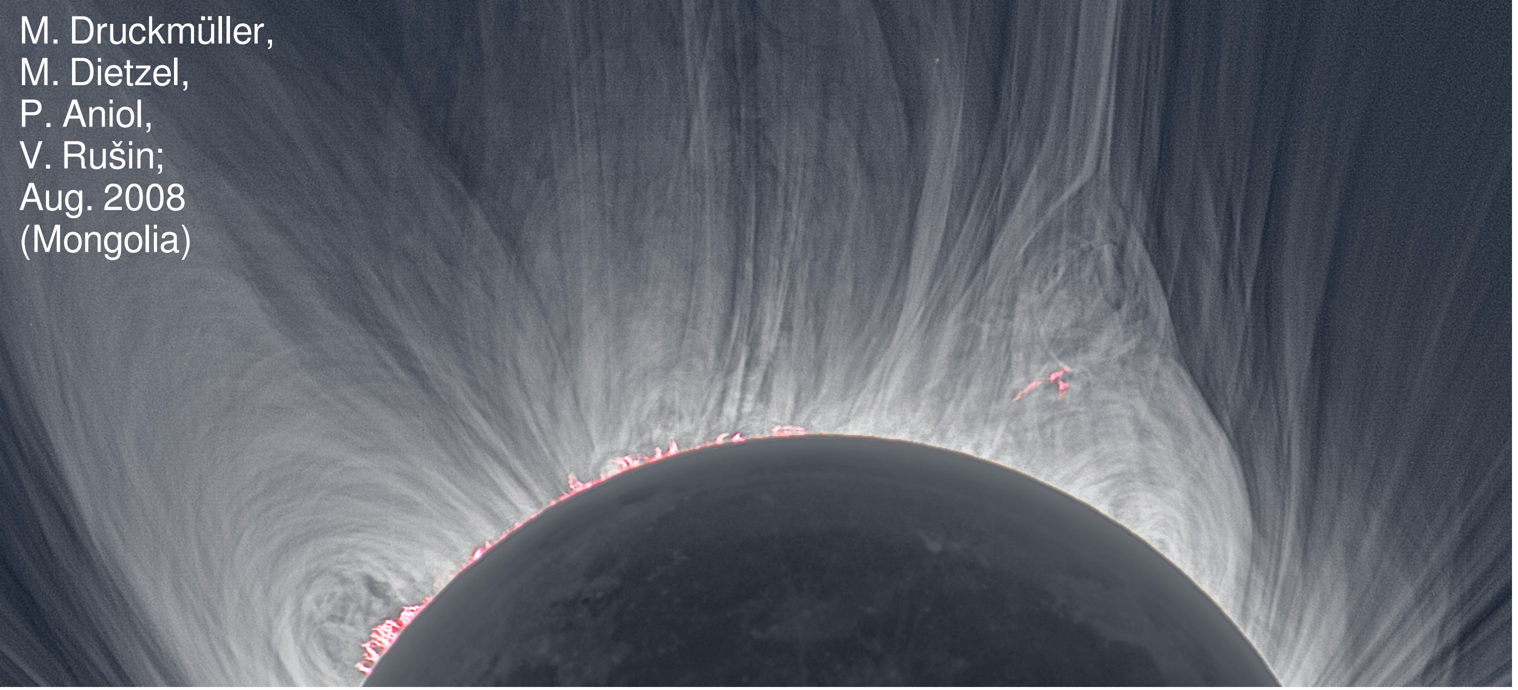


Evolution of the magnetic topology due to reconnection in a 3D MHD corona above an active region

(Magnetic Reconnection Workshop, NORDITA/Stockholm, 29th July 2015)

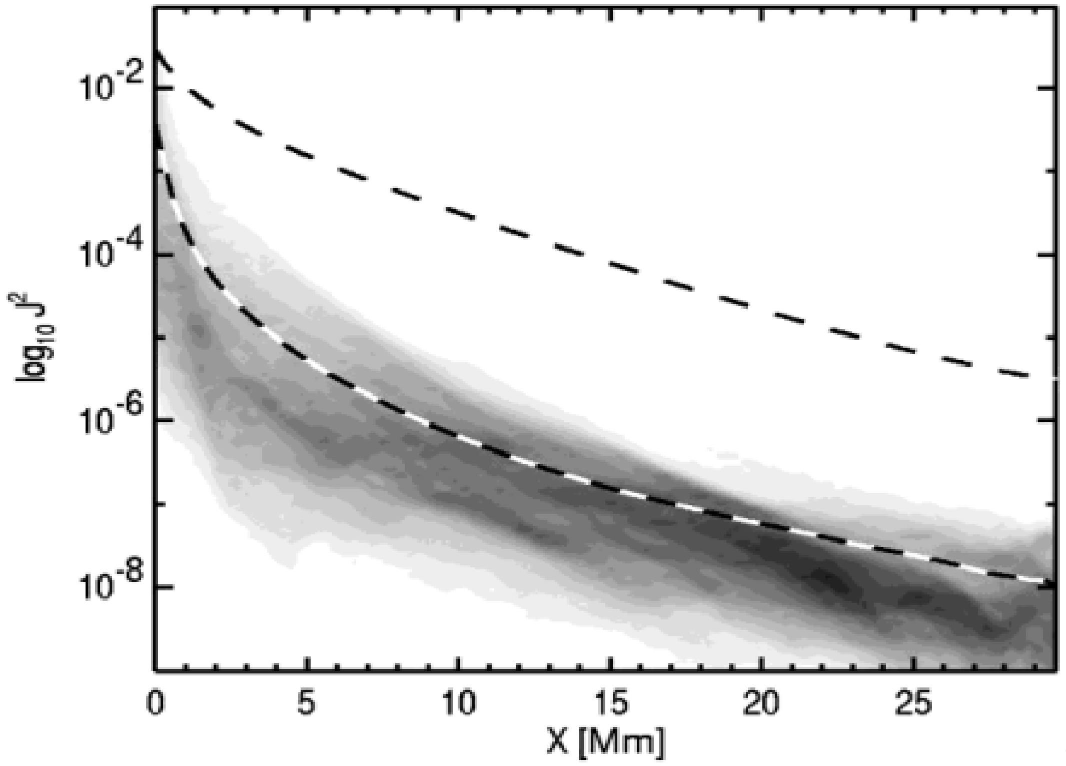
Philippe-A. Bourdin
(Space Research Institute, Austrian Academy of Sciences, Graz/Austria)

Overview:
* Time-evolution of magnetic field (and plasma bulk motion)
* Reconnection in the corona (and photospheric flux emergence)
* Electric fields in an MHD model...?
* Proton and Electron acceleration from electric fields in the corona

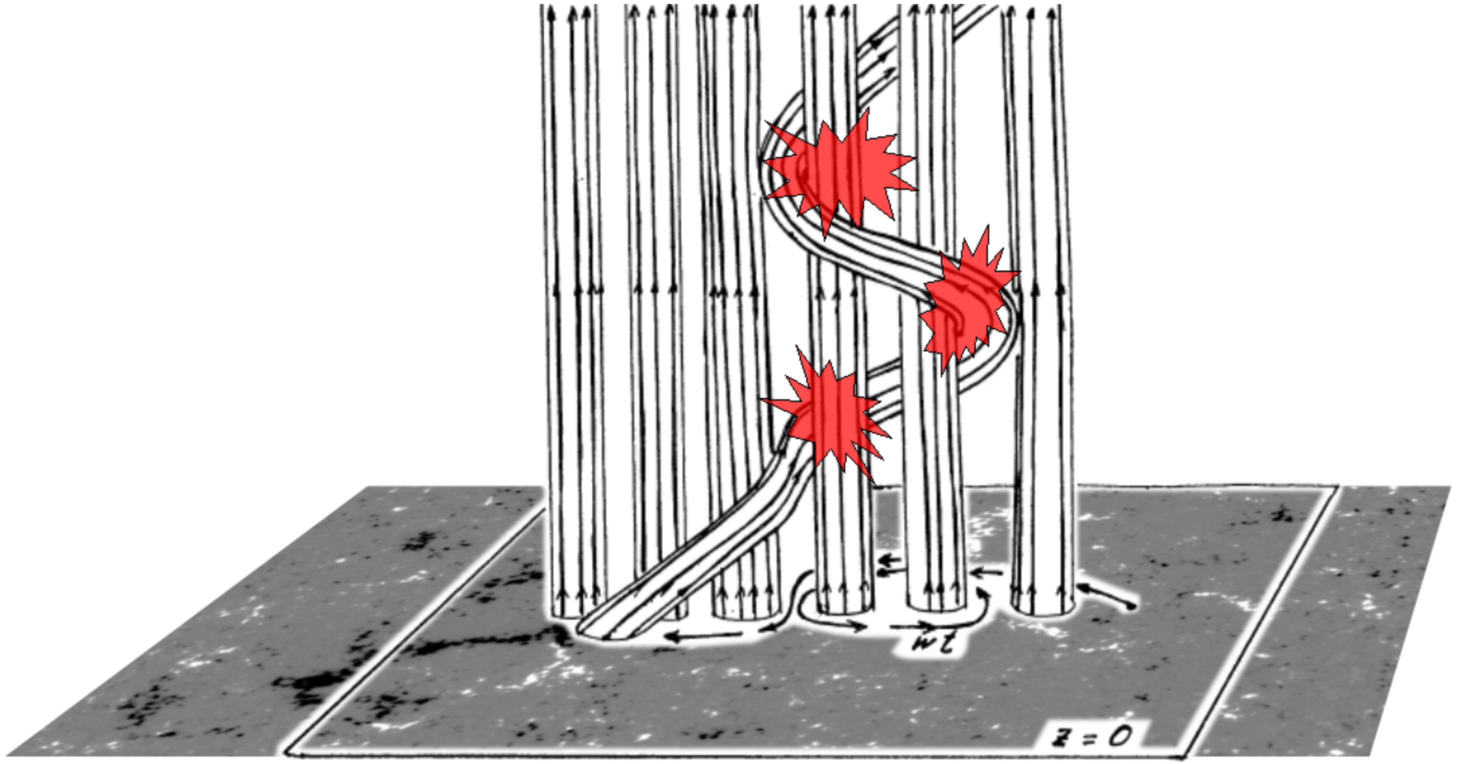
Coronal 3D MHD model

Observationally driven forward model (“field-line braiding”):

- Photospheric granulation advects small-scale magnetic fields
- Stress is induced into the magnetic field
- Braiding (or bending) of the field in the corona
- Currents are induced and dissipated to heat the corona

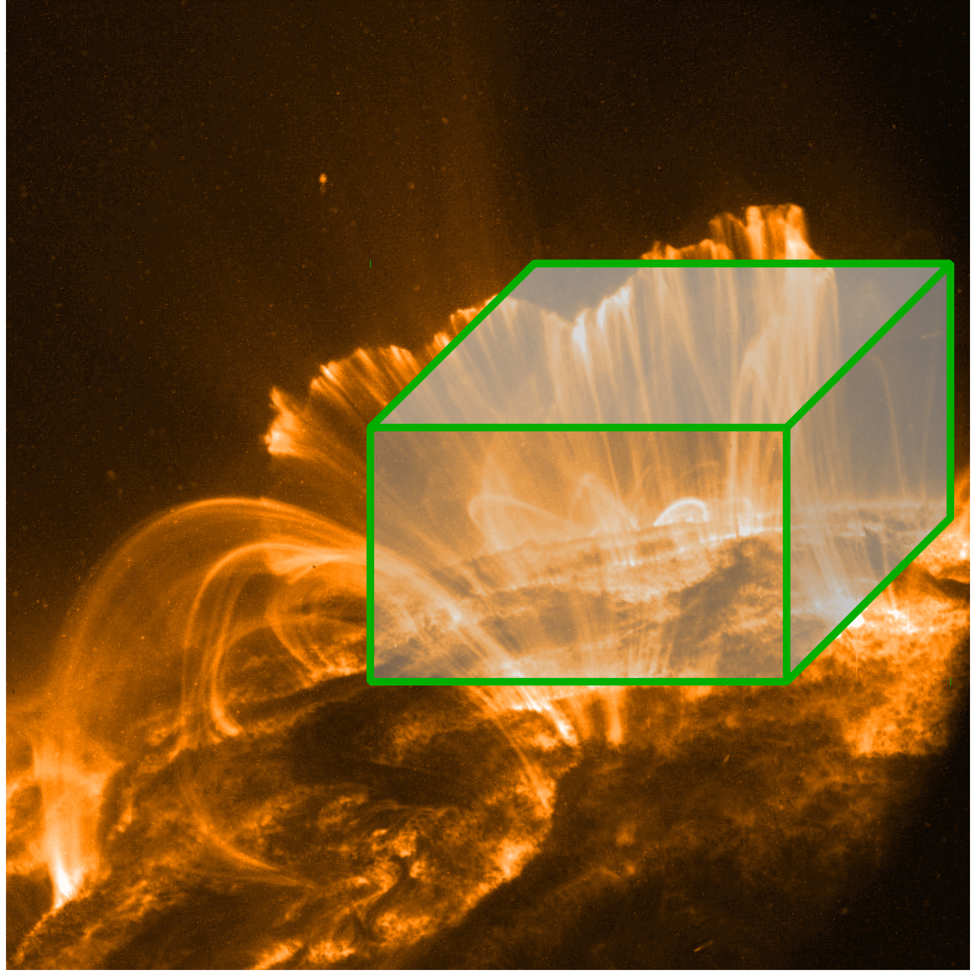


(Gudiksen & Nordlund, 2002)



(Parker, 1972, ApJ. 174, 499)

Model setup



(TRACE observation in Fe-IX/-X)

3D-MHD simulation:

- Large box: 235*235*156 Mm^3

- High resolution grid: 1024*1024*256

➡ Horizontal: 230 km, matches observation

➡ Vertical resolution: 100 – 800 km, sufficient to describe coronal heat conduction and evaporation into the corona

The Pencil Code:

http://Pencil-Code.Nordita.org/

(A. Brandenburg, W. Dobler, 2002, Comp. Phys. Comm. 147, 471-475)

- High-performance computing: NIC, GENCI, PRACE

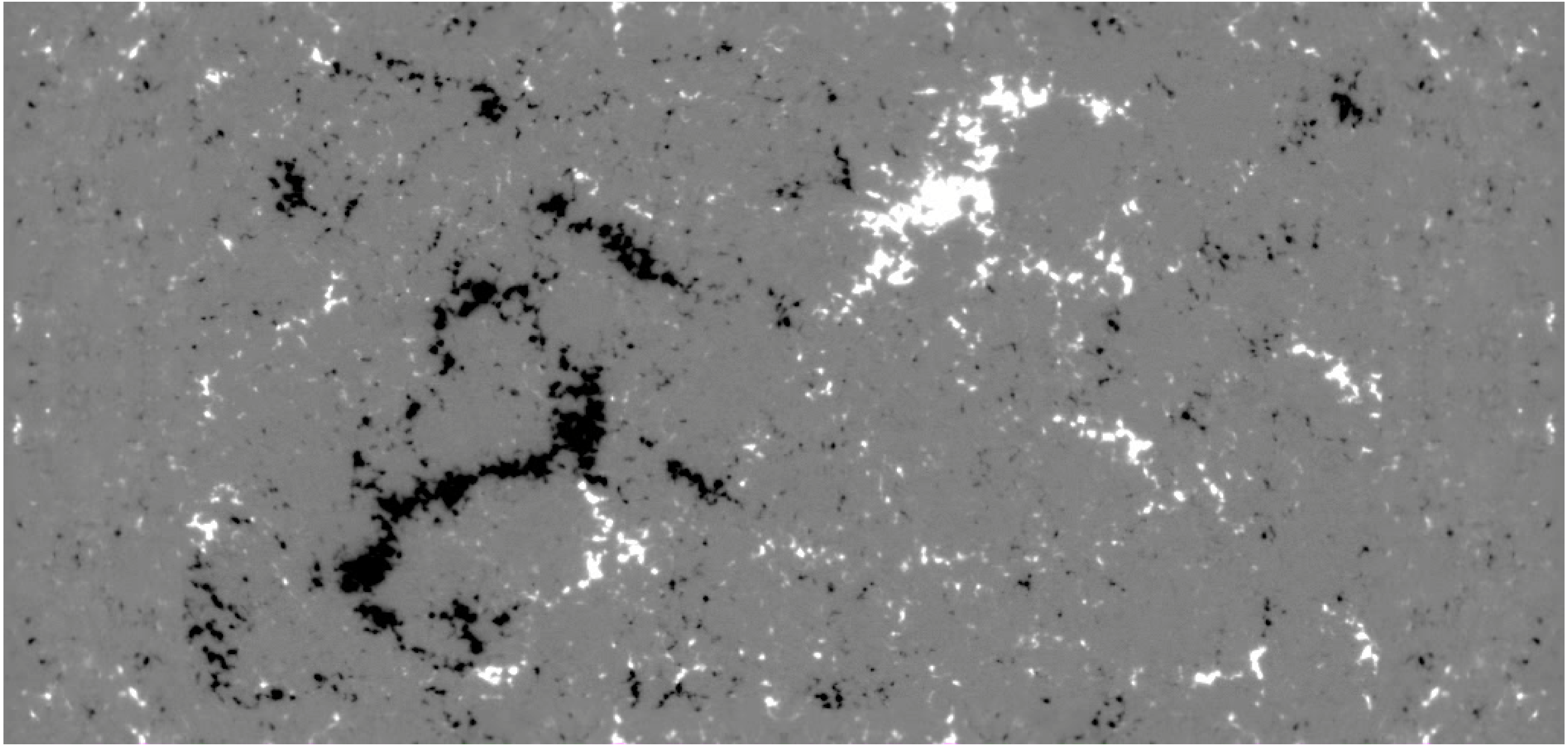
What is needed to solve the coronal heating problem...?

➡ General self-consistent model description on the observable scales

- Photospheric driving mechanism for coronal energy input of ~ 0.1-1 kW/m^2

Driving the simulation

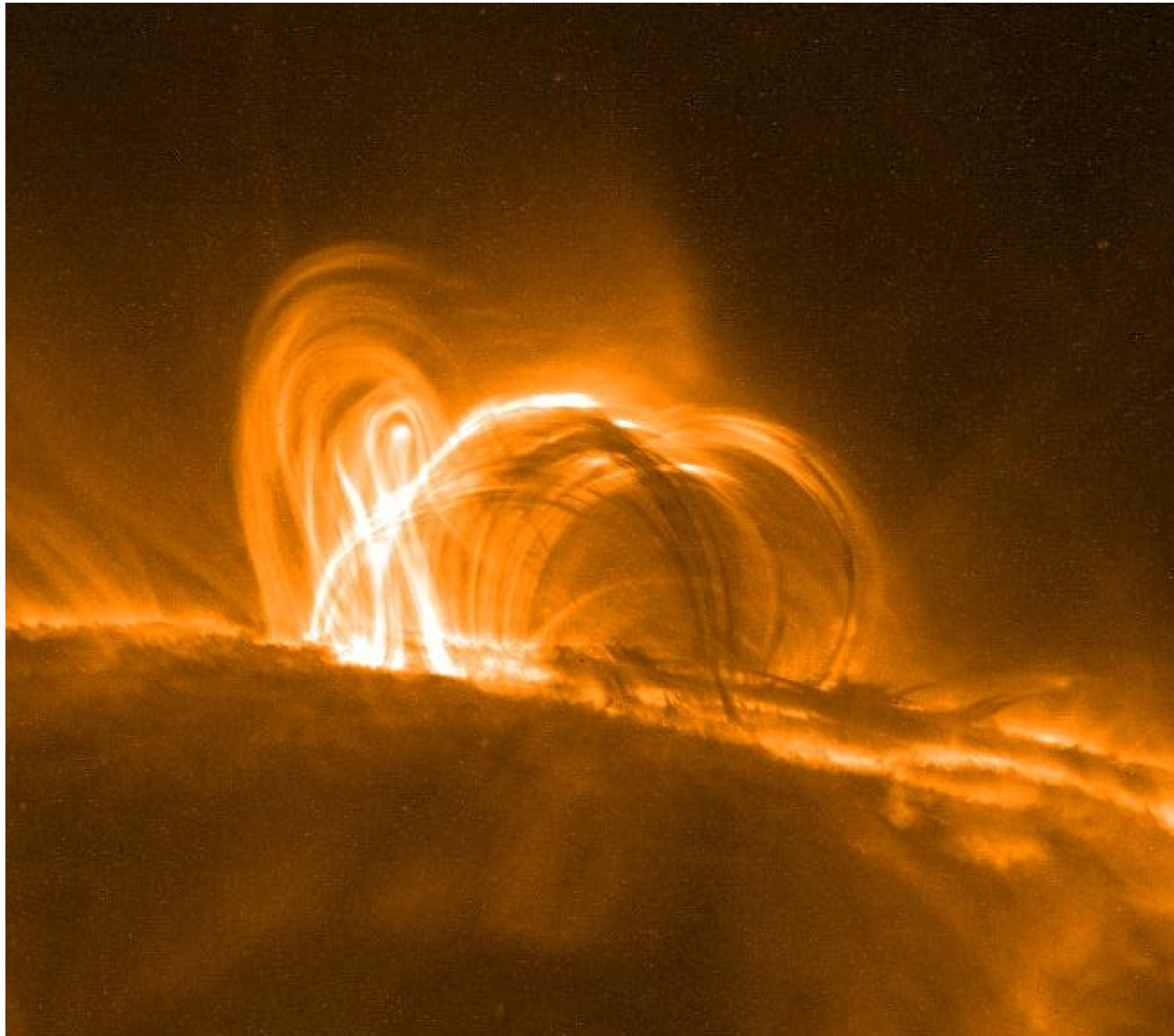
Hinode/SOT observation (14th November 2007, $15^{:00}$-$17^{:00}$ UTC)



What is needed to solve the coronal heating problem...?

General self-consistent model description on the observable scales

- Photospheric driving mechanism for coronal energy input of ~ 0.1-1 kW/m²
- Heat conduction that leads to chromospheric evaporation



What is needed to solve the coronal heating problem...?

General self-consistent model description on the observable scales

- Photospheric driving mechanism for coronal energy input of ~ 0.1-1 kW/m^2
- Heat conduction that leads to chromospheric evaporation
- Compressible resistive MHD

Compressible resistive magneto-hydrodynamics (MHD):

- Continuum equation: $$\frac{D\ln\rho}{Dt} = -\nabla\cdot\boldsymbol{u}$$

- Equation of motion: $$\frac{D\boldsymbol{u}}{Dt} = -c_S^2\nabla\left\{\frac{s}{c_P}+\ln\rho\right\}-\nabla\Phi_{Grav}+\frac{1}{\rho}\boldsymbol{j}\times\boldsymbol{B}$$
$$+\nu\left\{\nabla^2\boldsymbol{u}+\frac{1}{3}\nabla\nabla\boldsymbol{u}+2\boldsymbol{S}+\nabla\ln\rho\right\}+\zeta\left(\nabla\nabla\cdot\boldsymbol{u}\right)$$

- Induction equation: $$\frac{\partial\boldsymbol{A}}{\partial t} = \boldsymbol{u}\times\boldsymbol{B}-\mu_0\eta\boldsymbol{j}$$

- Energy balance: $$\rho T\frac{Ds}{Dt} = \mu_0\eta\boldsymbol{j}^2+\nabla\cdot\boldsymbol{q}_{Spitzer}-L_{rad}+2\rho\nu\boldsymbol{S}\odot\boldsymbol{S}+\zeta\rho\left(\nabla\cdot\boldsymbol{u}\right)^2$$

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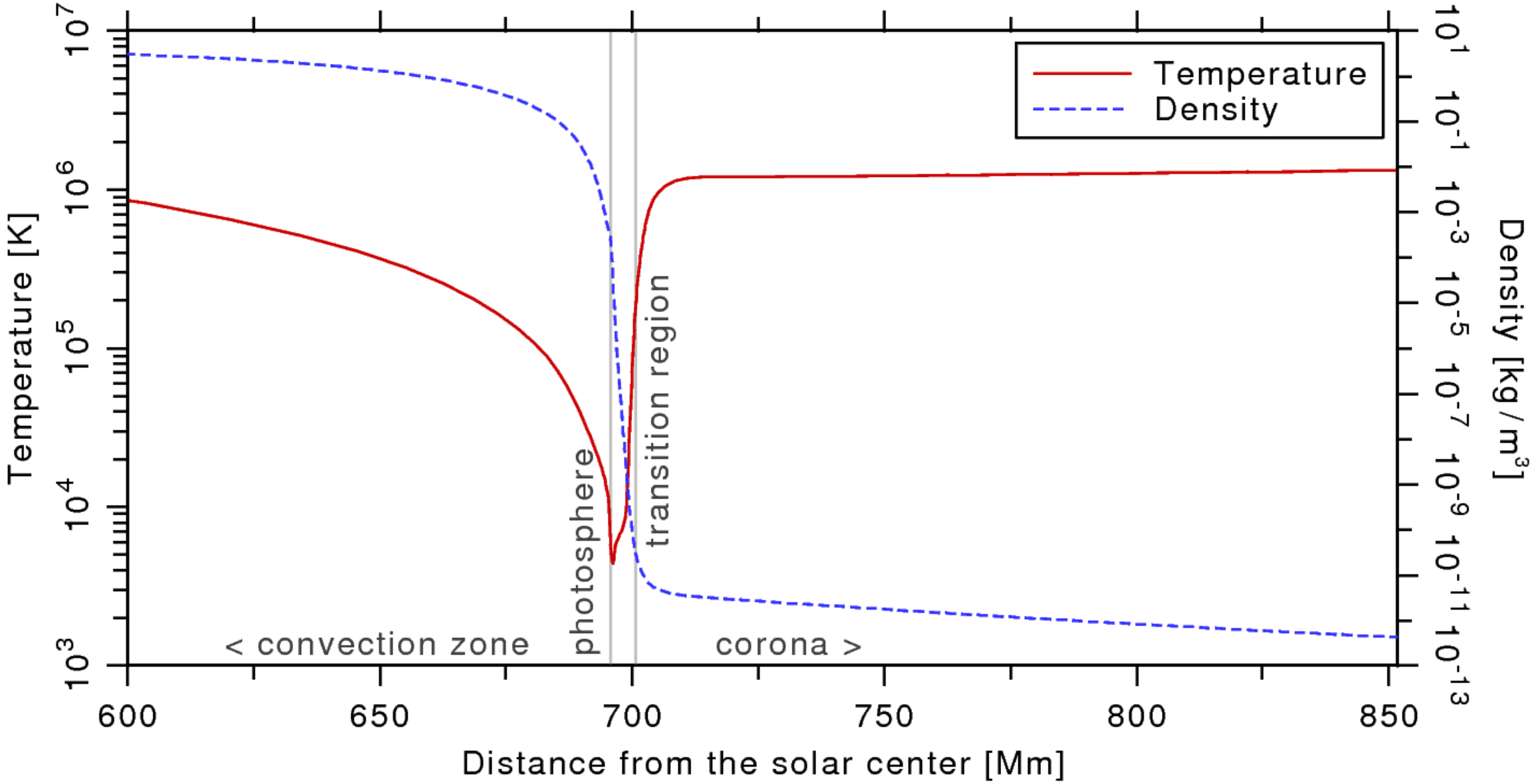
=> Radiative losses: $L_{rad}(\rho, T)$ (Cook et al., 1982)

=> Heat conduction: $\boldsymbol{q}_{Spitzer}\sim\kappa T^{5/2}\cdot\nabla T$ (Spitzer, 1962)

What is needed to solve the coronal heating problem...?

General self-consistent model description on the observable scales

- Photospheric driving mechanism for coronal energy input of ~ 0.1-1 kW/m²
- Heat conduction that leads to chromospheric evaporation
- Compressible resistive MHD
- Resolve strong gradients in density and temperature

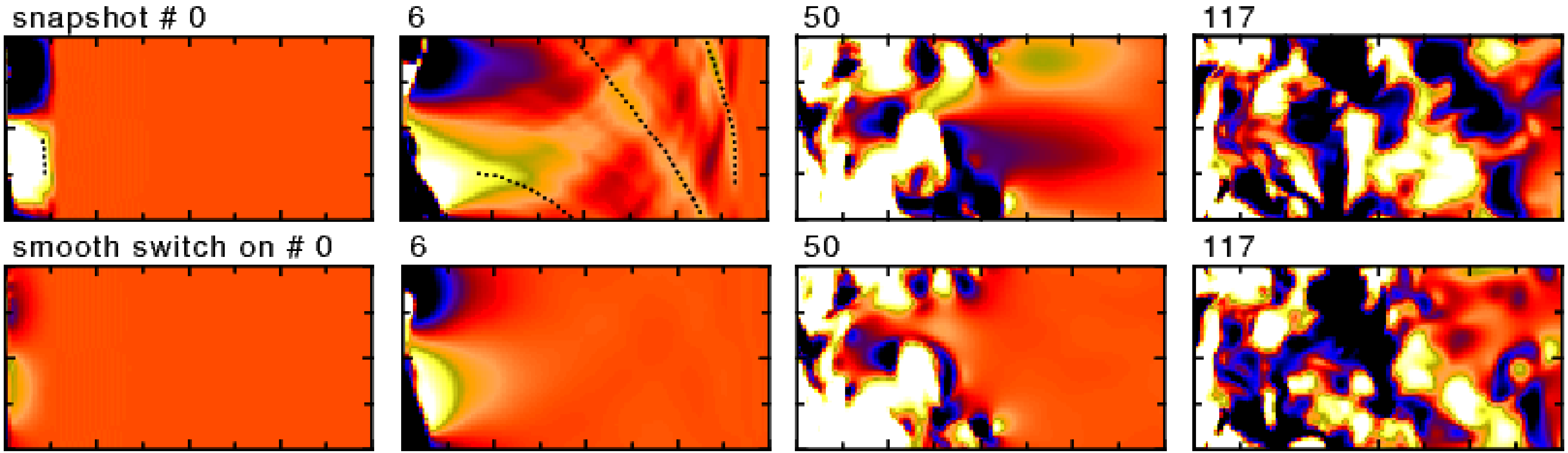


(Stix, 1989/2002) (**F**AL-C, 1993) (November-Kouchmy, 1996)

What is needed to solve the coronal heating problem...?

General self-consistent model description on the observable scales

- Photospheric driving mechanism for coronal energy input of ~ 0.1-1 kW/m²
- Heat conduction that leads to chromospheric evaporation
- Compressible resistive MHD
- Resolve strong gradients in density and temperature
- Avoid switching-on effects

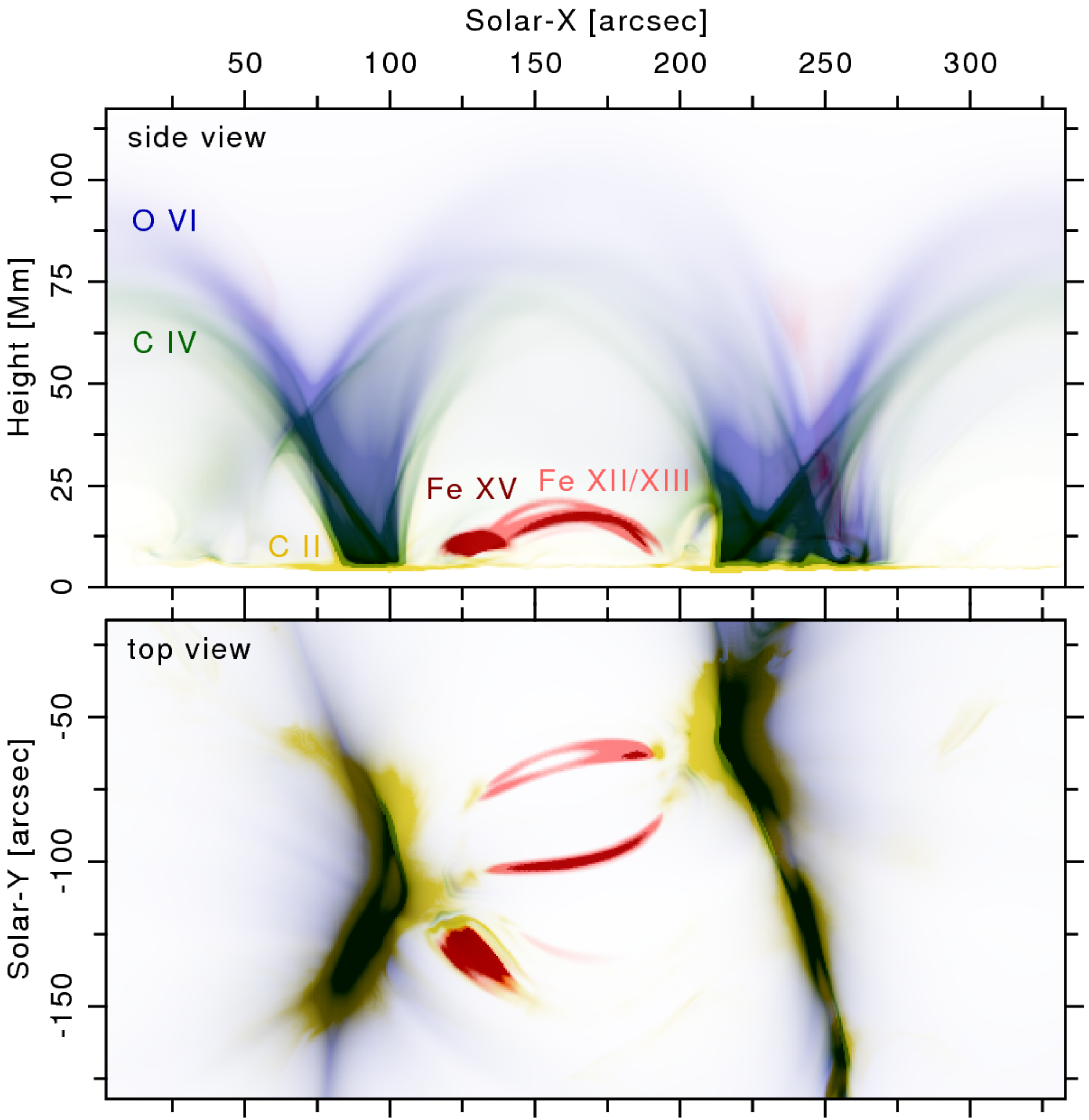


(Bourdin, Cent. Eur. Astrophys. Bull. 38/1, 1–10, 2014)

Synthesized emission (CHIANTI)

➡ hot loops in AR core

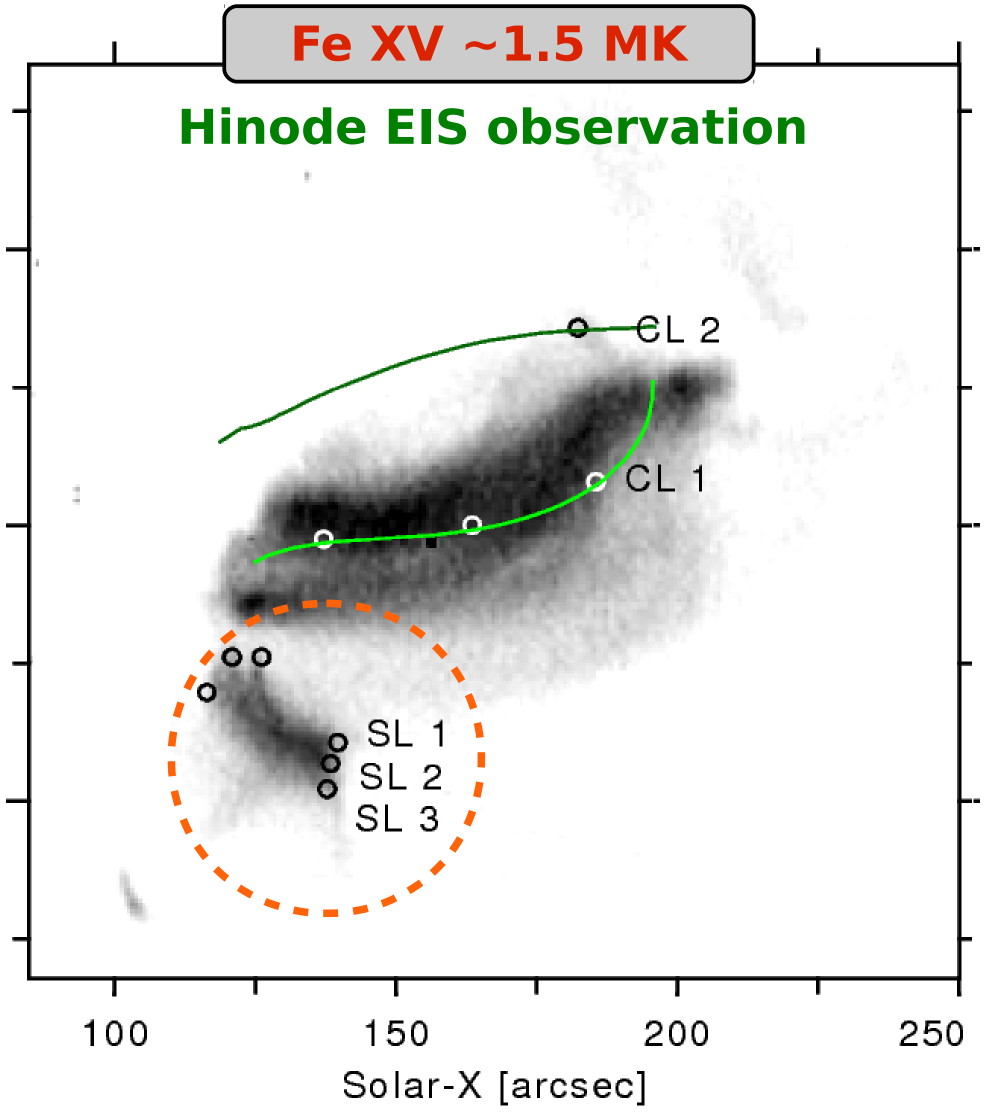
(Bourdin et al., PASJ 66/S7, 1–8, 2014)

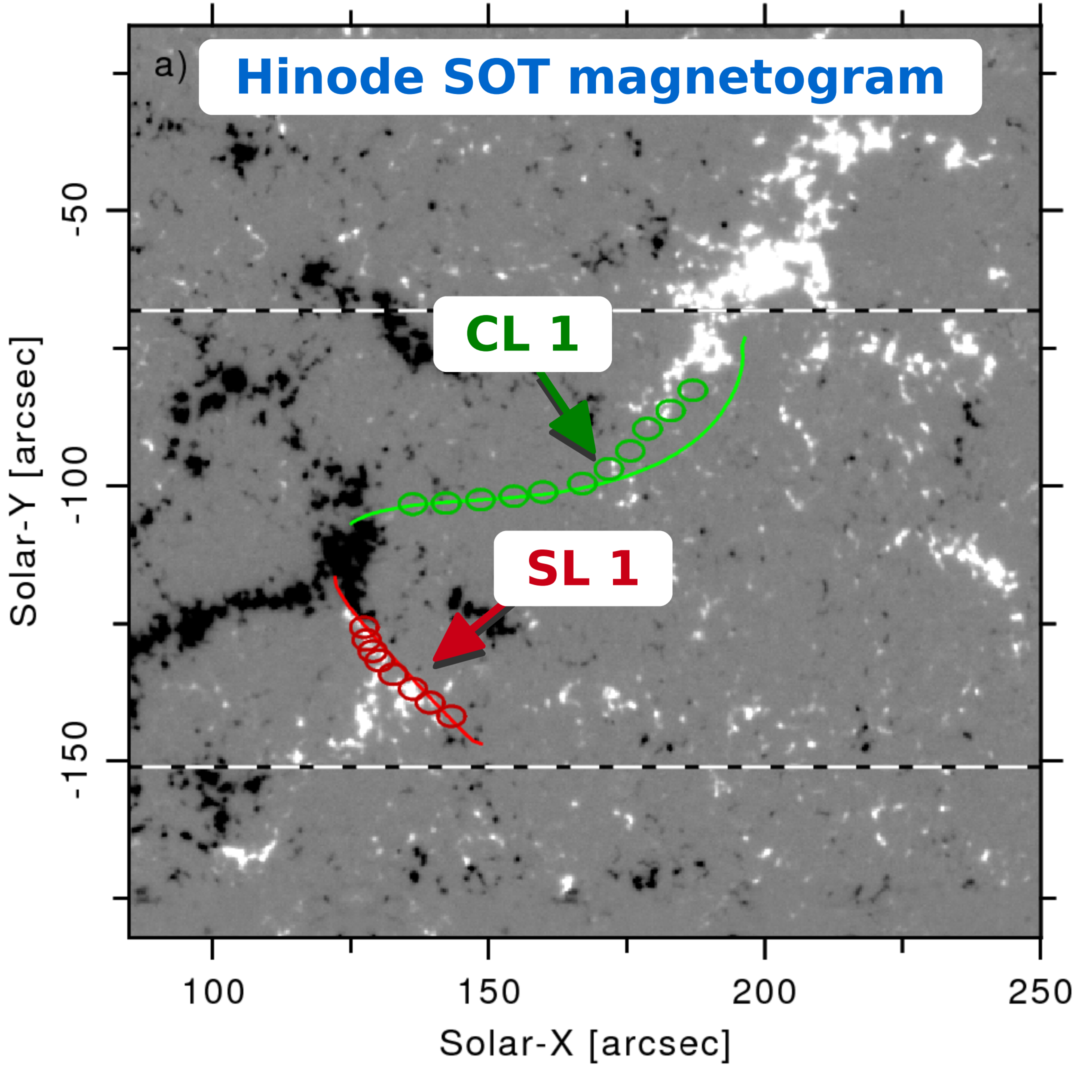


Comparing to observations

Comparing to observations (Hinode EIS/SOT)

Model fieldlines follow observed loops

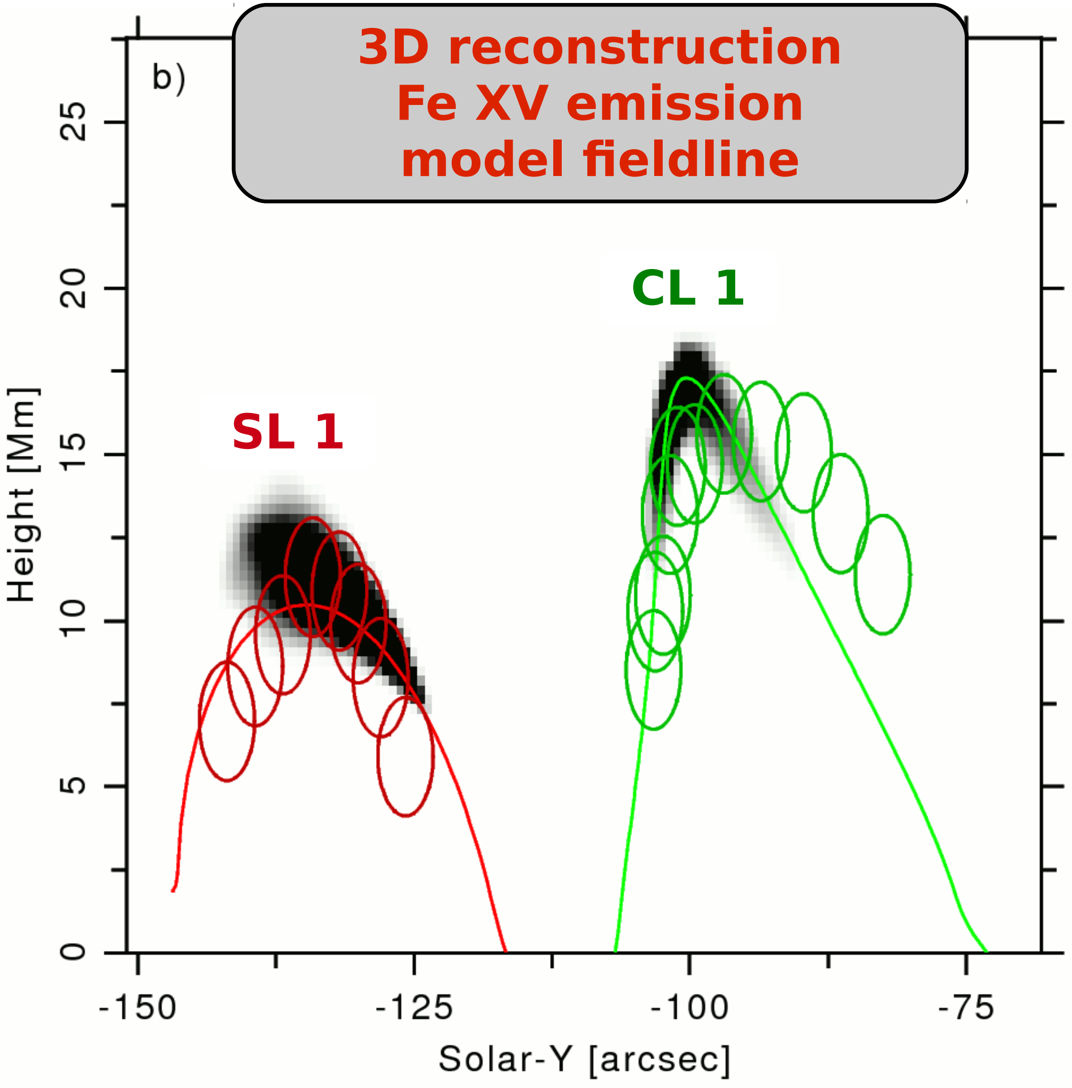


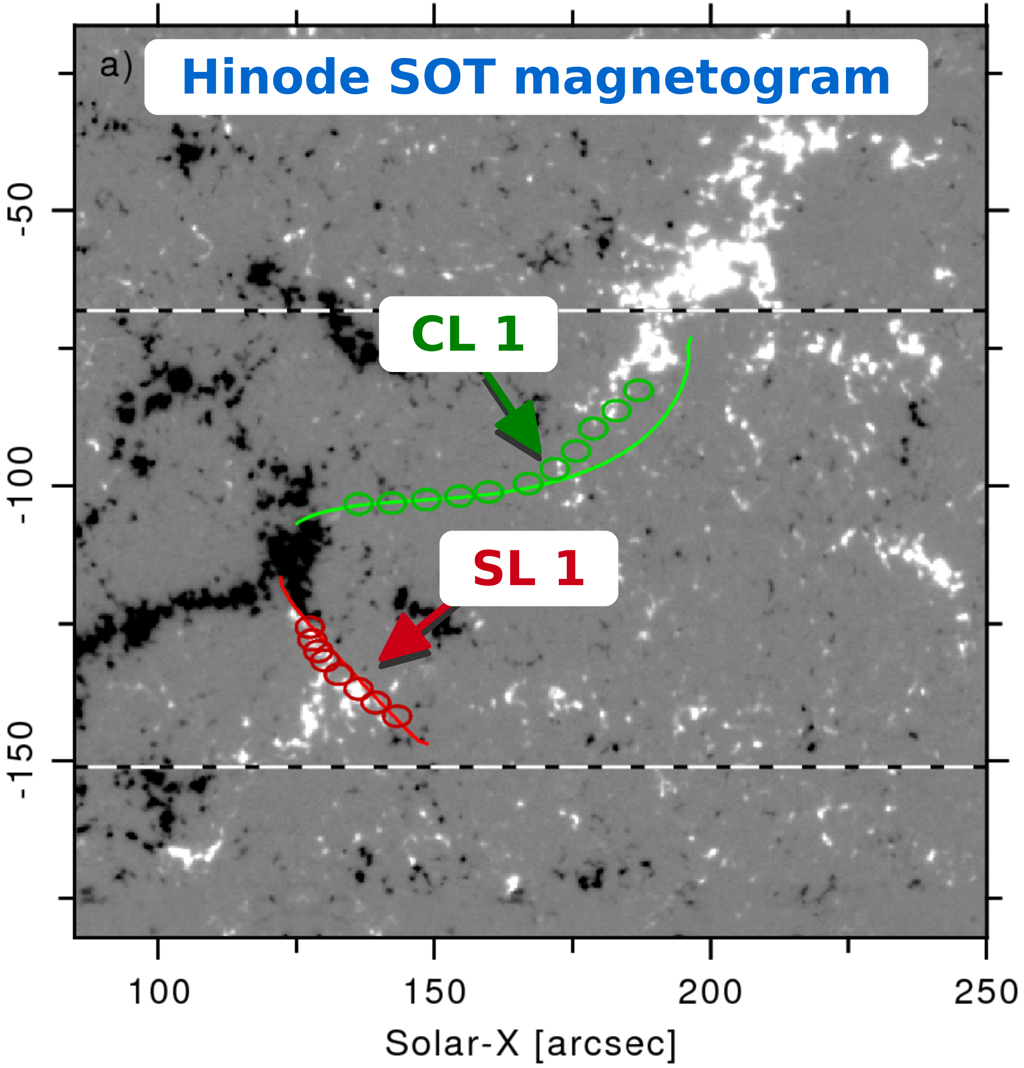


(Bourdin et al., A&A 555, A123, 2013)

Comparing to observations (STEREO A/B)

- 3D structure and height of model loops realistic
- Model fieldlines follow observed loops

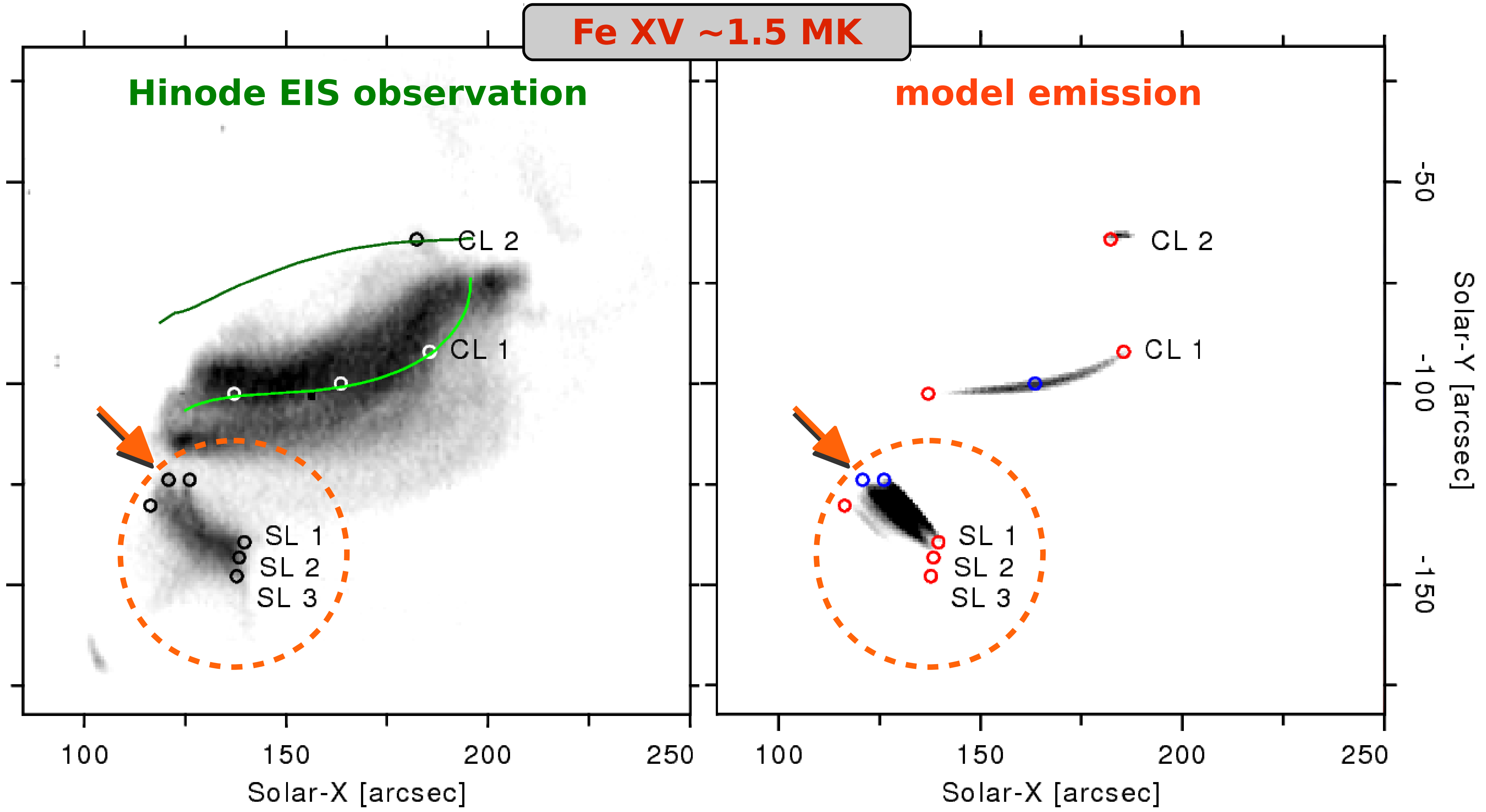




(Bourdin et al., A&A 555, A123, 2013)

Comparison of intensity

- Alignment accurate to 3 arcsec ➡ Small loops SL 1-3 at same position

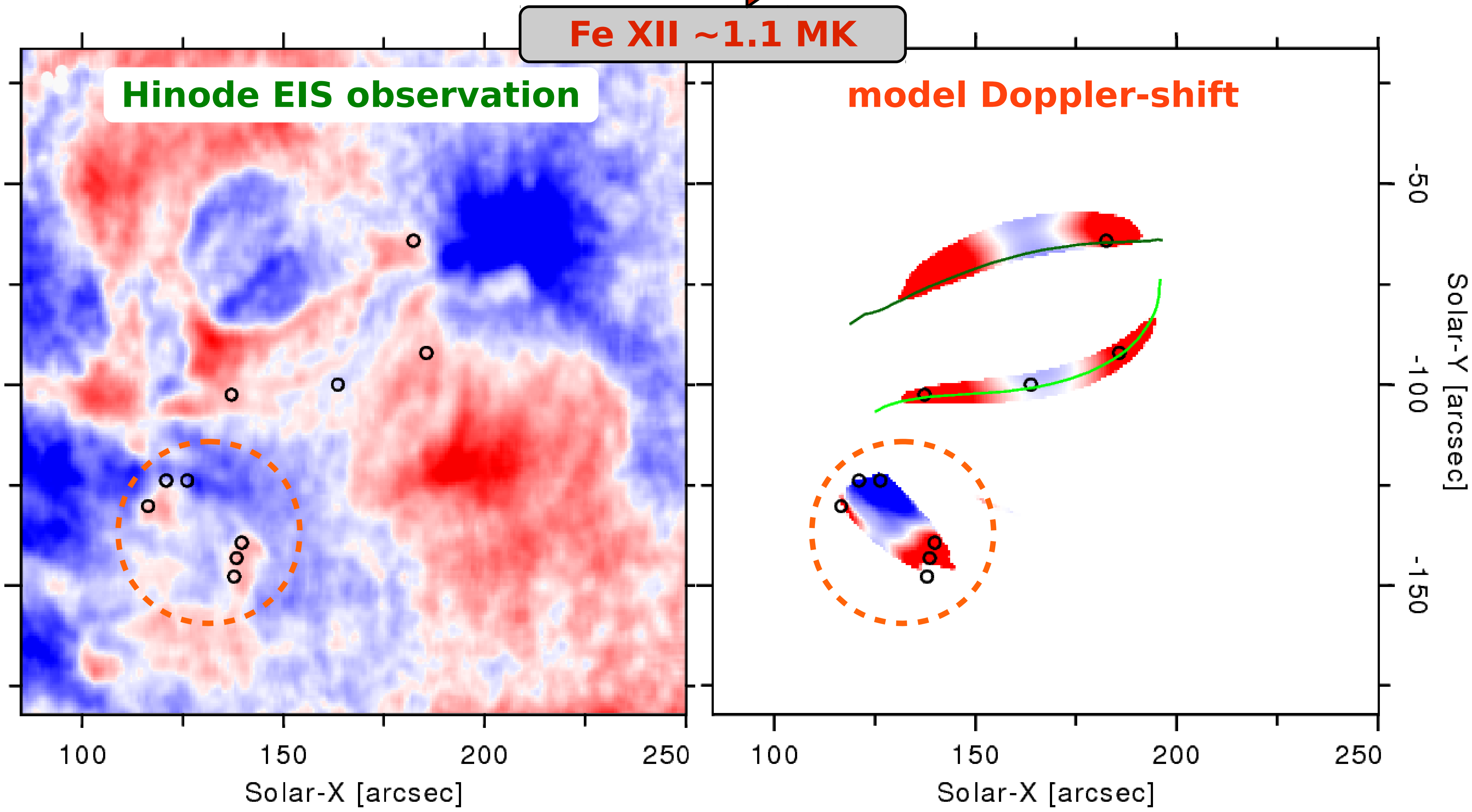


(Bourdin et al., A&A 555, A123, 2013)

Comparing to observations (Hinode EIS)

Comparison of Doppler-shifts:

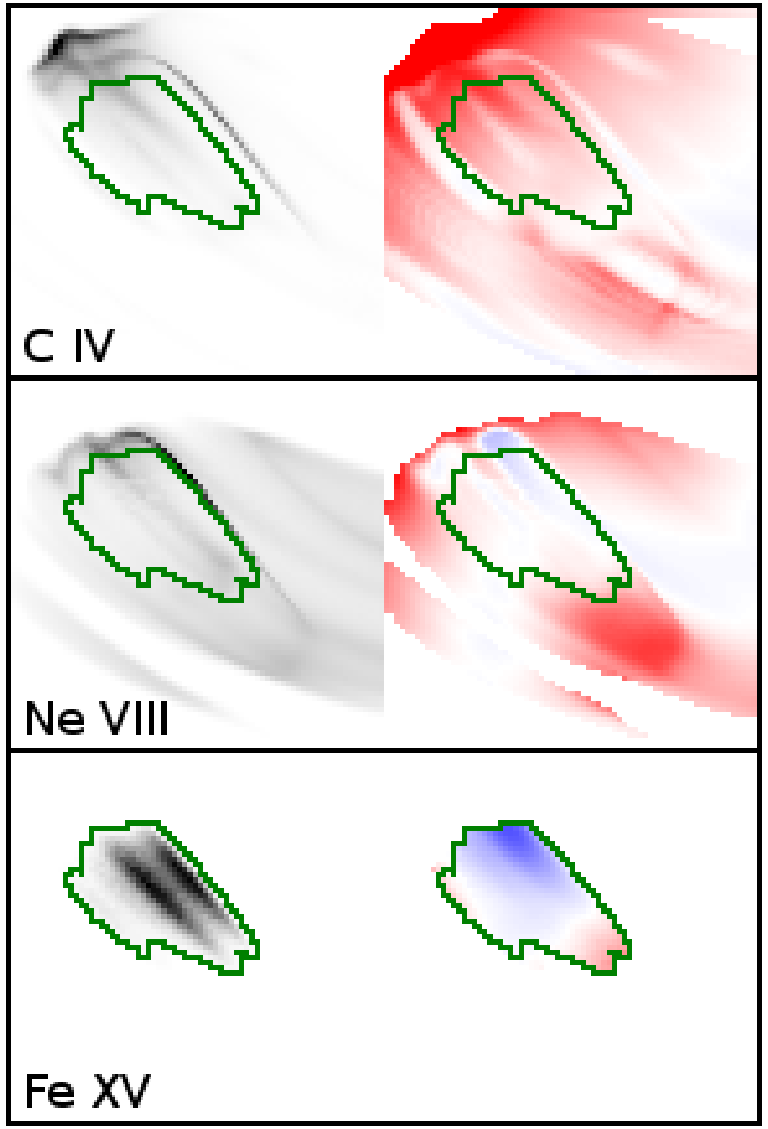
- Dynamics match!
- Loop top rises: 2 km/s (Solanki, 2003)



(Bourdin et al., A&A 555, A123, 2013)

Statistical Doppler-shift analysis

Intensity: Doppler shift: Line formation Temperature:

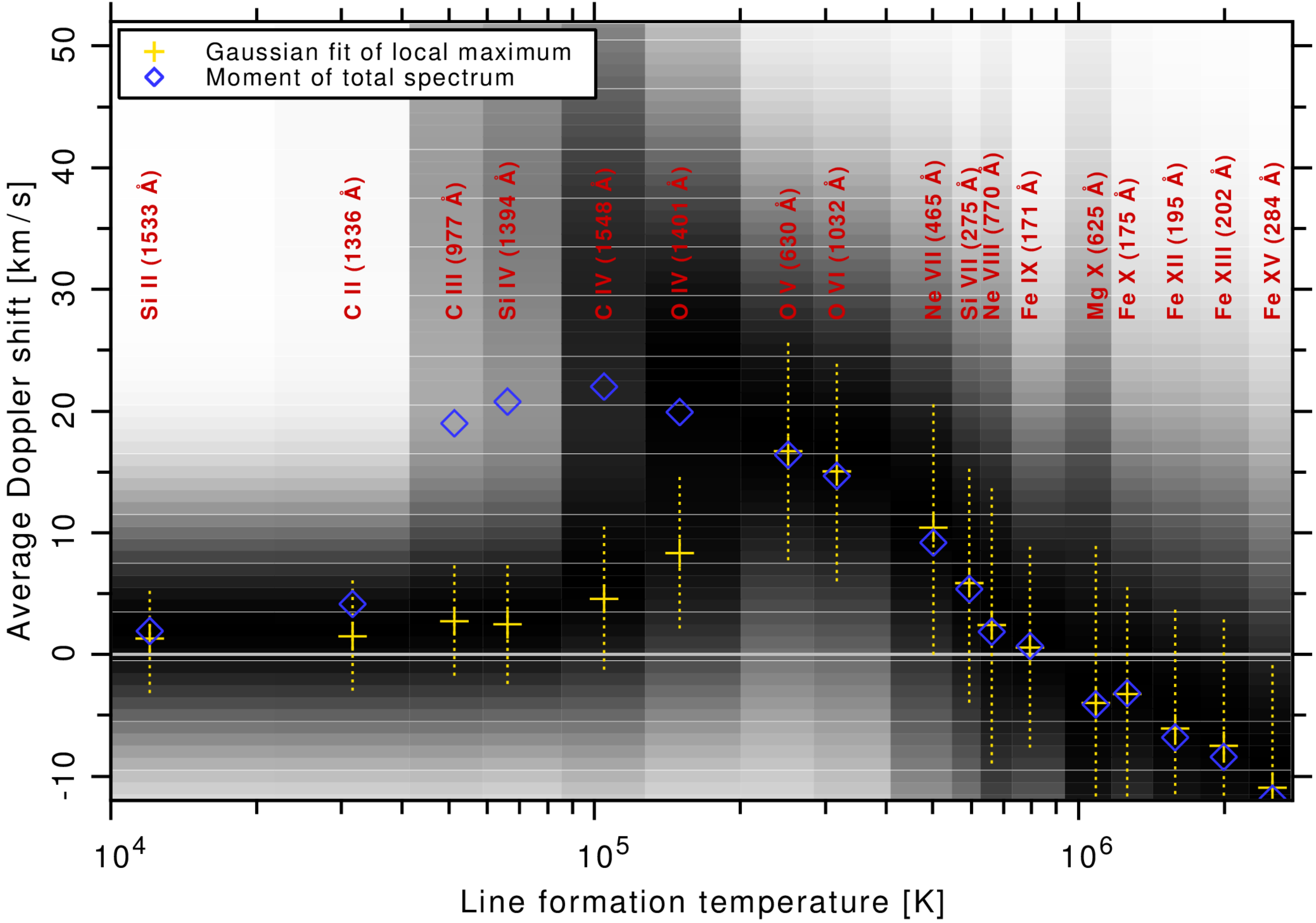


~ 100'000 K

~ 700'000 K

~ 1'500'000 K

Statistical Doppler-shift analysis



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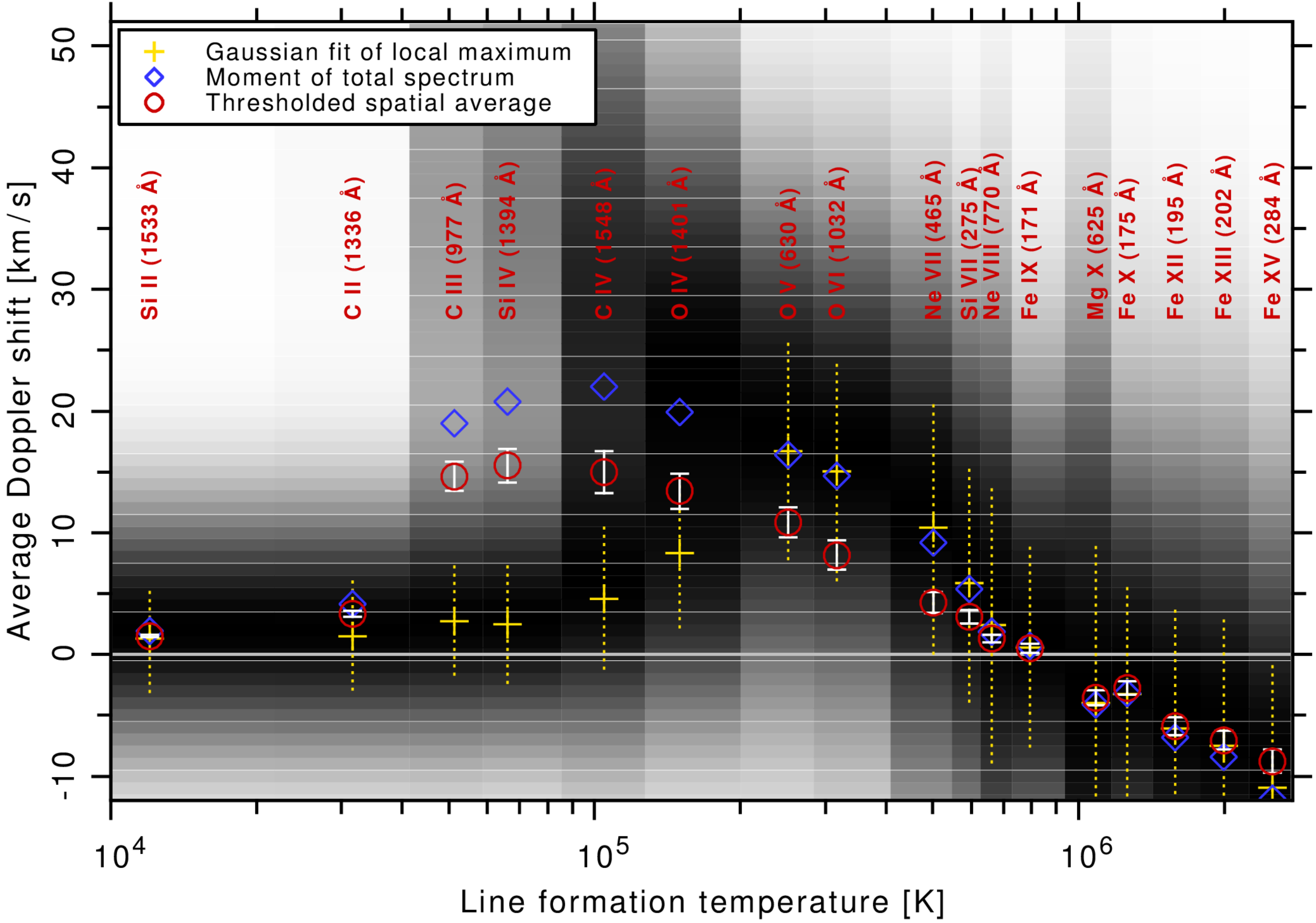
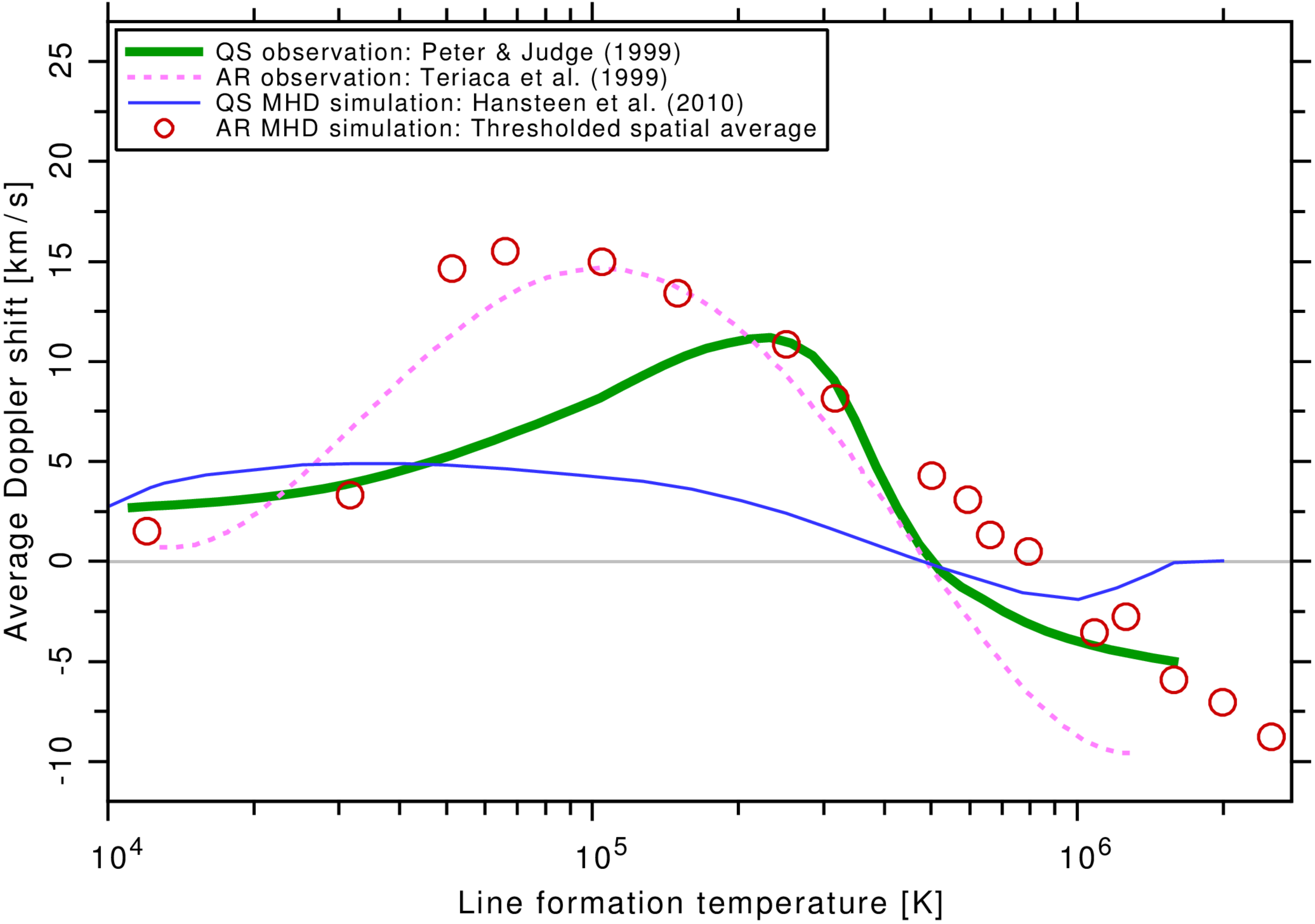


Statistical Doppler-shift analysis

Blue-shifts in the corona

Stronger Red-shifts above the AR as compared to QS (as observed)



Field topology

Field topology

Temperature:

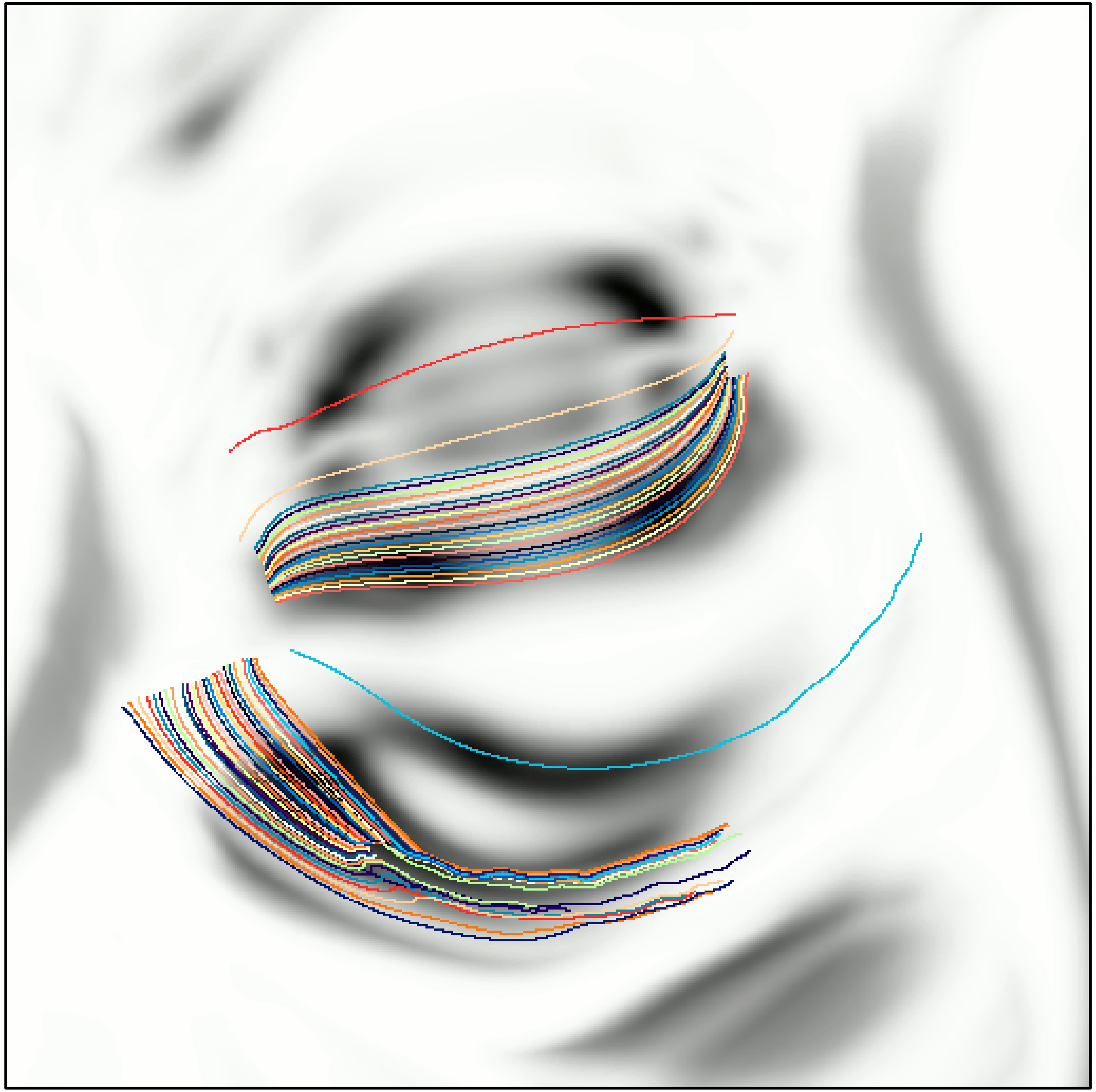
(horizontal cut)

(height: 11.2 Mm)

(black: 1.25 MK)

- Magnetic field quite parallel in the corona

- Braided field only in the lower atmosphere



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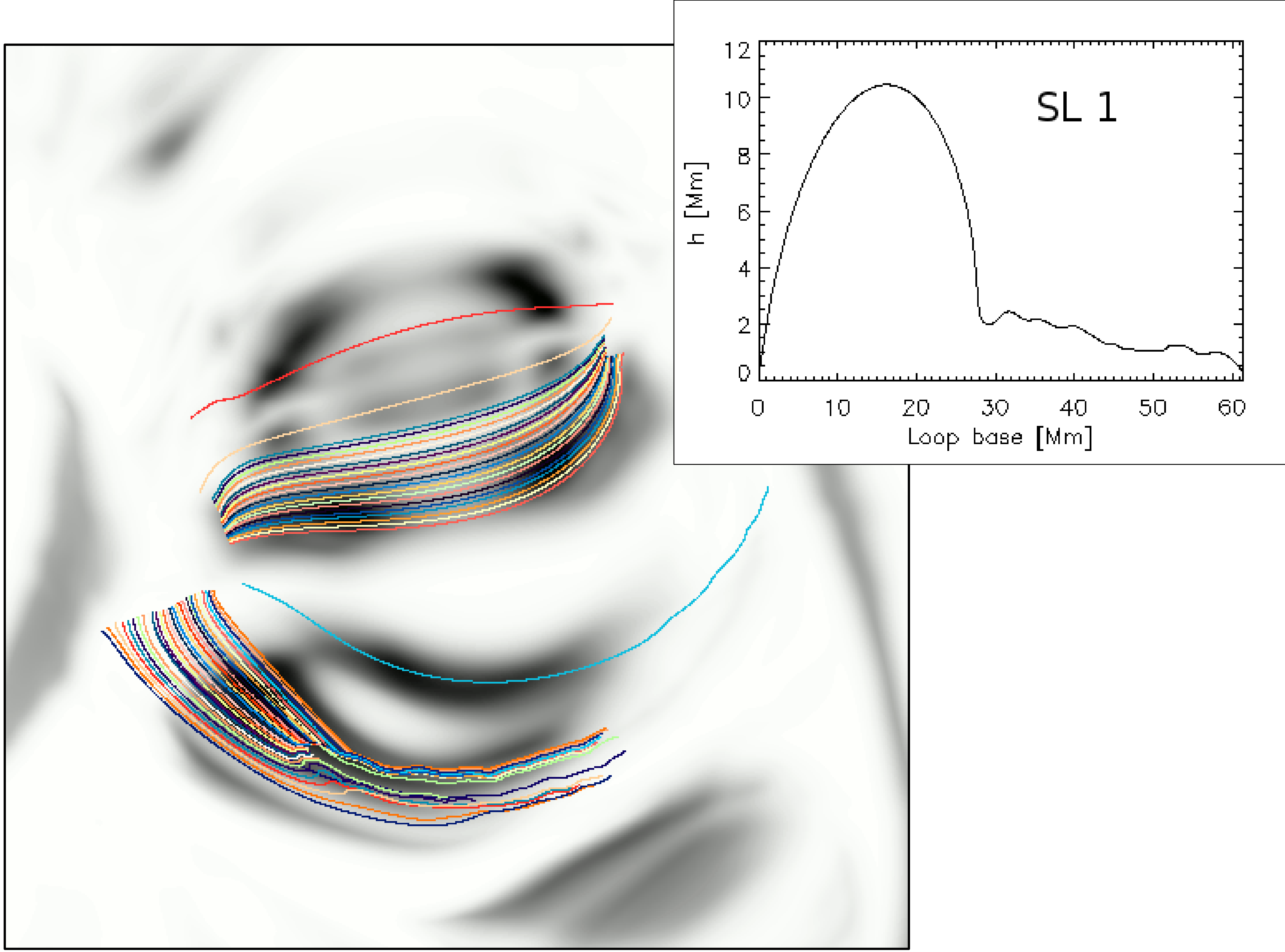
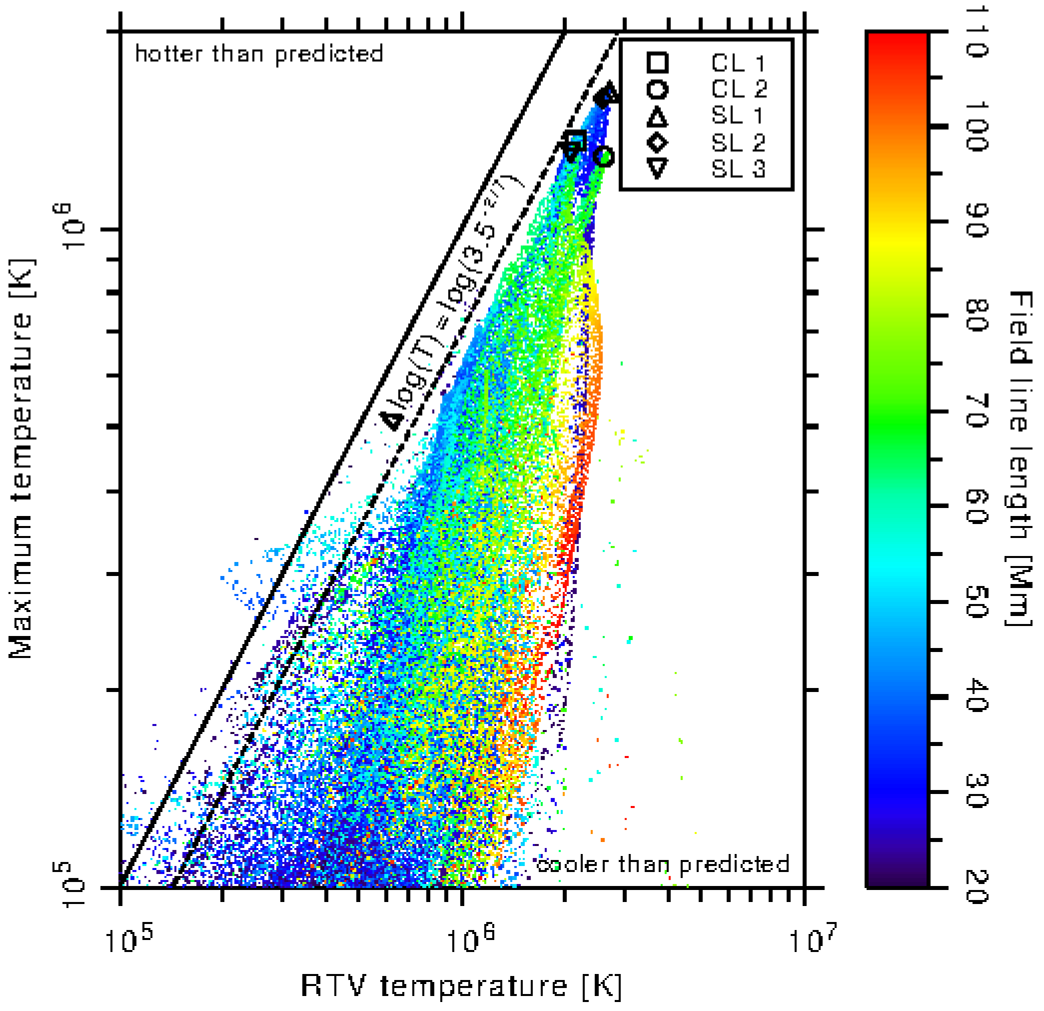


Testing scaling laws with field-line ensemble

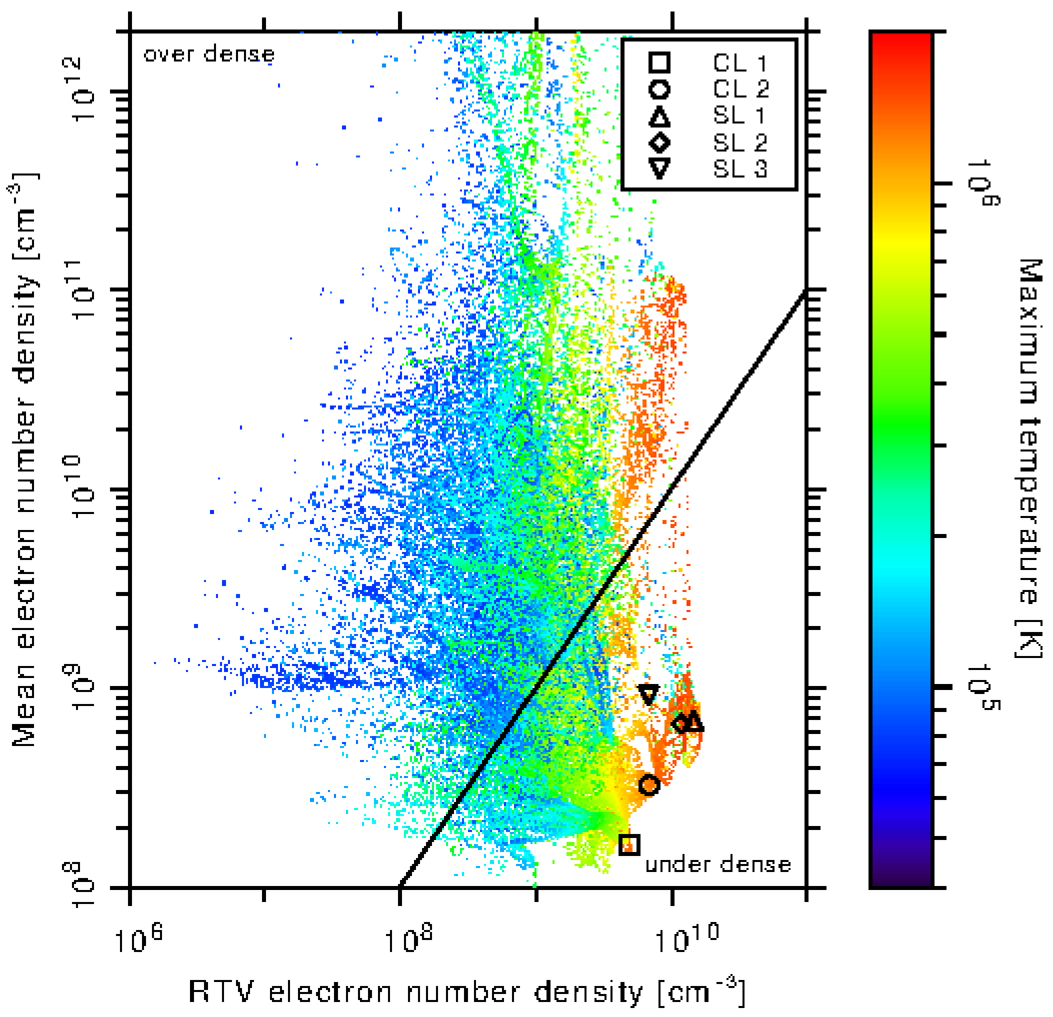
RTV temperature:

$$T = c_T \cdot c_H^{-2/7} \cdot {F_H}^{2/7} L^{2/7}$$



RTV density:

$$n_e = \frac{1}{2k_B} c_H^{-4/7} c_T^{-1} \cdot {F_H}^{4/7} L^{-3/7}$$



Temporal evolution of field lines (and bulk plasma motion)

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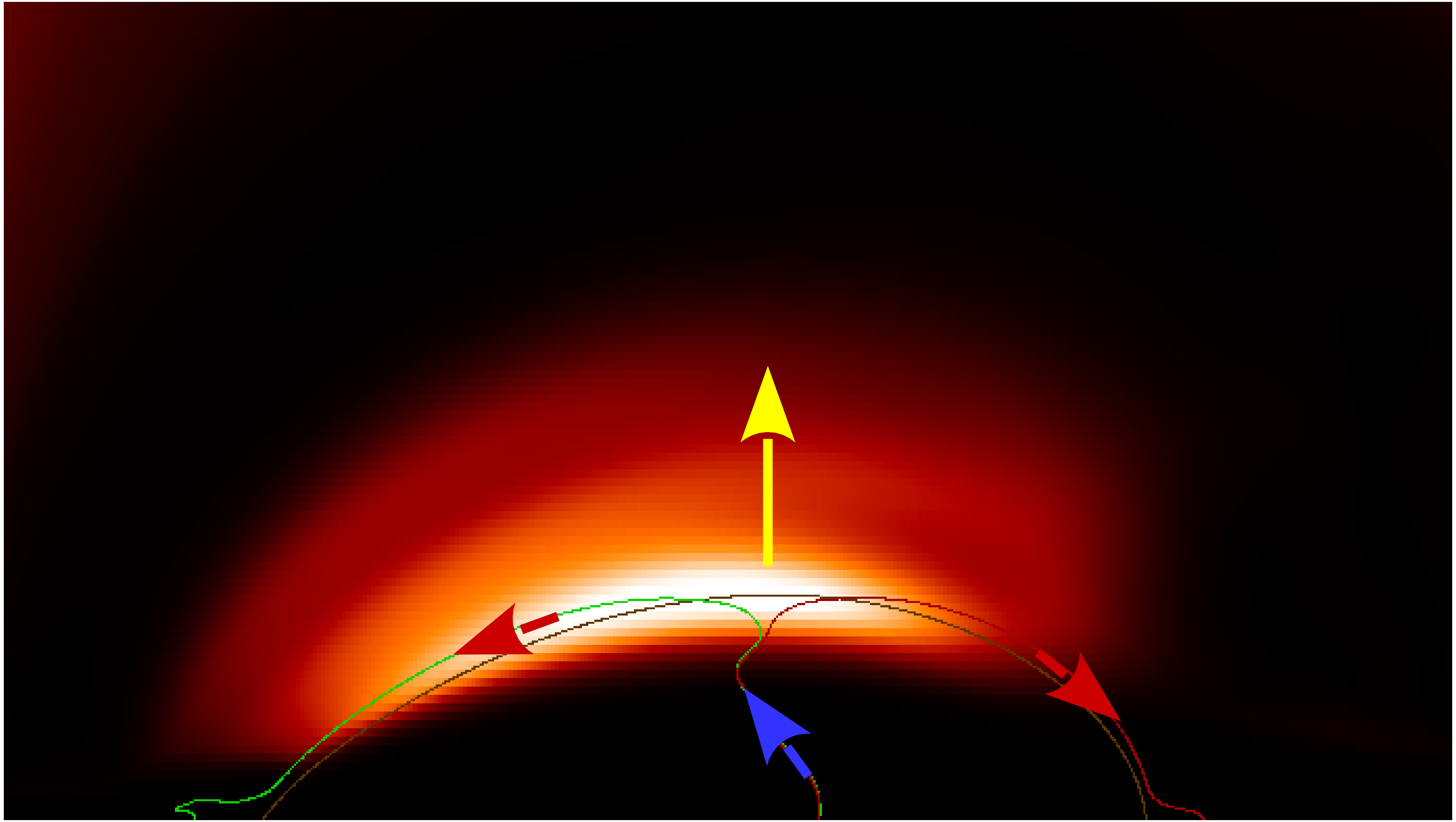


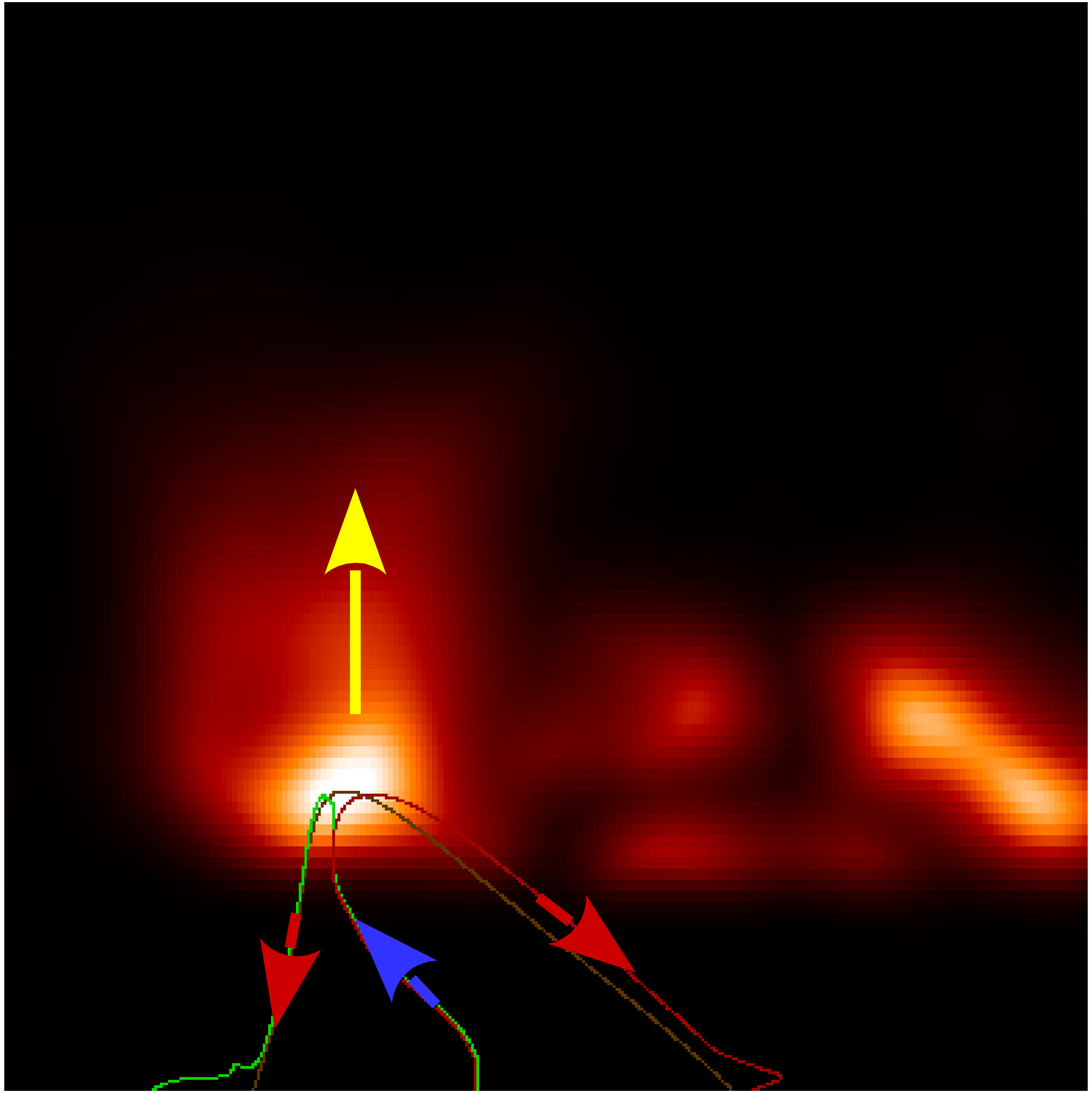
Temporal evolution of field lines (and bulk plasma motion)

Temperature:

(white: 1.2 MK)

- Bulk plasma rising together with field line
- Material draining then to the both sides of the loop

(steady flow of “coronal rain”?)



Reconnection and B-parallel electric fields

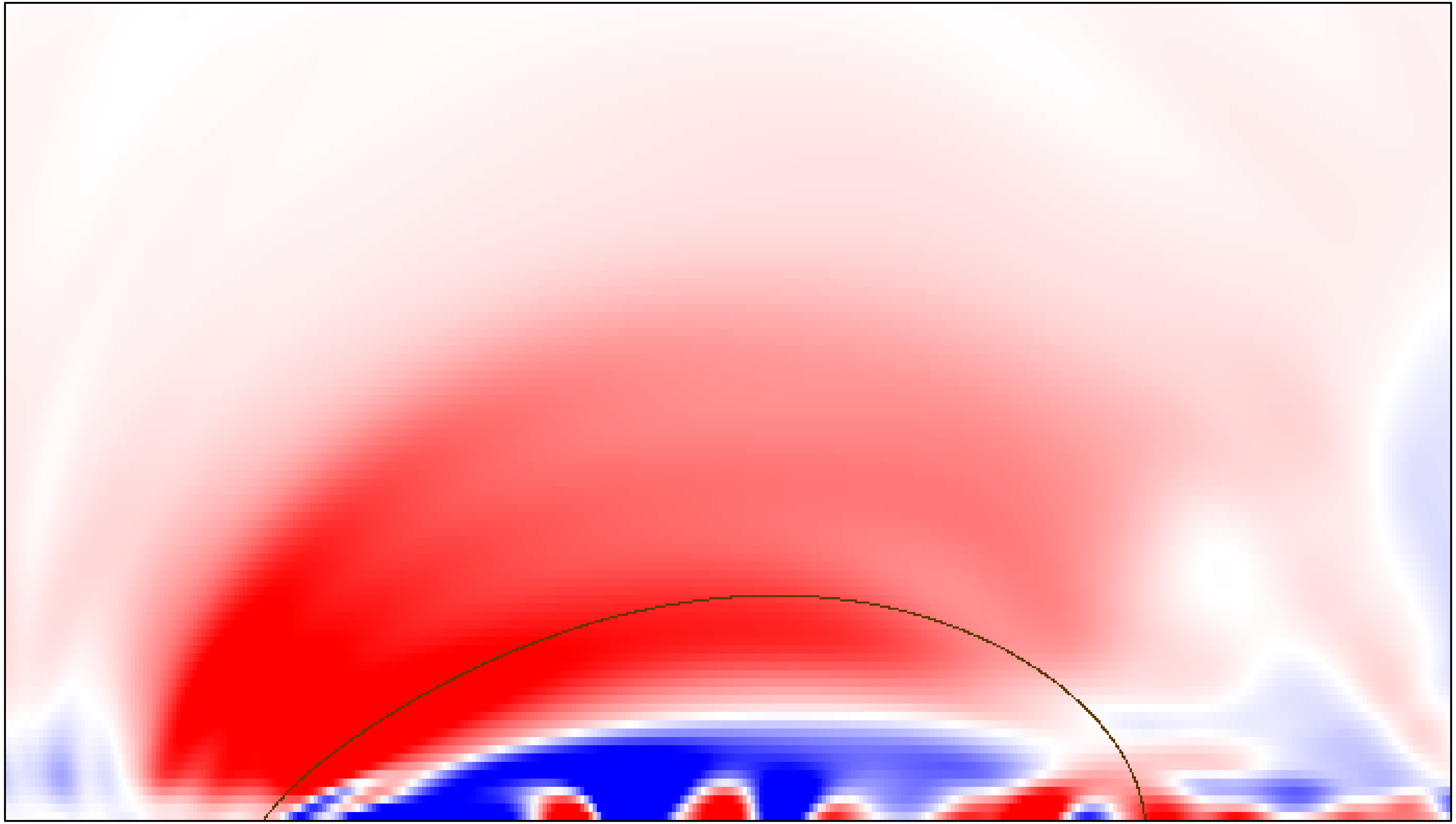
Reconnection and B-parallel electric fields

E_parallel:

(saturation level:

± 0.5 V)

- Loop in strong reconnection region (red)
- E_parallel rather uniform along loop



Particle acceleration from electric fields

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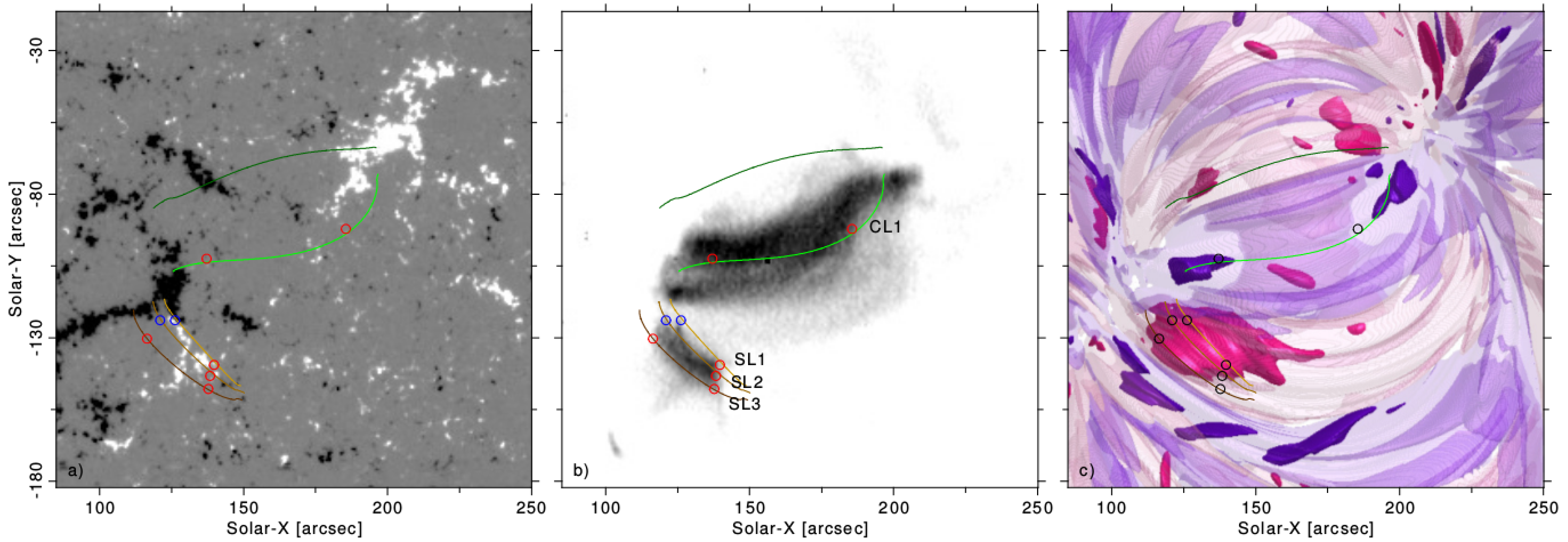
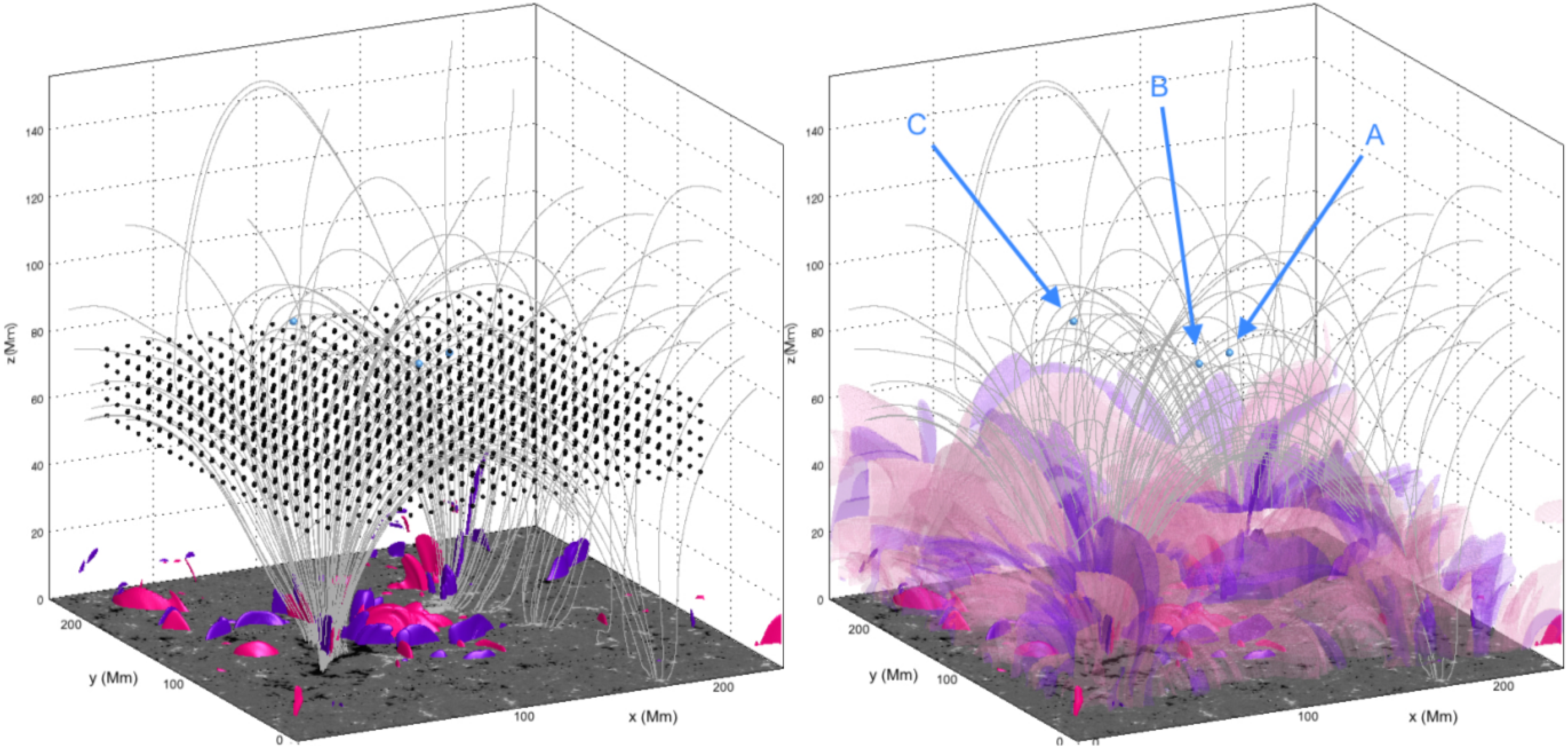


Particle acceleration from electric fields

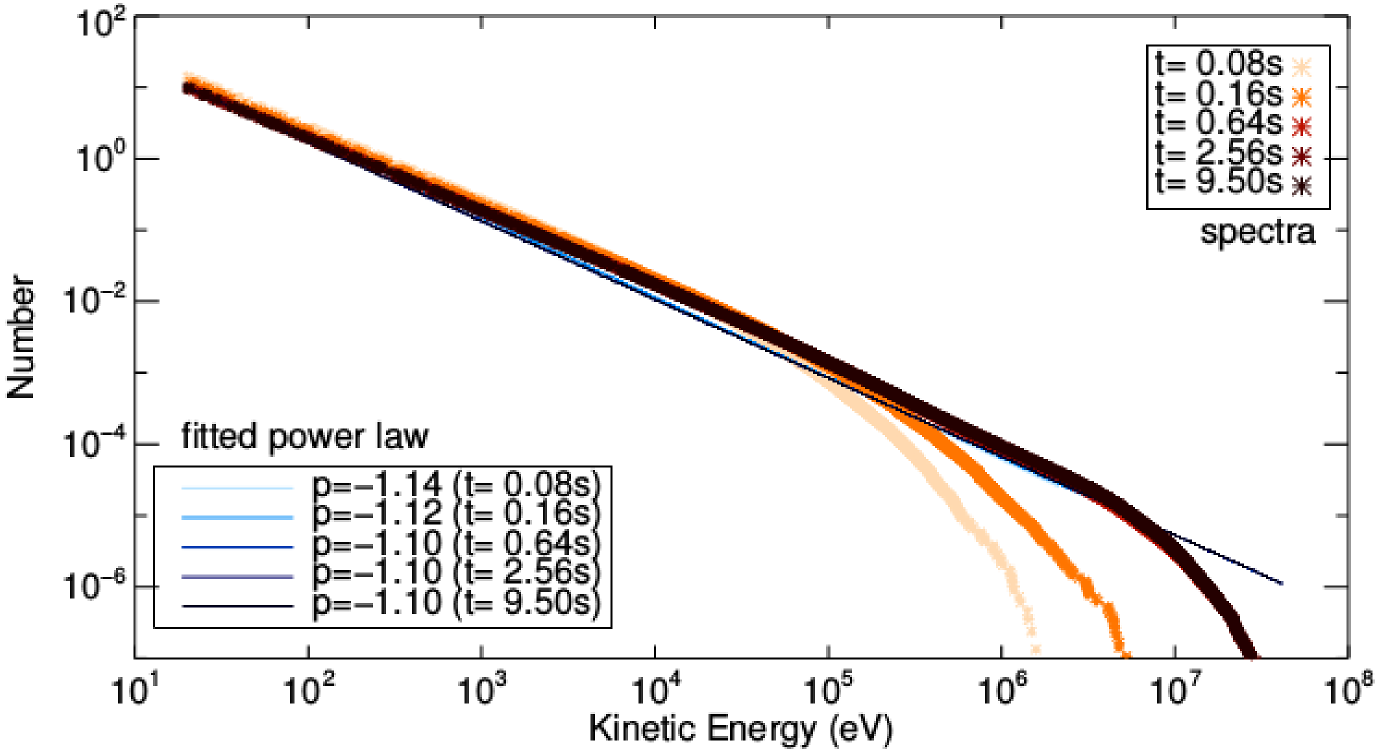


(a) Initial particle grid and high $E_{||}$ regions

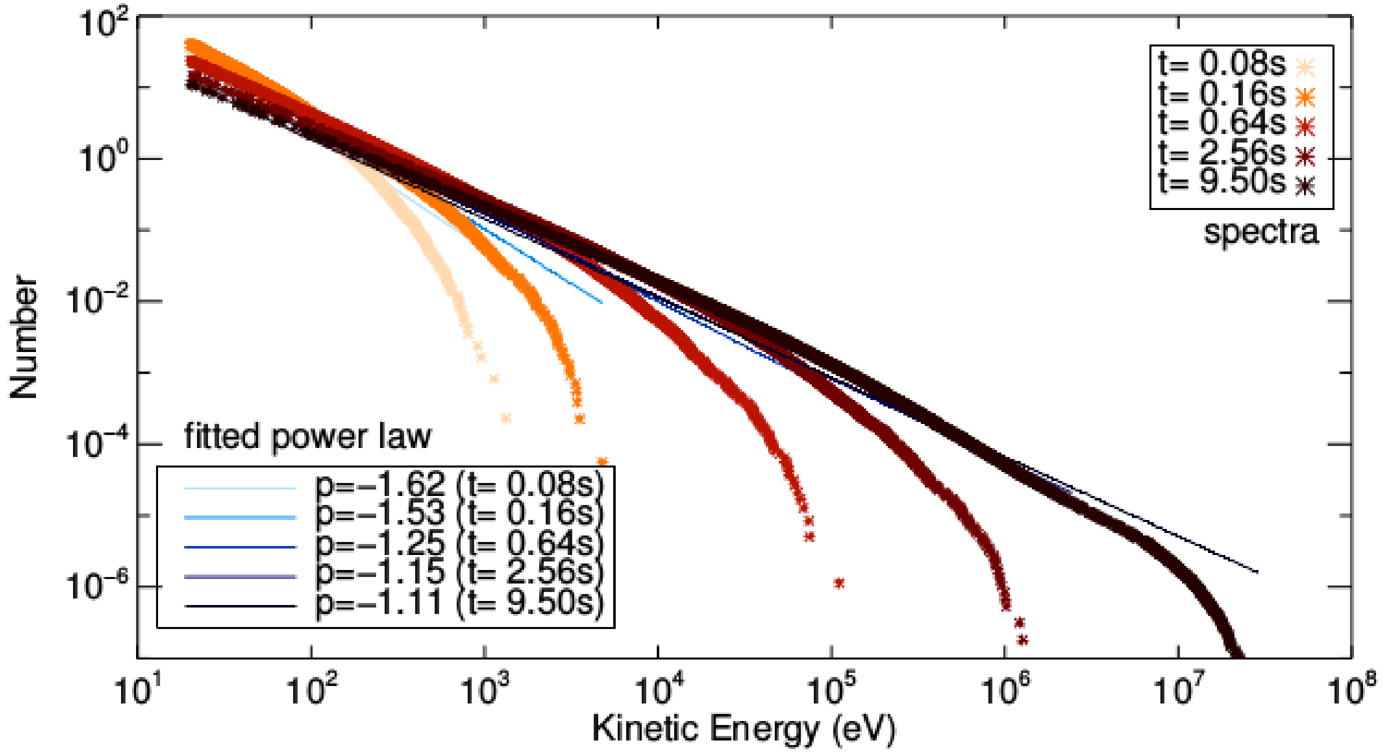
(b) Moderate and high $E_{||}$ regions

Statistical study: Evolution of particle power spectra

Electrons:



Protons:



Summary:

- First observationally driven 3D MHD “1:1” model of a full Active Region.

➡ Matches observation (3D structure of loop system in hot AR core & plasma flow dynamics).

➡ Ohmic (DC) heating from field-line braiding main contributor to the coronal heat input.
(rather slow “magnetic diffusion” than fast “nanoflares”)

➡ Model sufficiently describes the coronal heating mechanism
to explain a broad variety of coronal observations on the “real Sun”.

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to explain a broad variety of coronal observations on the “real Sun”.

More specific...?

=> Magnetic topology largely dominated by bipolar field, no sudden outbreaks or changes.

=> Heating and steady magnetic reconfiguration by “slow reconnection”.

=> Bulk plasma motion follows the raising field and leads to draining loop legs.

=> Particle acceleration by strong B-parallel electric fields yields up to MeV electrons.

“Dankeschön!”