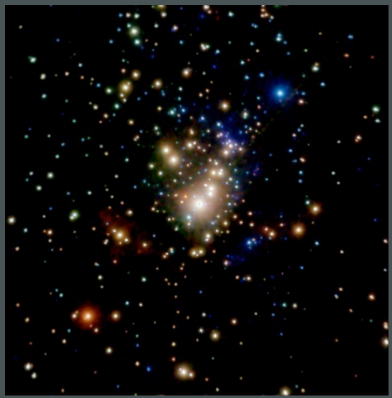
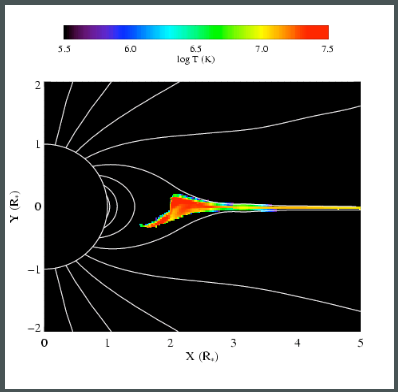
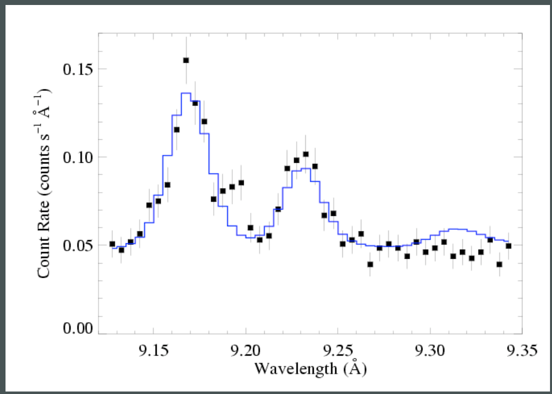
X-ray Diagnostics and Their Relationship to Magnetic Fields

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.

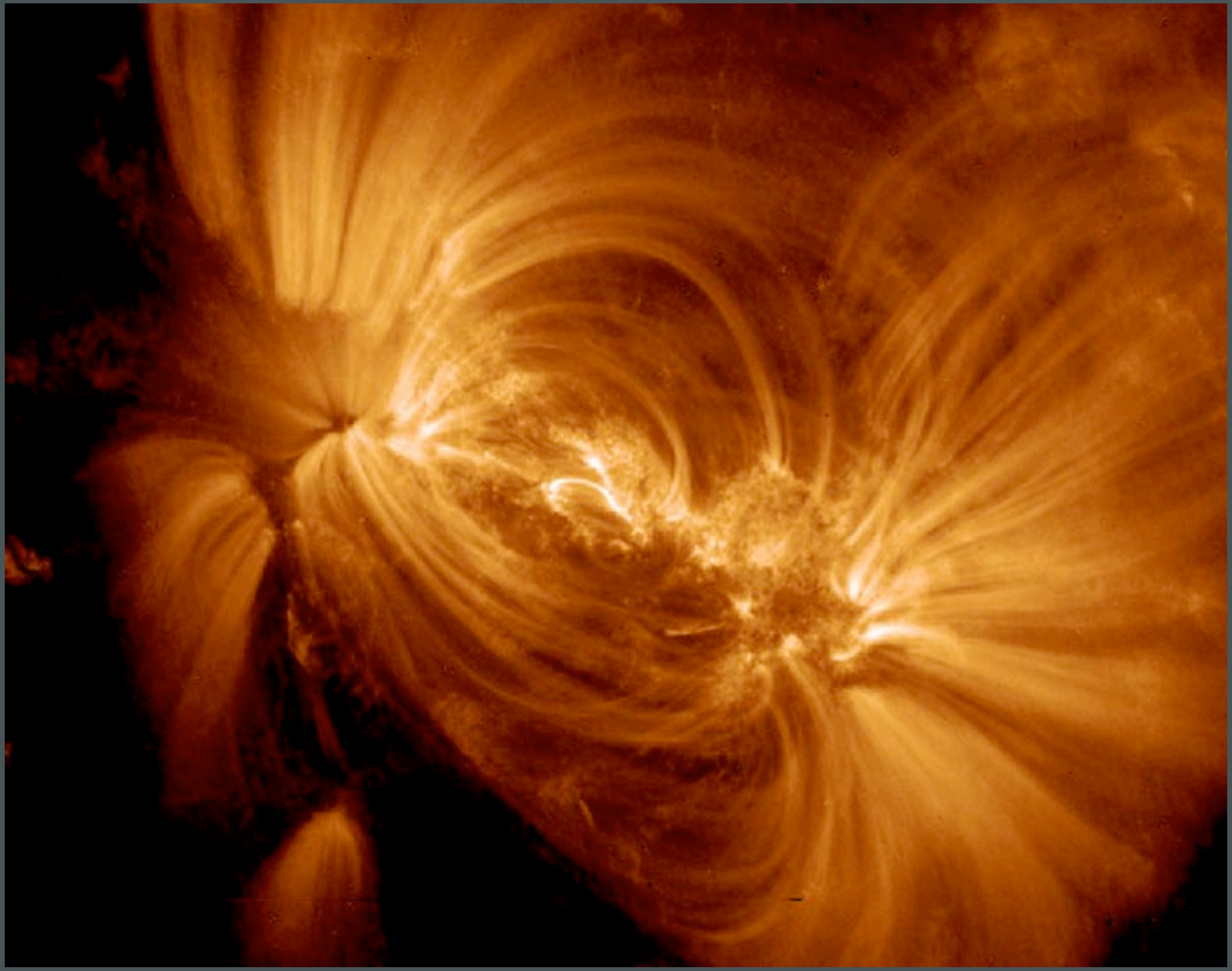
e.g. Which of the stars in this Chandra X-ray image of the Orion Nebula Cluster are massive magnetic stars?

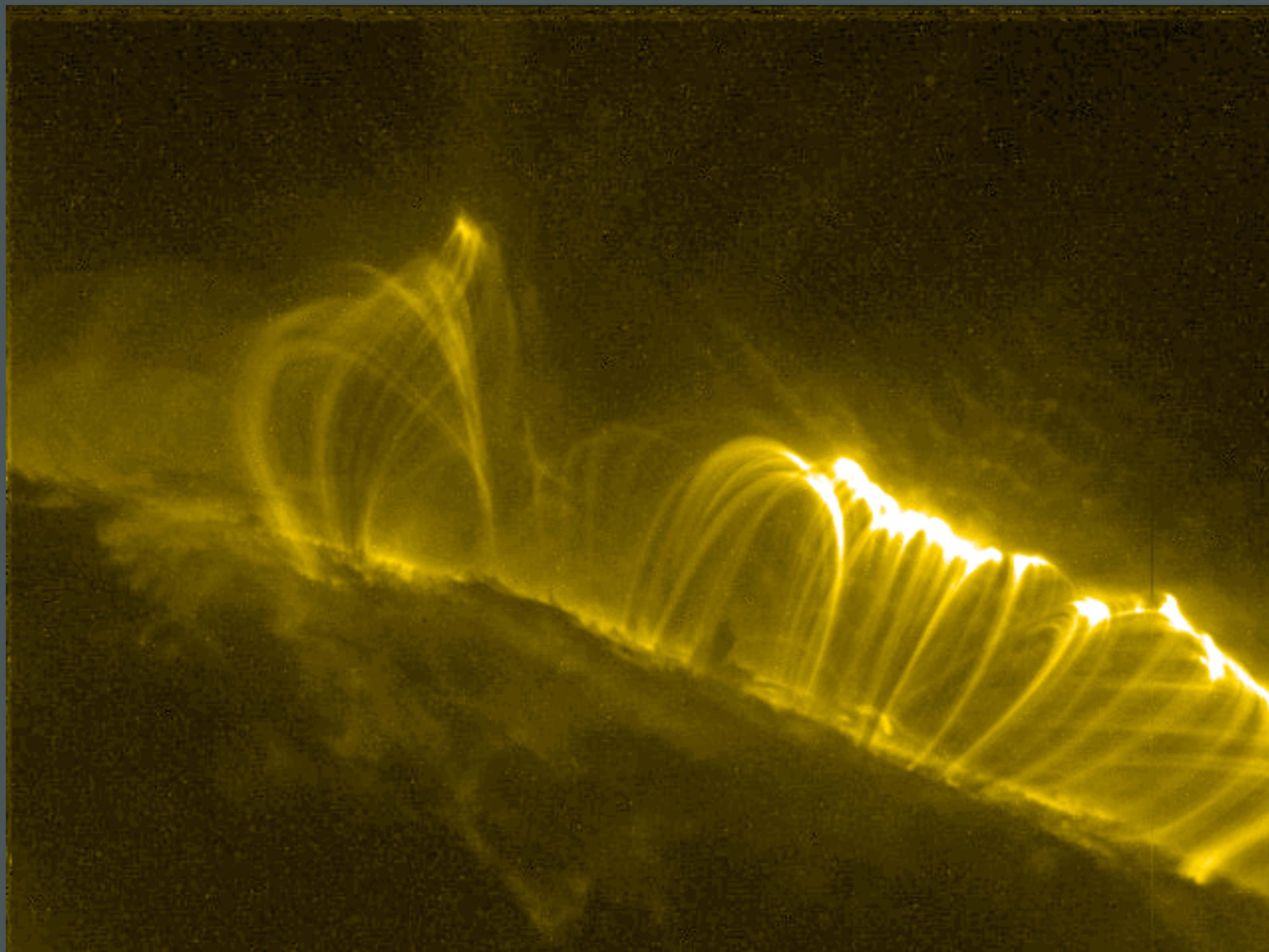
But we're not there yet…

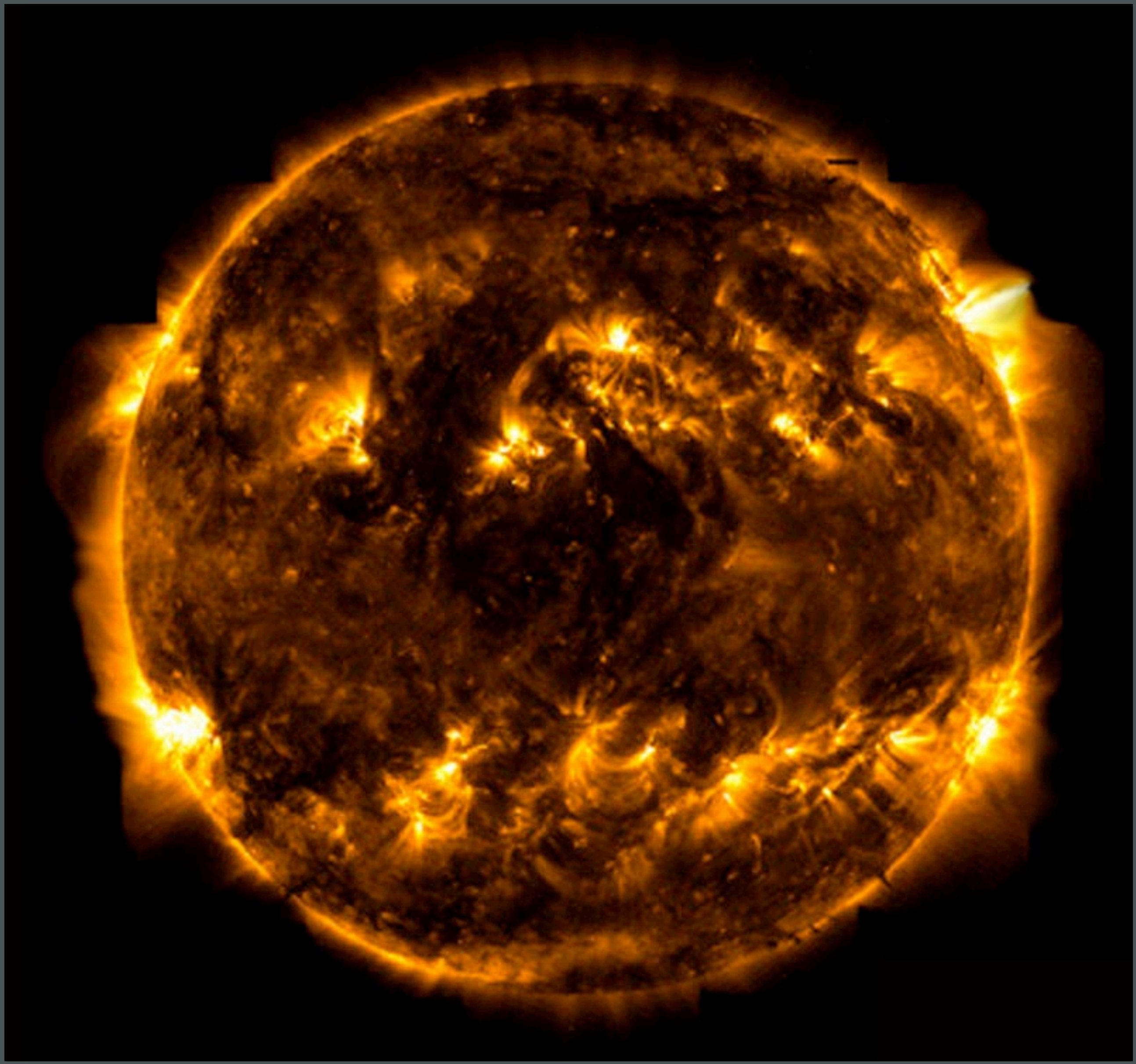
X-ray behavior of known magnetic massive stars is diverse.

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

The Sun: X-rays <-> Magnetic Fields



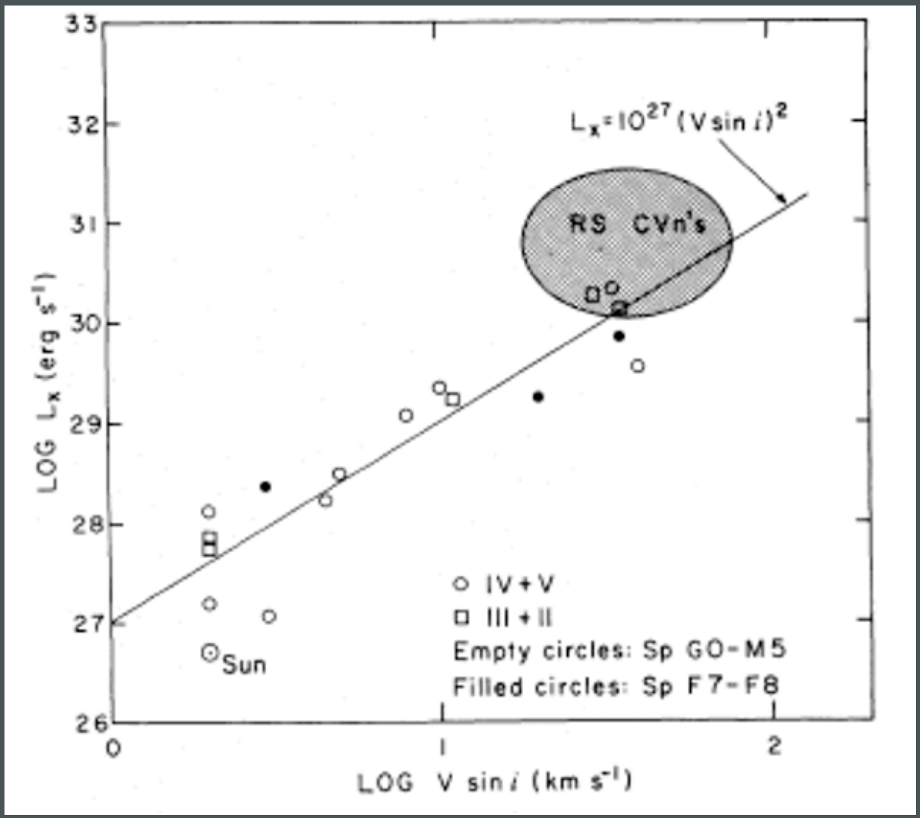




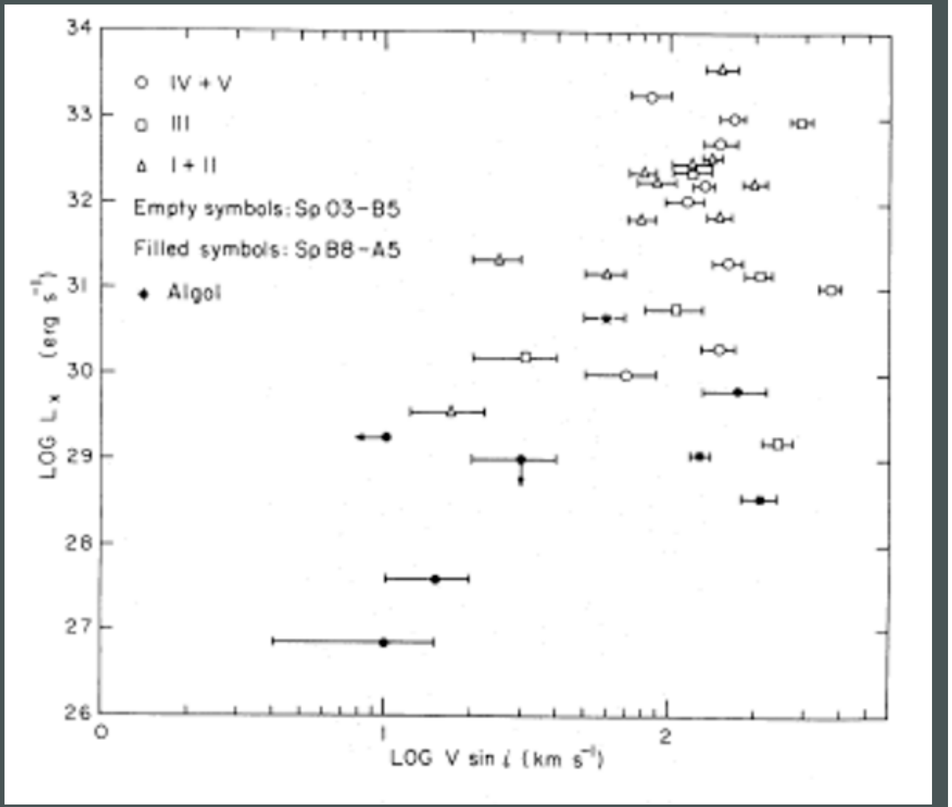
TRACE

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:

$$\tfrac{1}{2}\dot{M}v_\infty^2 \approx 3\times 10^{36} \quad \text{erg s}^{-1}$$
$$\approx .001 L_*$$

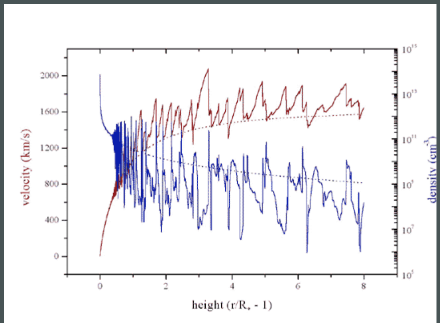
while the x-ray luminosity

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

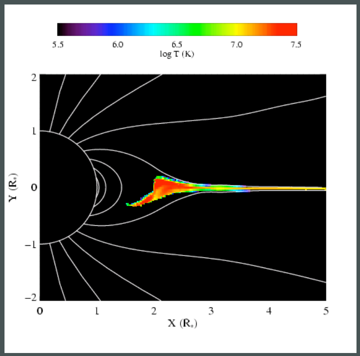
To account for the x-rays, only **one part in 10^{-4}** of the wind's mechanical power is needed to heat the wind

Three models for massive star x-ray emission

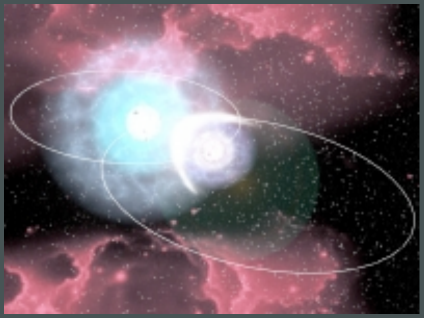
1. Instability driven shocks



2. Magnetically channeled wind shocks



3. Wind-wind interaction in close binaries



Three models for massive star x-ray emission

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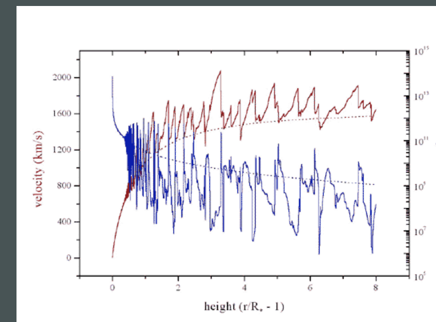

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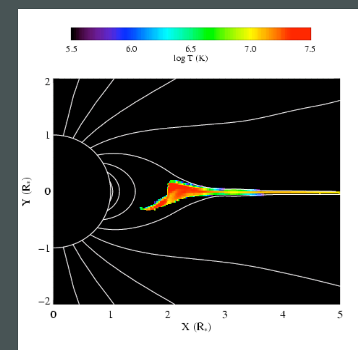


3. Wind-wind interaction in
   close binaries

What are these “X-rays” anyway?

…and what’s the available data like?

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

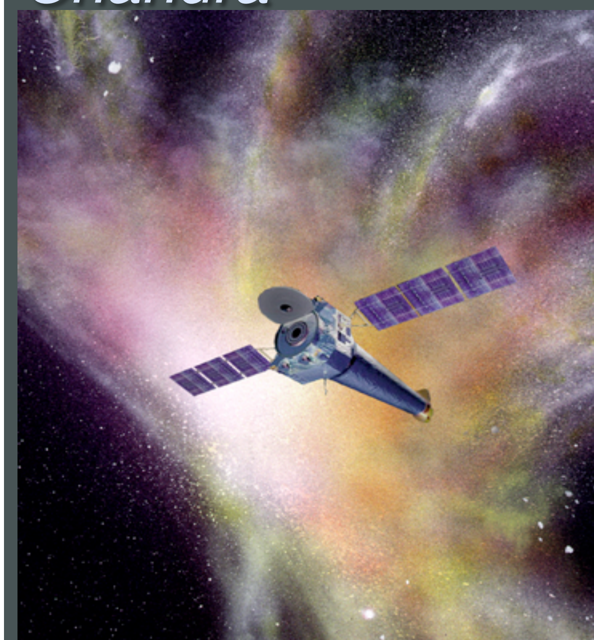
Chandra

sub-arcsecond resolution

XMM-Newton

XMM-Newton

Chandra



Both have CCD detectors for imaging spectroscopy:

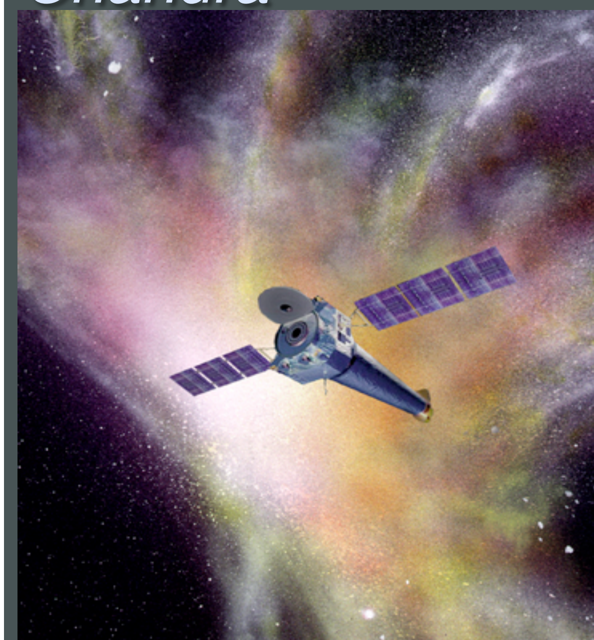
low spectral resolution: $R \sim 20$ to 50

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

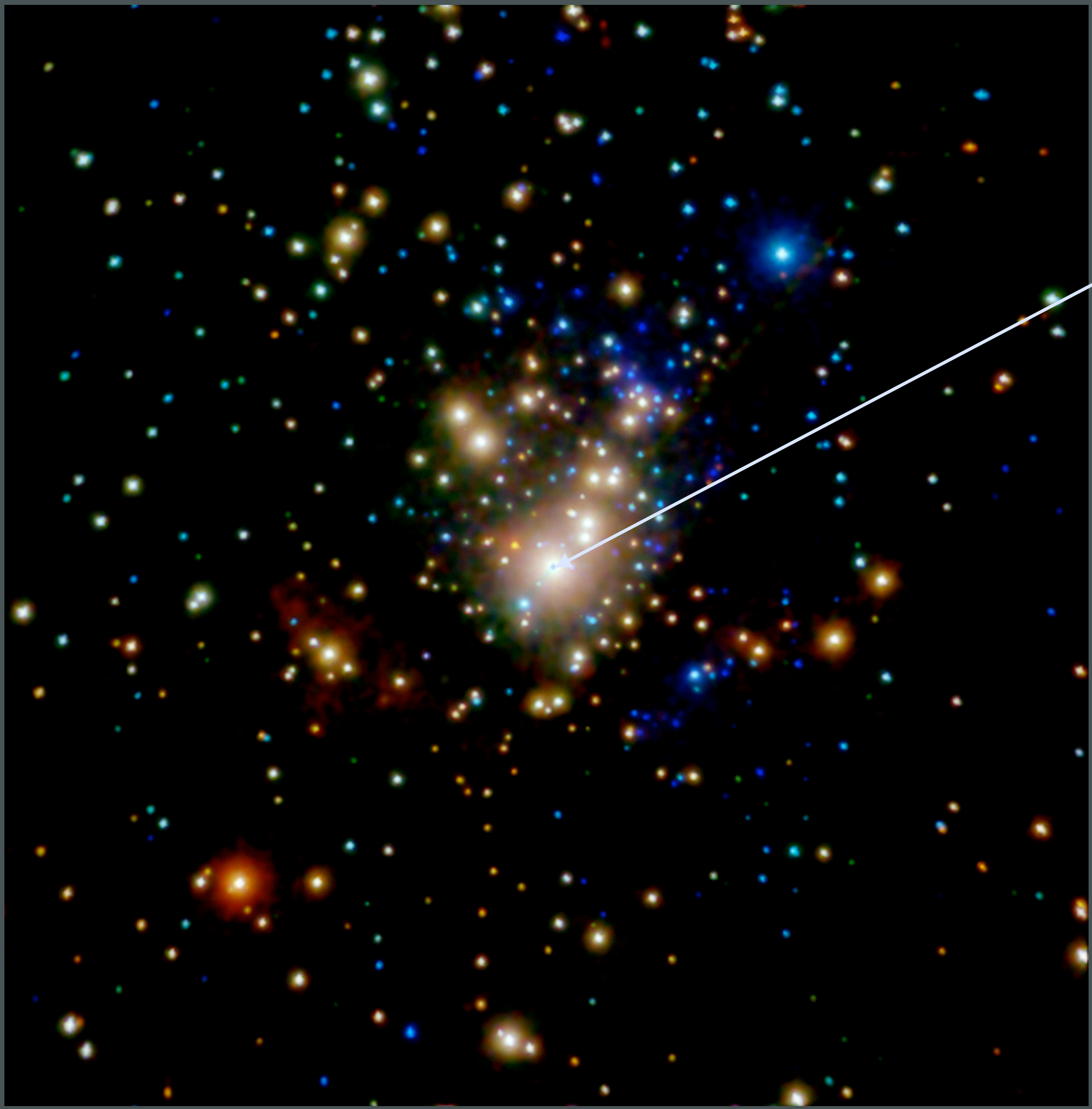
The Future:

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

International X-ray Observatory (IXO) … 2020+

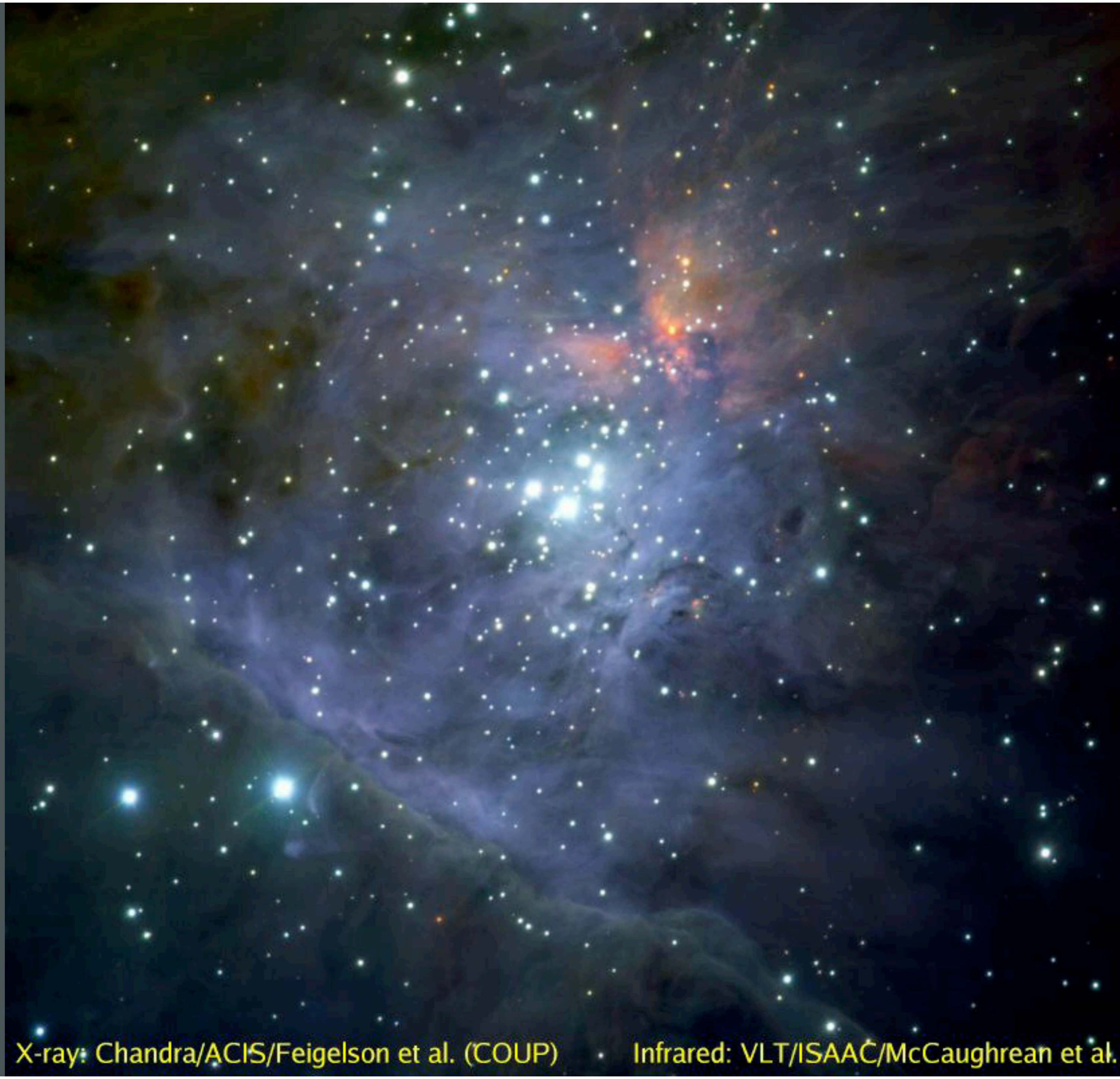
First, imaging (+ low resolution) spectroscopy with *Chandra*

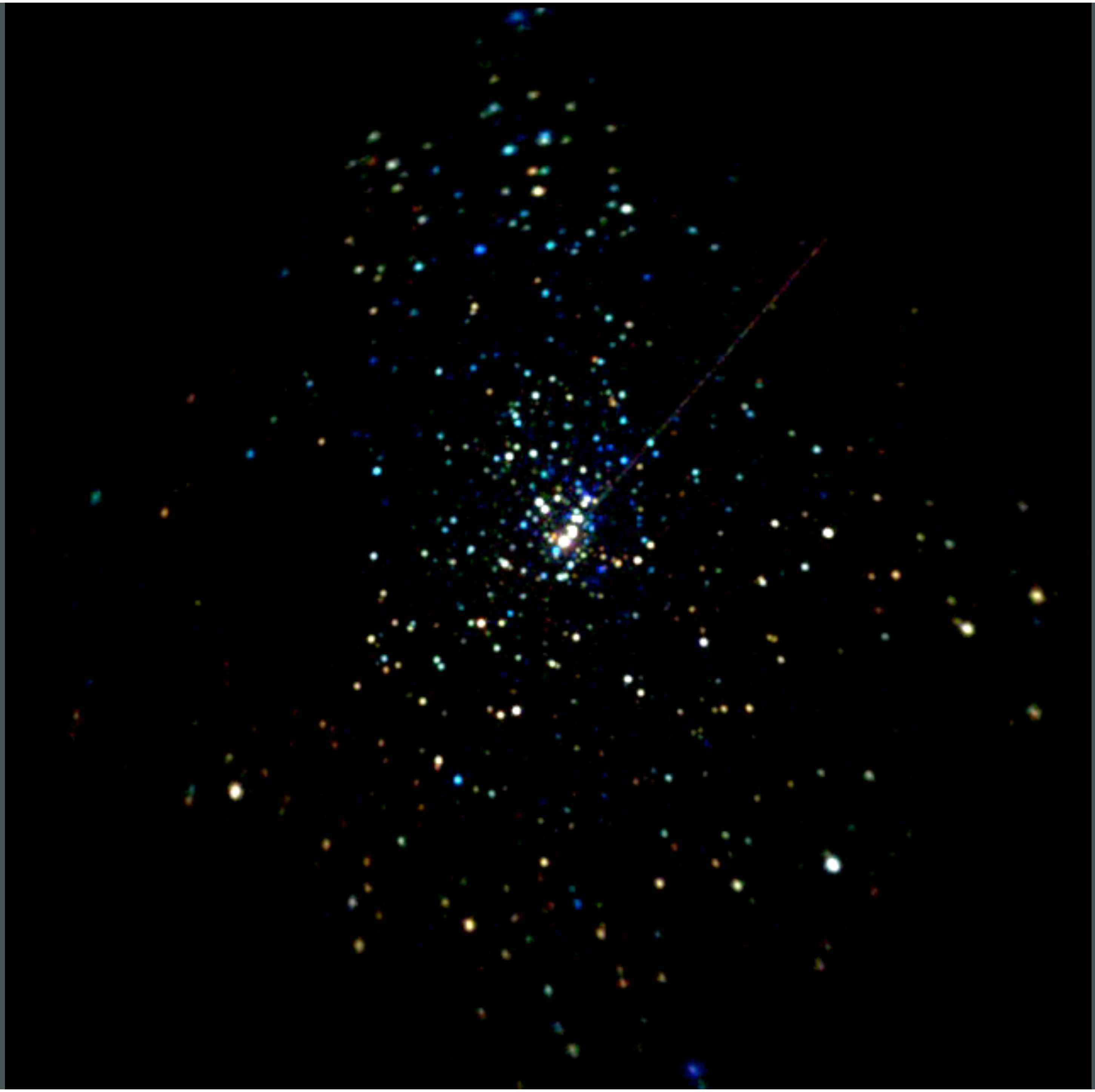
Chandra ACIS
Orion Nebula Cluster (COUP)



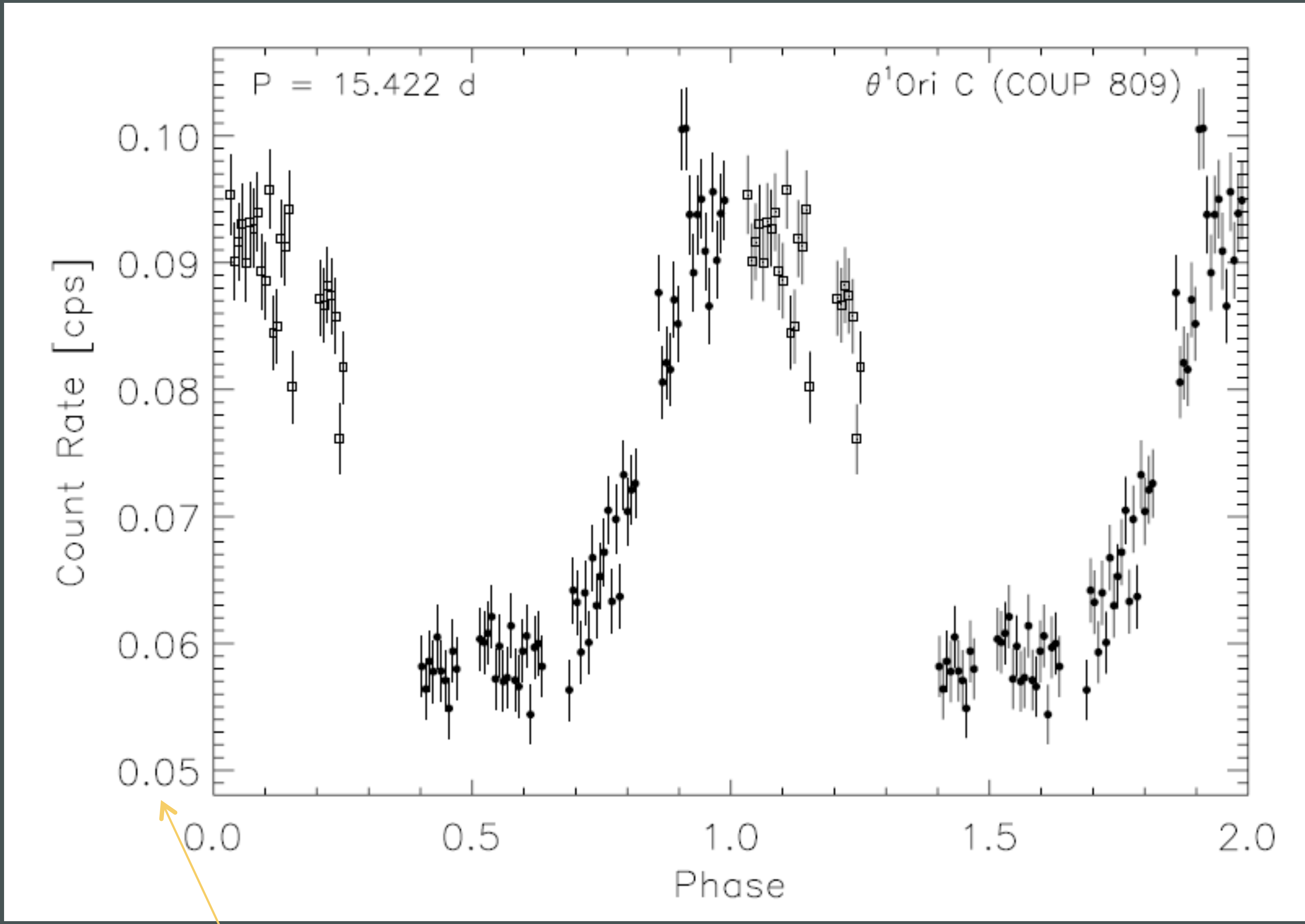
θ^1 Ori C

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


X-ray: Chandra/ACIS/Feigelson et al. (COUP)
Infrared: VLT/ISAAC/McCaughrean et al.

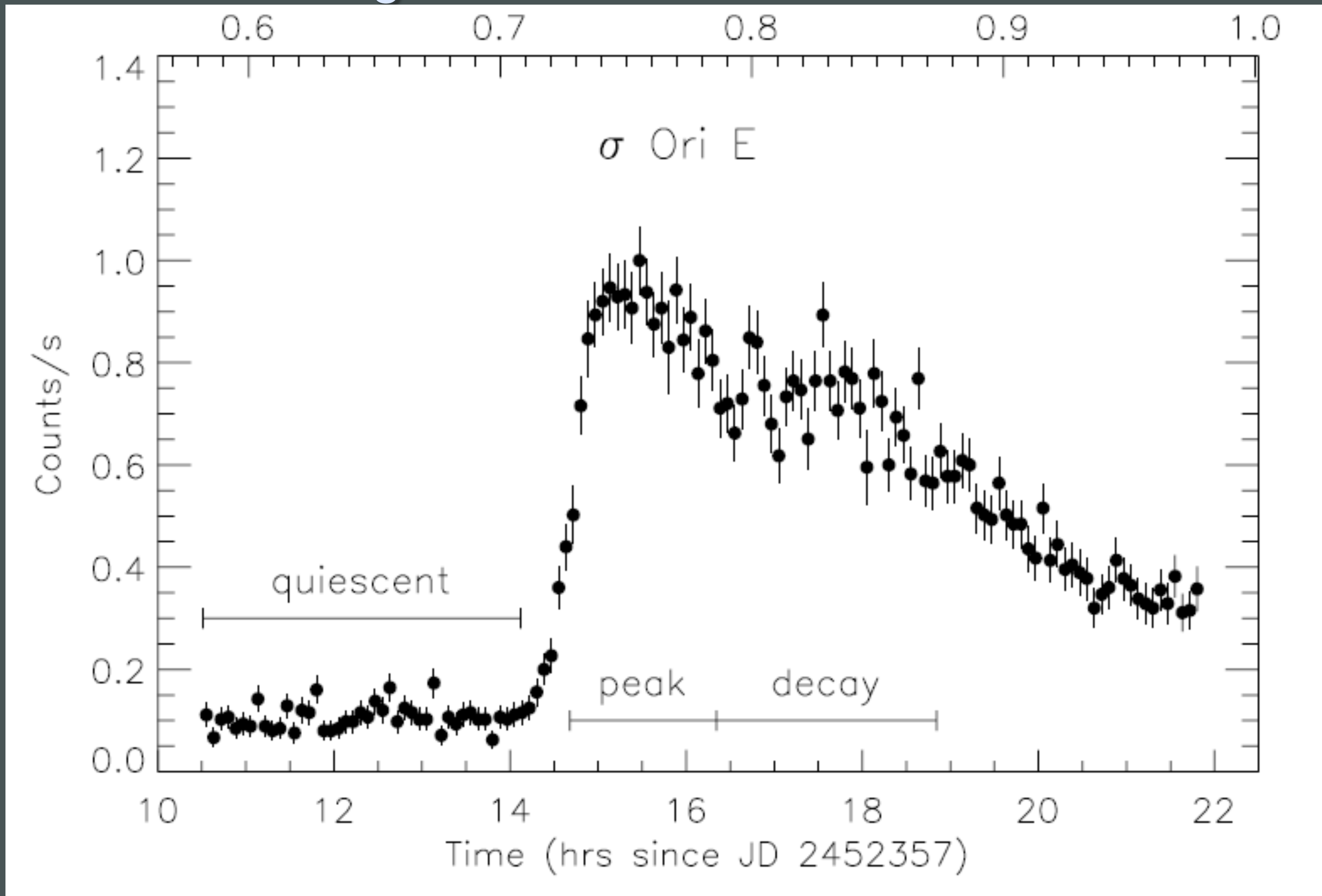


θ^1 Ori C: X-ray lightcurve



Stelzer et al. 2005

σ Ori E: *XMM* light curve



Sanz-Forcada et al. 2004

XMM EPIC spectrum of σ Ori E

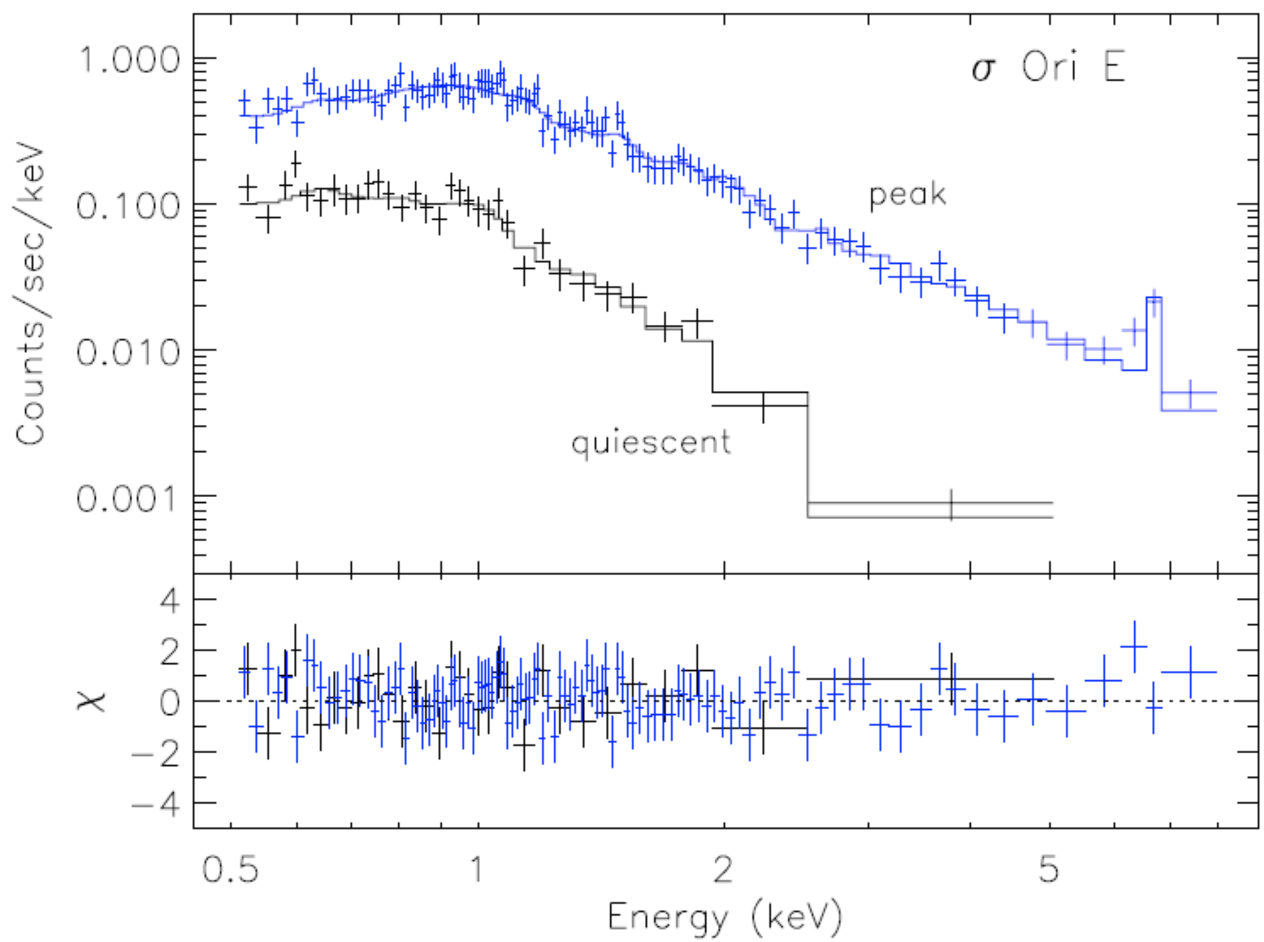
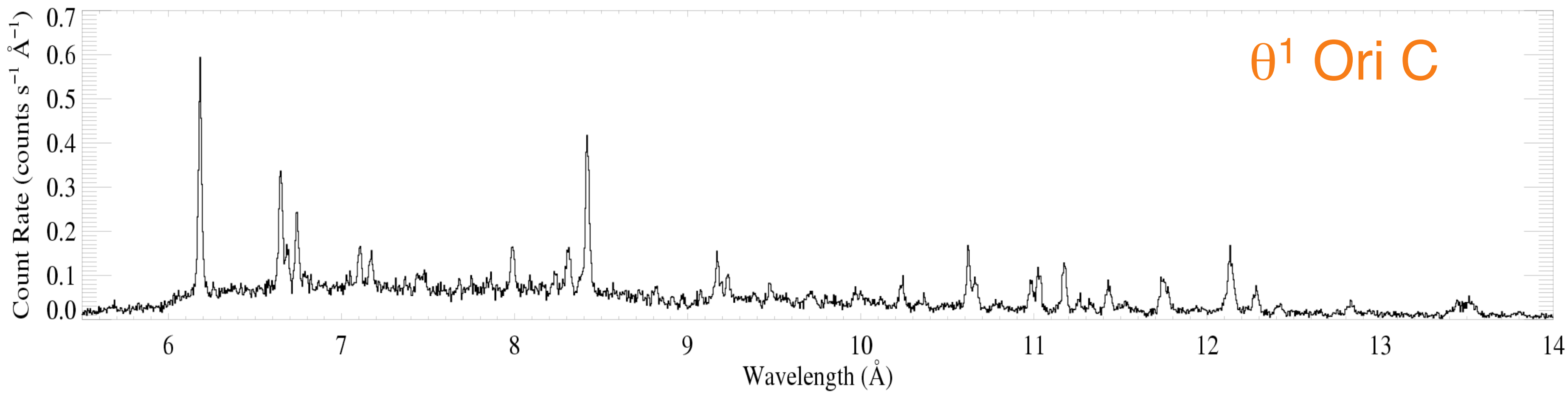
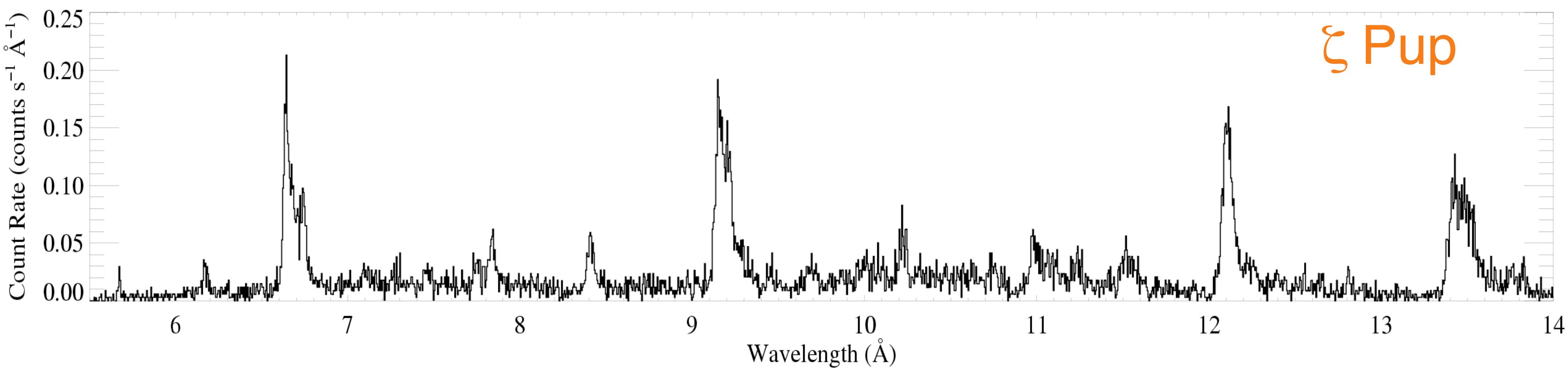


Fig. 9. PN spectra of σ Ori E during quiescence and at the peak of the flare. The best-fit model is also shown.

Sanz-Forcada et al. 2004

Chandra grating spectra: θ¹ 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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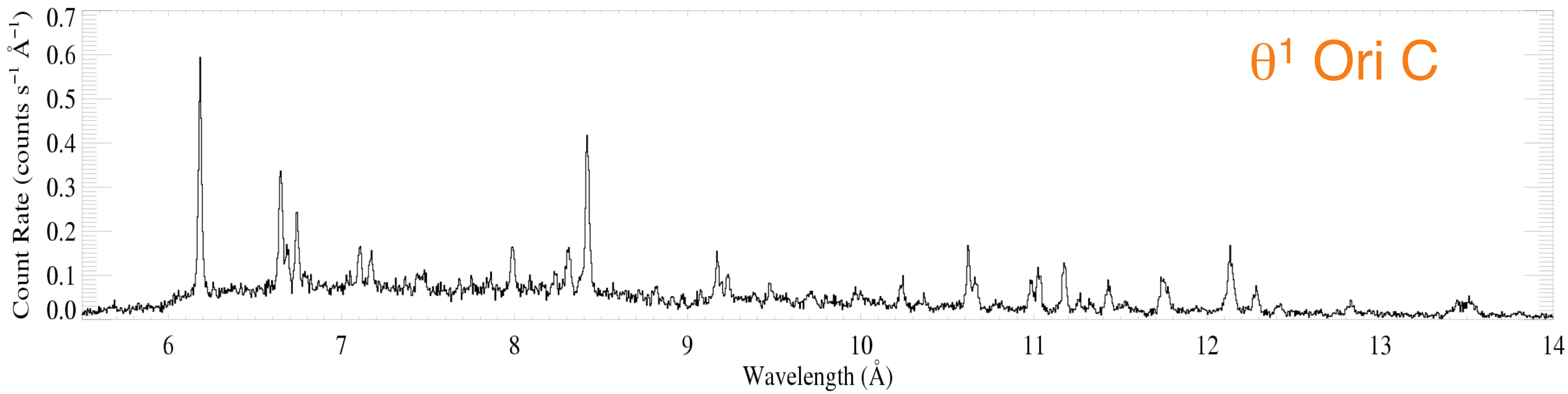
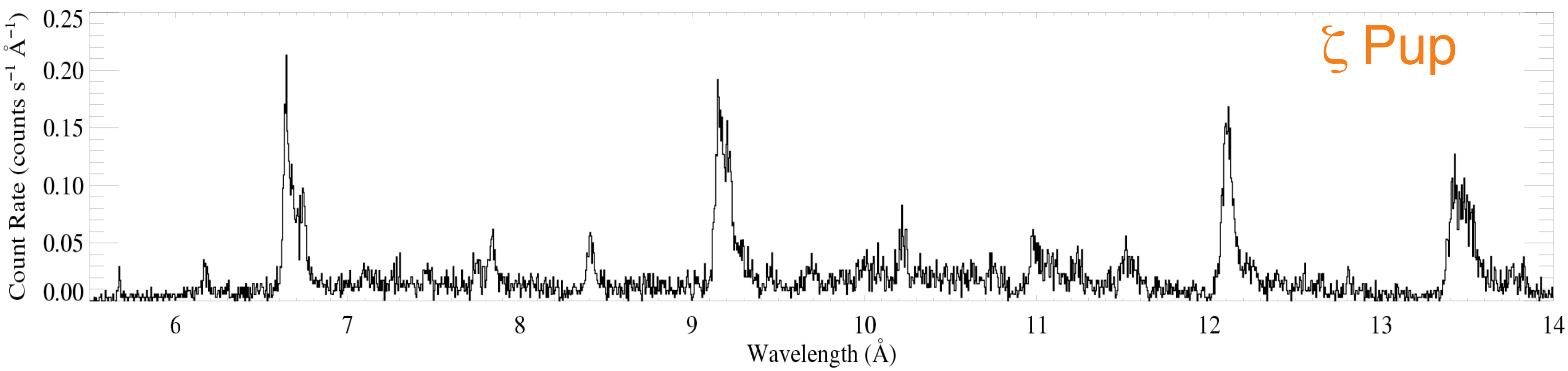
Chandra grating spectra: θ[1] Ori C and a non-magnetic O star





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

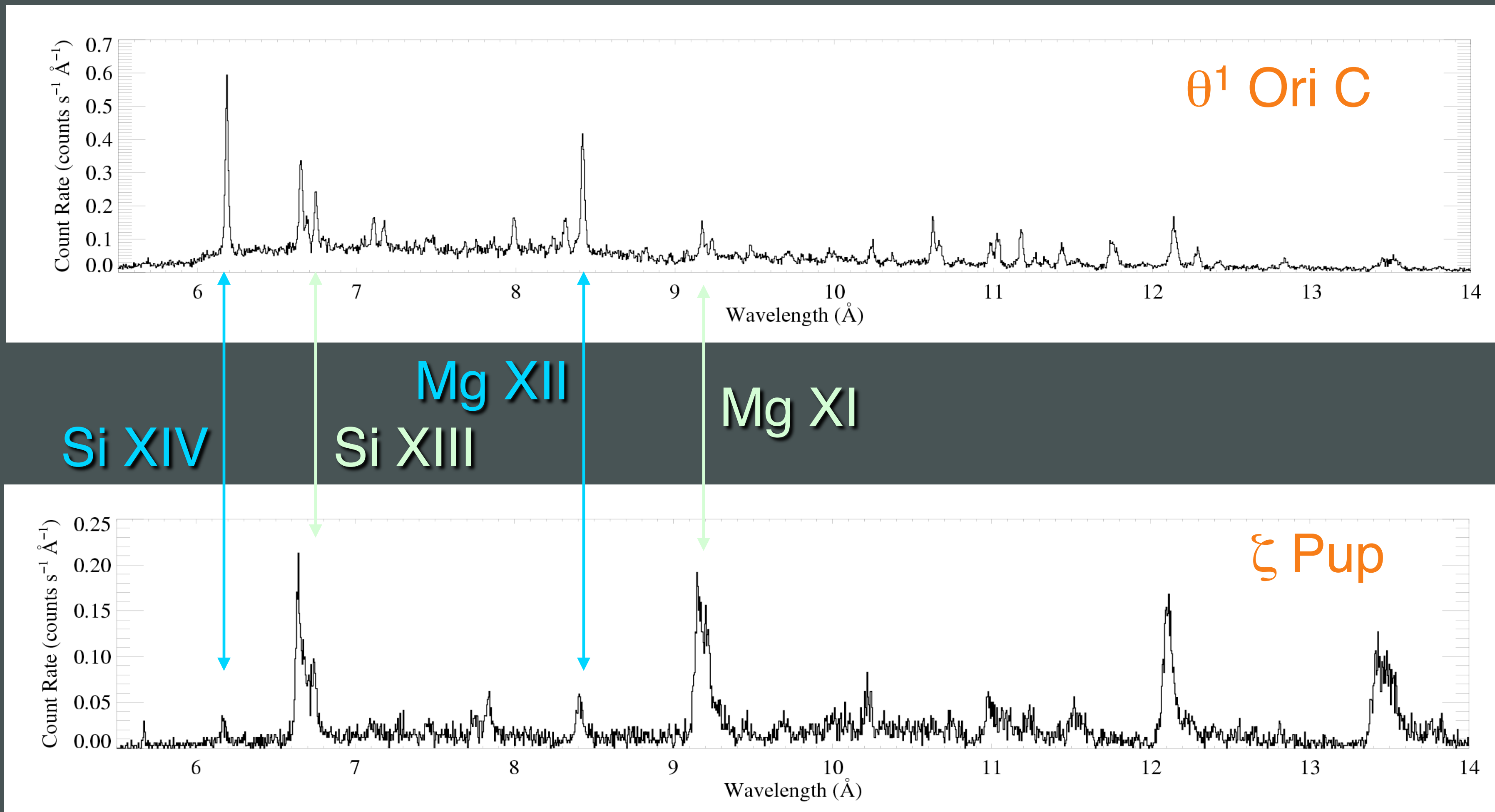
Energy Considerations and Scalings

1 keV ~ 12 × 10^6 K ~ 12 Å

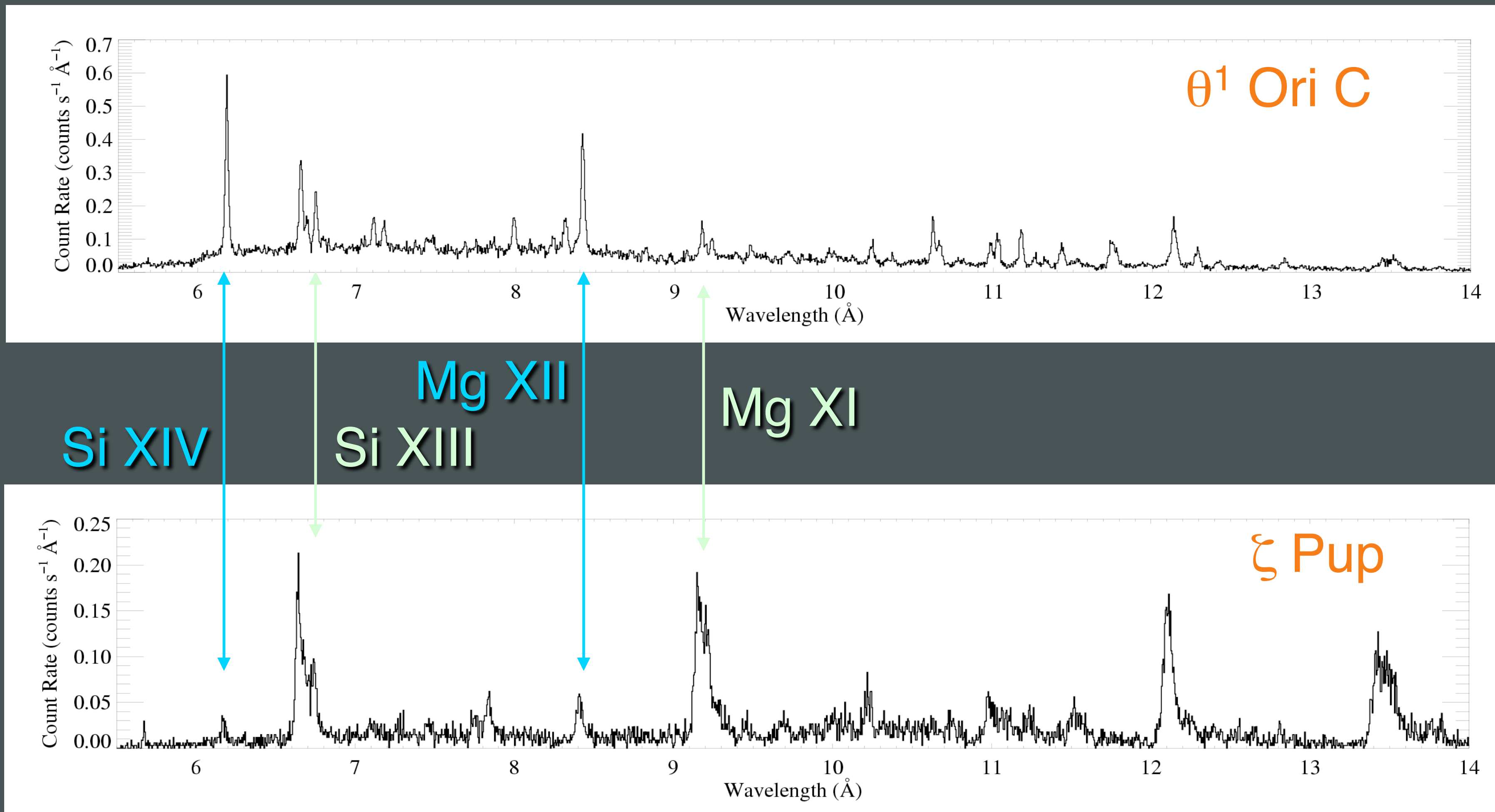
Shock heating: Δv = 1000 km/s
gives T ~ 10^7 K (and T ~ v^2)

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

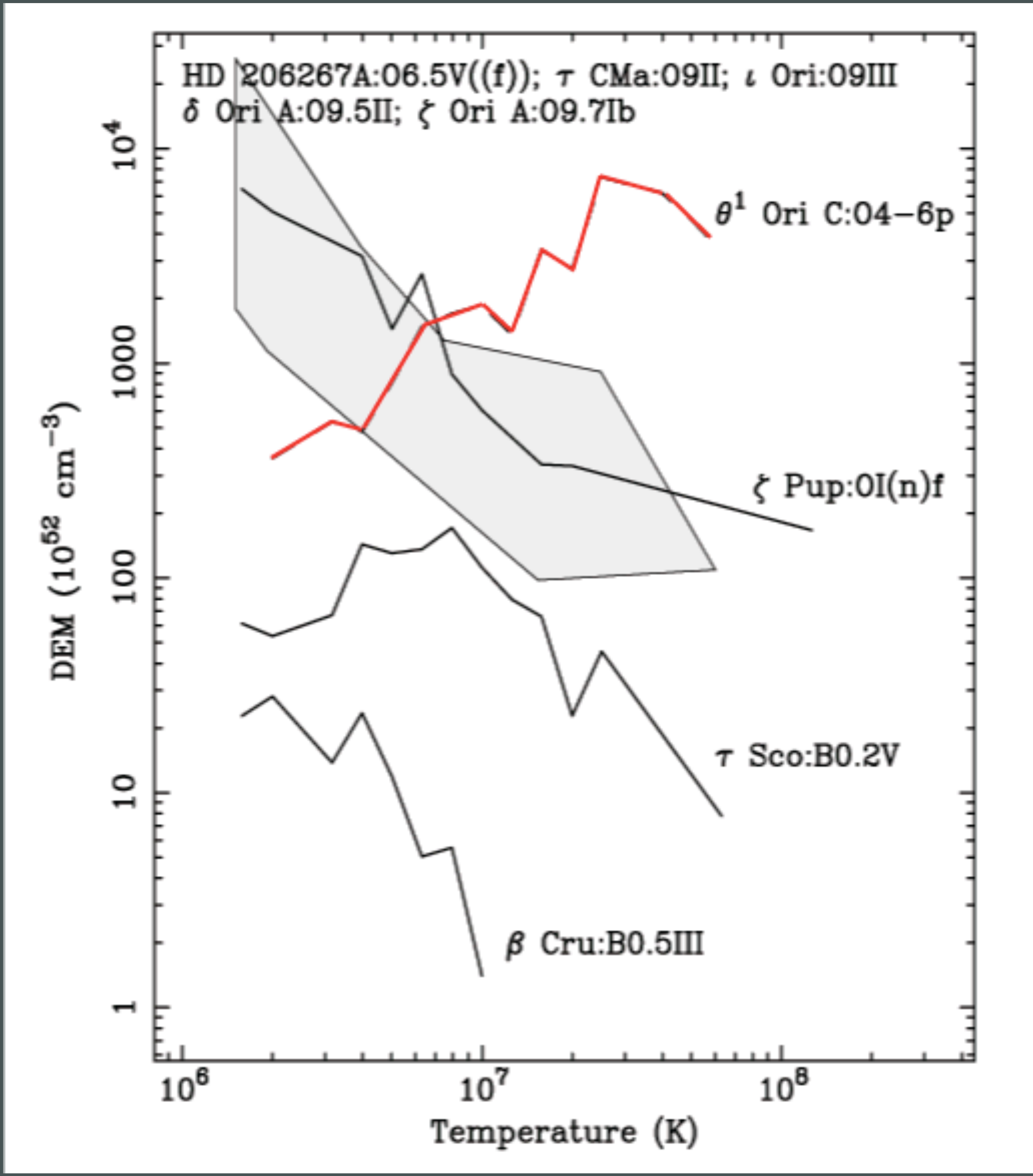


H/He > 1 in θ^1 Ori C

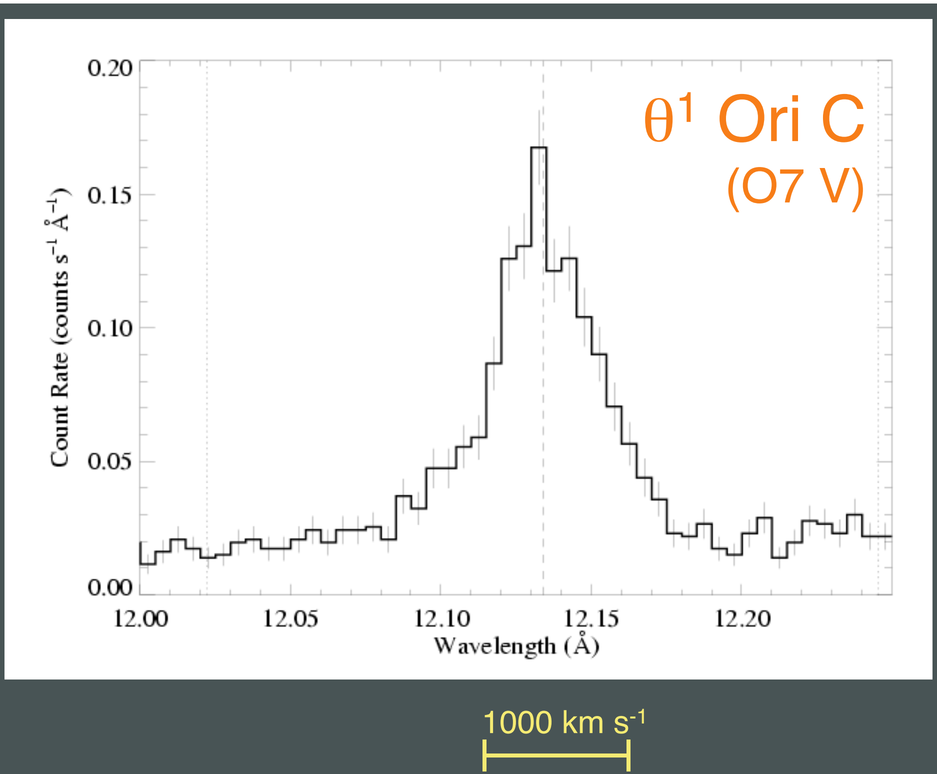
Differential Emission Measure

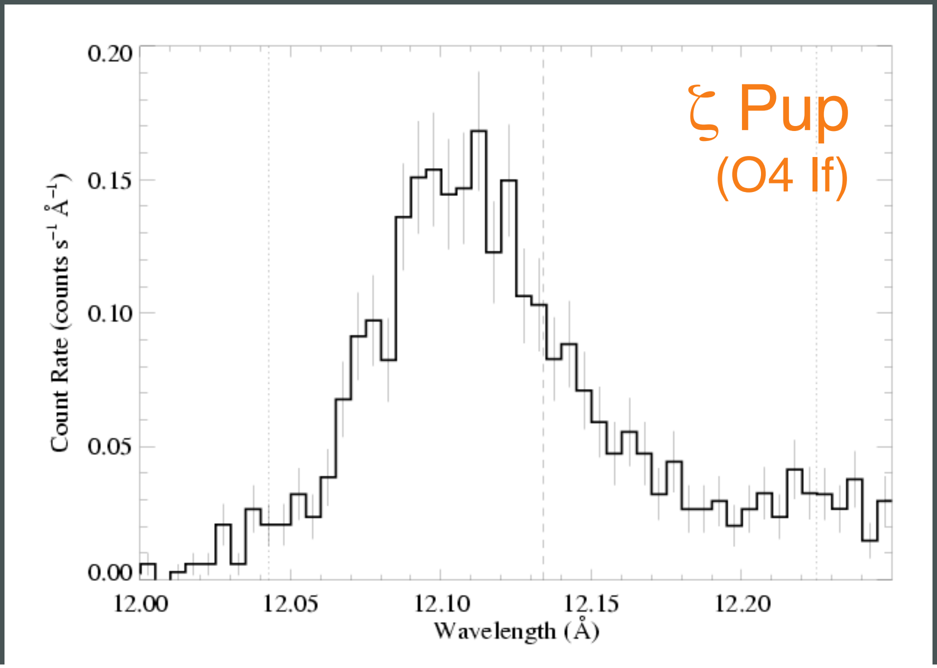
(temperature distribution)

θ^1 Ori C is much hotter



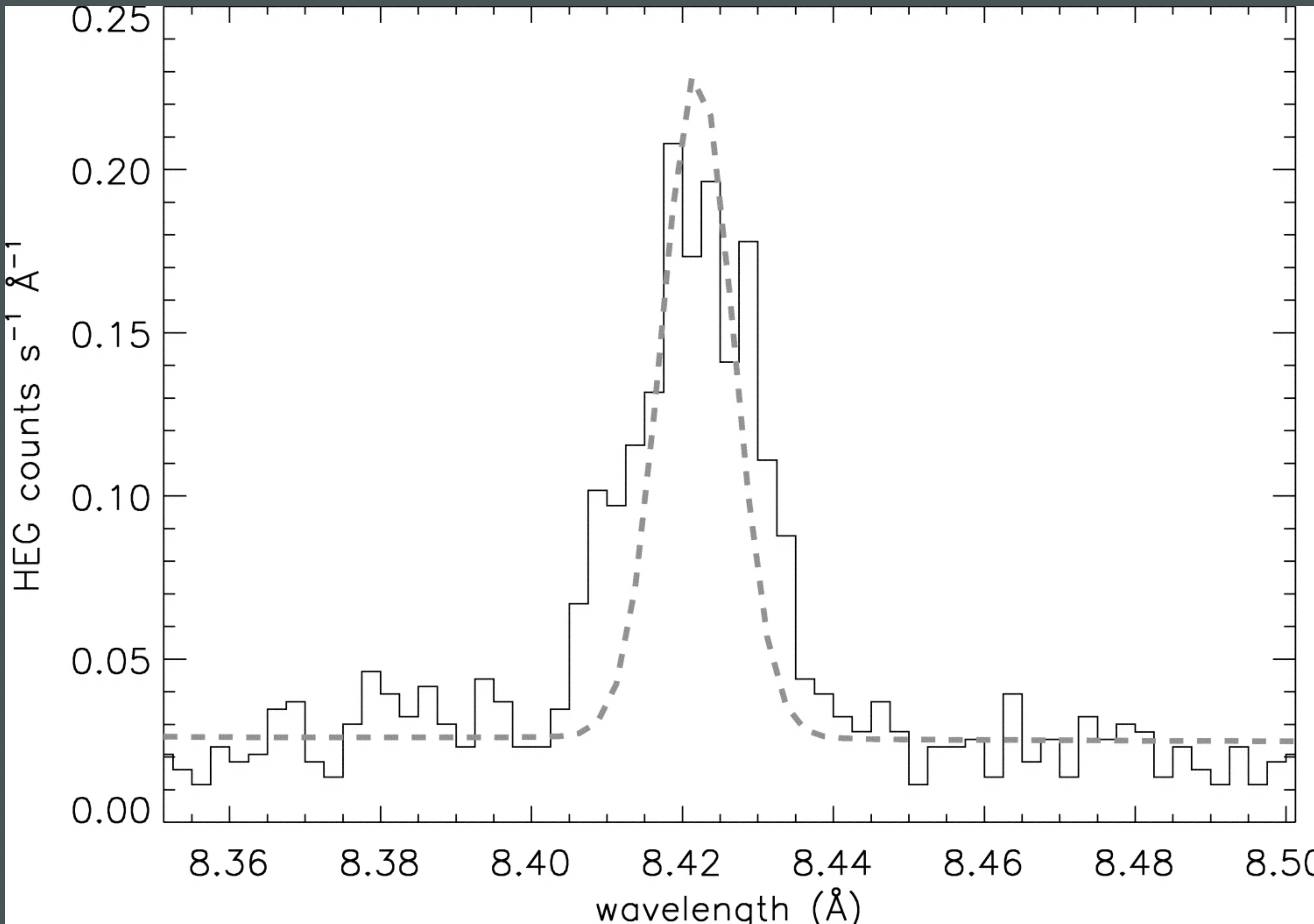
Wojdowski & Schulz (2005)



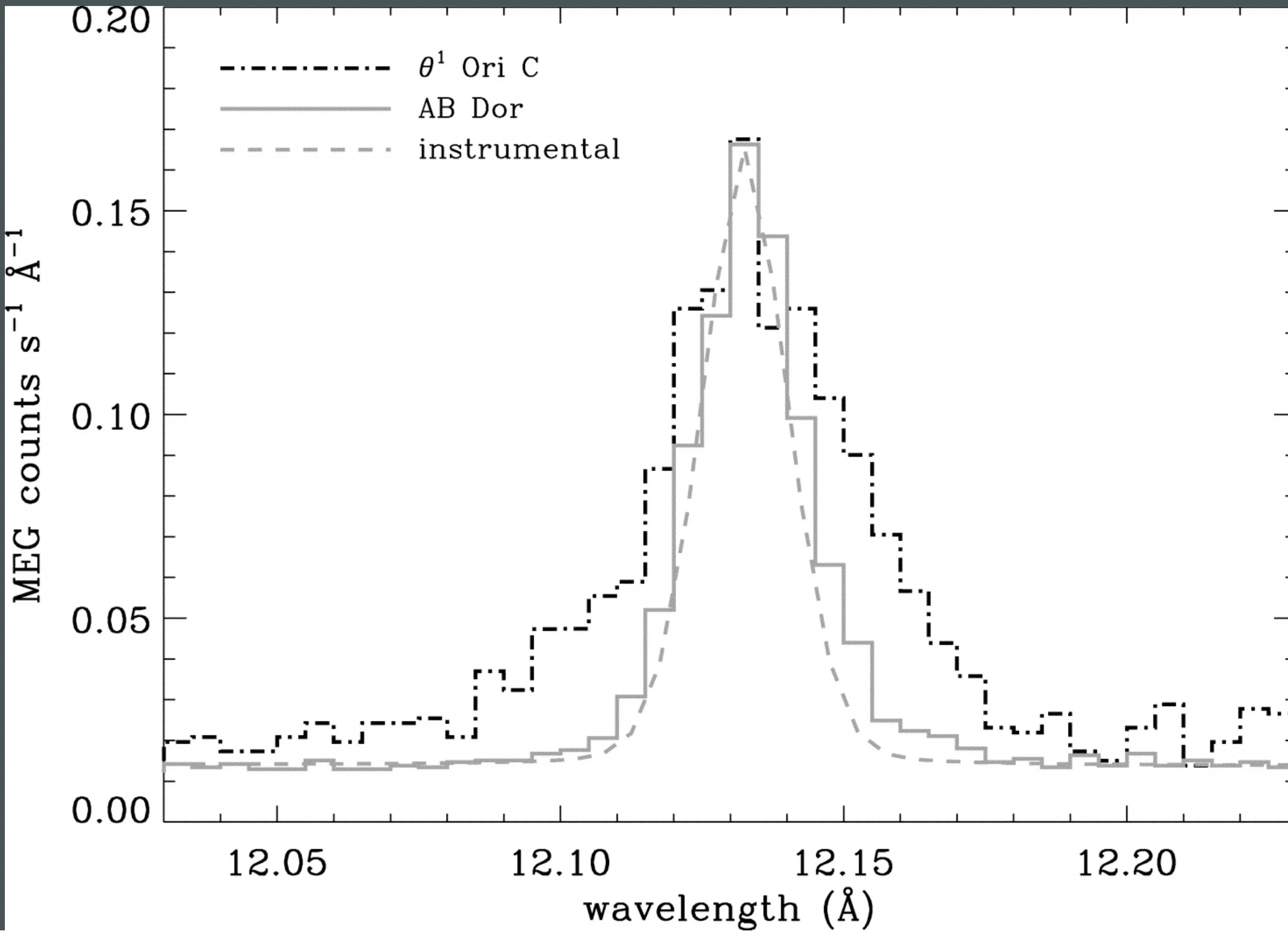


Emission lines are significantly **narrower**, too

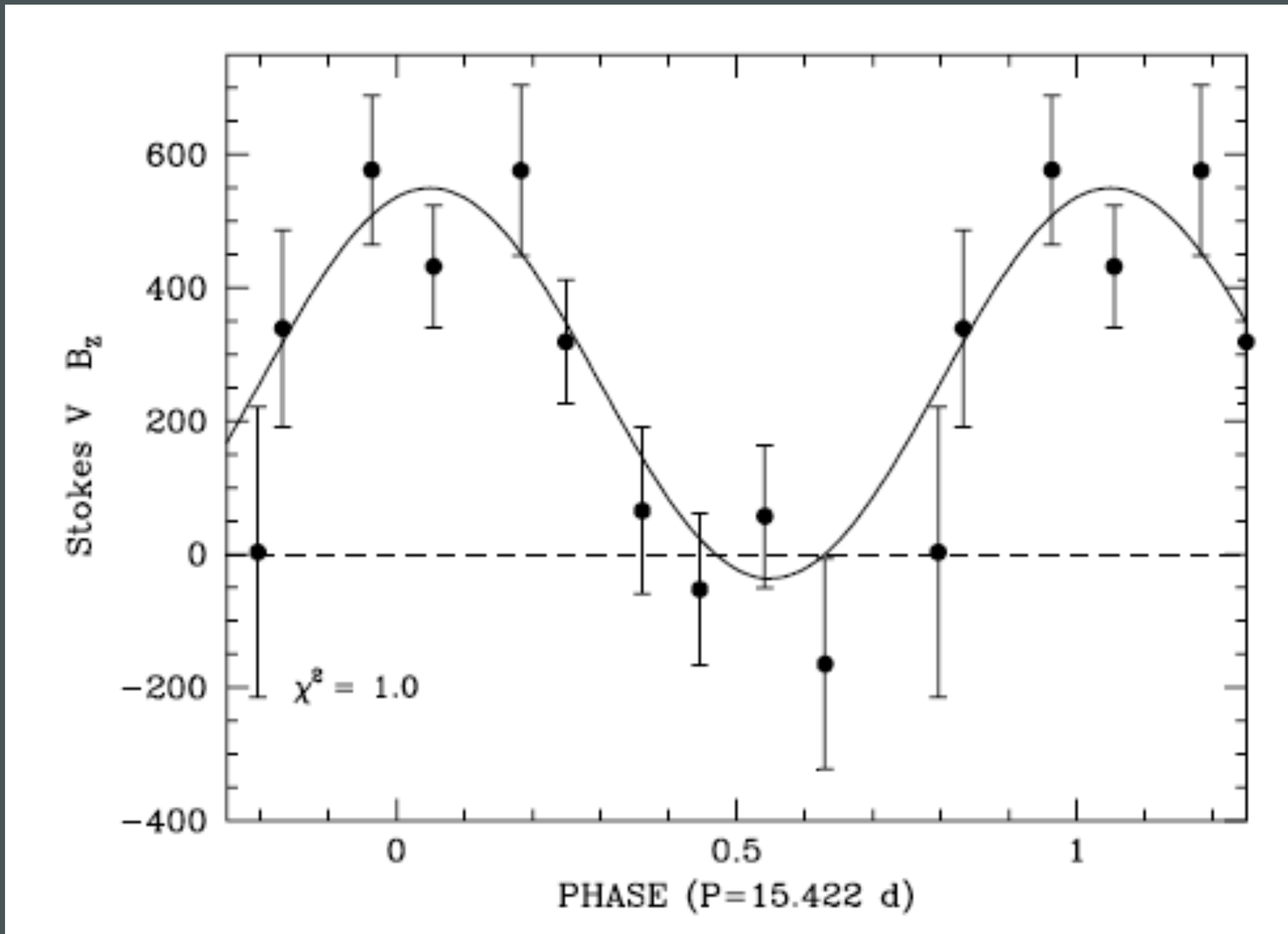
Mg XII Ly-α in θ^1 Ori C compared to instrumental profile



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



Dipole magnetic field



Wade et al. 2008

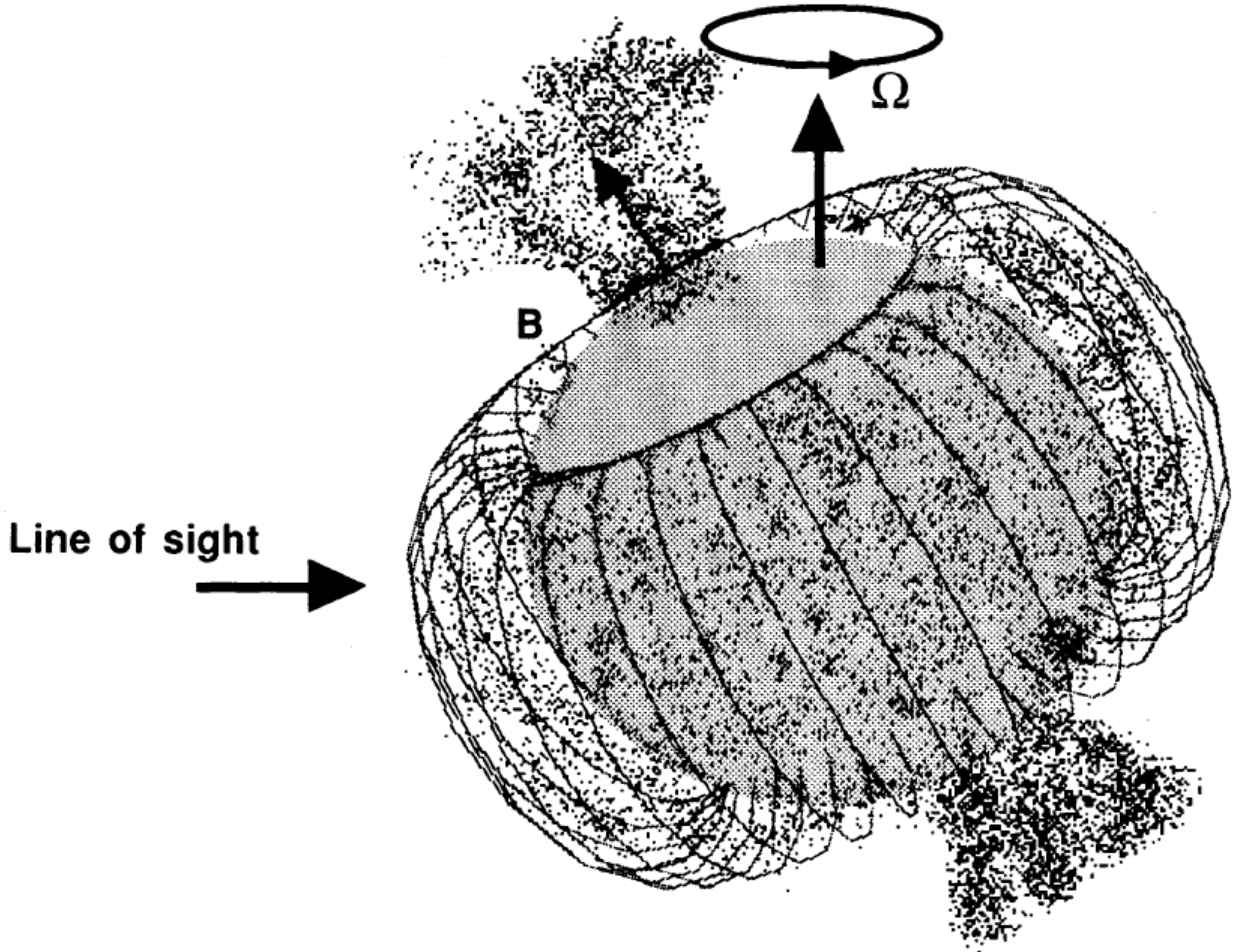
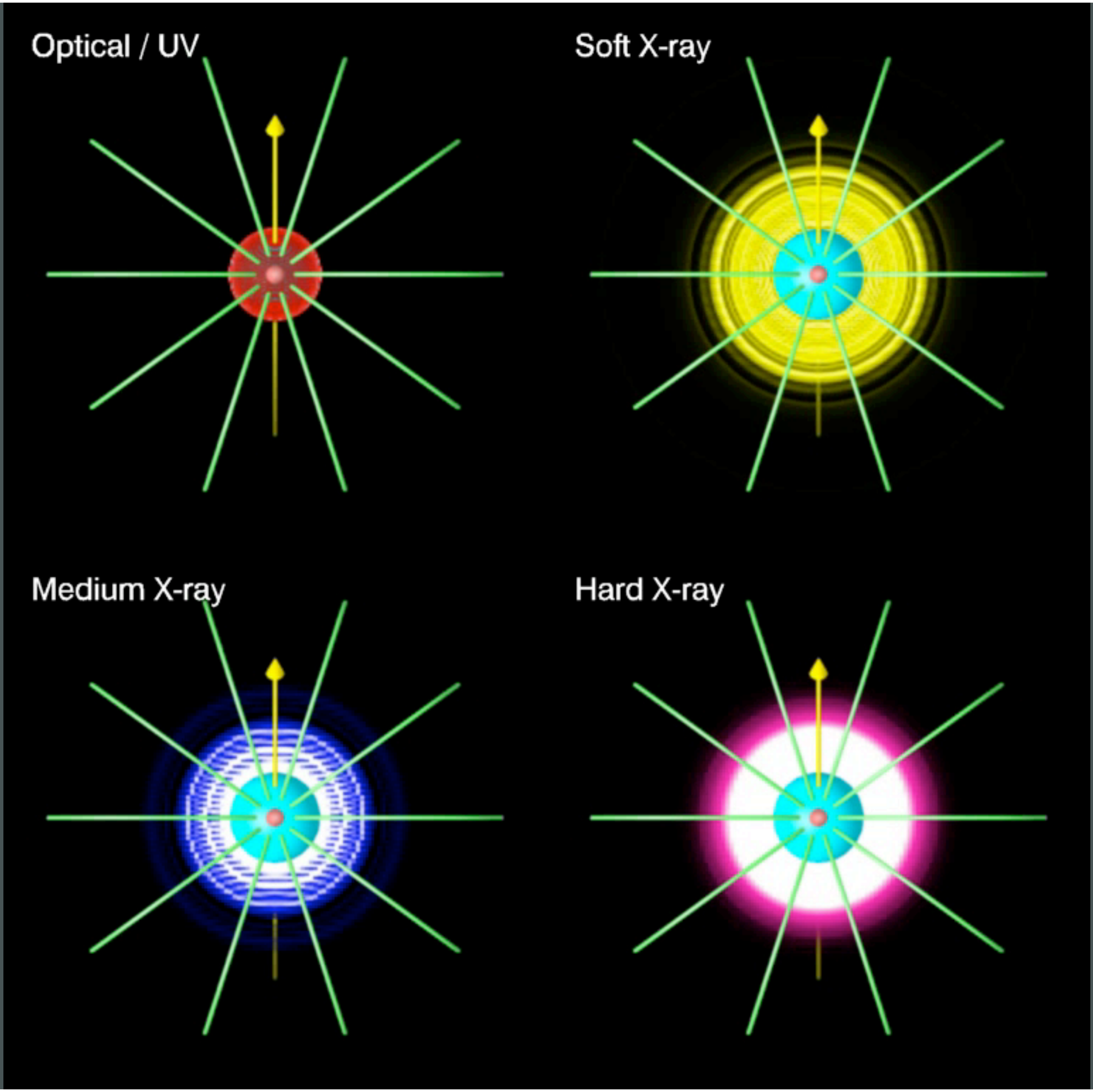


FIG. 11b

Shore & Brown, 1990


Optical / UV
Soft X-ray
Medium X-ray
Hard X-ray

There are *Chandra* observations at many different phases

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**?

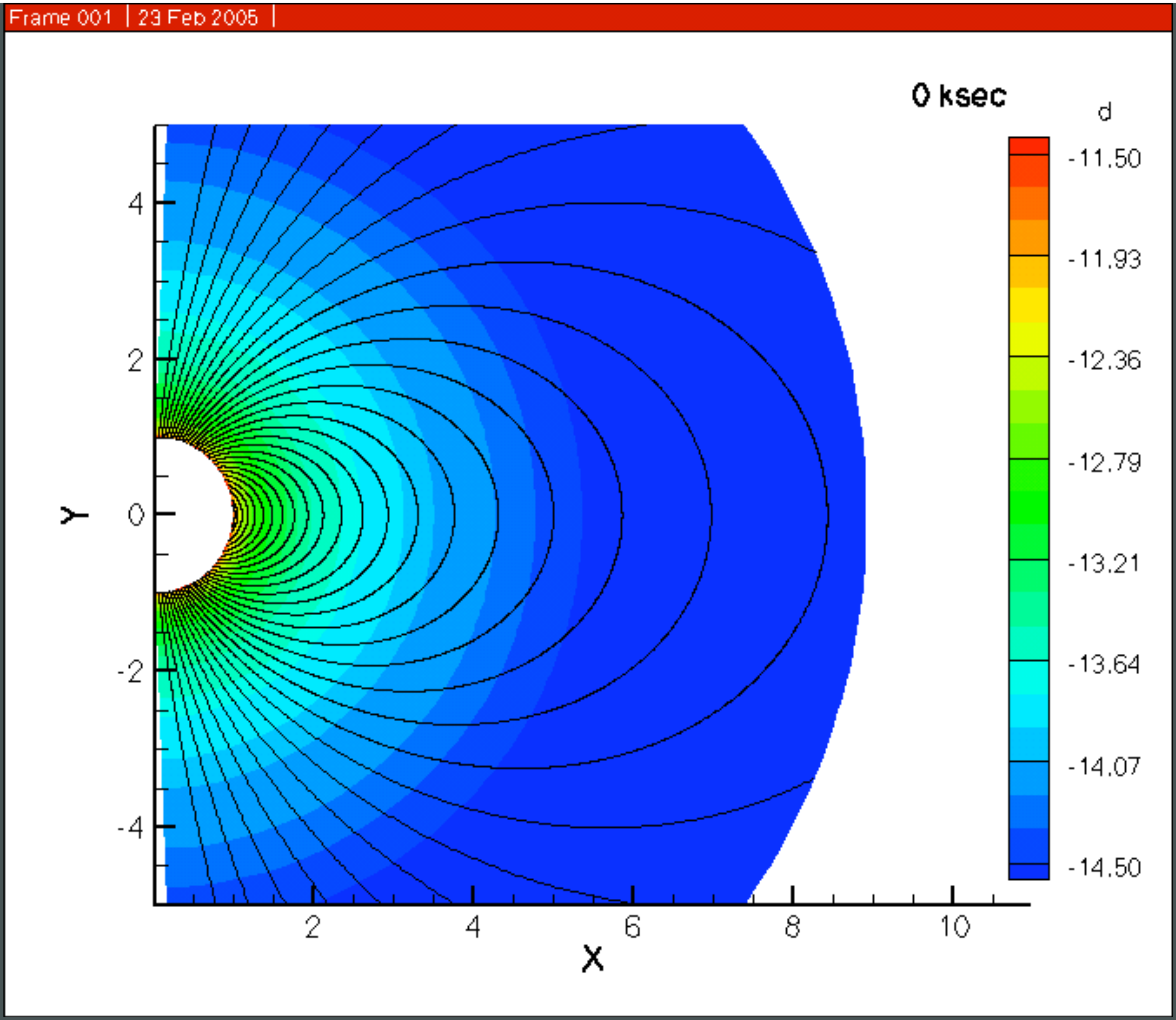
Recall:

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

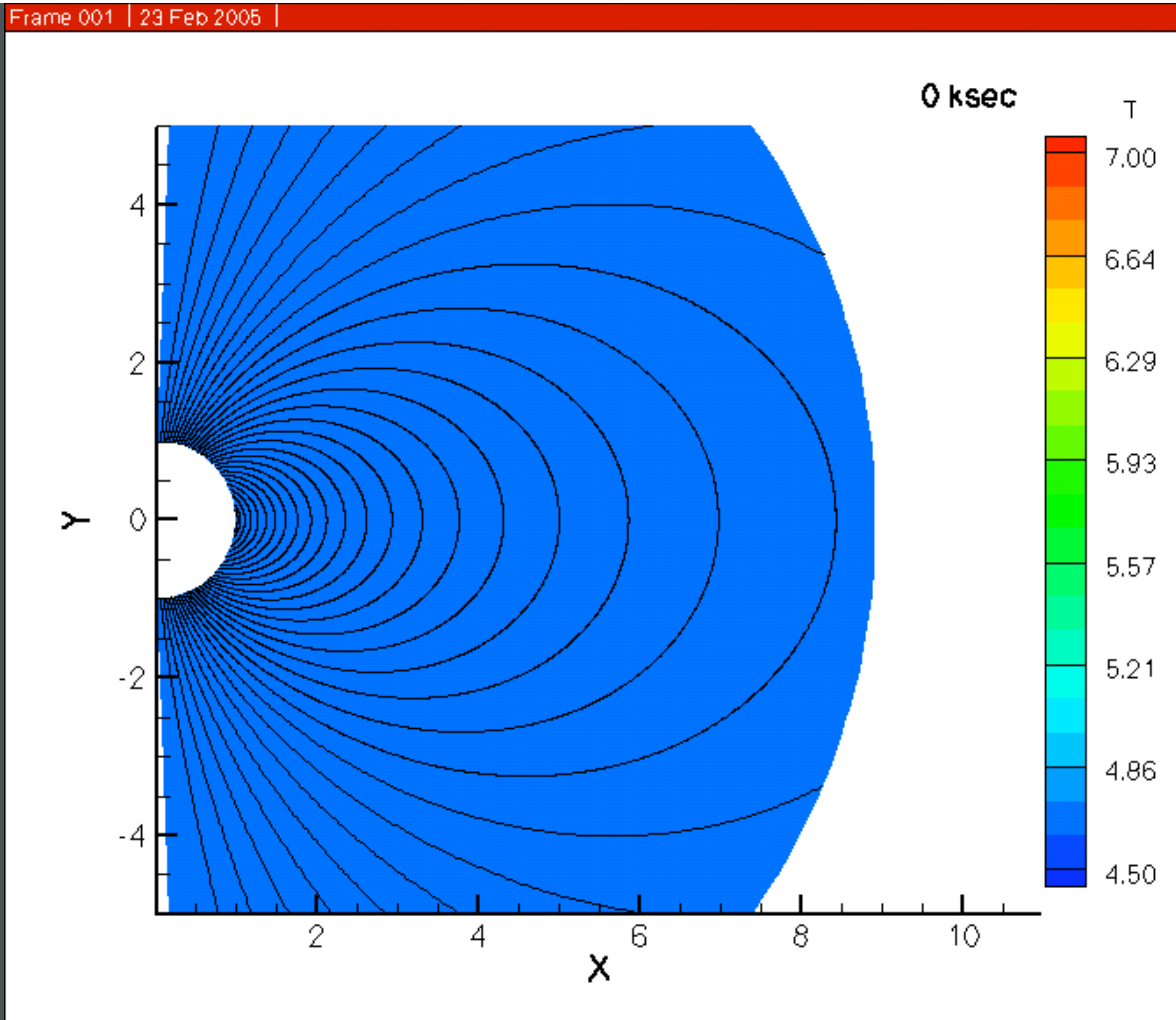
ζ Ori: $\eta_* \sim 0.1$: poor confinement

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

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



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



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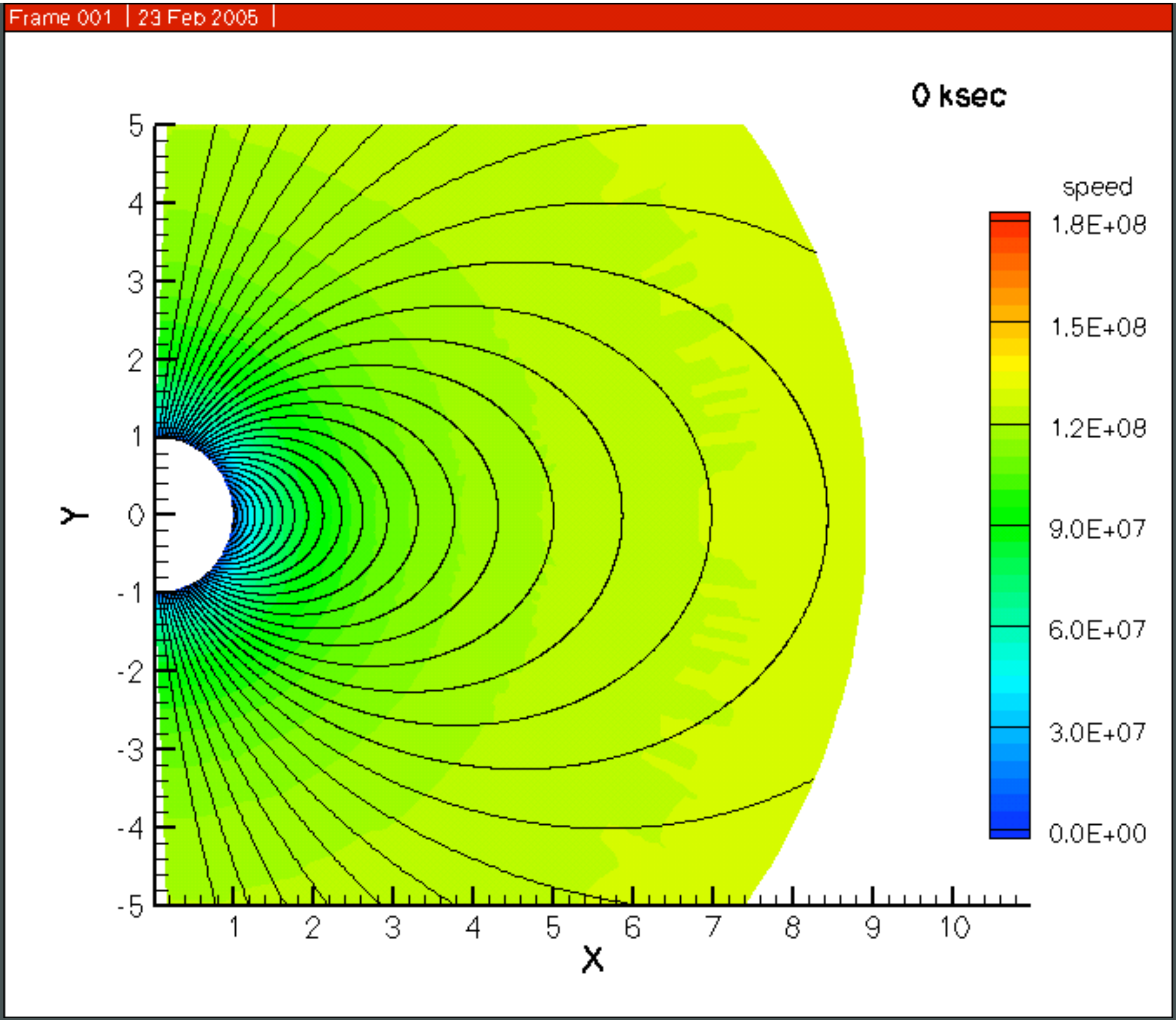
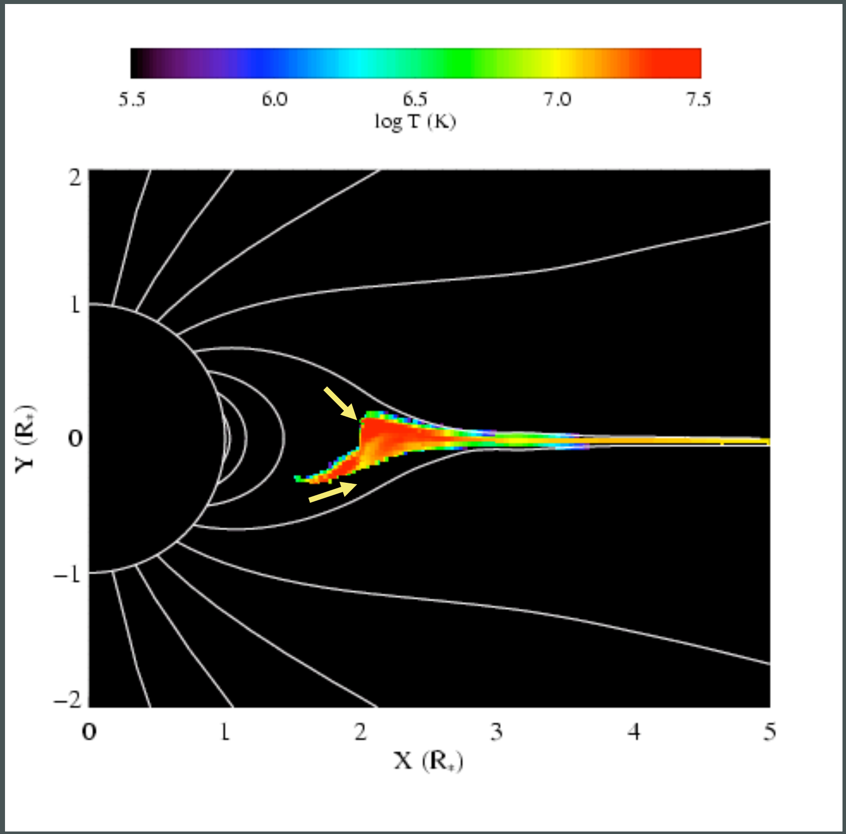


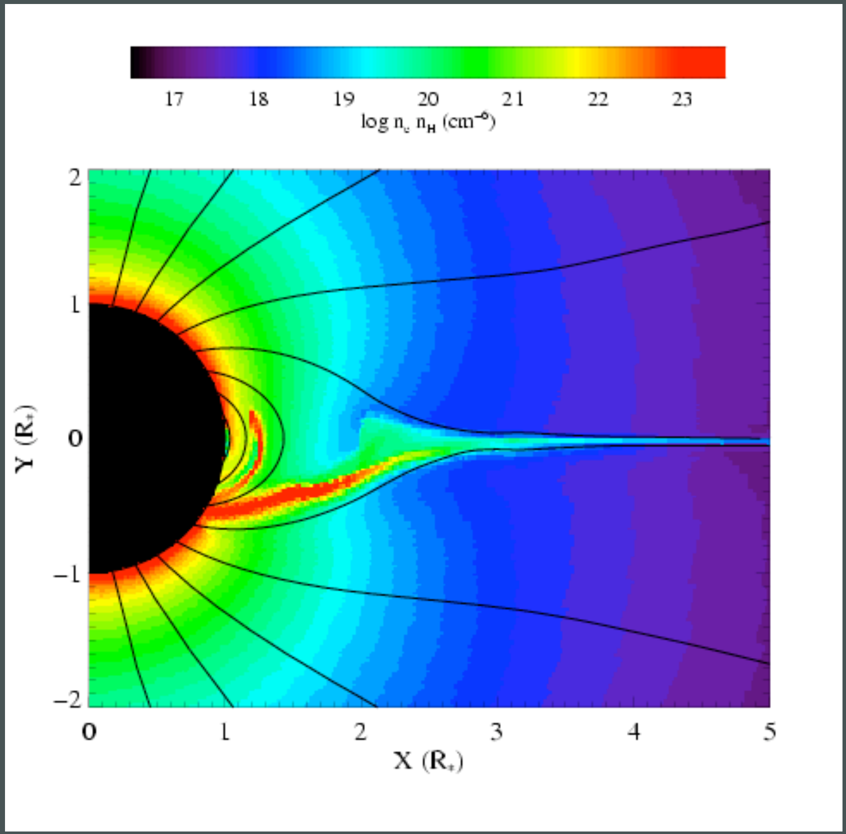
Simulation/visualization courtesy A. ud-Doula
Movie available at astro.swarthmore.edu/~cohen/presentations/apip09/t1oc-lowvinf-speed.avi

MHD simulations of magnetically channeled wind

temperature



emission measure

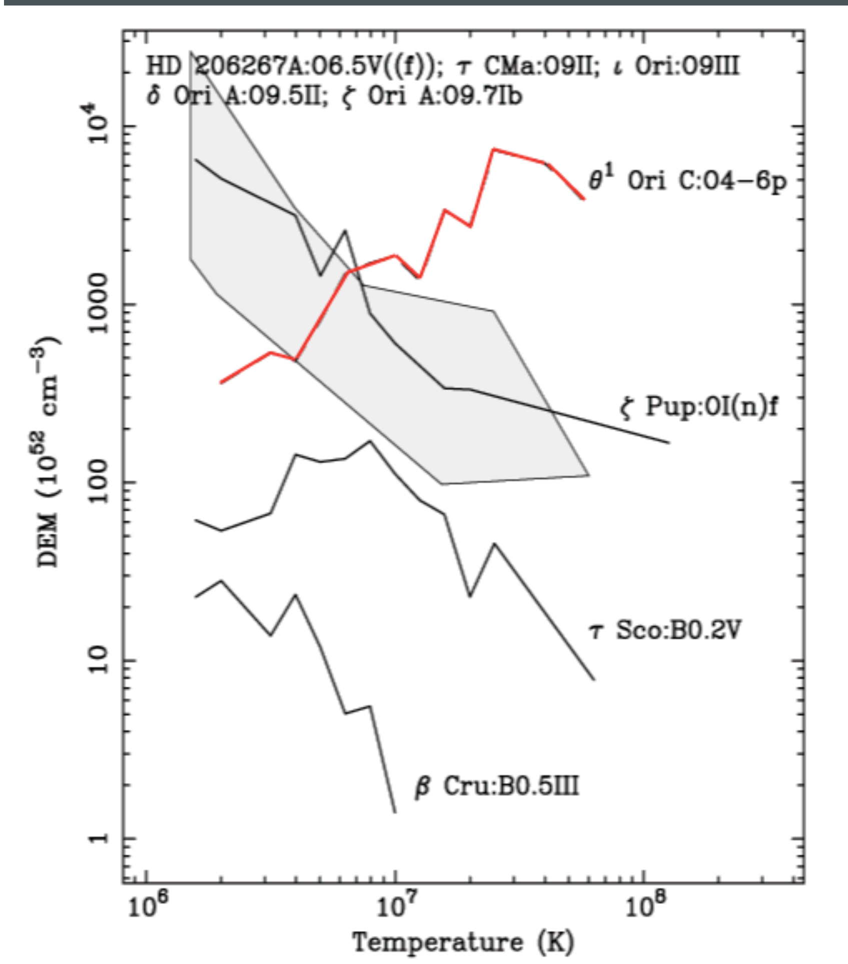


simulations by A. ud-Doula; Gagné et al. (2005)

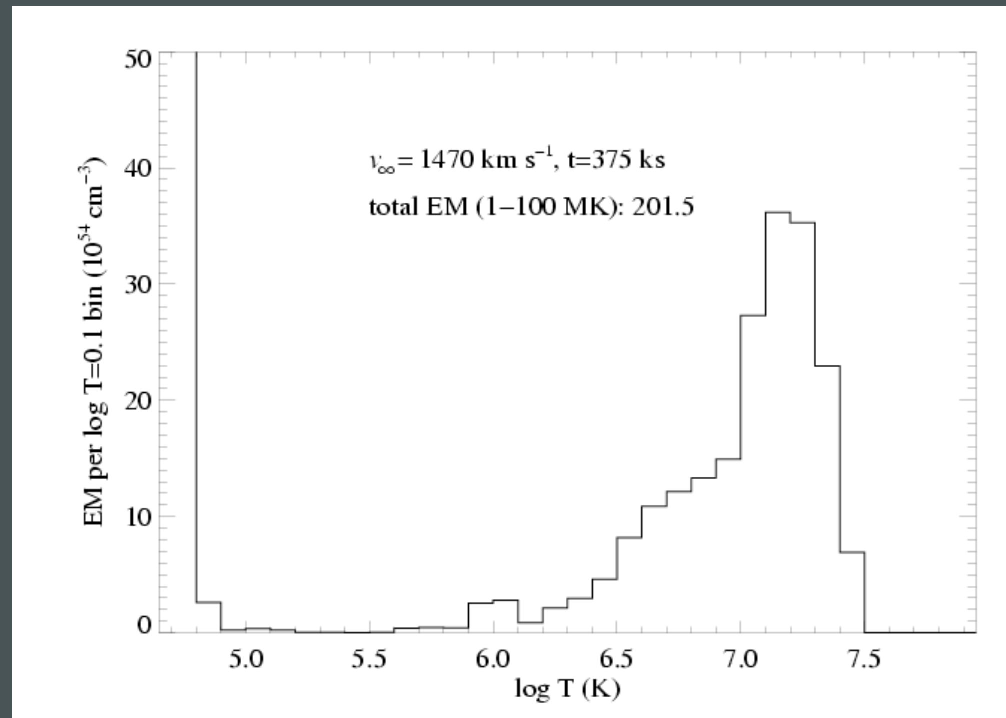
Channeled collision is close to head-on:

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

Differential emission measure
(temperature distribution)

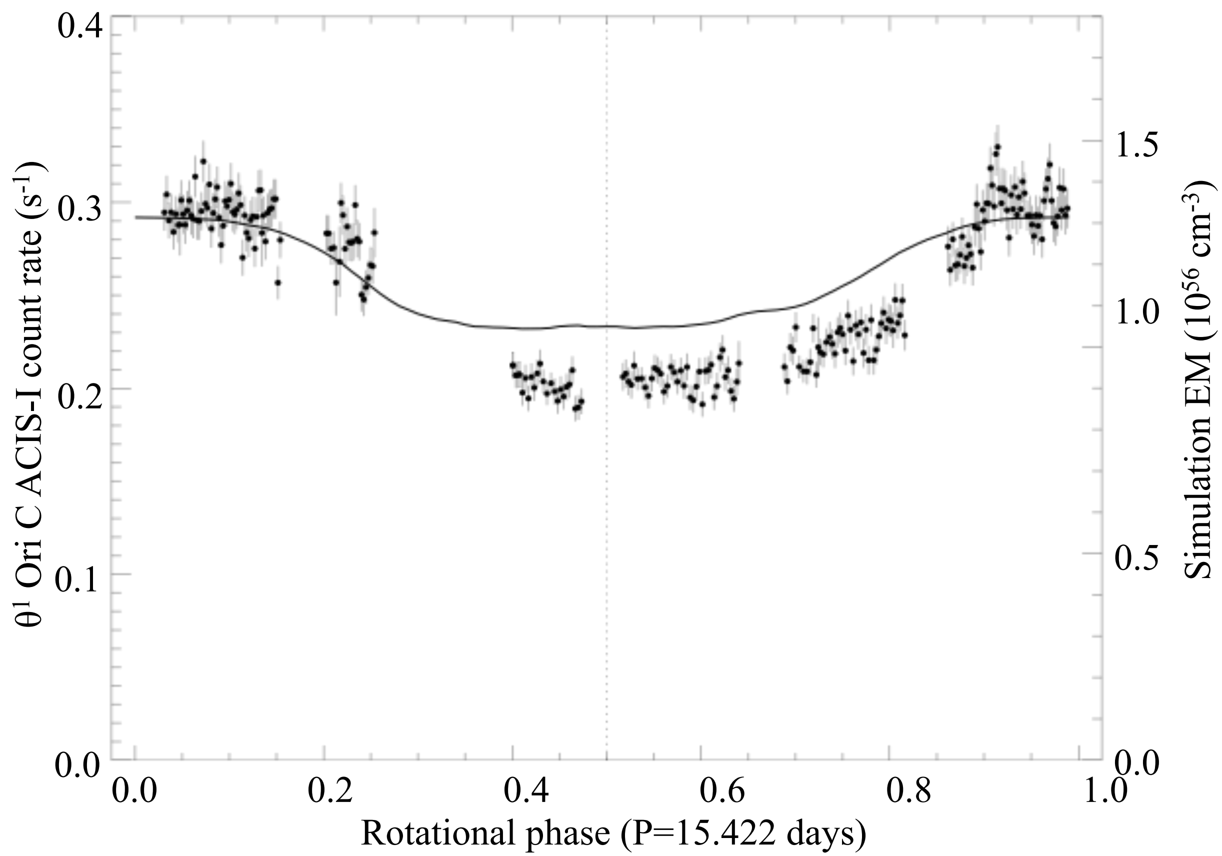


Wojdowski & Schulz (2005)



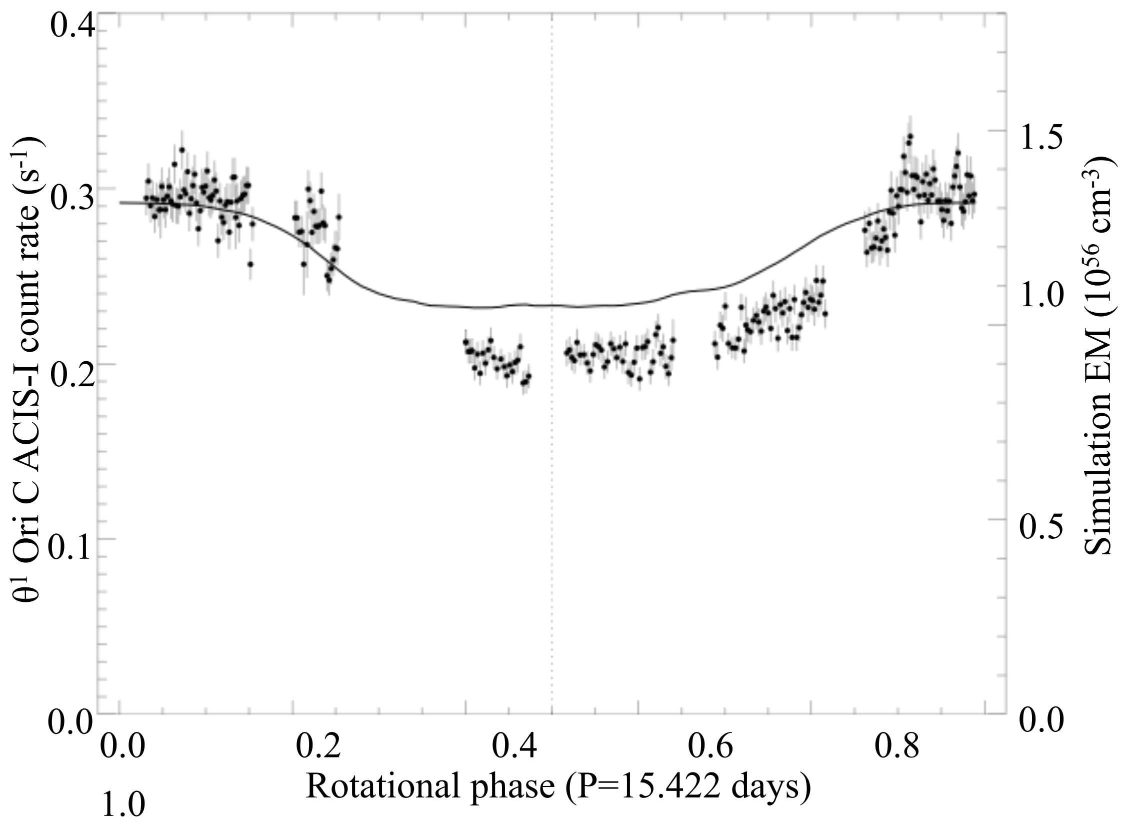
MHD simulation of θ^1 Ori C reproduces the observed differential emission measure

Chandra broadband count rate vs. rotational phase



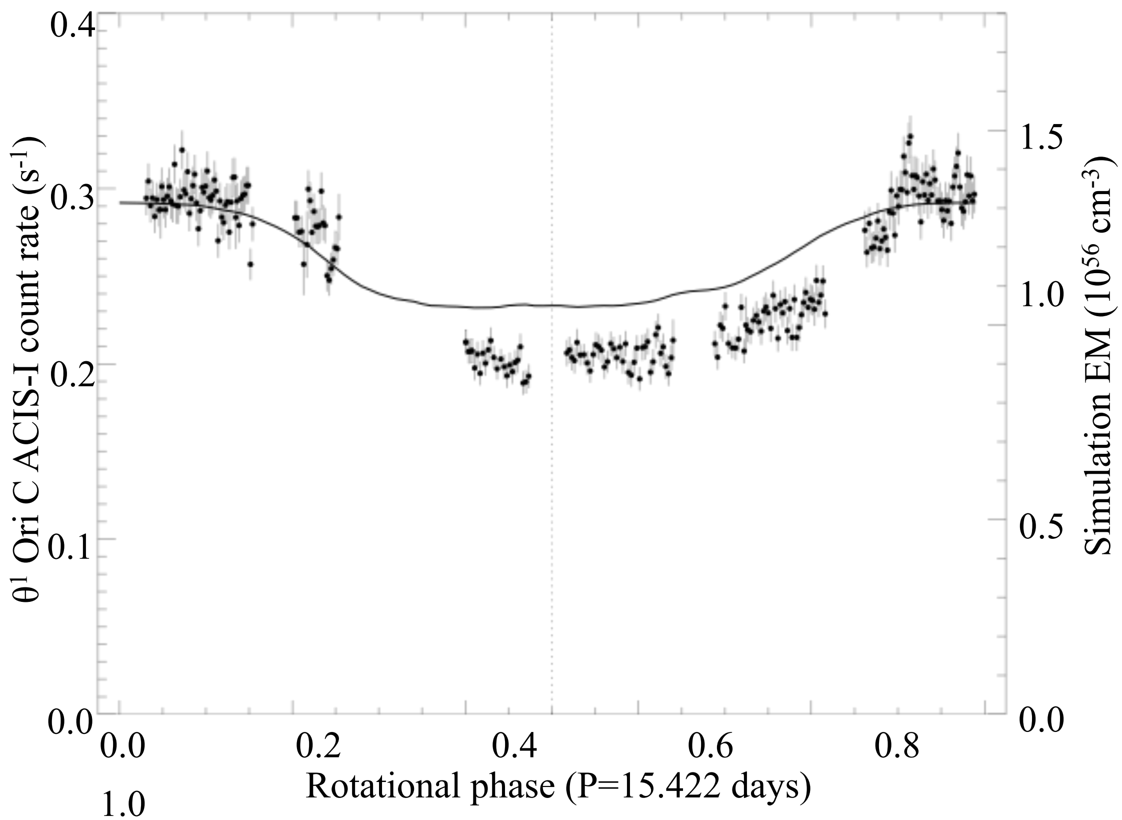
Model from MHD simulation

The star itself occults the hot plasma torus



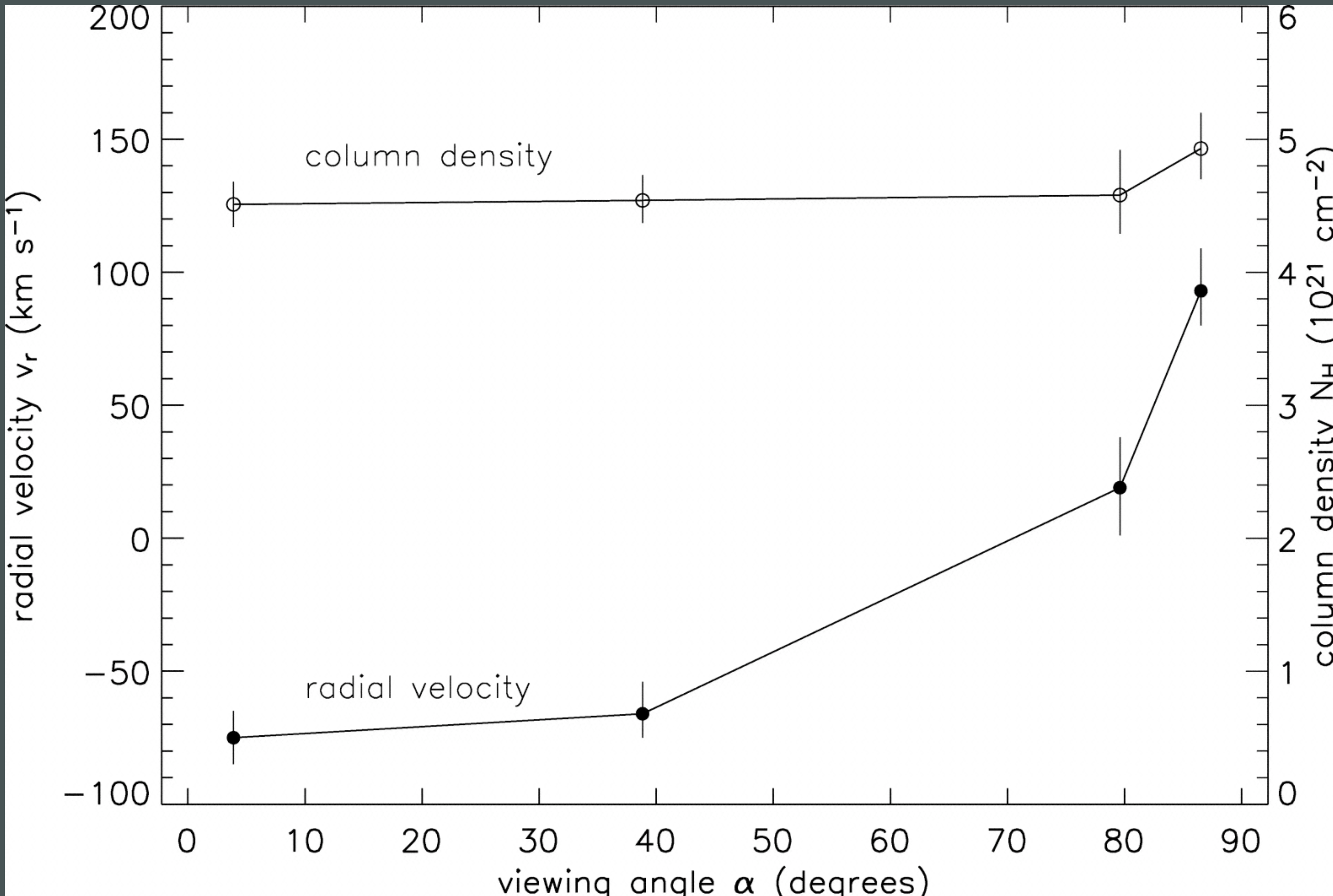
The closer the hot plasma is to the star, the deeper the dip in the x-ray light curve

The star itself occults the hot plasma torus



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

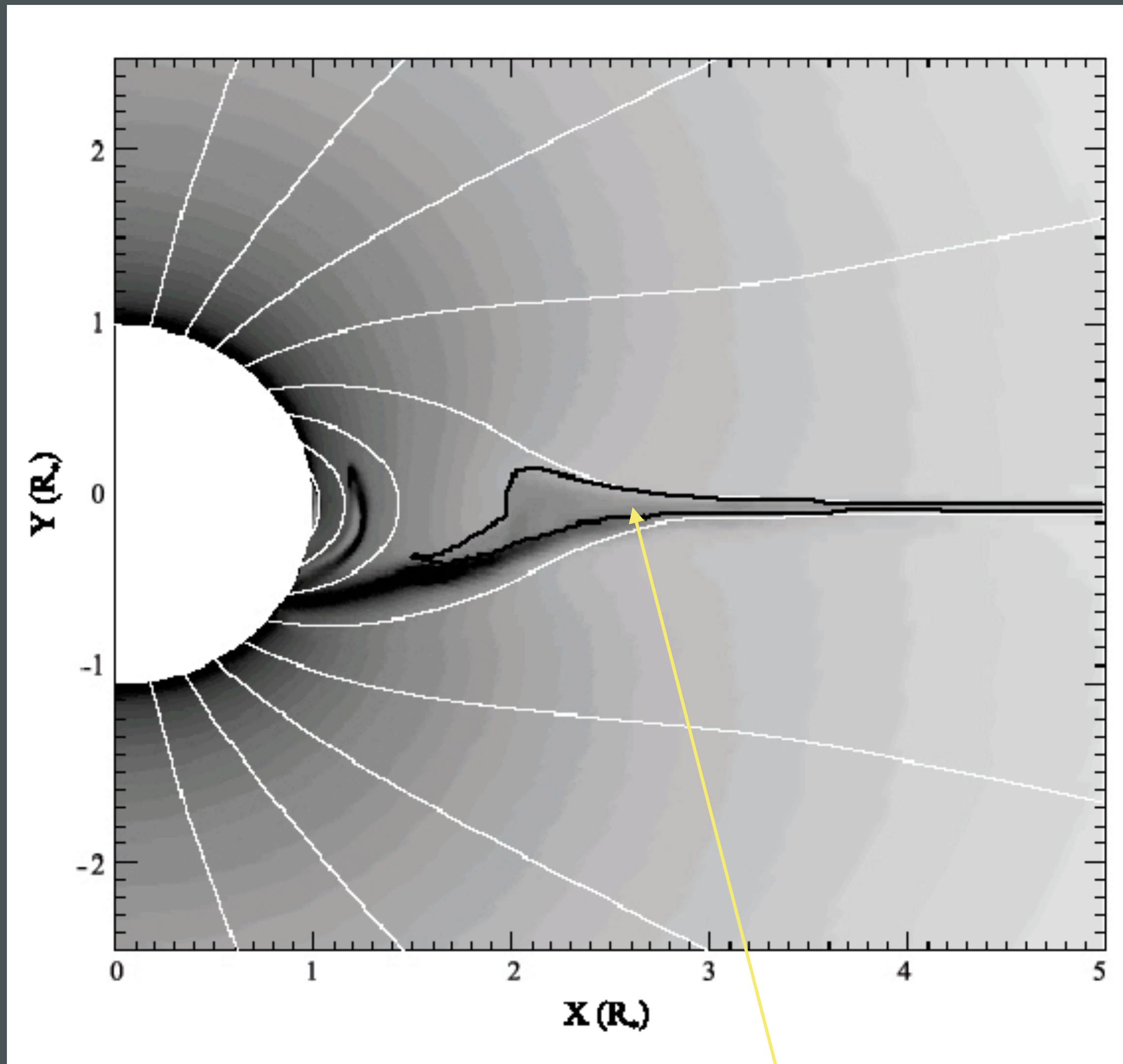
θ^1 Ori C column density (from x-ray absorption) vs. phase



pole-on

equator-on

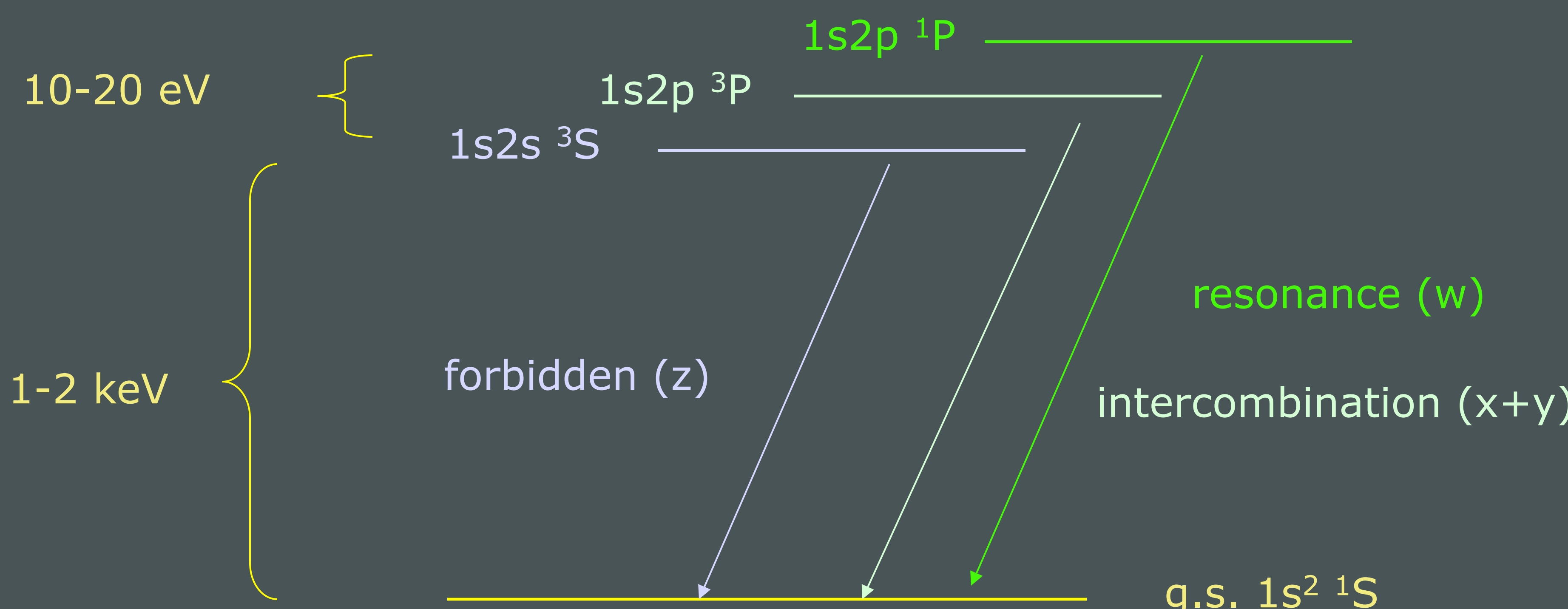
Emission measure



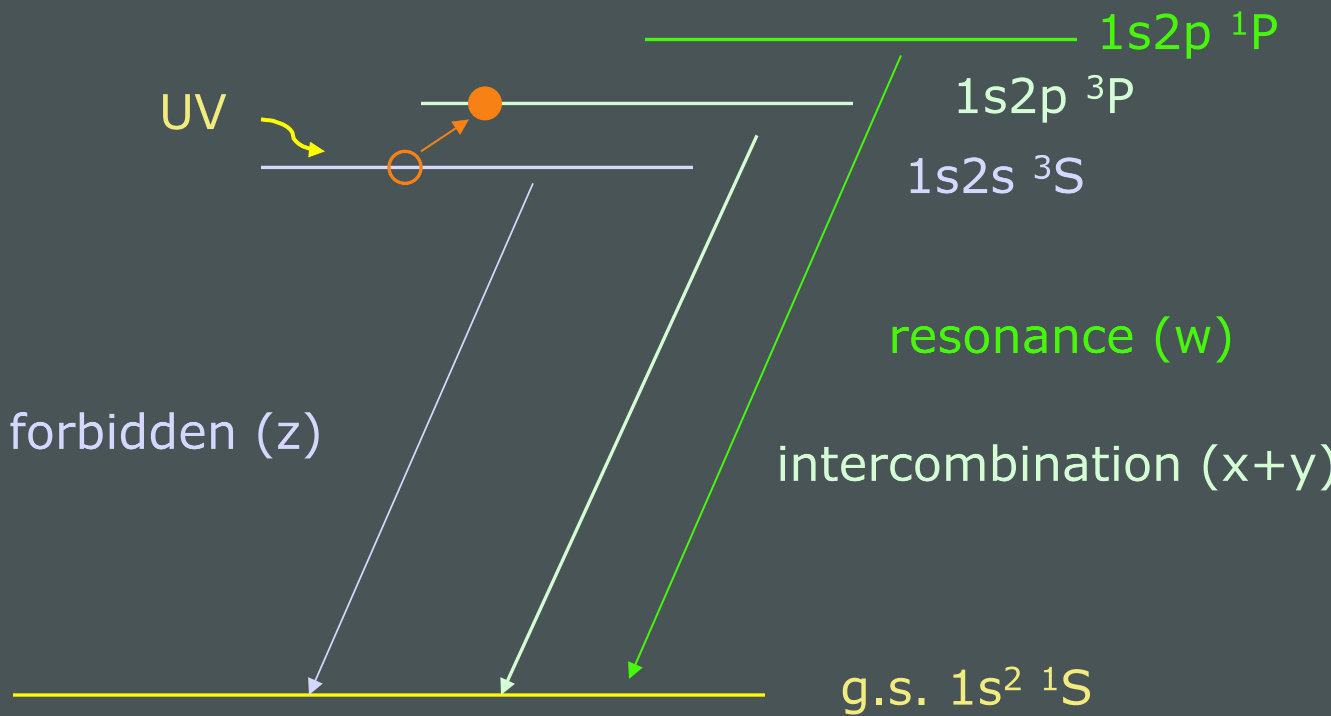
contour encloses $T > 10^6$ K

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

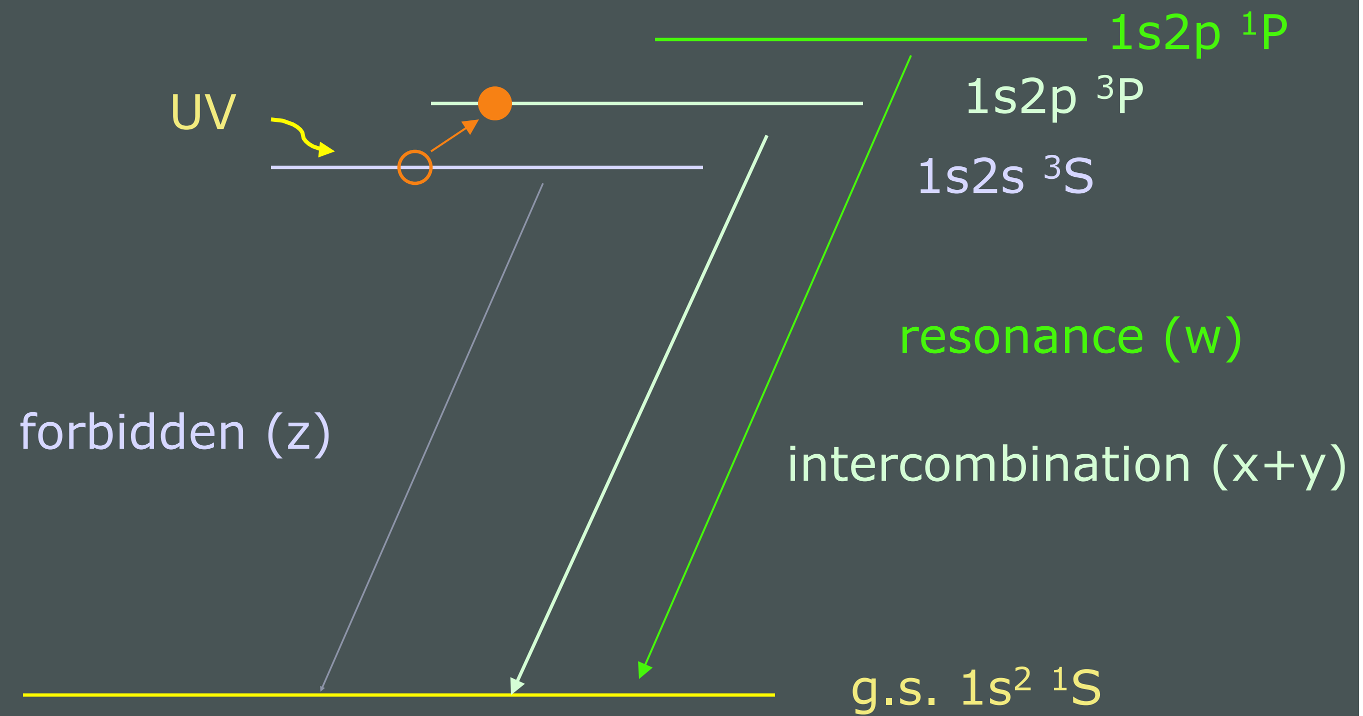
Helium-like ions (e.g. O^{+6}, Ne^{+8}, Mg^{+10}, Si^{+12}, S^{+14}) – schematic energy level diagram



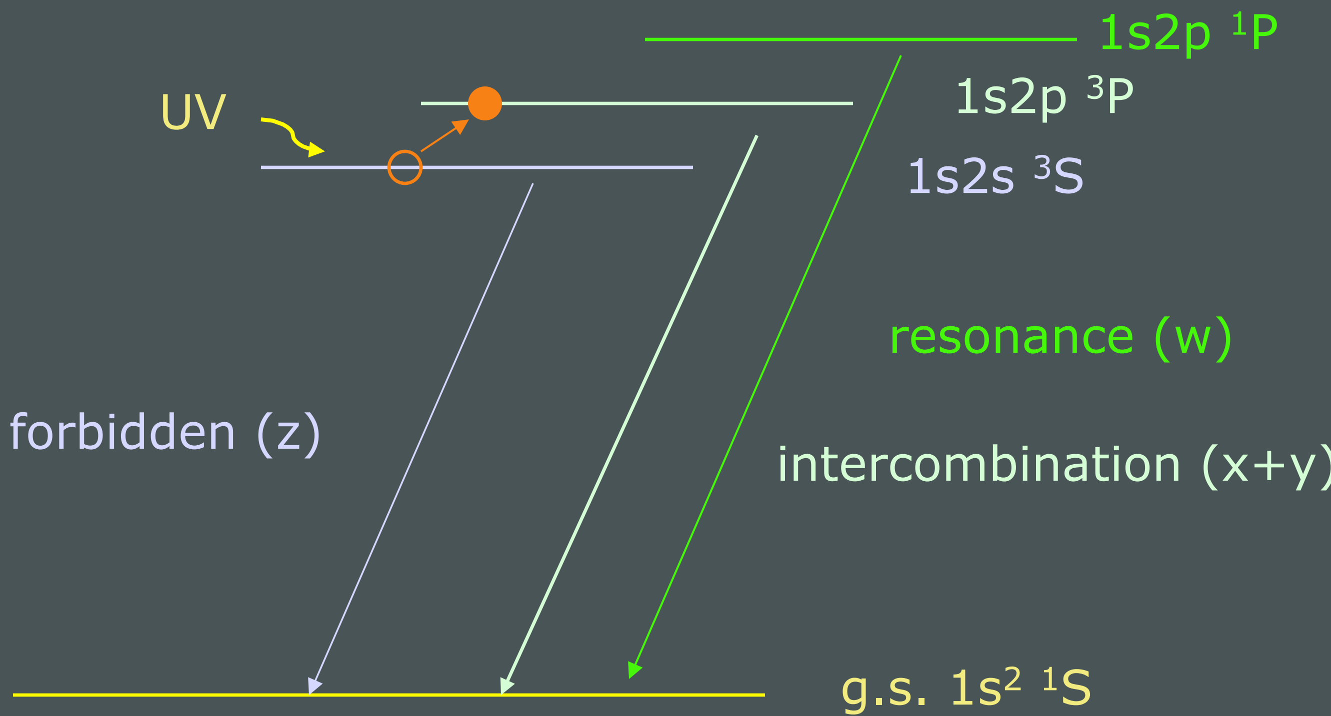
Ultraviolet light from the star's photosphere drives photoexcitation out of the ^3S level



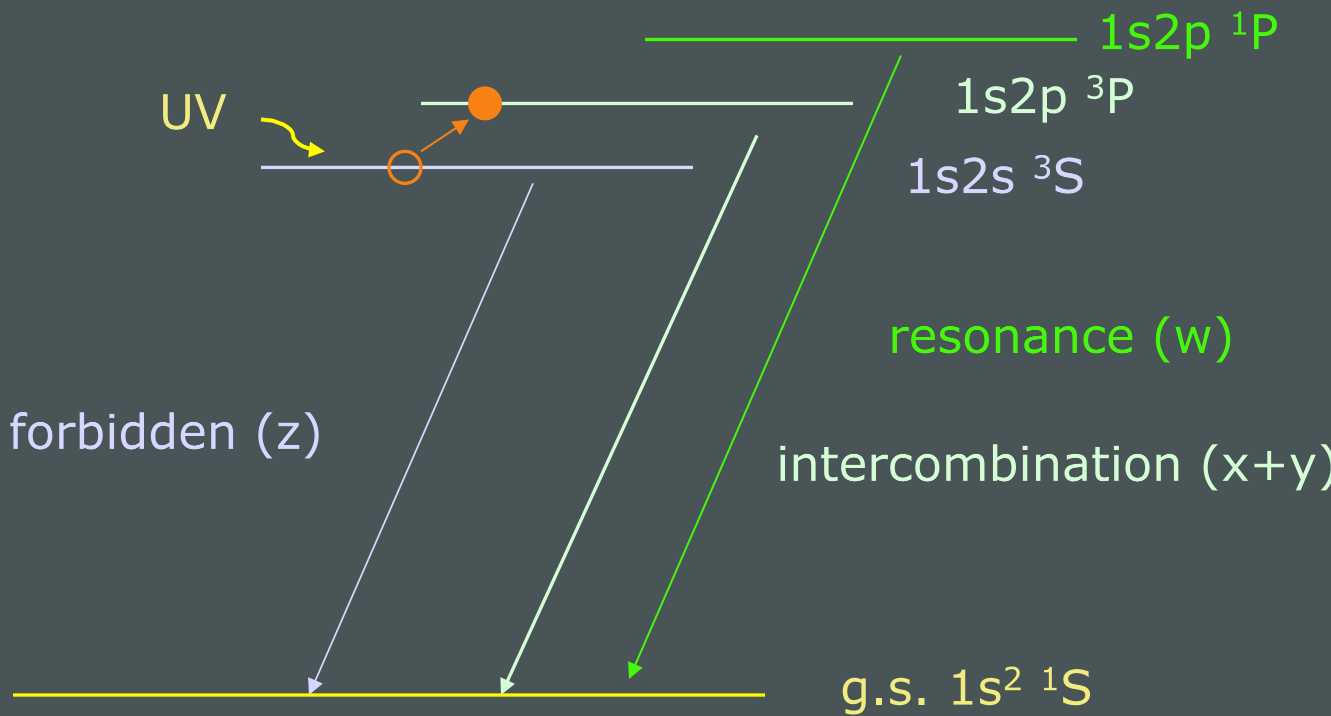
Weakening the forbidden line and strengthening the intercombination line

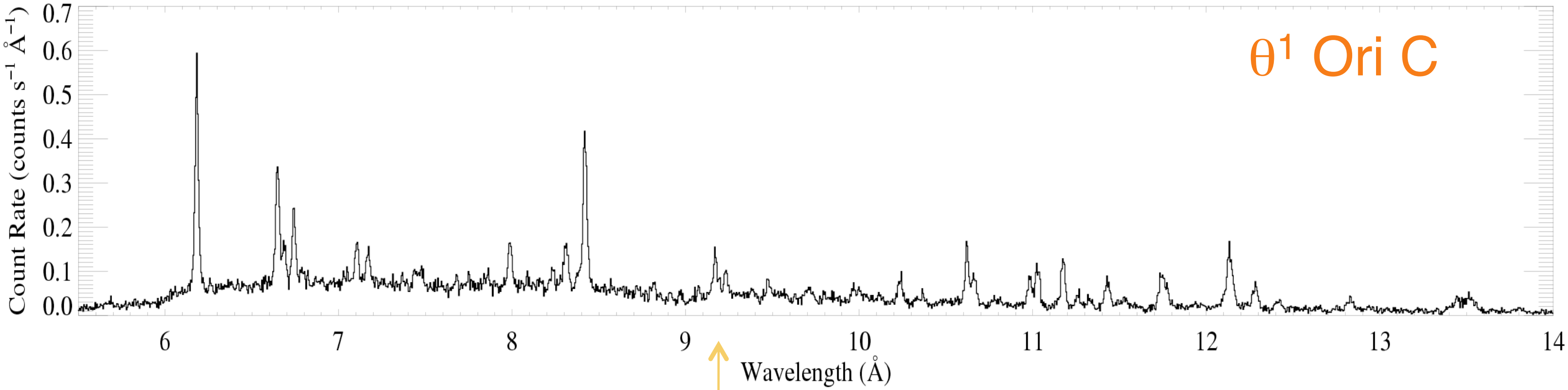


The f/i ratio is thus a diagnostic of the local UV mean intensity…

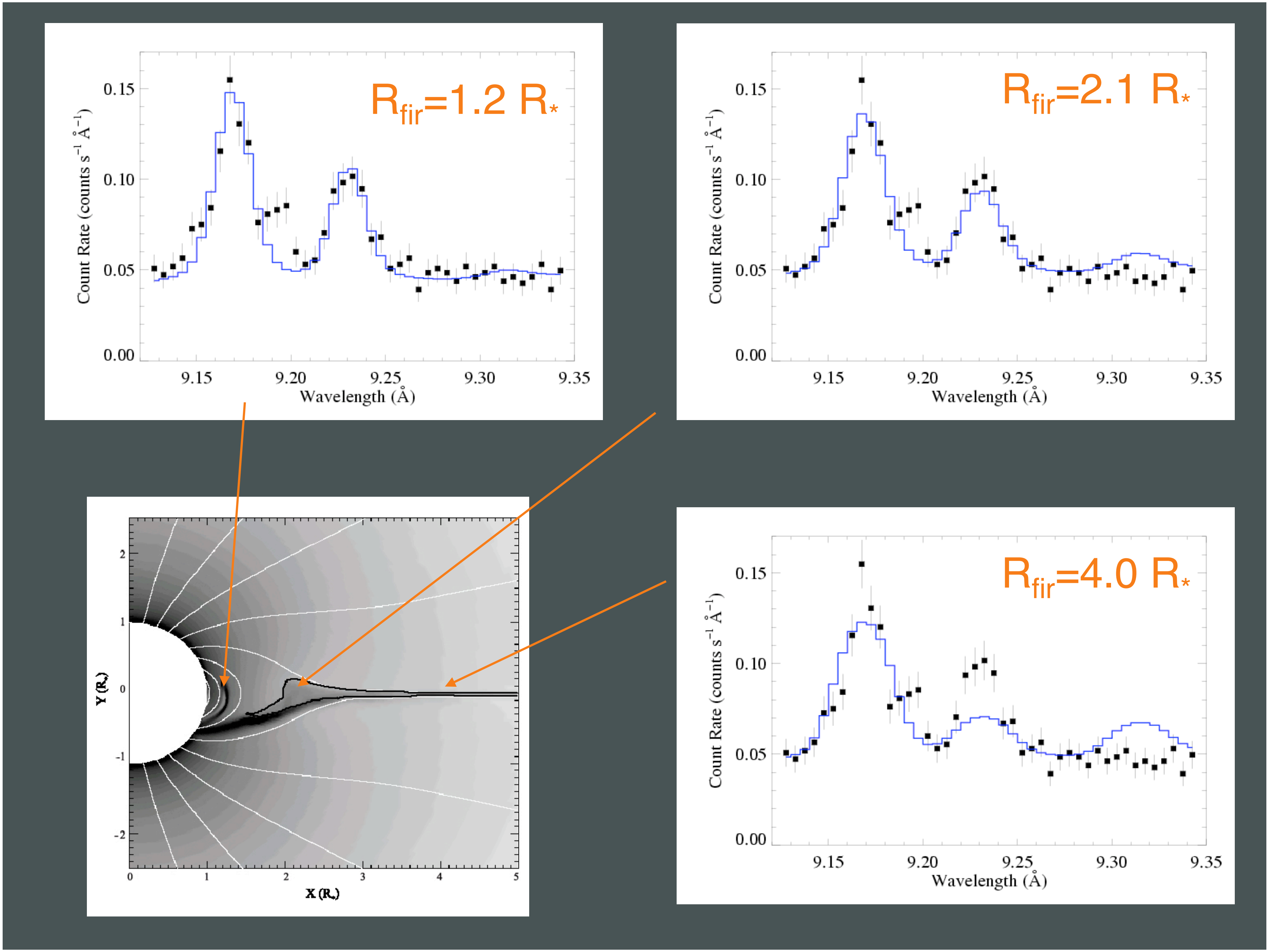


…and thus the distance of the x-ray emitting plasma from the photosphere




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



R_fir=1.2 R*
R_fir=2.1 R*
R_fir=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:

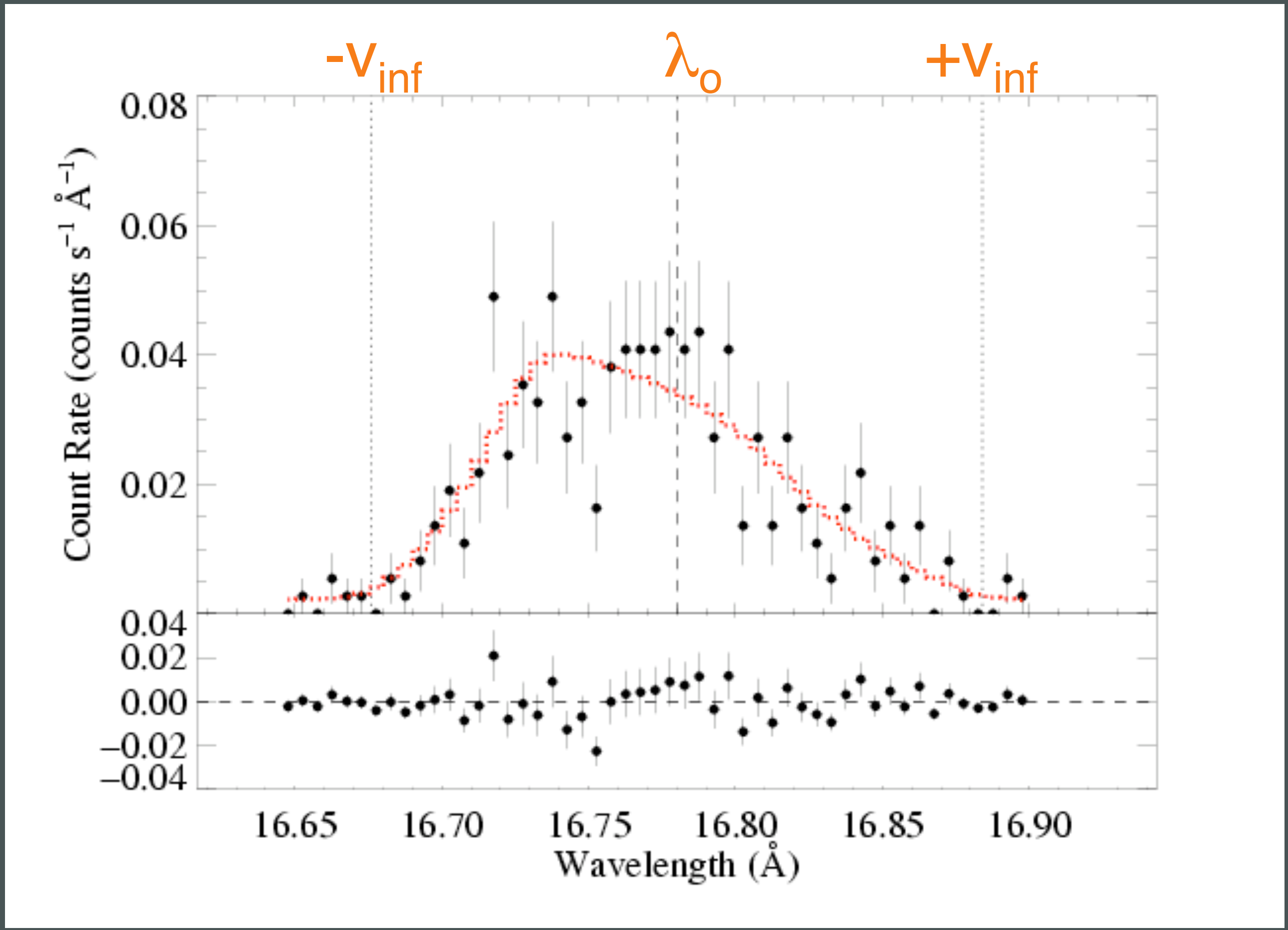
- High X-ray luminosity
- X-ray hardness (high plasma temperatures)
- Periodic variability (rotation and occultation)
- Narrow emission lines (confinement)
- f/i ratios quantify location

What about other magnetic massive stars?

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

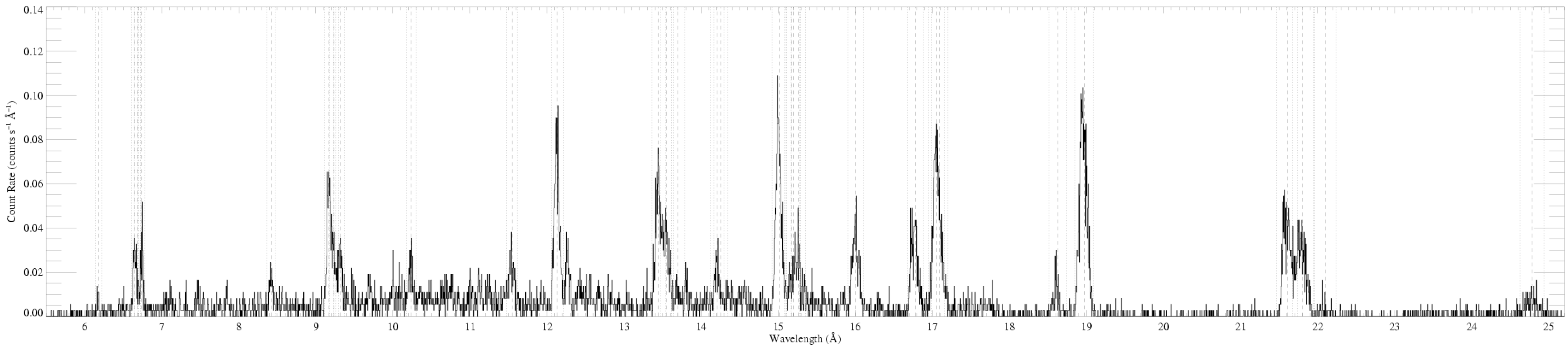
θ^1 Ori C has a hard X-ray spectrum with narrow lines

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

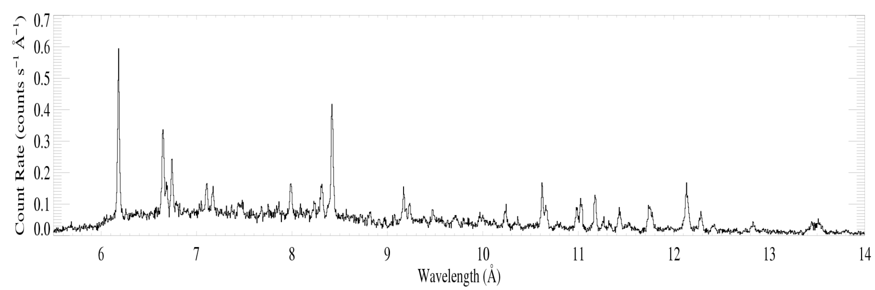


Fe XVII in ζ Ori

ζ Ori



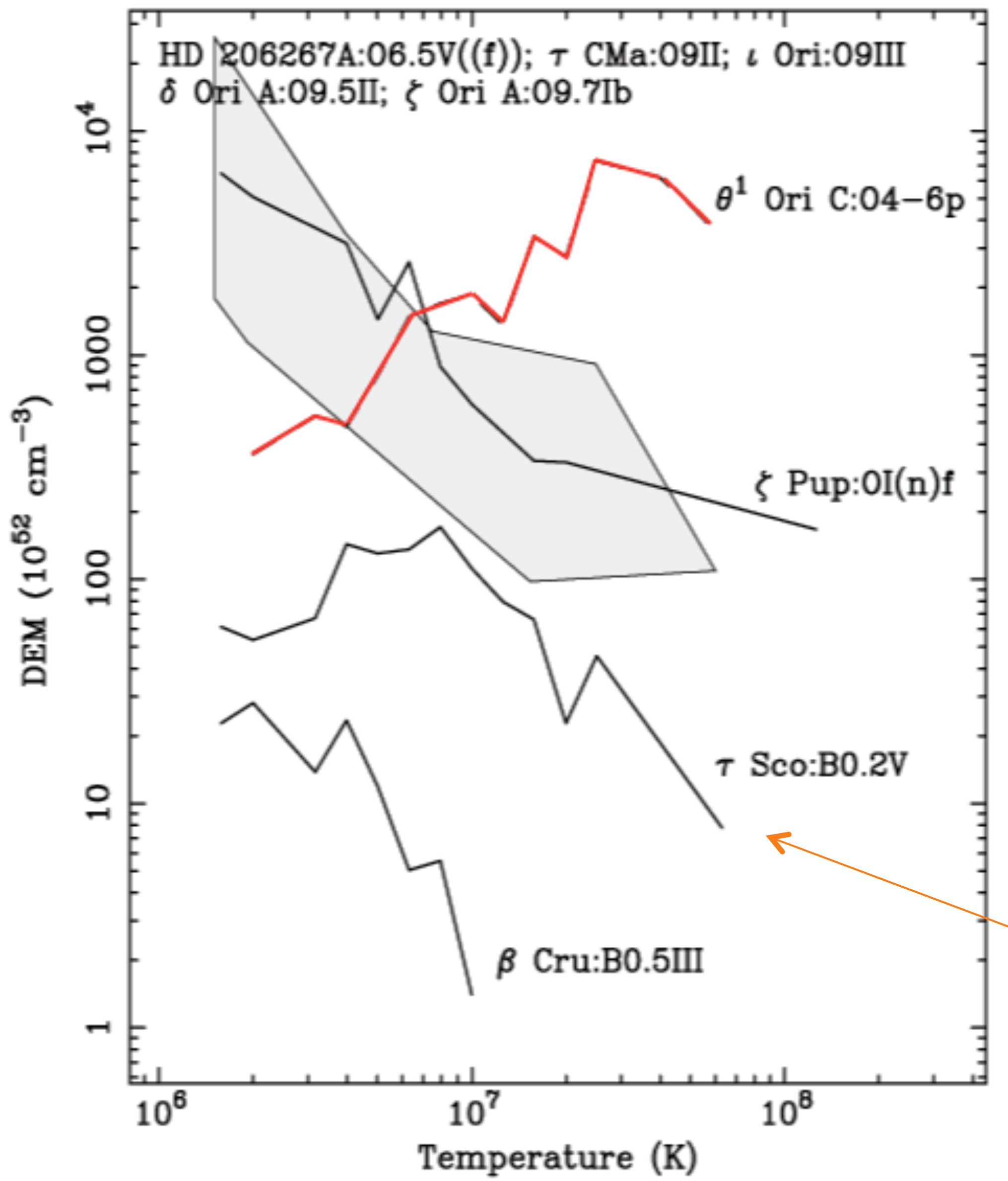
Count Rate (counts s⁻¹ Å⁻¹)
Wavelength (Å)

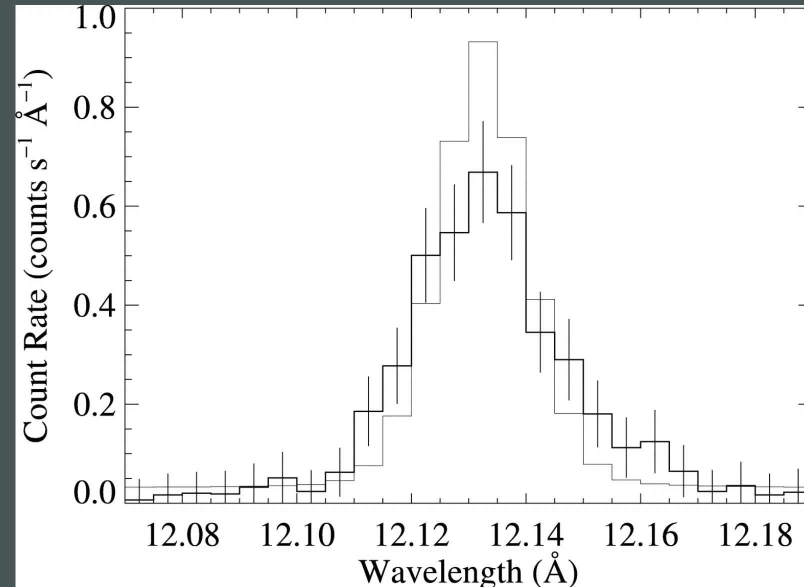


Count Rate (counts s⁻¹ Å⁻¹)
Wavelength (Å)

θ¹ Ori C

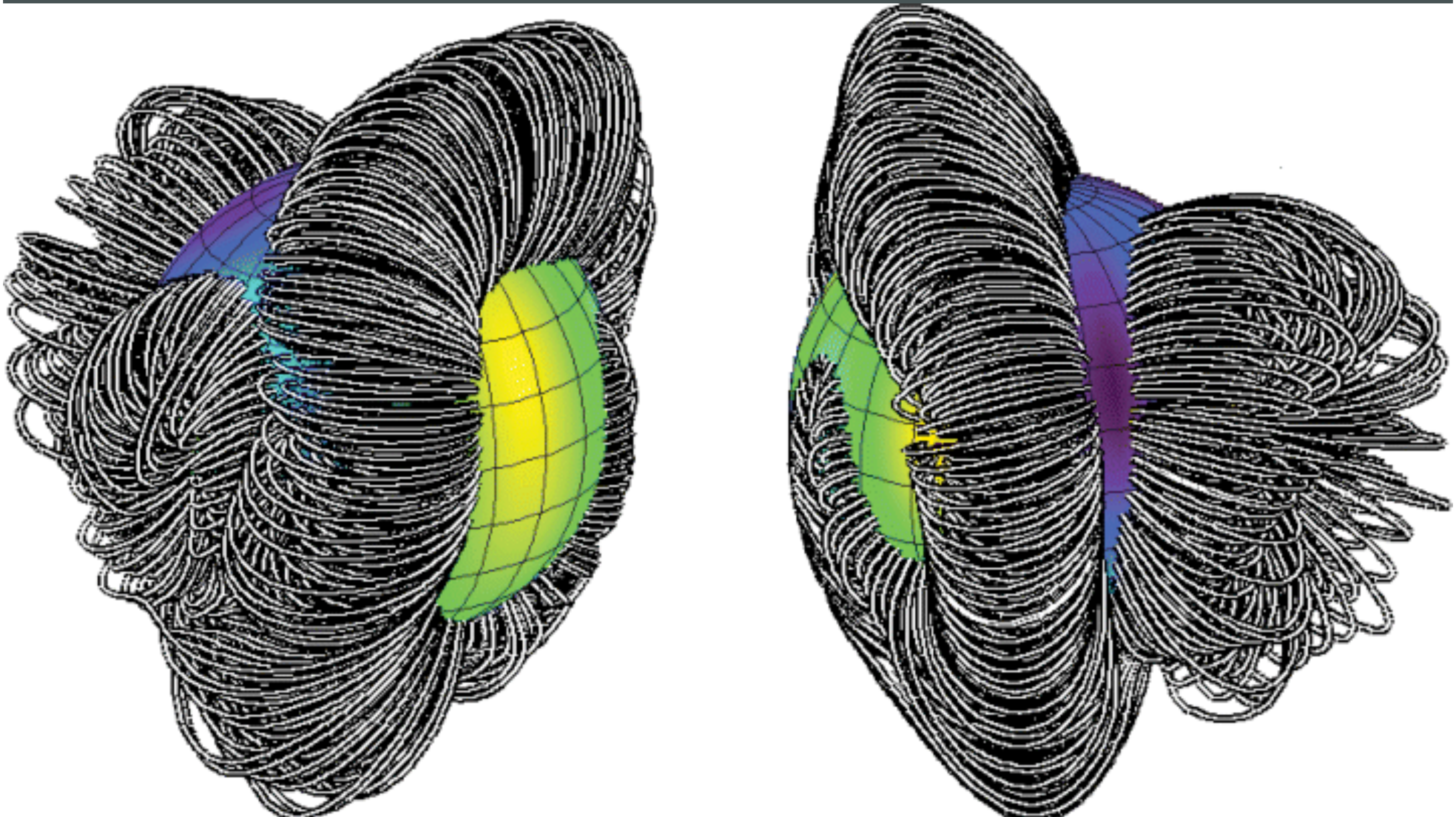
τ Sco *does* have a hard spectrum and narrow lines





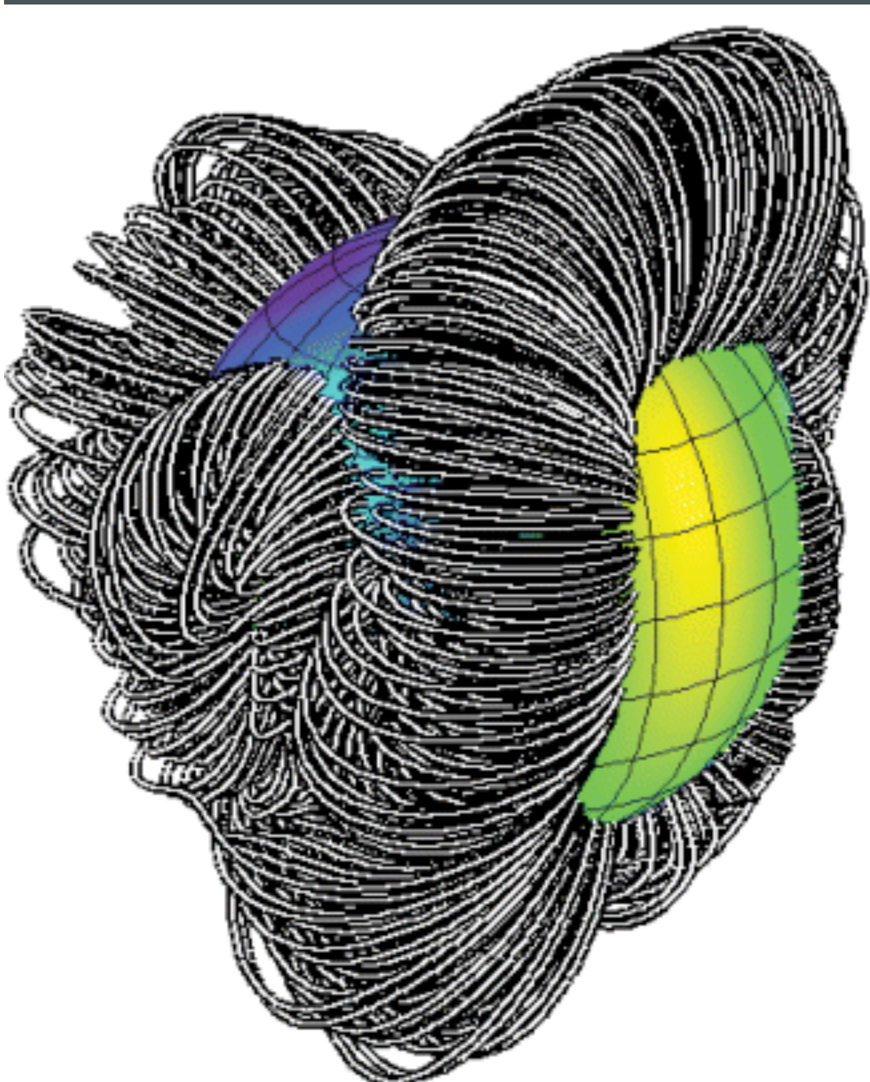
Ne Lyα compared to instrumental response: narrow

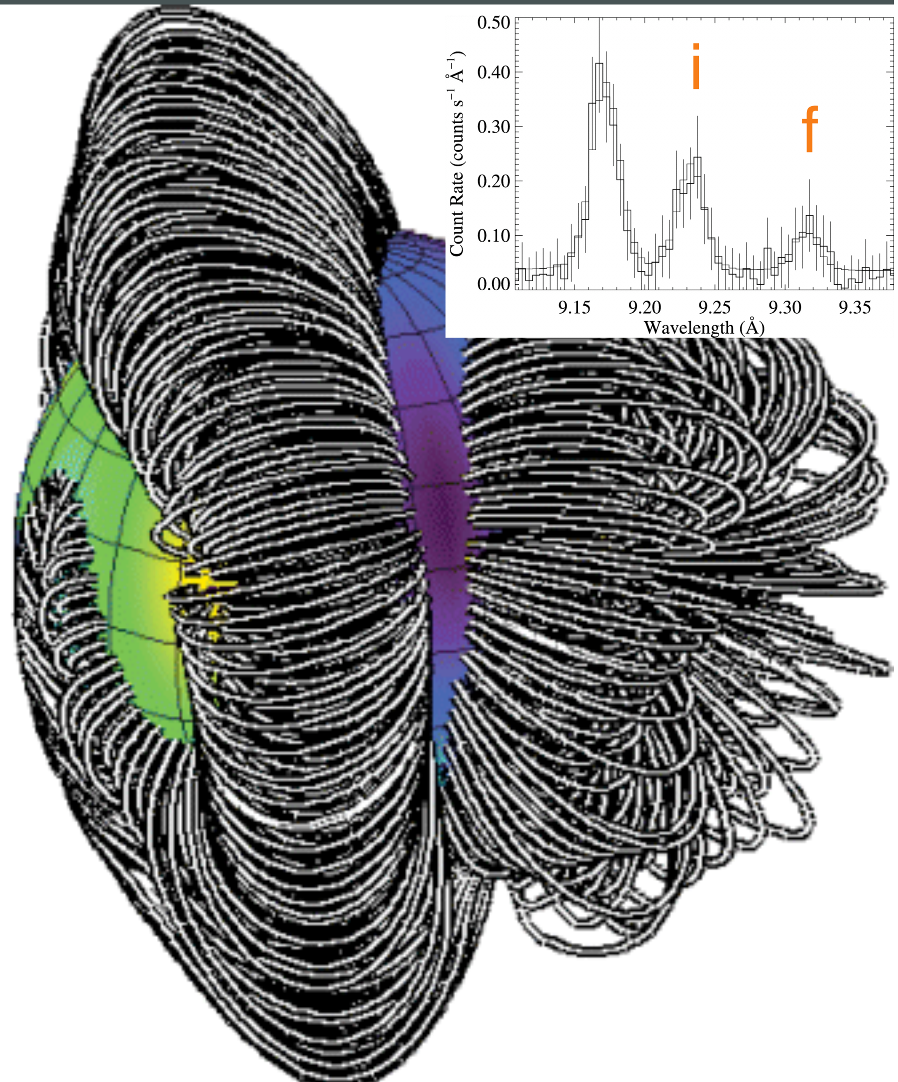
τ Sco: closed loop region is near the star…



τ Sco: closed loop region is near the star…

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



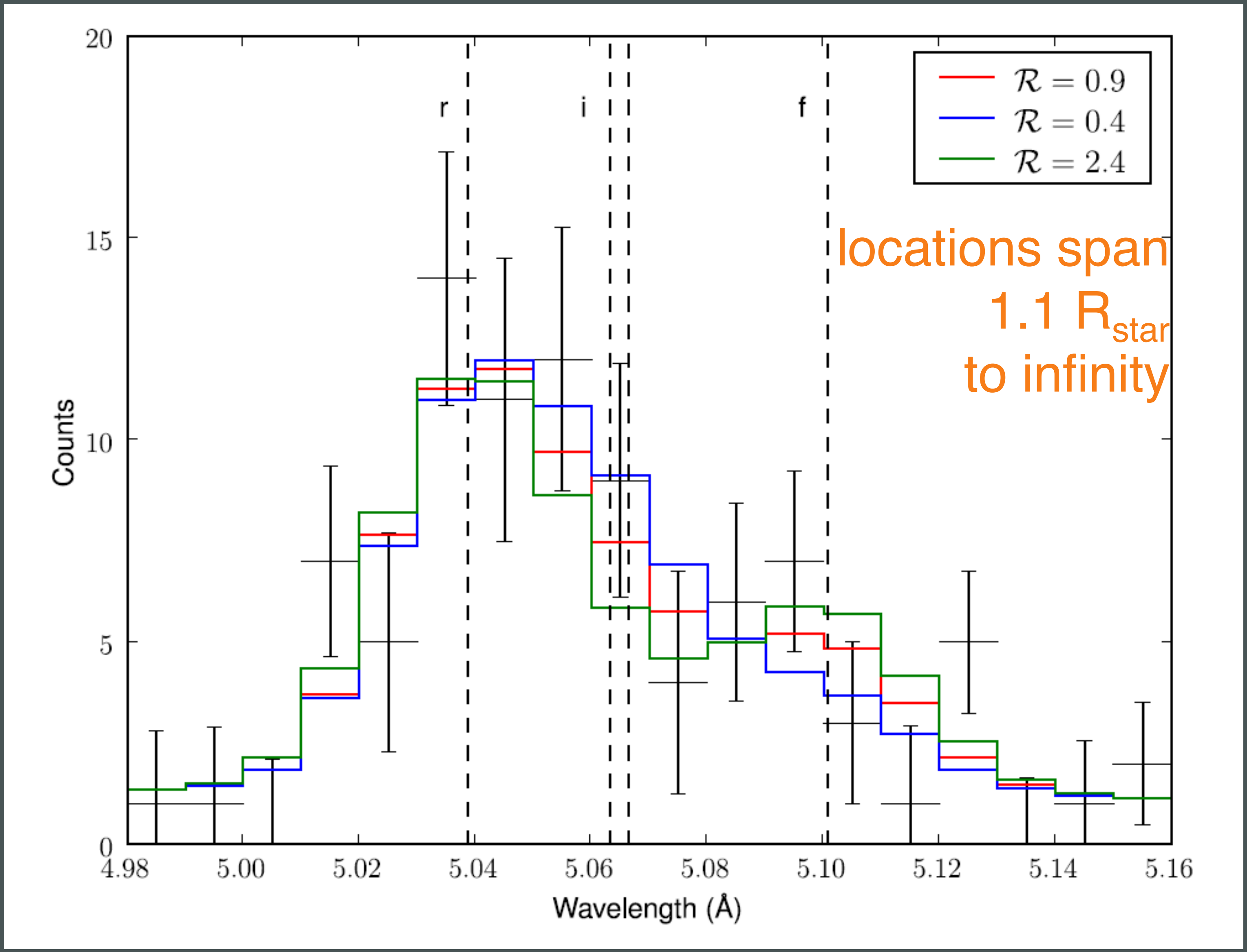


Do He-like f/i ratios provide evidence of hot plasma near the photospheres of O stars?

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

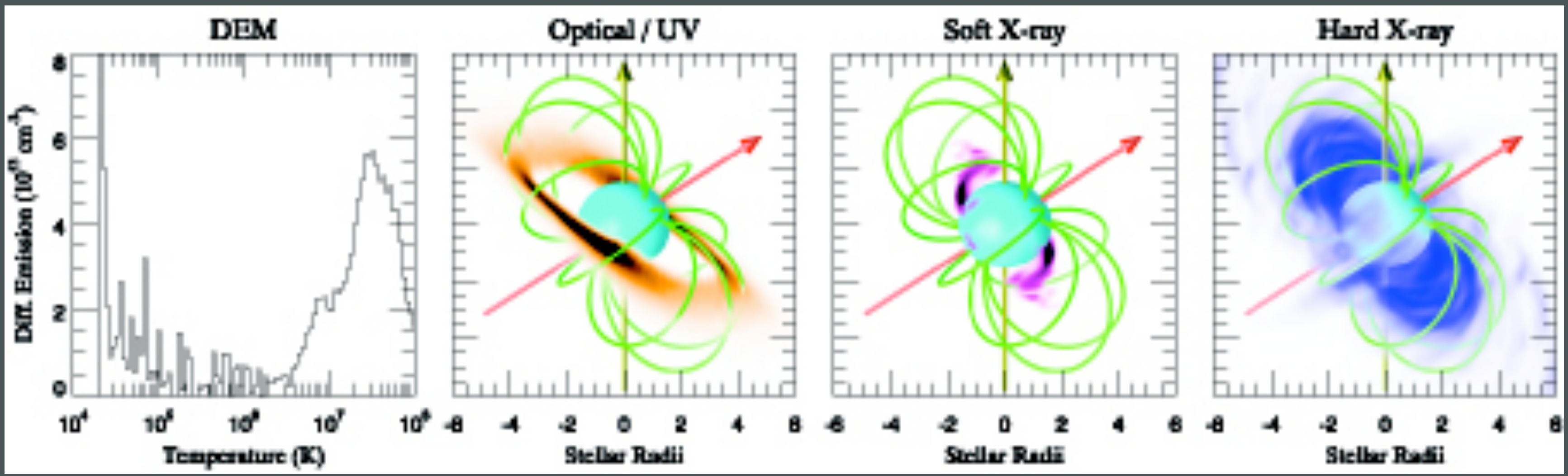
No, I’m afraid they do **not**.

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

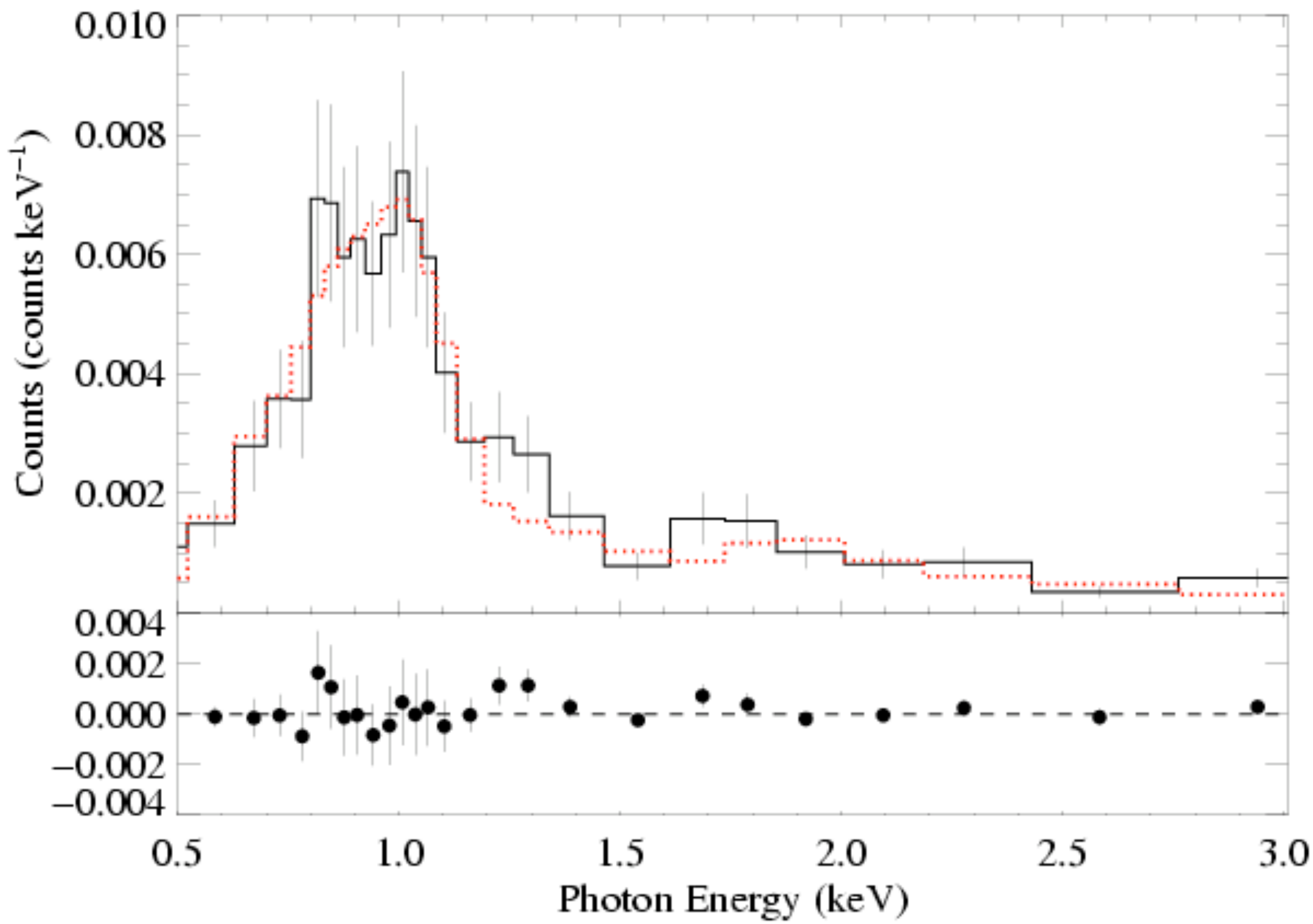


ζ Pup S XV *Chandra* MEG

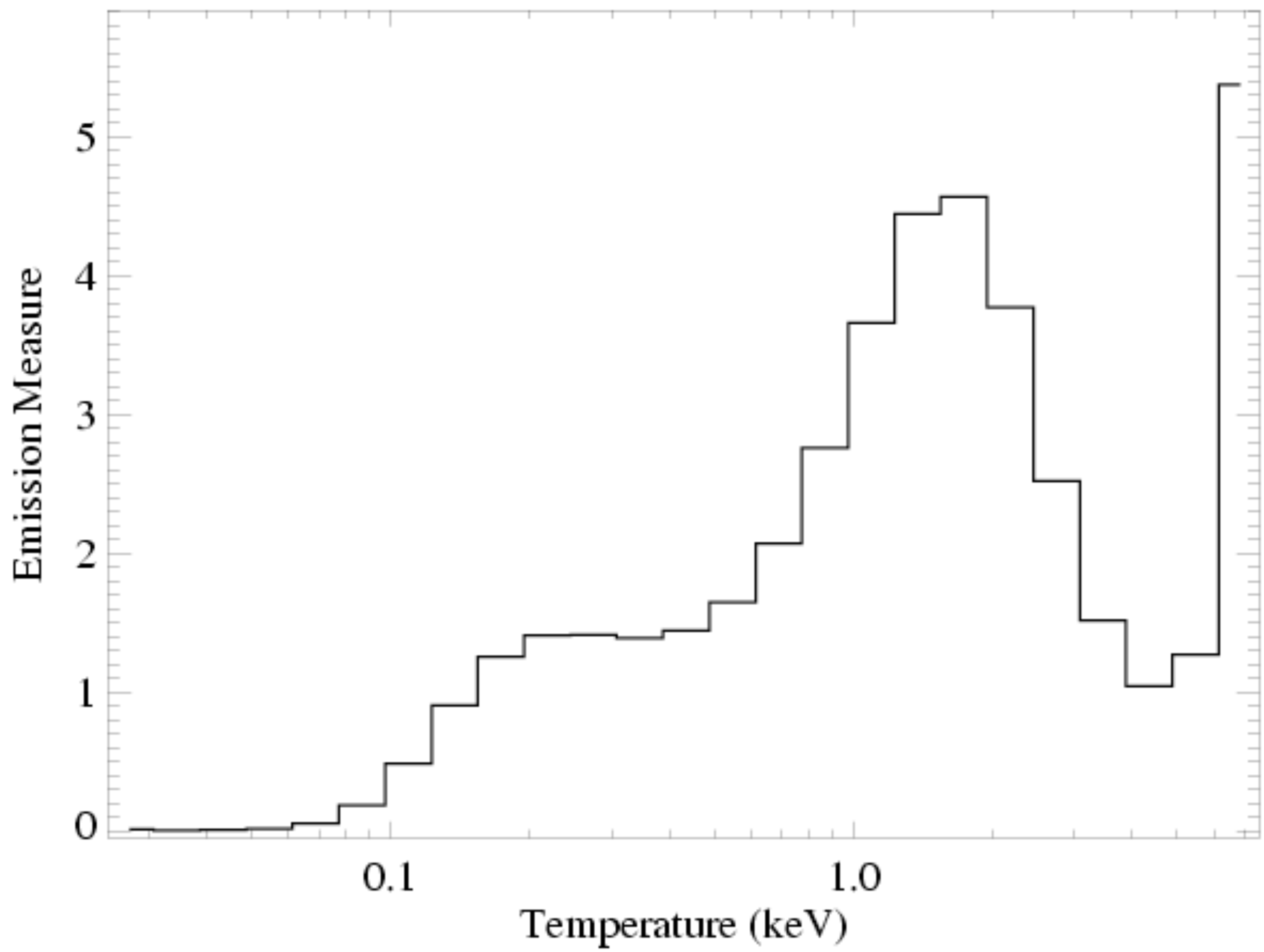
σ Ori E ($\eta_* \sim 10^7$: RRM+RFHD)



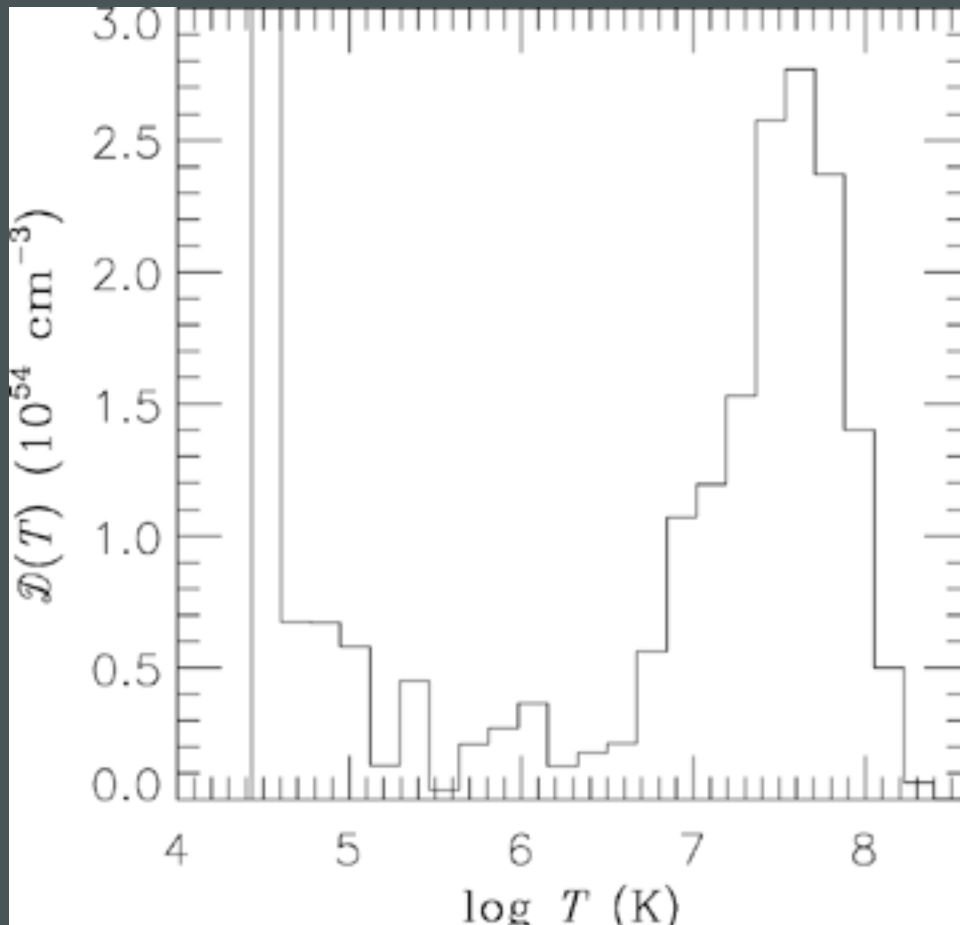
Chandra ACIS (low-resolution, CCD) spectrum



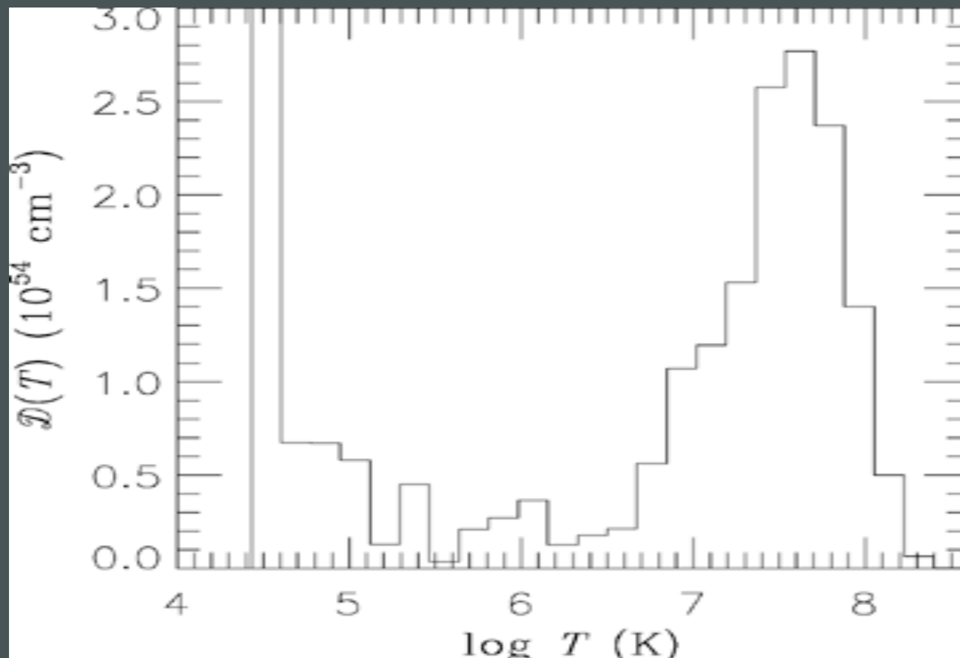
DEM derived from *Chandra* ACIS spectrum

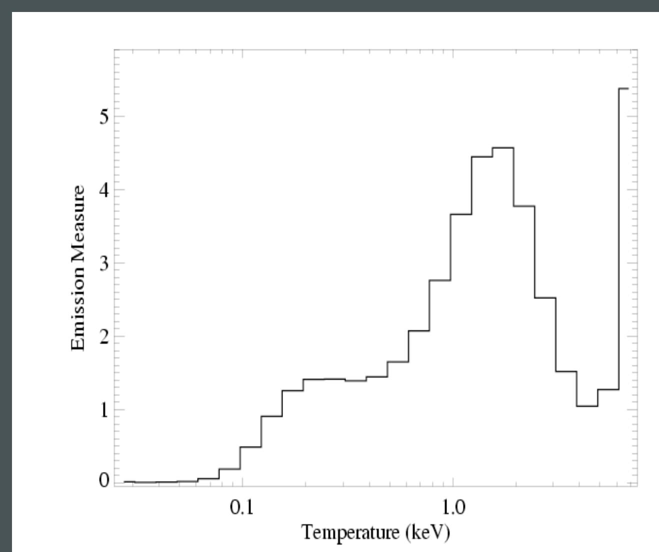


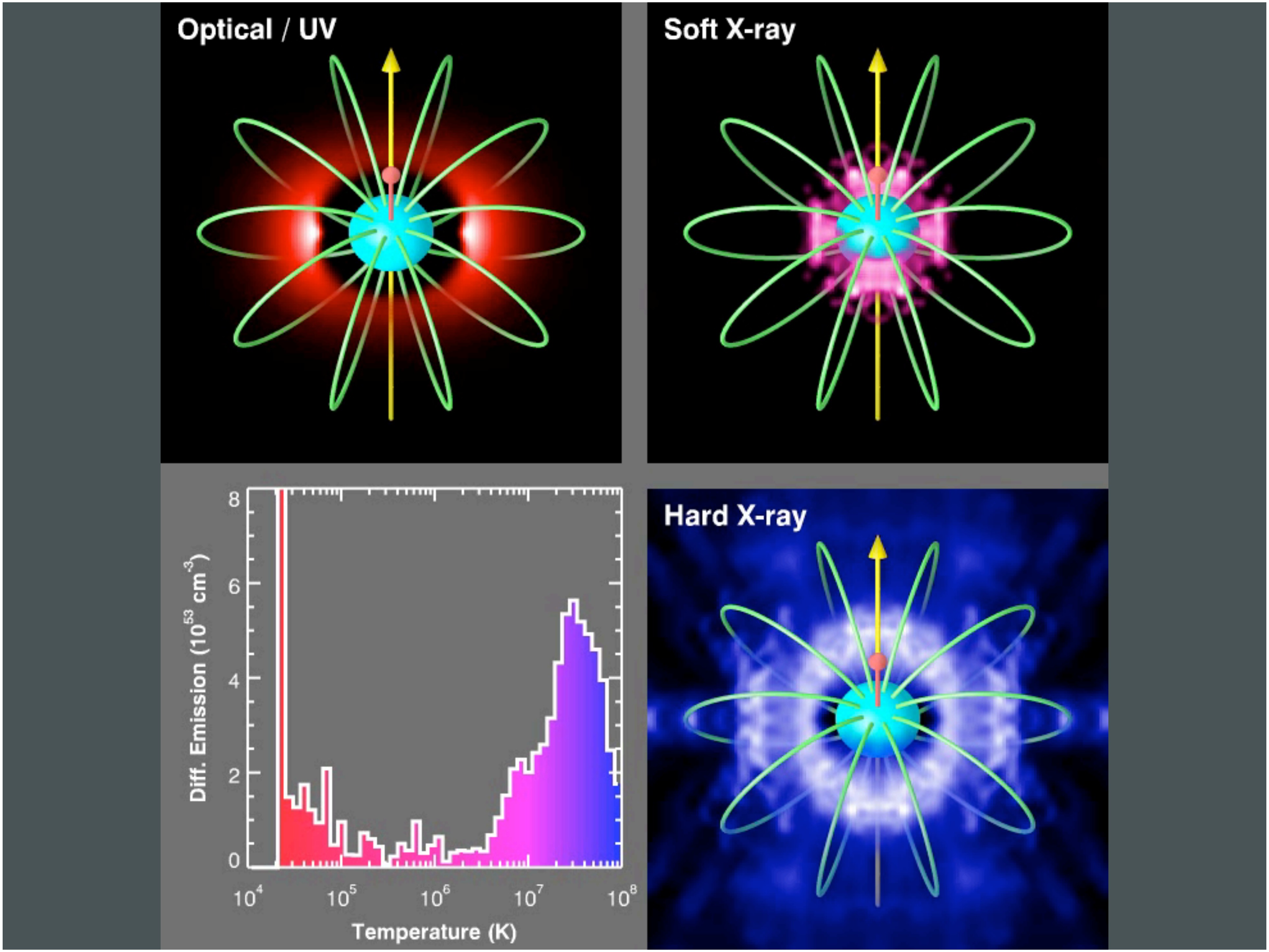
DEM from RFHD modeling



Observed & theoretical DEMs agree well






Optical / UV
Soft X-ray
Hard X-ray
Diff. Emission (10^{53} cm^{-3})
Temperature (K)
0
2
4
6
8
10^4
10^5
10^6
10^7
10^8

Conclusions

MCWS dynamical scenario explains θ^1 Ori C well… but, location of hot plasma may be even closer to the star; UV absorption line phase dependence isn't right.

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