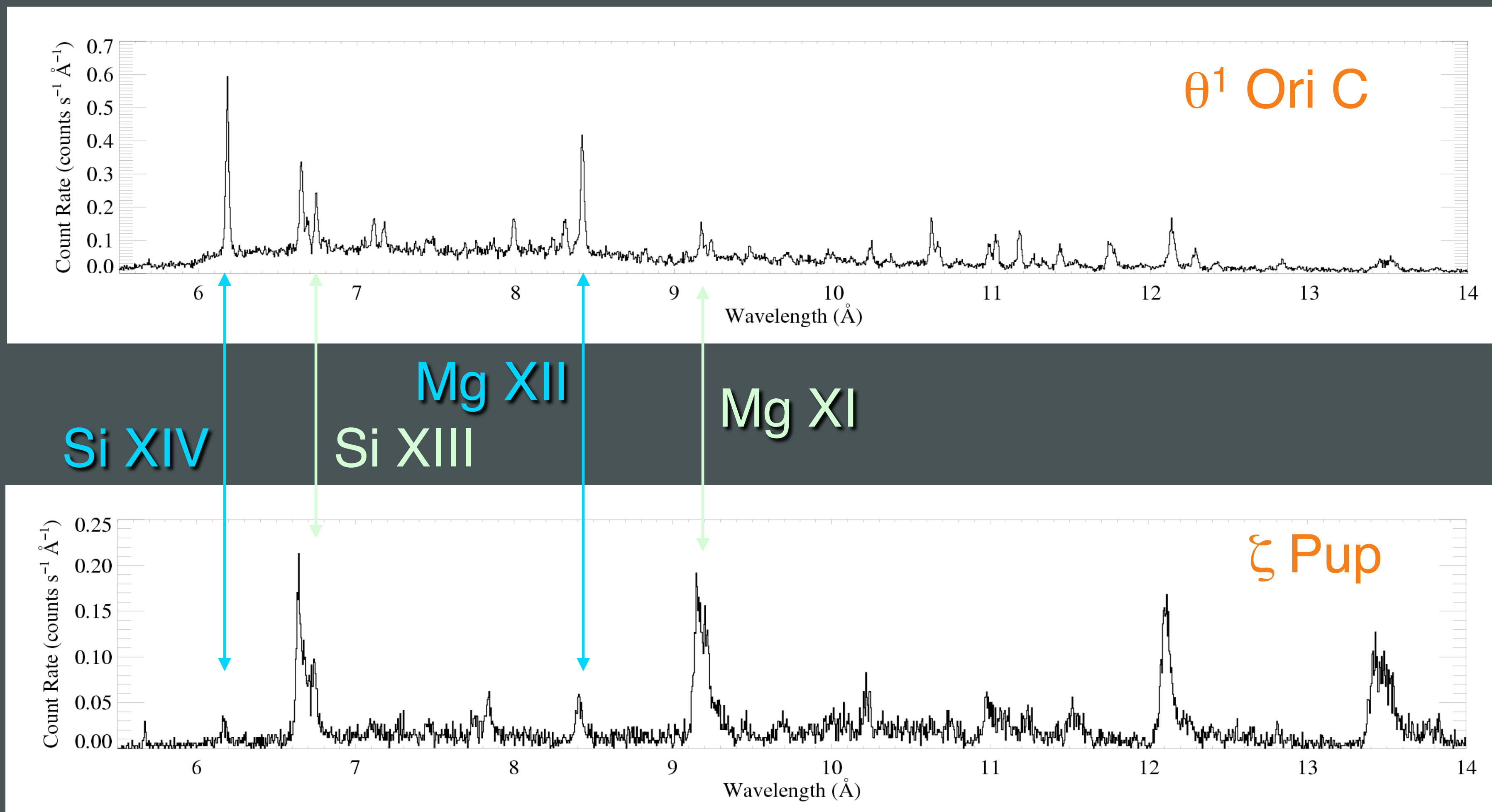


ζ Pup: cooler plasma, broad emission lines

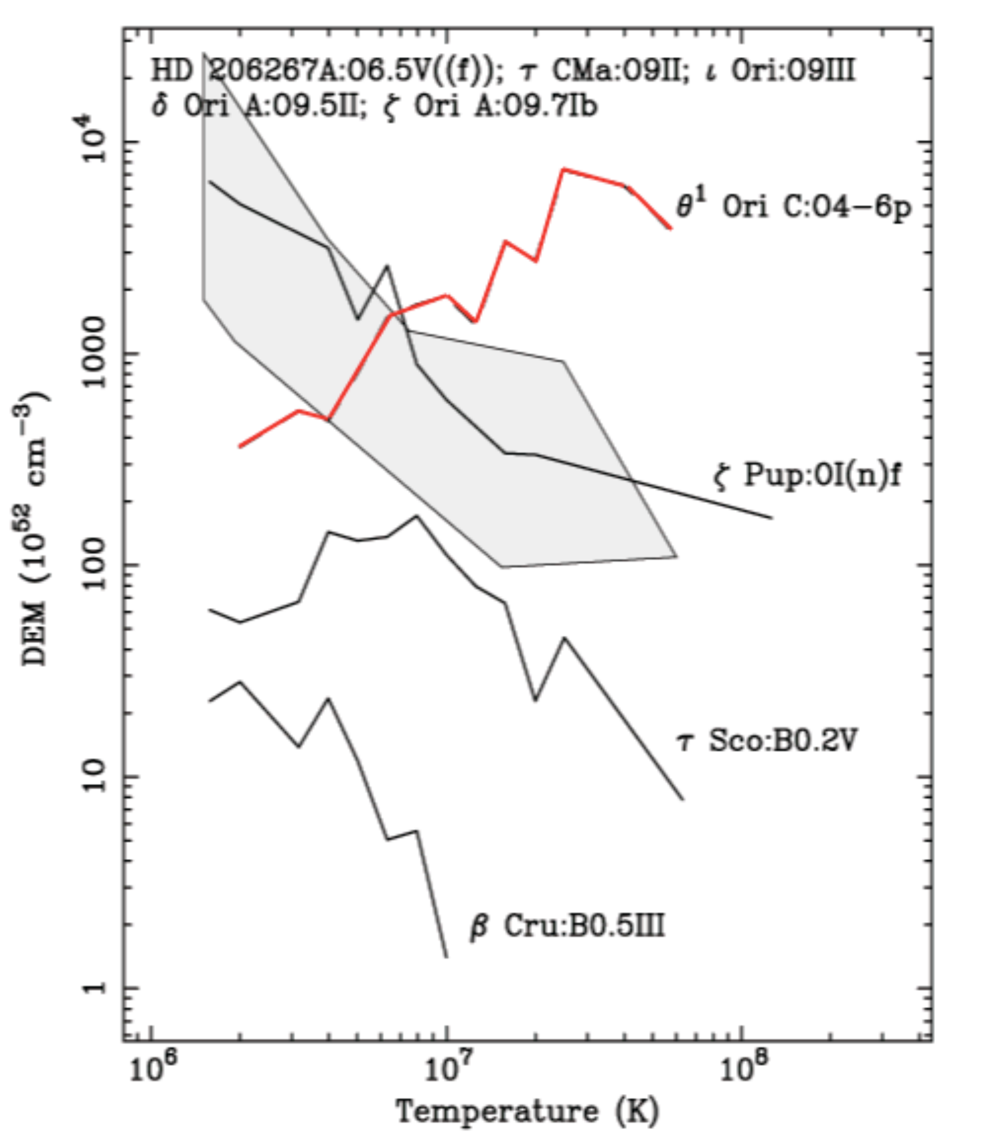
H-like/He-like ratio is temperature sensitive



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



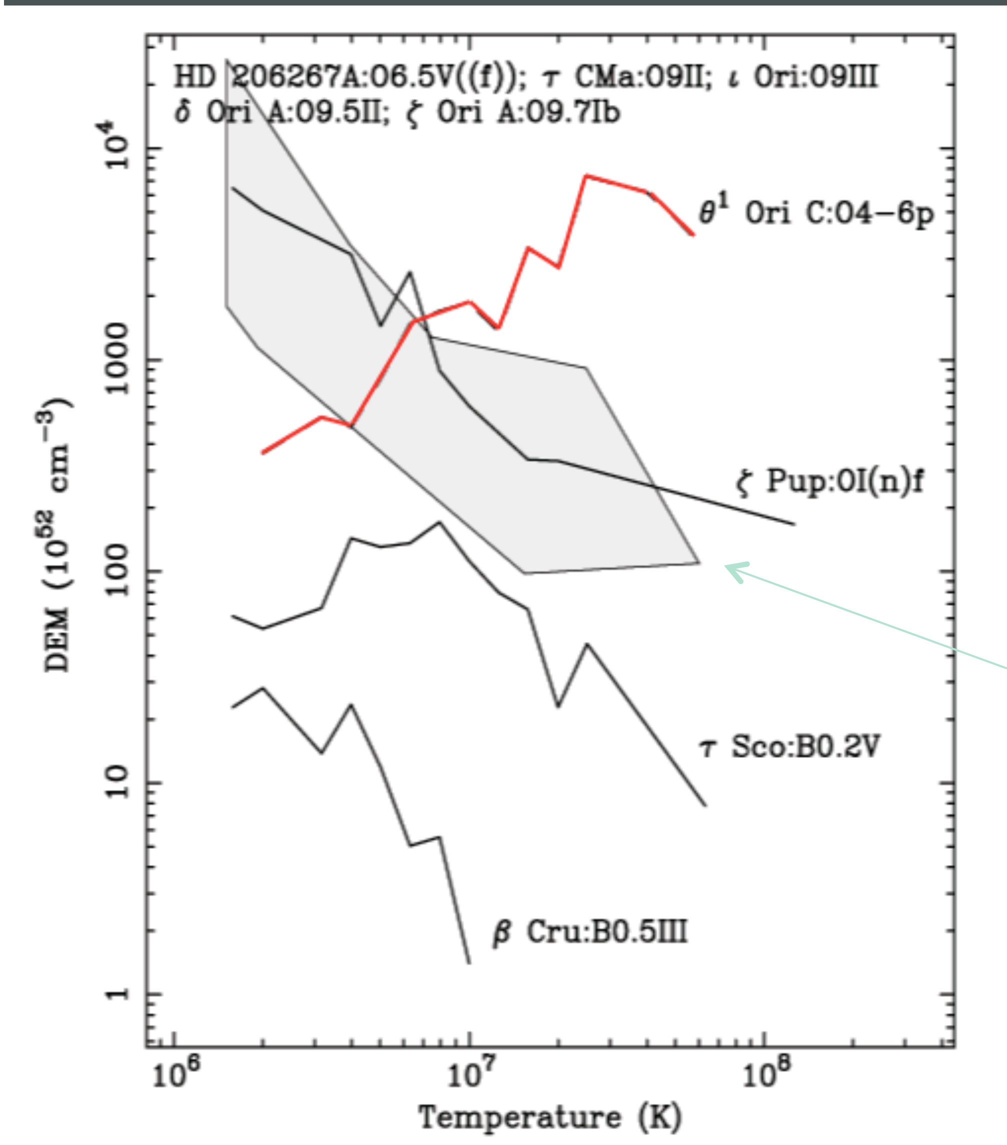
Differential emission measure
(temperature distribution)



Wojdowski & Schulz (2005)

θ^1 Ori C has bulk of its shock-heated plasma at 30 X 10^6 K and above

Differential emission measure
(temperature distribution)

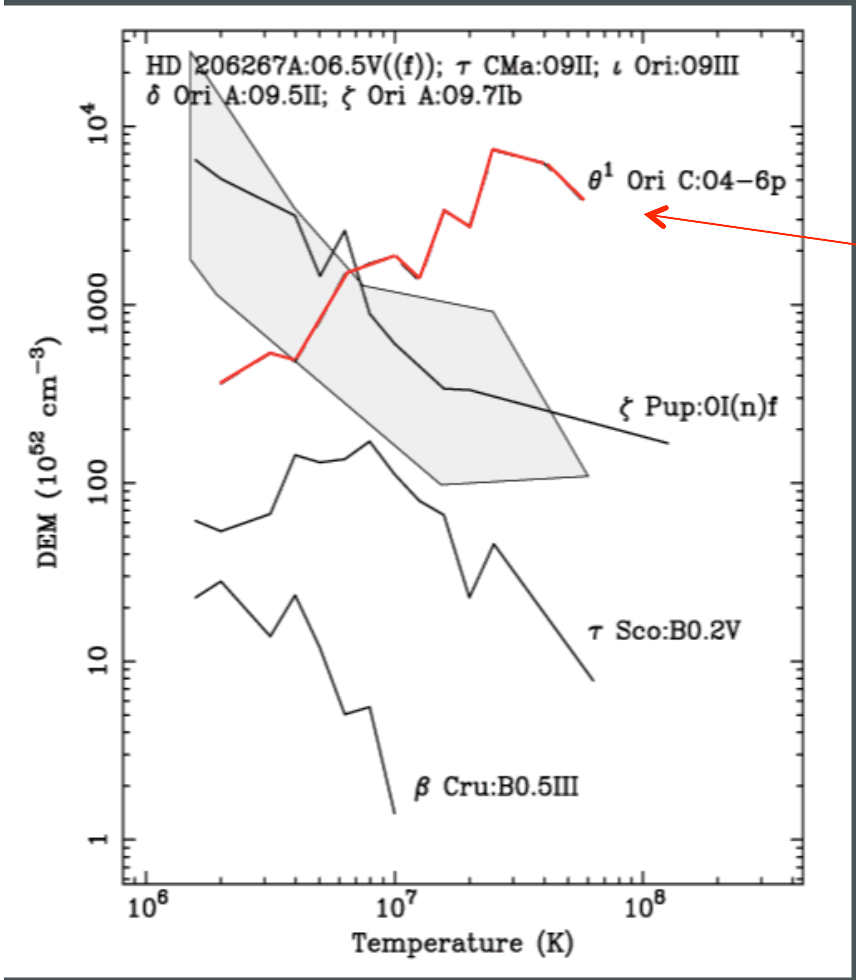


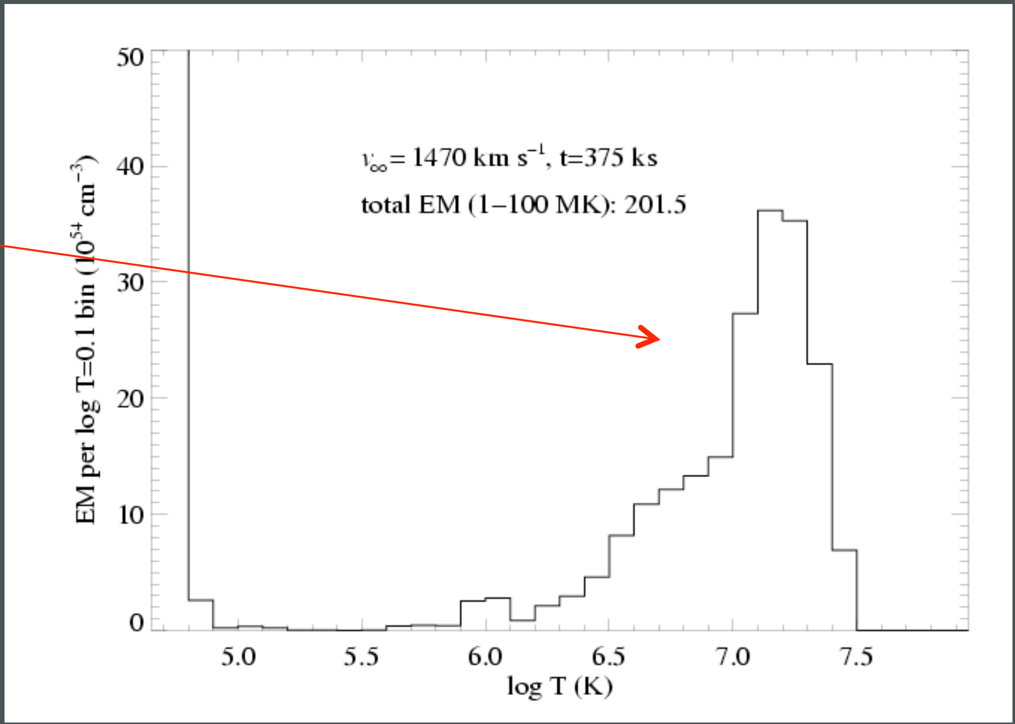
Wojdowski & Schulz (2005)

θ^1 Ori C has bulk of its shock-heated plasma at 30 X 10^6 K and above

six normal, non-magnetic O stars have much cooler DEMs, peaking at ~10^6 K

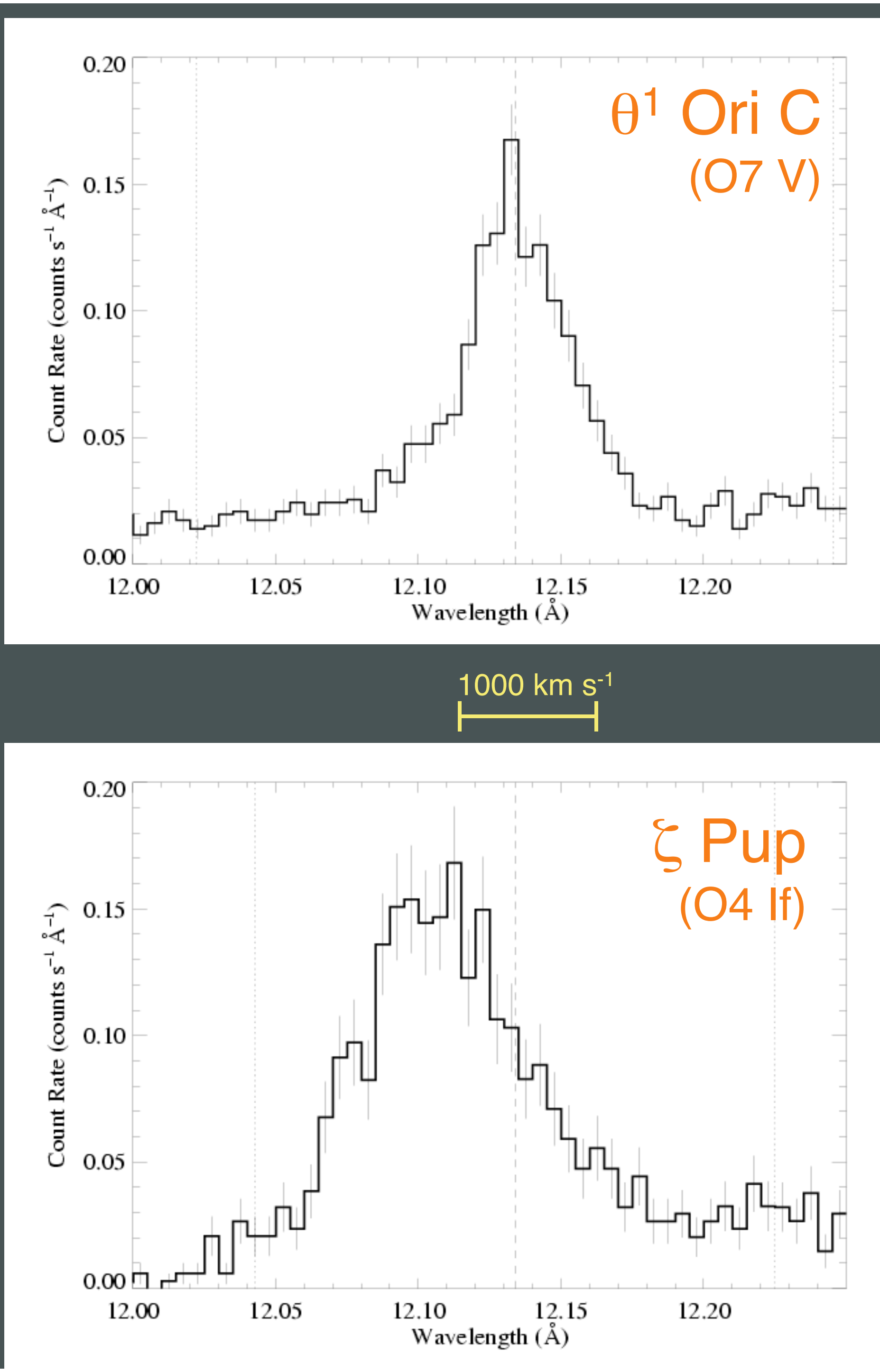
Differential emission measure
(temperature distribution)





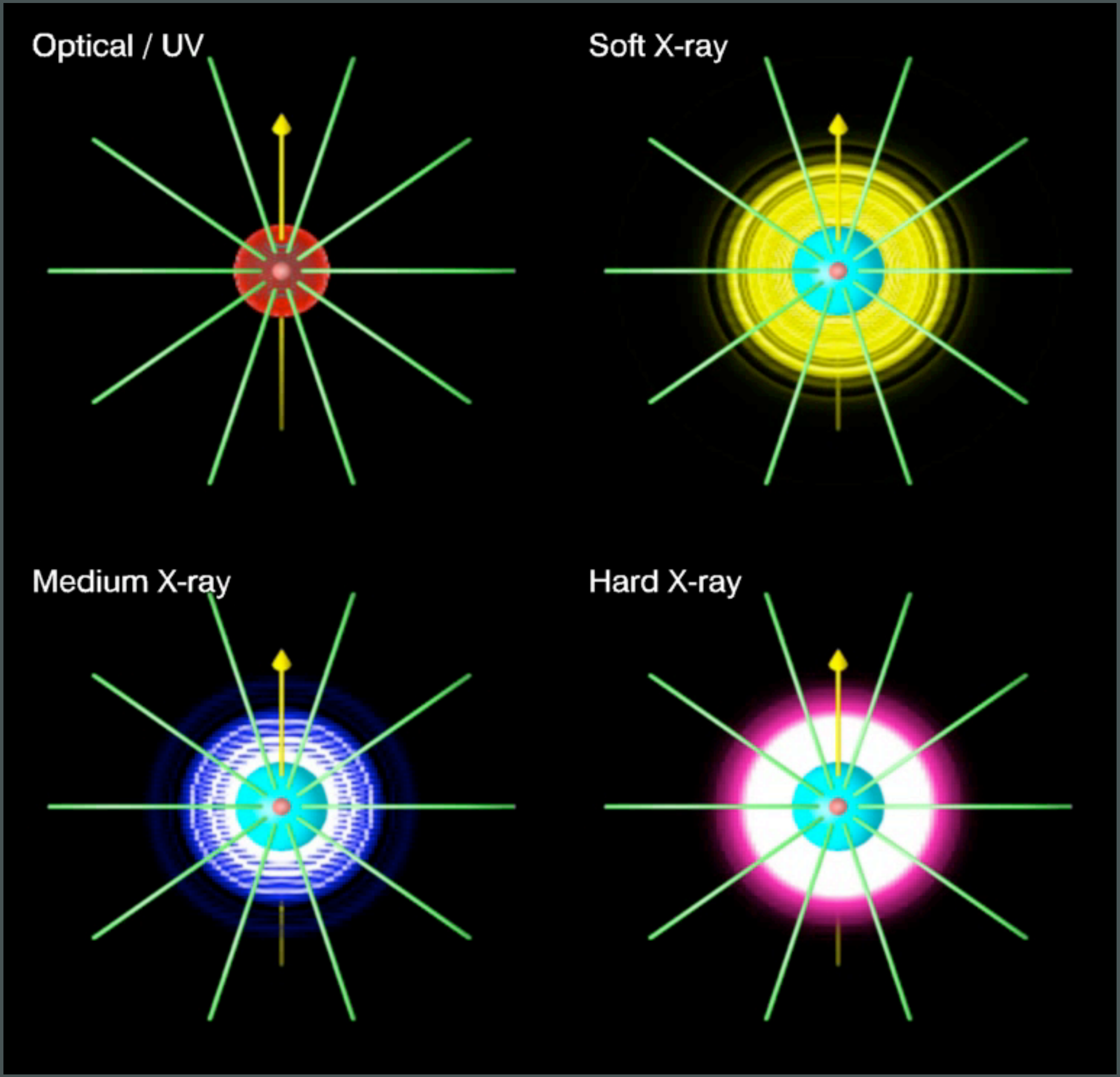
MHD simulation of θ1 Ori C reproduces the observed differential emission measure

Wojdowski & Schulz (2005)



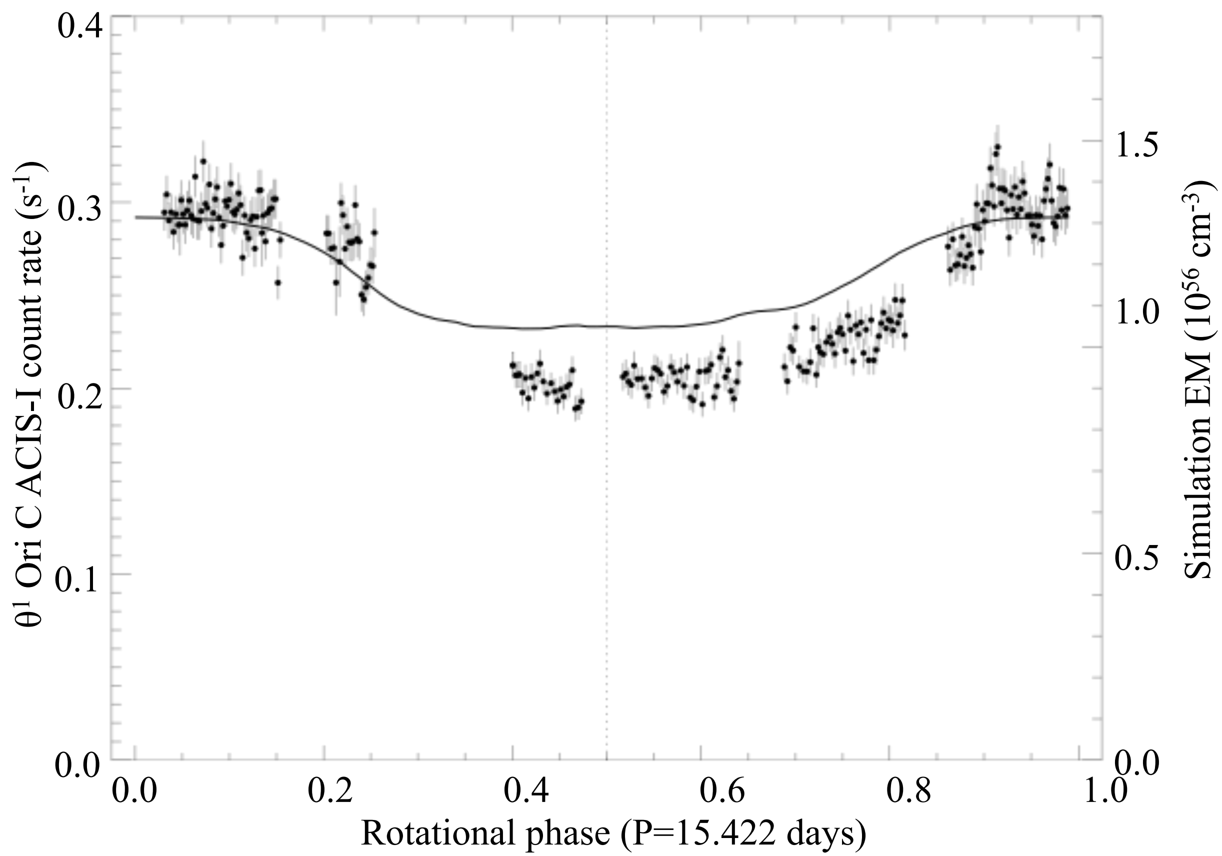
Emission lines *are* significantly narrower in the magnetic massive star's x-ray spectrum

The MHD simulations: different temperature intervals



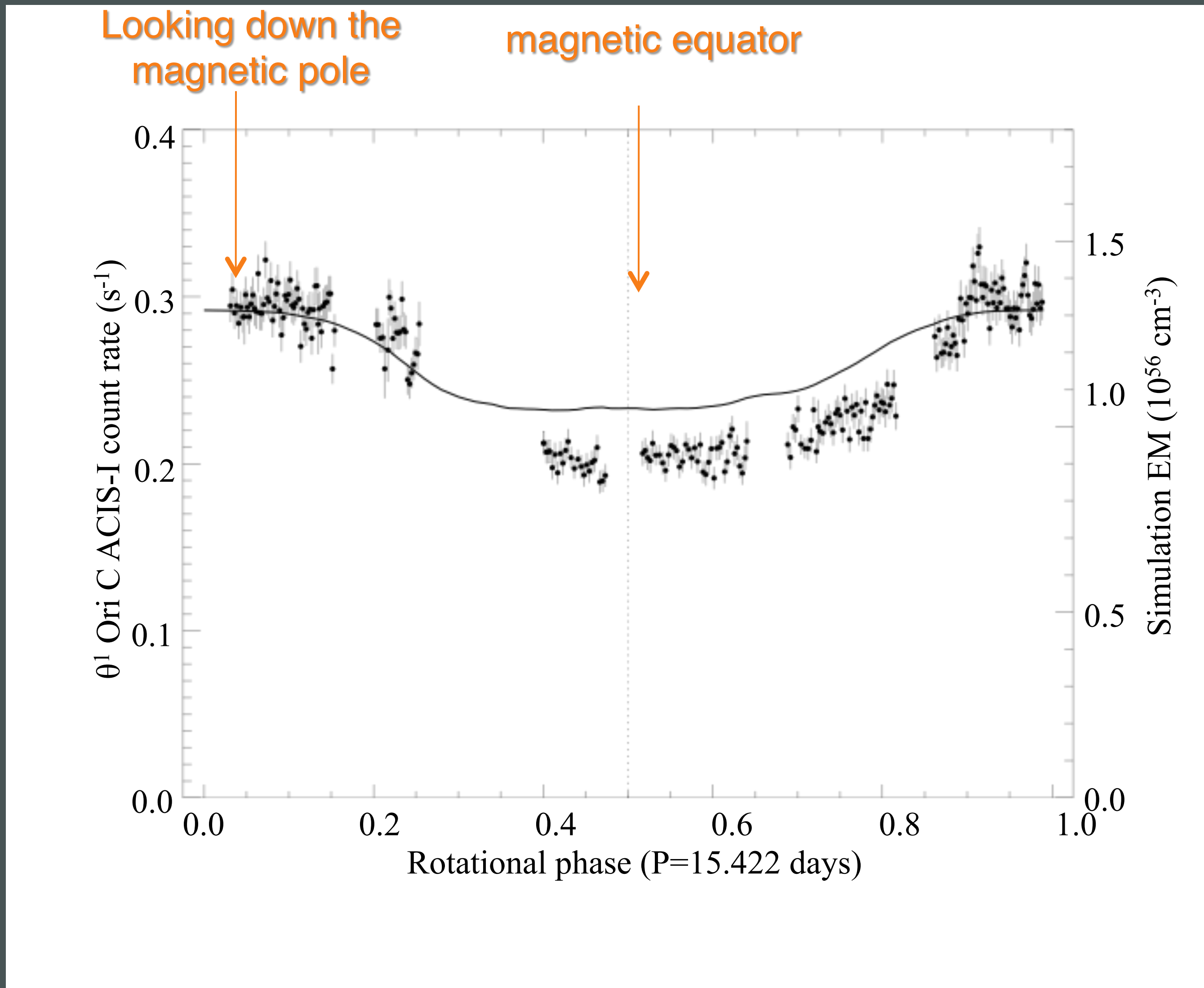
http://astro.swarthmore.edu/~cohen/movies/zeus-movie.avi (Asif ud-Doula & Richard Townsend)

Chandra broadband count rate vs. rotational phase



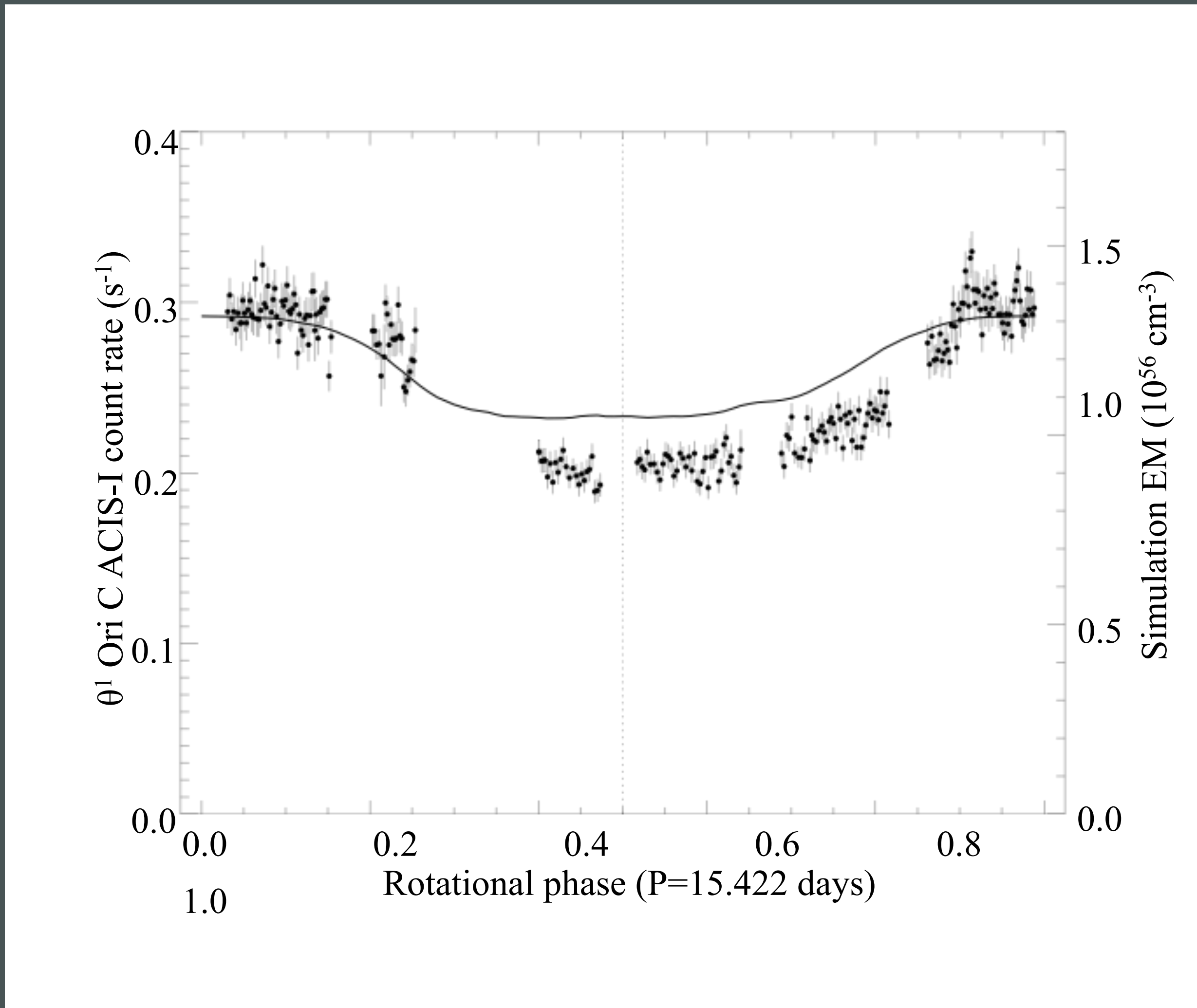
Points (Chandra data); Line (model from MHD simulation)

Chandra broadband count rate vs. rotational phase



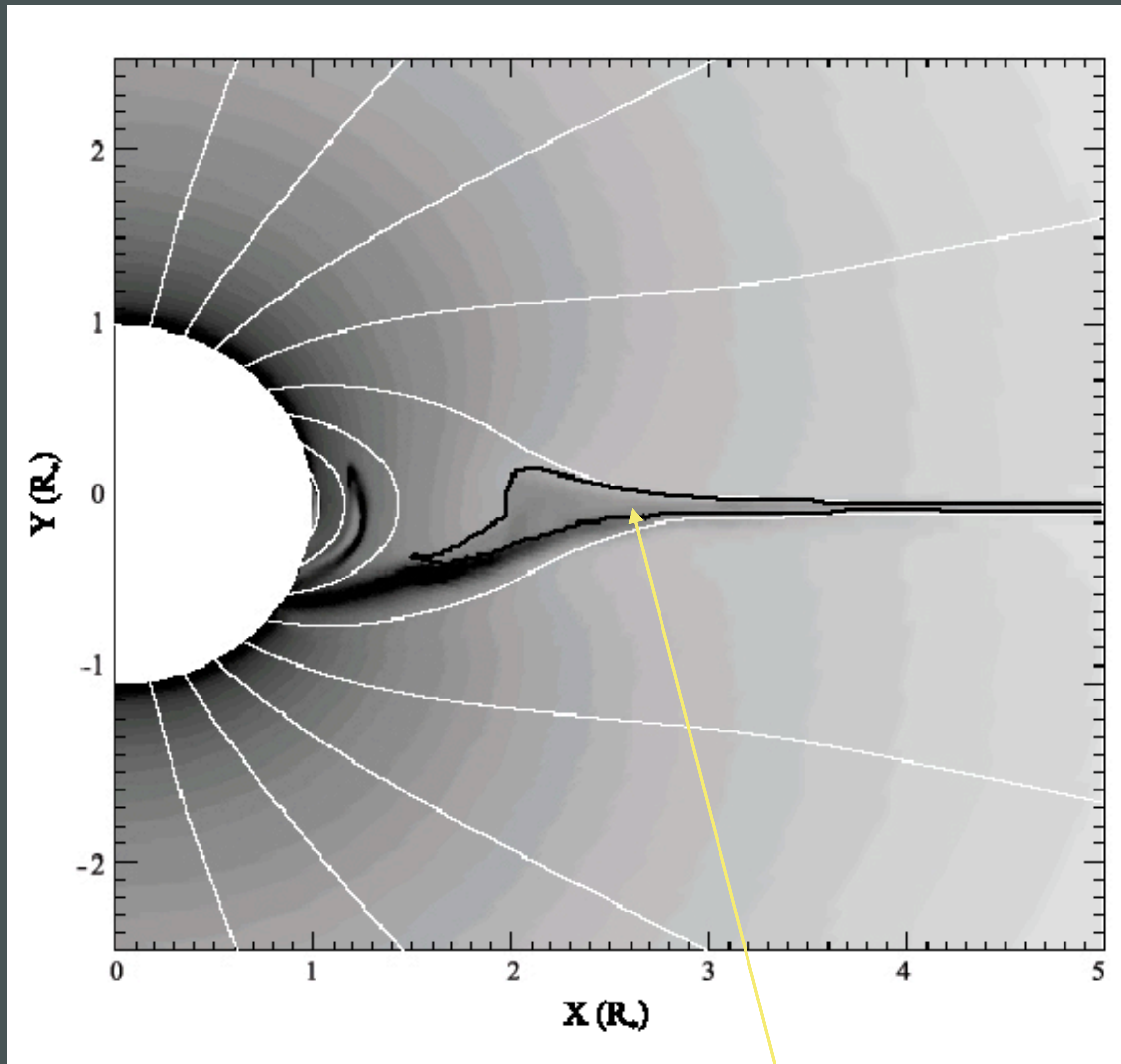
Points (Chandra data); Line (model from MHD simulation)

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 (gray scale)

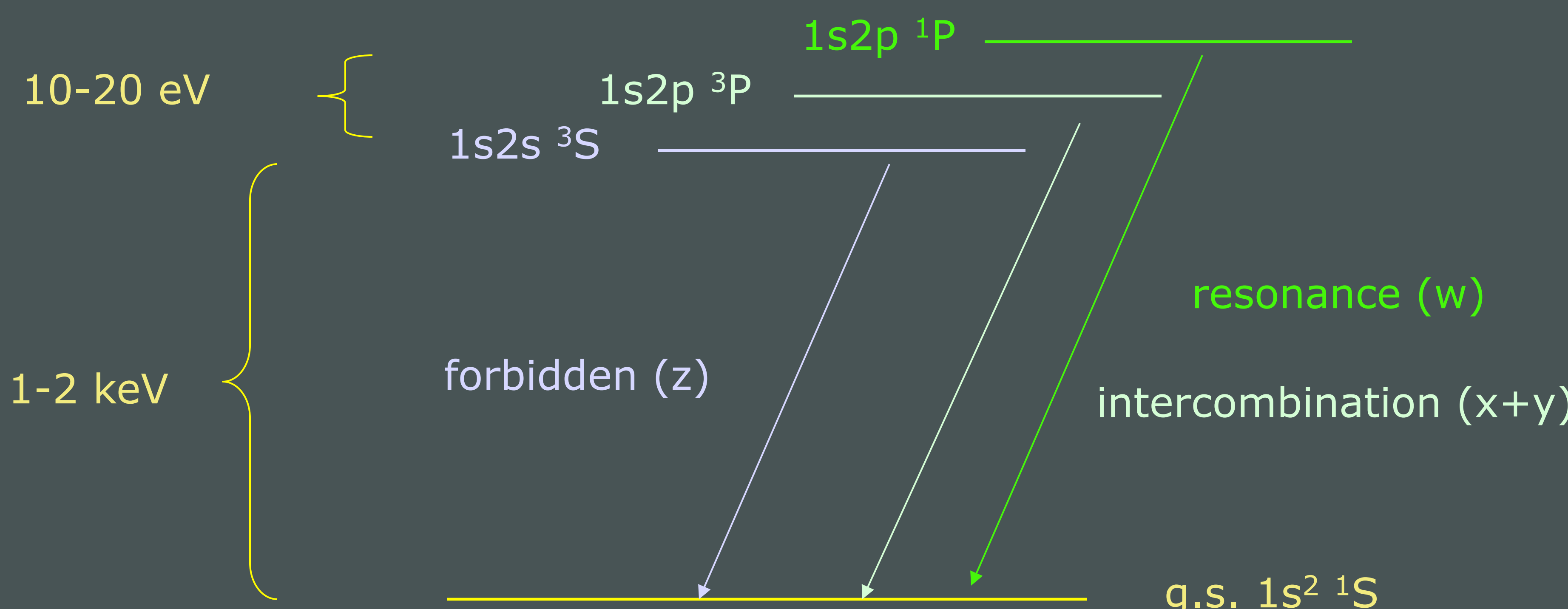


contour encloses T > 10^6 K

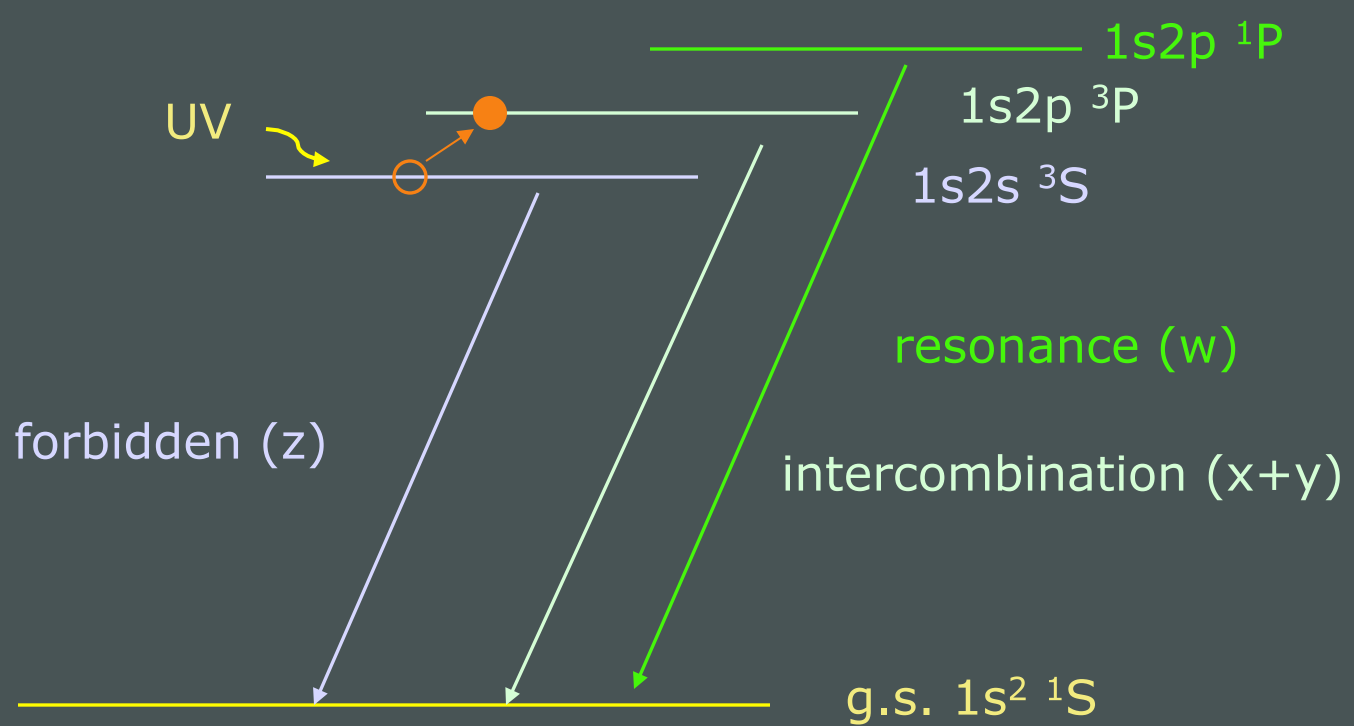
Helium-like species' forbidden-to-intercombination line ratios – $z/(x+y)$ – provide information about the *location* of the hot plasma

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

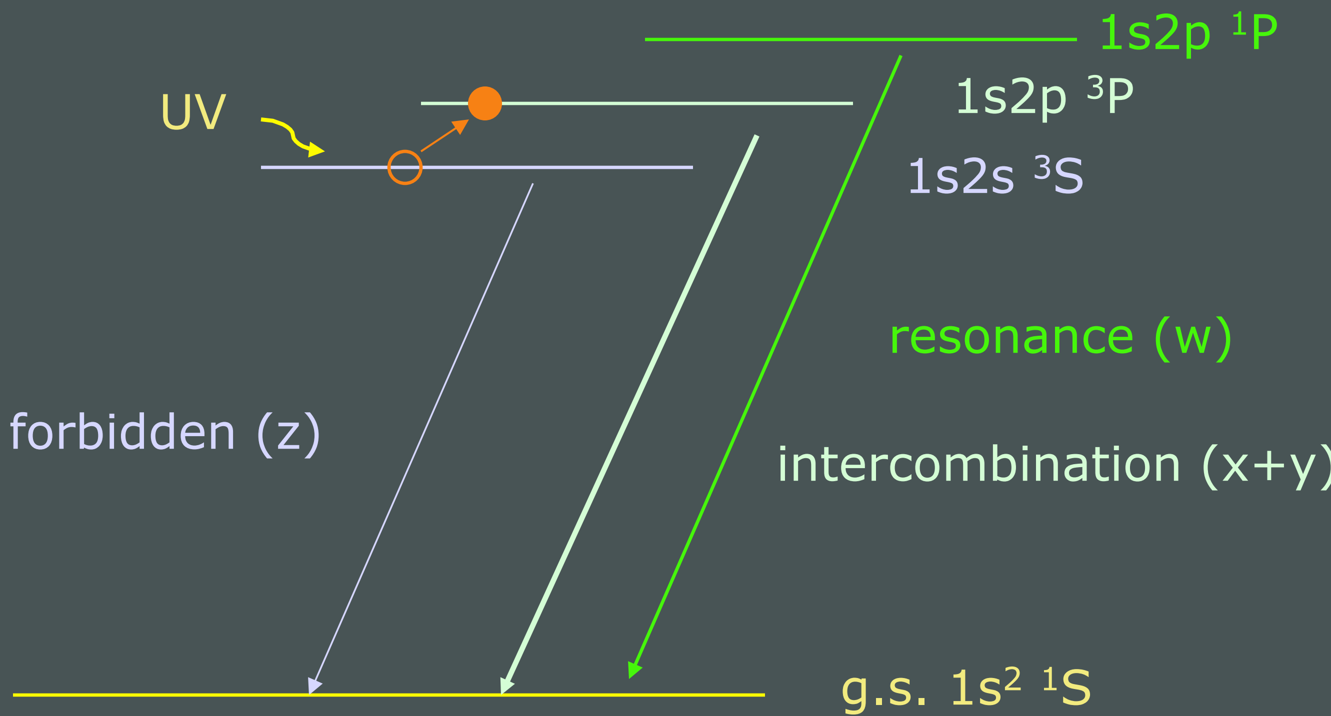
Helium-like ions (e.g. O^{+6}, Ne^{+8}, Mg^{+10}, Si^{+12}, S^{+14}) – schematic energy level diagram



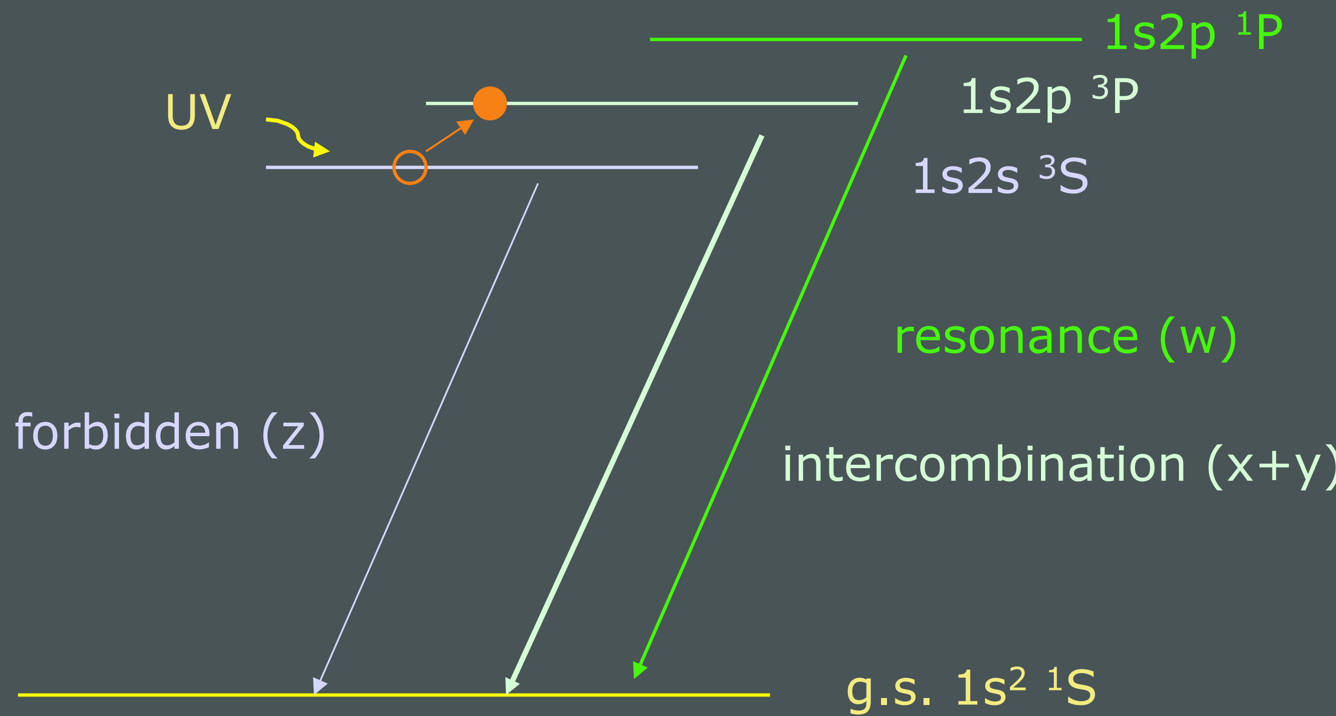
Ultraviolet light from the star's photosphere drives photoexcitation out of the ^3S level



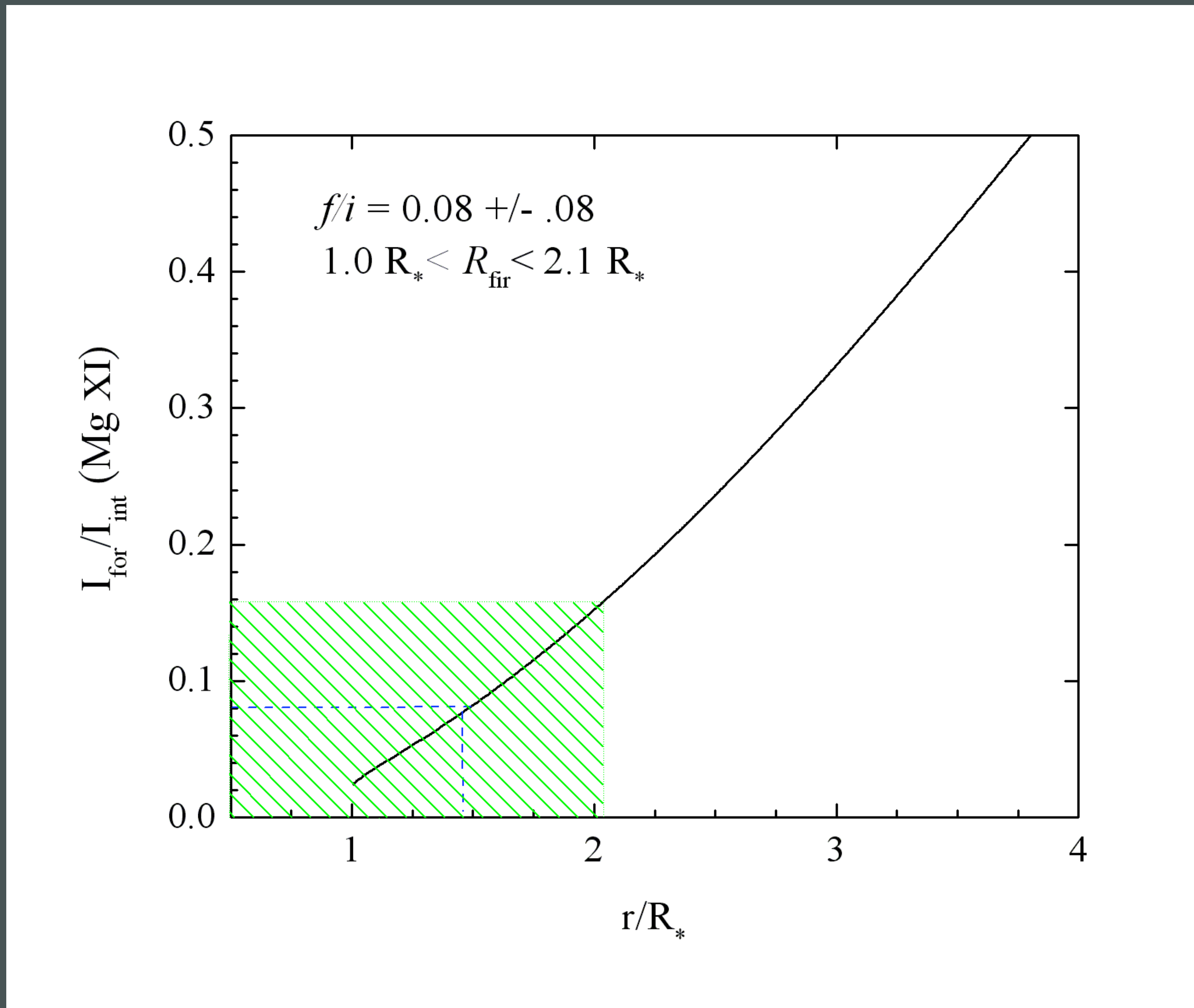
The **f/i ratio** is thus a diagnostic of the local UV mean intensity…

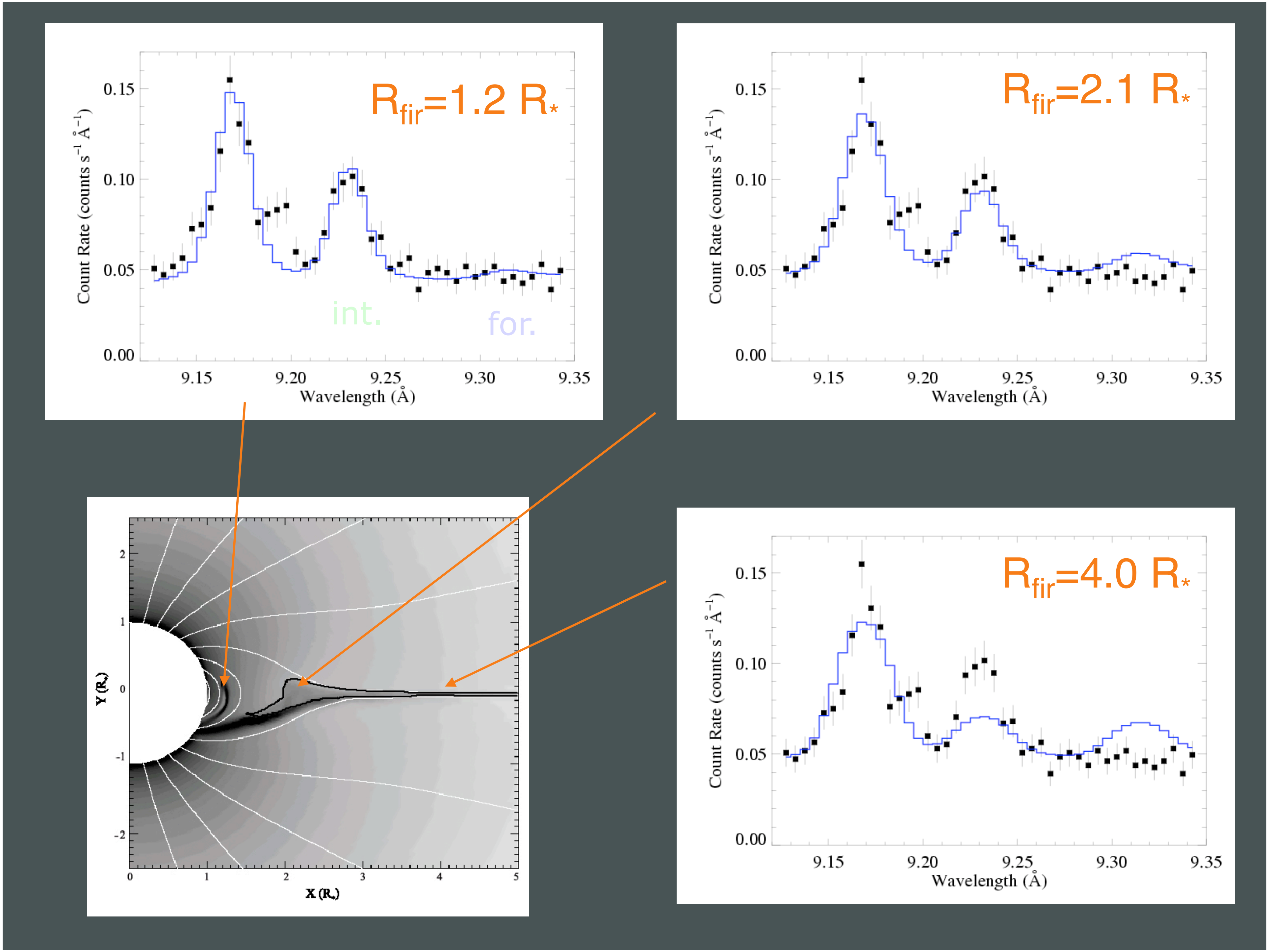


…and therefore also of the **distance** of the x-ray emitting plasma is from the photosphere



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



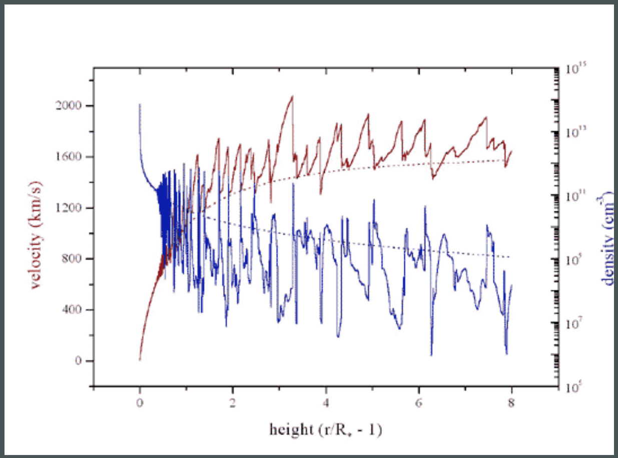


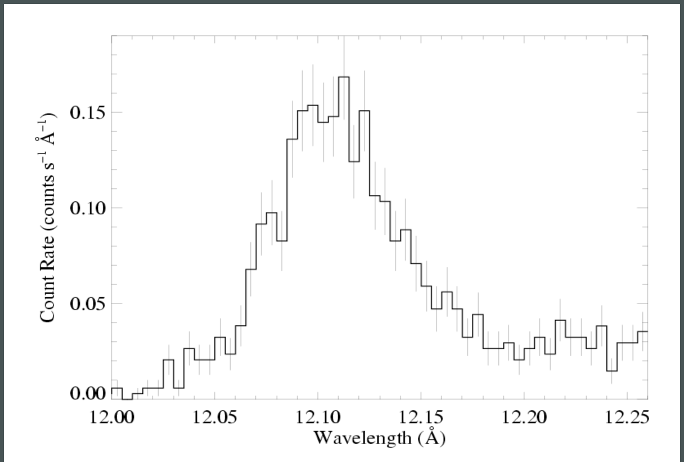
R_{fir}=1.2 R_*
R_{fir}=2.1 R_*
R_{fir}=4.0 R_*
int.
for.
Count Rate (counts s^{-1} Å^{-1})
Wavelength (Å)
0.00
0.05
0.10
0.15
9.15
9.20
9.25
9.30
9.35
Y (R_*)
X (R_*)

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.

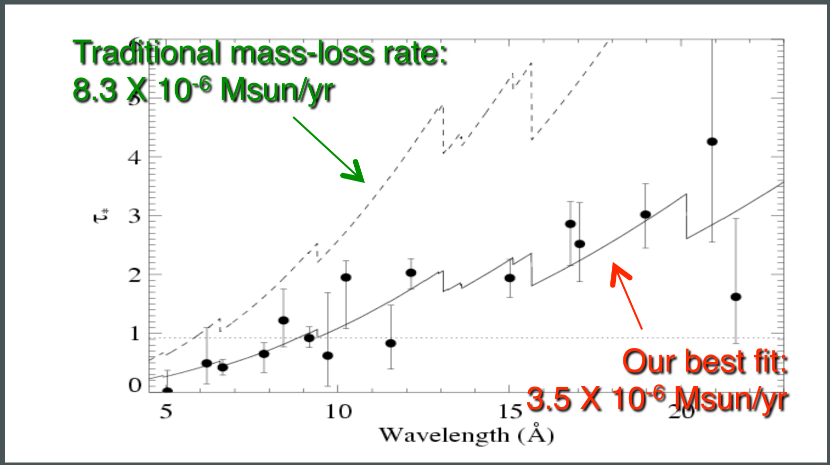




Conclusions

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*.

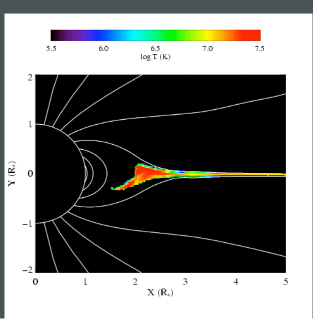


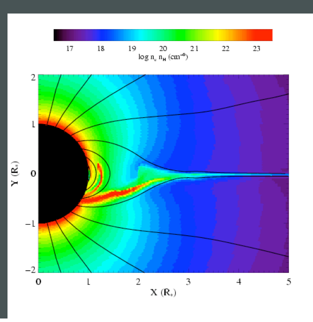
Conclusions

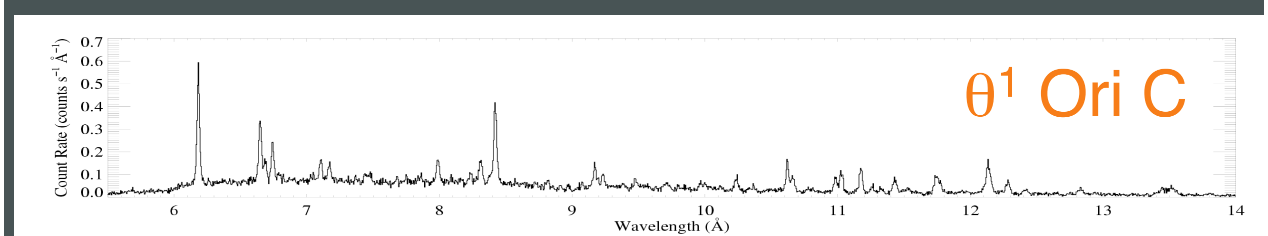
Normal massive stars have x-ray line profiles consistent with the predictions of the wind instability model.

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.







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