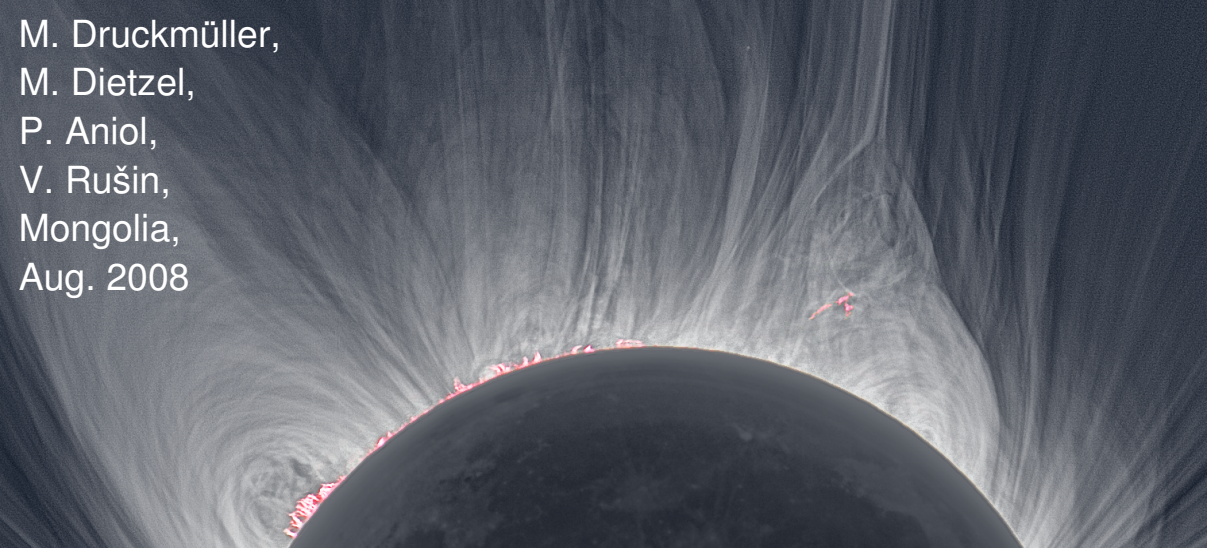

MAX-PLANCK-GESELLSCHAFT

MPS

SOLAR SYSTEM SCHOOL

Coronal loops above an active region observation versus model

Hinode-7, Takayama, 13.11.2013

Philippe-A. Bourdin[1,2], Sven Bingert[1], Hardi Peter[1]

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Overview:

* Model philosophy
* Scaling laws of coronal heating along field lines
* The transition region and coronal Doppler shifts riddle

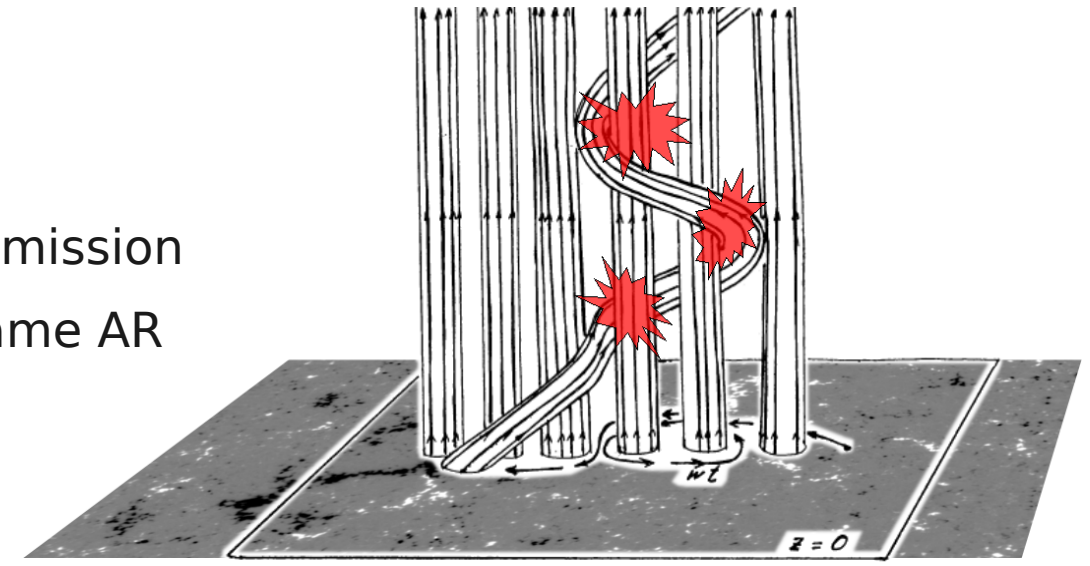
Model philosophy

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

1) Drive lower boundary with an observed Active Region,
   prescribe the photospheric magnetic field and horizontal velocities

2) Use 3D-MHD model to compute
   plasma properties in the corona
   $\{\ln T,\ \ln \rho,\ \vec{A},\ \vec{u}\}$

3) Direct comparison of synthetic emission
   to coronal observations of the same AR



(Parker, 1972, ApJ. 174, 499)

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

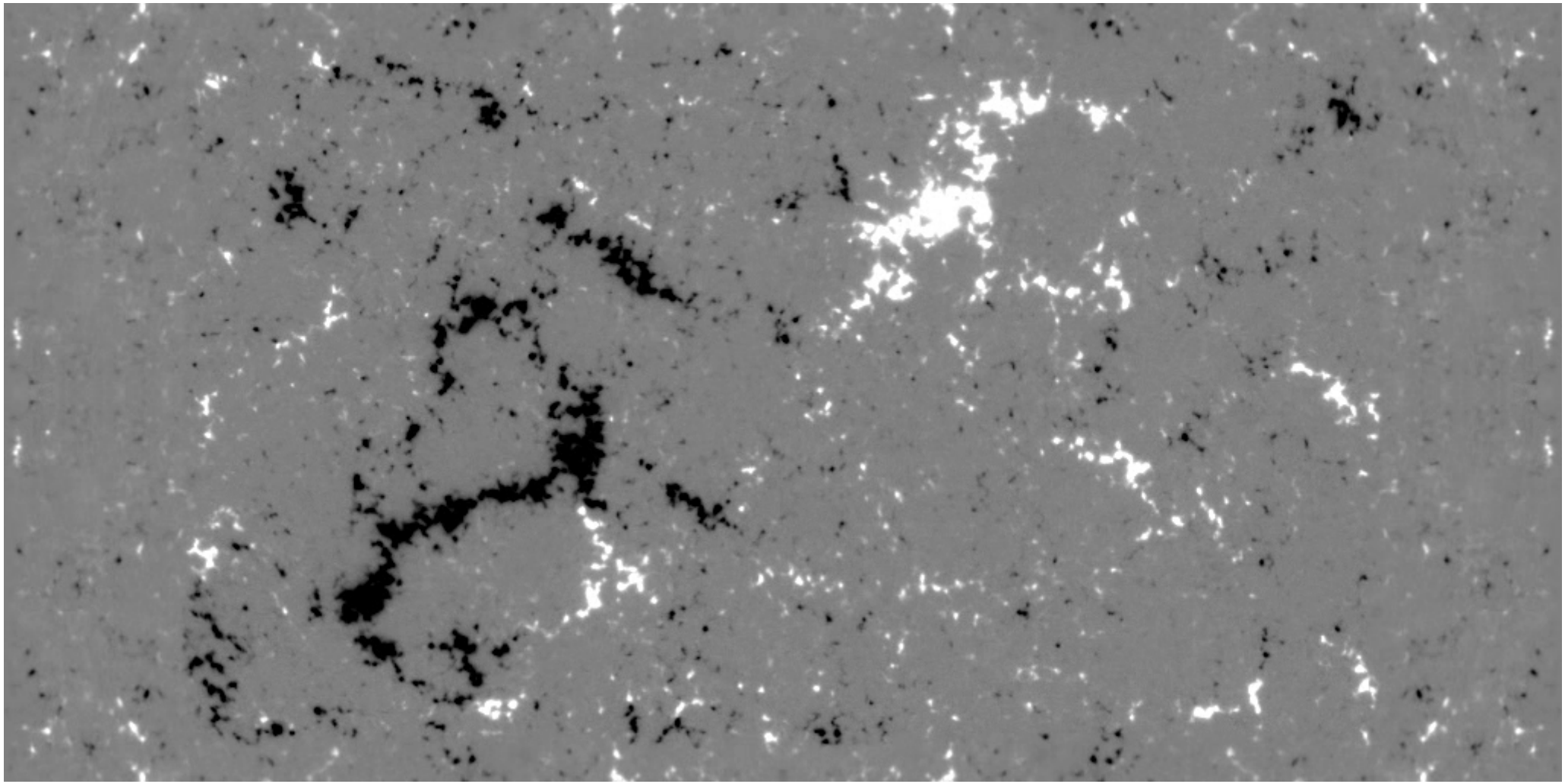
- Energy balance: $$\rho T \frac{D s}{Dt} = \mu_0 \eta \, \boldsymbol{j}^2 + \nabla \cdot \boldsymbol{q}_{Spitzer} - L_{rad} + 2 \rho \nu \, \boldsymbol{S} \odot \boldsymbol{S} + \zeta \rho \left(\nabla \cdot \boldsymbol{u} \right)^2$$

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

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

Model philosophy

LOS-magnetogram of an Active Region (bottom boundary condition)



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

Model philosophy

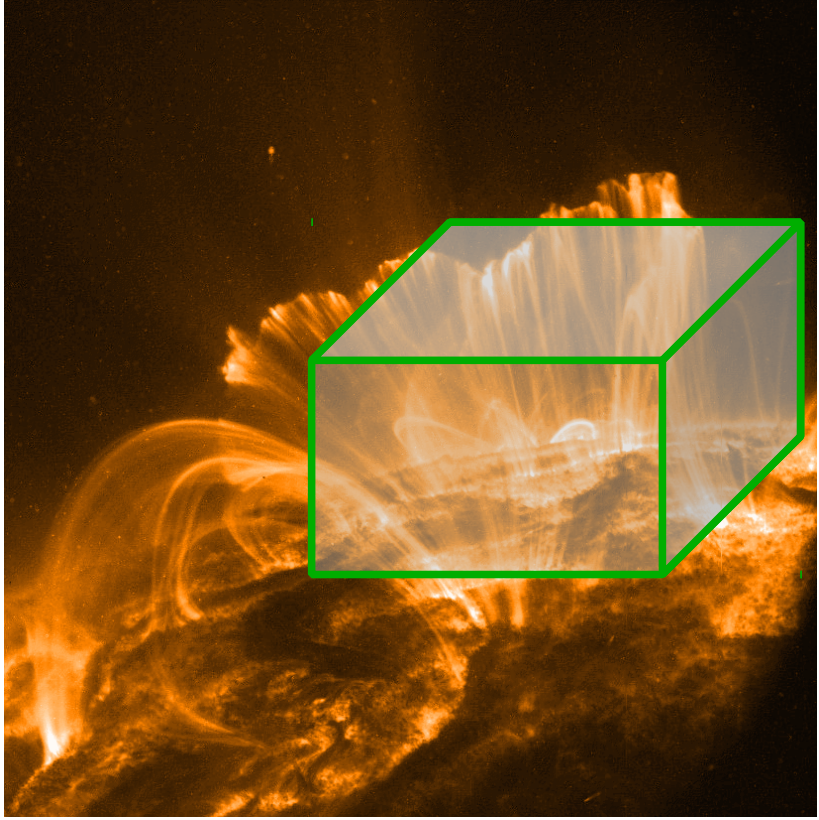
3D-MHD simulation:

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

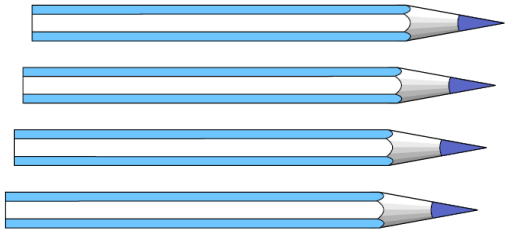
- High resolution grid: 1024*1024*256

➡ Horizontal: 230 km, matches observation

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



(TRACE observation in Fe-IX/-X)



The Pencil Code:

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

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

- High-performance computing:

Results: Synthetic emissivity

View from side: (integrated)

- Cool long peripheral loops
- Hot AR core loops

C IV @ 1584 Å and **Fe XII @ 195 Å**

O VI @ 1032 Å and **Fe XV @ 284 Å**

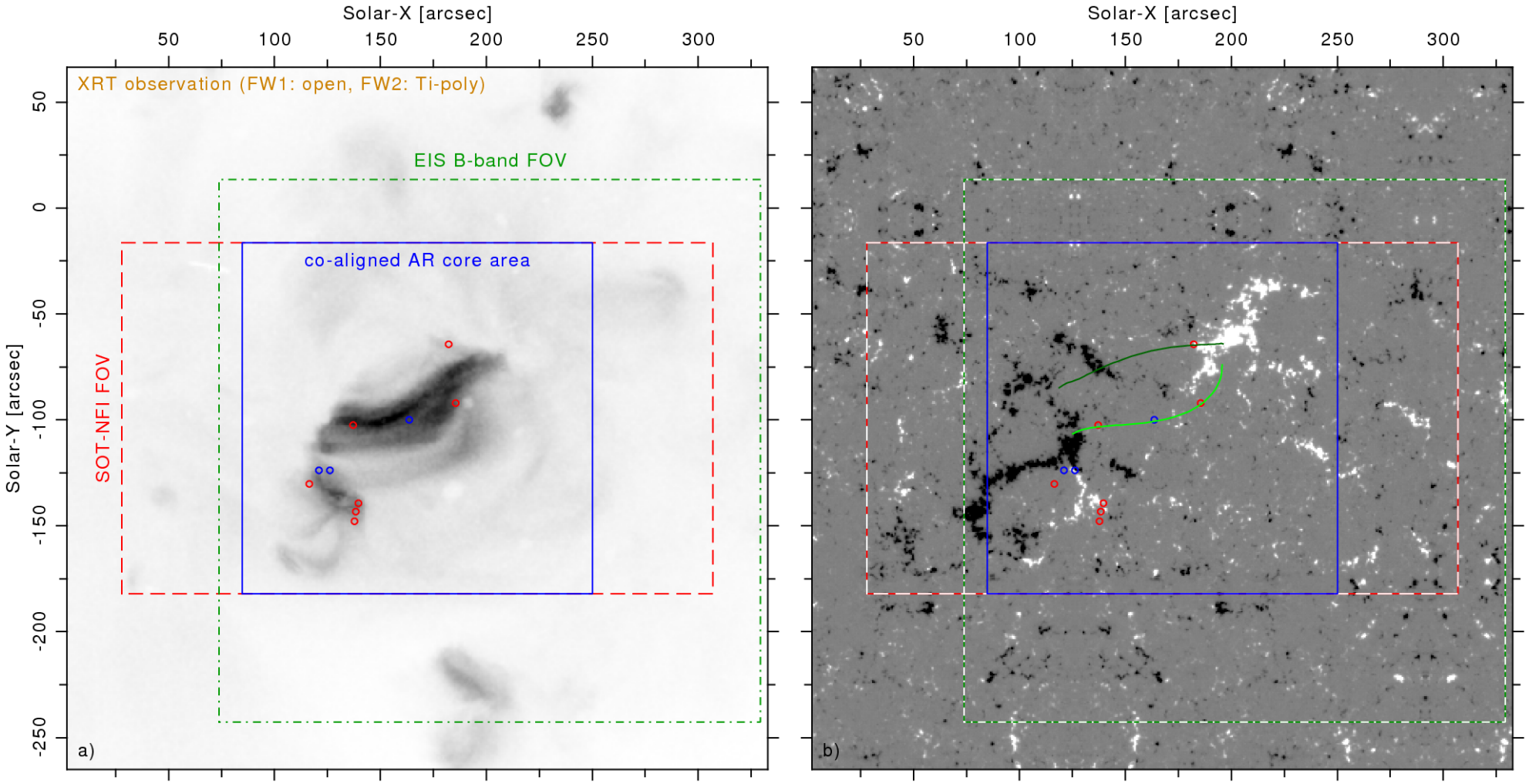
(IRIS provides some diagnostics)

Comparison to observations

Hinode XRT and SOT observations (vertical line-of-sight)

- X-ray emission (~1.5 MK)

- Photospheric magnetic field (AR+QS)

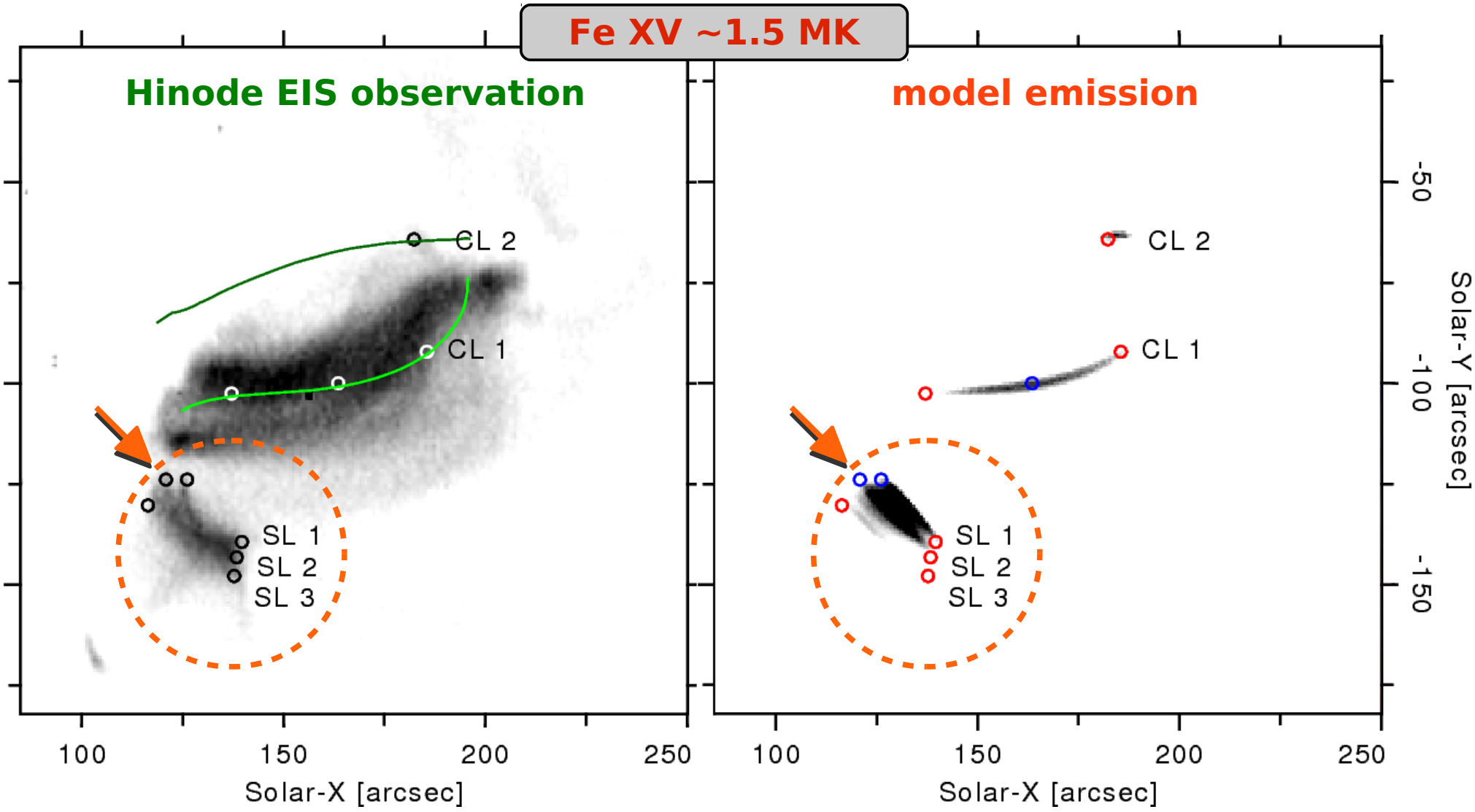


(Bourdin et al., A&A 555, A123, 2013)

Comparison of intensity

- Alignment accurate to 3 arcsec

Small loops SL 1-3 at same position

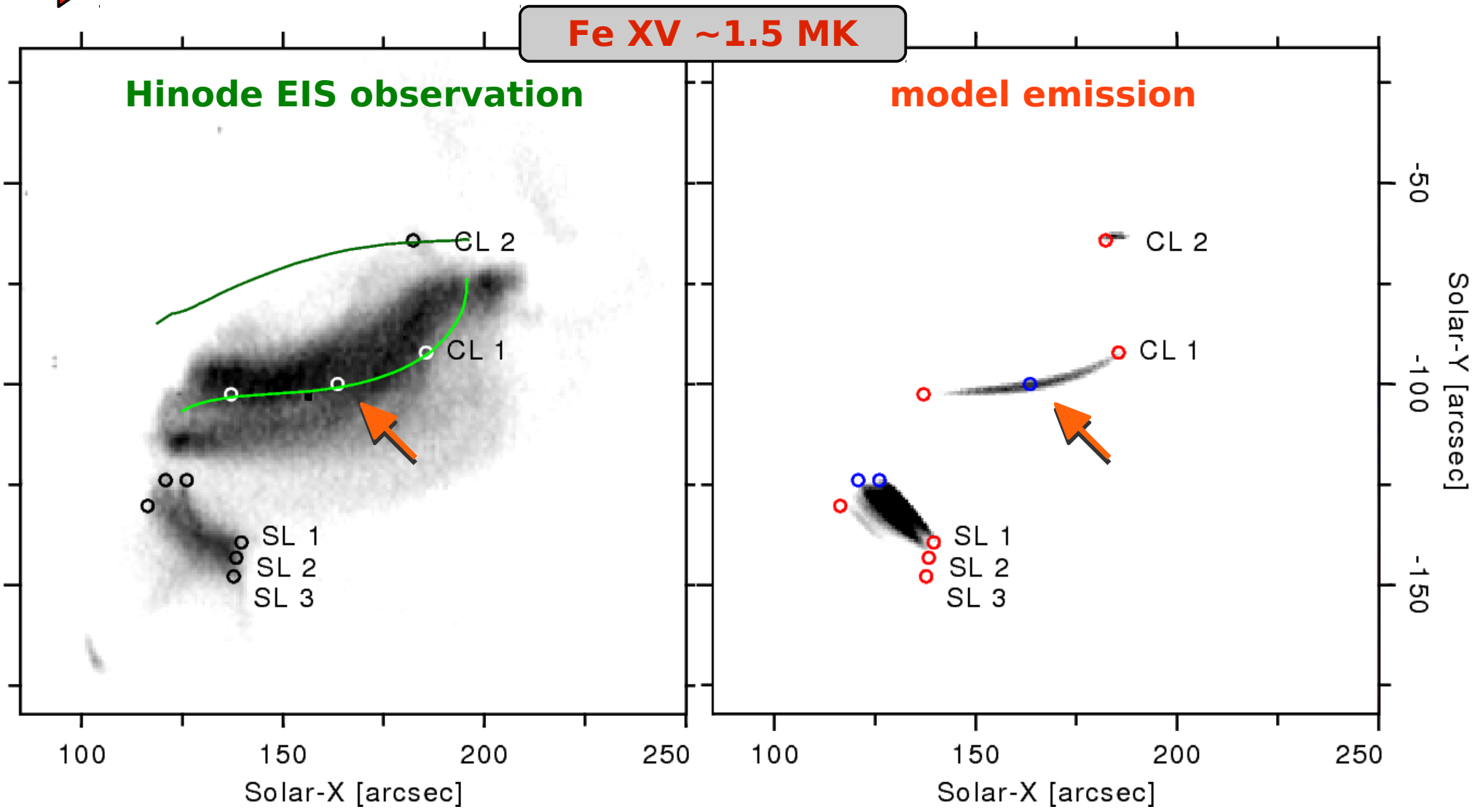


Comparison of intensity

- Alignment accurate to 3 arcsec

➡ Small loops SL 1-3 at same position

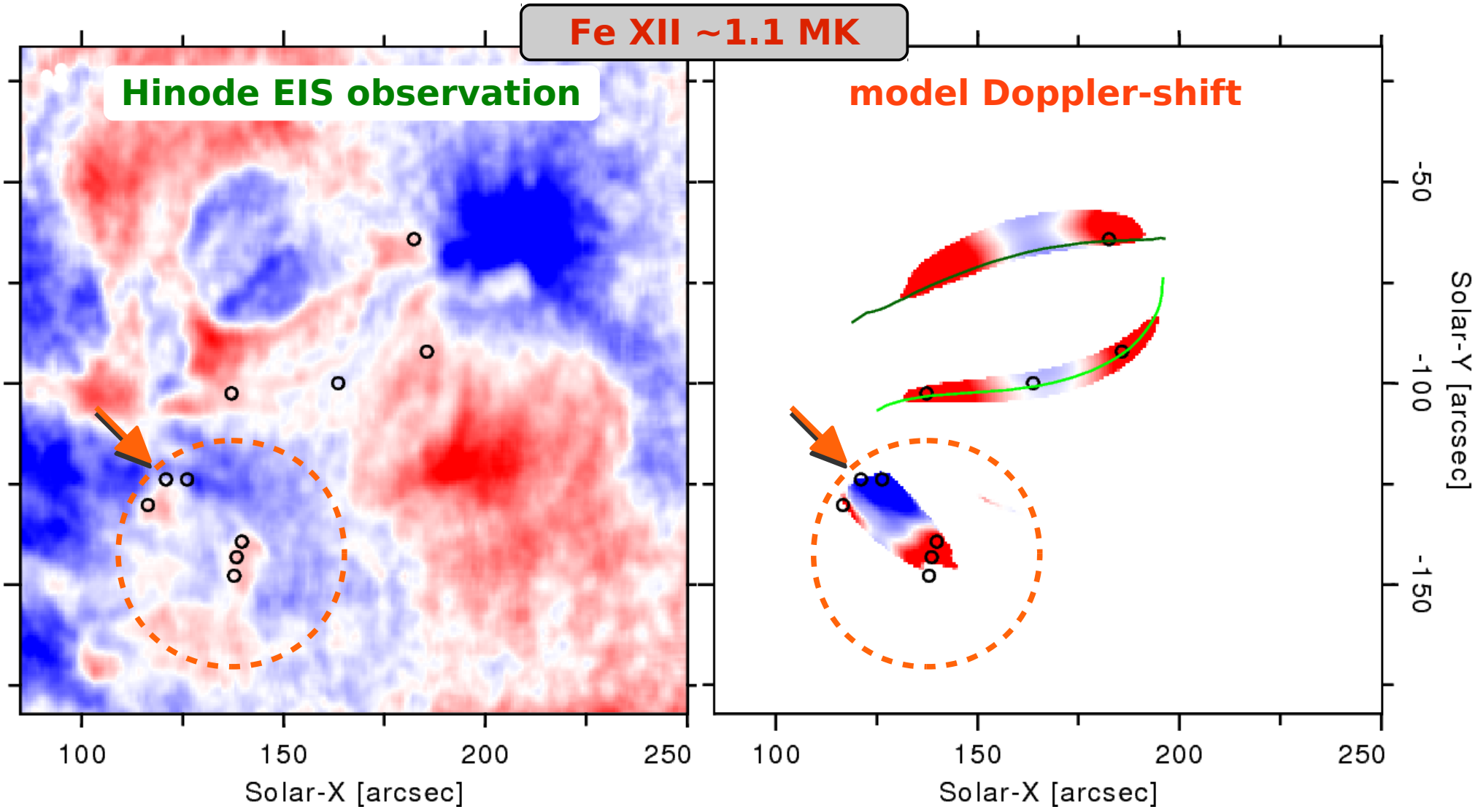
➡ AR core loop CL 1 has similar shape, but is still heating up in the model...



Hinode XRT and SOT observations (vertical line-of-sight)

Comparison of Doppler-shifts: ➡ Dynamics match!

(saturated at ±10 km/s)



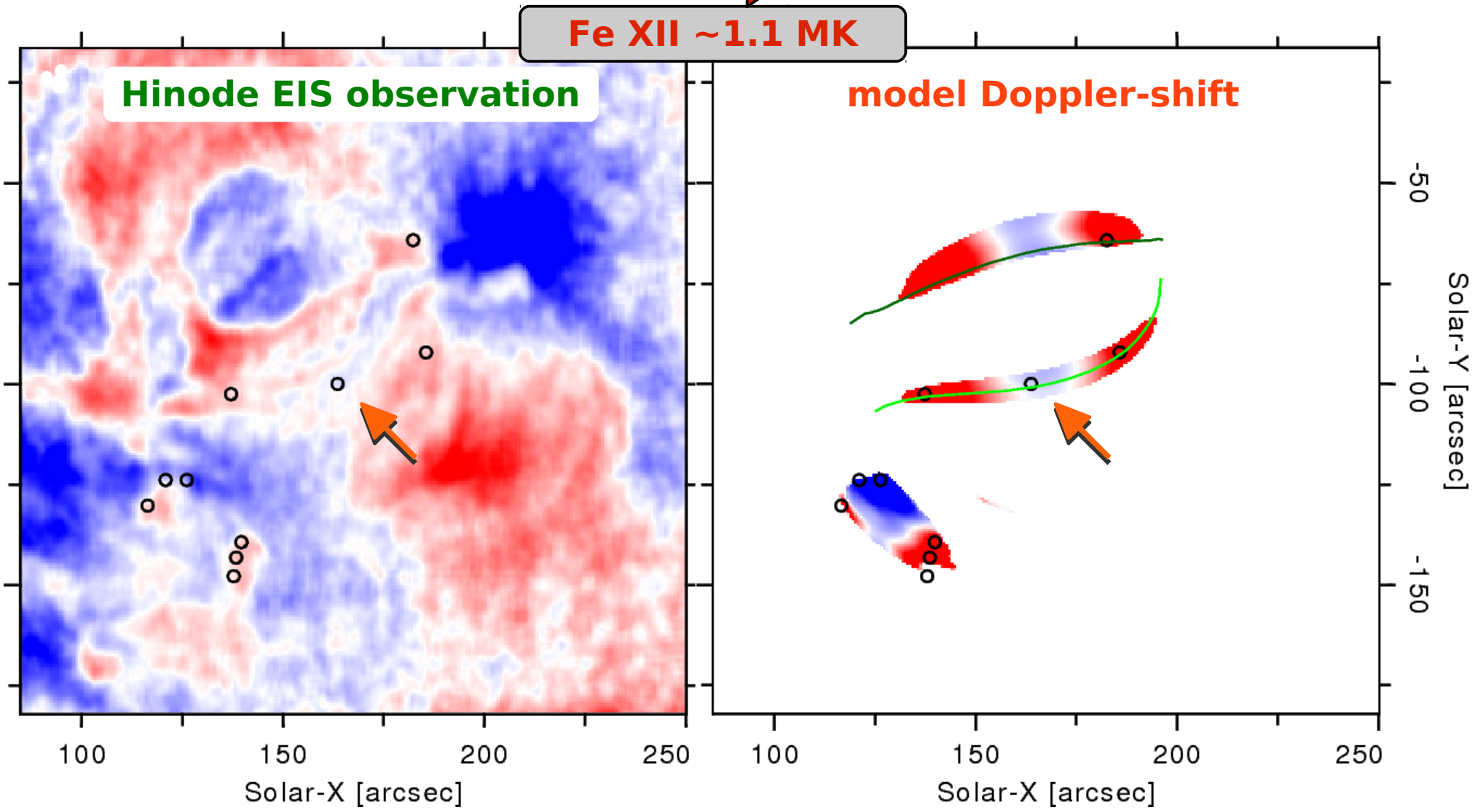
Hinode XRT and SOT observations (vertical line-of-sight)

Comparison of Doppler-shifts:

(saturated at ±10 km/s)

→ Dynamics match!

→ Loop top rises: 2 km/s (Solanki, 2003)



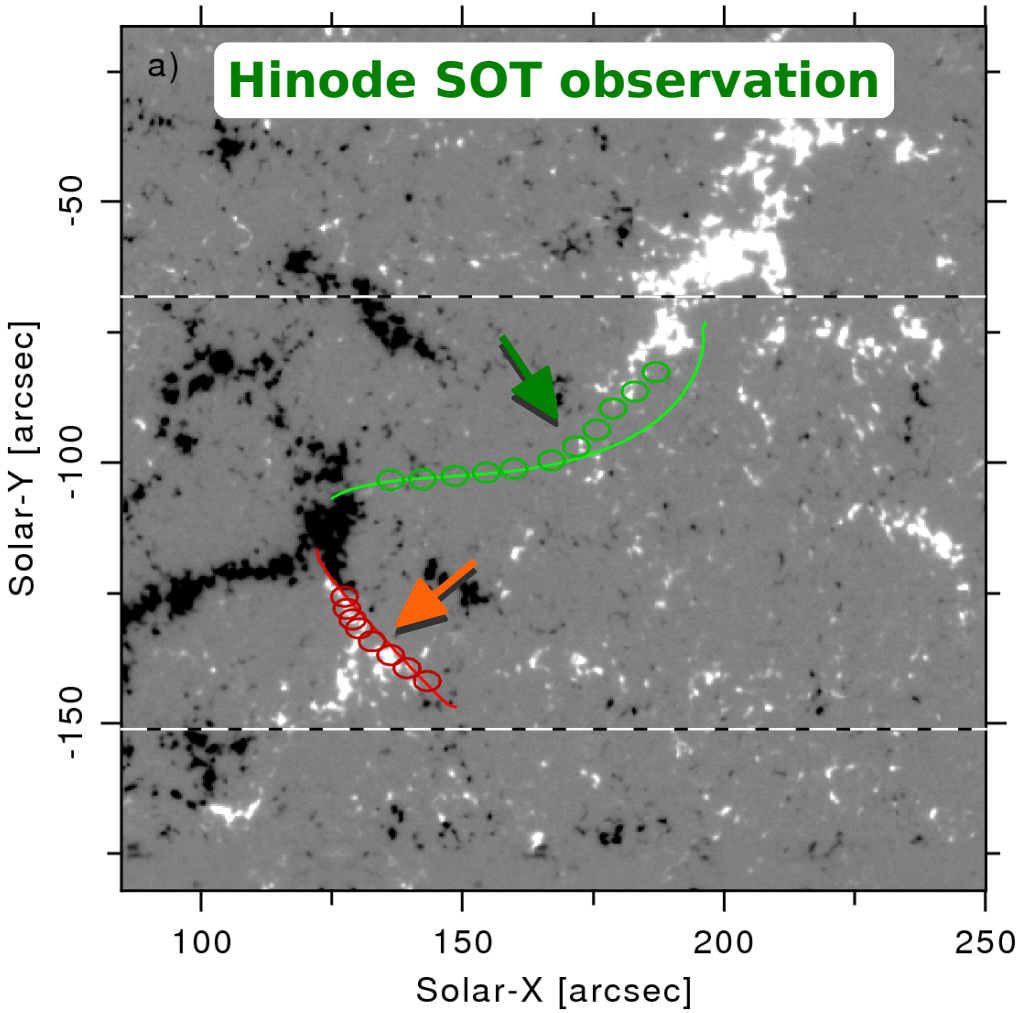
Stereo 3D reconstruction

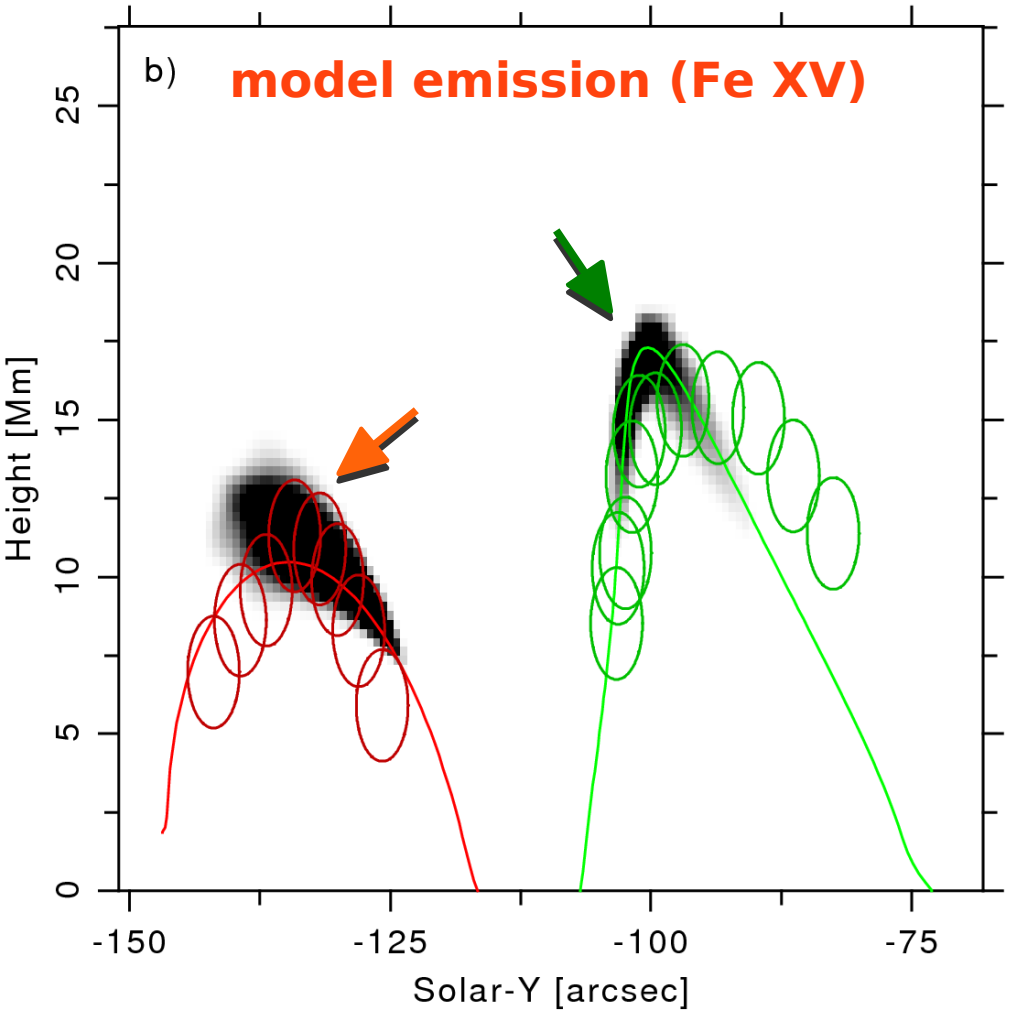
Vertical view from top:

(with reconstruction and field lines)

Horizontal view in the y-direction:

Height of coronal loops is realistic





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

Scaling laws – Model vs. Theory

Rosner, Tucker, Viana (RTV, 1978):

$$T_{RTV} \sim F_{Ohm}^{2/7} L^{2/7}$$

$$F_{Ohm} = \int_0^L H_{Ohm}(s) \cdot ds$$

$$n_{RTV} \sim F_{RTV}^{4/7} L^{-3/7}$$

Serio et al. (1981):

$$T_{Serio} \sim F_{Ohm}^{2/7} L^{2/7} \cdot E_T^{5/7}$$

$$E_T = \exp\left\{-0.04 \cdot L \left(\frac{2}{s_H} + \frac{1}{s_P} \right)\right\}$$

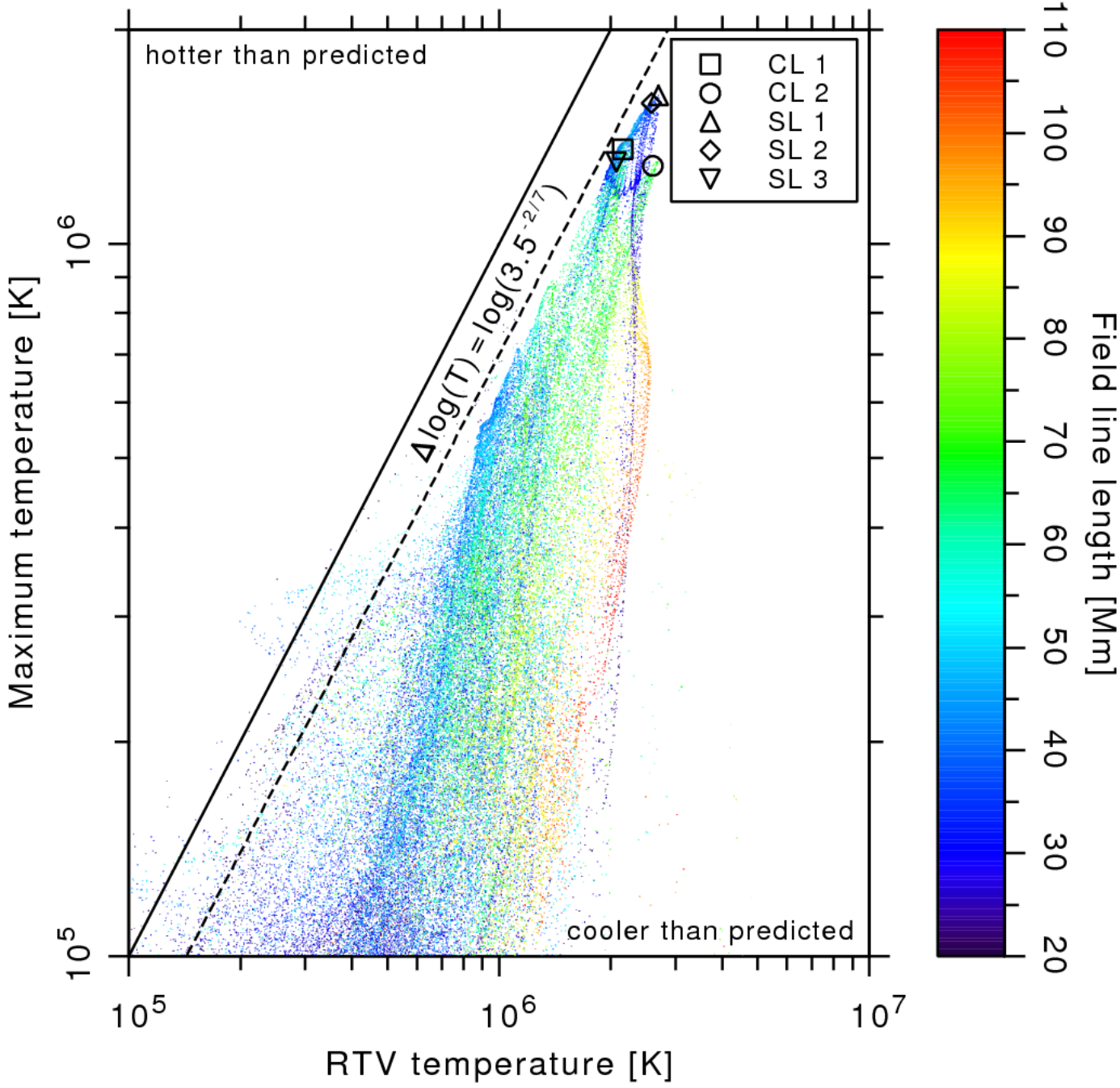
$$n_{Serio} \sim F_{RTV}^{4/7} L^{-3/7} \cdot E_T^{-1}$$

Scaling laws – Model vs. Theory

RTV temperature:

- Correction factor due to static equilibrium in 1D loop model fits better (c.f. Priest, 1982)

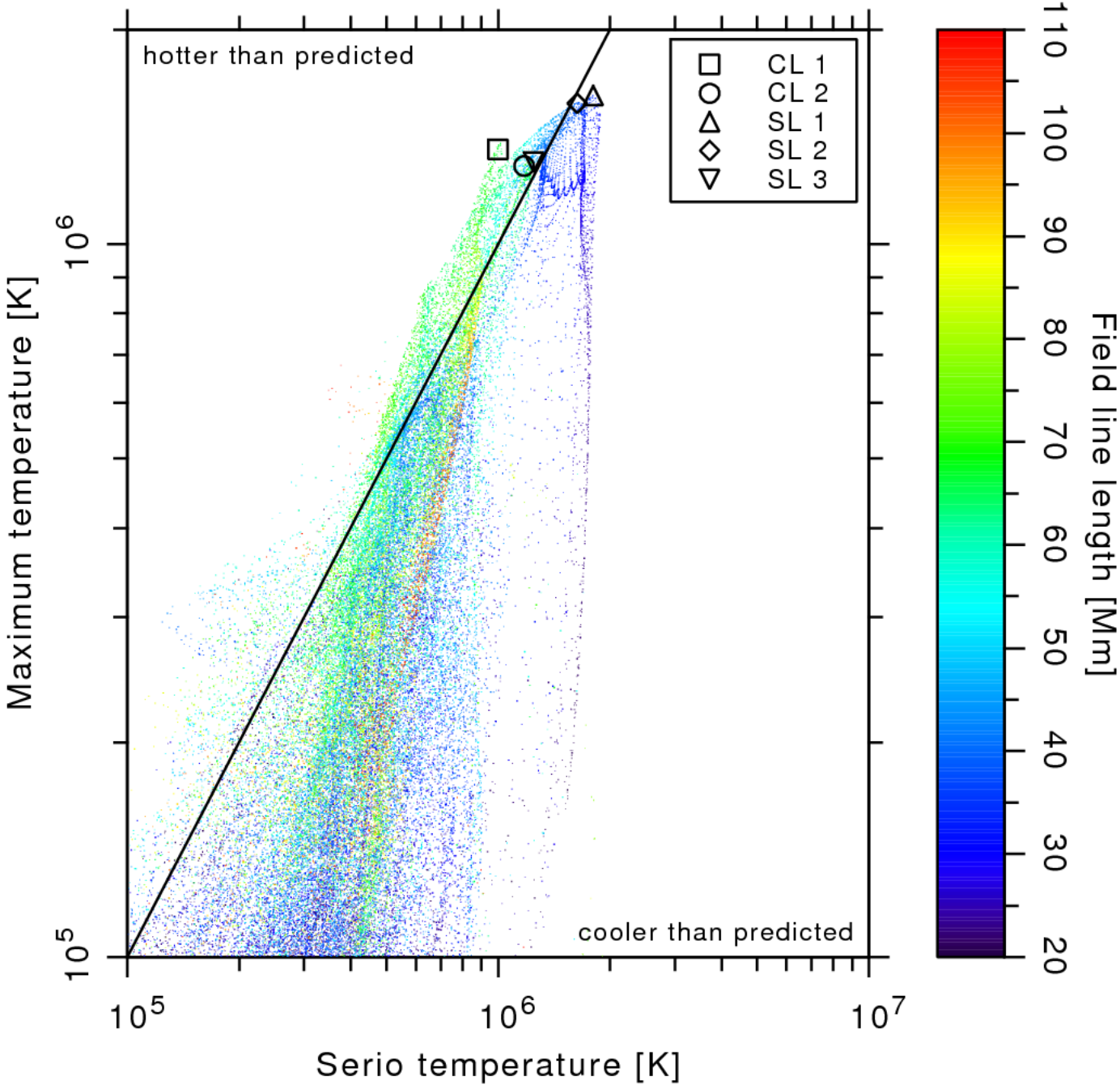
- Broad distribution, ordered by length



Scaling laws – Model vs. Theory

Serio temperature:

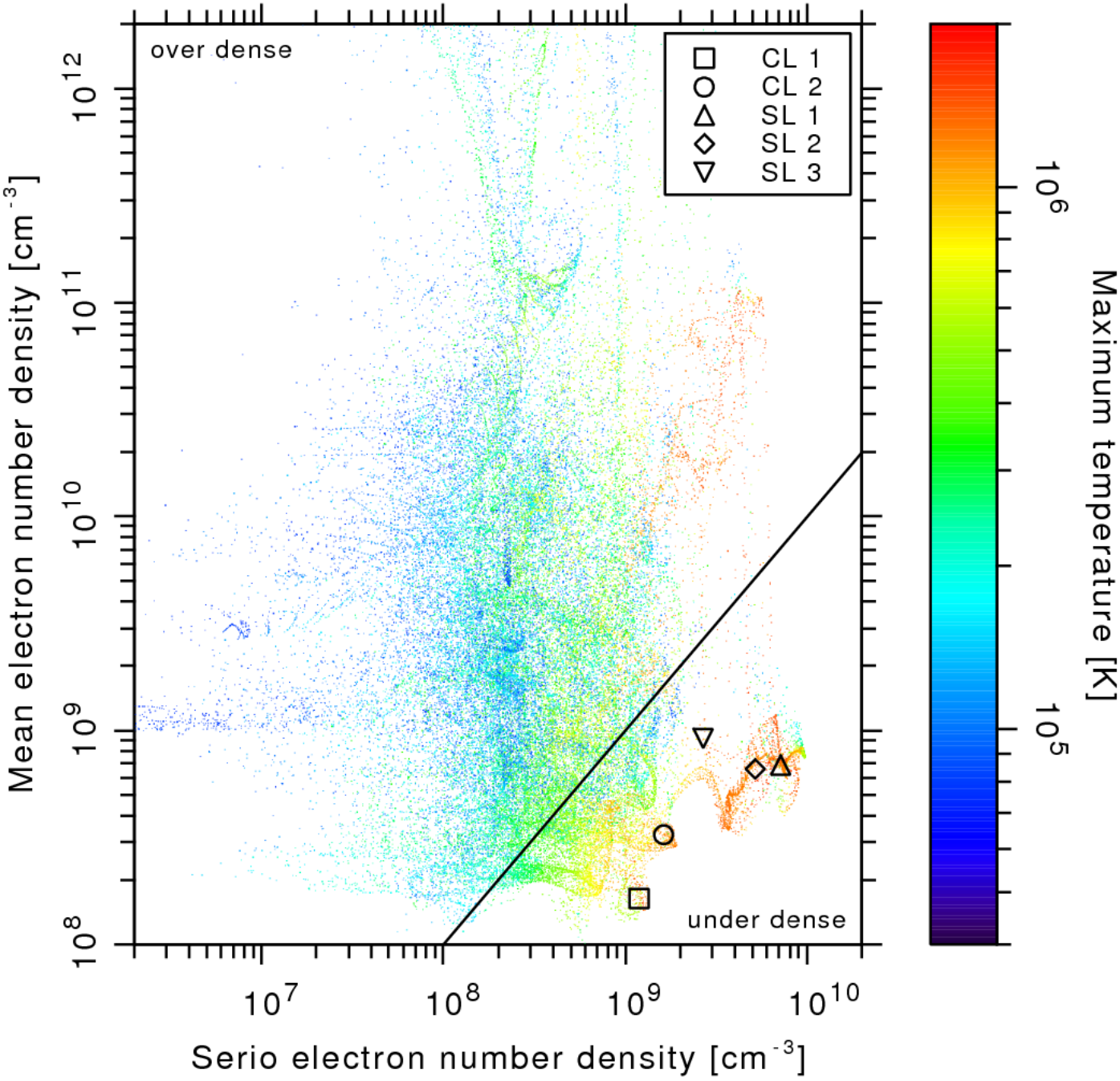
- Hot coronal loops mainly follow RTV and Serio scaling law trend
- Serio scaling law has narrower distribution



Scaling laws – Model vs. Theory

Serio density:

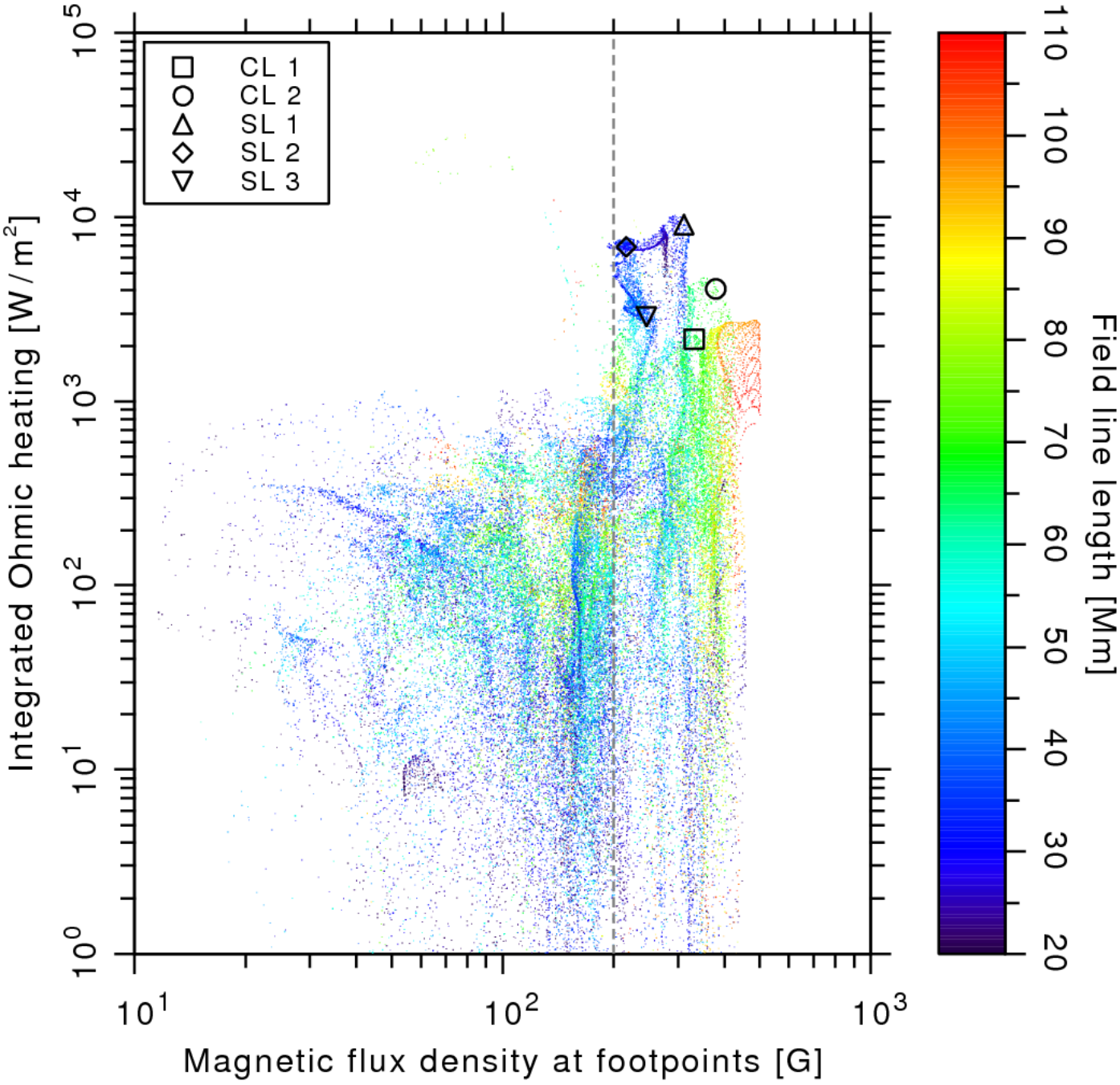
- Hot loops are "under dense" (Porter&Klimchuk, 1995, Yohkoh)
- Cooler loops are "over dense" (Aschwanden et al., 1999)



Scaling laws – Model vs. Theory

Magnetic flux:

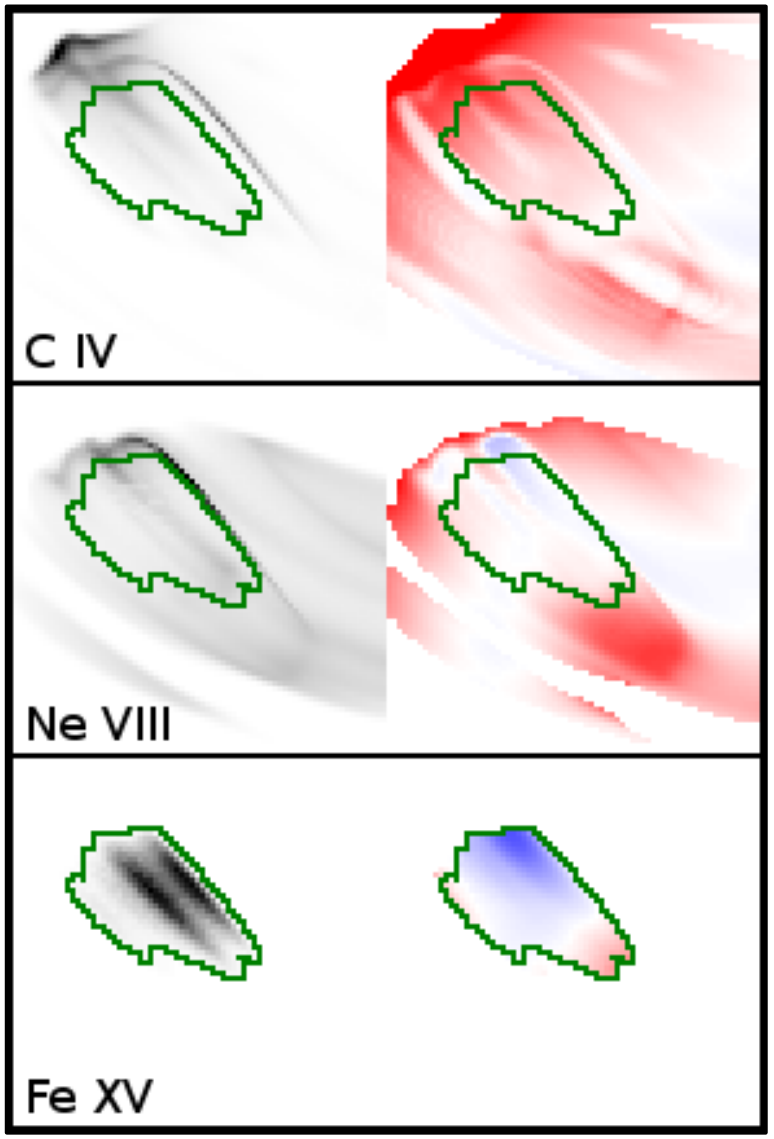
High Ohmic heating requires minimum magnetic flux at footpoints



Statistical Doppler-shift analysis – Observation vs. Model

Statistical Doppler-shift analysis – Observation vs. Model

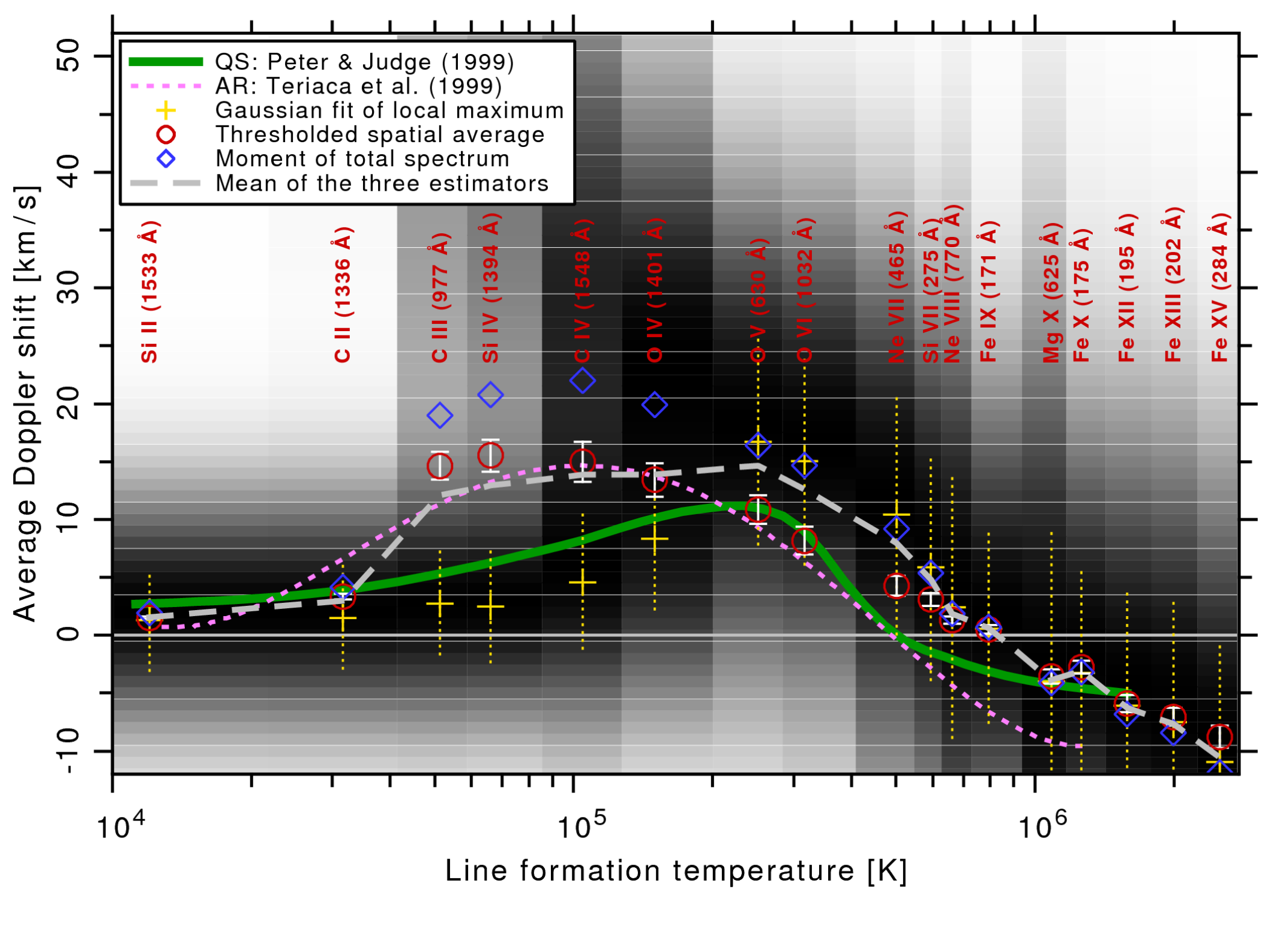
Intensity: Doppler shift: Line formation Temperature:



~ 100'000 K

~ 700'000 K

~ 1'500'000 K


QS: Peter & Judge (1999)
AR: Teriaca et al. (1999)
Gaussian fit of local maximum
Thresholded spatial average
Moment of total spectrum
Mean of the three estimators
Si II (1533 Å)
C II (1336 Å)
C III (977 Å)
Si IV (1394 Å)
C IV (1548 Å)
O IV (1401 Å)
O V (630 Å)
O VI (1032 Å)
Ne VII (465 Å)
Si VII (275 Å),
Ne VIII (770 Å)
Fe IX (171 Å)
Mg X (625 Å)
Fe X (175 Å)
Fe XII (195 Å)
Fe XIII (202 Å)
Fe XV (284 Å)
Average Doppler shift [km/s]
50
40
30
20
10
0
-10
10^4
10^5
10^6
Line formation temperature [K]

Summary:

- First observationally driven 3D MHD simulation of a full Active Region.

➡ Thin current structures in the corona produce thin emissivity structures.

➡ Ohmic heating dominates over viscous heating (in the corona).

- Synthesized emission of hot AR core loops matches real observation.

- Plasma flow dynamics within coronal loops are reproduced.

➡ Corona is heated by Ohmic dissipation of currents that are induced by magnetic foot-point motions in the photosphere.

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

有り難うございます