High temperature plasma as diagnostics of coronal heating

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Progress on EUV & X-ray spectroscopy and imaging

Wrocław 20-22 XI 2012

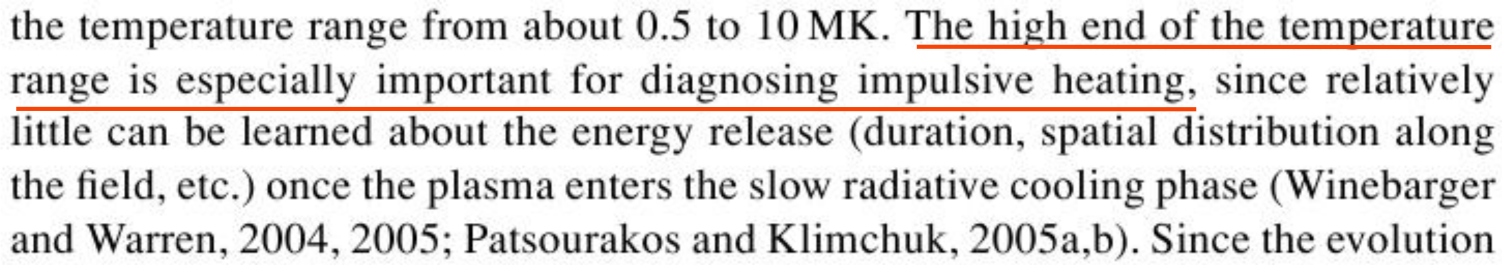
Outline

- Overview:
  - DEM diagnostics
  - Time analysis: light curves
  - Coronal fuzziness
- The role of SDO/AIA
- The role of SphinX

OVERVIEW

Hot plasma

- The importance: signature of impulsive heating (e.g. Klimchuk 2006)



the temperature range from about 0.5 to 10 MK. The high end of the temperature range is especially important for diagnosing impulsive heating, since relatively little can be learned about the energy release (duration, spatial distribution along the field, etc.) once the plasma enters the slow radiative cooling phase (Winebarger and Warren, 2004, 2005; Patsourakos and Klimchuk, 2005a,b). Since the evolution

- Hot loops may require temporarily T ~ 10 MK

- The problem: Difficult because expected at low EM and overwhelmed by lower T plasma, and of possible NEI effects (Reale & Orlando 2008, Bradshaw & Klimchuk 2011)

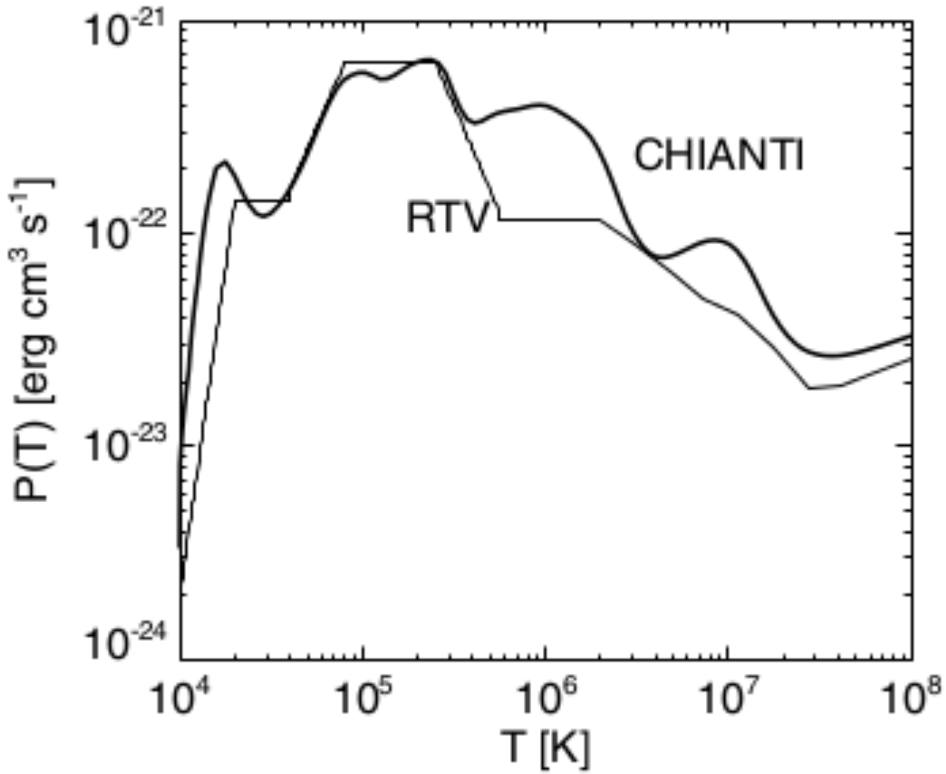
Measuring temperature in the corona

- Emission from optically thin plasma:

$$I = EM \;\; P(T)$$

$$EM = \int_V n^2 dV$$

$$P(T) = bT^\alpha$$



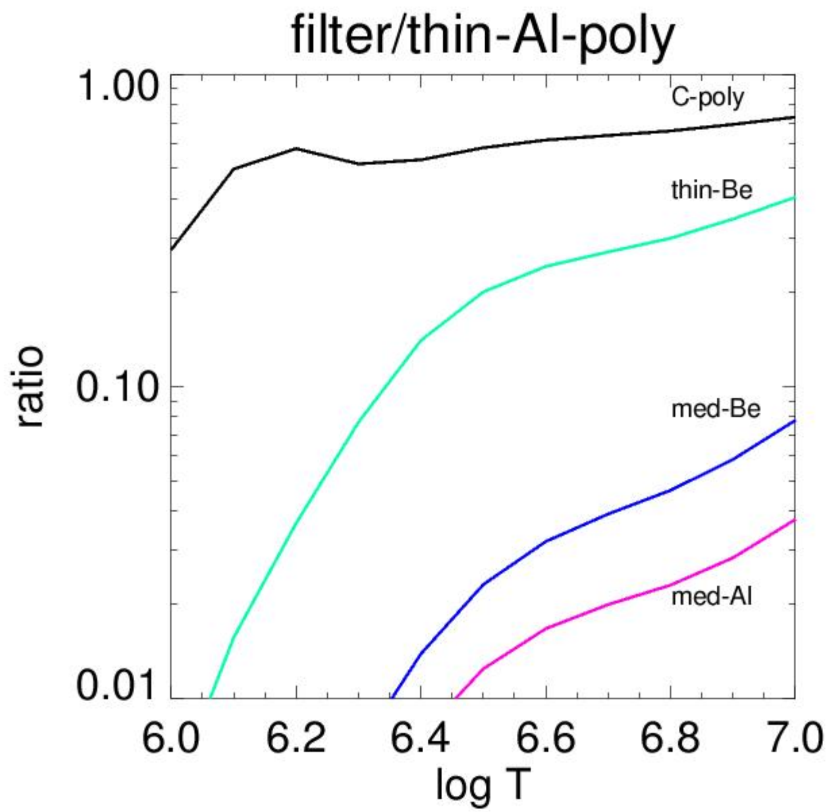
Measuring temperature: filter/line ratios

- For isothermal plasma ALOS, filter ratios provide T diagnostics (e.g. Vaiana et al. 1973)
  - Flux detected in j-th filter:

$$I_j = EM \times G_j(T)$$

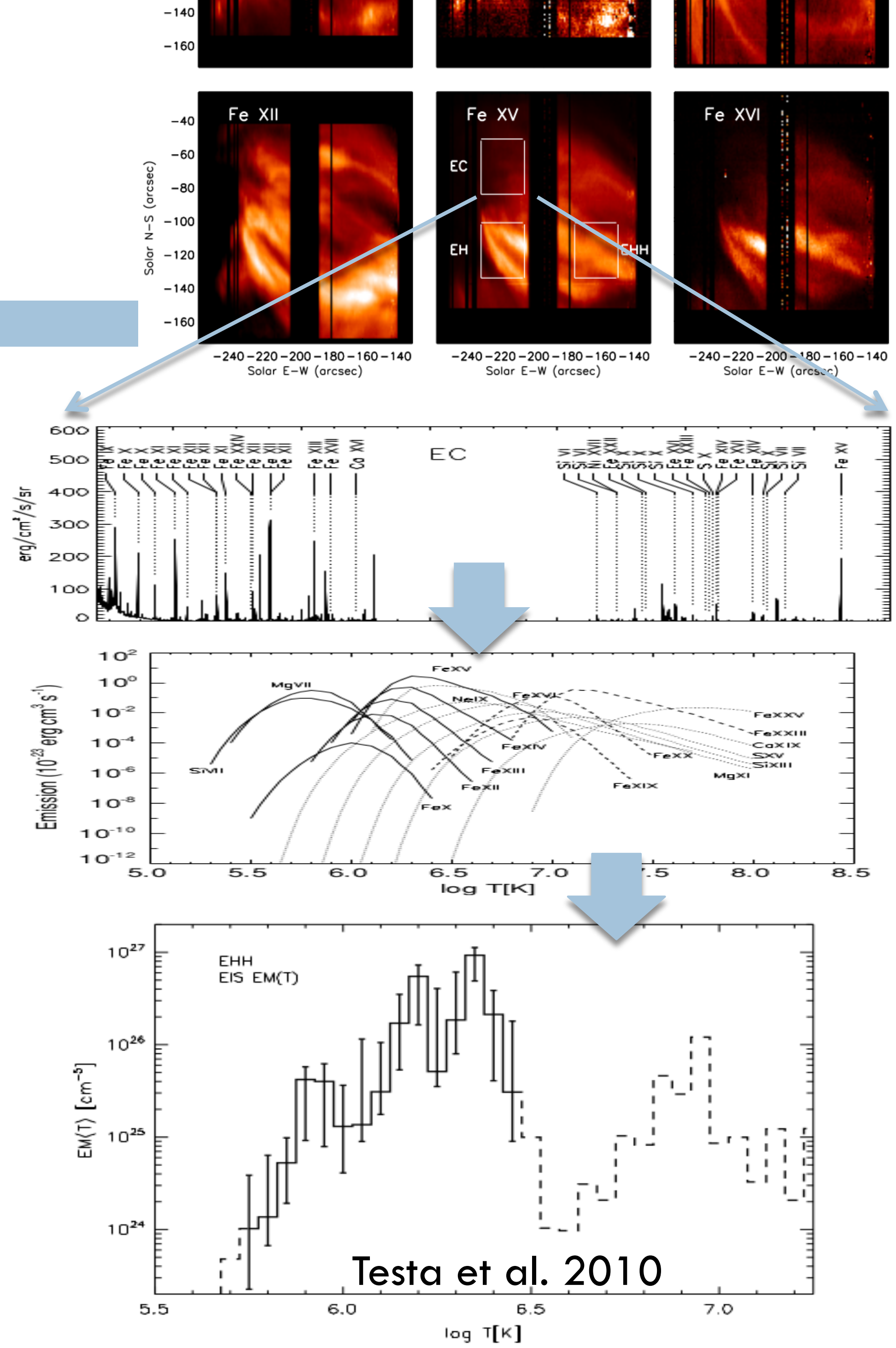
  - Filter ratio provides T (EM cancels out):

$$R_{ij} = \frac{I_i}{I_j} = \frac{G_i(T)}{G_j(T)}$$



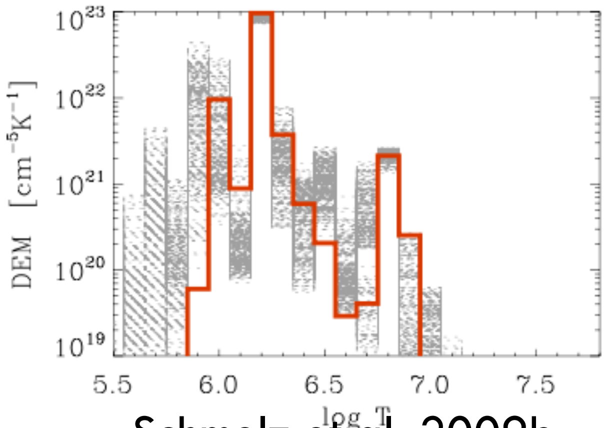
Measuring T: DEM reconstruction

- From multi-line or multi-band observations, we can recover multi-T structure
- Problems:
  - Method application
  - Background subtraction
  - Abundance issues

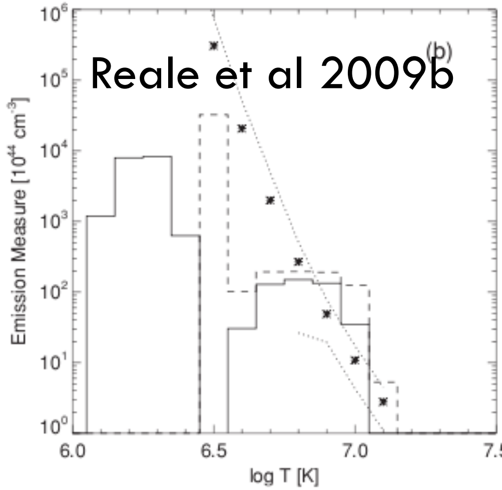


Hot plasma

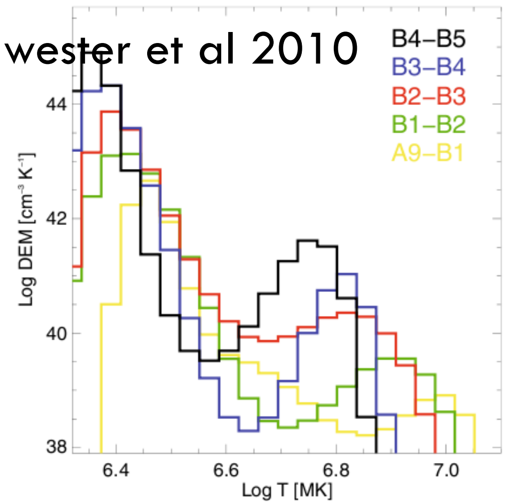
- Increasing evidence of a minor very hot component, especially in X-rays, but not conclusive: McTiernan 2009, Schmelz et al. 2009a,b, Patsourakos & Klimchuk 2009, Reale et al. 2009a,b, Sylwester et al. 2010



Schmelz et al. 2009b



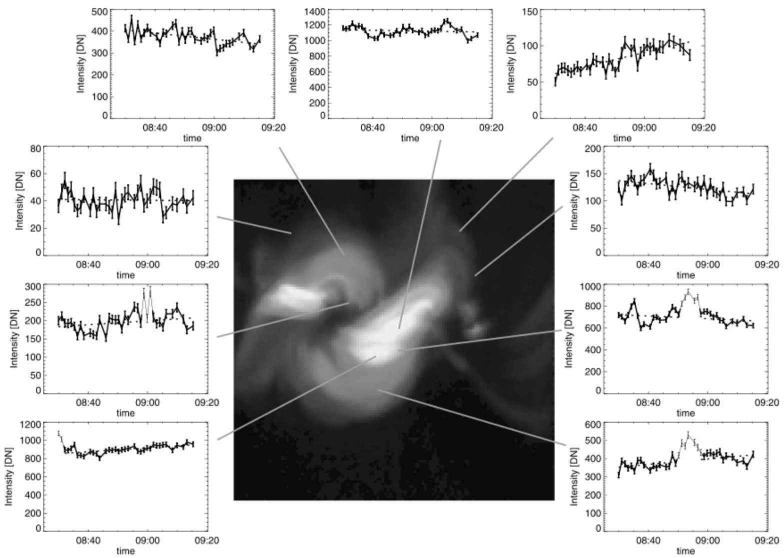
Reale et al 2009b



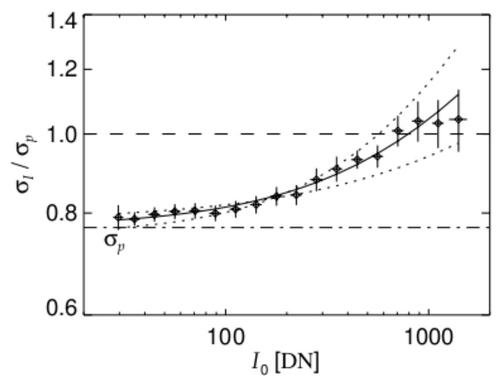
Sylwester et al 2010

Hot cooling plasma: Variability/Brightenings

- Light curves: Fine structuring and/or plasma response make detection of pulsed variability very hard
- Analysis of temporal series with various approaches: Shimizu 1995, Shimizu & Tsuneta 1997, Vekstein and Katsukawa 2000, Katsukawa & Tsuneta 2001, Sakamoto et al. 2008, 2009, Vekstein 2009, Terzo et al. 2011

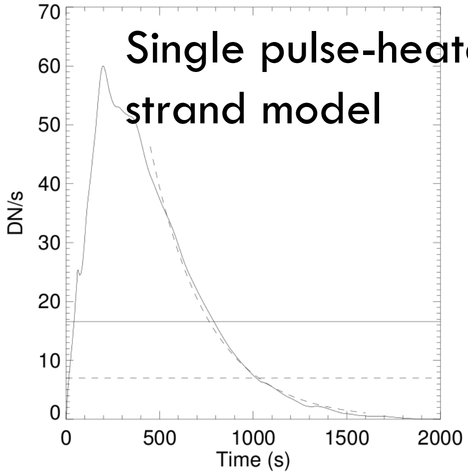


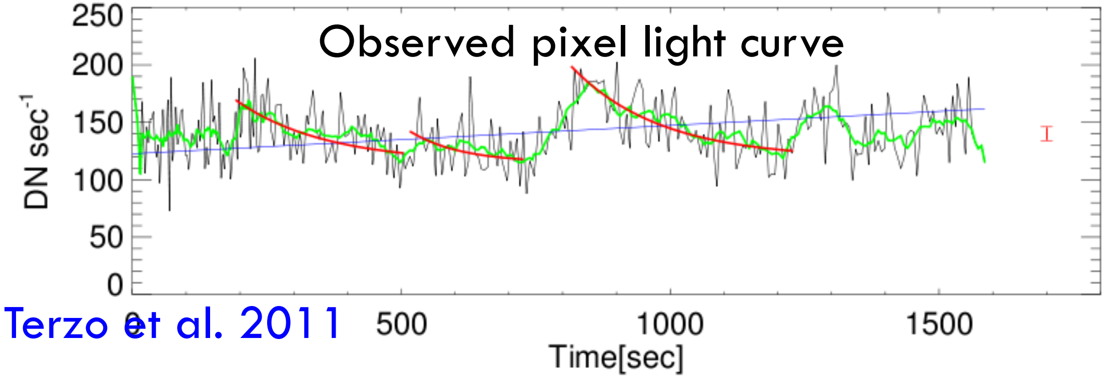
Katsukawa & Tsuneta 2001



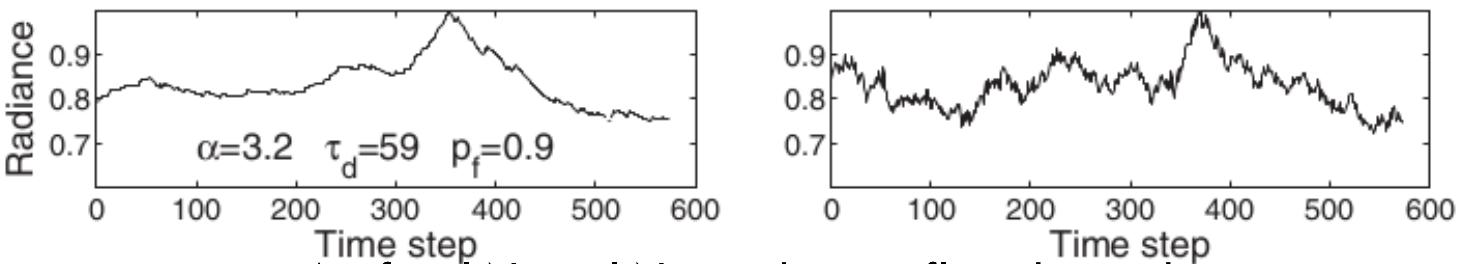
Dynamic temperature: heating/cooling cycle

- Recent evidence of continuous small scale fast heating/slow cooling in active regions from X-ray/EUV light curves (Terzo et al. 2011, Tajfirouzeh & Safari 2012, Viall & Klimchuk 2012)





Terzo et al. 2011

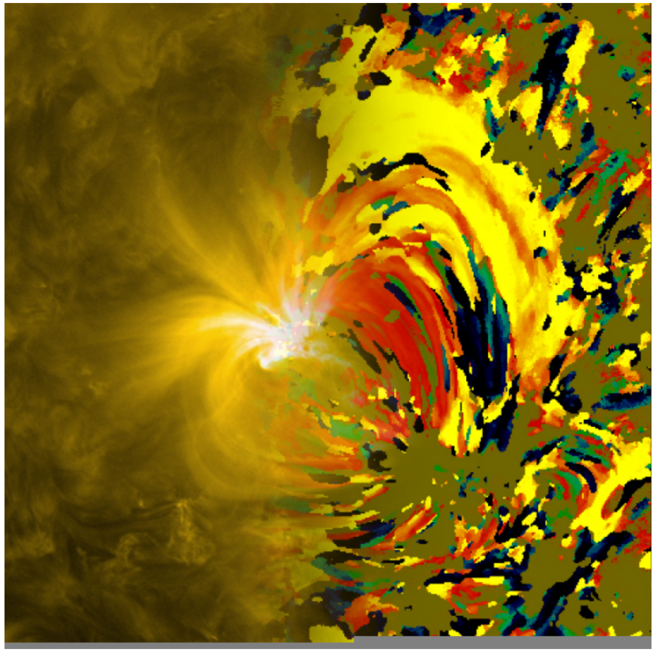


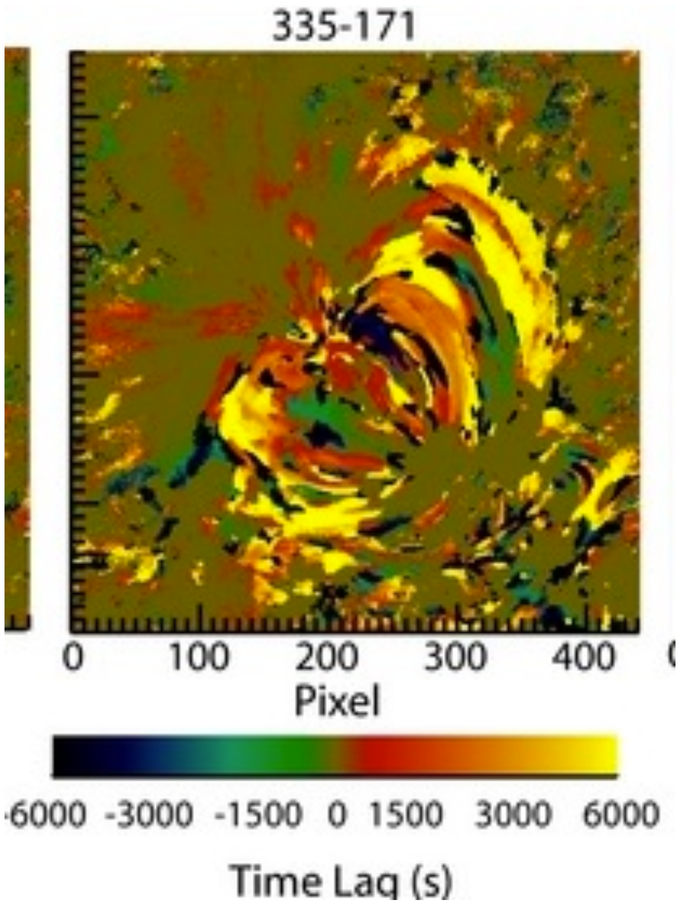
Artificial Neural Network: nanoflare-heated corona

Tajfirouzeh & Safari 2012

Cooling plasma: SDO
(Viall & Klimchuk 2012)

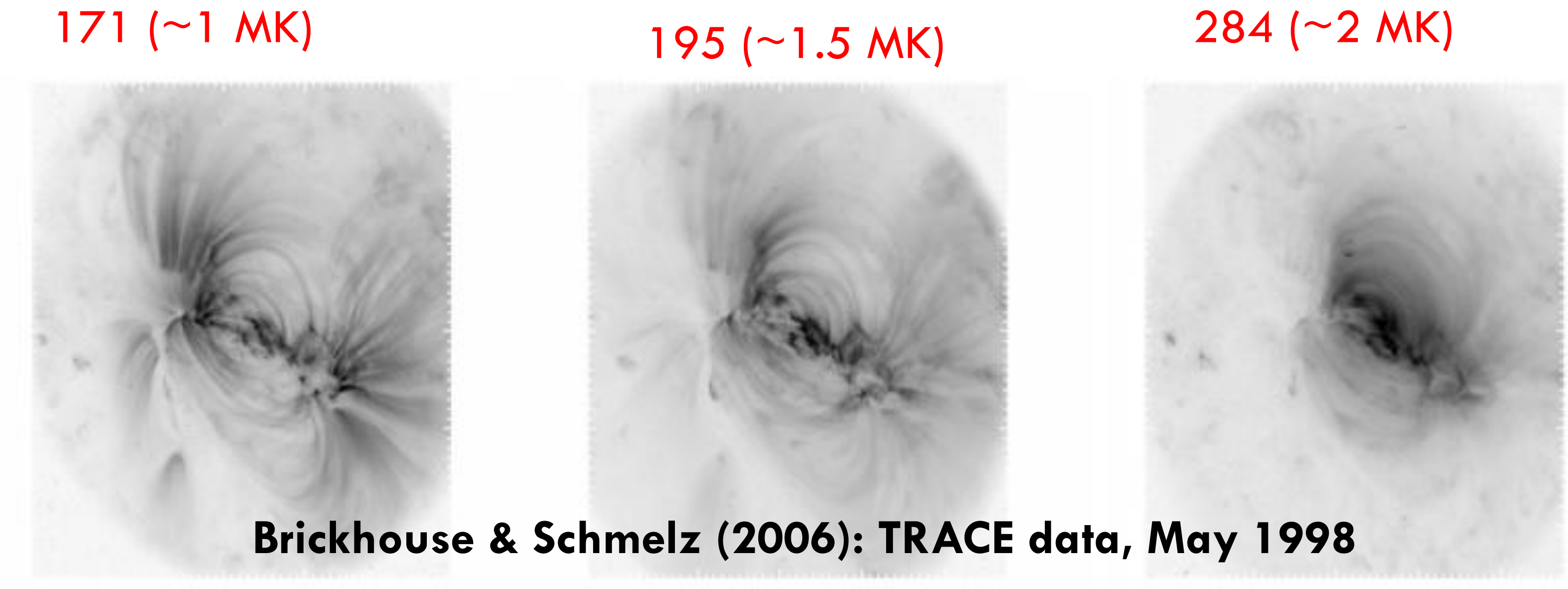
- Systematic delays of pixel brightenings in cooler and cooler EUV bands





Hot plasma from coronal "fuzziness"

- Evidence: fuzziness increasing with band hardness (T)
- Long known (Skylab) but not addressed
- Loops/active regions better defined in cooler UV lines (e.g. Brickhouse & Schmelz 2006; Tripathi et al. 2009)

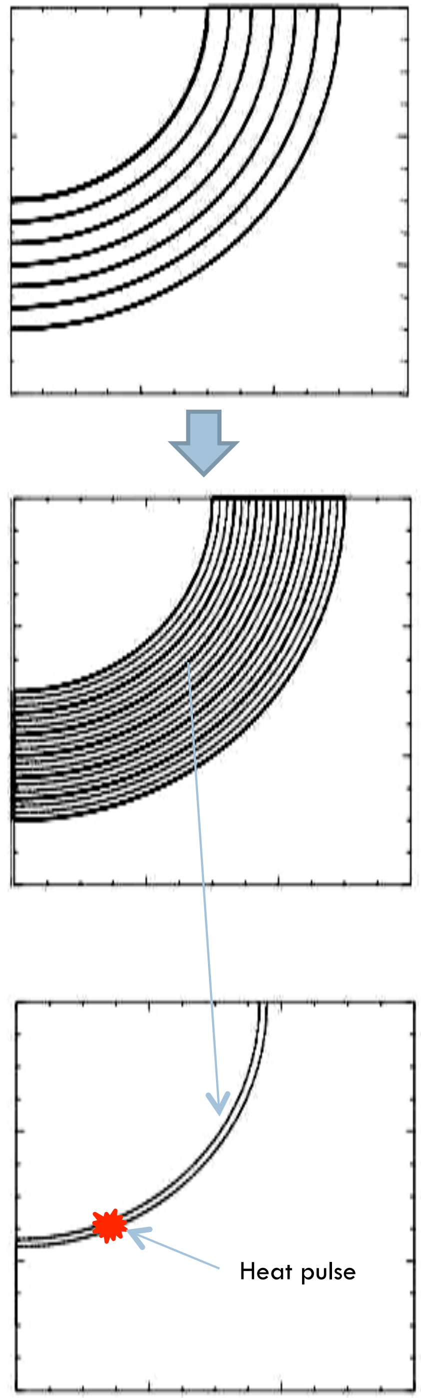


Brickhouse & Schmelz (2006): TRACE data, May 1998

Very hot plasma: Stranded/pulse-heated loop modeling

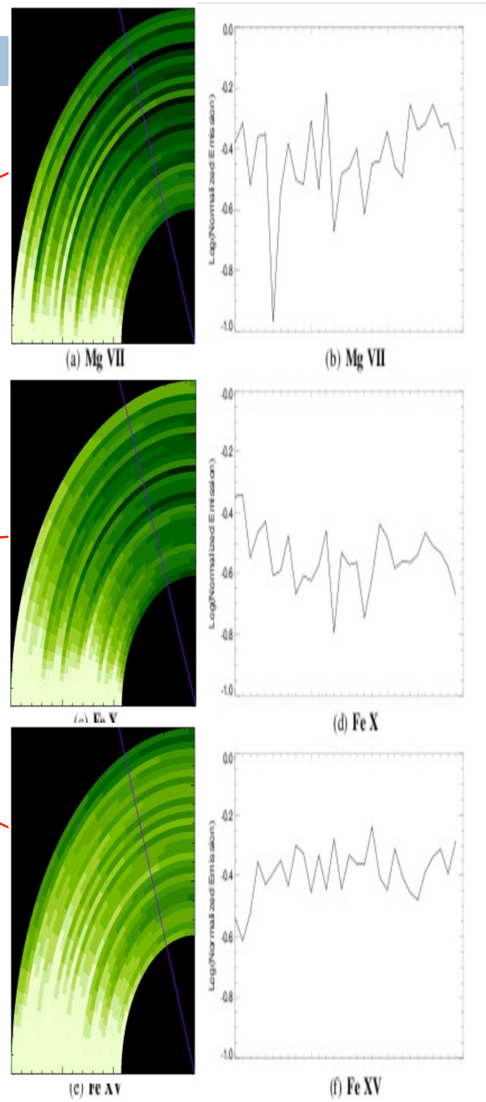
(Guarrasi, Reale & Peres, 2010)

- Loop as a bundle of many unresolved strands
- Each strand is pulse-heated once (1 min duration) to 10 MK, at random time
- 1D hydrodynamic simulation of plasma in a strand



Very hot plasma:
Model results
(Guarrasi, Reale & Peres, 2010)

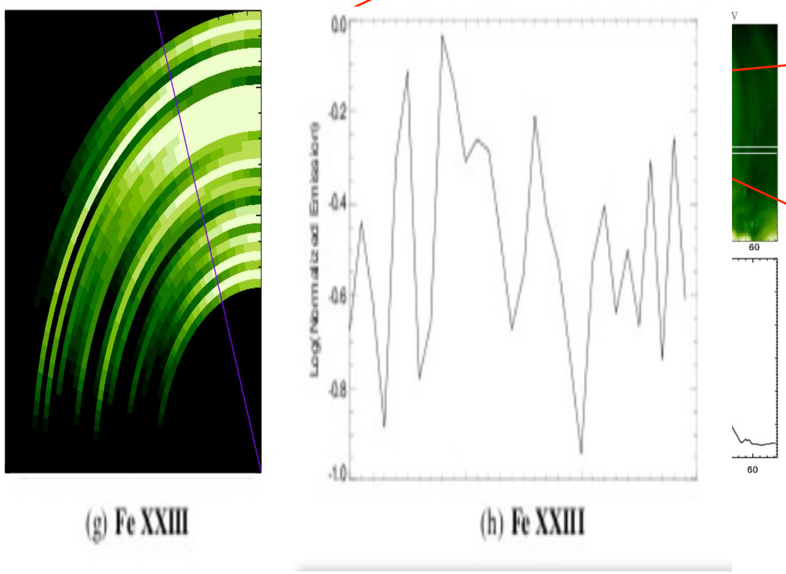
- The model explains increasing "fuzziness" with T
- EIS line images
- Fuzzy 6.0 < LogT < 6.4



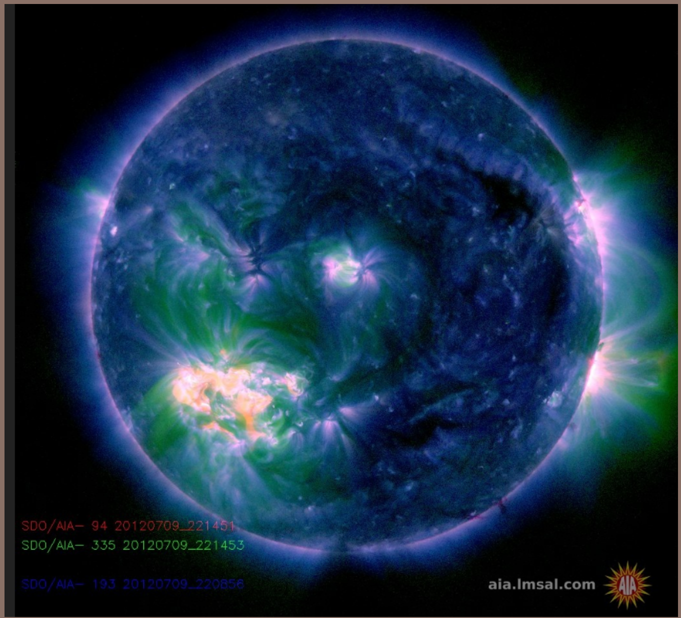
LogT = 5.8

LogT = 6.0

LogT = 6.4



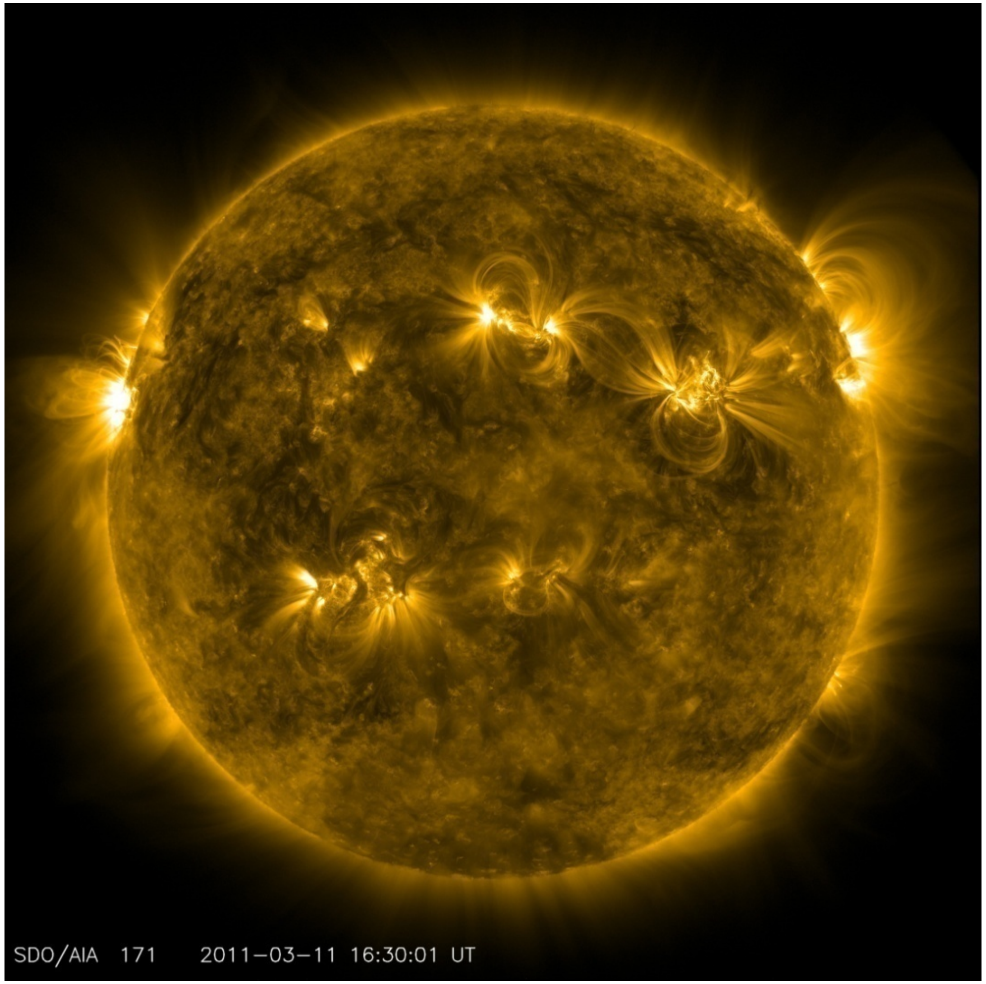
LogT = 7.1



THE ROLE OF SOLAR DYNAMICS OBSERVATORY

Solar Dynamics Observatory discovers thin high temperature strands in coronal active regions

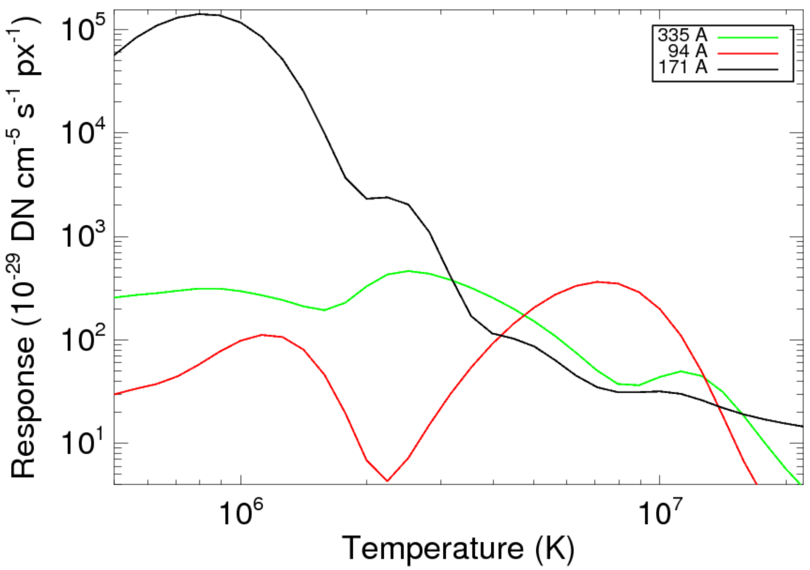
Reale, Guarrasi, Testa, DeLuca, Peres, Golub, 2011, ApJL, 736, L16

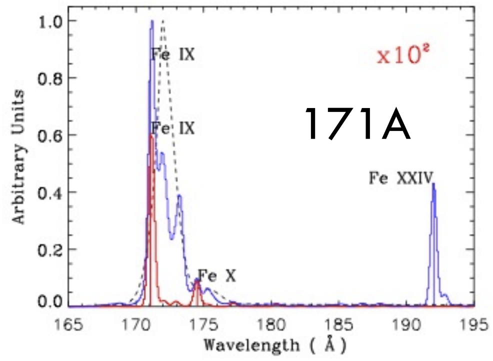


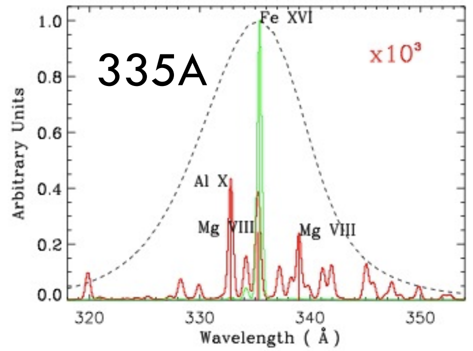
Atmospheric Imaging Assembly (AIA)

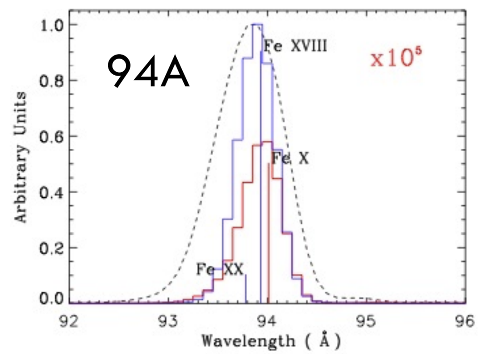
O'Dywer et al. 2010

- Normal Incidence telescope
- Narrow EUV bands
- Time: continuous high-cadence (~10s)
- Space: high resolution (0.6")

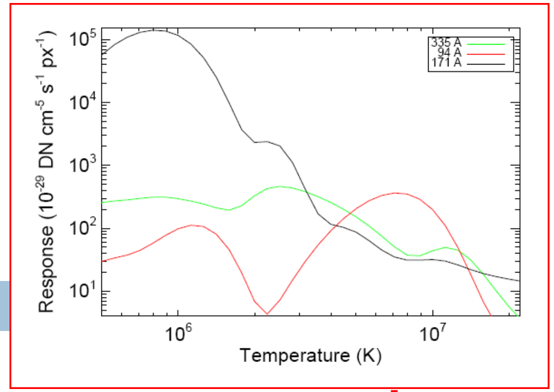








Very hot plasma:
The model prediction for SDO



The (hotter) 94 A channel should see more contrasted loops than the 335A channel

94A: 1+8MK

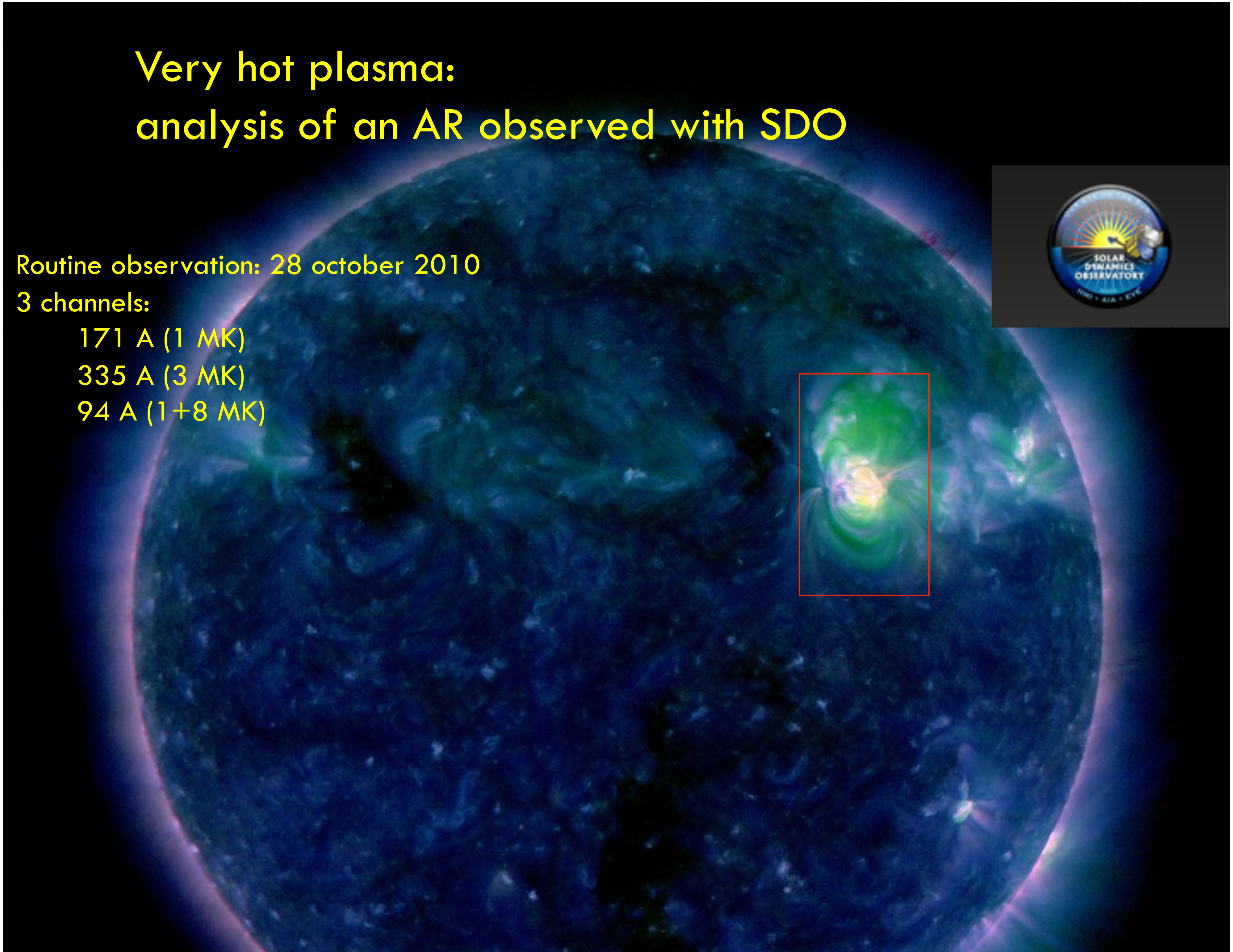
335A: 3MK

Very hot plasma:
analysis of an AR observed with SDO

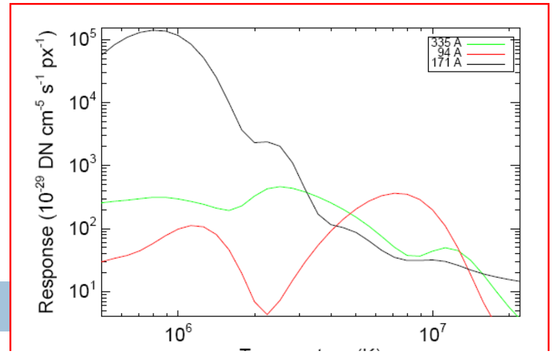
Routine observation: 28 october 2010

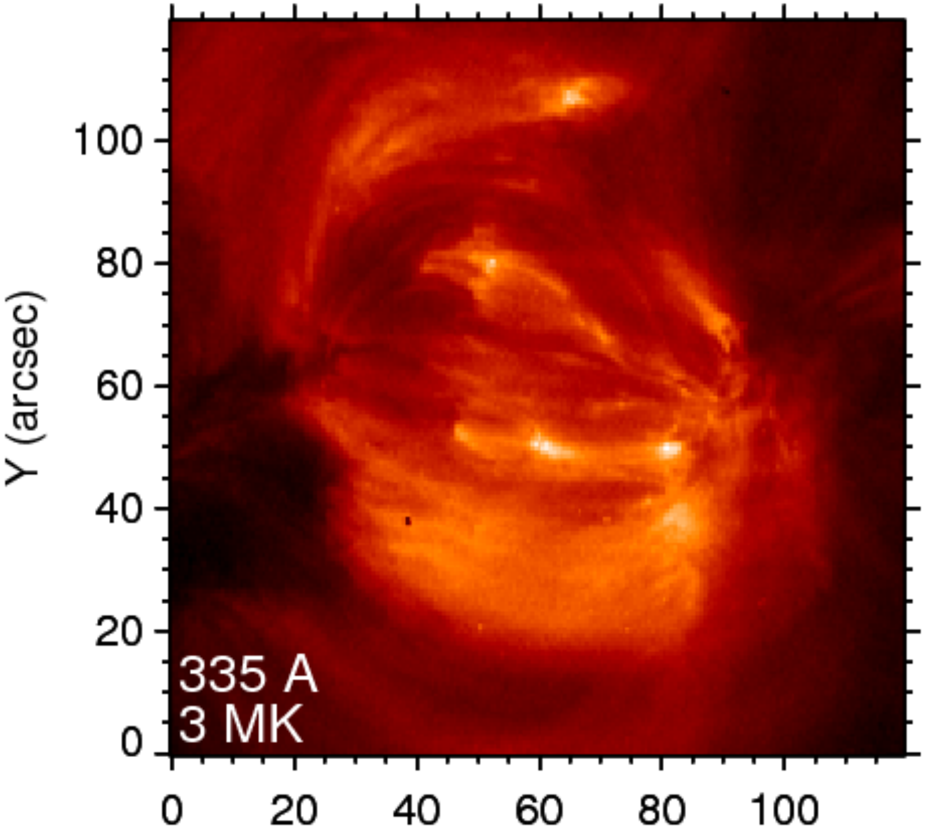
3 channels:

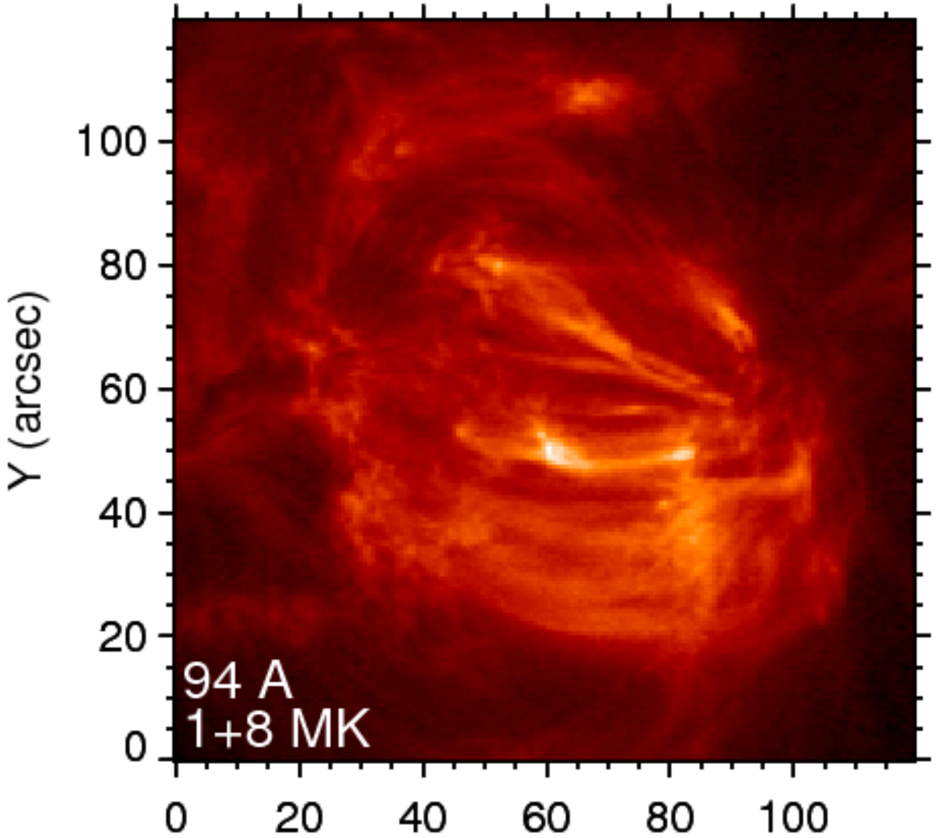
- 171 A (1 MK)
- 335 A (3 MK)
- 94 A (1+8 MK)



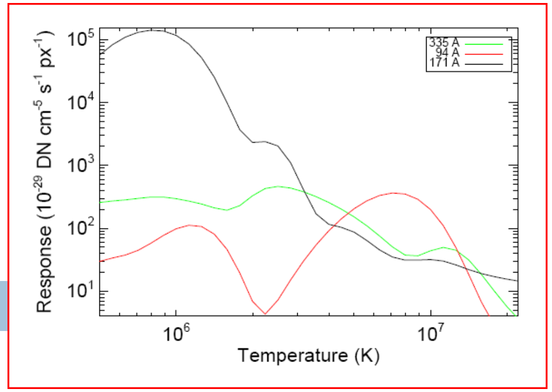
Very hot plasma: Comparison 335A vs 94A

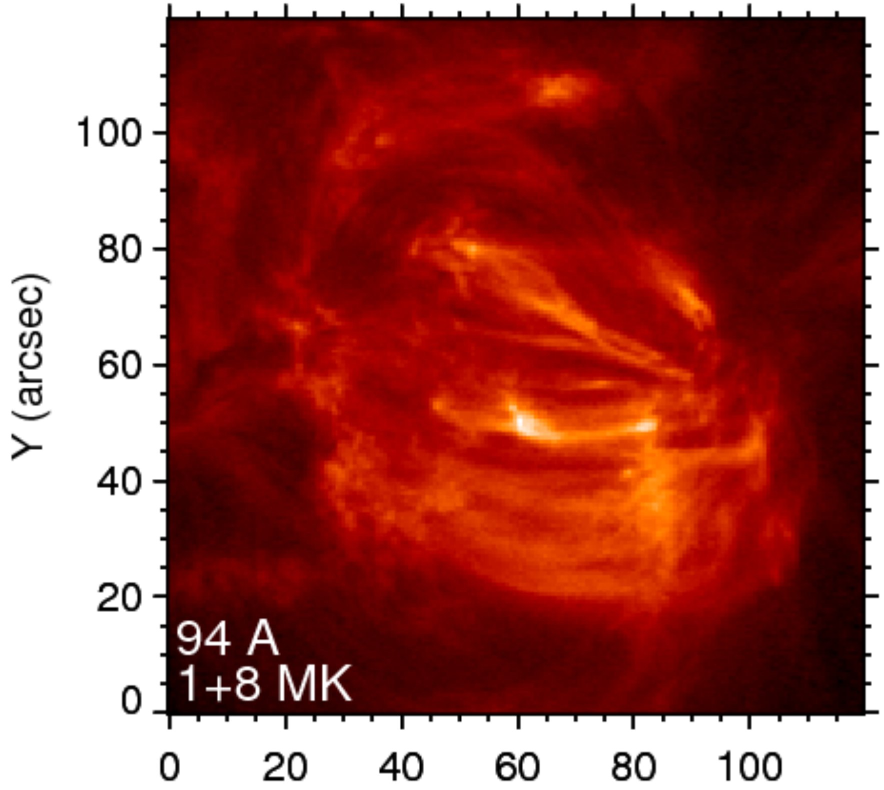


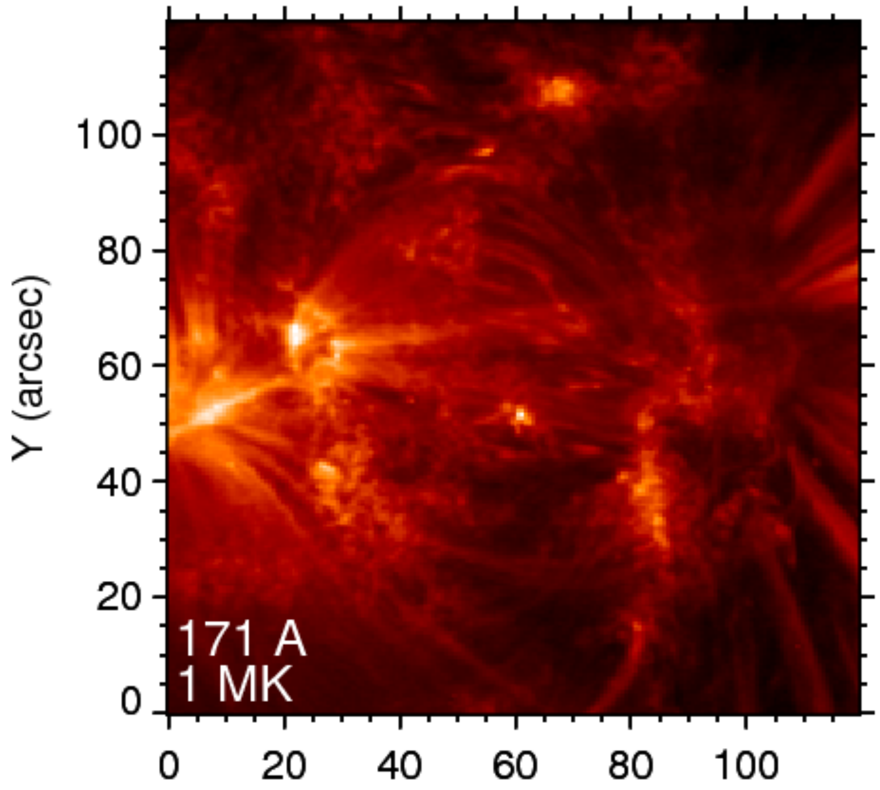




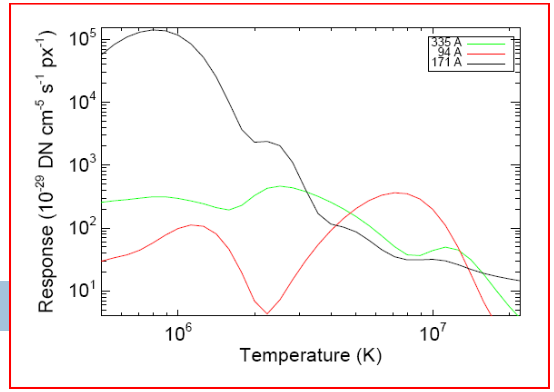
Very hot plasma:
Is it really hot plasma?

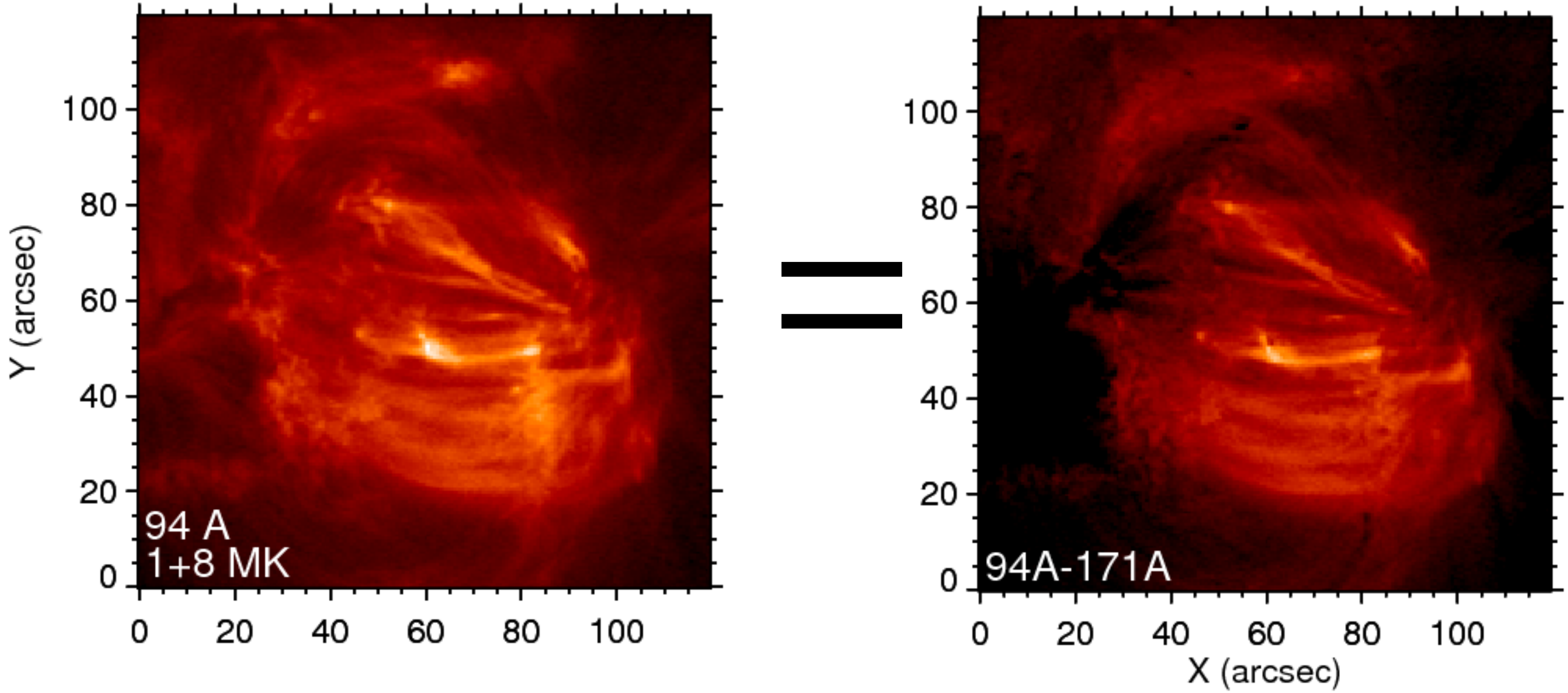






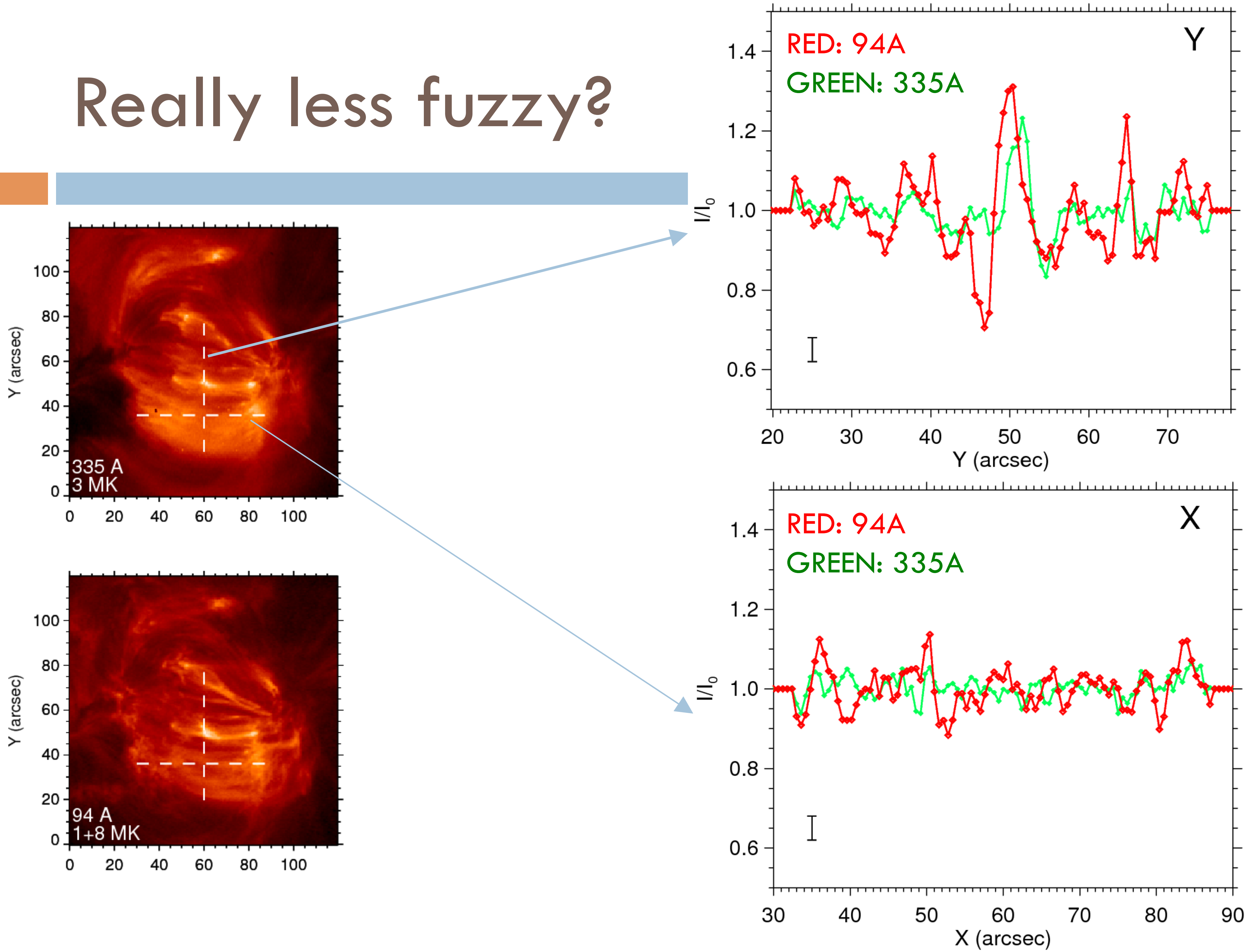
Very hot plasma:
Is it really hot plasma?





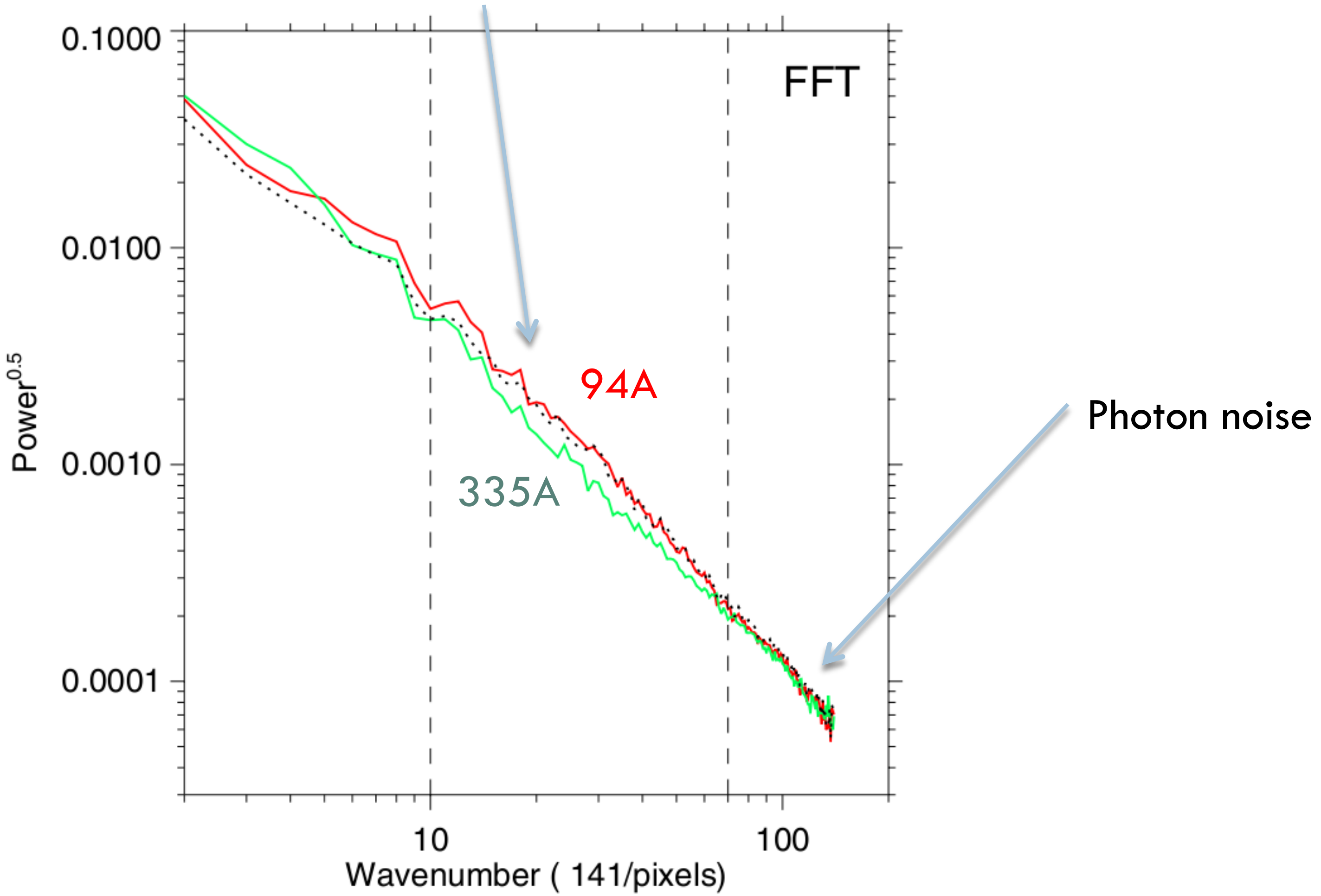
Cool component extrapolated from 171A image <u>with conservative assumptions</u>
and subtracted from 94A image

Really less fuzzy?

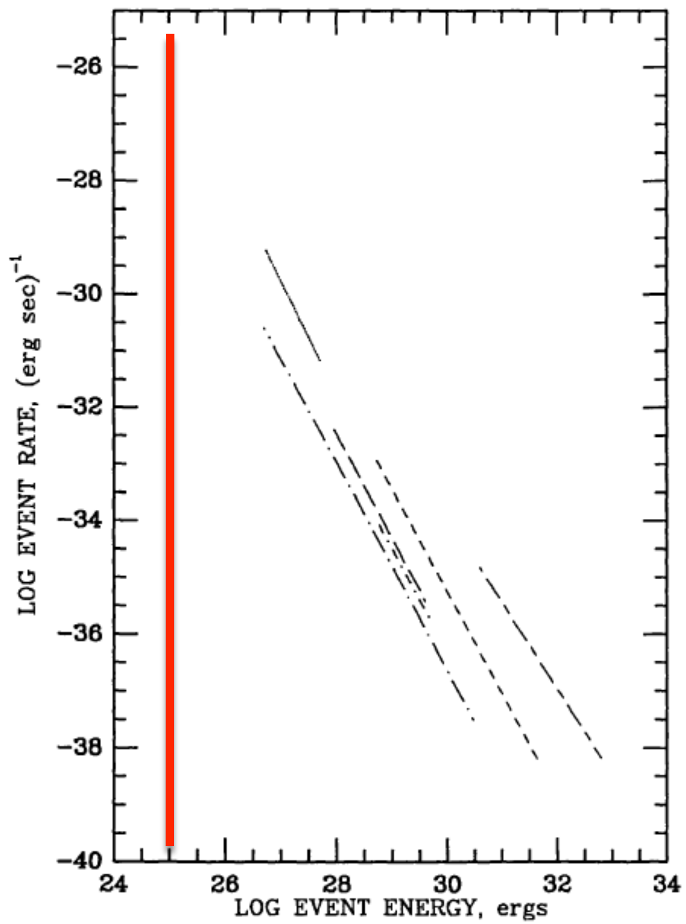


Fourier analysis: 2D FFT (Gomez et al. 1993)

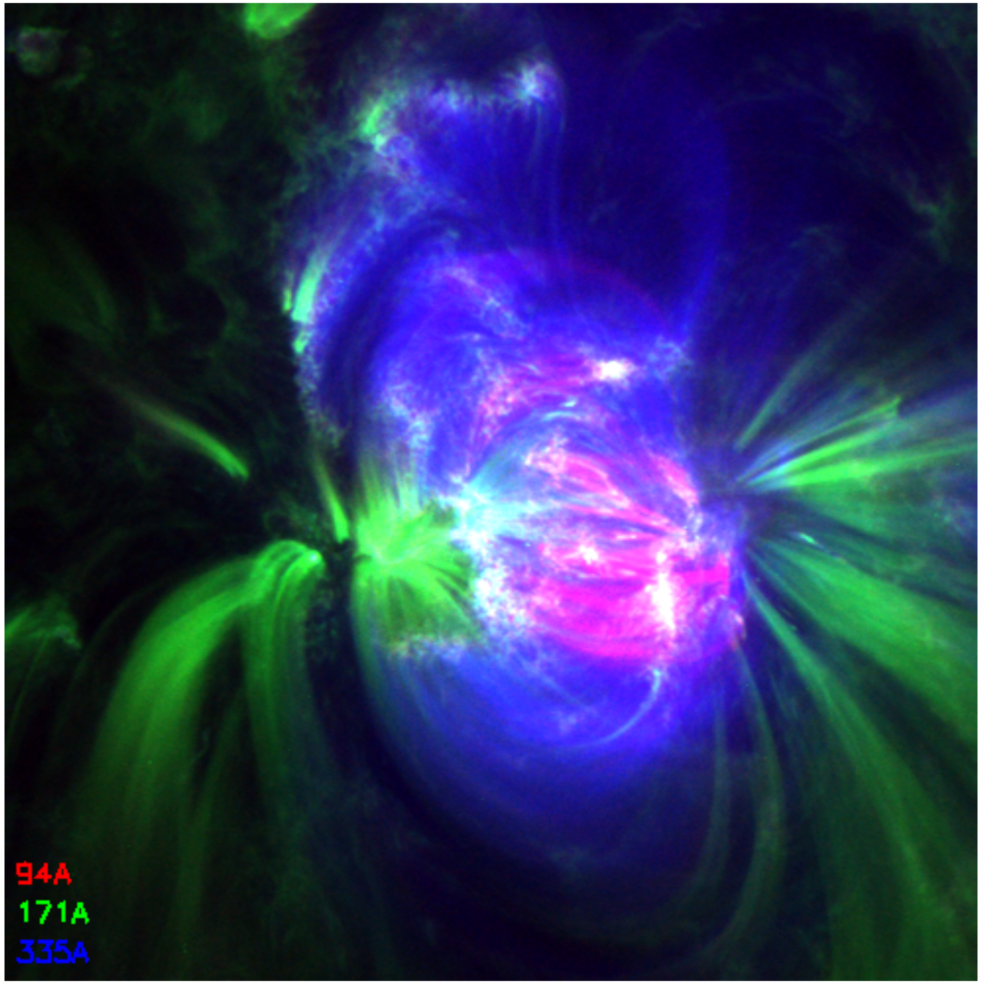
- High frequency: 94A > 335A power



Pulse energy

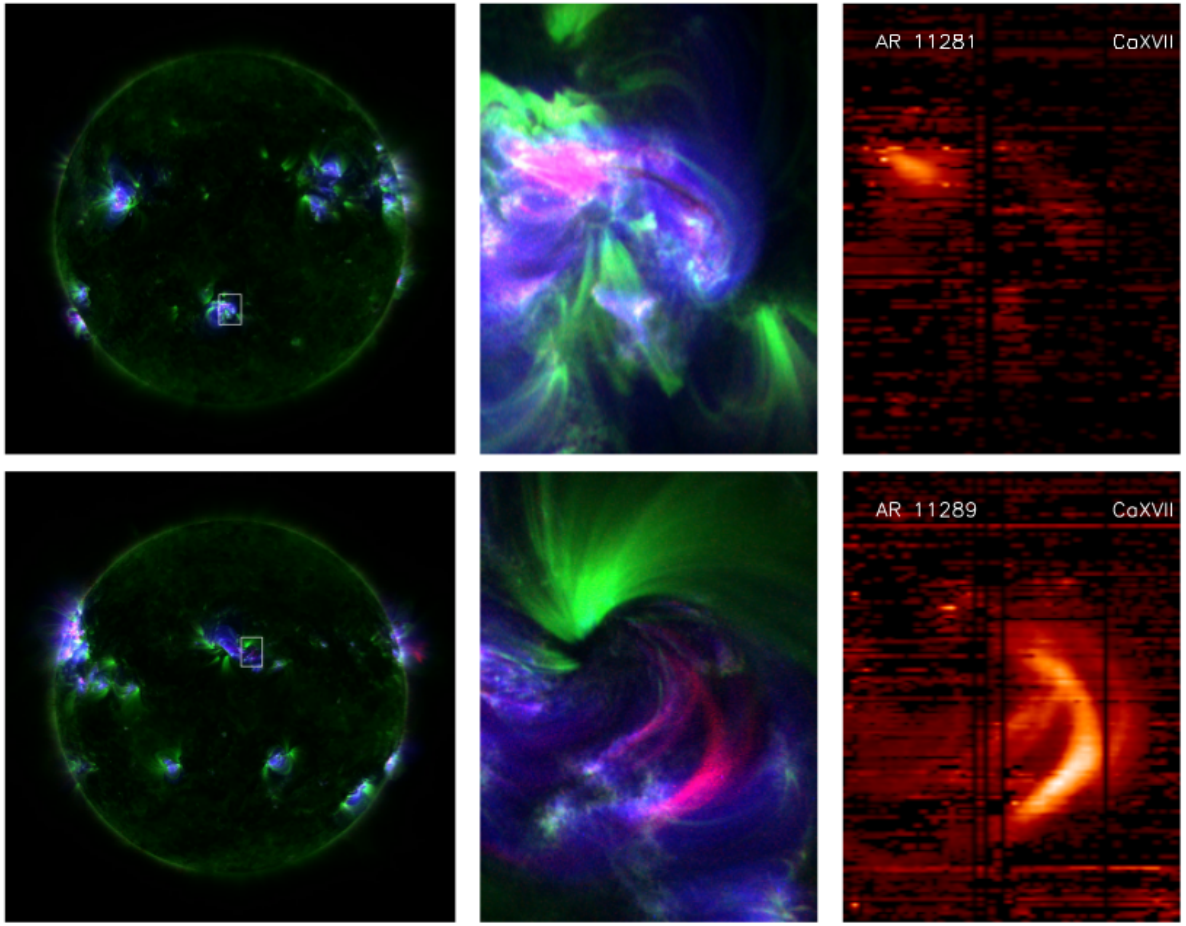


Very hot plasma - Color coding: pink is very hot (6-8 MK)



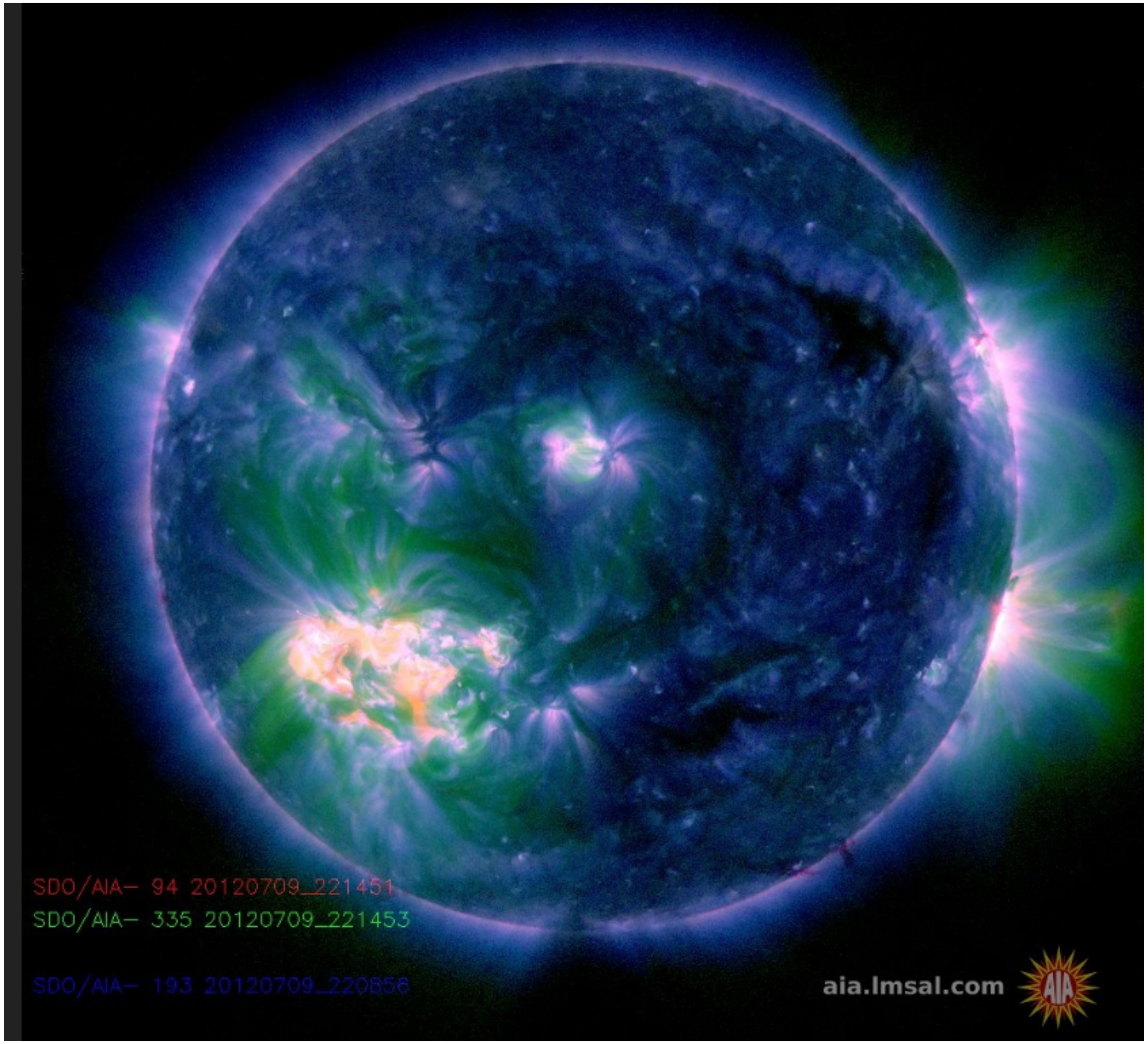
Very hot plasma:
Support from Ca XVII line

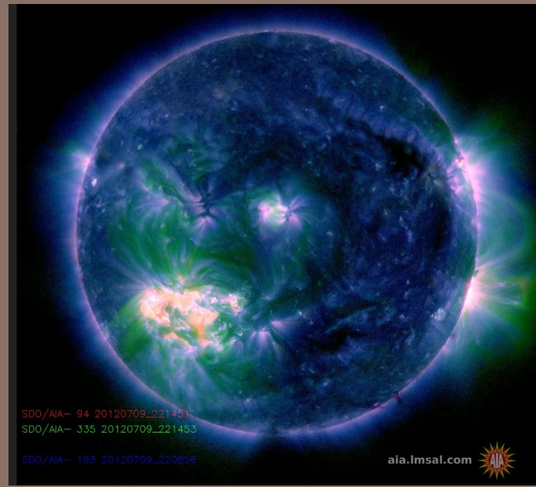
- Comparison with Hinode/EIS AR raster: Ca XVII line (~6 MK)
- Very similar morphology (Testa & Reale 2012)



Very hot plasma -
Do it at home: sdowww.lmsal.com/suntoday/

- Select: 94+335+193
- Yellow is hot!





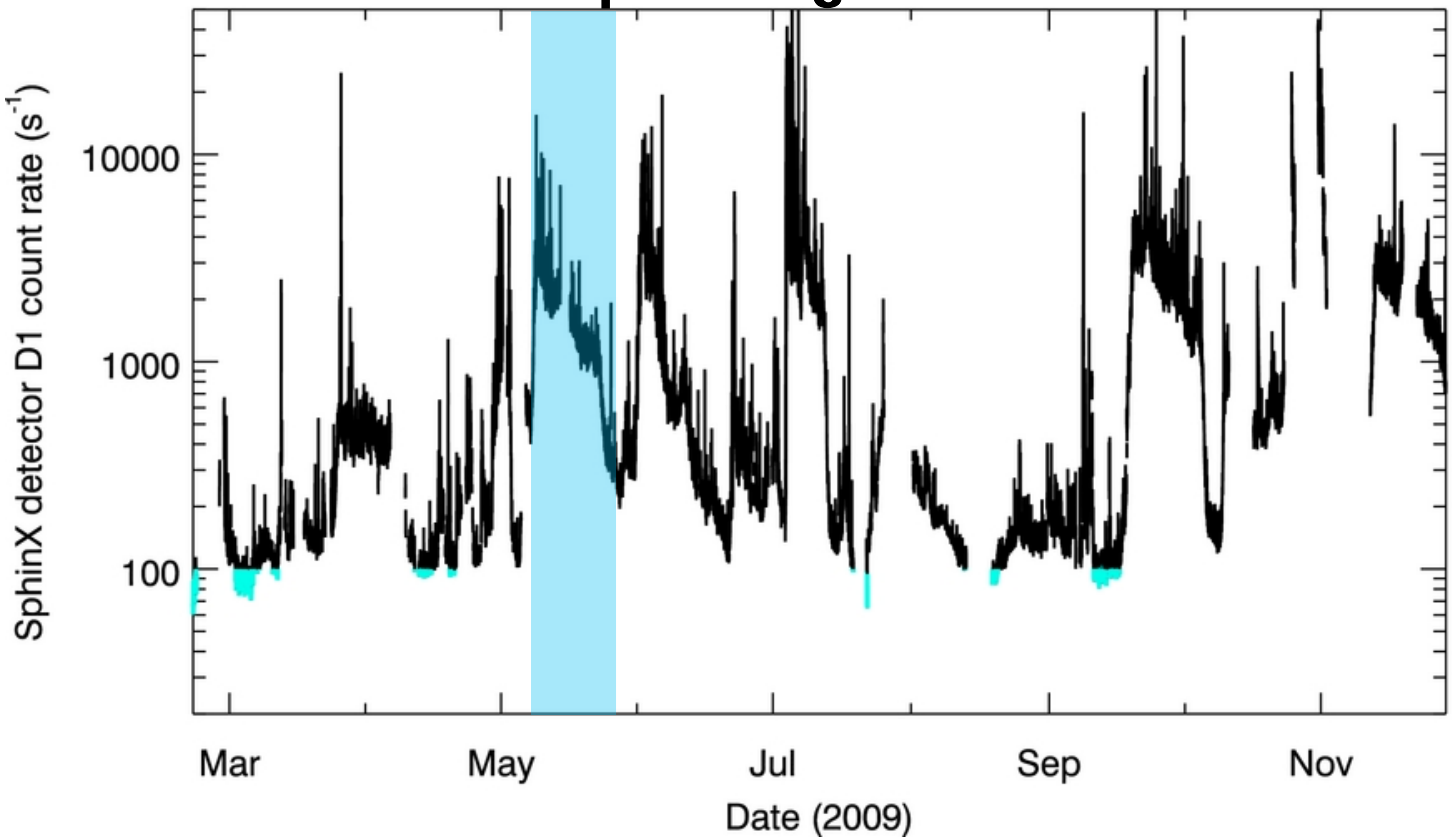
THE ROLE OF SPHINX:
X-RAY EMITTING HOT PLASMA IN SOLAR ACTIVE REGIONS OBSERVED BY THE SPHINX SPECTROMETER

Miceli, Reale, Gburek, Terzo, Barbera, Collura, Sylwester, Kowalinski, Podgorski, Gryciuk, A&A 544, A139 (2012)

The Data

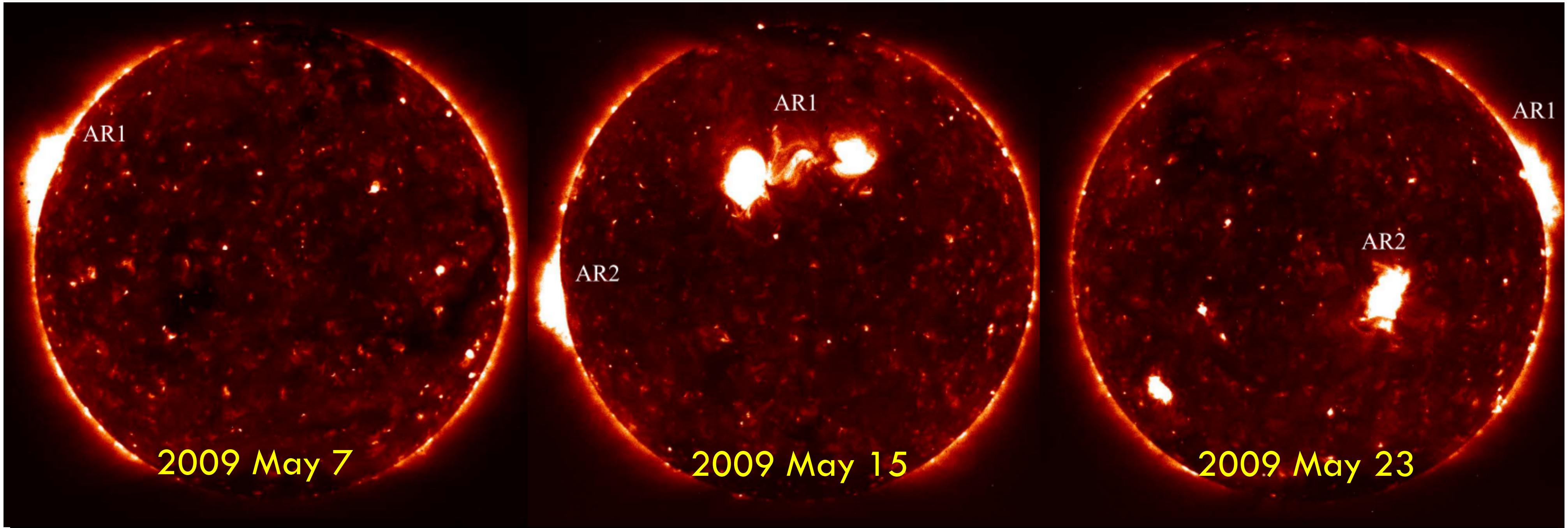
We analized spectra collected by the Solar Photometer In X-rays, **SphinX** (Sylwester et al. 2008, Gburek et al. 2011) a broadband (1.3-14.9 keV) spectrometer with moderate spectral resolution (~460 eV)

SphinX light curve



Time window: 7-24 May 2009 (rel. high X-ray flux, no significant flares)

The Data

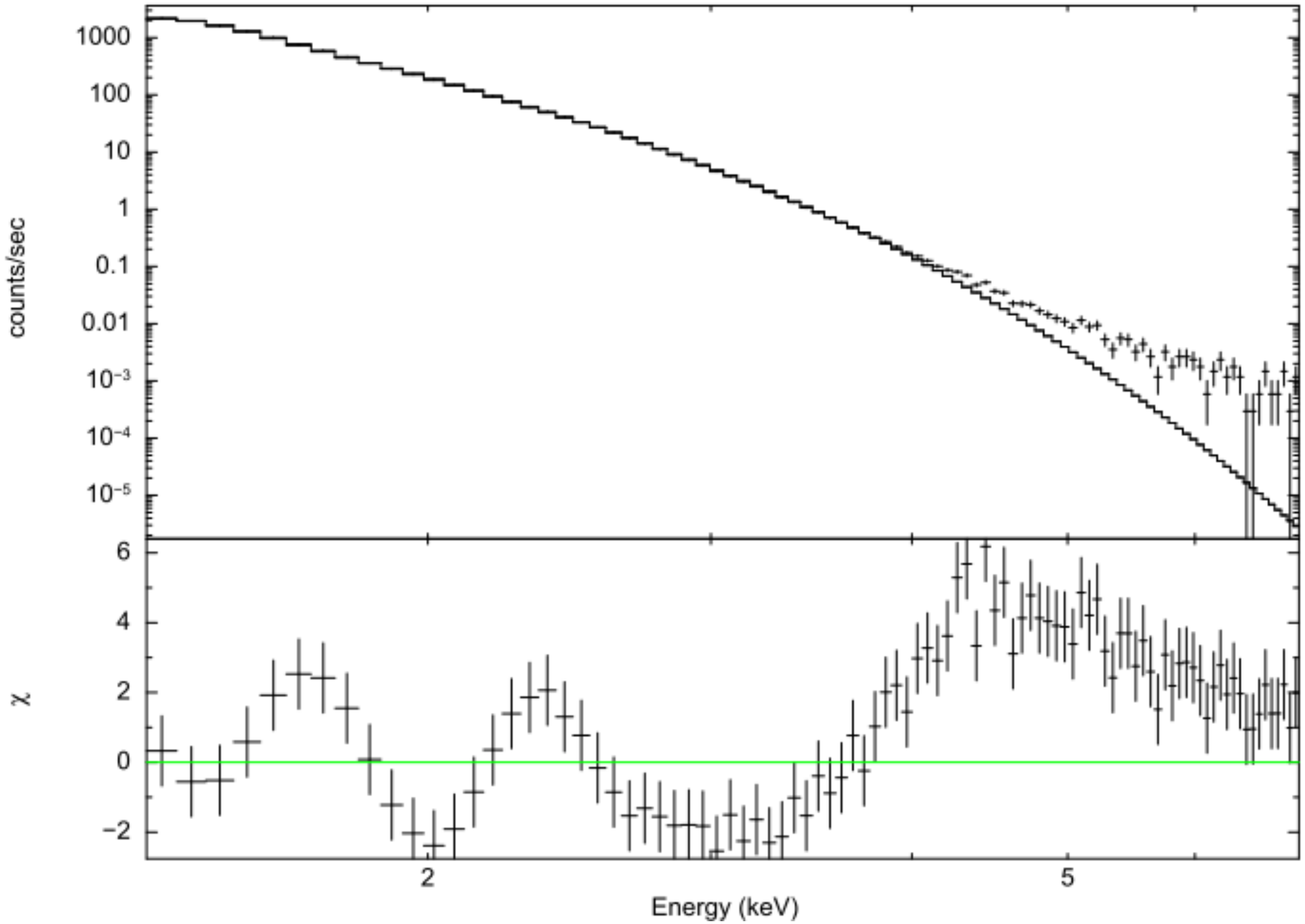


Hinode/XRT synoptic images of the solar corona in the Ti-poly filter

Data reduction:

- Inspection of light curves: removal of a B1.0 and a A5.9 flare
- Data filtering to remove spurious measurements (non-GTI events, particle related events, etc .)
- Filtered data: 3.9×10^7 events
- Filtered exposure time: 57 ks

Spectral analysis



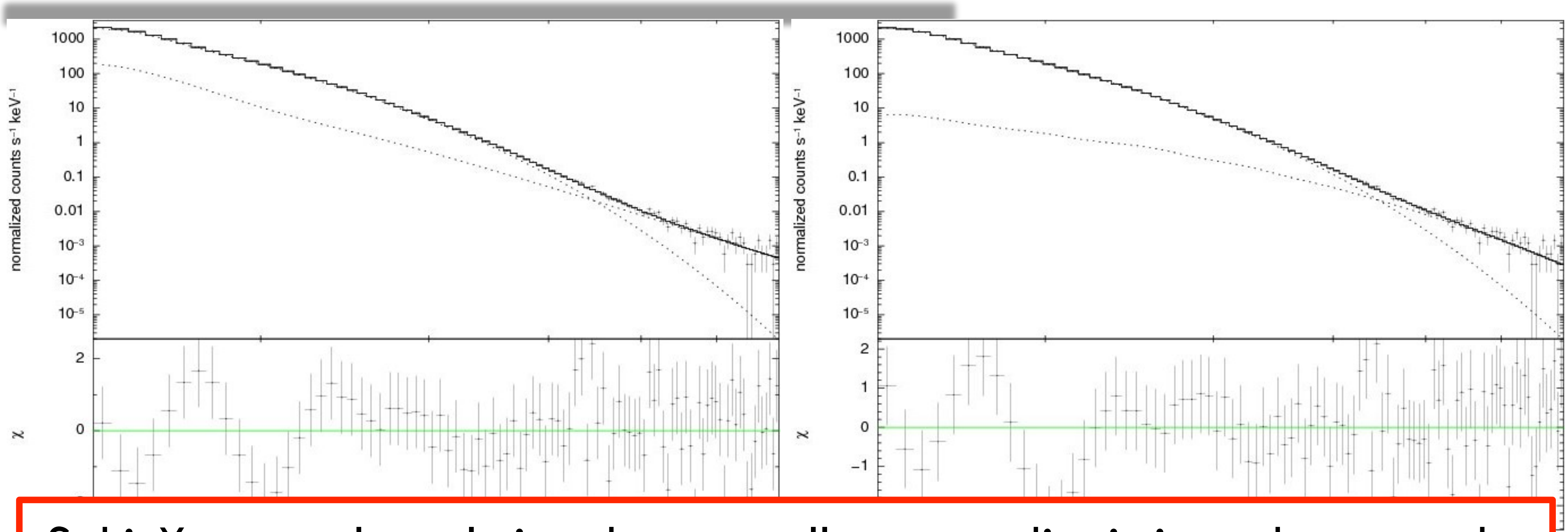
$T=2.83 \times 10^{6}$ K

$EM=5.36 \times 10^{47}$ cm^{-3}

$\chi^2=657.0$ (93 d. o. f.)

A single thermal component (optically thin isothermal plasma, APEC model in XPEC, based on AtomDB 2.0) **cannot fit** the broadband **solar spectrum**

Hard X-ray emission



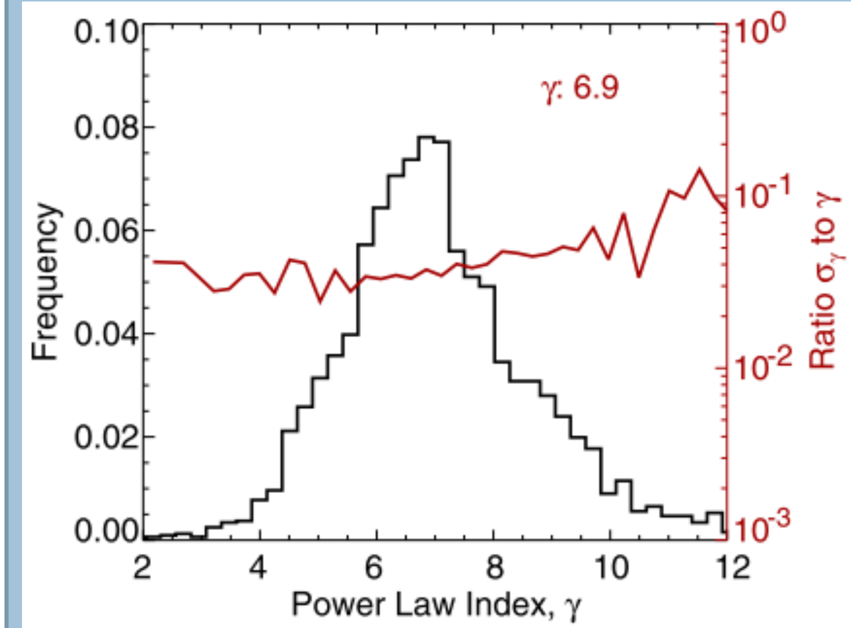
SphinX spectral resolution does not allow us to discriminate between the two scenarios

$T = 2.74 \pm 0.01$ (10^6 K)
$EM = 6.3 \pm 0.2$ (10^{47} cm^{-3})
$\gamma = 9.0 \pm 0.3$
$N = 7 \pm 2$ (10^4 cm^{-2} keV^{-1} s^{-1})
$\chi^2 = 94.0$ (91 d.o.f.)

$T_1 = 2.73 \pm 0.01$ (10^6 K)
$EM_1 = 6.3 \pm 0.2$ (10^{47} cm^{-3})
$T_2 = 6.6 \pm 0.3$ (10^6 K)
$EM_2 = 2.7 \pm 0.2$ (10^{44} cm^{-3})
$\chi^2 = 97.1$ (91 d.o.f.)

Origin of the hard X-ray emission

The **hard component** was not detected in the lowest activity periods of the 2009 solar minimim (Sylwester+ 2012) ➡ **link with active regions**



Distribution of the power-law index for RHESSI microflares (Hannah +2008)

Non-thermal scenario

γ~9 (thick target bremsstrahlung?) steeper than the average value (γ=6.9) observed in HXR microflares

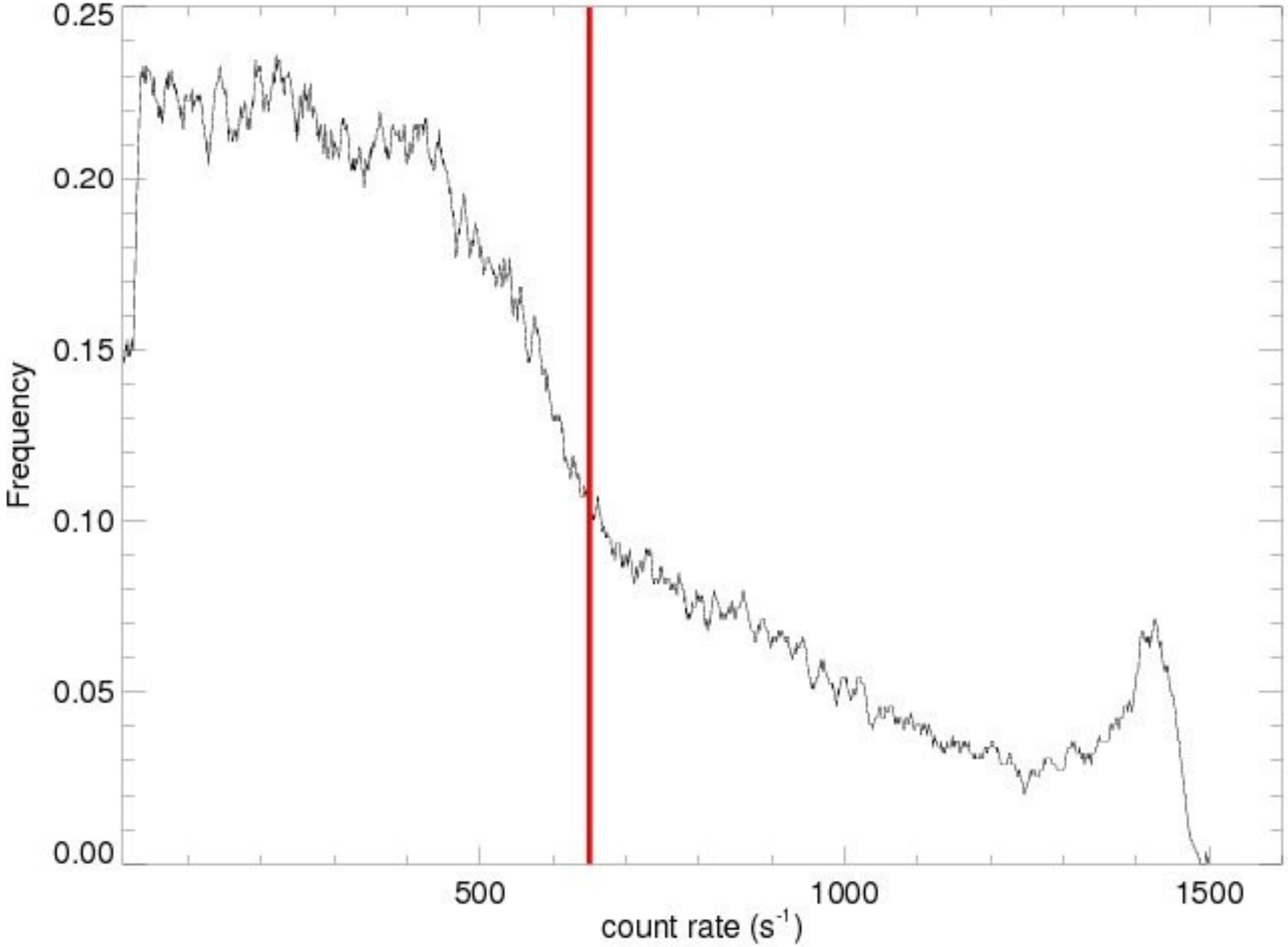
Thermal scenario

Temperature consistent with that found in active regions (Reale+2009, 2011; McTiernan 2009; Testa&Reale 2012)

A spectral resolution ΔE~100 eV in the 4-7 keV band is necessary to discriminate between the two scenarios

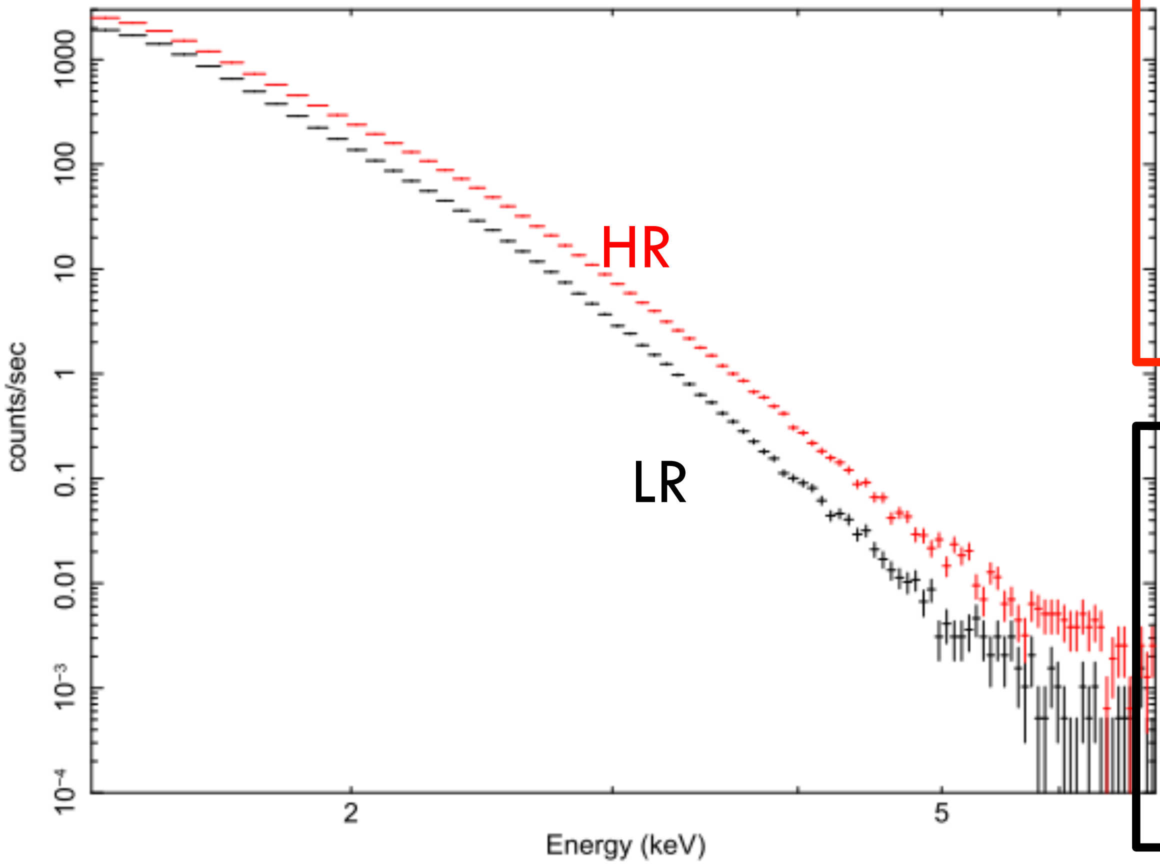
Count-rate resolved spectral analysis

Possible contribution from unresolved microflares: does the hard X-ray emission originate only during high flux periods?



We extracted a spectrum from time bins with count-rate >650 s^{-1} **(HR spectrum)** and from time bins with count-rate <650 s^{-1} **(LR spectrum)**

Count-rate resolved spectral analysis



$T_1 = 3.17 \pm 0.01$ (10^6 K)
$EM_1 = 4.3 \pm 0.1$ (10^{47} cm^{-3})
$T_2 = 8.0 \pm 1.0$ (10^6 K)
$EM_2 = 0.02 \pm 0.01$ (10^{47} cm^{-3})
χ^2=102 (91 d.o.f.)

$T_1 = 2.65 \pm 0.01$ (10^6 K)
$EM_1 = 6.1 \pm 0.2$ (10^{47} cm^{-3})
$T_2 = 6.4 \pm 1.0$ (10^6 K)
$EM_2 = 0.02 \pm 0.01$ (10^{47} cm^{-3})
χ^2=90 (91 d.o.f.)

Both LR & HR spectra still **cannot be fitted by a single thermal component** (χ^2=332.5 and 488.3, respectively, with 93 d.o.f.), though HR spectrum is harder

Living Reviews in Solar Physics

http://solarphysics.livingreviews.org/Articles/lrsp-2010-5/

- Review on Coronal loops

LIVING REVIEWS

in solar physics

"Coronal Loops:
Observations and Modeling of
Confined Plasma"
by
Fabio Reale