Analysis of high-temperature solar flare plasma

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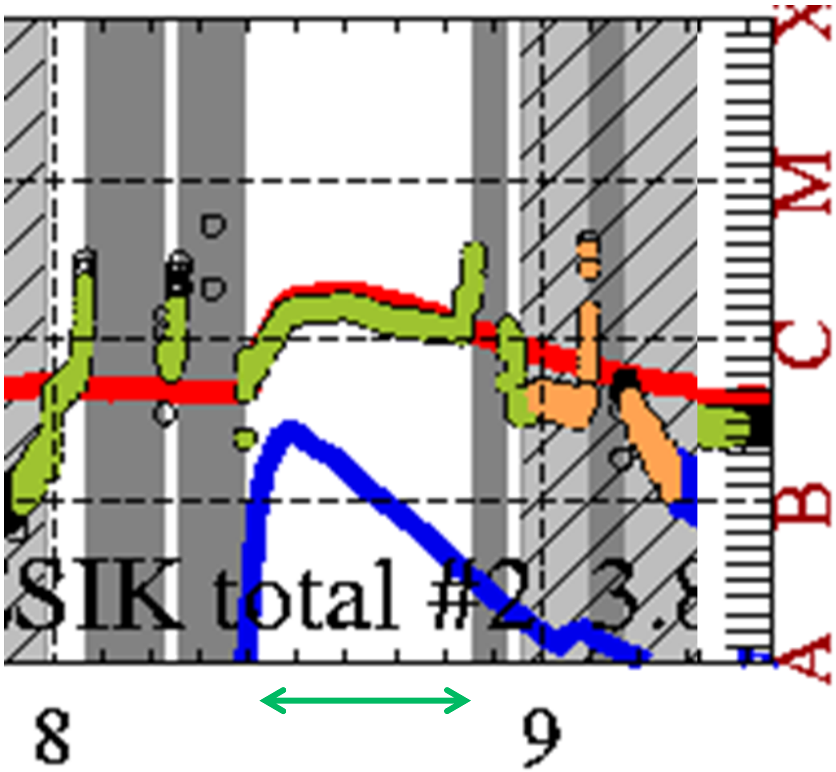
RESIK spectrometer

- RESIK is the Polish-led spectrometer launched on 2001 July 31 on Russian *CORONAS-F* satellite. It is the uncollimated bent crystal spectrometer consisting of two double-channel X-ray spectrometers designed to observe solar coronal plasmas in four energy bands. The nominal wavelength coverage of RESIK is 3.3 Å – 6.1 Å. Recorded spectra contain many spectral lines formed in H- and He-like ions of elements: Si, S, Ar and K. This range 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 are routinely observed for ions but for some flares we have observed enhanced emission in spectral features coinciding with transitions for n up to 9 or 10.
- The line and continuum is formed in hot coronal plasma (T-range 3 MK ÷ 30 MK) in various proportions for different spectral bands. This makes RESIK spectra uniquely suitable for investigations of the temperature structure of the source (differential emission measure - DEM) as well as the plasma elemental composition.
- Between 2002 and 2003, RESIK has collected numerous spectra of active regions and flares. The spectra for more than 100 flares and active regions reduced to Level_2 are available at: http://www.cbk.pan.wroc.pl/experiments/resik/RESIK_Level2/index.html
- The analysed flares were well observed also with the *RHESSI* hard X-ray telescope (NASA). *RHESSI* numerically reconstructed images allow to see the hot flaring source with the resolution sufficient to determine its size. With this supporting information the study of time variations of hot plasma density and energy content has been performed and will be discussed.

SOL2002-12-26T08:30 *GOES* C1.9

http://www.cbk.pan.wroc.pl/experiments/resik/resik_catalogue.htm

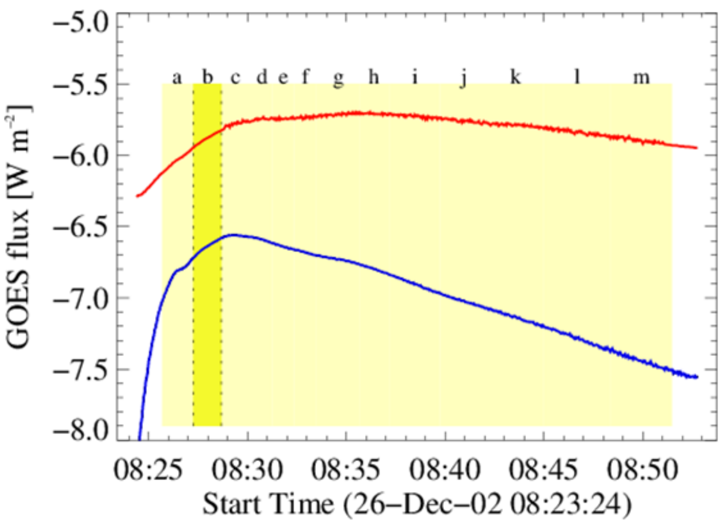


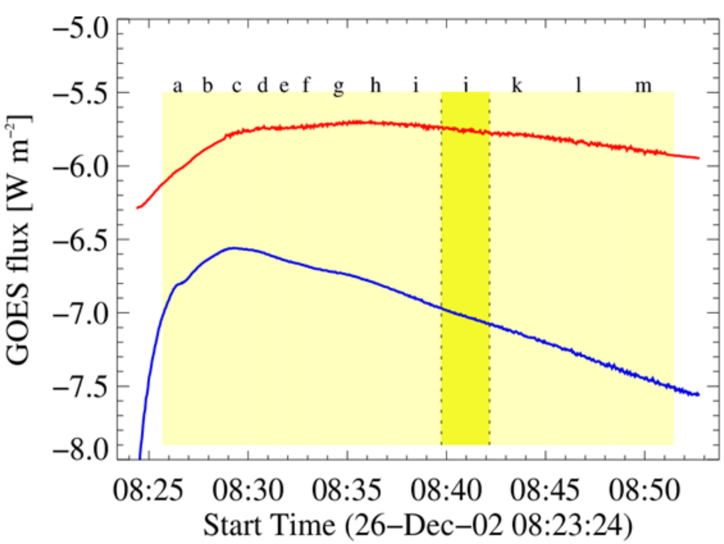
We selected 13 time intervals
Δt=75s ÷ 200s duration covering
this part of evolution of the event

Spectral nights as seen
by optical satellite sensor.

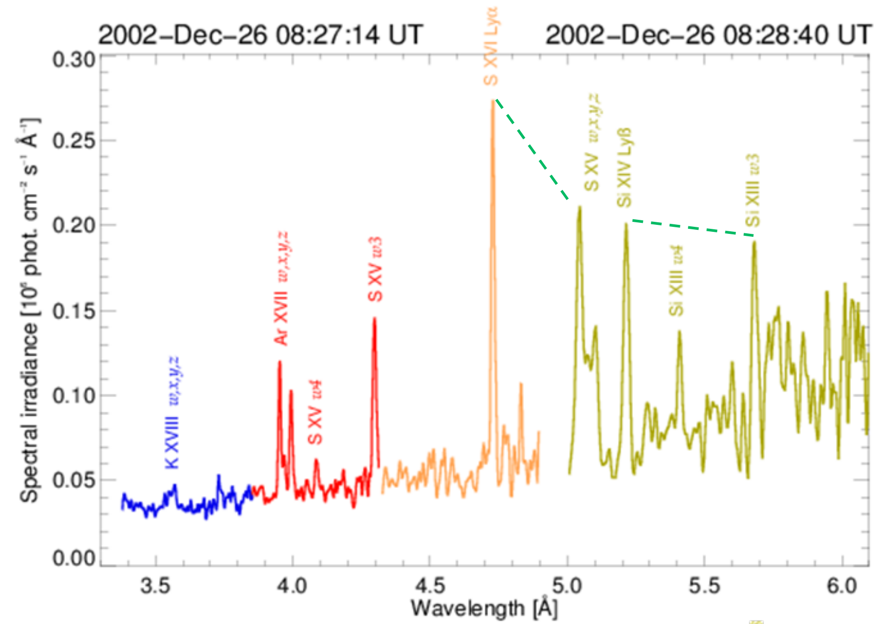
Dark grey areas denote
times of radiation belts
passages –
High Voltage is turned
OFF.

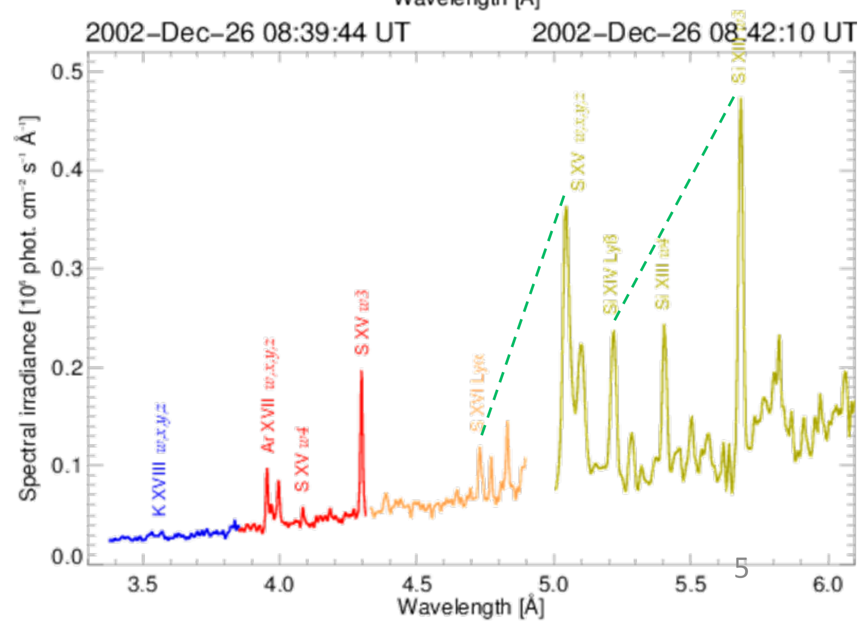
Spectral variability for SOL2002-12-26T08:30



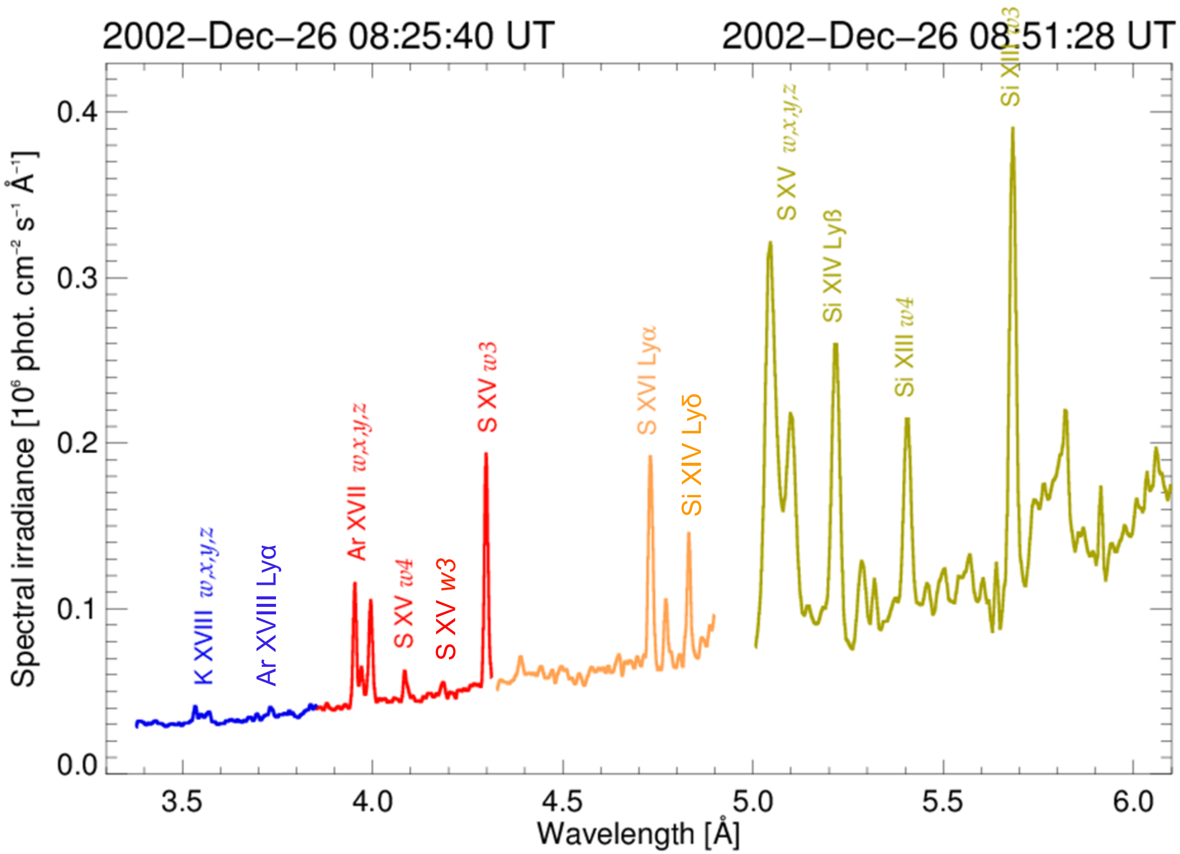


The ratios of lines indicated in the spectra changed dramatically during 13 min. (The slope of dashed lines connecting spectral features of H- and He-like S and Si ions is definitely different.) This is related to changing conditions in the flaring plasma (distribution of the emitting matter with temperature). This will be illustrated later.





RESIK spectrum analysis – multithermal analysis

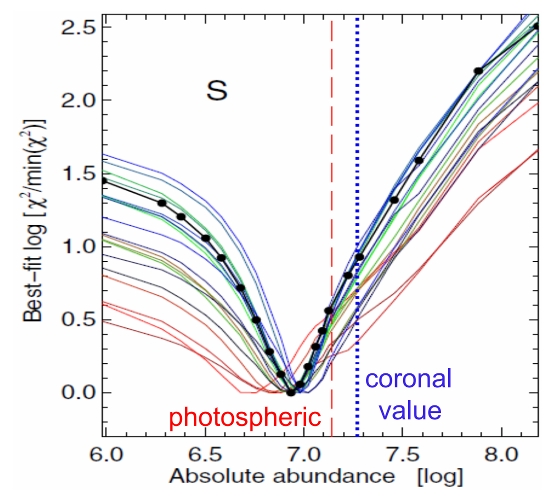


- 18 spectral intervals
- 4 elements (K, Ar, **S**, Si)
- Grid of 21 values of abundance for each element (0.1÷16 times coronal value)

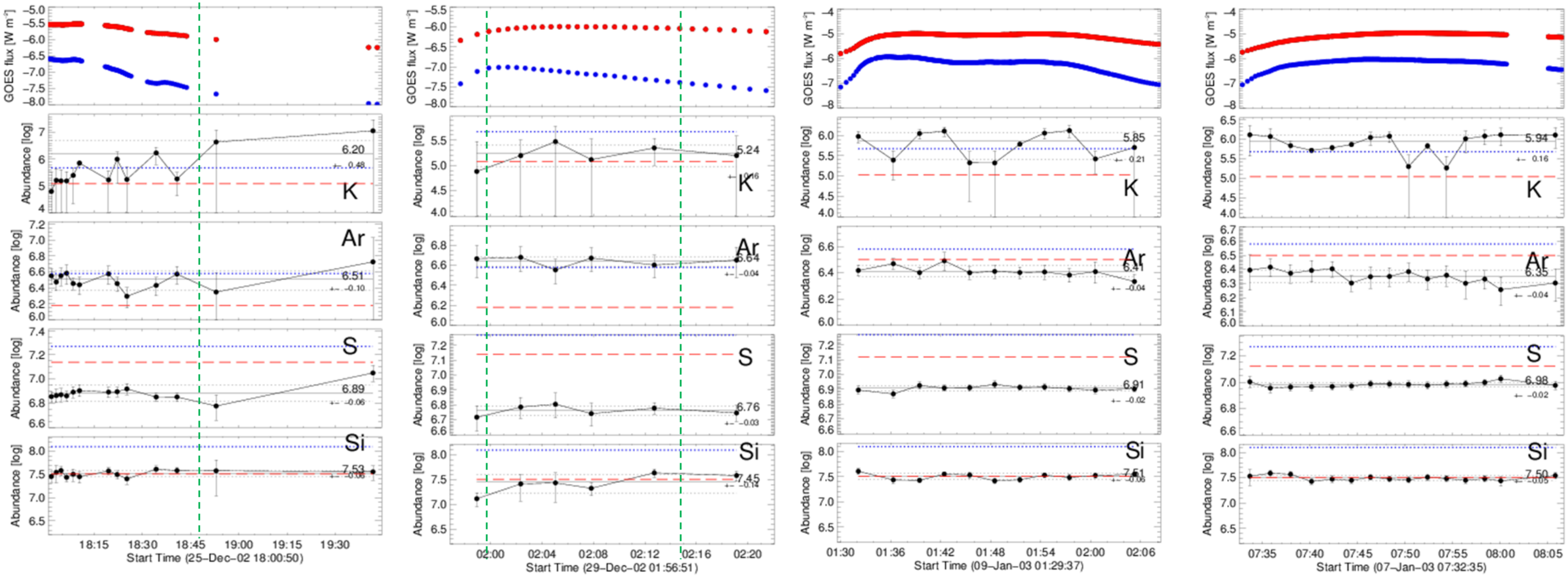
First step: abundances determination

Changing the abundance of an investigated element, the other are kept constant to their “coronal values” and the Withbroe-Sylwester (1980) iterative algorithm is used for the inversion.
The quality of the fit is noted after 1000 iterations and plots are constructed showing dependence of the fit quality on abundance. Sharp minimum is detected for elements with stronger lines. Abundance corresponding to min. χ2 is the optimum one.

$$F_i = A_i \int_{T=0}^{\infty} f_i(T)\,\varphi(T)\,\mathrm{d}T$$



Examples of abundances determined for selected flares



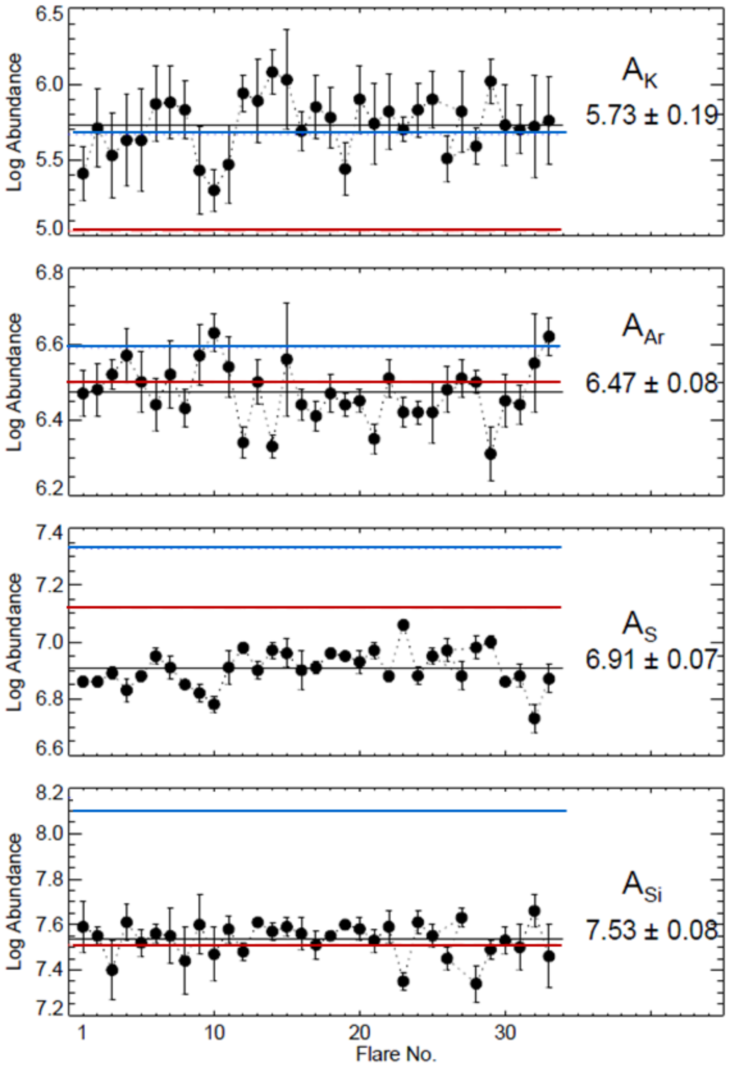
25 Dec. 2002 ~ 18:09 UT C2.9 | 29 Dec. 2002 ~ 02:59 UT B9.9 | 9 Jan. 2003~ 01:39 UT C9.8 | 7 Jan. 2003 ~ 07: 50 UT M1.0

Analysed 33 flares: located on the disc and limb, short and long duration, different X-ray classes (mainly C & M): 1 of B (B9.9), 26 of C, 5 of M and 1 of X (X1.5, rise & decay only).

There is only very little evidence of abundance variations with flare time evolution.

This analysis gave optimised abundances averaged over the main flare phases.

The main results published



Solar flare composition and thermodynamics from RESIK X-ray spectra; *B. Sylwester, J. Sylwester, K. J. H. Phillips, A. Kępa, and T. Mrozek, ApJ, 787, 122S, 2014*

RESIK solar X-ray flare element abundances on non-isothermal assumption; *B. Sylwester, K.J.H. Phillips, J. Sylwester, A. Kępa, ApJ, 805, 49S, 2015*

Coronal abundances (Feldman et al., 1992; from CHIANTI database for K)
Photospheric abundances (Asplund et al., 2009; for Ar from Lodders, 2008)

- The present estimates (multithermal approach) of abundances for **Ar** and **K** are very close to that obtained previously (isothermal analysis). This is because *GOES* temp. well describes Ar XVII and K XVIII lines. For S and Si values of obtained abundances are 1.8 and 2.1 times lower.
- Flare-to-flare variations seem to be ruled out for Si, S, and Ar but ±50% variations are not ruled out for K (but the larger uncertainty in its abundance estimate).

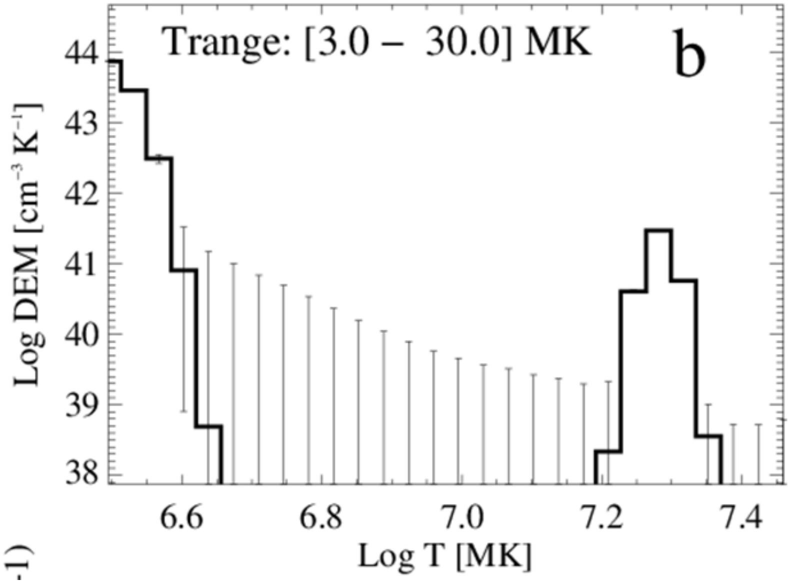
DEM determination

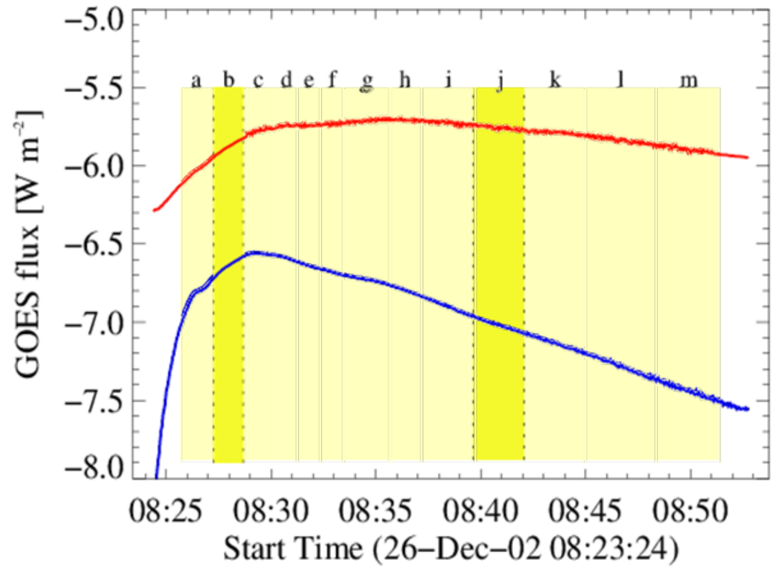
Second step: DEM determination (based on known abundances)

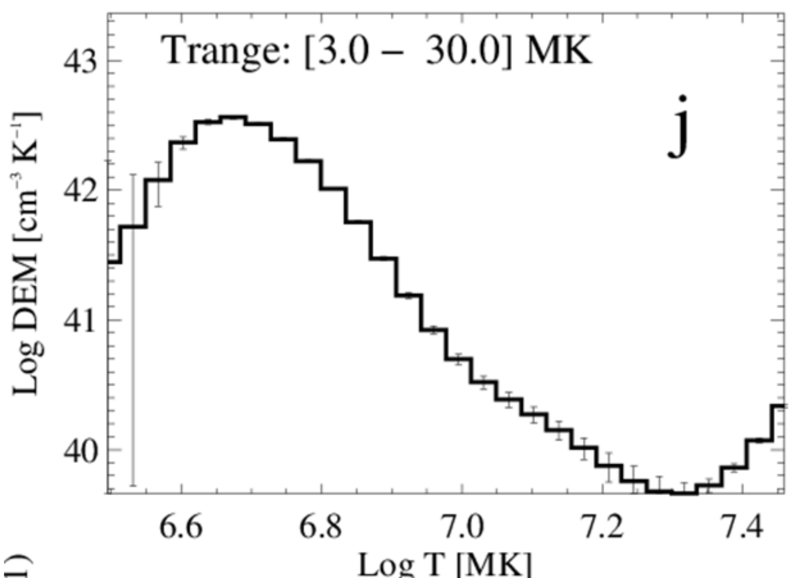
$$F_i = A_i \int_{T=0}^{\infty} f_i(T)\varphi(T)\mathrm{d}T$$

How does DEM (differential emission measure distribution) look for the rise and decay phase of the C1.9 flare on 26 Dec. 2002?

DEM examples: SOL2002-12-26T08:30

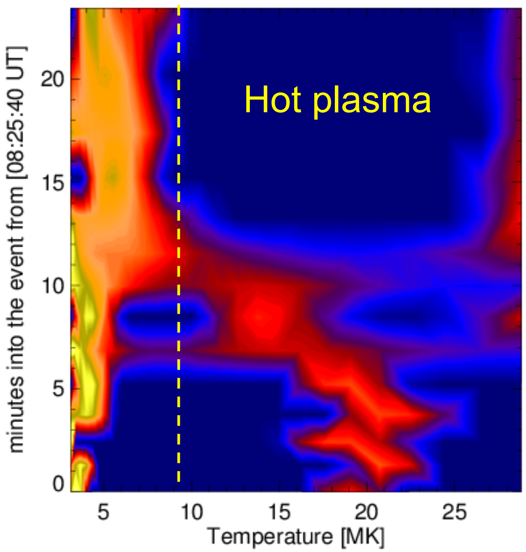


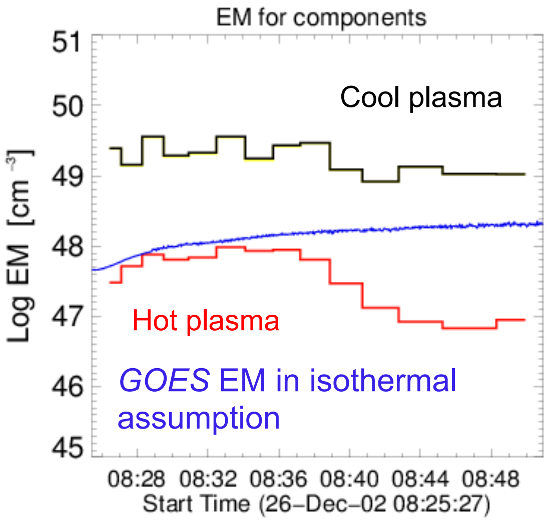




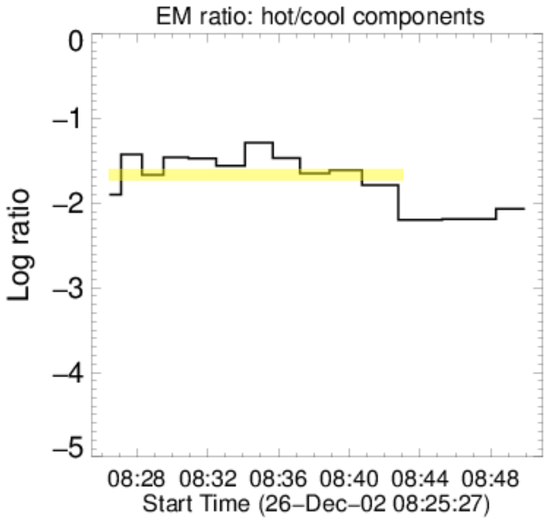
For each selected time interval
10 000 iterations for DEM inversion have been performed. Typically, better than 5 % agreement between observed and DEM predicted fluxes in every spectral band is reached.

26 Dec. 2002 ~08:35 UT C1.9 (limb)





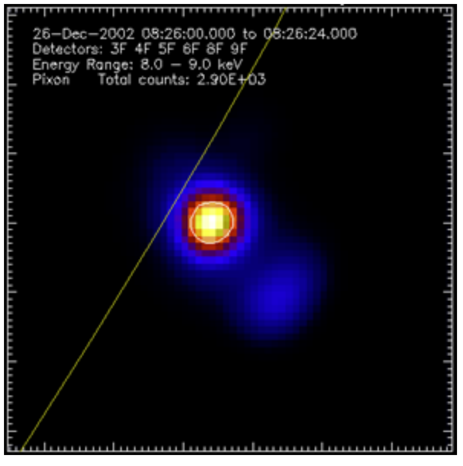
Message:
Commonly used *GOES* isothermal interpretation (T, EM) is BIASED: it represents the hot component during rise, later is complicated average.

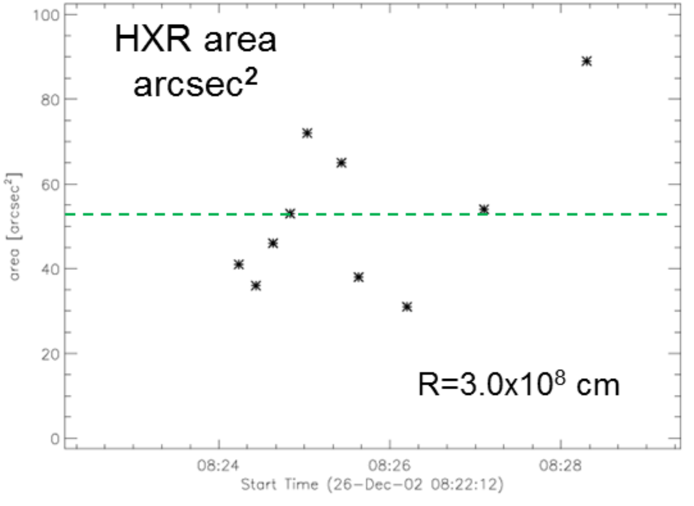


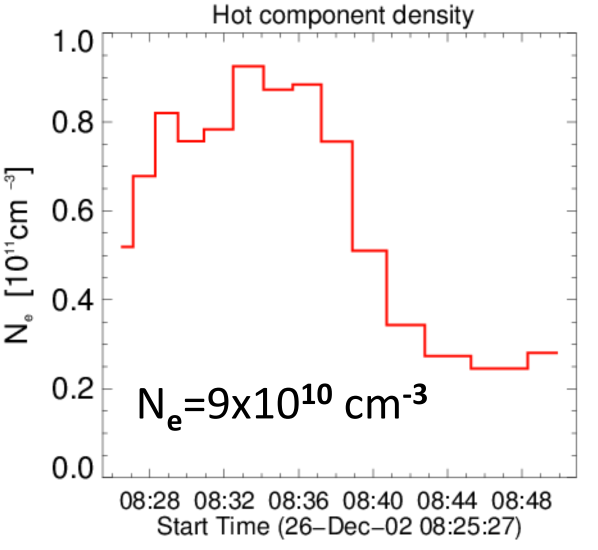
Rather constant ratio of hot and cool plasma up to the late decay can be noticed. The hot plasma constitutes a very small part of emitting plasma (0.025) but it is necessary to properly reproduce the observed spectra.

Density determination

$V = 4/3\pi R^3$ $N_e = (EM/V)^{½}$;





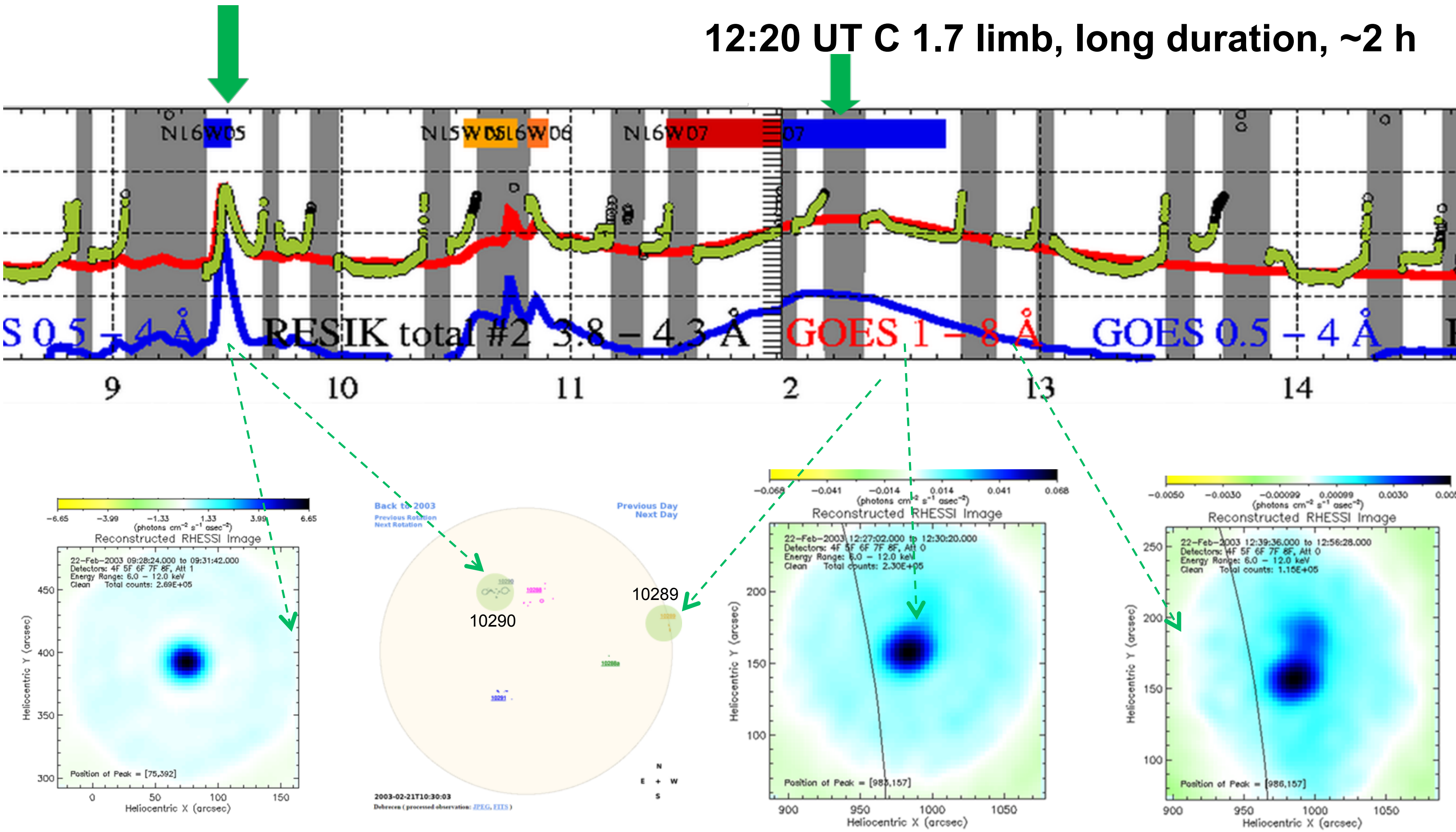


PIXON reconstructed *HXT* images (8-9 keV) provide spatial extend of the hotter component.

22 Feb. 2003 flares

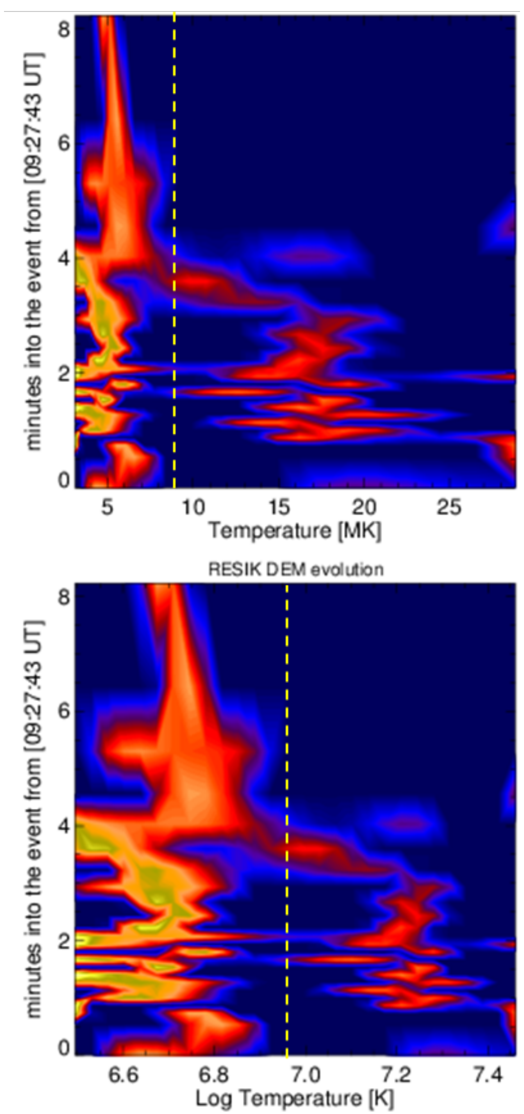
09:29 UT C 5.8 disc, short duration, ~8 min.

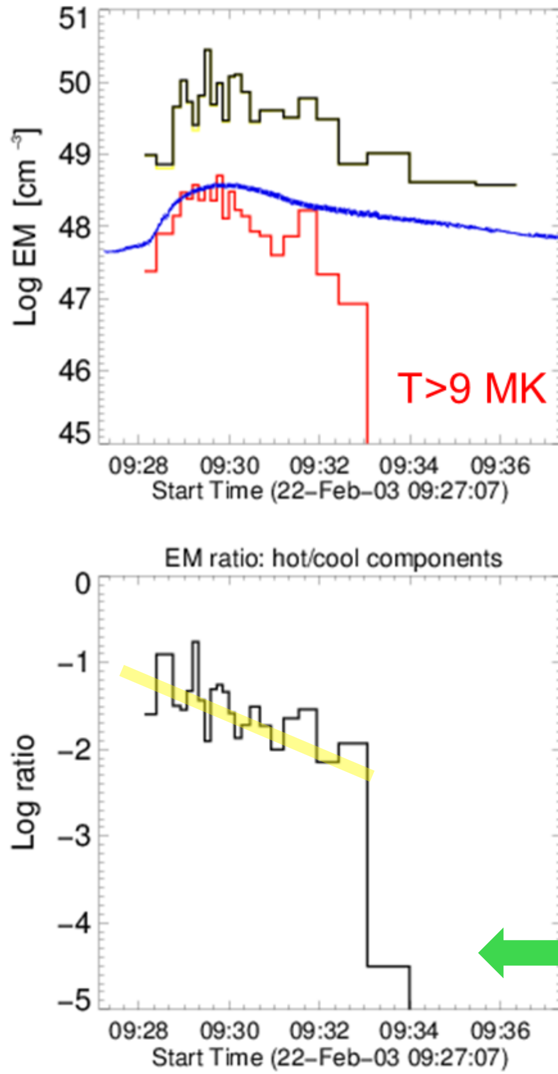
12:20 UT C 1.7 limb, long duration, ~2 h

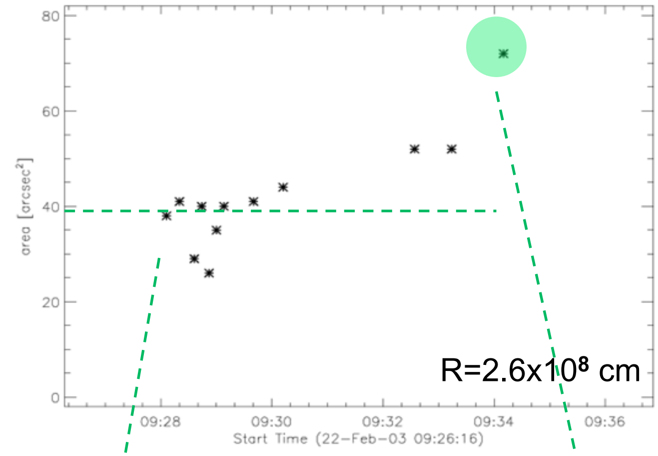


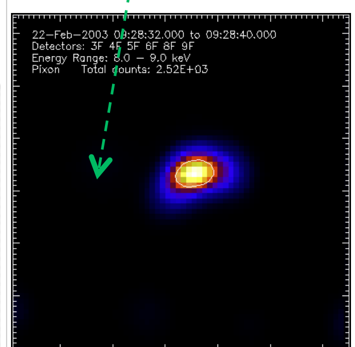
Debrecen map: http://fenyi.sci.klte.hu

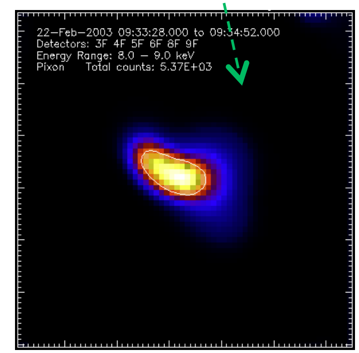
22 Feb. 2003 ~09:29 UT C5.8 (disc)





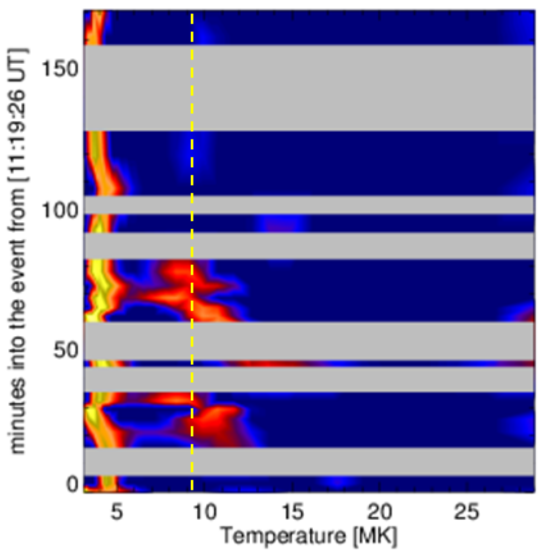


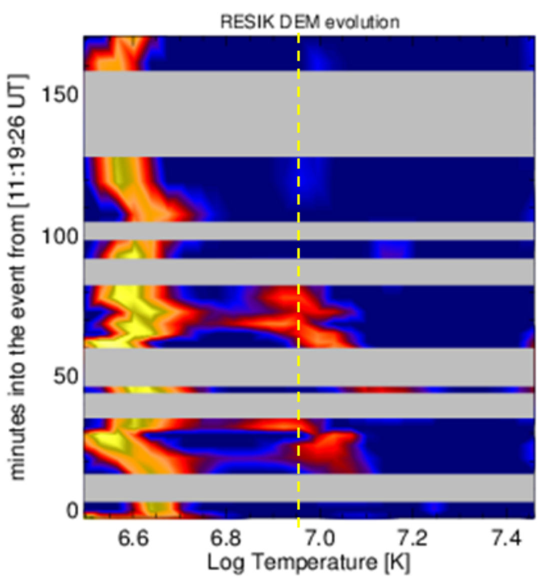


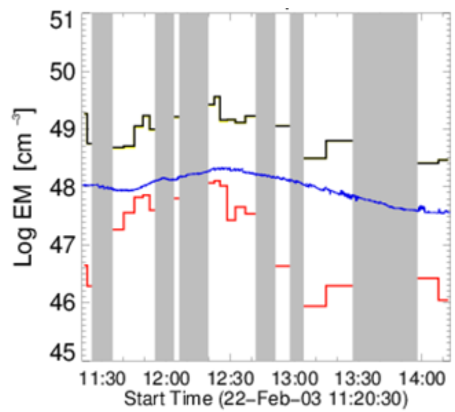


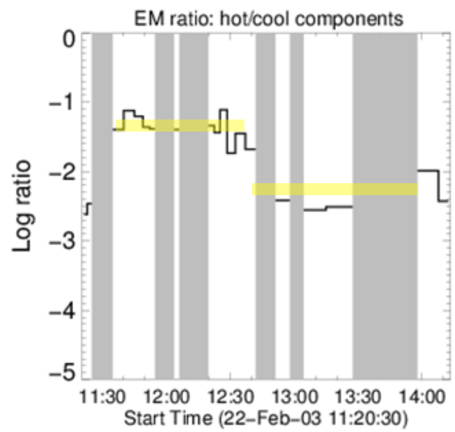
Descending trend (0.1→0.01) of the relative amount of hot and cold plasma.

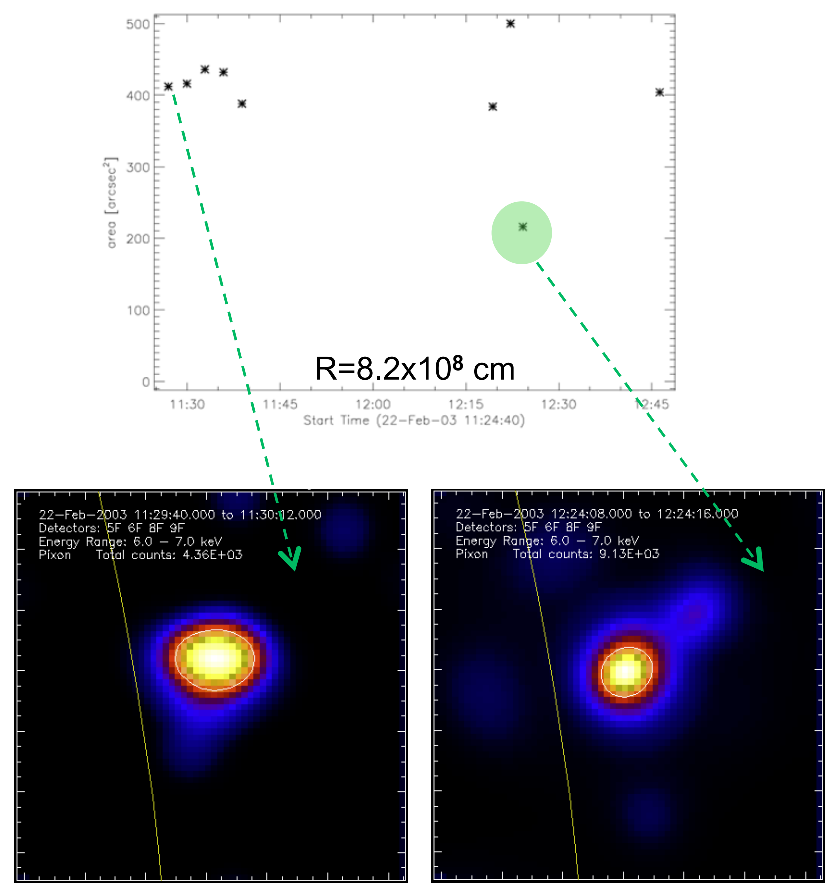
22 Feb. 2003 ~12:20 UT   C1.7 (limb)







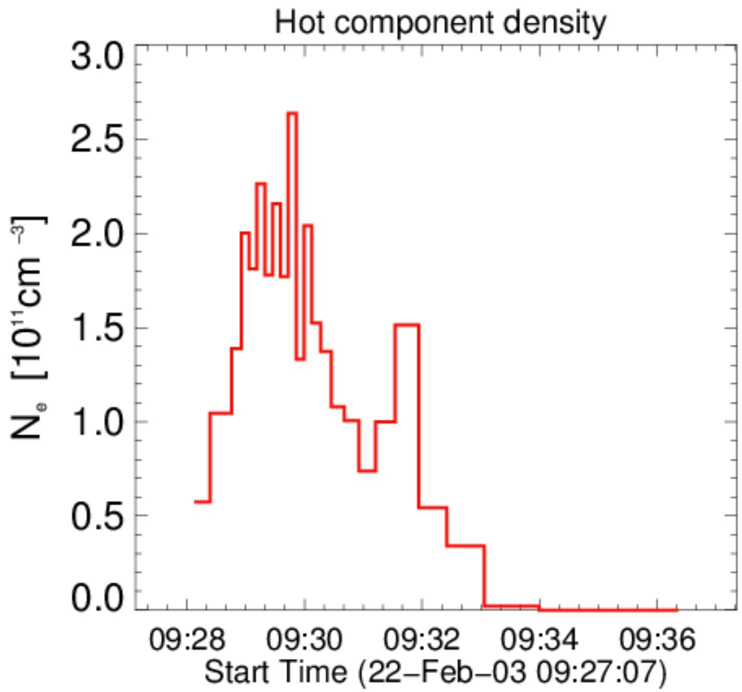




Two levels of relative amount of hot and cold plasma:
0.05 during the rise /maximum and 0.005 during the decay.

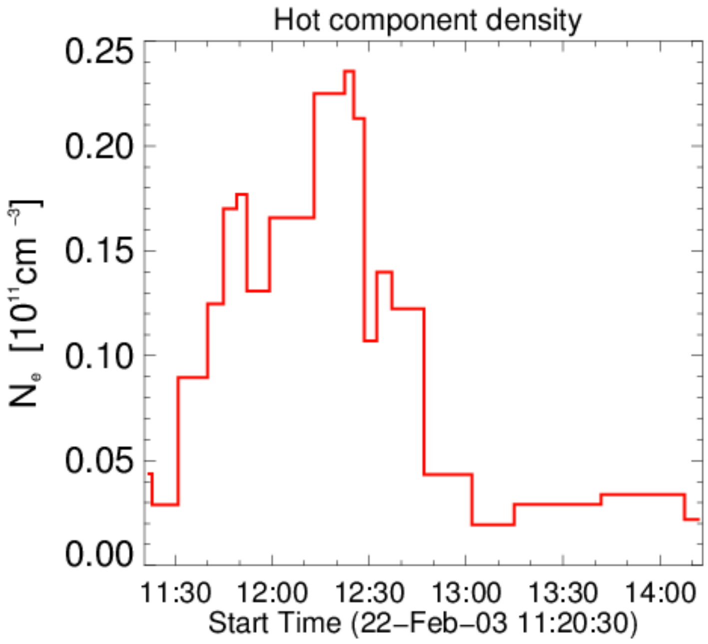
Densities for two flares on 22 Feb. 2003

C 5.8 disc flare, short duration



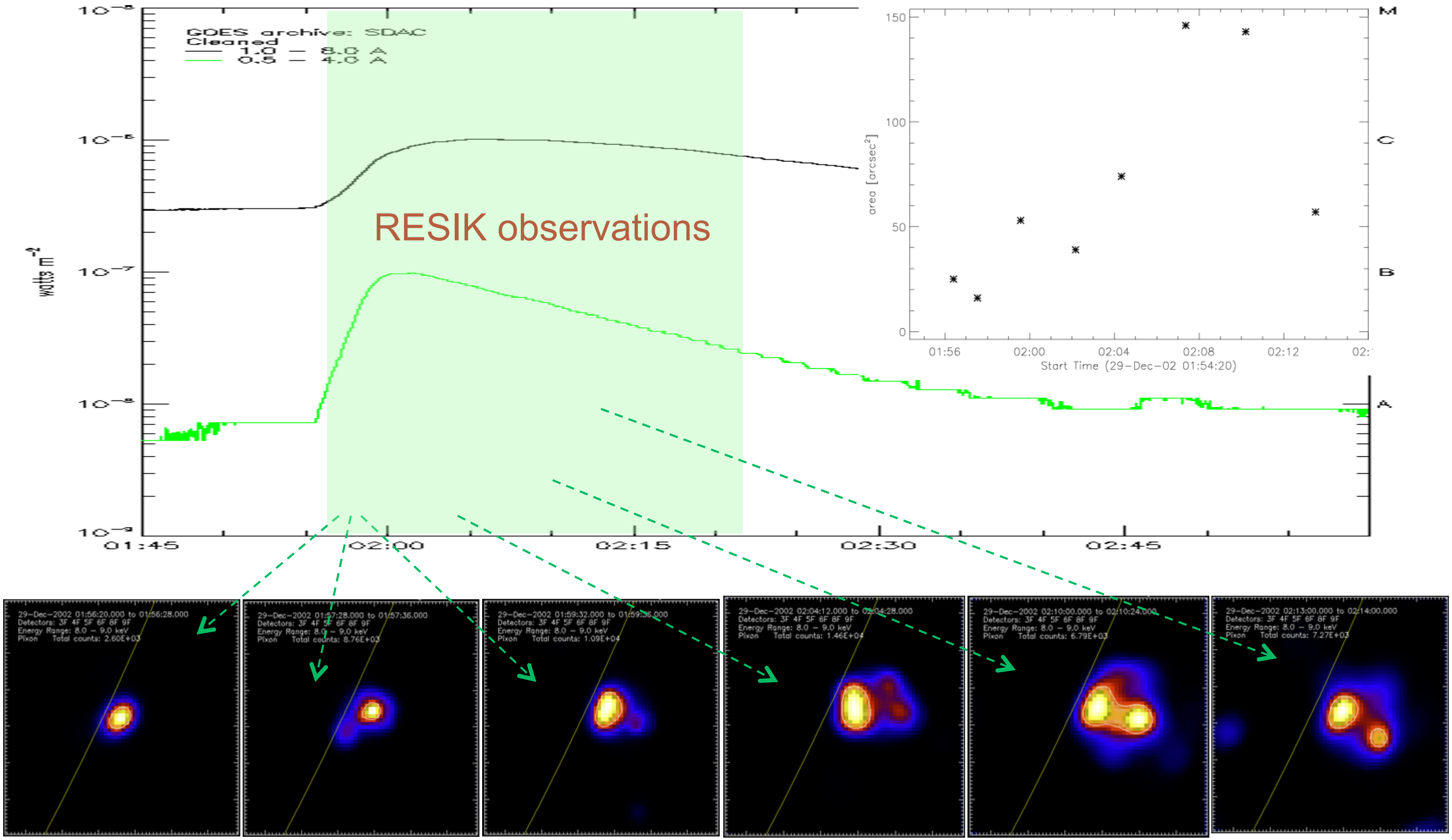
N_e=2 x 10^{11} cm^{-3}

C 1.7 limb flare, long duration



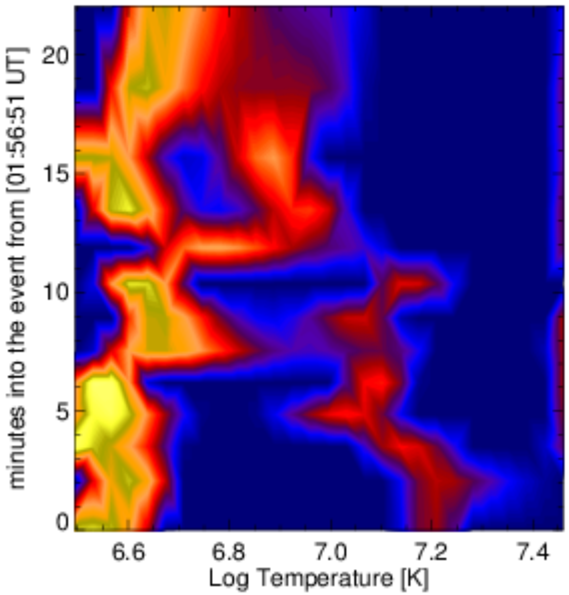
N_e=2 x 10^{10} cm^{-3}

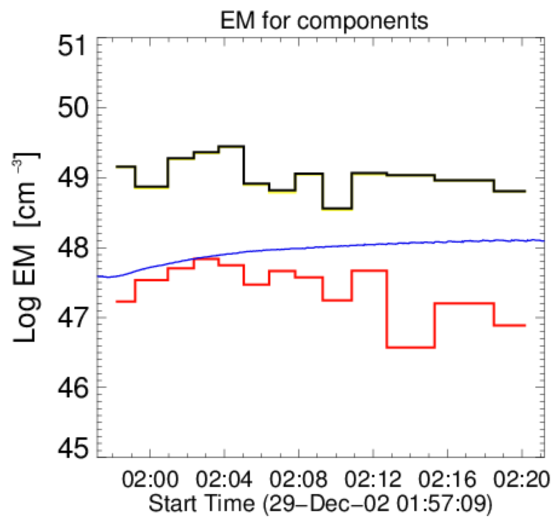
29 Dec. 2002 ~02:05 UT B9.9 the weakest analysed flare



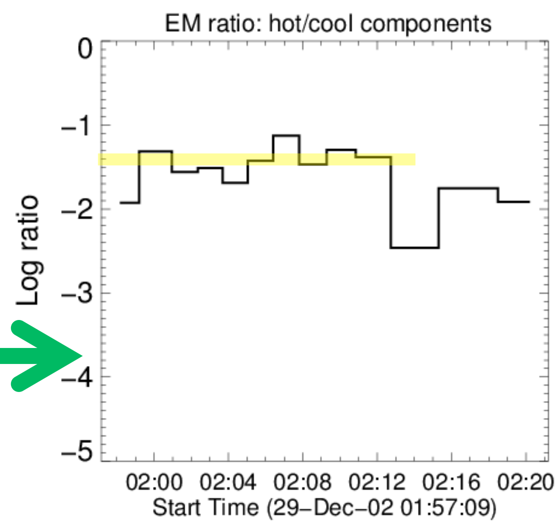
PIXON reconstructed *RHESSI* images→ changing volume of 8-9 keV emitting plasma

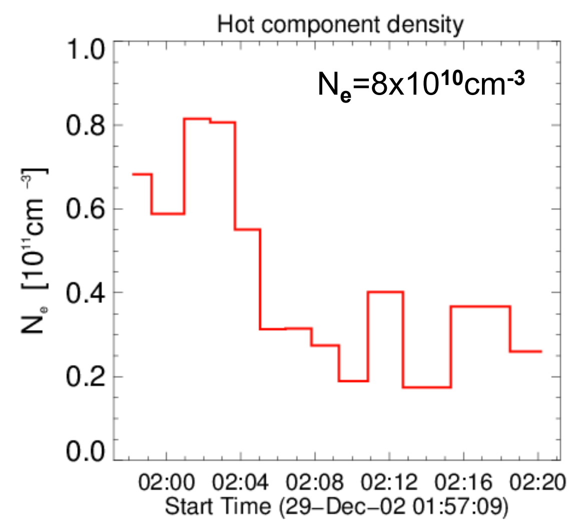
29 Dec. 2002 ~02:05 UT B9.9 (limb)





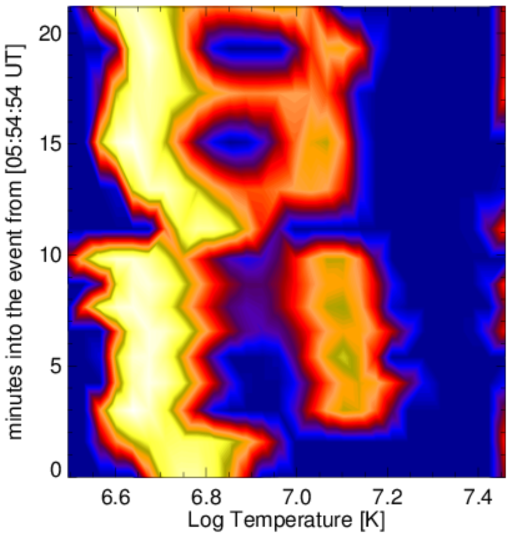
- The weakest analysed flare
- Changing volume of the emitting region; evident morphological evolution

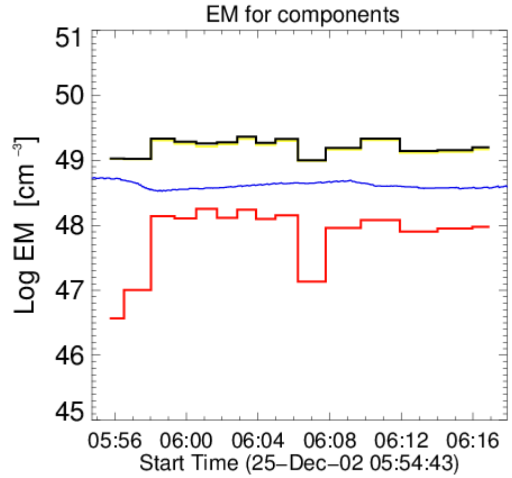


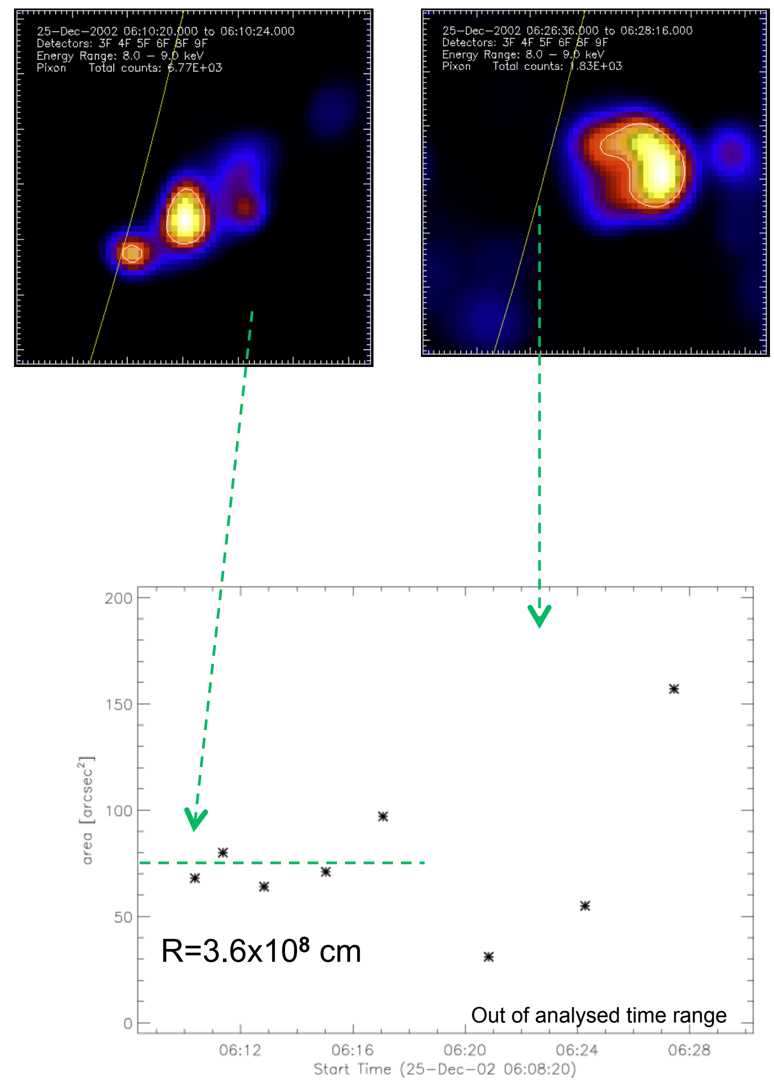


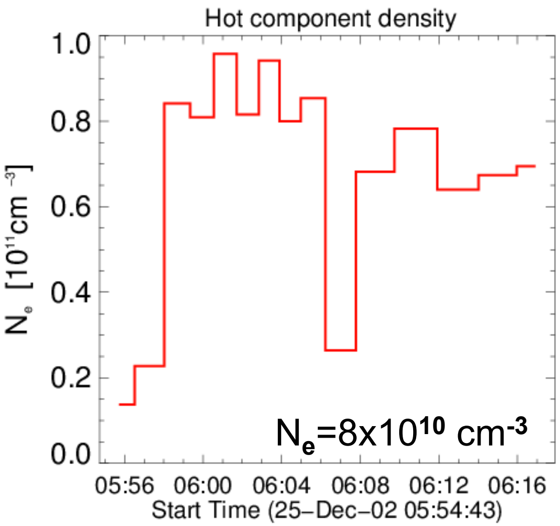
Nearly constant ratio (~0.04) of hot and cooler plasma.

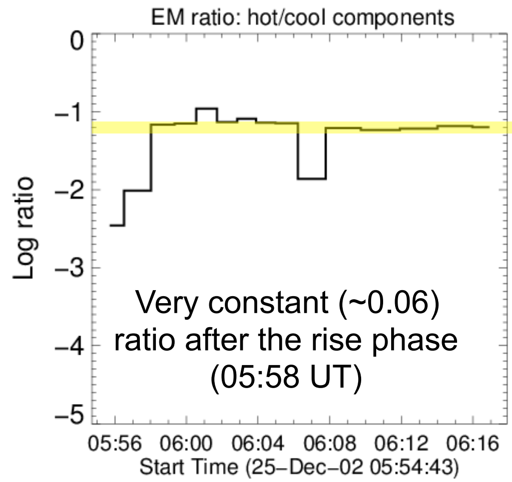
25 Dec. 2002 ~06:02 UT C4.0 (limb)



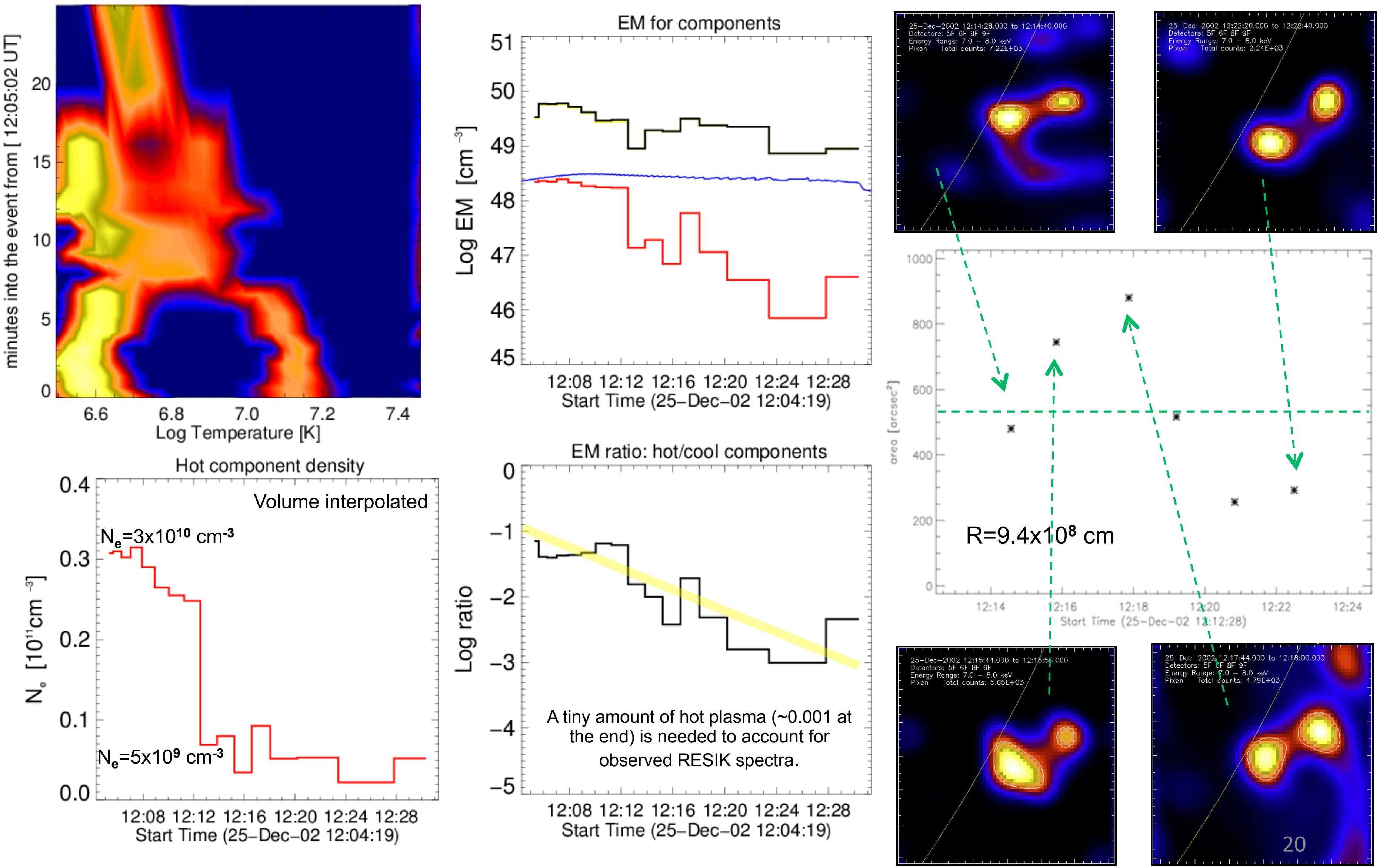








25 Dec. 2002 ~12:07 UT C3.5 (limb, double source)



Take home message & plans

- RESIK spectra allow us to determine abundances of main elements contributing to the spectra (K, Ar, S, Si) and also the time evolution of the differential emission measure (DEM) distributions.
- The DEM shapes indicate 2 components – a cooler component (T = 3 – 9 MK) and a hotter component (T>9MK). The amount of plasma in the cooler component is approx. constant with time but the hotter component (which accounts for a **tiny** fraction (0.01 – 0.001) of the total DEM) is variable.
- PIXON-reconstructed *RHESSI* maps when available enable estimates of the high-T emitting volumes to be made from which lower limits to electron densities can be set.
- For moderate-class flares, the lower limits of averaged hot plasma densities are between $2\text{x}10^{10}$ cm^{-3} and $2\text{x}10^{11}$ cm^{-3}.

- To calculate hot plasma thermal energy content:
  $E_{th}=3\ N_e\ k\ T\ V = 3kT\ EM^{1/2}\ V^{1/2}$
- Try to find the possible scaling laws which will allow to estimate the hot plasma density and/or thermal energy content based on the known class and duration of the flare.