Survey of X-rays from Massive Stars Observed at High Spectral Resolution with Chandra

Joy Nichols
Harvard & Smithsonian CfA

Based on Pradhan et al., 2023, ApJ. accepted

Team:
Pragati Pradhan
David Huenemoerder
Richard Ignace
Joy Nichols
A.M.T. Pollock

Plan of Talk

- Summary of X-ray emission line profiles in massive stars
- Sample of stars
- Methods of Data Analysis
- Line centroid and FWHM results
- FWHM vs V_{inf} and T_{eff}
- Other uses of the database
- Summary and Conclusions

Stellar Winds from Massive Stars

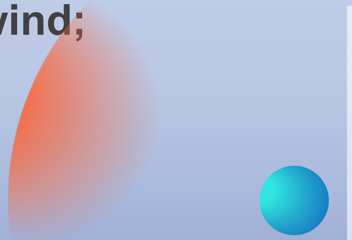
- Over their relatively short lifetimes, massive stars eject a significant portion of their mass in the form of stellar winds. The winds are driven by radiation pressure

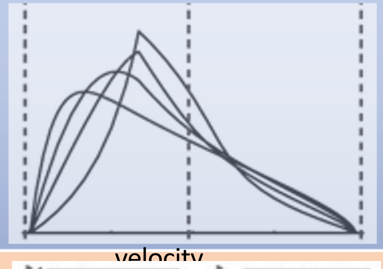
- Stellar winds play an important role in the evolution of their galaxy by enriching the interstellar medium repeatedly for each generation of stars

- A key mechanism used to explain multi-million degree gas in the winds is “line-de-shadowing instability (LDI).
- LDI can also explain the structure and clumping in the wind

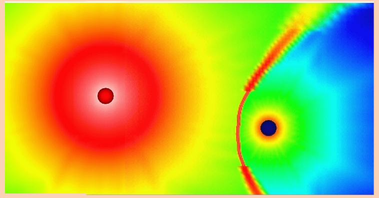
X-ray Line Profile Shapes in OB and WR stars

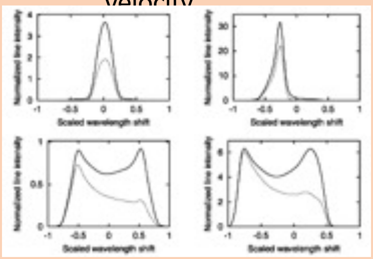
OB star line-driven winds: shocks embedded in the wind;
- broad lines, possibly non-Gaussian
- blue-shifted centroids
- suppressed forbidden lines (destroyed by UV flux)
- relatively cool (~2 MK)



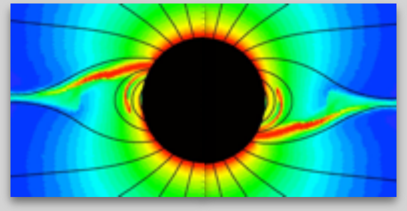


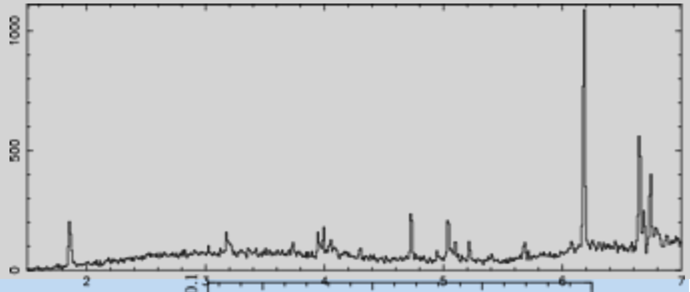
Binary systems — wind-wind collisions
- symmetric lines, or double-peaked lines
- relatively hot (~20 MK)
- strong forbidden lines
- strongly variable (geometric aspect)



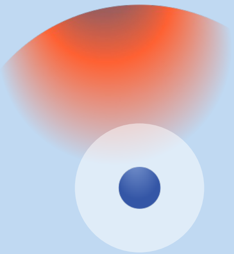


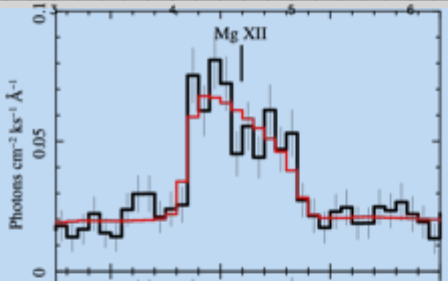
Magnetically confined winds:
- symmetric lines
- narrow, unshifted lines
- relatively hot (~20 MK)
- suppressed forbidden lines





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



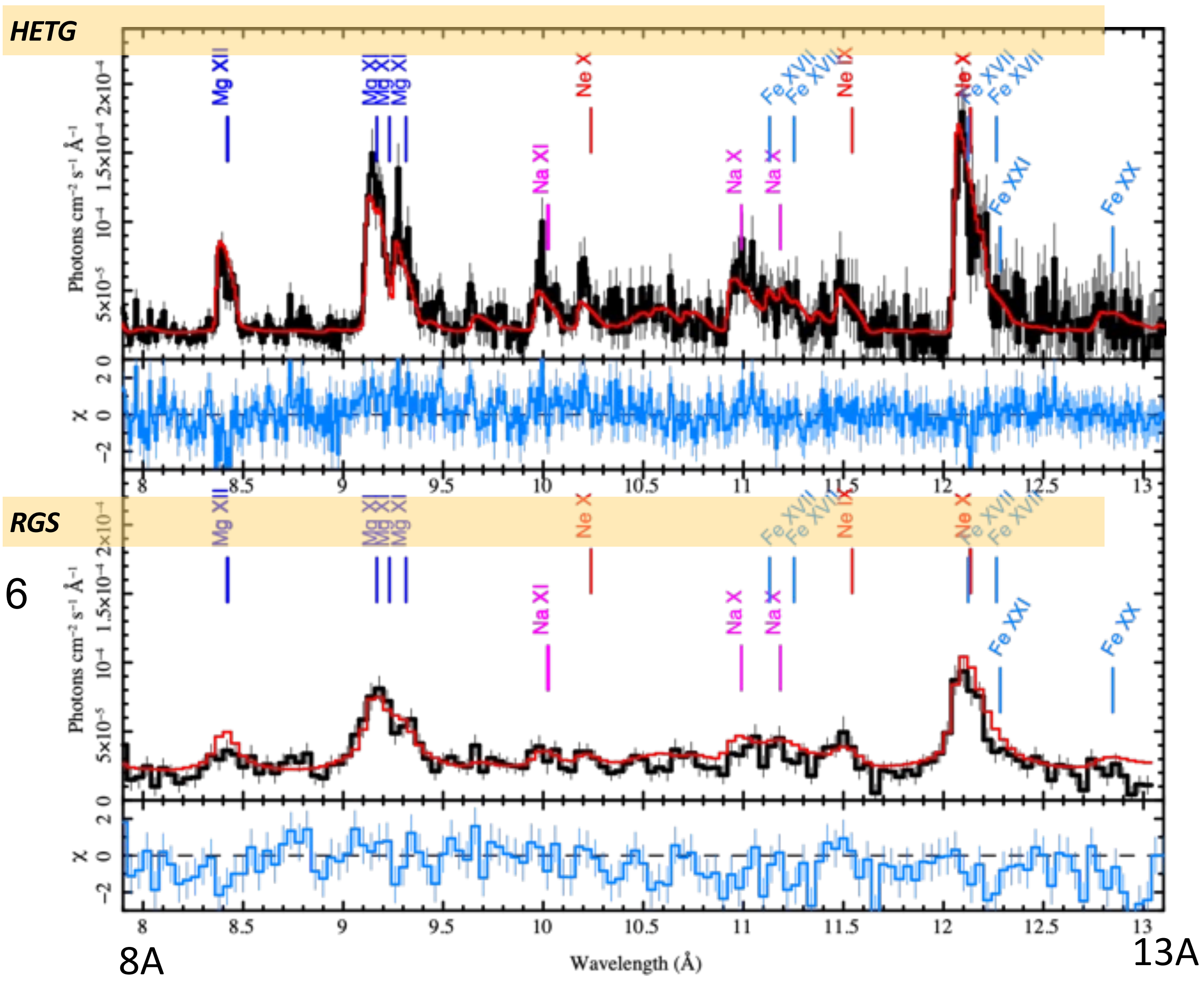


High resolution spectroscopy is essential for massive star research

Chandra HETG spectrum of WR 6

XMM-Newton RGS spectrum of WR 6

Insufficient for detailed profile shape fitting



(same photon flux scale; same model (red))

Selected sample of Stars

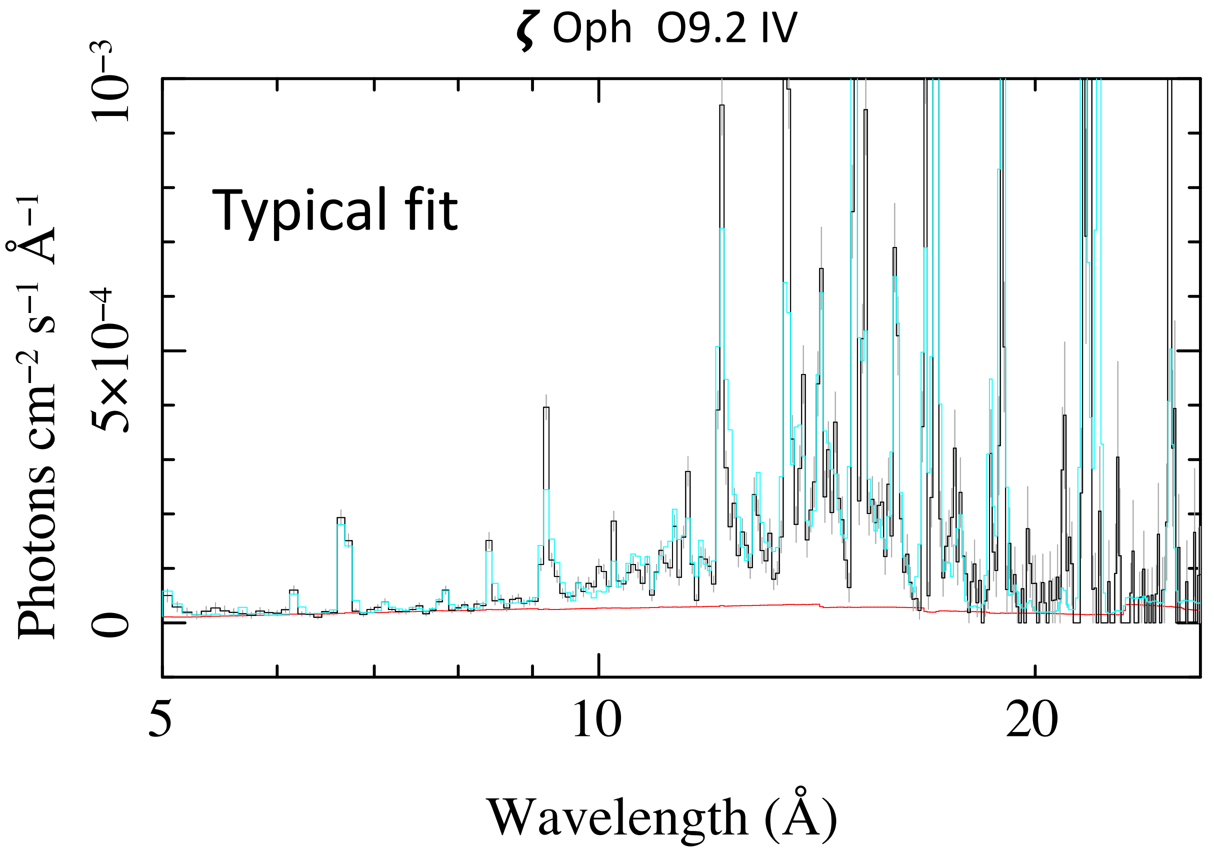
- Diverse sample from different investigations between 1999 and 2022
- criteria: - massive stars
  - HETG spectra available
  - sufficient S/N for line profile analysis

→ 37 OB+WR stars

- 25 O stars, 9 early B stars, 3 WR stars
- 8 probable single stars and 27 known binaries, and 2 of uncertain status
- 8 magnetic or magnetic candidate stars
- 3 ***γ*** Cas and analog stars
- 3 Cyg OB2 stars (anomalous characteristics)

Methods of Data Analysis

- CIAO tools scripted into the TGCat processing system
- Forward folding fit method to model spectrum
- Multi-temperature plasma model (cyan) used to define the continuum (red)
- Emission lines were fit with Gaussian profiles

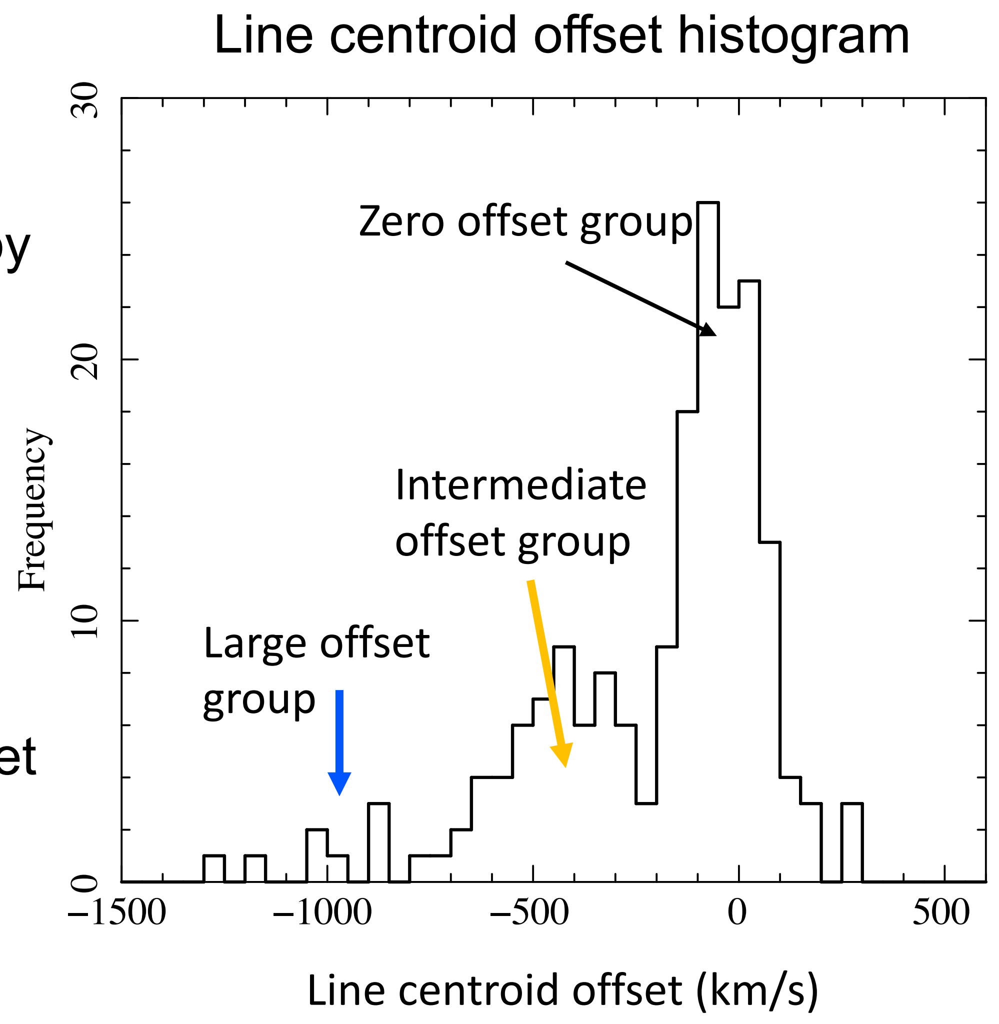


Line centroid offsets

Two fundamental wind diagnostics
1) Emission line centroid offsets, possibly blue-shifted by wind absorption
2) Line width, proportional to wind velocity

These are the primary products of our investigation

Resulting histogram shows three empirical groups
- group near v = 0 km/s → Low velocity offset
- group near v = -400 km/s → Intermediate velocity offset
- long tail of negative v → Large velocity offset

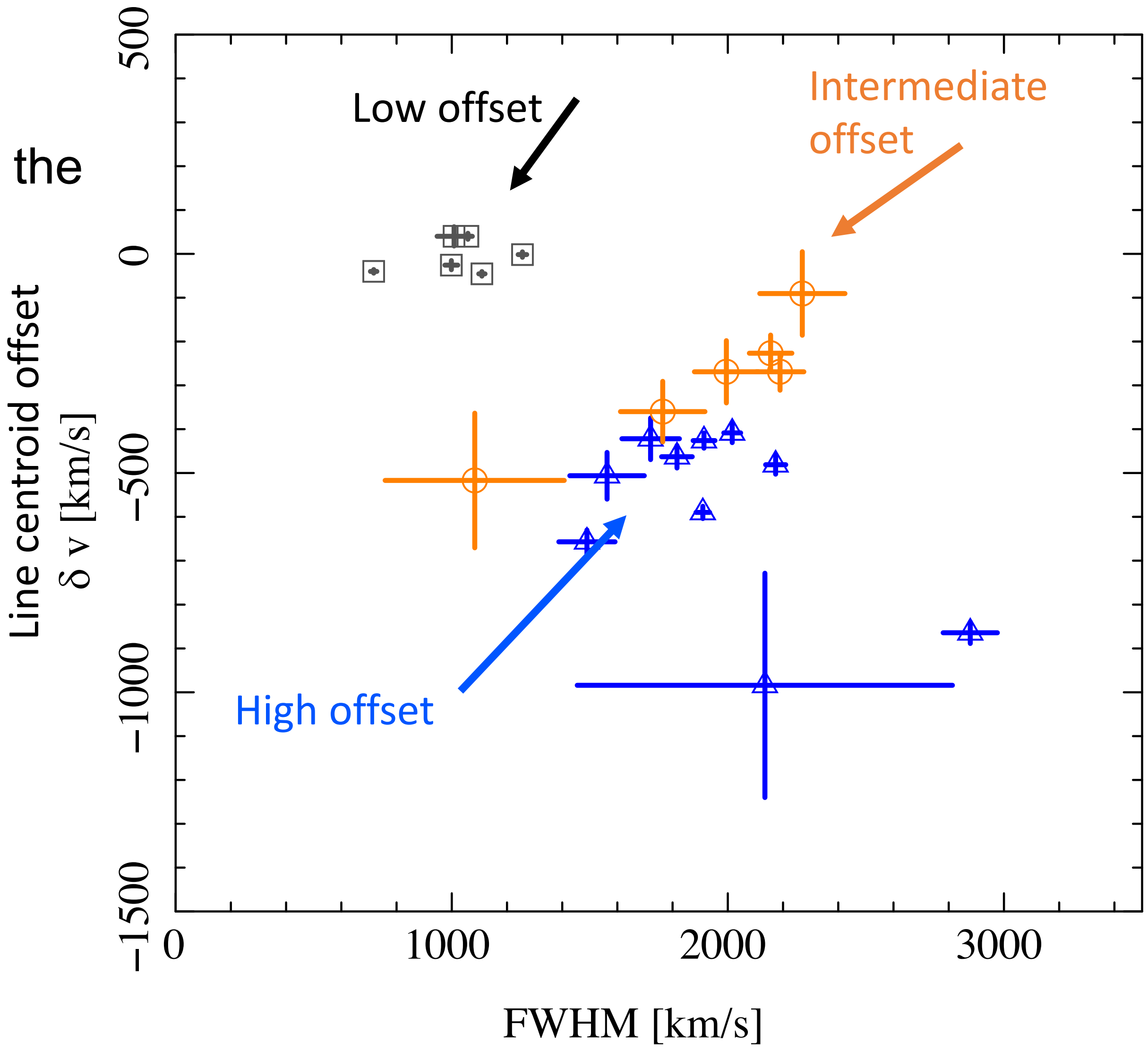


Line centroid offset vs FWHM of sample stars for 7.1-15.3Å

The centroid offset loosely correlates with the FWHM for the 3 subgroups

Black is "low" group,
Orange is "intermediate" group
Blue is "high" group.

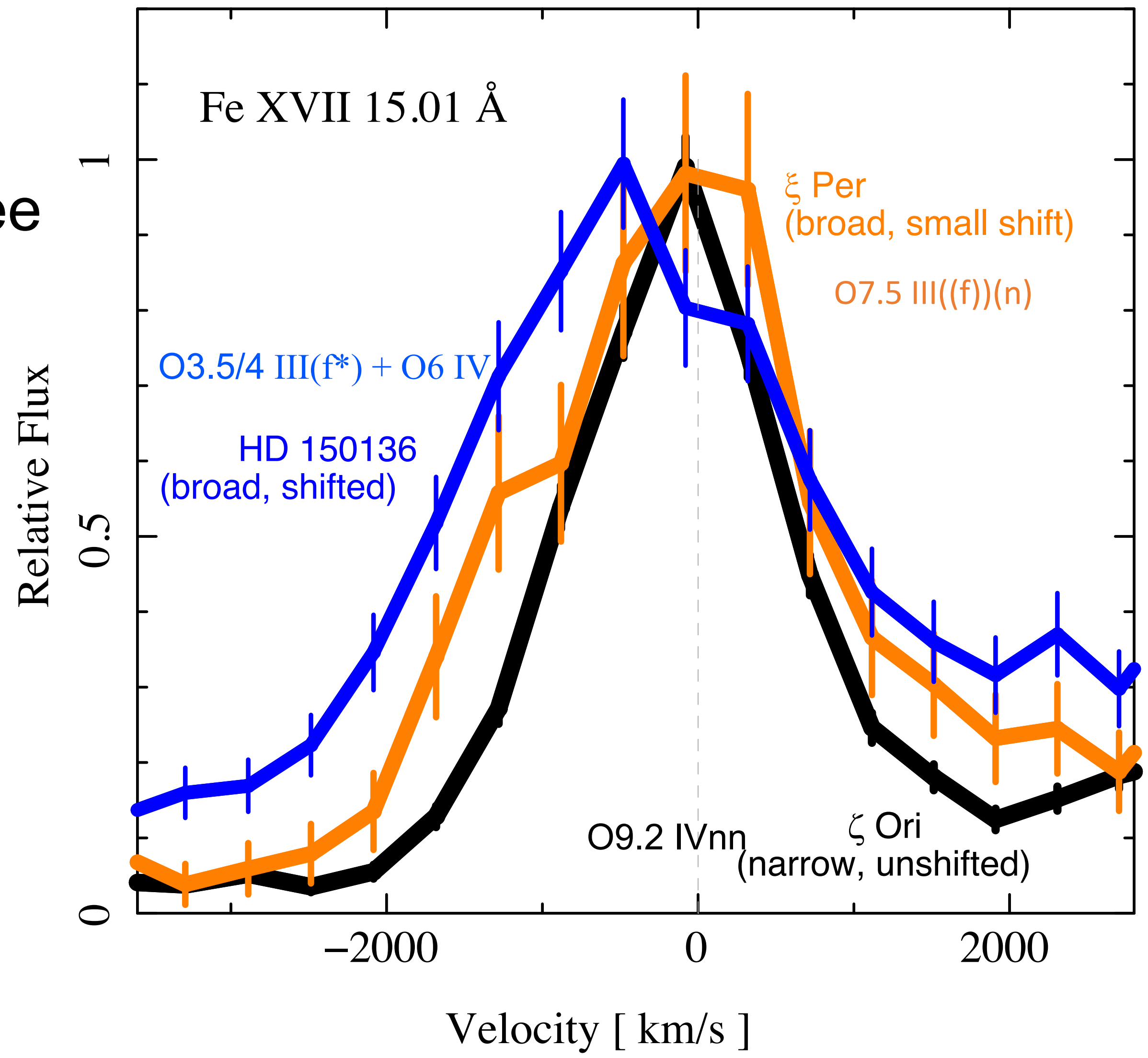
Trend: the larger the negative offset, the larger the FWHM of the emission line



Example Line Shapes for 3 Subgroups

Line profile from each of the three velocity-offset-selected groups

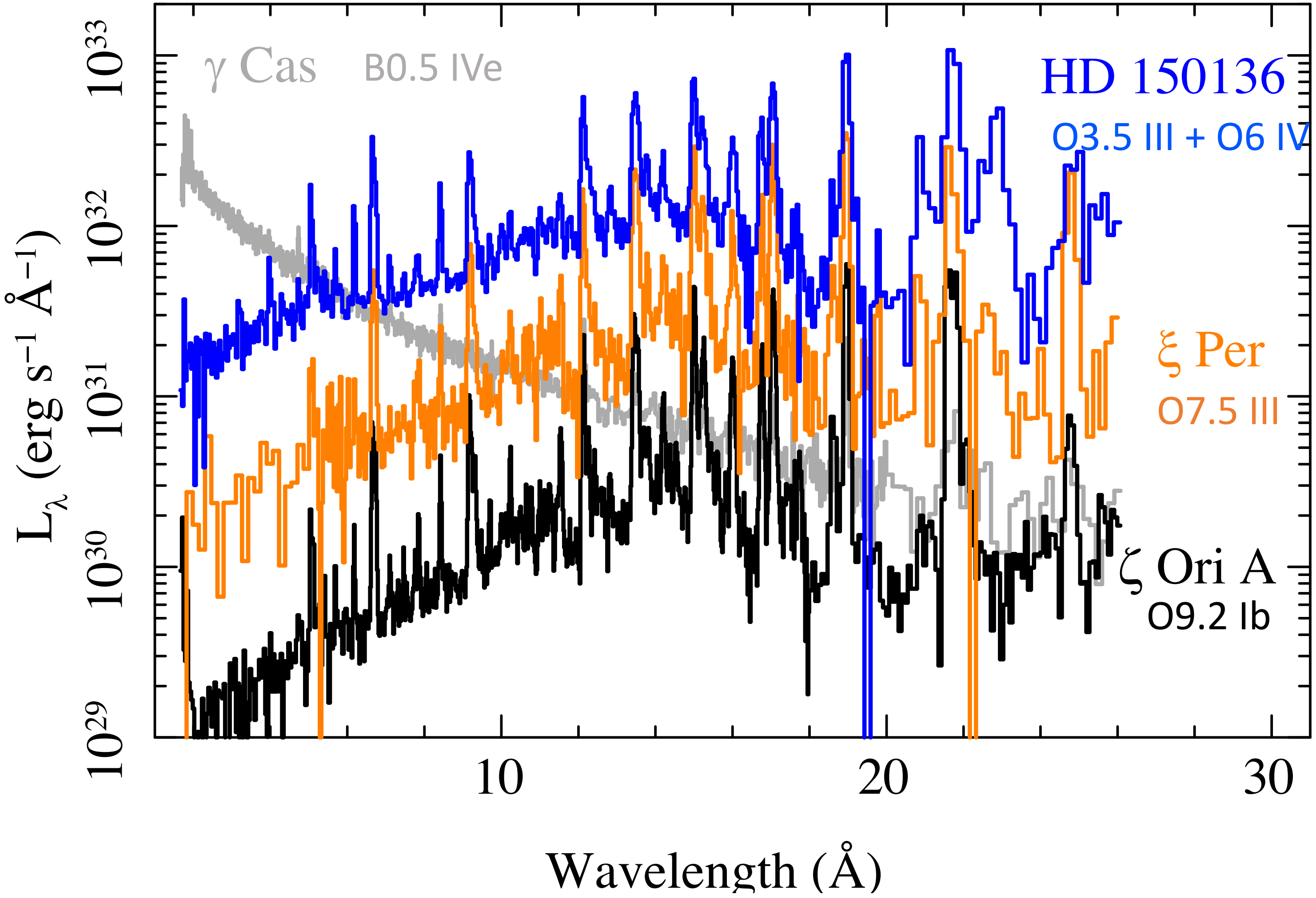
Black is “low” group,
Orange is ”intermediate” group
Blue is “high” group.



X-ray Luminosity Characteristics from each group

- X-ray luminosity vs wavelength has similar morphology for 3 examples
- A spectral break near 15 Å is suggested
- Above 20Å, apparent continuum flattening or even rise is artificial
- ***γ*** Cas spectrum shown for contrast

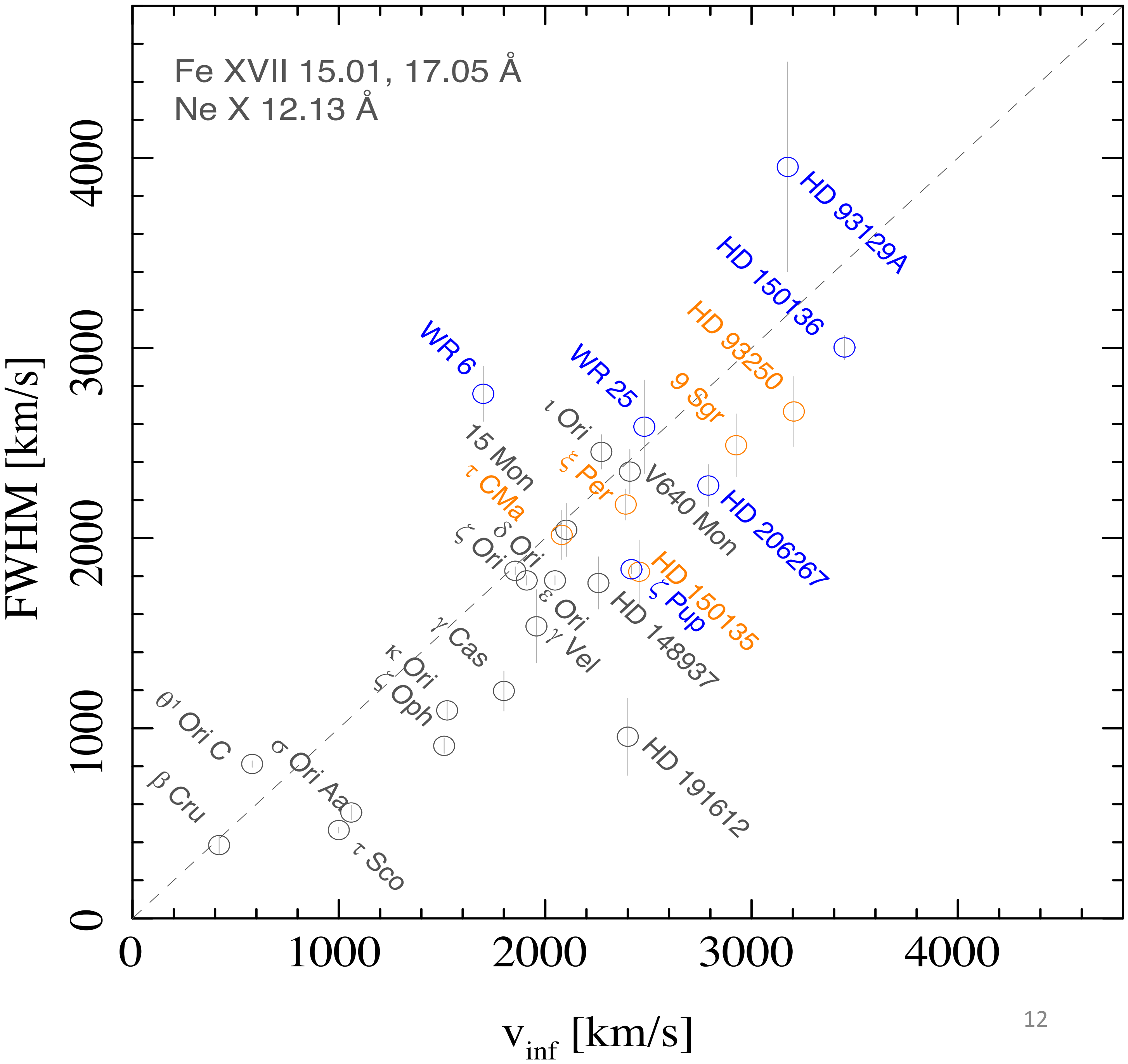
Black is "low" group,
Orange is "intermediate" group
Blue is "high" group.



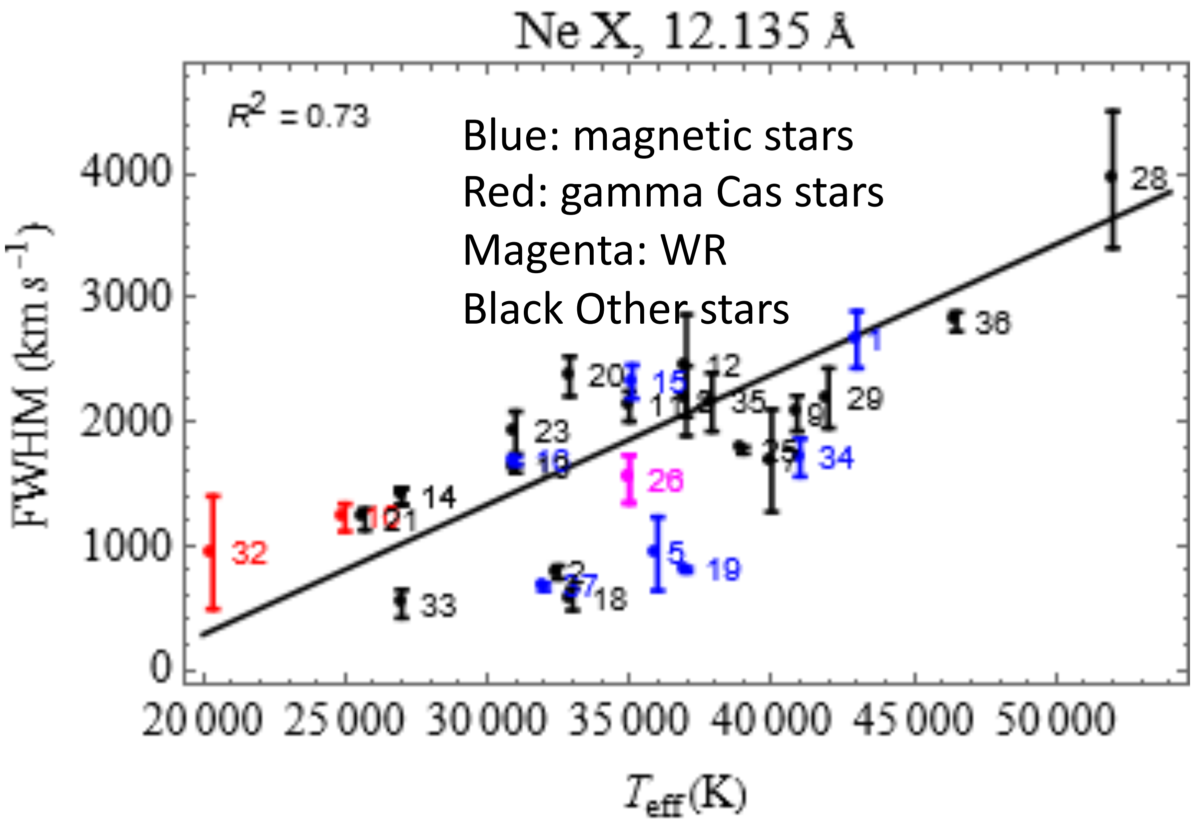
Line width is proportional to terminal wind velocity v_{inf}

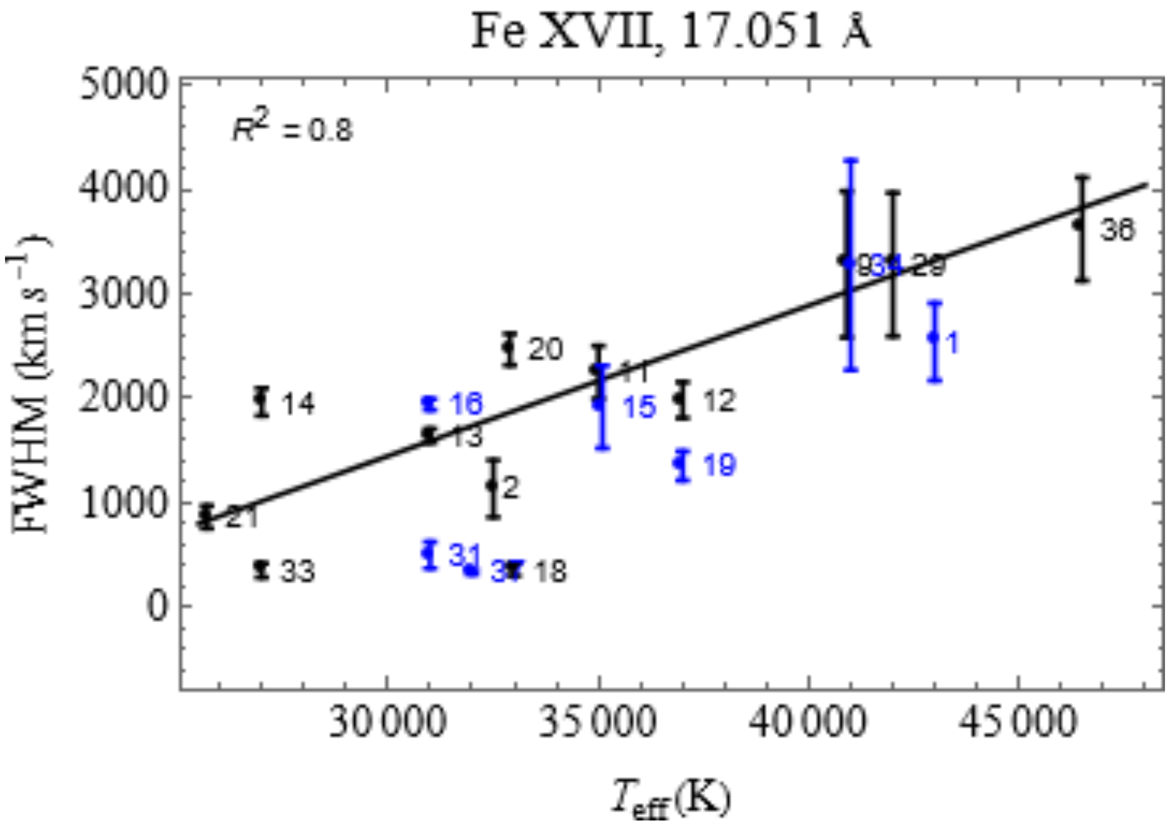
Terminal wind velocity from UV profiles vs the FWHM for Ne X, and Fe XVII (ƛ > 12Å)
(only sample stars with good FWHM measurements)

Black is “low” group,
Orange is ”intermediate” group
Blue is “high” group.



Line width is also proportional to T_{eff}





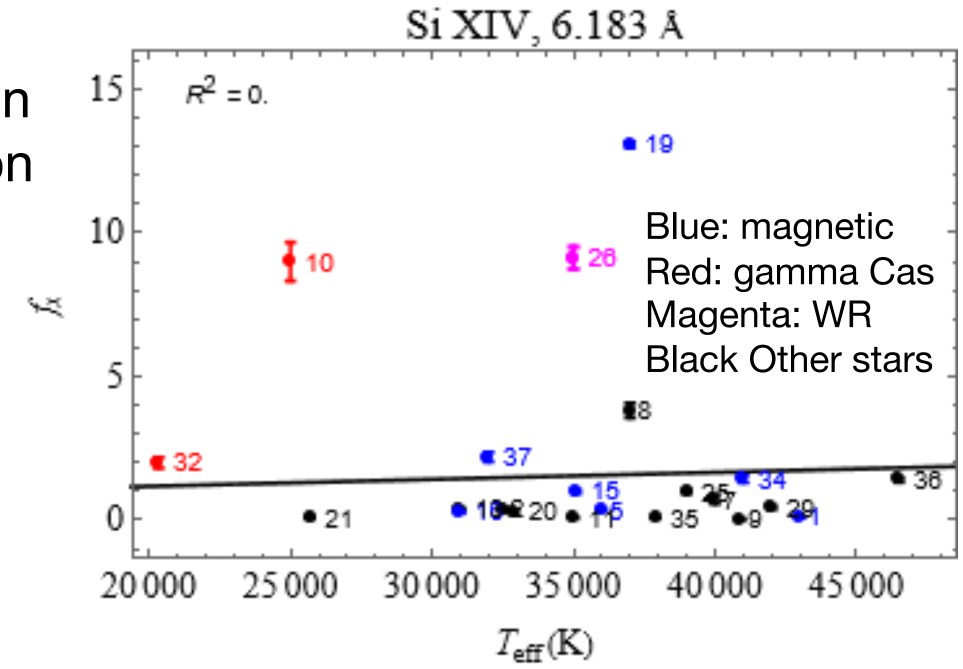
V_{inf} is approximately proportional to V_{escape}

Explanation requires knowledge of stellar parameters

Other possible uses of this database

Diagnostic of outliers

- Comparing NEW observations with trends seen here
- LINE WIDTH - TERMINAL WIND VELOCITY relation can be used for clusters stars with high UV extinction where measurements of terminal velocity are not available
- Investigating TRENDS for specific types of stars compared to the full set of spectra such as binaries, magnetic stars, etc.



Summary and Conclusions

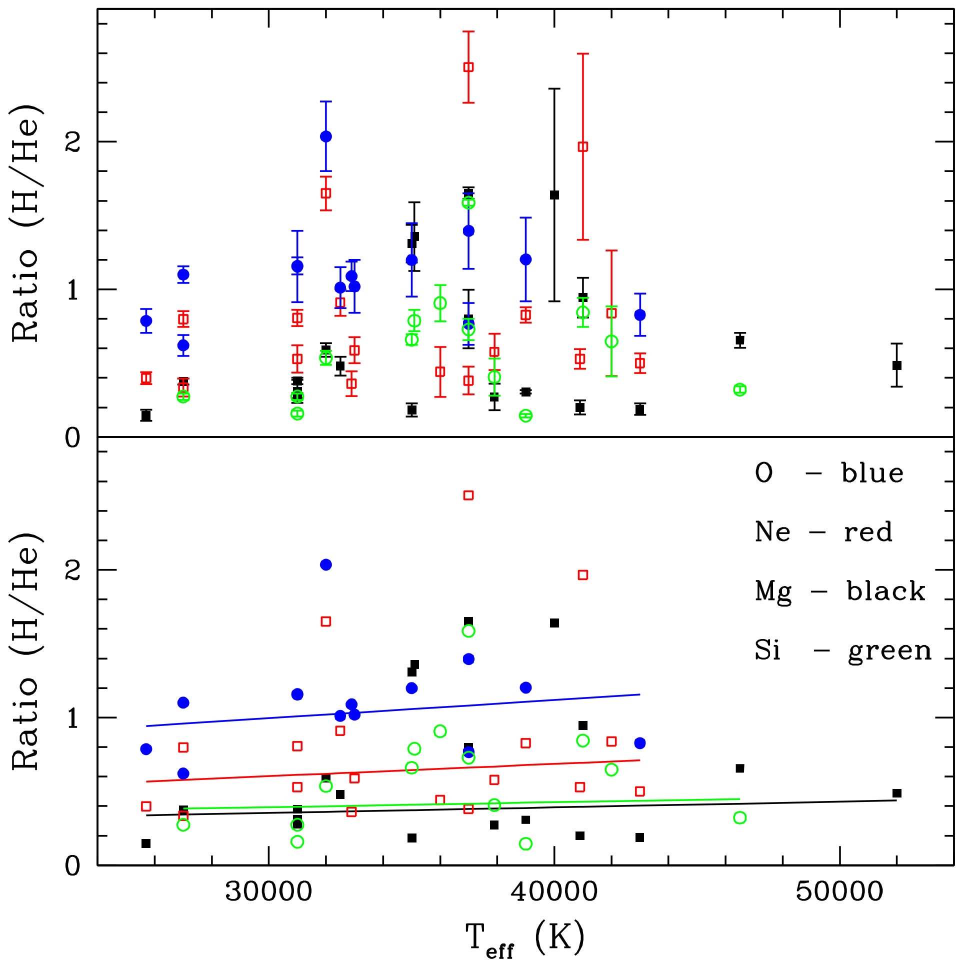
- Our database includes X-ray-determined spectral line-fitting parameters of 37 OB + WR stars
-
- A gallery of X-ray luminosity vs wavelength plots for each star puts the spectra in an intercomparable format
- X-ray parameters are well-described by optical spectral classification
- Three subgroups were identified in histogram of centroid velocity
- The subgroups are generally correlated with terminal wind velocity v_{inf}
- FWHM of Ne X and Fe XVII at $\lambda > 12$Å is a reasonable proxy for terminal wind velocity v_{inf}

Supplemental material

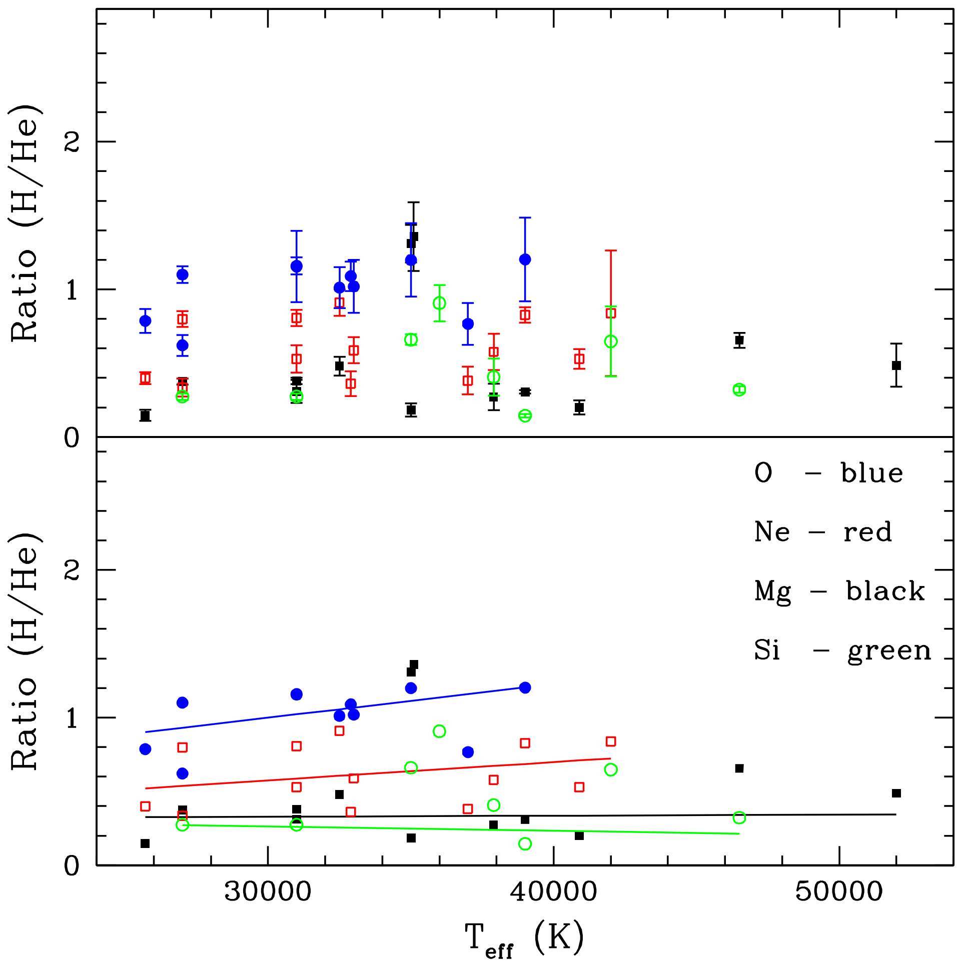
Flux ratio of K-shell H-like to He-like lines is an indication of X-ray temp and also T_eff

- Top plots: with error bars
- Bottom plots: with linear fits
- Abnormal stars account for many of the outliers
- Slope of linear fit to individual ions is consistent with models by Wojdowski & Shultz 2005; Cohen et al. 2021

H/He ratio vs T_eff for all sample stars

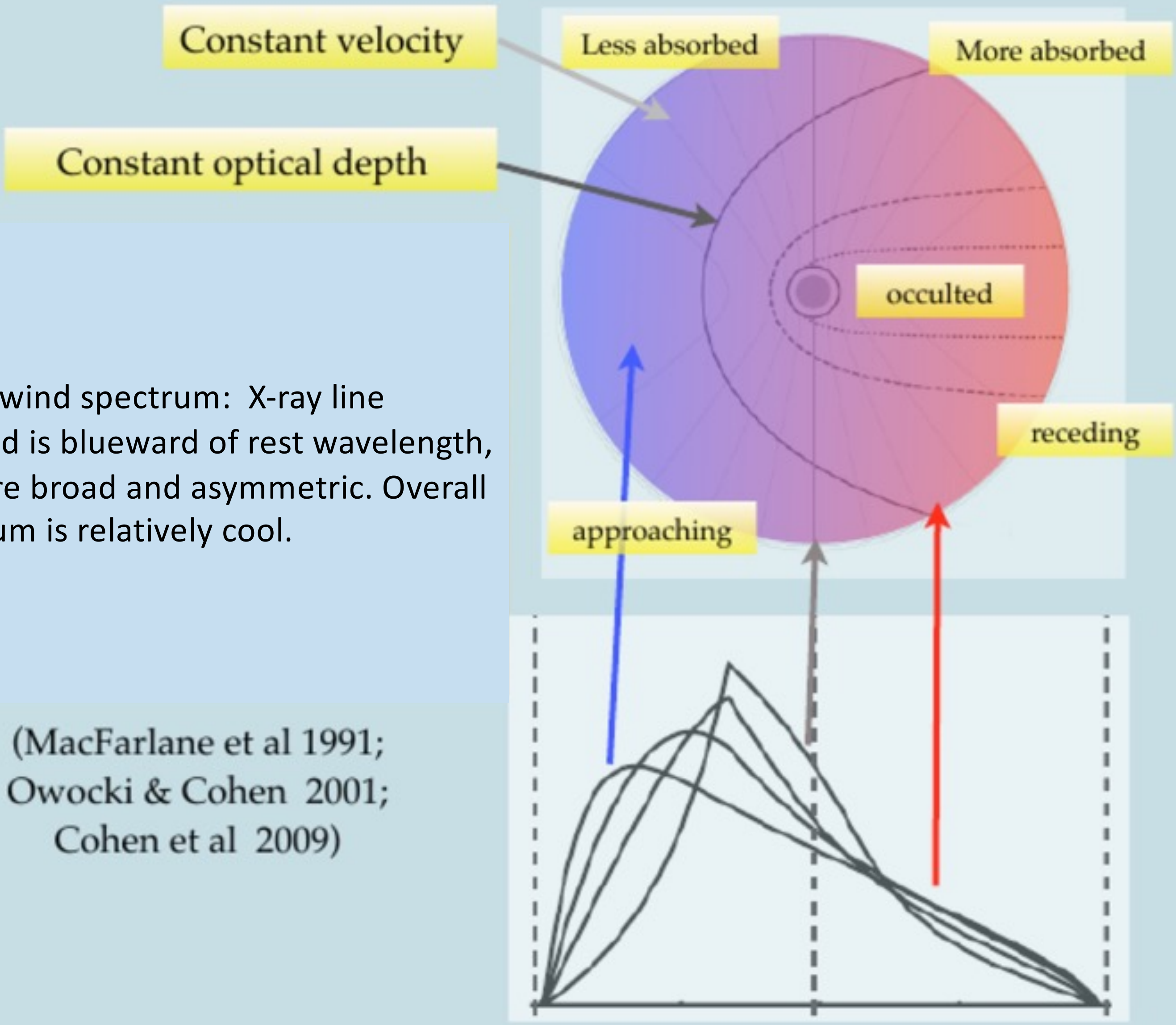


H/He vs T_eff for only normal stars



Conclusions

- We confirm that X-ray parameters presented here, in general, are well-described by optical spectral types
- Three subgroups of massive stars were identified in the delta-v vs FWHM relation.
- We find X-ray emission of the Mg XII line is a reasonable proxy for wind terminal velocity, can be useful for models
- Our database of X-ray-determined parameters, including velocity offsets, FWHM, and total flux for each of the 37 stars in our sample is available
- A gallery of specific luminosity vs wavelength plots for each star puts the spectra in an



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

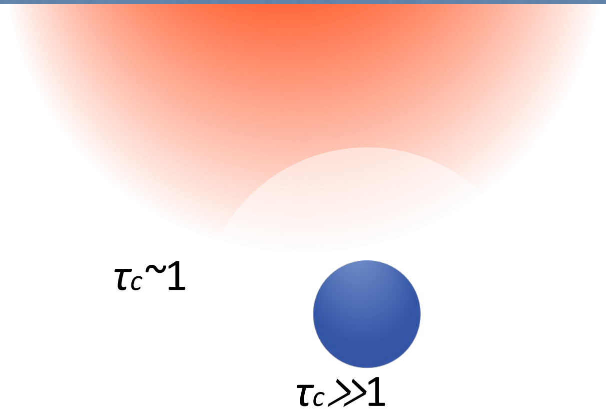
(MacFarlane et al 1991; Owocki & Cohen 2001; Cohen et al 2009)

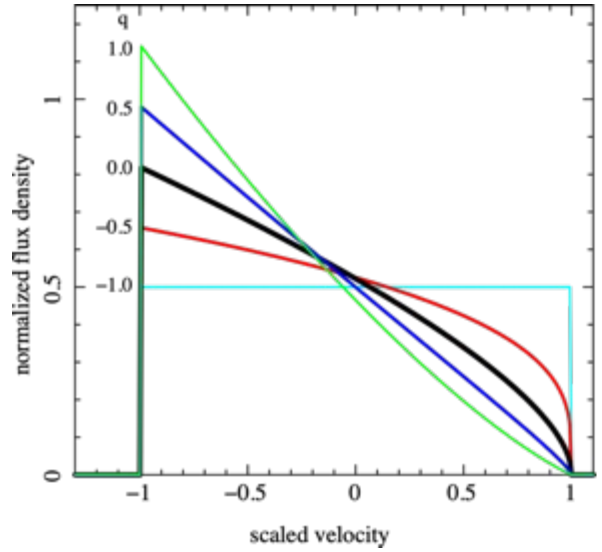
Velocity ffset

Assume:

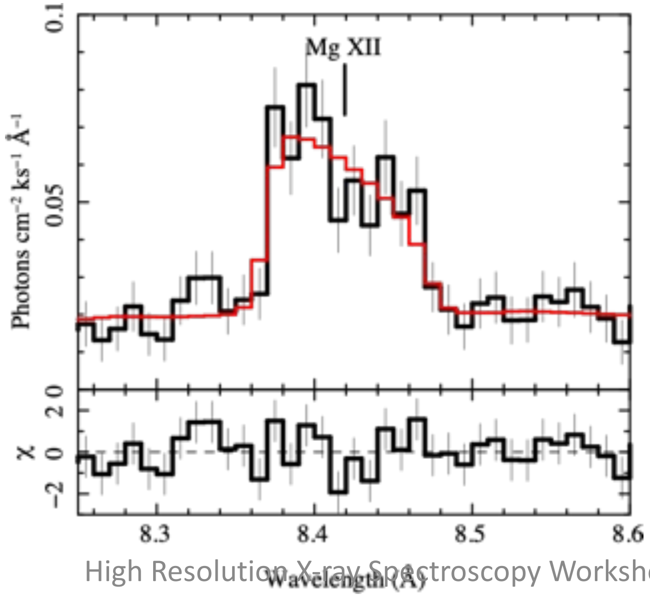
- ★ large photo-absorption
- ★ emissivity ~ $n_e^2 \times r^{-q}$
- ★ constant opacity vs λ

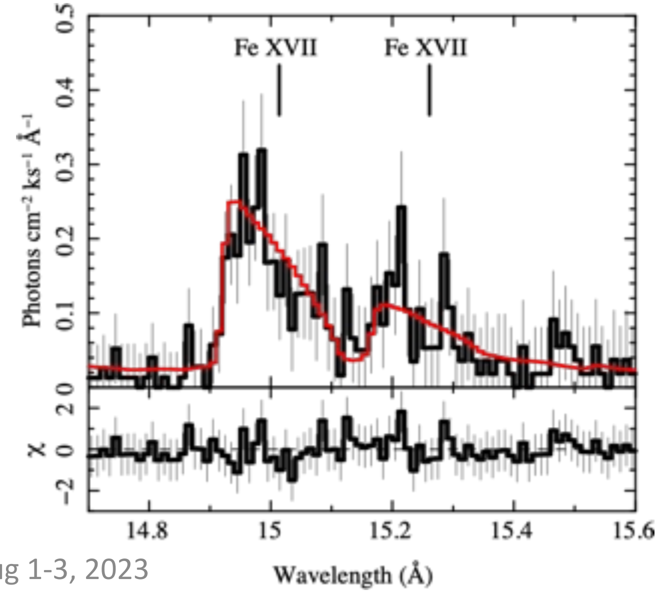
Obtain: simple analytic function for the line profile (see Ignace 2001)



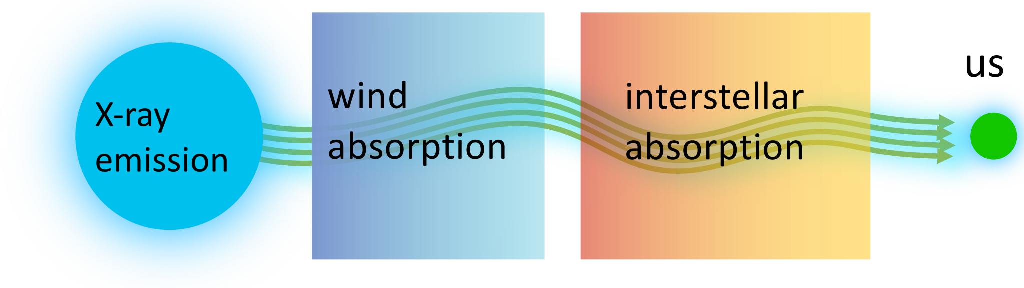


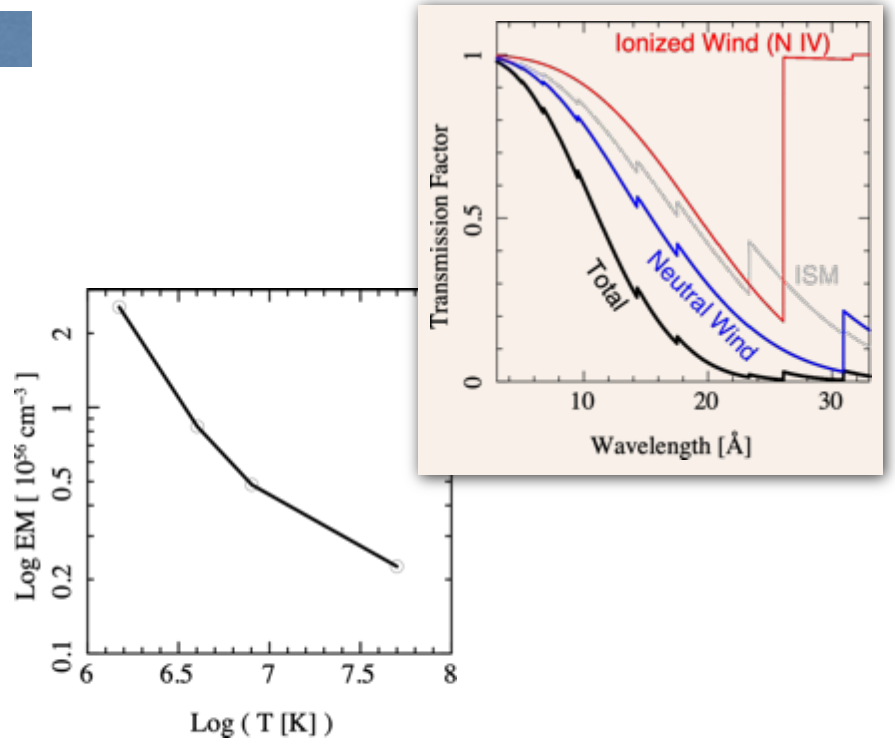
Example fits:

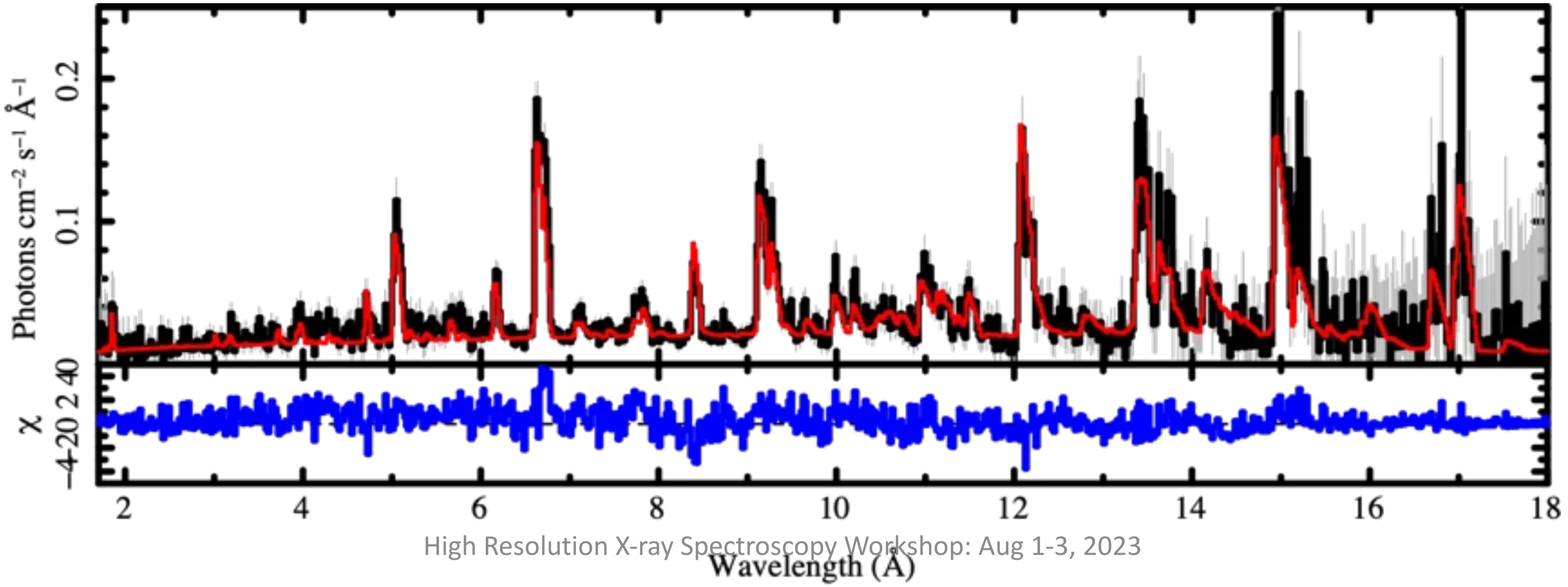




A naive model:

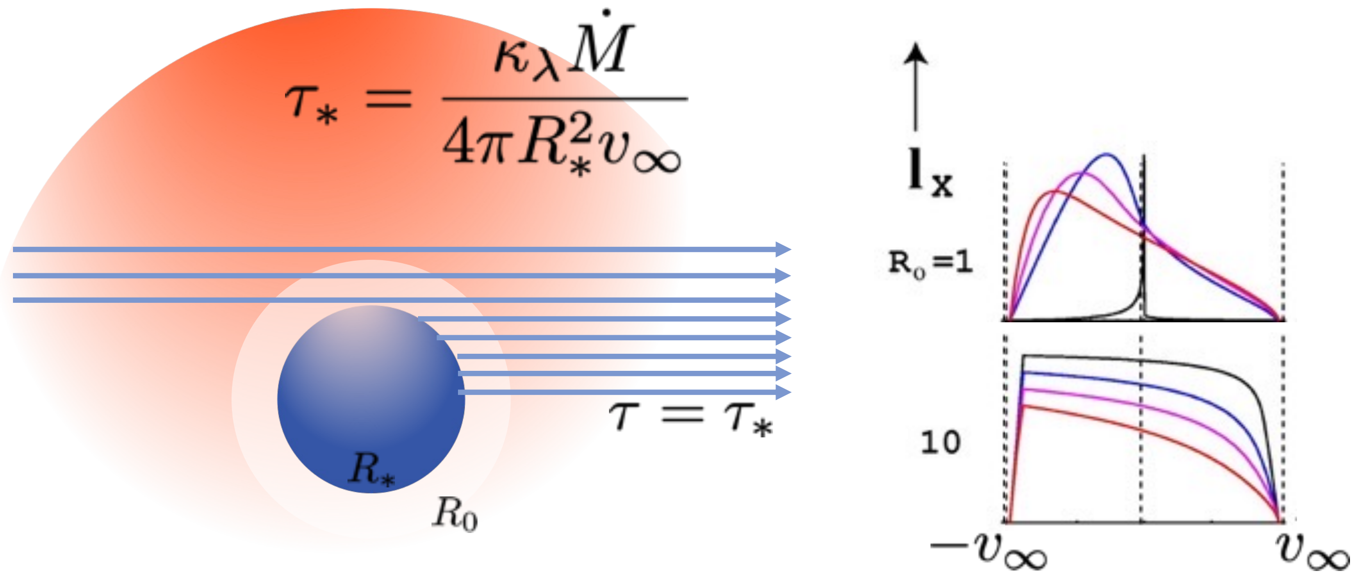






Spectral line fitting:

Assume velocity law;
Assume opacity;
Fit v_∞, R_0, τ_*;
⇒ mass loss rate



Global fitting: tricky! (*apec* × *abs*) is formally wrong because emission and absorption are distributed!

Recent modeling advances: Herve et al (2012), Leutenegger et al (2010), Cohen et al (2014)