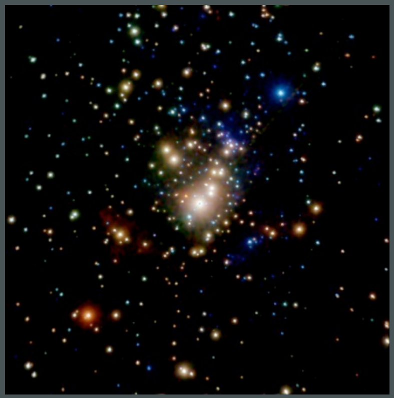
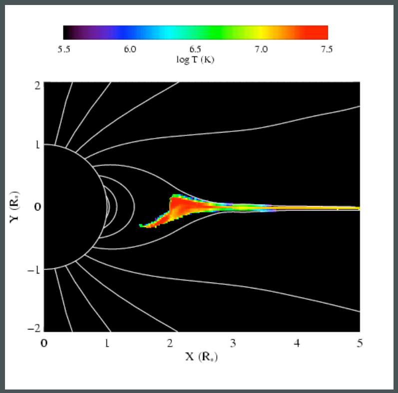
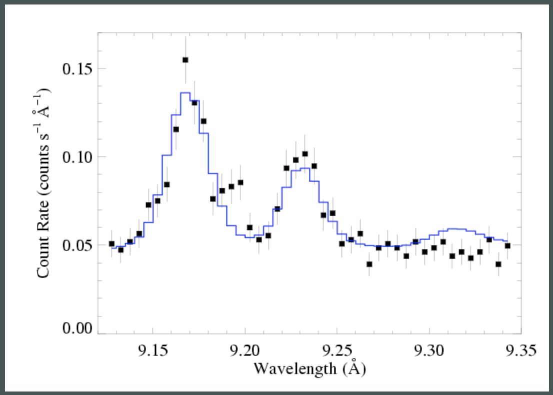
X-ray Diagnostics and Their Relationship to Magnetic Fields

David Cohen
Swarthmore College







If we understand the physical connection between magnetic fields in massive stars and X-rays, we could use X-ray observations to identify magnetic massive stars.

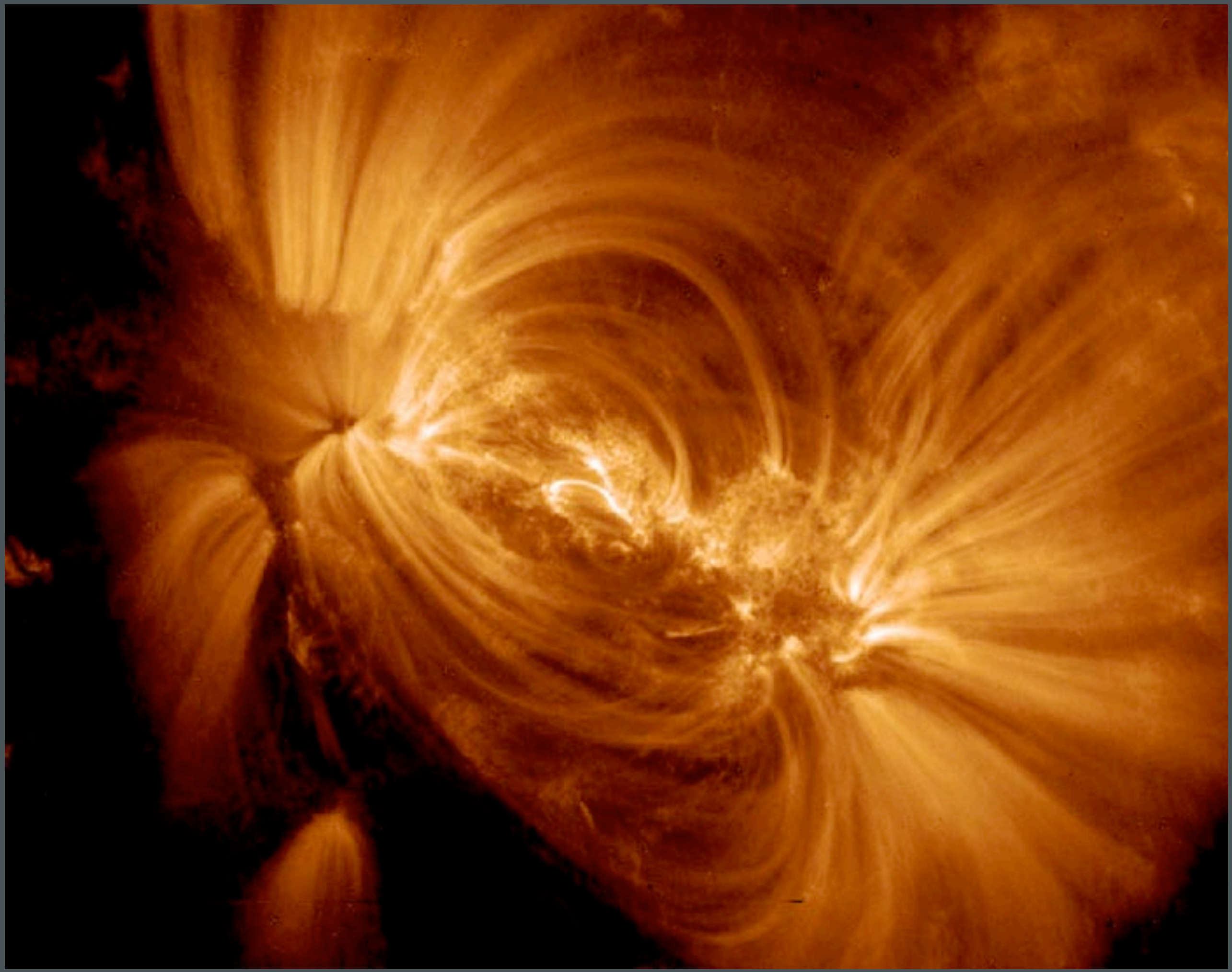
e.g. Which of the stars in this Chandra X-ray image of the Orion Nebula Cluster are massive magnetic stars?

But we're not there yet…

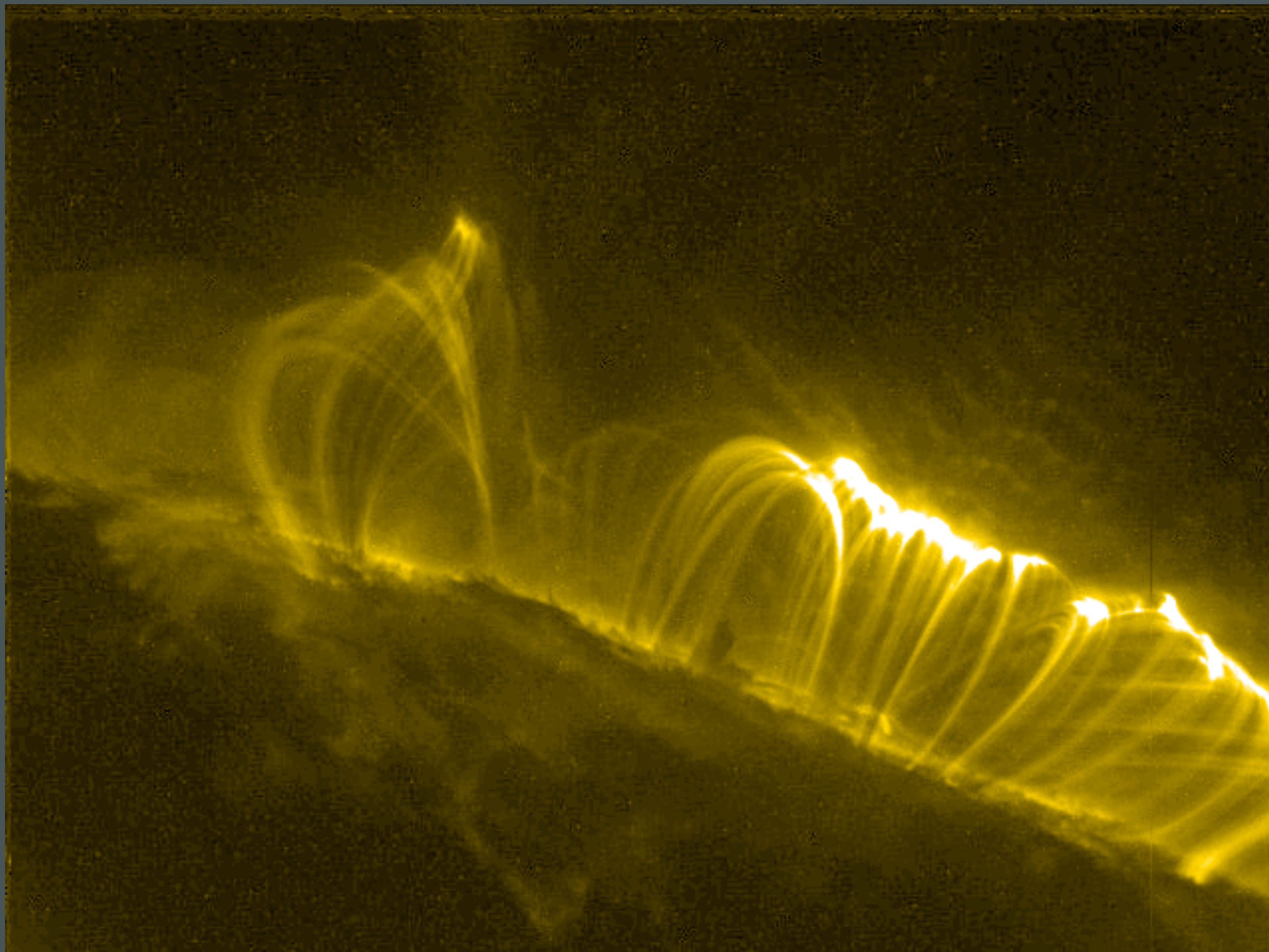
X-ray behavior of known magnetic massive stars is diverse.

We don't understand enough about the physical mechanisms of X-ray production in them.

The Sun: X-rays <-> Magnetic Fields



TRACE



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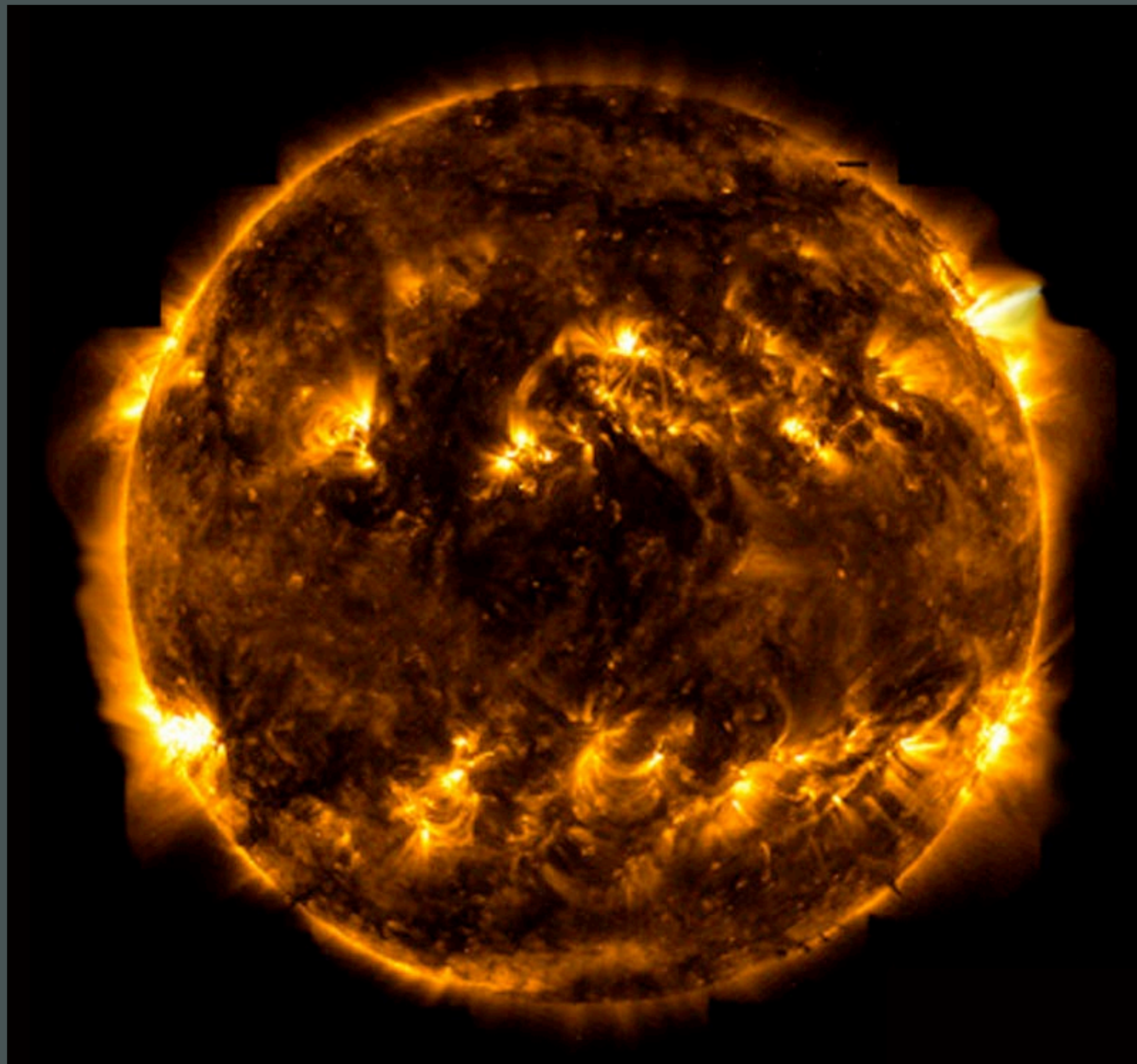
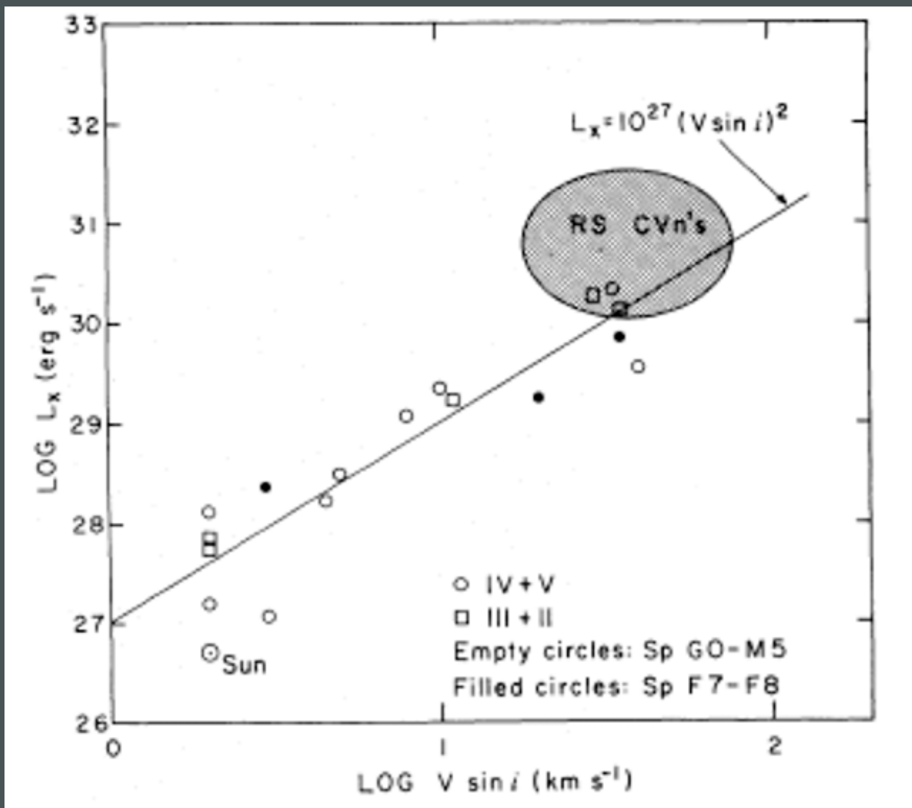


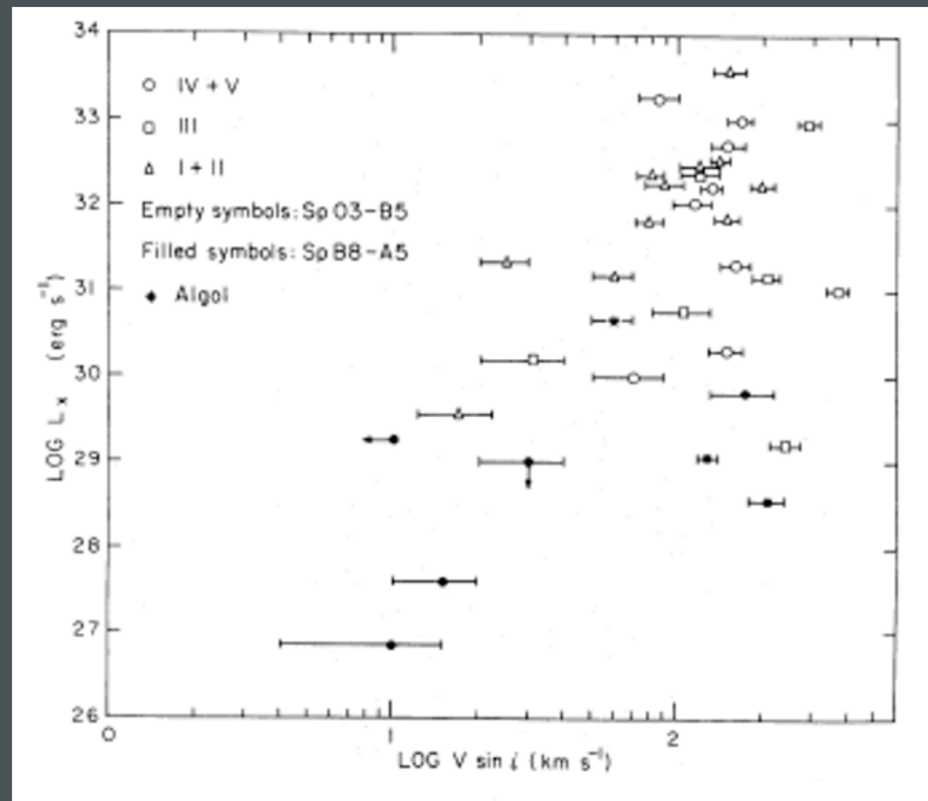
TRACE

Stellar rotation vs. X-ray luminosity

low-mass stars



high-mass stars



No trend

Massive star X-rays are not coronal

X-rays in massive stars are associated with their radiation-driven winds

Power in these winds:

$$\tfrac{1}{2}\dot{M}v_{\infty}^{2} \approx 3\times10^{36} \quad \text{erg s}^{-1}$$

$$\approx .001 L_{*}$$

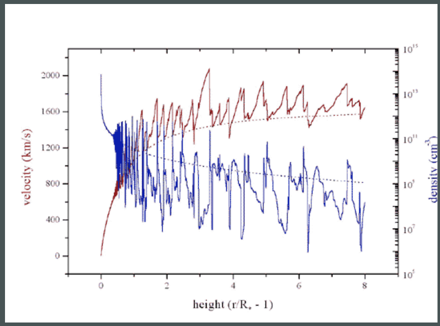
while the x-ray luminosity

$$L_X \approx 10^{-7} L_{*}$$

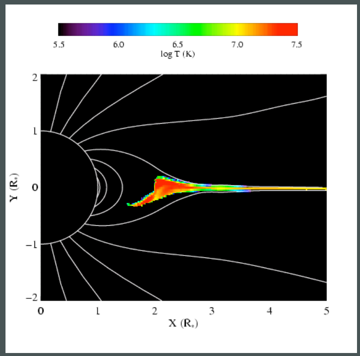
To account for the x-rays, only **one part in 10^{-4}** of the wind's mechanical power is needed to heat the wind

Three models for massive star x-ray emission

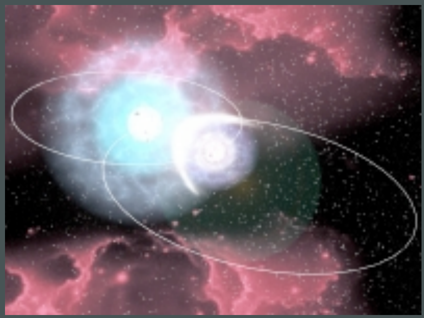
1. Instability driven shocks



2. Magnetically channeled wind shocks



3. Wind-wind interaction in close binaries



Three models for massive star x-ray emission

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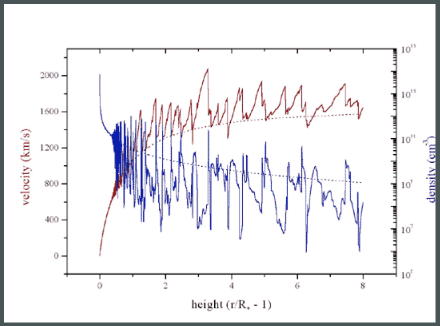

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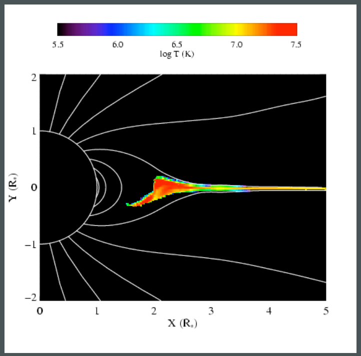

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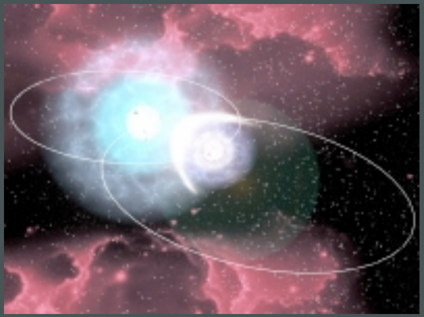


What are these “X-rays” anyway?

…and what’s the available data like?

Launched 2000: superior
sensitivity,
spatial resolution, and
spectral resolution

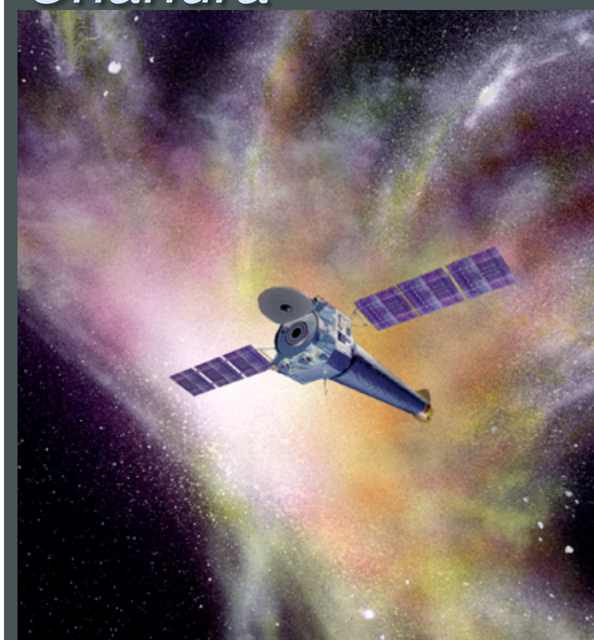
Chandra

sub-arcsecond resolution

XMM-Newton

XMM-Newton

Chandra



Both have CCD detectors for imaging spectroscopy:

low spectral resolution: $R \sim 20$ to 50

And both have grating spectrometers: $R \sim$ few 100 to 1000

300 km/s

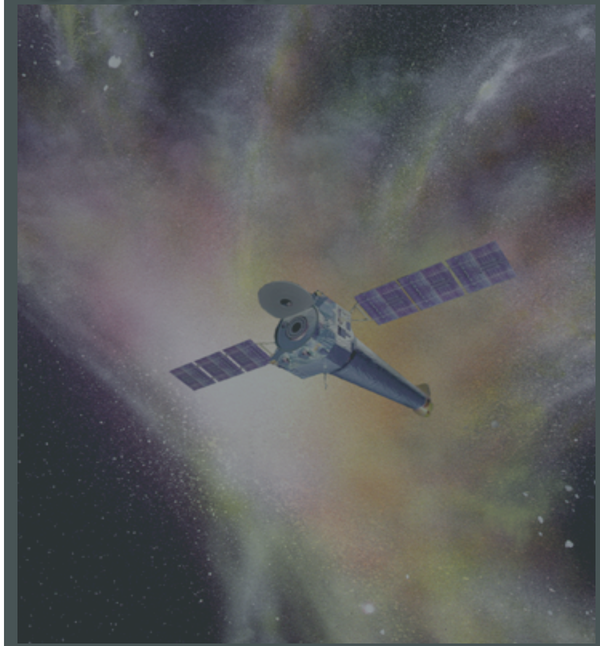
XMM-Newton

Chandra

The gratings have poor sensitivity…
We'll never get spectra for more than two dozen hot stars

XMM-Newton

Chandra



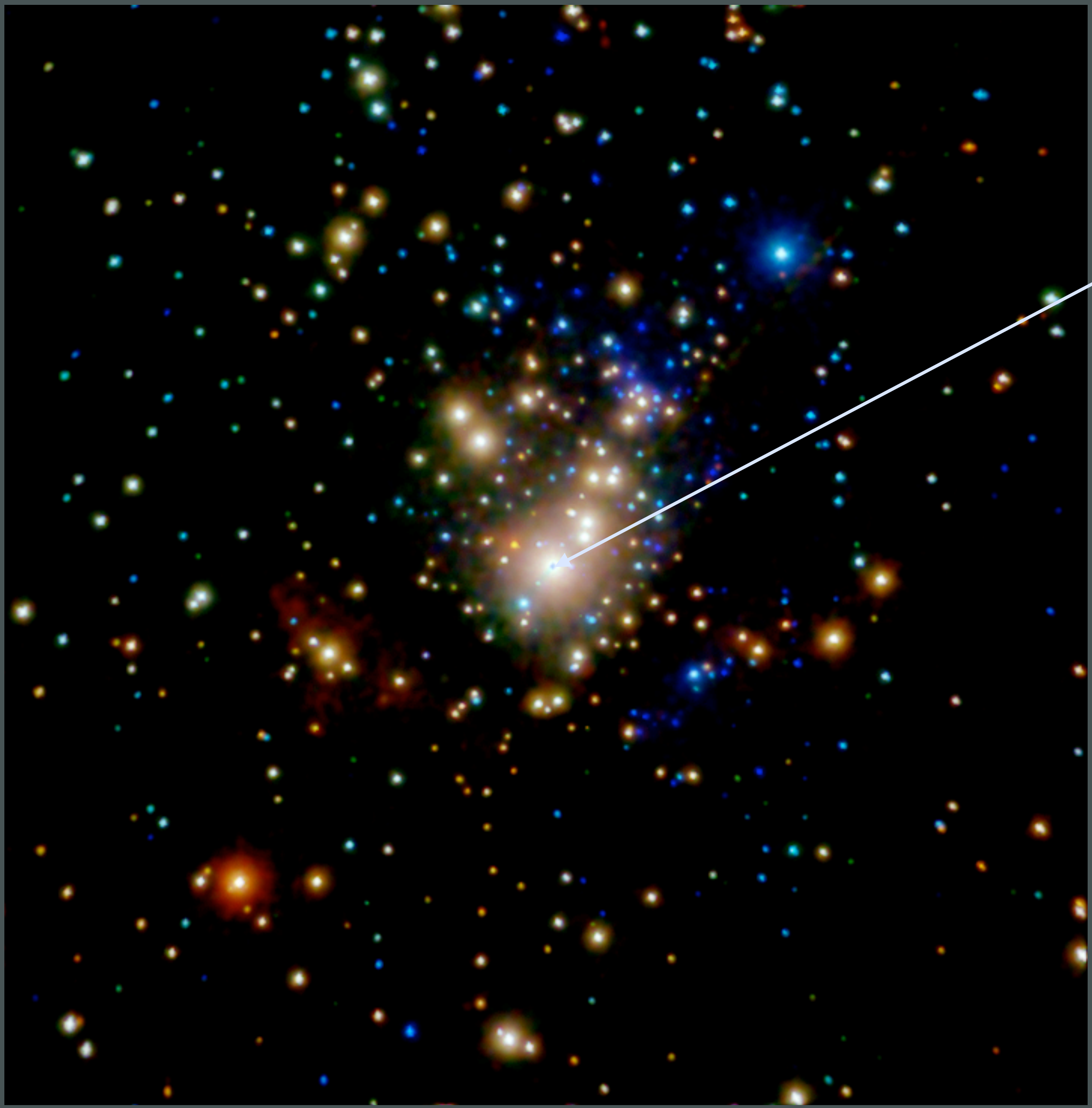
The Future:

Astro-H (Japan) – high spectral resolution at high photon energies …few years from now

International X-ray Observatory (IXO) … 2020+

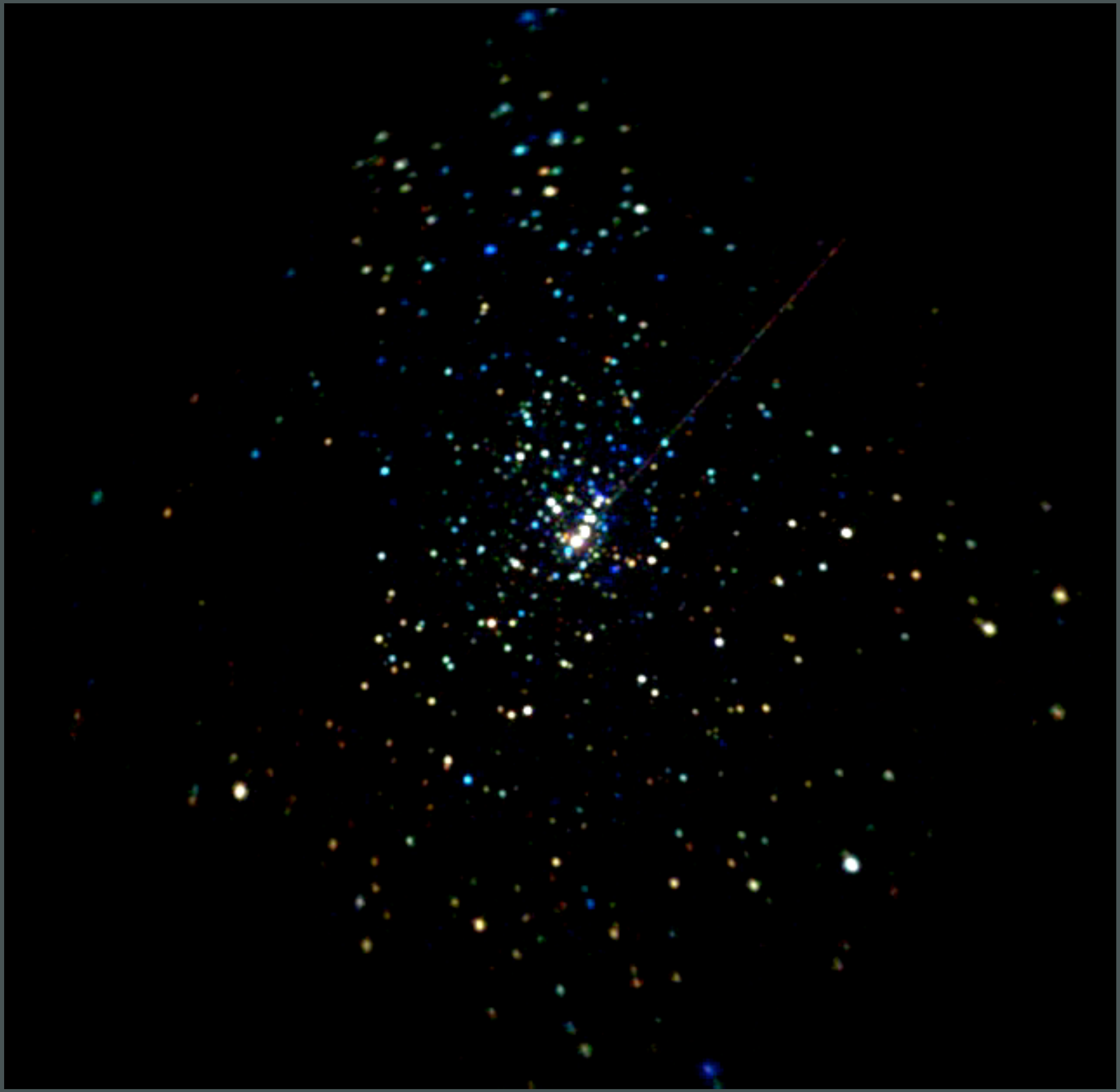
First, imaging (+ low resolution) spectroscopy with *Chandra*

Chandra ACIS
Orion Nebula Cluster (COUP)



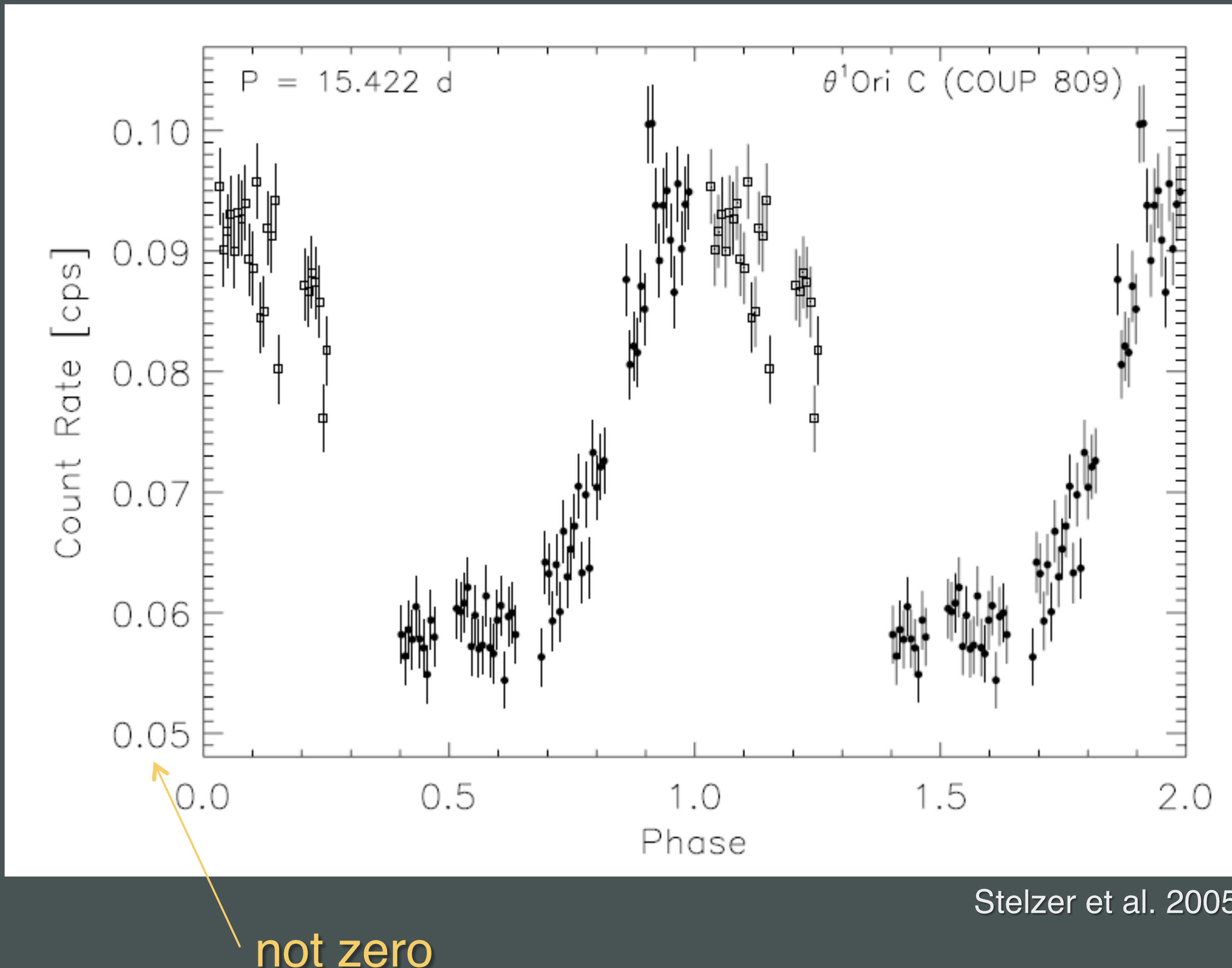
Color coded according to photon energy (red: <1keV; green 1 to 2 keV; blue > 2 keV)

Movie from the COUP team: astro.swarthmore.edu/~cohen/presentations/MiMeS2/COUP_optical_xray_m3.mov



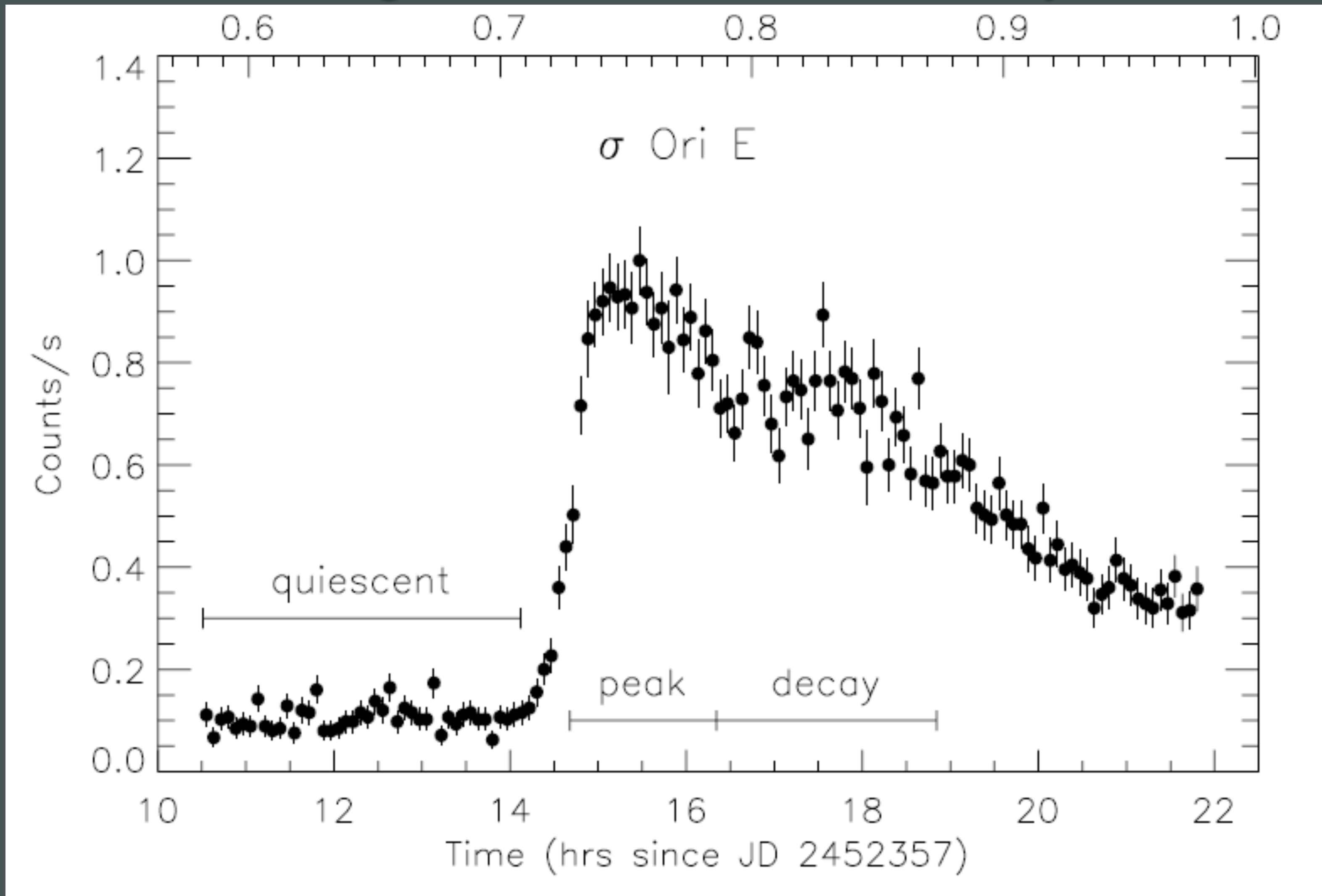
Movie from the COUP team: astro.swarthmore.edu/~cohen/presentations/MiMeS2/COUP_variability_m2.mpg

θ^1 Ori C: X-ray lightcurve – periodic variability



Stelzer et al. 2005

σ Ori E: *XMM* light curve: flare-like variability



Sanz-Forcada et al. 2004

Centrifugally driven breakout (ud-Doula, Townsend, & Owocki 2006, ApJ, 640, L191)
…or low-mass binary companion?

XMM EPIC spectrum of σ Ori E

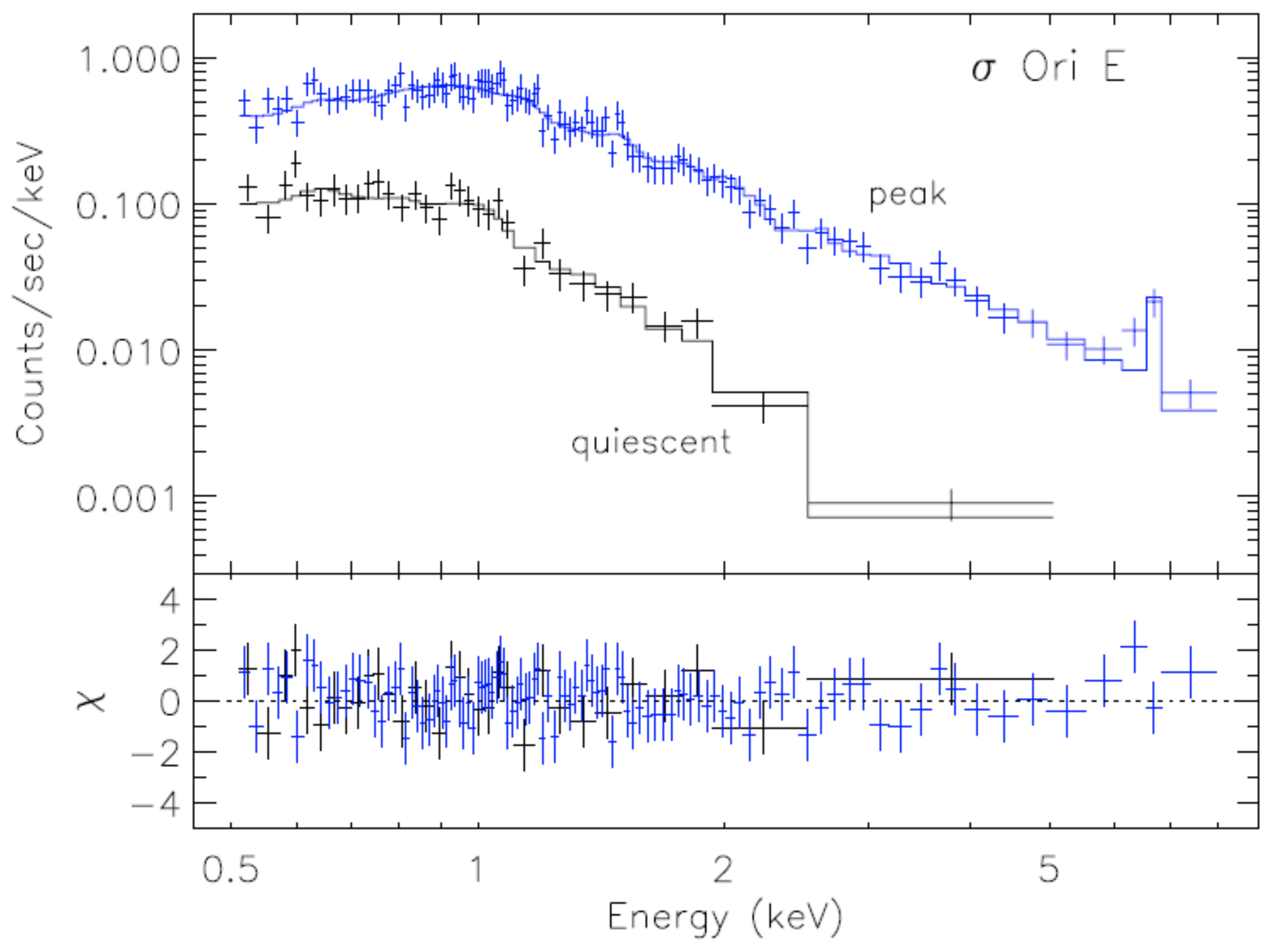
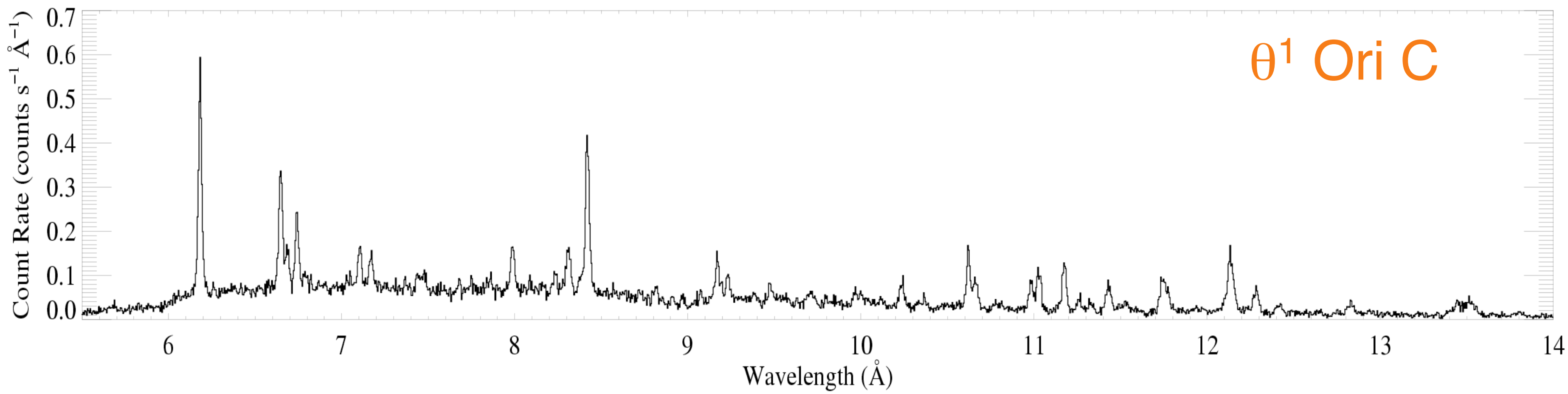
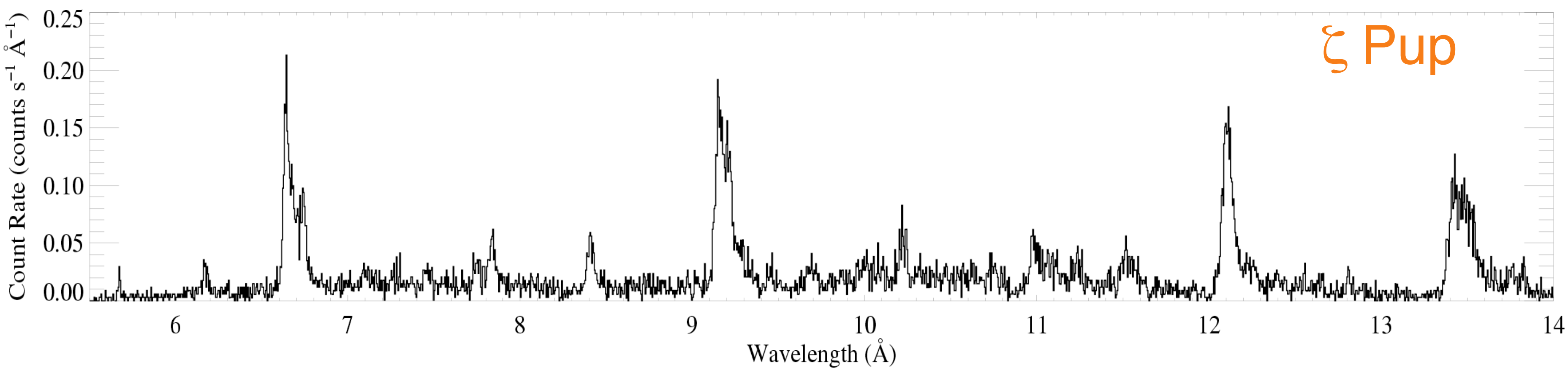


Fig. 9. PN spectra of σ Ori E during quiescence and at the peak of the flare. The best-fit model is also shown.

Sanz-Forcada et al. 2004

Chandra grating spectra: θ^1 Ori C and a non-magnetic O star





thermal emission

“coronal approximation” valid: electrons in ground state, collisions up, spontaneous emission down

optically thin

lines from highly stripped metals, weak bremsstrahlung continuum (continuum stronger for higher temperatures)

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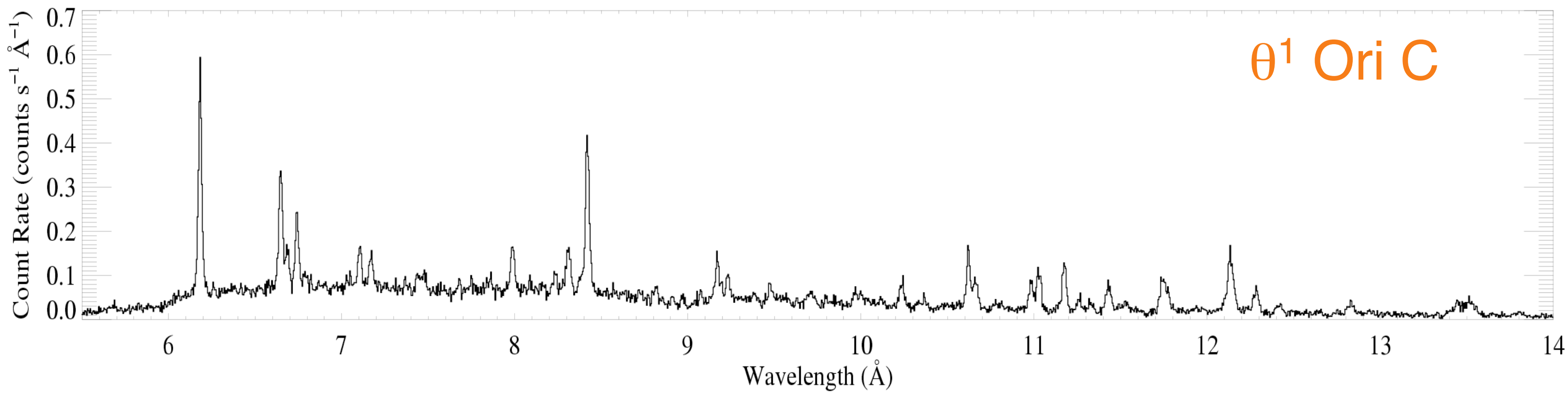
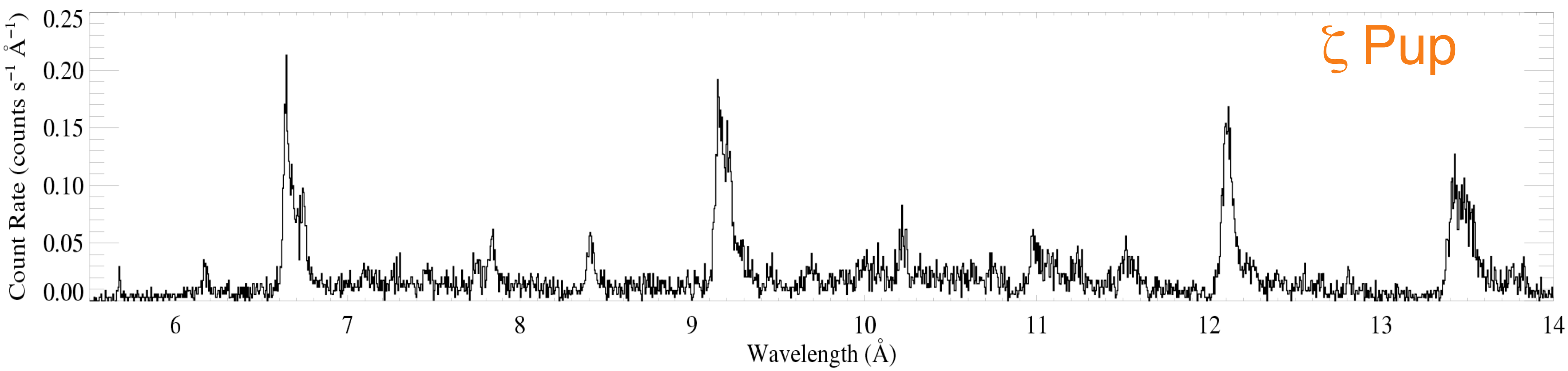
Chandra grating spectra: θ¹ Ori C and a non-magnetic O star





Energy Considerations and Scalings

1 keV ~ 12 × 10^6 K ~ 12 Å

Shock heating: Δv = 300 km/s
gives T ~ 10^6 K (and T ~ v^2)

ROSAT 150 eV to 2 keV
Chandra, *XMM* 350 eV to 10 keV

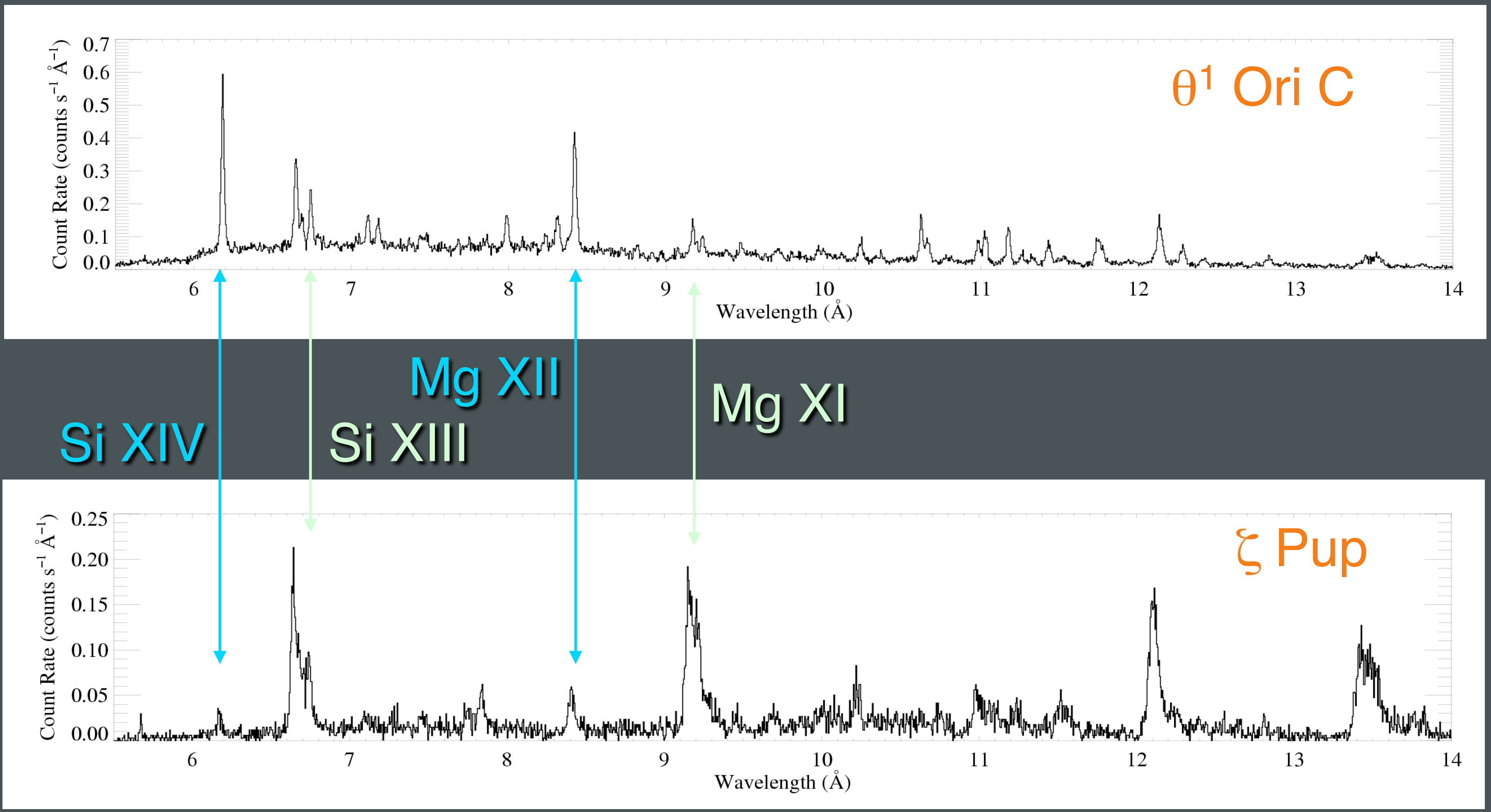
Energy Considerations and Scalings

1 keV ~ 12 × 10^6 K ~ 12 Å

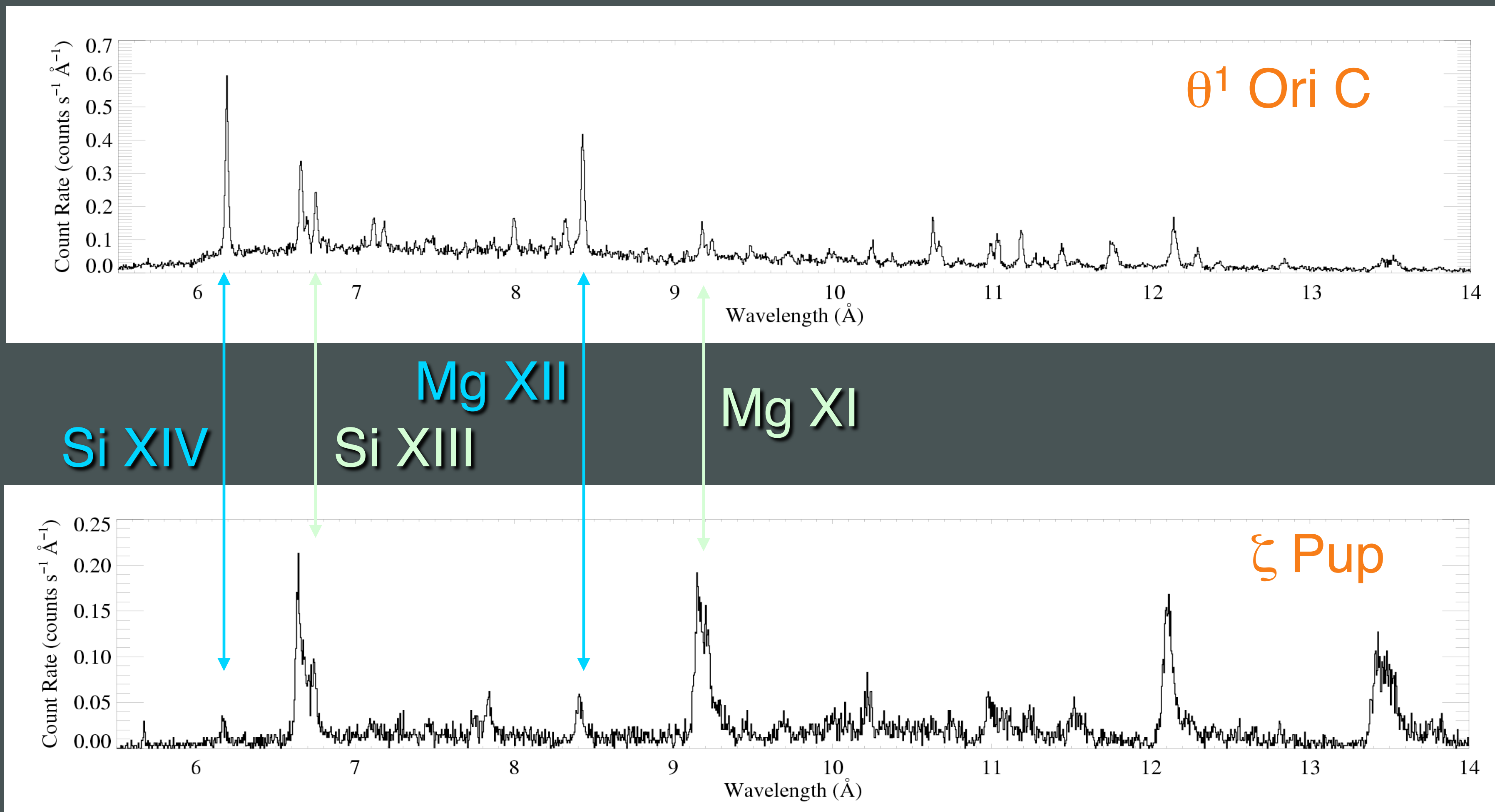
Shock heating: Δv = 1000 km/s
gives T ~ 10^7 K (and T ~ v^2)

ROSAT 150 eV to 2 keV
Chandra, *XMM* 350 eV to 10 keV

H-like/He-like ratio is temperature sensitive



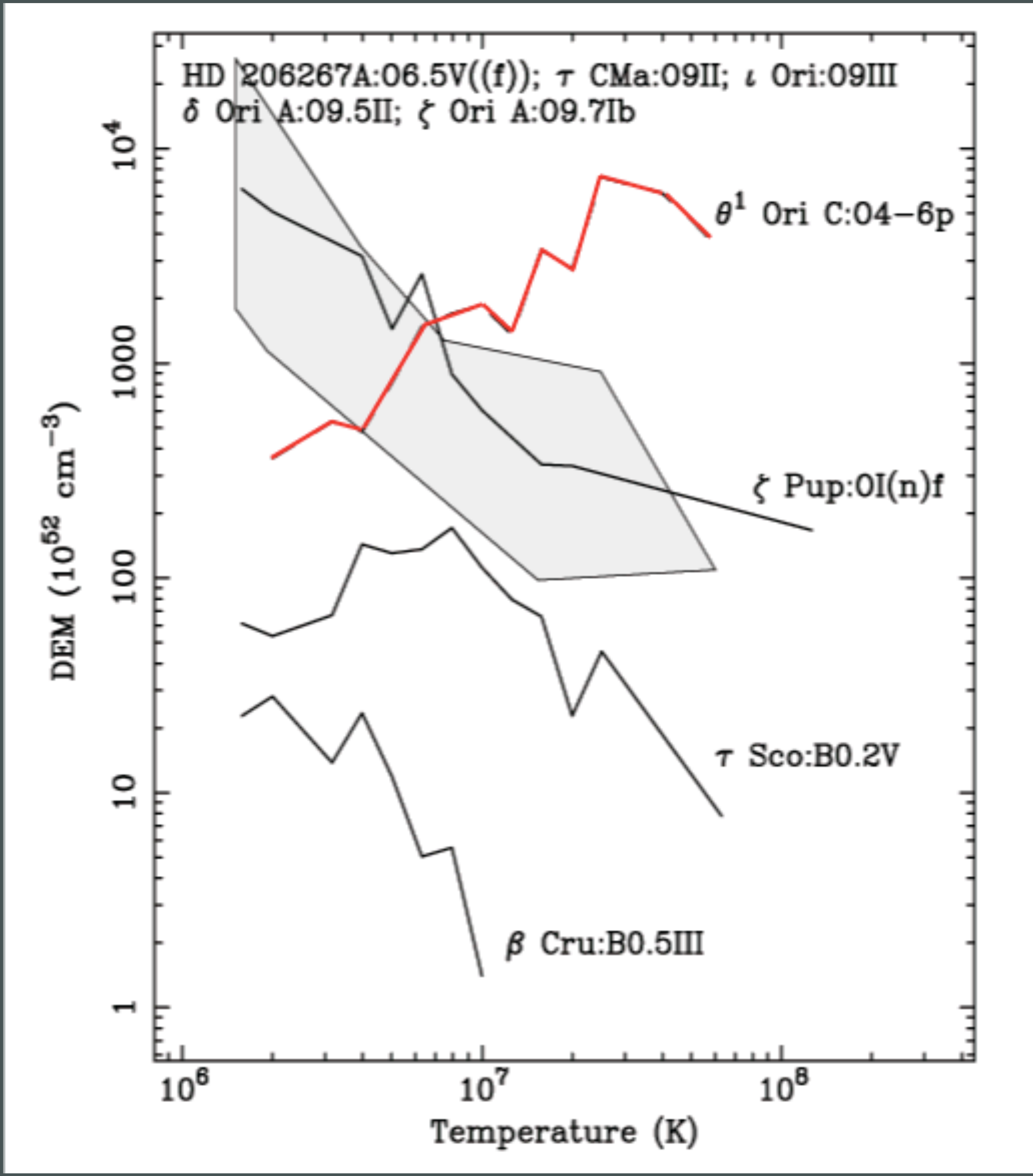
θ^1 Ori C – is hotter



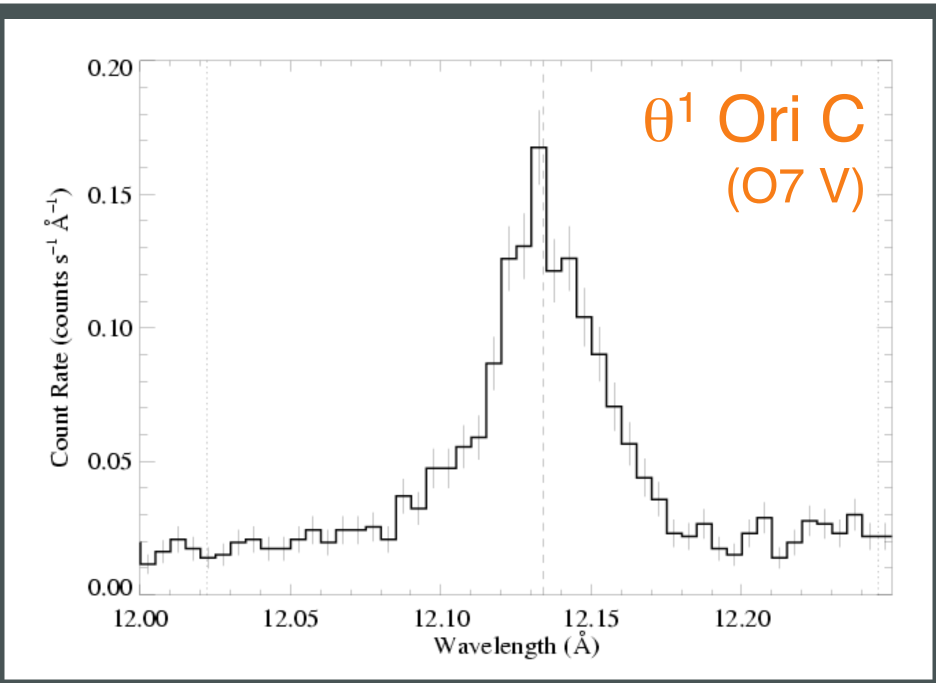
H/He > 1 in θ^1 Ori C

Differential Emission Measure
(temperature distribution)

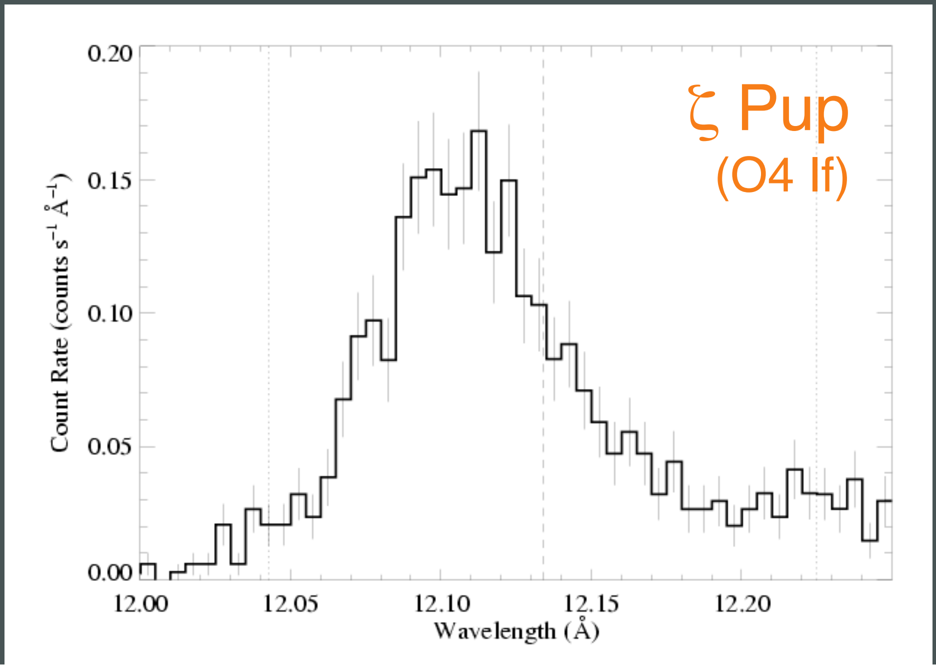
θ^1 Ori C is much hotter



Wojdowski & Schulz (2005)

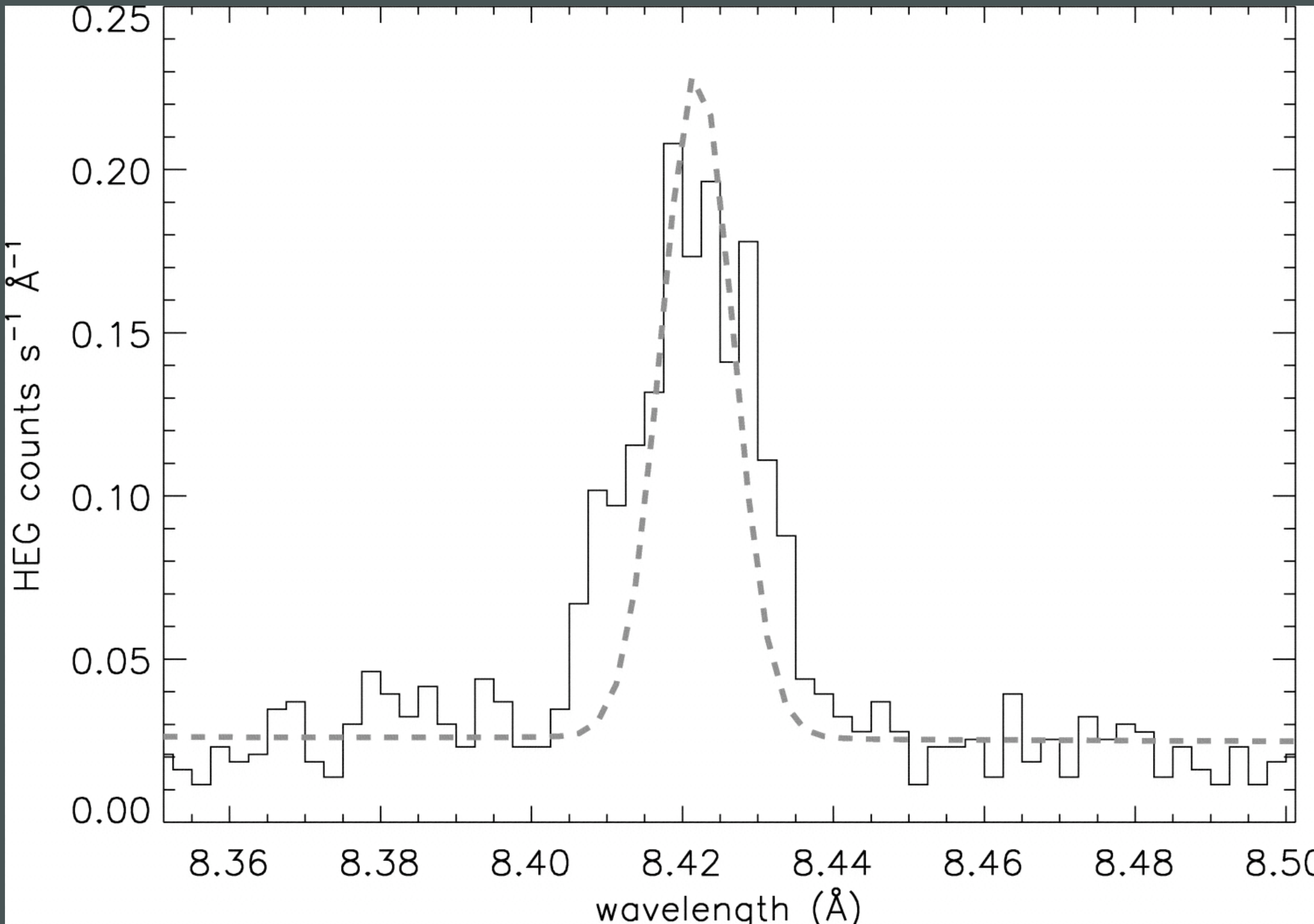


1000 km s-1

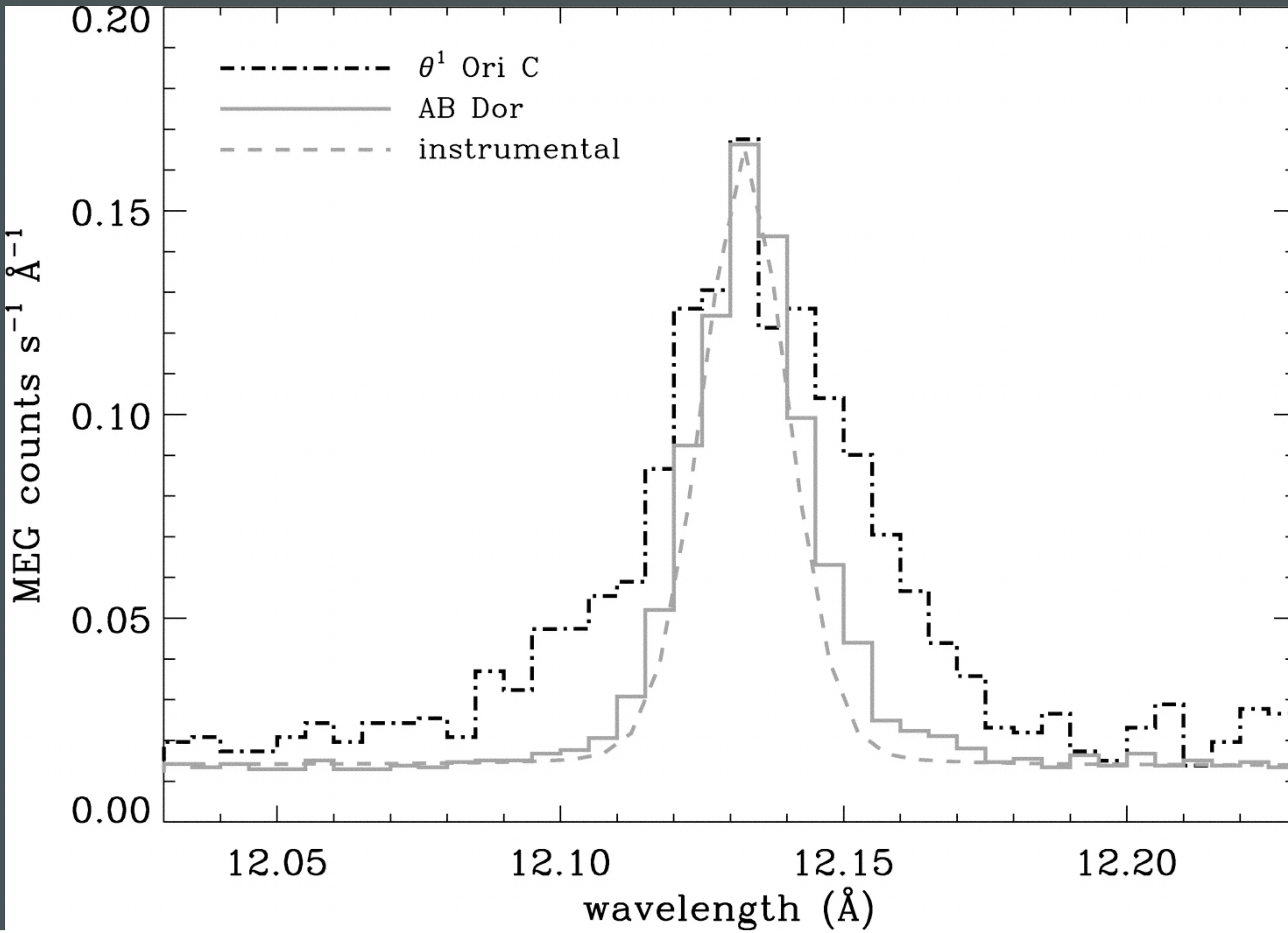


Emission lines are significantly **narrower**, too

Mg XII Ly-α in θ^1 Ori C compared to instrumental profile

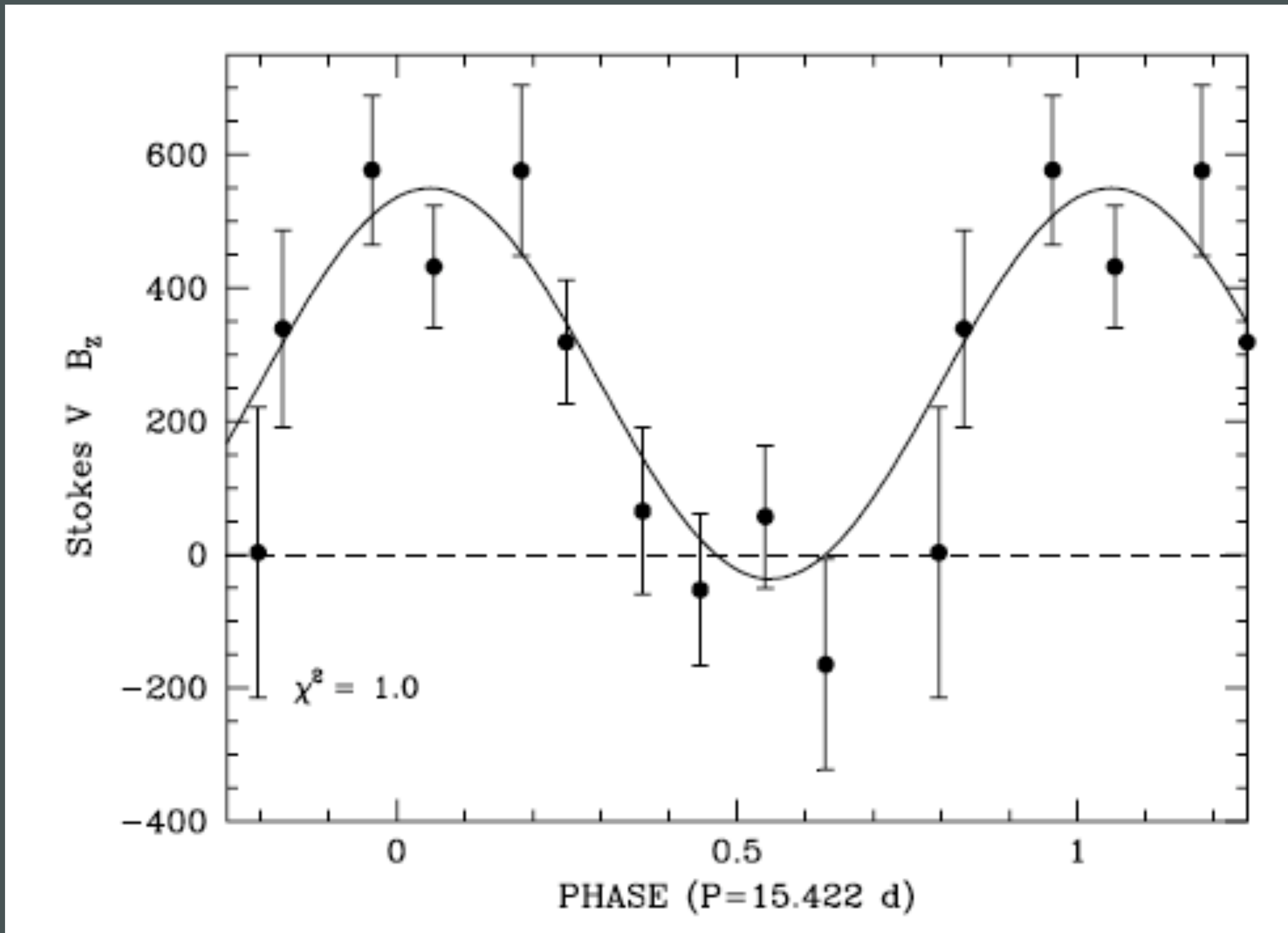


Ne X Ly-α in θ^1 Ori C : cooler plasma, broader – some contribution from "standard" instability wind shocks



The X-ray properties of θ^1 Ori C can be understood in the context of its magnetic field and the magnetically channeled wind shock (MCWS) mechanism

Dipole magnetic field



Wade et al. 2008

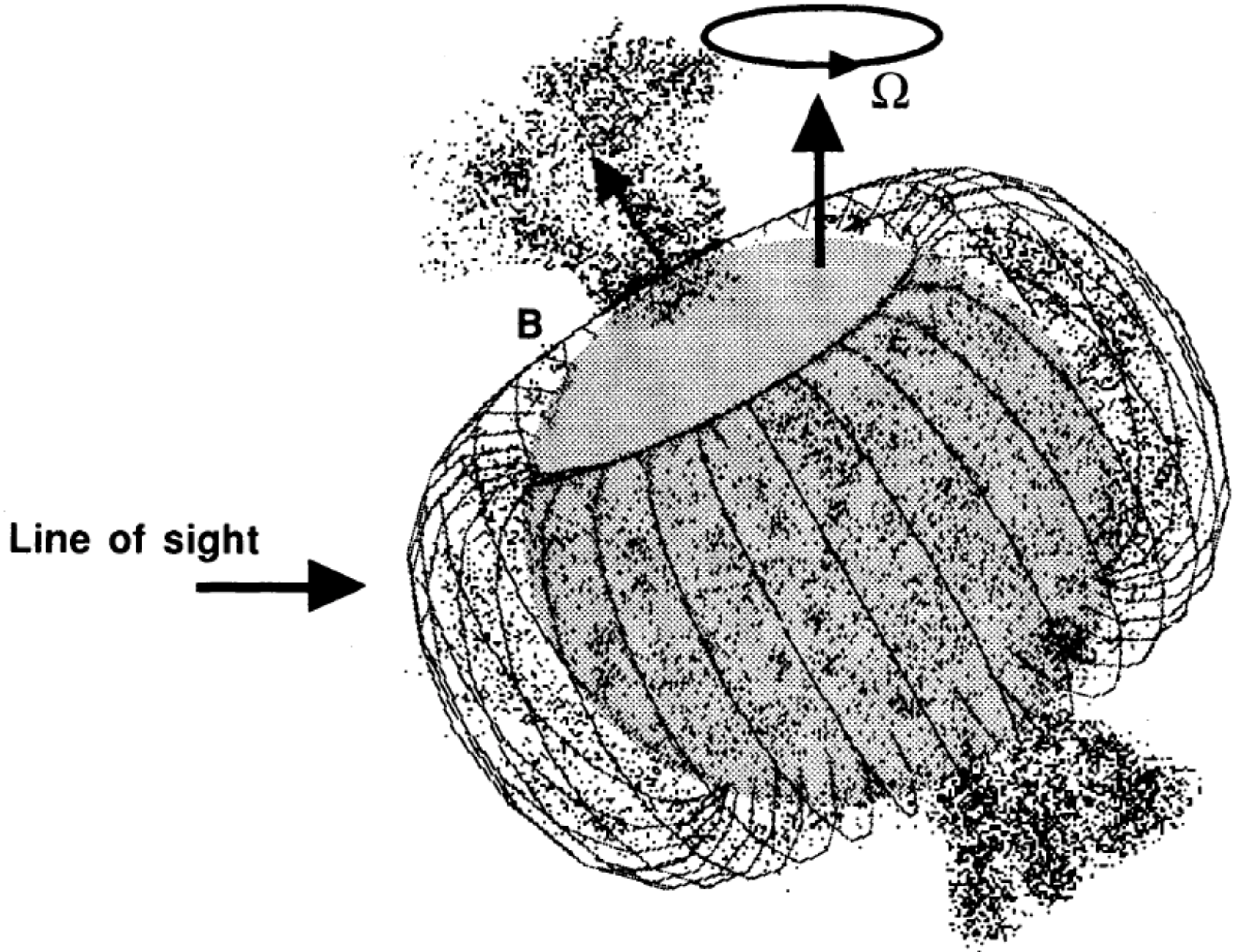


FIG. 11b

Shore & Brown, 1990

MCWS: Babel & Montmerle 1997

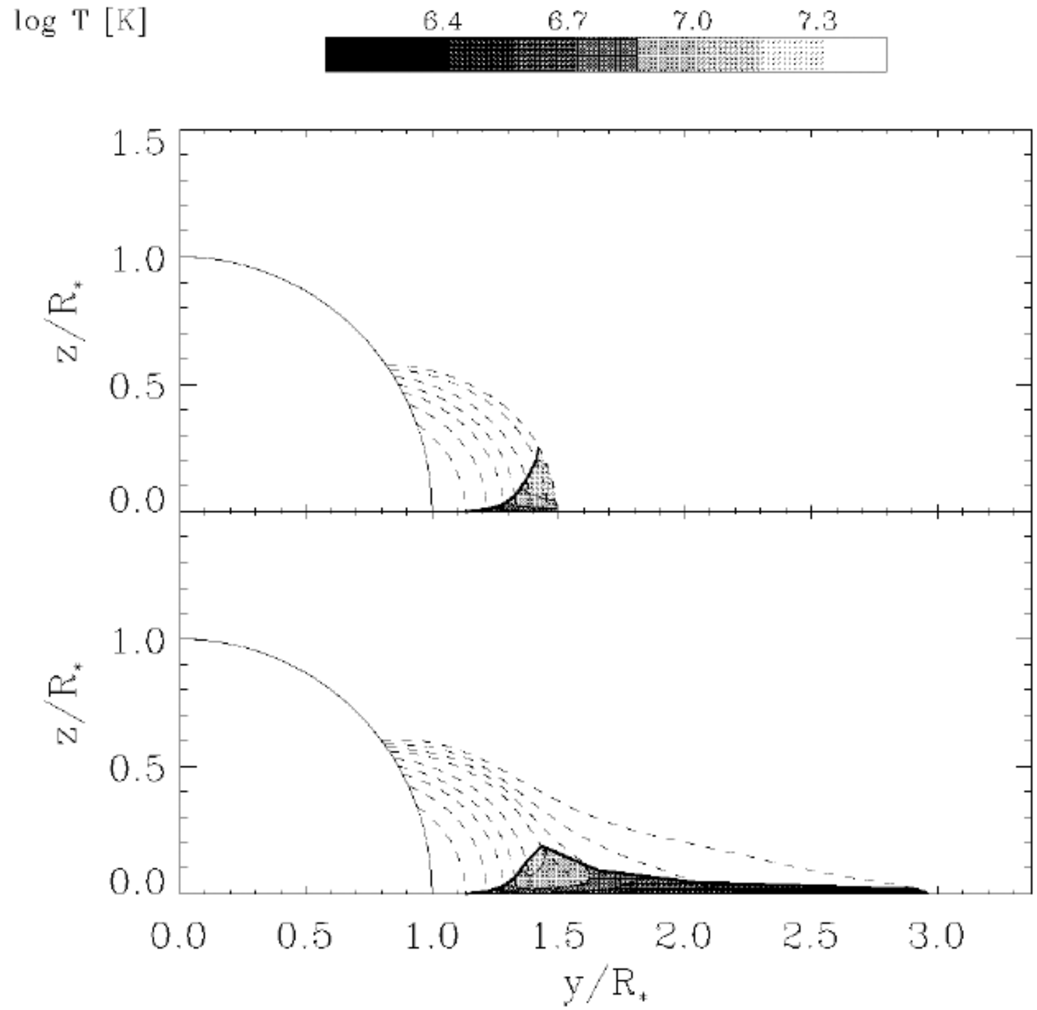
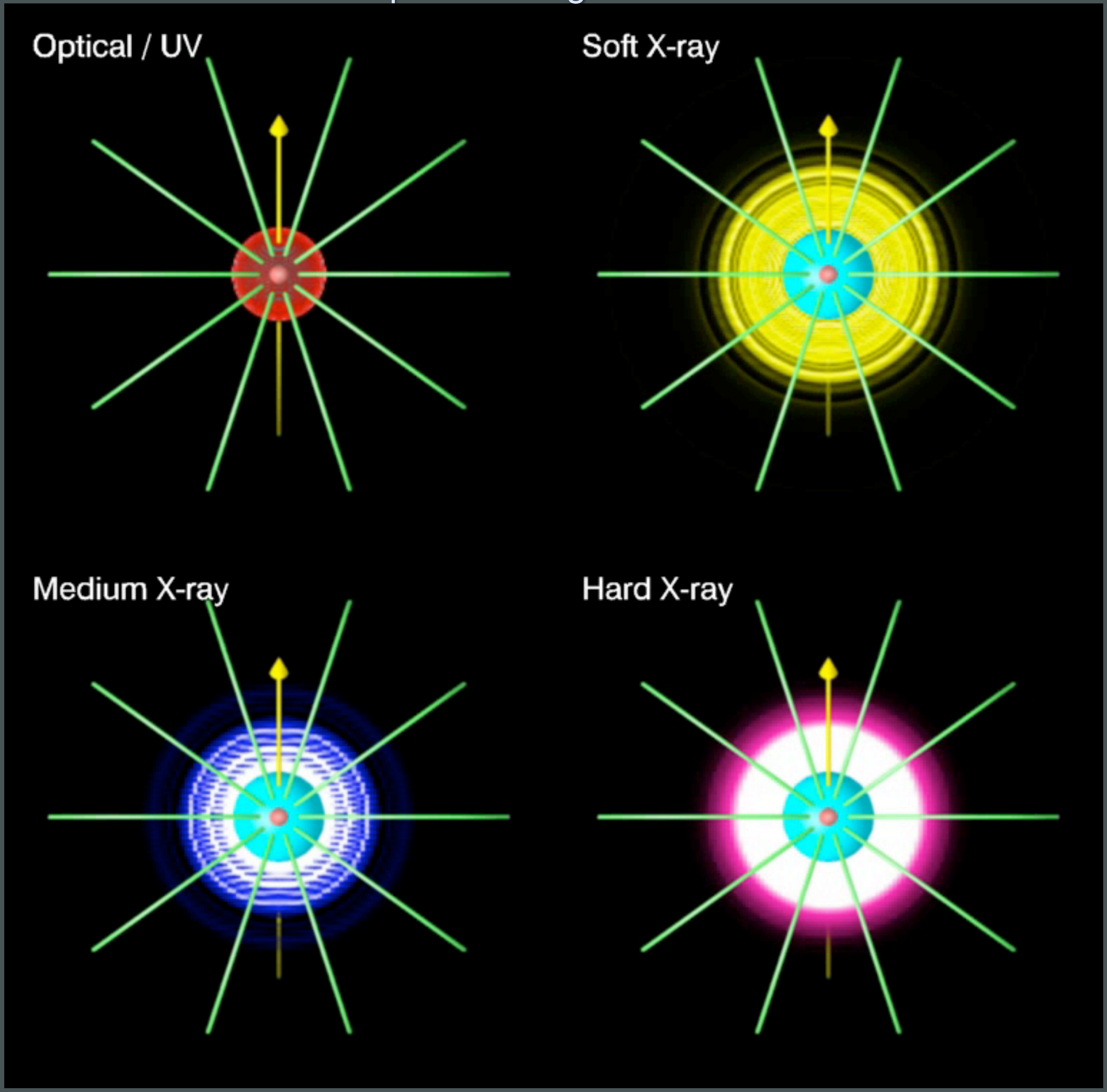


FIG. 1.—Temperature map for the postshock region in the approximation of a steady-state shock. The shock front is indicated by a heavy solid line and wind trajectories (or magnetic field lines) by dashed lines. *Upper panel:* closed magnetosphere, $L_A = 1.49$ ($B_*^e \simeq 370$ G). *Lower panel:* closed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

Dynamical models (ud-Doula; Townsend): color scale shows emission measure in different temperature regimes

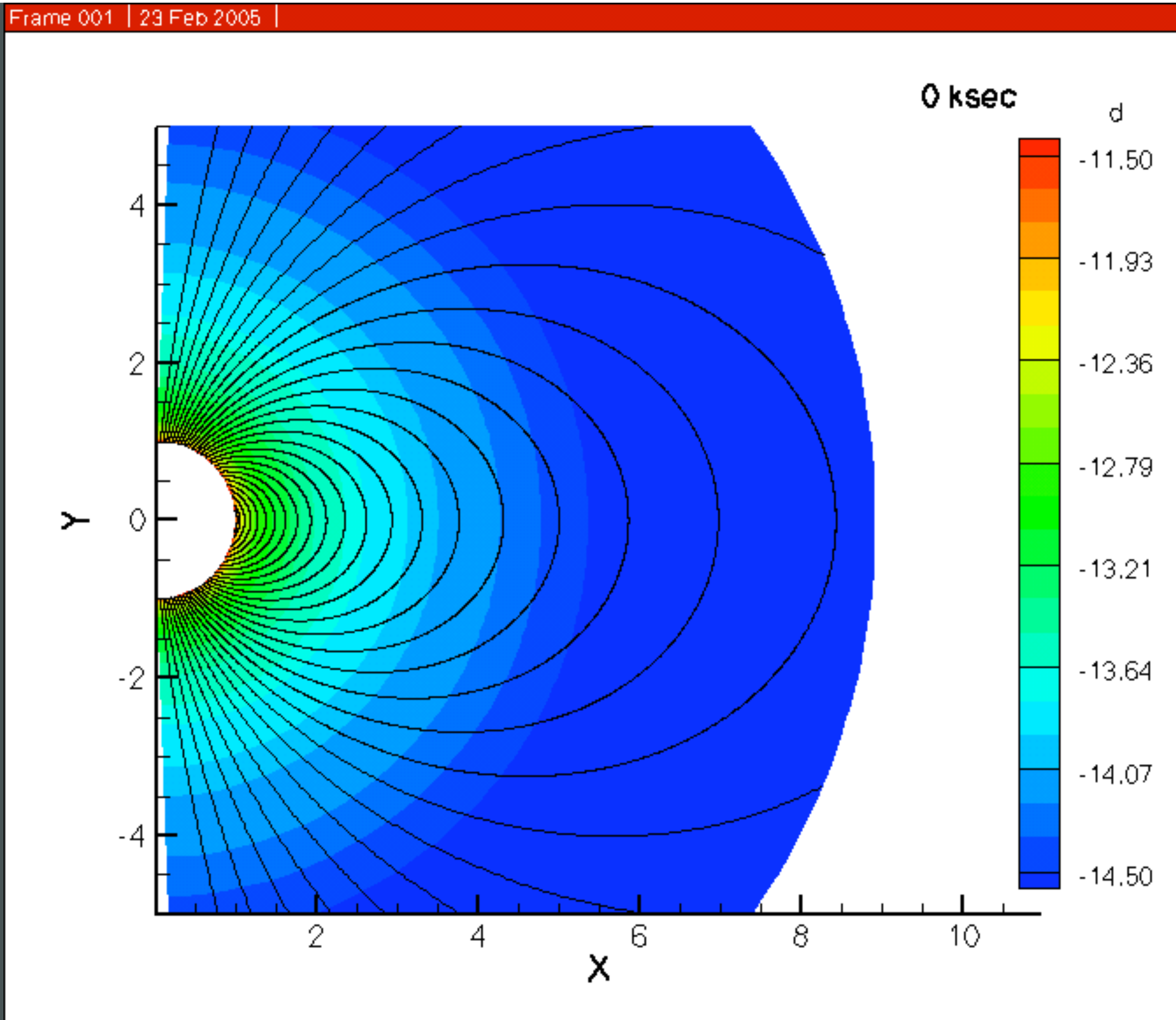


astro.swarthmore.edu/~cohen/presentations/MiMeS2/zeus-movie.avi

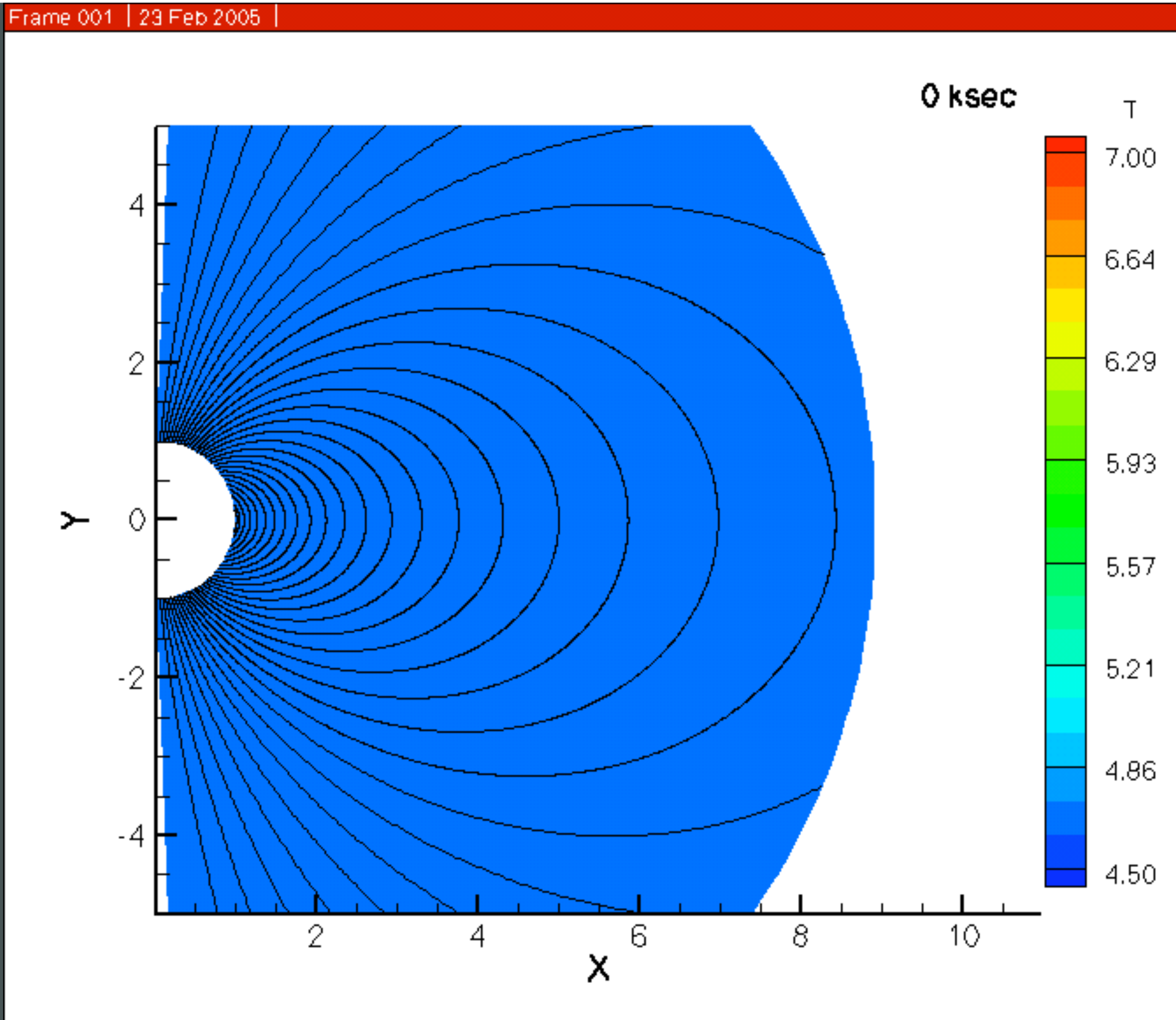
Looking at individual physical variables:

Note that the hot, post-shock plasma:

- has relatively low density,
- is concentrated near the tops of the largest closed-loop regions ($\sim 2R_{star}$),
- and is very slow moving (due to confinement)



Simulation/visualization courtesy A. ud-Doula
Movie available at astro.swarthmore.edu/~cohen/presentations/apip09/t1oc-lowvinf-logd.avi



Simulation/visualization courtesy A. ud-Doula

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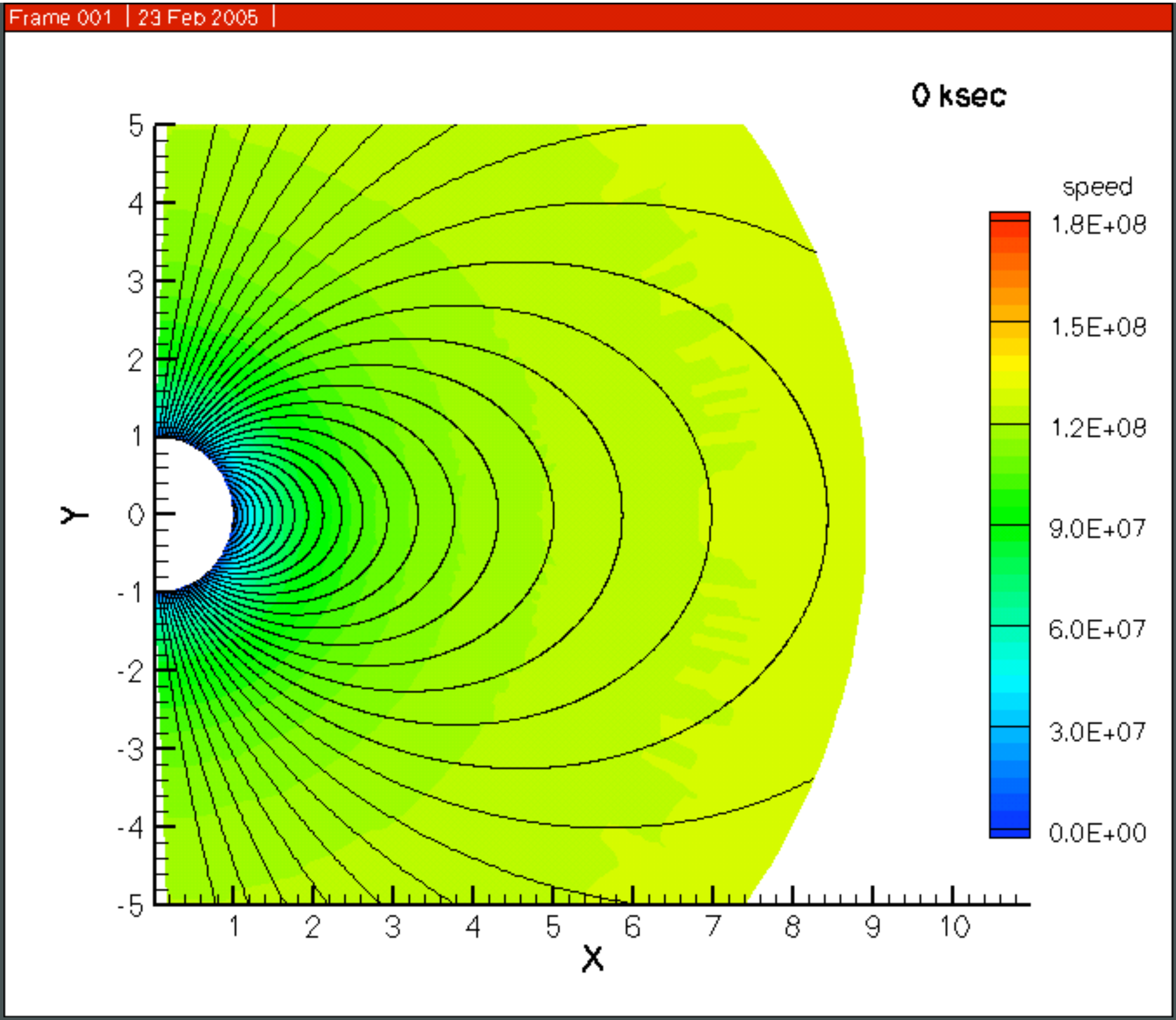
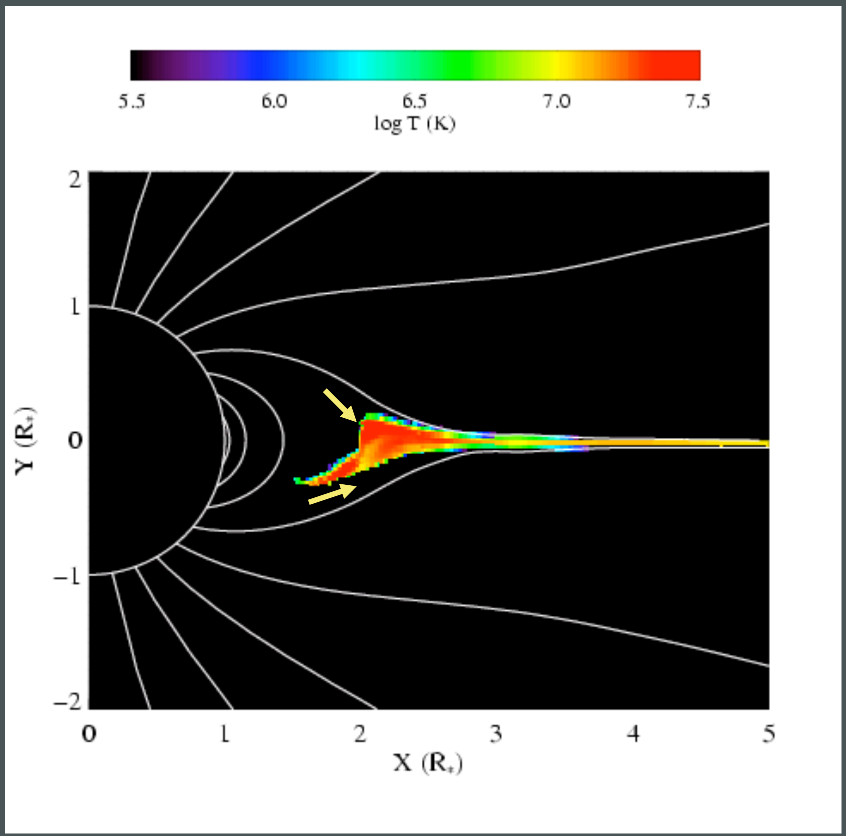


Simulation/visualization courtesy A. ud-Doula

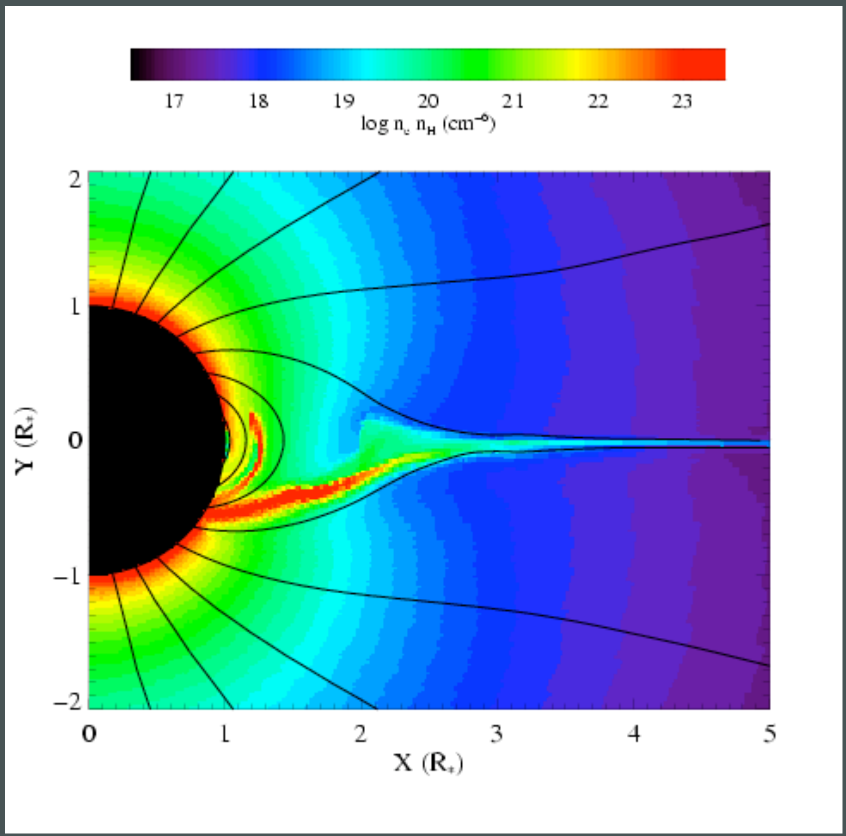
Movie available at astro.swarthmore.edu/~cohen/presentations/apip09/t1oc-lowvinf-speed.avi

MHD simulation summary

temperature



emission measure

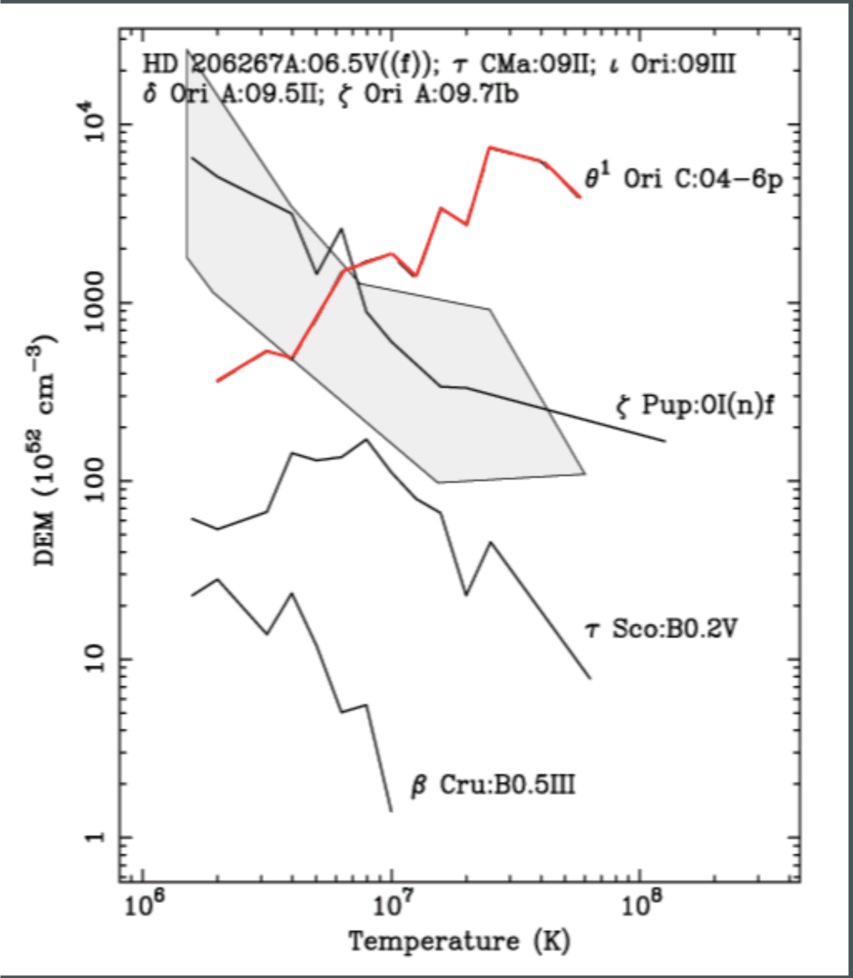


Gagné et al. (2005)

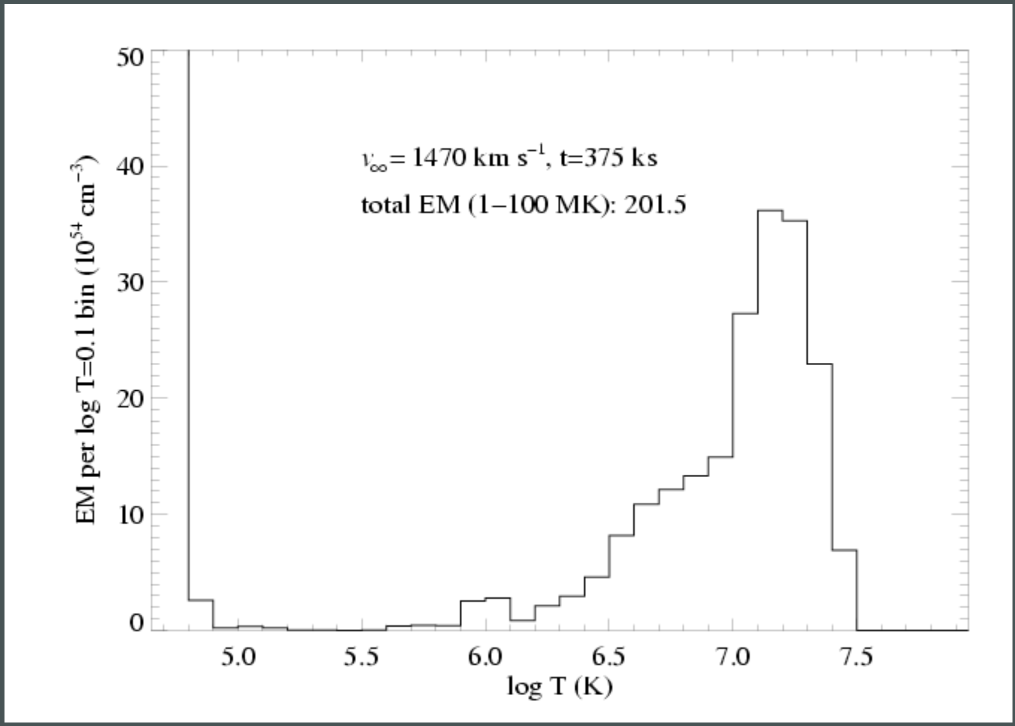
Channeled collision is close to head-on:

$\Delta v > 1000$ km s^{-1} : $T > 10^7$ K

Differential emission measure
(temperature distribution)



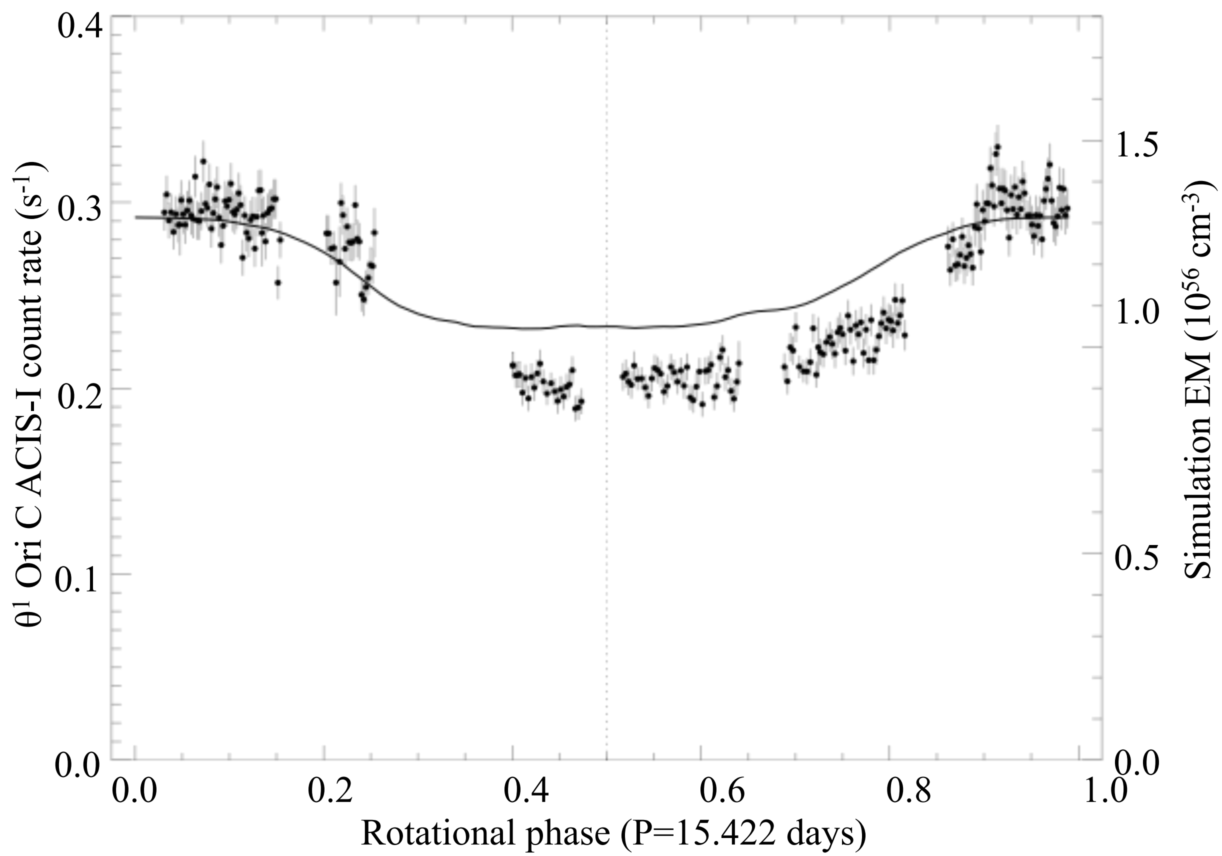
Wojdowski & Schulz (2005)



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

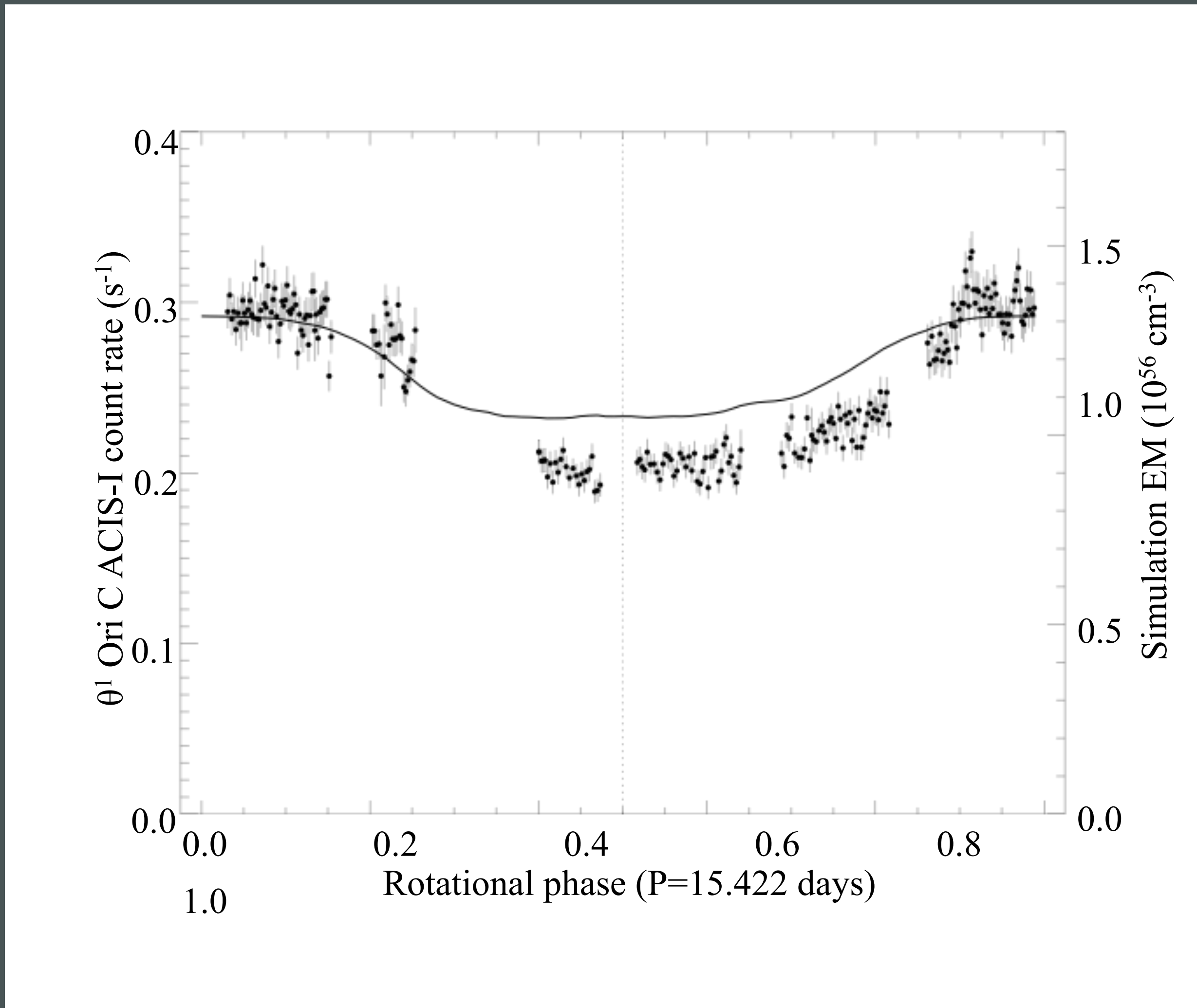
There are *Chandra* observations at many different phases

Chandra broadband count rate vs. rotational phase



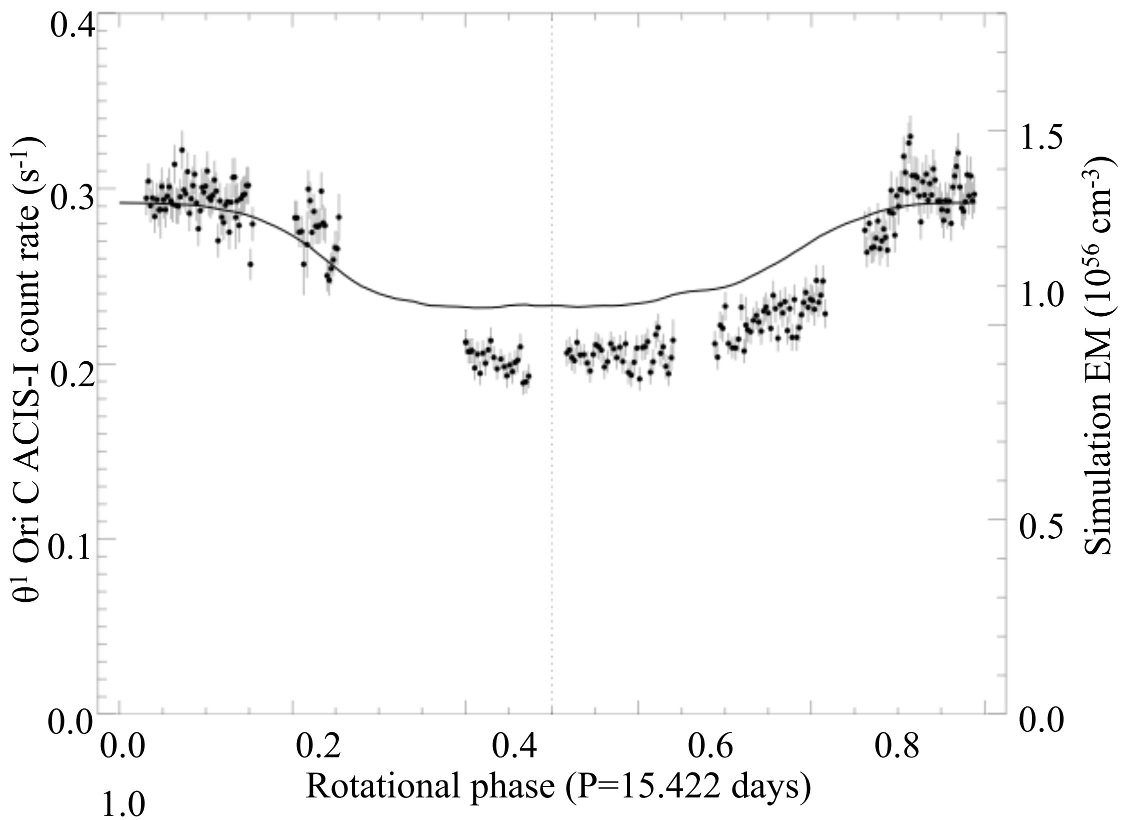
Model from MHD simulation

The star itself occults the hot plasma in the magnetosphere



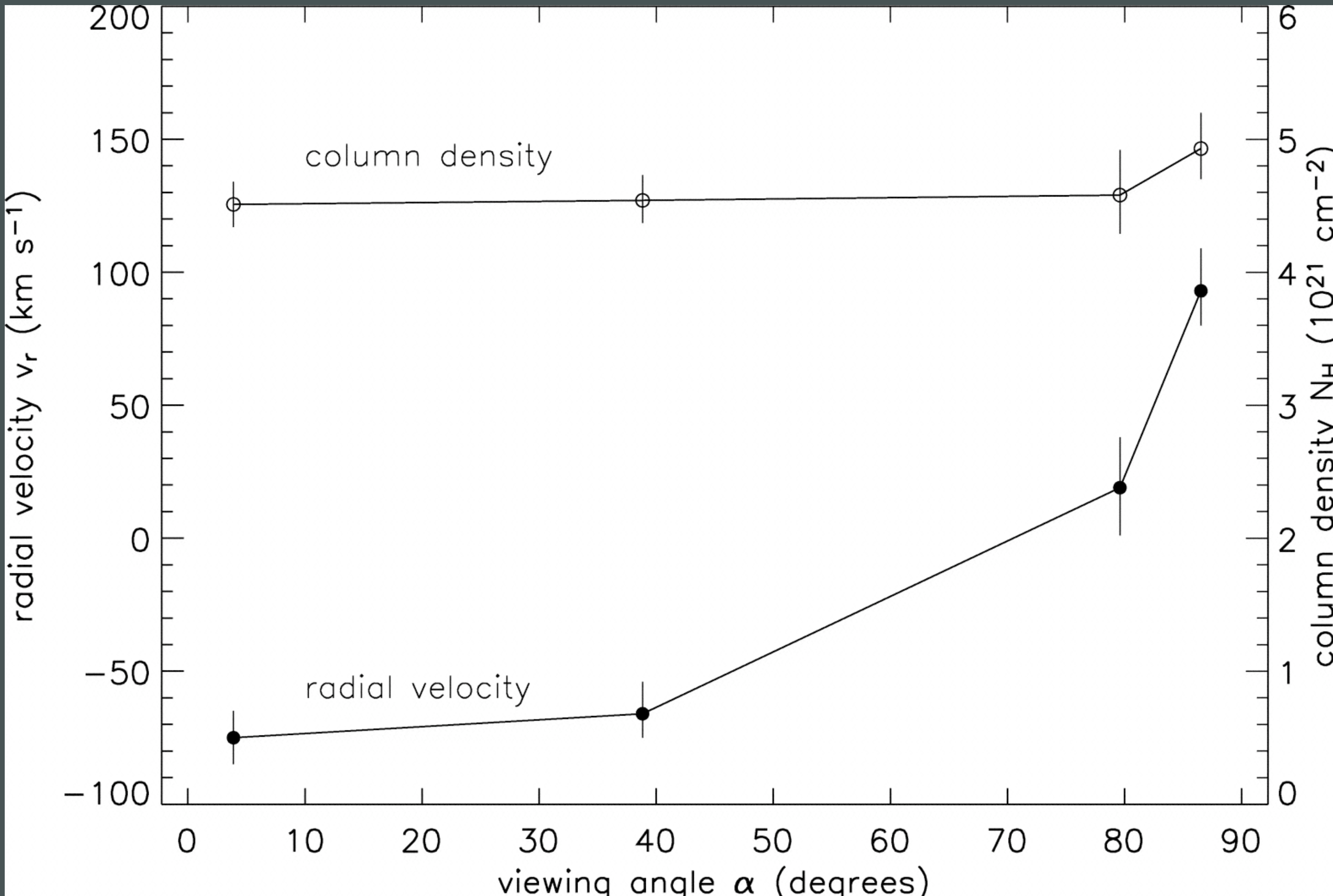
The closer the hot plasma is to the star, the deeper the dip in the x-ray light curve

The star itself occults the hot plasma in the magnetosphere



hot plasma is too far from the star in the simulation – the dip is not deep enough

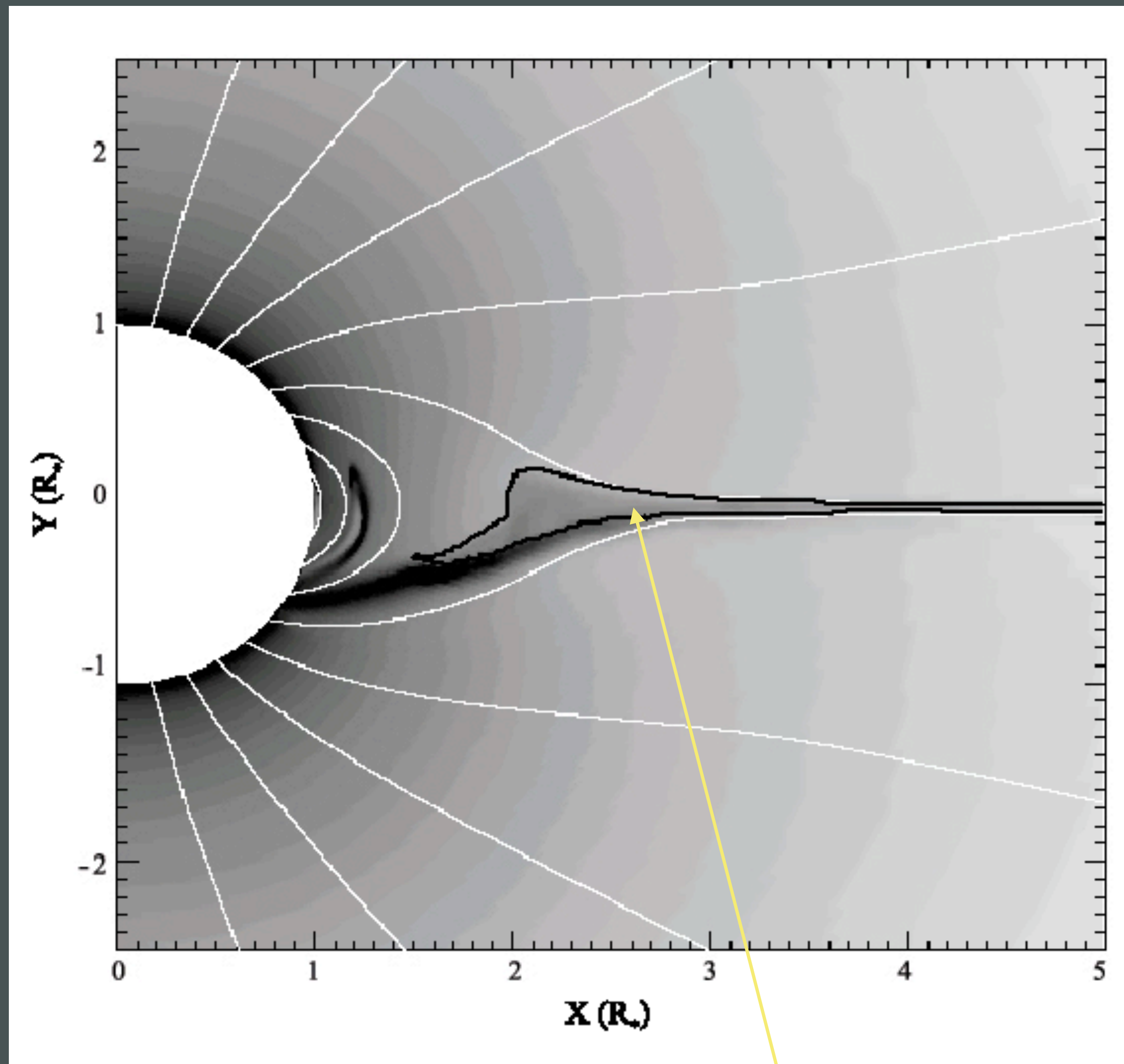
θ^1 Ori C column density (from x-ray absorption) vs. phase



pole-on

equator-on

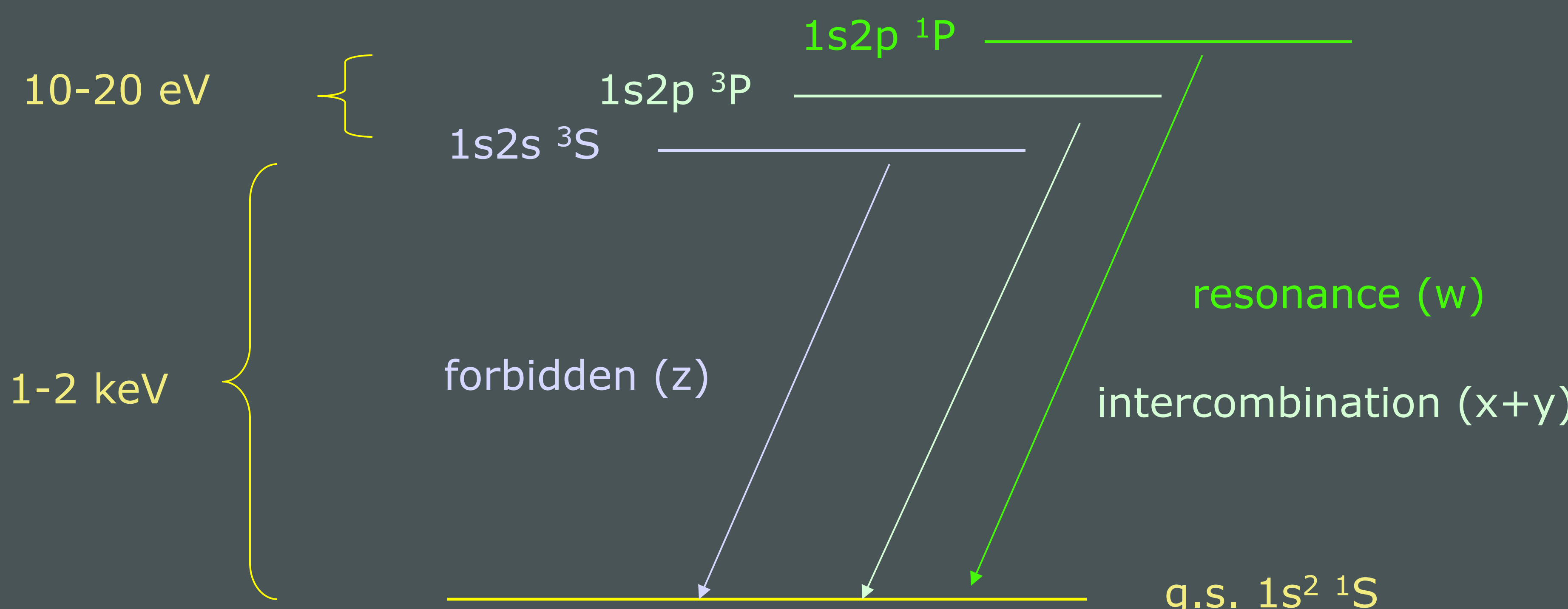
Emission measure



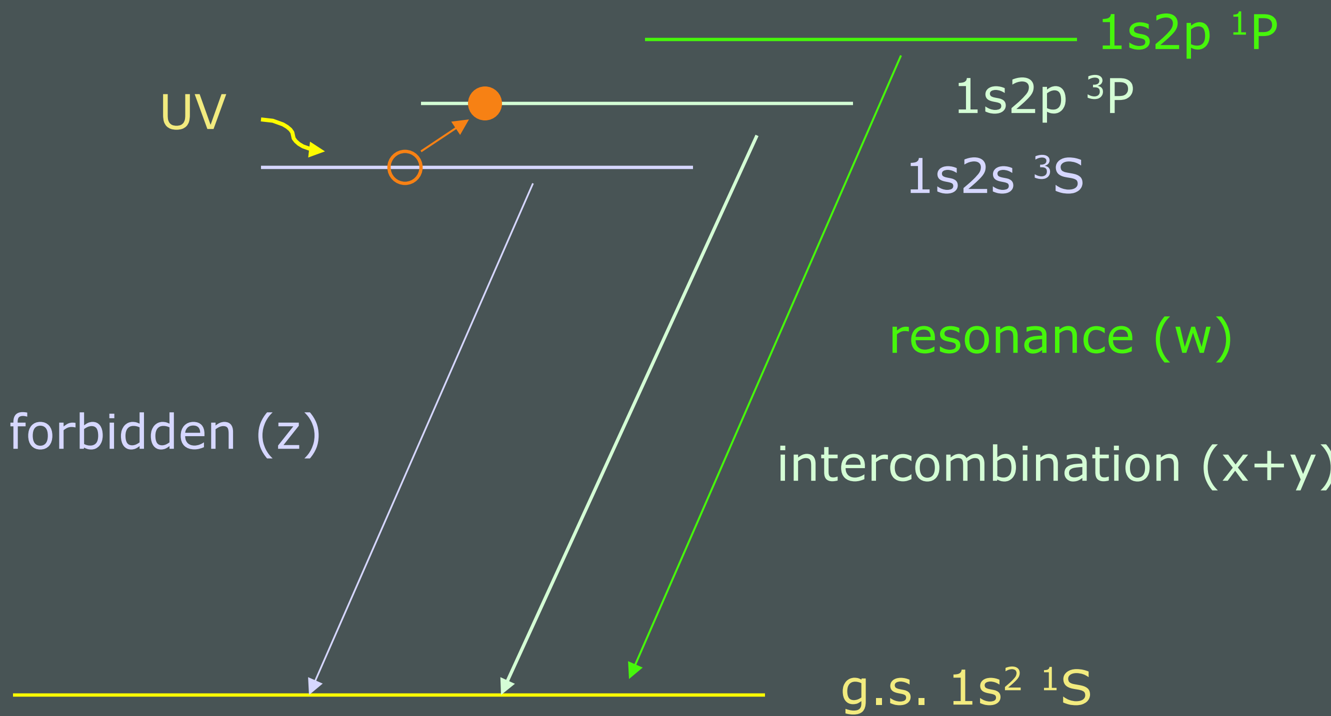
contour encloses $T > 10^6$ K

Helium-like species' forbidden-to-intercombination line ratios – *f/i* or z/*(x+y)* – provide information about the *location* of the hot plasma

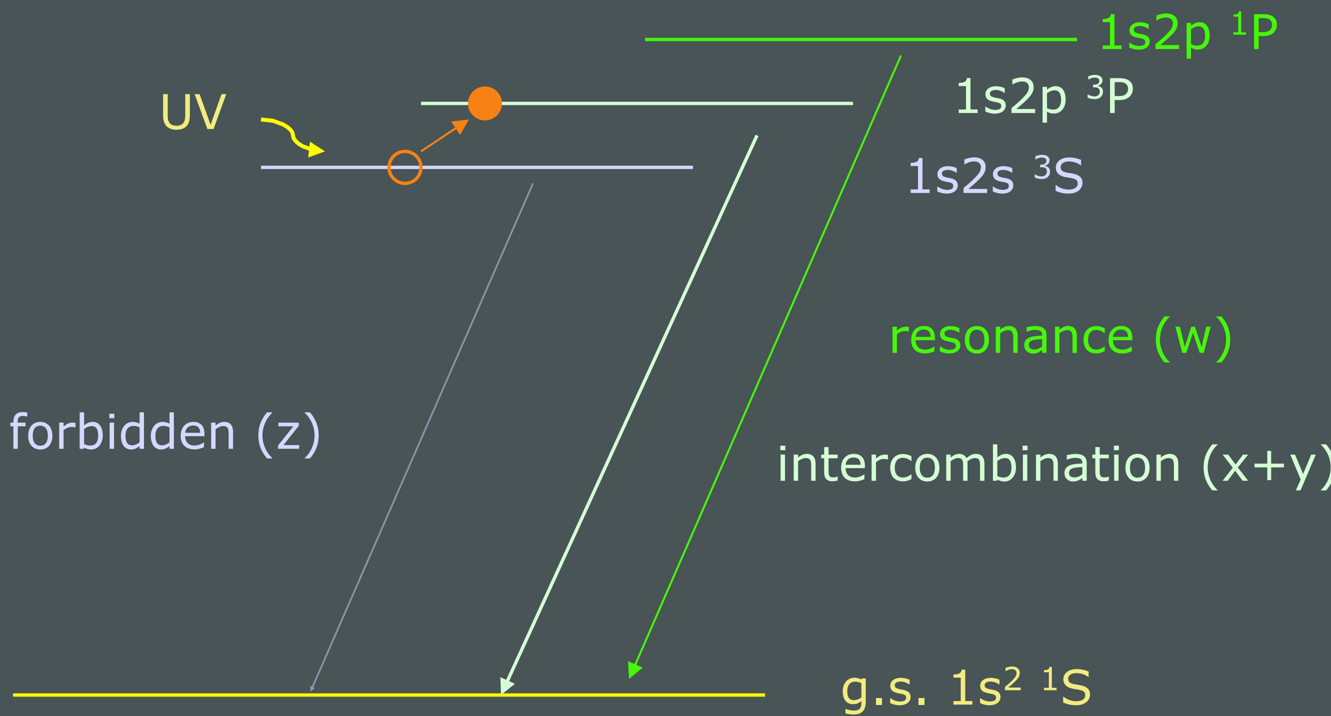
Helium-like ions (e.g. O^{+6}, Ne^{+8}, Mg^{+10}, Si^{+12}, S^{+14}) – schematic energy level diagram



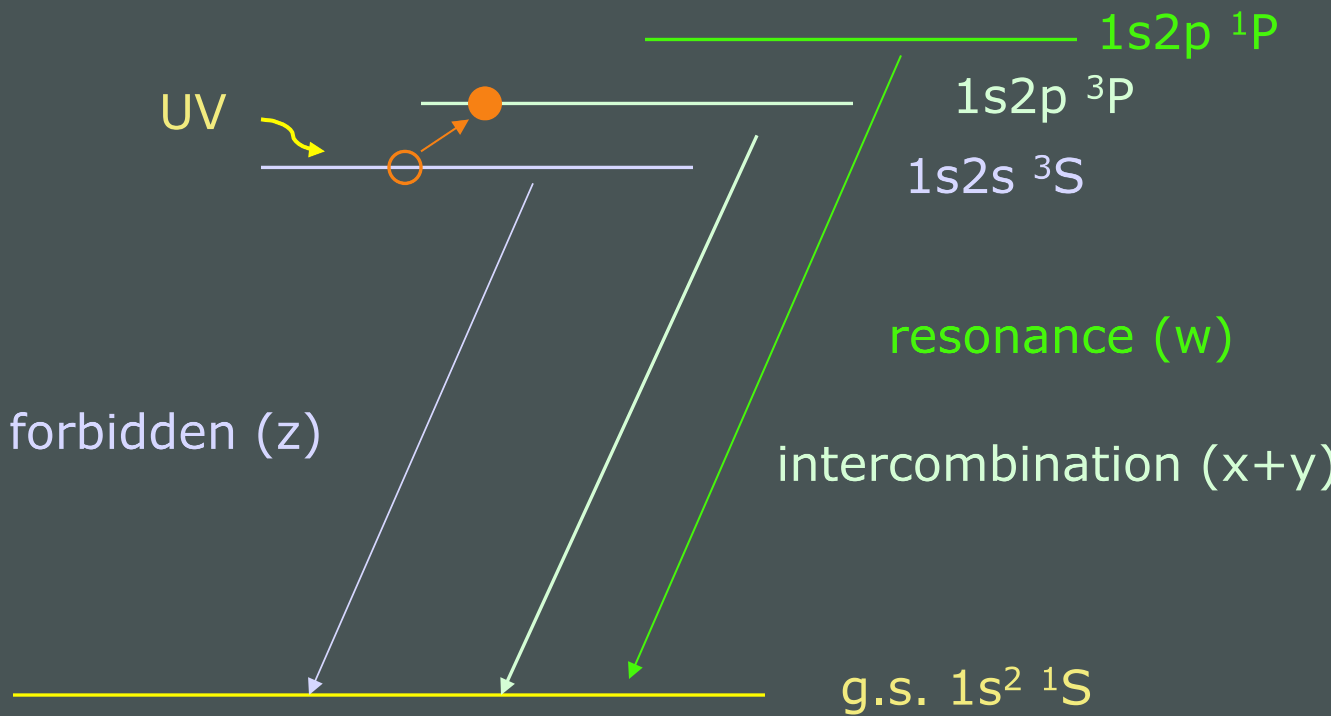
Ultraviolet light from the star's photosphere drives photoexcitation out of the ^3S level



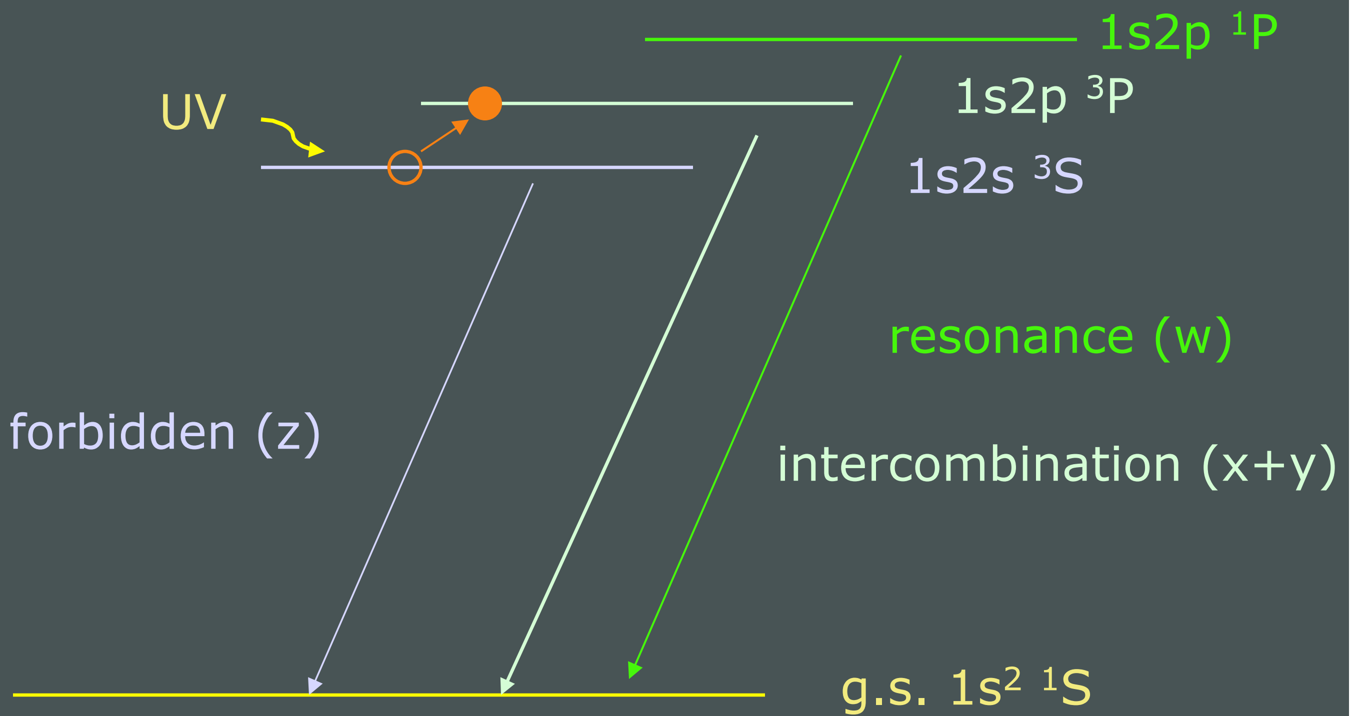
Weakening the forbidden line and strengthening the intercombination line

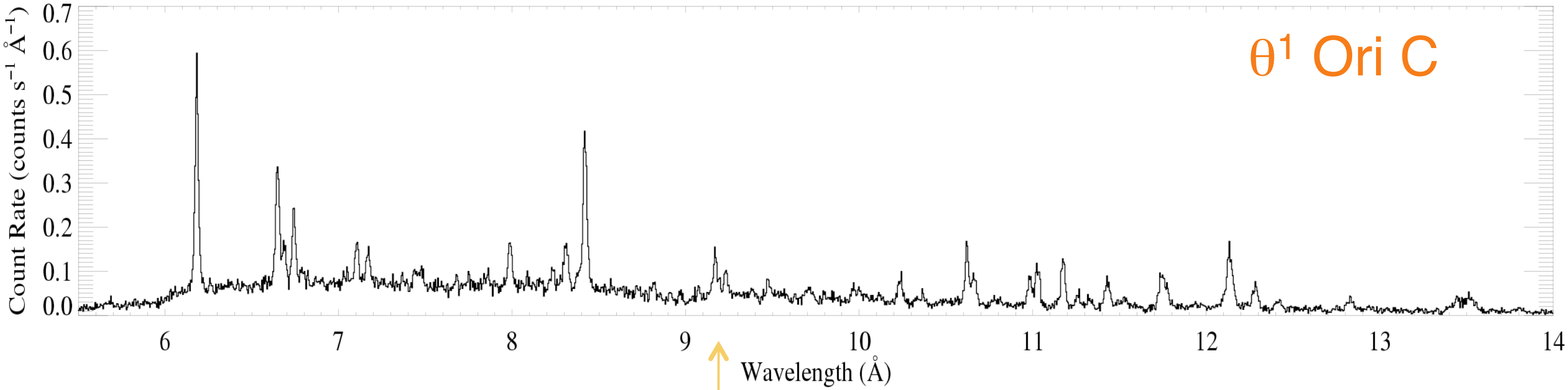


The f/i ratio is thus a diagnostic of the local UV mean intensity…

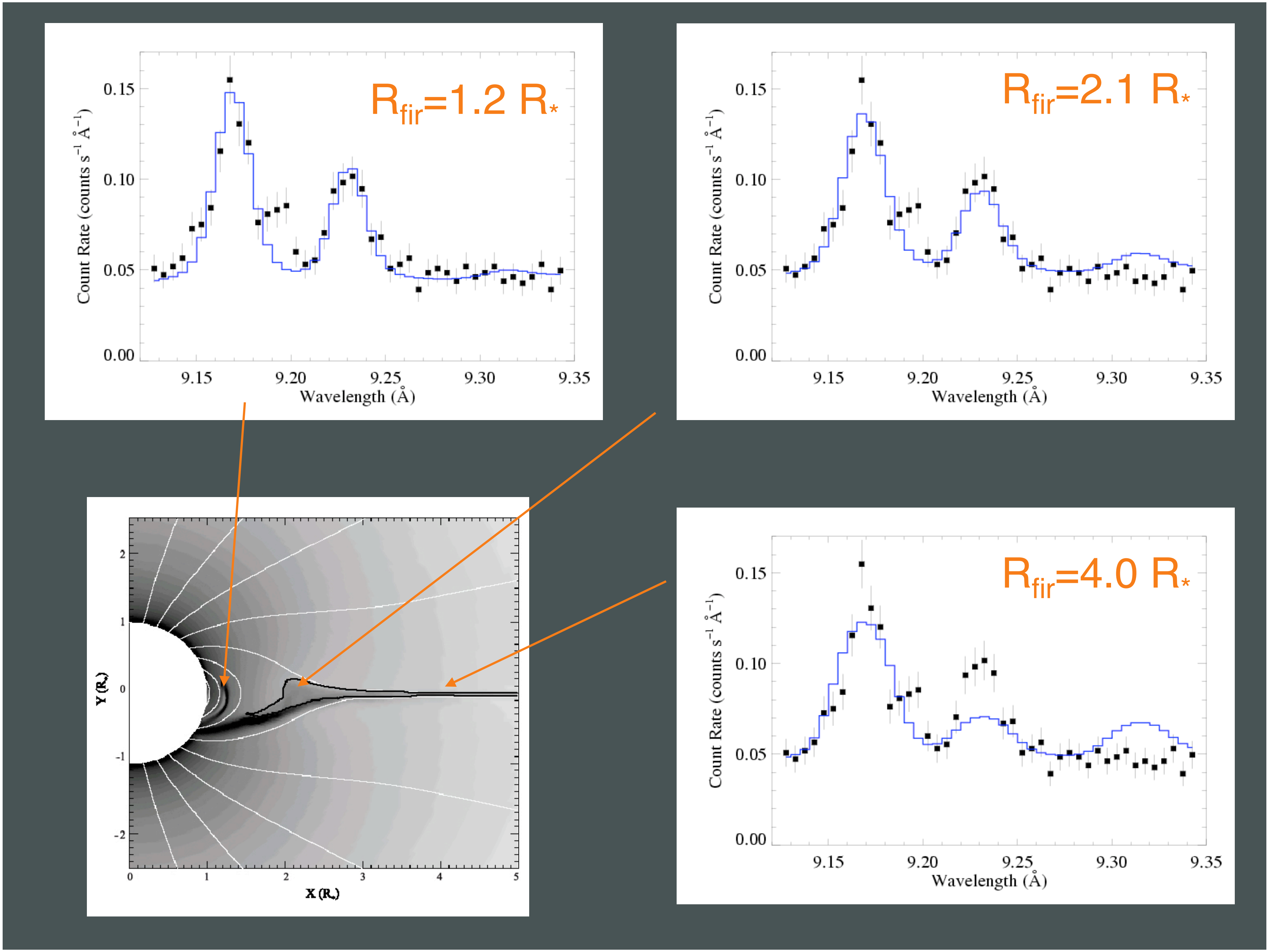


…and thus the distance of the x-ray emitting plasma from the photosphere




θ1 Ori C
Count Rate (counts s−1 Å−1)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
6
7
8
9
10
11
12
13
14
Wavelength (Å)

Mg XI



Rfir=1.2 R*
Rfir=2.1 R*
Rfir=4.0 R*
Count Rate (counts s−1 Å−1)
Wavelength (Å)
0.00
0.05
0.10
0.15
9.15
9.20
9.25
9.30
9.35
Y (R*)
X (R*)

He-like f/i ratios and the x-ray light curve both indicate that the hot plasma is somewhat closer to the photosphere of θ^1 Ori C than the MHD models predict.

So, in θ^1 Ori C, the X-rays tell us about the magnetospheric conditions in several ways:

- High X-ray luminosity
- X-ray hardness (high plasma temperatures)
- Periodic variability (rotation and occultation)
- Narrow emission lines (confinement)
- f/i ratios quantify location

What about other magnetic massive stars?

What about **confinement**?

Recall: $$\eta_* \equiv \frac{B^2 R_*^2}{\dot{M} v_\infty}$$

θ^1 Ori C: $\eta_* \sim 20$: decent confinement

What about **confinement**?

Recall:

$$\eta_* \equiv \frac{B^2 R_*^2}{\dot{M} v_\infty}$$

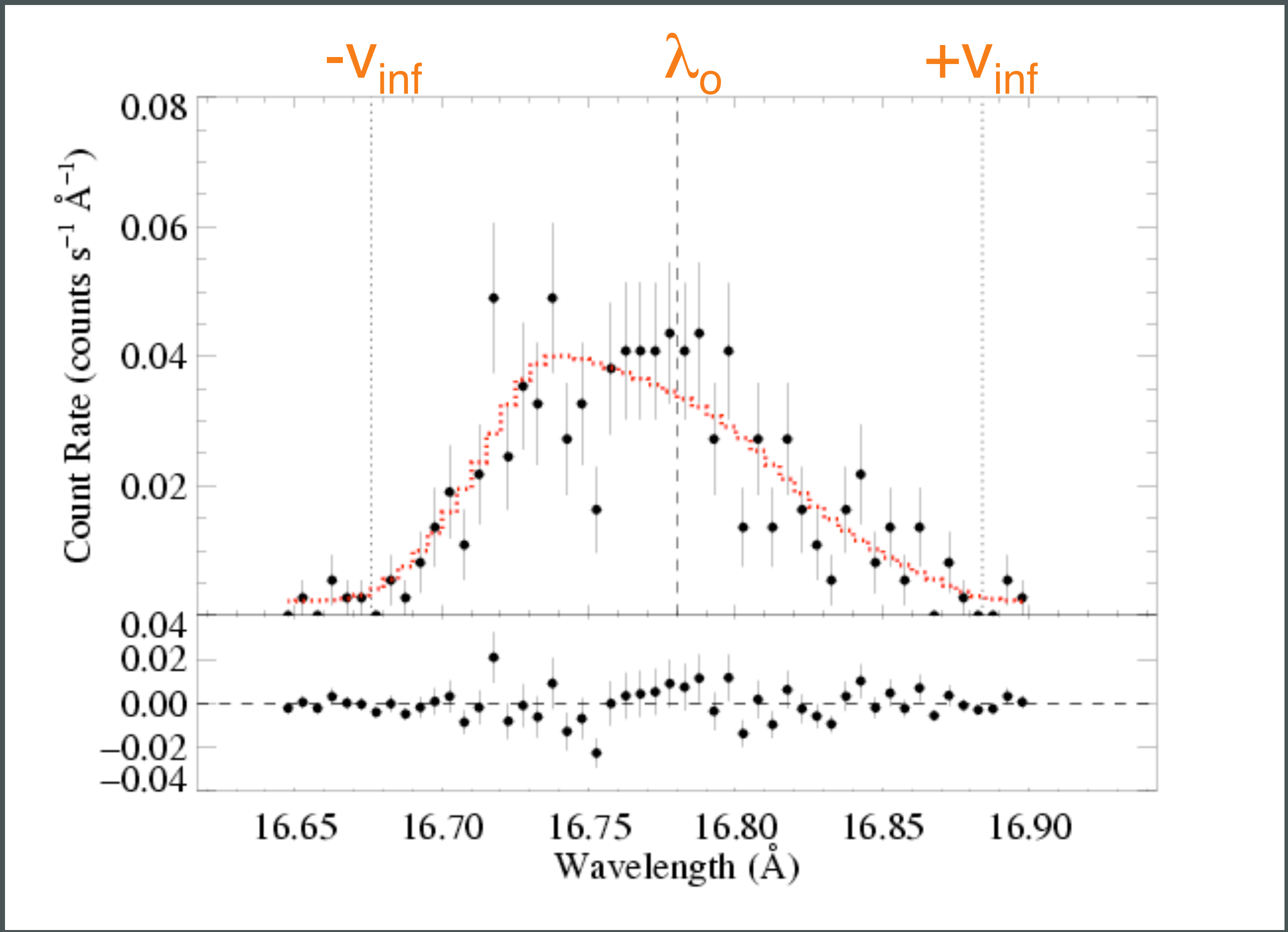
ζ Ori: $\eta_* \sim 0.1$: poor confinement

θ^1 Ori C: $\eta_* \sim 20$: decent confinement

σ Ori E: $\eta_* \sim 10^7$: excellent confinement

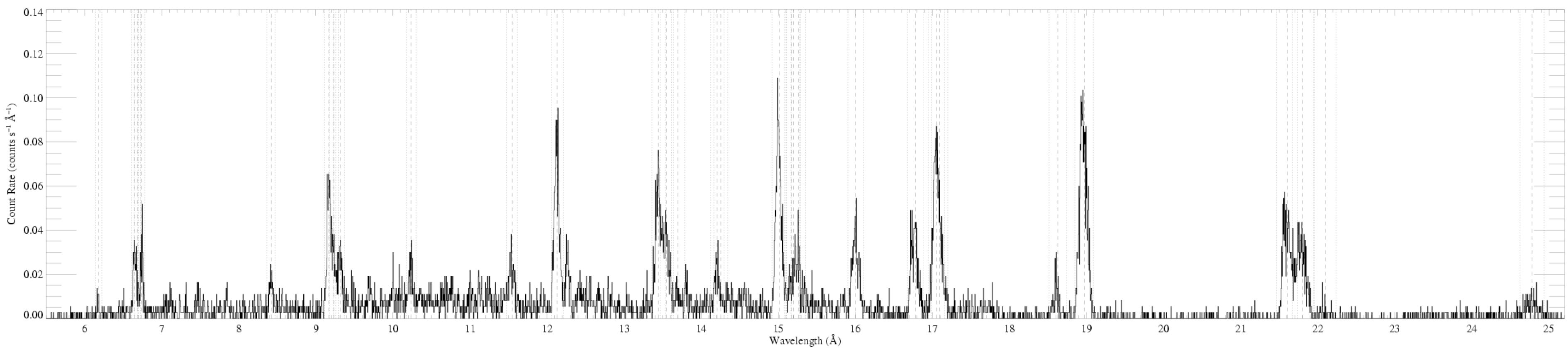
θ^1 Ori C has a hard X-ray spectrum with narrow lines

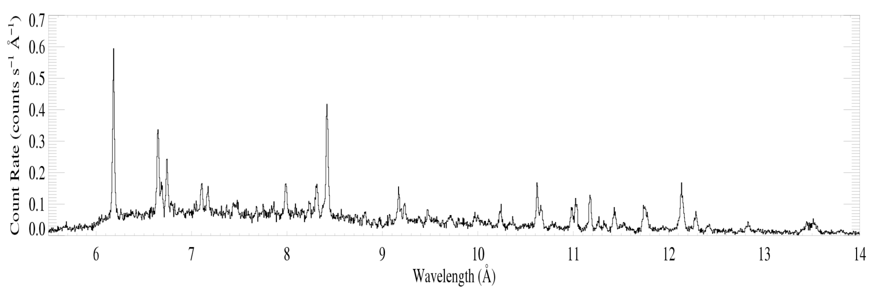
…HD191612 and ζ Ori have soft X-ray spectra with broad lines



Fe XVII in ζ Ori

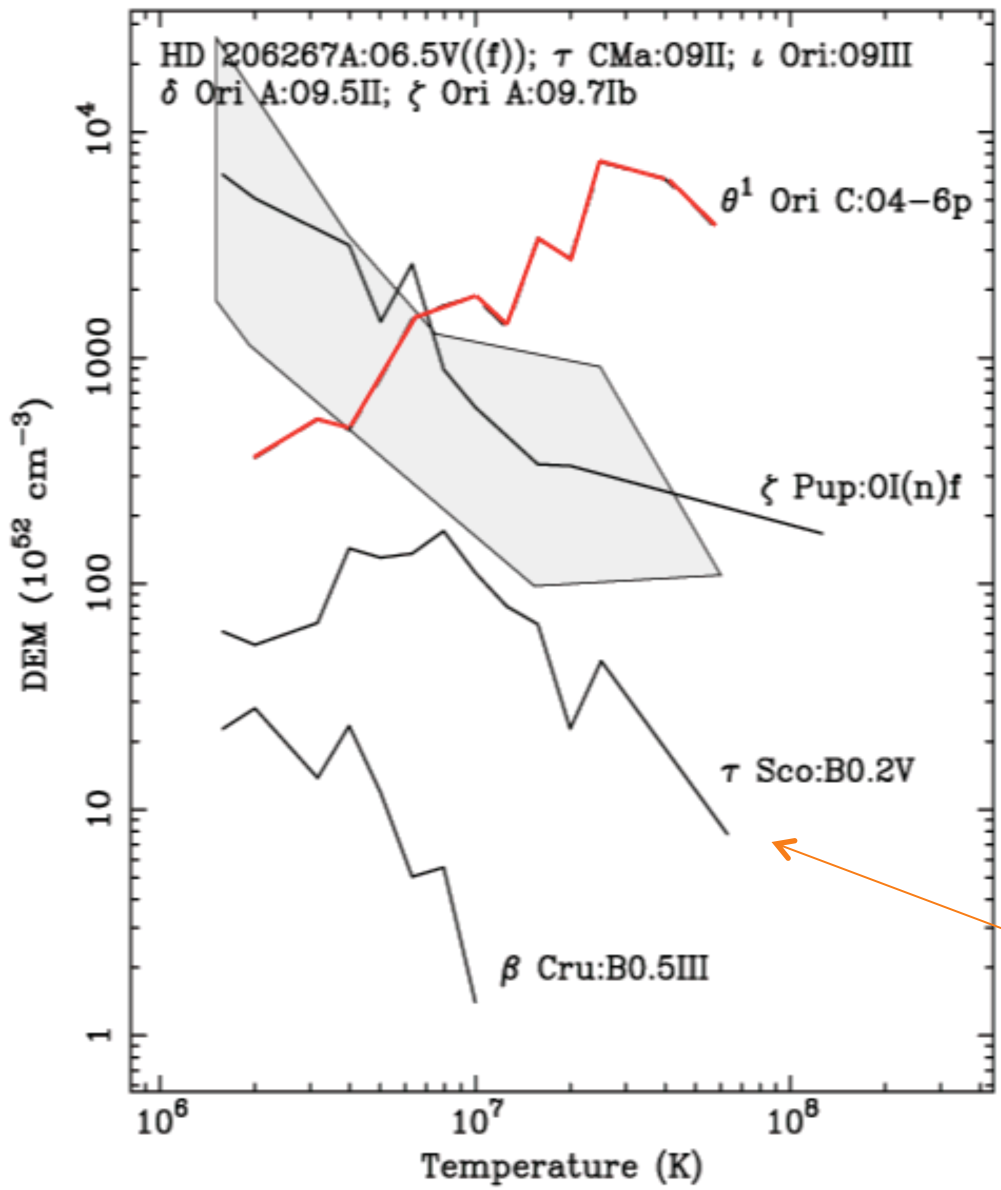
ζ Ori

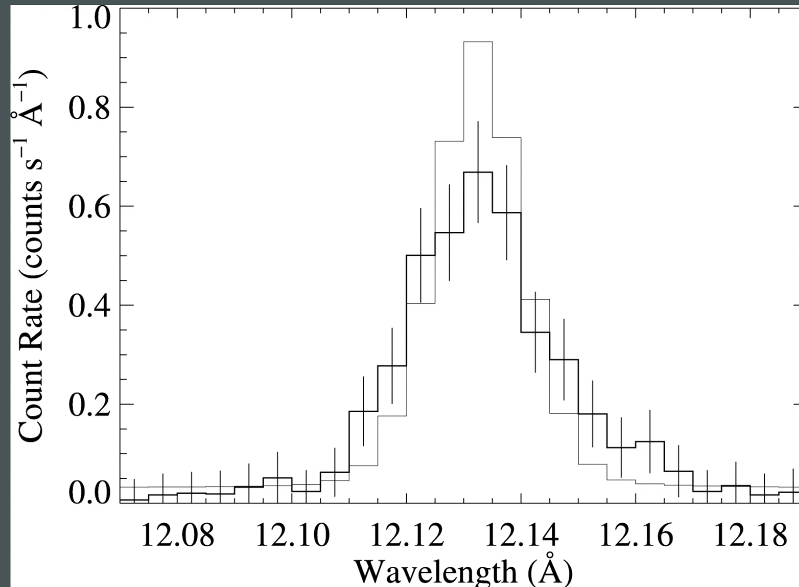




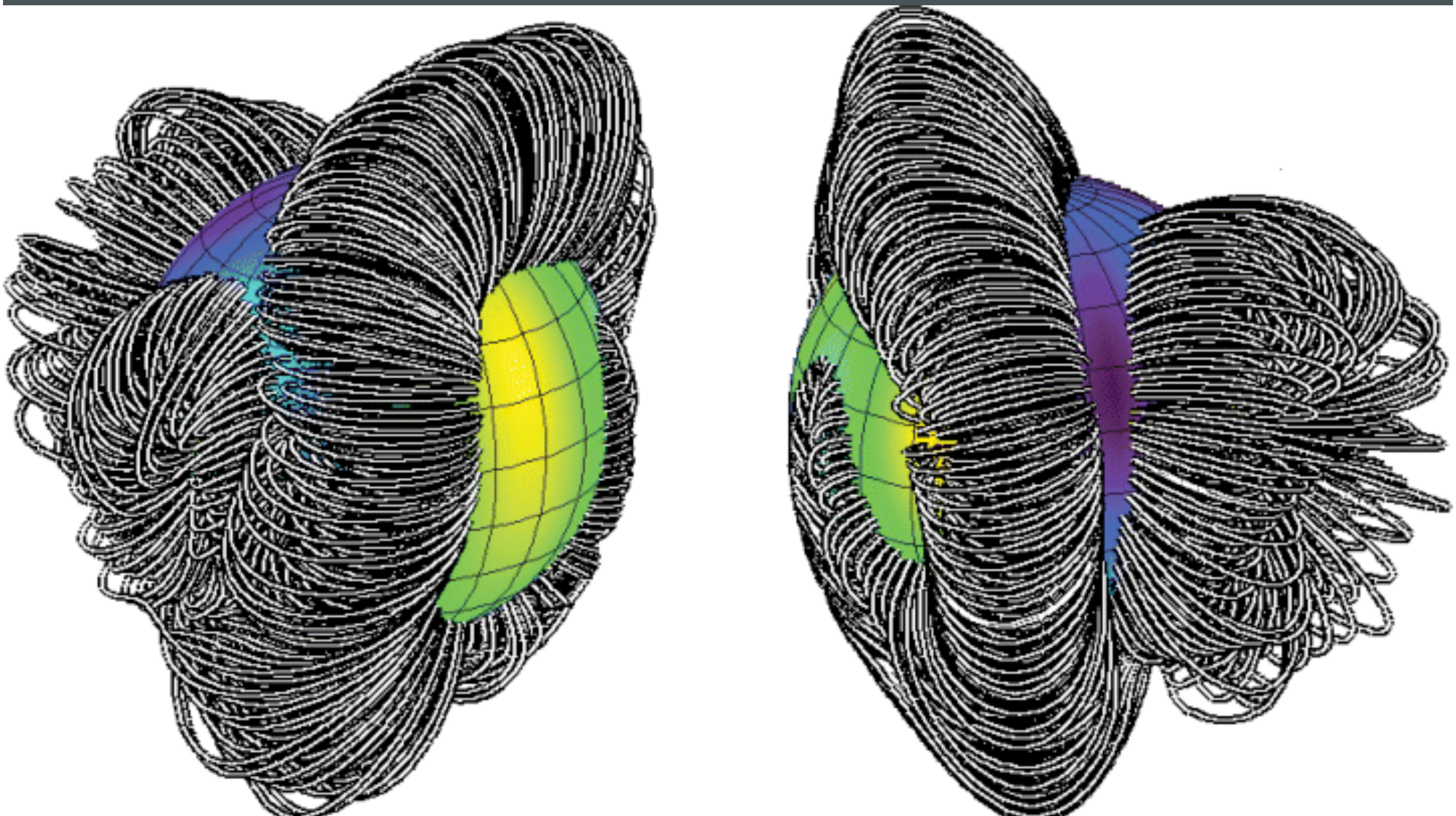
θ^1 Ori C

τ Sco *does* have a hard spectrum and narrow lines



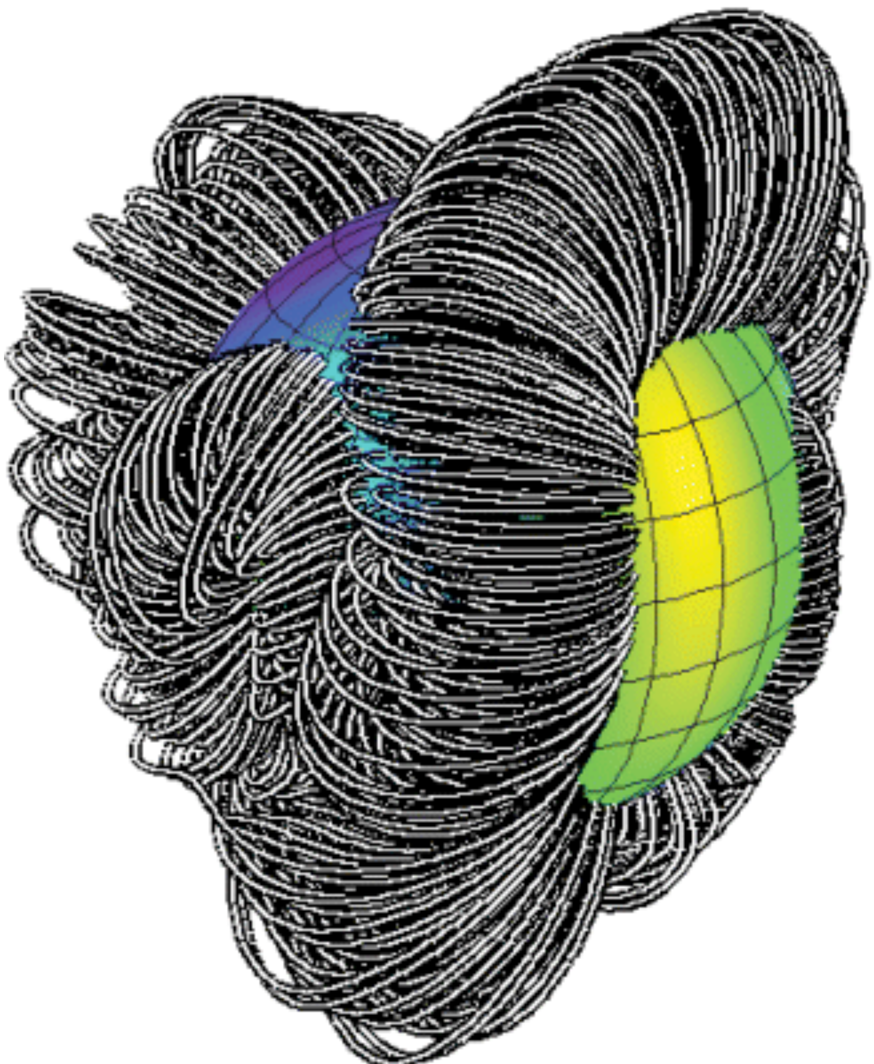


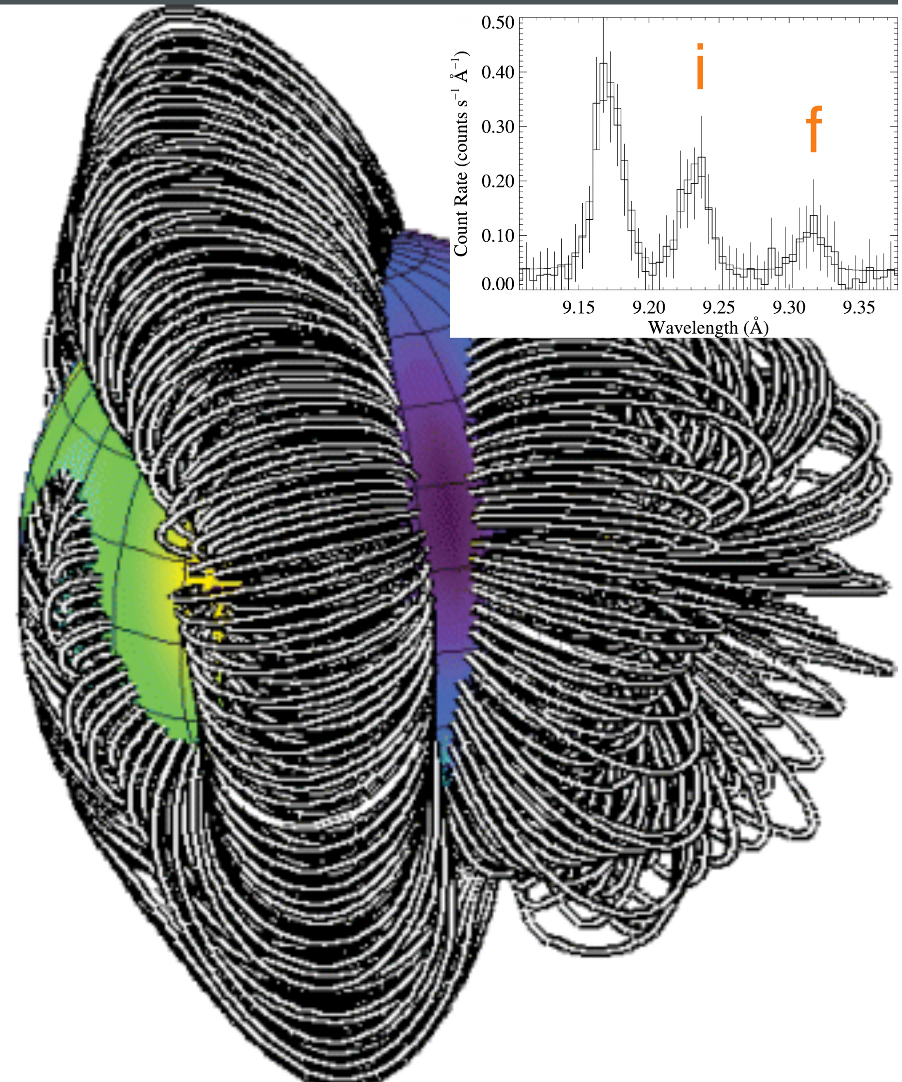
Ne Lyα compared to instrumental response: narrow τ Sco: closed loop region is near the star…



τ Sco: closed loop region is near the star…

…f/i ratios tell us X-rays are far from the star (~$3R_{star}$)



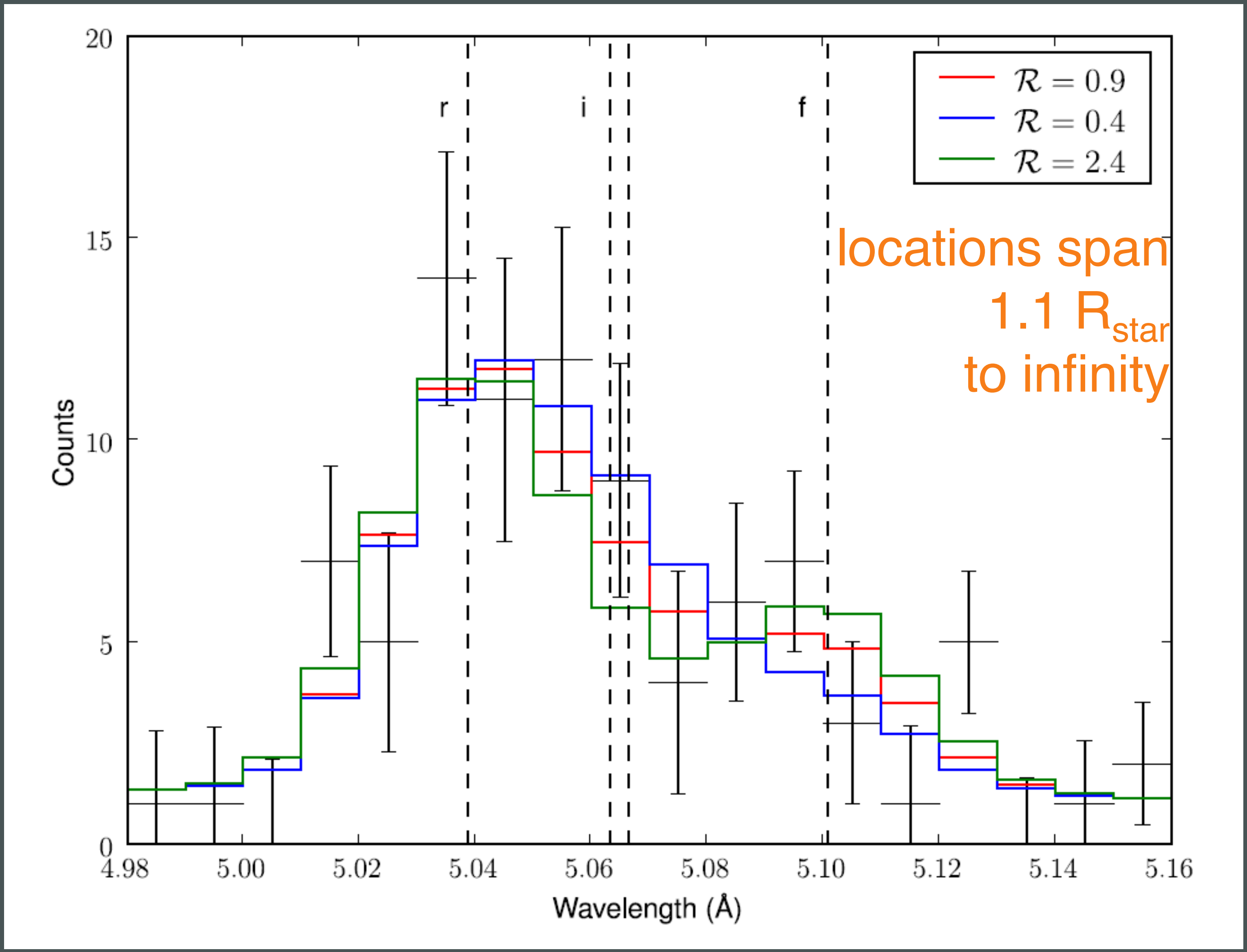


Do He-like f/i ratios provide evidence of hot plasma near the photospheres of O stars?

Do He-like f/i ratios provide evidence of hot plasma near the photospheres of O stars?

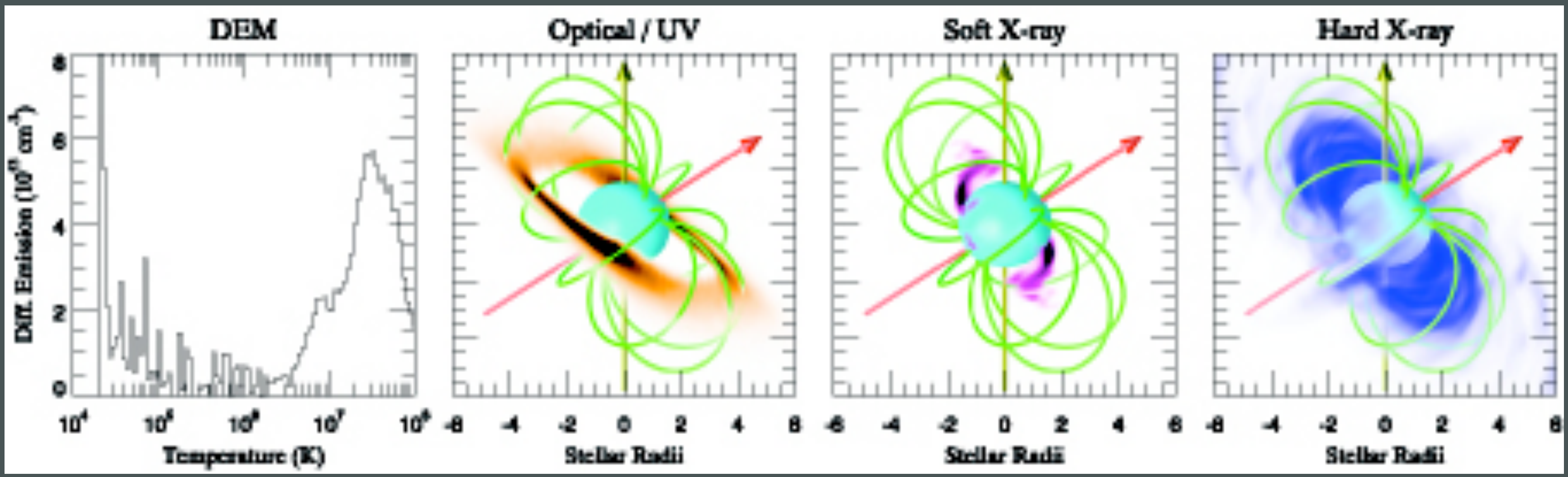
No, I’m afraid they do **not**.

Features are very blended in most O stars: here, the three models are statistically indistinguishable

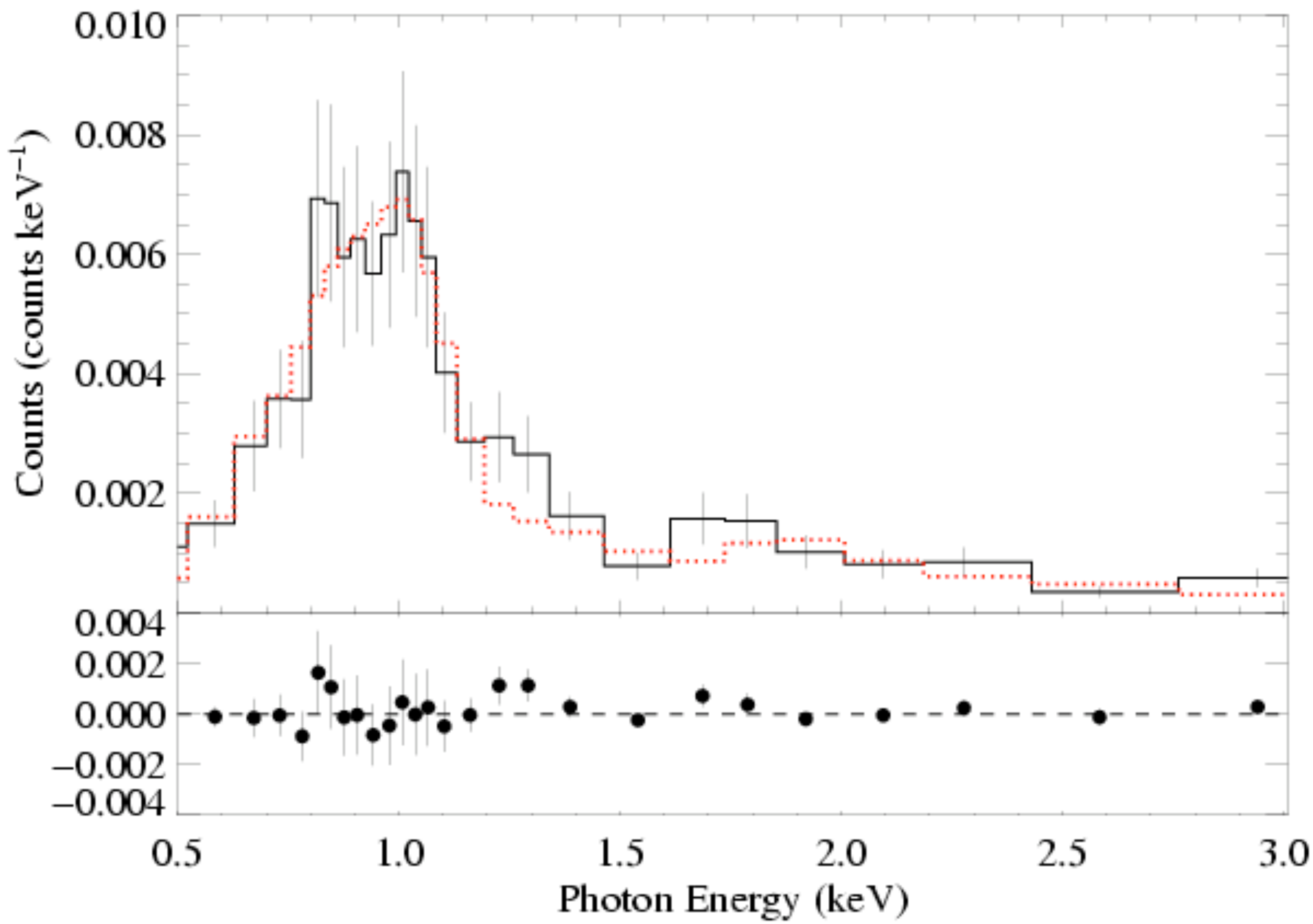


ζ Pup S XV *Chandra* MEG

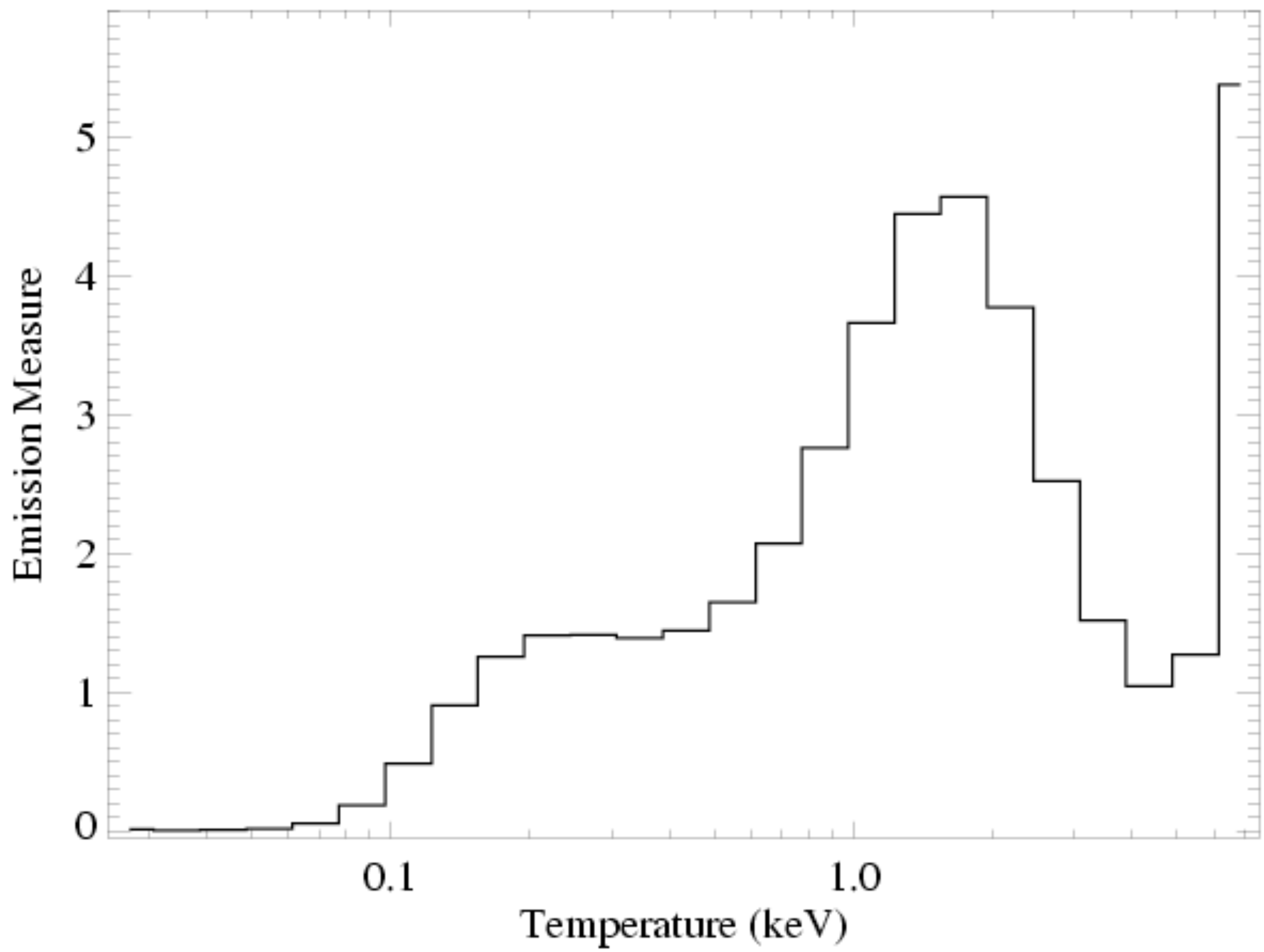
σ Ori E ($\eta_* \sim 10^7$: RRM+RFHD)



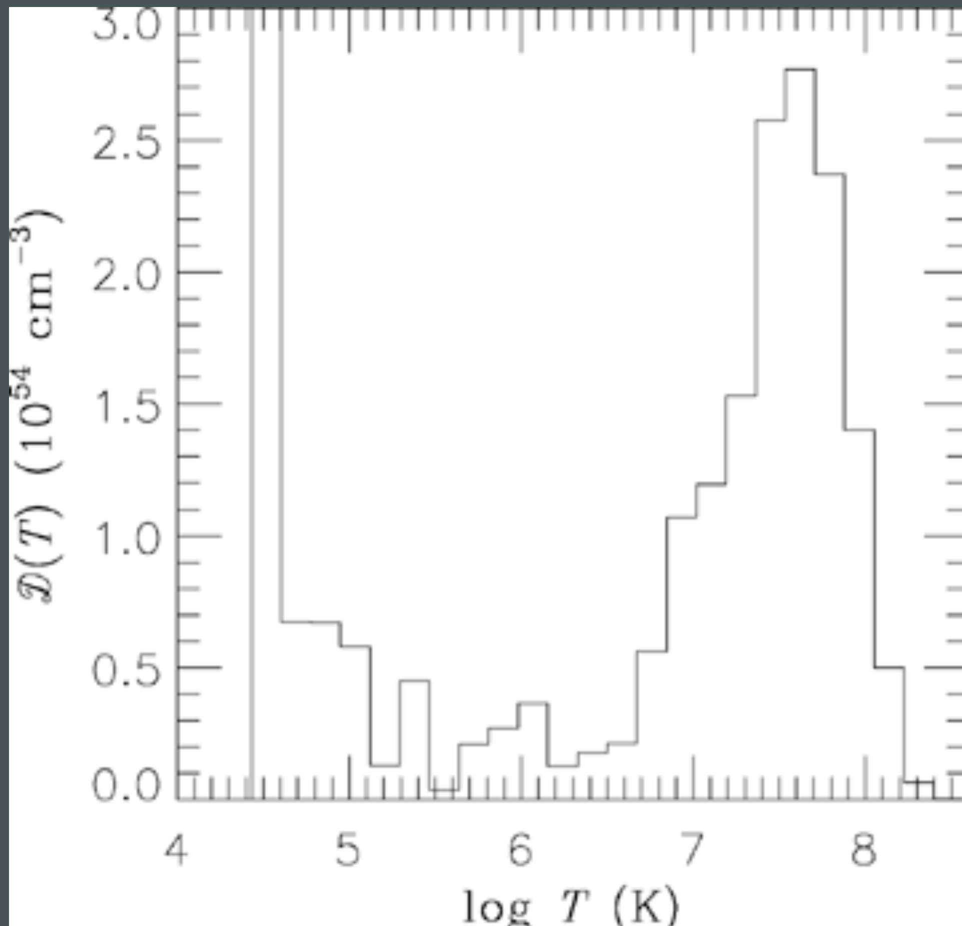
Chandra ACIS (low-resolution, CCD) spectrum



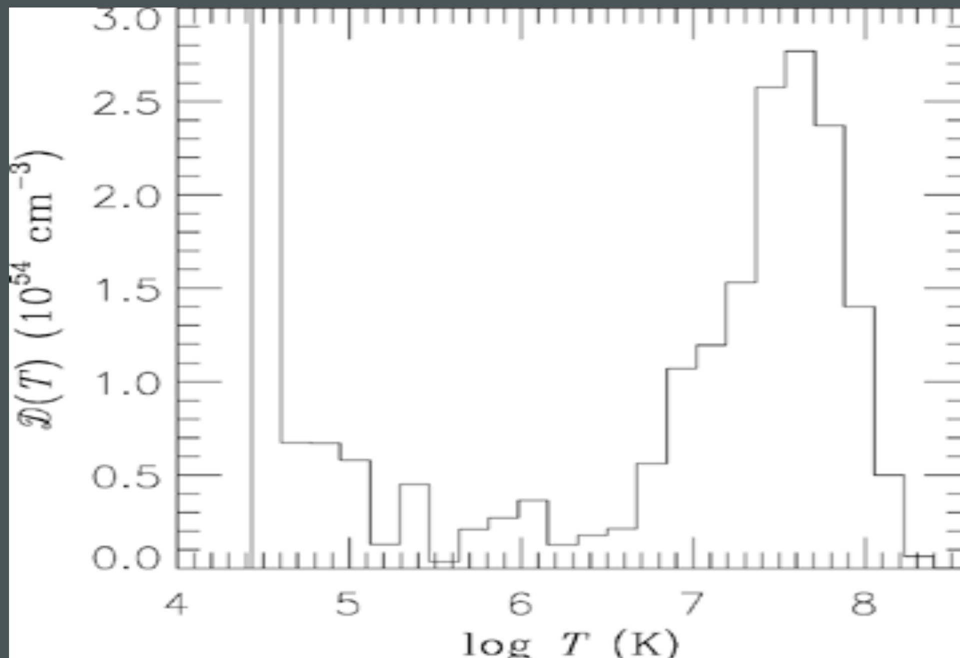
DEM derived from *Chandra* ACIS spectrum

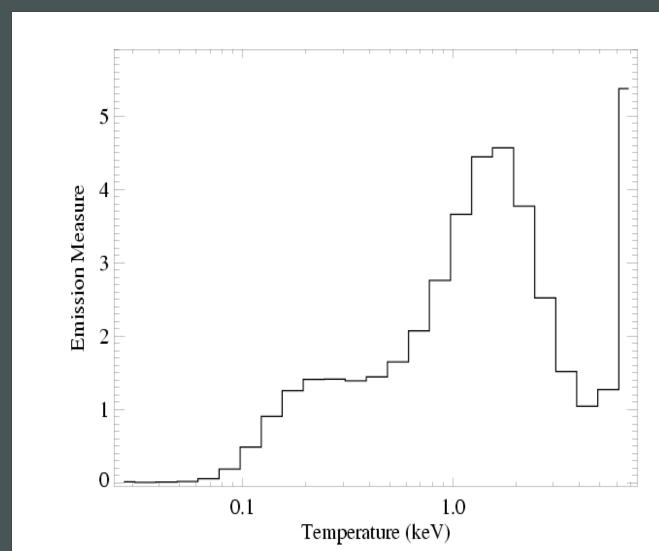


DEM from RFHD modeling

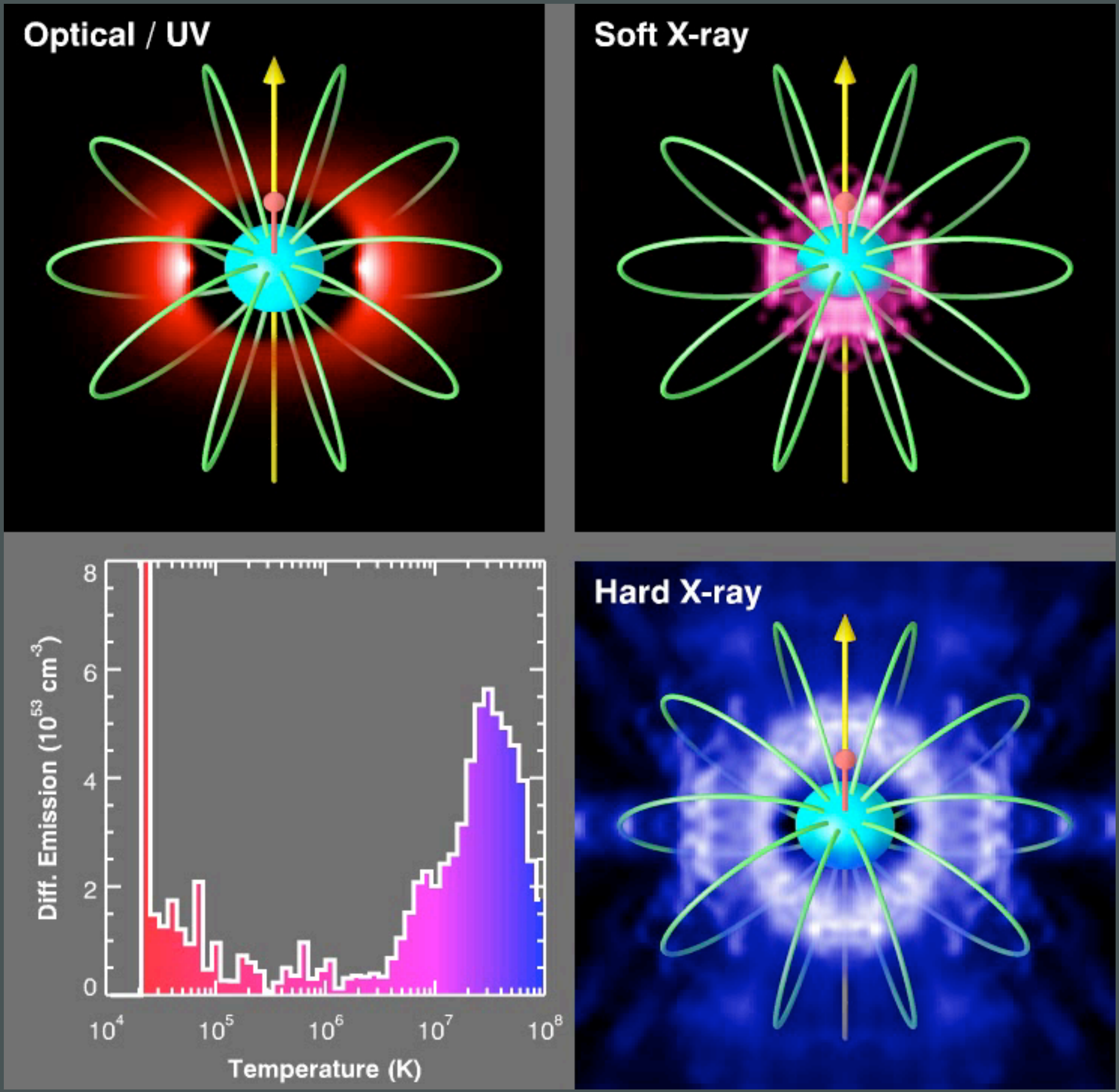


Observed & theoretical DEMs agree well





RFHD (Townsend, Owocki, & ud-Doula 2007, MNRAS, 382, 139)



astro.swarthmore.edu/~cohen/presentations/MiMeS2/hav-rfhd-4p.avi

Conclusions

MCWS dynamical scenario explains θ^1 Ori C well… but, in detail, MHD models do not reproduce all the observational properties

Most other magnetic massive stars have X-ray emission that is different from θ^1 Ori C

- Some have soft X-ray spectra with broad lines
- Closed field regions may not always be associated with the X-rays (τ Sco)

f/i ratios, hard X-rays, variability in massive stars…not unique to magnetic field wind interaction