25 Years of Massive Stars with HETG

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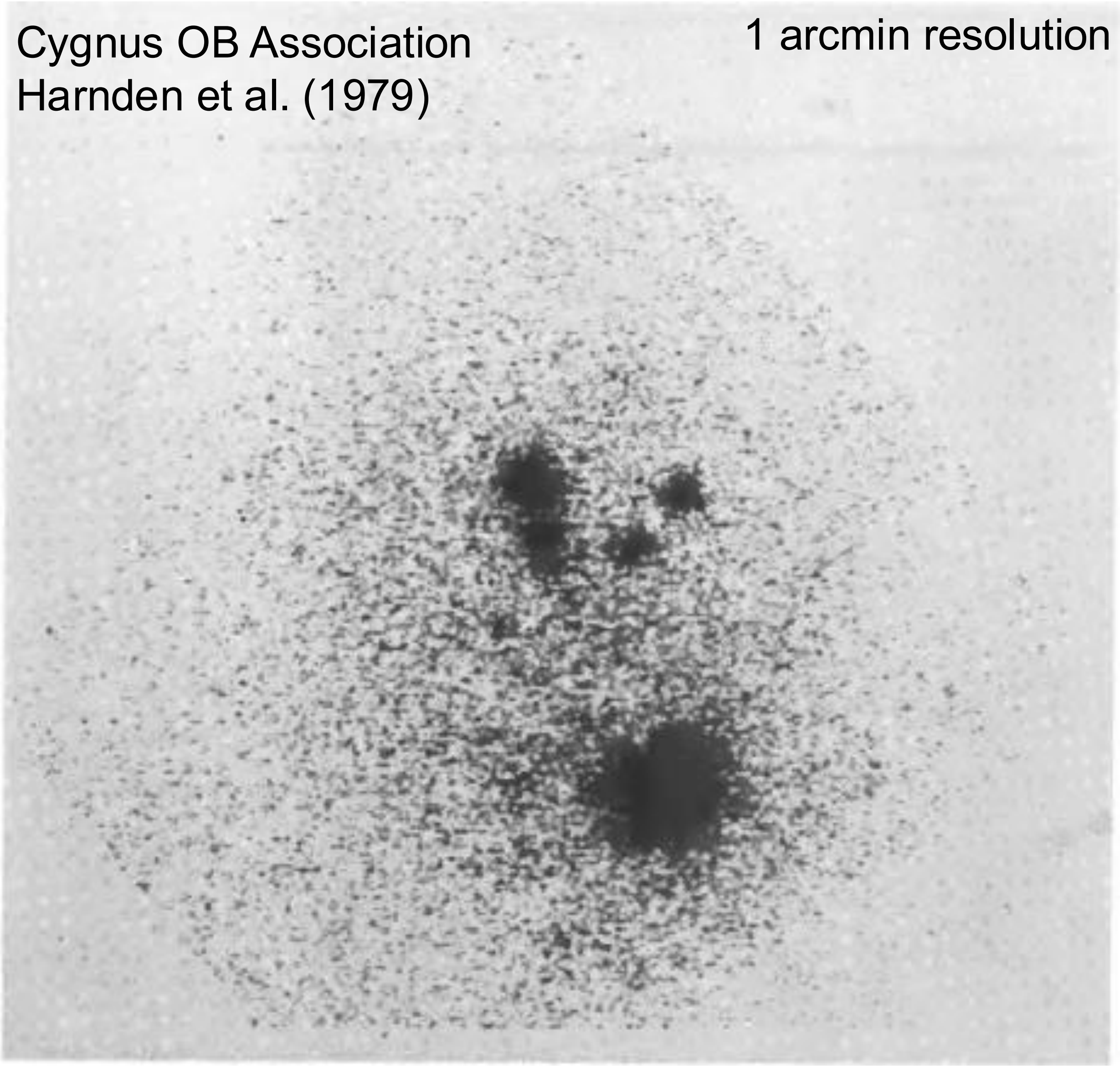
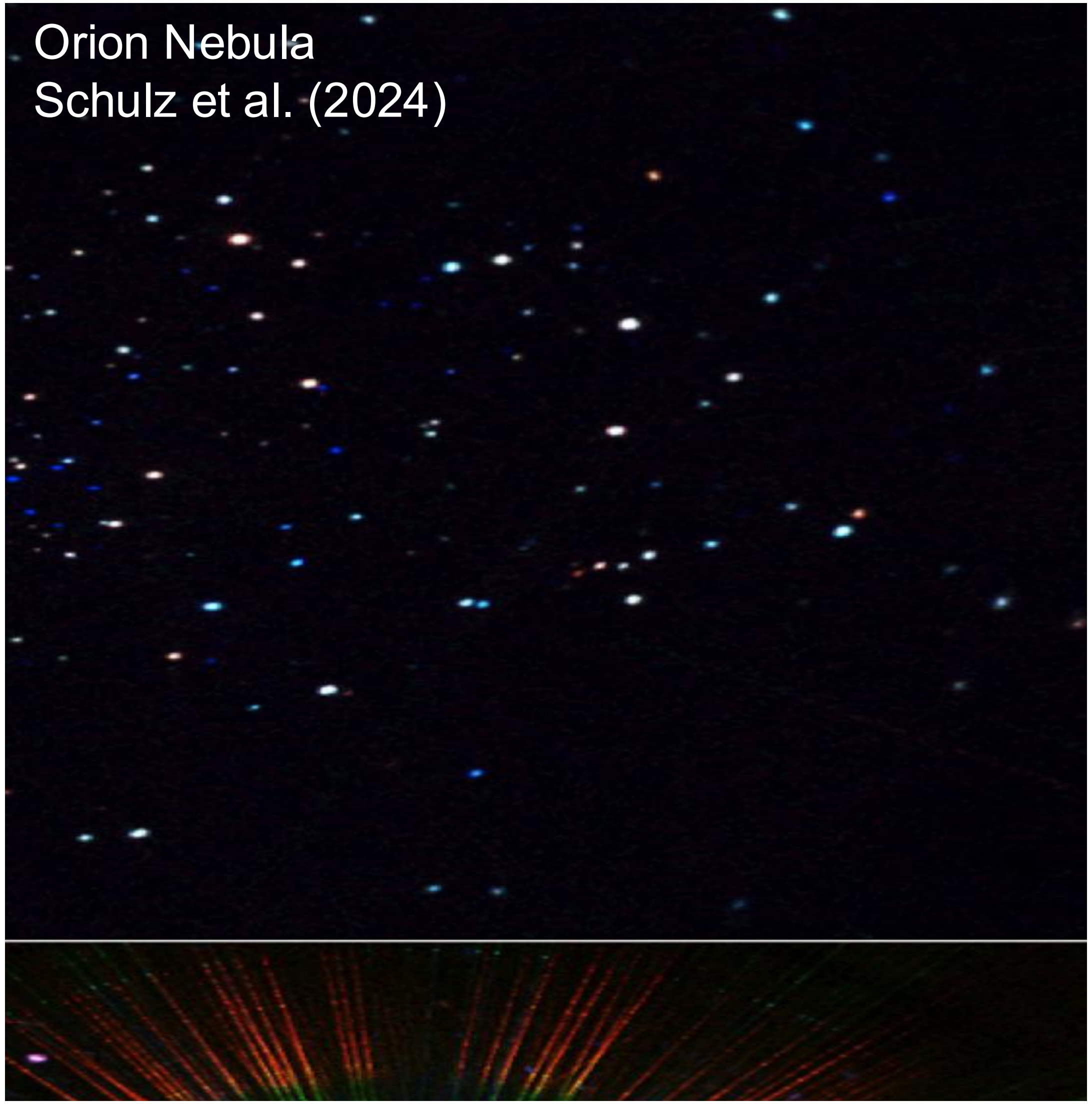
From *Einstein* to *Chandra*





Hot Star Wind Dynamics: Driving and Instabilities

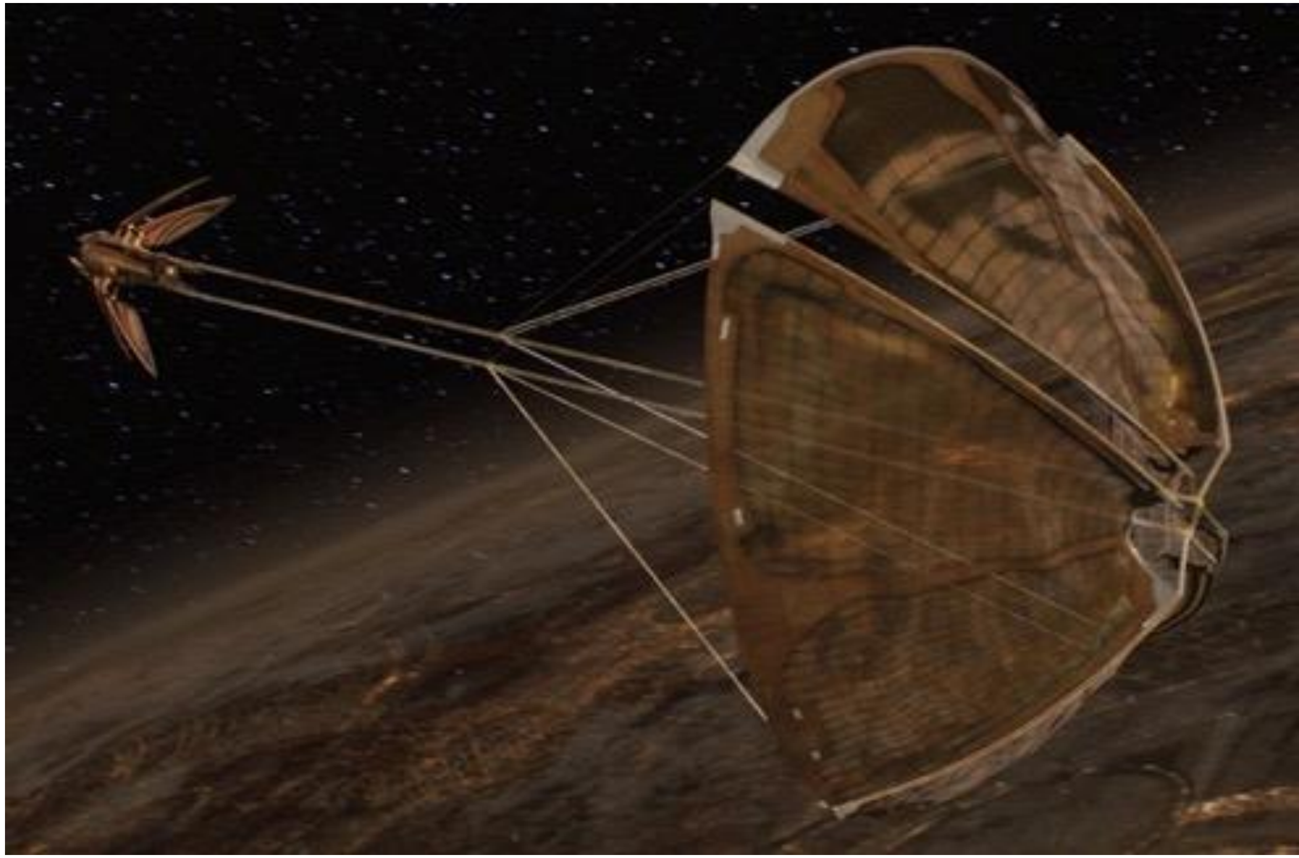
- RHD Momentum Equation

$$\left(1 - \frac{c_s^2}{u^2}\right) u \frac{du}{dr} = g_{\mathrm{rad}} - \frac{GM_*}{r^2}(1 - \Gamma_e)$$

$$g_{\mathrm{rad}} \gg \frac{dP}{dr} \Rightarrow g_{\mathrm{rad}} \approx 2000\, g \text{ (!!)}$$

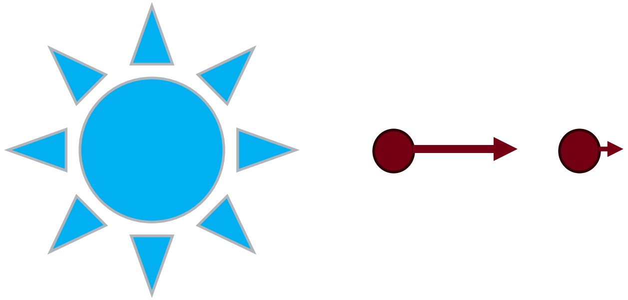
- Radiation pressure accelerates the winds
  - Specifically, UV metal line absorption

Geonosian solar sailer – *Star Wars Episode II*



https://www.starwars.com/databank/solar-sailer

Hot Star Wind Dynamics: Driving and Instabilities



(!!) Shadowing between ions reduces the acceleration

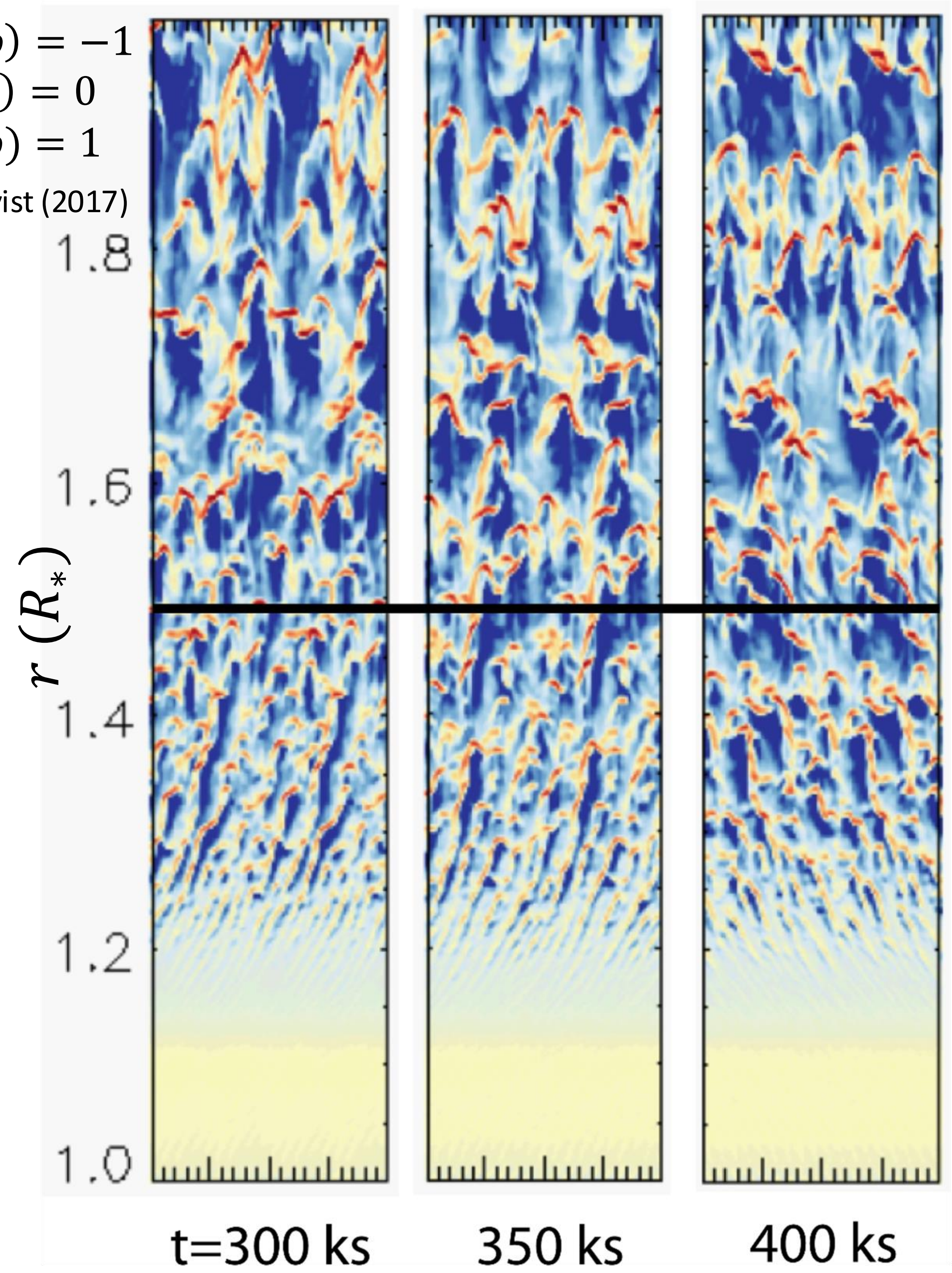
$$g_{\mathrm{rad}} \approx 2g$$

1. Shadowing is regulated by $\dot{M}$
   - Too little mass → Too much flux → $\dot{M}$ increase
   - Too much mass → Too little flux → $\dot{M}$ decreases

2. Causes shocks between clumps in the wind
   - Should produce lines that are blue shifted and slightly broadened

Blue $\log(\rho) = -1$
Yellow $\log(\rho) = 0$
Red $\log(\rho) = 1$

Owocki & Sundqvist (2017)



The first HETG spectra confirming our theories: ζ Ori

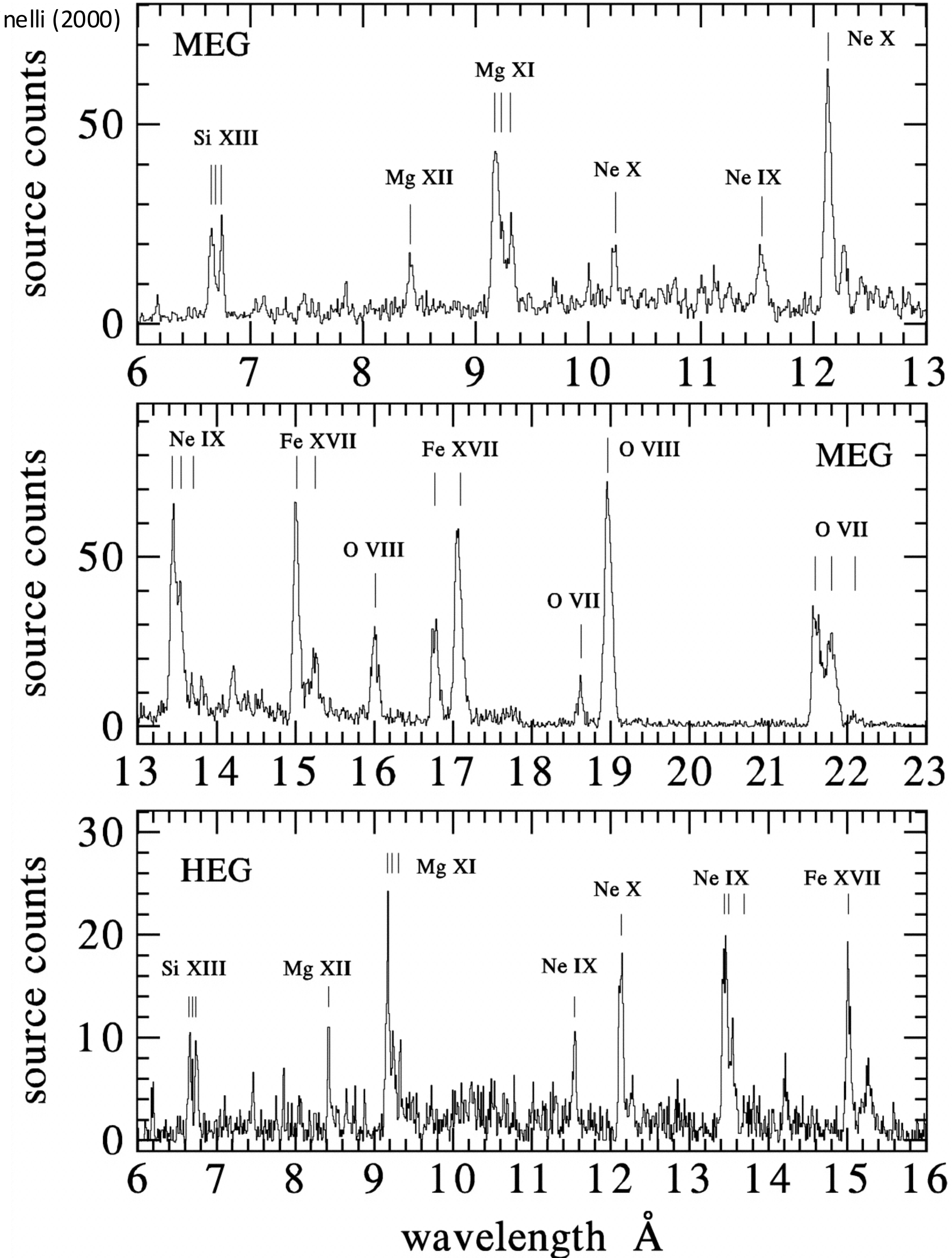
- Energy range: 0.5 – 3 keV

- Primarily thermal metal line emission
  - Very little continuum emission
  - Ion species imply 10 MK plasma

- Generally blue shifted with some broadening
  - $\Delta v \sim -0.1\, v_\infty$
  - $\mathrm{FWHM} \sim v_\infty$

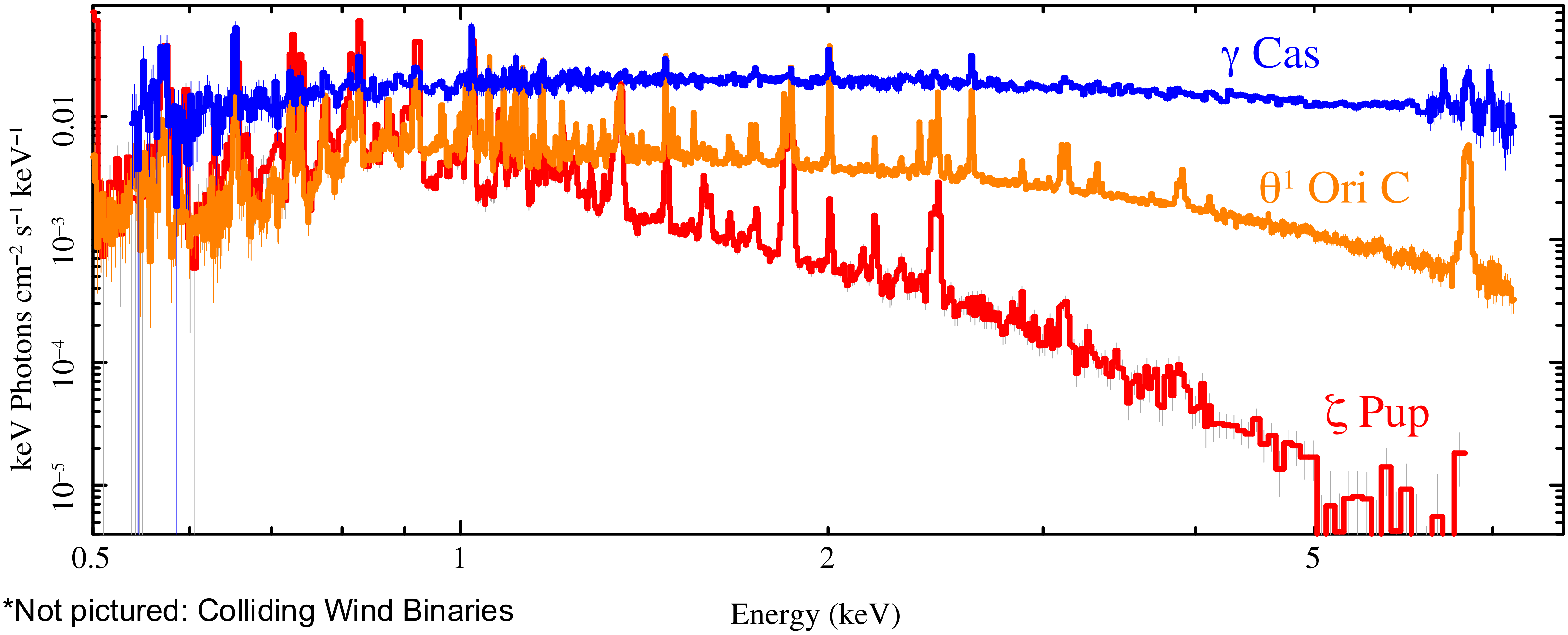
- Measured for the first time in ζ Ori by Waldron & Cassinelli (2000)

Waldron & Cassinelli (2000)



Hot star X-ray Spectra: A Whole Zoo

Red = Embedded Wind Shocks
Orange = Magnetically Confined Winds
Blue = γ Cas-emission ← Unkown!



*Not pictured: Colliding Wind Binaries

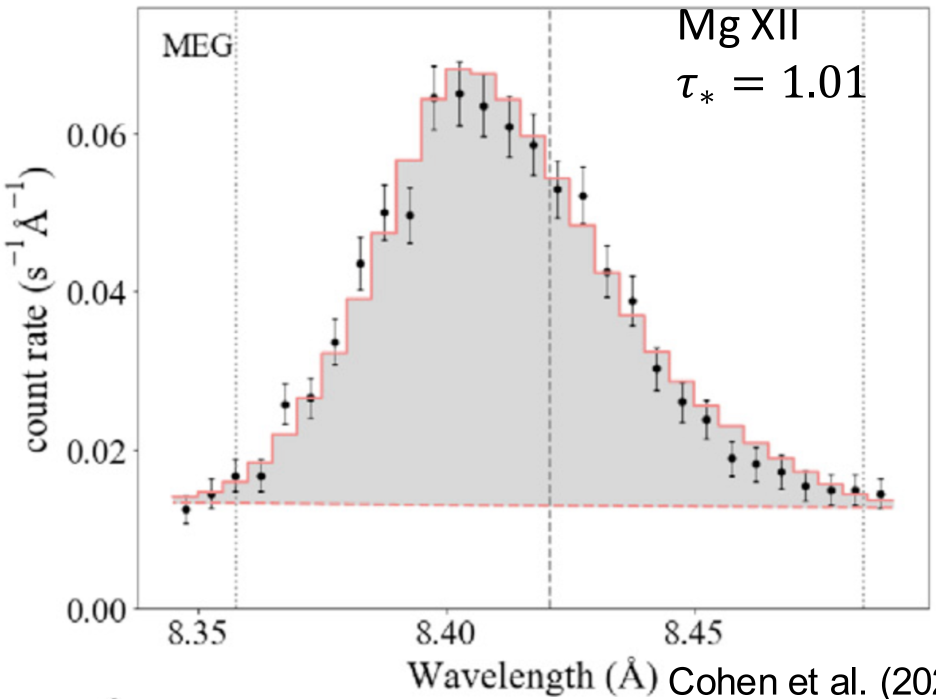
Hot Star Lines as Diagnostics: Determining Mass-loss Rates

- General line profile function for hot stars

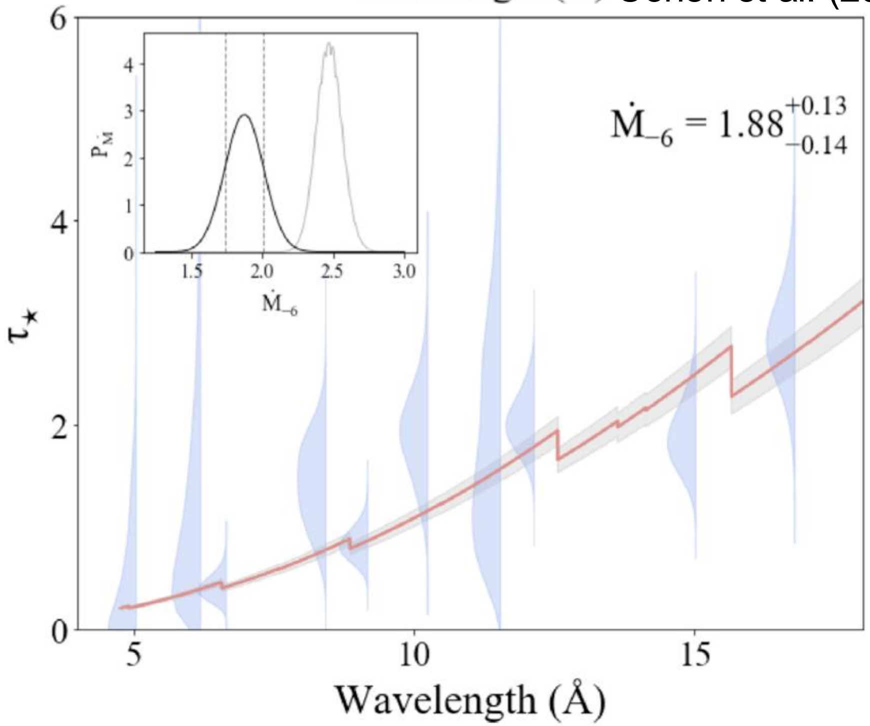
$$L(\lambda;\tau_*) = \int_{V_{\min}}^{\infty} S(\lambda, V)\, e^{-\tau(\lambda,V;\tau_*)} \mathrm{d}V$$

$$\tau_* \propto \dot{M}$$

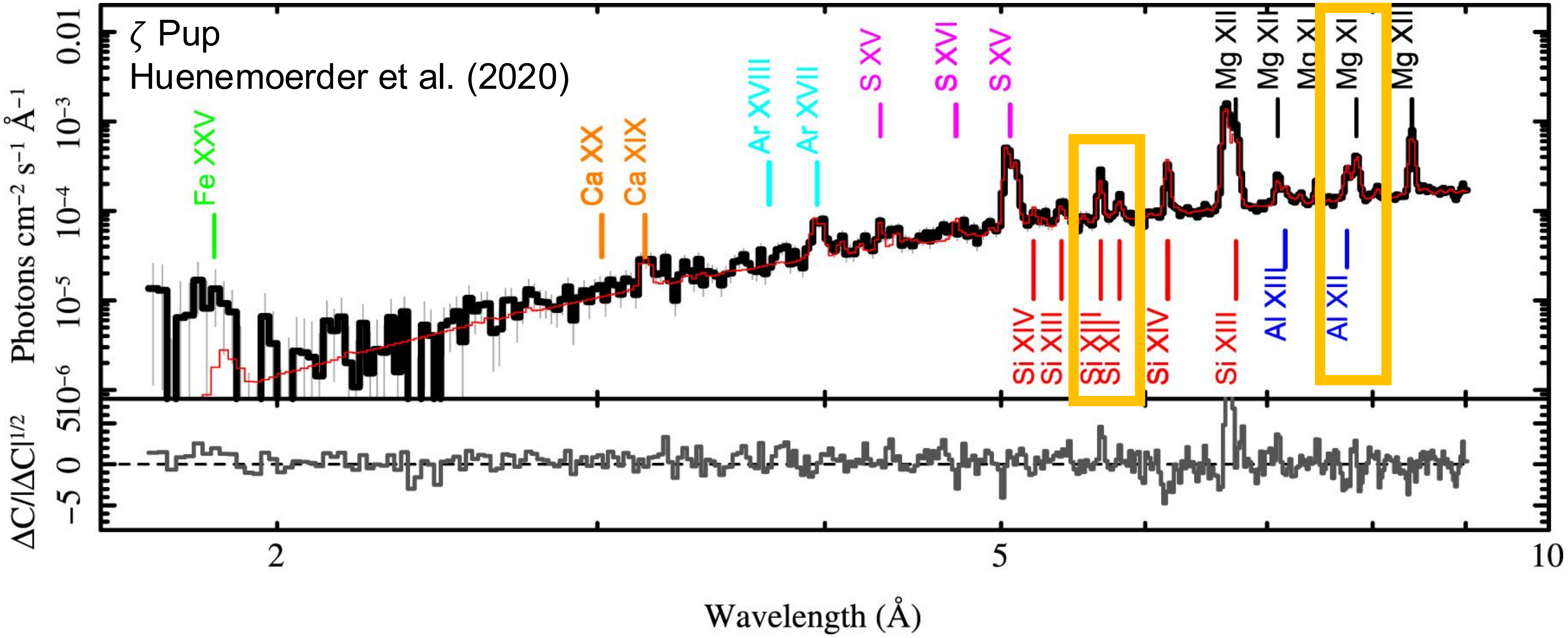
- Advantages to using X-rays:
  1. Independent of clumping
  2. Directly samples the amount of material in the wind column
- First shown to be feasible by Cohen et al. (2010)
  - Shown to be model-independent by Gunderson et al. (2022, 2024)



Cohen et al. (2020)



Hot Stars in the Megasecond club:
Testing Plasma Conditions

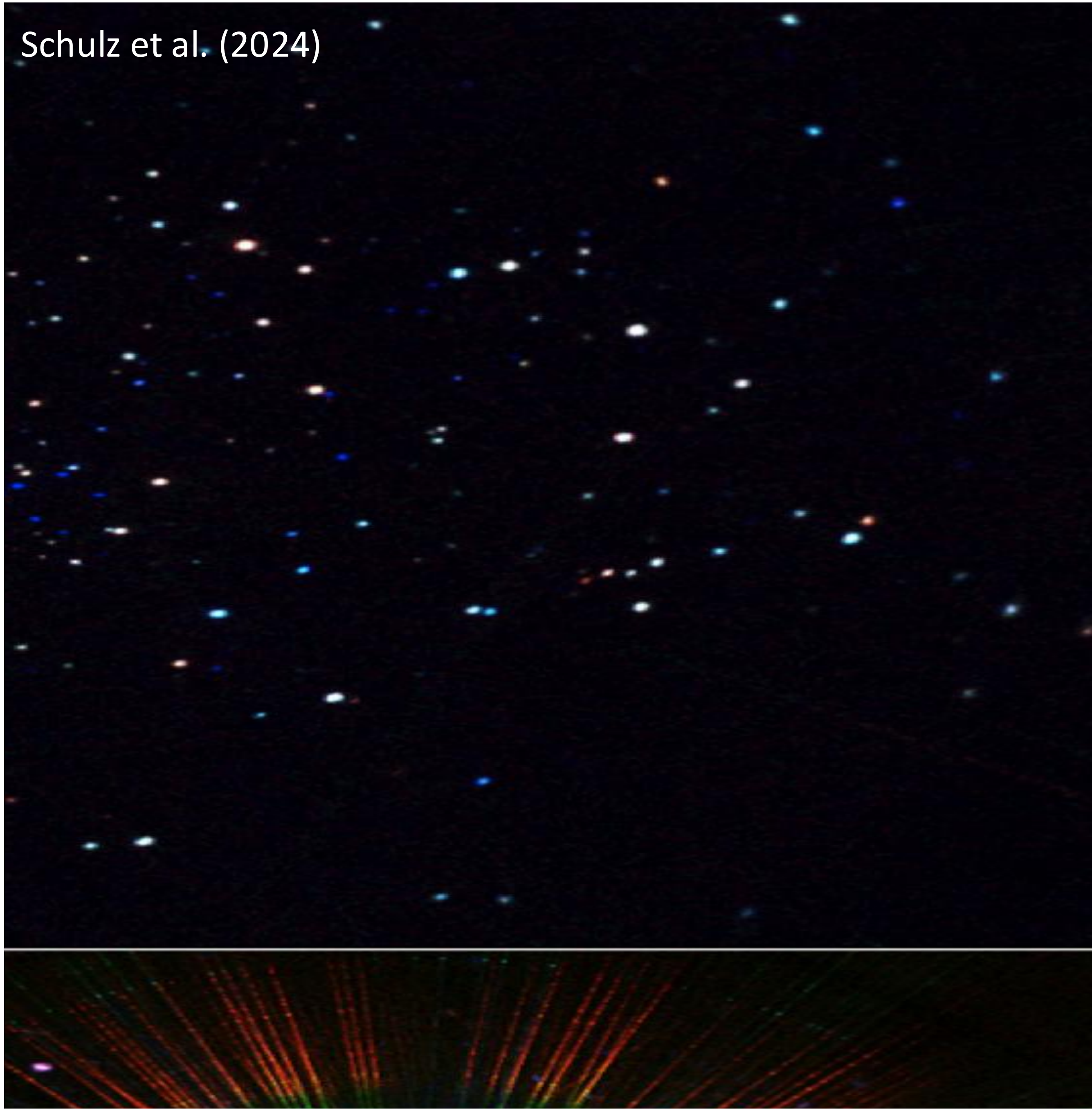


- DR Lines directly show the presence of hot electrons
- DR-to-Resonance line ratio can test the plasma state

Gunderson et al. (2022) showed CIE is achieved in ζ Pup

The Orion Legacy Project:
2.1 Ms of Exposure with HETG

- Chandra legacy project by Schulz et al. (2024)
- 36 HETG spectra extracted
  - Bright streaks = θ^1 Ori C
  - Dimmer Lines = Other sources
- All spectra available on TGCat
  - https://tgcat.mit.edu/



The Orion Legacy Project:
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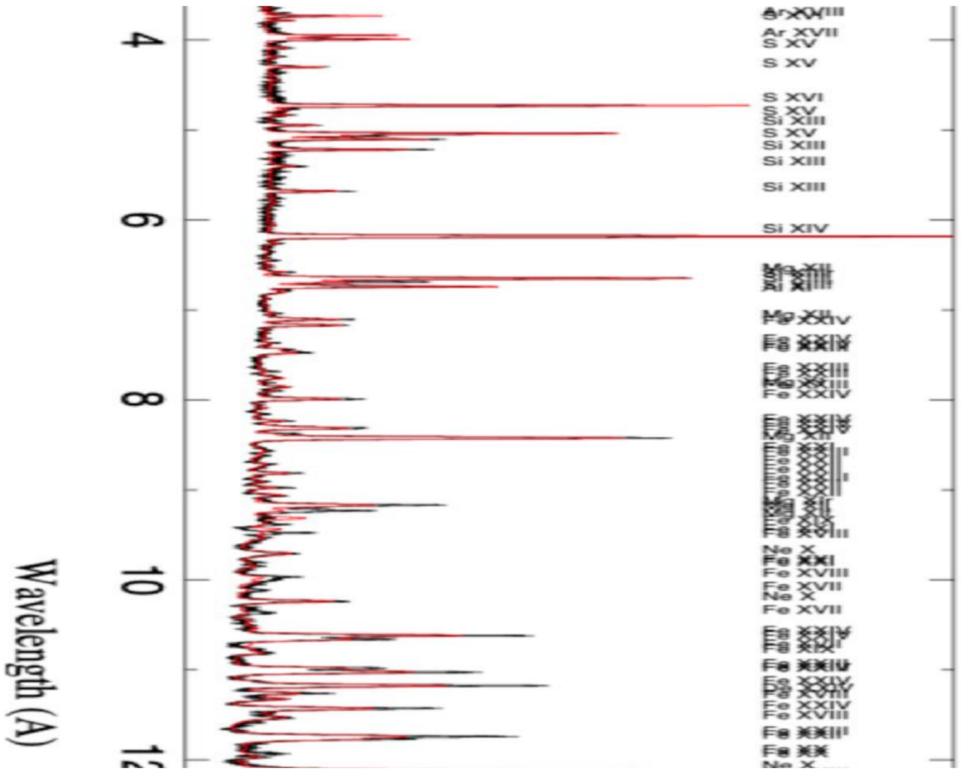

θ1 Ori C

2024 Astrophys. J. 970 doi:10.3847/1538-4357/ad47c2

s). Published by the American Astronomical Society.

- All spectra available in the SAO Chandra Archive
  - [https://asc.harvard.edu/cda/contributed sets.html](https://asc.harvard.edu/cda/contributedsets.html)

Link to the Orion Archive specifically

25-years of Chandra has shown

1. For single hot stars, X-rays are generated through embedded wind shocks
    - There's a whole zoo of other emission mechanisms
2. Mass-loss rates can be determined from high-res spectra
3. The shocks reach Collisional Ionization Equilibrium

What's next?

1. Mass-loss rates are still uncertain: $\dot{M}_{\mathrm{theory}}/\dot{M}_X \approx 2$
2. What exactly are γ Cas-type?
3. What is the actual shape of the lines?