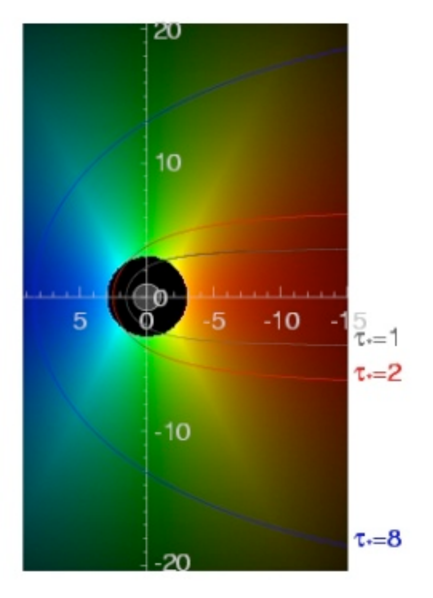
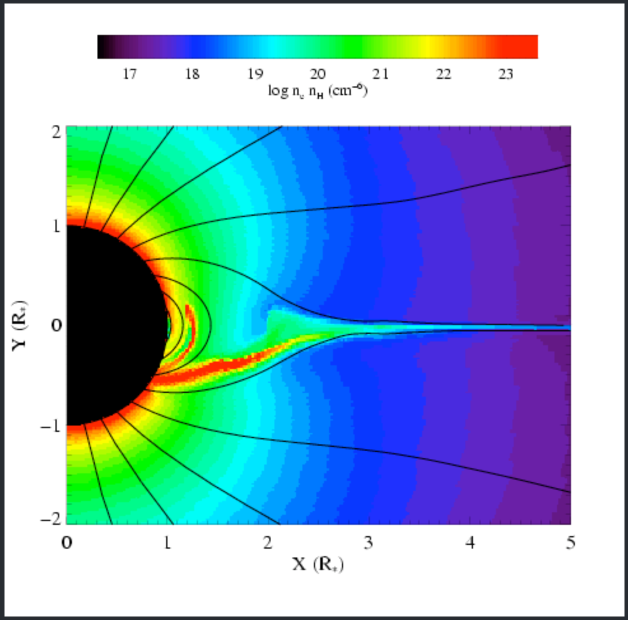
X-rays from Young Massive Stars

David Cohen
Swarthmore College





O Stars are the brightest X-ray sources in young clusters

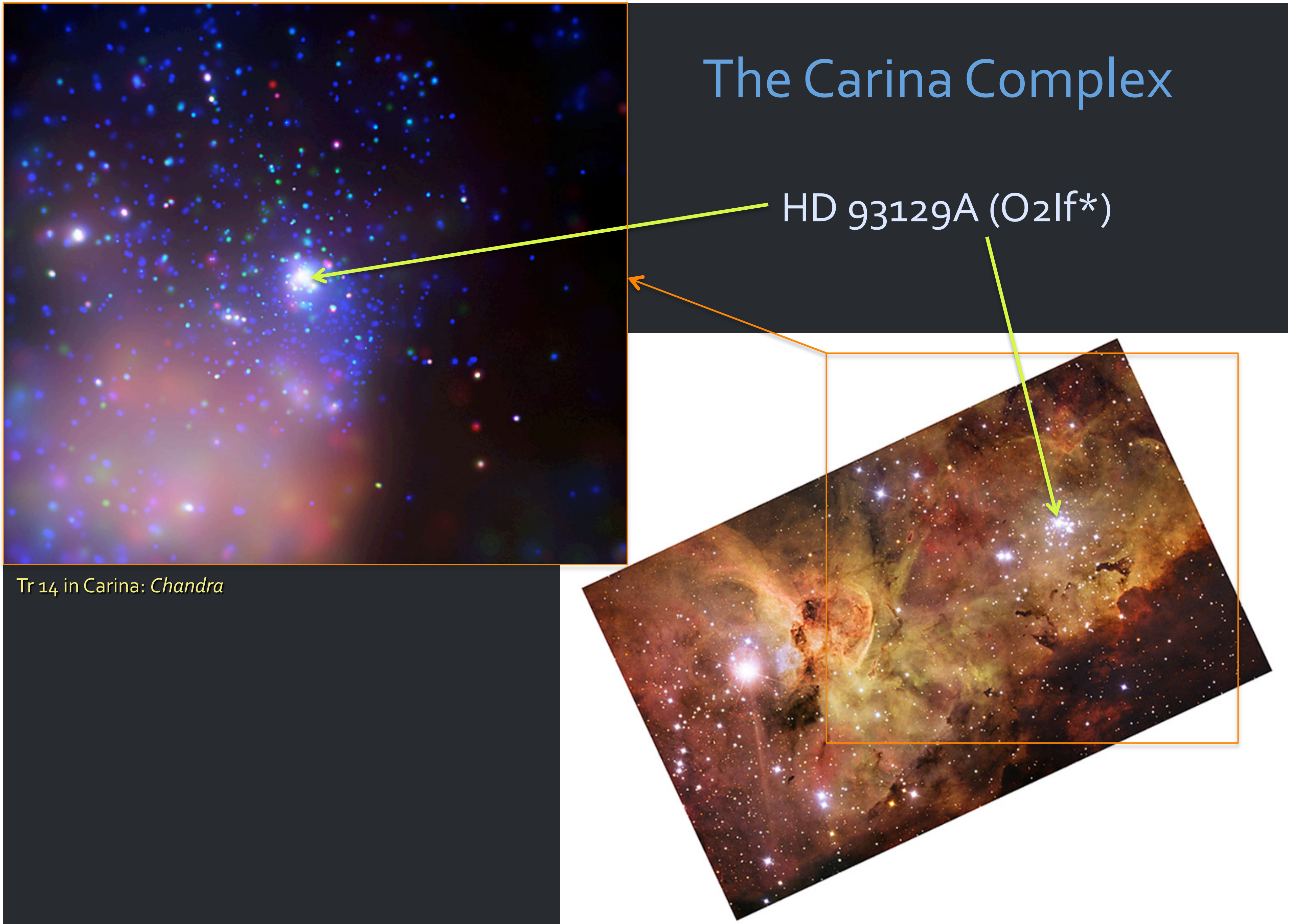
In addition to the X-ray and UV radiation from O stars

Prodigious matter, momentum, and kinetic energy input into the cluster environment via their winds

Tr 14 in Carina: *Chandra*

The winds are the site and energy source of the X-rays

The Carina Complex



HD 93129A (O2If*)

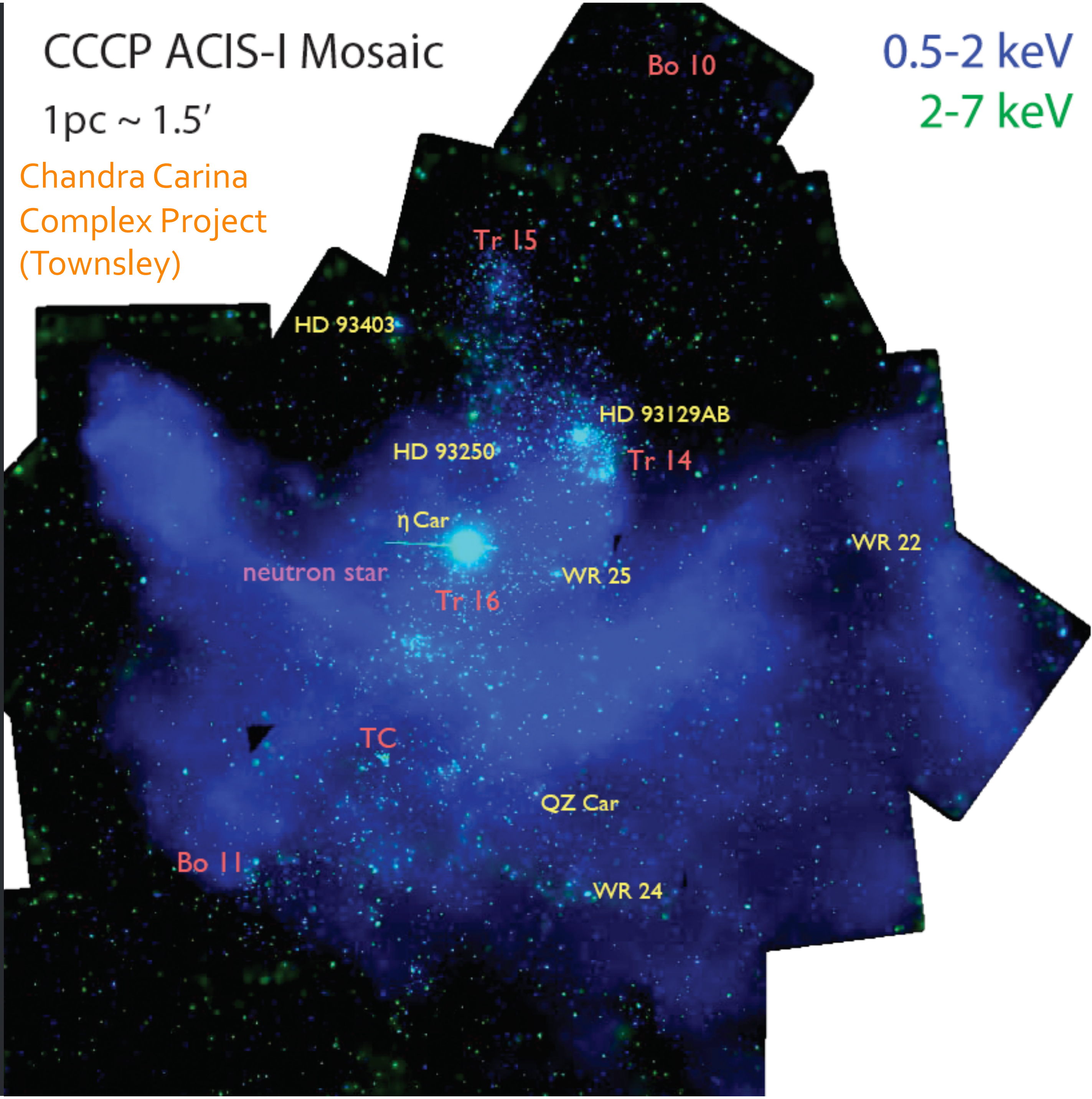
Tr 14 in Carina: *Chandra*

Carina: ESO

CCCP ACIS-I Mosaic

1pc ~ 1.5′

Chandra Carina Complex Project (Townsley)

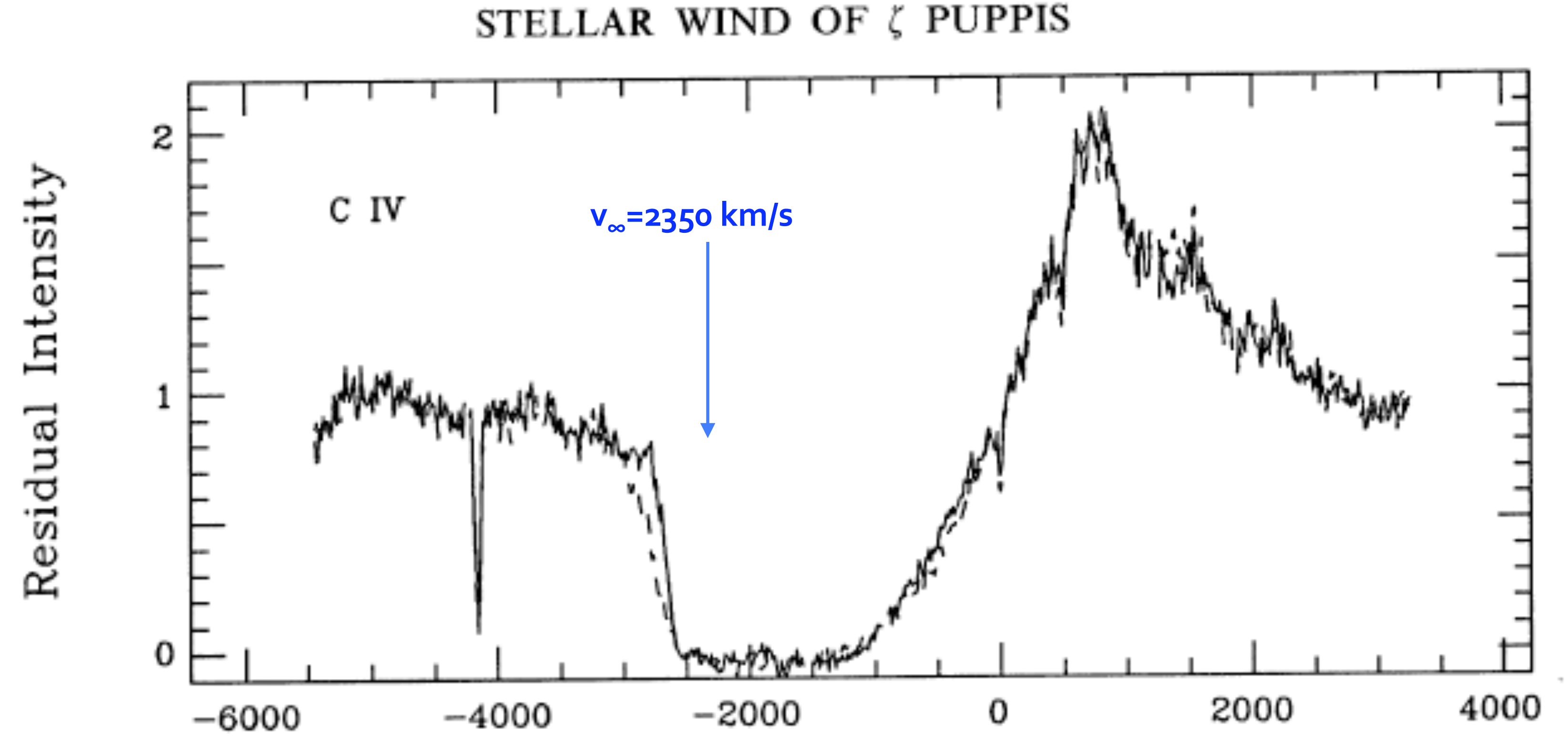



0.50 - 0.70 keV
0.70 - 0.86 keV
0.86 - 0.96 keV

Radiation-driven O star **winds**

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

UV spectrum: C IV 1548, 1551 Å

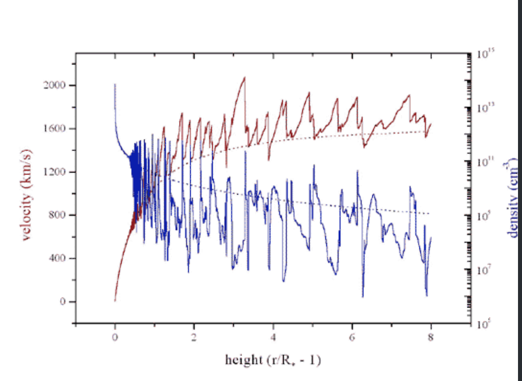


Velocity (km/s)

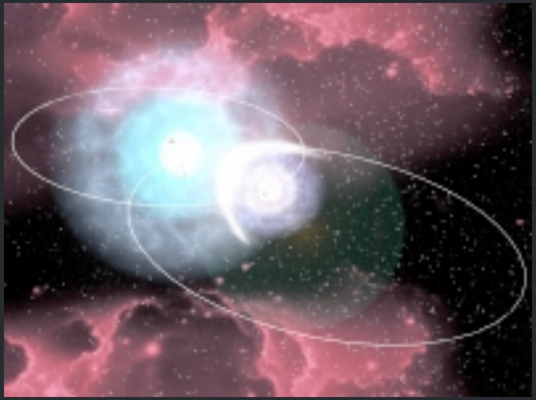
Prinja et al. 1992, ApJ, 390, 266

Three mechanisms for massive star x-ray emission

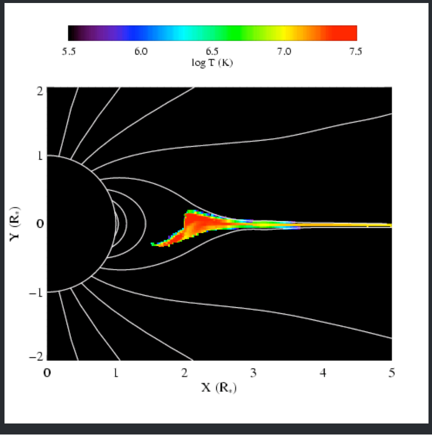
1. Instability driven shocks



2. Wind-wind interaction in close binaries

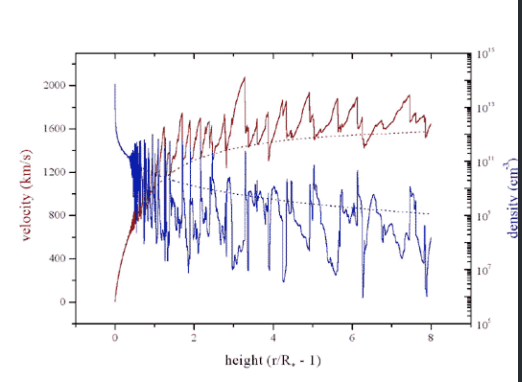


3. Magnetically channeled wind shocks



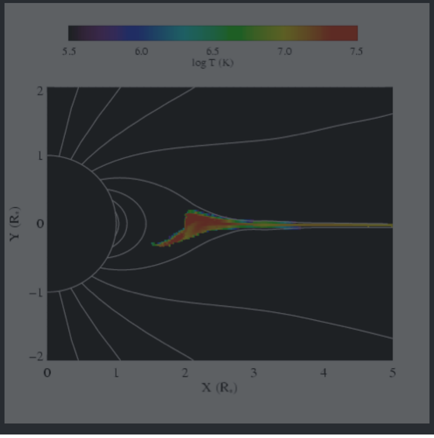
Three mechanisms for massive star x-ray emission

1. Instability driven shocks



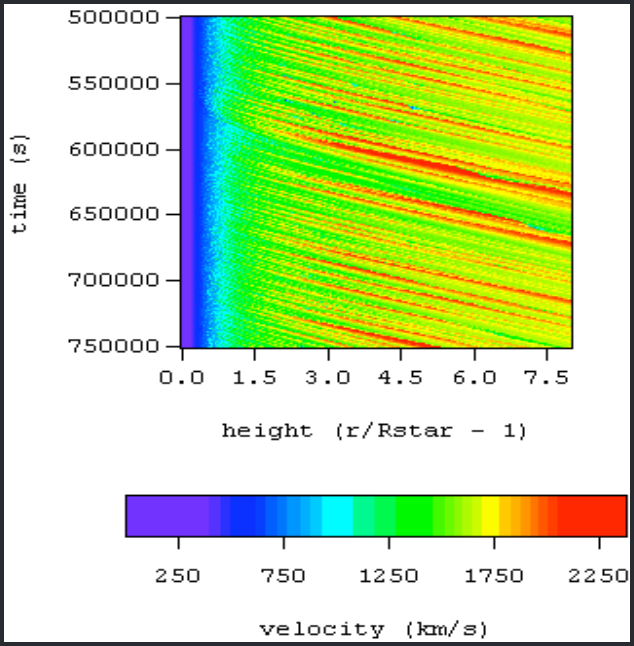
2. Wind-wind interaction in close binaries

3. Magnetically channeled wind shocks



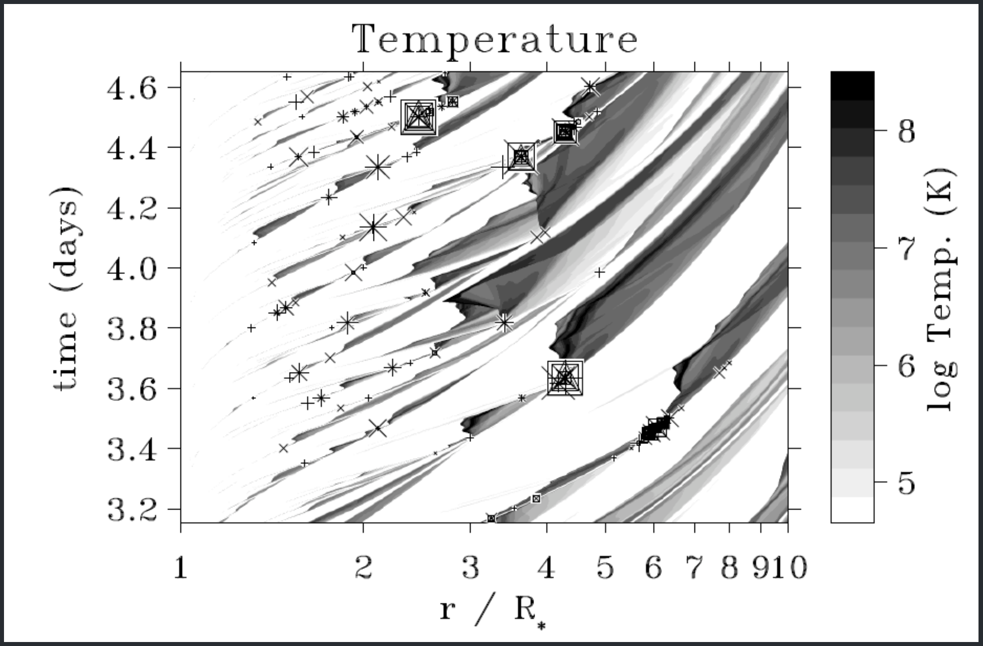
Radiation-driven winds are inherently unstable: shocks, X-rays

Self-excited instability



Owocki, Cooper, Cohen 1999

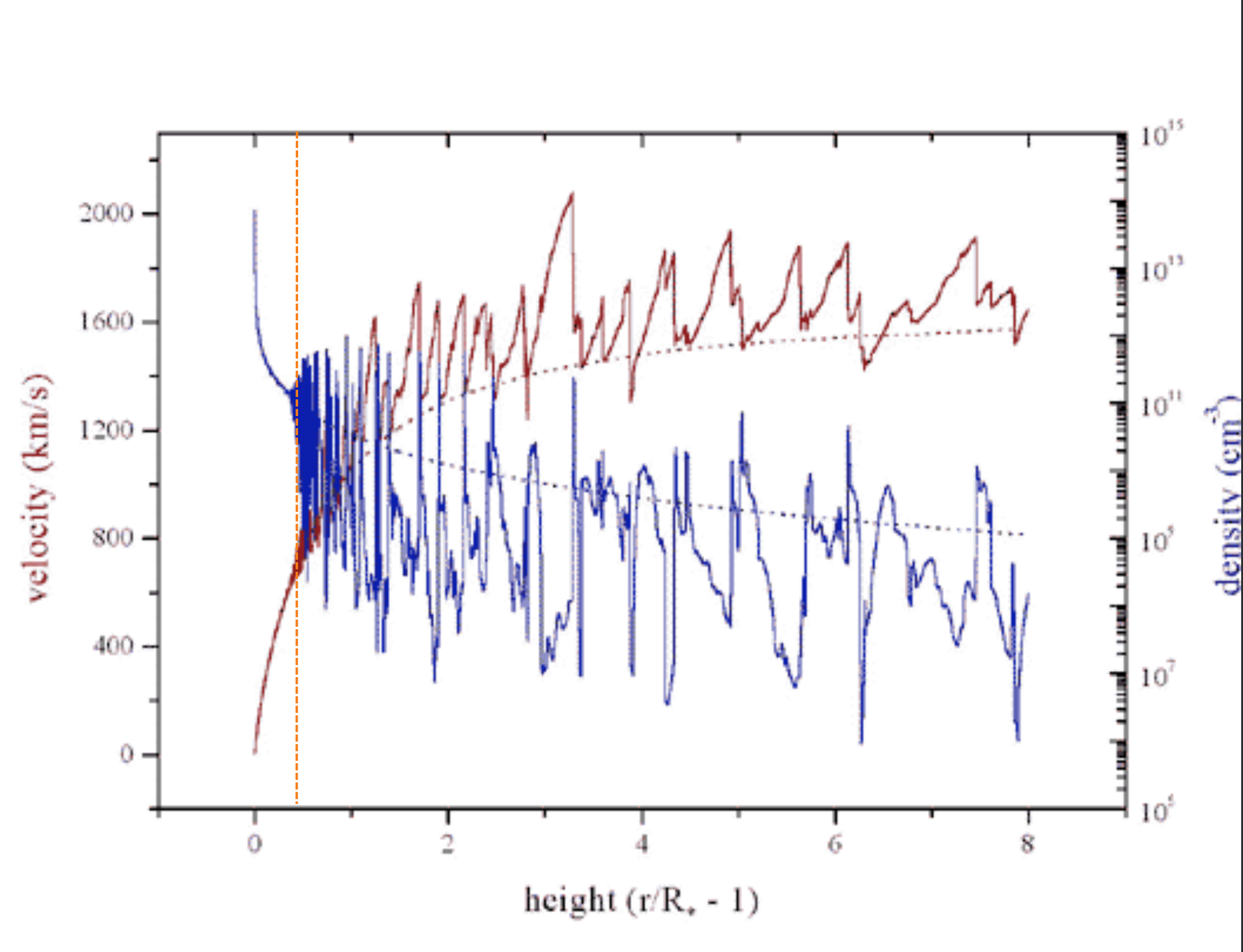
Excited by turbulence imposed at the wind base



Feldmeier,Puls, Pauldrach 1997

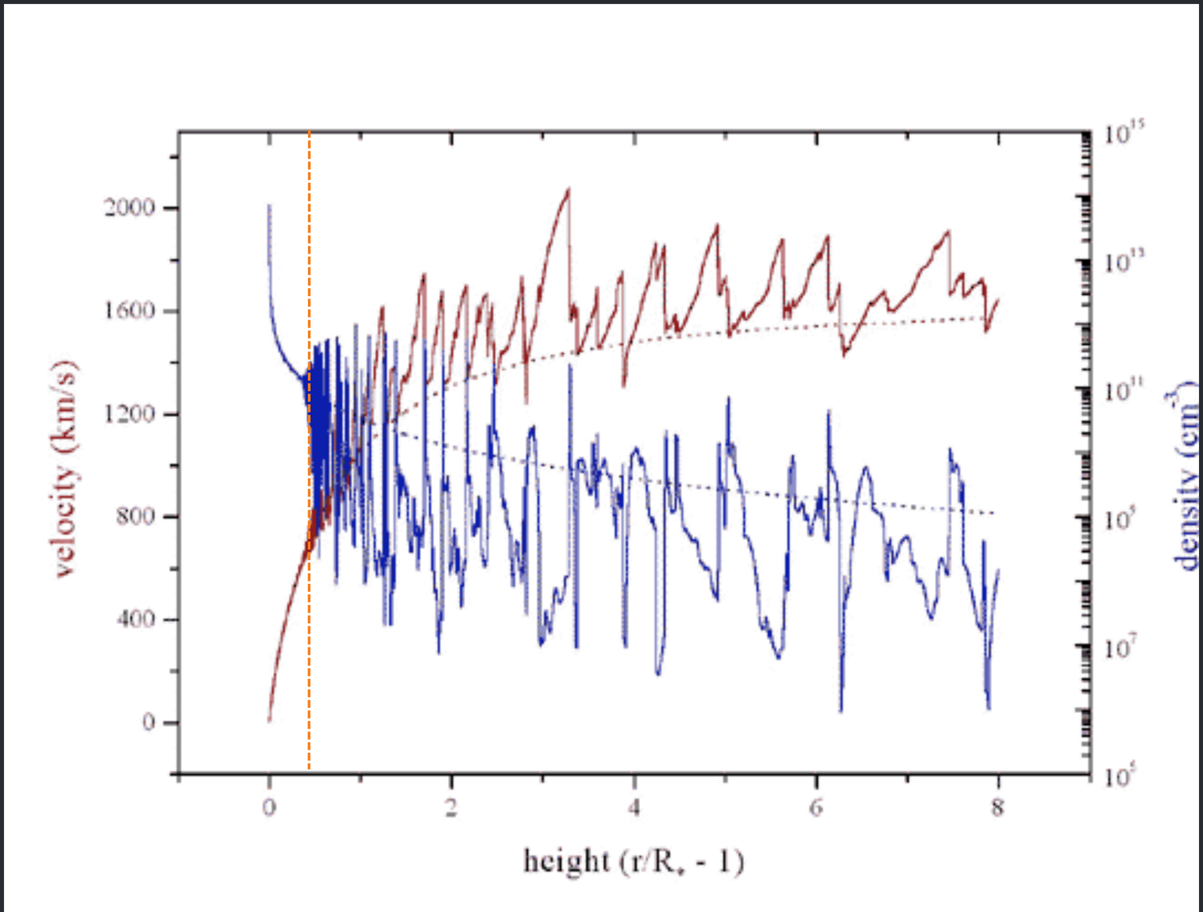
numerical simulations of the line-driving instability

Numerous shock structures, distributed above ~1.5 R_*



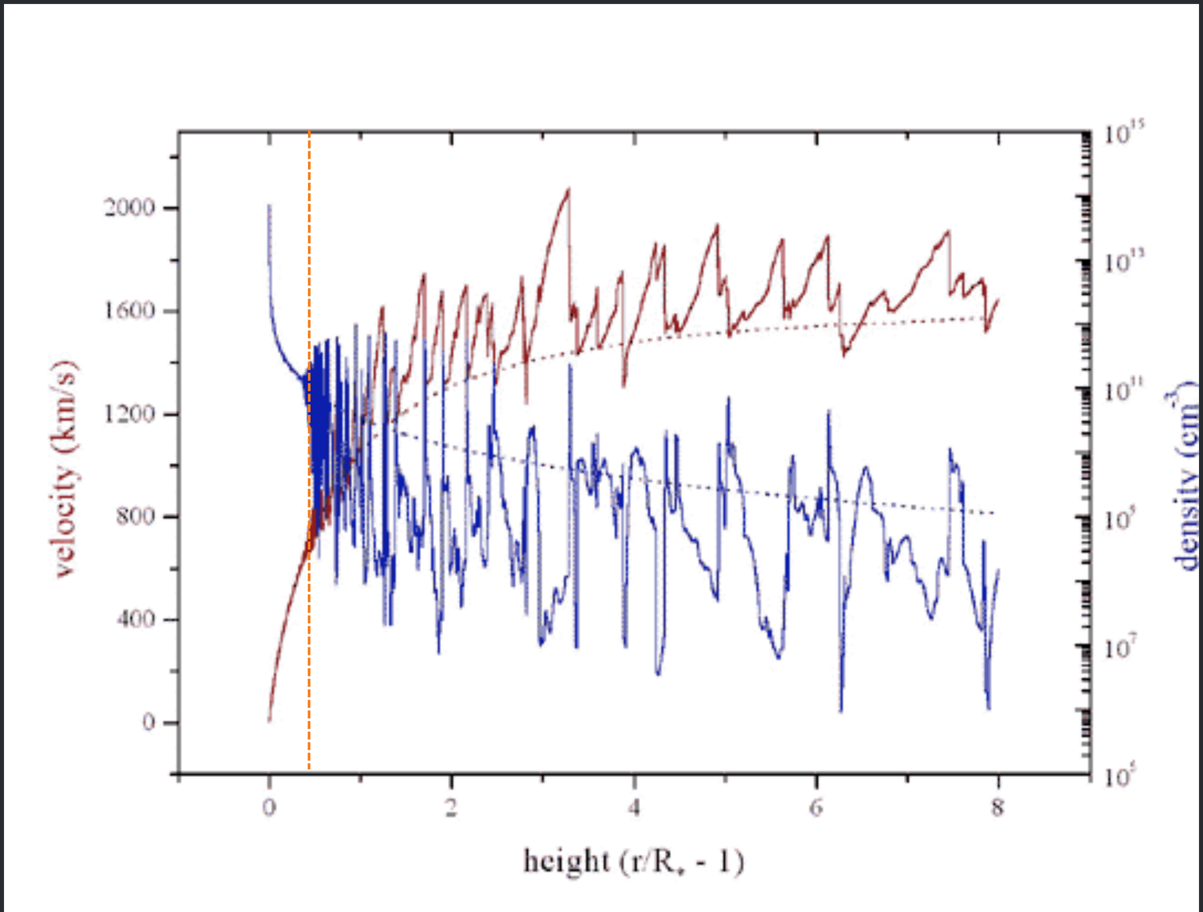
Shocked plasma is moving ~few 1000 km/s

Emission lines should be Doppler broadened



Only ~1% of the wind is shock heated at any given time

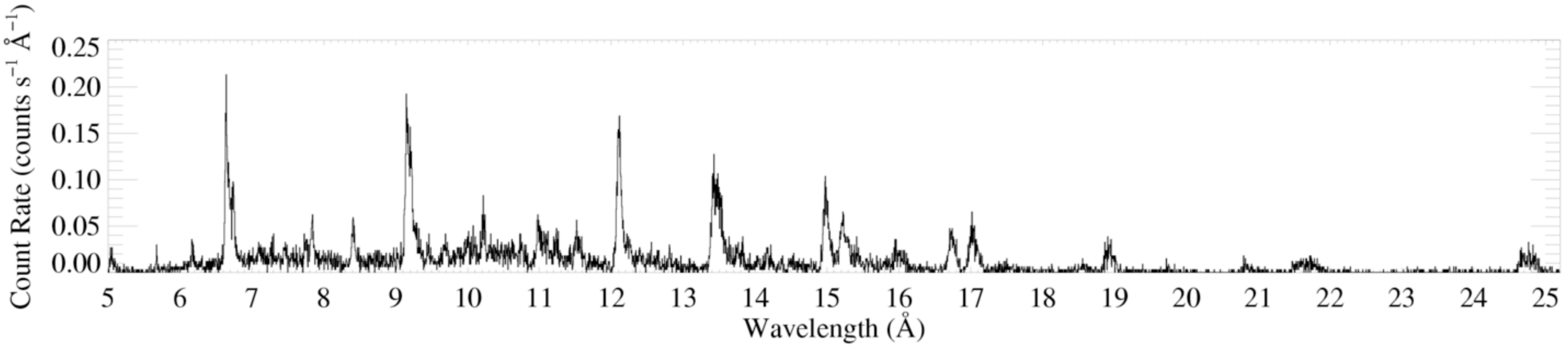
Bound-free absorption in the other
~99% of the wind

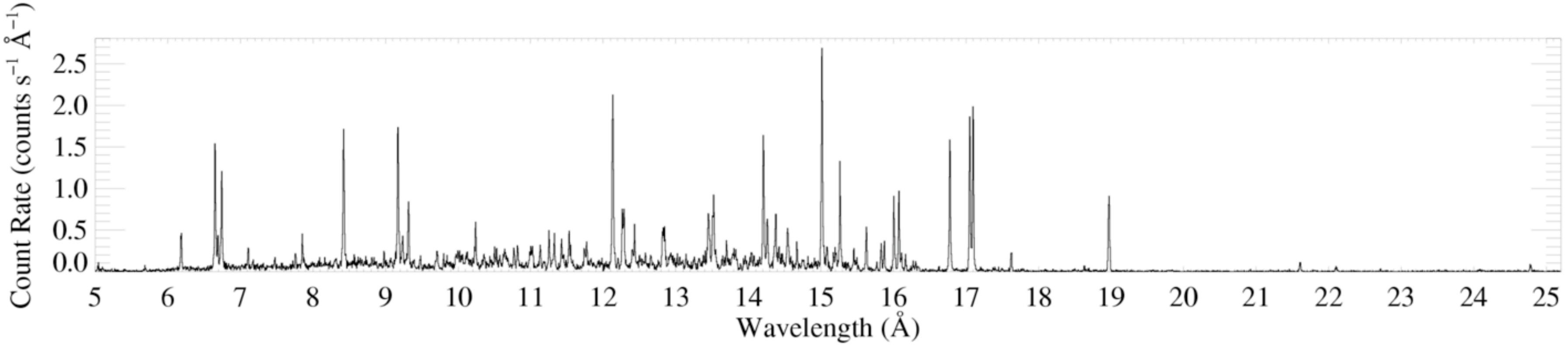


ζ Pup – as prototypical (and nearby at ~400 pc) – O star X-ray source

Chandra HETGS

ζ Pup (O4 If)





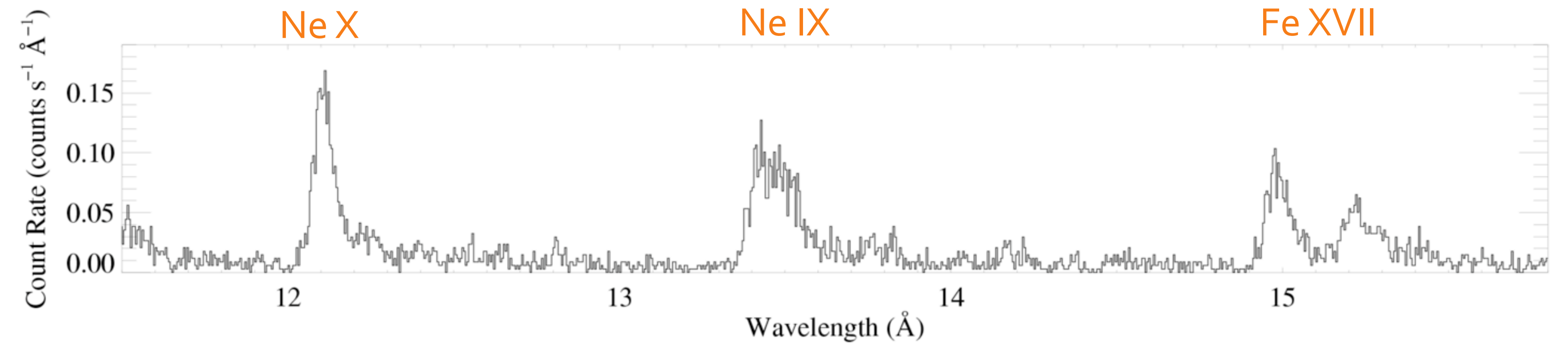
Capella (G5 III)

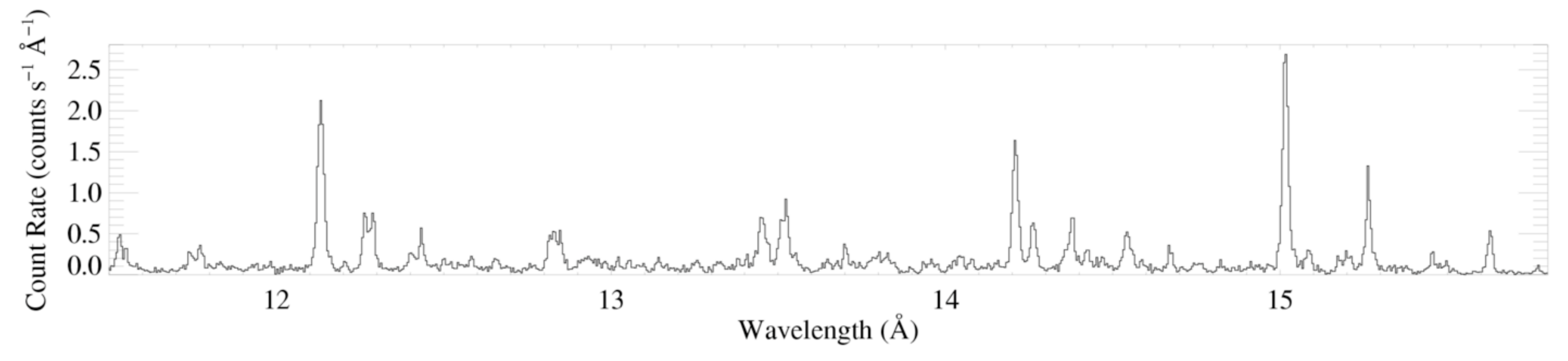
– coronal source

– for comparison

Morphology – line widths

ζ Pup (O4 If)

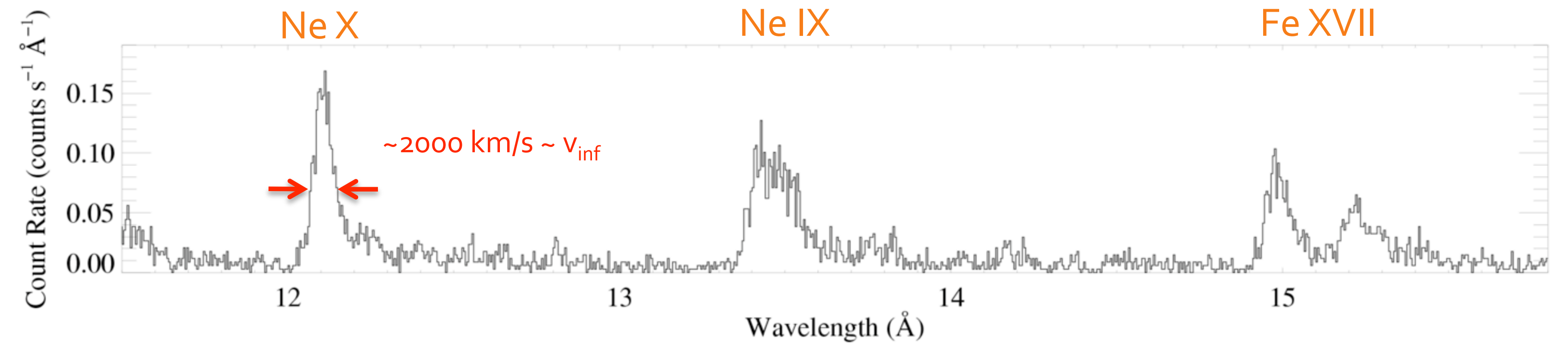




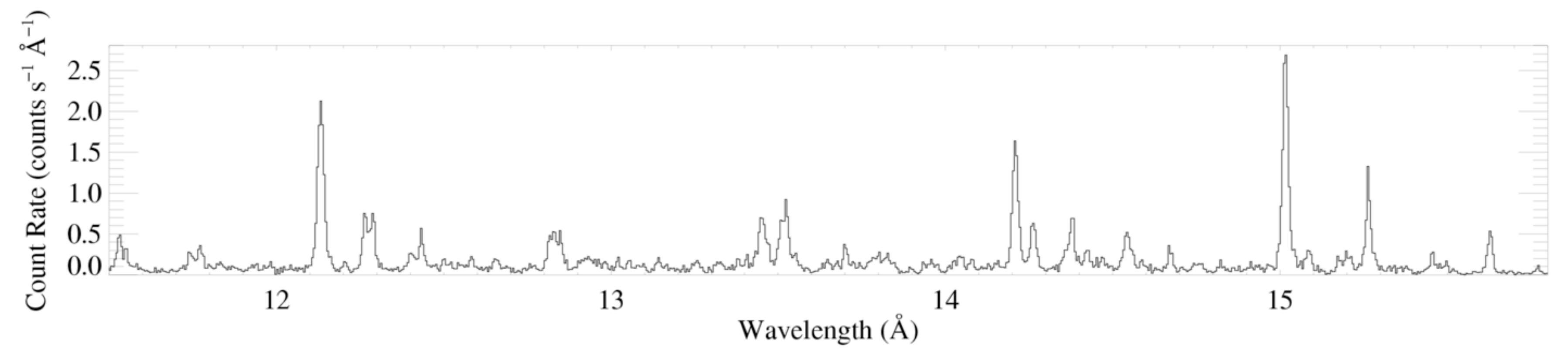
Capella (G5 III)
– coronal source
– for comparison

Morphology – line widths

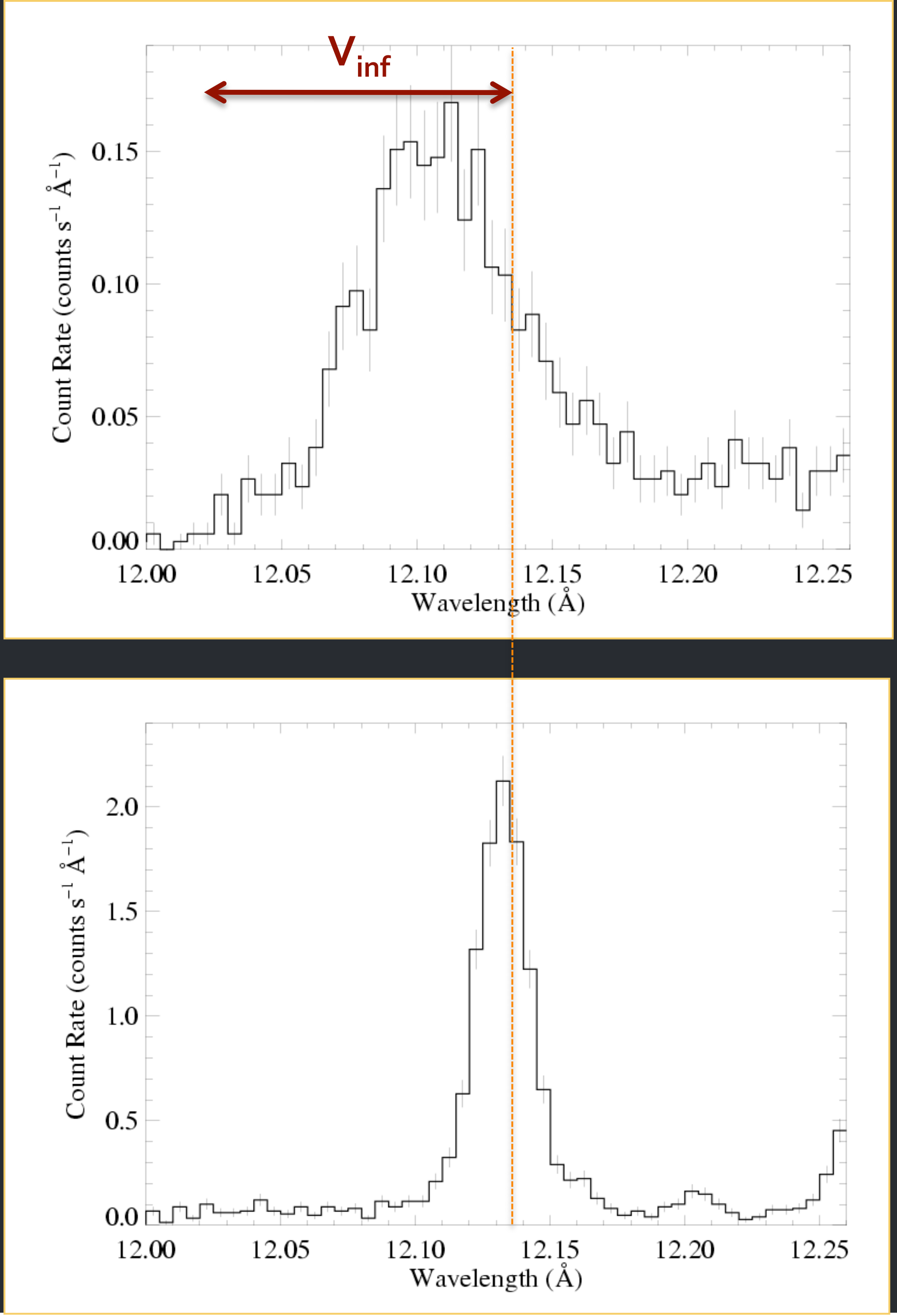
ζ Pup (O4 If)



~2000 km/s ~ v_{inf}

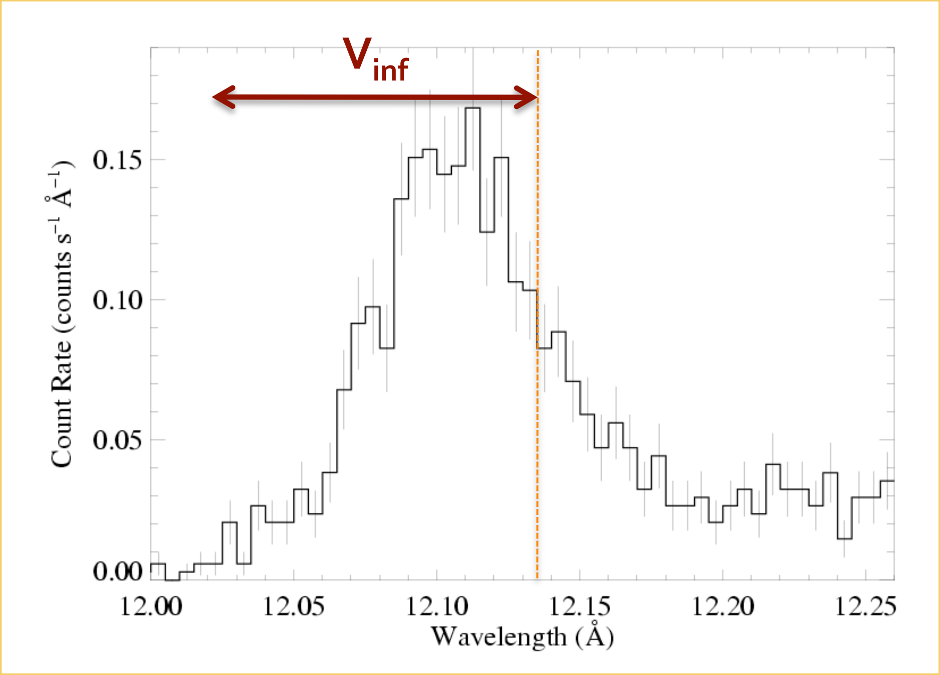


Capella (G5 III)
– coronal source
– for comparison



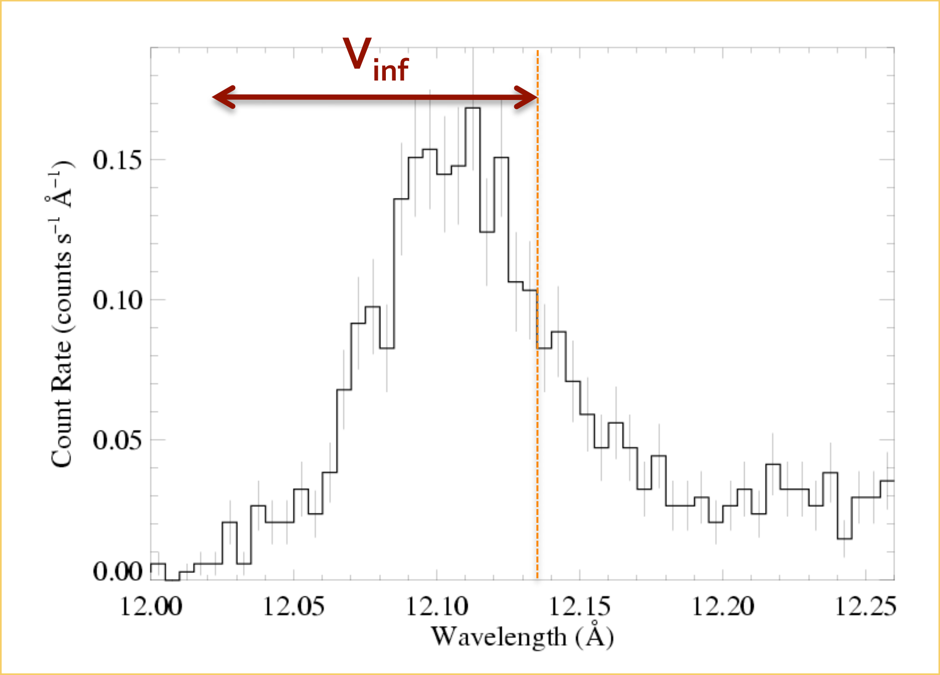
ζ Pup (O4 If)

Capella (G5 III) – *unresolved*



ζ Pup (O4 If)

Kinematics conclusions: consistent with X-rays arising in the stellar wind



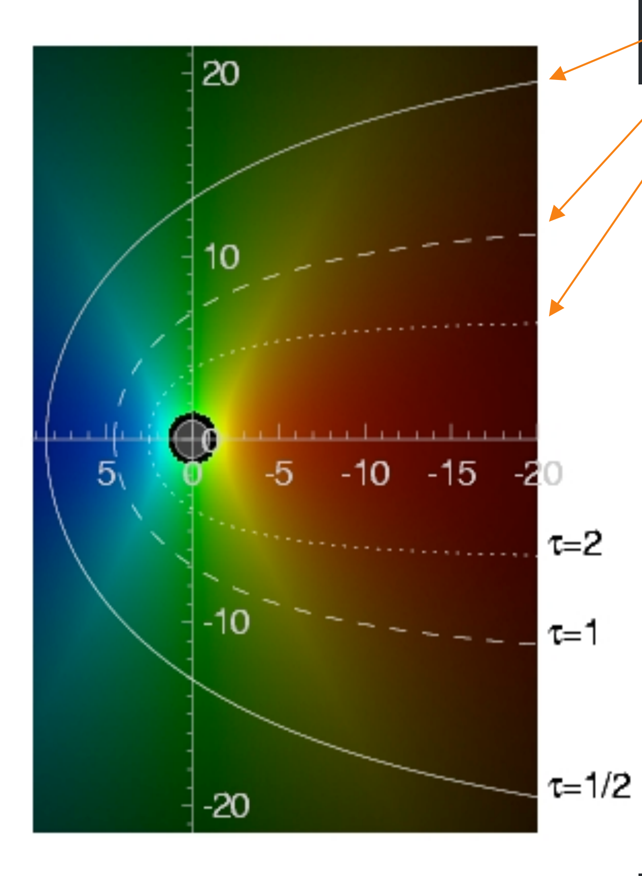
ζ Pup (O4 If)

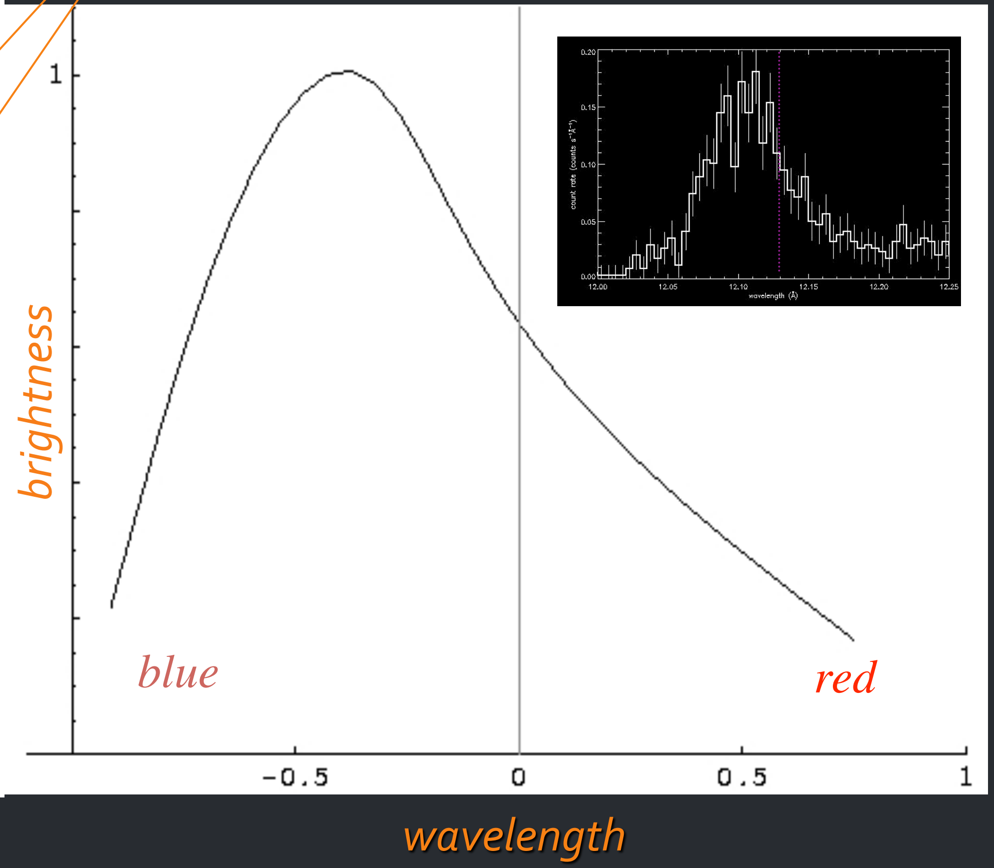
What about the distinctive profile shape?

blue shift

asymmetry

Contours of constant optical depth (observer is on the left)

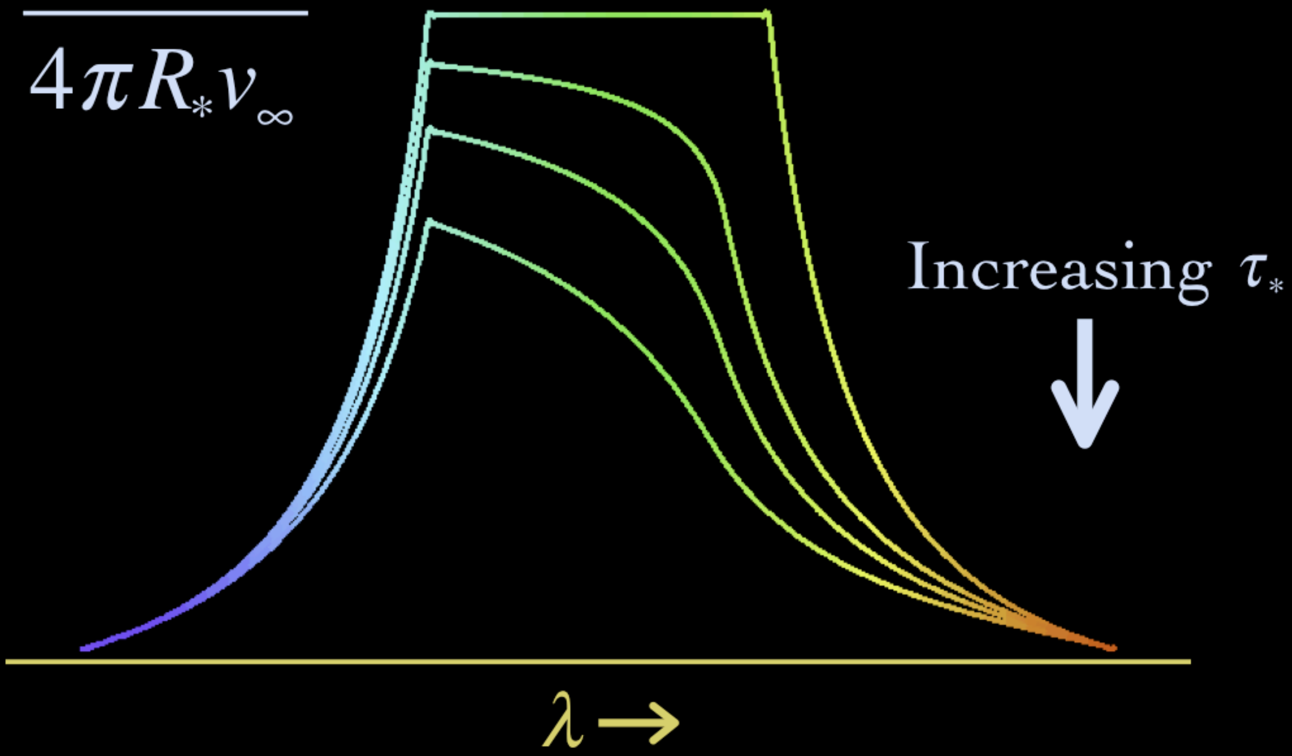




continuum absorption in the bulk wind preferentially absorbs red shifted photons from the far side of the wind

Wind Profile Model

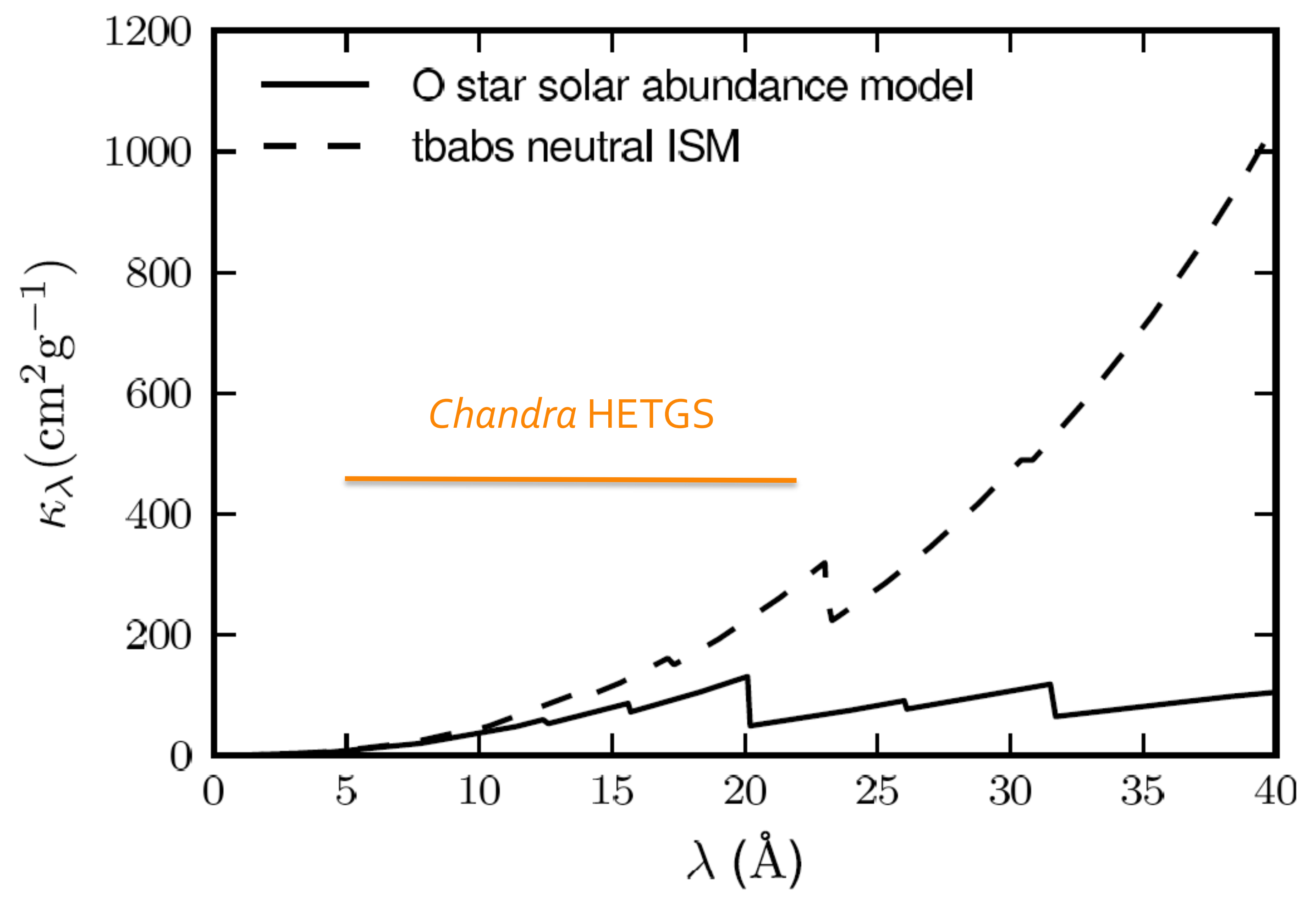
$$\tau_* = \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$



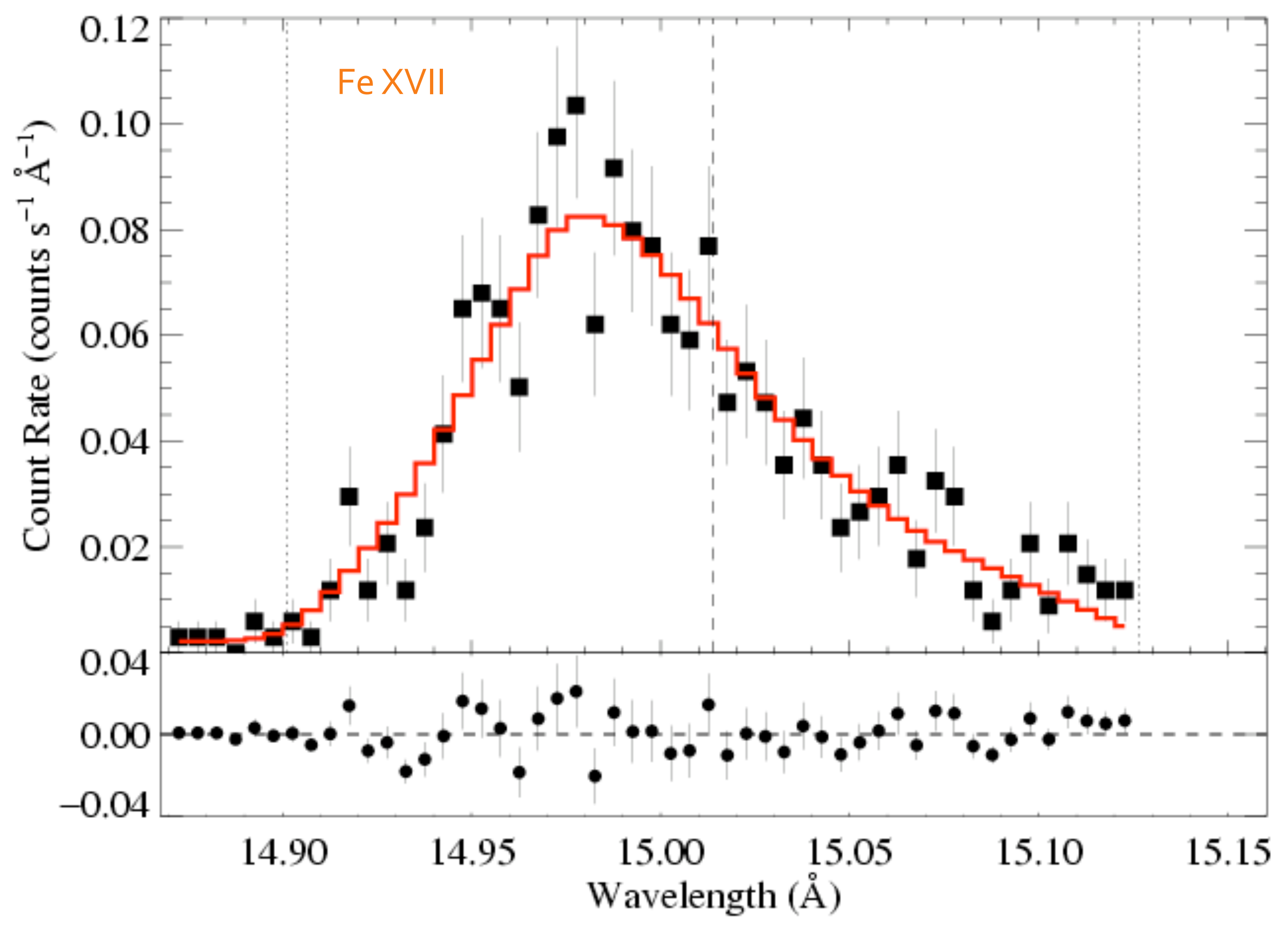
Wind opacity

due to bound-free transitions

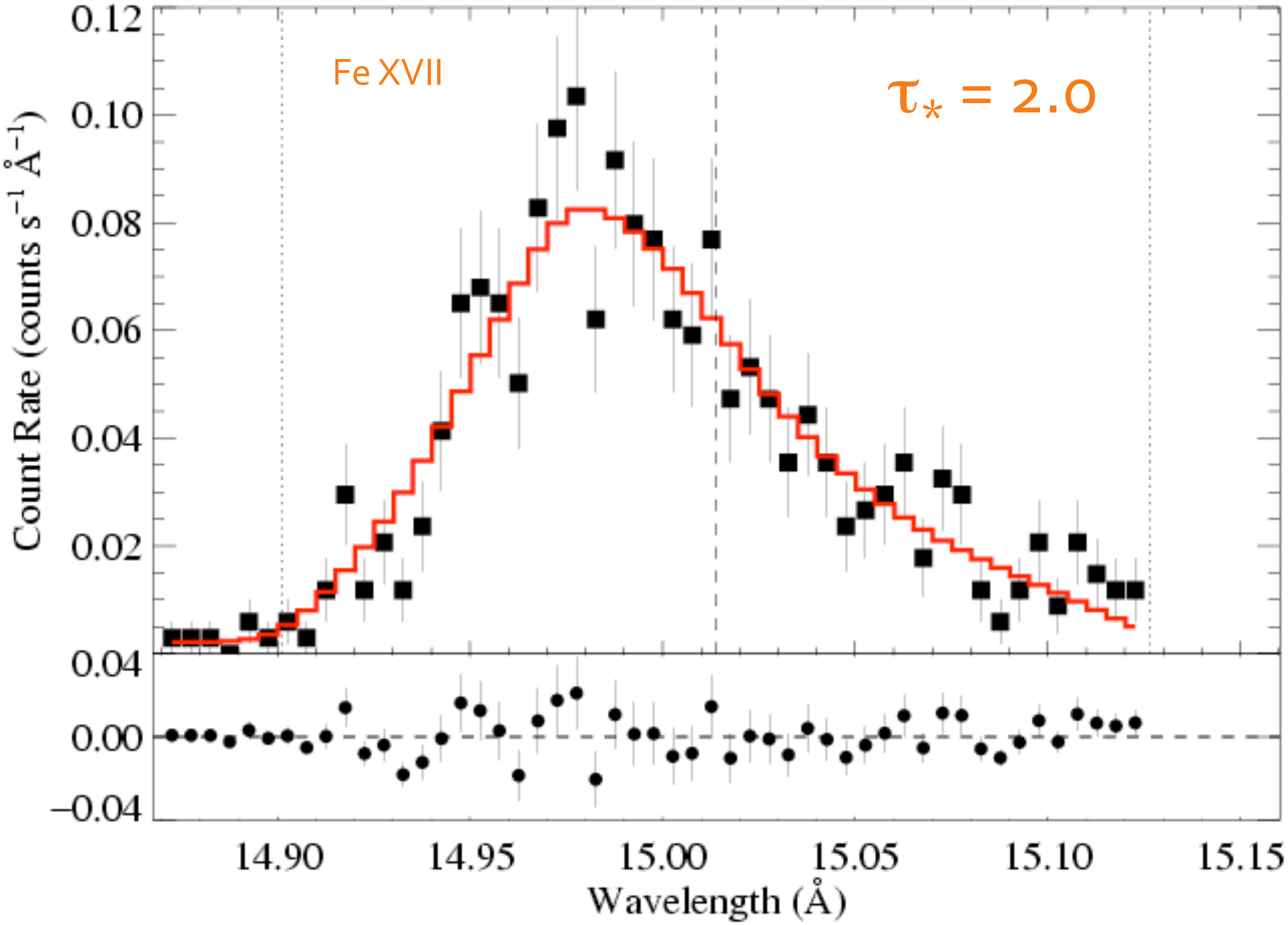
Opacity from partially ionized metals



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



And find a best-fit τ_*

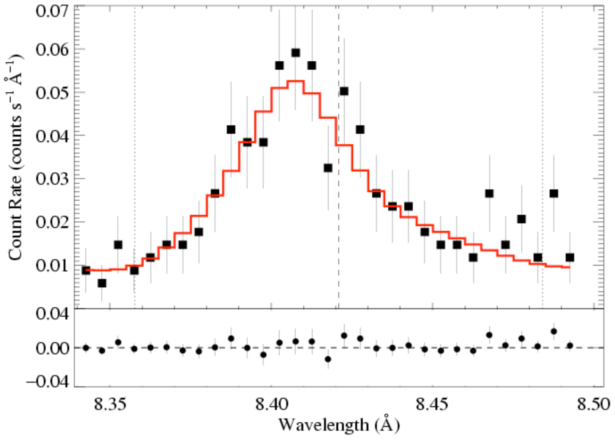


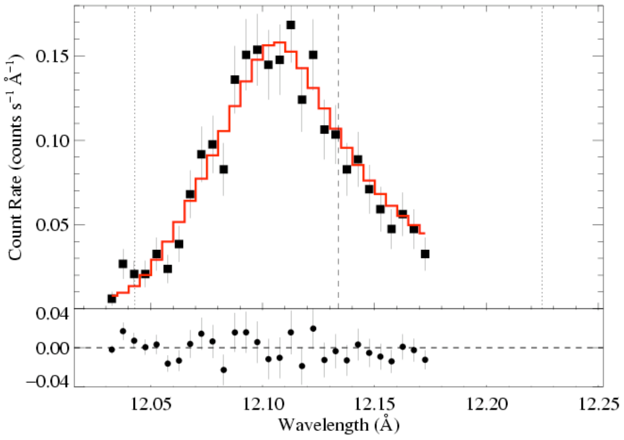
ζ Pup: three emission lines

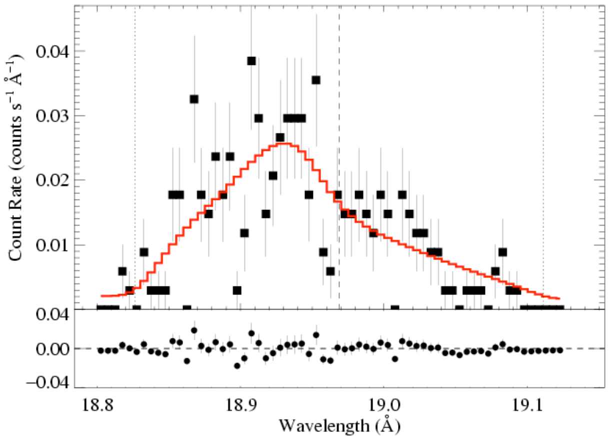
Mg Lyα: 8.42 Å

Ne Lyα: 12.13 Å

O Lyα: 18.97 Å







$\tau_* = 1$

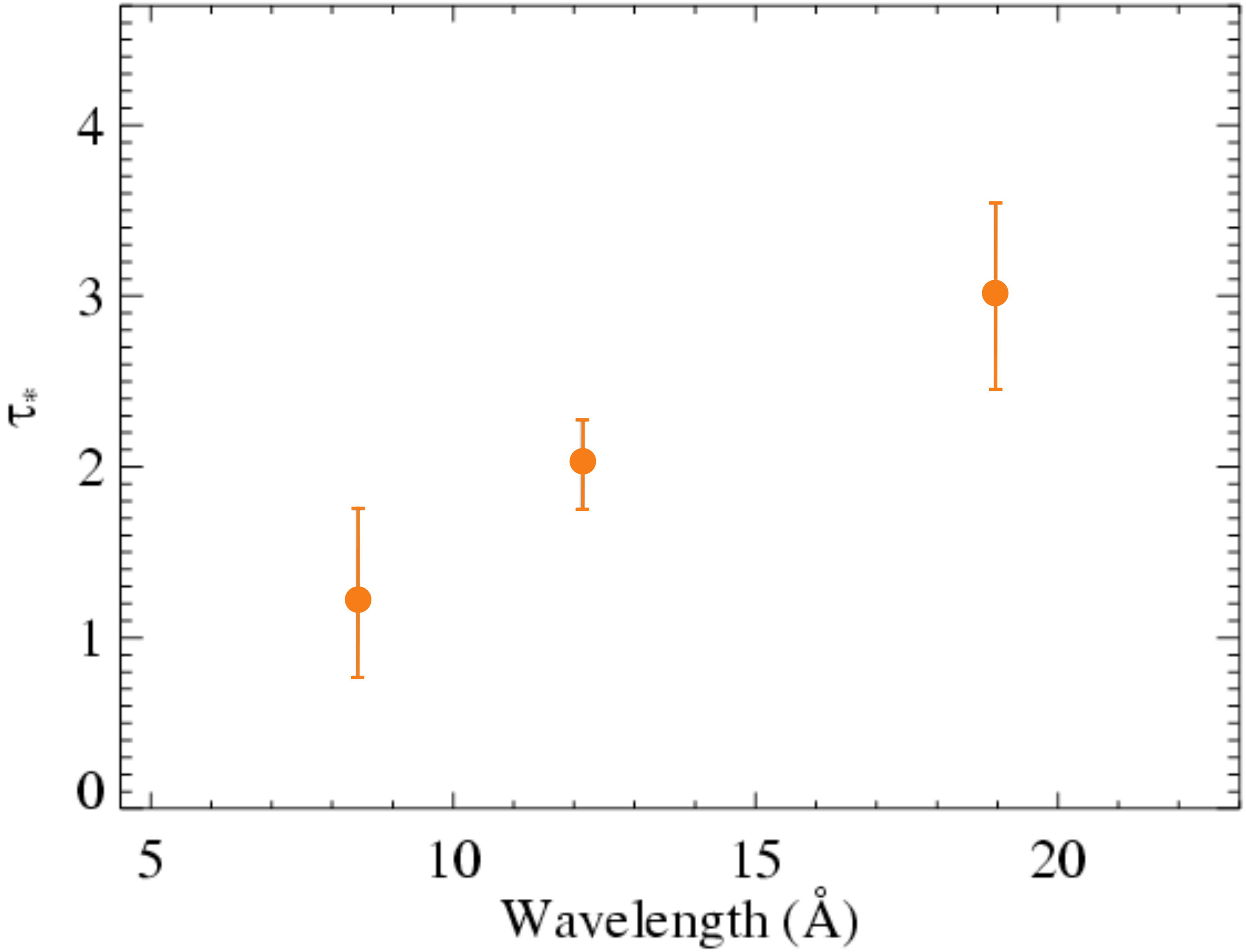
$\tau_* = 2$

$\tau_* = 3$

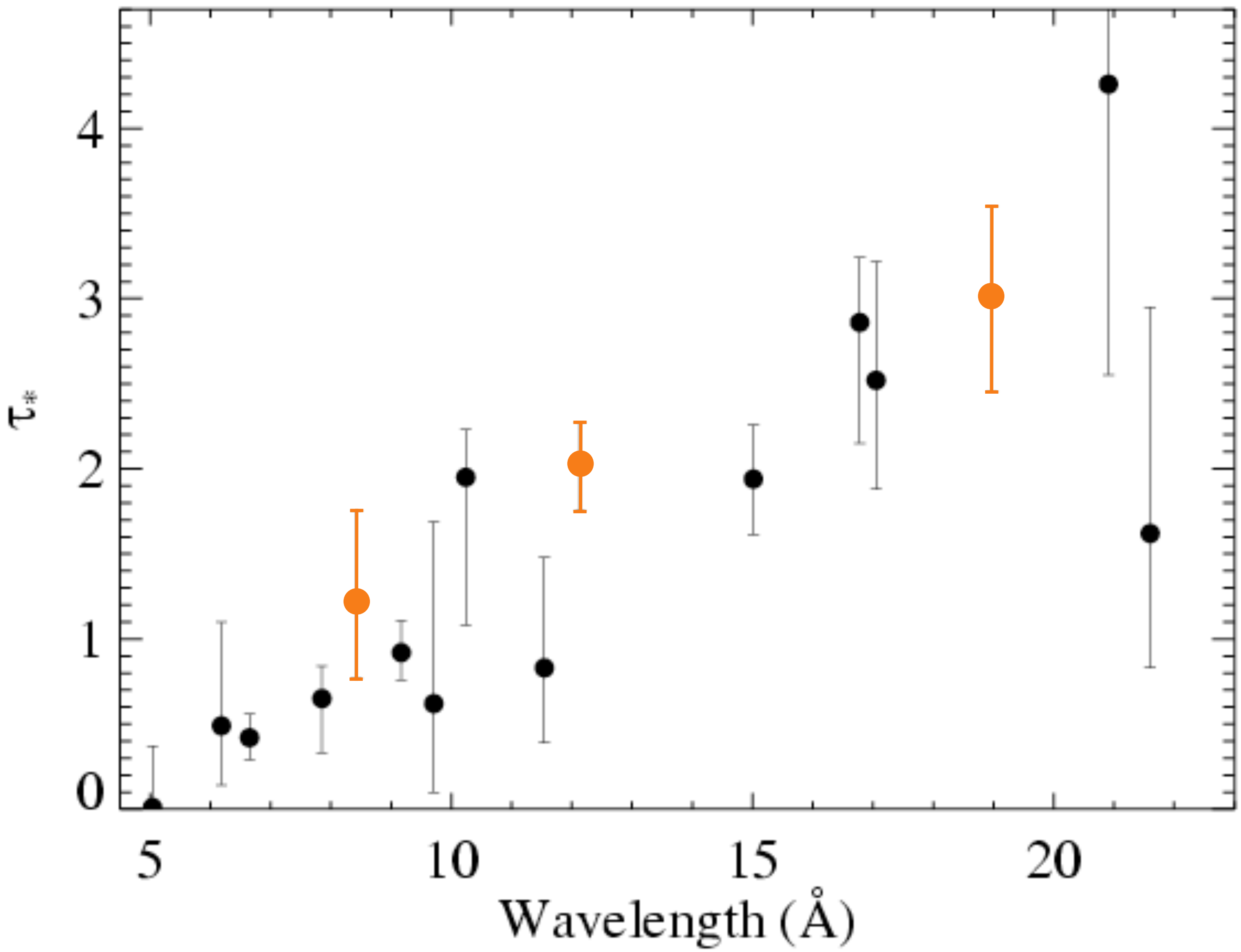
Recall:

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

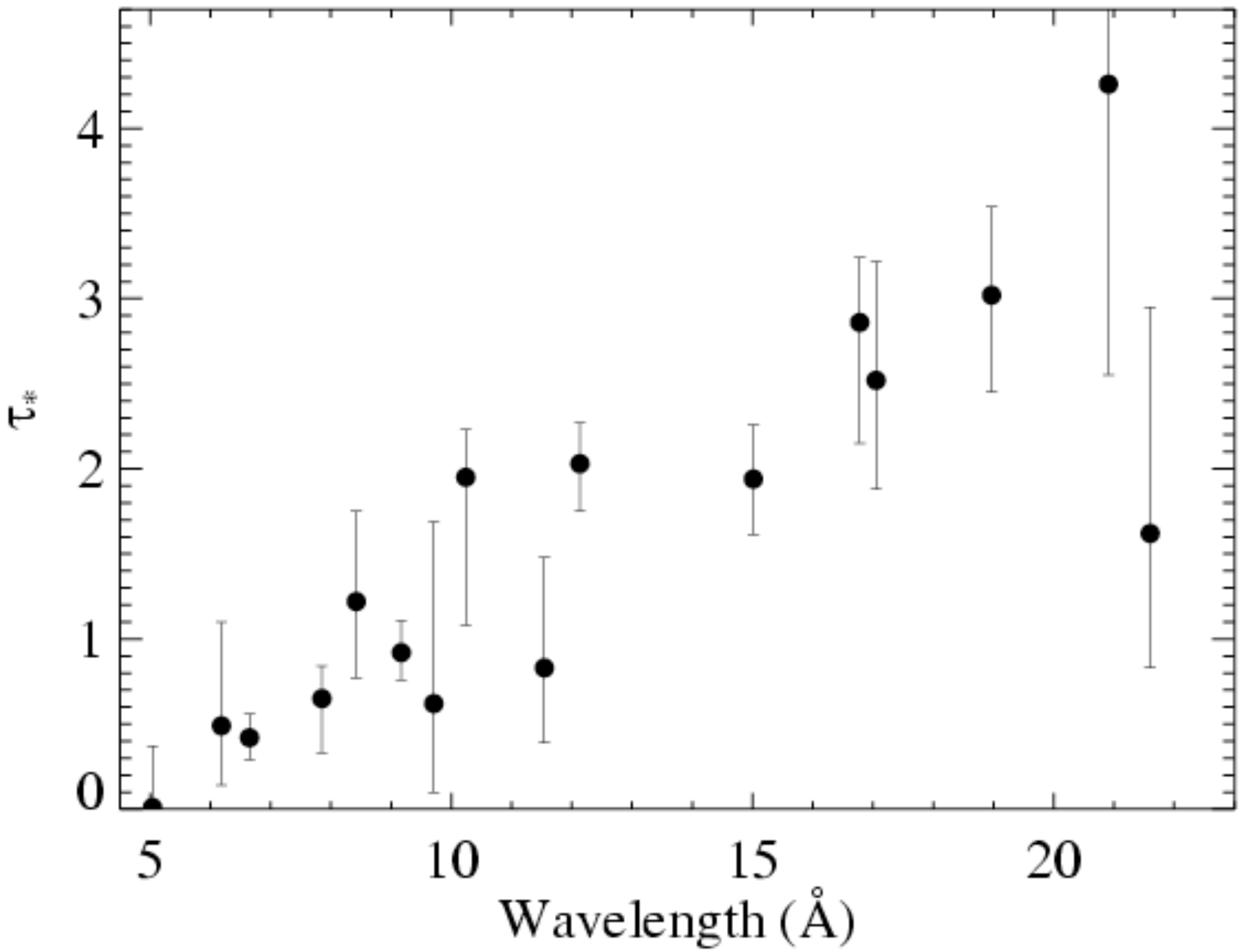
Results from the 3 line fits shown previously



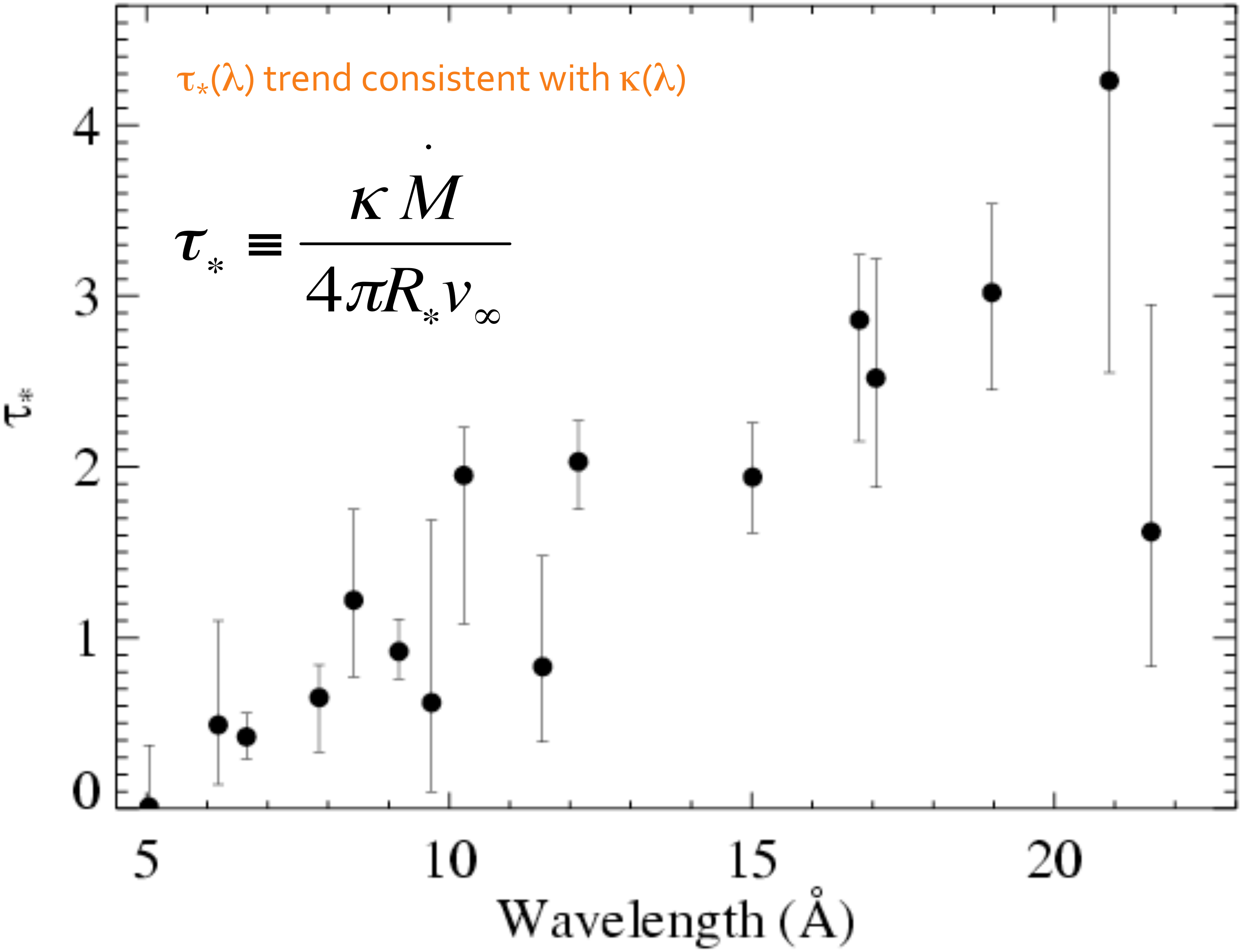
Fits to 16 lines in the *Chandra* spectrum of ζ Pup



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



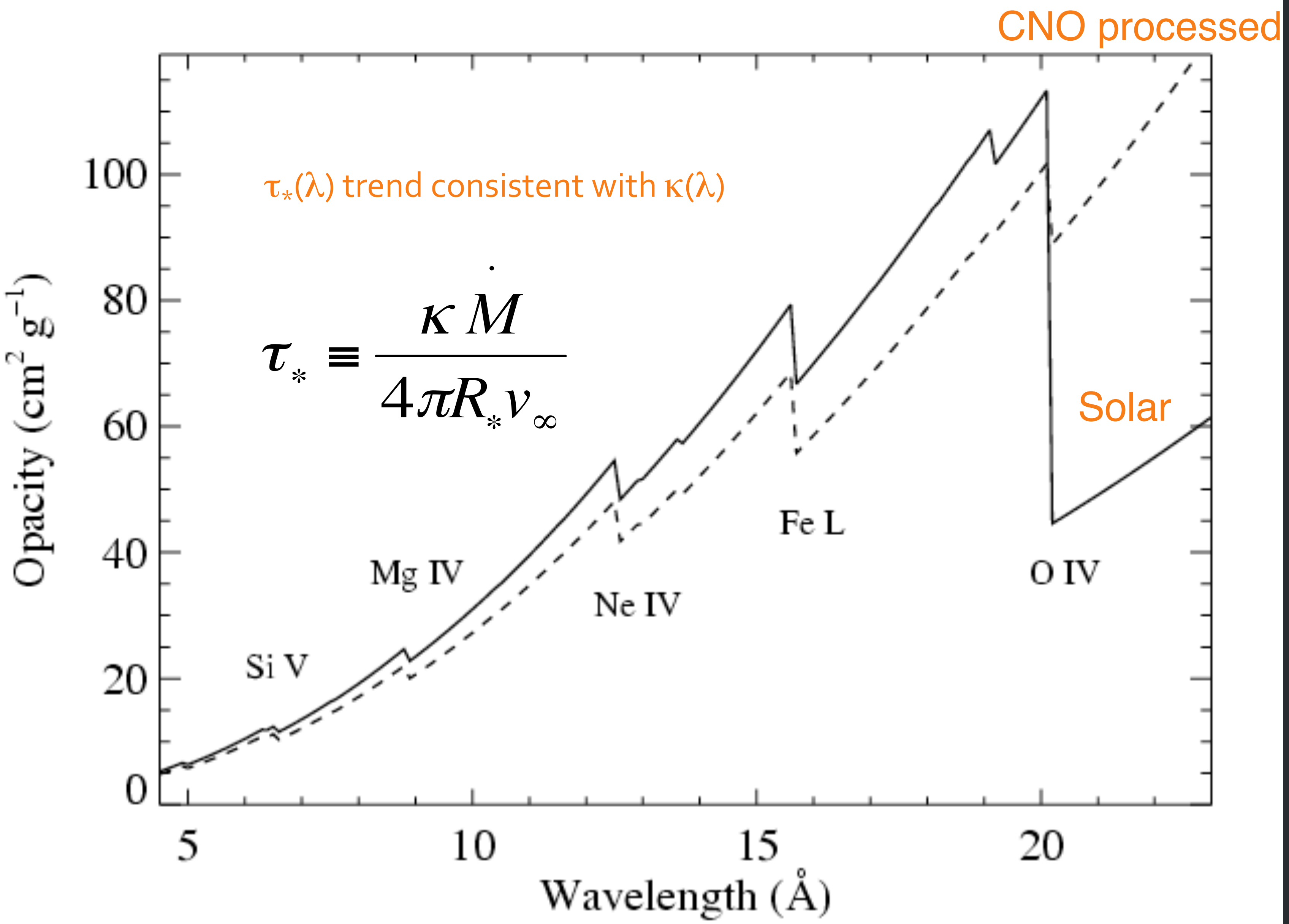
Fits to 16 lines in the *Chandra* spectrum of ζ Pup



$\tau_*(\lambda)$ trend consistent with $\kappa(\lambda)$

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

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

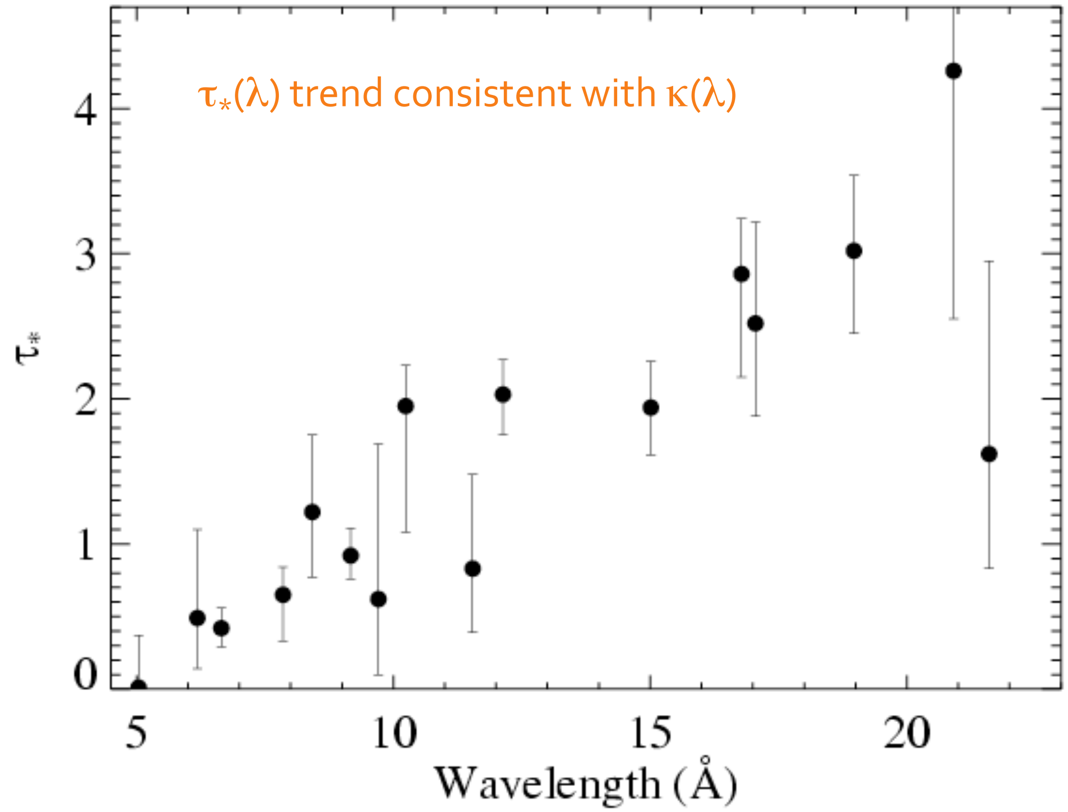


$\tau_*(\lambda)$ trend consistent with $\kappa(\lambda)$

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

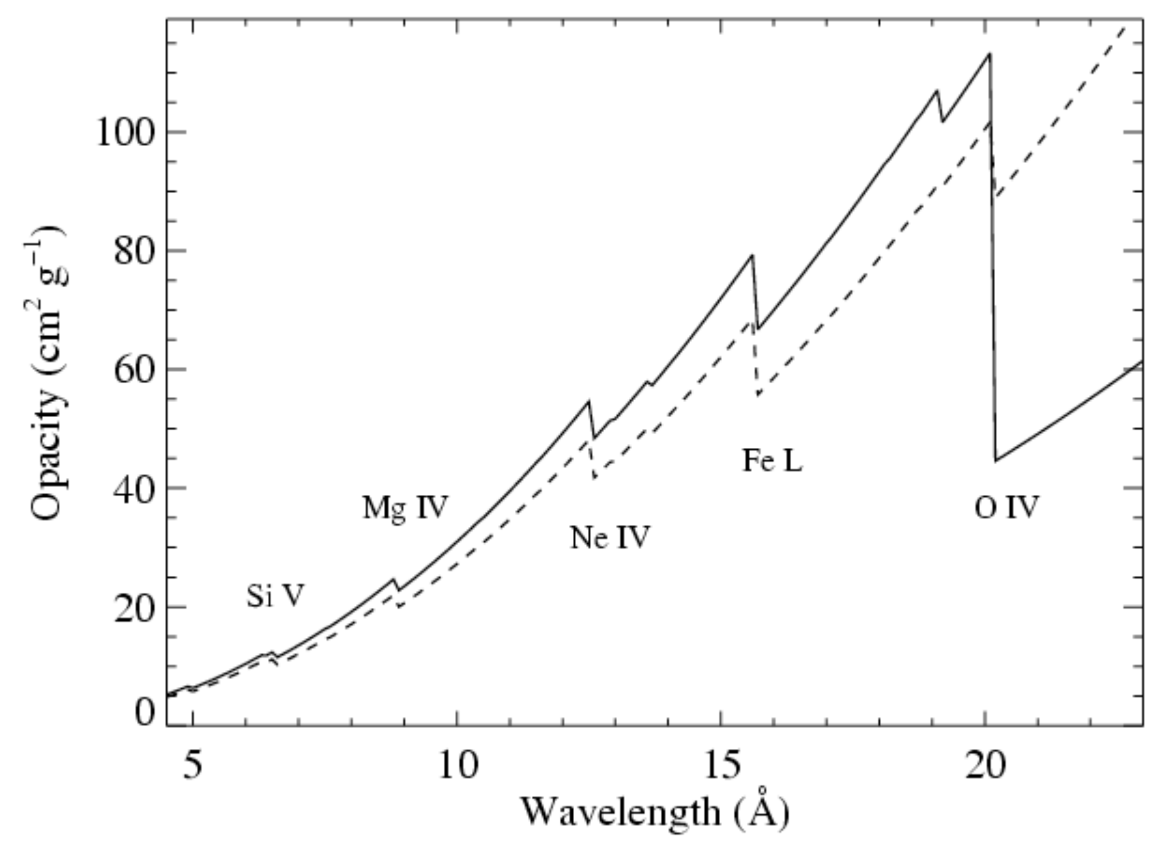
$$\tau_* \equiv \frac{\kappa \dot{M}}{4\pi R_* v_\infty}$$

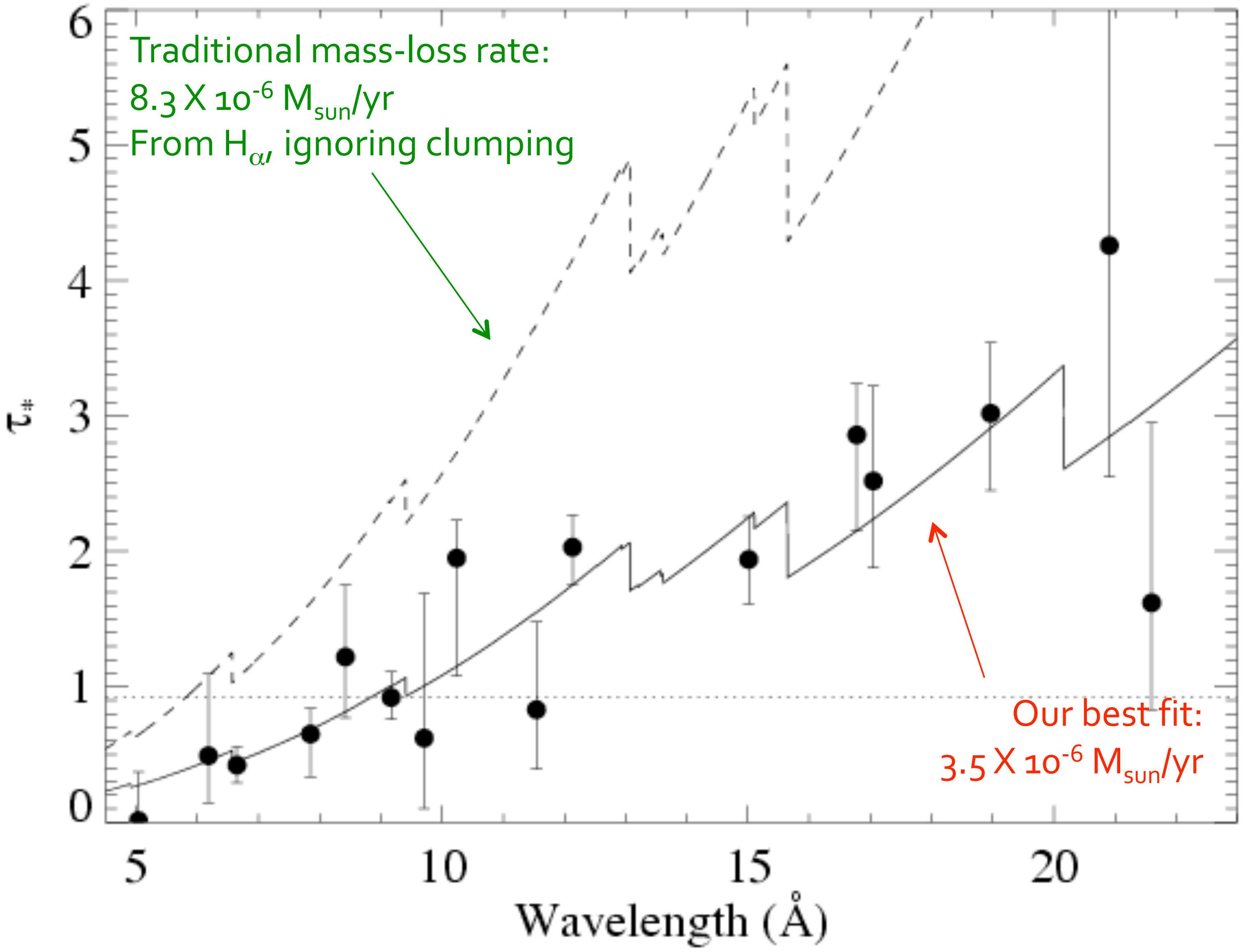
$\dot{M}$ becomes the free parameter of the fit to the $\tau_*(\lambda)$ trend



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

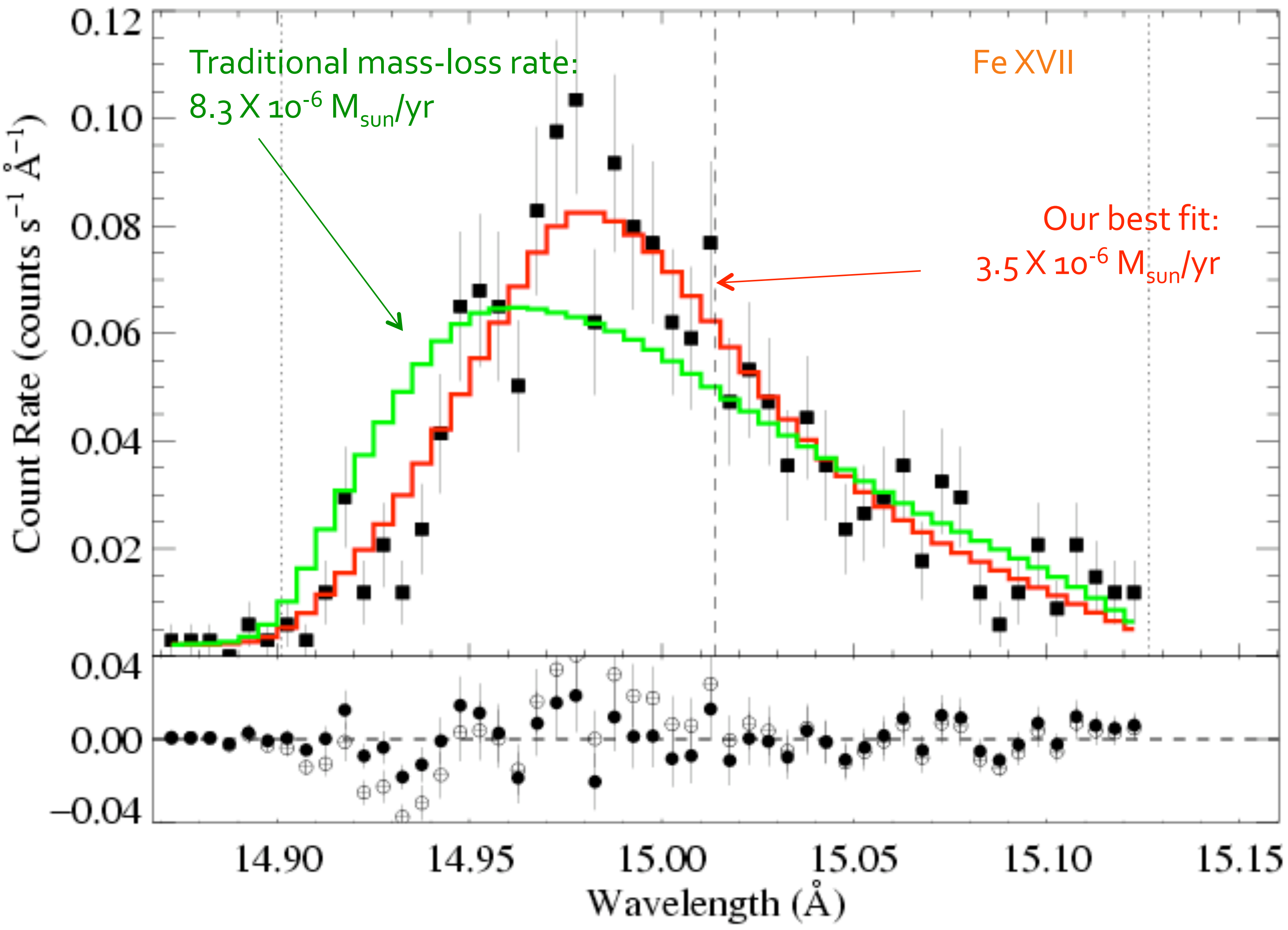
$\dot{M}$ becomes the free parameter of the fit to the $\tau_*(\lambda)$ trend





Traditional mass-loss rate:
$8.3 \times 10^{-6}\ M_{sun}/yr$
From H_α, ignoring clumping

Our best fit:
$3.5 \times 10^{-6}\ M_{sun}/yr$



Traditional mass-loss rate:
$8.3\ \mathrm{X}\ 10^{-6}\ M_{sun}$/yr

Fe XVII

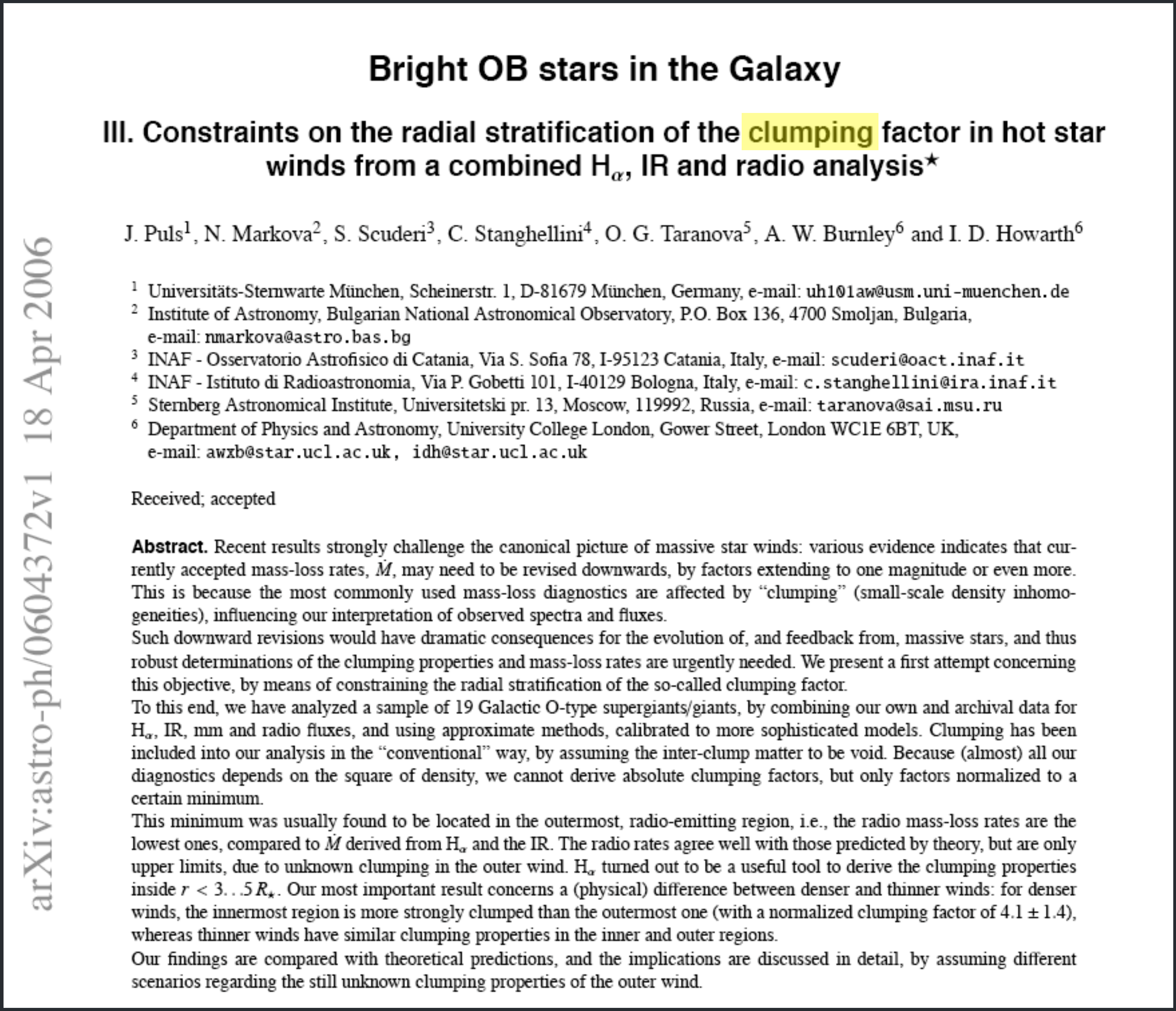
Our best fit:
$3.5\ \mathrm{X}\ 10^{-6}\ M_{sun}$/yr

Mass-loss rate conclusions

The trend of τ_* value with λ is *consistent* with :

- Mass-loss rate of 3.5×10^{-6} $M_{sun}/_{yr}$
- Factor of ~3 **reduction** w.r.t. unclumped H-alpha mass-loss rate diagnostics

ζ Pup mass-loss rate < $4.2 \times 10^{-6}\ M_{sun}$/yr



arXiv:astro-ph/0604372v1 18 Apr 2006

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, D-81679 München, Germany, e-mail: `uh101aw@usm.uni-muenchen.de`
[2] Institute of Astronomy, Bulgarian National Astronomical Observatory, P.O. Box 136, 4700 Smoljan, Bulgaria,
e-mail: `nmarkova@astro.bas.bg`
[3] INAF - Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 Catania, Italy, e-mail: `scuderi@oact.inaf.it`
[4] INAF - Istituto di Radioastronomia, Via P. Gobetti 101, I-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@star.ucl.ac.uk, idh@star.ucl.ac.uk`

Received; accepted

Abstract. 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.

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.

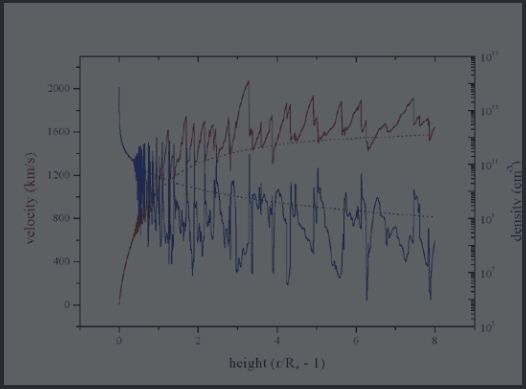
To this end, we have analyzed a sample of 19 Galactic O-type supergiants/giants, by combining our own and archival data for H_α, IR, mm and radio fluxes, and using approximate methods, calibrated to more sophisticated models. Clumping has been included into our analysis in the "conventional" way, by 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.

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 $r < 3 \ldots 5\,R_\star$. 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.

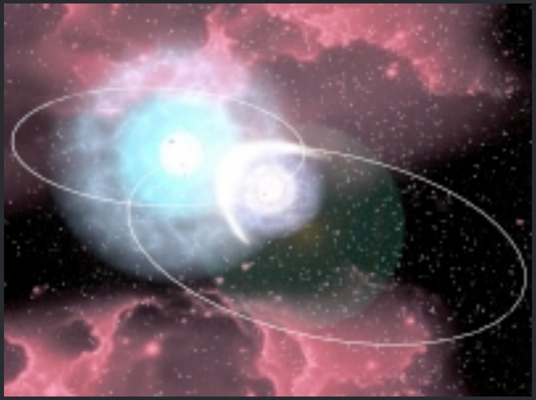
Our findings are compared with theoretical predictions, and the implications are discussed in detail, by assuming different scenarios regarding the still unknown clumping properties of the outer wind.

Three mechanisms for massive star x-ray emission

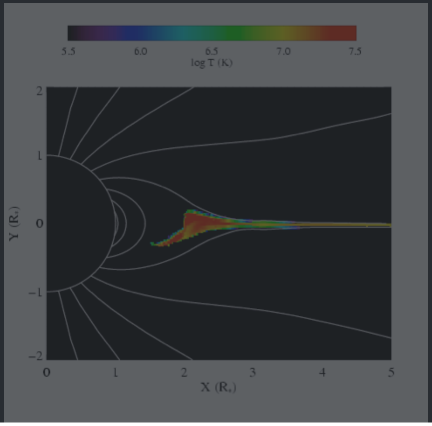
1. Instability driven shocks



2. Wind-wind interaction in close binaries



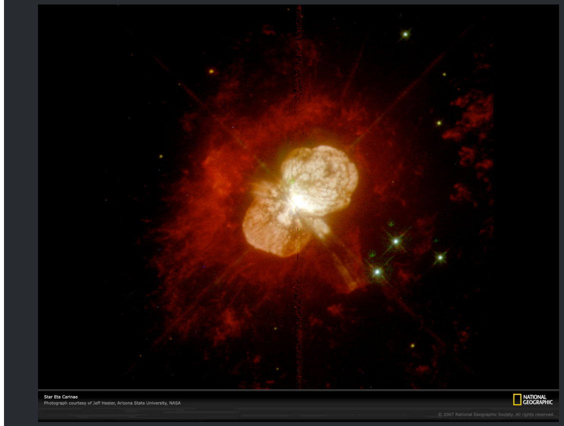
3. Magnetically channeled wind shocks

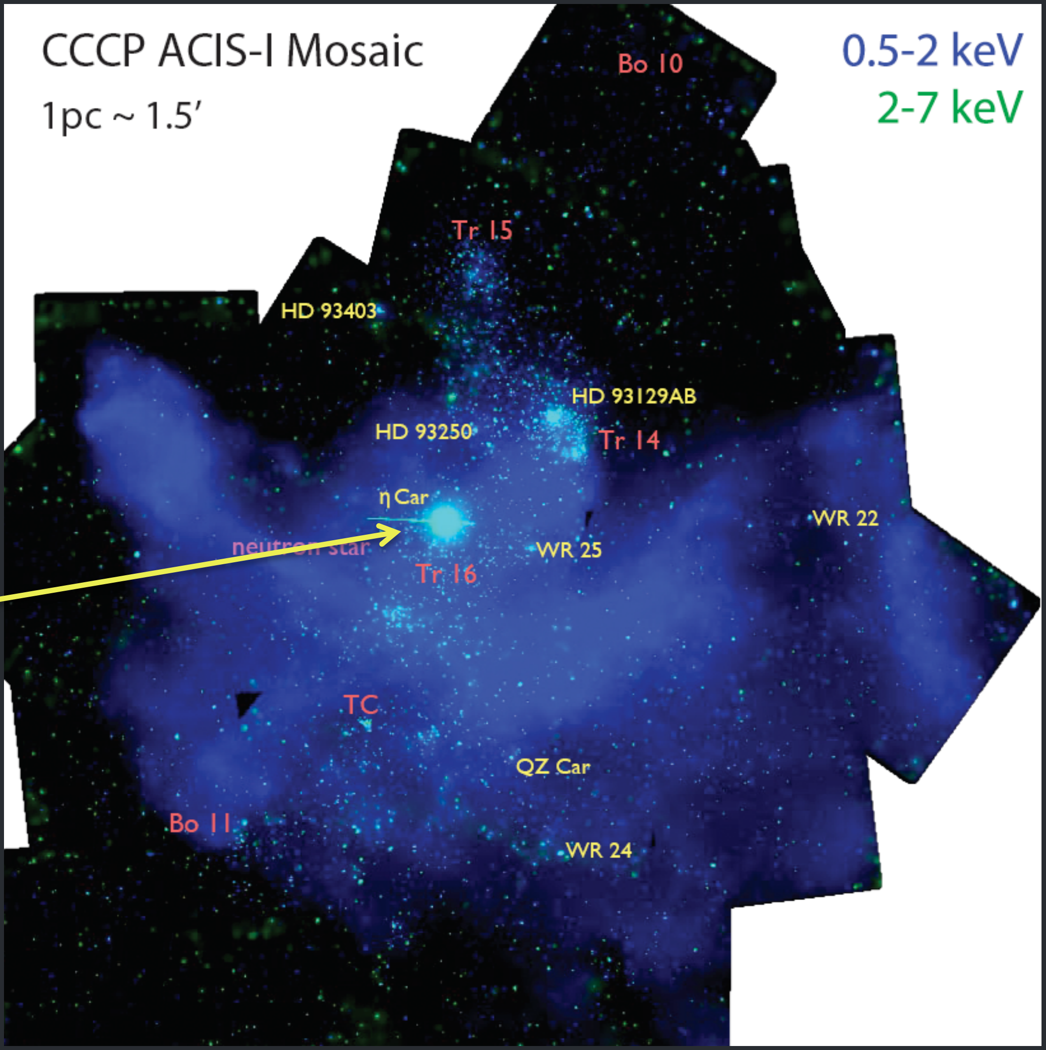


The embedded wind shock (EWS) mechanism should occur in all O stars

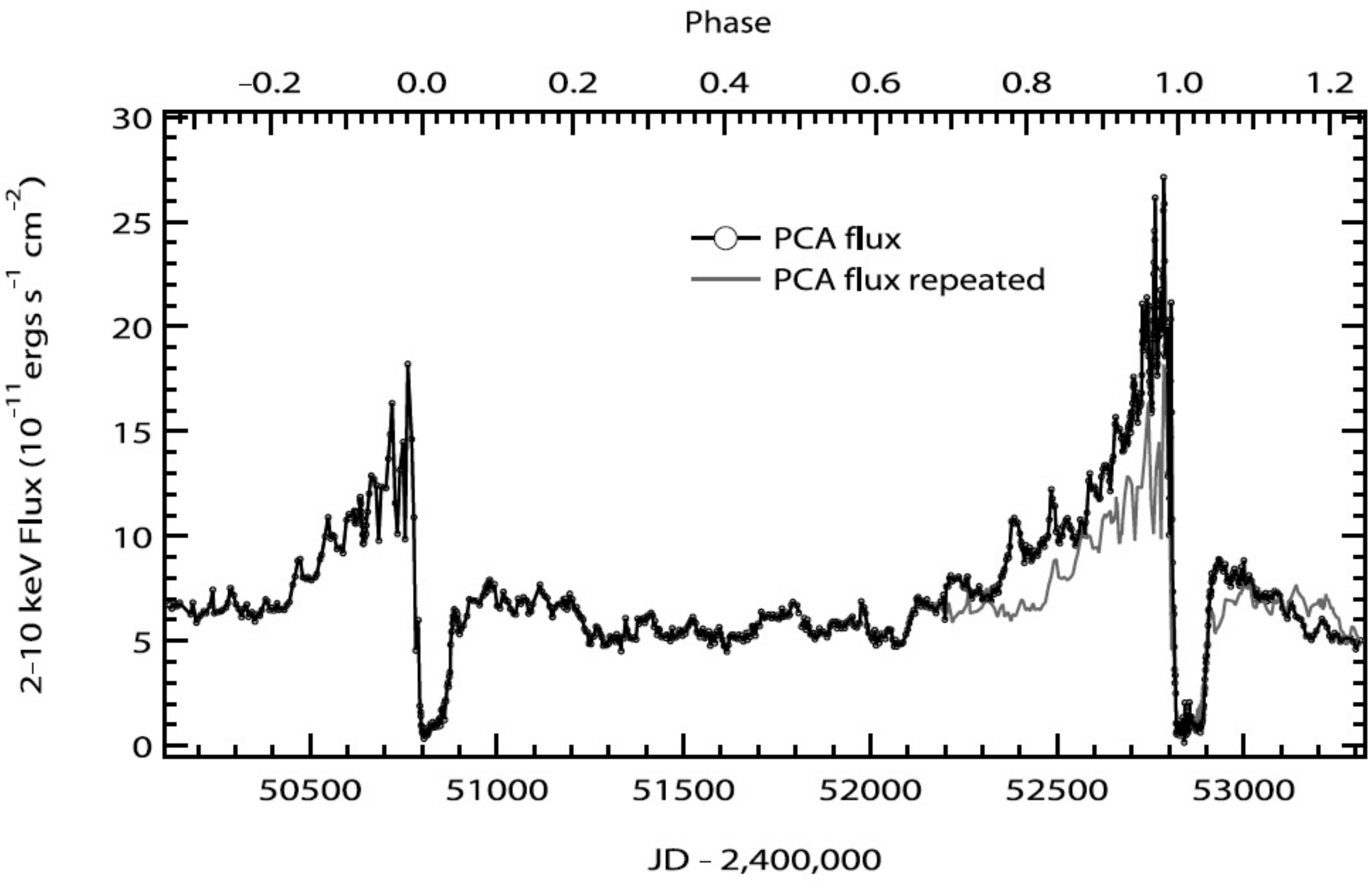
But other mechanisms can dominate, especially in young clusters/SFRs

Like colliding wind shocks (CWS) in η Car





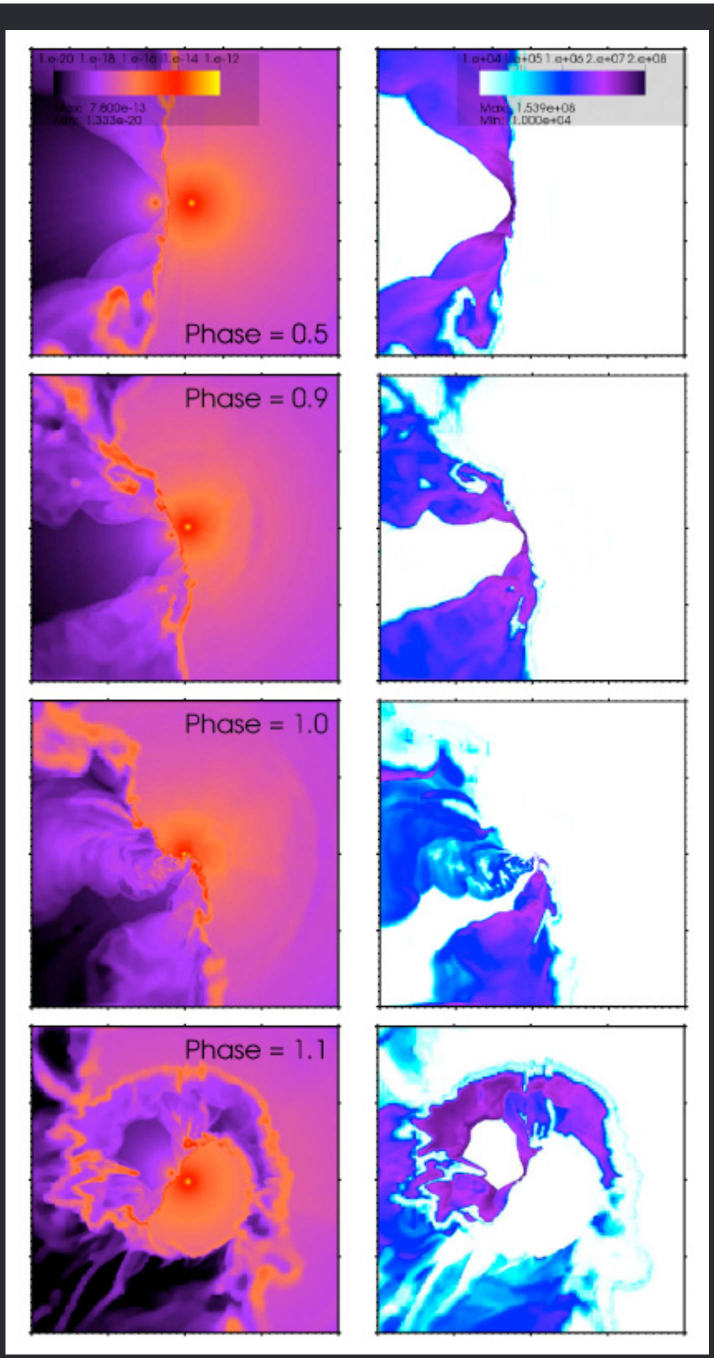
η Car RXTE X-ray light curve



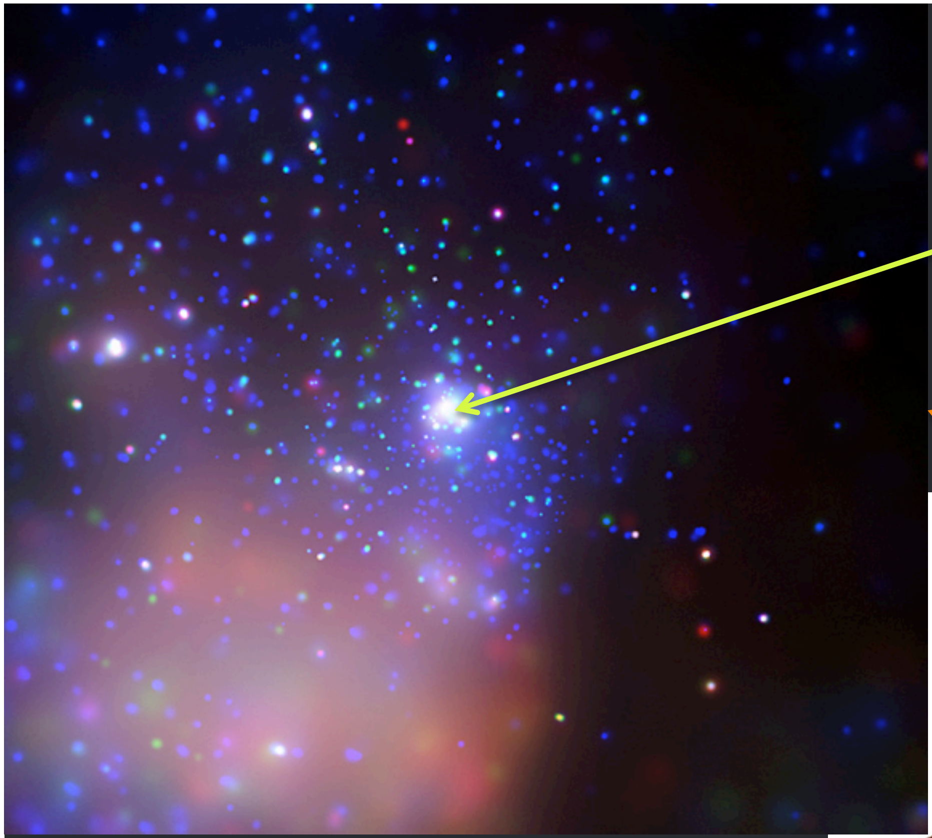
Corcoran et al. 2005

Hydrodynamics simulations of the colliding wind shock mechanism explain much of the observed X-ray properties

- hard emission (~5 keV)
- L_x ~ 10^{35} erg/s
- orbital modulation of X-rays

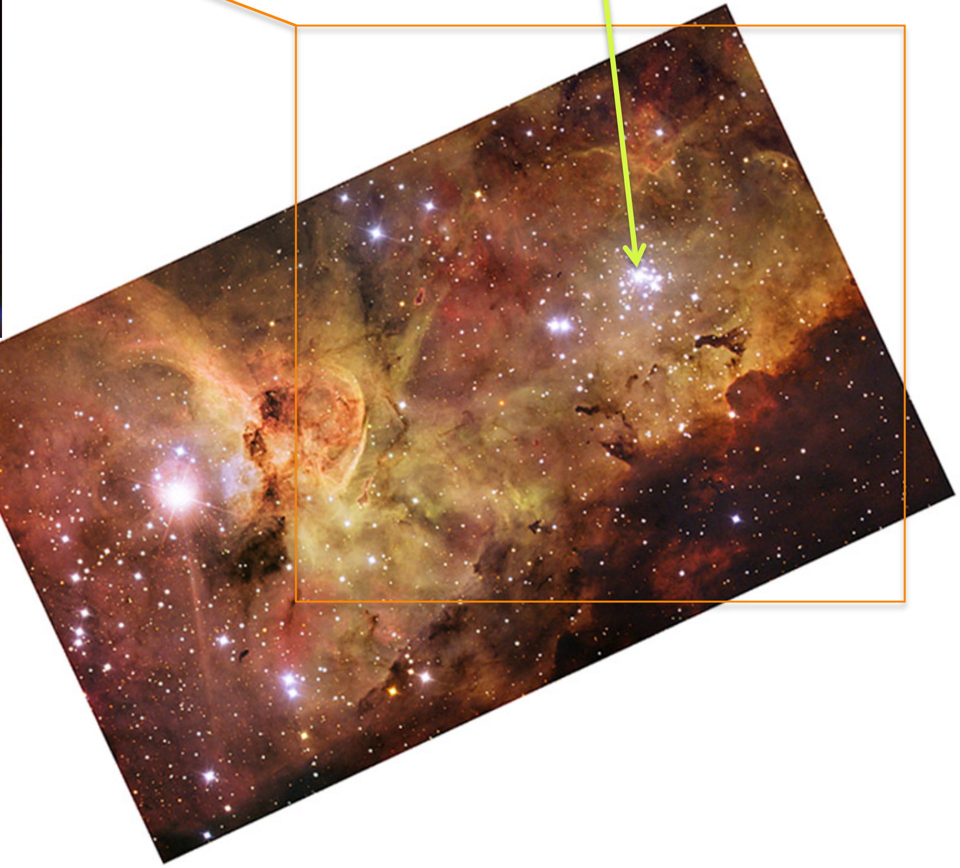


Parkin et al. 2011



Tr 14: *Chandra*

HD 93129A (O2If*)
is the 2nd brightest
X-ray source in Tr 14



Carina: ESO

HD93129A – O2 If*

Extremely massive (120 M_{sun}), luminous O star ($10^{6.1}$ L_{sun})

Strongest wind of any Galactic O star (2×10^{-5} M_{sun}/yr; v_{inf} = 3200 km/s)

From H-alpha, assuming a smooth wind

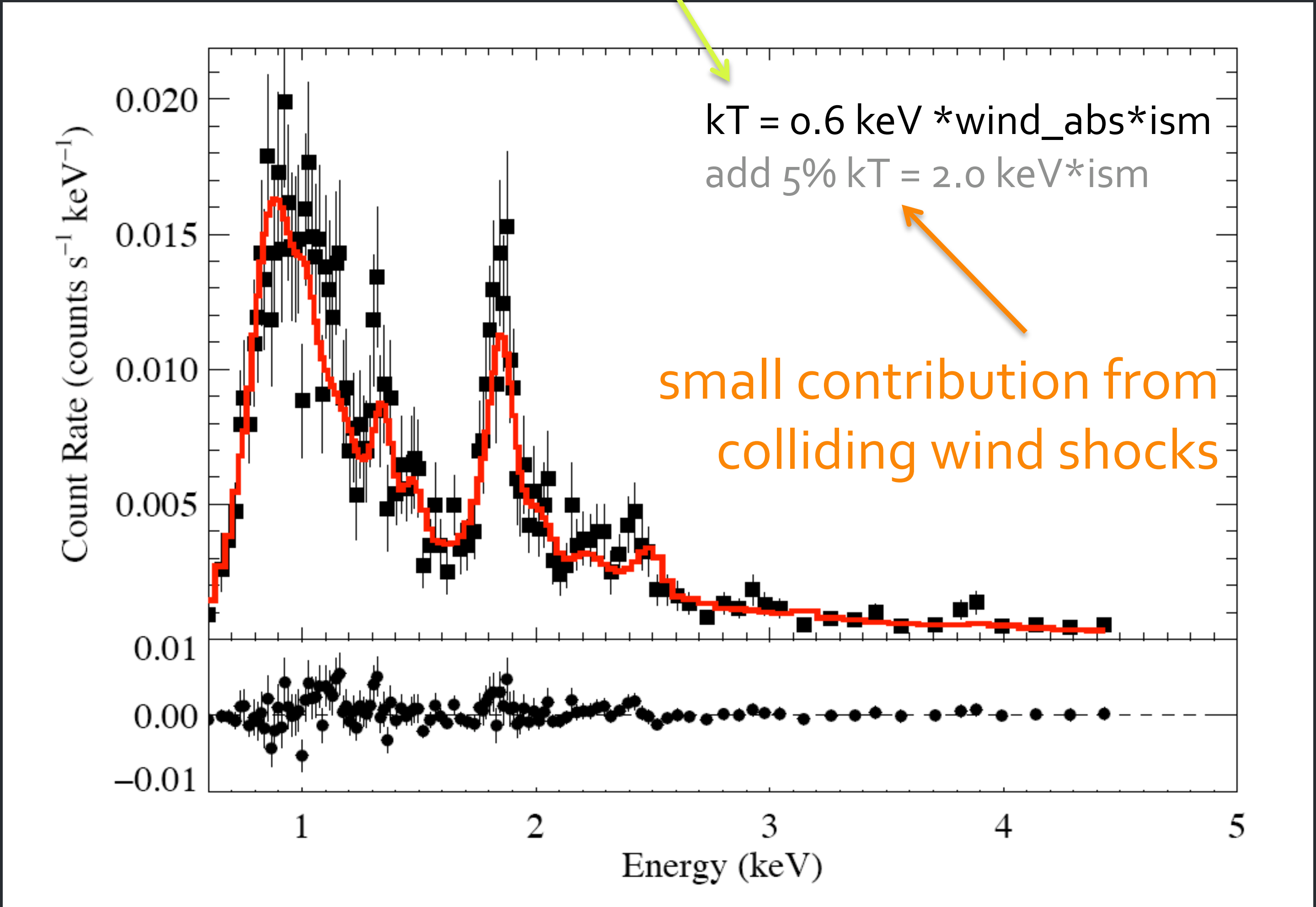
There is an O3.5 companion with a separation of ~100 AU

Non-thermal radio measurements indicate wind-wind interactions

But the vast majority of the X-rays come from embedded wind shocks in the O2If* primary

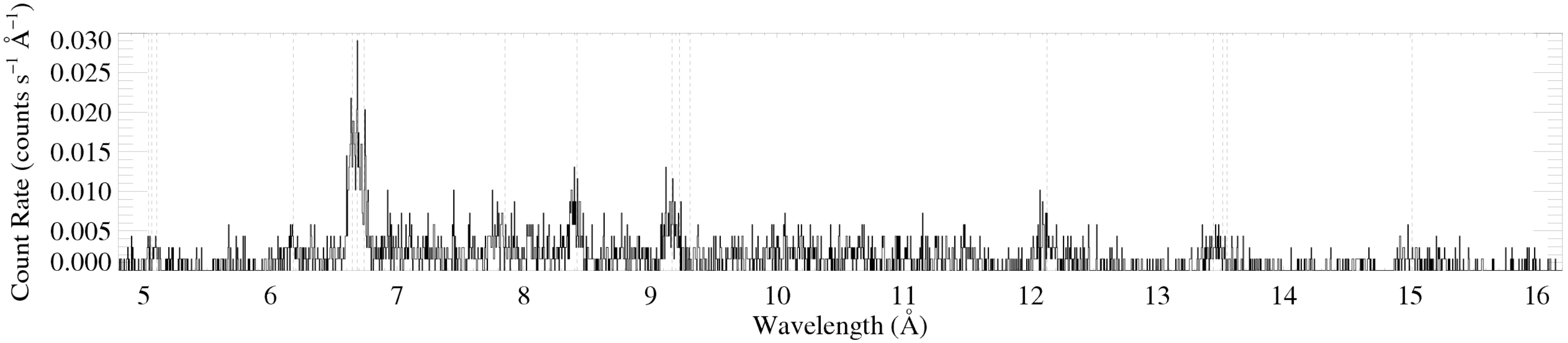
Chandra ACIS (low-res, CCD) spectrum of HD 93129A

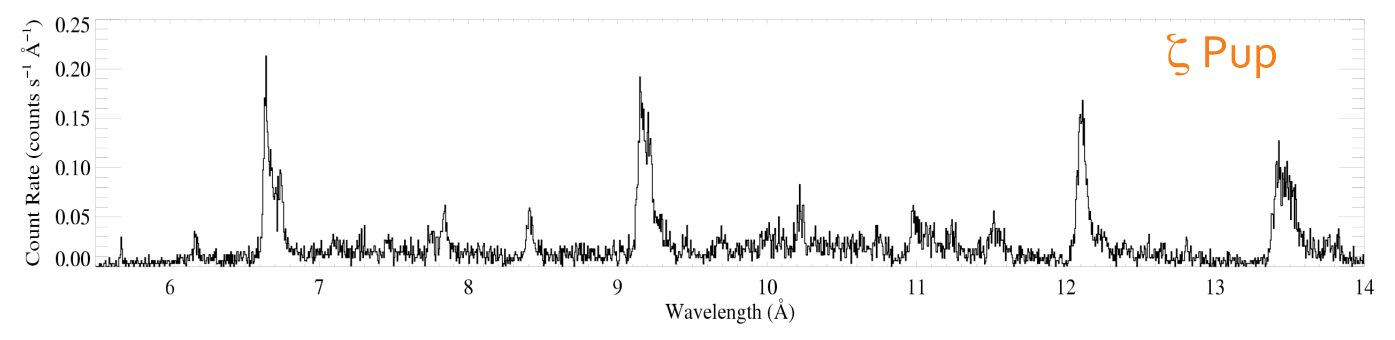
Typical of O stars like ζ Pup



Its X-ray spectrum is hard

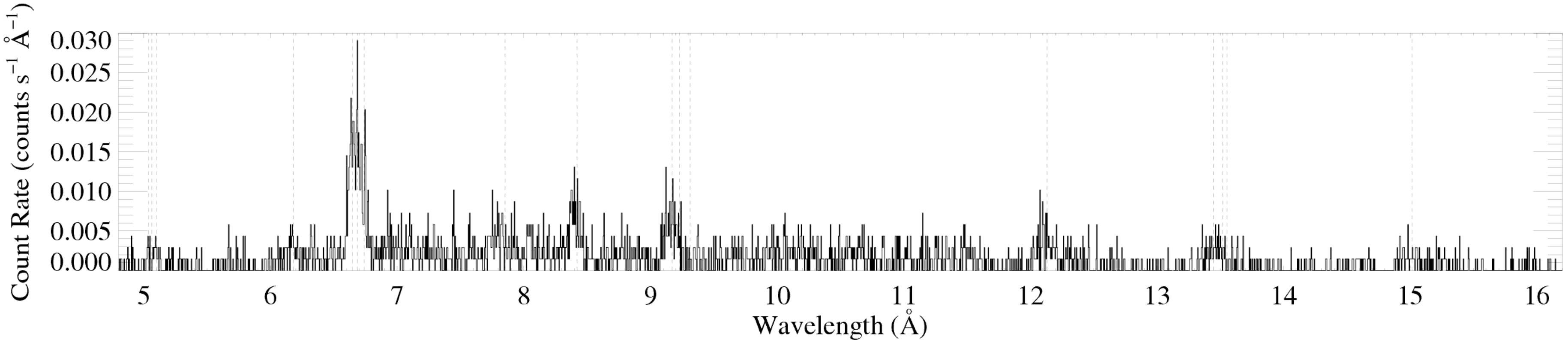
HD 93129A





Its X-ray spectrum is hard

HD 93129A

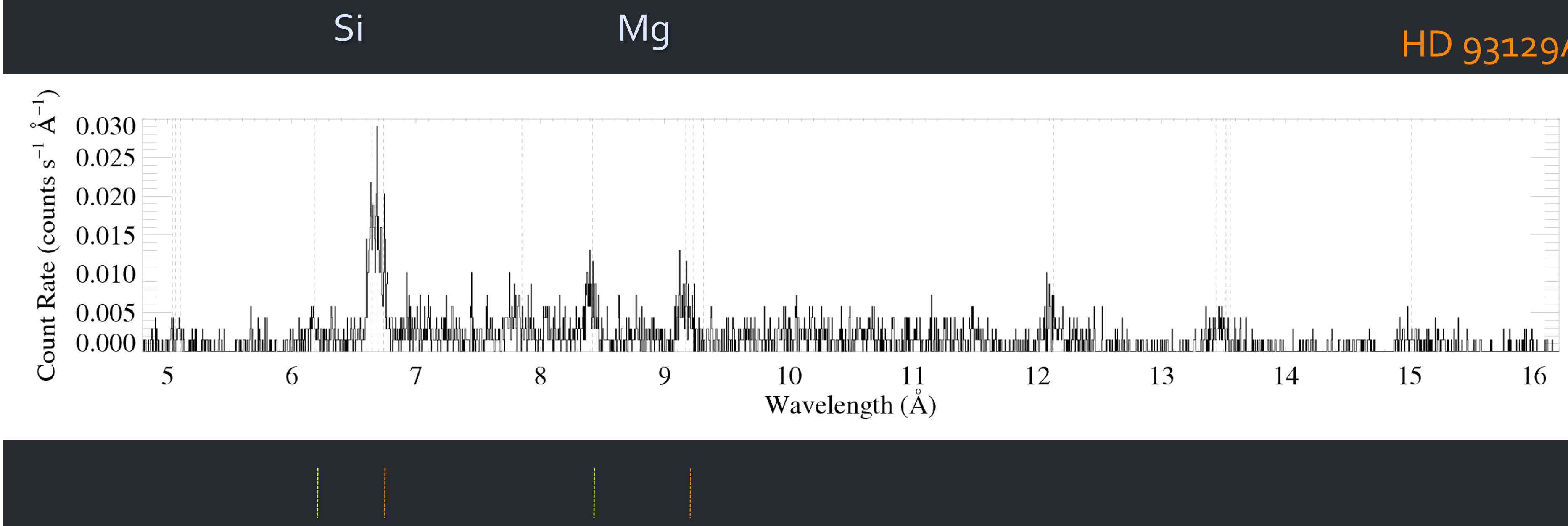


Si XIV Si XIII Mg XII Mg XI

H-like vs. He-like

Its X-ray spectrum is hard

HD 93129A



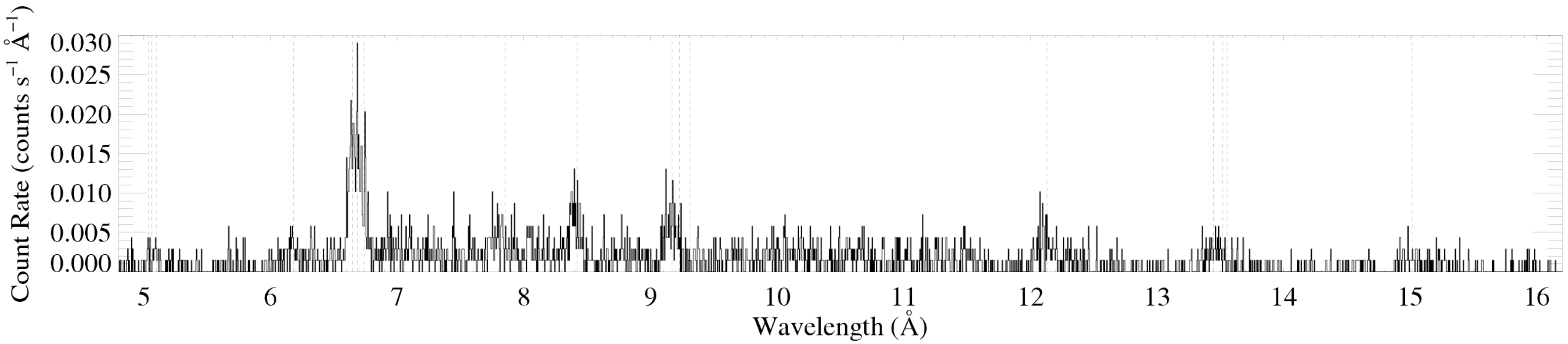
low H/He

But the plasma **temperature** is **low**:
little plasma with kT > 8 million K

Its X-ray spectrum is hard

Si

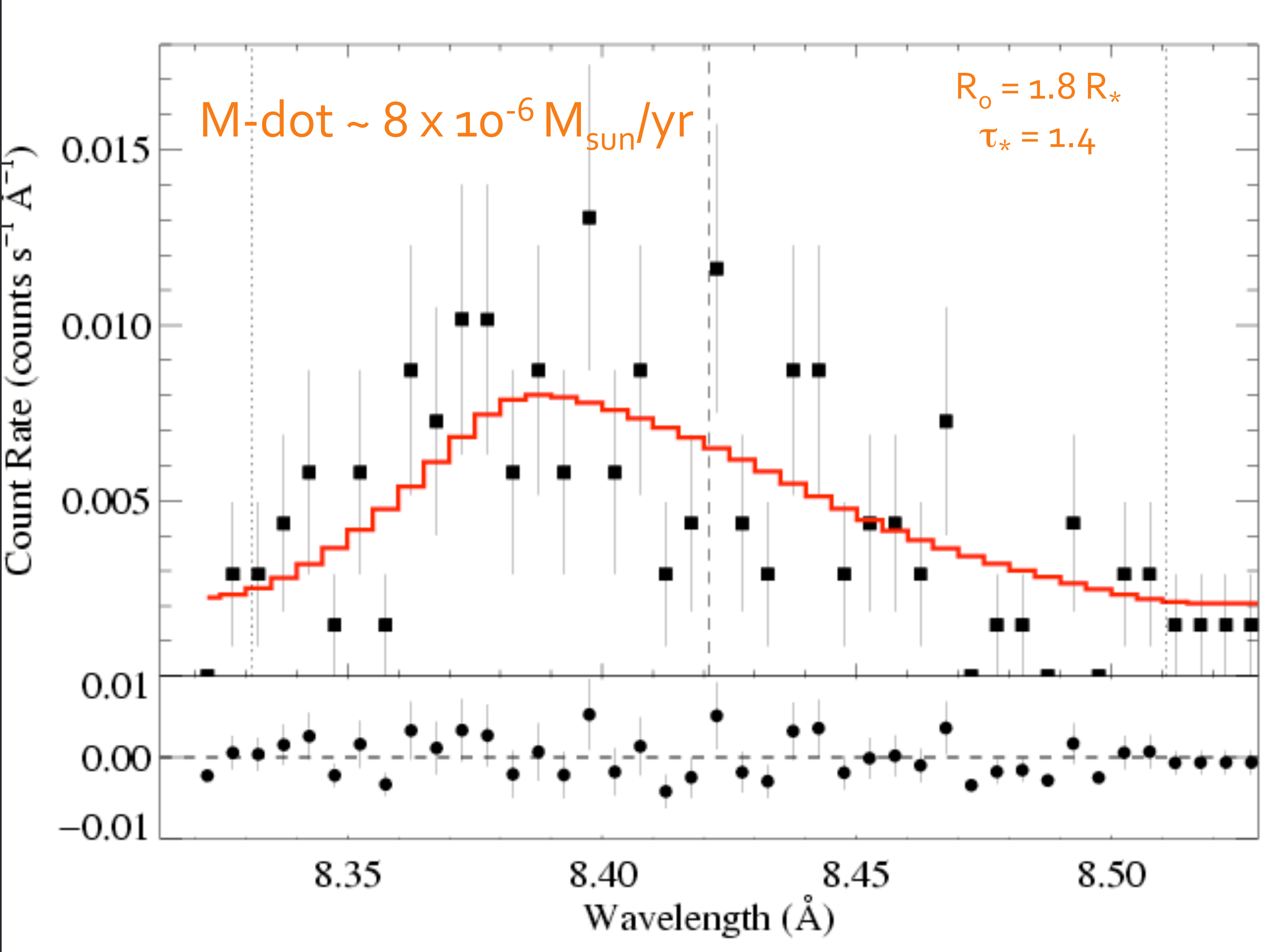
Mg



low H/He

Bound-free absorption in the wind is the cause of the observed X-ray hardness

X-ray line profiles show same characteristic shape



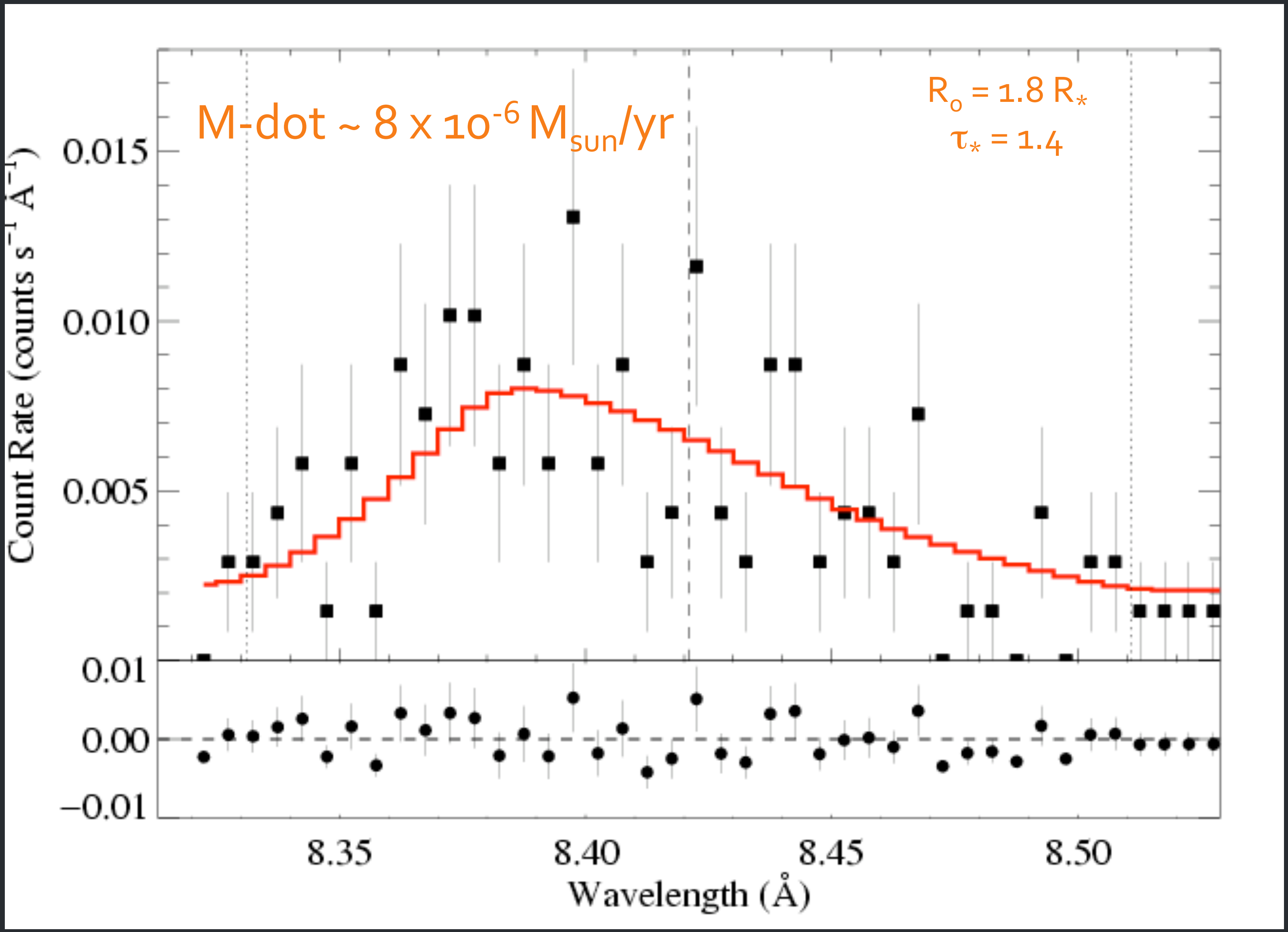
M-dot ~ $8 \times 10^{-6}\ M_{sun}/yr$

$R_o = 1.8\ R_*$
$\tau_* = 1.4$

M-dot ~ 2×10^{-5} M_{sun}/yr from **unclumped** Hα

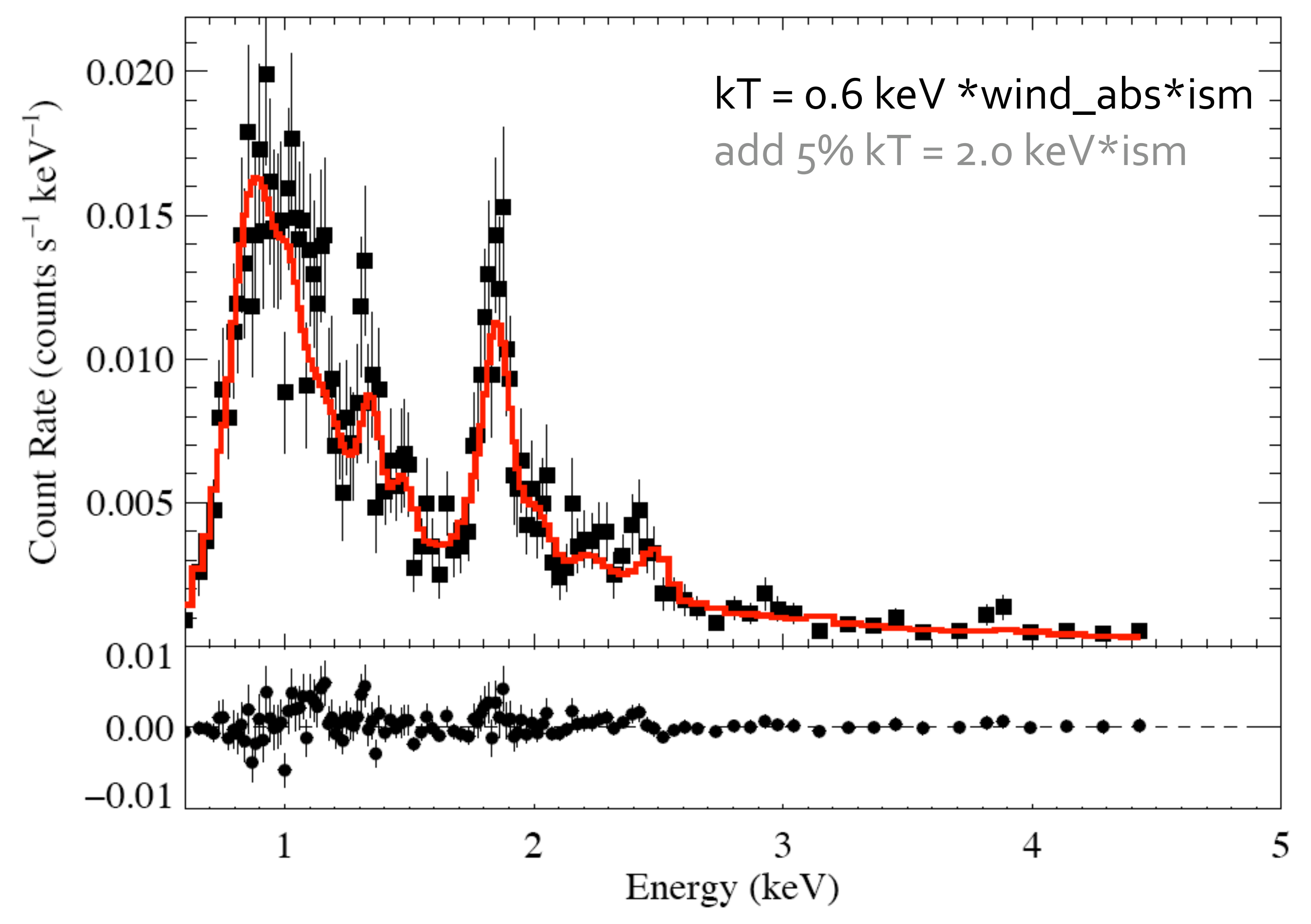
HD 93129A (O2 If*): Mg XII Lyα 8.42 Å

V_{inf} ~ 3200 km/s



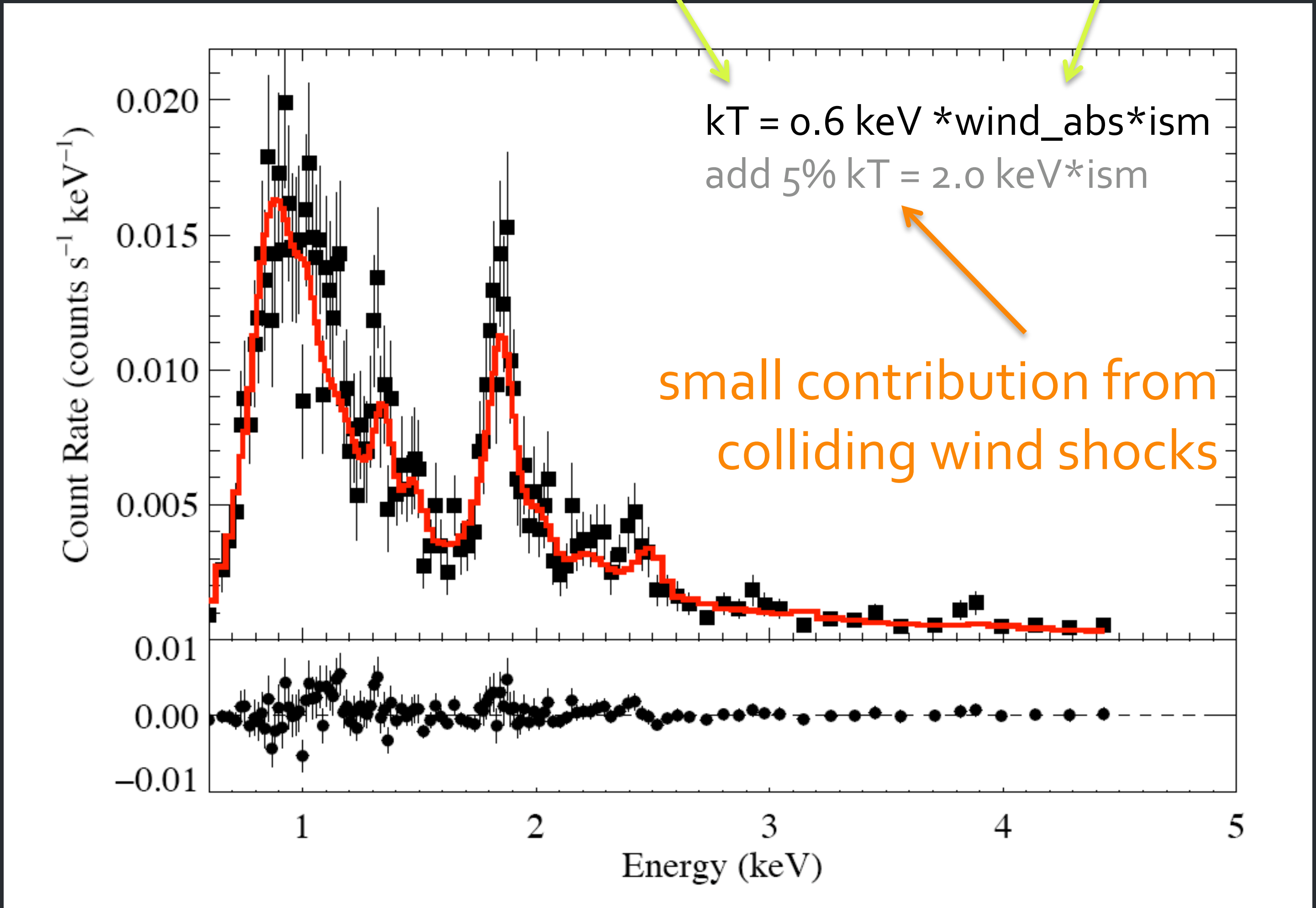
Low-resolution *Chandra* CCD spectrum of HD93129A

Fit: thermal emission with wind + ISM absorption *plus* a second thermal component with just ISM



τ_*/κ = 0.03 (corresp. ~ 8 x 10^{-6} M_{sun}/yr)

Typical of O stars like ζ Pup



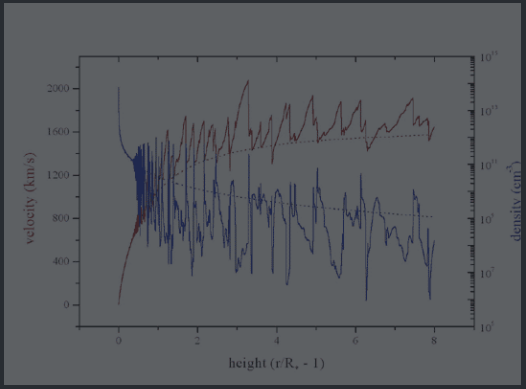
kT = 0.6 keV *wind_abs*ism

add 5% kT = 2.0 keV*ism

small contribution from colliding wind shocks

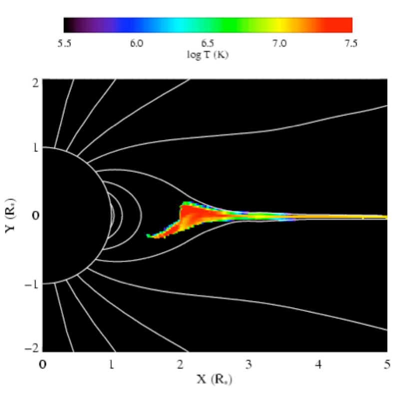
Three mechanisms for massive star x-ray emission

1. Instability driven shocks

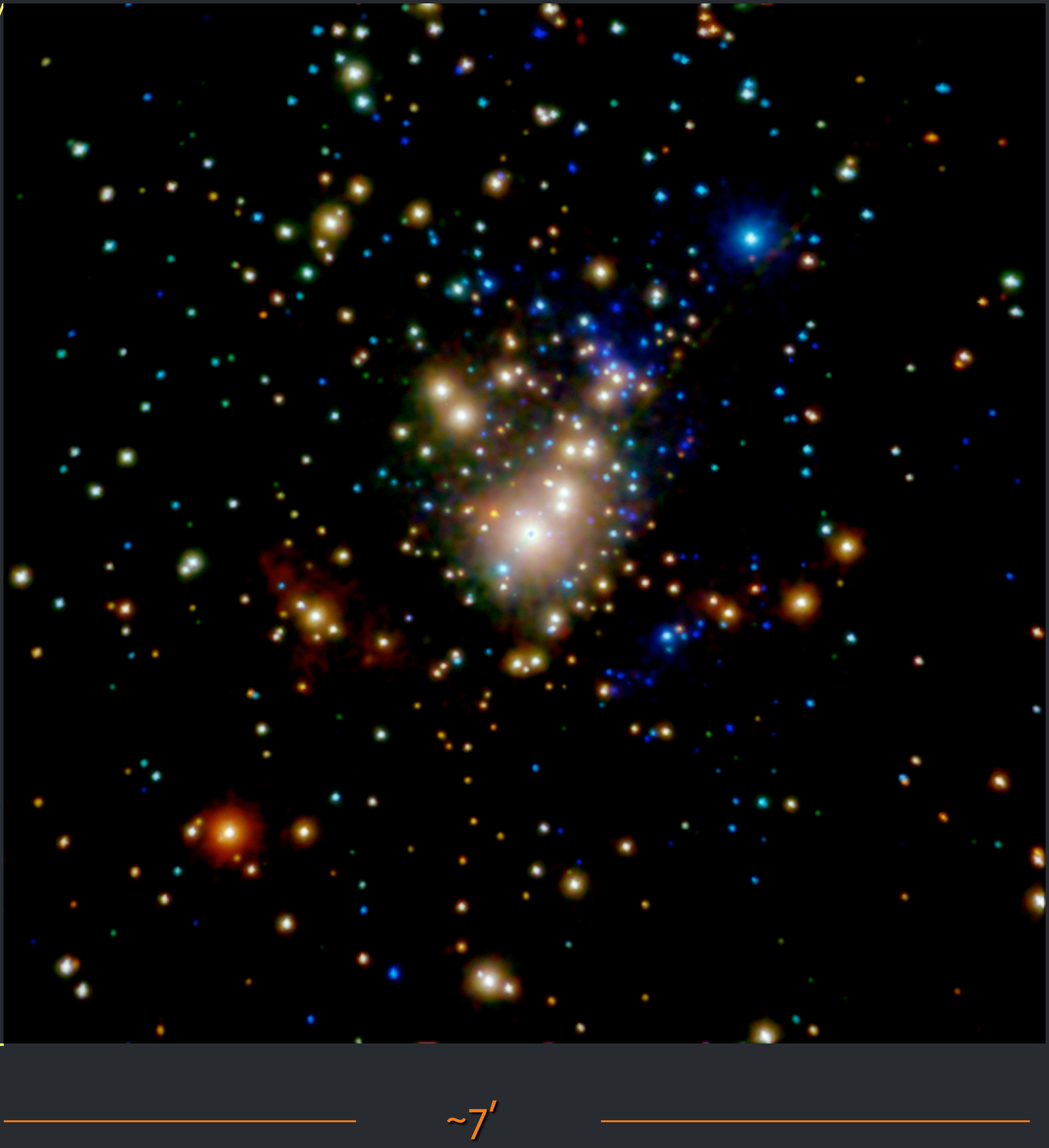


2. Wind-wind interaction in close binaries

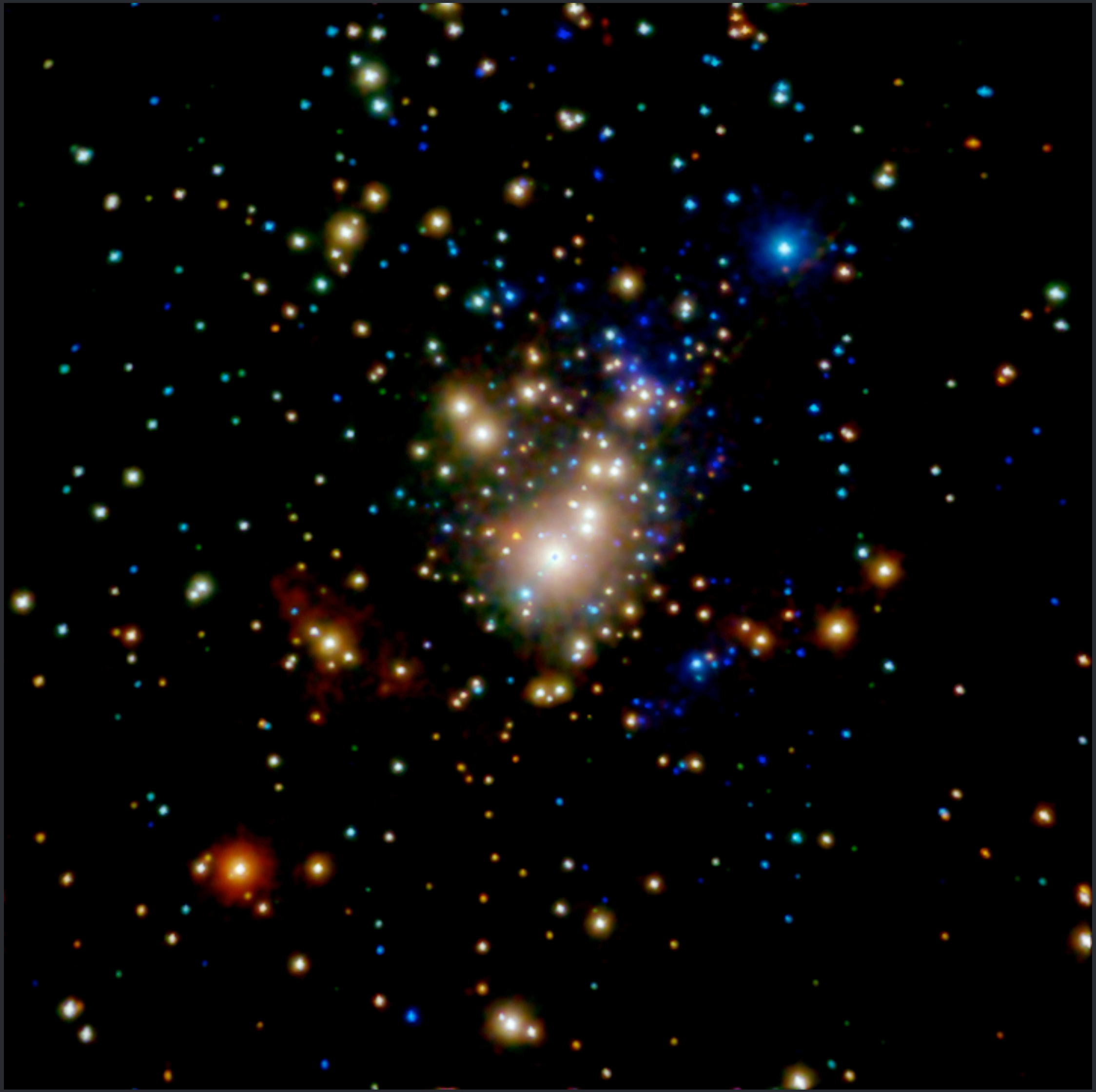
3. Magnetically channeled wind shocks



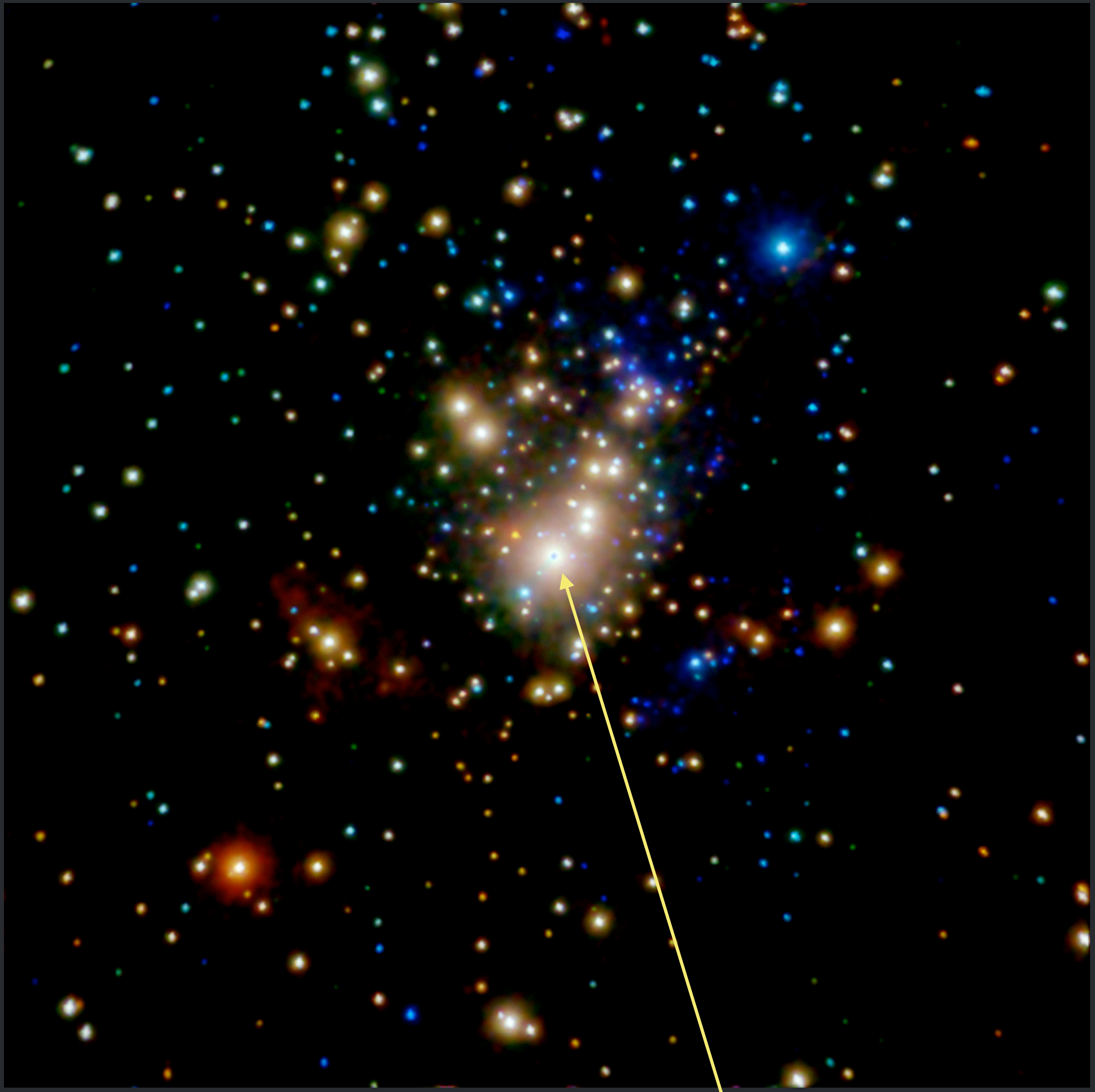
Orion Nebula Cluster: age ~ 1Myr; d ~ 450pc



Chandra ~10^6 seconds, COUP (Penn. St.)

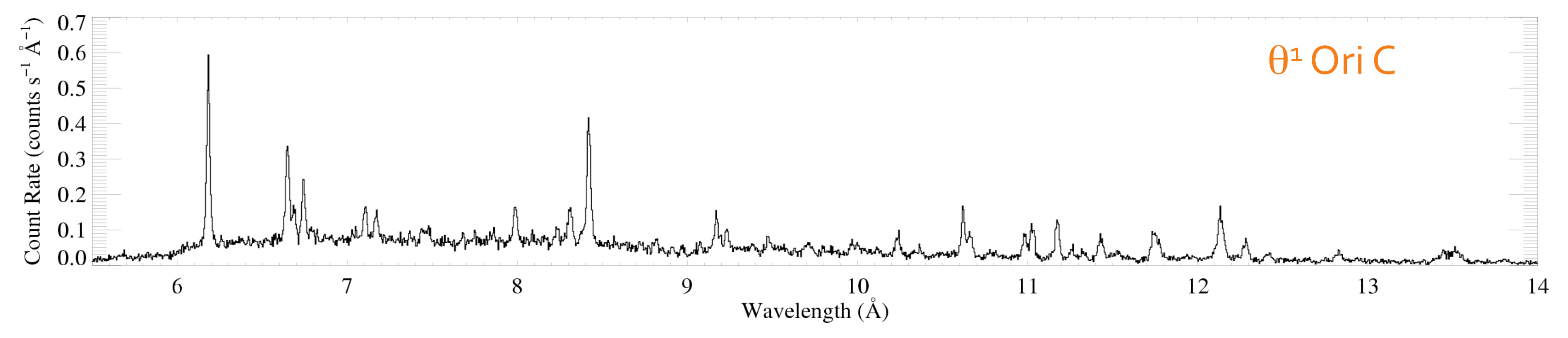


Color coding of x-ray energy: <1keV, 1keV < E < 2.5keV, >2.5keV

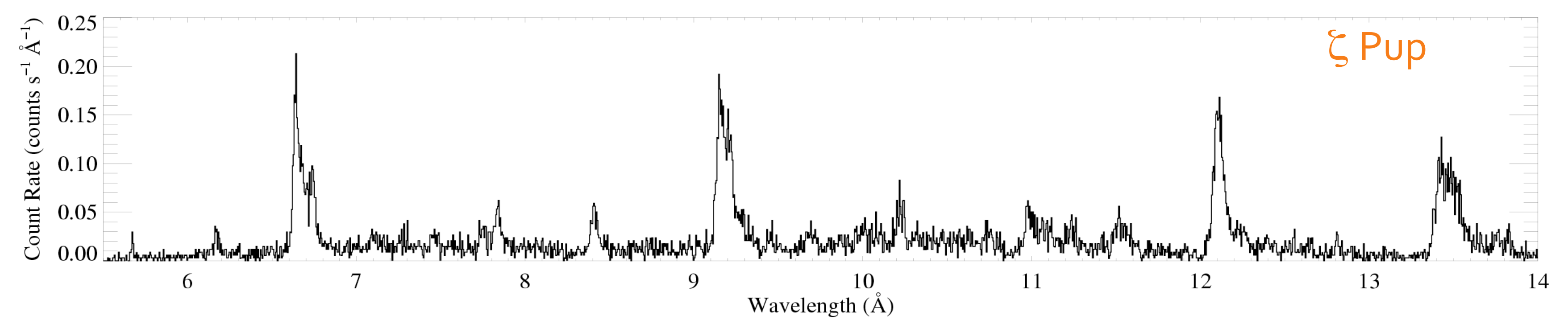


θ^1 Ori C (O7 V)

Chandra HETGS

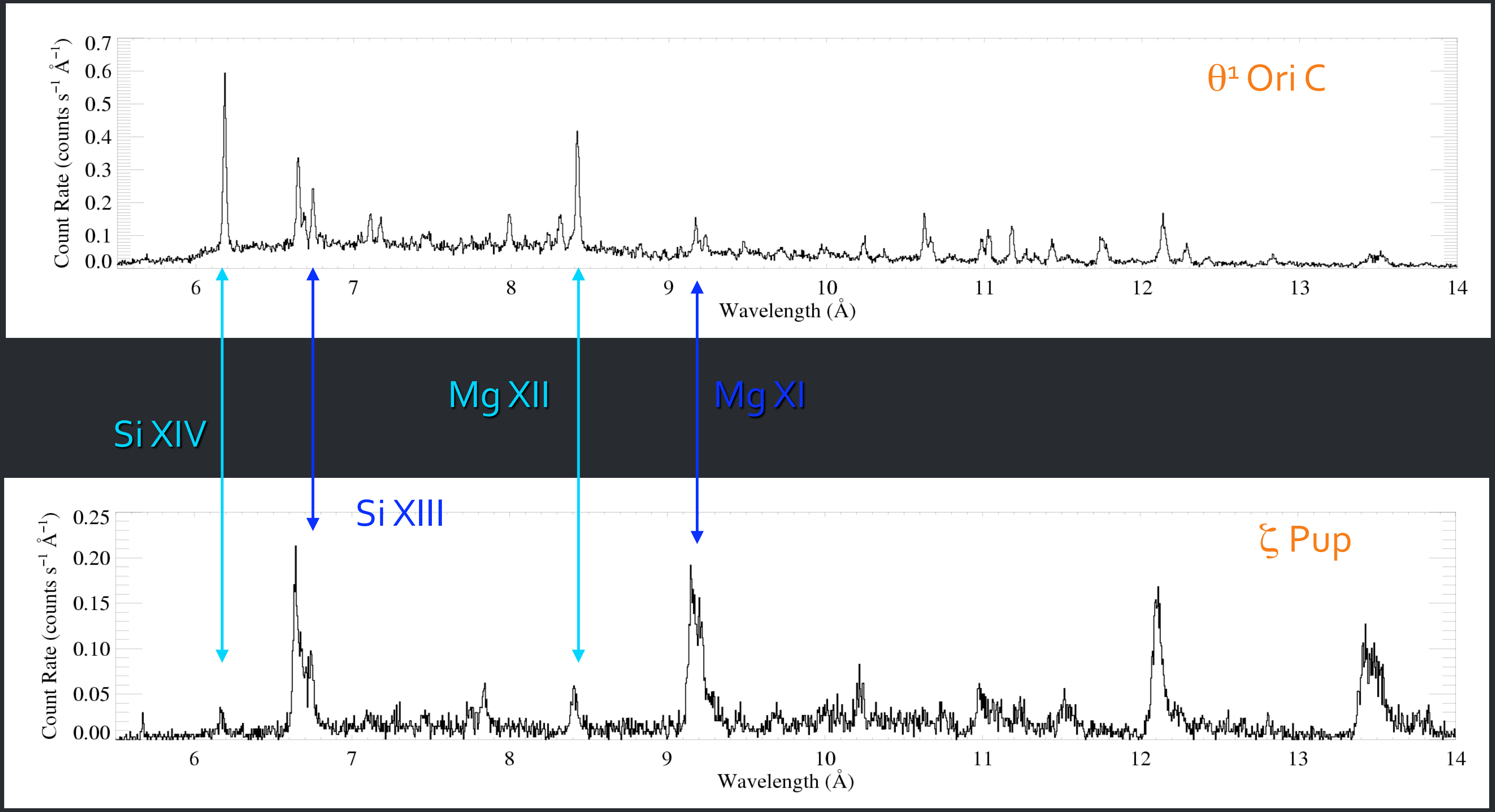


θ¹ Ori C: hotter plasma, narrower emission lines



ζ Pup (O4 I): cooler plasma, broad emission lines

H-like/He-like ratio is temperature sensitive



Si XIV

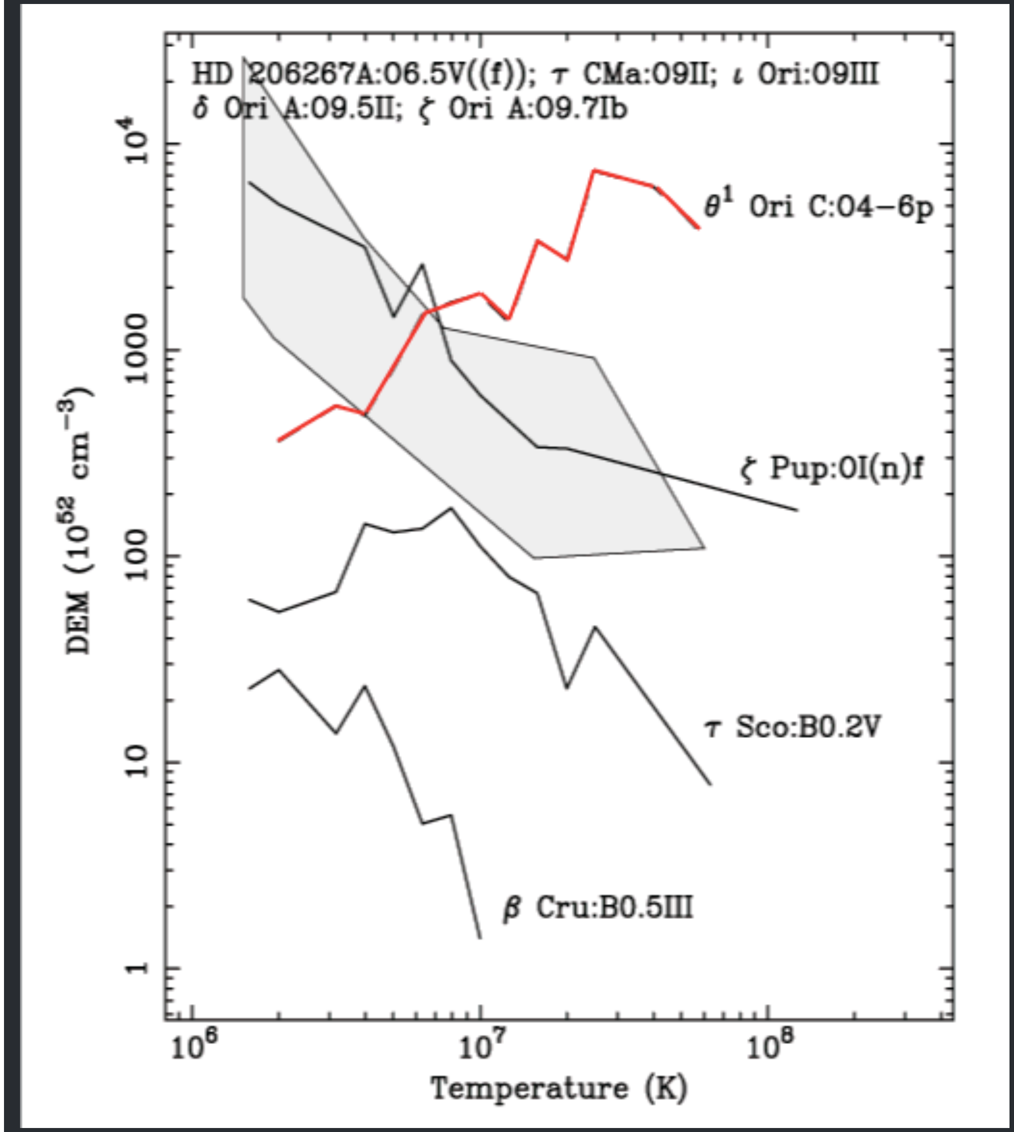
Si XIII

Mg XII

Mg XI

Differential emission measure

(temperature distribution)



Wojdowski & Schulz (2005)

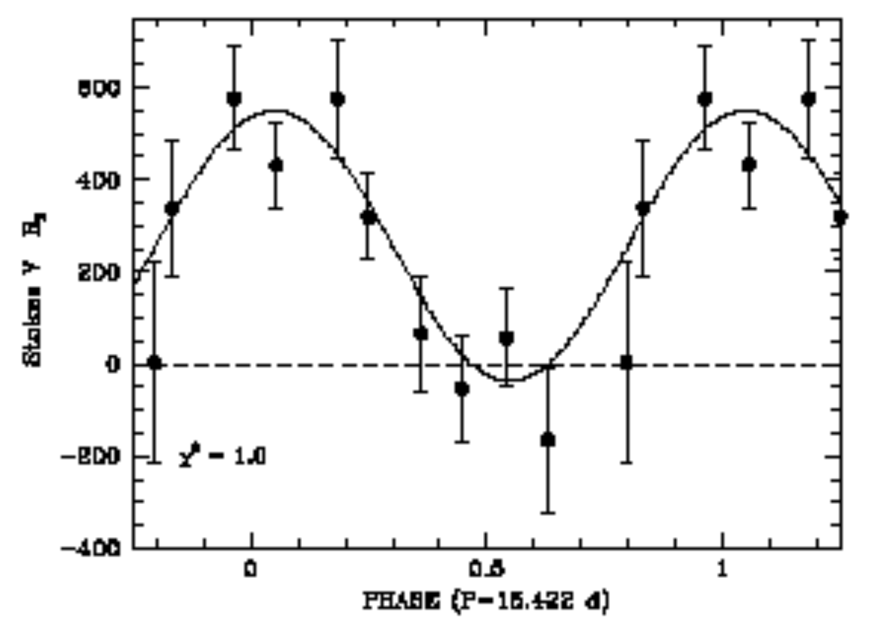
θ^1 Ori C:

peak near 30 million K

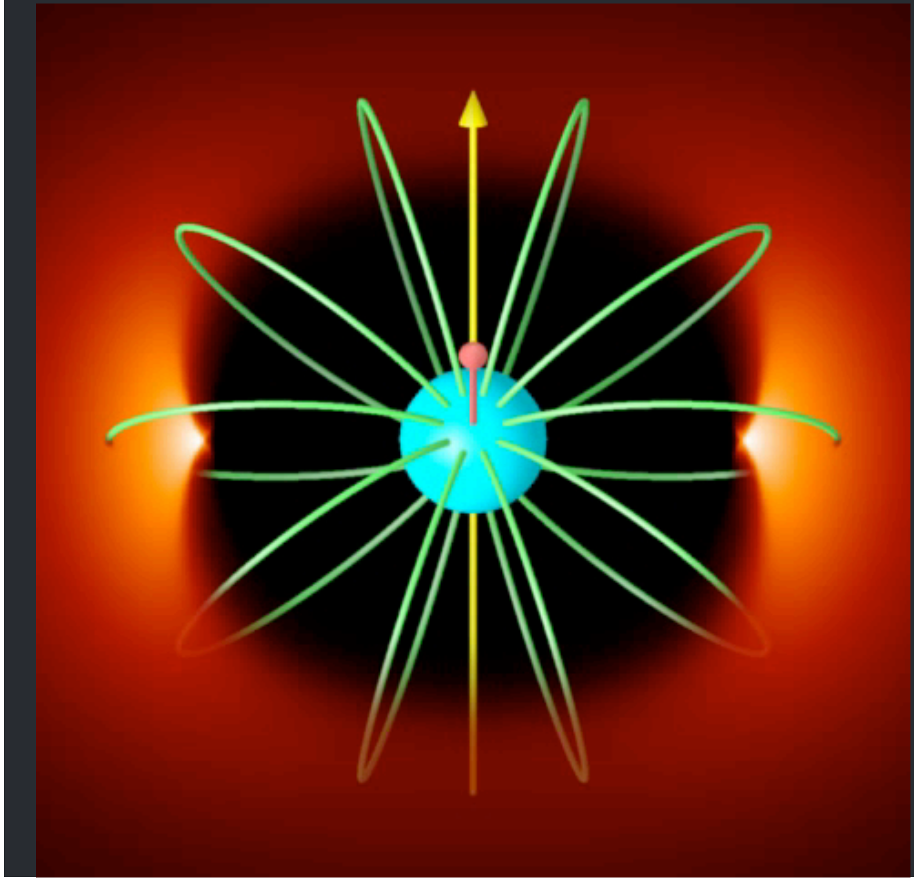
Non-magnetic O stars, peak at a few million K

Dipole magnetic field (> 1 kG) measured on θ^1 Ori C

Zeeman magnetic field measurements



Wade et al. (2006)

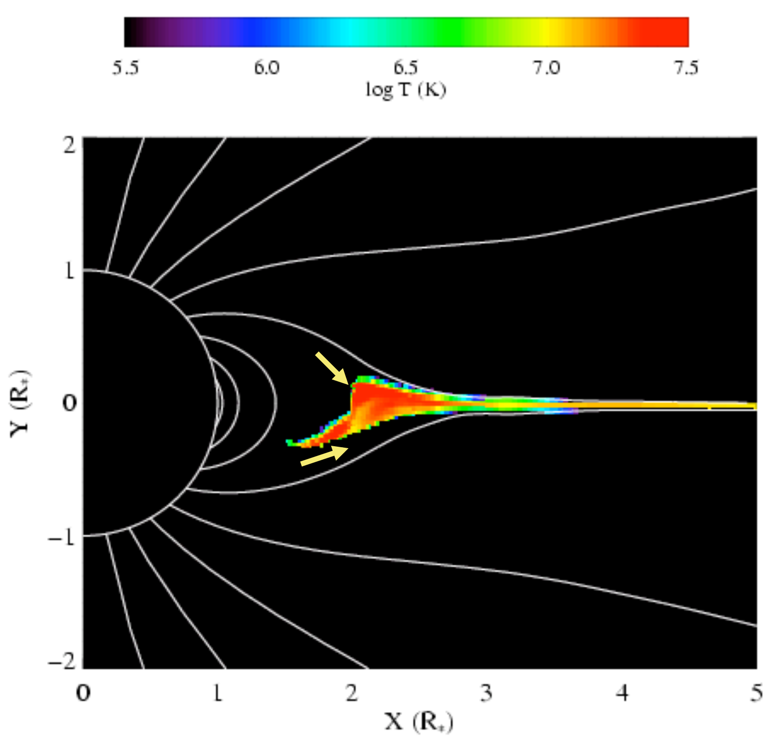


Magnetic field obliquity, $\beta \sim 45^\circ$

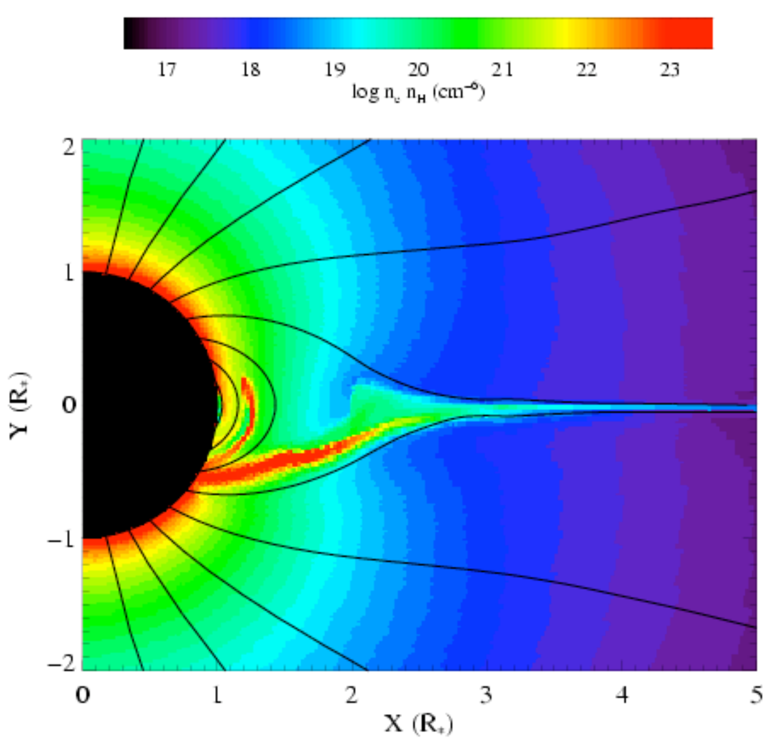
R. Townsend

MHD simulations of magnetically channeled wind

temperature



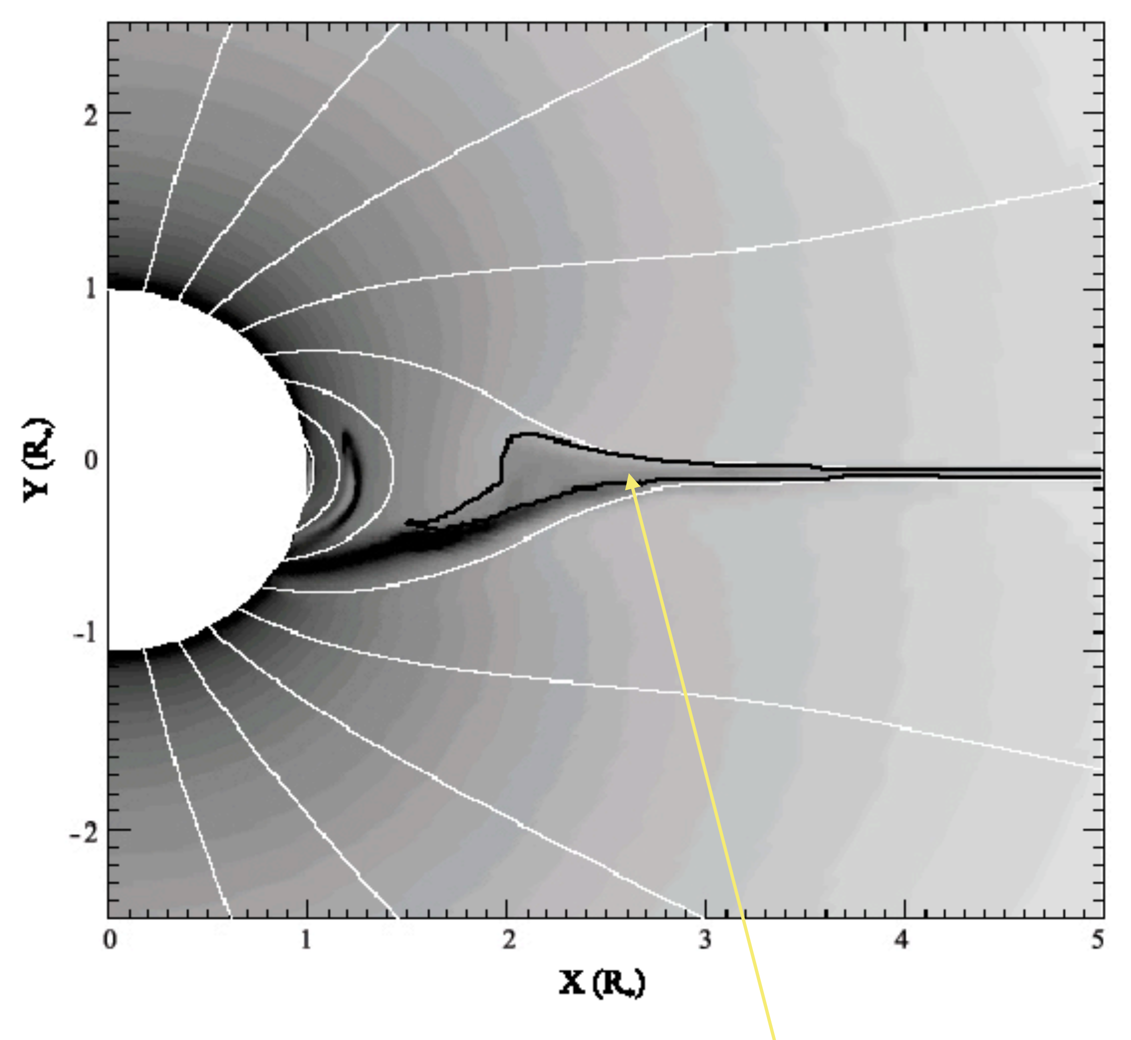
emission measure



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

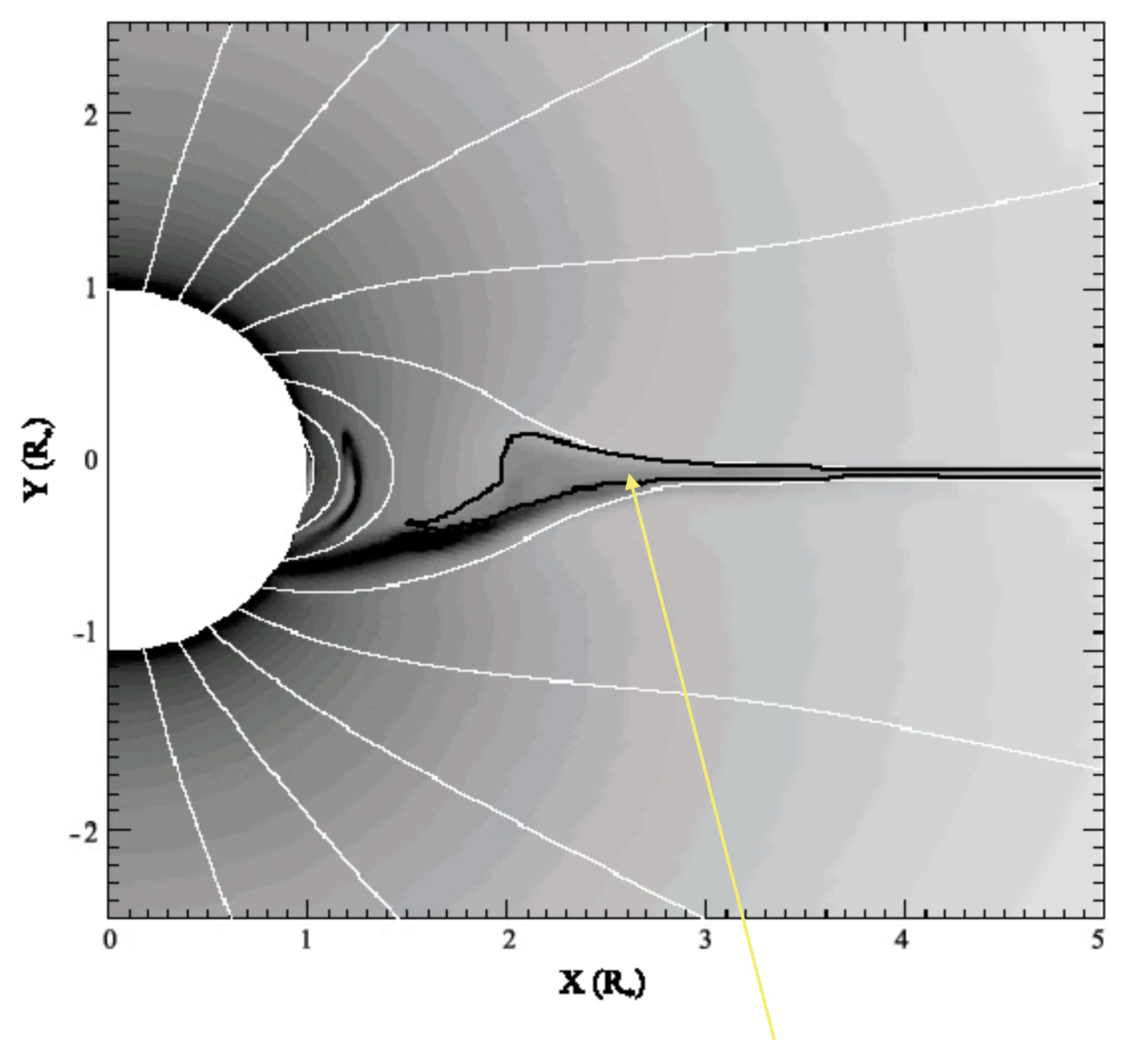
Channeled collision is close to head-on –
at 1000+ km s^{-1} : T = 10^7+ K

Emission measure



contour encloses T > 10^6 K

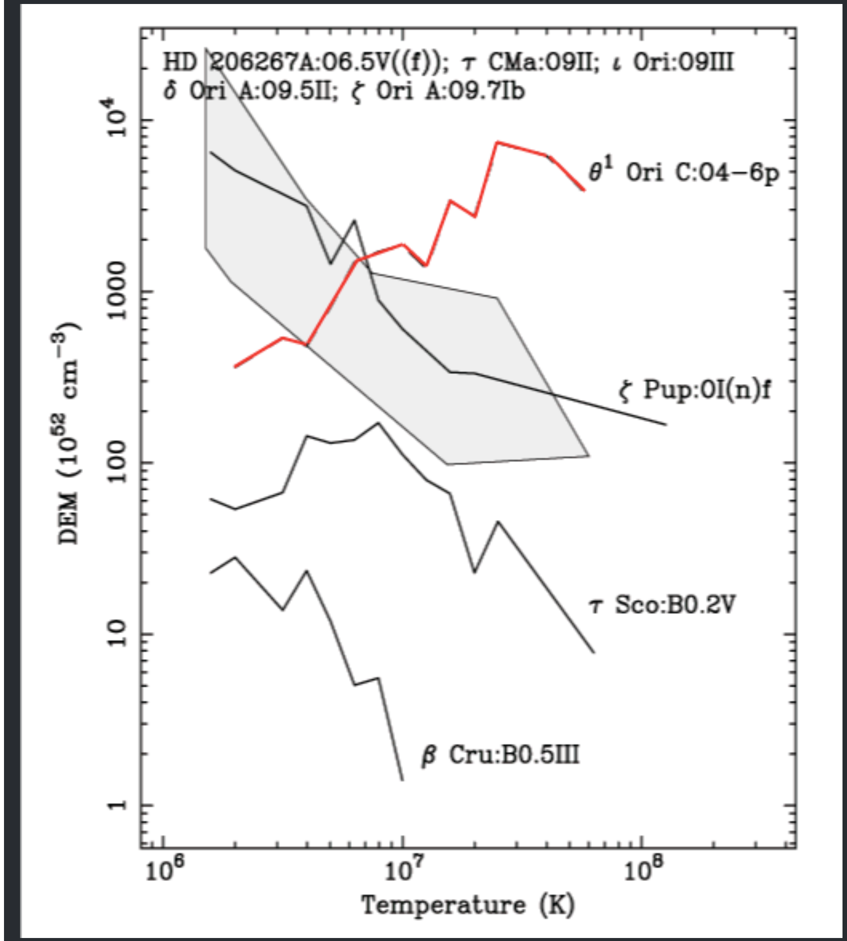
MHD simulations show multi-10^6 K plasma, moving slowly, ~$1R_*$ above photosphere

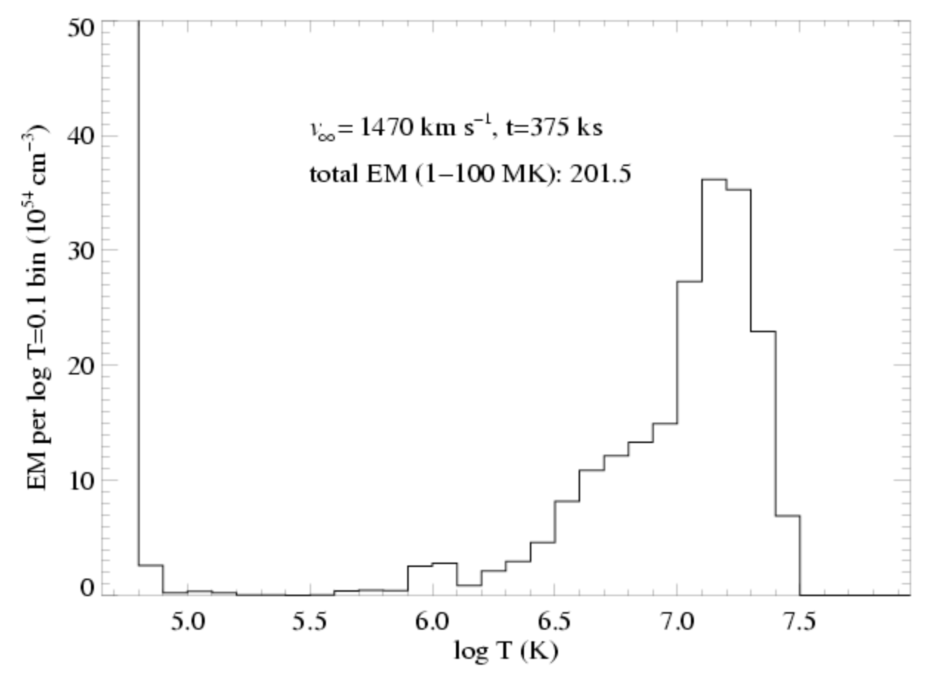


contour encloses $T > 10^6$ K

Differential emission measure

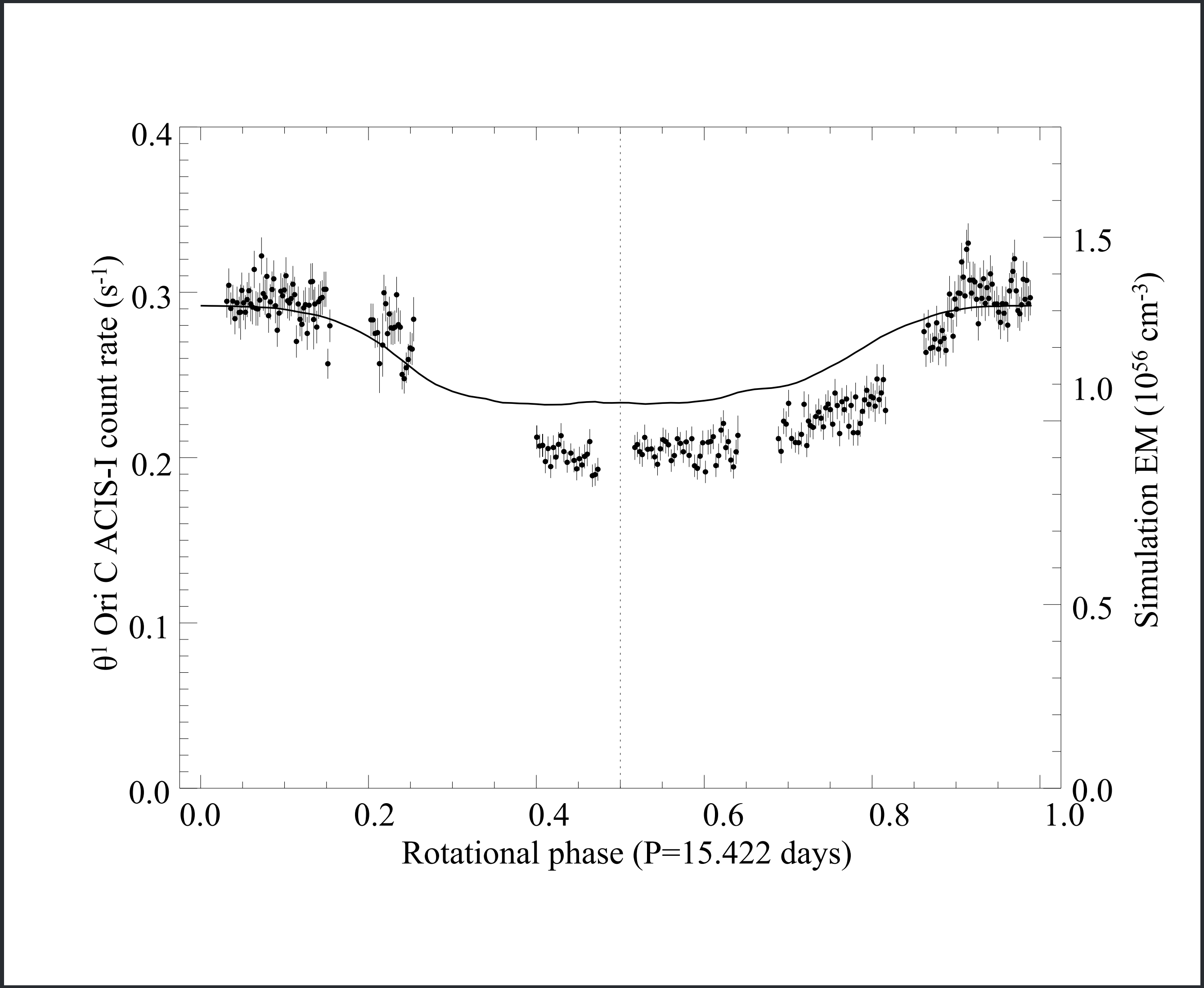
(temperature distribution)





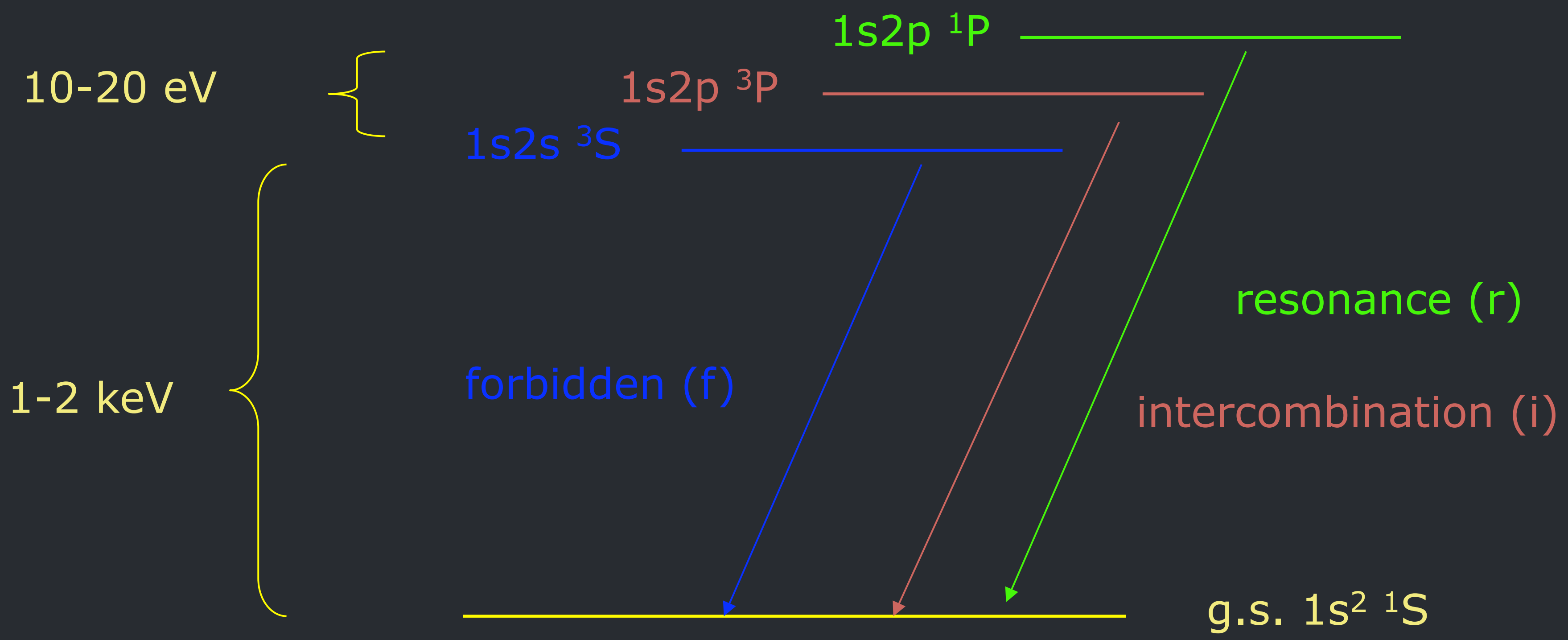
MHD simulation of θ^1 Ori C reproduces the observed differential emission measure

Chandra broadband count rate vs. rotational phase



Model from MHD simulation

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



1s2p ^{1}P

10-20 eV

1s2p ^{3}P

1s2s ^{3}S

resonance (r)

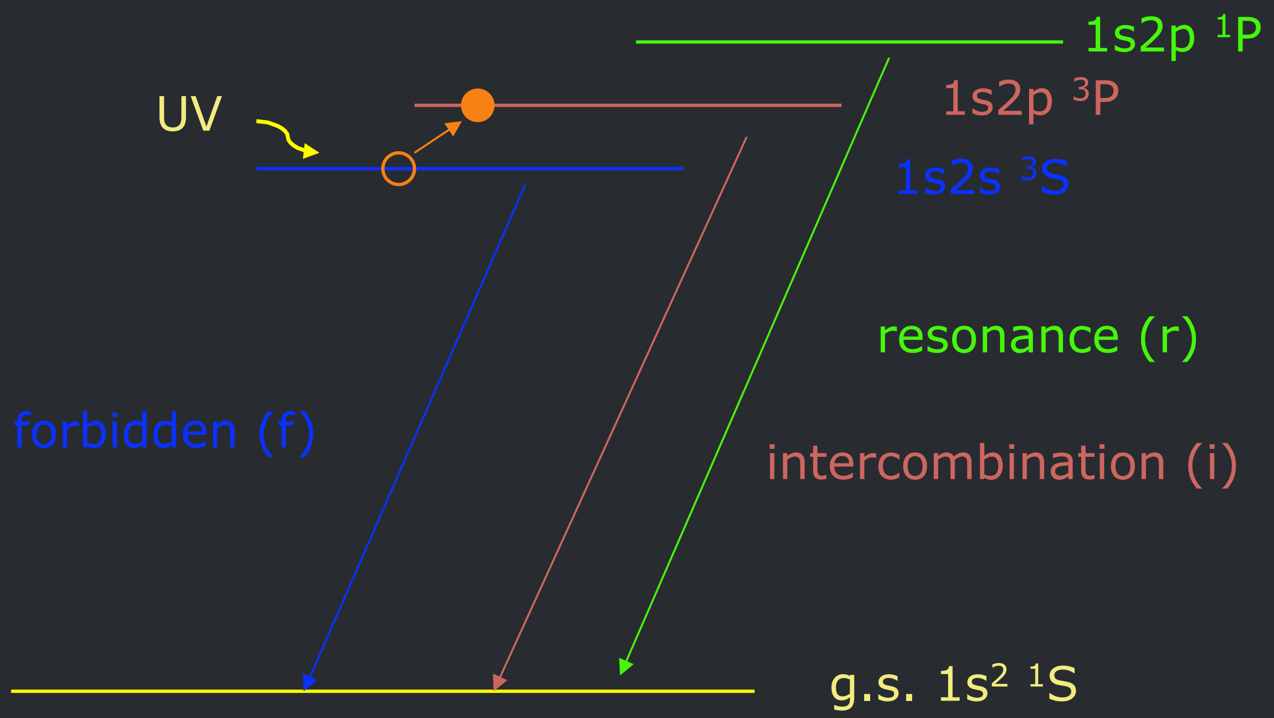
forbidden (f)

1-2 keV

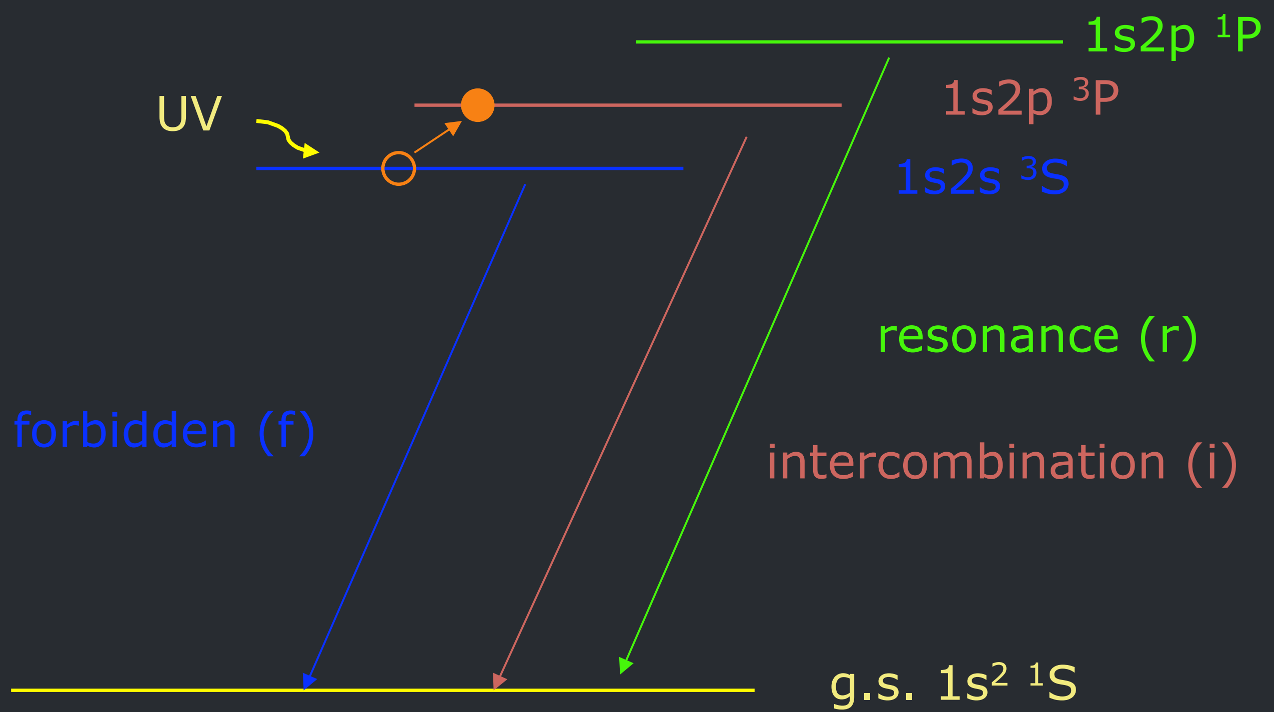
intercombination (i)

g.s. 1s^{2} ^{1}S

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



If you know the UV intensity emitted from the star's surface, it thus becomes a diagnostic of the distance that the x-ray emitting plasma is from the star's surface.



1s2p ^{1}P

1s2p ^{3}P

UV

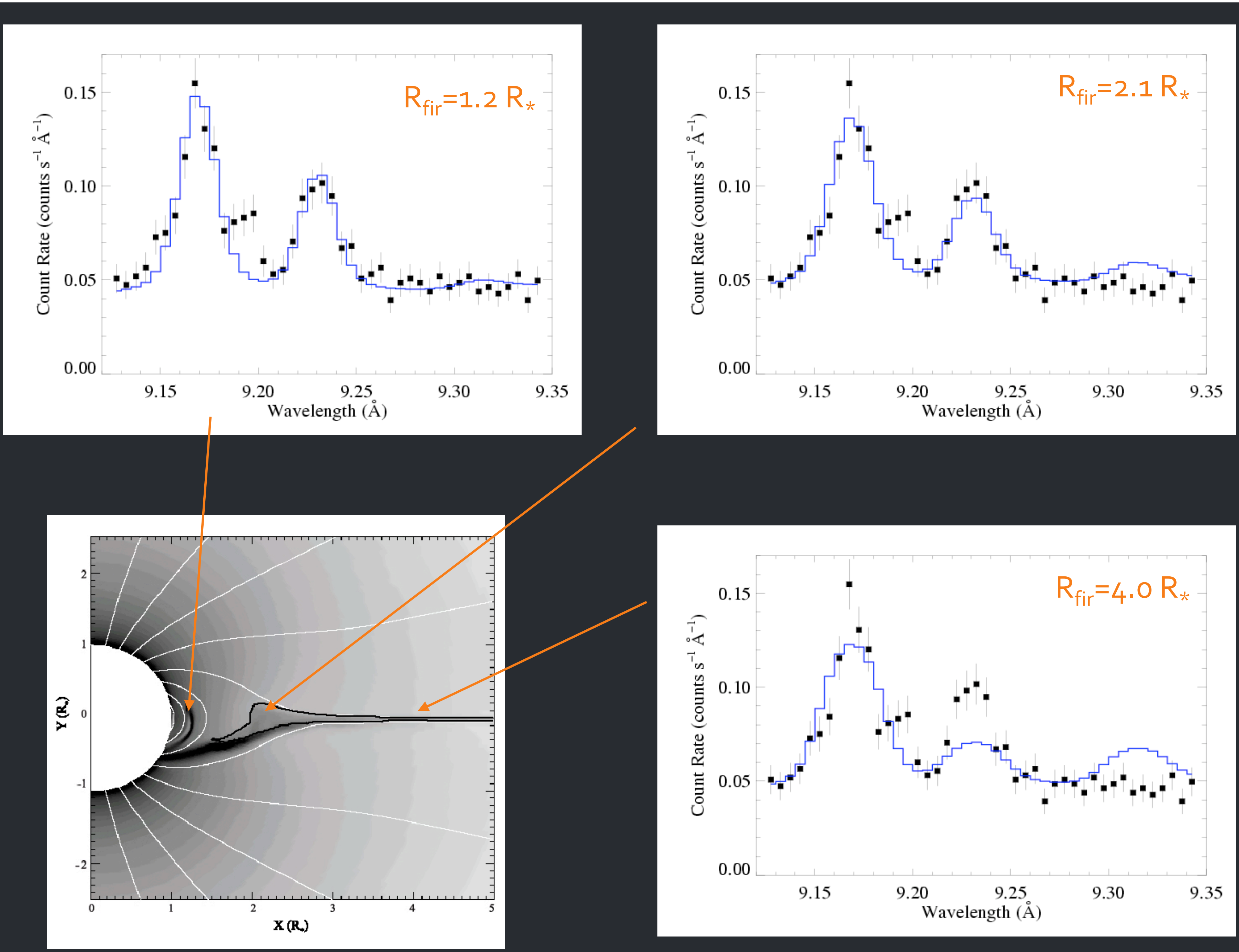
1s2s ^{3}S

resonance (r)

forbidden (f)

intercombination (i)

g.s. 1s^2 ^{1}S


Rfir=1.2 R*
Rfir=2.1 R*
Rfir=4.0 R*
Count Rate (counts s⁻¹ Å⁻¹)
0.00
0.05
0.10
0.15
Wavelength (Å)
9.15
9.20
9.25
9.30
9.35
Y (R*)
X (R*)
-2
-1
0
1
2
3
4
5

Conclusions

- **Shock processes in O star winds** convert kinetic energy to heat and X-rays
- Three different mechanisms can operate
- Harder and stronger emission from CWS and MCWS
- But significant and sometimes moderately hard X-ray emission from EWS too
- Wind absorption effects are significant and can be used as a clumping-independent mass-loss rate diagnostic: **mass lass rates are lower** (factors of 3 to 5) than previously thought