Coronal Heating through braiding of magnetic field lines

Solar eclipse, **11.8.1999**, Wendy Carlos & John Kern

Observable consequences

- 3D MHD model
- spectral synthesis
- results: Doppler shifts
  DEM
  variability
  spicules?
  plasma-beta

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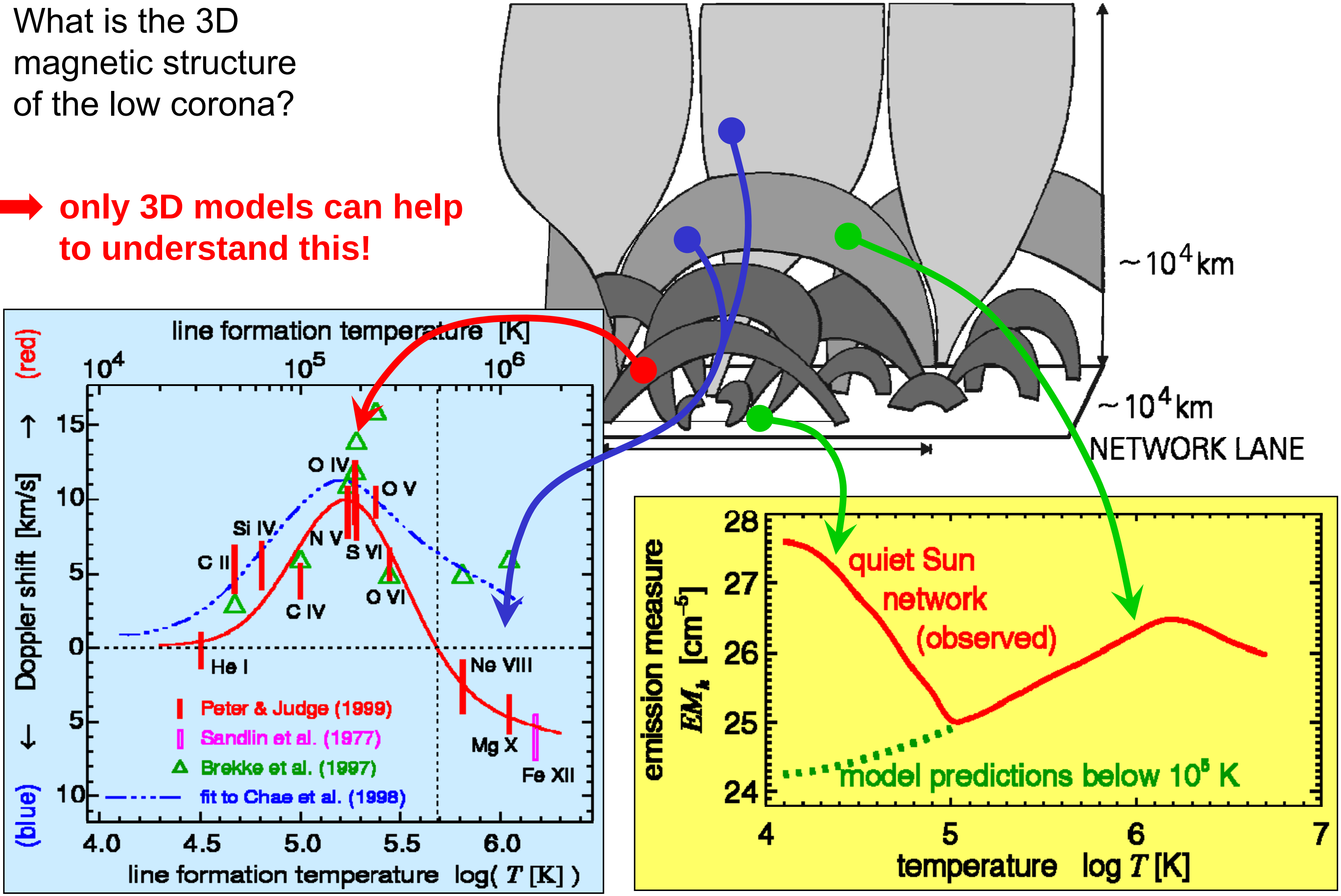
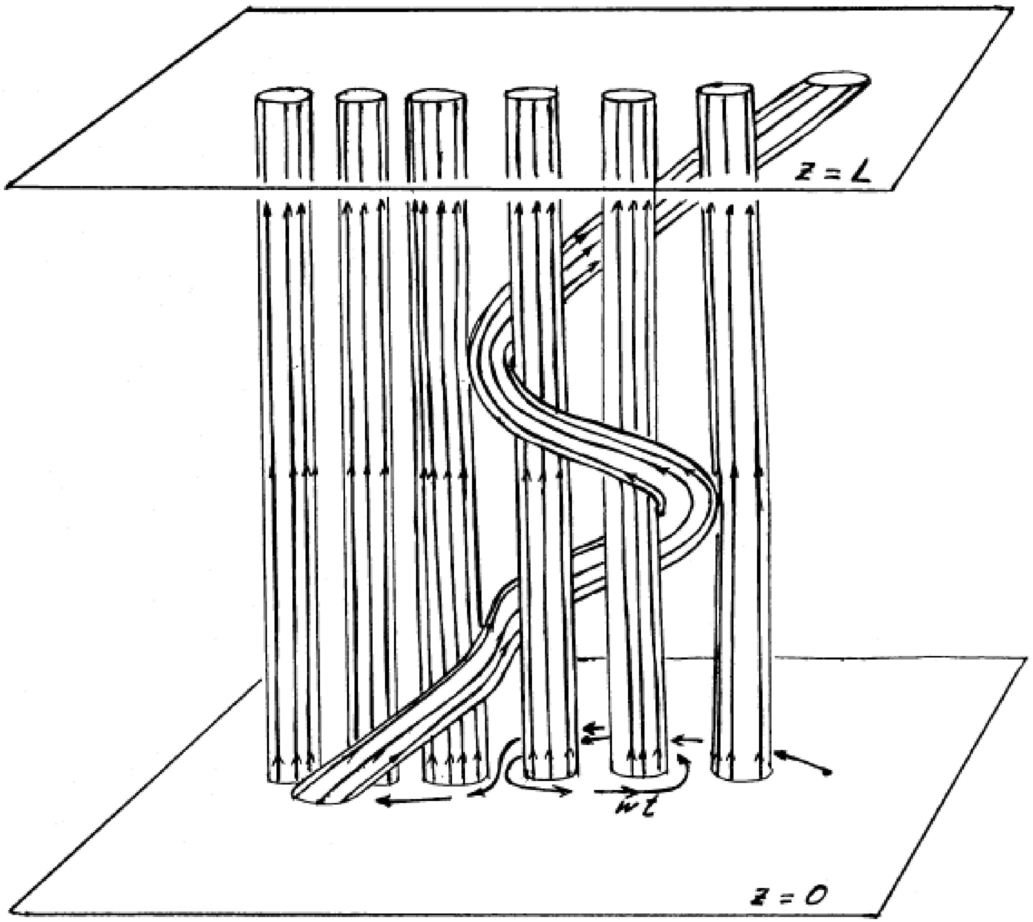
A multi–structured low corona

What is the 3D magnetic structure of the low corona?

➡ **only 3D models can help to understand this!**



A concept to heat the corona: magnetic braiding



Eugene Parker (1972, ApJ 174, 499):

braiding of magnetic field lines
through **random motions**
on the stellar surface

→ braided magnetic field
in the corona

→ strong currents
$\boldsymbol{j} \sim \nabla \times \boldsymbol{B}$

→ Ohmic dissipation
$H \sim \eta\, \boldsymbol{j}^2$

→ heating of the corona

***Problem*: a “realistic” computational model is “costly”…**

3D coronal modelling

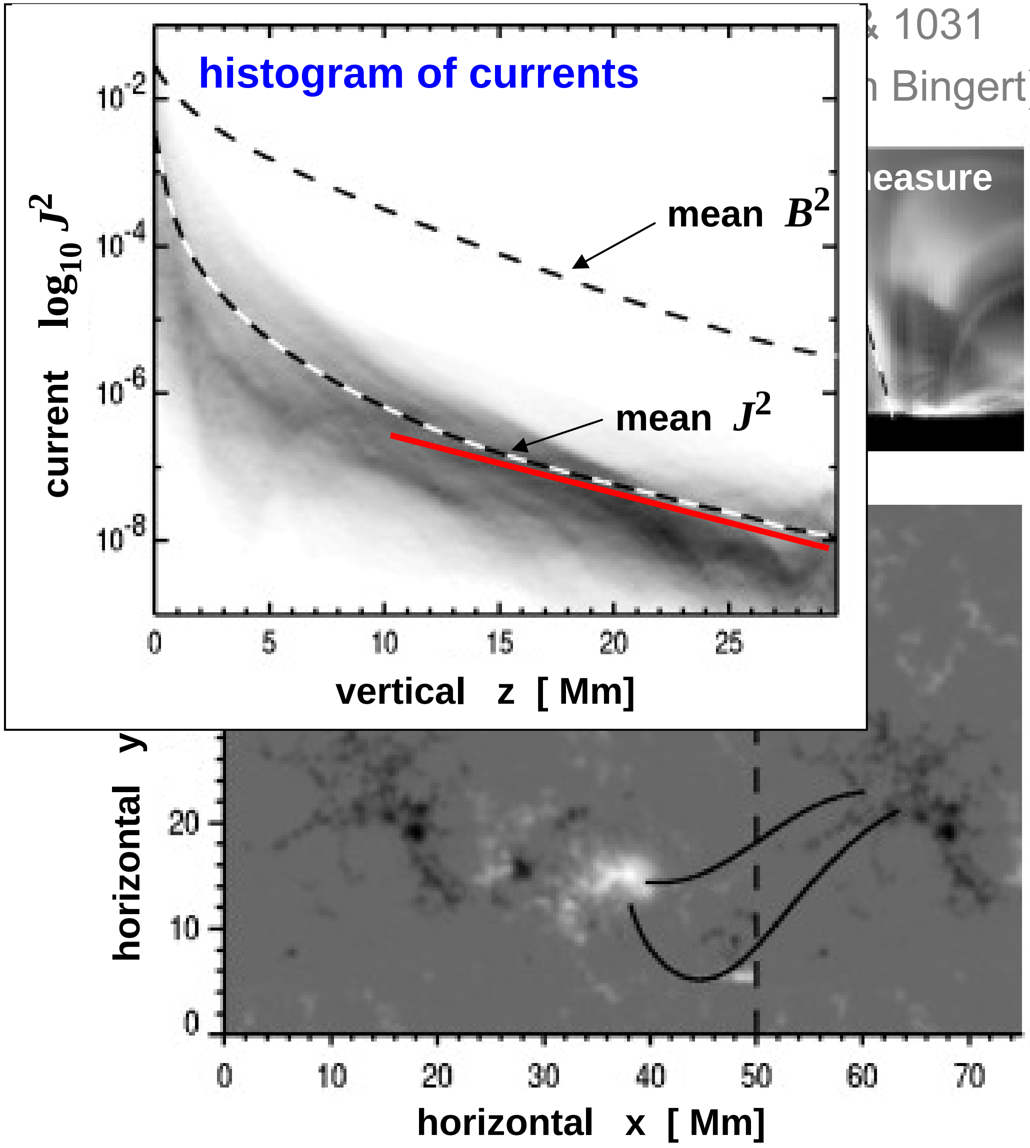
- 3D MHD model for the corona:
  50 x 50 x 30 Mm Box (now 150^3)
  – fully compressible; high order
  – non-uniform mesh
- full energy equation
  (heat conduction, rad. losses)
- starting with scaled-down
  MDI magnetogram
  – no emerging flux
- photospheric driver:
  foot-point shuffled by convection
- braiding of magnetic fields
  (Galsgaard, Nordlund 1995; JGR 101, 13445)

➔ heating: DC current dissipation
(Parker 1972; ApJ 174, 499)

➔ heating rate $\eta j^2 \sim \exp(- z/H)$

➔ loop-structured 10^6K corona

Gudiksen & Nordlund (2002) ApJ 572, L113



Emissivity from a 3D coronal model

From the MHD model: – density ρ (fully ionized) → n_e
– temperature → T
} { at each grid point and time

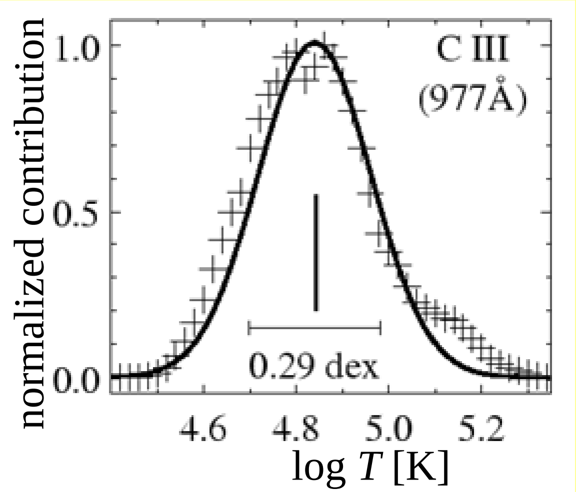
Emissivity at each grid point and time step:

$$\varepsilon(\boldsymbol{x},t) = h\nu\, n_2 A_{21} = n_e^2\, G(T,n_e) \quad \left[\frac{\mathrm{W}}{\mathrm{m}^3}\right]$$

$$G(T,n_e) = h\nu A_{21} \frac{n_2}{n_e\, n_{ion}} \frac{n_{ion}}{n_{el}} \frac{n_{el}}{n_H} \frac{n_H}{n_e}$$

- $\frac{n_H}{n_e}$: total ionization ≈0.8
- $\frac{n_{el}}{n_H}$: abundance = const.
- $\frac{n_{ion}}{n_{el}}$: ionization } ≈ $f(T)$
- $\frac{n_2}{n_e\, n_{ion}}$: excitation } ≈ $f(T)$

emissivity in the computational box as a function of T



Assumptions:

– equilibrium excitation and ionisation (not too bad...)

– photospheric abundances

use CHIANTI to evaluate ratios (Dere et al. 1997)

→ $\boldsymbol{G}$ depends mainly on T (and weakly on n_e)

Synthetic spectra

1) emissivity at each grid point → $\varepsilon(\mathbf{x},t)$
2) velocity along the line-of-sight from the MHD calculation → $v_{\rm los}$
3) temperature at each grid point → T

line profile at each grid point:

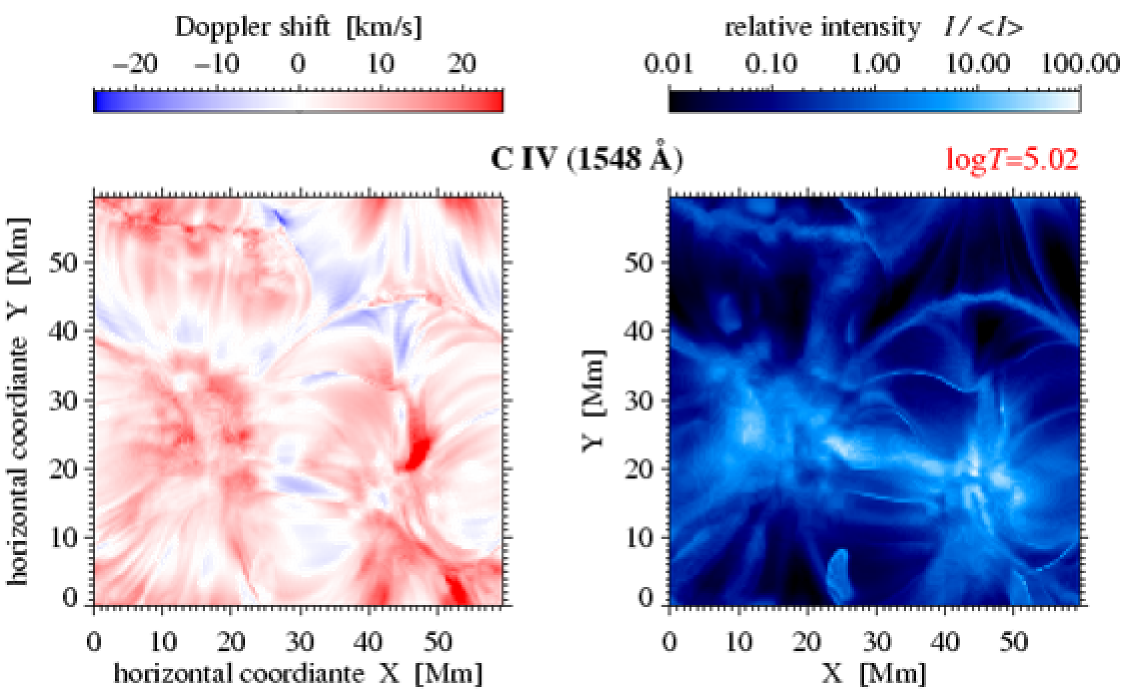
$$I_\nu(\mathbf{x},t) = I_0 \exp\left[-\frac{(v - v_{\rm los})^2}{w_{th}^2}\right]$$

line width corresponding to thermal width $\quad w_{th} = \sqrt{\frac{2\,k_{\rm B}\,T(\mathbf{x},t)}{m_{\rm ion}}}$

total intensity corresponding to emissivity $\quad I_0\, w_{\rm th} \propto \varepsilon(\mathbf{x},t)$

integrate along line-of-sight

maps of spectra
as would be obtained by a scan
with an EUV spectrograph,
e.g. SUMER



analyse these spectra like observations

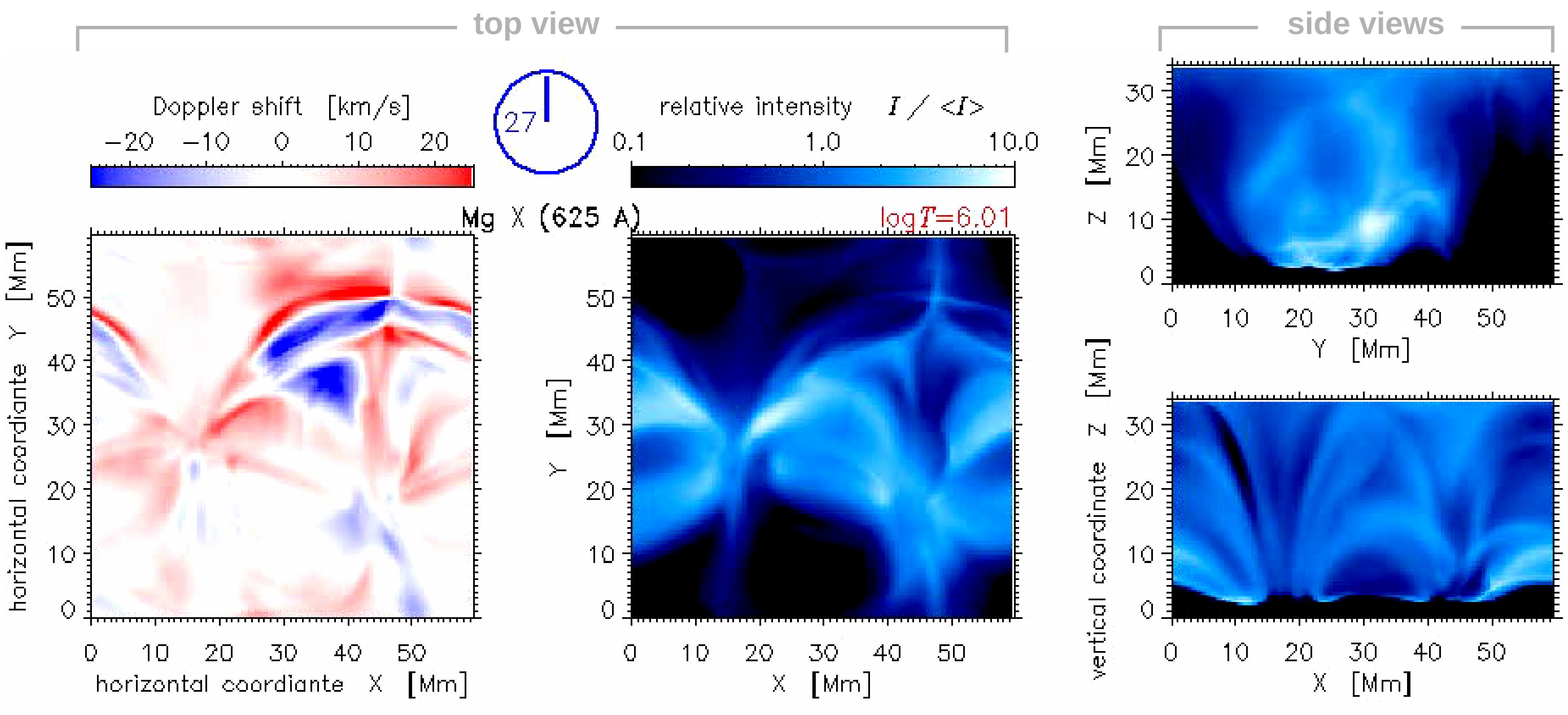
– calculate moments: line intensity, shift & width
– emission measure (DEM)
– etc. ...

Coronal evolution

Mg X (625 Å)
~10^6 K

- large coronal loops connecting active regions
- gradual evolution in line intensity ("wriggling tail")
- higher spatial structure and dynamics in Doppler shift signal

→ it is important to have full spectral information!



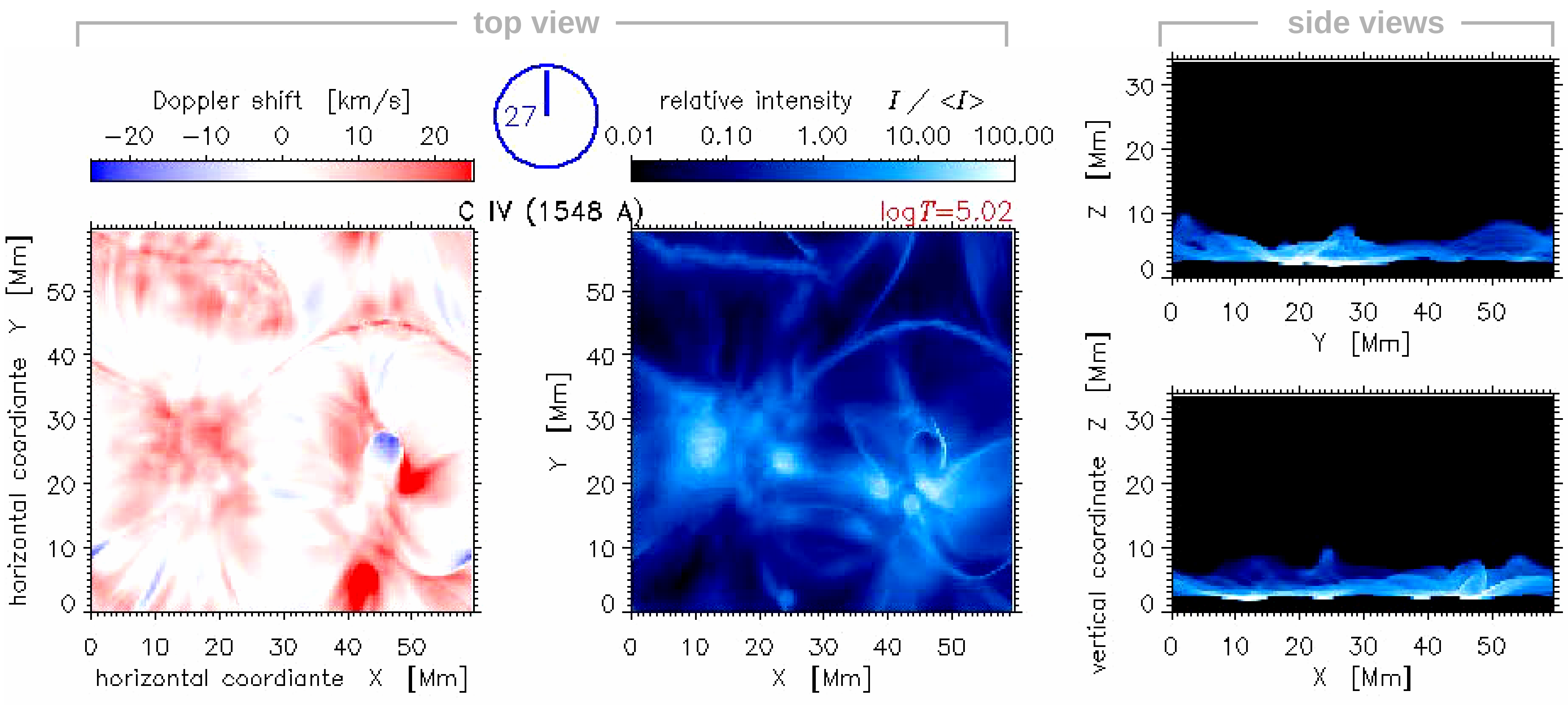
Transition region evolution

C IV (1548 Å)

~10^5 K

- very fine structured loops – highly dynamic
- also small loops connecting to “quiet regions”
- cool plasma flows – locks like “plasma injection”

→ dynamics quite different from coronal material !



Doppler shifts

spatial and temporal averages

+ very good match in TR

+ overall trend v_D vs. T quite good

– still no match in low corona

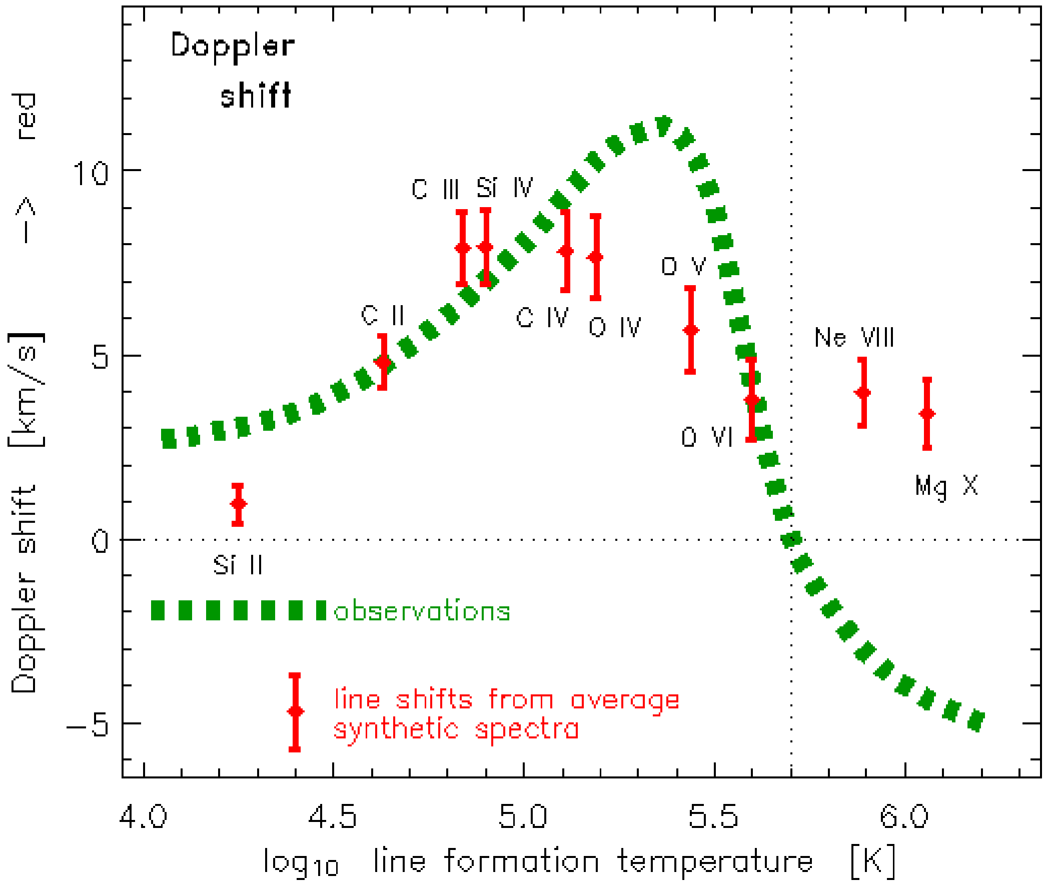
  $\rightarrow$ boundary conditions?

  $\rightarrow$ missing physics?

temporal variability

+ high variability as observed

o for some times almost net blueshifts in low corona!



➡ **no "fine-tuning" applied !**

➡ **best over-all match of models so far**

Emission measure

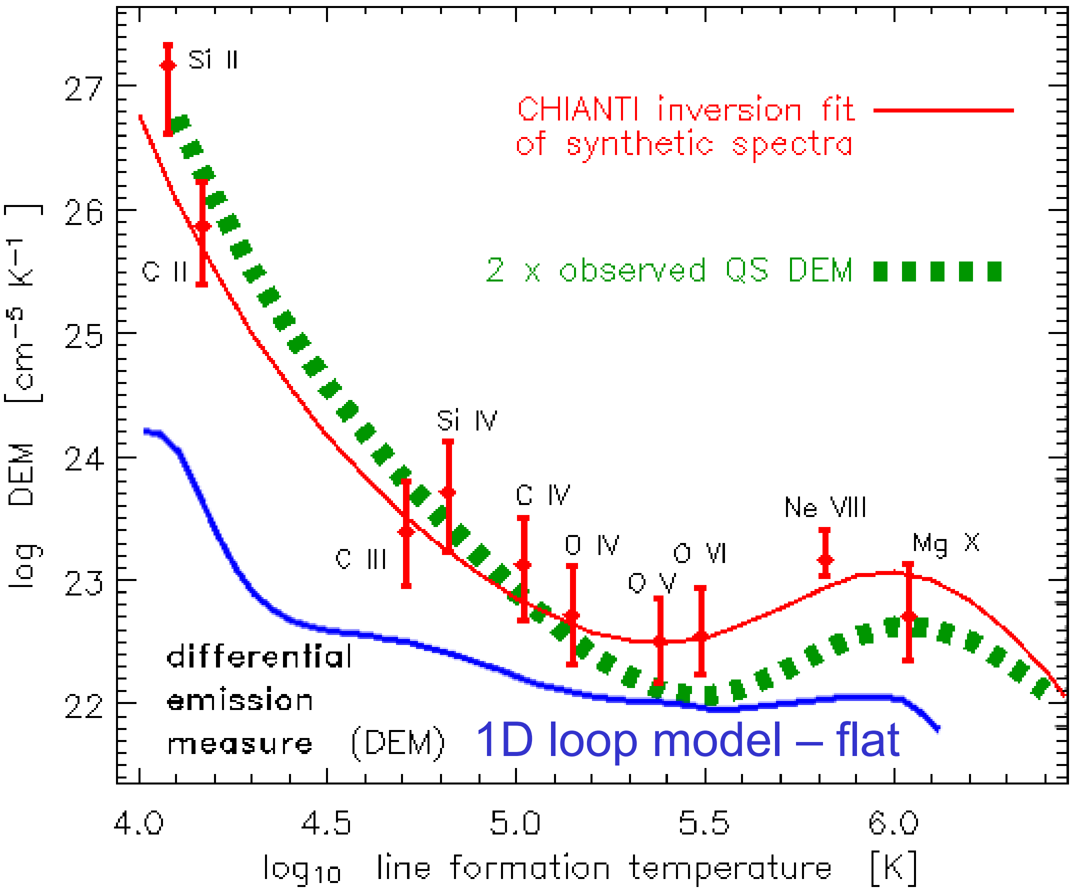
$$DEM = n_e^2 \frac{dh}{dT}$$

DEM inversion using CHIANTI:

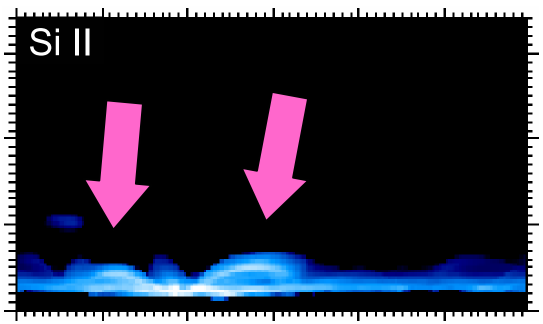
1 – using synthetic spectra derived from 3D MHD model

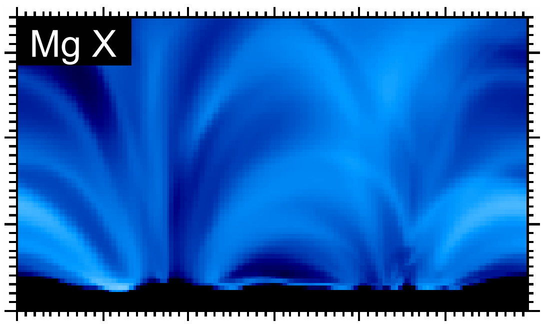
2 – using solar observations (SUMER, same lines)

➡ good match to observations!! DEM increases towards low *T* in the model !

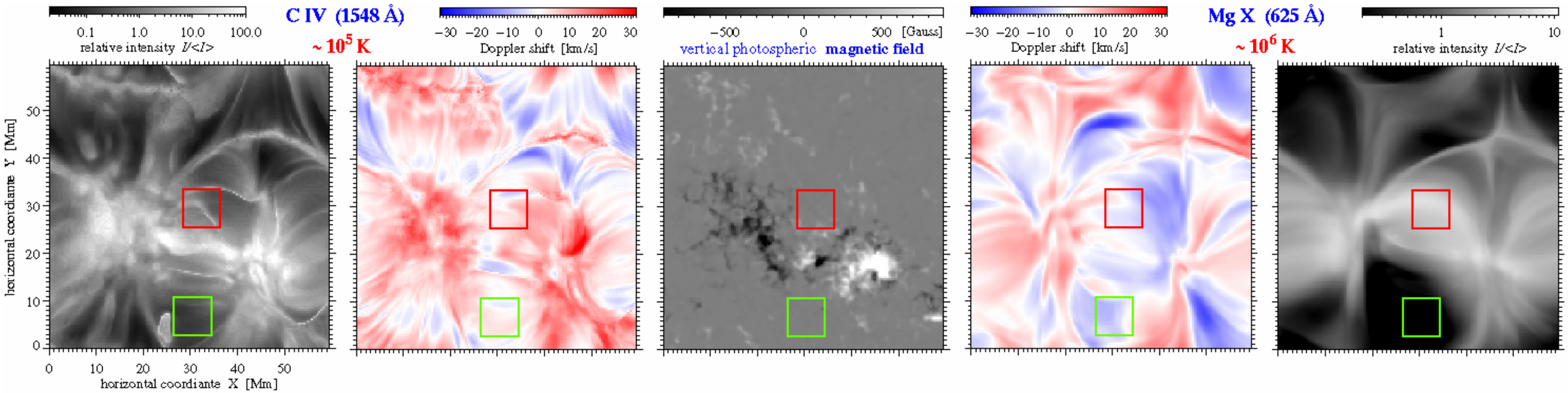


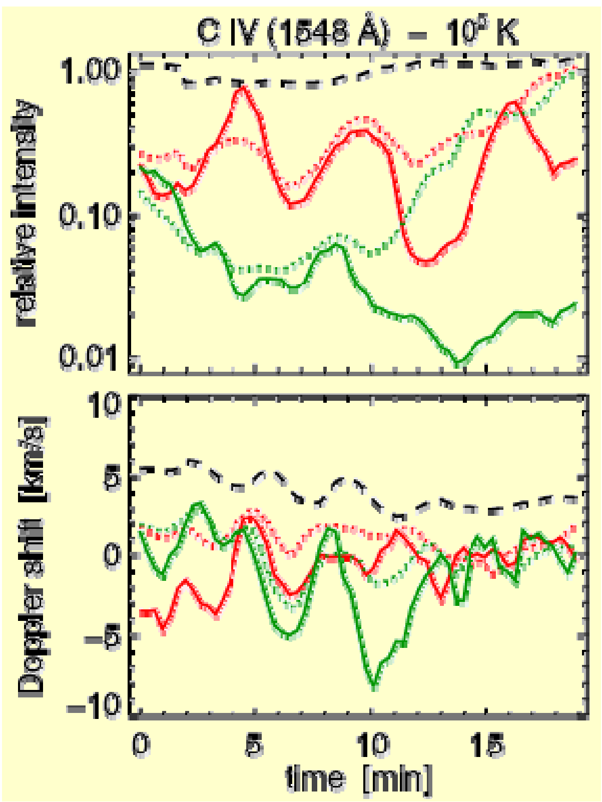
Supporting suggestions that numerous cool structures cause increase of DEM to low *T*





Temporal variability: individual examples





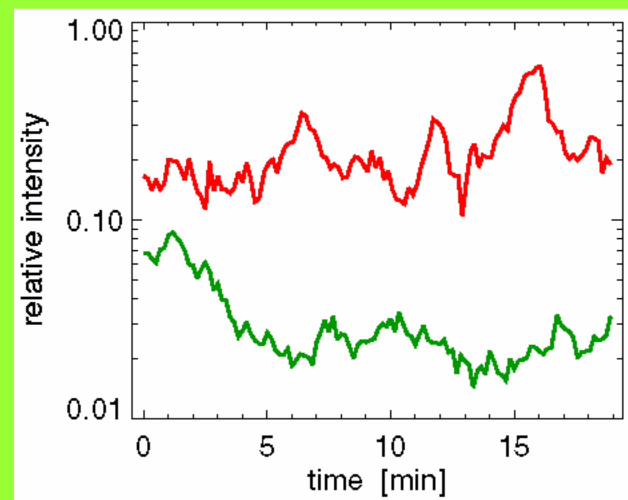
- large variability in TR
- smooth variation in coronal intensity
- variability in coronal shift comparable to TR !!
- ~5 – 7 min variability signature of the photospheric driver?
- similar variations found in observations!

A real observation:

SUMER / SOHO

S IV (1394 Å) ~ 10^5 K

1x1'', 10 sec exposures



Temporal variability: average properties

observations:

[Brković, Peter & Solanki (2003), A&A 403, 725]

- ➢ rms intensity fluctuations have pronounced peak at ~10^5 K
- ➢ rms Doppler shift variations increase monotonically

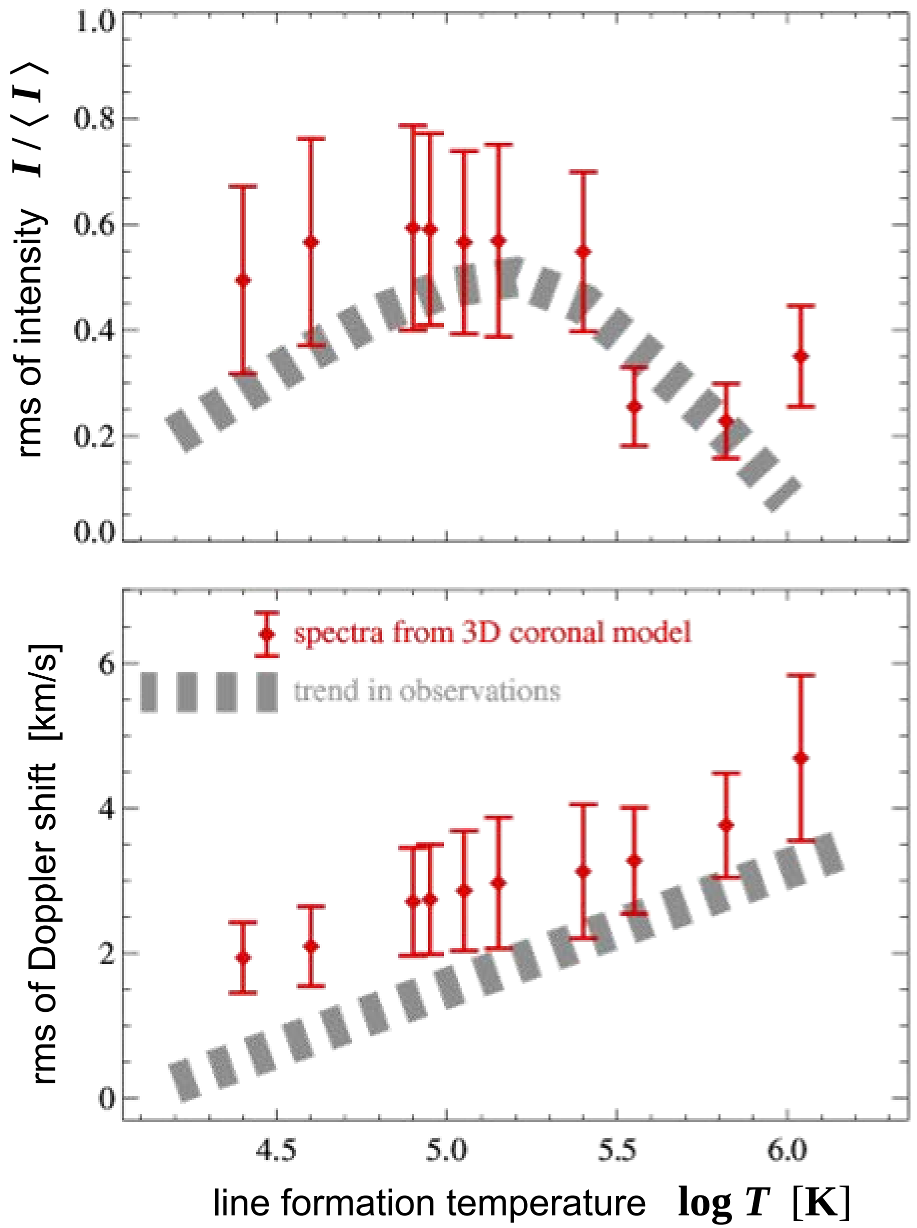
synthetic spectra from 3D model

+ very good match of observed trend(s)

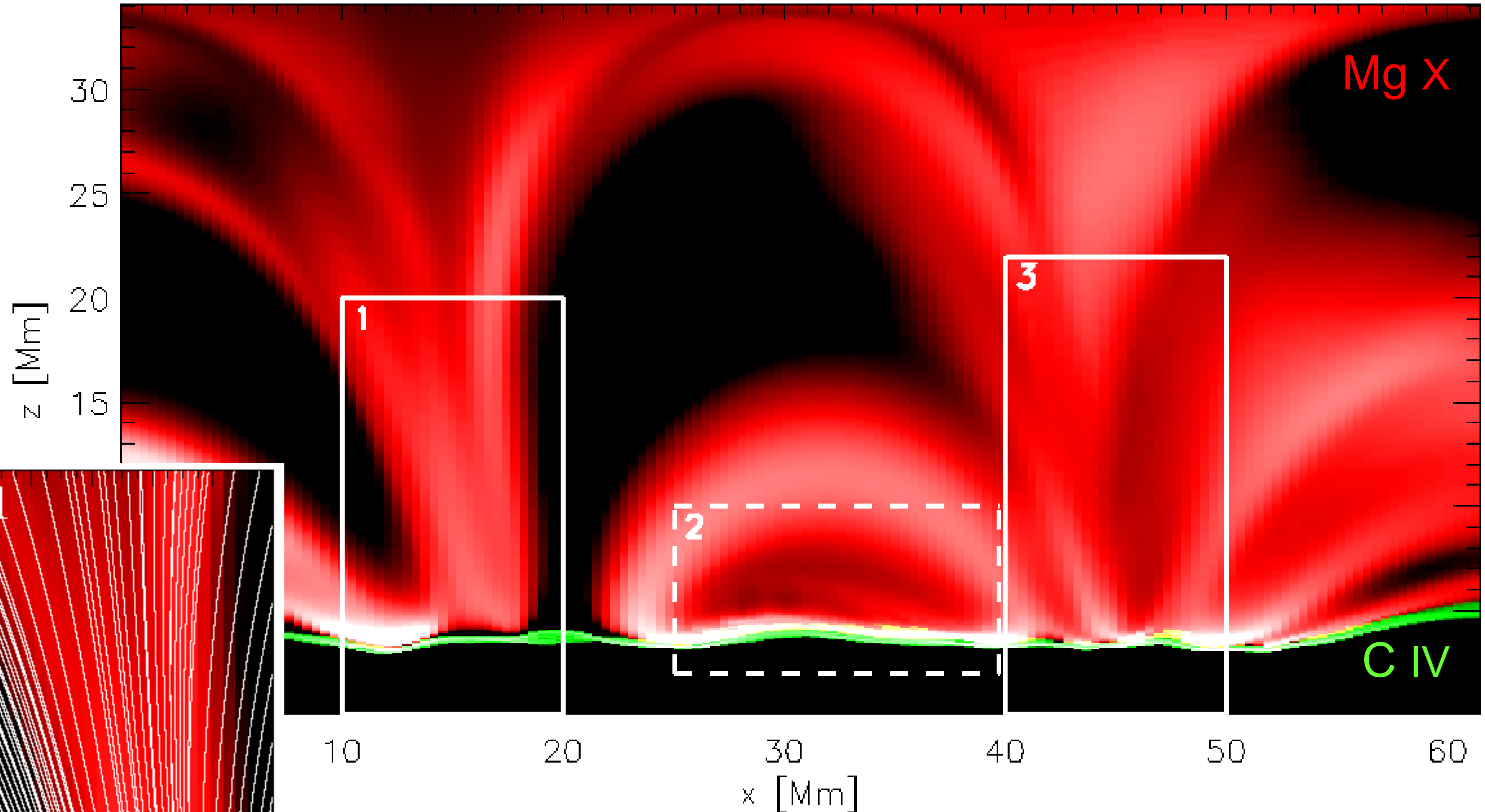
+ correct description of "overall" variability

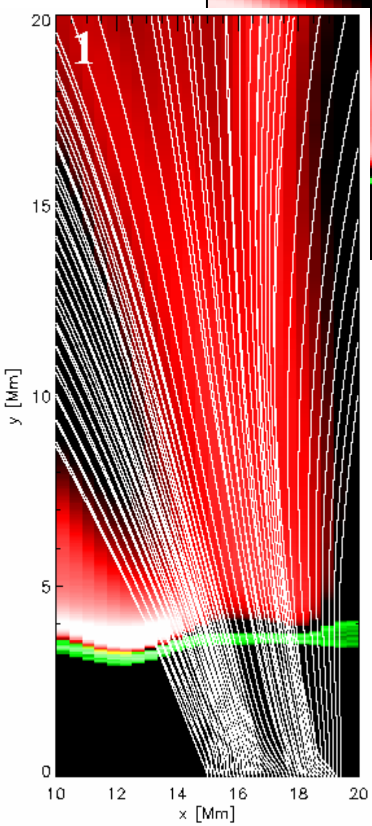
– real Sun shows variations on much shorter times (seconds)

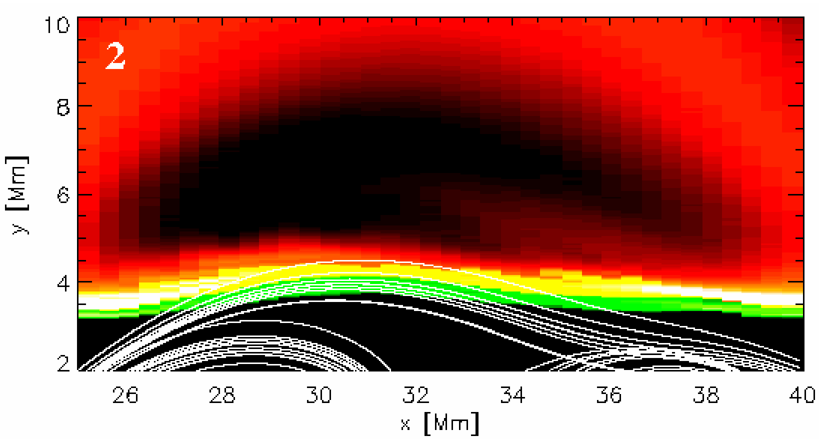
↪ lack of spatial resolution in 3D MHD model ?

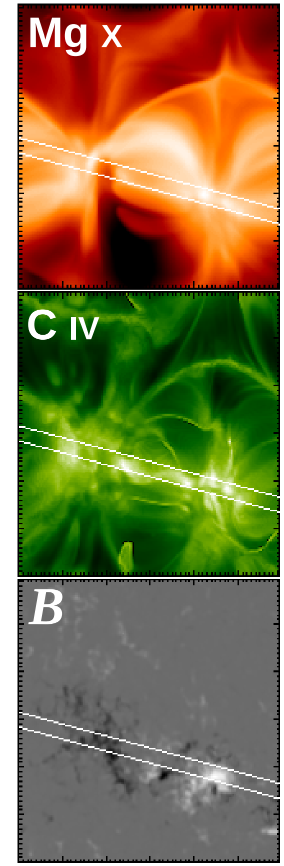


Magnetic structure: from TR → Corona









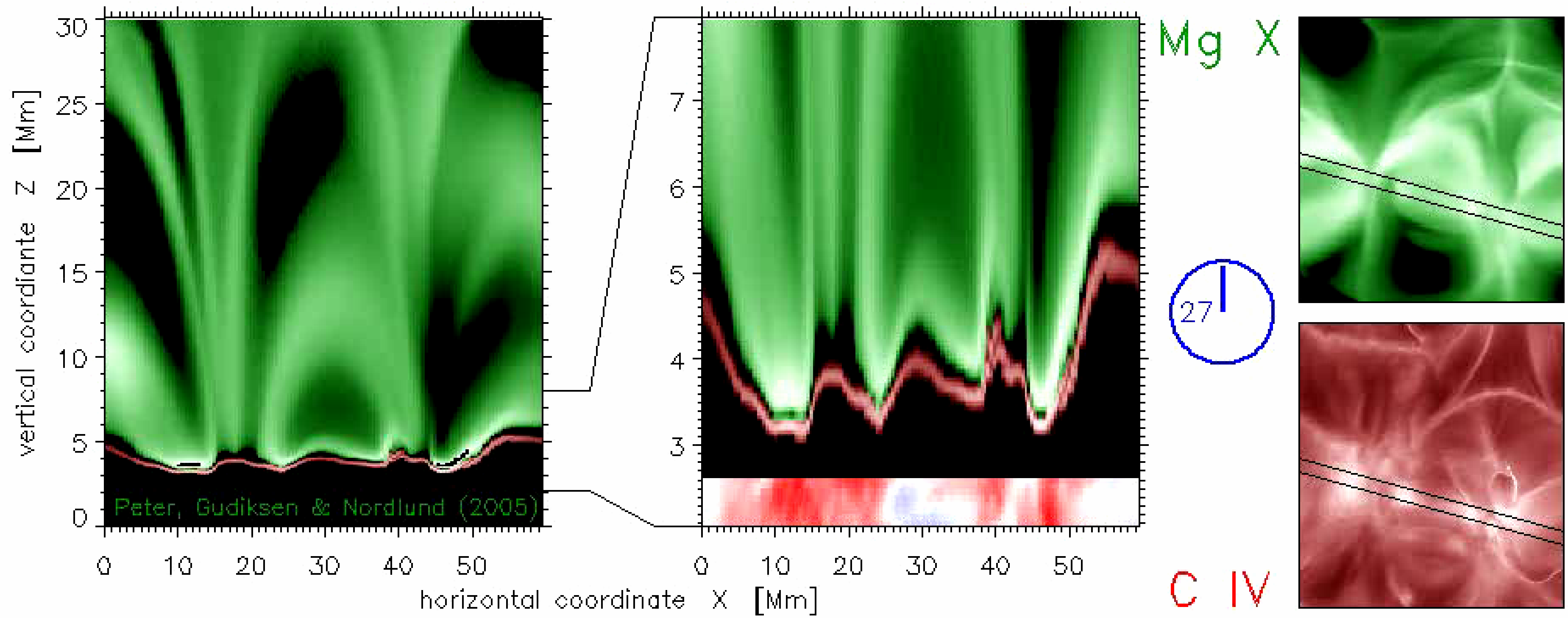
Bingert, Peter, Gudiksen & Nordlund (2005)

- no cool detached structures

(1) TR ⊥ ***B*** above magnetic concentrations

(2) TR || ***B*** above above non-magnetic areas

A cooling front: is this a spicule?



- ➢ transition region is intricately folded / highly convoluted (TR height some Mm)
- ➢ high time-variability

- ➢ upward moving cooling front || ***B***
  - – coronal material is falling down (C IV redshifted)
  - – TR shows apparent upward motion

➡ is a spicule hidden in the dark core ??

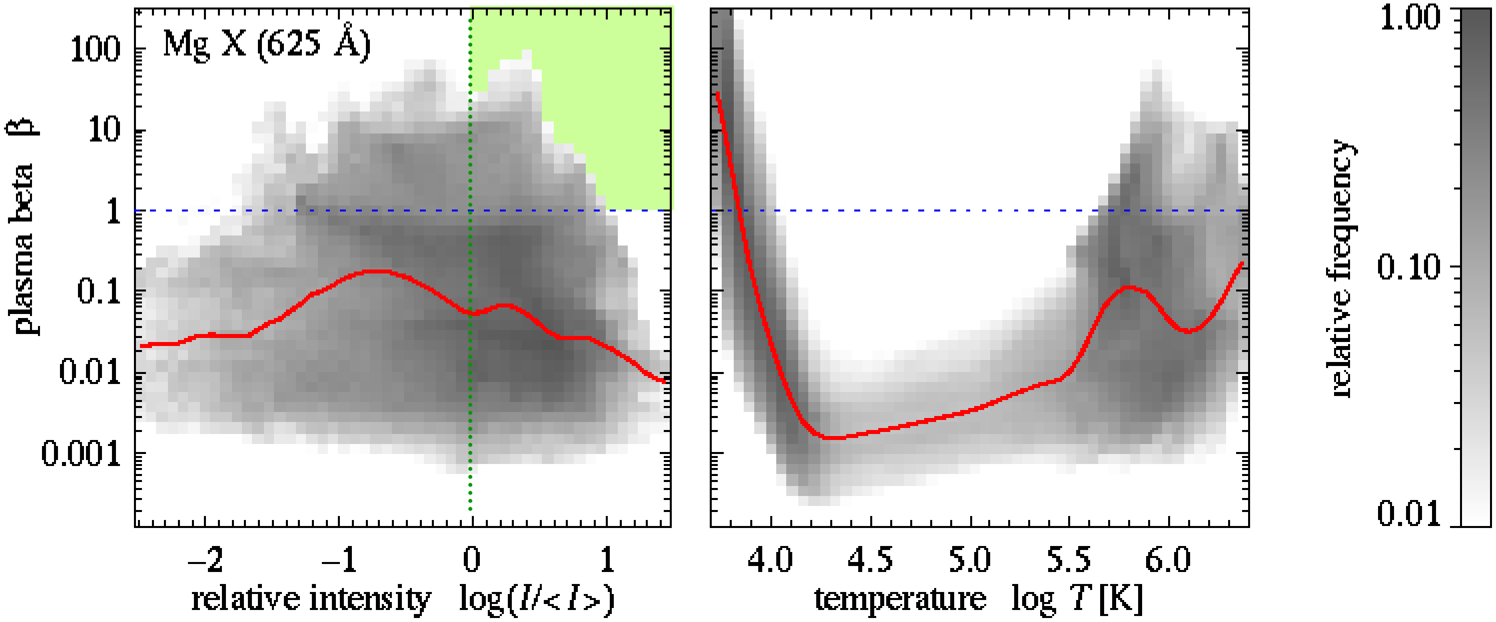
properties of cooling front

v_{up} ~ 20 km/s

height ~ 7 Mm

∅ dark core < 2 Mm

Coronal emission and plasma–β



- atmosphere is *mostly* in low–β state,
- numerous $\beta > 1$ regions even at high T (but mostly at low density)
- source region of coronal emission:
  90% of emission from $\log I/\langle I \rangle > 0$
  ➥ there ~5% of volume at $\beta > 1$
- corona is **not** in a pure low–β state:
  plasma able to distort magnetic field to some extent

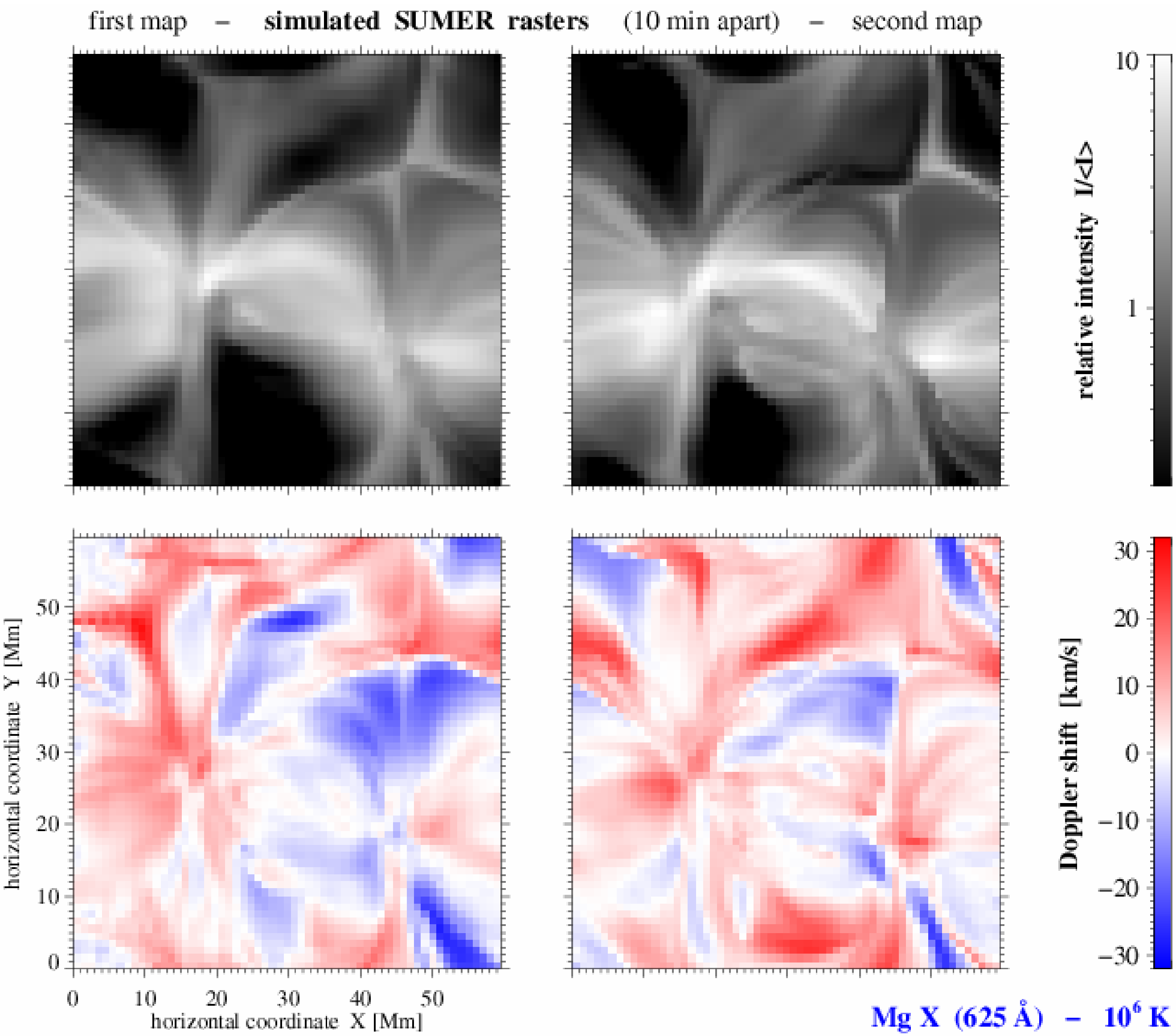
How would a spectrometer see the model?

- use synthetic spectra from 3D MHD model
- perform a raster as SUMER would see the model

- spat. resolution: 1 Mm
- exposure time: 10 sec
- one raster in: 10 min
- barely possible with SUMER (S/N)

two subsequent rasters:

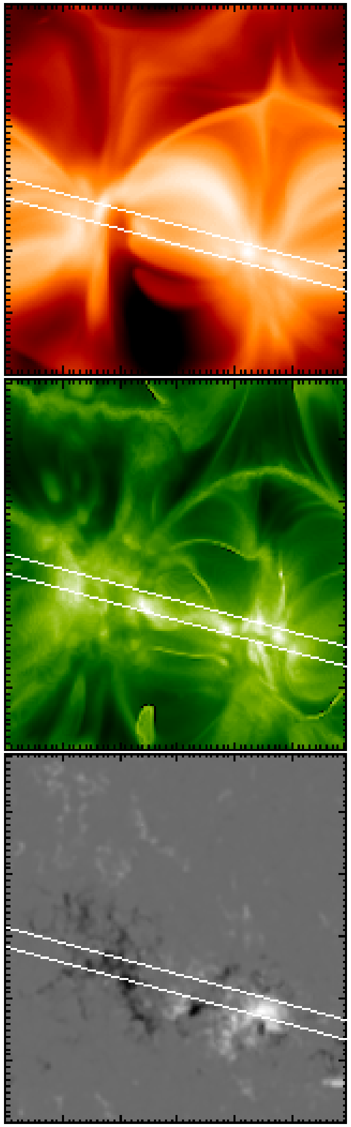
- similar appearance in intensity
- big difference in Doppler shift



➡ **necessity for fast scanning EUV spectrometer !**

Conclusions

- **spectra synthesized from the 3D model match observed...**
  - + TR Doppler shifts
  - + emission measure, especially at $T<10^5$ K
  - + variability in Doppler shift and line intensity
  - + apparent height of TR
- good arguments for **flux braiding as (the) heating mechanism** in moderately active regions
- transition region and low corona consist of a hierarchy of structures
  ➥ no cool *detached* TR structures
- corona is **not** in a pure low–β state:
  plasma able to distort magnetic field to some extent
- simulated raster scans show
  need for fast scanning EUV spectrometer



Outlook

- improve model – MHD & ionization
- apply to other structures: network
- stellar structures
- help for future instrumentation