X-ray Emission from O Stars

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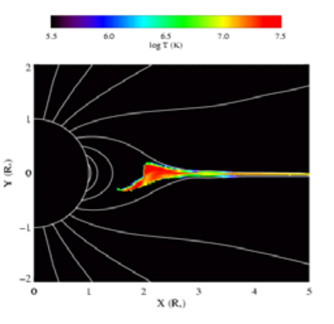
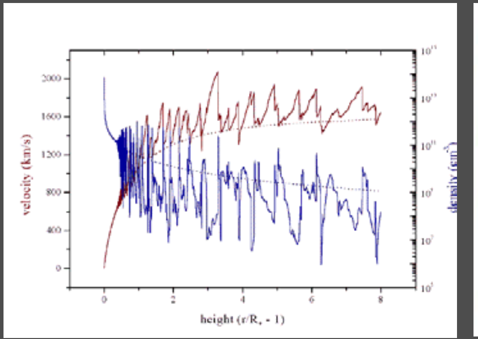
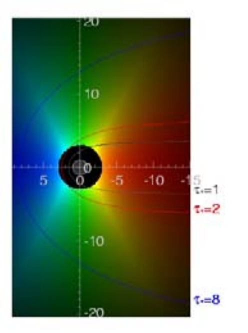


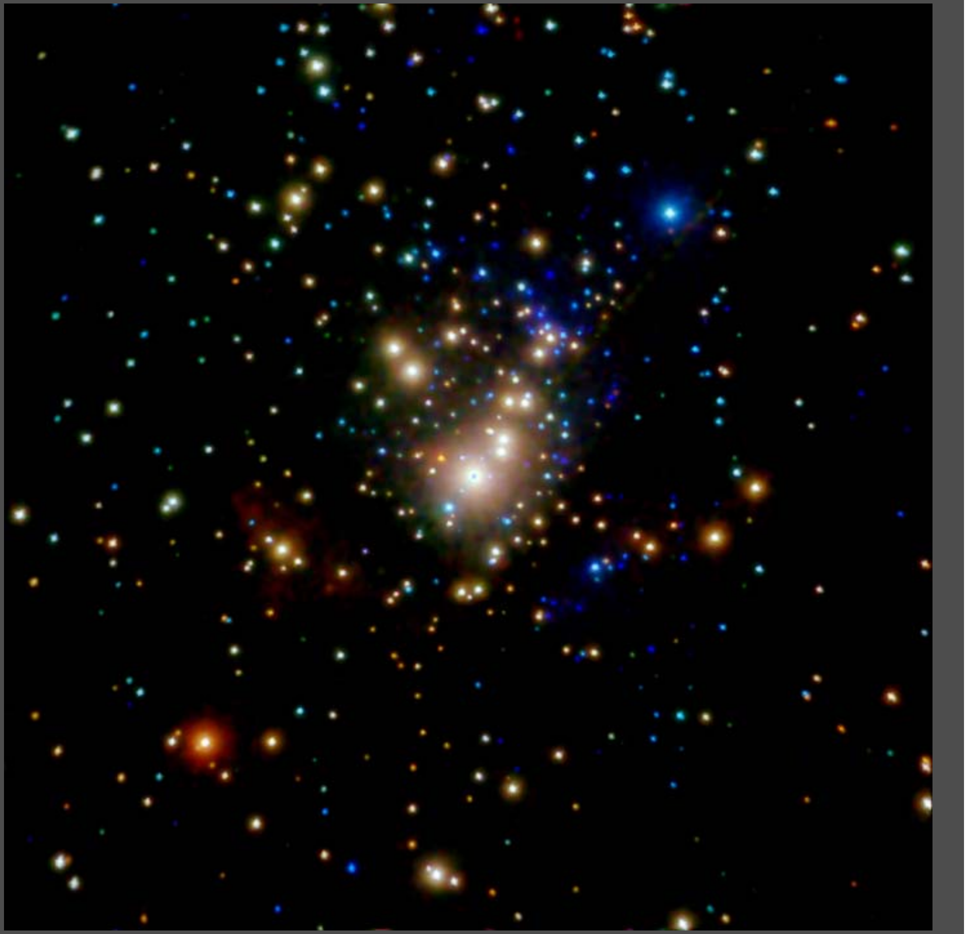




Young OB stars are very X-ray bright

L_x up to **~10^{34}** ergs s^{-1}

X-ray temperatures:
few up to 10+ keV (**10s to 100+ million K**)

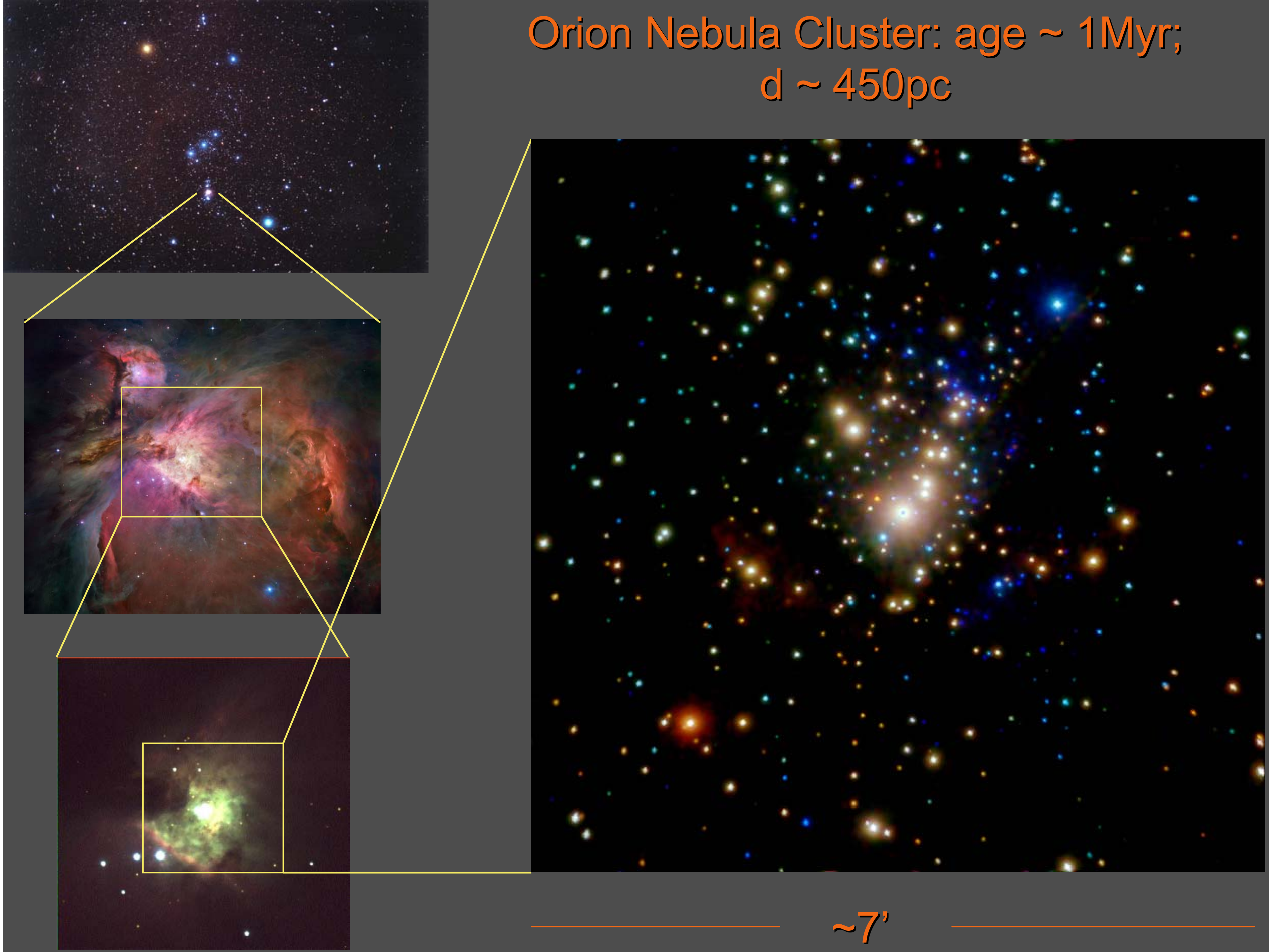


Orion; *Chandra* (Feigelson et al. 2002)

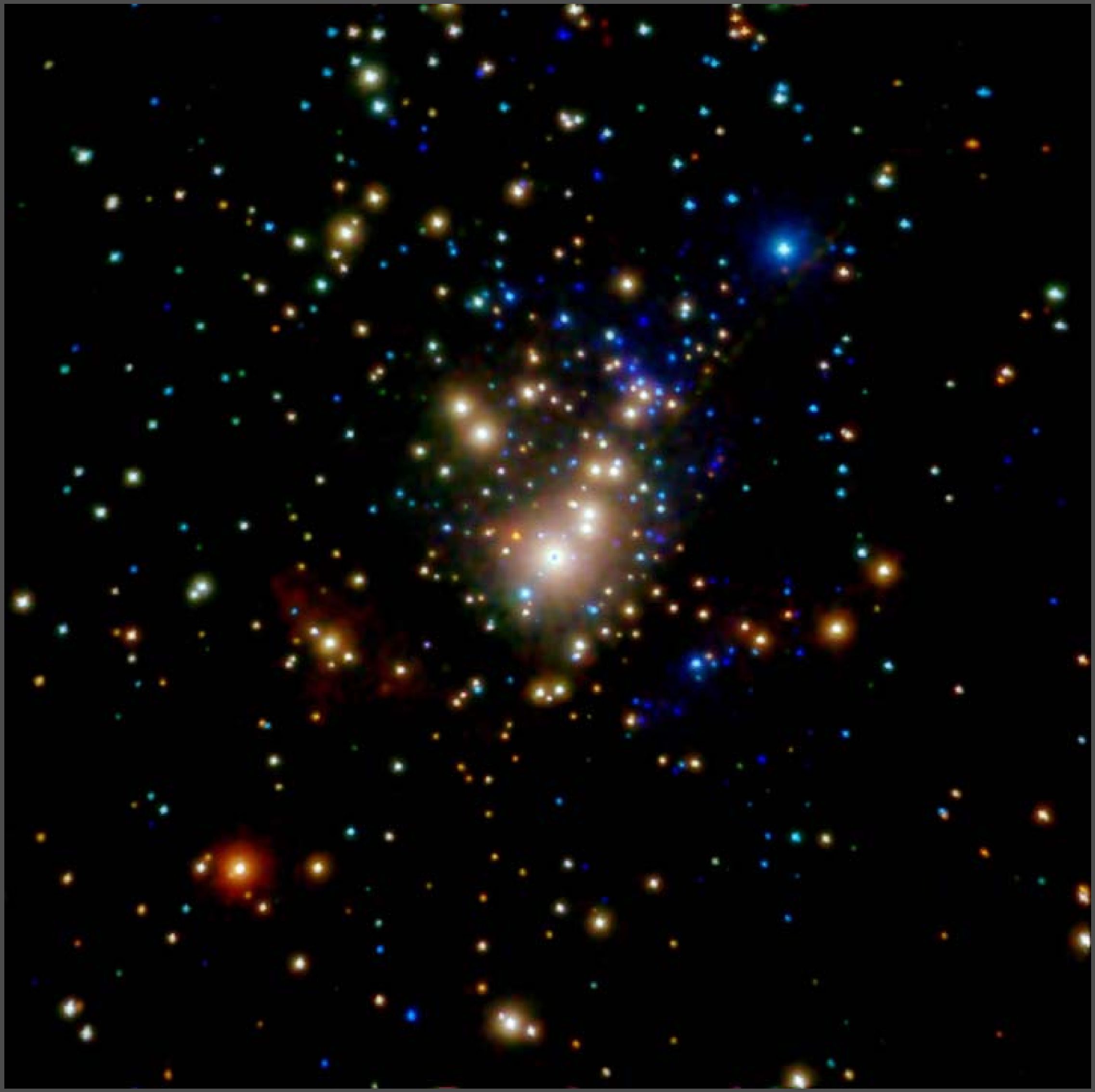
Outline – focus on single O stars

1. Young OB stars produce strong hard X-rays in their magnetically channeled winds
2. After ~1 Myr X-ray emission is weaker and softer: embedded wind shocks in early O supergiants
3. X-ray line profiles provide evidence of low mass-loss rates
4. Wind-wind binaries will not be discussed

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

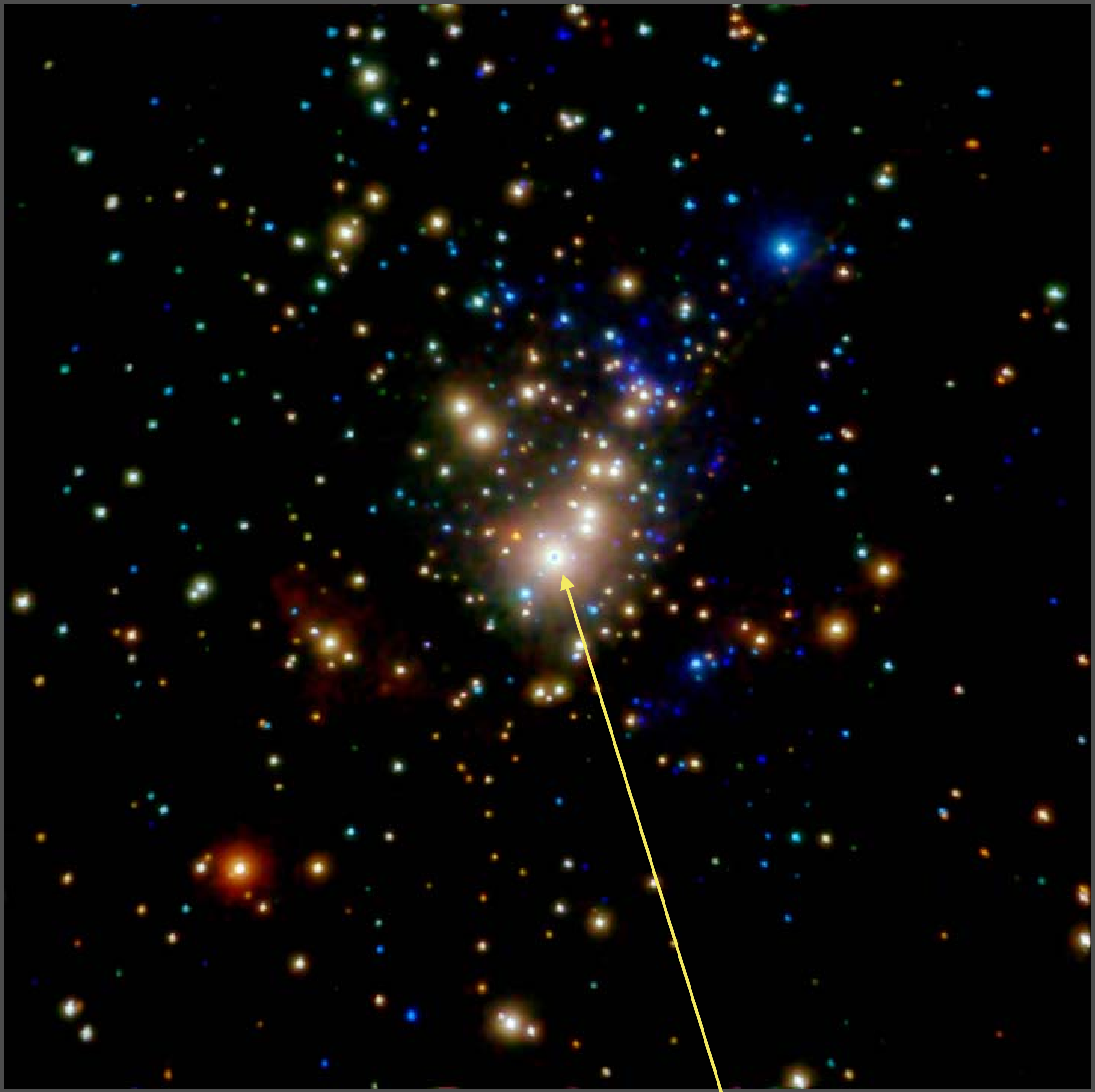


Chandra ~10^6 seconds, sub-arcsec resolution



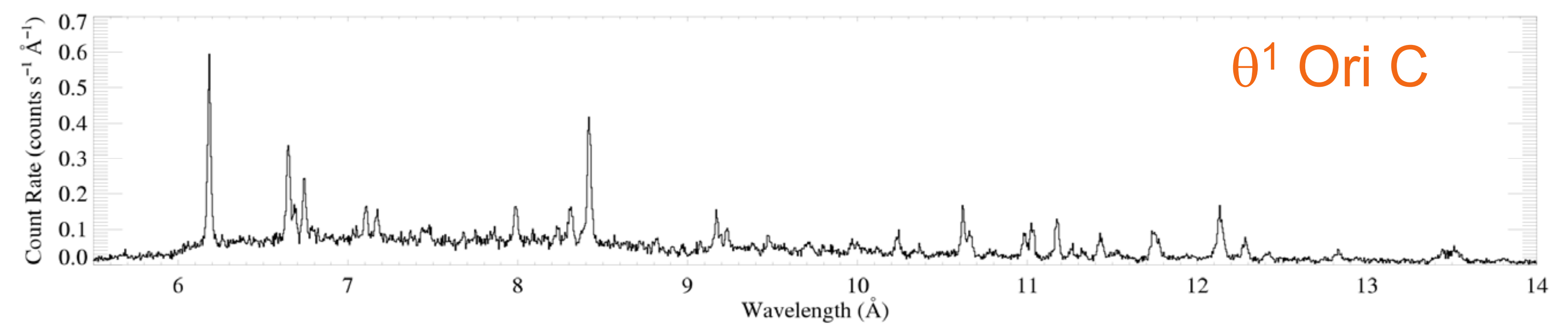
Color coding of x-ray energy: <1keV, 1keV < E < 2.5keV, >2.5keV

Brightest X-ray sources are OB stars

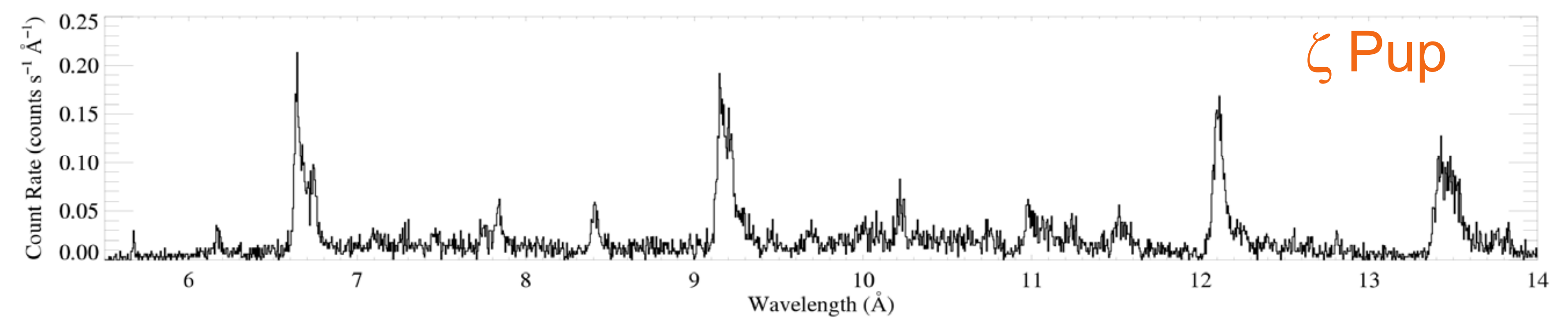


θ^1 Ori C (O7 V)

Chandra grating spectra (*R* ~ 1000 ~ 300 km s^{-1})

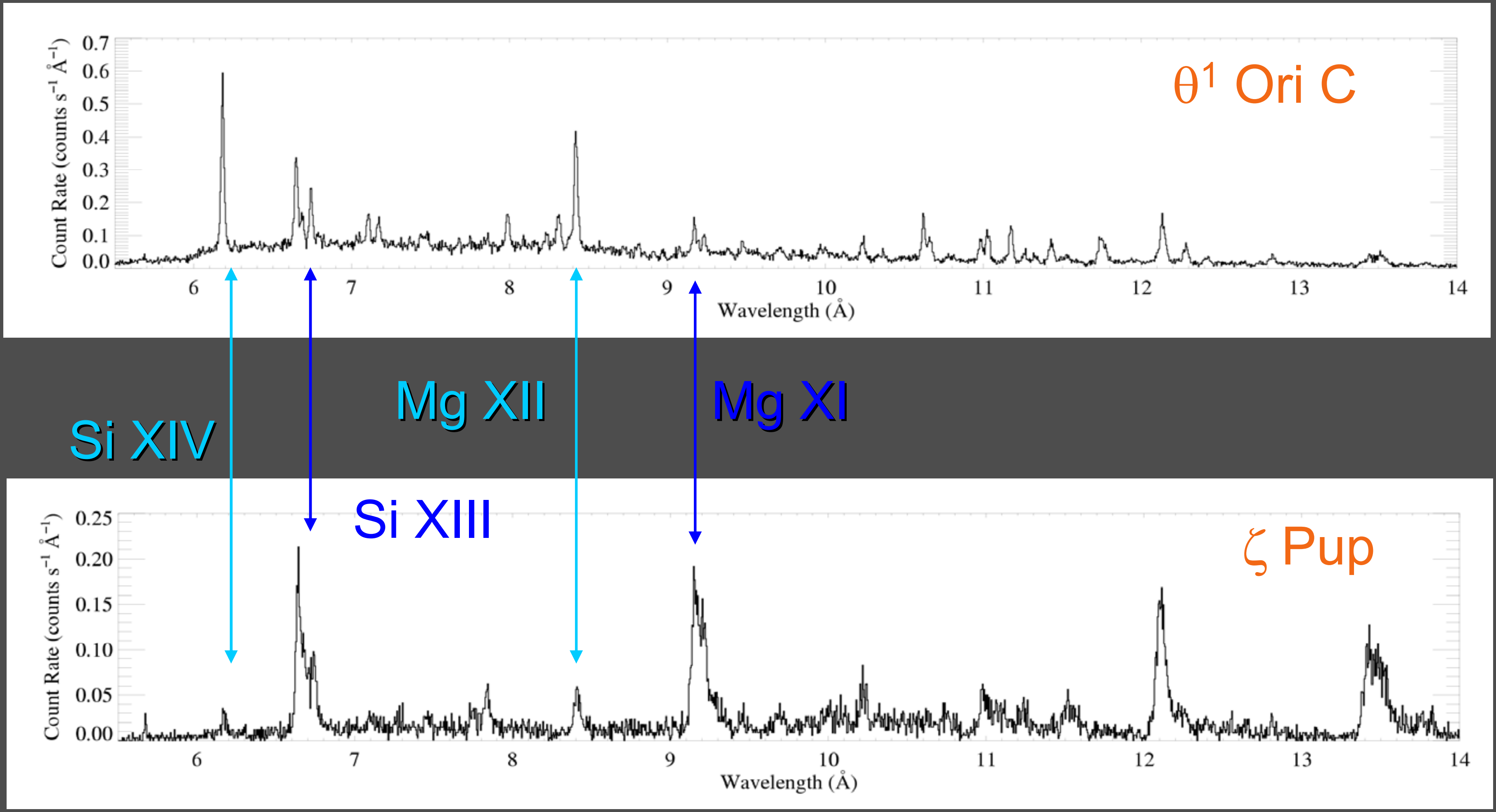


θ^1 Ori C: hotter plasma, narrower emission lines



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

H-like/He-like ratio is temperature sensitive



θ^1 Ori C

Si XIV

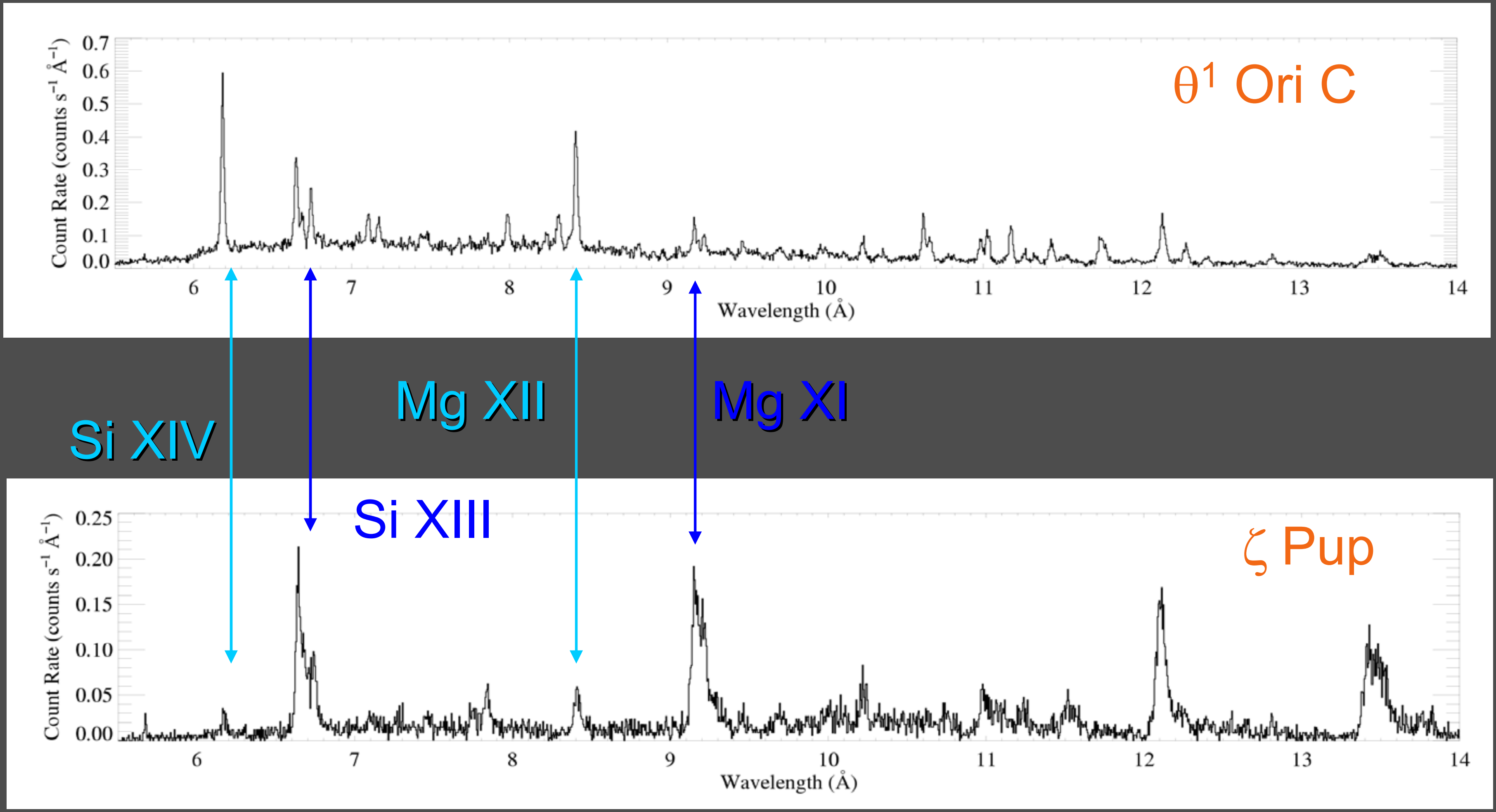
Mg XII

Mg XI

Si XIII

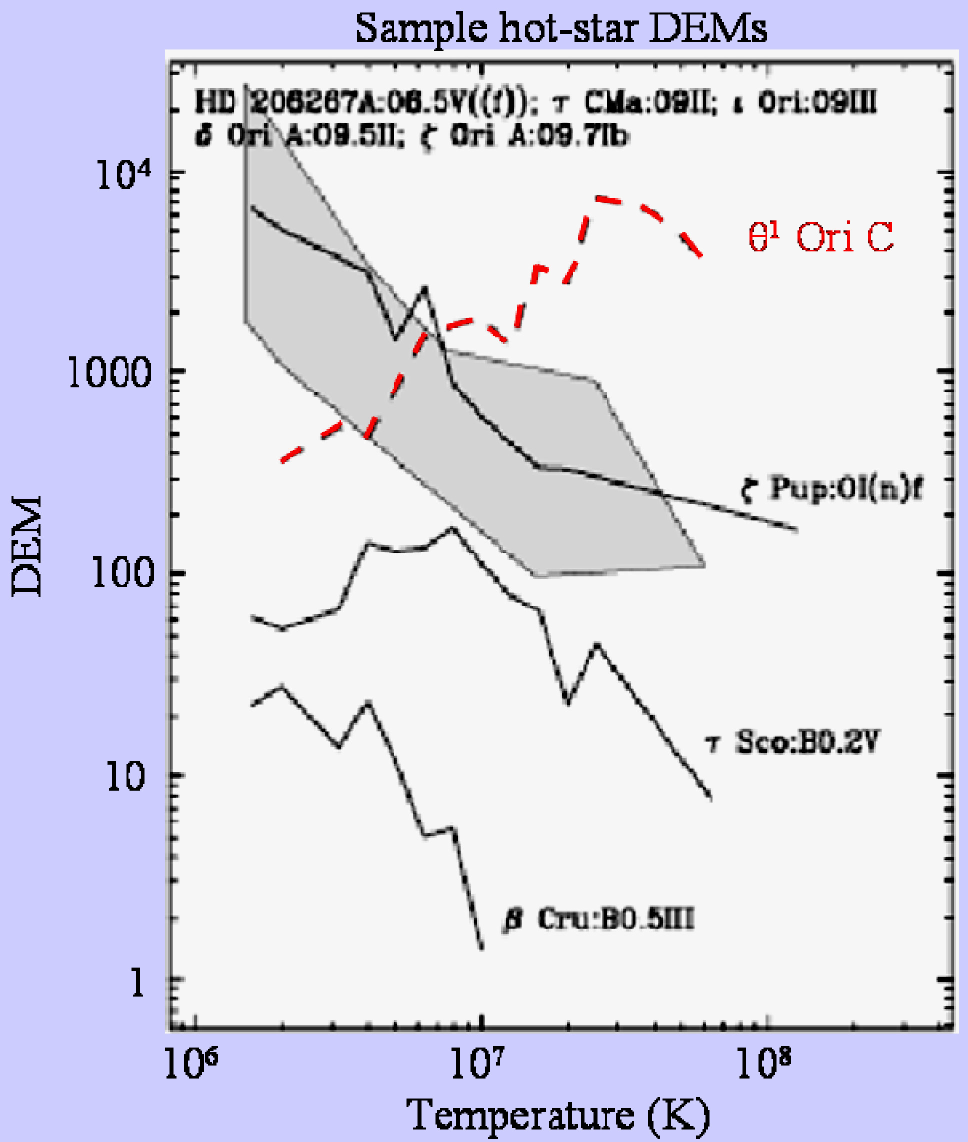
ζ Pup

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



Differential emission measure

(temperature distribution)



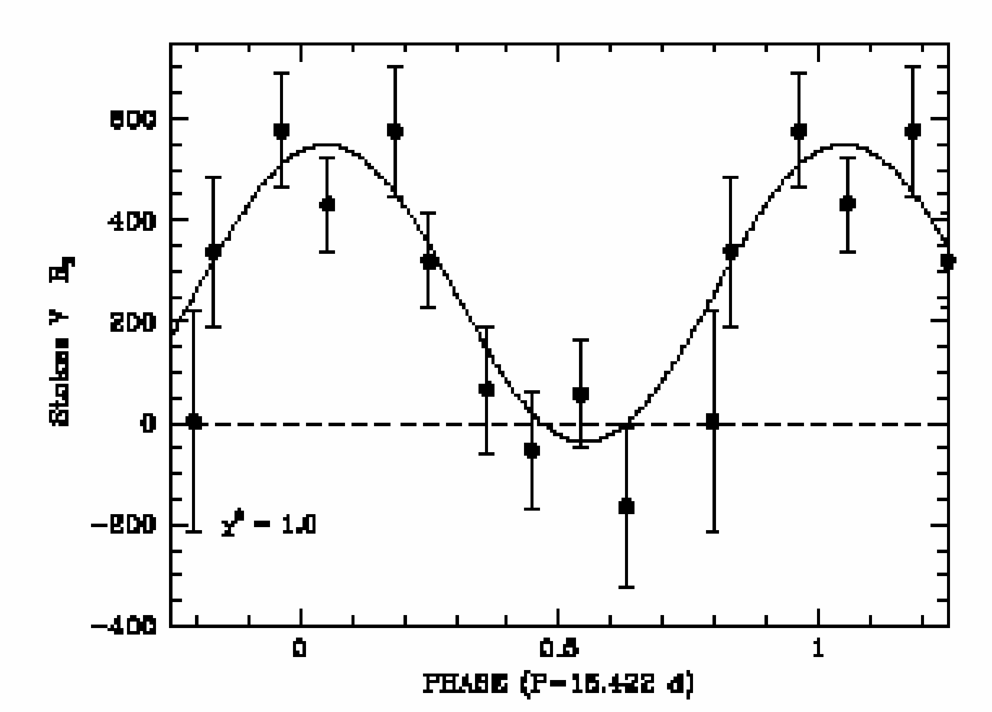
Wojdowski & Schulz (2005)

θ^1 Ori C:

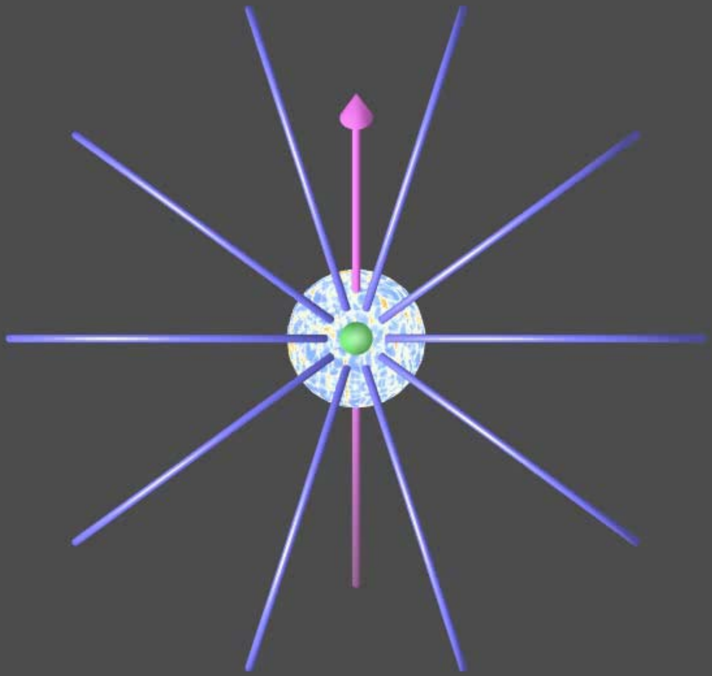
peak near 30 million K

evolved O stars, peak at a few million K

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



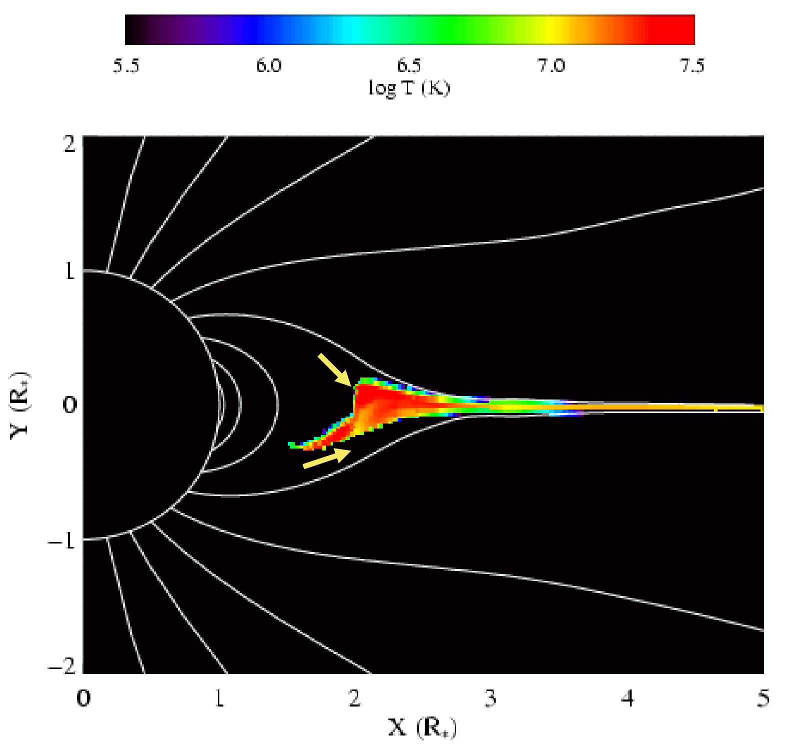
Wade et al. (2006)



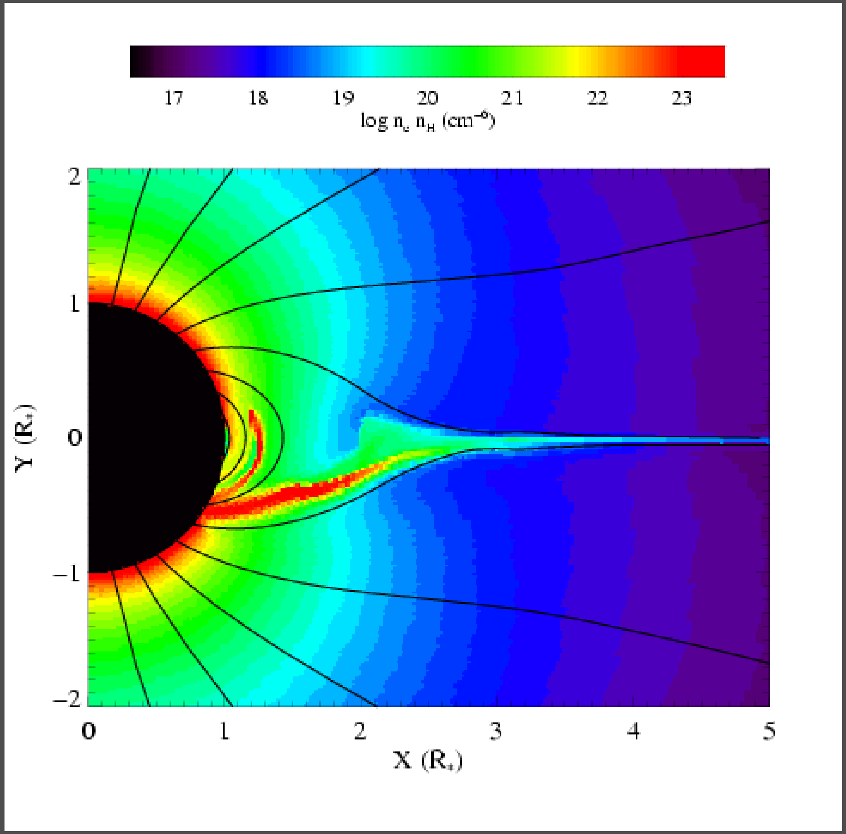
Magnetic field obliquity,
$\beta \sim 45^o$

MHD simulations of magnetically channeled wind

temperature



emission measure

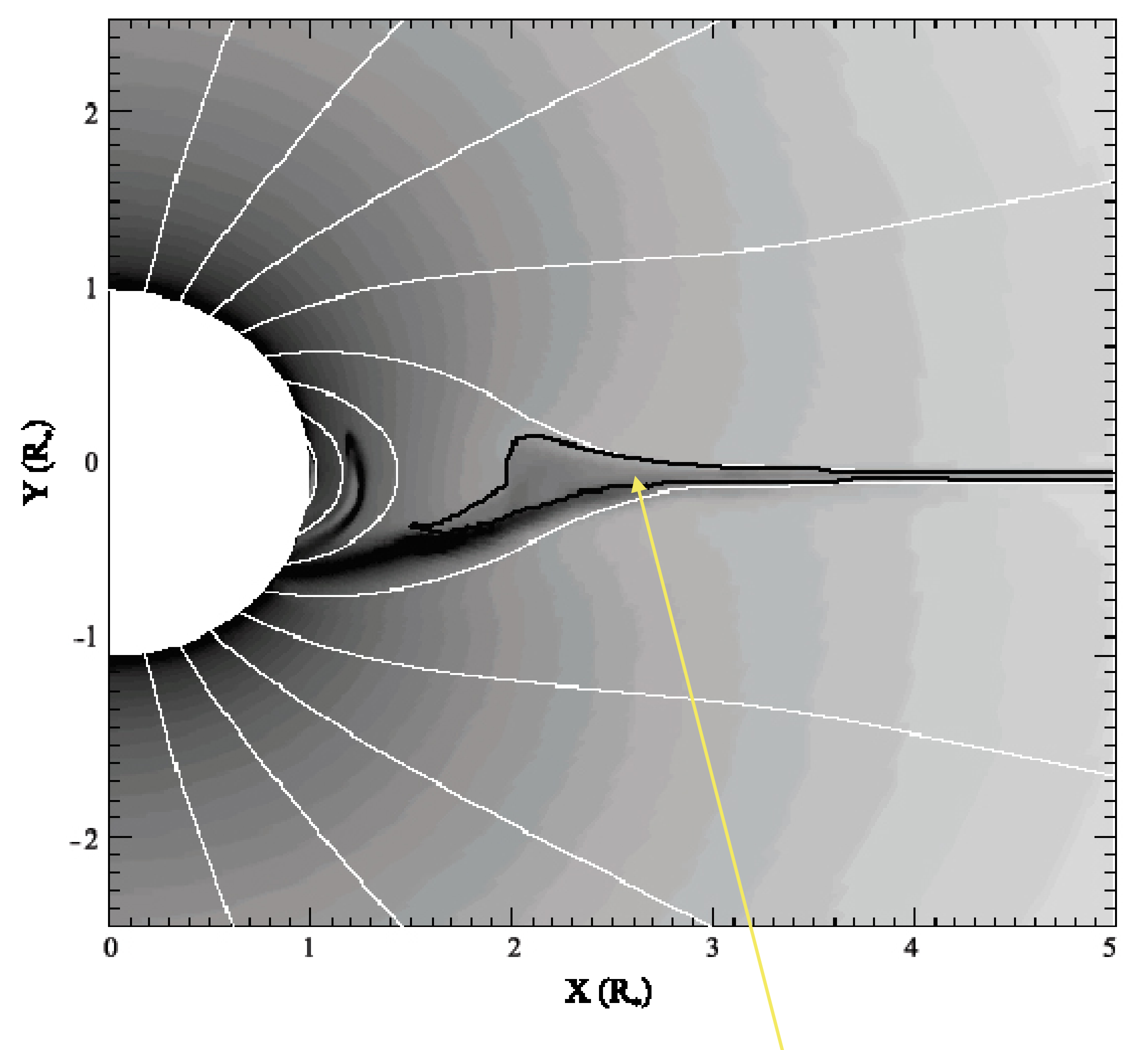


simulations by A. ud-Doula; Gagné et al. (2005)

Channeled collision is close to head-on –

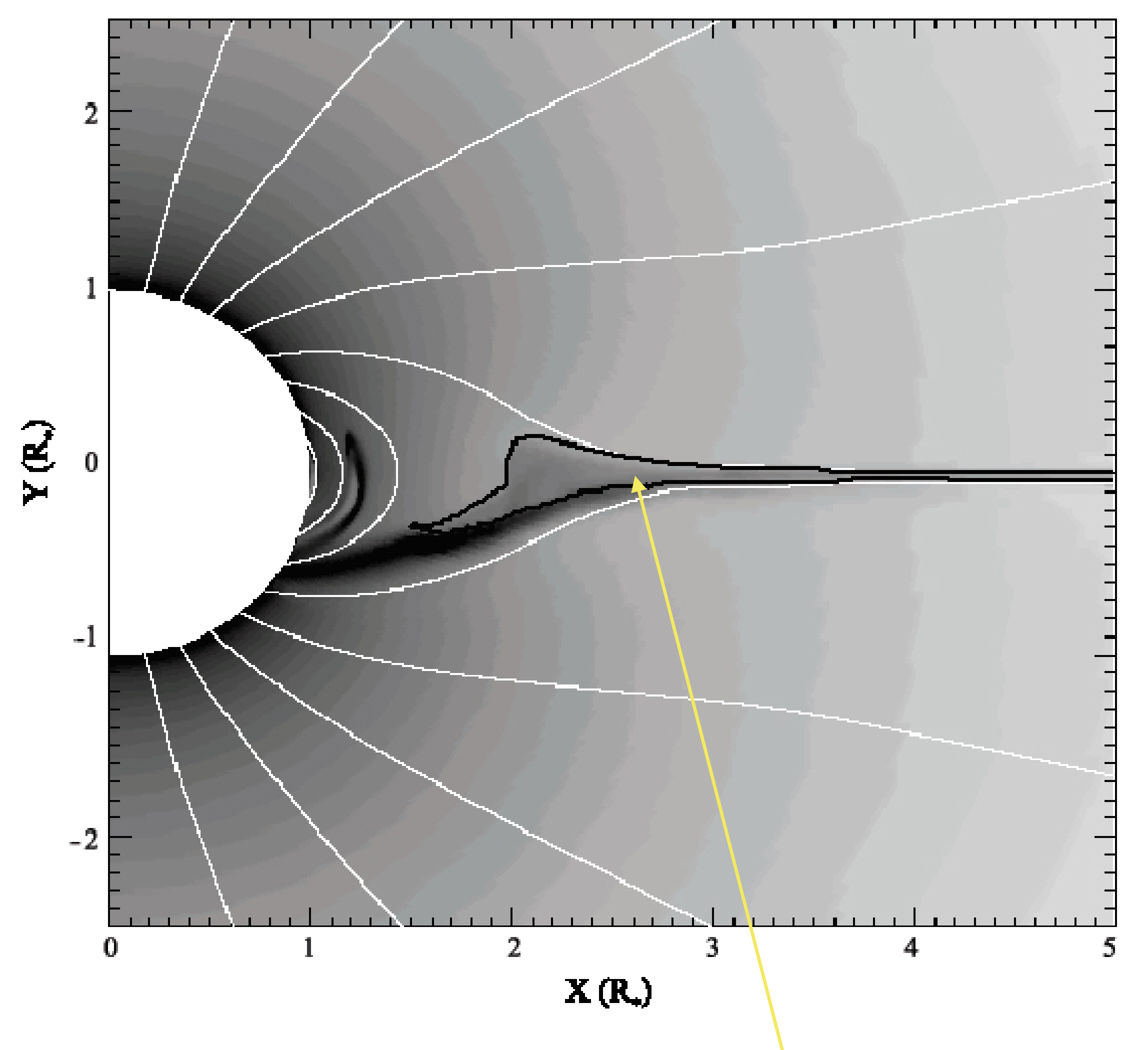
at 1000+ km s^{-1} : T = 10^{7}+ K

Emission measure



contour encloses $T > 10^6$ K

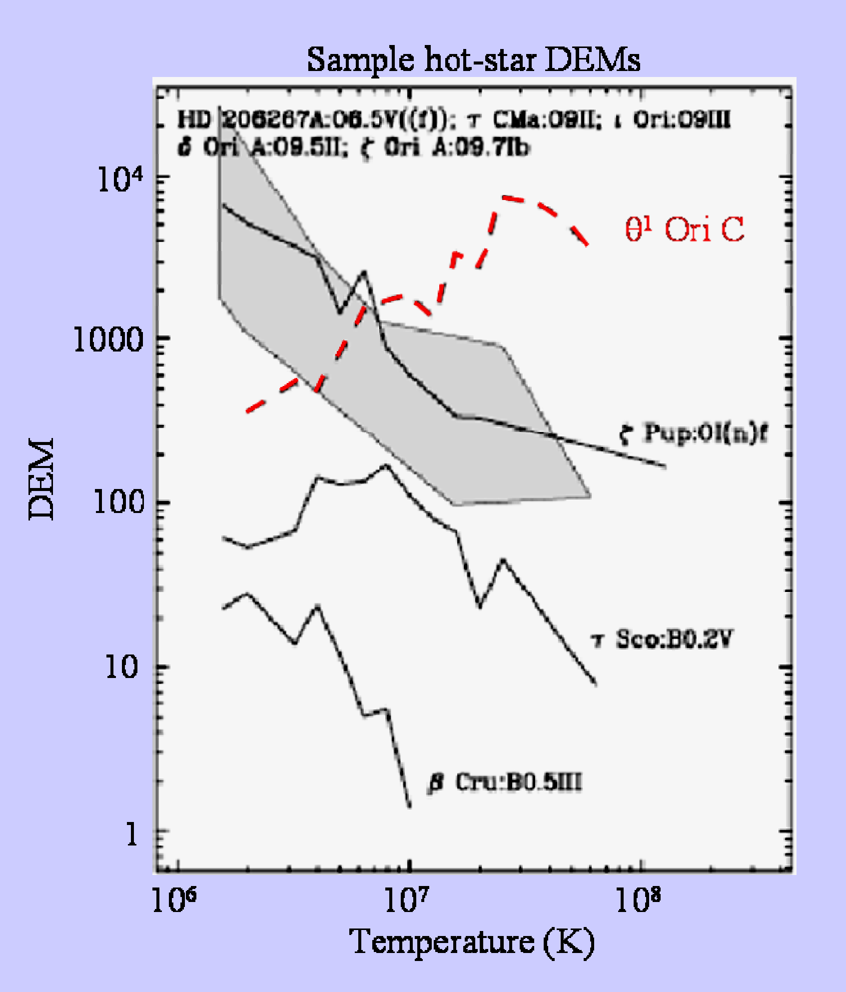
MHD simulations show multi-10^6 K plasma, moving slowly, ~$1R_*$ above photosphere



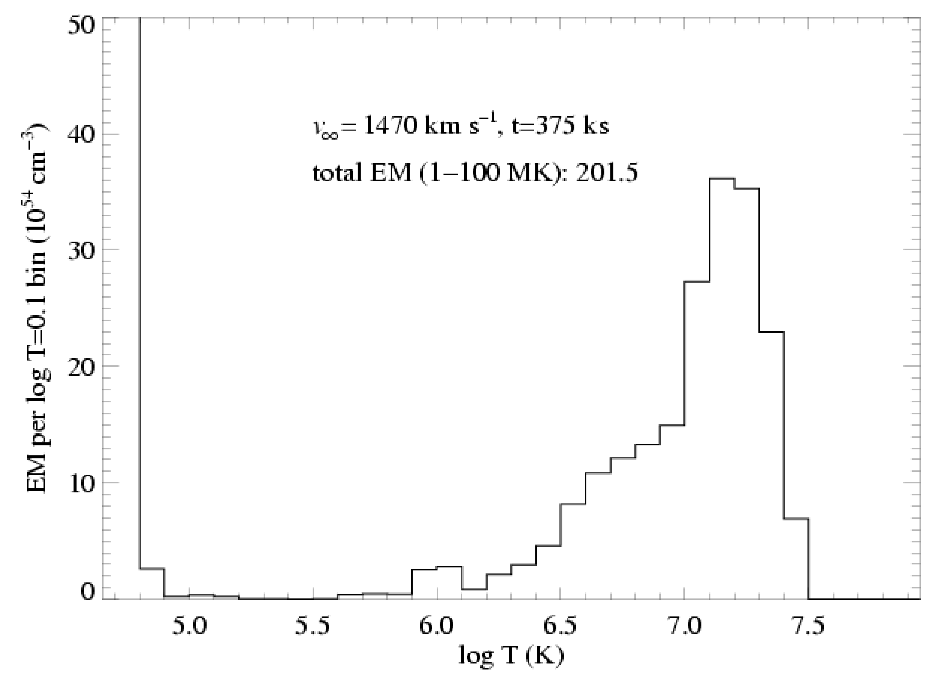
contour encloses $T > 10^6$ K

Differential emission measure

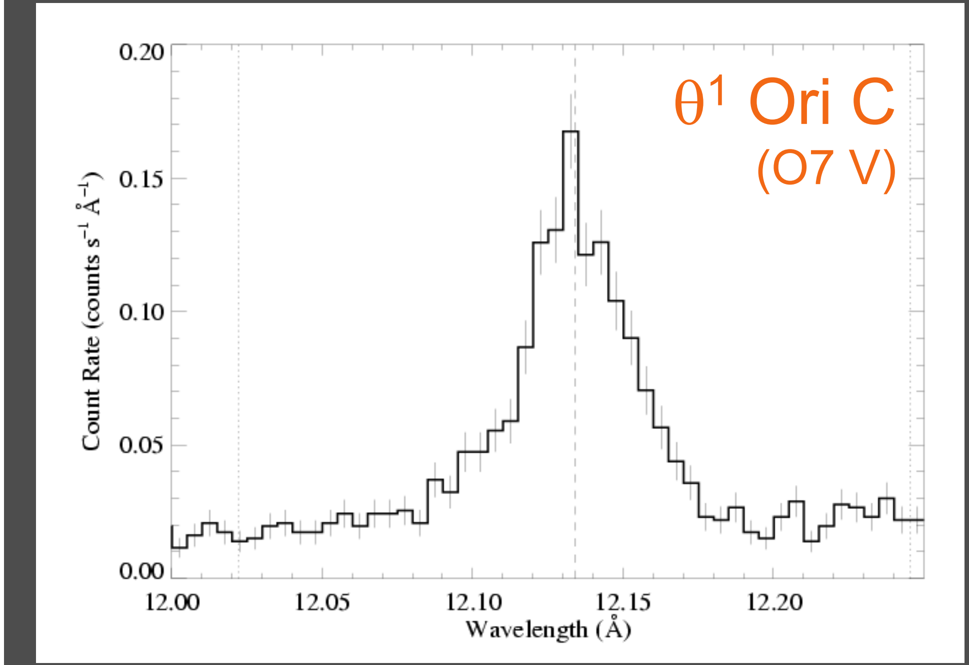
(temperature distribution)



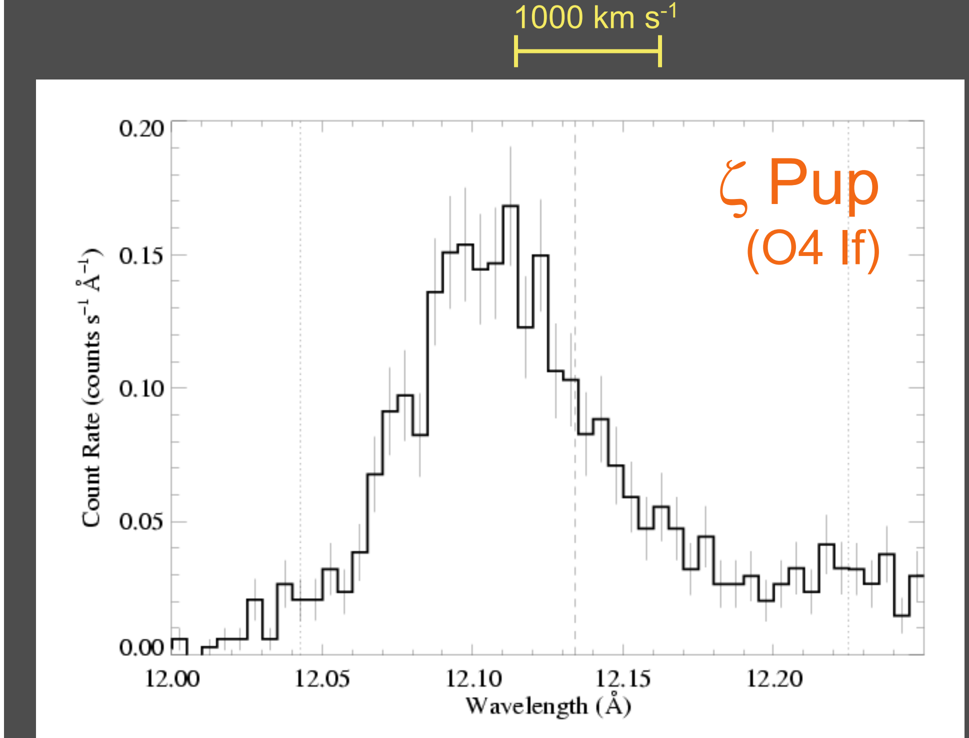
Sample hot-star DEMs



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



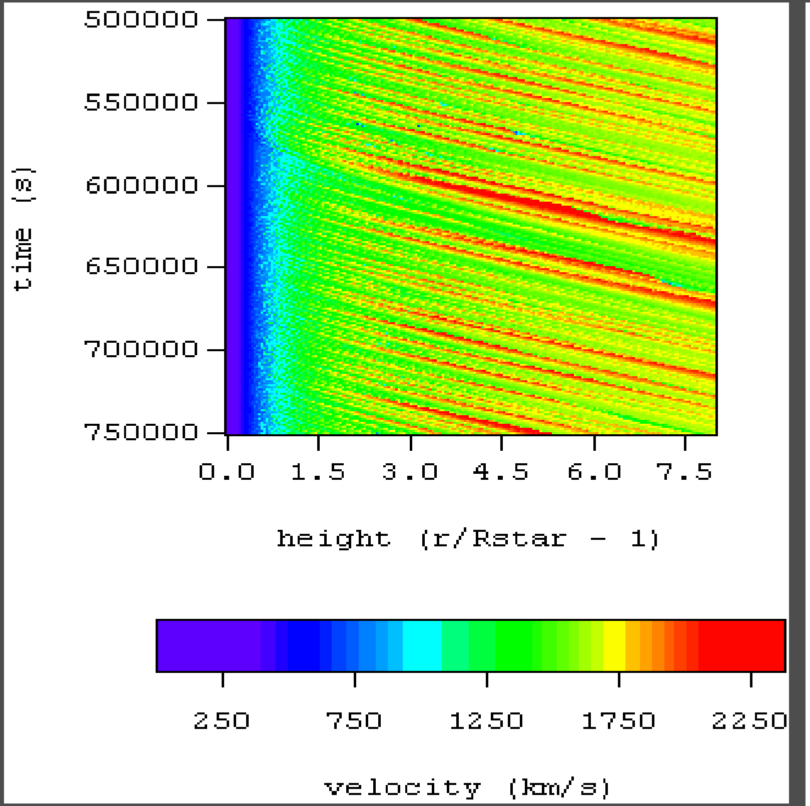
Young O stars have only modestly broad (few 100 km s^{-1}) X-ray emission lines

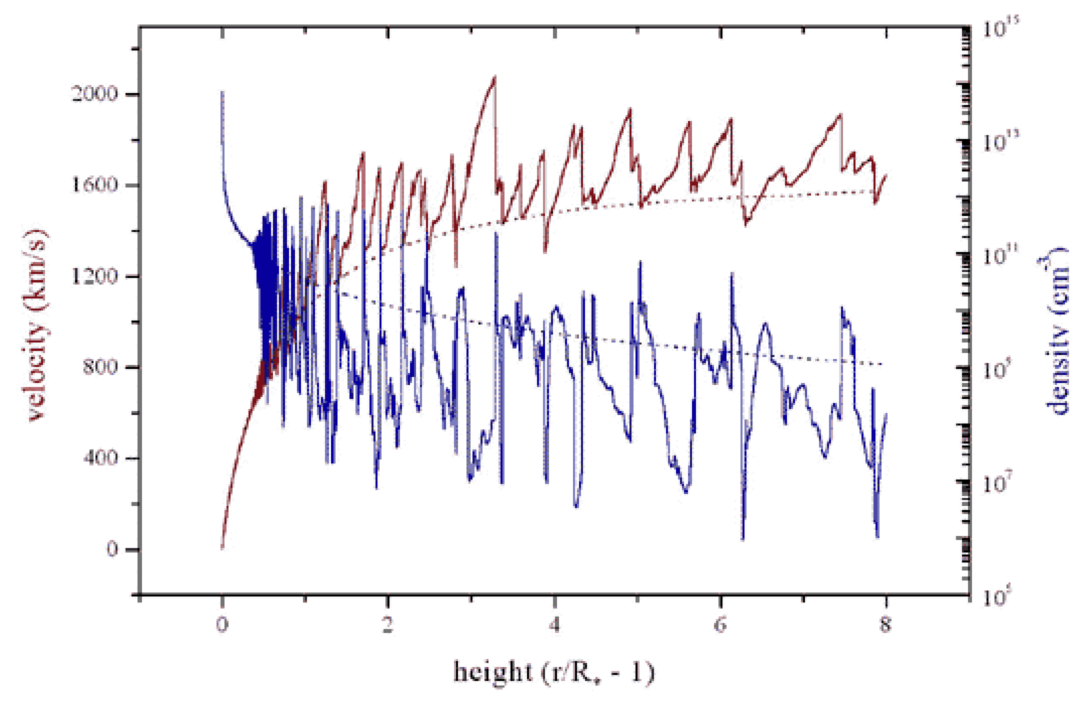


But **mature** O stars have broad (> 1000 km s^{-1}), asymmetric emission lines

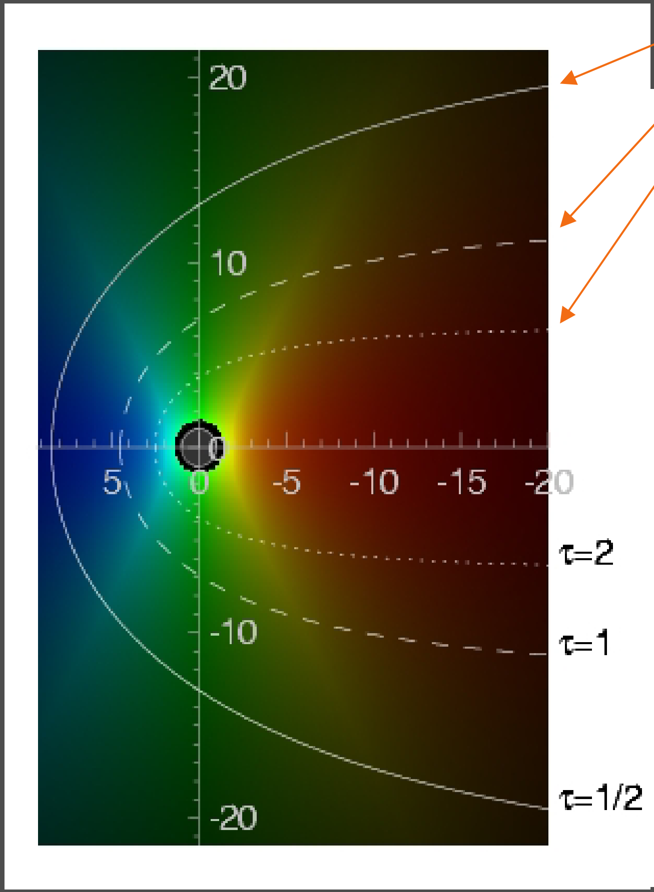
A **different** mechanism is responsible

1-D rad-hydro simulation of an O star wind

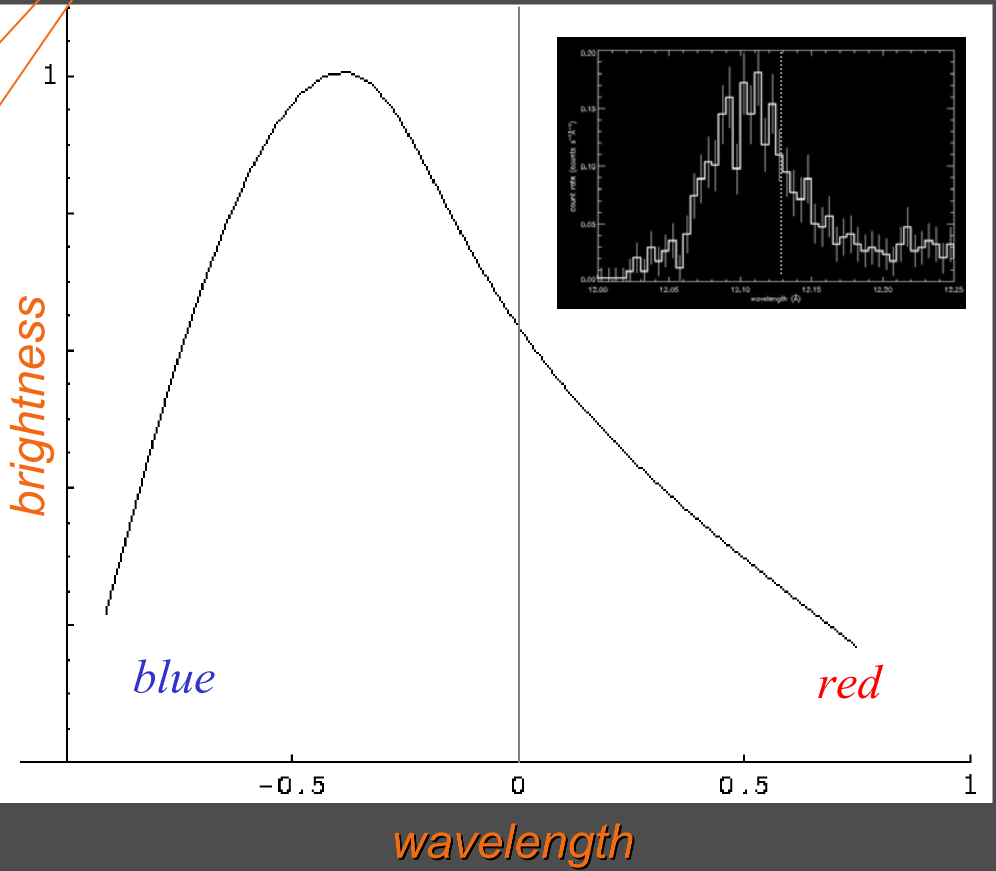




Radiation line driving is inherently unstable:
shock-heating and X-ray emission

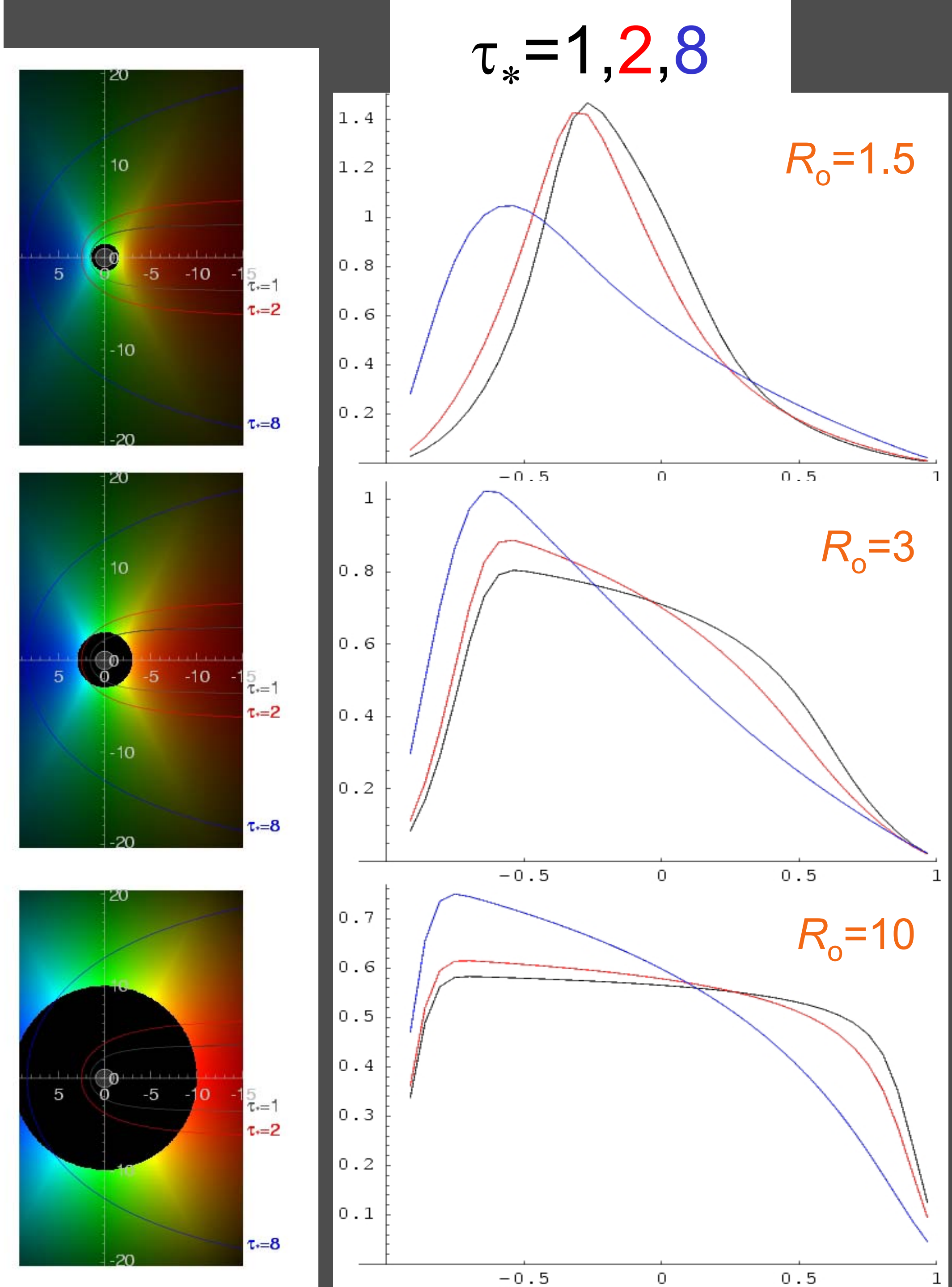


Contours of constant optical depth (observer is on the left)



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

The basic wind-profile model



key parameters: **R_o** & τ_*

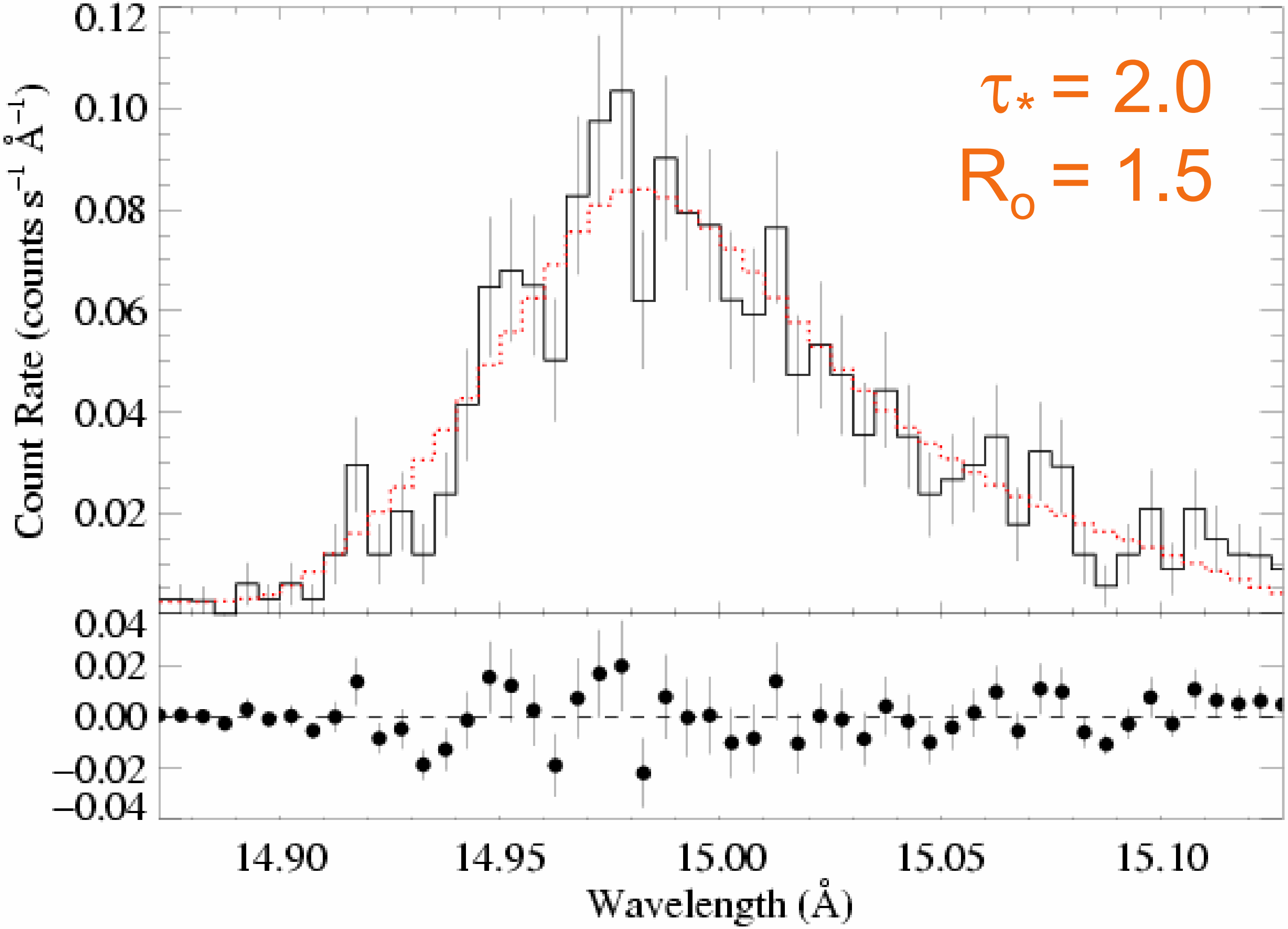
$j \sim \rho^2$ for $r/R_* > R_o$,

= 0 otherwise

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

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

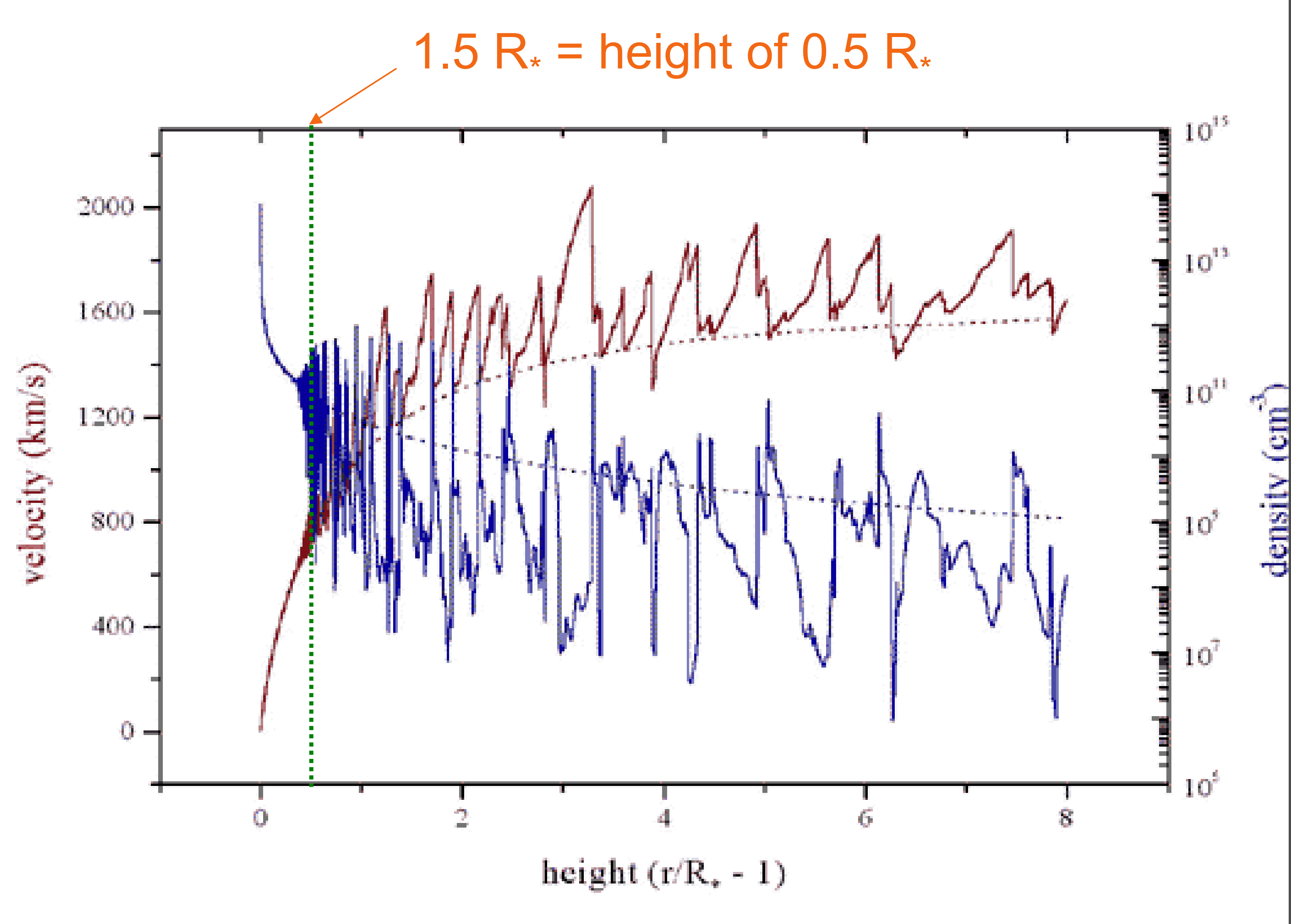
ζ Pup: Fe XVII line at 15.014 Å - *Chandra*



$\tau_* = 2.0$

$R_o = 1.5$

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



Wind optical depth constrains mass-loss rate

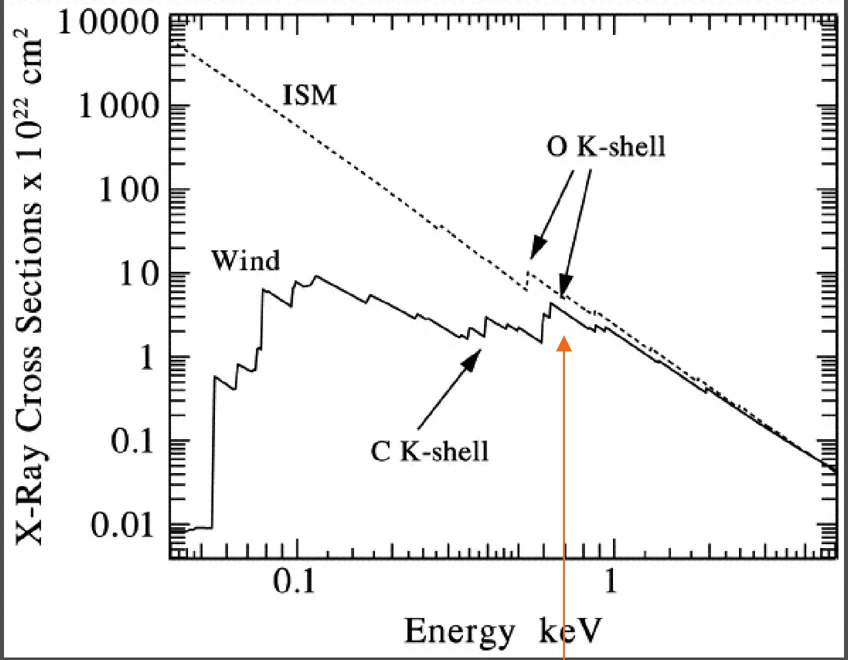
for $\tau_* = 2$

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

$$\tau_* = \frac{3.6\kappa_{150}\,\dot{M}_{-6}}{R_{12} v_{2000}}$$

$$\dot{M}_{-6} = \frac{\tau_* R_{12} v_{2000}}{3.6\kappa_{150}}$$

$1.5 \times 10^{-6}\ M_{sun}$/yr

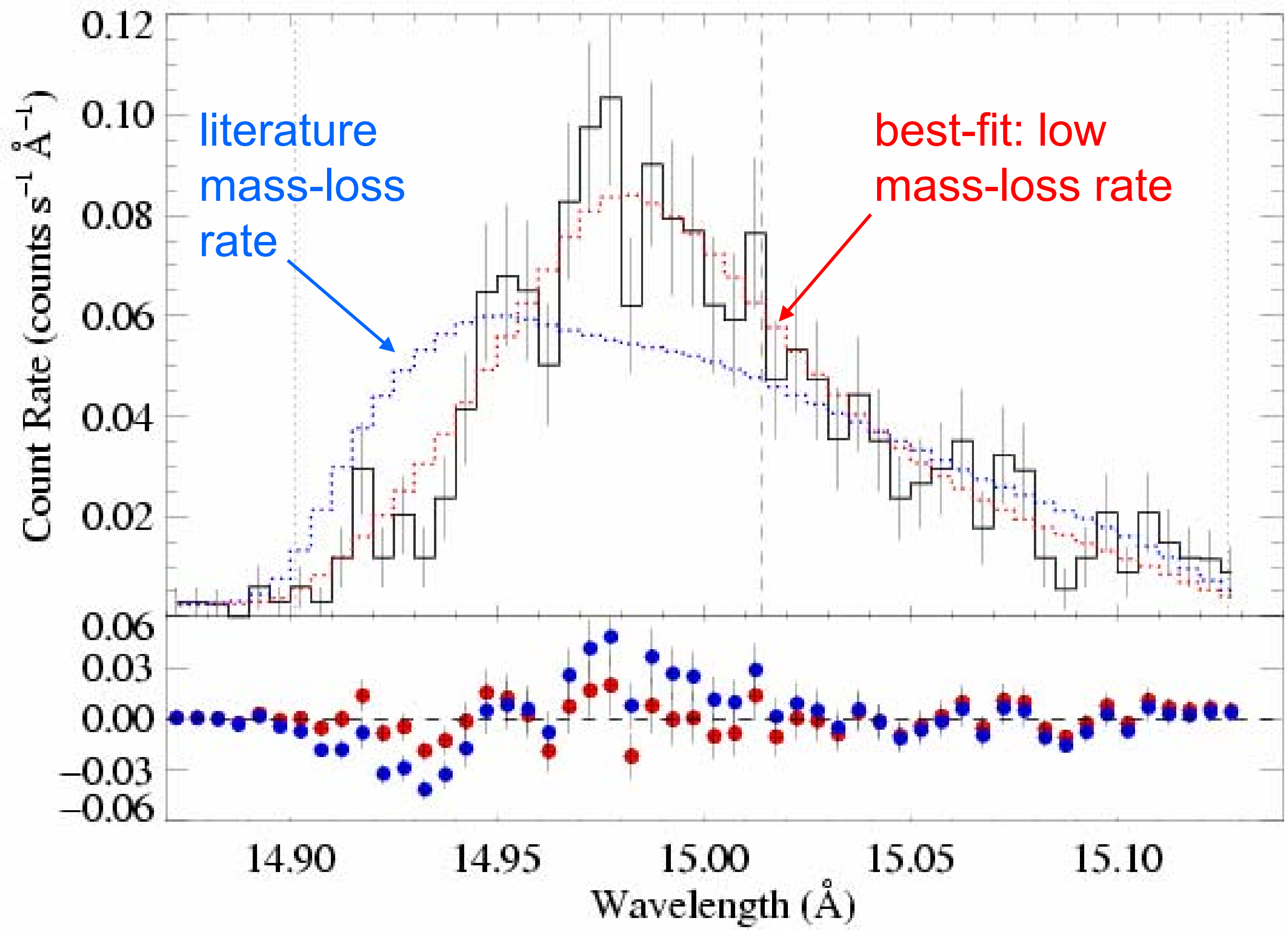


Waldron et al. (1998)

$\kappa \sim 70$ cm^2 g^{-1} @ 15 Å

A **factor of 4** reduction in mass-loss rate over the literature value of $6 \times 10^{-6}\ M_{sun}$/yr

ζ Pup: Fe XVII line at 15.014 Å - again

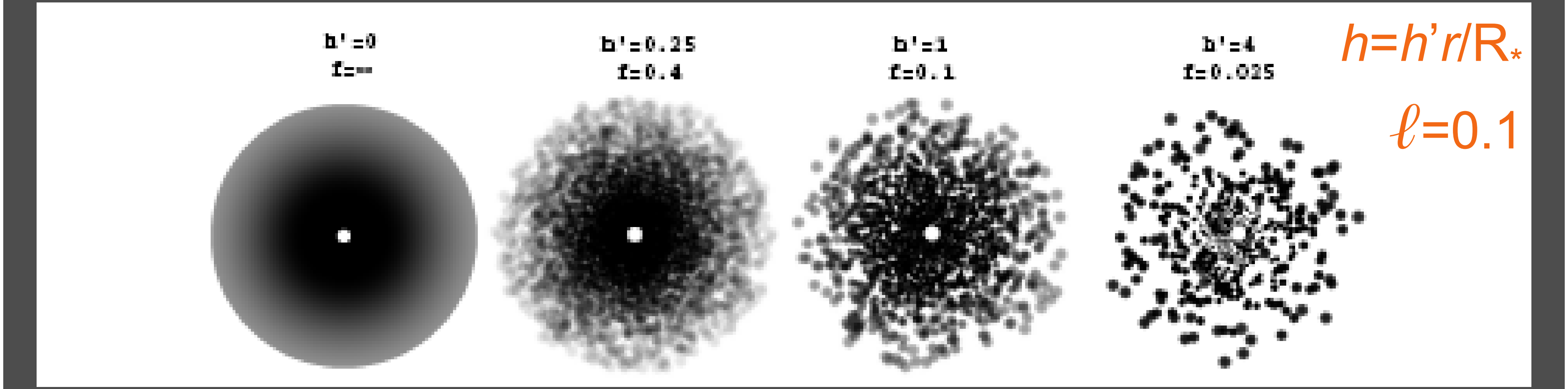


literature mass-loss rate

best-fit: low mass-loss rate

best-fit model, with $\tau_* = 2$, is preferred over the $\tau_* = 8$ model with >99.999% confidence

The **porosity** associated with a distribution of optically thick clumps acts to reduce the effective opacity of the wind



$h = h' r / R_*$

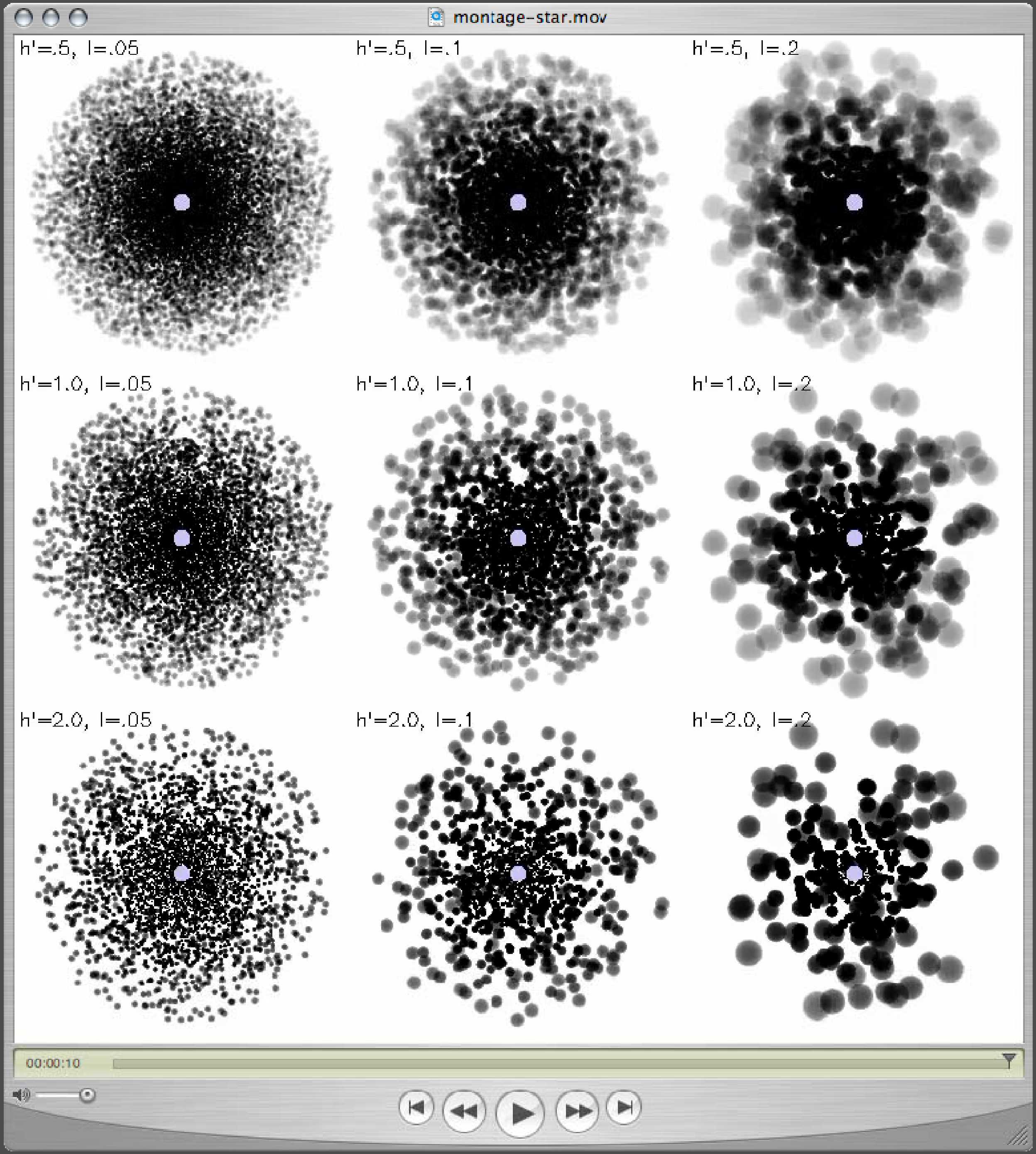
$\ell = 0.1$

Owocki & Cohen (2006)

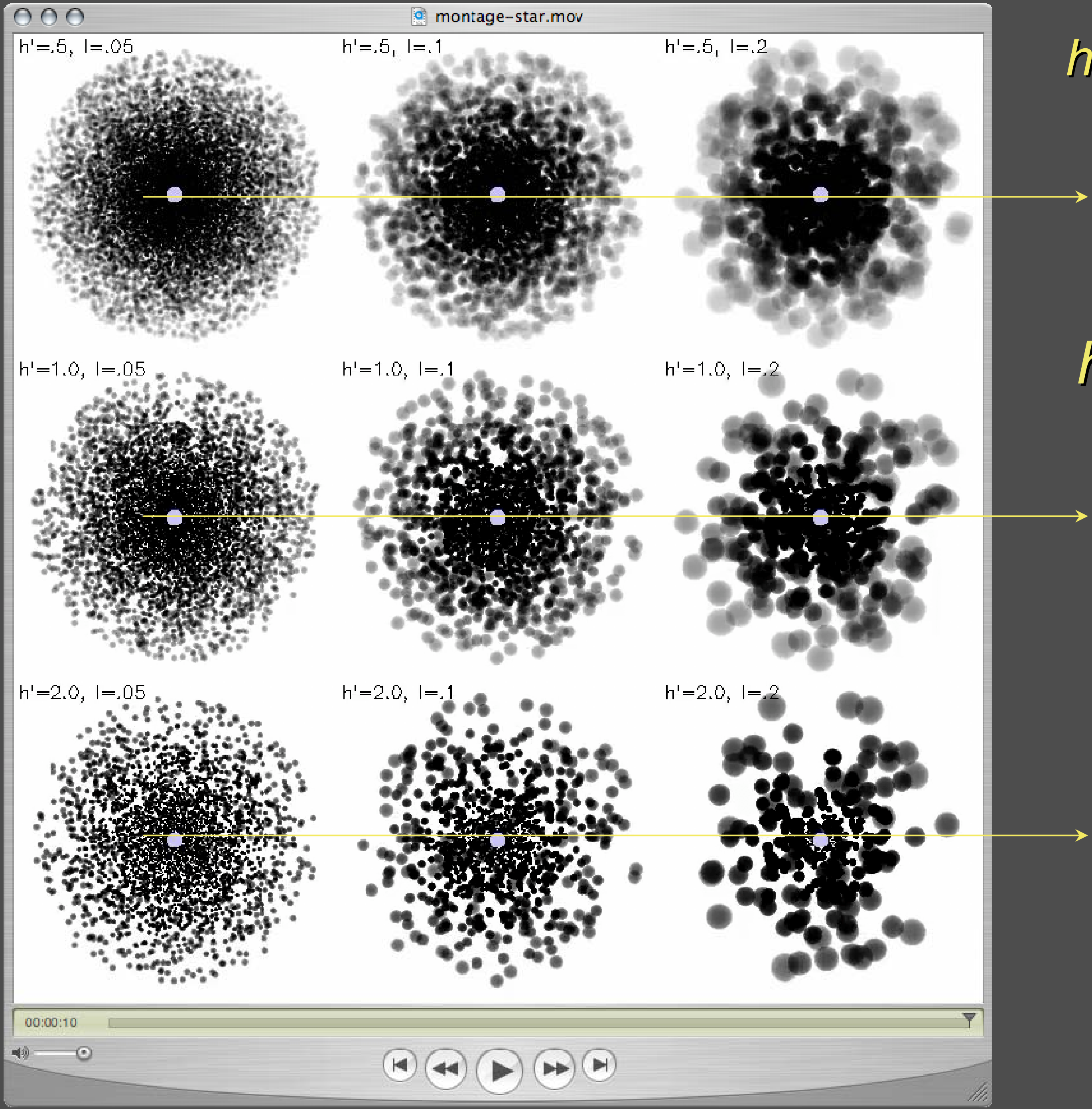
The key parameter is the **porosity length**,

$$h = (L^3/\ell^2) = \ell / f$$

Porosity reduces the effective wind optical depth once ***h*** becomes comparable to r/R_*



$$h = (L^3/\ell^2) = \ell/f$$



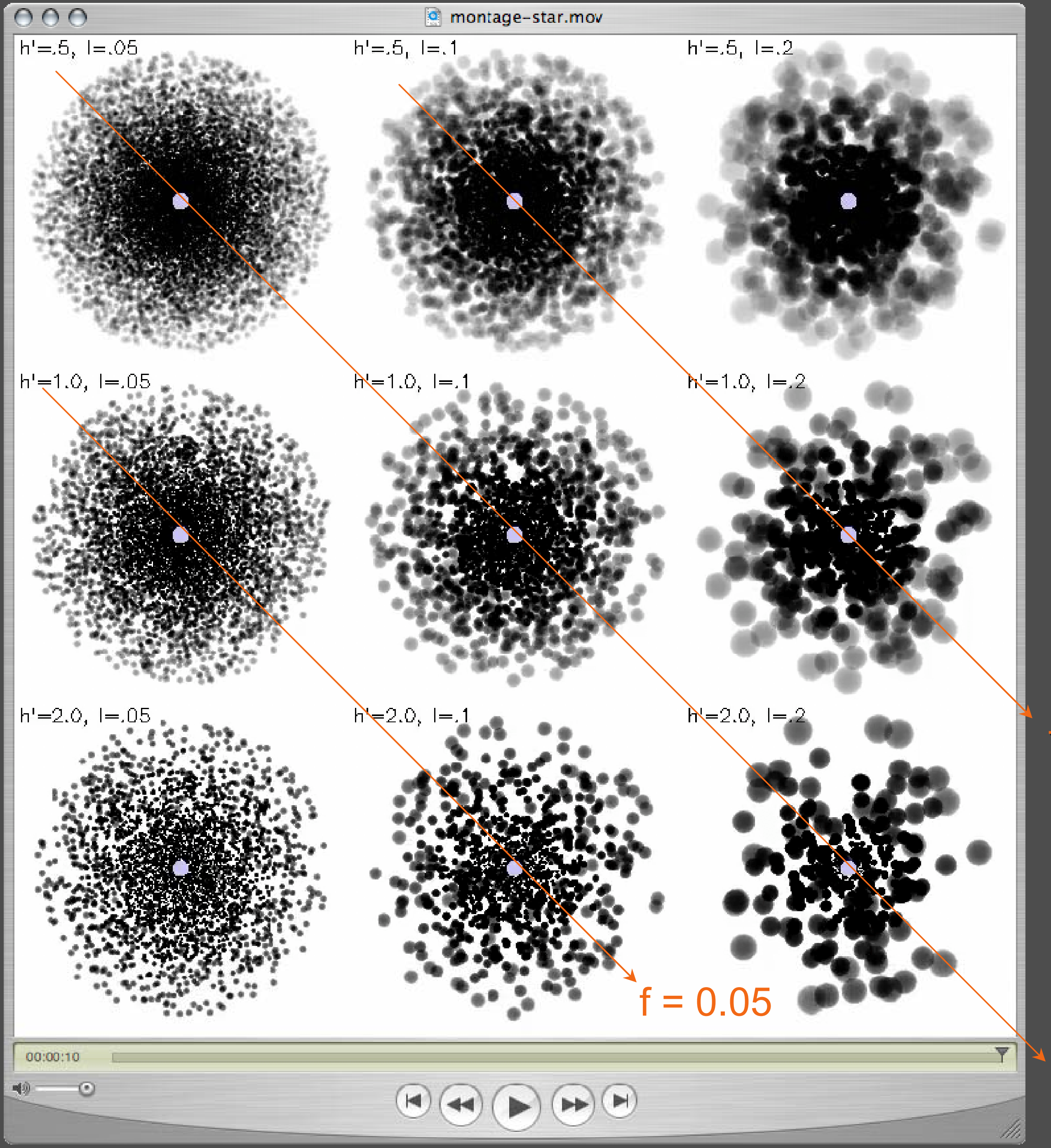
$h = h'r$

$h' = 0.5$

$$h = (L^3/\ell^2) = \ell/f$$

$h' = 1.0$

$h' = 2.0$



f = 0.2

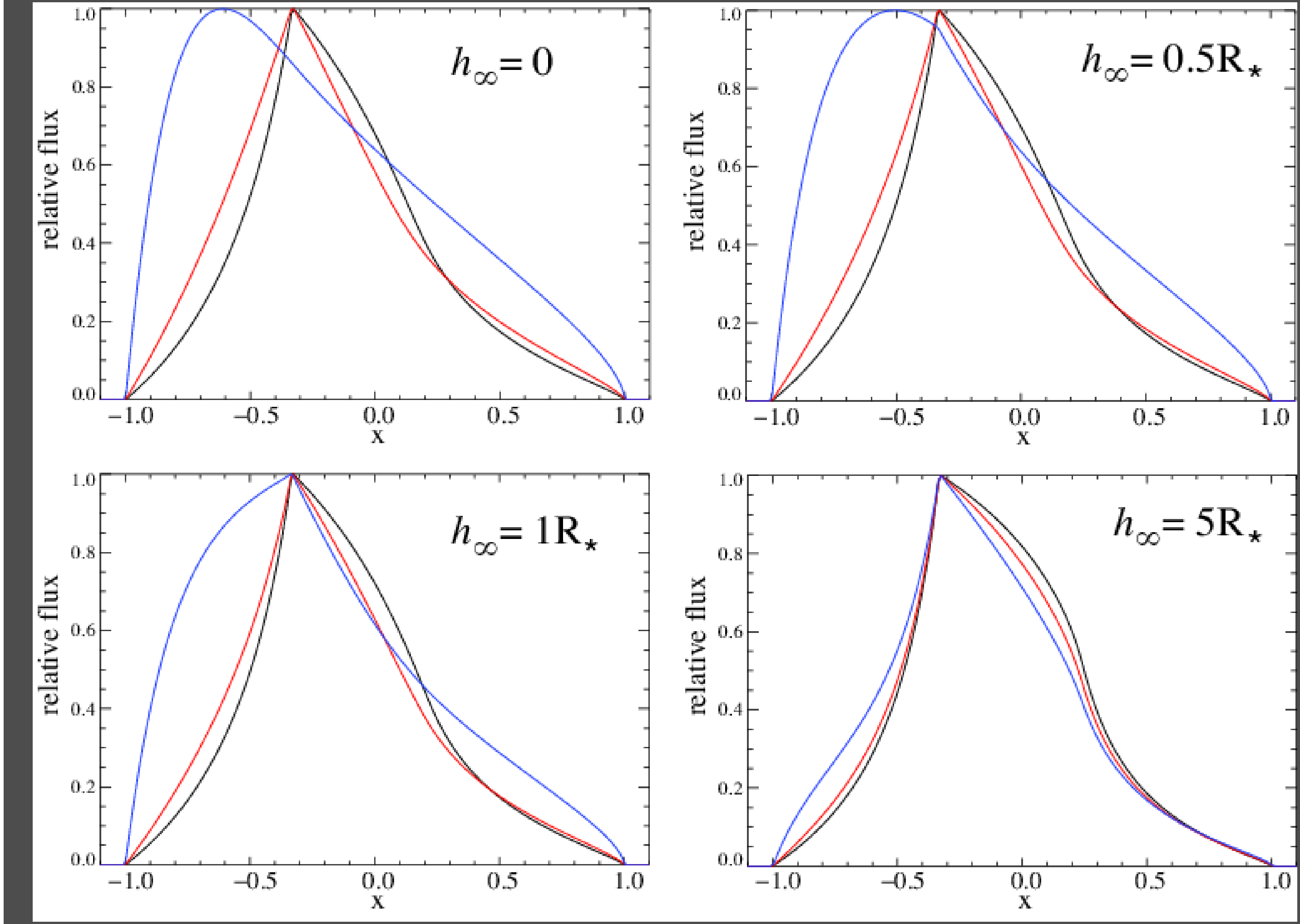
f = 0.05

f = 0.1

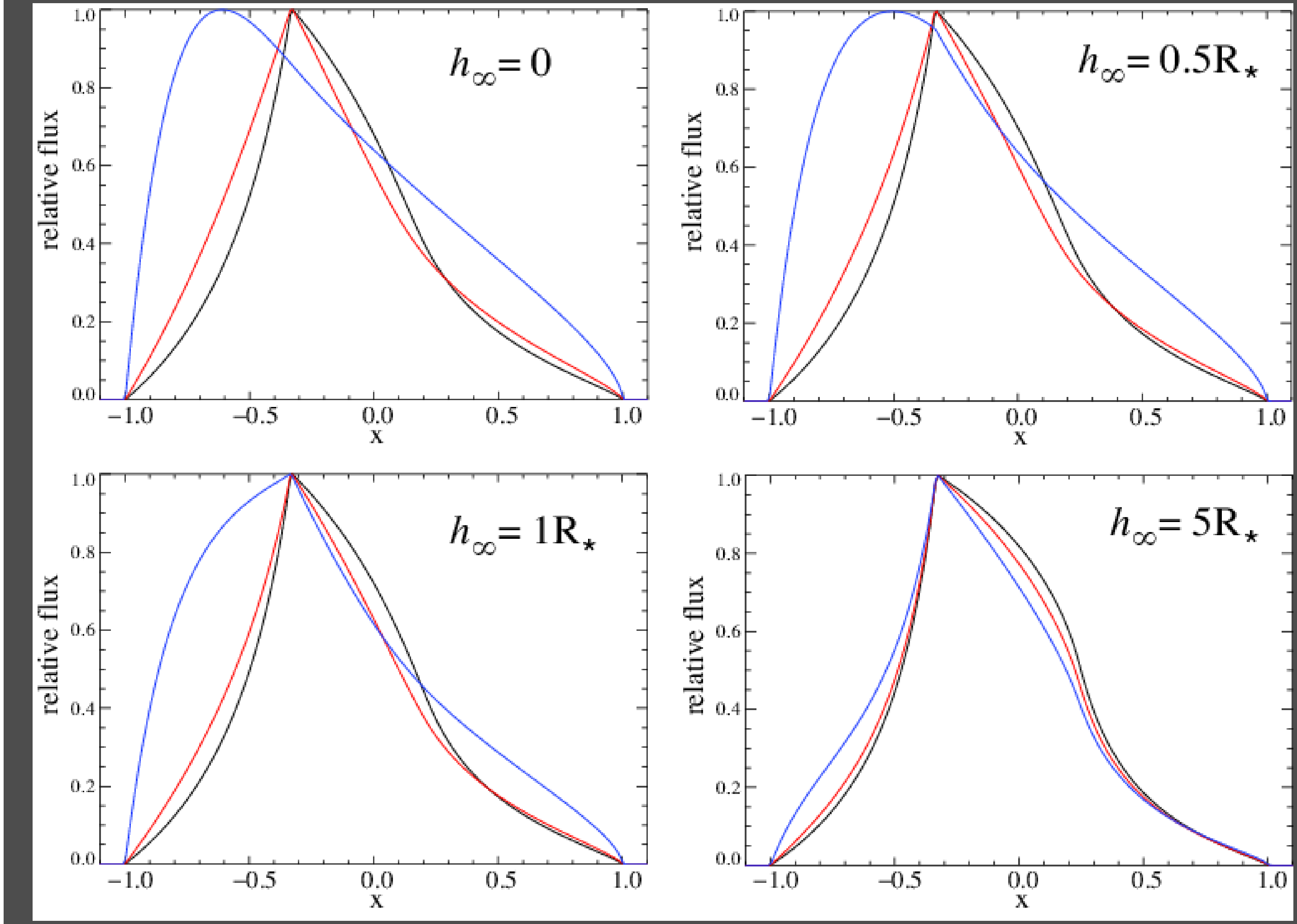
$$h = (L^3/\ell^2) = \ell/f$$

The optical depth integral is modified according to the clumping-induced effective opacity:

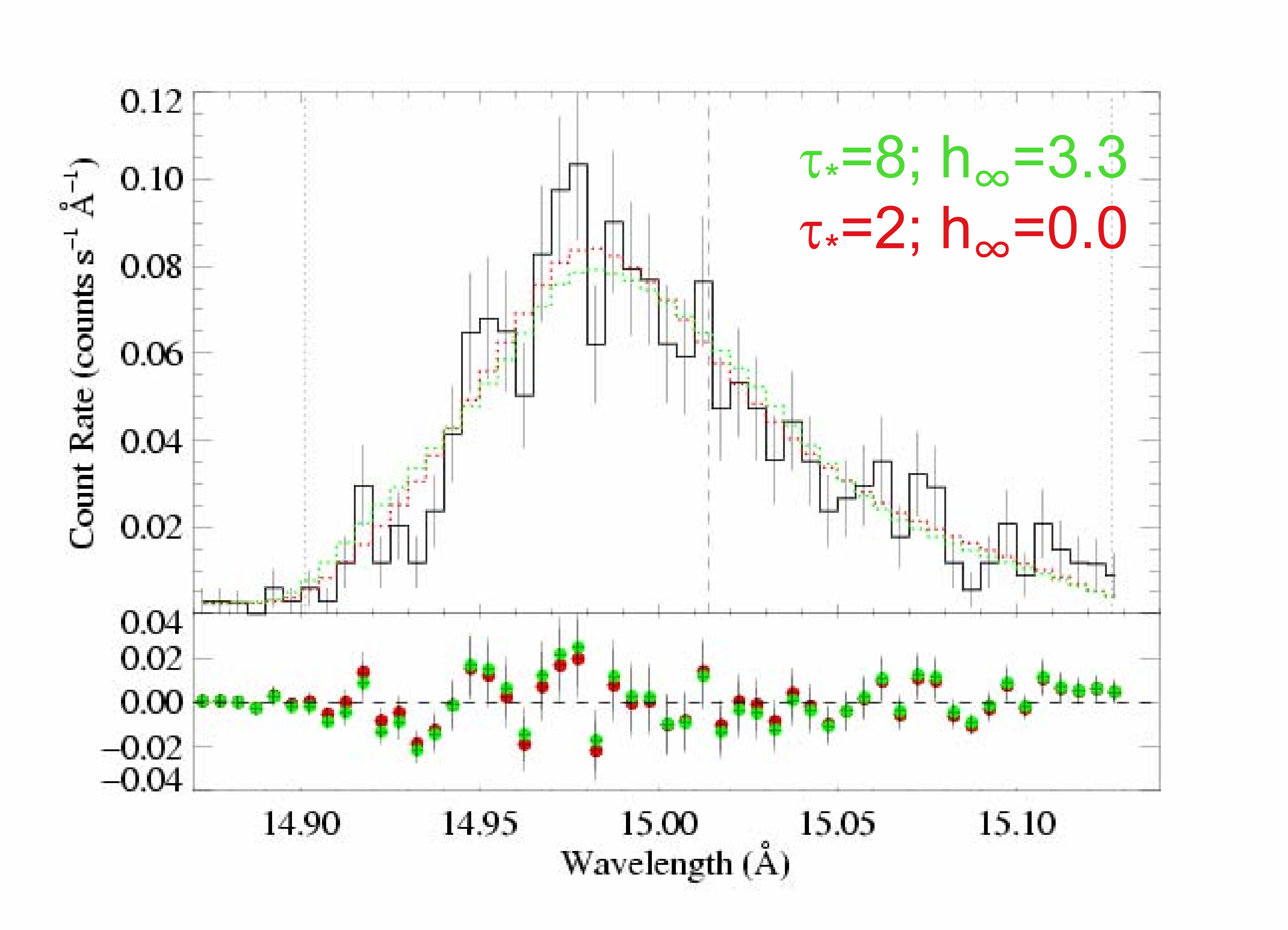
$$\kappa_{eff} = \frac{\kappa\left(1 - e^{-\tau_c}\right)}{\tau_c}$$



Porosity only affects line profiles if the porosity length (*h*) exceeds the stellar radius

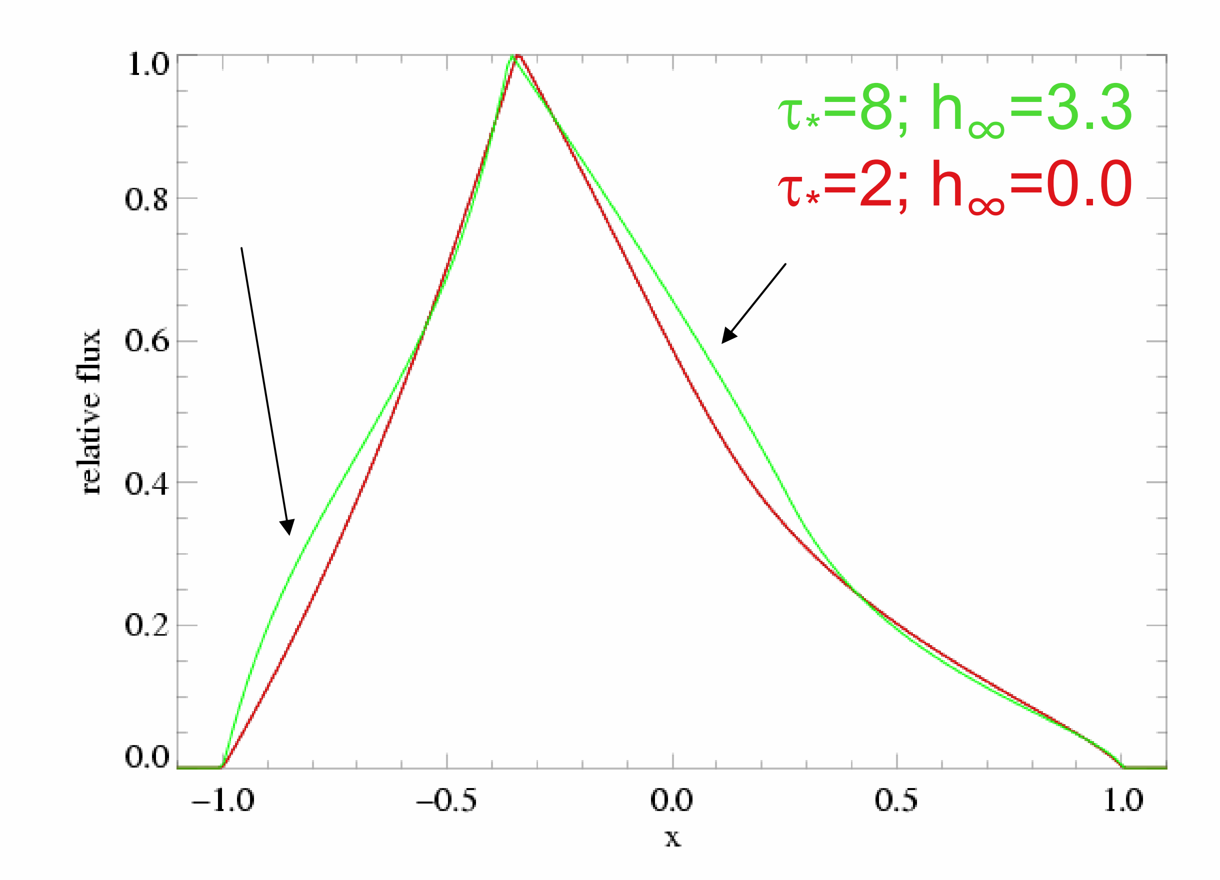


The *Chandra* line profiles in ζ Pup can be fit by a porous model…



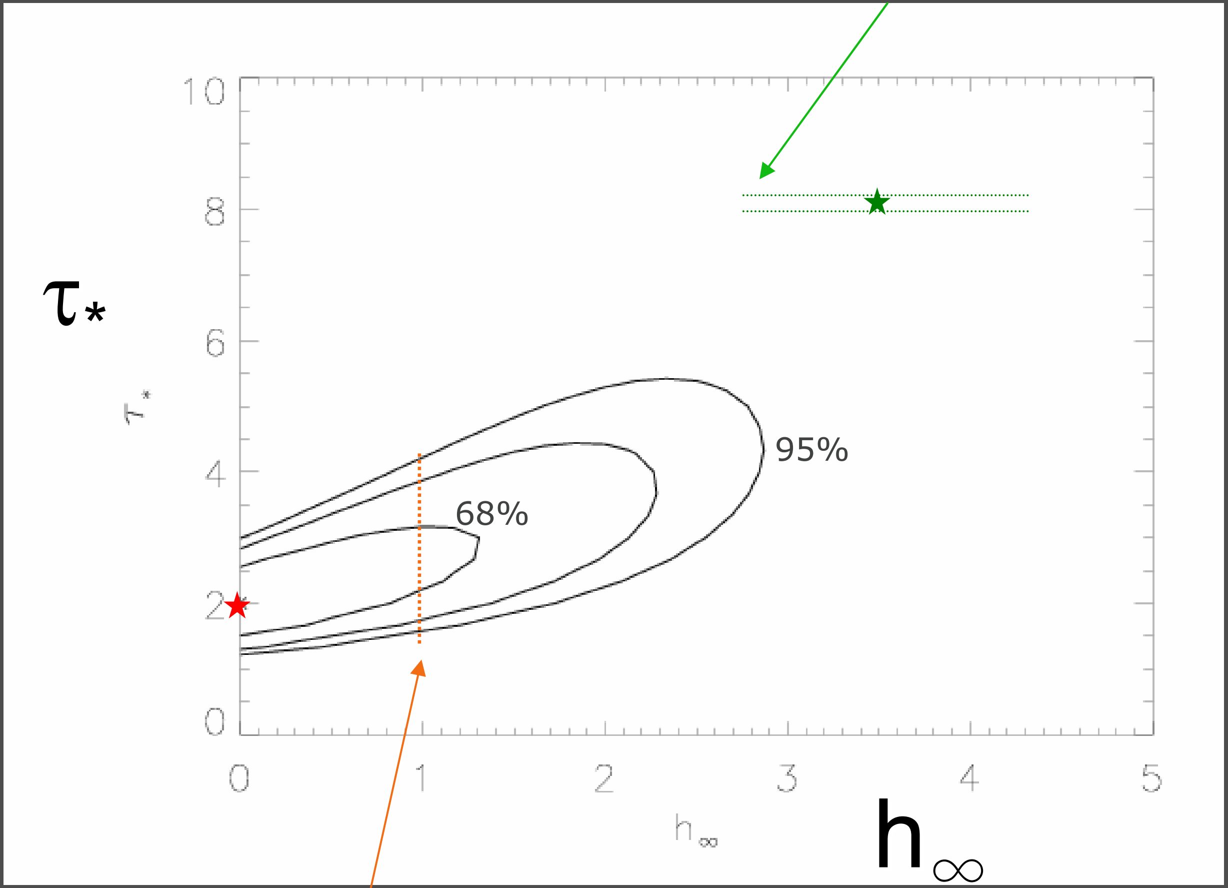
…but **huge** porosity lengths are required and the fits tend to be worse

Two models from previous slide, but with *perfect resolution*



Joint constraints on τ_* and h_∞

$h_\infty > 2.5$ is required if you want to “rescue” the literature mass-loss rate



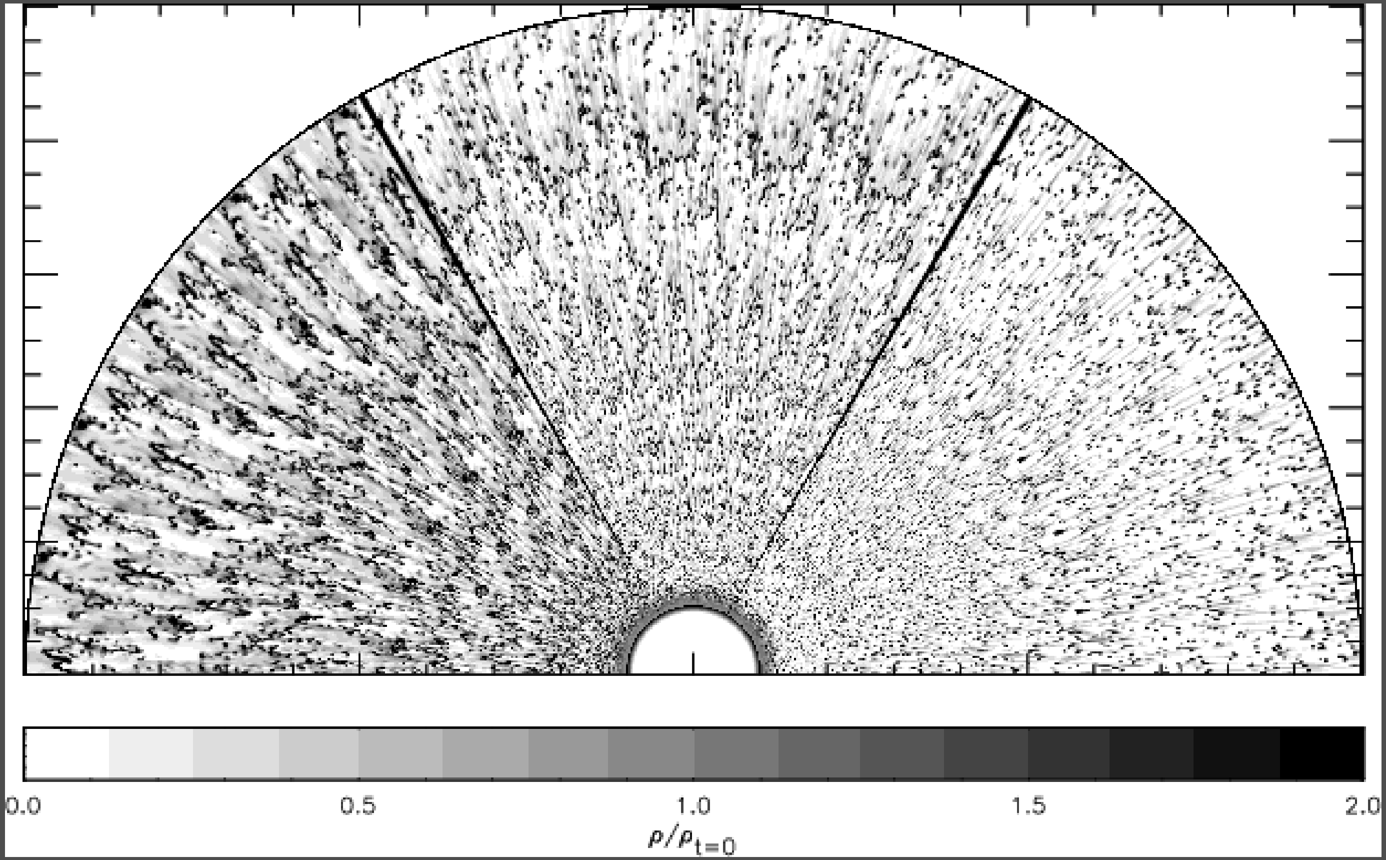
Even a model with h_∞=1 only allows for a slightly larger τ_* and, hence, mass-loss rate

There is NO evidence from X-ray line profiles for significant wind porosity

However, the profiles indicate reduced mass-loss rates, which imply significant small-scale clumping (*f* ~ 0.1)

The required degree of porosity is ***not*** expected from the line-driven instability.

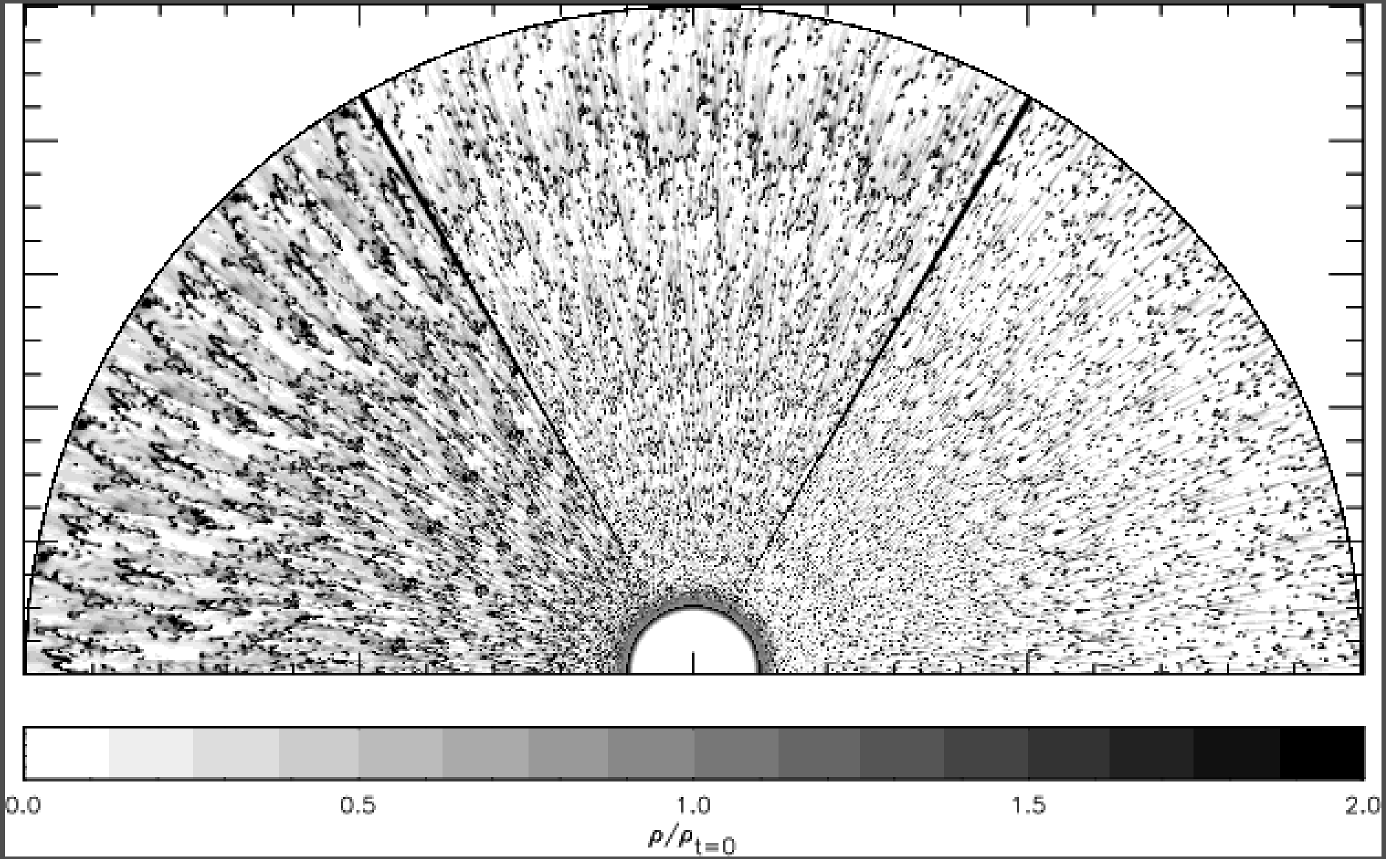
The clumping in 2-D simulations (below) is on quite *small scales*.



Dessart & Owocki 2003, *A&A*, 406, L1

The small-scale clumps affect density squared diagnostics: reduced mass-loss rates

But they do not affect the X-ray profiles directly



Dessart & Owocki 2003, *A&A*, 406, L1

Conclusions

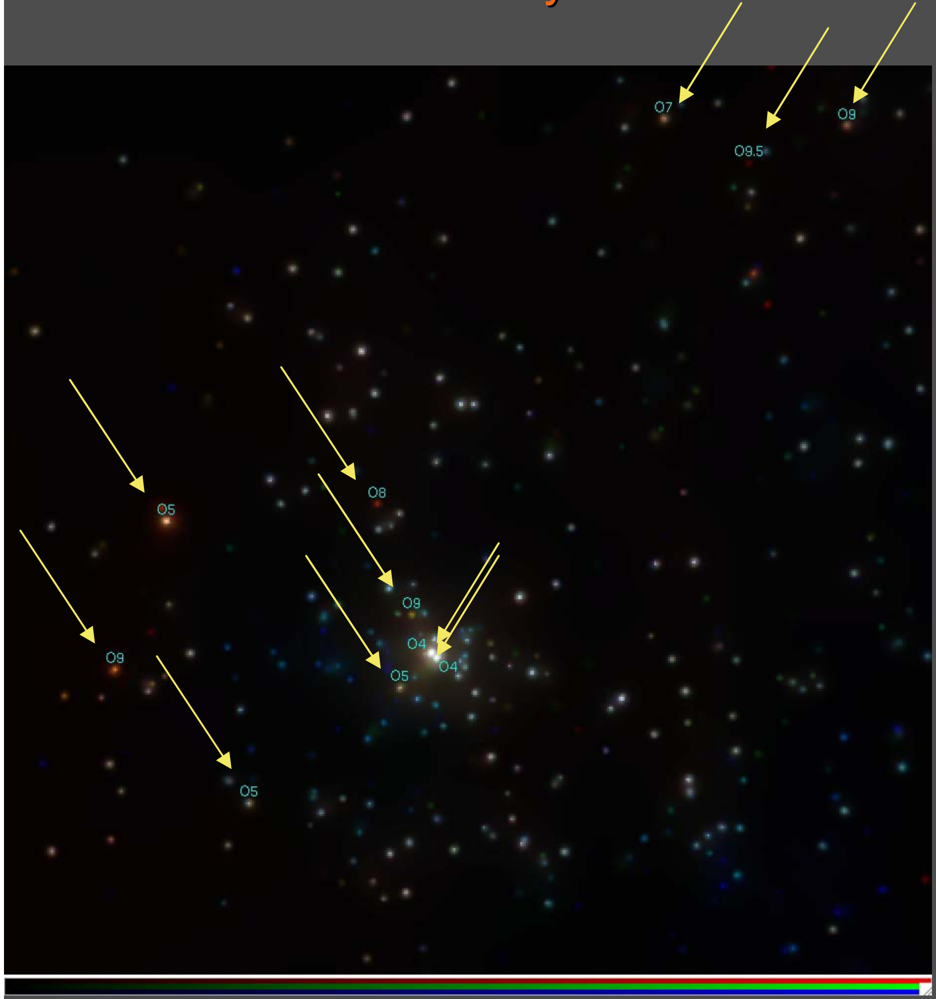
Many young (< 1Myr) O stars produce strong and hard X-ray emission in their magnetically channeled winds

As they age, softer and weaker X-ray emission is produced via embedded wind shocks in a spherically expanding wind

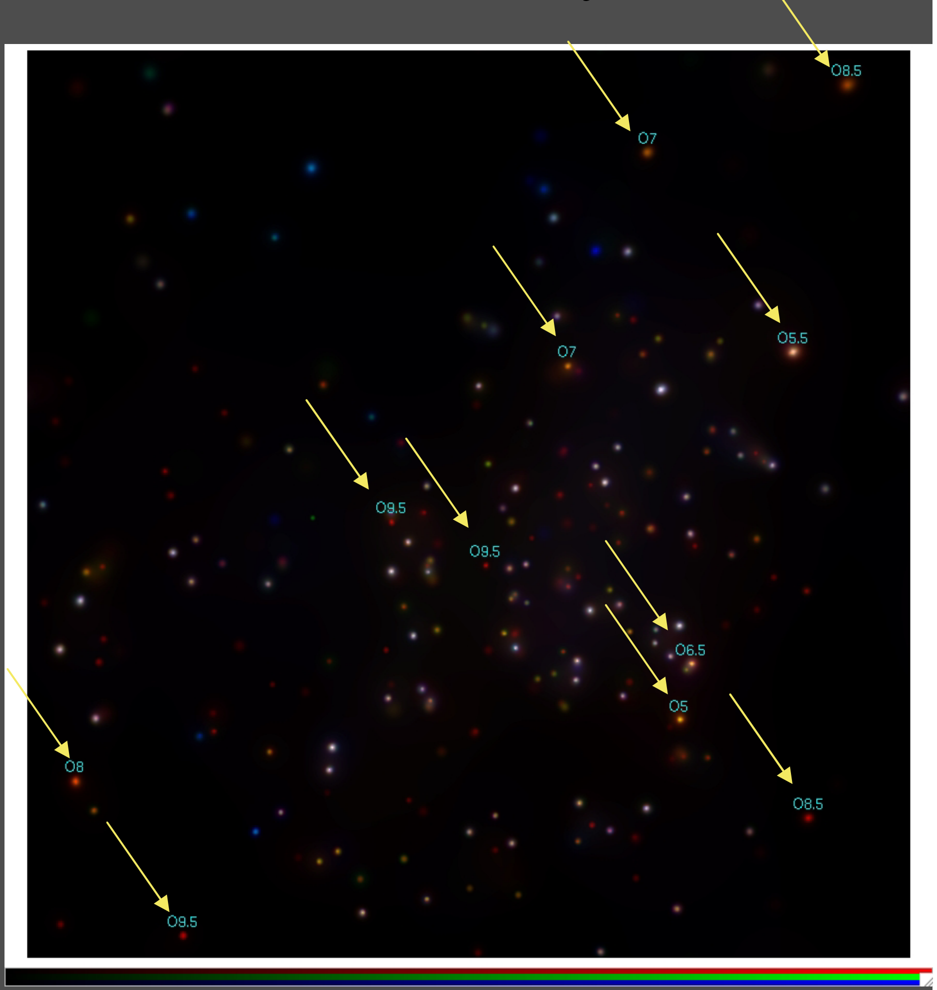
The X-rays themselves provide information about the wind conditions of O stars, including more evidence for reduced mass-loss rates

Chandra images – evolution of X-ray hardness

M17: ~0.5Myr



NGC 6611: ~5Myr



courtesy Marc Gagné

soft medium hard