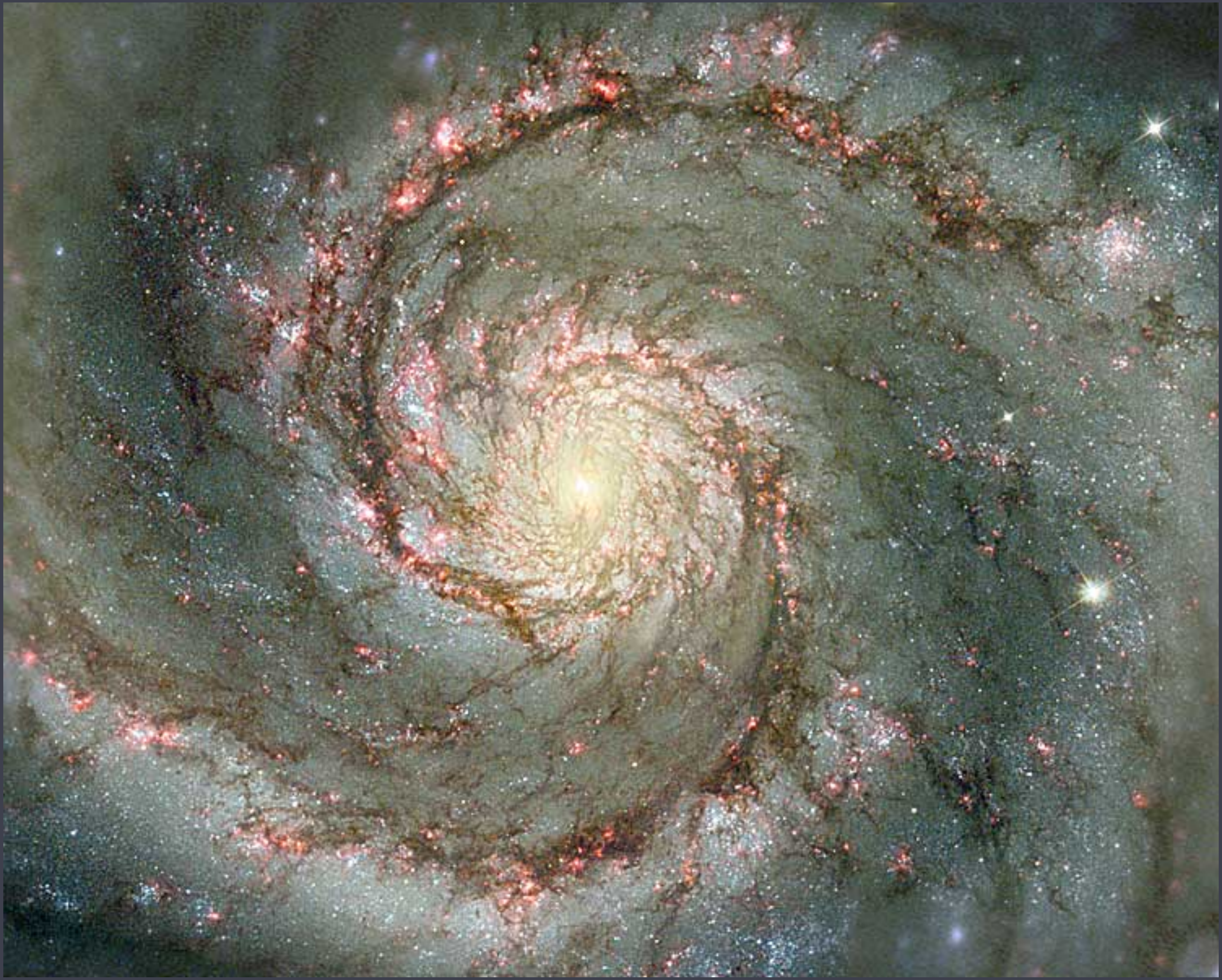
Massive stars in the galactic context

Their extreme luminosity, high surface temperatures, short lives, strong stellar winds, and dramatic (and energetic) deaths are some of their key features.

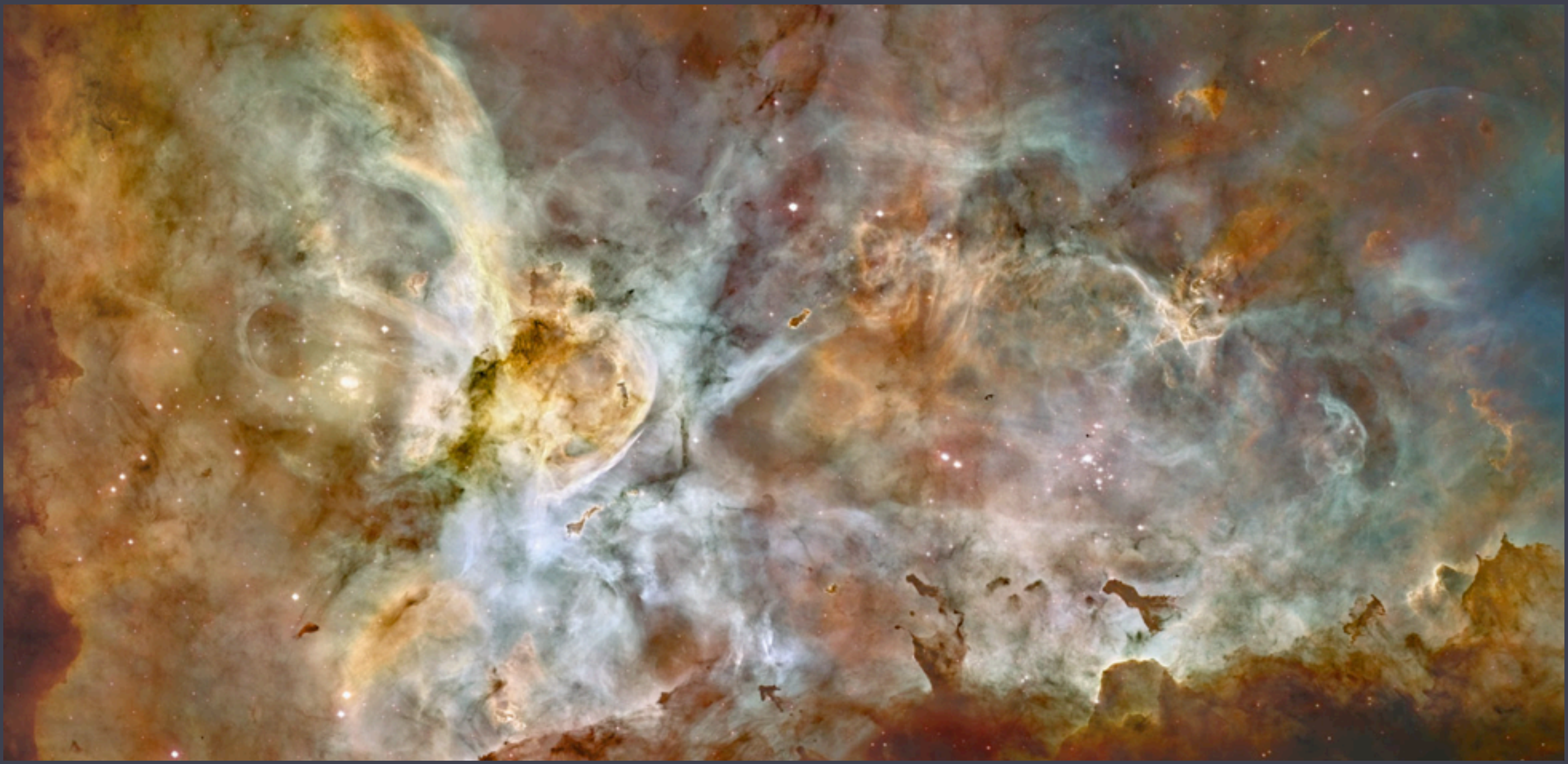


Whirlpool Galaxy, *Hubble Space Telescope*

Orion


Orion Nebula, *Hubble Space Telescope*

Orion Nebula, *Hubble Space Telescope*



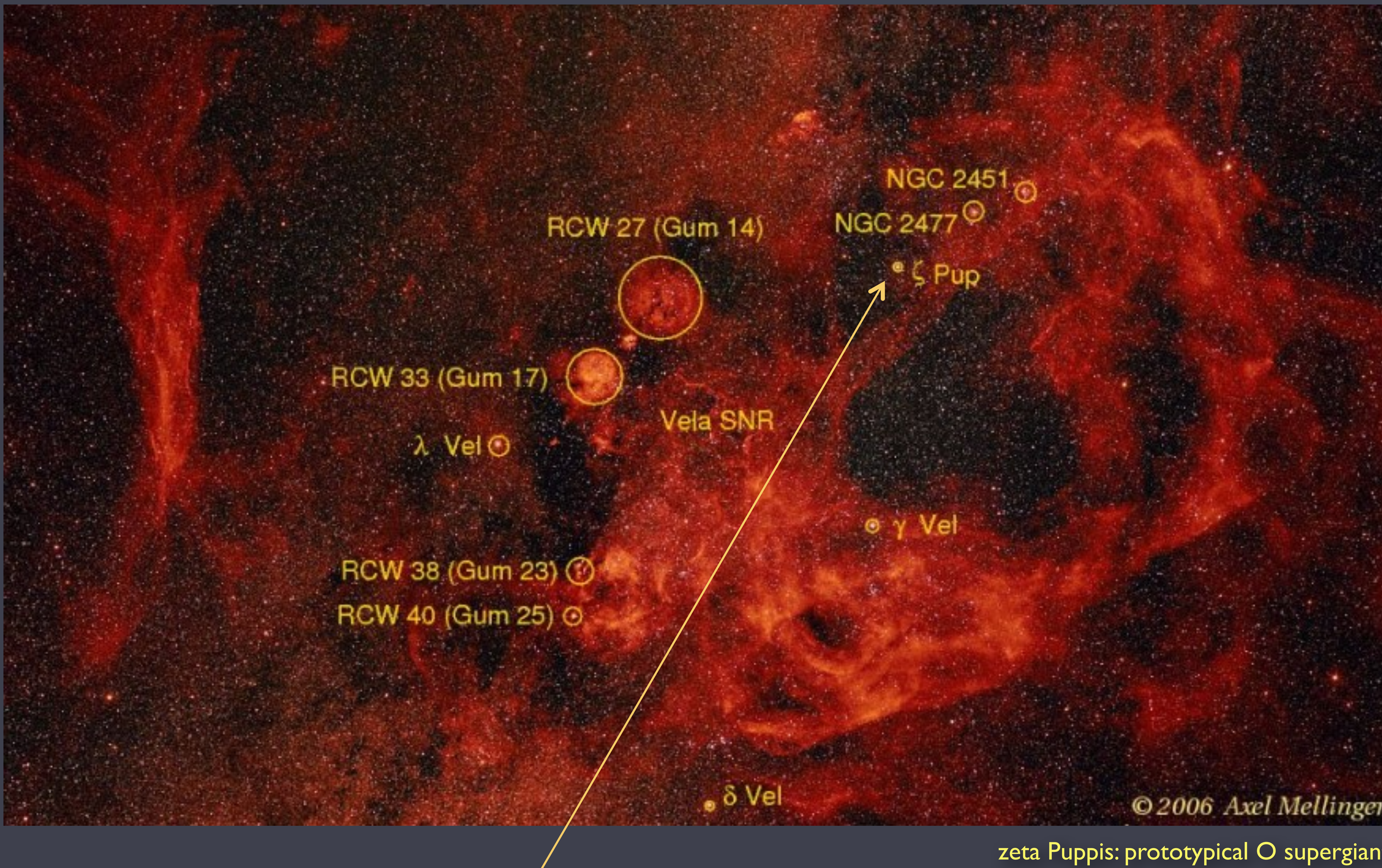
Carina Nebula, *Hubble Space Telescope*

Keyhole Nebula

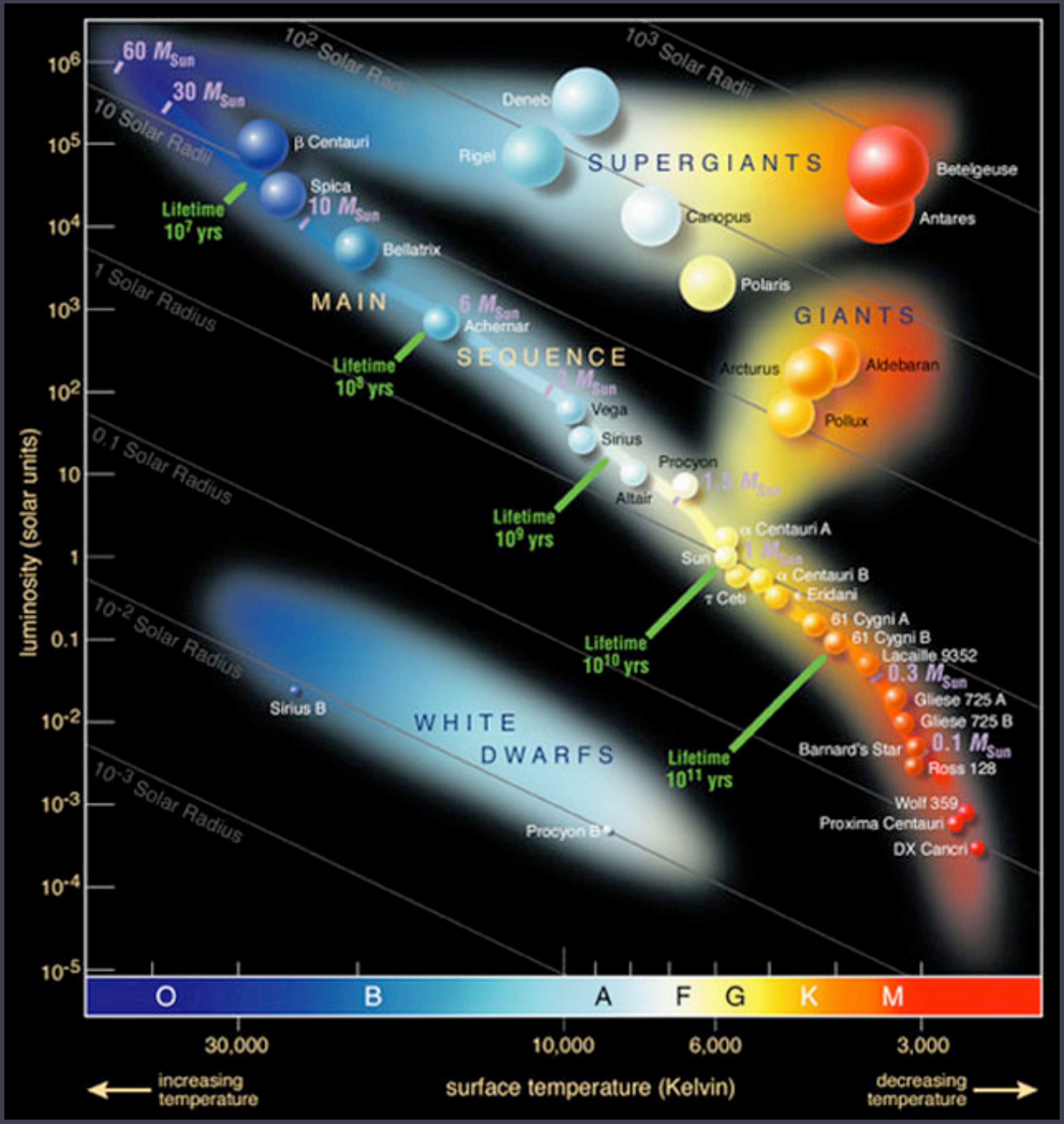
Hubble Heritage

NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC00-06

Some O stars are "runaways"



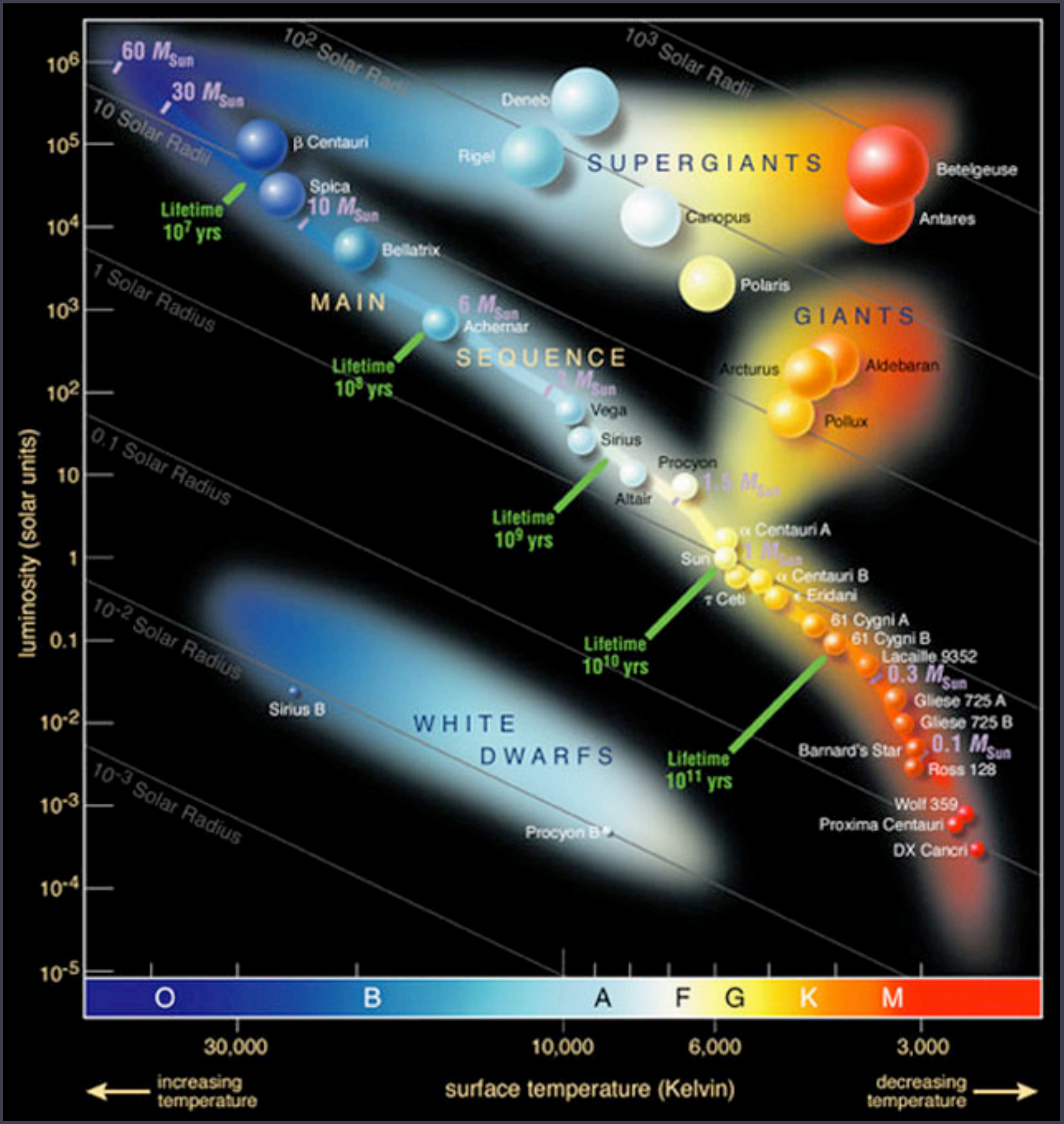
zeta Puppis: prototypical O supergiant



Bennett et al., *The Cosmic Perspective*

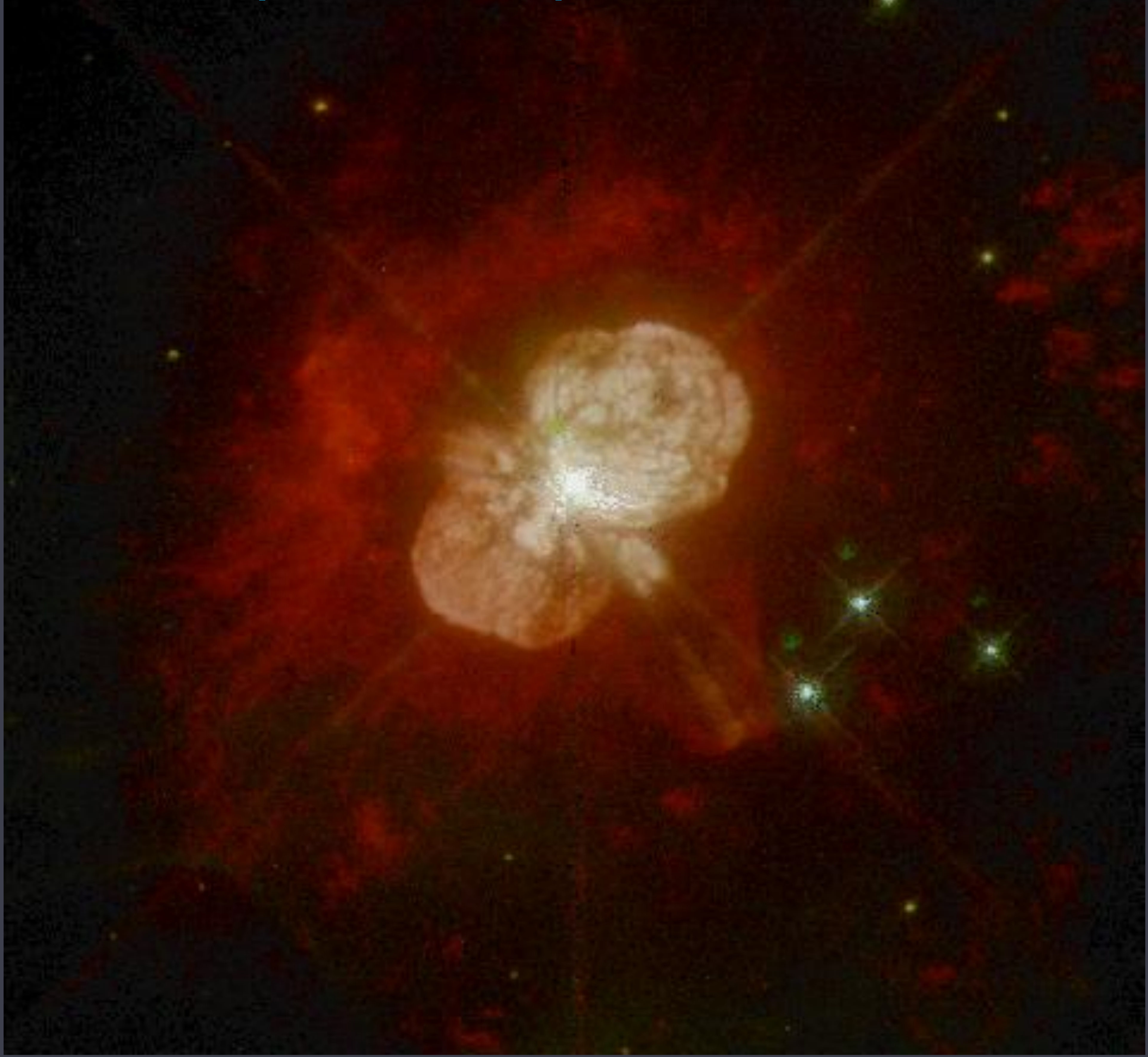
Basic properties of massive stars - O stars

mass ~ 50 M_{sun}
luminosity ~ 10^6 L_{sun}
surface temperature ~ 45,000 K



Bennett et al., *The Cosmic Perspective*

explosive/eruptive mass-loss



eta Carina, *HST*

~1000 year-old core-collapse supernova remnant

Crab Nebula, *WIYN*

Basic properties of massive stars - O stars

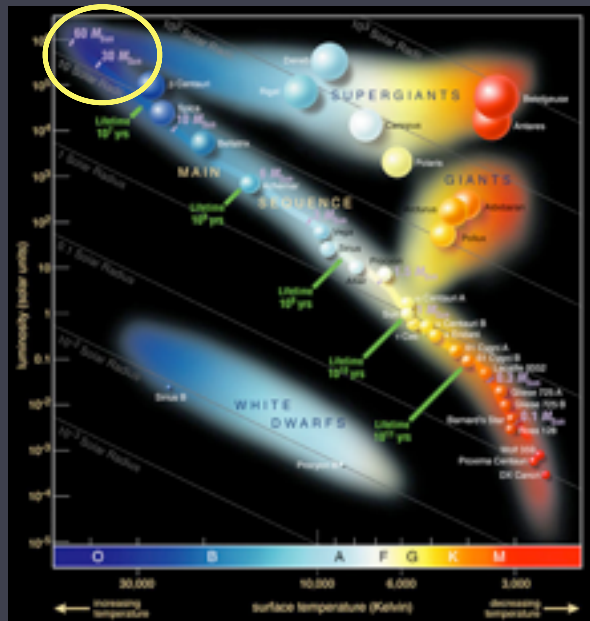
mass ~ 50 M_{sun}
luminosity ~ 10^6 L_{sun}
surface temperature ~ 45,000 K

Basic properties of massive stars - O stars

mass ~ 50 M_{sun}
luminosity ~ 10^6 L_{sun}
surface temperature ~ 45,000 K

*significant **momentum** in the photospheric radiation field*

Strong, radiation-driven stellar winds are a characteristic of massive stars

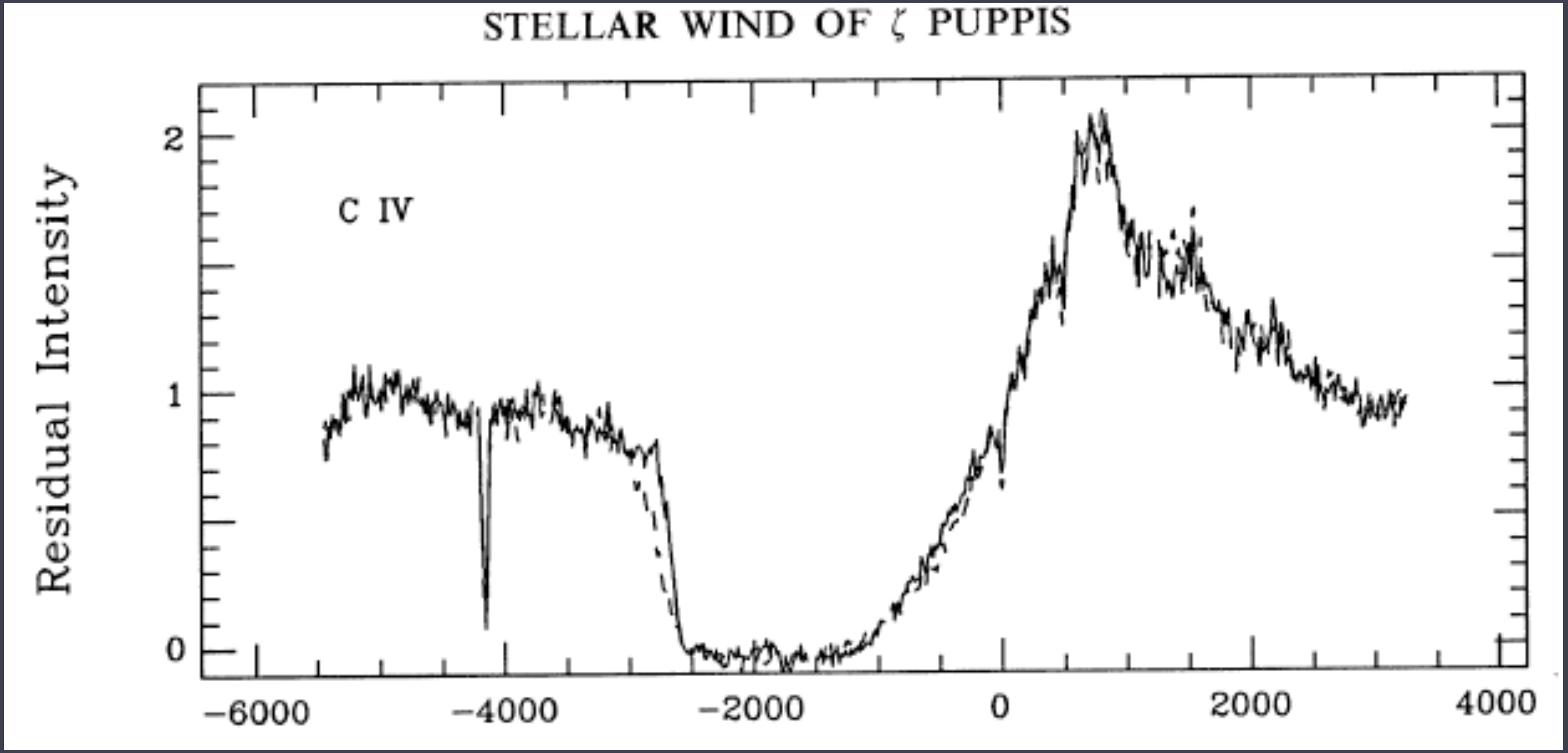


NGC 6888 Crescent Nebula - Tony Hallas

Radiation-driven O star winds

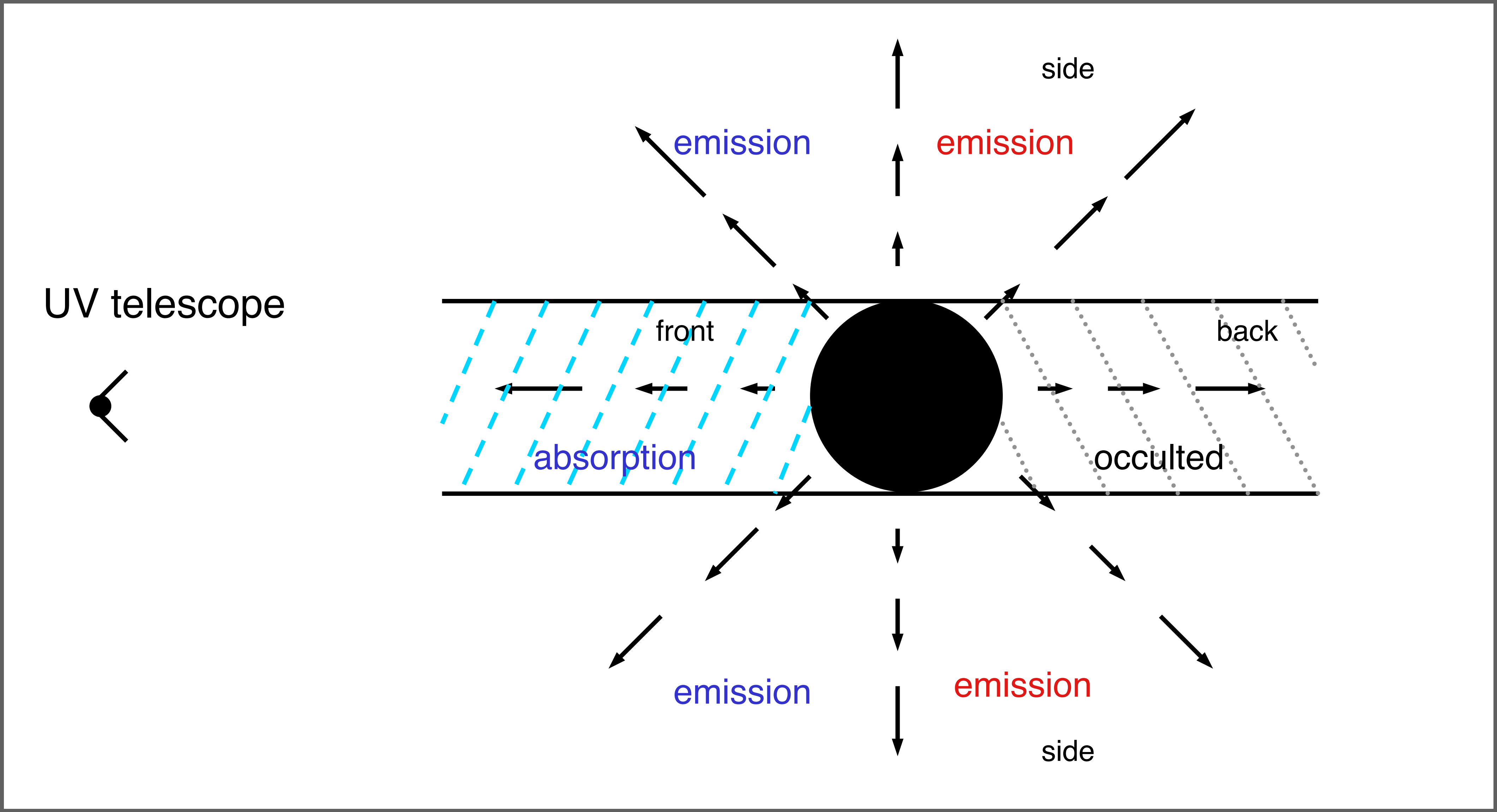
ζ Pup (O4 supergiant): $\dot{M} \sim$ few 10^{-6} M_{sun}/yr

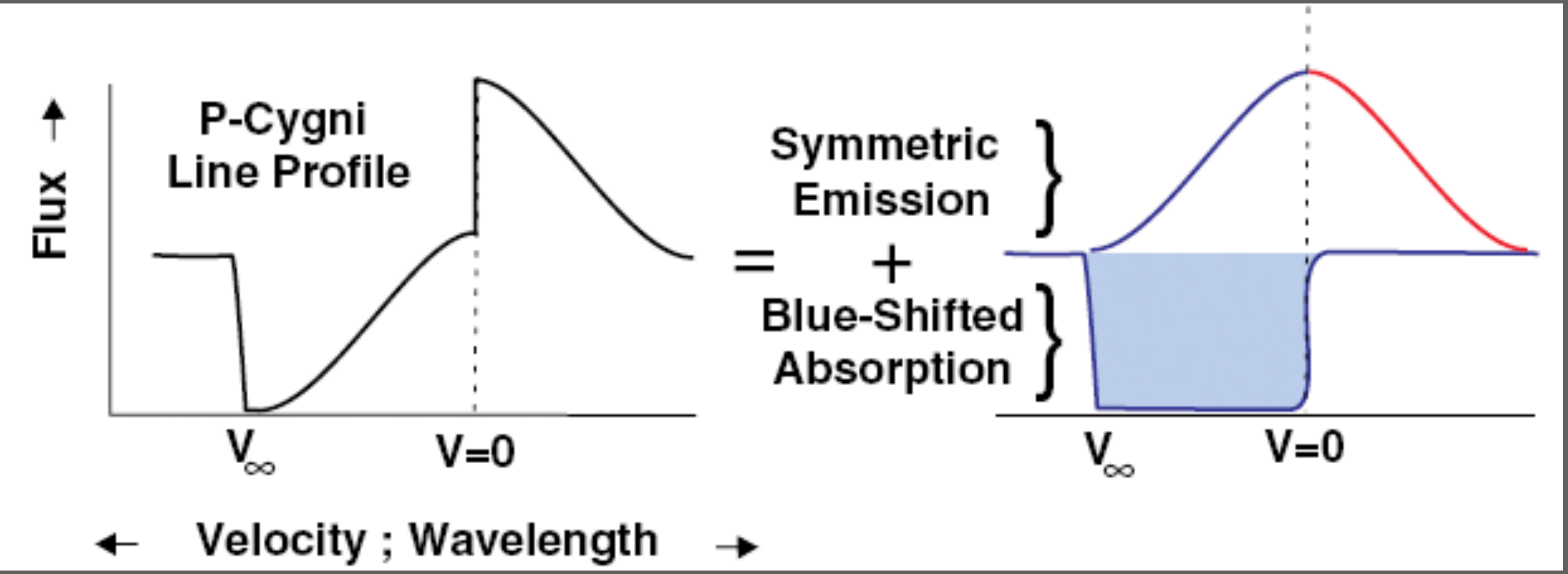
UV spectrum: C IV 1548, 1551 Å

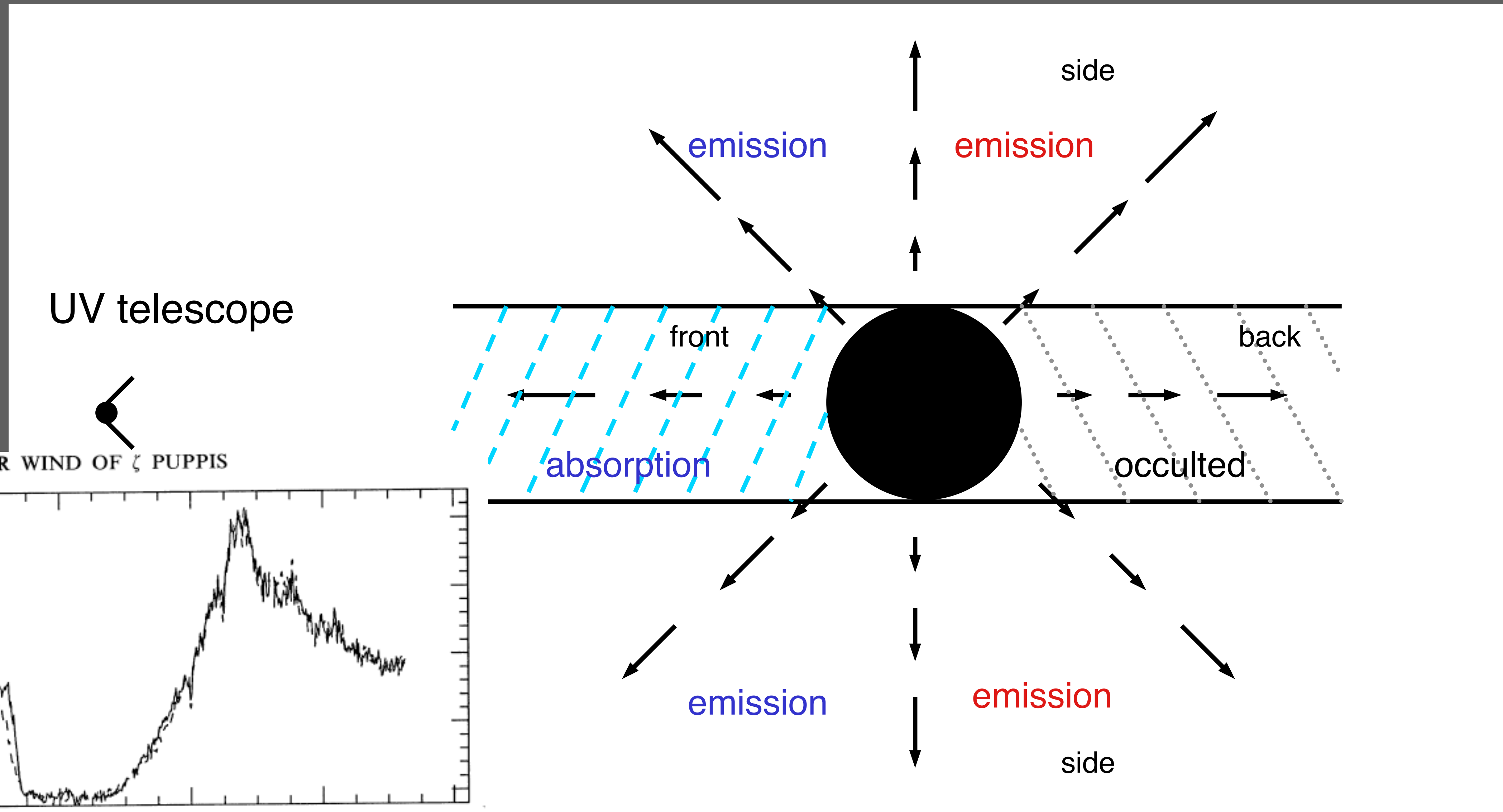


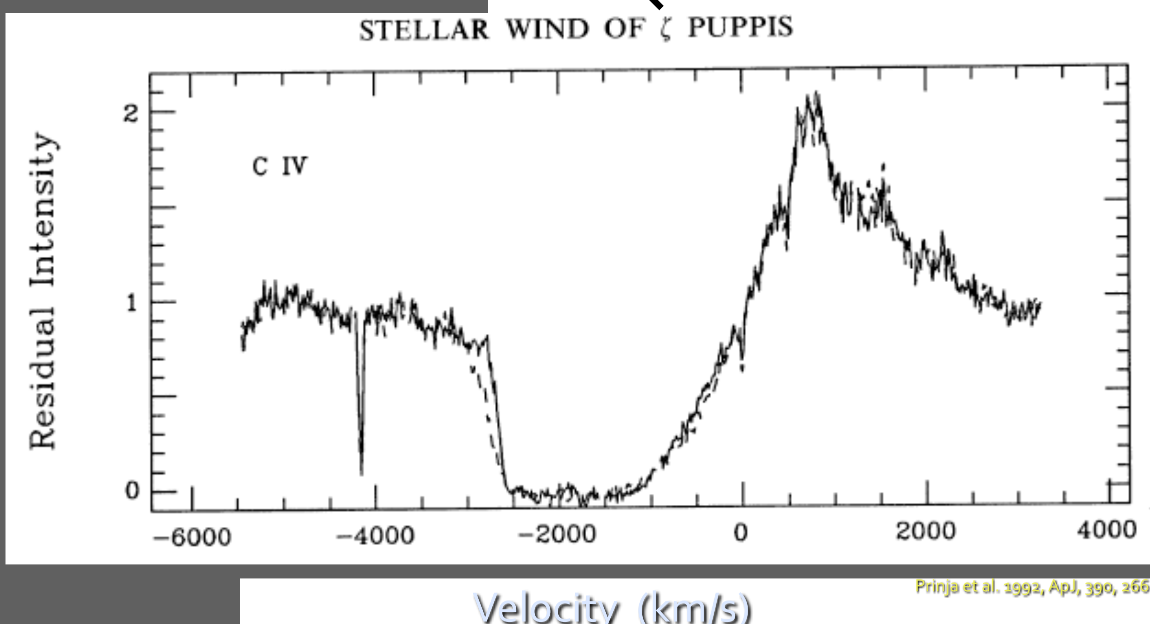
Velocity (km/s)

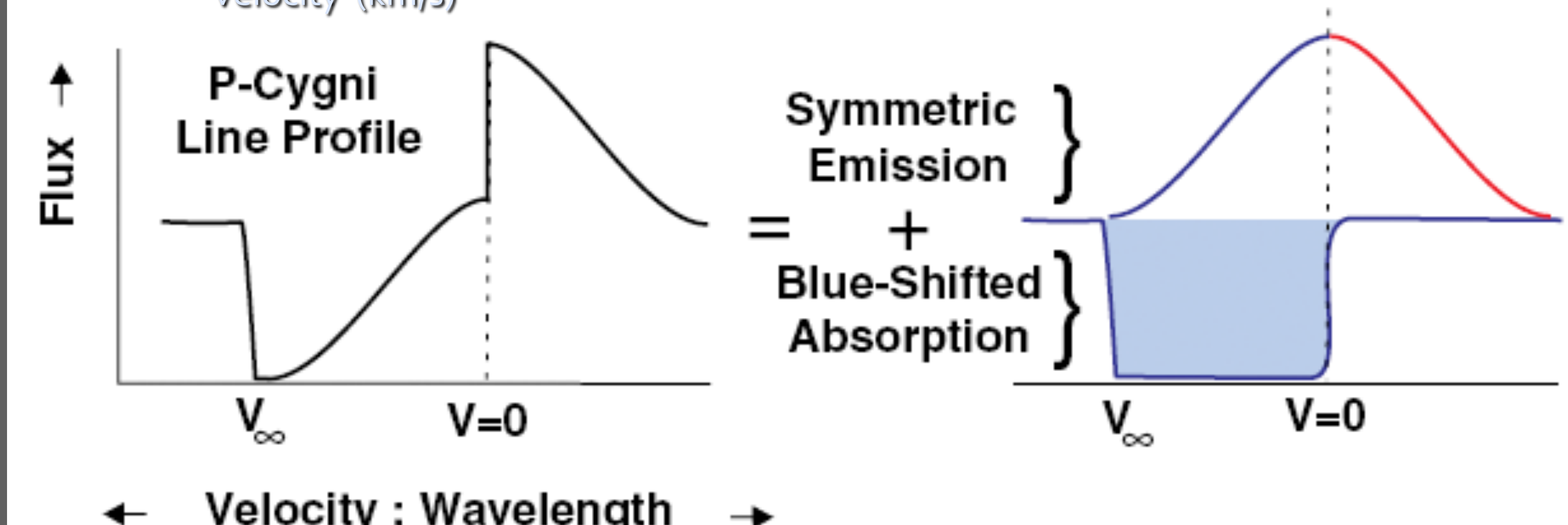
Prinja et al. 1992, ApJ, 390, 266


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


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


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


STELLAR WIND OF ζ PUPPIS
C IV
Residual Intensity
2
1
0
−6000
−4000
−2000
0
2000
4000
Velocity (km/s)
Prinja et al. 1992, ApJ, 390, 266


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

Radiation-driven O star winds

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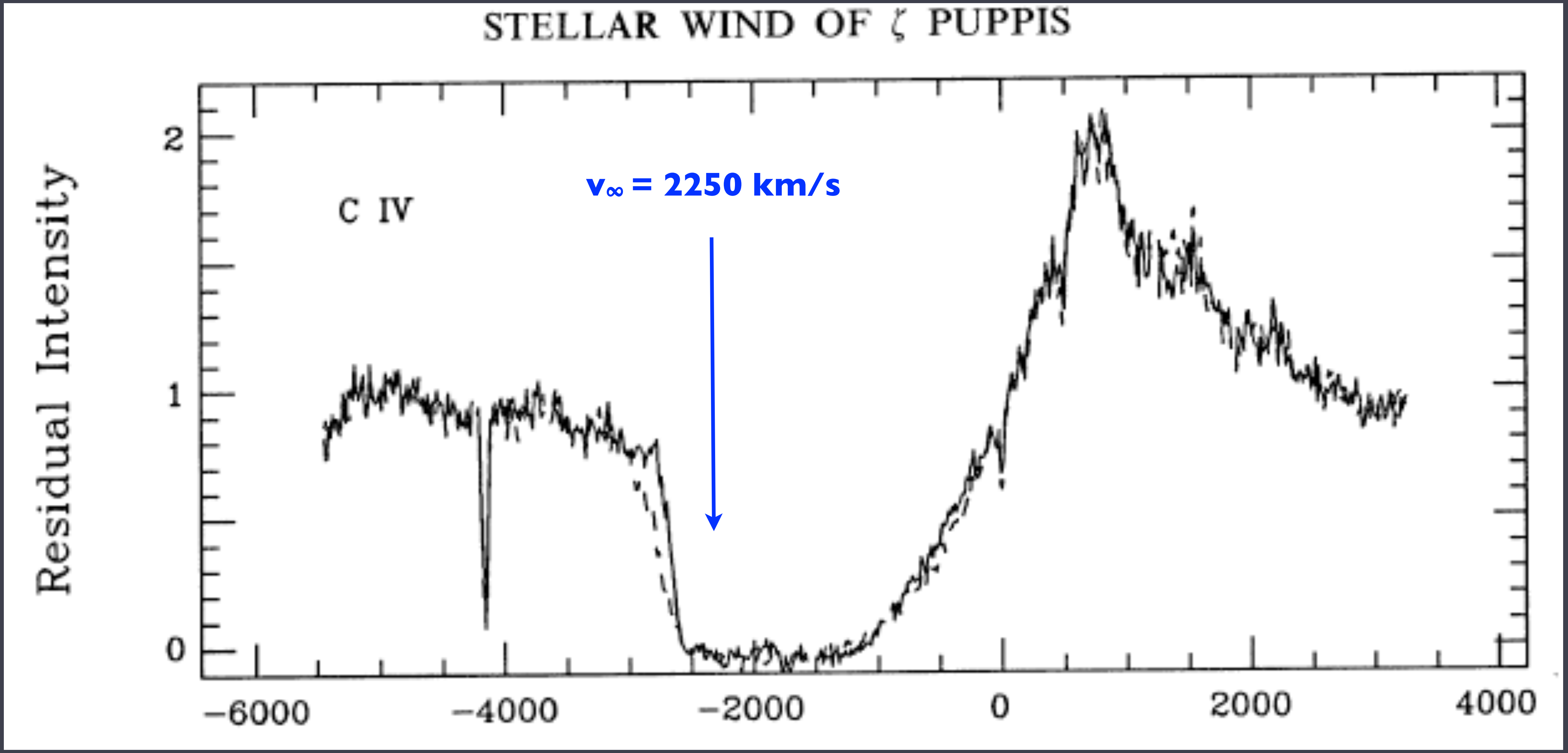
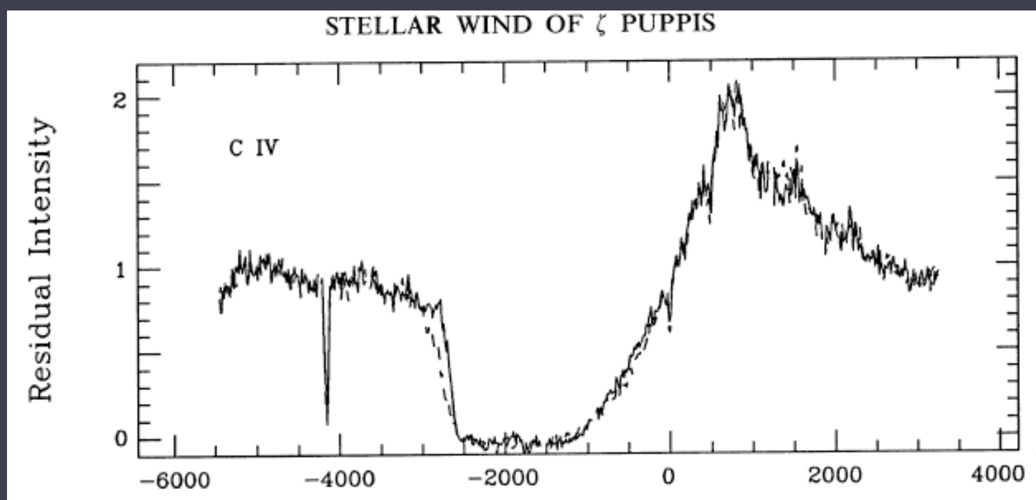
UV spectrum: C IV 1548, 1551 Å



Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

Wind mass-loss rates ($\dot{M}$) can be inferred from the strength of the absorption component



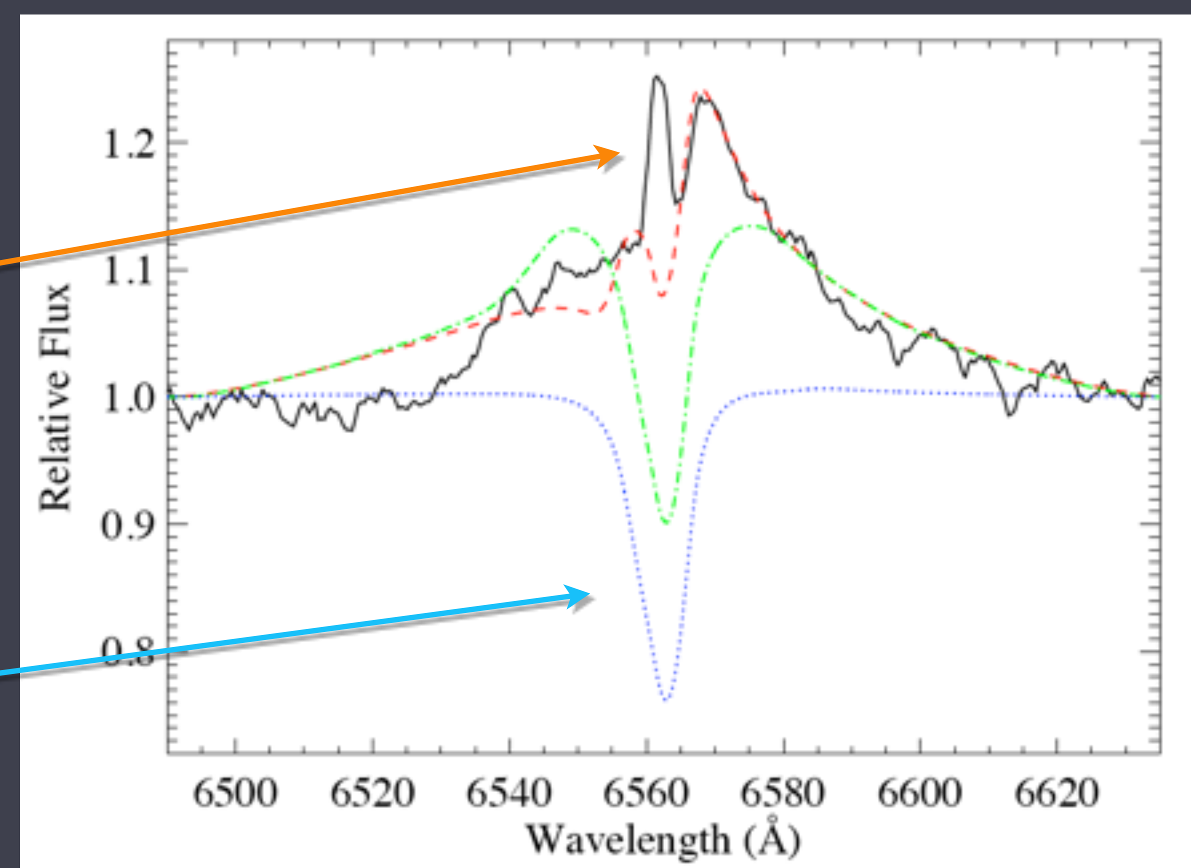
Velocity (km/s)

Prinja et al. 1992, ApJ, 390, 266

but, more reliable are emission lines such as Hα

emission from the wind

photosphere only (absorption), no wind



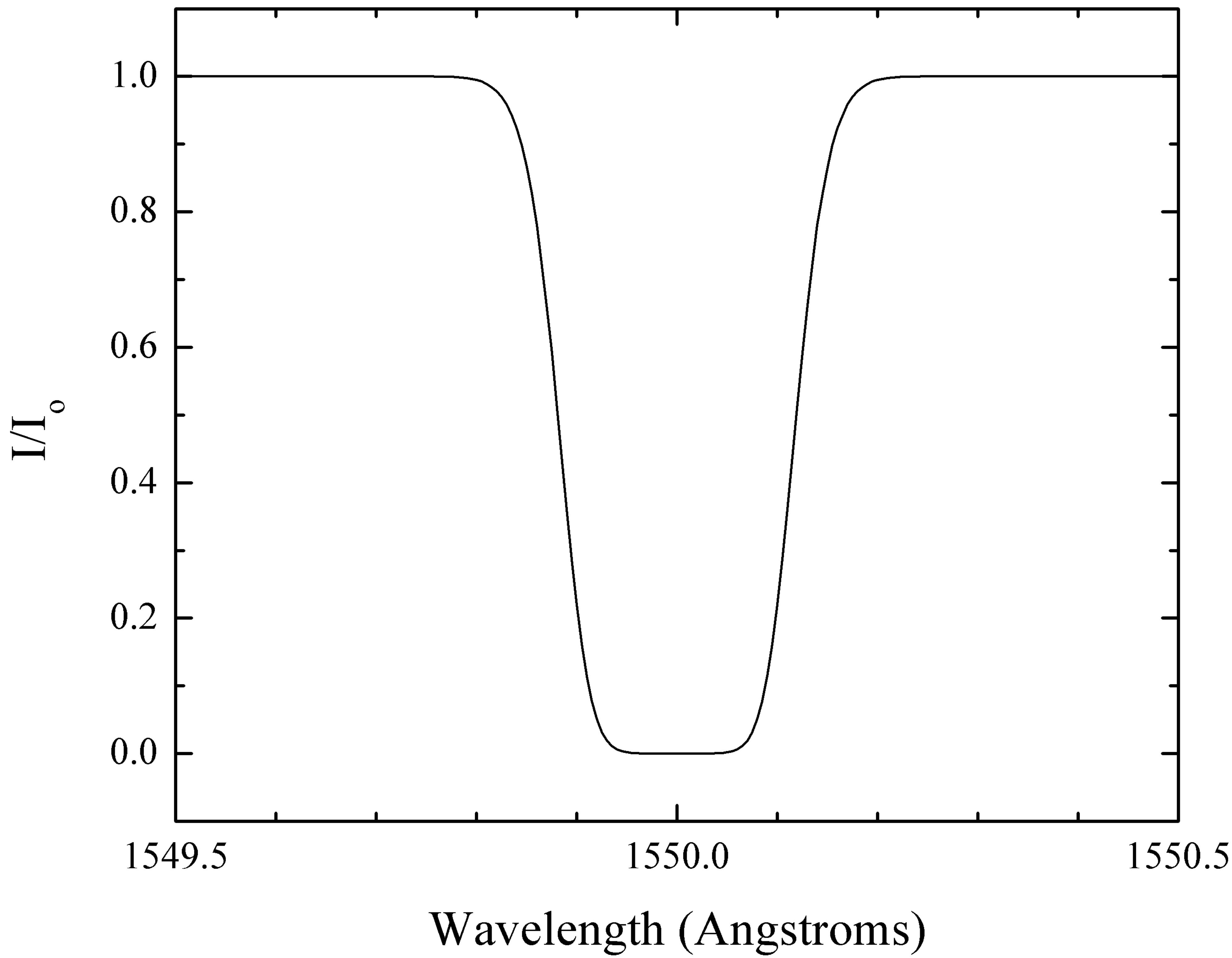
Radiation driving

L/c = momentum in the (mostly UV) radiation from the stellar surface > $\dot{M}v_\infty$ (wind momentum)

radiation couples to the matter in the wind via resonance line scattering

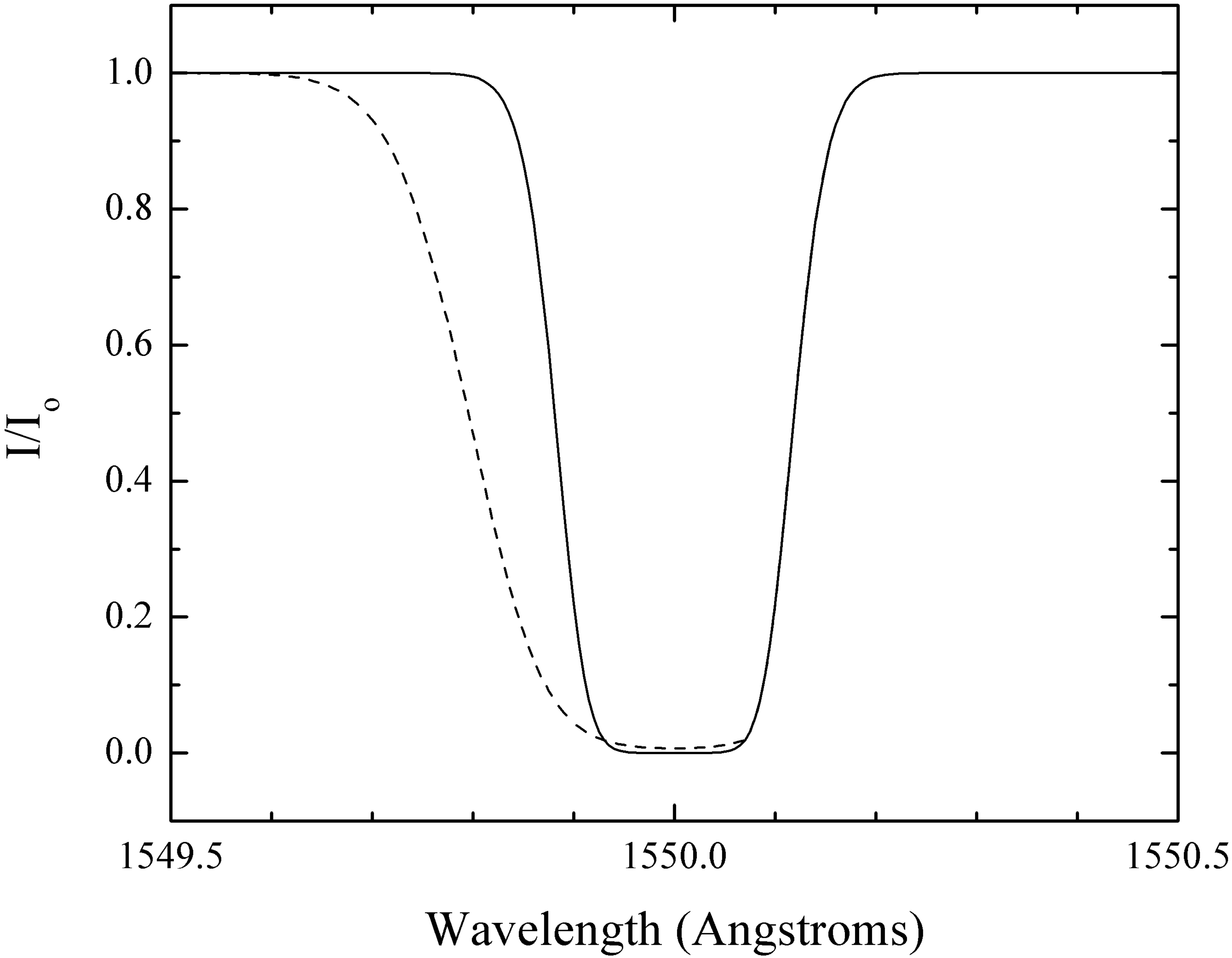
$\dot{M} \sim 10^{-6}\ M_{sun}/yr$ (10^8 times the Sun's value)

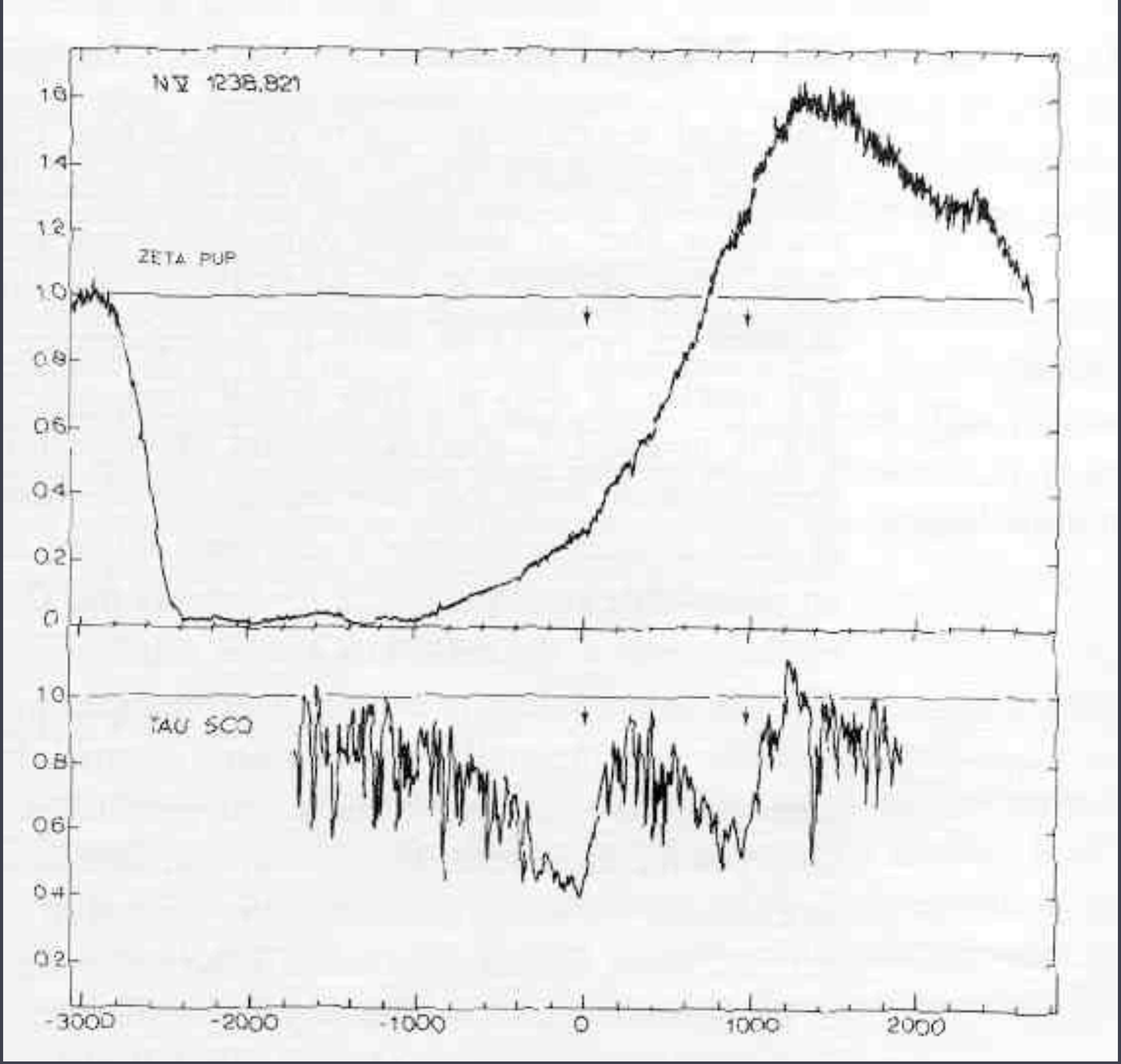
kinetic power in the wind = $1/2\ \dot{M}v_\infty^2$ ($\sim 10^{-3}\ L_{bol}$)



1.0
0.8
0.6
0.4
0.2
0.0
I/I$_o$
1549.5
1550.0
1550.5
Wavelength (Angstroms)

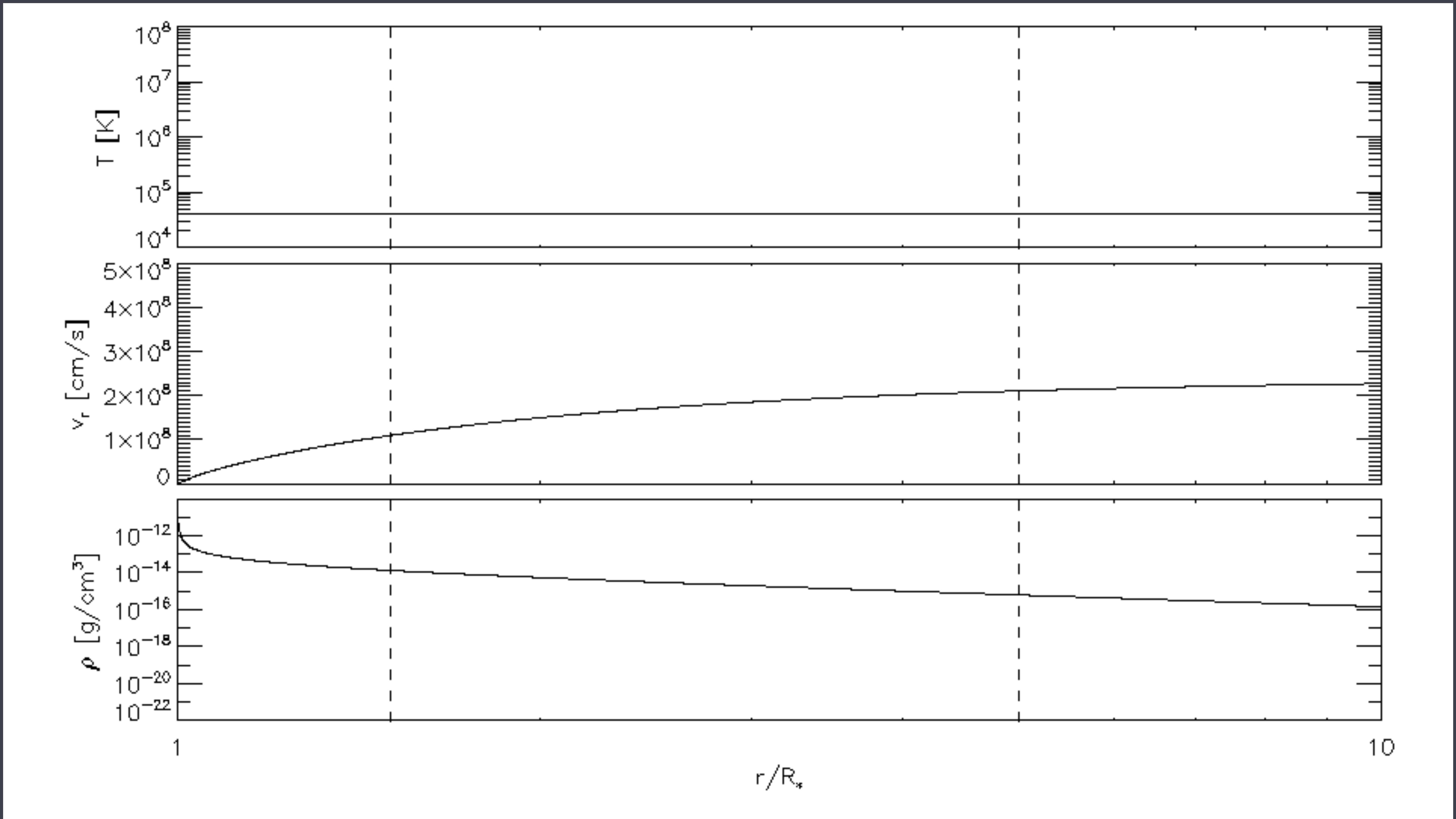
Doppler desaturation





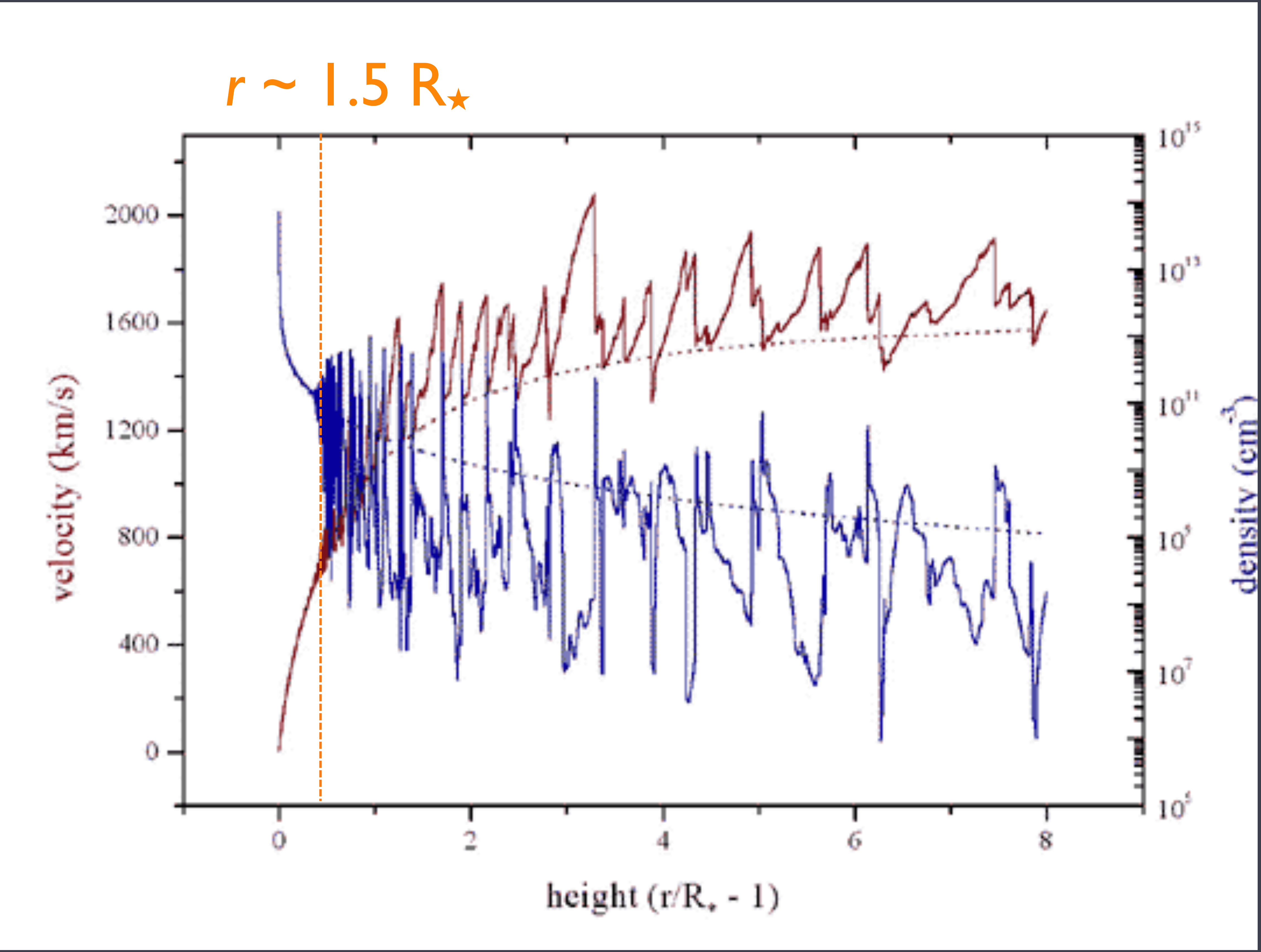
ζ Pup
(O4 I)

τ Sco
(B0 V)

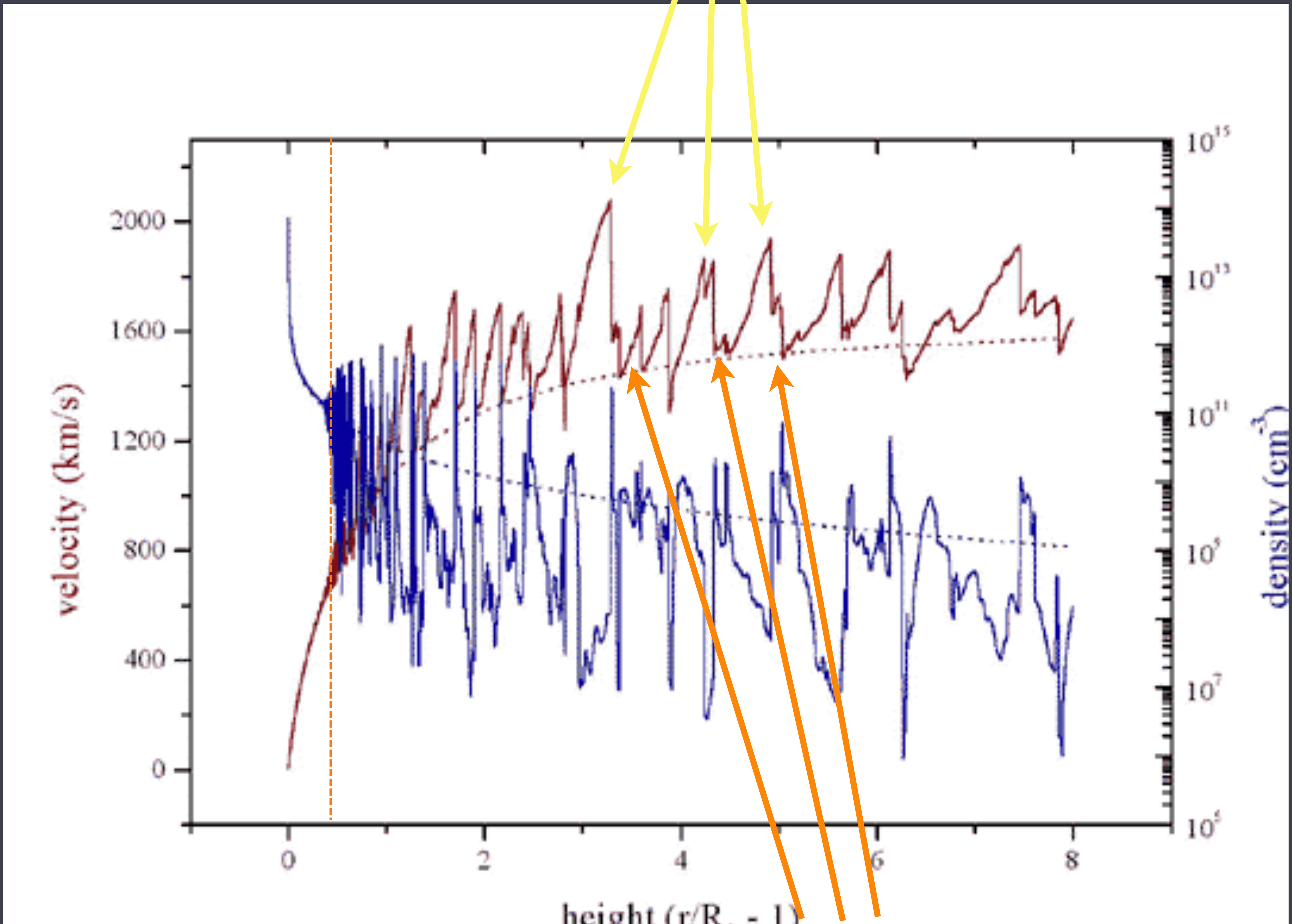


numerical simulation (J. Sundqvist) available at astro.swarthmore.edu/presentations/movies/xmbko1.e-2.avi

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

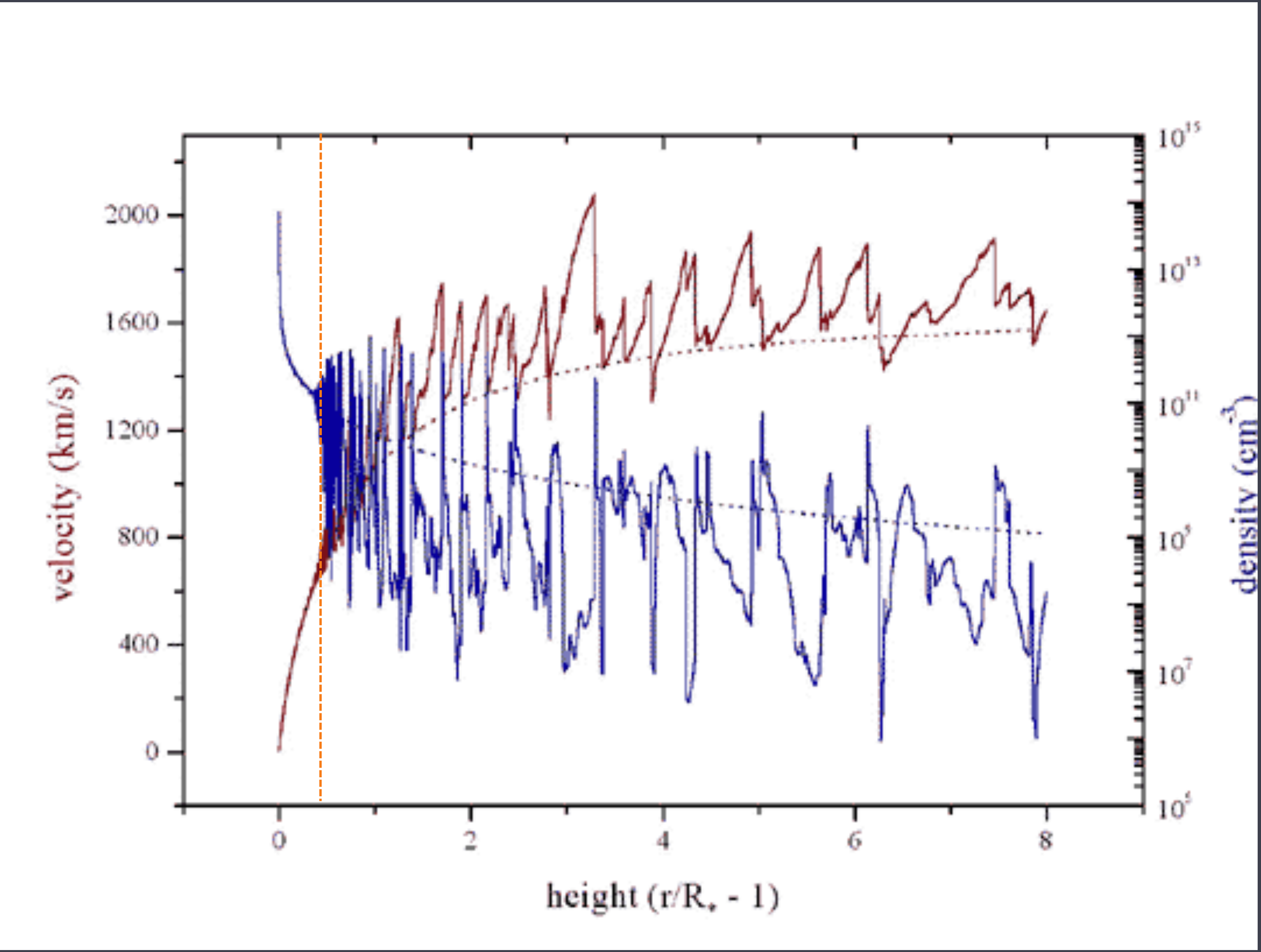


$V_{shock} \sim 300$ km/s : $T \sim 10^6$ K

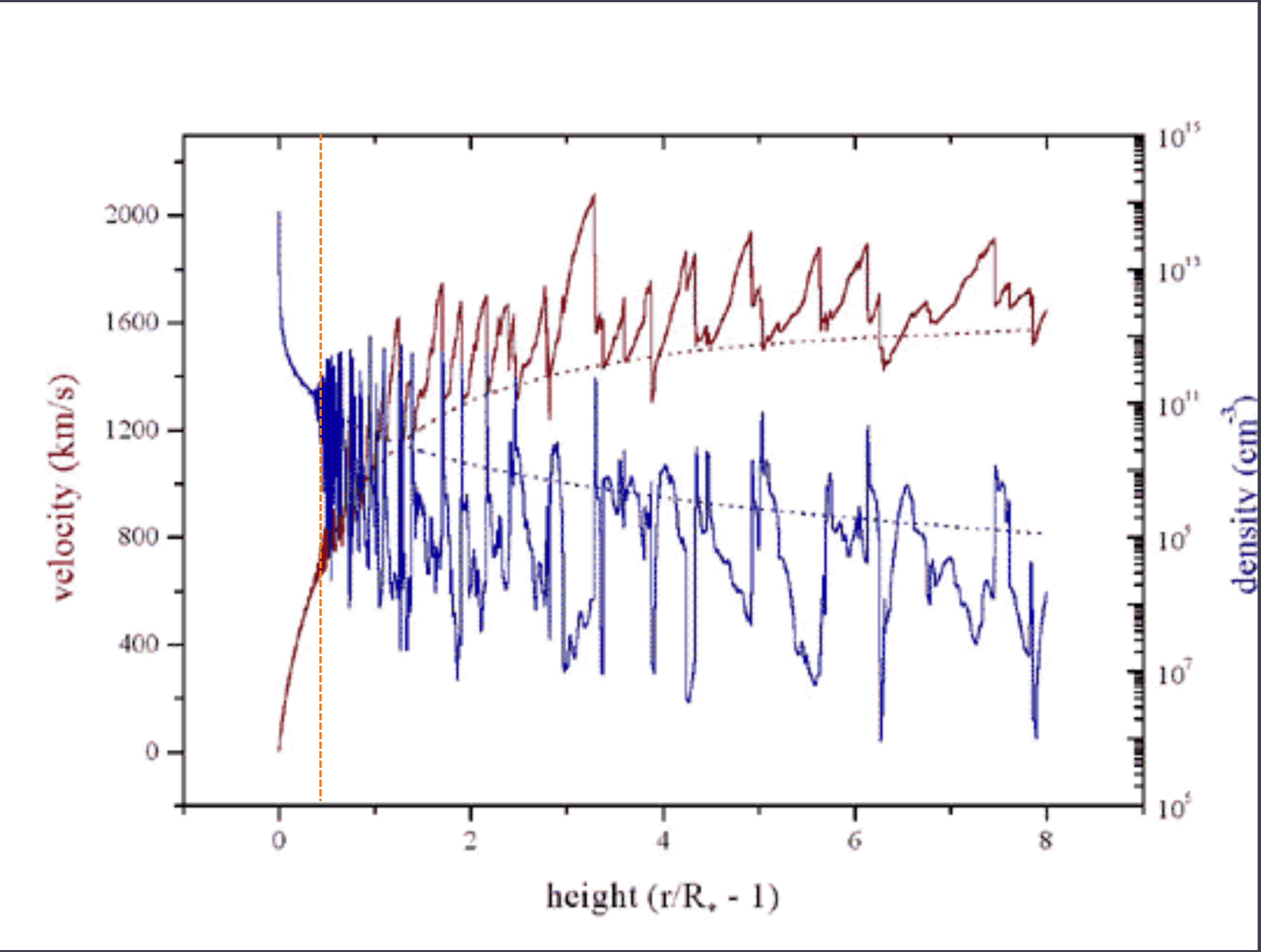


shocked wind plasma is decelerated back down to the local CAK wind velocity

Shocked plasma is moving at v ~ 1000 km/s

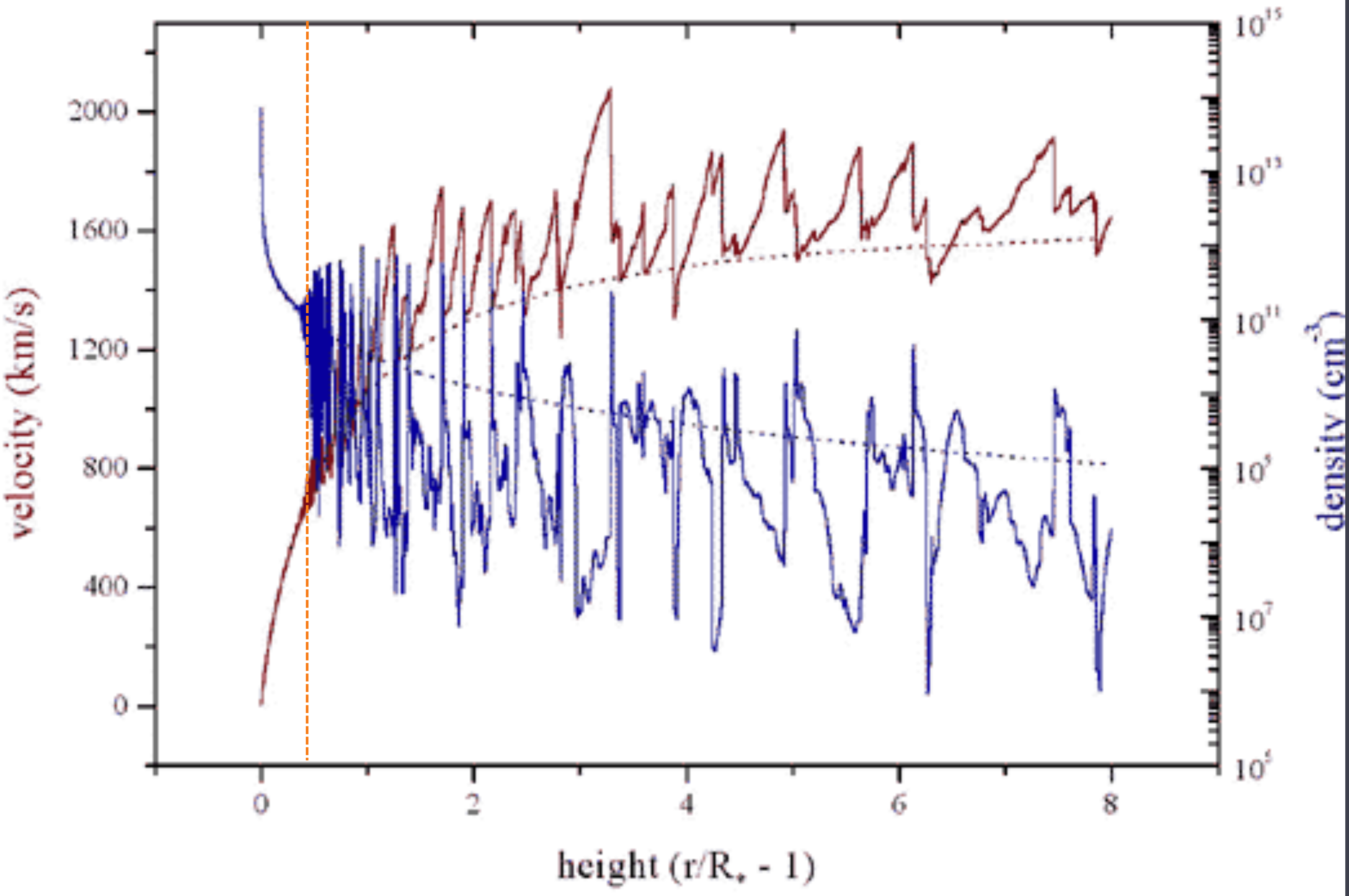


X-ray emission lines should be **Doppler broadened**

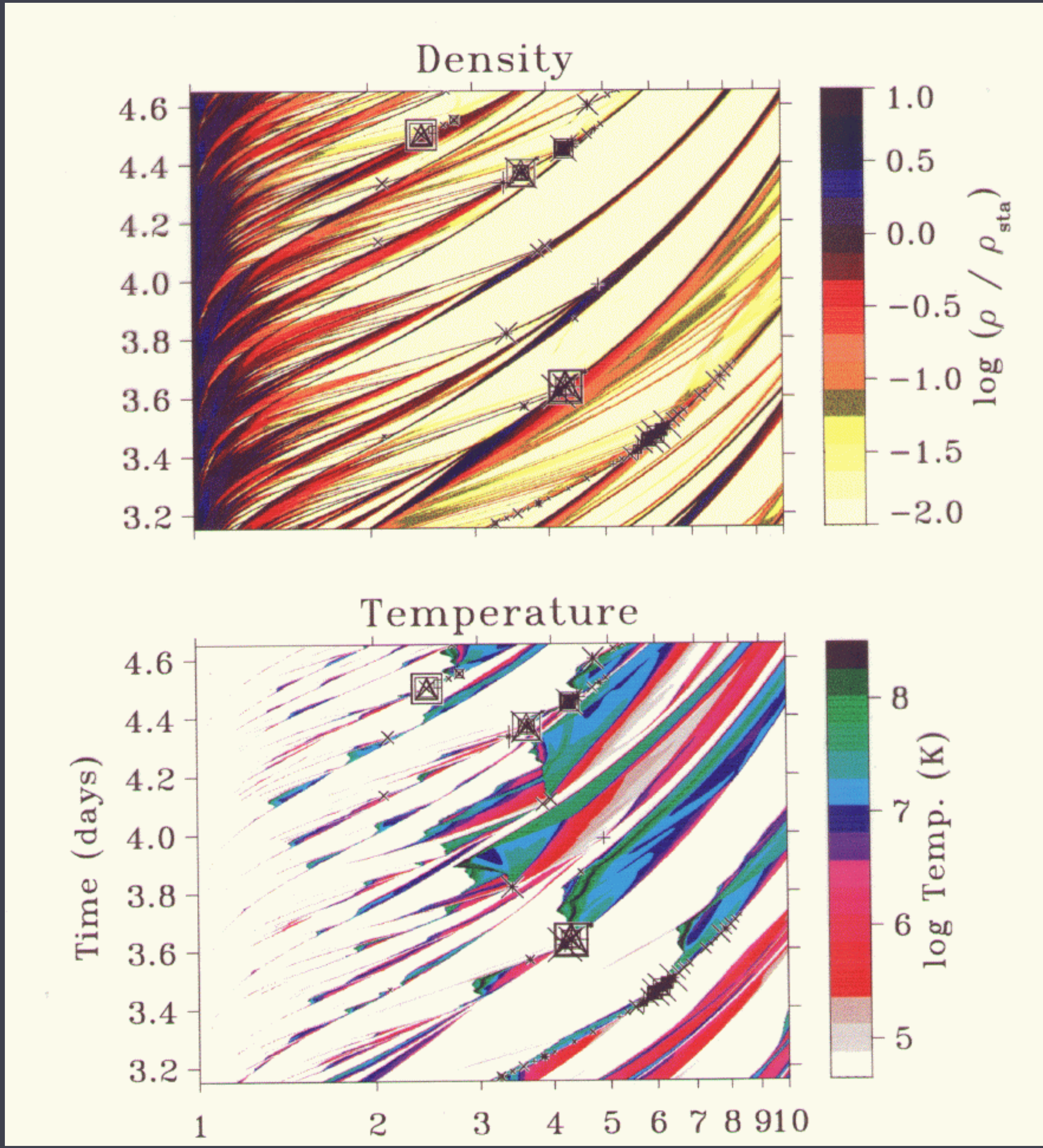


Less than 1% of the wind is emitting X-rays

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



how much plasma and how hot a plasma the LDI produces is not settled



Feldmeier et al. 1997

Chandra

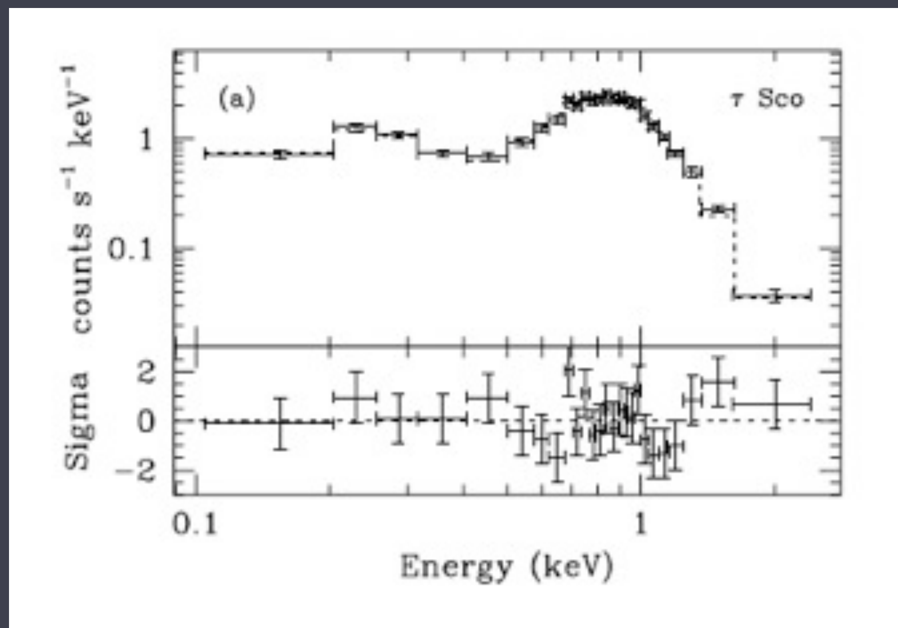
small effective area (poor sensitivity) but very low background and very well calibrated

X-ray imaging? > 0.5 arc sec, at best (100s of AU)
spectroscopy (R < 1000 corresp. >300 km/s)

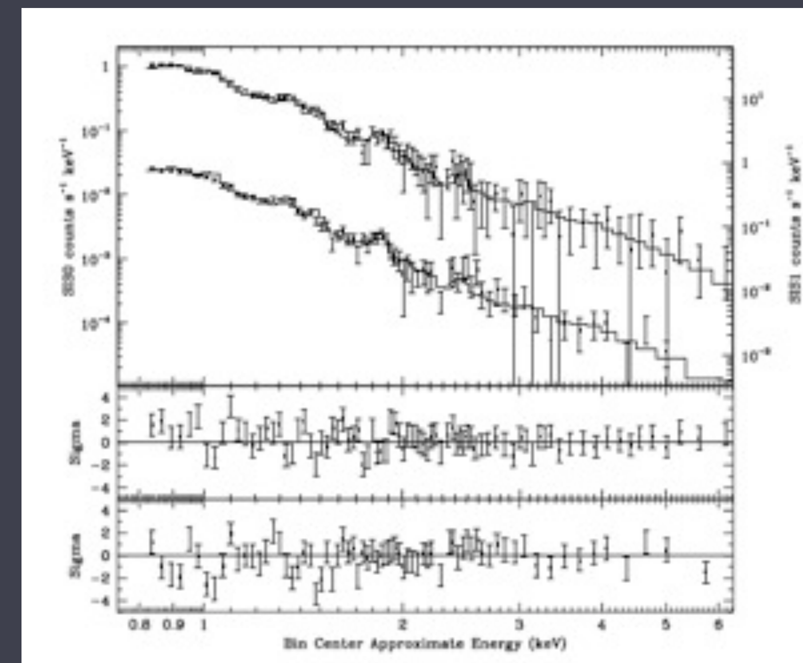
response to photons with hν ~ 0.5 keV up to a few keV
(corresp. ~5Å to 24Å)

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

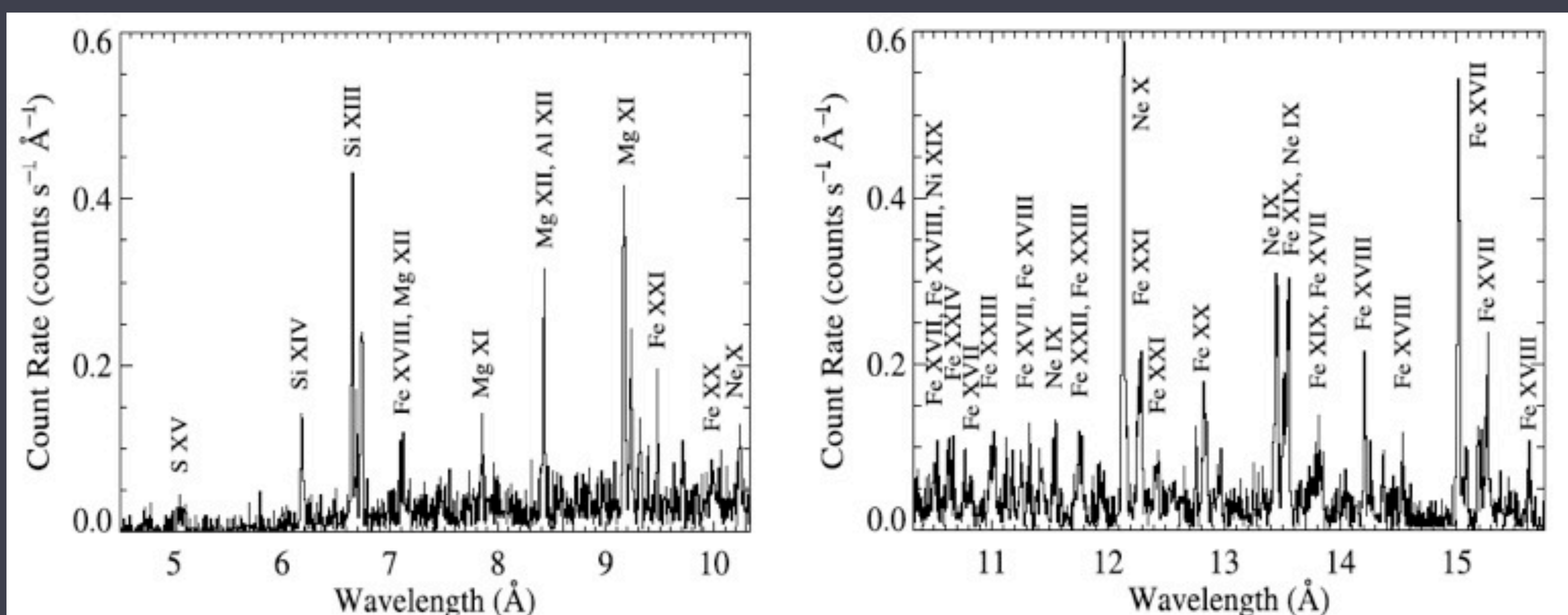
ROSAT 1991



ASCA 1994



Chandra 2001



Chandra grating spectroscopy (R < 1000)

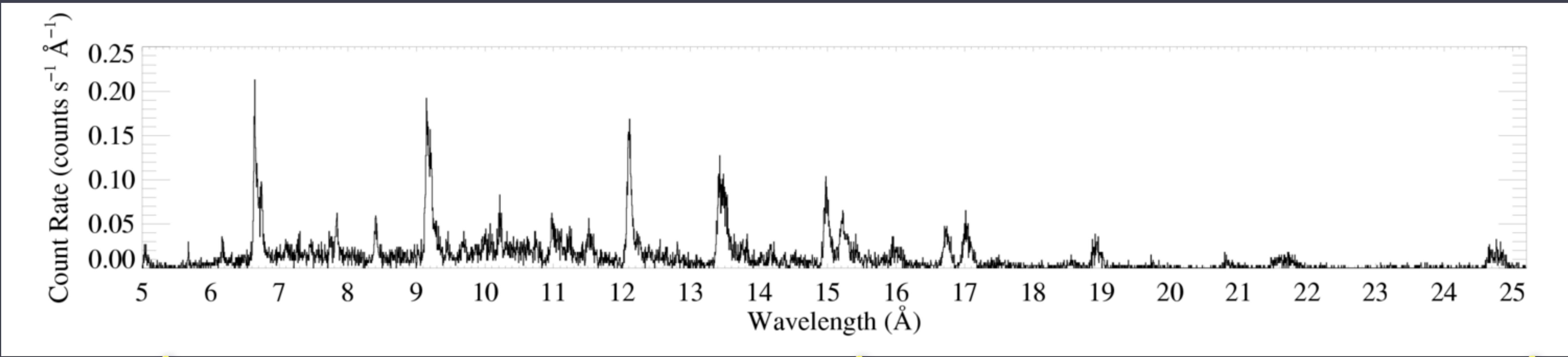
ζ Pup (O4 If)

cool stars vs. hot stars

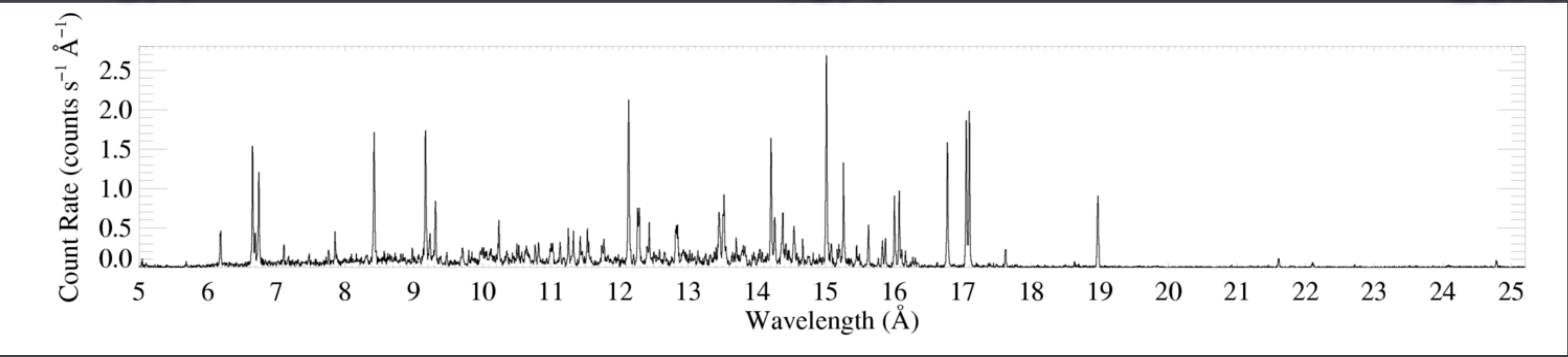
starfish, *in situ*, at the Monterey, California Aquarium (photo: D. Cohen)

Chandra grating (HETGS/MEG) spectra

ζ Pup (O4 If)

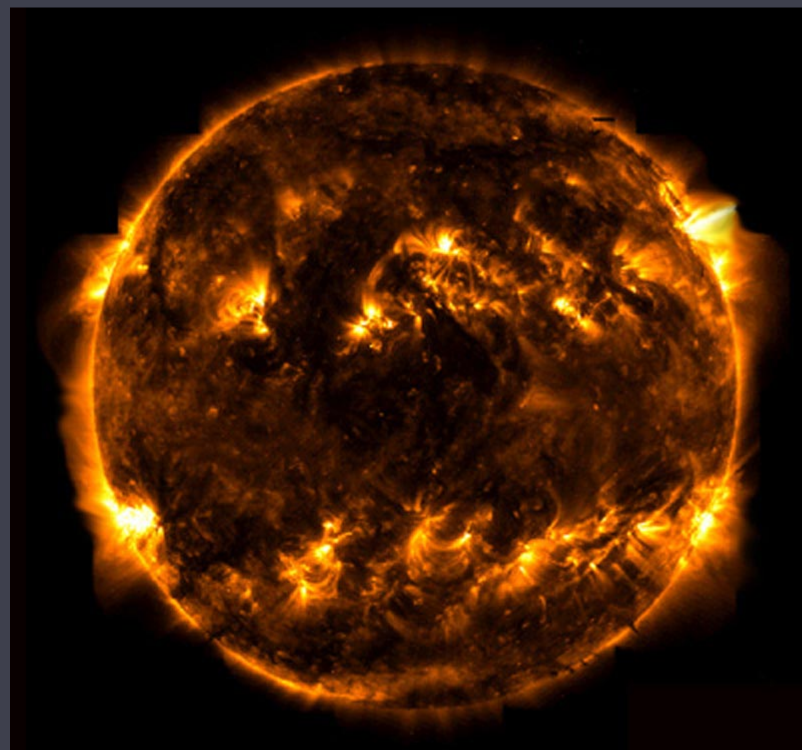


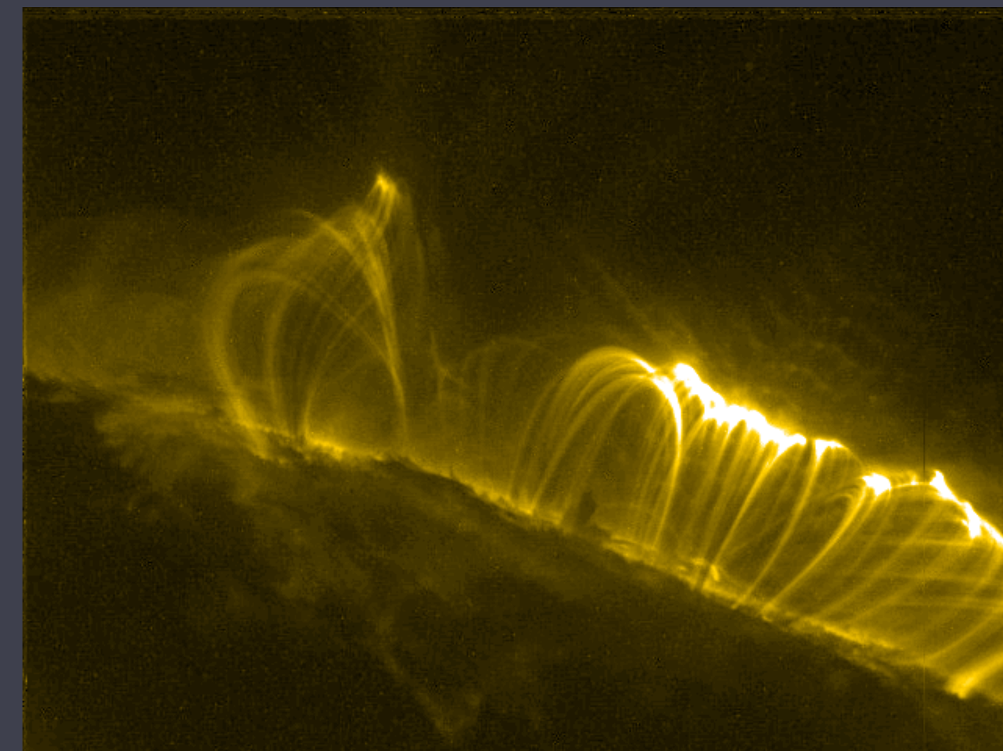
5Å 15Å 25Å



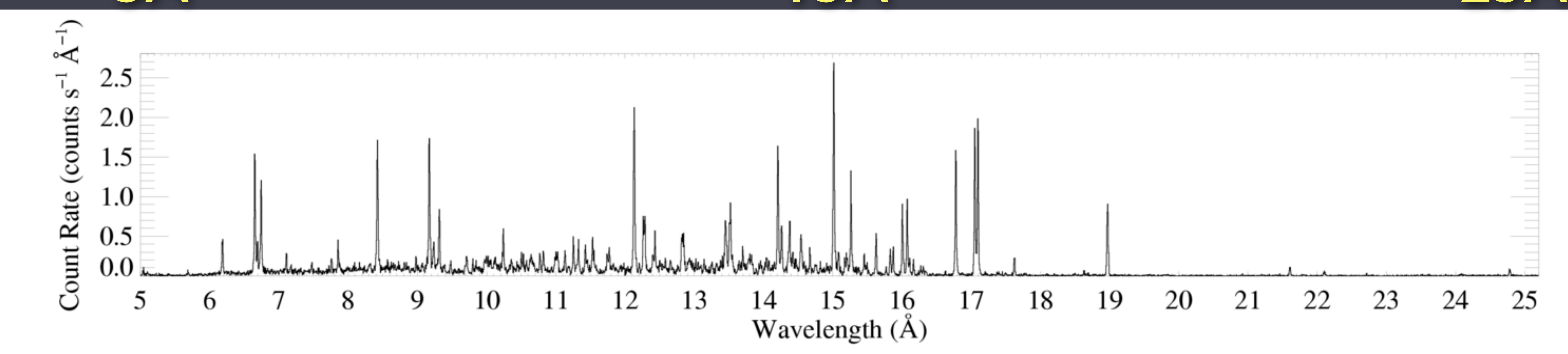
Capella (G5 III)

Capella is a nearby, solar-type star





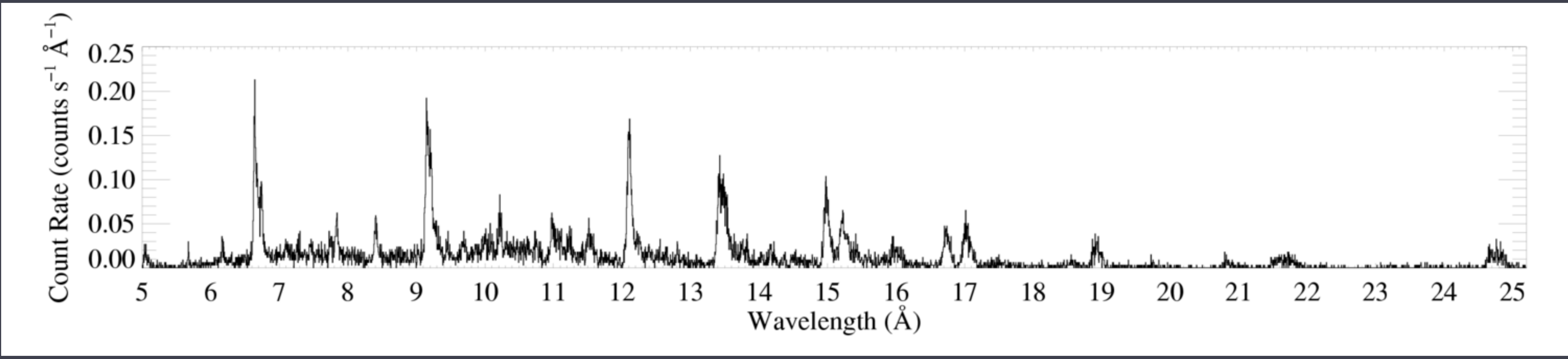
5Å 15Å 25Å

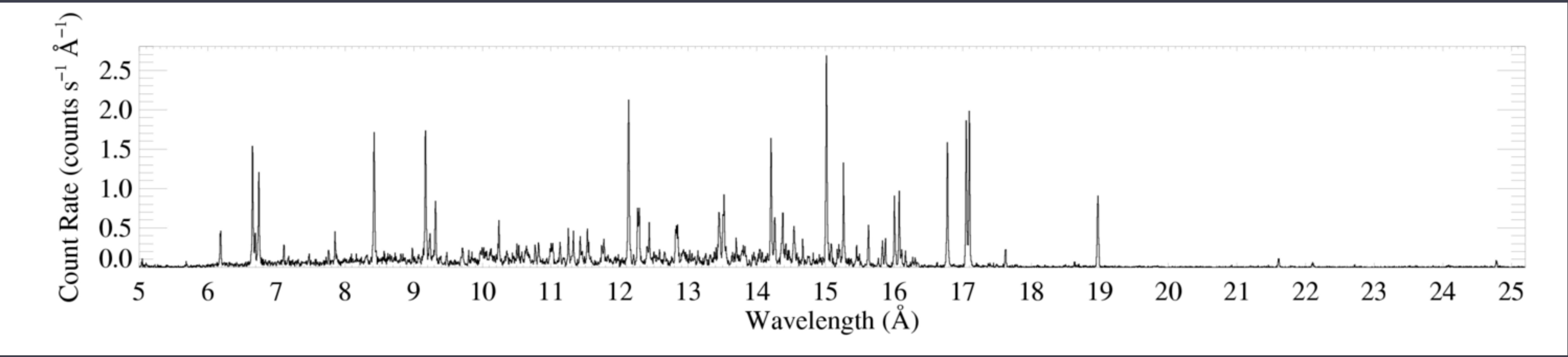


Capella (G5 III)

emission lines + bremsstrahlung + recombination

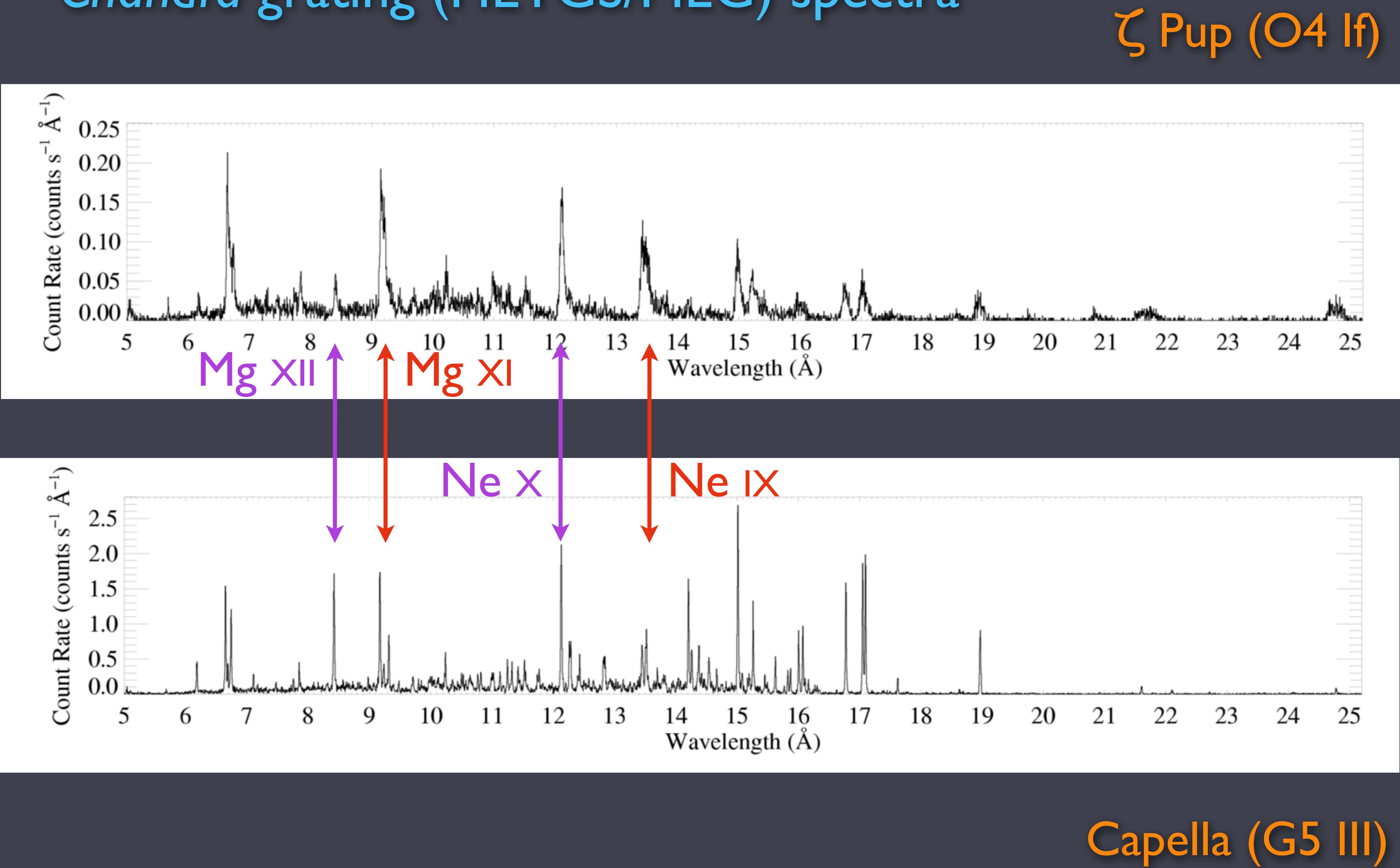
ζ Pup (O4 If)





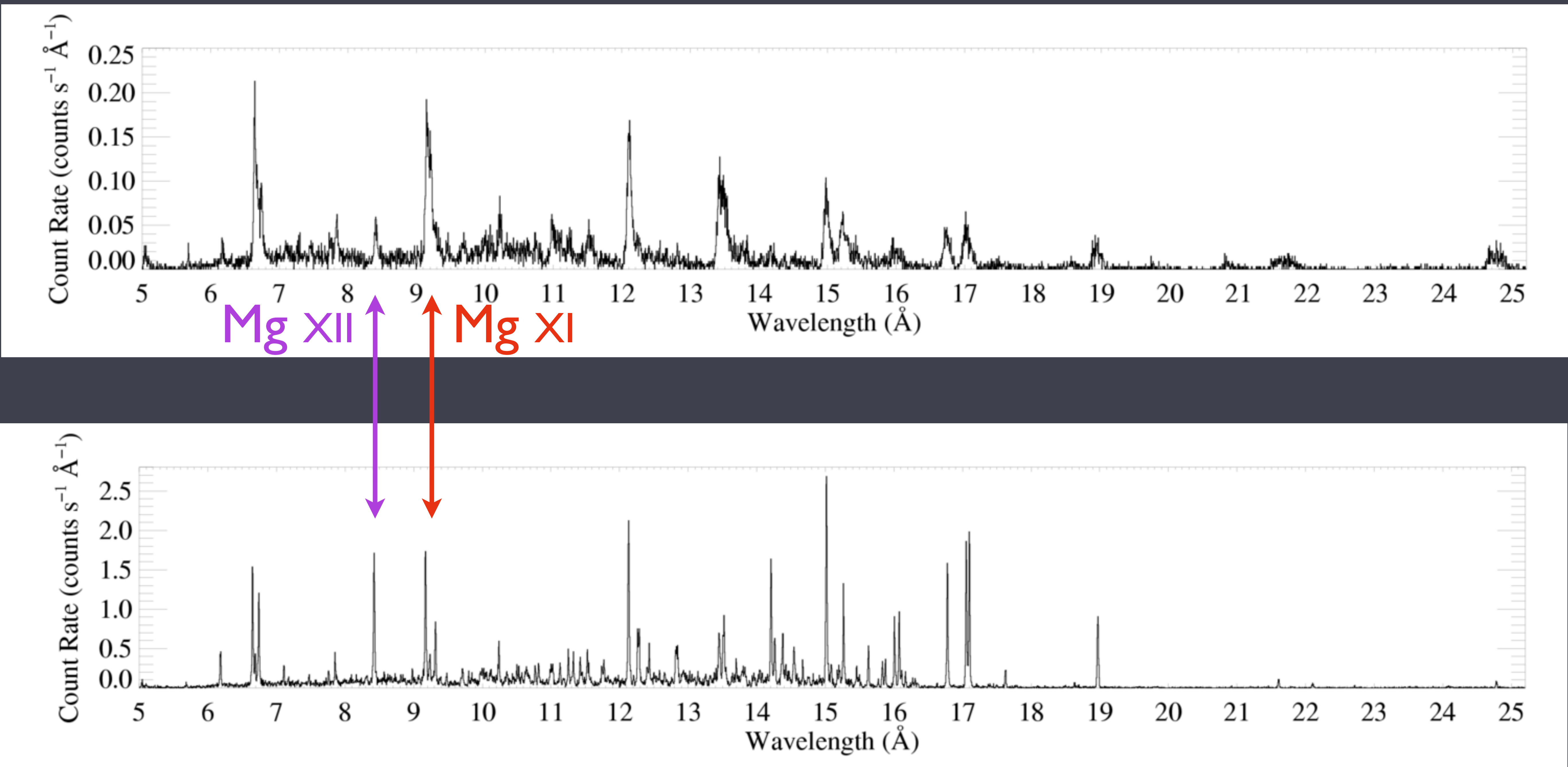
Capella (G5 III)

Chandra grating (HETGS/MEG) spectra



Temperature sensitivity: H-like/He-like is proportional to temperature

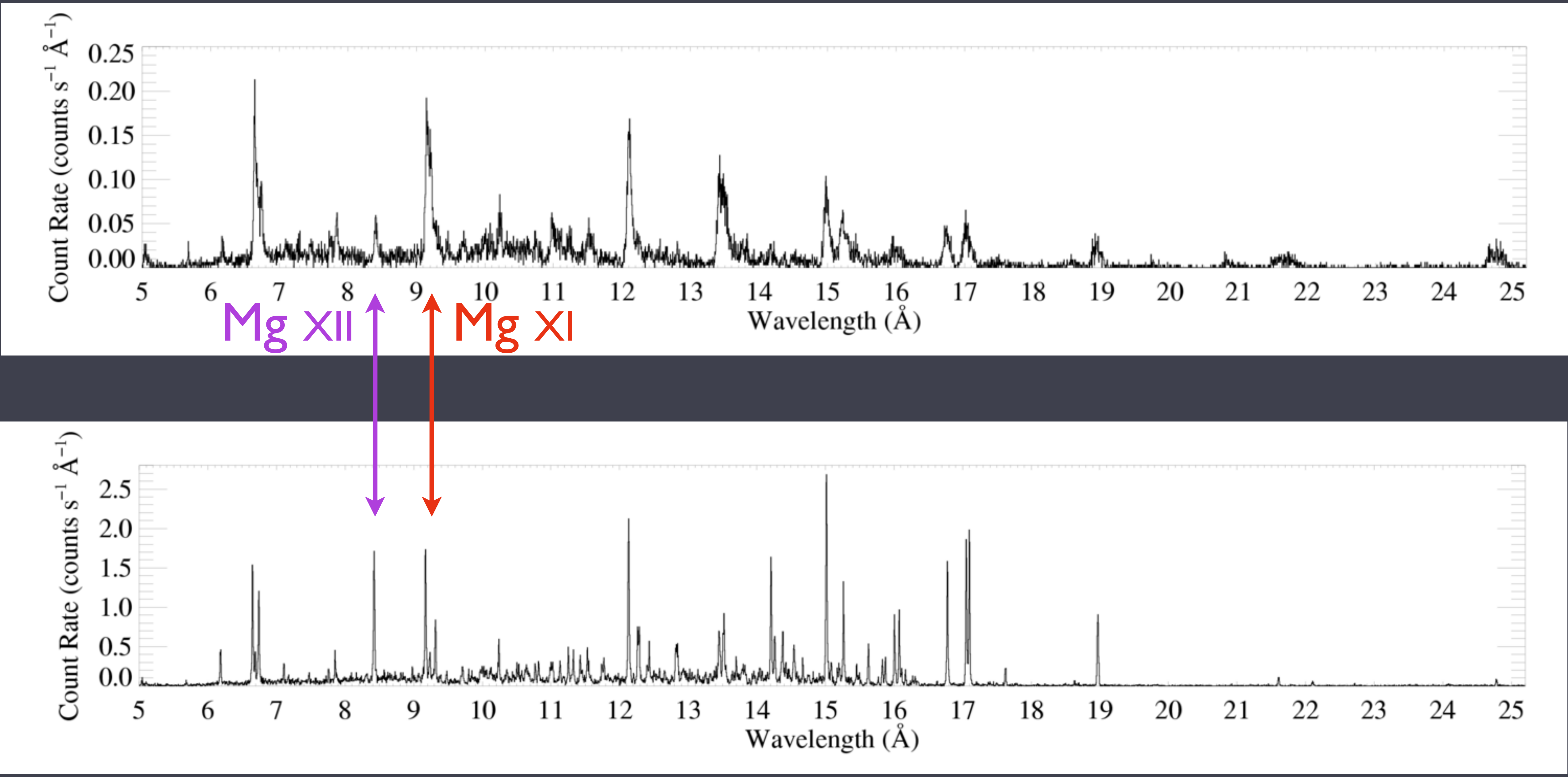
ζ Pup (O4 If)



Capella (G5 III)

typical temperatures $T \sim$ few 10^6 K
(late-type stellar coronae tend to be hotter)

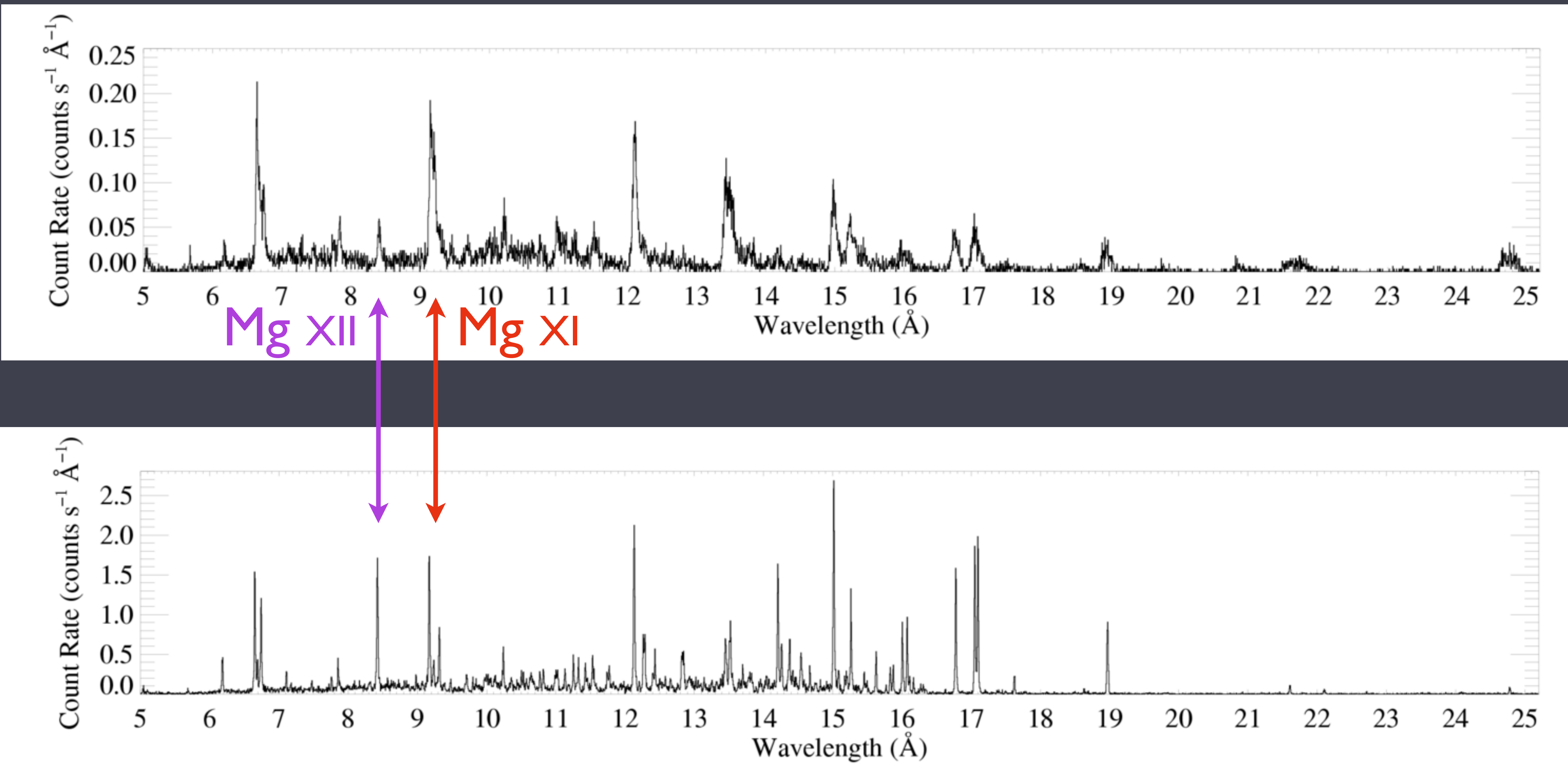
ζ Pup (O4 If)



Capella (G5 III)

but overall spectrum is higher energy (harder) in ζ Pup

ζ Pup (O4 If)



Capella (G5 III)

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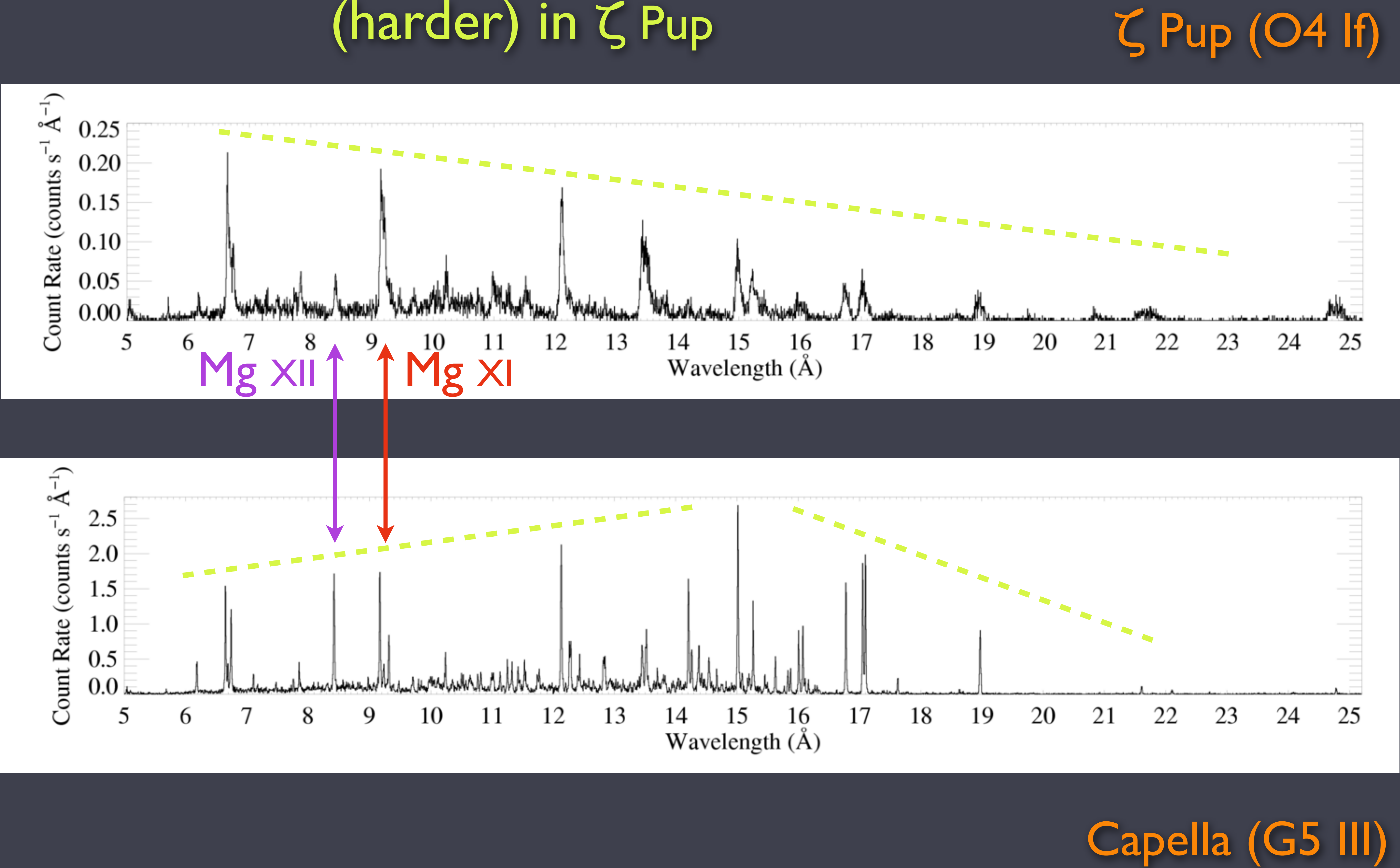
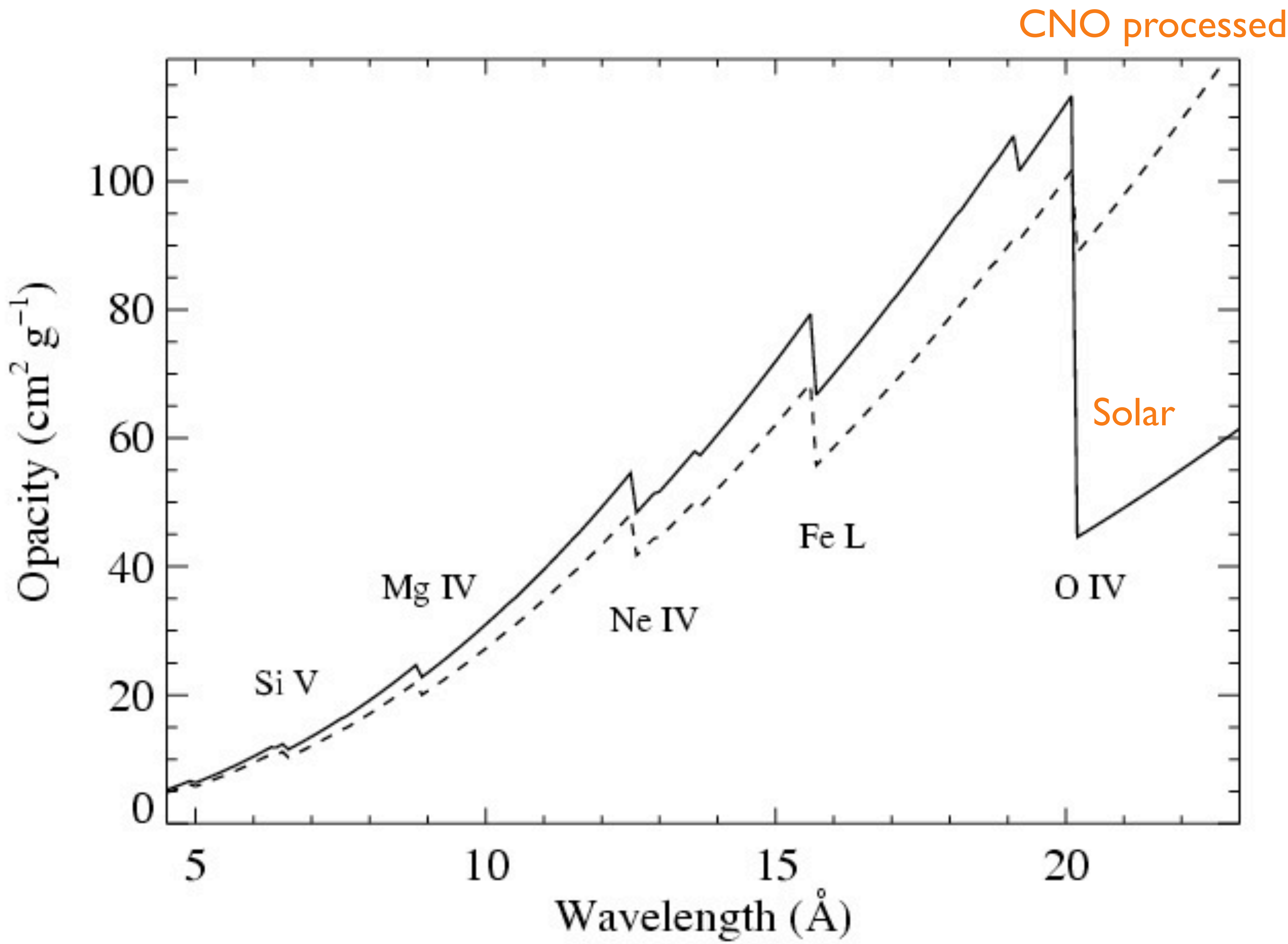
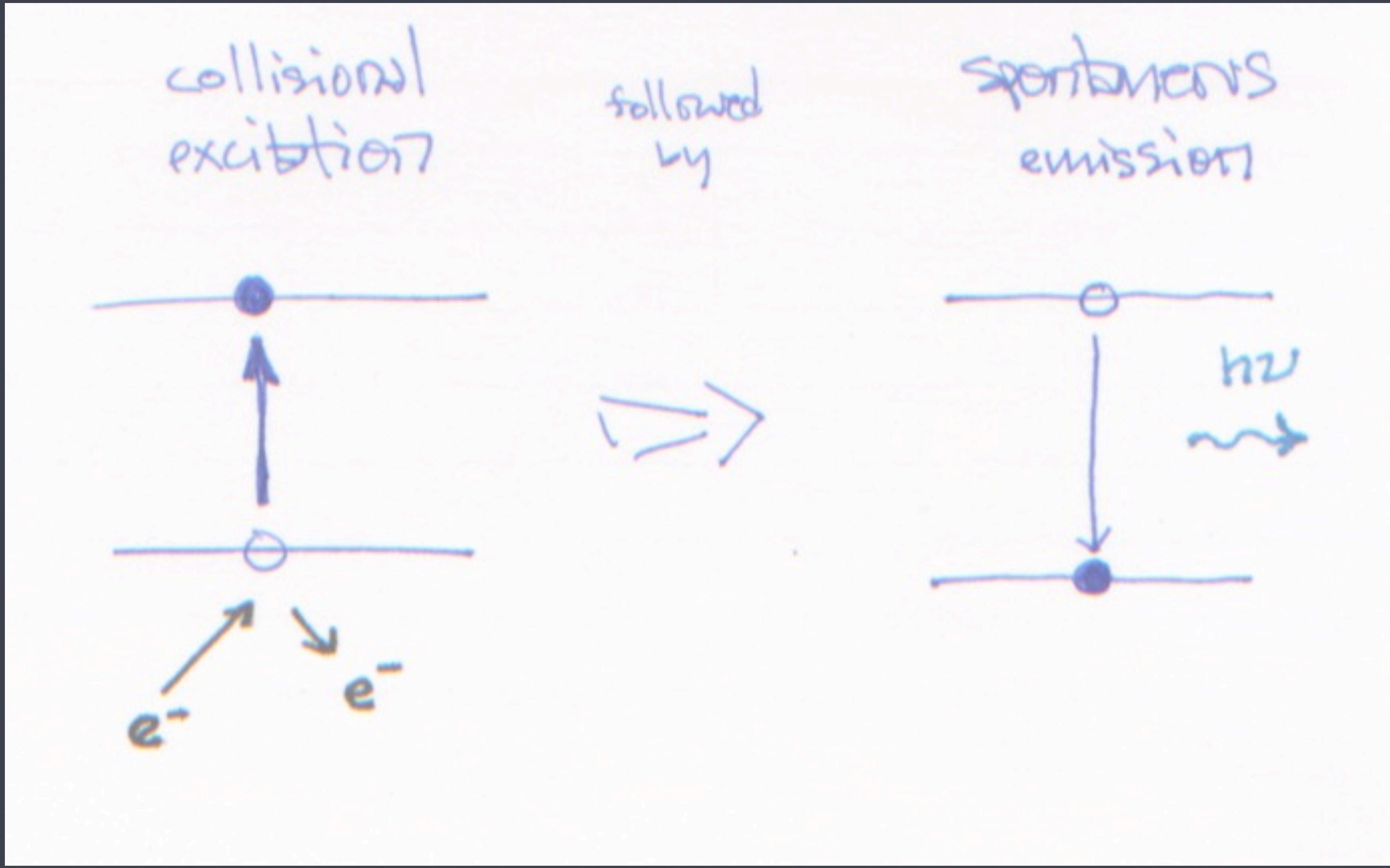




CNO processed
Solar
Opacity (cm^2 g^{-1})
0
20
40
60
80
100
5
10
15
20
Wavelength (Å)
Si V
Mg IV
Ne IV
Fe L
O IV

One more concept: X-ray emission

Line radiation: collisional excitation followed by spontaneous emission

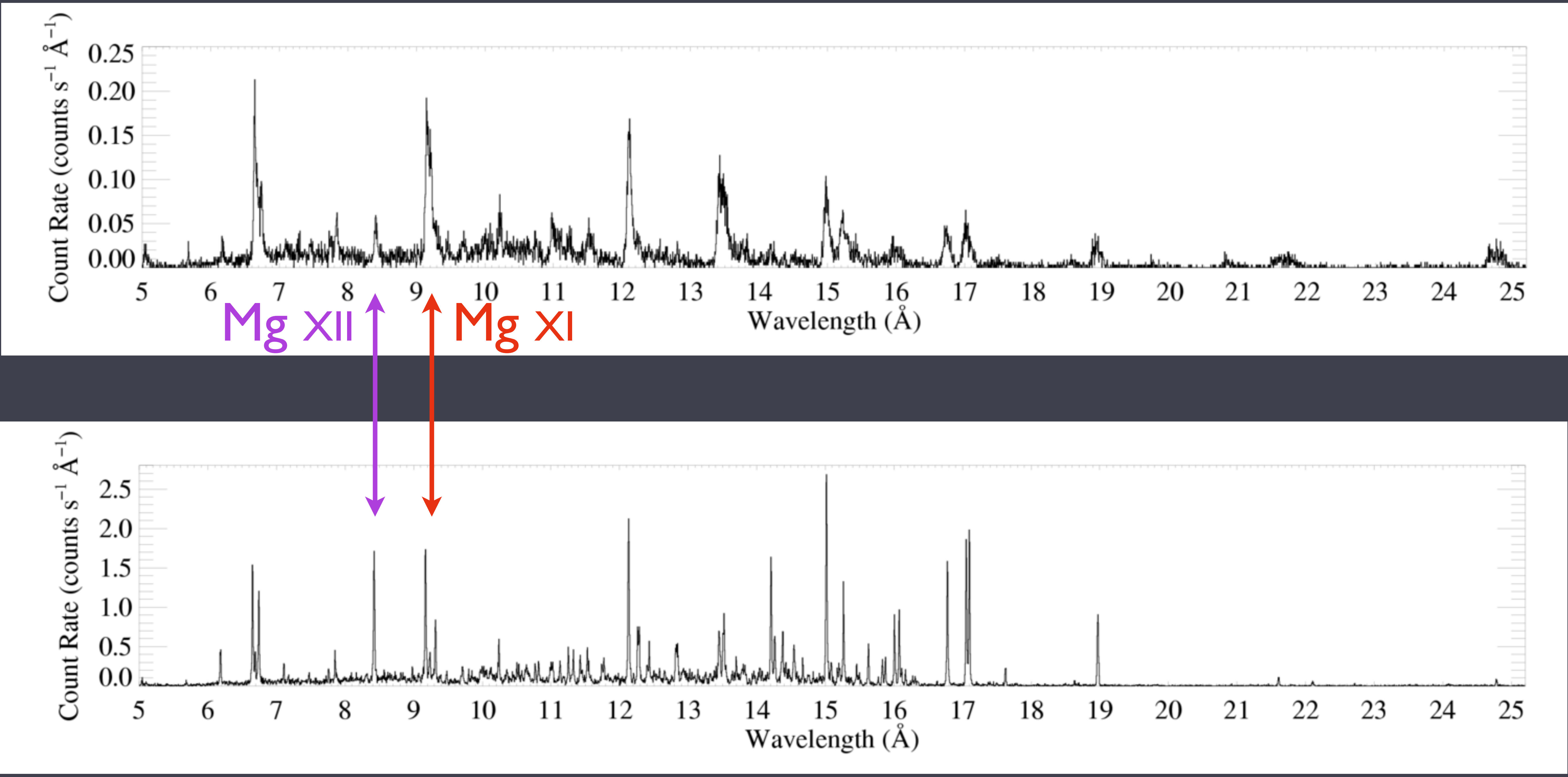


The X-ray photons we see are the photons that cool the shock-heated plasma

strongest lines are H- and He-like of C, N, O, Ne, Mg, Si, S (plus Fe states with more bound electrons)

Temperature sensitivity: H-like/He-like is proportional to temperature

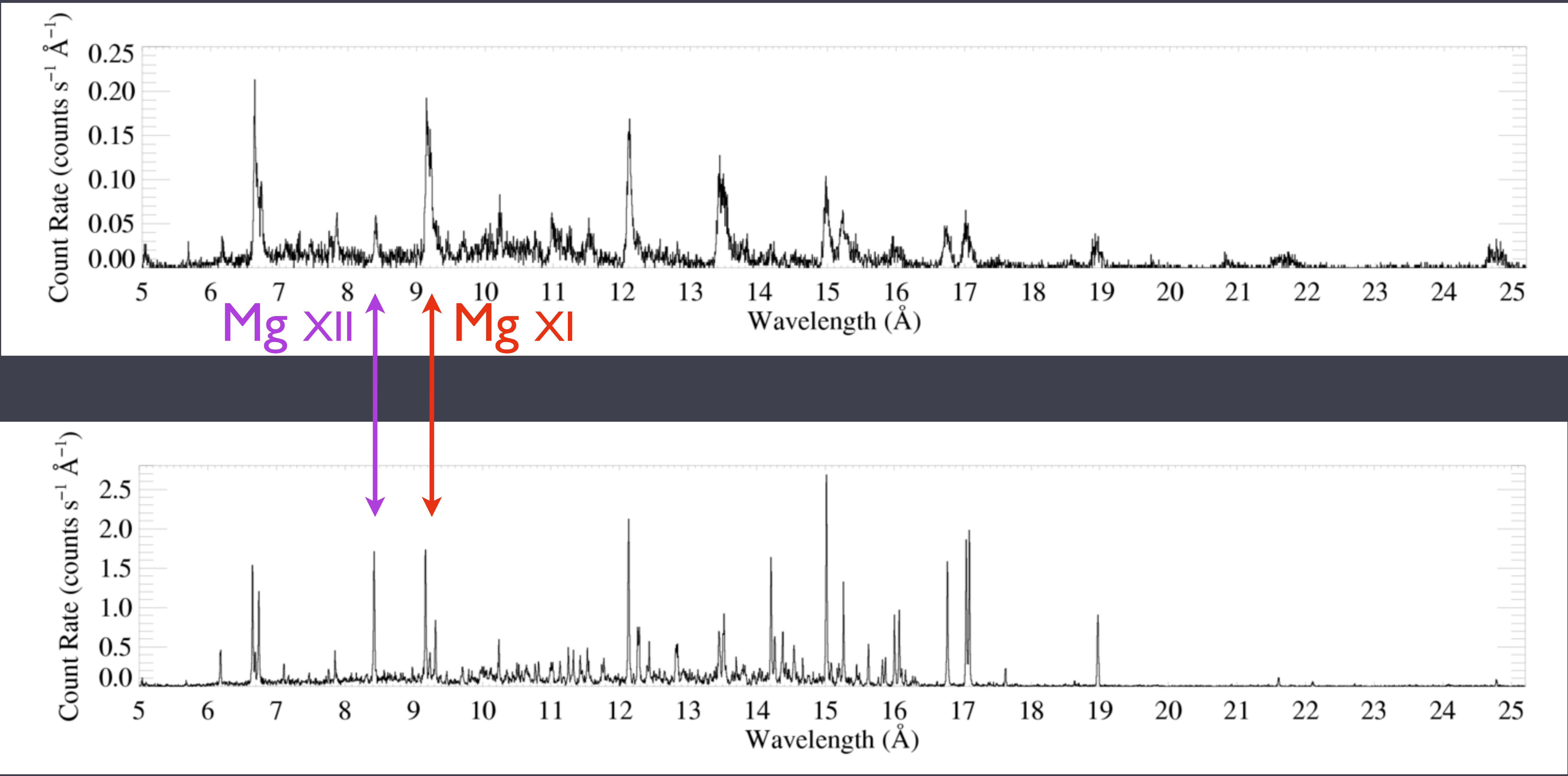
ζ Pup (O4 If)



Capella (G5 III)

temperature-dependent ionization is from collisional ionization* - radiative recombination balance

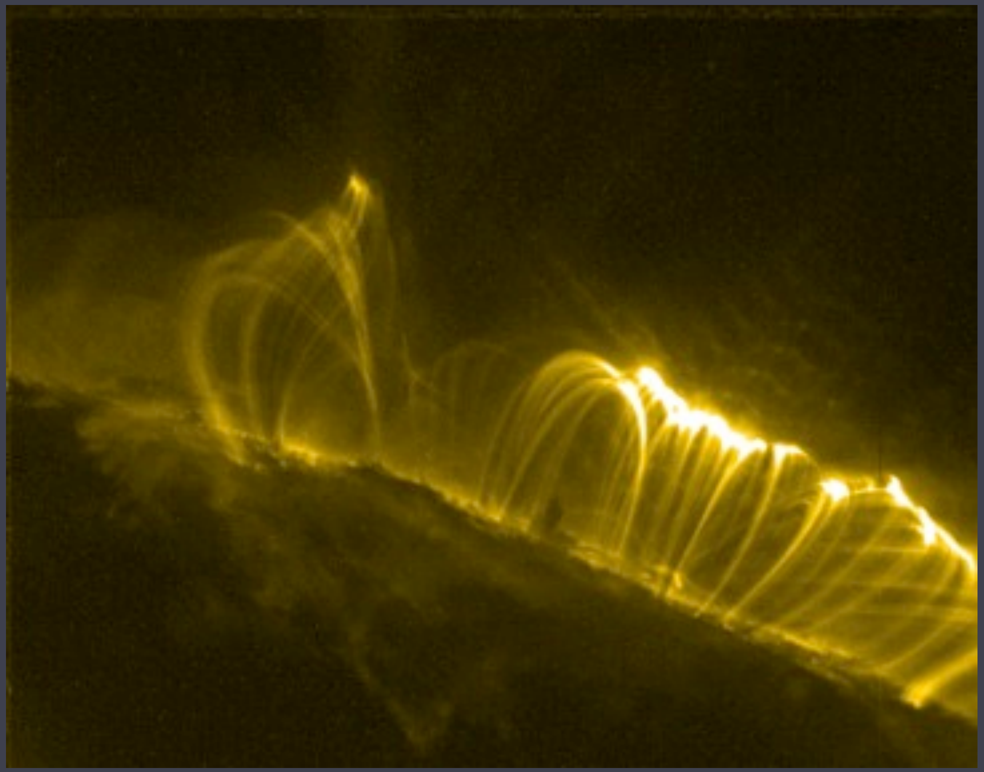
ζ Pup (O4 If)

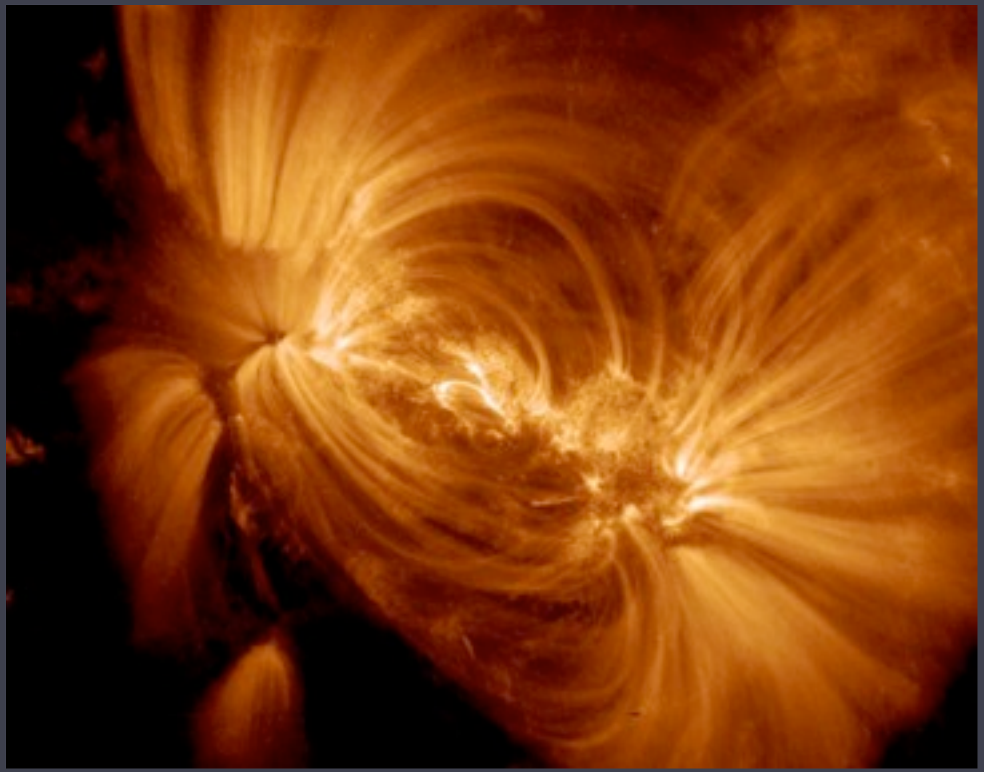


Capella (G5 III)

*Collisional ionization rates depend on the ionization potential of the ion (e.g. going from He-like to H-like requires a certain energy (100s of eV for low atomic number elements) and going from H-like to fully ionized might require almost twice as much energy).

X-ray emission mechanism is the same on the Sun (though the mechanism for *producing* the hot plasma is different)





NASA: *TRACE*

We want to know the temperature distribution in the plasma (how much plasma in each temperature bin). There are good tools for making these models (e.g. a code called APEC), largely because of decades of work modeling solar X-ray spectra.

It is the line intensity ratios that contain most of the temperature information. Elemental abundances, of course, also affect line ratios (except between lines of the same element). The *vapec* model in the spectral fitting software XSPEC allows the abundances of many elements to be free parameters of the model.

Absorption of the X-rays by the wind also affects the line intensity ratios if the lines are far apart in wavelength (so the wind opacity is different for the two lines). Our group has developed a code, WINDTABS, that can model this.

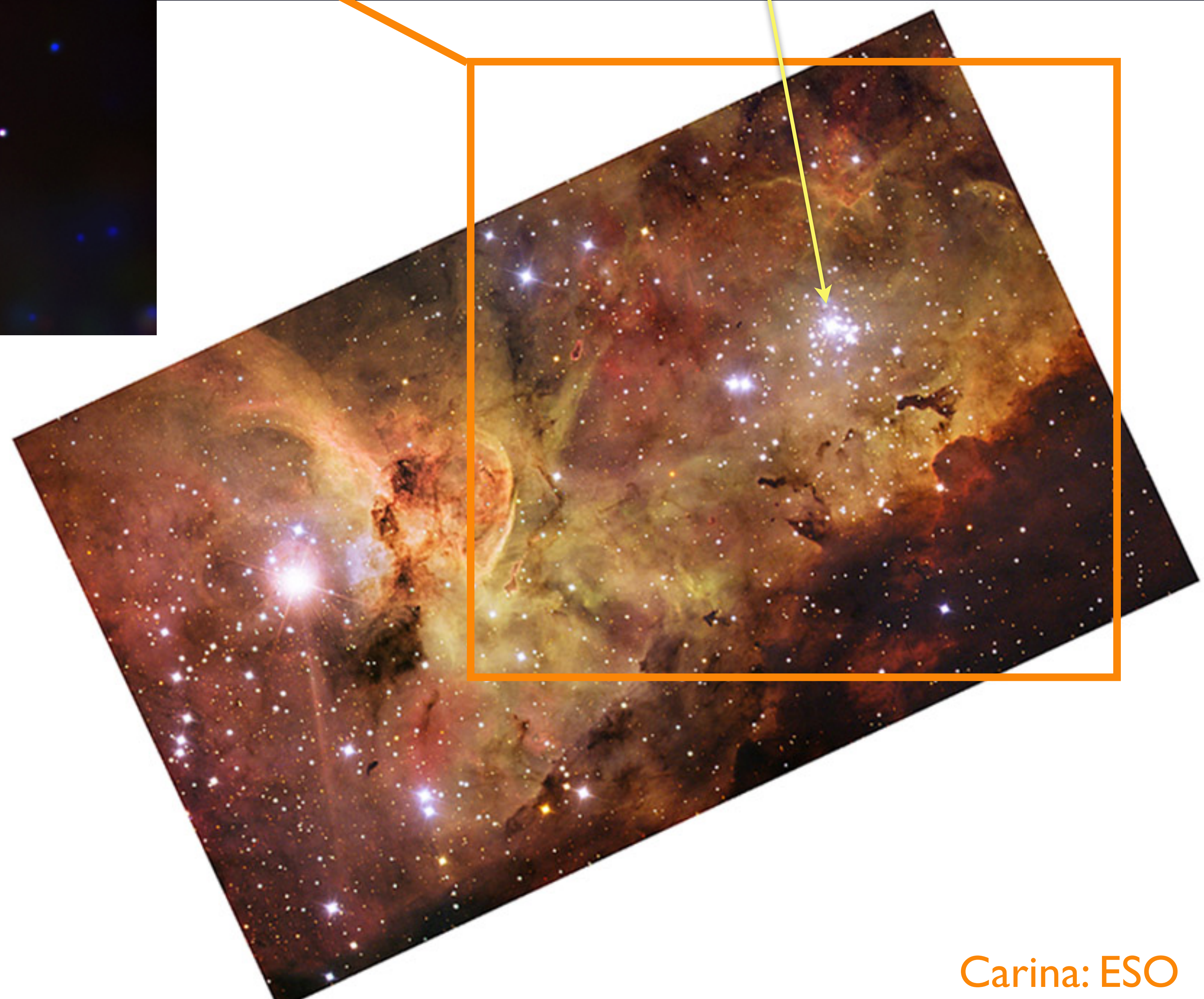
Overall X-ray emission levels

The Carina Complex

HD 93129A (O2If*)

Tr 14 in Carina: *Chandra*

The early O supergiant is the brightest X-ray source in the *Chandra* observation of the Trumpler 14 cluster in Carina



Carina: ESO

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

ASTRONOMY
AND
ASTROPHYSICS

All O stars are X-ray sources with $L_x \sim 10^{-7} L_{bol}$

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

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[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

Received 17 July 1996 / Accepted 26 November 1996

Abstract. The ROSAT all-sky survey has been used to study the X-ray properties for all OB-type stars listed in the Yale Bright Star Catalogue. Here we present a detailed astrophysical discussion of our analysis of the X-ray properties of our complete sample of OB-type stars; a compilation of the X-ray data is provided in an accompanying paper (Berghöfer, Schmitt & Cassinelli 1996).

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.

1979, Pallavicini *et al.* 1981, Chlebowski *et al.* 1989, Sciortino *et al.* 1990). However, the scatter for values of individual stars, 2 orders of magnitude, around the mean value is quite large. The widely accepted model for the X-ray emission from O stars assumes that it is produced by shock-heated gas propagating in the strong winds of these stars. In a phenomenological model Lucy & White (1980) and Lucy (1982) postulate the existence of shocks in the radiation driven winds of hot stars which are formed as a consequence of a strong hydrodynamic instability (e.g., Lucy & Solomon 1980). Hydrodynamical calculations for hot star winds (e.g., Owocki, Castor & Rybicki 1988) provide strong support for such a model. The base corona source of X-

for the O stars we're studying, we probably don't have to worry about pre-main sequence companions contaminating the X-ray spectra

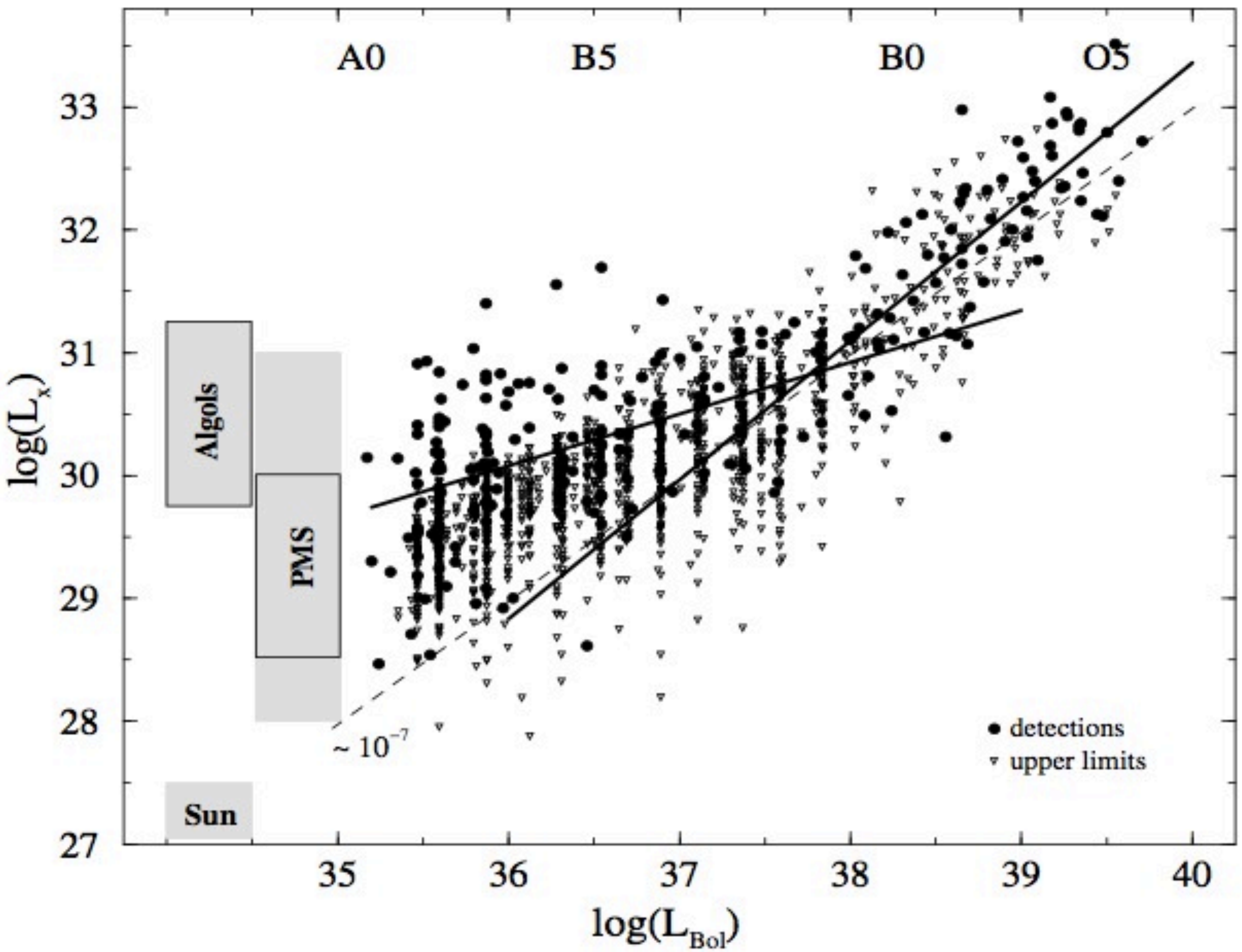

Fig. 4. X-ray luminosities L_x plotted versus bolometric luminosities L_{Bol}; solid lines represent regression lines for $L_{Bol} < 10^{38} erg\, s^{-1}$ and $L_{Bol} > 10^{38}$ erg s^{-1}, whereas the dashed line shows $L_x = 10^{-7} \times L_{Bol}$, grey bars at the left side show typical ranges for the X-ray luminosity of Algol-type systems, pre-main sequence stars (PMS), and our Sun.