Classical transition region vs. low-lying loops

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Jul 22, 2015

Coronal Loop Workshop 7, Cambridge

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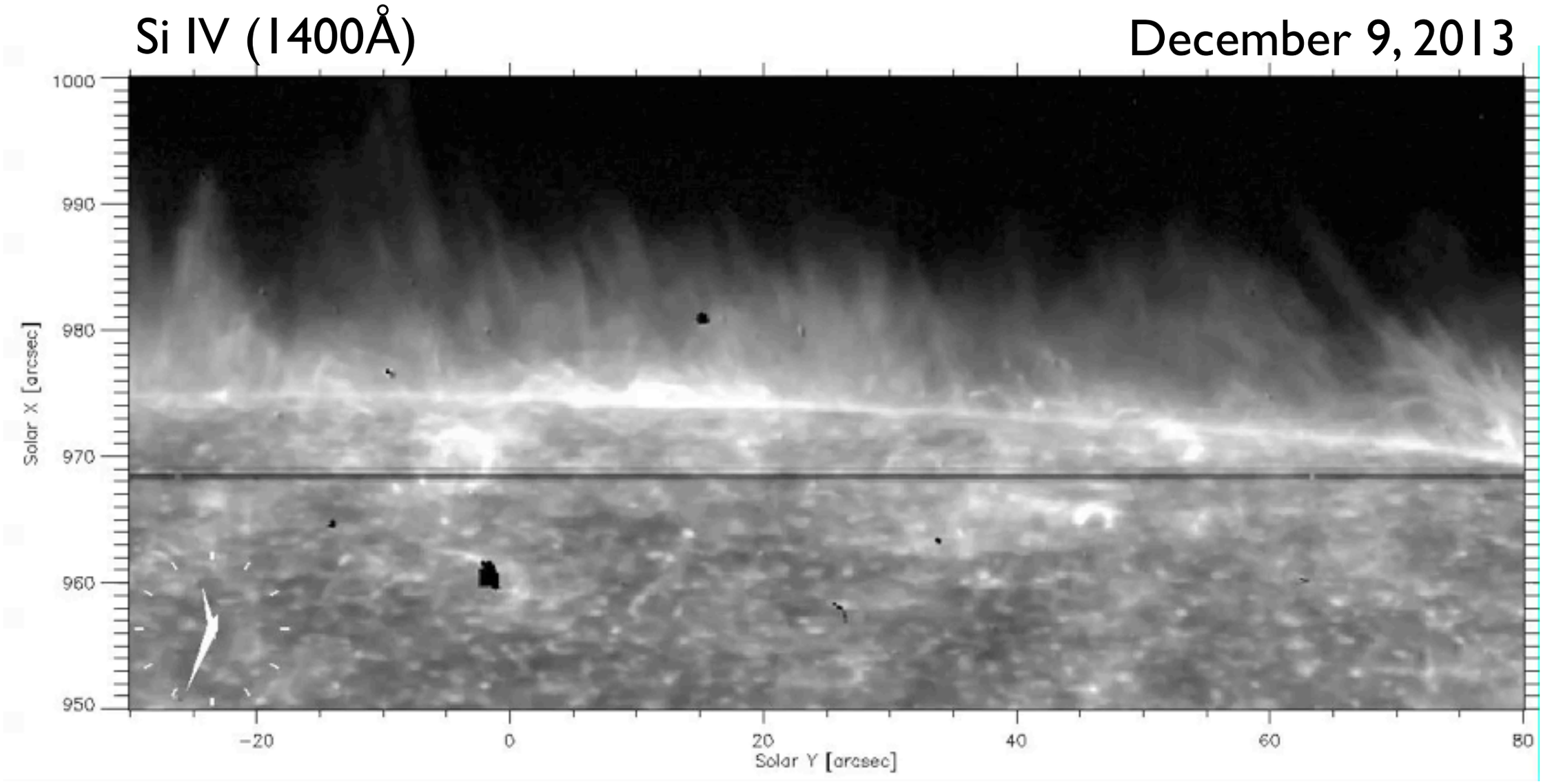
Outline

- Old standard picture of the solar transition region
- The discovery of UFS
- Two-component transition region
- Multi-component transition region
- Transient heating models
- UFS in IRIS observations
- UFS in 3D MHD models of the solar corona

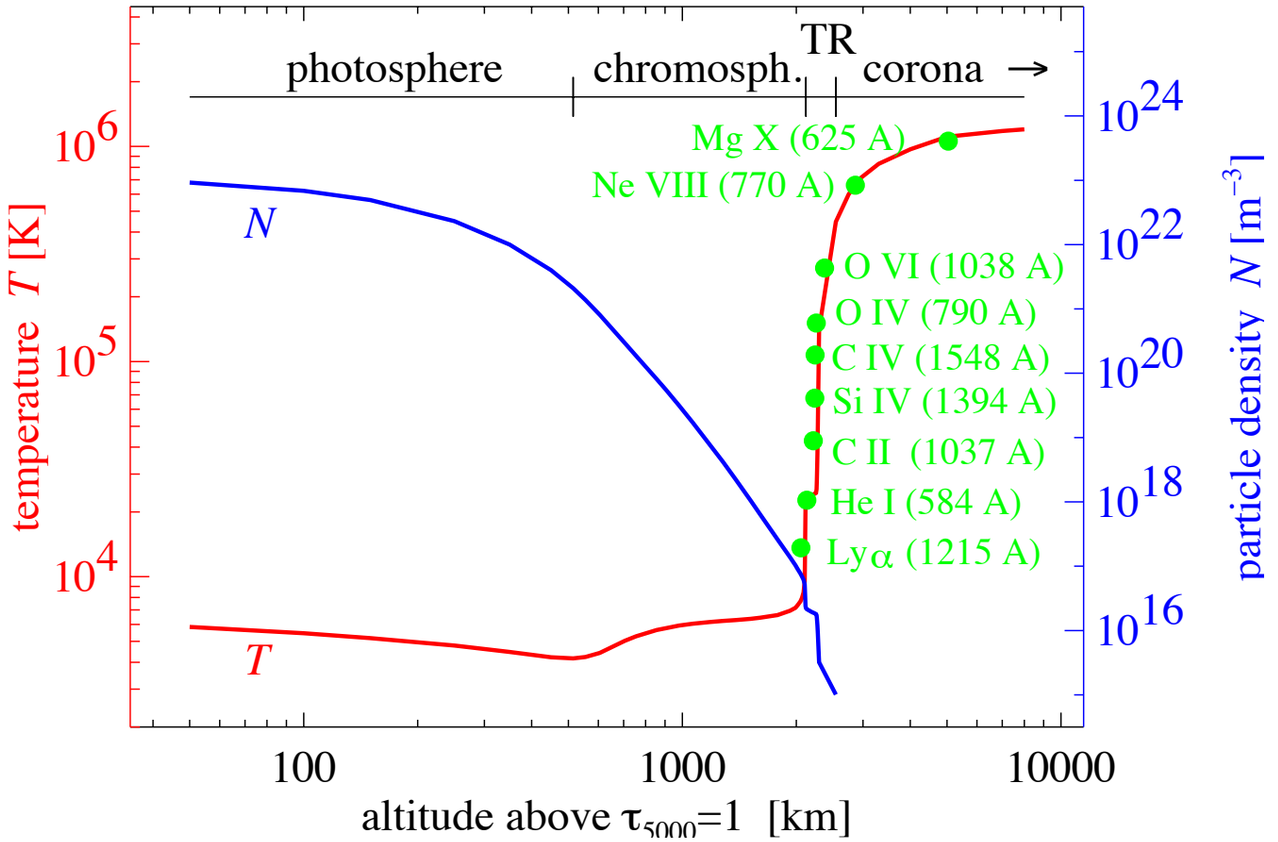
IRIS observations of UFS



Hansteen 2014

The solar transition region

temperature and density structure



courtesy of H. Peter

- steep rise in temperture
- short cooling time
- very dynamic
- emits almost only in the EUV

Observational challenges

- TR redshifts and coronal blueshifts
- shape of the DEM

Mariska, 1992

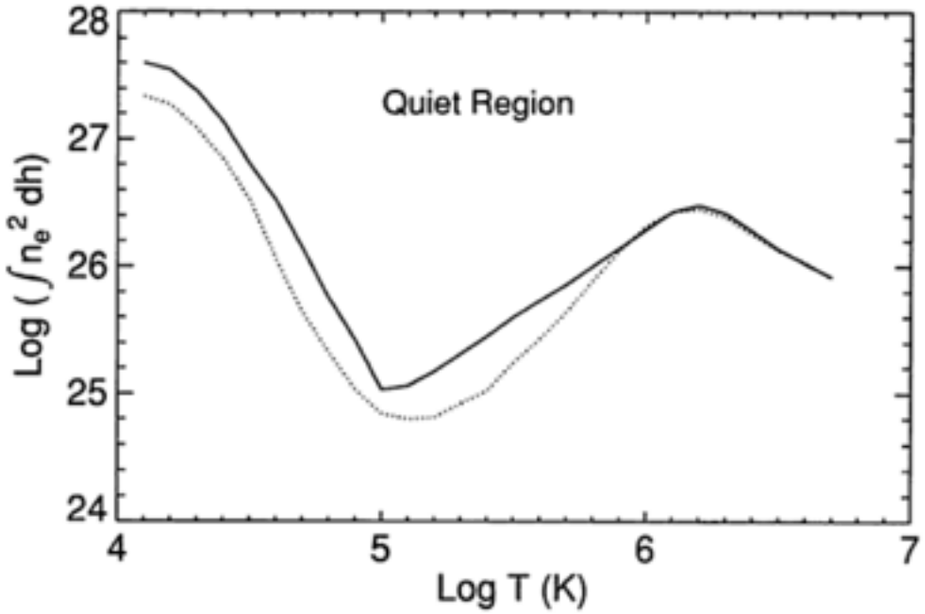
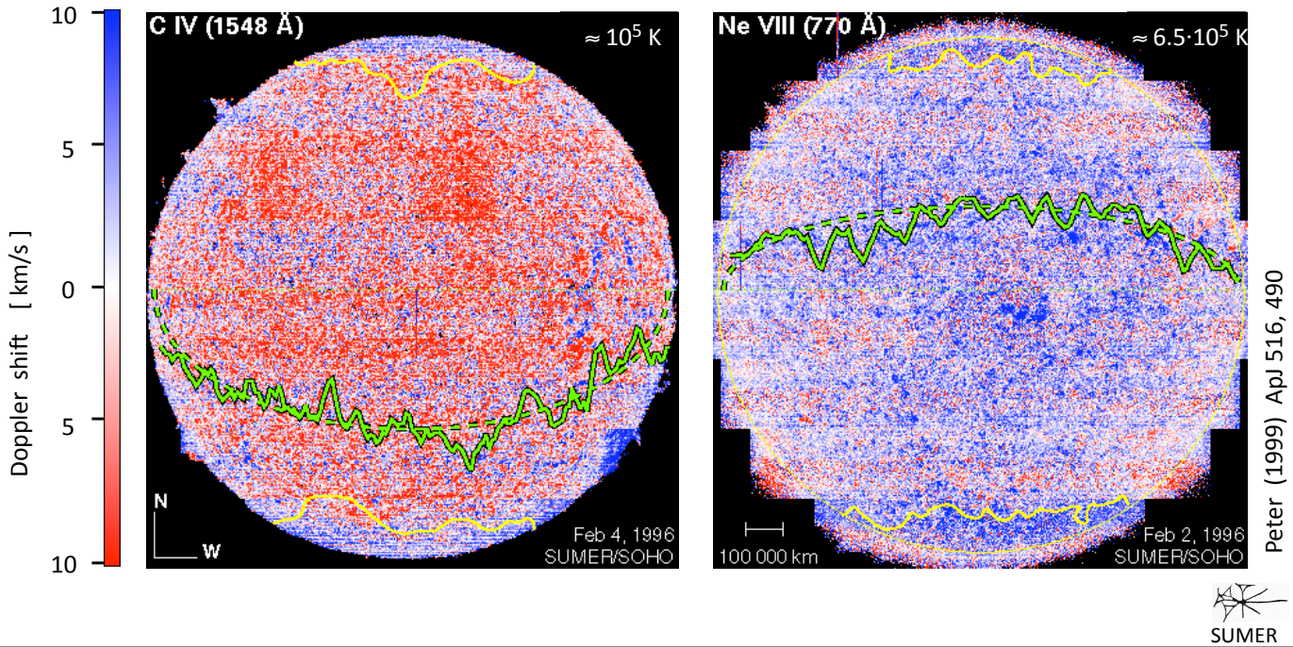
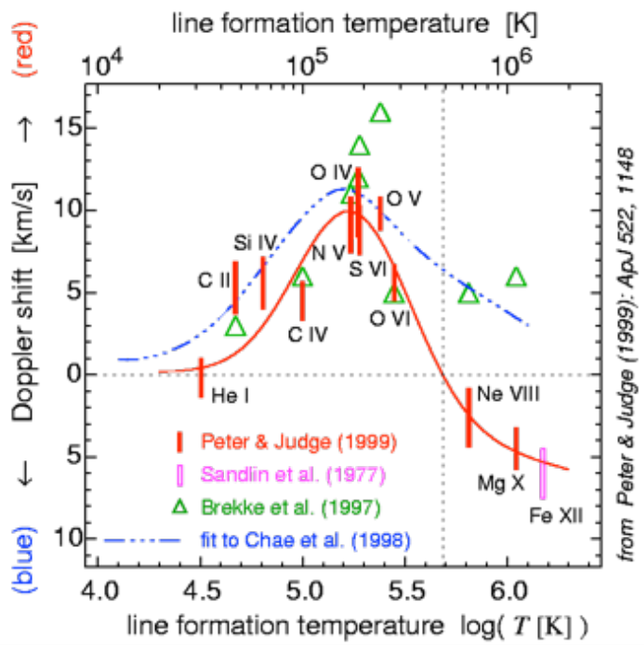


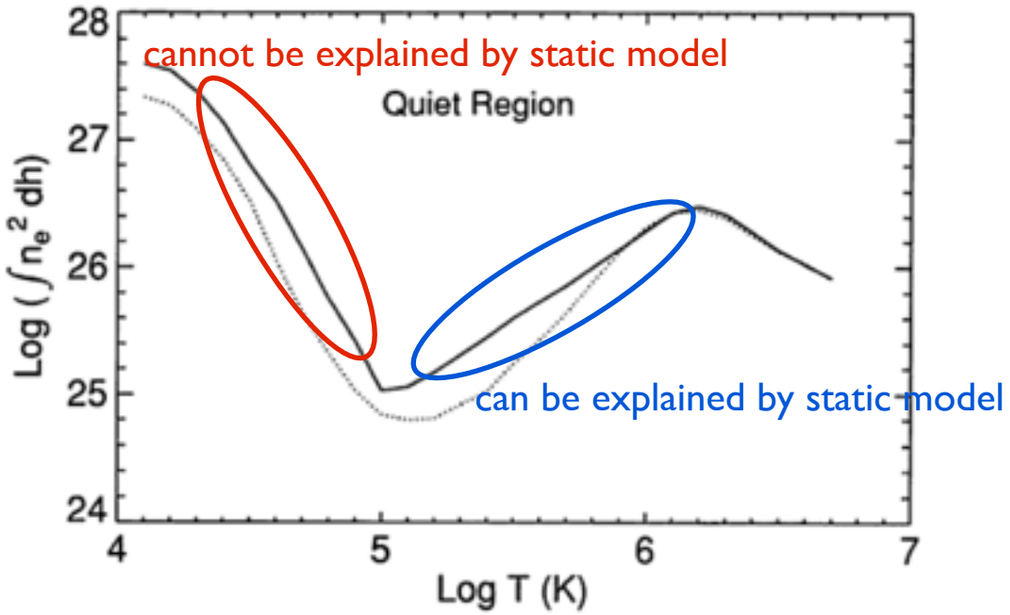
Fig. 4.1. Emission measure distribution for the quiet-Sun network (solid line) and cell center (dotted line) spectra of Vernazza and Reeves (1978). Each value of the emission measure plotted here is integrated over 0.1 in log T (data courtesy J. Raymond).





Emission measure distribution

Mariska, 1992



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- unique shape!
- minimum near T=105K
- power law with negative slope at lower temperatures
- power law with positive slope at higher temperatures
- turnover at coronal temperatures

- spicules (Athay 1984)?
- Ohmic dissipation (Moore & Rabin 1984)?

Old standard picture

Gabriel 1976

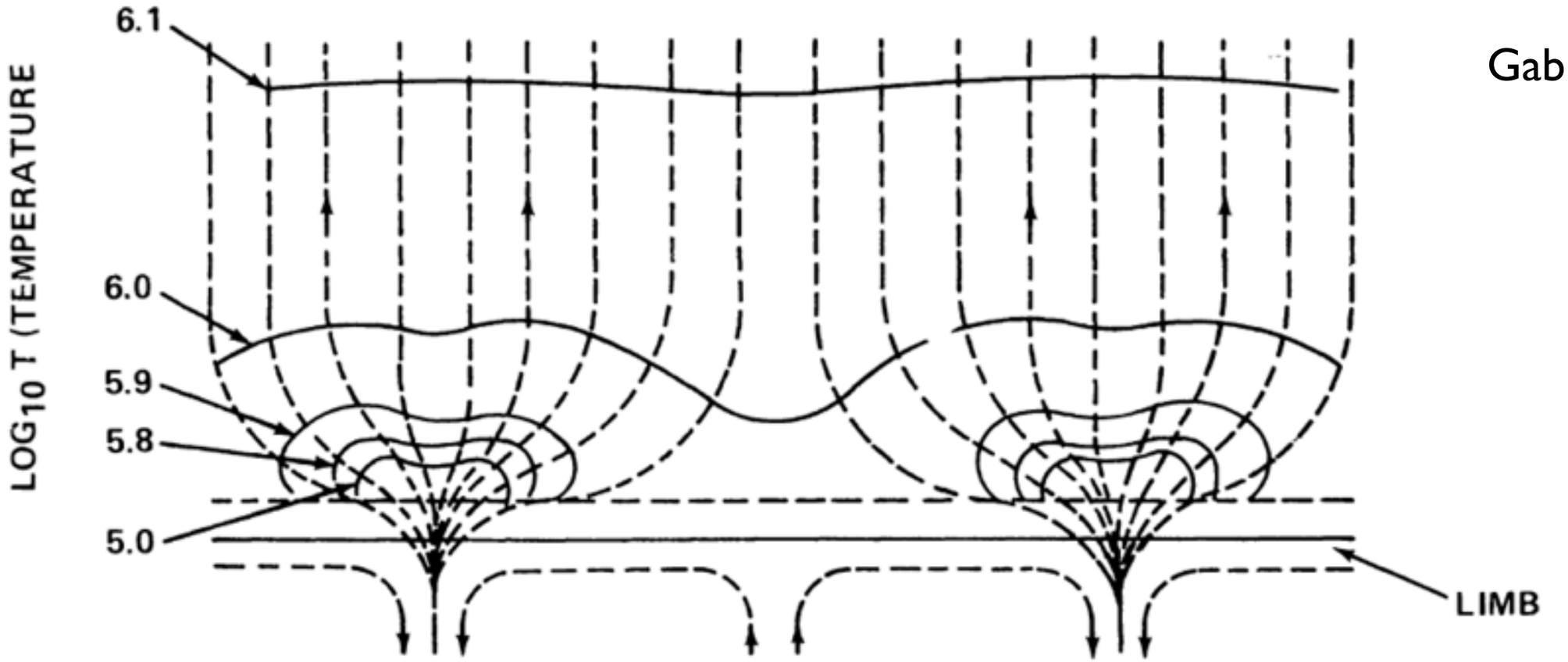

Fig. 1. The standard two-dimensional picture of magnetic structure in the transition region (after Gabriel, 1976). Field lines emerge from the network boundaries, where they are concentrated by supergranulation flow and from where they diverge rapidly with height until they are uniform and vertical in the corona. All of the flux that emerges from the surface eventually reaches the corona. It is tacitly assumed that the magnetic field is approximately uniform along the cell boundaries.

Uniform heating and RTV scaling laws (1978)

- hydrostatic solutions assuming uniform heating and uniform pressure
- $T \sim (pT)^{1/3}$, $EH \sim p^{7/6} H^{-5/6}$
- generalized by Serio et al. 1981: non-uniform heating and gravity
- analytical solution to hydrostatic solutions, e.g. Aschwanden&Schrijver 2002

The discovery of UFS

THE ASTROPHYSICAL JOURNAL, 275:367–373, 1983 December 1

ON THE UNRESOLVED FINE STRUCTURES OF THE SOLAR ATMOSPHERE IN THE 3×10^4–2×10^5 K TEMPERATURE REGION

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Received 1983 March 7; accepted 1983 May 11

ABSTRACT

The solar atmospheres from the chromosphere through the transition zone and all the way up into the corona usually are considered to be parts of one continuous structure. Now that stellar measurements in the far-ultraviolet have become available, an attempt is being made to apply solar physics ideas to solar type stars. The intention of this paper is to reexamine the experimental facts concerning the relations between the solar chromosphere, transition zone, and corona.

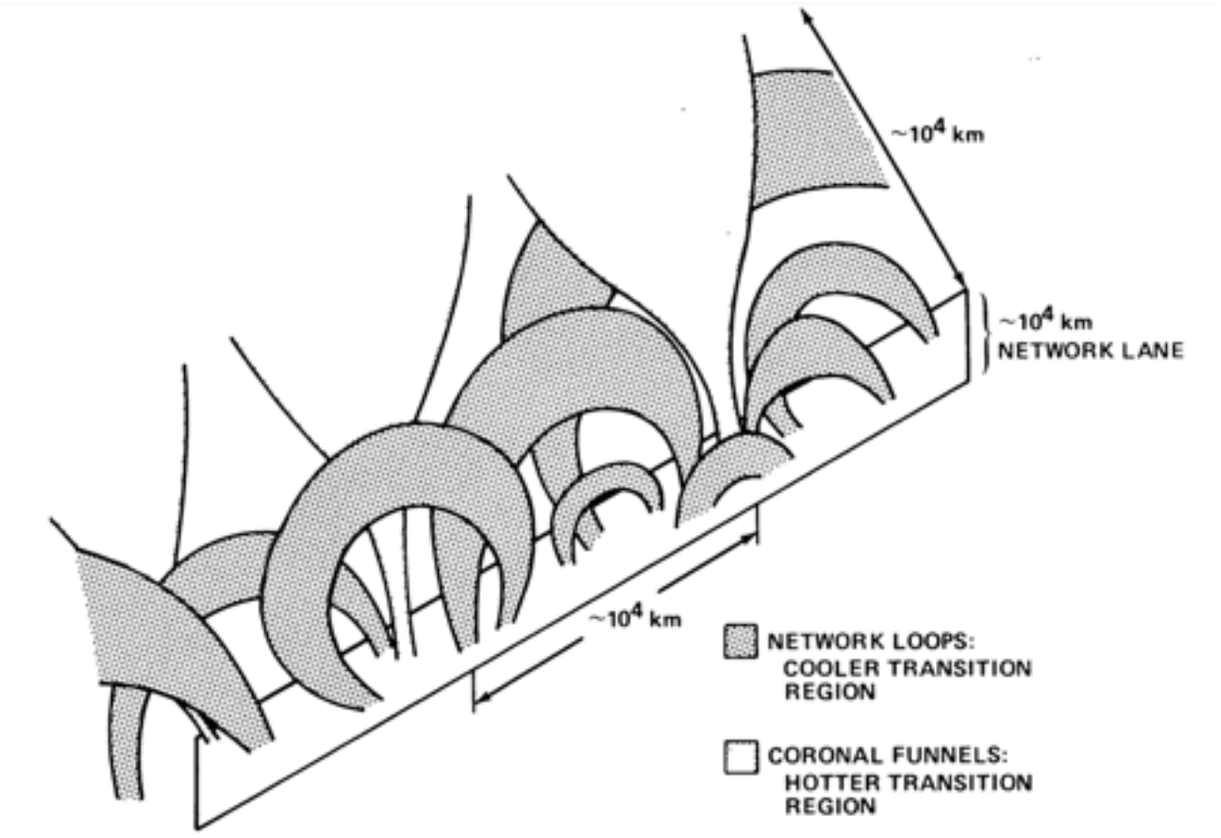
Experimental evidence is presented to argue that the solar plasma in the temperature region 4×10^4–2.2×10^5 K occurs in structures magnetically isolated from the chromosphere and corona. It is suggested that while a small part of the emission detected in the 4×10^4–2.2×10^5 K region consists of the "true" transition zone plasma, i.e., the interface between chromospheric and coronal temperatures, that most of it belongs to an altogether different entity. It is also suggested that this particular entity be called unresolved fine structures.

- introduced the term "UFS"
- Feldman 1987 extended temperature range to 2×10^5 K

Properties of UFS

- high non-thermal mass motion (18-26 km/s)
- emission peaks 2”-4” above the limb, still visible at 12”
- emission measure changes as a function of temperature above the limb
- different electron density at same temperature for different solar regions
- production of plasma depends little on the nature of the solar region
- net area occupied is extremely small in size/structures are unresolved
- redshifts corresponding to velocities of ~5 km/s

Two-component transition region



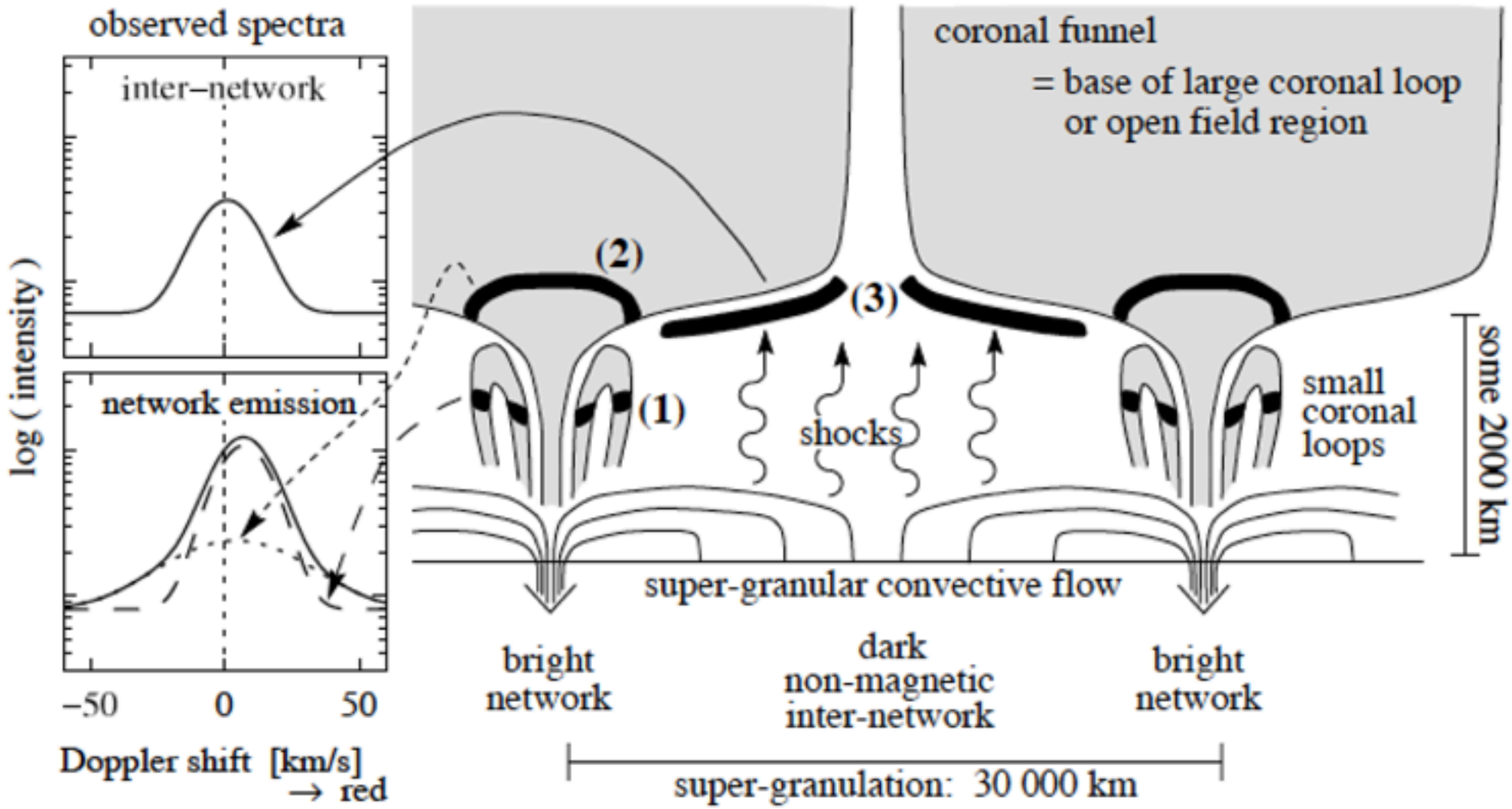
- low-lying loops:
  - lengths $<10^4$ km
  - internally heated
  - able to explain the DEM at low temperatures
- coronal funnels
  - do not contribute much to the TR emission
  - heated by back-heating from the corona

Dowdy et al. 1986

Antiochos & Noci 1987

Multi-component transition region

Peter 2000



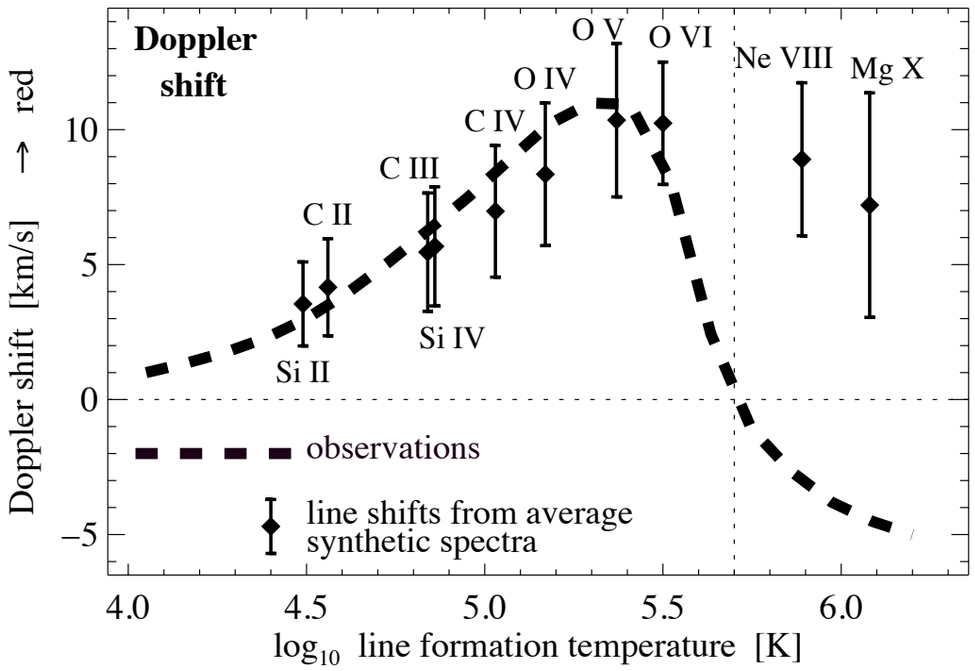
Transient heating models

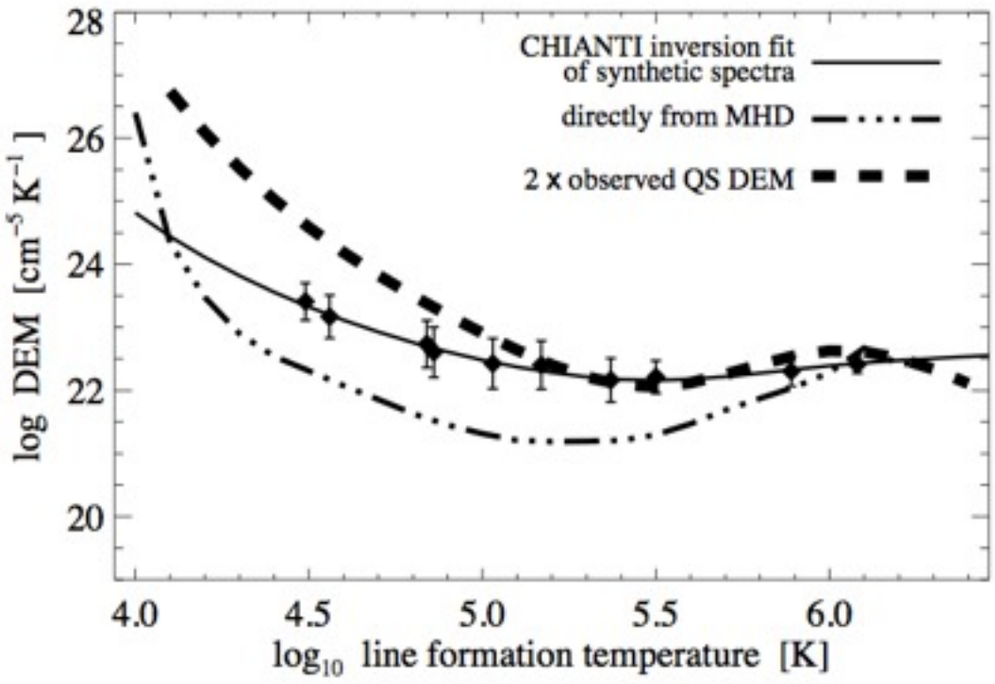
Spadaro et al. 2006

- small, cool magnetic loops undergoing transient heating spatially localized near the chromospheric footpoints
- 1D hydro code with adaptive grid method
- closest agreement with observations for heating timescales of 20s every 100s with heating length scale of the order of 1Mm and nanoflare scale
- reproduce redshifts of transition region lines and emission measure distribution in the range logT=4.7-6.1

3D MHD models of the photosphere-corona system

Gudiksen & Nordlund 2002, 2005
Peter et al. 2006
Zacharias et al. 2011





Zacharias et al. 2011

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Origin of redshifts and blueshifts

- downward propagating compressive waves, e.g., generated by nanoflares in the corona *(Hansteen 1993)*

- transient heating near the coronal loop footpoints *(Spadaro et al. 2006, Peter et al. 2006)*

- rapid, episodic heating at low heights of the upper chromospheric plasma to coronal temperatures *(Hansteen et al. 2010, Guerreiro et al. 2012)*

- upflows in the form of cool pockets that heat up slowly as they rise (*Zacharias et al. 2011a*)

- signatures of draining gas from the corona after reconnection of field lines (*Zacharias et al. 2011b*)

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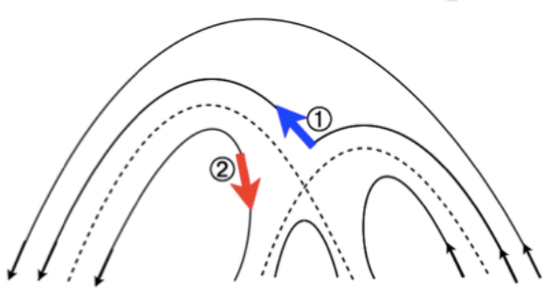
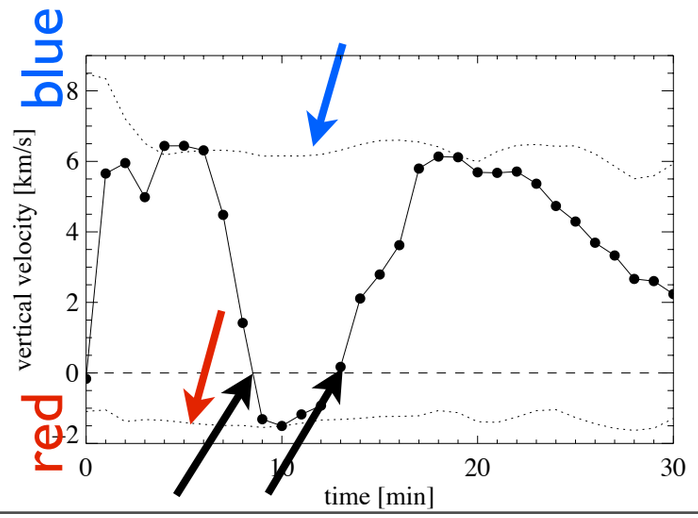
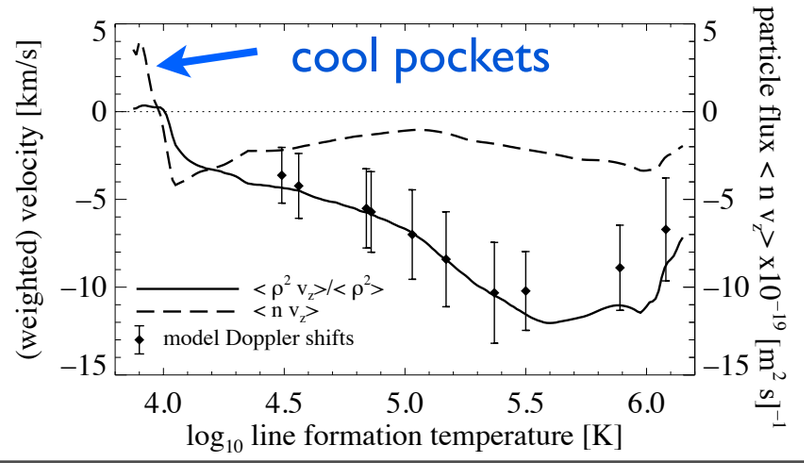






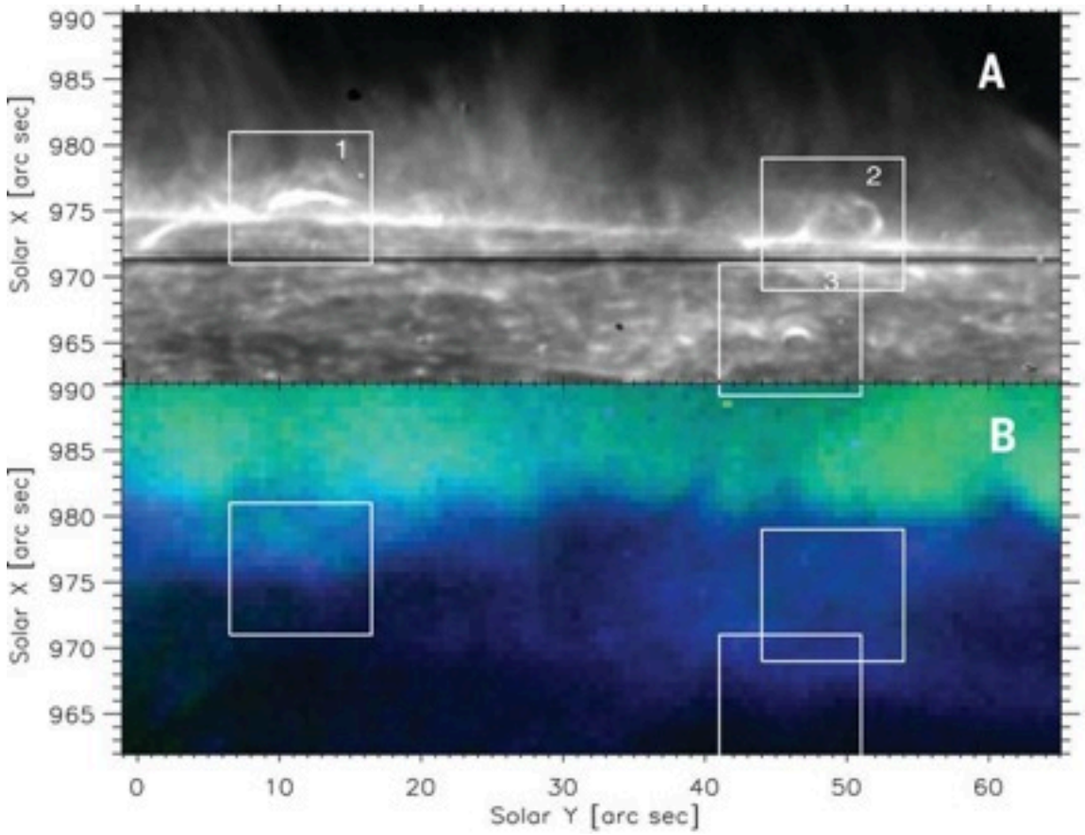
IRIS observations of UFS

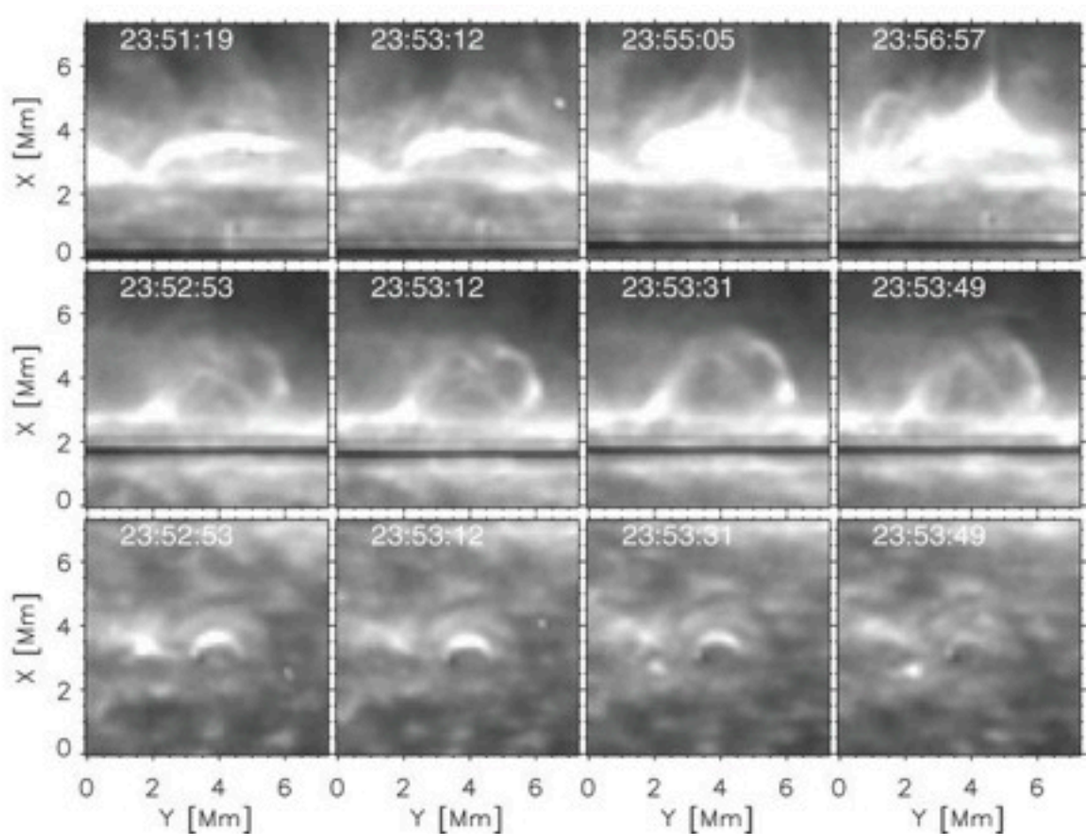
Hansteen 2014

- "plethora of short, low-lying loops at TR temperatures"
- change rapidly on the time scale of minutes
- very dynamic down to cadence of ~4s
- UFS loops are short, bright and low-lying

highly dynamic low-lying loops at transition region temperatures

Hansteen 2014





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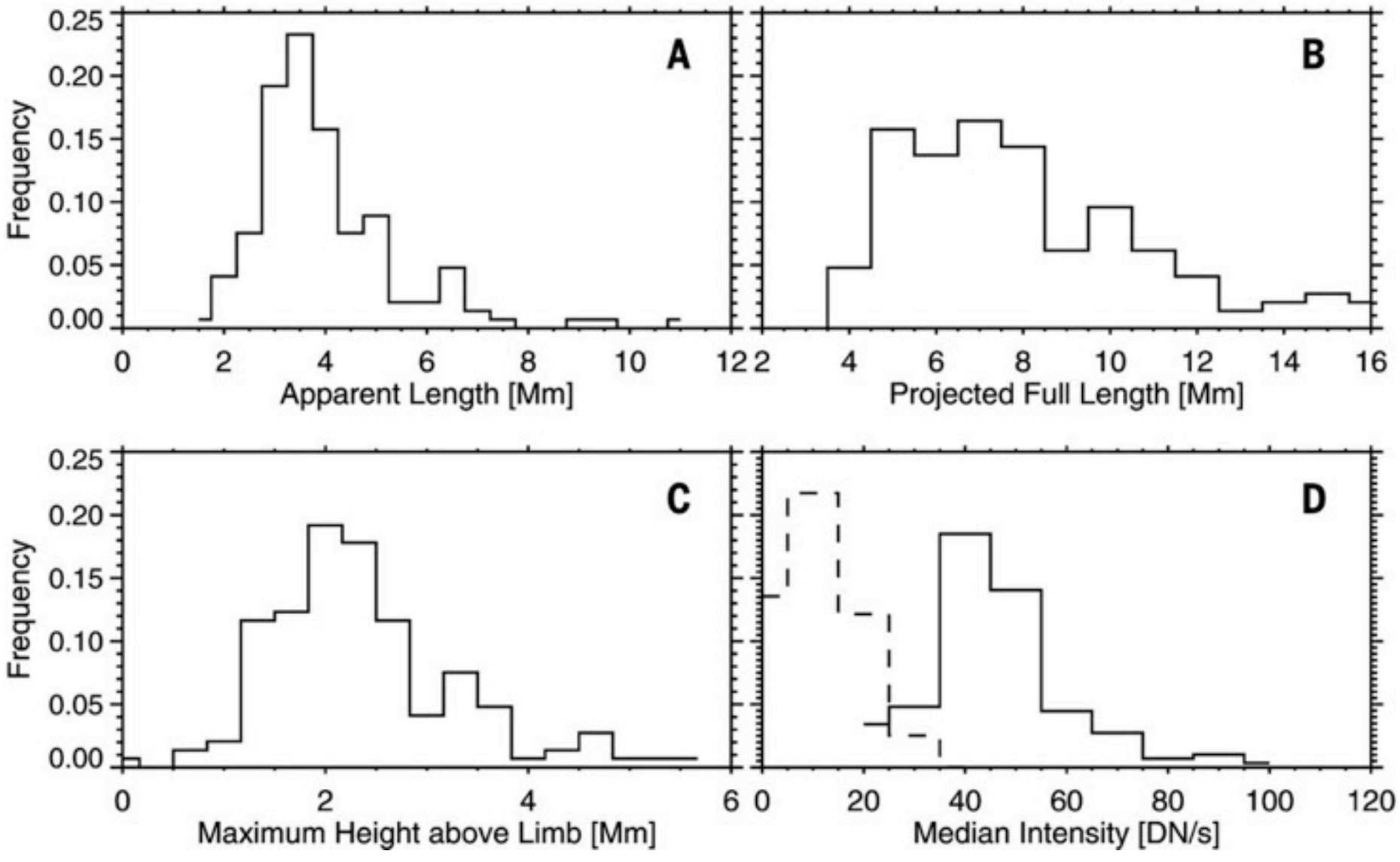
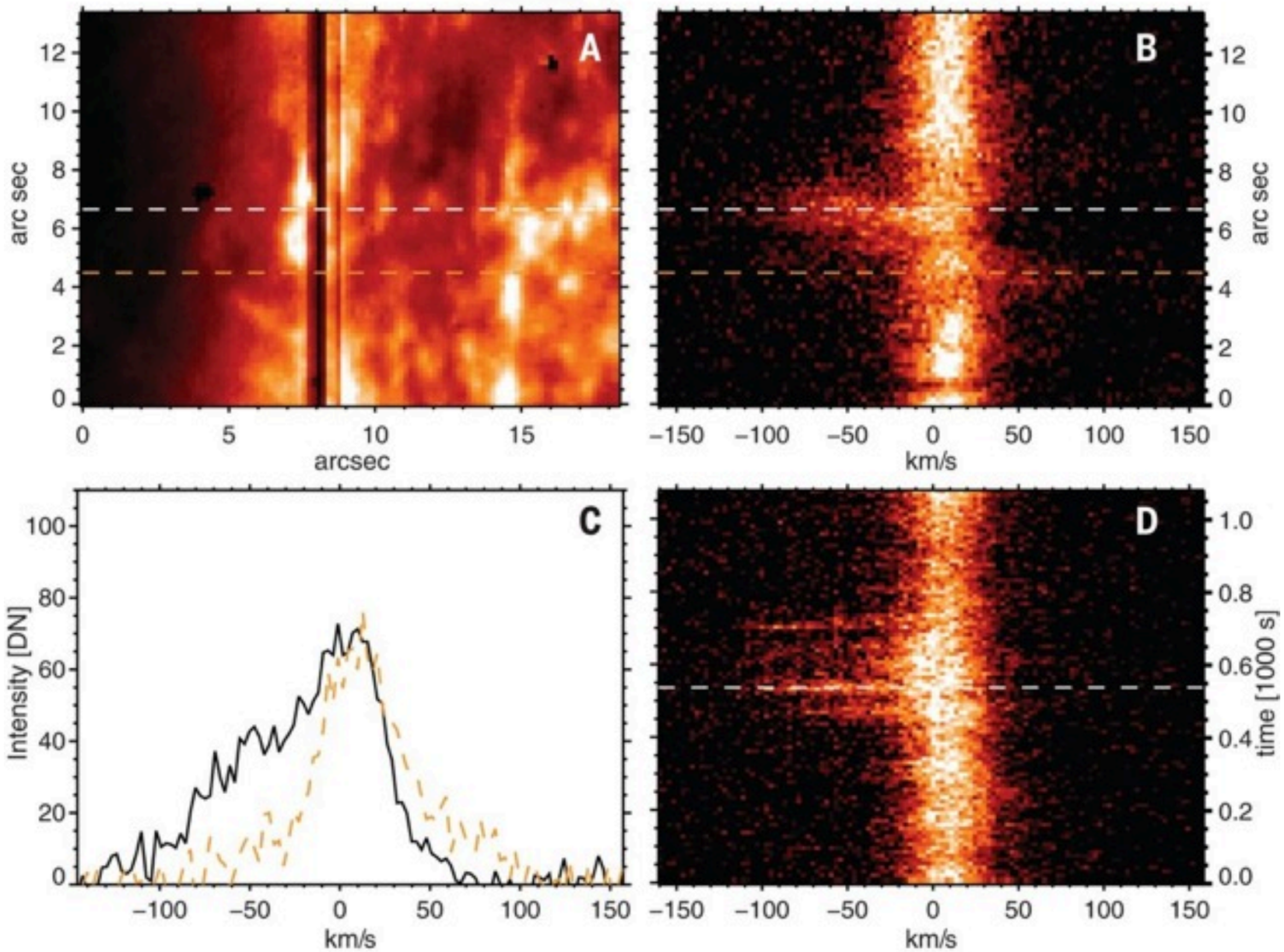
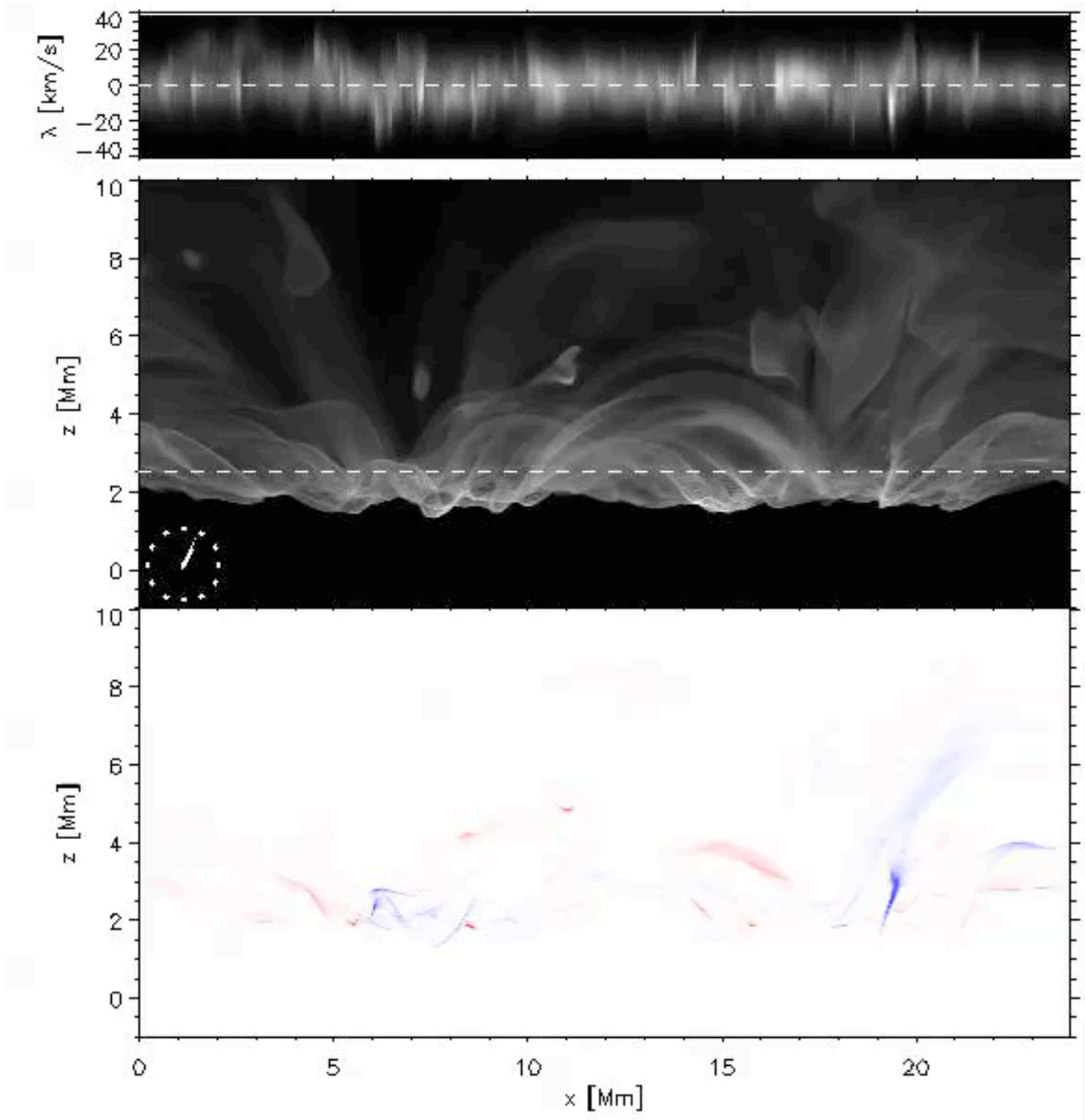


rapidly evolving Doppler shifts and nonthermal velocities

Hansteen 2014



episodic structures arise naturally in 3D rMHD simulations



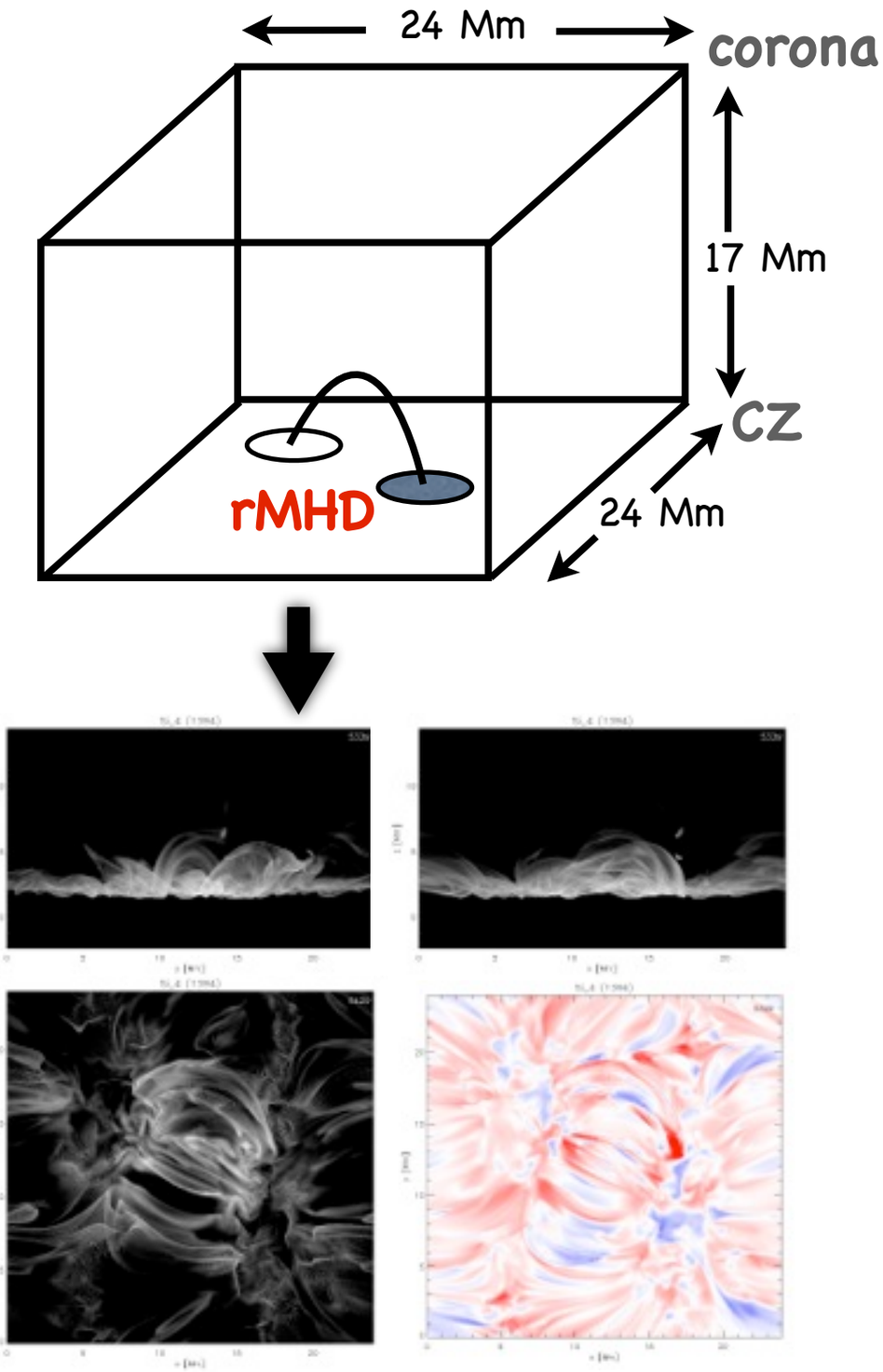
Hansteen 2014

3D rMHD models to investigate processes in the outer solar atmosphere

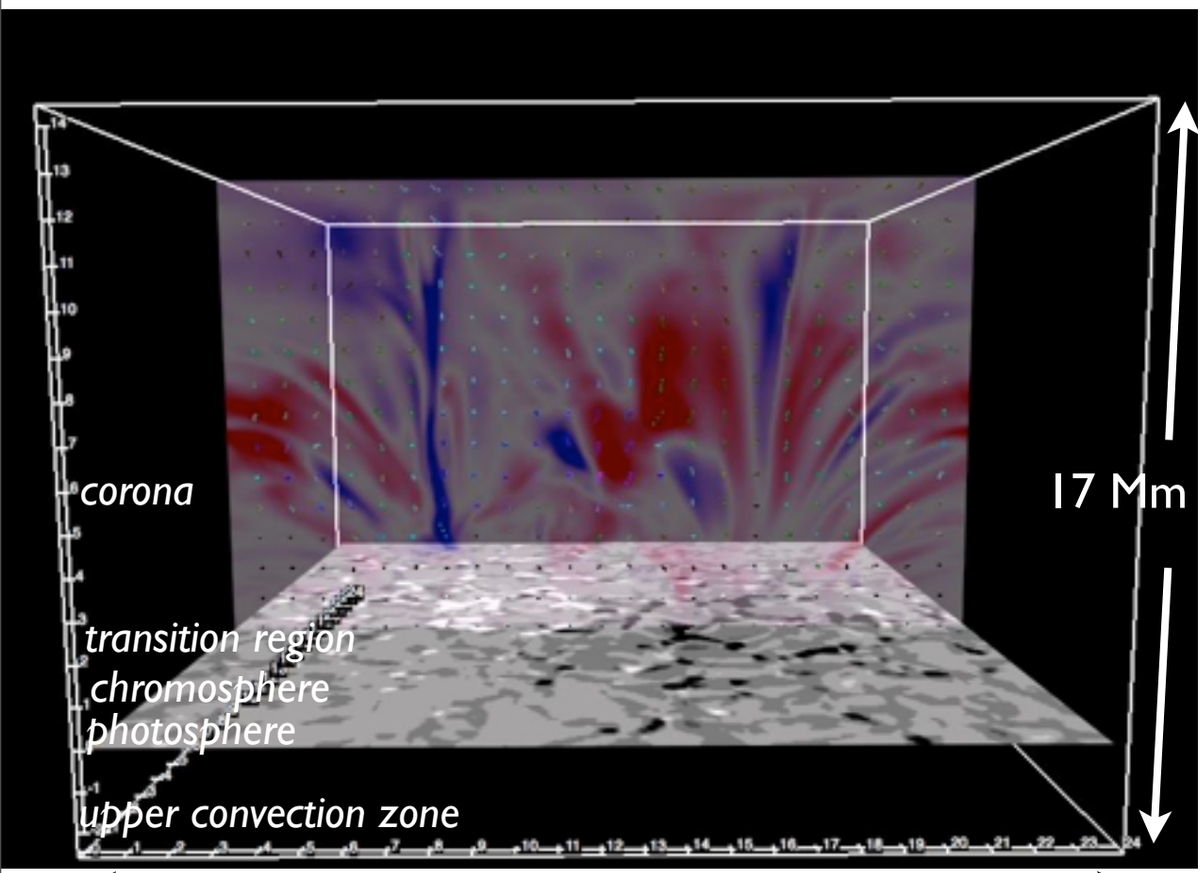
Bifrost code

Hansteen 2004; Hansteen, Carlsson, Gudiksen 2007; Martinez-Sykora, Hansteen, Carlsson 2008; Gudiksen et al. 2011

- 6th order scheme with artificial diffusion
- horizontally periodic box with open vertical boundaries
- field can be introduced through bottom boundary
- "realistic" equation of state
- detailed radiative transfer
- multi group opacities with scattering
- NLTE losses in the chromosphere, optically thin corona
- conduction along magnetic field lines



3D rMHD simulations using Bifrost



Passively advected tracer particles

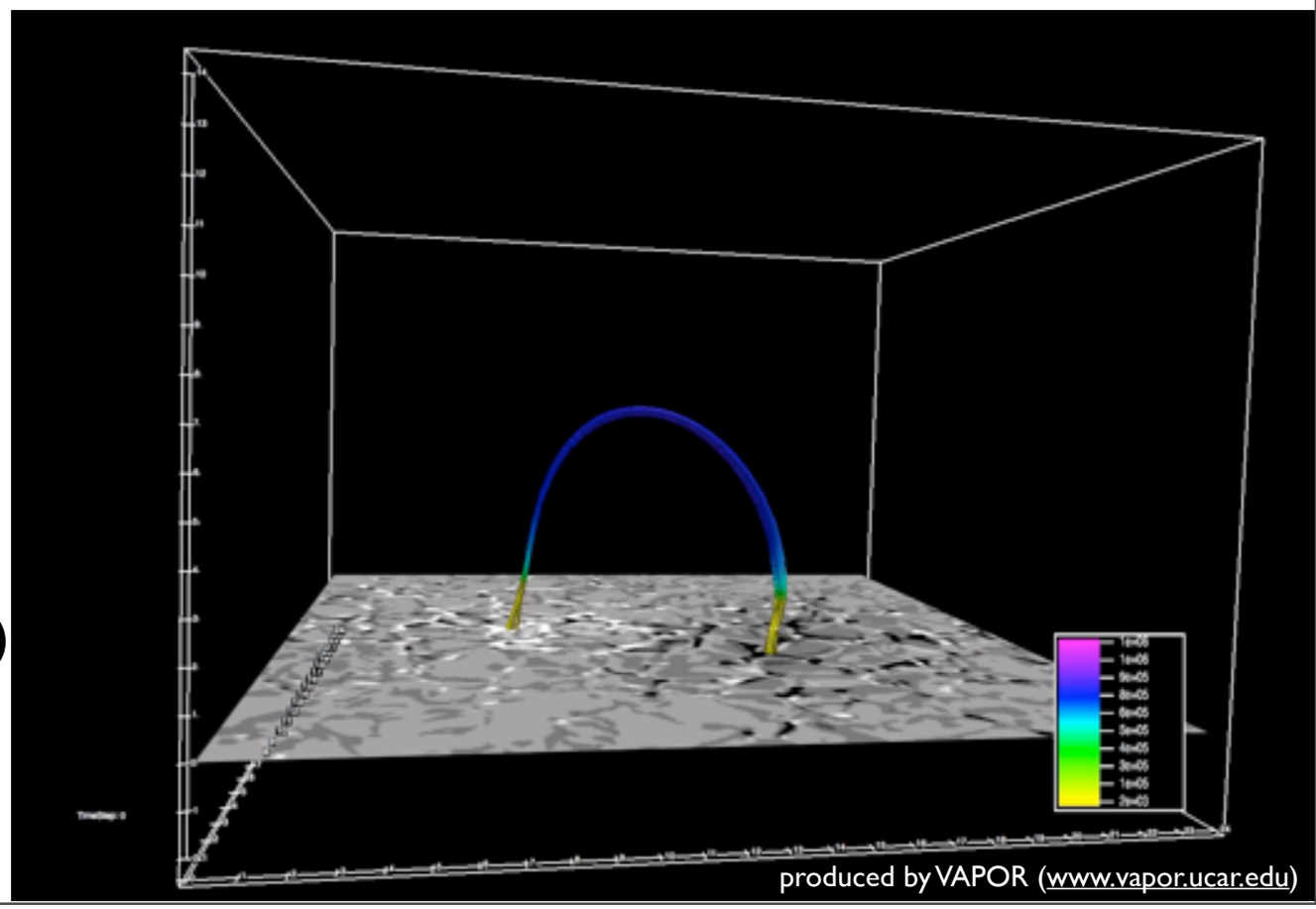
"corks"

- locations are calculated within the code during the simulation
- stored at snapshot cadence (10s/1s)

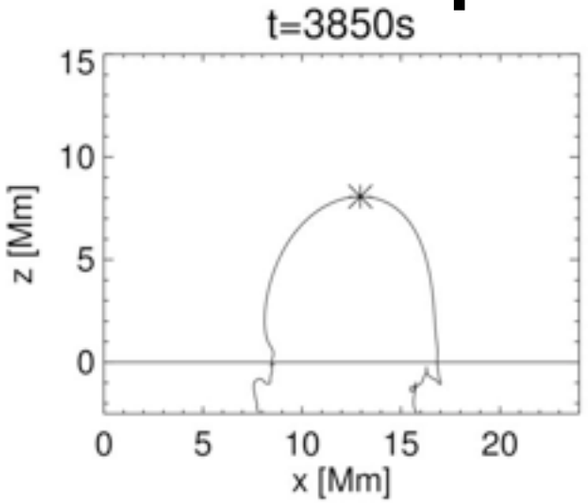
➜ trace different features, e.g., field lines over time

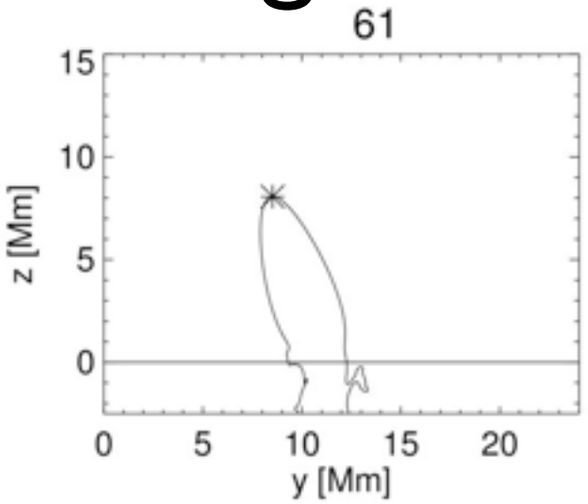
Computational setup

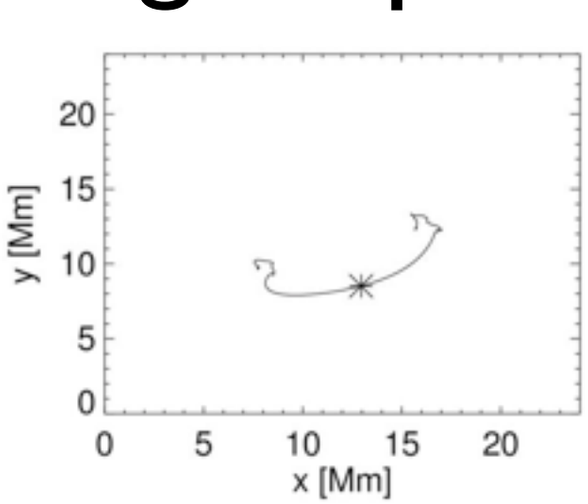
- domain size: 24x24x17 Mm^3
- grid: 504x504x496
- resolution: 48 km horizontally
- 19-97 km vertically (non-uniform in z-direction)
- polarities separated by 8 Mm, |<B>|=30-50 G

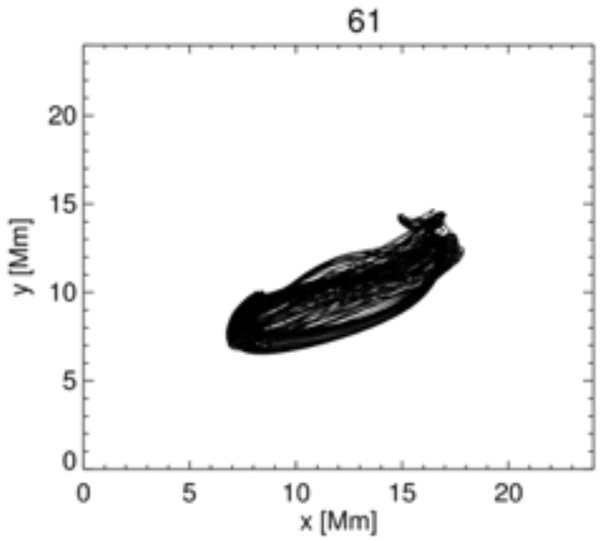


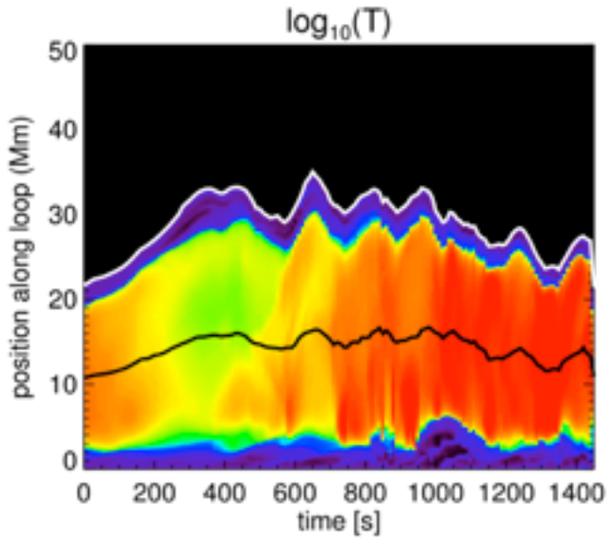
Example #1: high-reaching loop

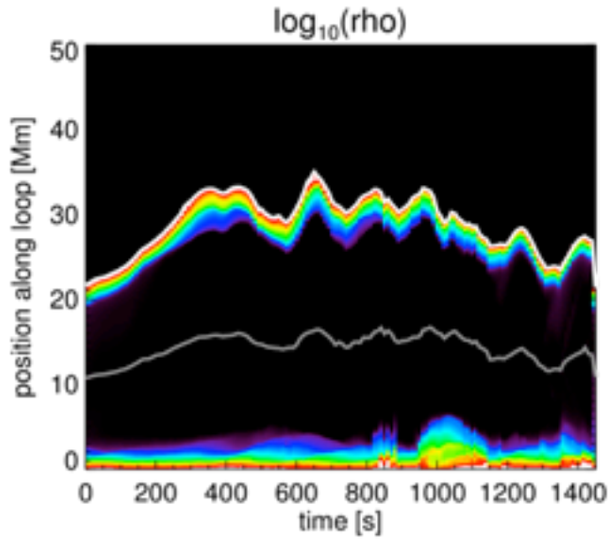


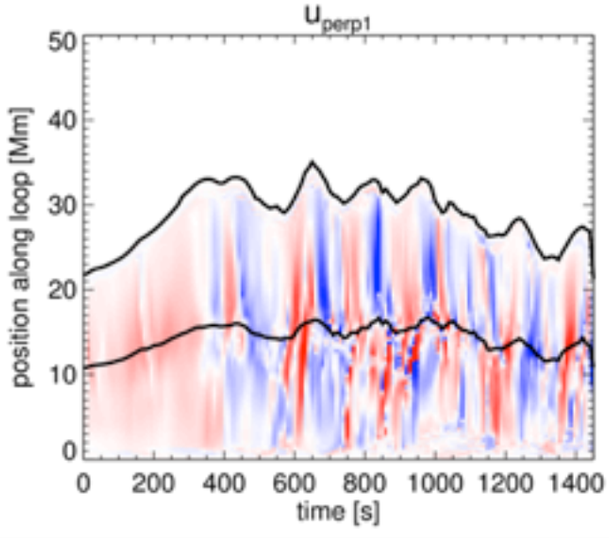


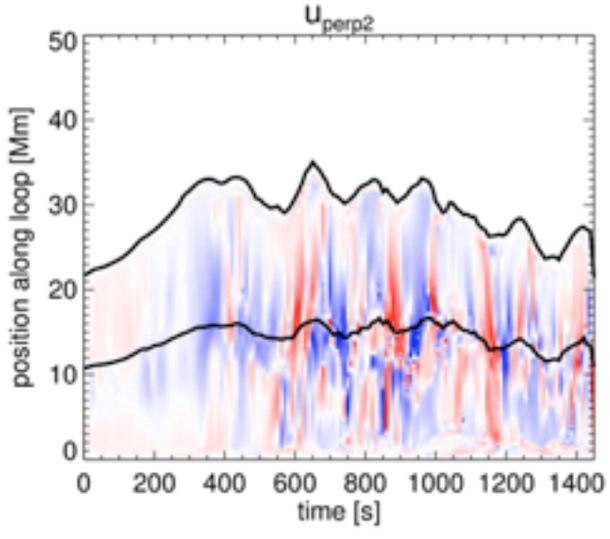


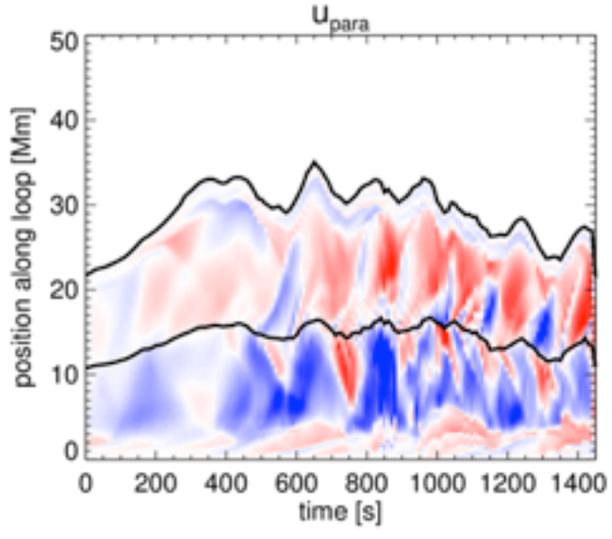




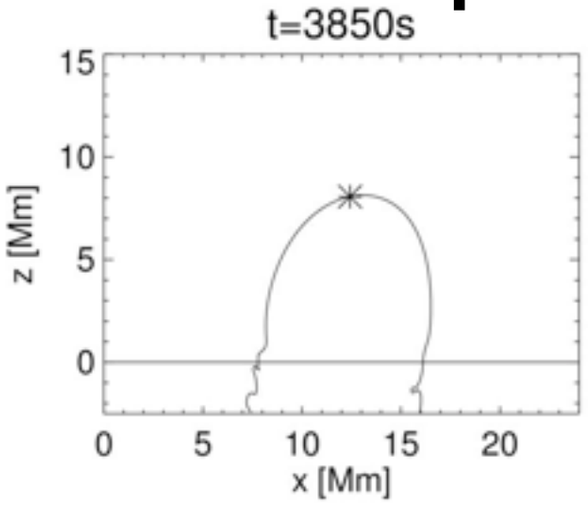


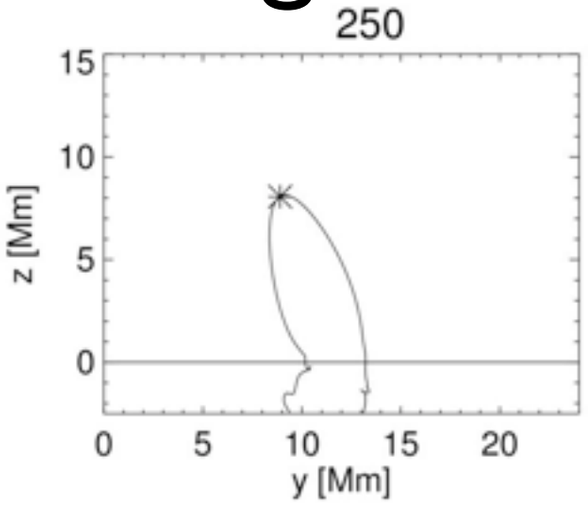


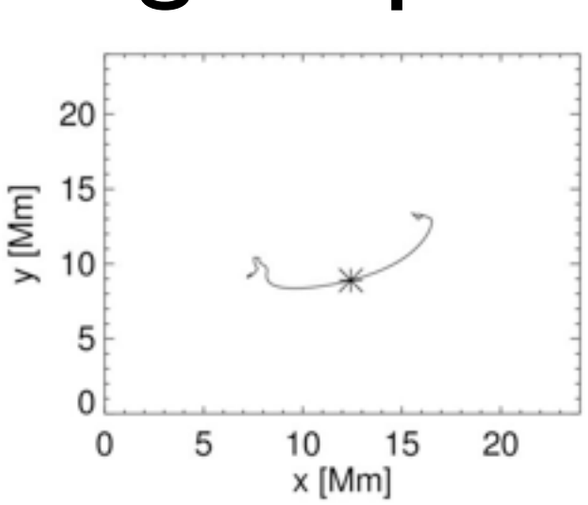


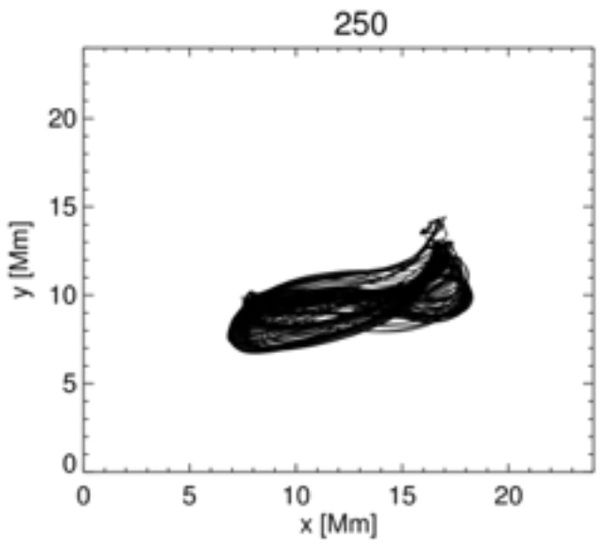


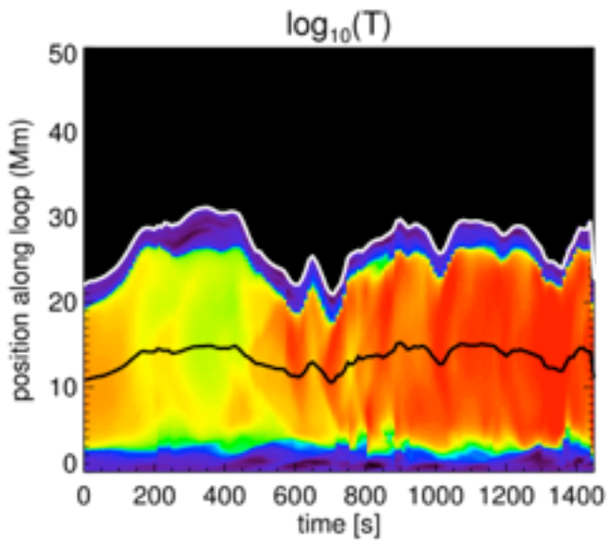
Example #2: high-reaching loop

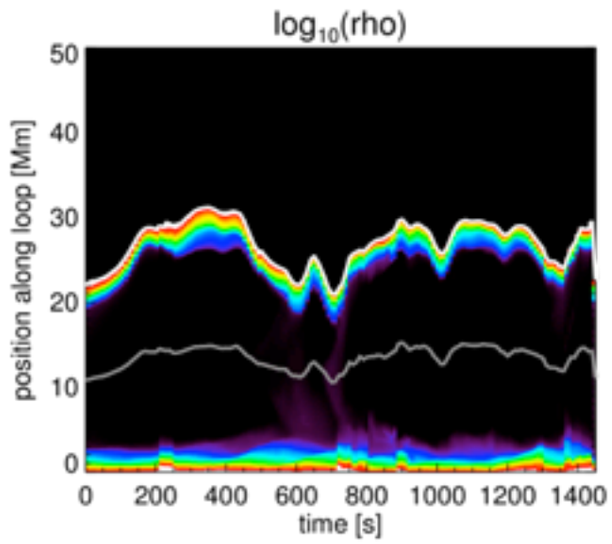


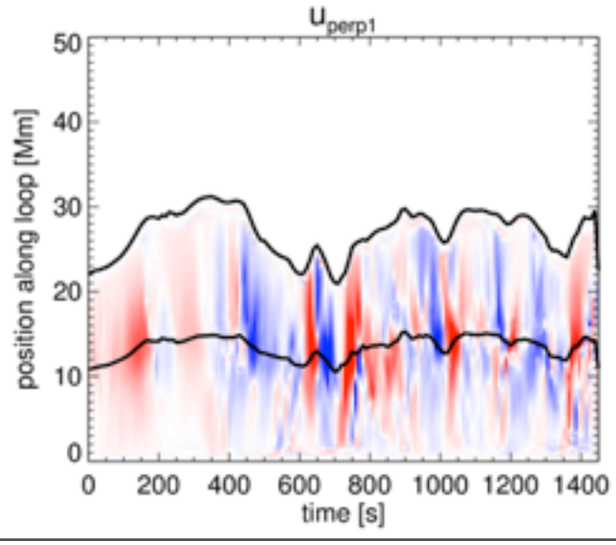


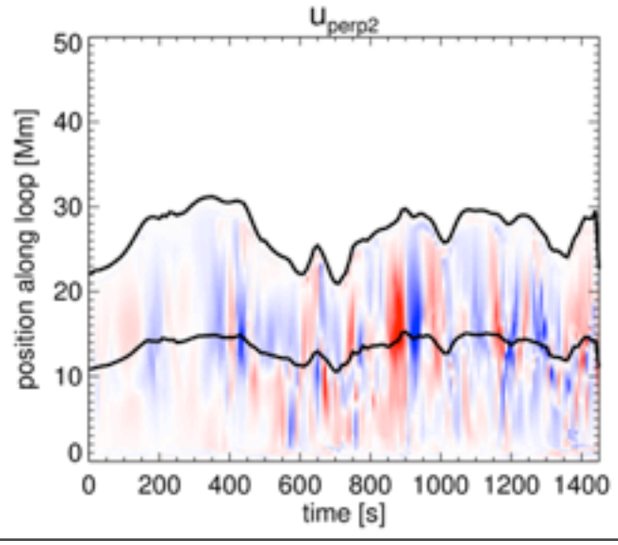


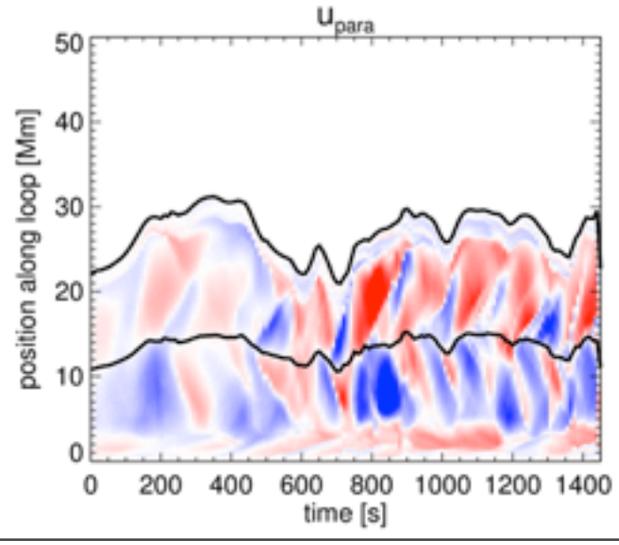




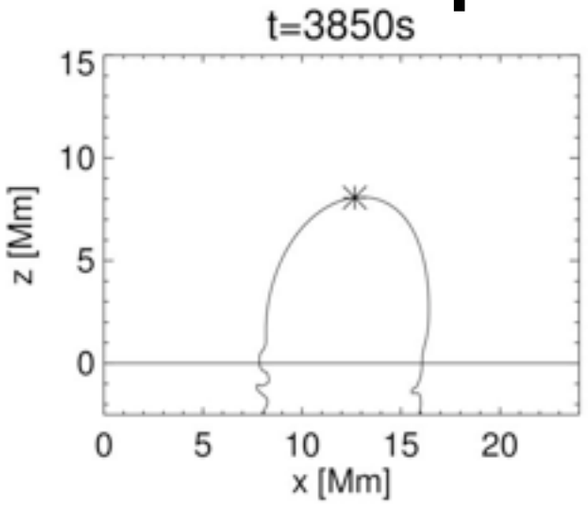


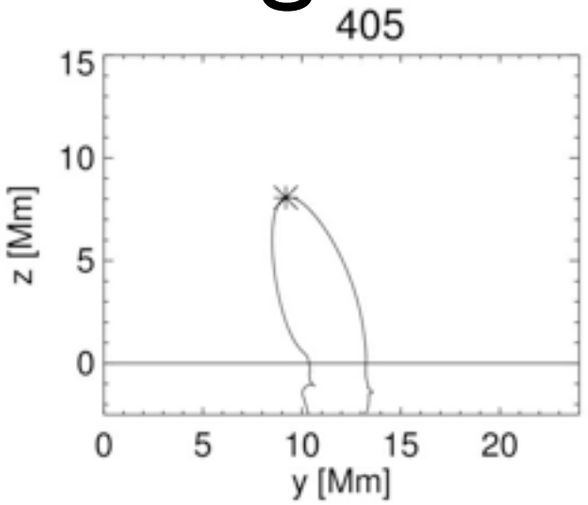


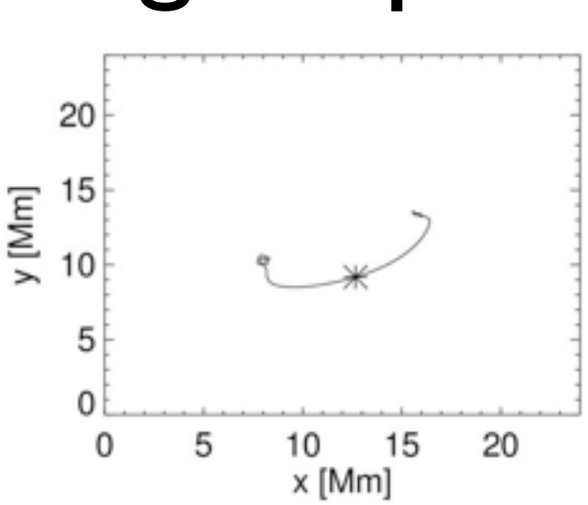


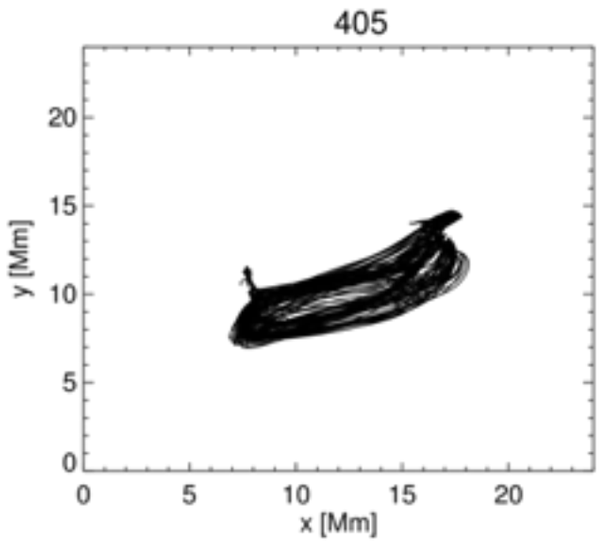


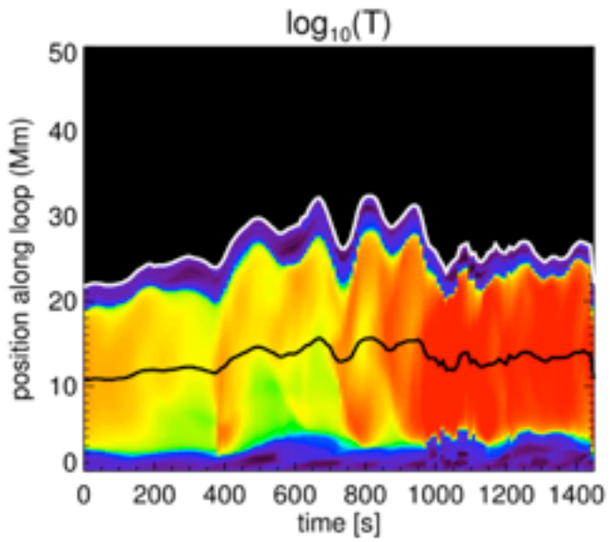
Example #3: high-reaching loop

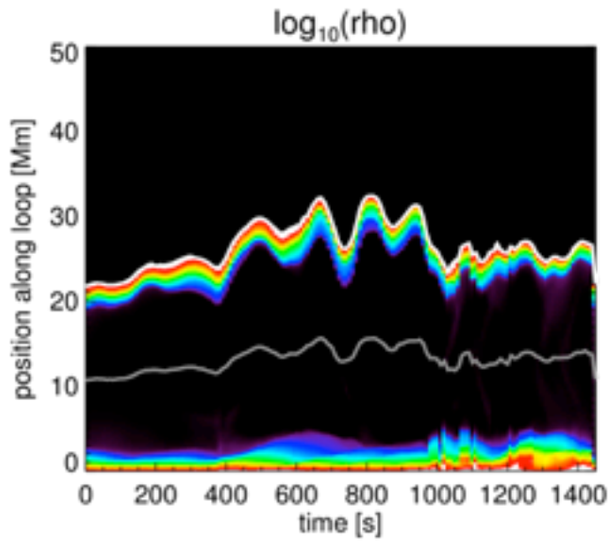


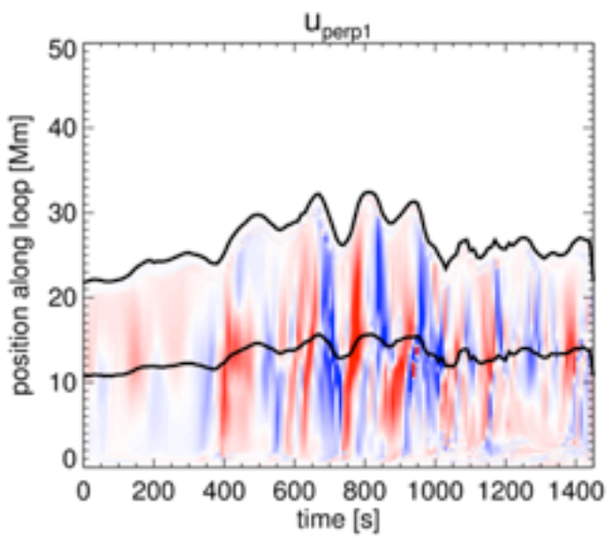


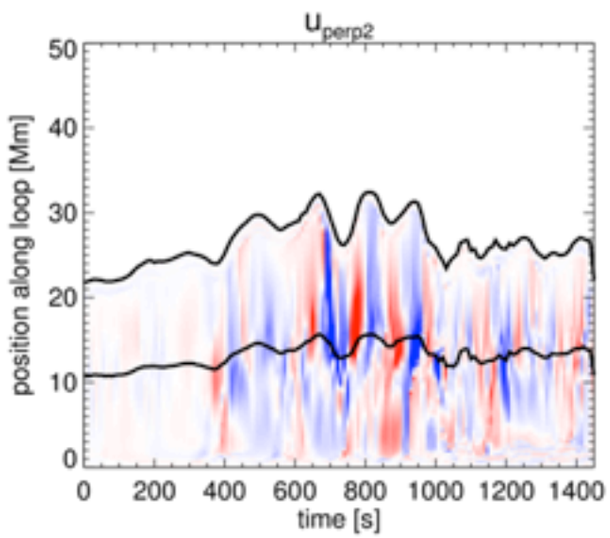


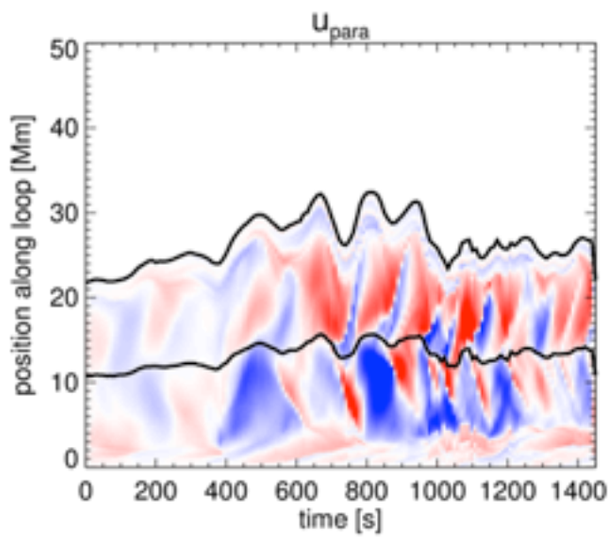






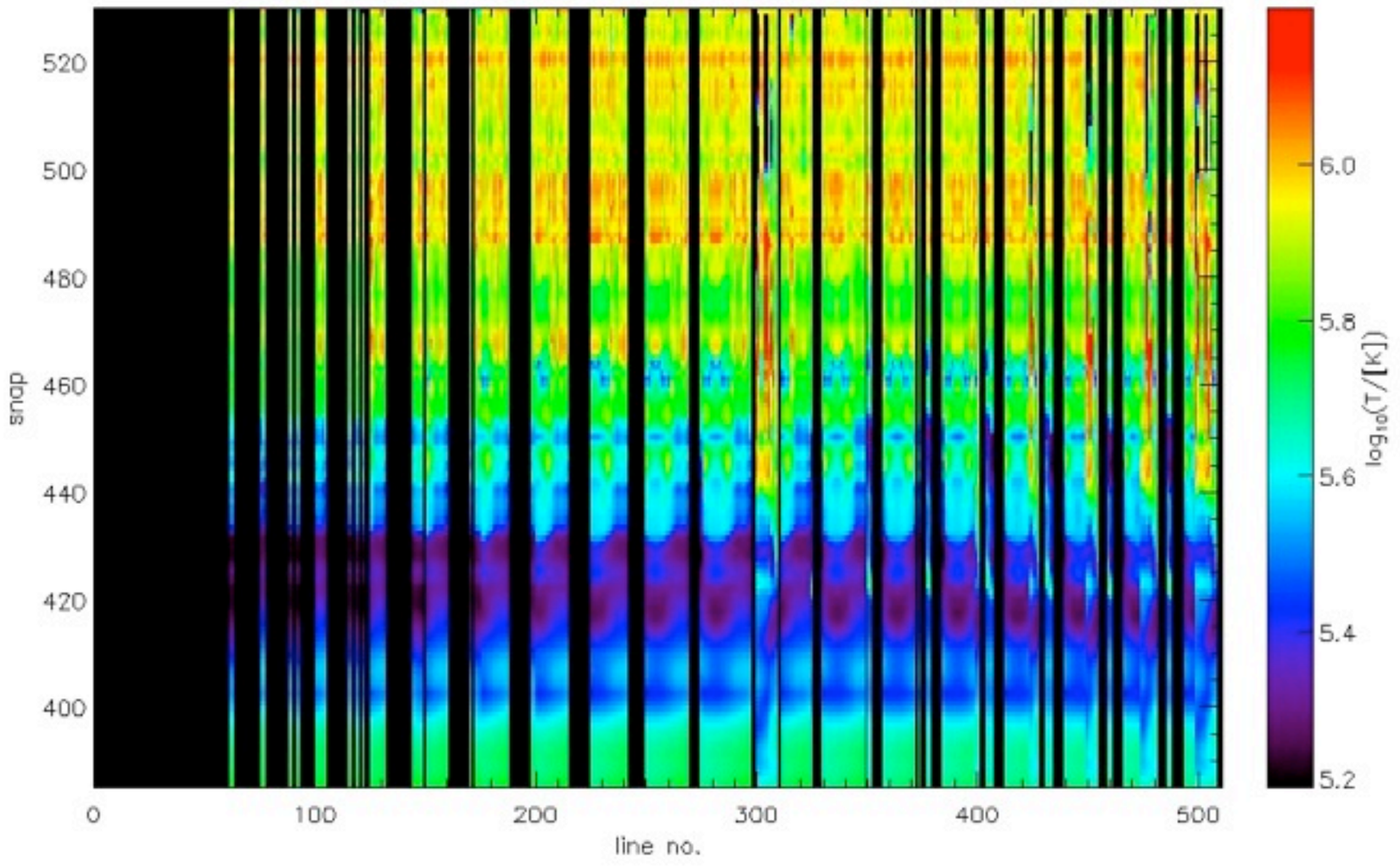




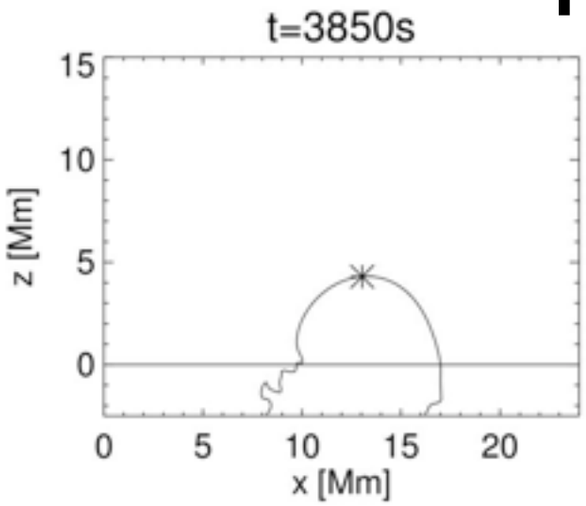


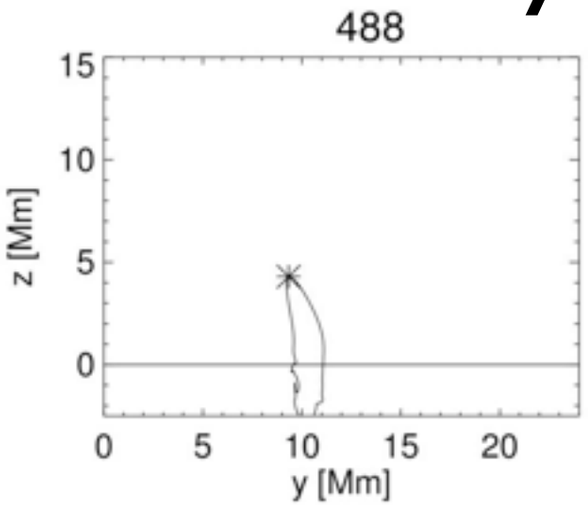
Apex temperatures for high-reaching loops

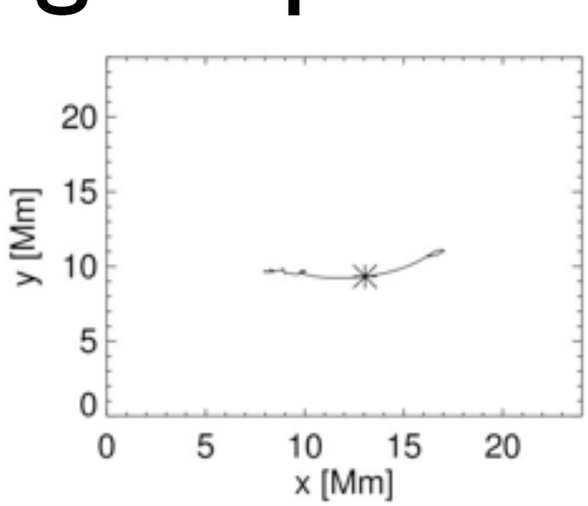
- sets of 500 field lines with seeds at x_{init}=[12.5,13.5] Mm, y_{init}=[8.5,9.5] Mm, z_{init}=4.3 Mm
- seed points are close to apex
- 60% of field lines are included/useful
- apex temperatures behave remarkably similar



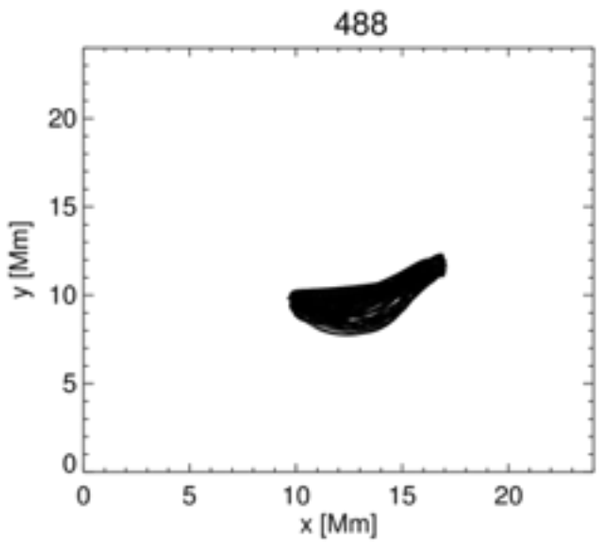
Example #1: low-lying loop

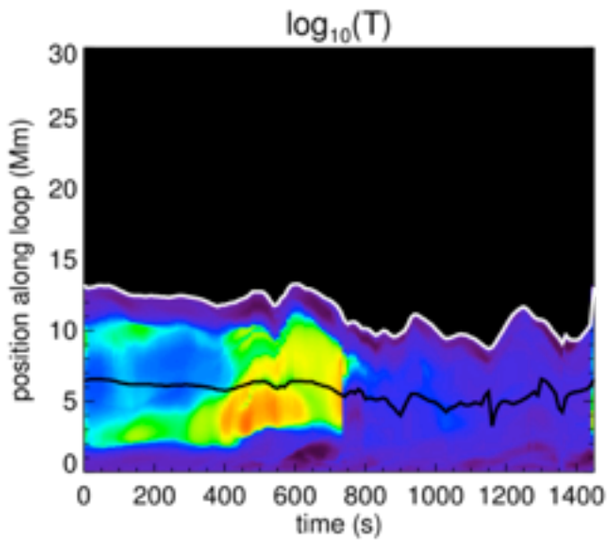


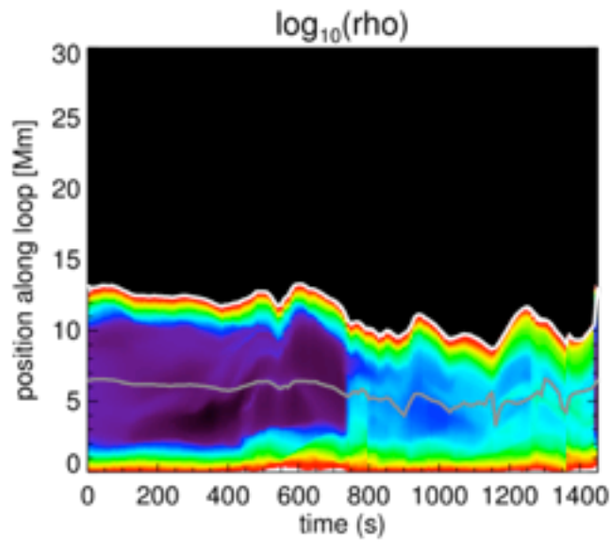




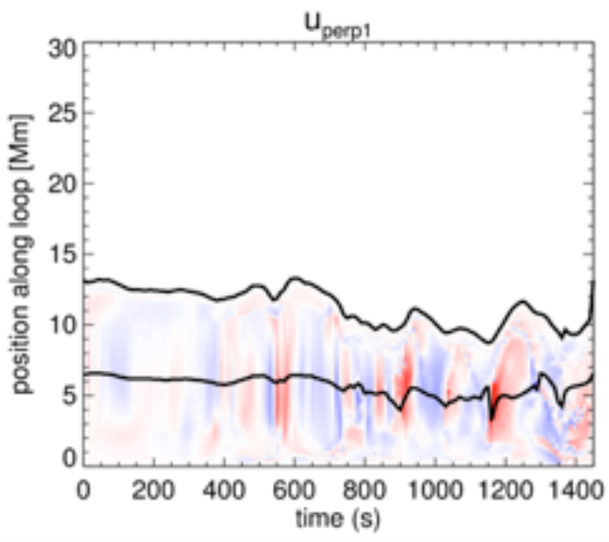
jump in temperature and density between 4580 & 4590s (730/740s into simulation), assoc. with small change in loop morphology

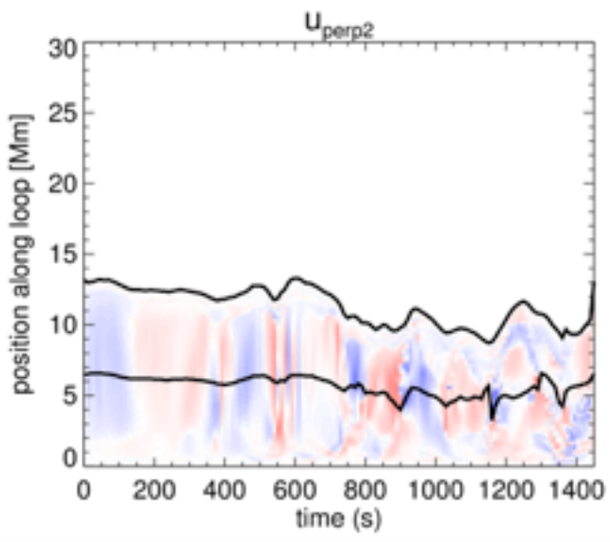


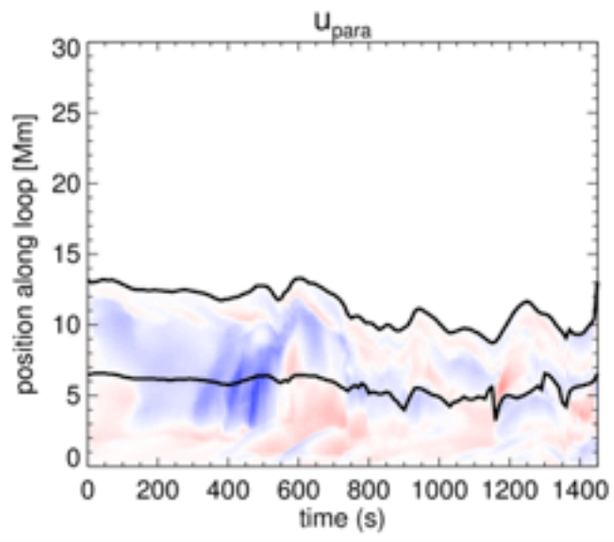




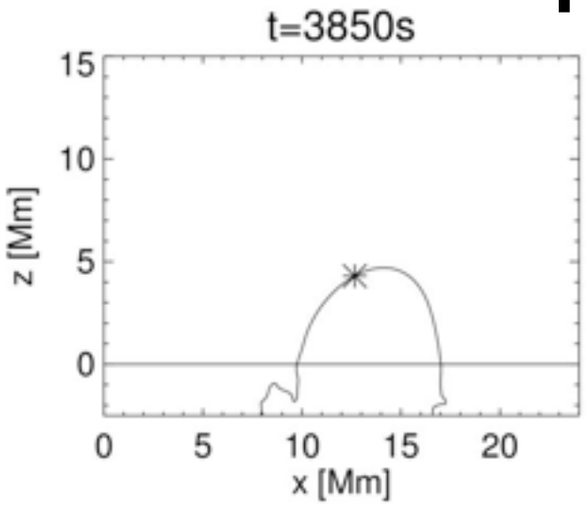
life time: 600-800s

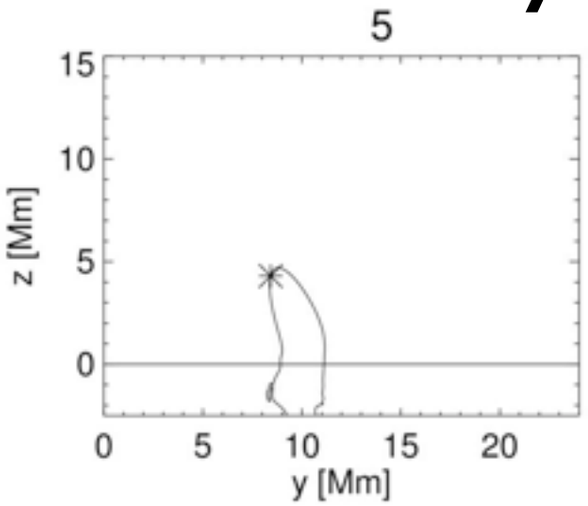


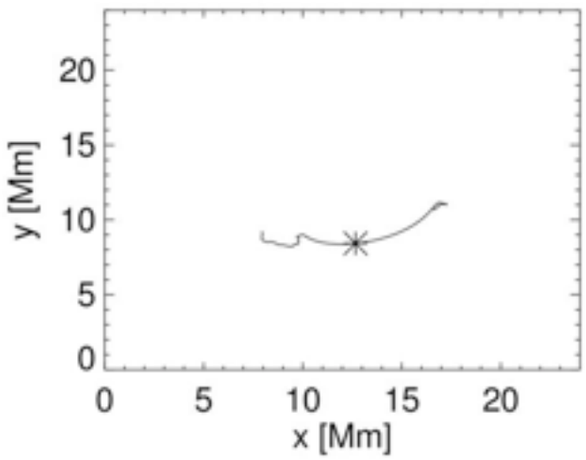




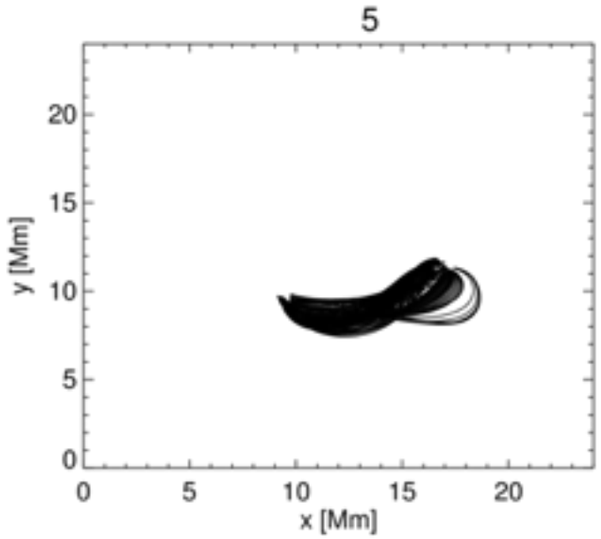
Example #2: low-lying loop

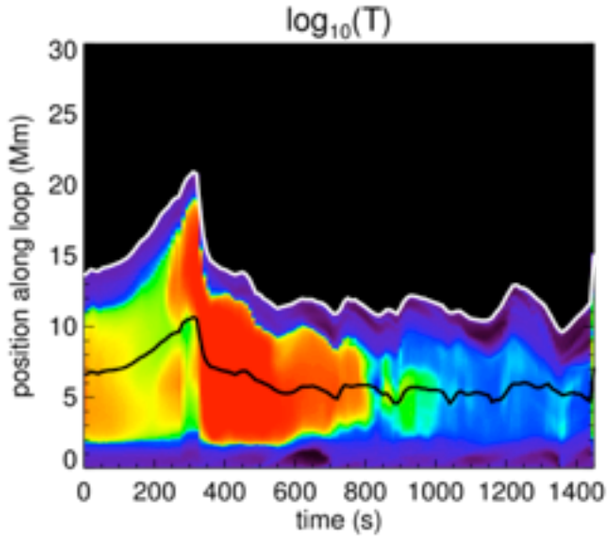


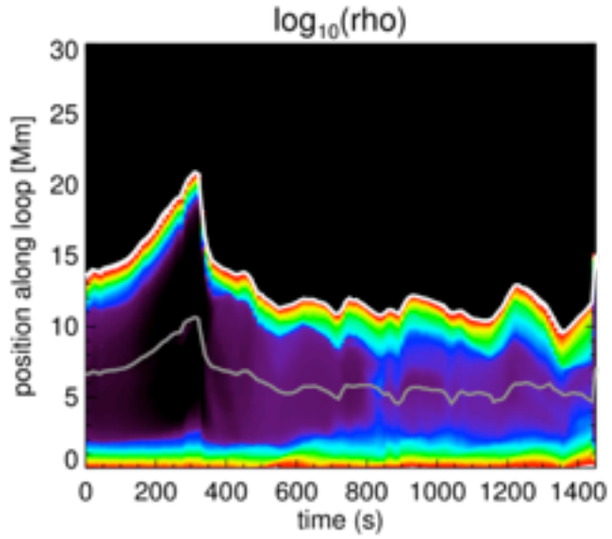




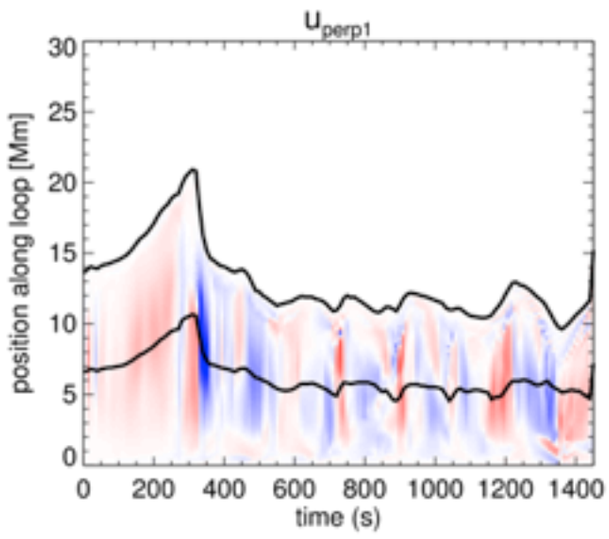
loop configuration changes between 4170s and 4180s

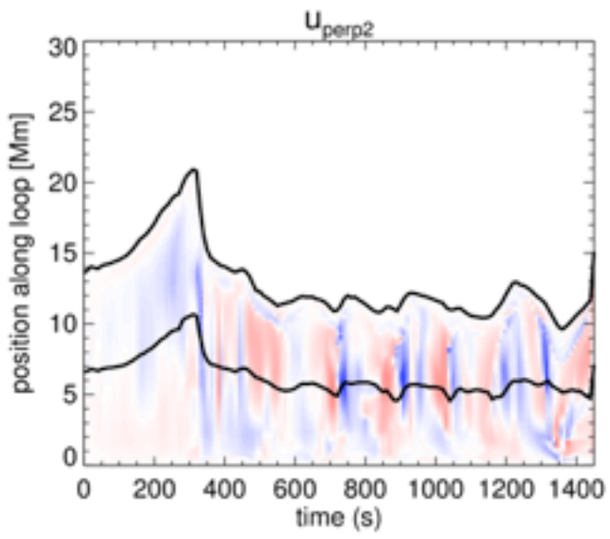


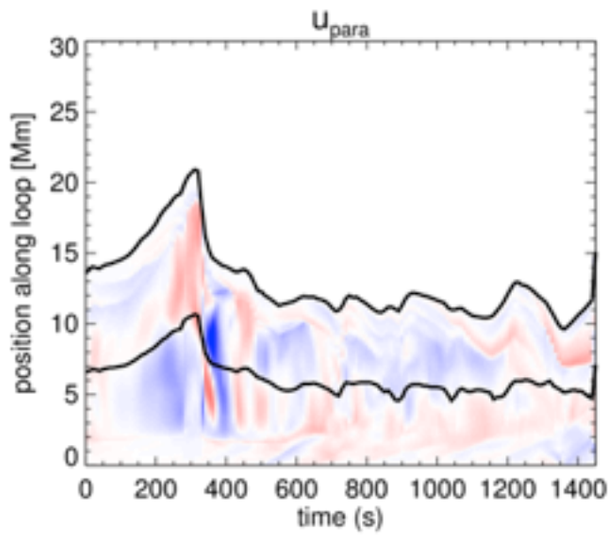




about 50% show similar behavior

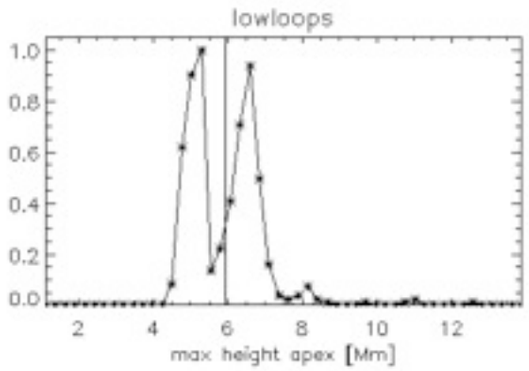


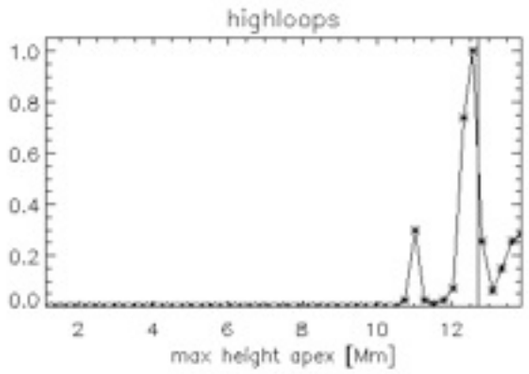




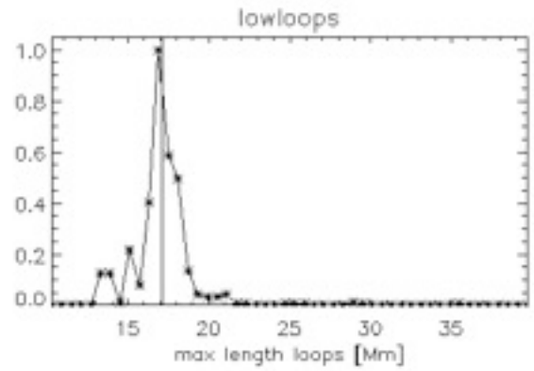
Statistics of loop parameters

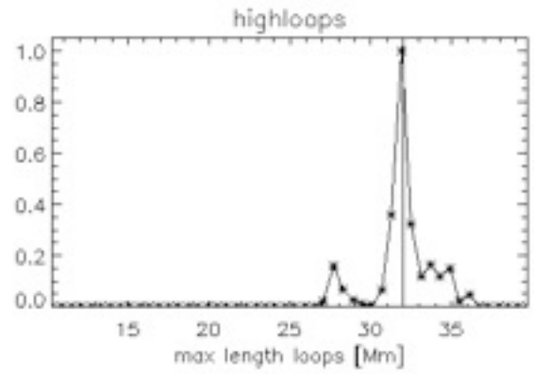
heights





lengths

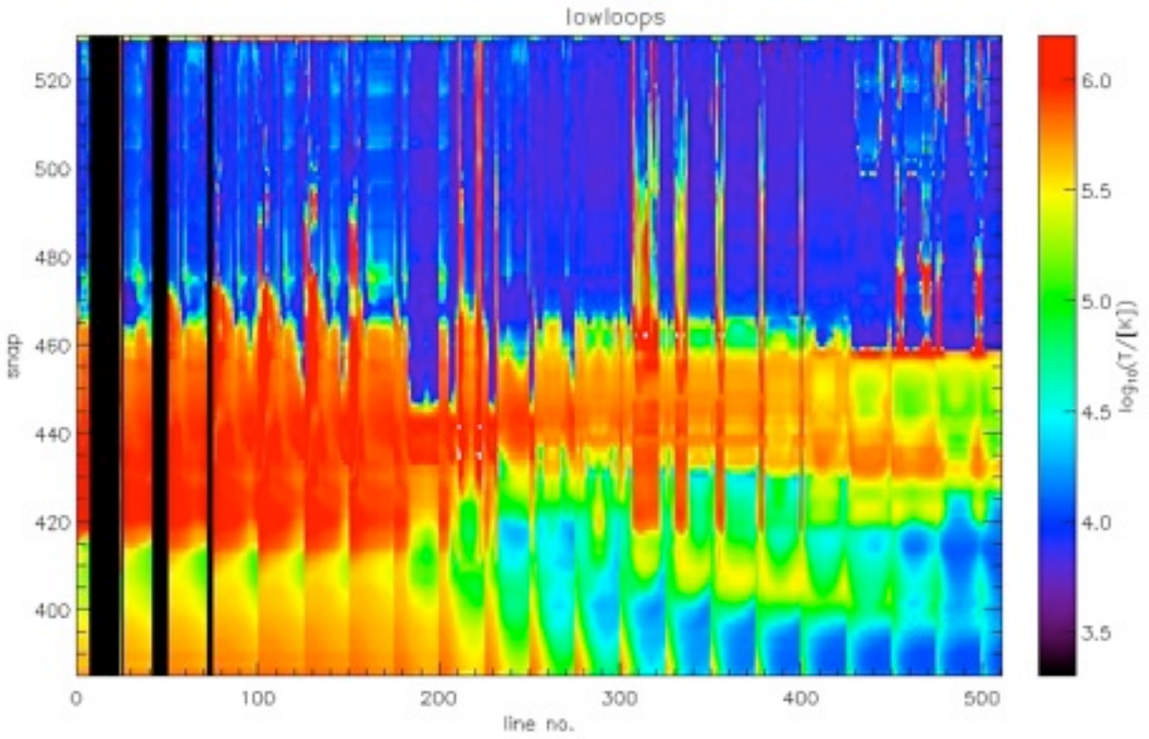




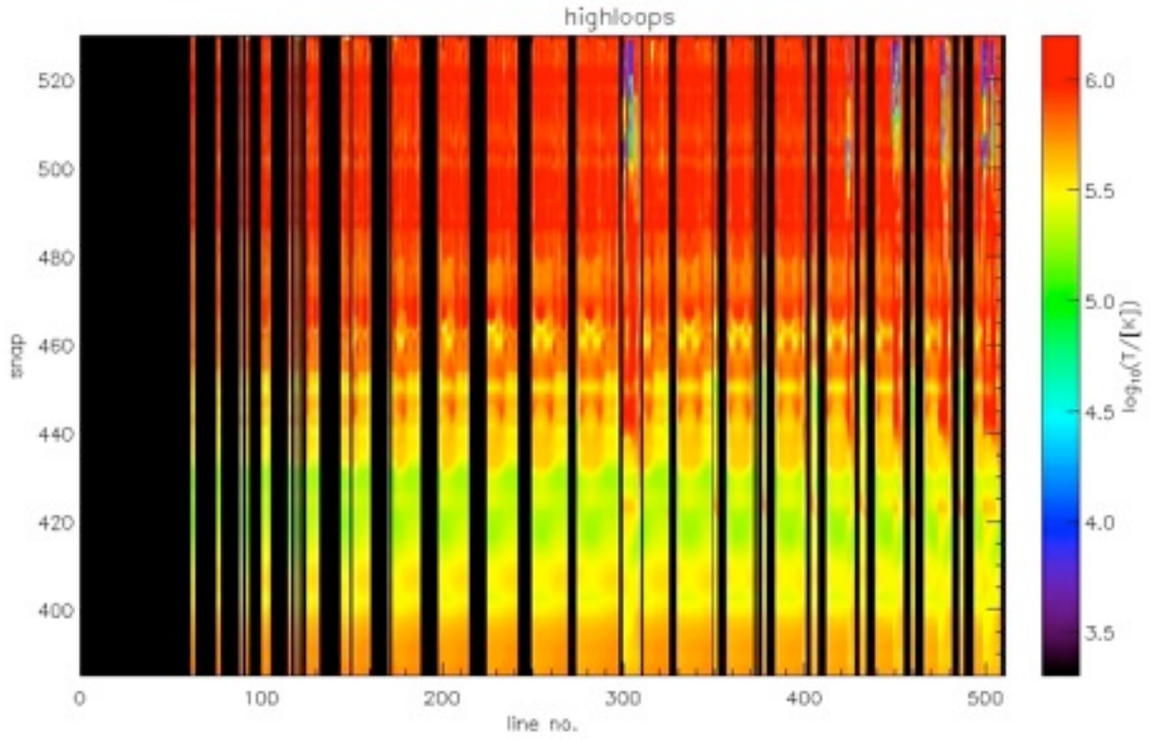
	avg. max. height [Mm]	avg. max. length [Mm]	# lines	h_{min} [Mm]
low loops	6+/-1	17+/-2	481/511	4.3
high loops	12.7+/-0.8	32+/-2	286/511	8.3

Comparison apex temperatures

lowloops



highloops



2 different types?

temperature range: log(T/[K])=[5.2,6.2]

temperature range: log(T/[K])=[4.2,5.7]

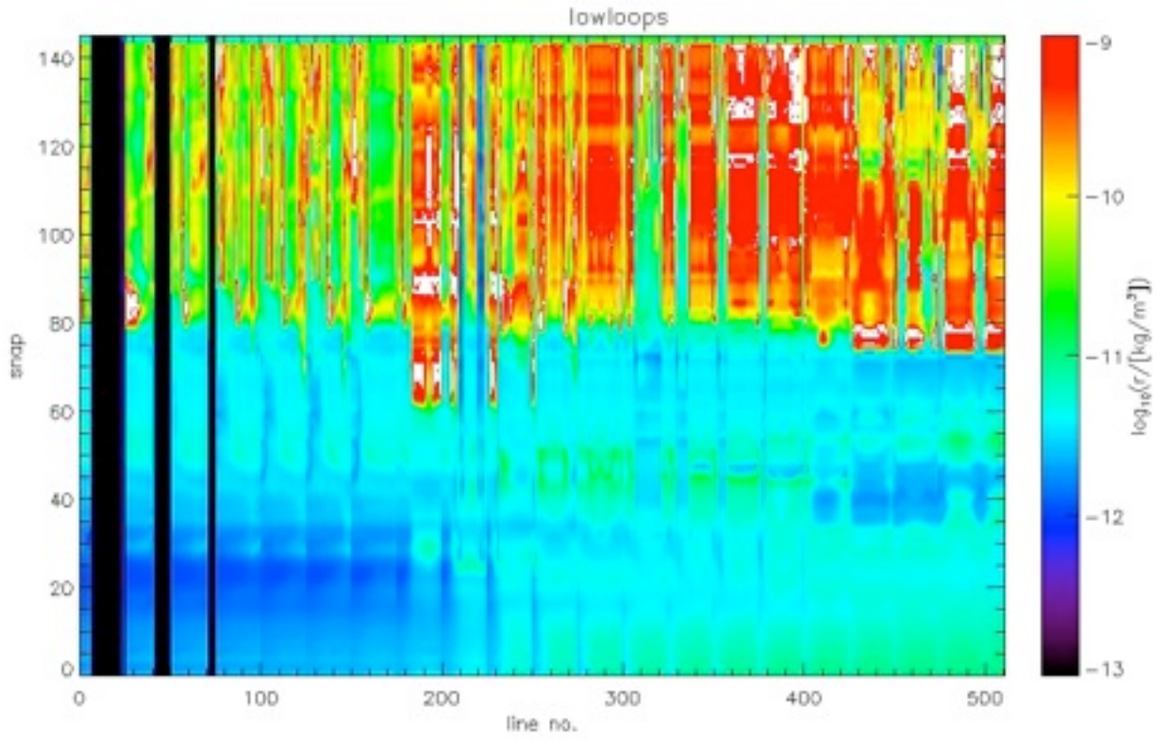
life times: 600-800s

temperature range: log(T/[K])=[5.2,6.2]

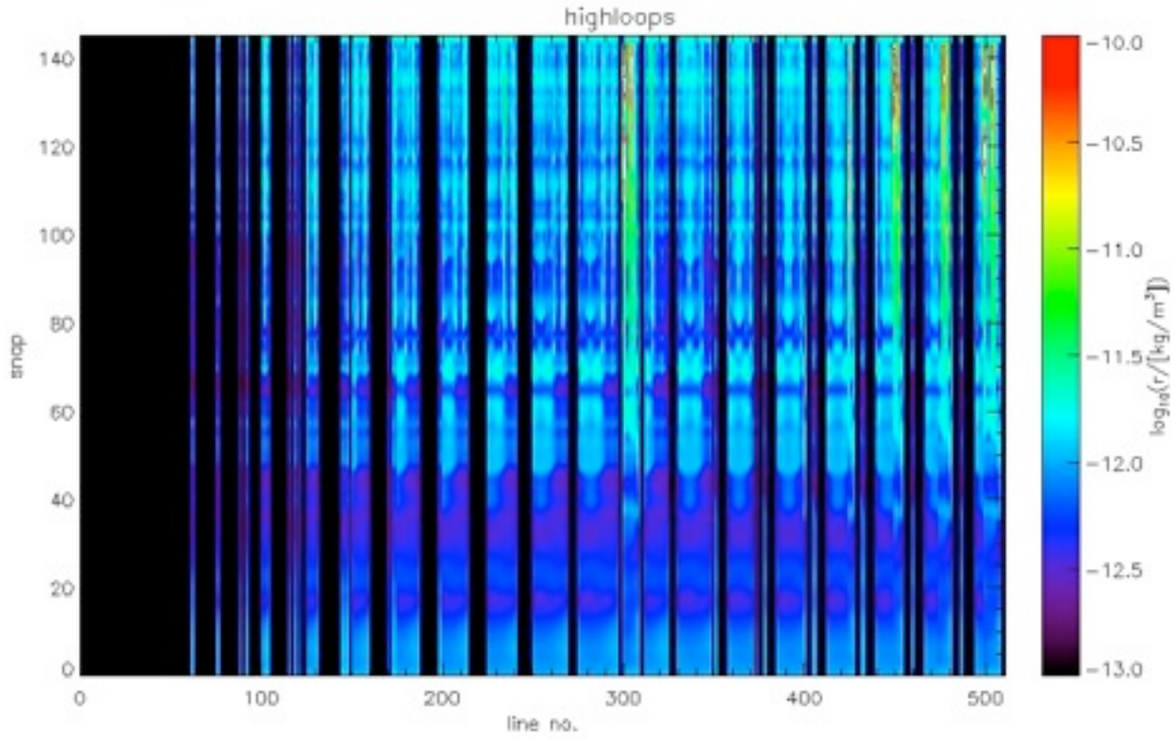
life times >1450s

Comparison apex densities

lowloops



highloops



2 different types?

density range: $\log(\rho/[kg/m^3])=[-11,-12]$

density range: $\log(\rho/[kg/m^3])=[-10.5,-11.5]$

life times: 600-800s

density range: $\log(\rho/[kg/m^3])=[-12.5,-11]$

life times >1450s

Summary and Outlook

- corks shows shocks, wave-like perturbations, formation of small-scale & large-scale structures

- tracing of magnetic field lines in the highly dynamic atmosphere possible

  - transverse motions propagating with Alfven speed

  - longitudinal waves/shocks moving with sound speed

  - detection of flow patterns assoc. with changing connectivity of field lines

- high-reaching vs. low-lying loops: extend data analysis

Outline

- Old standard picture of the solar transition region
- The discovery of UFS
- Two-component transition region
- Multi-component transition region
- Transient heating models
- UFS in IRIS observations
- UFS in 3D MHD models of the solar corona