

**UNIVERSITY OF
CAMBRIDGE**



Heating and Dynamics of Solar Active Regions: Observations

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University of Cambridge**

IUCAA, Pune, November 2014

Focus on recent work In collaboration with:

Giulio Del Zanna, DAMTP

Jim Klimchuk, GSFC/NASA

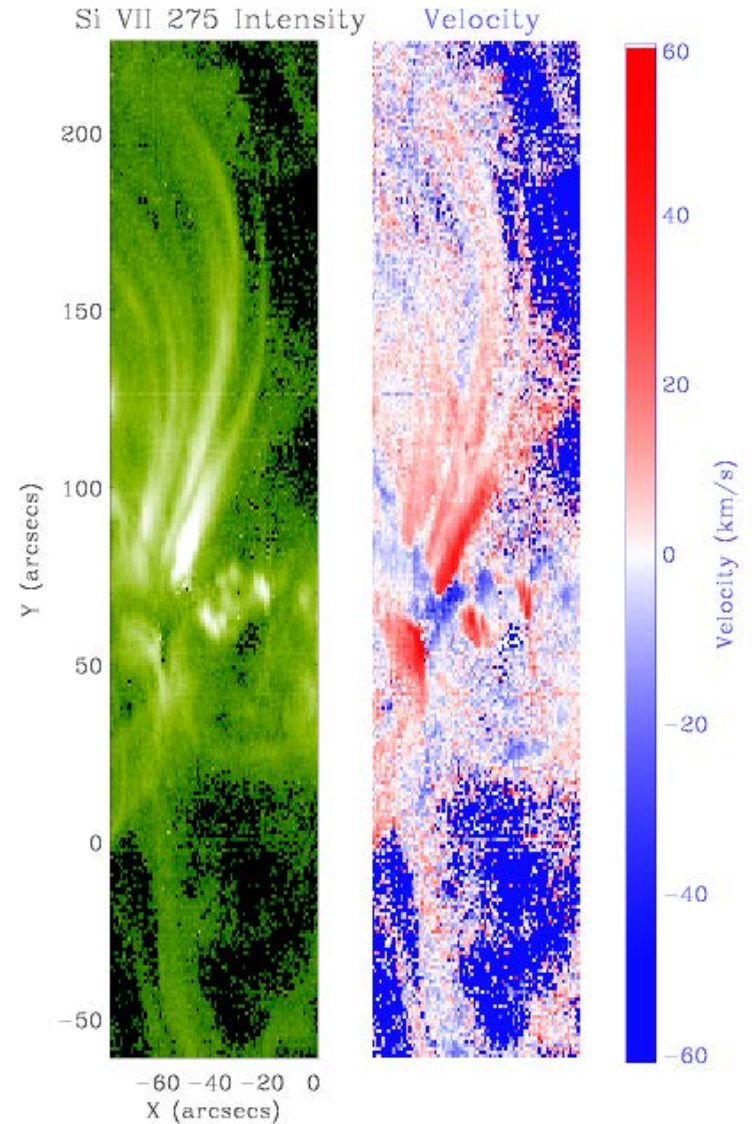
Durgesh Tripathi, Srividya Subramanian &

Girjesh Gupta, IUCAA, Pune



Overview of Talk

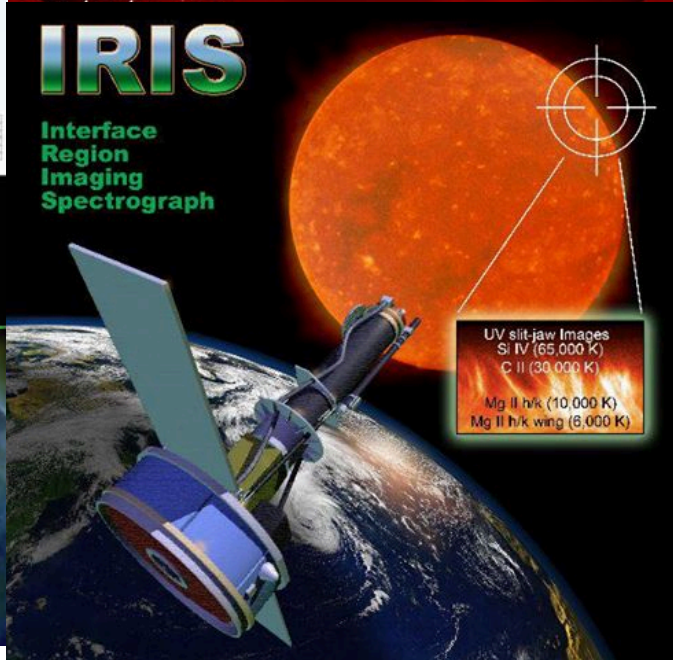
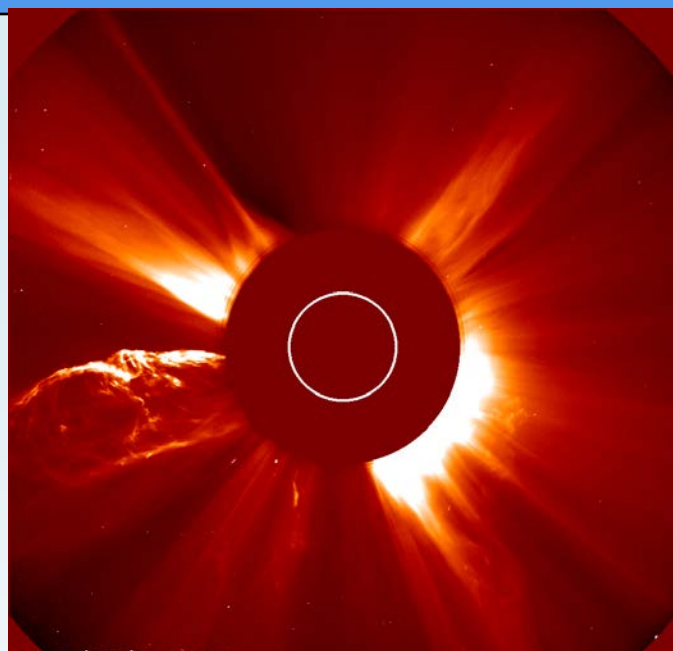
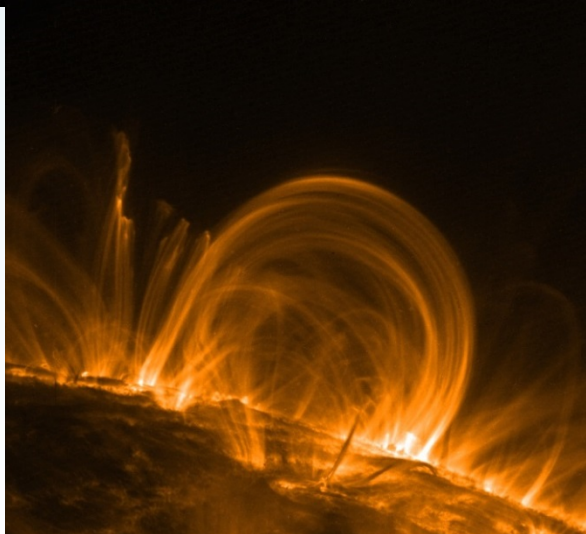
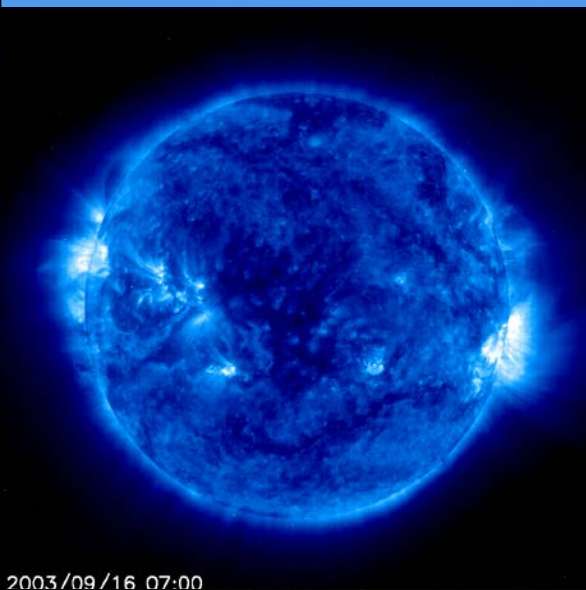
- Introduction
- Imaging & spectroscopy
- Plasma diagnostics
- Large fan loops
- Diffuse emission
- Hot core, 3MK, loops
- 1MK loop structures
- Global AR obs & models
- Summary



**Tripathi, Mason, Dwivedi,
Del Zanna & Young, 2009**

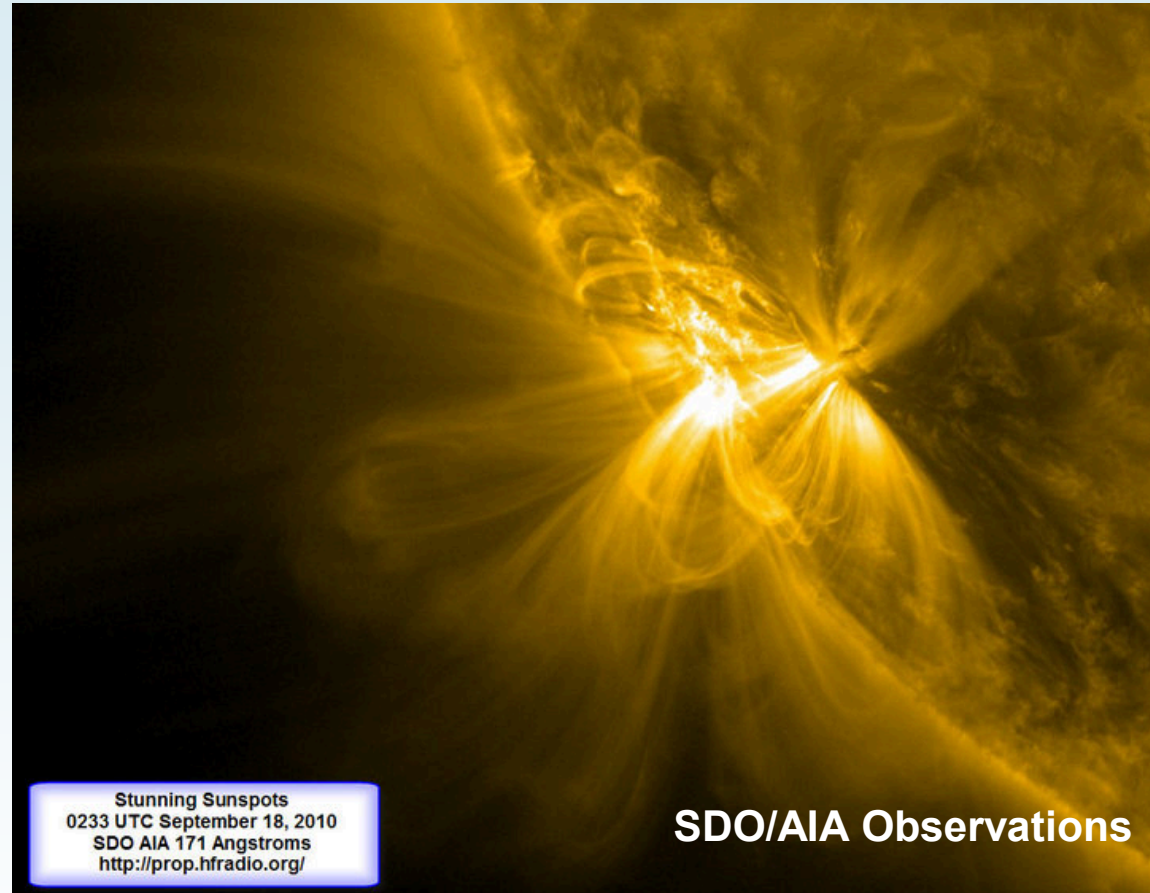
The Golden Age of Solar Space Observations

SOHO, 1995-
TRACE, 1998
RHESSI, 2002-
Hinode, 2006-
STEREO, 2006-
SDO, 2010-
IRIS, 2013



Characteristics of coronal loop structures for solar active regions

- **Large 1MK loops** seem to be “spatially resolved” by recent instruments such as TRACE & SDO/AIA but made up of many ‘strands’.
- The **hot core loops (3MK)** do not seem to be so well resolved. It is often better to study their footpoints regions (moss regions).
Micro-flare activity and **Dynamic core loops**
- **Very large ‘Fan’ loops (0.5-1MK)** reach far out into the corona, possibly joining remote ARs.
- **Diffuse Background**



RECENT REVIEWS

Reale, F. 2014, Solar Physics Living Review

Schmelz, J. & A. Winebarger, 2014, RS meeting, I

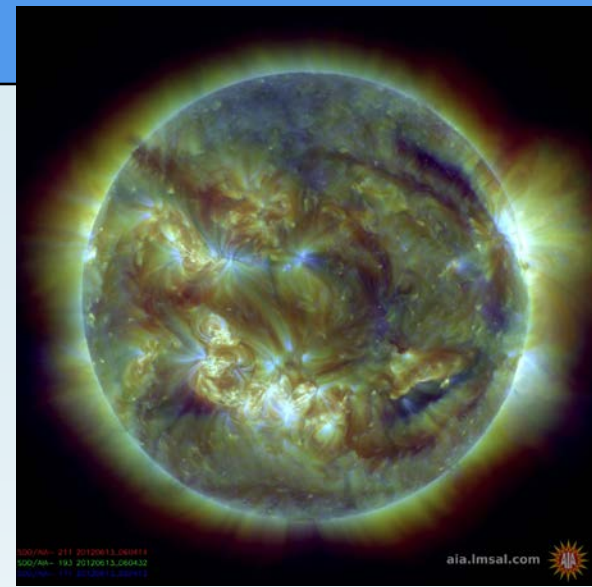
Imaging vs. Spectroscopy

	Advantages	Disadvantages
Imaging	High time cadence; easy to analyse	Ambiguous interpretations
Spectroscopy	Detailed plasma information: temperature, density, emission measure, abundances, velocities	Rasters can be slow; difficult to analyse; useful lines often weak

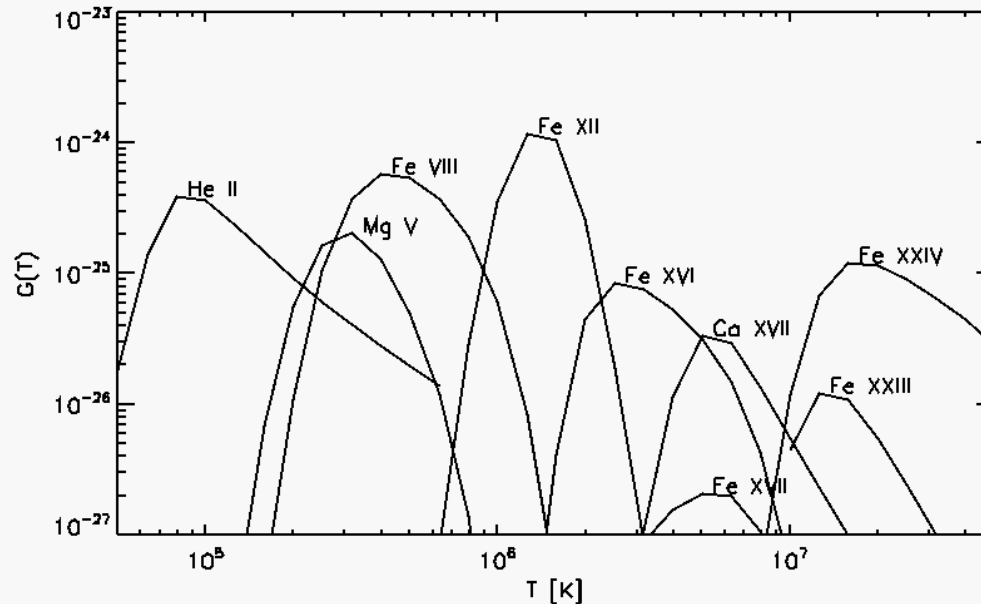
Best results are obtained by combining imaging and spectroscopic observations

SDO/AIA Channels (QS, CH & AR)

The AIA instrument observes solar plasma from photospheric to coronal temperatures, taking full-disk images, with high spatial resolution (~ 0.6 arcsec pixels) and with a cadence of 12 seconds.



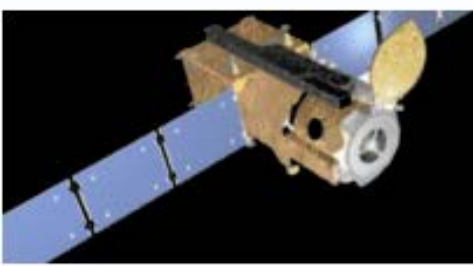
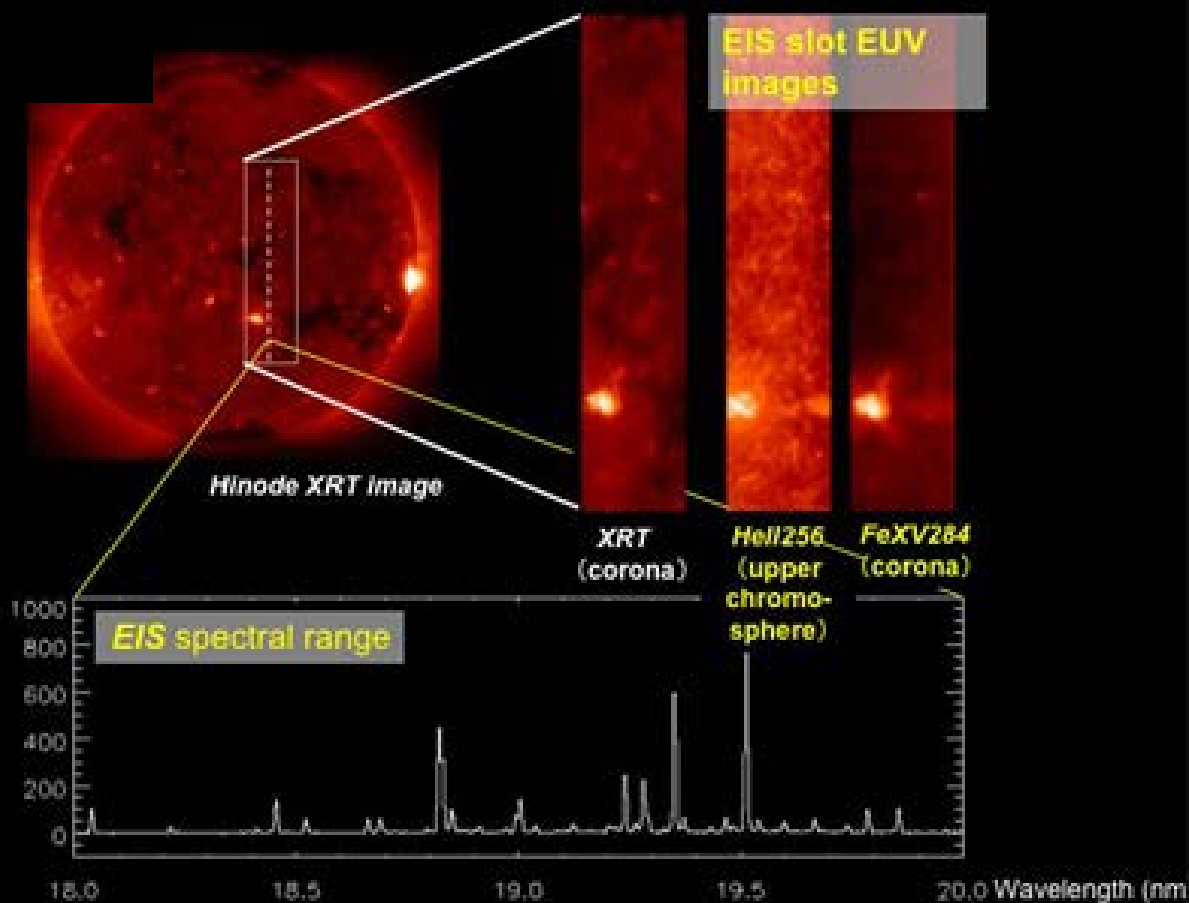
Channel	ion(s)	Region of atmosphere	log (T)
94 Å	Fe XVIII	flaring regions	6.8
131 Å	Fe VIII, Fe XXI	transition region, flare plasma	5.6, 7.1
171 Å	Fe IX	quiet corona	5.8
193 Å	Fe XII, Fe XXIV	corona and hot flare plasma	6.1, 7.3
211 Å	Fe XIV	active-region corona	6.3
304 Å	He II	chromosphere	4.7
335 Å	Fe XVI	active-region corona	6.4



Hinode EIS

Fig.3

Hinode EIS First Light



Hinode
EIS

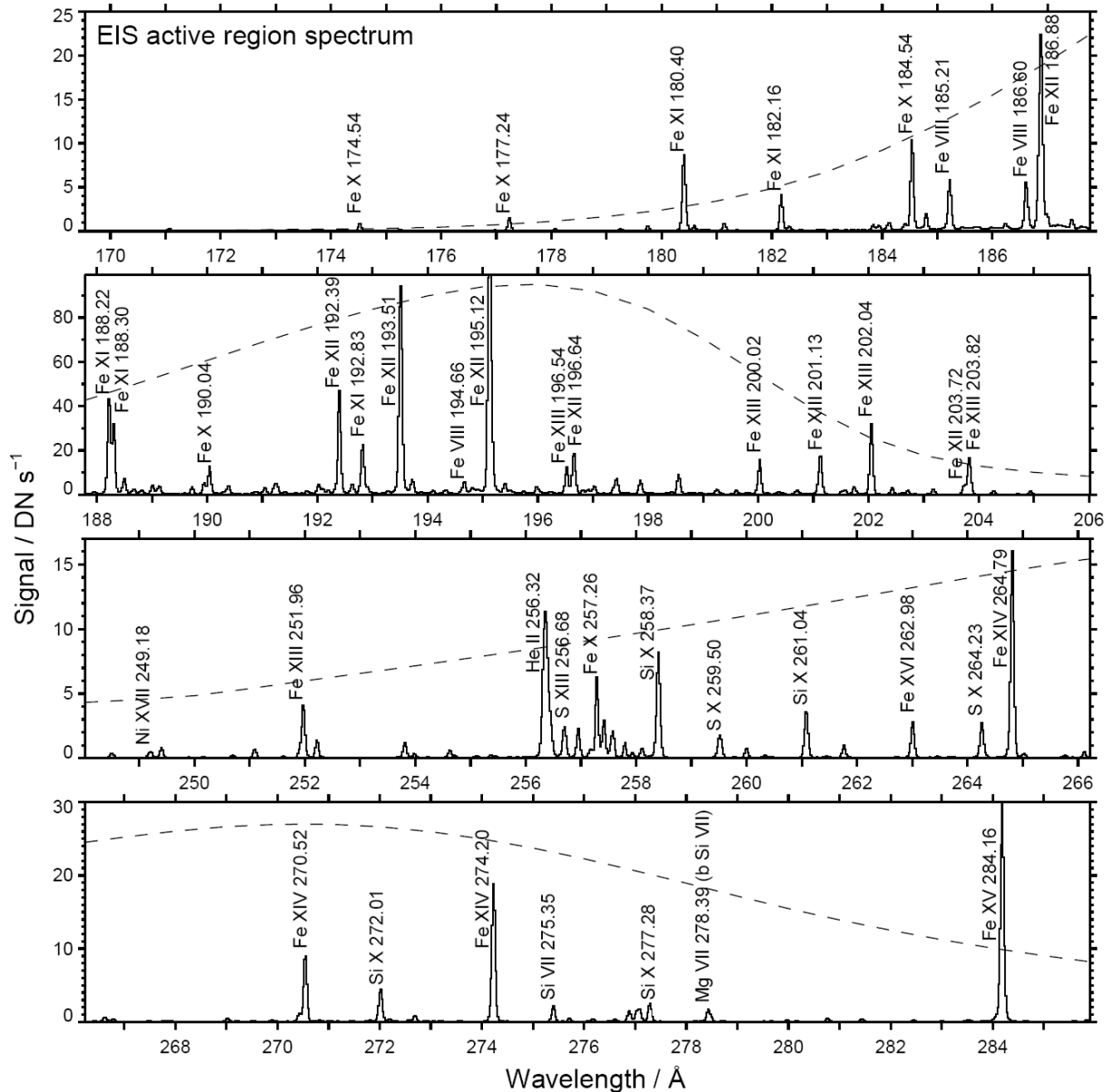


UCL

Hinode/EIS spectrum

- Spectrum dominated by coronal ions (iron, particularly)

Young, Mason et al. (2007)



Spectroscopic Diagnostics

The intensity of an optically thin emission line can be written as

$$I = 0.83 Ab(z) \int_h G(T_e, N_e) N_e^2 dh$$

$$G(T_e, N_e) = \frac{hc}{4\pi\lambda_{i,j}} \frac{A_{ji}}{N_e} \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)}$$

The expression for the line intensity can be expressed in this form:

$$I = 0.83Ab(z)G_0 \int N_e^2 dh.$$

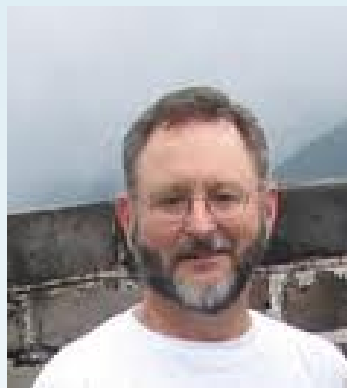
The emission measure, EM and filling factor, ϕ , for the emission line is then:

$$EM = \int N_e^2 dh$$

$$\phi = \frac{EM}{N_e^2 h_{app}}.$$

CHIANTI

An atomic database for astrophysics



Ken



Helen



Giulio



Enrico



Peter

- UK, USA, Italy
- First database to make atomic data freely available for astrophysics
- First released in 1996
- Latest release v7.1
- Improved coverage in X-ray range (addressing 94A)
- CHIANTI Py
- Over 1,800 citation
- CHIANTI v8, 2015

Landi, Young, Dere, Del Zanna & Mason, 2013, ApJ, 763

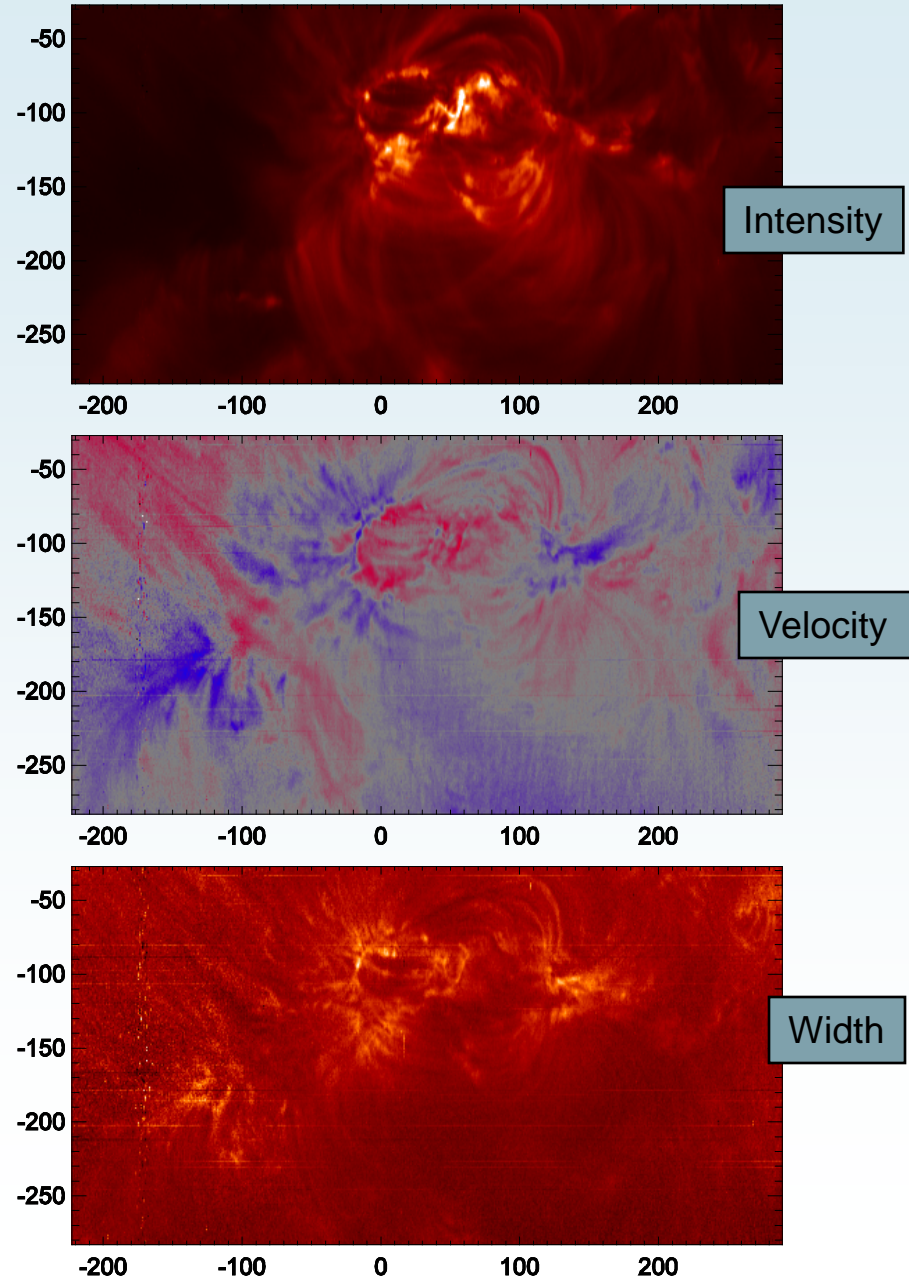
Hinode/EIS: Intensity, velocity and line width maps

Active region map in Fe XII 195.12 Å, 2MK

Hinode/EIS can provide **detailed** maps of intensity, electron density, temperature, flows, non-thermal broadenings, and fill factors.

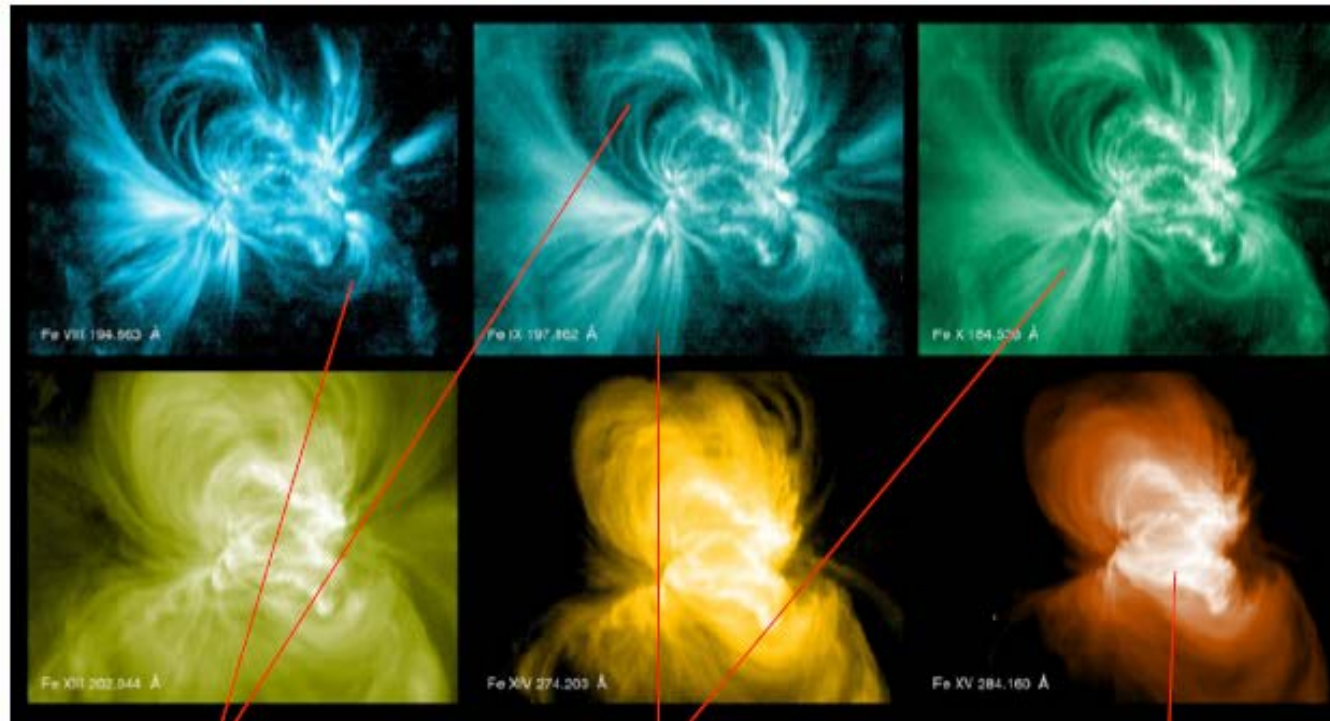
One of the most striking features of Hinode EIS data for active regions are the blueshifts and redshifts.

Young, 2007



AR features seen with Hinode EIS

Monochromatic images of an active region in spectral lines of iron ions formed at different temperatures from EIS/Hinode



warm loops (1 MK)

cool fan loops (< 1 MK)

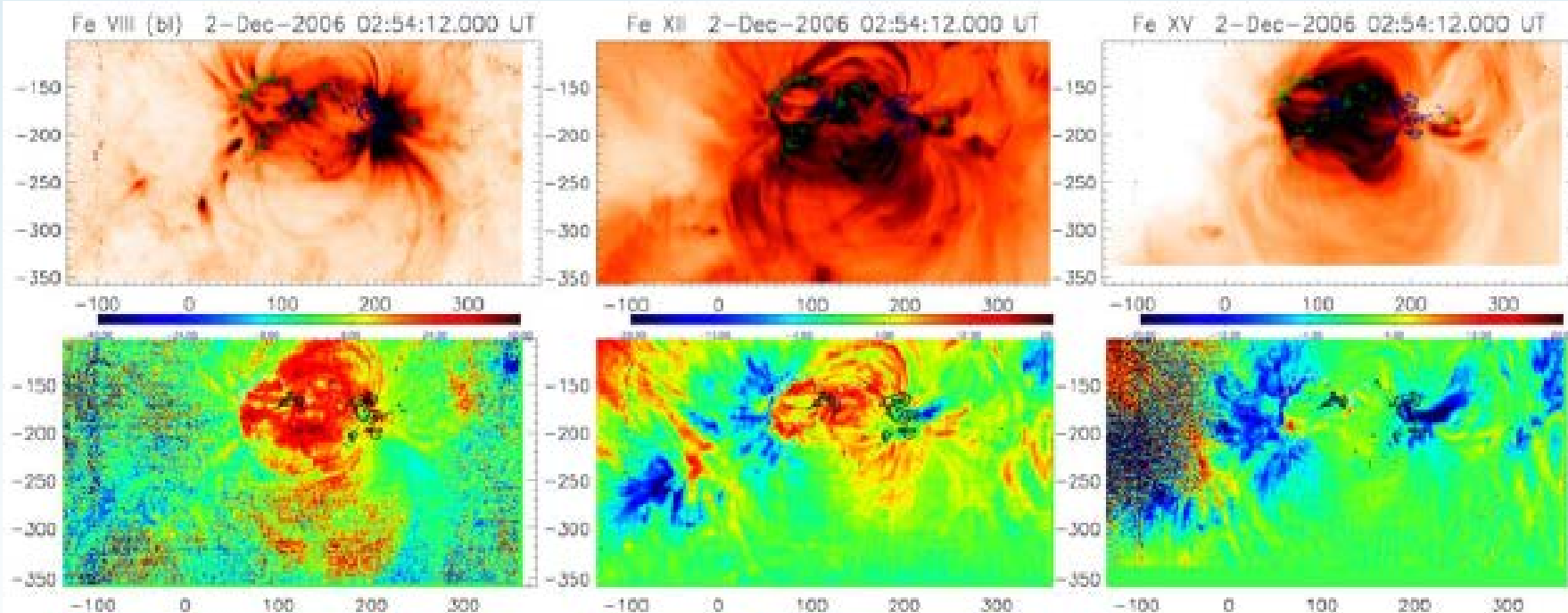
core (> 2 MK)

EIS – Intensity (reversed) and doppler maps

FeVIII – 1MK

FeXII – 2MK

FeXV – 3MK



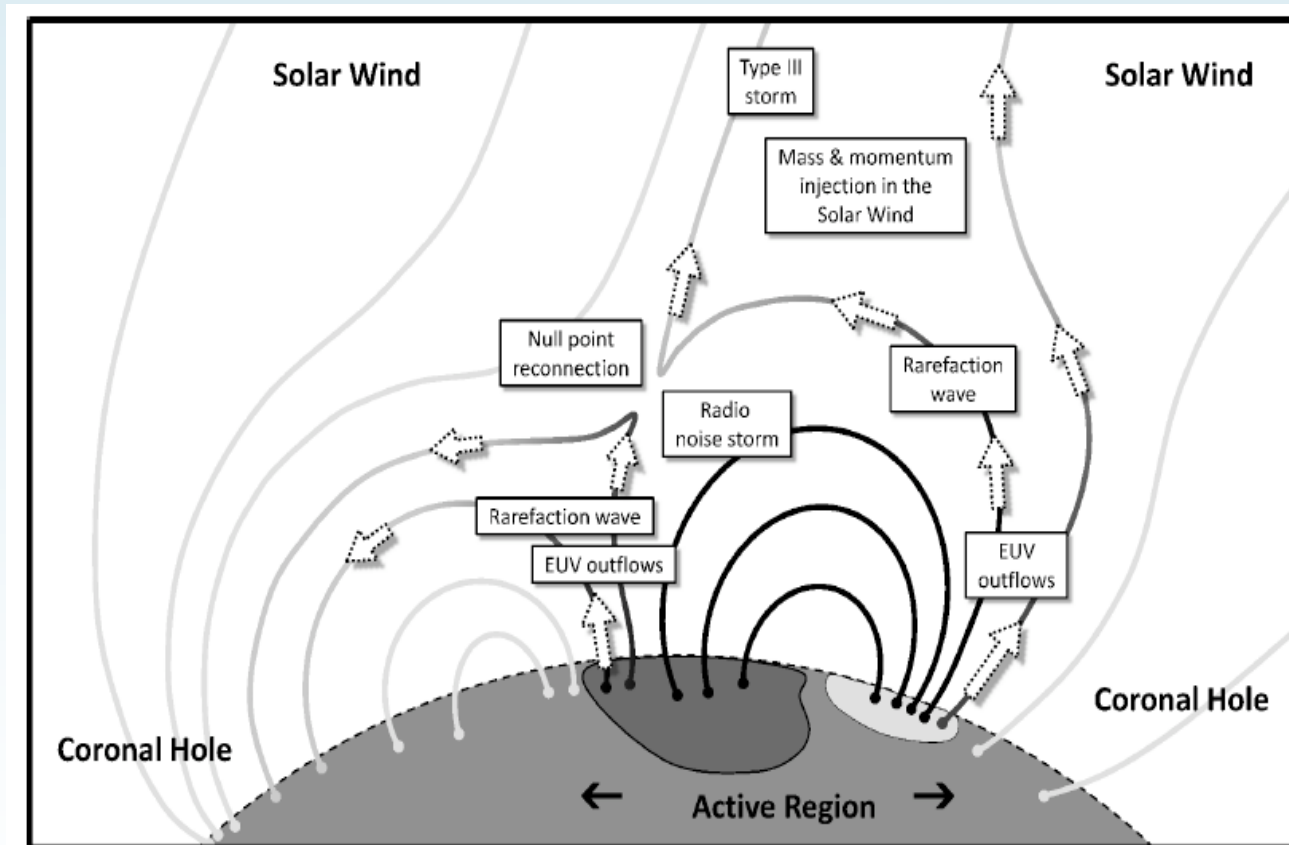
Monochromatic (negative) images and dopplergrams of an active region (NOAA 10926) observed with Hinode/EIS in Fe VIII, Fe XII, Fe XV lines.

Courtesy of G. Del Zanna

Hinode/EIS active regions – blue shifted emission

Del Zanna, Aulanier, Klein & Torok, 2011

Bradshaw, Aulanier & Del Zanna, 2011

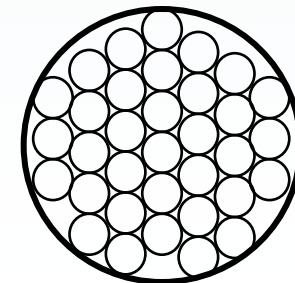
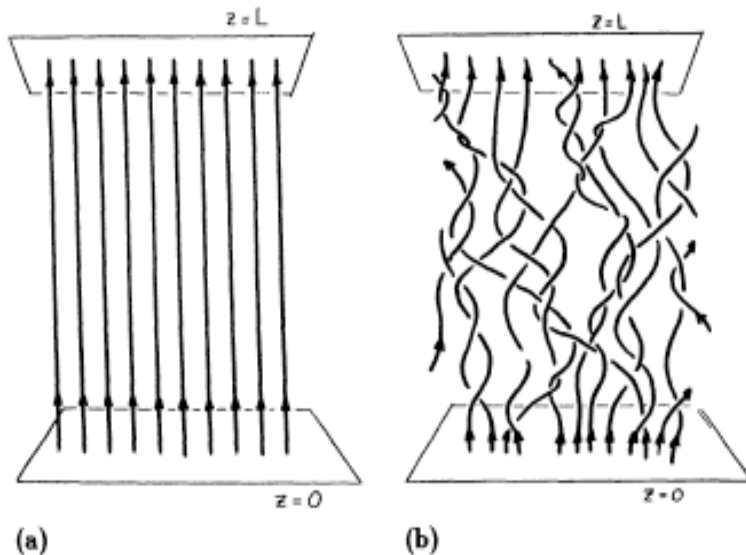
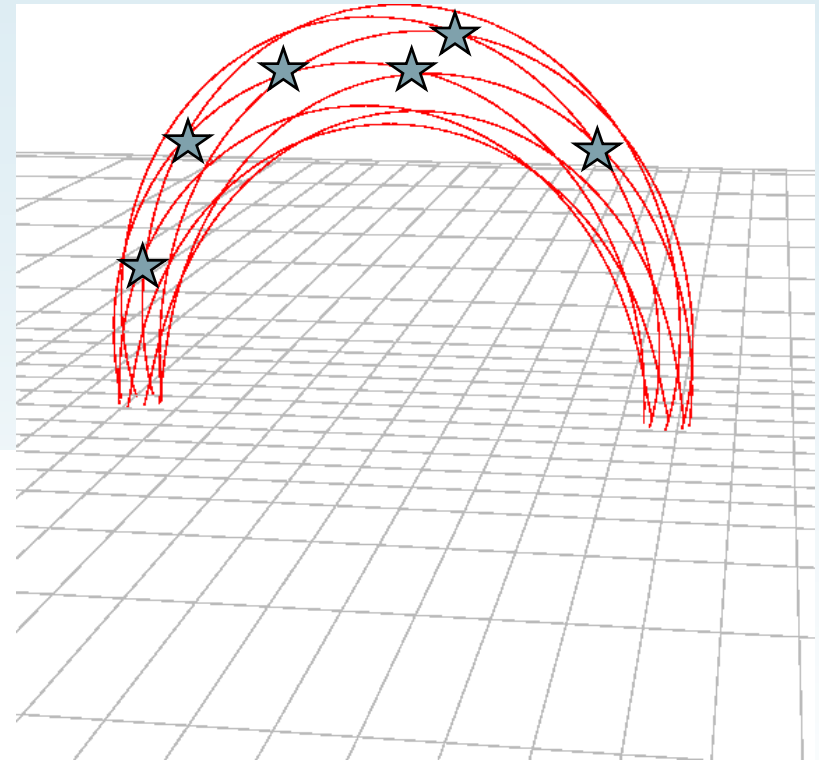
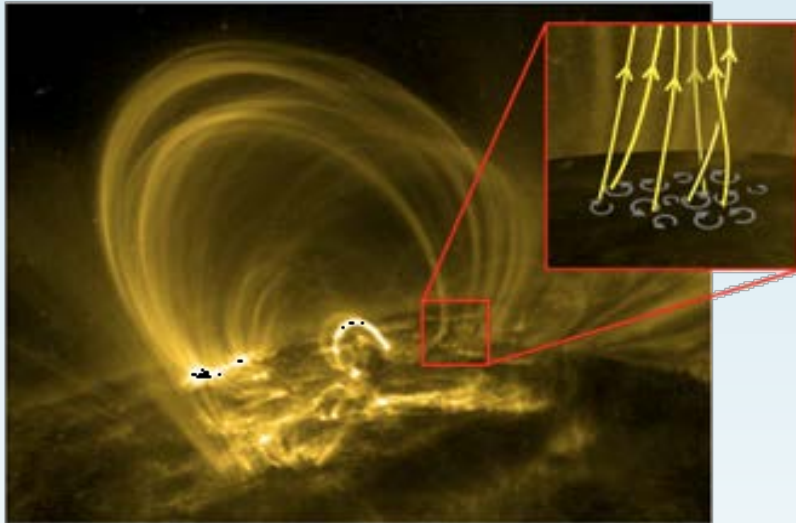


Interchange reconnection close to the null point, between the closed, high-density hot loops and the neighbouring open, low-density ones. Upflows driven by the rarefaction wave.

Some warm loops and some open loops would be formed in this way.

How are solar active regions heated ?

Braiding of the magnetic field and nano-flare heating – Parker, 1991

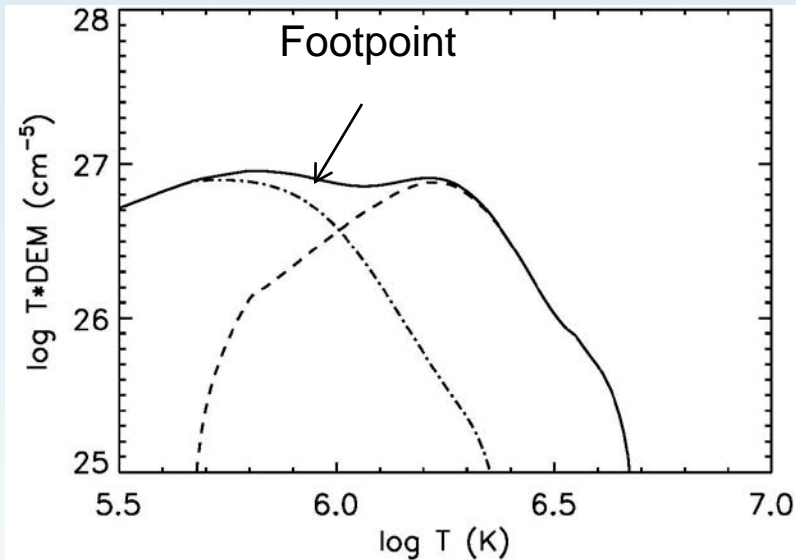


Strands
within
a loop
Structure ?

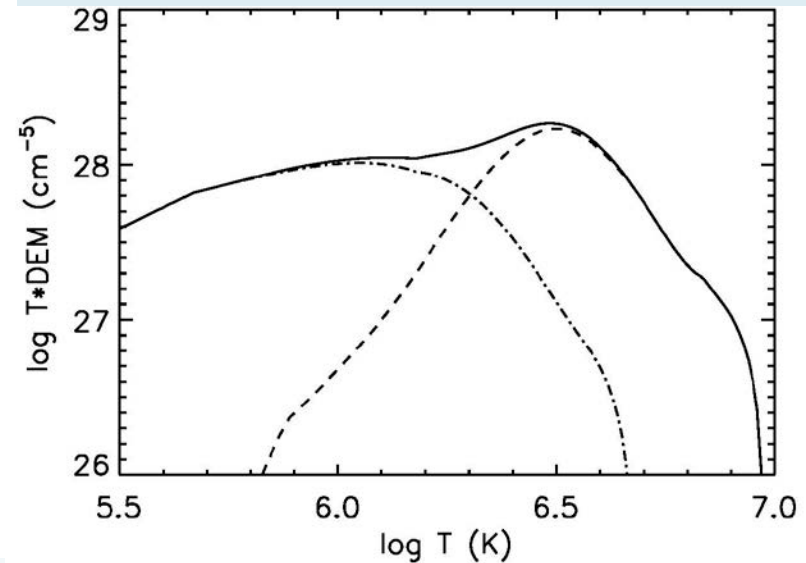
Fig. 2. (a) A sketch of the initial uniform magnetic field B_0 through $0 < z < L$. (b) A sketch of the continuous field of equation (2).

Shape of the DEM curves for different heating scenarios

Weak Impulsive (Nanoflare)



Strong Impulsive (Nanoflare)



EBTEL – Enthalpy Based Thermal Evolution of Loops

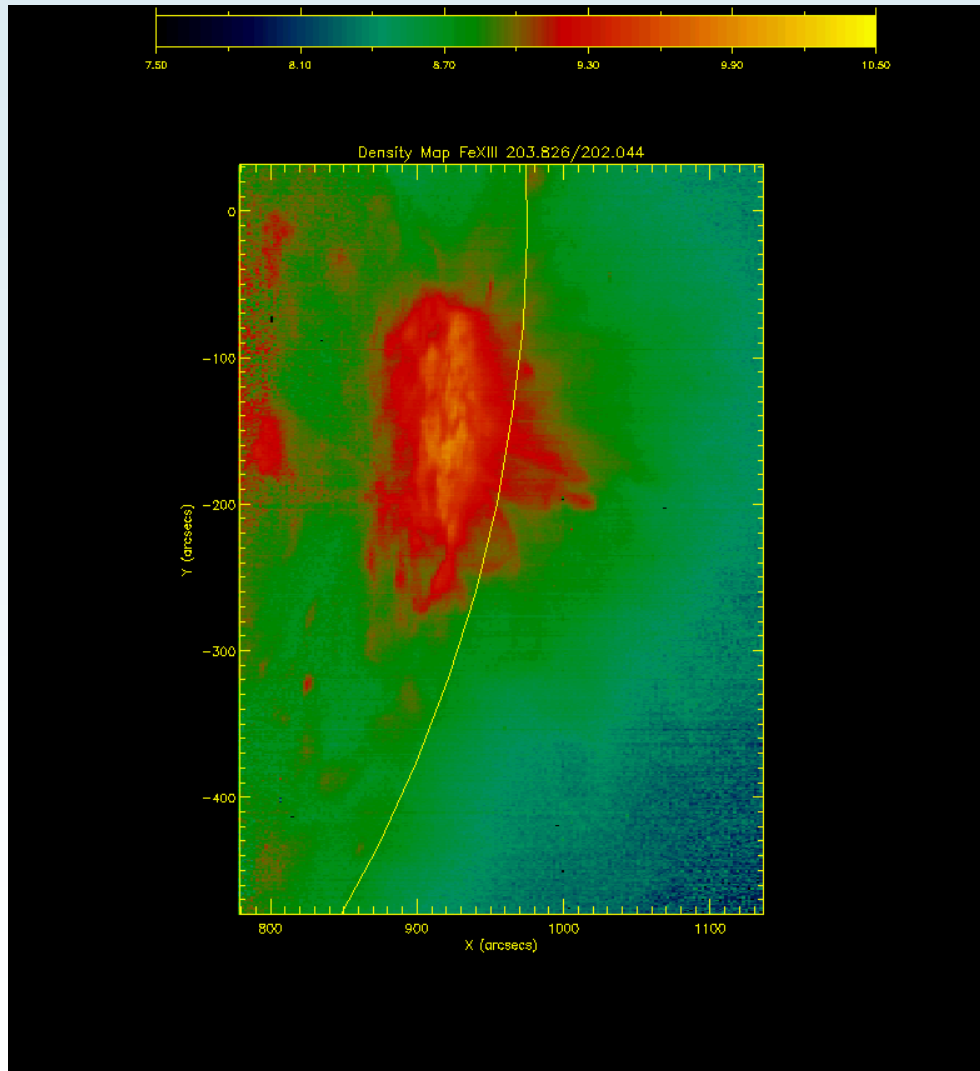
Hot plasma predicted to be **very faint** (short lived, rapid cooling, low Ne):
EM (cm⁻⁵) reduced by **1-1.5 orders** magnitude from peak

Do we see high temperature emission in non-flaring ARs?

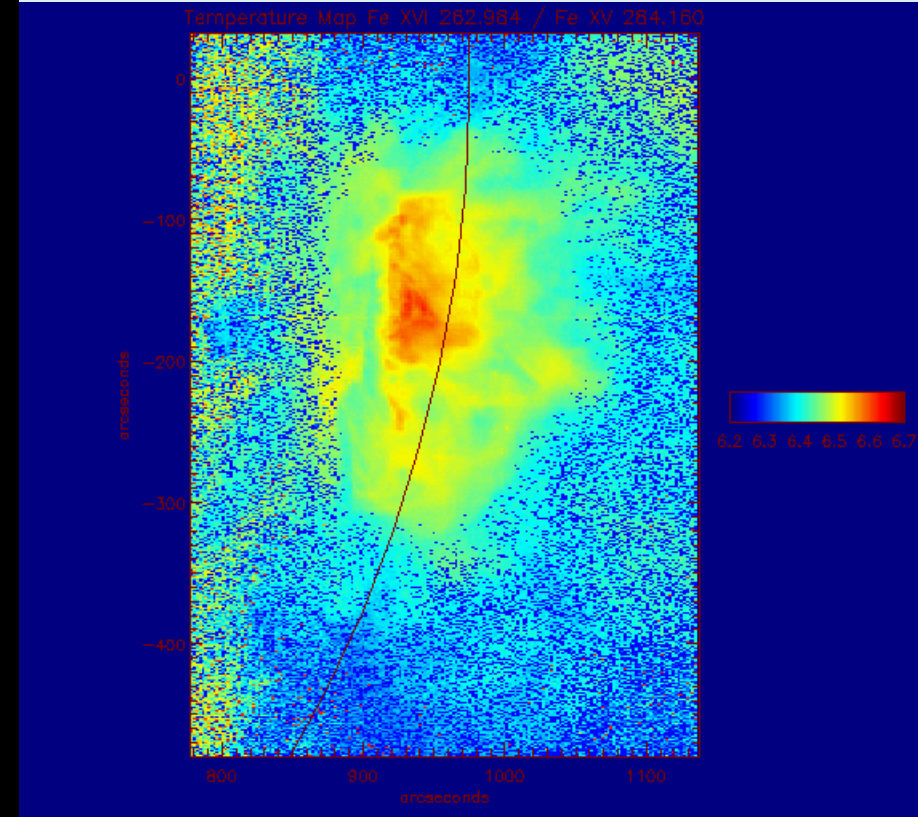
Klimchuk, Patsourakos and Cargill (2008)

Average temperature and density maps for the AR

Average electron density map from FeXIII lines



Temperature map from FeXVI/FeXV Red is Log T = 6.7, yellow is Log T = 6.5



O'Dwyer, Mason et al, 2011

AR EM distribution & implications for nano-flare heating

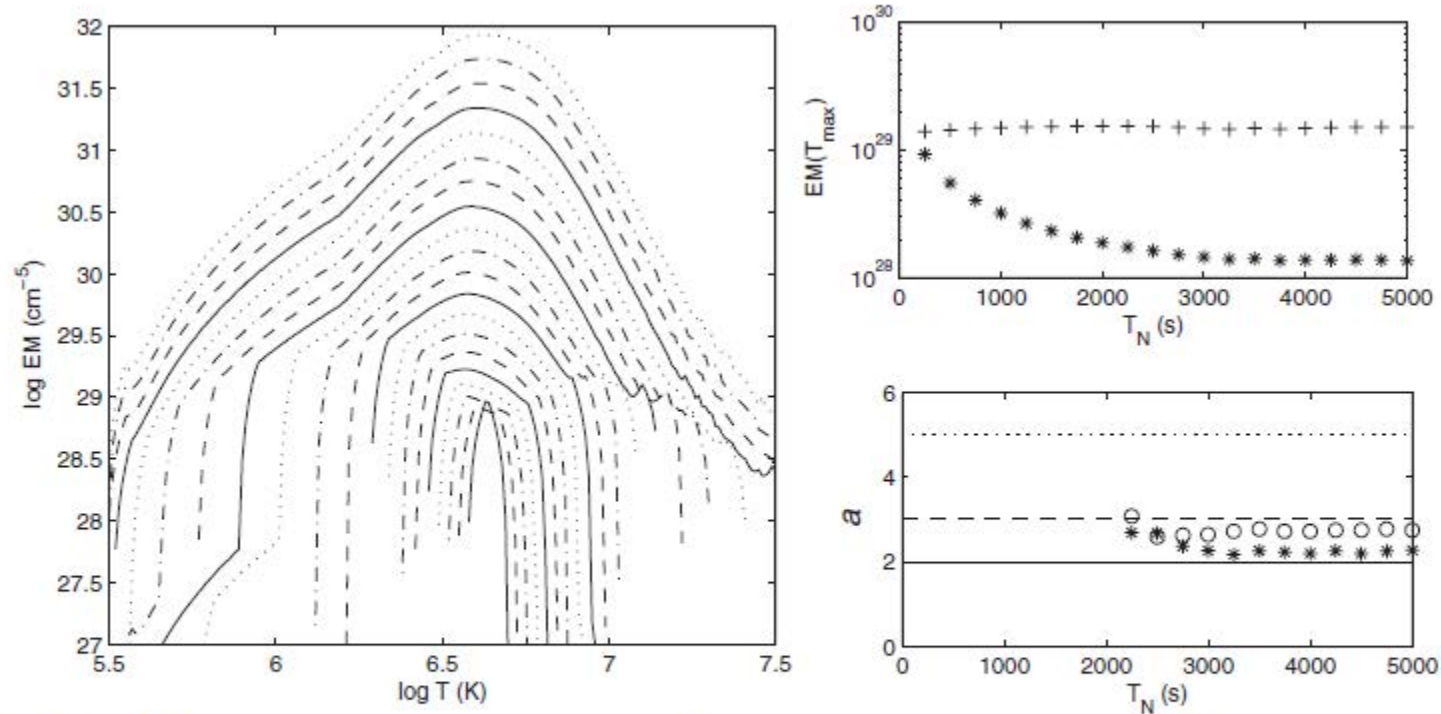
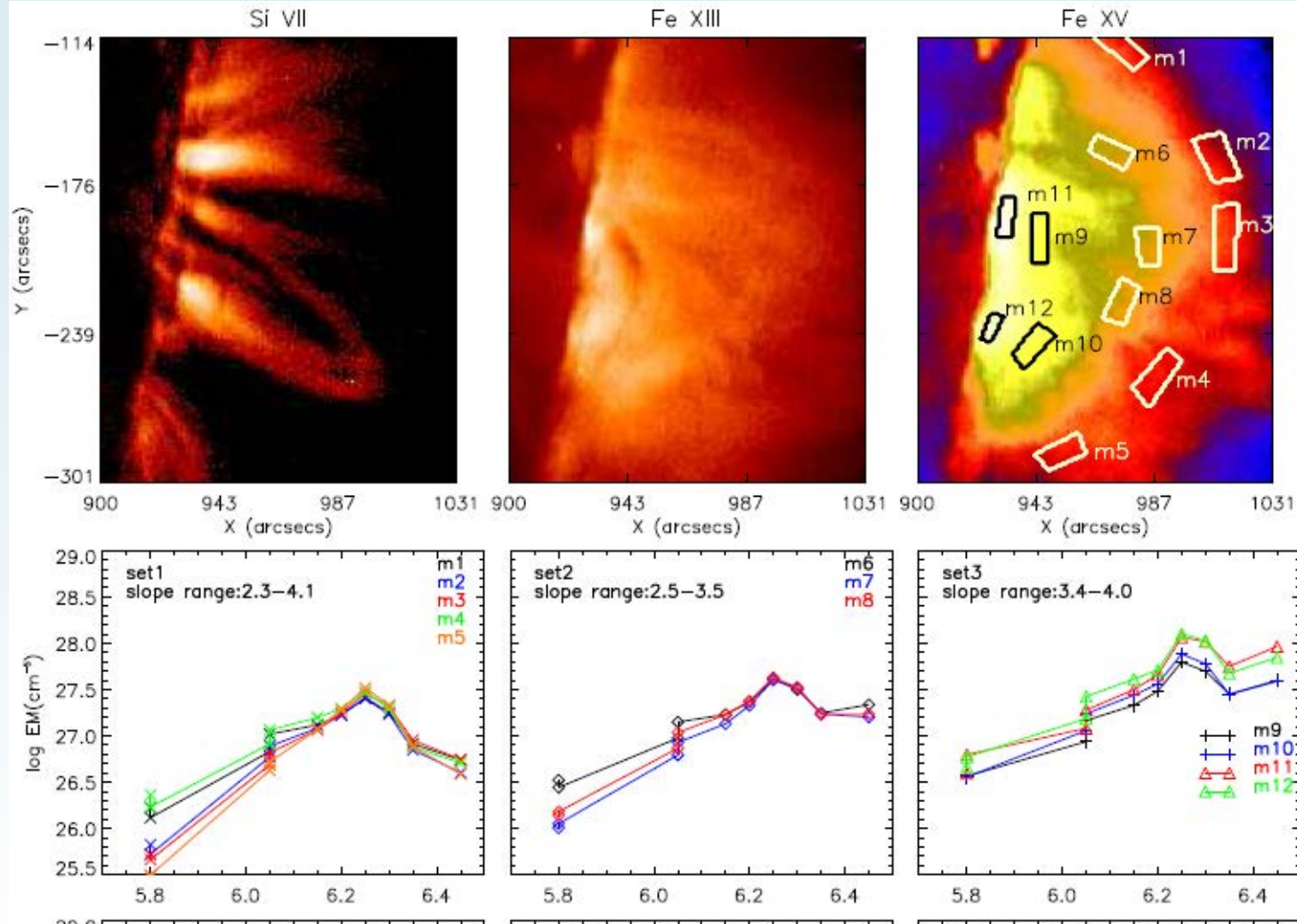


Figure 2. Left panel shows the emission measure as a function of temperature for nanoflare trains with constant energy nanoflares. The 20 curves are associated with different delay times between the nanoflares (T_N between 250 and 5000 s). The lowest curve corresponds to $T_N = 250$ s and the highest to $T_N = 5000$ s. Each curve is shifted vertically by 0.2 on a log scale with respect to the previous one as T_N increases. The four line styles break T_N up into groups of 1000 s. The top right panel shows the maximum value of the emission measure; the upper curve (+) shows the EM integrated over the entire temperature range. The lower right shows the slope of the emission measure below the maximum temperature. The three horizontal lines correspond to $a = 2, 3,$ and 5 . Solutions where the EM vanishes at a temperature above $10^{6.25}$ are not shown so that only the upper 12 curves on the left are represented. Stars and circles are the EBTEL08 and RL12 radiative losses.

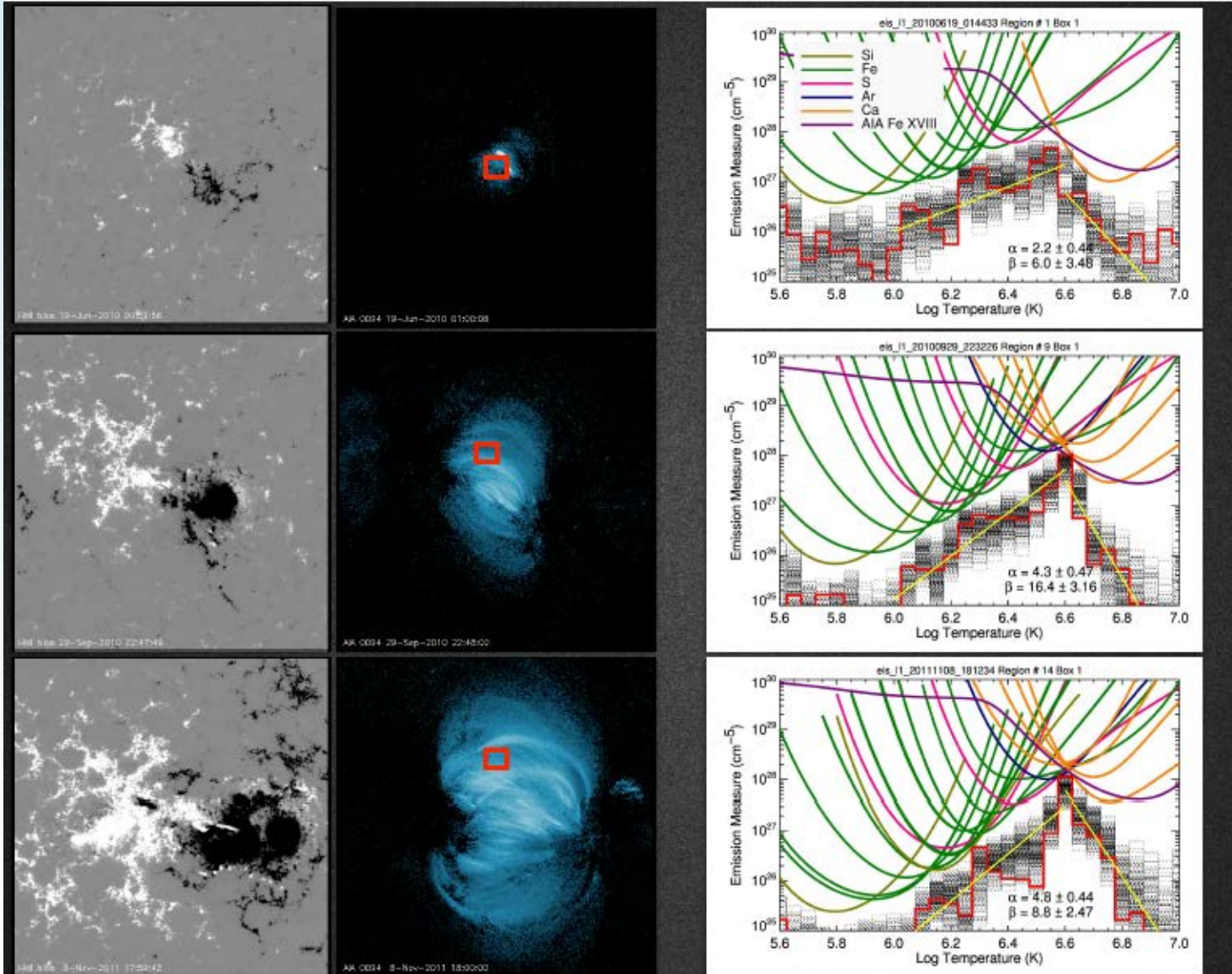
Cargill, 2014

EM Distribution for diffuse regions in ARs

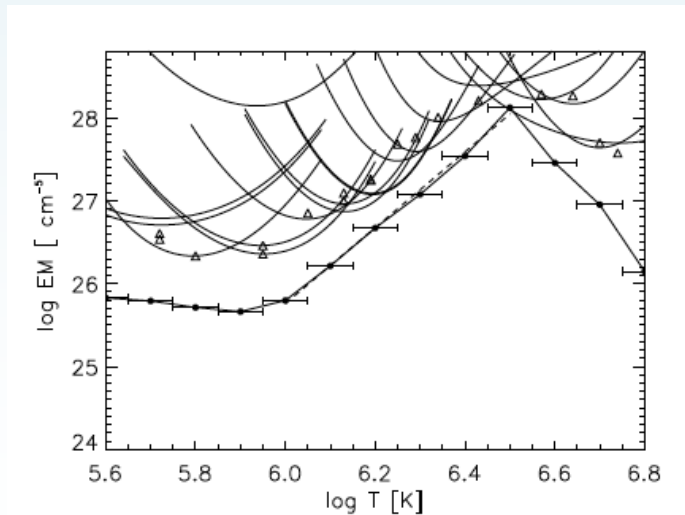
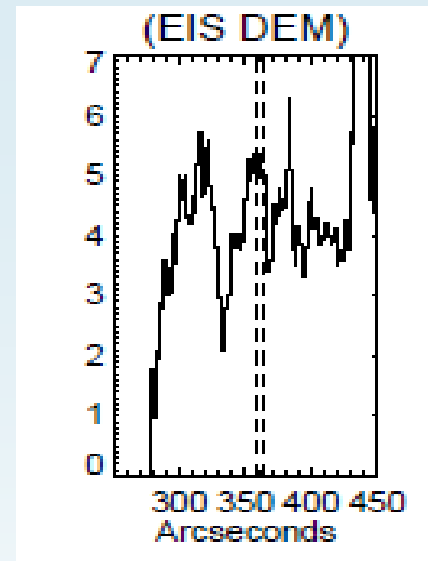
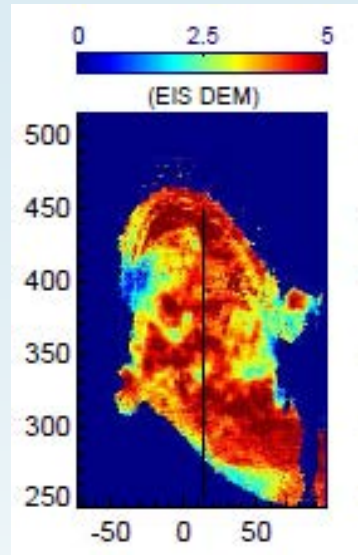
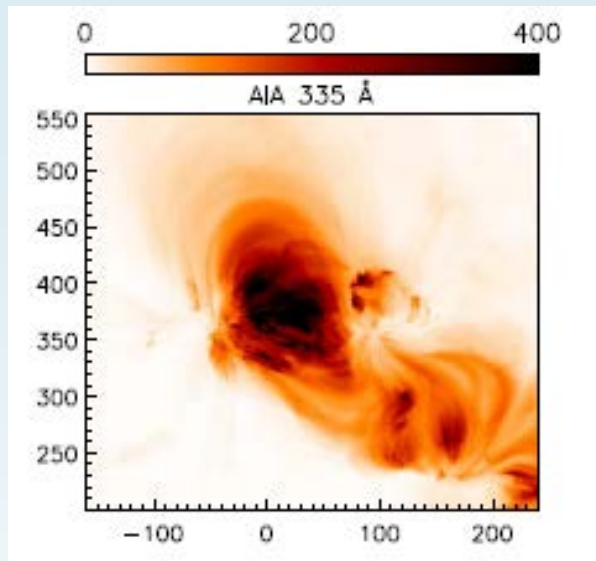


Diffuse region is Set 1
EM Peak at Log T = 6.5, EM slope = 2.3-4.1
Both low and high frequency impulsive heating

AR Core – Slope of EM between LogT = 6-6.6



Hot Core - Slope of the EM (1-3MK)

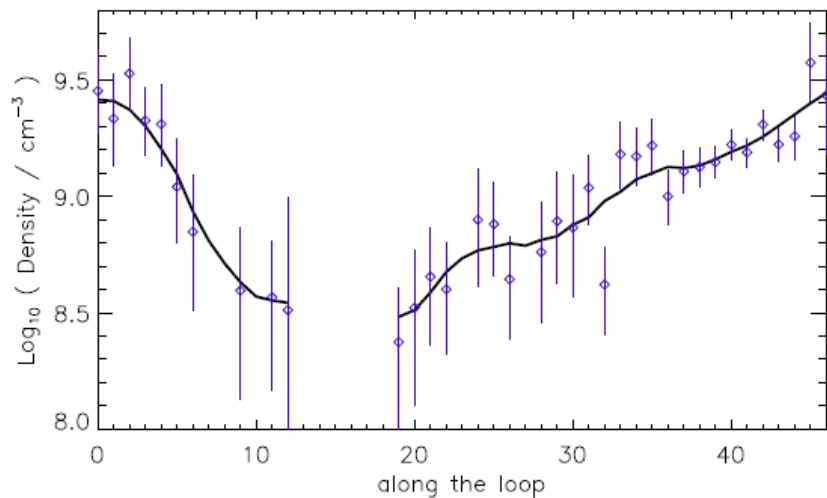


[EM(T) \propto T^b] in the 1–3 MK range

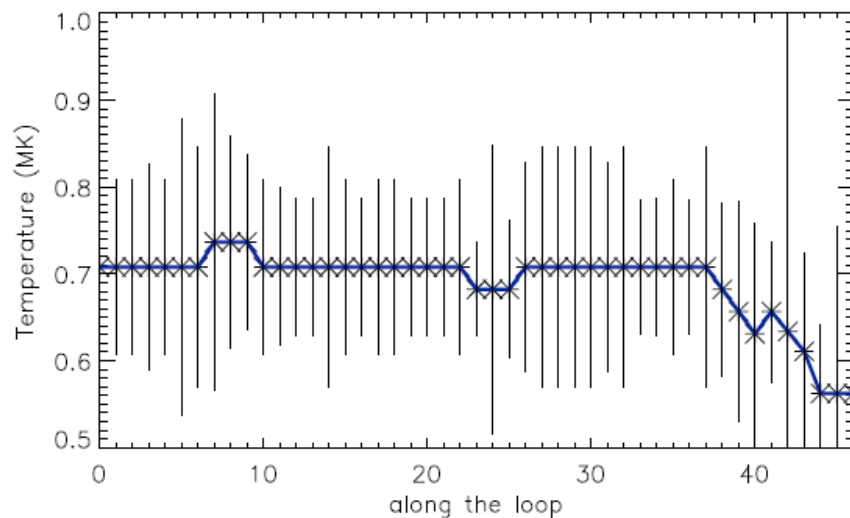
Result for slope, $b = 4.6$

Following on from earlier work by:
Tripathi, Mason and Klimchuk, 2010
Tripathi, Klimchuk and Mason, 2011

Density and Temperature variation along a loop

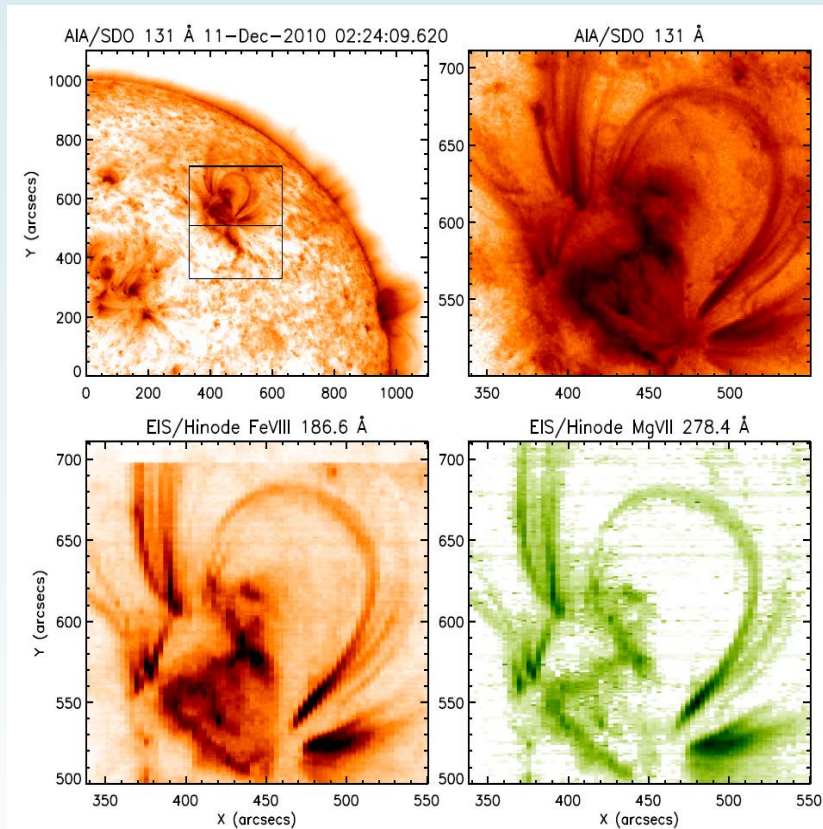


Density from MgVIII 280/278



Temperature from EM Locii method

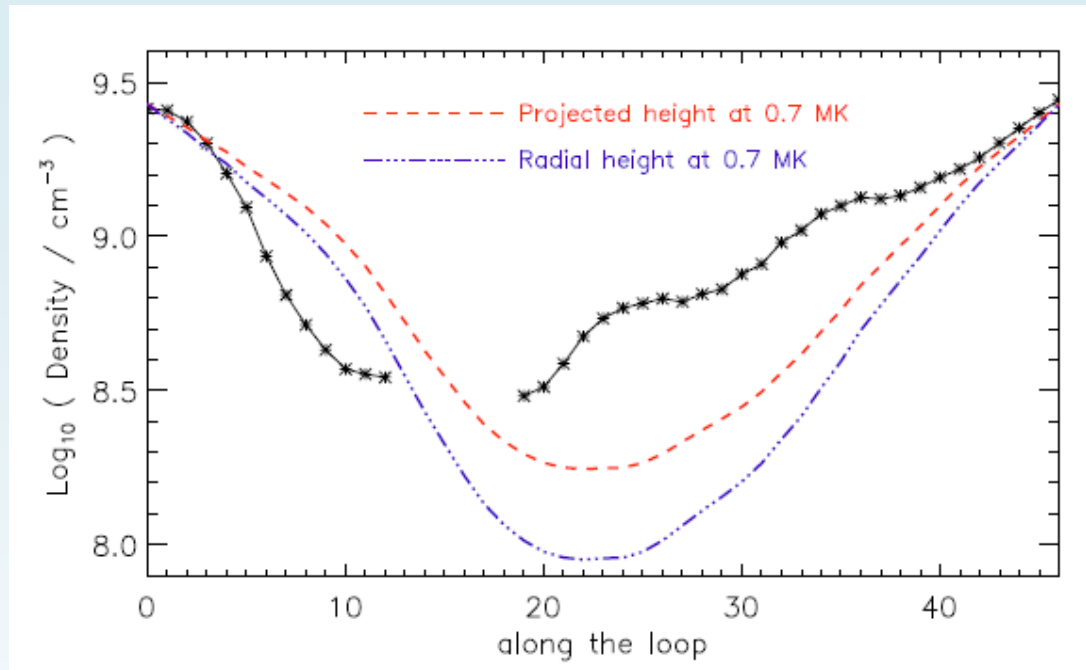
SDO/AIA and Hinode/EIS



Gupta, Tripathi & Mason, 2014

Following on from:
Tripathi, Mason, Dwivedi, Del Zanna & Young, 2009
Tripathi, Mason, Del Zanna & Bradshaw, 2012

Comparison with hydrostatic model



Loop is **asymmetric**

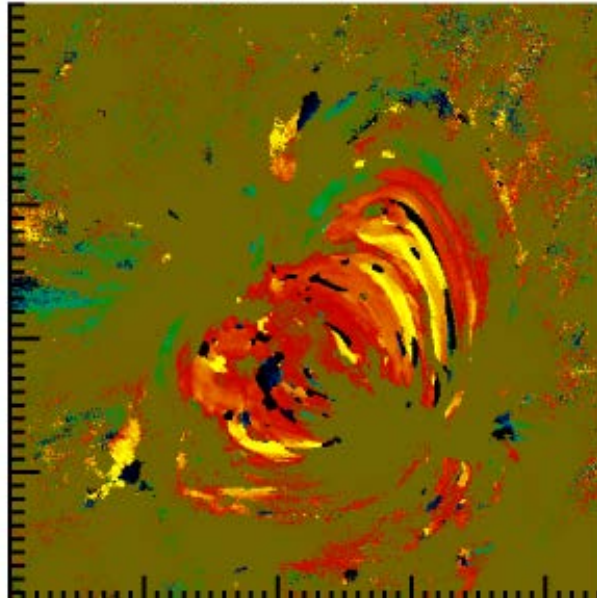
Right part of the loop - overdense

Left part of the loop - underdense

Gupta, Tripathi & Mason, 2014

Cooling in ARs is everywhere

335-211 (~3 MK~2 MK)



-6000 -3000 -1500 0 1500 3000 6000

Time Offset (s)

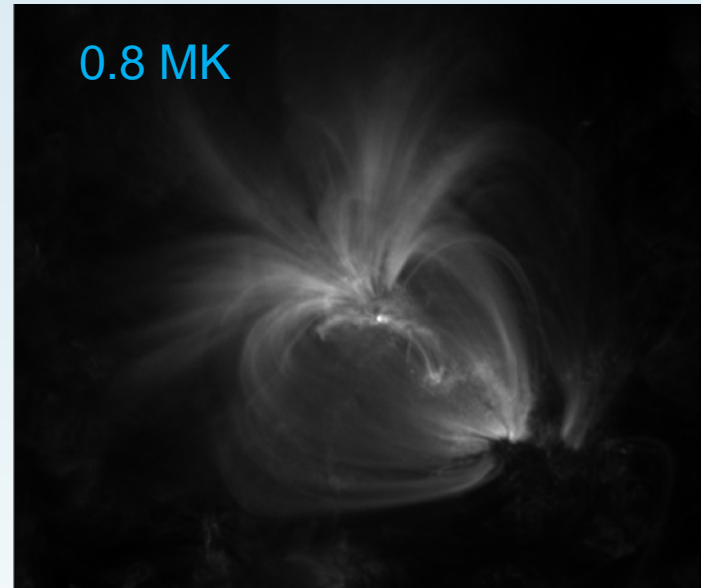
Negative time lags: noise; slow heating

zero time delay: transition region/moss

Positive time lags: post-nanoflare cooling

SDO/AIA 171

0.8 MK

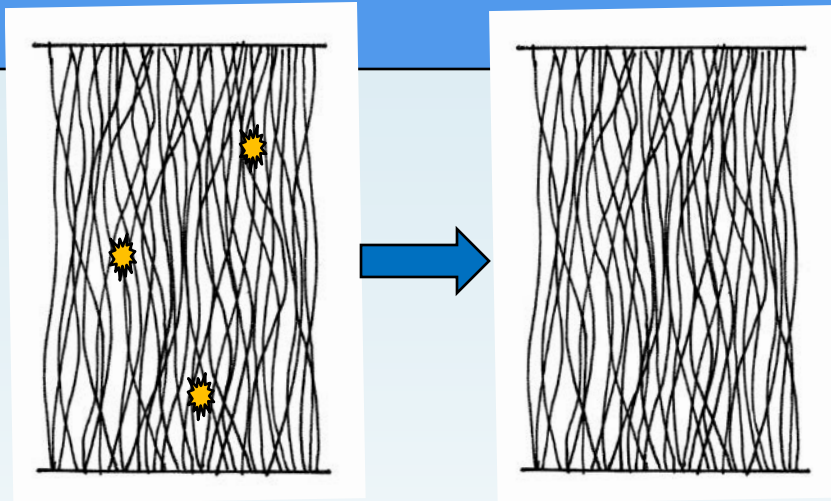


- Almost exclusively positive time lags
- Not just at a few discrete loops, but everywhere
- Persistent pattern of cooling throughout active region

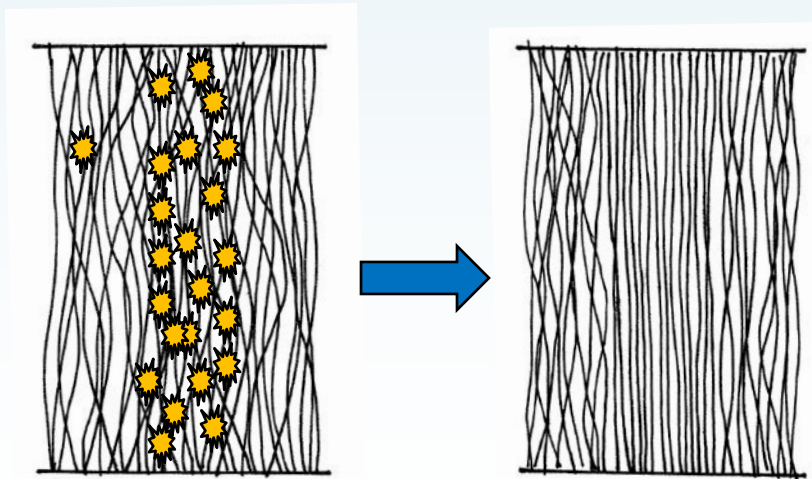
Viall & Klimchuk, 2012, 2013

1D Models (Klimchuk)

Impulsive energy release on a small cross-field spatial scale (regardless of mechanism)



Background corona



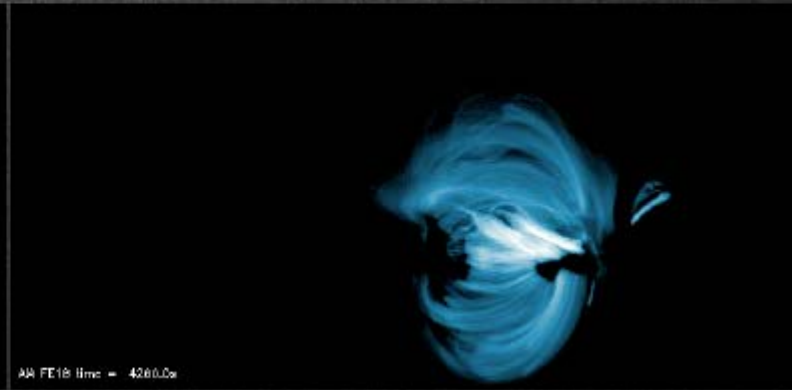
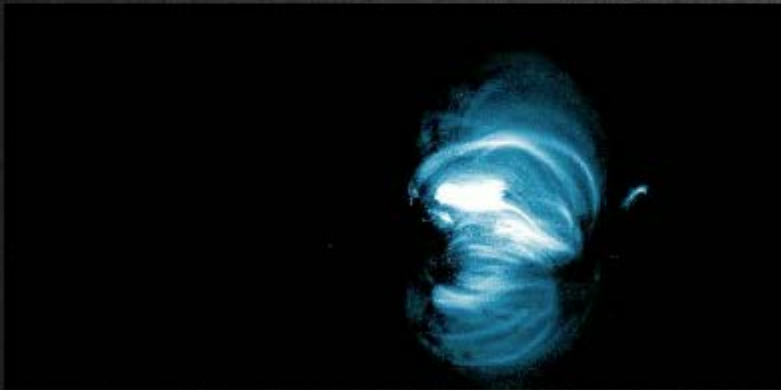
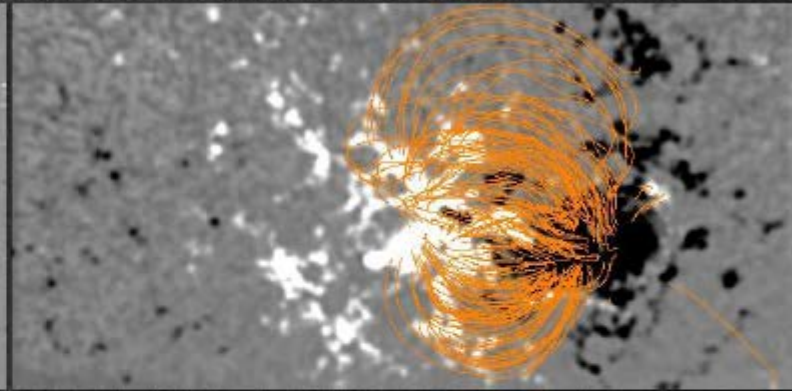
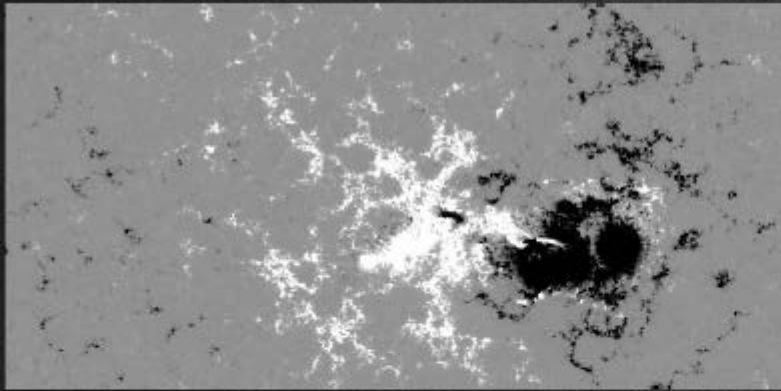
Loop brightening

Nanoflare
Storm

Needs time to
"recharge"

Simulating the heating of coronal loops

NLFF: Wiegelmann et al. (2012)



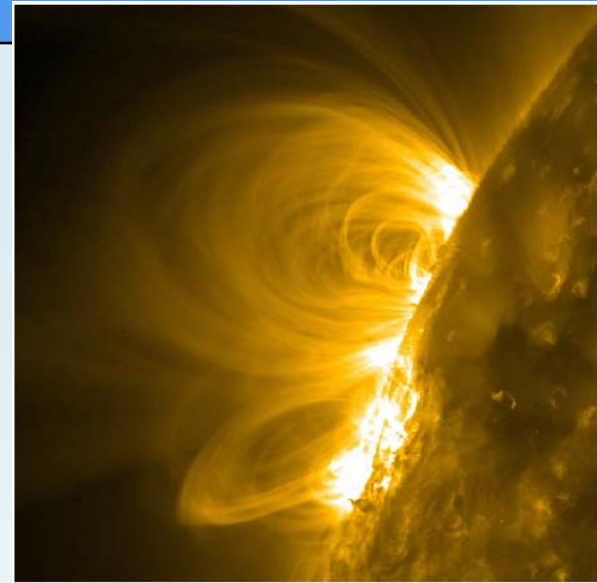
EBTELv2: Cargill et al. (2012)

- Magnetic field extrapolation
- Solve hydrodynamic equations for each loop
- Simulate observations in the UV
- Compare with REAL observations

Warren et al, 2014, also Bradshaw et al, 2014

Summary

- Observations are finally starting to contribute to the coronal heating problem
- The 0D and 1D Hydrodynamic models provide the best ‘observables’
- Coronal loops appear to be multi-thermal and multi-stranded
- 1MK loops have flows, may be asymmetric
- Caution – may be errors in analyses and atomic data (Gennou)
- EM diagnostics are consistent with impulsive heating
- ARs have a high temp ($>6\text{MK}$) component, FeXIX, (Innes, Brosius)
- Cooling is ubiquitous in ARs
- The hot core moss has transient components (HiC – Testa, 2014)
- Non-equilibrium? Non- Maxwellian?
- Best results from Imaging + Spectral instruments



LOOPS-7 – Cambridge, 20-24 July 2015

The End

