Closed magnetic structures

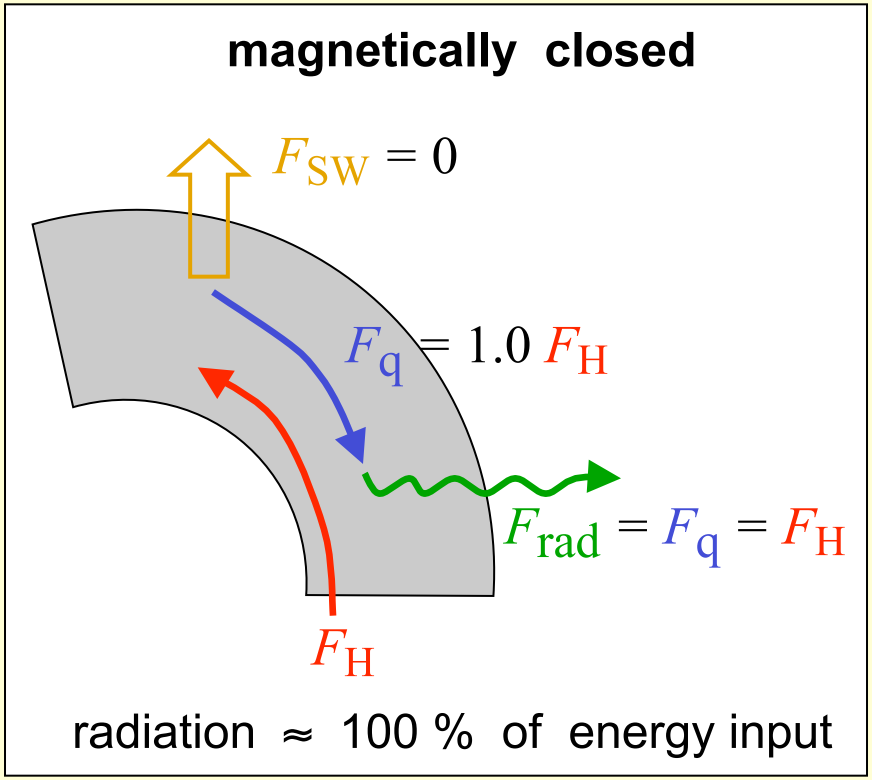
solar eclipse, **11.8.1999**, Wendy Carlos and John Kern

Hardi Peter

MAX-PLANCK-GESELLSCHAFT

MPS

Energy budget in the quiet corona



magnetically closed

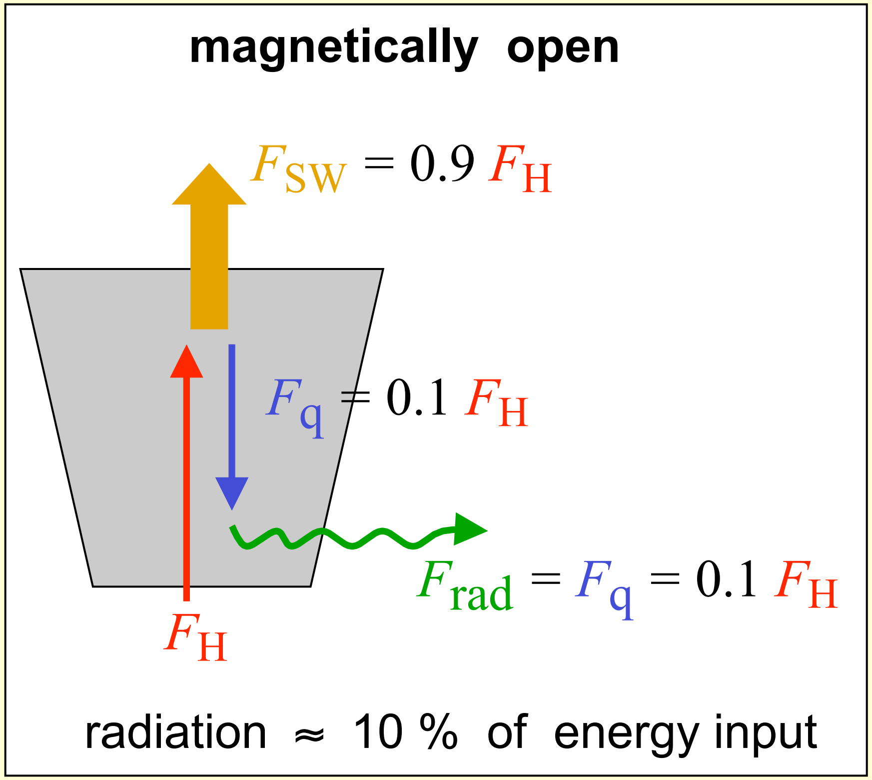
$F_{SW} = 0$

$F_q = 1.0\ F_H$

$F_{rad} = F_q = F_H$

F_H

radiation ≈ 100 % of energy input



magnetically open

$F_{SW} = 0.9\ F_H$

$F_q = 0.1\ F_H$

$F_{rad} = F_q = 0.1\ F_H$

F_H

radiation ≈ 10 % of energy input

following Holzer et al. (1997)

assume the same energy input into open and closed regions:

→ almost ALL emission we see on the disk outside coronal holes originates from magnetically closed structures (loops) !

The heating rate sets the coronal pressure

- dump heat in the corona F_H

  radiation is not very efficient in the corona (10^6K)

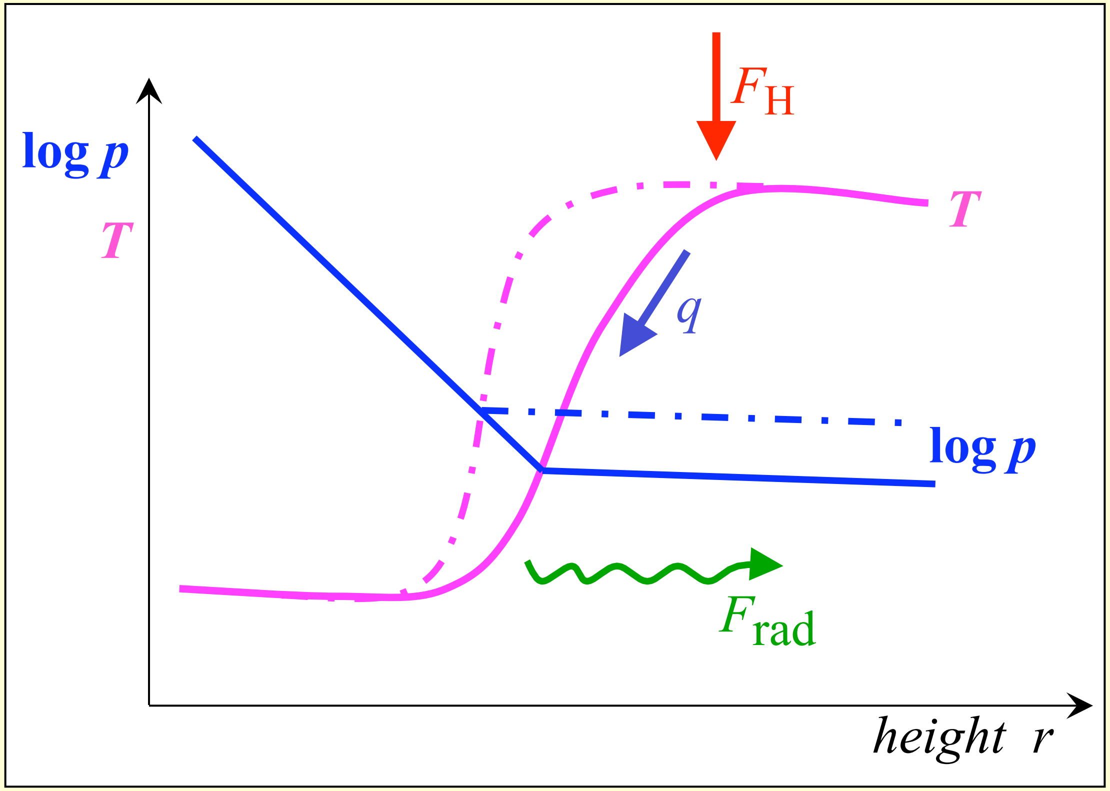
- heat conduction $\nabla \cdot q$ transports energy down

- energy is radiated in the low transition region and upper chromosphere F_{rad}

  radiation depends on particle density

  pressure: $p \sim F_{rad}$

➡ $p_{corona} \sim F_H$



increase the heating rate:

more has to be radiated ⇨ higher base pressure

➡ transition region moves to lower height !

The “details” might change (e.g. spatial distribution of heating) but the basic concept remains valid!

Basic building blocks I: coronal loops

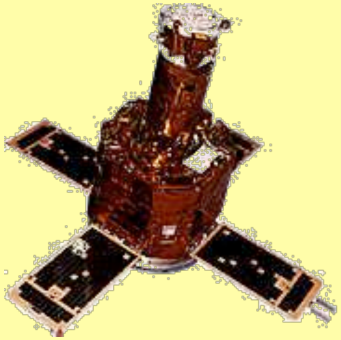
EUV / X-ray filtergrams

Fe IX / X (17.1 nm)

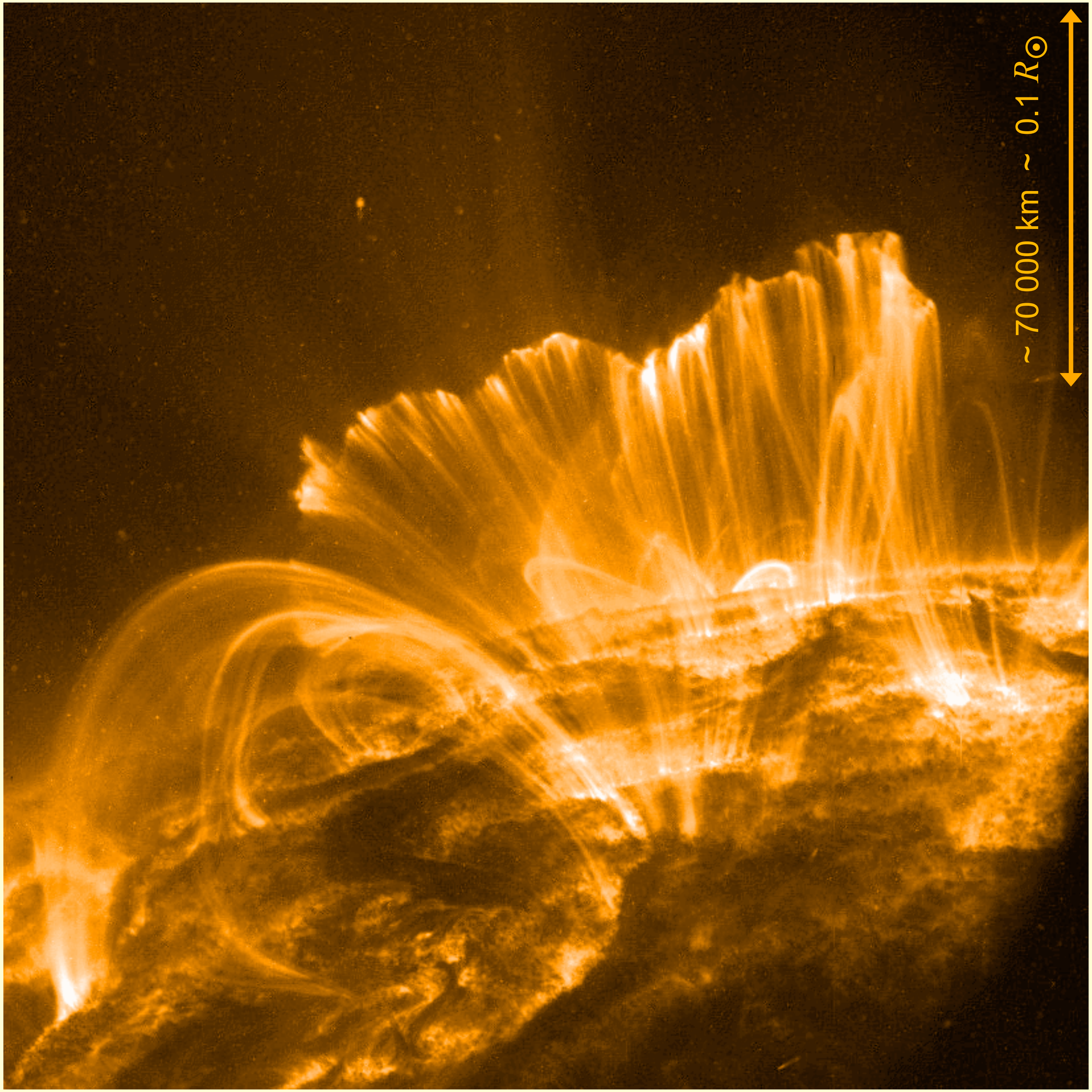
$\approx 10^6$ K

9. November 2000

Do loops really outline the magnetic field ?



Transition Region and Coronal Explorer (TRACE) — NASA

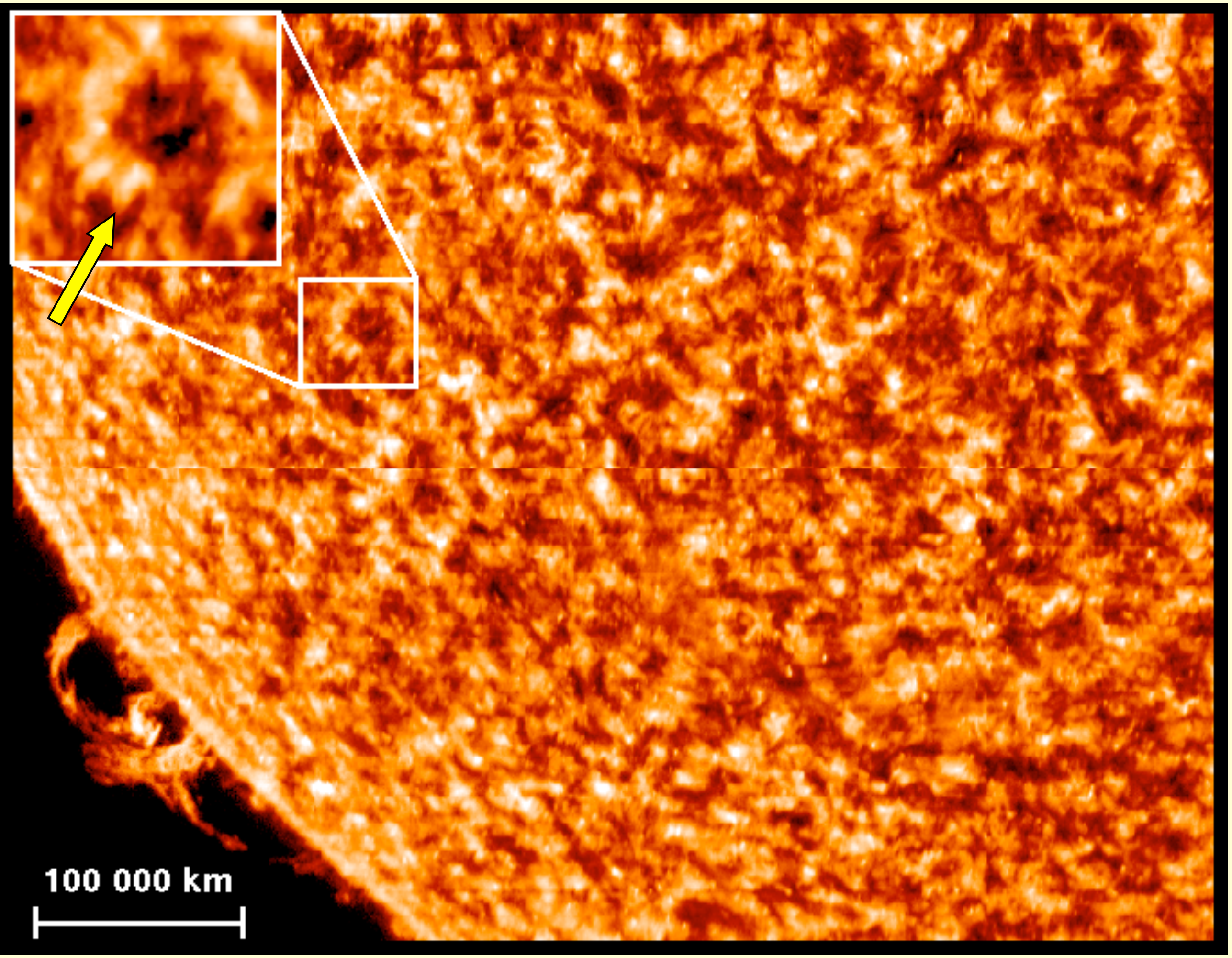


Basic building blocks II: transition region loops

transition region from chromosphere to corona

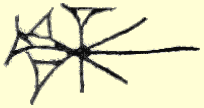
- small loops across network-boundaries
- low loops across cells

Certainly
not all structures are resolved!
➡ **is it all loops ?**



Peter (2001) A&A 374,1108

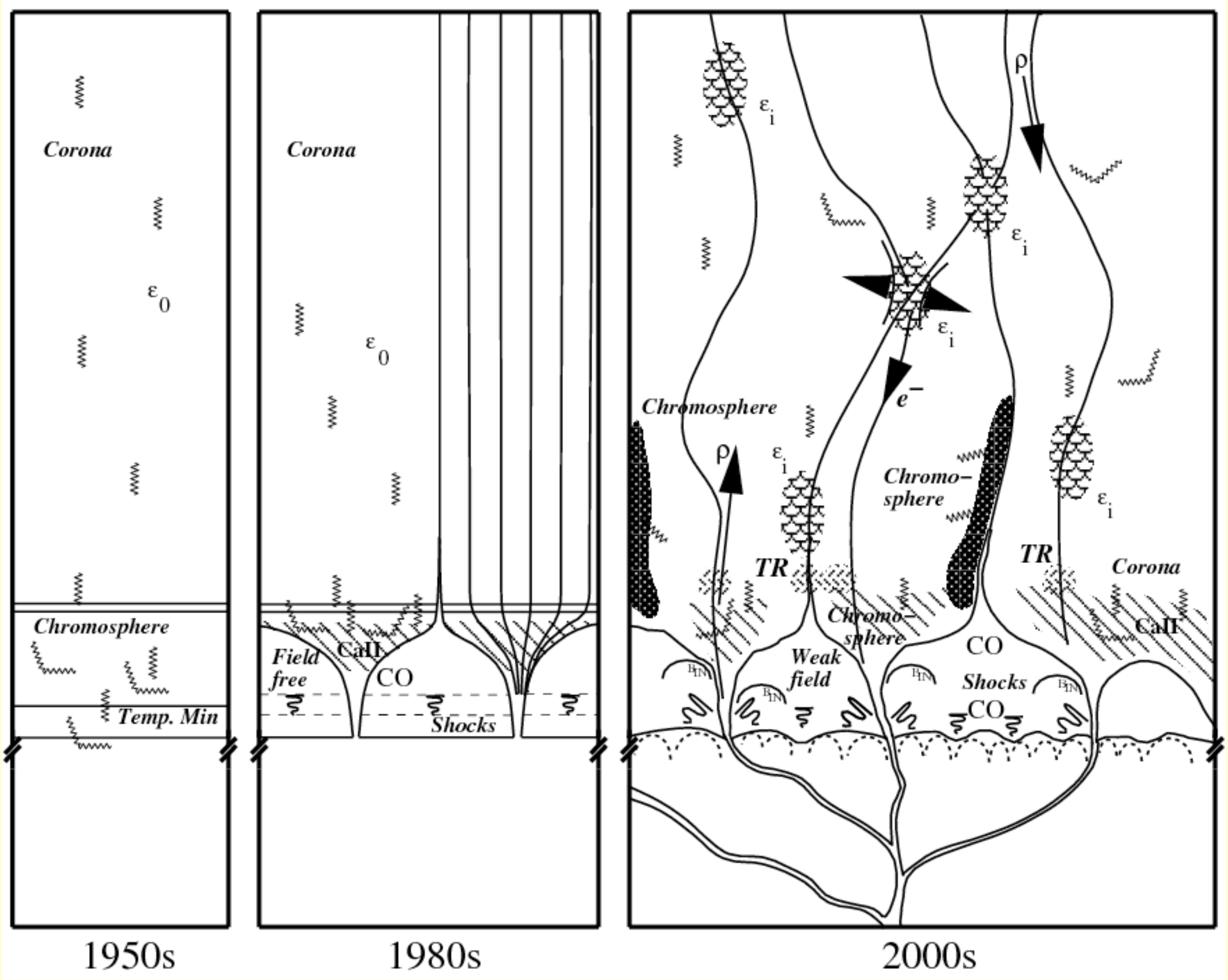
see also
Feldman et al. (2003),
ESA SP-1274:
"Images of the Solar
Upper Atmosphere
from SUMER on SOHO".



28.1.1996
C III (97.7 nm)
~80 000 K

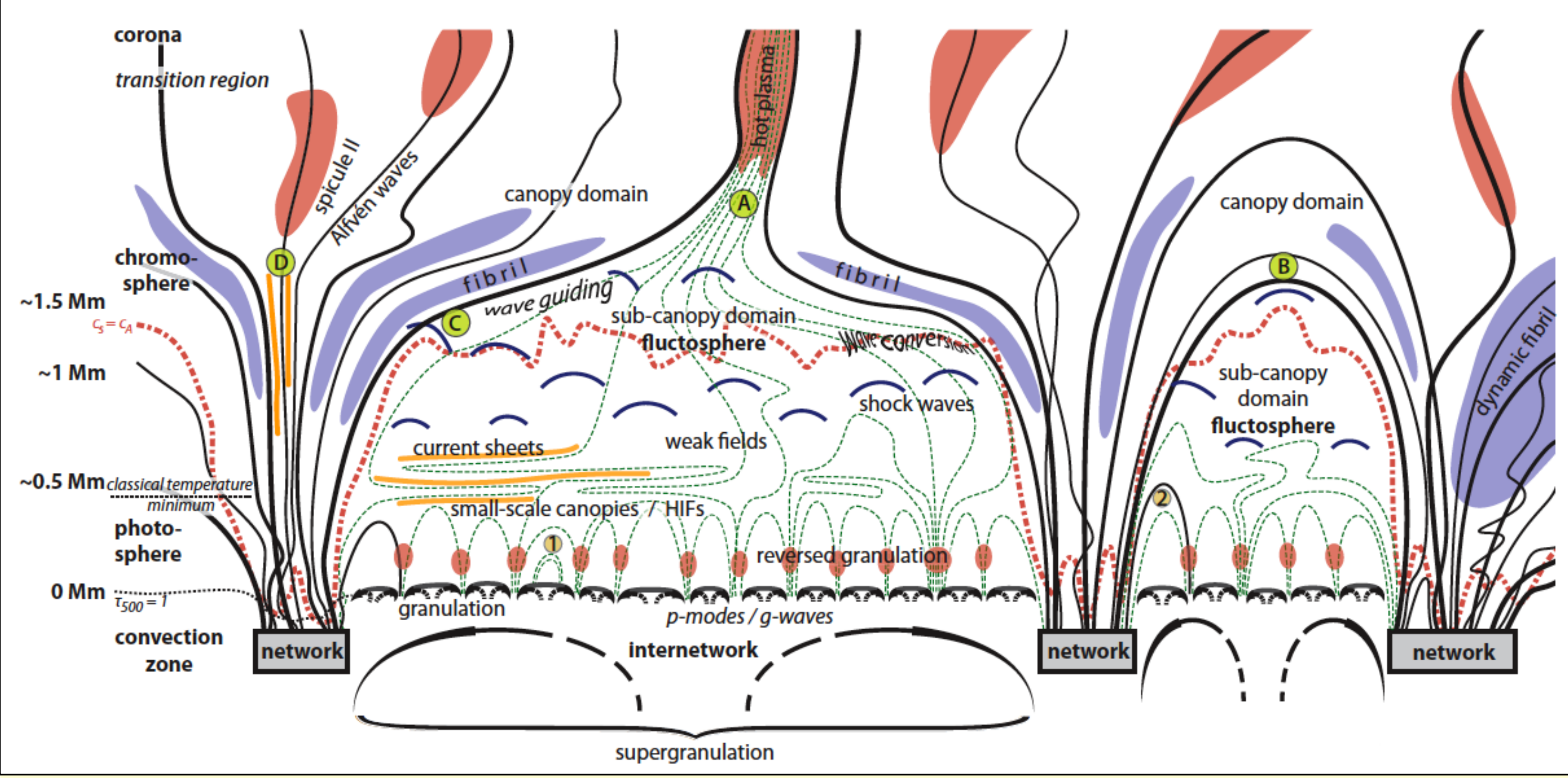
SUMER
EUV spectrograph

The structure of the solar atmosphere…



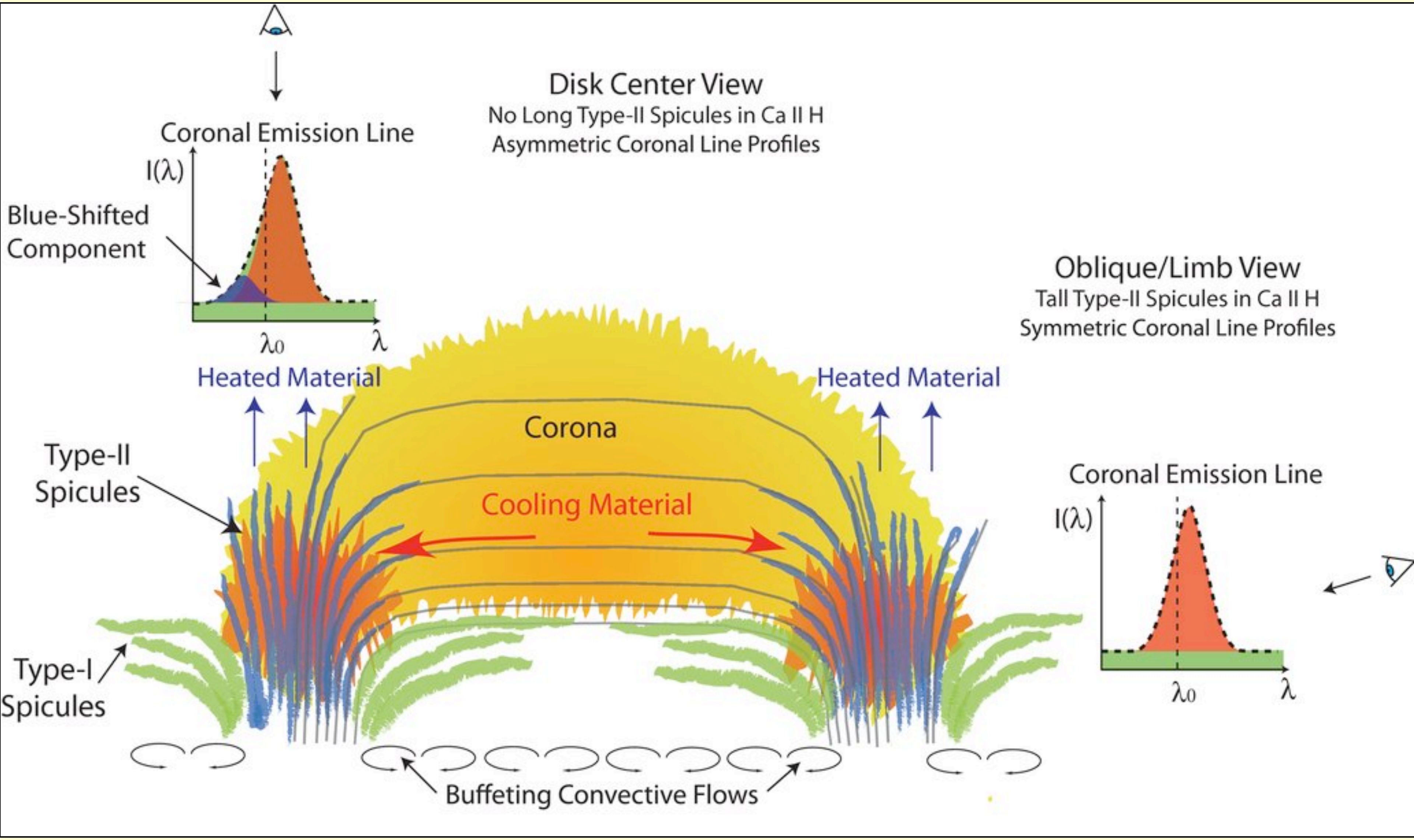
Schrijver (2001) Cool Stars 11 Proc., ASP Conf. Ser. Vol. 223 , p.131

… becoming ever more complicated



Wedemeyer-Böhm, Lagg & Nordlund (2009) SSR 144, 317

Back to simple… Where is the action ?



De Pontieu et al. (2009) ApJ 701, L1

MHD equations

$$\nabla\times\boldsymbol{B}=\mu\,\boldsymbol{j} \qquad \boxed{\nabla\cdot\boldsymbol{B}=0}$$

$$\nabla\times\boldsymbol{E}=-\partial_t\boldsymbol{B} \qquad \nabla\cdot\boldsymbol{E}=\frac{1}{\varepsilon}\,\rho_e$$

$$\boldsymbol{j}=\sigma(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B})$$

$$\boldsymbol{j}\times\boldsymbol{B}=\frac{1}{\mu}\,(\nabla\times\boldsymbol{B})\times\boldsymbol{B}$$

induction eq.

$$\partial_t\boldsymbol{B}=\underbrace{\nabla\times(\boldsymbol{v}\times\boldsymbol{B})}_{}-\underbrace{\nabla\times(\eta\,\nabla\times\boldsymbol{B})}_{}$$

$$\boxed{R_\mathrm{m}=\frac{U\,L}{\eta}=\frac{L^2}{\tau\,\eta}}$$

mag. diffusivity

$$\eta=\frac{1}{\mu\,\sigma}$$

continuity eq. $\partial_t\rho+\nabla\cdot(\rho\,\boldsymbol{u})=0$

momentum eq. $\rho\partial_t\boldsymbol{u}+\rho(\boldsymbol{u}\cdot\nabla)\,\boldsymbol{u}=-\nabla p+\rho\boldsymbol{g}+\boldsymbol{j}\times\boldsymbol{B}+\nabla\cdot\boldsymbol{\tau}$

viscous stess tensor $\boldsymbol{\tau}$:

$$\nabla\cdot\boldsymbol{\tau}=\rho\nu\Big(\Delta\boldsymbol{u}+\frac{1}{3}\nabla\,(\nabla\cdot\boldsymbol{u})\Big)$$

energy eq. $\big(\partial_t+\boldsymbol{u}\cdot\nabla\big)\,e+\frac{5}{2}\,p\,\nabla\cdot\boldsymbol{u}=-\nabla\cdot\boldsymbol{q}-L_\mathrm{rad}+\eta\,\boldsymbol{j}^2+Q_\mathrm{visc}$

internal energy: $e=n\,\frac{3}{2}k_\mathrm{B}T$

➡ for coronal diagnostics it is essential to get energy equation right

Dissipation mechanism – the kinetic point of view

where do the conductivity σ and
magnetic diffusivity $\eta = 1/(\mu\sigma)$ come from ?

$$\partial_t f + \boldsymbol{v}\cdot\nabla_x f + \frac{\boldsymbol{F}}{m}\nabla_v f \;=\; \left(\frac{\delta f}{\delta t}\right)_{\text{coll}} \underset{\uparrow}{\approx} -\frac{1}{\tau_c}(f - f_0) \;\Rightarrow\; \boxed{v\frac{\partial f_0}{\partial r} + \frac{F}{m}\frac{\partial f_0}{\partial v} = -\nu_c\, f_1}$$

BGK ~ 1954

linearized BGK (*)

moments of LHS result in
fluid equations (e.g. MHD)

$$f_0 = f_M = n\left(\frac{m}{2\pi k_\mathrm{B} T}\right)^{3/2}\exp\left(-\frac{m(\boldsymbol{v}-\boldsymbol{u}_0)^2}{2k_\mathrm{B}T}\right)$$

to investigate electric conductivity:

homogeneous: $\partial_x = 0 \;\; ; \;\; n, T = \text{const.}$
static: $\boldsymbol{u}_0 = 0$
const. *E* field: $\boldsymbol{F} = Ze\boldsymbol{E}$

(*) ➡

$$\frac{Z\,e\,E}{m}\frac{\partial f_0}{\partial v} = -\nu_c\, f_1 \qquad (**)$$

$$\frac{\partial f_0}{\partial v} = -\frac{m}{k_\mathrm{B}T}v f_0$$

$$\int v\,(**)\,\mathrm{d}v \;: \quad \frac{Z\,e\,E}{m}\frac{m}{k_\mathrm{B}T}\underbrace{\int v^2 f_0 \mathrm{d}v}_{= n\frac{k_\mathrm{B}T}{m}} = \nu_c \int v f_1 \mathrm{d}v \;\Longleftrightarrow\; \underbrace{\frac{Z^2\,e^2\,n}{m\,\nu_c}}_{\sigma}\;\underset{\updownarrow}{E} \;=\; \underbrace{Z\,e\int v f_1 \mathrm{d}v}_{=j}$$

$$\boxed{\sigma = \frac{Z^2\,e^2\,n}{m\,\nu_c}} \qquad \underbrace{\sigma \quad E \quad = j}_{\text{Ohm's law}}$$

Dissipation mechanism – the MHD point of view

Why is it (apparently) possible to ignore the fact that the magnetic Reynolds $R_{\rm m}$ number is huge, work with large scale near-singular structures, and get decent results?

(Åke Nordlund)

$$R_{\rm m} = \frac{U\,L}{\eta} = \frac{L^2}{\tau\,\eta}$$

simulations: $R_{\rm m}$ well below 1000

➡ relatively high resistivity η or low conductivity σ

dissipation generates subsidiary smaller and smaller scale structures

➡ until scales are small enough to support dissipation…

$$\text{dissipated power} = \frac{\text{dissipated energy}}{\text{volume and time}} = \frac{E/V}{\tau} \sim \underbrace{\partial_t(e) \sim \eta\,\boldsymbol{j^2}}_{\text{from the energy eq.: Ohmic dissipation}} \sim B^2\,\frac{\eta}{L^2}$$

Using η from transport theory: scales L very small (< km) ➡ too small for simulations

energy will always be dissipated at the smallest resolved scale…

➡ choose η, so that size of resulting current sheets L ≈ grid size

Radiative losses

in an optically thin medium in equilibrium through collisionally excited emission lines:

$$L_{\rm rad} = n_{\rm e}\, n_{\rm H}\, P_{\rm rad} \approx n^2 P_{\rm rad}$$

exitation: $C_{12} \propto n_{\rm e}$

emissivity: $\varepsilon \propto n_{\rm upper} \propto n_{\rm H}$

often:
piecewise
power law: $P_{\rm rad} = \chi\, T^{\alpha}$

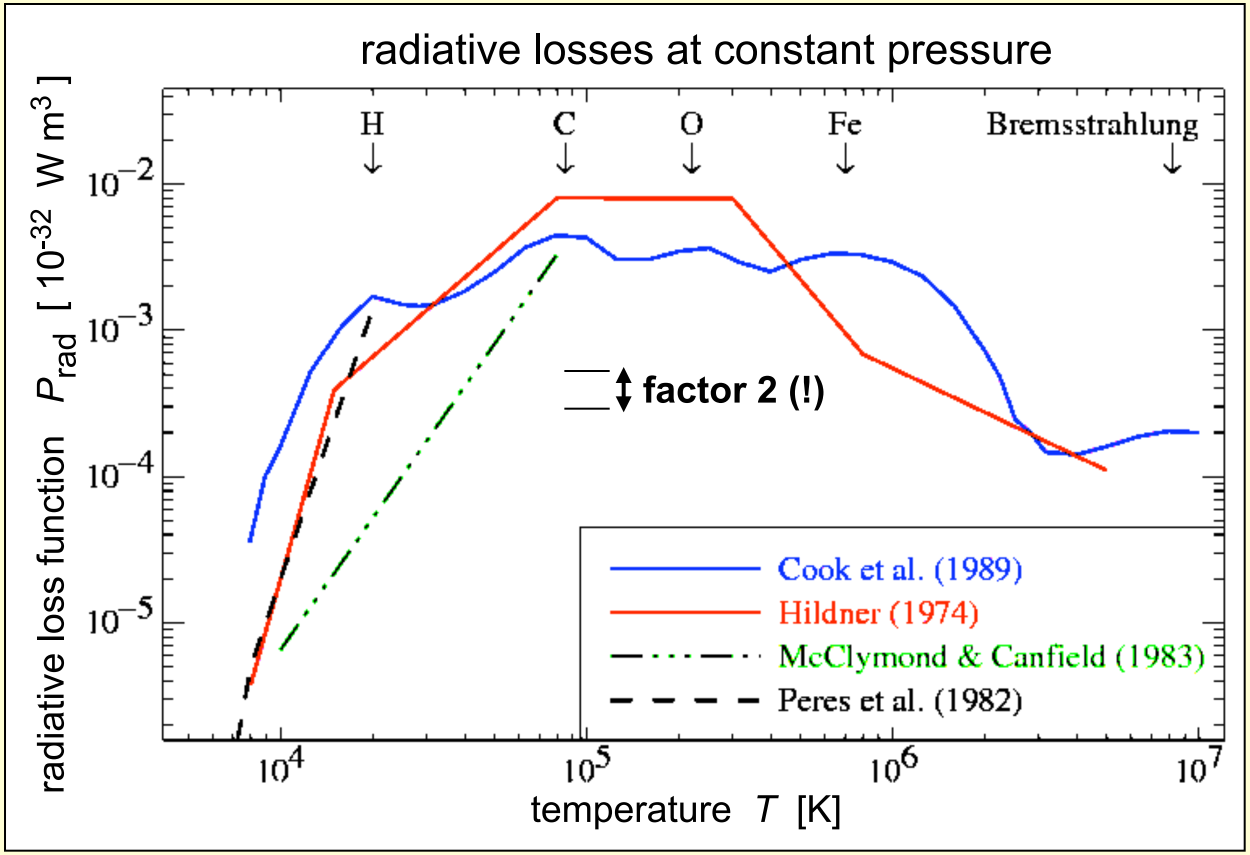
Problems:

- different studies give different losses: often factor 2x or more (!)
- ionization equilibrium may be bad assumption

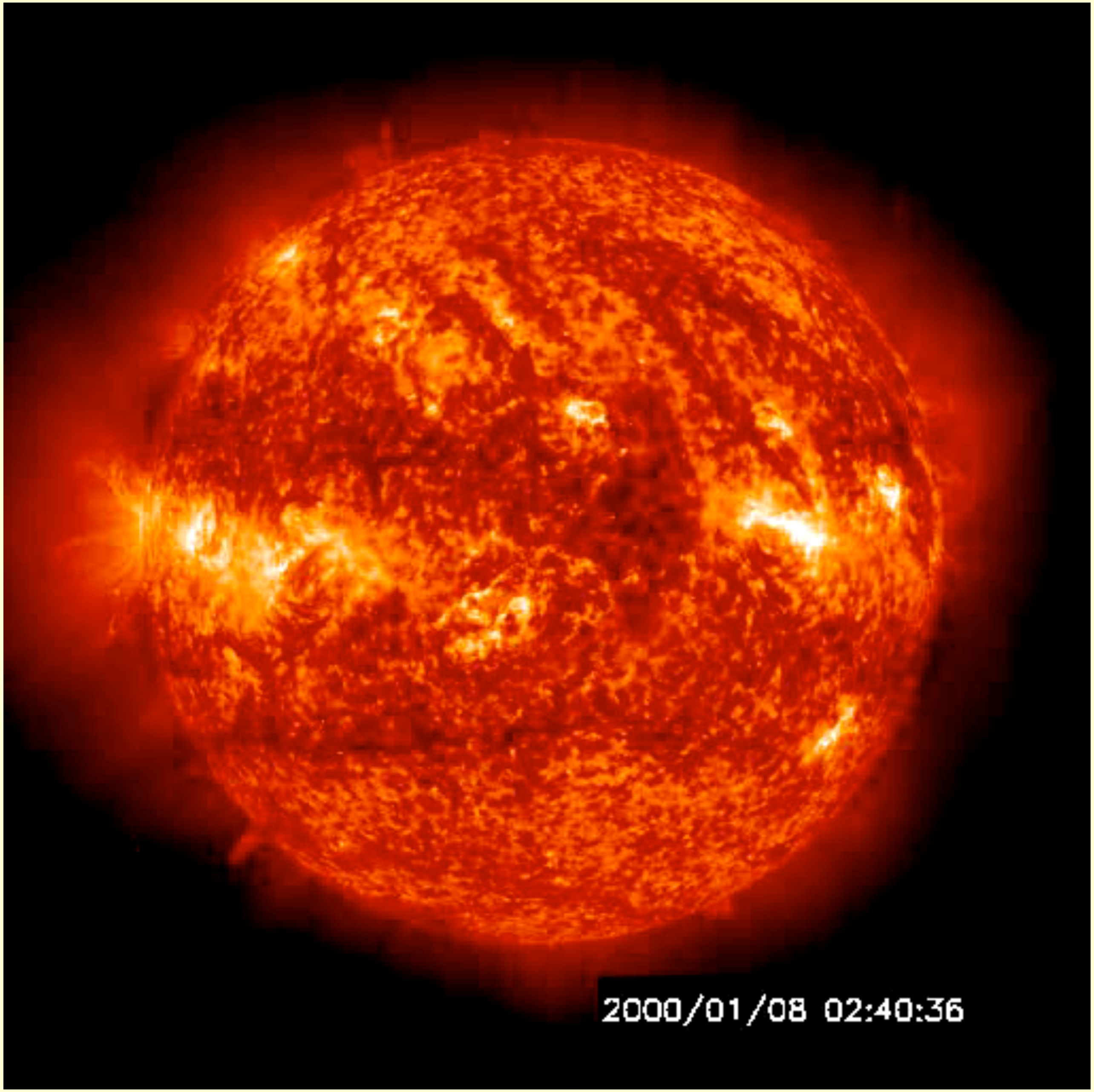
Needed (but difficult…):

self-consistent treatment:

- get ionization stages
- calc. dominant lines
- integrate for total losses
- feed into energy equation



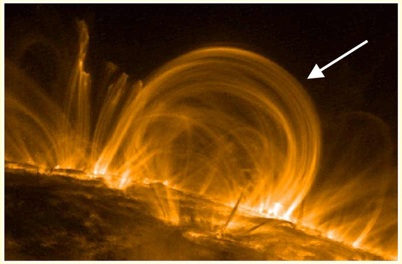
The dynamic Sun



SOHO / EIT
He II (304 Å)
~ 30 000 K

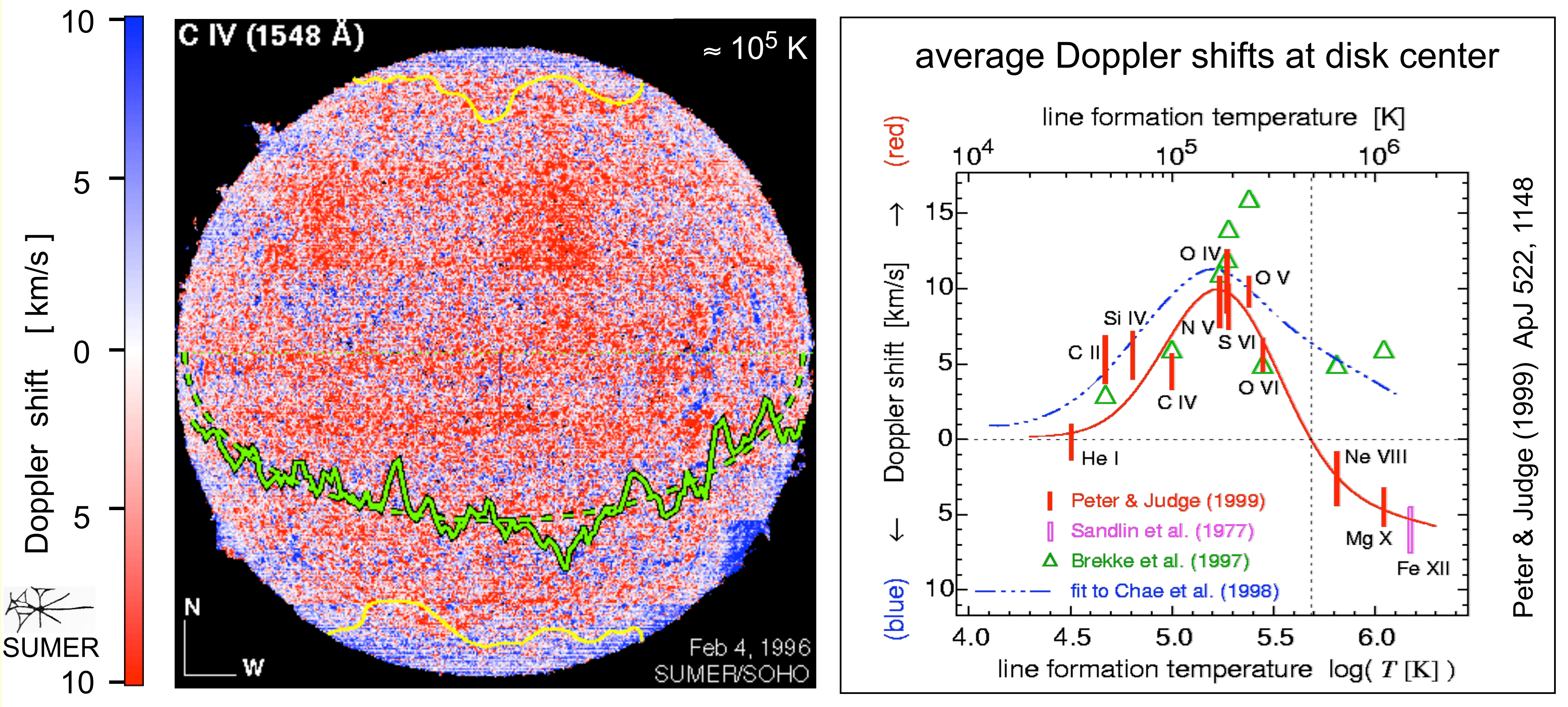
The Sun
is changing
everywhere
all the time!

How to describe this mess ? — Ask right questions!



- **investigate individual structures**
  pick a “good / typical” example – but what is “good / typical” ?
- **study “ensemble averages”**
  - structures on a star come in many types
  - it is not sufficient for a “good” model to reproduce a singular observation...

example for ensemble observations: **quiet Sun Doppler shifts**



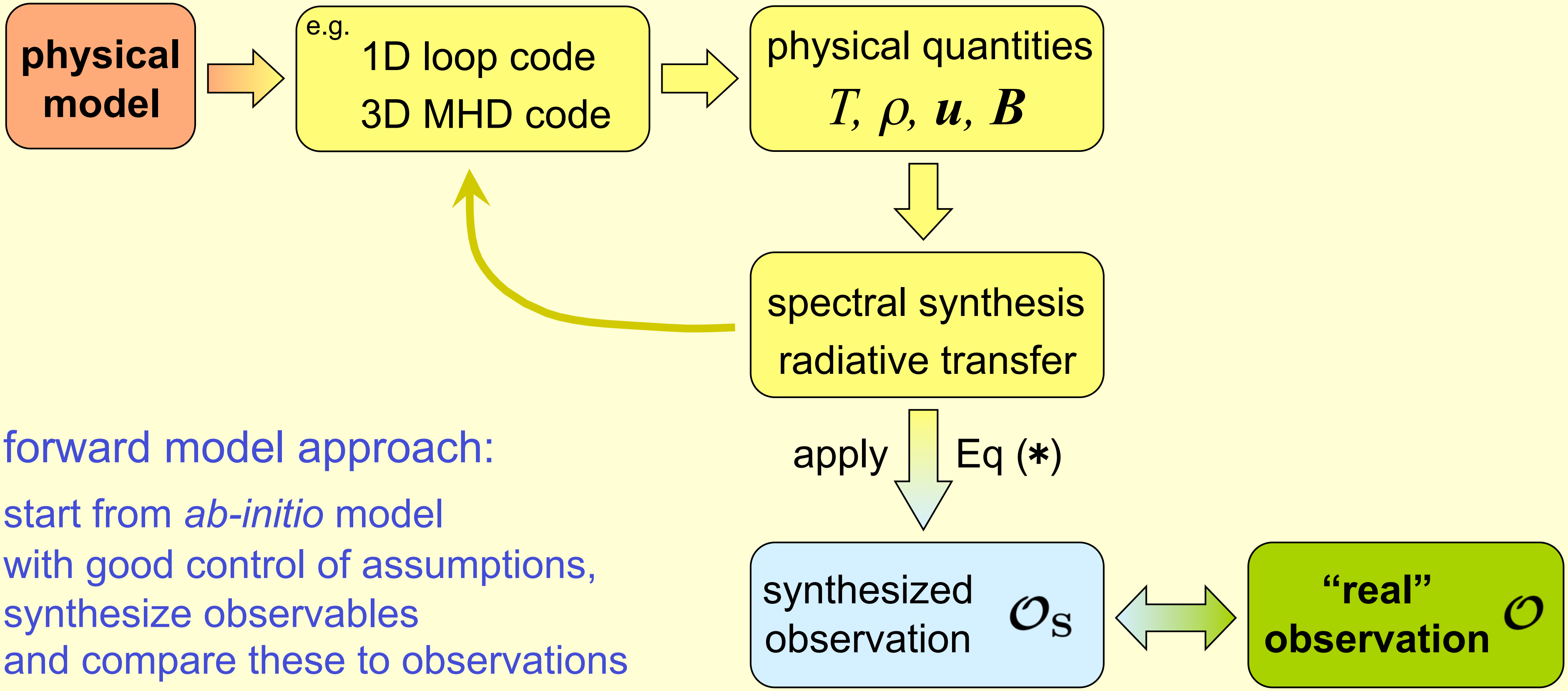
Modeling approach

We observe only photons: flux, polarisation, and energy

in general:

$$\boxed{\text{observed quantity} \quad \mathcal{O} = \int K(T, \rho, \boldsymbol{u}, \boldsymbol{B}, \ldots)\mathrm{d}l} \qquad (*)$$

with a kernel K including e.g. atomic physics, radiative transfer, etc...



physical model

e.g. 1D loop code
3D MHD code

physical quantities
$T,\ \rho,\ \boldsymbol{u},\ \boldsymbol{B}$

spectral synthesis
radiative transfer

apply Eq (*)

synthesized observation $\mathcal{O}_S$

“real” observation $\mathcal{O}$

forward model approach:

start from *ab-initio* model
with good control of assumptions,
synthesize observables
and compare these to observations

1D loop models

continuity equation

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial z}(\rho u) = 0$$

momentum equation

$$\rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial z} = \frac{\partial p}{\partial z} - \rho g_{\|}$$

- adaptive mesh
- proper energy equation
  - heat conduction
  - parameterized heating
- non-equilibrium ionization
- self-consistent treatment of radiative losses

Müller, Hansteen & Peter (2003)
A&A 411, 605

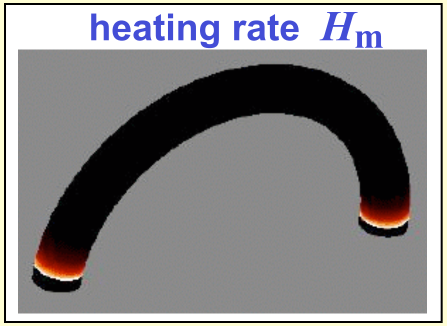
energy equation

$$\frac{\partial}{\partial t}(\rho e) + \frac{\partial}{\partial z}(\rho u e) + p\frac{\partial u}{\partial z} = -\frac{\partial q}{\partial z} + H_{\rm m} - L_{\rm rad}$$

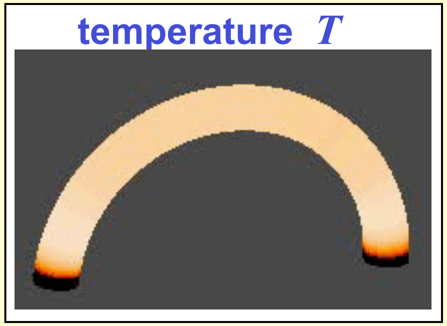
radiative losses: self-consistently or from table

heating: $H_{\rm m} \propto \exp(-z/\lambda_{\rm m})$

heat conduction: $q = \kappa_0 T^{5/2}\frac{\partial T}{\partial z}$



heating rate $H_{\rm m}$



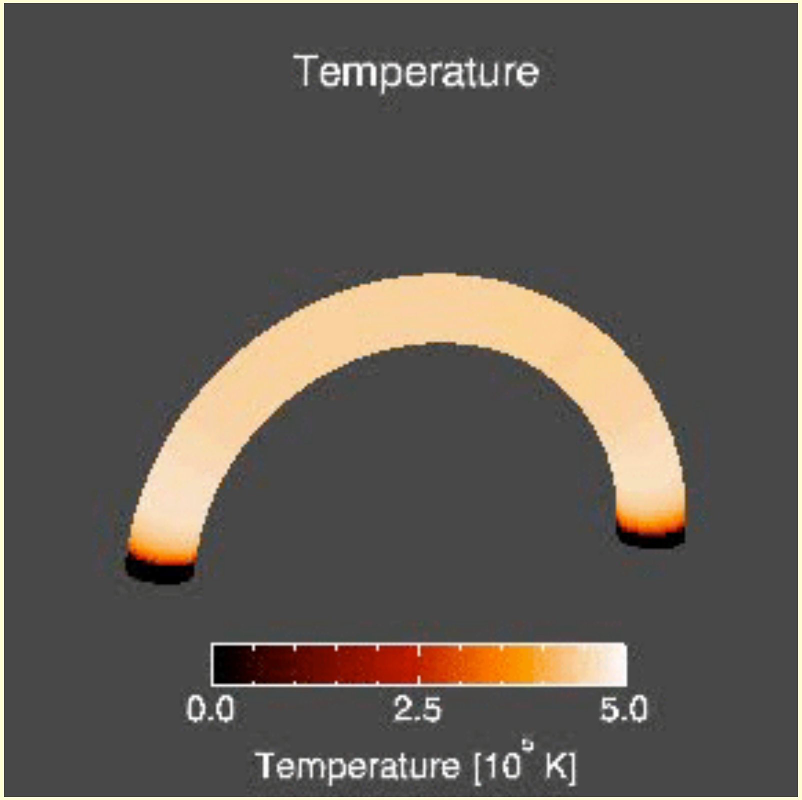
temperature T

rate equations for ionisation and radiation

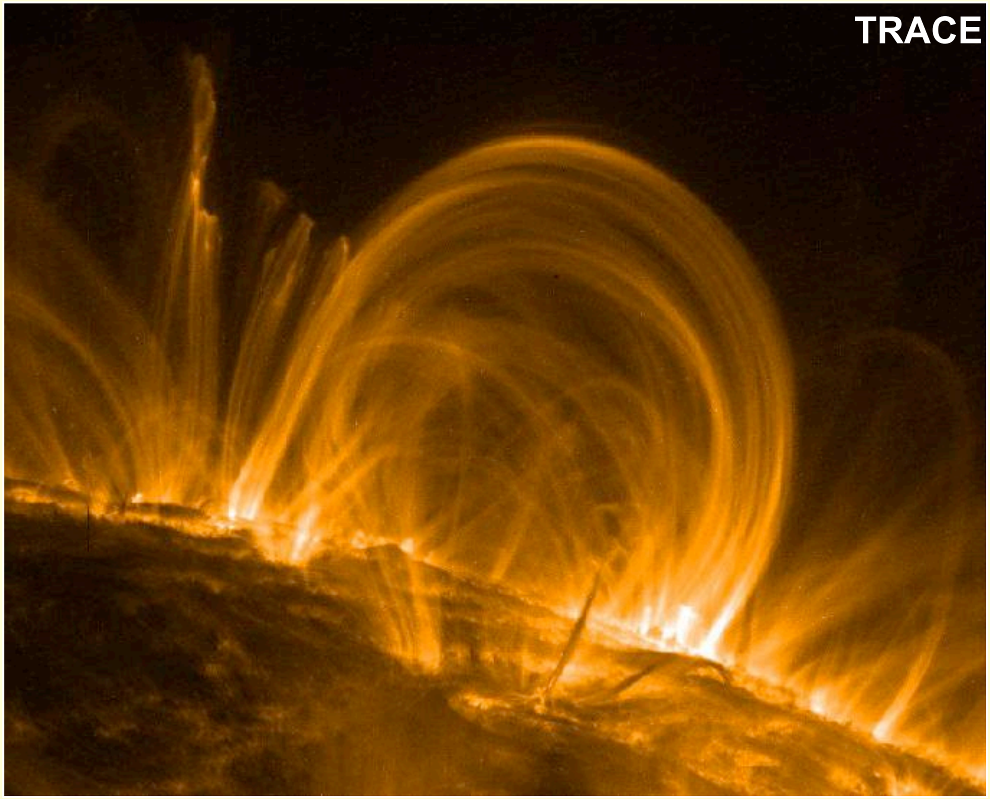
$$\frac{\partial}{\partial t}(n_{i,k}) + \frac{\partial}{\partial z}(n_{i,k}\,u) = \begin{cases} \text{ionization} + \text{recombination} \\ + \text{exitation} + \text{deexcitation} \end{cases}$$

Condensations in coronal loops

Müller, Peter & Hansteen (2004) A&A 424, 289



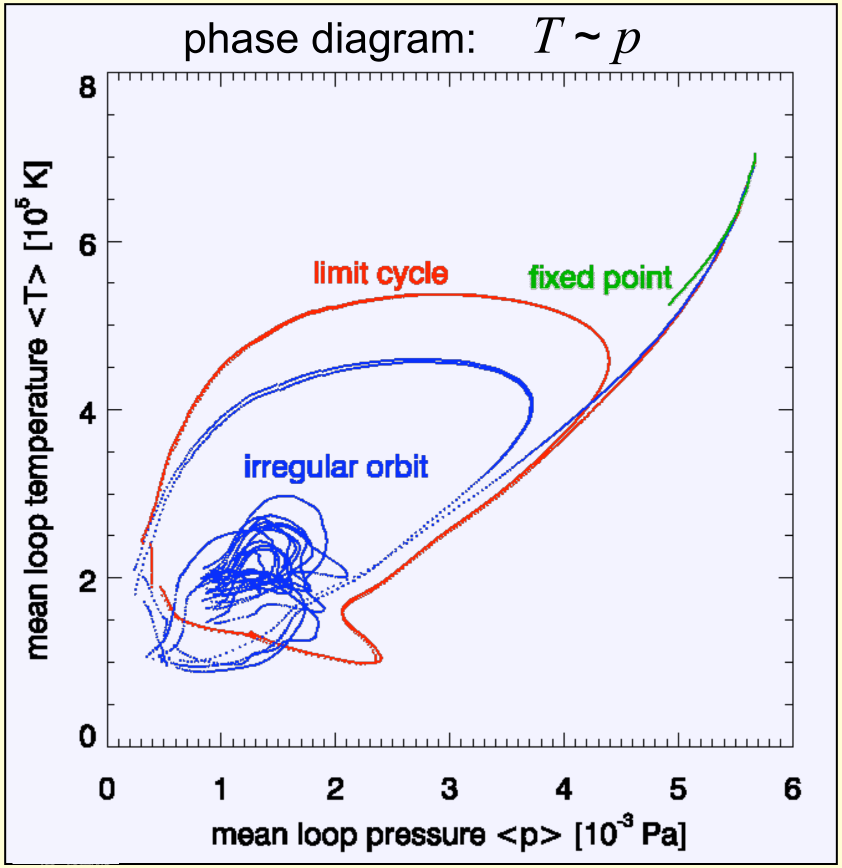
- vary damping length λ_m
  of heating rate $\propto \exp(-z/\lambda_m)$
  constant heating vs. footpoint concentrated
- for wide range of λ_m :
  thermal instability at top
  ➔ condensation



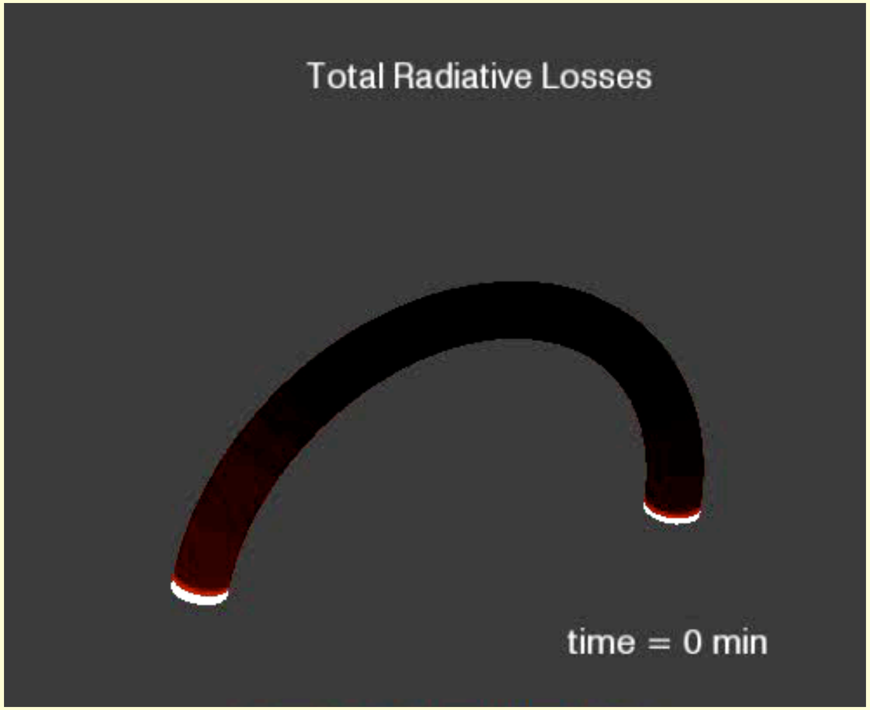
- spectral signatures comparable to observations (TRACE 1550 Å)

Condensations: observation and model

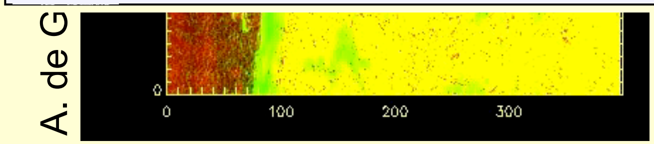
phase diagram: $T \sim p$



loop model: ~ 2 hours



Müller, Peter & Hansteen (2004) A&A 424, 289



EIT 17.1 nm / BBSO Hα

~10^6 K ~10^4 K

- thermal instability is driven by lack of heating in top part of the loop
- occurring even with **time-constant heating**
- due to non-linear interaction of heating, radiative losses and heat conduction

Multi-stranded nanoflare loop models

model one strand:

start with equilibrium:

uniform heating (0.03 mW / m³)

[150 Mm long loop ≈ 2000 W / m²]

→ loop with T_{max} = 2.5 MK

T and ρ stratification consistent with either

- ► true static loop or
- ► cooling loop

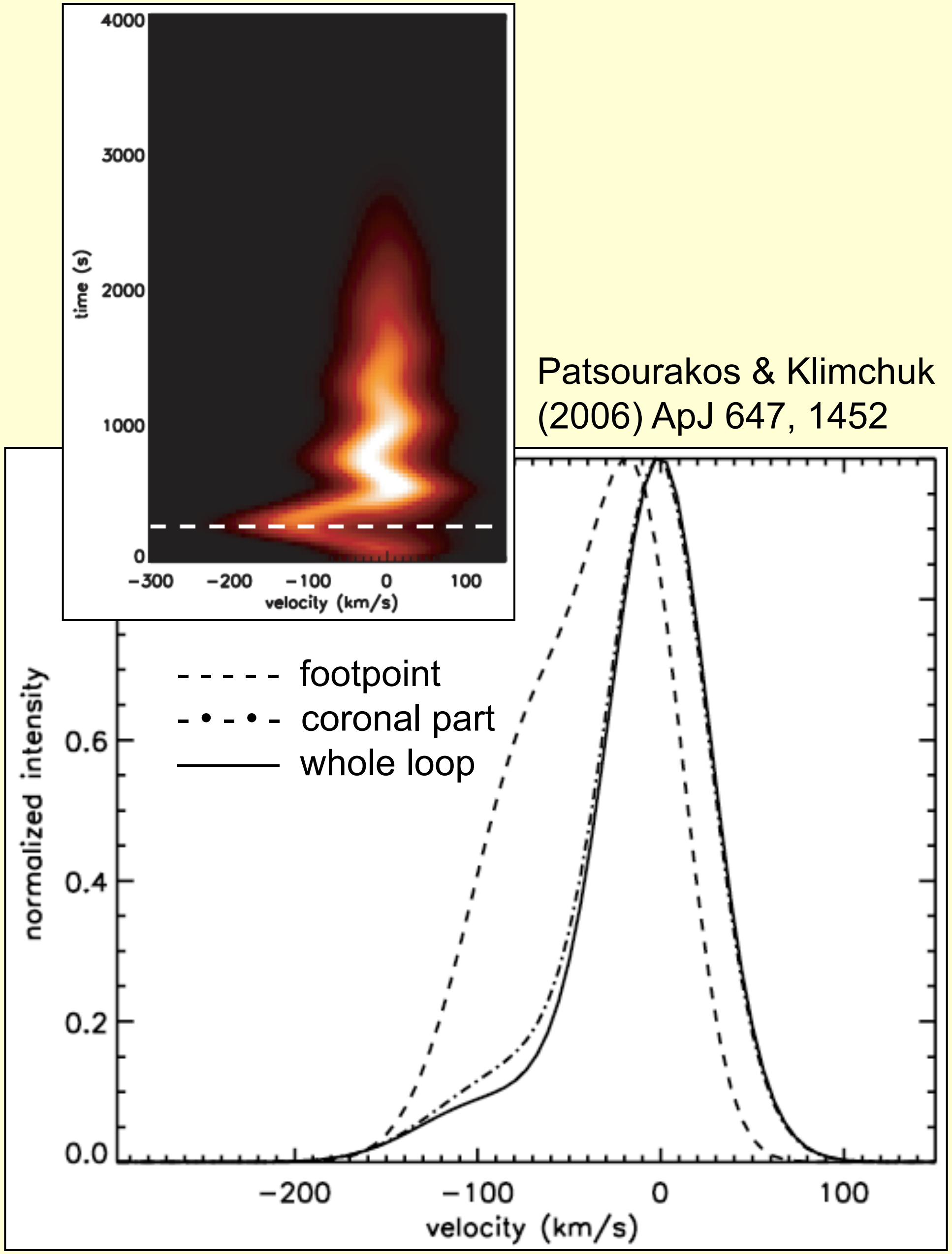
nanoflare:

uniform heating of 1 mW / m³ for 250 s

in strand with 60 km diameter 150 Mm length
this corresponds to 10^{17} J (10^{24} erg),
the nanoflare energy proposed by Parker !

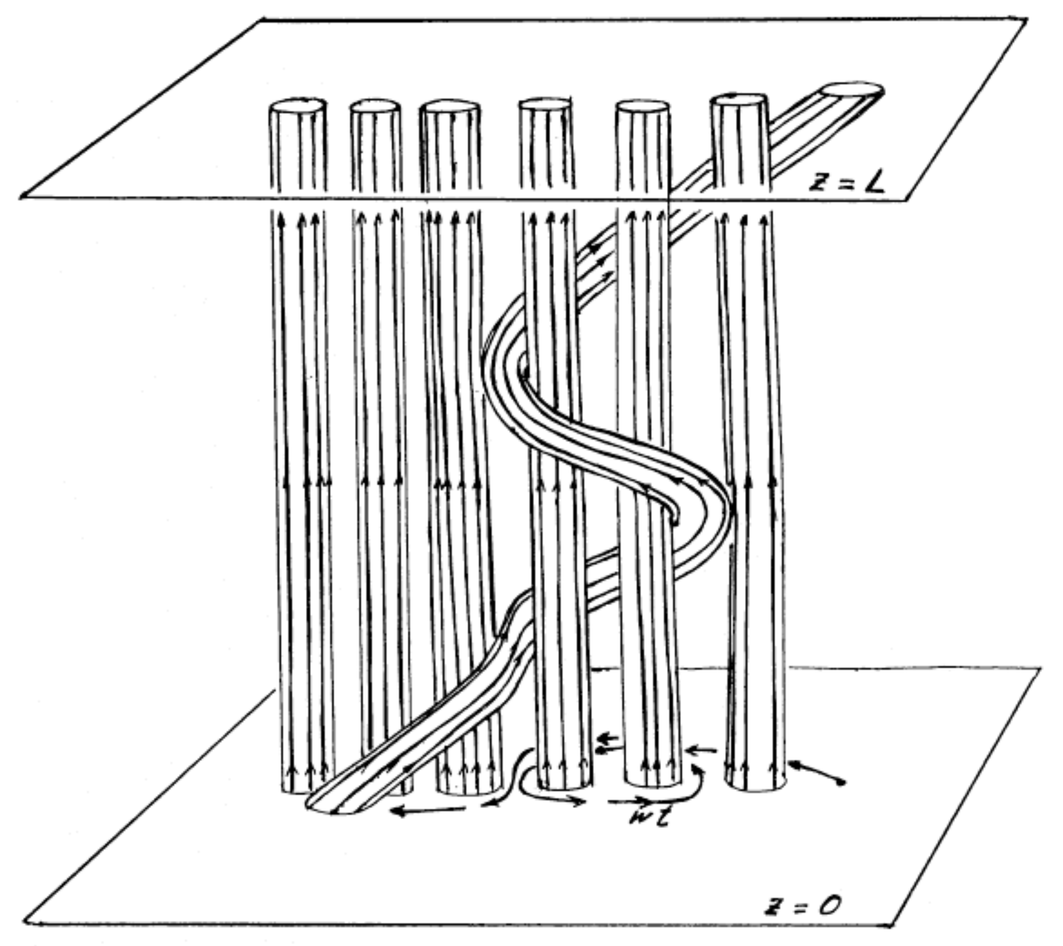
[typical loop with 3 Mm diameter: ≈1000 strands]

→ strong heating
  → evaporation at footpoints
    → upflows visible in line profile (?)



Patsourakos & Klimchuk (2006) ApJ 647, 1452

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

$$j \sim \nabla \times B$$

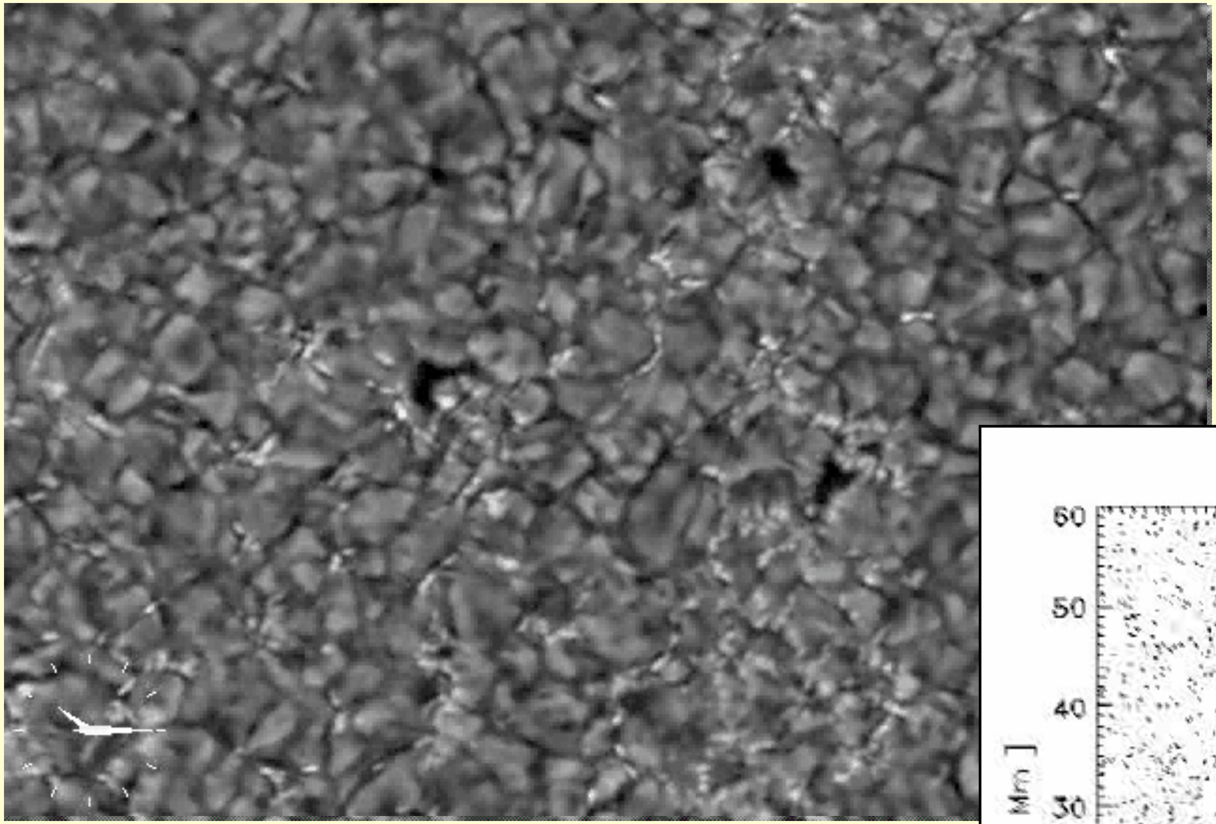
→ Ohmic dissipation

$$H \sim \eta j^2$$

→ heating of the corona

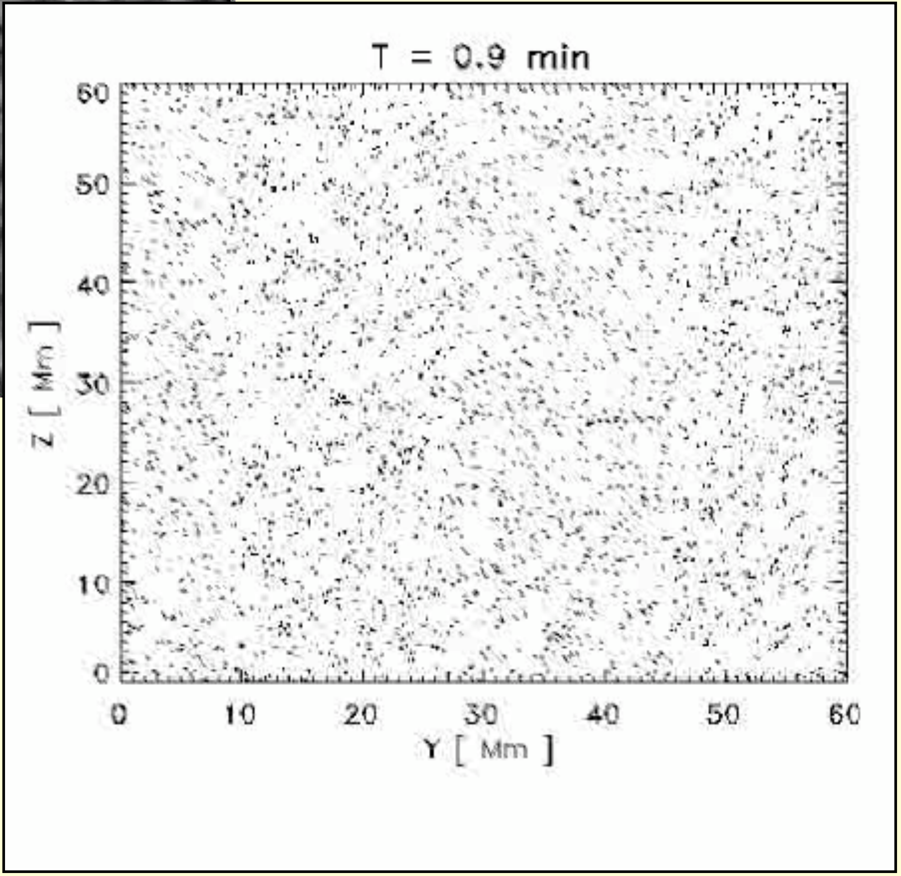
***Problem*: a "realistic" computational model is "costly"…**

The driving force in the photosphere



Dutch Open Telescope, La Palma
12. Sept. 1999 (Sütterlin & Rutten)
≈ 38 000 km x 25 000 km, ≈ 27 min

⌶ 2 Mm



simulated granulation (Voronoi tessellation):

- "corks" on the solar surface (Boris Gudiksen)
- matches solar velocity and vorticity spectra (observed + convection simulations)

3D MHD coronal modeling

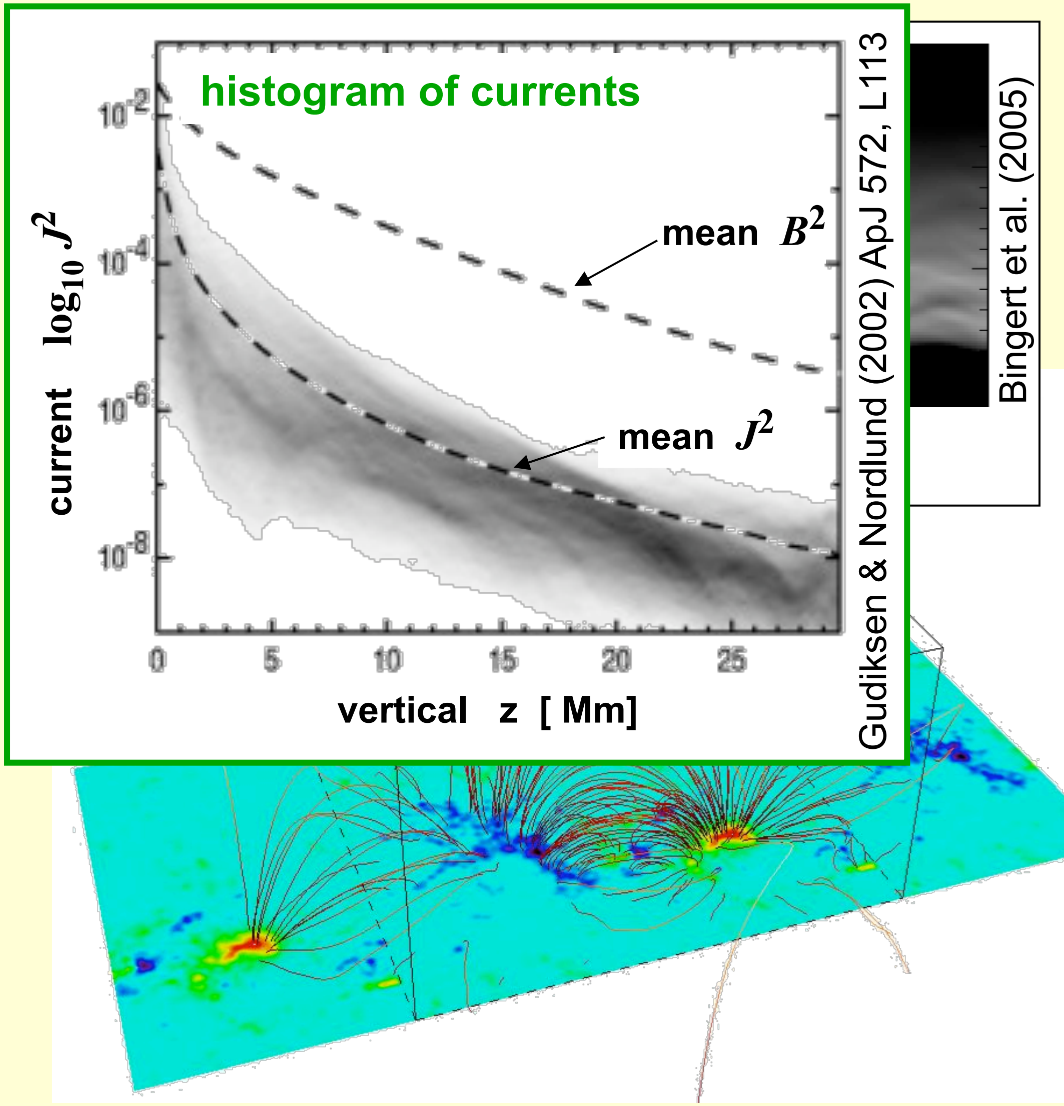
- 3D MHD model for the corona:
  50 x 50 x 30 Mm Box (150^3)
  - fully compressible; high order
  - non-uniform mesh
- full energy equation
  (heat conduction, rad. losses)
- starting with scaled-down
  MDI magnetogram
  - no emerging flux
- photospheric driver:
  foot-point shuffled by convection
- braiding of mag 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
(2005) ApJ 618, 1020 & 1031
Bingert, Peter, Gudiksen & Nordlund (2005)



Gudiksen & Nordlund (2002) ApJ 572, L113

Bingert et al. (2005)

Emissivity from a 3D coronal model

From the MHD model: – density ρ (fully ionized) → n_e
– temperature → T

$\left.\begin{matrix} n_\mathrm{e} \\ T \end{matrix}\right\}$ at each grid point and time

Emissivity at each grid point and time step:

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

$$G(T,n_\mathrm{e}) = h\nu\, A_{21}\, \underbrace{\frac{n_2}{n_\mathrm{e}\, n_\mathrm{ion}}}_{\text{excitation}}\; \underbrace{\frac{n_\mathrm{ion}}{n_\mathrm{el}}}_{\text{ionization}}\; \underbrace{\frac{n_\mathrm{el}}{n_\mathrm{H}}}_{\text{abundance = const.}}\; \underbrace{\frac{n_\mathrm{H}}{n_\mathrm{e}}}_{\text{total ionization} \approx 0.8}$$

ionization, excitation $\Big\} \approx f\,(T)$

Assumptions:

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

– photospheric abundances

use CHIANTI atomic data base 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 – $f(\rho,T)$ – → $\varepsilon\,(\boldsymbol{x},t)$
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:

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

line width corresponding to thermal width

$$w_{th} = \sqrt{\frac{2\,k_{\rm B}\,T\,(\boldsymbol{x},t)}{m_{\rm ion}}}$$

total intensity corresponding to emissivity

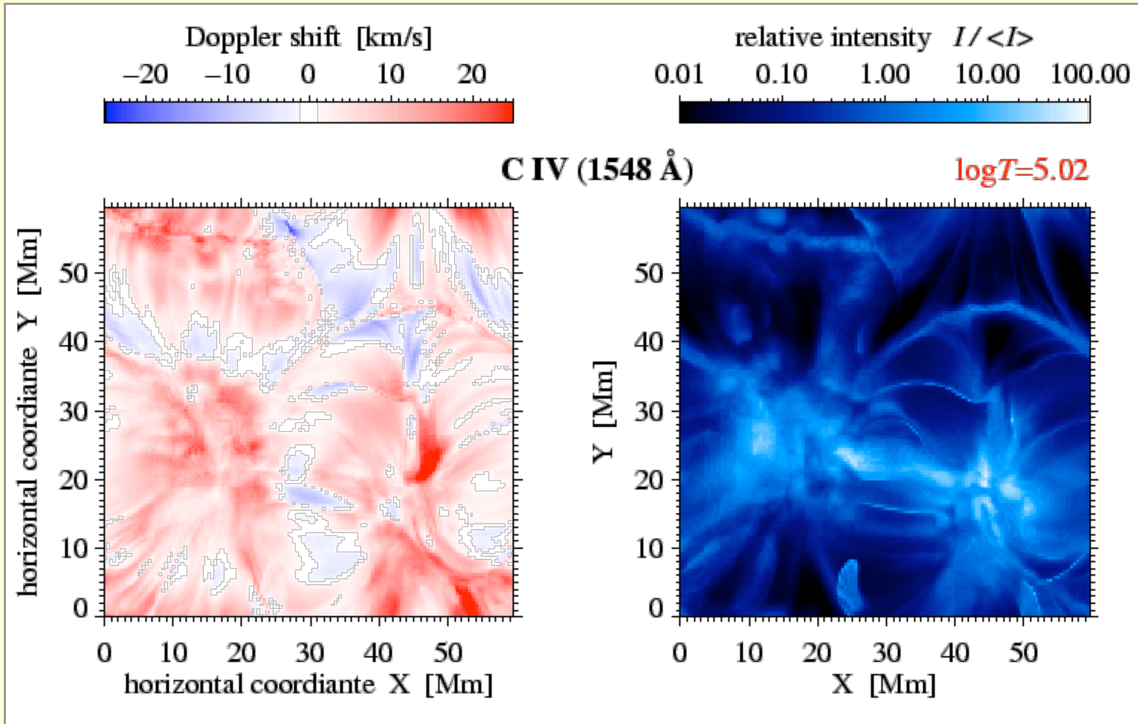
$$I_0\, w_{\rm th} \propto \varepsilon\,(\boldsymbol{x},t)$$

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. ...



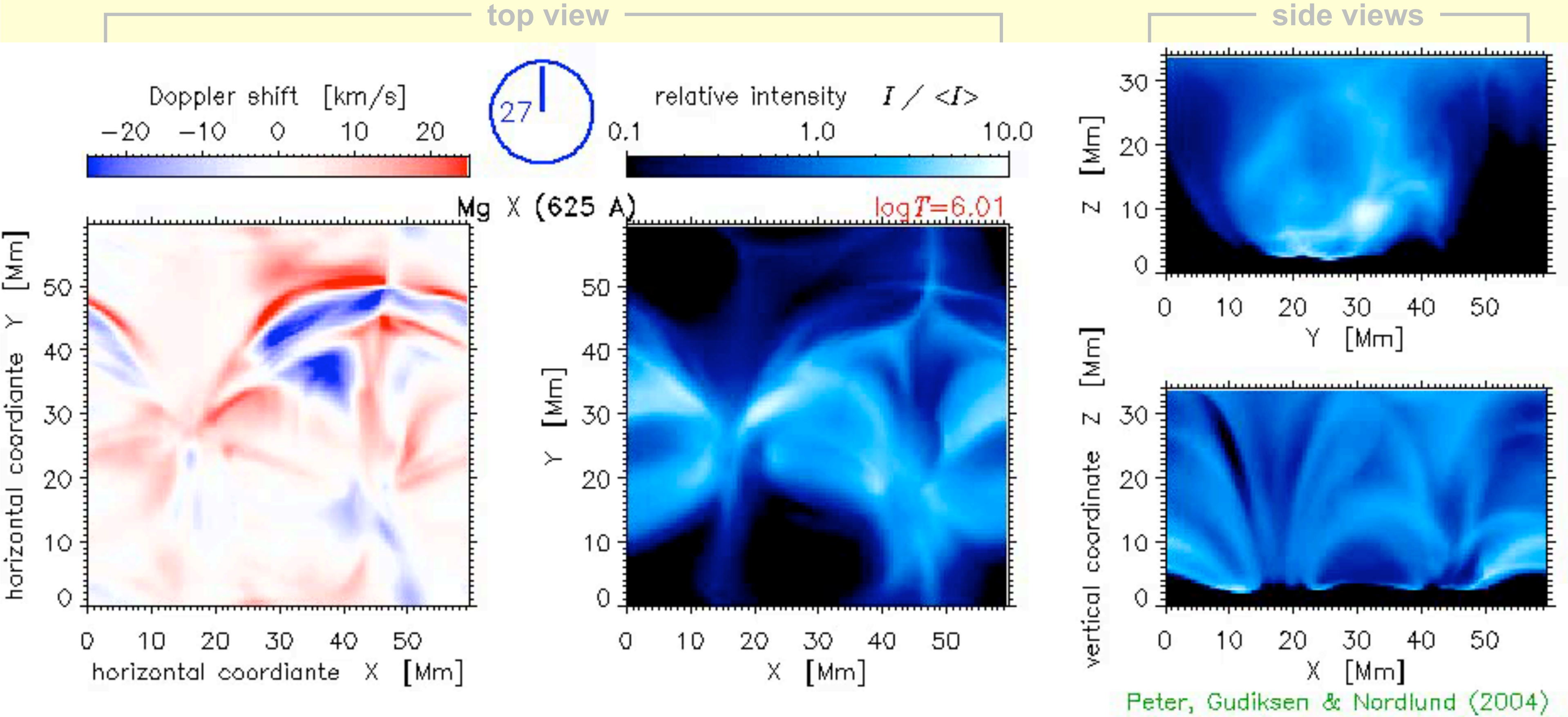
Coronal evolution

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!



Peter, Gudiksen & Nordlund (2004)

TR evolution: C IV (1548 Å)

C IV (1548 Å)

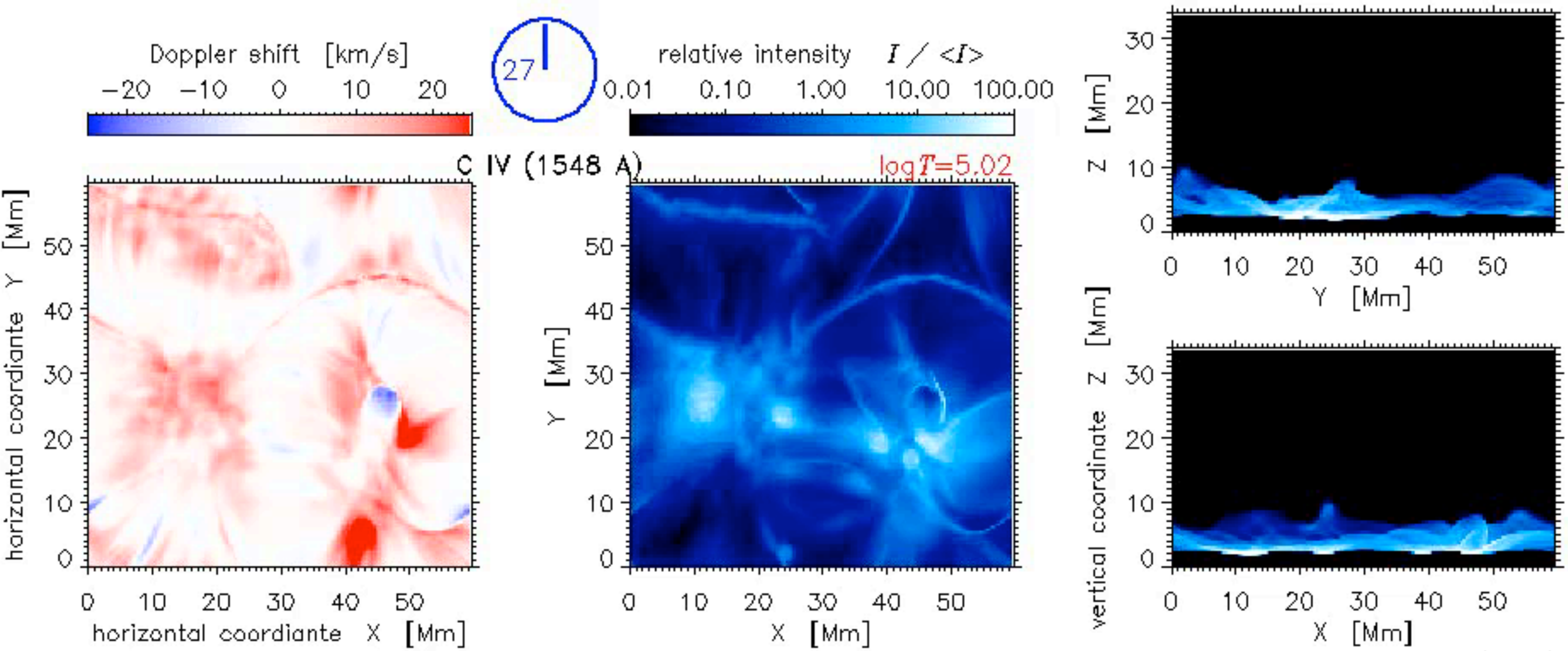
~10^5 K

- 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 !

top view

side views



Peter, Gudiksen & Nordlund (2004)

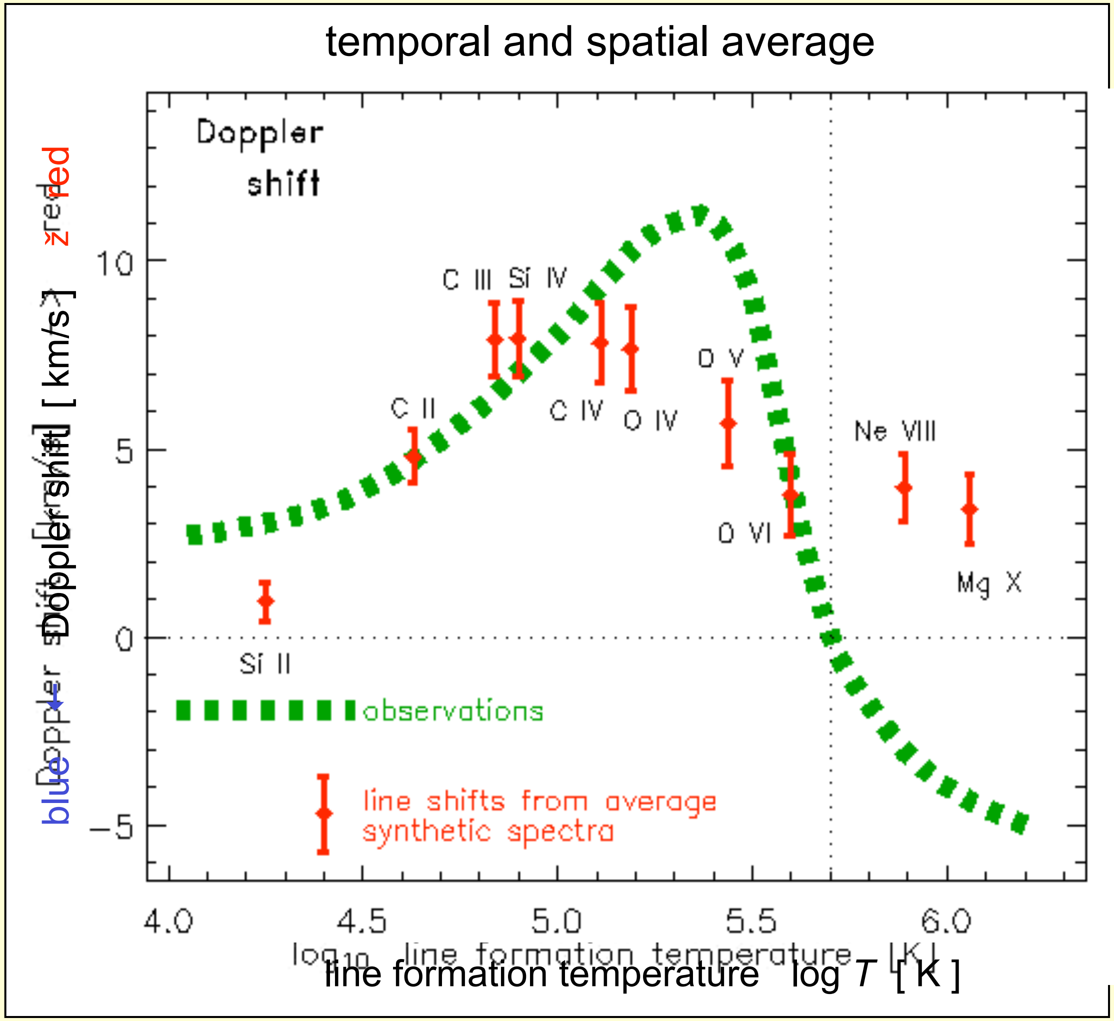
Doppler shifts

spatial 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!



temporal and spatial average

Peter, Gudiksen & Nordlund (2004) ApJ 617, L85

➡ no "fine-tuning" applied !

➡ best over-all match of models so far

Emission measure

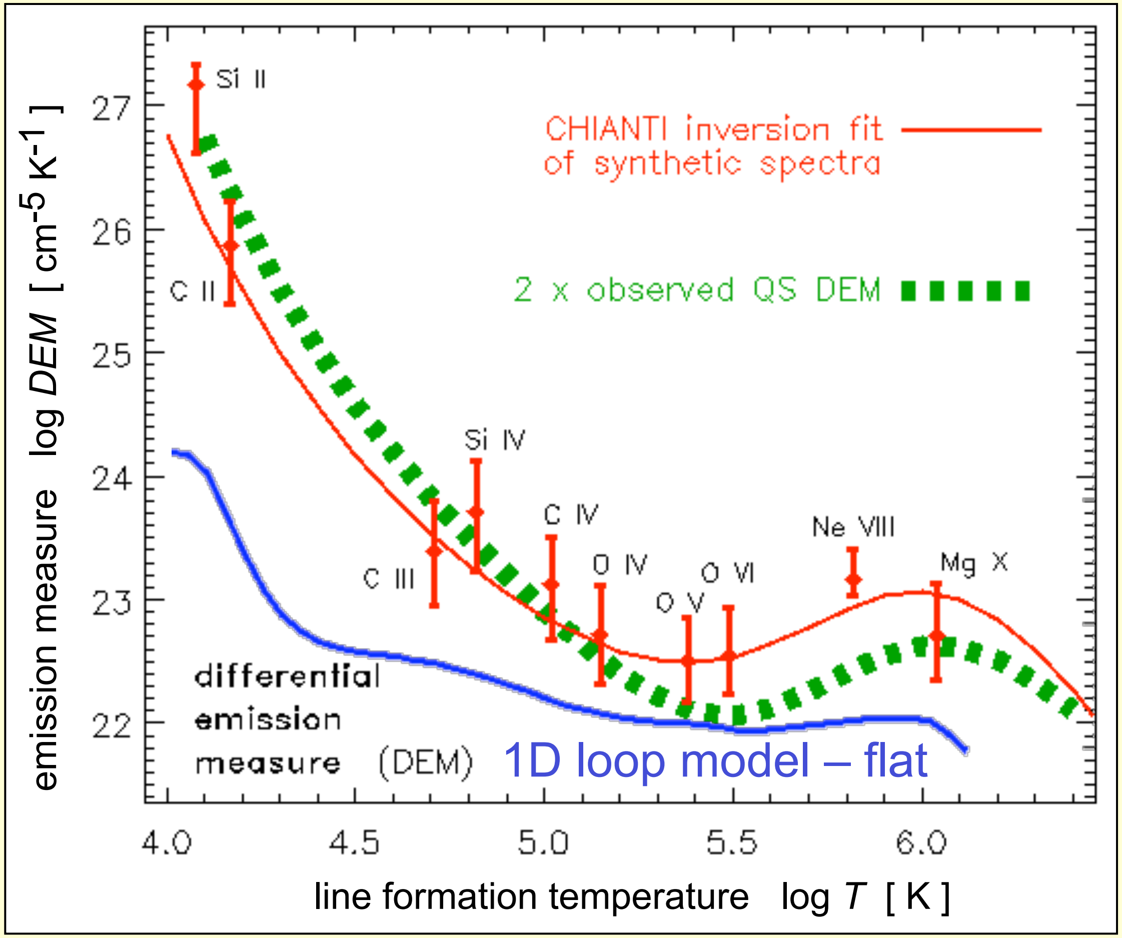
$$DEM = n_{\mathrm{e}}^2 \frac{\mathrm{d}h}{\mathrm{d}T}$$

DEM inversion using CHIANTI:

1 – using synthetic spectra derived from 3D MHD model

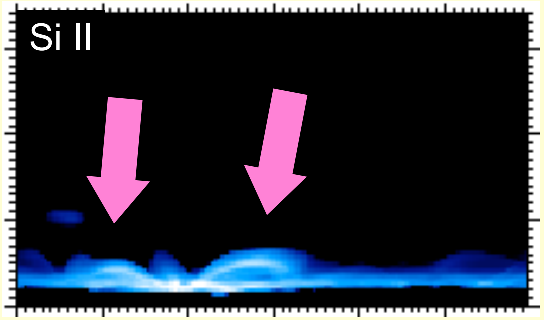
2 – using solar observations (SUMER, same lines)

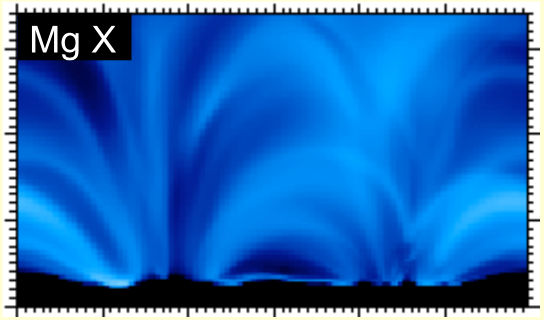
➡ good match to observations!!
DEM increases
towards low *T* in the model !



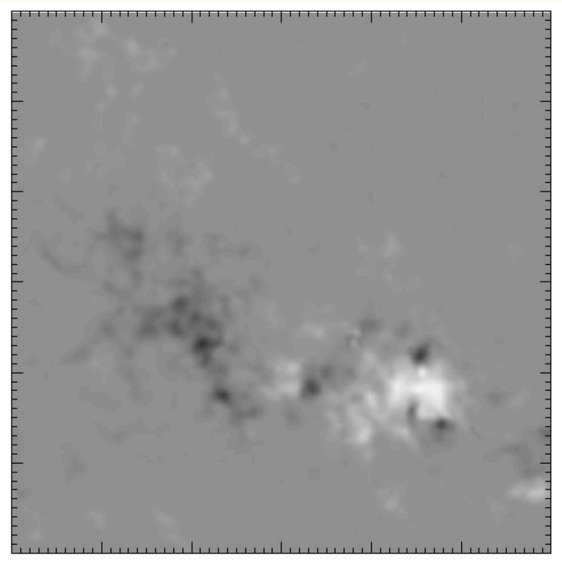
Peter, Gudiksen & Nordlund (2004) ApJ 617, L85

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

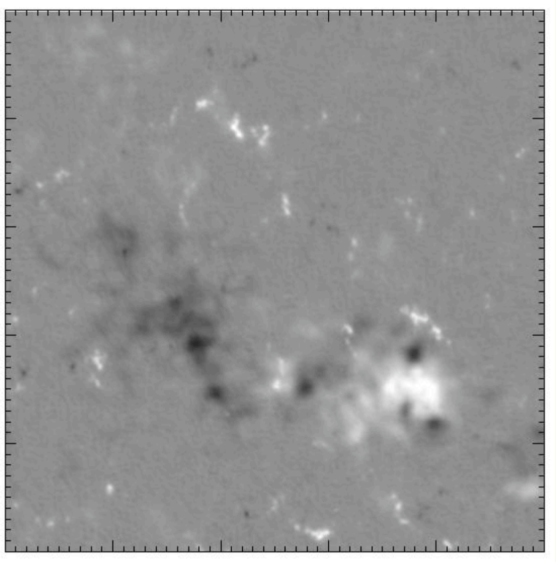


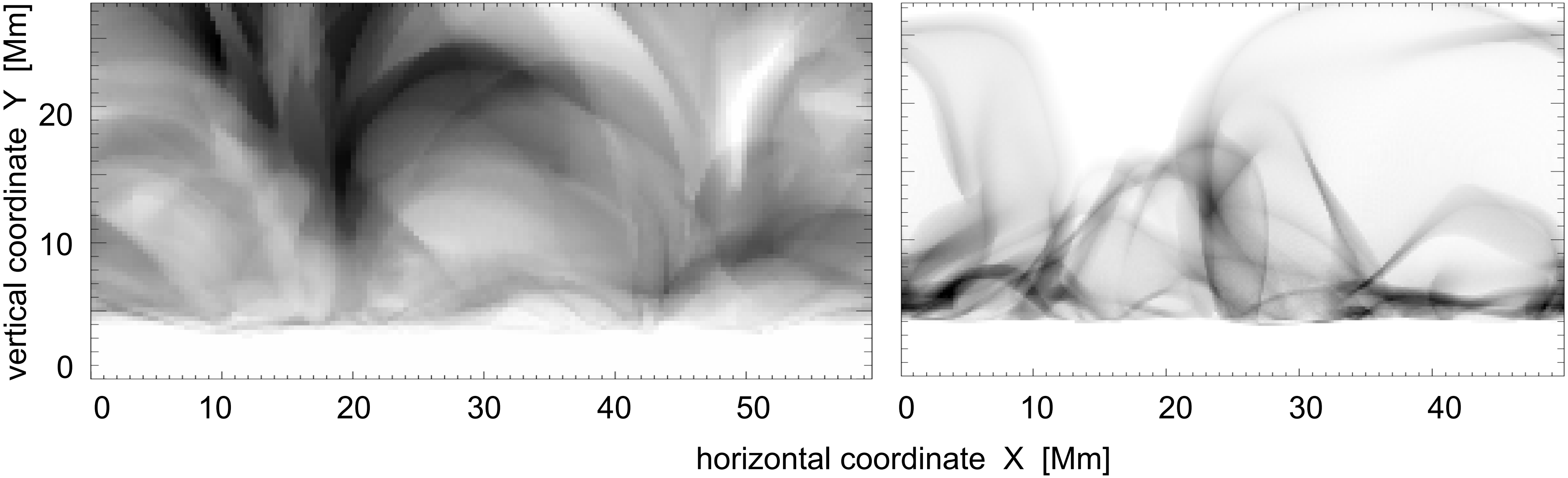


Sample views of different experiments



depending on setup
of lower boundary
(photospheric *B*)
the corona looks different



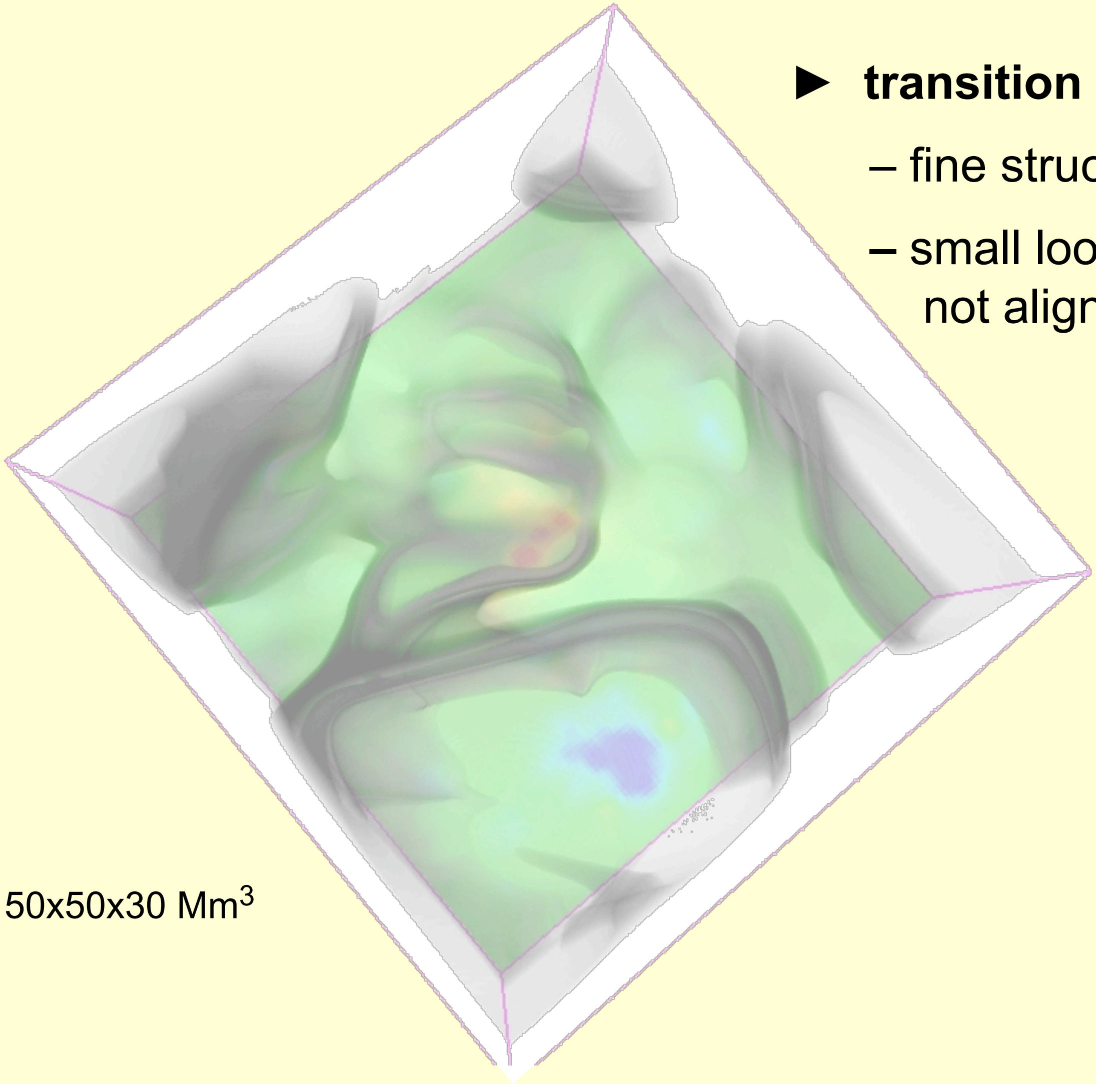


Ne VIII (770 Å) / TRACE 171 Å

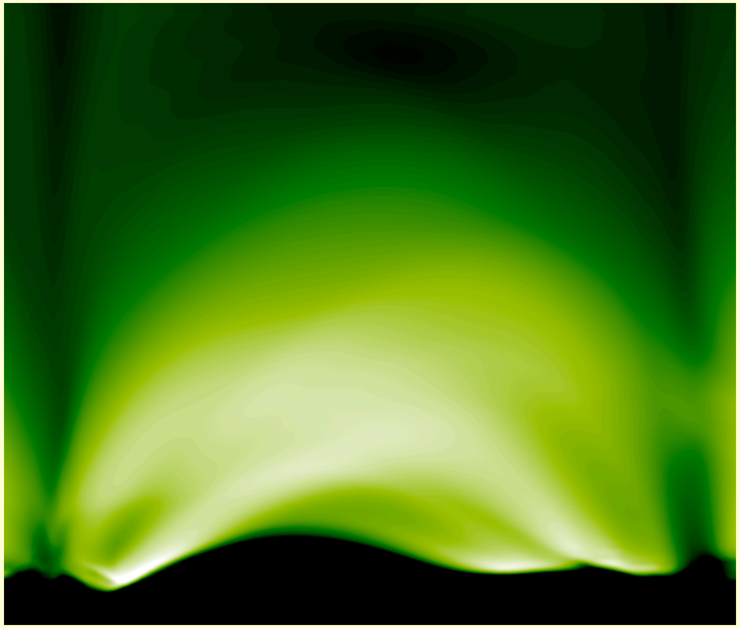
Bingert, hp, Zacharias & Gudiksen (2009)

Spatial coronal structure from 3D model

- **transition region** O VI 1032 Å; 300.000K
  - – fine structures
  - **–** small loop-like structures not aligned with $\boldsymbol{B}$: *iLoops*



50x50x30 Mm^3

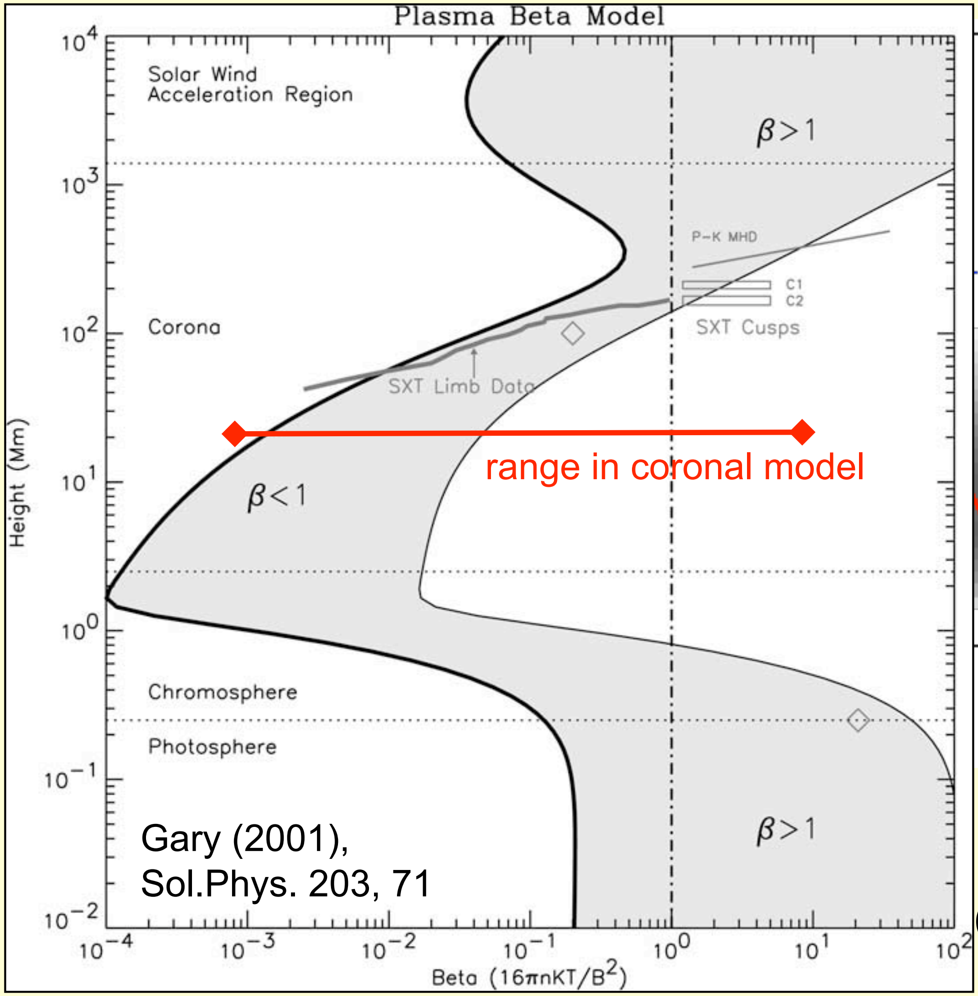


- **corona:** – more diffuse emission

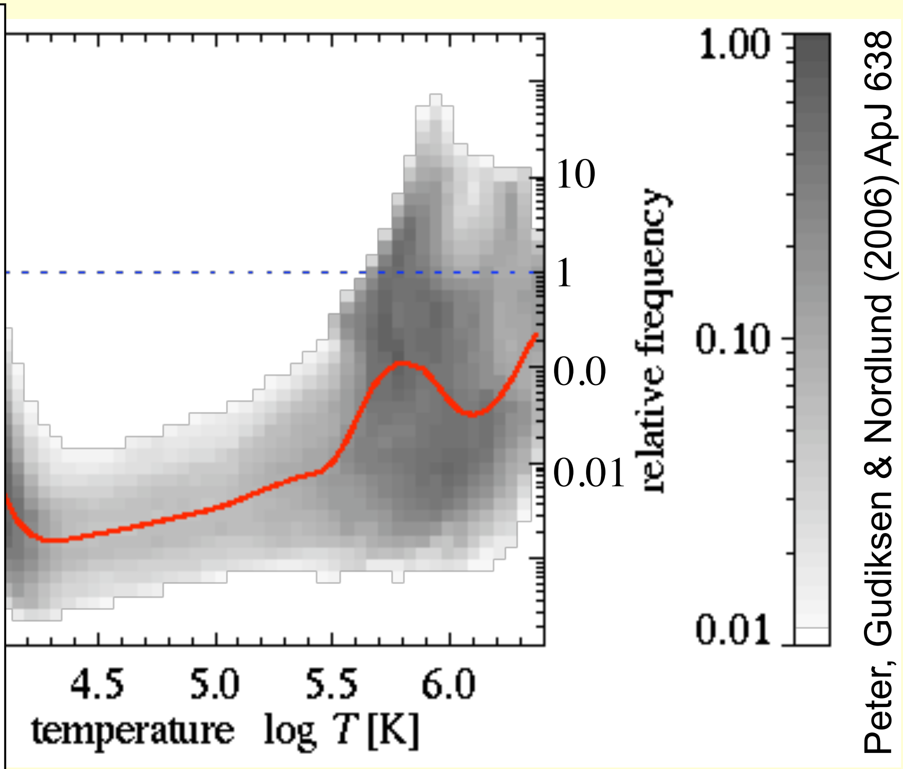
Mg X 625 Å – large-sale loop system

10^6 K aligned with $\boldsymbol{B}$: *bLoops*

Coronal emission and plasma–β



Gary (2001),
Sol.Phys. 203, 71



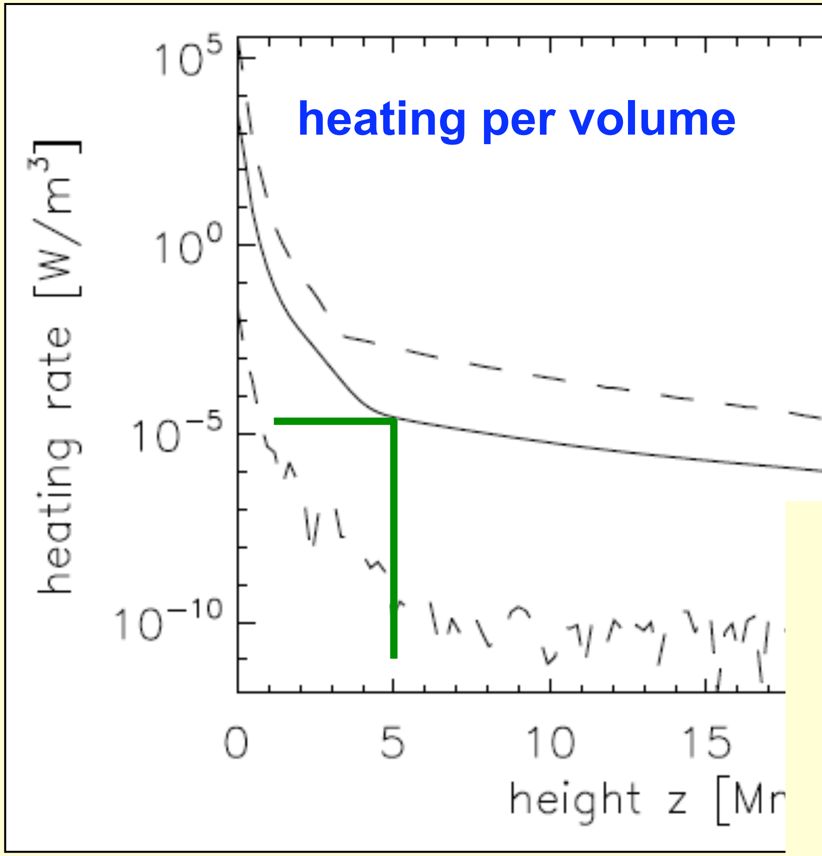
Peter, Gudiksen & Nordlund (2006) ApJ 638

(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 β >1

- corona is **not** in a pure low–β state:
  plasma able to distort magnetic field
  to some extent

Horizontally averaged heating rate

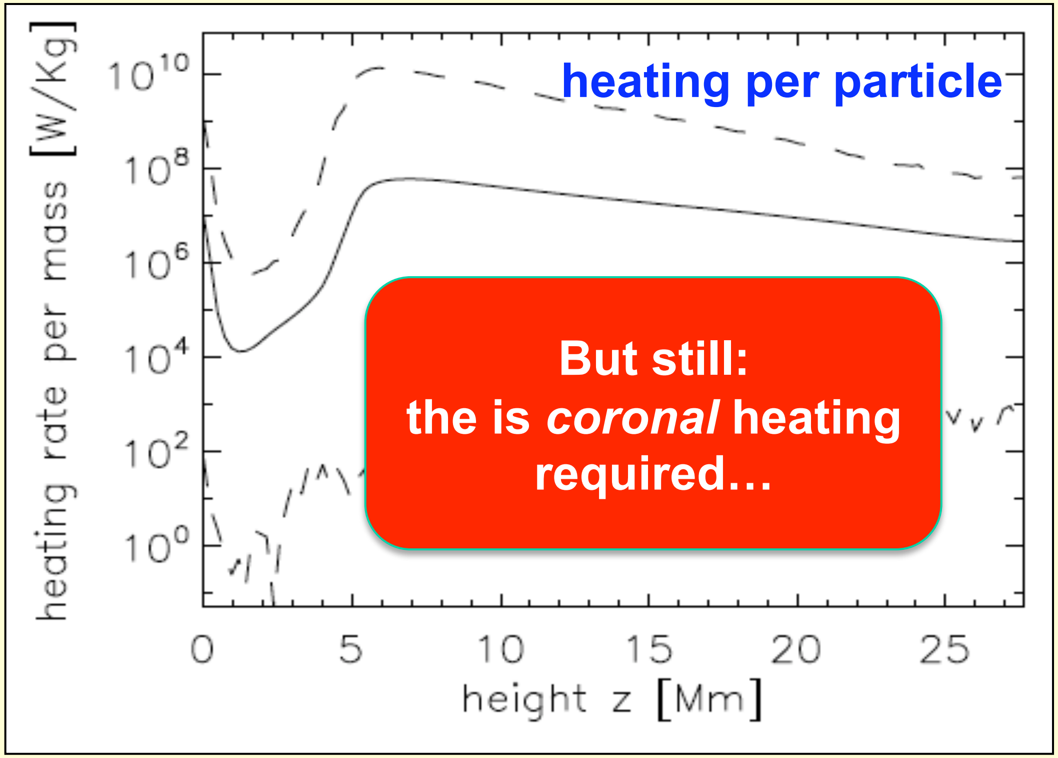


heating rate drops with height
scale height ~10 Mm
Bingert & hp (2009)

→ seems to be a "general" property

→ various properties point to heating concentrated low down
(Aschwanden et al. 2007; ApJ 659, 1673)

matches heating rate from self-consistent models for convection-photosphere-corona
(Carlsson 2009)

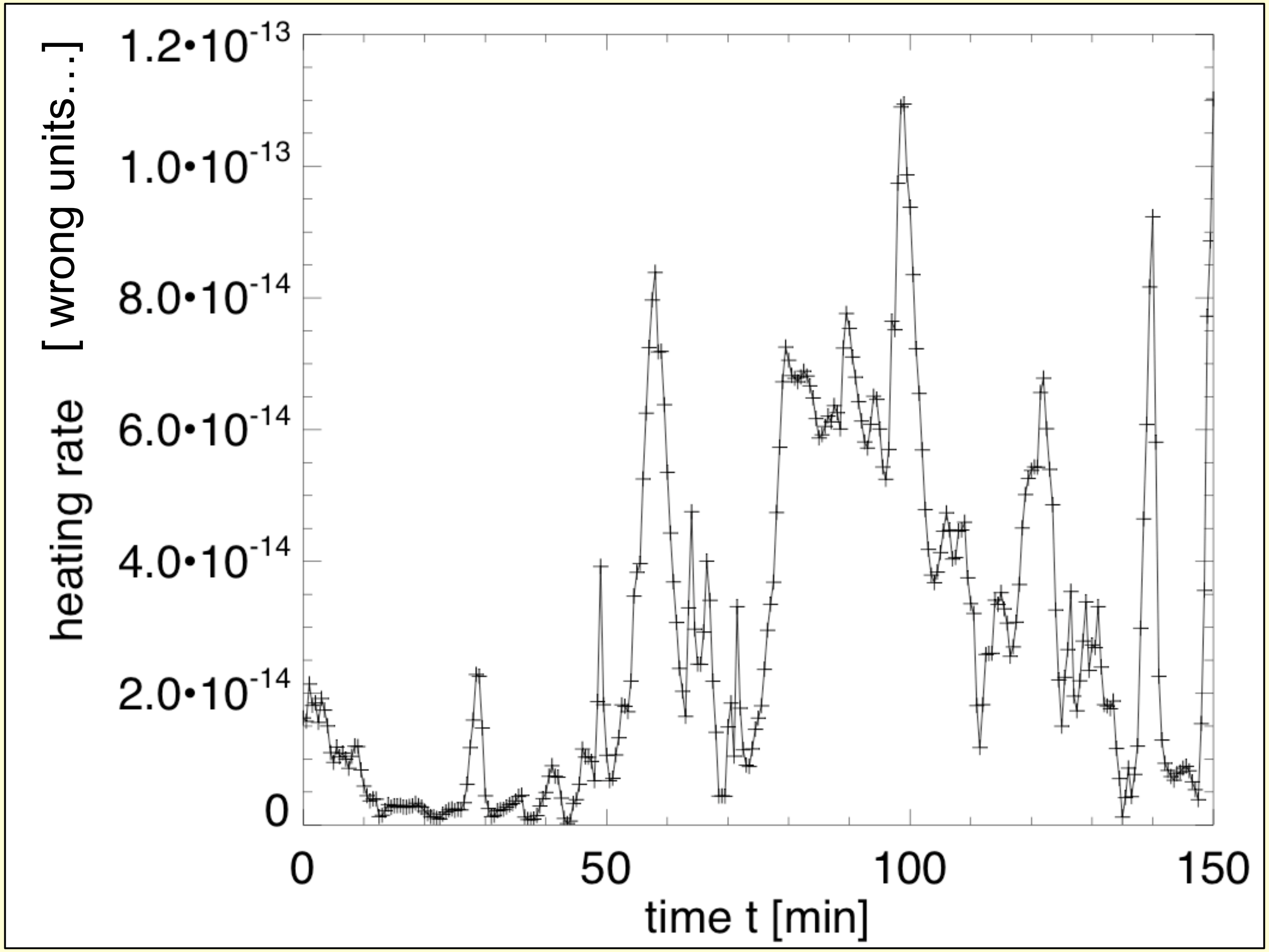


But still:
the is *coronal* heating required…

Heating per mass (particle)
also shows exponential drop
Bingert & hp (2009)

Time-dependent heating rate in 3D model

energy deposition in a single “grid point” (fixed point in space – not on the same “field line”)



Bingert, hp (2009)

“events” can have energies of **10^{20} – 10^{25} erg** depending on height and length

Is this the same as “nanoflare storms” ?

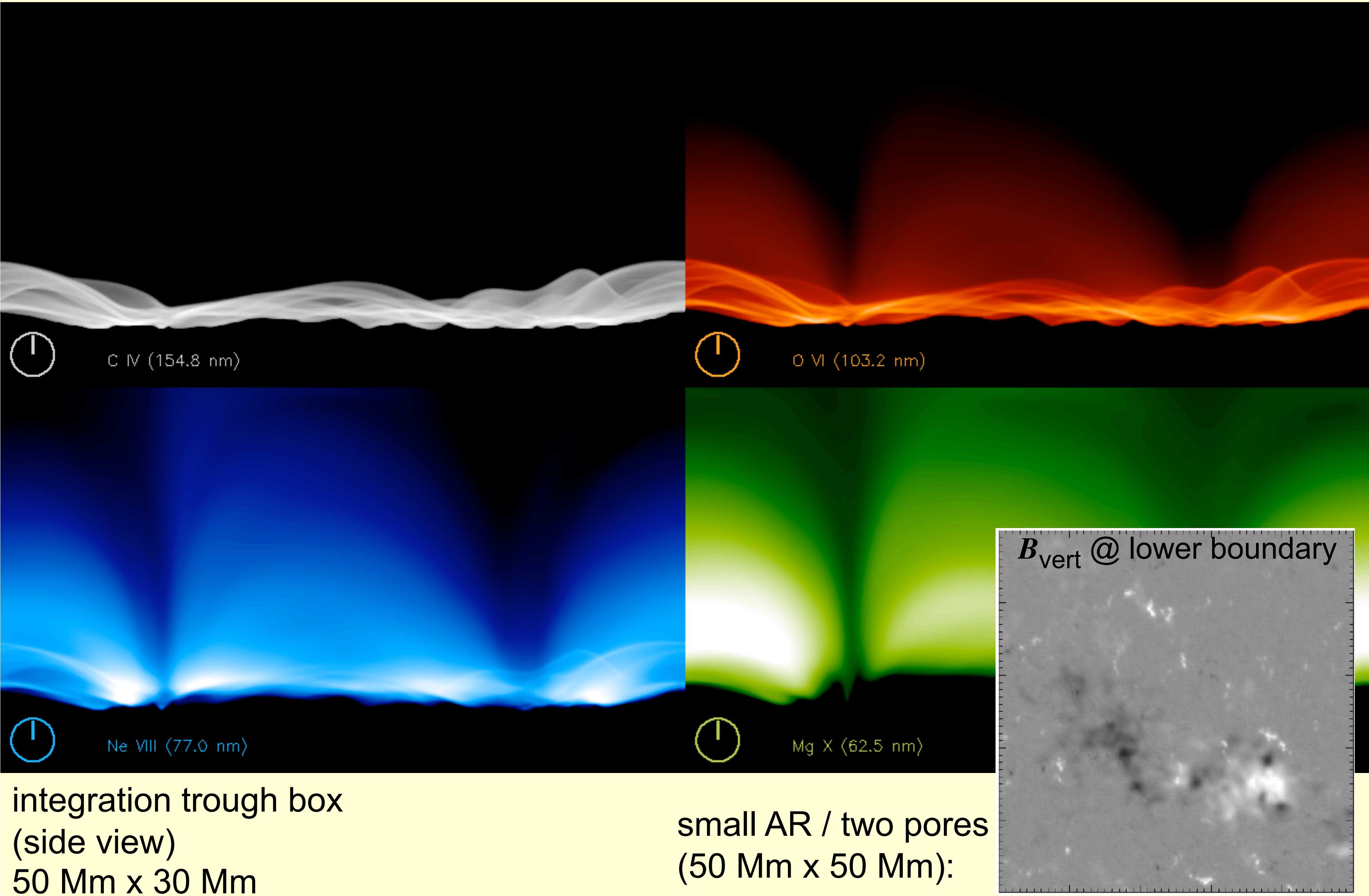
700 s

“short storm” ?

4500 s

“long storm” ?

A recent experiment…

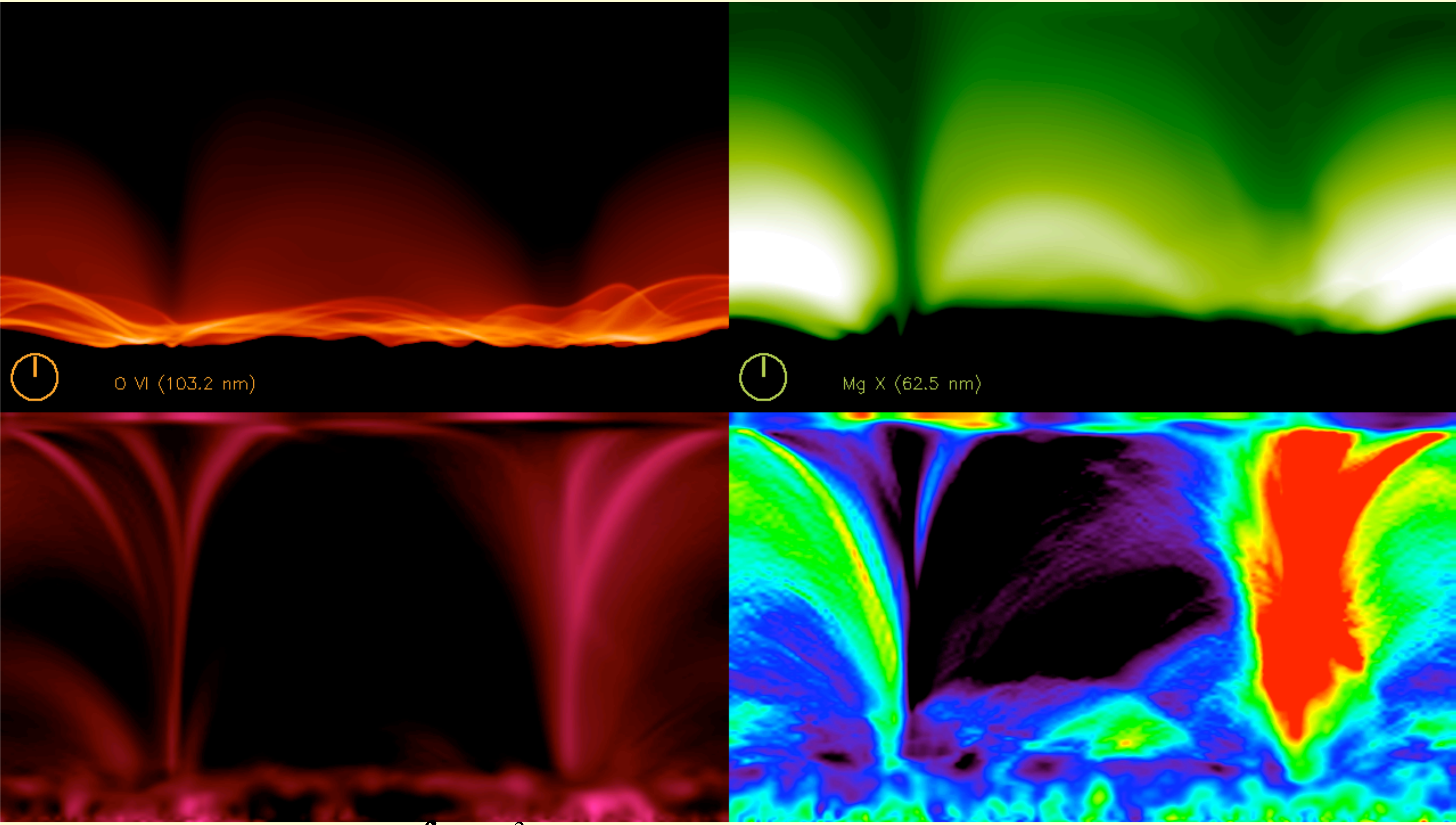


integration trough box
(side view)
50 Mm x 30 Mm

small AR / two pores
(50 Mm x 50 Mm):

Ejection of gas driven by “low TR” heating event

or chromospheric



integration trough box
(side view)
50 Mm x 30 Mm

$$\frac{\int_{\mathrm{los}} j^2(x,y,z\,;t)\,\mathrm{d}y}{\left\langle \int_{\mathrm{los}} j^2\,\mathrm{d}y \right\rangle_{\mathrm{time},x}}$$

$$\int_{\mathrm{los}} \frac{j^2(x,y,z)}{\left\langle j^2(x,y,z) \right\rangle_{\mathrm{time}}}\,\mathrm{d}y$$

Summary / lessons learnt

- in the quiet corona emission is dominated by magnetically closed regions
- loops are basic building blocks
- heating rate sets coronal base pressure
- forward modeling allows reliable comparison to observations
  – one observes only photons (and not T, ρ, $\boldsymbol{v}$, $\boldsymbol{B}$)
- loops evolve very dynamically, even when not driven
- braiding of magnetic field lines is good candidate to heat the corona
  - produces a MK loop-structured corona
  - properties of inferred spectra match observations (line shift, intensity, etc)
  - dynamics as with observations
- however: MHD coronal box model describes “Mm-scale” heating,
  but it does not describe the "real" microphysical processes!