Effects of non-thermal particle distributions on the EUV flare lines

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Motivation

We study the emission – we need to know the microphysics

Observations:

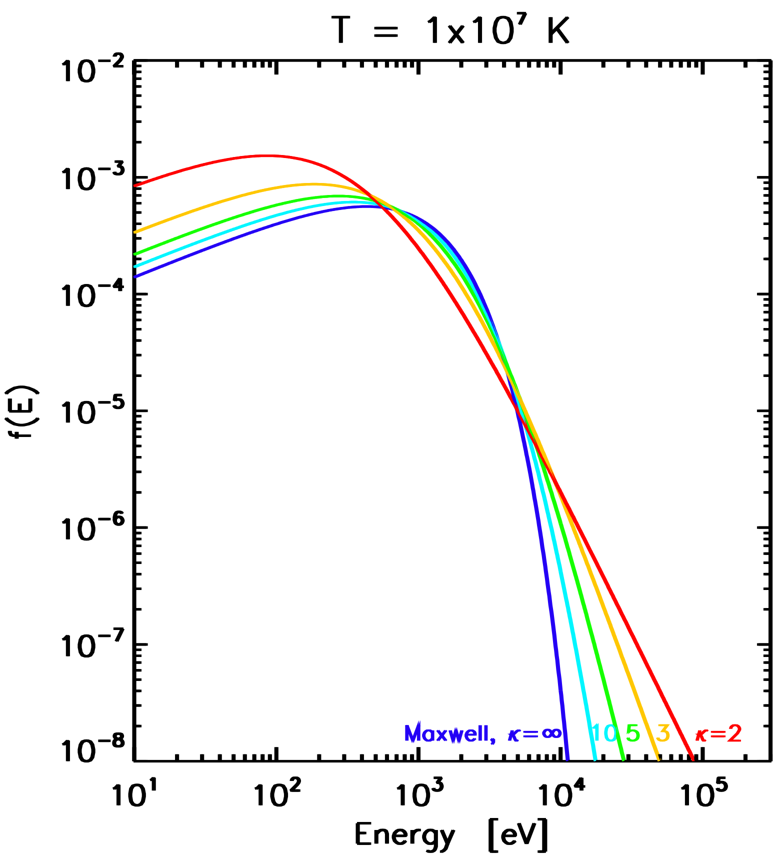
- Maksimovic et al. (1997): solar wind velocity distribution is well approximated by a κ–distribution
- Kašparová & Karlický , 2009; Oka *et al.*, 2013: coronal flare X-ray sources can be described by a κ–distribution

Theory:

- Collier (2004): if the mean particle energy is not held constant, the entropy is *not* maximalized by a Maxwellian, but by a κ–distribution
- Bian *et al.*, 2014 ApJ 796, 142 - formation of the κ–distribution in solar flares

κ–distribution can simulate effect of the power-law electron beam!

Non-thermal
κ - distribution



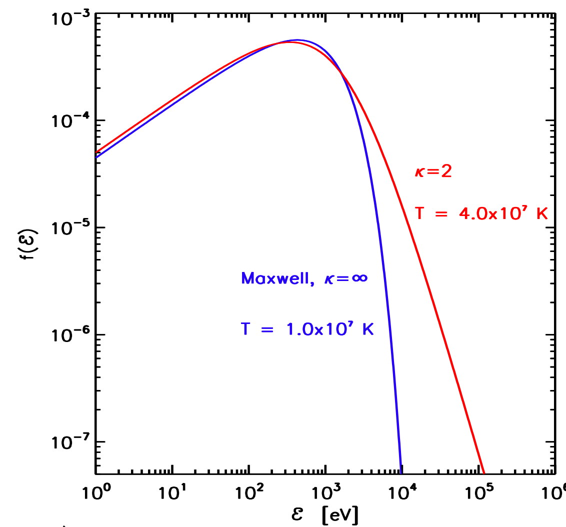
$$f_\kappa(E) = A_\kappa \frac{2E^{1/2}dE}{\pi^{1/2}(kT)^{3/2}}\left(1+\frac{1}{(\kappa-1.5)kT}\right)^{-(\kappa+1)}$$

$$\langle E_\kappa \rangle = \frac{3}{2}kT$$

$$p = nkT$$

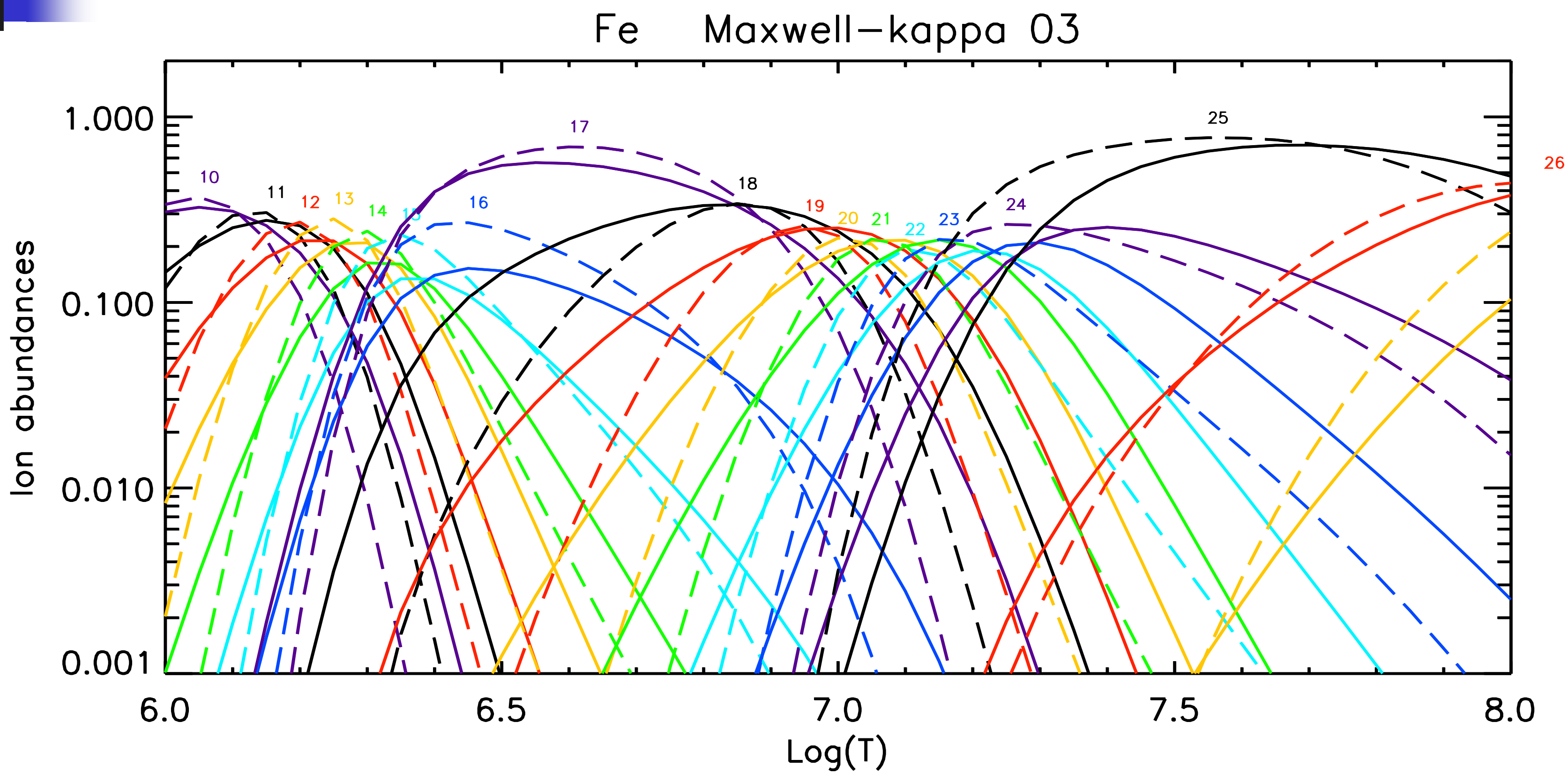
$$E \to \infty:$$

$$f(E) \approx const. \times E^{-(\kappa+0.5)}$$



Distribution shape affects ionization & excitation equilibrium

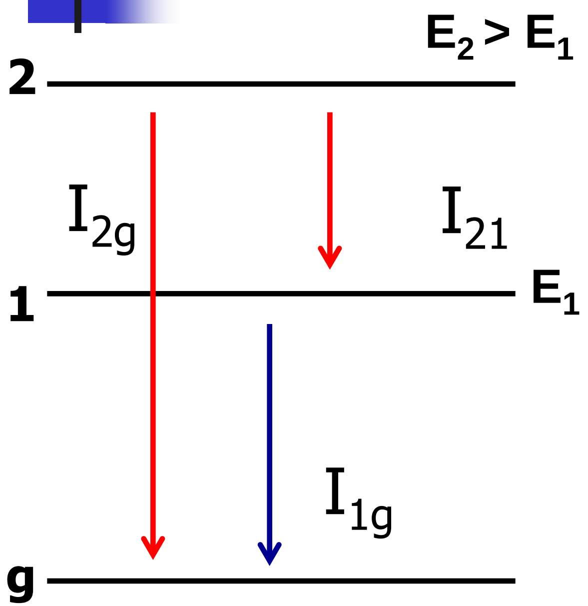
Ionization Equilibrium
κ - distribution



Dzifčáková & Dudík, 2012

atomic data correspons to Dere (2007), Landi *et al*. (2013) (Maxwellian distribution)

κ - distribution and the line intensities



κ-distribution ⟶ enhancement of the population of the high energy levels in comparison with the Maxwellian distribution at the same temperature

Temperature and parameter κ must be diagnosed simultaneously

Two pairs of lines are needed, one originates from levels with different excitation energy and second one is sensitive to temperature

Spectrograph – wide spectral range, high sensitivity (low lines intensities) and spectral resolution – problem

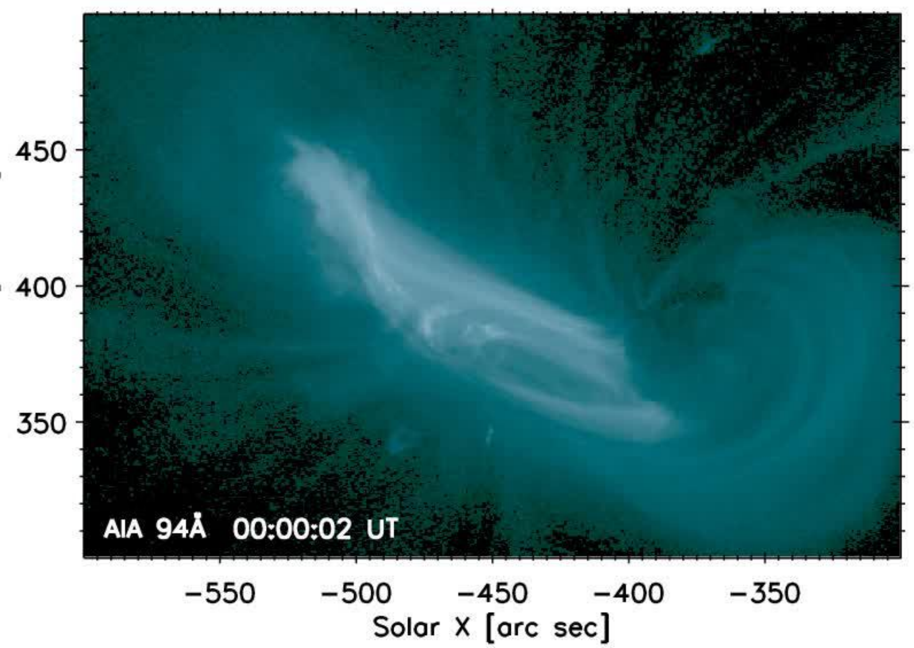
EVE – ≥ 1Å resolution between 50-1050 Å – low spectral resolution, blended lines

Kappa package (**http://kappa.asu.cas.cz**) was used to calculate the synthetic line intensities for $n_e = 10^{10}$-10^{12} cm^{-3}, κ = 2, 3, 5, 7, 10 and Maxwellian distribution.

The intensities of Fe blends were included to the line intensities to propose diagnostics of κ for iron lines in flares using sdo/EVE

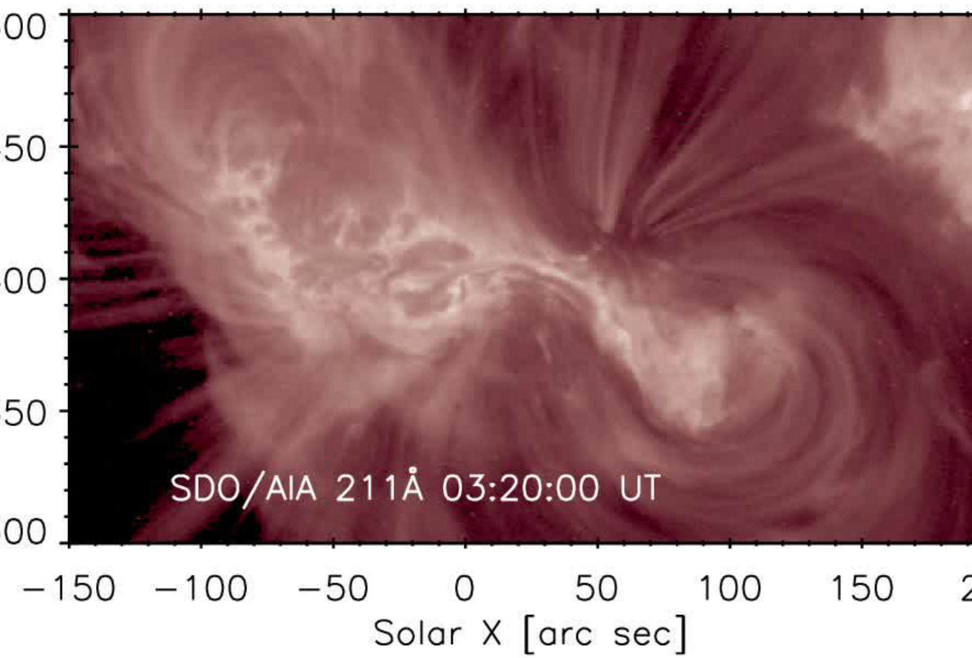
EVE Flares - AR 11429

X5.6, 2012 Mar 07, 00:02–00:24–00:40 UT



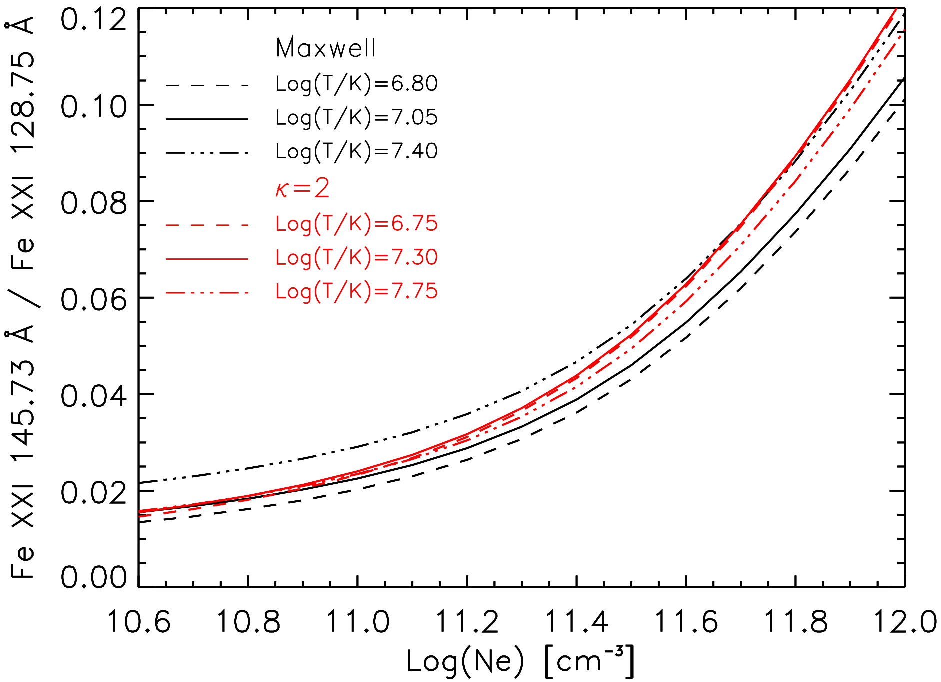
00:10 – 00:50 UT
1-min averaged data

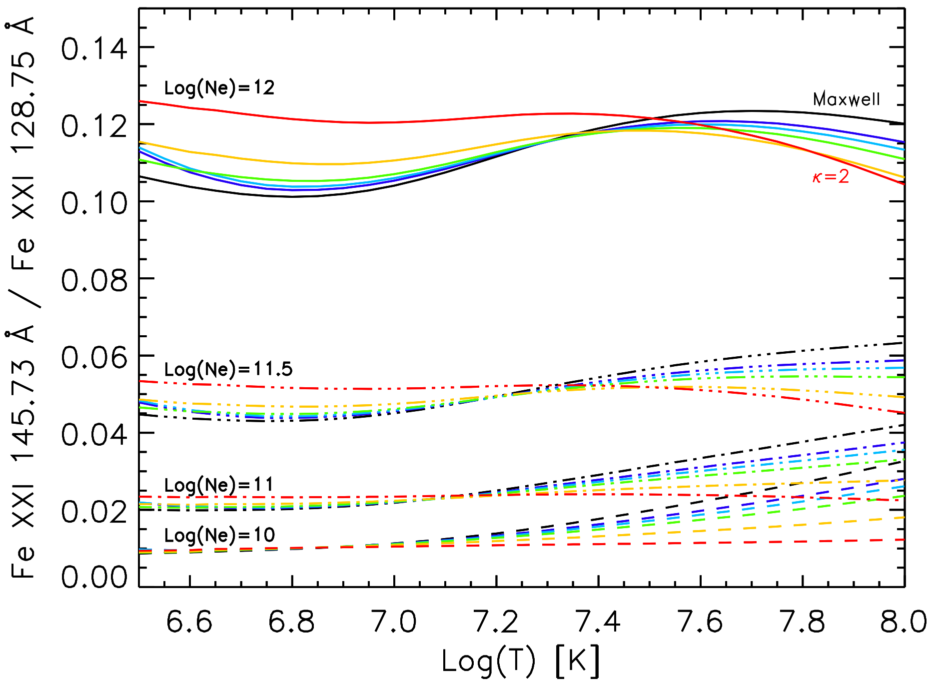
M6.3 2012 Mar 09, 03:22–03:53–04:18 UT



03:26 – 04:30 UT
1-min averaged data - strong lines
2-min averaged data - weak lines

Density Diagnostics
Fe XXI 145.73 / 128.75 Å



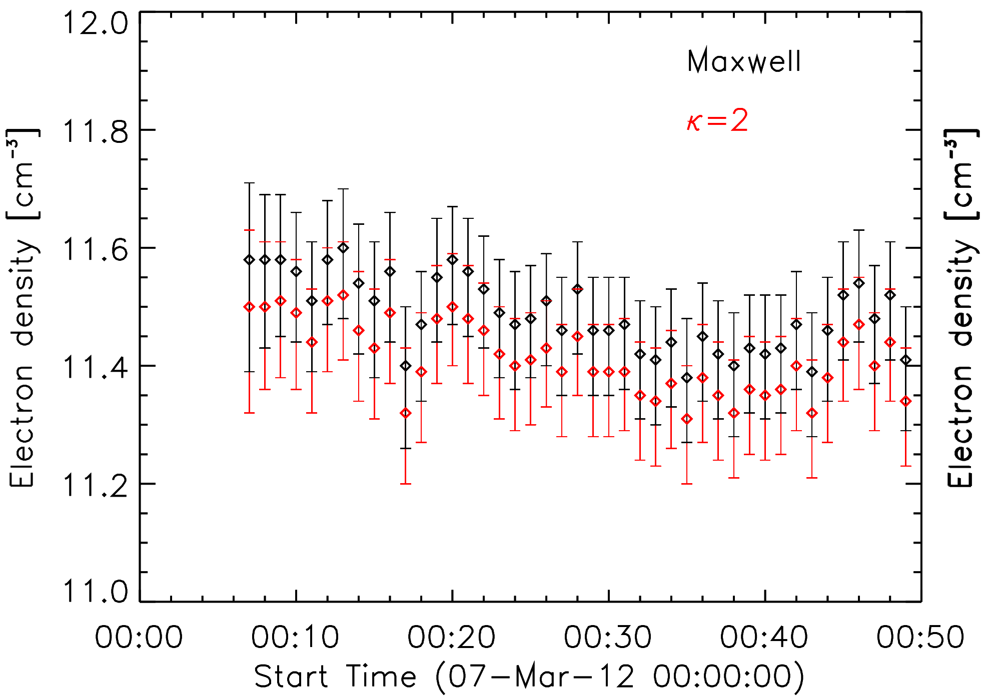


sensitivity to κ

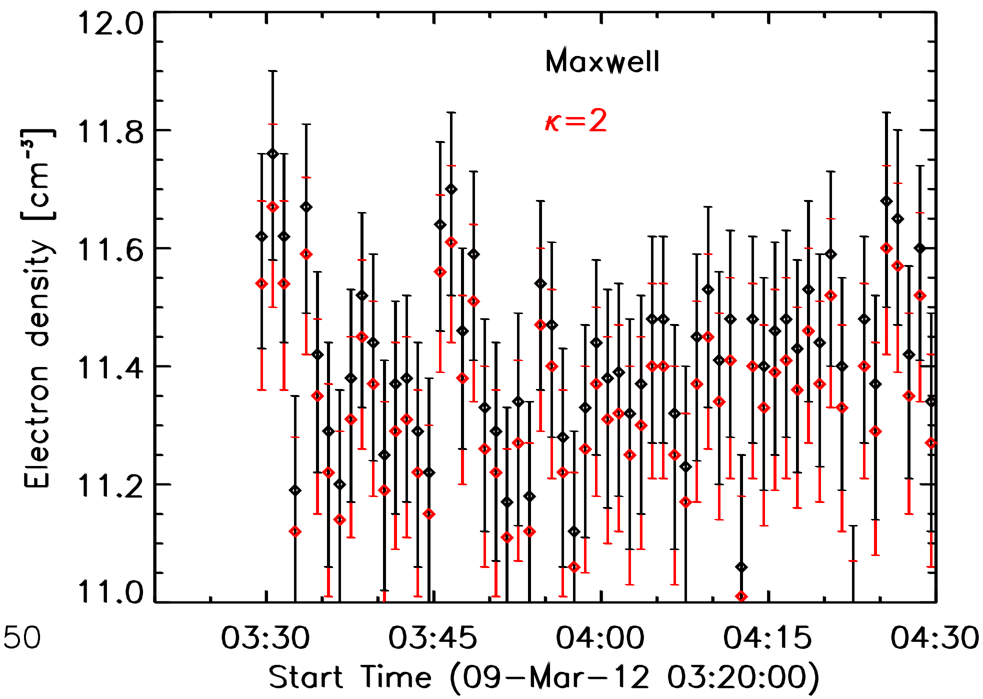
sensitivity to T

Density Diagnostics Fe XXI 145.73/128.75 Å

X5.6



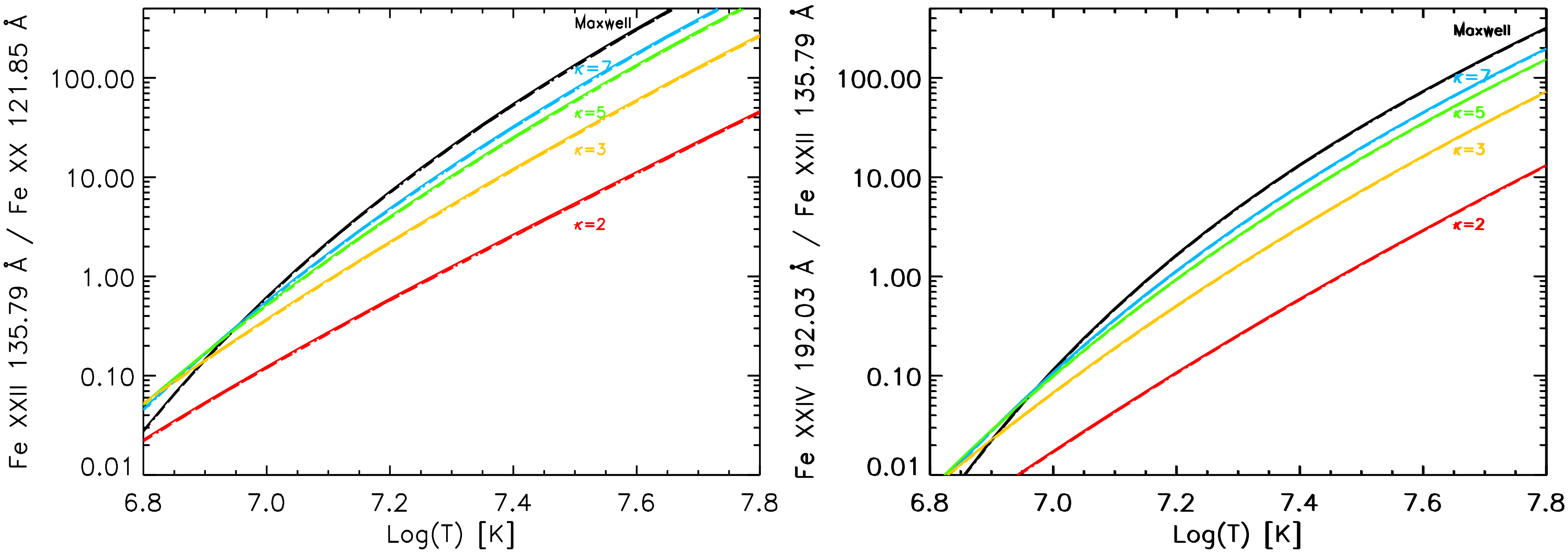
M6.4



Electron densities for κ-distribution with κ=2 are ≈ 0.1 deg lower than for the Maxwellian distribution

precision is given by photon statistics

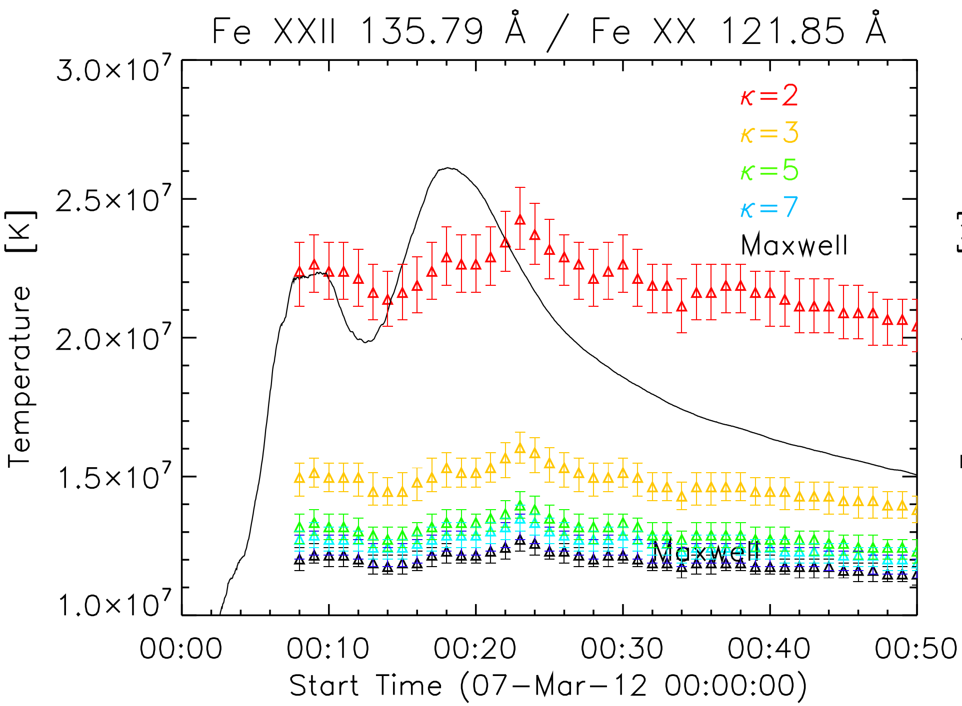
Temperature Diagnostics Line Ratios of Different Ions



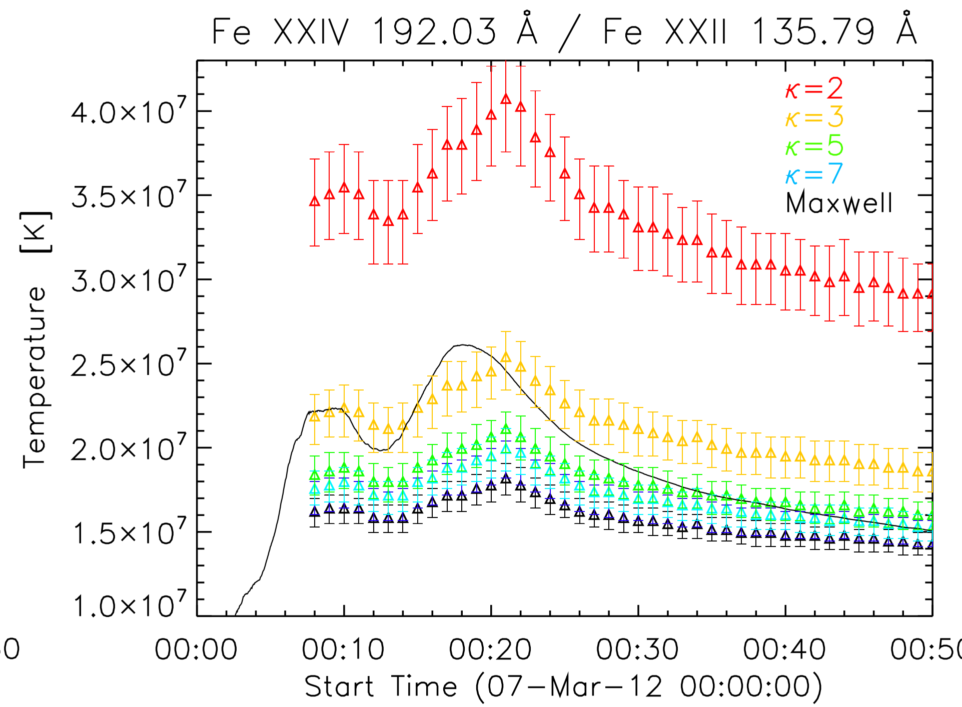
Diagnosed temperature depends on the used ion lines and the distribution function – for κ=2 temperature can be ≈ 2-times higher!

Temperature Diagnostics
Line Ratios of Different Ions

X5.6



X5.6

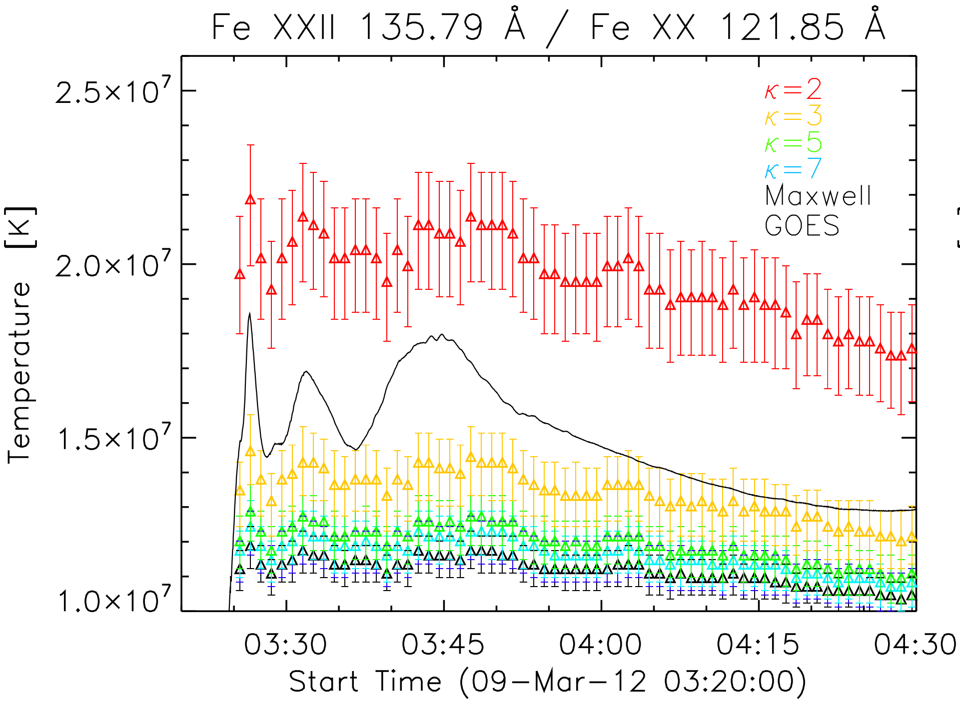


Diagnosed temperature depends on the ion and the distribution function – for κ=2 temperature can be ≈2-times higher!

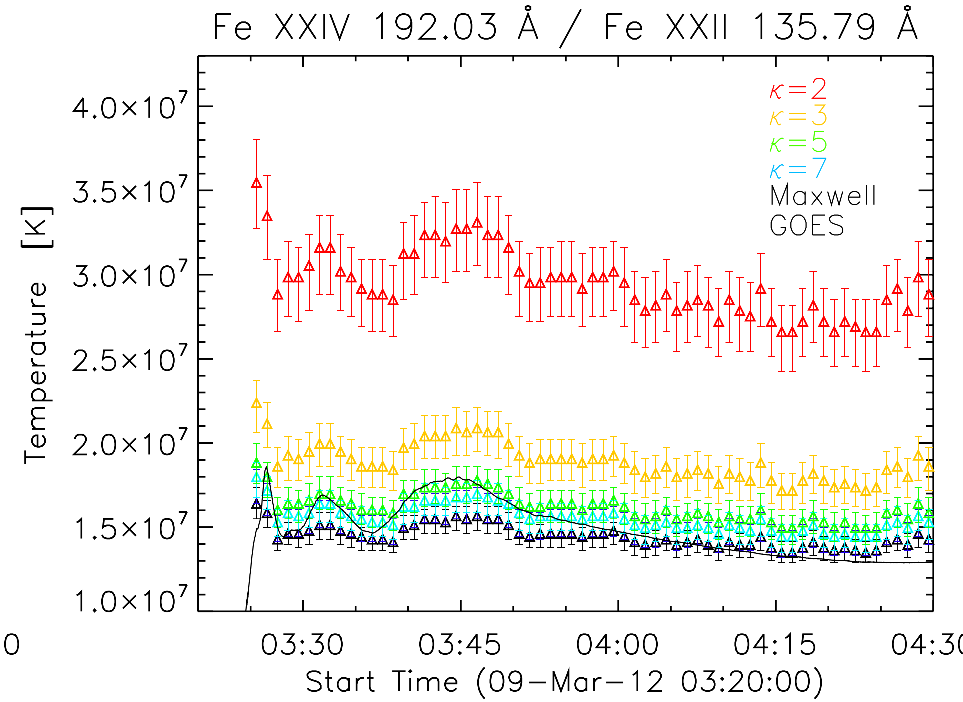
Black line – GOES temperature

Temperature Diagnostics
Line Ratios of Different Ions

M6.3



M6.3

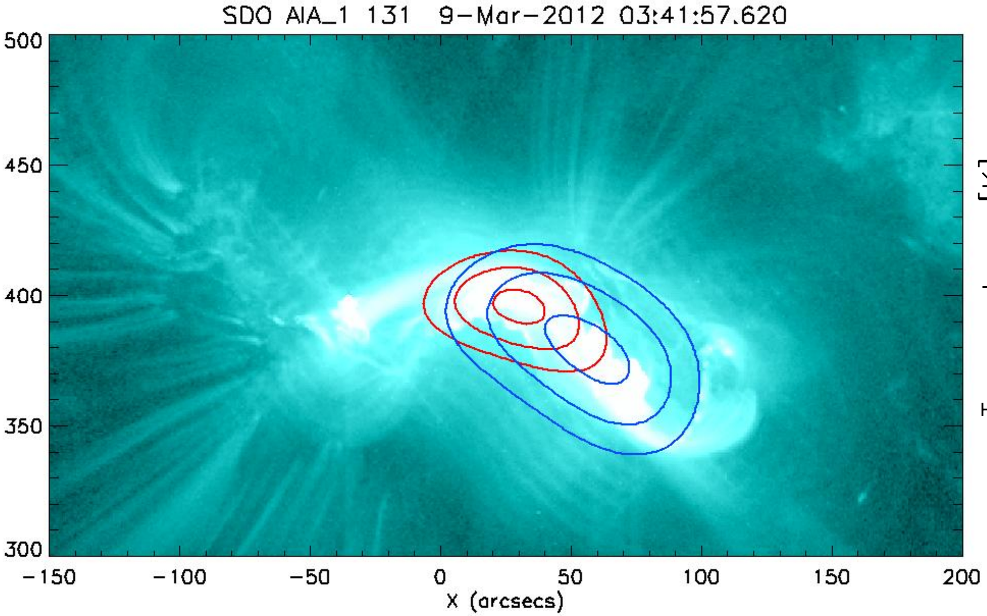


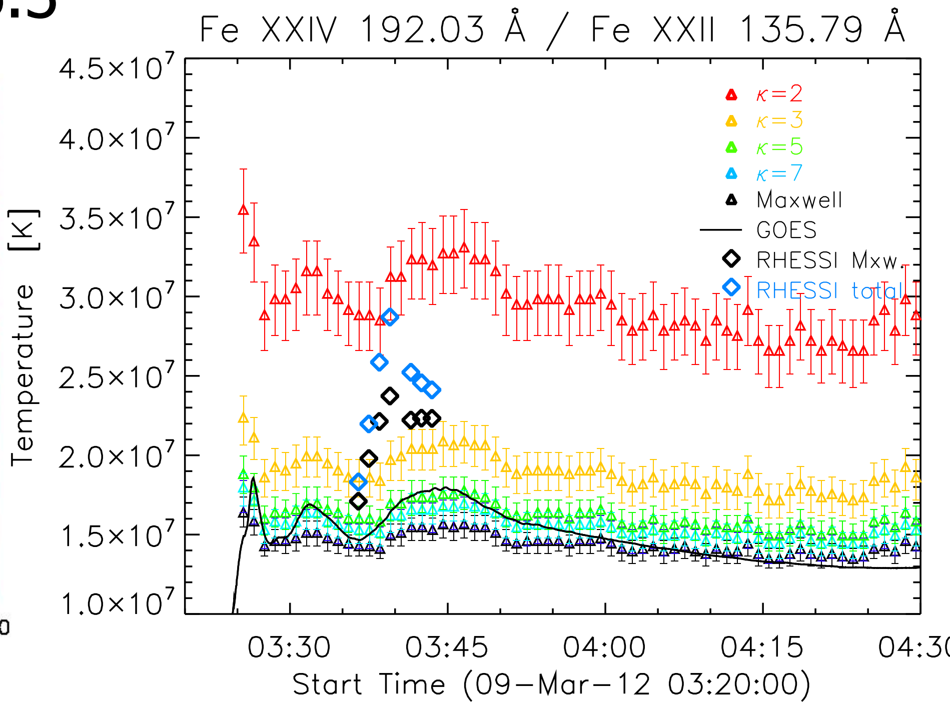
Diagnosed temperature depends on the ion and the distribution function – for κ=2 temperature can be ≈2-times higher!

Black line – GOES temperature

Temperature Diagnostics Line Ratios and RHESSI

M6.3



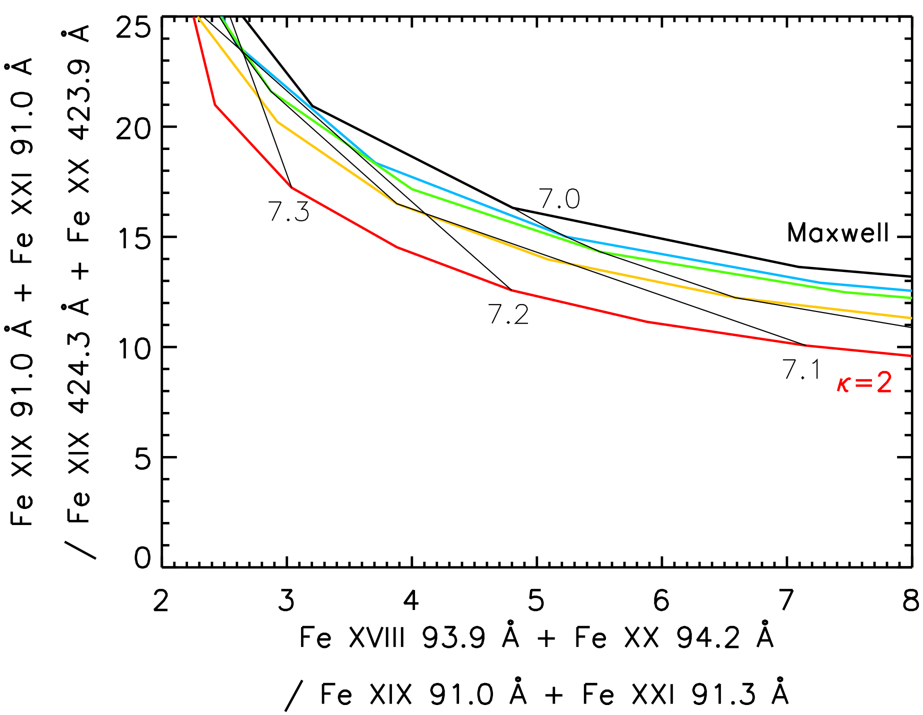


X-Ray RHESSI spectra 03:36 – 03:44 – temperature of Maxwellian core

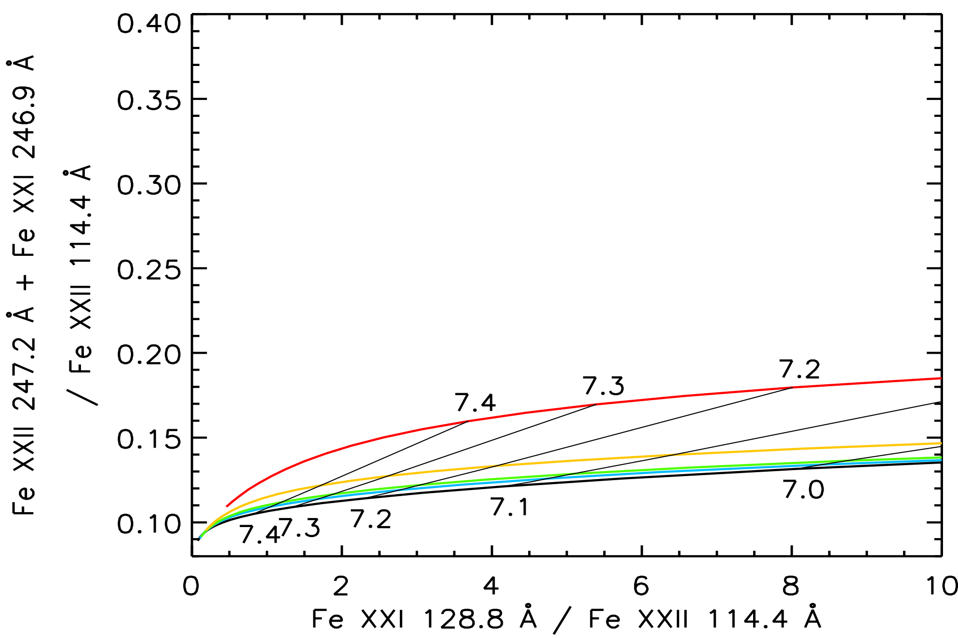
- power law index
- emissivity
- electron flux

Diagnostics of the Distribution

Multi-ions diagnostics

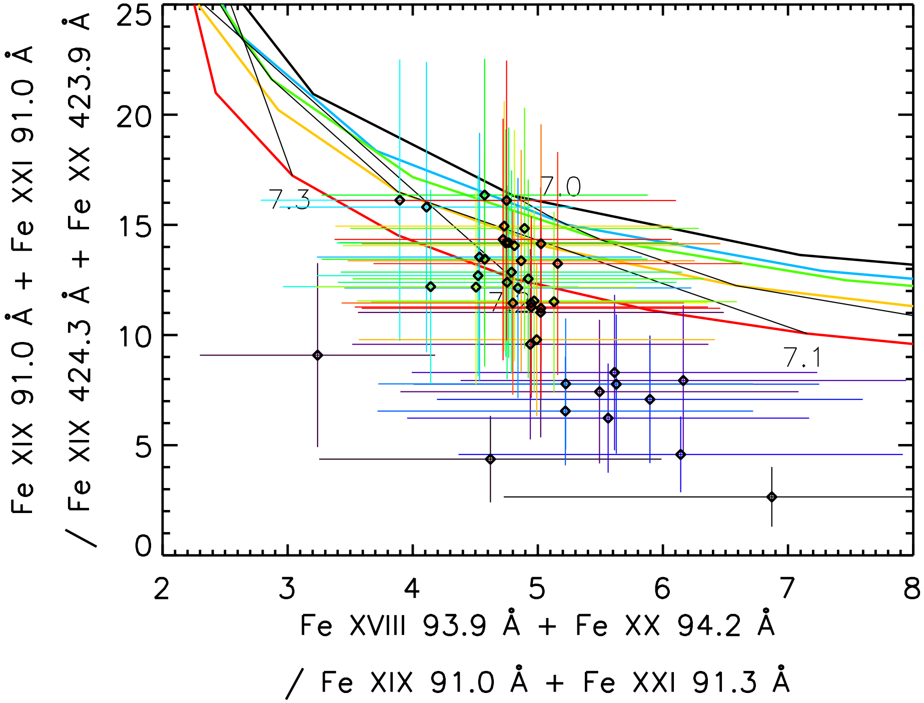


Fe XXII-XXI diagnostics

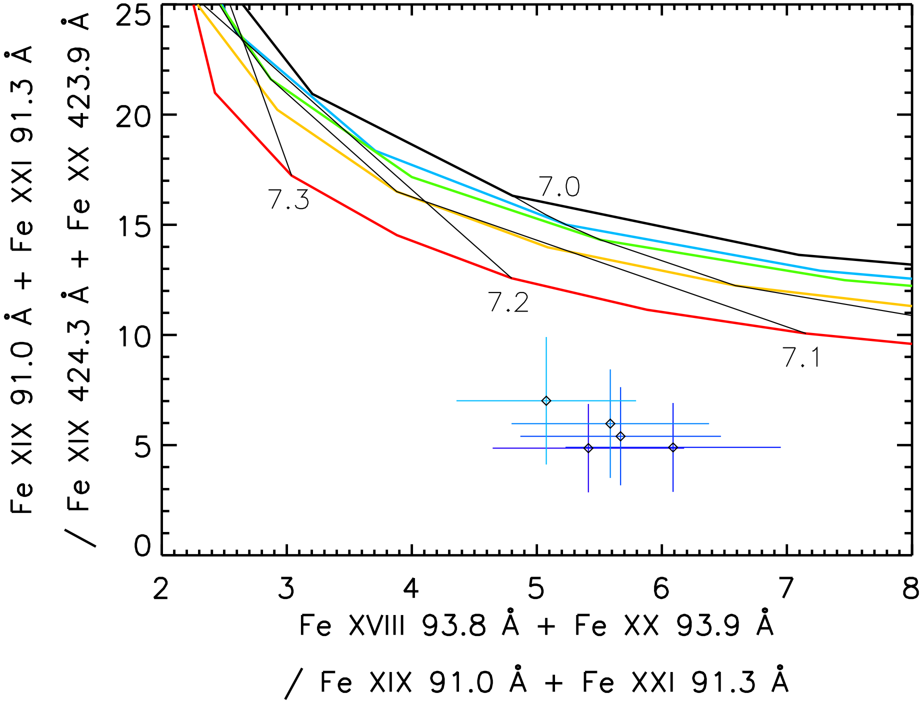


Multi-ions Diagnostics of the Distribution

X5.6



M6.3



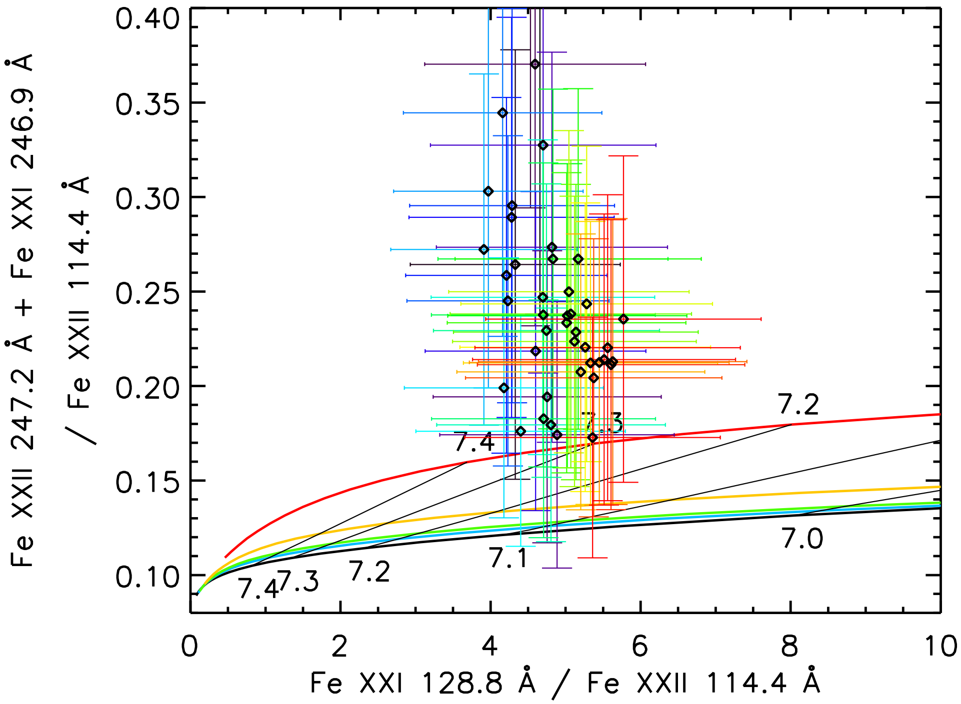
Error ≈ 40%

Time:

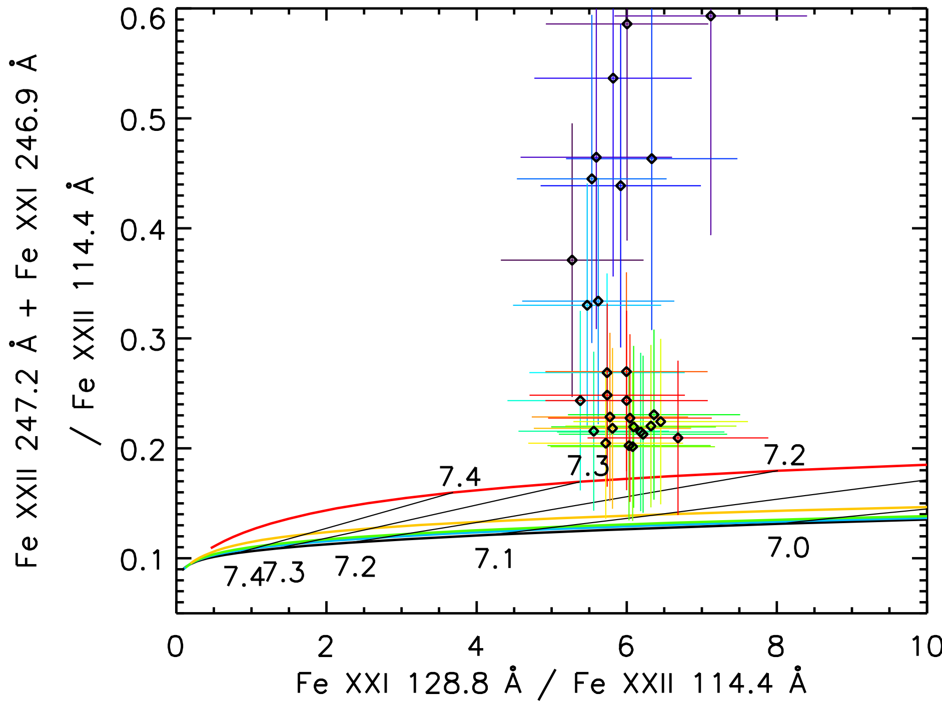
black ⟶ blue ⟶ green ⟶ yellow ⟶ red

Fe XXII-XXI Diagnostics of the Distribution

X5.6



M6.3



Error ≈ 40%

Time:

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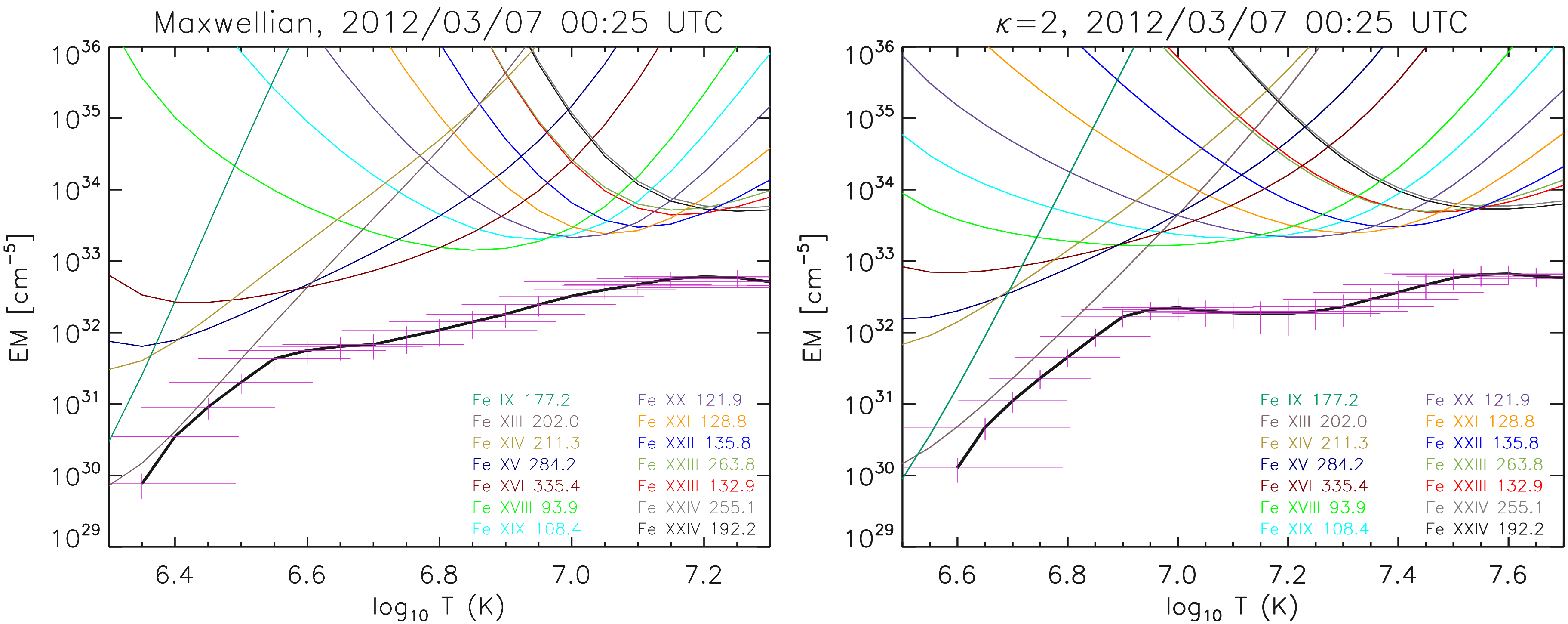
DEM

X5.6

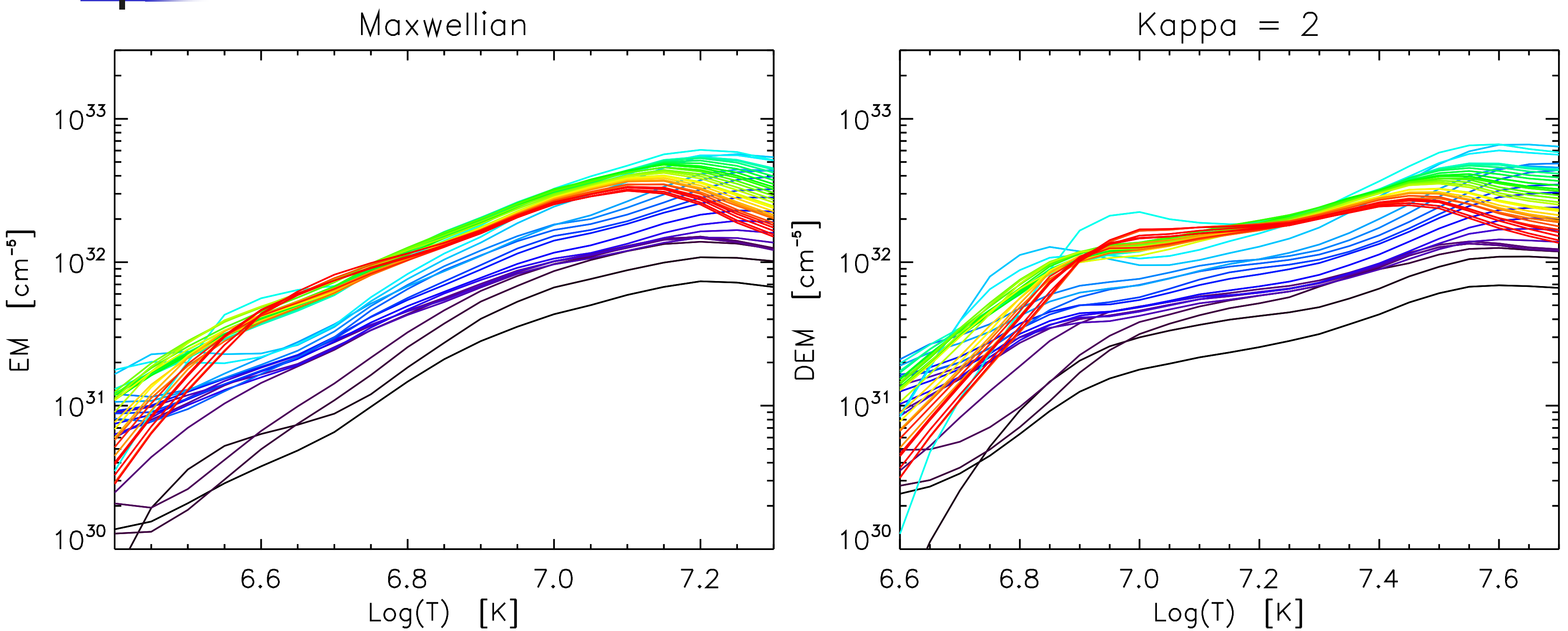


- plasma is multi-thermal for both Maxwellian and κ-distributions
- good constraint in the low temperature part
- DEMs look similarly, only temperature ranges are different !

Maxwell: 6.3 – 7.3
kappa=2: 6.5 – 7.7

DEM

X5.6



- similar slope, maximum temperature decreases with time
- effect of multi-thermal plasma on the proposed diagnostics?

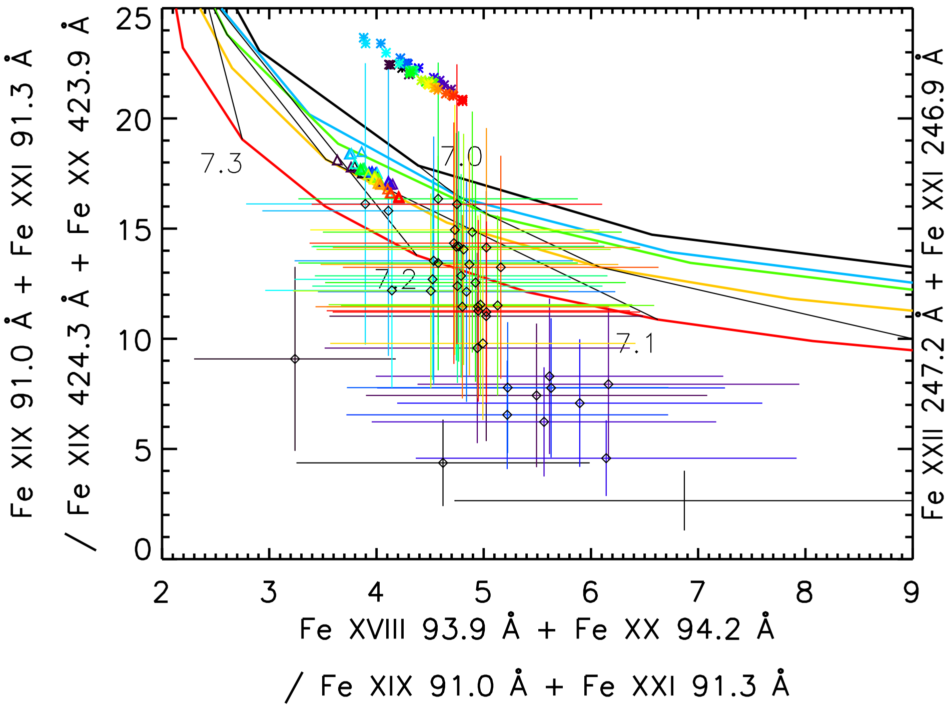
Time:

black → blue → green → yellow → red

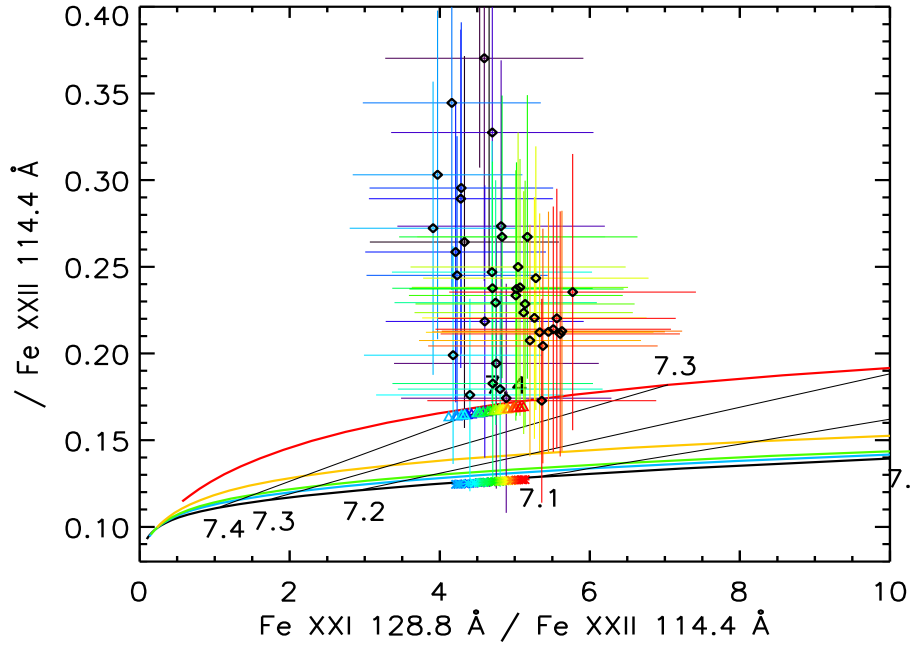
Distribution Diagnostics and DEM

X5.6

Fe XVIII , Fe XIX, Fe XX, Fe XXI



Fe XXI , Fe XXII



Time:

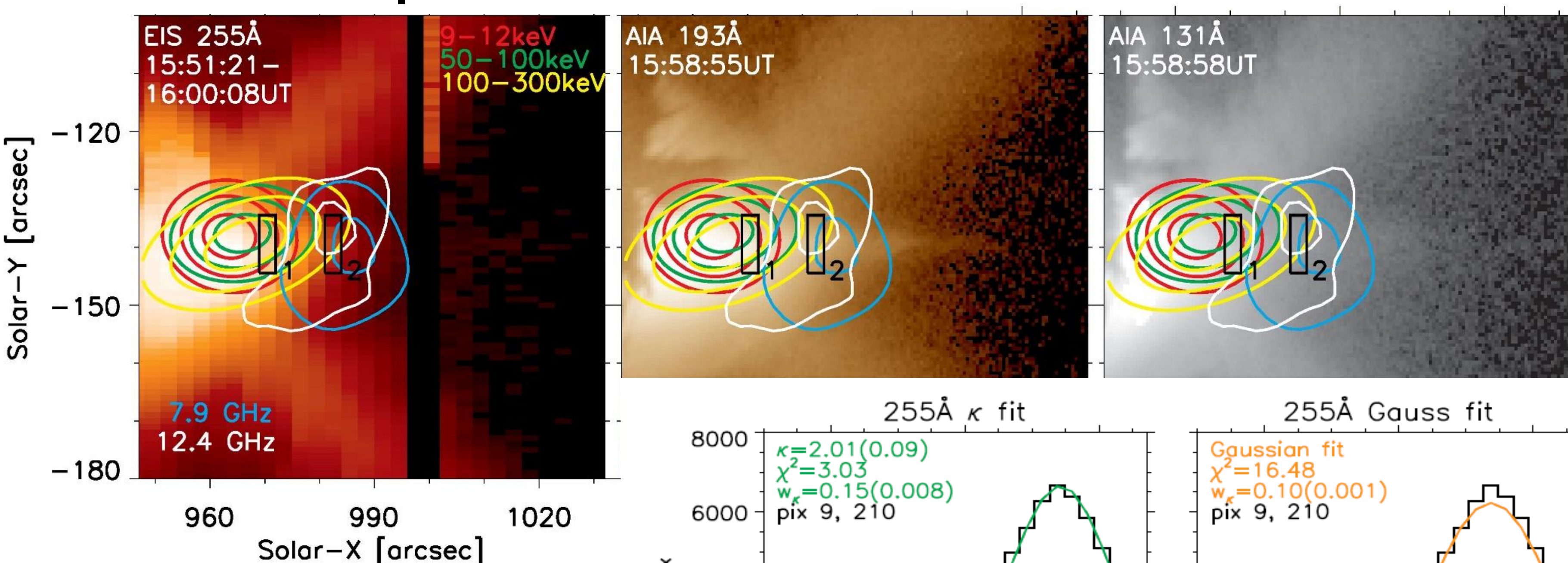
black ⟶ blue ⟶ green ⟶ yellow ⟶ red

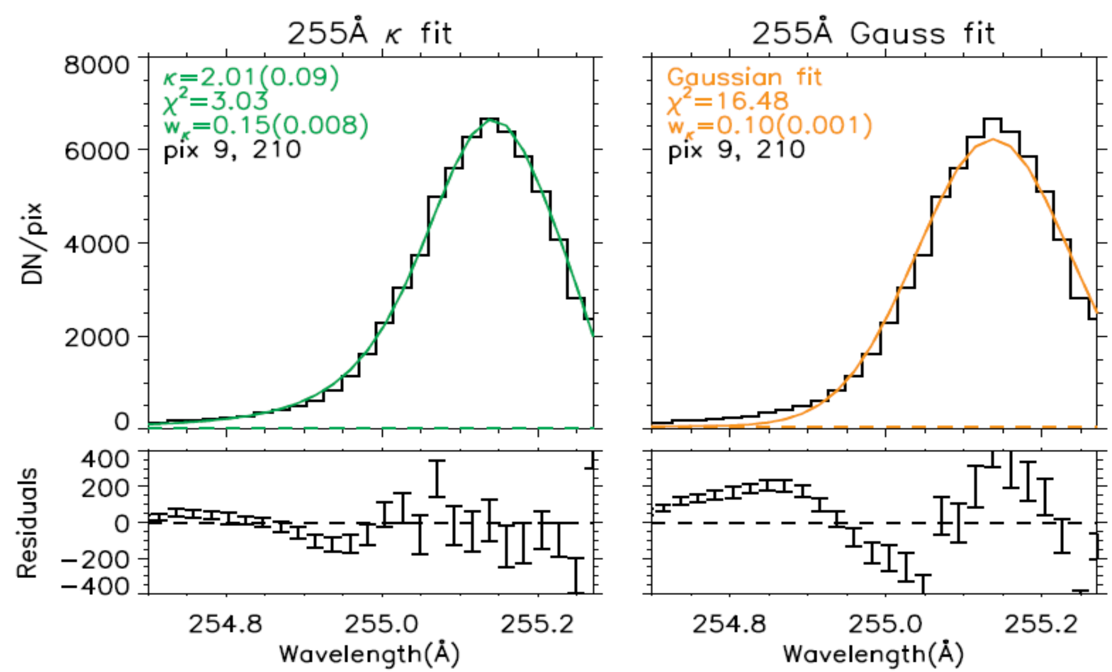
Conclusion

- EVE spectra allow us to diagnose distribution function (or presence of enhanced number of particles in the high-energy tail) although the precision of diagnostics relatively low
- Diagnostic results of X5.6 and M6.4 flares indicate the presence a high number of the accelerated particles during the impulsive and also decay phase (signature of the reconection?)
- presence of the κ-distribution or similar distribution affects mainly the diagnostics of the temperature, the shift can be by a factor ≈2

Flare line profiles

X8.3 on 2017 Sep. 10 - HINODE/EIS





- kappa profiles seen in the X8.3-flare of 2017 Sept 10
- EIS Fe XXIV with $\kappa \approx 2$
- only in RHESSI sources
- Ion acceleration ($T > 10^8$ K)
- Turbulence ($v_{nth} > 200$ km/s)

Polito, et al. (2018), ApJ 864, 176


Thank you very much
for your attention