Winds of Massive Stars: Line Profiles and Variability

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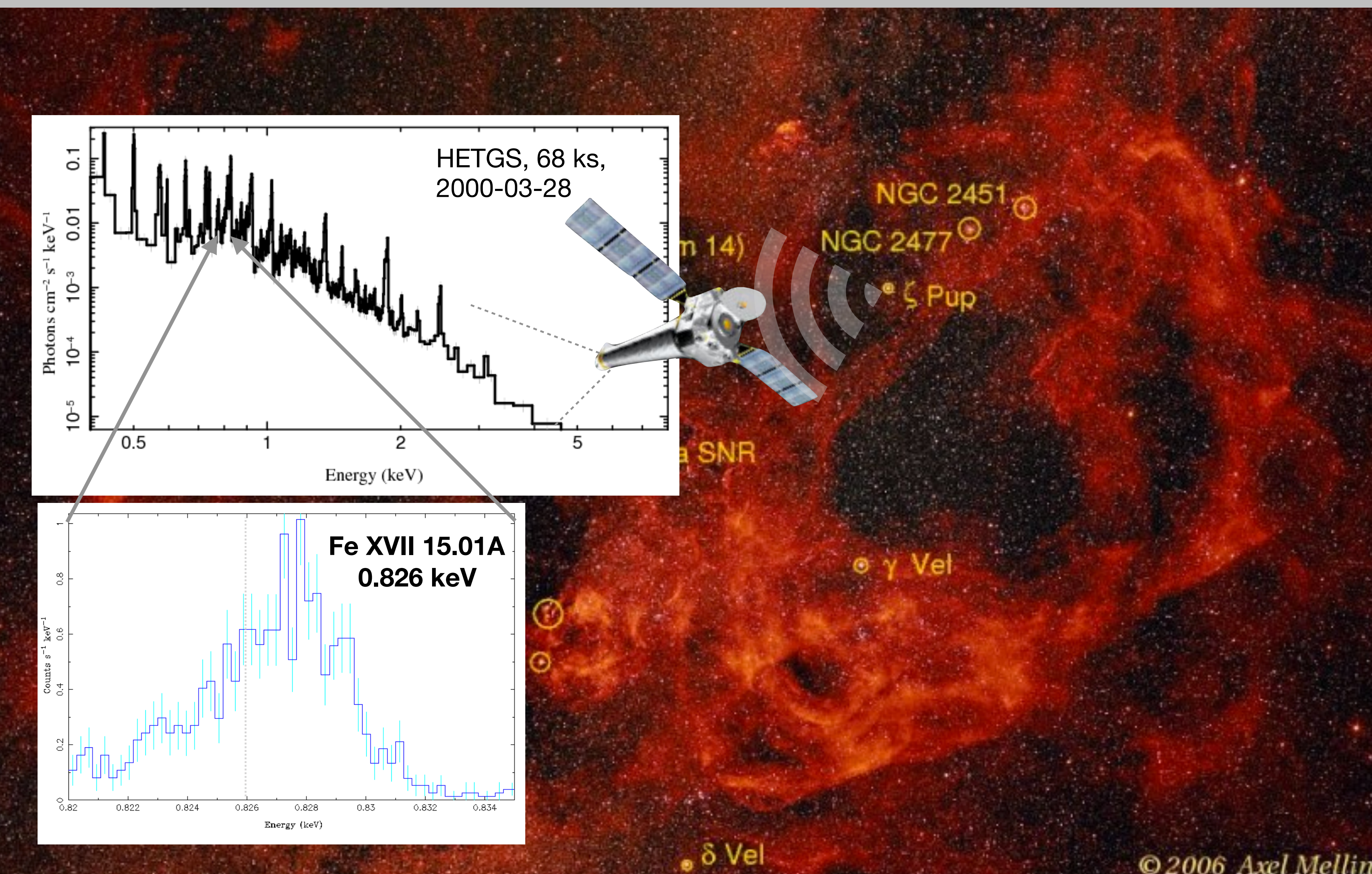
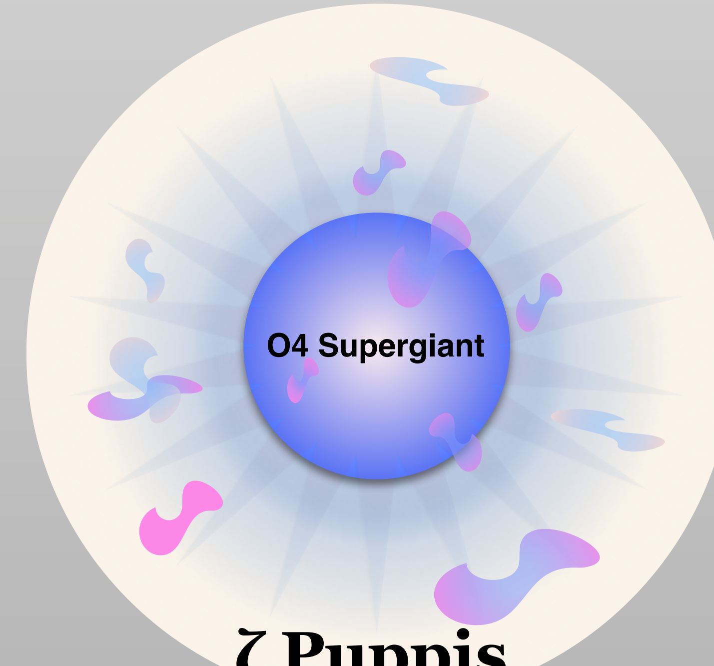
Generally accepted theory: Winds are driven by UV radiation pressure on millions of lines. Instabilities create shocks in the wind, generating soft X-rays from a small volume of hot plasma. (Lucy & White 1980)





ζ Puppis

Runaway, *single* star

Type: O4 If

$T_{\rm eff}$ =42,400 K

$R \sim 16\ R_\odot$

$M \sim 20$—$60\ M_\odot$

$L_{\rm bol} \sim 6 \times 10^5\ L_\odot$

$v \sin i = 230$ km/s

$P_{\rm phot} = 1.78$ d

$v_\infty = 2200$ km/s

$d = 330$ pc

$\dot{M} \sim 3{\times}10^{-6}\ M_\odot$/yr

$f_x \sim 1.5 \times 10^{-11}$ ergs/cm²/s

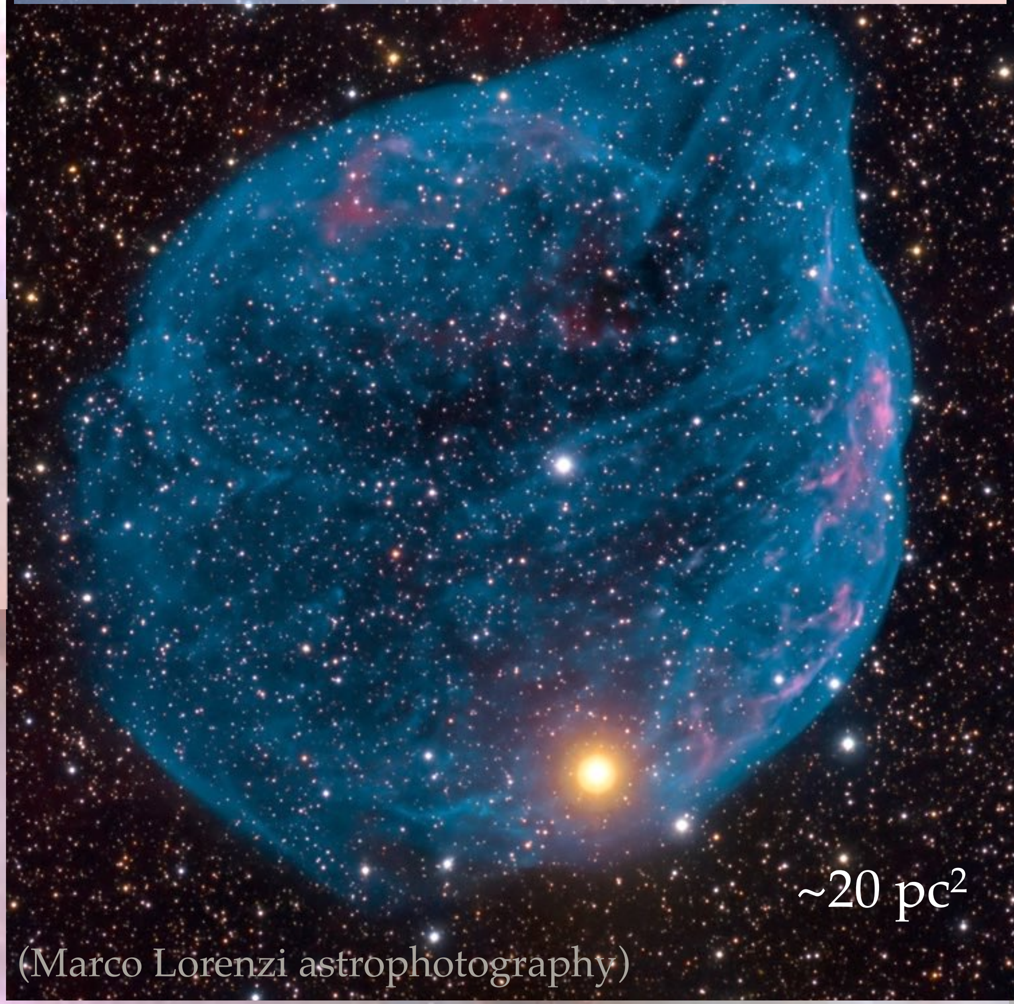
$L_x \sim 2 \times 10^{32}$ ergs/s

$L_x/L_{\rm bol} \sim 10^{-7}$

Context

Massive stars are rare but influential over their ~4 Myr lifetime!
Key components of *cosmic feedback:* comparable radiation and momentum output to final supernova.

WR 6 (EZ CMa) WN 4



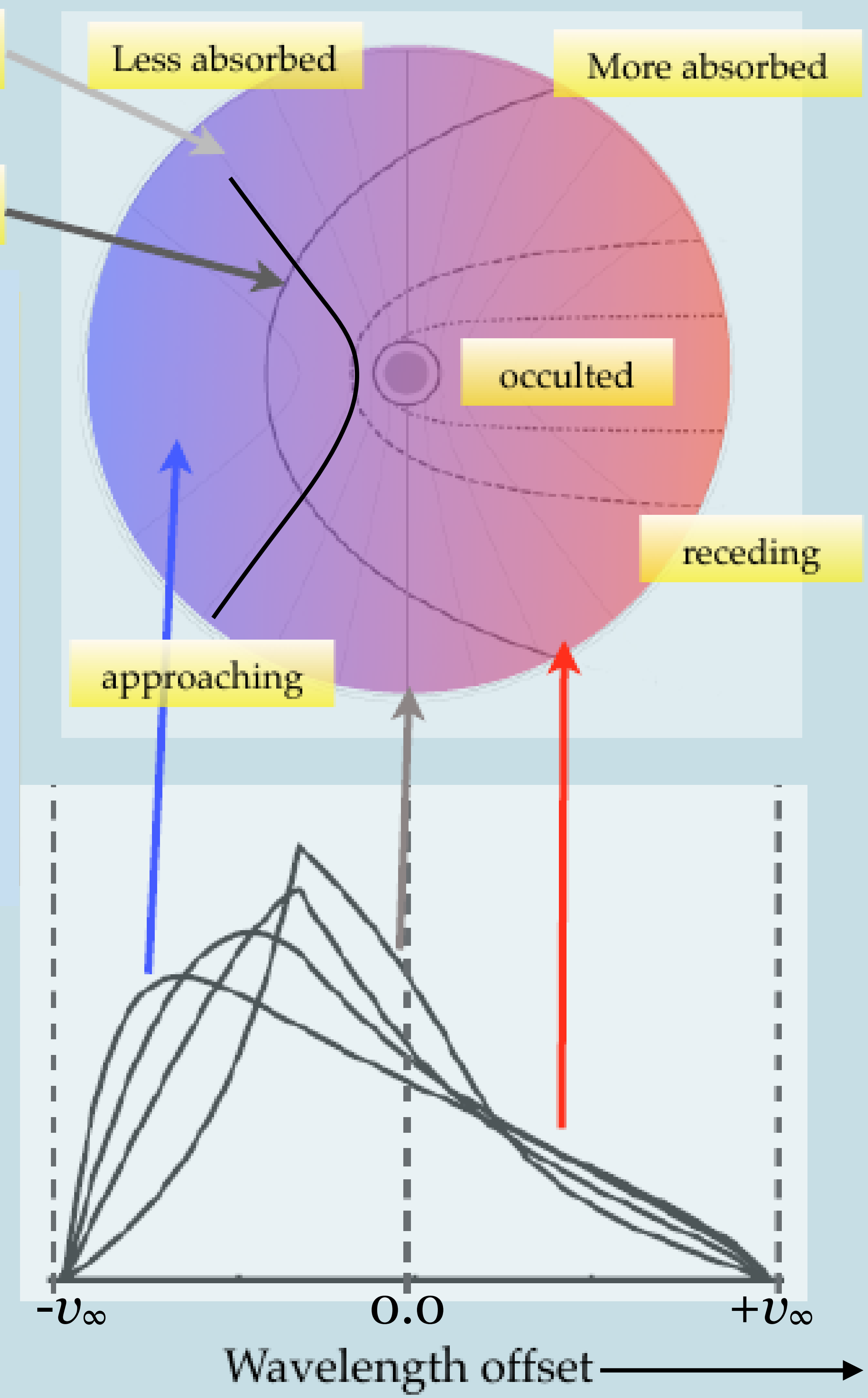
Starburst Region NGC 3603 (VLT ANTU + ISAAC)

ESO PR Photo 38a/99 (13 October 1999)

Problem: estimated *vs*. theoretical mass-loss rates (*$\dot{M}$*) can differ by *over an order of magnitude* (depending on model details).

High resolution X-ray spectra provide an *independent determination of wind properties* (relative to UV/Optical diagnostics).

Wind Line Profile Basics (for a smooth spherical wind)



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

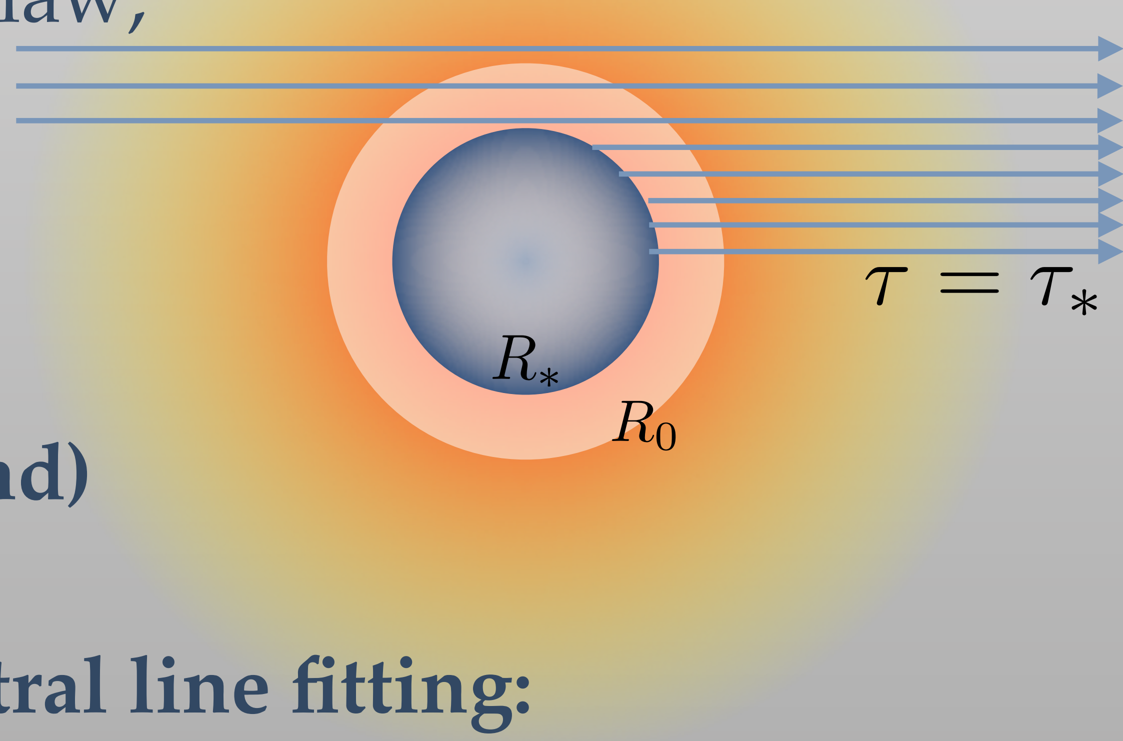
X-ray line formation is ***simple***: *no radiative transfer*! Coronal ionization equilibrium ("CIE"; collisional excitation from ground state, followed by radiative decay. Only continuum opacity in the wind).

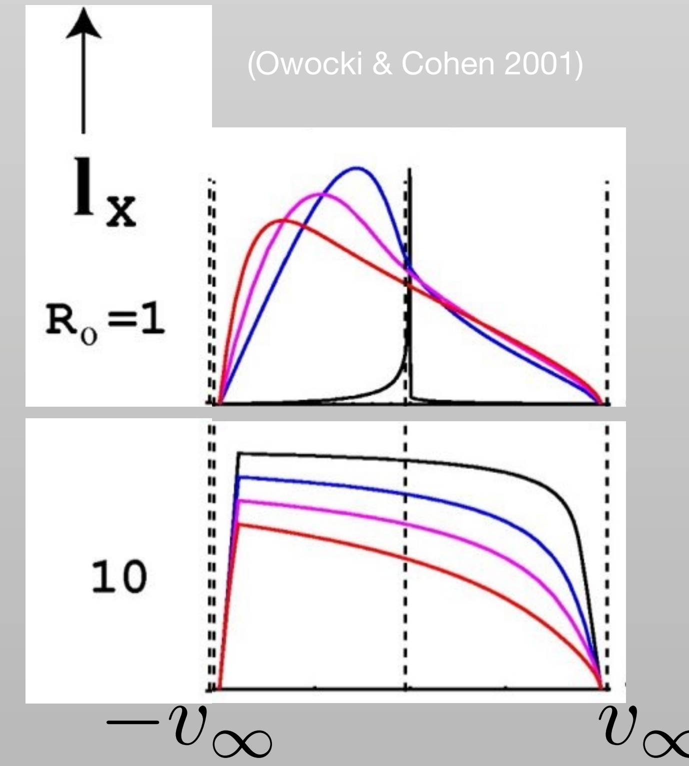
(MacFarlane et al 1991;
Owocki & Cohen 2001;
Cohen et al 2009)

X-ray spectral line fitting: $\tau_* = \frac{\kappa_\lambda \dot{M}}{4\pi R_*^2 v_\infty}$

Assume velocity law;
Assume opacity;
Fit v_∞, R_0, τ_*;
$\Rightarrow$ mass loss rate

(for a *smooth* wind)





UV/Optical spectral line fitting:

Model atmospheres, radiative transfer, in moving frame.
(*CMFGEN*: Hillier et al; *PoWR*: Hamann et al.)

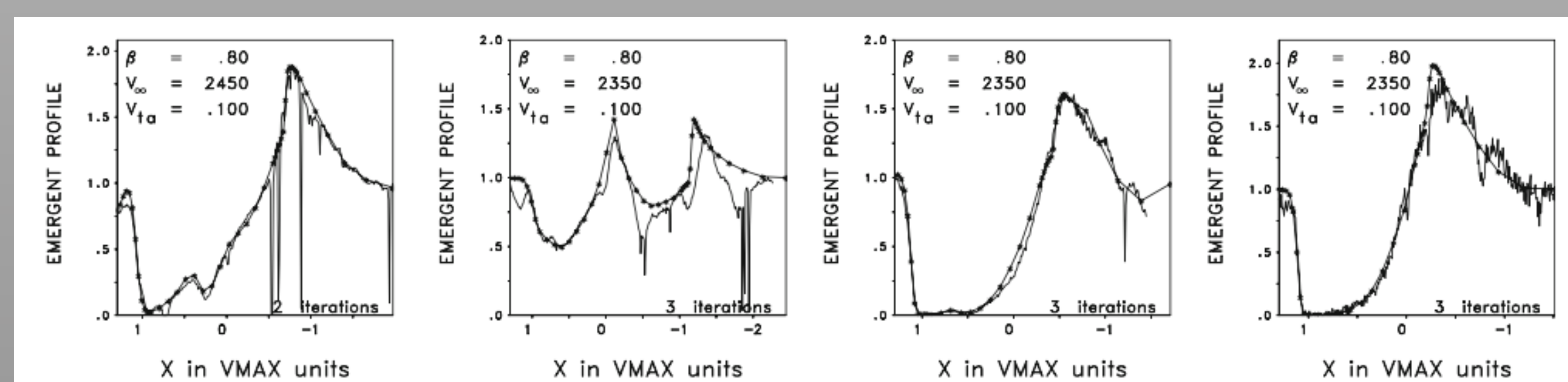


Fig. 8 SEI fits to the P Cygni profiles of O VI, P V, N V and C IV of ζ Pup (O4I(f)) as observed by COPERNICUS (Morton and Underhill 1977). An almost unique solution with $v_\infty = 2,350\ \mathrm{km\,s^{-1}}$ and $\beta = 0.8$ is

(Puls et al 2008)

But …

Winds are *not* uniform.

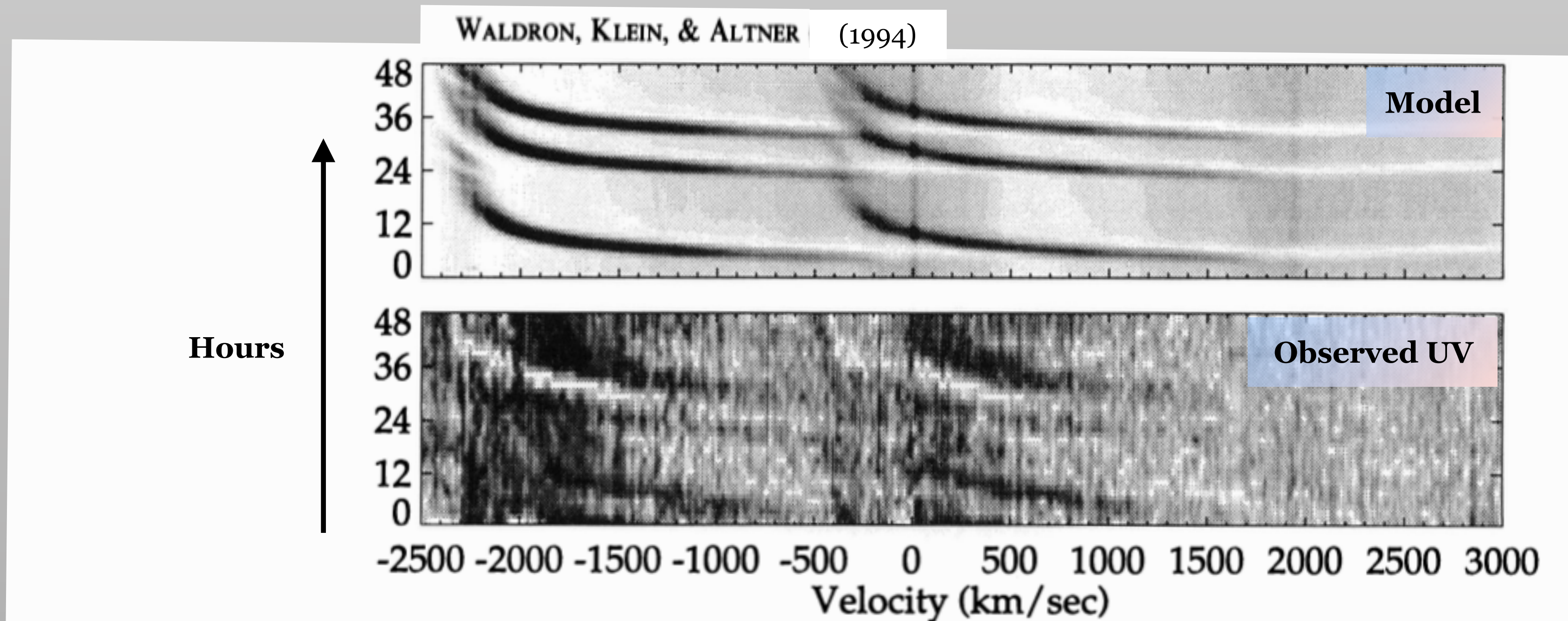


FIG. 8.—Gray-scale representations of the DACs in *IUE* short wavelength prime spectra of ζ Puppis (*bottom panel*) for the Si IV doublet

ζ Pup is variable.

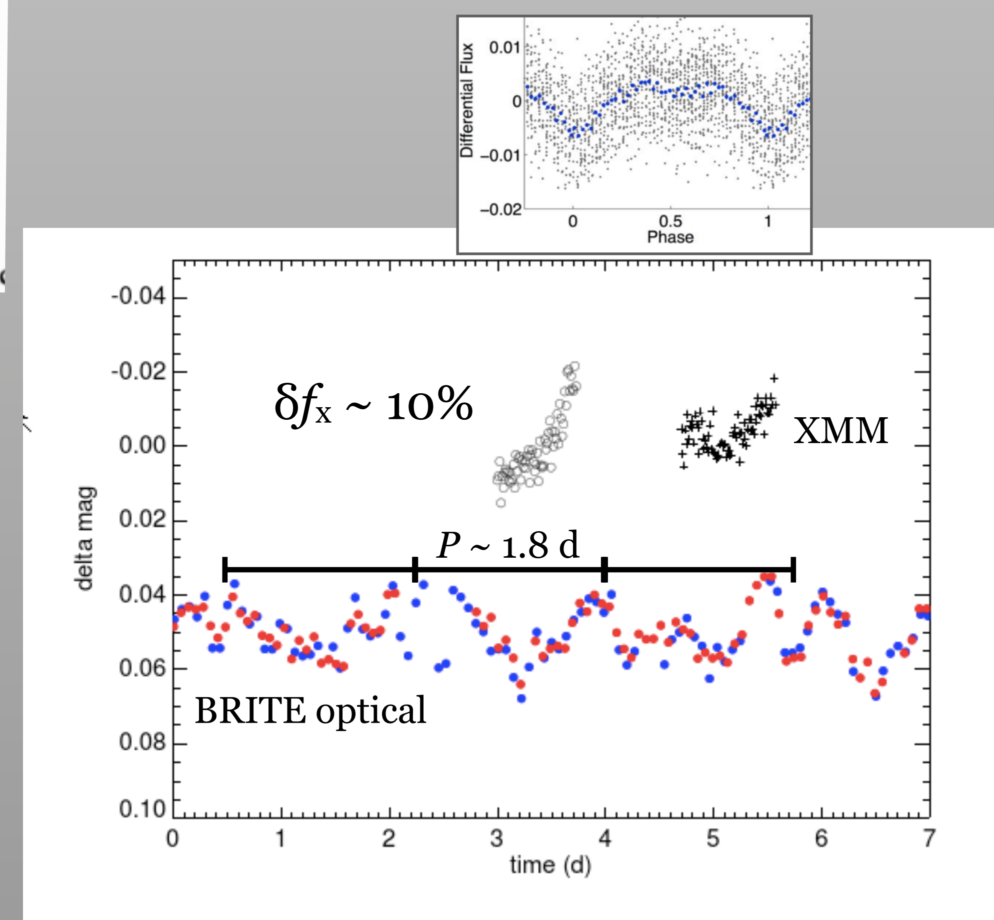
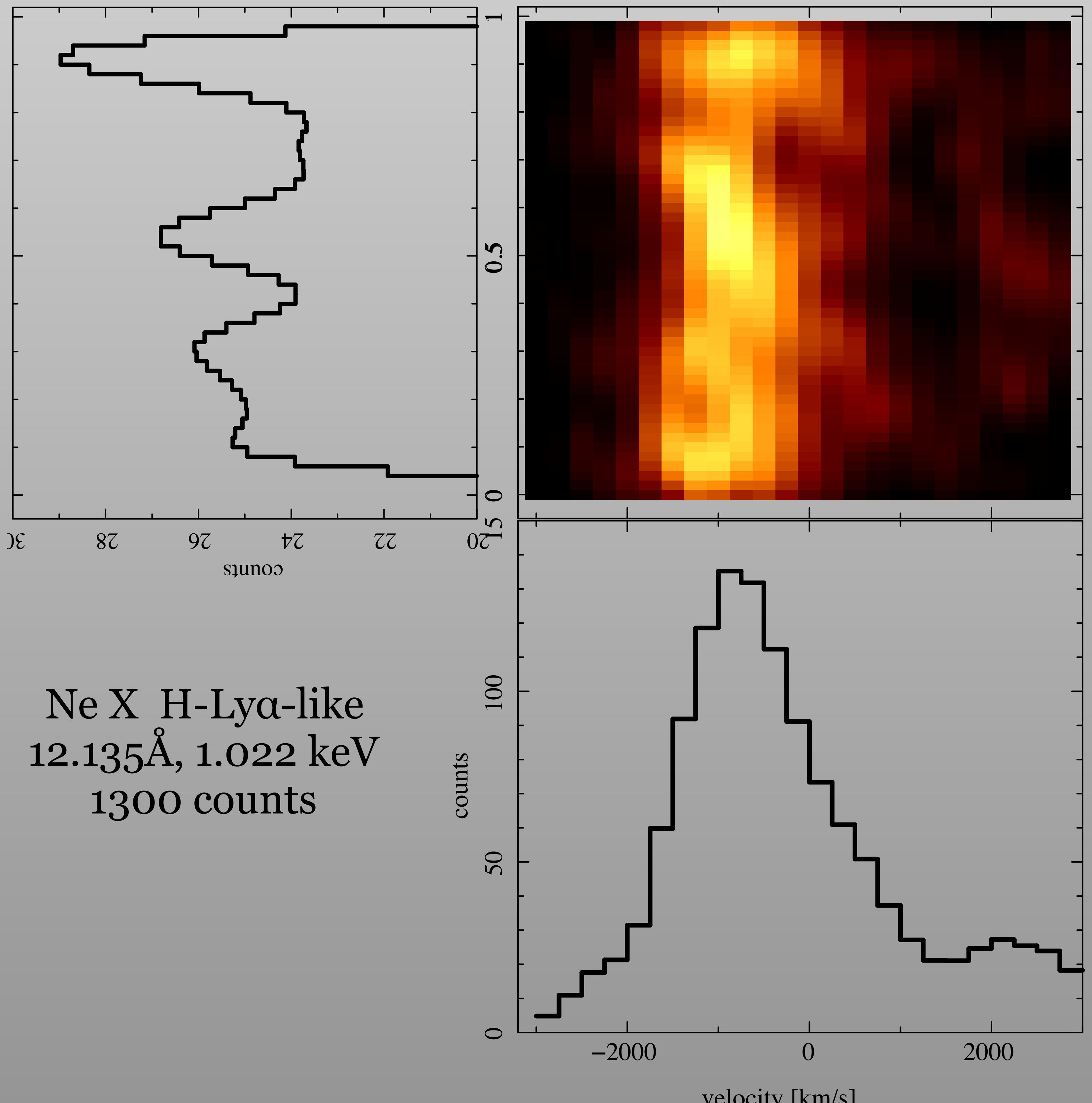


Figure 2: BRITE light curve (blue, red) with two examples of the X-ray variability from Nazé et al. (2013) with black symbols.

DAC: ***D**iscrete **A**bsorption **C**omponent*

CIR: ***C**o-rotating **I**nteraction **R**egion*

ζ Puppis, *Chandra*/HETG, 68 ks, 2000-03-28



Ne X H-Lyα-like
12.135Å, 1.022 keV
1300 counts

ζ Puppis, *Chandra*/HETG, dynamic profiles.

Ne X + Fe XVII | Fe XVII | Ne X

Observed

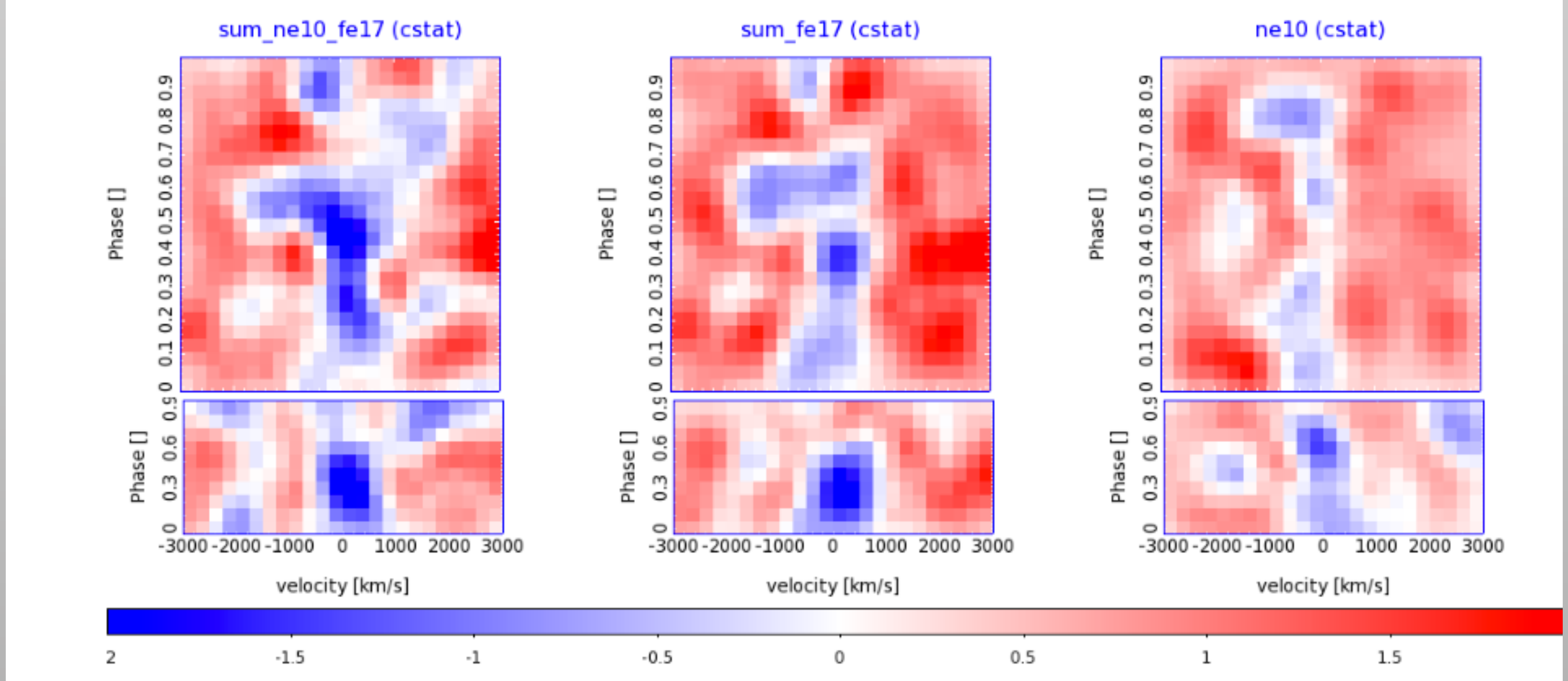


Figure 4: Dynamic spectra, observed, Cash stastic for different line groupings and time-binning (25, and 10 time bins)

Simulated (and constant)

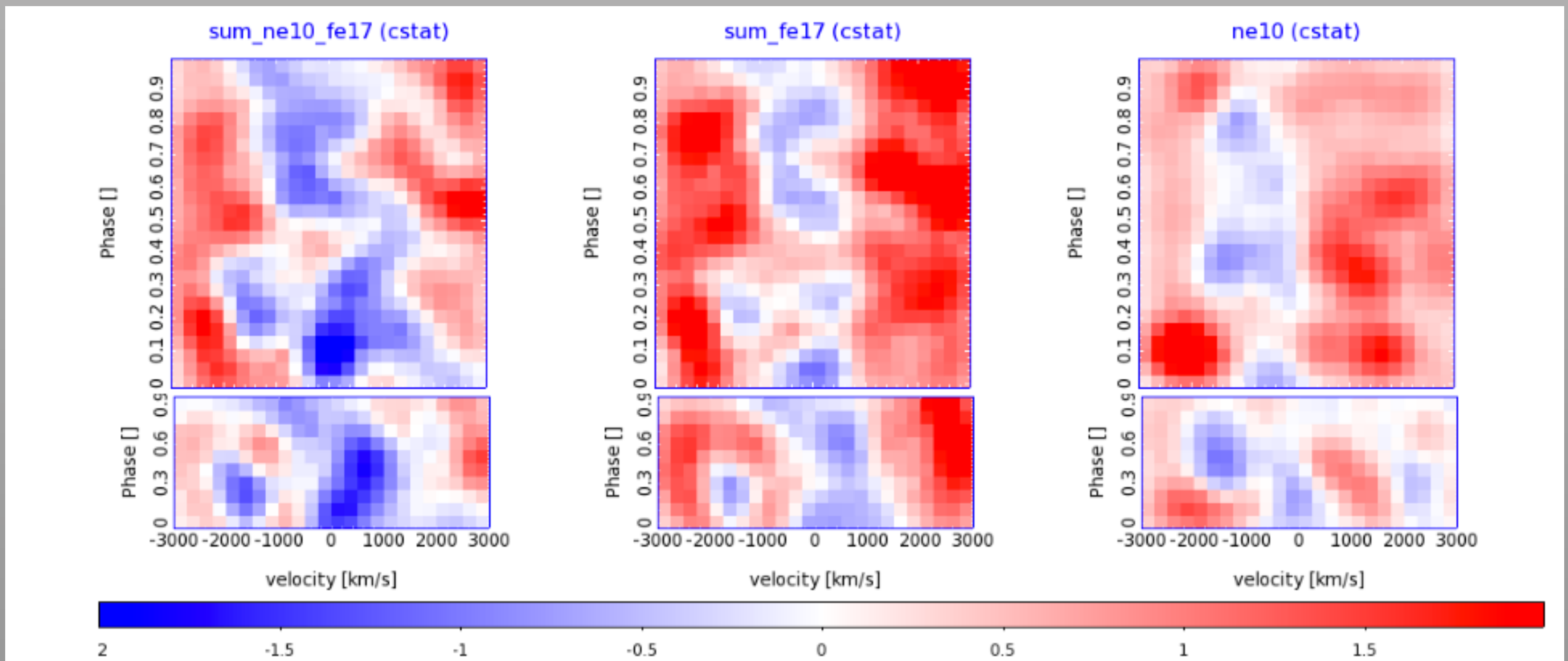
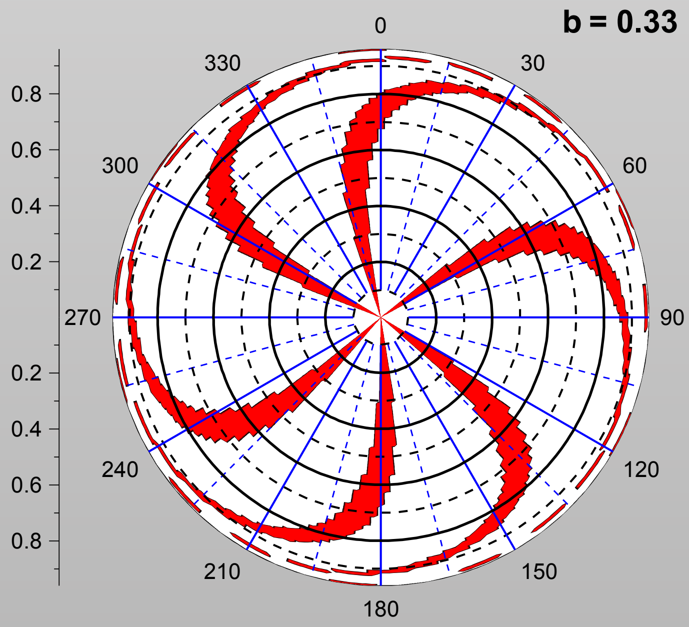


Figure 5: Dynamic spectra, faked constant, Cash stastic for different line groupings and time-binning (25, and 10 time bins)

Modeling in progress ...

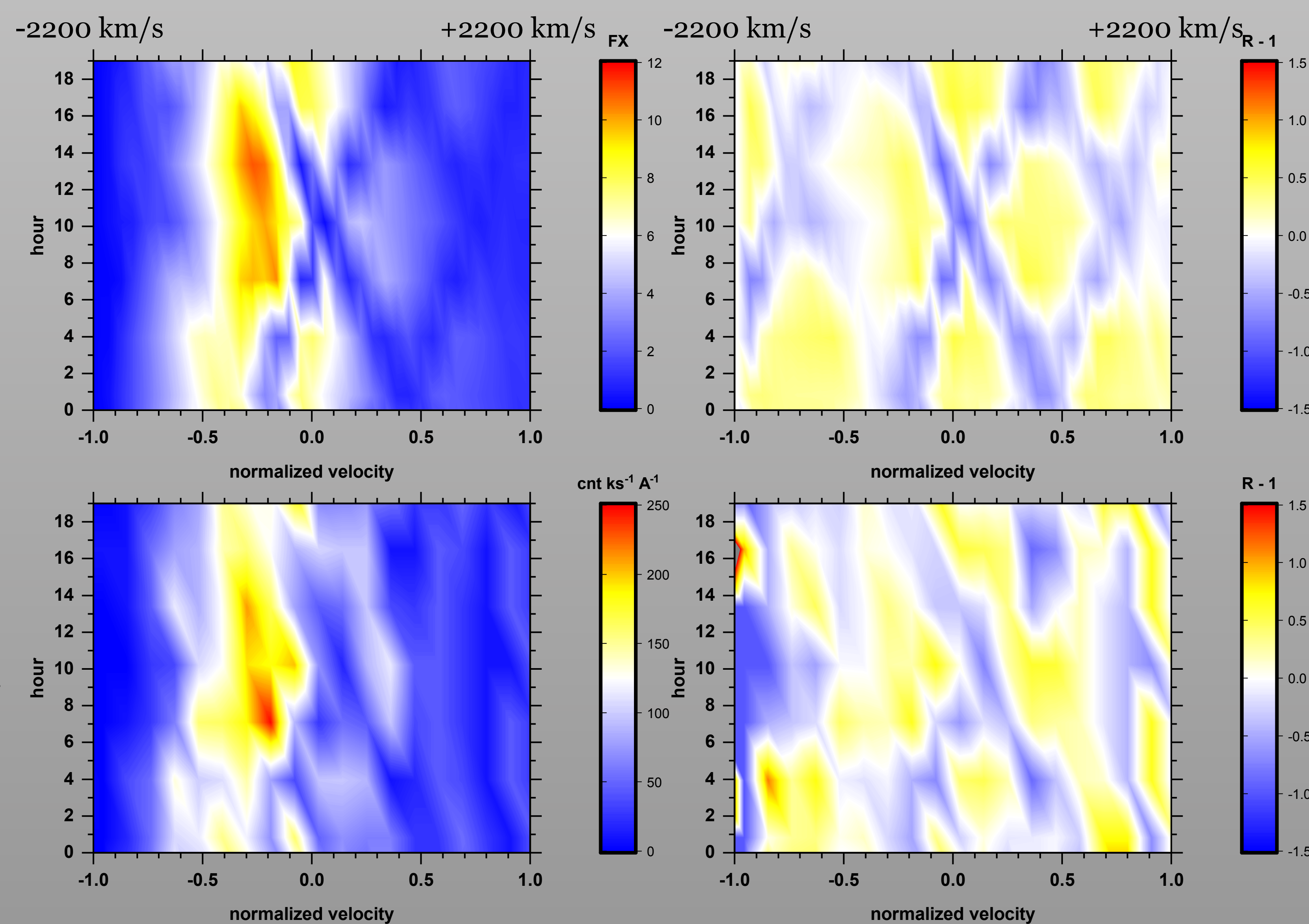


One model of structure; red represents holes in the wind — lack of X-ray absorption.

counts Ne X residuals

Model

Observed



Future Work

Lynx (or *Arcus)* could *easily obtain time-dependent profiles*. (Resolving power >1500, bandpass 0.3 — 6 keV to cover H- and He-like ions from C to Fe).

But in the mean time… *Chandra*/Cycle 19 review approved an
840 ks HETG observation of ζ Pup.

Mean profiles can distinguish clumpy from smooth models.

current data	simulated data, 840 ks

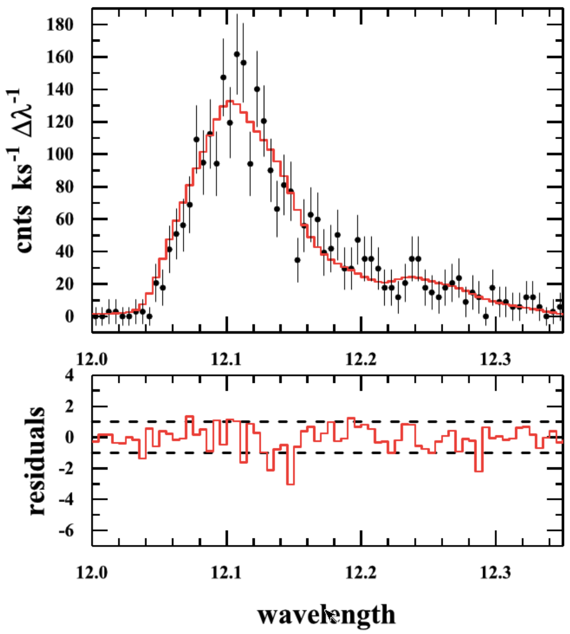


Figure 3: Comparison of the MEG Ne X region clump model (red) to a model simulation (black) of this region showing predicted cnts ks^{-1} $\Delta\lambda^{-1}$ ($\delta\lambda = 0.005$ Å). This is based on current exposure time illustrating the large errors per bin. The residuals = (model - simulated model) divided by the simulated error for each bin.

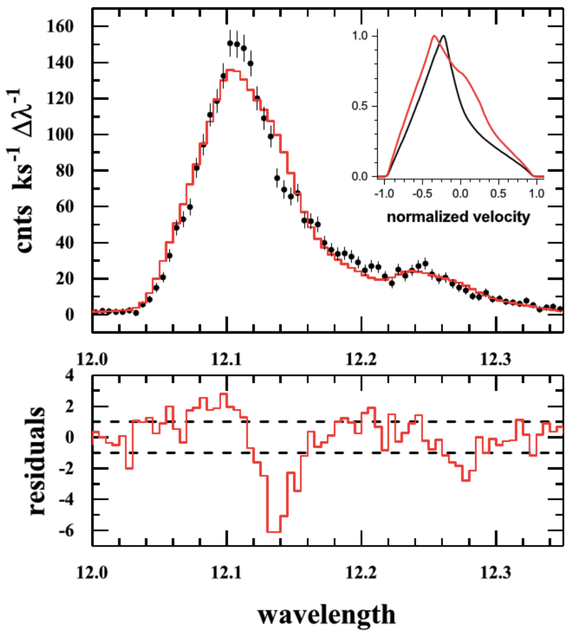


Figure 4: Same as Figure 3 except we use our requested exposure time. Clearly we will have the ability to differentiate models as evident in the predicted residuals. The inset shows the normalized theoretical line profile models used for these simulations as a function of the normalized velocity scale, i.e., 0 represents the line rest wavelength.

(Oskinova et al 2006)

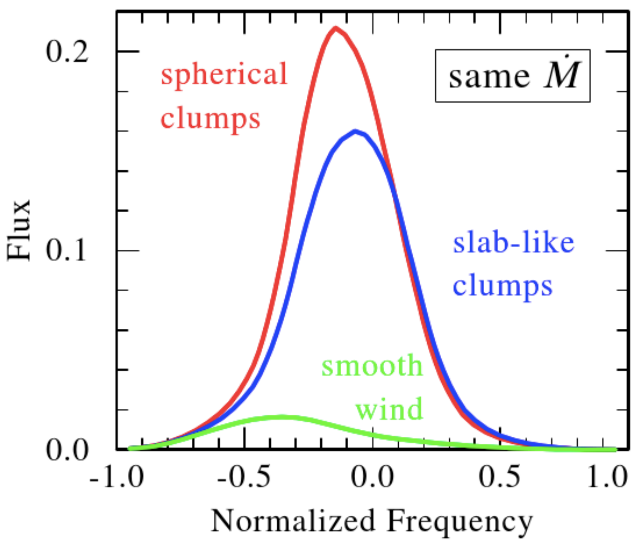


Figure 1. Model X-ray emission line profiles. The same stellar parameters were assumed for all three profiles, except of different clumping properties as indicated.

We expect to obtain some long X-ray (~*P*) observations, with coordinated optical spectra (He II 4686) and photometry (BRITE).

Team of observers & theorists:

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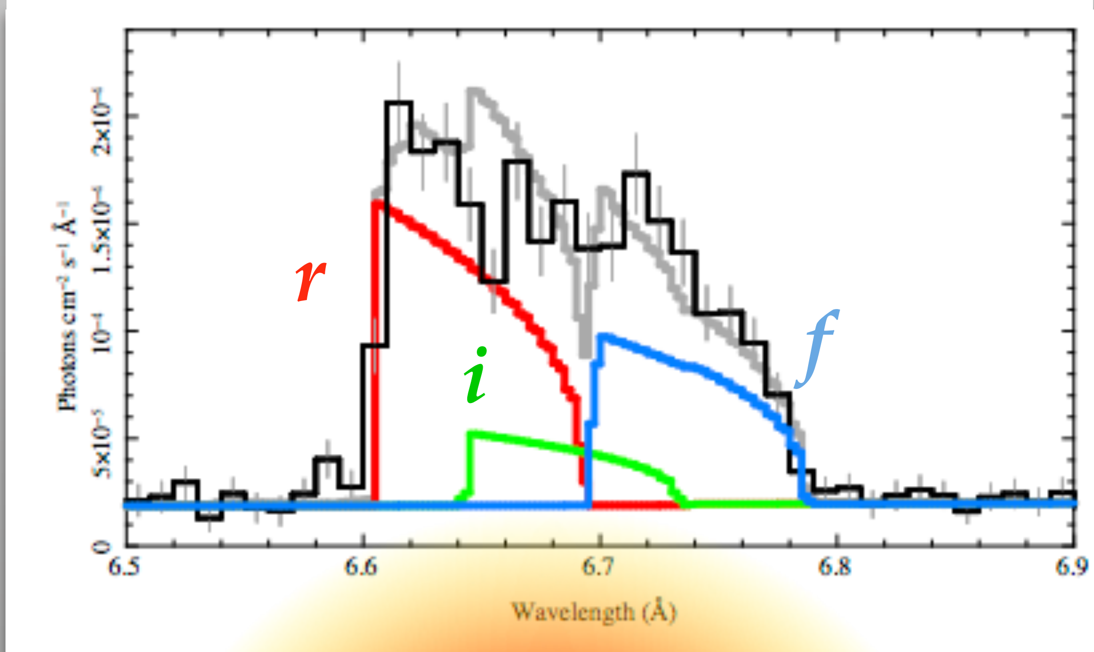
Matthew Dahmer	SAO
Ken Gayley	U. Iowa
Wolf-Rainer Hamann	U. Potsdam
David Huenemoerder	MIT
Richard Ignace	ETSU
Jen Lauer	SAO
Nathan Miller	U. Wisc-EC
Anthony Moffat	U. Montreal
Yael Naze	U. Liege
Joy Nichols	SAO
Lida Oskinova	U. Potsdam
Noel Richardson	U. Toledo
Tahina Ramiaramanantsoa	U. Montreal
Tomer Shenar	U. Potsdam

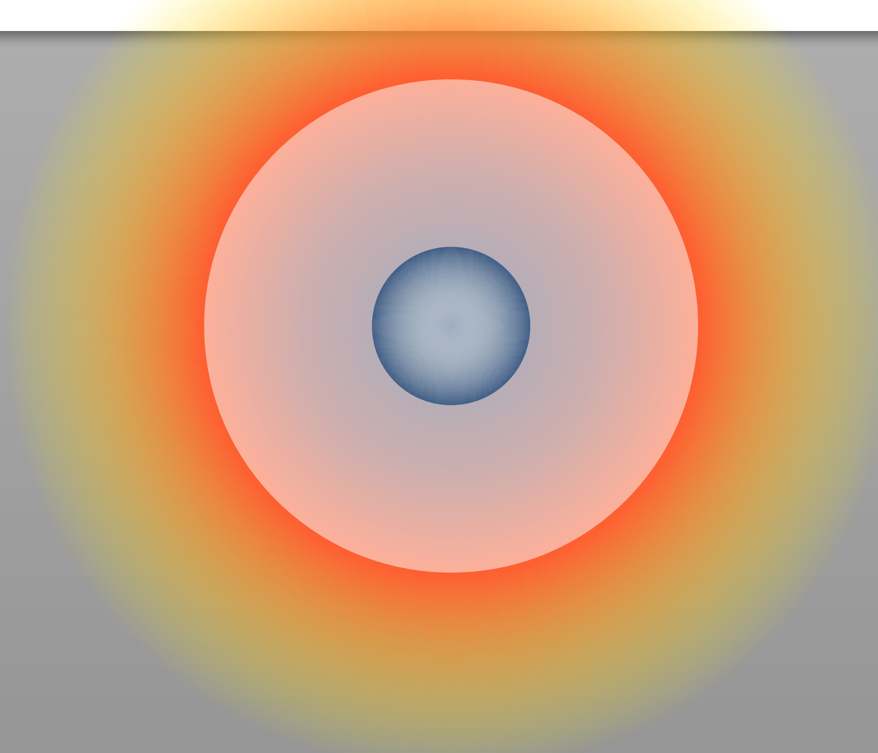
EXTRA Stuff

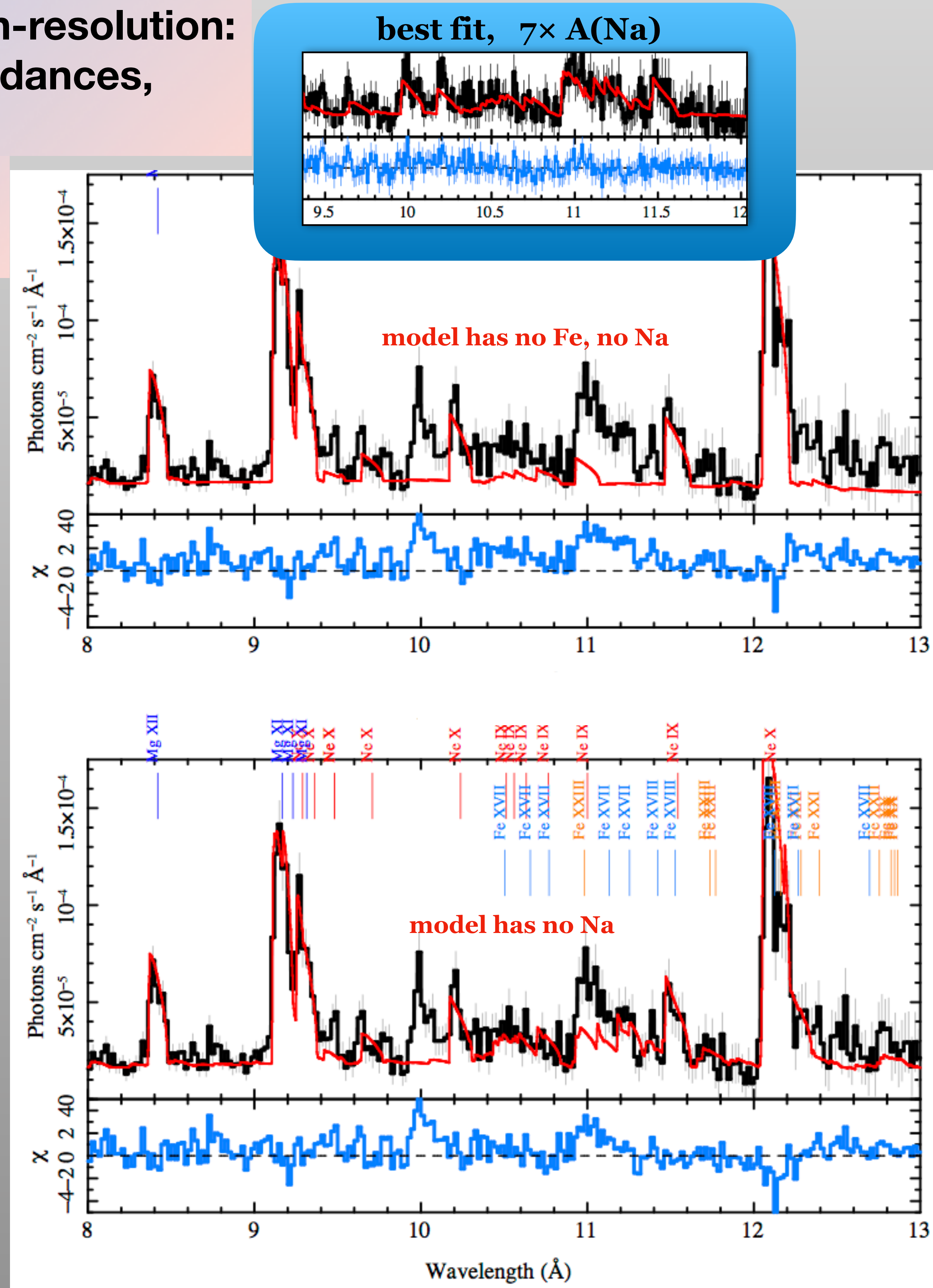
Another example of importance of high-resolution: WR-star (WR 6), line profiles, abundances, nucleosynthesis

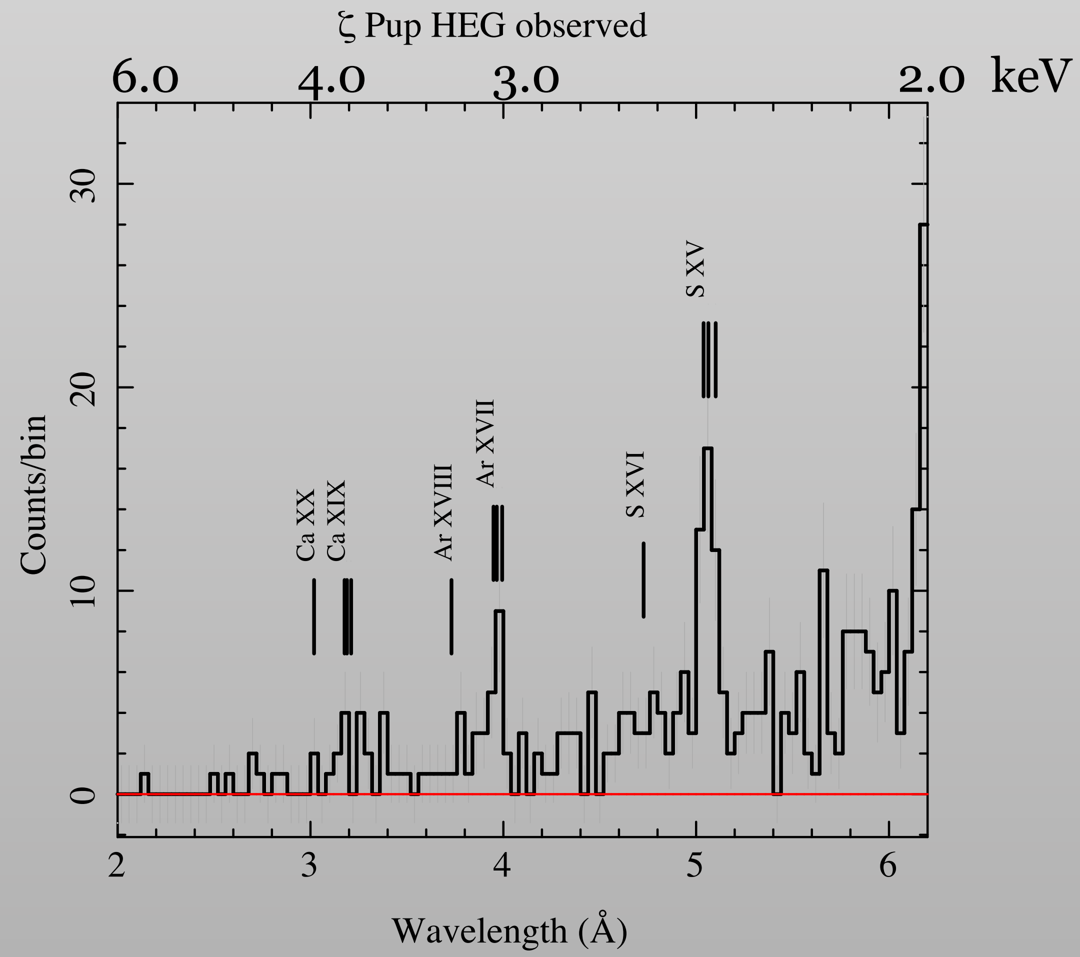
WR 6 (EZ CMa); WN 4, HETG 450 ks

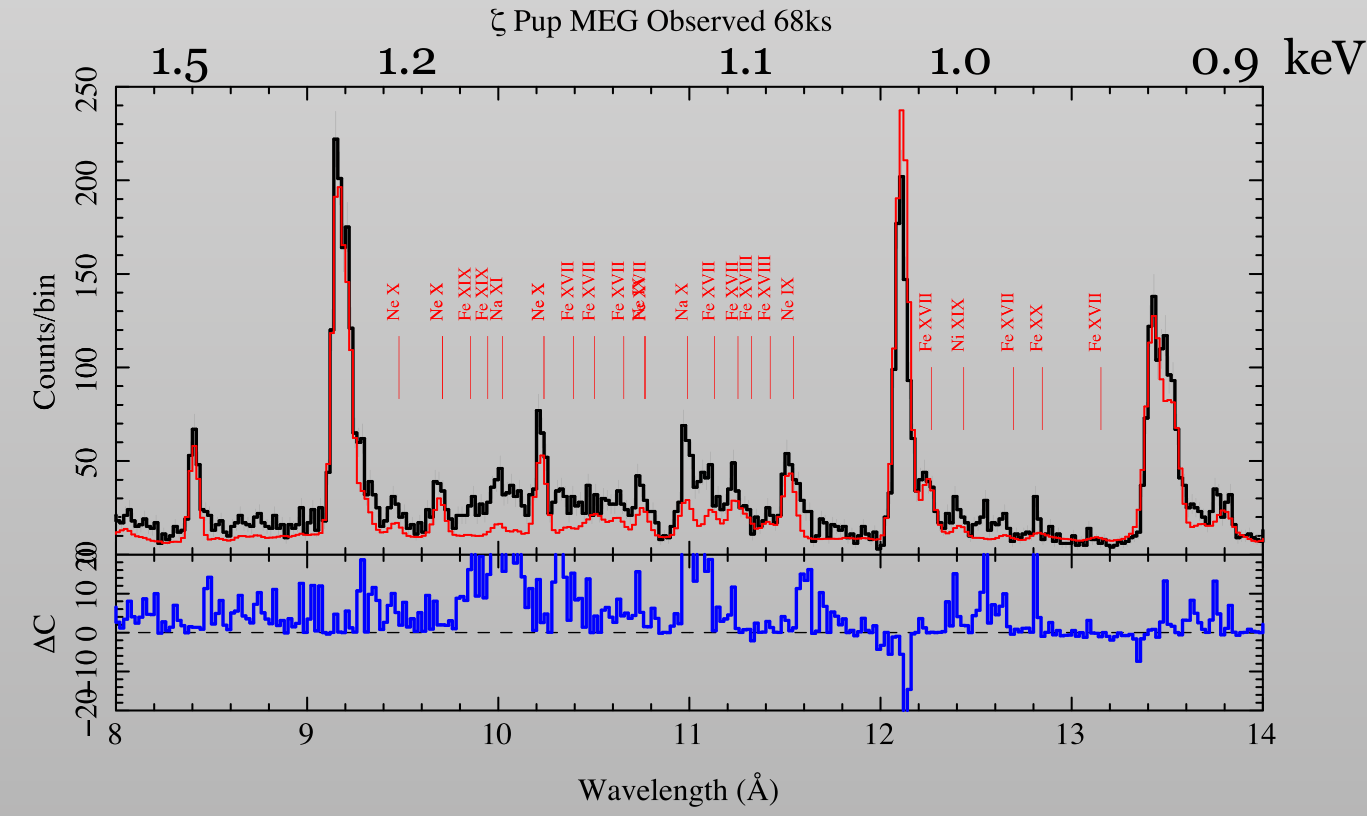
Profiles imply thick, uniformly expanding spherical wind





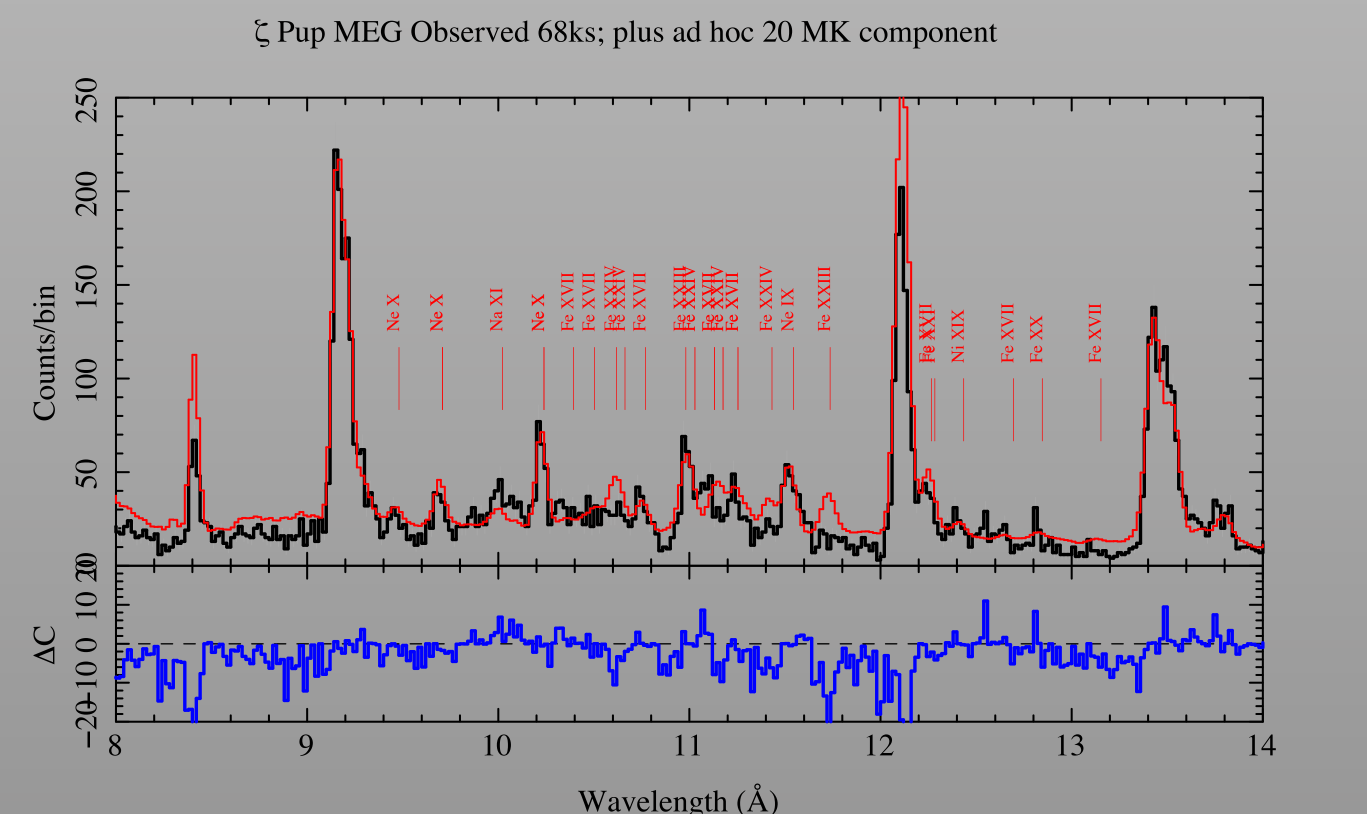




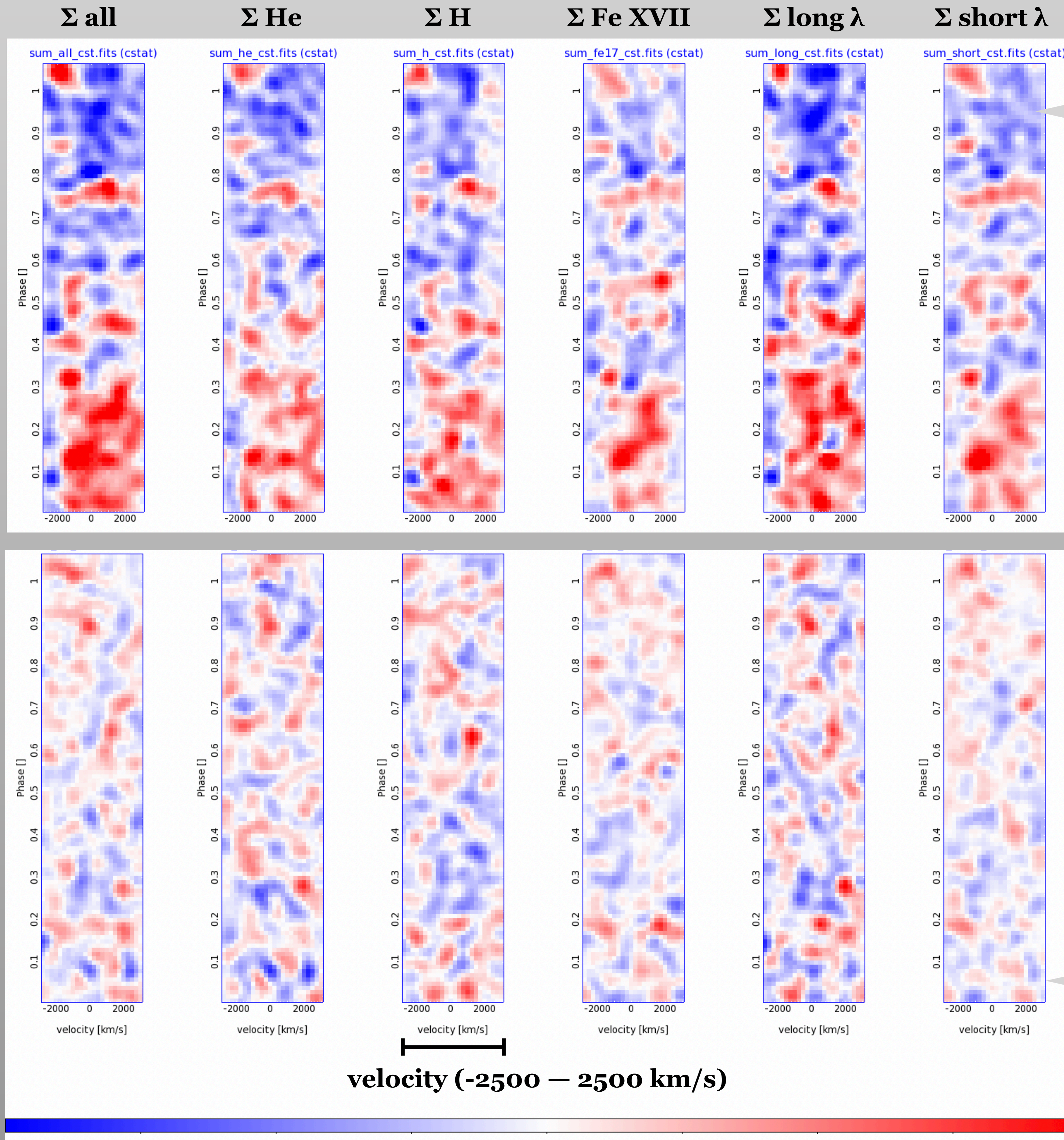


ζ Pup does have high temperature plasma (~20 MK, ~1.7 keV).

Need high-res and high sensitivity to model better (and look for variability).

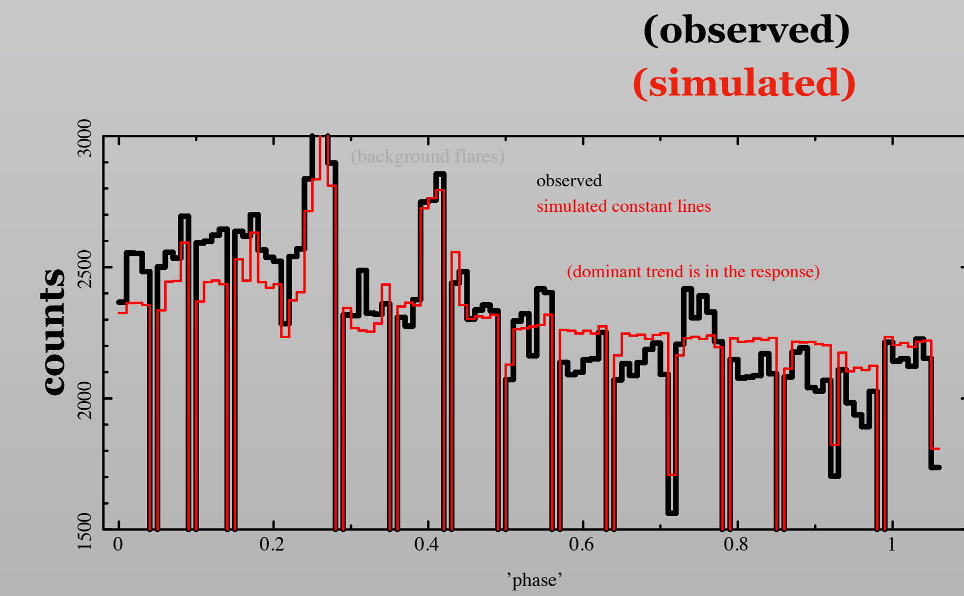


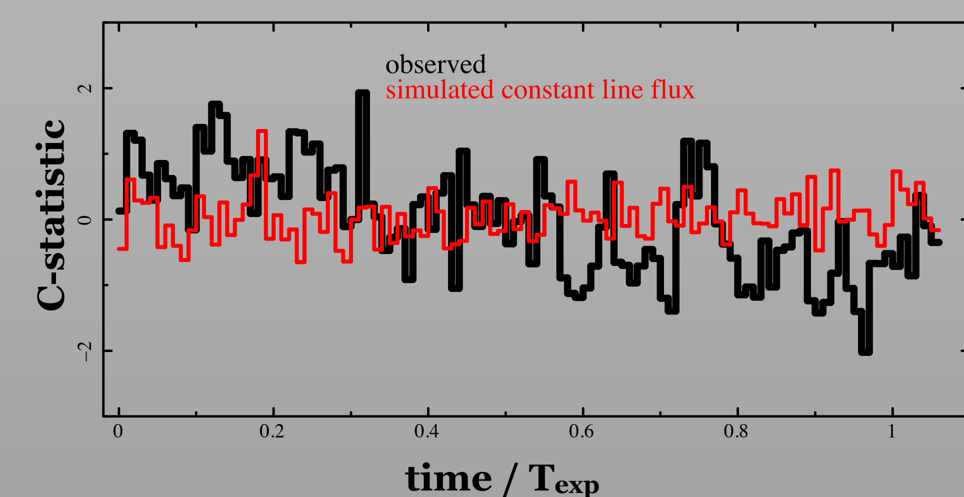
XMM/RGS Dynamic Line Spectra of ζ Puppis

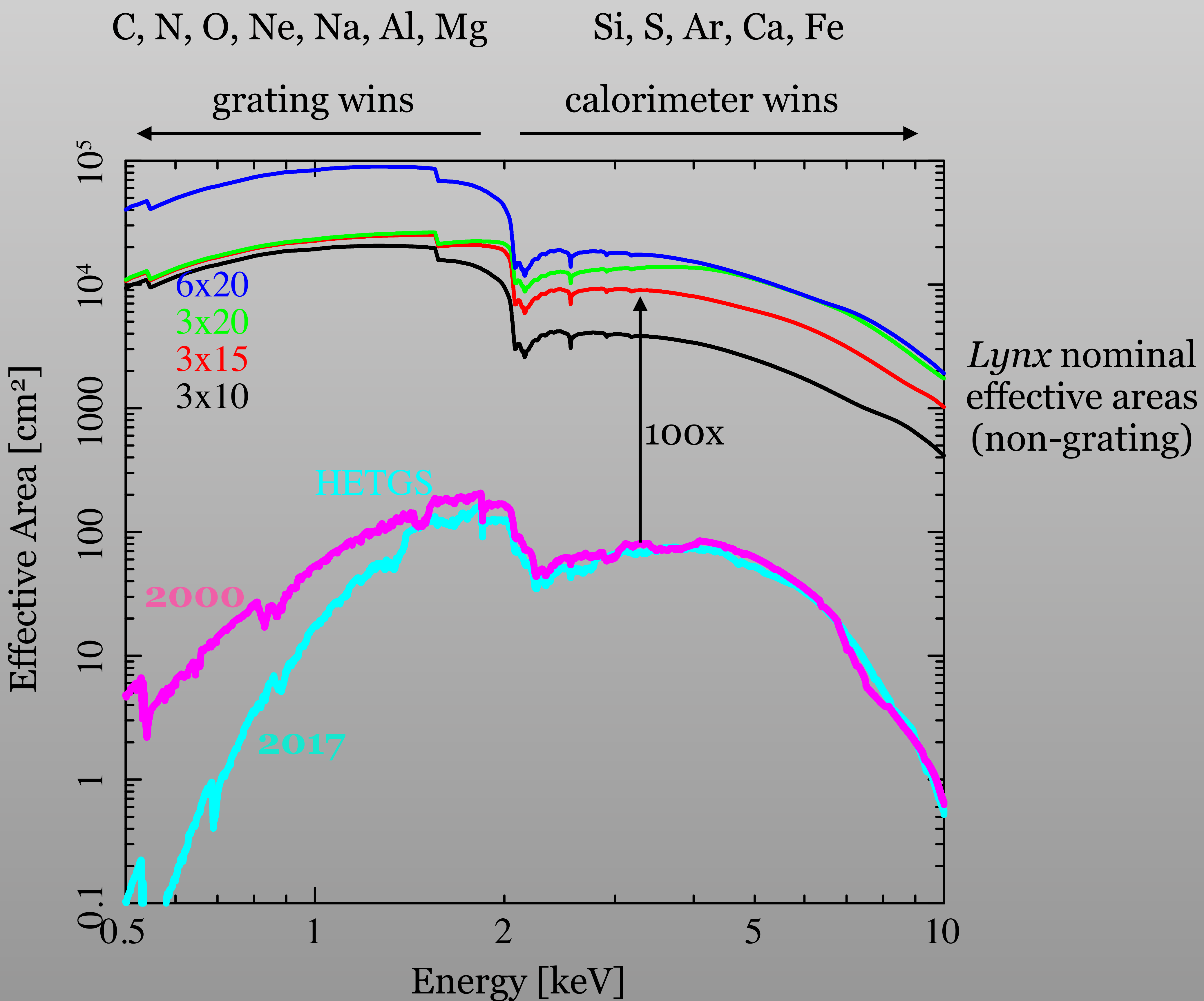


observed

simulated







C, N, O, Ne, Na, Al, Mg
Si, S, Ar, Ca, Fe
grating wins
calorimeter wins
6x20
3x20
3x15
3x10
100x
Lynx nominal effective areas (non-grating)
HETGS
2000
2017
Effective Area [cm²]
Energy [keV]
0.1
1
10
100
1000
10⁴
10⁵
0.5
1
2
5
10