A Deep Exposure in High Resolution X-Rays Reveals the Hottest Plasma in the ζ Puppis Wind

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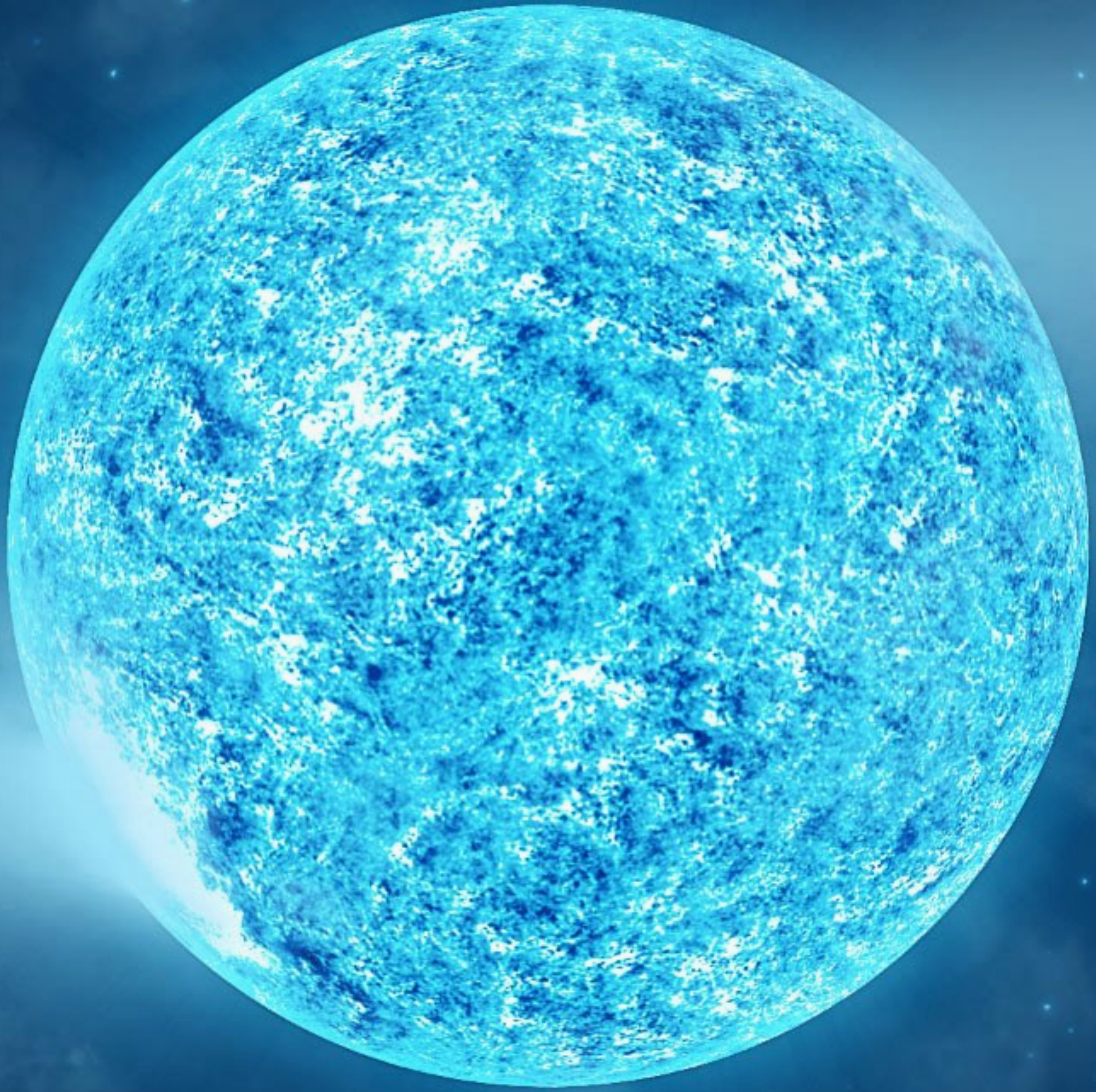
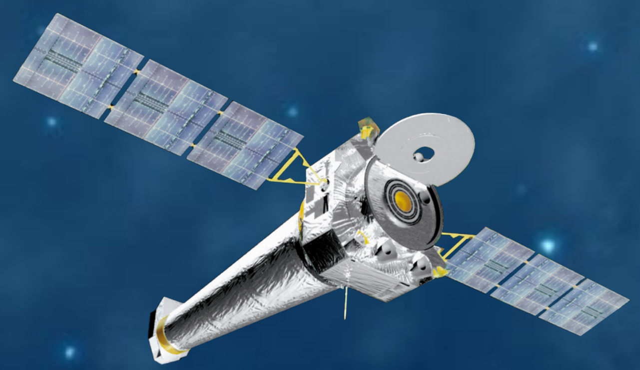
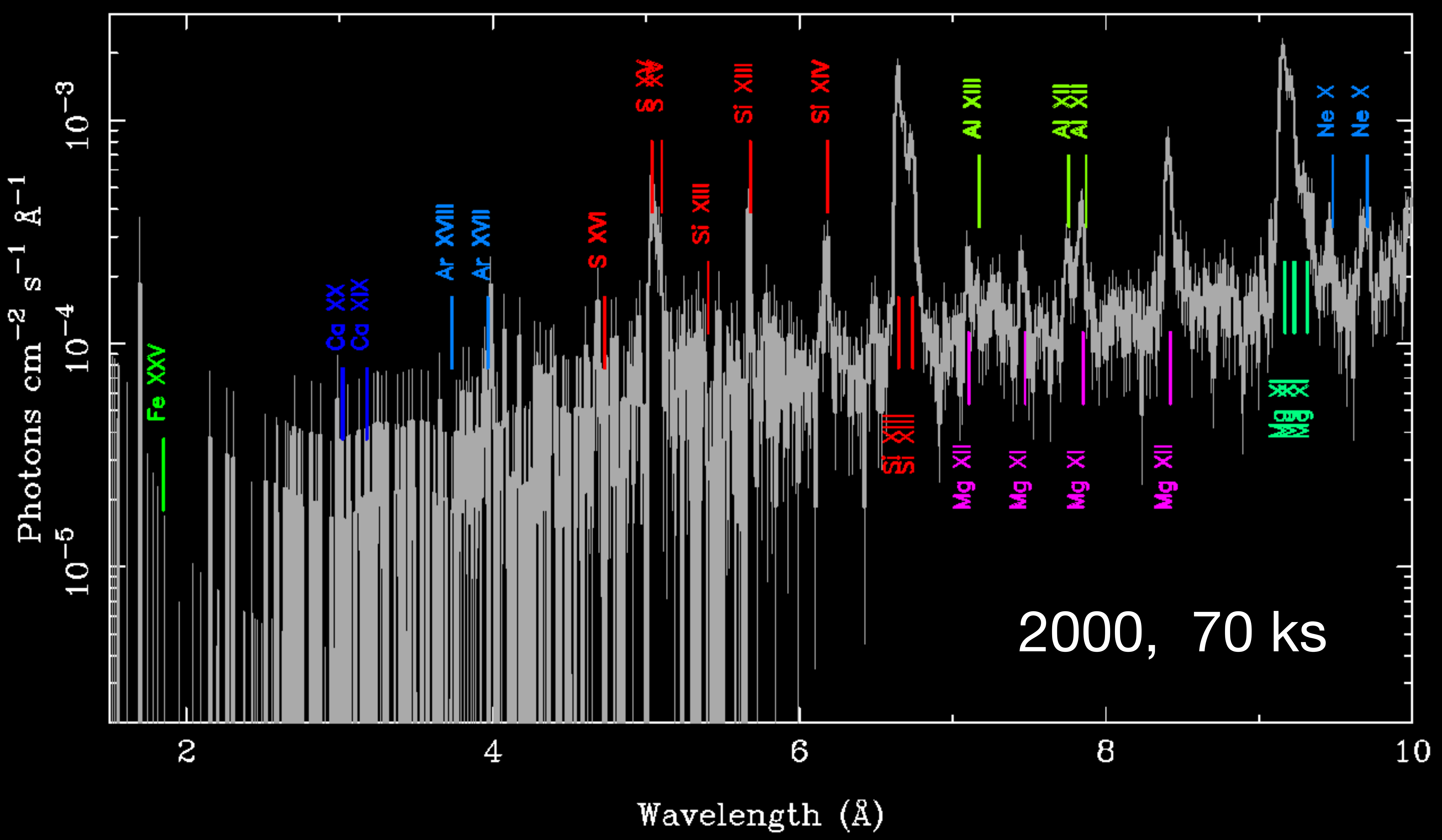


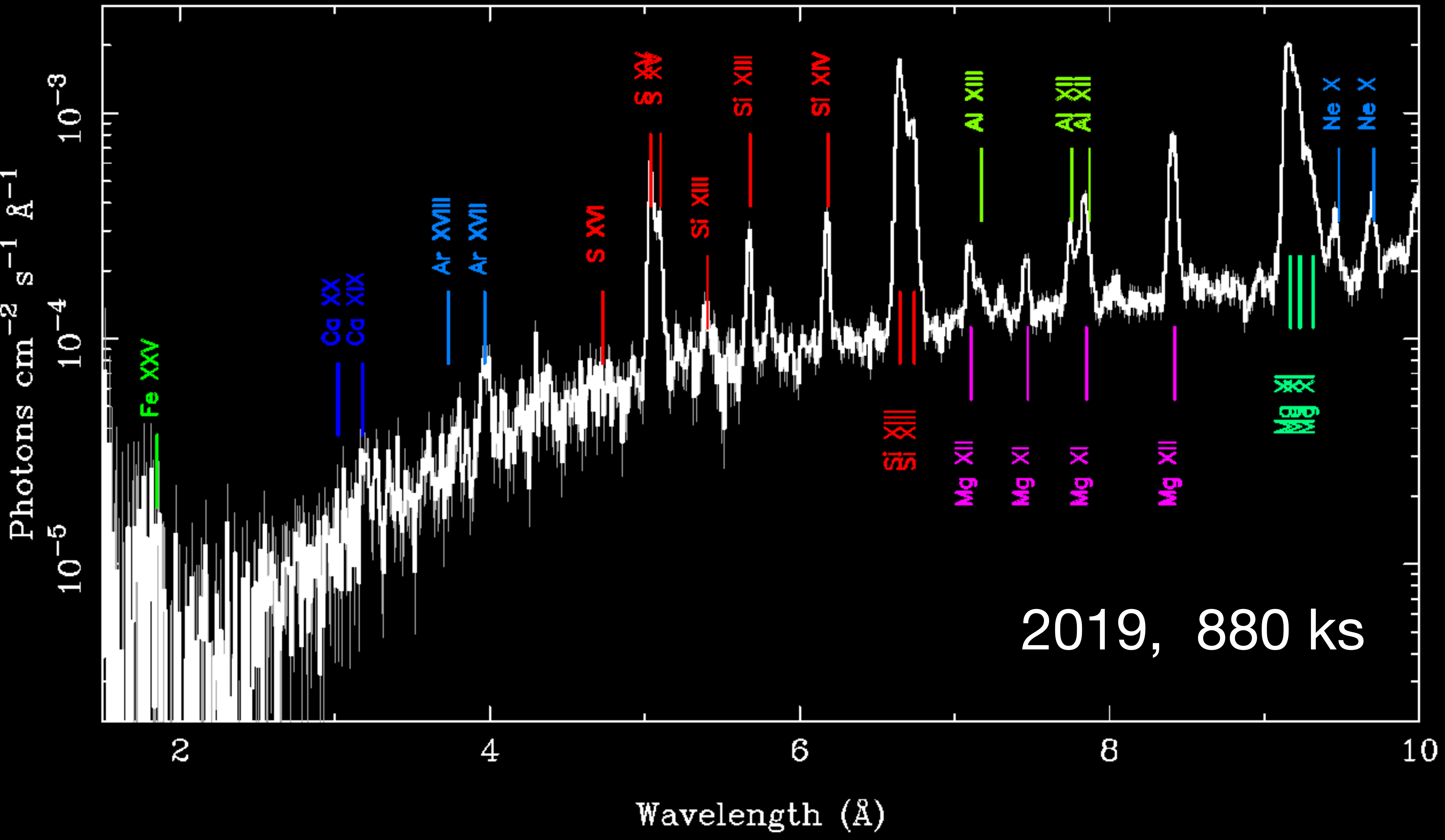
Runaway, *single* star
Type: O4 If
T_{eff} =40,000 K
$R \sim 20\ R_\odot$
$M \sim 60\ M_\odot$
$L_{\mathrm{bol}} \sim 6 \times 10^5\ L_\odot$
$v\sin i$ = 230 km/s
P_{phot} = 1.78 d
v_∞ = 2200 km/s
d = 460 pc
$\dot{M} \sim 2\times10^{-6}\ M_\odot$/yr
$f_X \sim 1.5 \times 10^{-11}$ ergs/cm^2/s
$L_X \sim 4 \times 10^{32}$ ergs/s
$L_X/L_{\mathrm{bol}} \sim 10^{-7}$

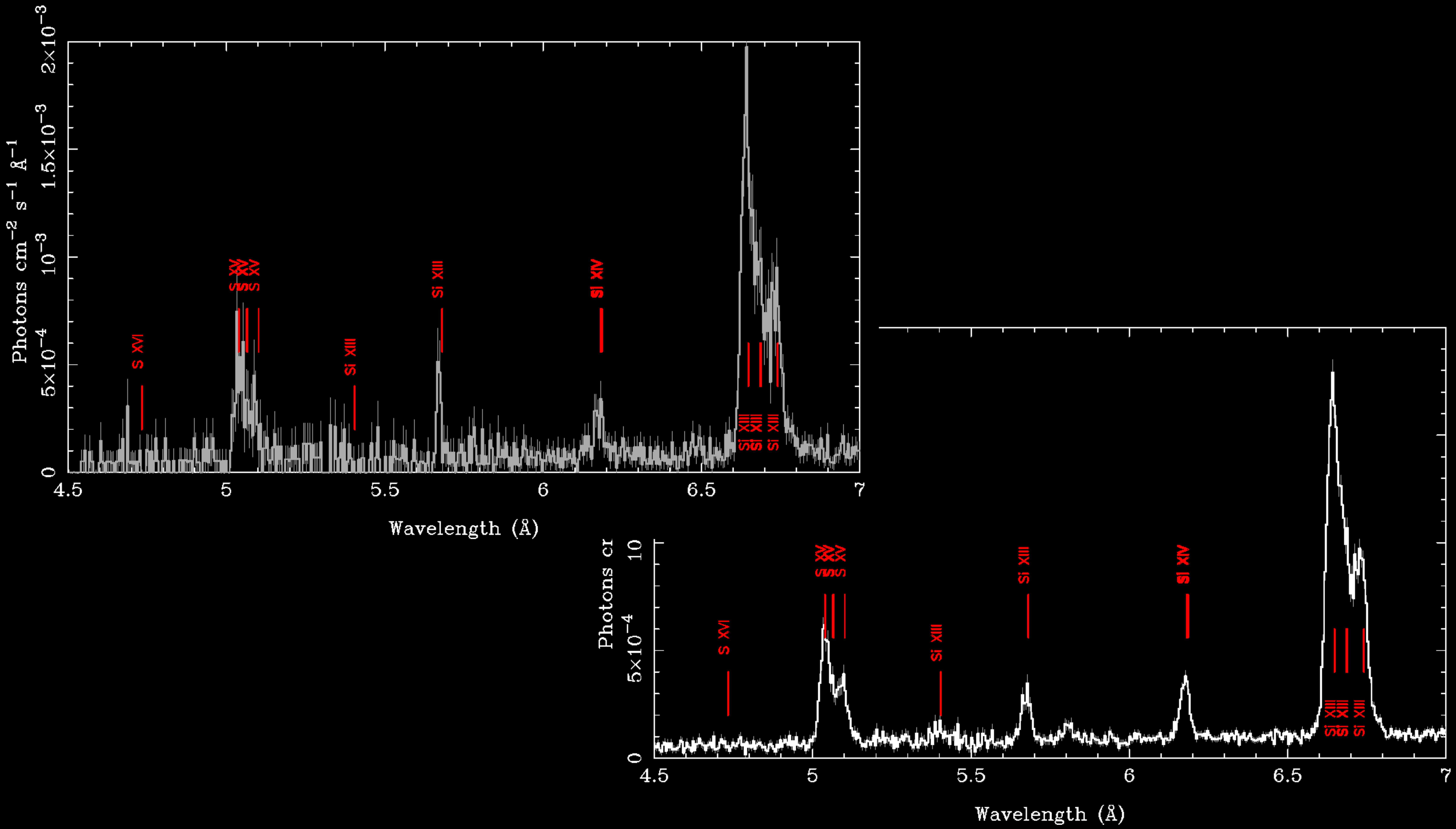


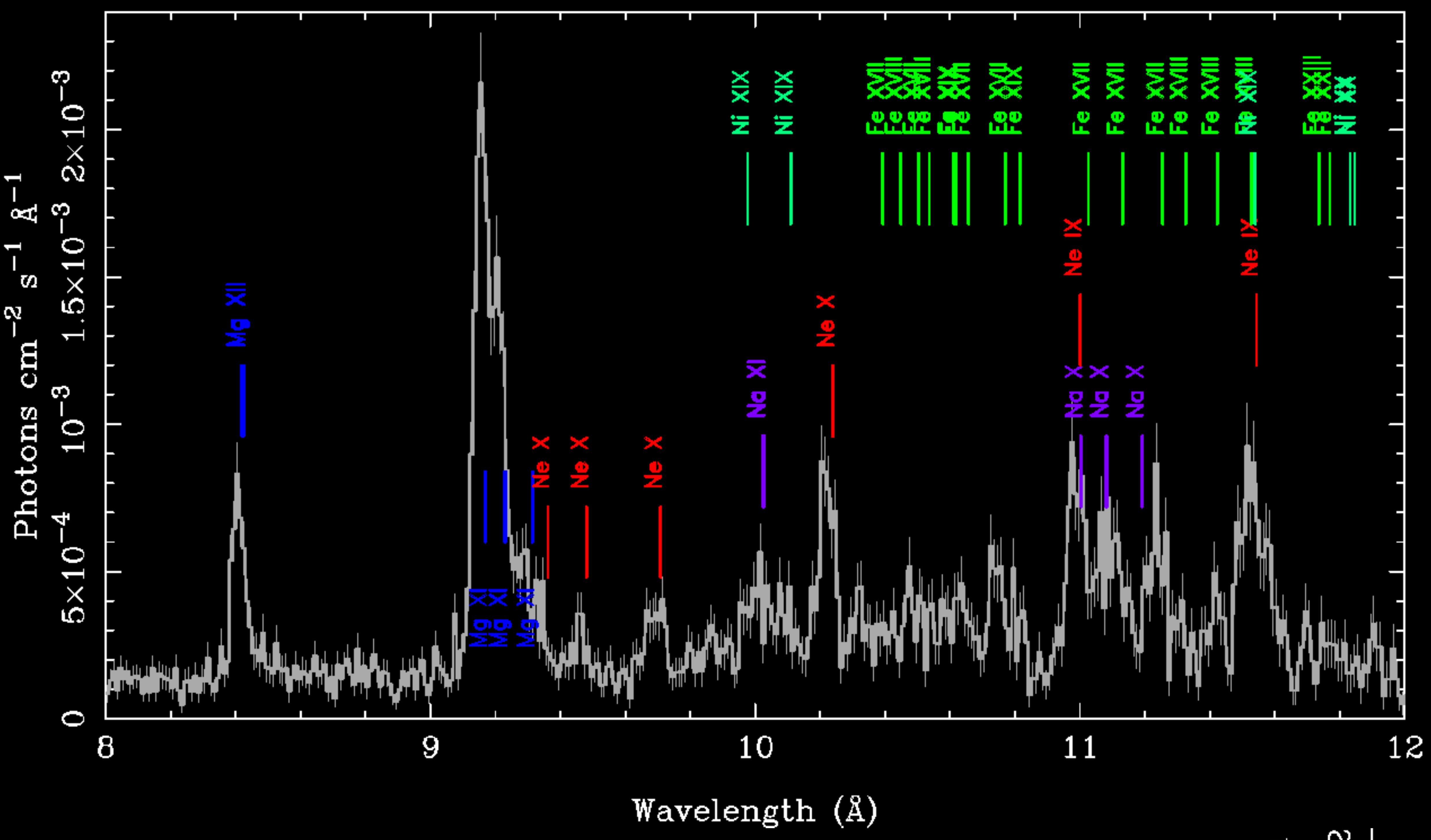
[Image credits: Tahina Ramiaramanantsoa]



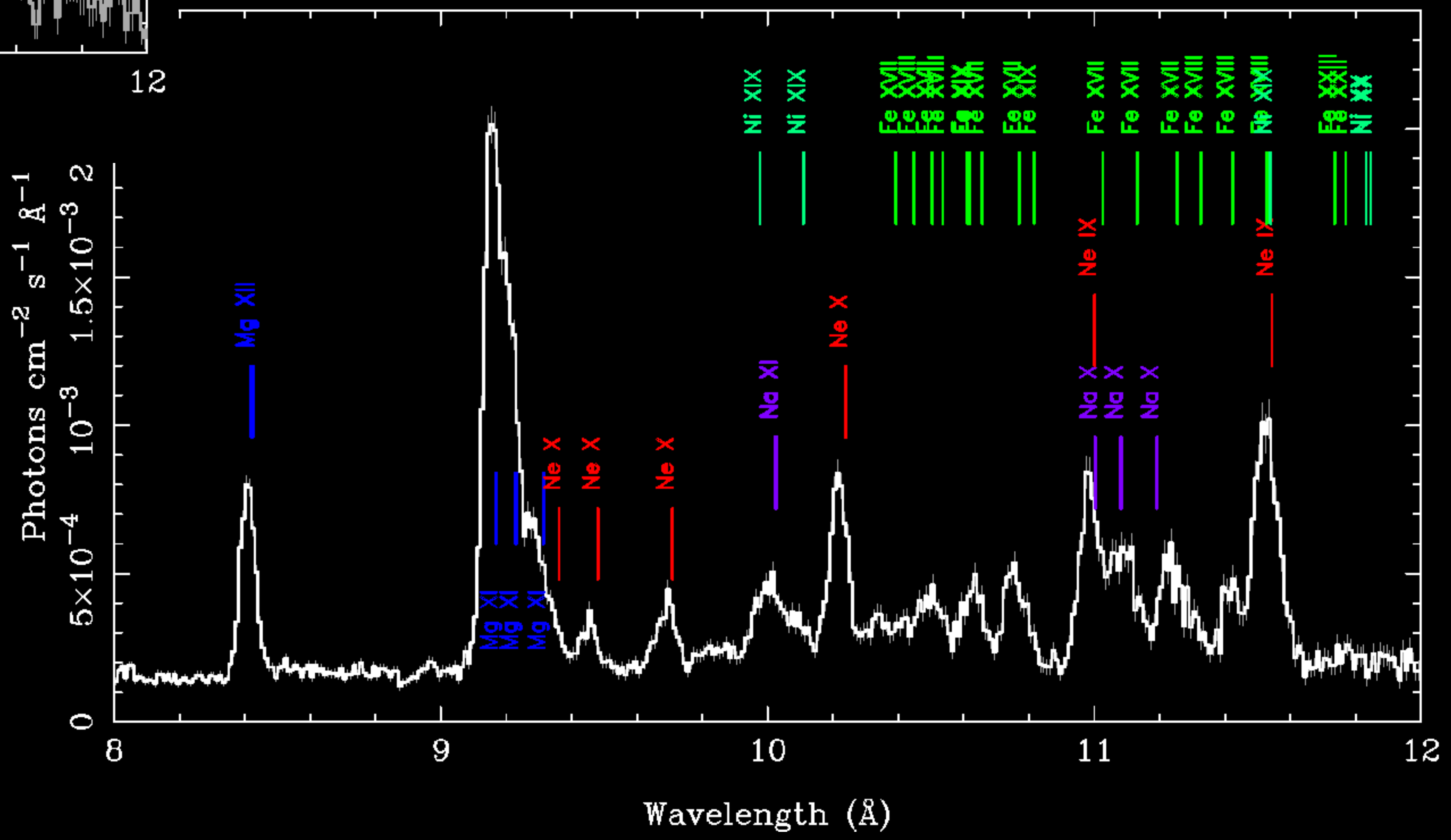
Photons cm^{-2} s^{-1} Å^{-1}
Wavelength (Å)
Fe XXV
Ca XX
Ca XIX
Ar XVIII
Ar XVII
S XVI
S XV
Si XIII
Si XIV
Al XIII
Al XII
Ne X
Mg XII
Mg XI
2000, 70 ks


Photons cm^{-2} s^{-1} Å^{-1}
Wavelength (Å)
Fe XXV
Ca XX
Ca XIX
Ar XVIII
Ar XVII
S XVI
S XV
Si XIII
Si XIII
Si XIV
Si XIII
Mg XII
Mg XI
Mg XI
Mg XII
Al XIII
Al XII
Mg XI
Ne X
Ne X
2019, 880 ks

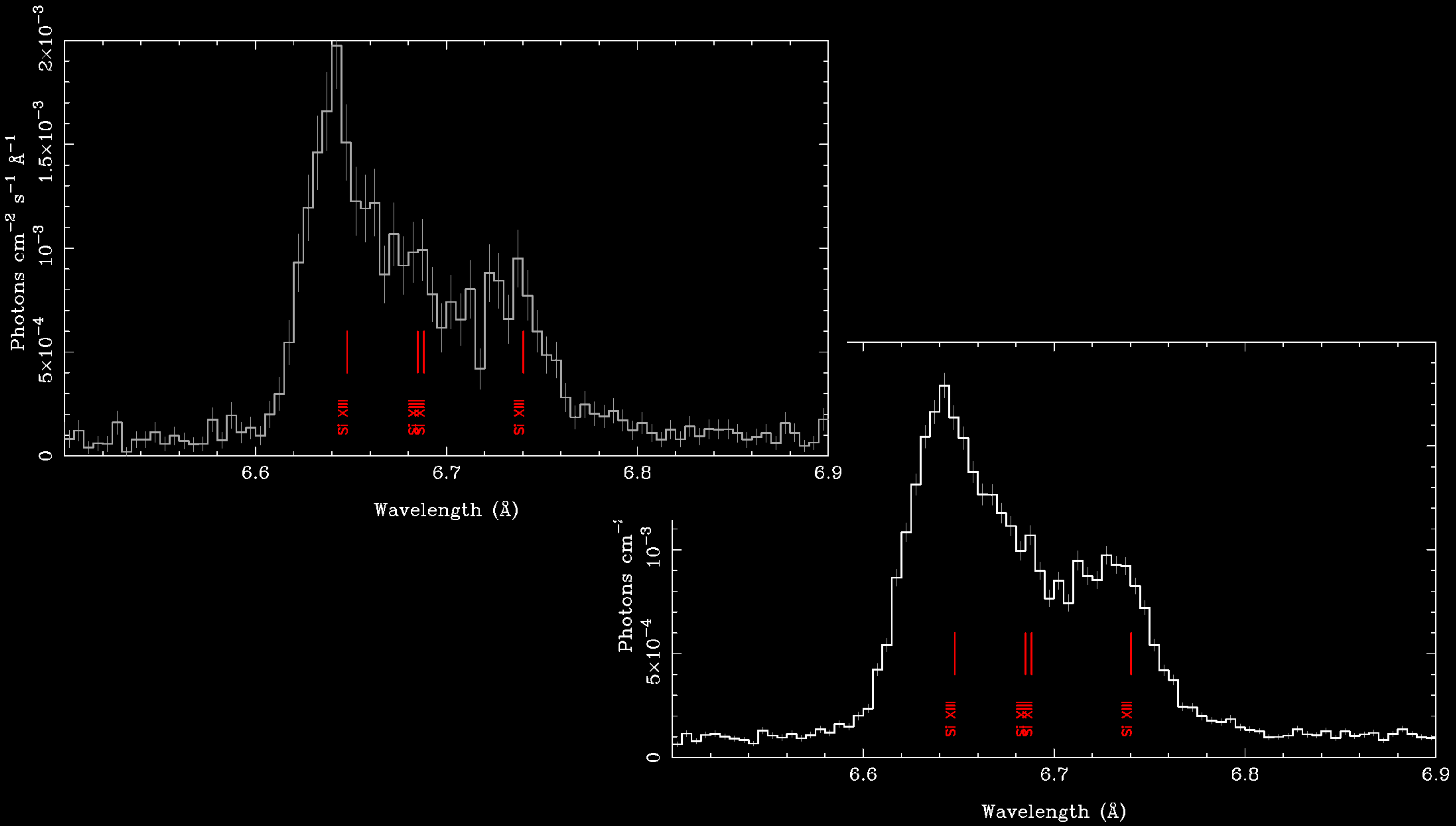

Photons cm^{-2} s^{-1} Å^{-1}
Wavelength (Å)
S XVI
S XV
Si XIII
Si XIV
Photons cr
Wavelength (Å)



Photons cm^{-2} s^{-1} Å^{-1}
Wavelength (Å)
0
5×10^{-4}
10^{-3}
1.5×10^{-3}
2×10^{-3}
8
9
10
11
12
Mg XII
Mg XI
Ne X
Na XI
Na X
Ne IX
Ni XIX
Fe XVII
Fe XVIII

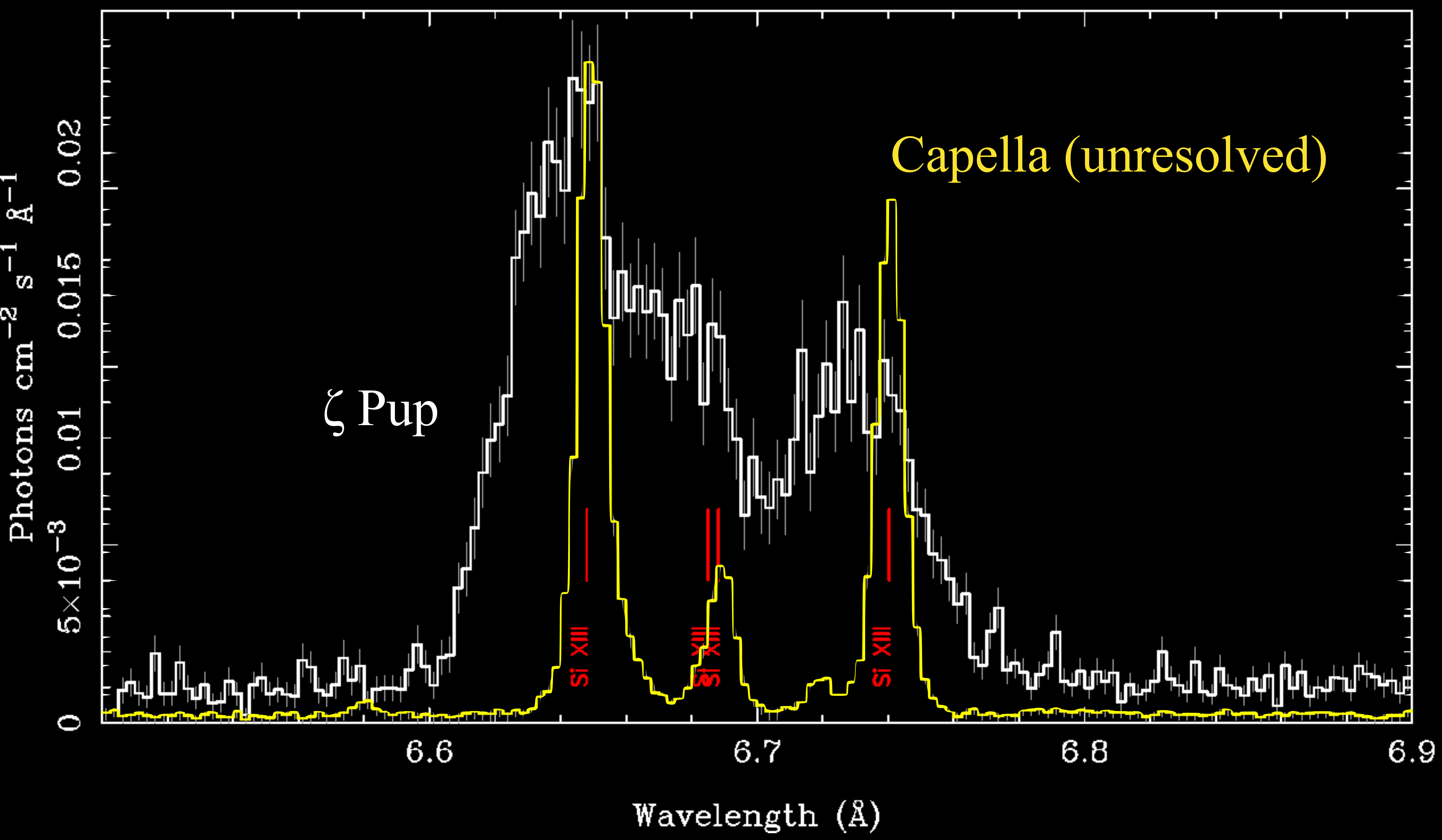


Photons cm^{-2} s^{-1} Å^{-1}
Wavelength (Å)
0
5×10^{-4}
10^{-3}
1.5×10^{-3}
2
8
9
10
11
12
Mg XII
Mg XI
Ne X
Na XI
Na X
Ne IX
Ni XIX
Fe XVII
Fe XVIII



Photons cm^{-2} s^{-1} Å^{-1}
Wavelength (Å)
Si XIII
Si XIII
Si XIII
Si XIII
6.6
6.7
6.8
6.9
0
5×10^{-4}
10^{-3}
1.5×10^{-3}
2×10^{-3}

Si XIII



Capella (unresolved)
ζ Pup
Si XIII
Si XIII
Si XIII
Si XIII
Photons cm^{-2} s^{-1} Å^{-1}
0
5×10^{-3}
0.01
0.015
0.02
6.6
6.7
6.8
6.9
Wavelength (Å)

A spectral model for the emission

X-ray emitting shocks in the wind — use the maximum X-ray plasma temperature to infer the maximum shock velocity.

Assume a powerlaw emission measure distribution up to a cutoff:

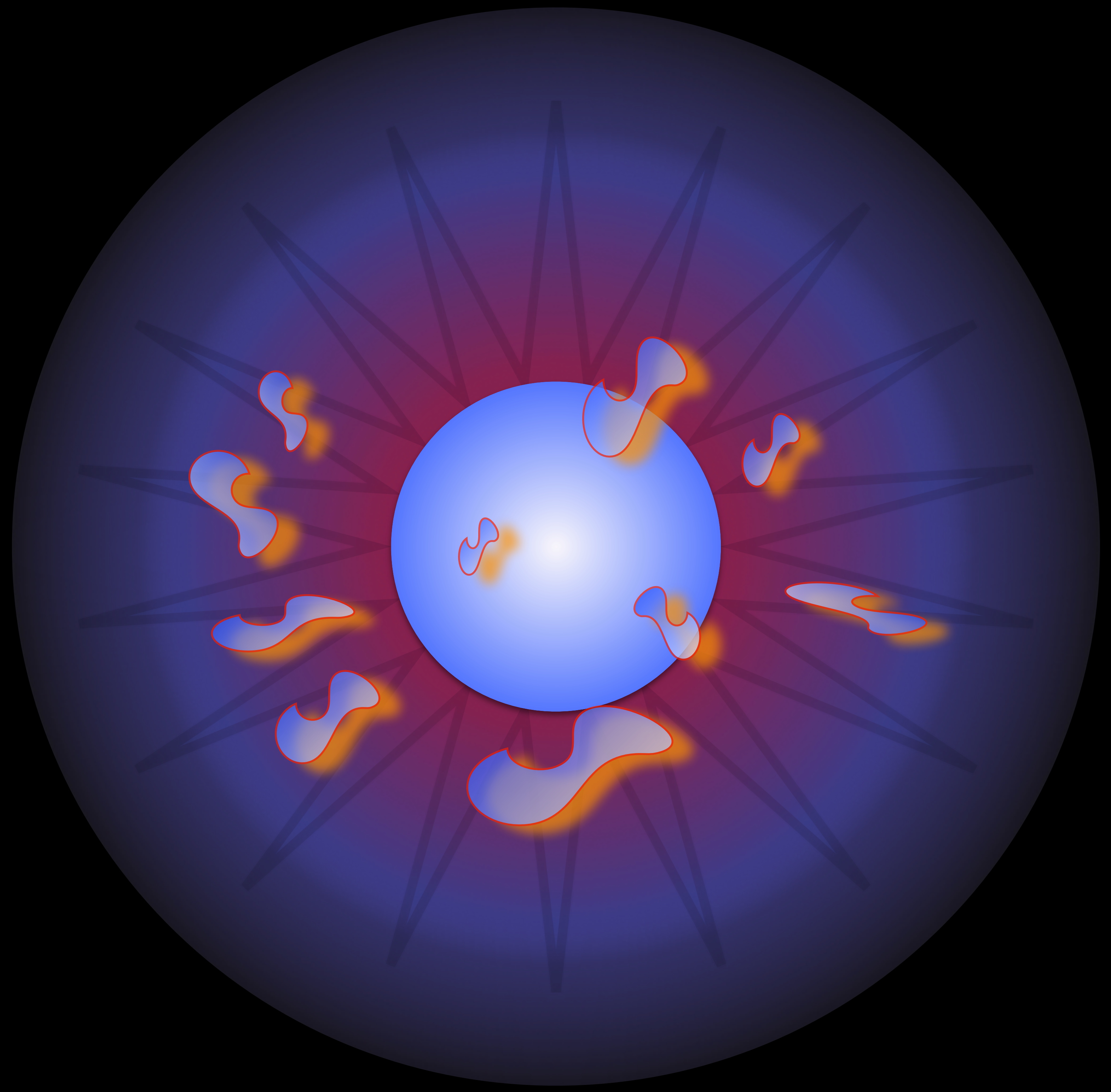
$$\mathrm{DEM}(T) \sim (T/T_{max})^{-\beta}.$$

Assume T_{max}, β same everywhere in the wind's hot plasma.

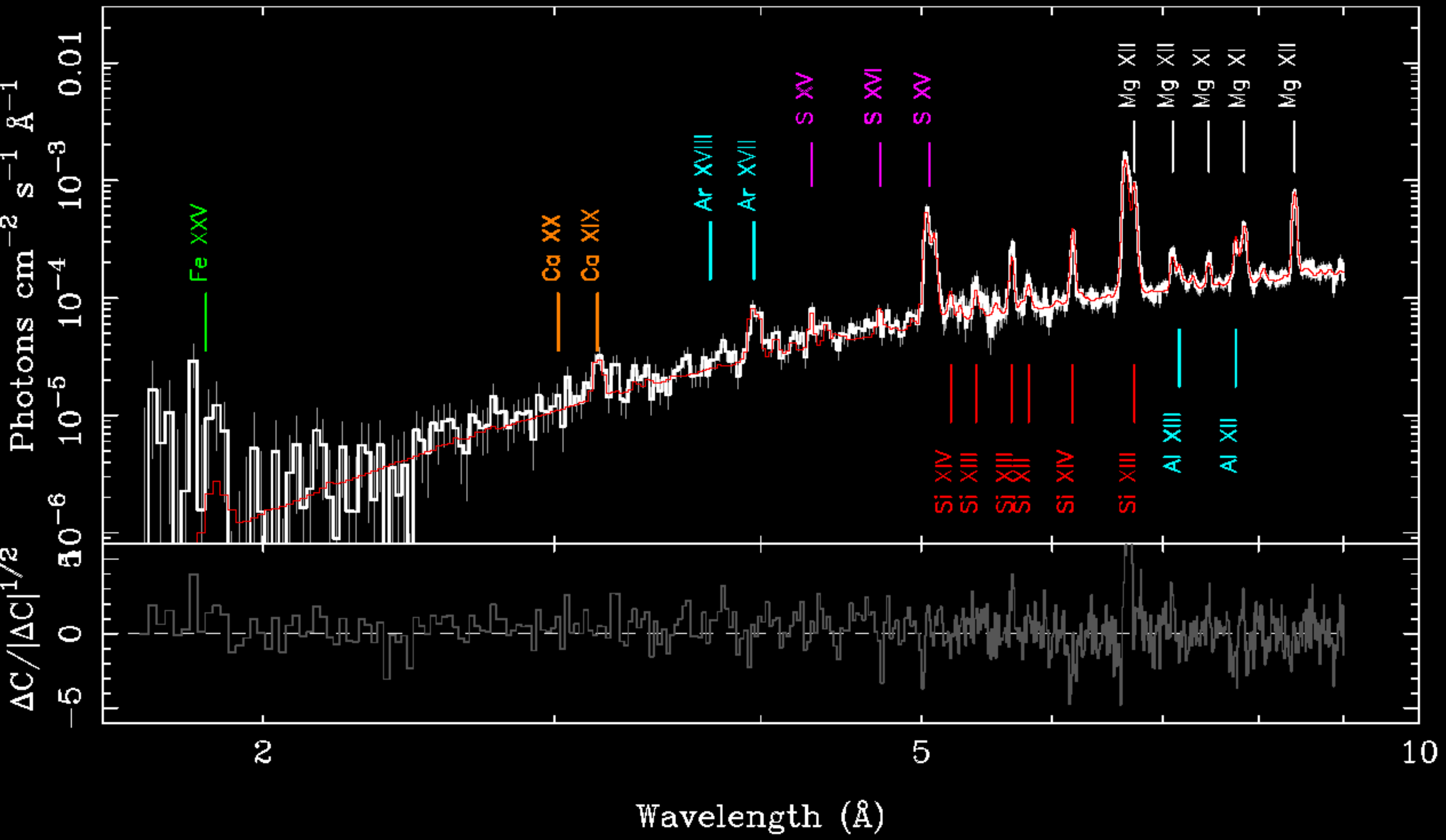
Assume thermal bremsstrahlung cooling.

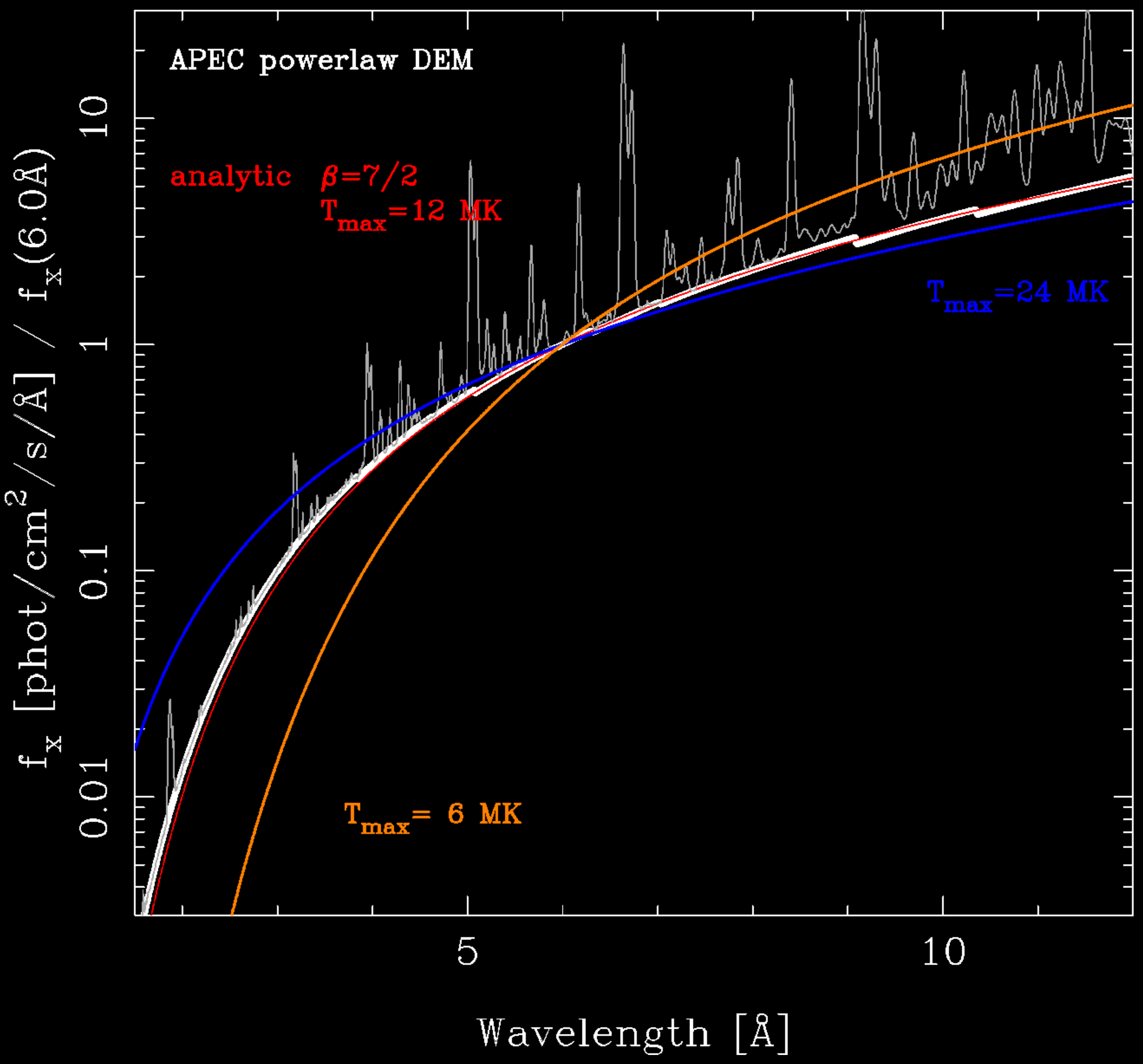
=> yields an analytic form for the continuum spectrum, with a short-wavelength cutoff in the X-ray band.

Use that DEM(T) with APEC (CIE) plasmas to model the spectrum at short wavelengths (<10Å) where *wind absorption effects are small*, and where *continuum contribution is significant*.

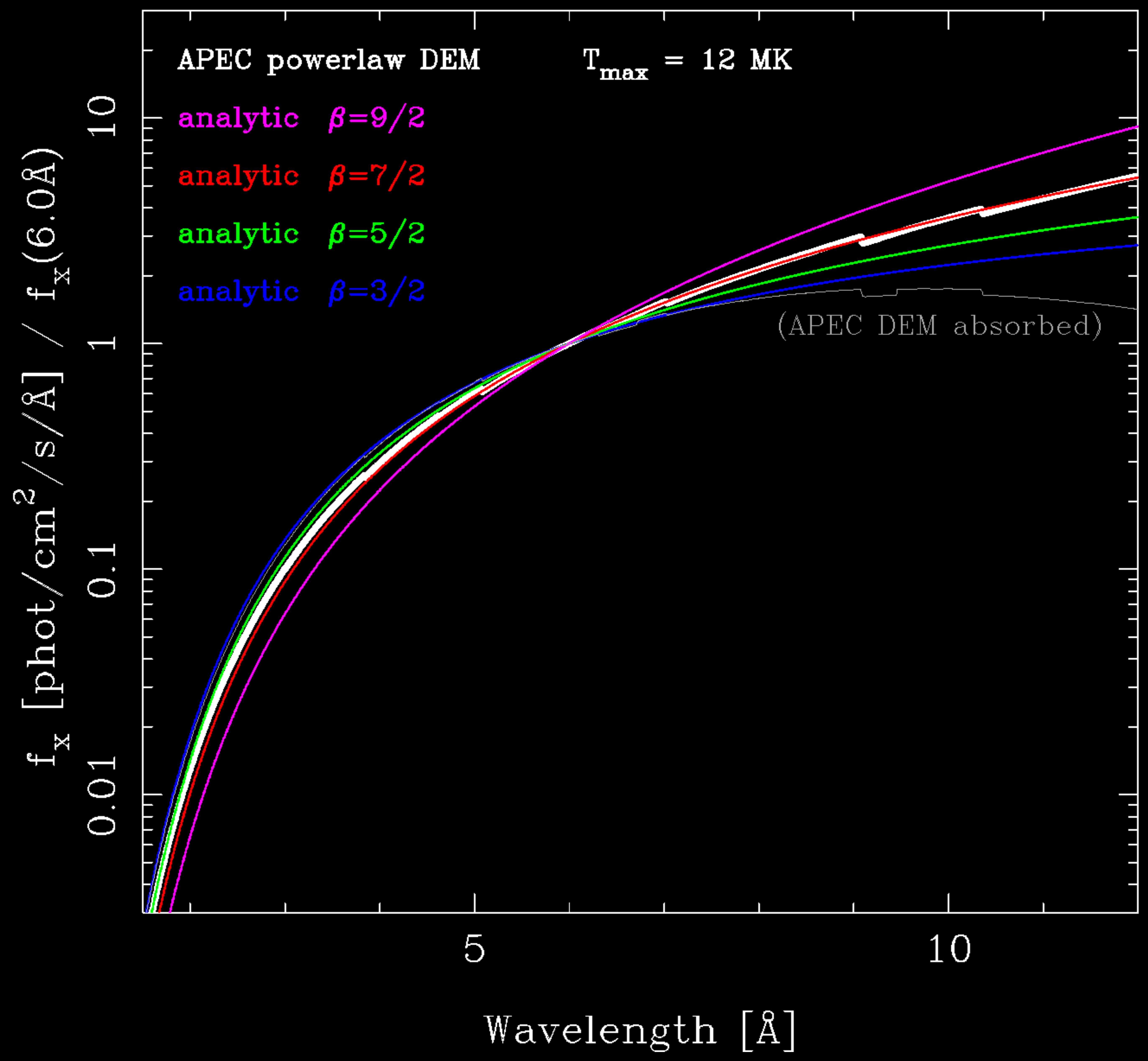


Fit results: T_{max} = **12 MK**, *β = 2.6*, $N_H = 7\times10^{21}$ cm^{-2} *(10% uncertainties)*





APEC powerlaw DEM
analytic β=7/2
T_max=12 MK
T_max=24 MK
T_max= 6 MK
f_x [phot/cm^2/s/Å] / f_x(6.0Å)
0.01
0.1
1
10
5
10
Wavelength [Å]



APEC powerlaw DEM
T_{max} = 12 MK
analytic β=9/2
analytic β=7/2
analytic β=5/2
analytic β=3/2
(APEC DEM absorbed)
f_x [phot/cm^2/s/Å] / f_x(6.0Å)
10
1
0.1
0.01
5
10
Wavelength [Å]

Summary

T_{max} = 12 MK => v_{shock} ~ 900 km/s; good, since v_∞ = 2200 km/s.

BUT: difficult to accommodate in standard Line-Driven-Instability models IF spectrum is formed deep in the wind (as low continuum opacity & line shapes strongly suggest).

β = 2.6: consistent with shocked clump models (Cassinelli et al 2009) or hydro models (Krtička et al 2009) (but β is not strongly constrained).

Wind models may require perturbations near the photosphere which are then amplified as the flow expands in order to obtain high shock velocities close to the star.