Chandra High Resolution X-Ray Spectra of WR 6

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WR 6 (EZ CMa)

Type: WN4 (single)

$d = 1.82\,\mathrm{kpc}$

$T_{\mathrm{eff}} = 90\,\mathrm{kK}$

$L/L_{\odot} = 10^{5.6}$

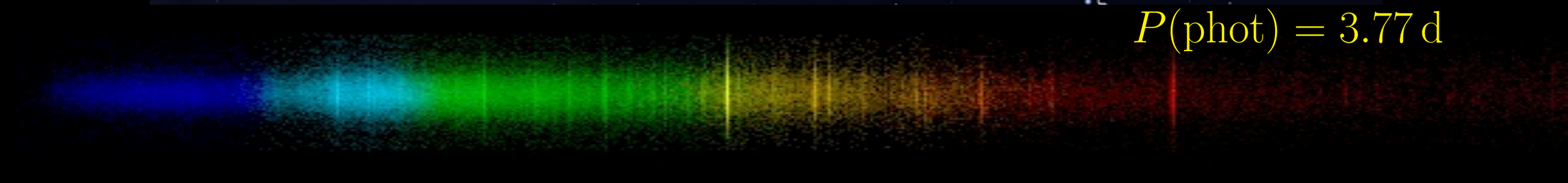
$M/M_{\odot} = 20$

$R/R_{\odot} = 2.6$

$\dot{M} = 2 \times 10^{-5}\,M_{\odot}\mathrm{yr}^{-1}$

$v_{\infty} = 2000\,\mathrm{km\,s}^{-1}$

$P(\mathrm{phot}) = 3.77\,\mathrm{d}$

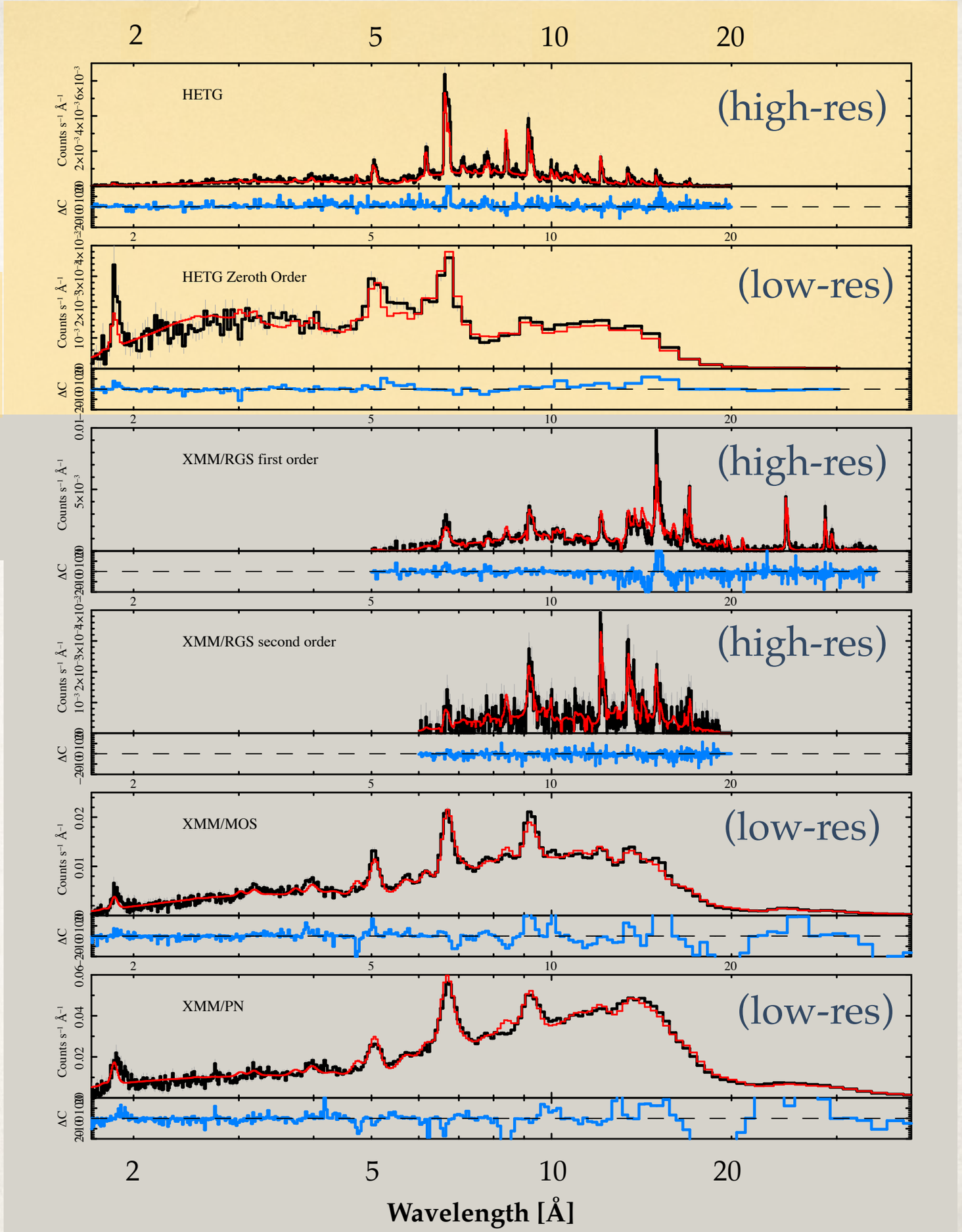


Overview of X-ray Spectra of WR 6:

Chandra/HETG
(440 ks)

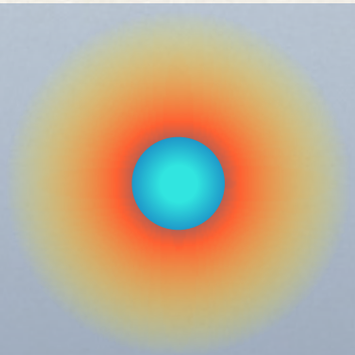
XMM/Newton
(400 ks)

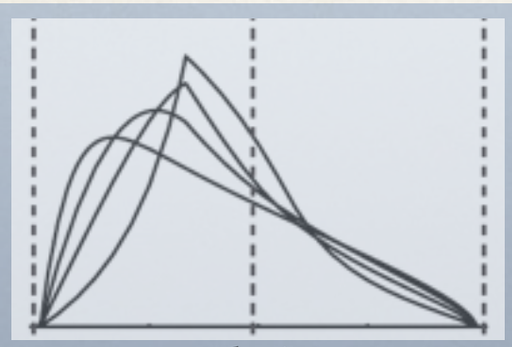
- ★ H- and He-like emission lines of abundant species, plus Fe-L lines
- ★ Emission lines are broad
- ★ No Oxygen or Carbon
- ★ Strong continuum
- ★ Strong Fe XXV



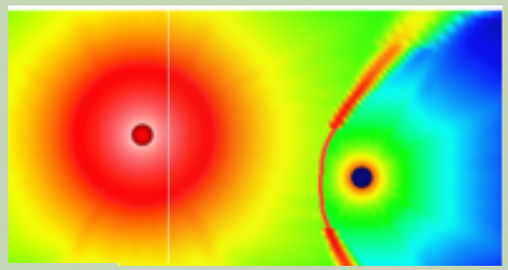
X-Ray Production Mechanisms in Hot Stars

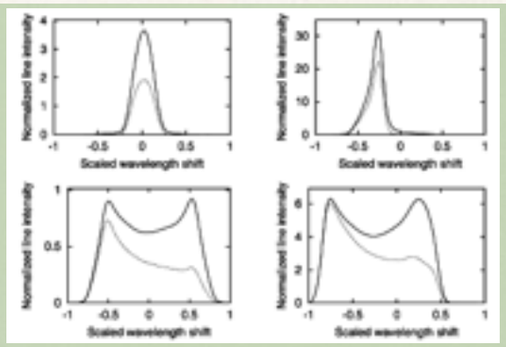
OB-star line-driven winds: shocks embedded in the wind;
- broad lines, possibly non-Gaussian
- blue-shifted centroids
- suppressed forbidden lines (destroyed by UV flux)
- relatively cool (~2 MK)



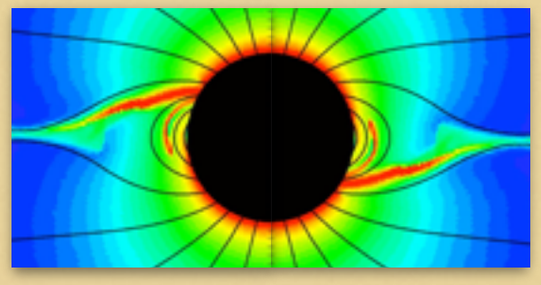


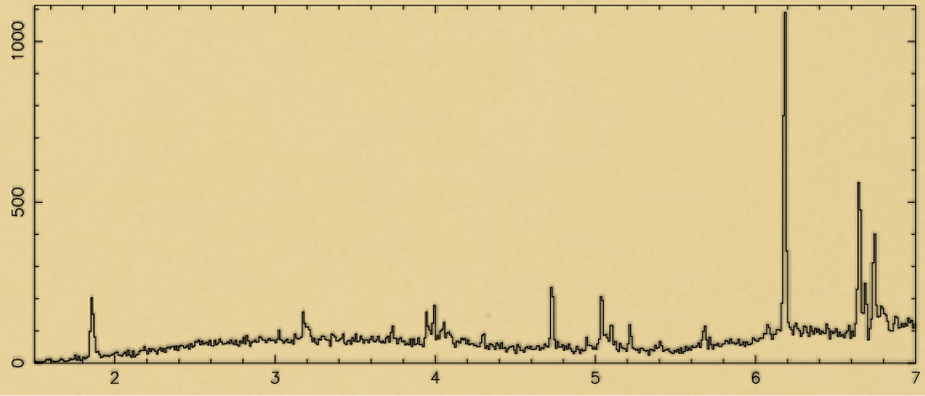
Binary systems of OB-stars, or WR stars — wind-wind collisions
- symmetric lines, or double-peaked lines
- relatively hot (~20 MK)
- strong forbidden lines
- strongly variable (geometric aspect)





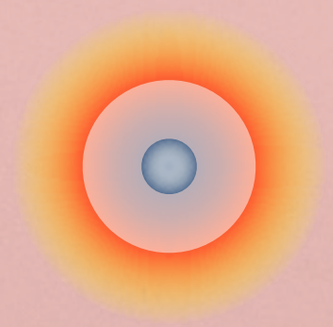
Magnetically confined winds of OB-stars:
- symmetric lines
- narrow, unshifted lines
- relatively hot (~20 MK)
- suppressed forbidden lines

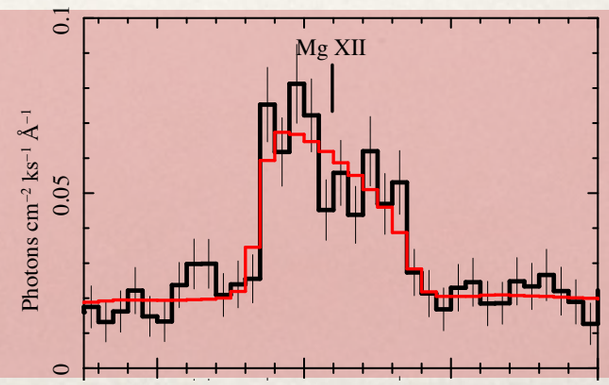




Luminous Blue Variables, Super-Eddington Winds:
- don't emit X-rays

WR star line-driven winds: dense, massive winds
- broad lines, "fin" shaped
- strong forbidden lines
- relatively hot (~10 MK)

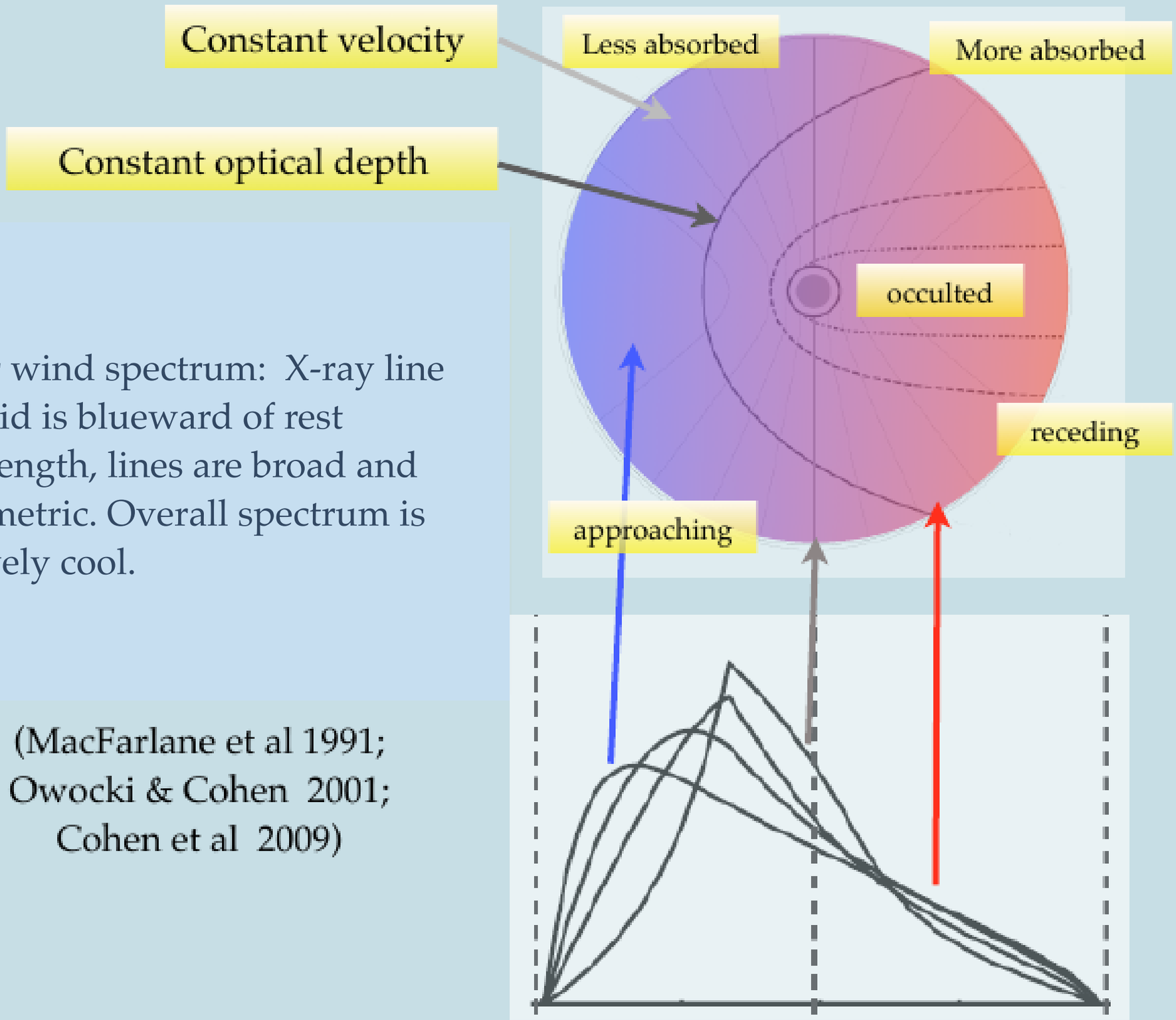




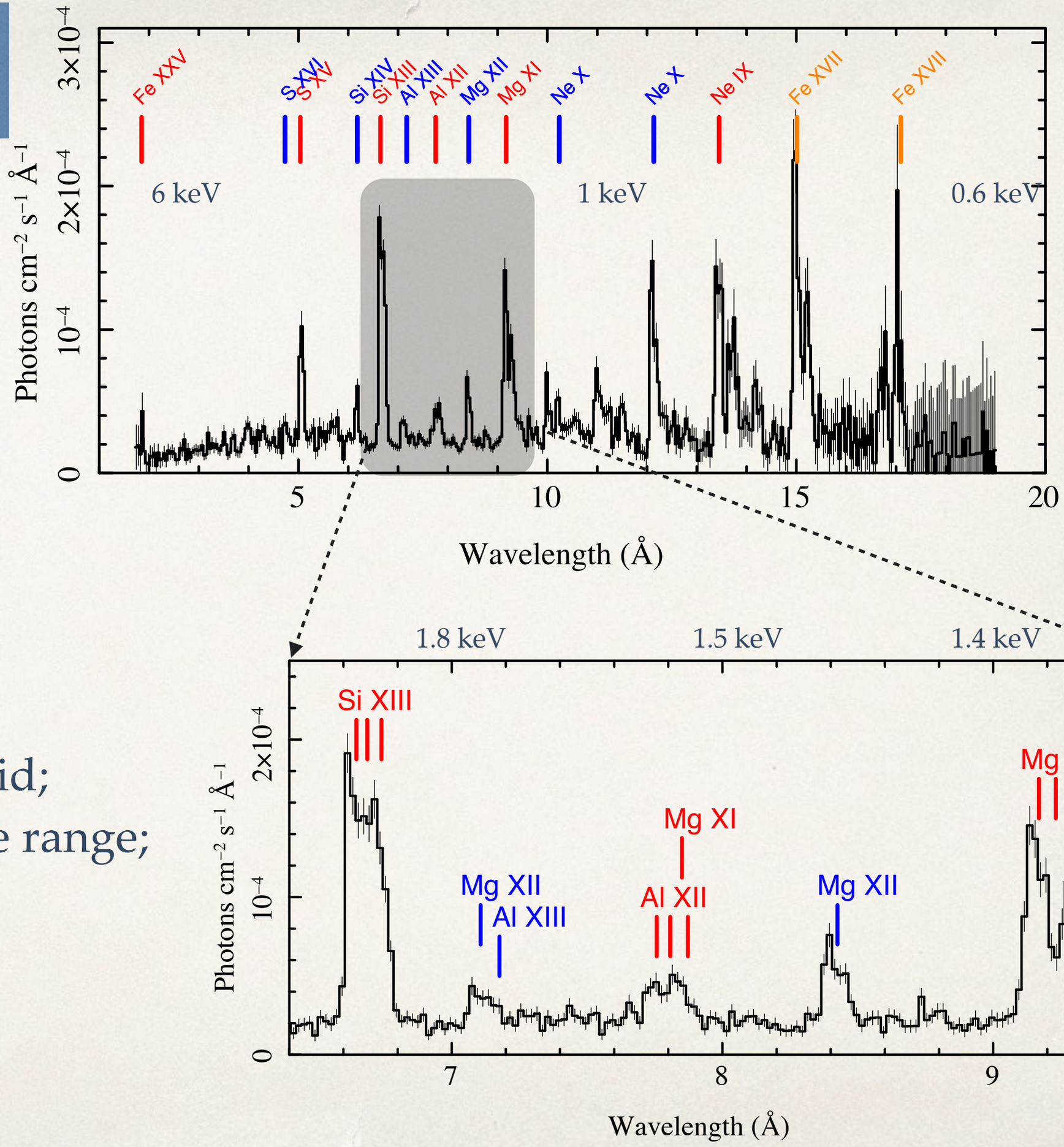
Wind Line Profile Basics

Stellar wind spectrum: X-ray line centroid is blueward of rest wavelength, lines are broad and asymmetric. Overall spectrum is relatively cool.

(MacFarlane et al 1991;
Owocki & Cohen 2001;
Cohen et al 2009)



Chandra/HETG Spectrum of WR 6



Broad lines;

Sharp blue wing;

Blueshifted centroid;

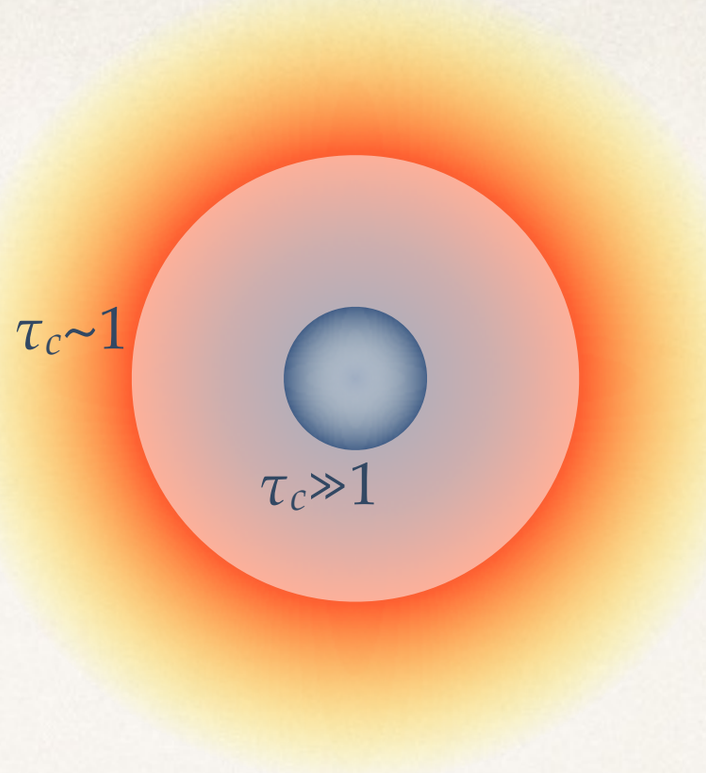
Broad temperature range;

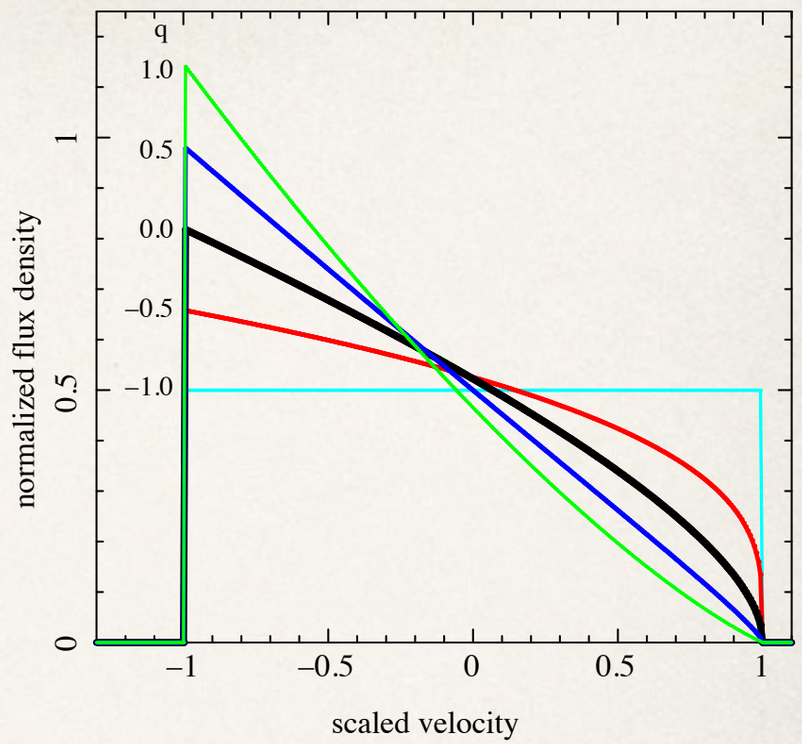
Modeling the Line Profile: Constant Spherical Expansion

Assume:

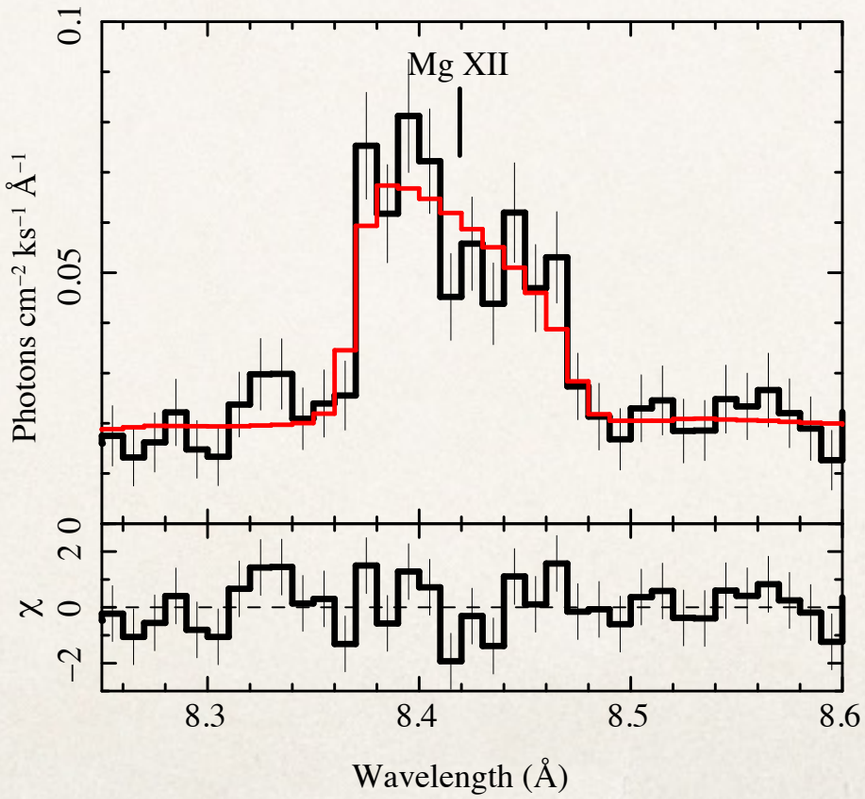
- ★ large photo-absorption ($v \sim v_\infty$)
- ★ emissivity ~ $n_e^2 \times r^{-q}$
- ★ constant opacity vs λ

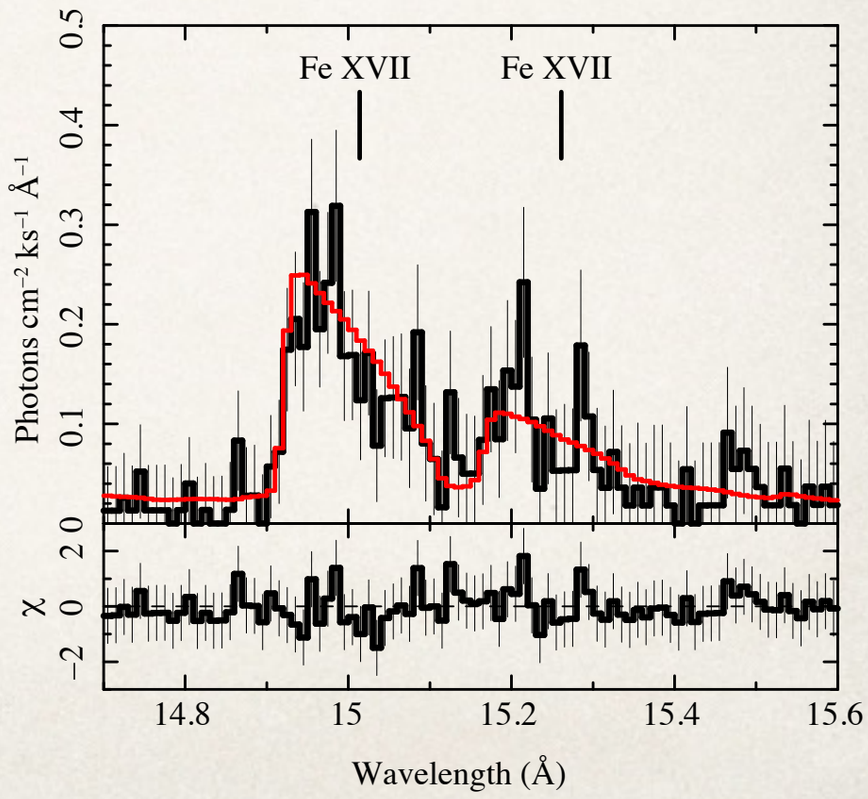
Obtain: simple analytic function for the line profile (see Ignace 2001)





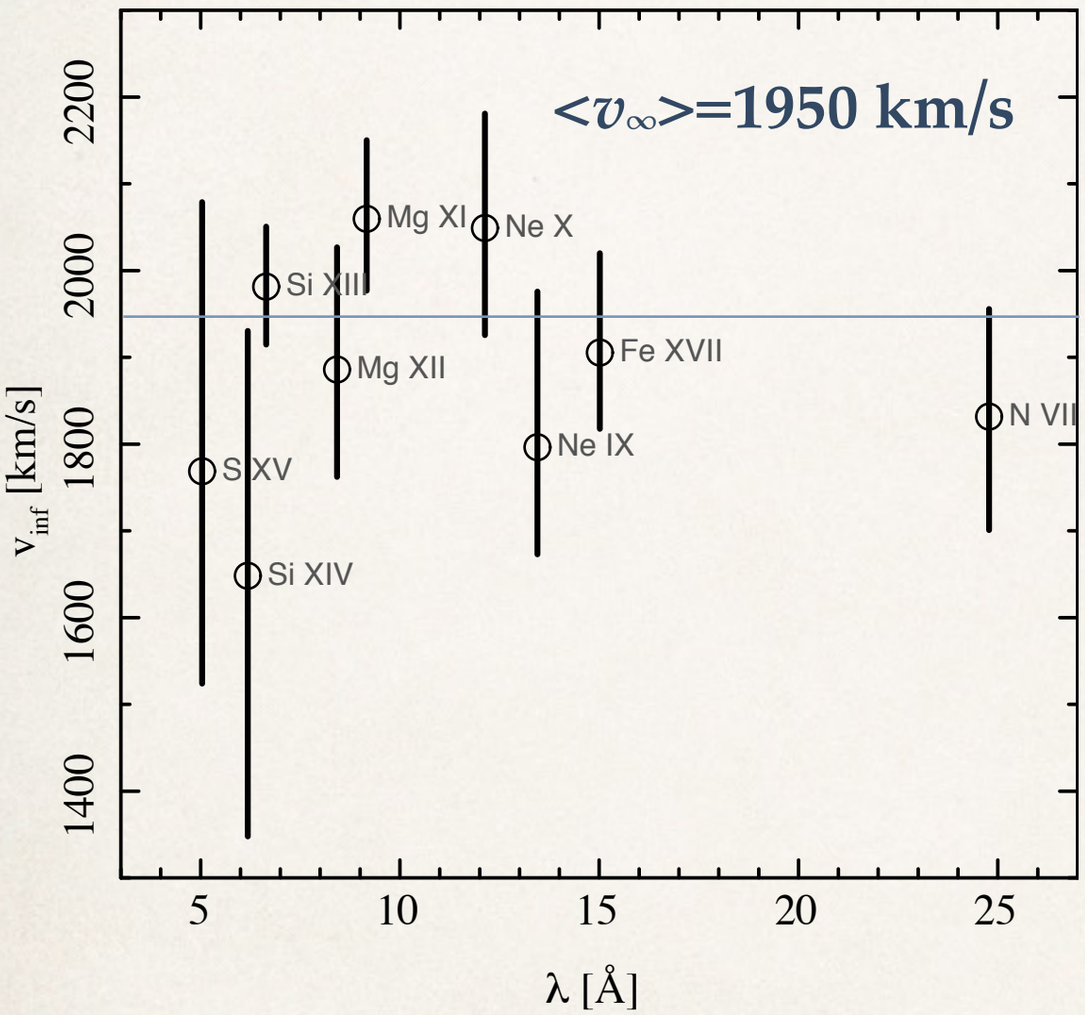
Example fits:



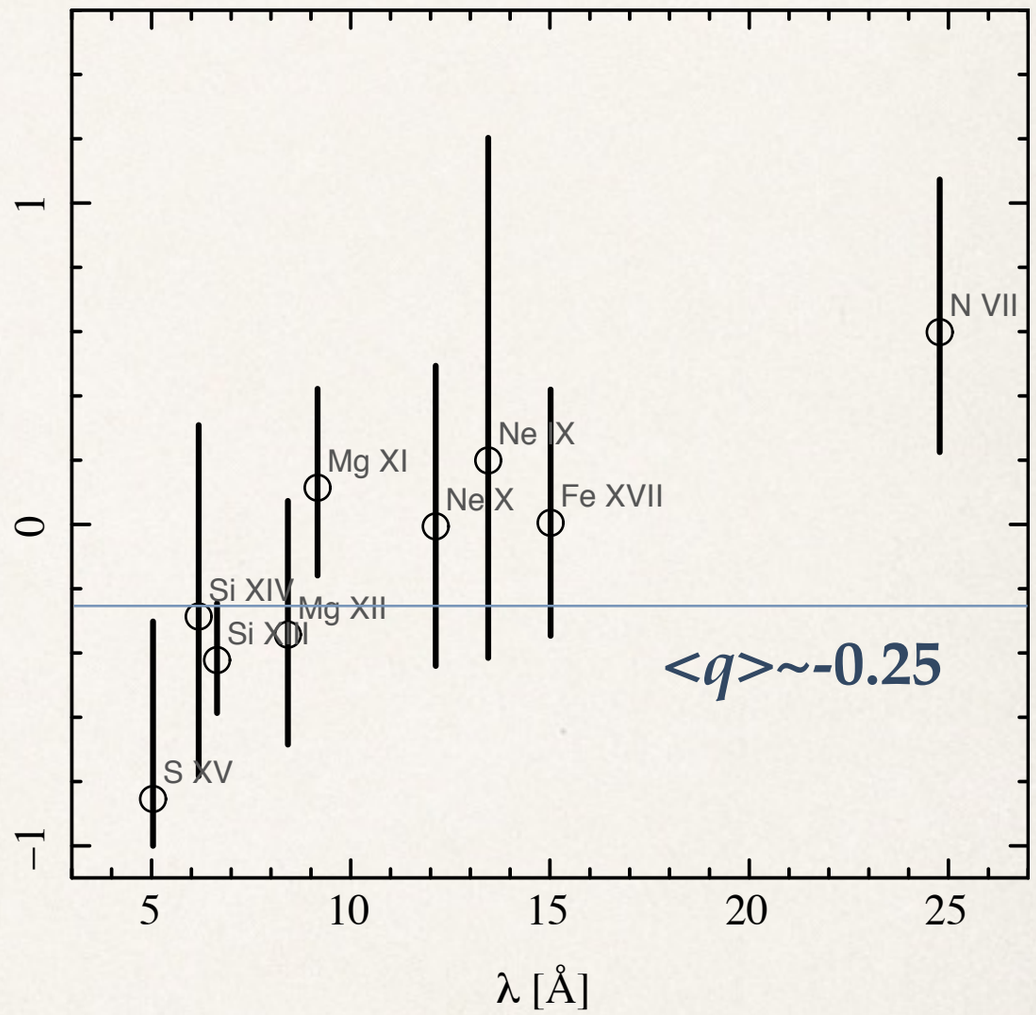


Line Profile Fitting Results

Velocity is indeed ~constant



Largely consistent with nominal shape (q=0), but hint of trend.

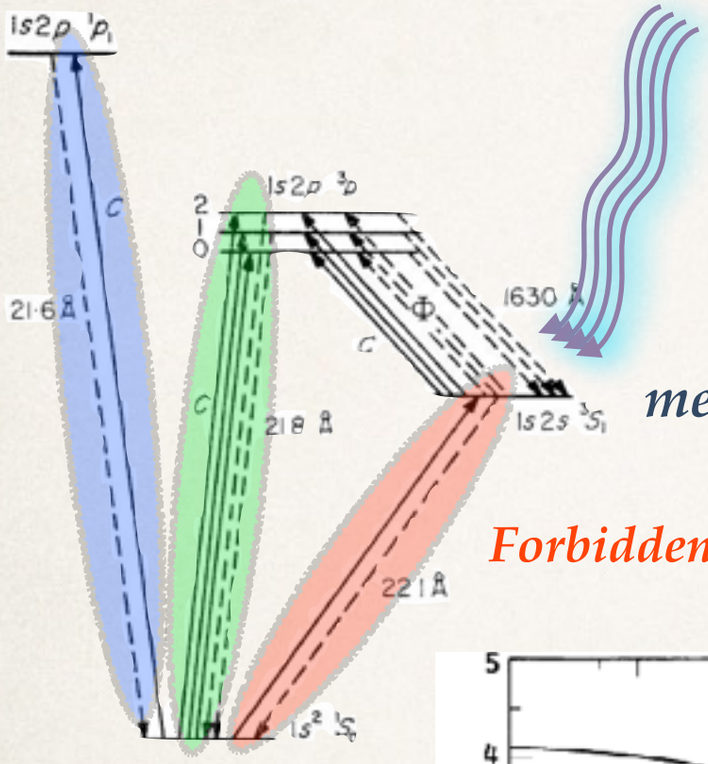


(errorbars show 90% confidence intervals)

He-like Ion Diagnostics

Resonance (r)

UV photo-excitation

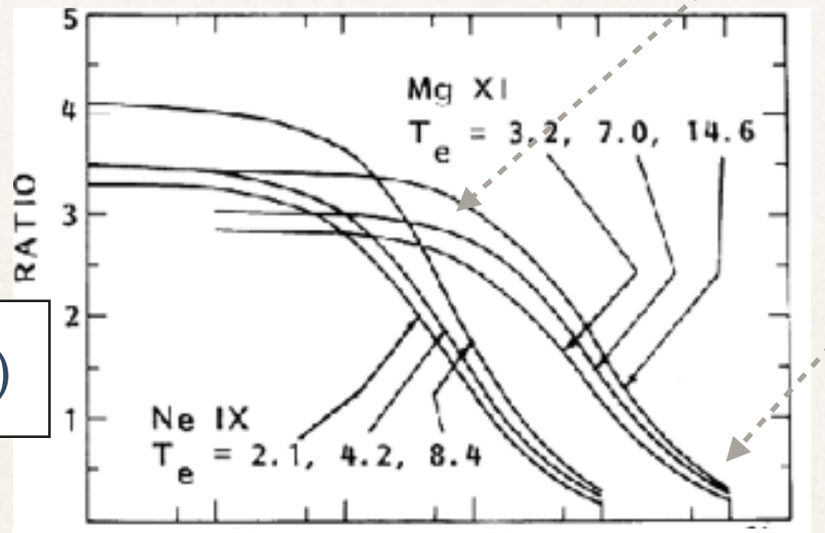


metastable level

Forbidden (f)

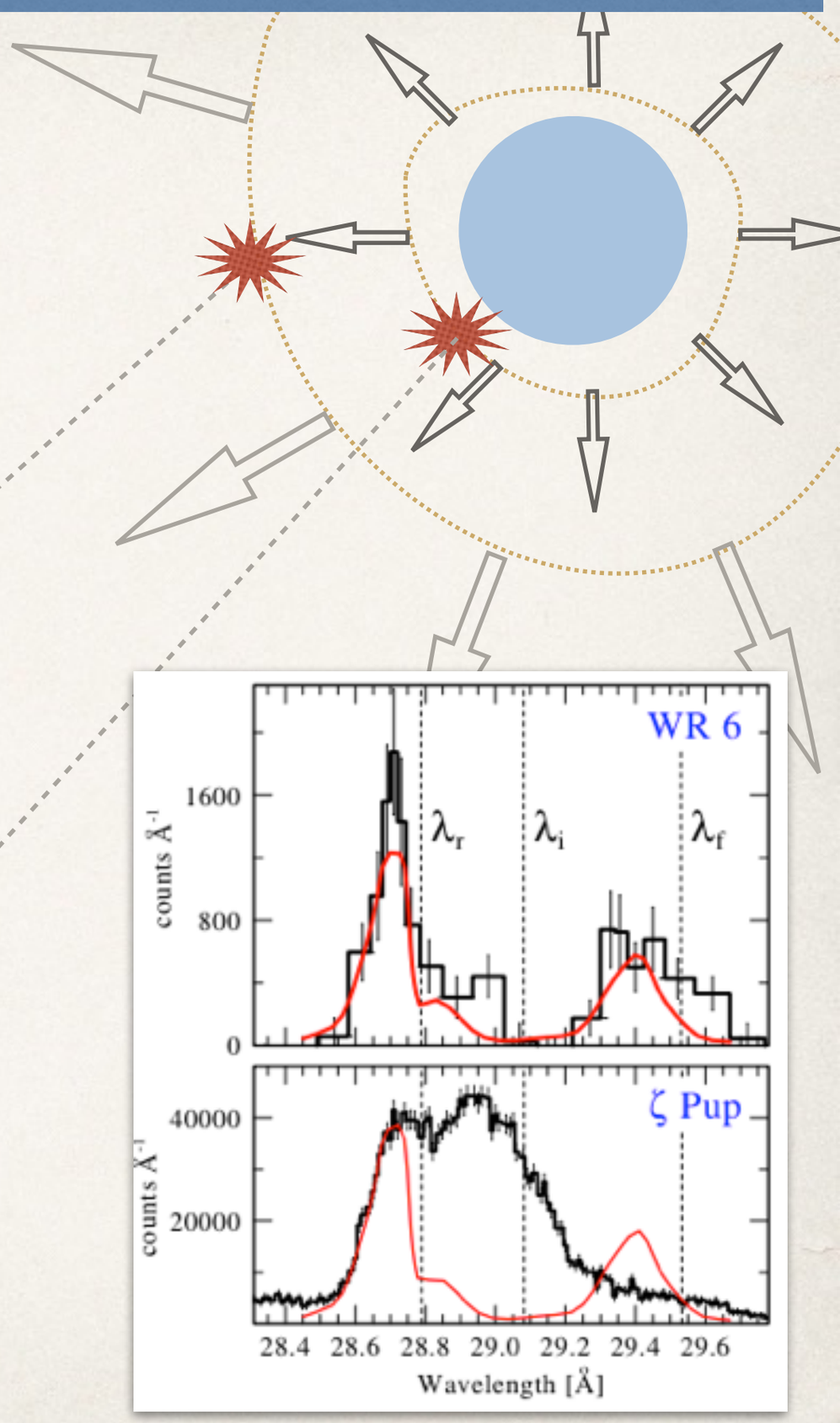
Intercombination (i)

$$R = \text{flux}(f) / \text{flux}(i)$$



UV flux density —->

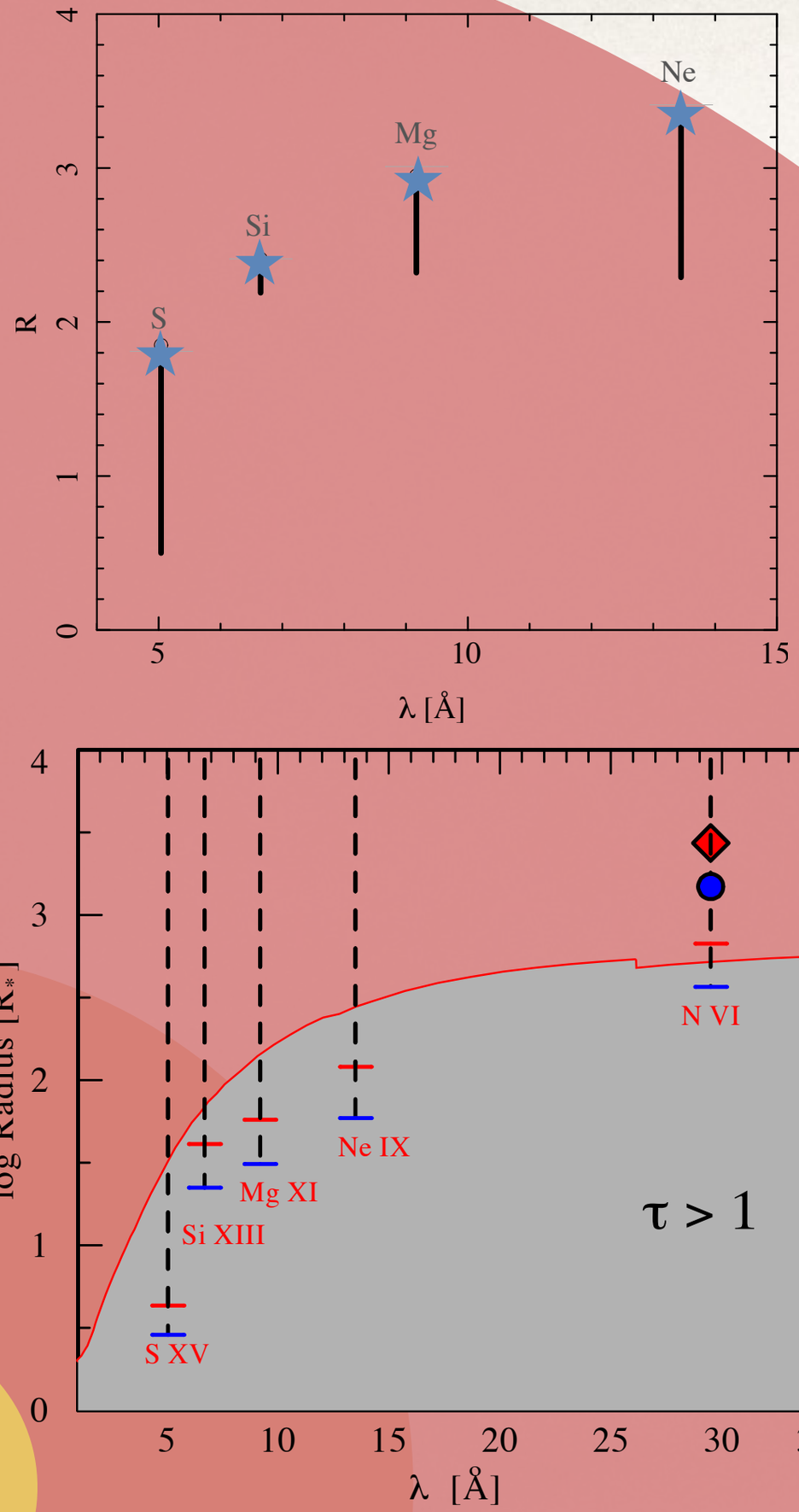
<—- height



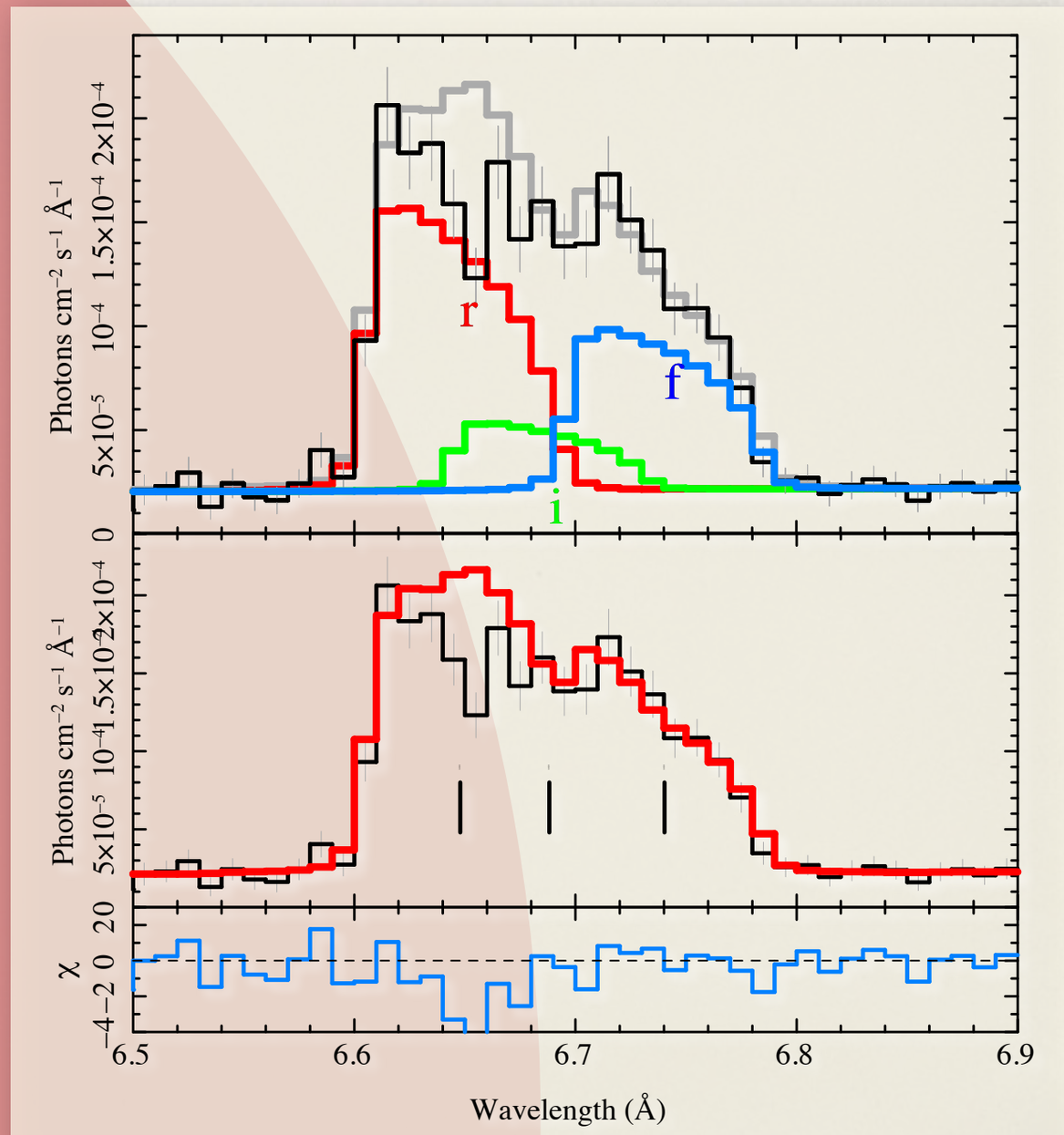
(Oskinova et al 2012)

Diagrams from:
Gabriel and Jordan 1969 MNRAS 145, 241;
Wolfson et al 1983 ApJ 269, 319

He-like Ion Diagnostics: Results

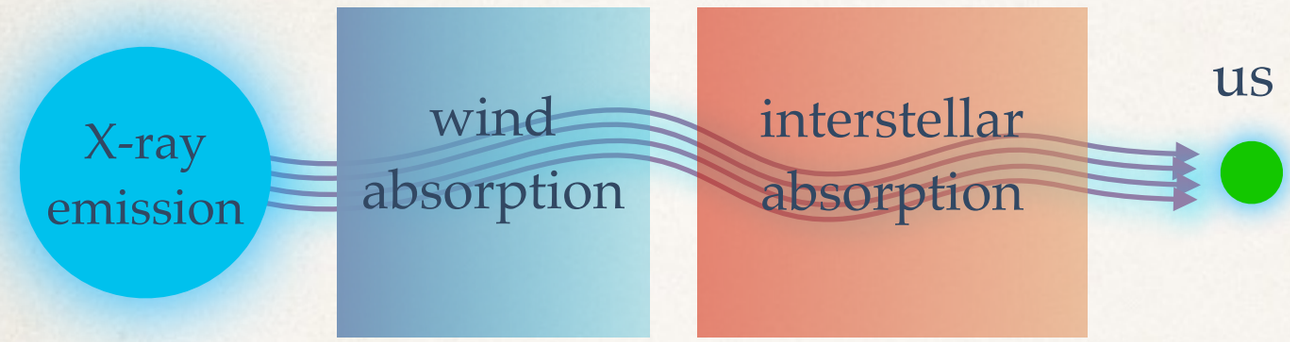


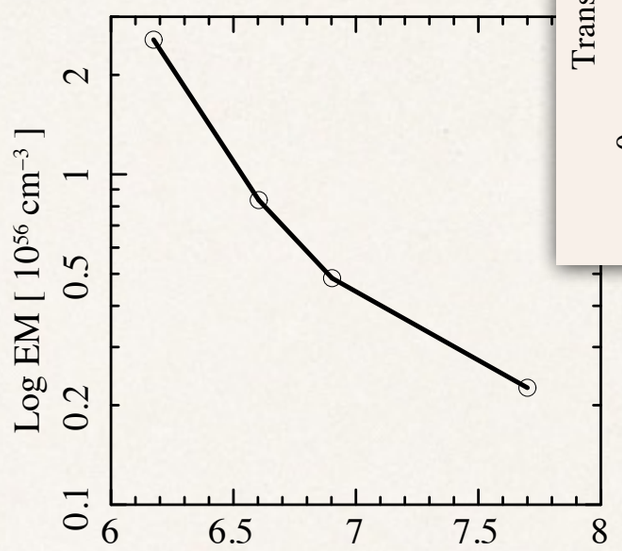
All f/i ratios are at the no-photo-excitation limit.
90% confidence limits are near $\tau_c(\lambda)=1$ (*lower limit* to radius of formation)

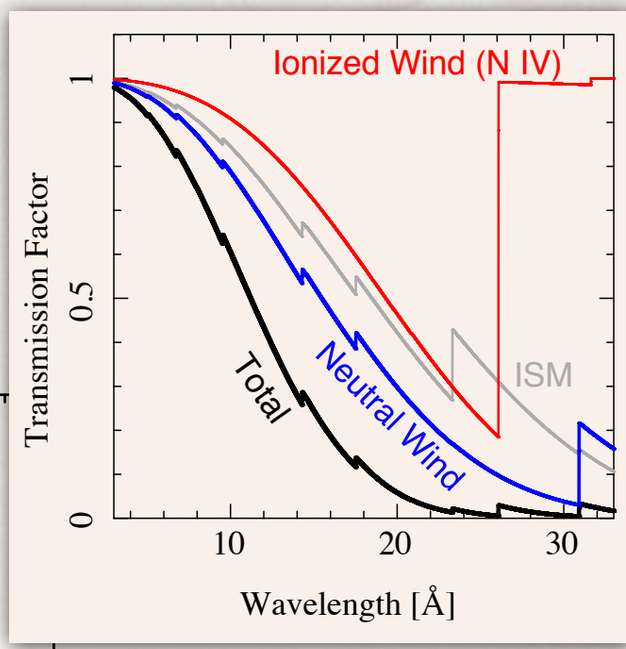


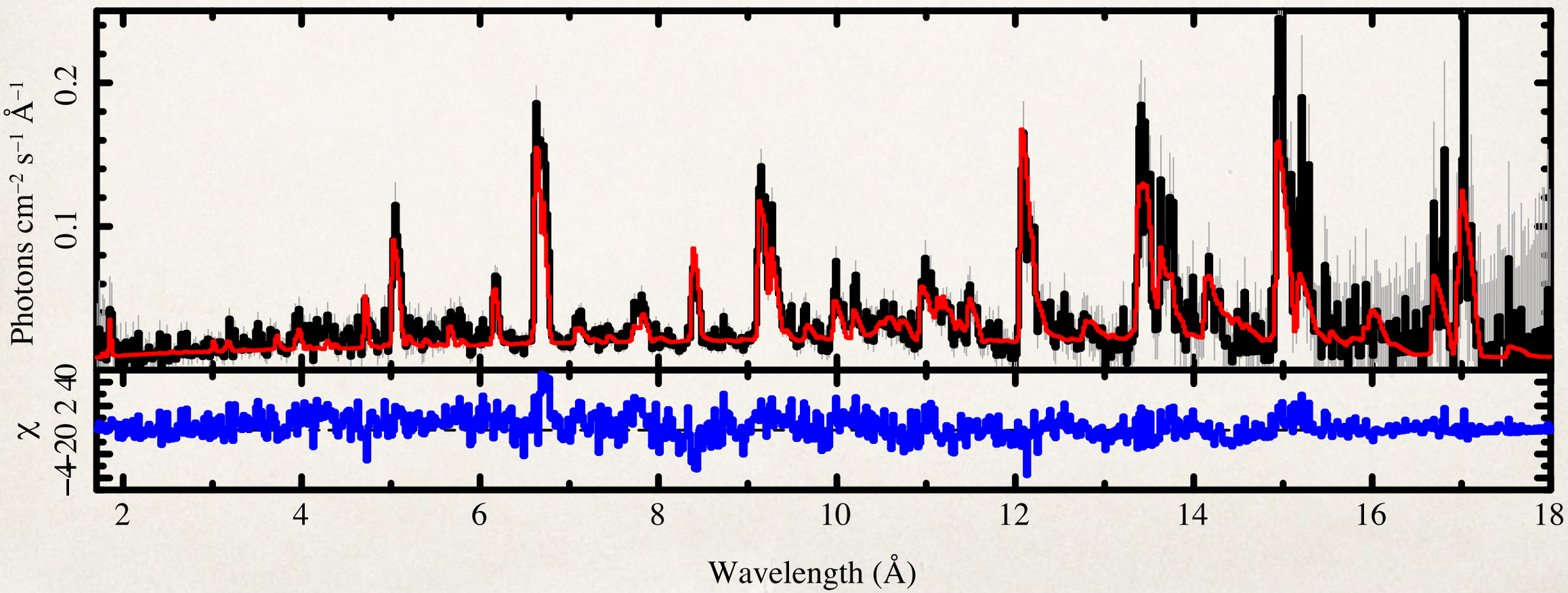
Global Spectral Modeling

A naive model:



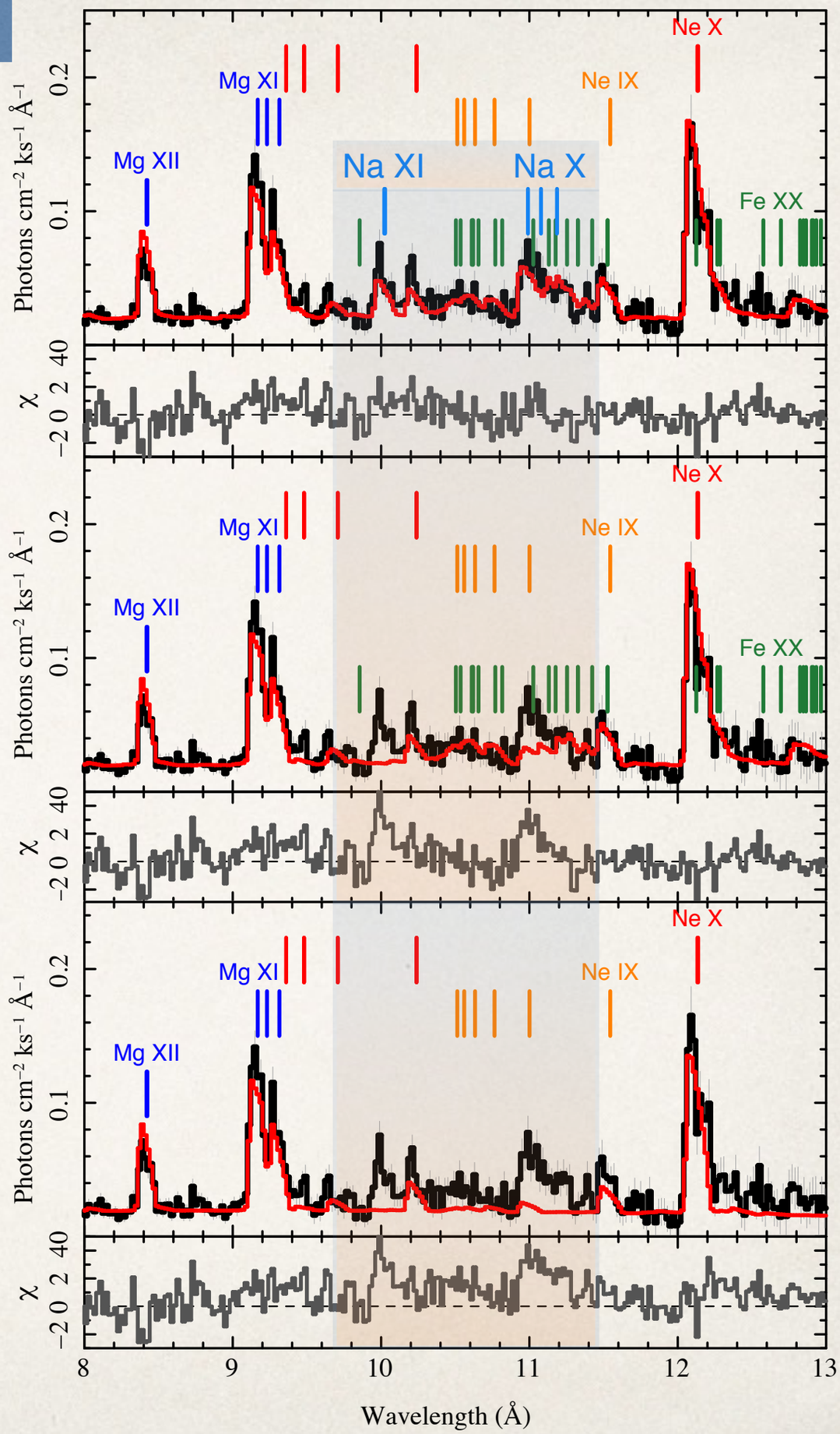




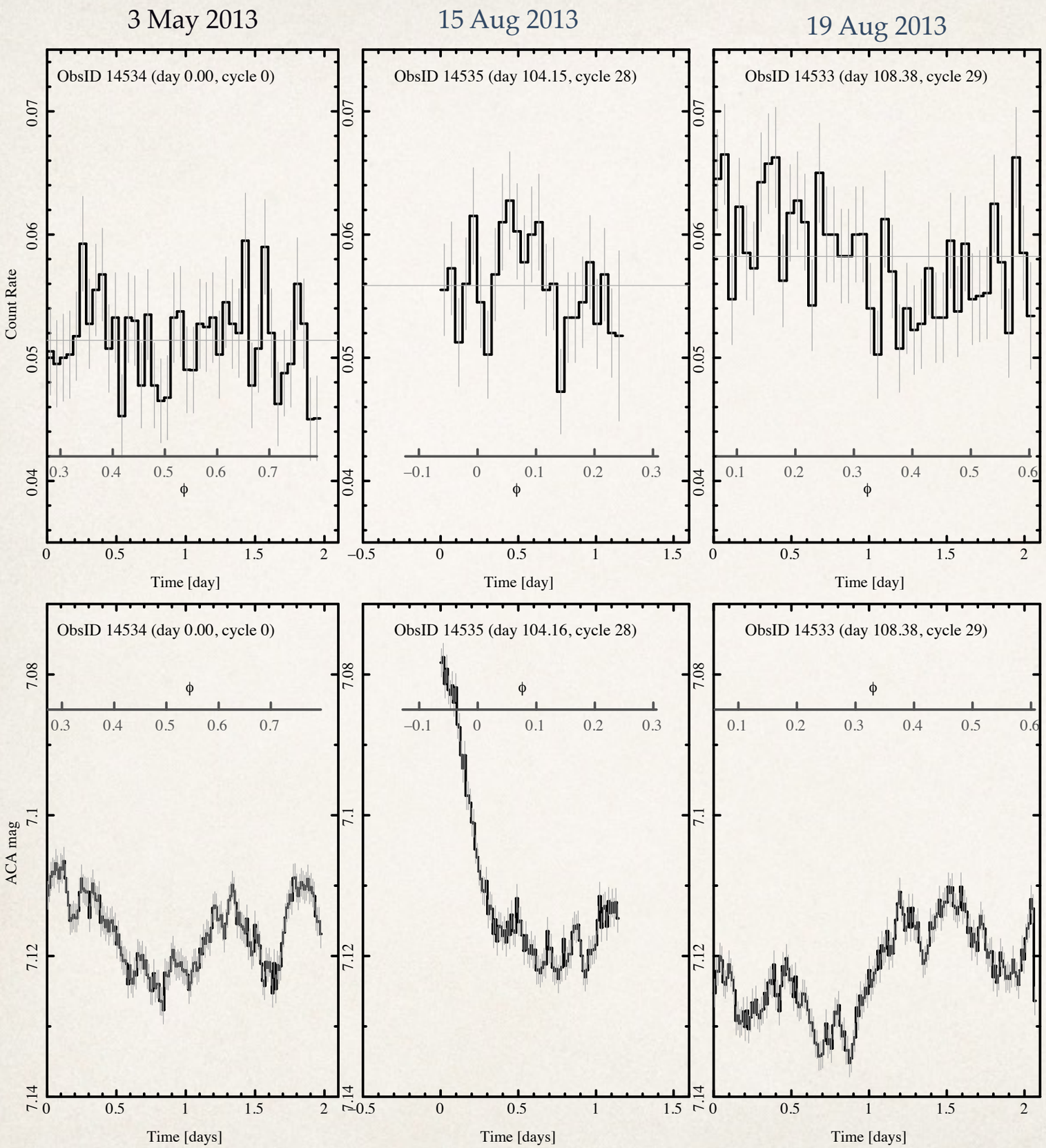


An abundance puzzle:

The global plasma model requires an enhanced sodium abundance.



Variability



X-ray — *HETG*

Visual — *Chandra* Aspect Cam

Modulation

(max-min)/(max+min):

X-ray: ~15%

Visible: ~4%

Conclusions/Questions

★ Emergent X-rays from WR 6 come from far out in the wind, under uniform spherical expansion

★The plasma has a high-temperature component, so relatively energetic shocks occur at large radii

How are X-rays produced?

Why does X-ray flux vary?