Temporal evolution of differential emission measure and electron distribution function in solar flares based on joint RHESSI and SDO observations

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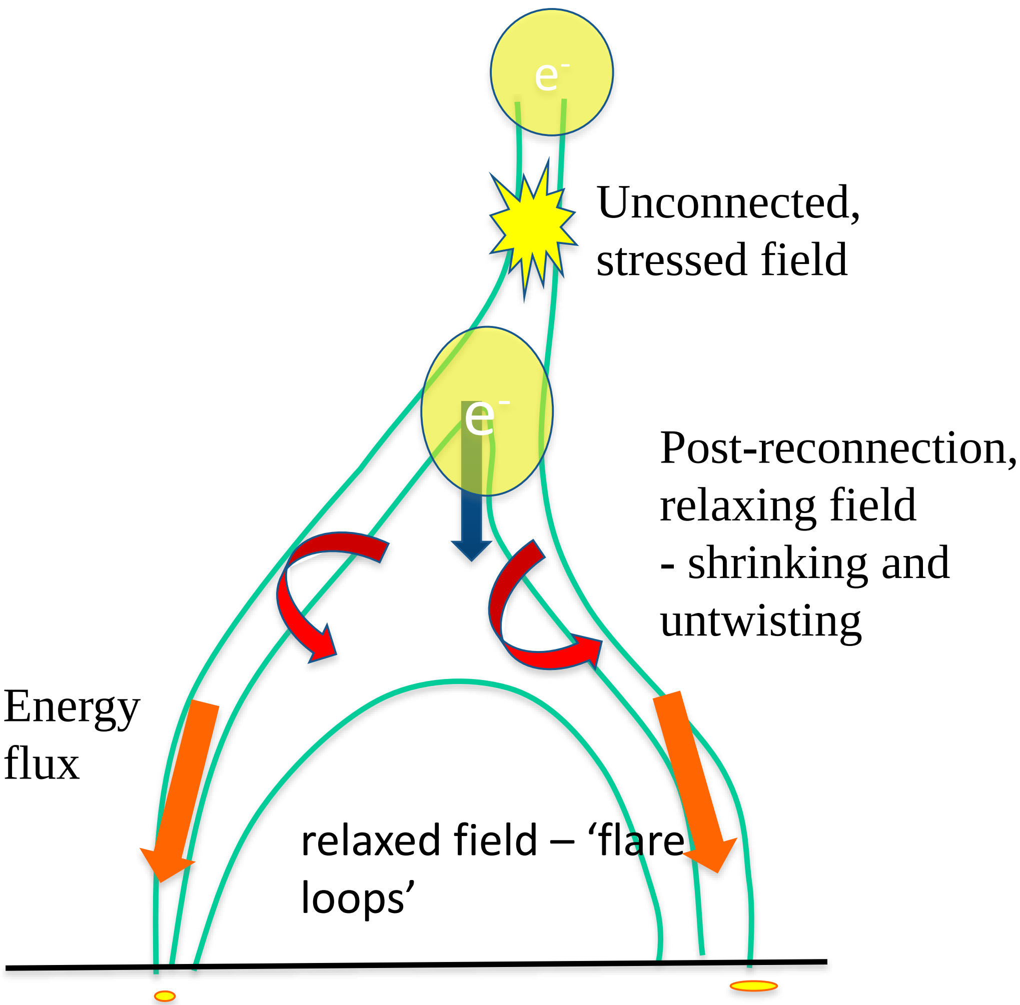
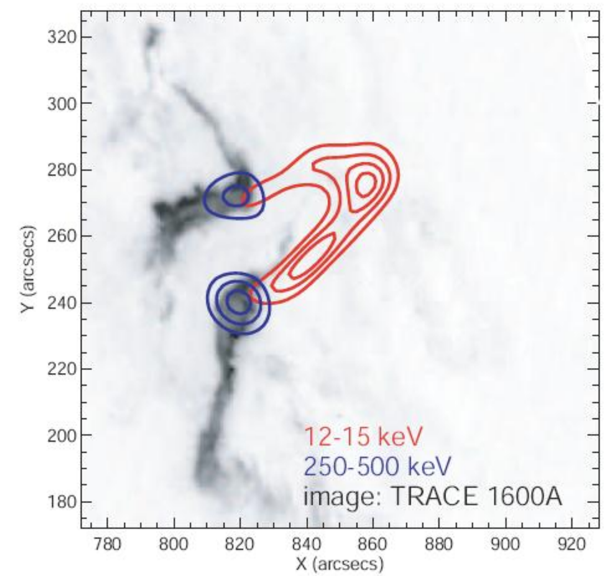
Standard flare model



Footpoint emission, fast electrons/ions (~50% of flare energy)



(Krucker et al., 2007)

Diagnostics of flaring plasma

- Observe signatures of accelerated electrons in X-ray and EUV.
- Infer properties of the electron population that causes both the X-ray and EUV emission.
- Determine the total electron number (crucial for working out total flare energetics and constraining models of solar flares).
- Use X-ray and EUV observations (RHESSI & AIA/SDO) to find the mean electron flux spectrum $<n\,VF>$.

EVE/SDO & RHESSI (Caspi et al., 2014);

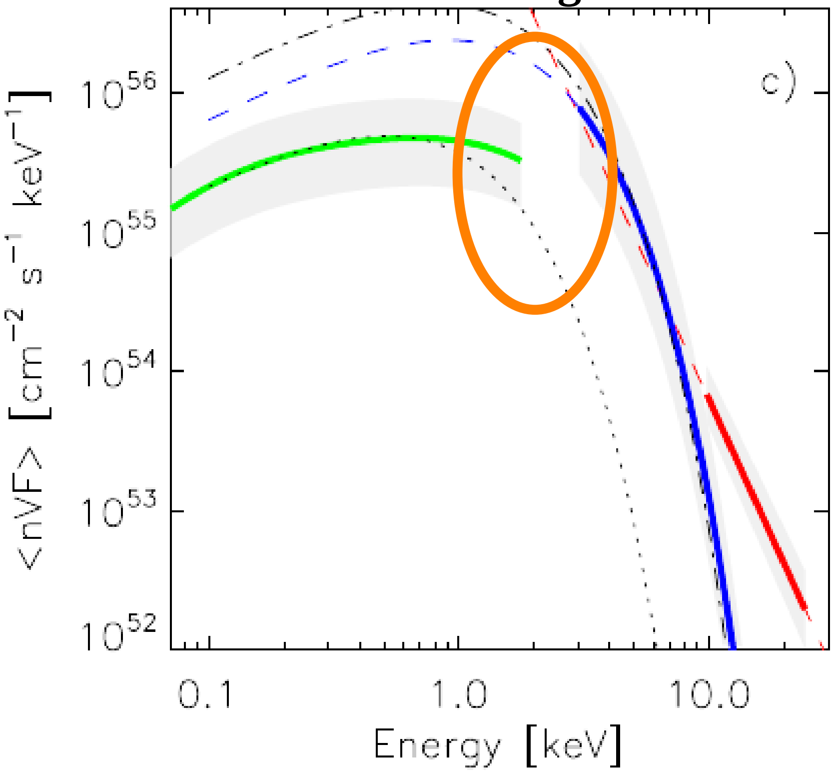
AIA/SDO & RHESSI (Battaglia & Kontar, 2013; Inglis & Christe, 2014);

AIA/SDO & EVE/SDO & RHESSI & GOES (Aschwanden 2015)…

(look at Marina Battaglia’s talk)

Motivation
Why do we need to combine SDO/AIA and RHESSI?

Flare 14-Aug-2010



(M. Battaglia & E.P. Kontar, 2013)

- AIA and RHESSI are more sensitive in different energy ranges;
- The extrapolation of the RHESSI thermal distribution (blue line) into AIA range is a factor ~ 3 larger than the distribution from AIA (green line);
- Different techniques were used for inferring <*nVF*> from AIA and <*nVF*> from RHESSI

Motivation
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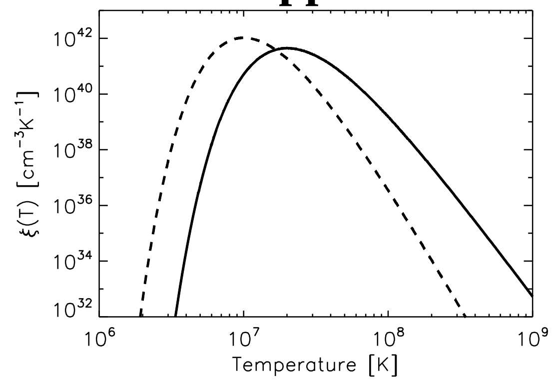
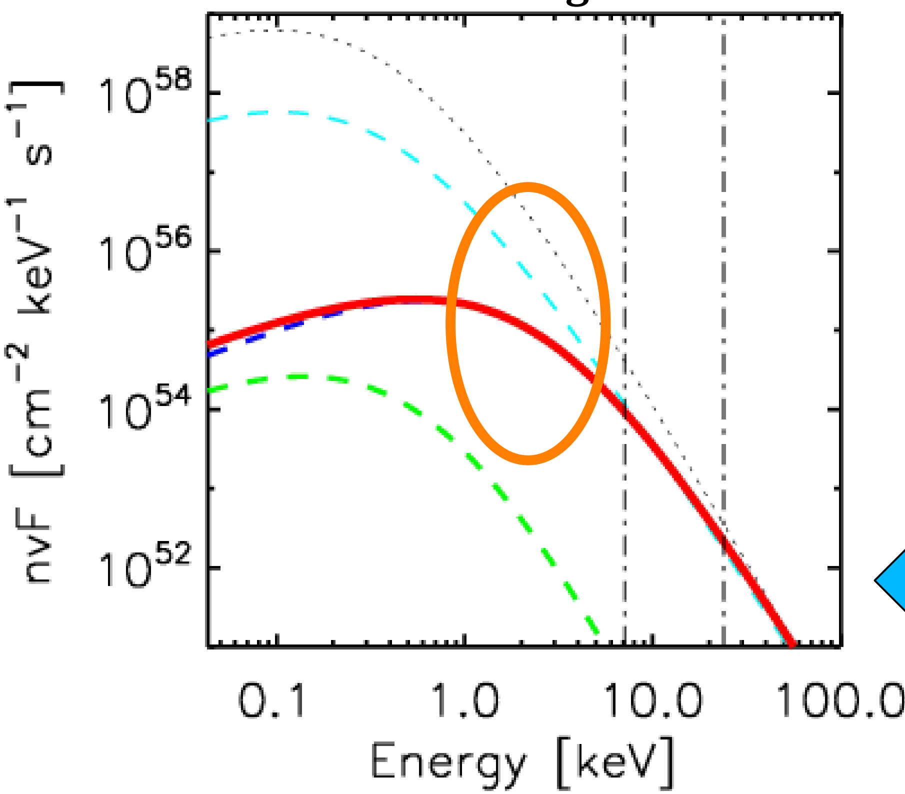
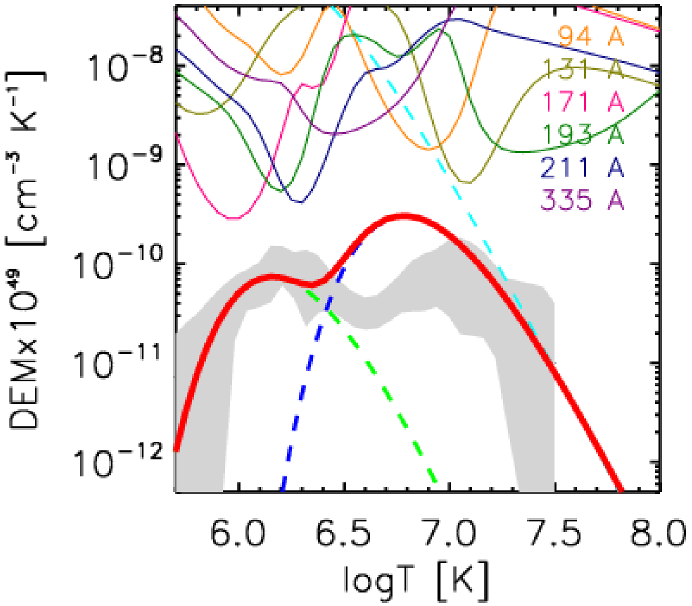
two kappa-DEMs



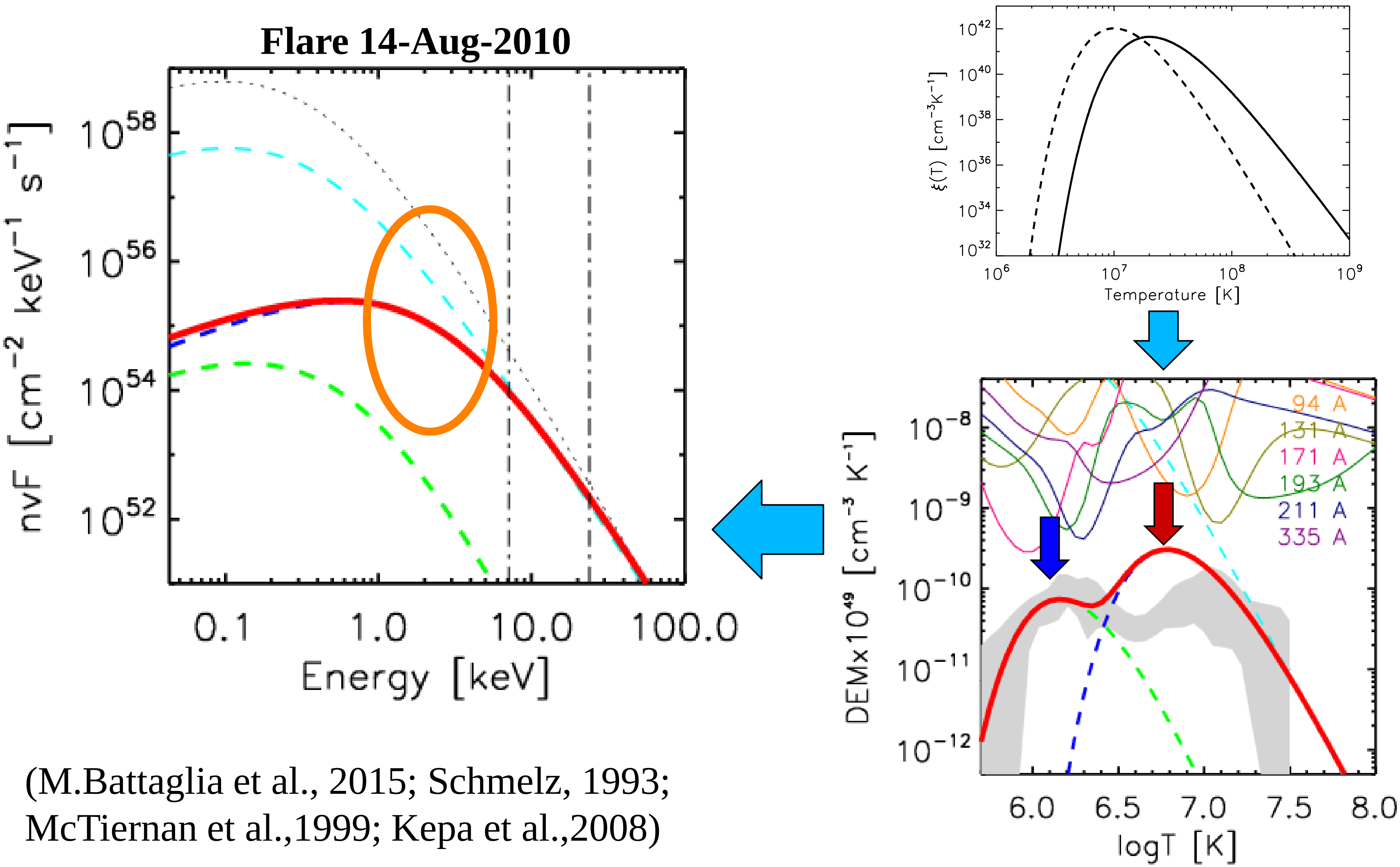
Flare 14-Aug-2010





(M.Battaglia, G.Motorina, E.P.Kontar, 2015)

Motivation
Why do we need to combine SDO/AIA and RHESSI?



(M.Battaglia et al., 2015; Schmelz, 1993; McTiernan et al.,1999; Kepa et al.,2008)

SDO/AIA

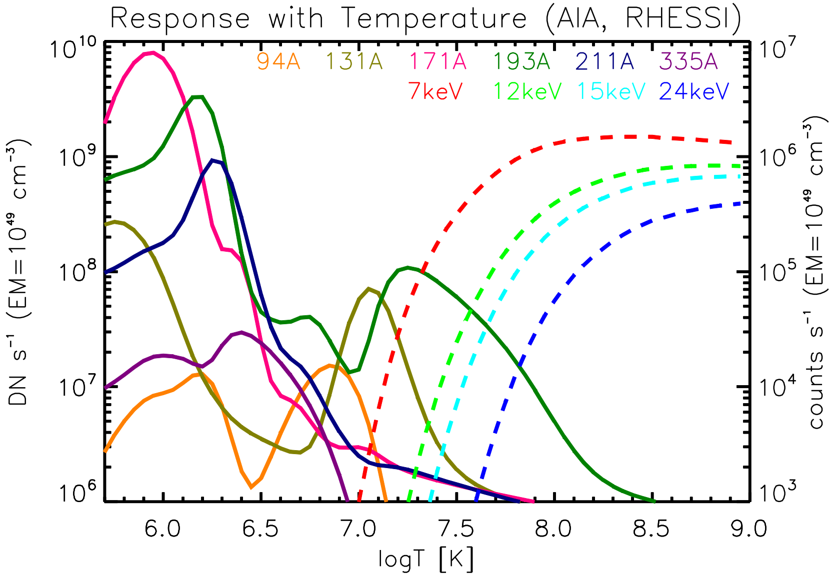
SDO/AIA (Lemen et al., 2012)

- Observations of the full solar disk, matrix of 4096×4096 pixels, 1pixel~0.6''(435km)
- 6 EUV channels were chosen with wavelengths 94, 131, 171, 193, 211, 335 Å (Fe VIII, IX, XII, XIV, XVI, XVIII)
- Temperature range: T ≈ 0.6 MK to ∼16 MK
- Images in each filter every 12s

RHESSI

RHESSI (Lin et al., 2002)

1. X-ray (3—100 keV) & gamma-ray (>100 keV) spectra
2. Images of solar flares (help to confirm the source of emission)
3. Information about thermal component of radiation (>10 MK~0.8 keV)



Temperature response for

6 EUV channels of SDO/AIA (131, 171, 193, 211, 335, 94 Å) и X-ray RHESSI (7 keV, 12 keV, 15 keV, 24 keV)

Simultaneous fitting of AIA and RHESSI data

The observed data $\boldsymbol{g} = (a_1, \ldots, a_6, h_1, \ldots, h_N)$ for temperatures $T_1, \ldots, T_M$ from 0.043 (0.5 MK) to 85 keV:

$$\boldsymbol{g} = \boldsymbol{R}\xi + \delta\boldsymbol{g}$$

$$\begin{bmatrix} AIA \\ data \\ \\ RHESSI \\ data \end{bmatrix} = \begin{bmatrix} AIA \\ \text{Response Functions} \\ \\ RHESSI \\ \text{Detector Response Matrix} \end{bmatrix} \times \begin{pmatrix} \xi(T_1) \\ \cdot \\ \cdot \\ \cdot \\ \xi(T_M) \end{pmatrix}$$

Where

$\delta\boldsymbol{g}$ is the errors,

the new matrix $\boldsymbol{R}$ is the combination of AIA response functions and RHESSI Detector Response Matrix (DRM) (Motorina & Kontar, 2015; Battaglia et al., 2015)

Background

Differential emission measure (DEM), $\xi(T)$, [$cm^{-3}K^{-1}$]

$$EM = \int_0^\infty \xi(T)dT \qquad (1)$$

The mean electron flux spectrum $<nVF(E)>$ of a thermal source can be represented as (Brown & Emslie, 1988; Battaglia & Kontar, 2013):

$$< nVF(E) > = \frac{2^{3/2}E}{\sqrt{\pi m_e}} \int_0^\infty \frac{\xi(T)}{(k_B T)^{3/2}} \exp\left(-\frac{E}{k_B T}\right) dT \qquad (2)$$

using the change of variables: $t = 1/T$, can be written as the Laplace transform of a function $f(t) = \xi(T(t))/t^{1/2}$, $exp(-st)=exp(-Et/k_B)$:

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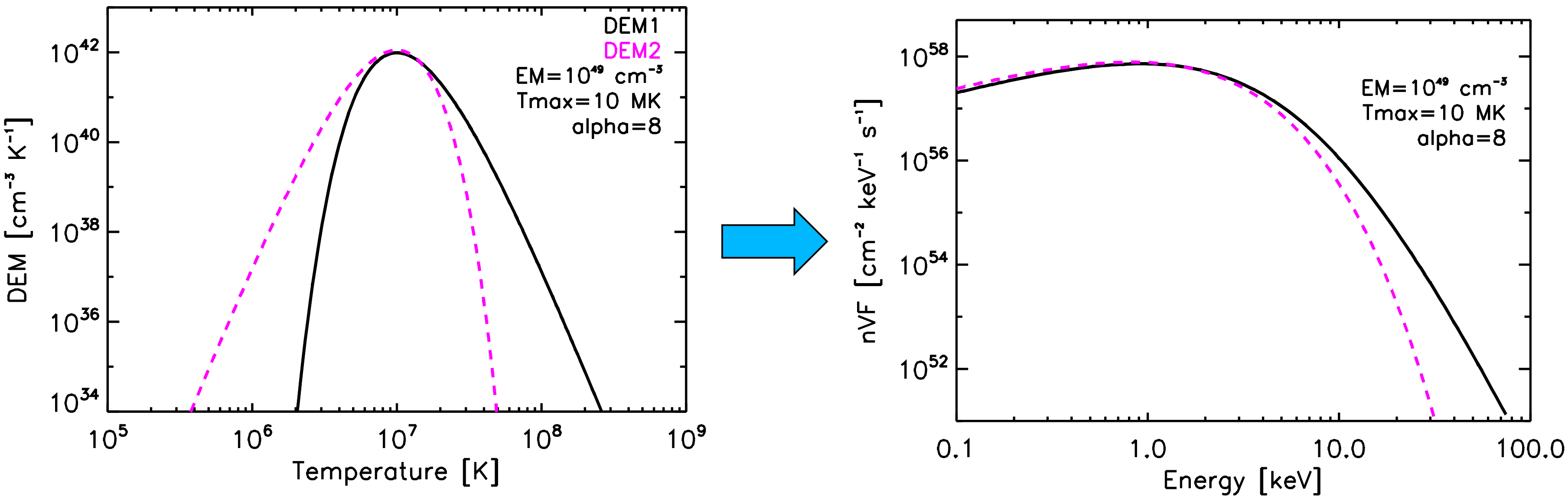
$$<nVF> = \frac{2^{3/2}E}{\sqrt{\pi m_e} k_B^{3/2}} \int_0^\infty \frac{\xi(T(t))}{t^{1/2}} \exp(-Et/k_B) dt \qquad (3)$$

i.e. to find <*nVF*> we need to choose DEM so that *f(t)* has analytical form of the Laplace transform

Introduction of DEM



DEM functions (left panel) and $\langle nVF \rangle$ (right panel) with $EM=10^{49}\ cm^{-3}$, $T_{max}=10\ MK$, $\alpha=8$:
multi-thermal κ-distribution function (black line) (Kašparová & Karlický, 2009; Oka et al. 2013, 2015; Battaglia et al., 2015);
multi-thermal α-distribution function (purple line) (Motorina & Kontar, 2015)

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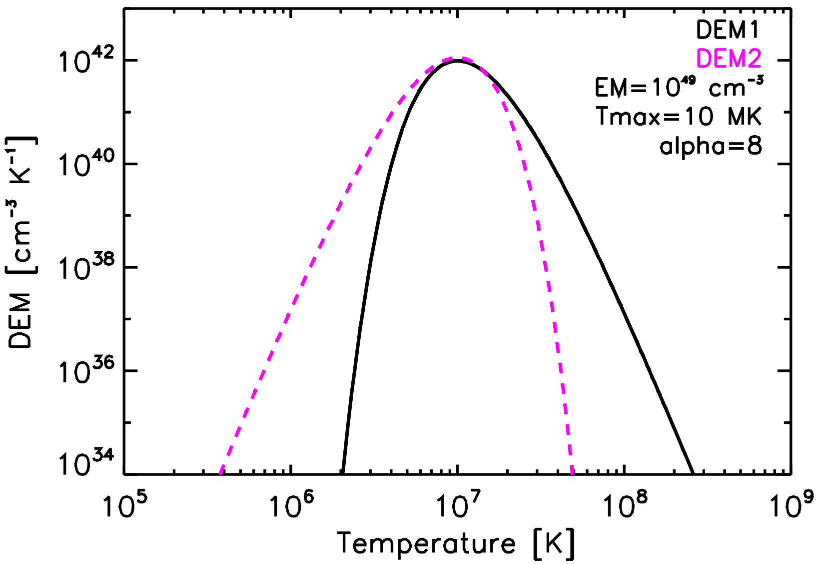

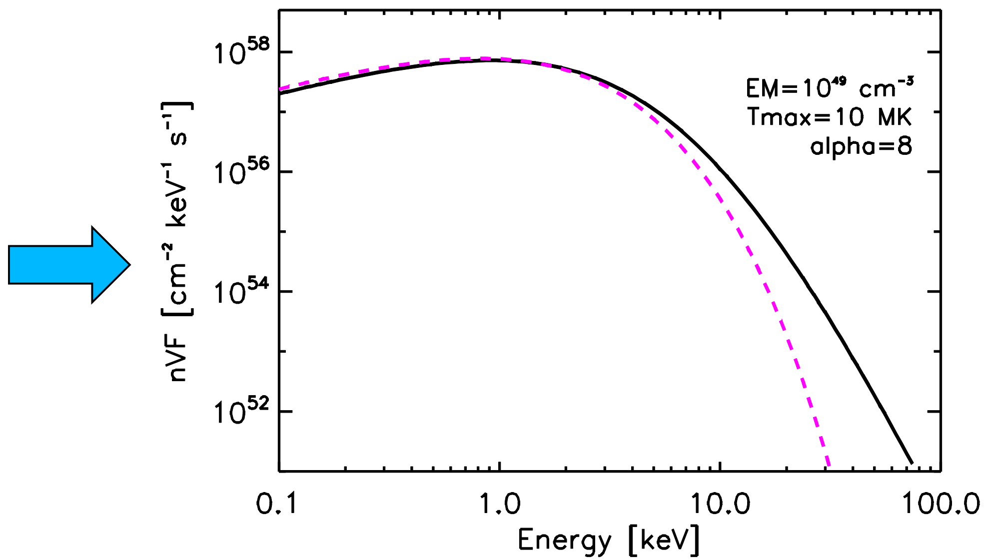

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Both DEMs have analytical representation of <*nVF*> and physical parameters (*EM*, <*T*>, *n*, *U*)

Two-temperature plasma

$$\xi_{\alpha\kappa}(T) = \xi_{\alpha}(T) + \xi_{\kappa}(T)$$

1. Emission measure

$$EM_{\alpha\kappa}(T) = EM_{\alpha}(T) + EM_{\kappa}(T)$$

2. Mean temperature

$$T_{\alpha\kappa} = \frac{EM_{\alpha}T_{\alpha} + EM_{\kappa}T_{\kappa}}{EM_{\alpha} + EM_{\kappa}}$$

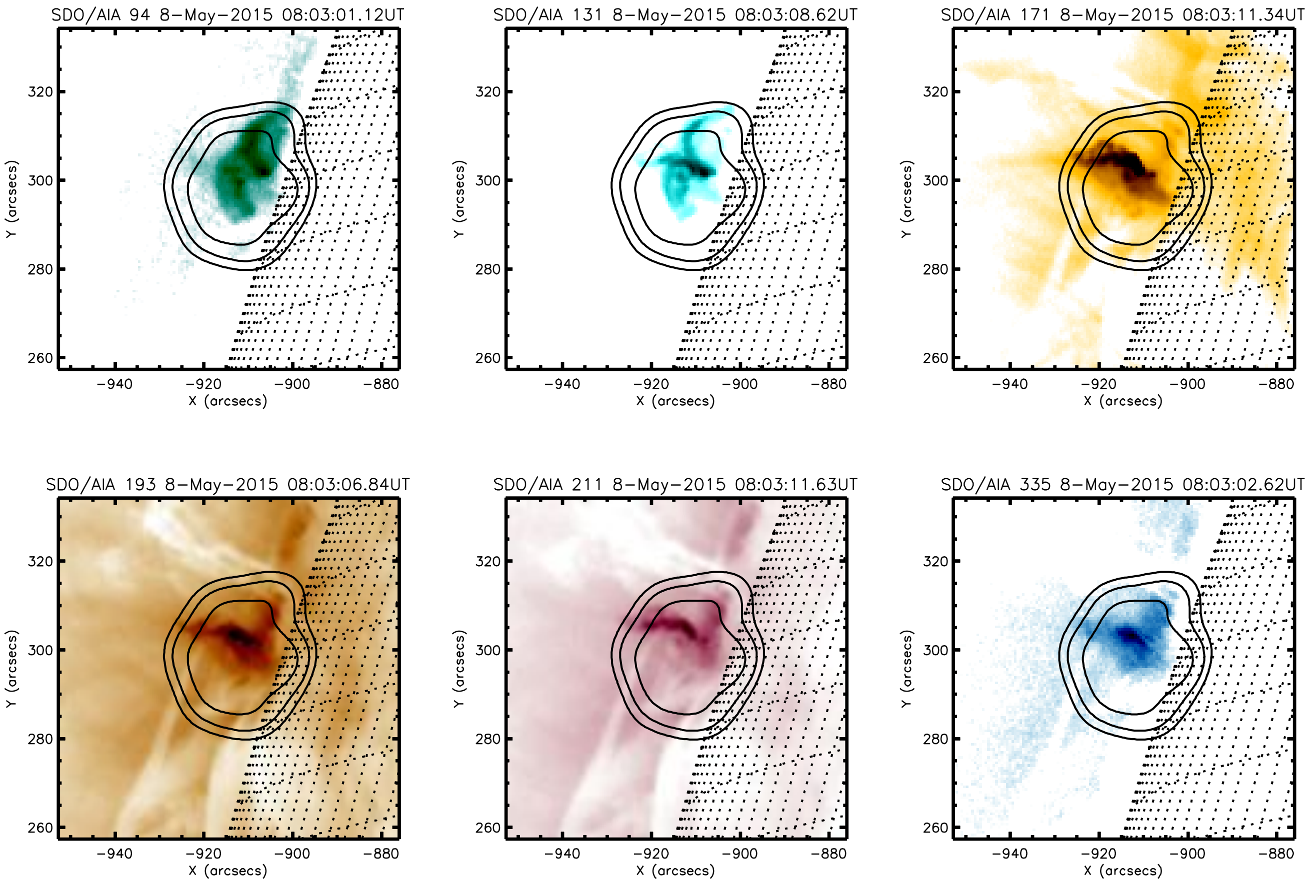
3. Electron number density

$$n_{\alpha\kappa} = \sqrt{\frac{EM_{\alpha\kappa}}{V}}$$

3. Total energy density

$$U_{\alpha\kappa} = \frac{3}{2} n_{\alpha\kappa} k_B T_{\alpha\kappa}$$

Flare 8-May-2015 (GOES class C1.5)
AIA data



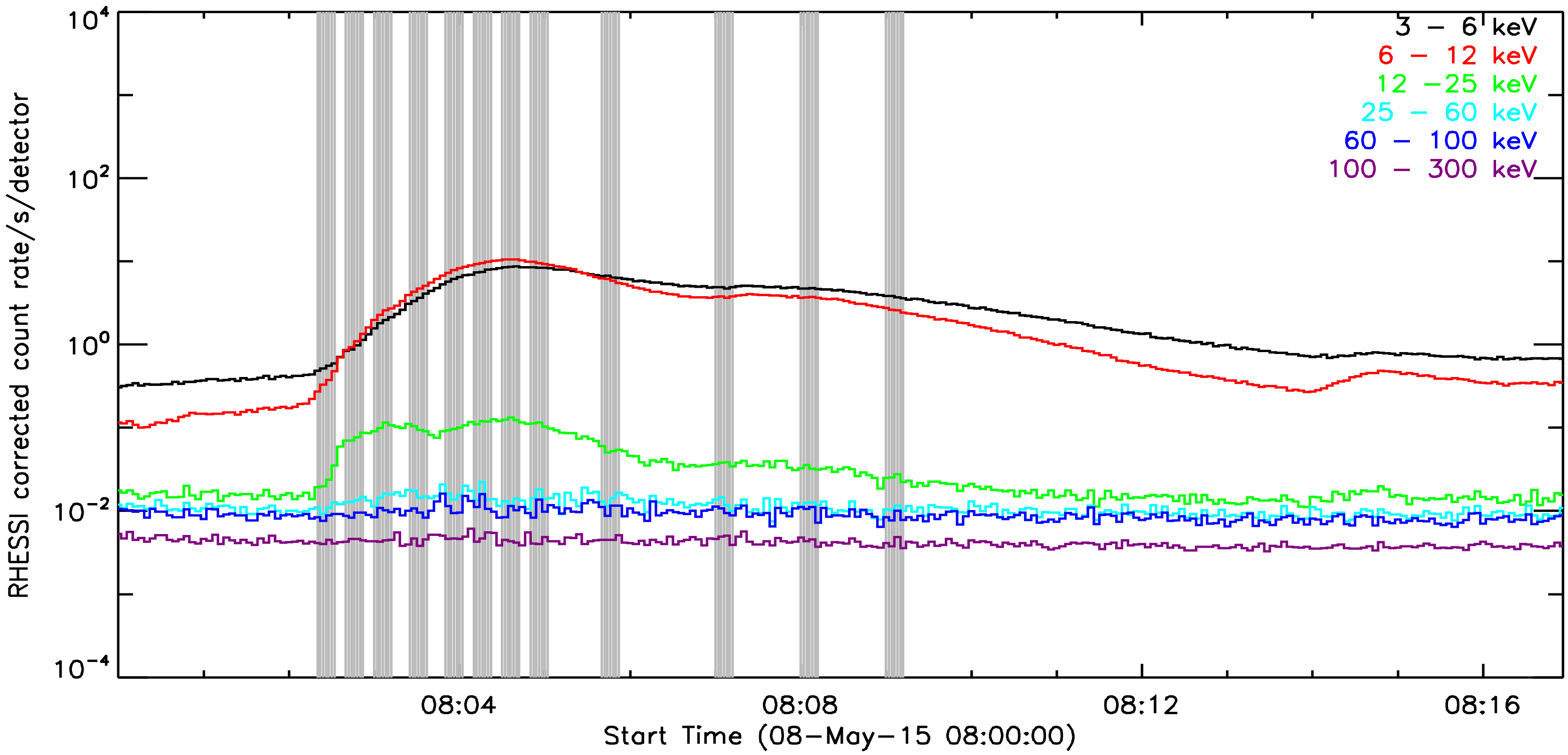
AIA image overlaid with RHESSI contours (black: 20, 30, 50% in 6-10 keV CLEAN image).

Assumptions:

- the same emitting plasma is observed in all wavelengths

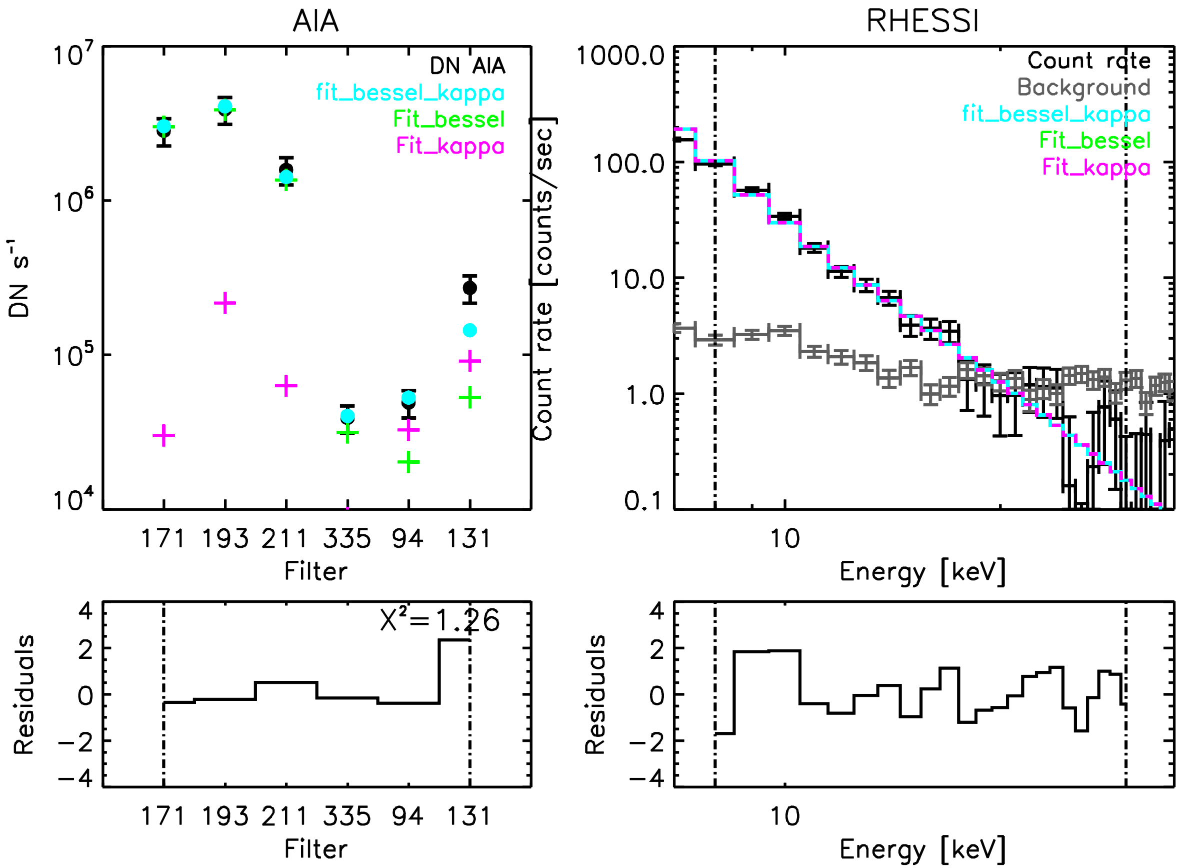
RHESSI data

GOES class C1.5:
start at 8:00:40 UT; end at 8:13:44 UT; peak at 8:04:30 UT
RHESSI attenuator: A0



Flare 8-May-2015 (GOES class C1.5)
AIA + RHESSI data

Models: multi-thermal “alpha” function + multi-thermal “kappa” function



Parameters of the fit

For α-DEM function:

EM = 4.6×10^{46} cm^{-3}

T_{max} = 0.18 keV (2.1 MK)

α= 4.7

For κ-DEM function:

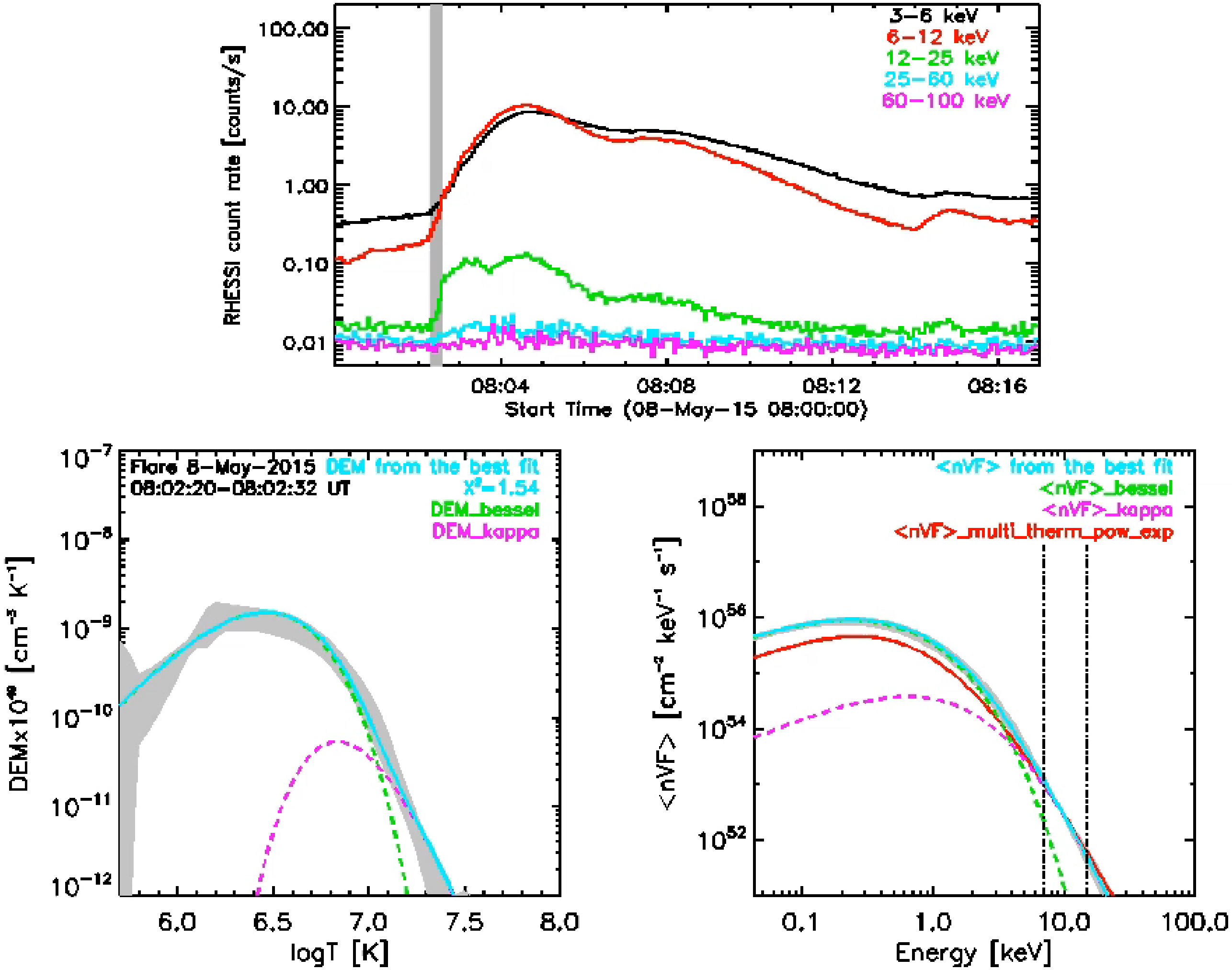
EM = 5.3×10^{46} cm^{-3}

T_{max} = 0.47 keV (5.45 MK)

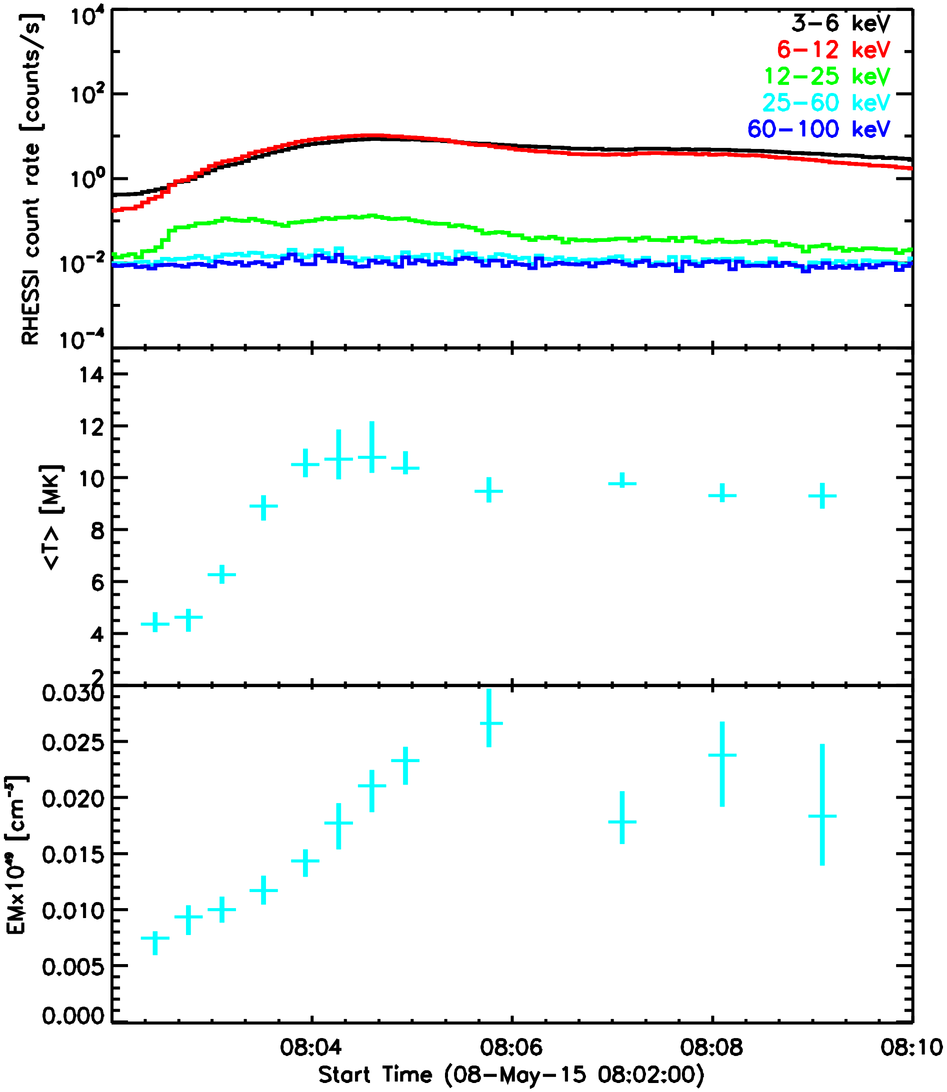
κ= 4.2

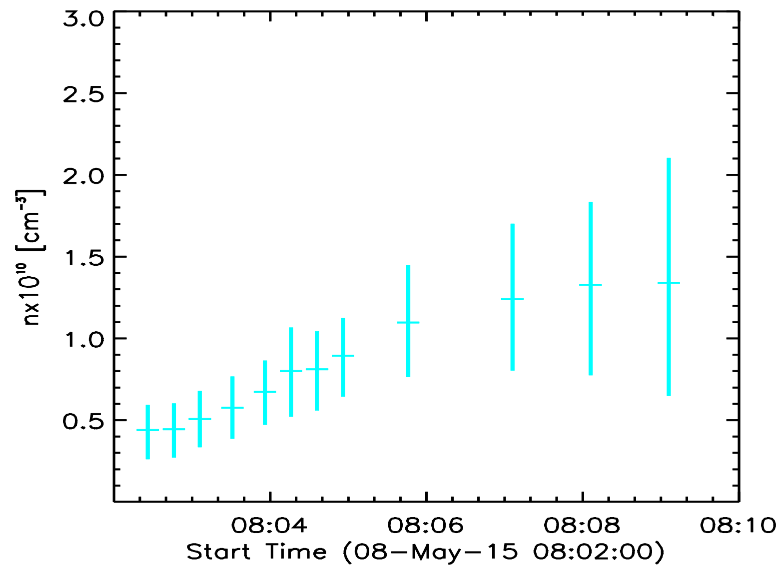
Simultaneous fit (blue) of AIA (left panel) and RHESSI (right panel) data with multi-thermal α-DEM function (green) and multi-thermal κ-DEM function (red).

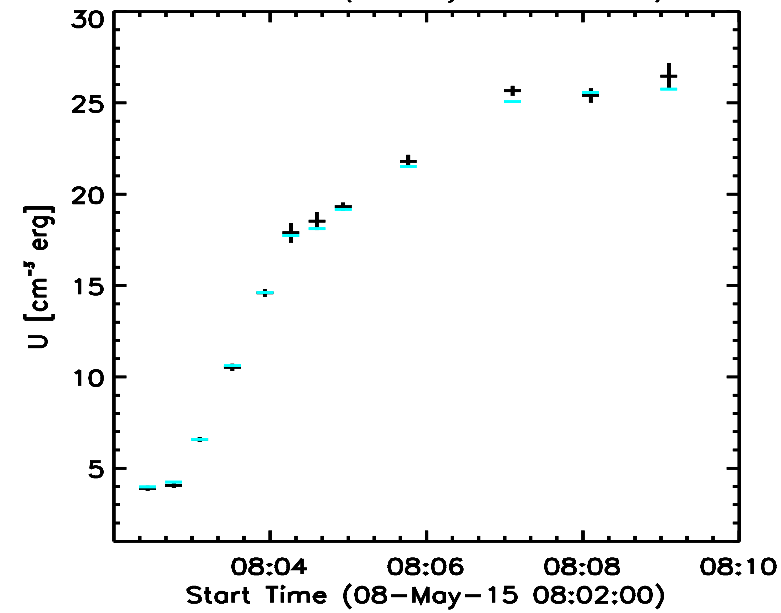
Temporal evolution of DEM and <nVF>



Parameters from joint AIA and RHESSI fits







"The latter emissions result from energy release in a loop with a higher density and temperature is a result of the initial energy release" (Dennis&Zarro, 1993)

Conclusions

1. Combination of the two DEM functions, which are related to the two components, are observed during all time intervals. The results are consistent with the previous studies by Schmelz, 1993; McTiernan et al.,1999; Kepa et al.,2008; Battaglia et al.,2015, where for solar flares two-component DEM distributions have been found.
2. For the first time the analytical representation of the two-temperature plasma with its $DEM_{\alpha\kappa}$, $\langle nVF \rangle_{\alpha\kappa}$, plasma parameters ($EM_{\alpha\kappa}$, $T_{\alpha\kappa}$, $n_{\alpha\kappa}$, $U_{\alpha\kappa}$) was presented and applied to Flare 8-May-2015.
3. The mean temperature $T_{\alpha\kappa}$ coincides with the temporal evolution of X-ray, while $EM_{\alpha\kappa}$ is ~2 minutes delayed (Neupert effect), and the electron number density and the total energy density gradually increase.

Thank you!