# Update on θ¹ Ori C: the Magnetically Confined Wind Shock model does a pretty good job

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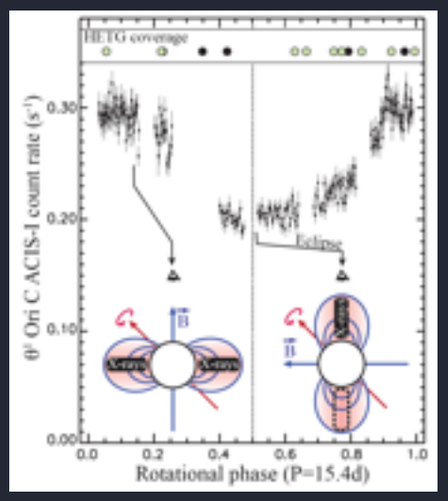
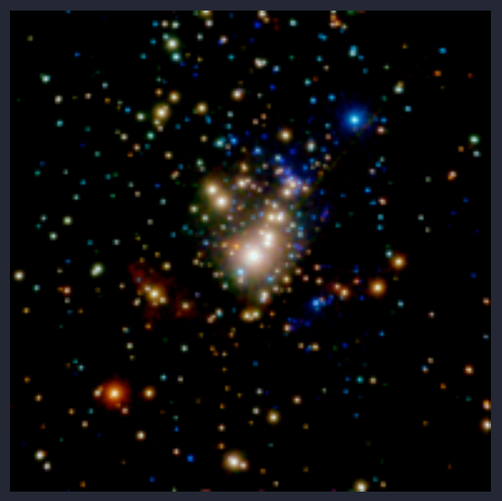
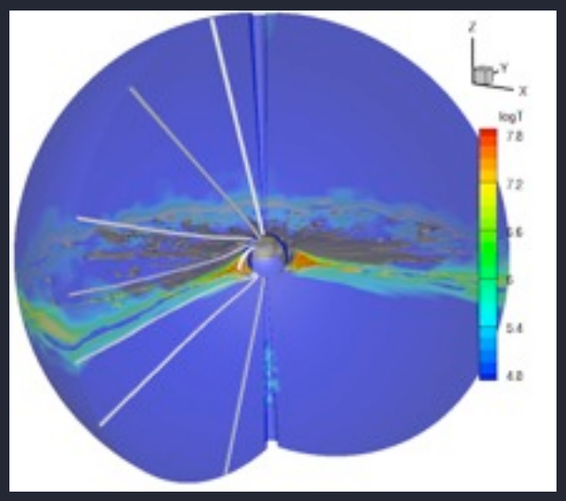
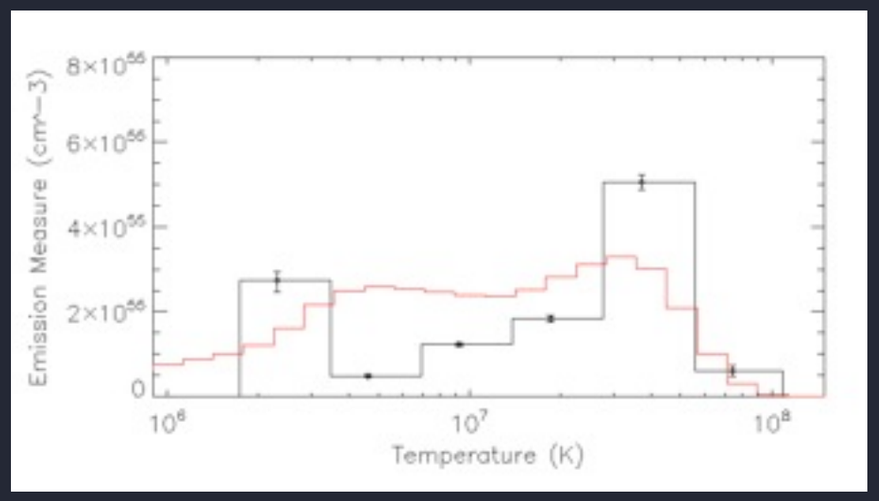
Maurice Leutenegger, Marc Gagné, and
Jackie Pezzato (Swarthmore '17), Randy Doyle (Swarthmore '16)



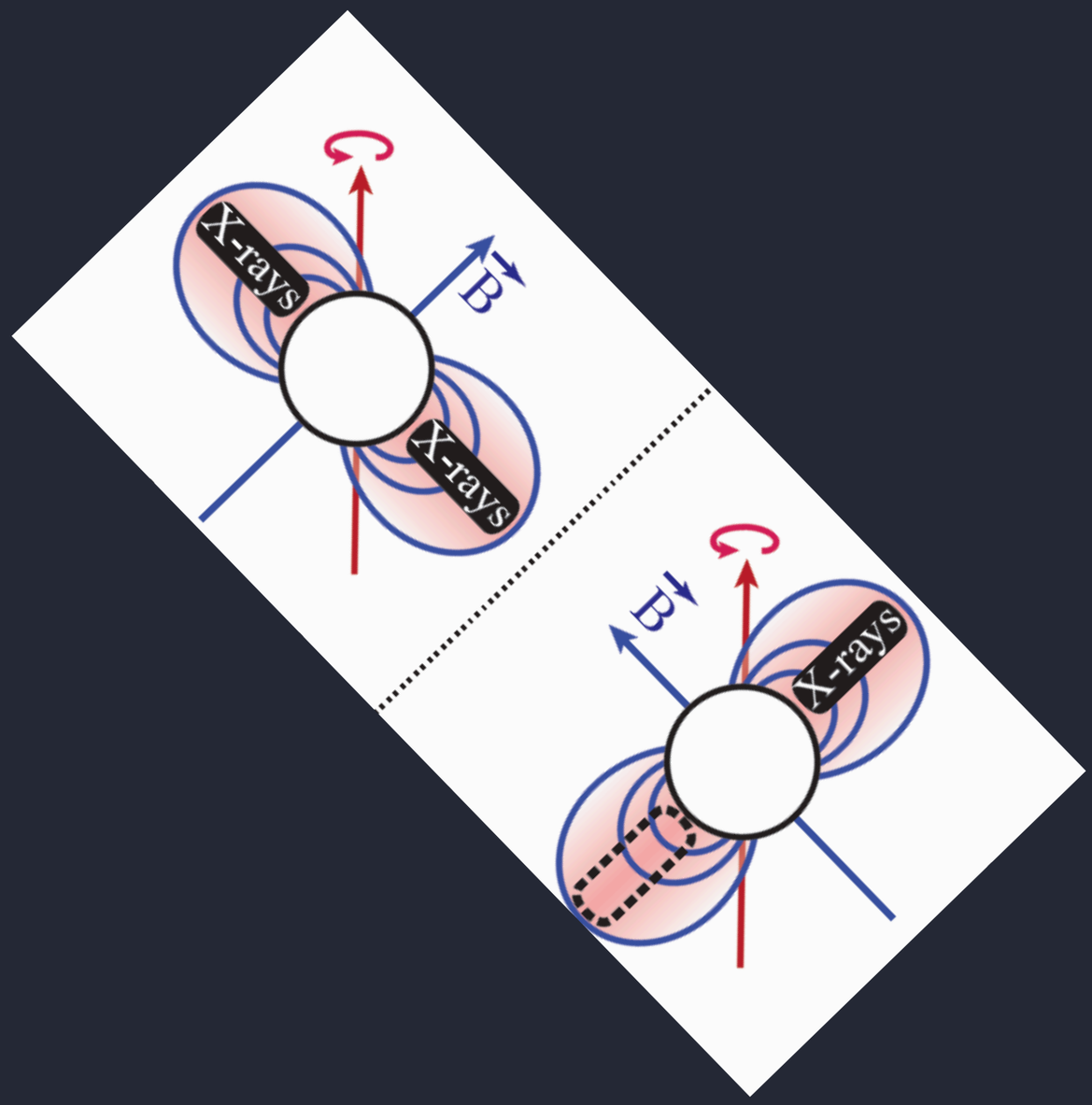




# Outline/overview:

θ¹ Ori C is a magnetic prototype: tilted dipole, slow rotator, moderate confinement ($\eta_* \sim 20$)

X-rays trace the dissipation of wind KE in the magnetosphere



# Properties of $\theta^1$ Ori C

O7V (but with some reported variation)
age < 1 Myr
$T_{eff}$ ~ 42,000 K
luminosity ~ $10^{5.4}$ $L_{sun}$

$\dot{M}$ ~ 5 X $10^{-7}$ $M_{sun}$/yr
$v_\infty$ ~ 2500 km/s

tilted dipole, $B_p$ ~ 1 kG
i ~ β ~ 45°

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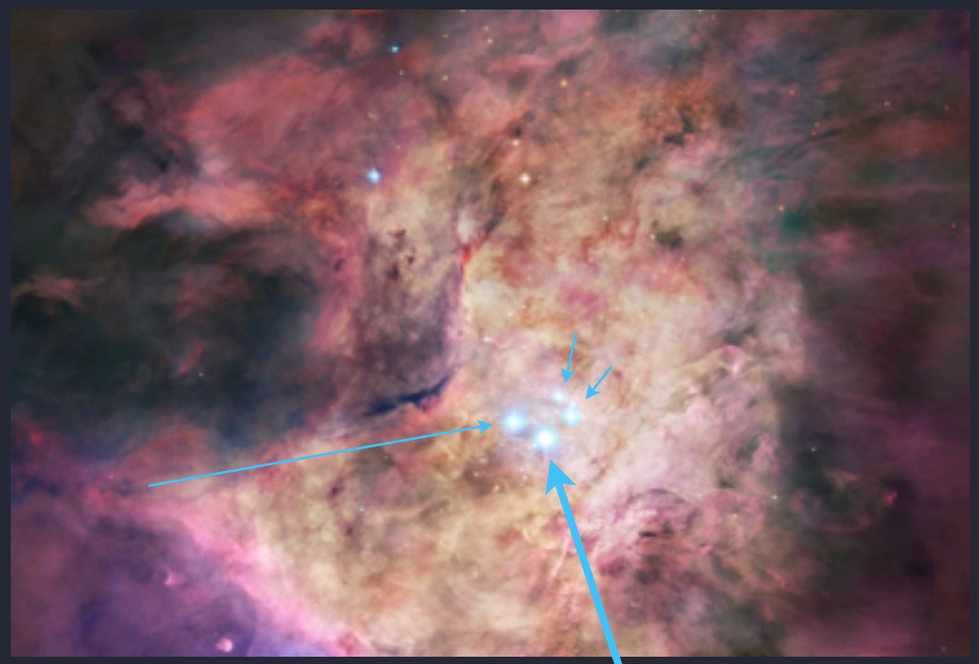
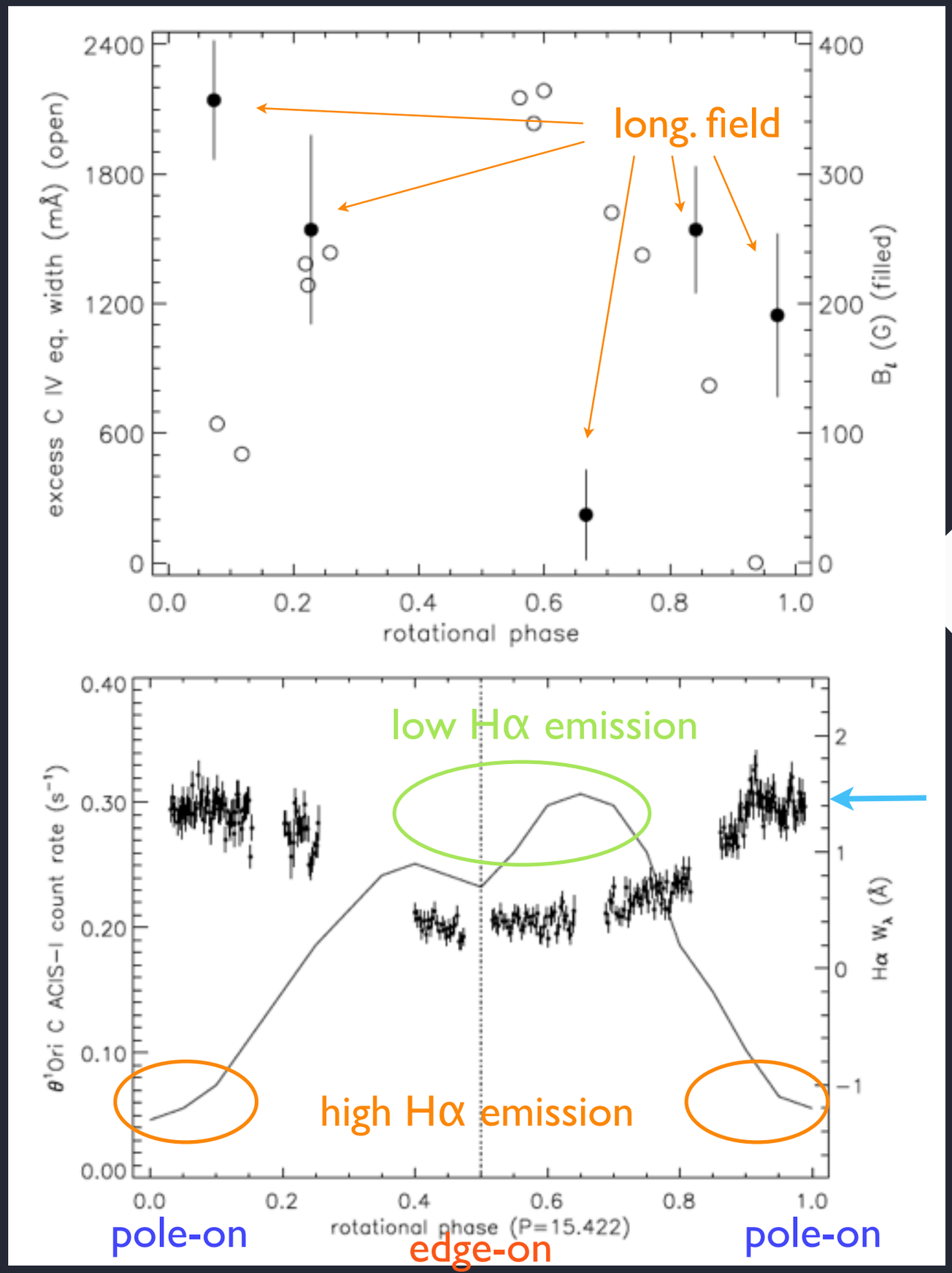


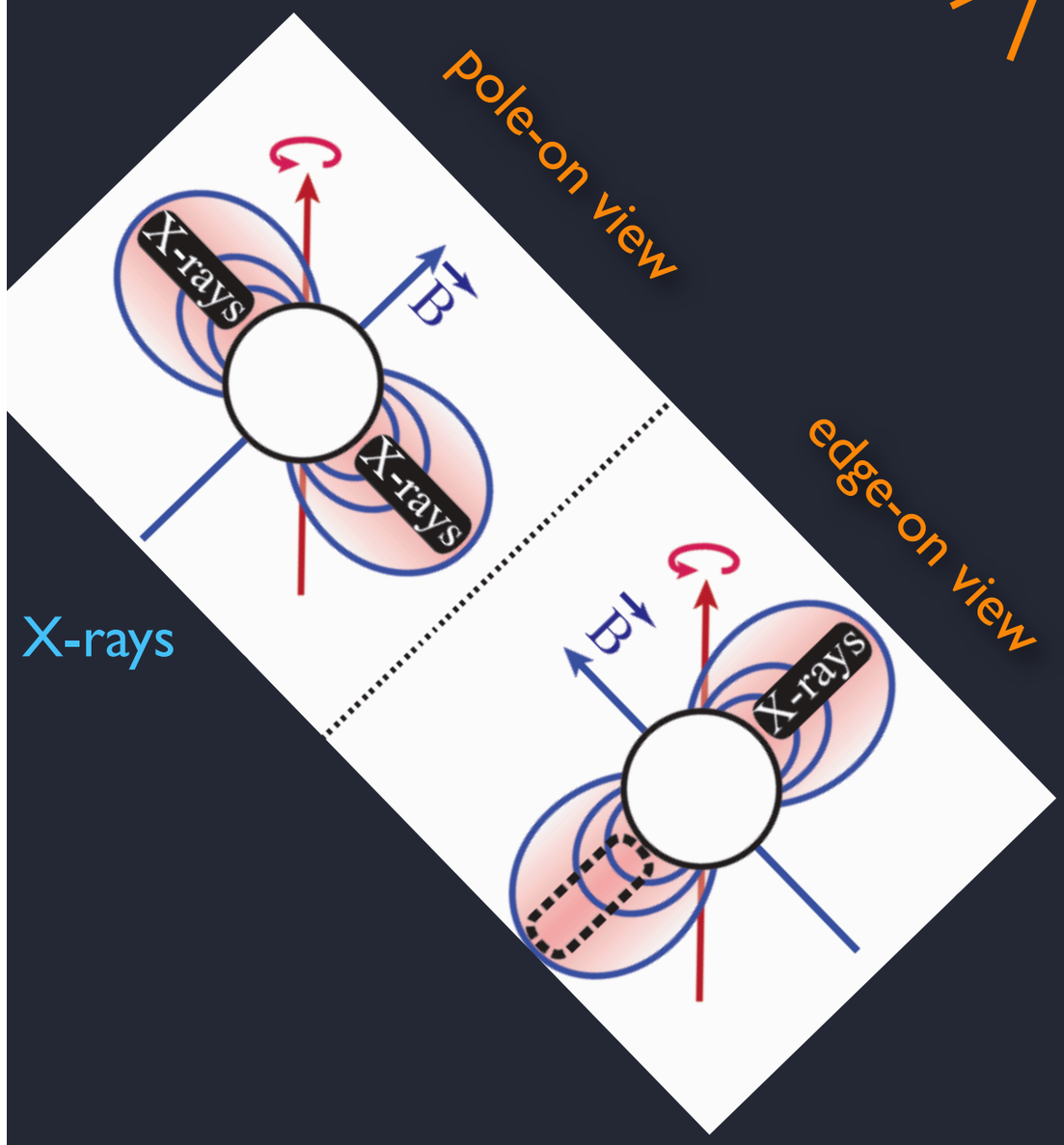
$\theta^1$ Ori C

One of only two O stars in the ONC

# tilted dipole: oblique magnetic rotator



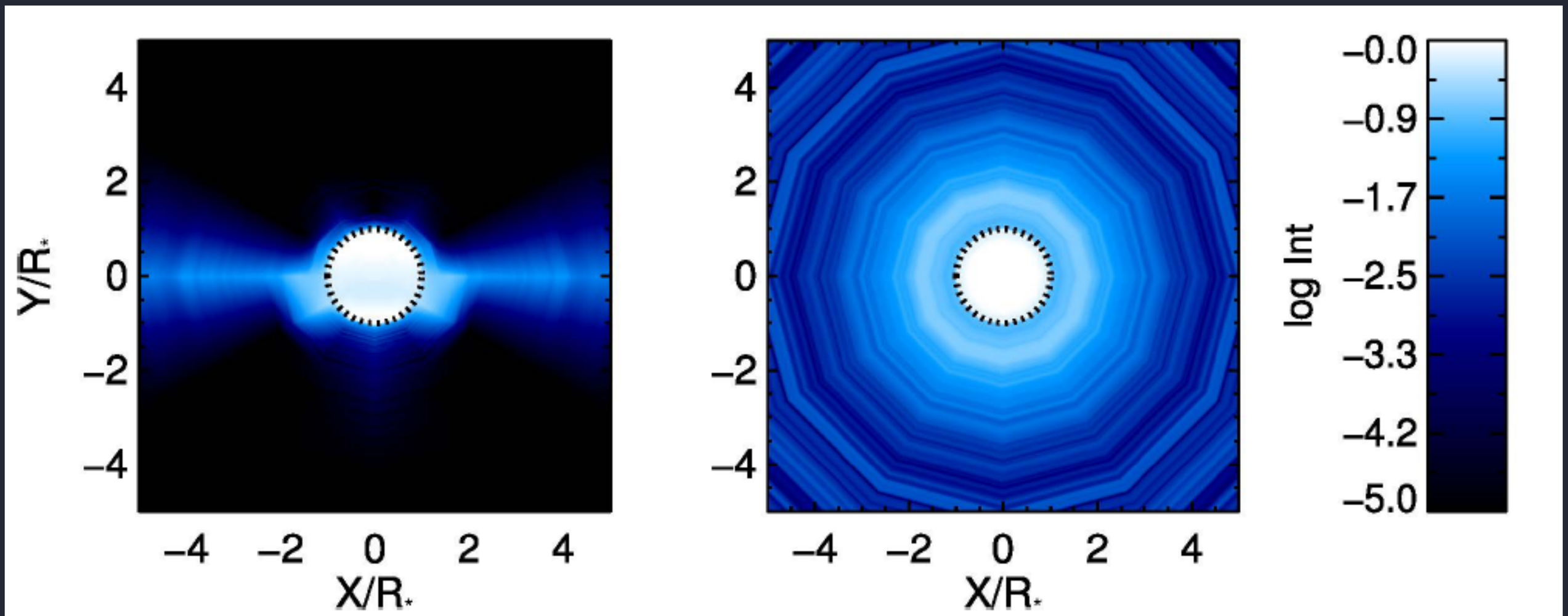

X-rays



# $H\alpha$ intensity map (ADM model)

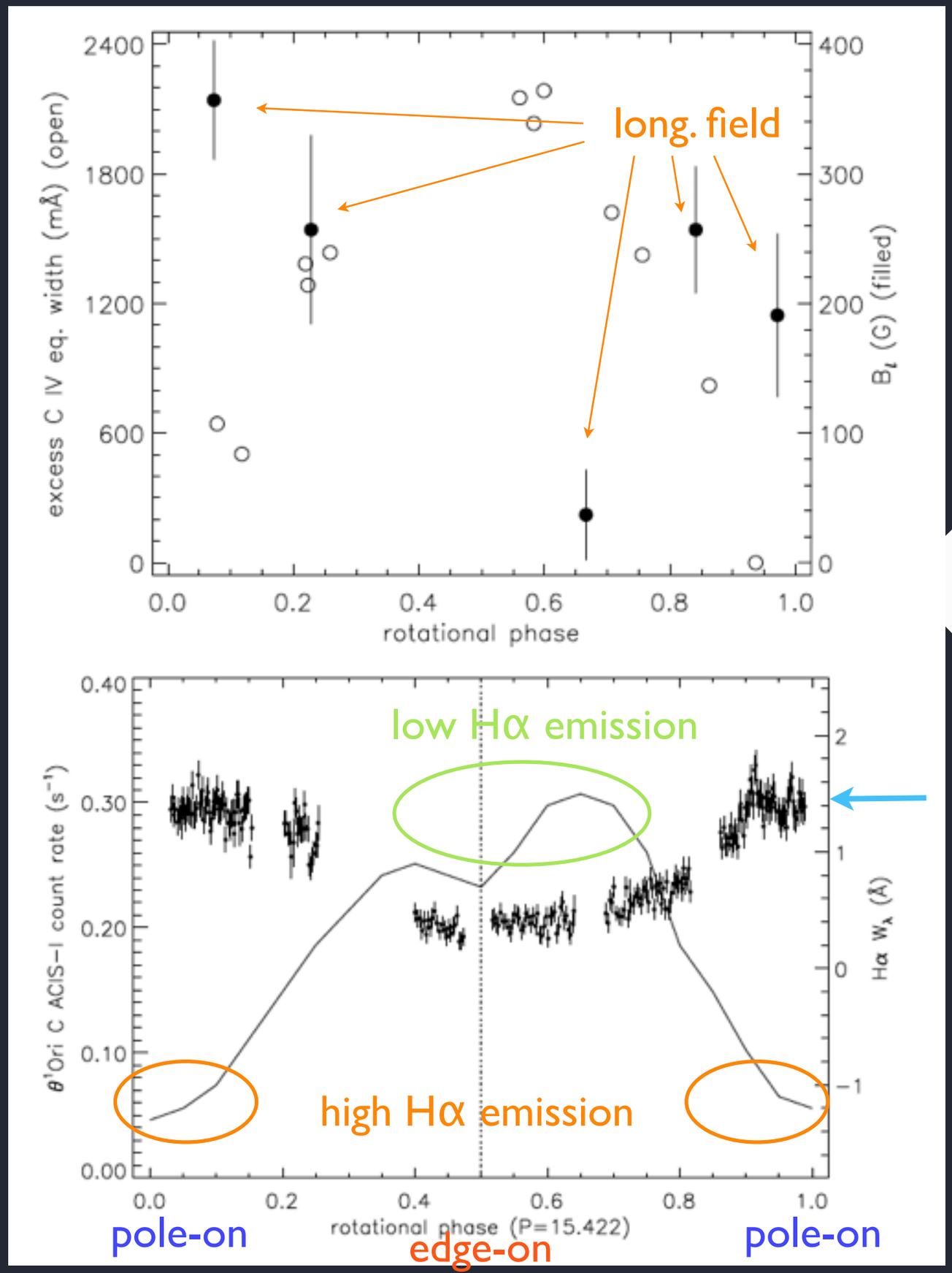
edge-on: $H\alpha$ weaker

pole-on: $H\alpha$ stronger

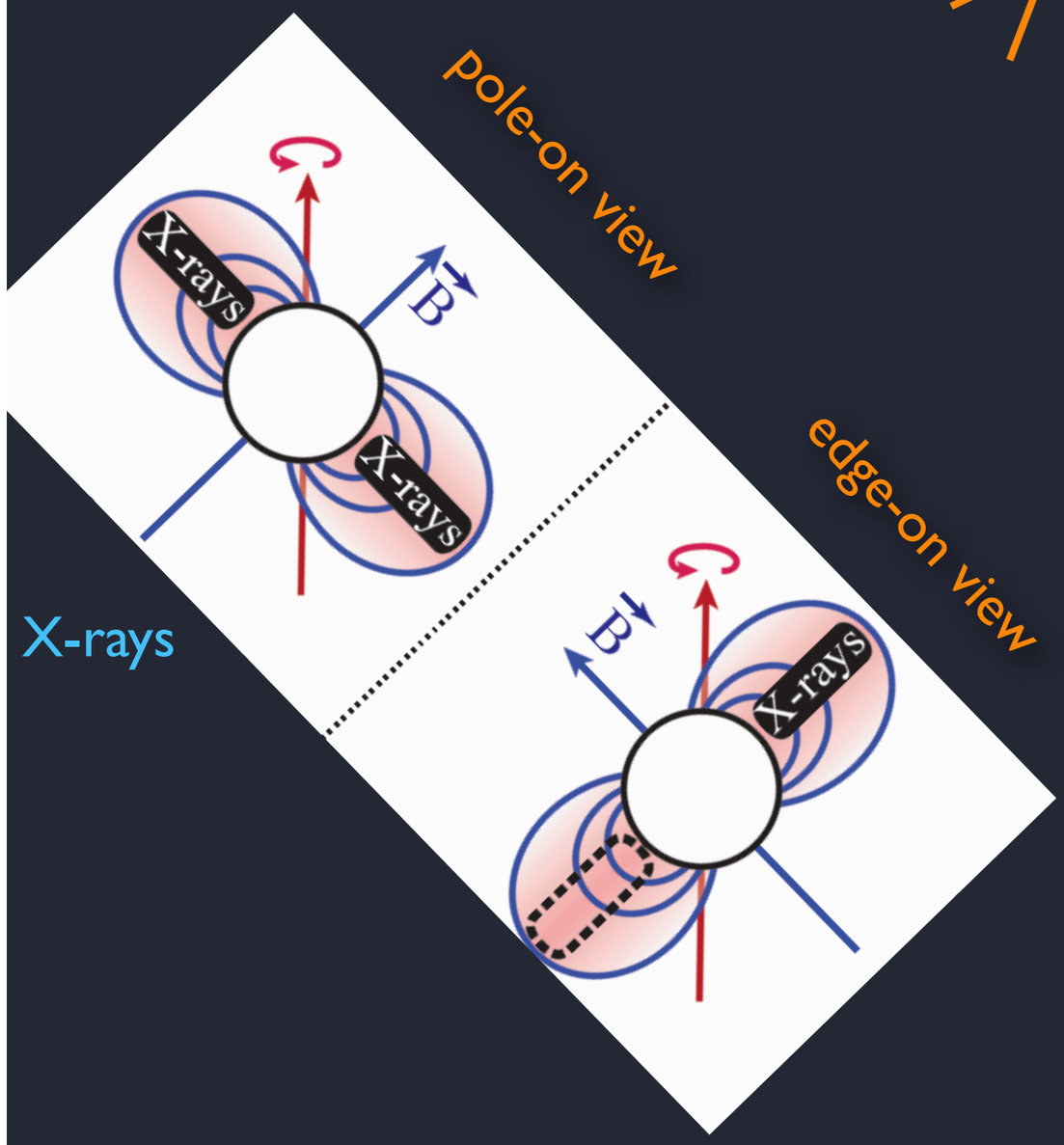



Sundqvist et al. 2012

# tilted dipole: oblique magnetic rotator




X-rays



# MHD simulations: 2-D, hemispherical slice

density temperature X-ray emission

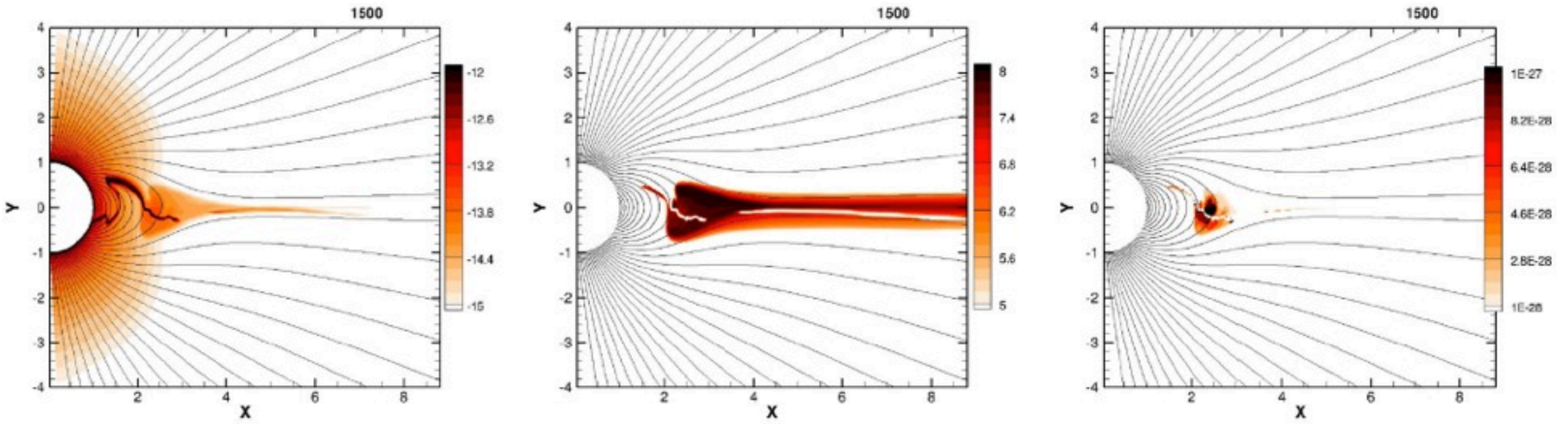
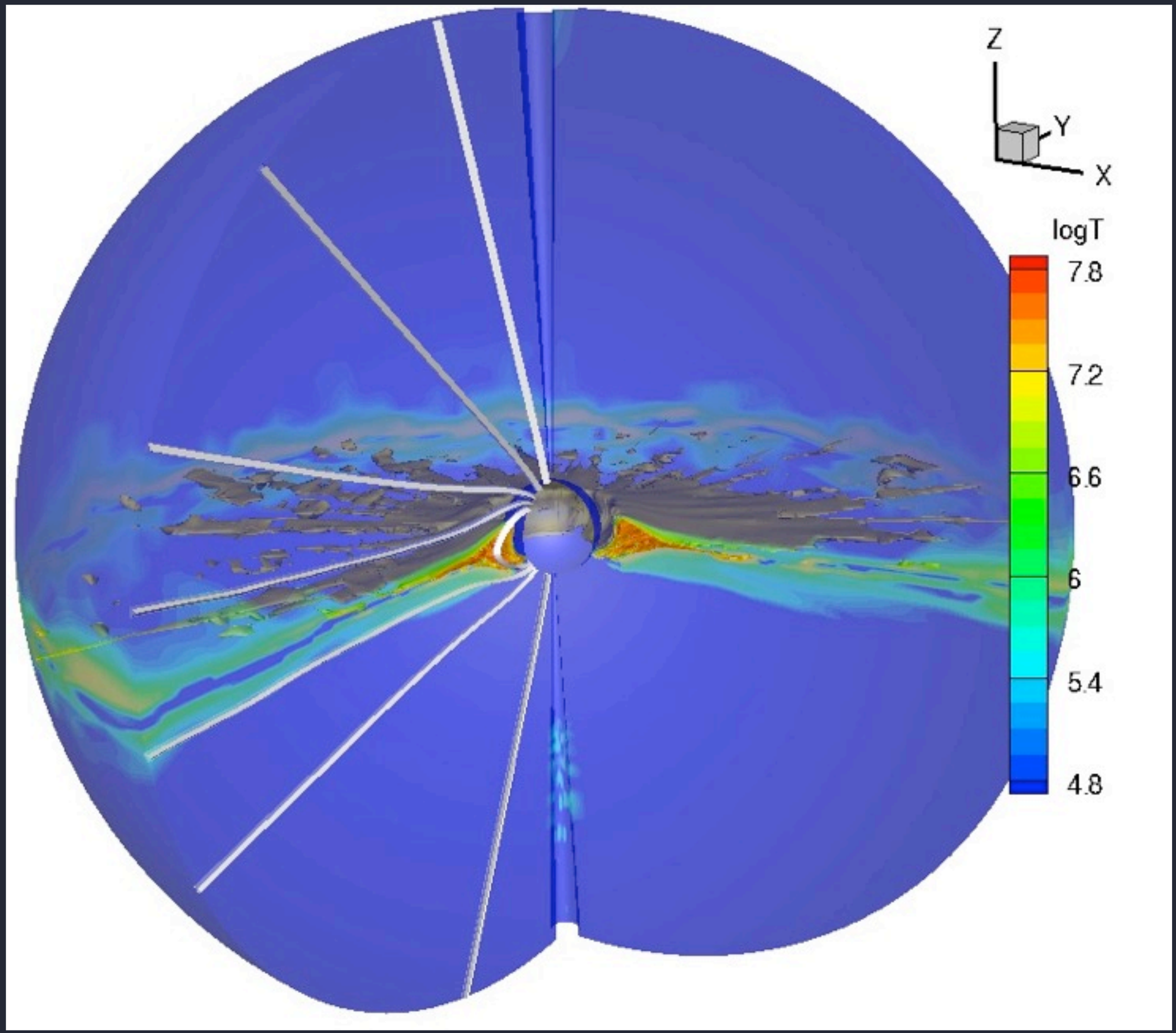



**Figure 4.** Colour plots of log density (left) and log temperature (middle) for arbitrary snapshot of structure in the standard model with $\eta_* = 100$ and no IC cooling. The right-hand panel plots the proxy X-ray emission $\mathrm{XEM}_{T_x}$ (weighted by the radius $r$) from (26), on a *linear* scale for a threshold X-ray temperature $T_x = 1.5$ MK.

ud-Doula et al. 2014

# 3-D MHD simulation: log Temperature




from A. ud-Doula

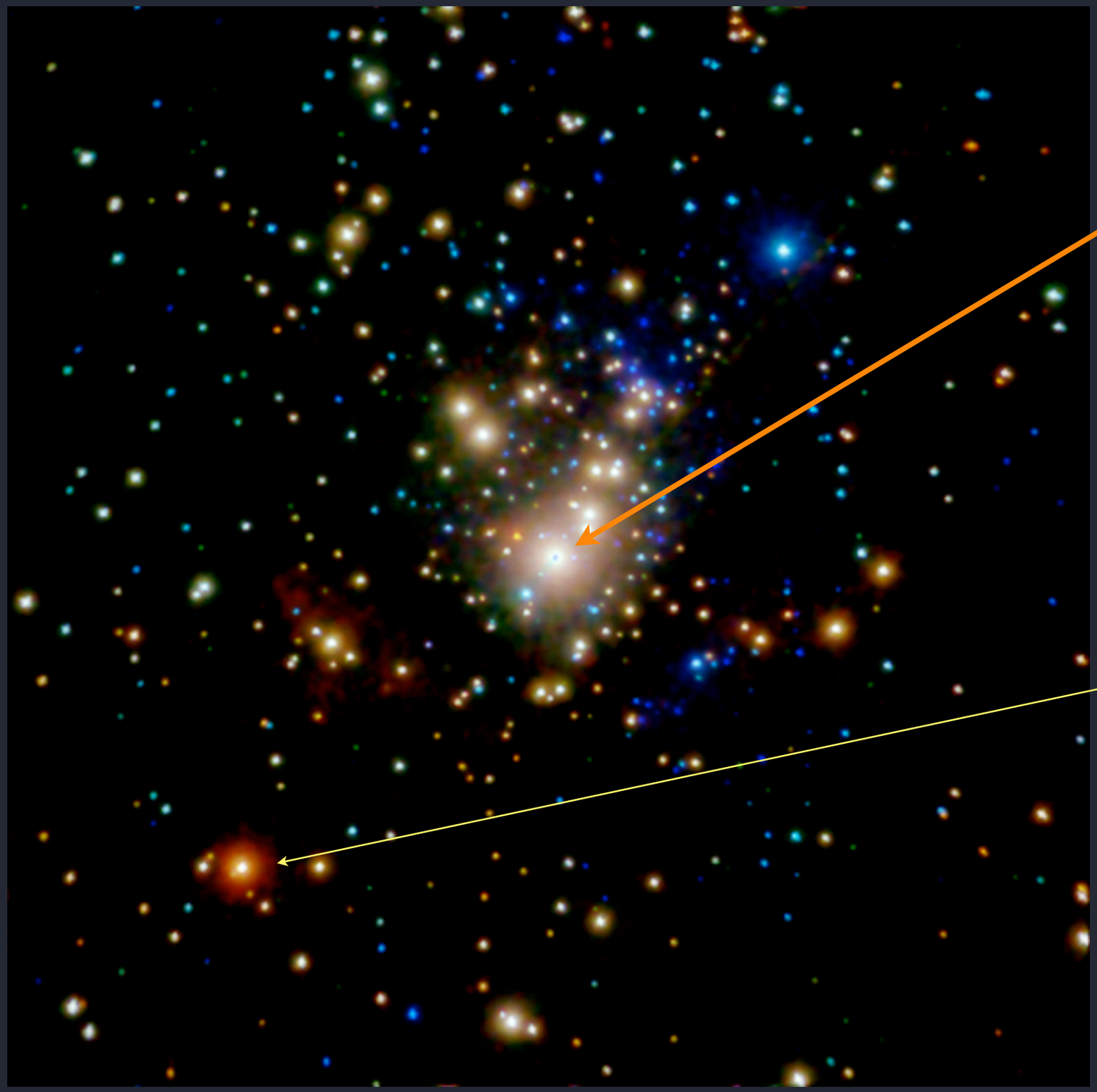
# *Chandra*


Orion Nebula Cluster - *Chandra*
color-coded by X-ray hardness

response to photons with hν ~ 0.5 keV up to a few keV
(corresp. ~5Å to 24Å)
spectroscopy (R < 1000 corresp. >300 km/s)

small effective area (poor sensitivity)
but very low background and very well calibrated

kT = hν gives
T ~ 12 X $10^6$ K
for 1 keV

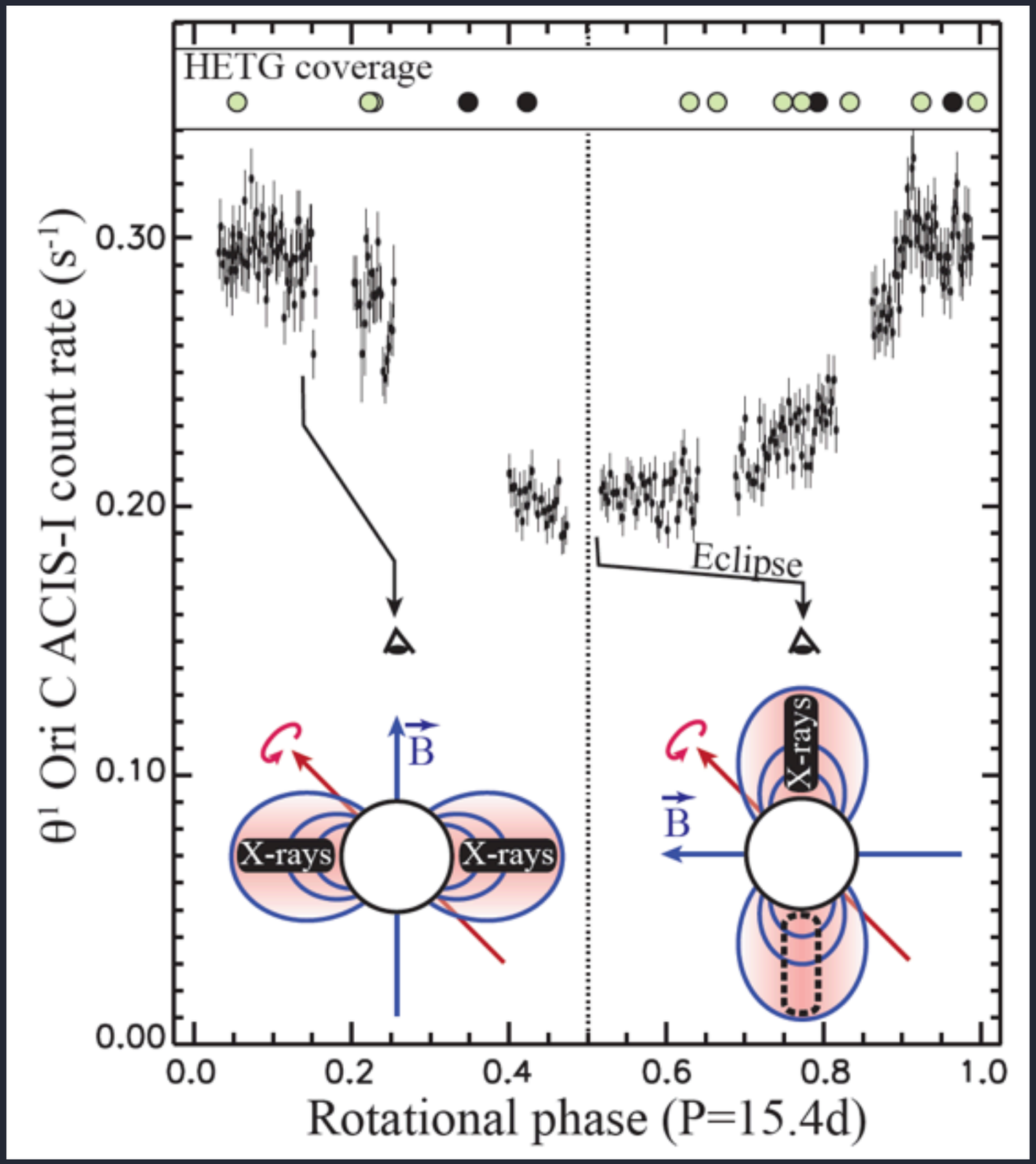


$\theta^1$ Ori C: strongest X-ray source in the cluster

$\theta^2$ Ori A: non-magnetic O star with *softer* X-rays

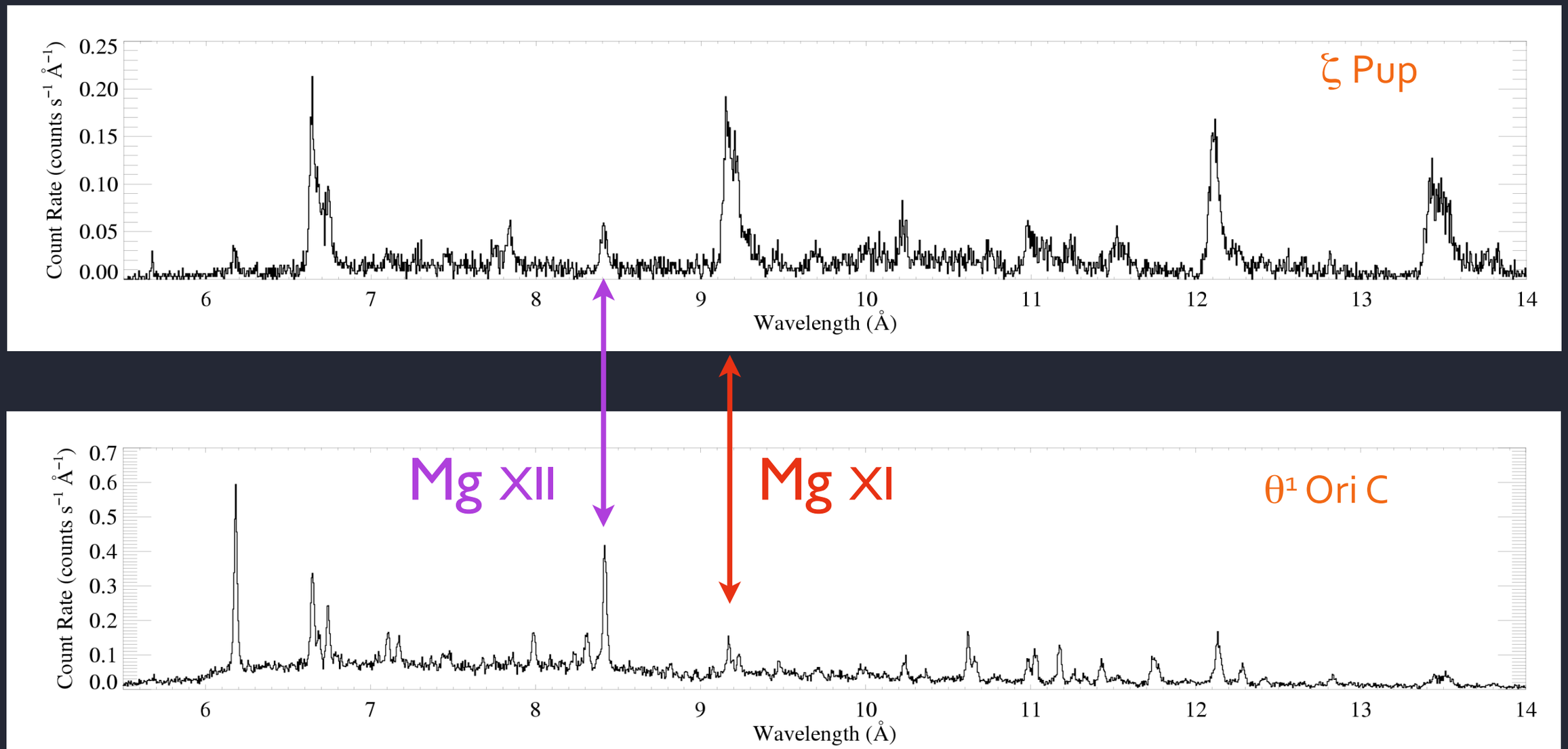
Orion Nebula Cluster - *Chandra*
color-coded by X-ray hardness

# X-ray light curve: phase coverage: new data (11 new pointings to supplement 4 in Gagne et al. 2005)



# Line ratios as temperature indicators

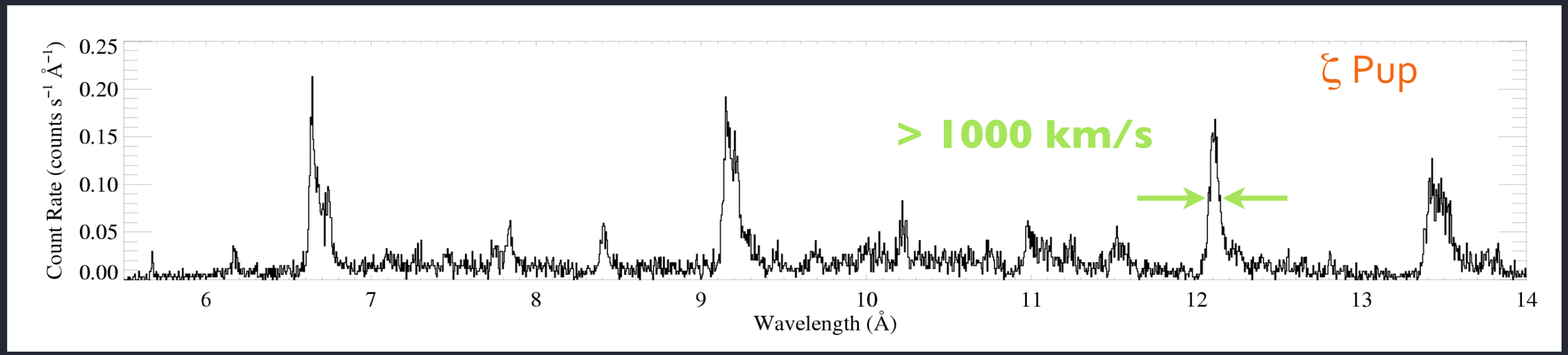
## Mg XII / Mg XI is proportional to temperature

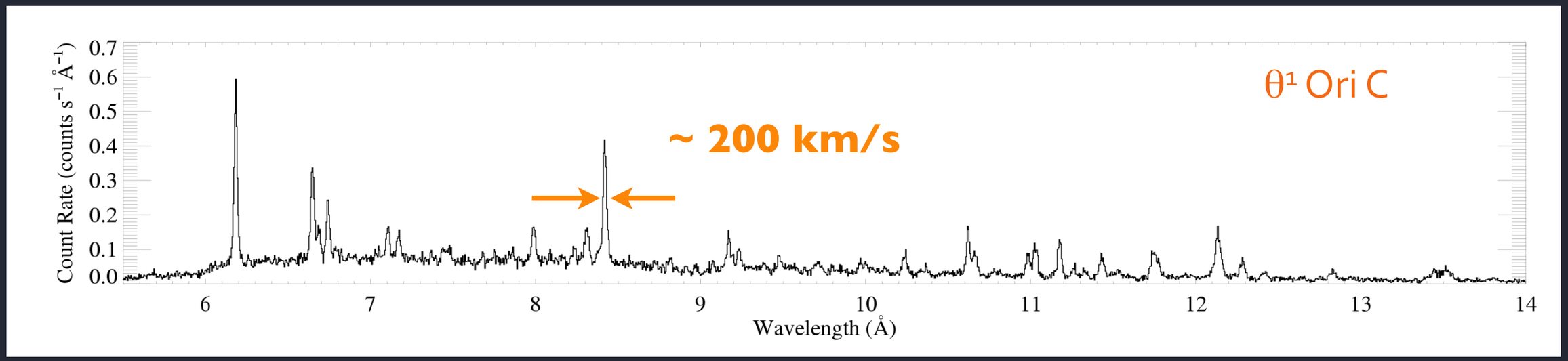



*Chandra* spectra of prototype non-magnetic (zeta Pup, top) and magnetic ($\theta^1$ Ori C, bottom) stars

# Line widths from gas kinematics

non-magnetic O stars: $v_{line} \sim v_{wind}$ but MCWS: $v_{line} < v_{wind}$

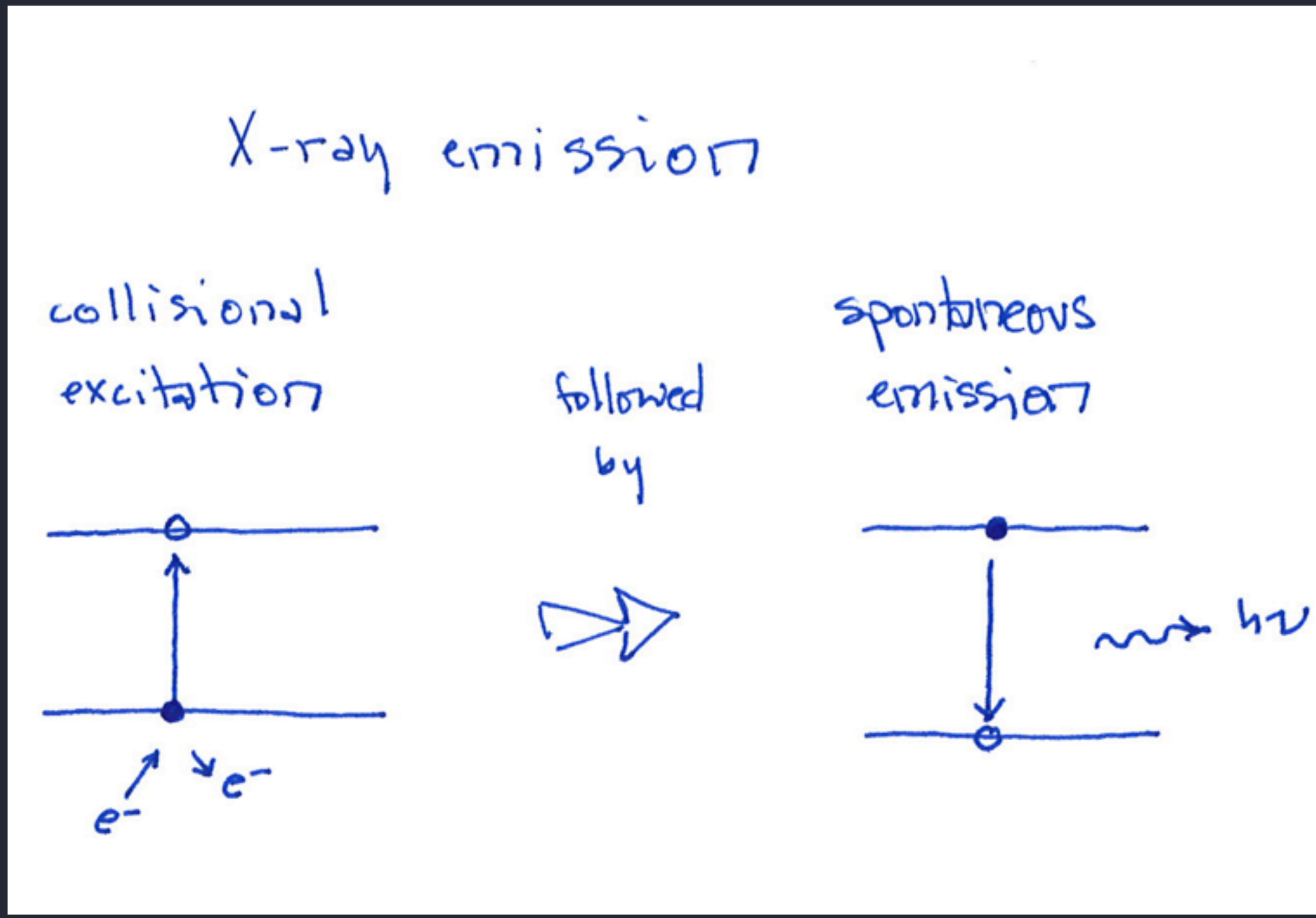



*Chandra* spectra of prototype non-magnetic (zeta Pup, top) and magnetic ($\theta^1$ Ori C, bottom) stars

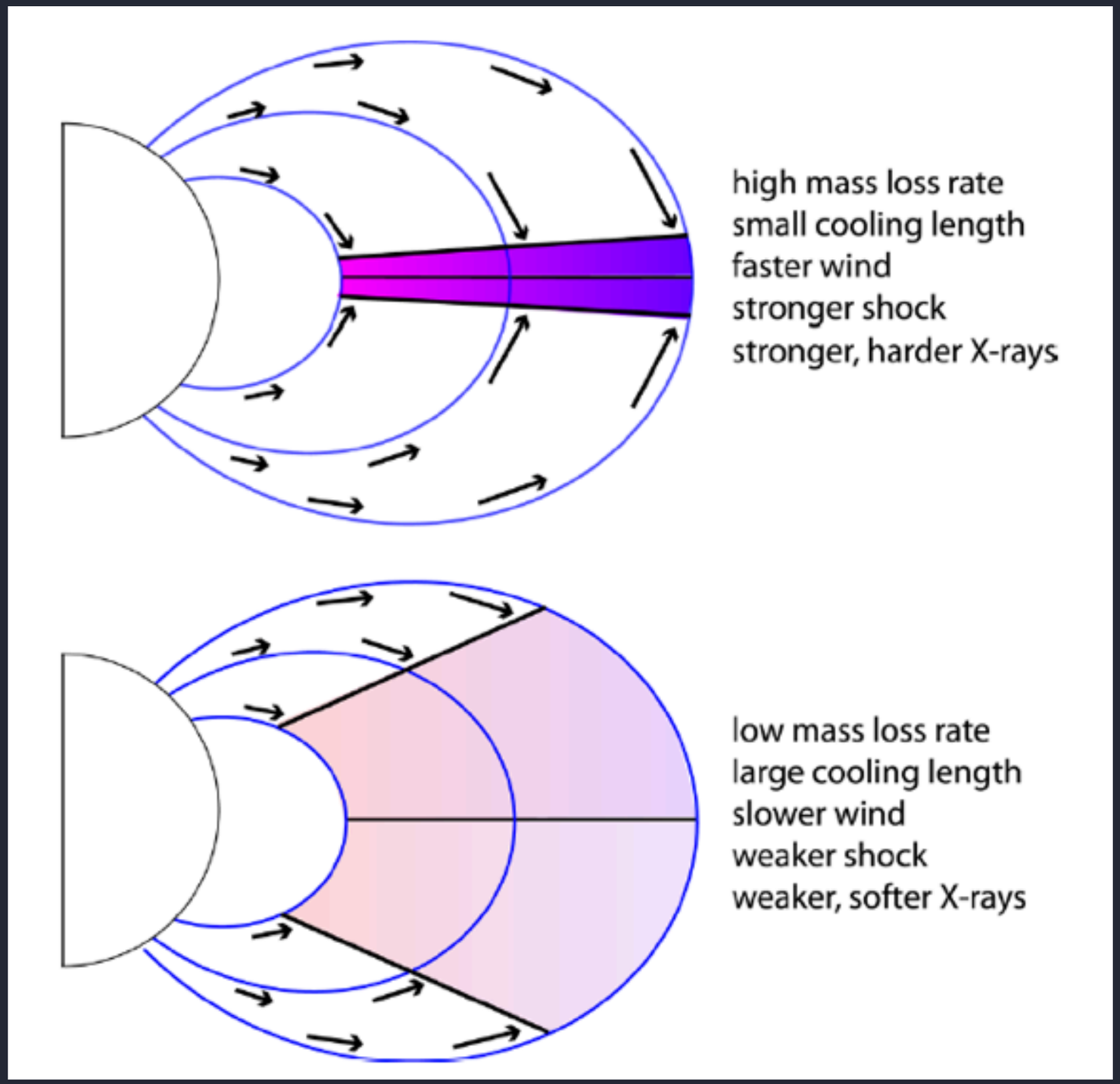
# X-ray line emission process

## thermal emission from collisional plasma



# Plasma heating from hydrodynamic shock

## wind kinetic energy converted to heat: $T \sim 10^6 \, (v_{shock}/300 \text{ km/s})^2$ K




from ud-Doula et al. 2014

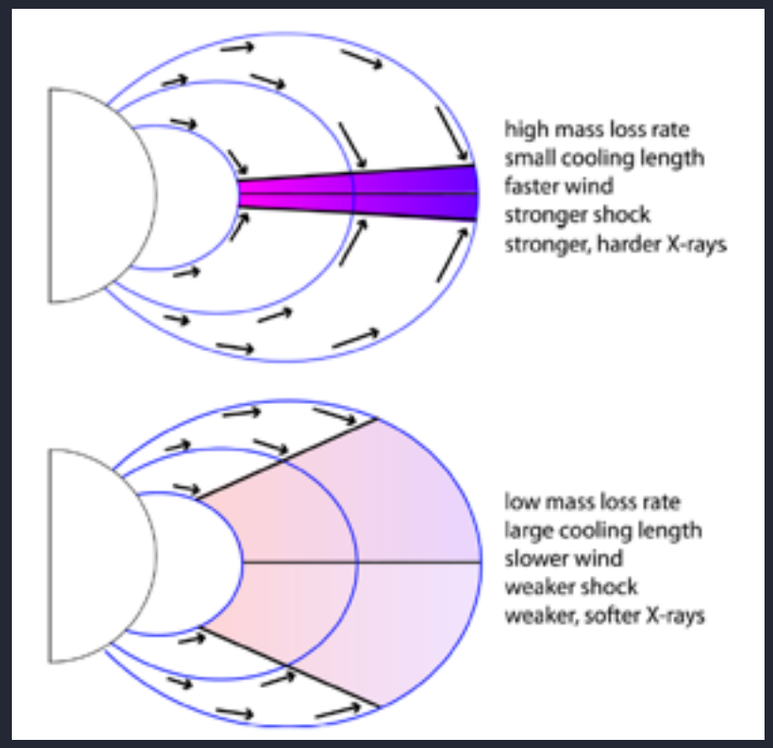
# Overall level and hardness of X-ray emission

## affected by:

amount of wind material fed into the magnetosphere

efficiency of shock heating (duty cycle of shock build up vs. fall-back/downflow)

specific kinetic energy: shock velocity (pre-shock wind velocity)

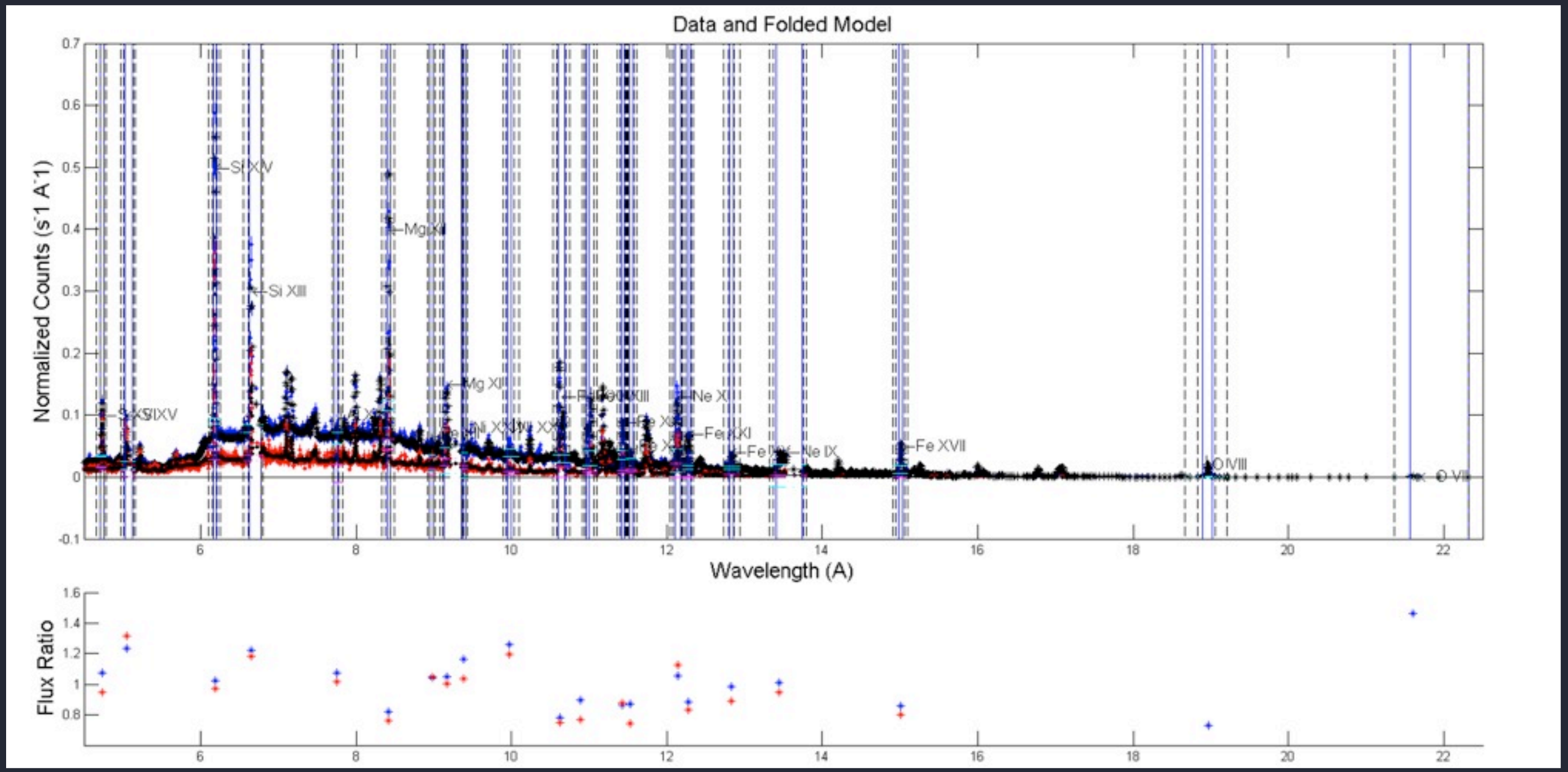



from ud-Doula et al. 2014

*Goal:* use the X-ray spectrum to measure the amount of hot plasma and its temperature distribution, compare results to simulations

# Spectral modeling: coadded 15 observations

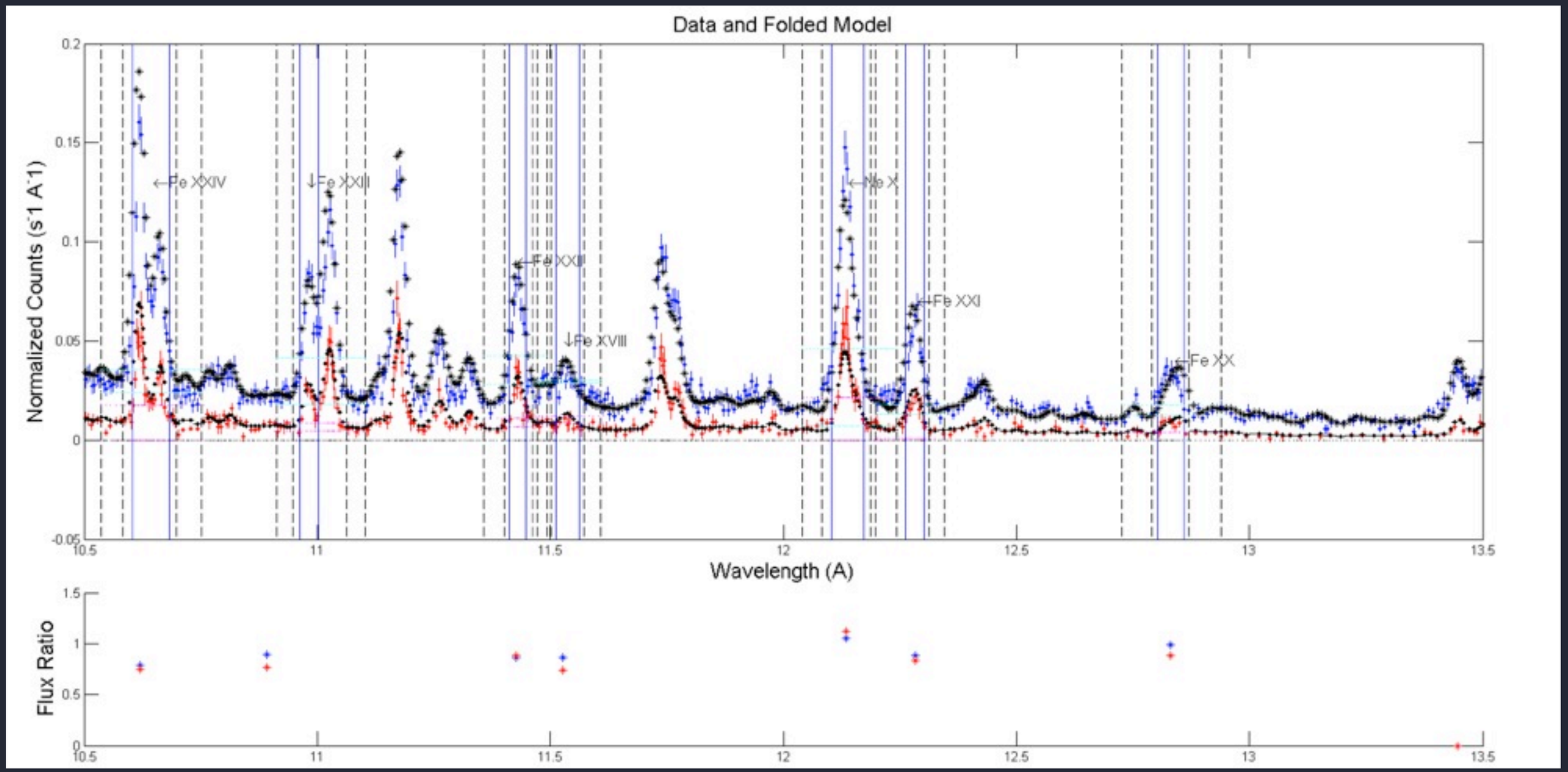
collisional-radiative equilibrium model (APEC): temperature and emission measure are free parameters, along with line widths and (potentially) abundances




fit to *Chandra* spectrum

# Spectral modeling

**zoom-in**: black = model; red, blue = data (two grating arrays on *Chandra* produce two spectra, simultaneously)




fit to *Chandra* spectrum

data - model agreement is quite good

# Spectral modeling

work presented here is preliminary

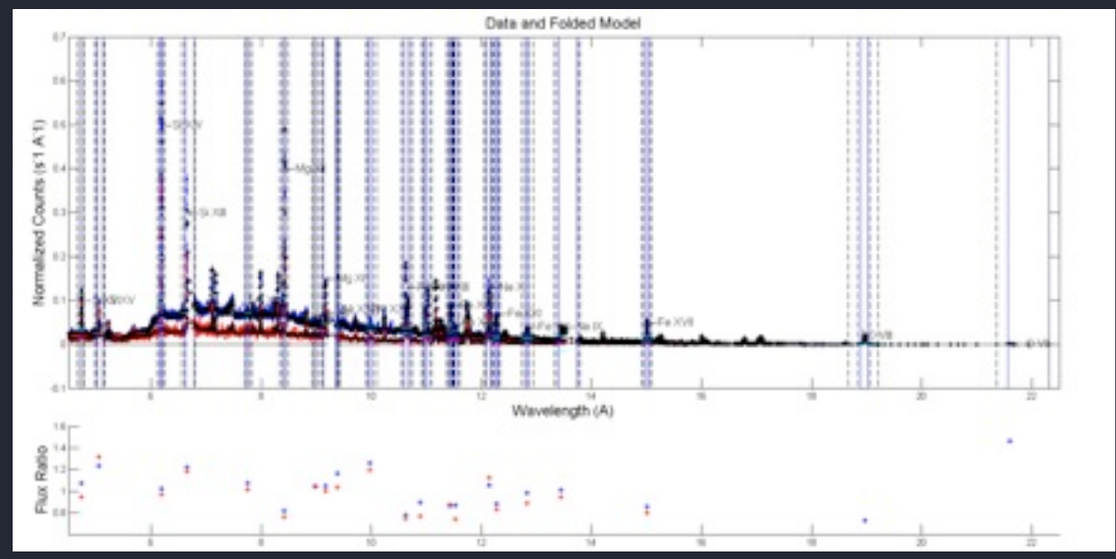
best-fit model parameters: temperature distribution in the plasma, line widths, absorption

```
========================================================================
Model (bapec<1> + bapec<2> + bapec<3> + bapec<4> + bapec<5> + bapec<6>)TBabs<7>
Source No.: 1   Active/On
Model Model Component  Paraneter  Unit     Value
 par  comp
   1    1   bapec      kT         keV      0.200000     frozen
   2    1   bapec      Abundanc              1.00000     frozen
   3    1   bapec      Redshift              0.0         frozen
   4    1   bapec      Velocity   km/s       290.281     +/-  2.52376
   5    1   bapec      norm                  1.11264E-02 +/-  5.74059E-04
   6    2   bapec      kT         keV      0.400000     frozen
   7    2   bapec      Abundanc              1.00000     frozen
   8    2   bapec      Redshift              0.0         frozen
   9    2   bapec      Velocity   km/s       290.281     = 1.0*4
  10    2   bapec      norm                  2.00501E-03 +/-  1.13754E-04
  11    3   bapec      kT         keV      0.800000     frozen
  12    3   bapec      Abundanc              1.00000     frozen
  13    3   bapec      Redshift              0.0         frozen
  14    3   bapec      Velocity   km/s       290.281     = 1.0*4
  15    3   bapec      norm                  5.02117E-03 +/-  9.06196E-05
  16    4   bapec      kT         keV      1.60000      frozen
  17    4   bapec      Abundanc              1.00000     frozen
  18    4   bapec      Redshift              0.0         frozen
  19    4   bapec      Velocity   km/s       290.281     = 1.0*4
  20    4   bapec      norm                  7.56200E-03 +/-  1.89407E-04
  21    5   bapec      kT         keV      3.20000      frozen
  22    5   bapec      Abundanc              1.00000     frozen
  23    5   bapec      Redshift              0.0         frozen
  24    5   bapec      Velocity   km/s       290.281     = 1.0*4
  25    5   bapec      norm                  2.07156E-02 +/-  4.52703E-04
  26    6   bapec      kT         keV      6.40000      frozen
  27    6   bapec      Abundanc              1.00000     frozen
  28    6   bapec      Redshift              0.0         frozen
  29    6   bapec      Velocity   km/s       290.281     = 1.0*4
  30    6   bapec      norm                  2.45517E-03 +/-  3.00636E-04
  31    7   TBabs      nH         10^22     0.616796     +/-  4.19245E-03
------------------------------------------------------------------------

Fit statistic : C-Statistic =       13812.32 using 4807 PHA bins and 4799 degree
s of freedom.

Warning: cstat statistic is only valid for Poisson data.
    Source file is not Poisson


Test statistic : Chi-Squared =        9258.43 using 4807 PHA bins.
 Reduced chi-squared =        1.92924 for   4799 degrees of freedom
 Null hypothesis probability =  2.369129e-286
```



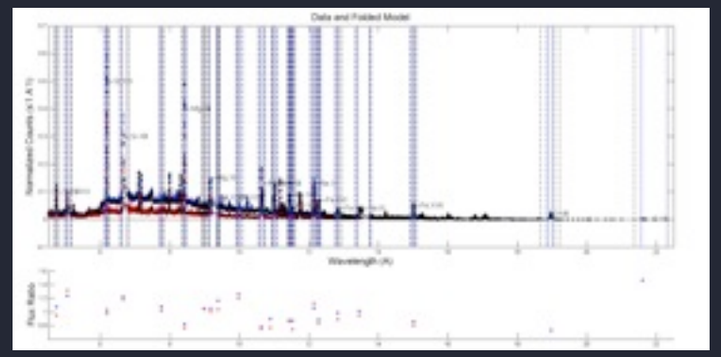

fit to *Chandra* spectrum

line widths ~ 300 km/s

ISM column density ~ 6 X $10^{21}$ $cm^{-2}$
(maybe a bit more than ISM)

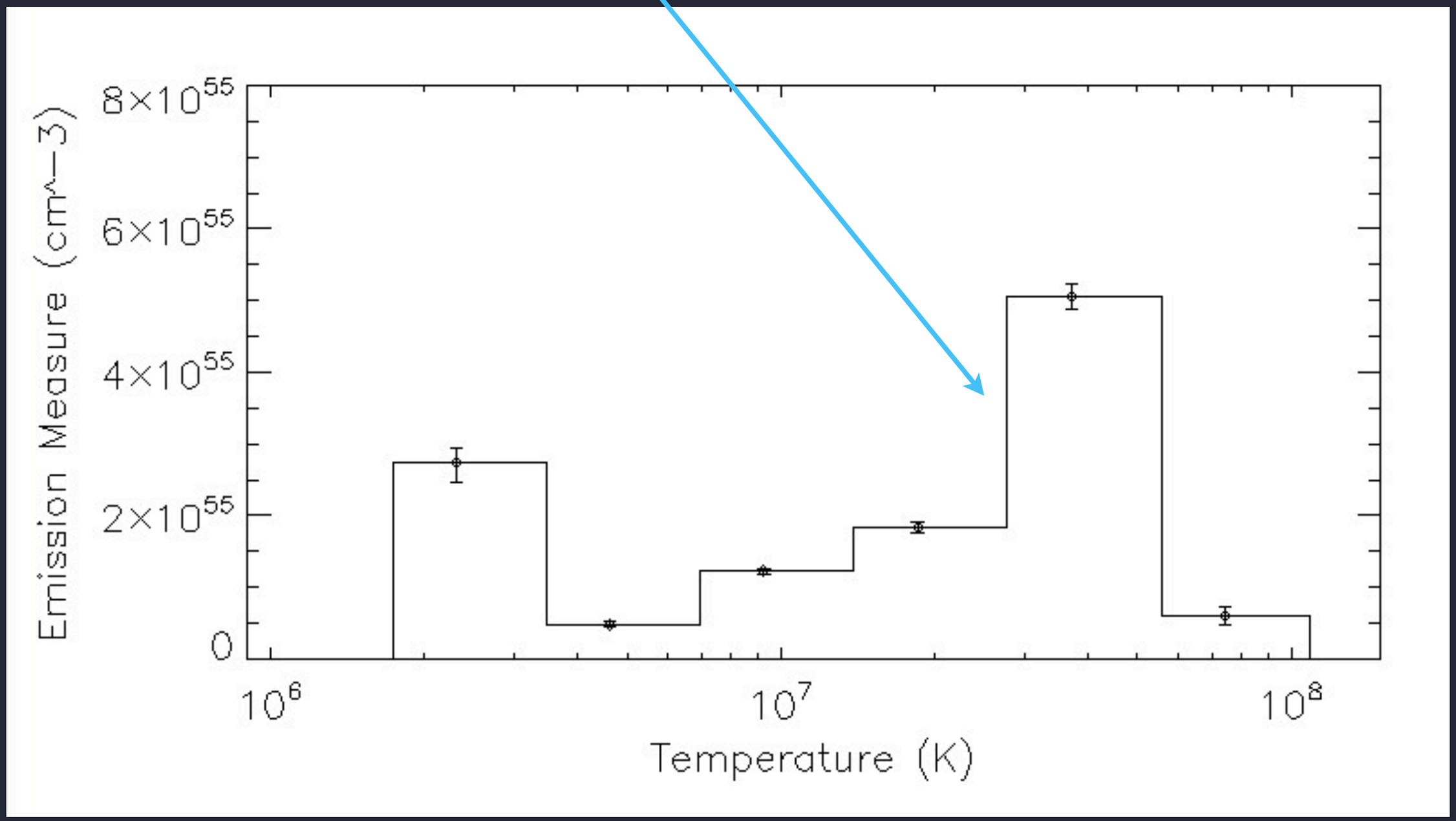
# Spectral modeling

## temperature distribution



fit to *Chandra* spectrum

from the APEC spectral fit



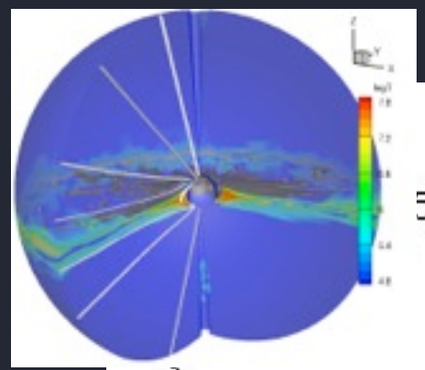
# Spectral modeling

The overall amount of hot plasma produced in the MHD simulations is in excellent agreement with the data; the temperature distribution is in good agreement, too.

Emission Measure (EM) distribution

from 3-D MHD simulation

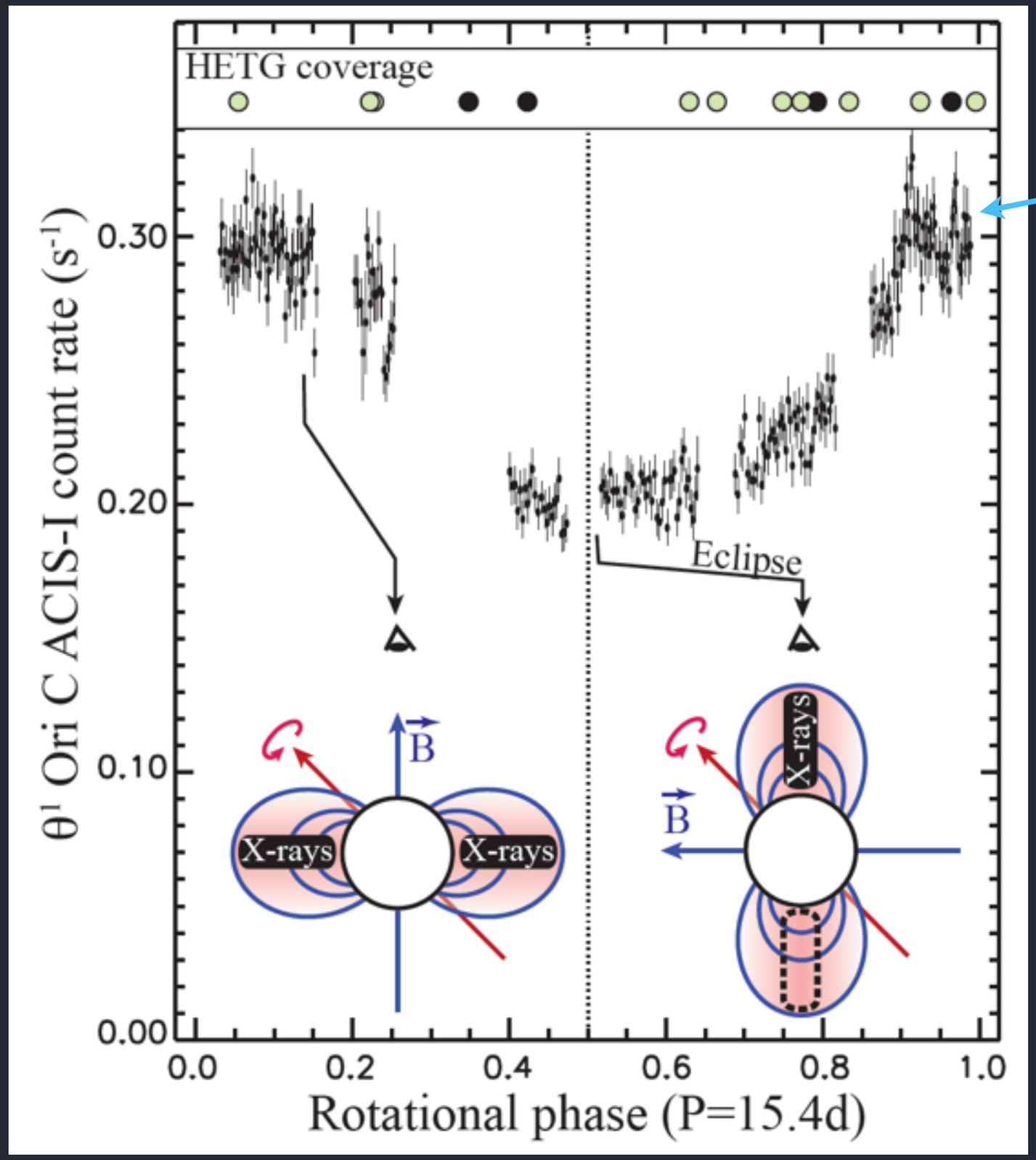
APEC spectral fit



rotationally modulated X-ray variability

# X-ray light curve: phase coverage: new data (11 new pointings to supplement 4 in Gagne et al. 2005)

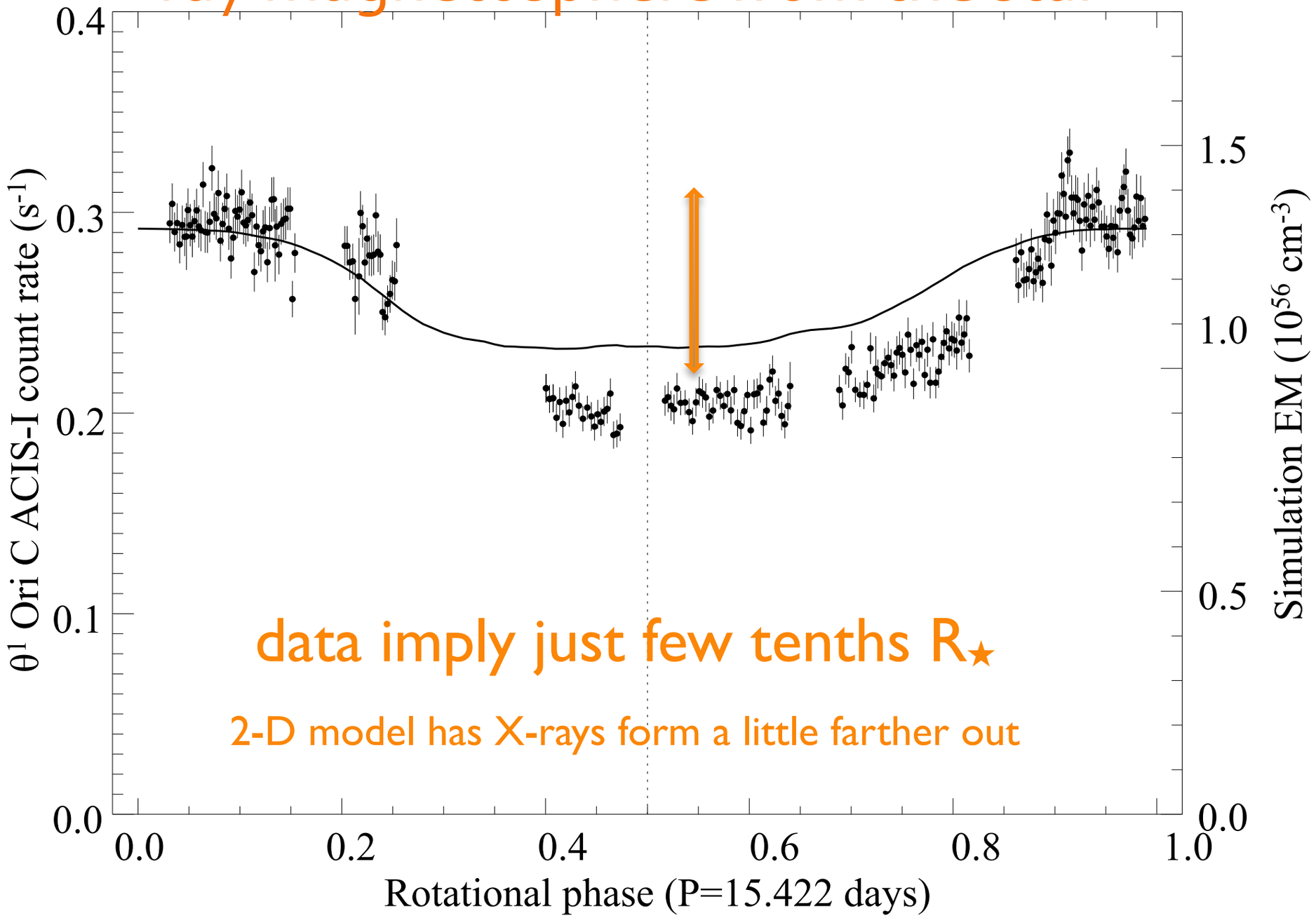
work presented here is preliminary




X-rays: occultation causes the magneto-spheric eclipse

# Location of hot plasma from eclipse depth: *occultation*

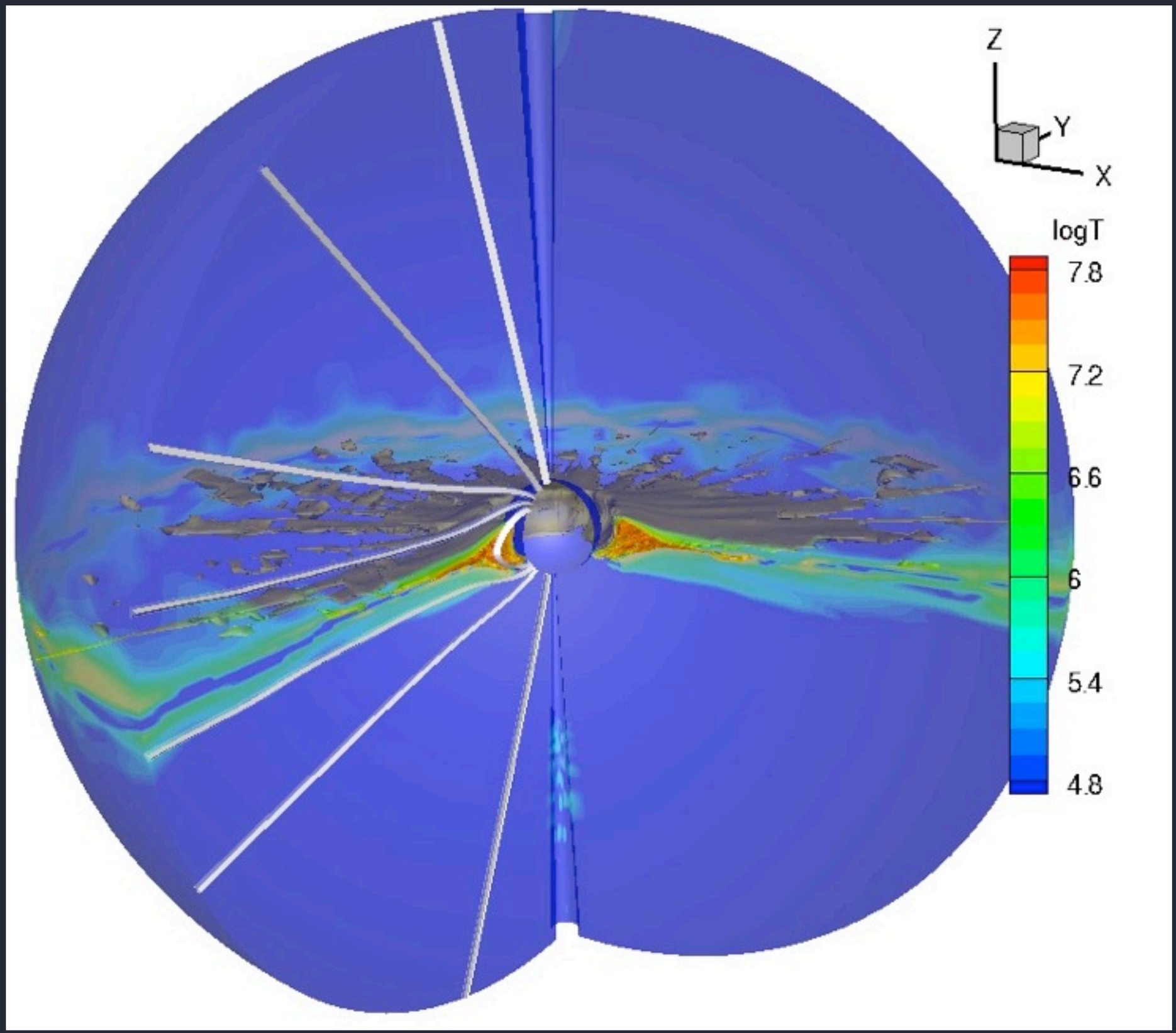
Eclipse depth depends on distance of X-ray magnetosphere from the star




data imply just few tenths $R_\star$

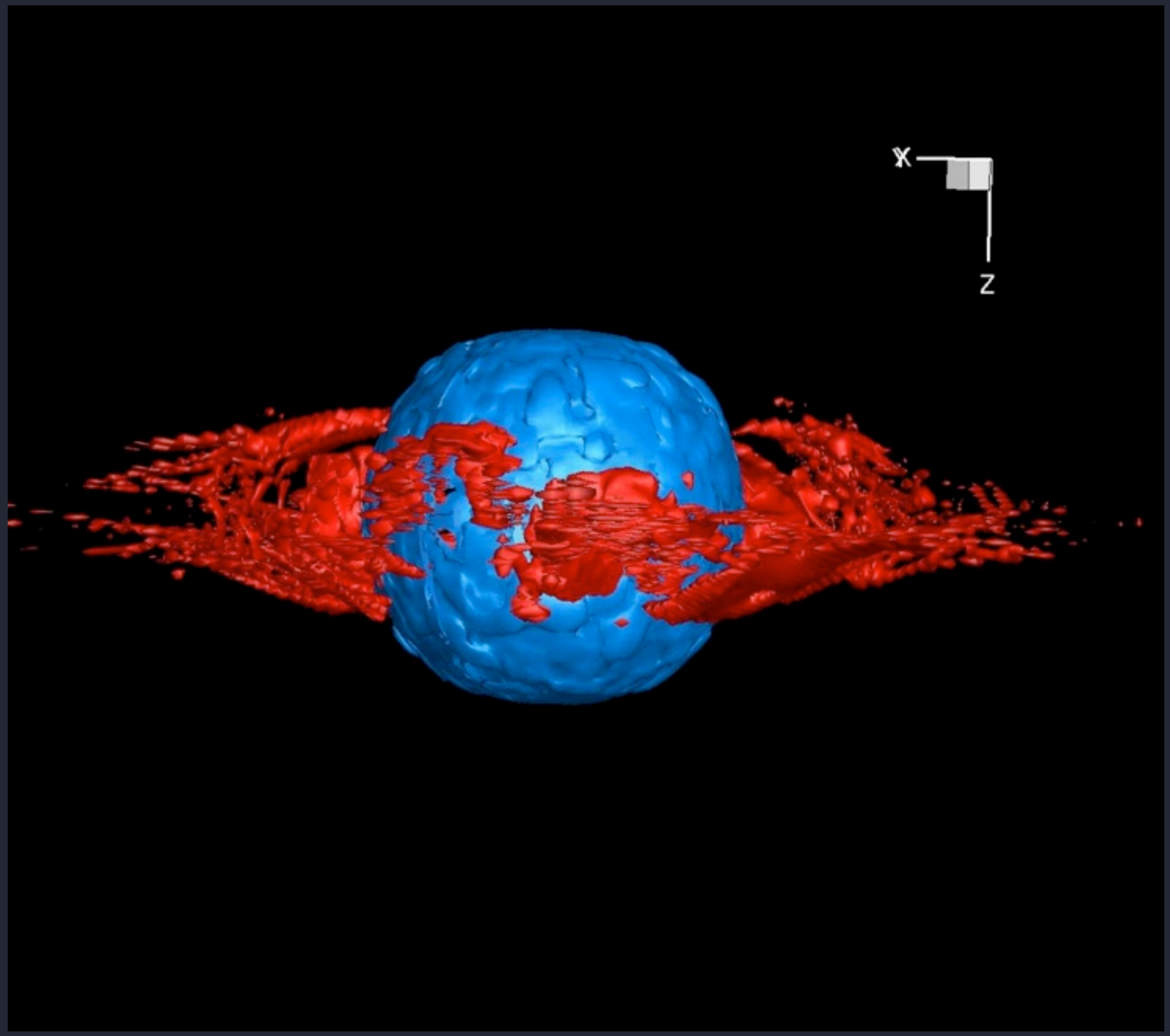
2-D model has X-rays form a little farther out

# 3-D MHD simulation: what about 3-D?




from A. ud-Doula

# 3-D MHD simulation: what about 3-D?




from A. ud-Doula

# 3-D MHD simulation: what about absorption?

## optical depth - in ADM model



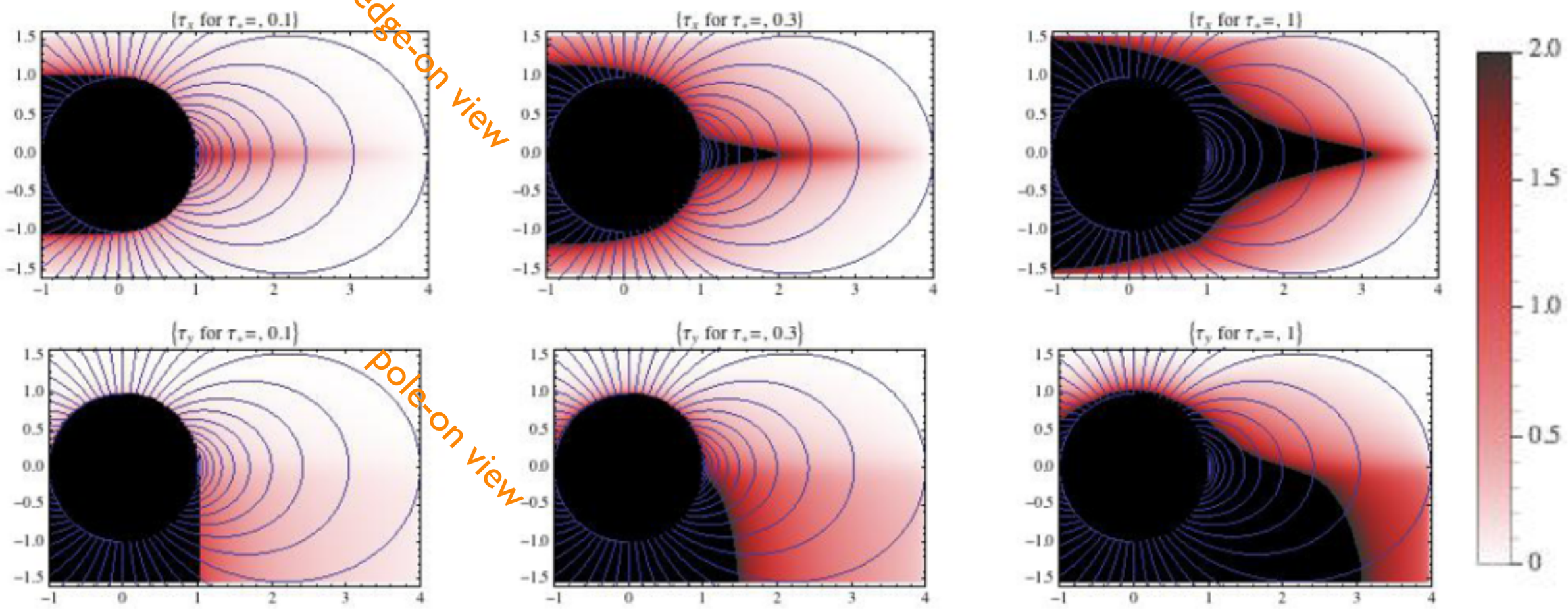
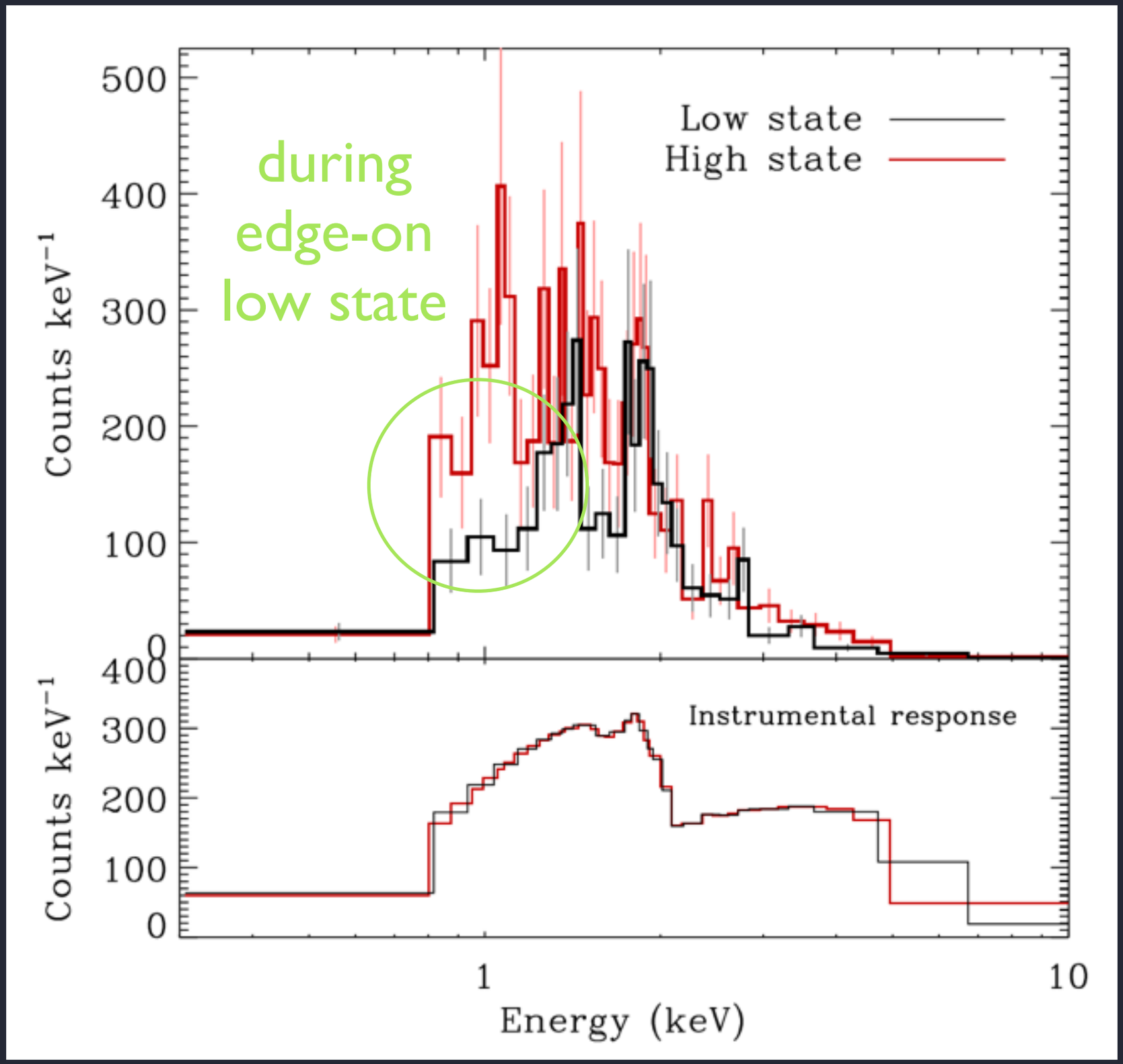



**Figure 7.** Spatial variation of optical depth for bound-free absorption of X-ray emission by both the cool downflow and wind outflow components of the ADM model, as well as by occultation of the opaque star. The top row shows results for a distant observer to the right, with an equator-on view, while the bottom row is for an observer at the top, with a pole-on view. The model assumes an apex smoothing length $h = 0.1R_*$, and a terminal speed $V_\infty = 3v_e$ for a corresponding unmagnetized wind. The left, middle and right columns show cases with a corresponding wind optical depth $\tau_* = 0.1, 0.3$ and 1.

# Spectral signature of absorption in NGC 1624-2

Of?p with giant magnetosphere

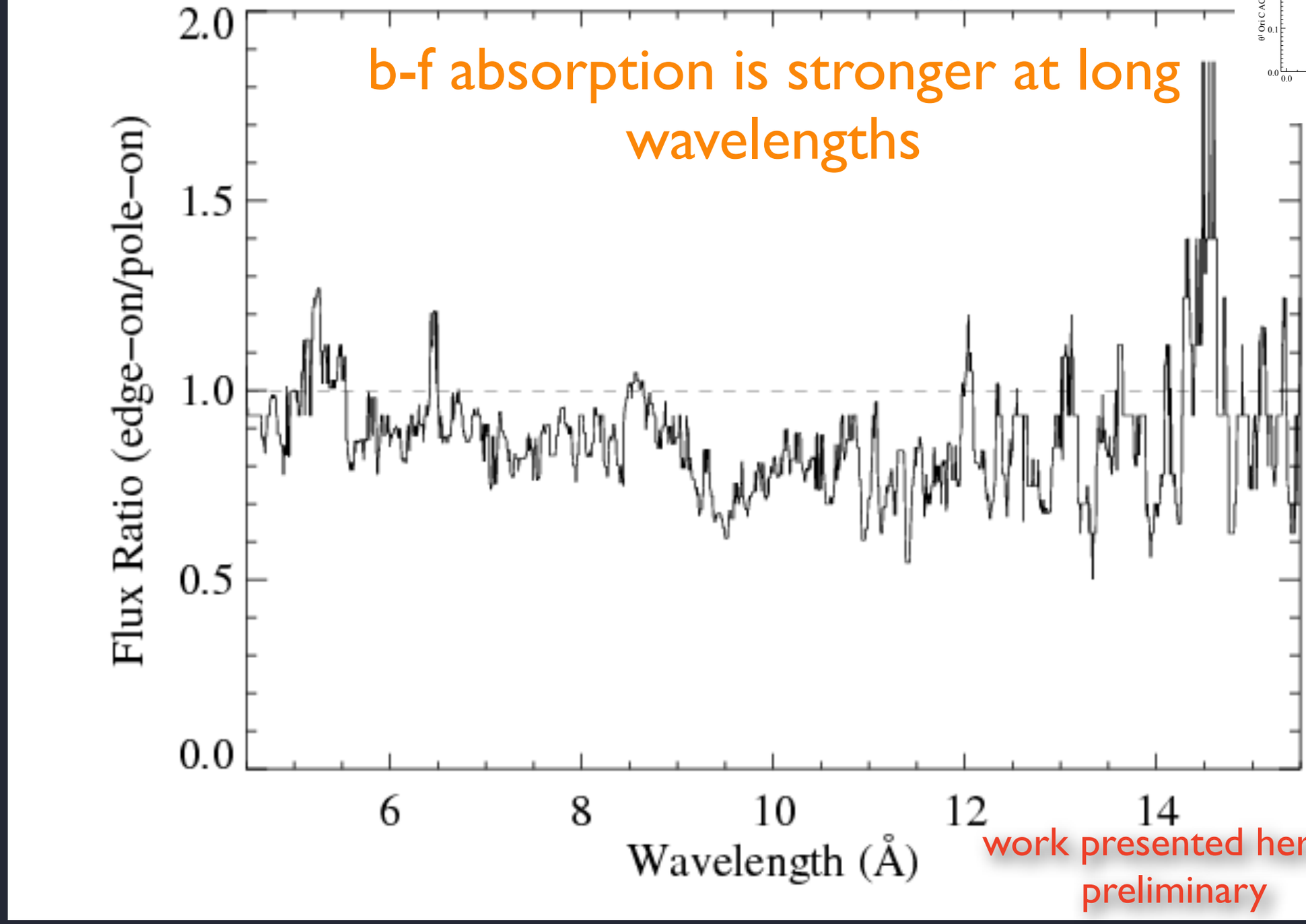


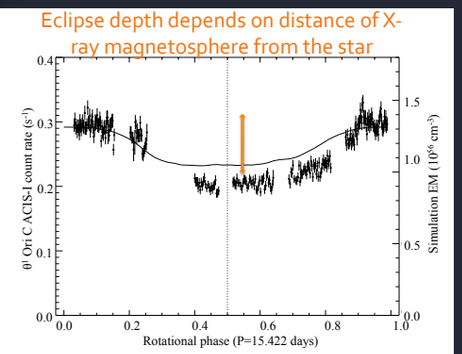

from V. Petit

# Ratio of edge-on to pole-on spectra for θ¹ Ori C

occultation should be gray

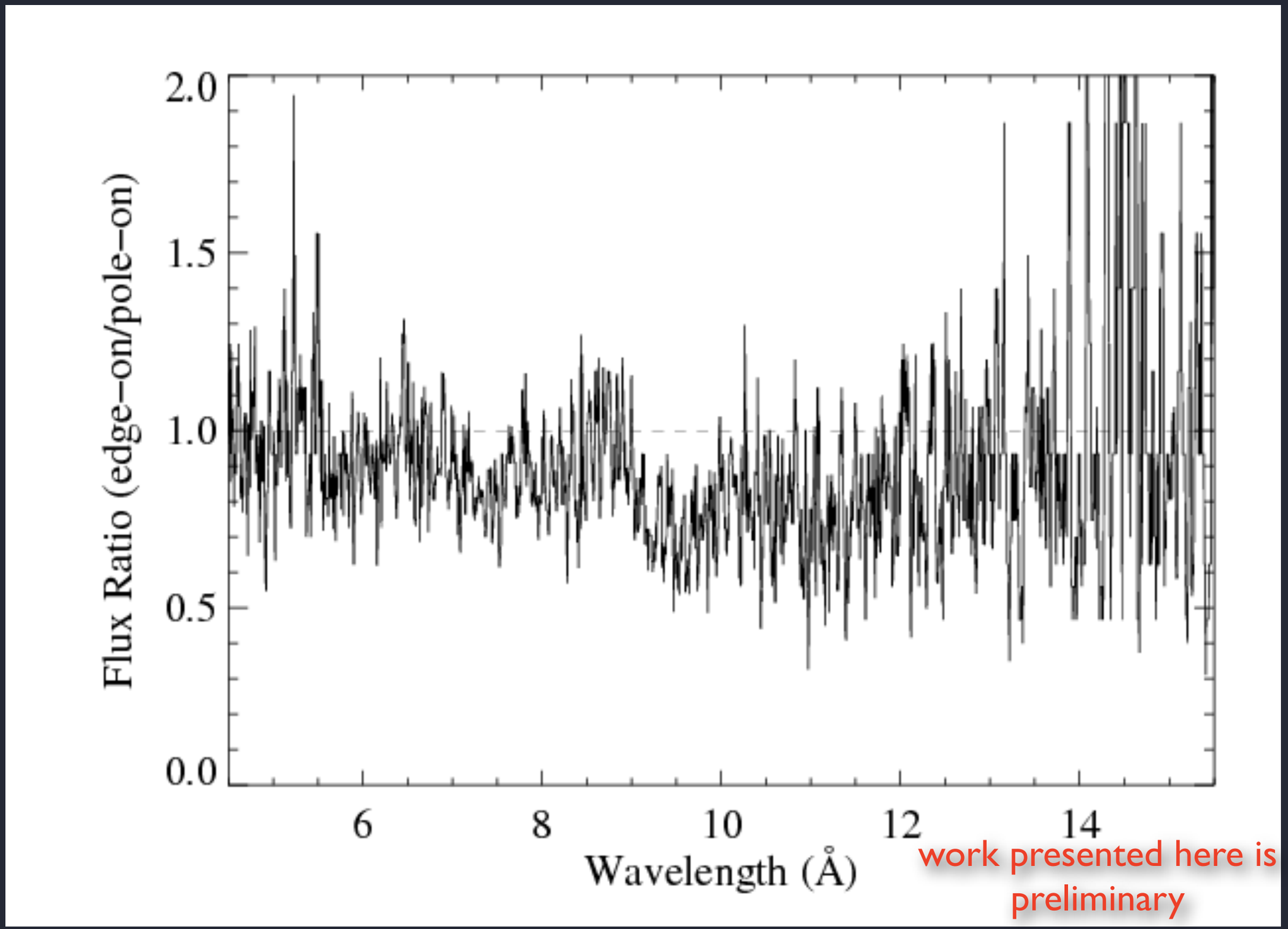
b-f absorption is stronger at long wavelengths



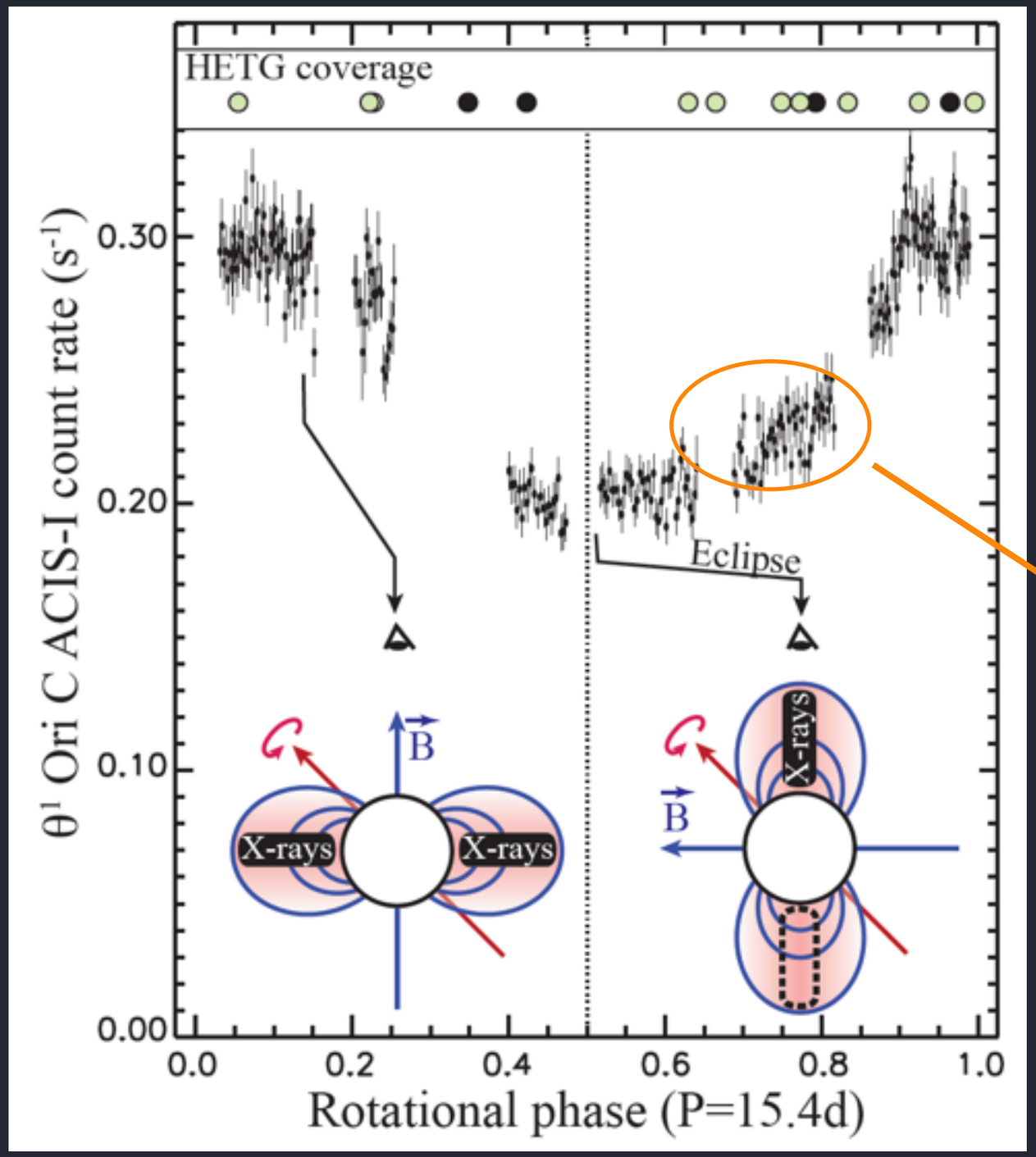

work presented here is preliminary

# Ratio of edge-on to pole-on spectra for θ¹ Ori C

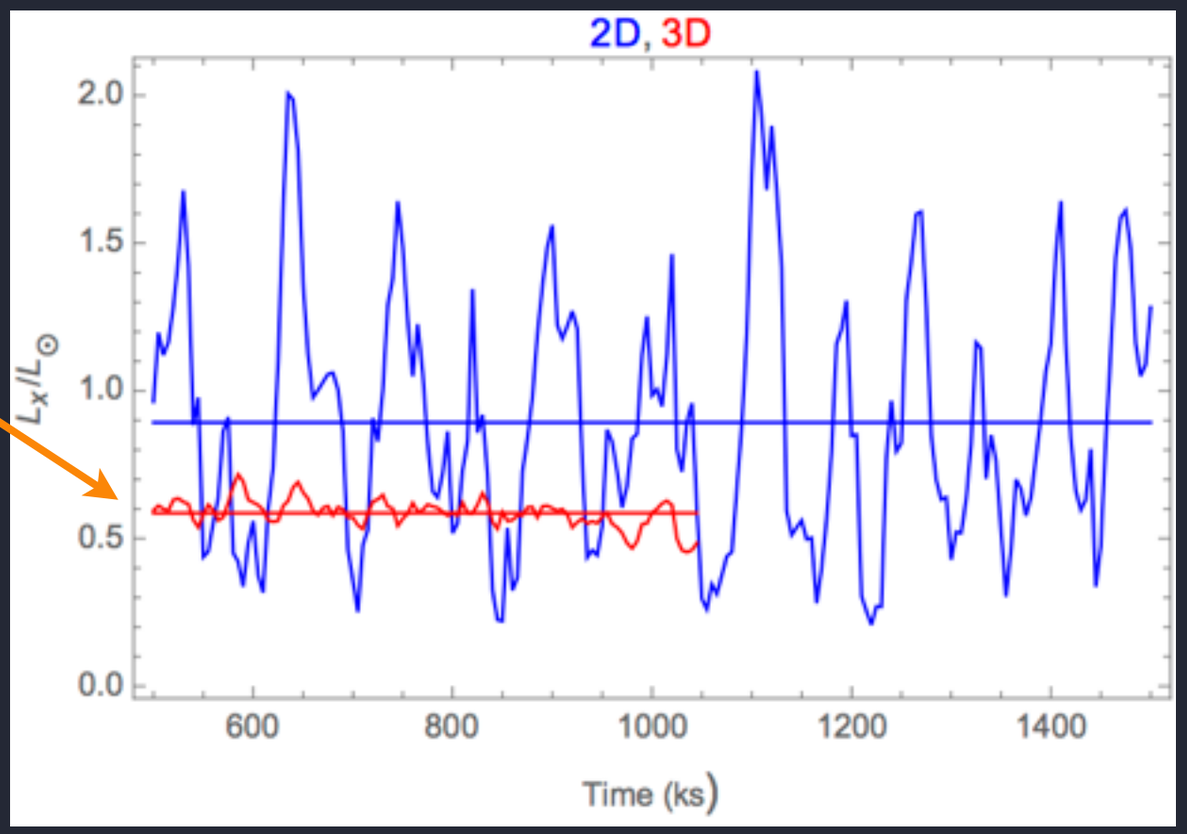



work presented here is preliminary

# X-ray light curve: focus on the stochastic, short-term variability




variability of < 10%
consistent with 3-D model:
lateral structure



# Other magnetic O stars?

# Other magnetic O stars: HD 191612 (Of?p)

## X-ray luminosity almost as high as $\theta^1$ Ori C

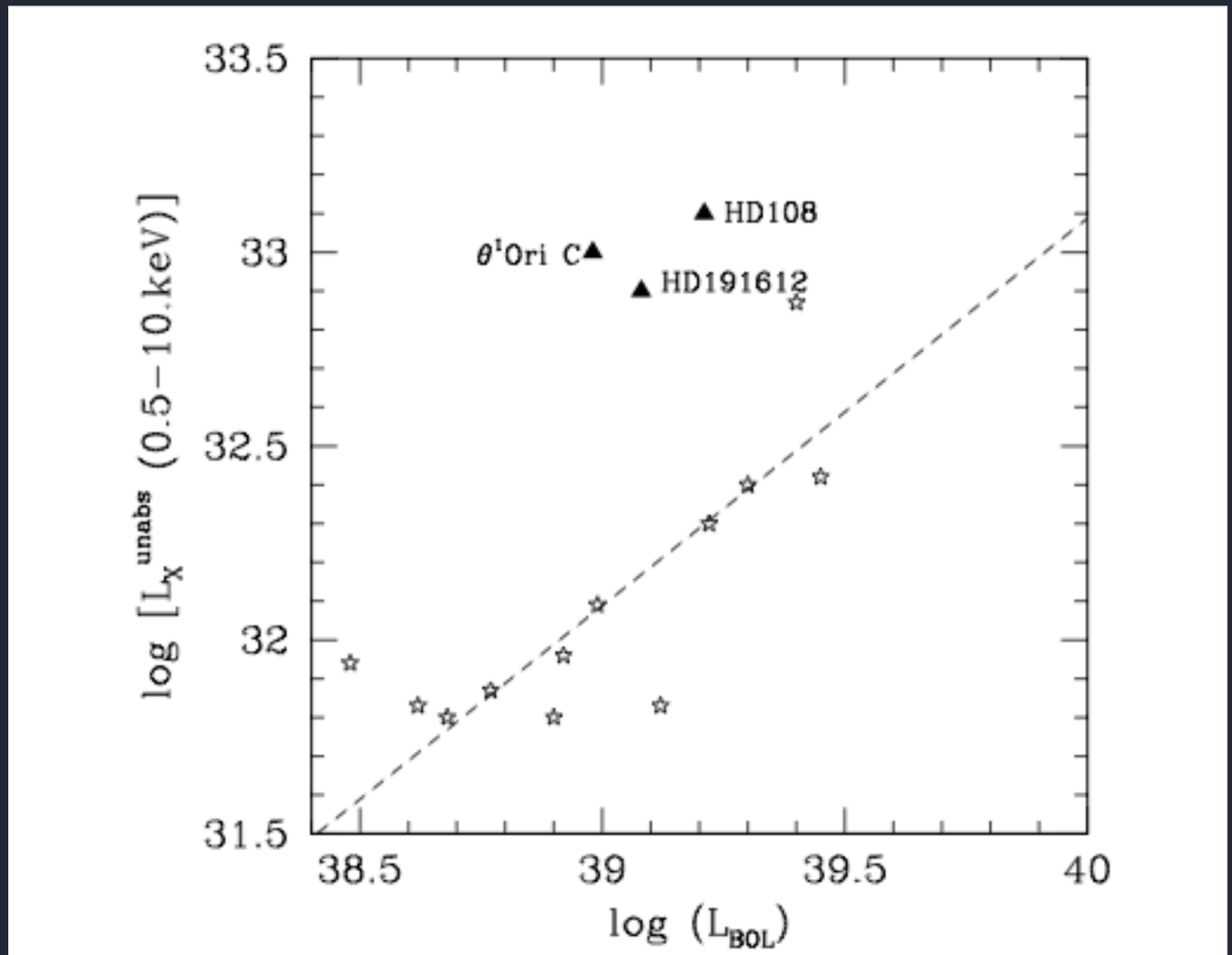
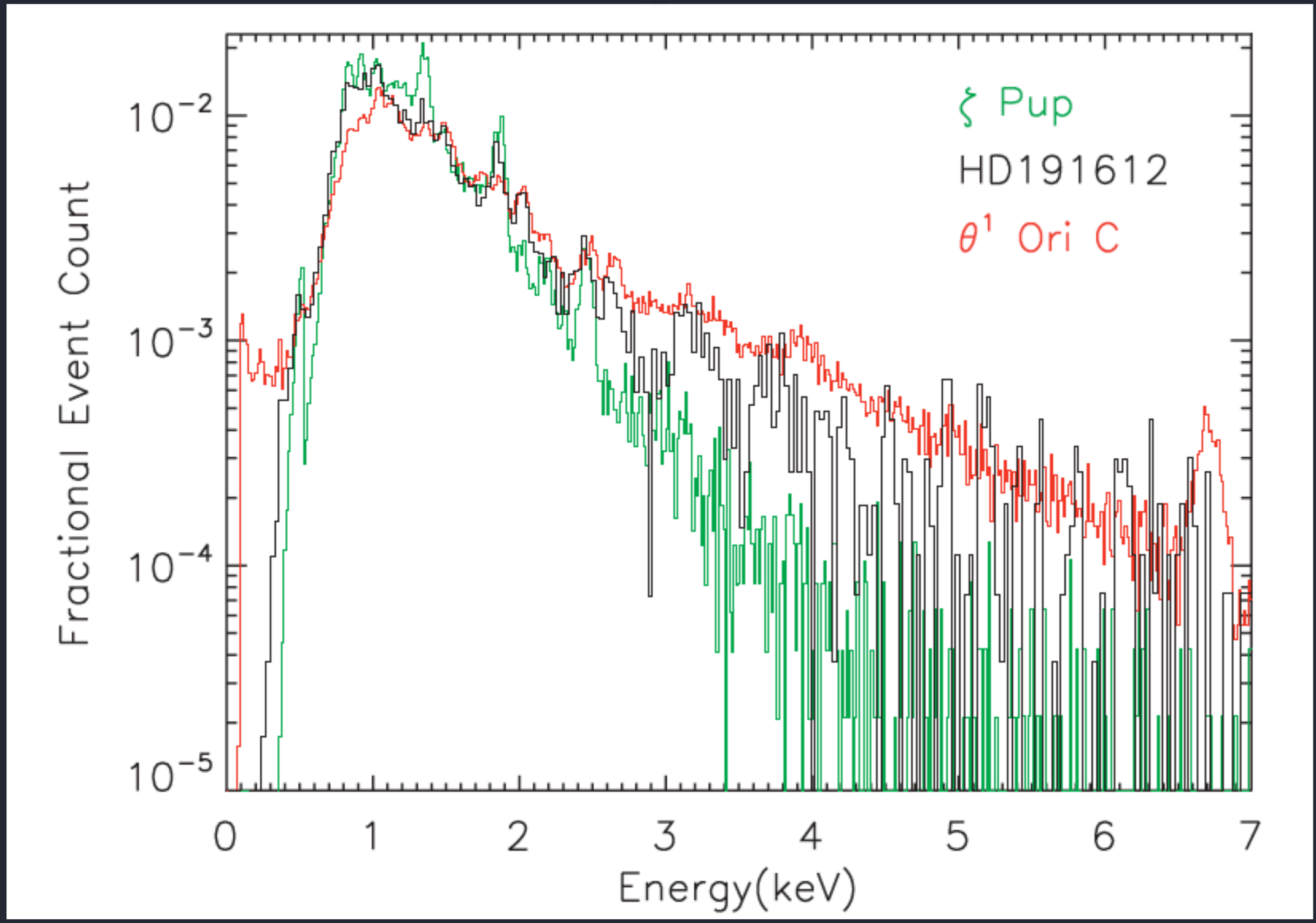



**Figure 4.** Diagram showing the X-ray luminosity (in erg $s^{-1}$) versus bolometric luminosity (in erg $s^{-1}$). The dashed line indicates the typical relation for O stars (from Sana et al. 2006); HD 108, HD 191612 and $\theta^1$ Ori C all lie above it. Asterisks show the position of hot stars in NGC 6231 (Sana et al. 2006) with three outliers: the two objects lying above the line are CW binaries whereas the one lying below is a Wolf–Rayet binary.

Nazé et al., 2007, MNRAS, 375,145

# Broadband X-ray spectra: HD 191612

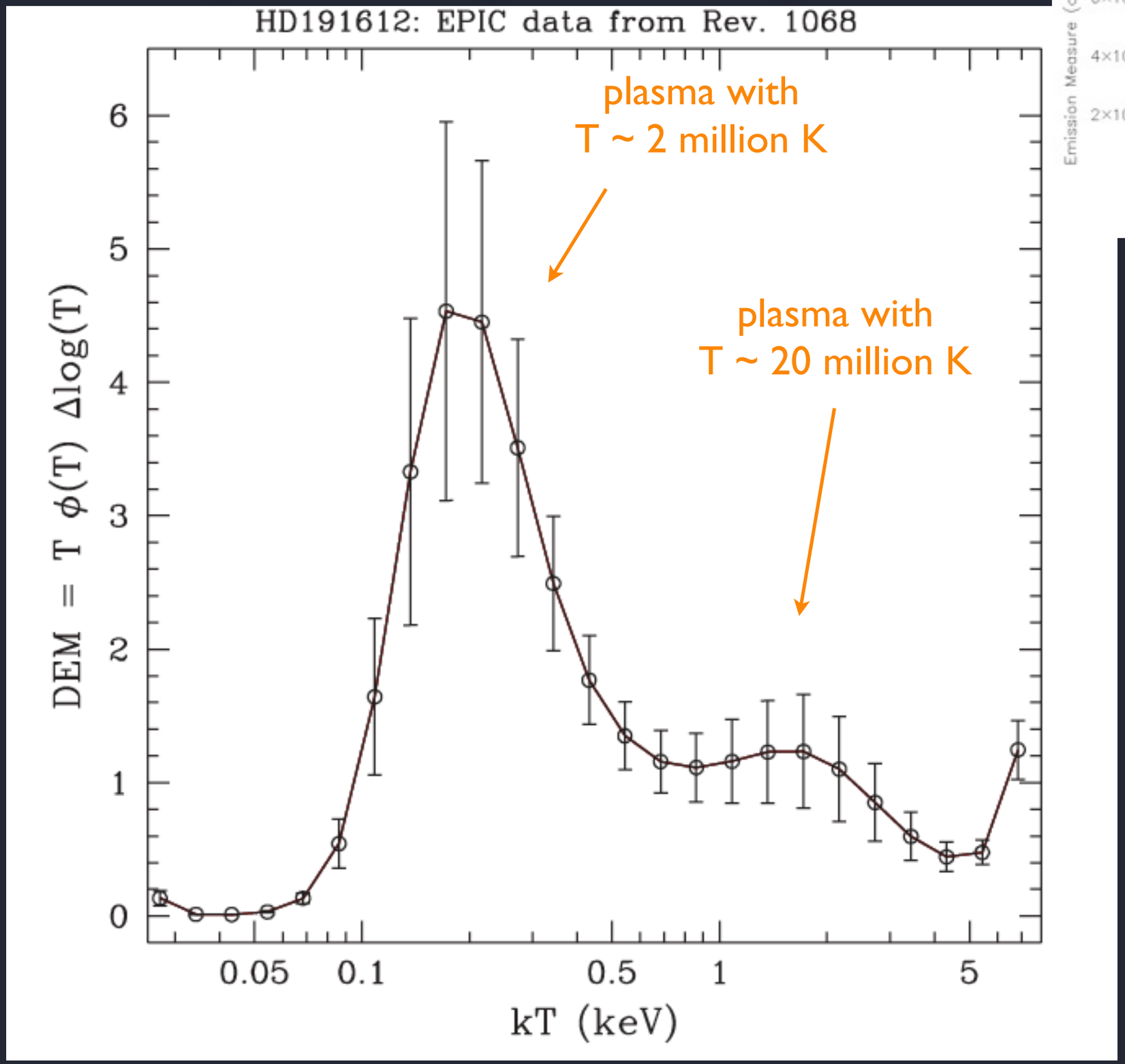
## spectrum softer than $\theta^1$ Ori C

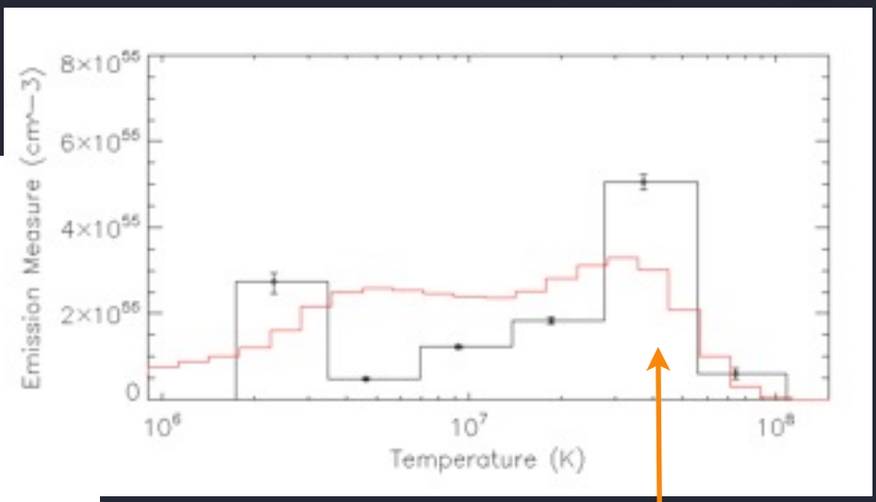



Nazé et al., 2007, MNRAS, 375, 145

# HD 191612: some very hot plasma but mostly cooler (few $10^6$ K)

θ¹ Ori C




Nazé et al., 2007, MNRAS, 375, 145

# Conclusions:

The MCWS scenario, and MHD simulations specifically, predict the observed amount of hot magnetospheric plasma and its temperature distribution

Mass-loss rate, wind speed, magnetic confinement are as expected

*Future analysis*: absorption, line widths - phase-dependence; also shock-heating rate from emission line strengths can constrain duty-cycle/efficiency ADM vs. MHD

What's different about other magnetic O stars with softer spectra and broader lines?