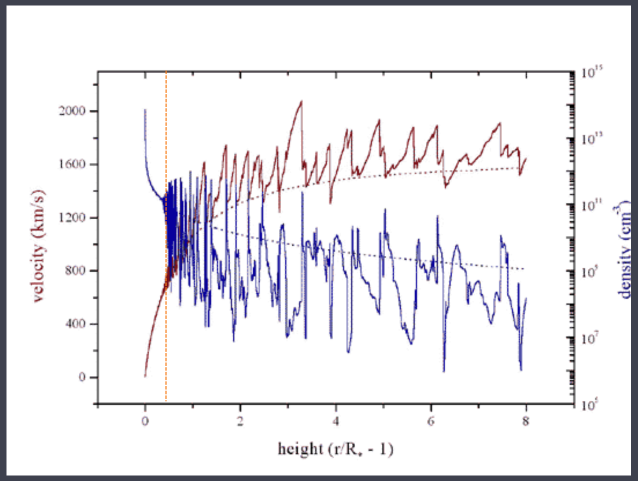
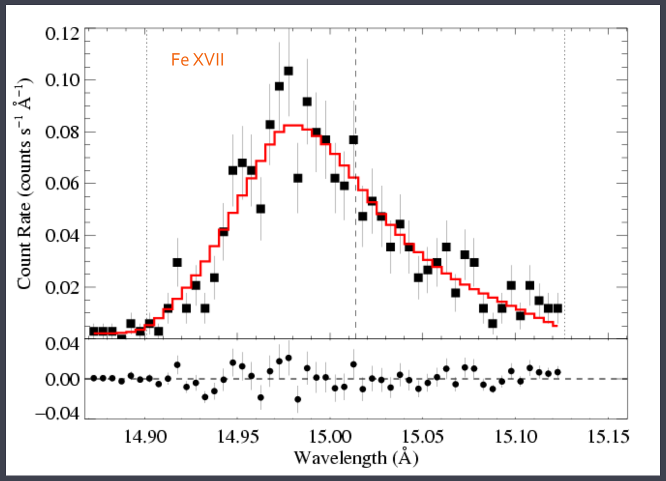
X-rays from the Winds of Massive Stars

David Cohen
Swarthmore College

with Stan Owocki (U. Delaware), Maurice Leutenegger (GSFC), Jon Sundqvist (Leuven), Véronique Petit (Florida Tech), Gregg Wade (RMC), Marc Gagné (West Chester University)
and
Emma Wollman (Swarthmore '09; JPL), Roban Kramer (Swarthmore '03), James MacArthur (Swarthmore '11; Stanford), Jackie Pezzato (Swarthmore '17)





Stellar surface temperatures range from 3000 to 50,000 K : red to blue

red stars are low mass and blue ones are massive

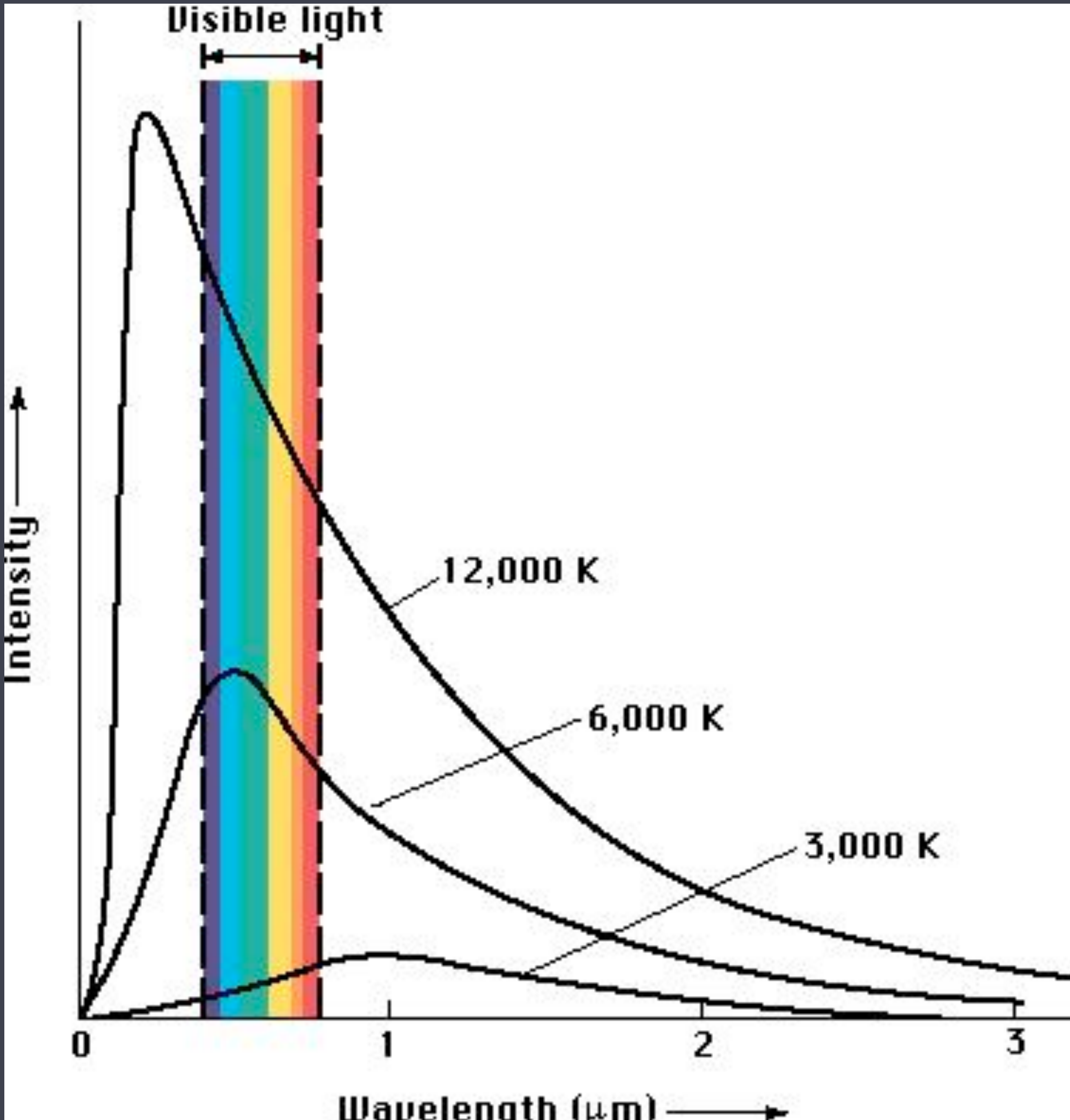
Basic properties of massive stars - O stars

mass ~ 50 M_{sun}
luminosity ~ 10^6 L_{sun} (Watts of radiated power)
surface temperature ~ 45,000 K ~ 8 T_{sun}

zeta Ori :
brightest O
star in the sky

Sun and full Moon - factor of a million (10^6) in brightness

Star's surface emission is basically blackbody



above T ~ 10,000 K most of a star's emission is in the UV

O stars are even more extreme: T > 30,000 K

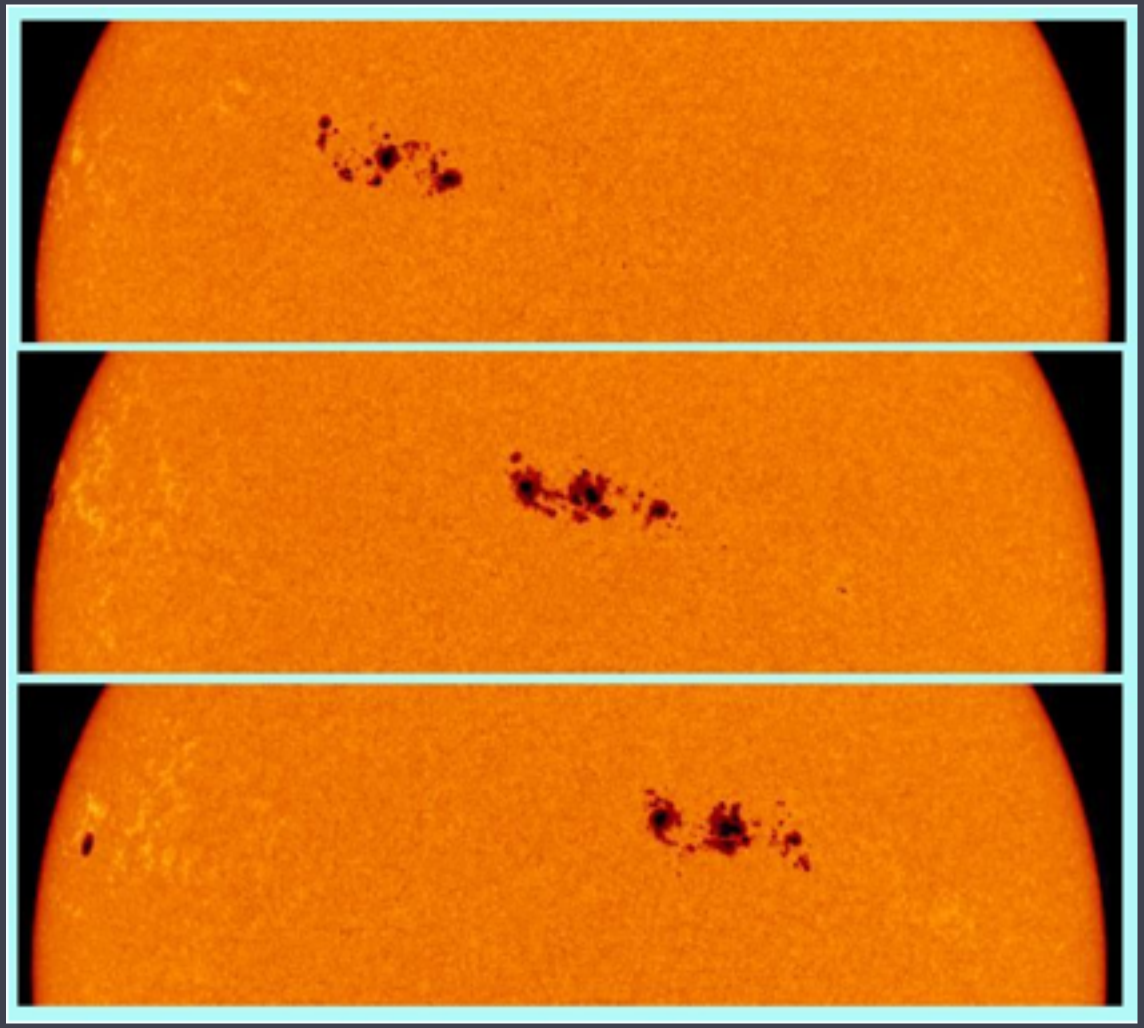
even so, **no X-ray** emission from the photospheres (surfaces) of even the hottest stars

cool stars vs. hot stars

starfish, *in situ*, at the Monterey (California) Aquarium

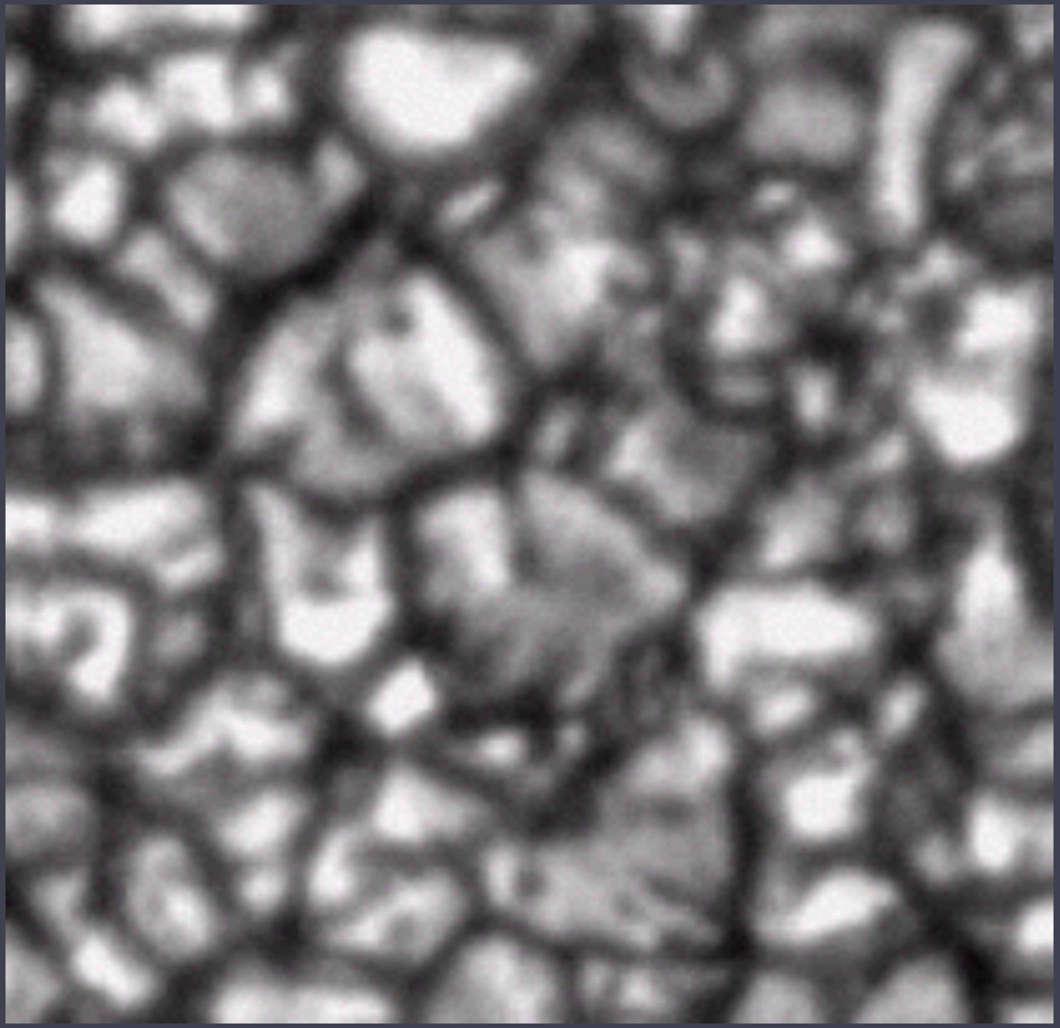
The Sun's **X-ray emission** is associated with its magnetic dynamo (rotation + convection are key ingredients)

rotation



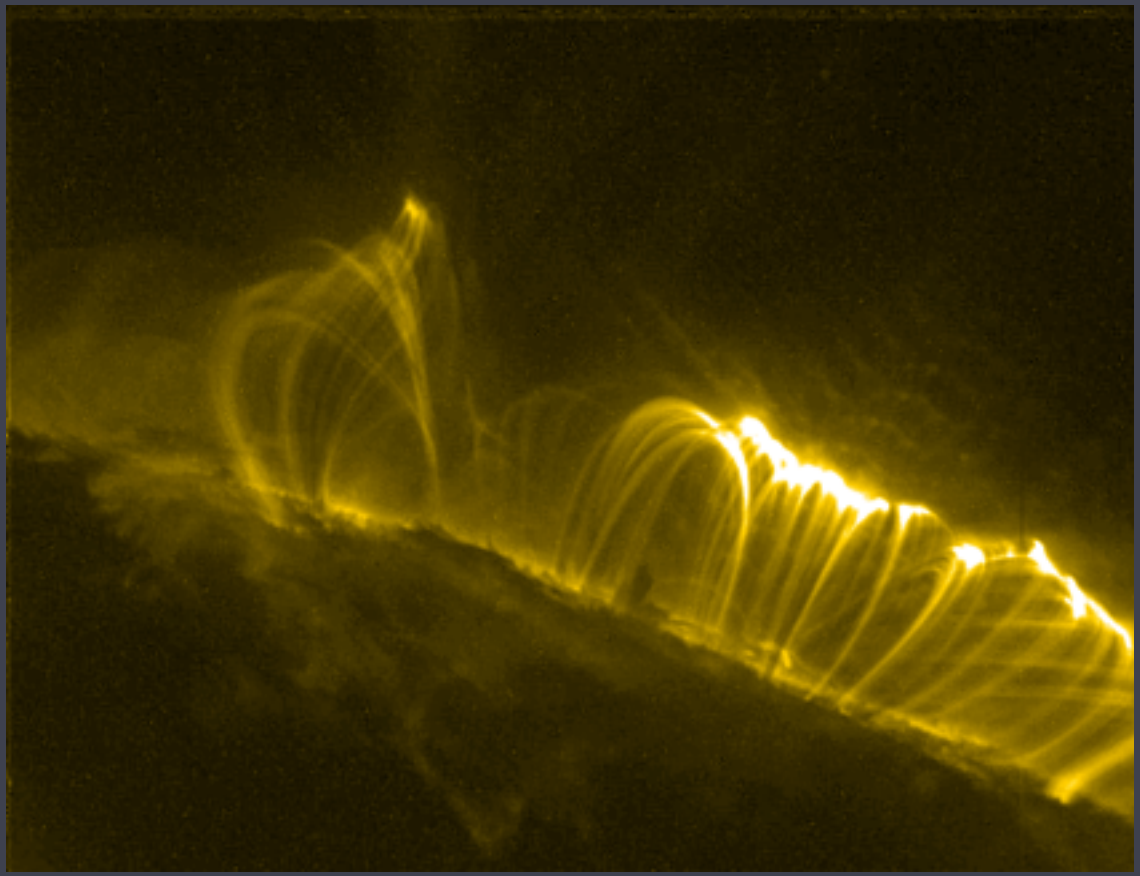
sunspots rotate across our field of view in a few days

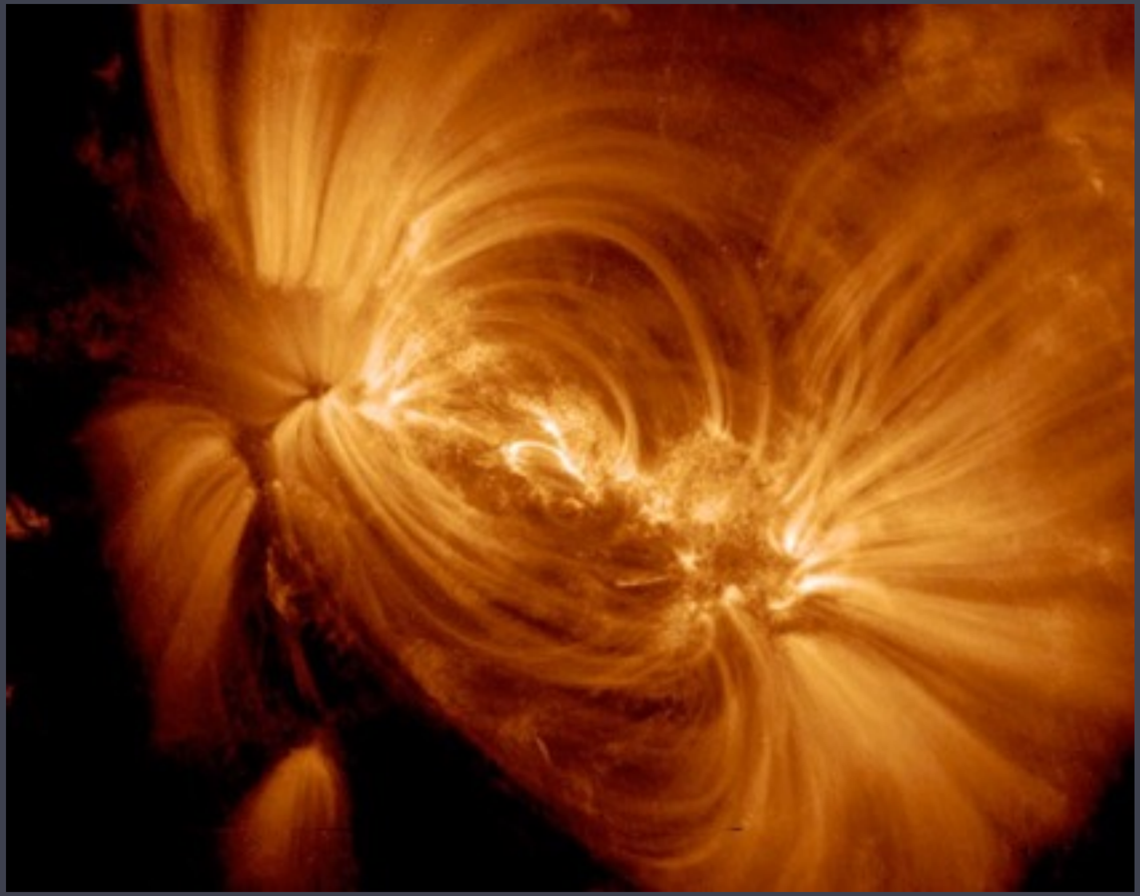
convection

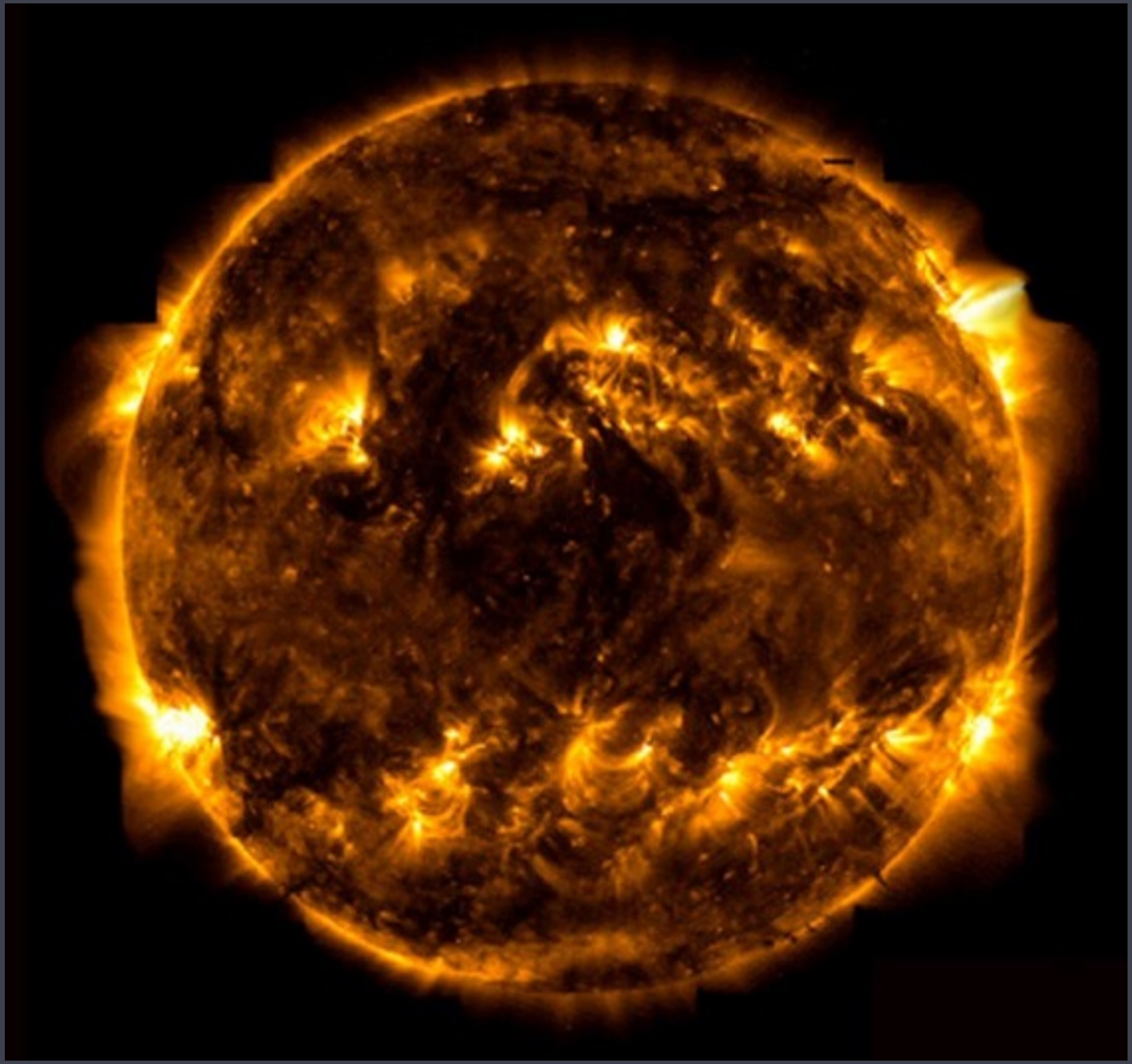


area roughly the size of the Earth

The Sun in the extreme ultraviolet







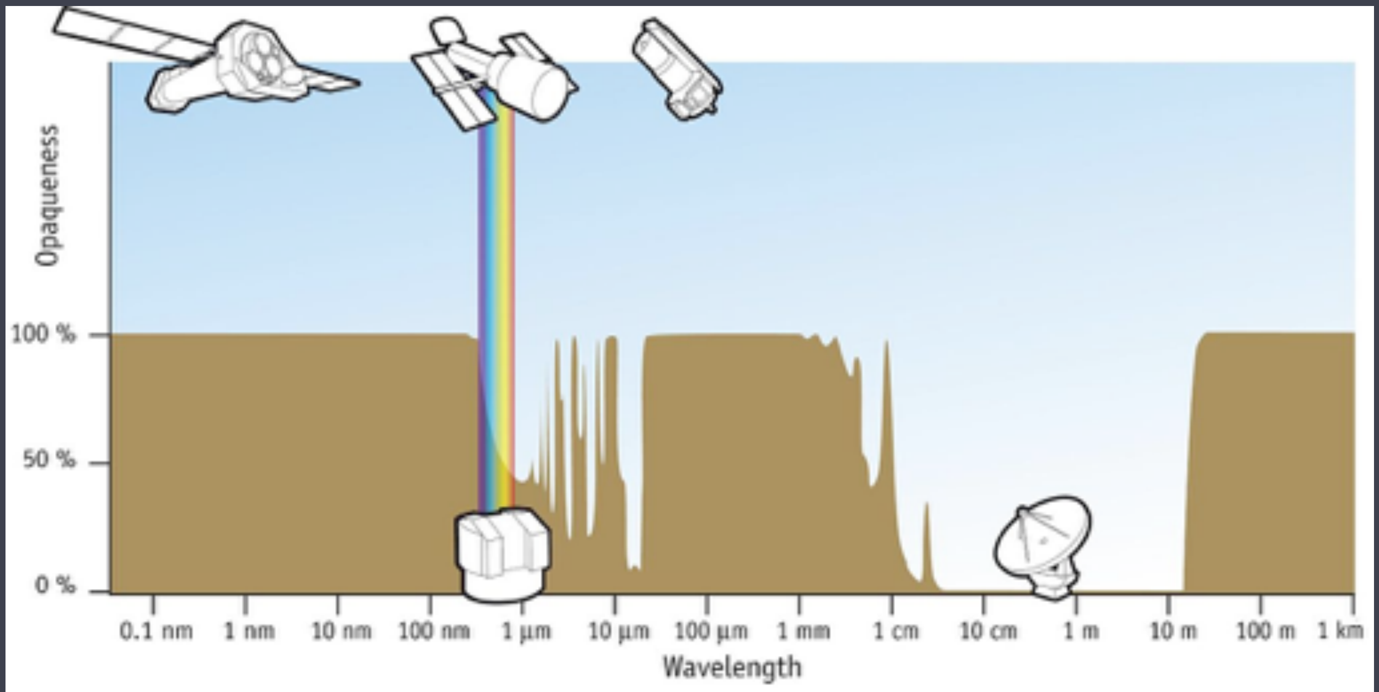
NASA: TRACE

X-ray Astronomy was born in the 1960-70's

state of knowledge in the mid-70s:

Massive stars don't have convective surfaces

And they don't have magnetic fields (with a few notable exceptions)



F. Granato (ESA/Hubble) - ESA/Hubble

Einstein X-ray Observatory launched 1978

unexpected discovery of massive star X-ray emission in 1979

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
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ABSTRACT

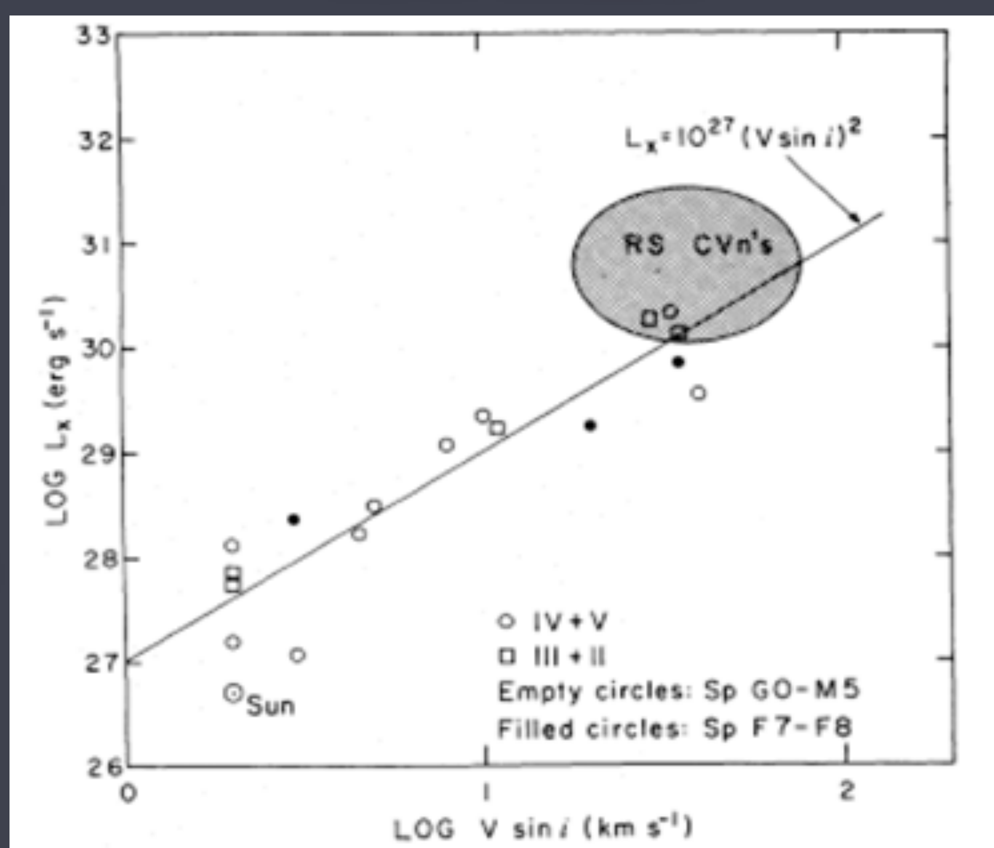
A group of six X-ray sources located within 0°.4 of Cygnus X-3 has been discovered with the *Einstein* Observatory. These sources have been positively identified and five of them correspond to stars in the heavily obscured OB association VI Cygni. The optical counterparts include four of the most luminous 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 $N_H \sim 10^{22}$ cm^{-2}, and therefore comprise a new class of low-luminosity galactic X-ray sources associated with early-type stars.

Massive star X-ray emission is different from low-mass stellar X-ray emission

No observed correlation between rotation and X-rays for the massive stars

low mass

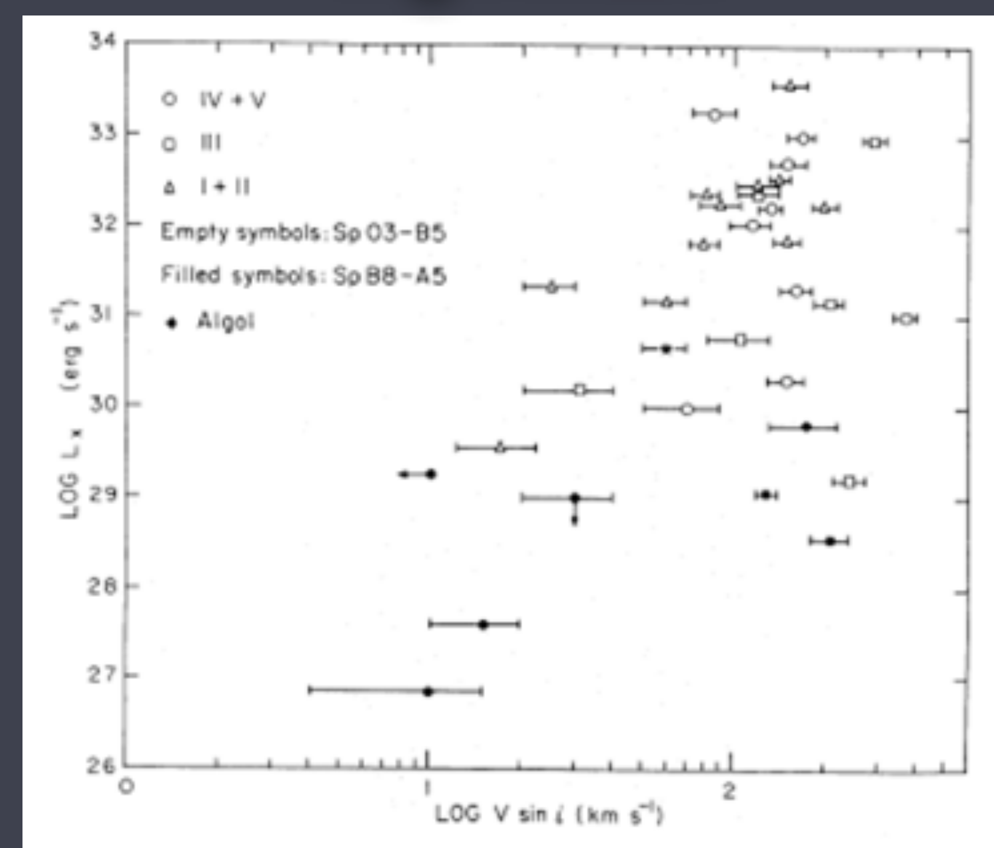
X-ray luminosity



rotation

high mass

X-ray luminosity



rotation

Astron. Astrophys. 322, 167–174 (1997)

ASTRONOMY
AND
ASTROPHYSICS

X-ray properties of bright OB-type stars detected in the ROSAT all-sky survey

T.W. Berghöfer[1,2*], J.H.M.M. Schmitt[1], R. Danner[1,3], and J.P. Cassinelli[4]

[1] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstr, 1, D-85740 Garching, Germany
[2] Center for EUV Astrophysics, 2150 Kittredge Street, University of California, Berkeley, CA 94720, USA
[3] Division of Physics, Mathematics, and Astronomy, Caltech 105-24, Pasadena, CA 91125, USA
[4] University of Wisconsin - Madison, Department of Astronomy, 475 North Charter Street, Madison, WI 53706-1582, USA

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We demonstrate that the "canonical" relation between X-ray and total luminosity of $L_x/L_{Bol} \approx 10^{-7}$ valid for O-type stars extends among the early B-type stars down to a spectral type B1–B1.5; for stars of luminosity classes I and II the spectral type B1 defines a dividing line for early-type star X-ray emission.

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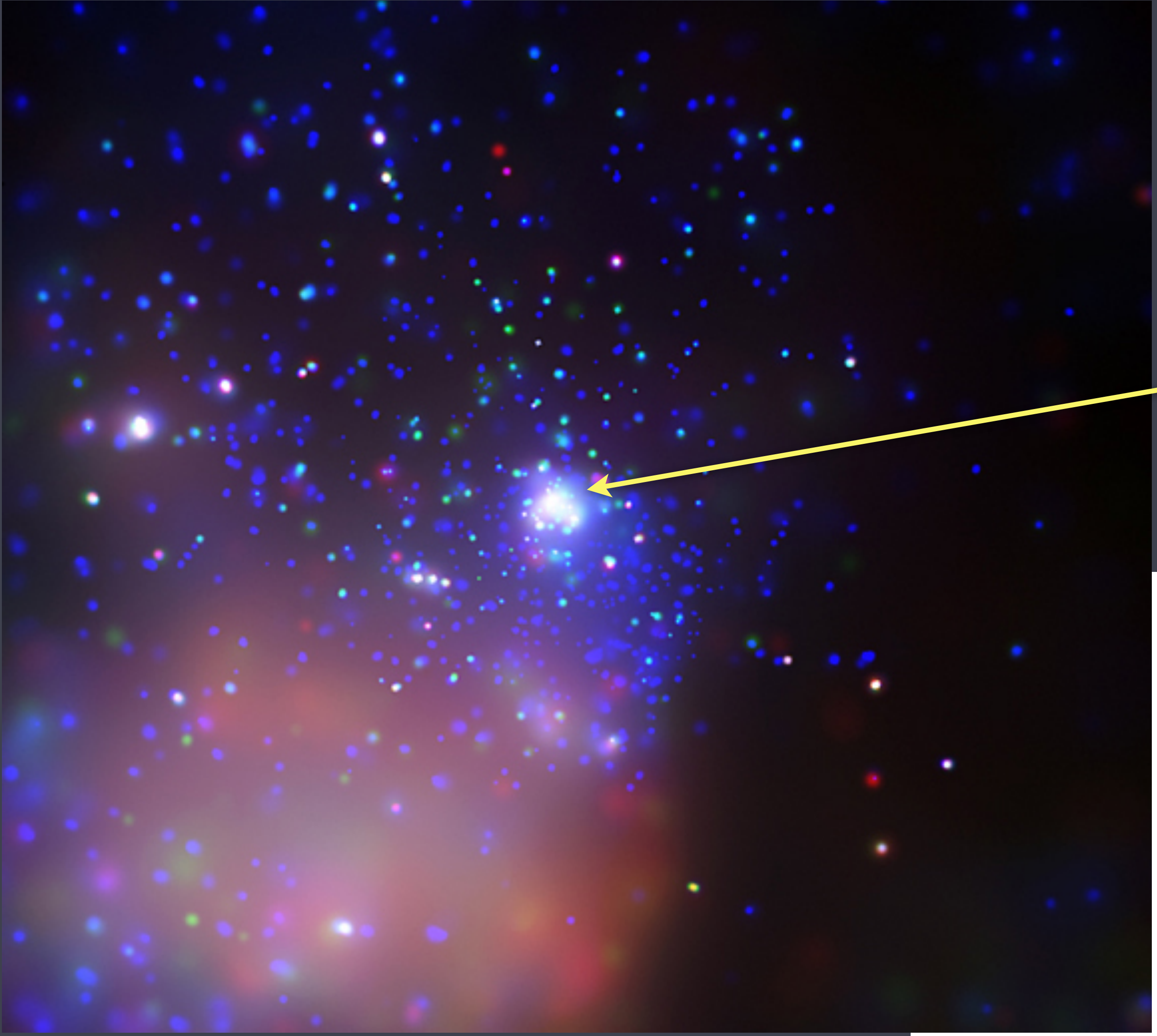
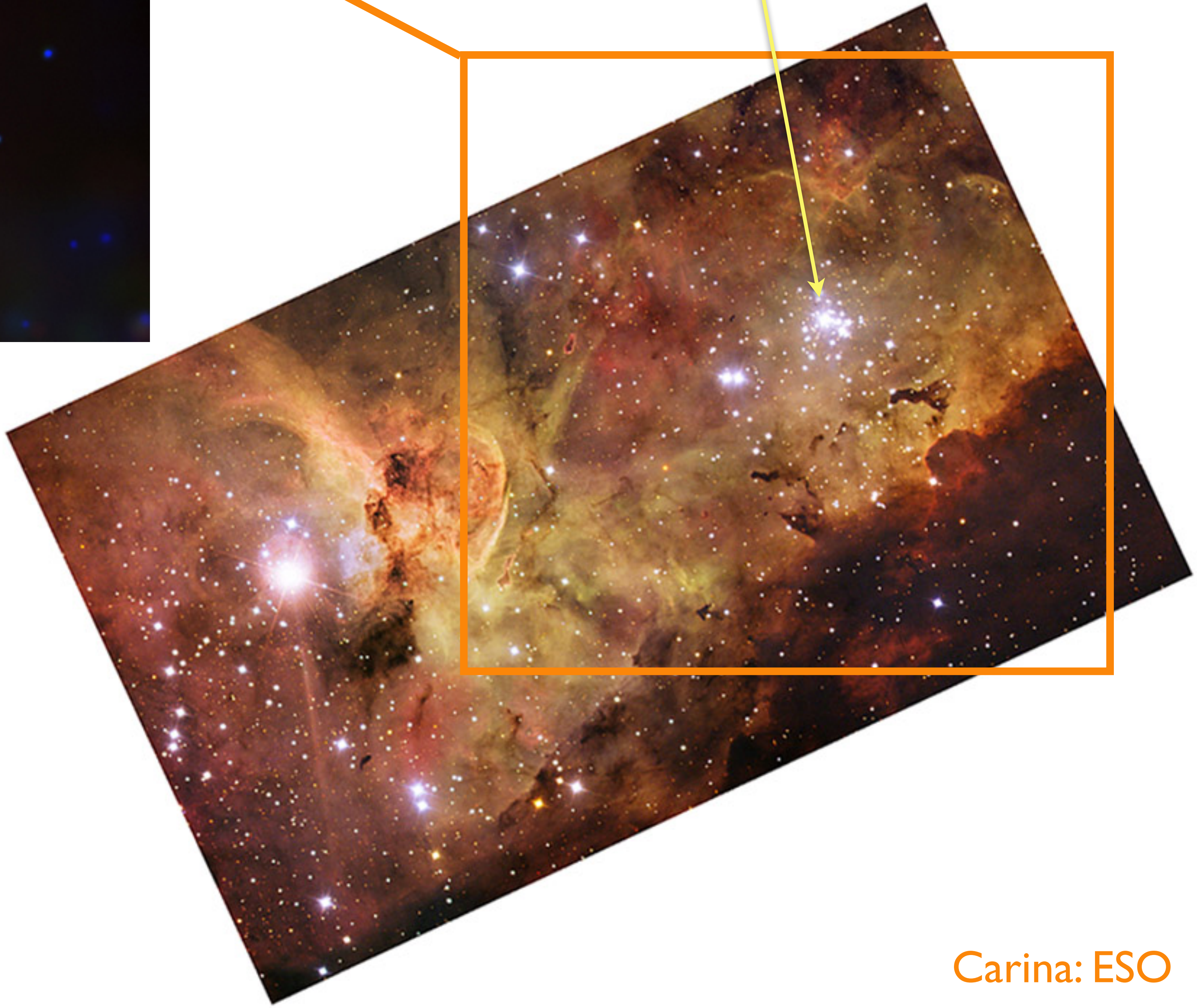
The Carina Complex

X-ray image to the left

HD 93129A (O2If*)



Tr 14 in Carina: *Chandra*



Carina: ESO

O Stars are characterized by their dense **stellar winds**

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

Carina (Hubble Space Telescope)

These winds are the site and energy source of the X-ray emission

Carina (Hubble Space Telescope)

wind-blown bubble around a massive star

NGC 6888 Crescent Nebula - Tony Hallas

In general, X-ray **imaging** of massive stars is not so useful

...use **spectroscopy** as a proxy for imaging

Chandra launched in 1999 - first high-resolution X-ray spectrograph

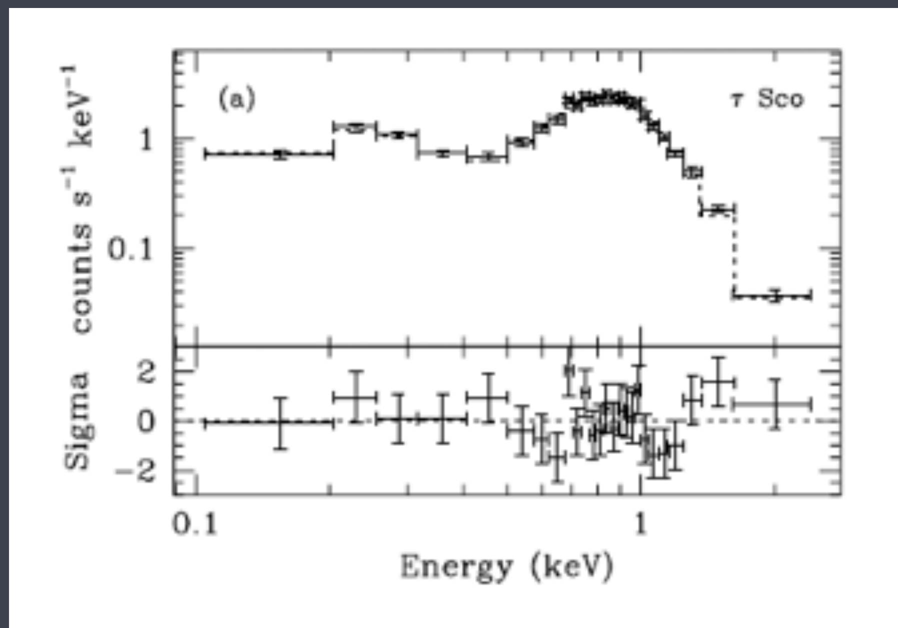
response to photons with $h\nu$ ~ 0.5 keV up to a few keV (corresp. ~5Å to 24Å)

X-ray imaging? > 0.5 arc sec, at best (100s of AU)

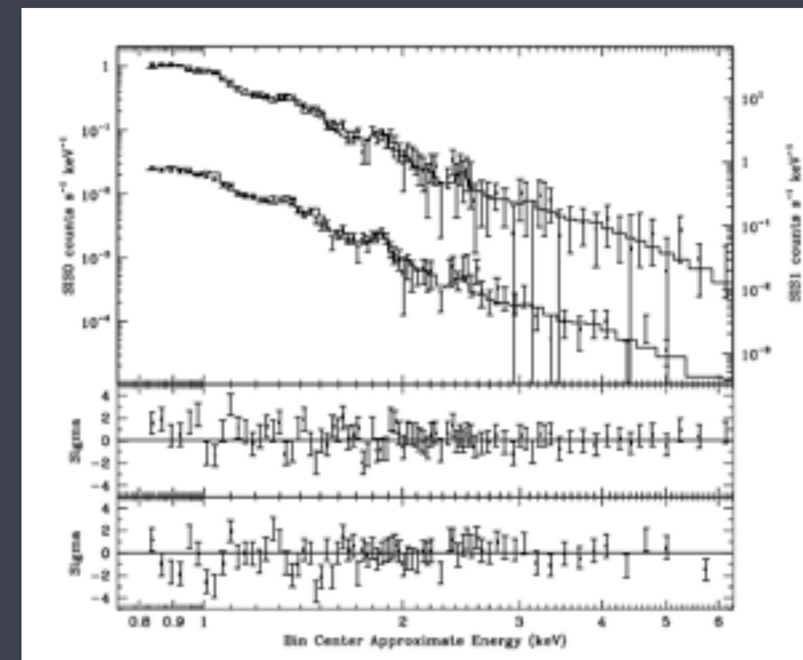
spectroscopy ($\lambda/\Delta\lambda$ < 1000 corresp. v > 300 km/s)

now for some X-ray data... the same star (tau Sco) observed with three different X-ray telescopes

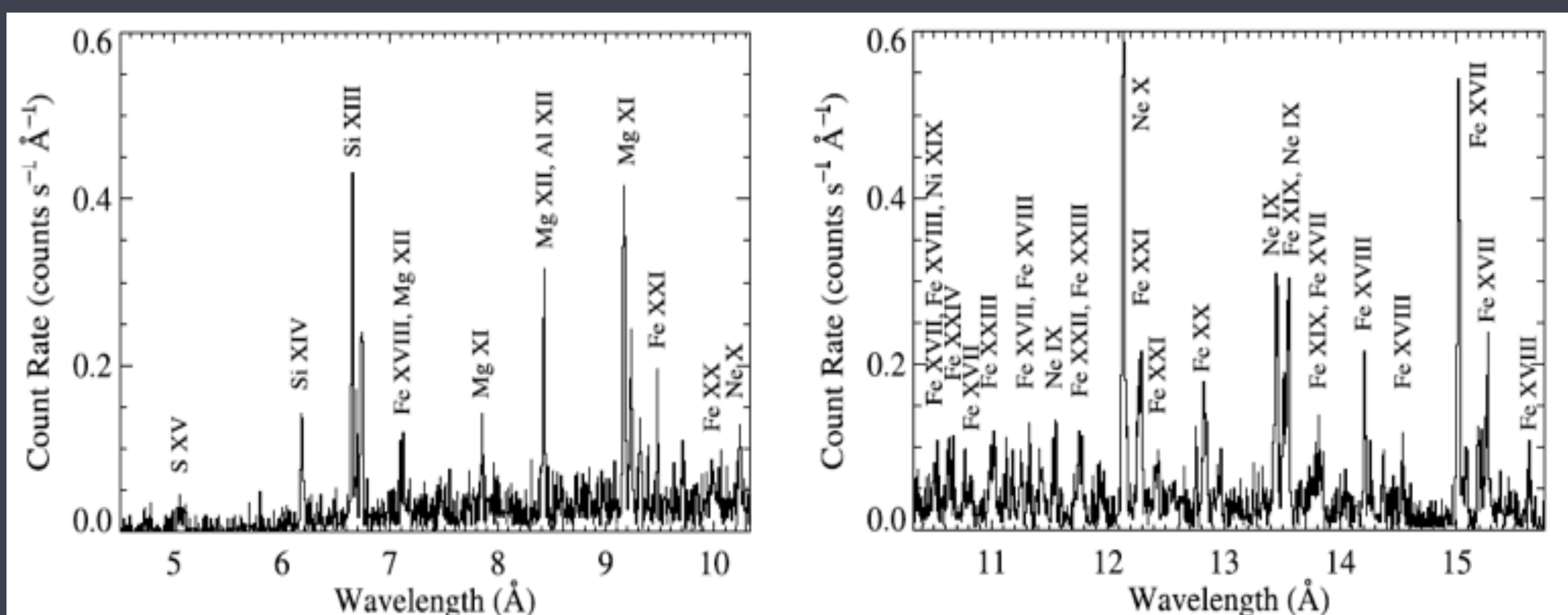
ROSAT 1991



ASCA 1994

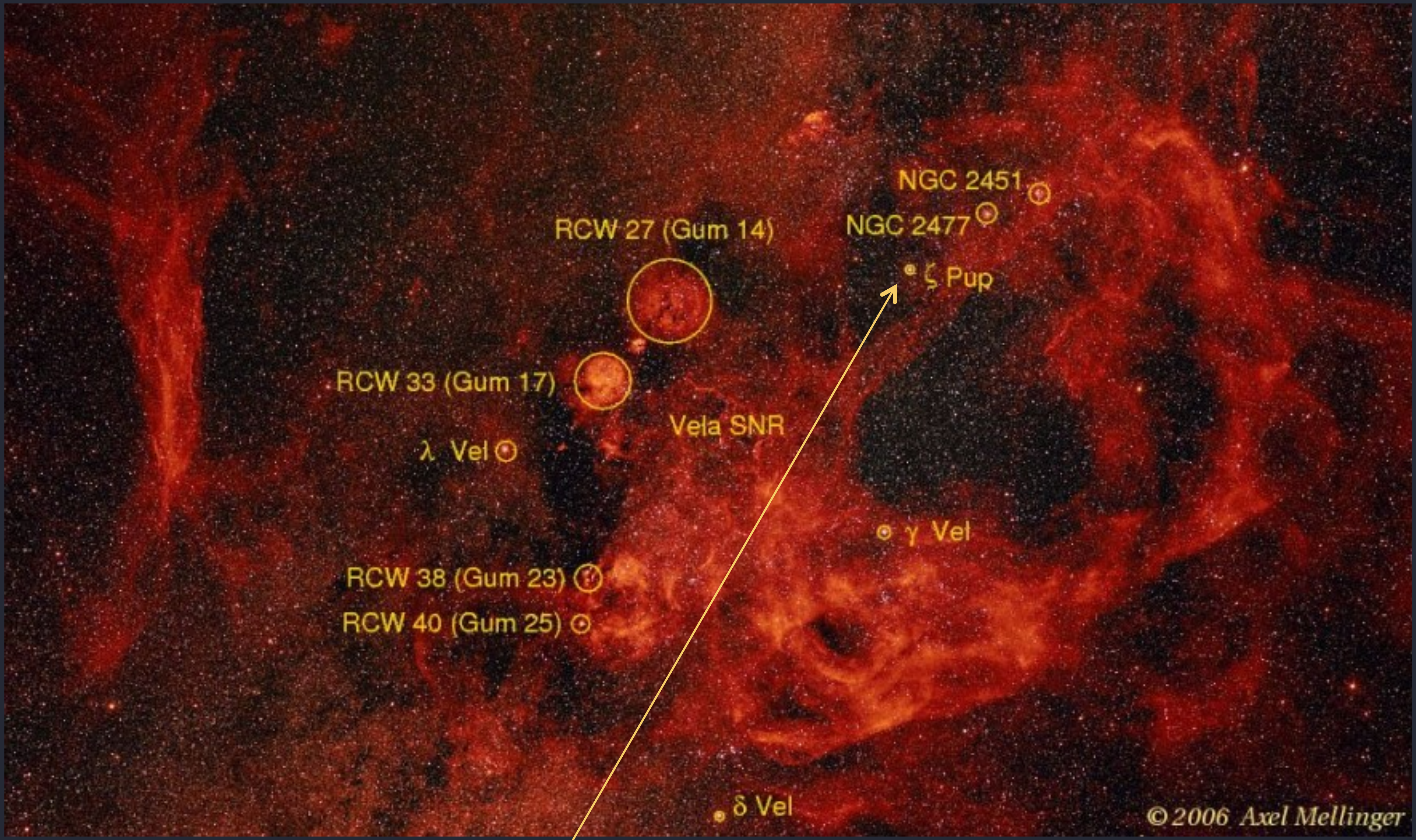


Chandra 2001



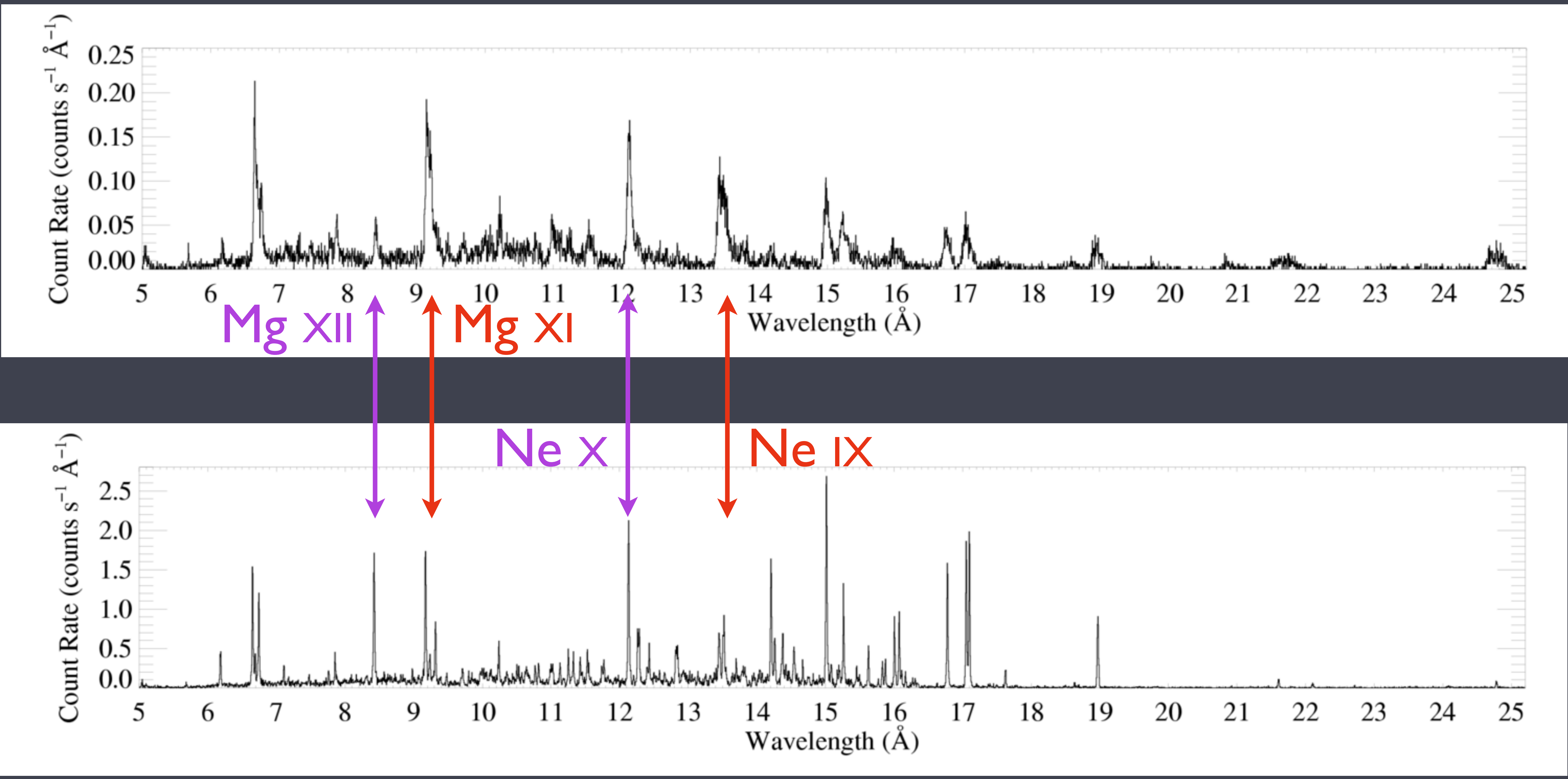
Chandra grating spectroscopy

ζ Pup (O4 If)



Chandra grating (HETGS/MEG) spectra

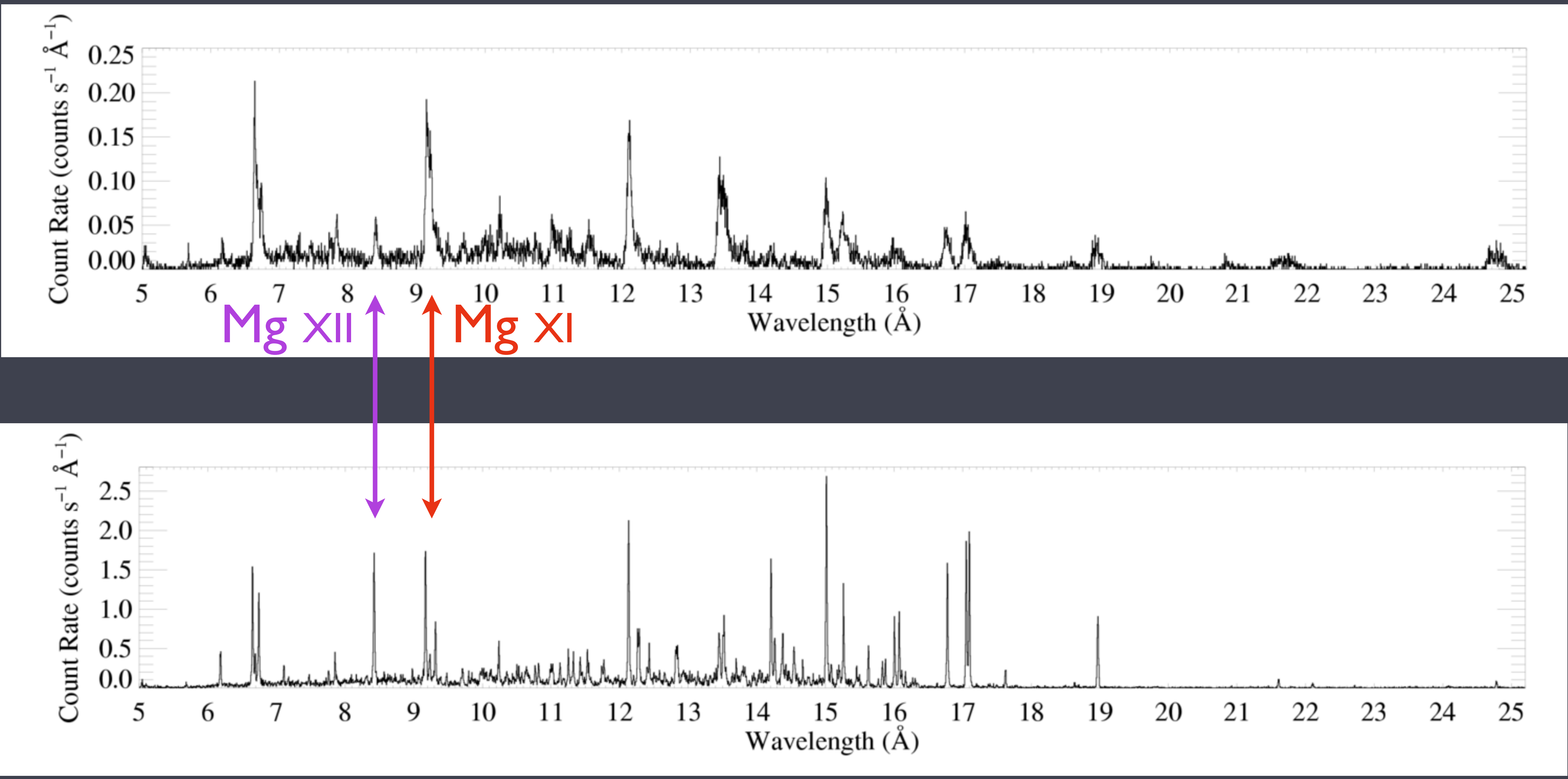
ζ Pup (O4 If)



Capella (G5 III)

typical temperatures $T \sim$ few 10^6 K
(low-mass stars' coronae tend to be hotter)

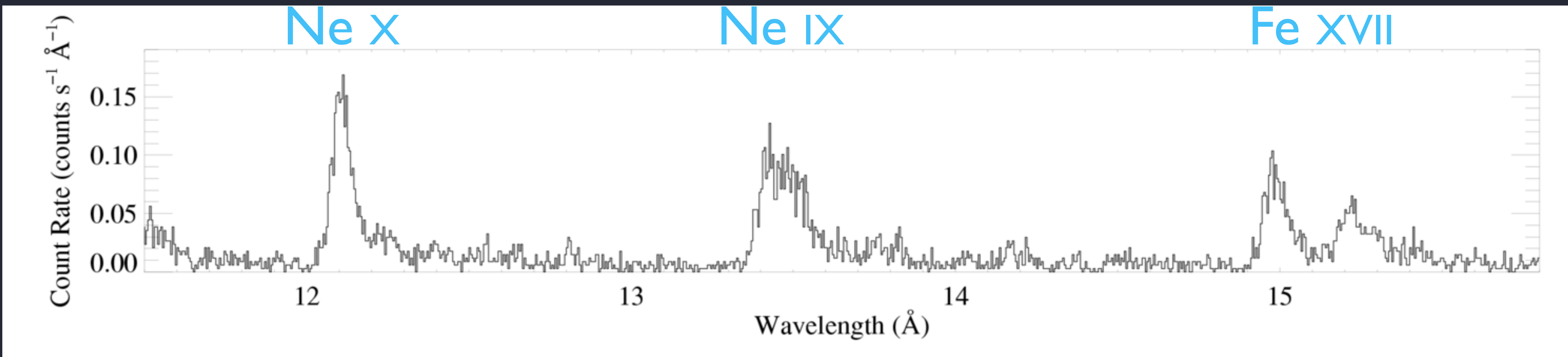
ζ Pup (O4 If)

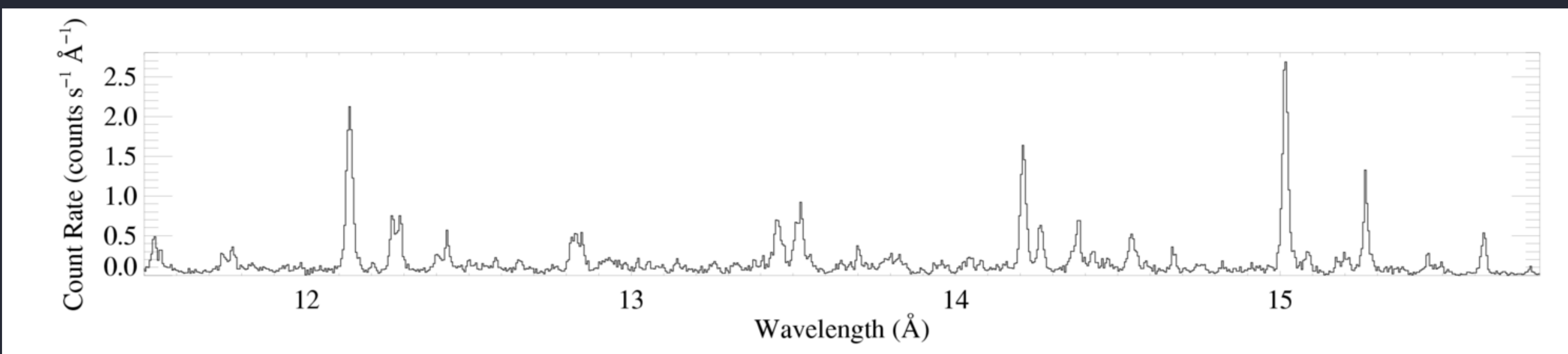


Capella (G5 III)

Zoom in

ζ Pup (O4 If)

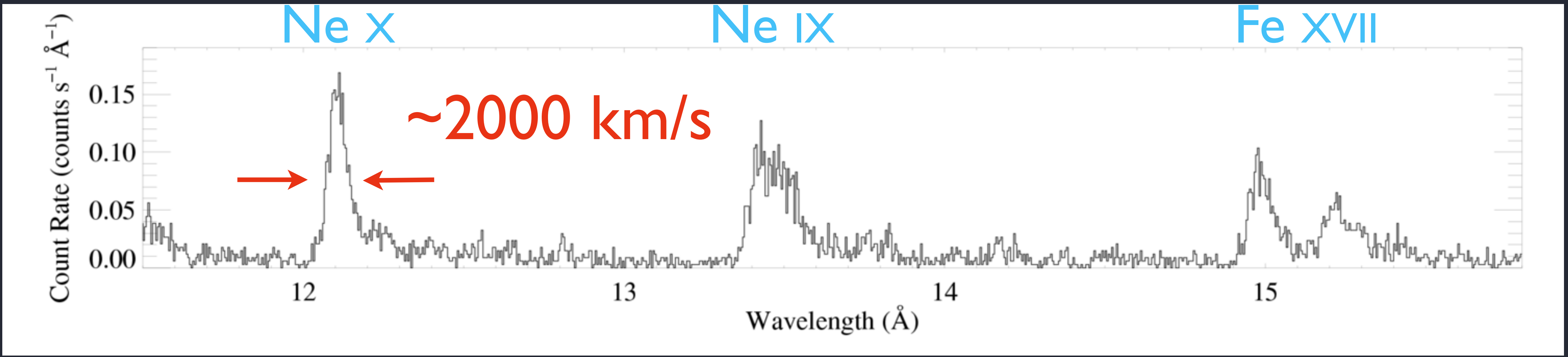


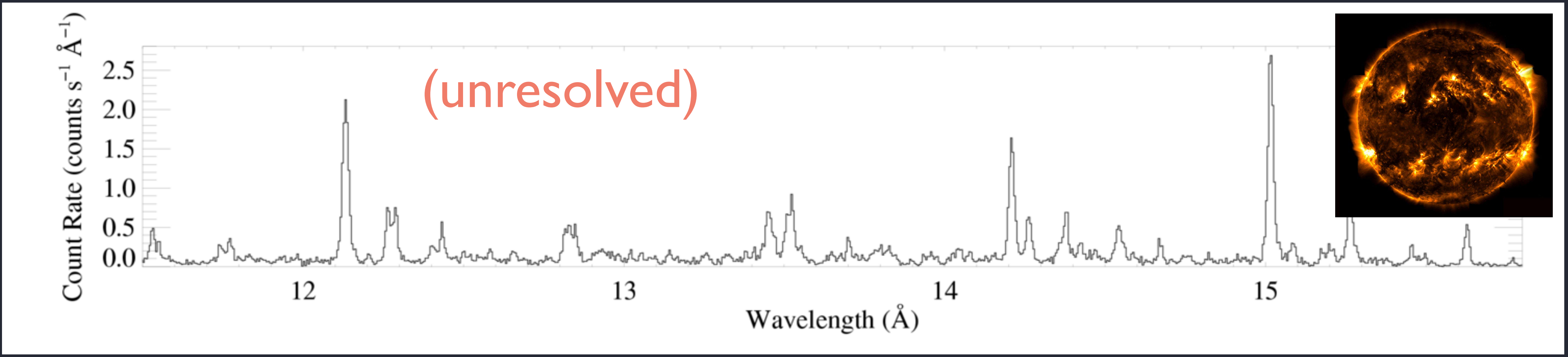


Capella (G5 III)

Zoom in

ζ Pup (O4 If)

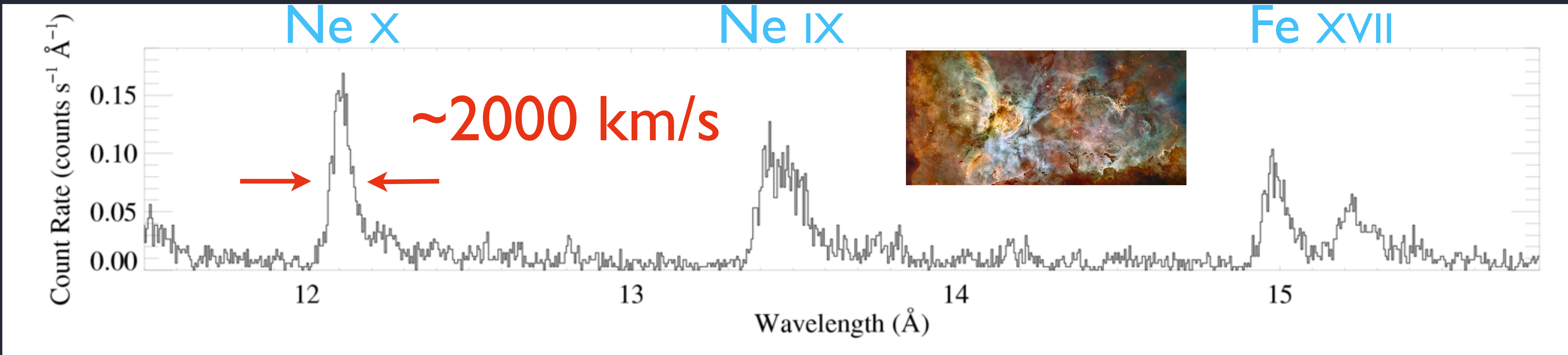


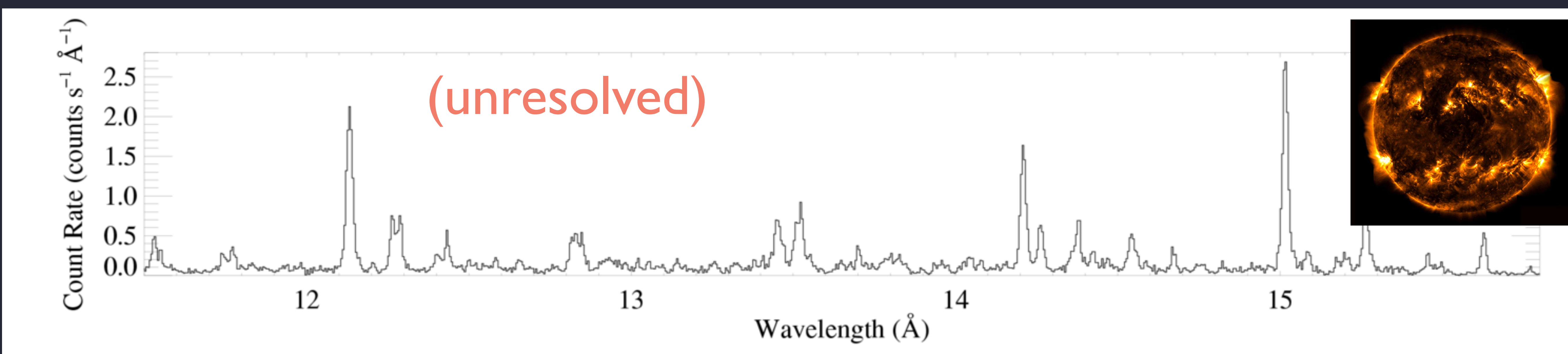


Capella (G5 III)

conclusive evidence that the X-ray plasma is in the stellar wind

ζ Pup (O4 If)





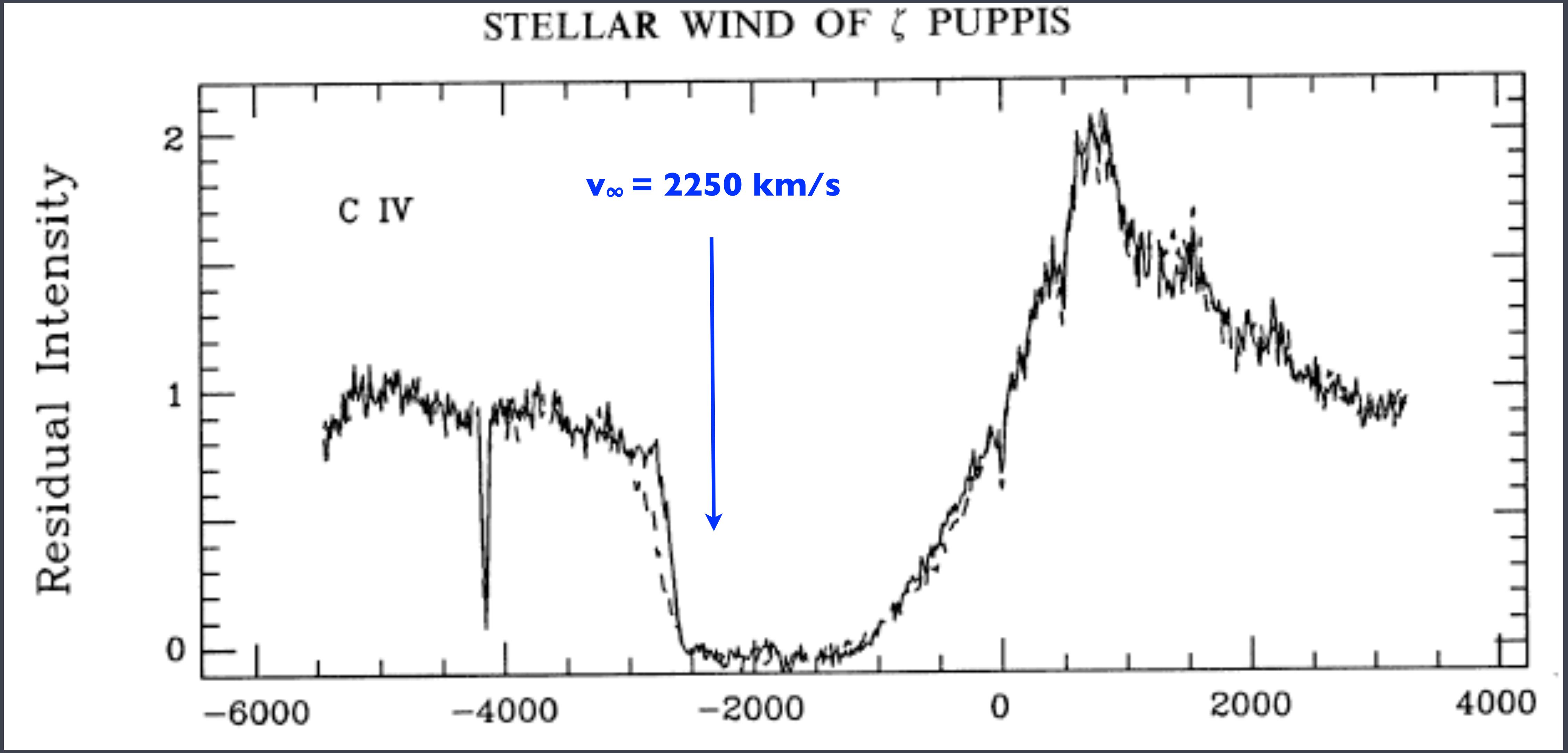
Capella (G5 III)

radiation-driven winds

Ultraviolet spectral line: wind signature "P Cygni profile"

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

UV spectrum: C IV 1548, 1551 Å

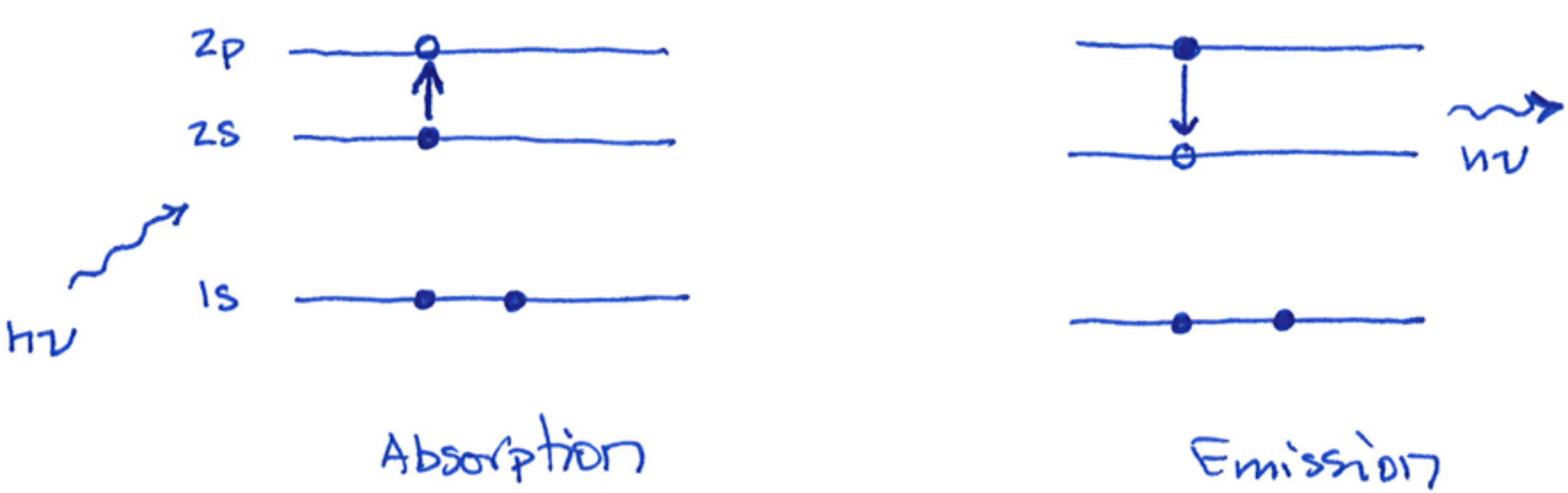


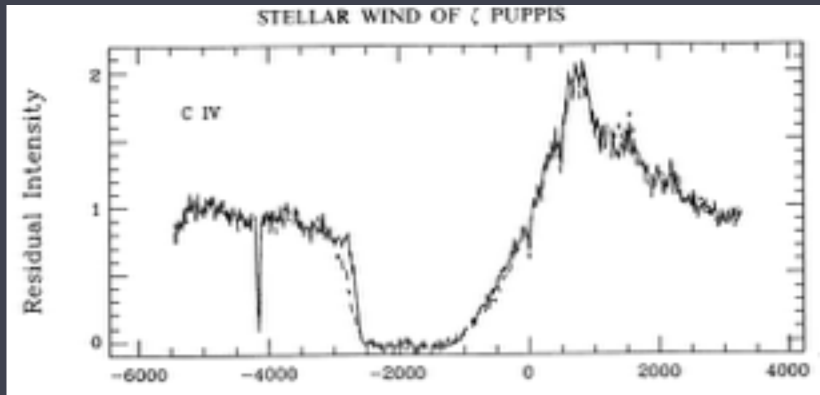
Velocity (km/s)

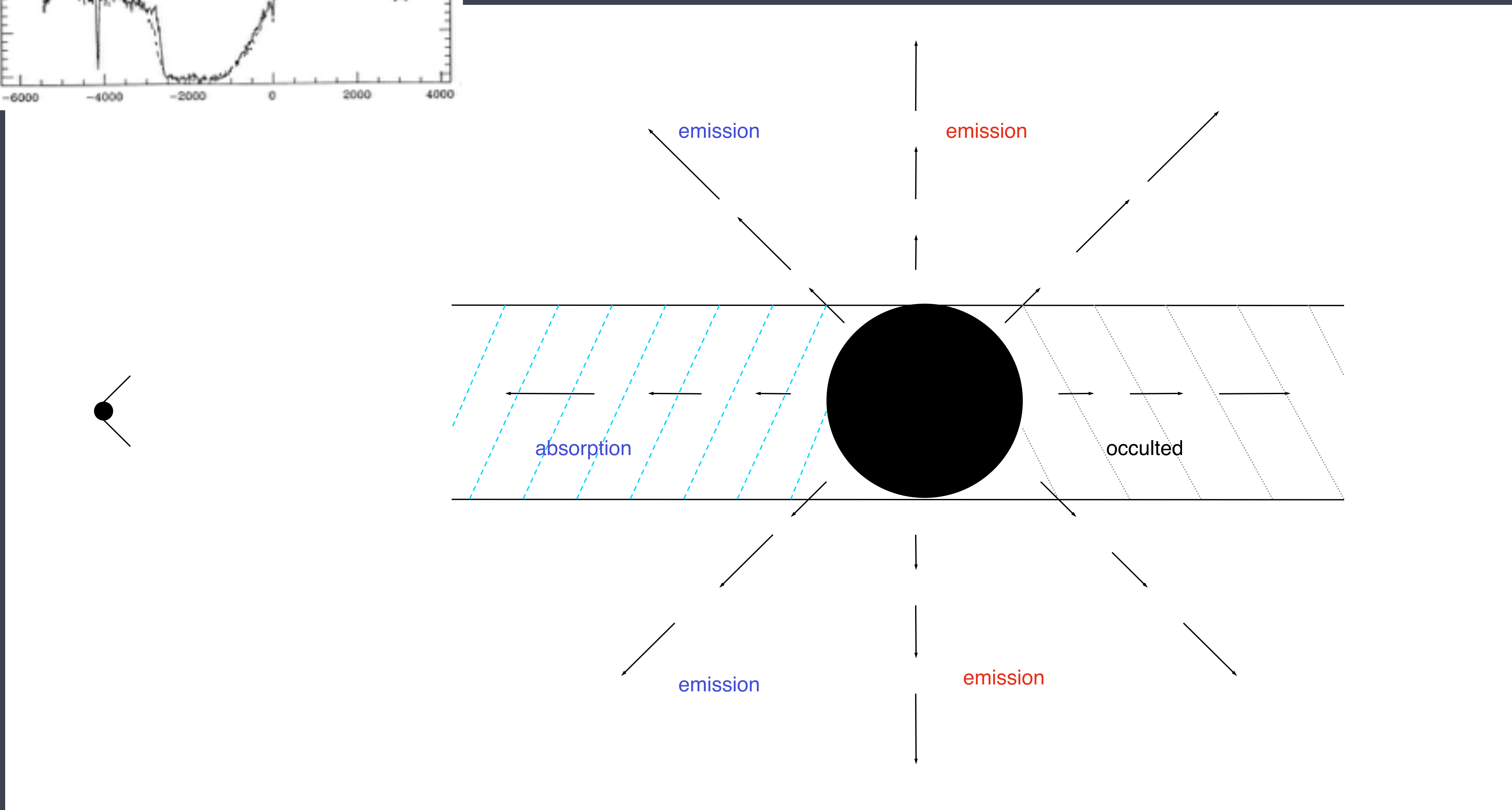
Prinja et al. 1992, ApJ, 390, 266

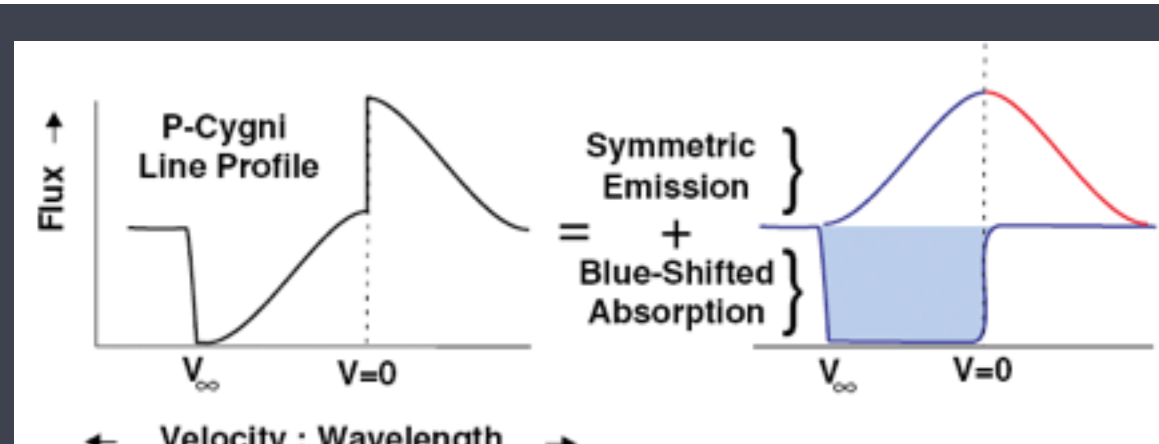
absorption and emission: atomic energy level diagrams

C^{+3} is lithium-like




STELLAR WIND OF ζ PUPPIS
C IV
Residual Intensity
2
1
0
-6000
-4000
-2000
0
2000
4000

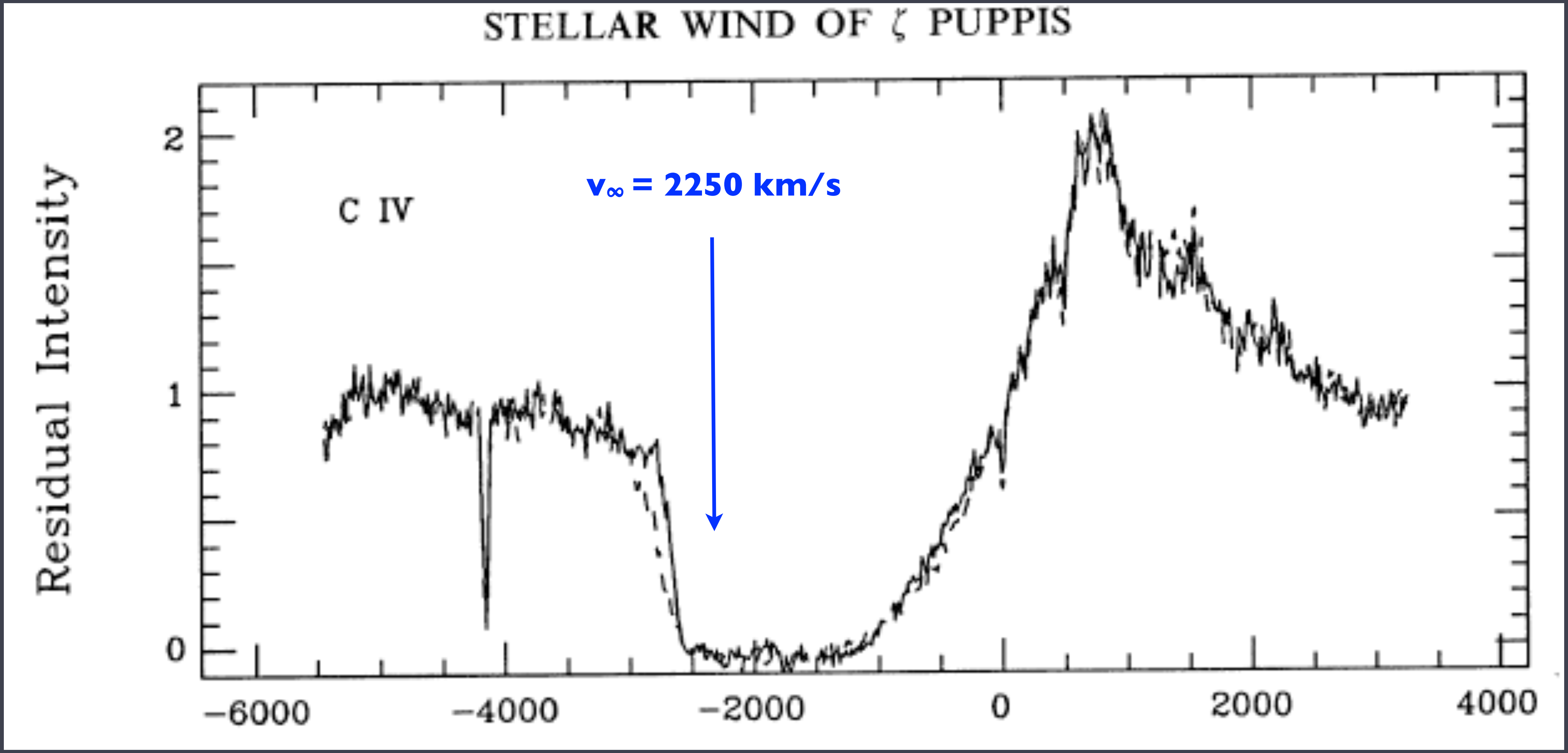

emission
emission
absorption
occulted
emission
emission


Flux
P-Cygni
Line Profile
Symmetric
Emission
=
+
Blue-Shifted
Absorption
V∞
V=0
V∞
V=0
Velocity ; Wavelength

Terminal (asymptotic) wind velocity

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

UV spectrum: C IV 1548, 1551 Å



Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

Physics of line-driven winds

radiation couples the momentum in the starlight to the matter in the wind via resonance line scattering in C, N, O, Fe,…

$\dot{M} \sim 10^{-6}\ M_{sun}/yr$ (10^{8} times the Sun's value)

kinetic power in the wind = $1/2\ \dot{M} v_{\infty}^{2}$ ($\sim 10^{-3}\ L_{star}$)

Radiation Force on an atom

$h\nu$ (energy)

$\frac{h\nu}{c}$ (momentum, p)

<u>rate</u> at which atom absorbs momentum $\quad \frac{dp}{dt} = F_{rad}$

luminosity, star's power output (watts)

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

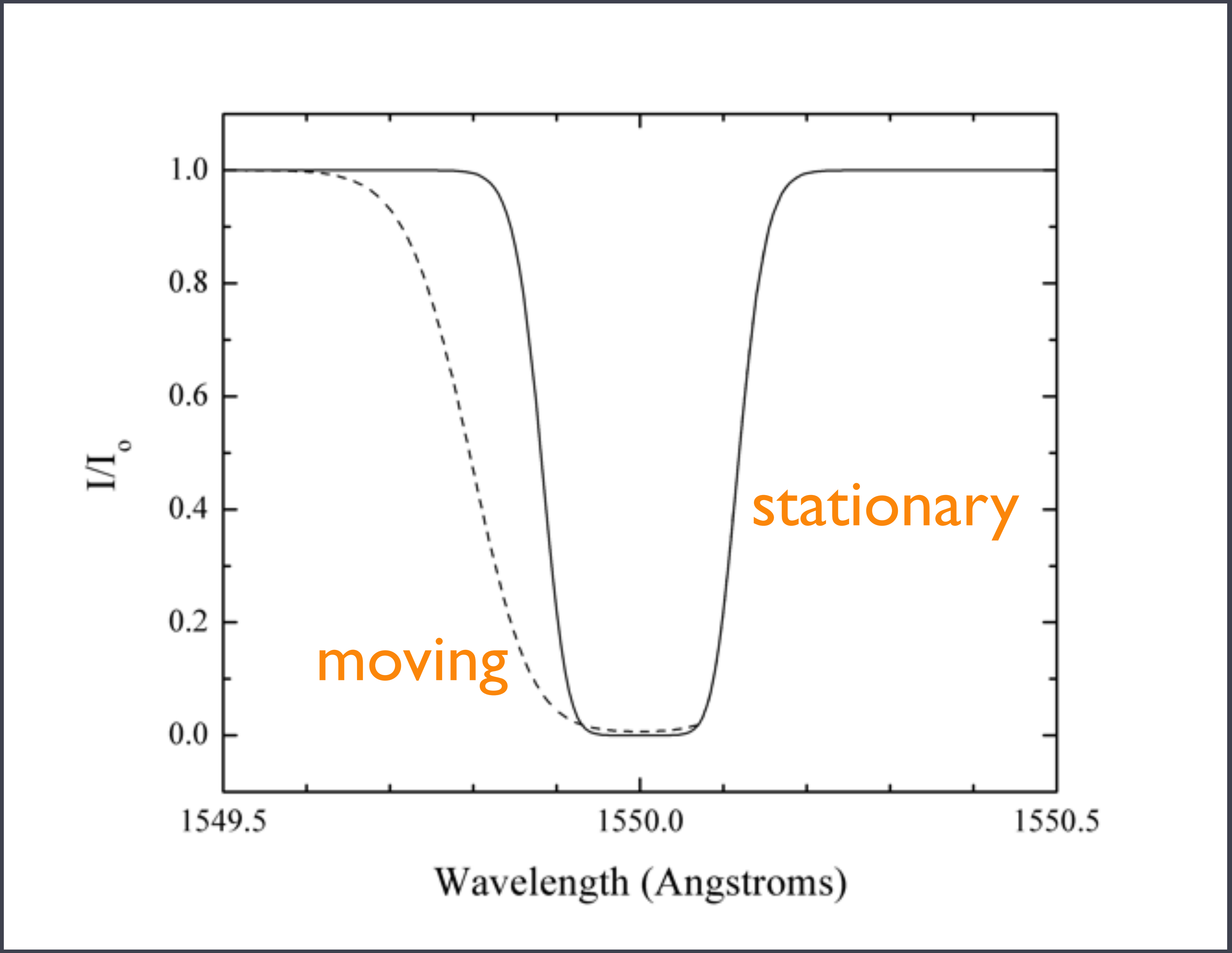
absorption cross section of atom (m^2)

Three things to consider when we consider *line*-driven winds

1. Bound electrons (10^7 times as efficient as free electrons)
2. But strong lines are saturated
3. Doppler shift will *desaturate* them

Doppler desaturation is key to line-driven winds

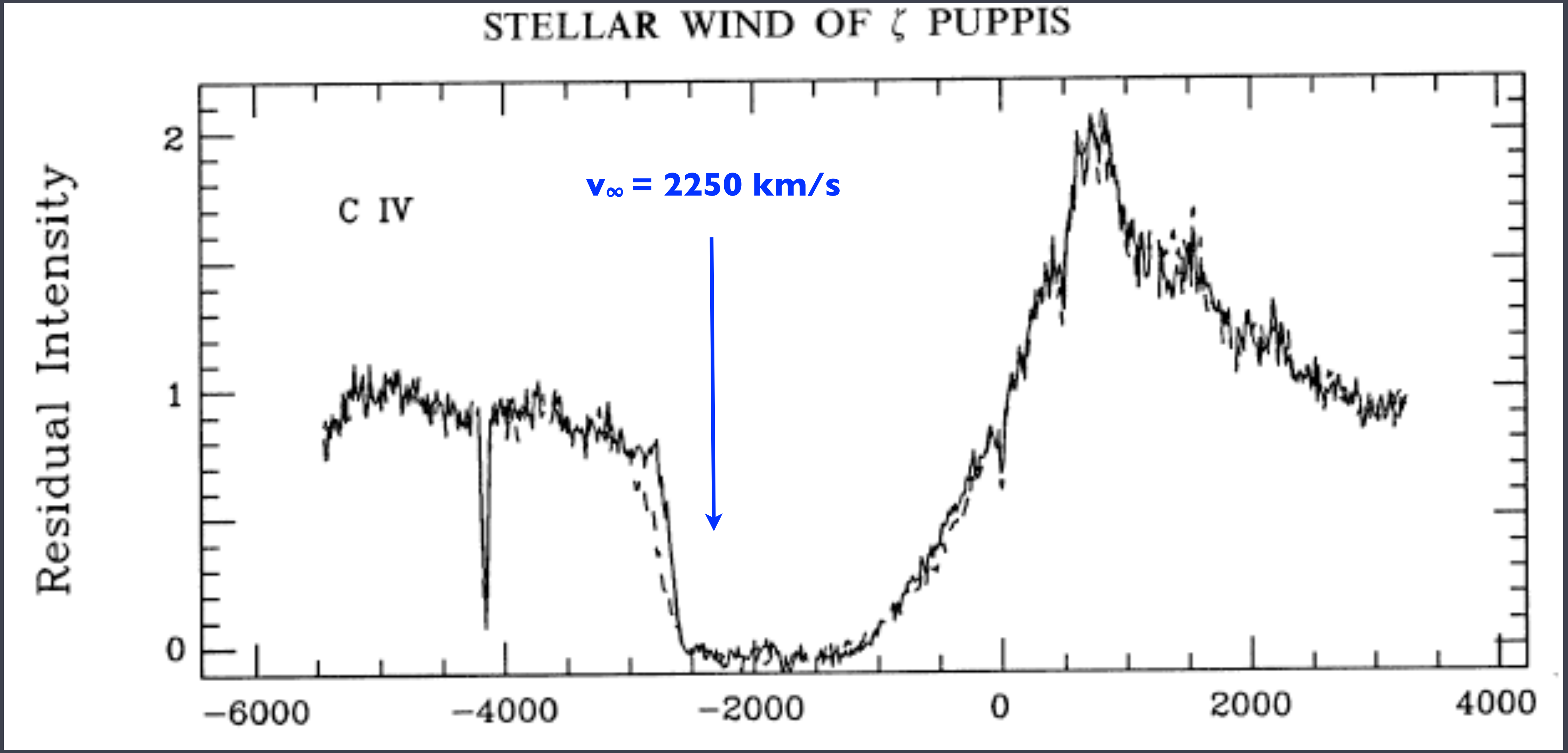
line strength increases in a moving medium



~10^{-3} of the radiative power of the star goes into the wind

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

UV spectrum: C IV 1548, 1551 Å



Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

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ASTRONOMY AND ASTROPHYSICS

~10^{-4} of the wind power is converted to X-rays

X-ray properties of bright OB-type stars detected in the ROSAT all-sky survey

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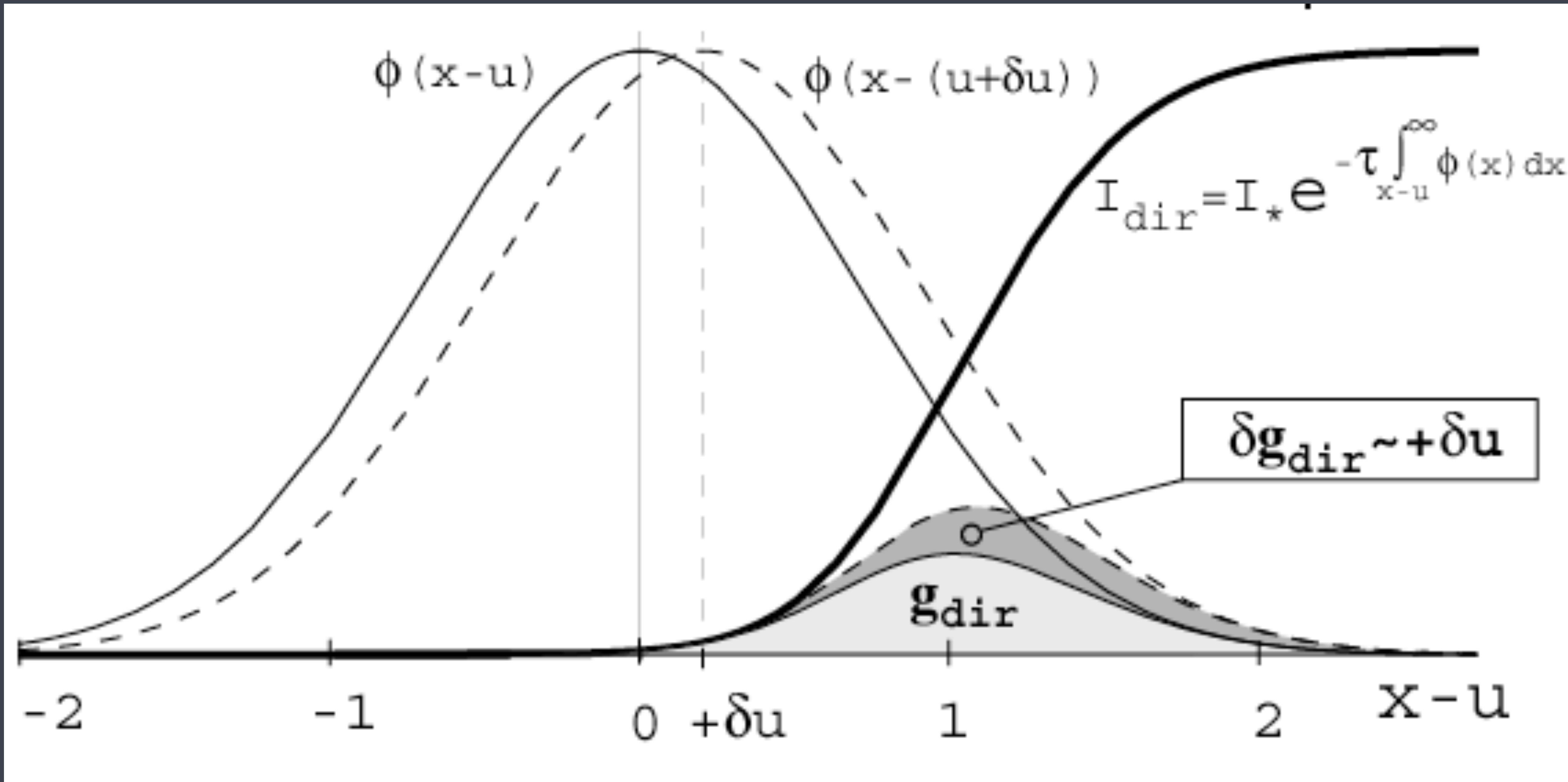
The line-deshadowing instability (LDI)

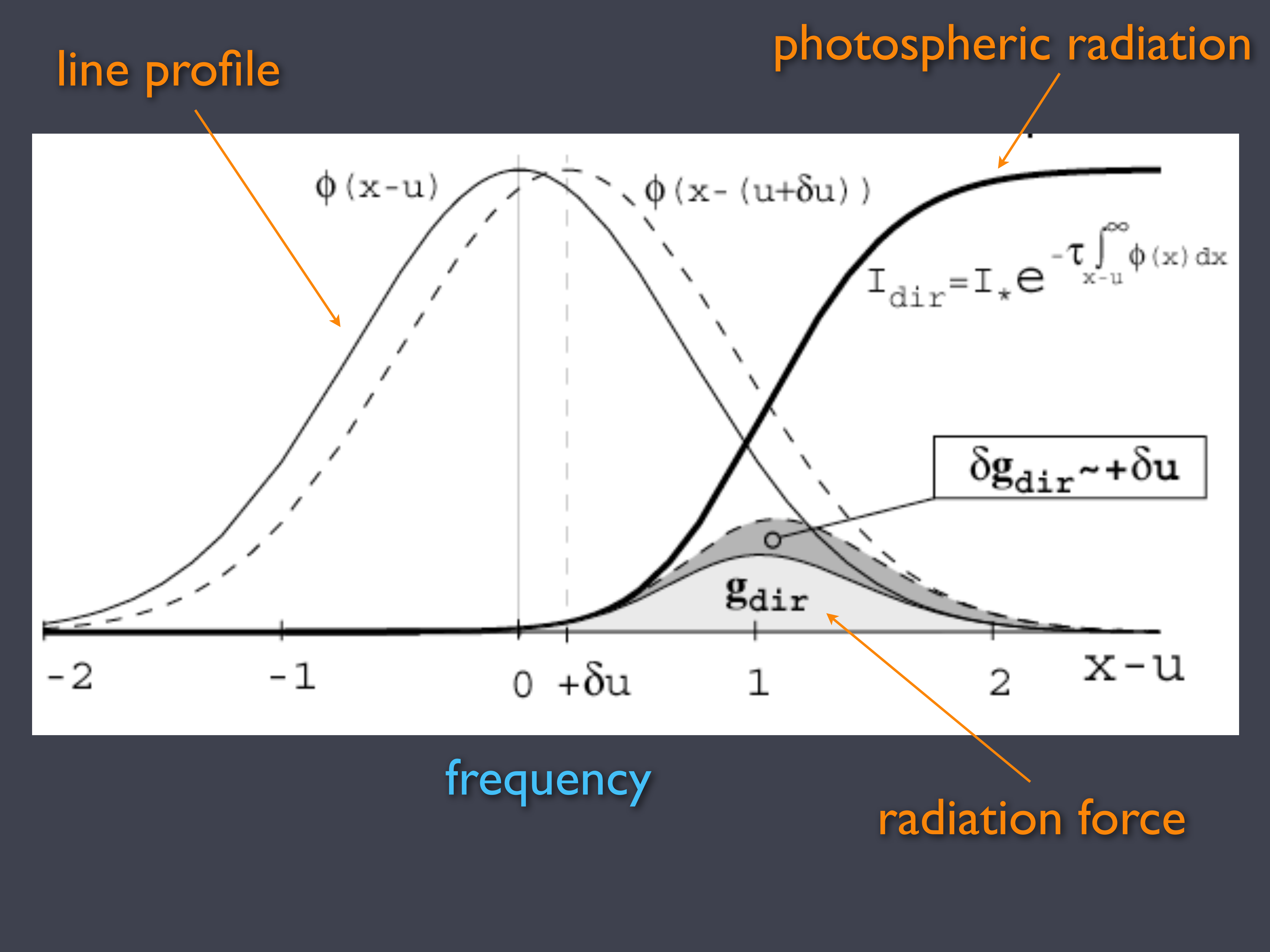
causes fast, rarefied wind plasma to slam into slower, denser wind plasma

the resulting shocks heat the wind plasma

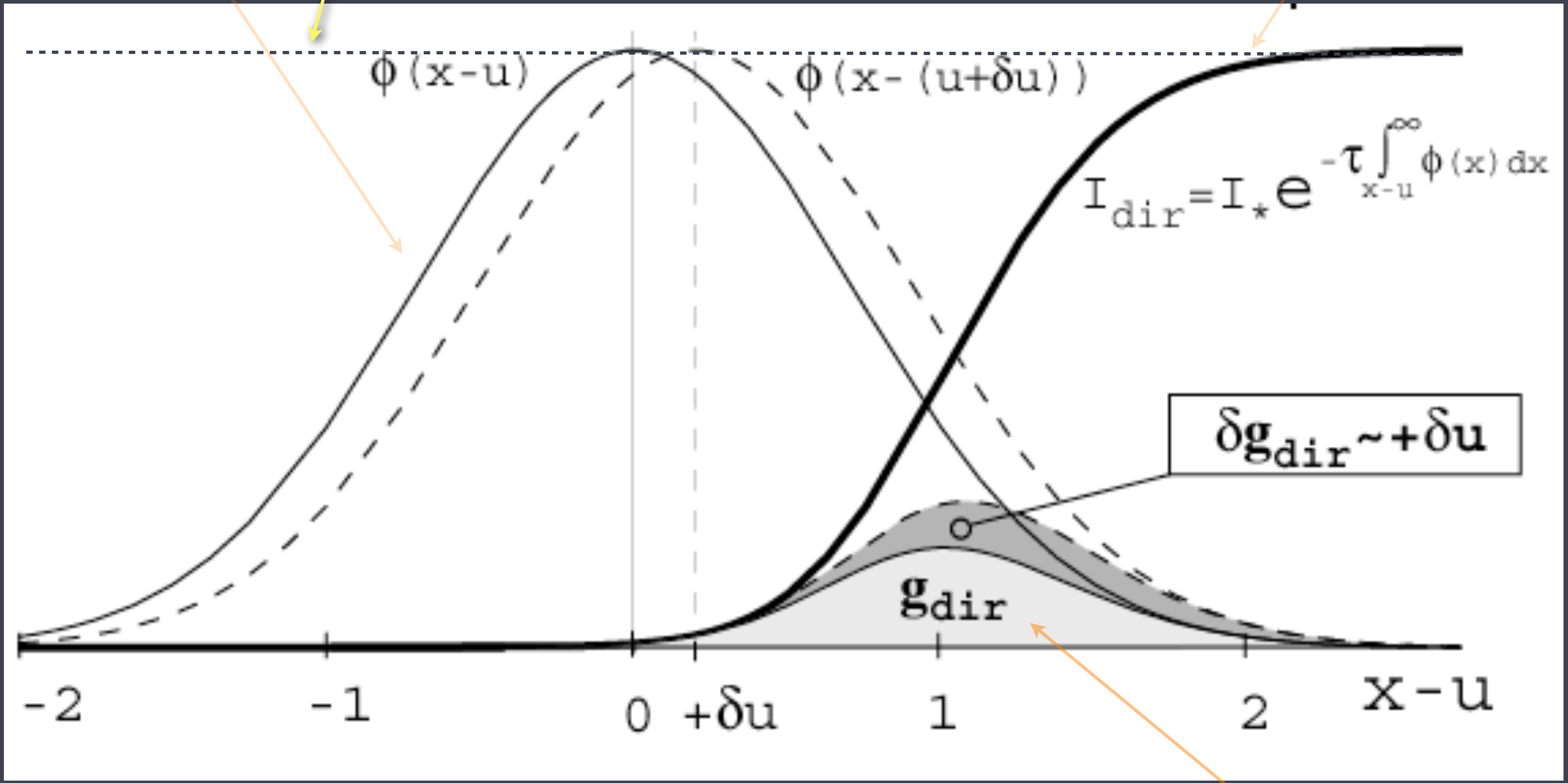
general result from shock theory:
$T \sim 10^6(\Delta v_{shock}/300\ \mathrm{km/s})^2$



ϕ(x-u)
ϕ(x-(u+δu))
$I_{dir}=I_{*}e^{-\tau\int_{x-u}^{\infty}\phi(x)\,dx}$
$\delta g_{dir} \sim +\delta u$
g_{dir}
-2
-1
0
+δu
1
2
x-u

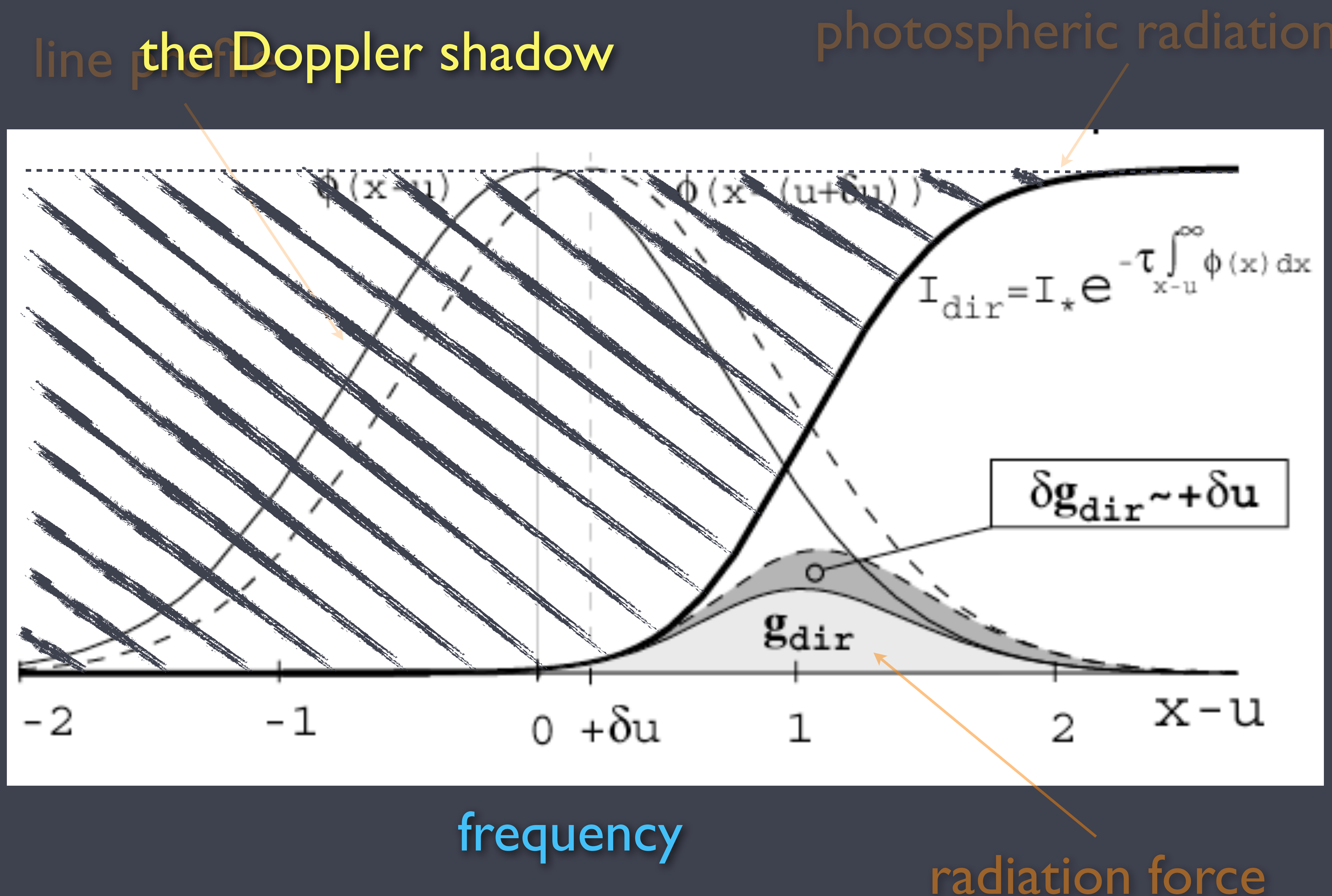

line profile
photospheric radiation
ϕ (x-u)
ϕ (x- (u+δu))
$I_{dir}=I_* e^{-\tau \int_{x-u}^{\infty} \phi(x)\, dx}$
$\delta g_{dir} \sim +\delta u$
g_{dir}
-2
-1
0
+δu
1
2
x-u
frequency
radiation force

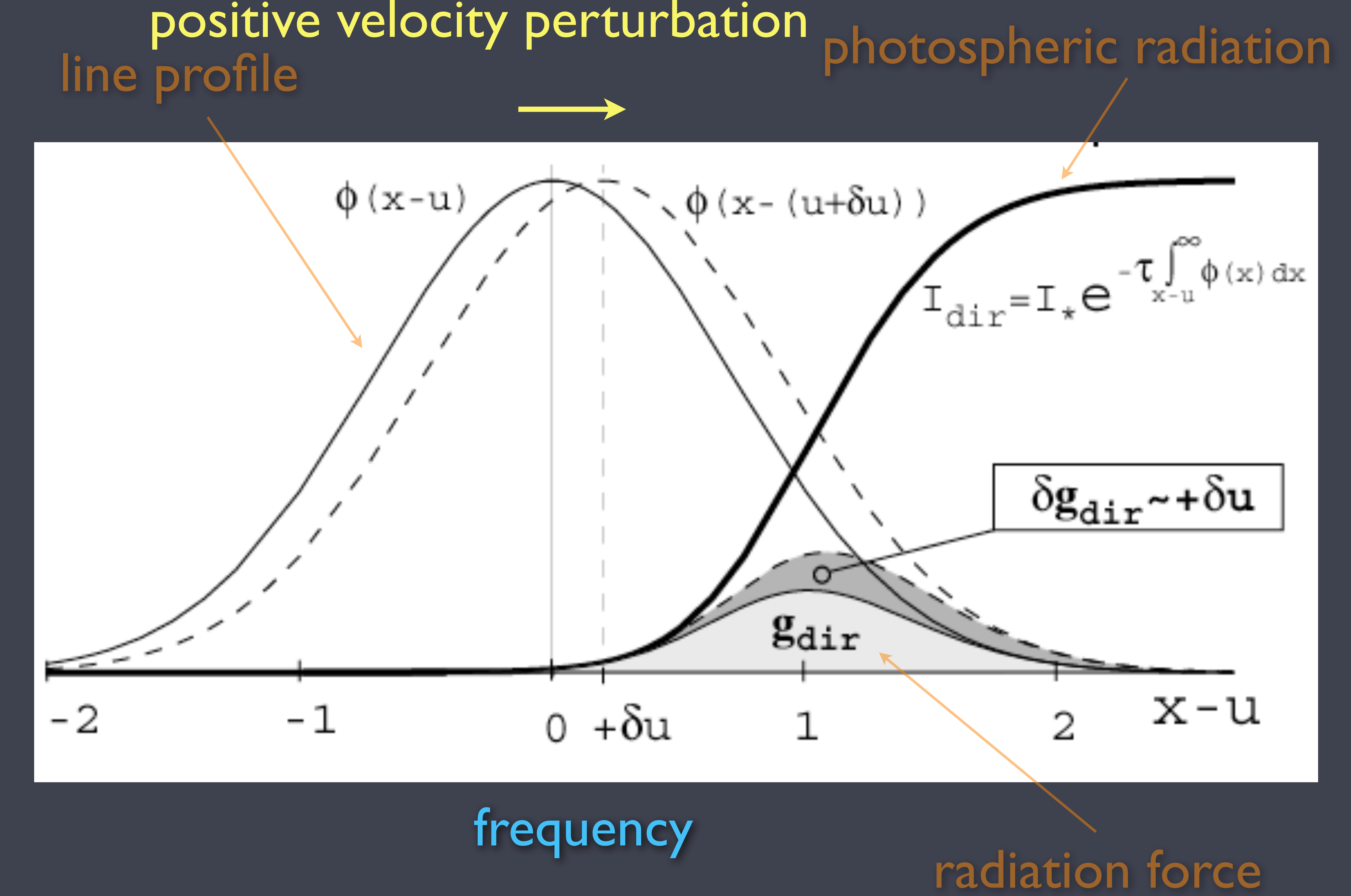
photospheric radiation if there were no absorption by slower-moving parts of the lower portion of the wind

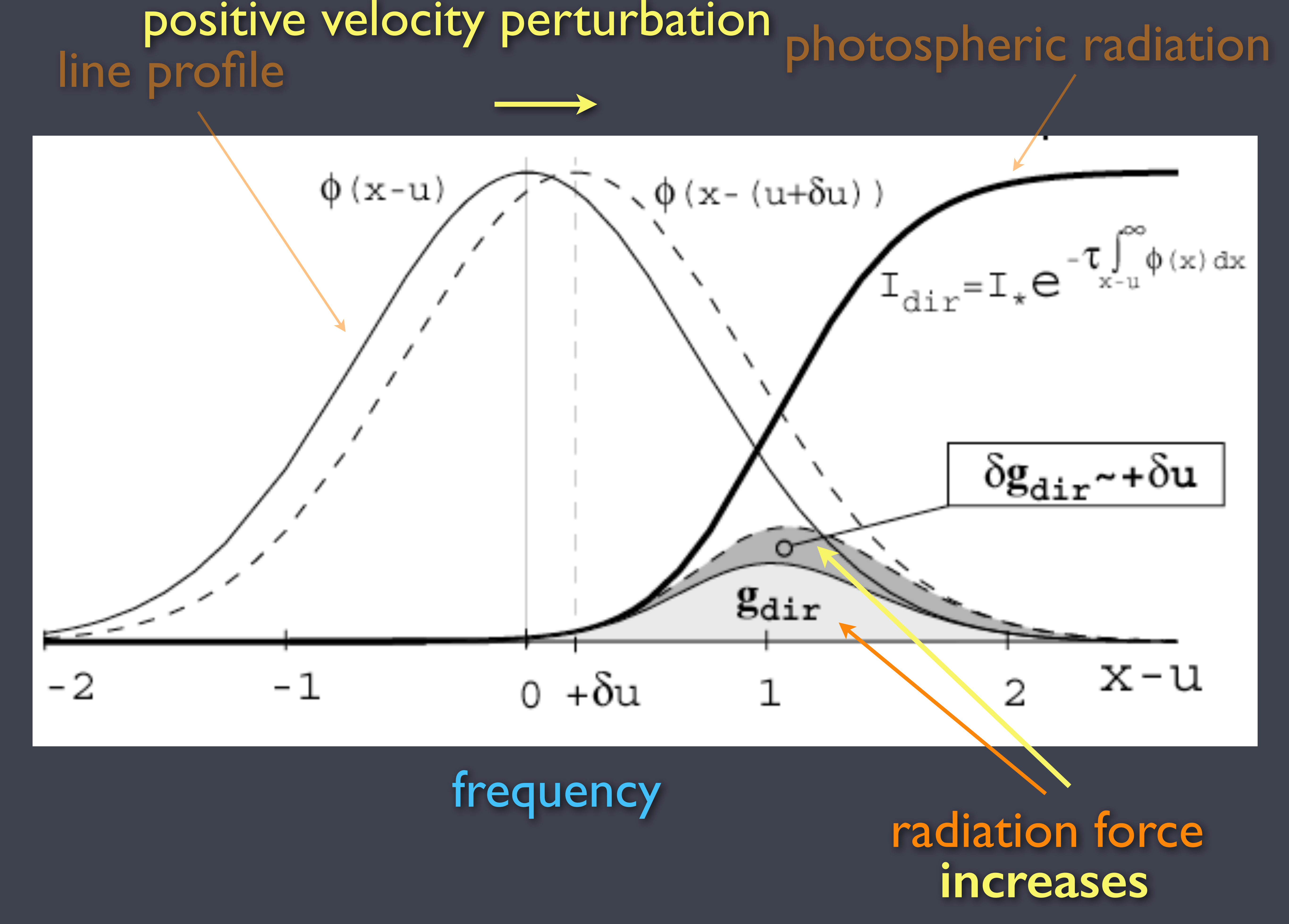


frequency

radiation force


line profile
the Doppler shadow
photospheric radiation
$\phi(x-u)$
$\phi(x-(u+\delta u))$
$I_{dir}=I_{*}e^{-\tau\int_{x-u}^{\infty}\phi(x)\,dx}$
$\delta g_{dir}\sim+\delta u$
g_{dir}
-2
-1
0
$+\delta u$
1
2
x-u
frequency
radiation force

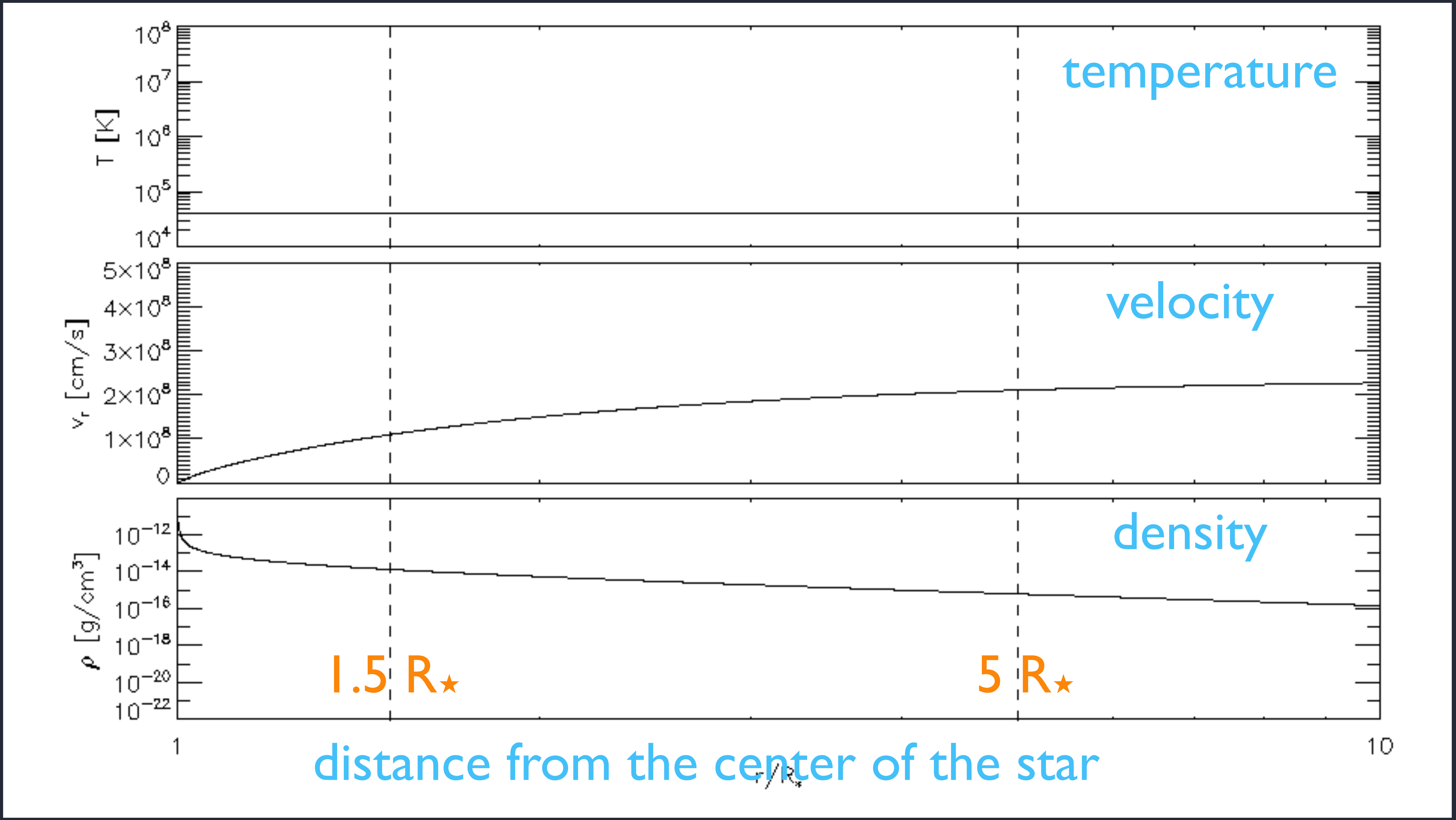

positive velocity perturbation
line profile
photospheric radiation
$\phi(x-u)$
$\phi(x-(u+\delta u))$
$I_{dir}=I_* e^{-\tau \int_{x-u}^{\infty} \phi(x)\,dx}$
$\delta g_{dir} \sim +\delta u$
g_{dir}
-2
-1
0
$+\delta u$
1
2
x-u
frequency
radiation force


positive velocity perturbation
line profile
photospheric radiation
ϕ (x-u)
ϕ (x- (u+δu))
$I_{dir}=I_* e^{-\tau \int_{x-u}^{\infty} \phi(x)\,dx}$
$\delta g_{dir} \sim +\delta u$
g_{dir}
-2
-1
0
+δu
1
2
x-u
frequency
radiation force
increases

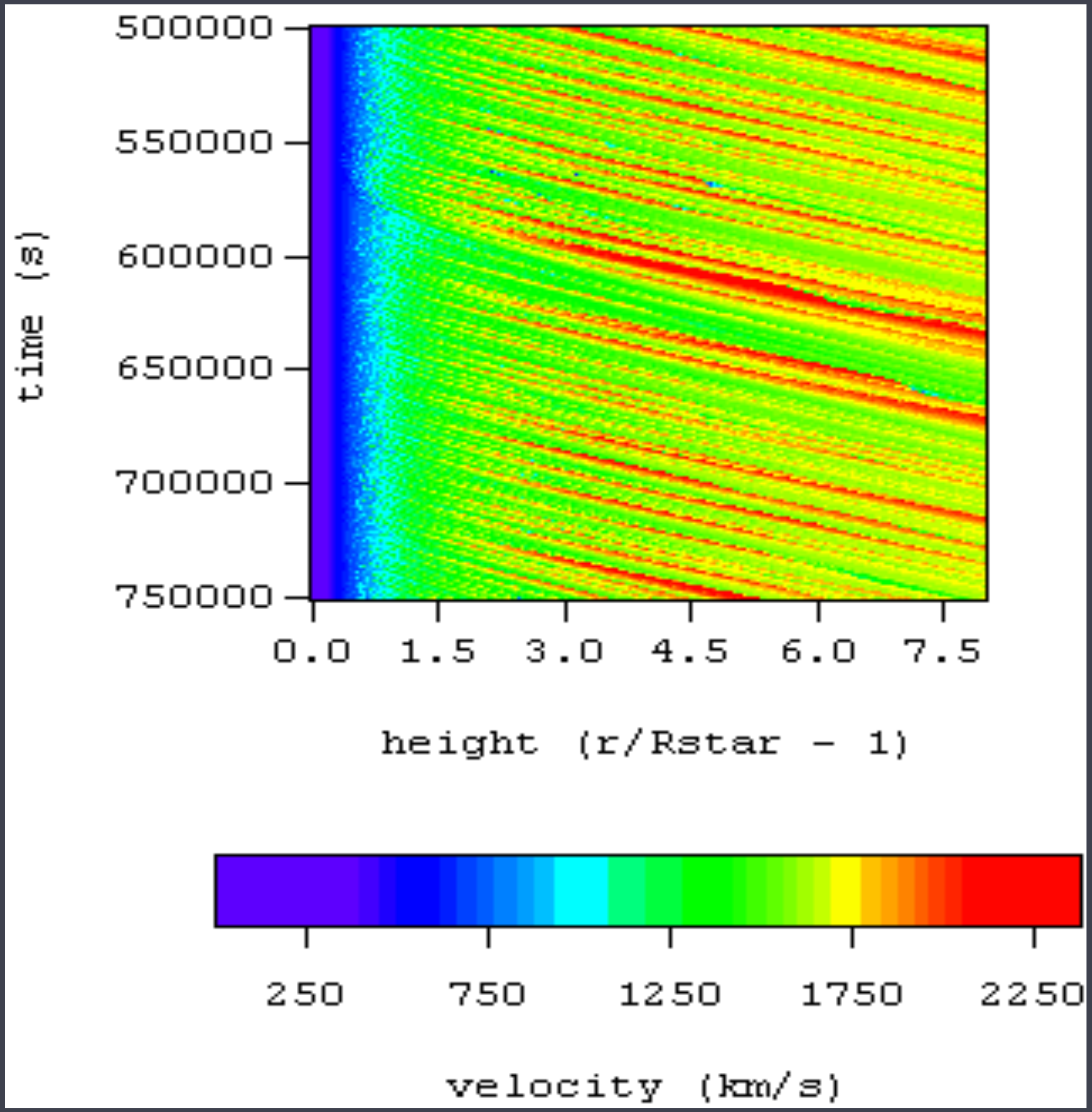
X-ray emitting plasma is embedded in the wind

intrinsic instability of radiative driving, Line Deshadowing Instability (LDI), leads to shock-heating of the wind

http://astro.swarthmore.edu/~cohen/projects/ldi/ifrc3_abbott0.65_xkovbc350._xmbko1.e-2_epsabs-1.e-20.gif



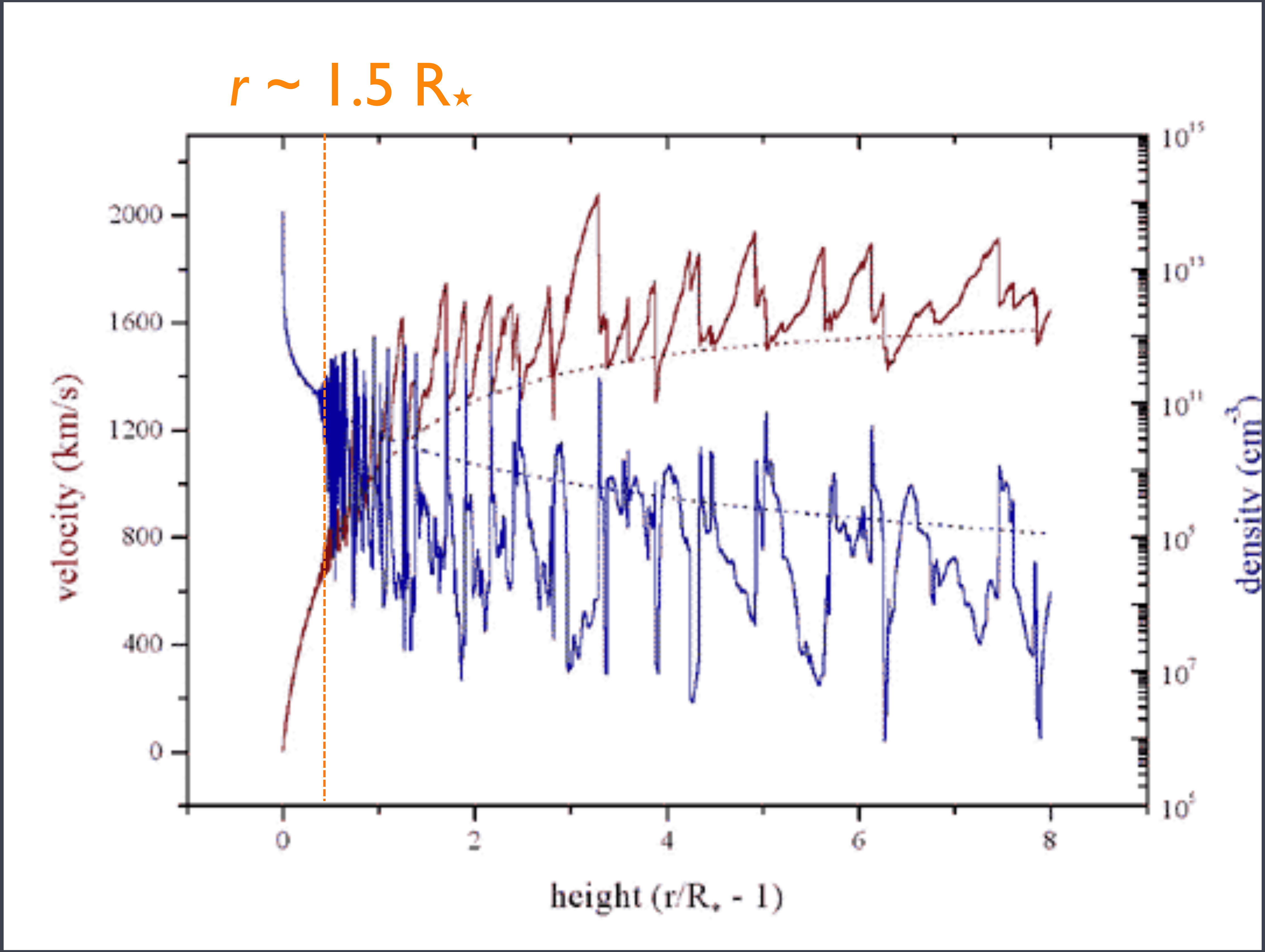
Numerical simulations of the line-deshadowing instability (LDI)



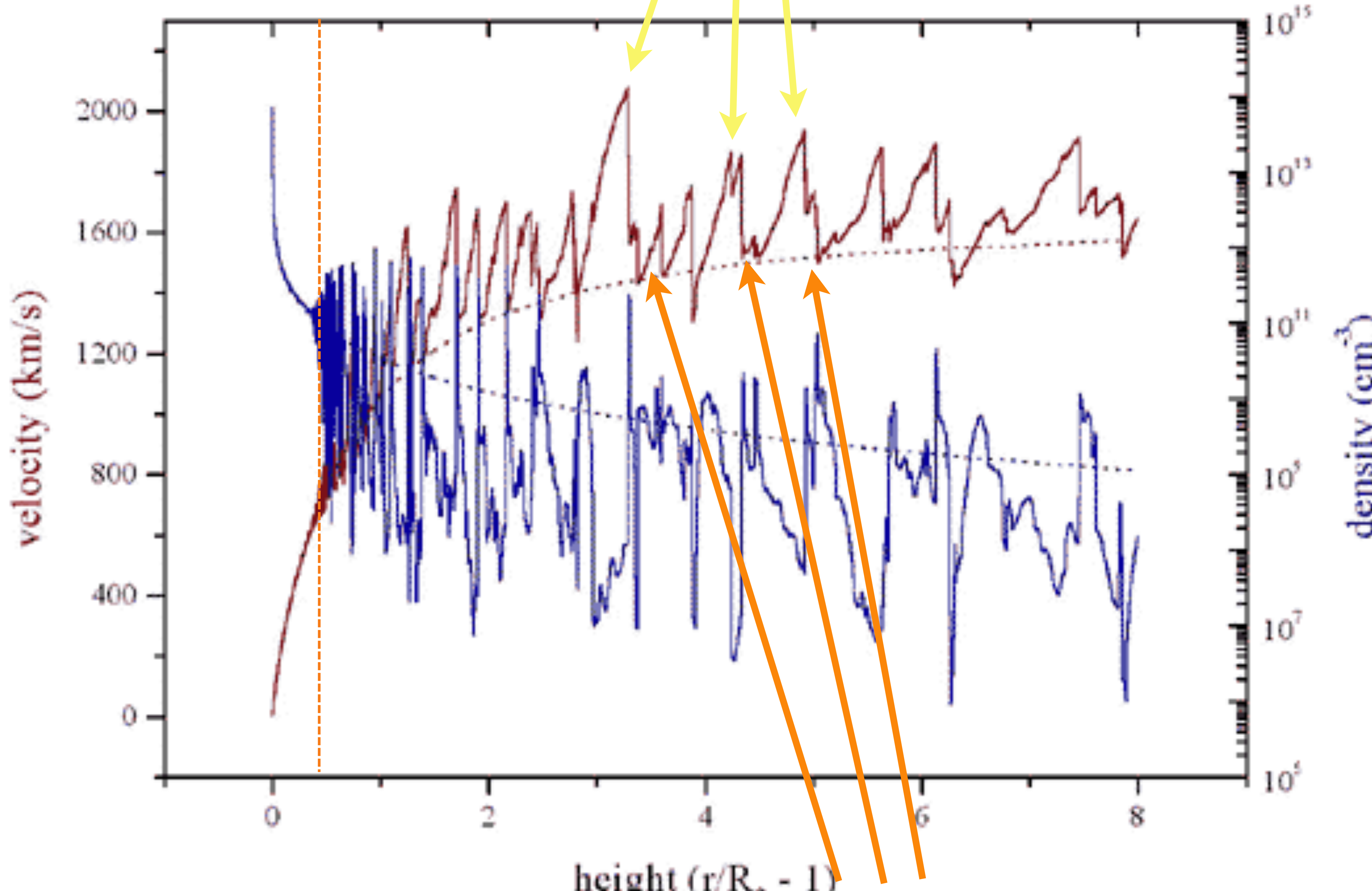
Owocki, Cooper, Cohen 1999

shock jump velocities ~ few 100 km/s

Numerous shock structures distributed above $r \sim 1.5\ R_\star$

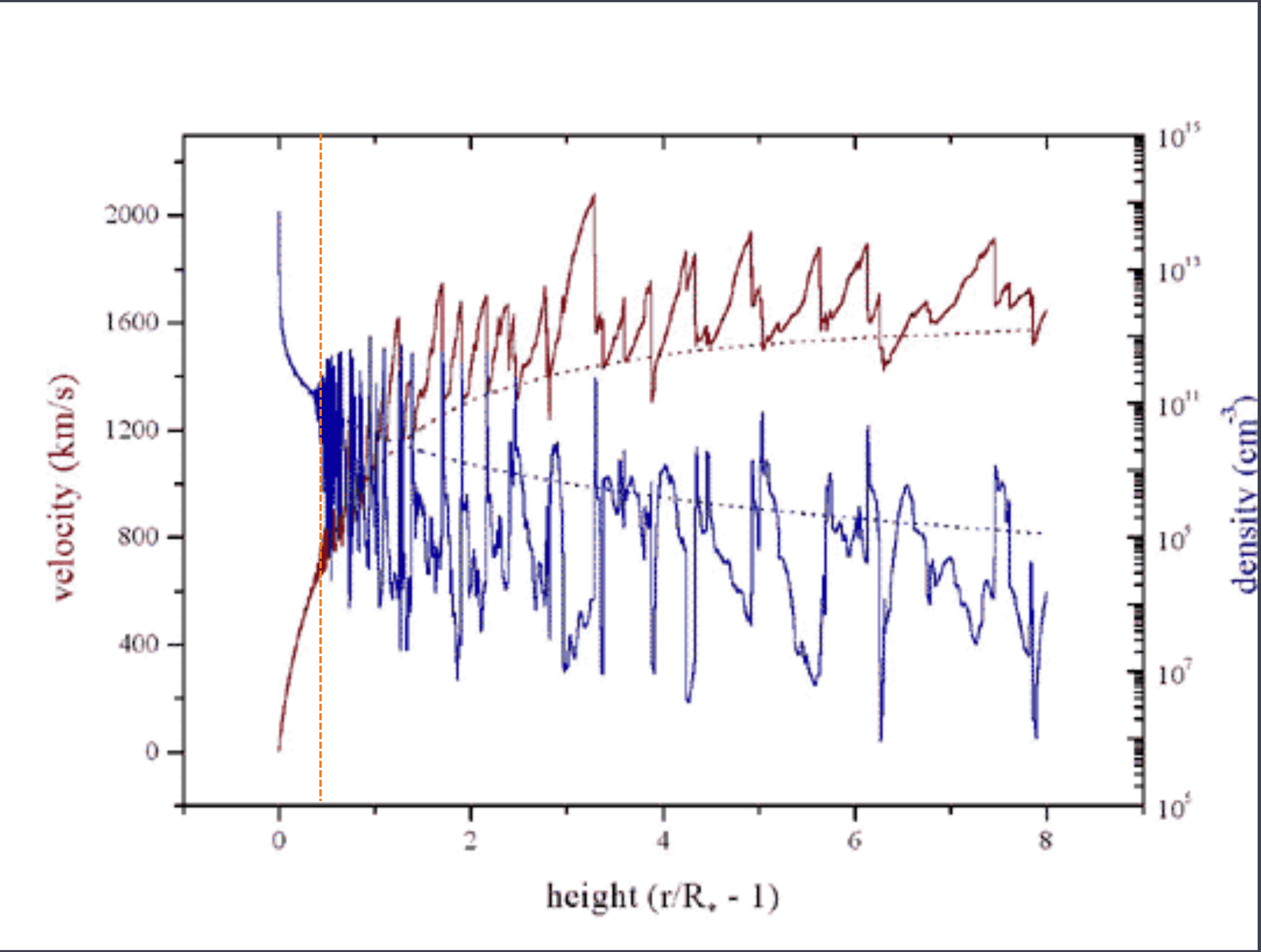


$V_{shock} \sim 300$ km/s : $T \sim 10^6$ K

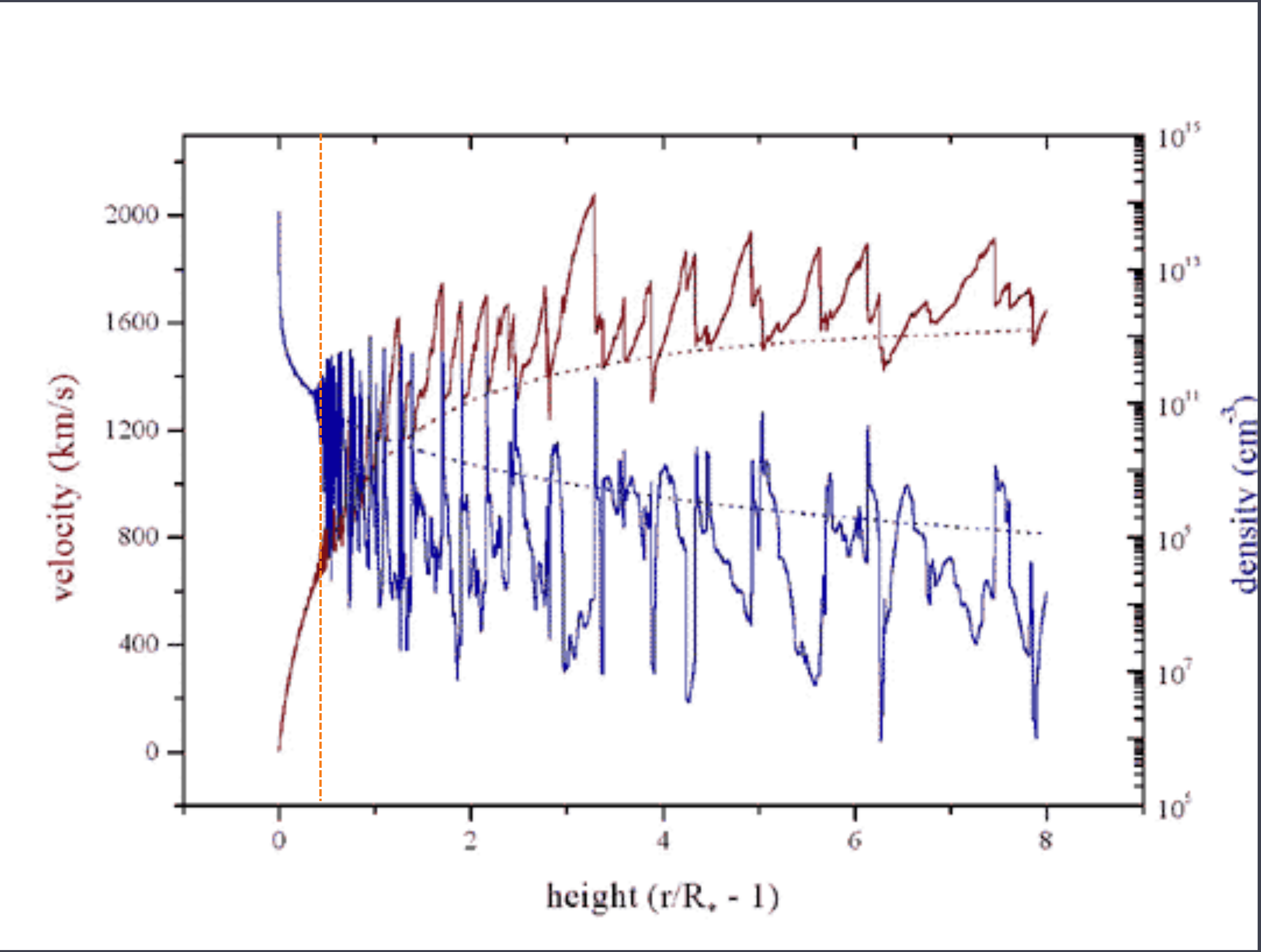


shocked wind plasma is decelerated back down to the local CAK wind velocity

Shocked plasma is moving at v ~ 1000 km/s

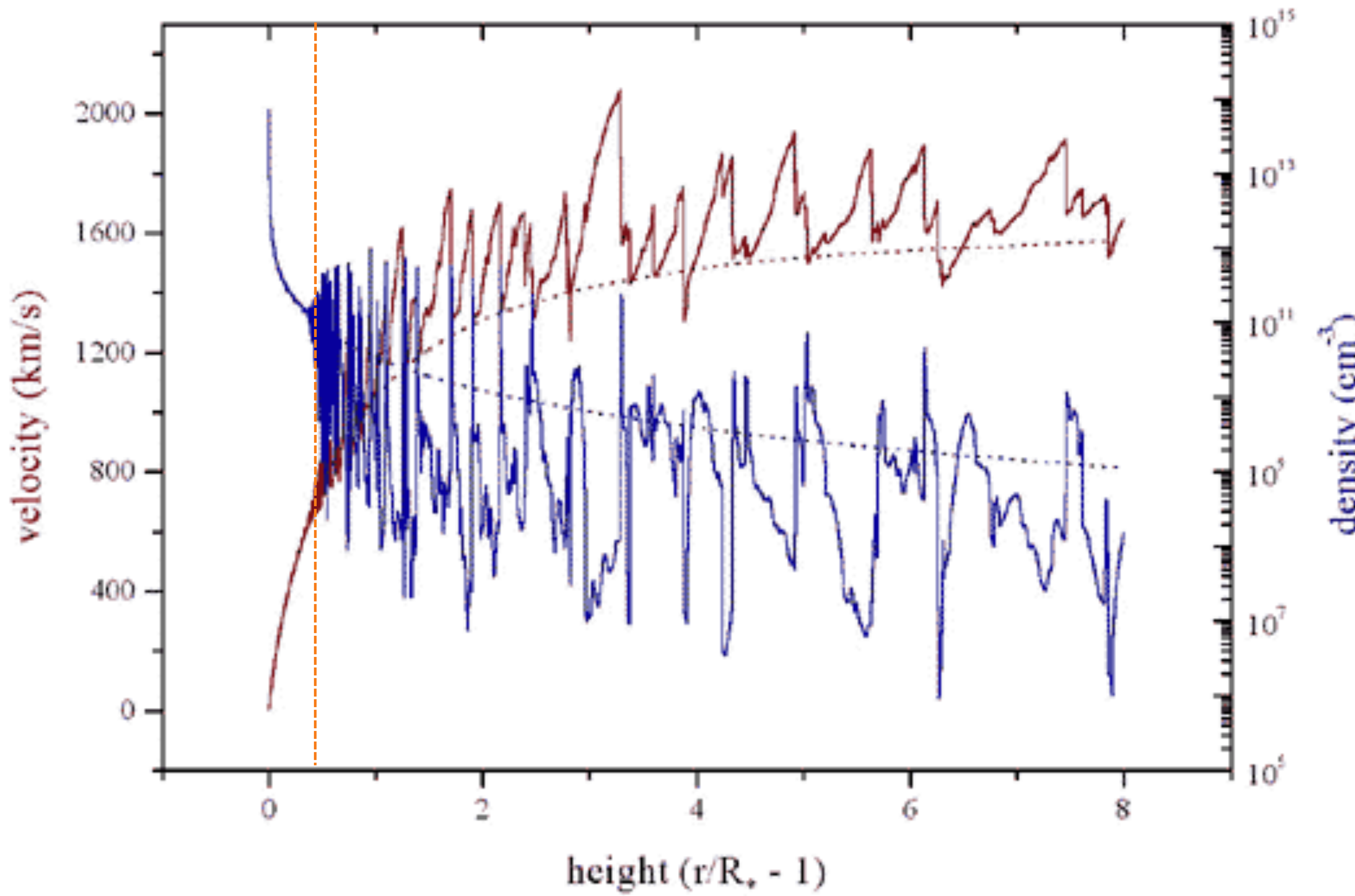


X-ray emission lines should be Doppler broadened



Less than 1% of the wind is emitting X-rays

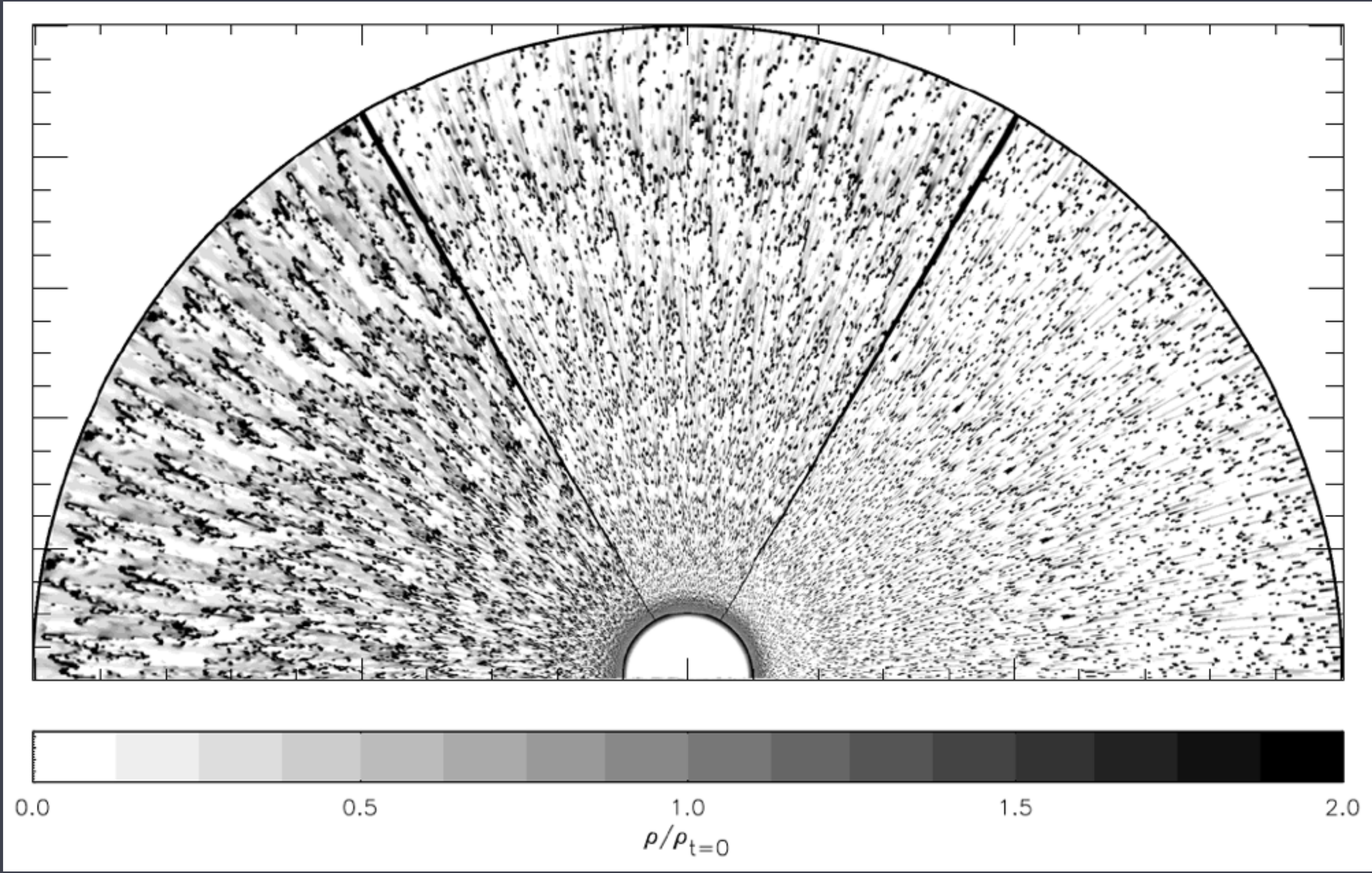
>99% of the wind is cold and X-ray *absorbing*



1-D is a severe limitation

lack of observed time variability suggests numerous (>100) individual post-shock cooling volumes in the wind

2-D simulations

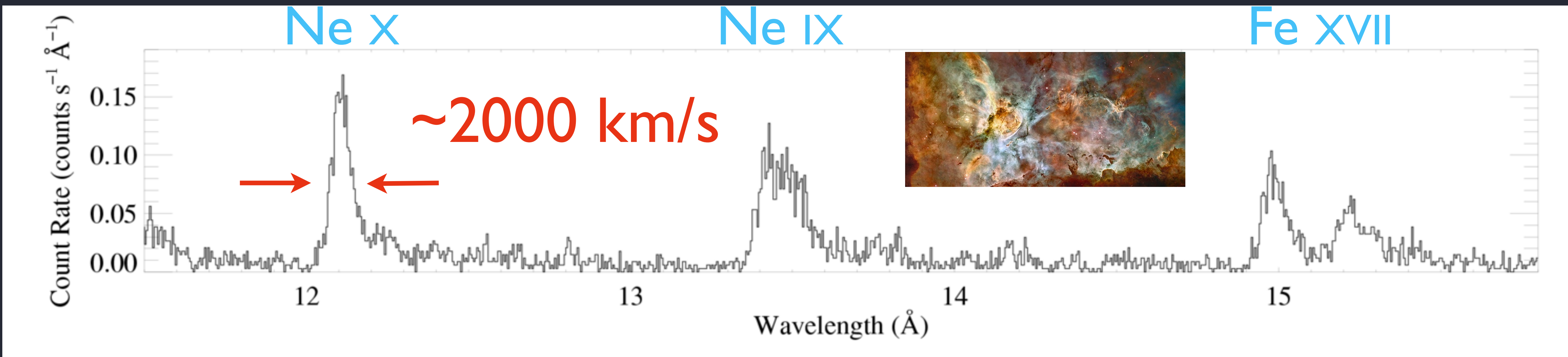


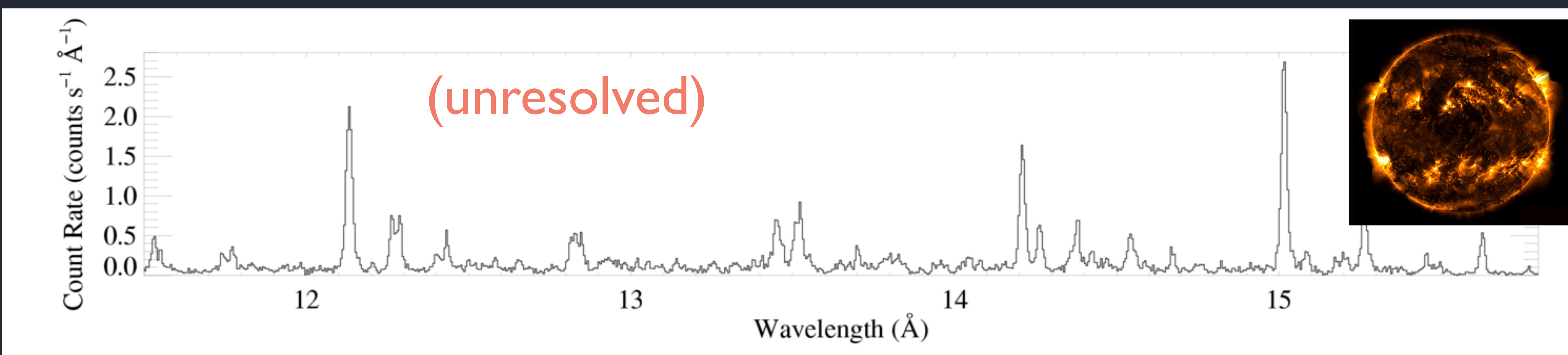
Dessart & Owocki 2003

Quantitative modeling of the X-ray spectrum based on these LDI numerical hydro simulations

conclusive evidence that the X-ray plasma is in the stellar wind

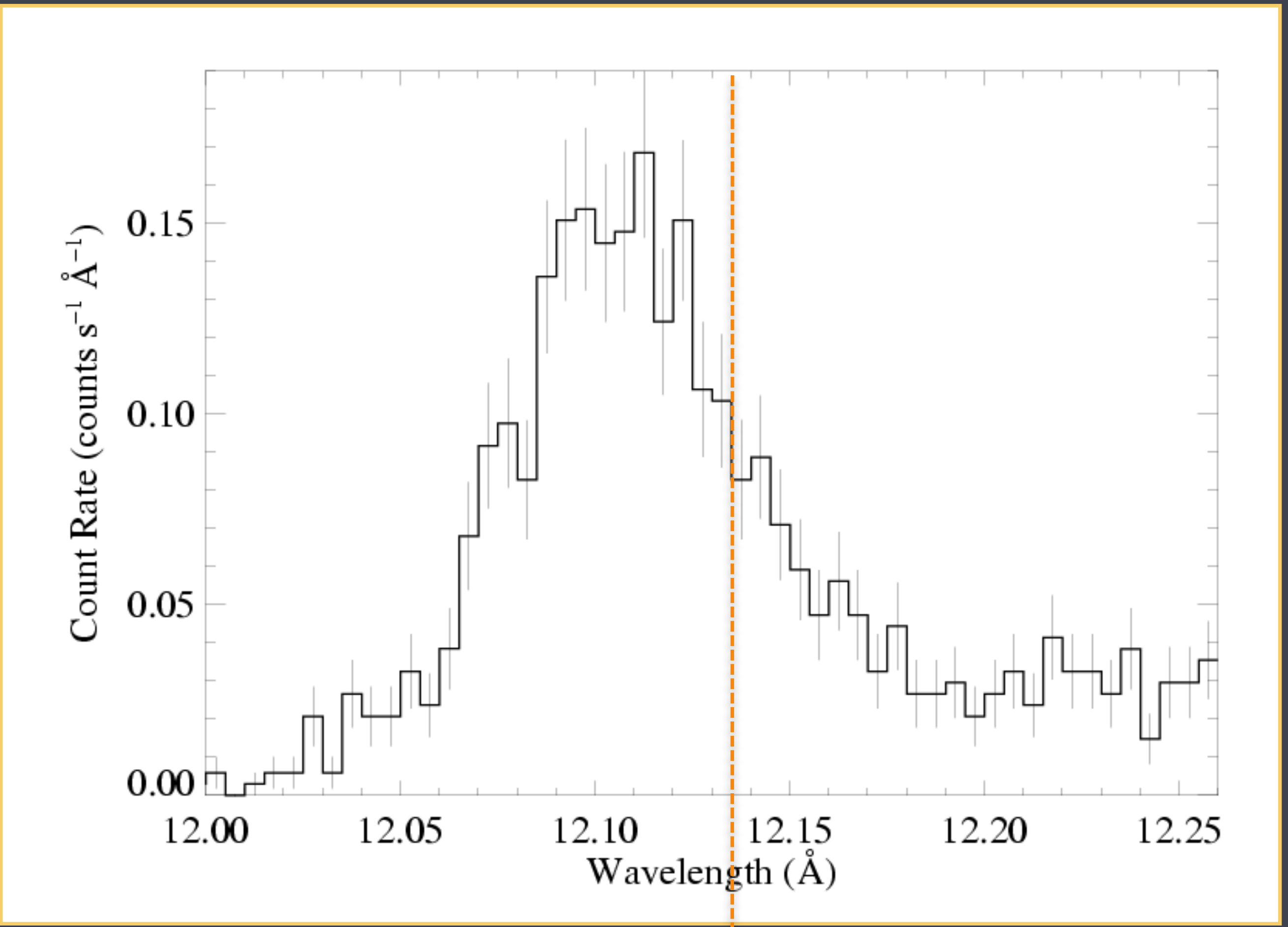
ζ Pup (O4 If)



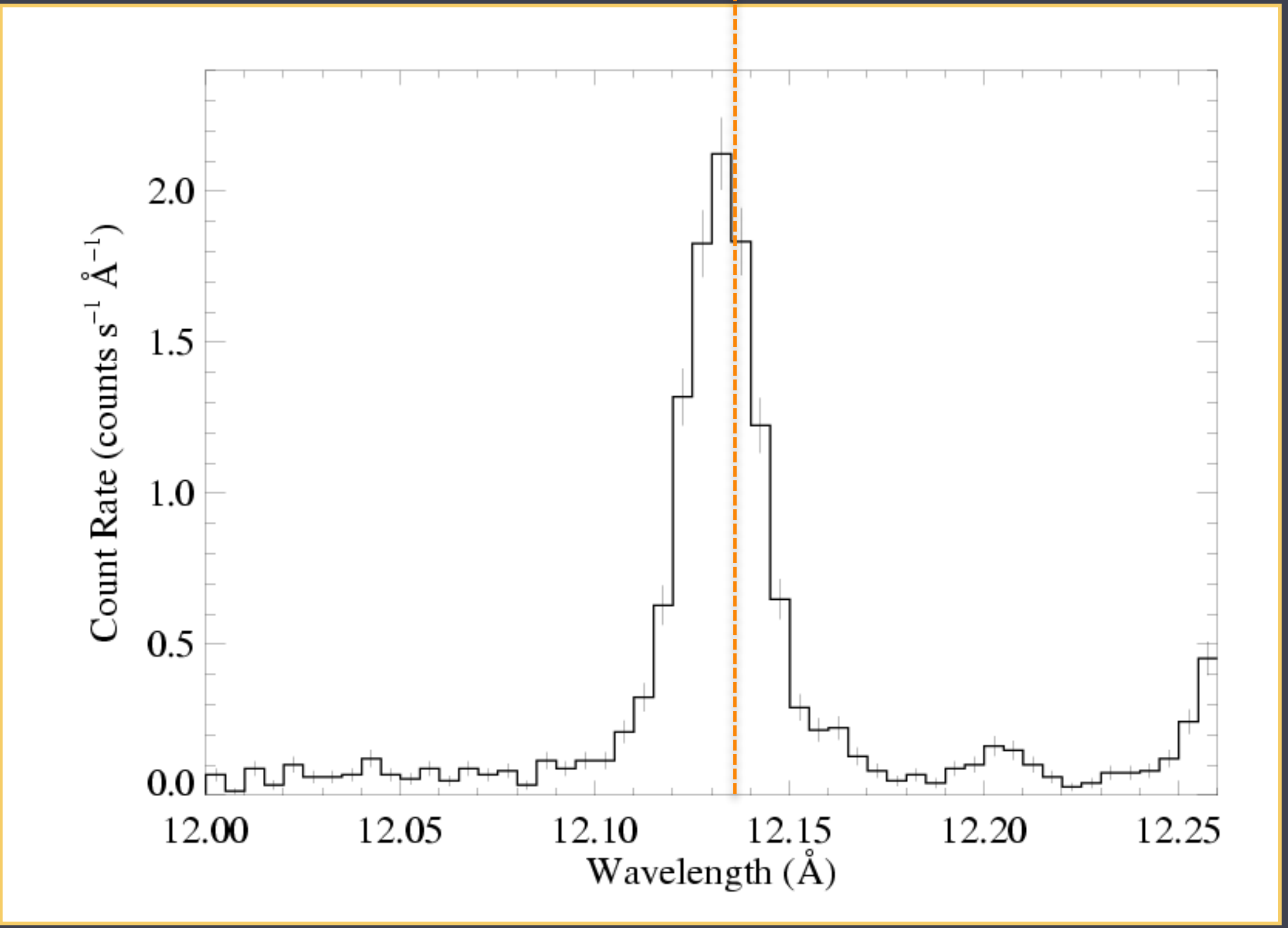


Capella (G5 III)

lines are asymmetric

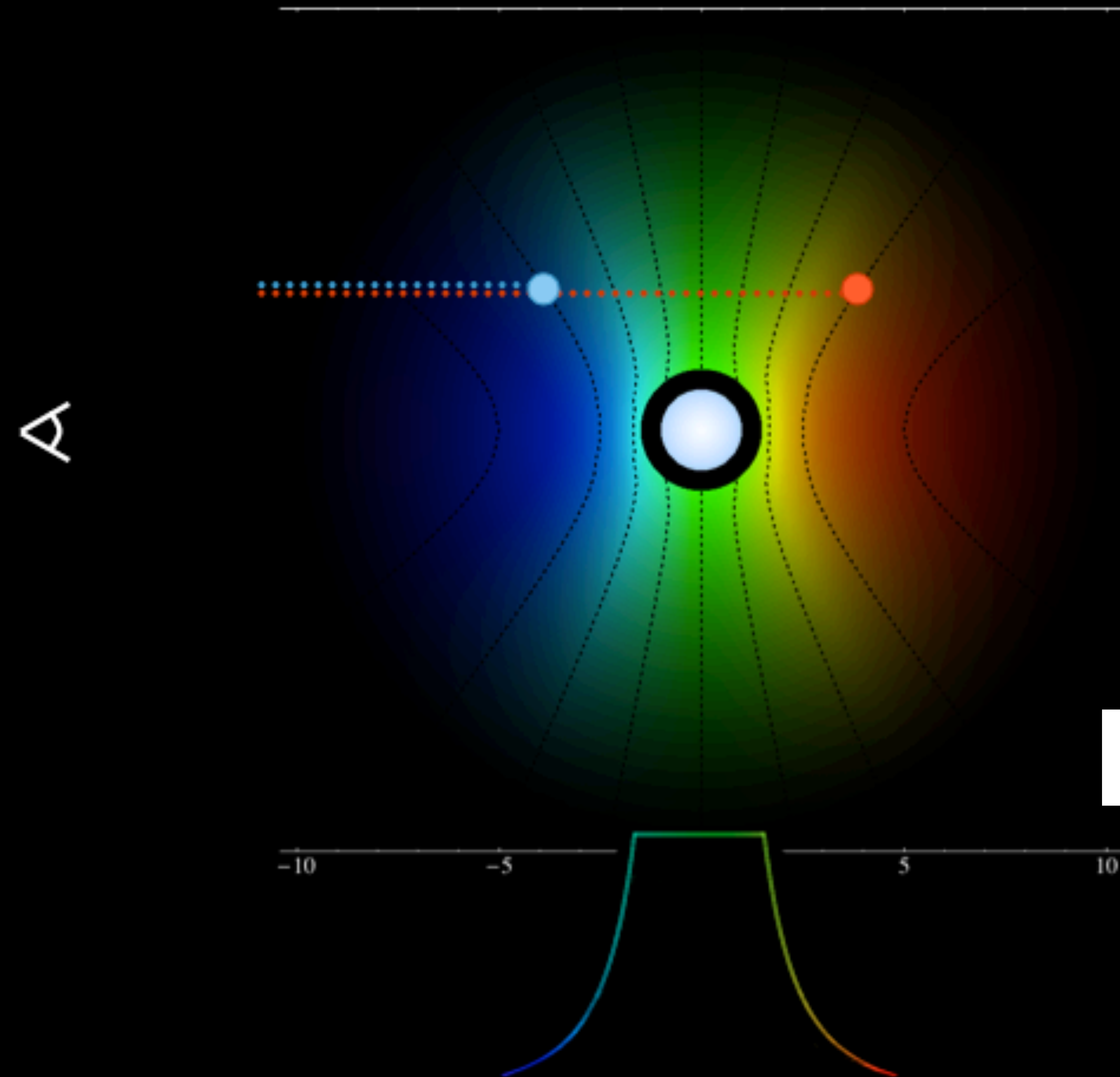


ζ Pup (O4If)



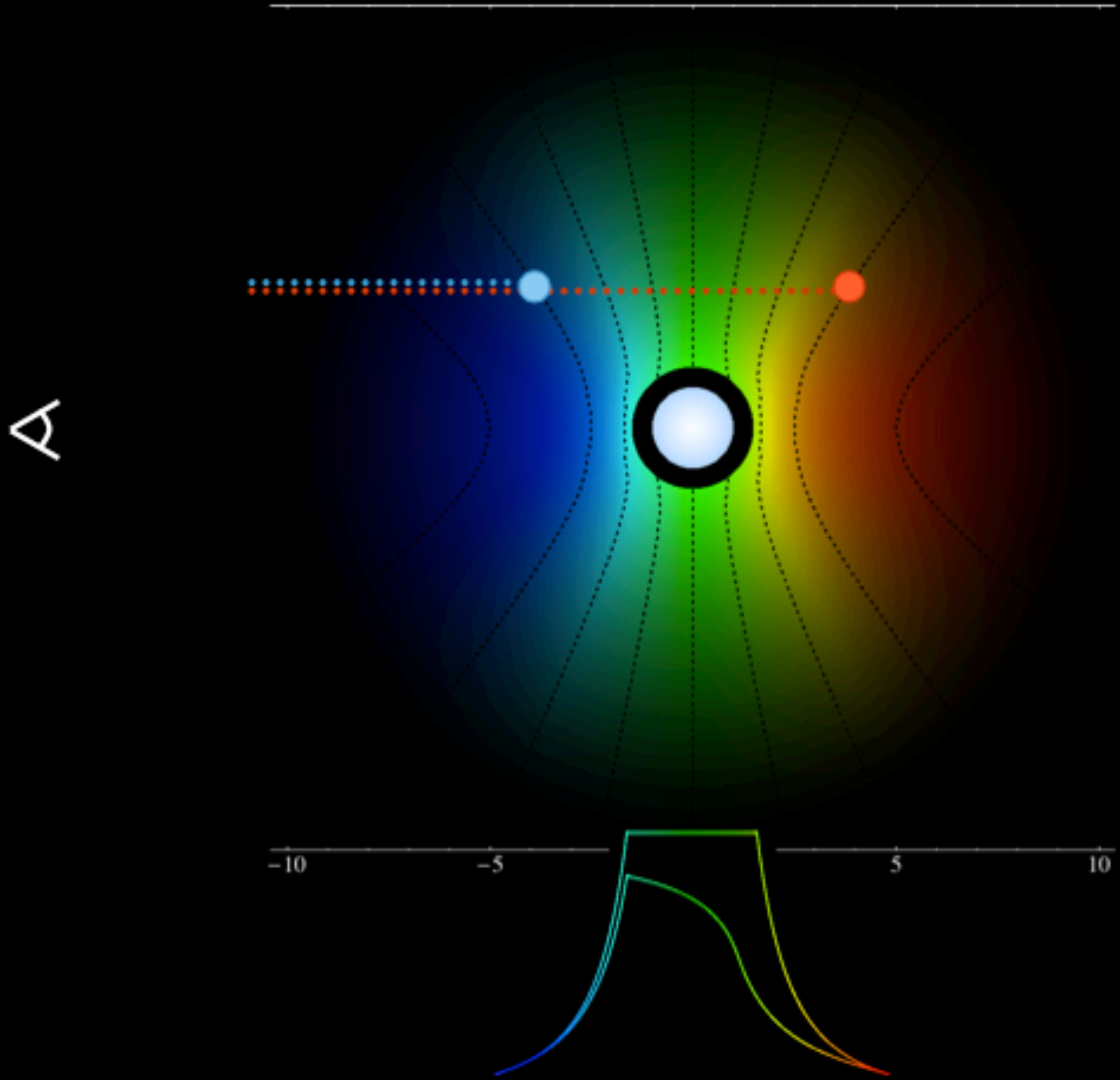
Capella (G5 III)

Line Asymmetry



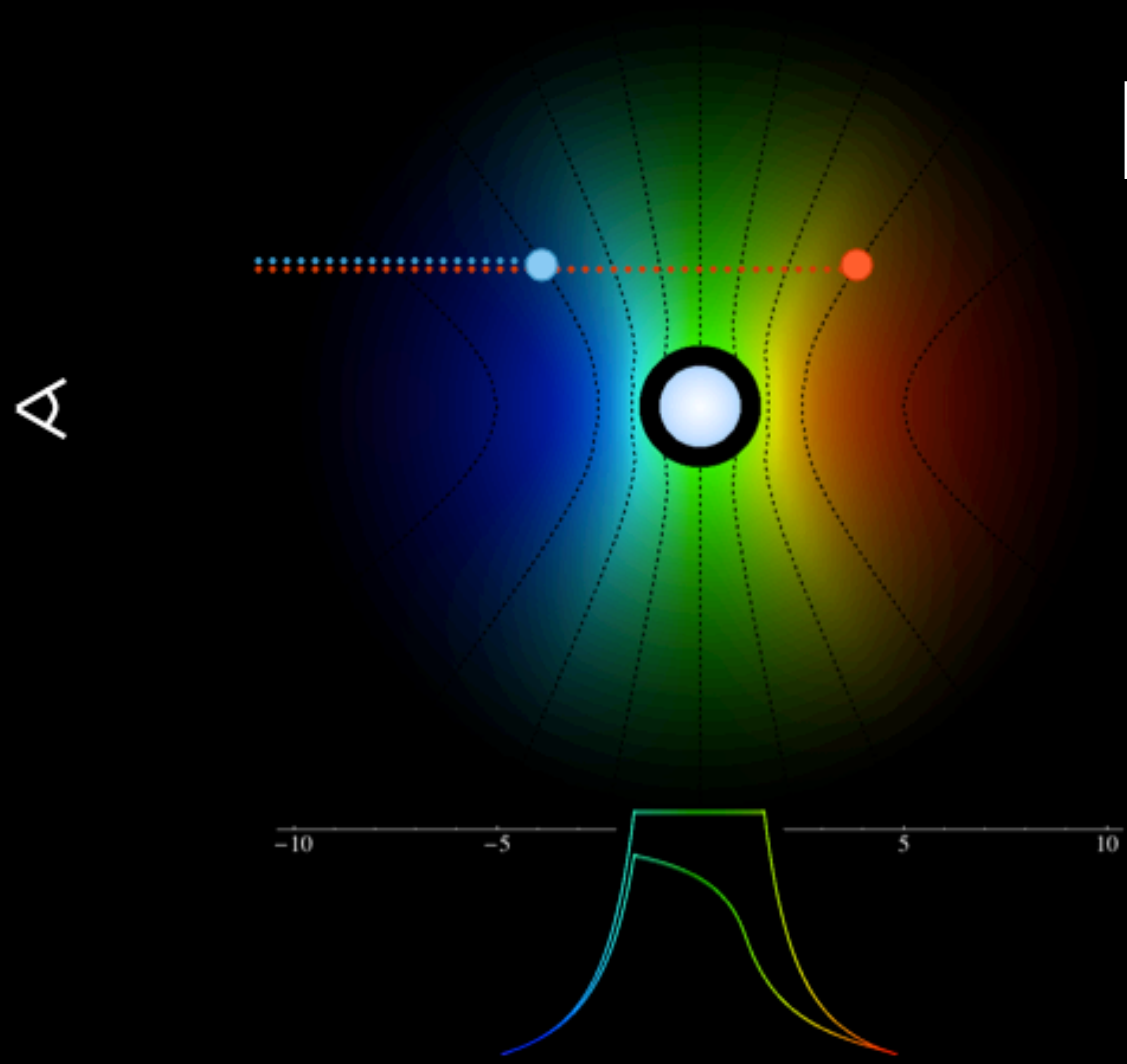
$$v = v_\infty(1\text{-}r/R_\star)^\beta$$

Line Asymmetry



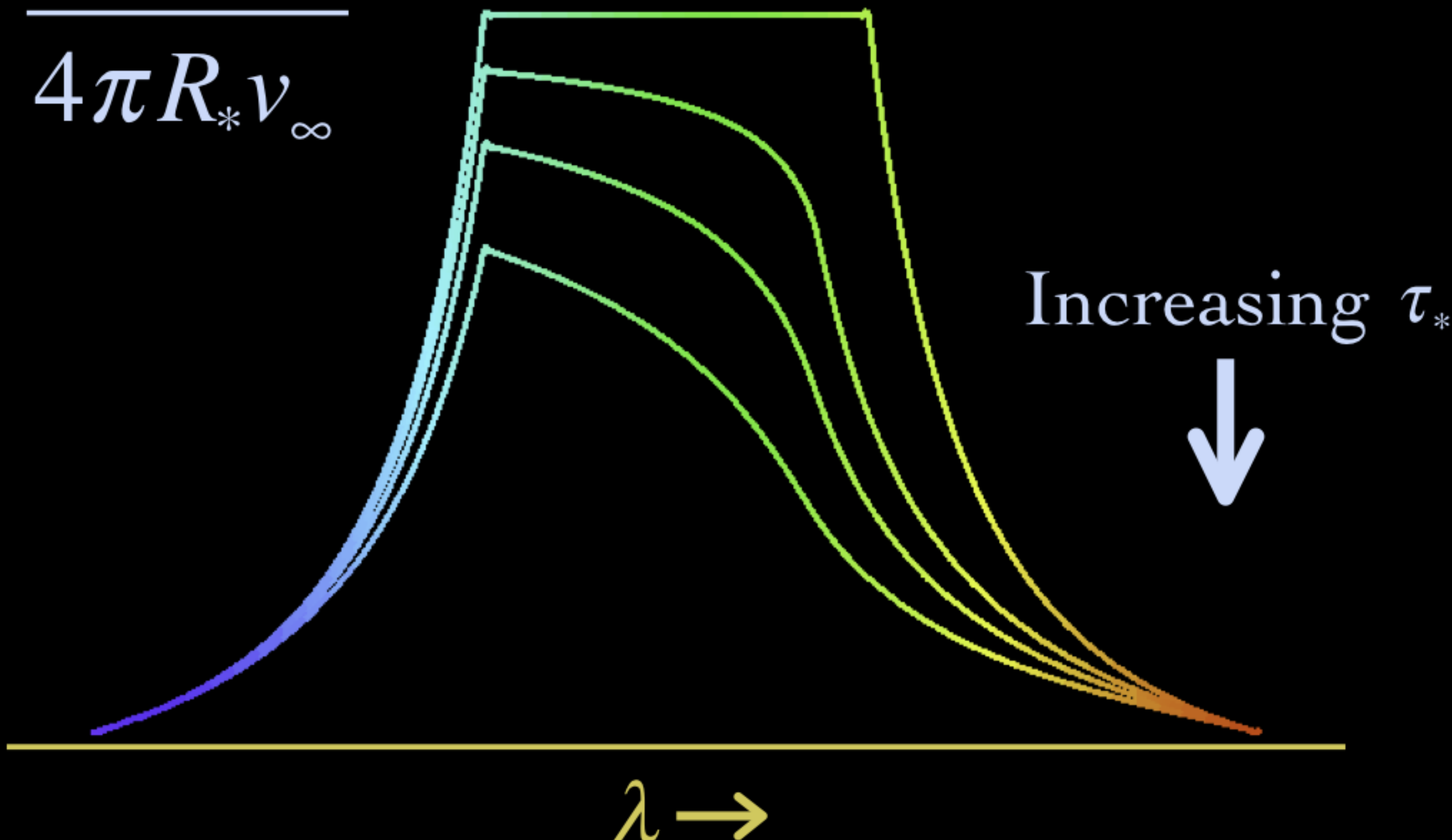
Line Asymmetry

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

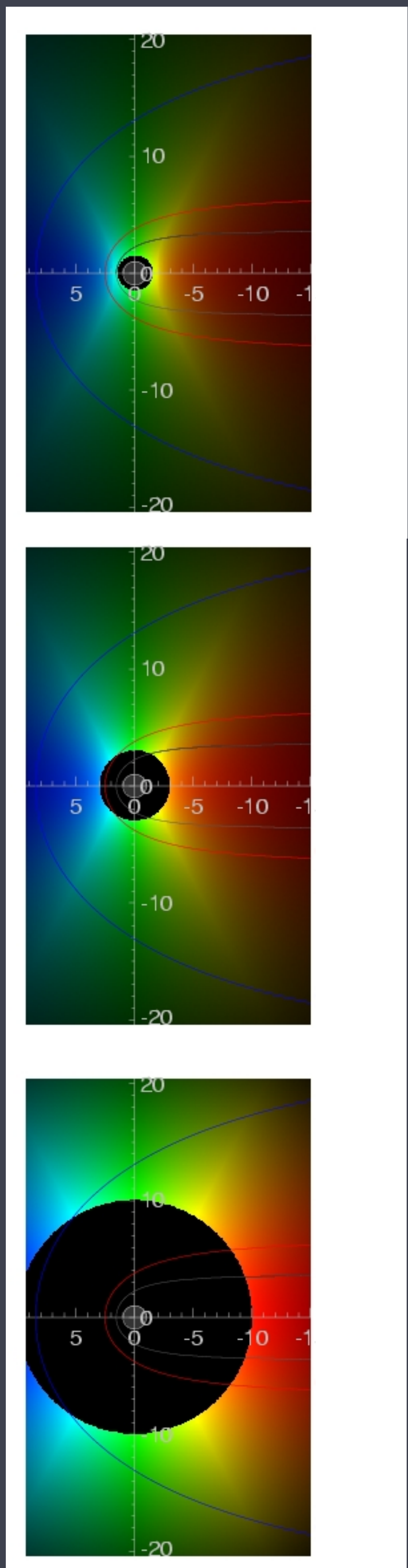


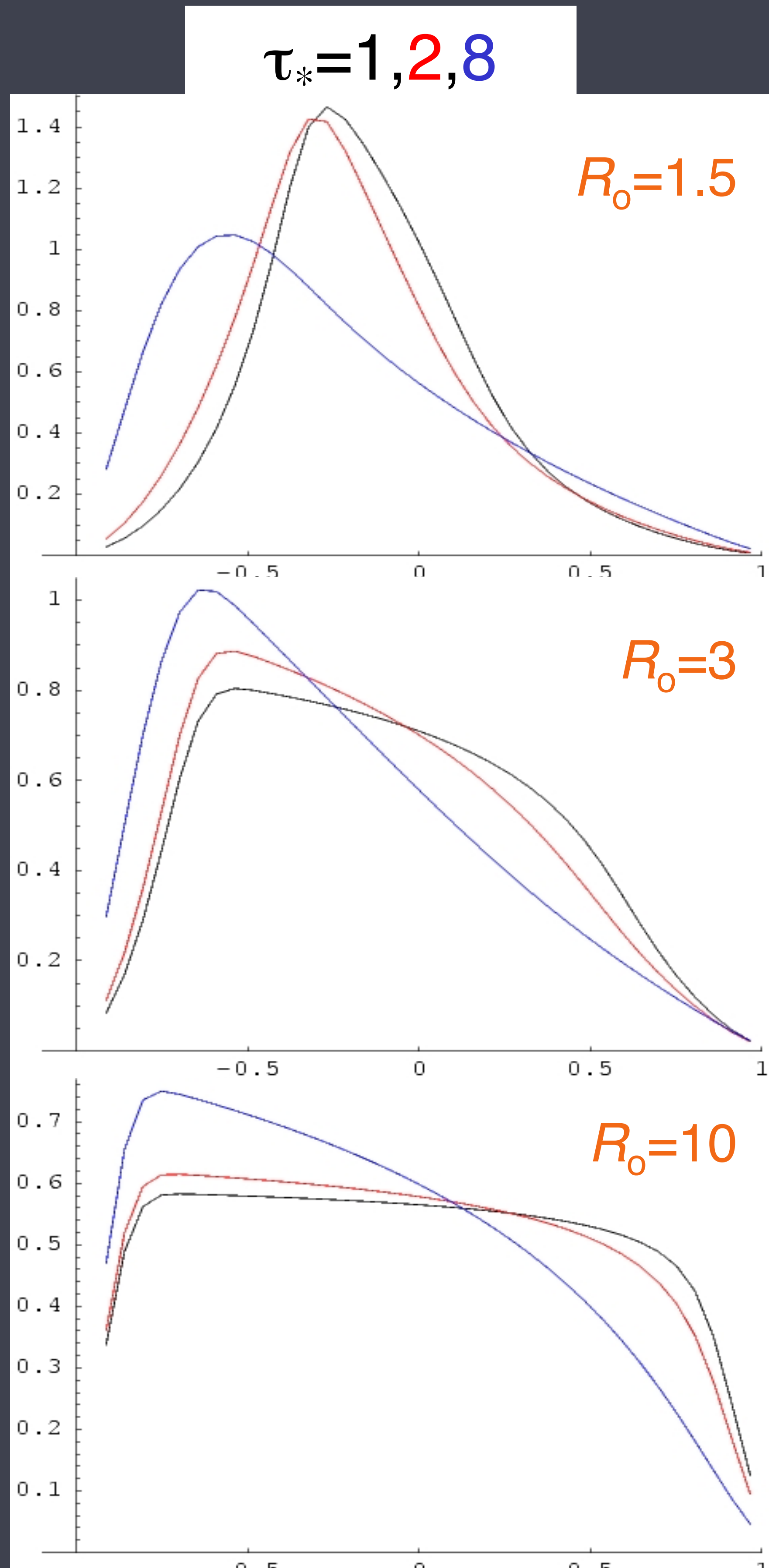
Wind Profile Model

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



Line profile shapes





key parameters: R_o & $\tau_\star$

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

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

$= 0$ otherwise

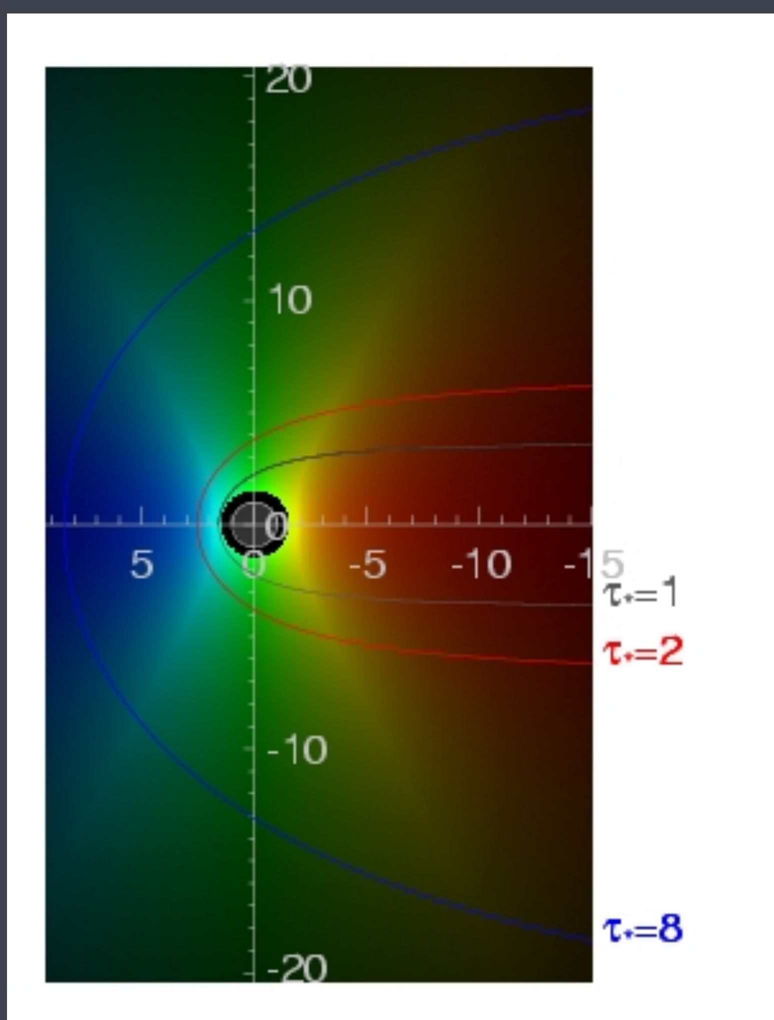
$$\tau = \tau_* \int_z^\infty \frac{R_* dz'}{r'^2 (1 - R_*/r')^\beta}$$

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

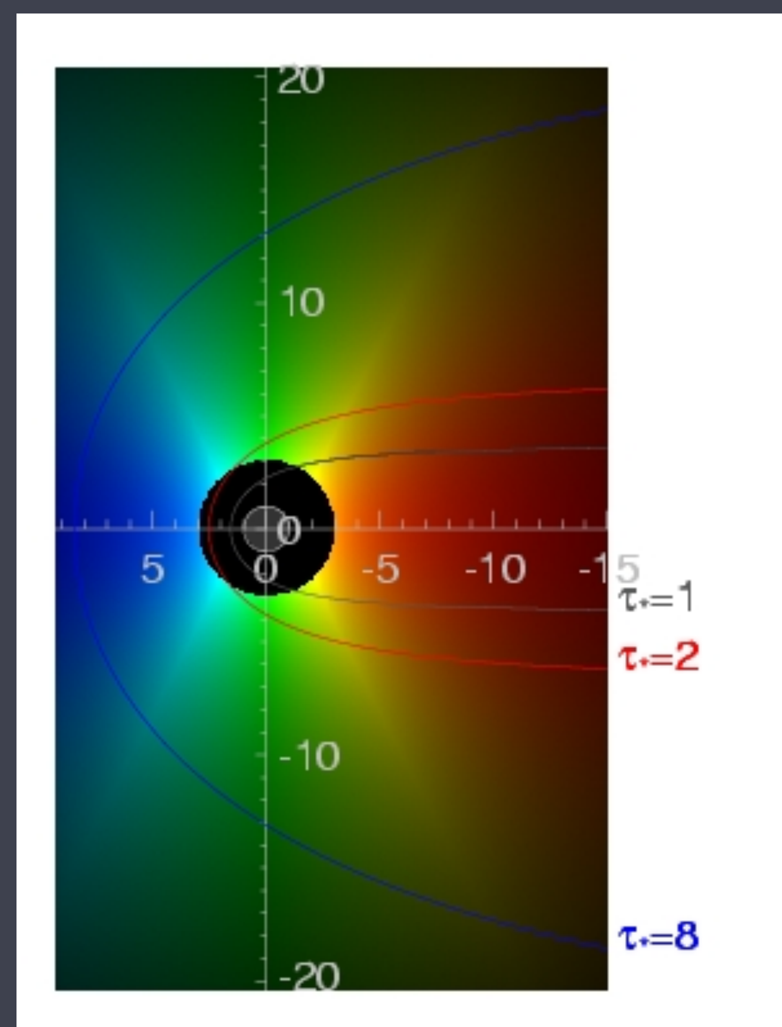
Hot plasma kinematics and location

R_o controls the line width via v(r)

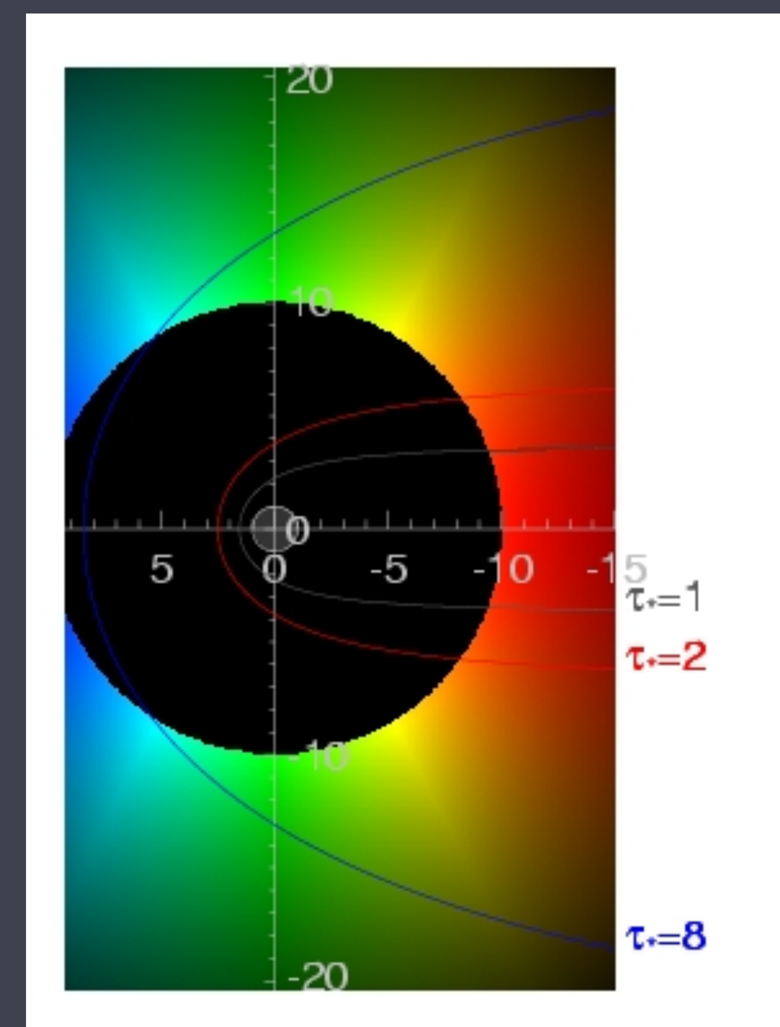
$R_o = 1.5\ R_\star$



$R_o = 3\ R_\star$

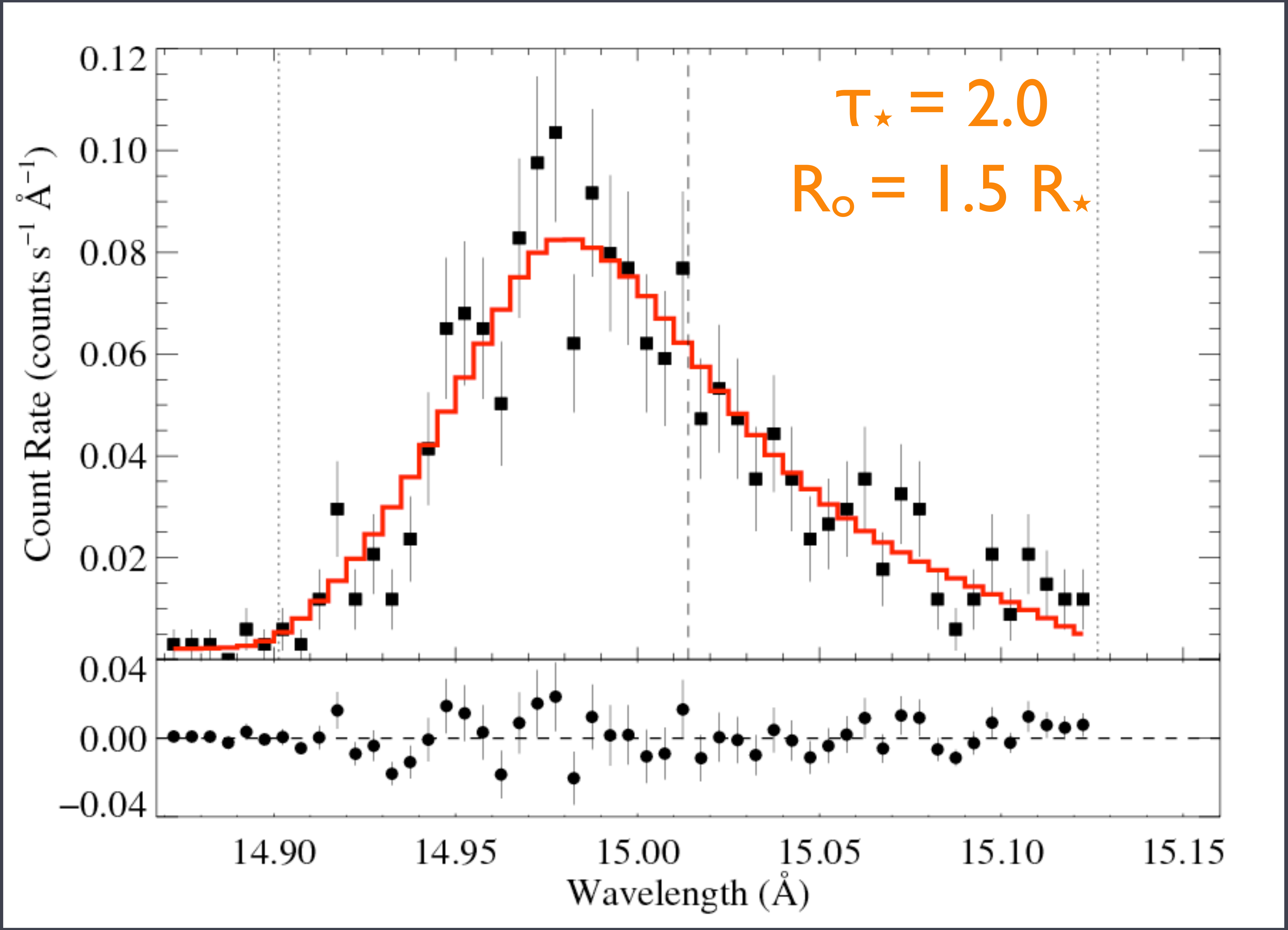


$R_o = 10\ R_\star$



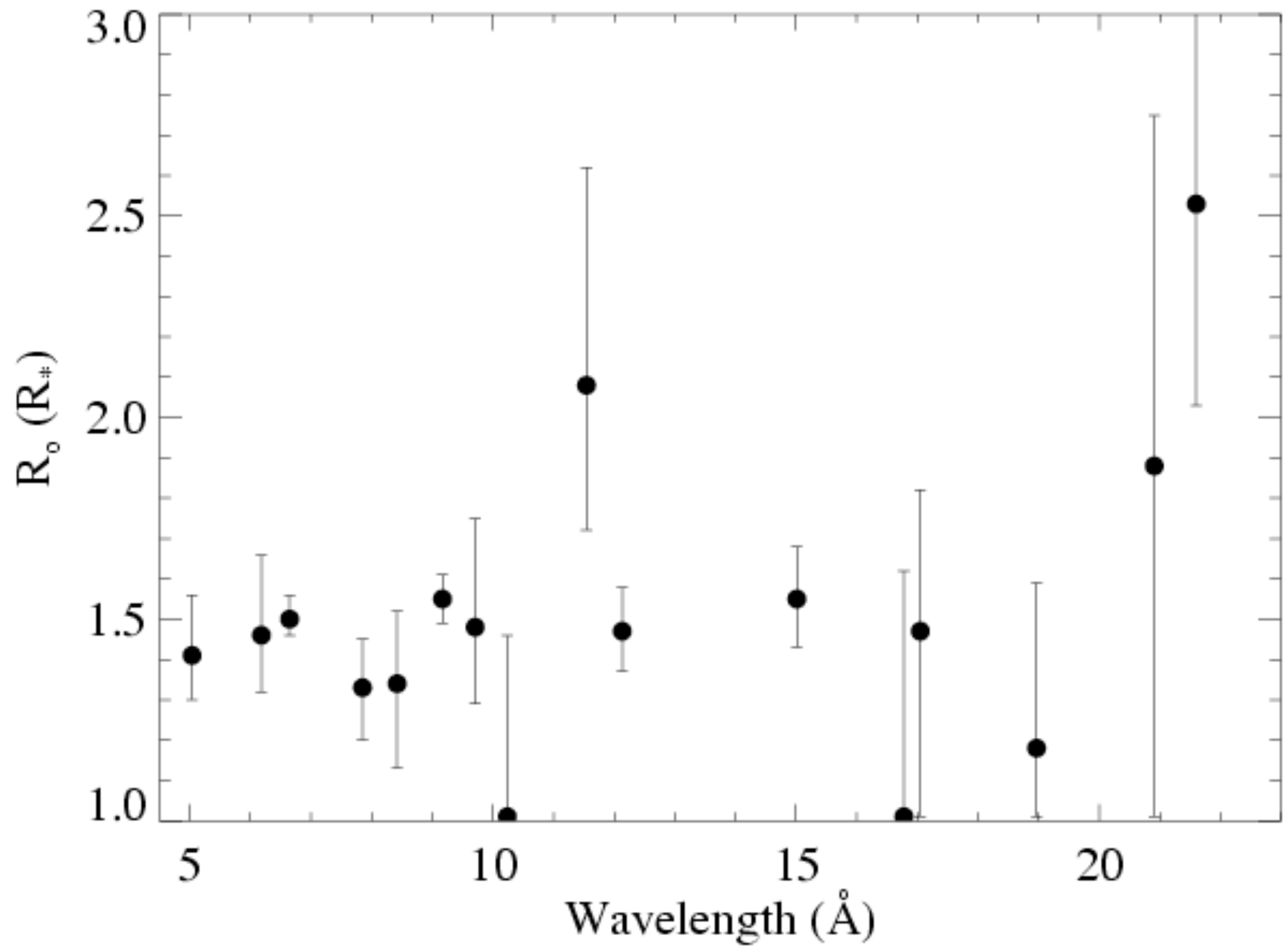
ζ Pup: *Chandra* MEG

Fe XVII

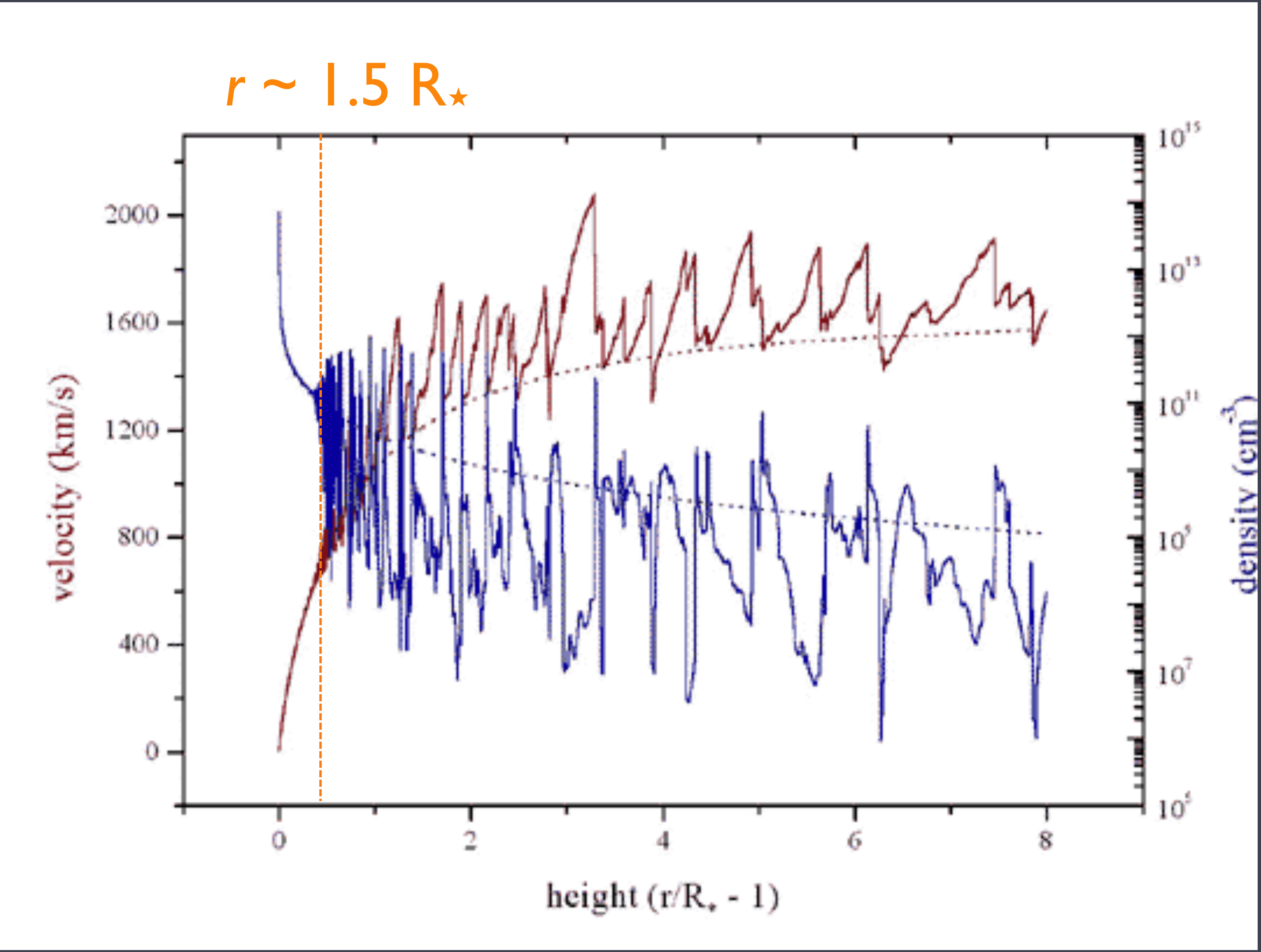


Distribution of R_o values for ζ Pup

consistent with a global value of $R_o = 1.5\ R_\star$



Numerous shock structures distributed above $r \sim 1.5\ R_\star$



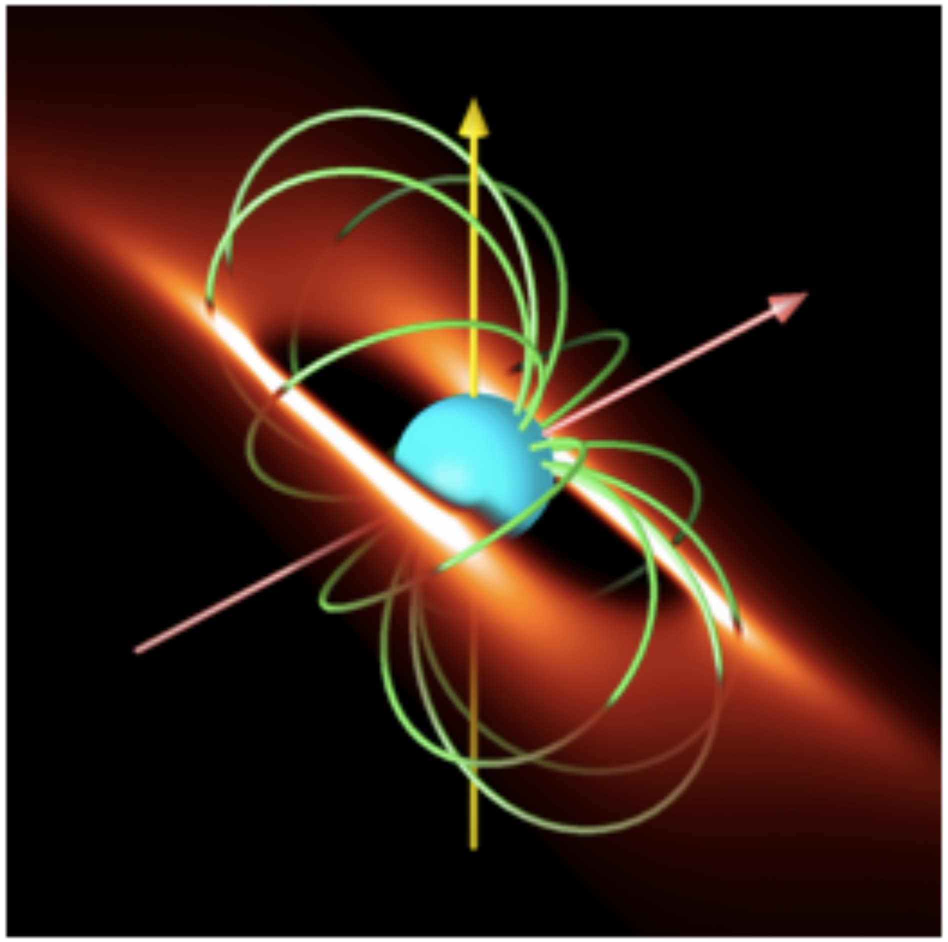
A subset of massive stars have large-scale magnetic fields

this provides a variation on the wind-shock mechanism…

the Magnetically Channeled Wind Shock mechanism (MCWS)

~10% of massive stars are magnetic

unlike solar type magnetism, though: time-constant, not dynamo generated, often large-scale dipole



A simulation of the circumstellar matter distribution of σ Ori E, as predicted by the Rigidly Rotating Magnetosphere mode

R. Townsend

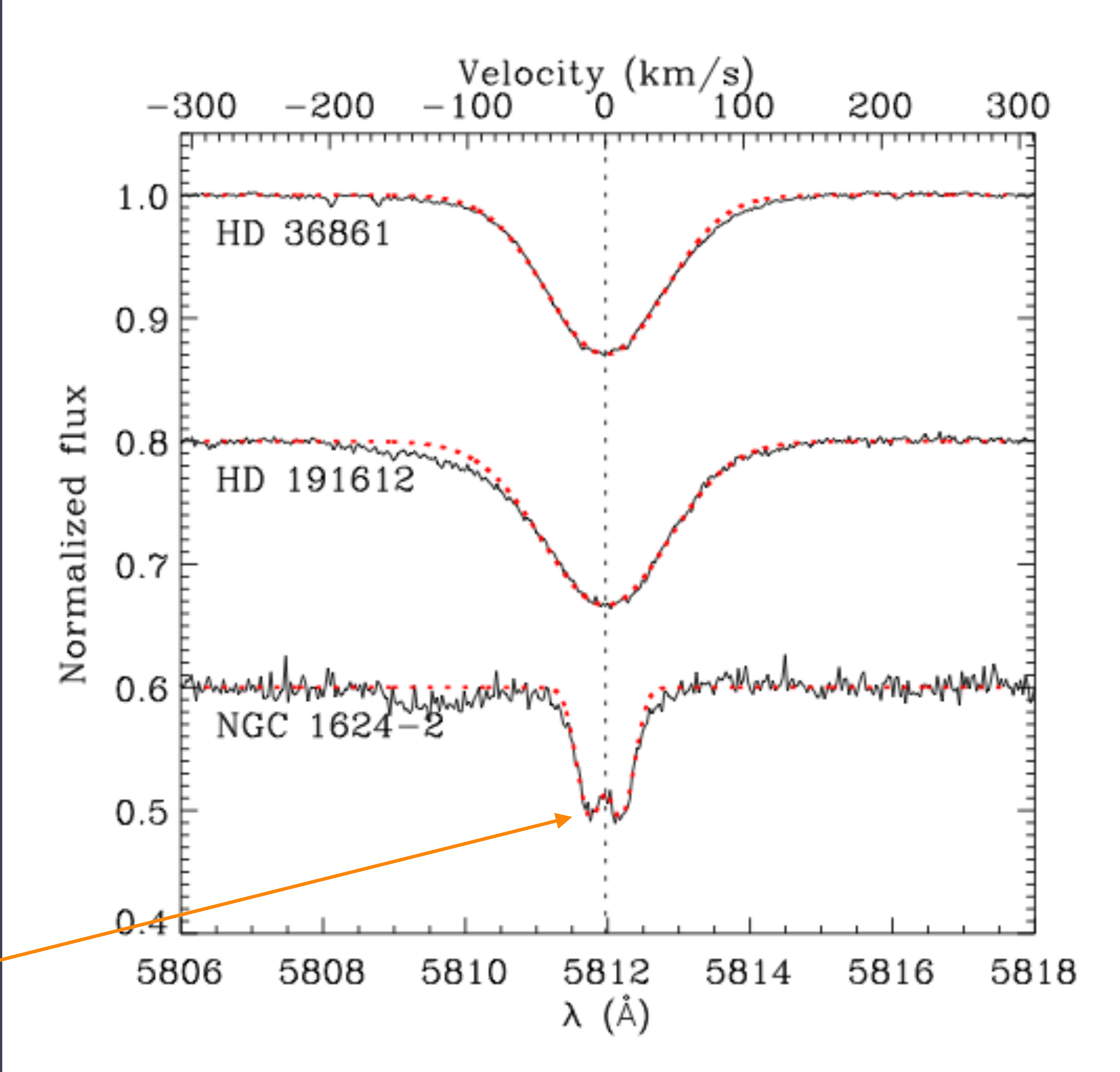
The MiMeS project: overview and current status

Gregg A. Wade[1], Evelyne Alecian[2], David A. Bohlender[3], Jean-Claude Bouret[4], David H. Cohen[5], Vincent Duez[6], Marc Gagné[7], Jason H. Grunhut[1], Huib F. Henrichs[8], Nick R. Hill[9], Oleg Kochukhov[10], Stéphane Mathis[11], Coralie Neiner[12], Mary E. Oksala[13], Stan Owocki[13], Véronique Petit[7], Matthew Shultz[1], Thomas Rivinius[14], Richard H. D. Townsend[9], Jorick S. Vink[15] and the MiMeS collaboration†

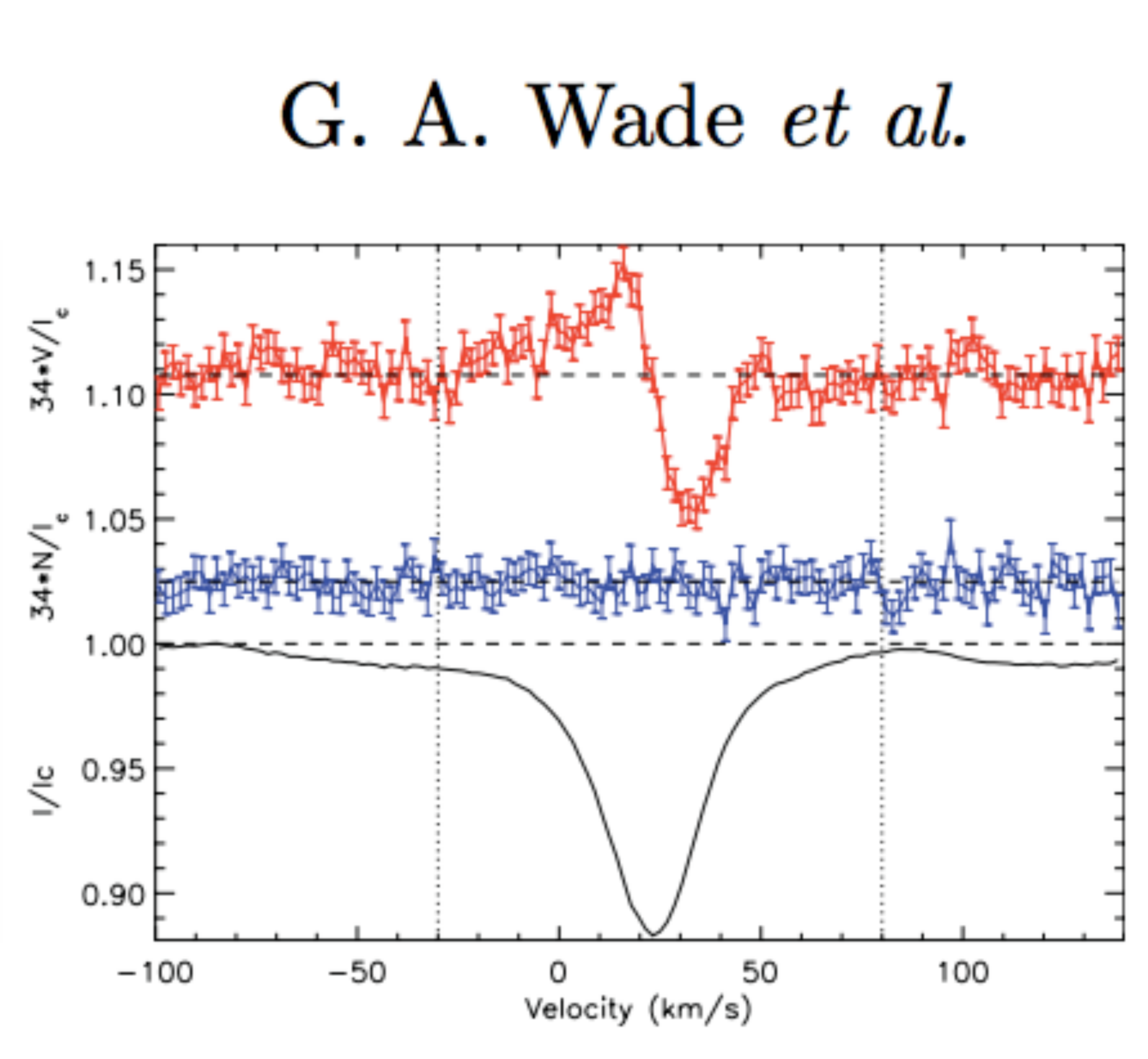
[1]Kingston, Canada, [2]LOAG, France, [3]HIA, Canada, [4]LAM, France, [5]Swarthmore, USA, [6]Argelander, Germany, [7]West Chester, USA, [8]Amsterdam, Netherlands, [9]Madison, USA, [10]Uppsala, Sweden, [11]CEA, France, [12]Paris Observatory, France, [13]Delaware, USA, [14]ESO, Chile, [15]Armagh, UK

Abstract. The Magnetism in Massive Stars (MiMeS) Project is a consensus collaboration among many of the foremost international researchers of the physics of hot, massive stars, with the basic aim of understanding the origin, evolution and impact of magnetic fields in these objects. At the time of writing, MiMeS Large Programs have acquired over 950 high-resolution polarised spectra of about 150 individual stars with spectral types from B5-O4, discovering new magnetic fields in a dozen hot, massive stars. The quality of this spectral and magnetic matériel is very high, and the Collaboration is keen to connect with colleagues capable of exploiting the data in new or unforeseen ways. In this paper we review the structure of the MiMeS observing programs and report the status of observations, data modeling and development of related theory.

Zeeman splitting can be measured



and for weaker magnetic fields, the Zeeman signal can be seen in circularly polarized light



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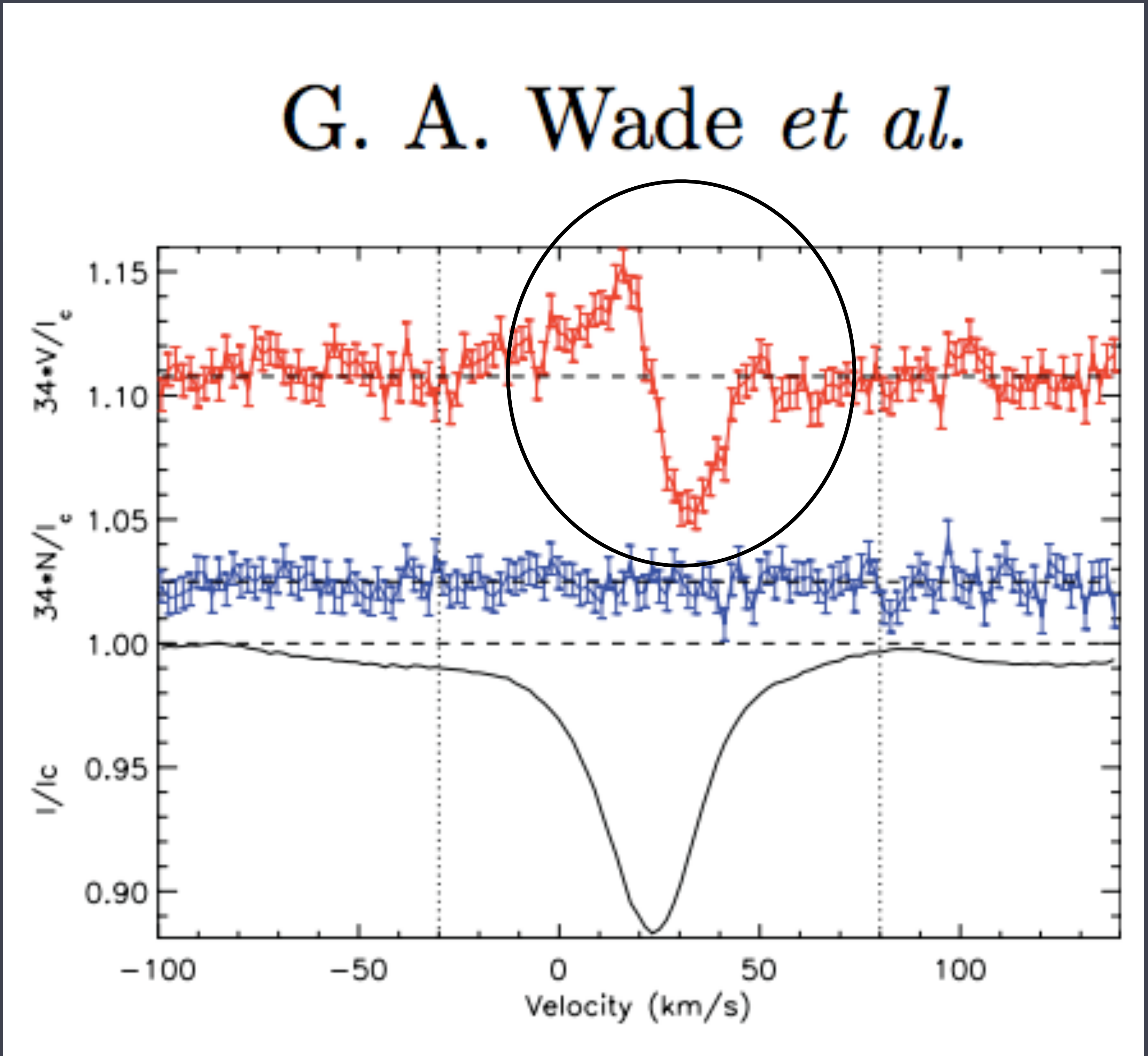
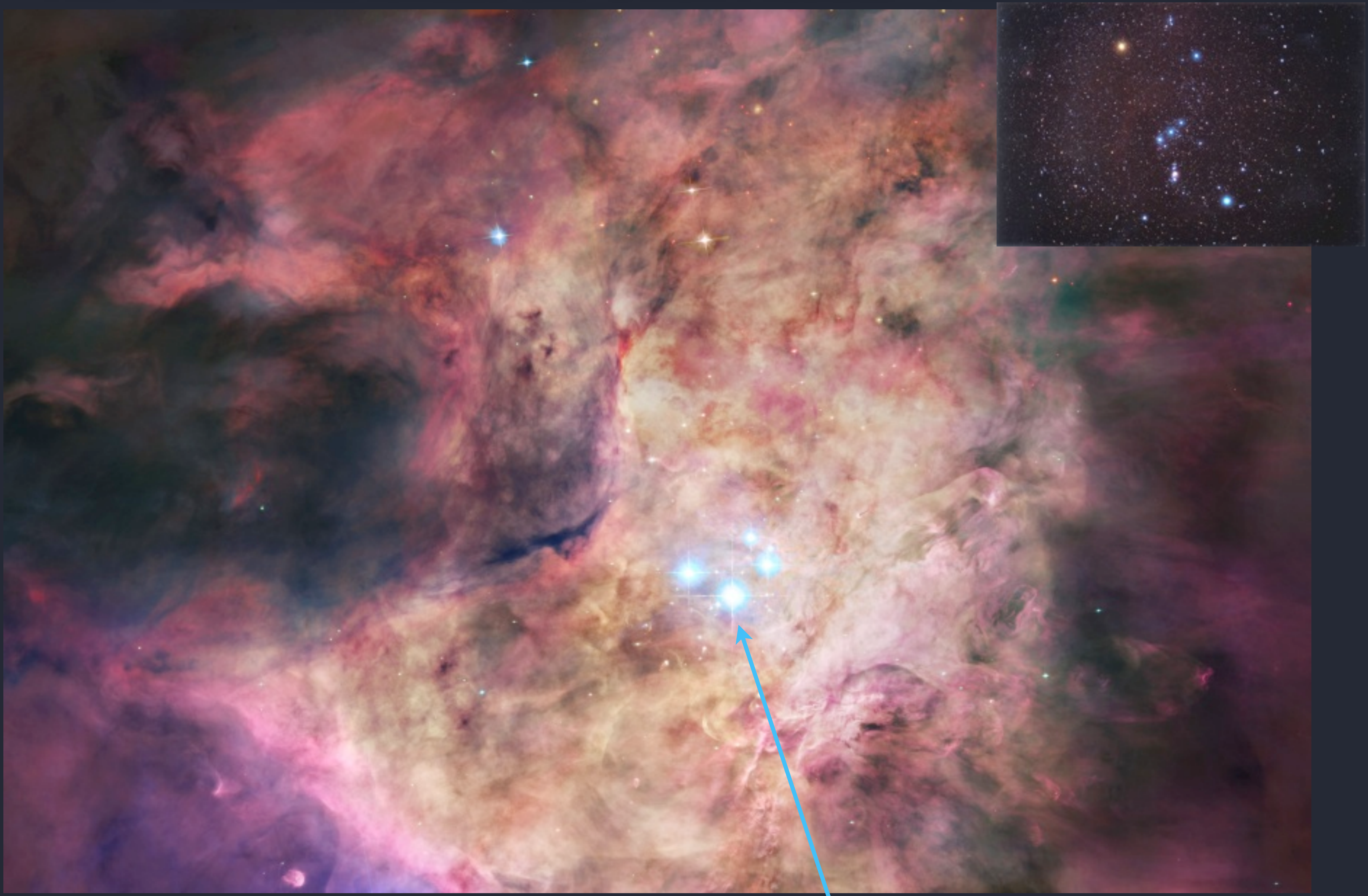


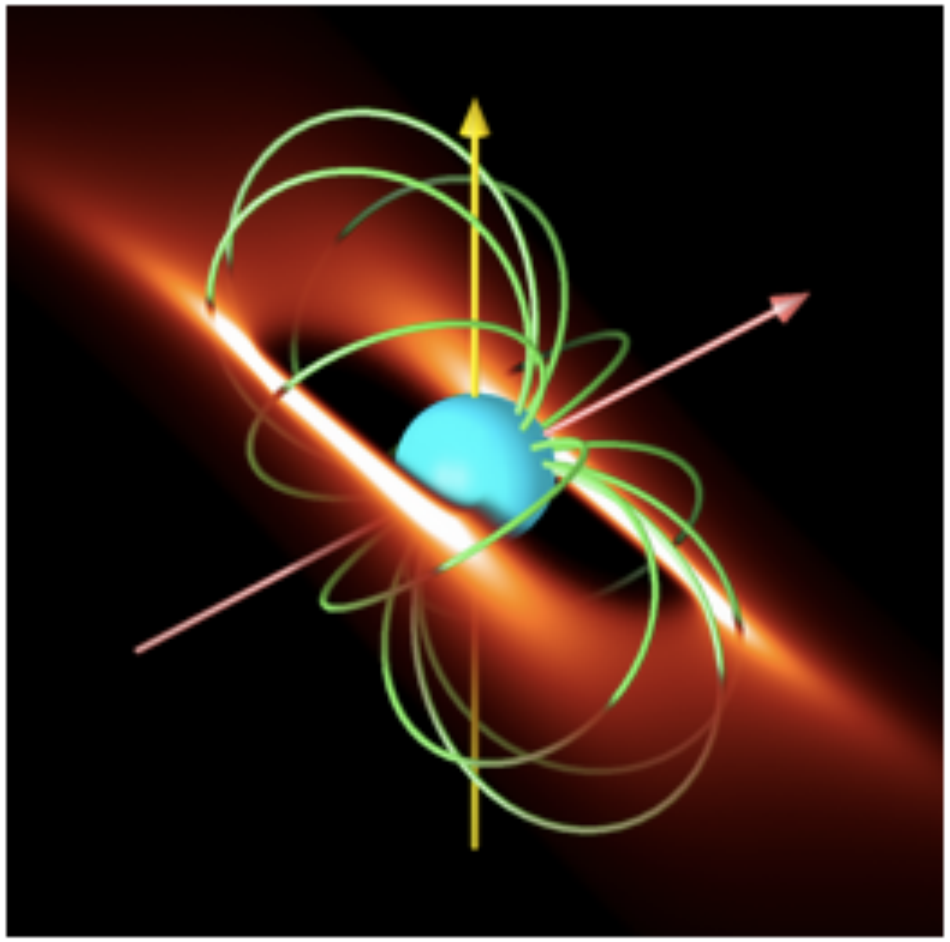
The O star that ionizes the Orion Nebula: ~1 kG tilted dipole



Chandra X-ray image of the Orion Nebula Cluster

Magnetic Wind Channeling

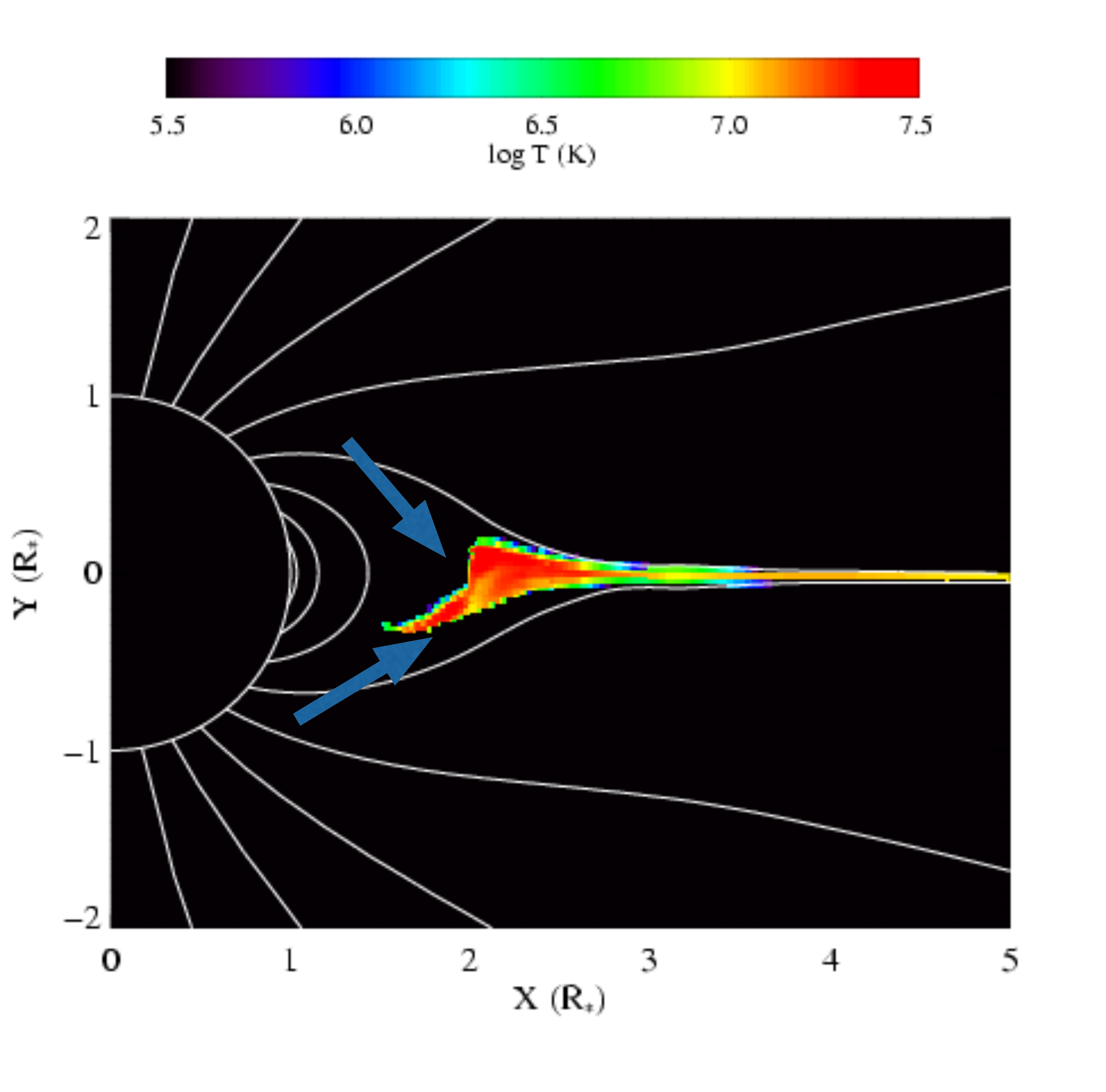
wind flows up magnetic footprints from each hemisphere and collides and is compressed in the magnetic equator



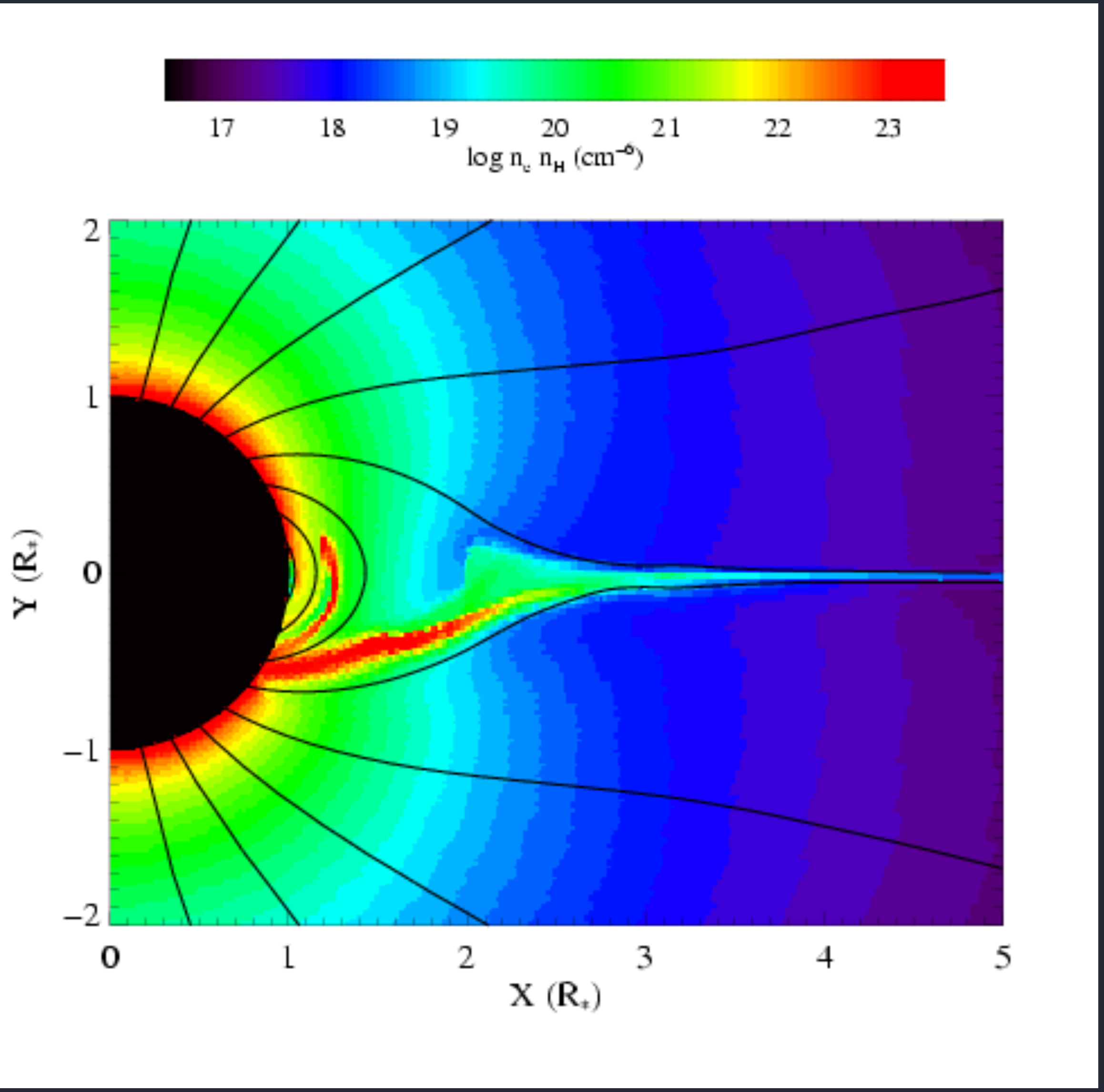
A simulation of the circumstellar matter distribution of σ Ori E, as predicted by the Rigidly Rotating Magnetosphere mode

MHD simulations of θ¹ Ori C: prototype magnetic O star

temperature

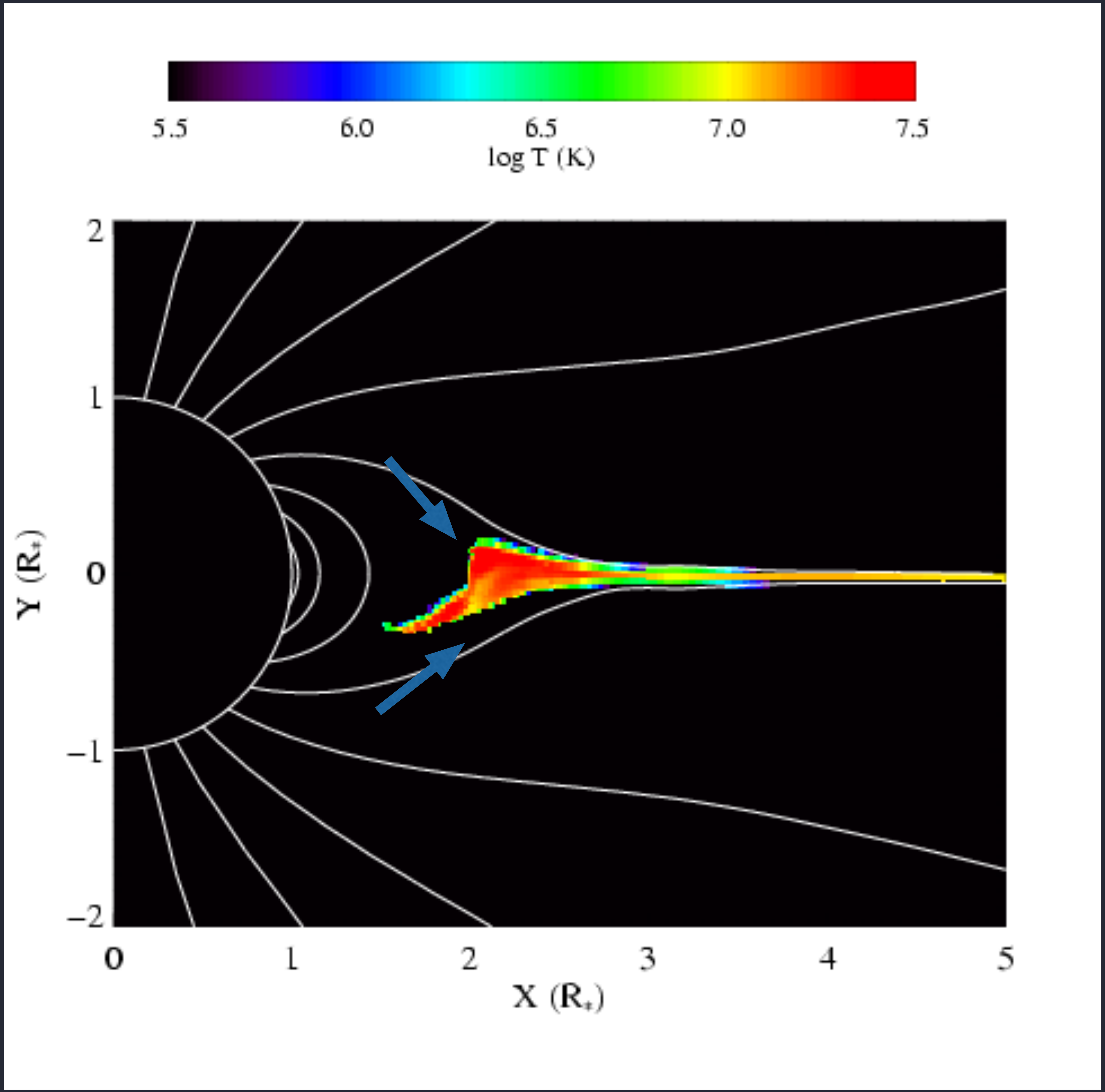


emission measure



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

opposite-directed flows along field lines collide nearly head on at the magnetic equator



The line-deshadowing instability (LDI)

causes fast, rarefied wind plasma to slam into slower, denser wind plasma

the resulting shocks heat the plasma

the X-rays we see are the thermal emission from this hot wind plasma

general result from shock theory:

$$T \sim 10^6(\Delta v_{shock}/300\ \mathrm{km/s})^2$$

Magnetically Channeled Wind Shock model

magnetic channeling causes wind flows from **opposite** hemispheres to collide in the magnetic equator

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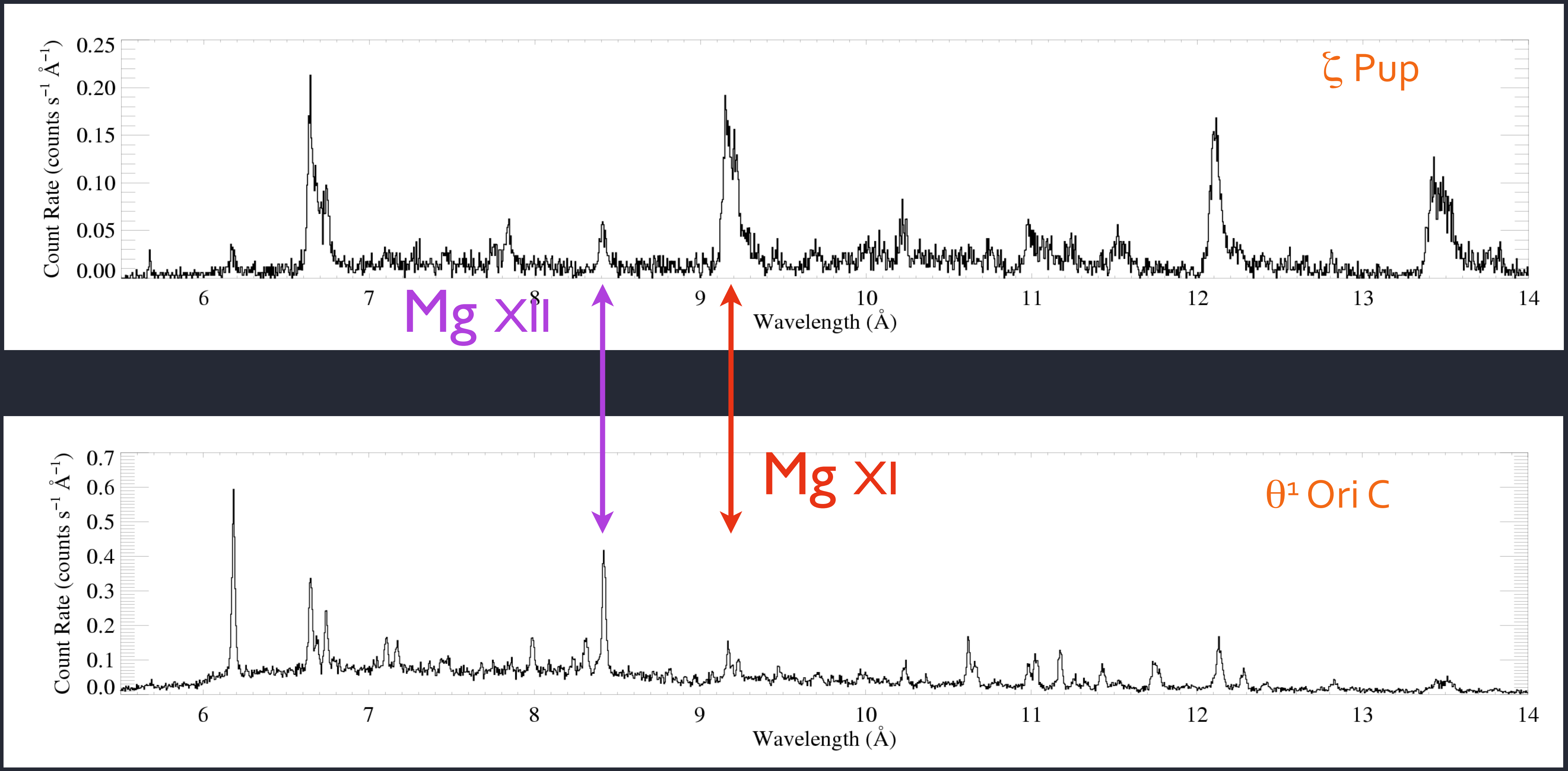
MCWS shocks have higher shock velocities because the magnetic channeling leads to more head-on collisions

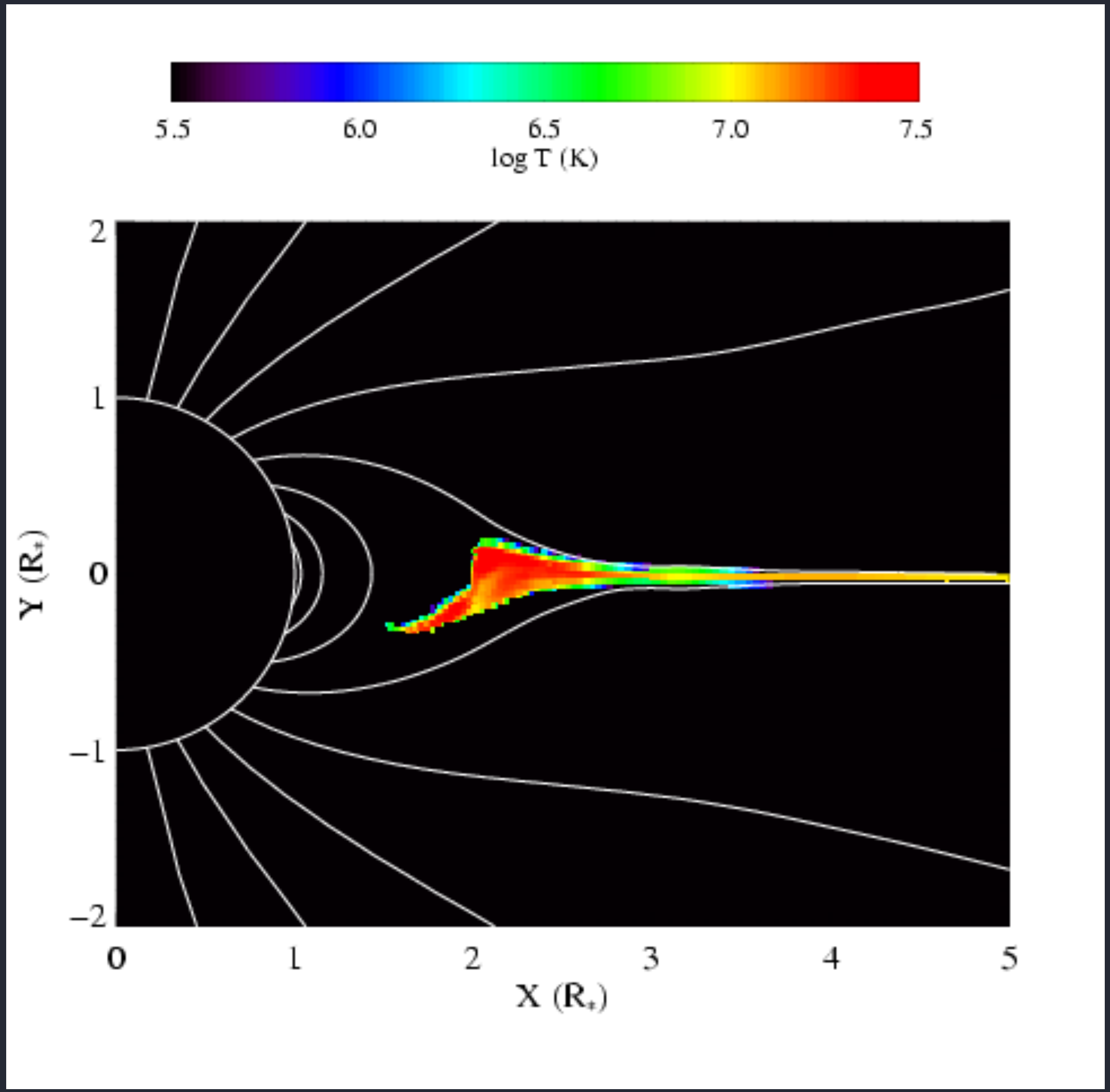
θ¹ Ori C: hotter plasma, narrower lines

Mg XII / Mg XI is proportional to temperature



θ[1] Ori C: prototype magnetic O star

temperature



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

magnetic channeling : strong shocks = hotter plasma

magnetic confinement : low post-shock velocity = narrower lines

Conclusions

- Massive star X-ray emission is due to shocks embedded in their winds (LDI mechanism)
- Subset of massive stars with magnetic fields also emit wind-shock X-rays (MCWS mechanism)
- High-resolution X-ray spectroscopy is an excellent tool for studying the wind-shock physics