O Star Winds: Shocked Plasma Temperatures and Mass-Loss Rates

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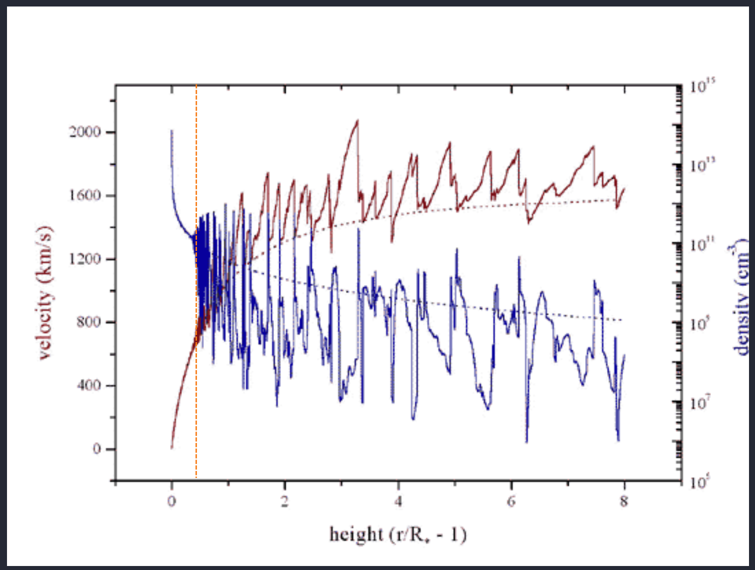
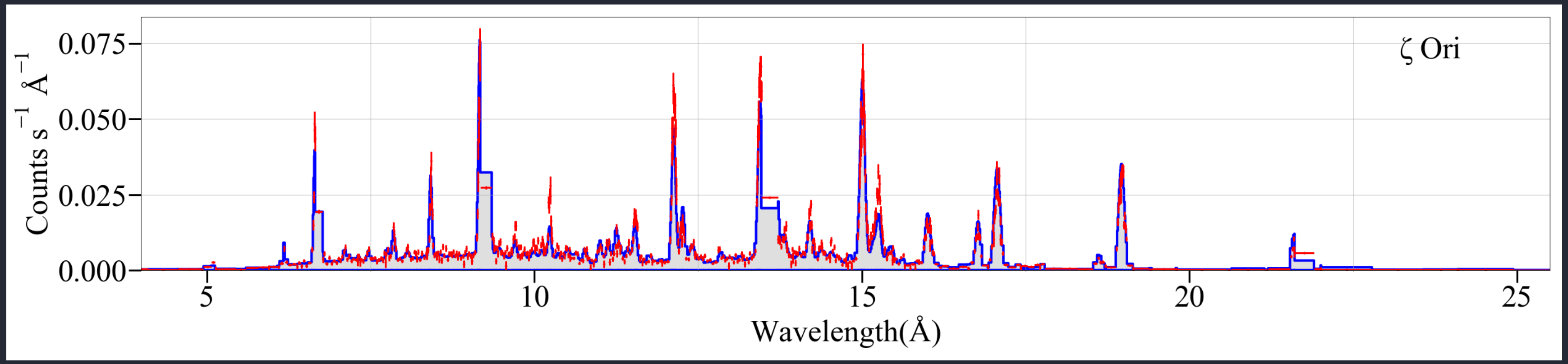


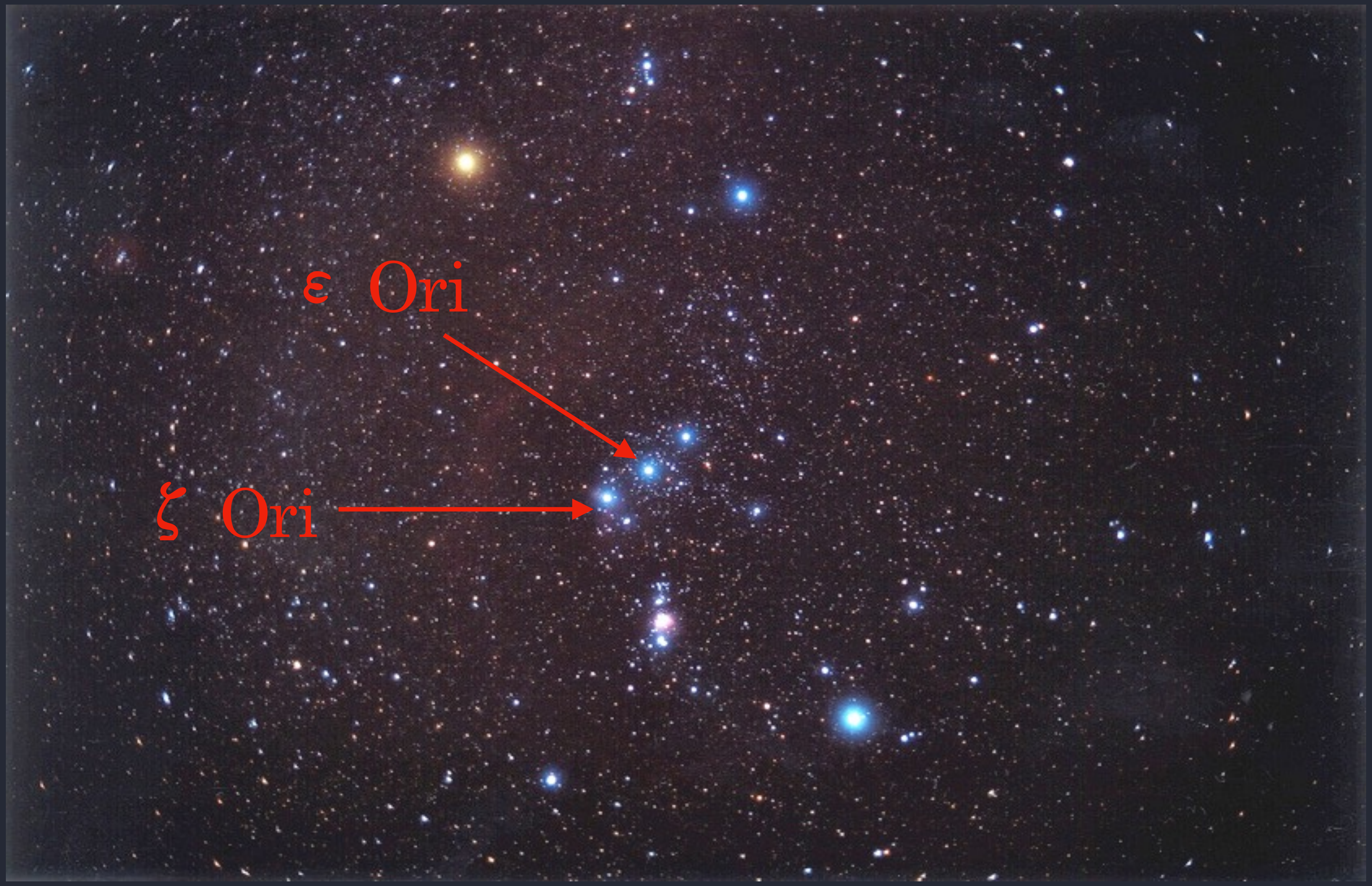


Our Sample

Effectively single, non-magnetic

Typical mass-loss rate ~ 10^{-6} M_{sun} yr^{-1}

Wind terminal velocity ~ 2,000 km s^{-1}



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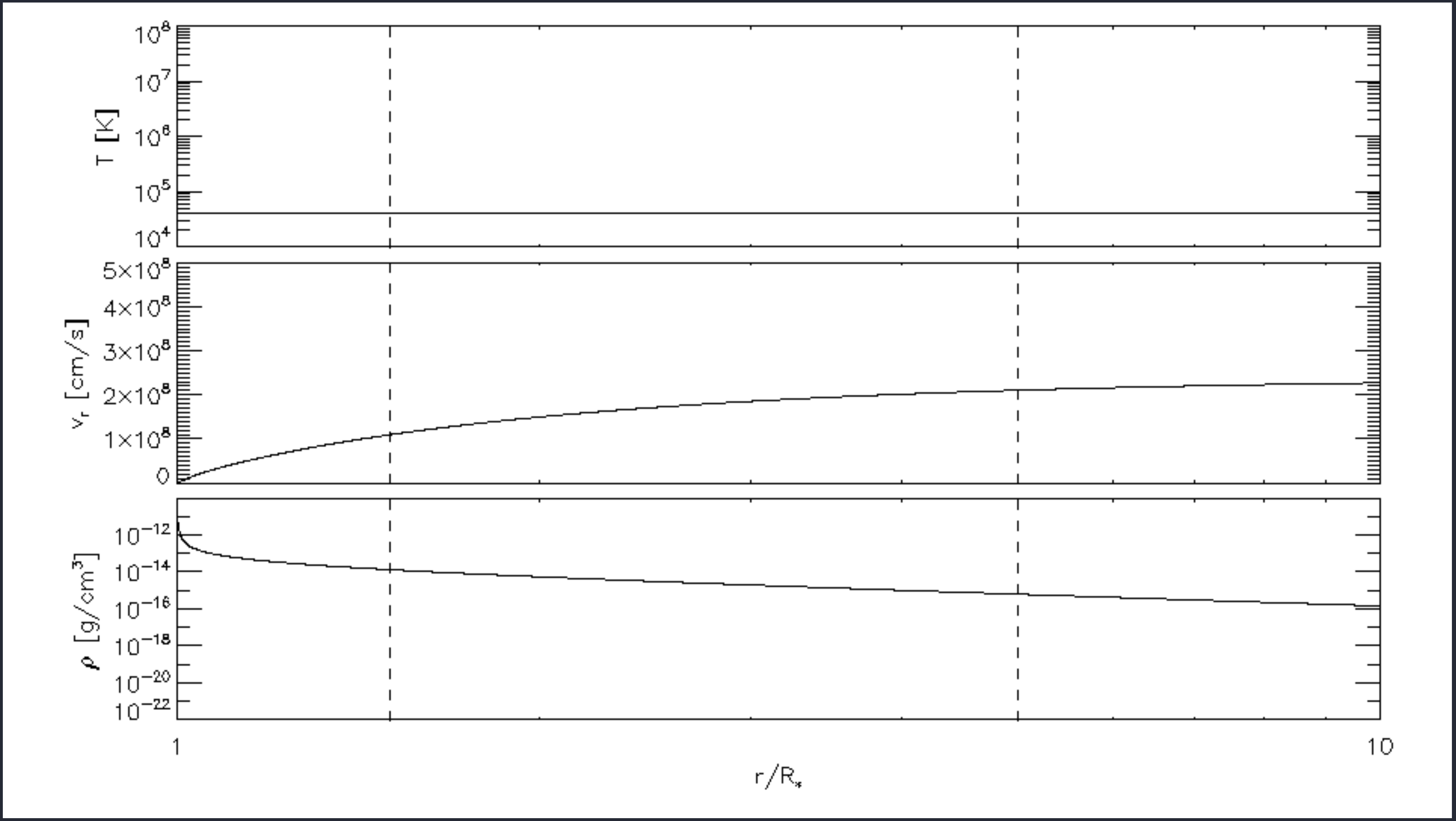
Star	Spectral Type	Distance (pc)	R_* ($R_\odot$)	v_∞ (km s^{-1})	$\dot{M}_{theory}$ ($M_\odot$ yr^{-1})	N_{ISM} (10^{22} cm^{-2})
ζ Pup	O4 If	460^c	18.9^d	2250	6.4×10^{-6}	0.01
9 Sgr	O4 V	1300^a	12.4^b	3100	2.1×10^{-6}	0.22
ζ Ori	O9.7 Ib	226^e	22.1^b	1850	1.2×10^{-6}	0.03
ϵ Ori	B0 Ia	363^g	32.9^g	1600	1.2×10^{-6}	0.03
ξ Per	O7.5 III	382^e	14.0^f	2450	9.3×10^{-7}	0.11
ζ Oph	O9.5 V	112^e	8.9^f	1550	1.8×10^{-7}	0.06

X-Rays from Embedded Wind Shocks (EWS)

- Line Deshadowing Instability (LDI) leads to shock-heating of wind
- heated plasma cools by radiating x-rays
- many shocks above ~ $1.5R_{star}$

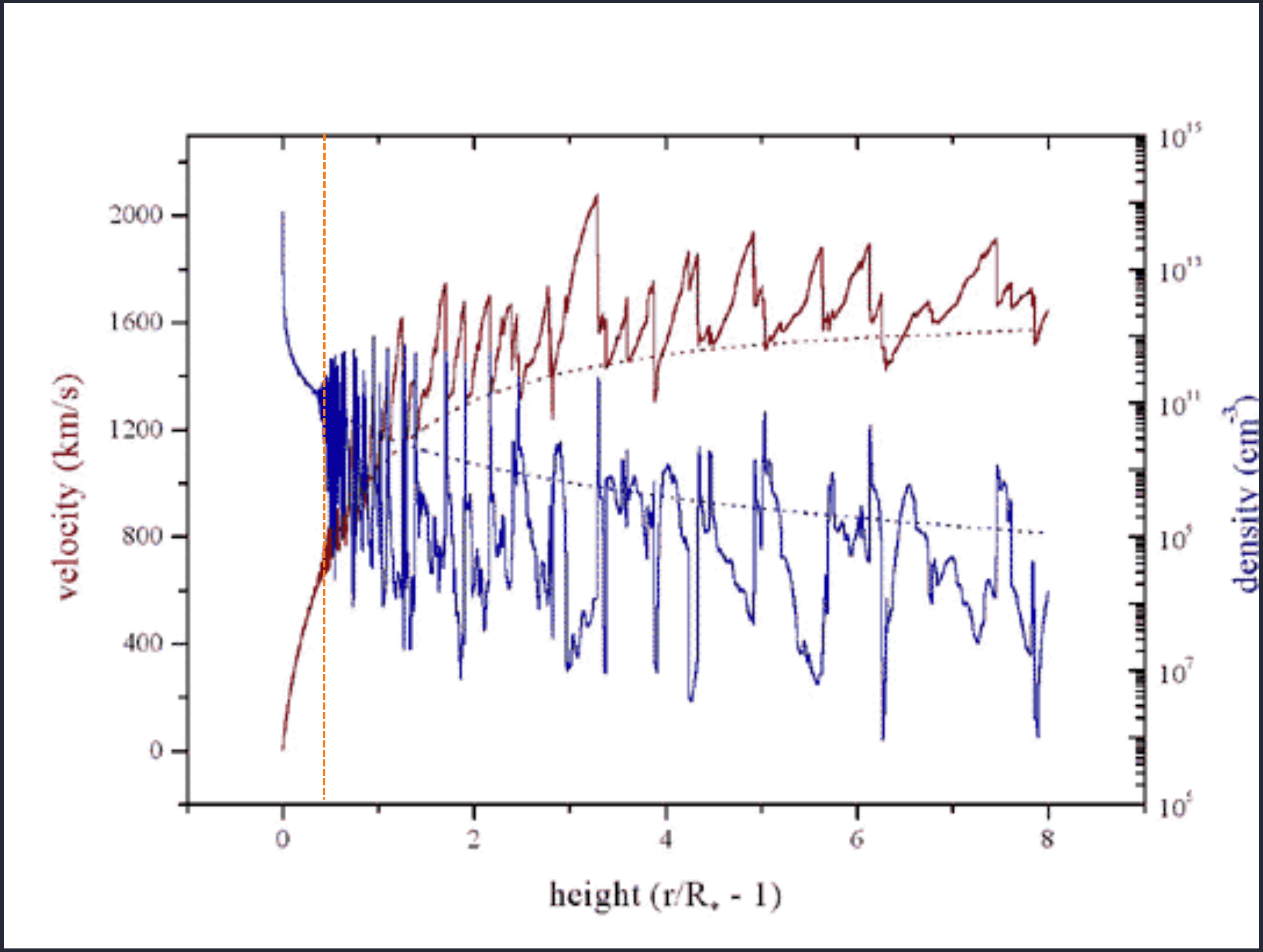
1-D hydro simulation (J. Sundqvist)



Shocked Wind Structure

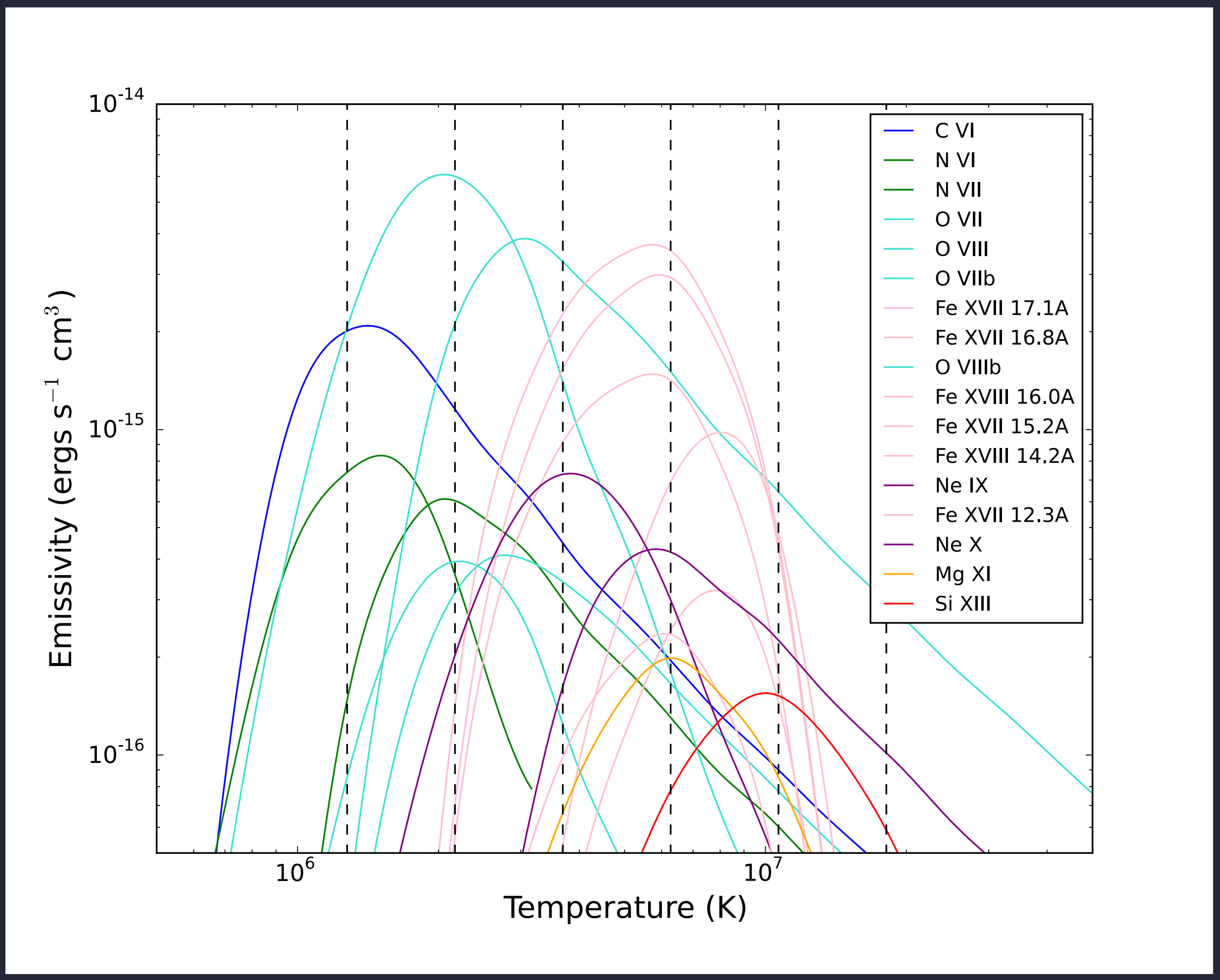
- reverse shocks dominate: pre-shock velocity > ambient wind velocity
- post-shock T ~ few 10^6 K up to few 10^7 K
- but 99% of wind is cold, **absorbs** x-rays

1-D hydro simulation (J. Sundqvist)



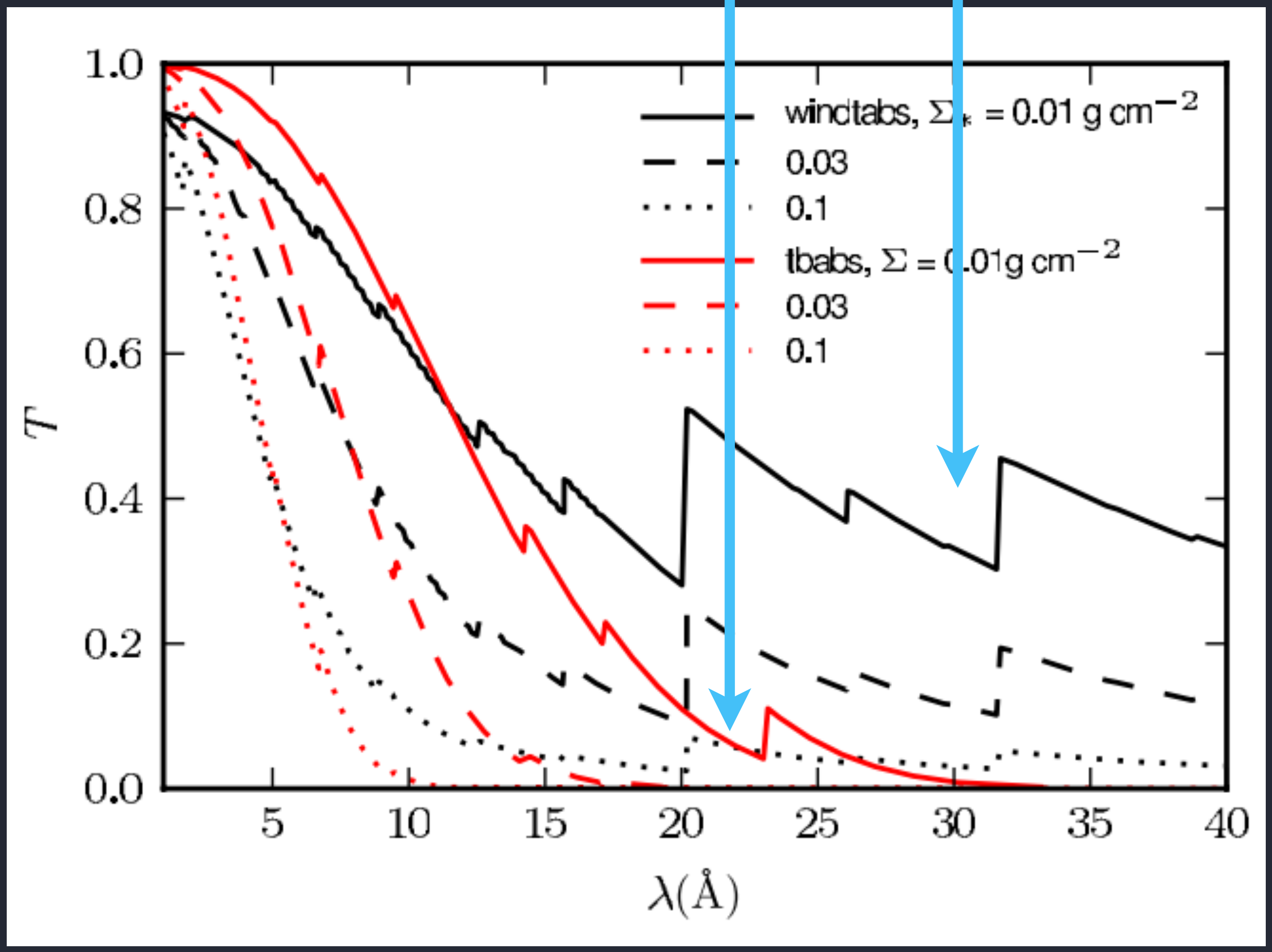
Our Model

- 6 fixed-temperature **bvapec** emission components
- log (T) spacing samples lines' peak emissivities
- **vwindtabs** wind absorption: spatially distributed
- tbabs ISM absorption



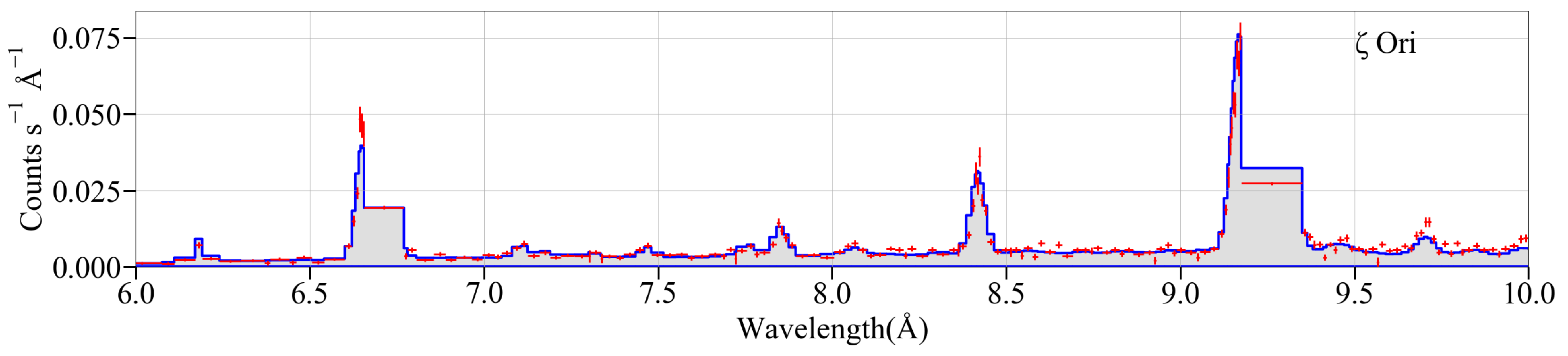
windtabs

slab



Fitting

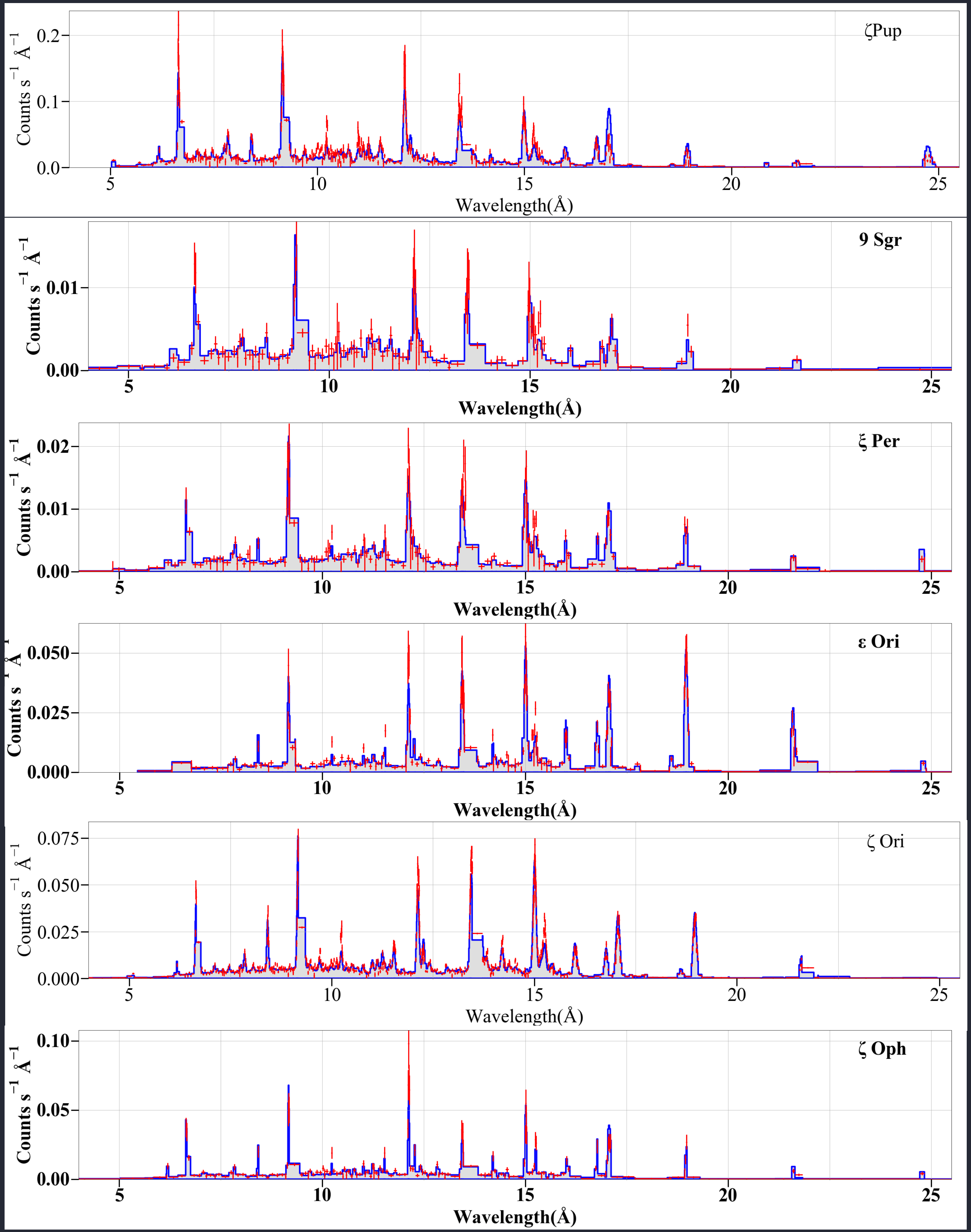
- lines and continuum fit well
- data are adaptively grouped and f,i lines grouped



Fitting (continued)

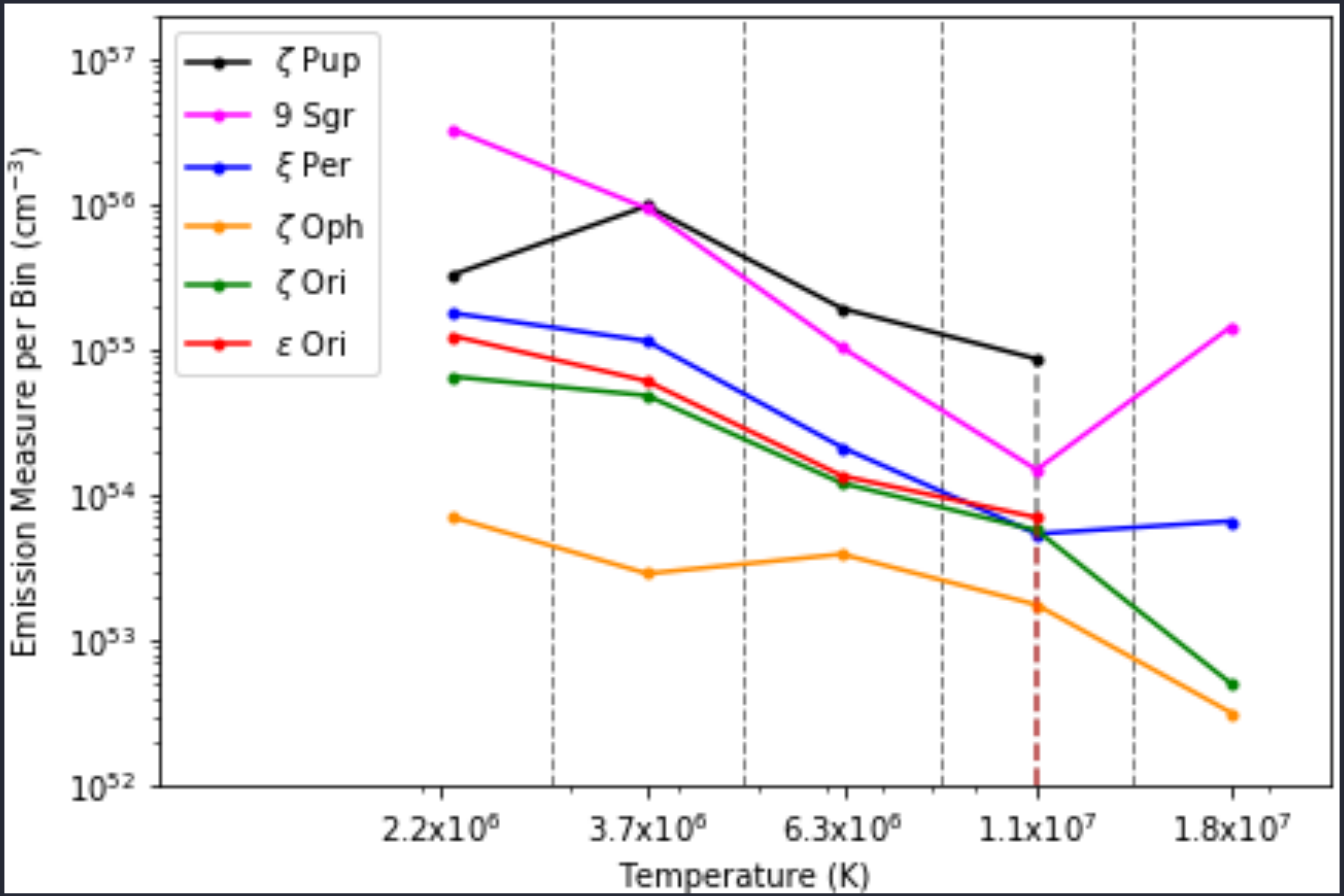
- a consistent method for our 6 stars fits all stars well
- DEMs and mass-loss rates determined
- line widths consistent w/ wind terminal velocities
- N elevated in stars like ζ Pup, where expected

This model fitting technique is a compromise between detailed non-LTE multi wavelength wind modeling and simple variable-two-temperature and excess-ISM absorption modeling



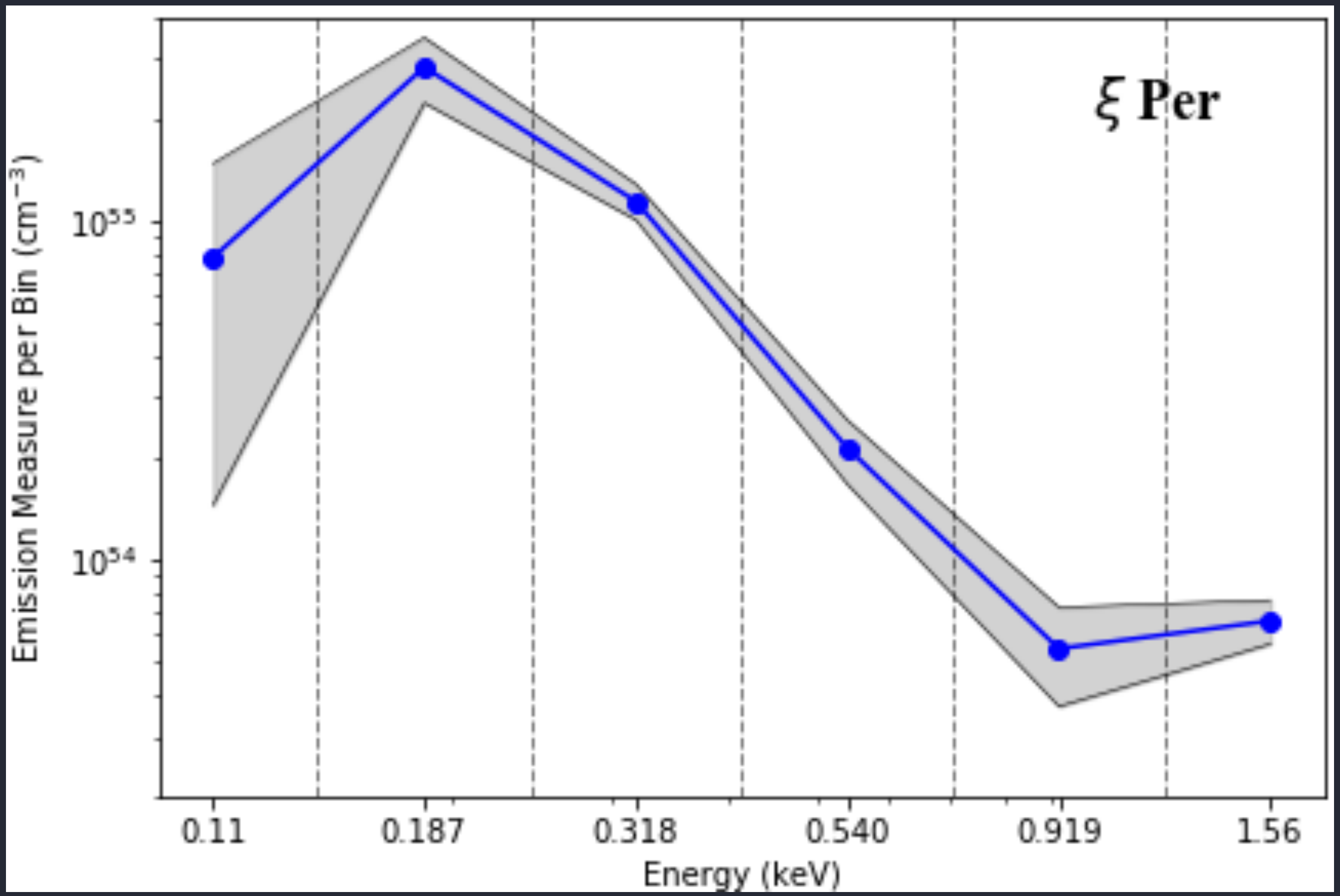
EM vs. T

- universal shape (power law w/ slope ~ -2.5)
- very little emission above 12 X 10^6 K (<2% of total)
- broadly consistent with LDI



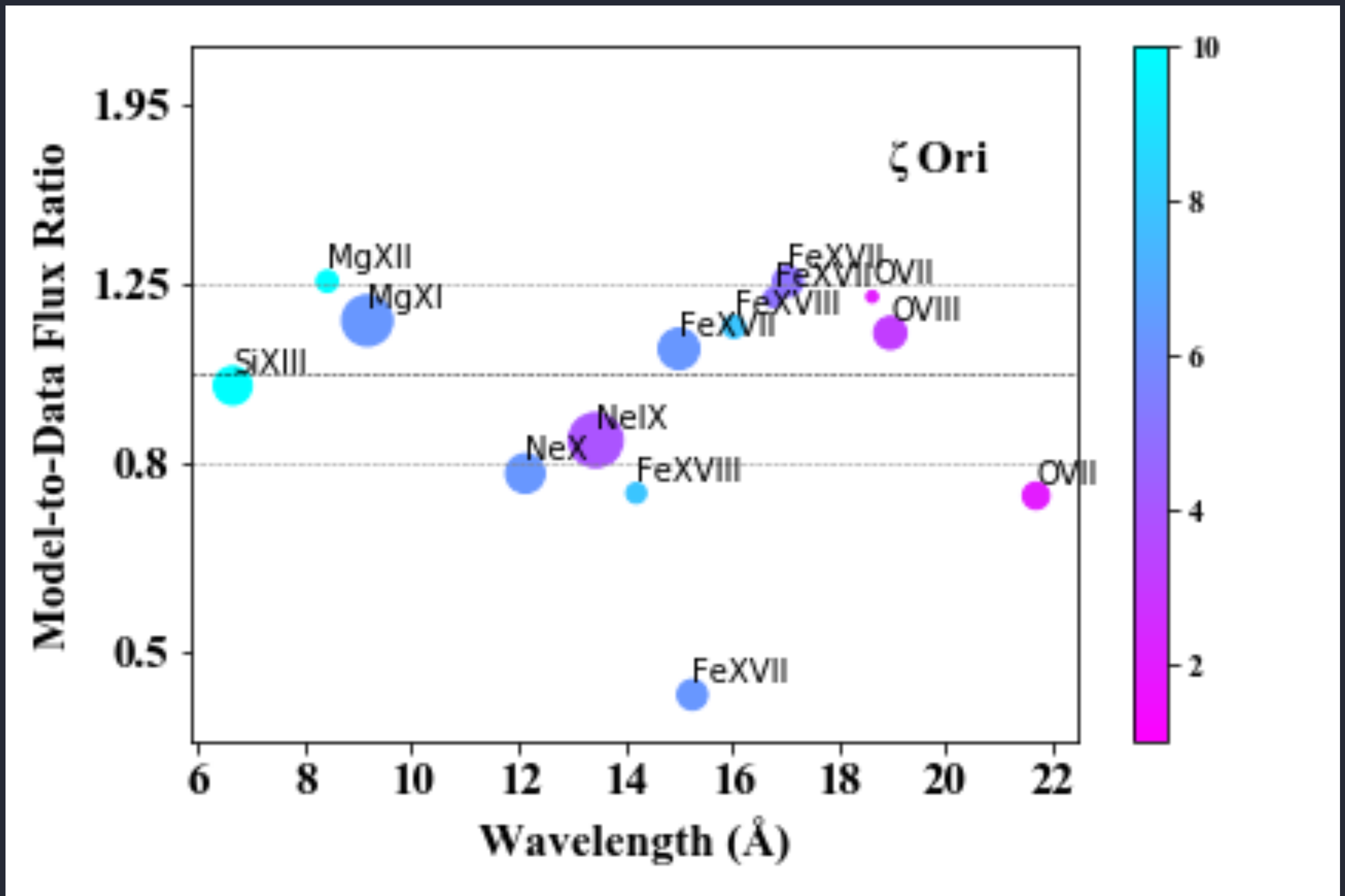
formally good fits

EM vs. T well constrained



statistically poor fits

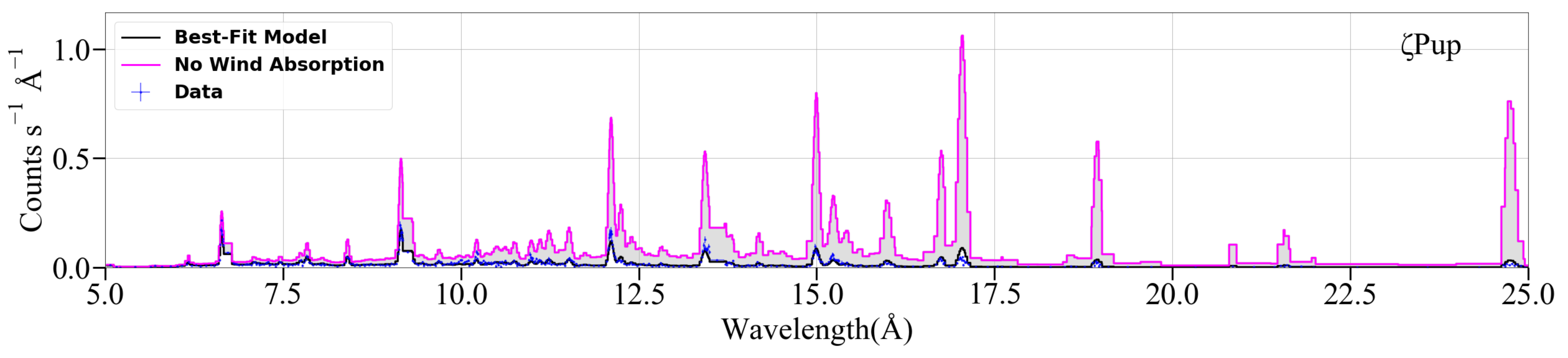
line flux ratios agree within 25%



- high S/N data, dominated by systematics
- atomic physics model uncertainties, line shapes

Wind Absorption

- ~90% of emitted X-ray flux from z Pup is absorbed by the wind
- the wind absorption provides a mass-loss rate measurement



Mass-Loss Rates

Star	Spectral Type	Theory: Vink et al. 2001 ($M_\odot$ yr^{-1})	Cohen et al. 2014 ($M_\odot$ yr^{-1})	this work ($M_\odot$ yr^{-1})
ζ Pup	O4 I	6.4×10^{-6}	1.8×10^{-6}	1.5×10^{-6}
9 Sgr	O4 V	2.1×10^{-6}	3.7×10^{-7}	5.4×10^{-7}
ζ Ori	O9.7 I	1.2×10^{-6}	3.4×10^{-7}	3.9×10^{-7}
ϵ Ori	B0 I	1.2×10^{-6}	6.5×10^{-7}	4.3×10^{-7}
ξ Per	O7.5 III	9.3×10^{-7}	2.2×10^{-7}	5.1×10^{-7}
ζ Oph	O9 V	1.8×10^{-7}	1.5×10^{-9}	1.2×10^{-7}

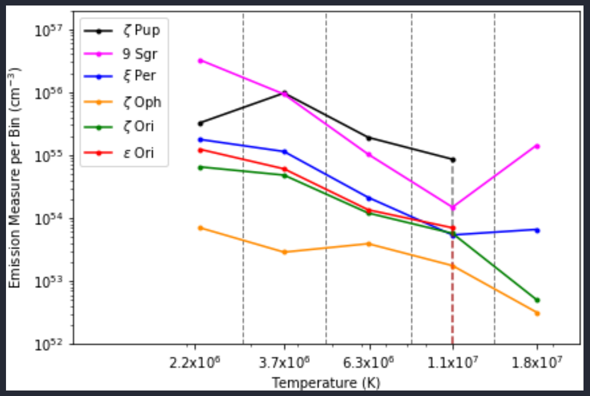
- consistent with determinations from other methods: X-ray line profiles, H-alpha and radio free-free that includes clumping

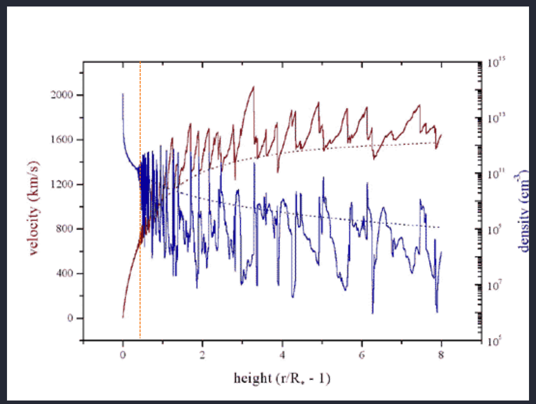
- lower than classic Vink et al. (2001) theoretical calculations

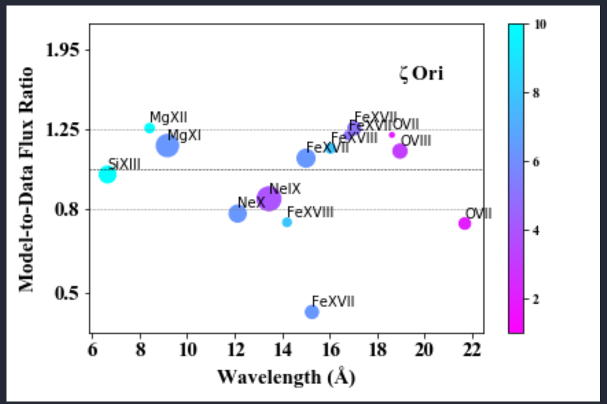
Conclusions

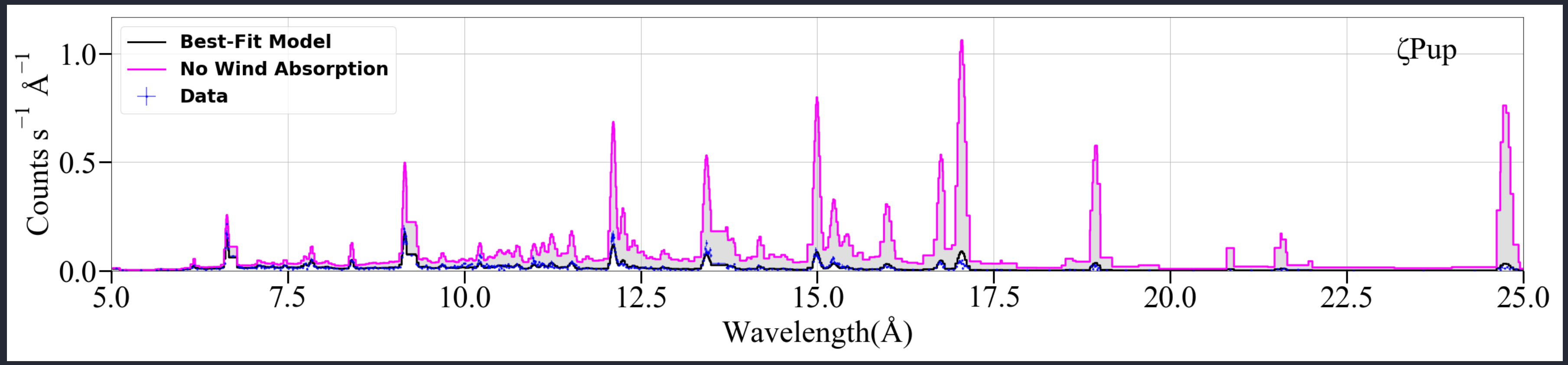
our simple model-fitting method yields DEMs and wind mass-loss rates for O stars with embedded wind shocks:

- strongly decreasing EM vs. T, with little plasma with T > 12 million K
- wind absorption is significant
- mass-loss rates several times lower than theory









Extra Slides

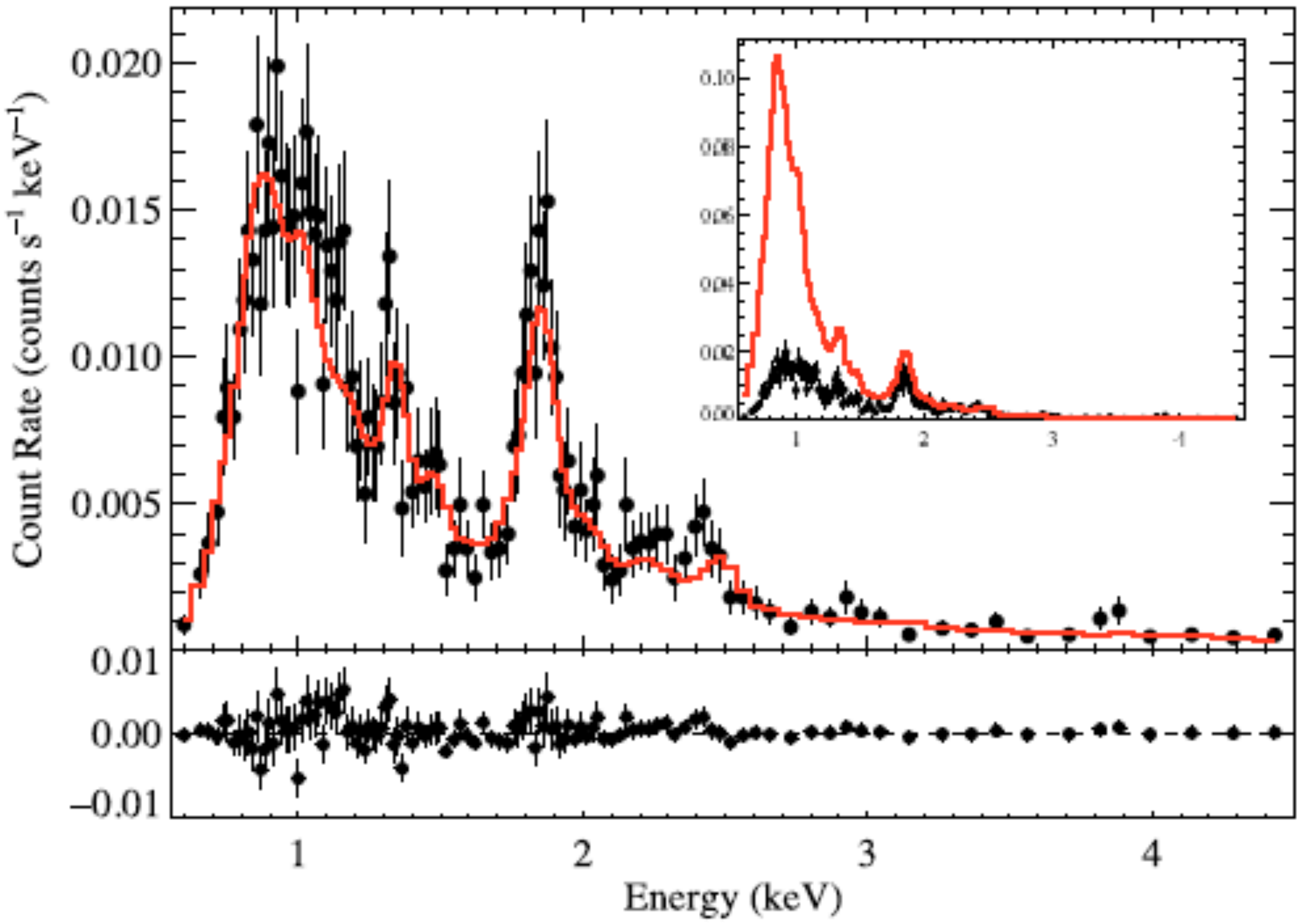


Figure 9. The same zeroth order ACIS CCD spectrum shown in Fig. 2, here fit with a two-temperature *apec* thermal emission model (red histogram), where one temperature component (0.6 keV) is attenuated by the stellar wind as well as the interstellar medium and the other (3.3 keV) is attenuated only by the ISM. Note the presence of strong Si XIII emission just below 2 keV. The vast majority of the emission in this spectrum is line emission, but due to the low resolution of the detector as well as the presence of many weak, blended lines, the spectrum looks relatively smooth. The inset figure shows the same data with a model identical to the best-fit model, except that the wind absorption (Σ_* in *windtabs*) is zeroed out. This model spectrum makes the significance of the wind absorption effect quite obvious. Nearly 80% of the emitted EWS X-rays are absorbed before they can escape from the wind.

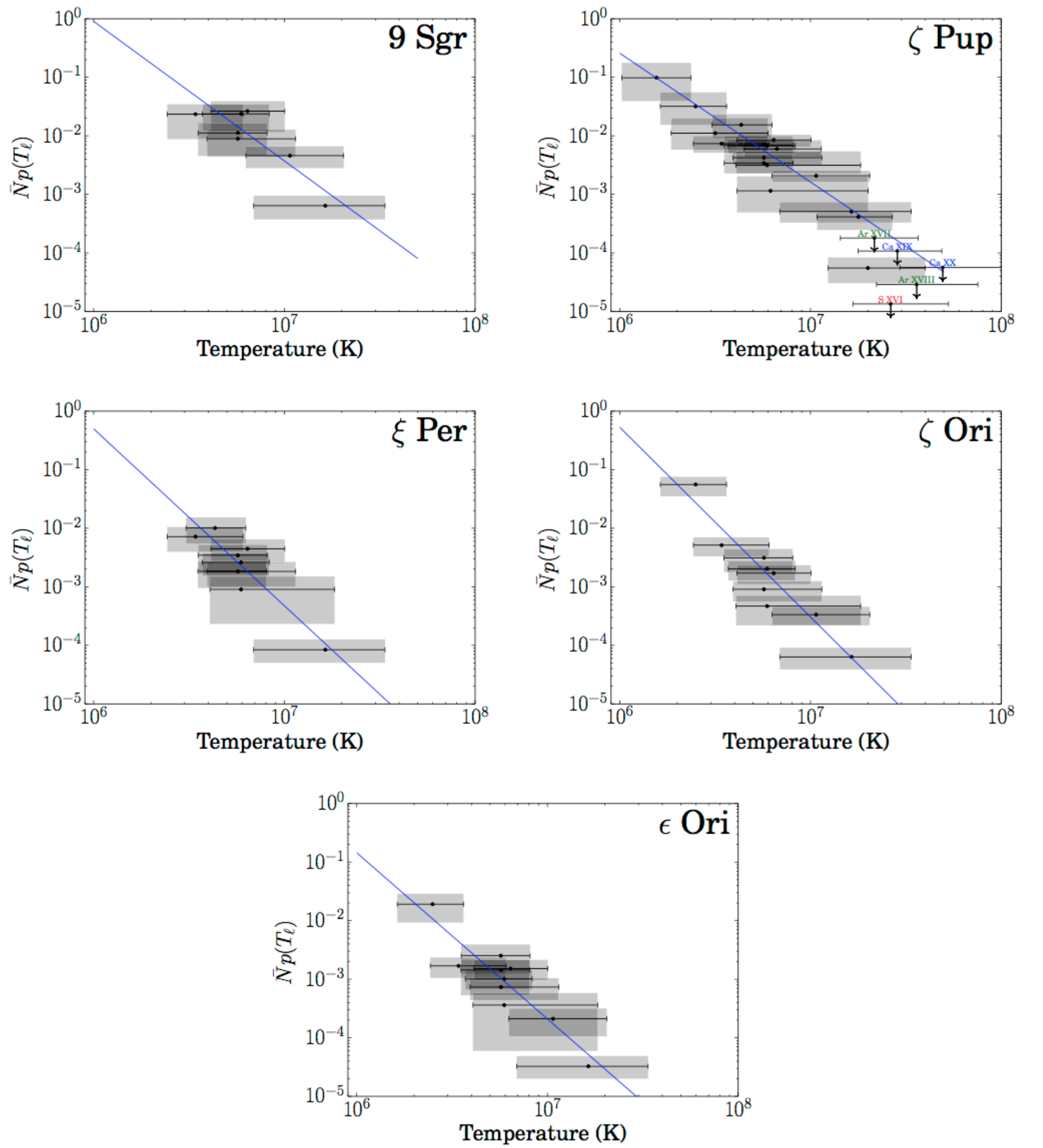
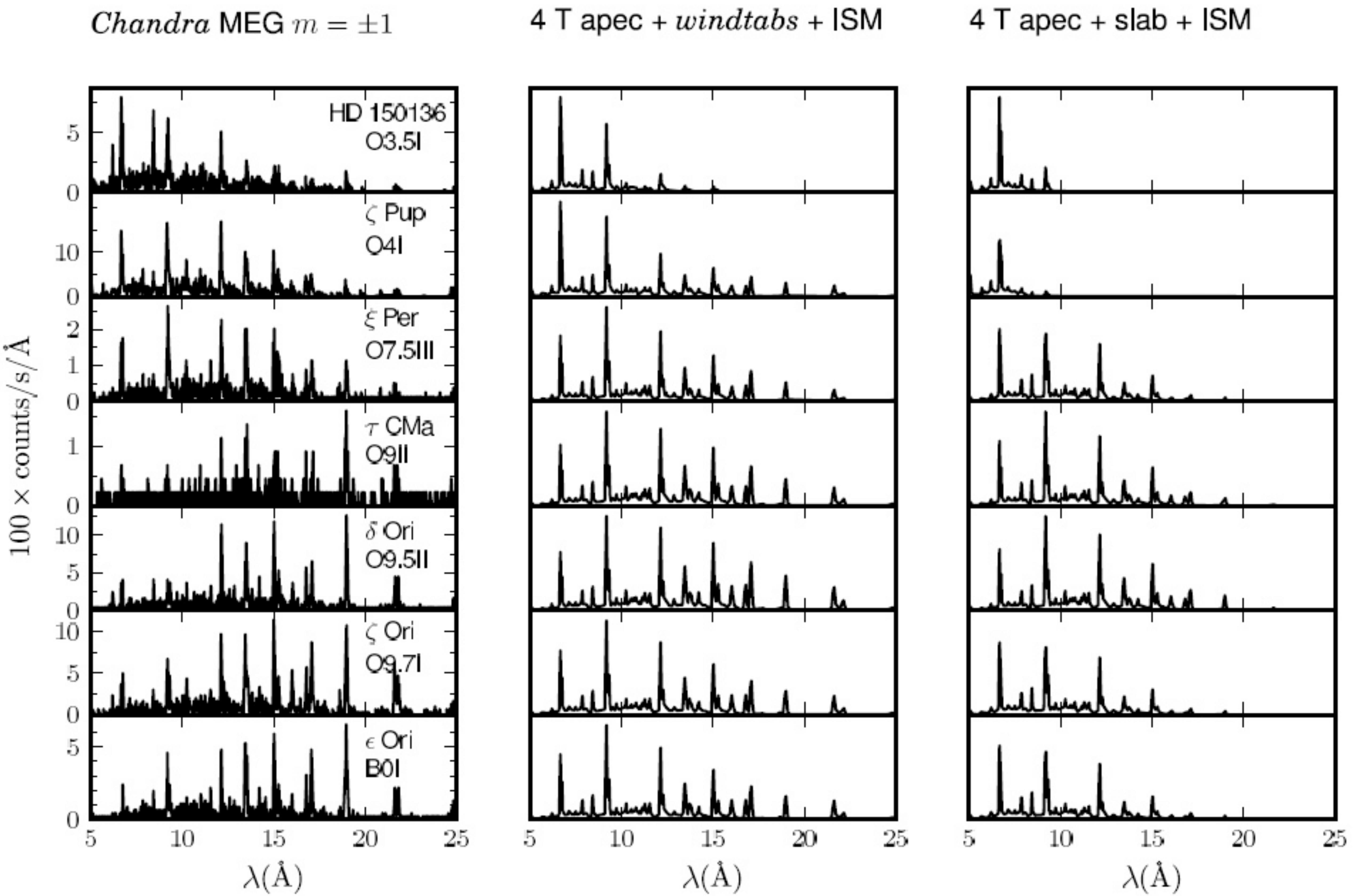


Figure 5. The shock heating rate, $\bar{N}p(T_\ell)$, is shown with the uncertainty on its value (vertical extent of each gray box) as well as the FWHM of the line emissivity ratio, $\Lambda_\ell(T)/\Lambda(T)$ (horizontal extent, visually reinforced by the horizontal error bars). The points are at T_ℓ for each line. The best-fit power law to each set of values is shown as a blue line in each panel. For ζ Pup, the lowest temperature point corresponds to the N VI feature measured with *XMM-Newton*. And for this star, upper limits are included for five additional lines, none of which are detected in the *Chandra* spectrum.



$Chandra$ MEG $m = \pm1$
4 T apec + $windtabs$ + ISM
4 T apec + slab + ISM
HD 150136
O3.5I
ζ Pup
O4I
ξ Per
O7.5III
τ CMa
O9II
δ Ori
O9.5II
ζ Ori
O9.7I
ϵ Ori
B0I
$100 \times$ counts/s/Å
λ(Å)