

# Anomalous intensities of lines observed in RESIK soft X-ray flare spectra

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# RESIK

The RESIK instrument (**R**entgenovskij **S**pectrometer s **I**zognutymi **K**ristalami) consists of two double detector (spares from *Yohkoh* BCS) and four mono-crystal wafers of Quarts and Si bent to desired radius. This X-ray spectrometer collected spectra in four bands:

channel 1: 3.37 - 3.88 Å

channel 2: 3.82 - 4.33 Å

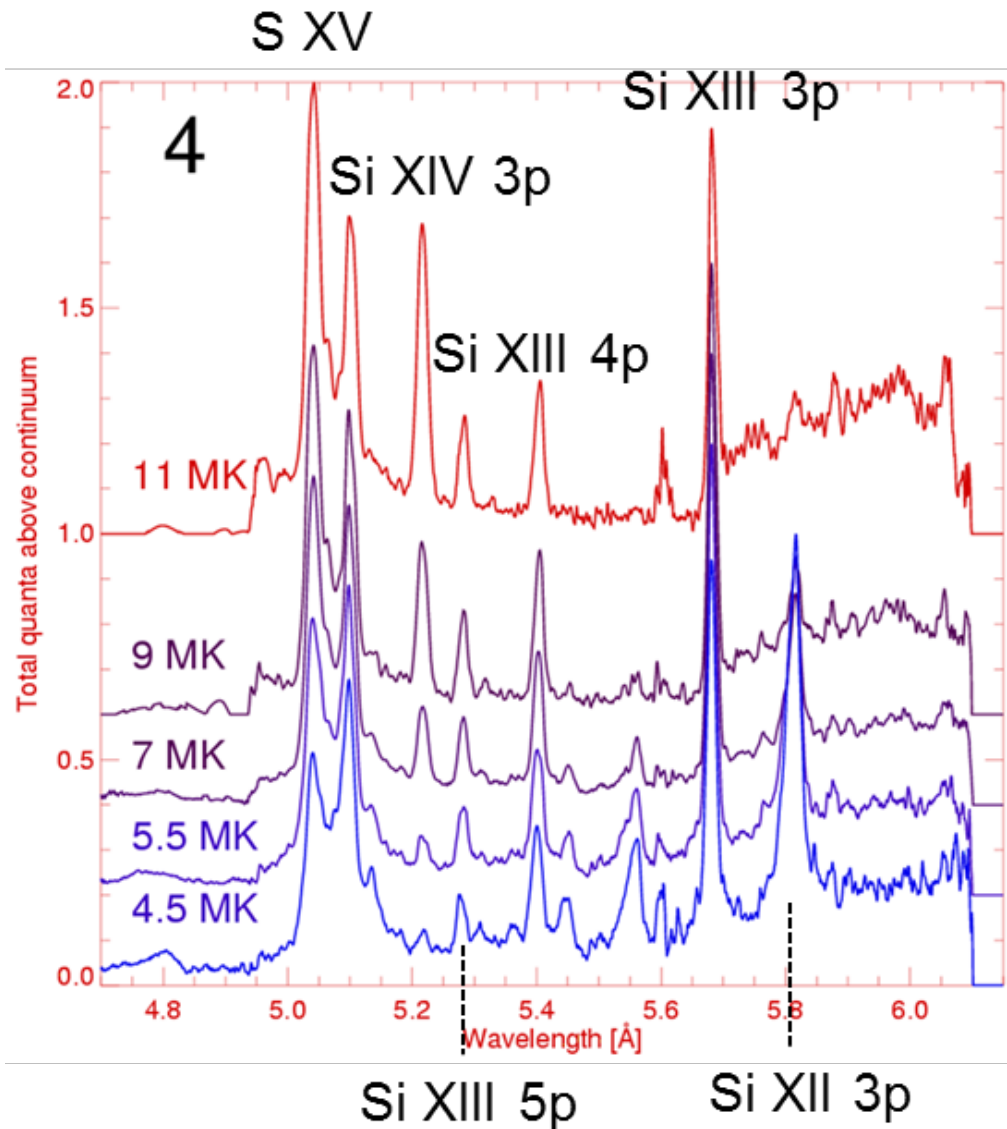
channel 3: 4.31 - 4.89 Å

channel 4: 4.96 - 6.09 Å

RESIK was the most recent solar soft-X-ray Bragg spectrometer, flown in 2001. Resik observed numerous (>100) flares as well as active region emissions. During large flares, the spectra collection times (DGI- data gather interval) could be as short as 2 s. For non-flaring periods DGI was ~5 min. By now the spectra for 75 flares have been reduced to so-called level 2 (science grade absolute fluxes).

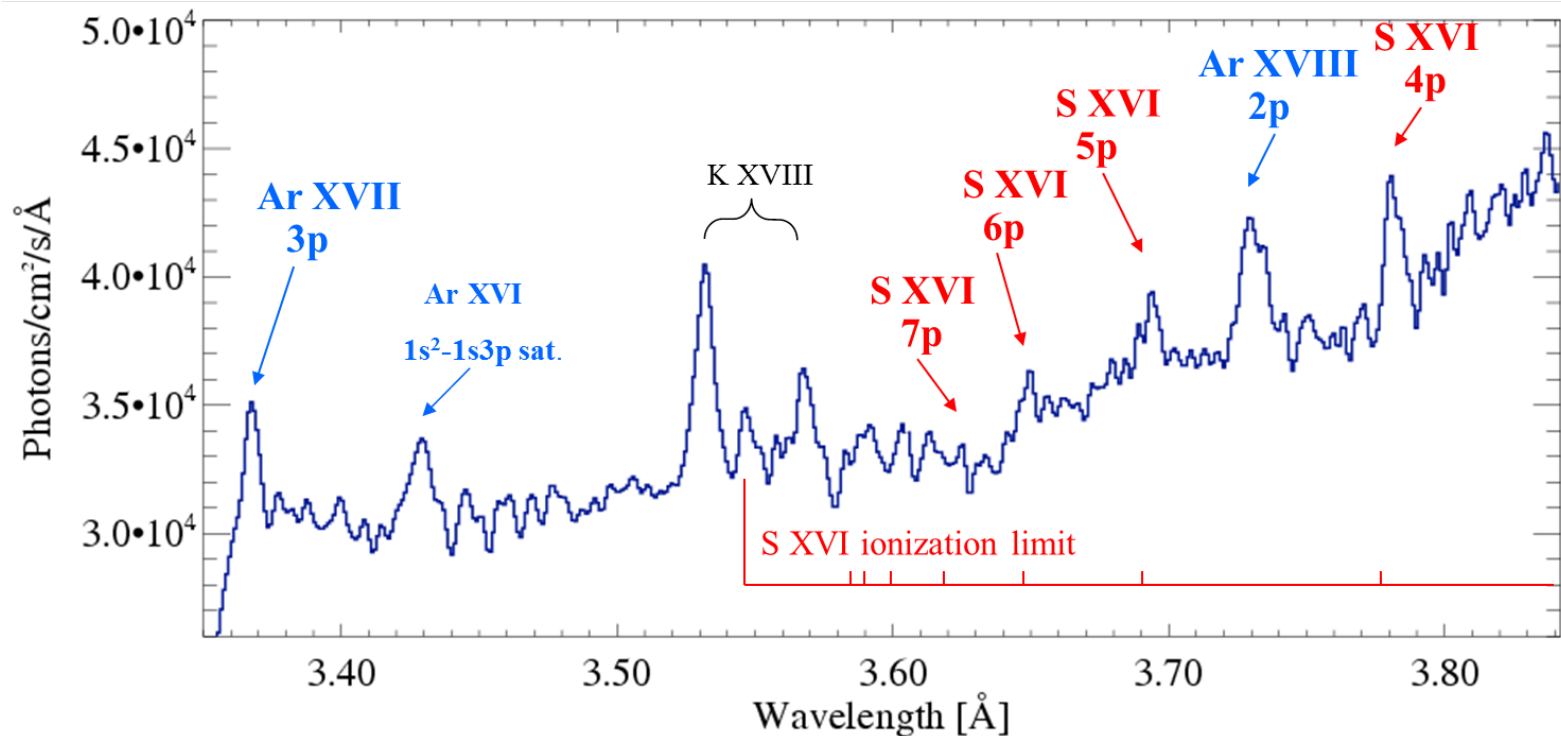
Many measurements were taken during the flares' rise phase. For some impulsive events peculiar line intensity ratios are sometimes observed, reflecting presence of non-"standard" conditions in flaring plasma. For some lines, observed intensity ratios cannot be explained even in the multi-temperature approach.

# Temperature ordered channel 4 spectra



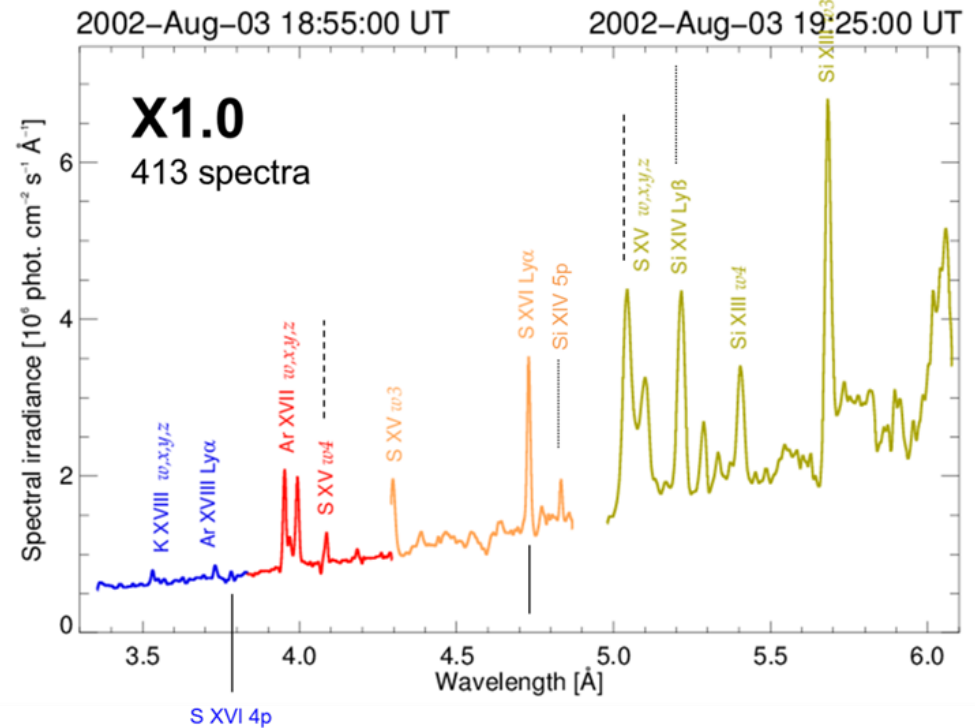
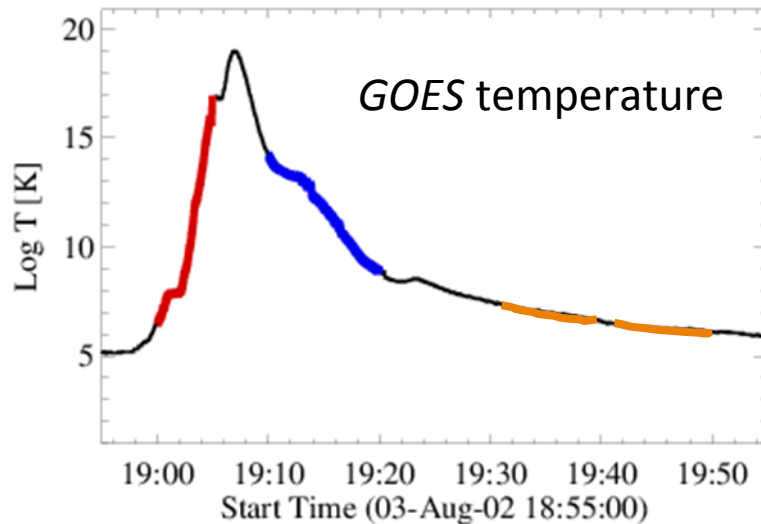
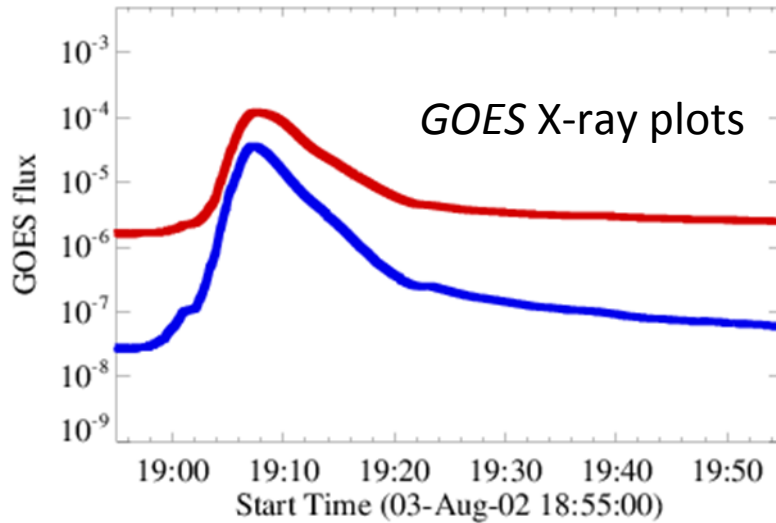
1163 RESIK spectra collected between 1 January and 14 March 2003 (best observing sequences) were grouped according to the emitting plasma temperature and averaged in order to reveal spectral features in detail. The collected set of spectra covers as well lower class events ( $\sim$ B4) as few M class flares. (Sylwester, B. et al., Adv. Space Res., 38, 1534, 2006)

# Average channel 1 spectrum for 14 flares (2003, $\Delta t \approx 9\text{h}$ )



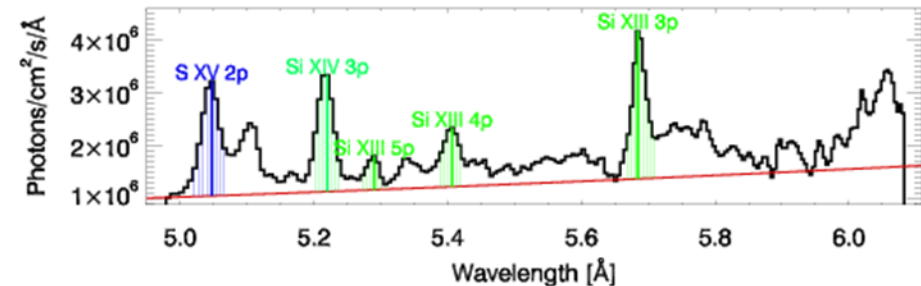
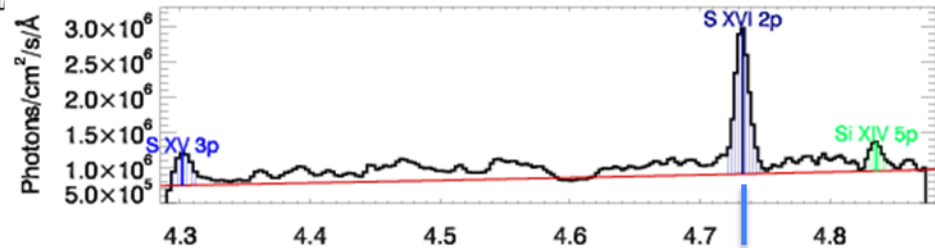
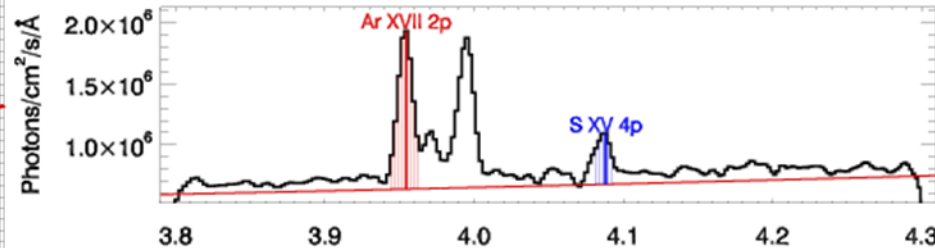
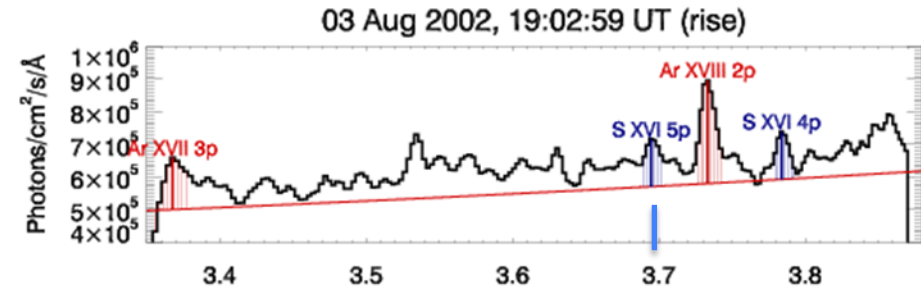
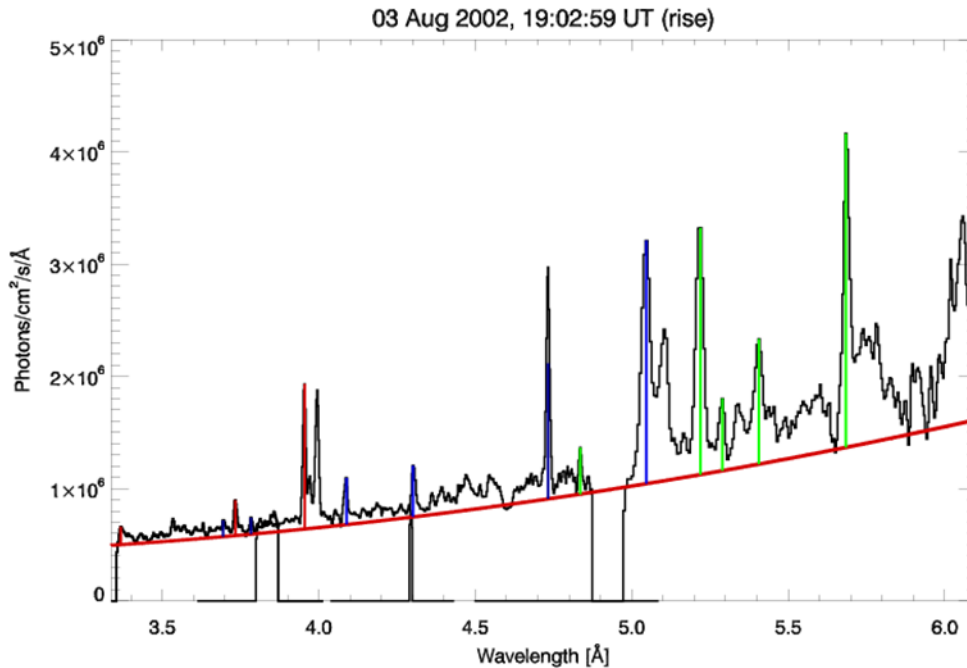
RESIK channel 1 (3.37 Å to 3.83 Å) includes many strong emission lines due to transitions  $1s^2 - 1s(np)$  and  $1s - np$ , in He-like and H-like ions respectively; the  $n = 2$  and 3 lines have been routinely observed for Si, S and Ar ions in numerous previous experiments. Here, for the first time we have observed for some flares enhanced emission in spectral features coinciding with transitions for  **$n$  up to 7**. Respective observed line series intensity decrements have been determined and discussed in the paper by Kepa et al., 2006 (Adv. Space Res., 38, 1538).

# SOL2002-08-03T19:07



GOES lightcurves and the temperature profile – red part denotes rise phase observed with RESIK and blue decay phase. Close to maximum, detectors were saturated as the flare was a strong X1 flare. RESIK observed also late decay part (orange) of the evolution. **This was the most intense flare recorded by RESIK!**

# Flare rise time spectra



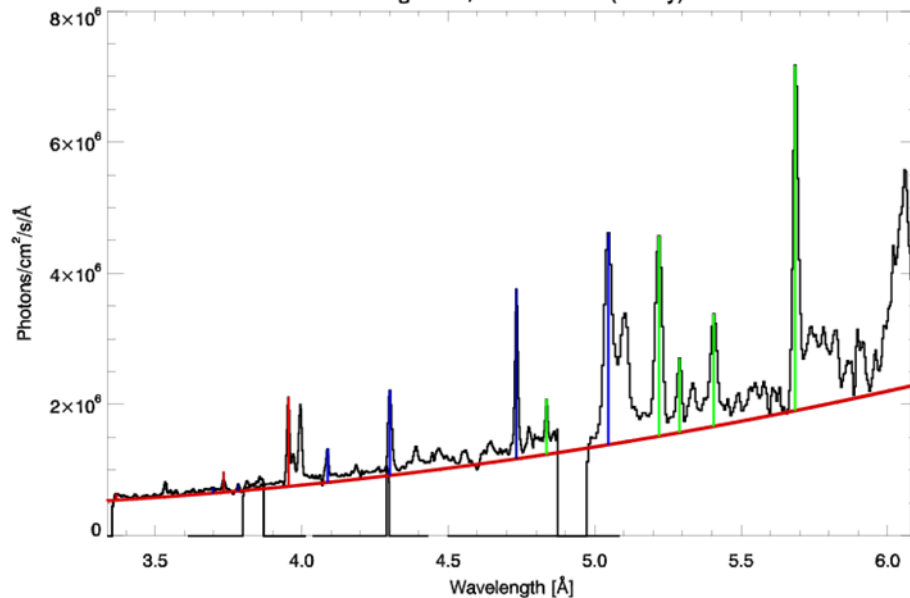
SOL2002-08-03T19:07 rise phase spectrum.

The continuum is shown as the red line.

**Fluxes in line features were estimated as corresponding to count rates seen above the continuum.** Colours represent respective elements. Features corresponding to  $n=2, 3, 4$  &  $5$  transitions are clearly seen.

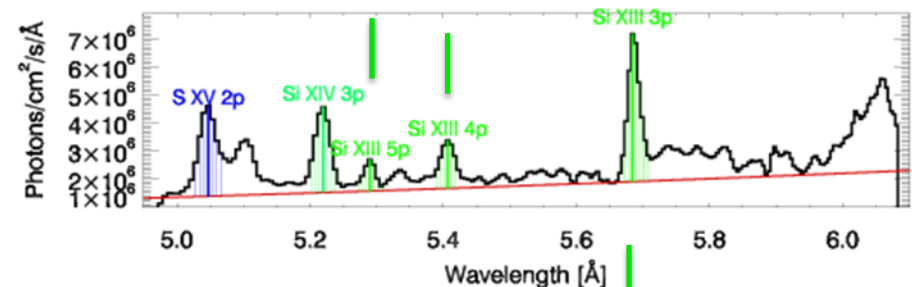
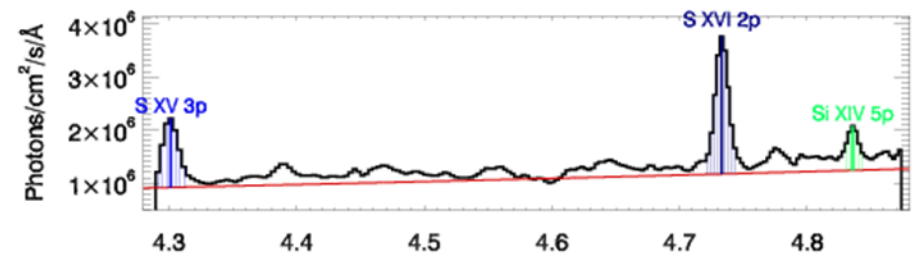
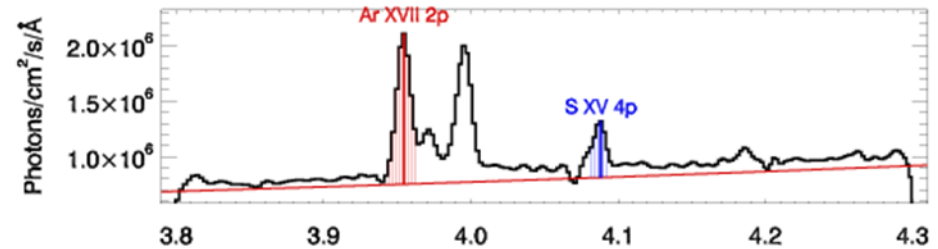
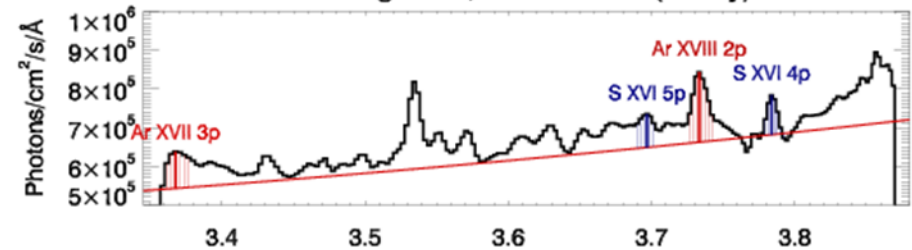
# Flare decay time spectra

03 Aug 2002, 19:15:38 UT (decay)

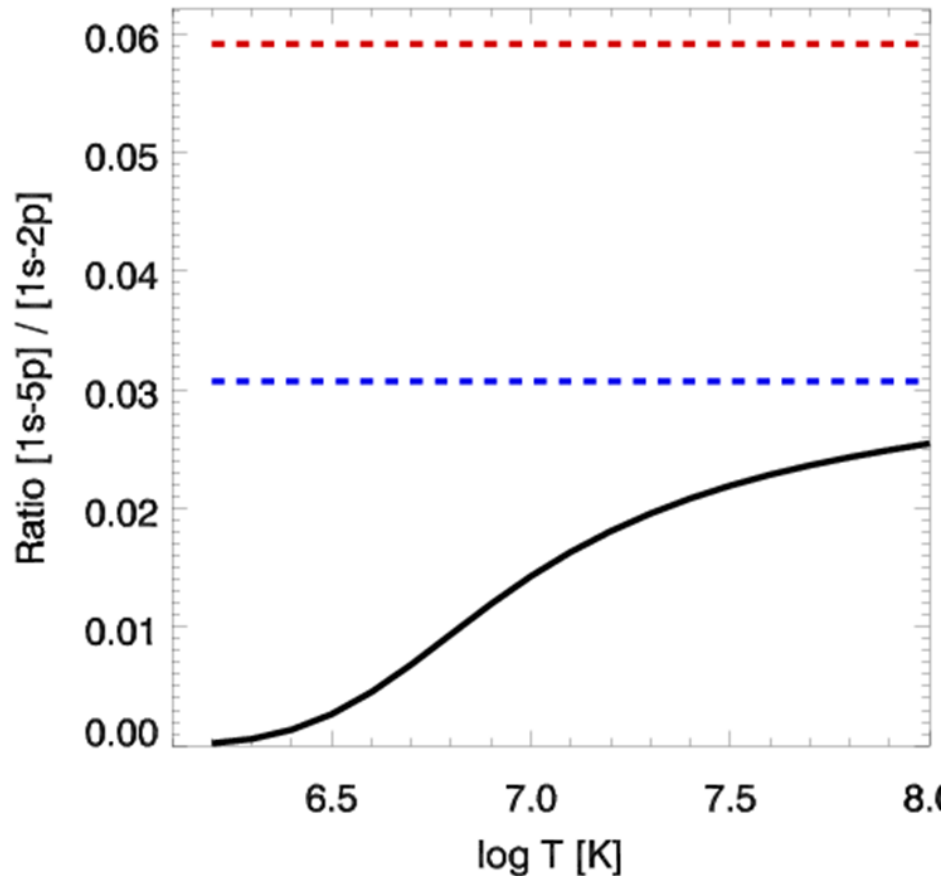


SOL2002-08-03T19:07 decay phase spectrum. The continuum is indicated. Colours represent respective elements. Again, spectral features corresponding to  $n=2$ , 3, 4 & 5 transitions are well pronounced.

03 Aug 2002, 19:15:38 UT (decay)

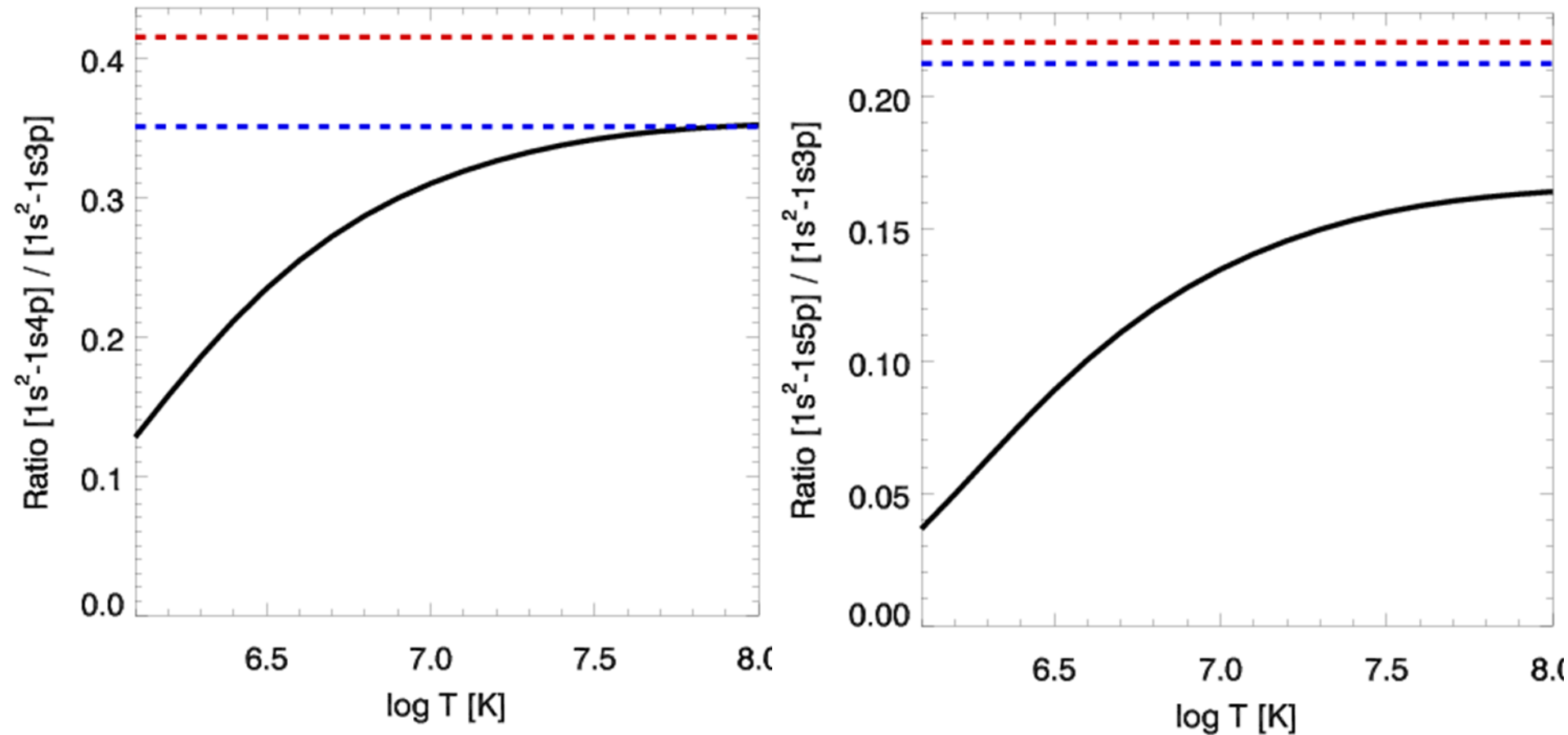


# The **S XVI** hydrogen-like ion intensity ratio $n=5$ to $n=2$ transitions



Based on the observed count rate in lines, their averaged fluxes have been determined for the **rise phase** and the **decay**. Respective intensity ratios have been determined (dashed lines) and compared with the theoretical predictions. As the lines originate from the same ion by collisional excitation, their ratios can be calculated easily. Here we have calculated values of this ratio using CHIANTI 7.0 routines (**solid black line**) for a number of temperatures assuming maxwellian particle distribution function (pdf). For both the rise and decay phases, the observed ratios are above theoretical - possibly indicating non-maxwellian pdf.

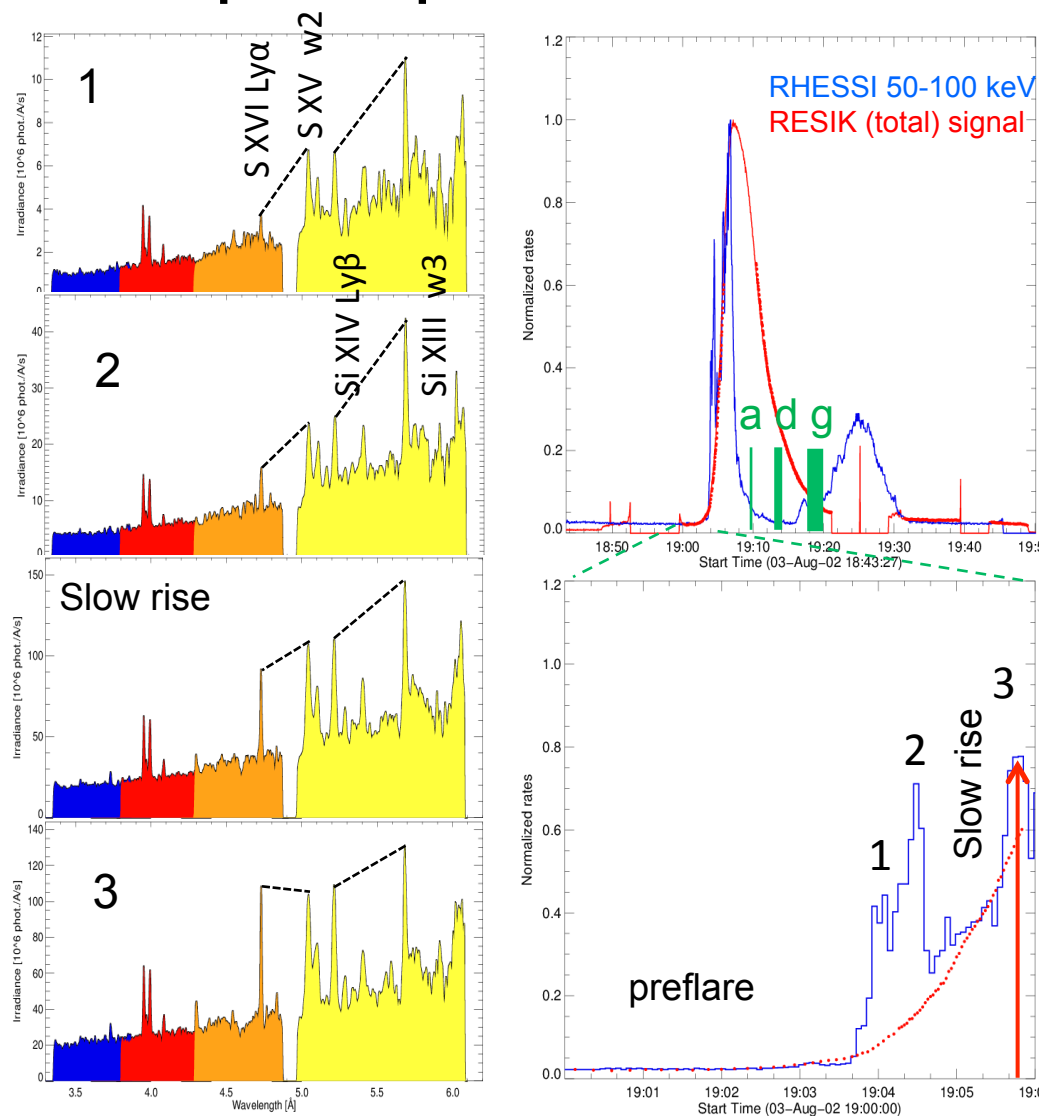
# The **Si XIII** helium-like ion intensity ratio: $n=4$ & 5 to $n=3$ transitions



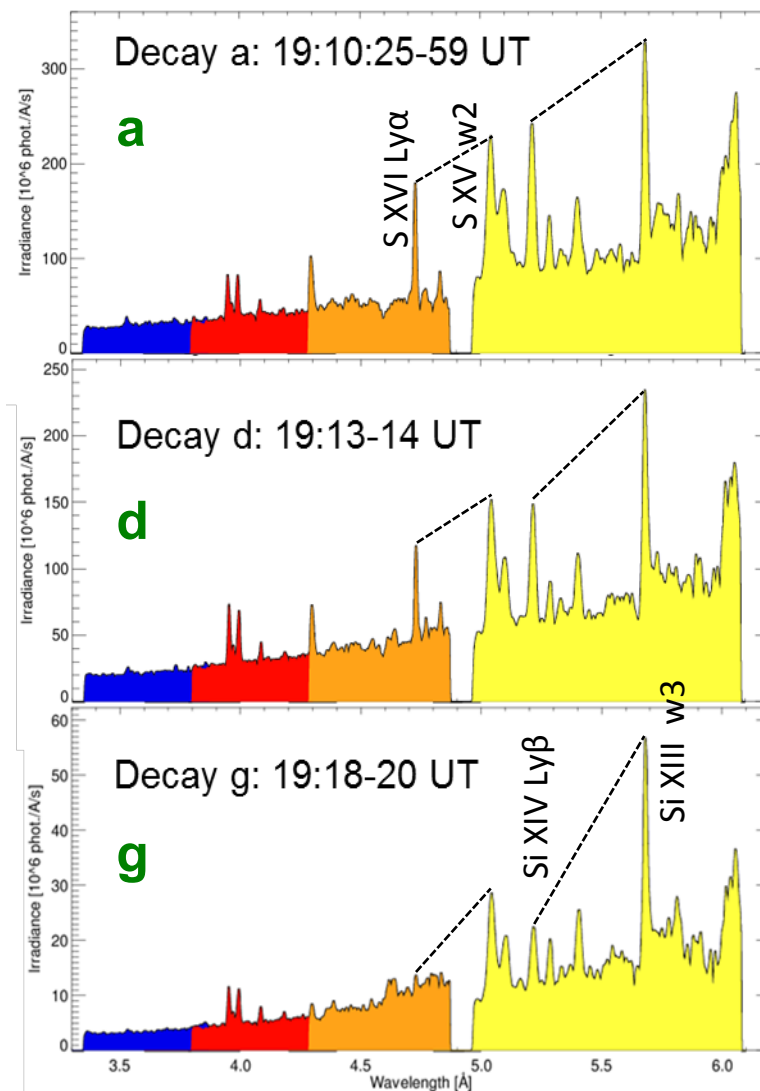
A similar pattern is observed, **excluding** assumed thermal character of upper-level population

# Details of SOL2002-08-03T19:07 spectra & their evolution

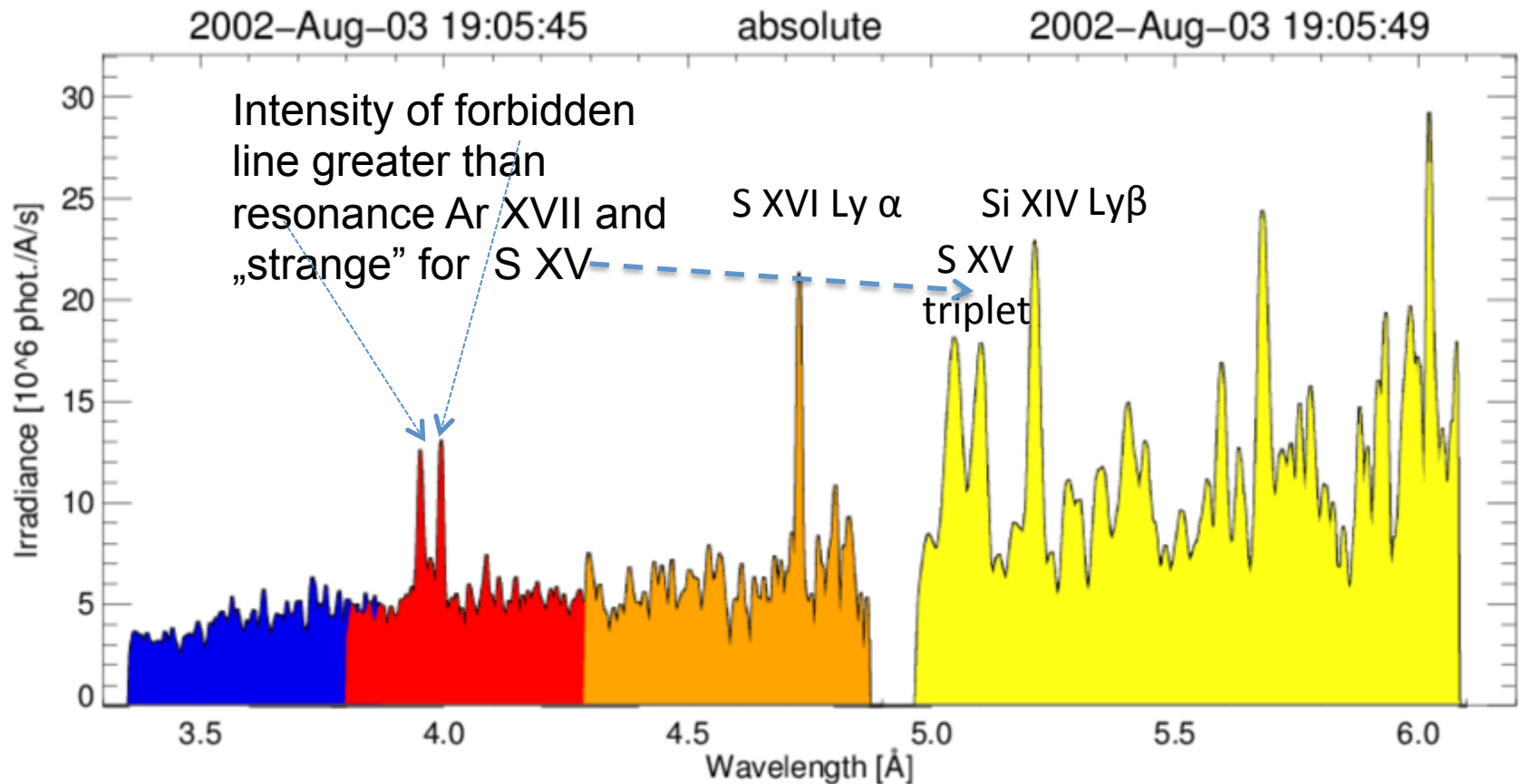
## RISE phase spectra



## DECAY

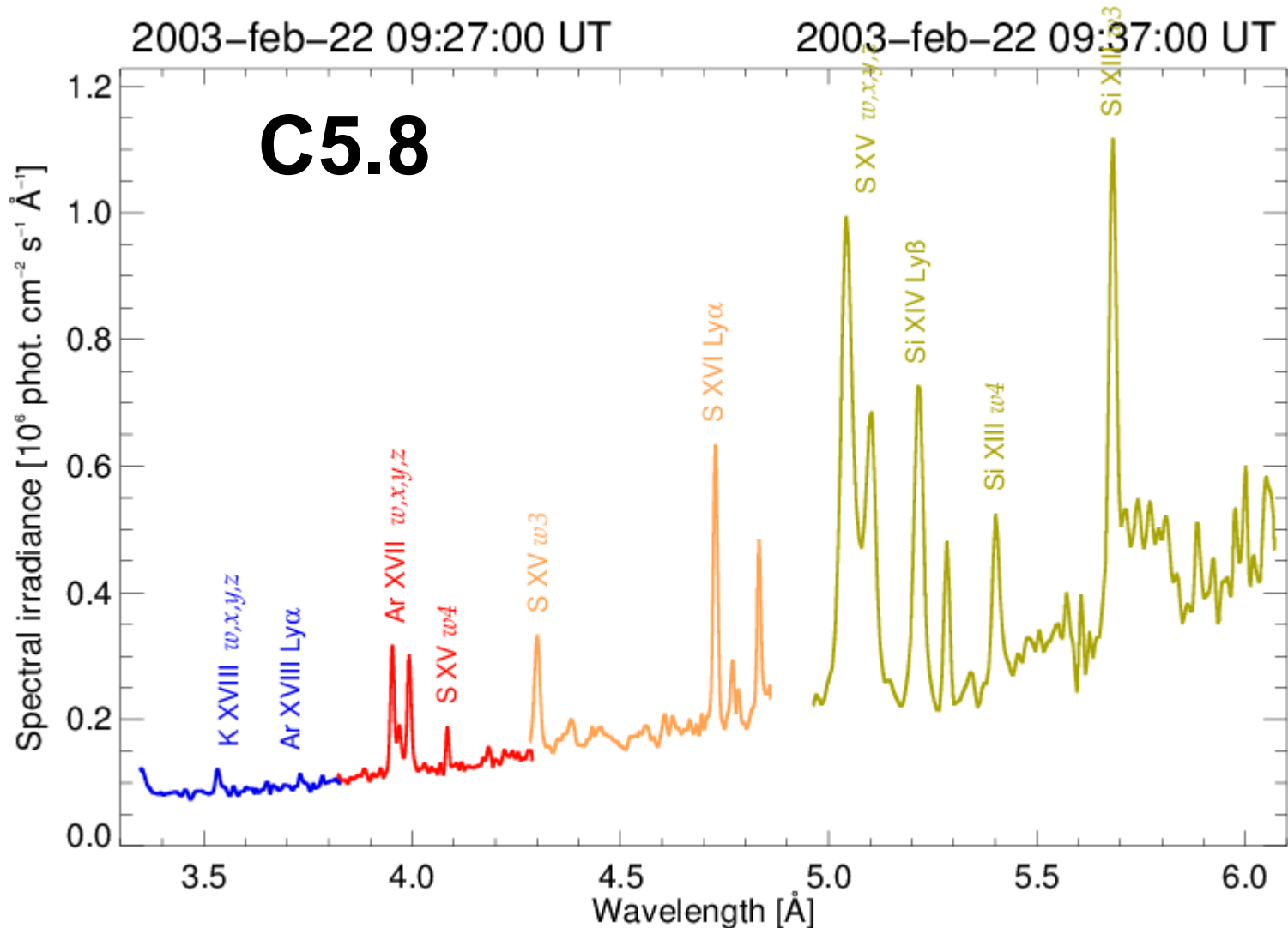


# The unusual 4s DGI spectrum seen at the peak of HXT impulse „3” (red arrow)



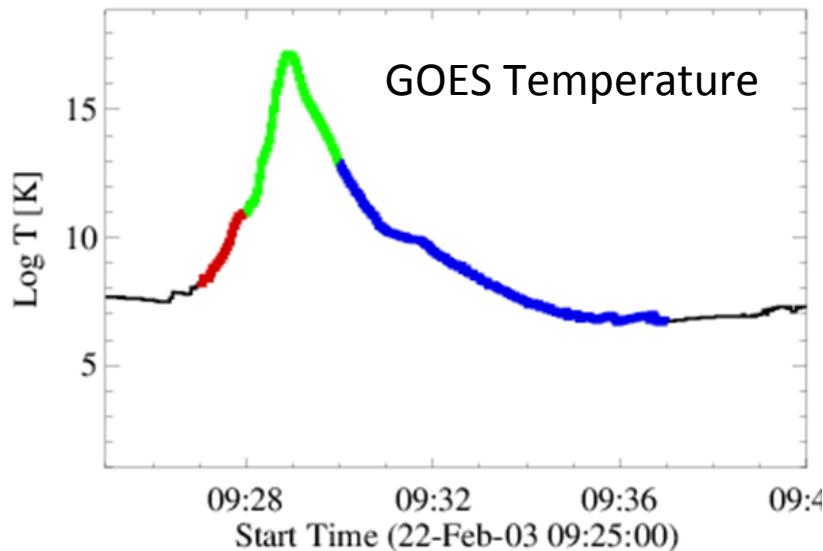
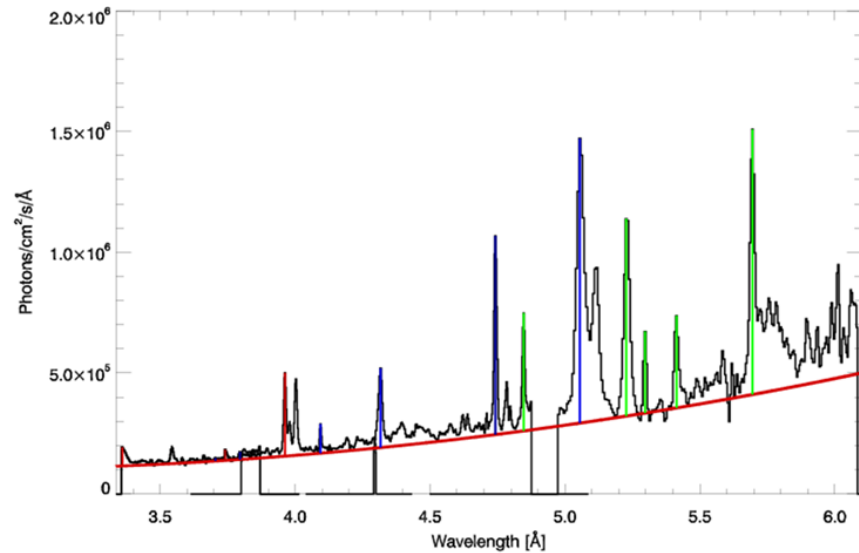
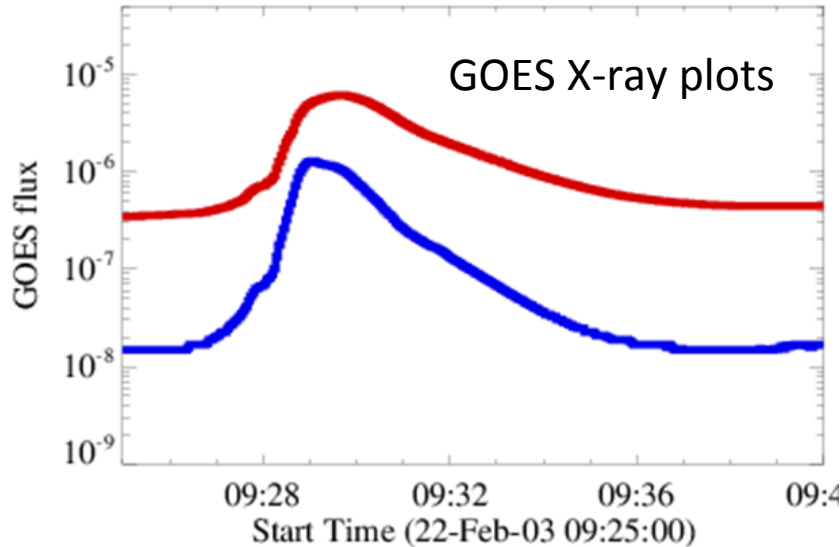
In **hot** thermal plasma, the intensities of triplet lines preserve a well known pattern with the strongest resonance transition, weaker forbidden and the weakest intercombination lines. The relative intensity of Si XIV Ly  $\beta$  line exceeds the S XVI Ly  $\alpha$  line intensity which is unusual.

# Another flare: SOL2003-02-22T09:29



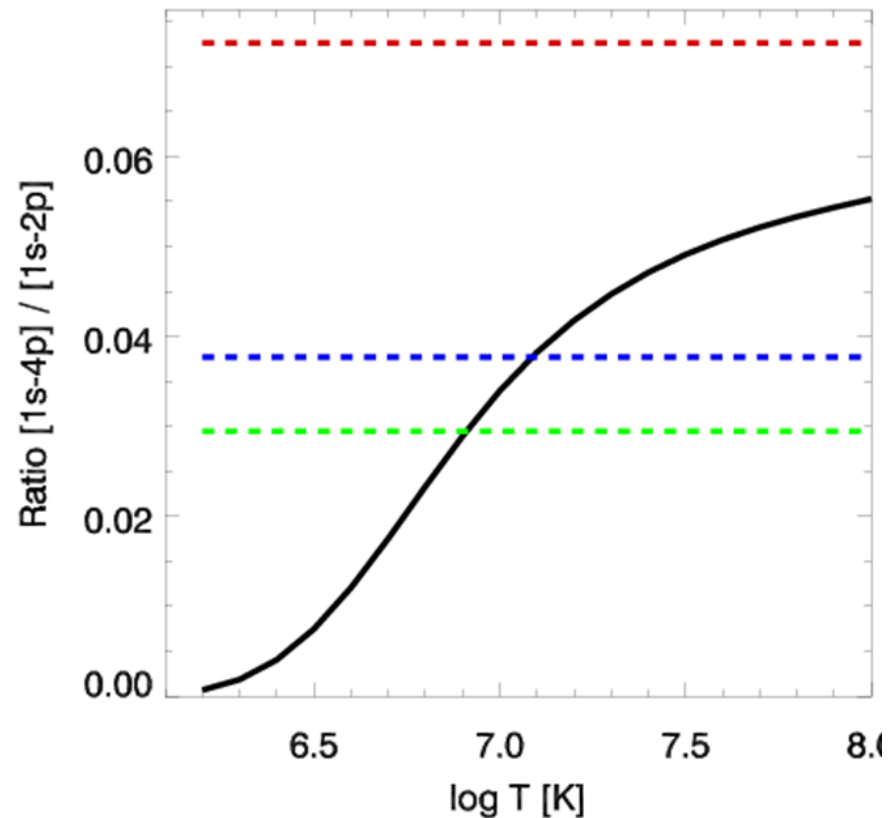
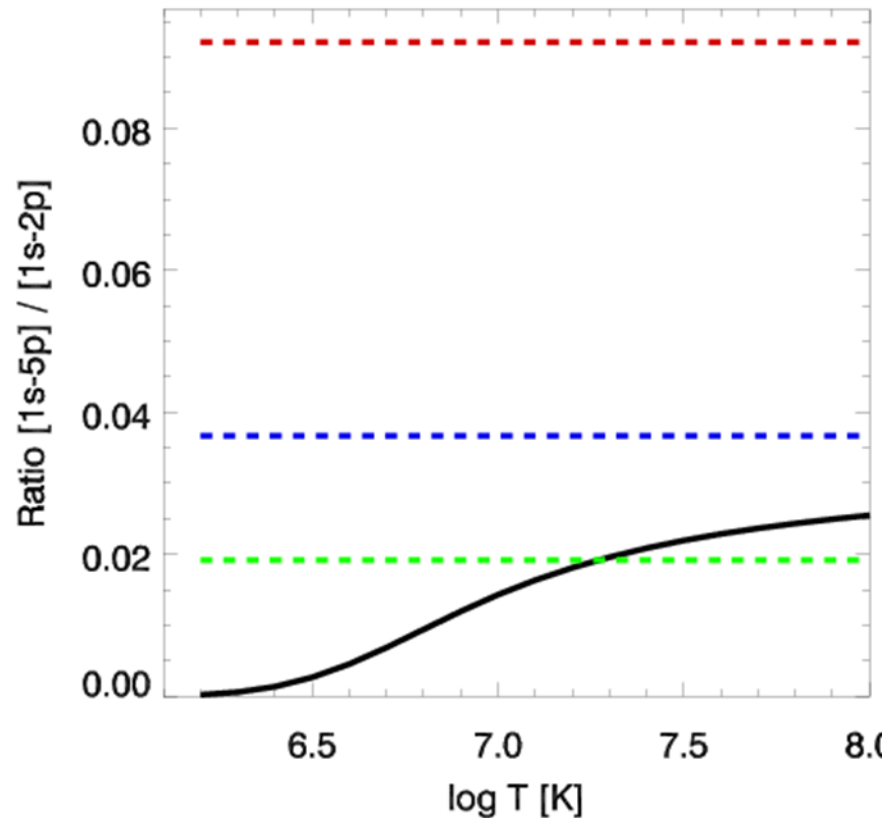
Event  
summed  
spectrum.  
Spectrum  
collection time  
was 600 s.

# 2003/02/22 09:29:00 C5.8



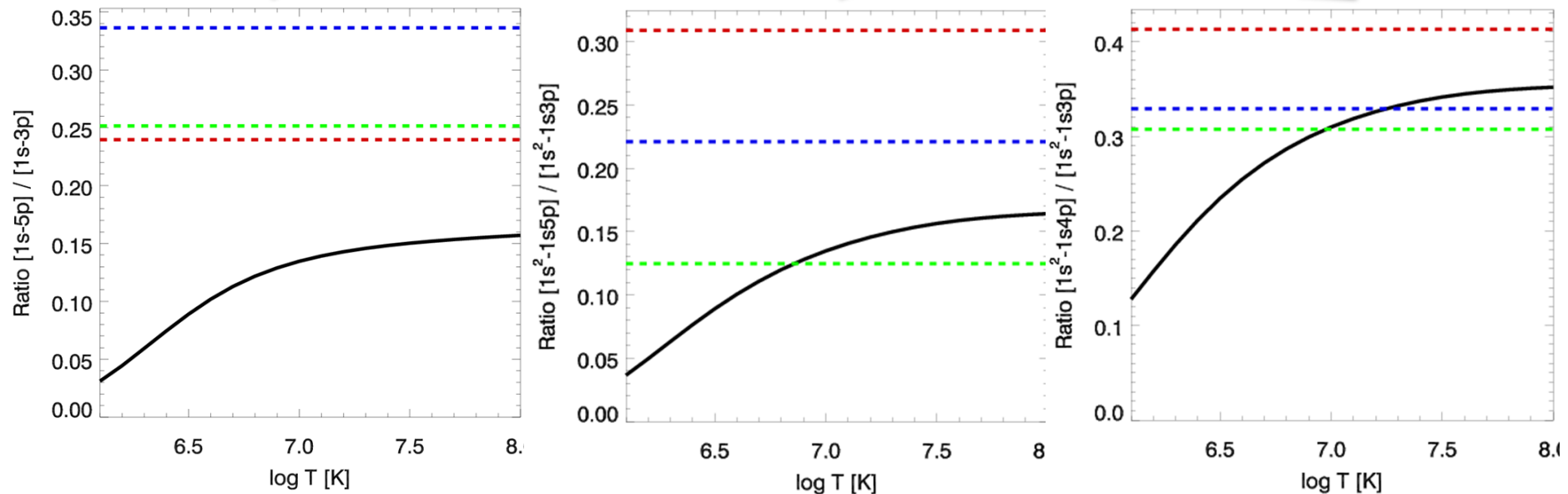
GOES lightcurves and the temperature profile for a **moderate class** flare. The RESIK spectrum above was time integrated over the maximum phase. Here the colours indicate: **the rise phase**, **maximum**, and the **decay**.

# The **S XVI** hydrogen-like ion intensity ratio $n=5$ & 4 to $n=2$ transitions



In this case, thermal excitation model is marginally possible for maximum and decay flare phase but **NOT** for rise phase.

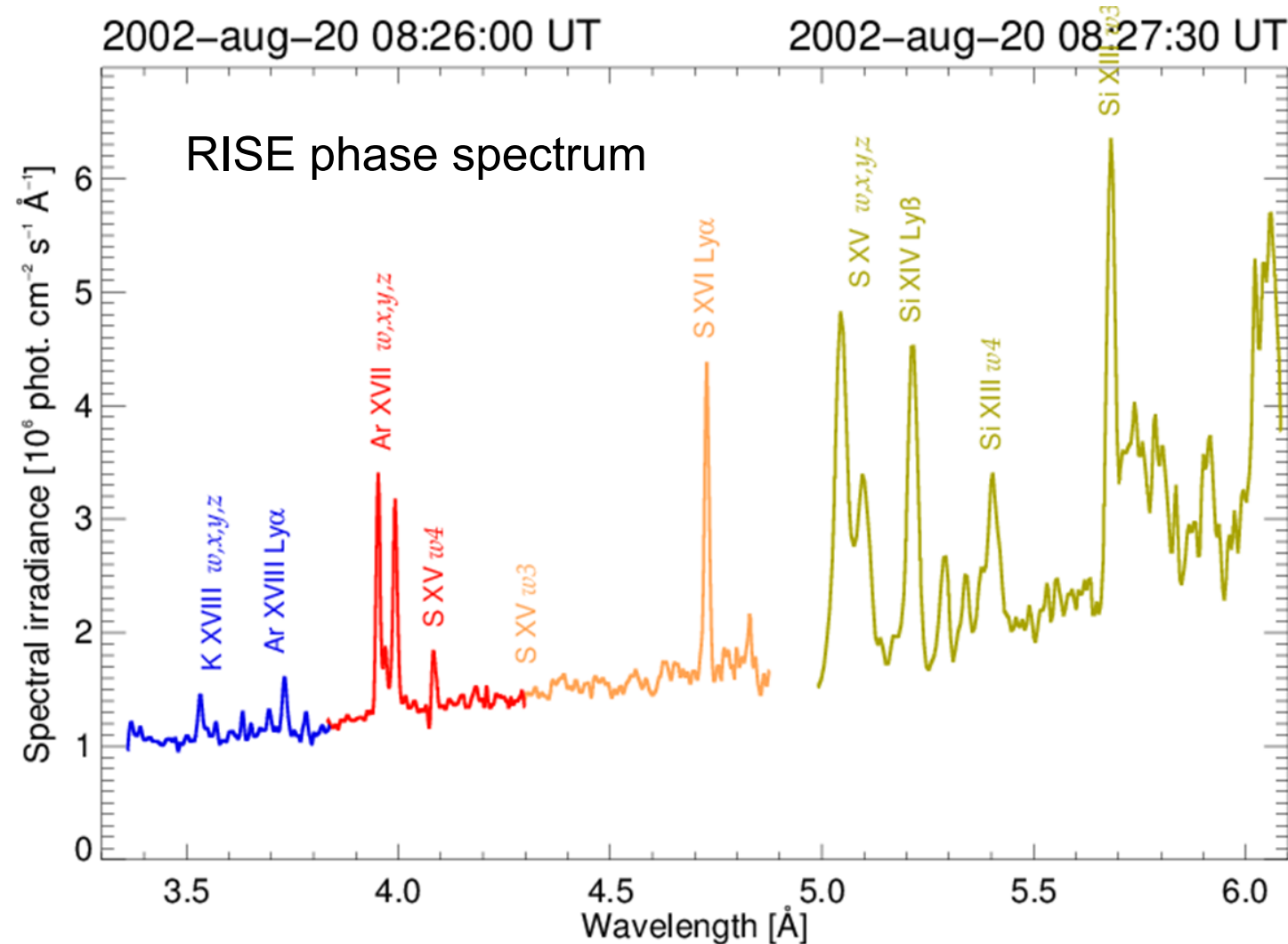
# The **Si XIV** H-like and **Si XIII** He-like ion intensity ratios for $n=5$ & 4 to $n=3$ transitions



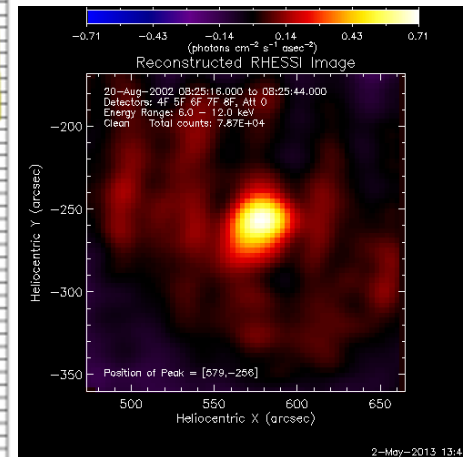
Again, thermal excitation model is marginally possible for maximum and decay flare phase, but only in case of helium-like ion transitions.

H-like excitations cannot be explained in the coronal equilibrium excitation scenario.

# Another flare: SOL2002-08-20T08:25

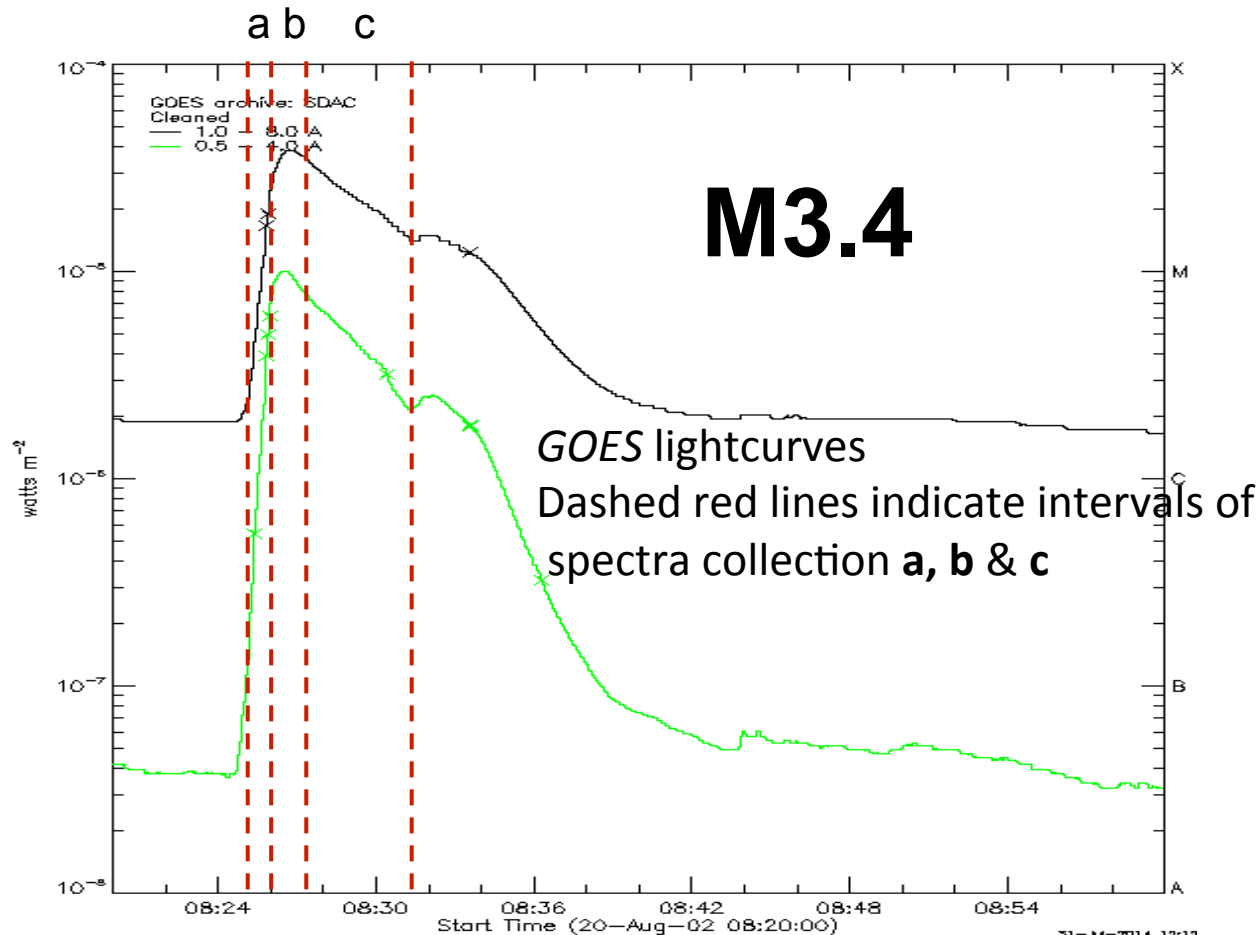


Spectrum summed over 90 s during the impulsive rise phase.



*RHESSI*  
reconstructed  
image (6-12 keV,  
maximum phase).

# This SOL2002-08-20T08:25 was the most impulsive among the events analysed



Also for this flare we were not able to account for some observed lines' intensities in the framework of standard Maxwellian particle distribution function.



Idea of K distributions

# Can frequently used $\kappa$ (kappa) – distributions help in the interpretation of the presented strange lines' intensity pattern?

$\kappa$  distributions for  $\kappa=2, 3, 5, 10, 25$  and the Maxwellian distribution ( $\log T(K)=6.0$ )

The  $\kappa$  distributions of electron energies  $E$  represent a family of non-Maxwellian distributions characterised by a power-law high-energy tail with two parameters,  $\kappa$  and  $T$ :

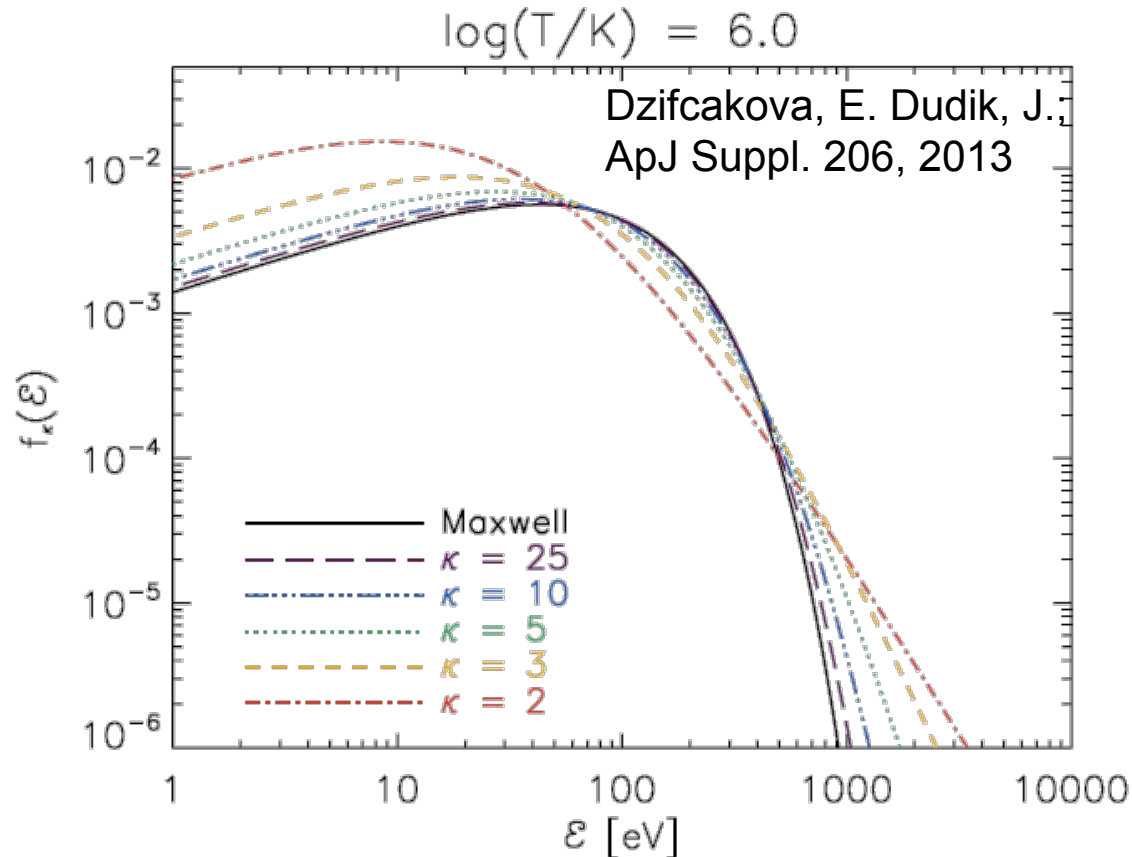
$A_\kappa$  – normalised constant

$k_B$  – Boltzmann constant

$\kappa \rightarrow 3/2$  corresponds to the largest deviation from Maxwellian distribution

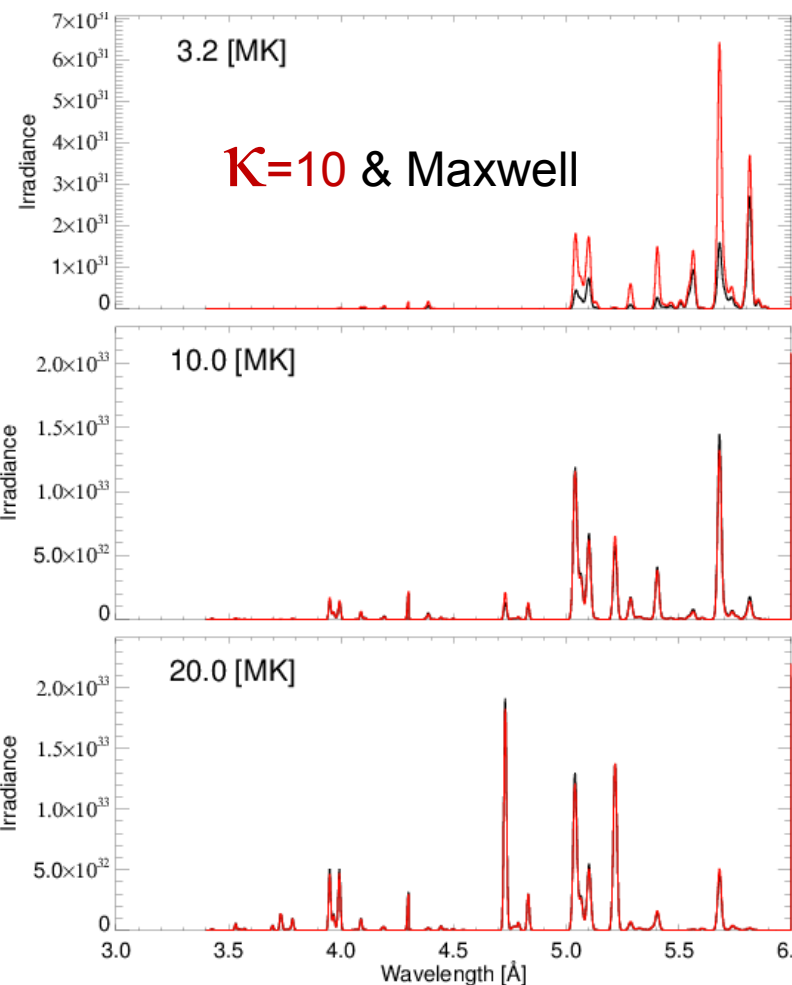
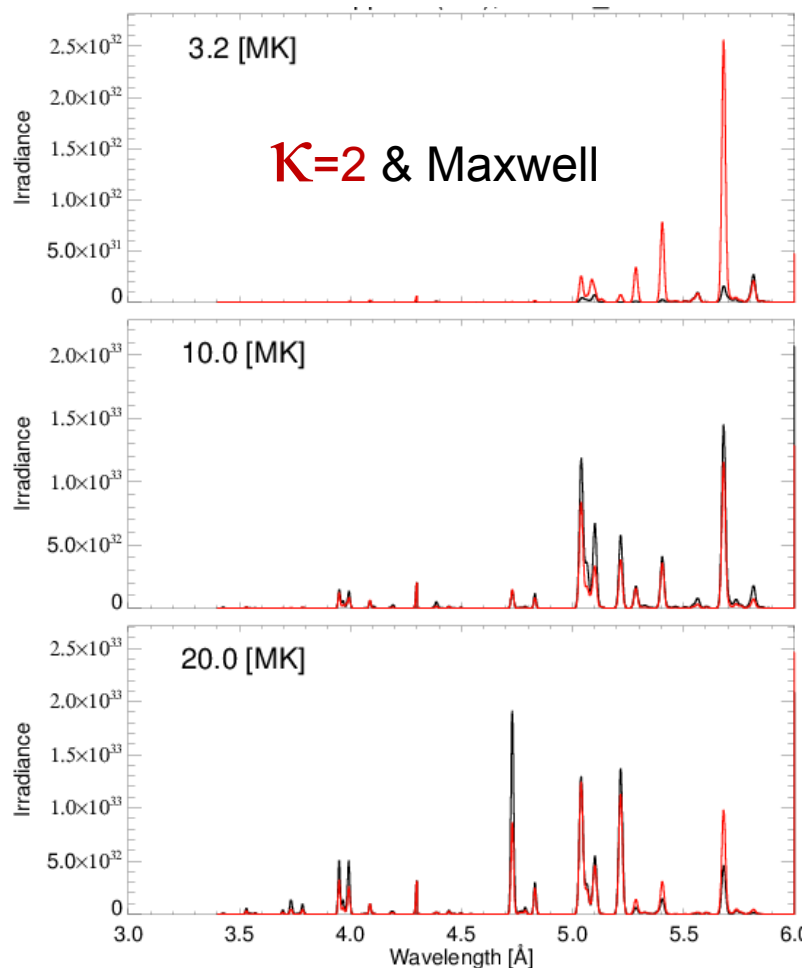
$\kappa \rightarrow \infty$  corresponds to Maxwellian distribution

$\langle E \rangle = 3k_B T/2$  the mean energy of  $\kappa$  distribution



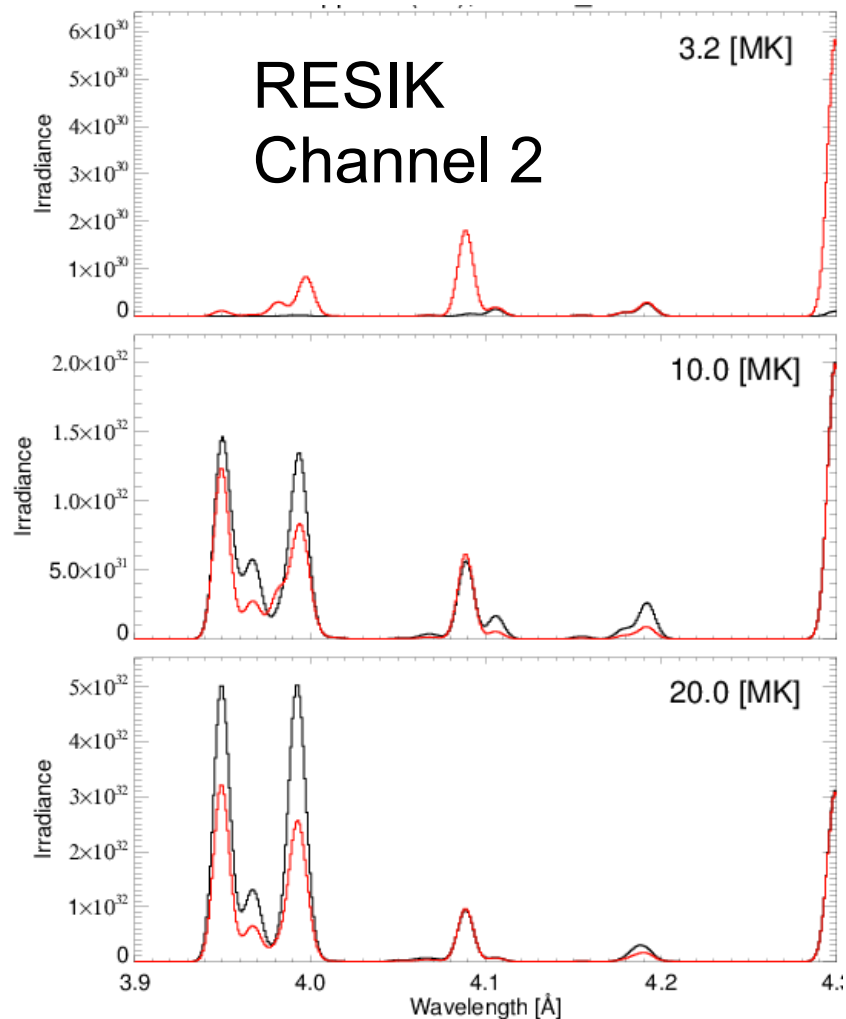
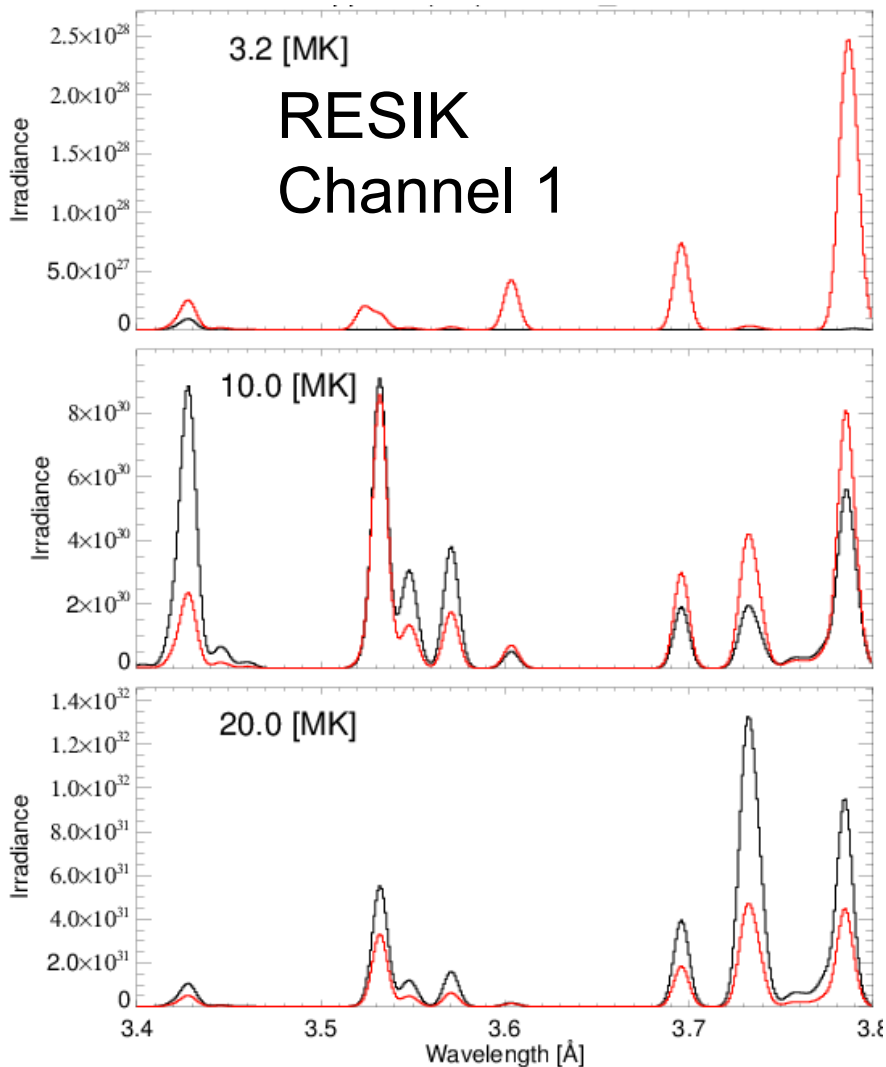
$$f(E, \kappa) dE = A_\kappa \frac{2}{\sqrt{\pi} (k_B T)^{3/2}} \frac{E^{1/2} dE}{\left(1 + \frac{E}{(\kappa - 3/2) k_B T}\right)^{\kappa+1}}$$

# Model appearance of RESIK spectra for Maxwellian and $\kappa$ plasmas

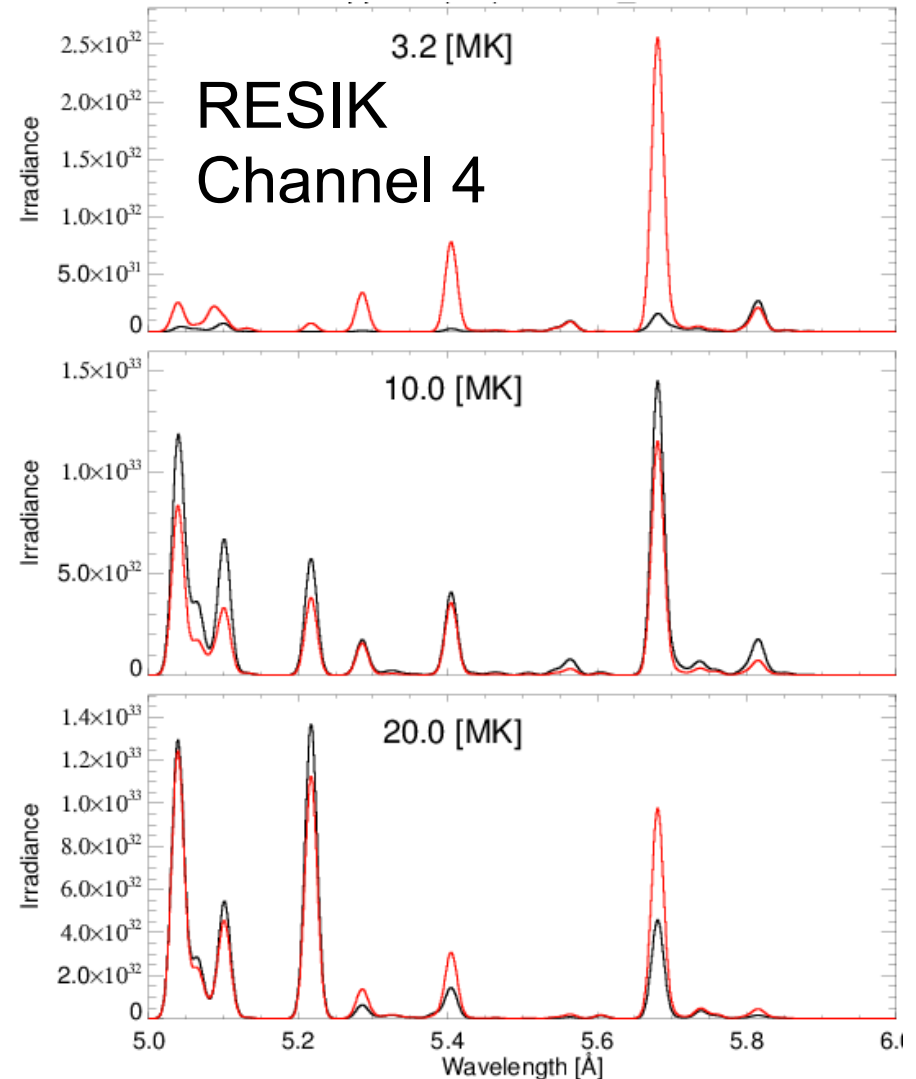
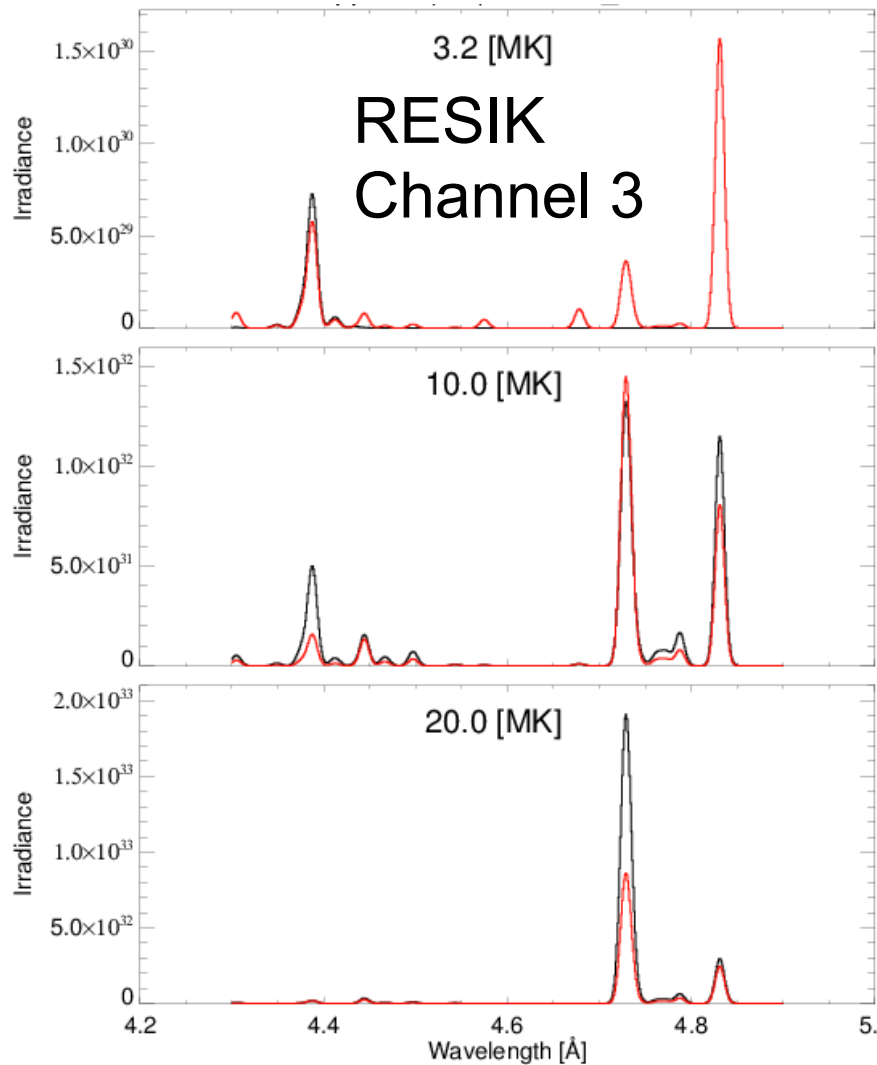


The most of deviations from Maxwellian appearance are seen at lower temperatures.

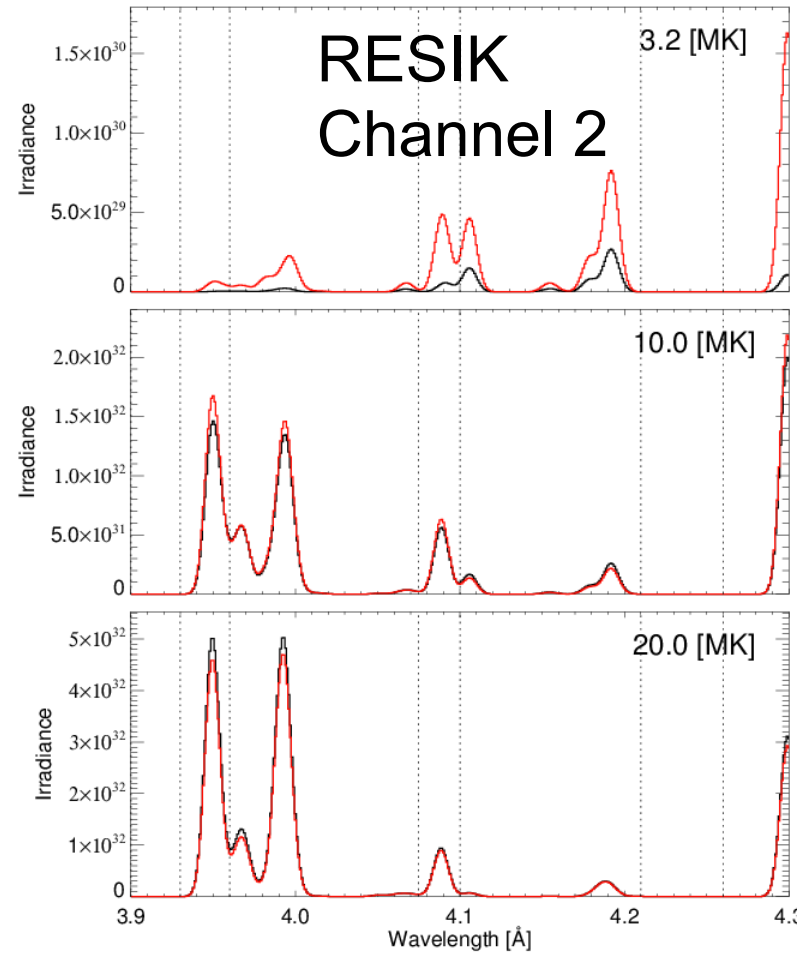
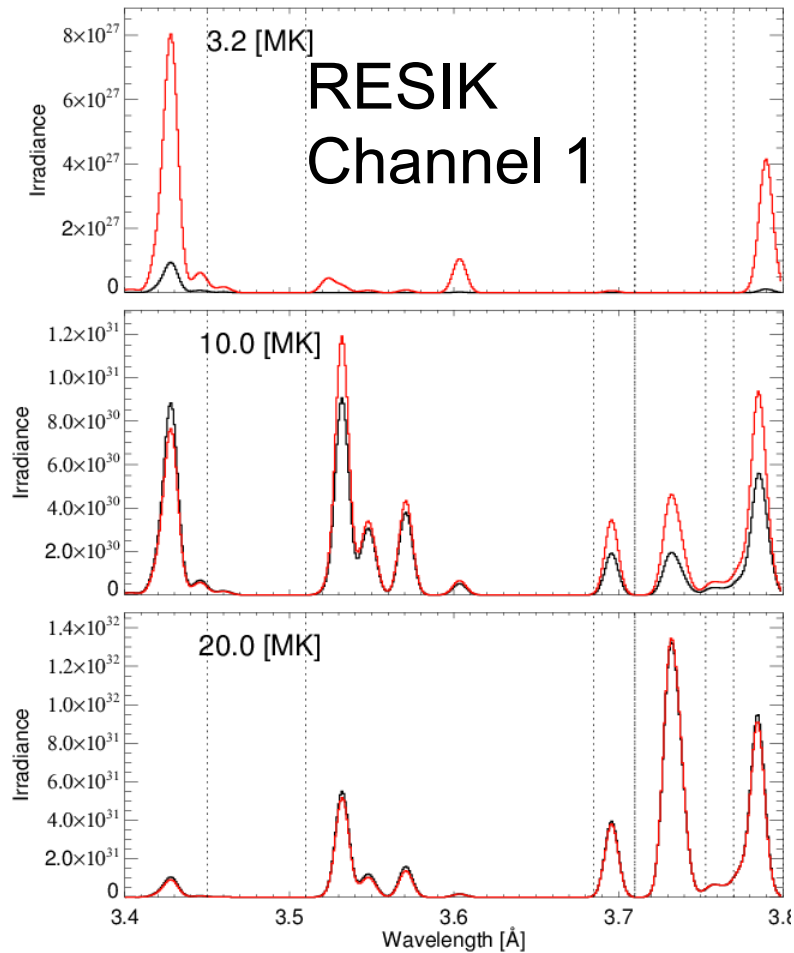
# Model appearance of RESIK spectra for Maxwellian and $\kappa=2$ plasmas



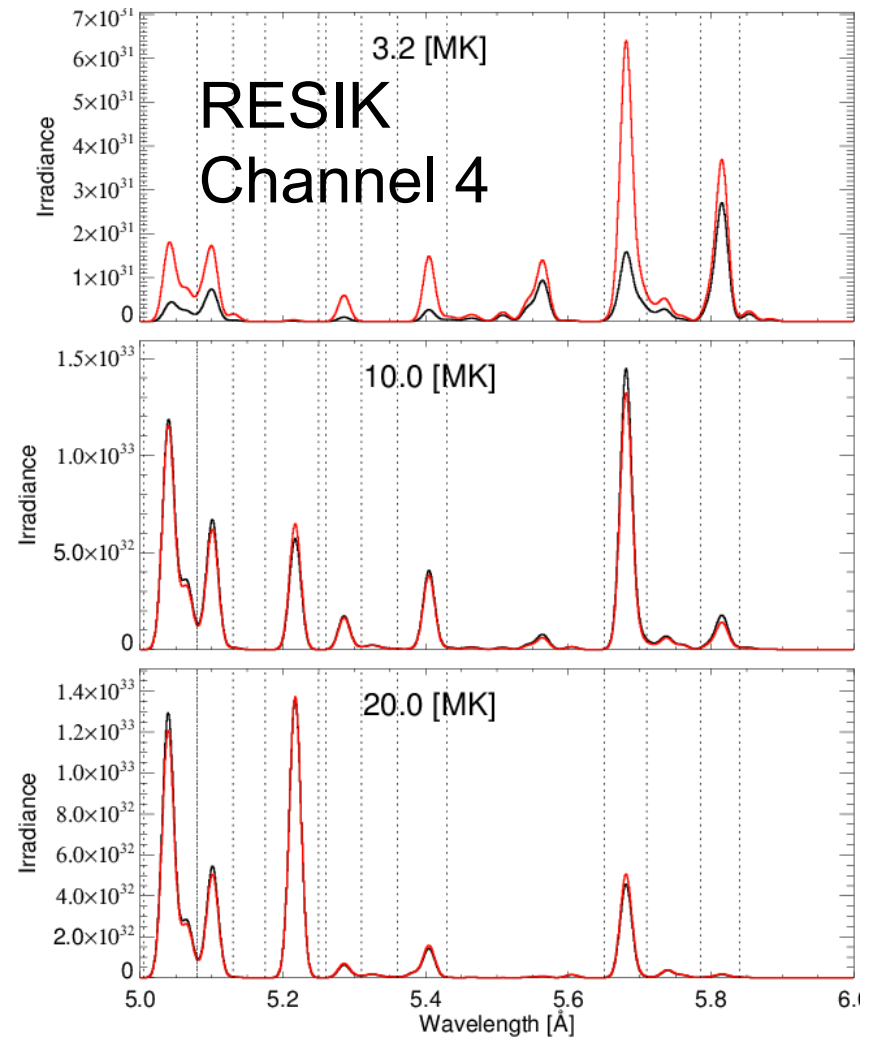
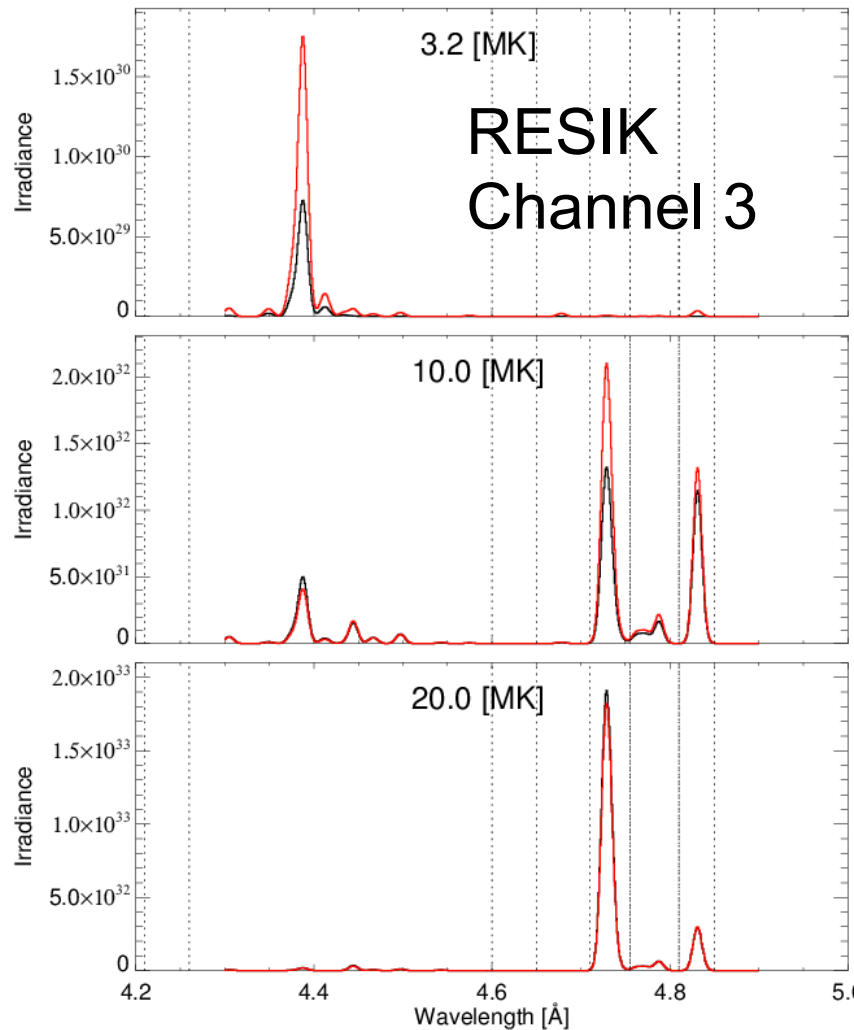
# Model appearance of RESIK spectra for Maxwellian and $\kappa=2$ plasmas



# Model appearance of RESIK spectra for Maxwellian and $\kappa=10$ plasmas

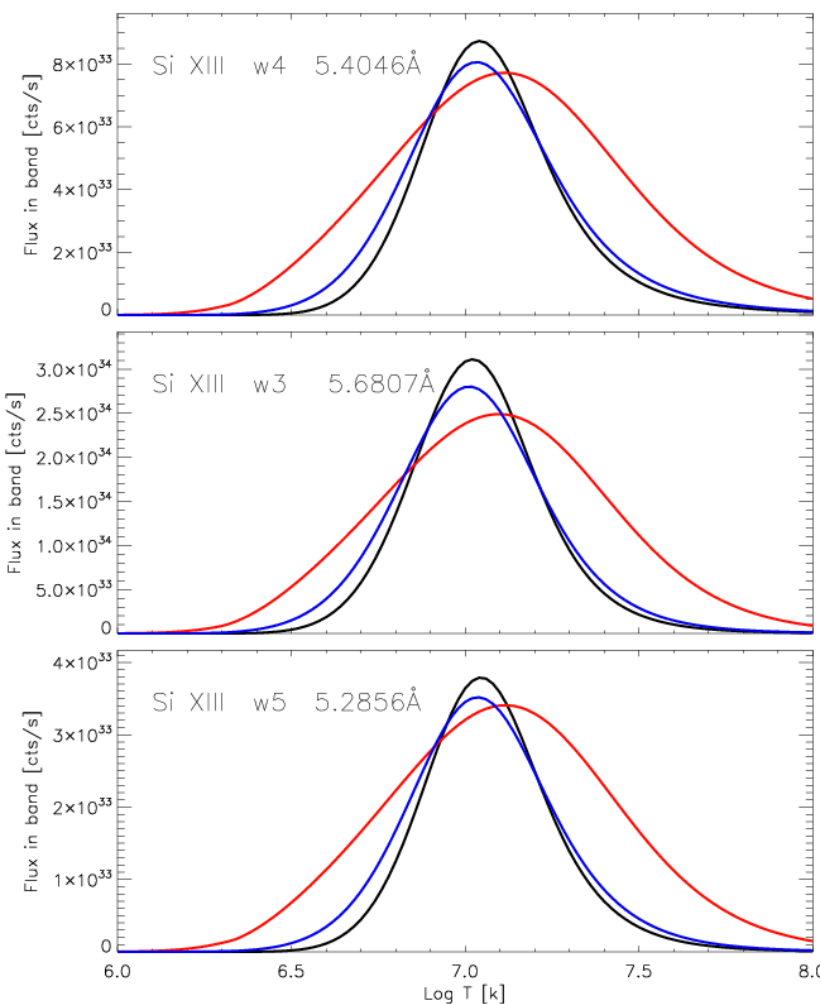
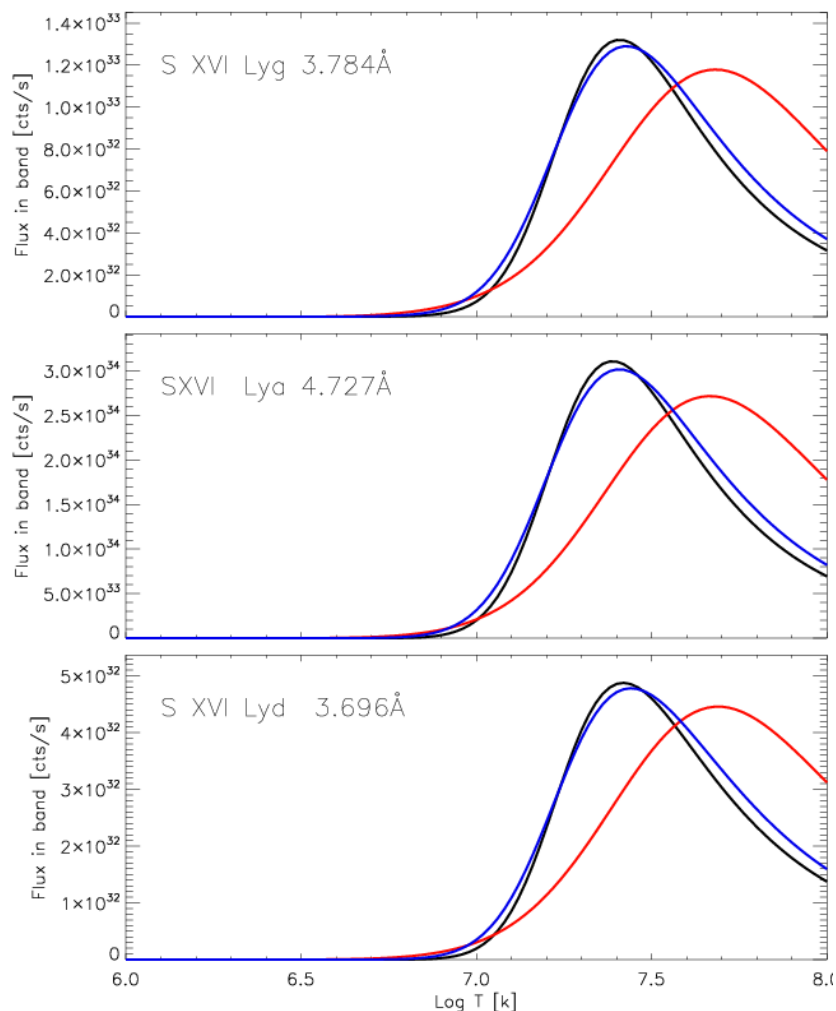


# Model appearance of RESIK spectra for Maxwellian and $\kappa=10$ plasmas



# Equivalent temperature dependence of selected lines' intensities

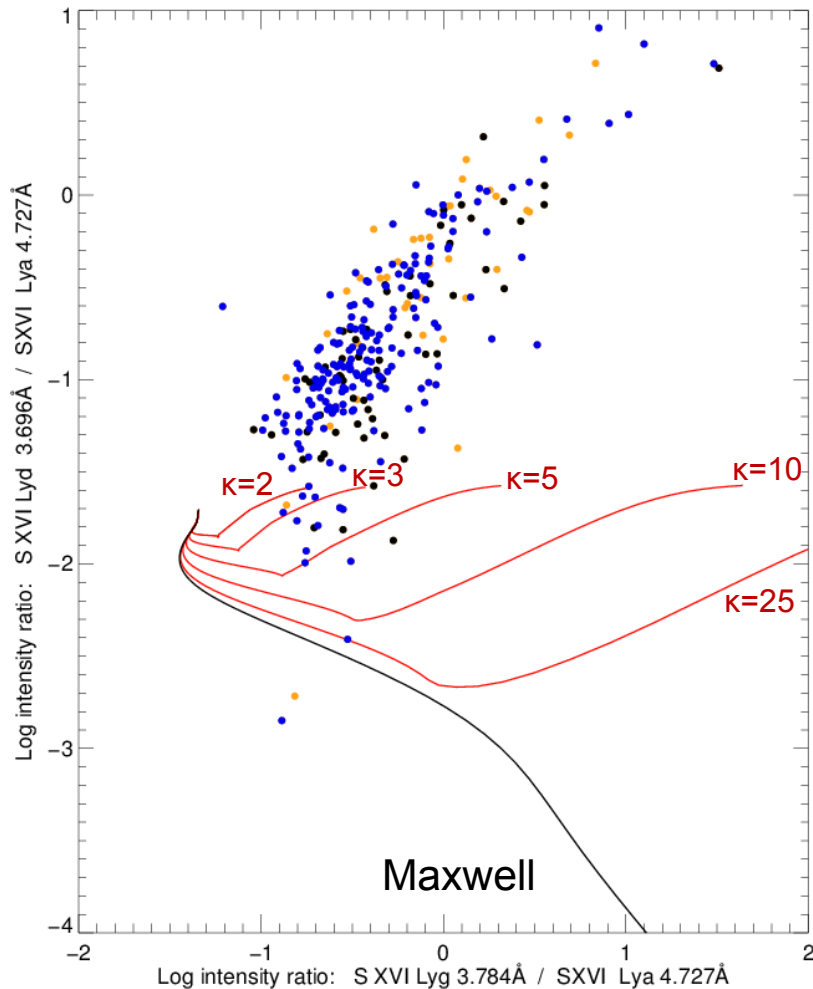
black  $\rightarrow$  Maxwell, blue  $\rightarrow \kappa=10$ , red  $\rightarrow \kappa=2$



Important are effects on „ionisation equilibrium” and collisional excitations

# Do observations support $\kappa$ -type plasmas?

## Case for SOL2002-08-03T19:07



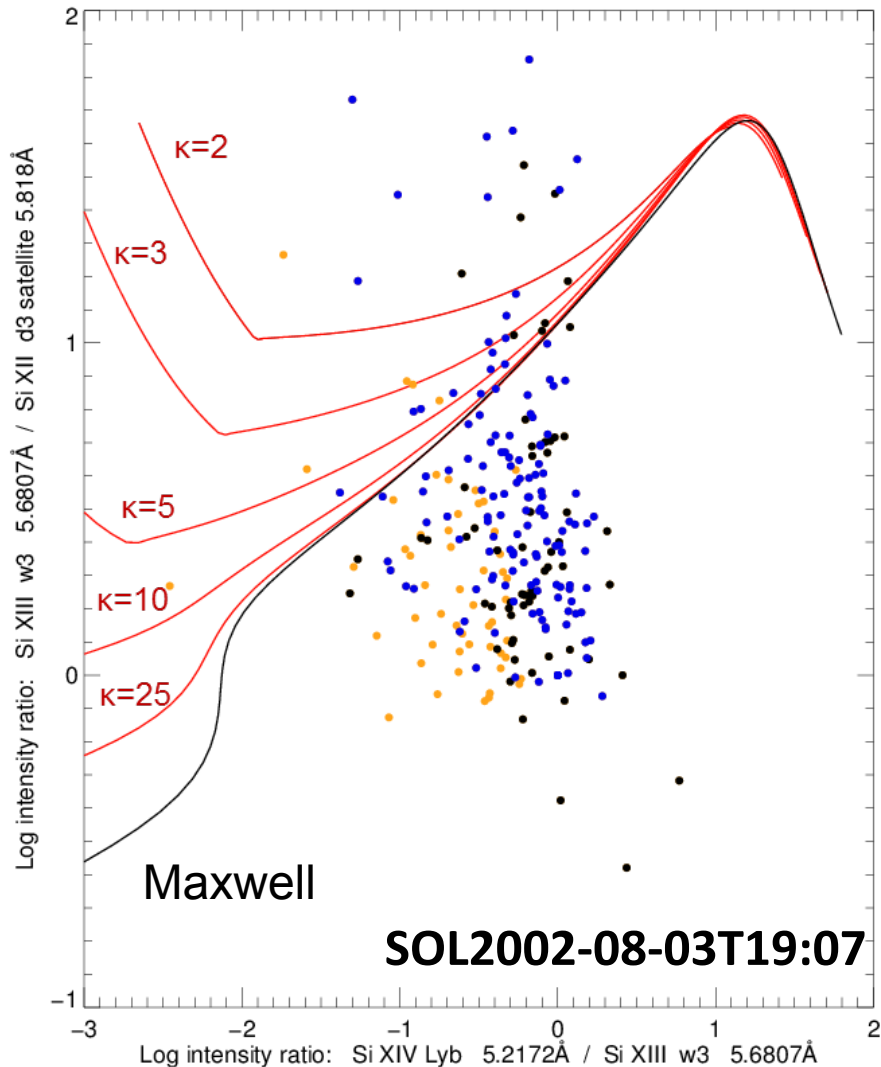
For the comparison, ratios of S XVI Ly $\delta$ /S XVI Ly $\alpha$  against S XVI Ly $\gamma$ /S XVI Ly $\alpha$  have been selected. Red lines correspond to various  $\kappa$ -type plasmas with the limit of  $\kappa \rightarrow \infty$  (i.e. Maxwellian, thermal plasma). Points represent the observed ratios for individual spectra:

Blue  $\rightarrow$  rise phase

Black  $\rightarrow$  decay

Orange  $\rightarrow$  late decay

# SOL2002-08-03T19:07



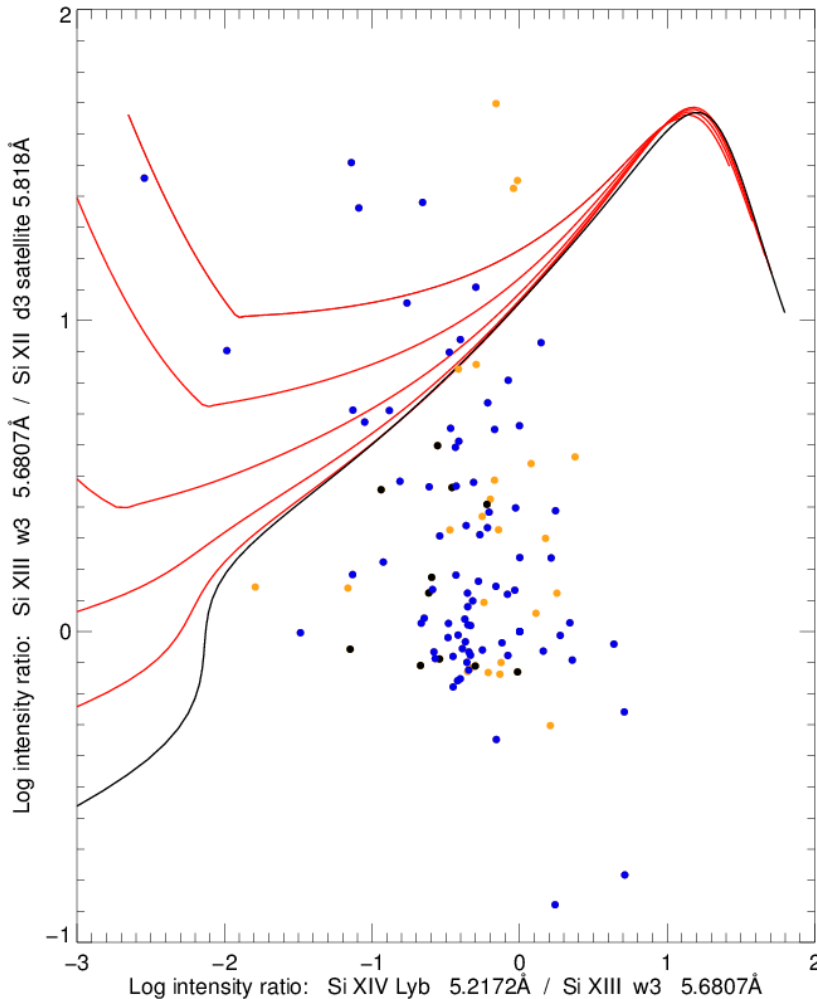
Here, ratios of  
Si XIII w3/S XII d3 against  
Si XIV Ly $\beta$ /S XIII w3 have been  
selected. Red lines correspond to  
various  $\kappa$ -type plasmas with the limit of  
 $\kappa \rightarrow \infty$   
(i.e. Maxwellian, thermal plasma).  
Points represent the observed ratios for  
individual spectra:

Blue  $\rightarrow$  rise phase

Black  $\rightarrow$  decay

Orange  $\rightarrow$  late decay

# SOL2002-08-20T08:25



Similar plot for the most impulsive flare studied. Again, ratios of Si XIII w3/S XII d3 against Si XIV Ly $\beta$ /S XIII w3 are considered. Red lines correspond to various  $\kappa$ -type plasmas with the limit of  $\kappa \rightarrow \infty$  (i.e. Maxwellian, thermal plasma). Points represent the observed ratios for individual spectra:

Blue  $\rightarrow$  rise phase (a)

Orange  $\rightarrow$  maximum (b)

Black  $\rightarrow$  decay (c)

# Take home message

- Observed intensities of higher- $n$  transitions are much higher than for an equilibrium, Maxwellian plasmas. This striking measurements need further reconfirmation (ChemiX). Even assuming the presence of non-Maxwellian  $\kappa$ -type electron distributions does not help in this respect. So, the present situation is that we are not able to account for the observed intensities of higher- $n$  ( $n>3$ ) transitions in H- and He-like ions.
- One of the possible explanation may be that there are unresolved blends from yet unknown transitions which contribute to the estimated line fluxes. Better spectral resolution may help to clarify this.
- Another possibility is that constantly recombining transient ionization conditions prevail in the source region causing overpopulation of higher- $n$  levels. The similar idea has been suggested ~45 years ago by A. Dupree (ApJ, 152):

„Significant departures from thermodynamic equilibrium are found for the populations of high levels of coronal ions. These overpopulations can lead to observable effects on the solar emission spectrum”.

The end

# Abstract

RESIK was a high-resolution solar X-ray Bragg spectrometer, the most recent ever to be launched, being operational from 2001 to 2003. Its nominal wavelength coverage, 3.3 Å – 6.1 Å, has considerable diagnostic potential. RESIK observed numerous flares as well as non-flaring active regions. During flares, the data gathering intervals were as short as 2 s. Analysis of the data continues to the present time; at the time of writing, data for more than 50 flares have been reduced to science grade (level 2). The spectra include spectral lines formed by H- and He-like ions of various elements as well as continuum. The lines and continua are formed in the hot coronal plasma corresponding to temperatures  $T > 2$  MK if interpreted thermally. This makes RESIK spectra uniquely suitable for investigations of the physical conditions of the hotter plasma component of flares and active regions. Many spectra were taken during the rise phase of flares. For some events, anomalous line intensity ratios are evident, possibly reflecting the presence of non-equilibrium conditions in flaring plasma -- the observed intensity ratios are not easily explained by isothermal or multi-thermal assumptions. In our presentation, we will show examples of such observations and give possible interpretations.