New X-ray Observations and Numerical Modeling of the Prototype Magnetic O Star θ^1 Ori C

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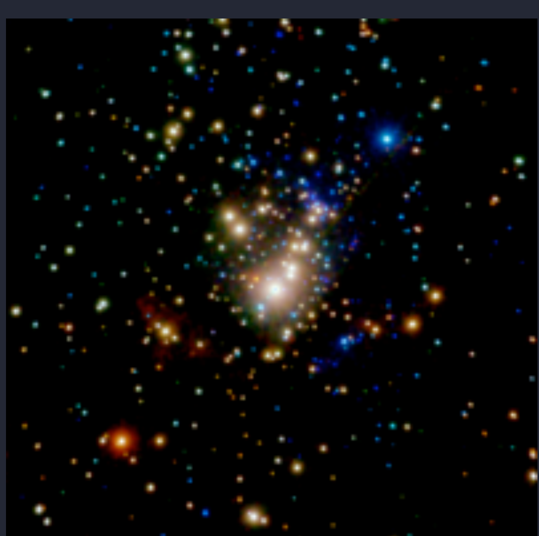
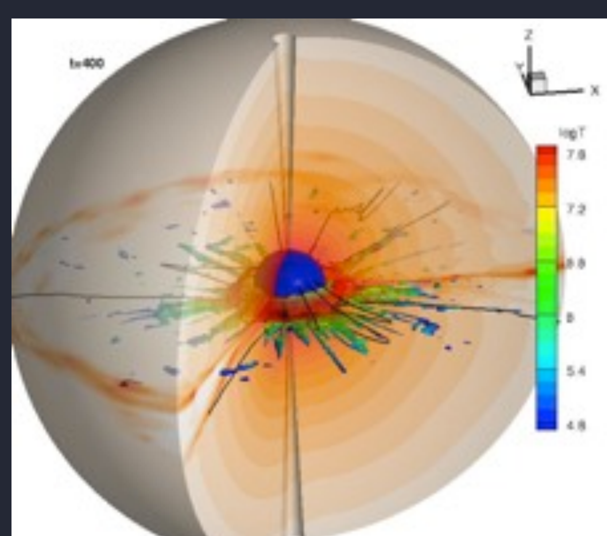
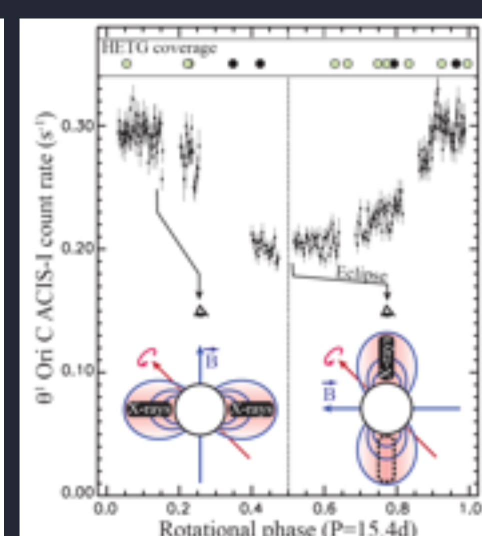
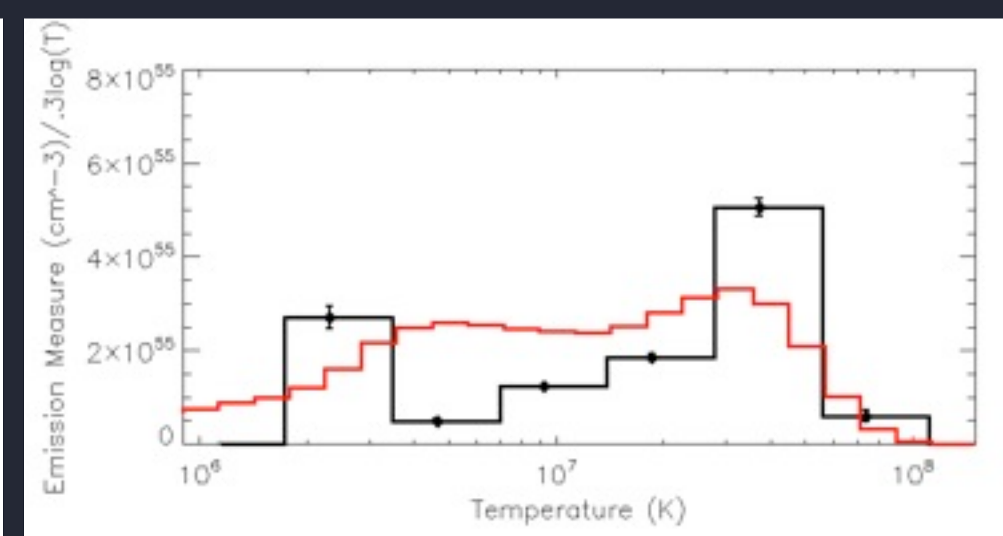
Asif ud-Doula, Véronique Petit, Stan Owocki, Maurice Leutenegger, Marc Gagné, Rich Townsend,
Gregg Wade, Alex Fullerton, Jon Sundqvist, and
Jackie Pezzato (Swarthmore '17) and Randy Doyle (Swarthmore '16)



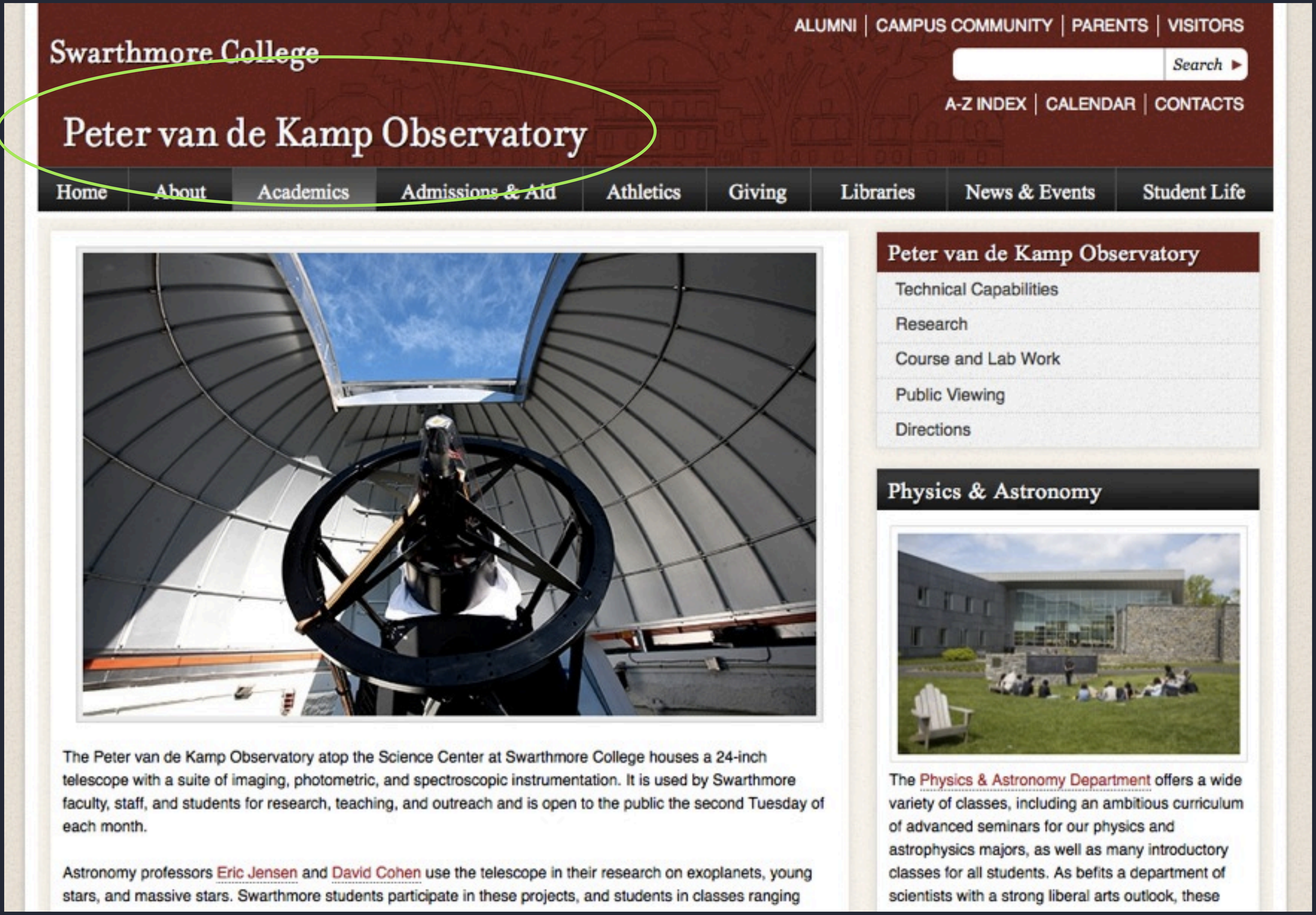






Physics & Astronomy @ Swarthmore College

Physics & Astronomy @ Swarthmore College

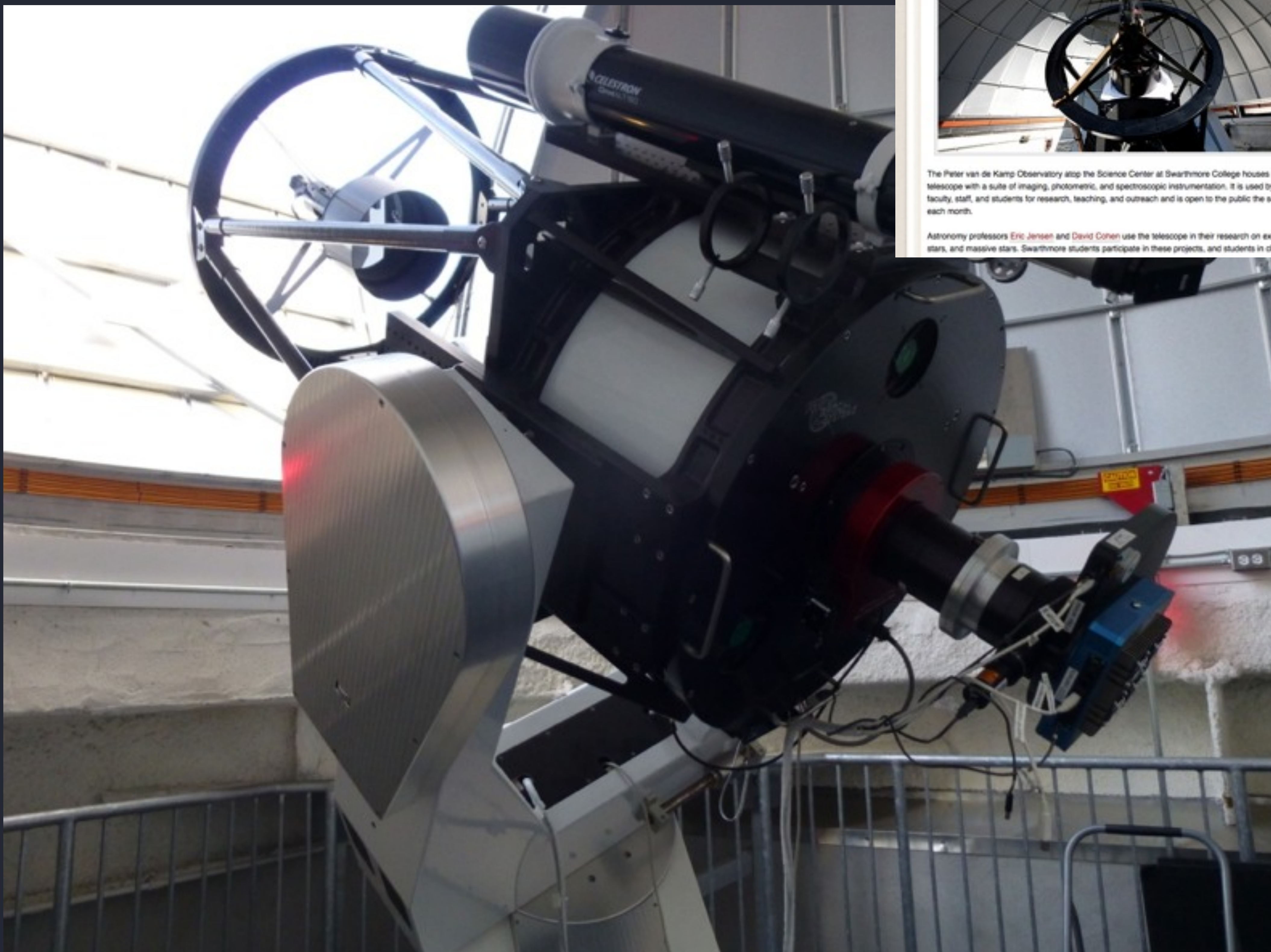


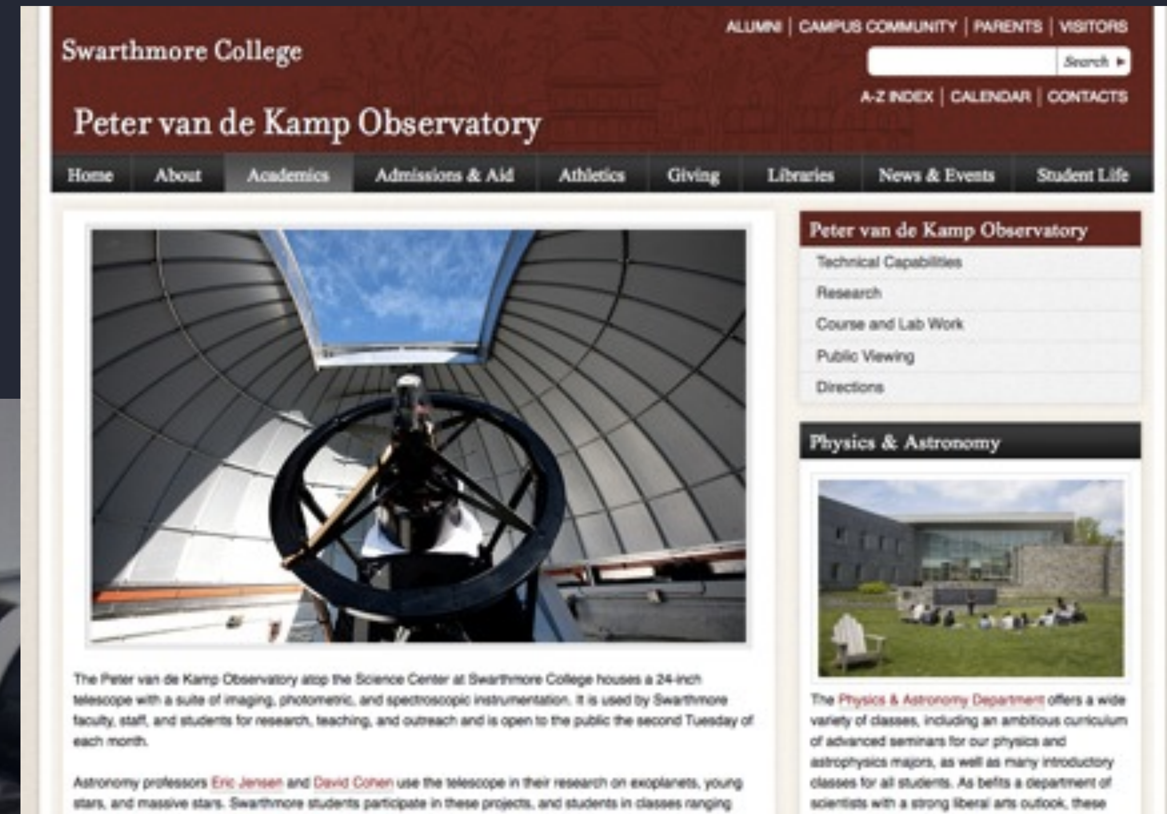
Peter van de Kamp
director, Sproul Observatory
Swarthmore College
(1937-1972)

Sproul Observatory
Swarthmore College
(1912)

24-inch refractor (f/17)

Peter van de Kamp Observatory established 2009

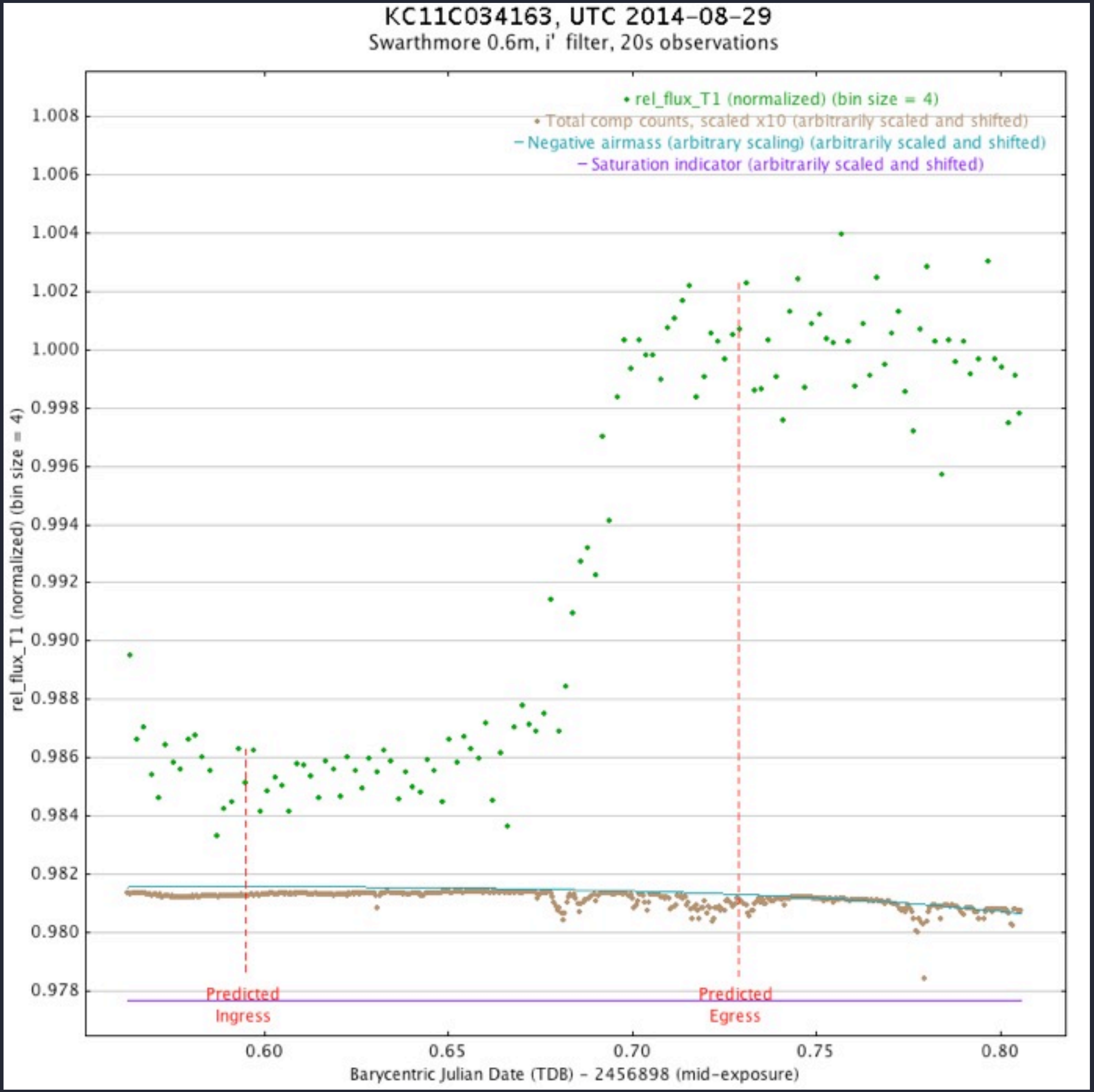




Physics & Astronomy @ Swarthmore College

24-inch (0.61 m) RCOS telescope: mostly exoplanet transit photometry

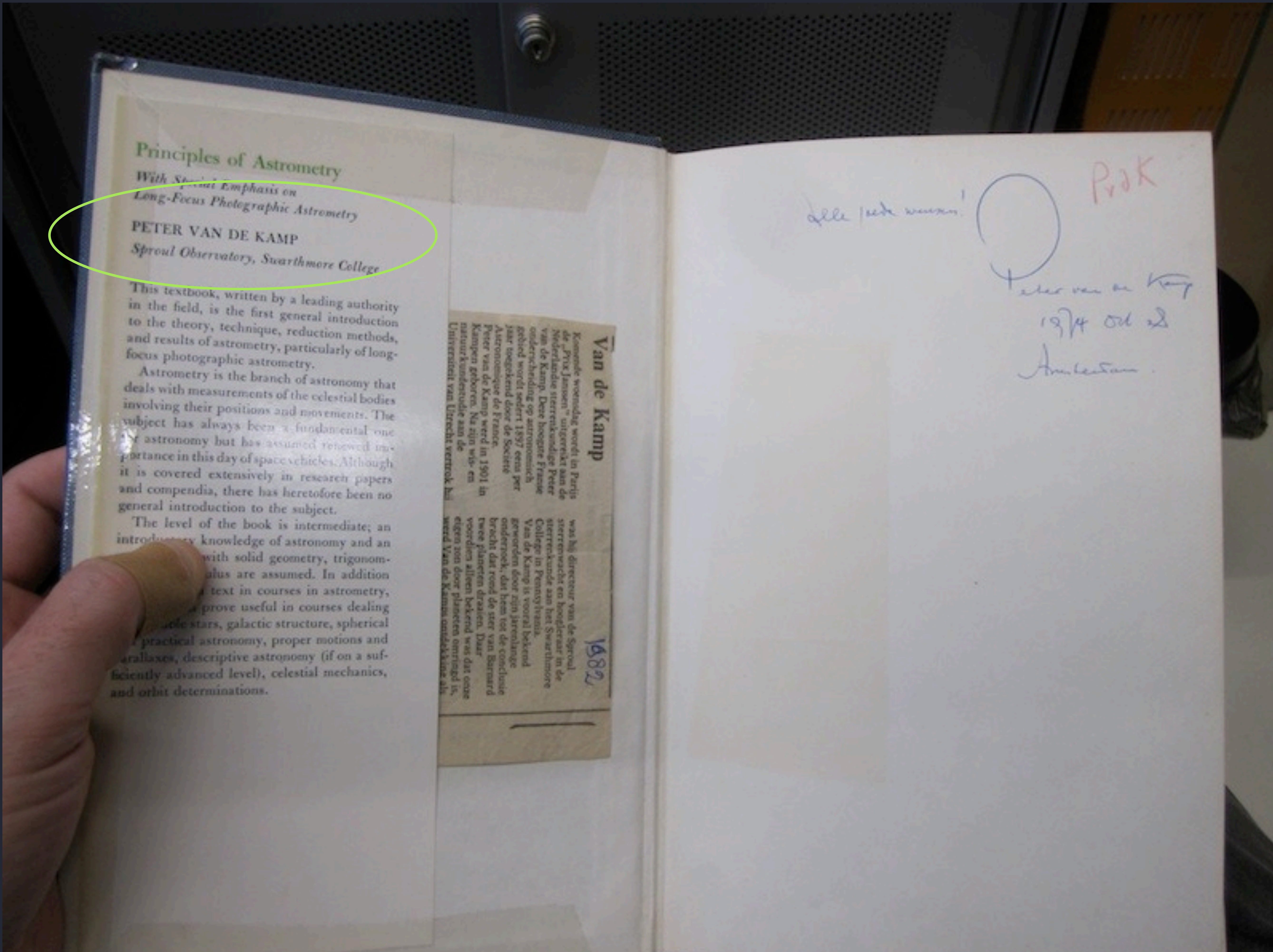
exoplanet transit candidate: ~1 mmag precision



2011 visit to UvA: APO

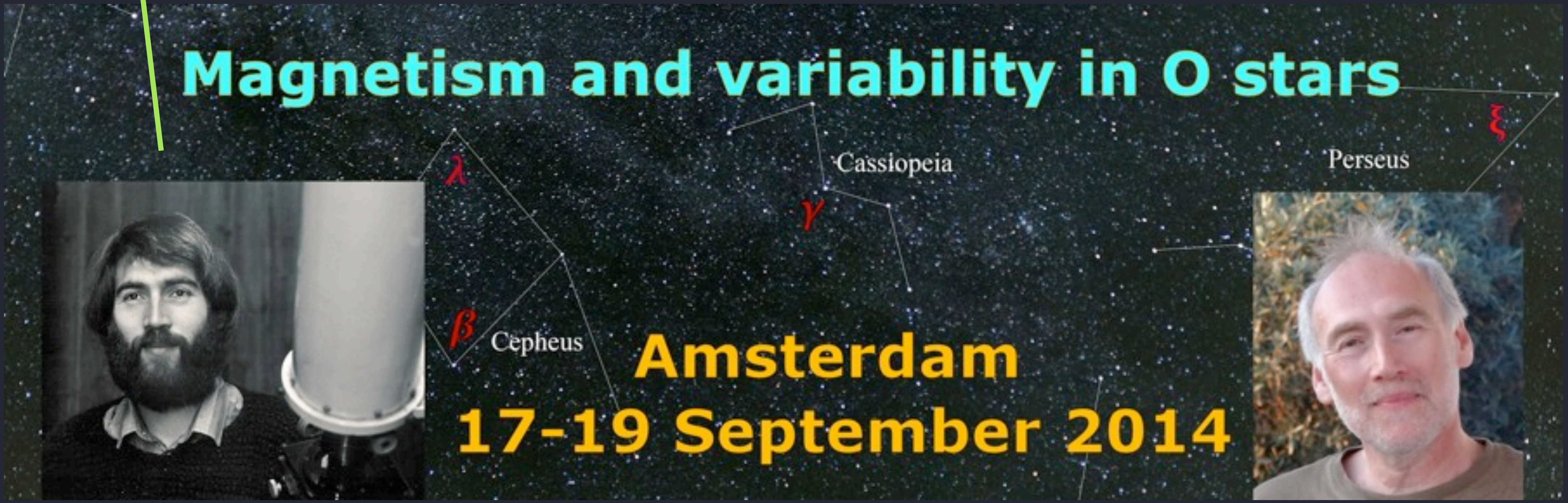
it's windy on the roof

nearly the same set-up as PvdK Observatory


Principles of Astrometry
With Special Emphasis on
Long-Focus Photographic Astrometry
PETER VAN DE KAMP
Sproul Observatory, Swarthmore College
This textbook, written by a leading authority in the field, is the first general introduction to the theory, technique, reduction methods, and results of astrometry, particularly of long-focus photographic astrometry.
Astrometry is the branch of astronomy that deals with measurements of the celestial bodies involving their positions and movements. The subject has always been a fundamental one for astronomy but has assumed renewed importance in this day of space vehicles. Although it is covered extensively in research papers and compendia, there has heretofore been no general introduction to the subject.
The level of the book is intermediate; an introd... knowledge of astronomy and an ... with solid geometry, trigonom... ...lus are assumed. In addition ... text in courses in astrometry, ... prove useful in courses dealing ... stars, galactic structure, spherical ... practical astronomy, proper motions and ...arallaxes, descriptive astronomy (if on a sufficiently advanced level), celestial mechanics, and orbit determinations.
Van de Kamp
1982
Komende woensdag wordt in Parijs de „Prix Janssen" uitgereikt aan de Nederlandse sterrenkundige Peter van de Kamp. Deze hoogste Franse onderscheiding op astronomisch gebied wordt sedert 1897 eens per jaar toegekend door de Société Astronomique de France.
Peter van de Kamp werd in 1901 in Kampen geboren. Na zijn wis- en natuurkundestudie aan de Universiteit van Utrecht vertrok hij
was hij directeur van de Sproul sterrenwacht en hoogleraar in de sterrenkunde aan het Swarthmore College in Pennsylvania.
Van de Kamp is vooral bekend geworden door zijn jarenlange onderzoek, dat hem tot de conclusie bracht dat rond de ster van Barnard twee planeten draaien. Daar voordien alleen bekend was dat onze eigen zon door planeten omringd is, werd Van de Kamp's ontdekking als
PvdK
Peter van de Kamp
1974 Oct 28
Amsterdam

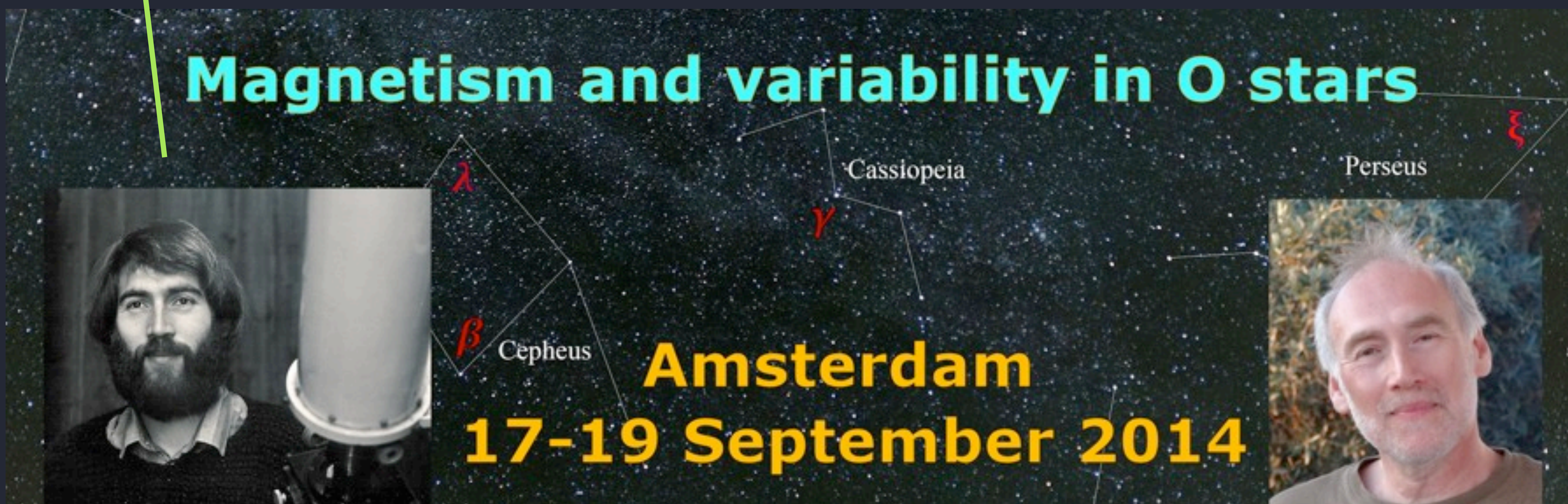
Magnetism and Variability in O Stars

the look of a prophet



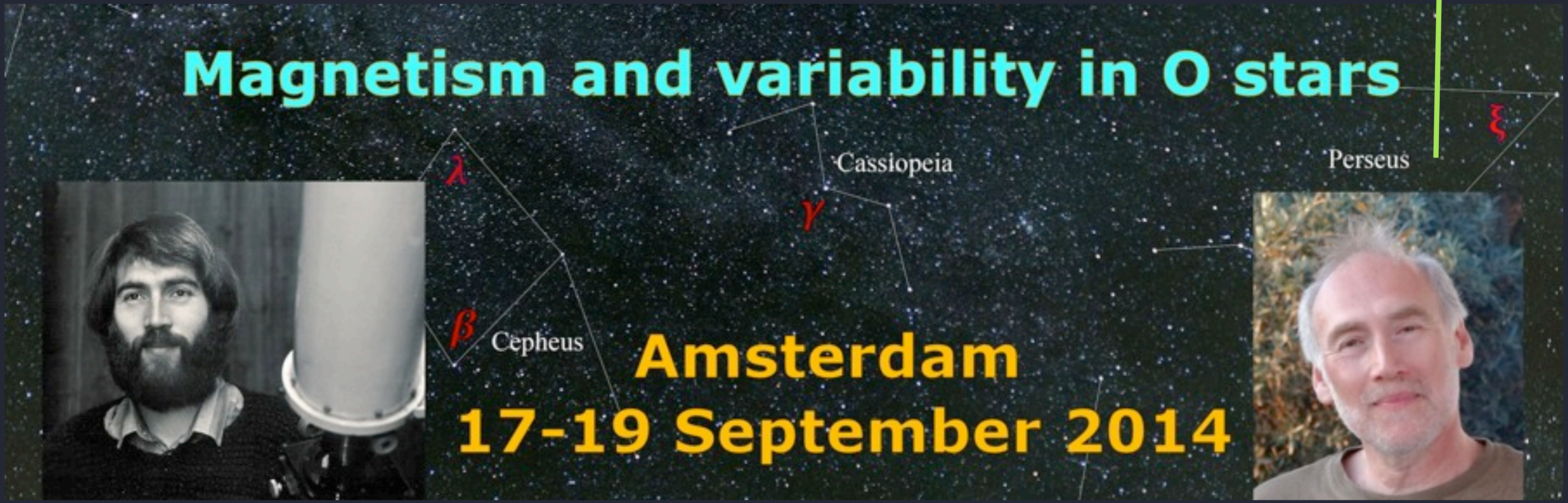
Magnetism and Variability in O Stars

C IV DAC... I think I see a magnetic field



Magnetism and Variability in O Stars

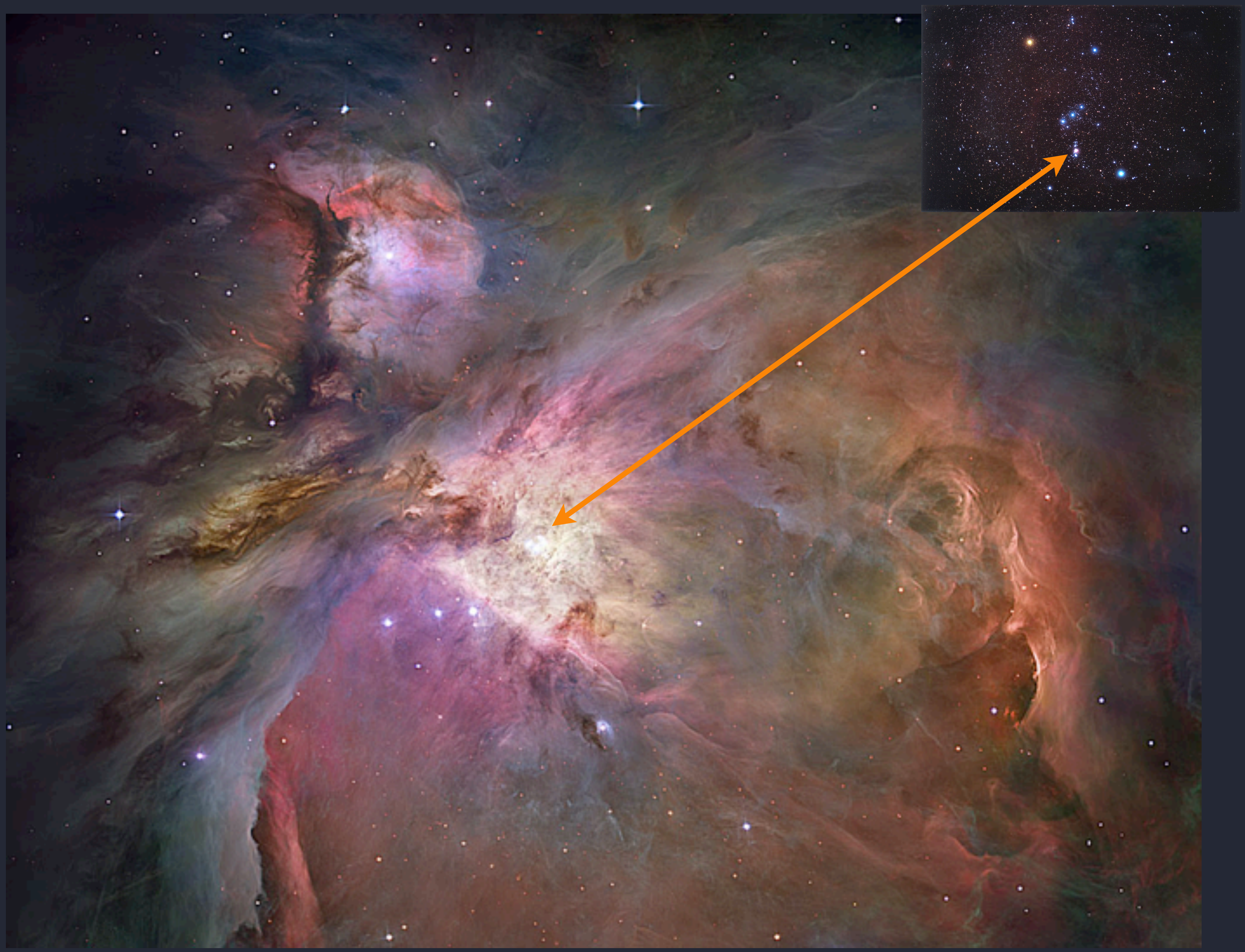
the mature scientist: ...now
we've measured it

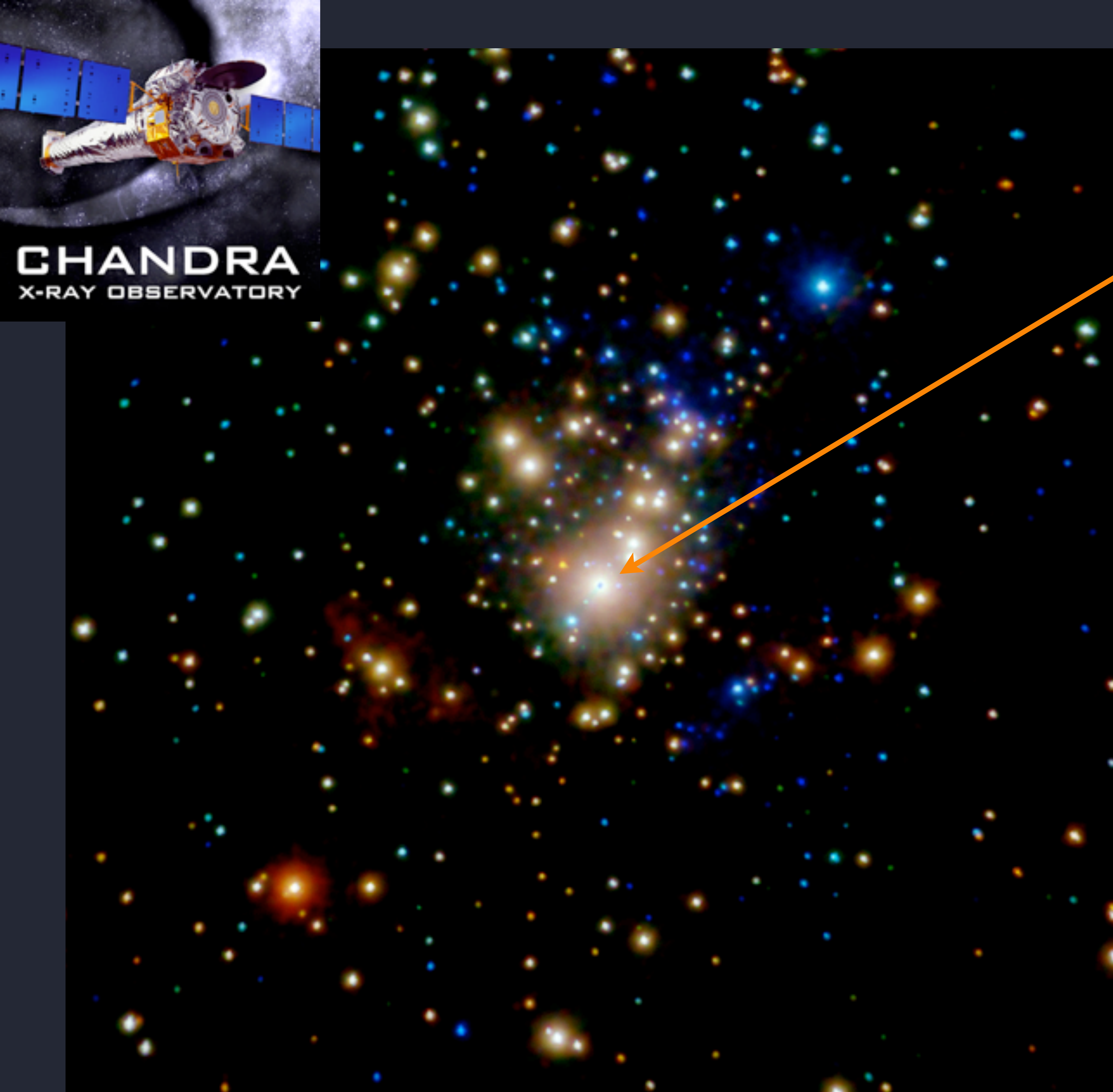


Outline/overview:

$L/L_{sun} = 10^{5.4}$
$\dot{M} \sim 5 \times 10^{-7}\ M_{sun}/yr$

θ^1 Ori C is a young (< 1 Myr) O7 star





θ^1 Ori C: the strongest X-ray source in the cluster

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

θ^1 Ori C is a magnetic O star prototype: tilted dipole, confined magnetosphere

$i \sim \beta \sim 45°$

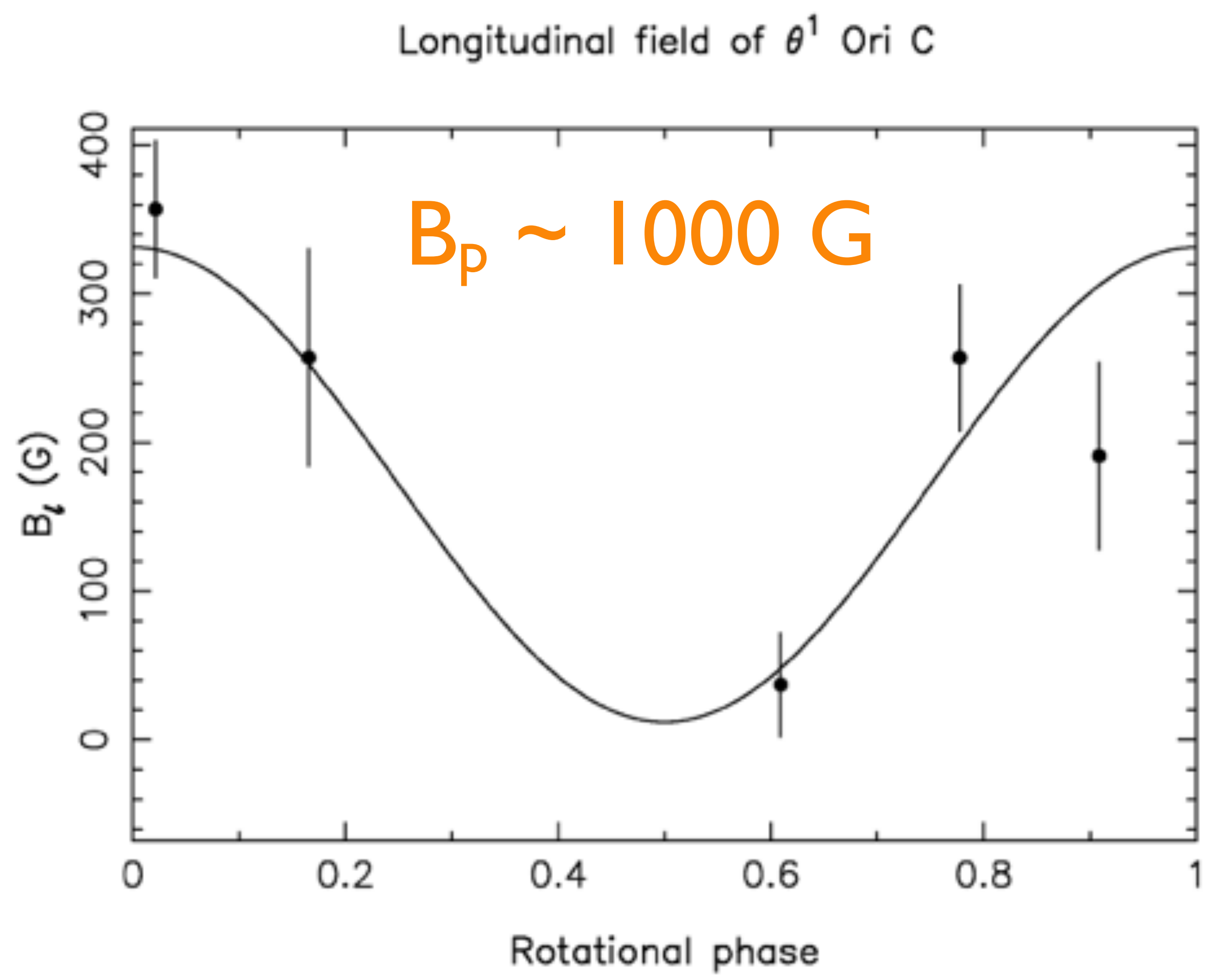
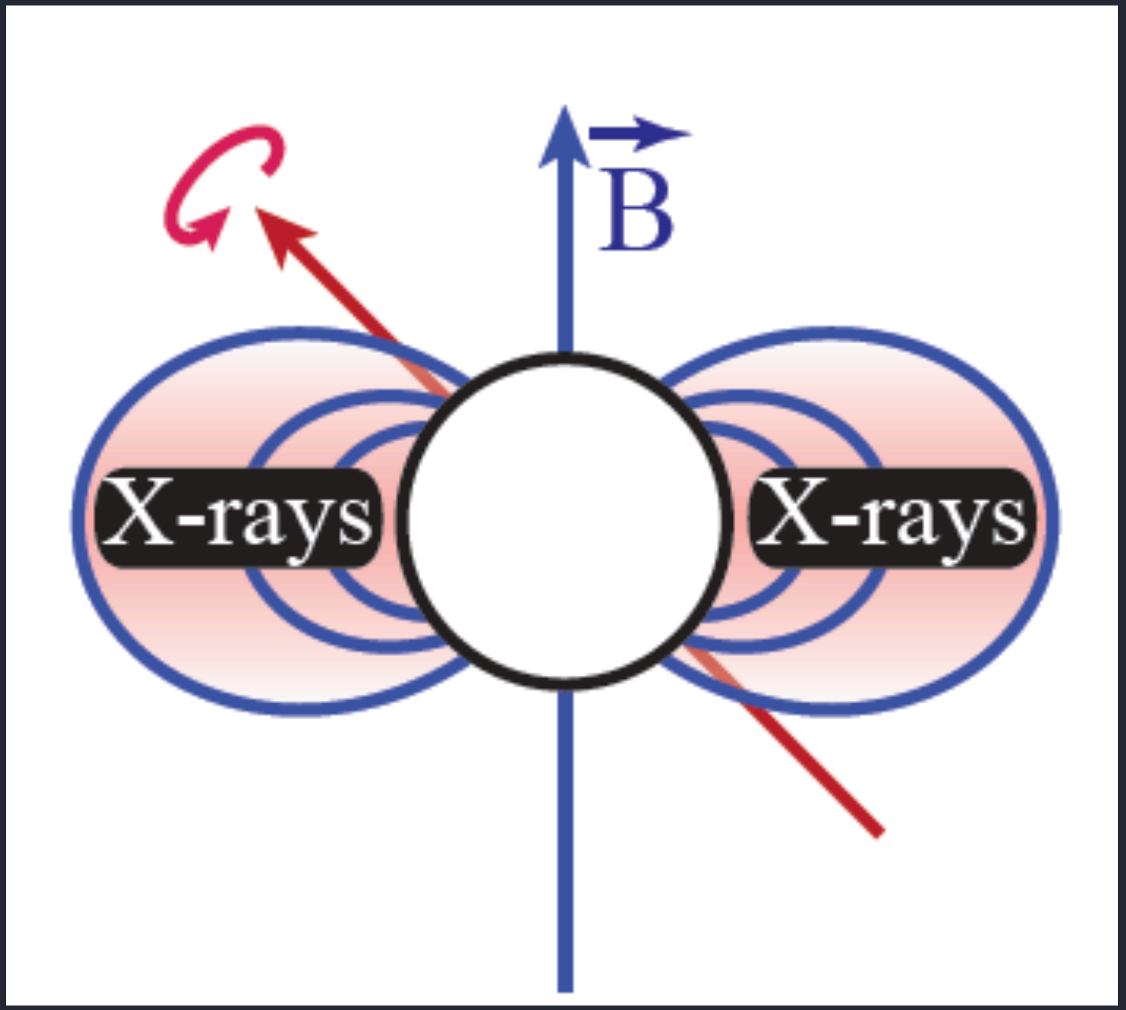


Figure 2. Longitudinal field estimates (filled circles) and error bars derived from our five mean LSD Stokes profiles, as a function of rotational phase (using the ephemeris of Stahl 1998). The full line depicts the least-squares cosine fit to the data.

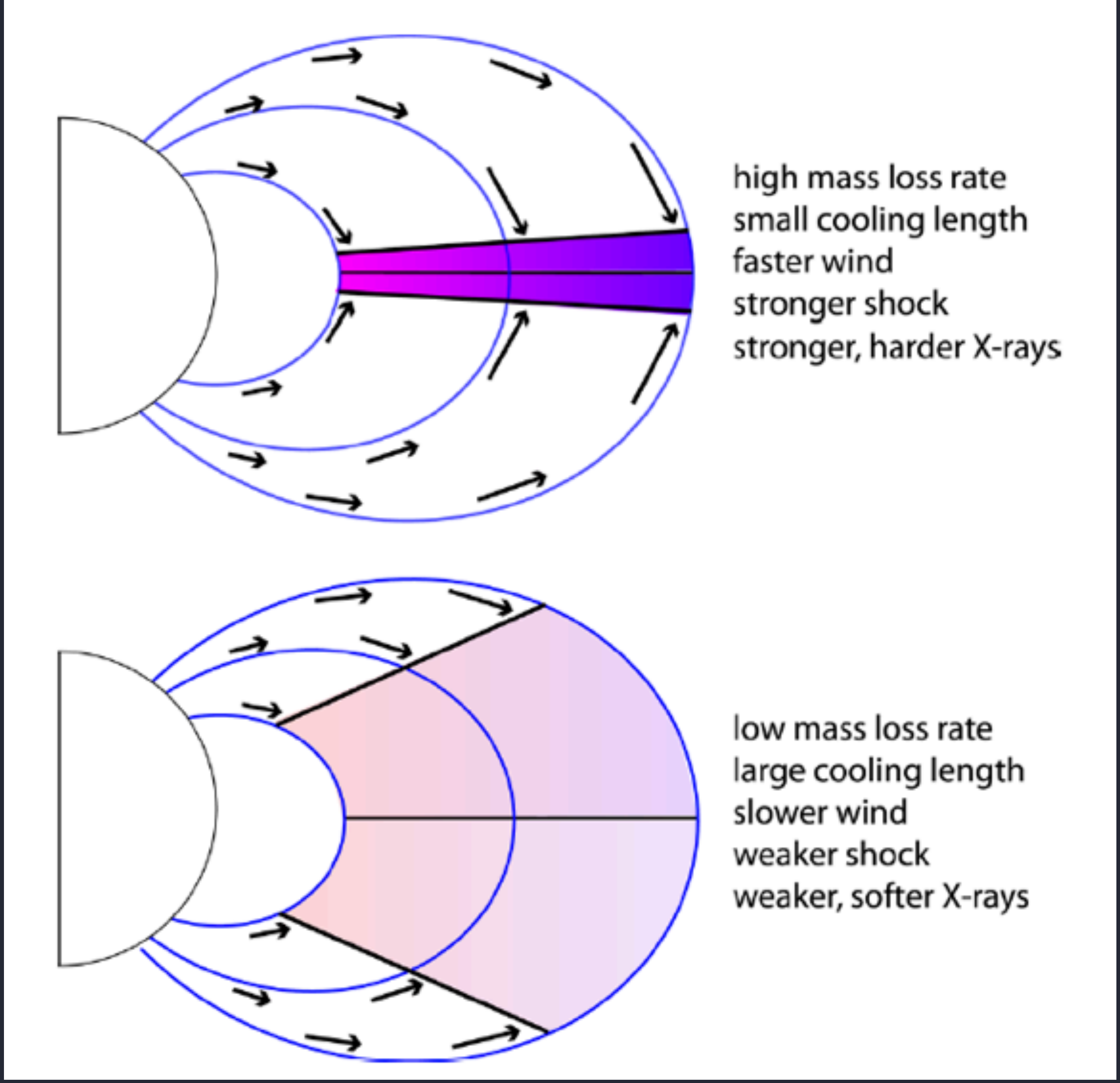
Donati et al. 2002



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

Plasma heating from hydrodynamic shocks

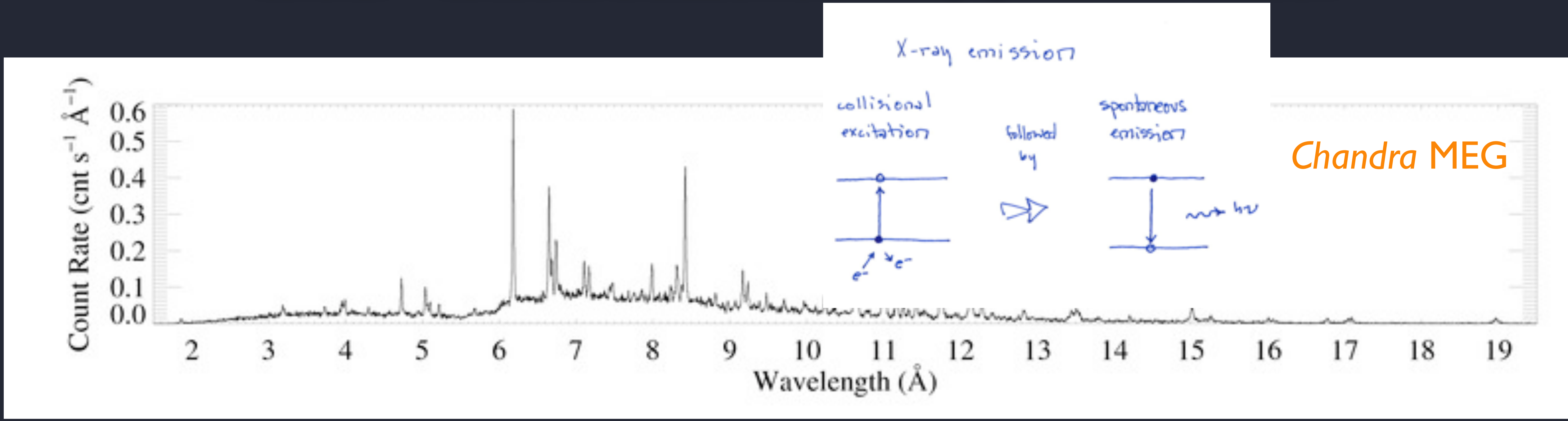
wind kinetic energy converted to heat: $T \sim 10^6 (v_{shock}/300\ \mathrm{km/s})^2$ K

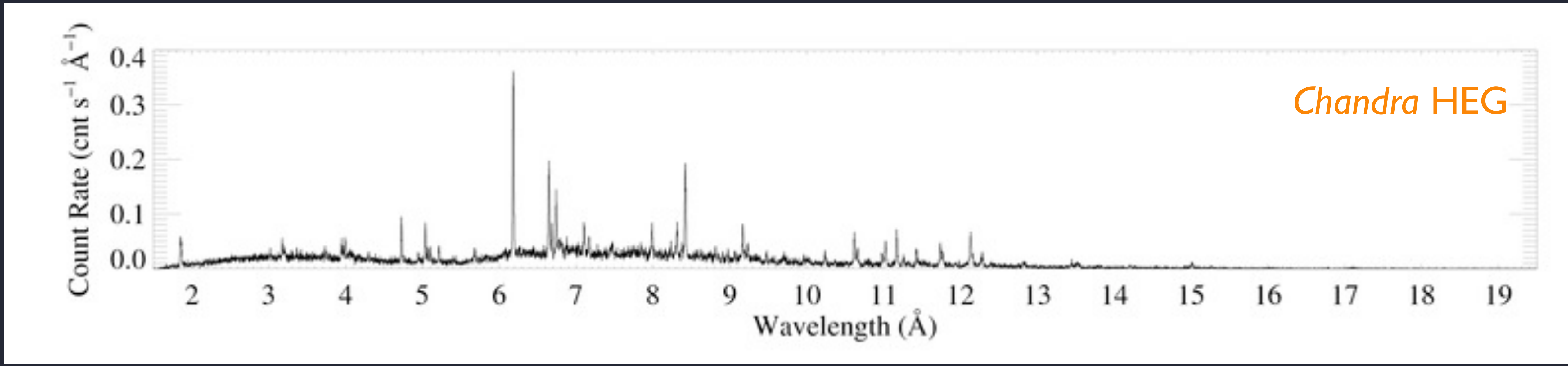


ud-Doula et al. 2014

X-rays are optically thin line emission

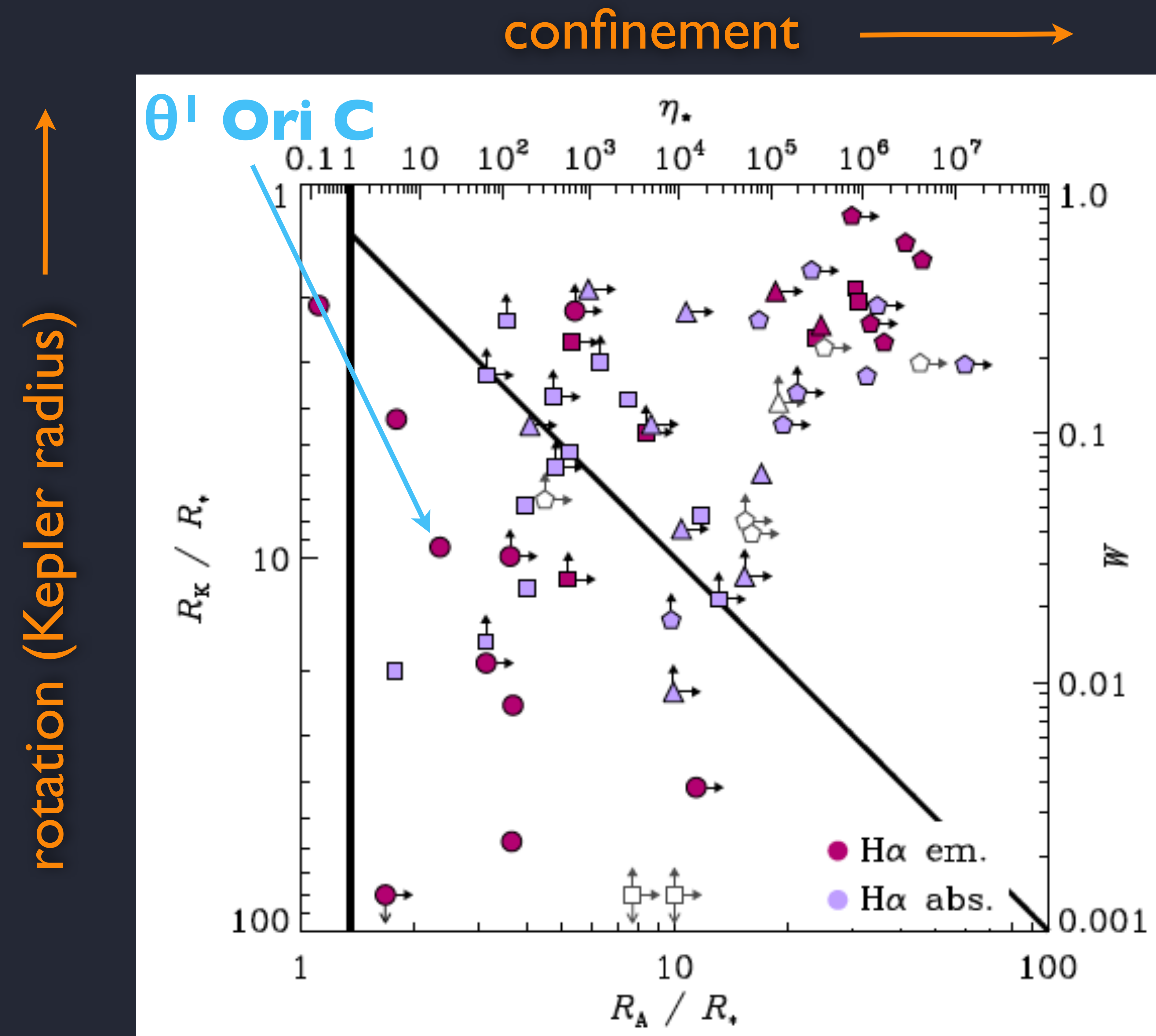
"coronal" = collisional excitation followed by spontaneous emission





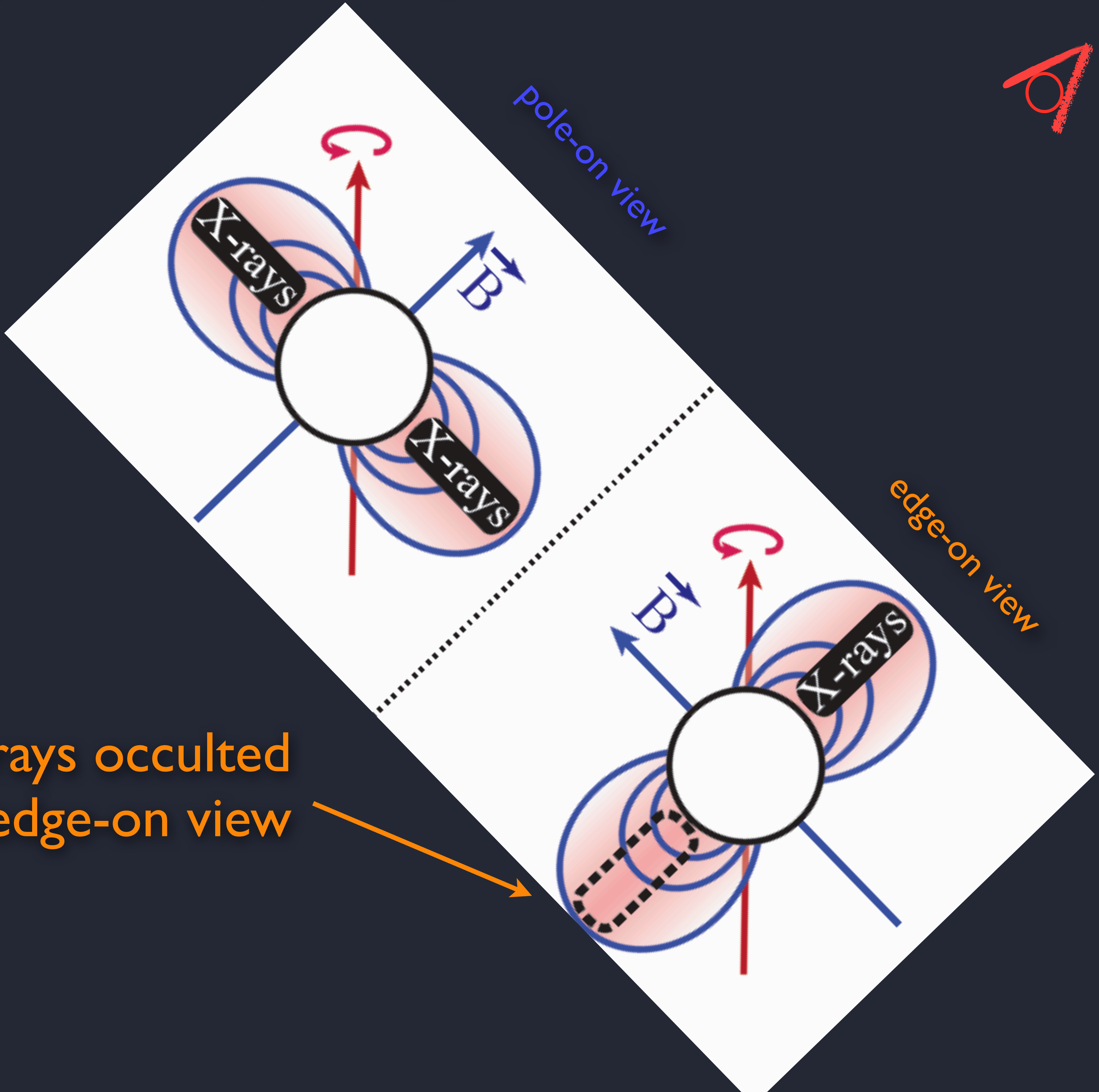
relative line strengths are dependent on **temperature** and **abundance**, primarily

θ^{I} Ori C is a slow rotator, moderate confinement ($\eta_* \sim 20$) = DM (dynamical magnetosphere); no centrifugal support



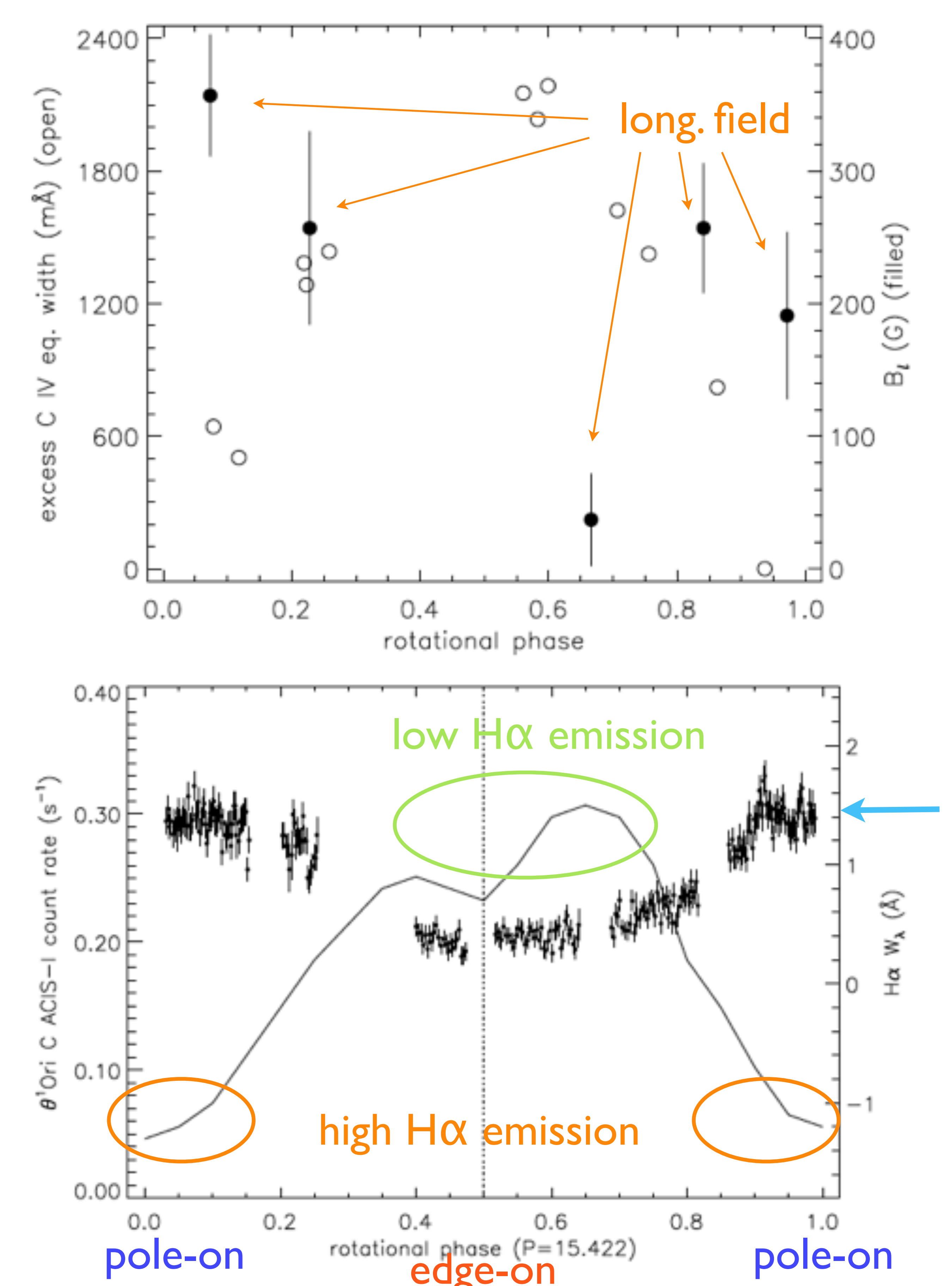
Petit et al. 2013

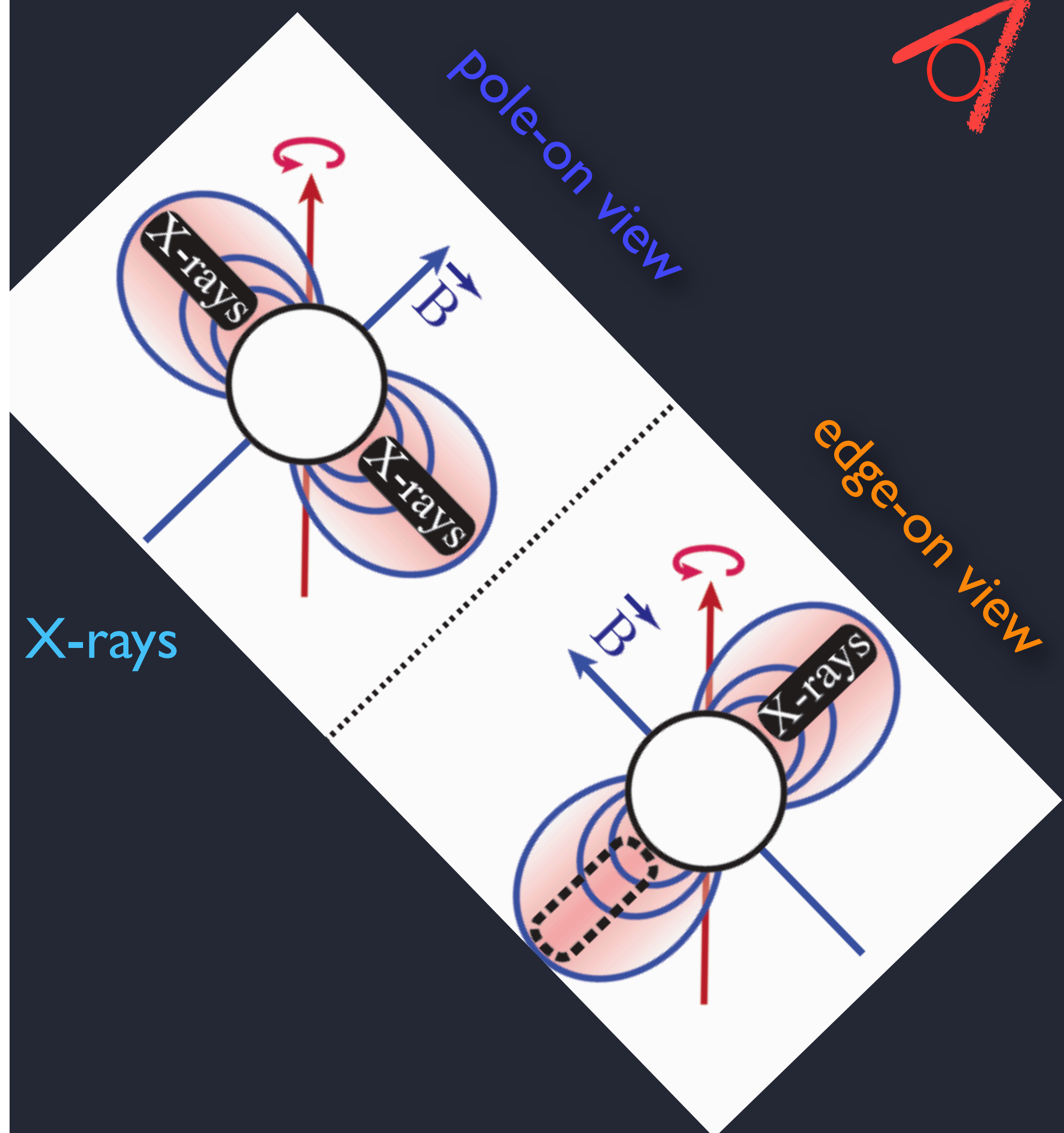
tilted dipole: oblique magnetic rotator



some X-rays occulted
in edge-on view

tilted dipole: oblique magnetic rotator





V. Petit

Gagne et al. 2005

Goals: use multiwavelength diagnostics and rotational modulation to probe the physical properties of the magnetosphere, the shock-physics, the wind mass-loss rate...and constrain numerical simulations

MHD simulations: 2-D, hemispherical slice

density temperature X-ray emission

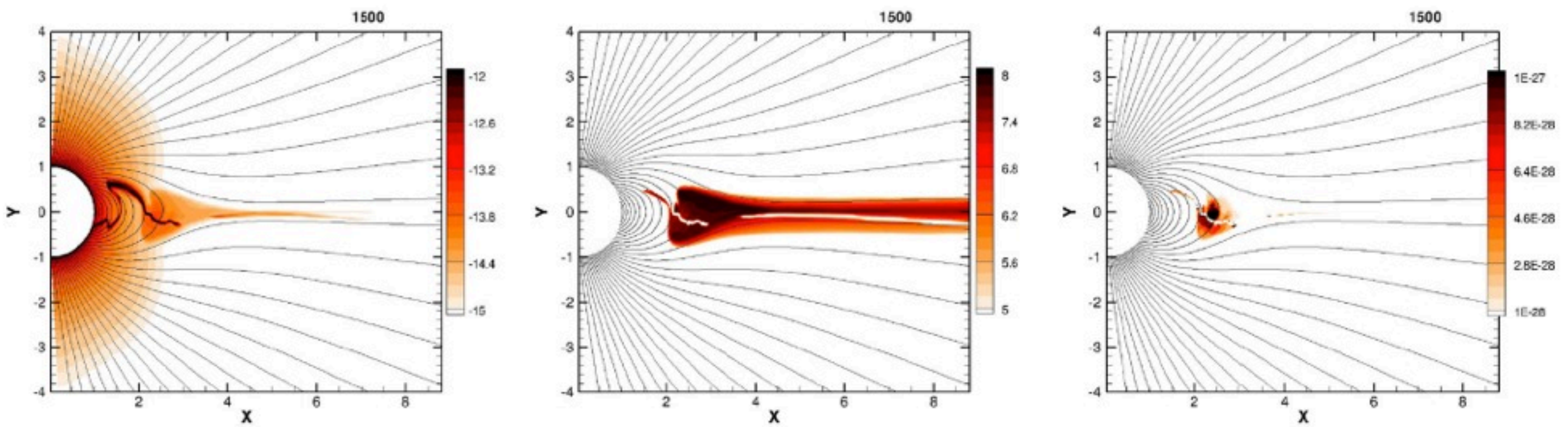
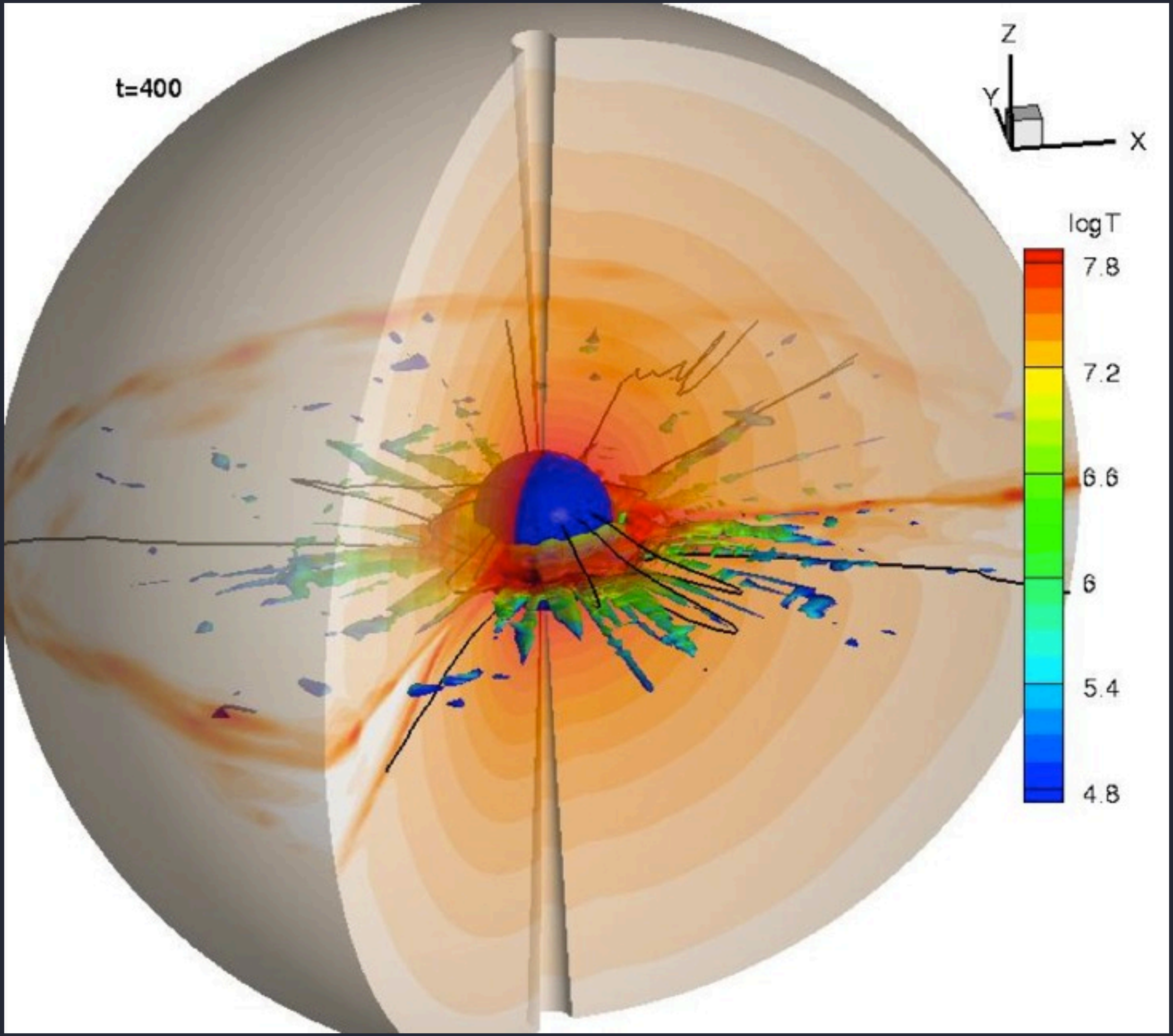


Figure 4. Colour plots of log density (left) and log temperature (middle) for arbitrary snapshot of structure in the standard model with $\eta_* = 100$ and no IC cooling. The right-hand panel plots the proxy X-ray emission XEM_{T_x} (weighted by the radius r) from (26), on a *linear* scale for a threshold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

ud-Doula et al. 2014

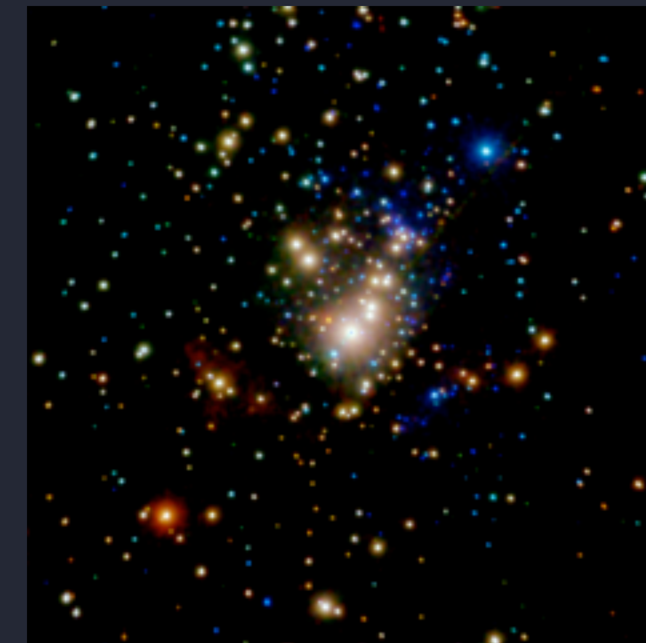
3-D MHD simulation: log Temperature



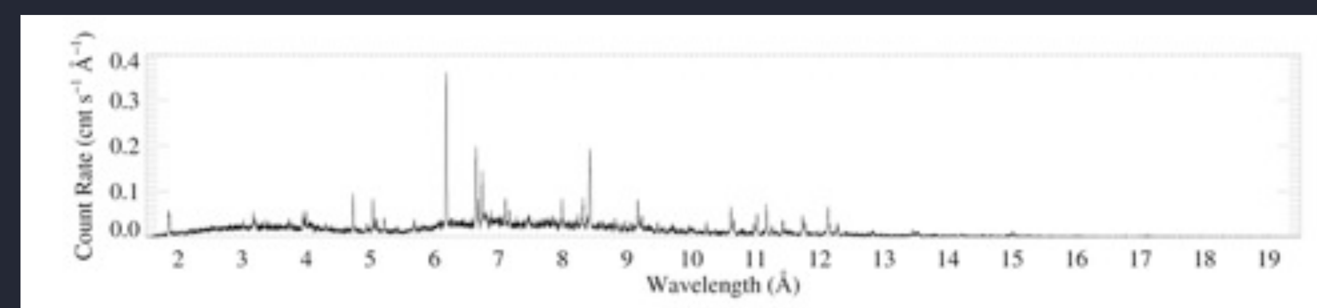
from A. ud-Doula

Chandra

Orion Nebula
Cluster - *Chandra*



Chandra grating spectroscopy



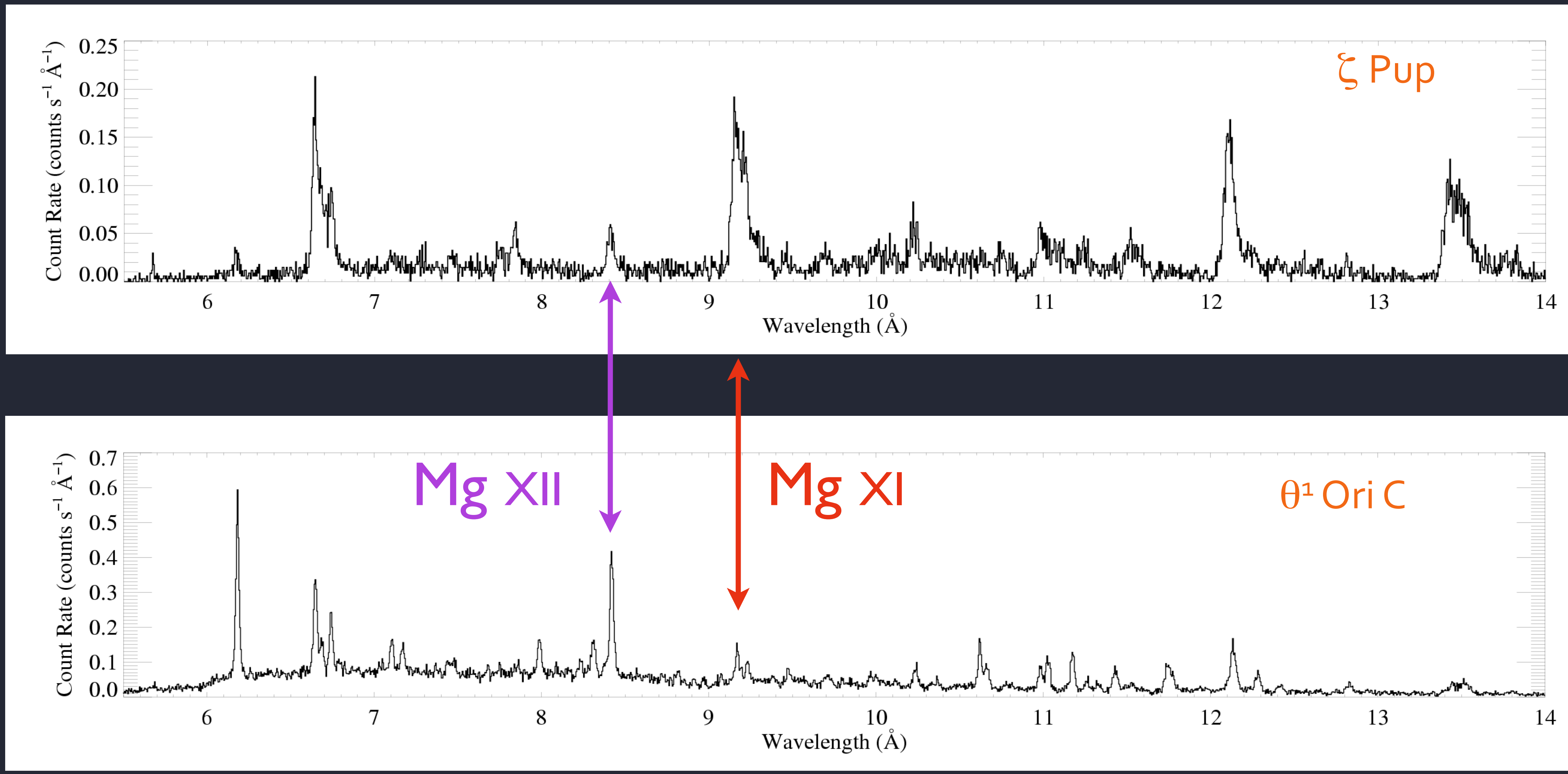
response to photons with hν ~ 0.5 keV up to a few keV
(corresp. ~5Å to 24Å)
spectroscopy (R < 1000 corresp. >300 km/s)

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

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

Line ratios as temperature indicators

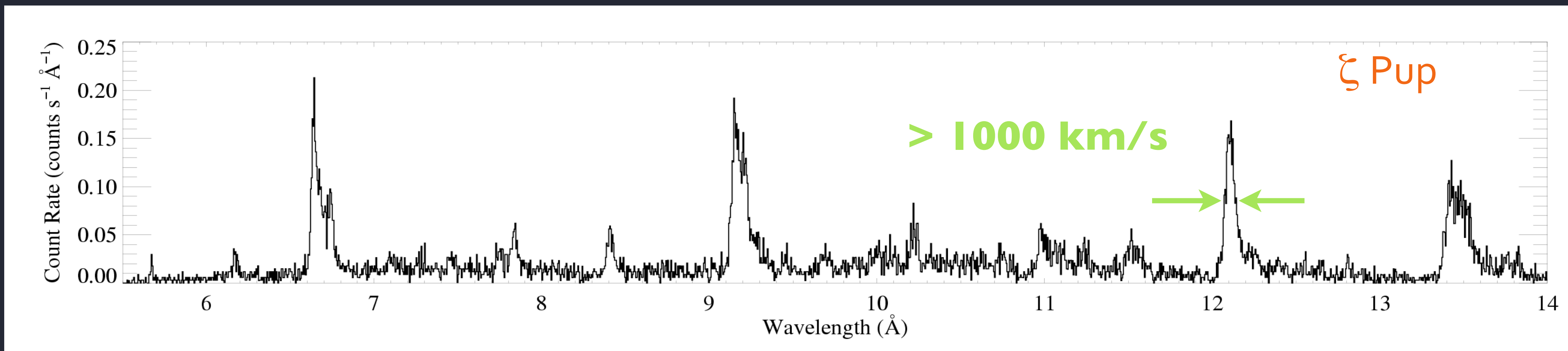
Mg XII / Mg XI is proportional to temperature

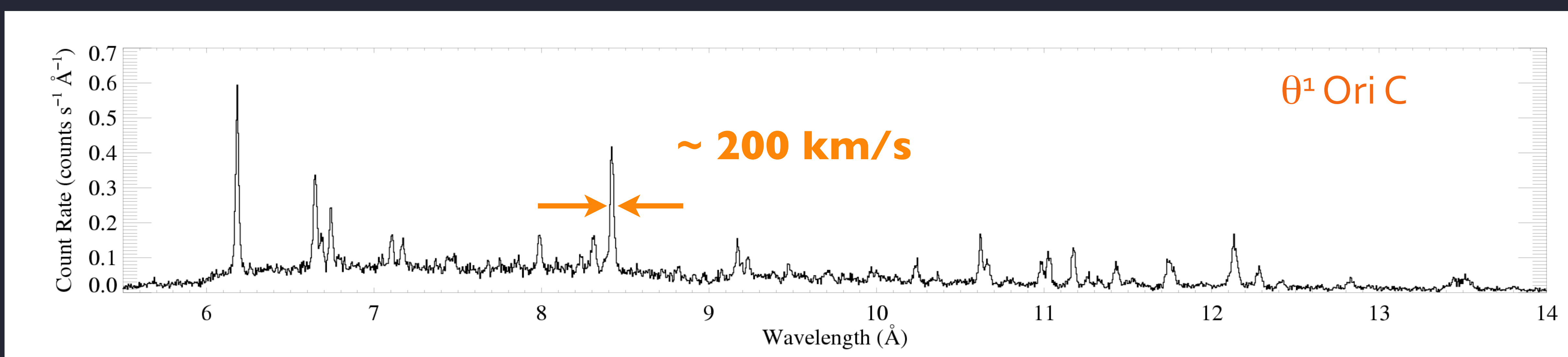


Chandra spectra of prototype non-magnetic (zeta Pup, top) and magnetic (θ[1] Ori C, bottom) stars

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 (θ^1 Ori C, bottom) stars

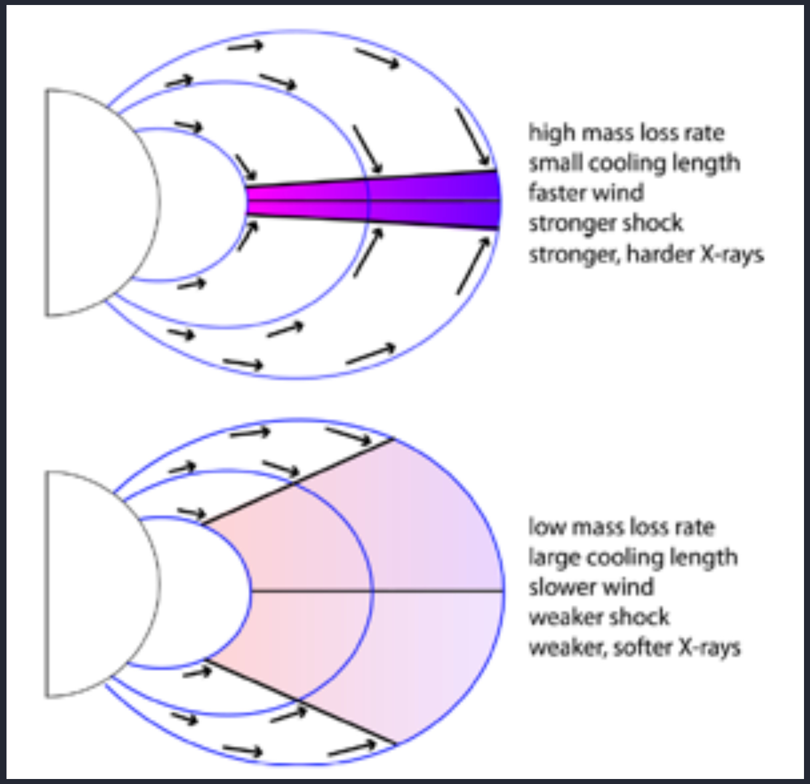
Overall level and hardness of X-ray emission

affected by:

amount of wind material fed into the magnetosphere

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

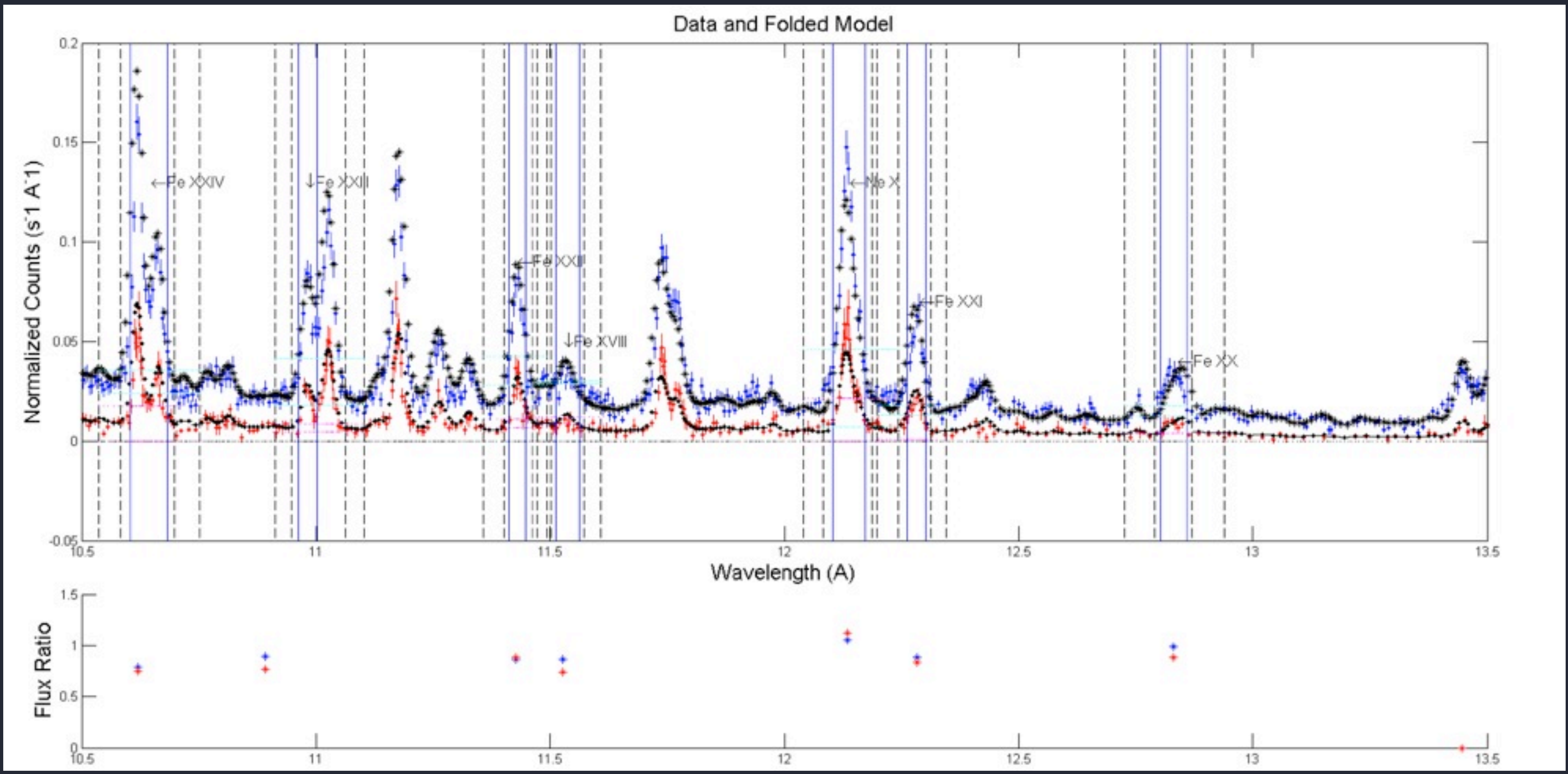
specific kinetic energy: shock velocity (pre-shock wind velocity)



from ud-Doula et al. 2014

traditional approach: spectral modeling

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



fit to *Chandra* spectrum

emission measure: traditional normalization of X-ray emission spectra

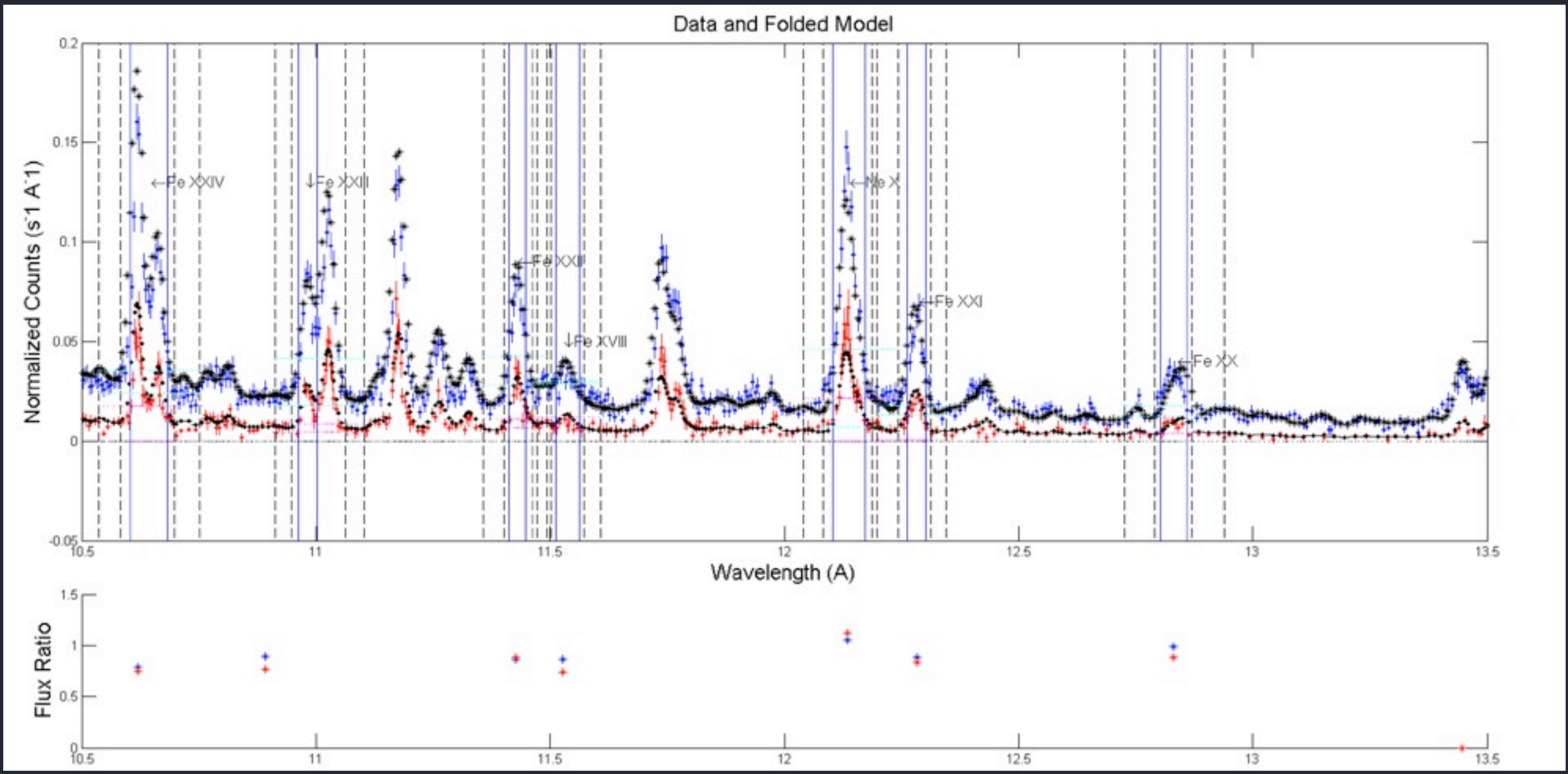
$$\mathcal{E}M \equiv \int n_{\mathrm{e}} n_{\mathrm{H}} \, \mathrm{d}V$$

a DEM, $\phi(\hat{T})$, where

$$\phi(\hat{T}) = n_e n_H \frac{dV}{dT}$$

traditional approach: 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

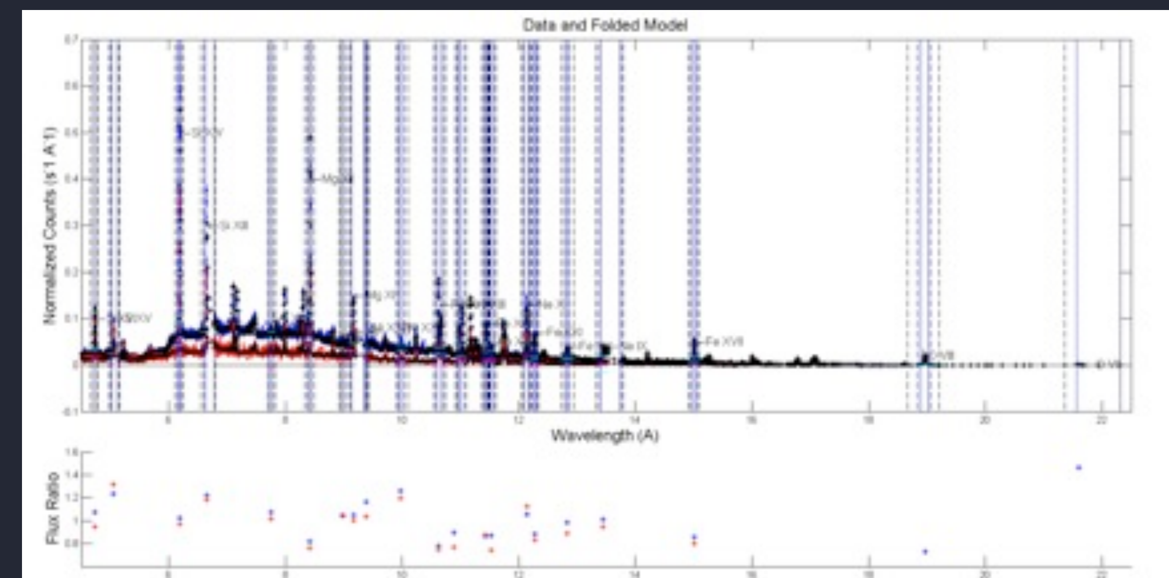
best-fit model parameters: temperature distribution in the plasma, line widths, absorption

```
========================================================================
Model (bapec<1> + bapec<2> + bapec<3> + bapec<4> + bapec<5> + bapec<6>)TBabs<7>
Source No.: 1   Active/On
Model Model Component  Parameter  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
```



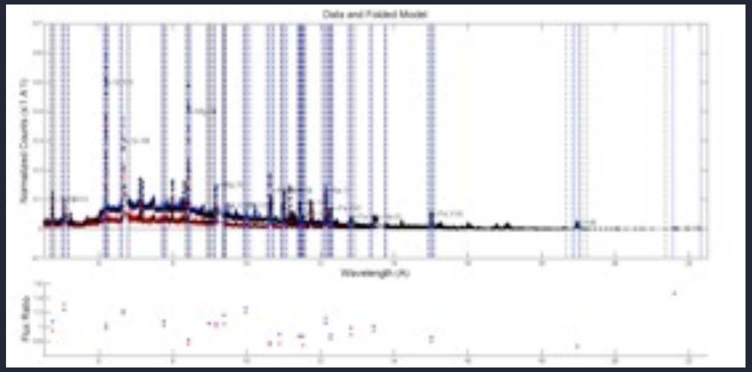
fit to *Chandra* spectrum

line widths ~ 300 km/s

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

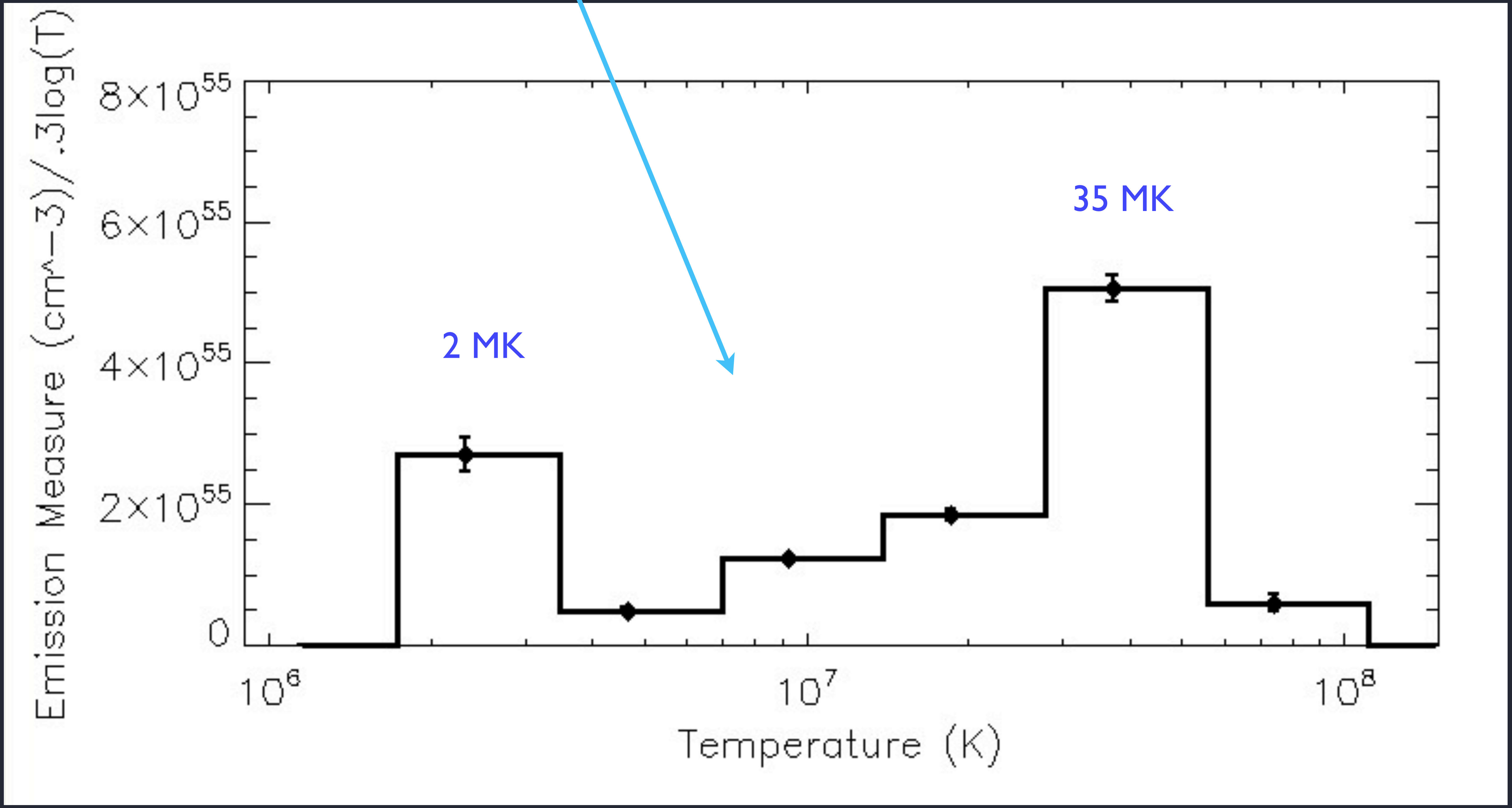
Spectral modeling

temperature distribution



fit to *Chandra* spectrum

from the APEC spectral fit



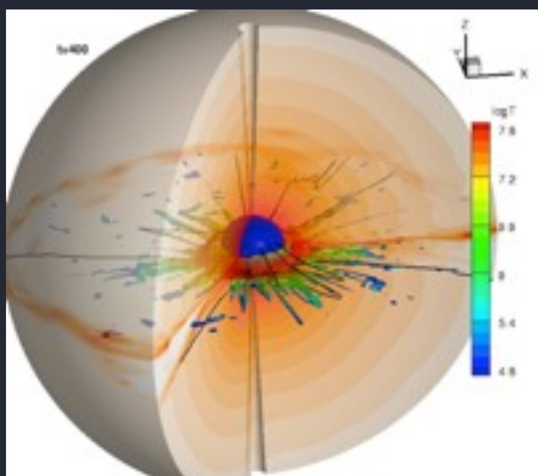
Spectral modeling

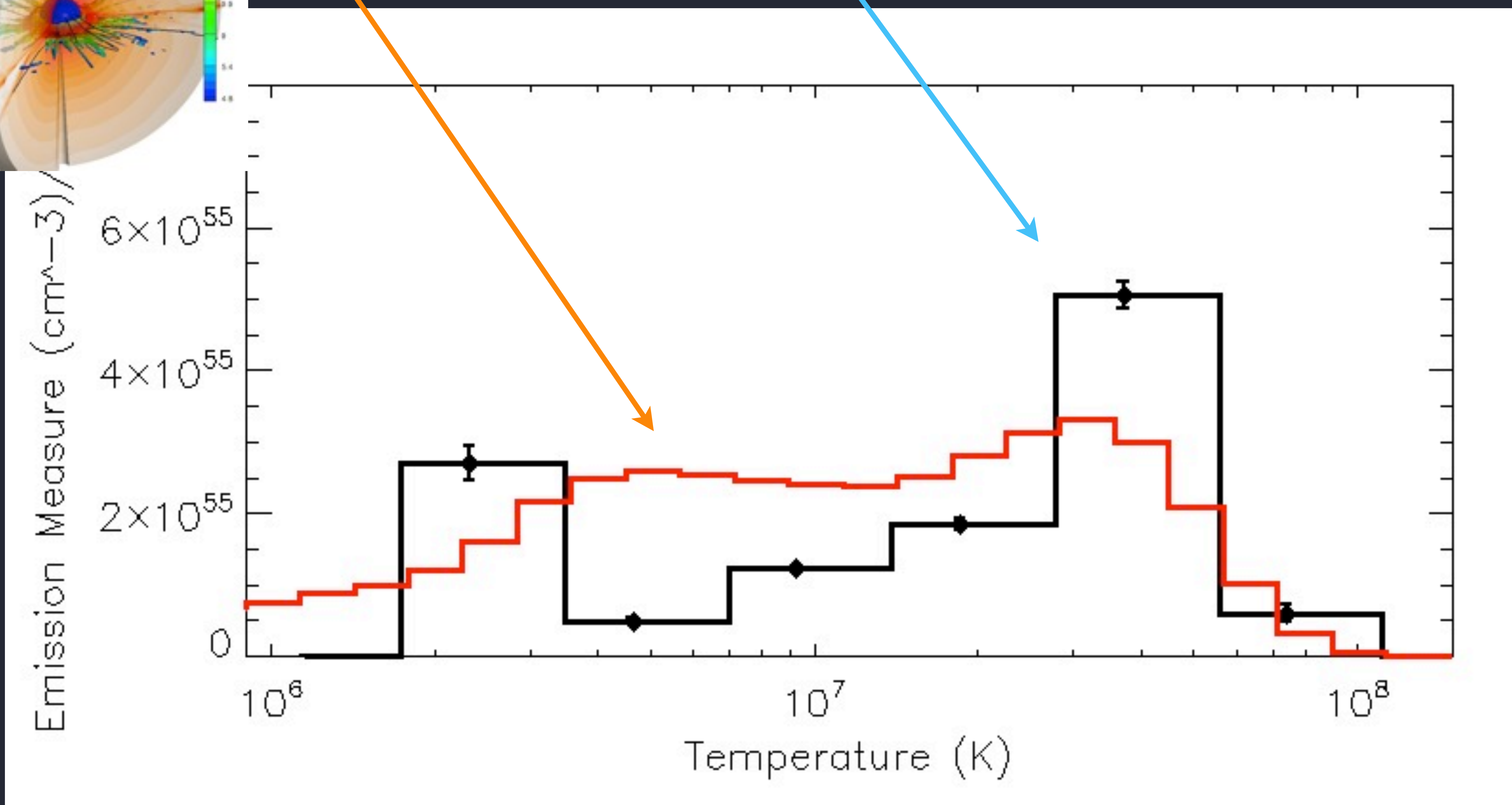
The overall amount of hot plasma produced in the MHD simulations is in good agreement with the data (but a **factor of 3 too high**); the temperature distribution is in good agreement, too.

Emission Measure (EM) distribution

APEC spectral fit

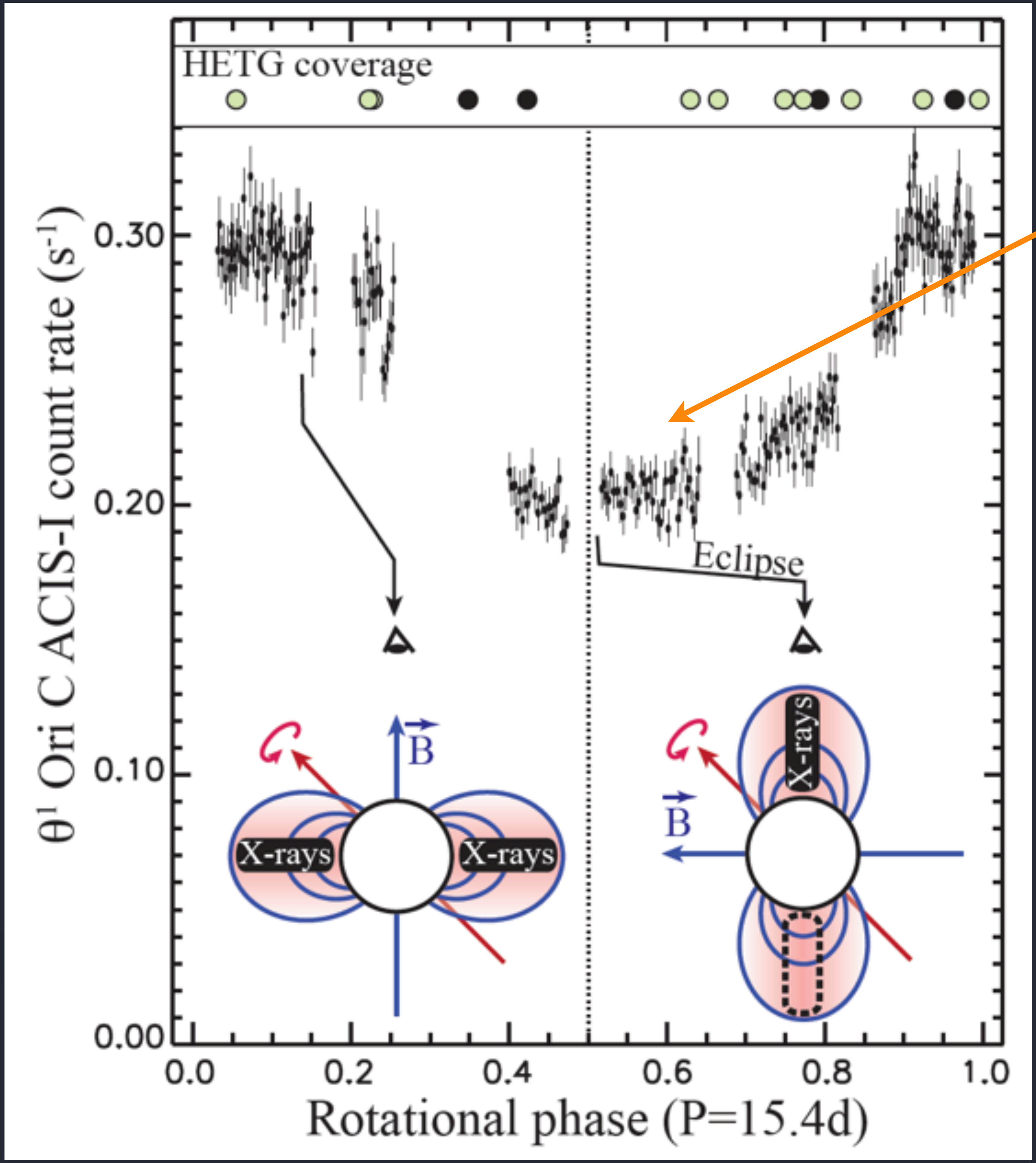
from 3-D MHD simulation





rotationally modulated X-ray variability

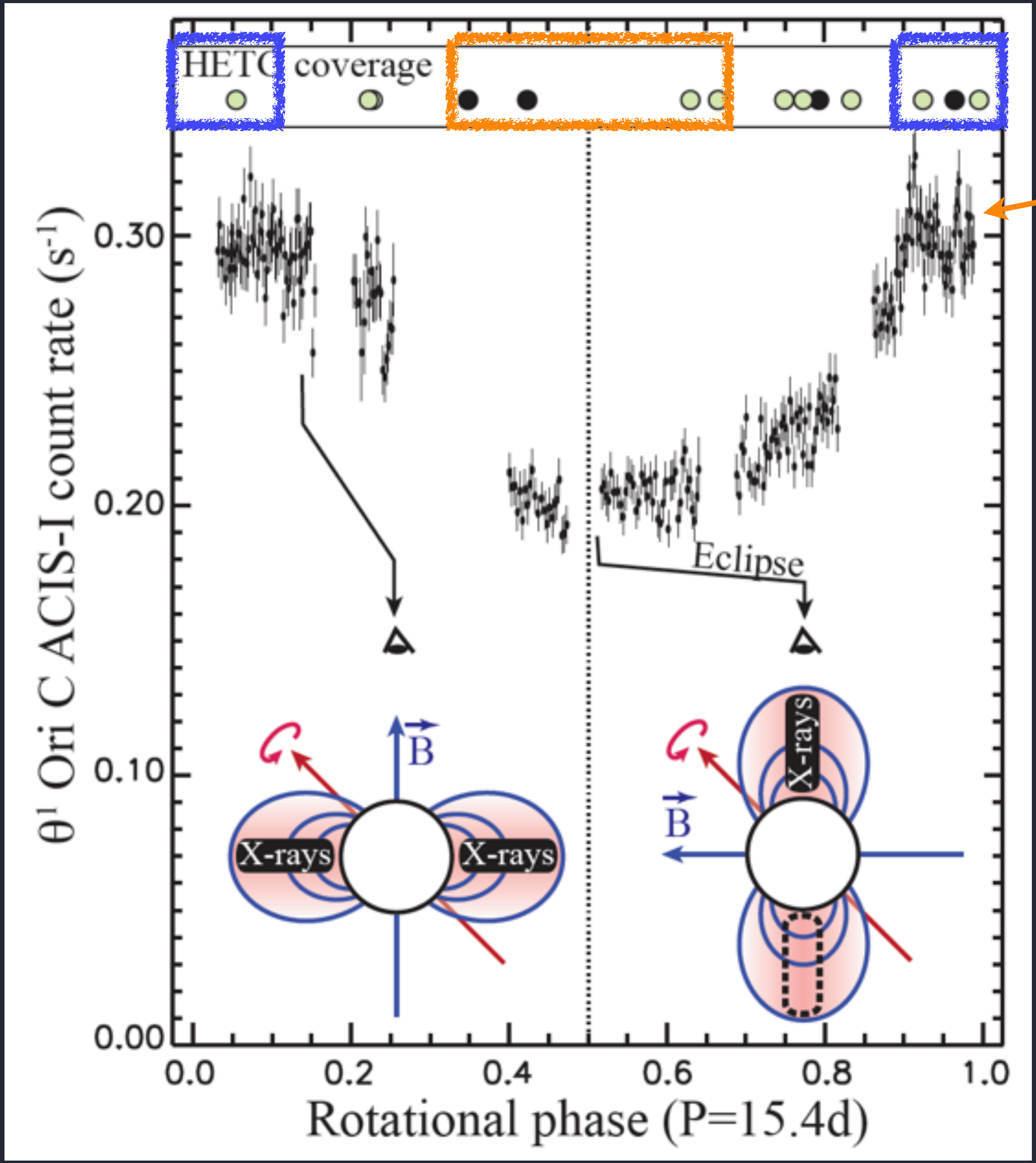
X-ray light curve: phase coverage: new data (11 new pointings (N. Schulz, PI) to supplement 4 in Gagne et al. 2005)



X-rays: occultation causes the magneto-spheric eclipse

work presented here is preliminary

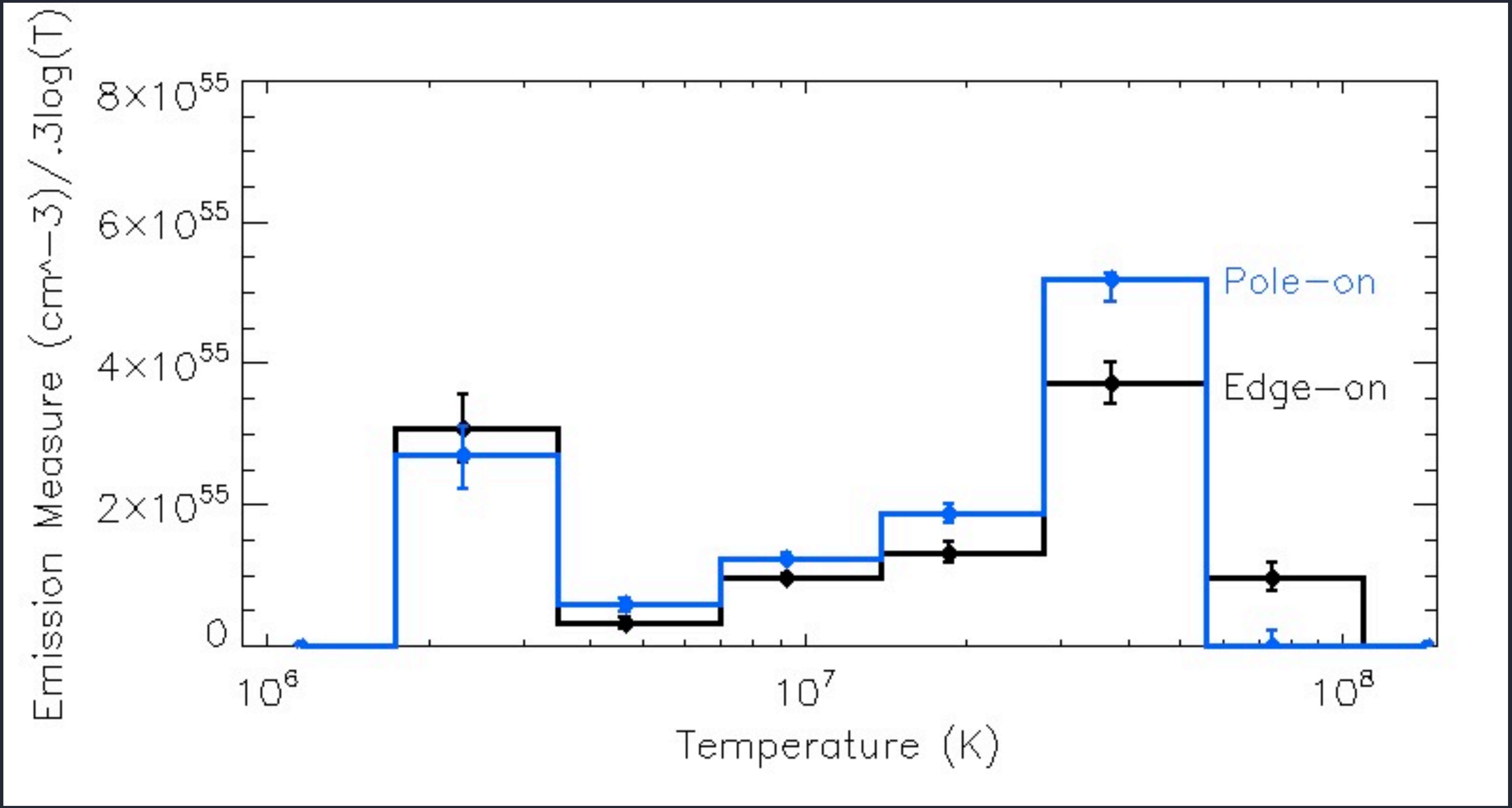
Look at the most pole-on and most edge-on observations



X-rays: occultation causes the magneto-spheric eclipse

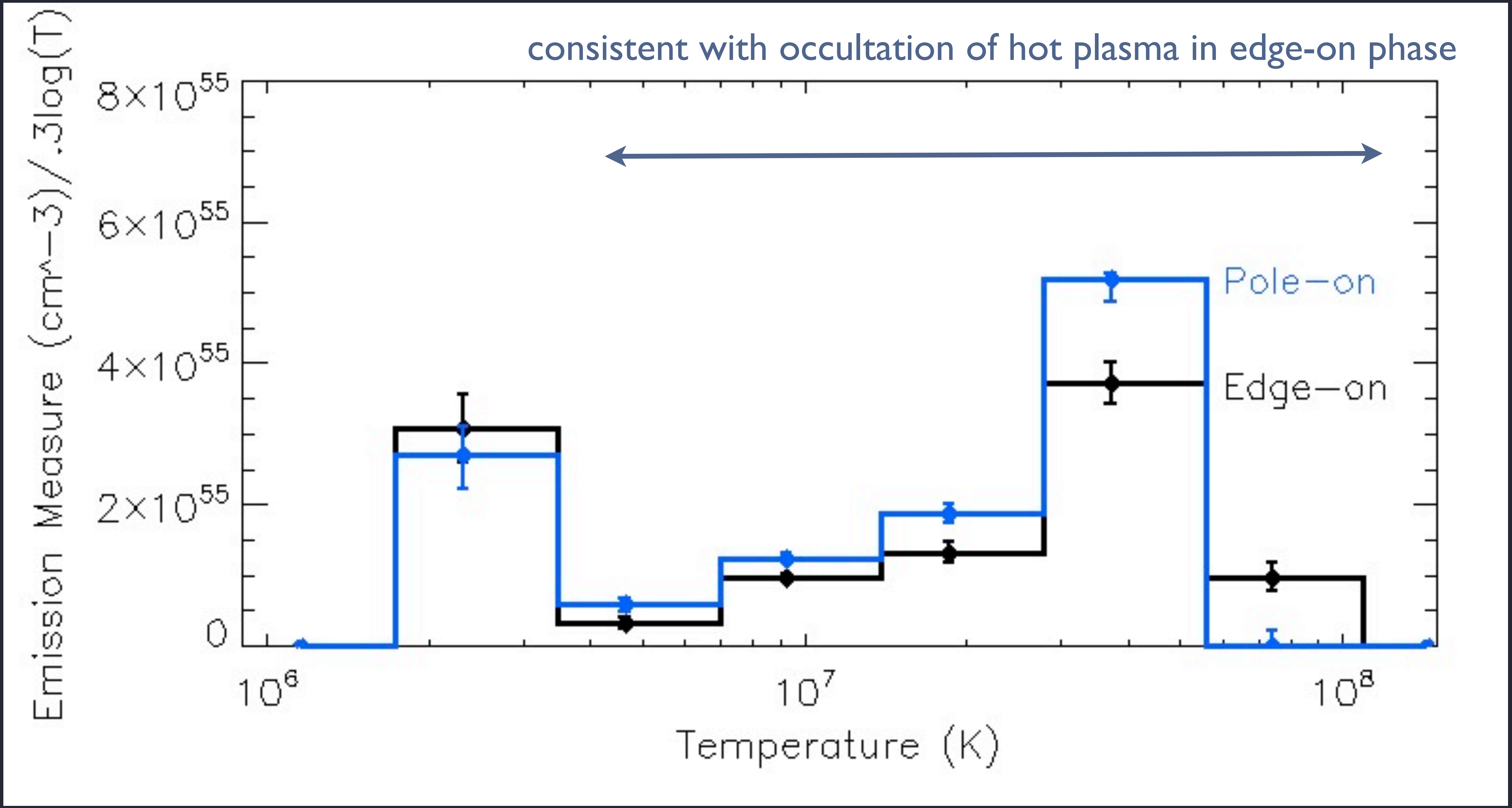
Spectral modeling: coadded 4 observations ea. pole-on and edge-on

emission measure distributions



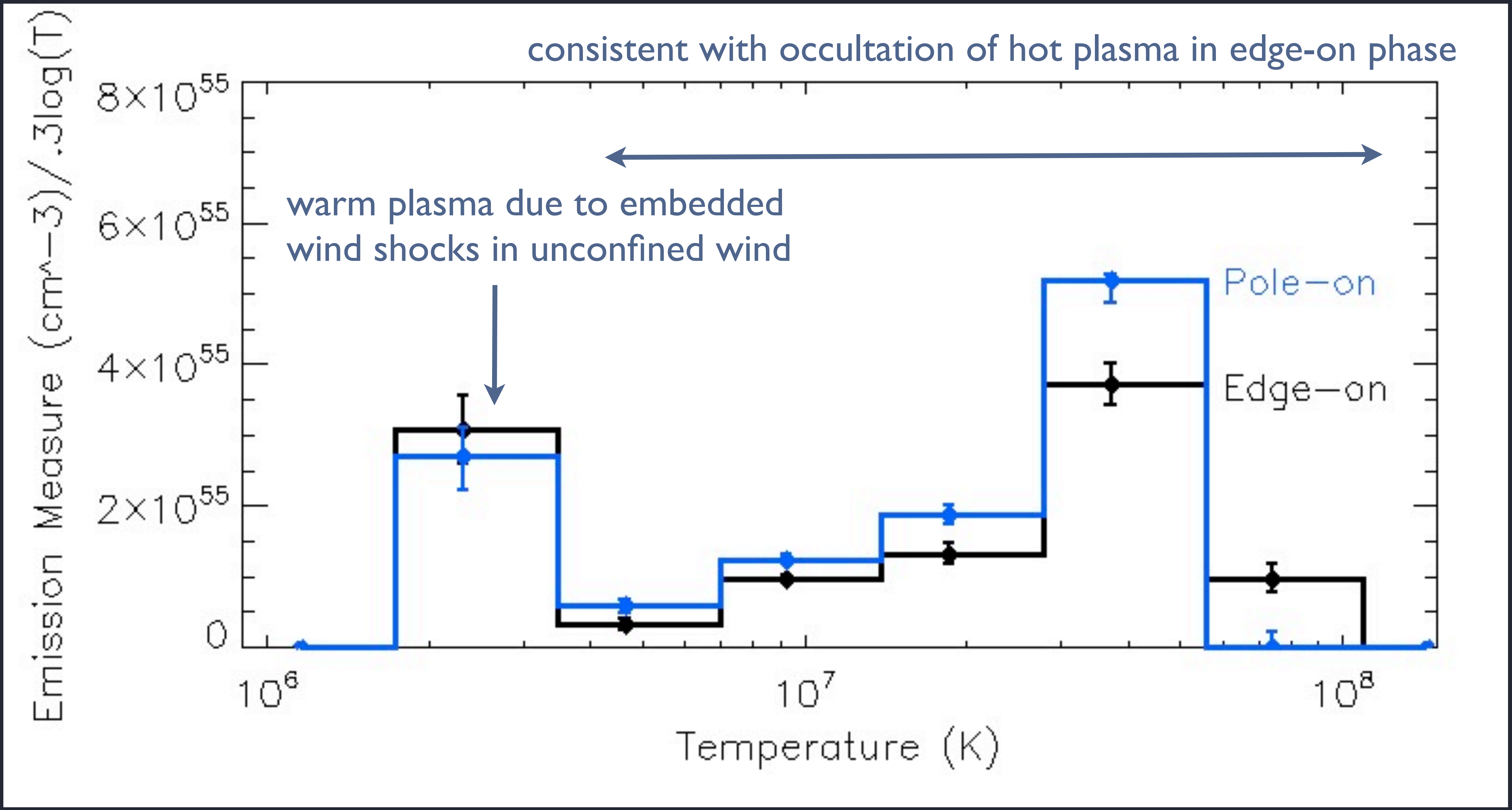
Spectral modeling: coadded 4 observations ea. pole-on and edge-on

emission measure distributions



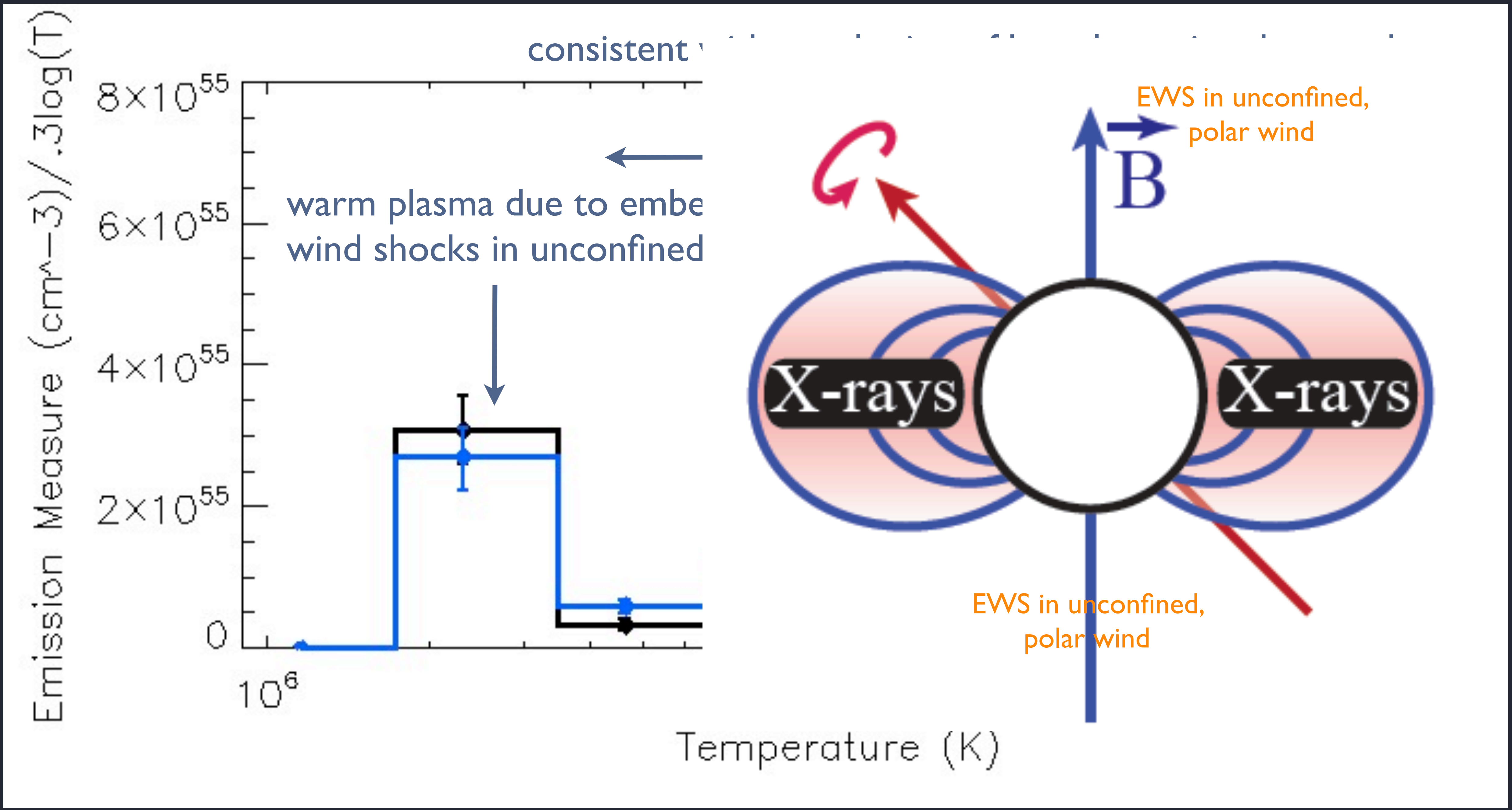
Spectral modeling: coadded 4 observations ea. pole-on and edge-on

emission measure distributions



Spectral modeling: coadded 4 observations ea. pole-on and edge-on

emission measure distributions



A different way to extract information from the X-ray spectrum

DEM (temperature distribution) tells us about the heating and cooling's combined effects

MCWS X-ray production physics and models are fundamentally about the heating

Because the cooling is primarily radiative, we can in some sense correct for it

THE ASTROPHYSICAL JOURNAL, 788:90 (21pp), 2014 June 10 doi:10.1088/0004-637X/788/1/90

THERMAL X-RAY SPECTRAL TOOLS. I. PARAMETERIZING IMPULSIVE X-RAY HEATING WITH A CUMULATIVE INITIAL TEMPERATURE (CIT) DISTRIBUTION

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ABSTRACT

In collisional ionization equilibrium, the X-ray spectrum from a plasma depends on the differential emission measure (DEM), distributed over temperature. Due to the well-known ill conditioning problem, no precisely resolved DEM can be inverted directly from the spectrum, so often only a gross parameterization of the DEM is used to approximate the data, in hopes that the parameterization can provide useful model-independent constraints on the heating process. However, ill conditioning also introduces ambiguity into the various different parameterizations that could approximate the data, which may spoil the perceived advantages of model independence. Thus, this paper instead suggests a single parameterization for both the heating mechanism and the X-ray sources, based on a model of impulsive heating followed by radiative cooling. This approach is similar to a "cooling flow" approach but allows injection at multiple initial temperatures and applies even when the steady state is a distribution of different shock strengths, as for a standing shock with a range of obliquities, or for embedded stochastic shocks that are only steady in a statistical sense. This produces an alternative parameterization for X-ray spectra that is especially streamlined for higher density plasmas with efficient radiative cooling and minimal thermal conduction and mixing. The method also provides some internal consistency checks on the validity of its assumptions. A heuristic general version is then applied over a wide range of astrophysical applications to schematically explore potential alternative models for these phenomena.

Key words: line: formation – methods: analytical – radiation mechanisms: thermal – techniques: spectroscopic – X-rays: general

new paper: Gayley 2014

Measuring the shock-heating rate in the winds of O stars using X-ray line spectra

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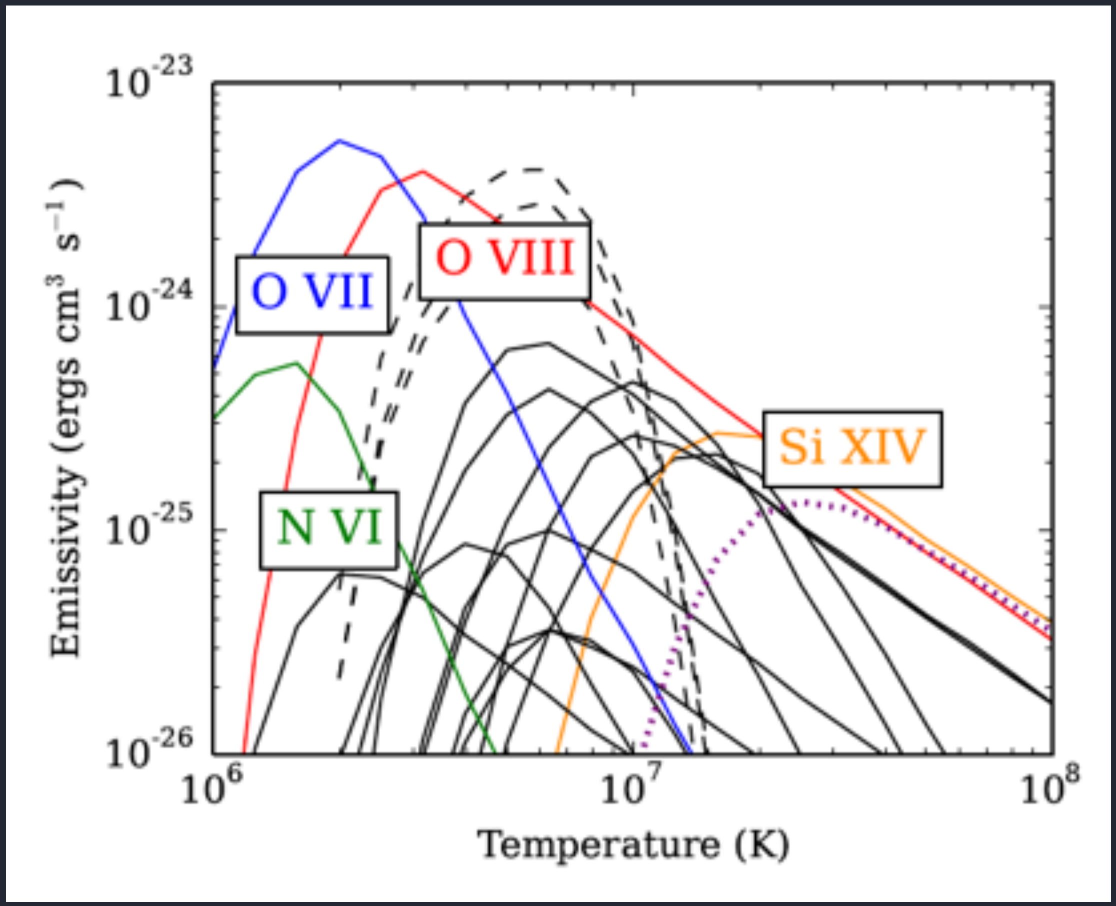
new paper applying the Gayley method to non-magnetic O stars with embedded wind shocks: see today's Massive Star News!



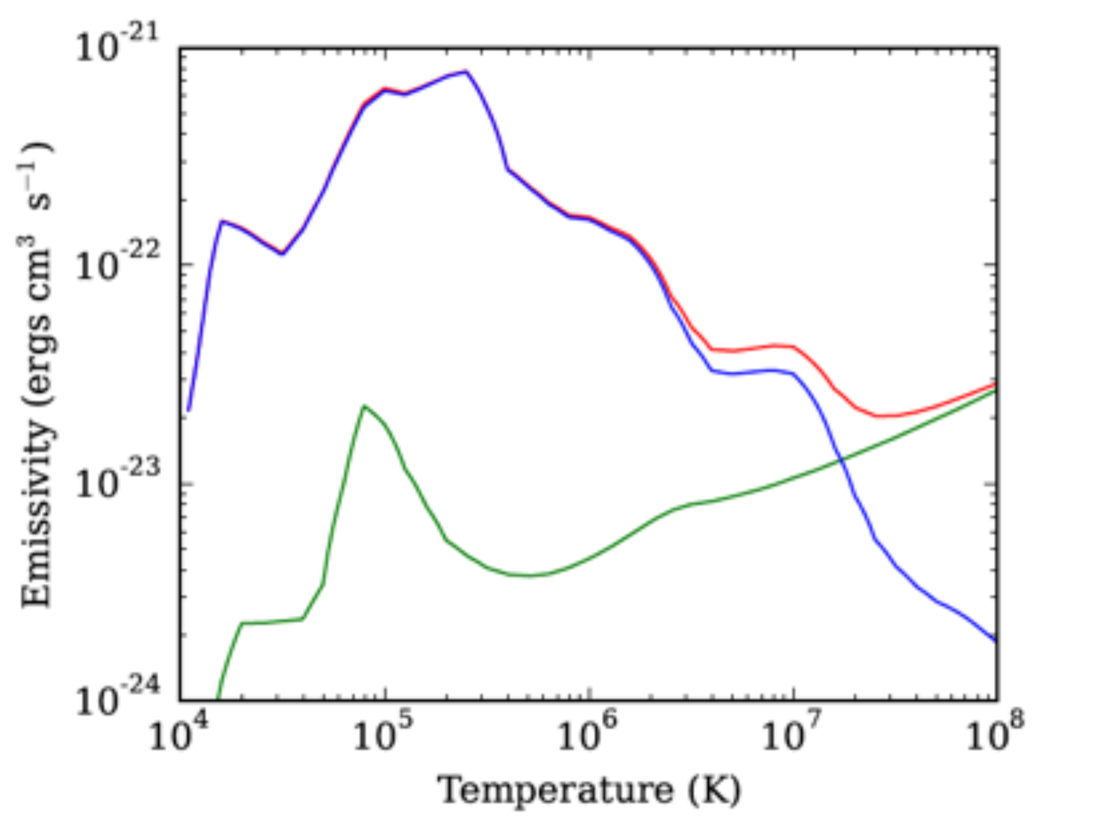


Figure 2. The contribution of all emission lines (blue) to the total radiated power (red), along with the contribution of continuum processes (green).

ratio of line emissivity to total emissivity: line luminosity "branching ratio"

$$f_\ell(T_s) = \int_0^{T_s} \frac{\Lambda_\ell(T)}{\Lambda(T)} \frac{dT}{T_s}$$

$$\Delta T_\ell \equiv \int_0^{\infty} \frac{\Lambda_\ell(T)}{\Lambda(T)} dT$$

line luminosity

shock heating probability

$$L_\ell = \dot{M} \frac{5k\Delta T_\ell}{2\mu m_p} \bar{N} p(T_\ell)$$

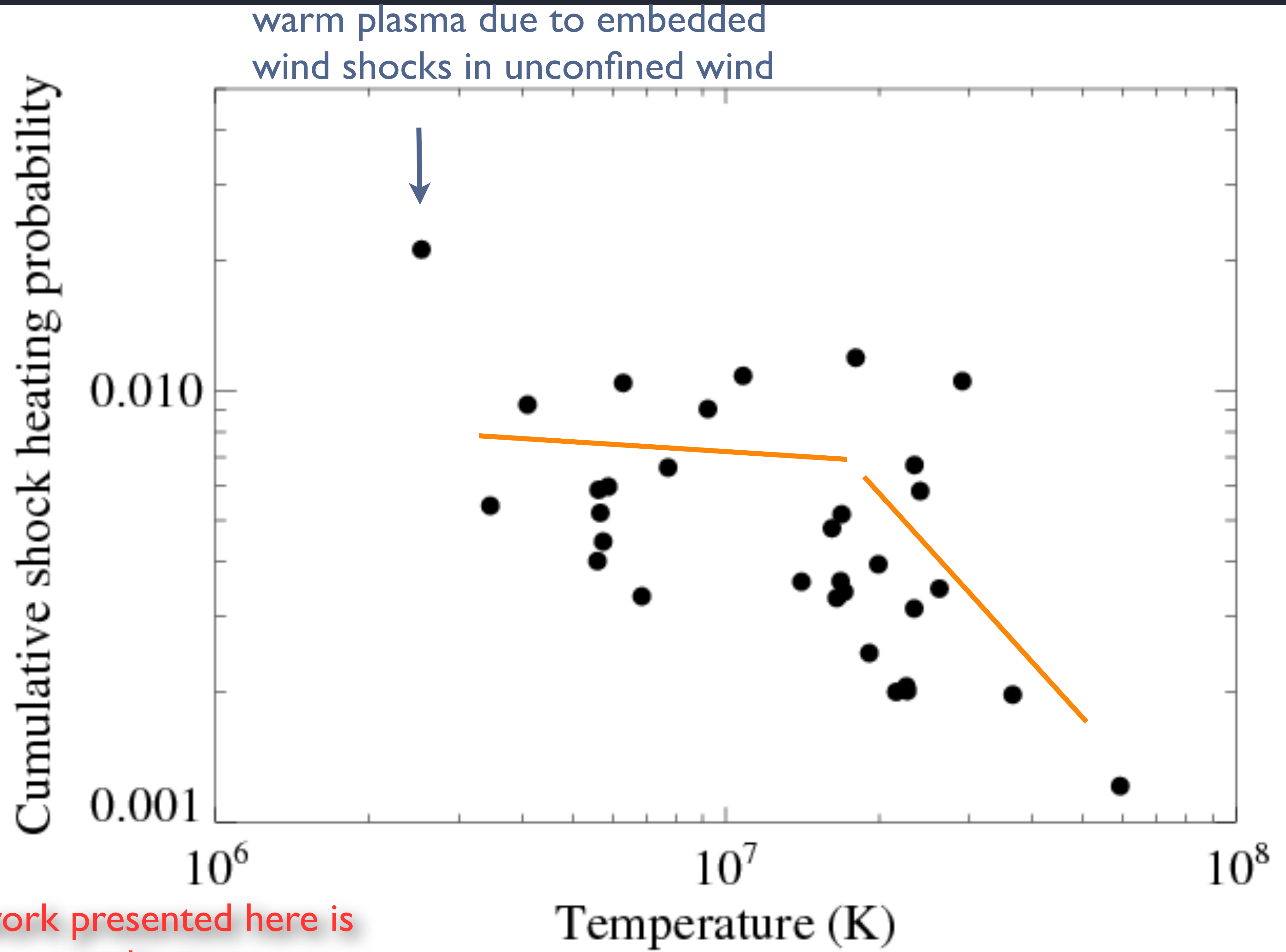
A different way to extract information from the X-ray spectrum

Impulsively heated plasma in the magnetosphere cools radiatively, emitting photons in all lines with characteristic temperatures equal to or less than the shock temperature

The spectral line luminosities naturally provide a **cumulative distribution of shock strengths**

And the heating rate normalization is naturally expressed as a mass-loss rate times a shock efficiency factor

Shock heating rate for each line vs. temperature probed by the line



work presented here is preliminary

Np(T) derived from the Chandra spectrum - fraction of wind that is shock-heated

Np(T) ~ 0.01 @ 20 or 30 MK

assumes Mdot = 5e-7 (~1/3)

must be corrected for fraction of the wind that's confined (~1/2)

and corrected for the tilted surface field reduction in mass-flux (~1/3)

comparison of the ADM and MHD simulations - duty cycle/efficiency factor (~1/5)

Conclusions:

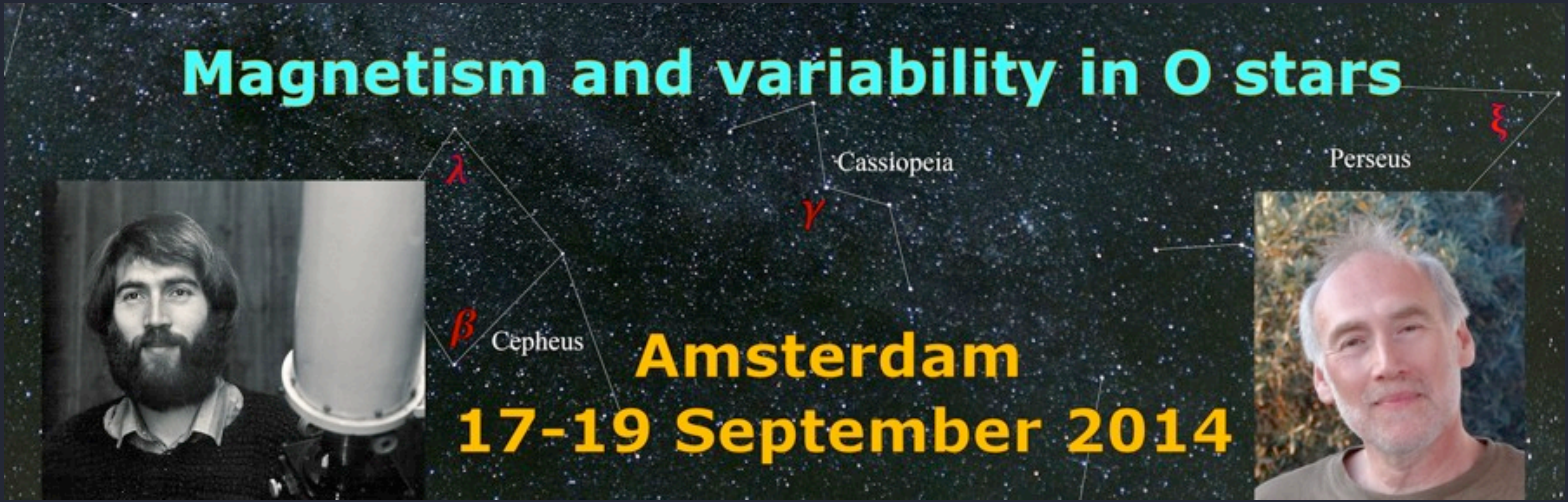
X-ray properties of θ^1 Ori C remarkably consistent with MHD simulations & analytic MCWS/ADM models

rotational modulation of X-rays consistent with occultation in edge-on view *but* lowest-temperature plasma component due to EWS in polar wind

shock-heating rate measurement: efficiency factor/duty cycle + mass-loss rate

Magnetism and Variability in O Stars

the prophet was right!



Extra Slides
(answering audience questions)

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

X-ray luminosity almost as high as θ¹ Ori C

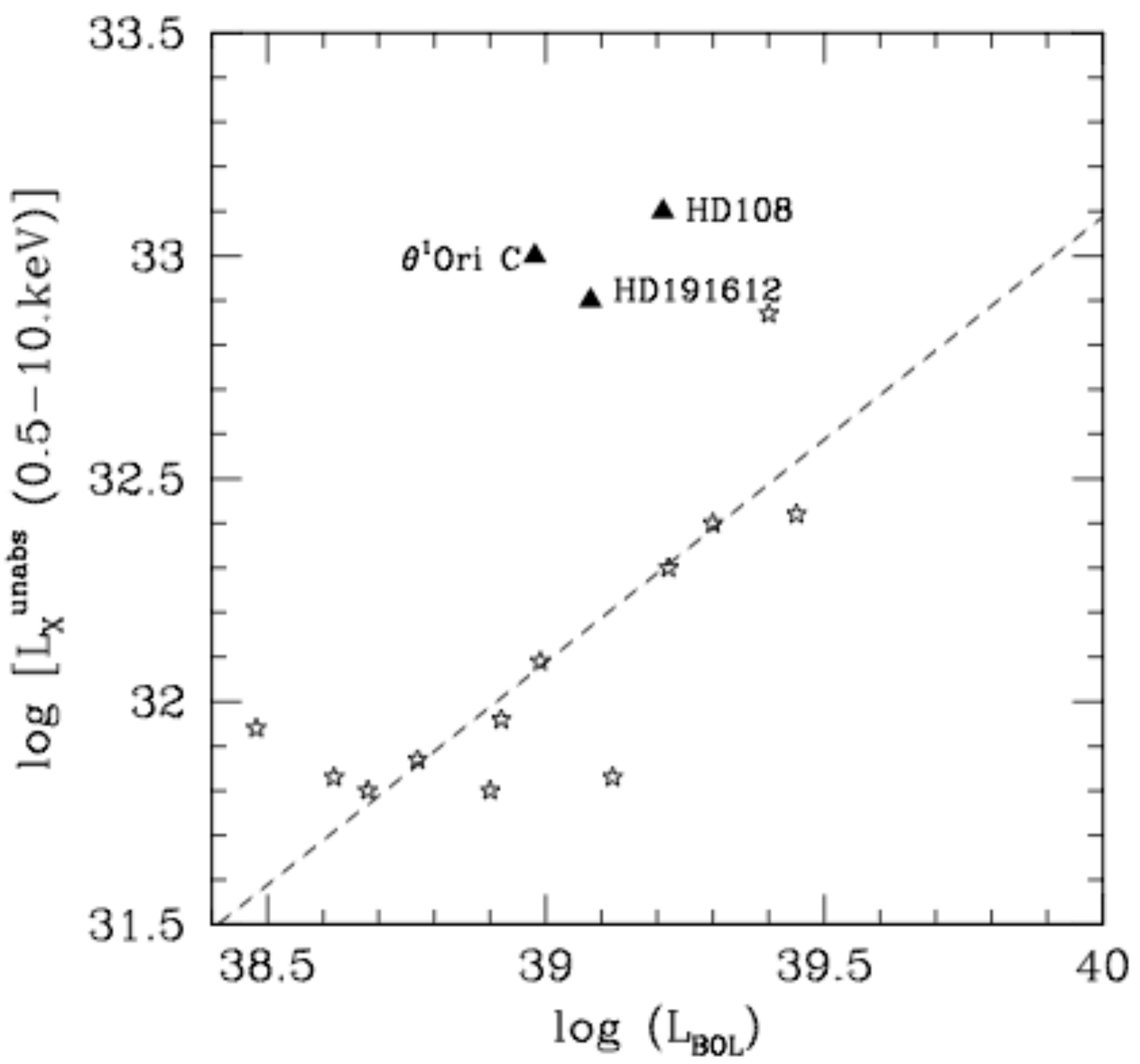
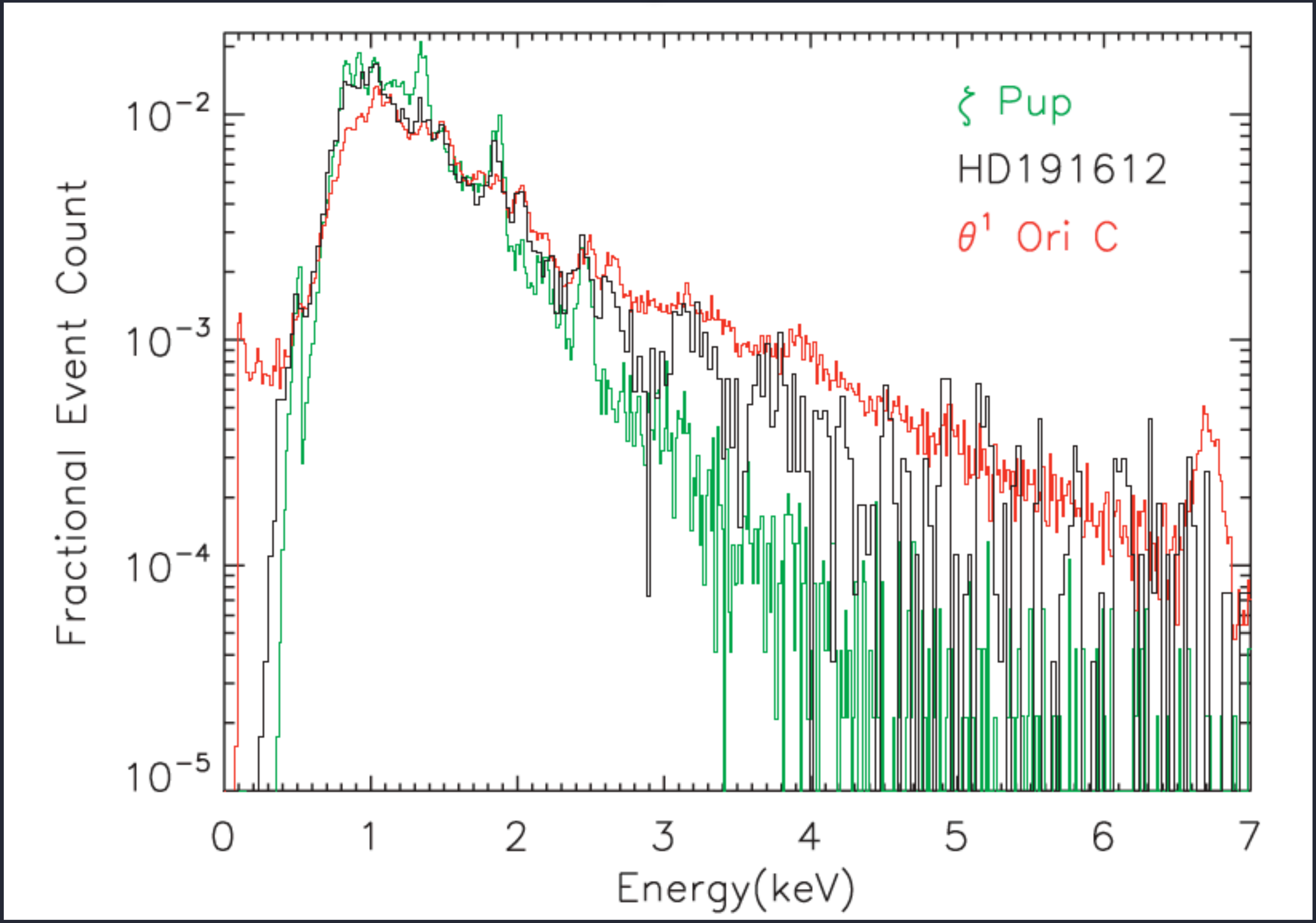


Figure 4. Diagram showing the X-ray luminosity (in erg s^{-1}) versus bolometric luminosity (in erg s^{-1}). The dashed line indicates the typical relation for O stars (from Sana et al. 2006); HD 108, HD 191612 and θ^1 Ori C all lie above it. Asterisks show the position of hot stars in NGC 6231 (Sana 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

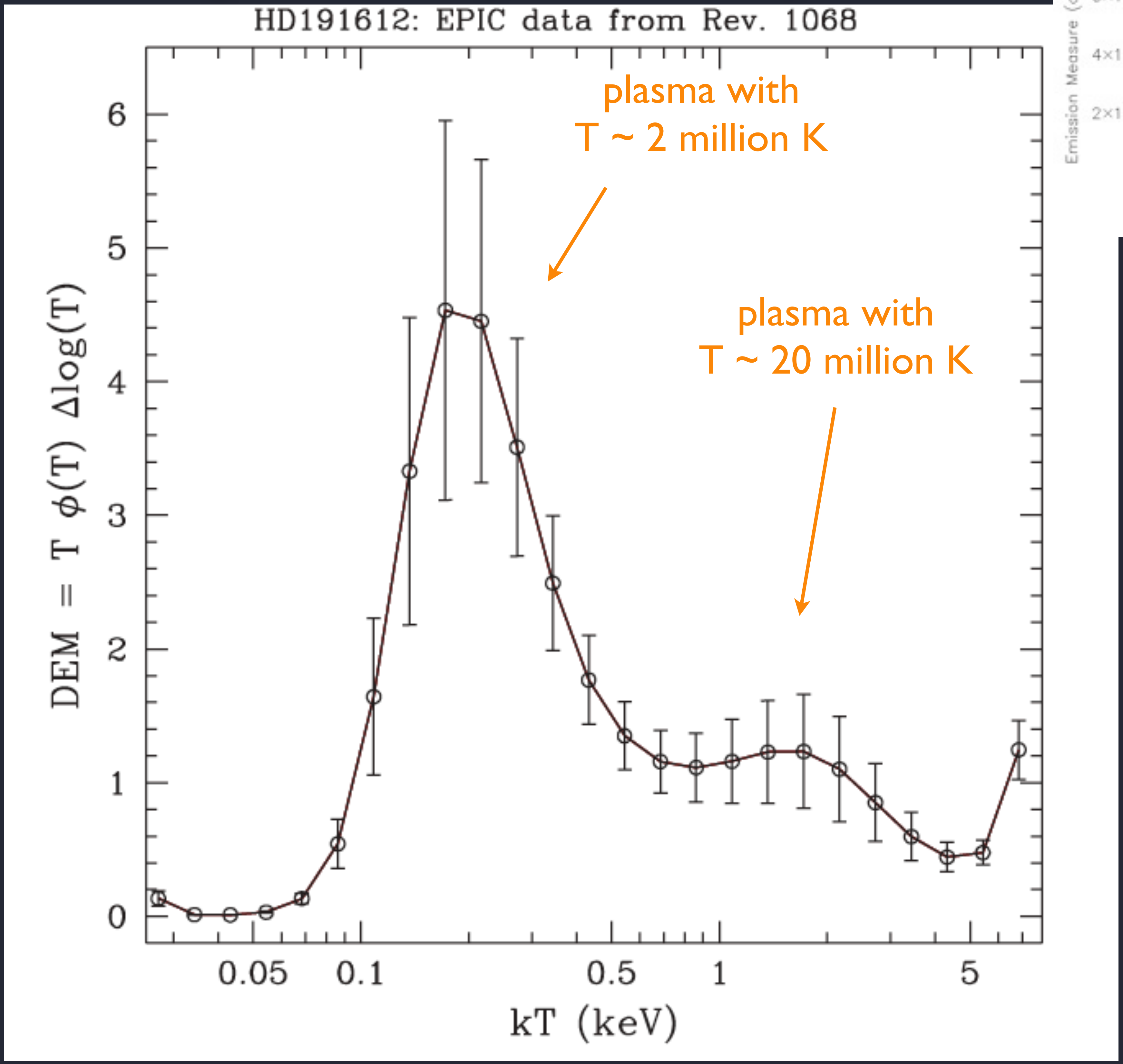
spectrum softer than θ^1 Ori C

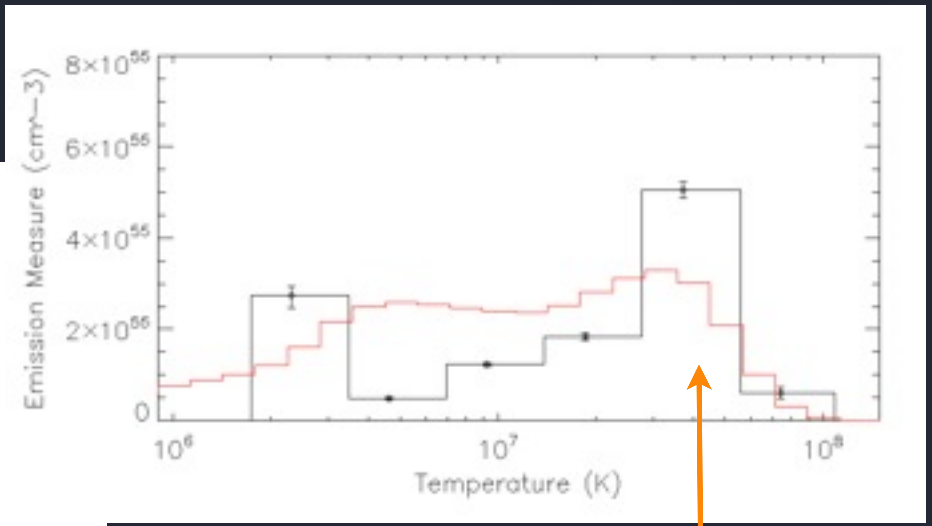


Nazé et al., 2007, MNRAS, 375, 145

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

θ^1 Ori C

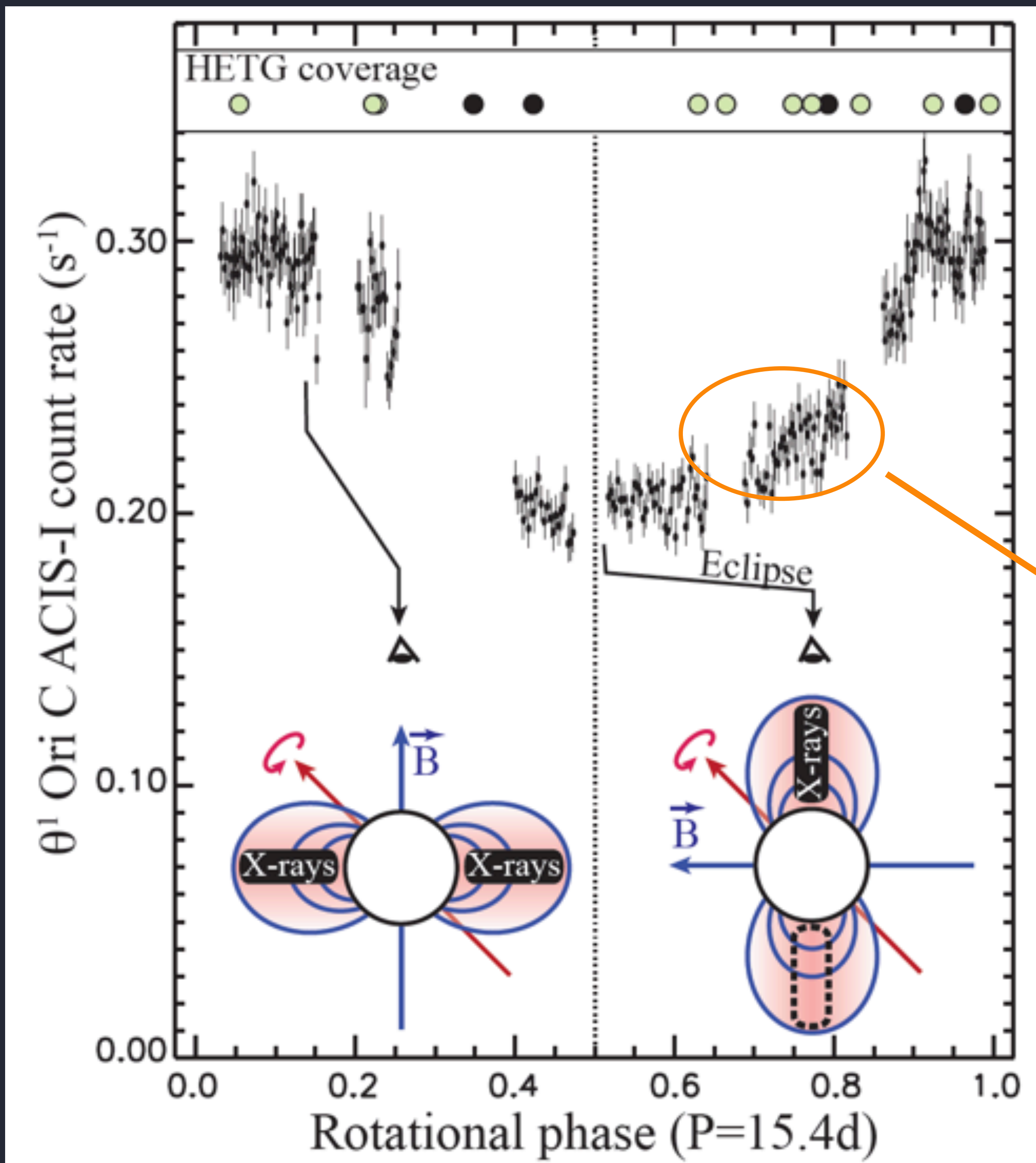




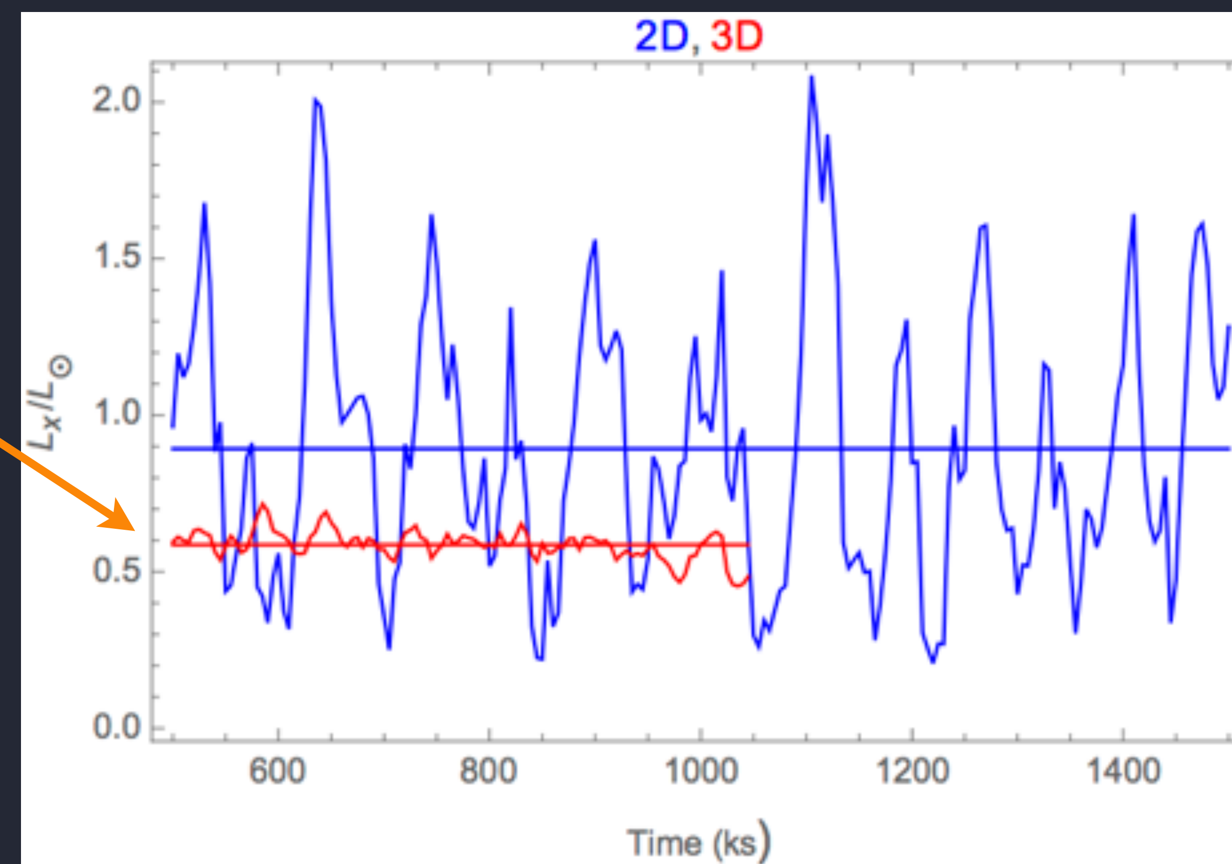
kT ~ 3 keV
(35 million K)

Nazé et al., 2007, MNRAS, 375, 145

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



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



3-D MHD simulation: what about absorption?

optical depth - in ADM model

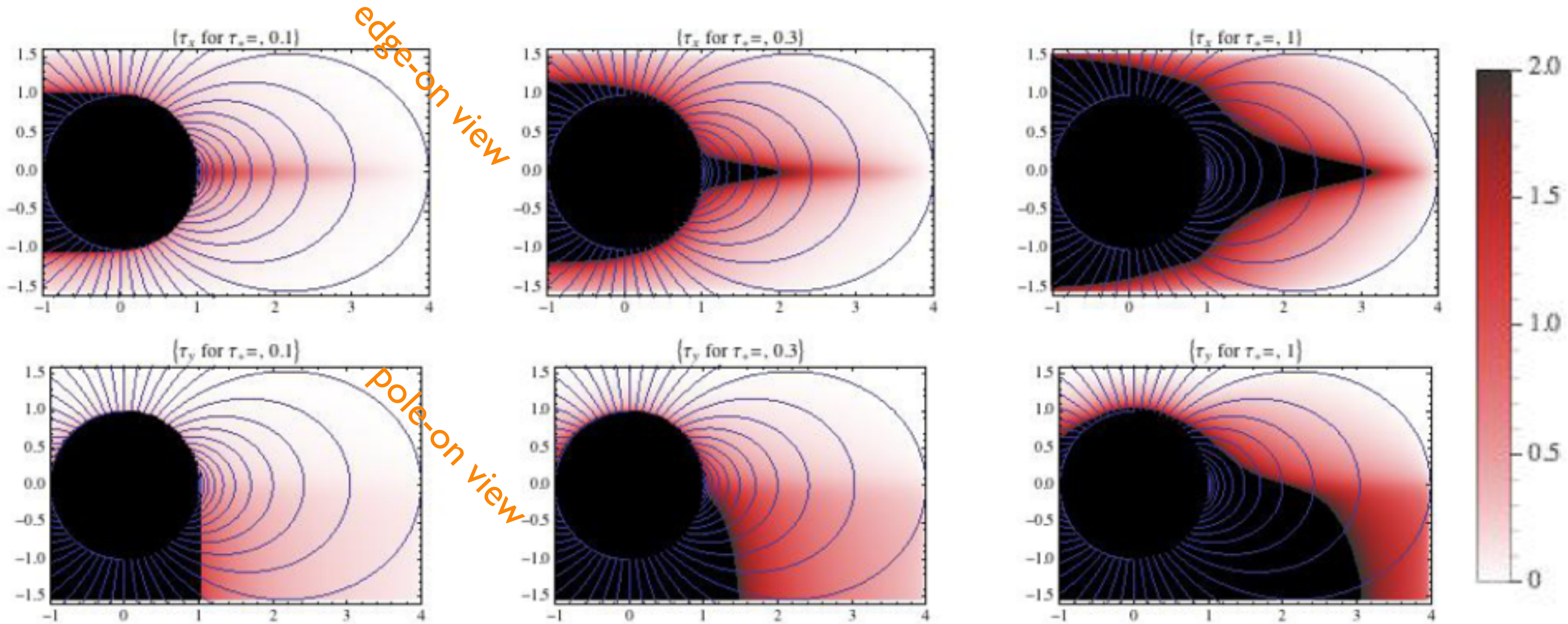
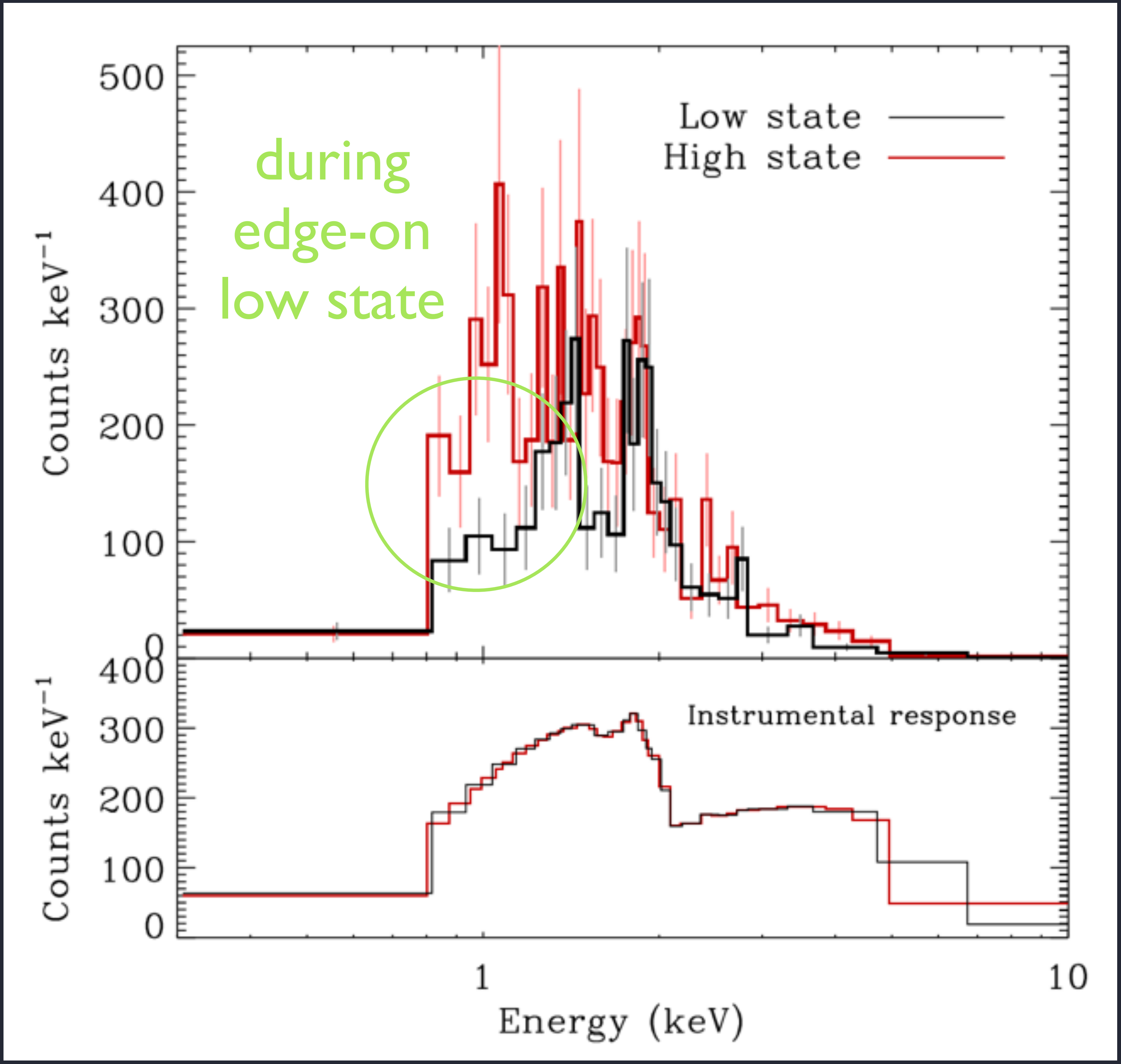


Figure 7. Spatial variation of optical depth for bound-free absorption of X-ray emission by both the cool downflow and wind outflow components of the ADM model, as well as by occultation of the opaque star. The top row shows results for a distant observer to the right, with an equator-on view, while 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