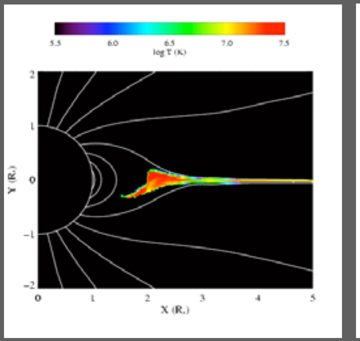
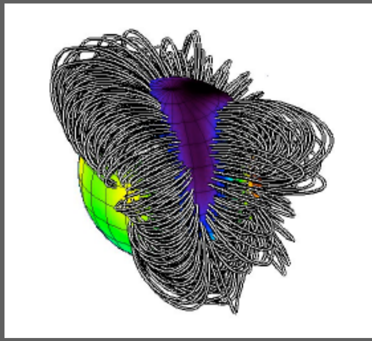
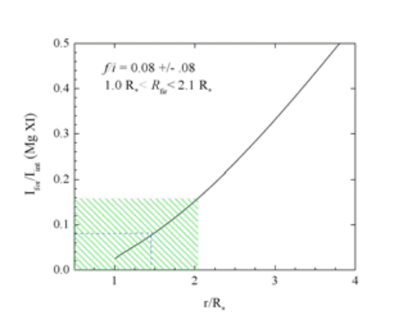
X-rays from Magnetically Channeled Winds of OB Stars

David Cohen

Swarthmore College

with M. Gagné, S. St. Vincent, A. ud-Doula, S. Owocki, R. Townsend

What can X-rays do for us?

Identify embedded, active young OB stars

Can they discriminate magnetic sources from non-magnetic ones?

Diagnostics of the properties of the hot ($>10^6$ K) plasma in the extended atmospheres of magnetic OB stars

(Somewhat) passive probe of cooler circumstellar material

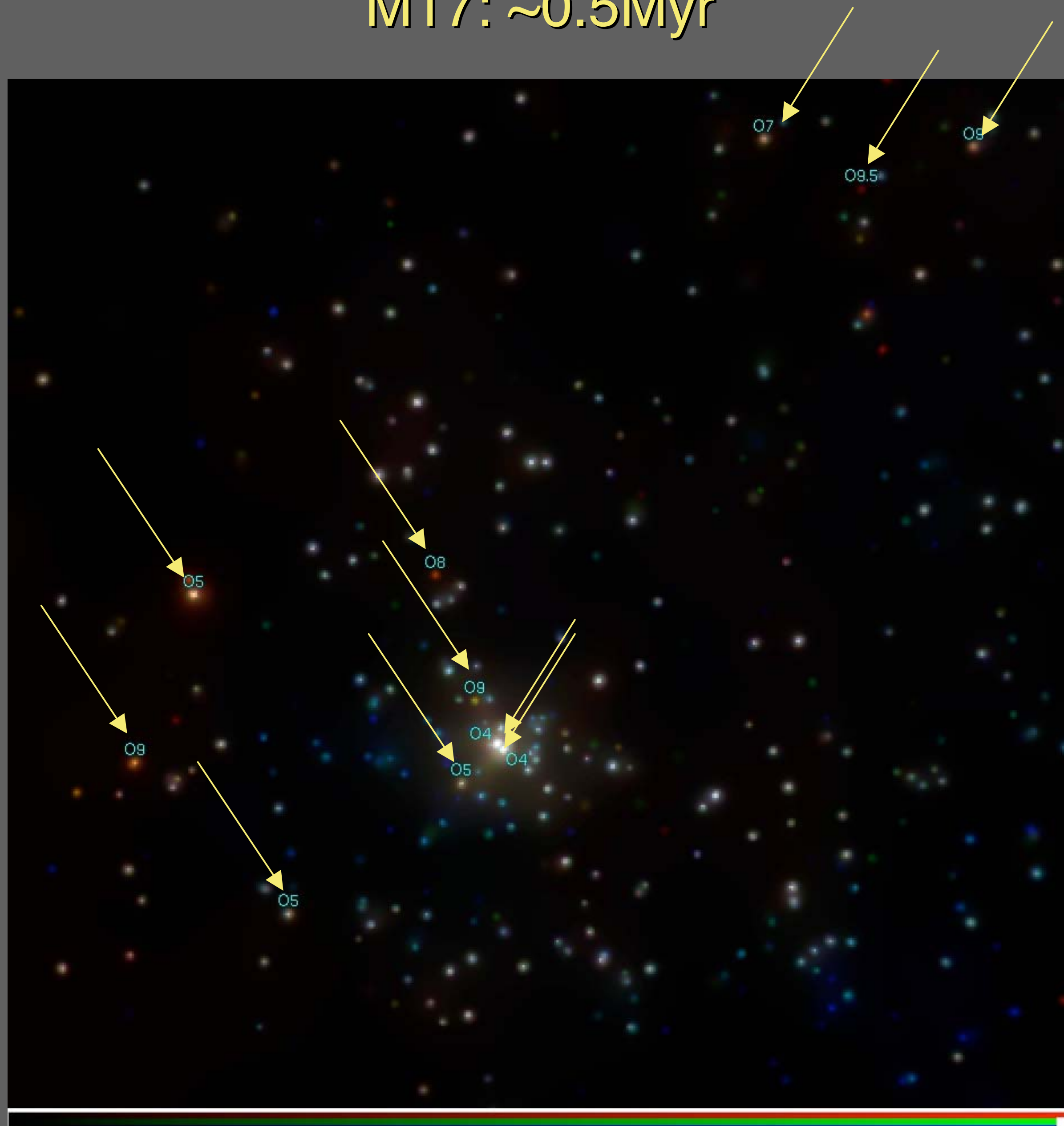
Outline

Context

θ^1 Ori C and the MCWS mechanism

Other applications of MCWS and X-rays

M17: ~0.5Myr



soft

medium

hard

courtesy M. Gagné

4′

Orion Nebula Cluster: ~1Myr

dashed arrows point to very early B stars

courtesy M. Gagné

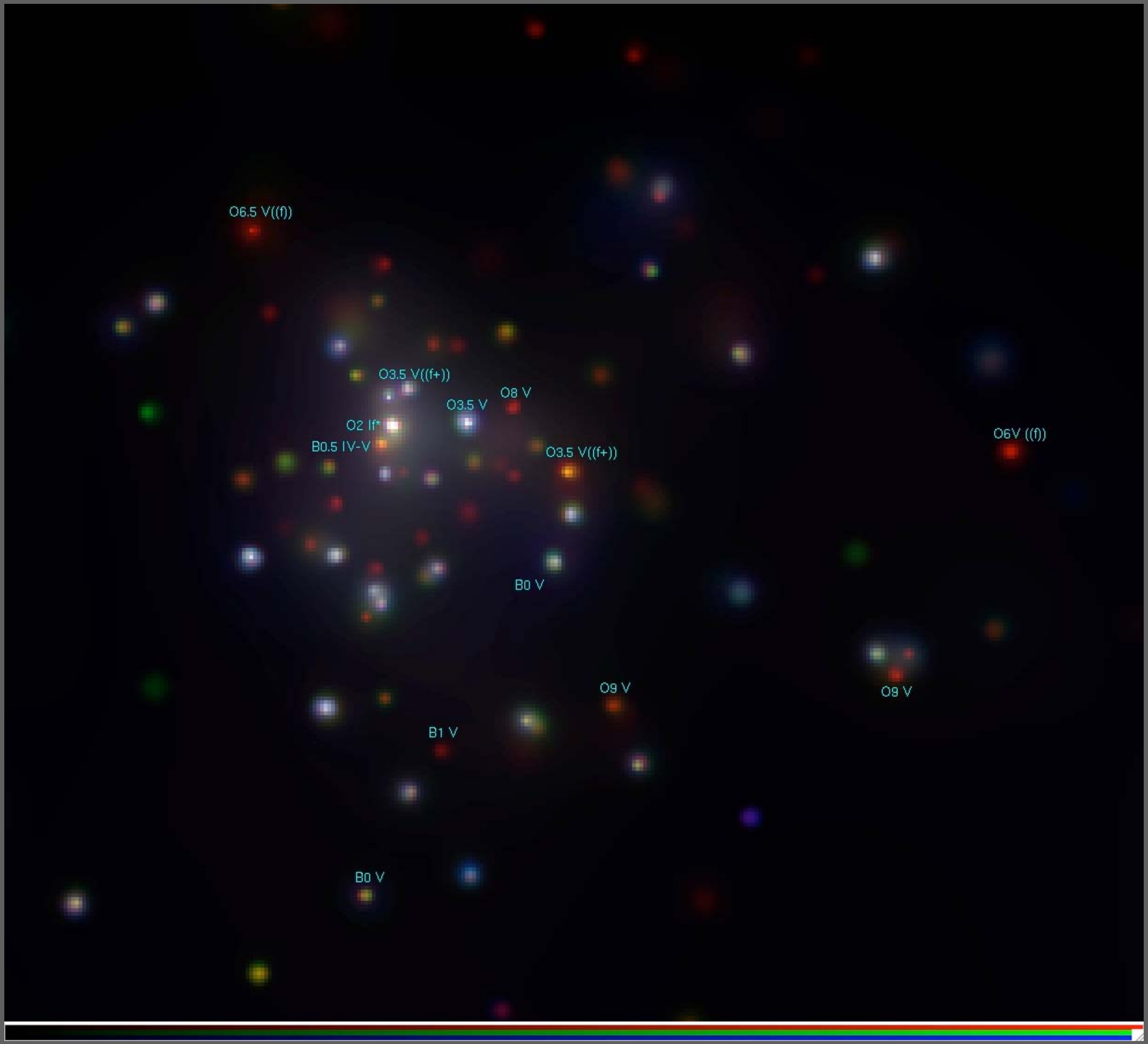
4′

soft

medium

hard

Tr 14: ~0.5 - 2 Myr



soft

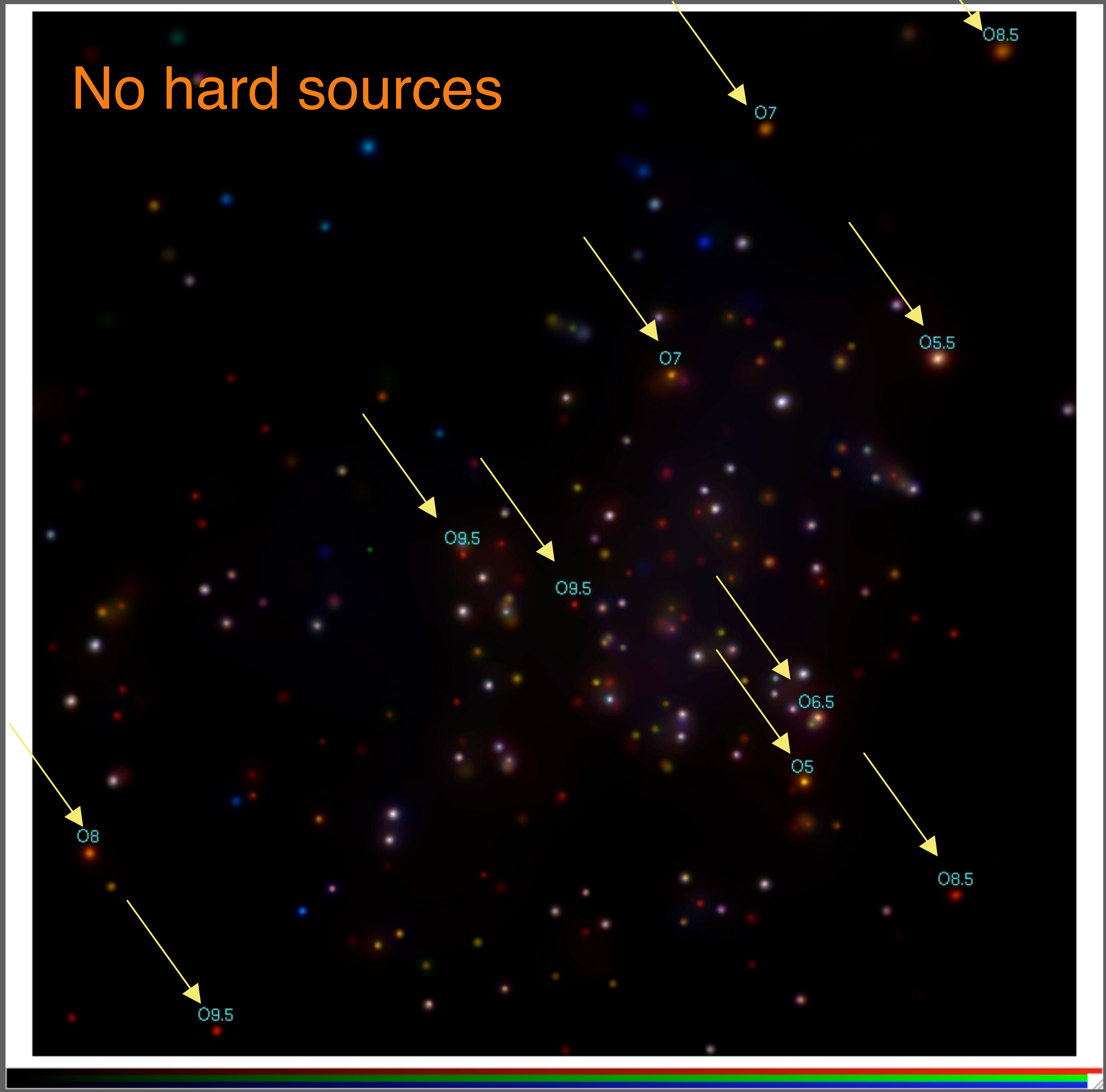
medium

hard

courtesy M. Gagné

4′

NGC 6611: ~5Myr



soft

medium

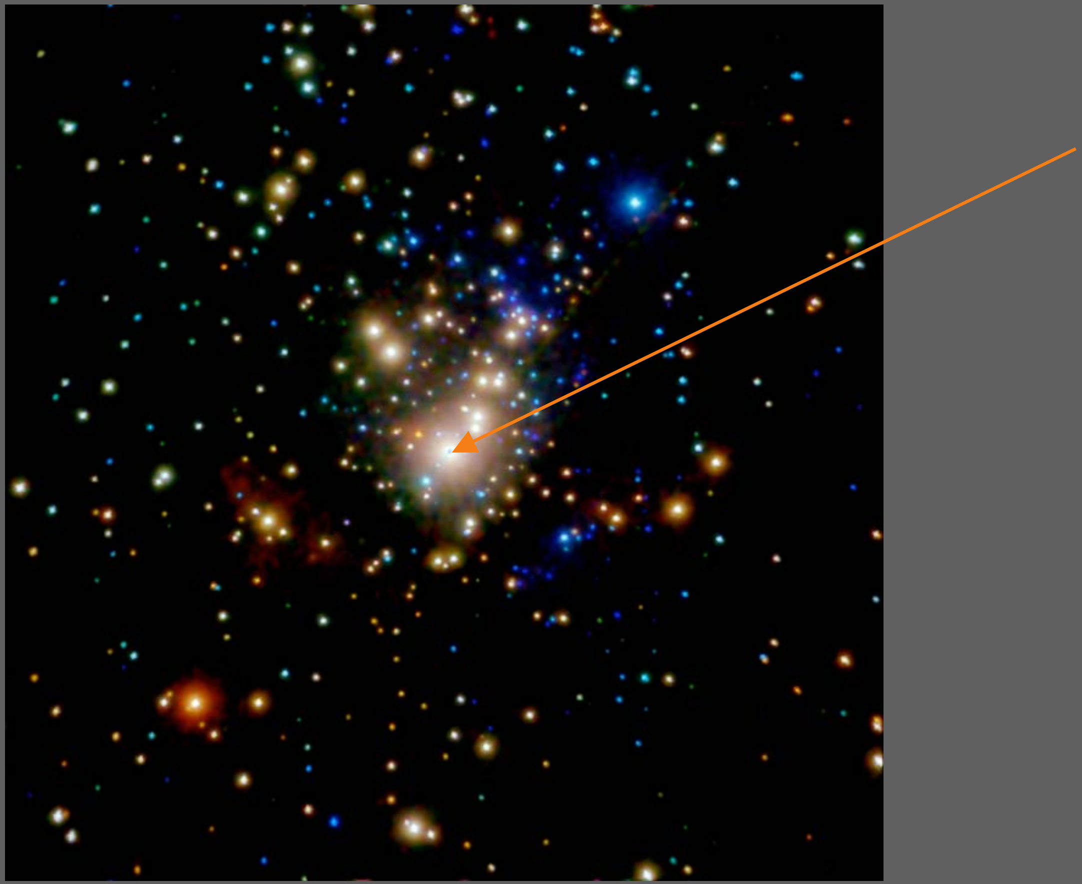
hard

courtesy M. Gagné

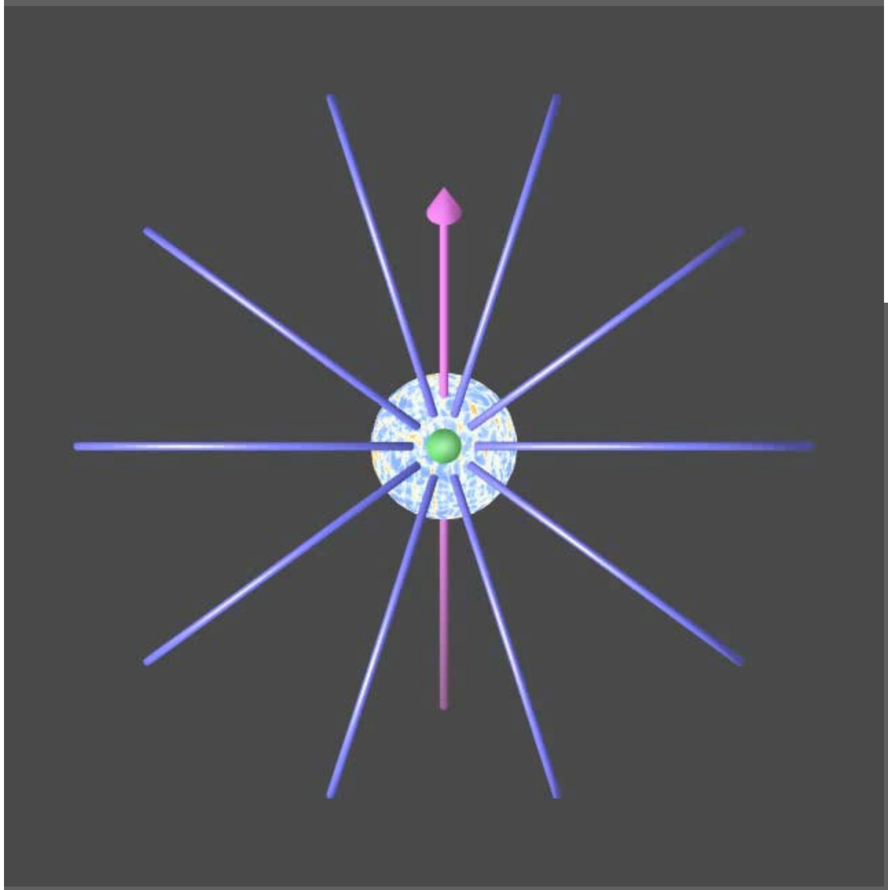
7′

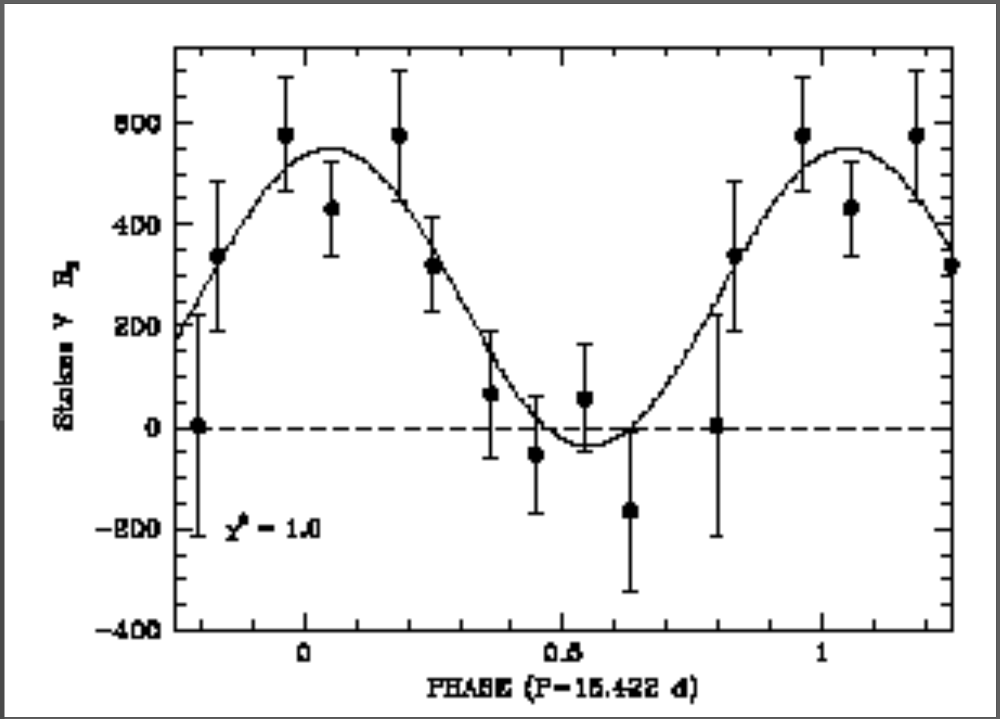
What's happened to the hard, variable O stars by 5 Myr?

Let's focus on one well-understood magnetic hot star: θ^1 Ori C



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





Wade et al. (2006)

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

Babel and Montmerle (1997a,b)

Channeling, confinement, shock-heating

Steady state? Cooling disk?

Insights such as centrifugal acceleration

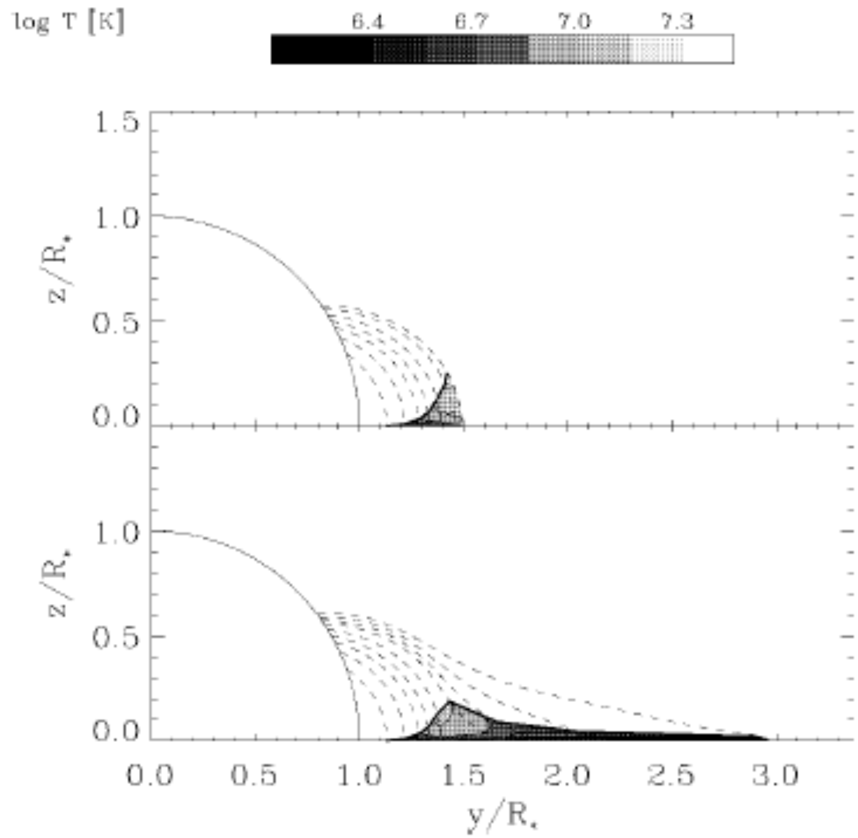
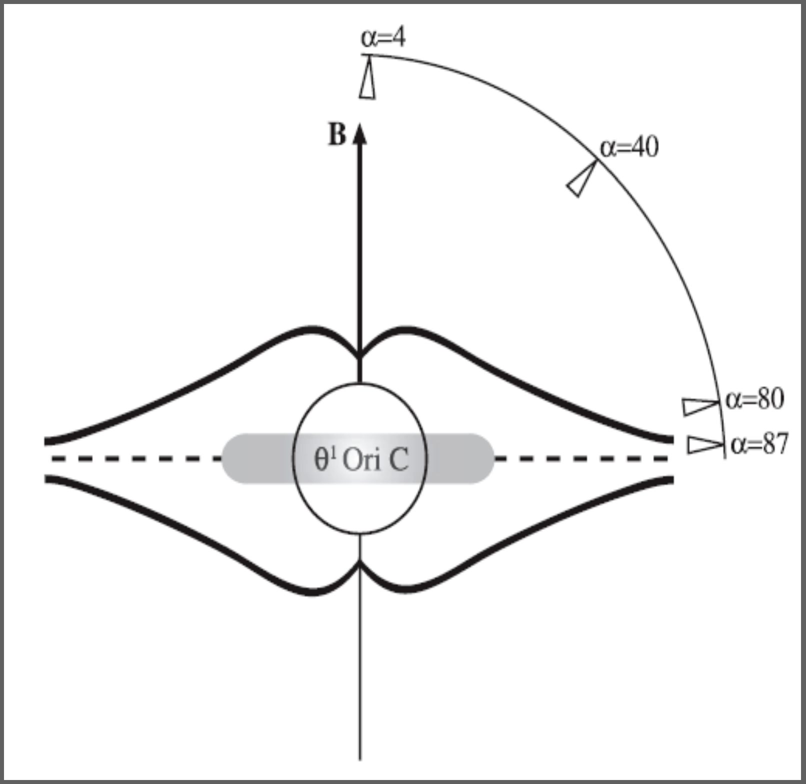
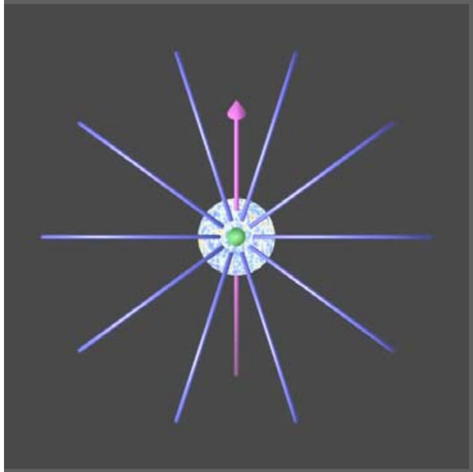


FIG. 1.—Temperature map for the postshock region in the approximation of a steady-state shock. The shock front is indicated by a heavy solid line and wind trajectories (or magnetic field lines) by dashed lines. *Upper panel:* closed magnetosphere, $L_A = 1.49$ ($B_*^c \simeq 370$ G). *Lower panel:* closed and open magnetosphere, $L_A = 1.39$ ($B_*^c \simeq 300$ G).

Fortuitous access to all viewing angles of the magnetic field

Cartoon showing viewing angles of θ[1] Ori C for *Chandra* observations. Phase 0 is when the disk is viewed face-on (α=4 deg), while phase 0.5 occurs when the disk is viewed edge-on (α=87 deg)

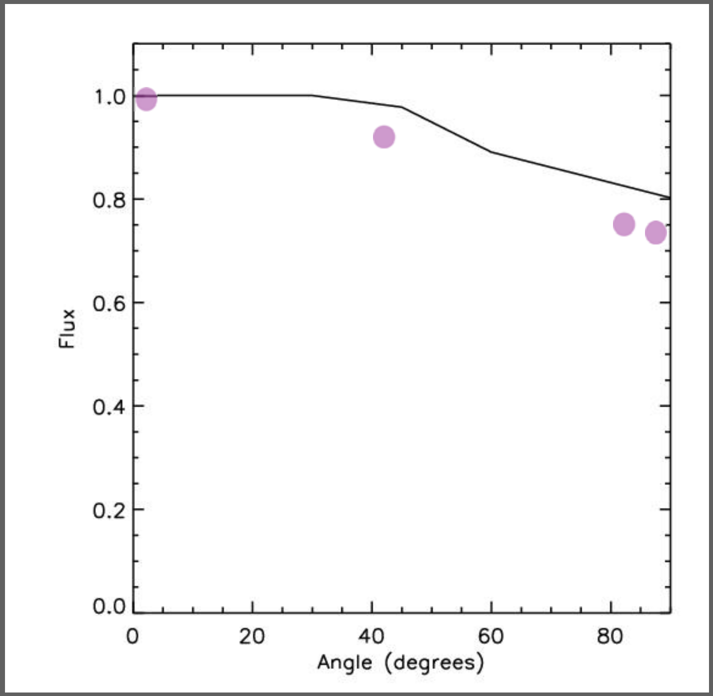


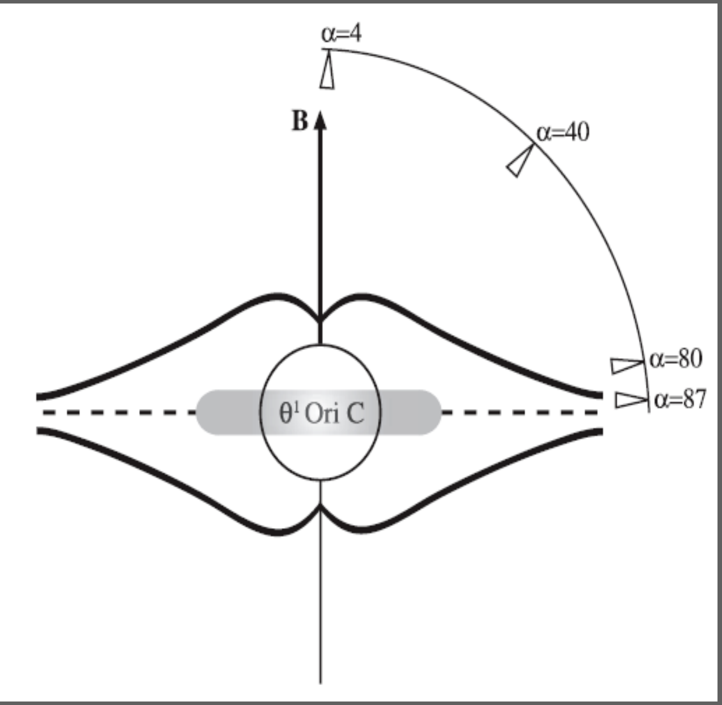


Note: slow rotation (centrifugal force negligible); field consistent with large-scale dipole

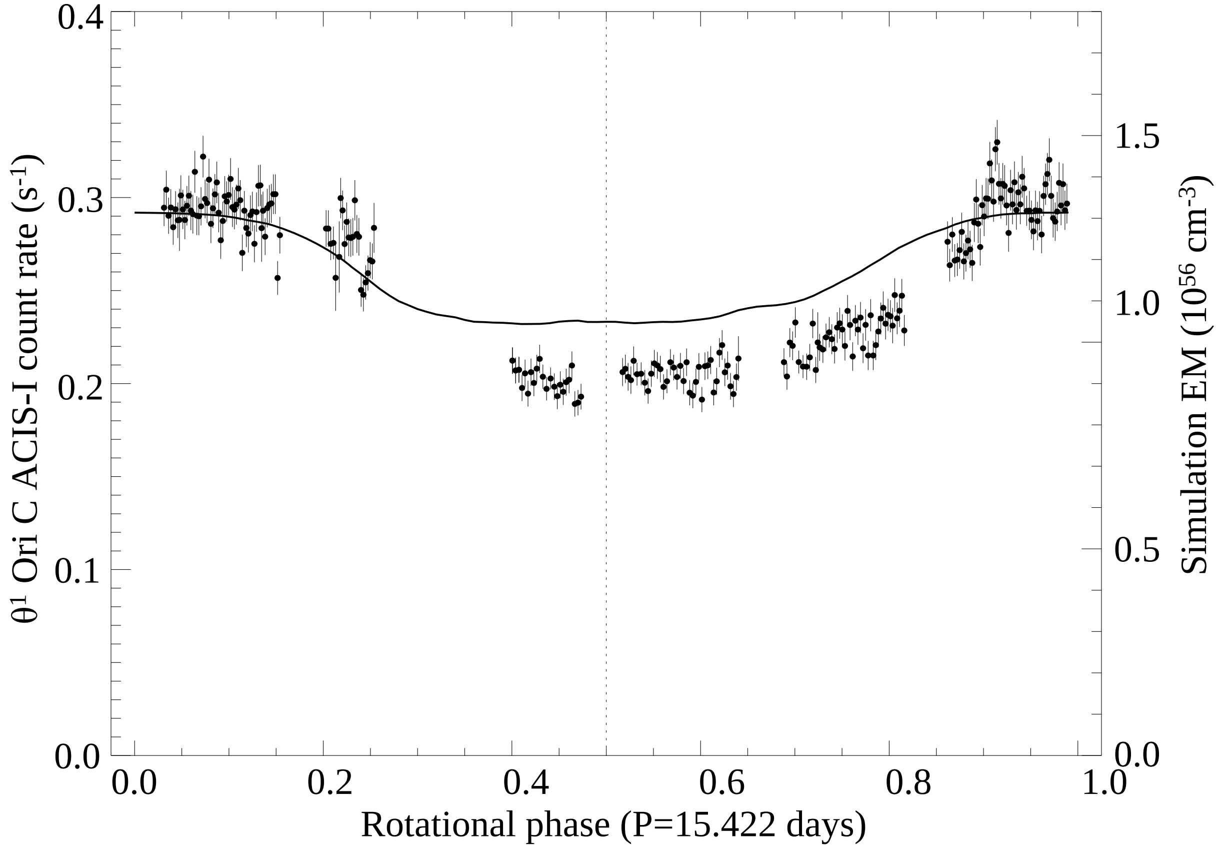
Rotational modulation of the X-ray emission simply from variation in the occultation of the x-ray emitting magnetosphere by the star

To 1st order: depth of eclipse depends on how close the shock-heated plasma is to the star





Chandra broadband count rate vs. rotational phase



Model from MHD simulation

Subsequent numerical MHD simulations by ud-Doula & Owocki (2002, etc.)

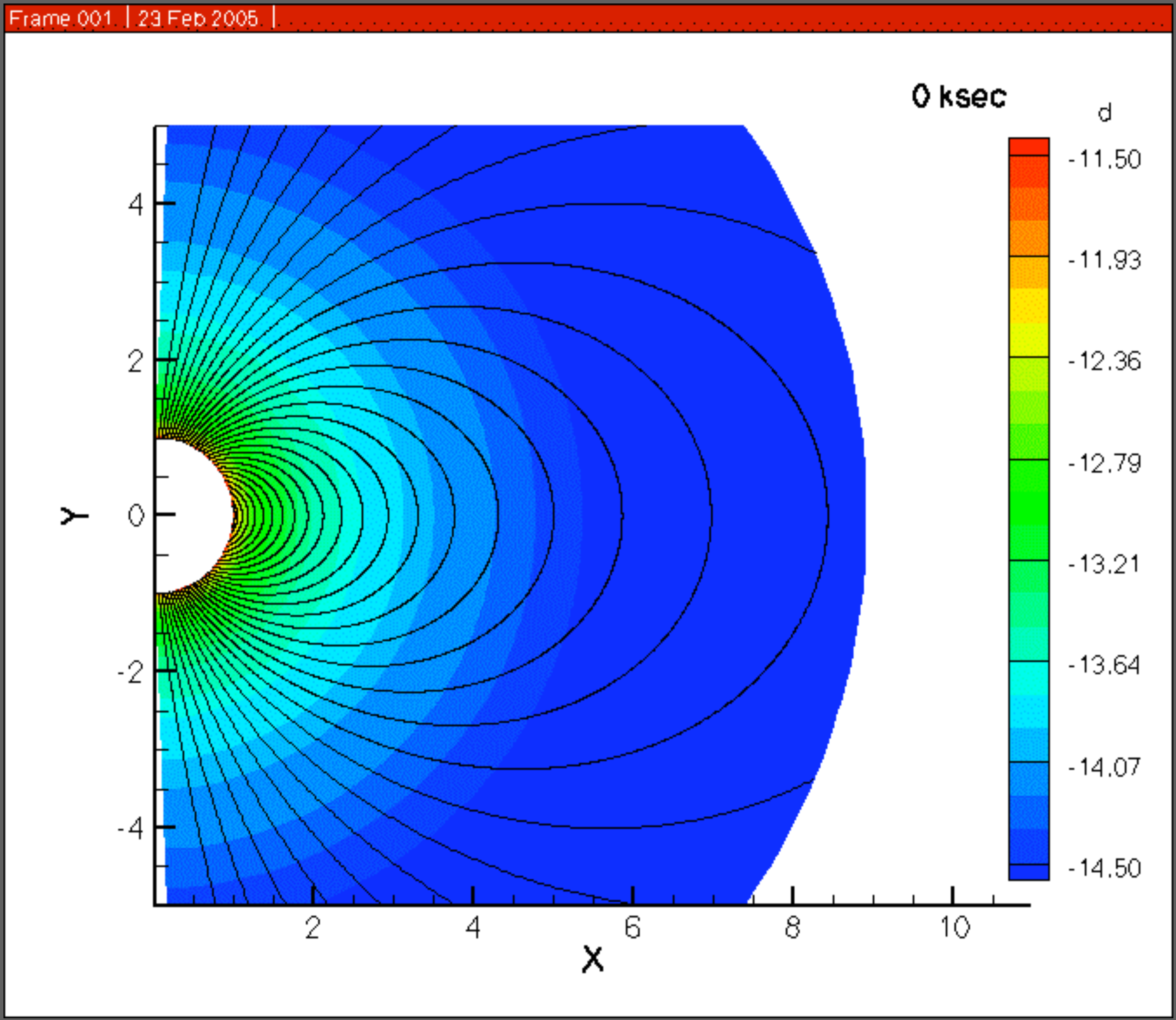
Interplay between magnetic tension and wind kinetic energy – self-consistent field configuration

Dynamical treatment (what happens as material accumulates at the tops of closed magnetic loops?)

Aside: enhanced UV wind absorption at disk-on viewing angles rather than pole-on viewing angles

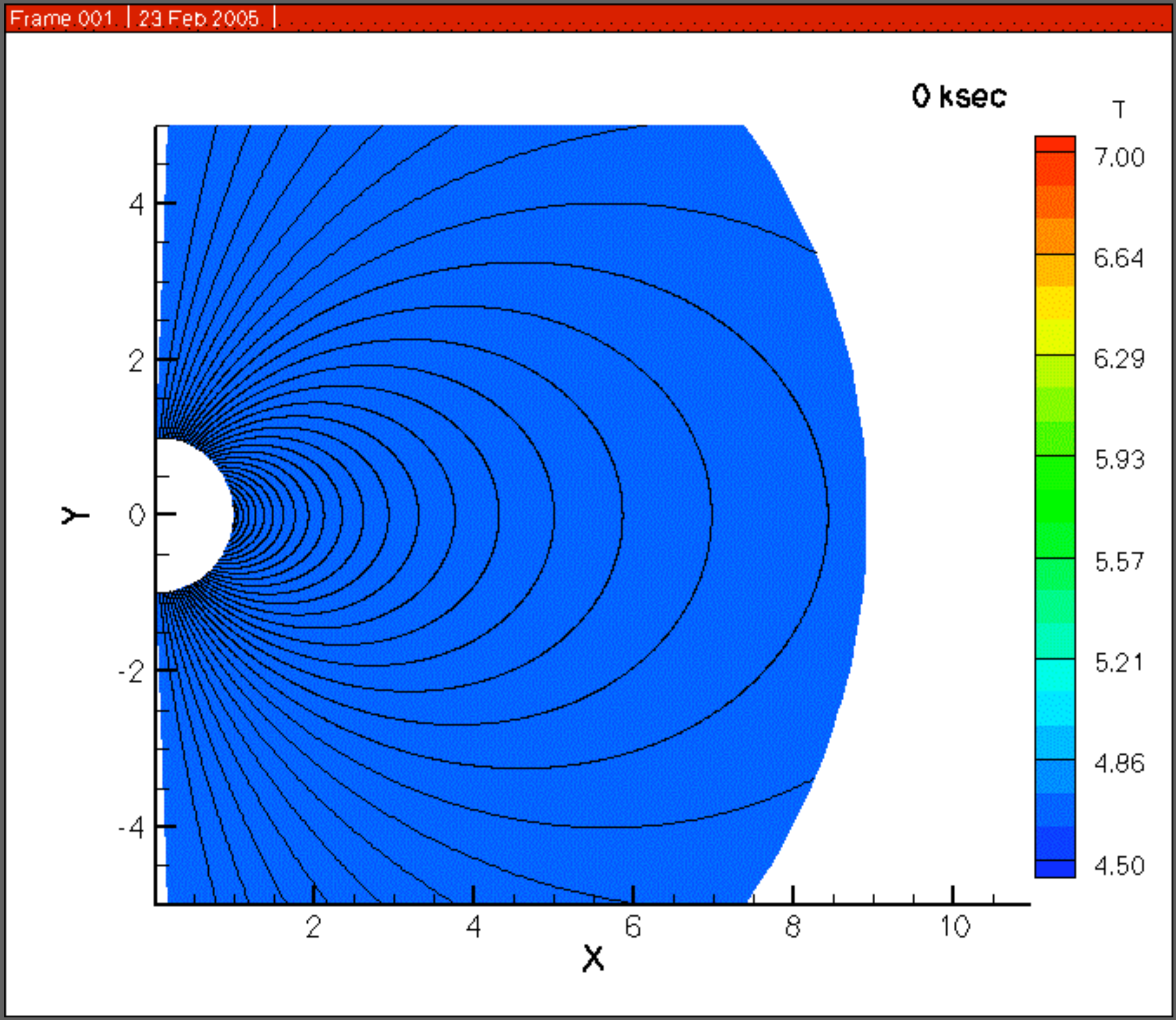
Complementary analyses: RRM, RFHD

2-D MHD simulation of θ^1 Ori C: **density**



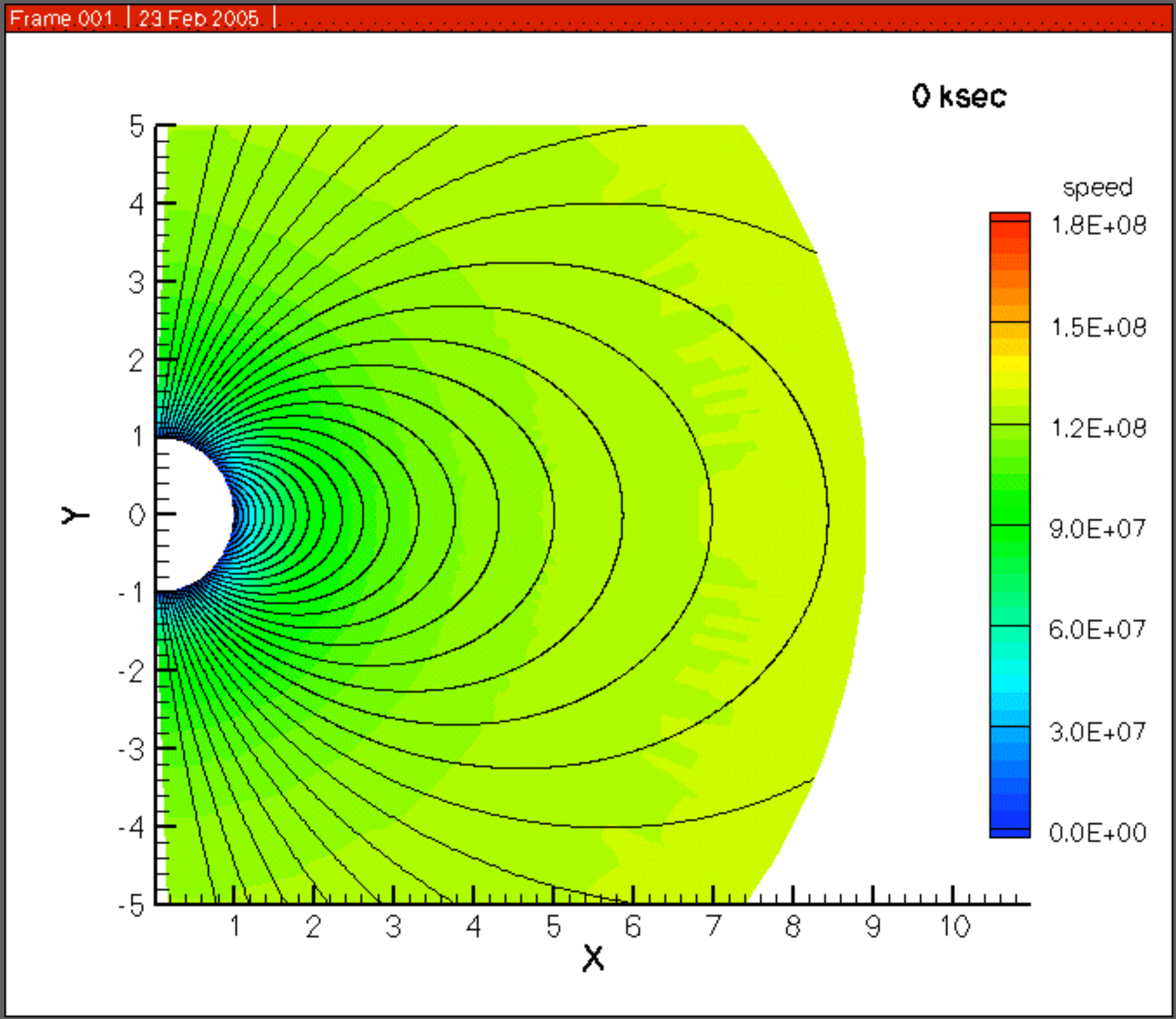
courtesy A. ud-Doula

2-D MHD simulation of θ^1 Ori C: **temperature**



courtesy A. ud-Doula

2-D MHD simulation of θ^1 Ori C: **speed**



courtesy A. ud-Doula

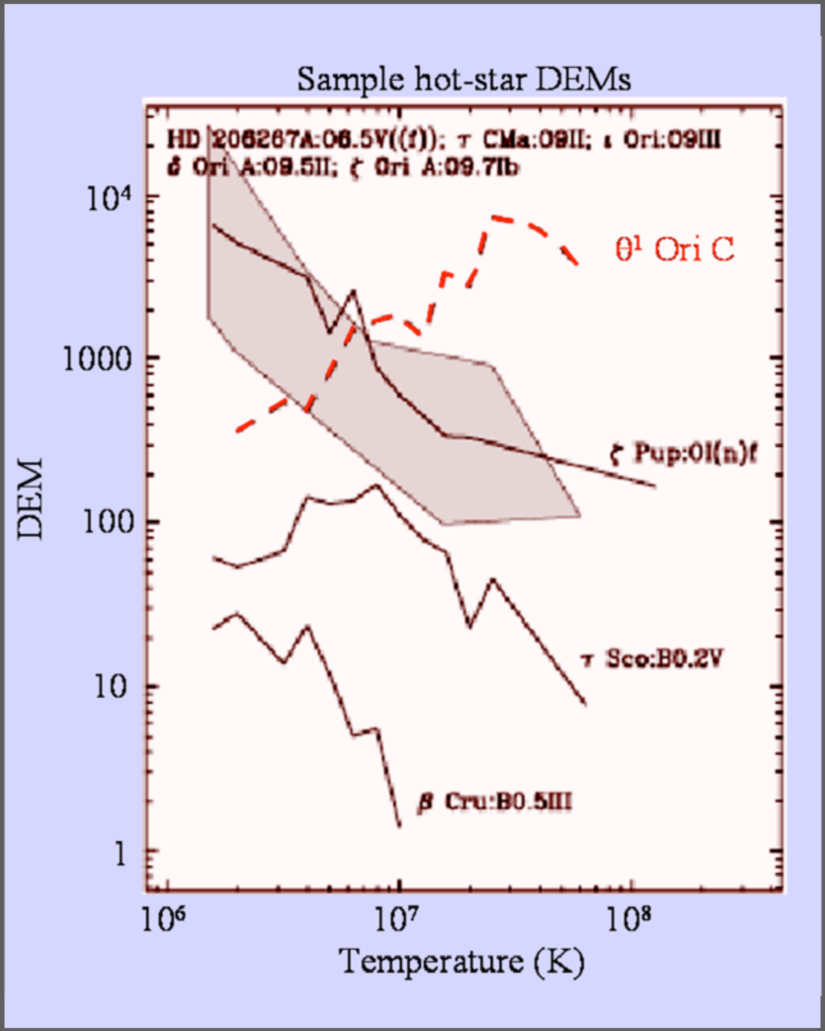
Predictions from MHD simulations (and original analysis of Babel and Montmerle):

Strong shocks – plasma very hot (few 10^7 K)

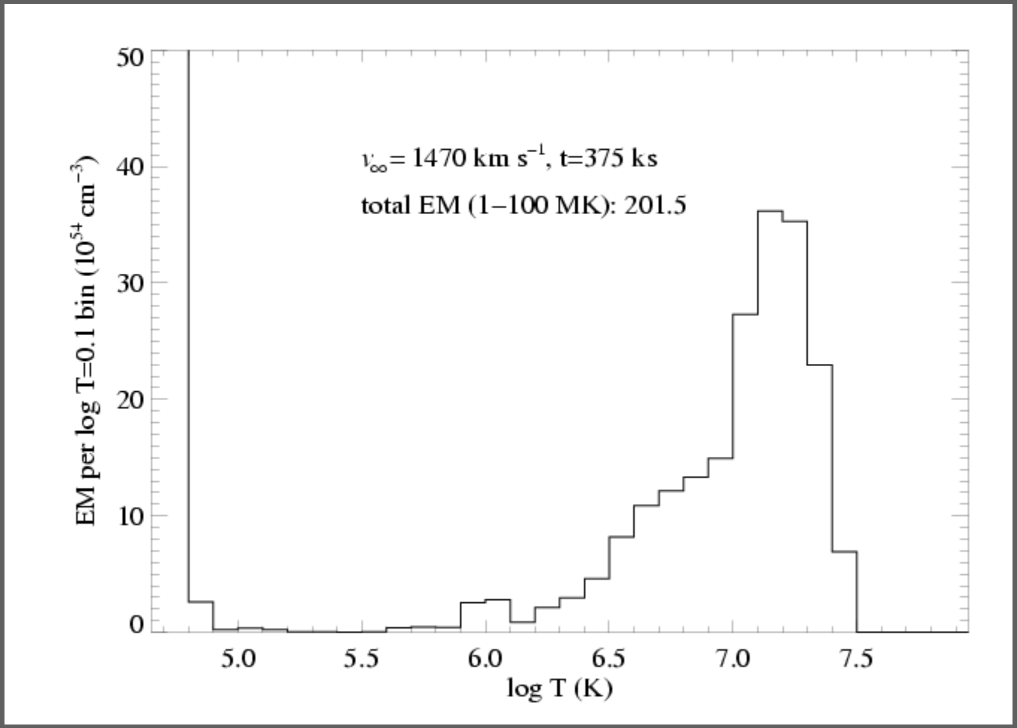
Post-shock plasma moving quite slowly (Doppler broadening of X-ray emission lines should be quite modest – will there be a dependence on viewing angle?)

Bulk of hot plasma is in the closed field region (< Alfven radius; $\eta(r) < 1$)

Differential emission measure
(temperature distribution)

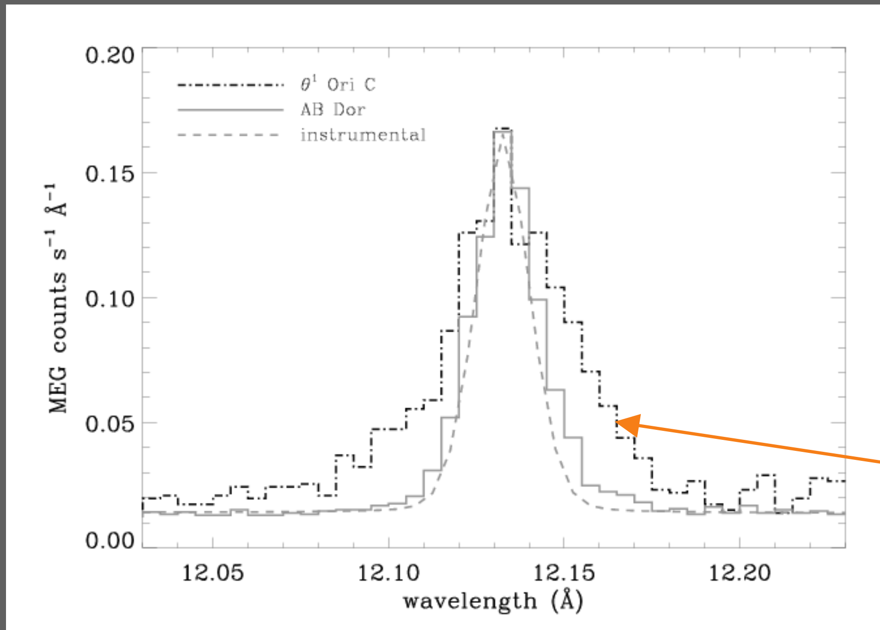


Wojdowski & Schulz (2005)

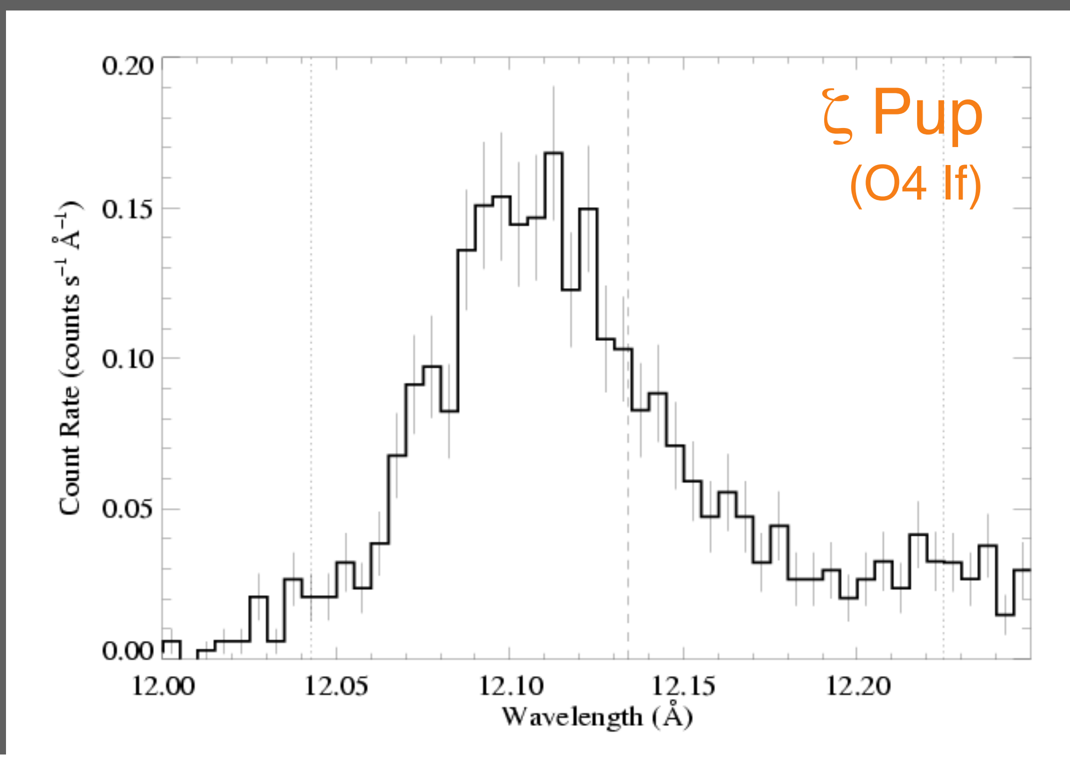


MHD simulation of θ^1 Ori C reproduces the observed differential emission measure

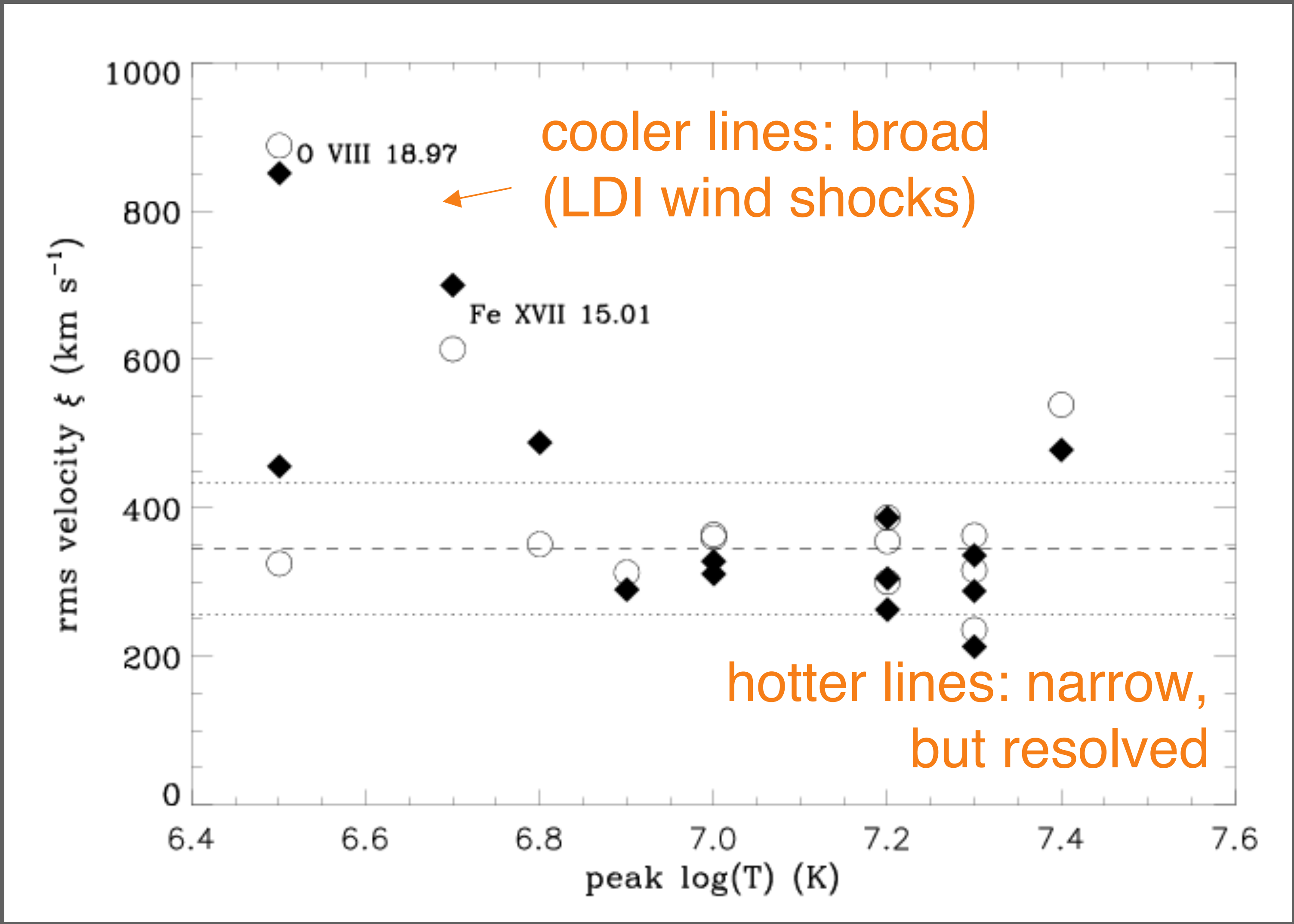
Line profiles:
resolved, but narrow



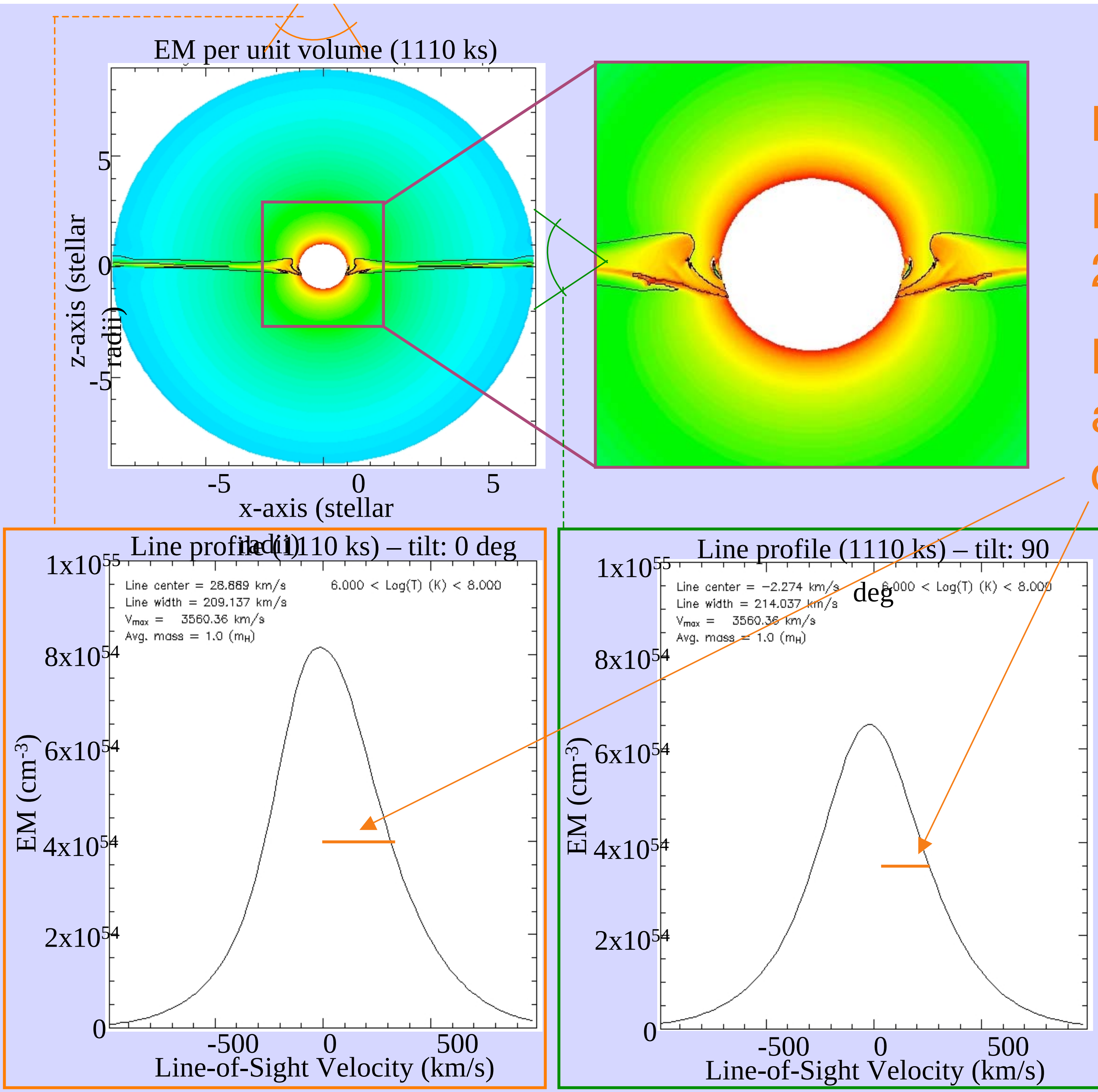
θ^1 Ori C: Ne X
Ly-alpha



Distribution of X-ray line widths in θ^1 Ori C



Gagné et al. (2005)



MHD sims:

HWHM ~ 200 km/s

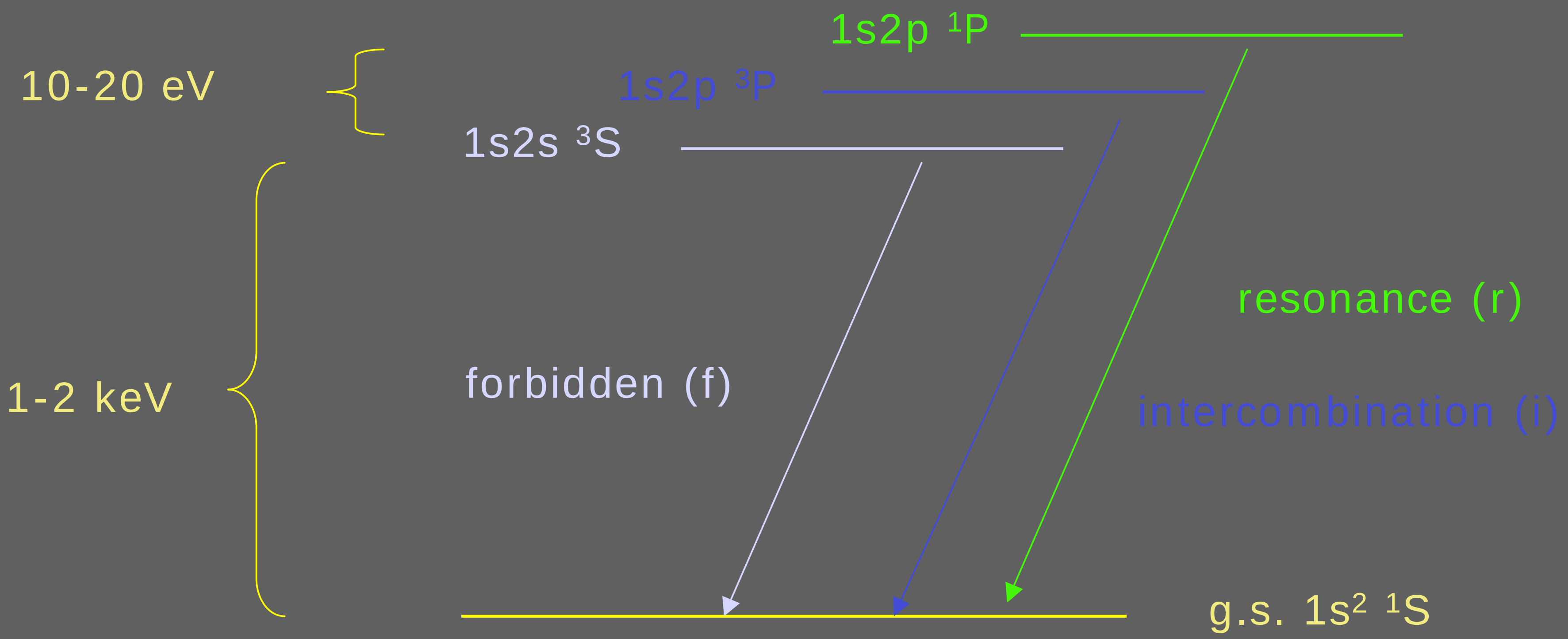
No viewing angle dependence

There's one more powerful x-ray spectral diagnostic that can provide useful information to test the wind-shock scenario:

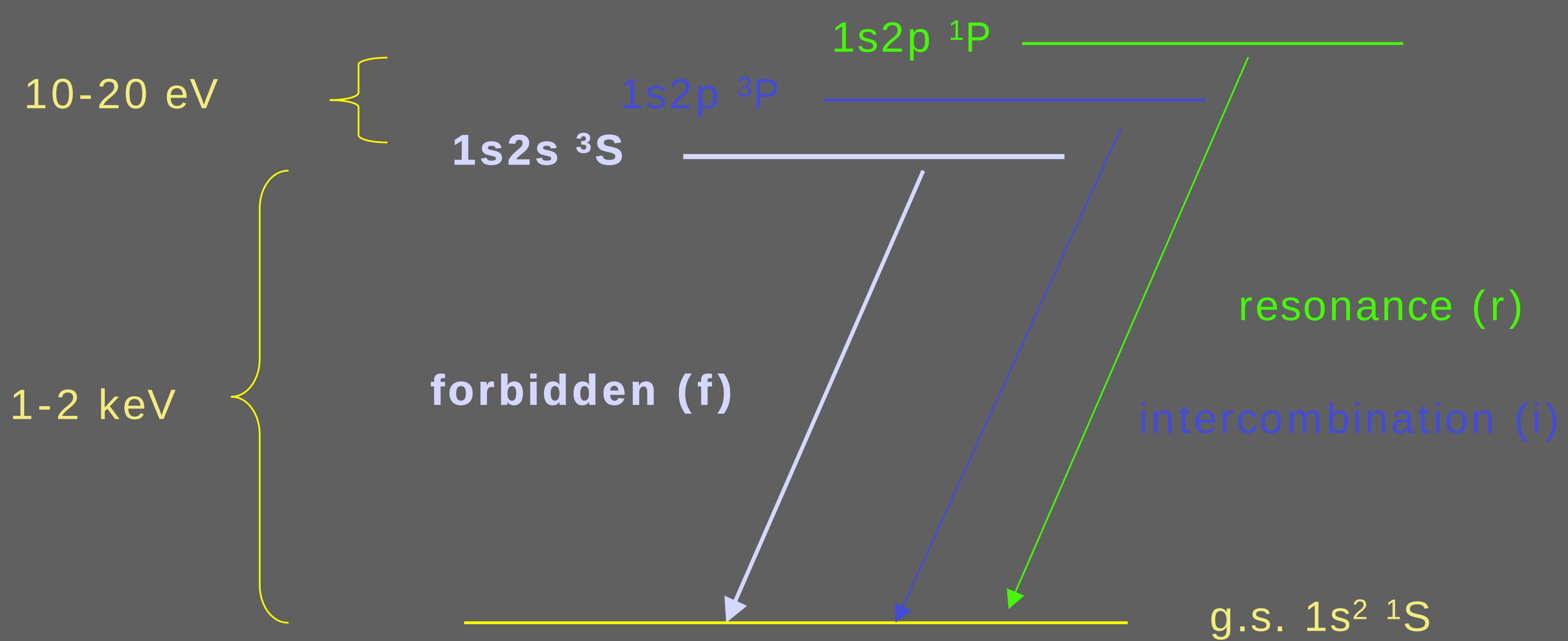
Certain x-ray **line ratios** provide information about the location of the x-ray emitting plasma

Distance from the star via the line ratio's sensitivity of helium-like f/i ratios to the local UV radiation field

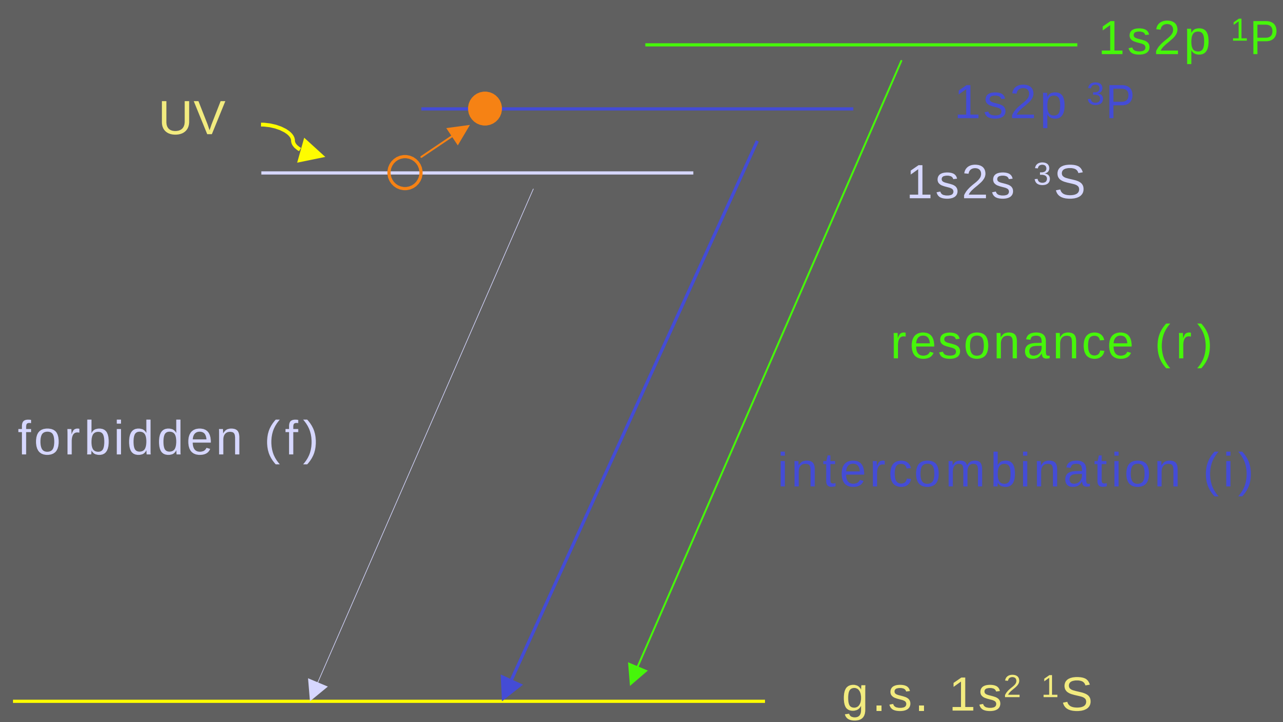
Helium-like ions (e.g. O^{+6}, Ne^{+8}, Mg^{+10}, Si^{+12}, S^{+14}) – schematic energy level diagram



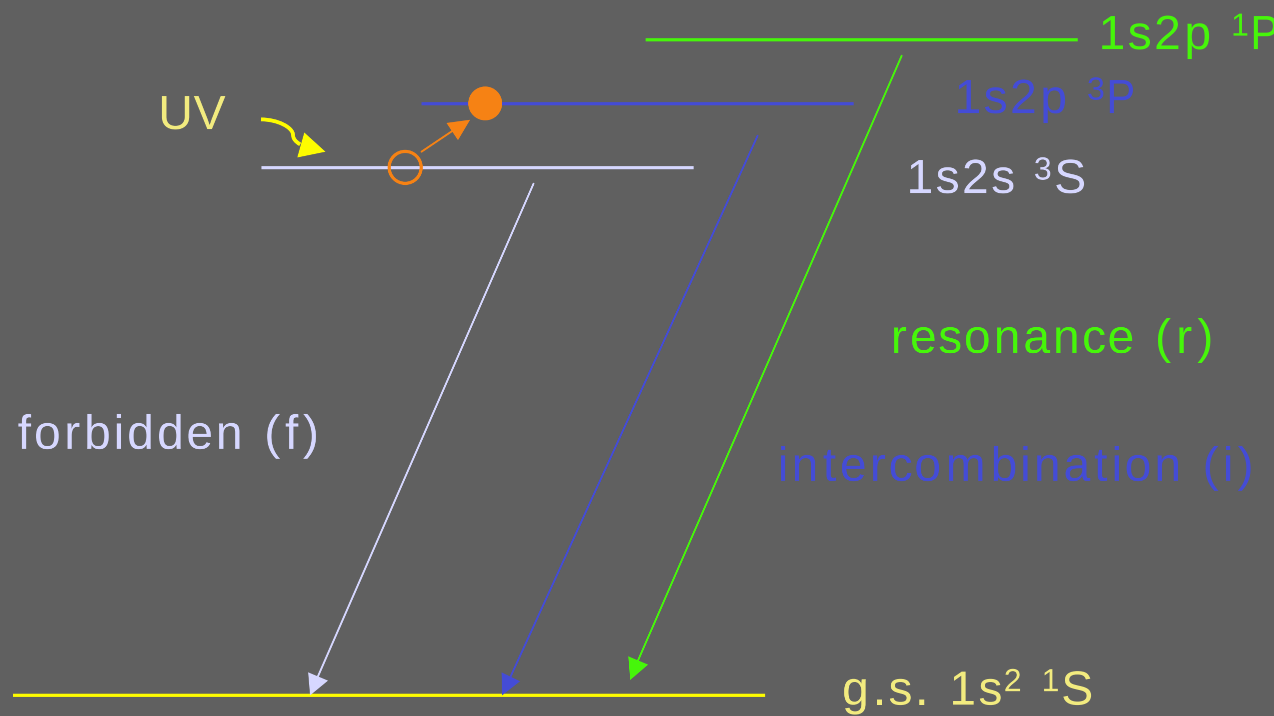
The upper level of the forbidden line is very long lived – *metastable* (the transition is dipole-forbidden)



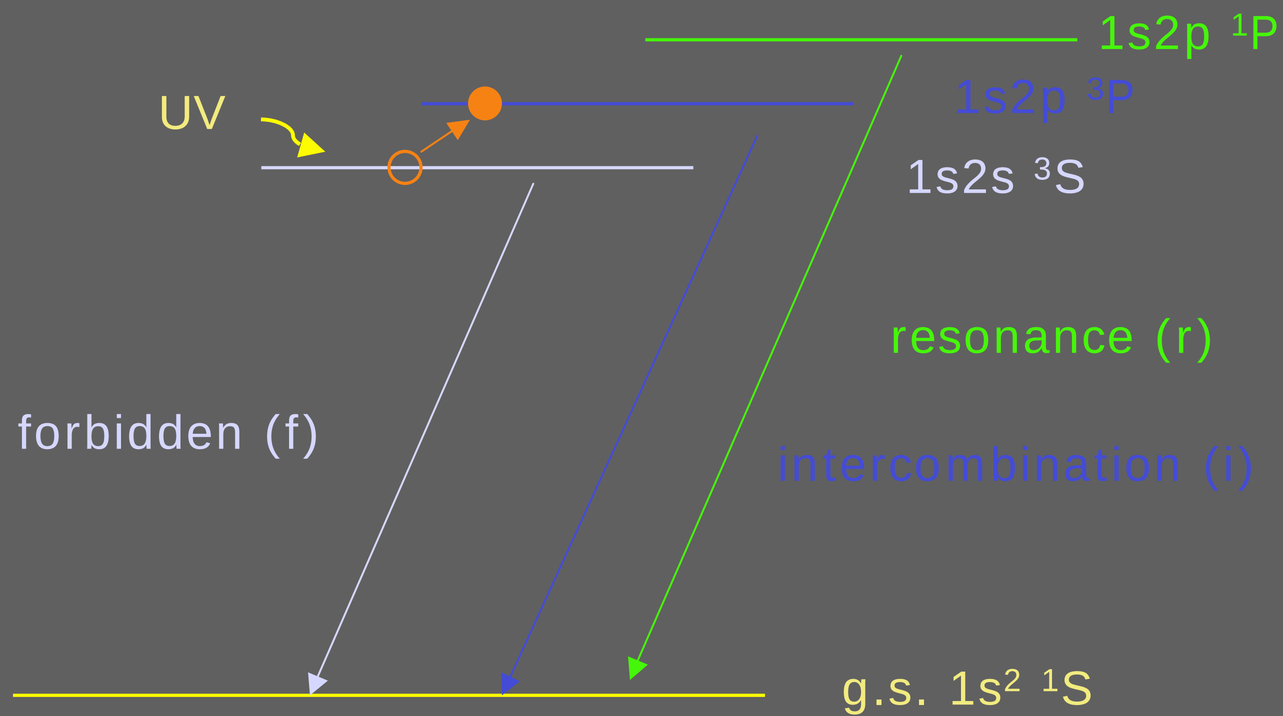
While an electron is sitting in the metastable ^3S level, an ultraviolet photon from the star's photosphere can excite it to the ^3P level – this decreases the intensity of the forbidden line and increases the intensity of the intercombination line.



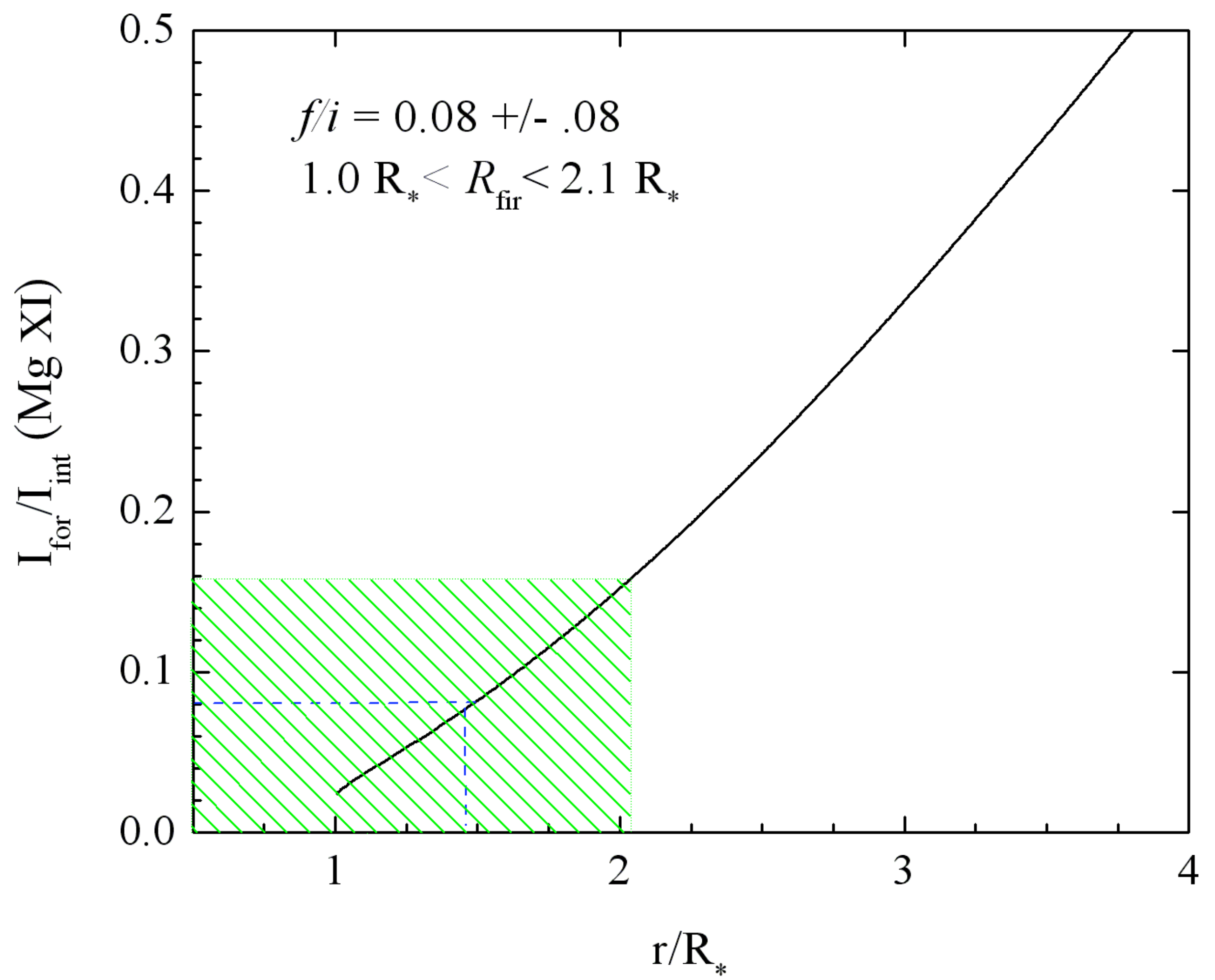
The *f/i* ratio is thus a diagnostic of the strength of the local UV radiation field.

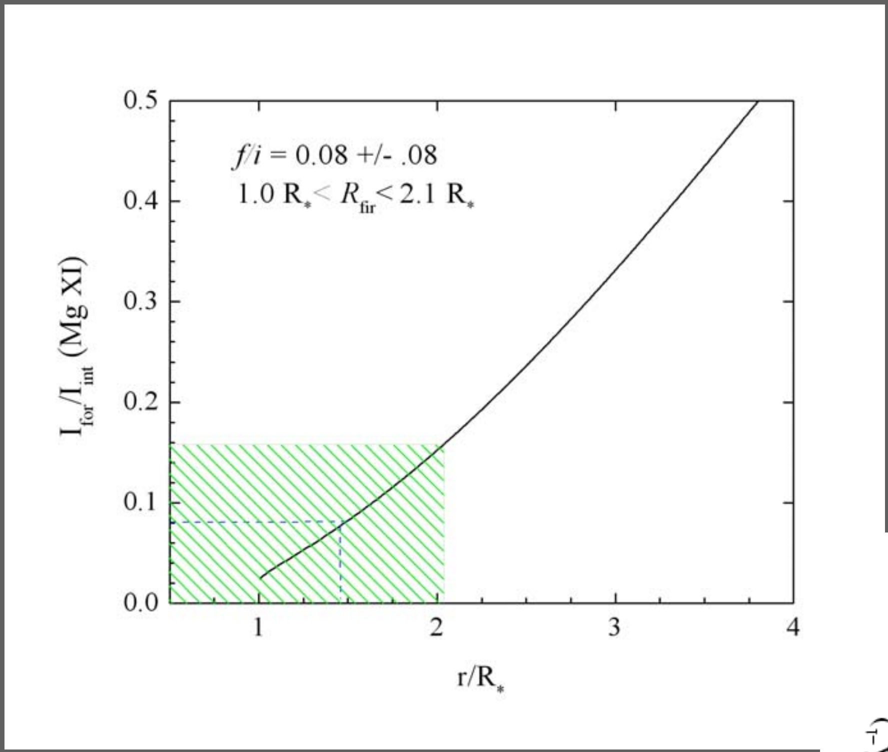


If you know the UV intensity emitted from the star's surface, it thus becomes a diagnostic of the distance that the x-ray emitting plasma is from the star's surface.

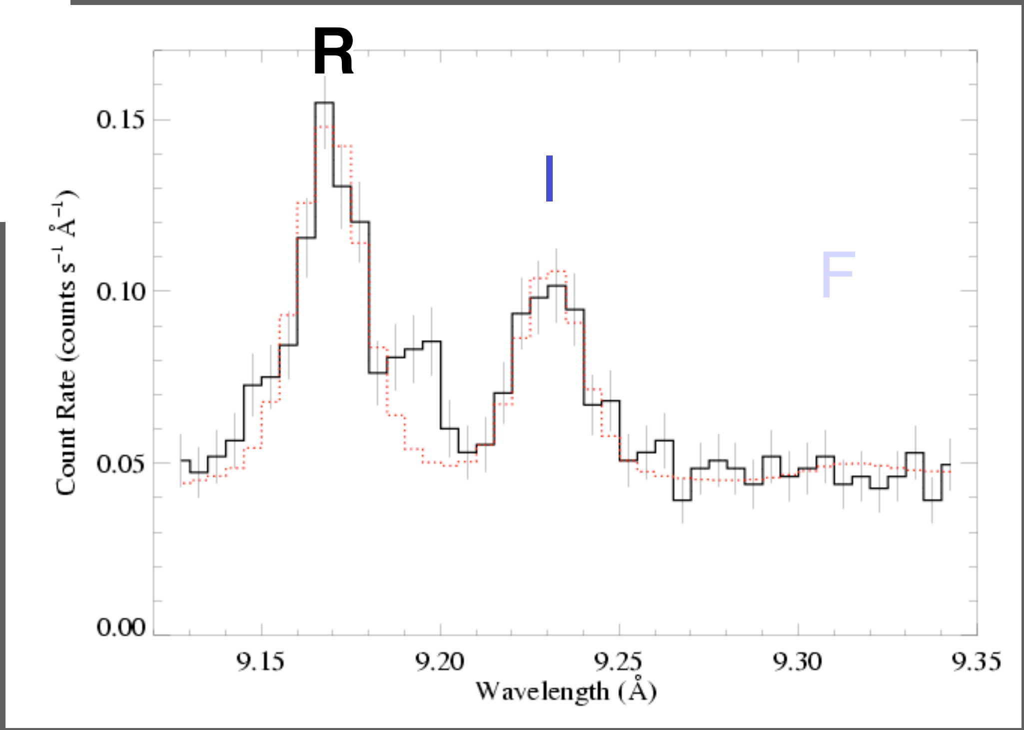


Model of f/i ratio dependence on dilution factor (radius)





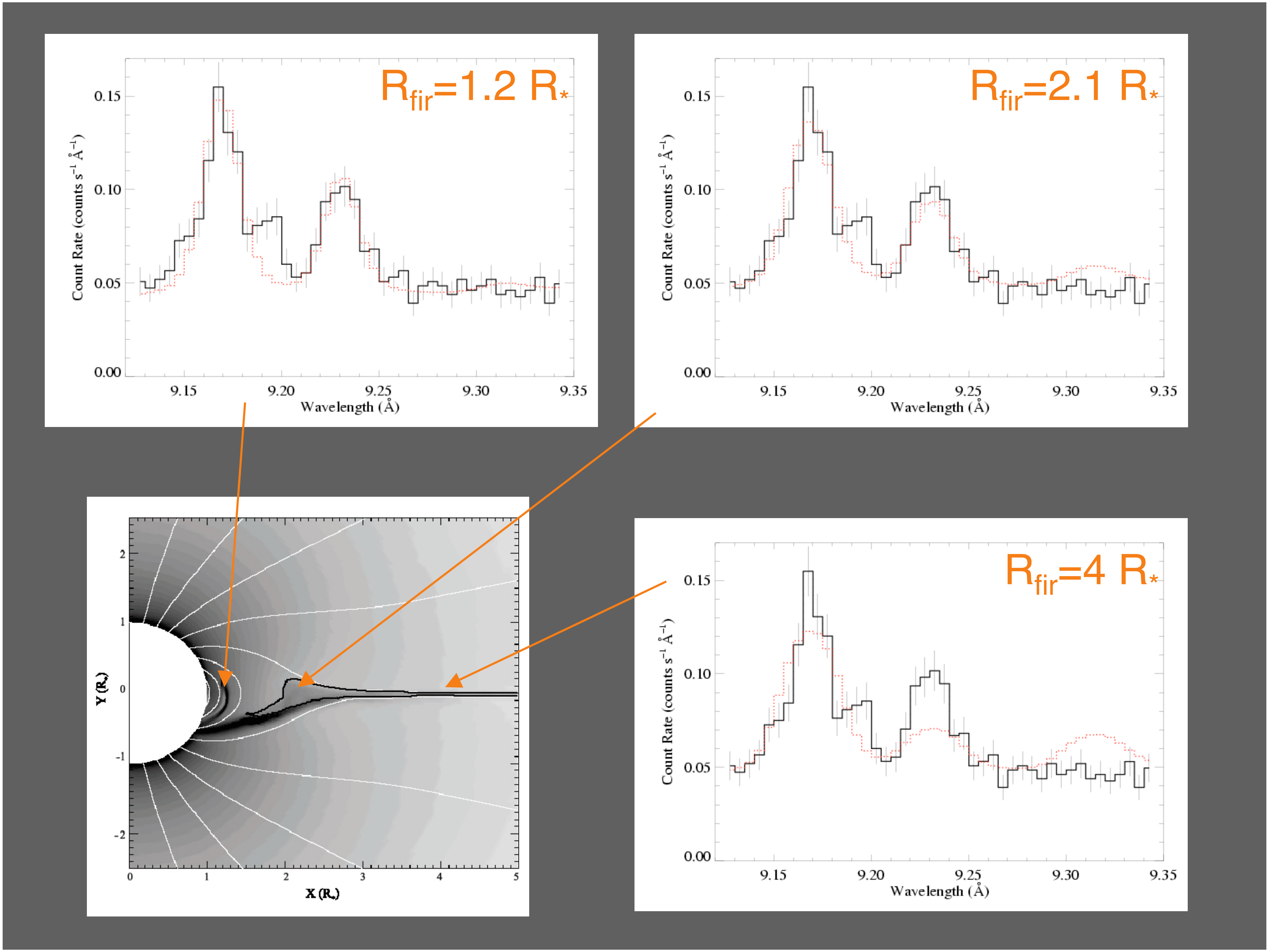
helium-like magnesium
Mg XI
in θ^1 Ori C



Single source radius assumed

Data constrain:

$1.0 < R_{fir} < 2.1\ R_*$



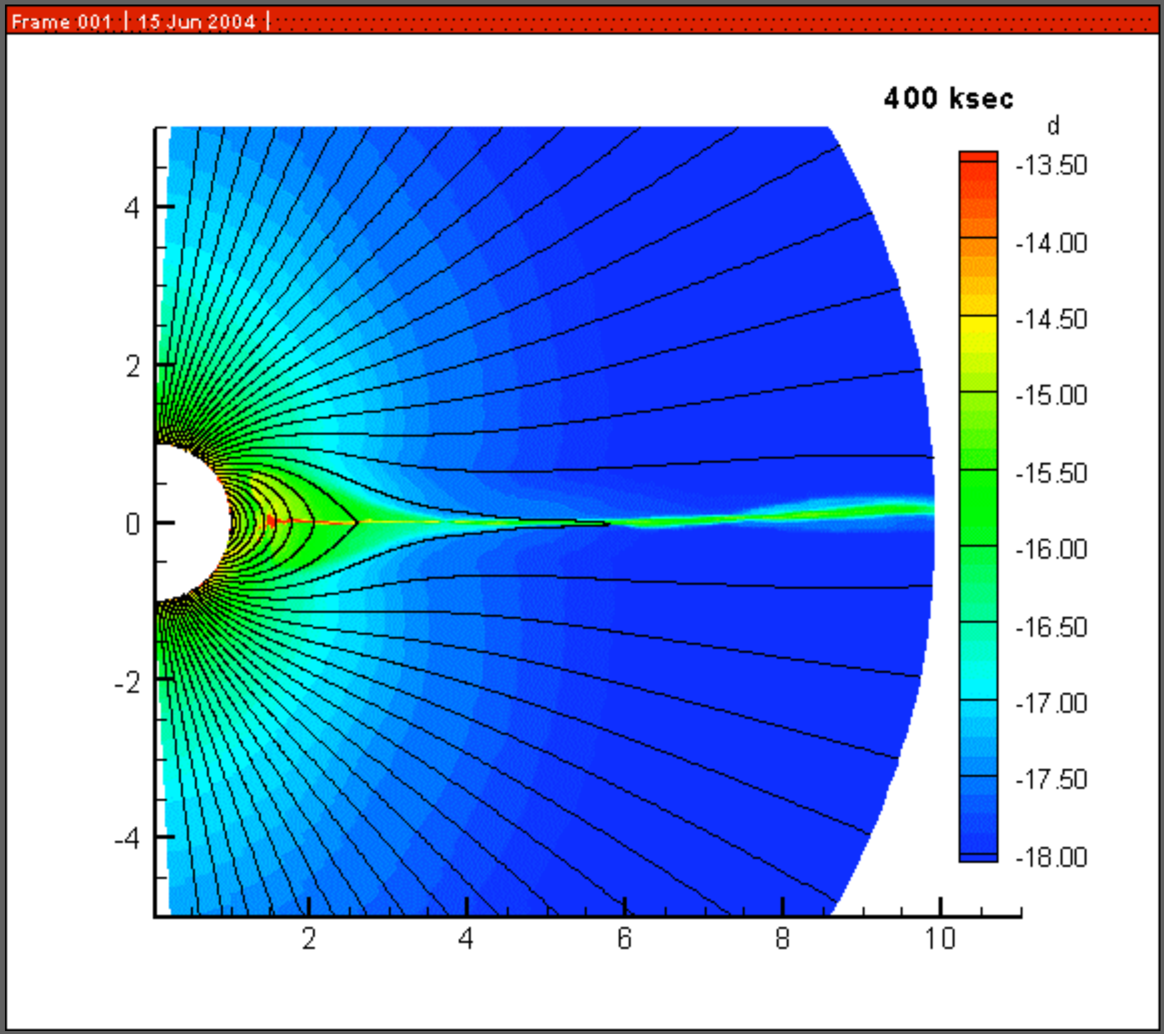
Rfir=1.2 R*
Rfir=2.1 R*
Rfir=4 R*
Count Rate (counts s⁻¹ Å⁻¹)
0.00
0.05
0.10
0.15
9.15
9.20
9.25
9.30
9.35
Wavelength (Å)
Y (R*)
X (R*)

He-like f/i ratios have the potential for discriminating MCWS from wind-wind sources –

close to photosphere in the former case, not so much in the latter

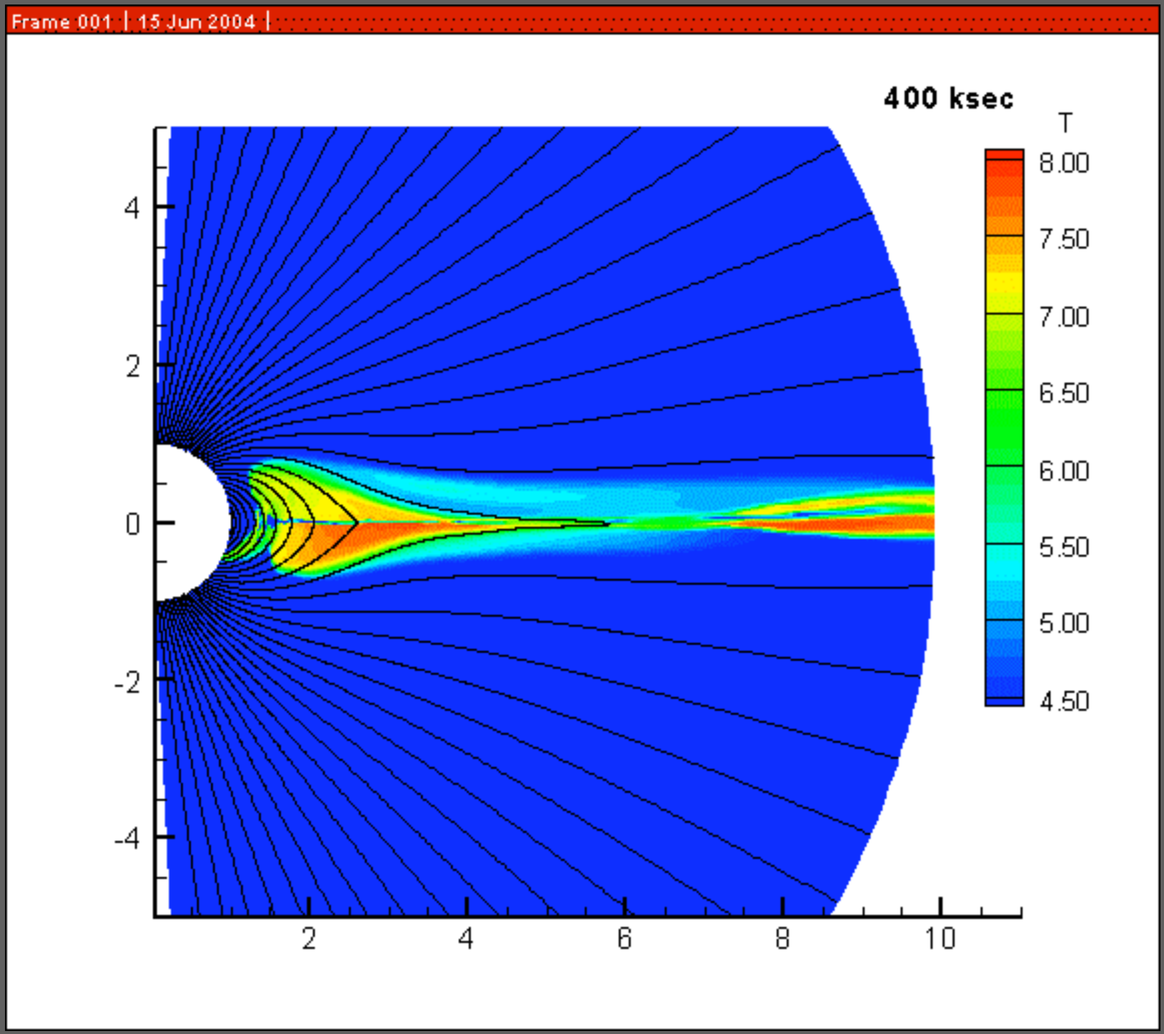
MHD with rotation revealed the potential for breakout-driven magnetic reconnection …source of x-ray flaring in σ Ori E (B2Vp)?

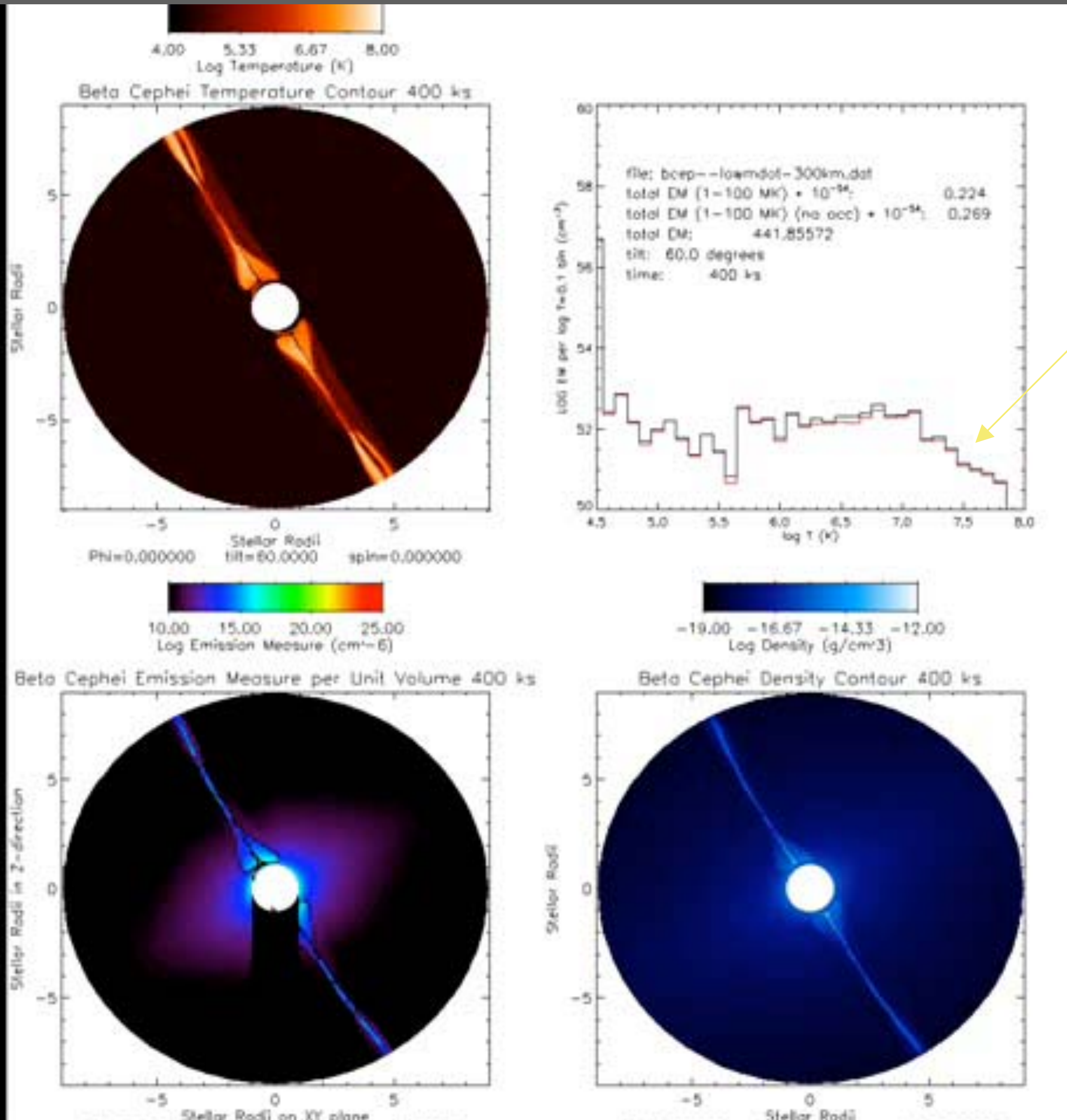
MHD simulation of MCWS: higher magnetic confinement and rapid rotation



Note, though: confinement parameter of σ Ori E is much higher than in this MHD simulation

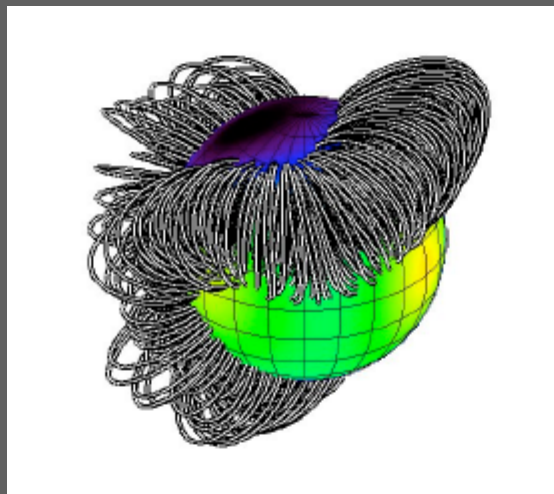
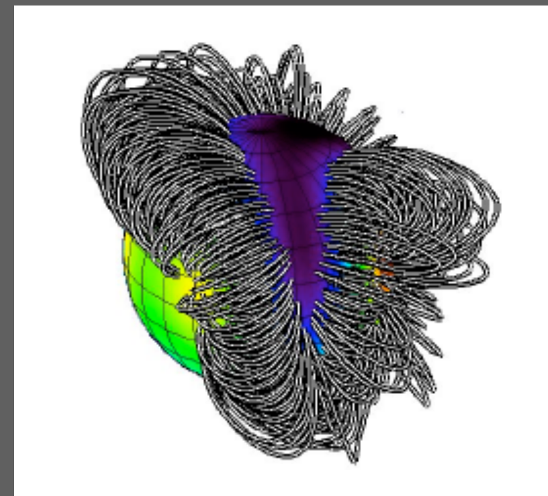
temperature





Not much emission measure at very high temperatures from the reconnection (but maybe with larger confinement parameter?)

Another application: slowly rotating magnetic B star with a more complex field – τ Scorpii (B0.2 V)

Donati et al. (2006)

f/i ratios imply location of hot plasma between 2 and 3 R_*…

T ~ 20 MK – is there enough room in the closed field region for wind to accelerate to the required velocity?

Rotational modulation?

MHD? RFHD?

Conclusions

Magnetic OB stars with strong, large-scale dipole fields have distinctive X-ray properties:

- High X-ray luminosities
- Hard emission
- Narrow lines
- Rotational modulation (if magnetic obliquity .ne. 0)

Specific, quantitative diagnostics for studying MCWS (but only some utility for identification)

More…

Smaller scale magnetic structures…may have different effects on X-rays

Centrifugally driven breakout and reconnection? But X-rays may not be very sensitive to it