Fachhochschule
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RHESSI and EUV observations as diagnostic of accelerated electrons and atmospheric response in solar flares

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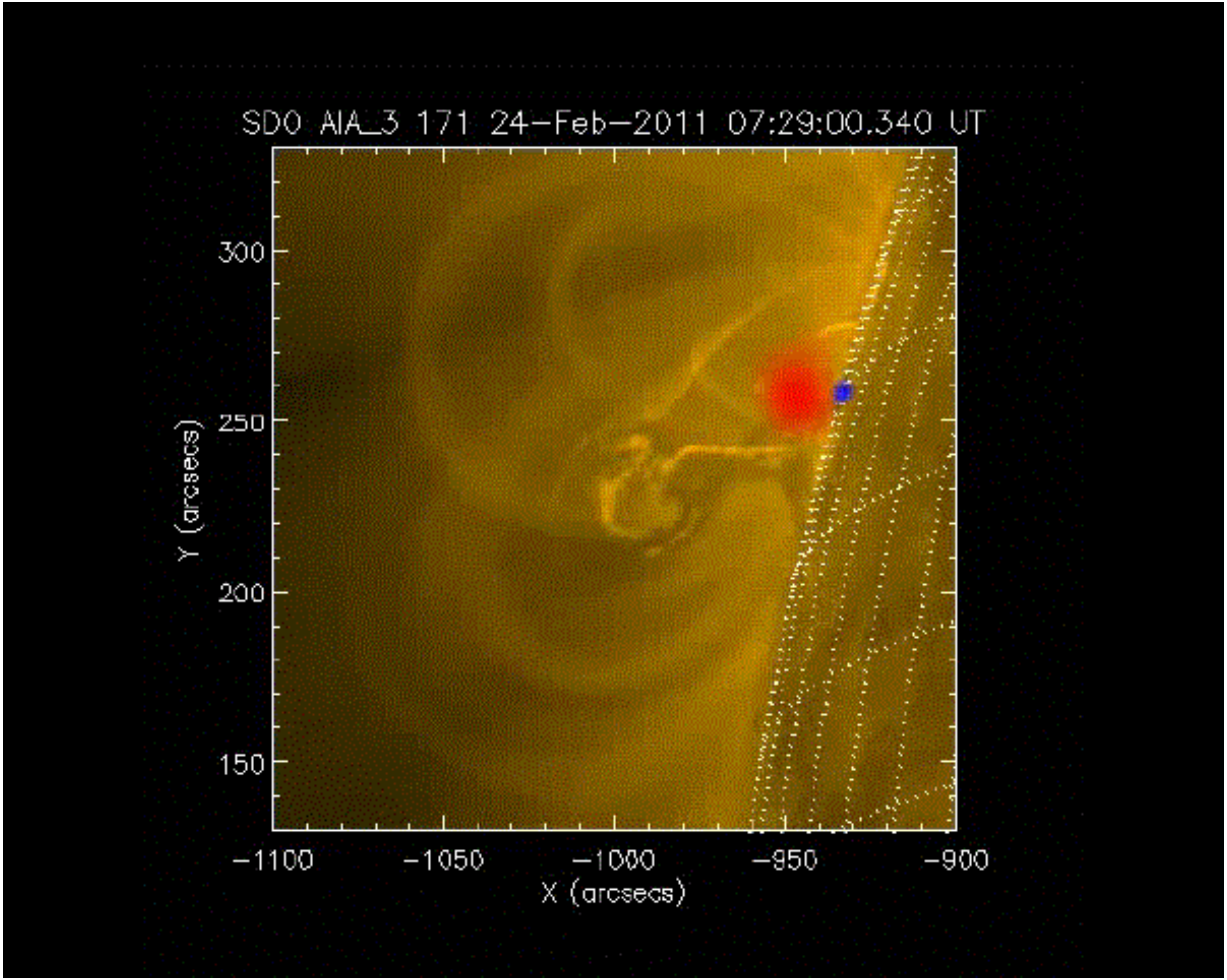
SDO AIA_3 171 24-Feb-2011 07:29:00.340 UT
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Overview

1. Some open questions in solar flare physics
2. X-ray and EUV emission in the standard solar flare model
3. Diagnostic of flaring processes at EUV and X-ray wavelengths
   3.1 Differential emission measures
   3.2 EUV line spectroscopy
4. Selected recent examples
   4.1 Location and drivers of chromospheric evaporation
   4.2 Electron distribution functions
   4.3 Acceleration region diagnostic
5. Summary and Conclusions

1. Some open question in solar flare physics

Particle acceleration and transport

Where and how are electrons accelerated?

How much energy goes into accelerated electrons?

How are electrons transported close to the Sun and away from the Sun?

Atmospheric response

What is the chromospheric response to electron beam heating?

What is the total flare energy?

Where and how is white light emission generated?

How is chromospheric evaporation triggered and how does it evolve?

1. Some open question in solar flare physics

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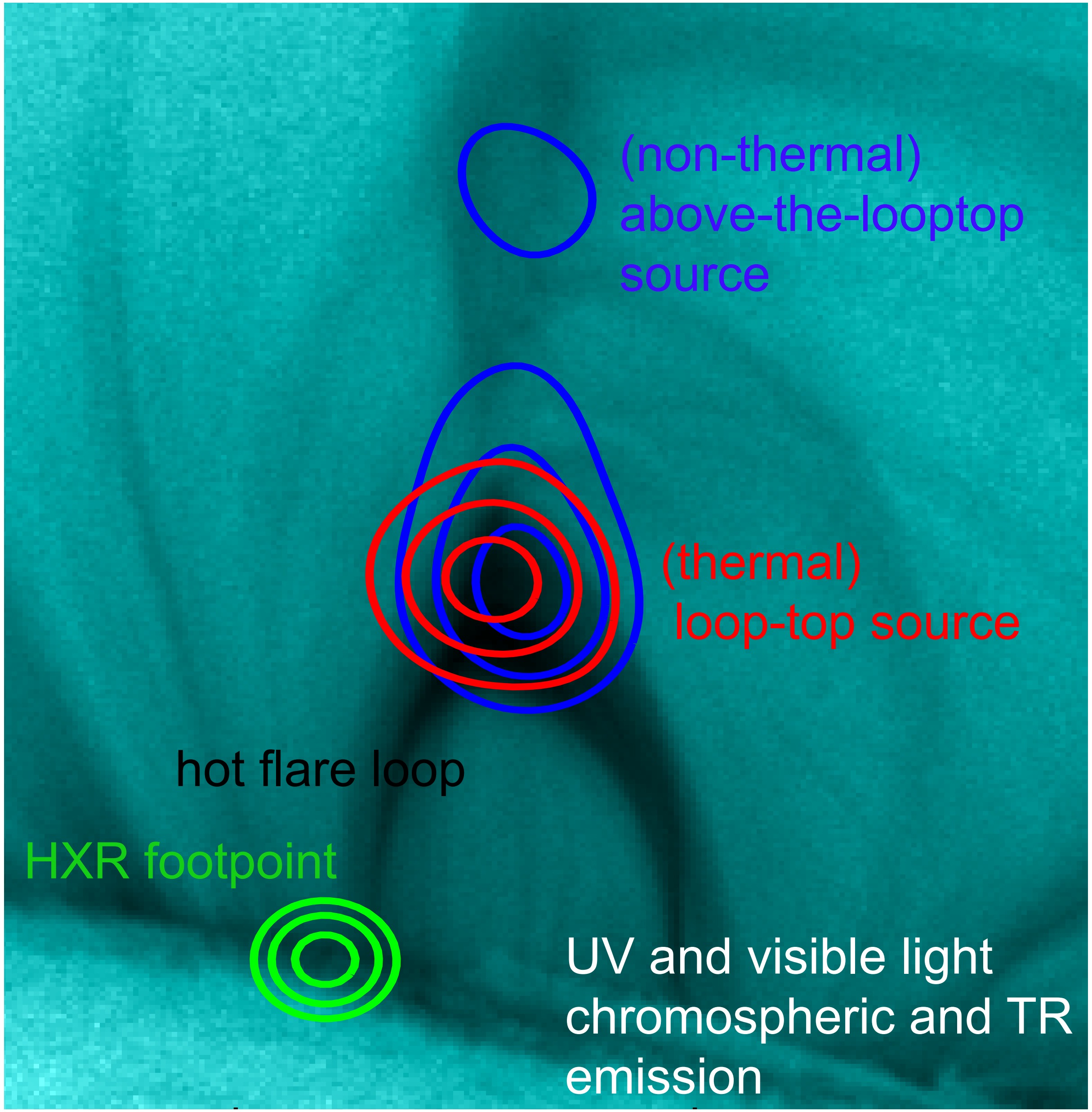
2. X-ray and EUV emission in the standard solar flare model

1) Release of magnetic energy by magnetic reconnection

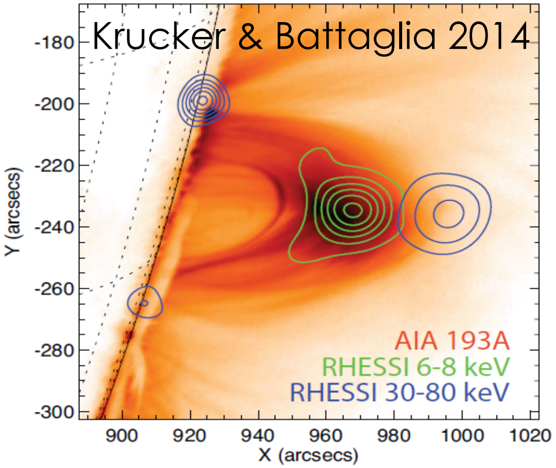
2) Particle acceleration and heating

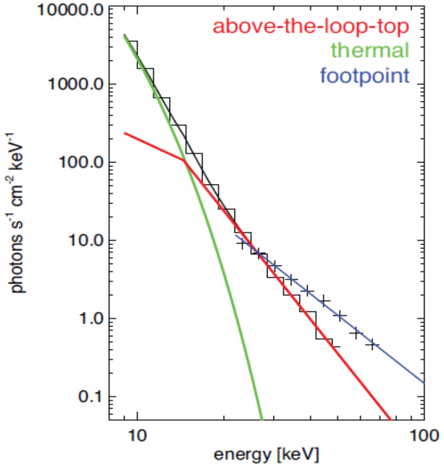
3) Accelerated electrons produce HXR emission and heat chromosphere

4) “Chromospheric evaporation”, hot plasma fills coronal loop



3. Diagnostic of flaring processes at X-ray and EUV wavelengths



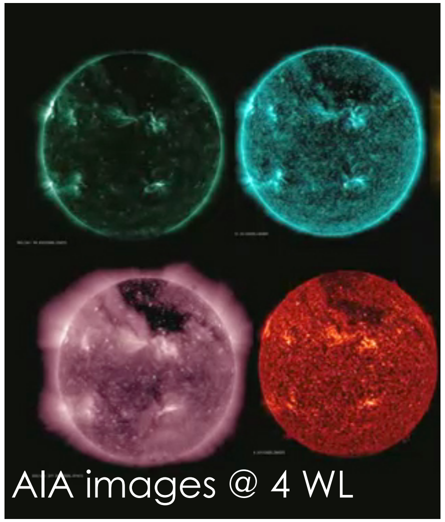


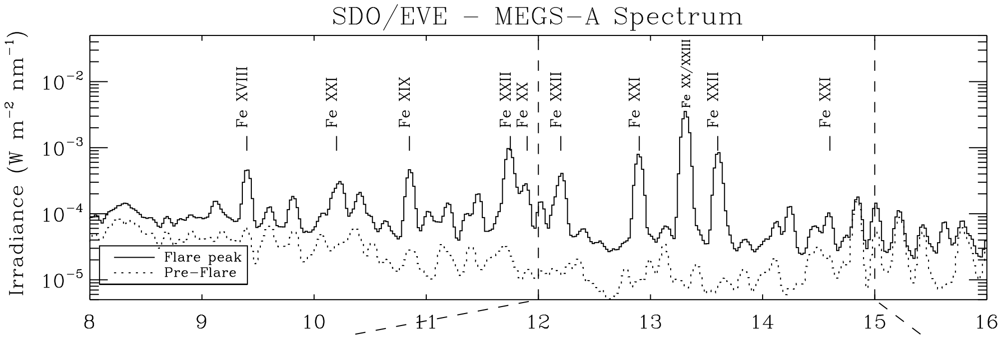
RHESSI imaging spectroscopy:

- Location of energy deposition
- Acceleration region
- Hot flare loop
- Electron flux distributions

EUV:

- Different wavelengths for different temperatures
- Multi-thermal diagnostic of whole atmosphere
- Flows (evaporation, coronal rain, ….)

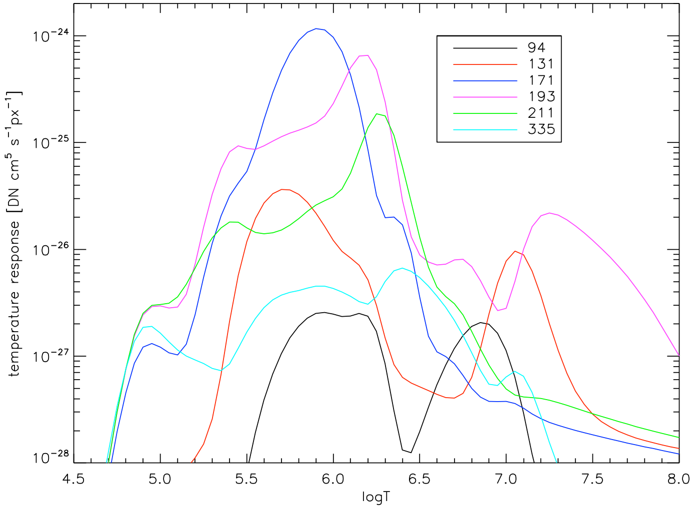




Milligan et al. 2012

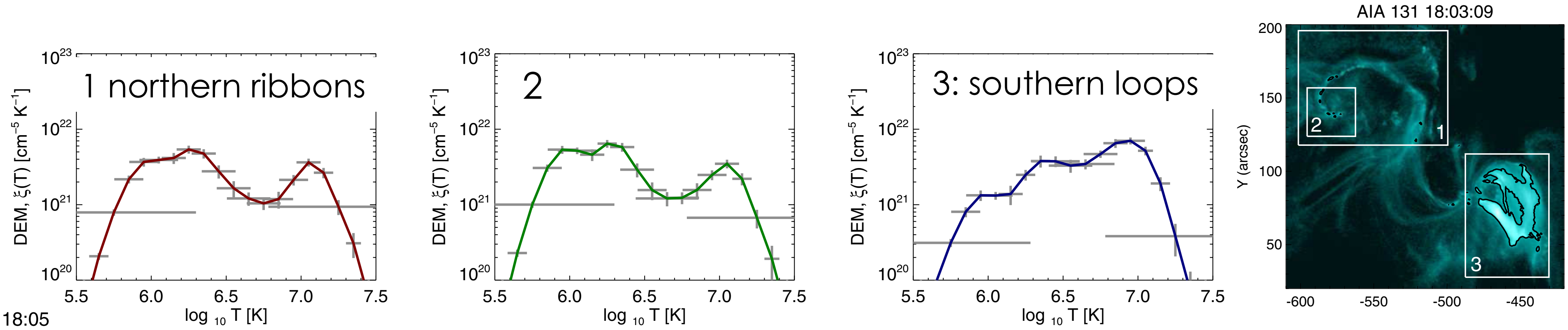
3.1 EUV diagnostic of plasma heating and energetic electrons using differential emission measures

Differential emission measure along line of sight: $$\xi(T) = n^2 \frac{dl}{dT} \ (\mathrm{cm}^{-5}\,\mathrm{K}^{-1}),$$



AIA temperature response

Fletcher et al. 2013



Inferring DEMs from observations

Challenge:

$$g_i = \int_T K_i(T)\xi(T)\mathrm{d}T + \delta g_i$$

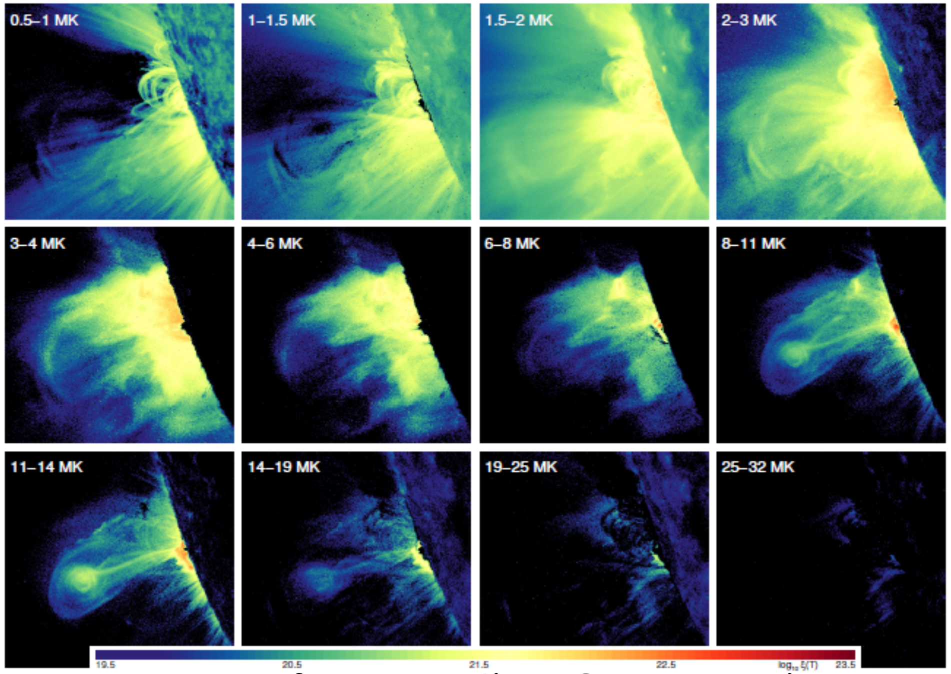
Error of observed intensity

Observed intensity

Temperature response

DEM

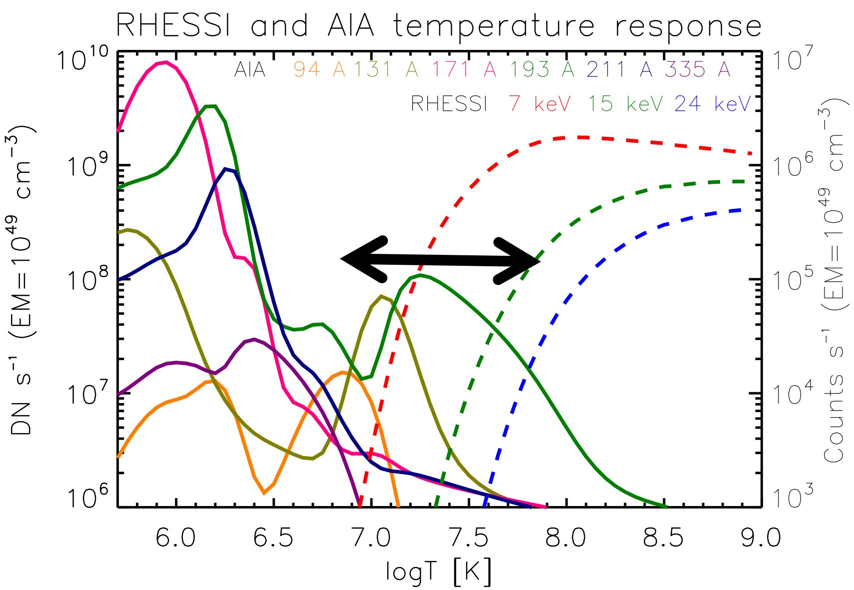
- Several methods exist
  - Regularized inversion (Hannah & Kontar 2012)
  - Forward fitting model DEM (e.g. Aschwanden & Boerner 2011, Ryan et al. 2014)
  - Monte-Carlo Markov Chain (e.g. Testa et a. 2012)
  - ……



DEM-maps of an erupting CME seen in SDO/AIA (Hannah & Kontar 2013)

- Aschwanden 2015: Benchmark test of 11 methods for active regions using response functions for SDO/AIA, SDO/EVE, RHESSI, and GOES

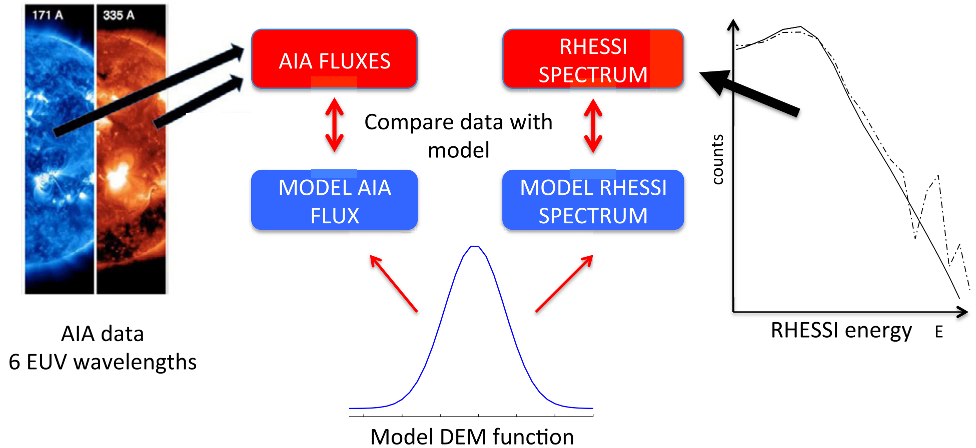
DEMs from simultaneous X-ray and EUV observations



AIA is only sensitive to temperatures ~< 16 MK
RHESSI is sensitive to temperatures ~> 8 MK

Different approaches for simultaneous data exploitation exist

Inglis & Christe 2014



Caspi et al. 2014

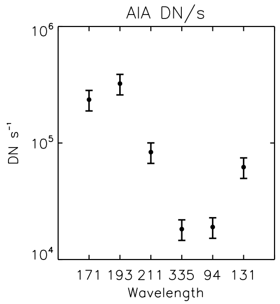
Simultaneous fits of *full Sun* EVE and RHESSI spectra with multiple Gaussian DEMs

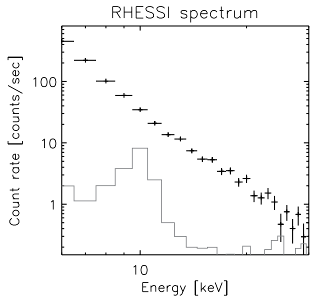
Gaussian and uniform DEM model (Epstein function)

Simultaneous forward fits to RHESSI and AIA data

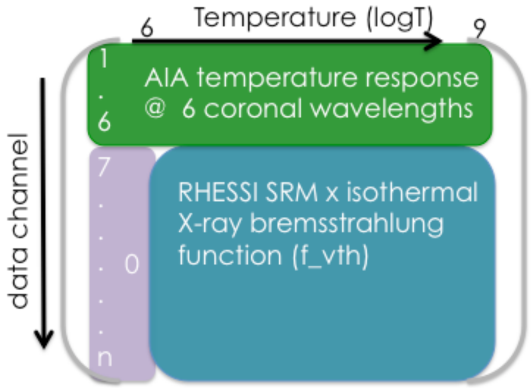
Motorina & Kontar 2015:

- Treat RHESSI and AIA data as one dataset



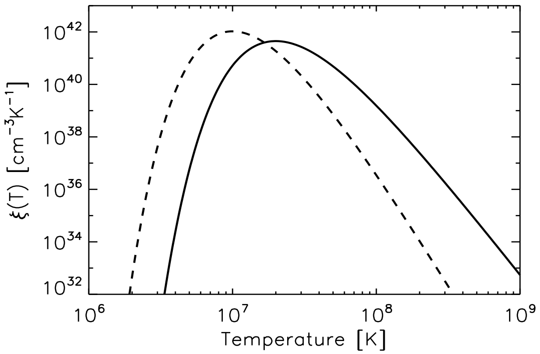


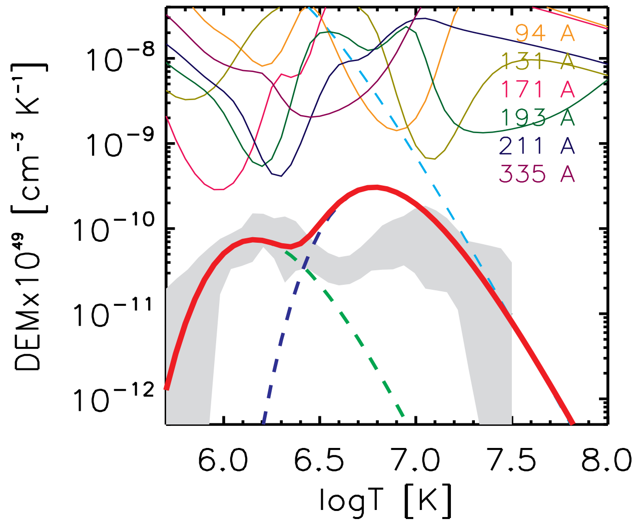
- Generate one temperature response matrix



- Forward-fit model DEM

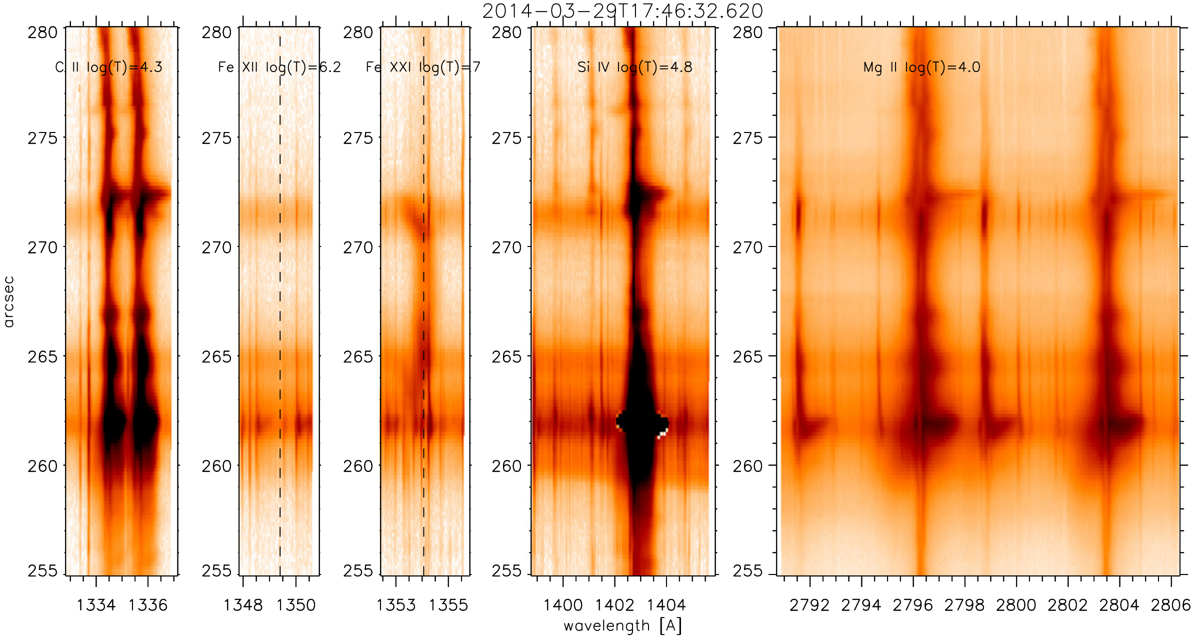
$$\xi(T) \propto T^{-(\kappa+0.5)} \exp\left(-\frac{T_\kappa}{T}(\kappa - 1.5)\right)$$

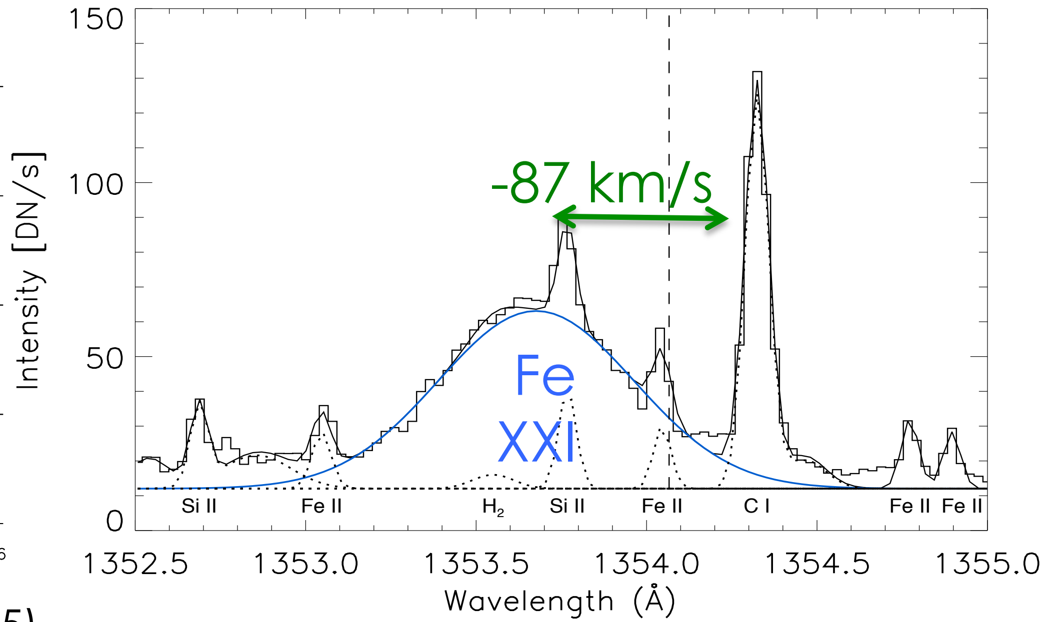




This DEM has a physical meaning: It represents a kappa-distribution!

Line spectroscopy





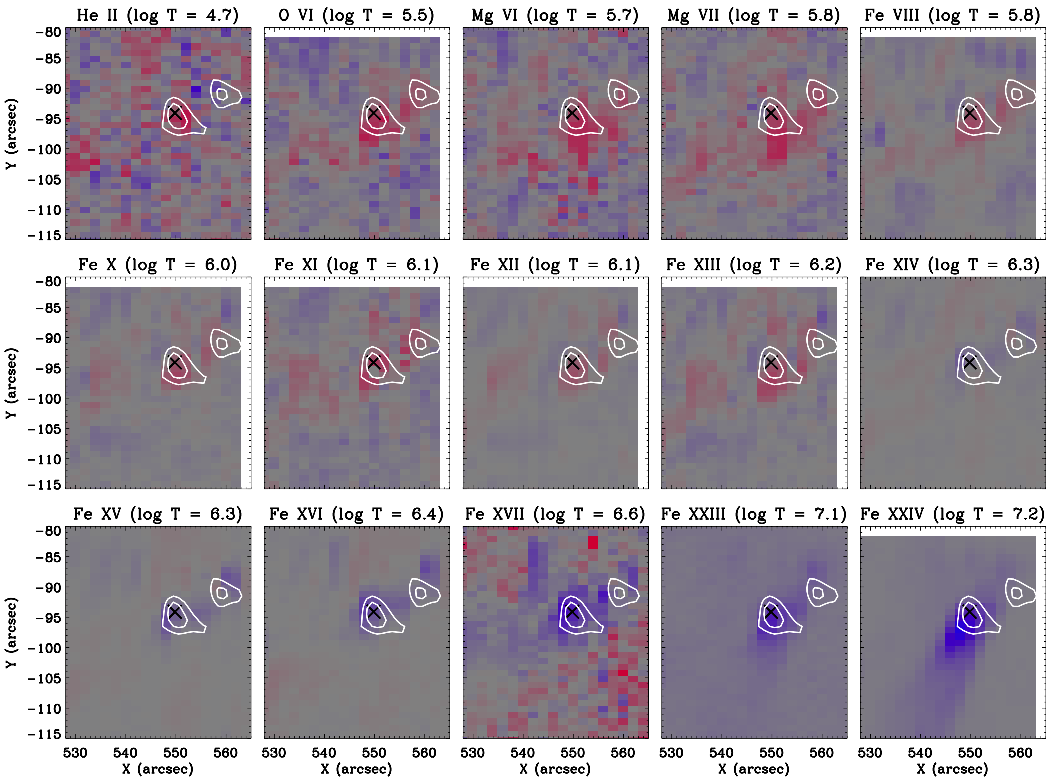
Example of an IRIS flare spectrum (Battaglia et al. 2015)

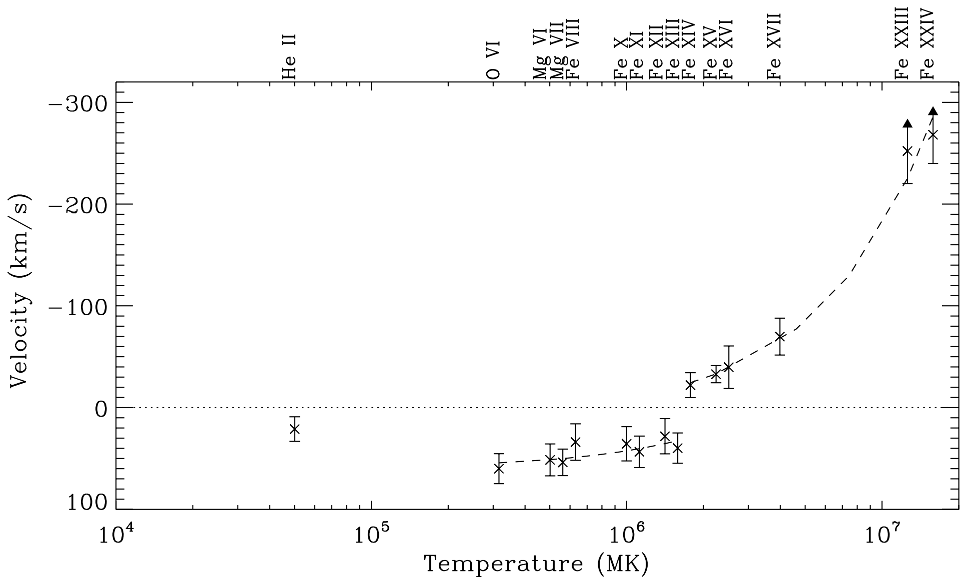
Different lines are formed under different conditions (temperature, density)
→ diagnostic of photosphere up to corona
→ tracing of flows (chromospheric evaporation, coronal rain, filament eruptions, ...)

4 Selected recent examples

4.1: Location and drivers of chromospheric evaporation

Milligan et al. 2009: Velocities of evaporating plasma observed with Hinode/EIS

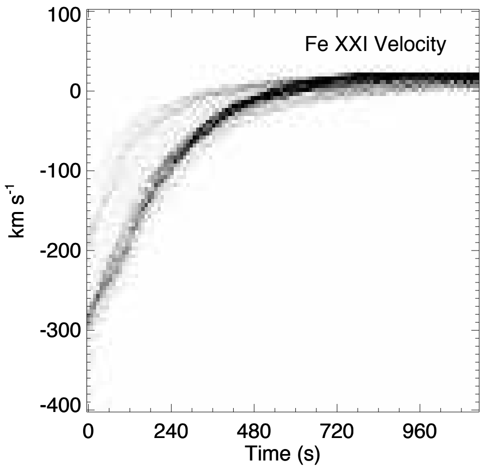


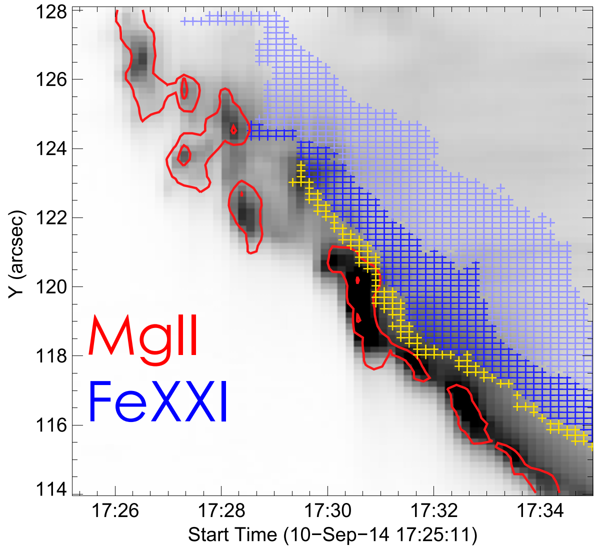


Temporal and spatial correlation of HXR emission with upflows and downflows
→ explosive evaporation driven by non-thermal electron beam

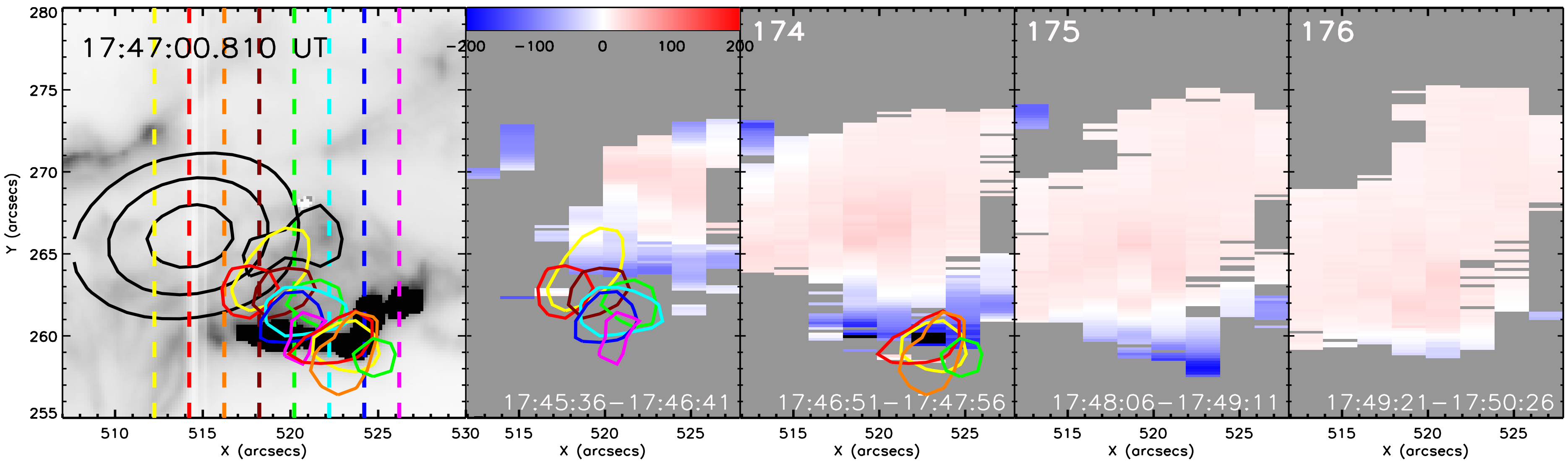
Graham & Cauzzi 2015: high resolution observations of evaporation and condensation with IRIS

- very high evaporation velocities (up to 300 km/s)
- time-lag between condensations and evaporation
- Same behavior for each pixel → elementary flare kernels





Battaglia et al. 2015: spatial and temporal evolution of chromospheric evaporation with IRIS and RHESSI → sustained evaporation after impulsive phase due to thermal conduction



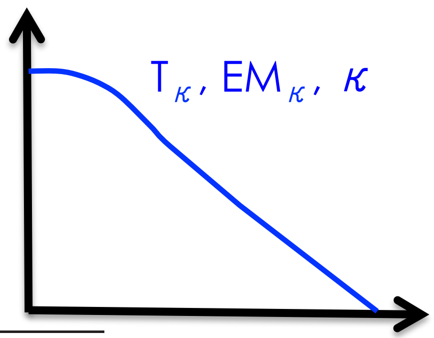
4.2: Electron distribution functions

DEM is directly related to mean electron flux spectrum **<nVF>**

$$\langle nVF\rangle = \frac{2^{3/2}E}{(\pi m_e)^{1/2}}\int_0^\infty \frac{\xi(T)}{(k_B T)^{3/2}}\exp(-E/k_B T)\,dT.$$

Battaglia et al. 2015: Electron distribution function from simultaneous fits

Model DEM $\xi(T) \propto T^{-(\kappa+0.5)}\exp\left(-\frac{T_\kappa}{T}(\kappa-1.5)\right)$



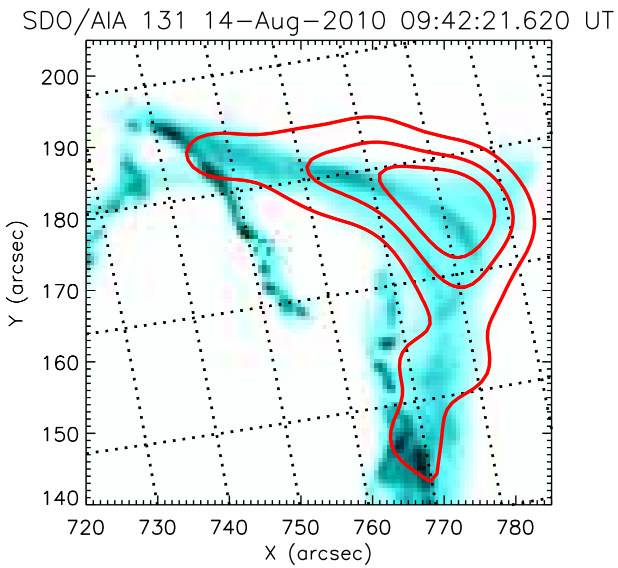
represents the kappa-distribution:

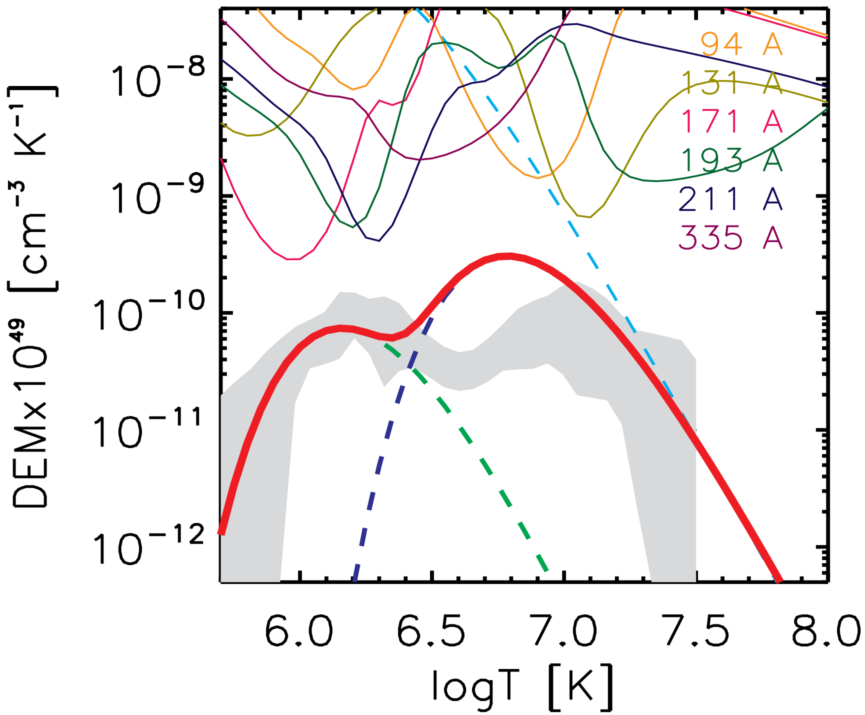
$$\langle nVF(E)\rangle = n^2 V \frac{2^{3/2}}{(\pi m_e)^{1/2}(k_B T_\kappa)^{1/2}}\frac{\Gamma(\kappa+1)}{(\kappa-1.5)^{1.5}\Gamma(\kappa-1/2)}\frac{E/k_B T_\kappa}{(1+E/k_B T_\kappa(\kappa-1.5))^{\kappa+1}}$$

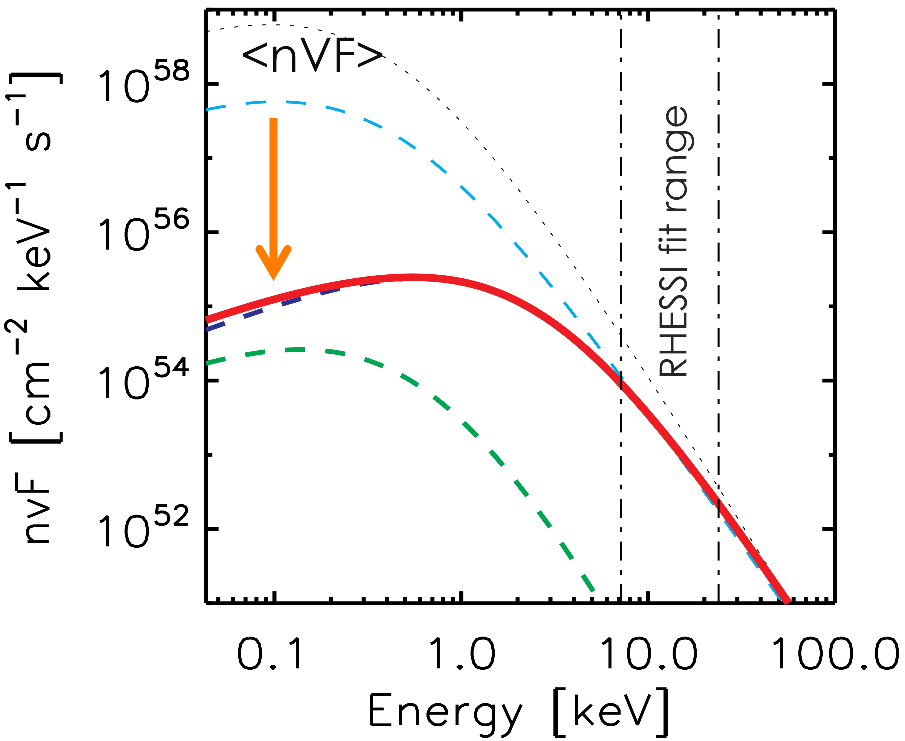
Advantages of kappa-distribution:

- Single analytic function to describe whole spectrum
- No cutoff needed
- Supported by stochastic acceleration models (e.g. Bian et al 2014)

Applied to RHESSI data by e.g. Kasparova & Karlicky 2009, Oka et. al. 2013/2015







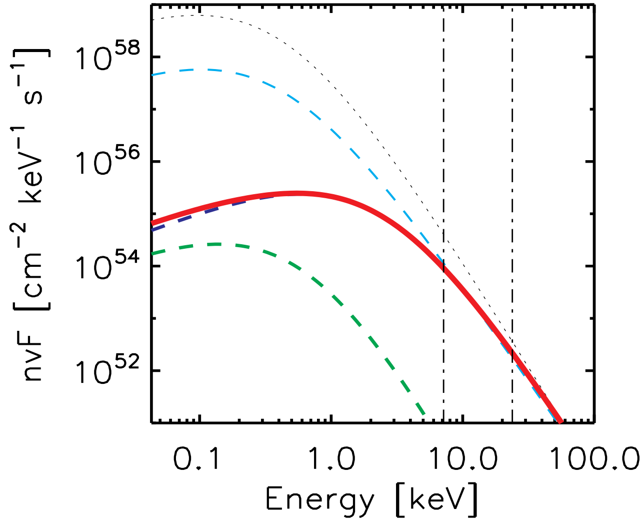
Comparison of mean electron flux spectrum from different fit methods

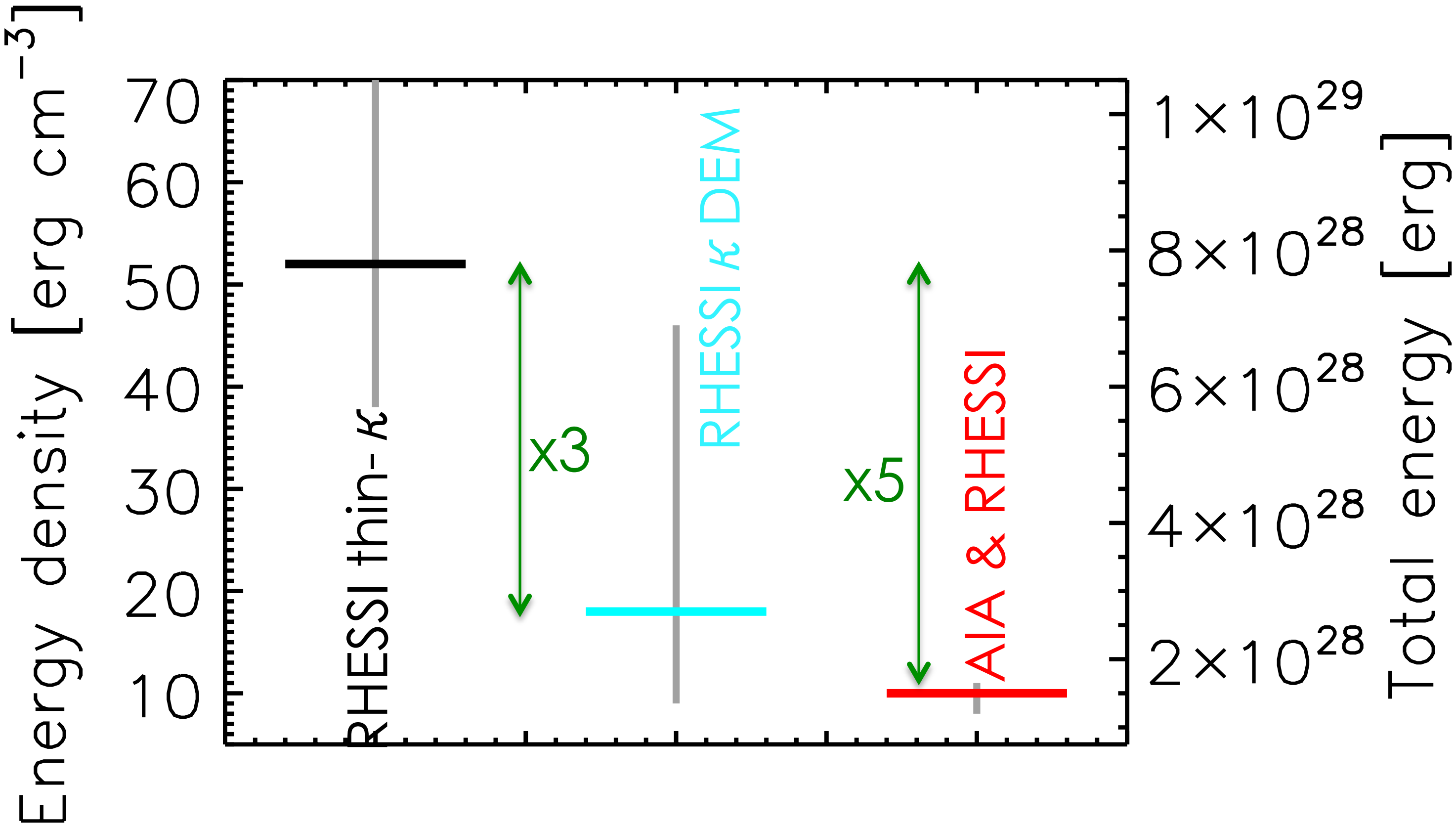
ξκ(T) on RHESSI data, only
ξκ(T)on RHESSI and AIA data combined (low and high T component)
AIA DEM from regularized inversion

Comparison of total energy

Total energy density $U_\kappa = \frac{3}{2} k_B n T_\kappa$

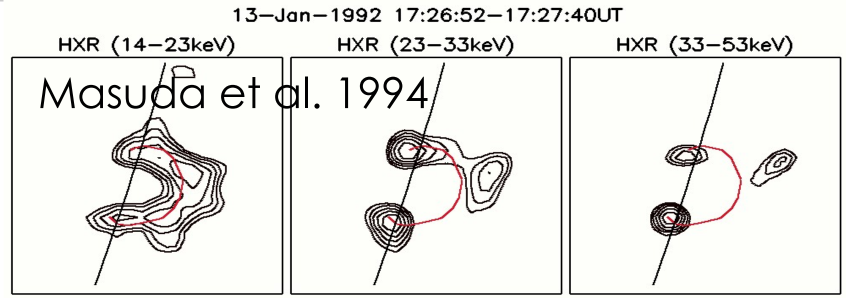
Total energy: $U_\kappa V$ where $V \approx 1.5\text{x}10^{27}$ cm^3



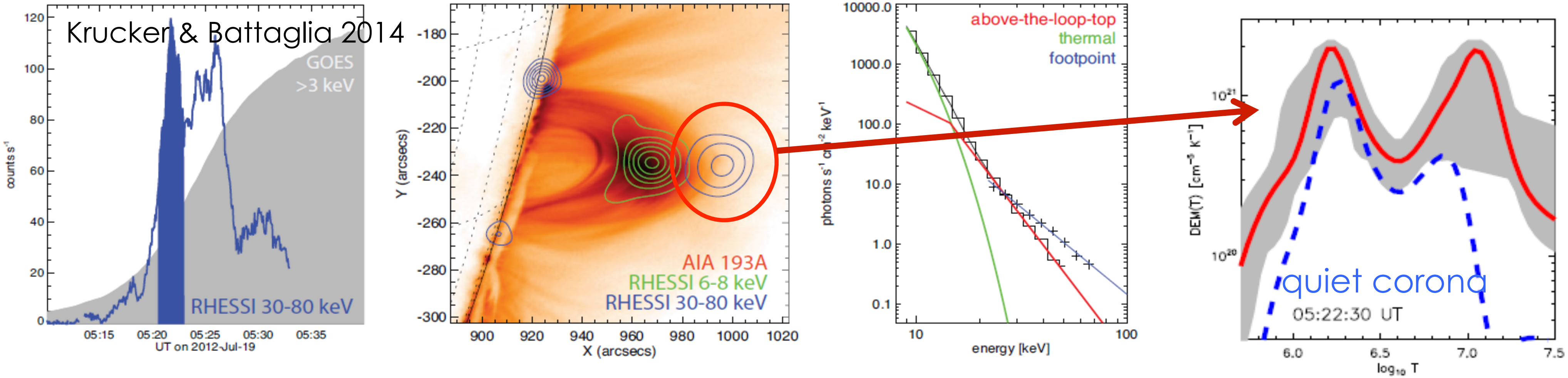


→ Without low-energy constraint, total energies derived from RHESSI data could be over-estimated by factor ~5

4.3 Acceleration region diagnostic



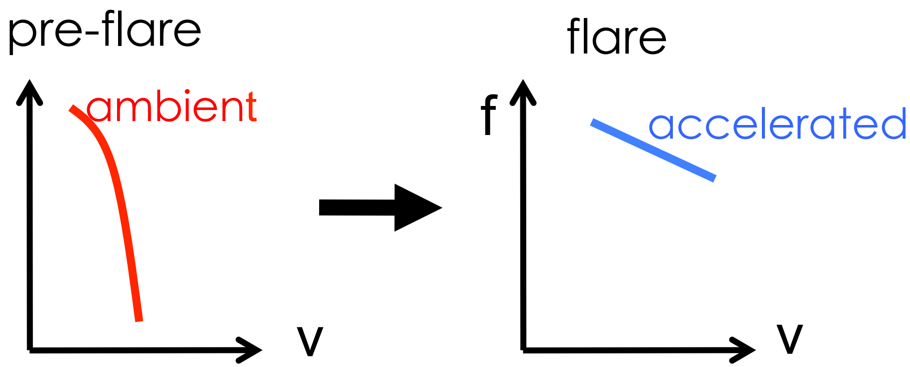
Krucker & Battaglia 2014: Bulk acceleration in above-the-looptop source



- RHESSI imaging spectroscopy to infer density of accelerated electrons: n_{nt}~10^9 cm^{-3}
- SDO/AIA differential emission measure analysis to determine ambient density n_0

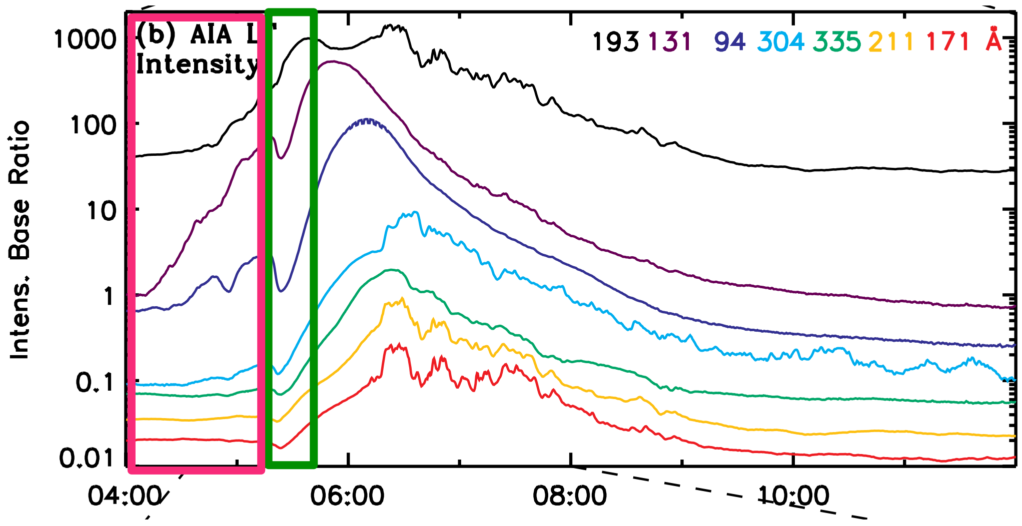
→ ratio n_{nt}/n_0 is close to 1

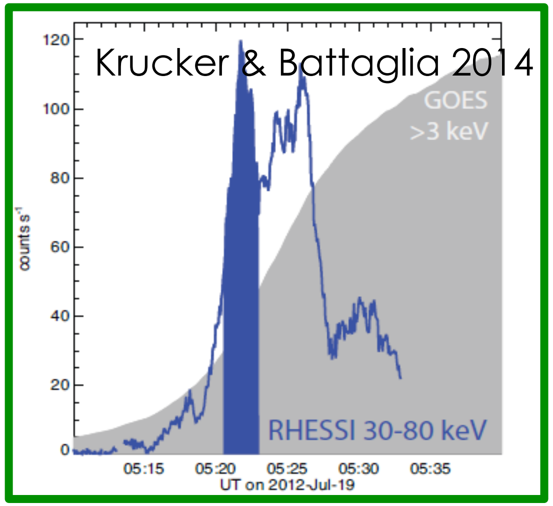
Interpretation: Entire plasma is accelerated (non-thermal) in bulk energization process
Above the loop-top-source is acceleration region



Liu et al. 2013: Particle acceleration in magnetic reconnection outflow regions

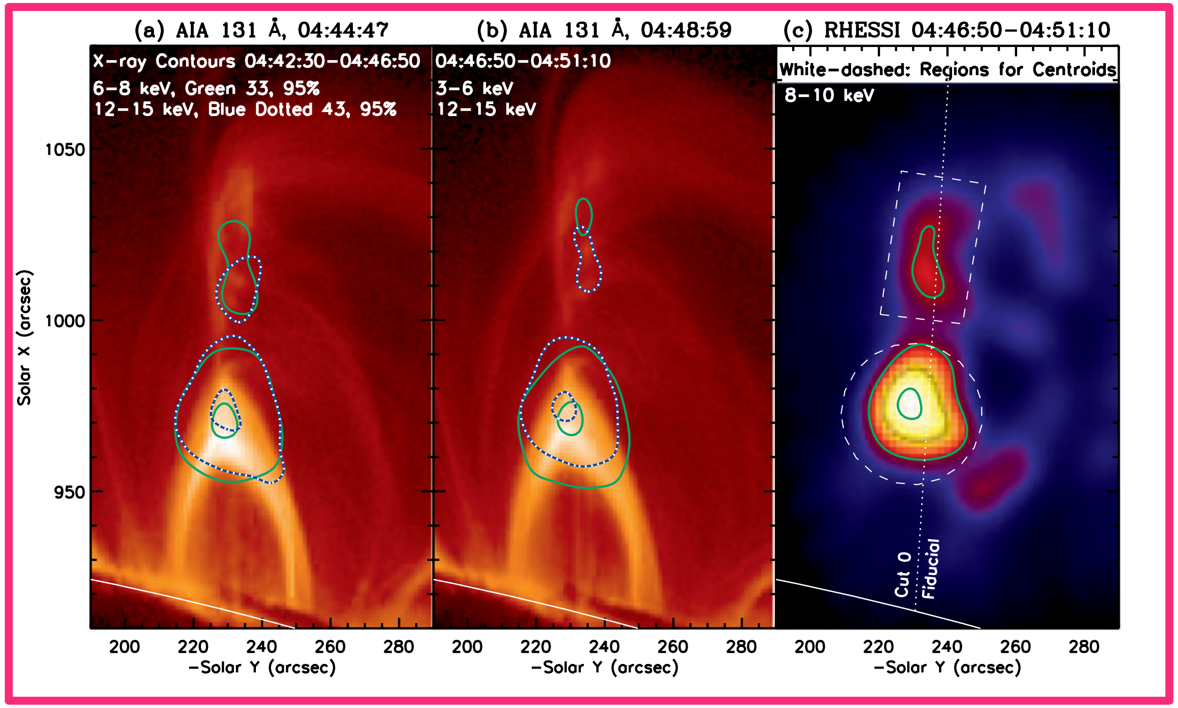
Same event:
19 July 2012

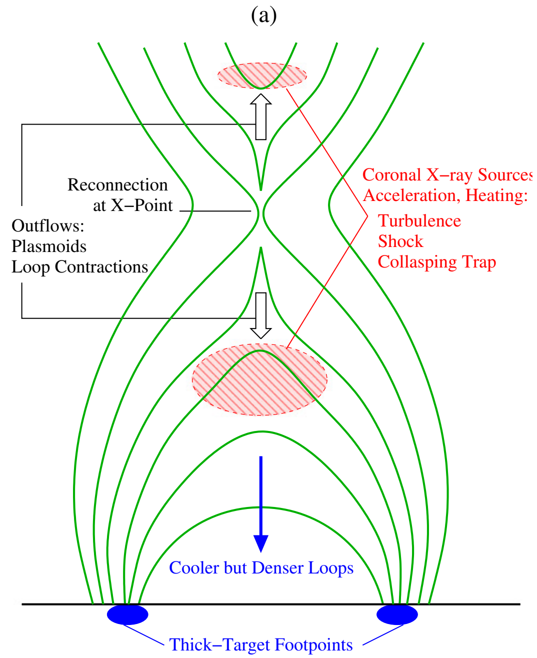




pre-impulsive phase

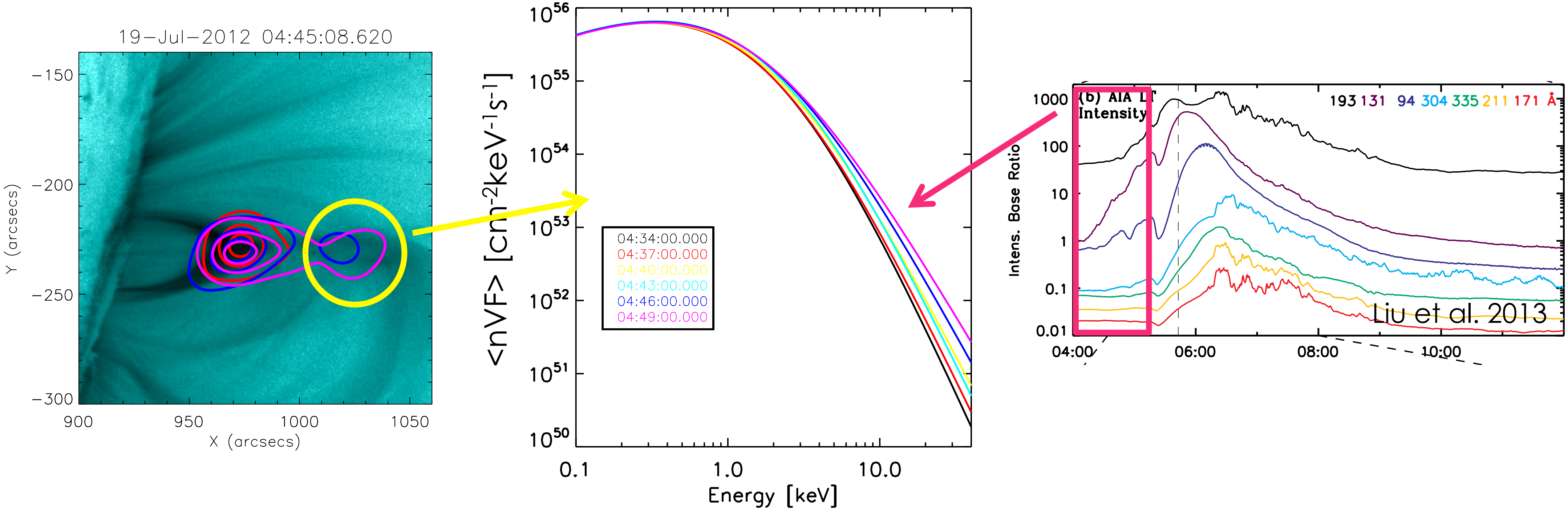
Main HXR peak





Sneak preview: Quantitative analysis of electron acceleration in the outflow region during the pre-impulsive phase

Fitting a kappa-distribution to RHESSI and AIA data simultaneously we find a hardening spectrum at ~ constant temperature → acceleration



Summary and Conclusions

- Combining RHESSI observations with EUV measurements from instruments such as SDO/AIA, SDO/EVE, IRIS, ……. provides unprecedented diagnostic of accelerated electrons and chromospheric response to flare energy input
- Many different methods for combining those rich datasets exist

→ Follow the presentations in the respective working groups and talk to the relevant people