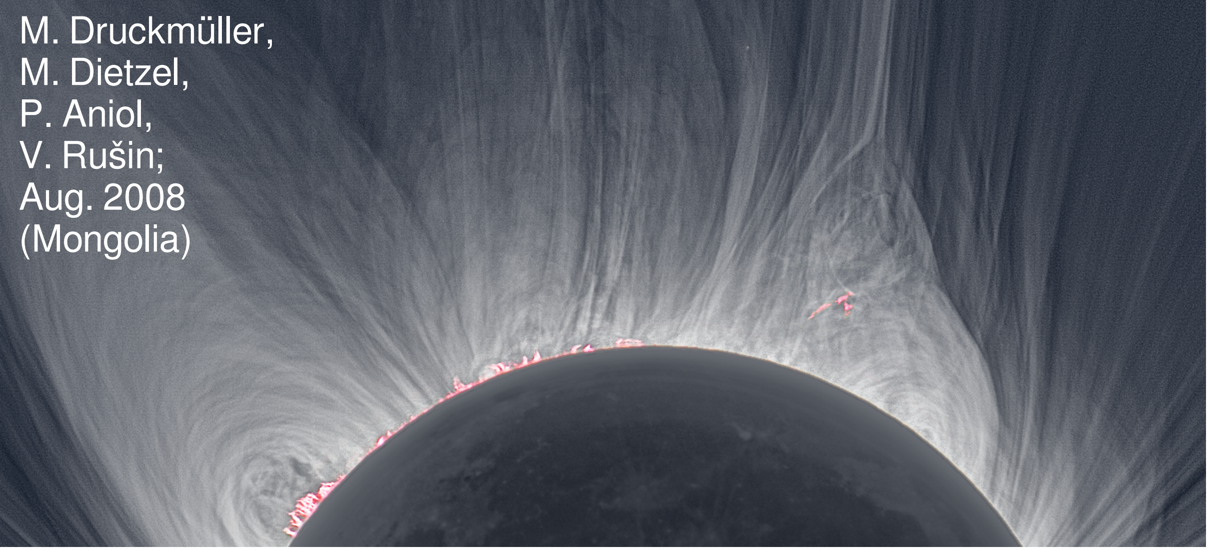


Hinode and the Coronal heating problem
An active region on the Sun

(Carpați workshop, Bâlea Lac, 15. September 2015)

Philippe-A. Bourdin
Institute for Space Research of the Austrian Academy of Sciences, Graz/Austria
phone: +43-316-4120-592, email: Philippe.Bourdin@oeaw.ac.at

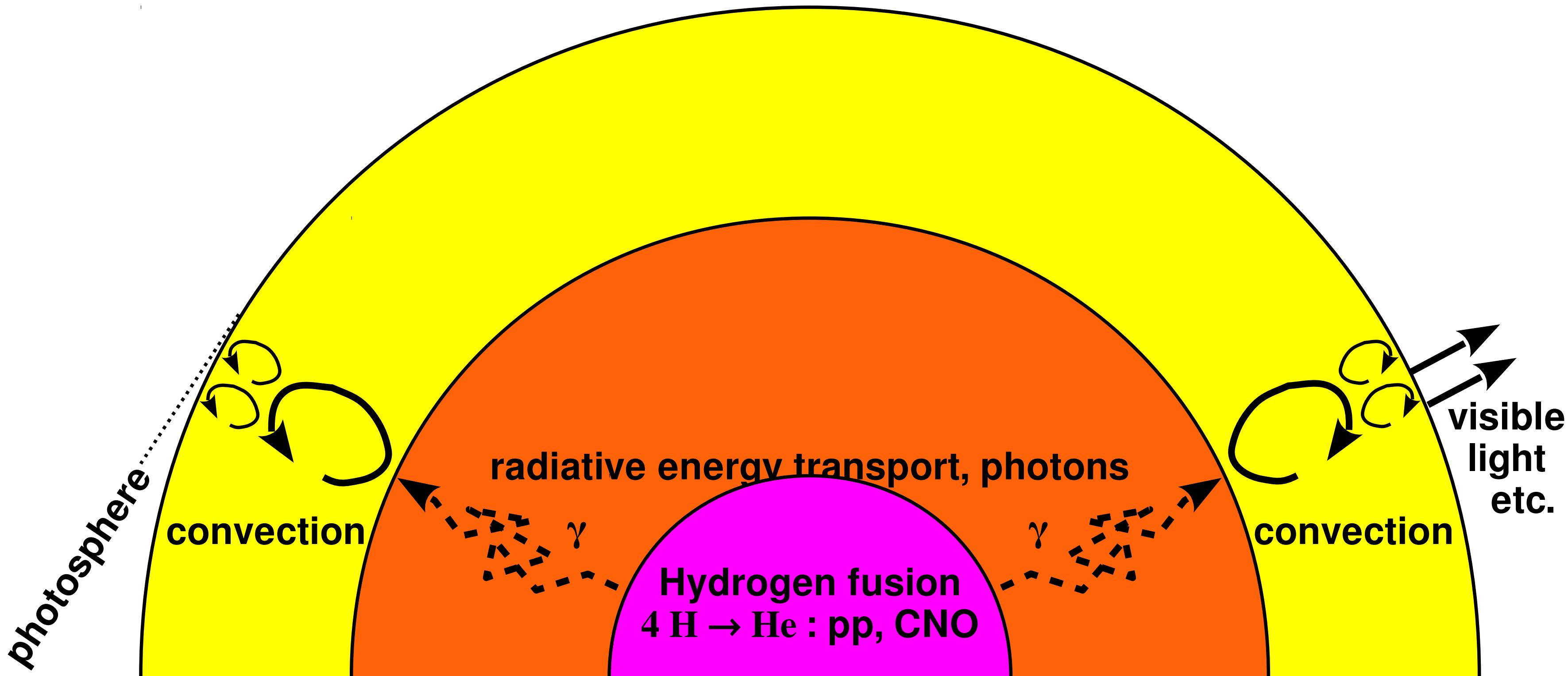
Overview:

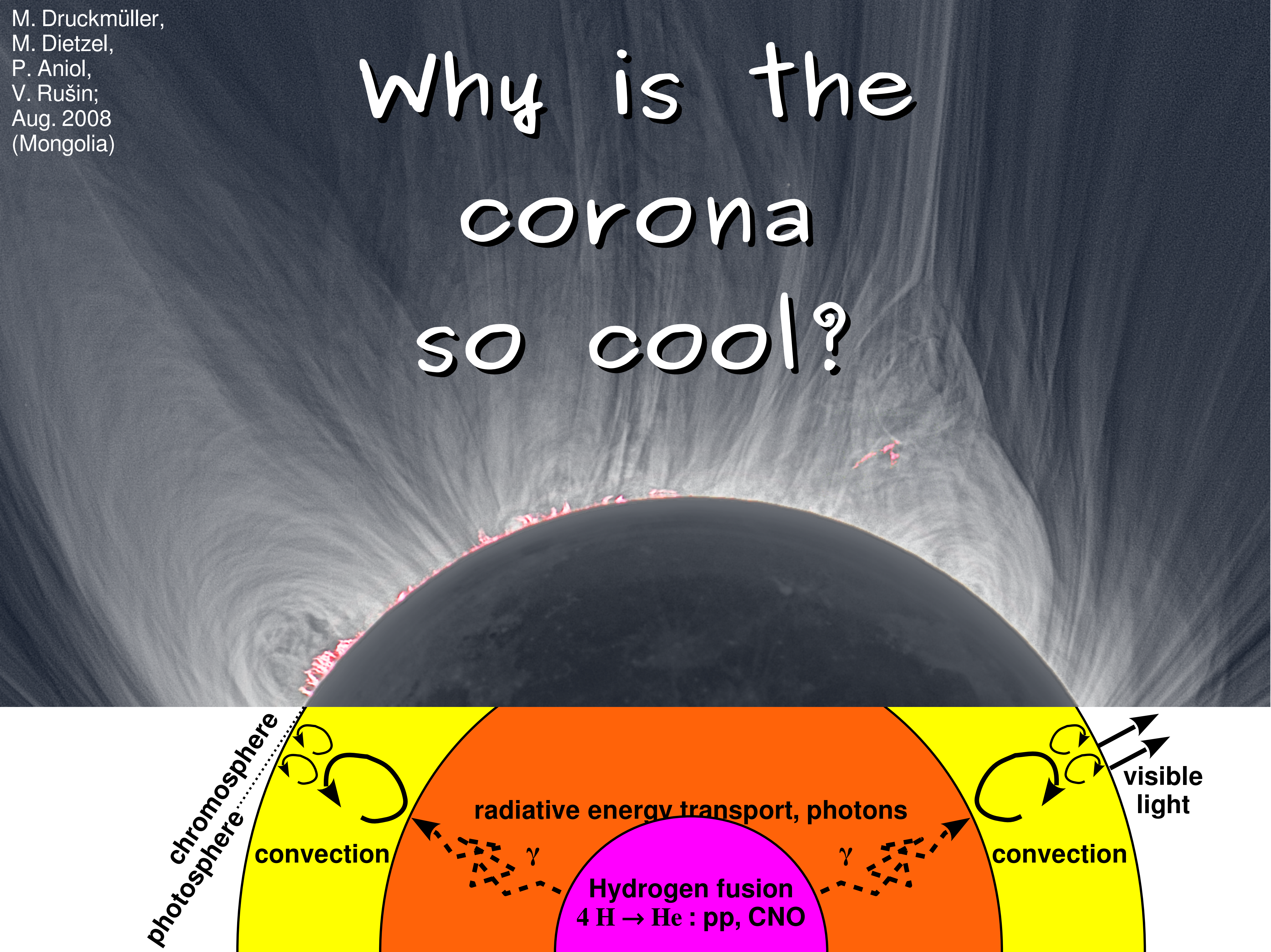
* What actually is the coronal heating problem...?
* What is needed to solve it...?
* What can we omit...?
* How do we compare to observations...?
* Where is still work to do...?

What actually is the coronal heating problem...?

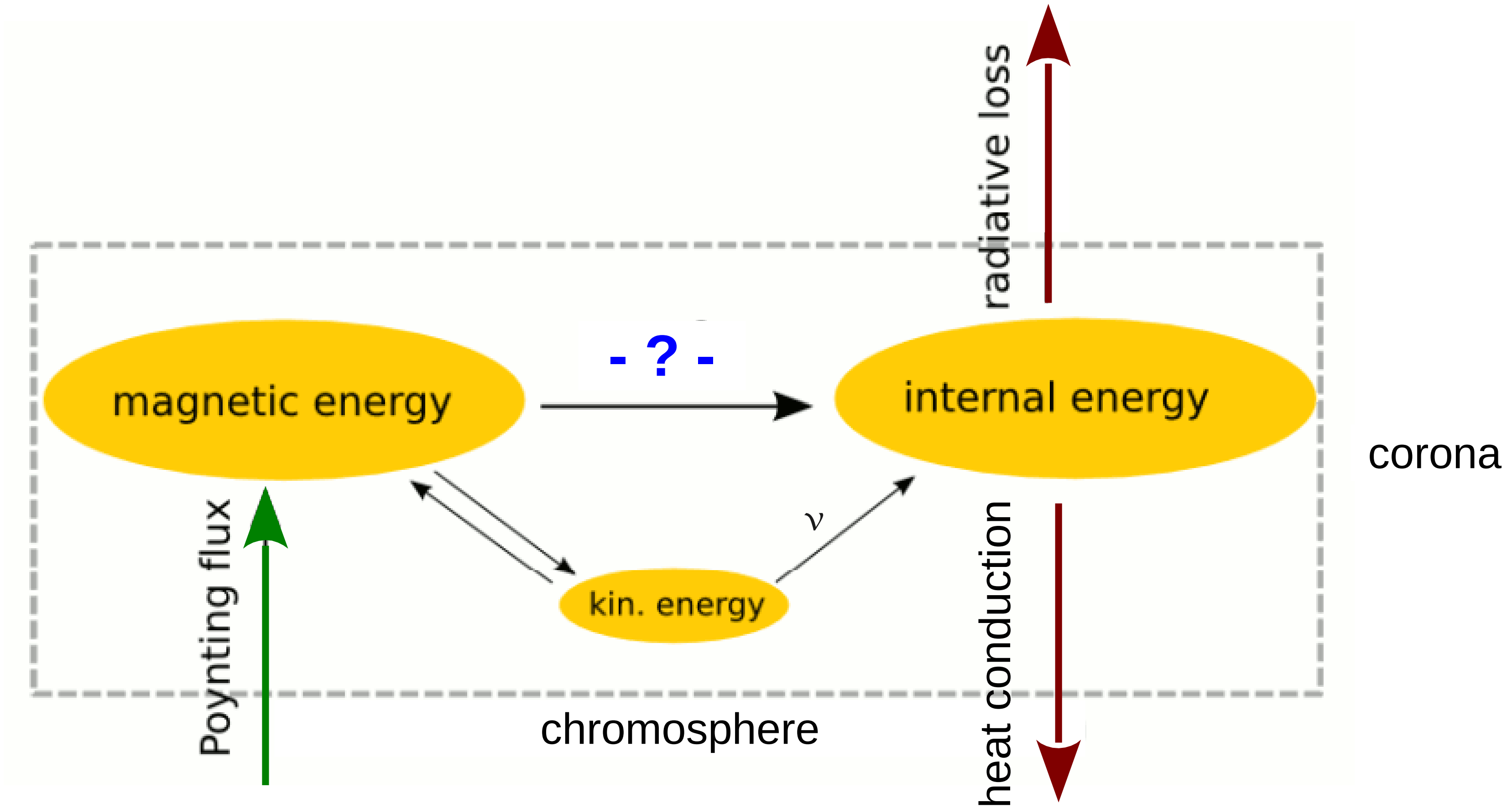
Sun: ⊙ spectral class G
$M_\odot = 2 \cdot 10^{30}$ kg
$T_\odot = 6 \cdot 10^{3}$ K
surface energy flux ≈ 100'000 kW/m^2
$R_\odot$ = 700 Mm ≈ ¼ ° ≈ R●

Corona:
$M_{cor} \approx 1 \cdot 10^{28}$ kg
$T_{cor} \approx 2 \cdot 10^{6}$ K
required energy input ≈ 0.1-1 kW/m^2
⇒ coronal energy dissipation ≈ 0.2 %



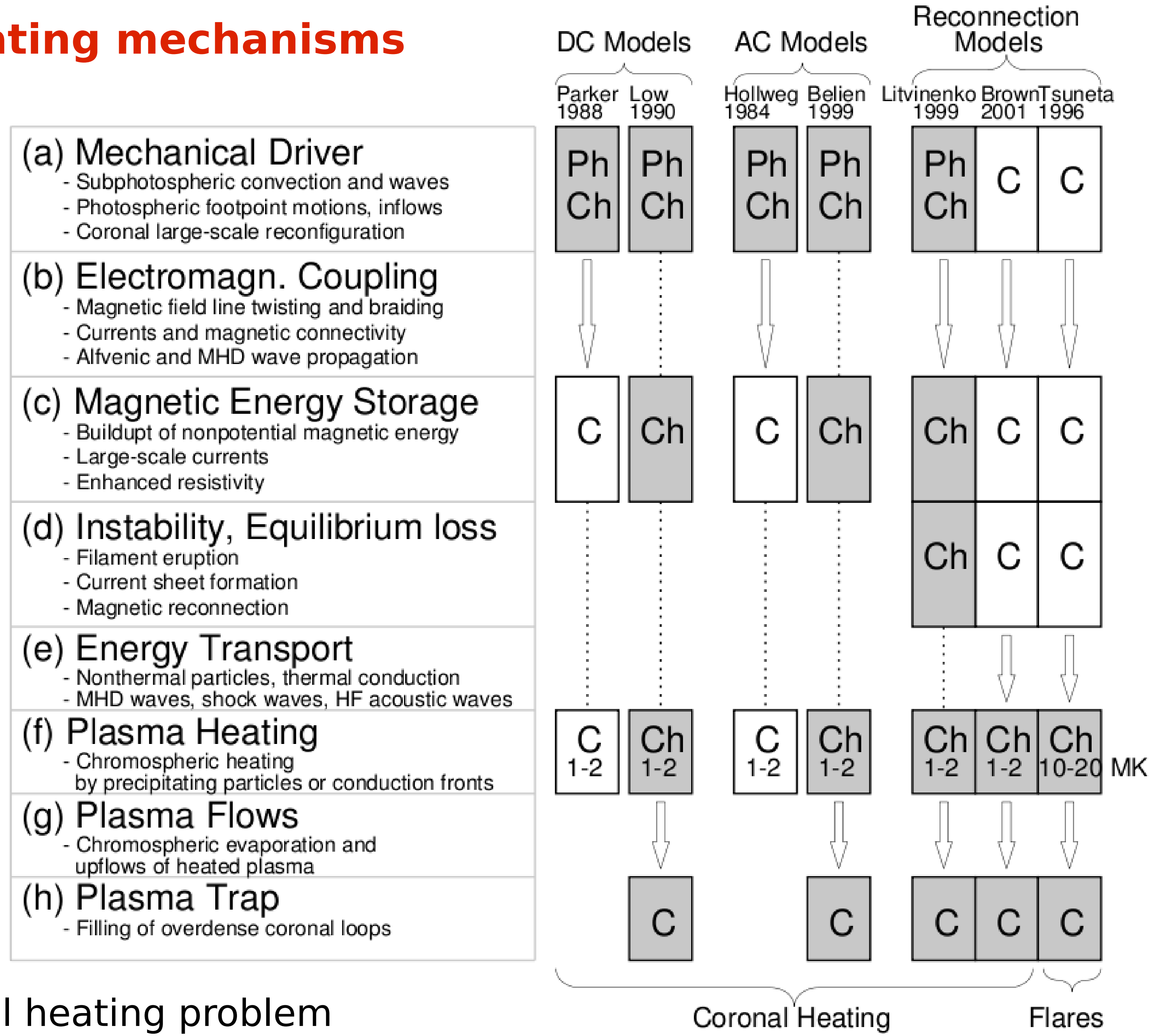

M. Druckmüller,
M. Dietzel,
P. Aniol,
V. Rušin;
Aug. 2008
(Mongolia)
Why is the
corona
so cool?
chromosphere
photosphere
convection
radiative energy transport, photons
γ
γ
convection
visible
light
Hydrogen fusion
4 H → He : pp, CNO

Sketch of the coronal energy conversion processes:



(Bingert, PhD thesis, 2009)

Coronal heating mechanisms

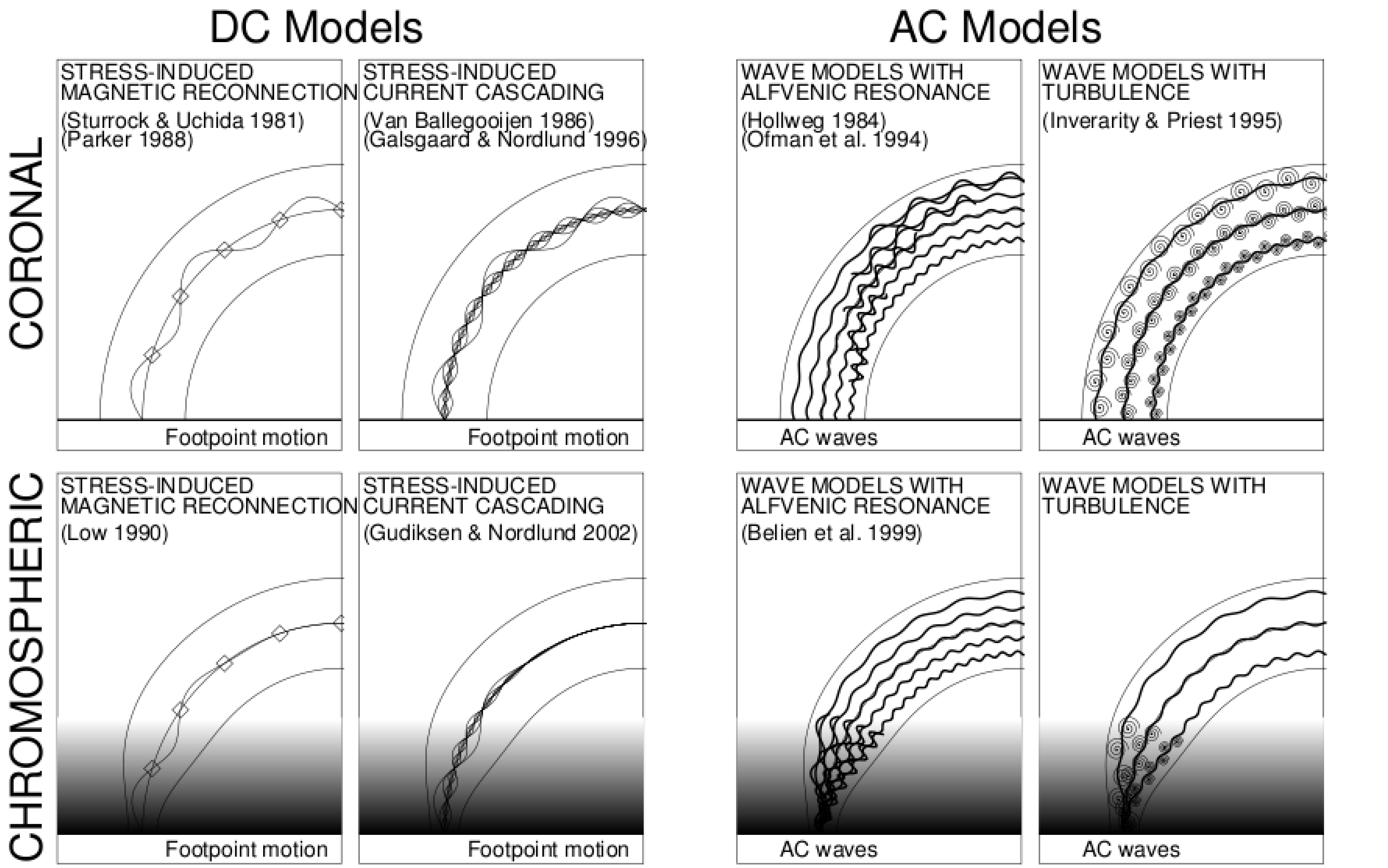


the coronal heating problem

does **not** end at **(e)**

(Aschwanden, text book, 2002)

Coronal heating mechanisms



(Aschwanden, text book, 2002)

Where are we now...?

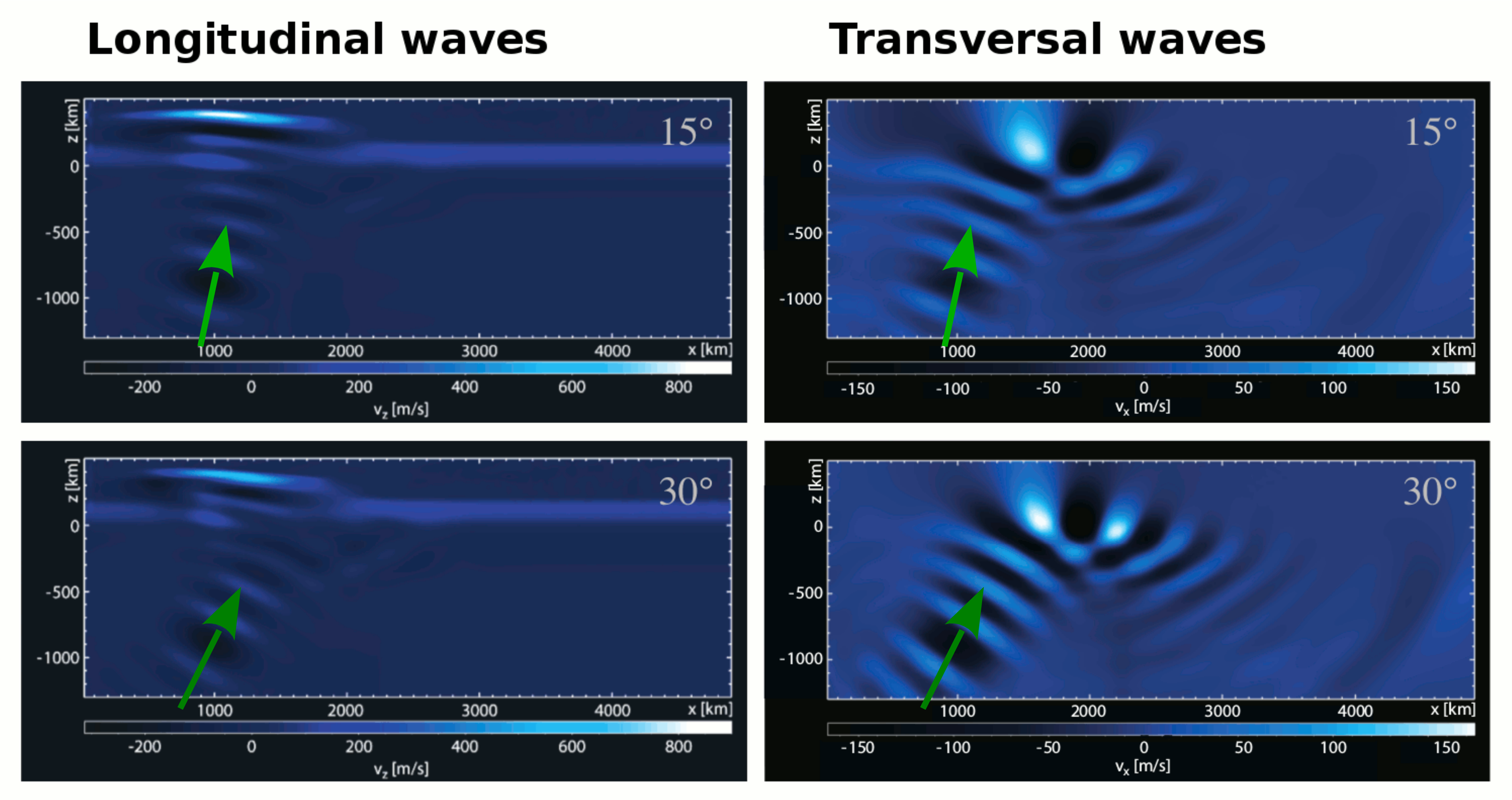
Where are we now...?

- AC heating due to waves from photosphere => unlikely

Coronal heating mechanisms

Alfvén waves from the solar interior:

➡ transversal waves reflected back at density gradient

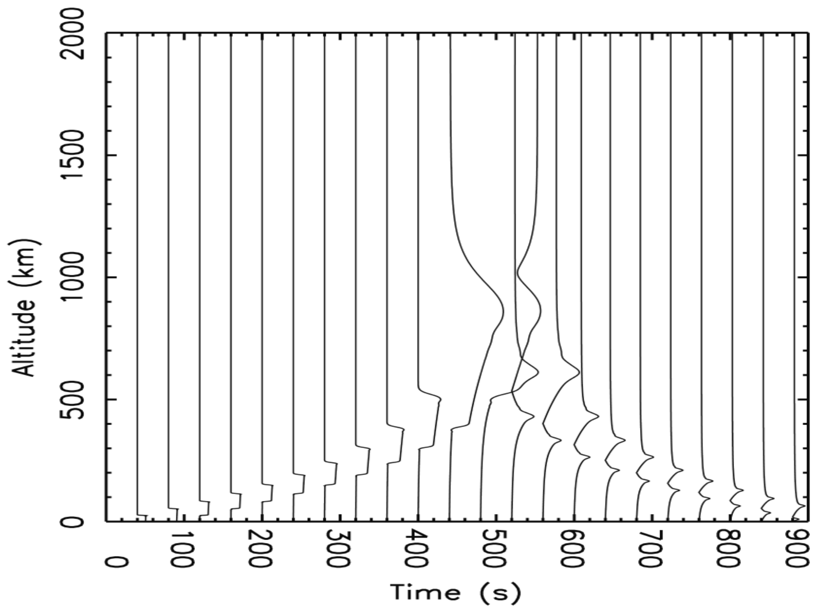


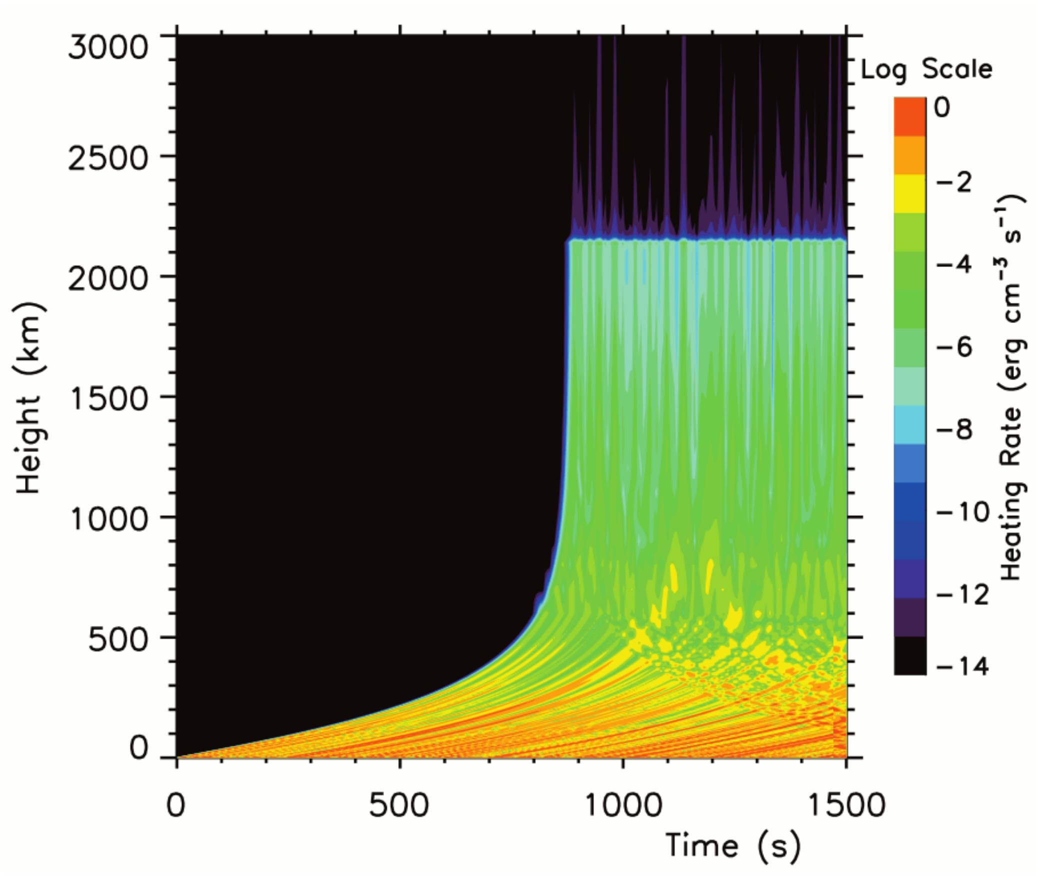
(Nutto et al., ESPM-12 poster, 2008)

Coronal heating mechanisms

Alfvén waves from the chromosphere:

most power reflected back to the chromosphere at the transition region





(Tu & Song, ApJ 777:53, 2013)

Where are we now...?

- AC heating due to waves from photosphere => unlikely

- AC heating due to coronal fast reconnection events => unlikely

Where are we now...?

- AC heating due to waves from photosphere => unlikely

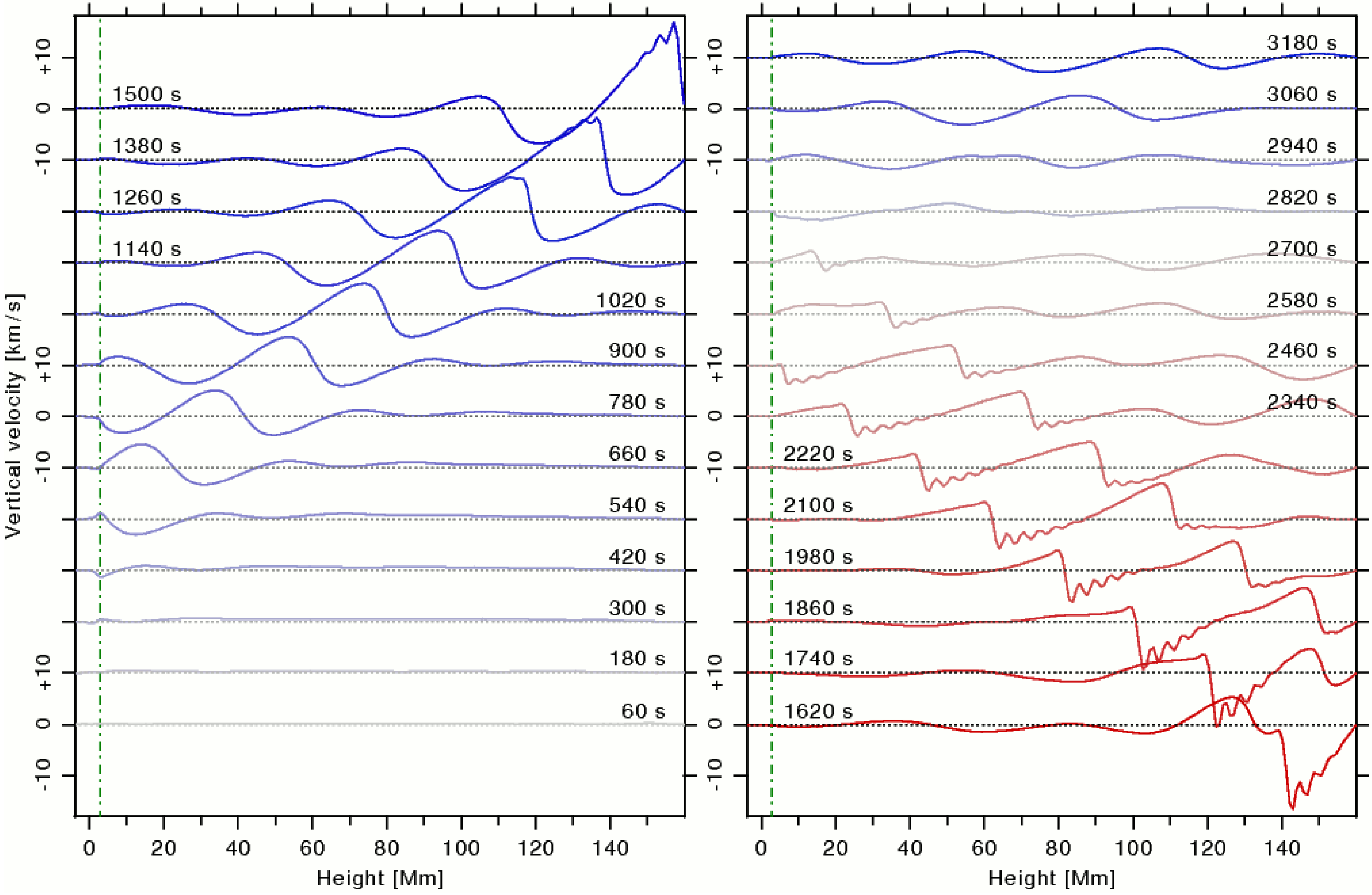
- AC heating due to coronal fast reconnection events => unlikely

- Shock waves from photosphere => unlikely

Coronal heating mechanisms

Compressional shock waves crossing the corona:

shocks can lead to compressional heating, followed by adiabatic cooling



(Bourdin, CEAB, 2014, submitted)

Where are we now...?

- AC heating due to waves from photosphere => unlikely

- AC heating due to coronal fast reconnection events => unlikely

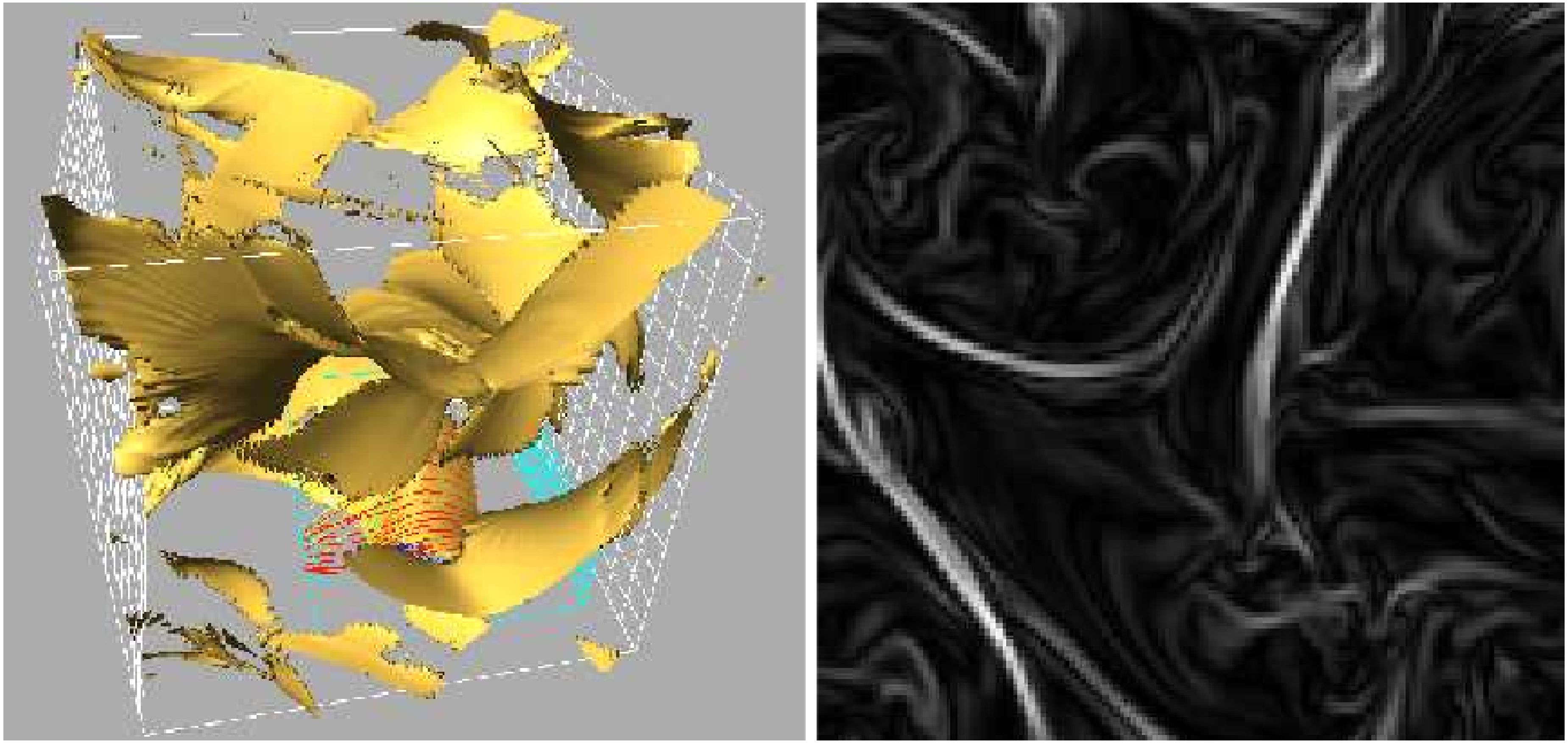
- Shock waves from photosphere => unlikely

- Ion cyclotron heating => unlikely

Coronal heating mechanisms

Example for driven MHD turbulence:

➡ leads to thin current density structures (Galsgaard & Nordlund, 1999)



=> similar to the „coronal tectonics“ (Priest et al., 2002)

Where are we now...?

- AC heating due to waves from photosphere => unlikely

- AC heating due to coronal fast reconnection events => unlikely

- Shock waves from photosphere => unlikely

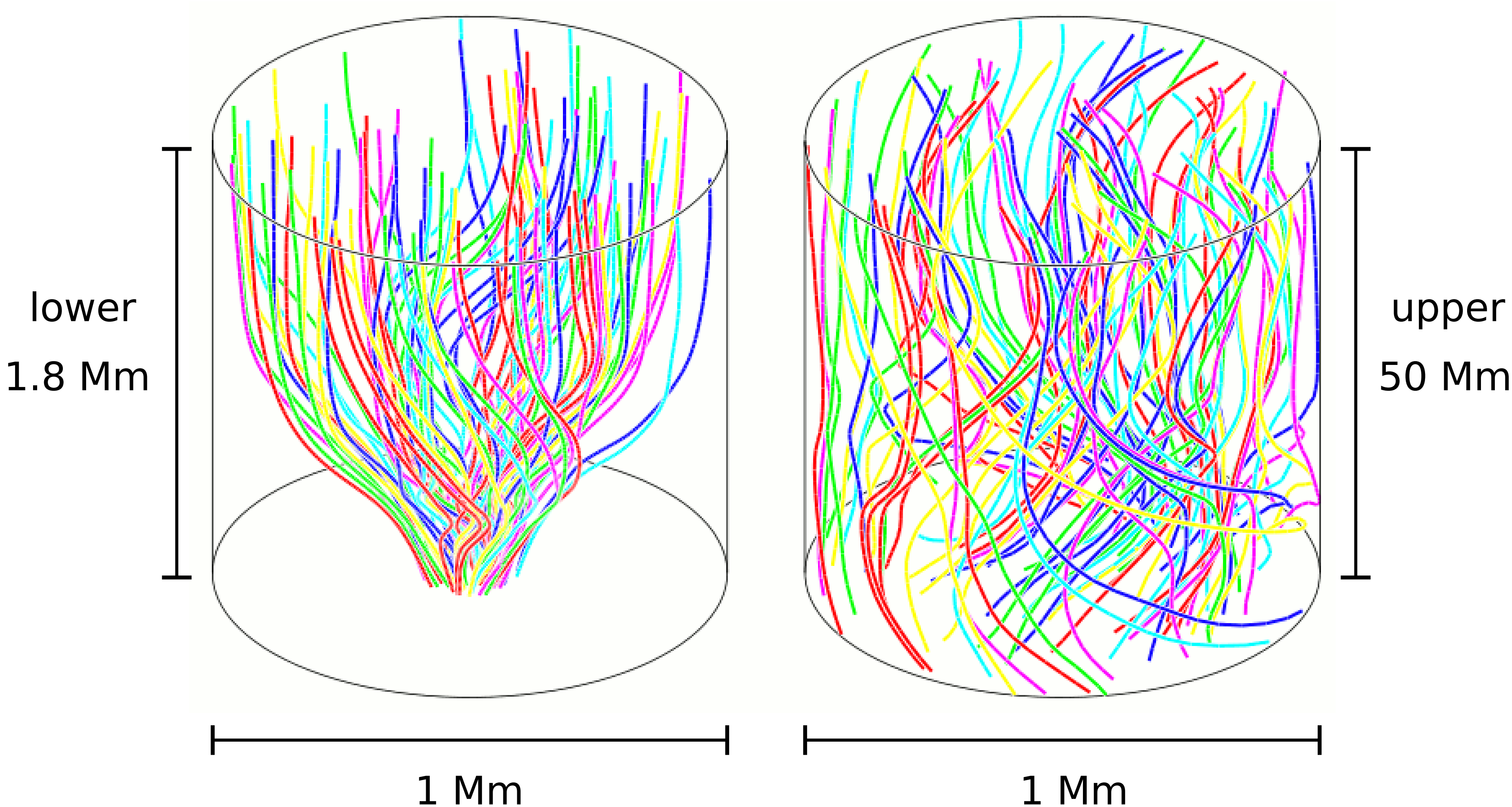
- Ion cyclotron heating => unlikely

- MHD instabilities after MHD waves (kink, tearing, etc.) => unlikely

Coronal heating mechanisms

Example for AC (wave) heating:

➡ heats a multi-stranded “straight loop”

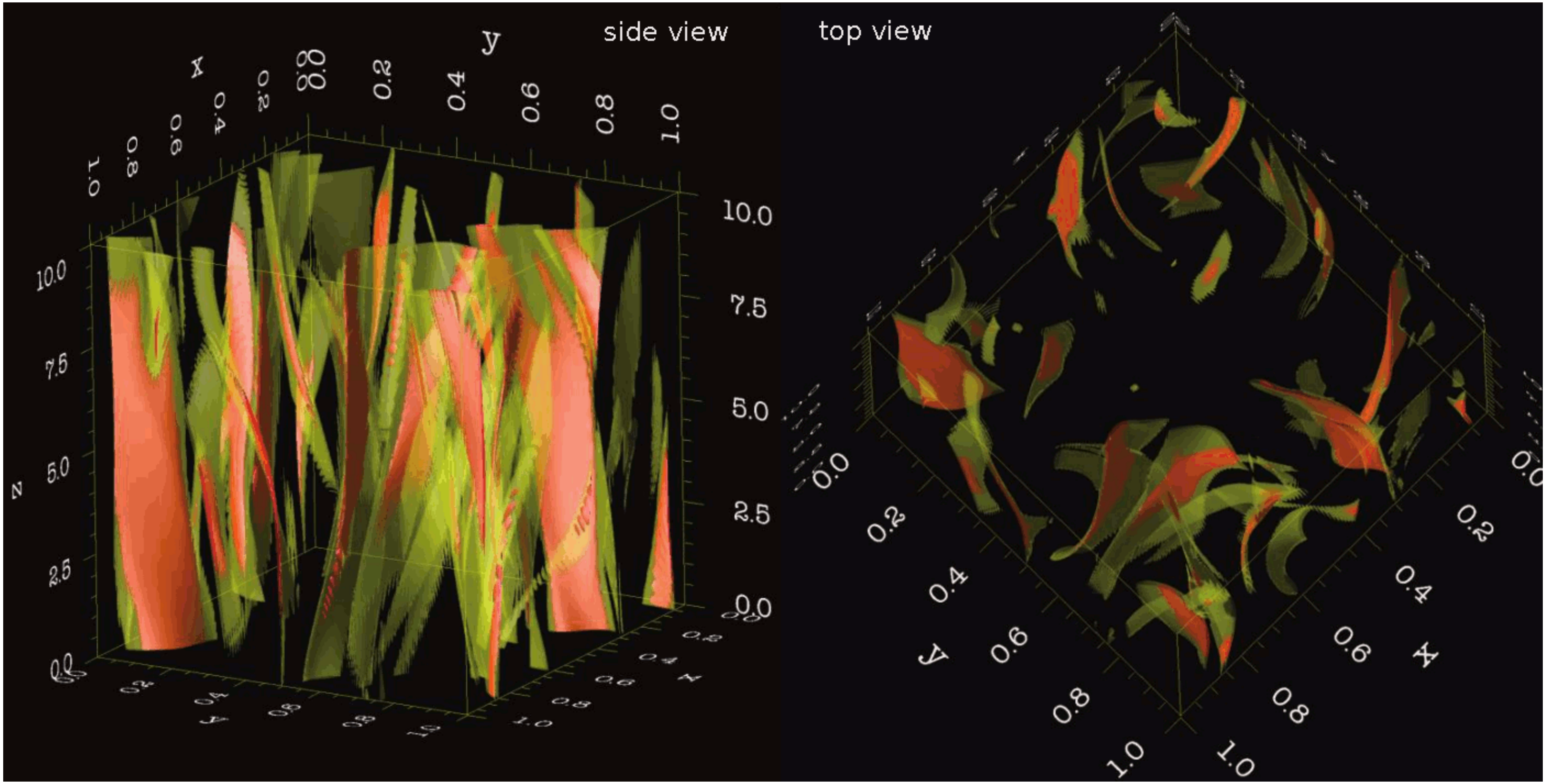


(van Ballegooijen et al., 2002)

Coronal heating mechanisms

Example for DC (Ohmic) heating:

➡ heats a single-stranded “straight loop”

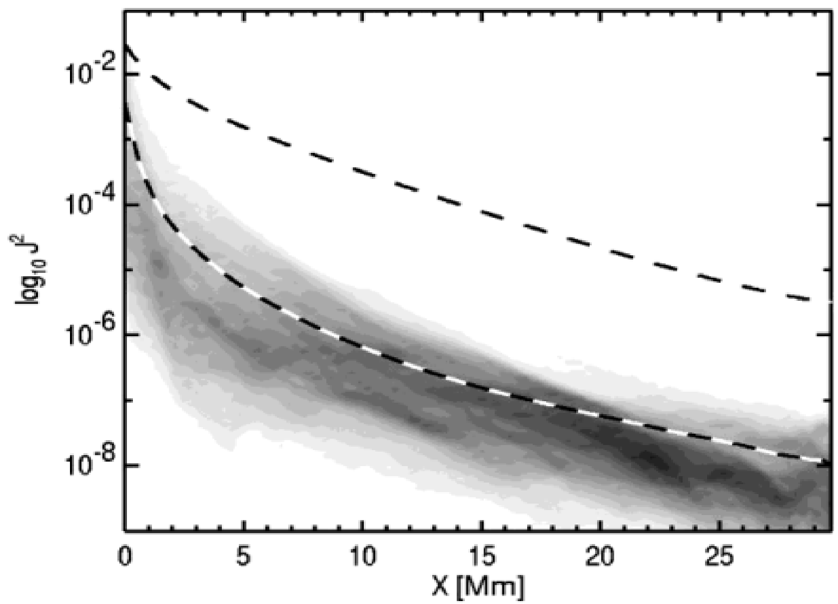


(Rappazzo et al., 2007)

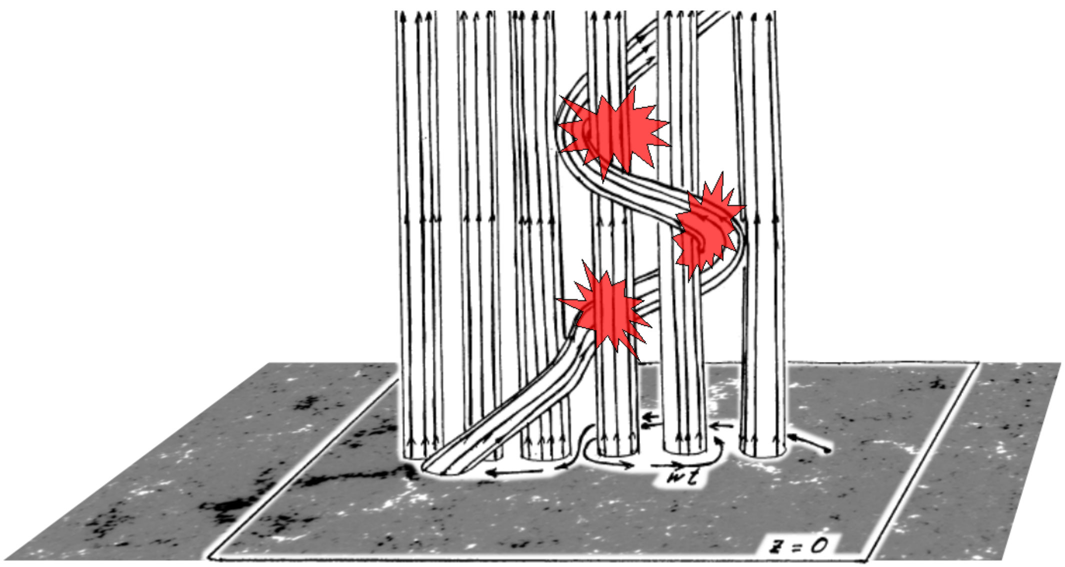
Coronal heating mechanisms

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)

Where are we now...?

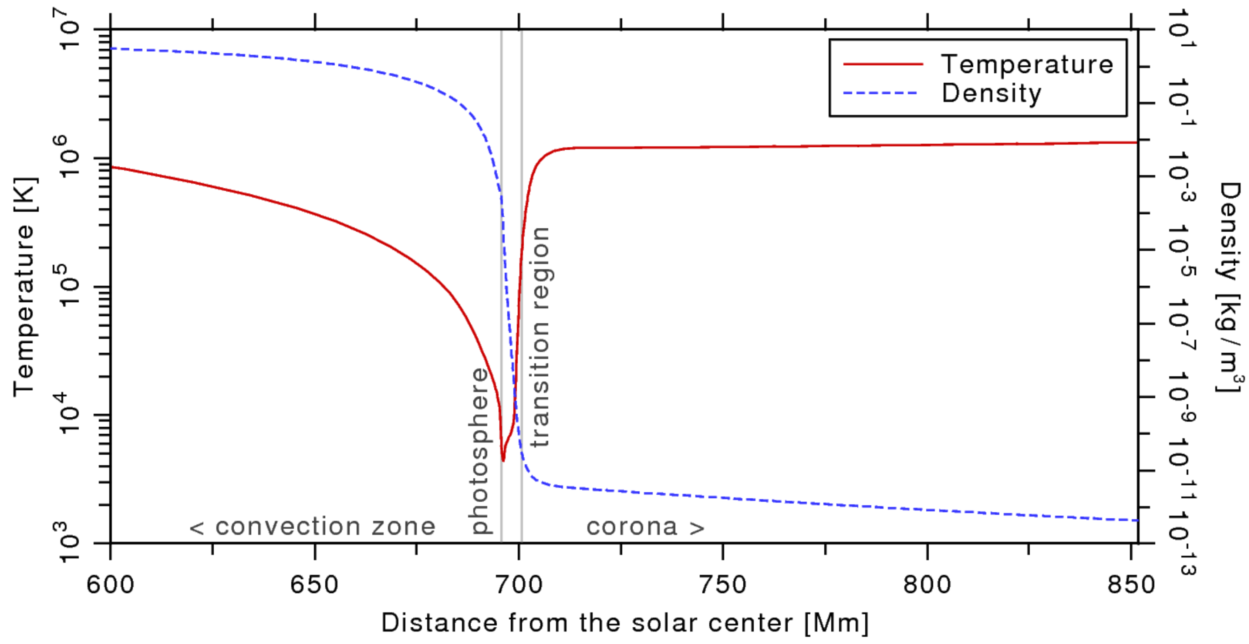
- AC heating due to waves from photosphere => unlikely
- AC heating due to coronal fast reconnection events => unlikely
- Shock waves from photosphere => unlikely
- Ion cyclotron heating => unlikely
- MHD instabilities after MHD waves (kink, tearing, etc.) => unlikely
- Coronal tectonics (DC heating) => why not?
- Field-line braiding (DC heating) => why not?

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

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

General self-consistent model description on the observable scales

- 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

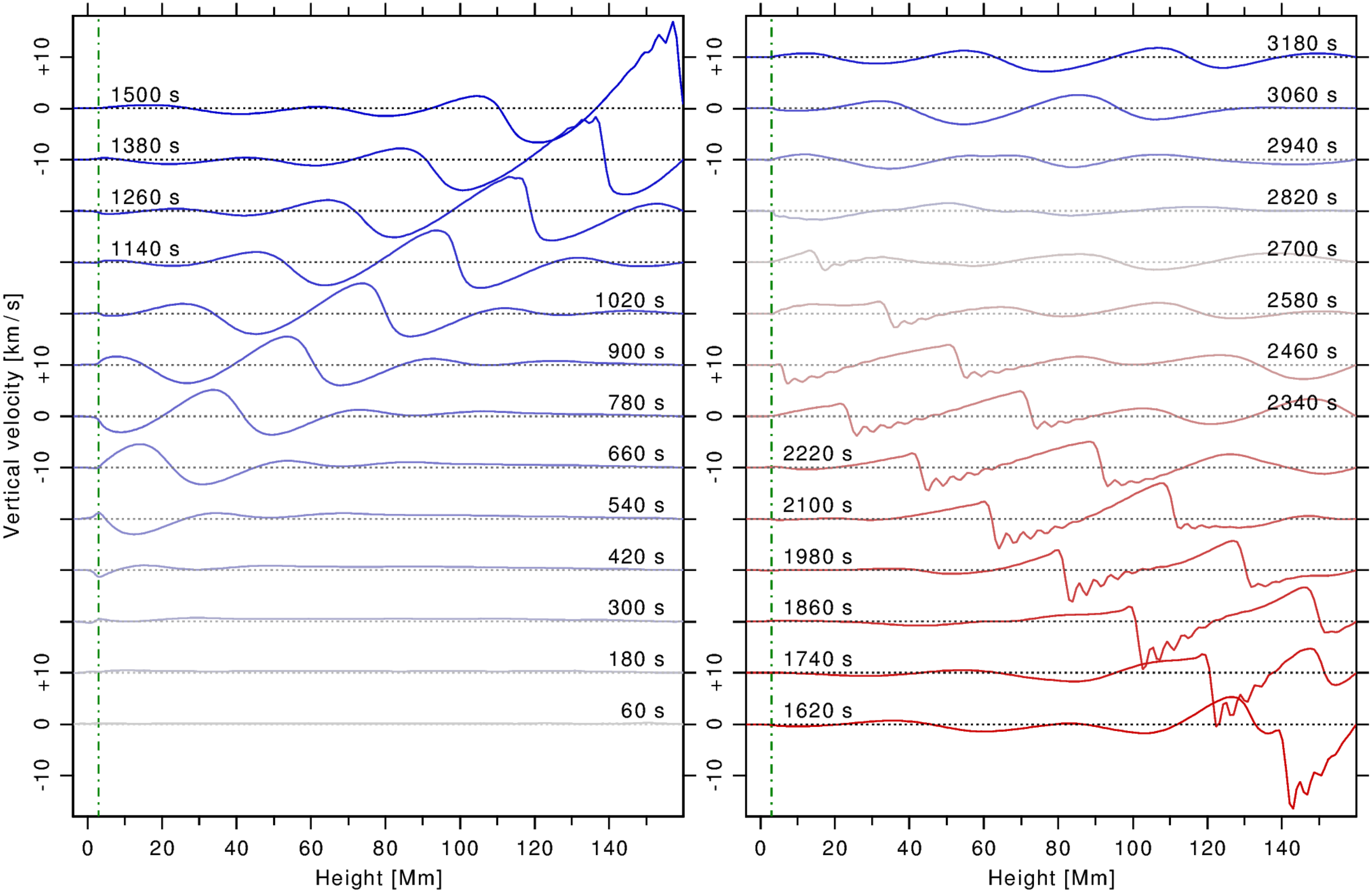


(Stix, 1989/2002) (**F**AL-C, 1993) (November-Kouchmy, 1996)

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

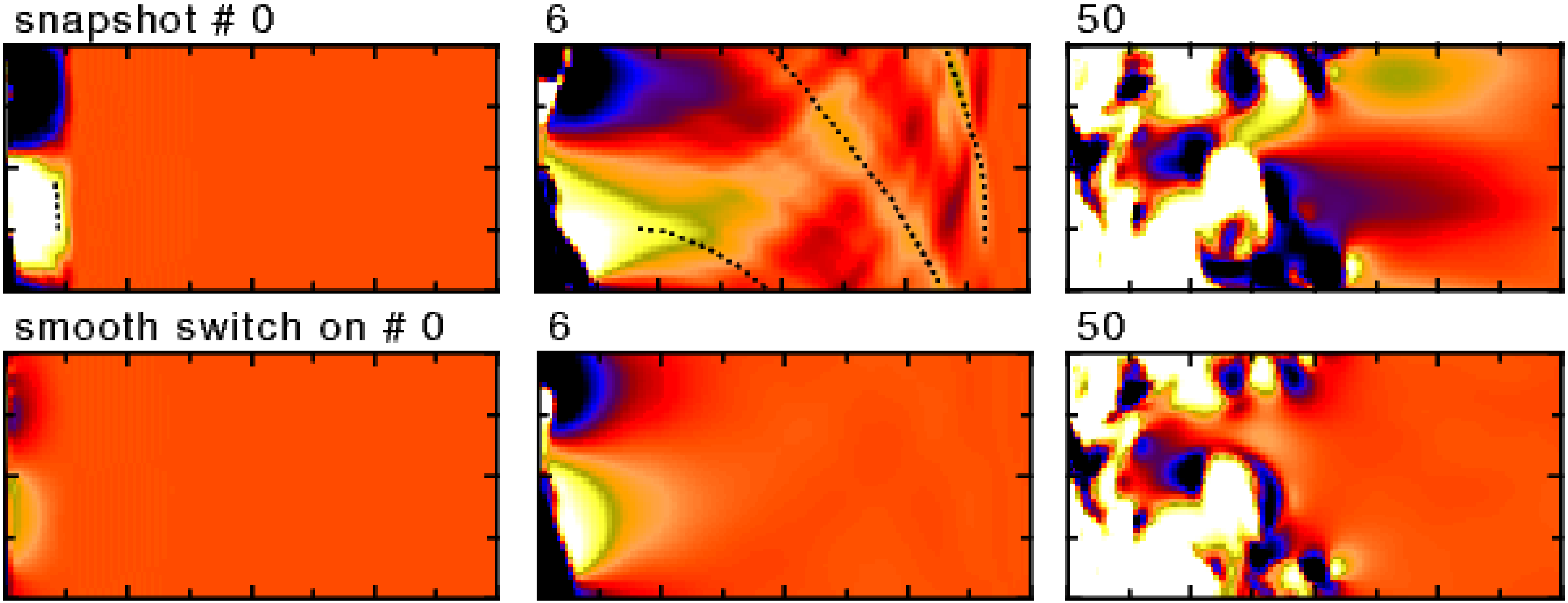
Avoid switching-on effects

(Bourdin, 2014, CEAB, 38, 1–10)



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

➡ Avoid switching-on effects (Bourdin, 2014, CEAB, 38, 1–10)



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

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

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

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

What else is needed...?

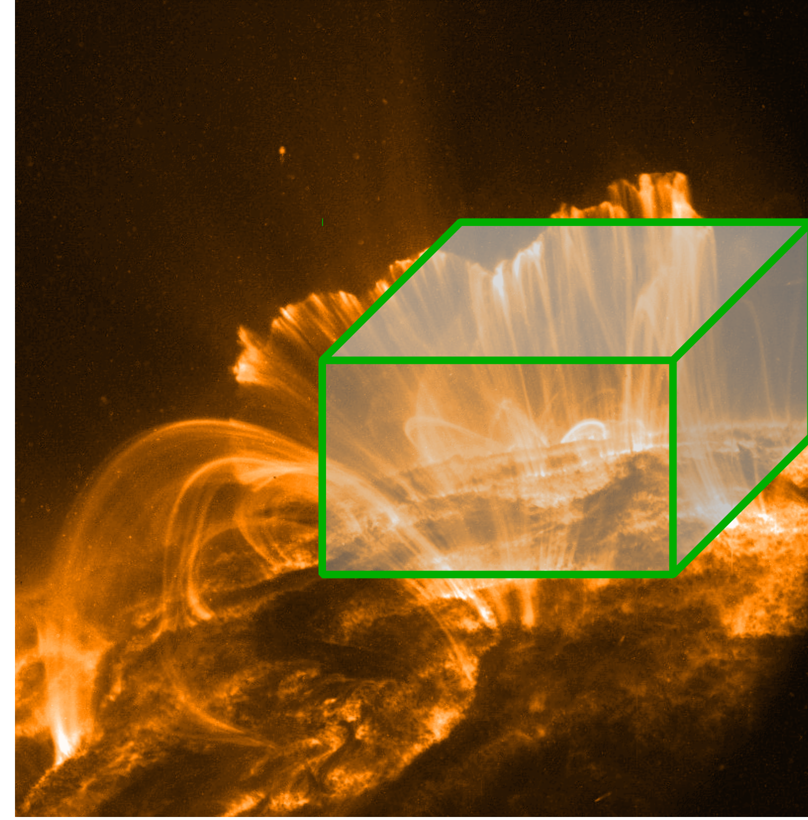
3D-MHD simulation:

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

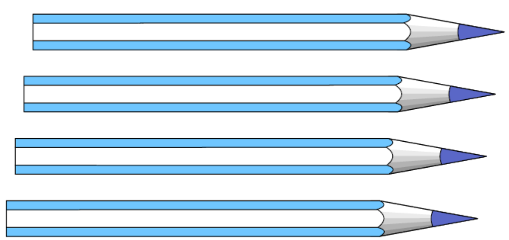
- High resolution grid: 1024*1024*256

→ 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: NIC, GENCI, PRACE

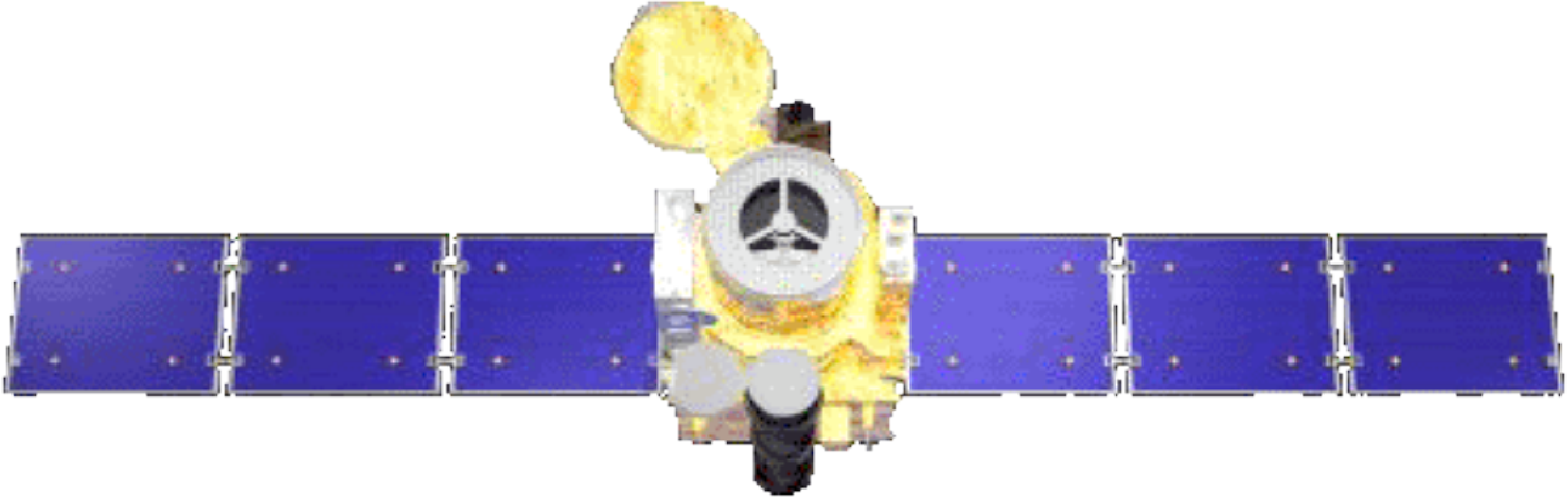
Observational instruments

➡ Simultaneous observations of different layers of the solar atmosphere

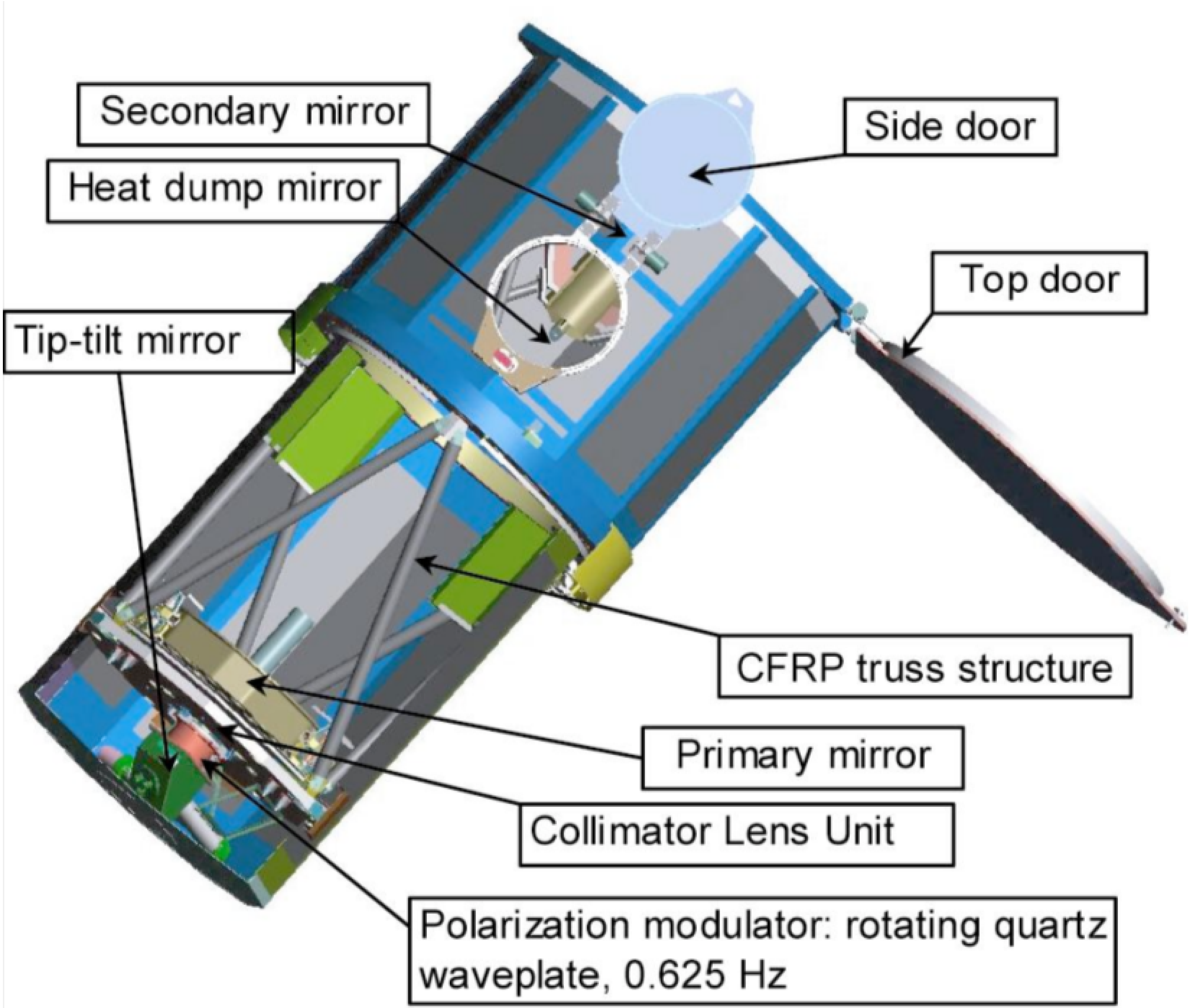
Observational instruments

Hinode Solar Optical Telescope Data Analysis Guide

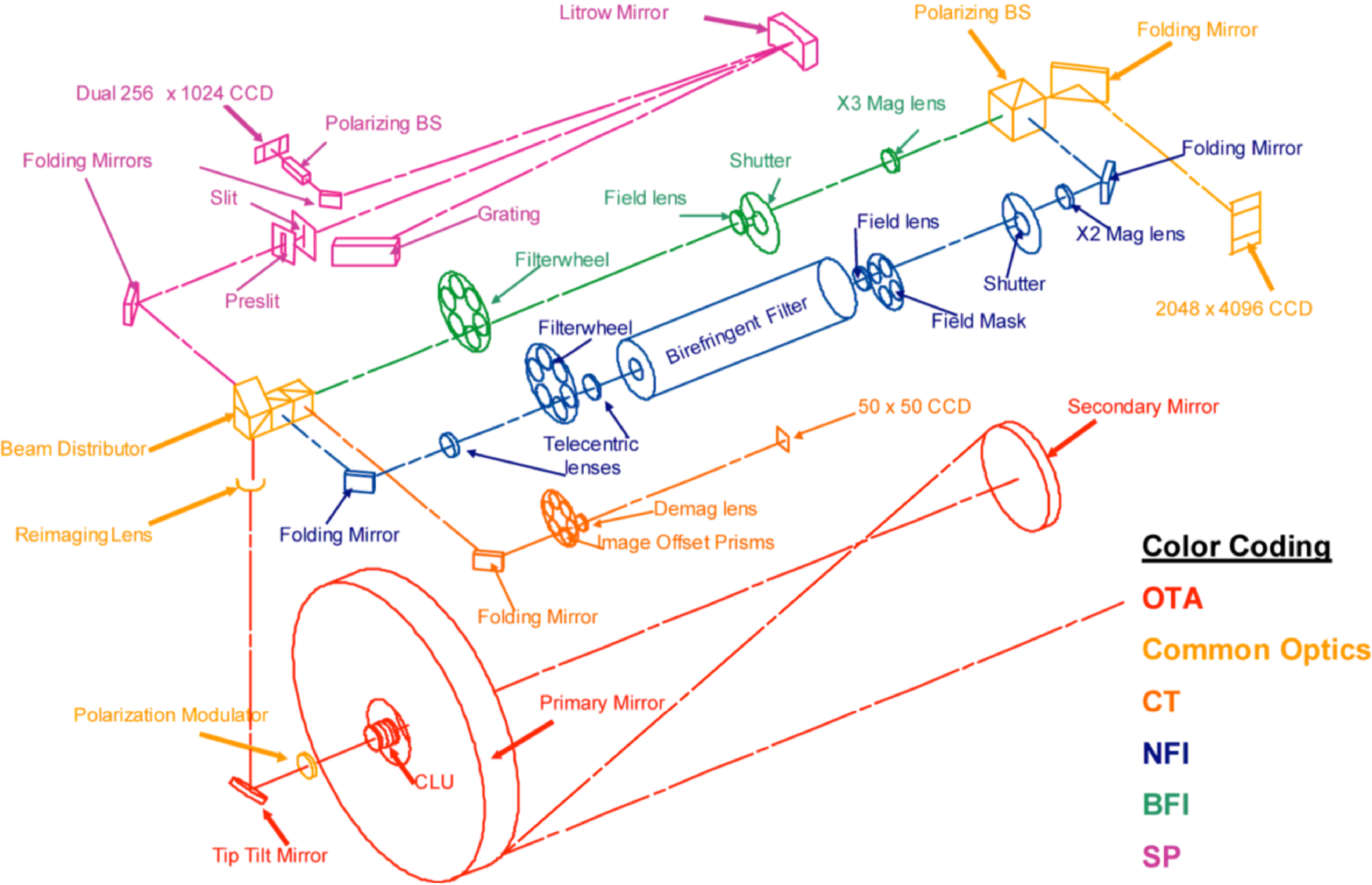
Version 3.3



Hinode structure



Hinode optical path

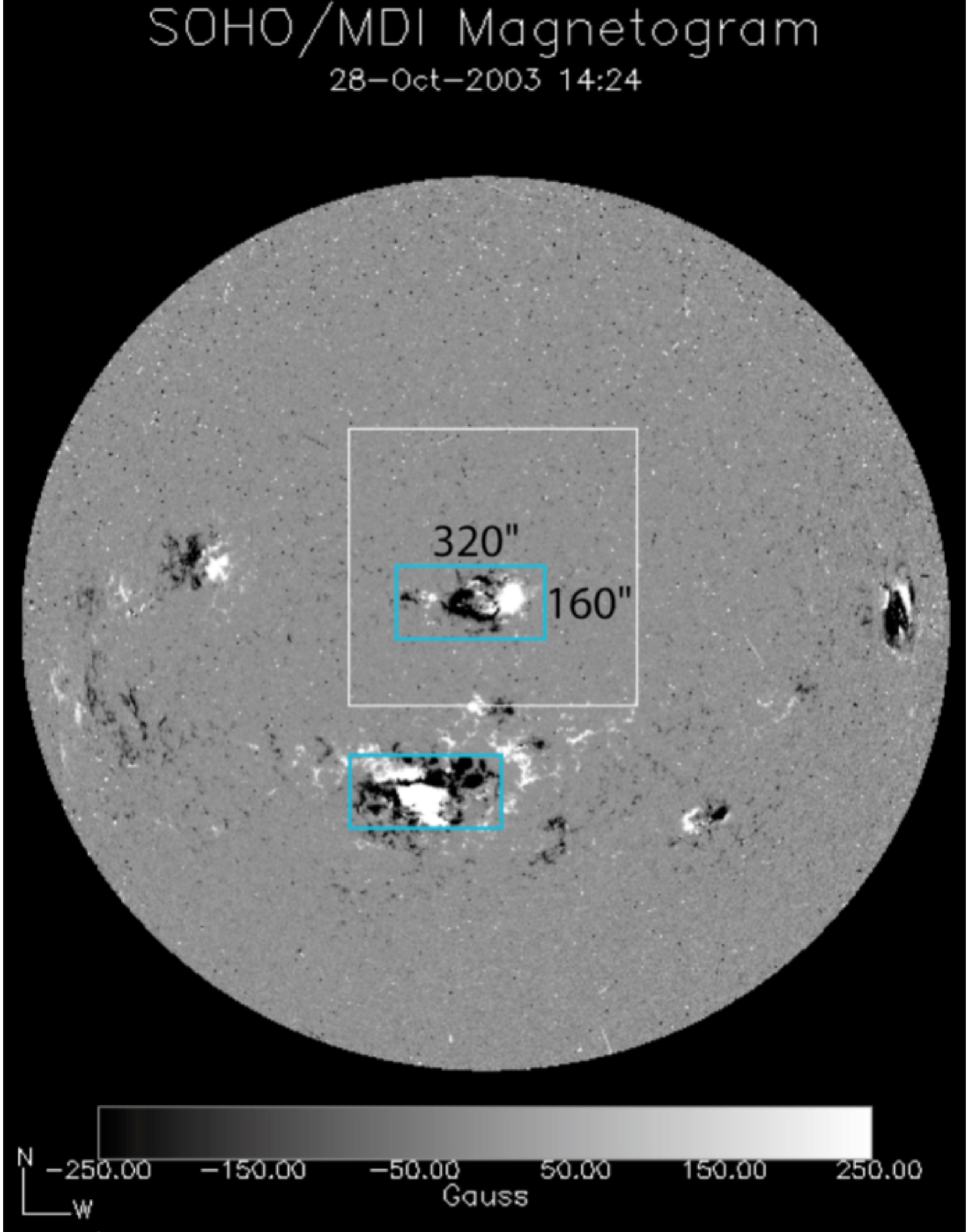


Observable atmospheric layers

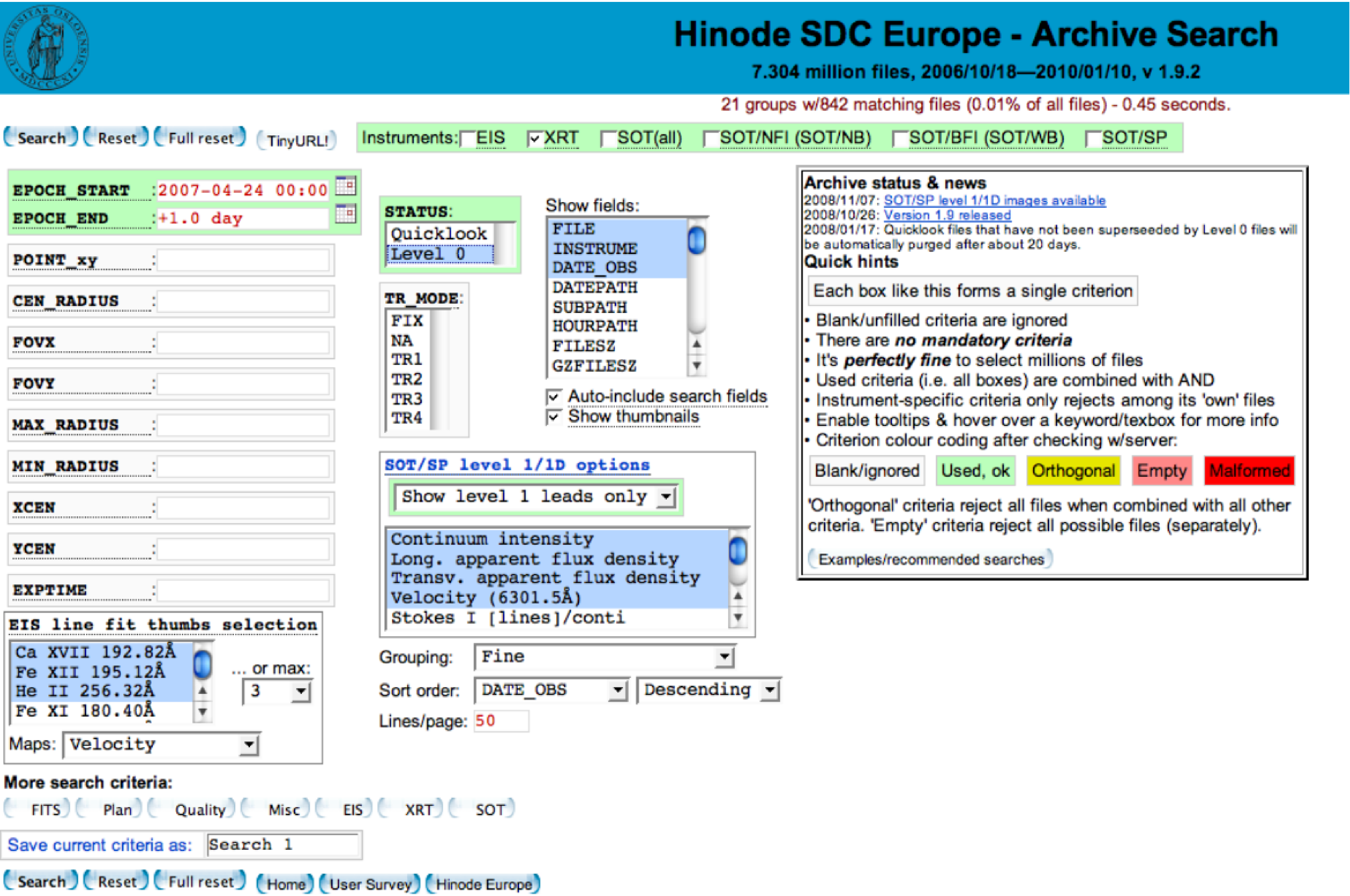
Wavelength nm	Spectral Region	Diffraction Limit arcsec
388.3	CN molecular band, photospheric network	0.19
430.5	CH molecular “G-band”, photospheric network	0.22
512.7	Chromospheric magnetograms	0.26
525.0	Photopheric magnetograms	0.26
557.6	Photospheric dopplergrams	0.28
589.6	Na I D chromospheric magnetograms	0.30
630.2	Fe I photospheric magnetograms	0.32
656.3	H-alpha chromospheric diagnostics	0.33

Table 1. Diffraction limits for spectral bands available in the FPP.

Hinode FOV


SOHO/MDI Magnetogram
28-Oct-2003 14:24
320"
160"
N
W
-250.00
-150.00
-50.00
50.00
150.00
250.00
Gauss

Scientific data center



Hinode SDC Europe - Search results

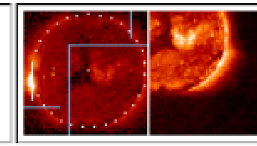
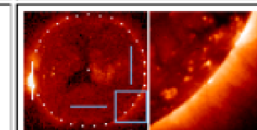
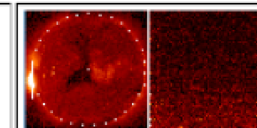
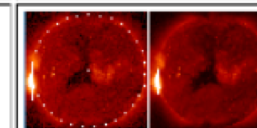
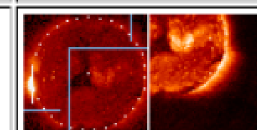
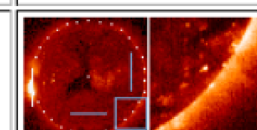
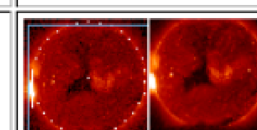
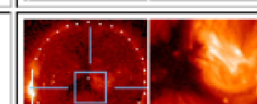
Search completed in 0.27 sec. Showing 10 groups representing 717 matching files, out of 21 groups w/842 matching files (0.01% of all files). Page 1 of 3.

Modify search | Zoom | Retrieve | File paths | ASCII | Summarise | TinyURL!

1 2 3

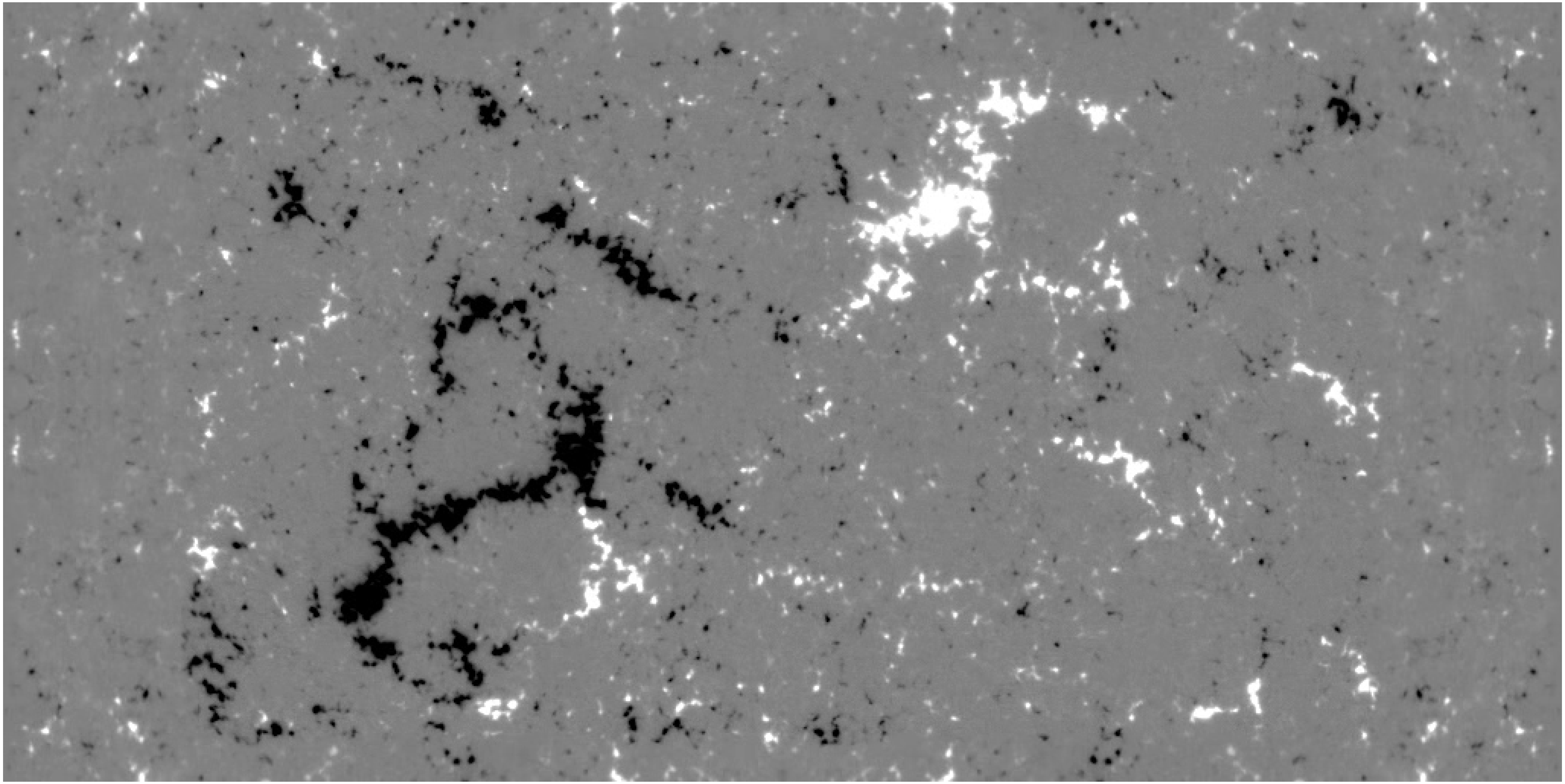
Add fields: Common | N-valued | EIS | XRT | SOT | SOT/FG | SOT/SP | SOT/XRT

Rows/page: 10 Grouping: Fine ☑ Thumbnails

Select All:	Actions/ N files	FILE	INSTRUME	DATE_OBS	STATUS	FOV/data images
	33	XRT20070424_180301.5	XRT	2007-04-24 18:03:01	Level 0	
	332	XRT20070424_175303.4	XRT	2007-04-24 17:53:03	Level 0	
		XRT20070424_174402.2d	XRT	2007-04-24 17:44:02	Level 0	
	2	XRT20070424_174301.6	XRT	2007-04-24 17:43:01	Level 0	
	25	XRT20070424_131203.7	XRT	2007-04-24 13:12:03	Level 0	
	253	XRT20070424_130203.5	XRT	2007-04-24 13:02:03	Level 0	
	6	XRT20070424_120201.8	XRT	2007-04-24 12:02:01	Level 0	
	62	XRT20070424_115203.7	XRT	2007-04-24 11:52:03	Level 0	

What else is needed...?

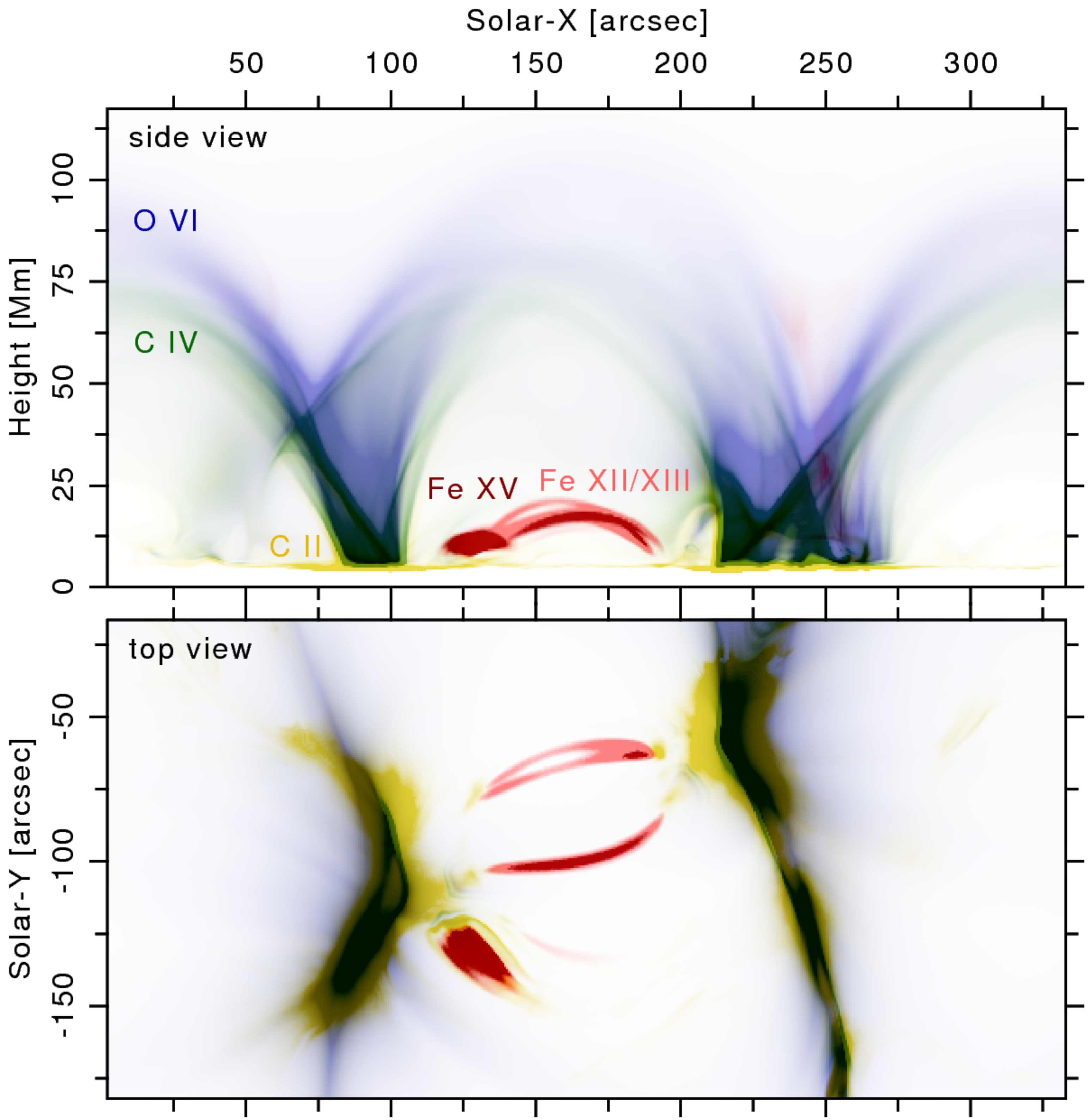
- Magnetic field of an Active Region



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

Synthesized emission (CHIANTI)

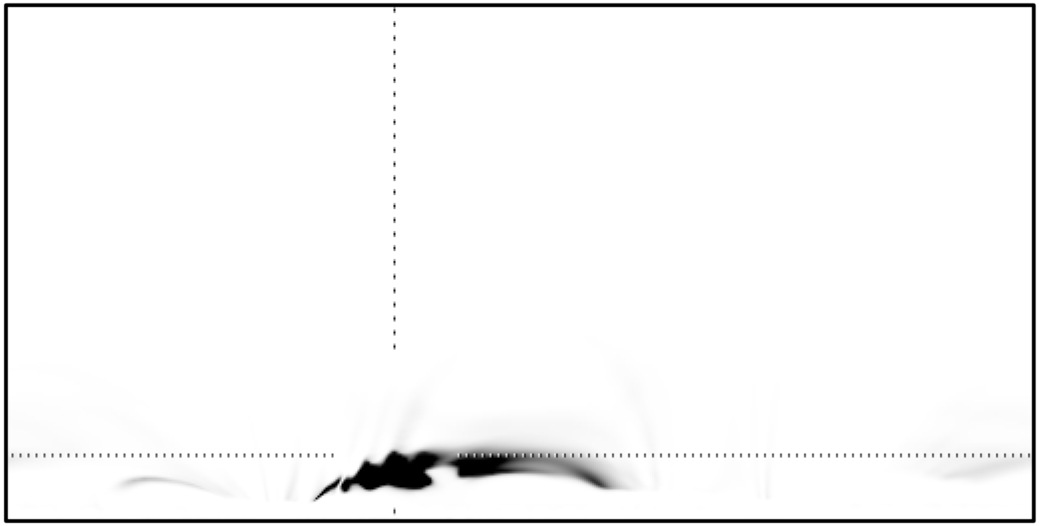
→ hot loops in AR core



(Bourdin, PhD thesis, [available online](), uni-edition, Berlin, 2014)

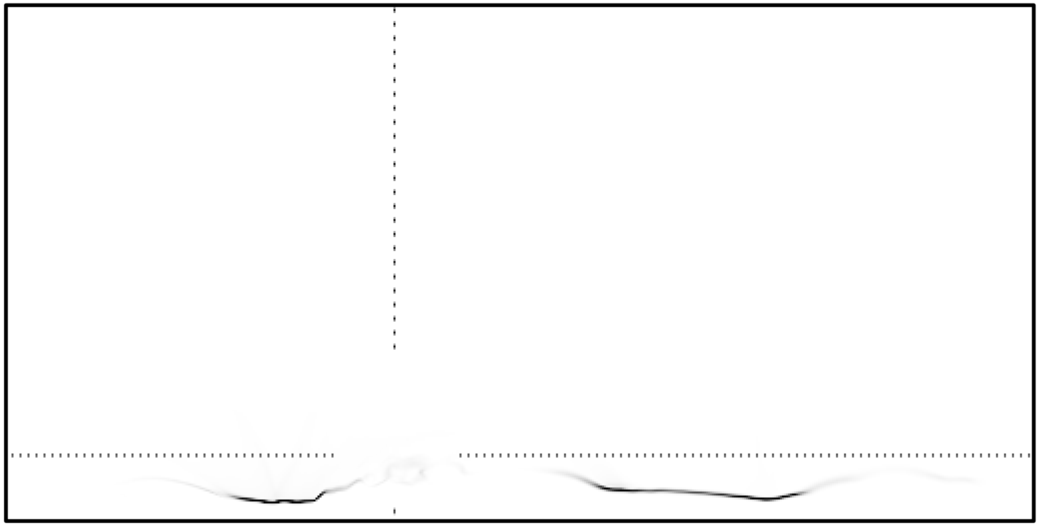
Coronal heating mechanisms

Ohmic heating per particle:



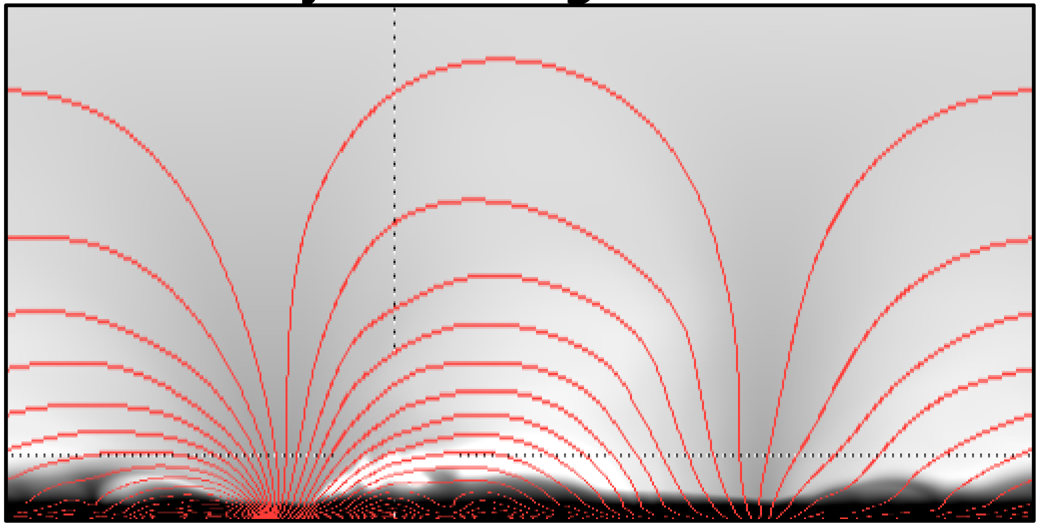
(saturation level: $2*10^{-19}$ W)

Viscous heating per particle:



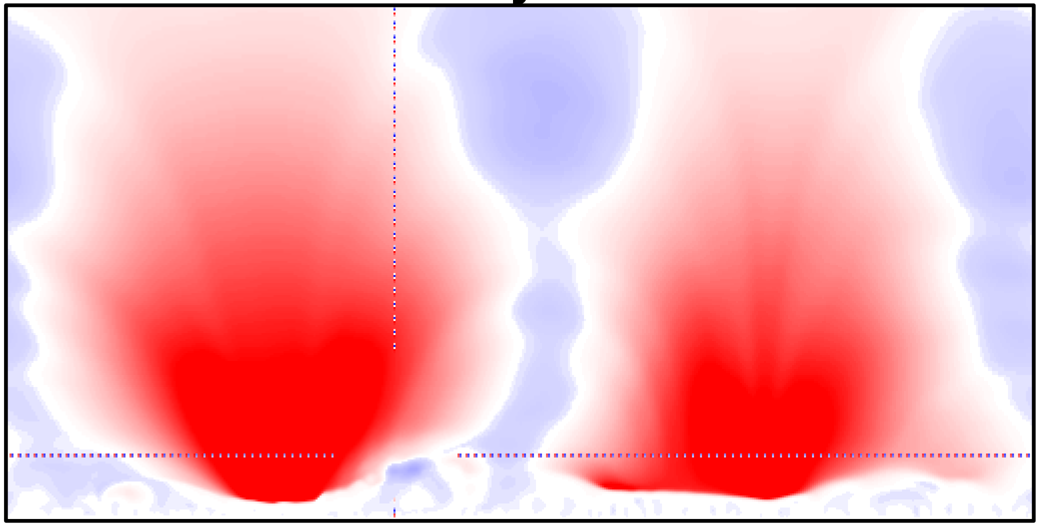
(saturation level: $2*10^{-19}$ W)

Density with magnetic field:



(saturation level: 10^{-8} kg/m³)

Vertical velocity:



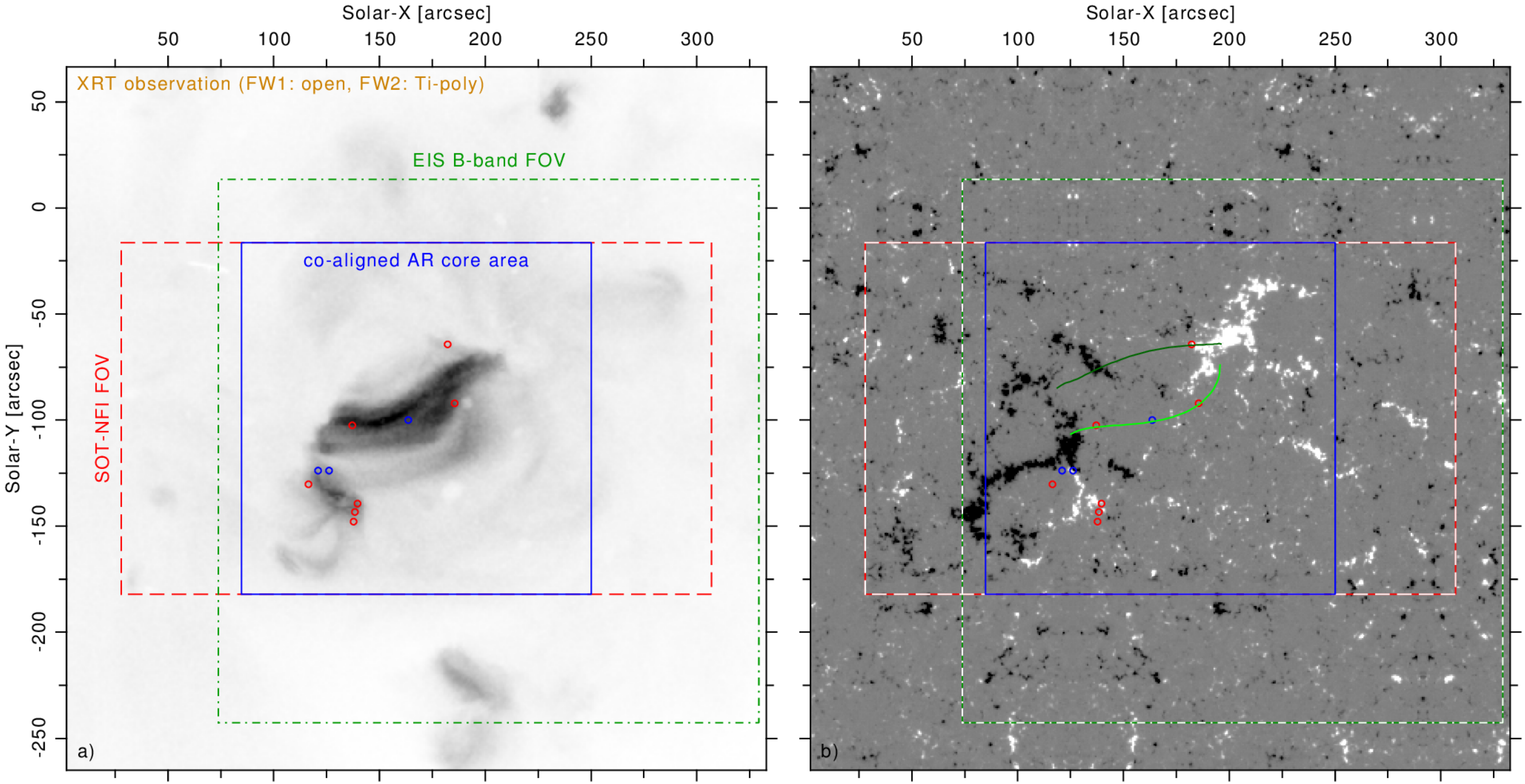
(saturation level: -70 km/s)

Comparison to observations

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

- X-ray emission (~1.5 MK)

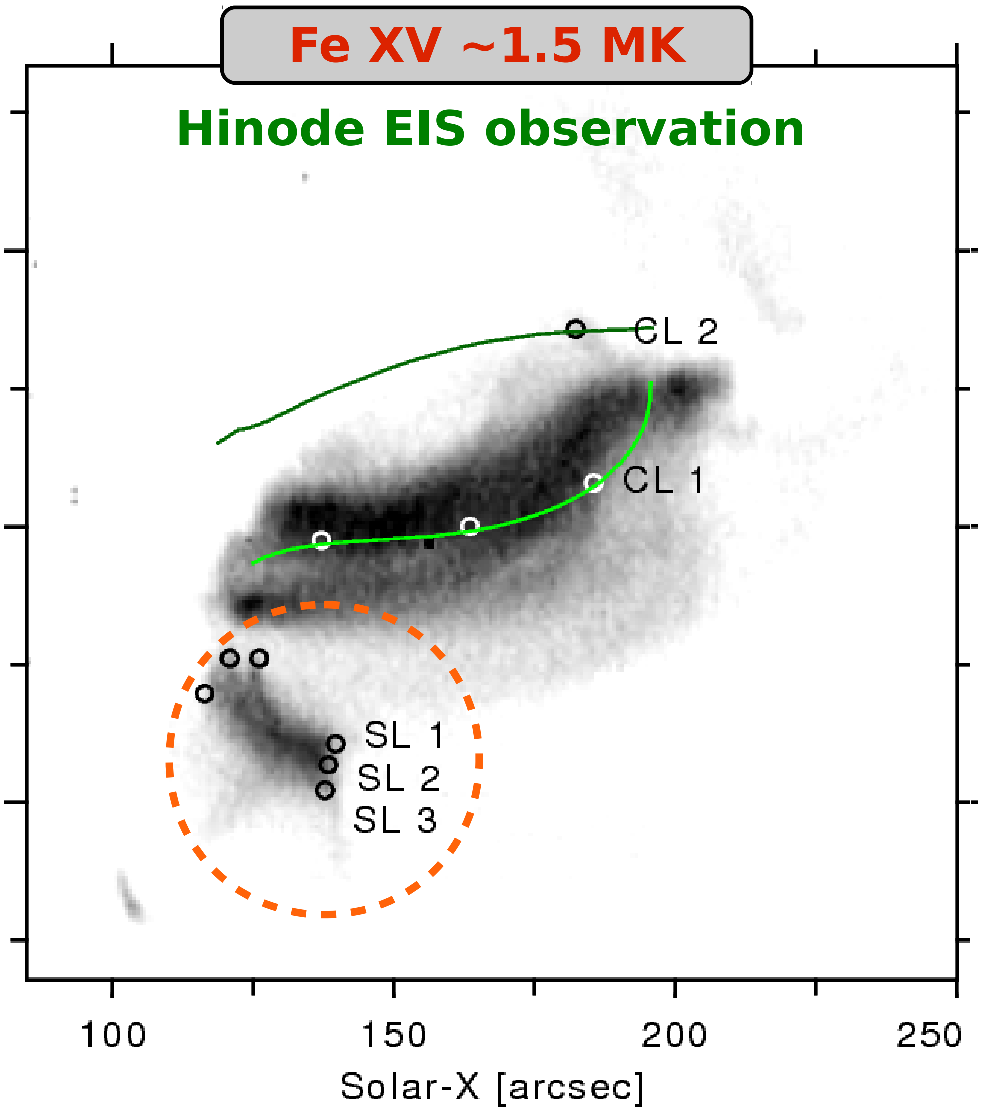
- Photospheric magnetic field (AR+QS)

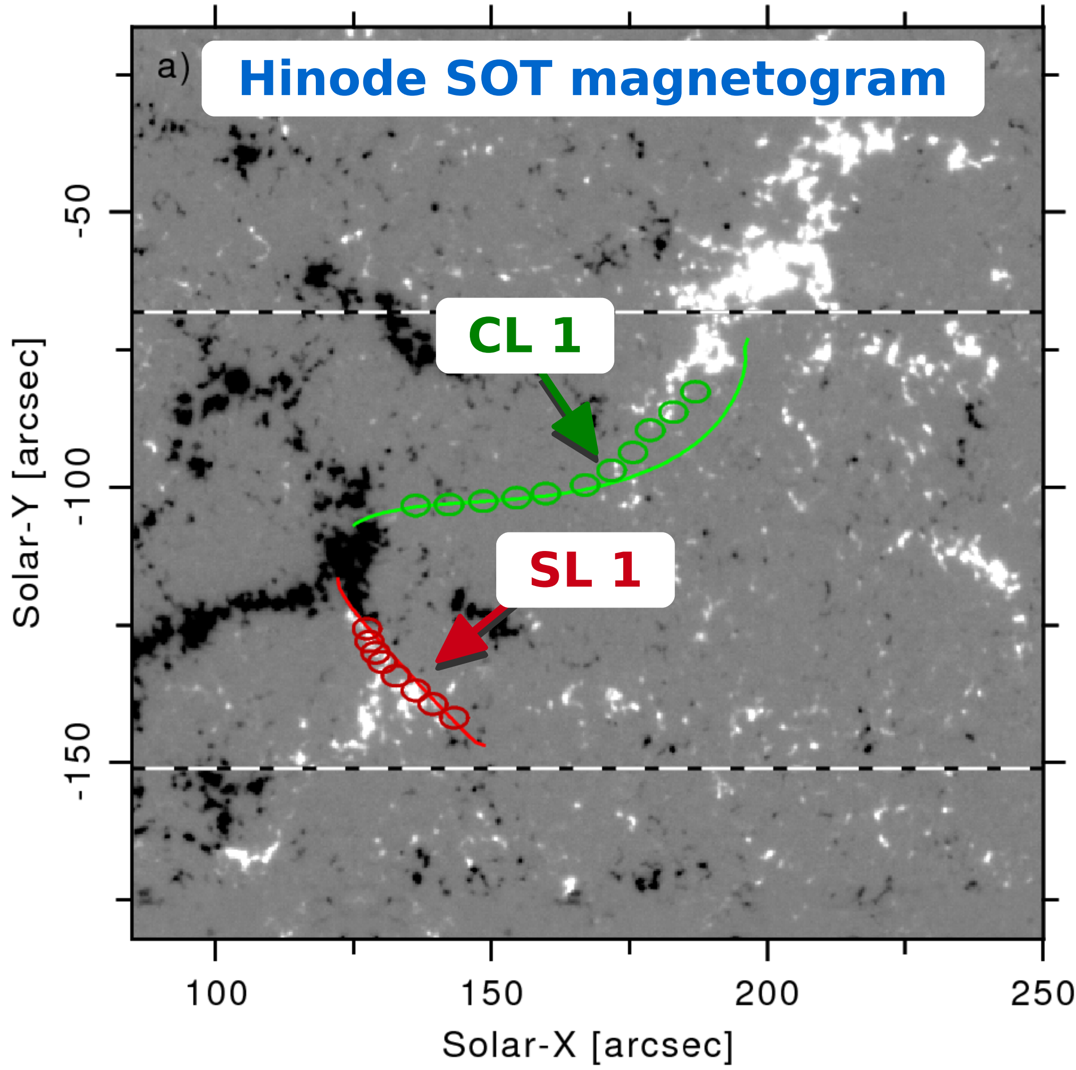


(Bourdin et al., 2013, A&A 555, A123)

Comparing to observations (Hinode EIS/SOT)

➡ Model fieldlines follow observed loops

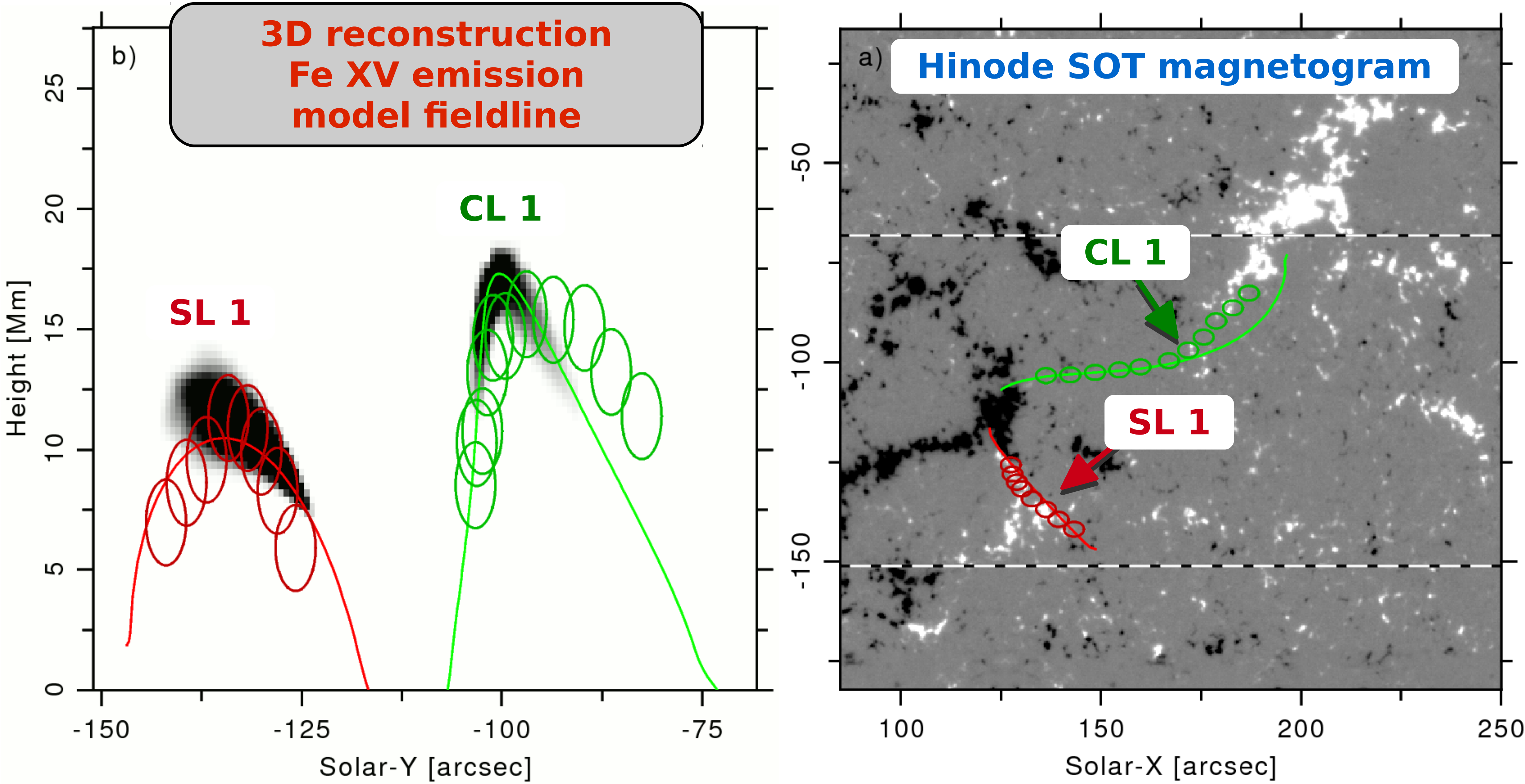




(Bourdin et al., A&A 555, A123, 2013)

Comparing to observations (STEREO A/B)

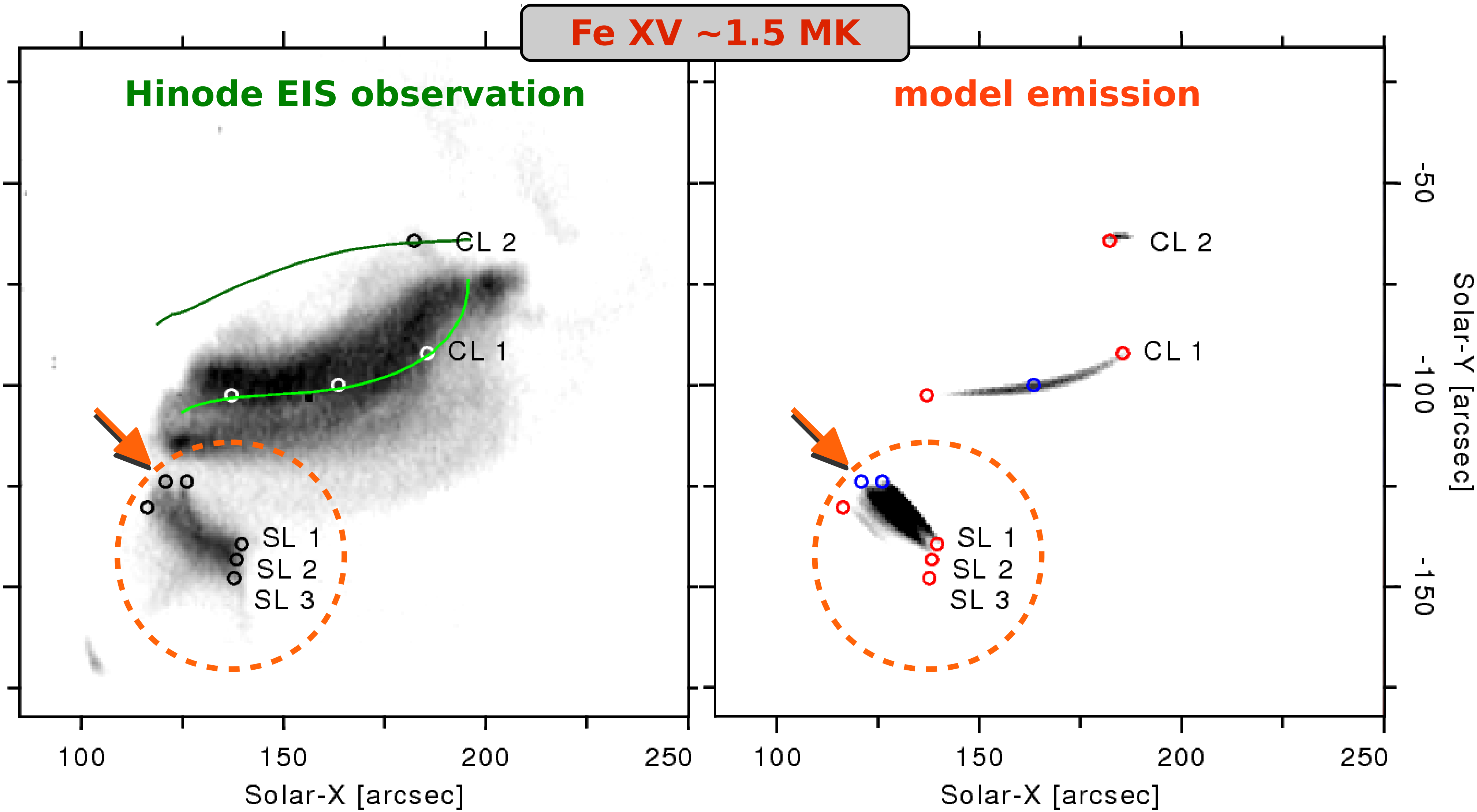
- 3D structure and height of model loops realistic
- Model fieldlines follow observed loops



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

Comparison of intensity

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



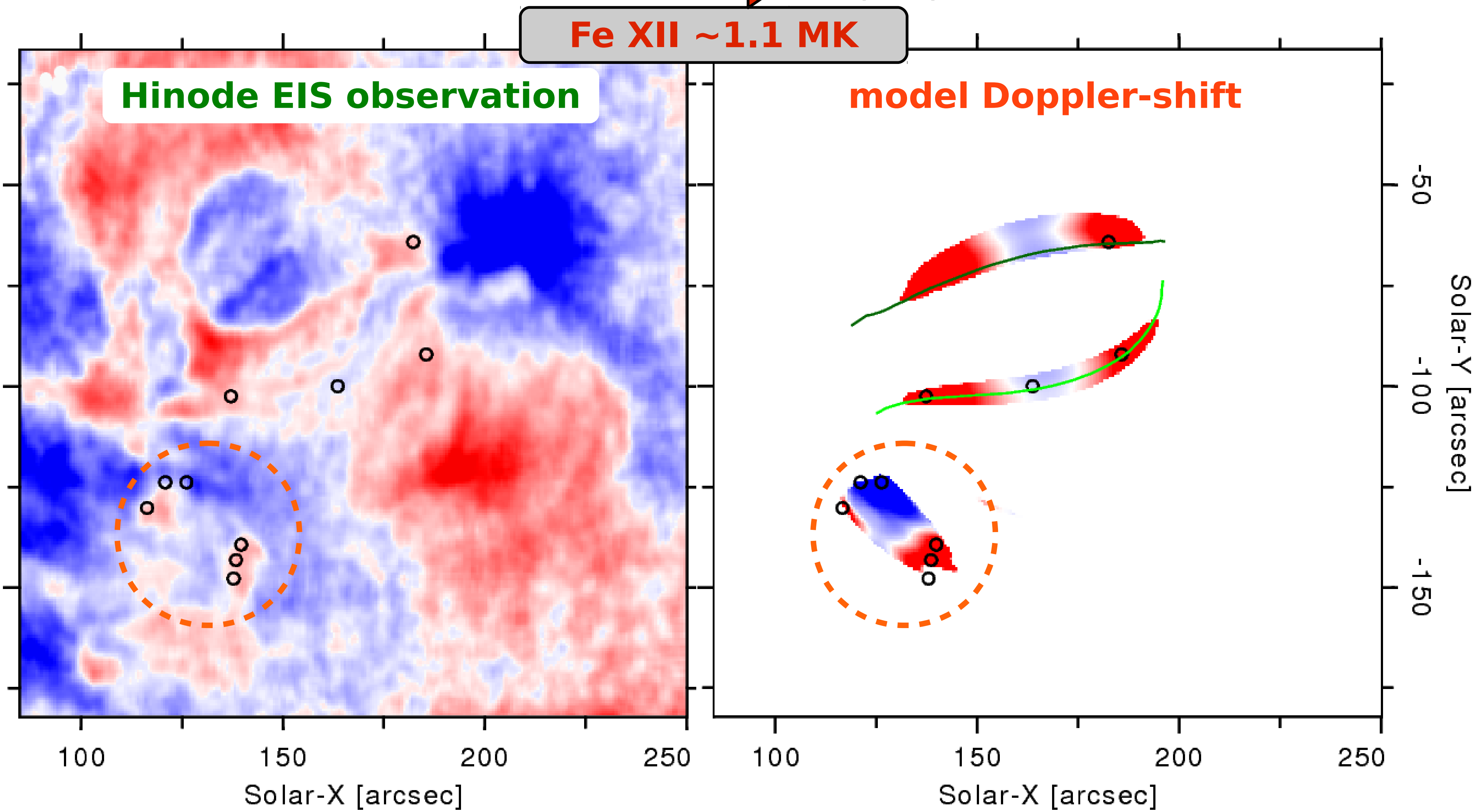
(Bourdin et al., 2013, A&A 555, A123)

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)

Coronal heating and energy source

Coronal heating

Temperature:

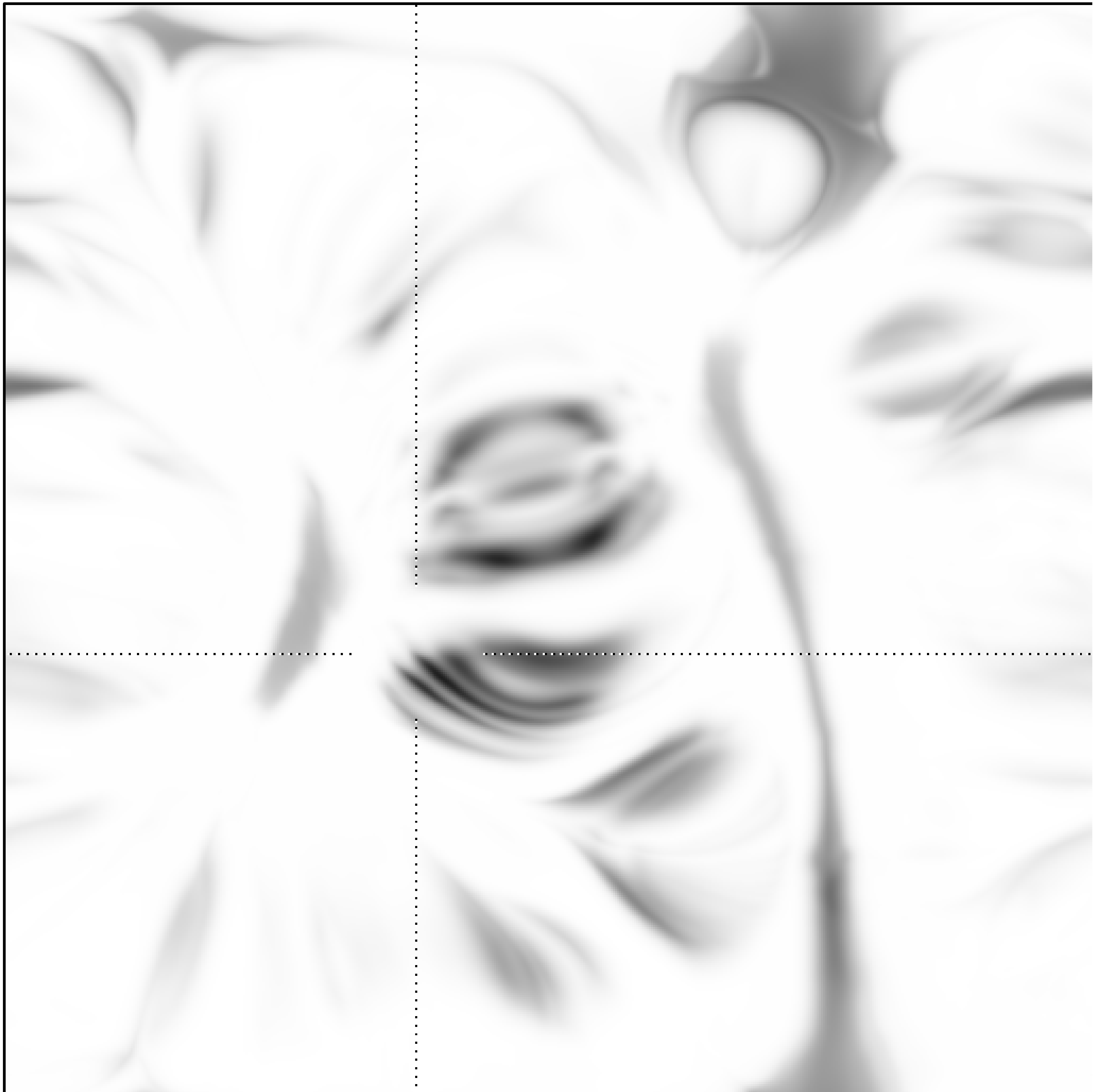
(horizontal cut)

(black: 1.65 MK)

- Structures span between main polarities

- Connectivity to surrounding plage & network

(height: 11.2 Mm)

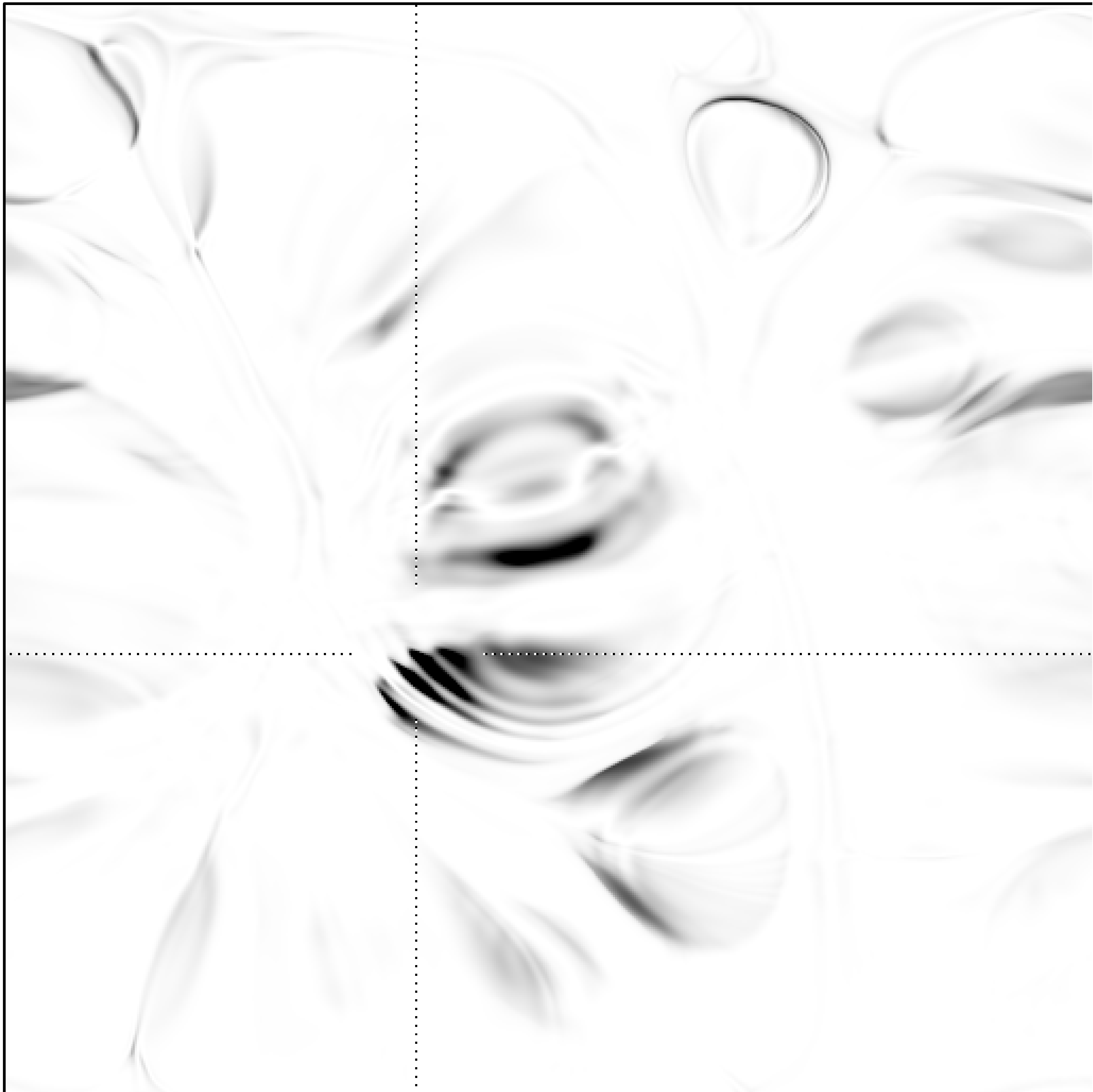


Coronal heating

Ohmic heating per particle: (horizontal cut)

- Structures mostly follow Ohmic heating
- Ohmic heating is predominant in the corona

(height: 11.2 Mm)



Energy source

Vertical

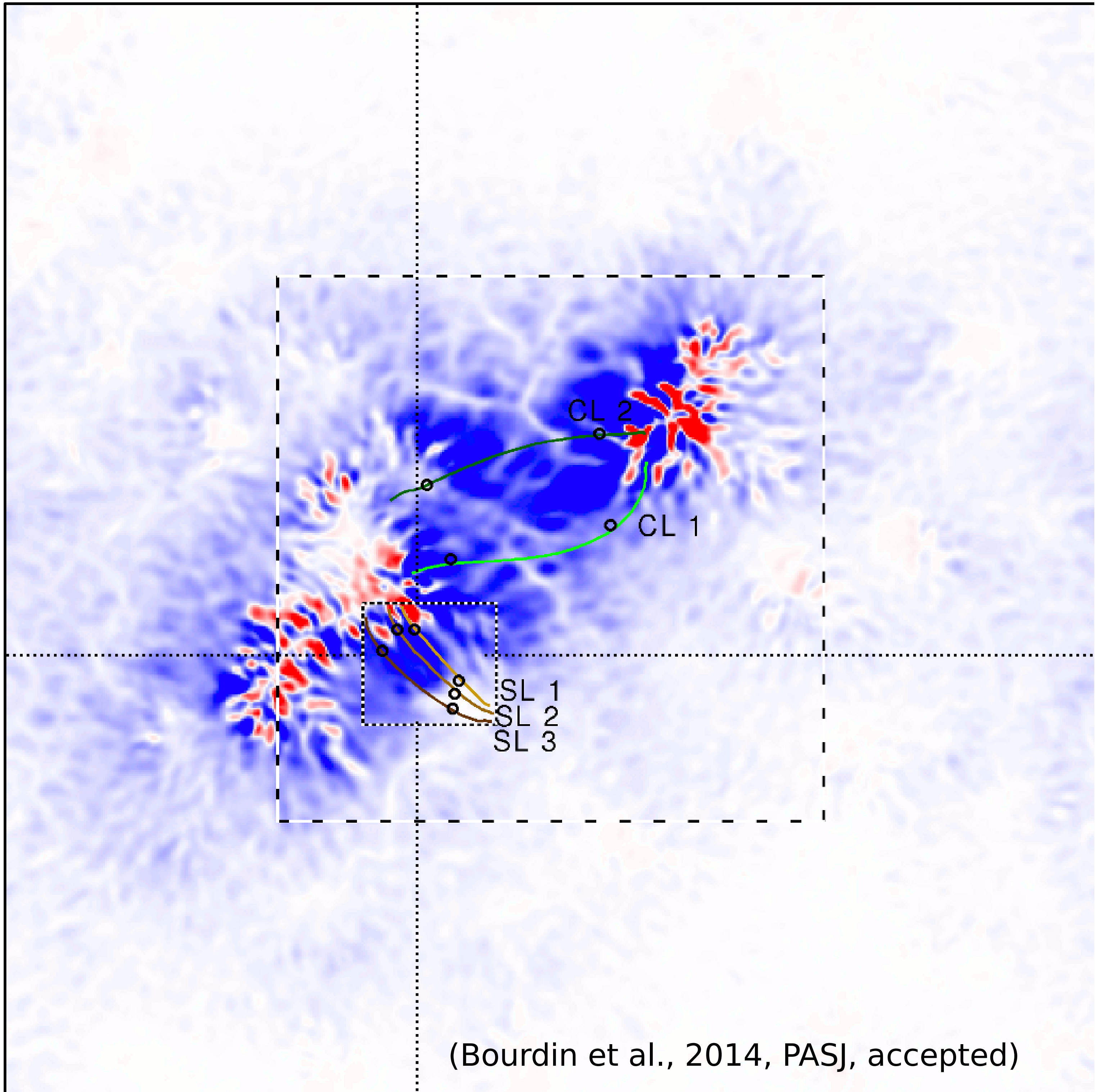
Poynting flux:

(horizontal cut)

(± 50 kW/m²)

- Hot AR core located where Poynting flux towards corona is high

(height: 3 Mm)



(Bourdin et al., 2014, PASJ, accepted)

Energy source

Temperature:

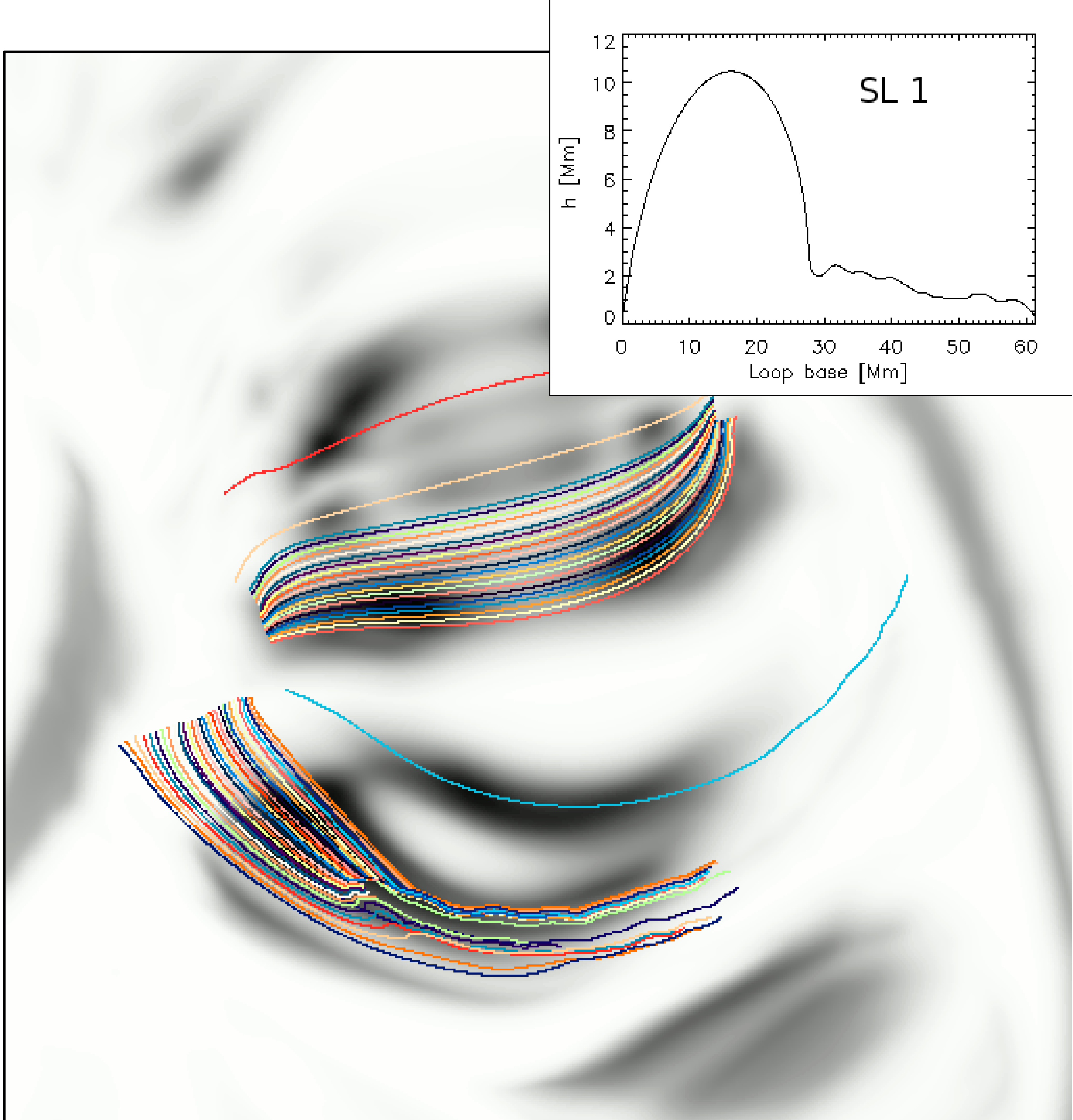
(horizontal cut)

(black: 1.25 MK)

- Structures mostly follow field lines

- Magnetic field quite parallel in the corona

(height: 11.2 Mm)



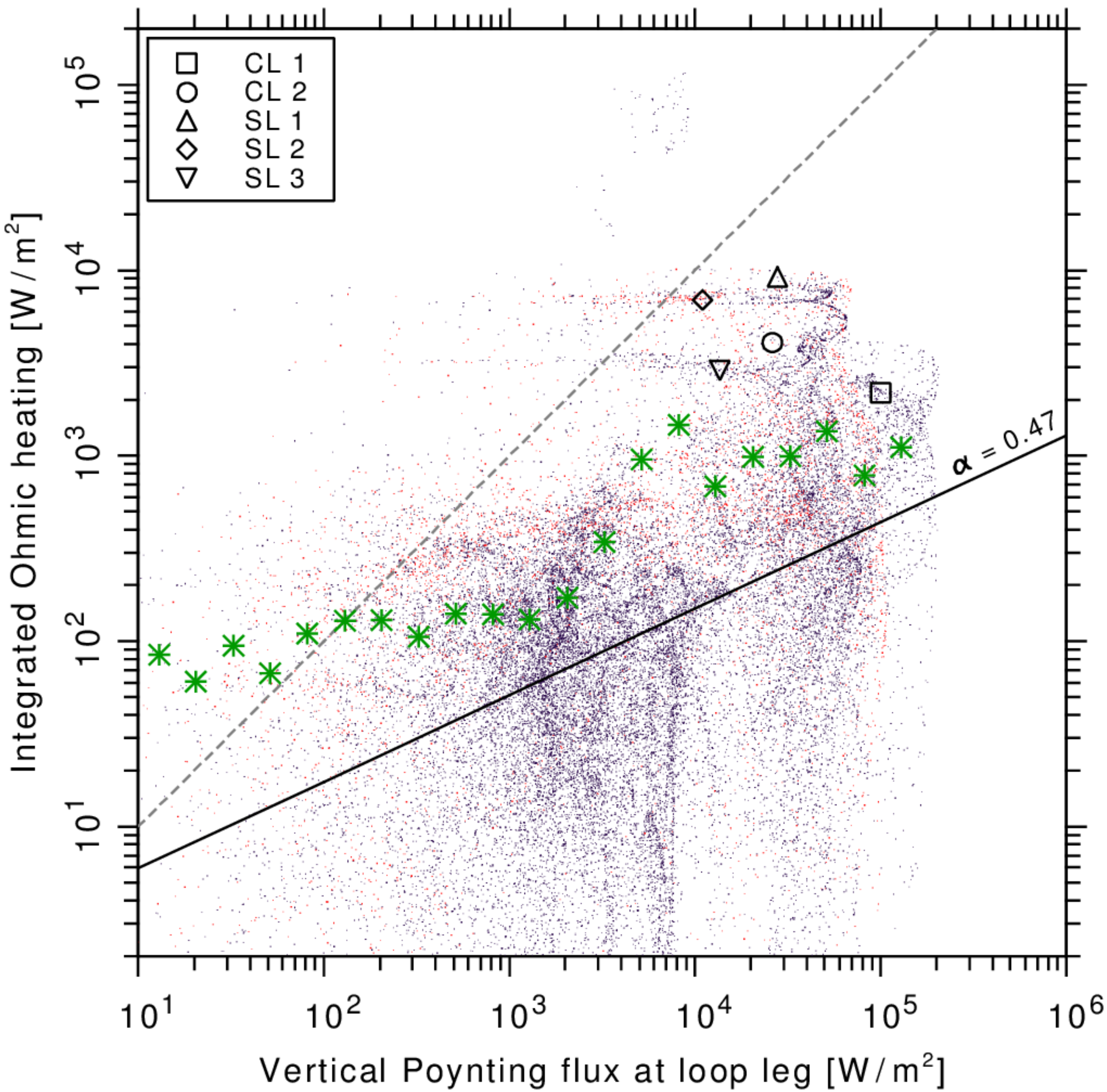
Energy source

67'000 field lines:

(AR core area)

Integrated Ohmic heating scales with Poynting flux:

$F_{Ohm} \sim P^{1/2}$



$$P = \eta(\nabla\times\boldsymbol{B})\times\boldsymbol{B} + (\boldsymbol{u}\times\boldsymbol{B})\times\boldsymbol{B}/\mu$$

Scaling laws – Model vs. Theory

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):

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

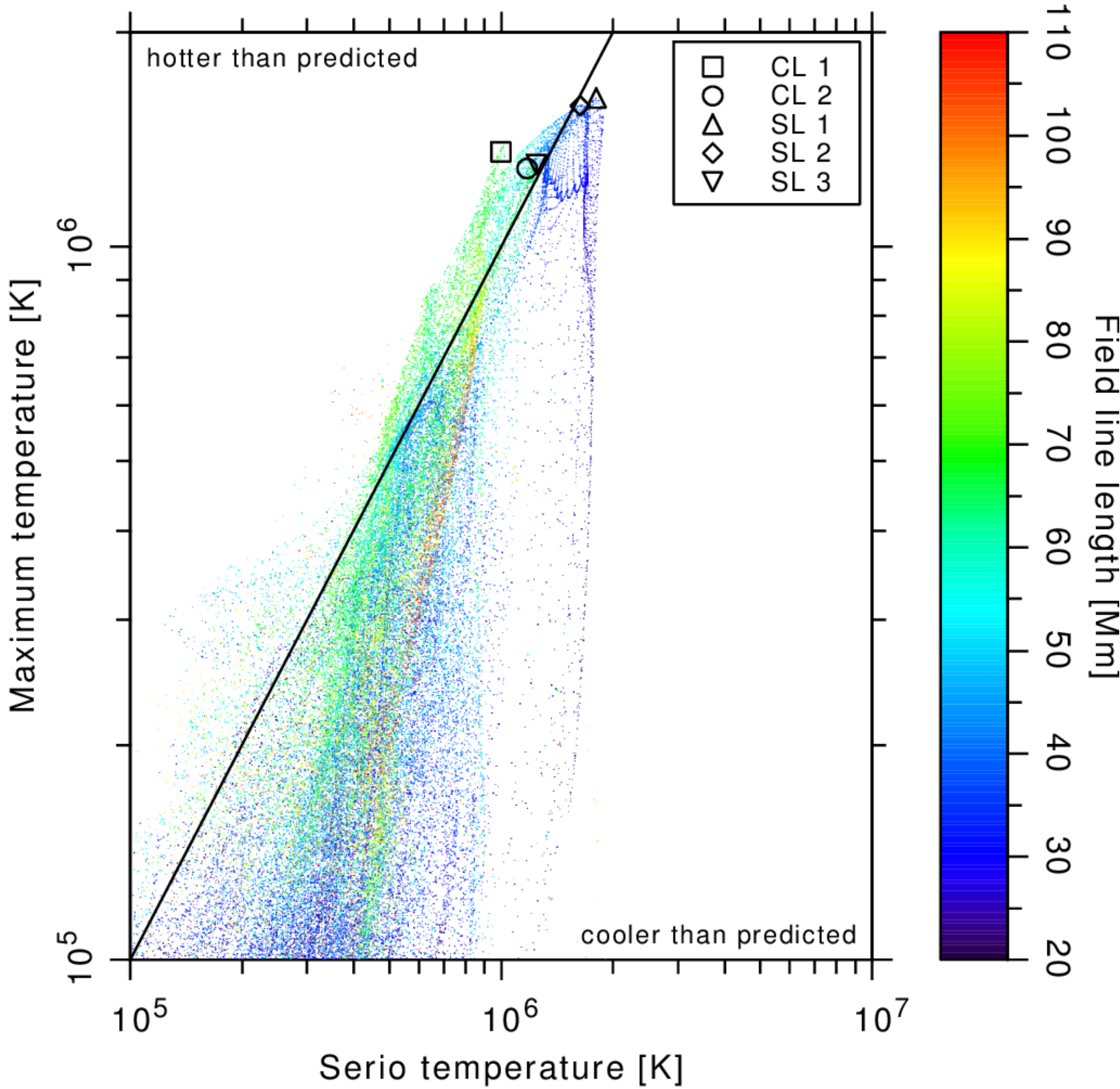
$$E_T = \exp\left\{ -0.04 \cdot L \left(\frac{2}{s_H} + \frac{1}{s_P} \right) \right\}$$

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

Scaling laws – Model vs. Theory

Serio temperature:

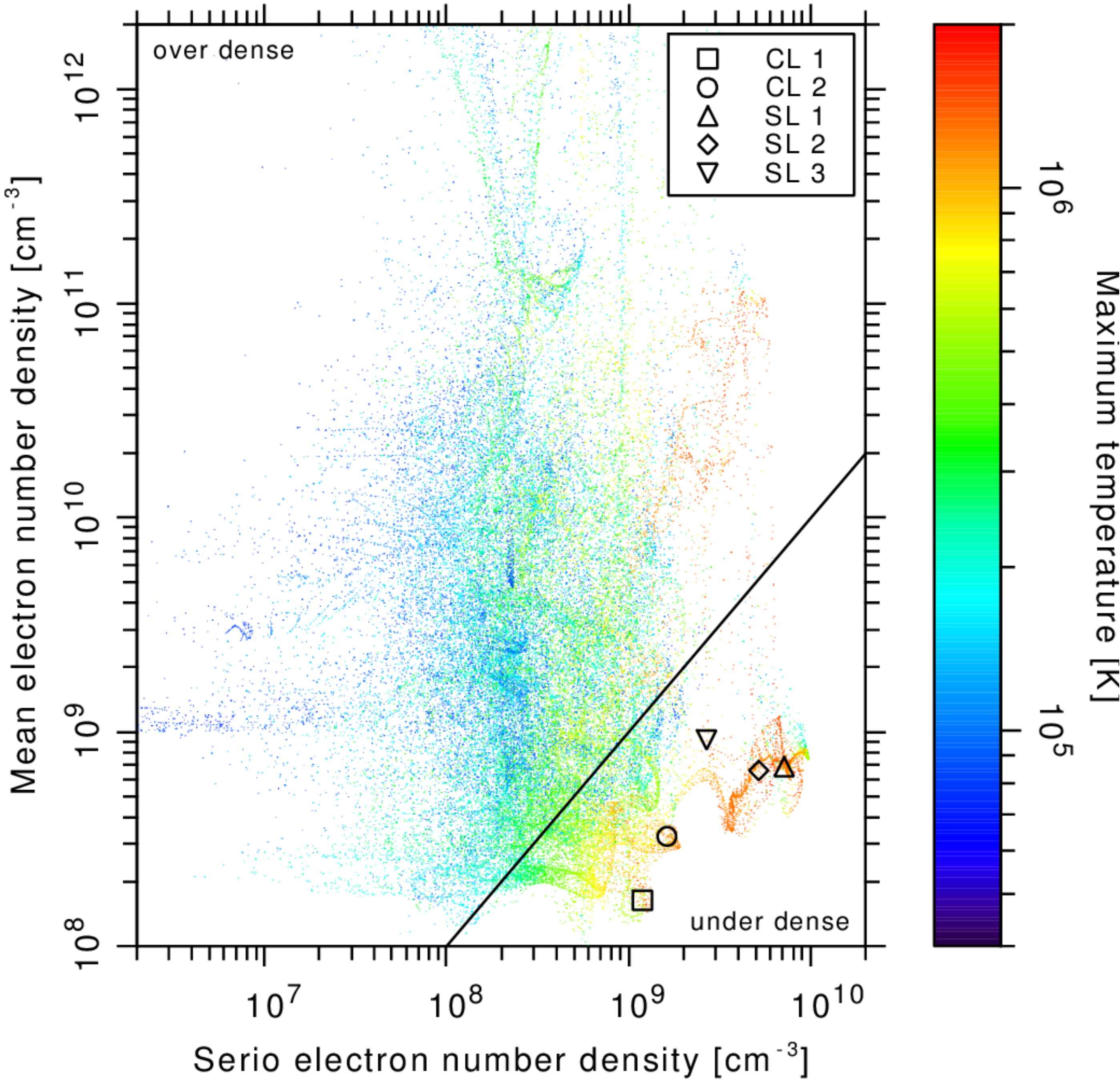
Coronal loops mainly follow RTV and Serio scaling law trend, but there can be large scatter.



Scaling laws – Model vs. Theory

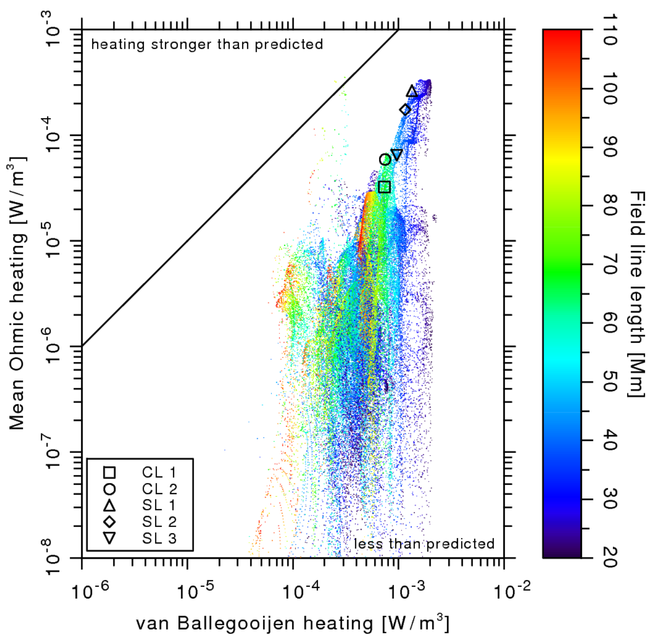
Serio density:

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

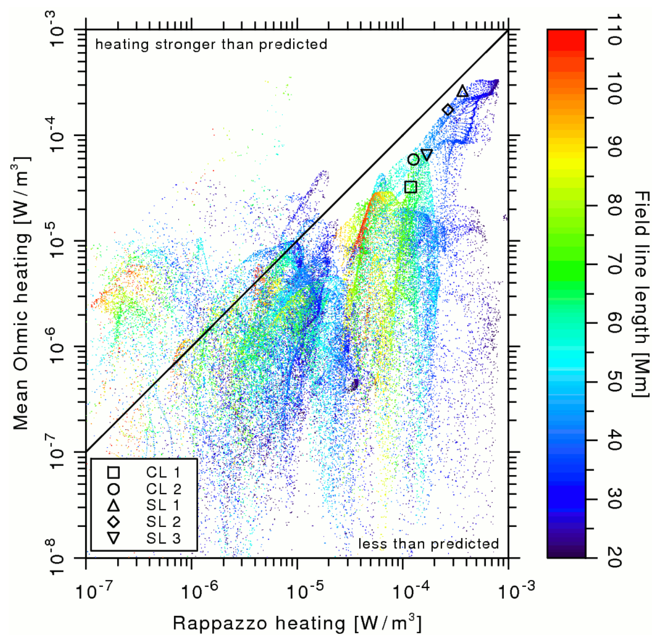


Scaling laws – Model vs. Theory

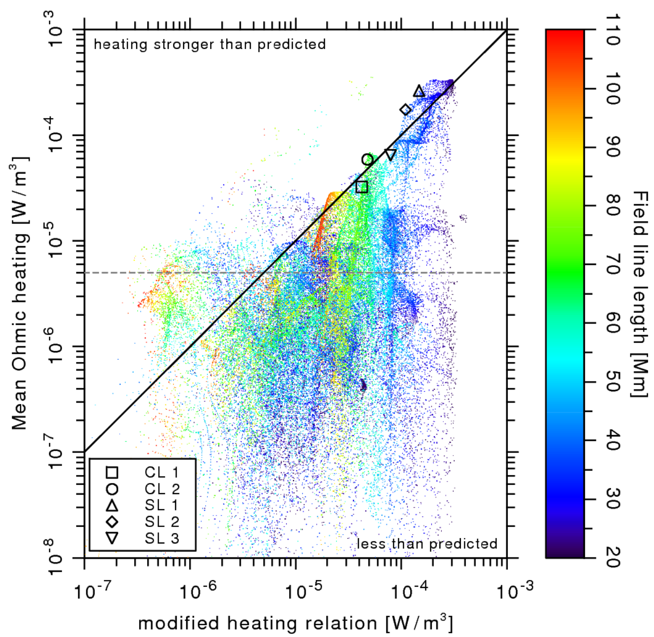
AC (van Ballegooijen)



MHD turb (Rappazzo)



AR (pab, thesis, 2013)



=> $$Q_{Ohm} = 2.9 \cdot 10^{-3} \cdot \frac{120\,\mathrm{s}}{\tau_A + 60\,\mathrm{s}} \cdot \left(\frac{n_\rho}{10^{15}}\right)^{\omega} \cdot \left(\frac{B_{cor}}{50\,\mathrm{G}}\right)^{\beta} \cdot \left(\frac{L}{50\,\mathrm{Mm}}\right)^{\gamma} \cdot \left(\frac{v_{RMS}}{1.48\,\mathrm{km/s}}\right)^{\delta} \; [\mathrm{W/m^3}]$$

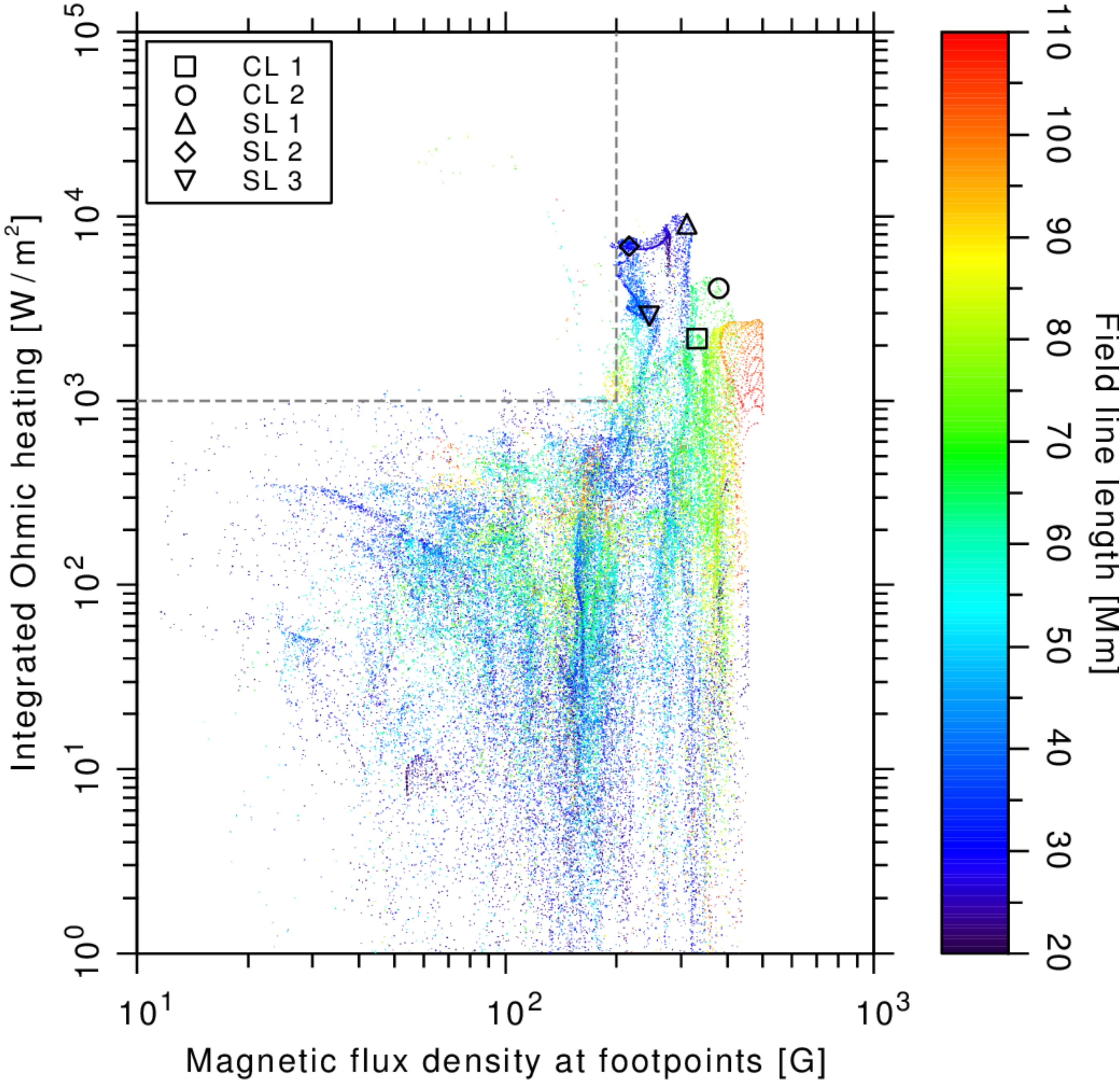
(Bourdin et al., 2014, PASJ, accepted)

Parameter	van Ballegooijen	Rappazzo	this work
β	0.55	1.75	1.25 ± 0.32
γ	−0.92	−1.75	−1.65 ± 0.42
δ	1.65	1.25	1.78 ± 0.51

Scaling laws – Model vs. Theory

Magnetic flux:

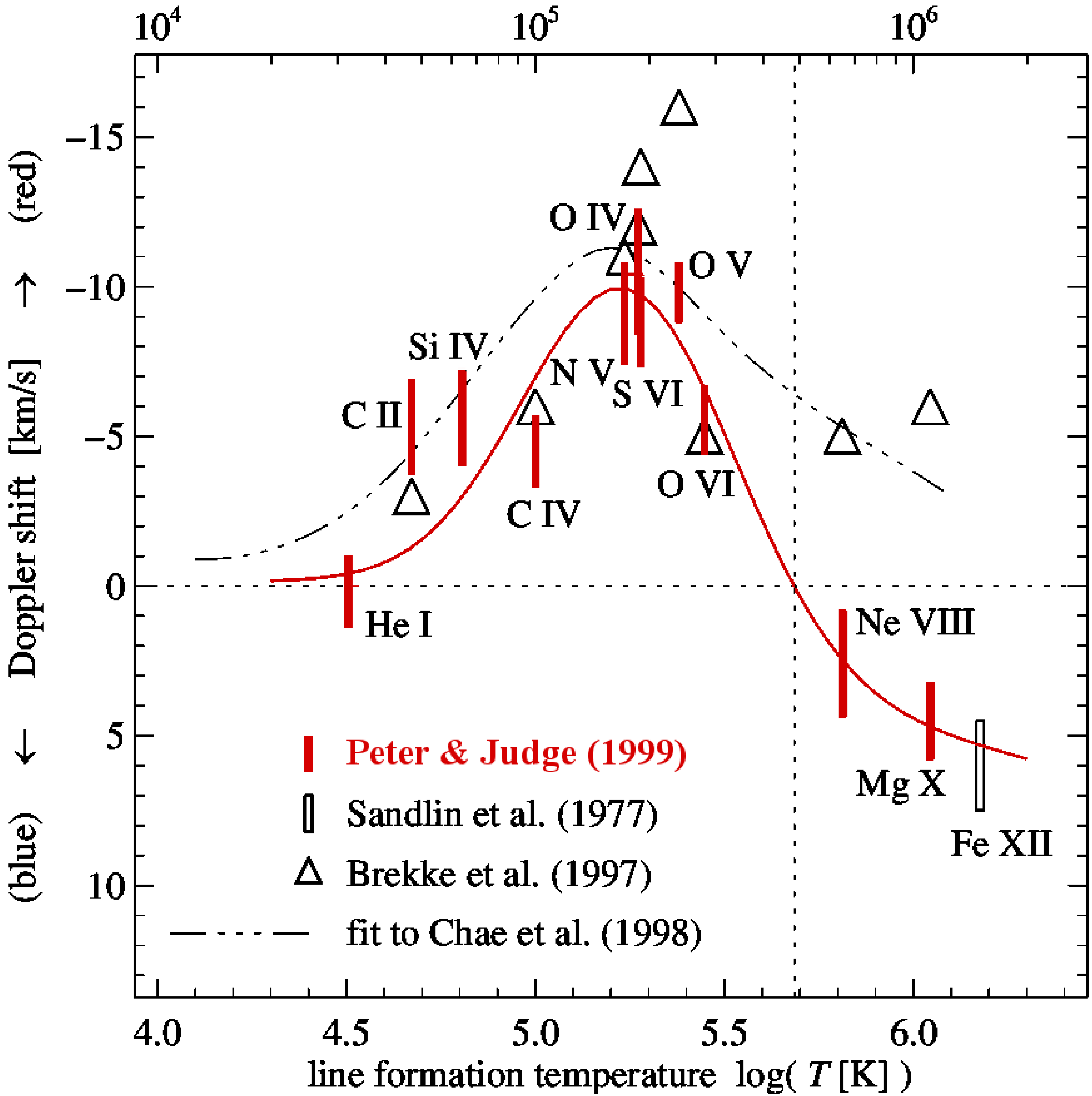
High Ohmic heating requires minimum magnetic flux at footpoints



Transition region and coronal Doppler-shift riddle

What is the Doppler-shift riddle?

- No infinite mass source @ log(T) = 5.7
- Atmosphere is typically not in a continuous flow-equilibrium



What is the Doppler-shift riddle?

- No infinite mass source @ log(T) = 5.7
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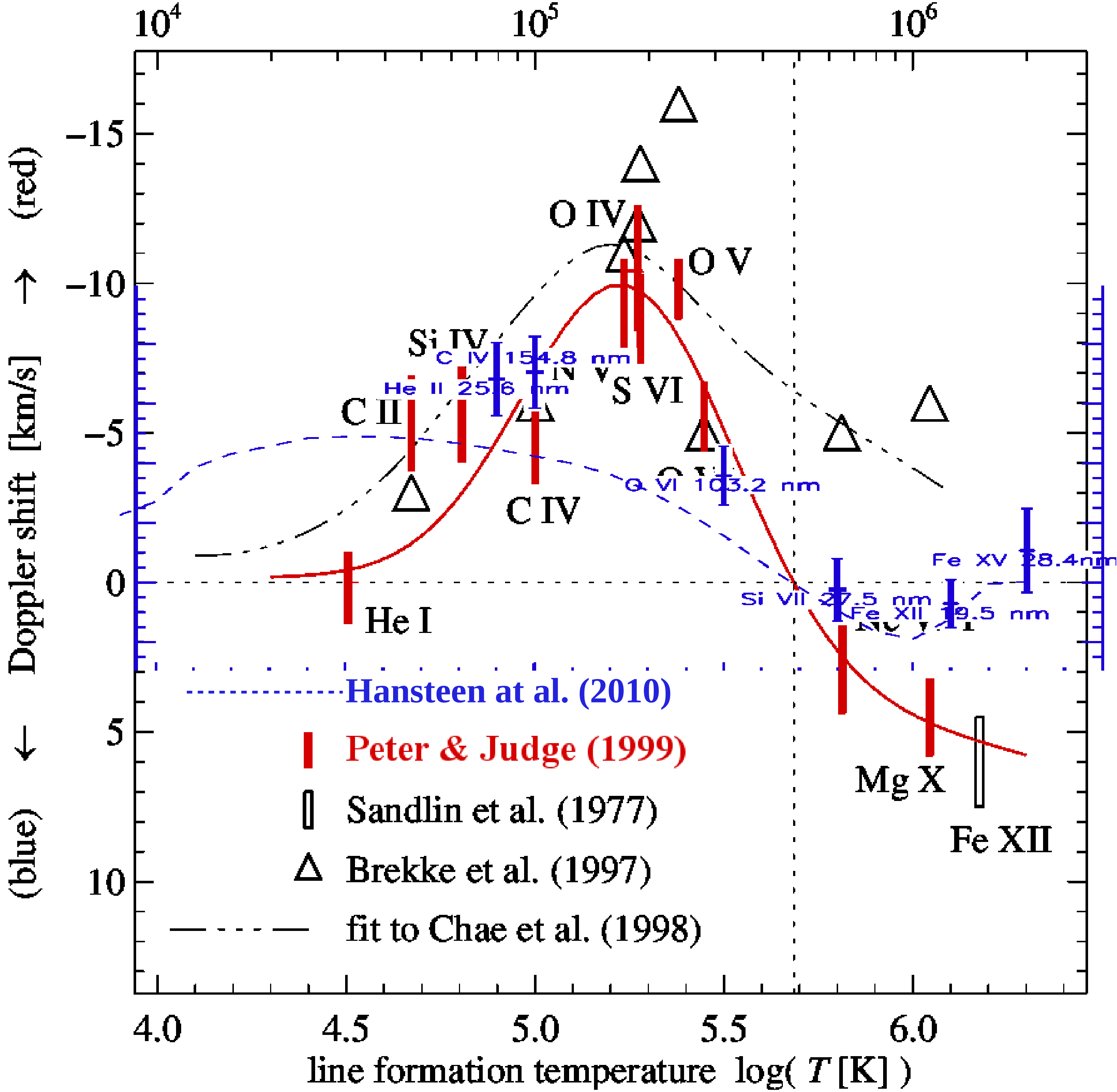
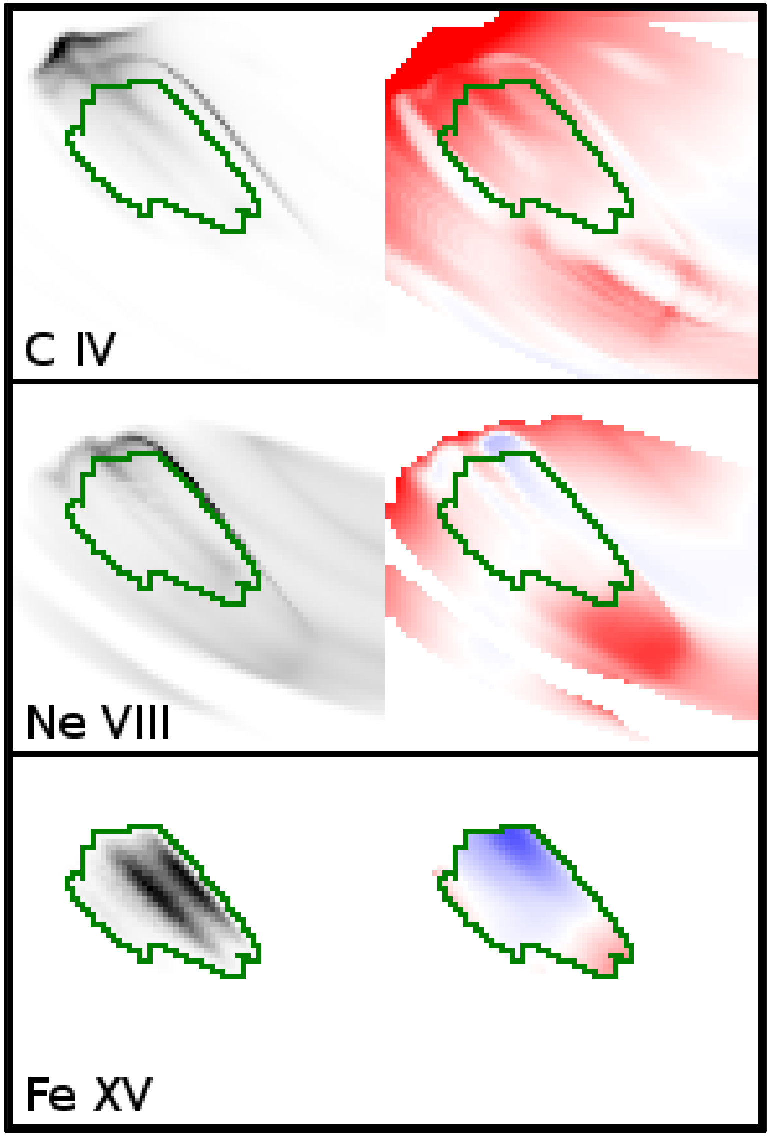


Statistical Doppler-shift analysis – Observation vs. Model

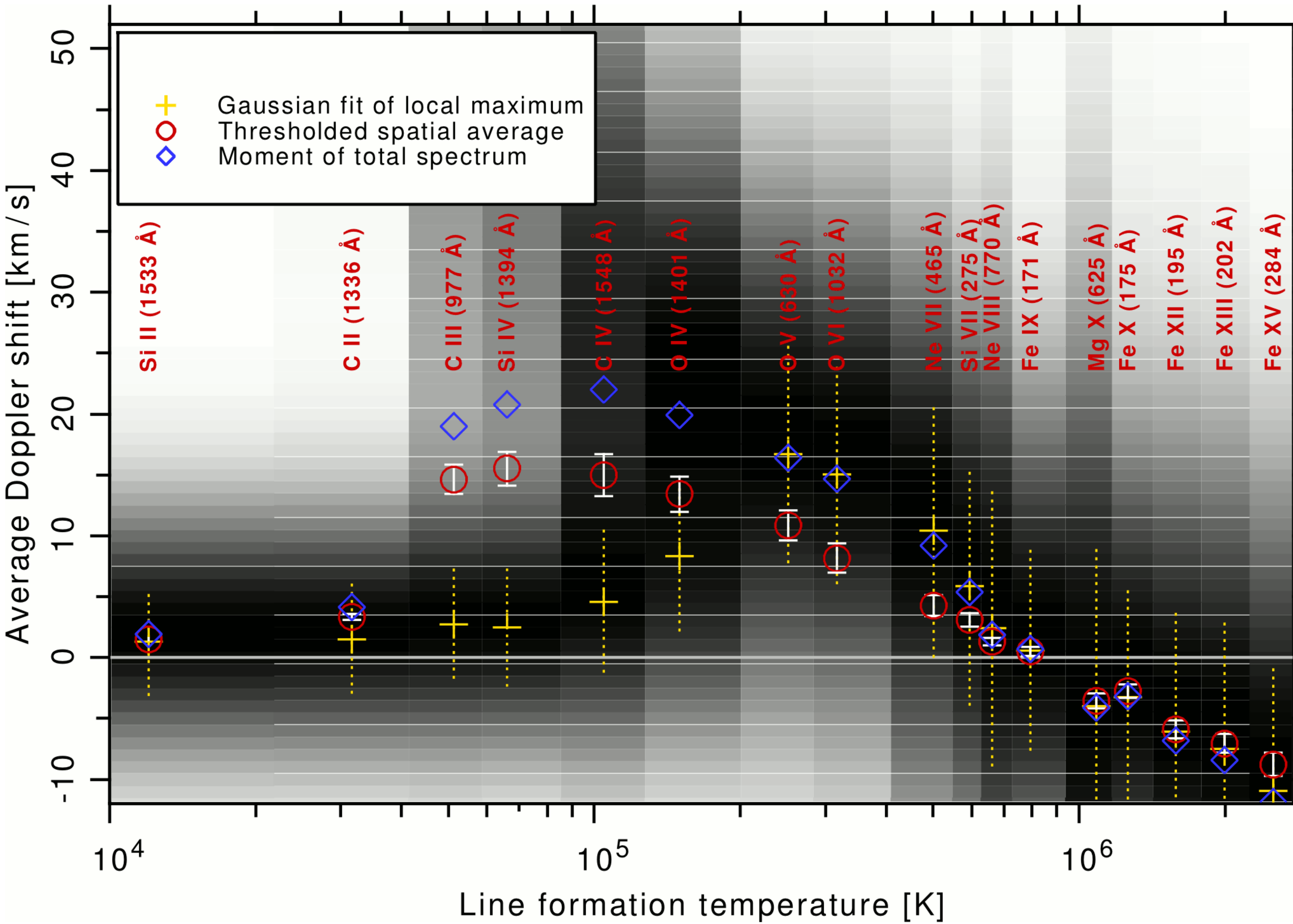
Intensity: Doppler shift: Line formation Temperature:



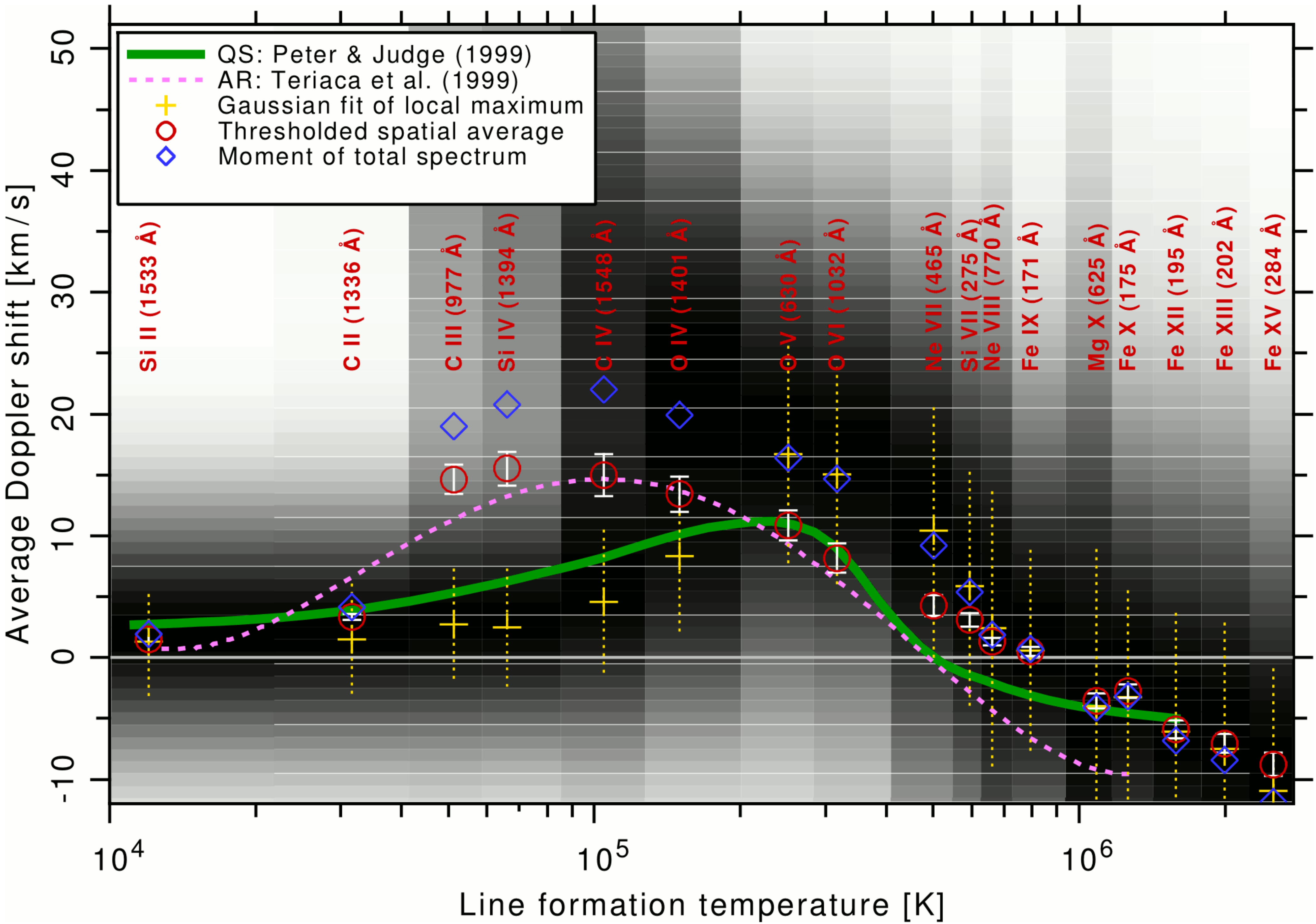
~ 100'000 K

~ 700'000 K

~ 1'500'000 K



Gaussian fit of local maximum
Thresholded spatial average
Moment of total spectrum
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]
Line formation temperature [K]
50
40
30
20
10
0
-10
10^4
10^5
10^6


QS: Peter & Judge (1999)
AR: Teriaca et al. (1999)
Gaussian fit of local maximum
Thresholded spatial average
Moment of total spectrum
Si II (1533 Å)
C II (1336 Å)
C III (977 Å)
Si IV (1394 Å)
C IV (1548 Å)
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Average Doppler shift [km/s]
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50
40
30
20
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0
-10
10^4
10^5
10^6

Summary:

Summary:

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

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

➡ Ohmic (DC) heating from field-line braiding drives 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”.

More specific...?

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

=> 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 E-parallel fields yields up to MeV electrons.

“Dankeschön!”