

Synthetic EUV spectra from 3D MHD model

understanding emission measures and Doppler shifts



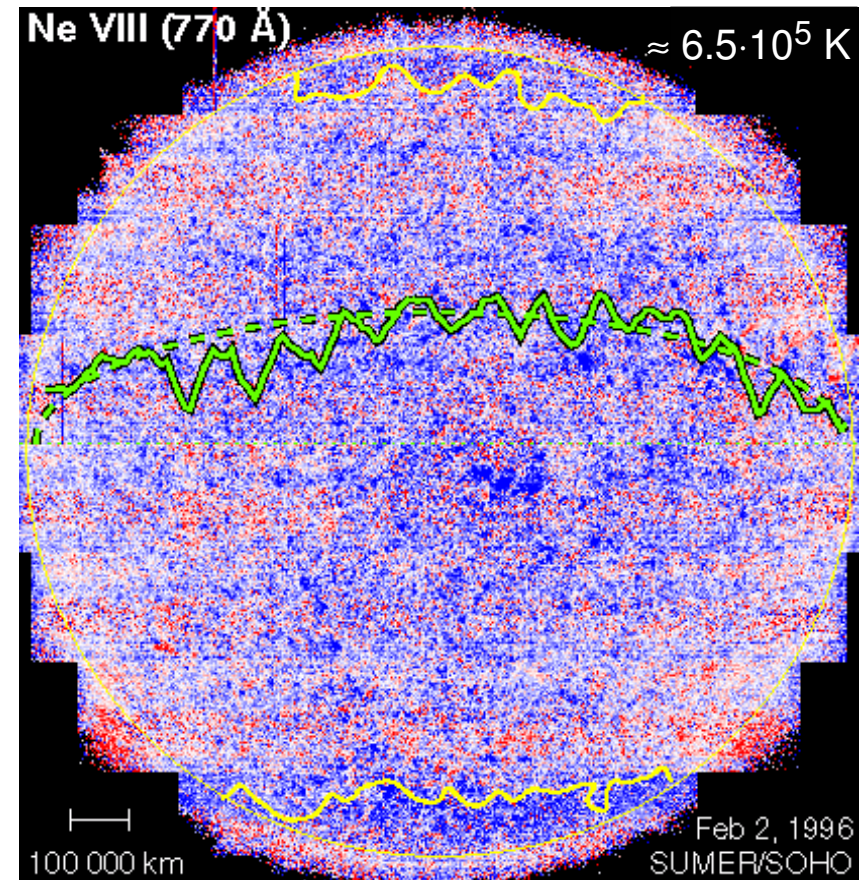
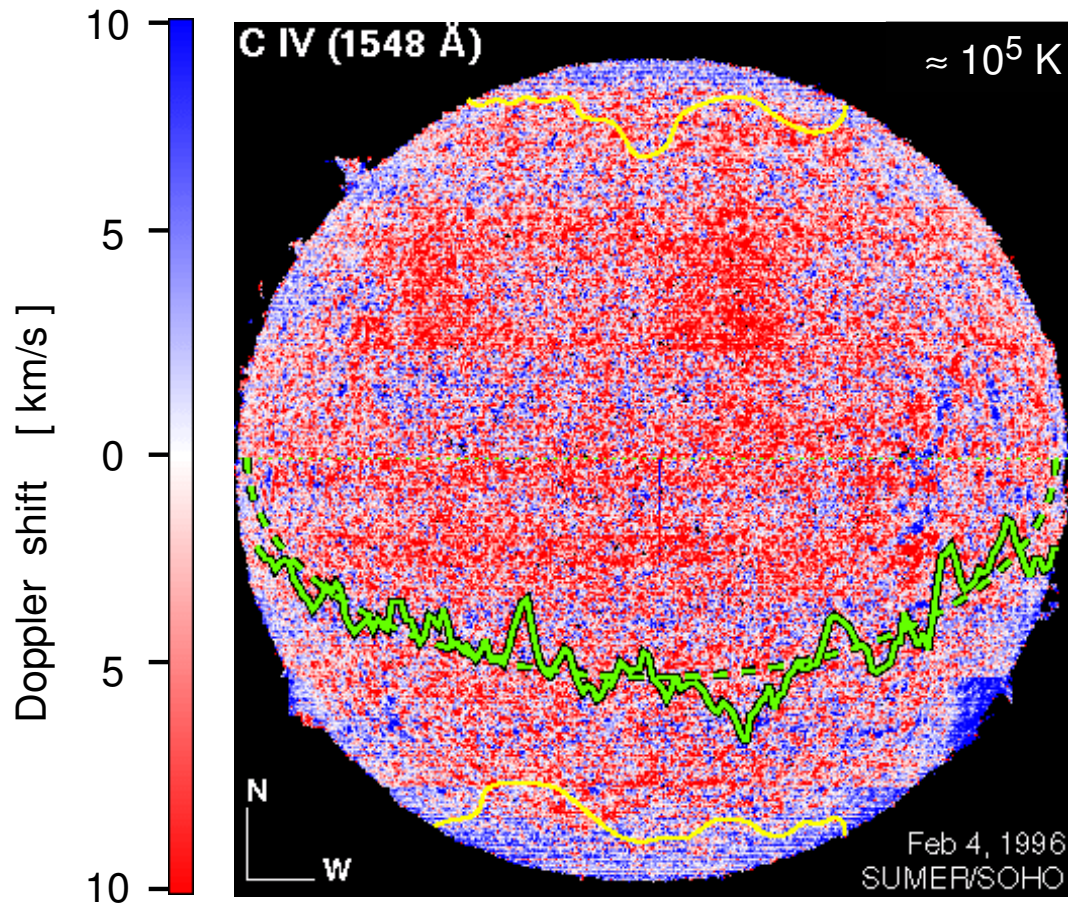
- observational constraints
- 3D MHD model
- spectral synthesis
- results: structures
Doppler shifts
DEM

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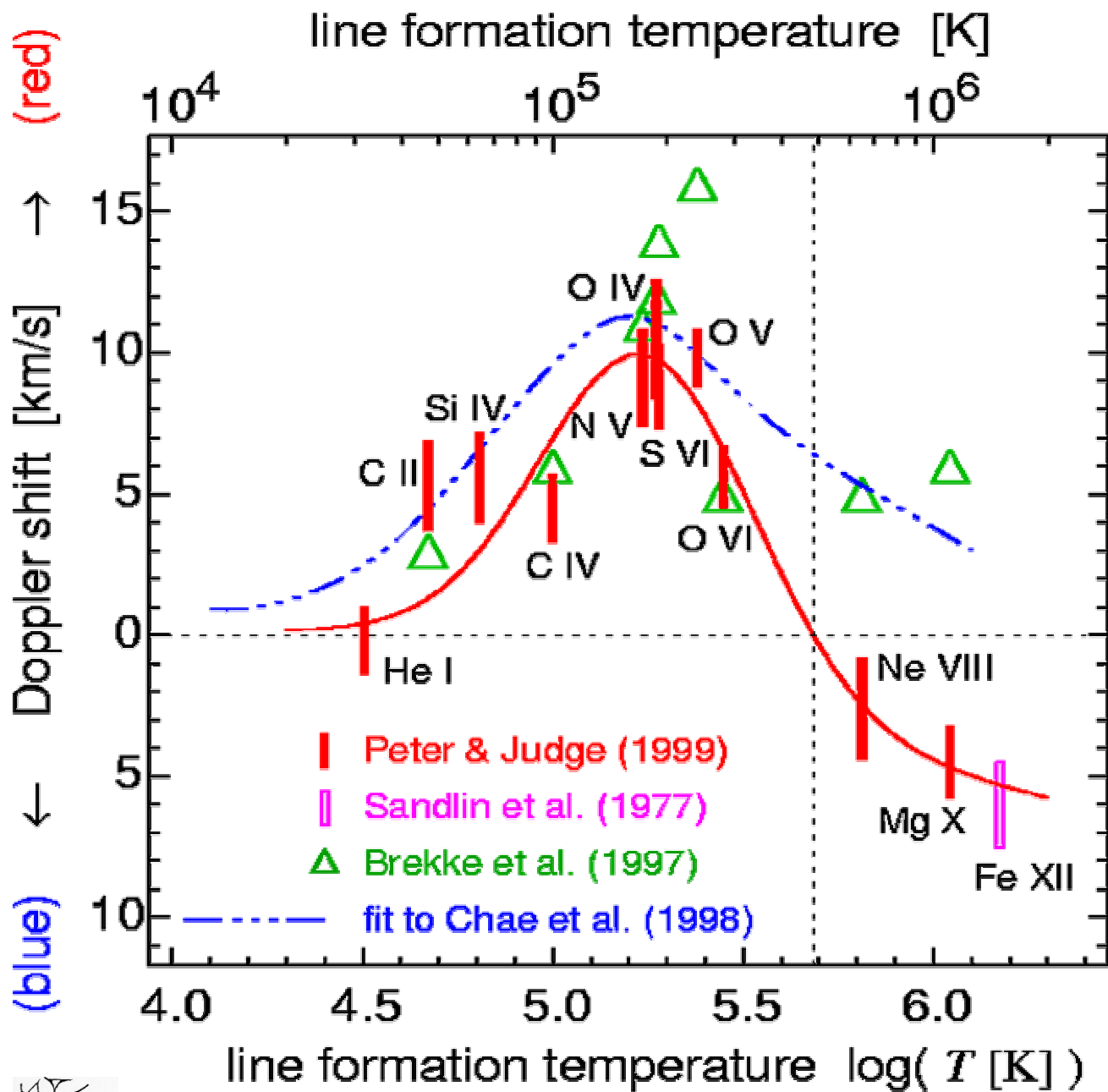
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Doppler shifts in the solar transition region



Peter (1999) ApJ 516 490

Doppler shifts in the low corona & TR



mean quiet Sun
Doppler shifts
at disk center

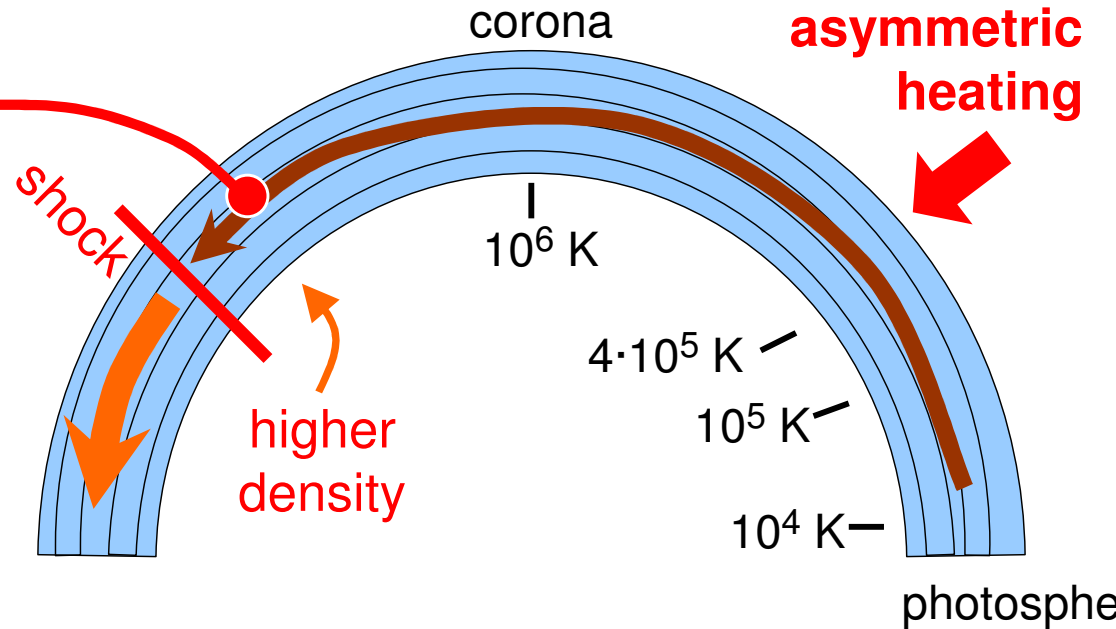
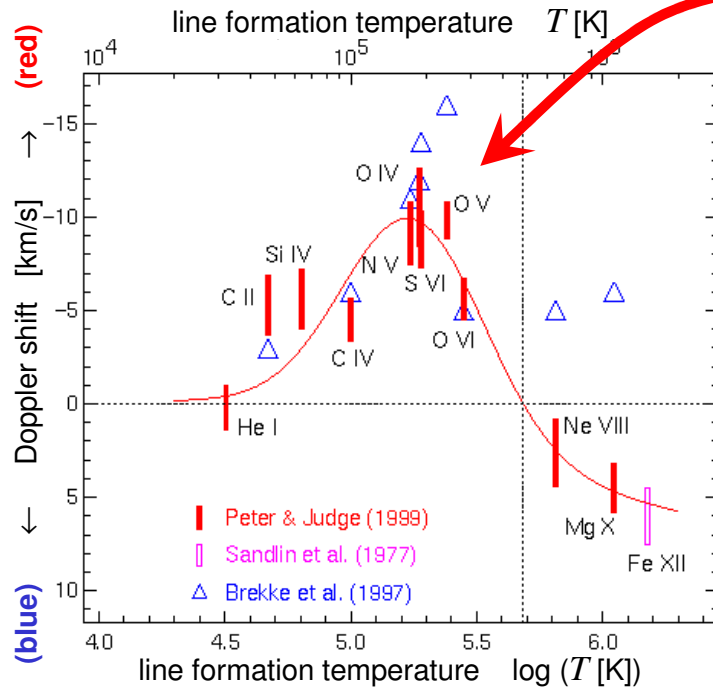
➤ similar for active region line shifts but higher amplitude

➤ qualitatively similar in solar-like stars – smaller for small activity

Net Doppler shifts in 1D models

e.g.: asymmetric heating → flows or waves

Doppler shift as a function of temperature



A by far incomplete list of suggestions to understand the red / blueshifts by using loop models:

- Antiochos (1984) ApJ 280, 416
- McClymont & Craig (1987) ApJ 312, 402
- Mariska (1988) ApJ 334, 489
- Klimchuk & Mariska (1988) ApJ 328, 334
- Hansteen (1993) ApJ 402, 741
- Peter & Judge (1999) ApJ 522, 1148
- Teriaca et. al. (1999) A&A 349, 636

no satisfactory model yet reproducing the v_D vs. T curve qualitatively and quantitatively!!

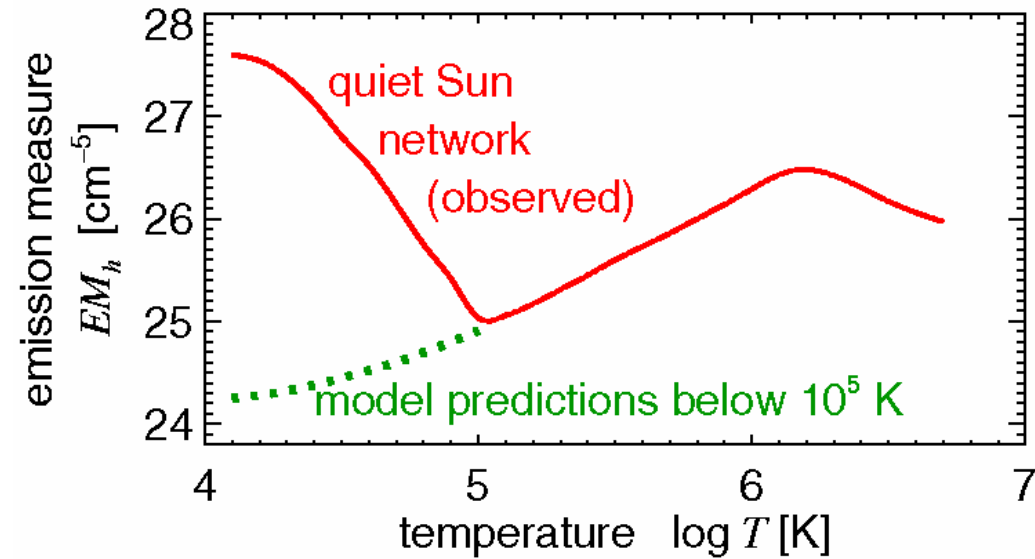
Emission measure in the (low) corona

$$F_{\text{line}} / h^\nu \quad \leftarrow \quad G(T) n_e^2 dh$$

atomic physics:
 – excitation
 – ionisation ...

emission measure:

$$EM_h = n_e^2 dh$$



The problem:

below 10^5 K ∇T is very steep ($q \propto T^{5/2} \nabla T$)

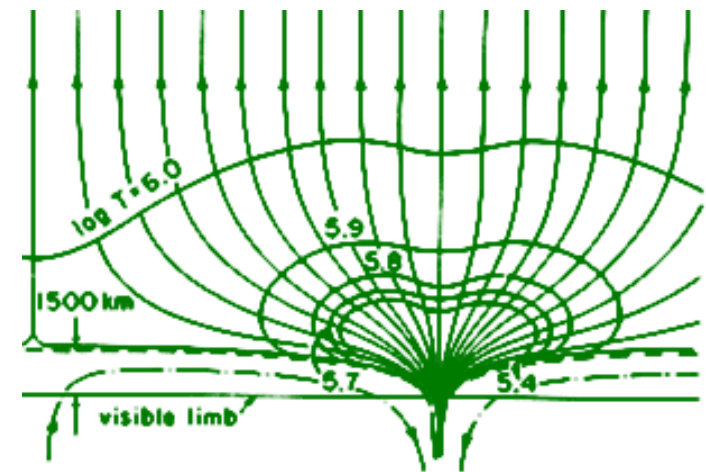
→ in stratified models:

∇T is so steep

that EM decreases below 10^5 K !

possible scenarios:

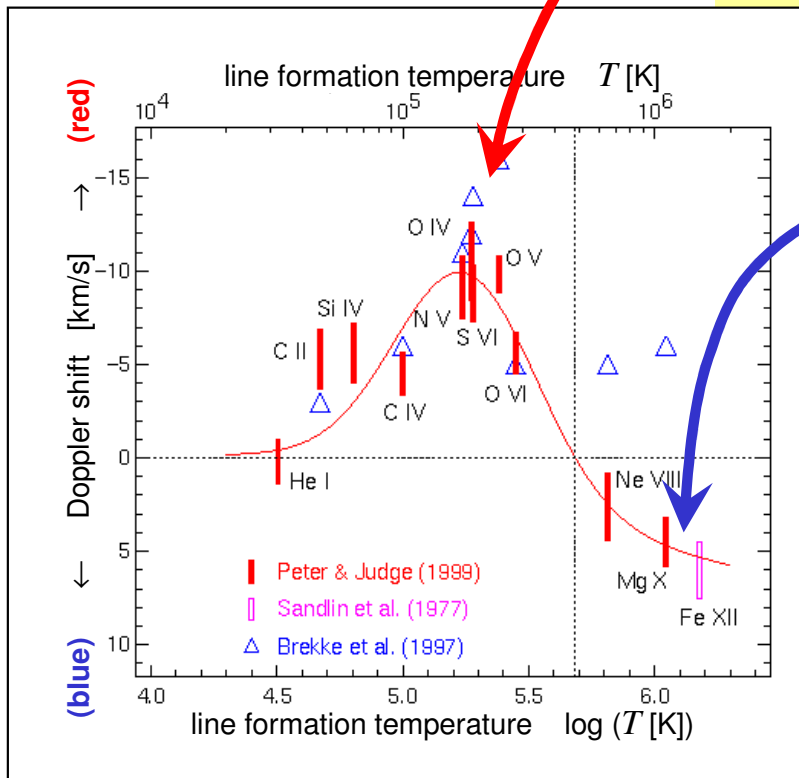
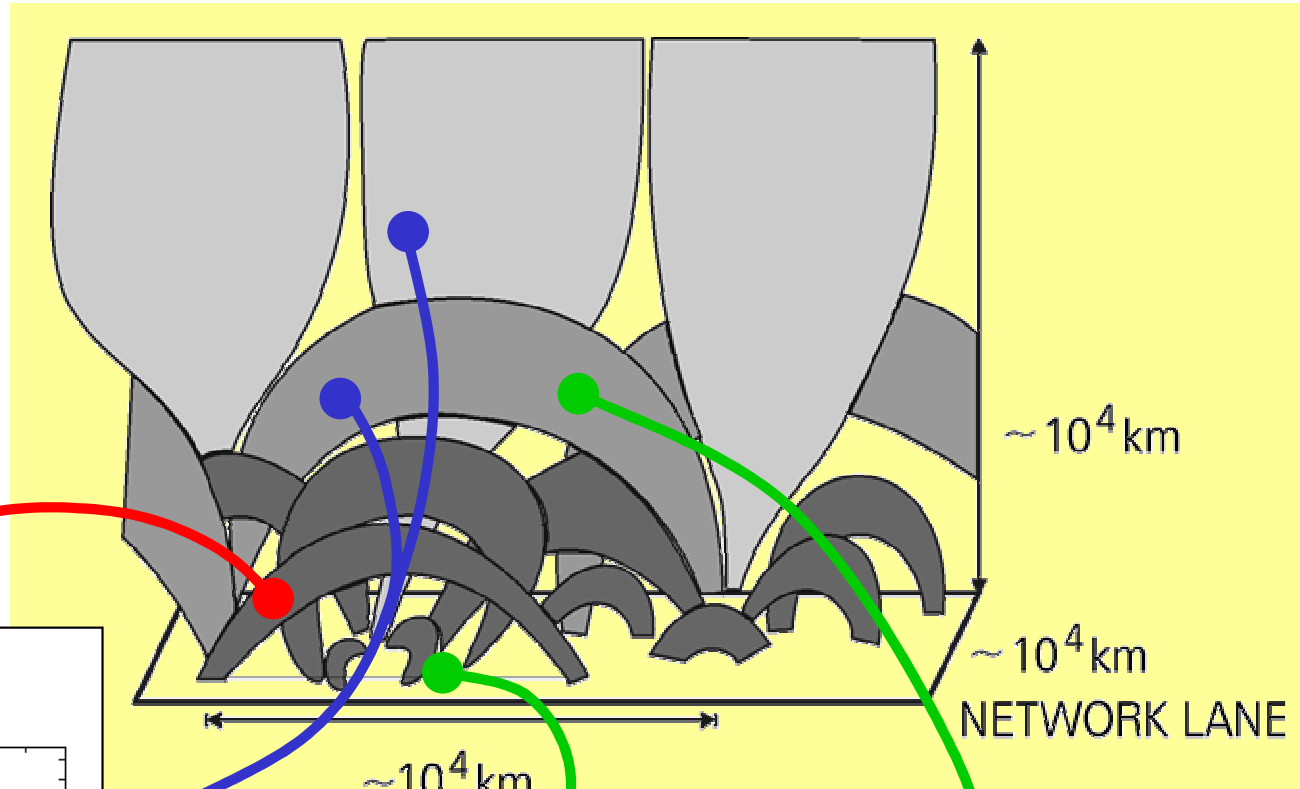
- additional dense cool structures
- increased heat-conduction below 10^5 K
- heat transport across the field...



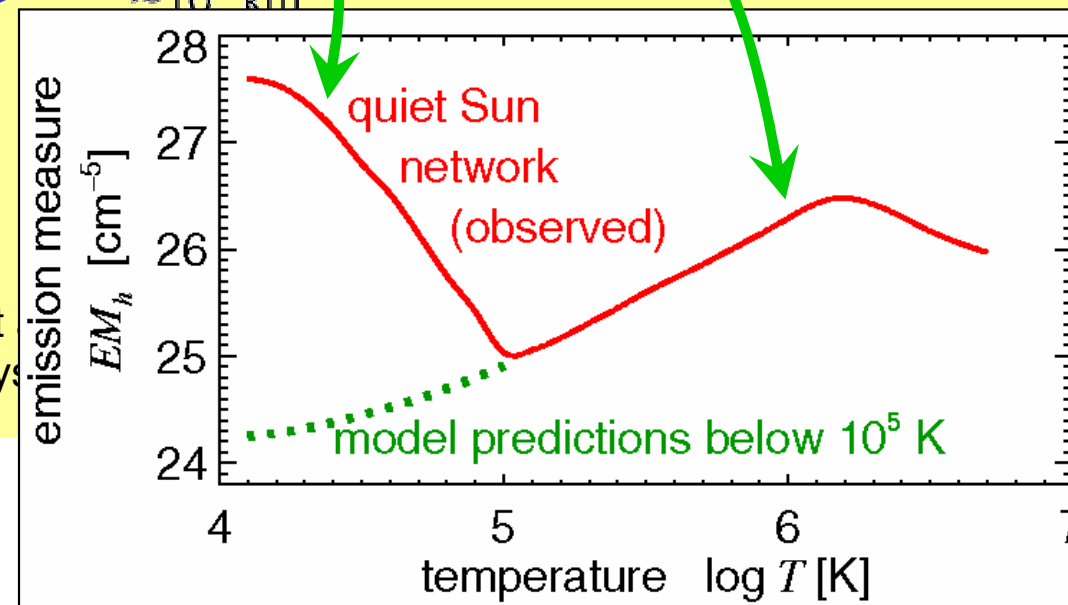
A multi-structured low corona

do we have to deal
with a multitude
of individual structures?

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



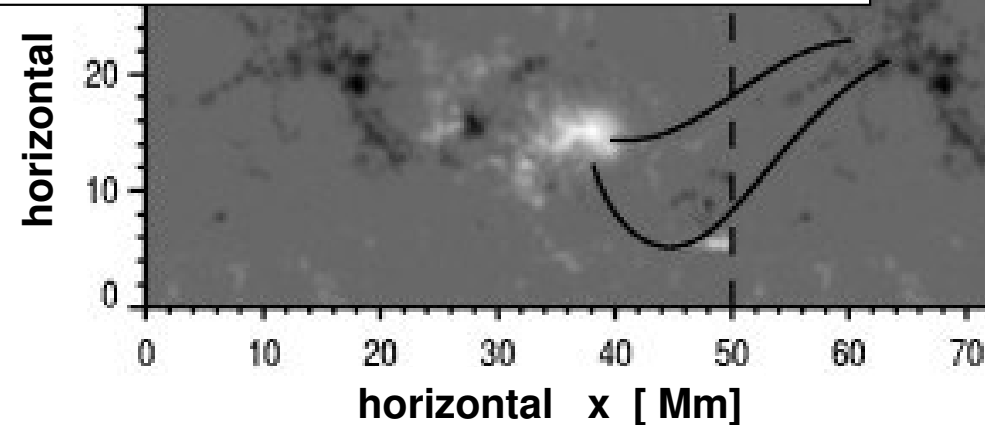
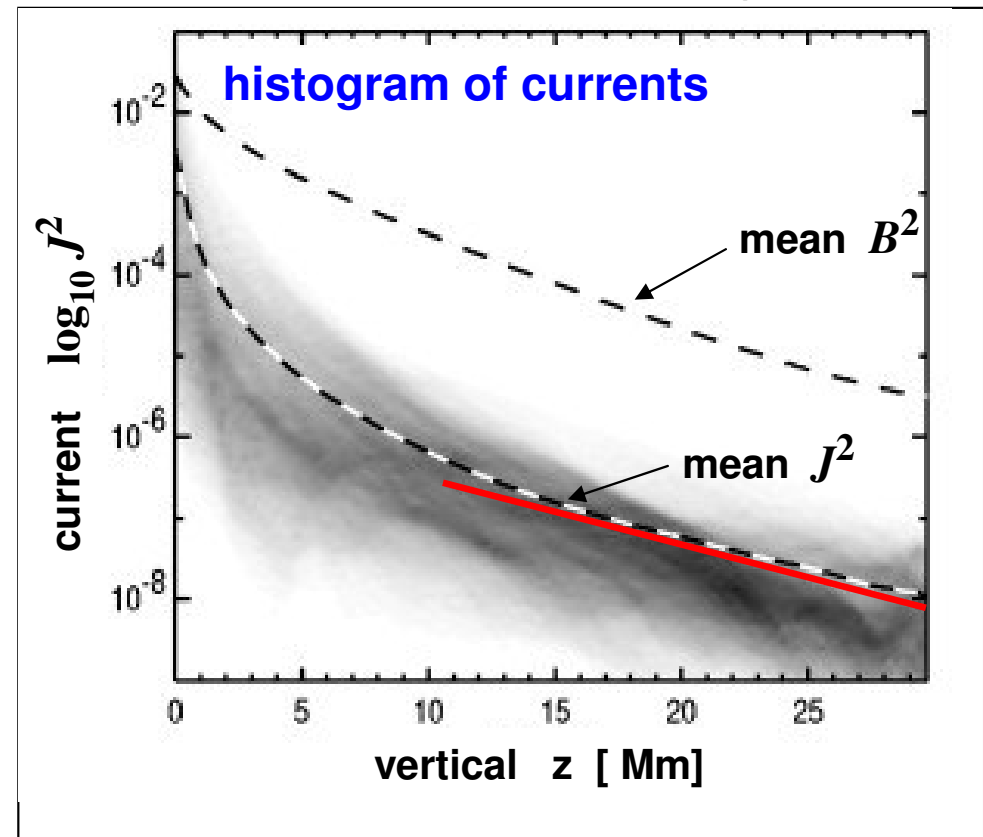
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3D coronal modelling

- 3D MHD model for the corona:
50 x 50 x 30 Mm Box (now 150³)
 - fully compressible; high order
 - non-uniform staggered 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 $J^2 \sim \exp(-z/H)$
 - ➔ loop-structured 10⁶K corona

Gudiksen & Nordlund (2002) ApJ 572, L113



Emissivity from a 3D coronal model

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

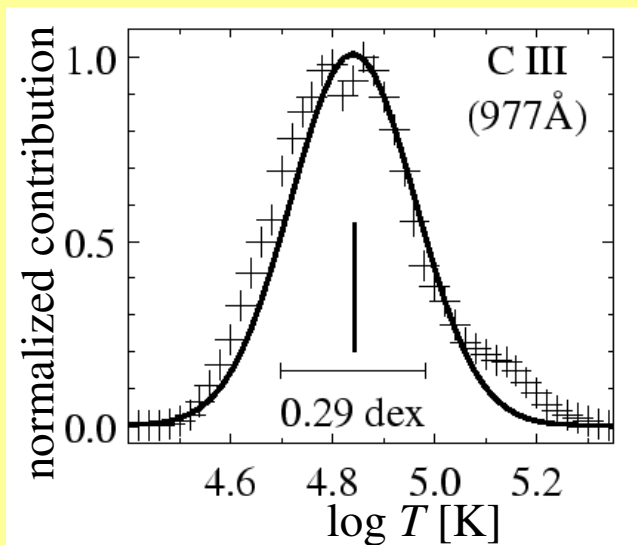
Emissivity at each grid point and time step:

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

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

$\left. \begin{array}{l} \text{total ionization} \approx 0.8 \\ \text{abundance} = \text{const.} \end{array} \right\}$
ionization
excitation

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)

$\rightarrow G$ depends mainly on T (and weakly on n_e)

Synthetic spectra

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

line profile at each grid point:

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

line width corresponding to thermal width

$$w_{\text{th}} = \sqrt{\frac{2k_B T(\mathbf{x}, t)}{m_{\text{ion}}}}$$

total intensity corresponding to emissivity

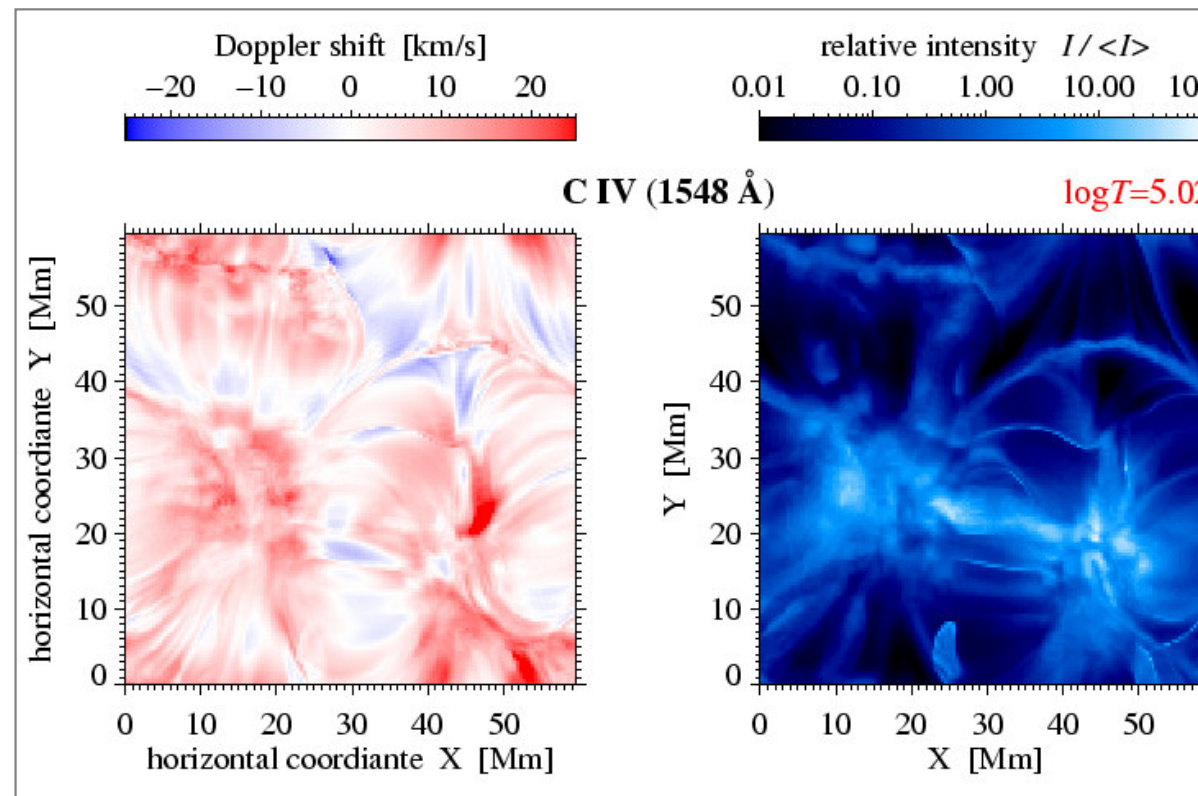
$$I_0 w_{\text{th}} \propto \varepsilon(\mathbf{x}, t)$$

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. ...



A note on ionization equilibrium

ionization equilibrium is a severe assumption for a dynamic environment

→ *but it is not too bad for the present problem...*

flow time:

how long does it take to flow across a temperature difference $\Delta \log T$ with a velocity v ?

$$\frac{1}{\tau_{\text{flow}}} = \frac{\nabla(\log T) \cdot \hat{v}}{(\Delta \log T)_{\text{ion}}} |v|$$

$(\Delta \log T)_{\text{ion}} = 0.1$ according to ion.equilibrium

$\nabla(\log T)$ and v from MHD calculation

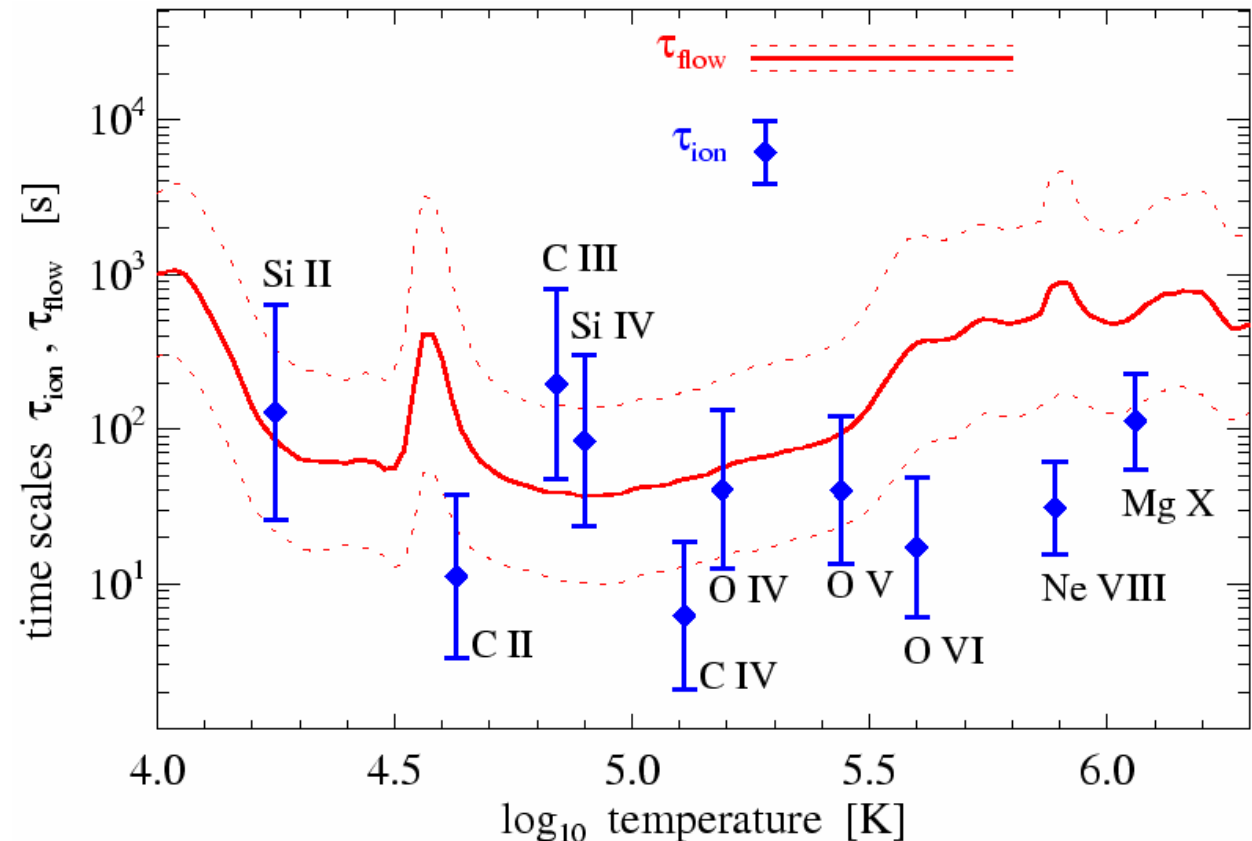
ionization time:

what is the ionisation rate?

$$\frac{1}{\tau_{\text{ion}}} = n_e C_{\text{ion}}$$

n_e from MHD calculation

$C_{\text{ion}}(T)$ from Arnaud & Rothenflug (1985)

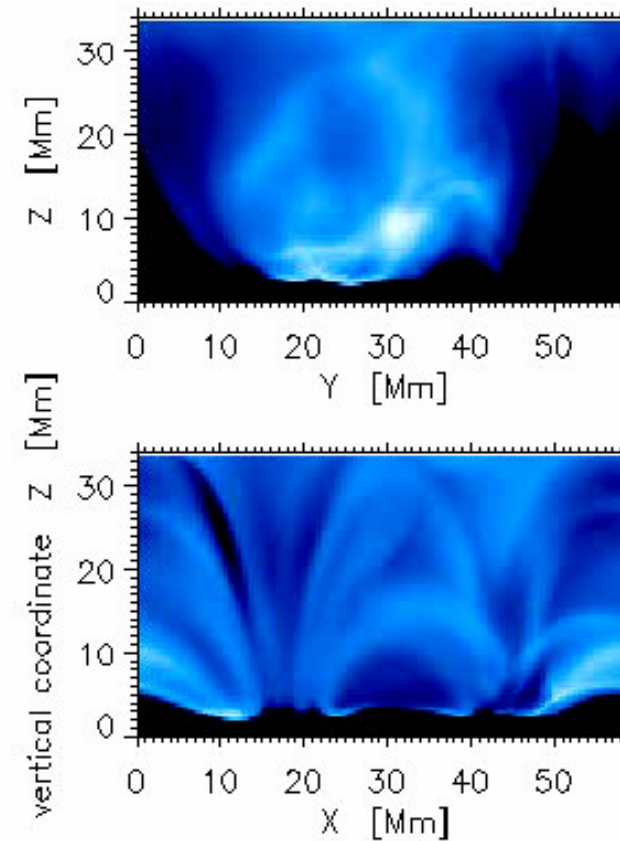
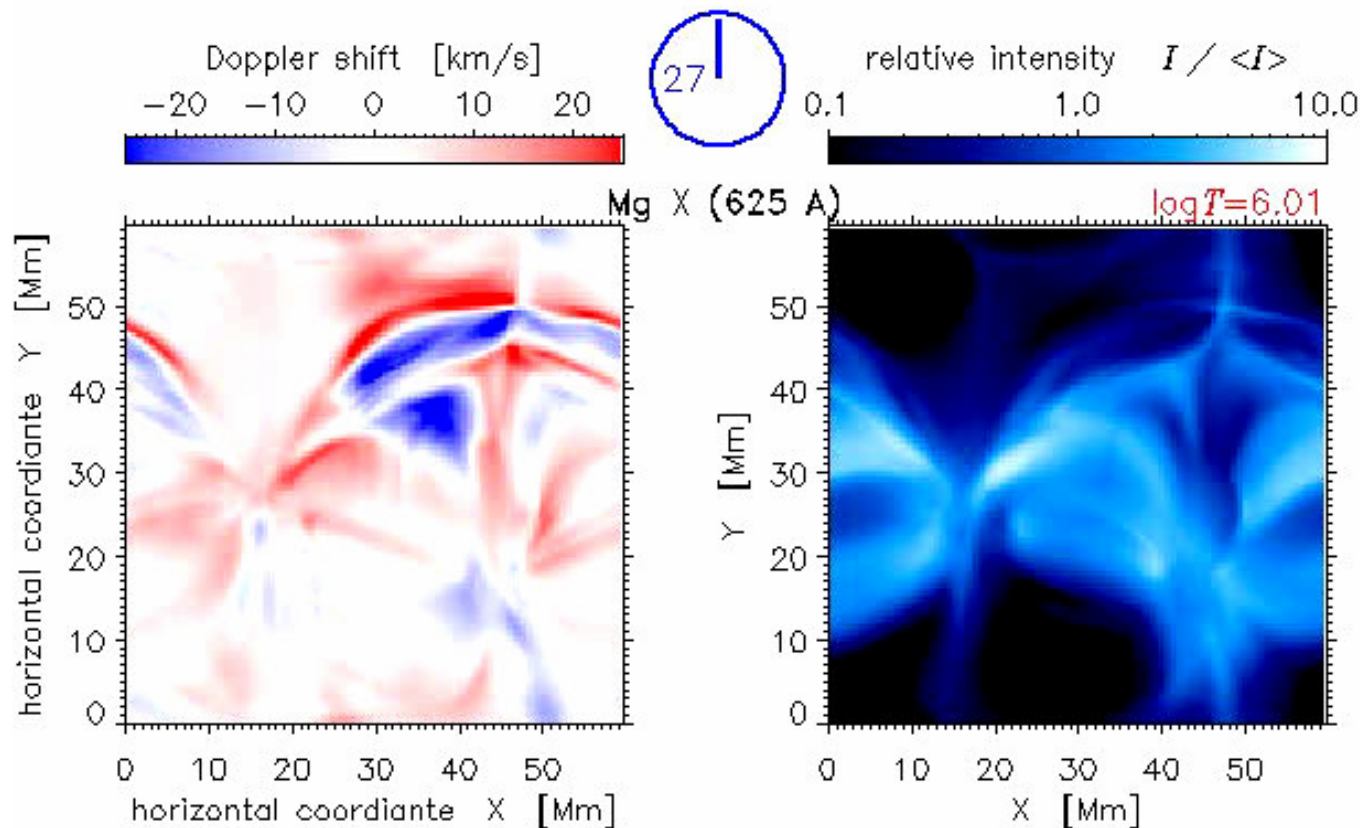


Coronal evolution

Mg X (625 Å)

$\sim 10^6$ 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!



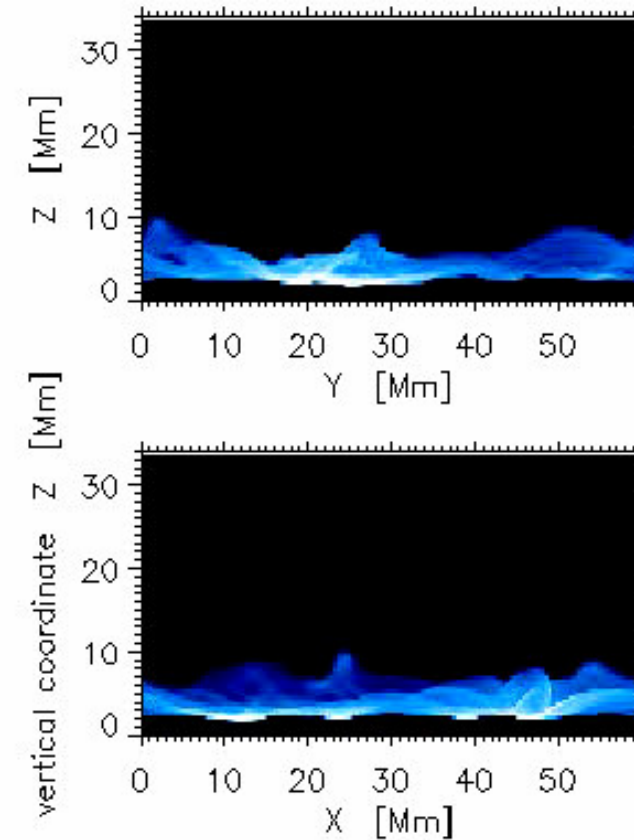
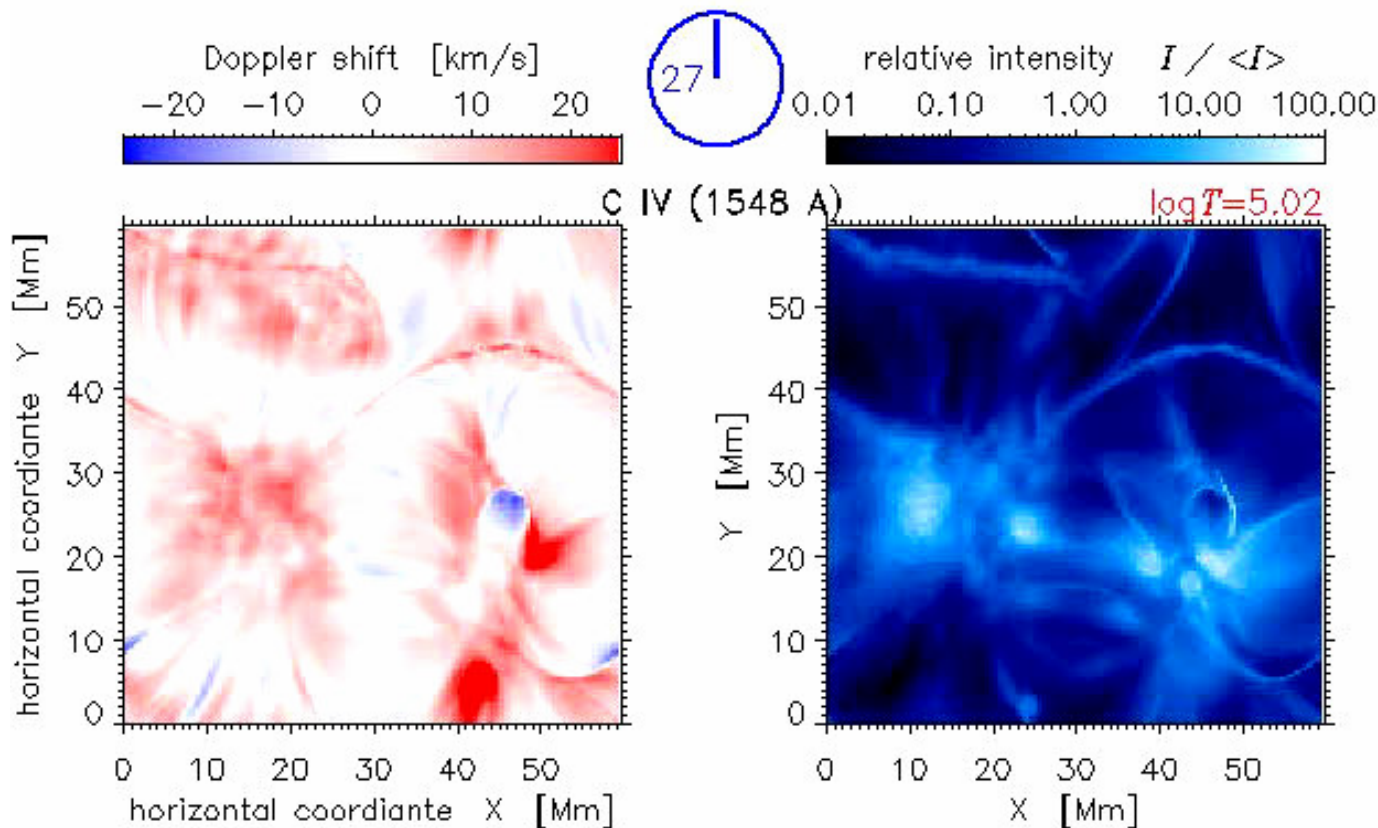
TR evolution: C IV (1548 Å)

C IV (1548 Å)

$\sim 10^5$ K

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

→ dynamics quite different from coronal material !



Doppler shifts

spatial and temporal averages

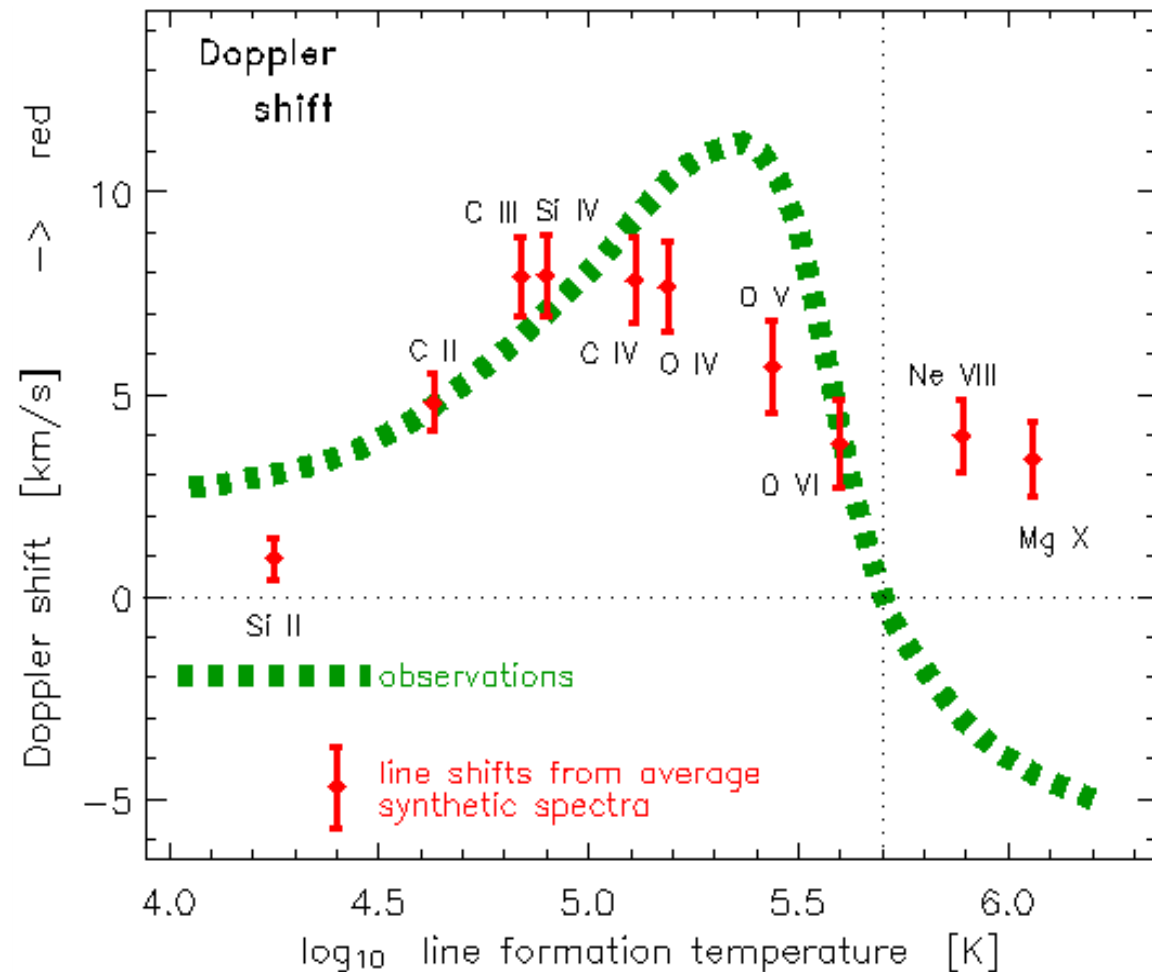
- very good match in TR
- overall trend v_D vs. T quite good
- still no match in low corona
 - boundary conditions?
 - missing physics?

temporal variability

- high variability as observed
- for some times almost net blueshifts in low corona!

➔ no “fine-tuning” applied !

➔ best over-all match of models so far



Emission measure

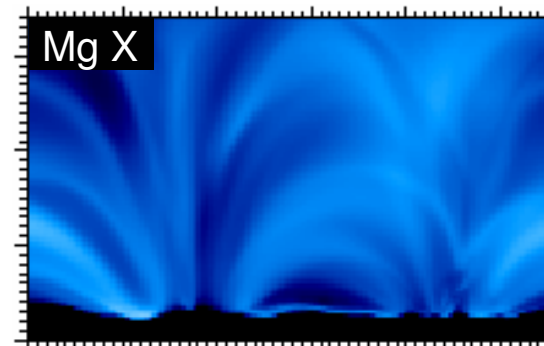
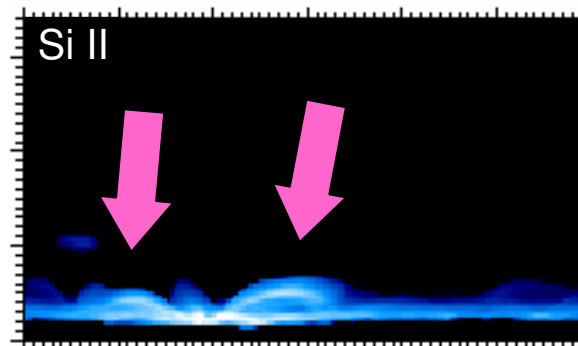
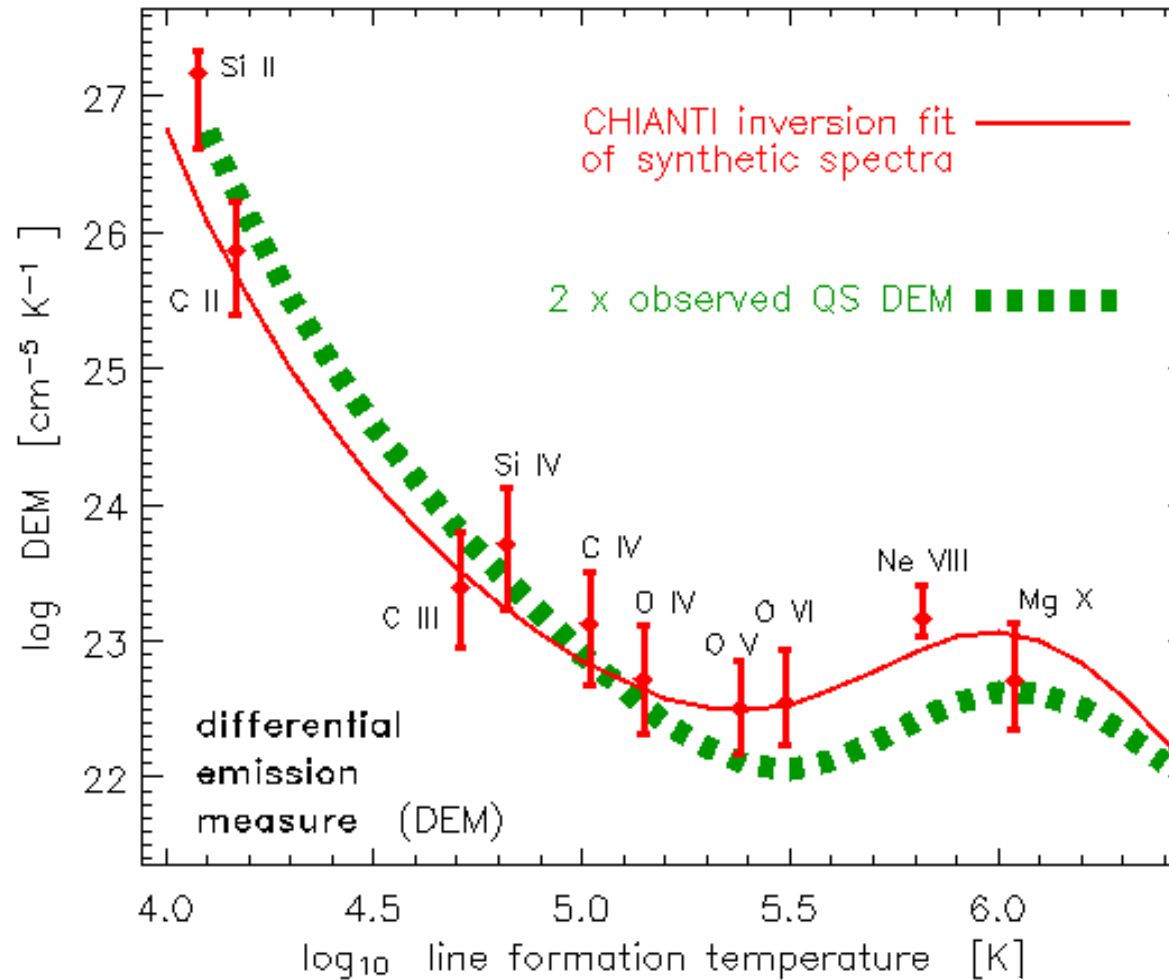
$$DEM = n_e^2 \frac{dh}{dT}$$

DEM inversion using CHIANTI:

- 1 – using synthetic spectra derived from MHD model
- 2 – using solar observations (SUMER, same lines, quiet Sun)

➔ 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

Conclusions

- Synthetic spectra from a 3D MHD model of a small active region on the Sun
- Smooth evolution in corona, but variable Doppler shifts
- highly structured in TR lines

➔ *2D spectral imaging in TR lines is highly desirable:
not only imaging and not only corona!*

- For the first time we get a
 - reasonable good match to TR and coronal Doppler shifts
 - very good match to Emission Measure (especially $< 10^5$ K)
- good arguments for **flux braiding as (the) heating mechanism** in moderately active regions

Outlook

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

