

# Features in the Transition Region and Corona and a view by IRIS



MAX-PLANCK-GESELLSCHAFT

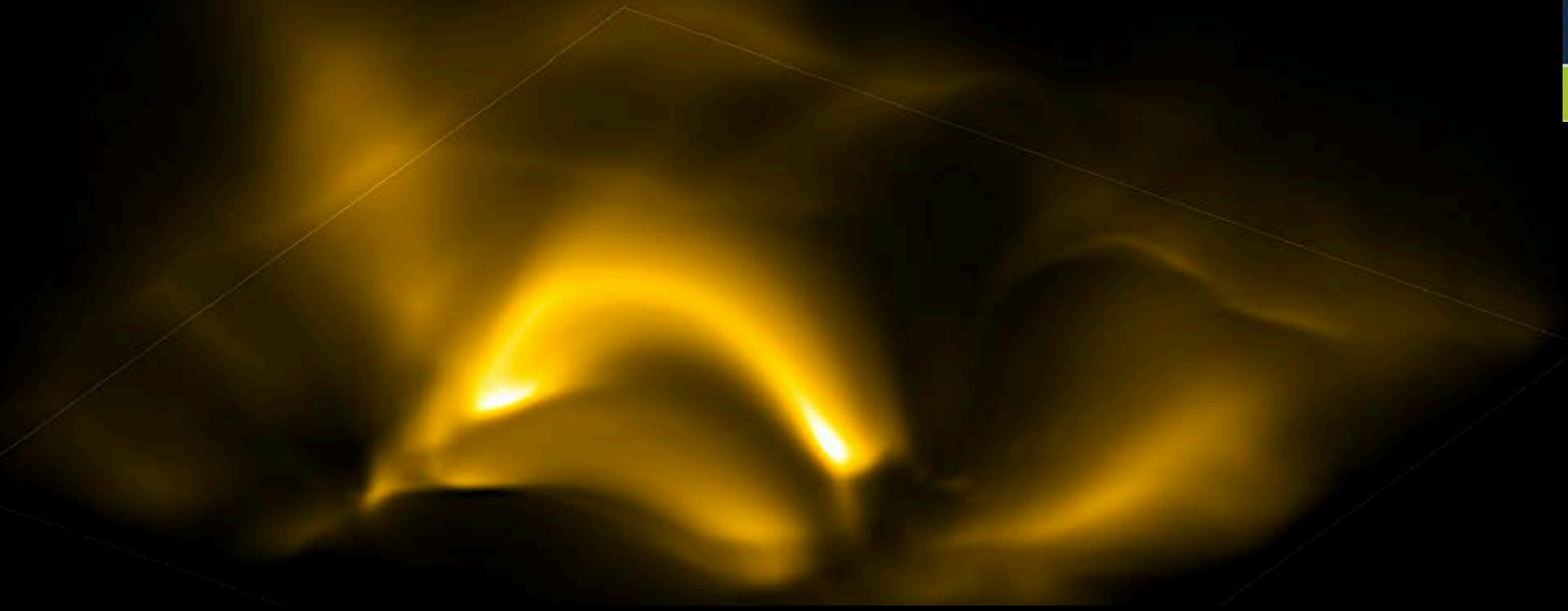


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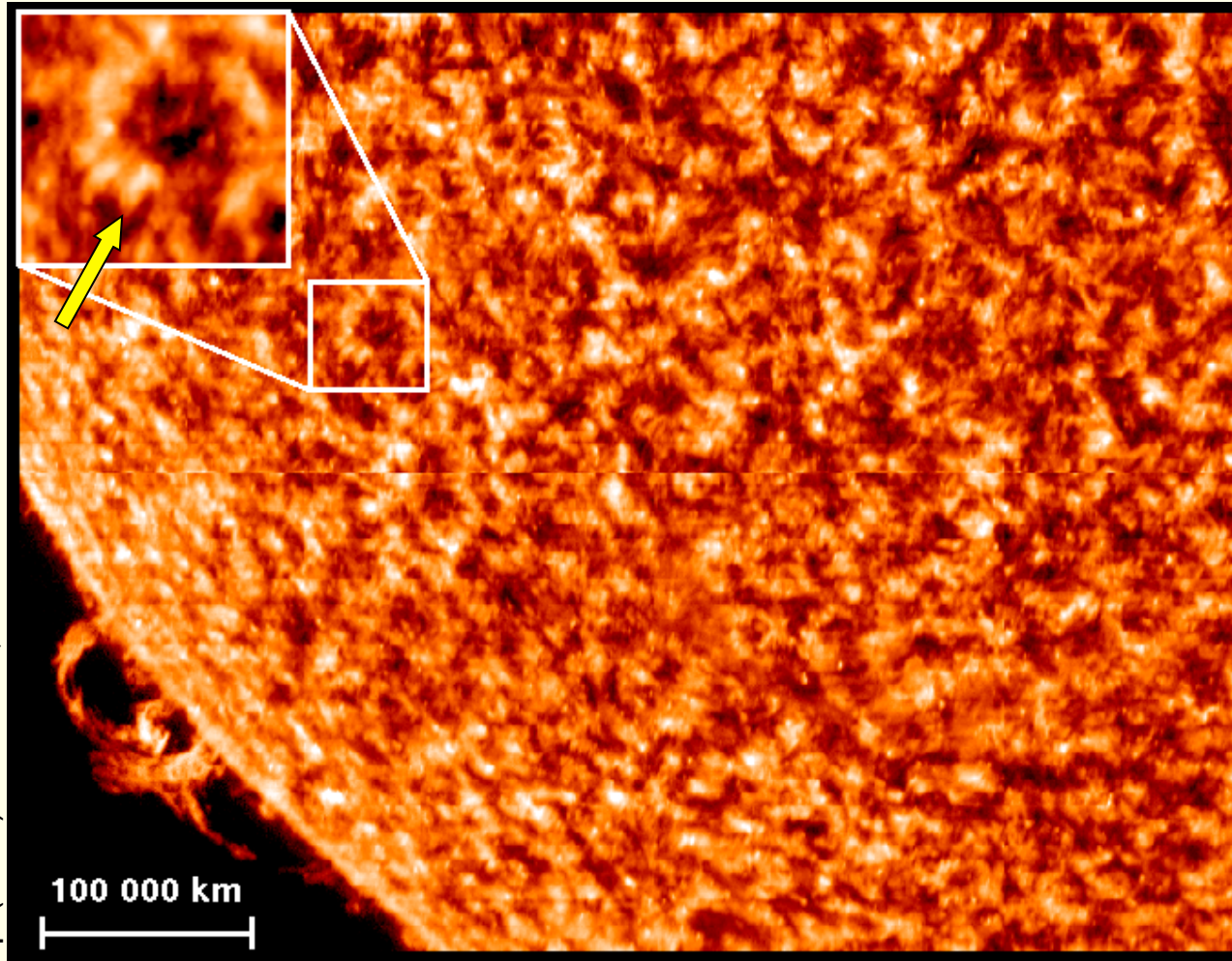
**Loops  
throughout  
the  
atmosphere**

# Transition region: small loops

- small loops across network-boundaries
- low loops across cells

see also

Feldman et al. (2003), ESA SP-1274:  
"Images of the Solar Upper Atmosphere  
from SUMER on SOHO".



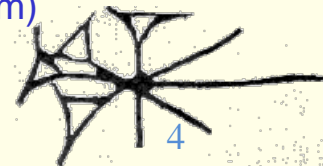
28.1.1996

C III (97.7 nm)

~80 000 K

**SUMER**

**EUV spectrograph**



# Unresolved fine structures with IRIS

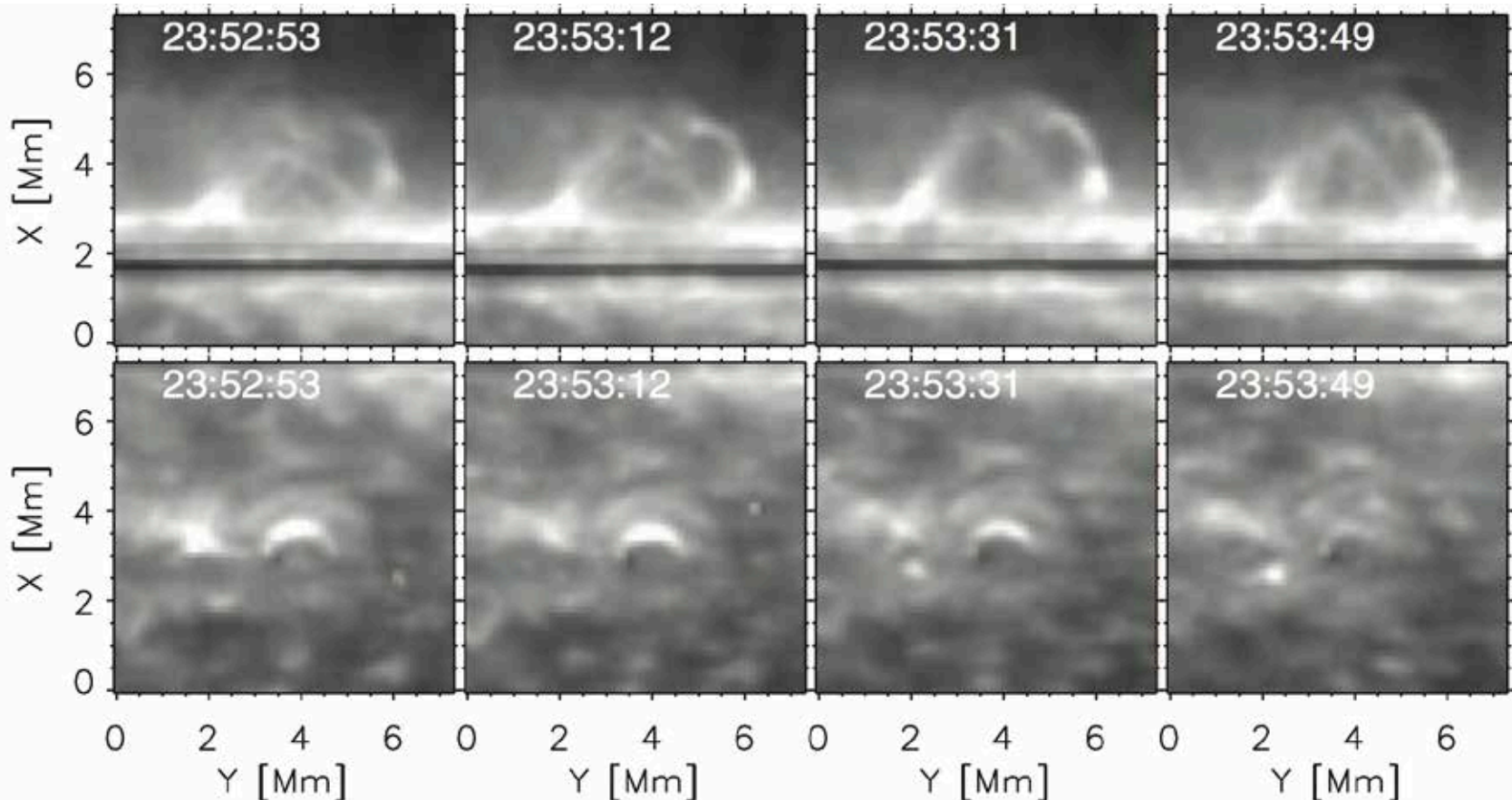
- ▶ **IRIS** shows ubiquitous small short-lived cool loops

(Hansteen et al. 2014, Sci 346, 1255757)

- ▶ short lifetime expected because such cool loops cannot find equilibrium

(Hood et al. 1979, A&A 77, 233)

temporal evolution over 1 minute with IRIS:



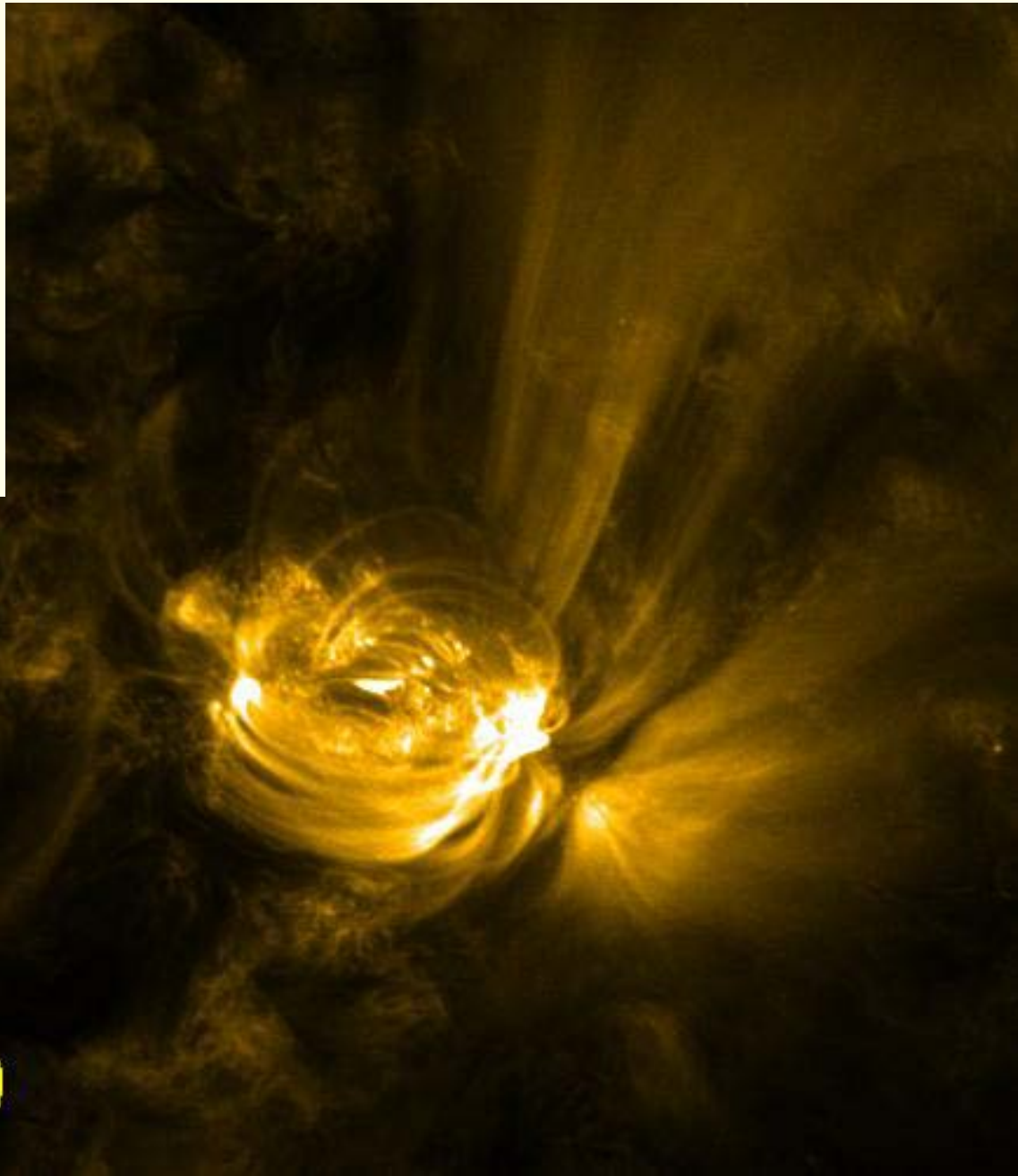
Hansteen et al. (2014) Sci 346, 1255757

# The popular coronal loops

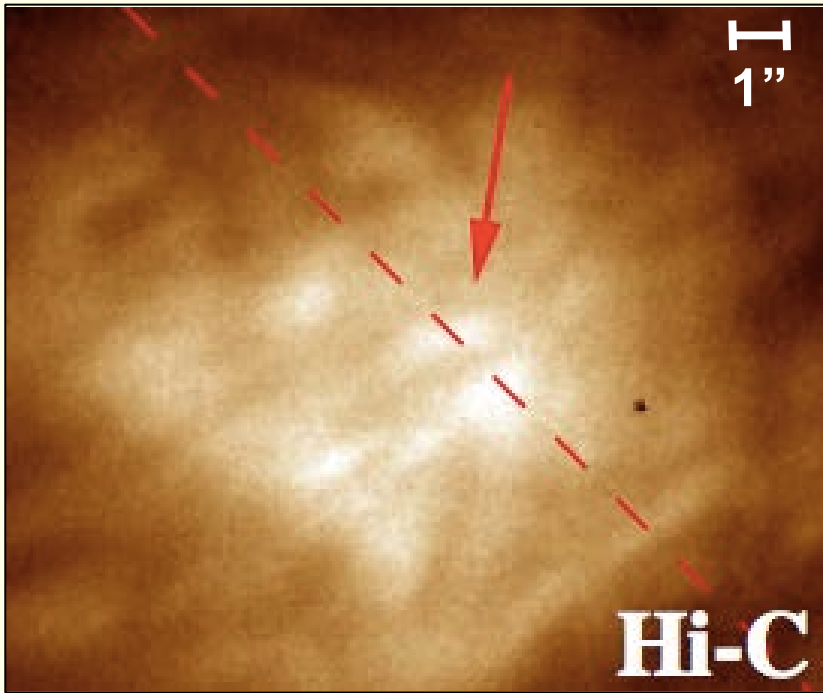
## Questions:

- ▶ brightness along loops
  - ▶ (internal) structure across  $B$
  - ▶ (variation of) loop width
  - ▶ appearance at different  $\lambda$  (or  $T$ )
  - ▶ temporal evolution
  - ▶ relation to magnetic field
- 
- ▶ are the same processes at work as in small TR loops?
  - ▶ are there small hot loops, too ?

AIA / SDO (171 Å)  
~10<sup>6</sup> K

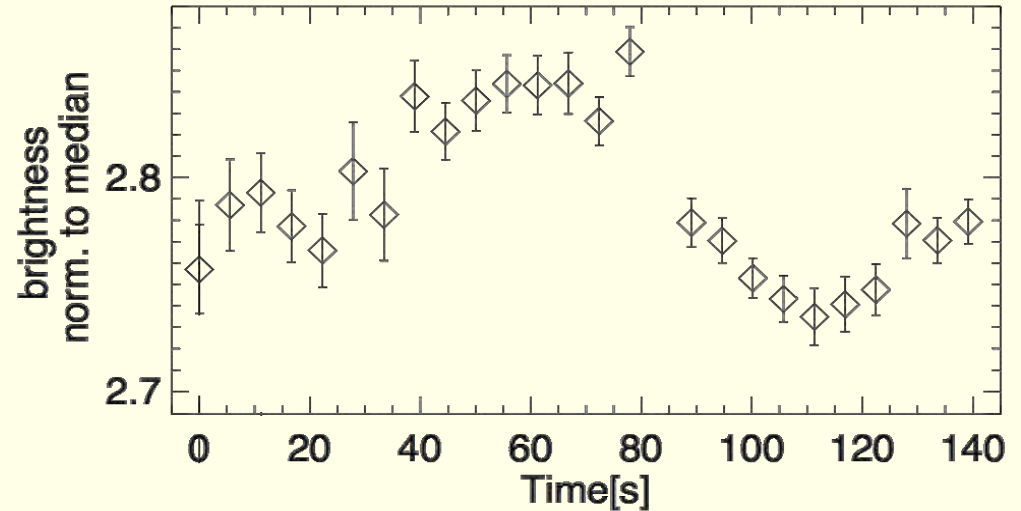


# Small-scale hot loops?

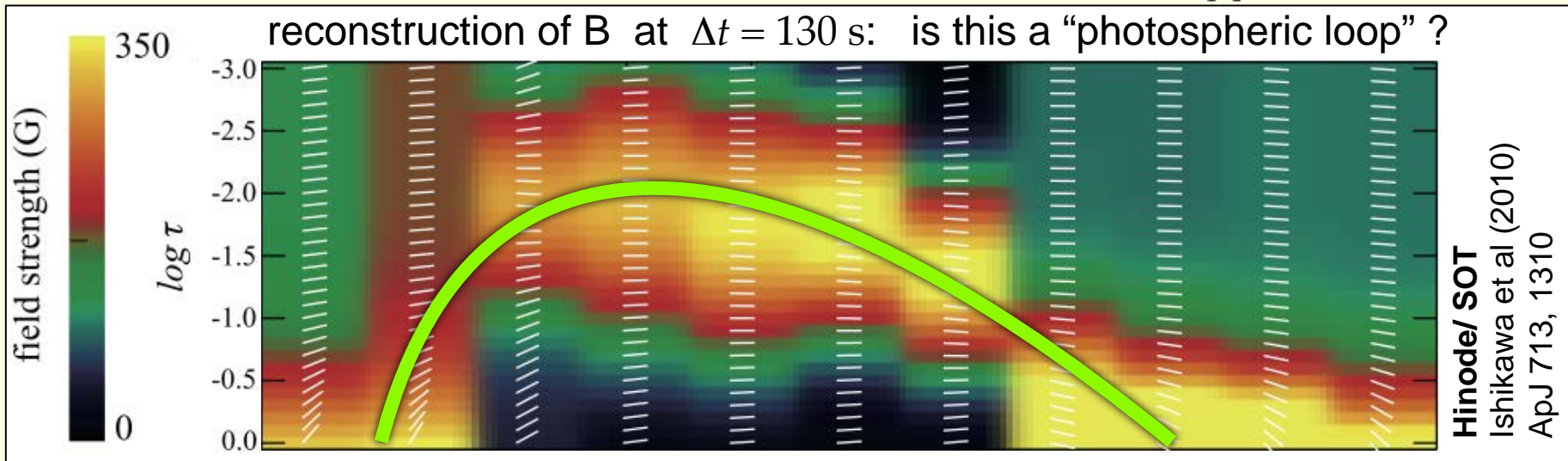


hp, Bingert, Klimchuk et al (2013) A&A 556, A104

- ▶ HiC data show small 1" long hot features short-lived, just as TR UFD loops
- ▶ related to small-scale flux emergence ? similar to Guglielmino et al (2010) ApJ 724, 1083 ?



Barczynski, hp, Savage (2014)

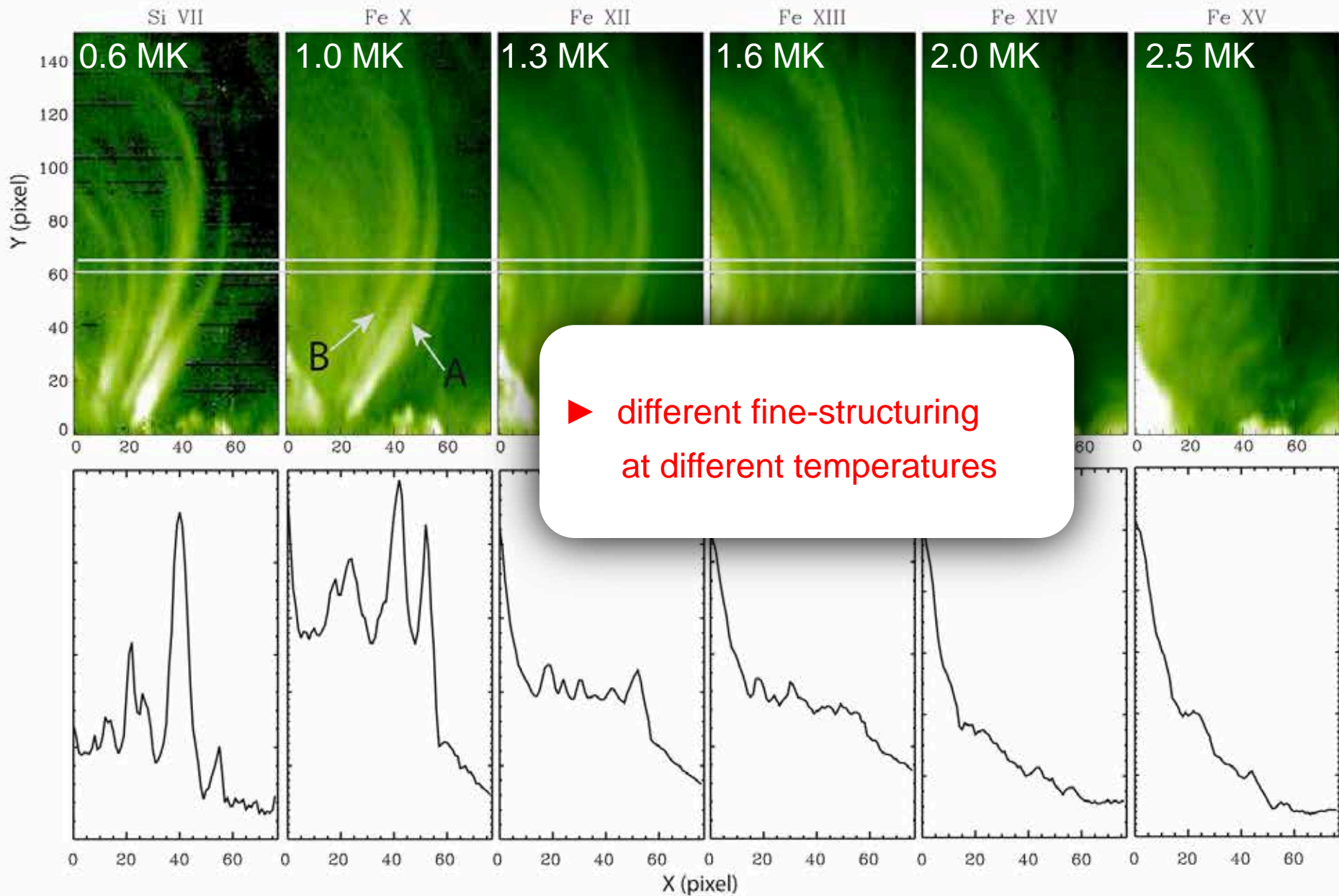


Hinode/ SOT  
Ishikawa et al (2010)  
ApJ 713, 1310

**Fundamental  
width of loops  
(is there any?)**

# Loop system at different wavelengths (or $T$ , but ...)

Tripathi et al. (2009) ApJ 694, 1256

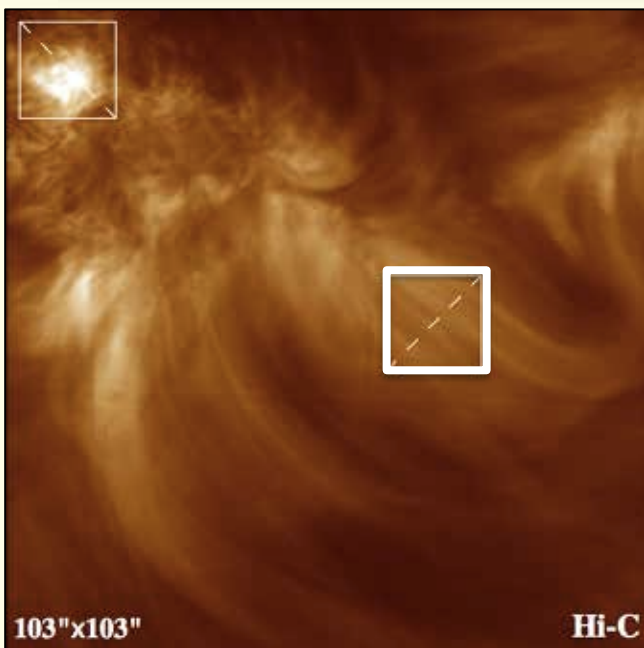
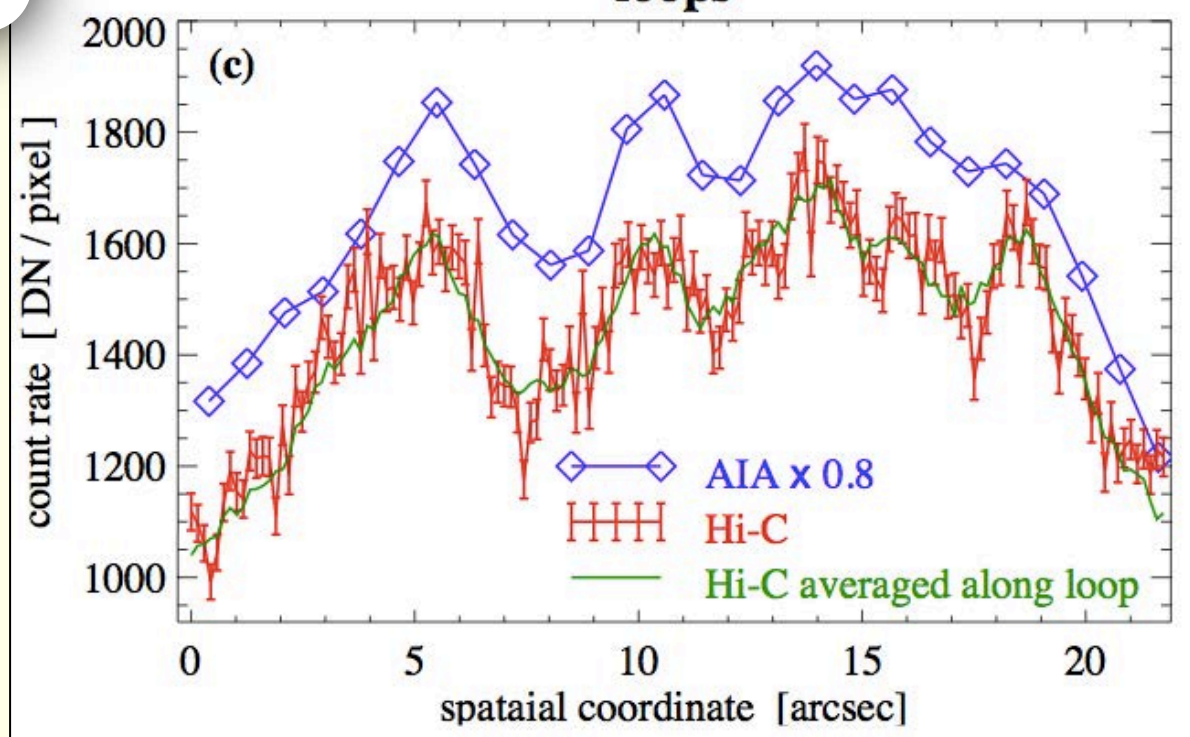
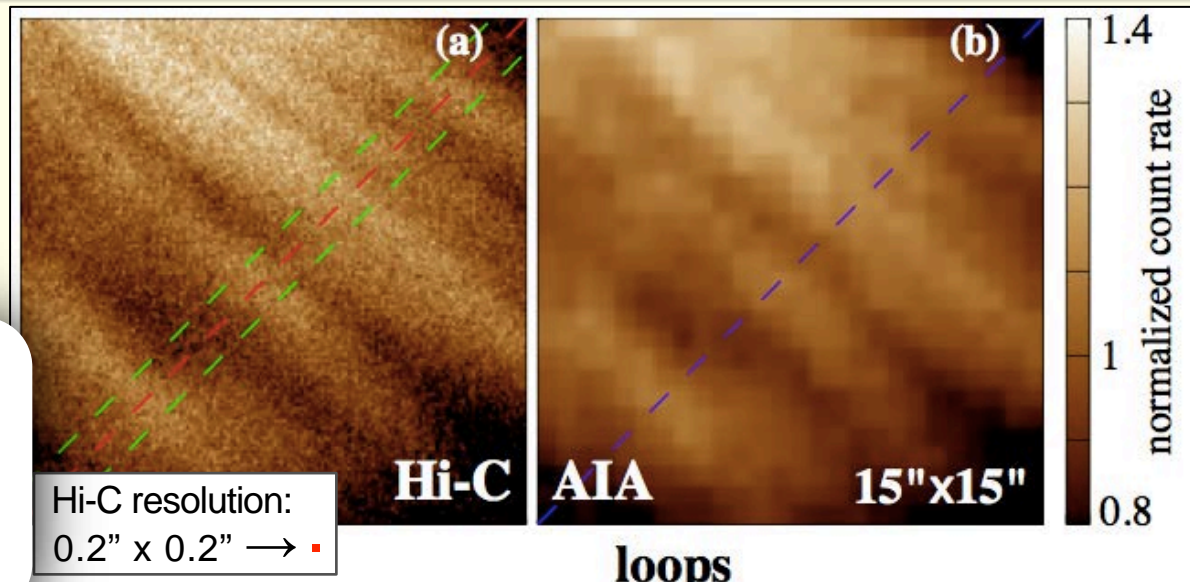


# No sub-structure of in some loops

- ▶ Hi-C shows no substructure for *some* AIA loops

(many features seen at HiC resolution limit...)

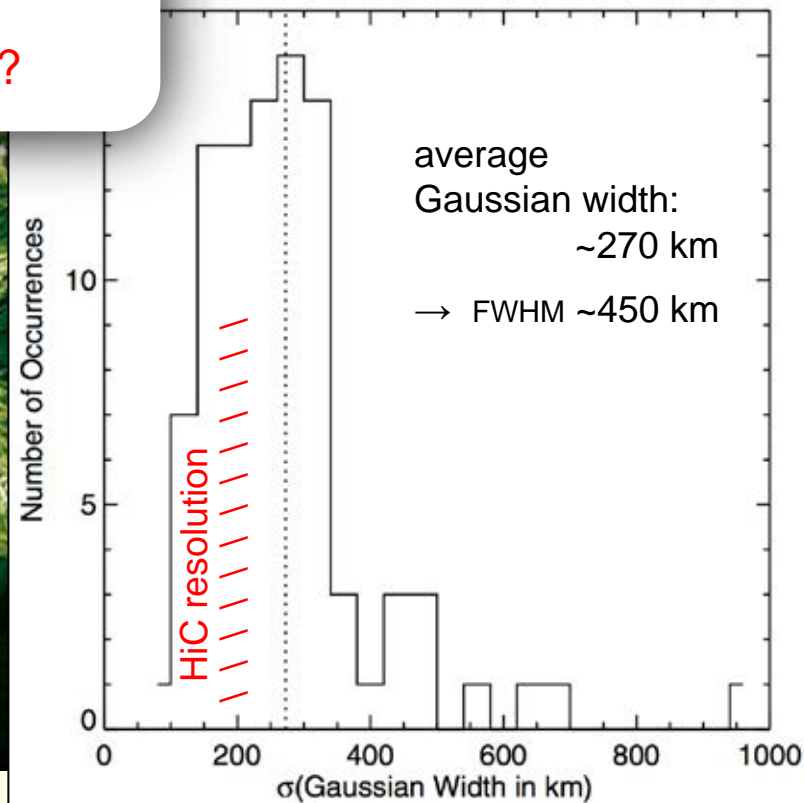
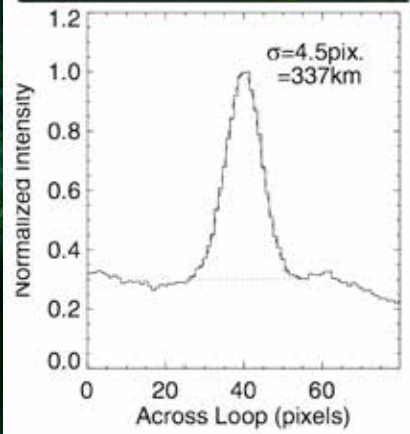
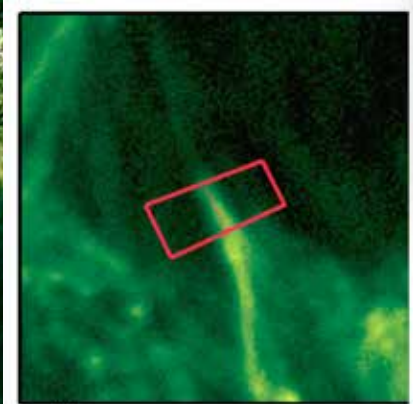
- ▶ what determines width of these loops of  $\sim 1-2''$  ?



# Typical width of structures in HiC

- ▶ (not only loops):  
FWHM  $\sim 450$  km  
Brooks et al. (2013) ApJ 772, L19
- ▶ consistent with experiments  
for substructures not (fully)  
resolved with EIS and AIA  
Brooks et al. (2012) ApJ 755, L33

▶ is there a  
“fundamental width”  
for coronal structures ?



# Morphological comparison to model

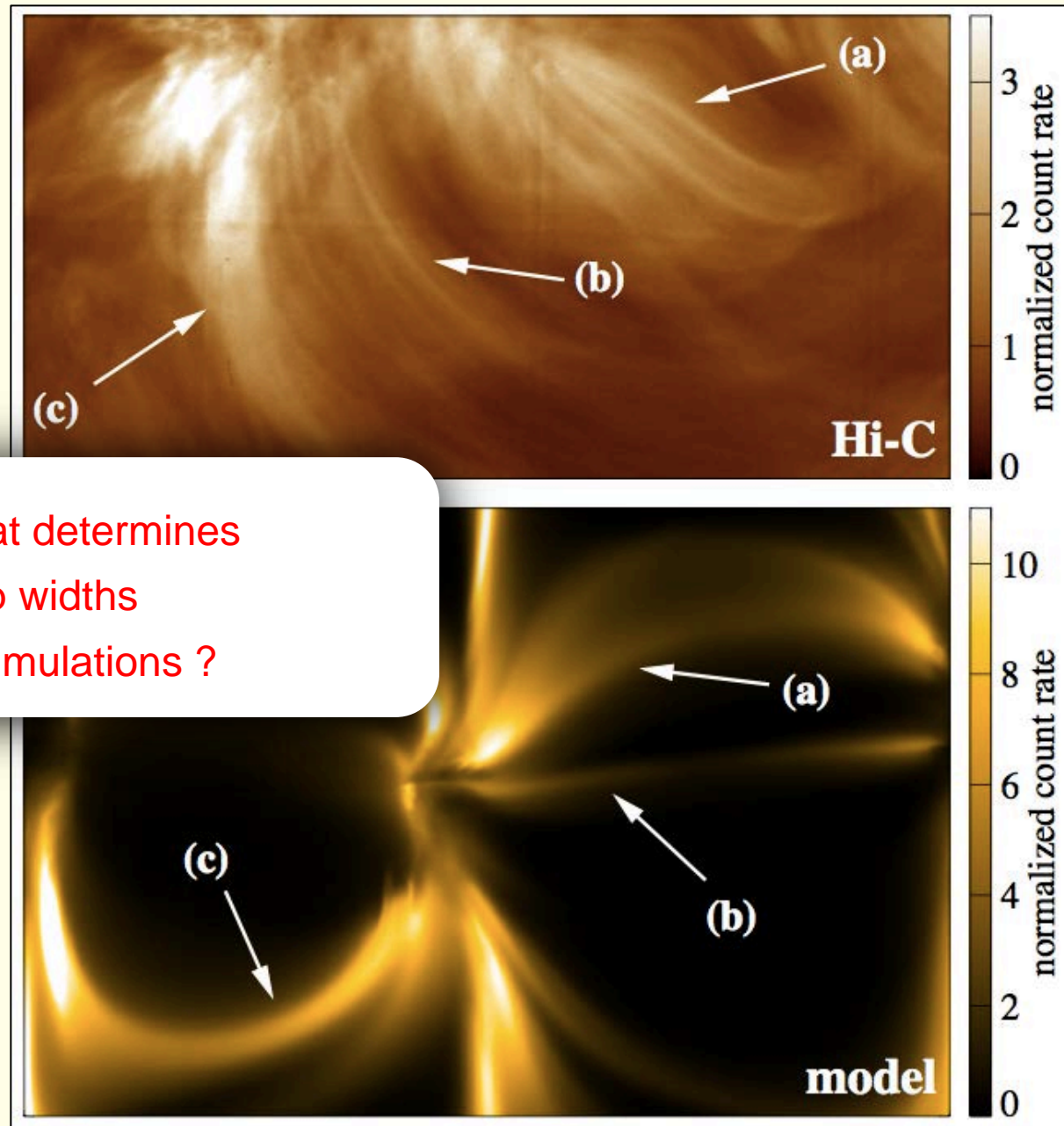
observations show:

- (a) constant cross-section loops in expanding envelope
- (b) thin individual loops
- (c) thick non-expanding structures

3D MHD models show similar features

→ more work is needed for quantitative comparison...

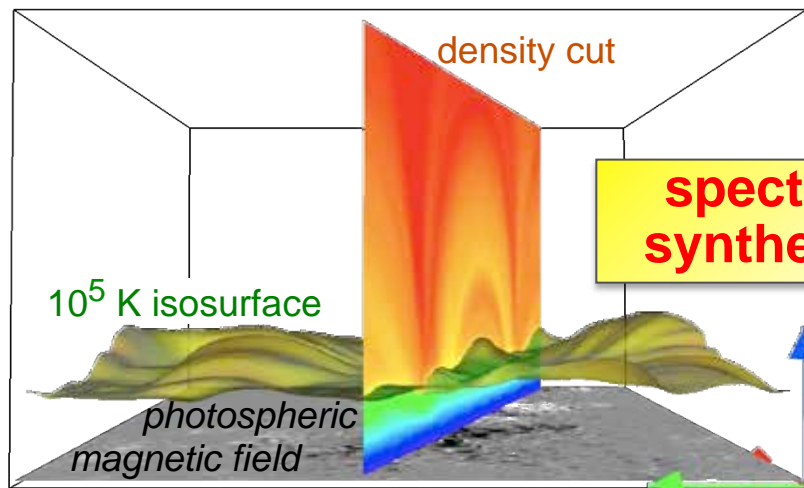
► What determines loop widths in simulations ?



**3D model**

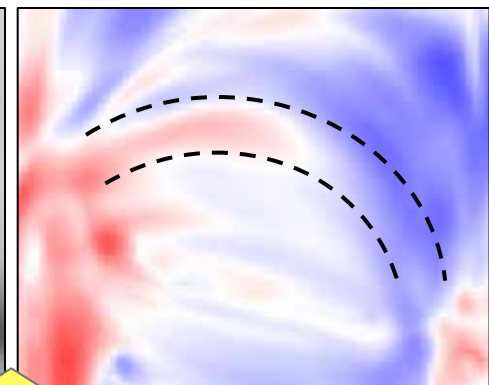
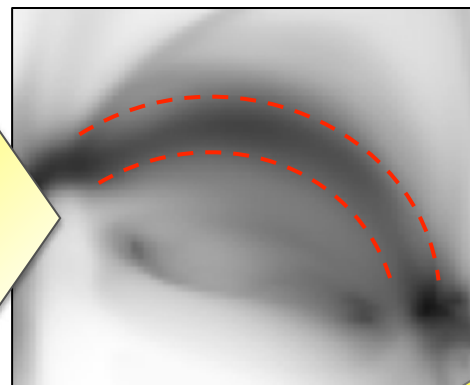
# 3D MHD coronal model including spectral synthesis

3D MHD model:  $T, \rho, v, B$



spectral synthesis

synthesized coronal emission Mg x 625 Å



intensity map (inv.)

Doppler map

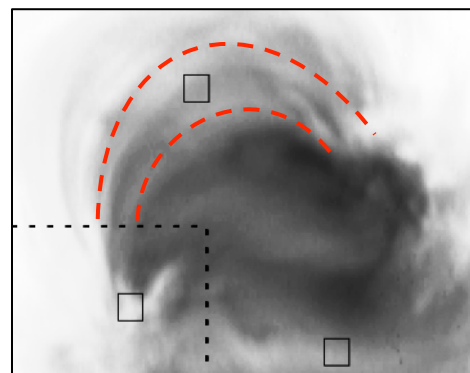
compare

→ full energy equation  
(heat conduction, radiative losses)

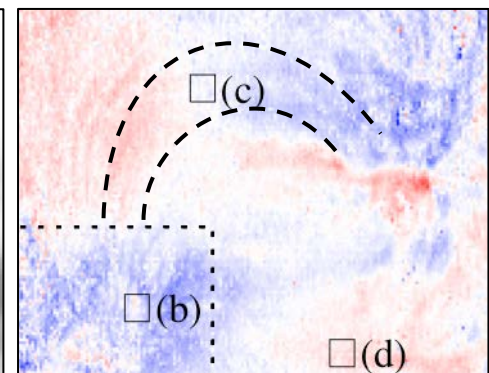
- ▶ corona driven by (horizontal) motions in the photosphere
- ▶ up to 1024 x 1024 x 512 grid
- ▶ horizontally periodic, open top
- ▶ resistivity set by  $R_m \sim 1$  at grid scale (but similar results for different  $\eta$  models)

real observations

Hinode / EIS Fe xv 284 Å



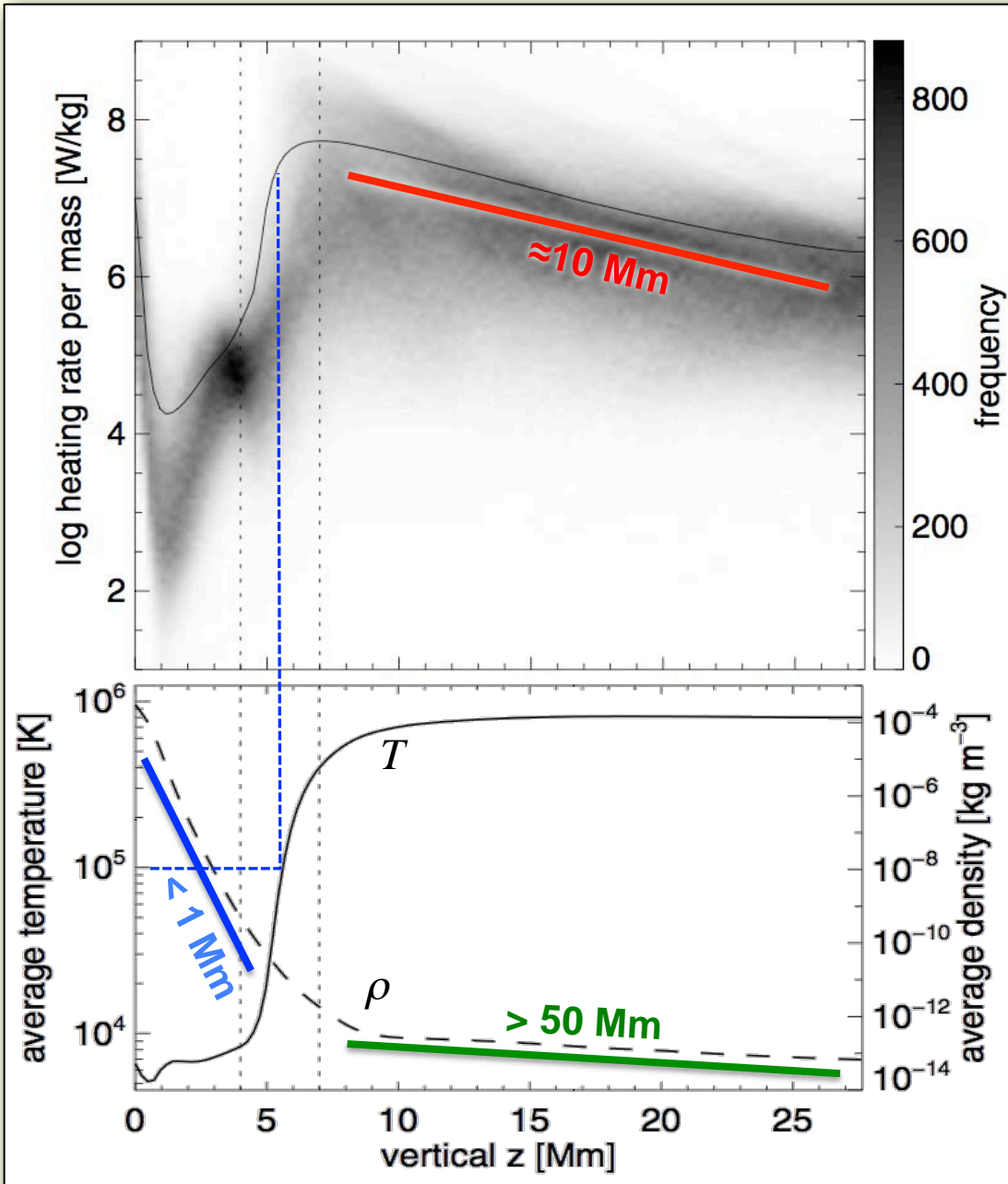
-20 Doppler shift [km/s] 20



Bingert & hp (2011) A&A 530, A112

hp (2010) A&A 521, A51

# Horizontally averaged heating rate (per particle)



- ▶ heating concentrated in low atmosphere
- ▶ maximum heating/particle in transition region
- ▶ but there is still heating needed in corona !

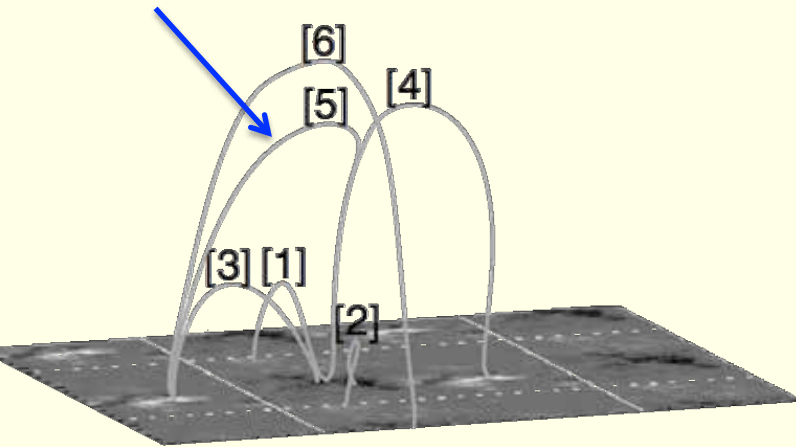
→ is because of scale heights:

- $\rho$  chromosphere:  $< 1 \text{ Mm}$
- Ohmic heating:  $\approx 10 \text{ Mm}$
- $\rho$  corona:  $> 50 \text{ Mm}$

similar results by all 3D MHD models with Ohmic heating, e.g.  
 Gudiksen et al. (2002) ApJ 572, L113  
 Hansteen et al. (2010) ApJ 718, 1070

already hinted at by  
 Galsgaard & Nordlund (1996)

# Intermittent heating in space and time



► heating concentrated towards footpoints  
(dropping roughly exponential)

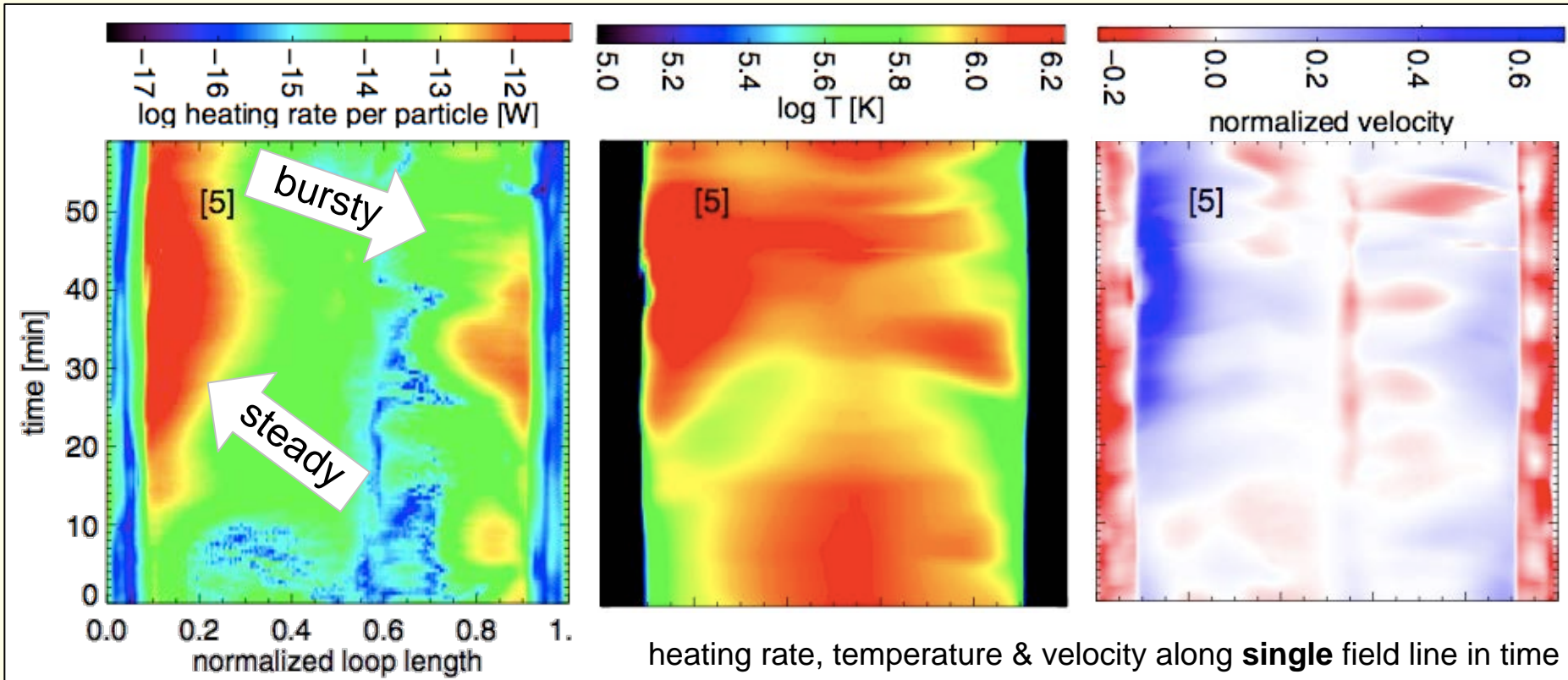
► intermittent in space and time

– steady heating:  $\tau_{\text{heat}} > \tau_{\text{cool}}$

– impulsive heating:  $\tau_{\text{heat}} < \tau_{\text{cool}}$

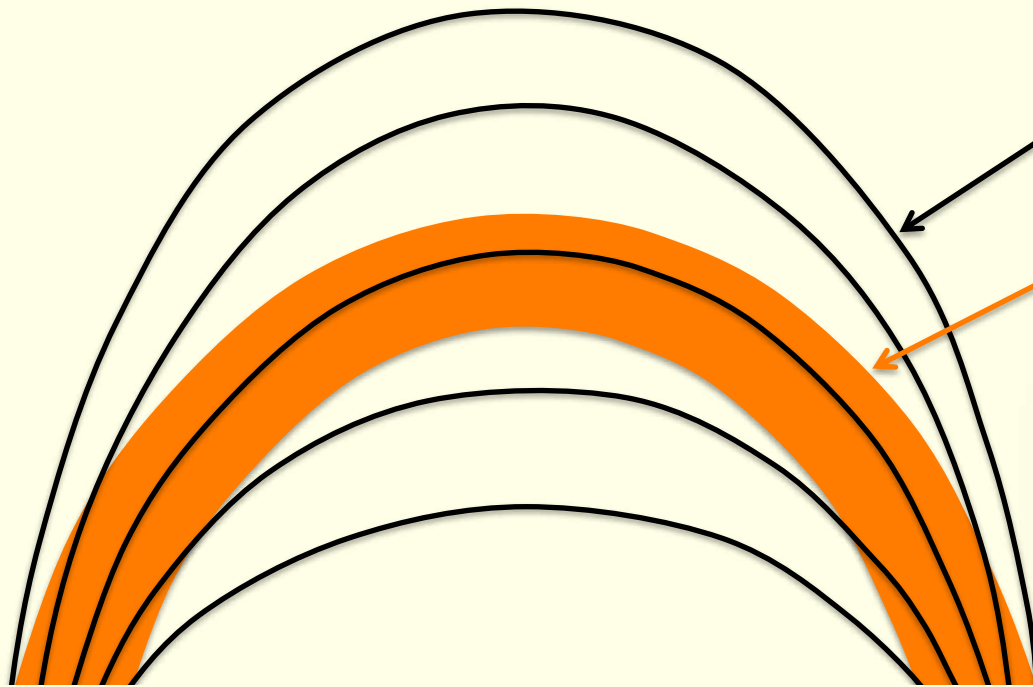
→ “steady” and “intermittent” heating coexist  
even on same fieldline / in same loop !!

Bingert & hp (2011) A&A 530, A112



**(Missing)  
expansion  
of loops**

# Constant cross section: the problem

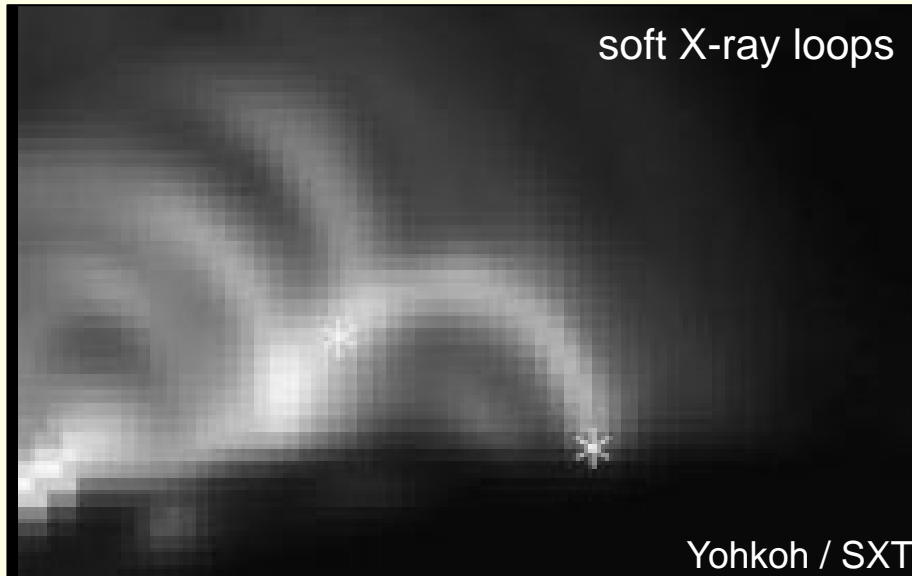


a potential-like magnetic field which expands with height.

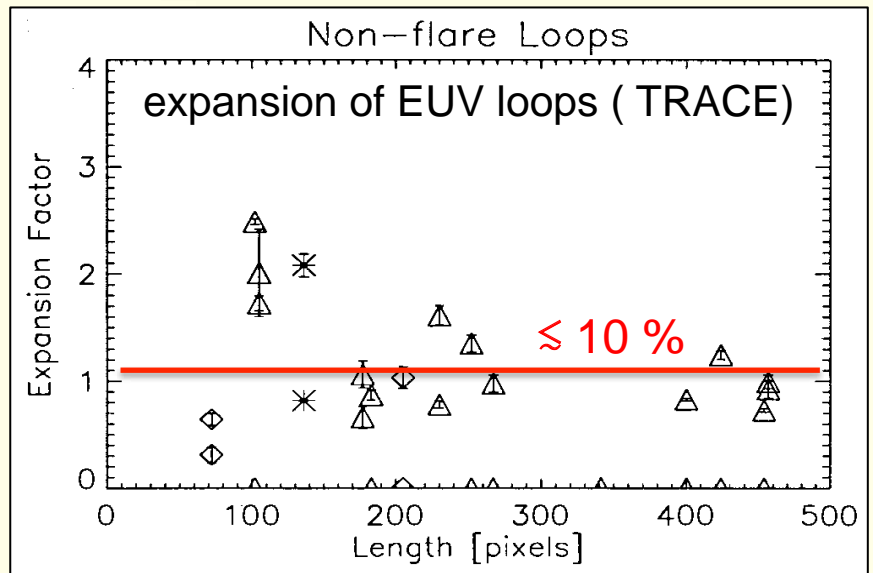
loop seen in coronal emission with constant cross section

► if the plasma is confined within magnetic flux tubes, how can this be ?!

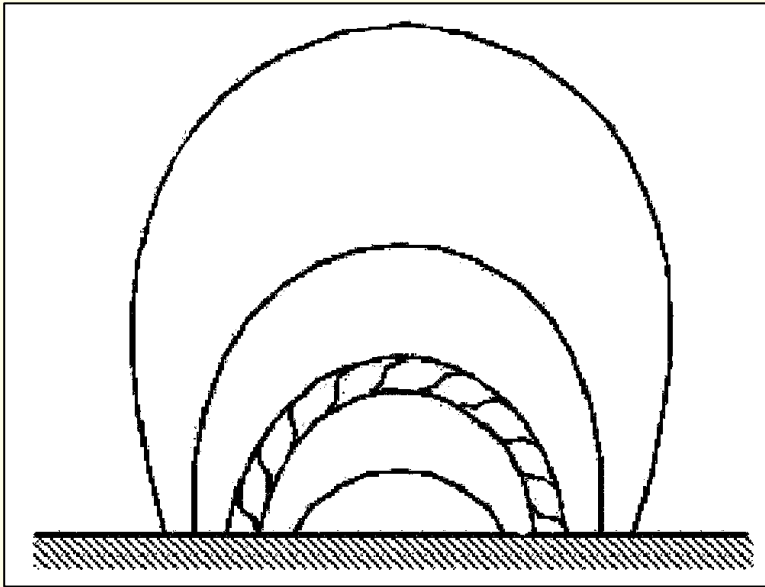
soft X-ray loops



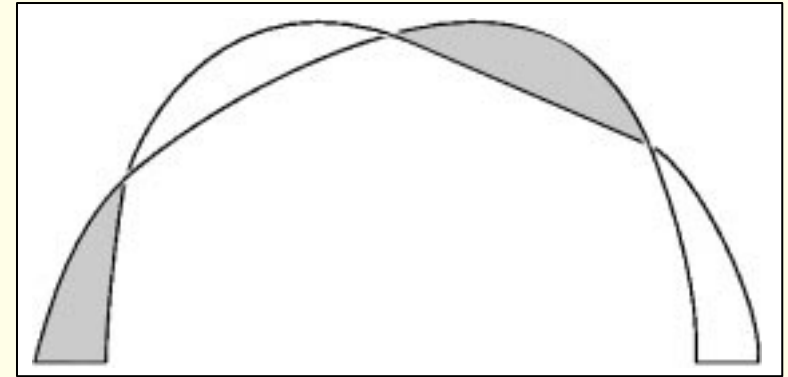
Yohkoh / SXT



# Constant cross section: suggestions



twisted flux tube surrounded  
by untwisted expanding field

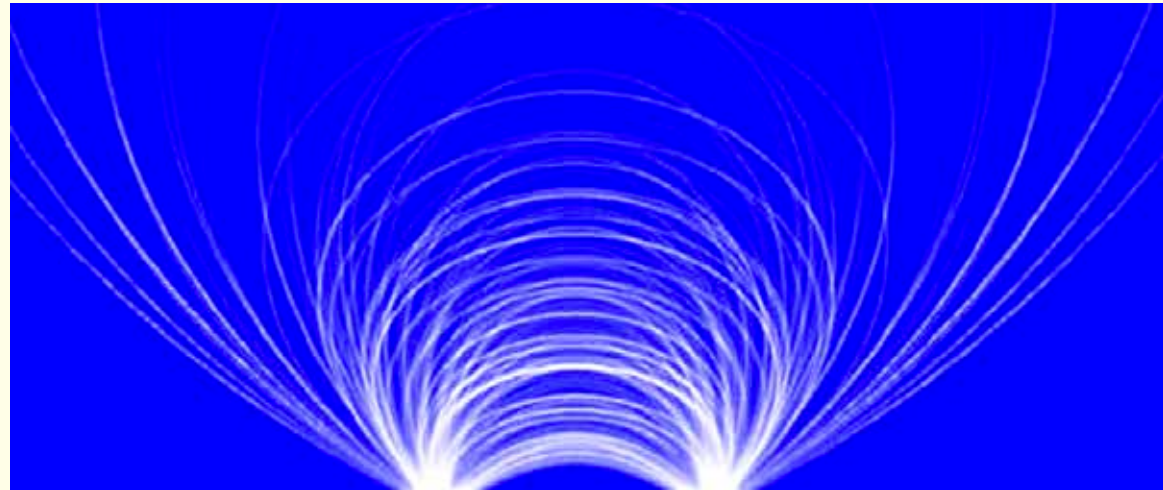


hypothetical ribbon-like loop  
that is twisted

Klimchuk (2000) Sol.Phys. 193, 53

superposition of  
not resolved tapered strands

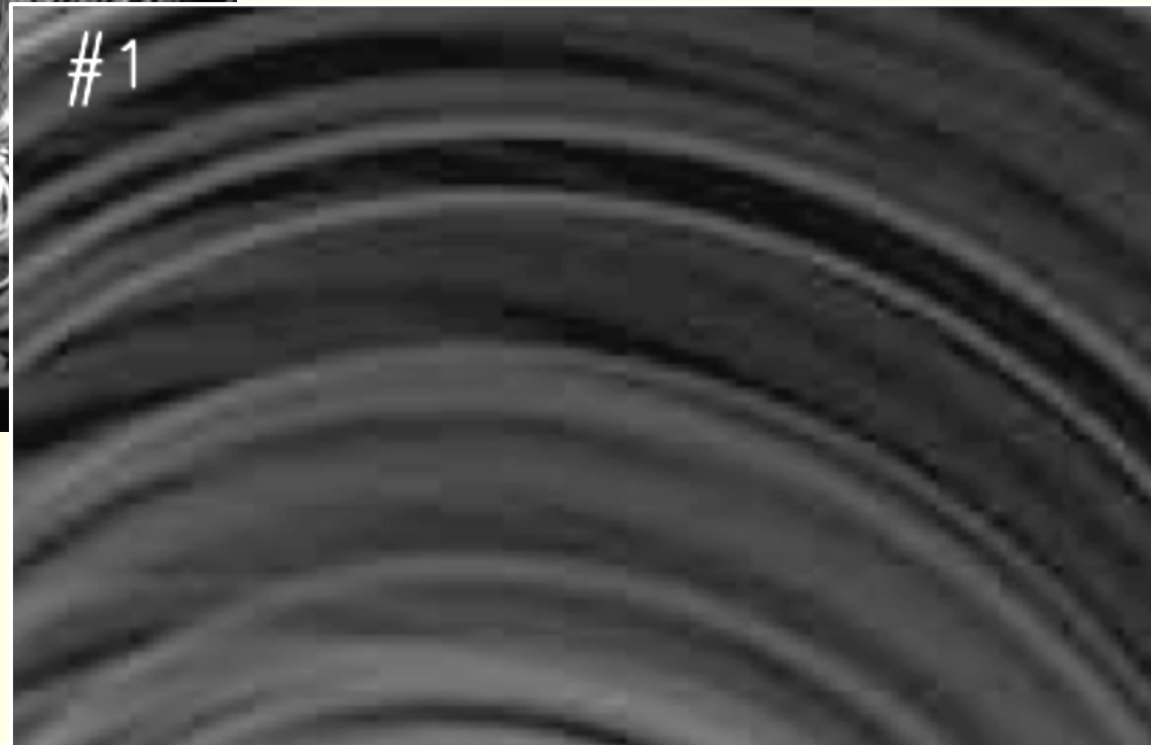
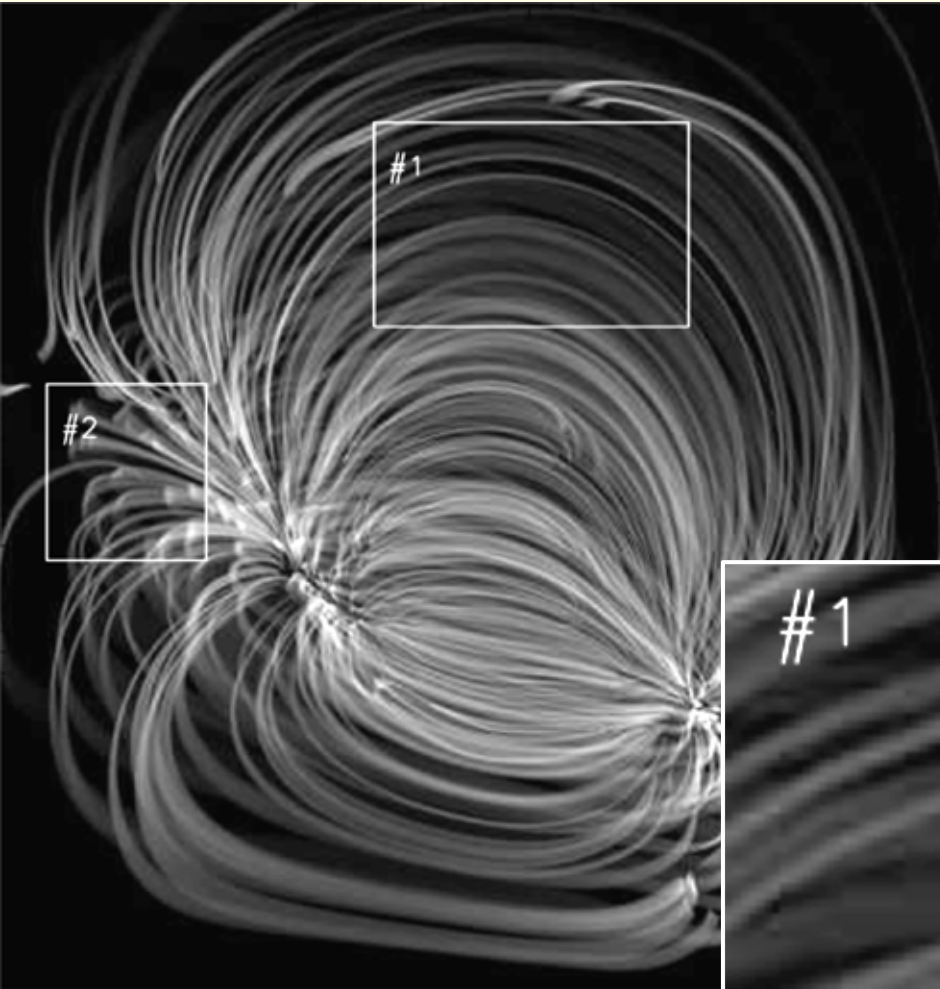
DeForest (2007) ApJ 661, 532



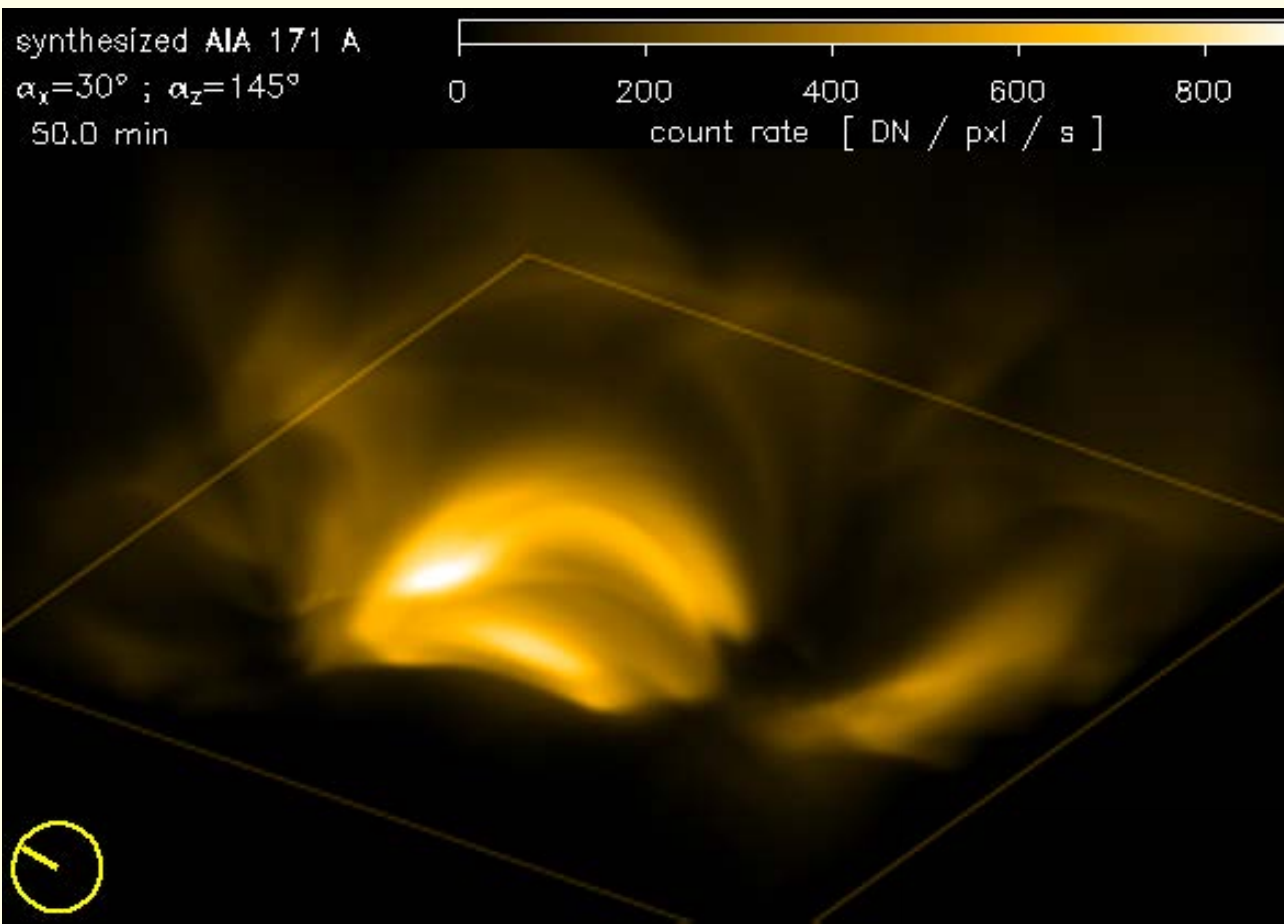
# Rendering of loops with “oblate” cross section

- ▶ Klimchuk et al. ruled out pure magnetic effect
- ▶ but: loops / flux tubes have non-circular cross-sections changing along the loop

Malanushenko & Schrijver (2013)  
ApJ 775, 120



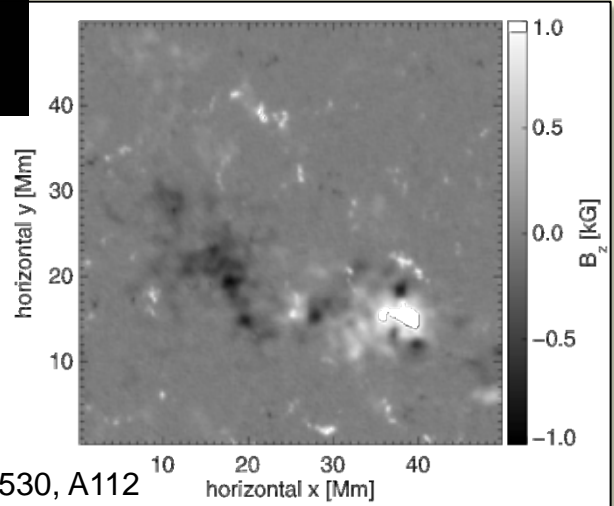
# Thermal and magnetic effects: MHD model



50x50x30 Mm<sup>3</sup>

- ▶ coronal box model above an active region
- ▶ field line braiding → currents → dissipation
- ▶ heating  $\eta j^2$  variable in time and space
  - produces discrete loop structures
  - these evolve in time

magnetic field at lower boundary driven by horizontal motions

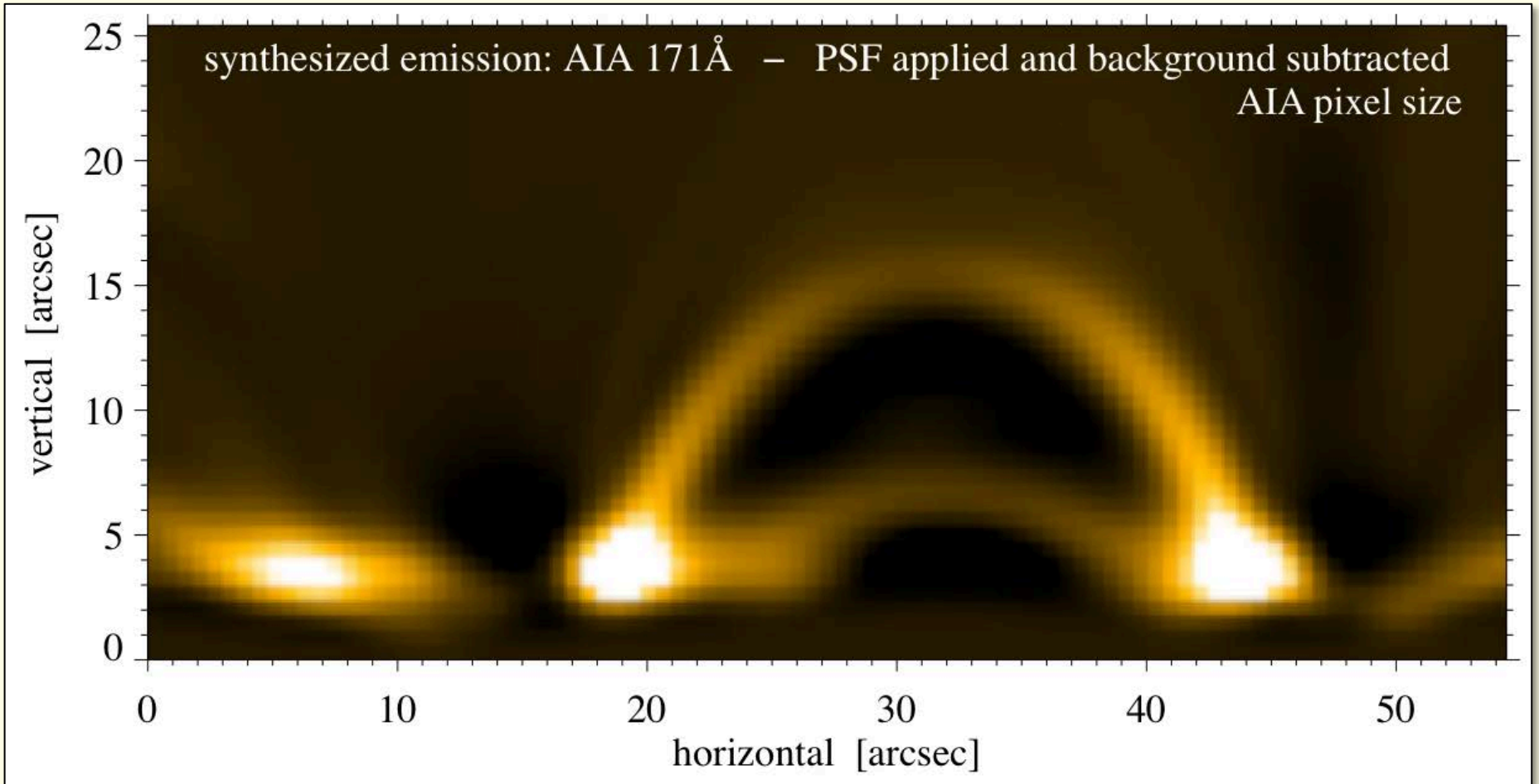


Bingert & hp (2011) A&A 530, A112

# Constant cross section loop in 3D MHD model

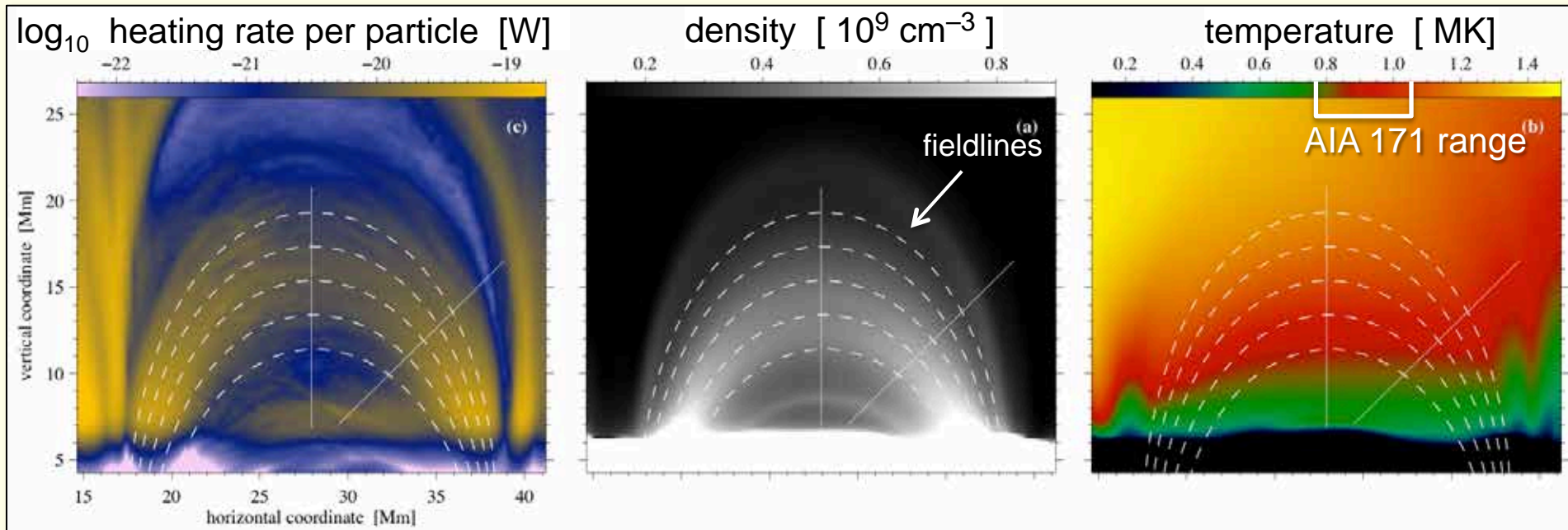
synthetic AIA 171 Å ( $10^6$  K)

loop has cross section of  $\sim 2x$  AIA PSF width (PSF  $\approx 1.3'' \approx 2.5$  pxl)



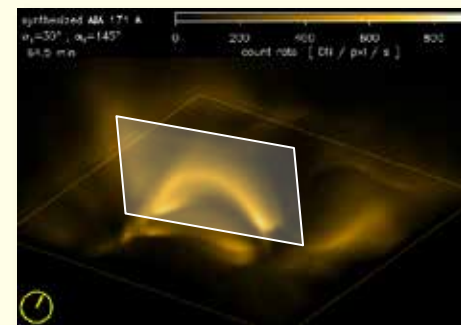
horizontally integrated  
through computational box

# Cut in loop plane: heating $\rightarrow n, T$

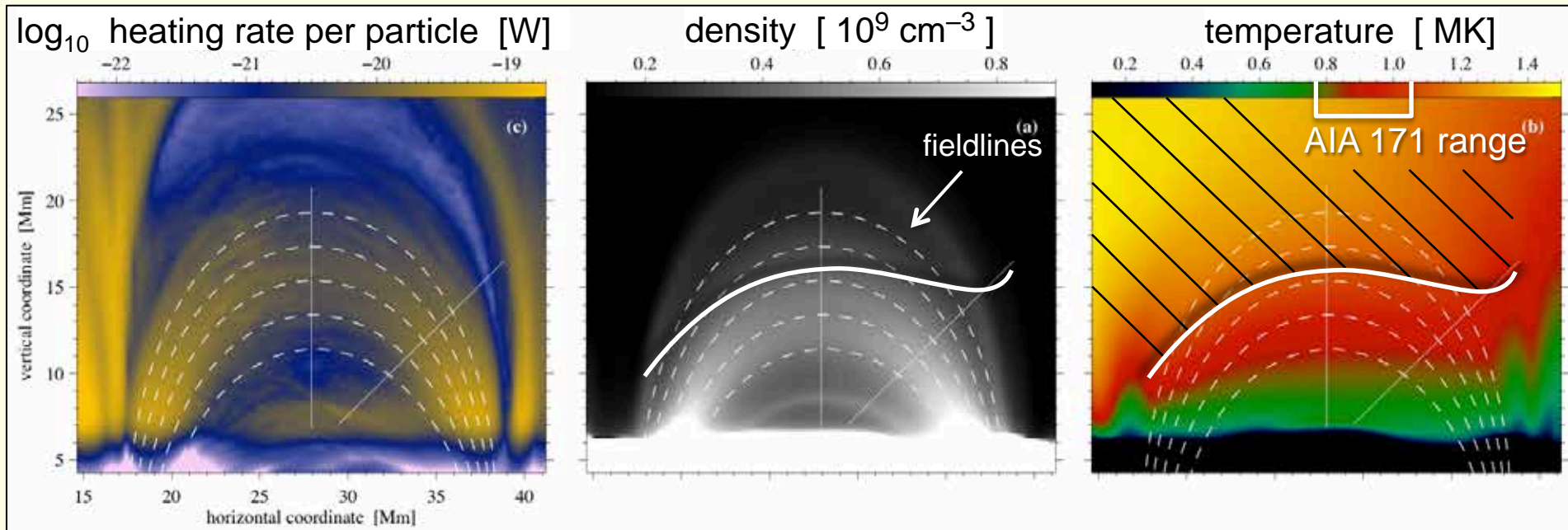


## From heating rate to thermal structure:

- ▶ heating rate follows magnetic structure
- ▶ increased heating rate leads to evaporation
- ▶ plasma filled in expanding magnetic structure
- ▶ **“plasma loop” (density) expands with height**
- ▶ temperature higher in “outer” part of loop  $\rightarrow \nabla T \perp$  loop  
scaling laws: longer loops are hotter (at same heating rate)



# Cut in loop plane: emission

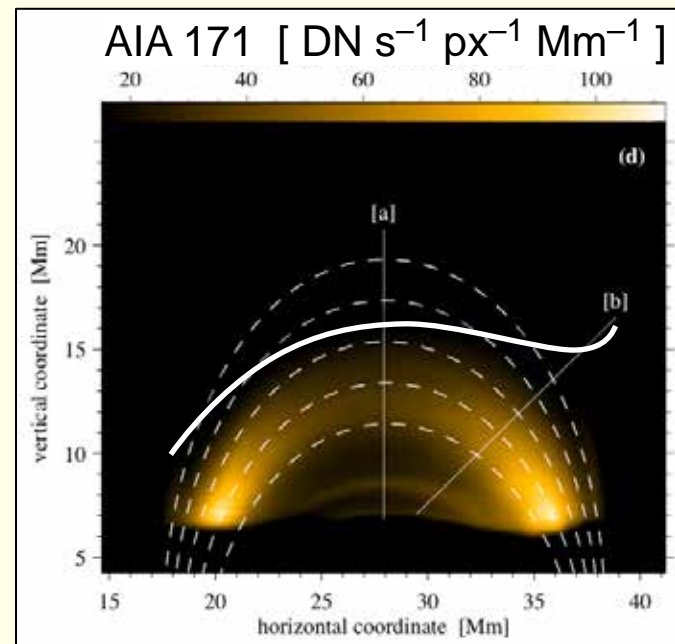


## From thermal structure to EUV loop:

- ▶ part of plasma loop too hot to contribute to EUV emission in respective band

- ▶ top part of loop is “cut off”  
→ **approx. constant cross section**

here: width determined by  $\nabla T \perp$  loop ...



# Loop formation

# Coronal model driven by emerging flux simulation

## flux-emergence simulation

from / similar to Cheung et al (2010) ApJ 720, 233

– flux rope rises from bottom and breaks through surface

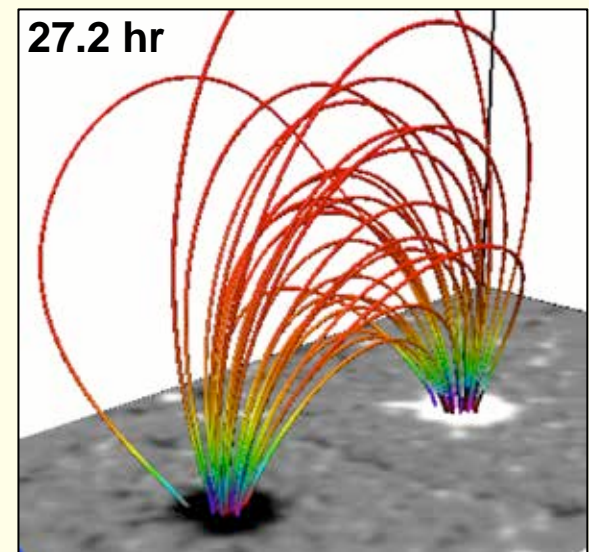
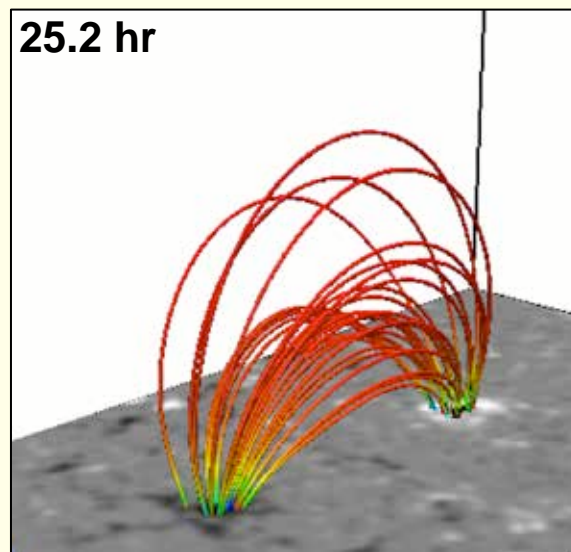
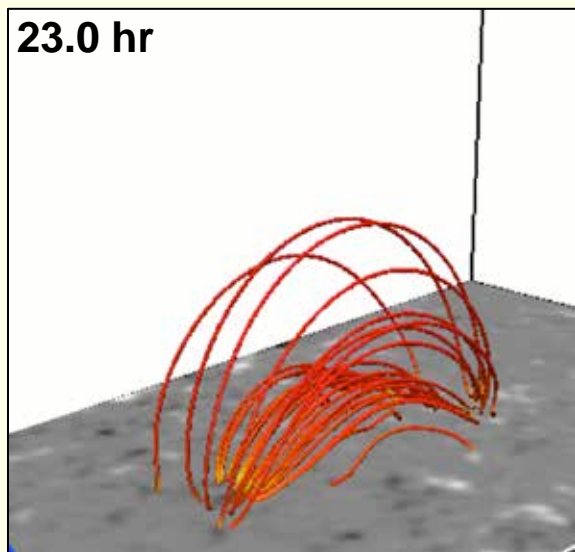
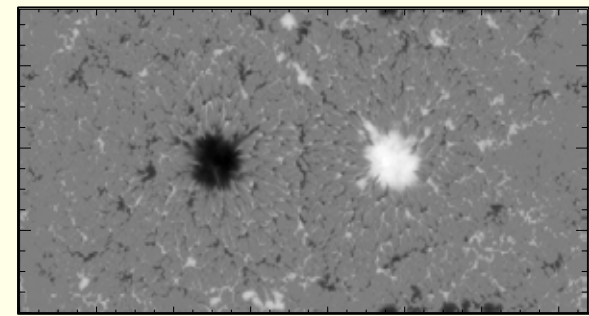
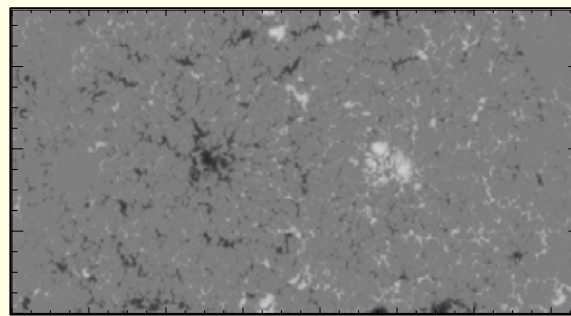
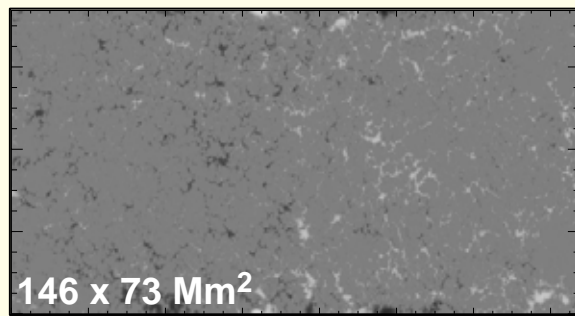
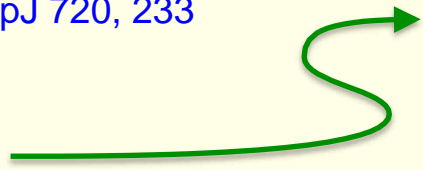
→ pair of sunspots

## coronal simulation

– use photospheric layer  $(T, \rho, v, B)$  as time-dependent lower boundary

→ magnetic field expands

→ coronal loops form



Chen, Bingert, hp, Cheung (2013)

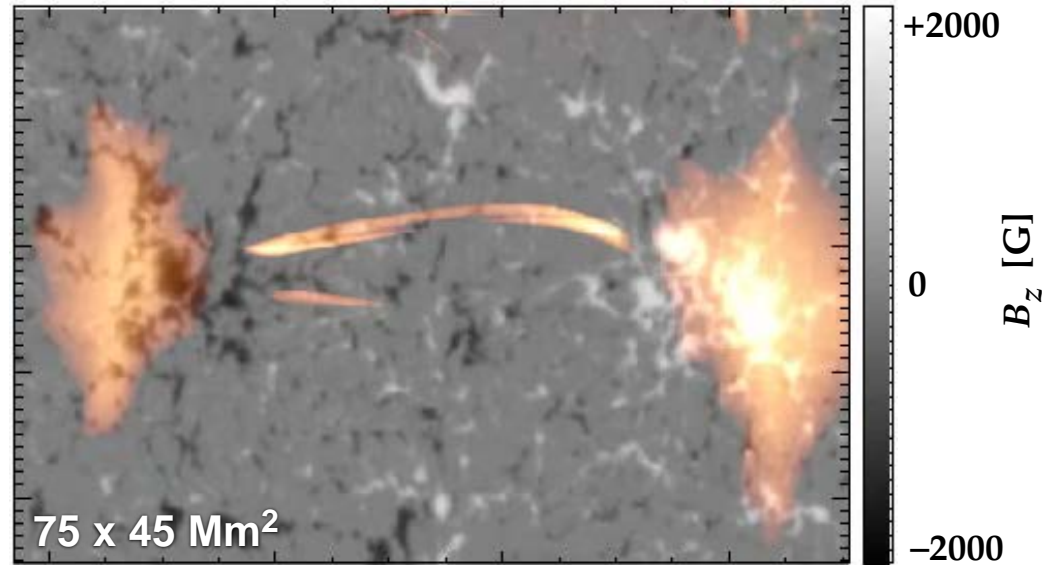
# Coronal model driven by emerging flux simulation

- ▶ loops form at different places at different times after the sunspots have formed
- ▶ loop footpoints are in sunspot periphery (penumbra)
- ▶ loops form where Poynting flux in the photosphere peaks  
→ where / when flux is pushed into sunspot

zoom into central part of computational domain

Chen, hp, Bingert, Cheung (2014)  
A&A 564, A12

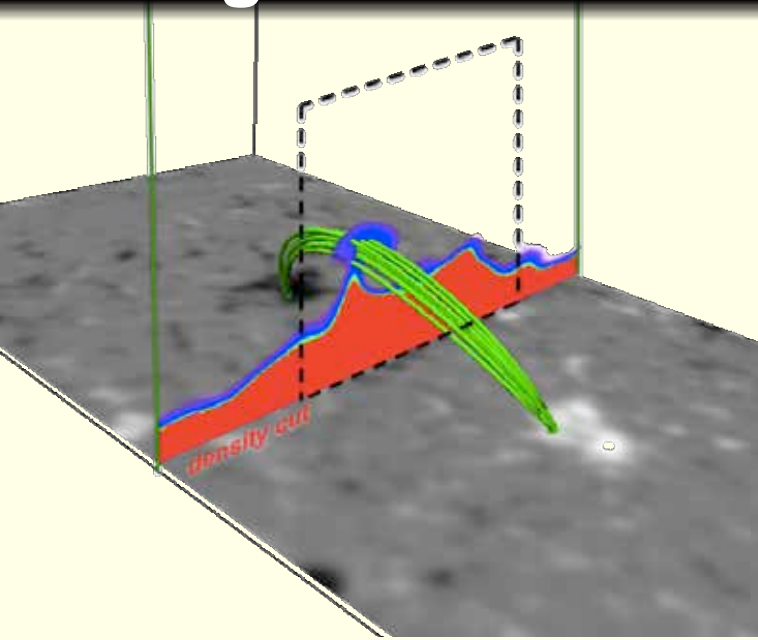
view from top:  $B_{\text{vert}}$  @ bottom + AIA 193 Å



from side  $t = 60.000$  min

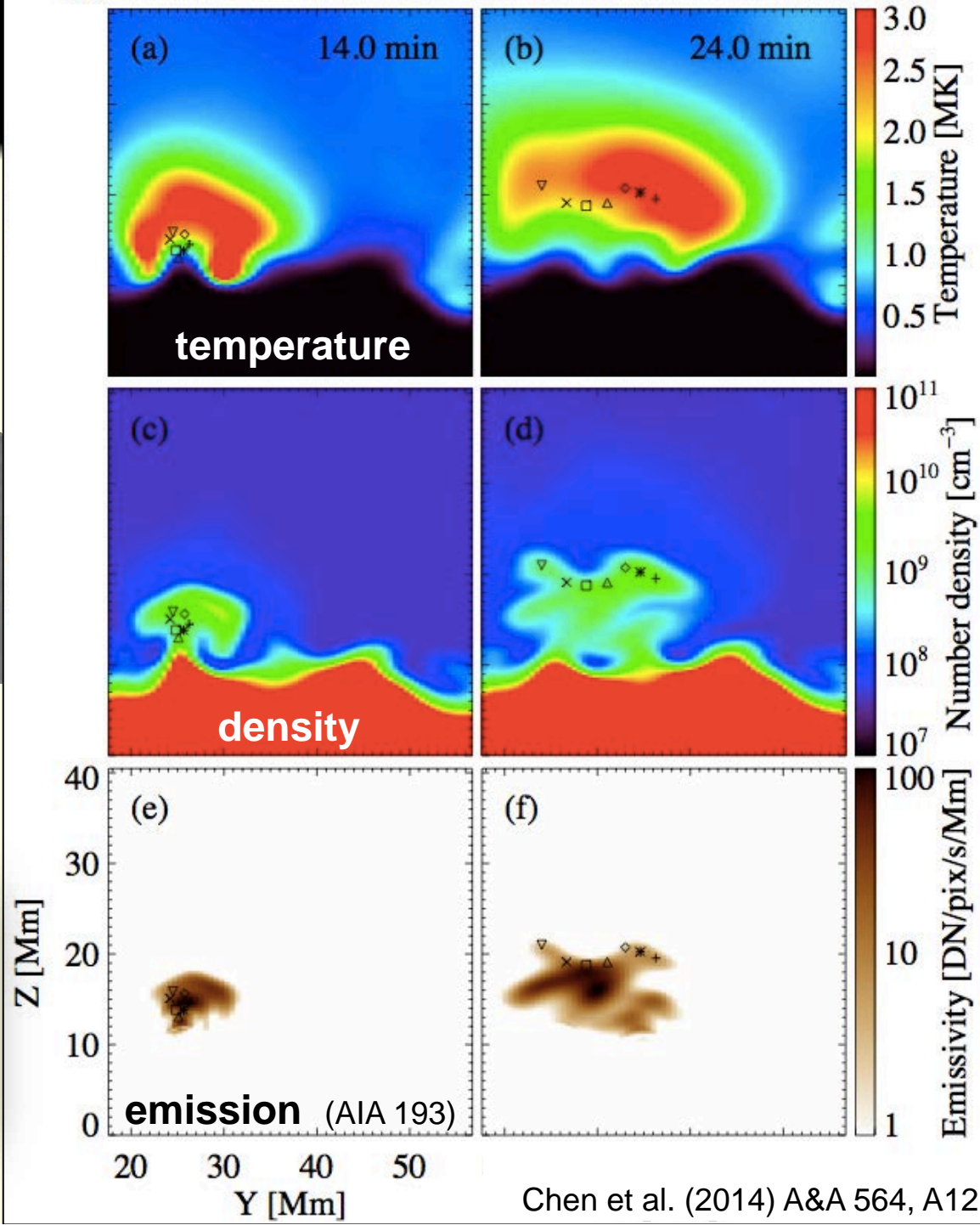


# Expansion and “fragmentation”



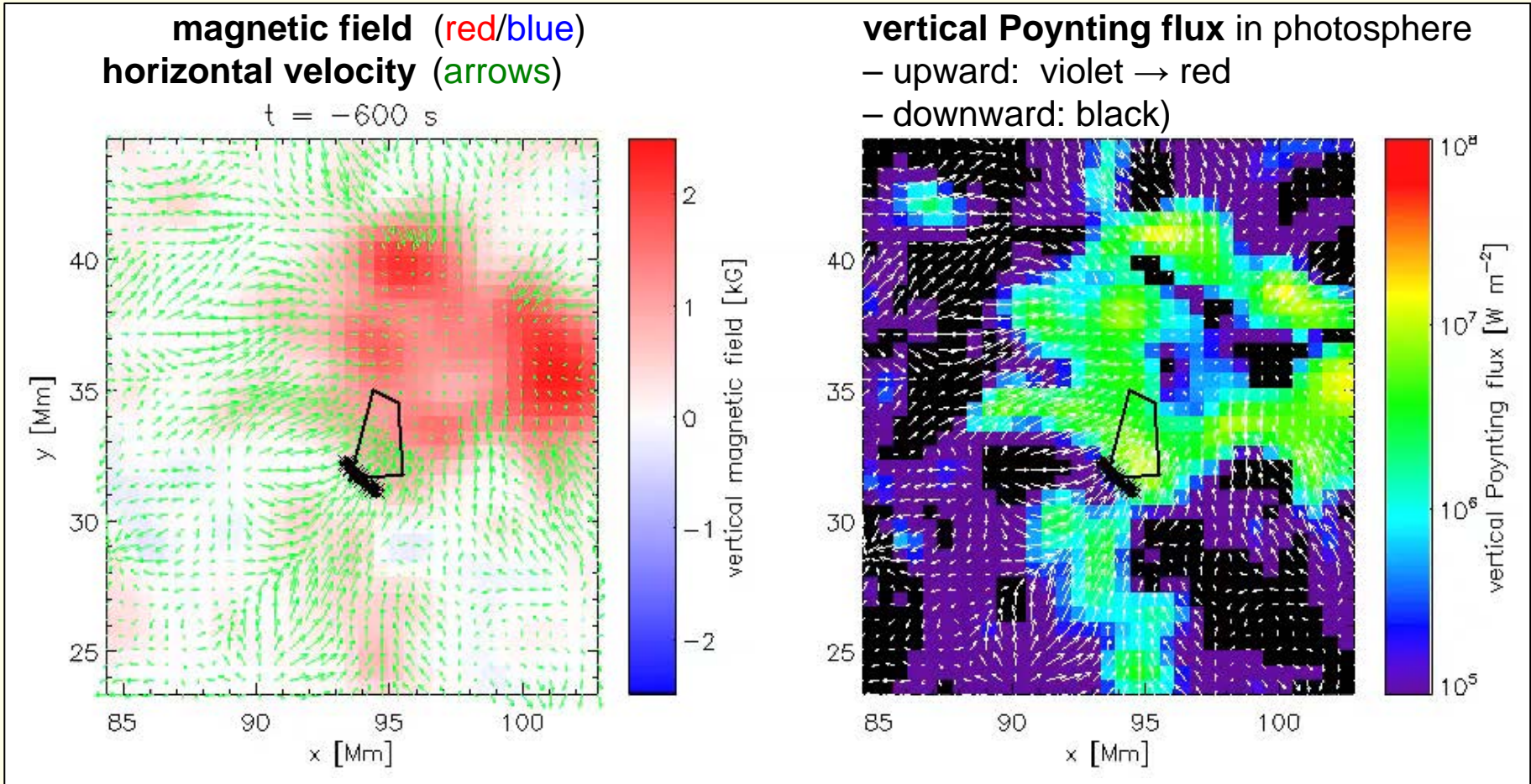
- ▶ magnetic tube expands mostly horizontally

- ▶ emission structure is not co-spatial with density and temperature structure
- ▶ emission is convolution of  $T, \rho$



# Motion of loop footpoints

through enhanced Poynting flux at the sunspot periphery



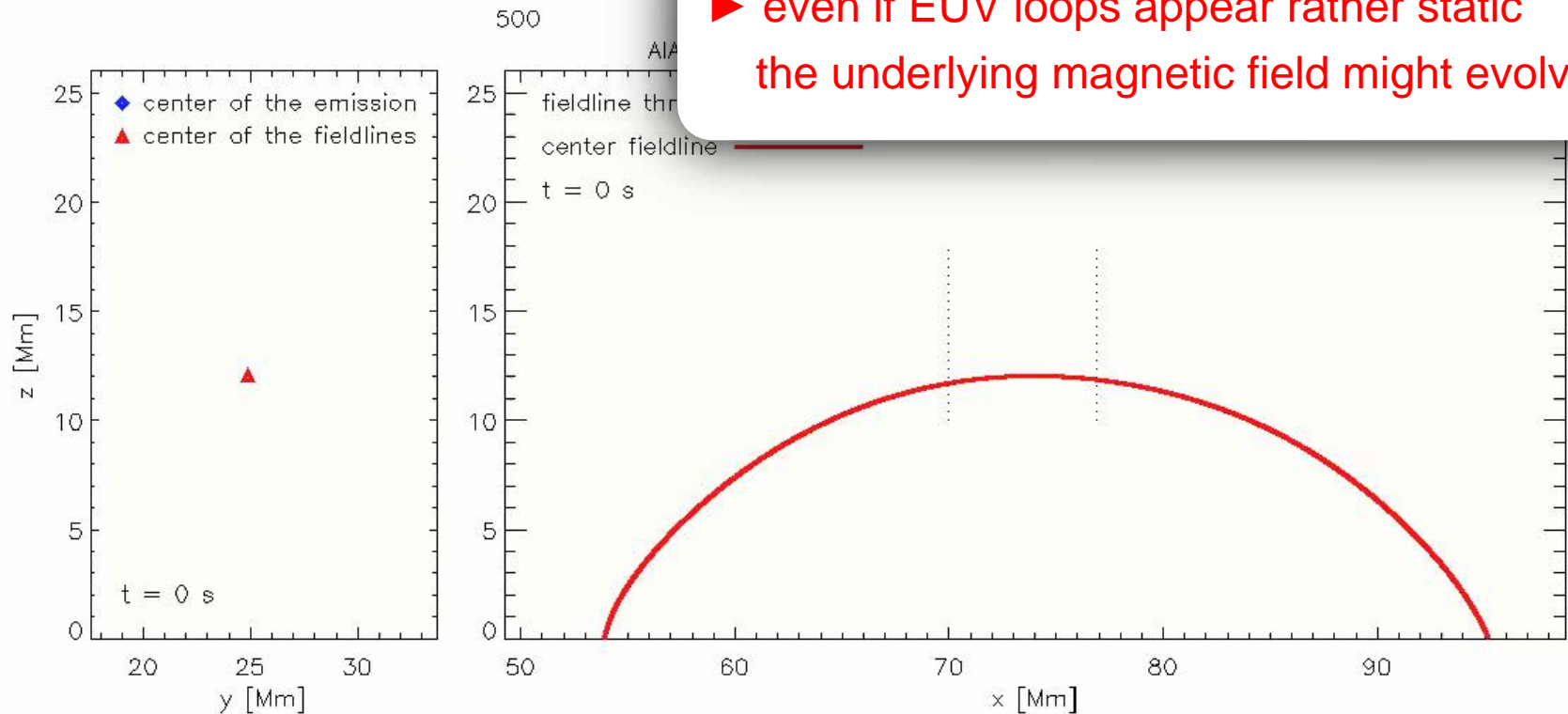
Chen, hp, Bingert, Cheung (2014)

- coalescent flow (gradient) at edge of sunspot causes enhancement of Poynting flux (similar to flux-tube tectonics by Priest, Heyvaerts, Title (2002) ApJ 576, 533)
- footpoints of loops are dragged through this region of higher Poynting flux (“hot spot”)
- temporal enhancement of energy input into fieldlines

# Evolving magnetic field – localized loop

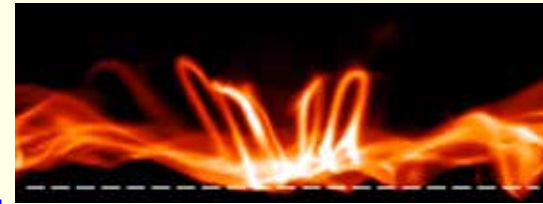
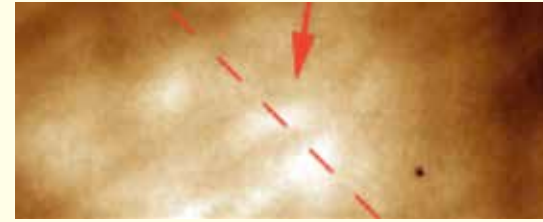
- in response to the emerging flux region the magnetic field expands
- in contrast resulting EUV loop remains at the same place !
- each fieldline brightens up  
when it crosses the “hot spot” of Poynting flux in the photosphere
- at each given time the EUV loop is aligned with one fieldline

▶ even if EUV loops appear rather static  
the underlying magnetic field might evolve !!



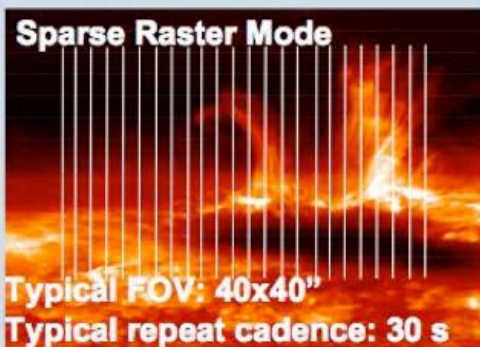
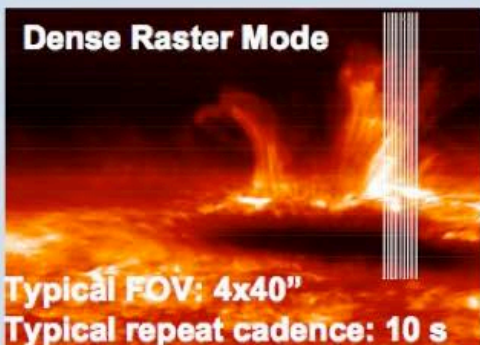
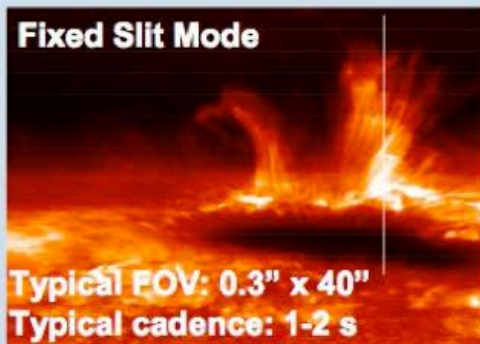
# Conclusions // Part I

- ▶ **loops at all sizes and temperatures.**  
(sort of) new: – cool network loops (UFS)  
– hot network/plage loops only 1 Mm long ?
- ▶ **some coronal loops might be resolved** (even by AIA)  
– indications for substructures to be  $> 300$  km  
– unclear what determines this width
- ▶ **getting closer to understand constant cross section**  
→ combination of magnetic and thermal structure
- ▶ **EUV loops might evolve differently than magnetic field !**  
be careful when interpreting magnetically evolving ARs.  
→ loops are 3D objects (and not 1D...)





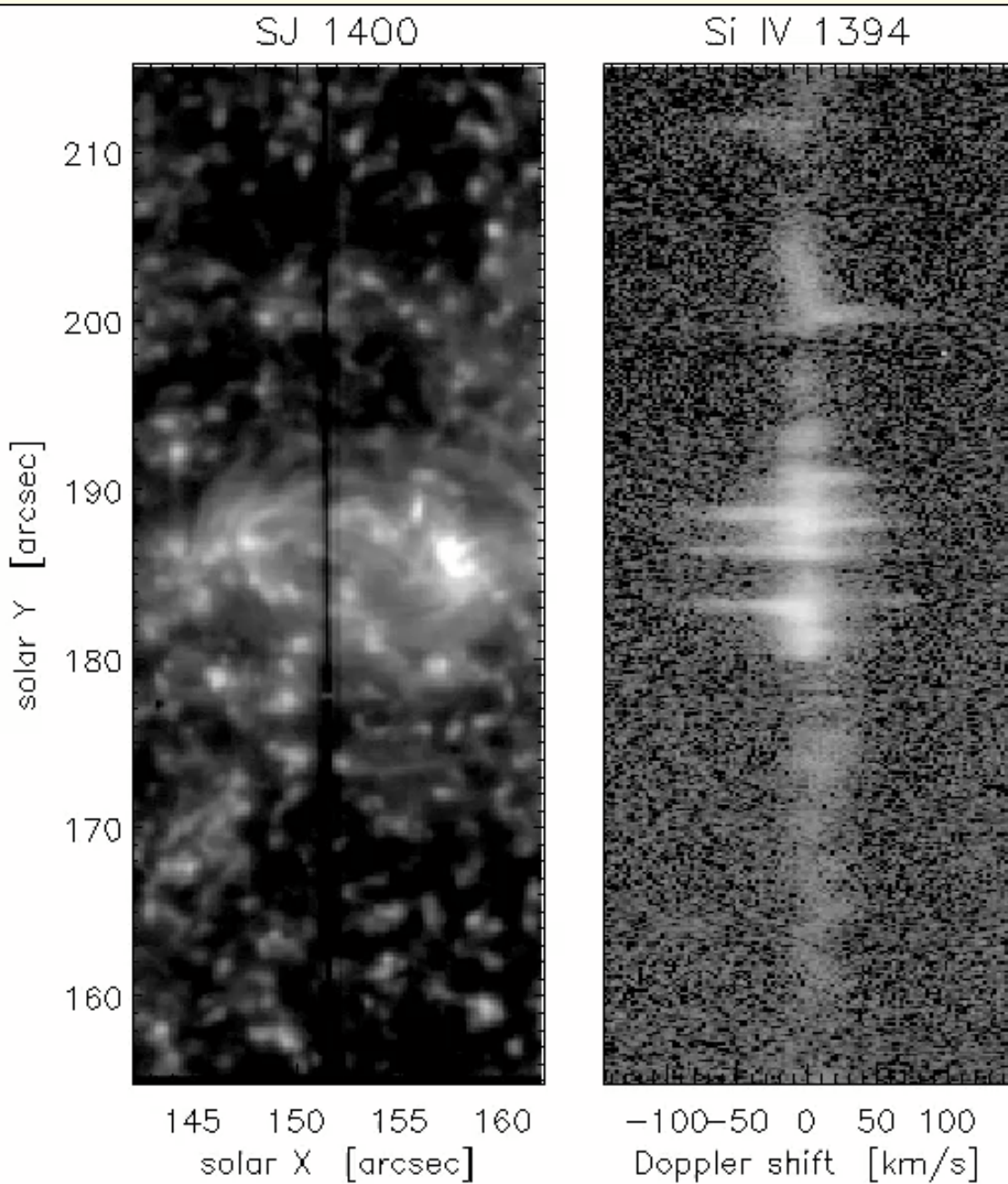
# IRIS observation modes and line list



Ion Spectrum	$\lambda$	$\Delta\lambda$	Log T	Estimated Count Rate (counts/s/line/spatial pixel)			Detector
	Å	mÅ	K	Quiet Sun	Active Region	Flare	
<b>UV Spectra</b> (effective area of 1.8 cm <sup>2</sup> for far-UV, 0.25 cm <sup>2</sup> for Mg passband, continuum is 1 Å)							
†: Count rates for Mg II wing, h and k are in counts/s/spectral pixel/spatial pixel							
Mg II wing	2820	25	3.7-3.9	3500†	12500†	12500†	3
O I	1356	12.5	3.8	60	165	410	1
Mg II h	2803	25	4.0	1400†	5400†	20000†	3
Mg II k	2796	25	4.0	1800†	7300†	15000†	3
C II	1335	12.5	4.3	670	4300	45000	1
C II	1336	12.5	4.3	920	5700	55000	1
Si IV	1403	12.5	4.8	170	3000	3e6	2
Si IV	1394	12.5	4.8	370	6000	9e6	2
O IV	1401	12.5	5.2	50	230	4e5	2
O IV	1400	12.5	5.2	10	70	1e5	2
Fe XII	1349	12.5	6.2	20	50	500	1
Fe XXI	1354	12.5	7.0	10	40	4e4	1
<b>UV Slit-Jaw Images</b>				<b>Estimated Count Rate (counts/s/pixel)</b>			
Effective area 0.003 cm <sup>2</sup> with 4 Å FWHM filter for Mg II; 0.45 cm <sup>2</sup> with 40 Å FWHM for far-UV.							
Mg II wing	2831		3.7-3.9	1800	4100	4100	4
Mg II k	2796		4.0	450	2100	5100	4
C II	1335		4.3	500	1600	16000	4
Si IV	1400		4.8	380	1500	3e5	4

from IRIS proposal

# IRIS: spectrograph and slit jaw imager



- specialized instrument:
  - limited  $\lambda$ -range ( $T$ -coverage)
    - chromosphere (Mg II, C II)
    - transition region (Si IV)
    - flares (Fe XXI)
- first slit jaw imager combined with EUV spectrograph
- 5x better spatial resolution than HRTS, SUMER, EIS
- 3x better spectral resolution than HRTS, EIS
- much higher time cadence than SUMER (4x ?)

covering ~1 hr  
8s exposure times of spectra  
27 s cadence of slit jaw images

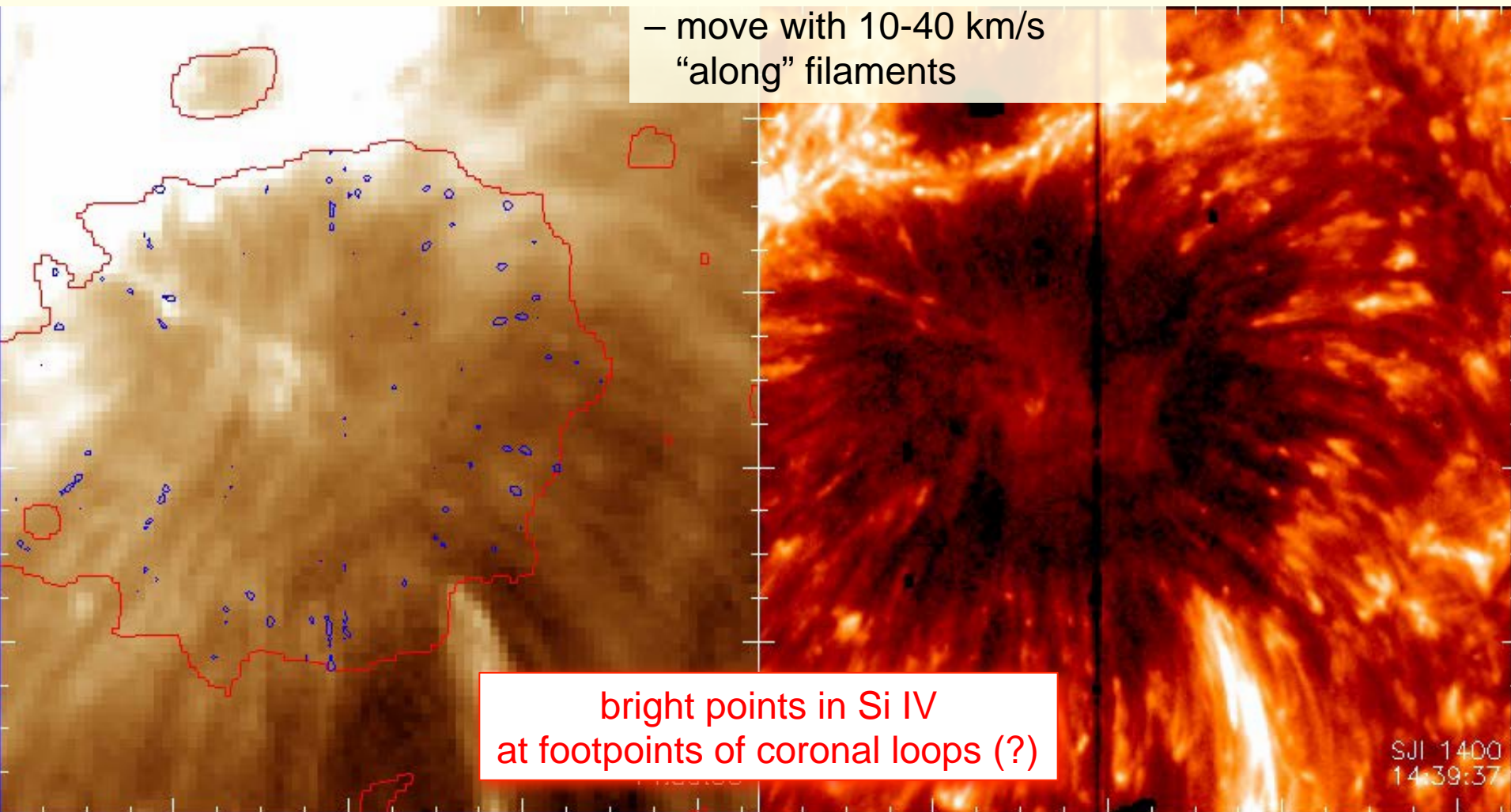
**IRIS:**  
**sunspot**

# Sunspot penumbra: corona and transition region

corona:  
AIA 193 Å  
(Fe XII ~1.5 MK)

bright dots in Si IV:  
– size <500 km (elongated)  
– lifetime < 1 min (mostly)  
– move with 10-40 km/s  
“along” filaments

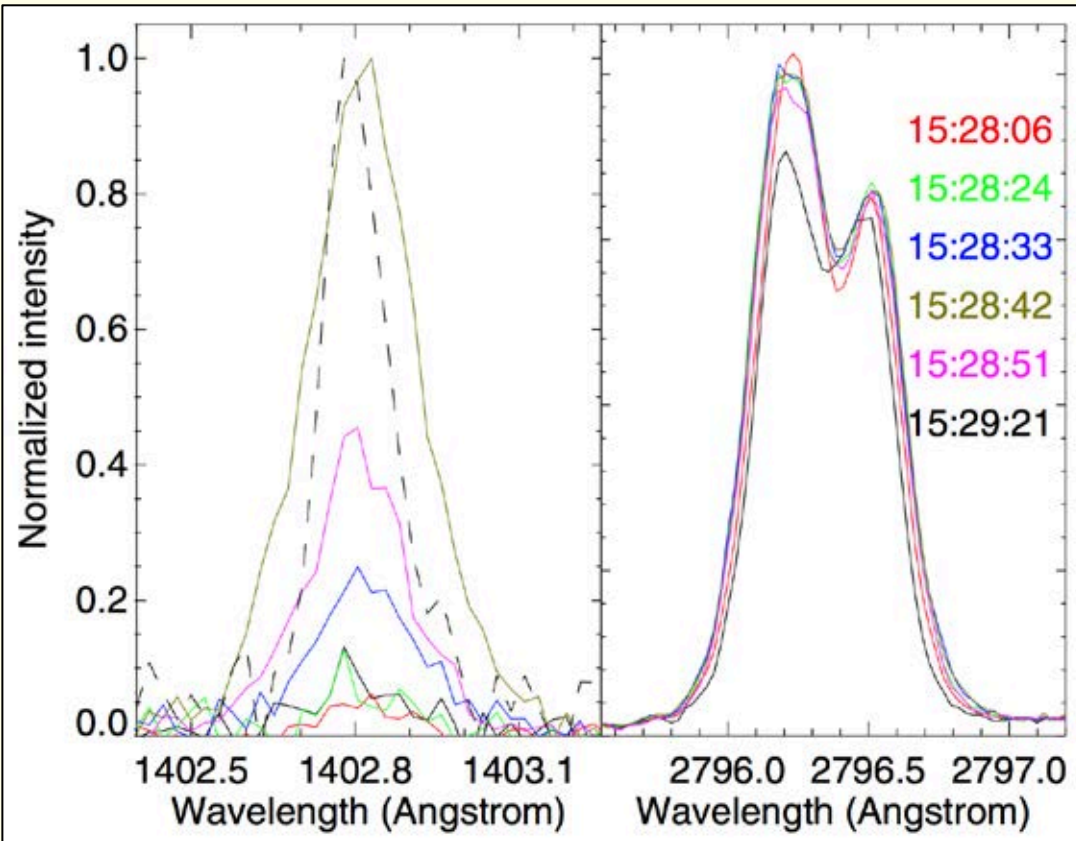
transition region:  
IRIS 1400 Å  
(Si IV ~0.1 MK)



~1 hour

Tian, Kleint, hp, et al (2014) ApJ 790, L29

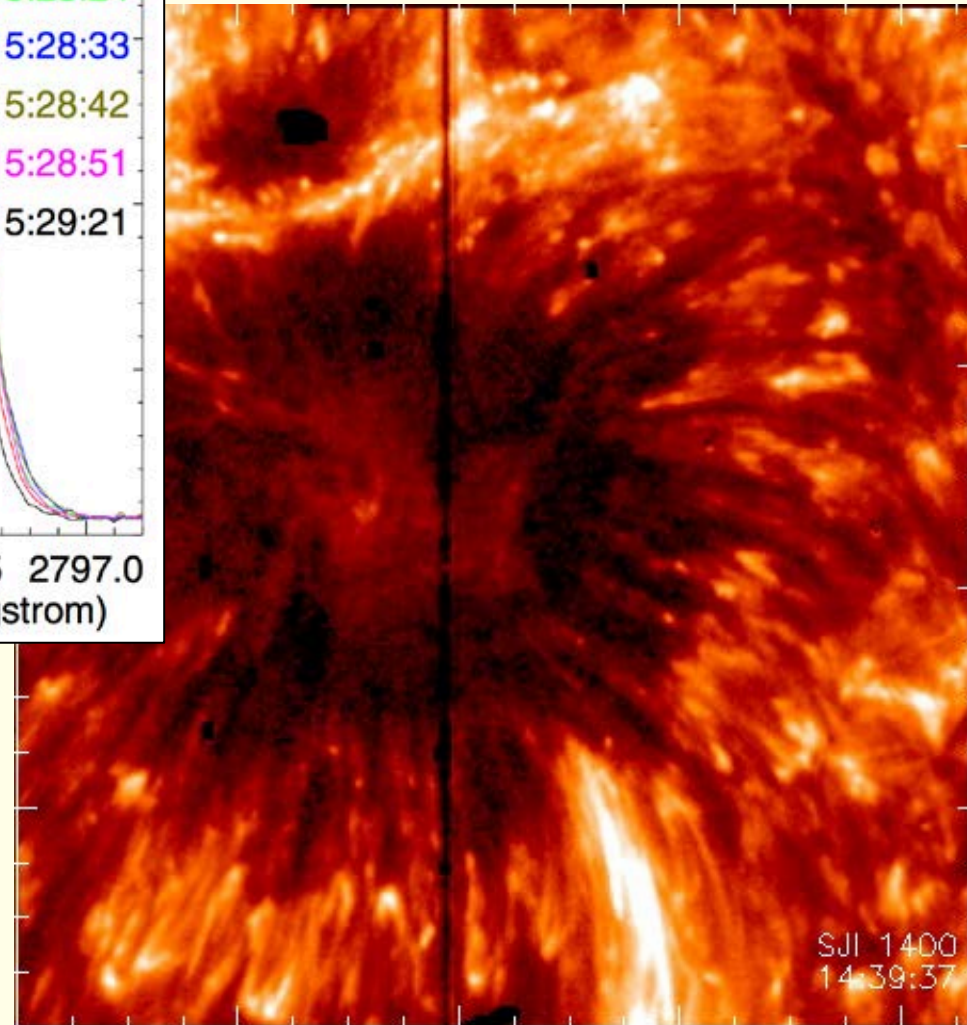
# Sunspot penumbra: corona and transition region



transition region:

IRIS 1400 Å

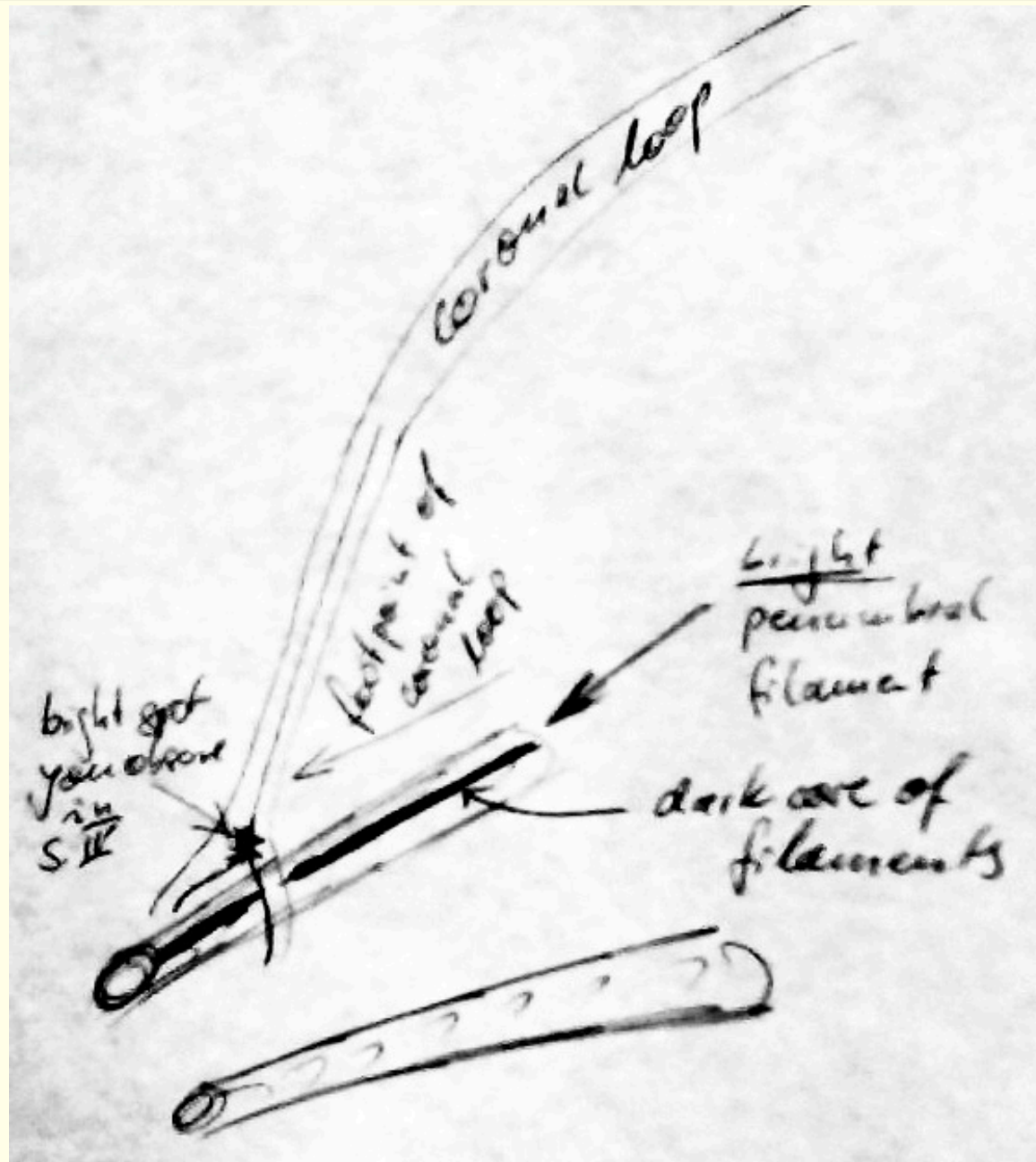
(Si IV ~0.1 MK)



## Spectra:

- little change in Mg II
- strong increase and (symmetric) broadening in Si IV
- much higher dynamics in TR than in chromosphere

# Did we find the footpoints of coronal loops ?



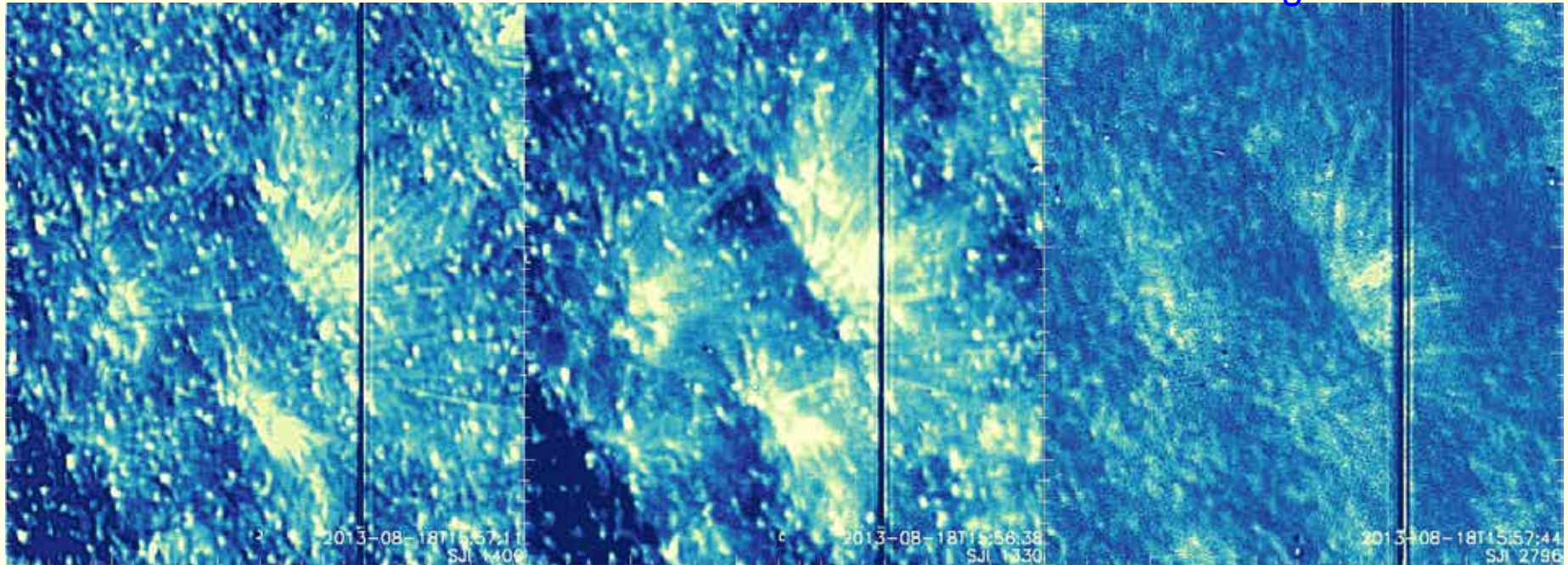
**IRIS:  
network  
and  
twisting**

# Prevalent network jets

Si IV

C II

Mg II



Tian et al. (2014) Sci. 346, 1255711

99s cadence; 41"x44" FOV

- apparent speed: 80 - 250 km/s (mostly)
- lifetime: 20 - 80 s (limited by the cadence)
- width: <300 km
- extension: 4-10 Mm (some reach ~15 Mm)

- some might be connected to spicules
- implications for mass supply to corona / solar wind
- direct imaging of the blue component in network TR spectra

# Structure of the TR emission in network

SJI 1330

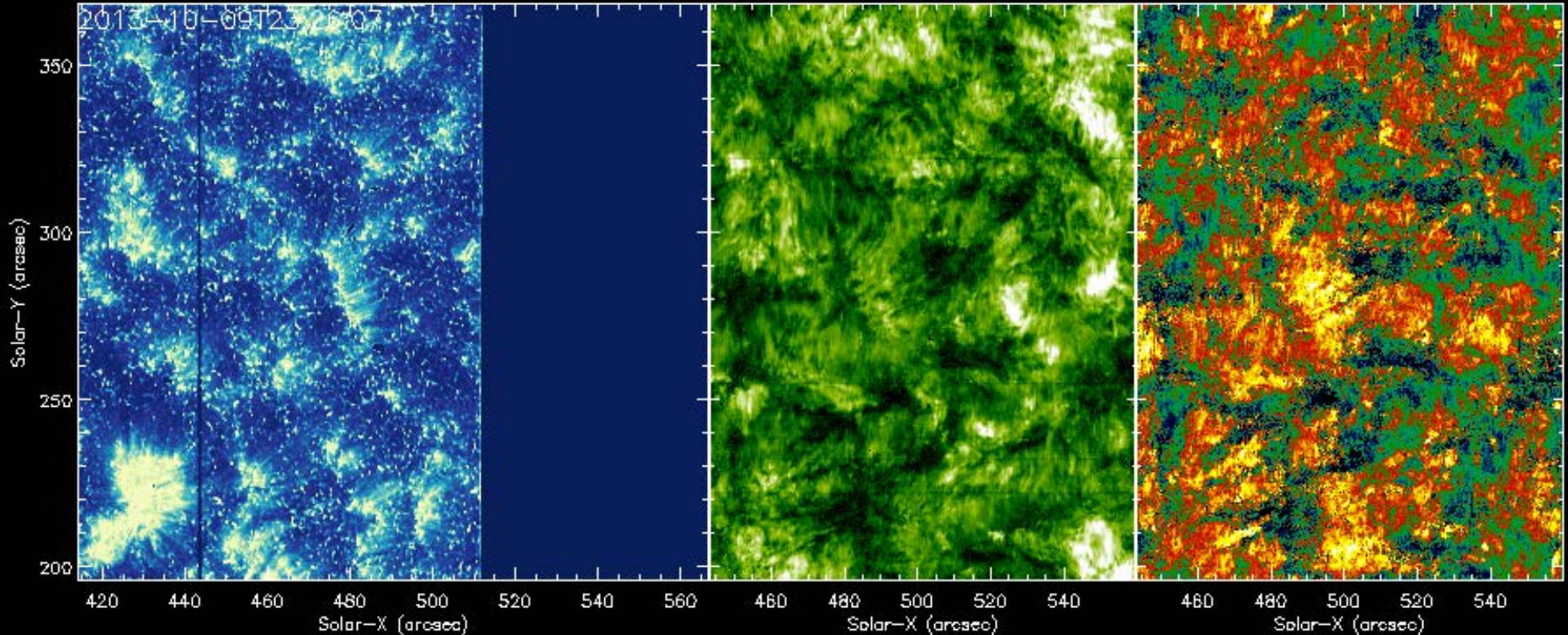
INT Si IV

WID Si IV

(A) Slit-jaw 1330 Intensity

(B) Peak Intensity

(C) Line Width [km/s]

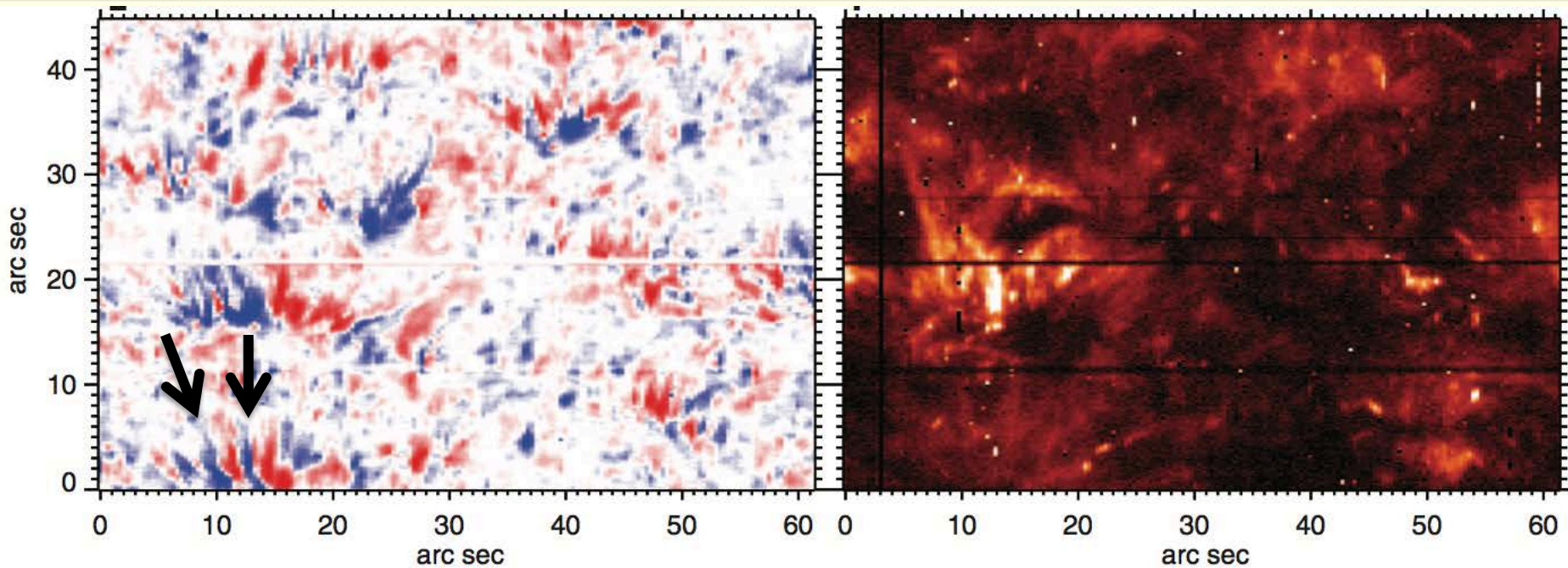


Tian et al. (2014) Sci. 346, 1255711

- network built up by
- prevalent network jets
  - small transient network loops

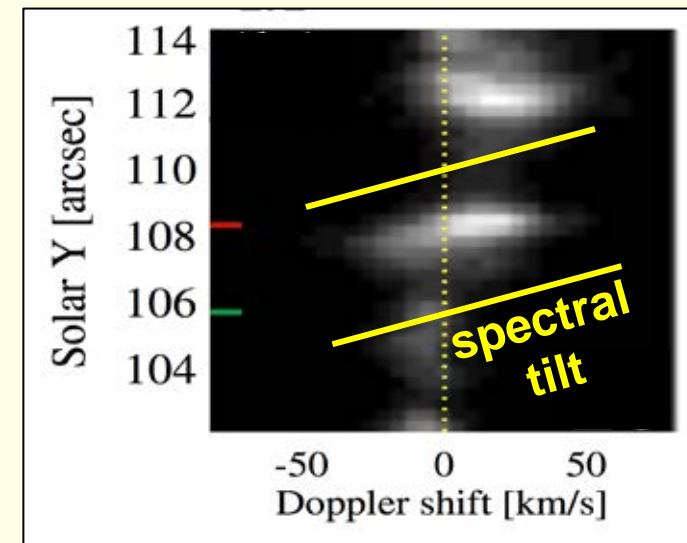
be careful when interpreting structures seen in raster maps...

# Prevalence of twist: quiet Sun, network, ARs...



De Pontieu et al. (2014) Sci. 346, 1255732

- ▶ twisting / torsional motions are found everywhere
- ▶ they could be
  - signature of Alfvén waves launched by small-scale photospheric vortices
  - result from the reconnection, e.g. as a result of flux emergence
  - ...
- ▶ they could have impact on helicity budget



Li, hp, Chen, Zhang (2014) A&A 570, A93

**IRIS:  
flares**

# A flare observed by IRIS

IRIS 1400

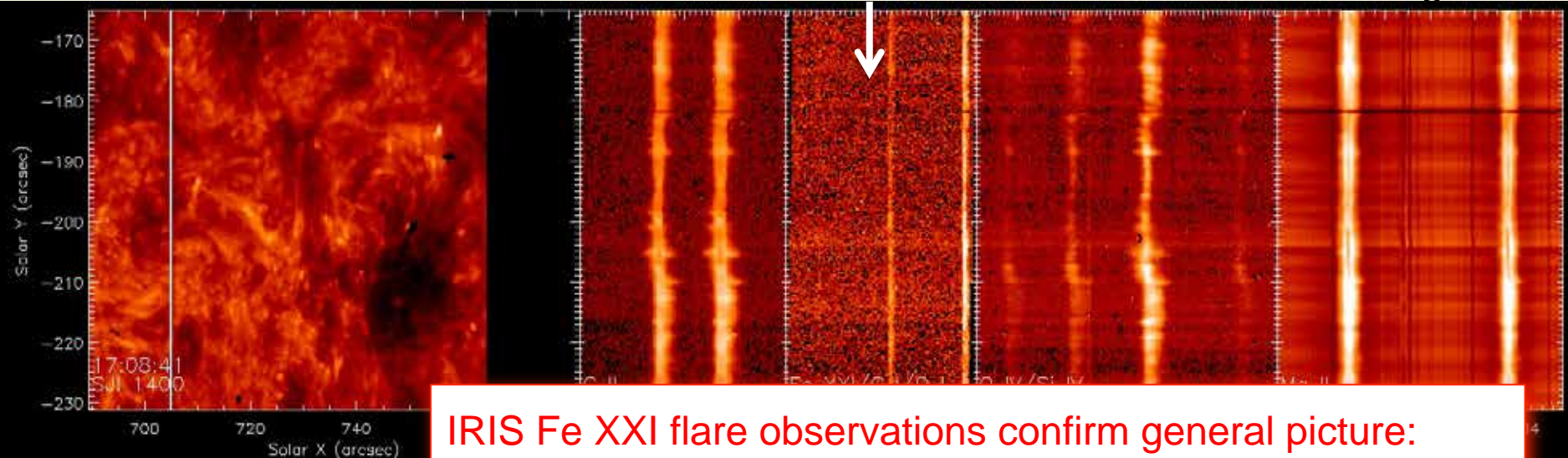
C II

Fe XXI

O IV

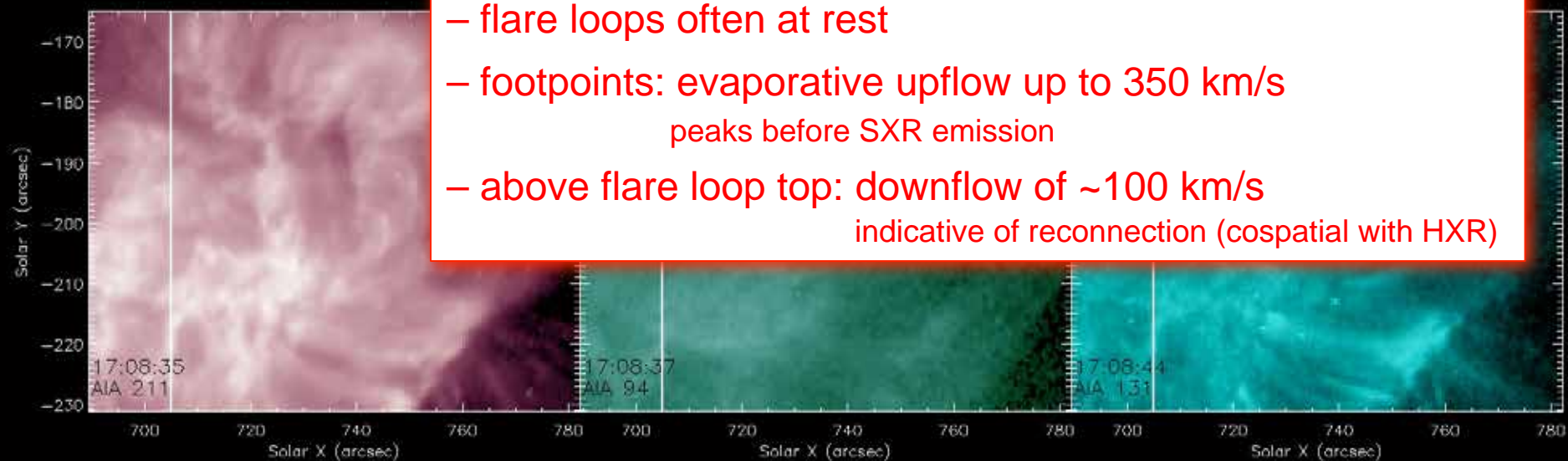
Si IV

Mg II



IRIS Fe XXI flare observations confirm general picture:

- flare loops often at rest
- footpoints: evaporative upflow up to 350 km/s  
peaks before SXR emission
- above flare loop top: downflow of ~100 km/s  
indicative of reconnection (cospatial with HXR)



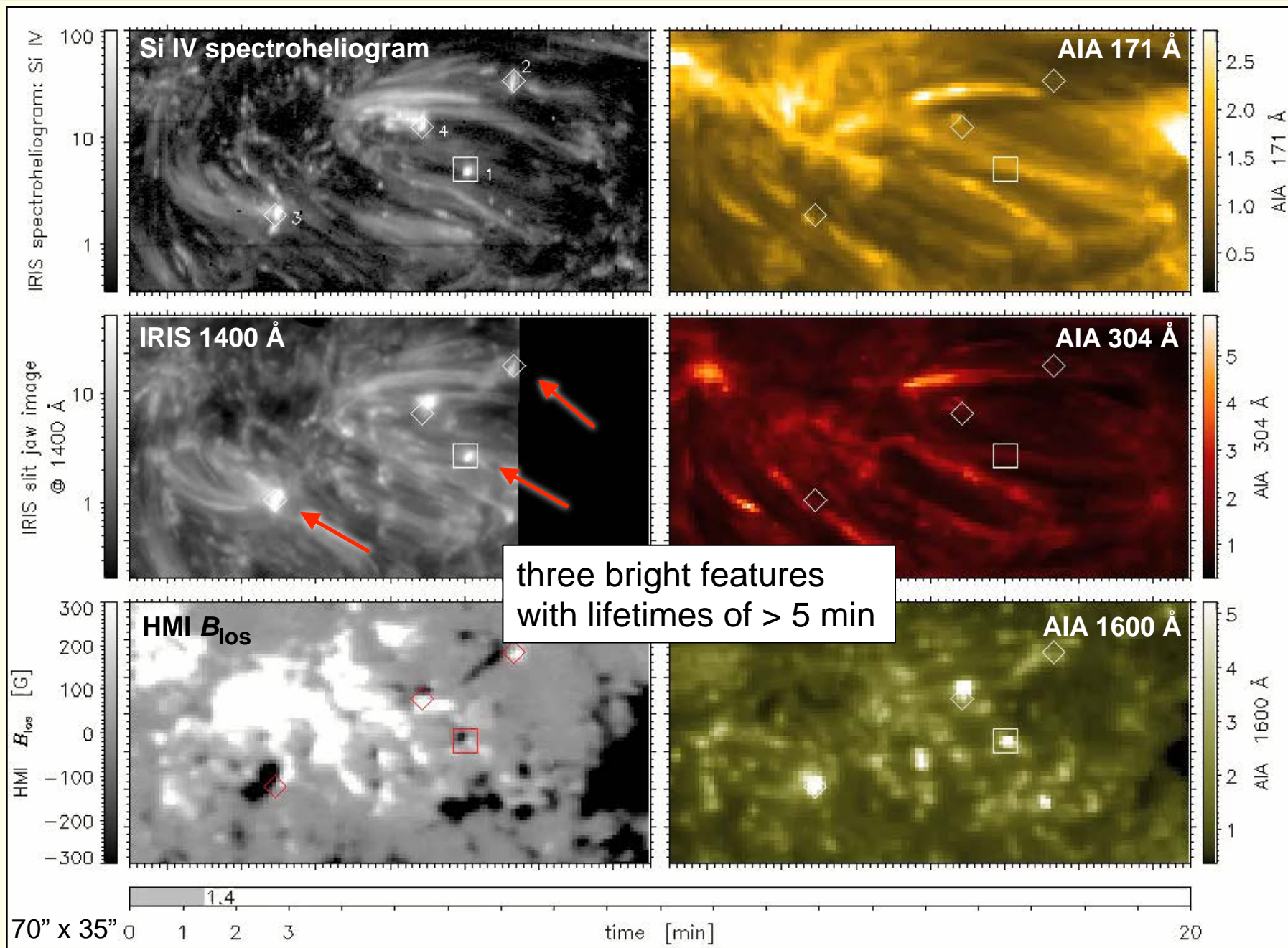
AIA 211

AIA 94

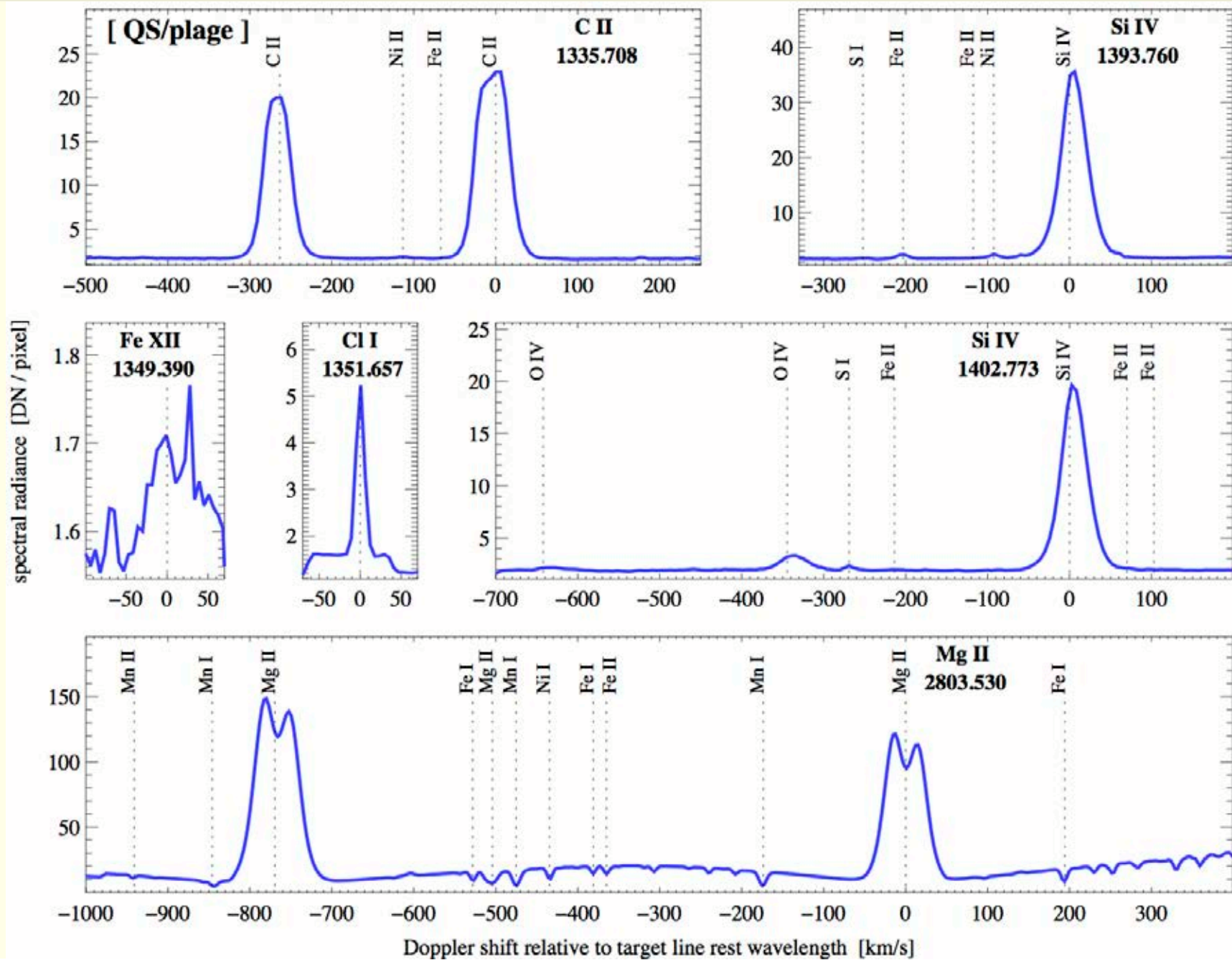
AIA 131

**IRIS:  
Ellerman  
bombs?**

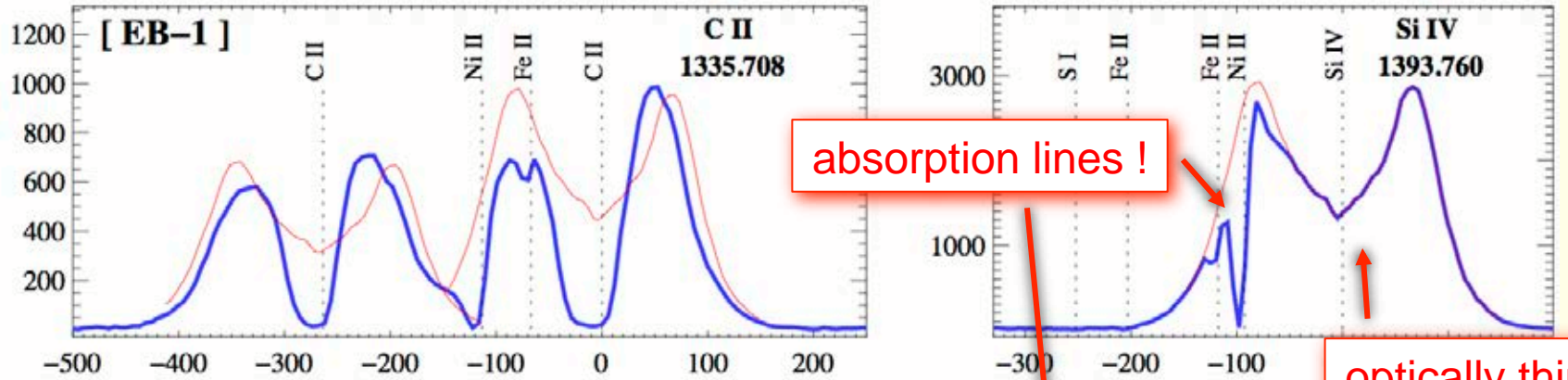
# Emerging AR (24. Sep. 2013): IRIS & SDO



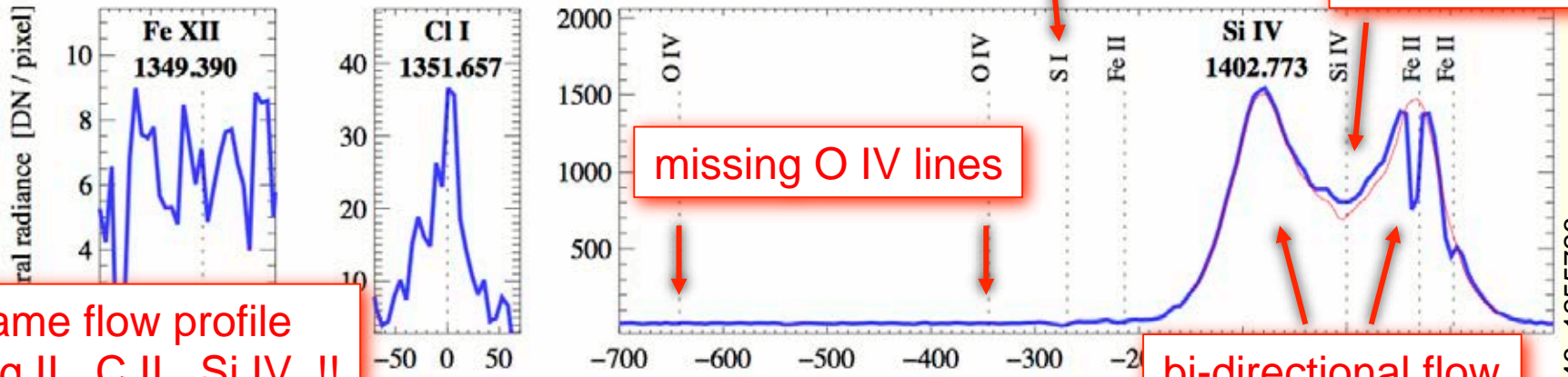
# Normal spectrum: average plage



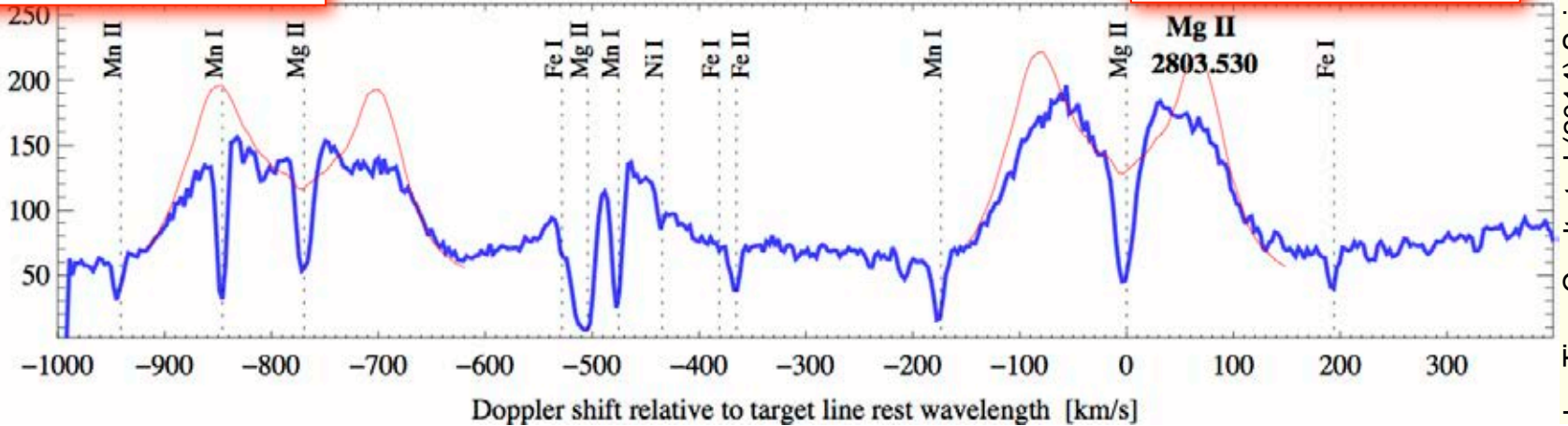
# Strange spectra: in a (Ellerman?) bomb



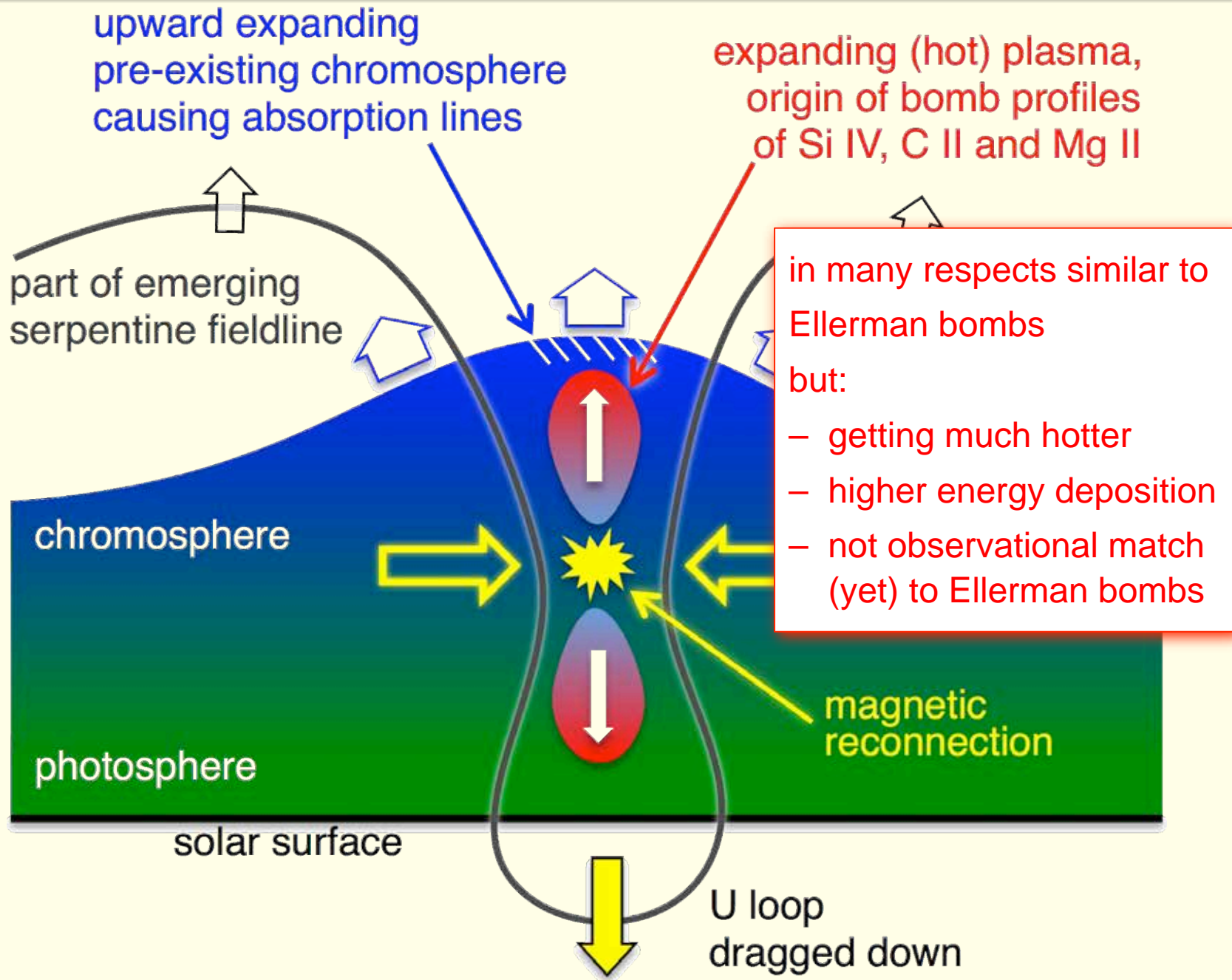
optically thin



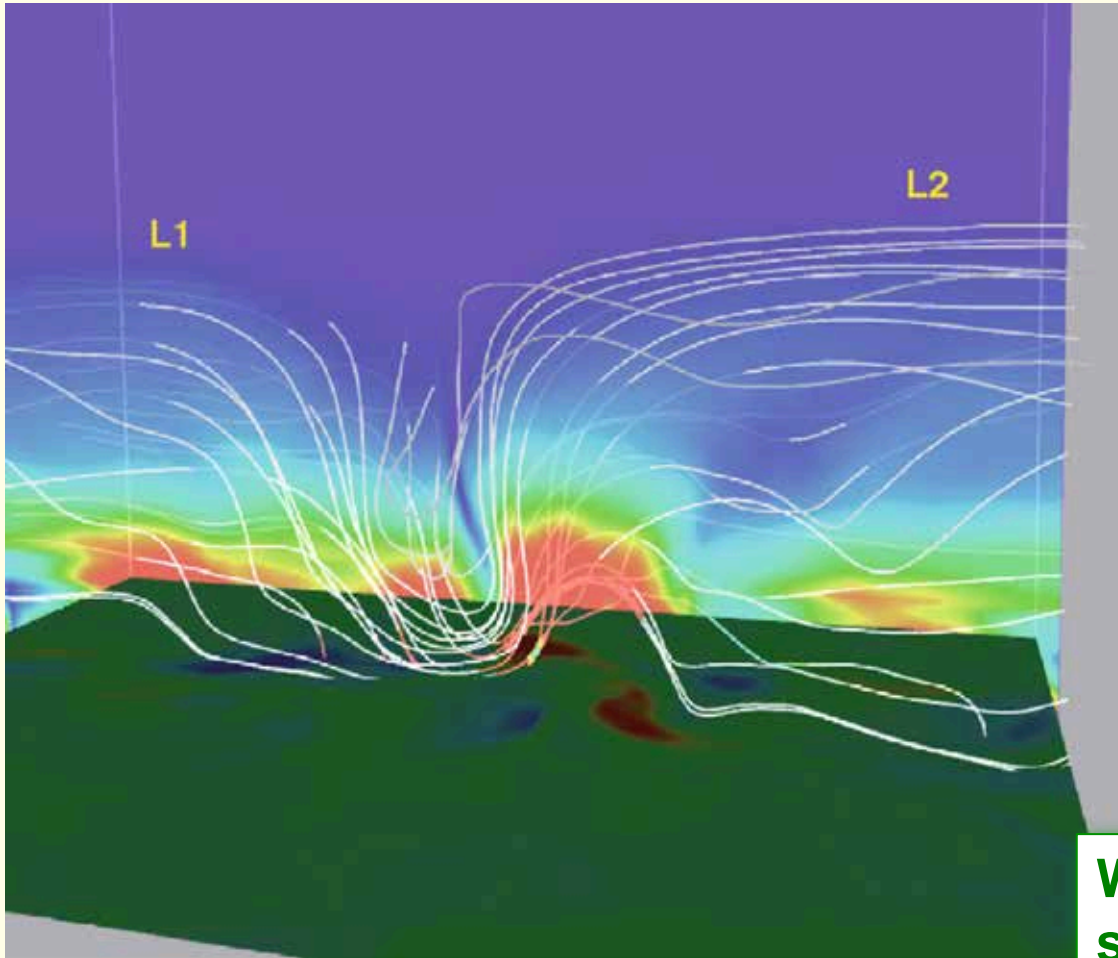
same flow profile  
in Mg II, C II, Si IV !!



# Scenario for the (Ellerman?) bombs



# How to produce so high $T$ in the chromosphere ?



such (Ellerman bomb-like) magnetic configurations are also found in 3D MHD models (Archontis & Hood, 2009, A&A 508, 1469)

→ but:  $T$  enhancement only a few 1000 K...

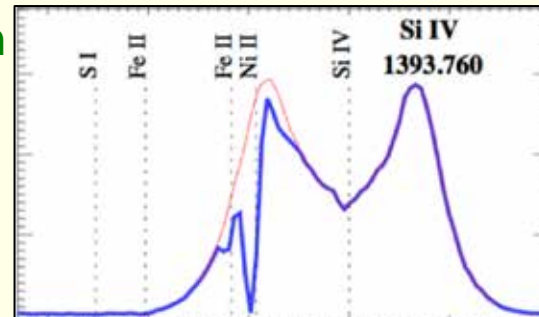
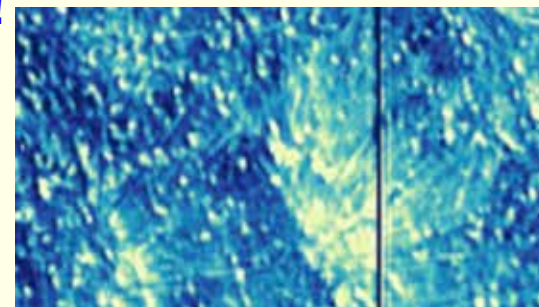
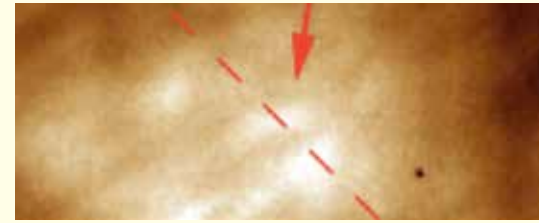
→ how can the dense chromospheric plasma be heated to almost 100.000 K ?

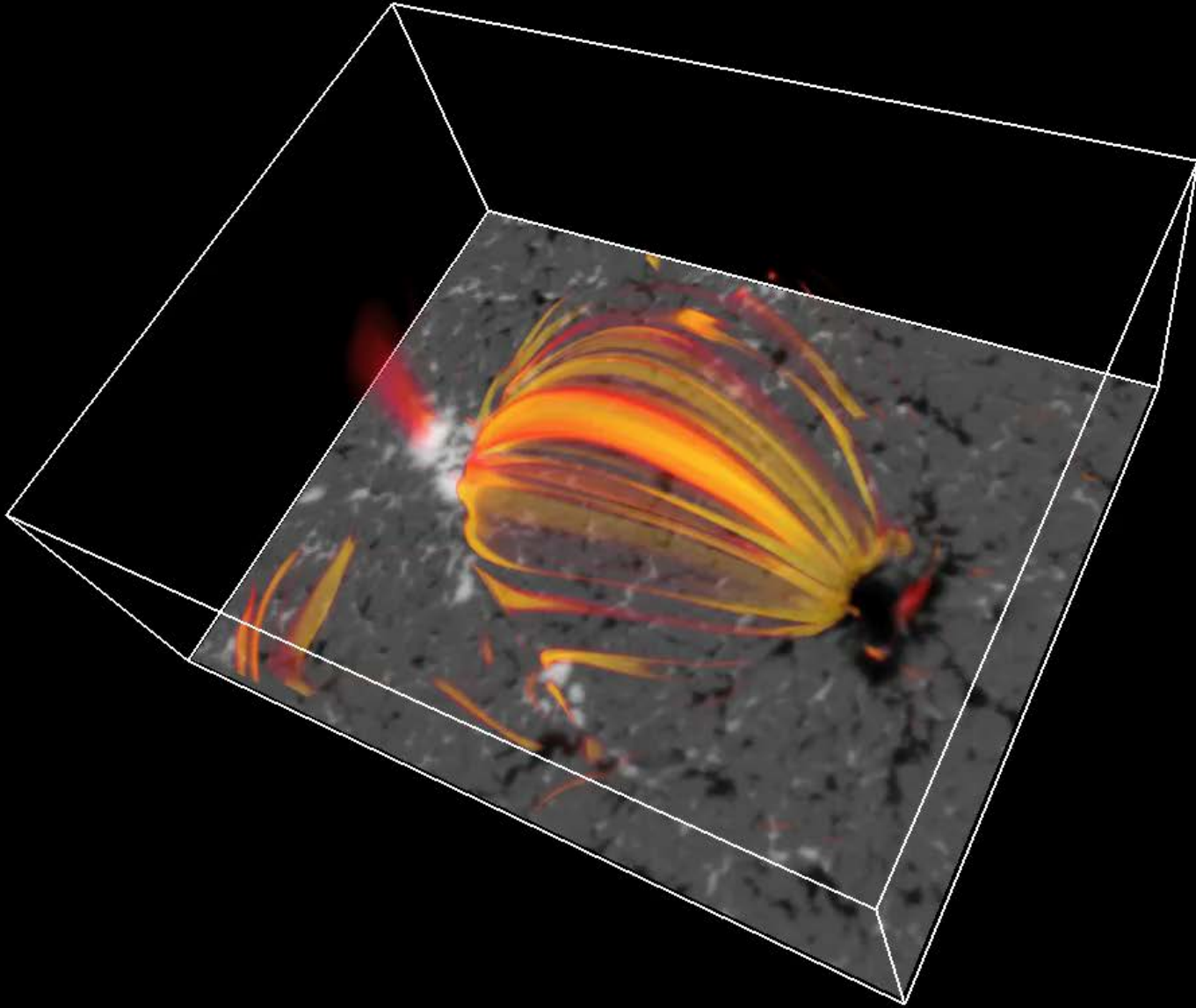
**What is the nature of small-scale extreme events?**

**Conclusions**

# Conclusions

- ▶ **loops at all sizes and temperatures.**  
(sort of) new: – cool network loops (UFS)  
– hot network/plage loops only 1 Mm long ?
- ▶ **some coronal loops might be resolved** (even by AIA)  
– indications for substructures to be  $> 300$  km  
– unclear what determines this width
- ▶ **getting closer to understand constant cross section**  
→ combination of magnetic and thermal structure
- ▶ **EUV loops might evolve differently than magnetic field !**  
be careful when interpreting magnetically evolving ARs.  
→ loops are 3D objects (and not 1D...)
- ▶ **IRIS:**
  - fantastic spectra
  - greatly increased spectral, spatial and temporal resolution
  - best for chromospheric and TR dynamics and structure
  - interesting flare diagnostics
  - ...





**thanks...**