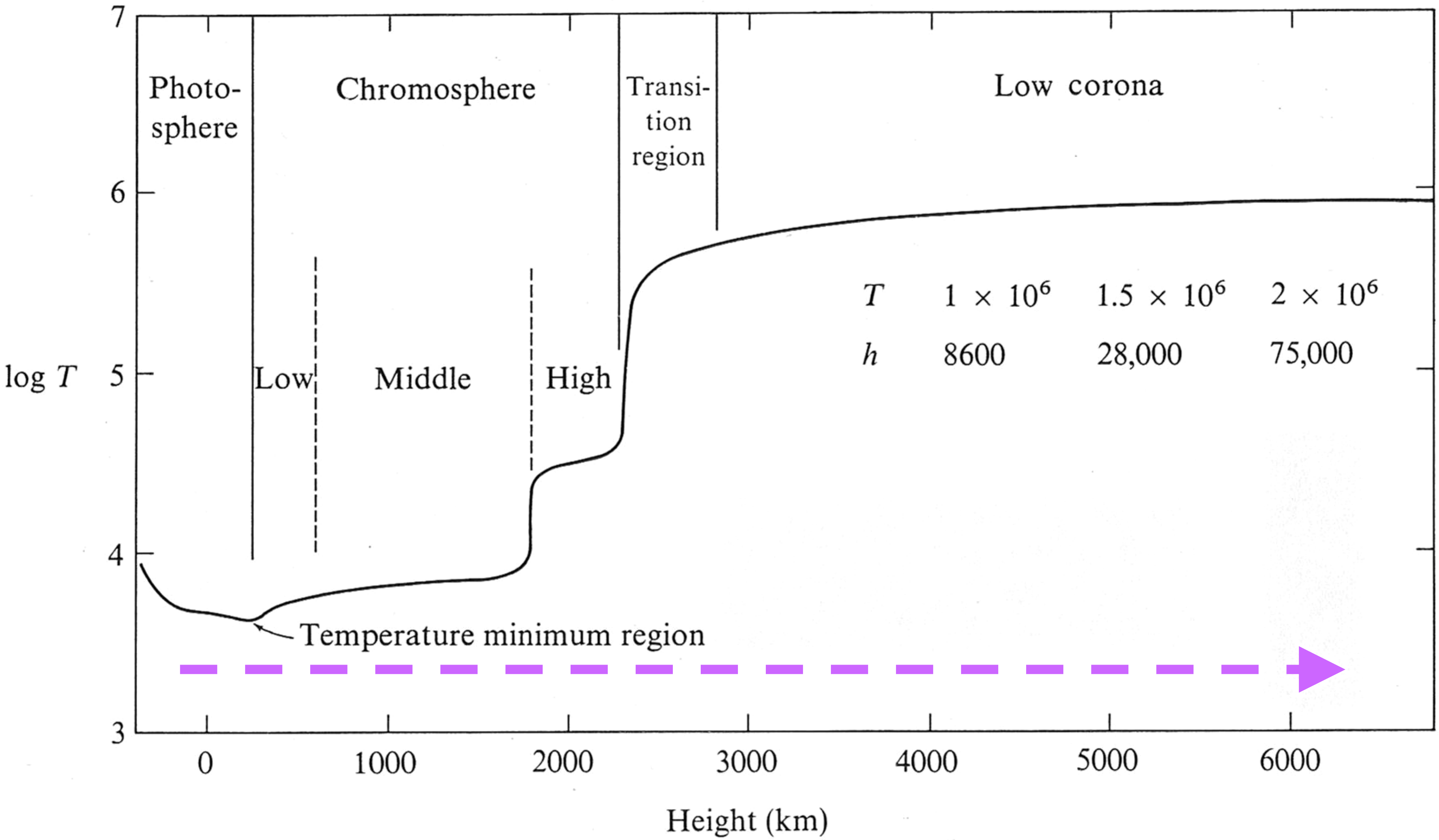
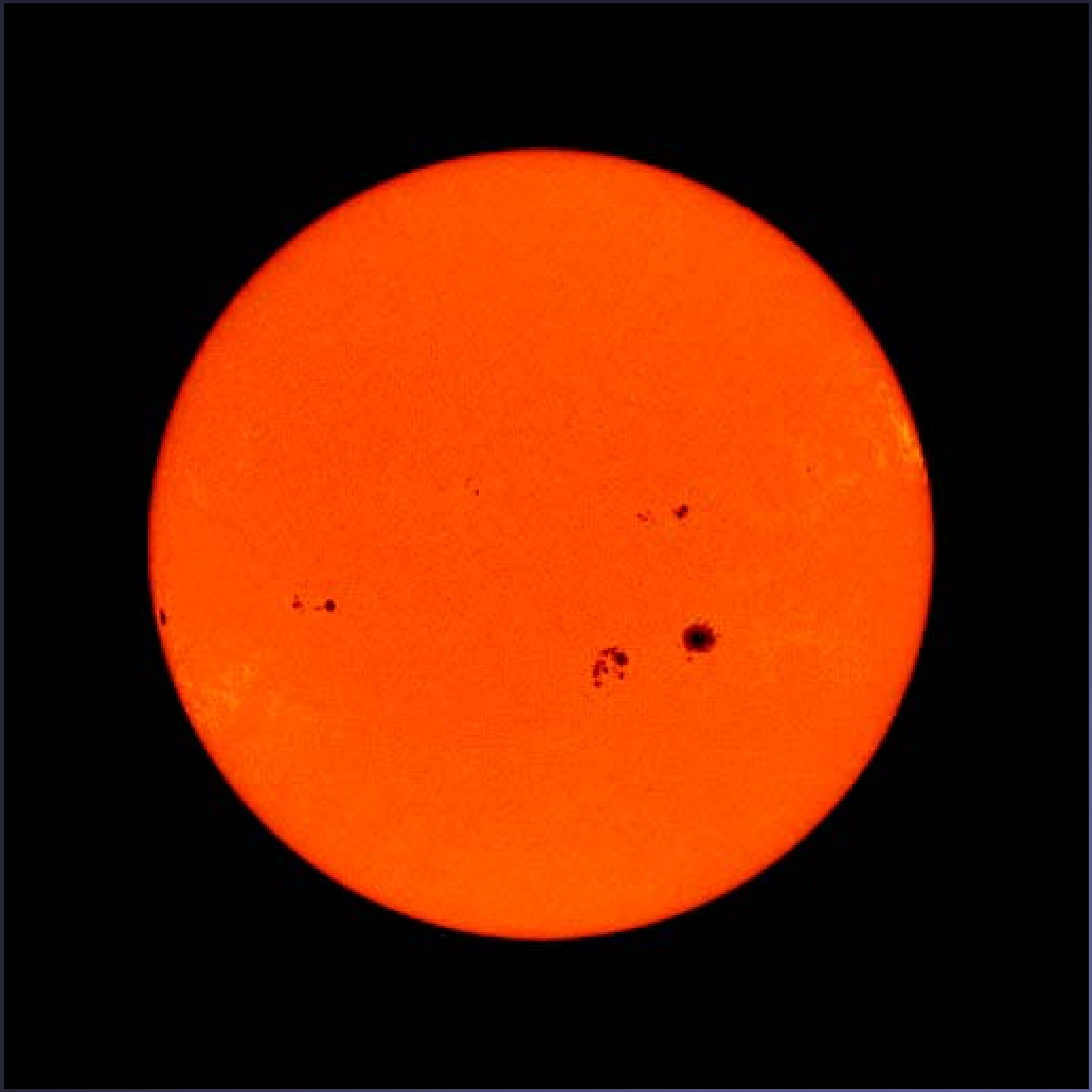
Manifestations of the magnetic field in the Sun's atmosphere

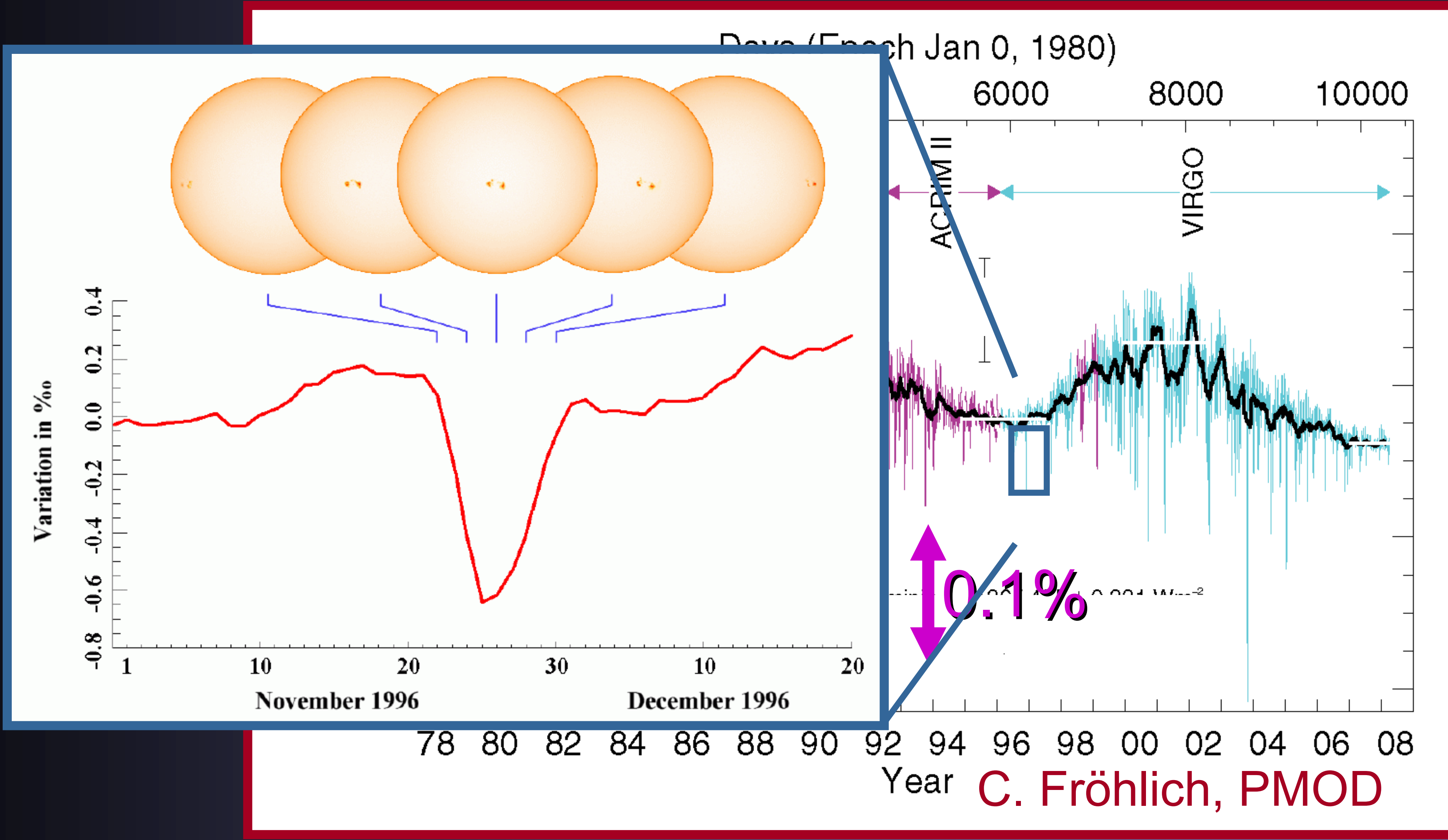
1-D stratification of the solar atmosphere

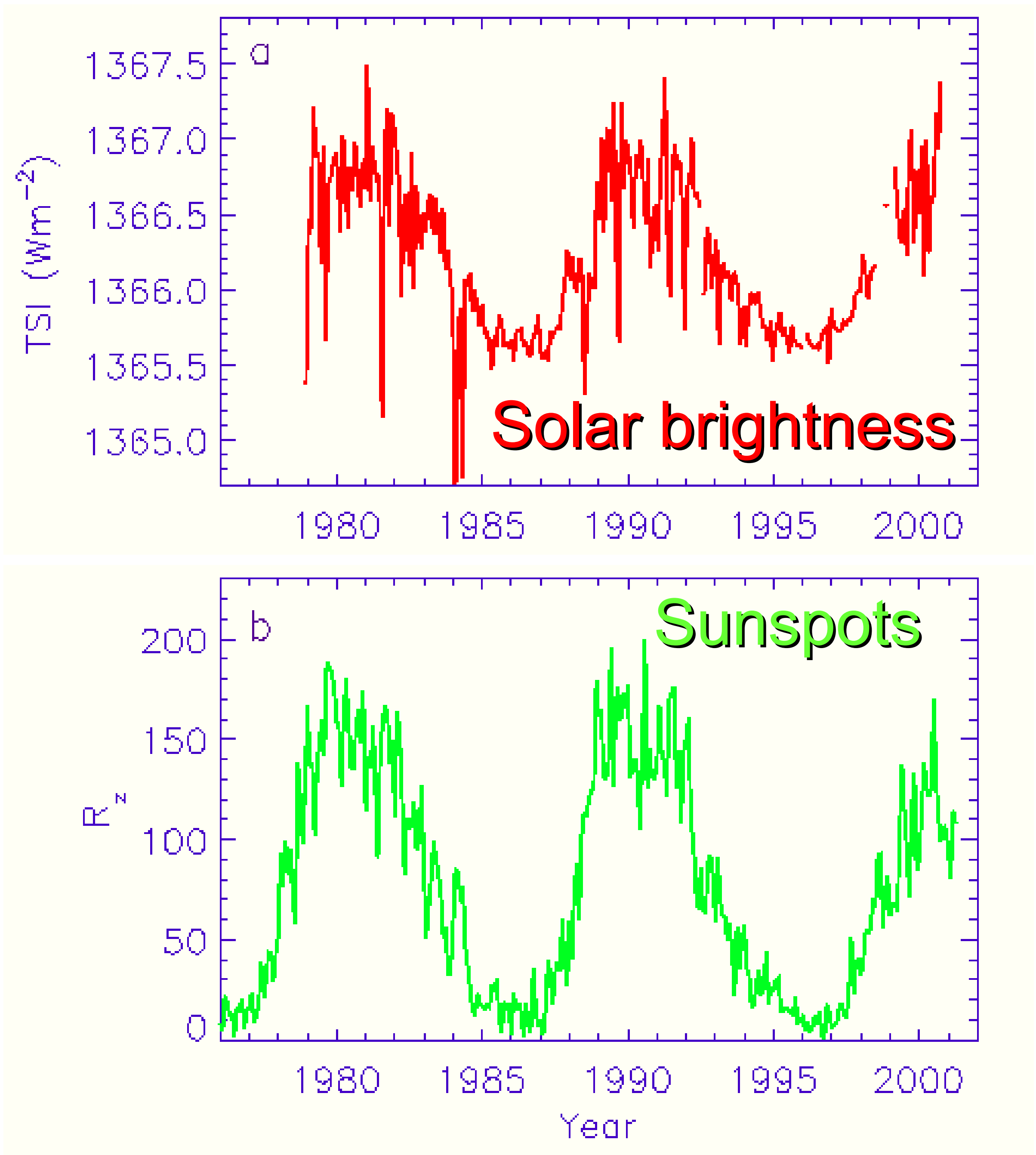


Sun’s magnetic field correlates with brightness in most atmospheric layers



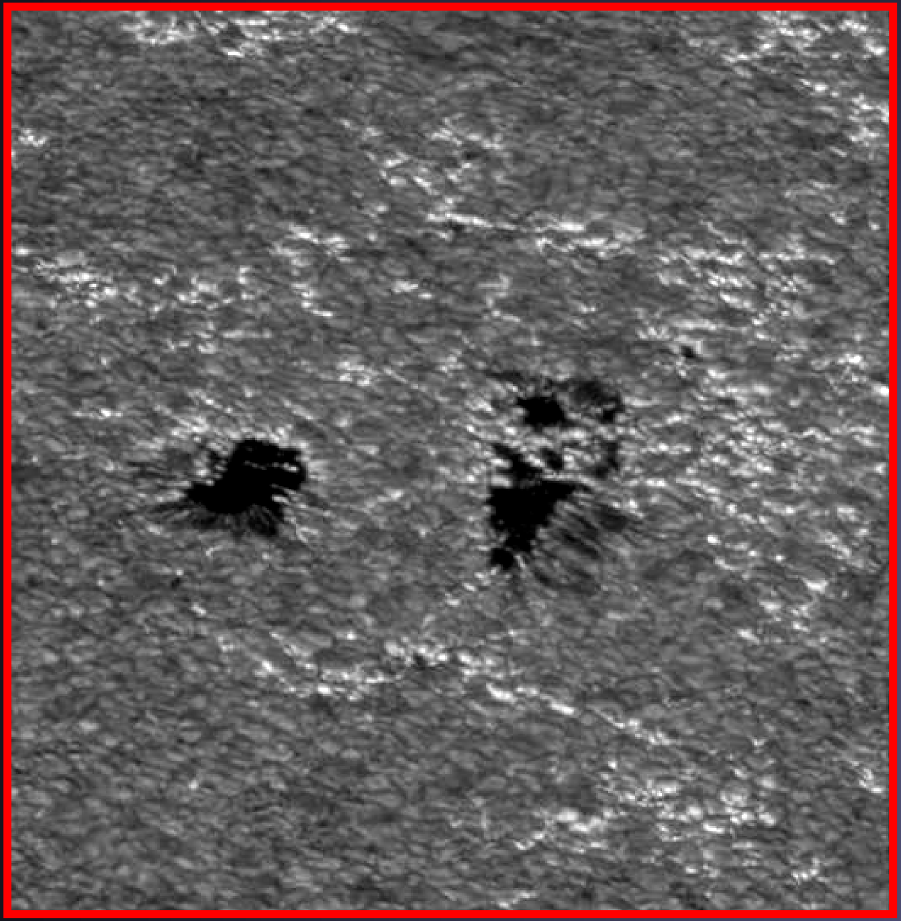
Photospheric influence of field: variations of total irradiance





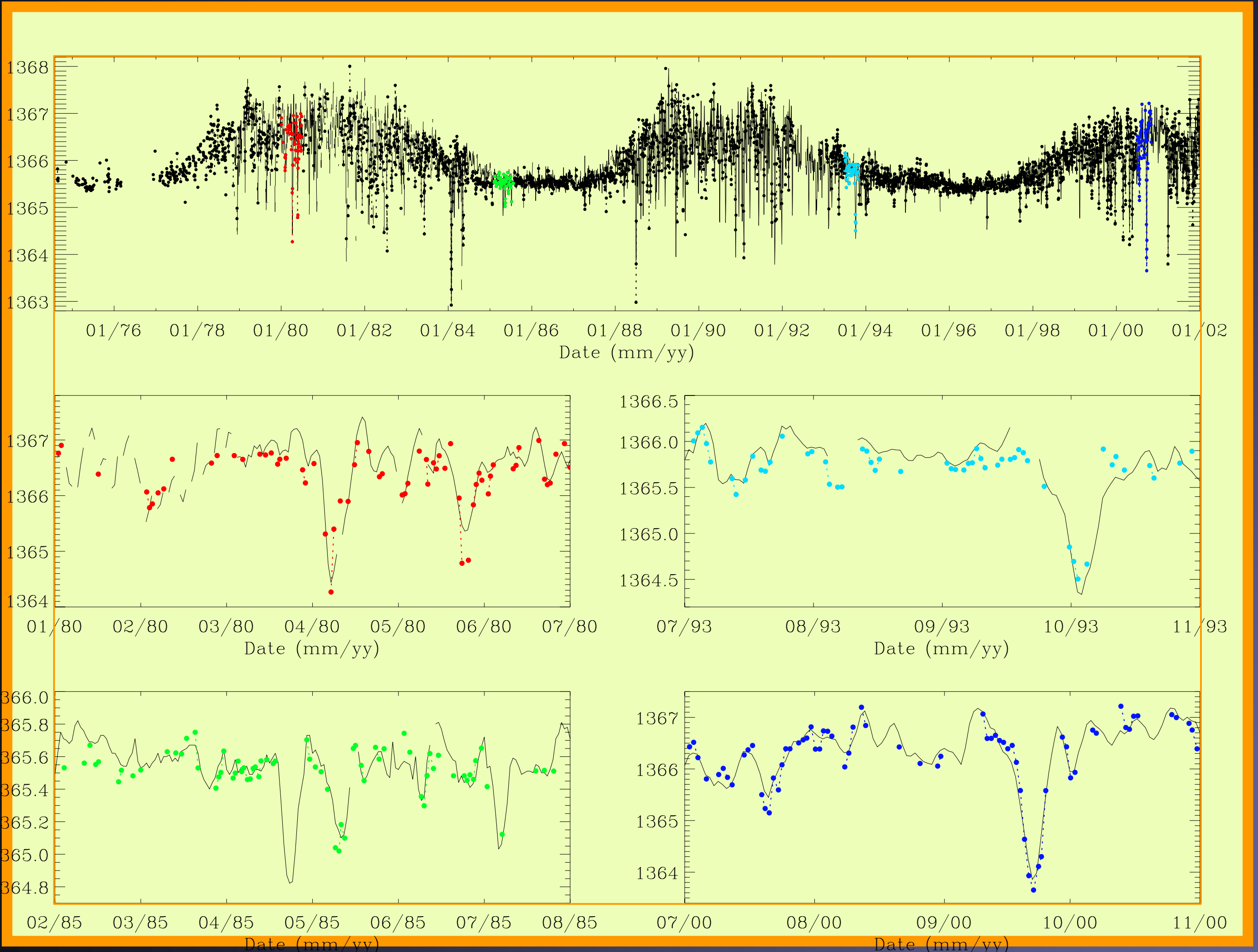
a
Solar brightness
TSI (Wm^{-2})
1367.5
1367.0
1366.5
1366.0
1365.5
1365.0
1980
1985
1990
1995
2000
b
Sunspots
R_z
200
150
100
50
0
1980
1985
1990
1995
2000
Year

Faculae



Area covered by faculae increases faster from Min. to Max. of solar activity than the area covered by sunspots

Magnetic Field & Brightness Changes

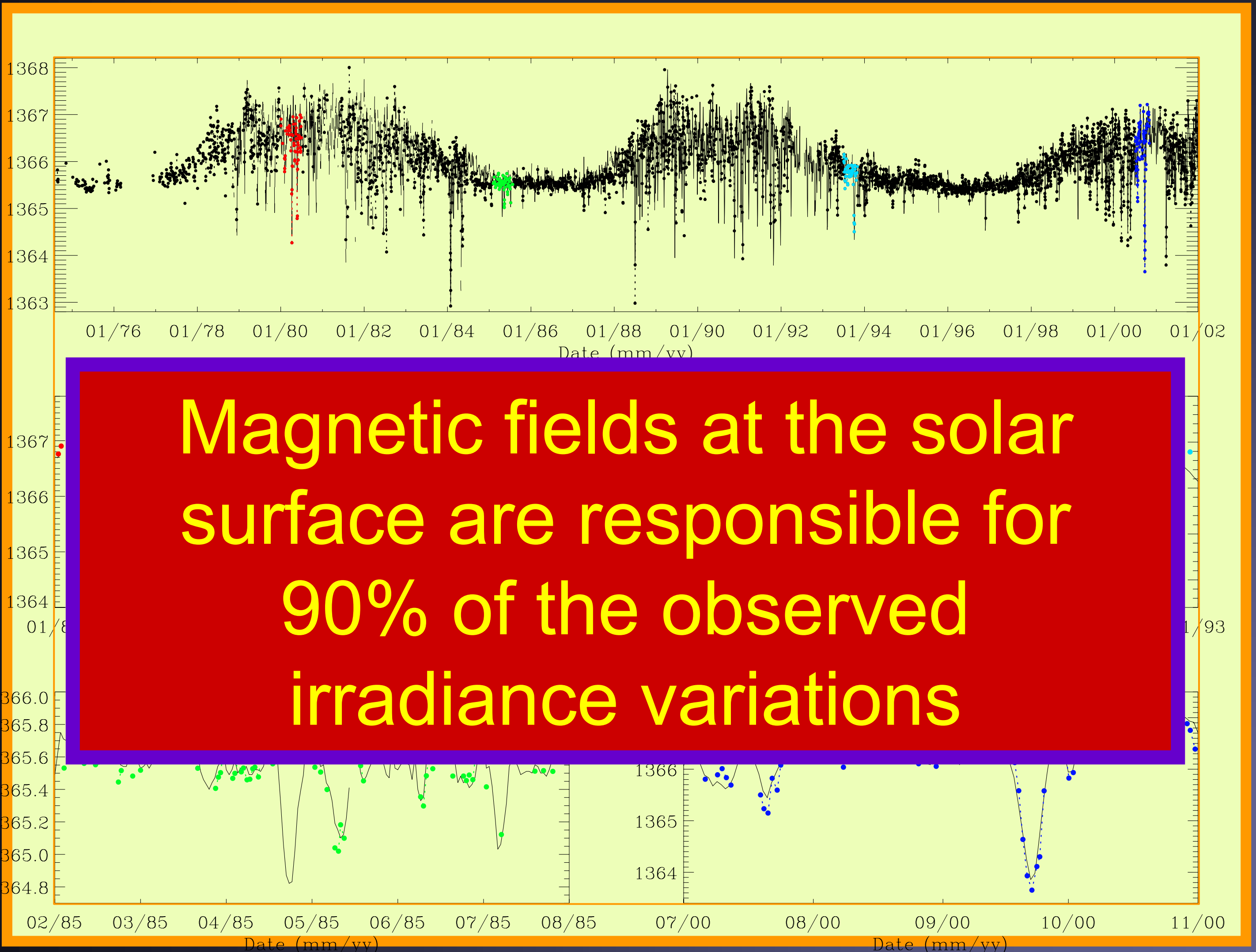


Wenzler et al. 2006

Model: based on assumption that brightness changes are caused by magnetic field at solar surface

Obs.: by various Instruments

Magnetic Field & Brightness Changes



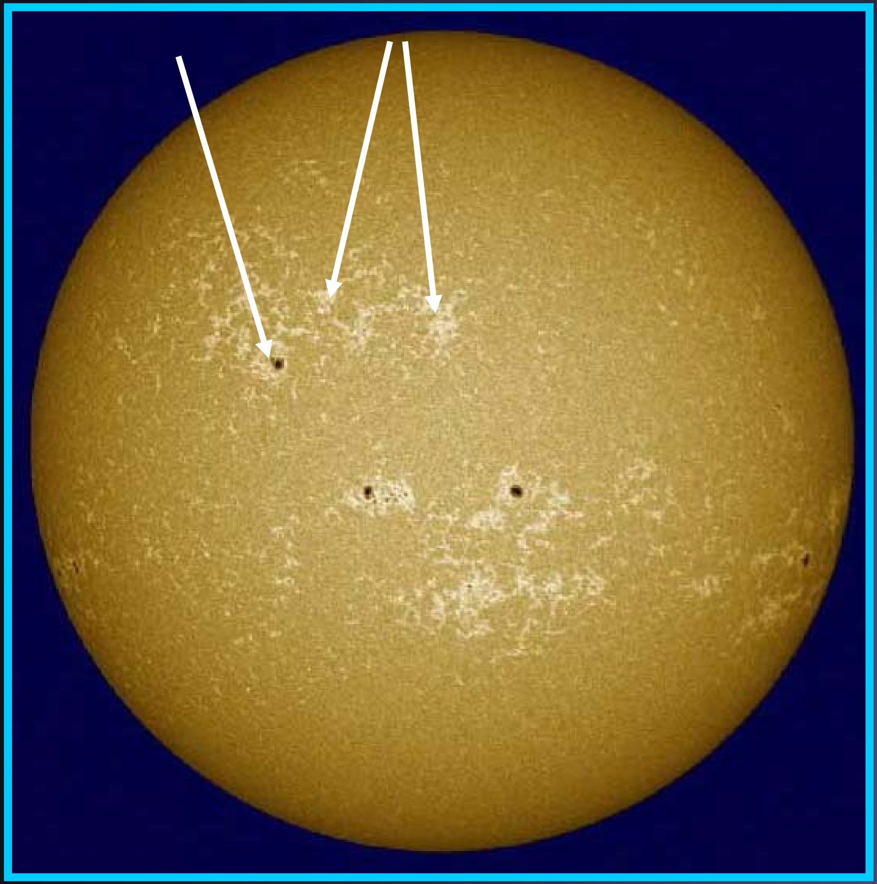
Magnetic fields at the solar surface are responsible for 90% of the observed irradiance variations

Model: based on assumption that brightness changes are caused by magnetic field at solar surface

Obs.: by various Instruments

Wenzler et al. 2006

Chromospheric structure and magnetic field

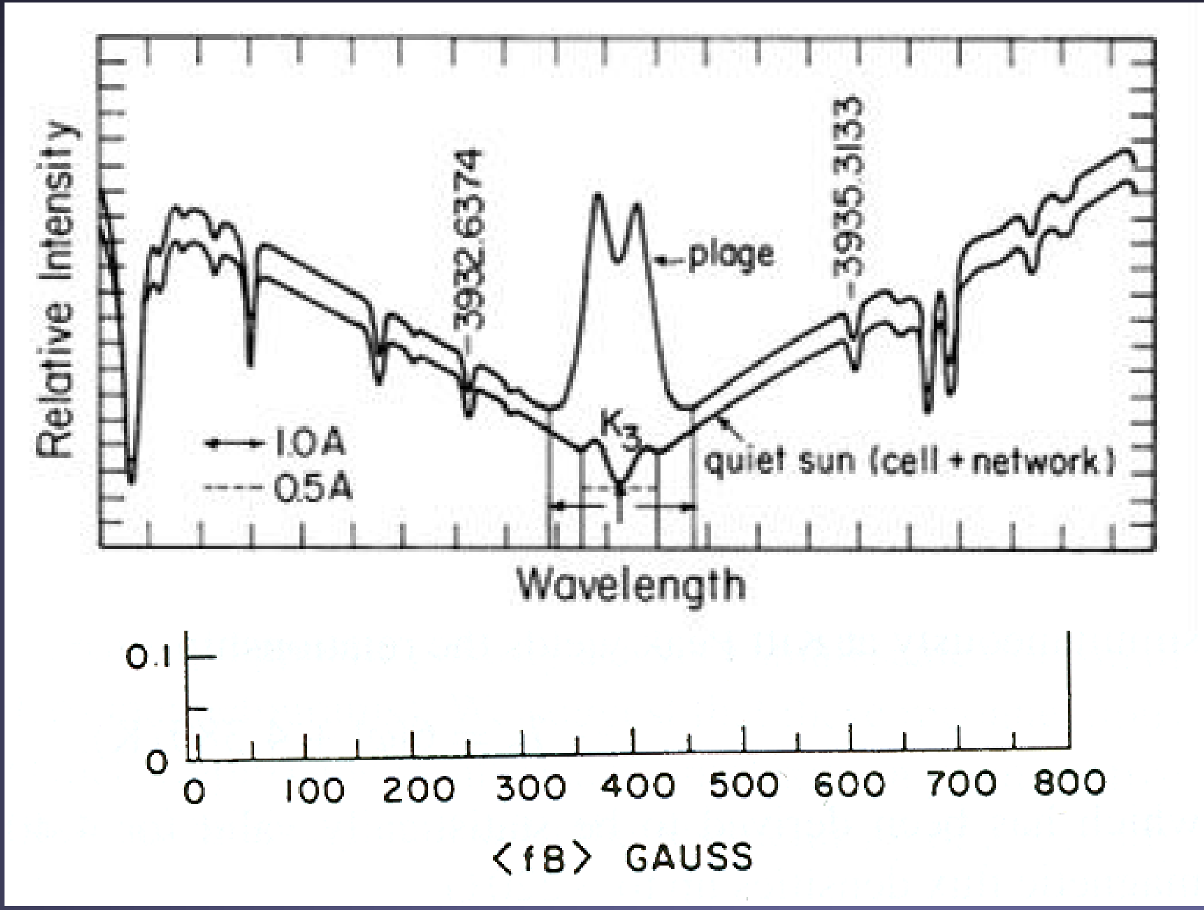


7000 K gas Ca II K

$5\ 10^4$ K gas (EIT He 304 Å)

Ca II K as a magnetic field proxy

- Ca II H and K lines, the strongest lines in the visible solar spectrum, become brighter with non-spot magnetic flux.
- $I_{core}/I_{wing} \sim \langle B \rangle^{0.6}$
- Magnetic regions (except sunspots) appear bright in Ca II H+K ➔ Ca plage and network regions

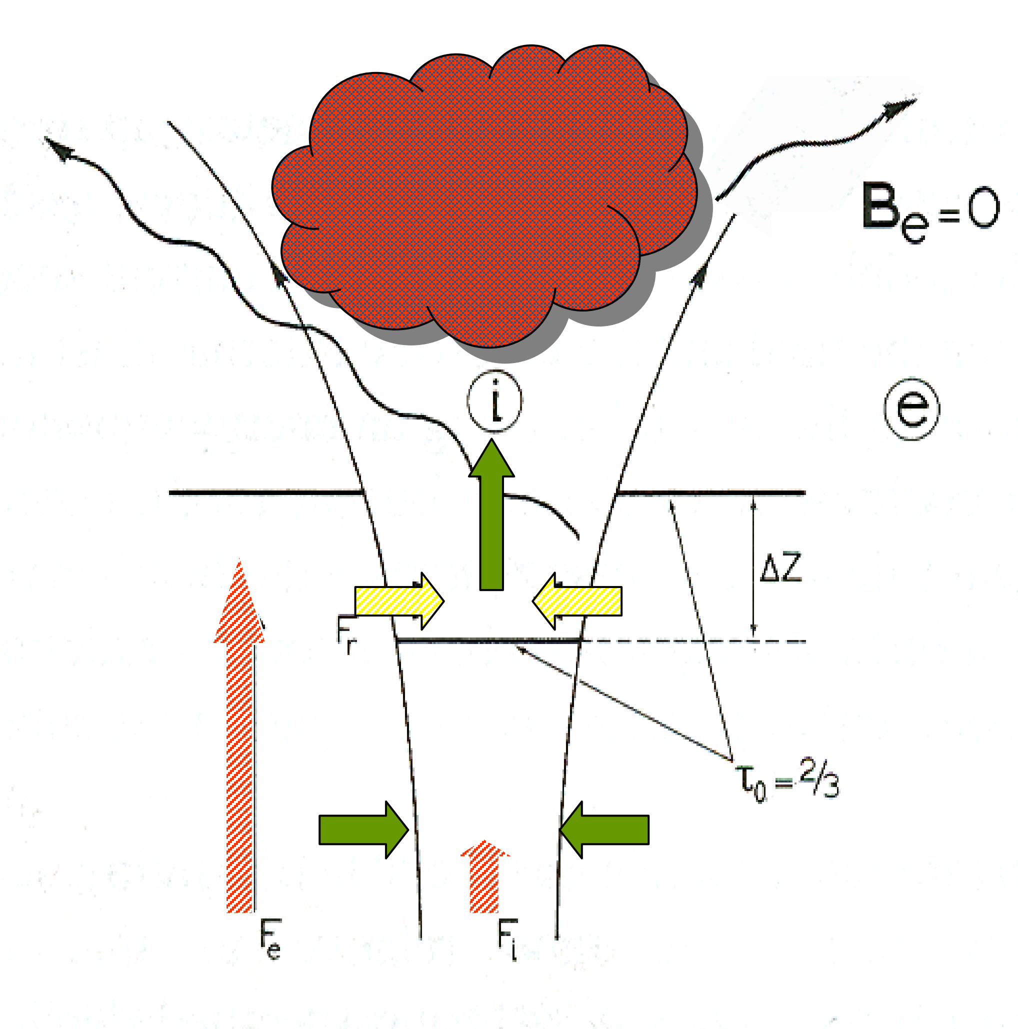


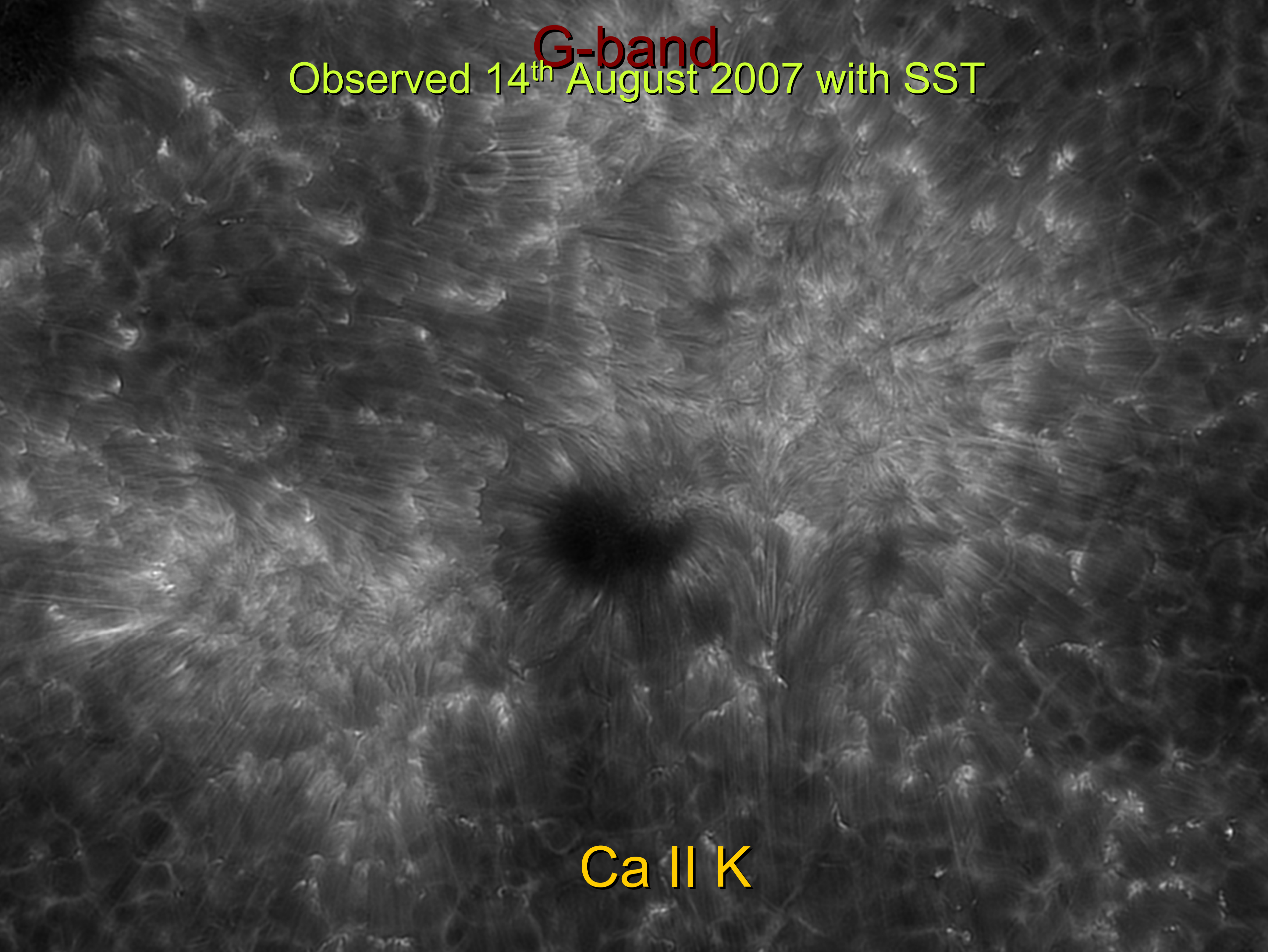
Schrijver et al. 1989, Rezaei et al. 2007

Important for tracing stellar activity

Why are magnetic elements bright in the chromosphere?

- **Photosphere:** energy enters flux tube through shaking by convection. Transported up by waves, or is stored as excess energy in field (tension forces)
- **Chromosphere:** release of excess energy channelled by field to higher layers (MHD wave dissipation)



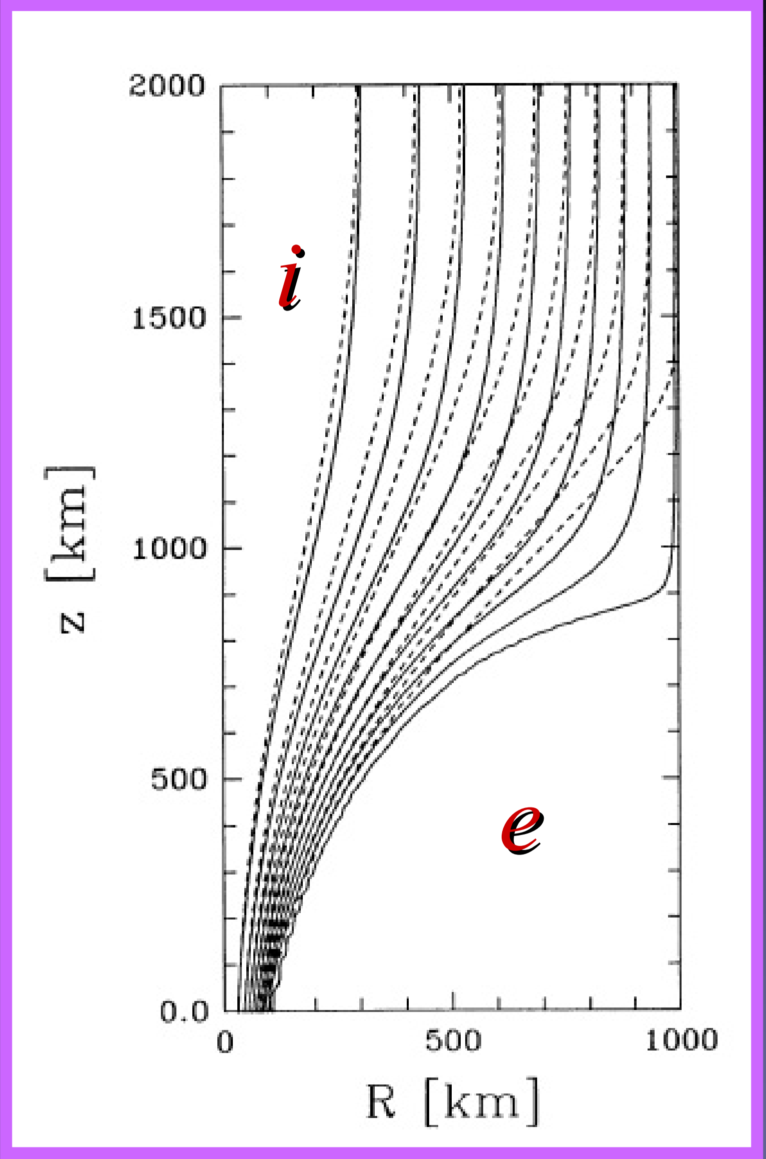

G-band
Observed 14th August 2007 with SST
Ca II K

Magnetic canopies

- Observational evidence exists for the presence of horizontal fields in chromosphere
- Can be produced with FT model if interior of FT is hotter than surroundings
- Pressure scale height $H_P \sim T$
- $T_i > T_e$ ➔ $H_{P,i} > H_{P,e}$ ➔ above a critical height Z_c: $P_i > P_e$

➔ above Z_c field is not confined & expands horizontally

➔ above Z_c field fills all corona

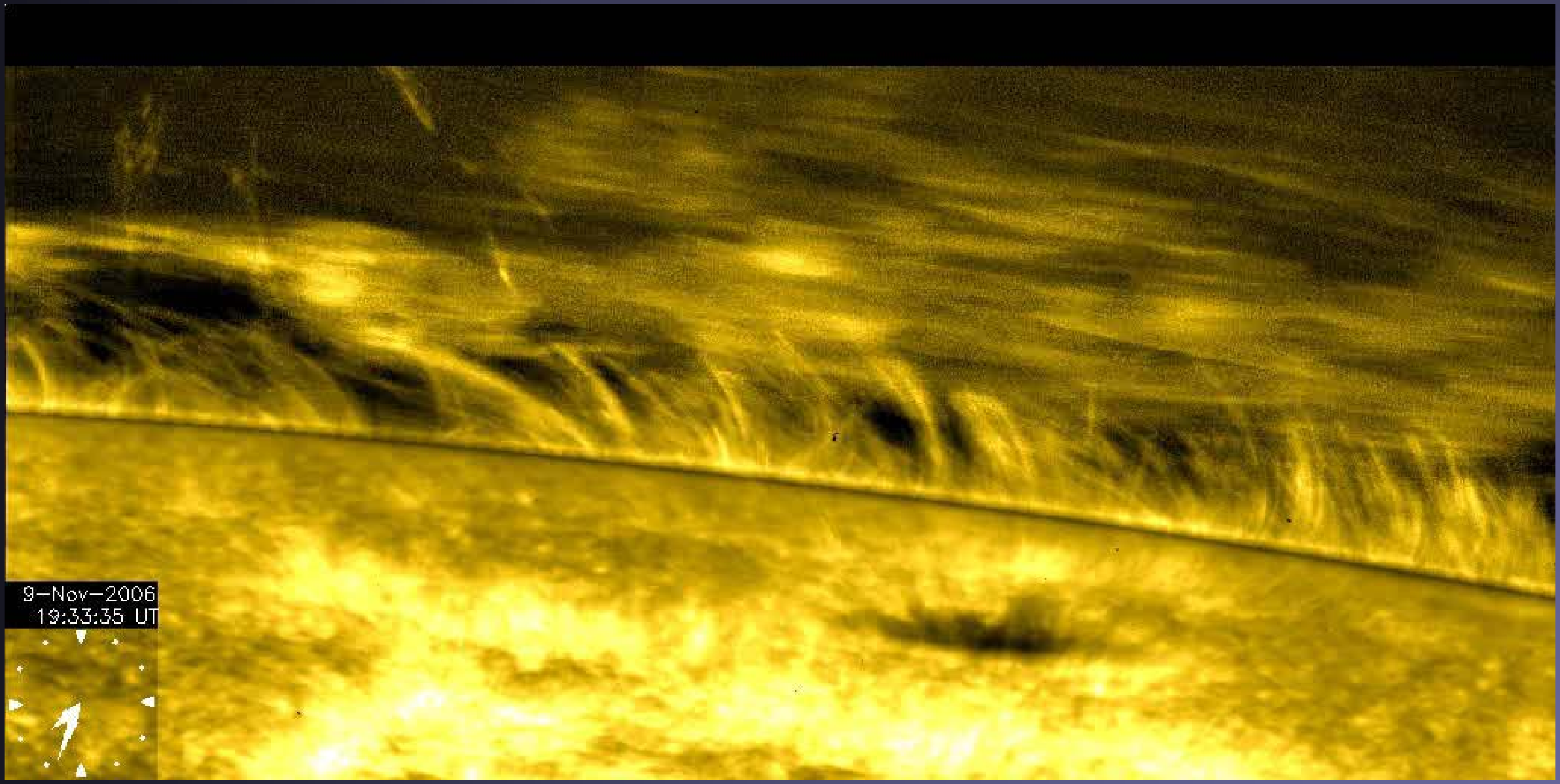


$T_i = T_e$ ....

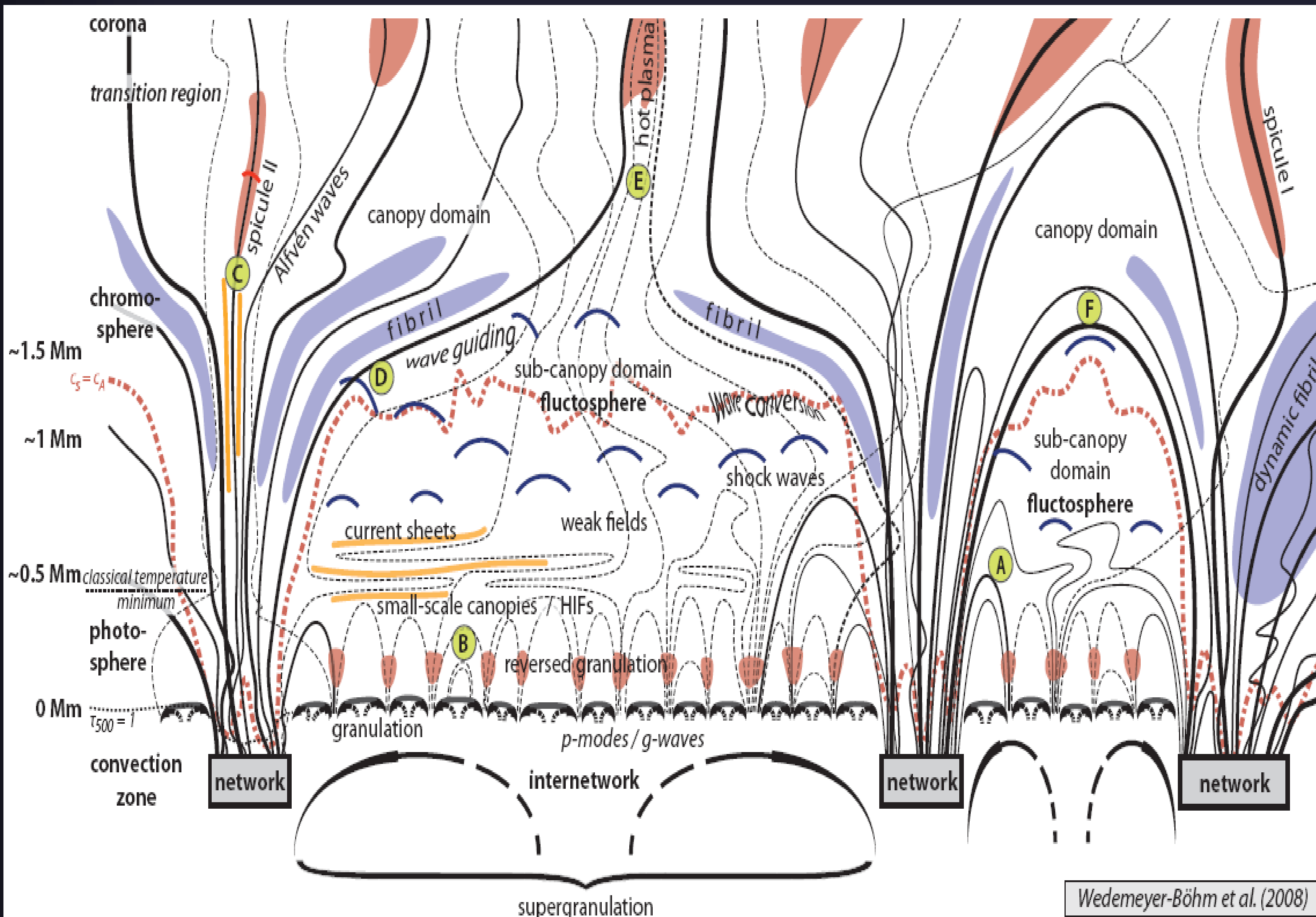
$T_i > T_e$ ——

Chromospheric structure

- Spicules
- Prominences and filaments

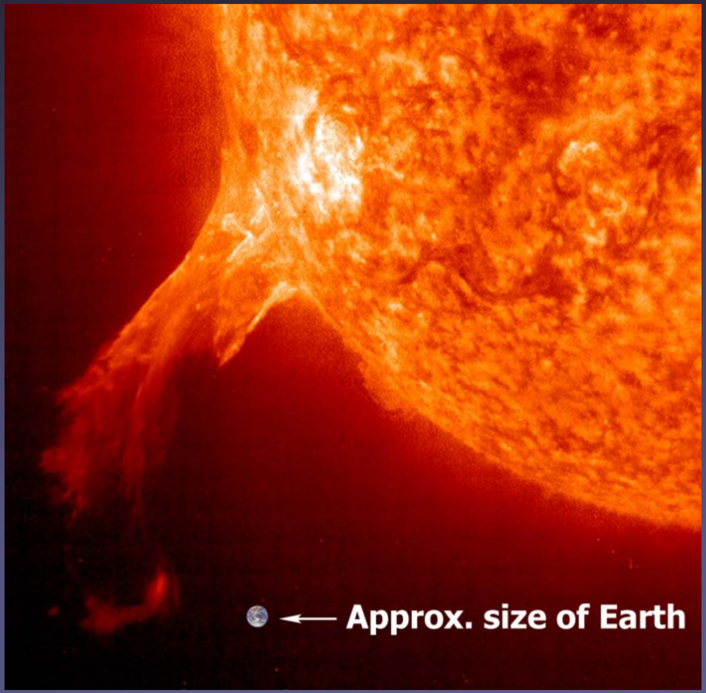


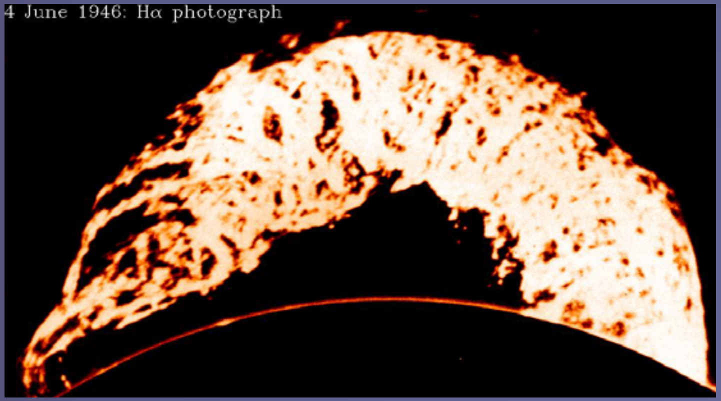
Cartoon of quiet Sun atmosphere



Prominence material supported by magnetic field

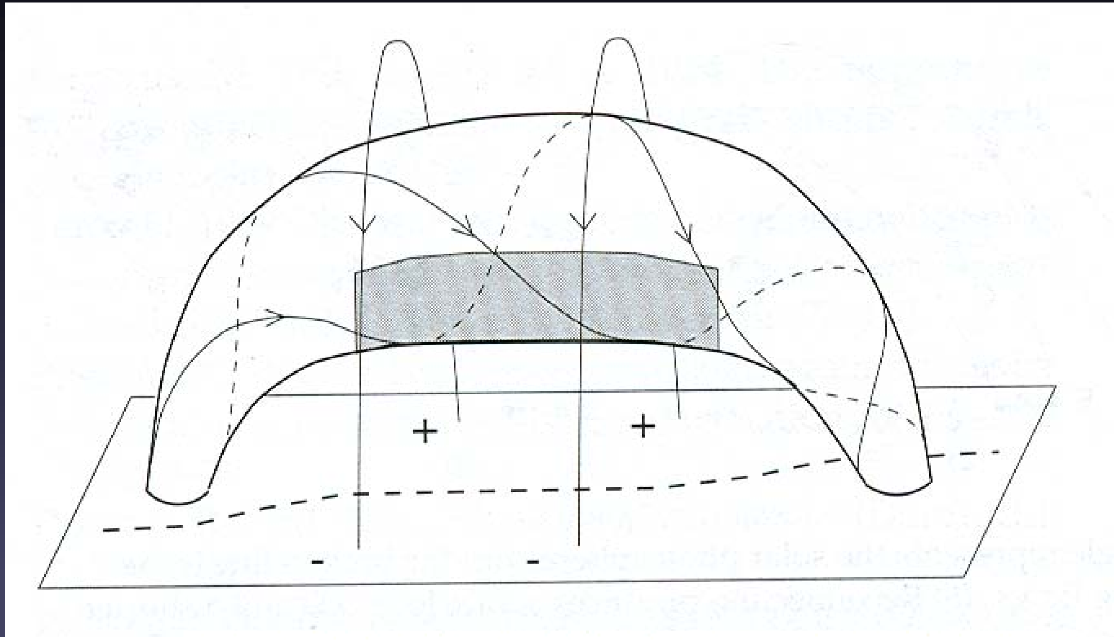
- Density of prominence material is ~2 orders of magnitude higher than of surrounding corona
- Prominence gas has to be supported against gravity
- Magnetic field curved upward can provide this support, since ionized gas can only flow along field lines

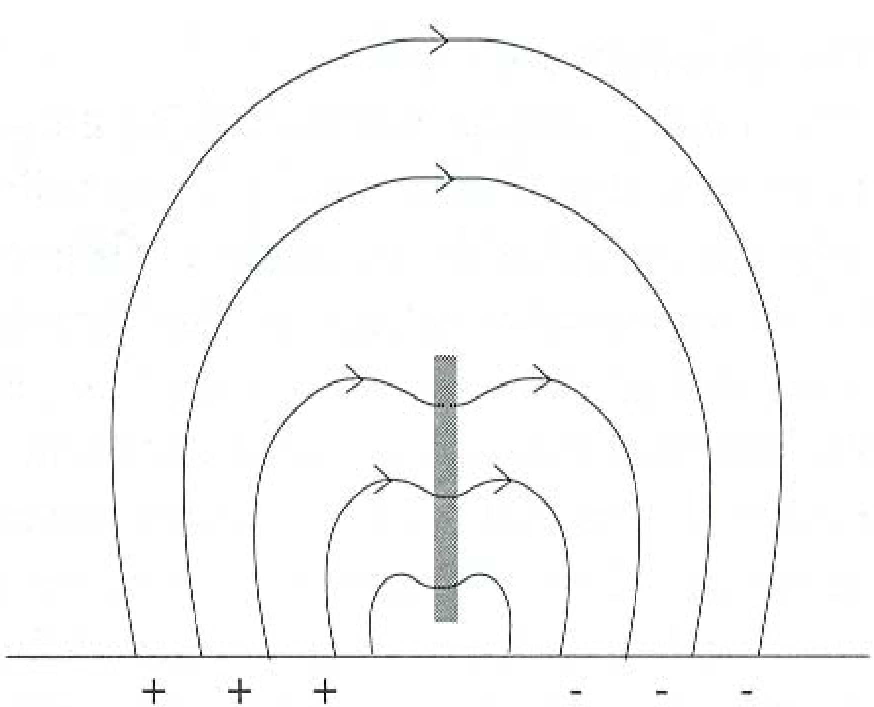


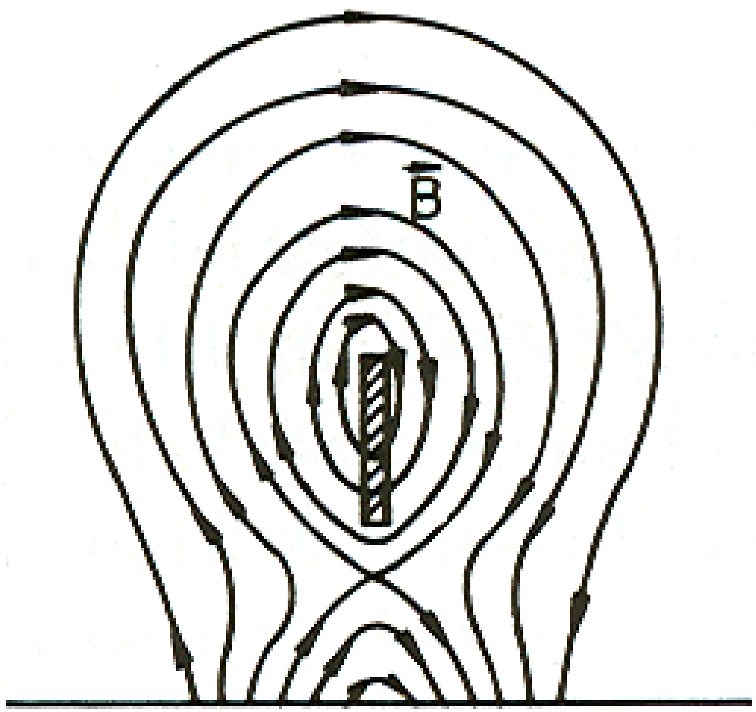


Prominence models

Kippenhahn-Schlüter (below), Kuperus-Raadu (below right) and flux tube (right; 3-D Kuperus-R.)

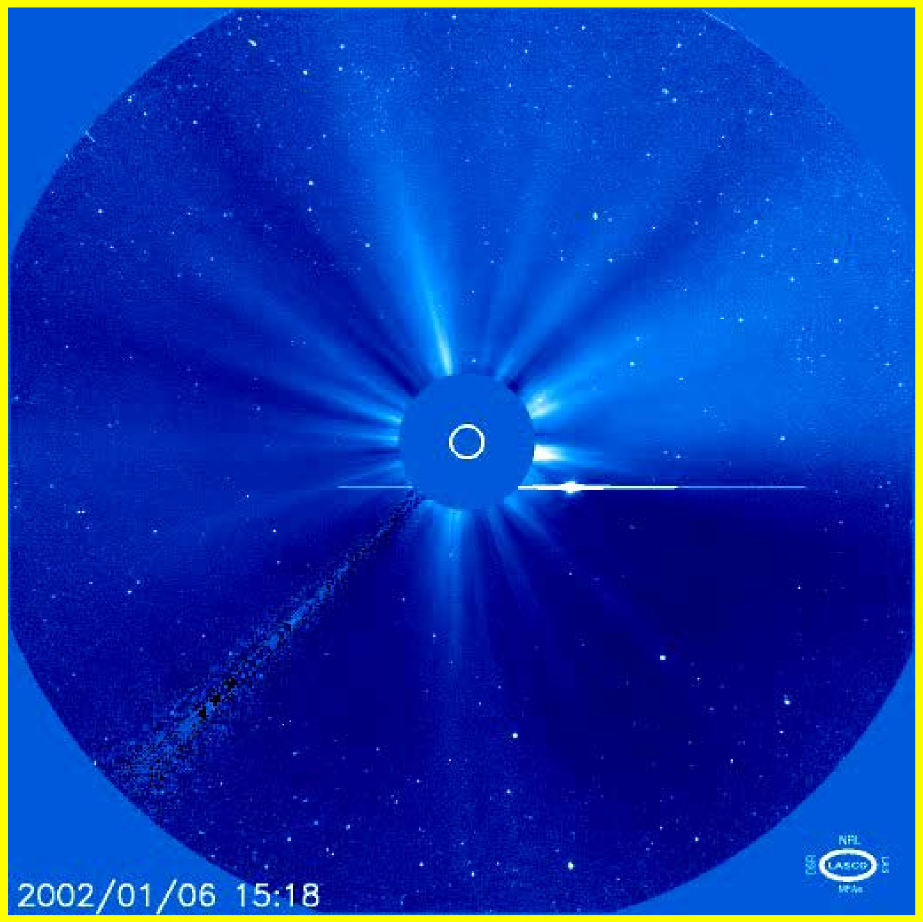






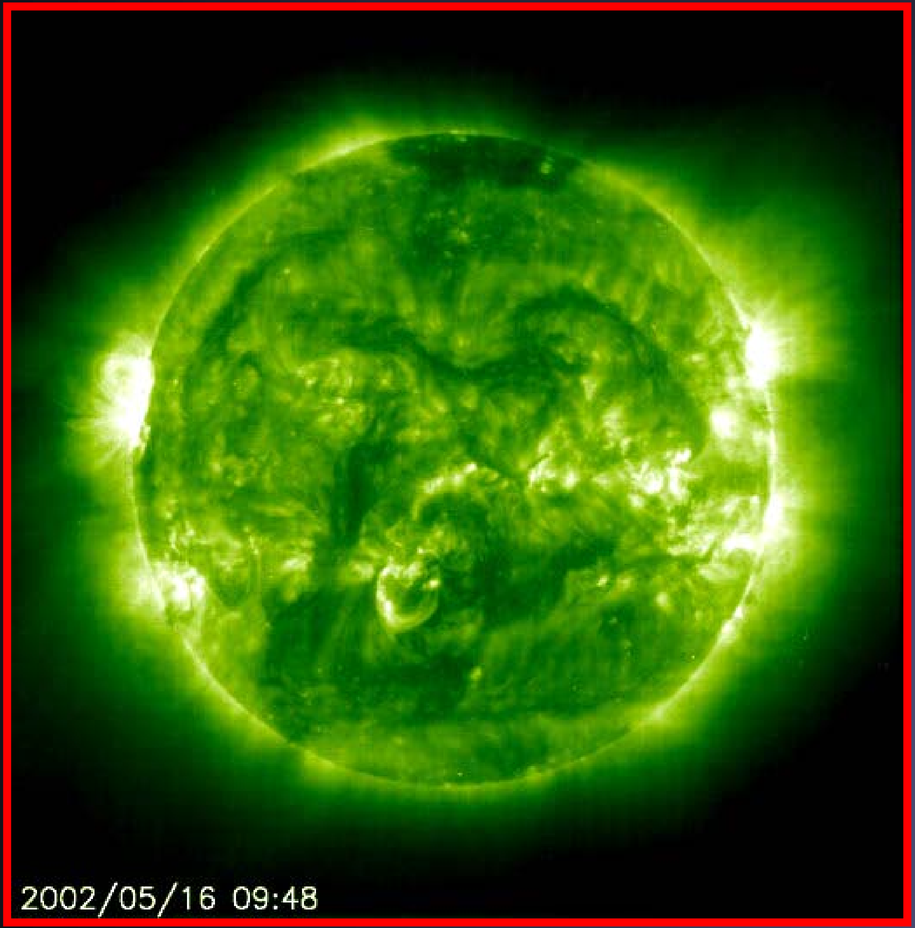
The Hot and Dynamic Corona

Corona during an Eclipse

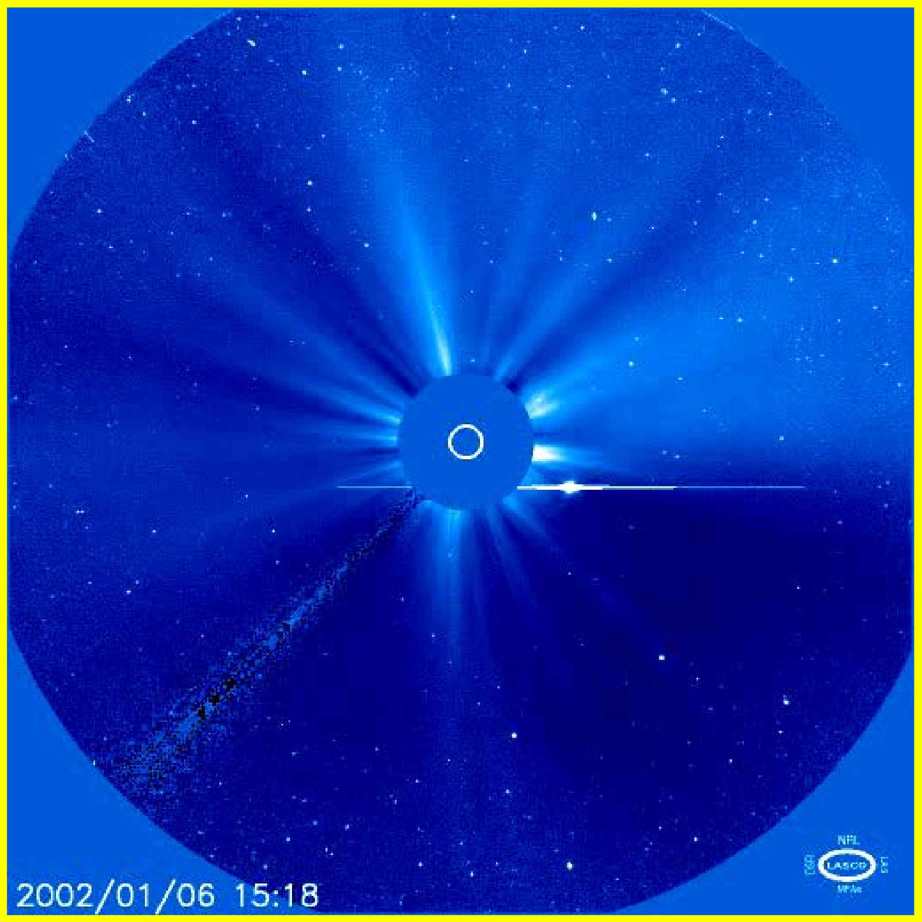


Coronagraphic observations (LASCO C3 / SOHO, MPS)

The Hot and Dynamic Corona

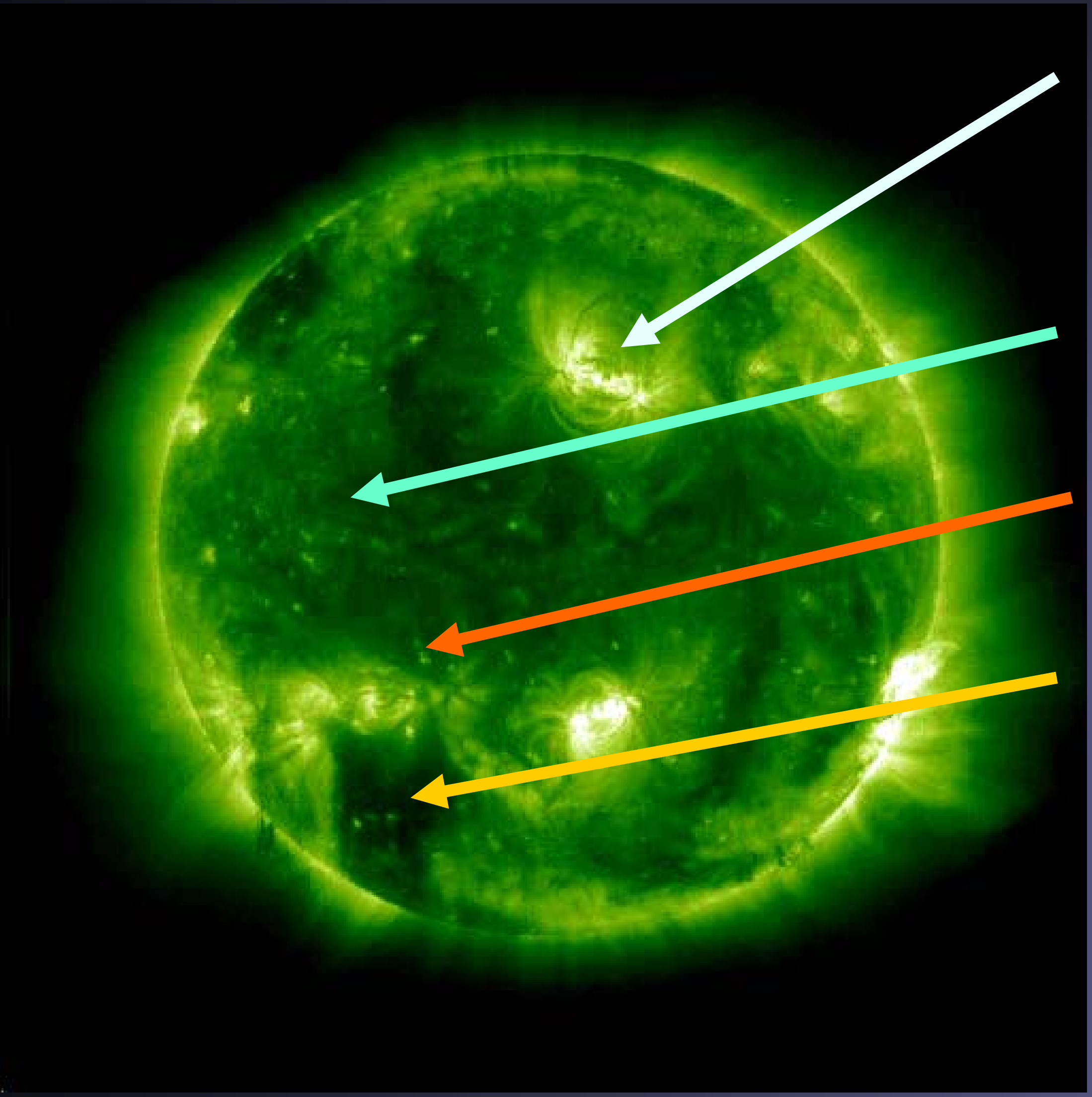


EUV Corona: Plasma at >1 Mio K (EIT 195 Å)



Coronagraphic observations (LASCO C3 / SOHO, MPS)

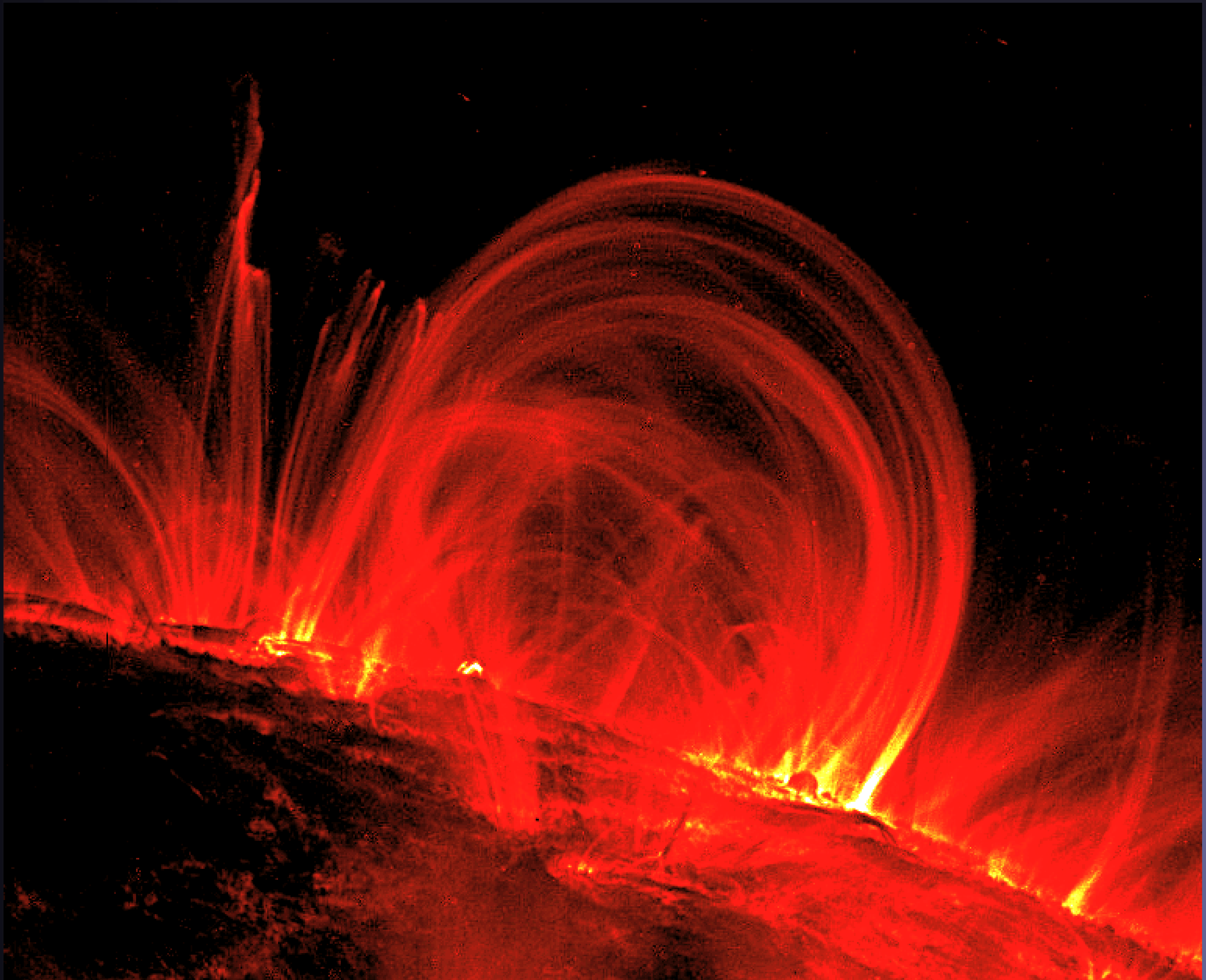
Coronal structures



- Active region (loops)
- Quiet Sun
- X-ray bright point
- Coronal hole
- Arcades

Fe XII 195 Å
(1.500.000 K)
17 May - 8 June 1998

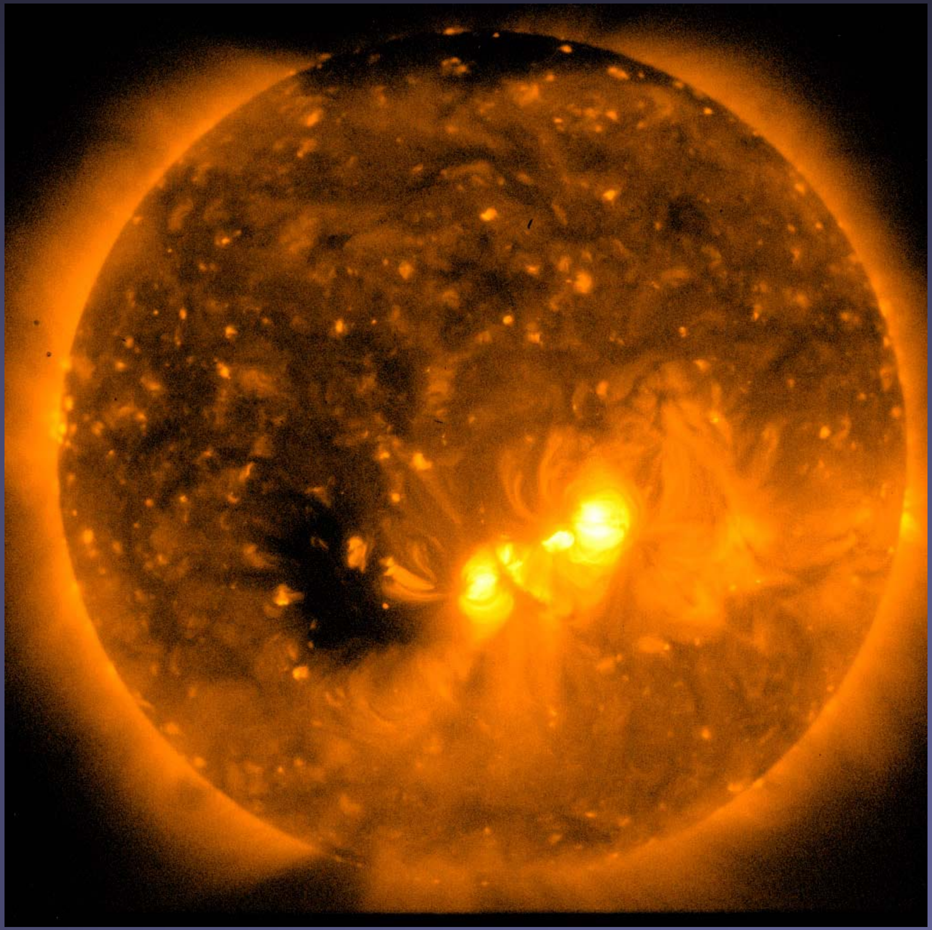
Coronal structure: active region loops



TRACE, 1999

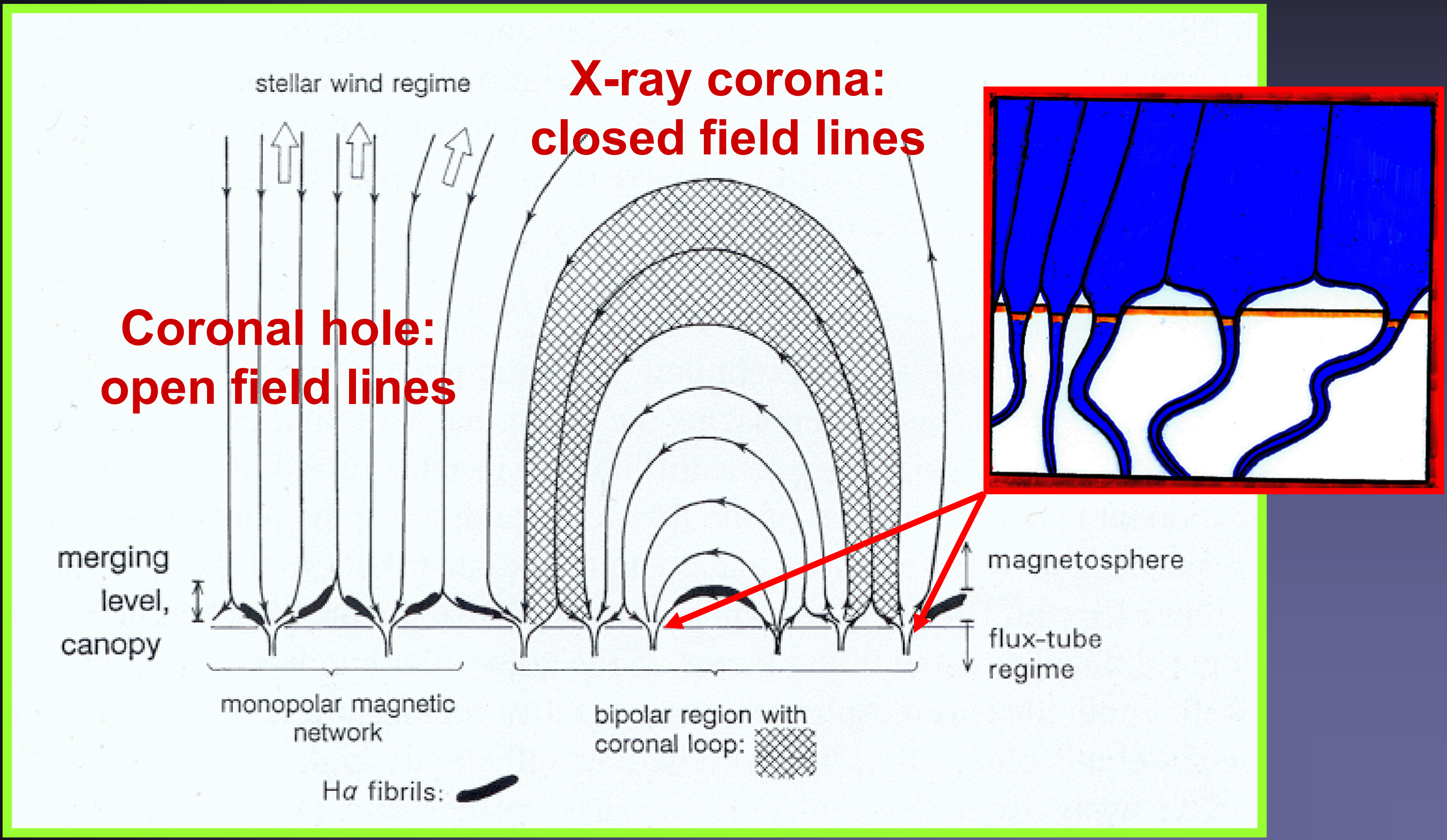
Coronal temperature & density

- Different temperatures & densities co-exist in the corona
- Range of temps: <1 MK (Coronal hole) to 10 MK (act. region)
- e^- densities (inner corona):
  - Loop: 10^{10} particles cm^{-2}
  - Coronal hole: 10^7 particles cm^{-2}



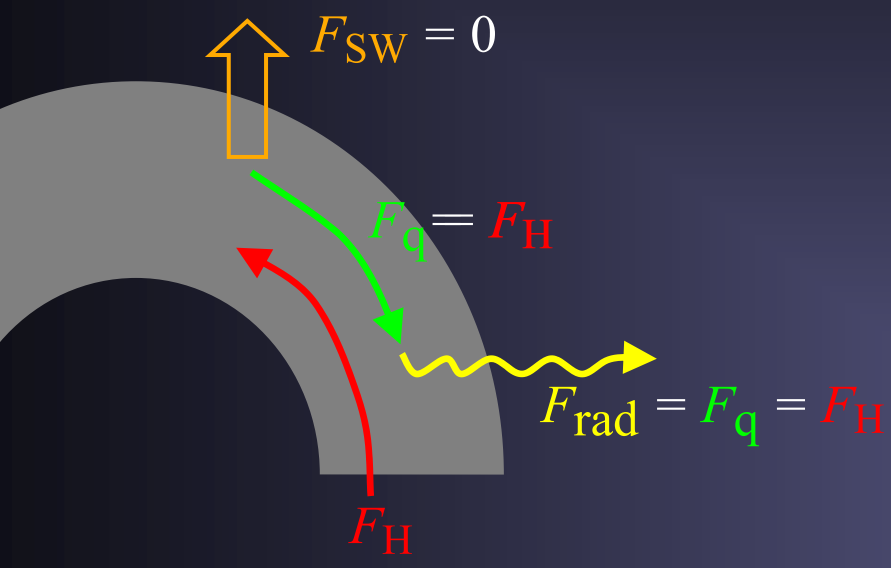
Hinode XRT: 2-5MK gas

Flux Tubes, Canopies, Loops and Funnels



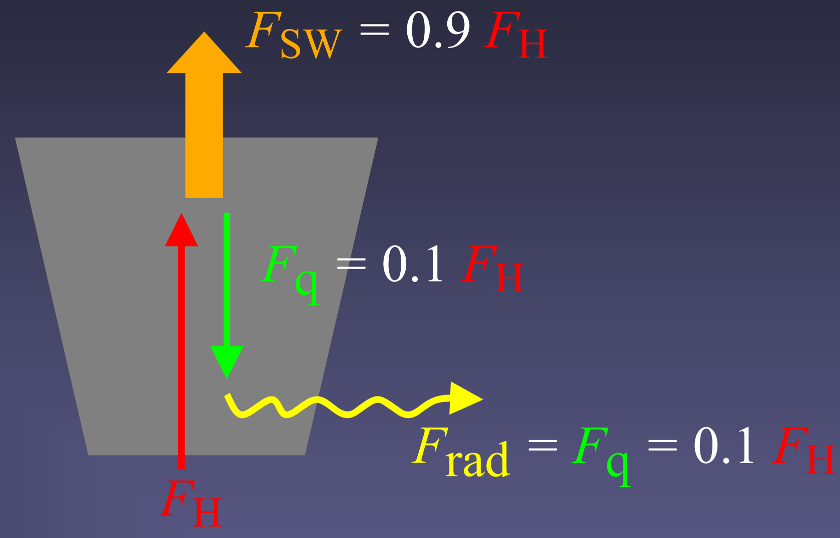
Energy budget: Open & closed coronal field

magnetically closed



radiation ≈ 100 % of energy input

magnetically open



radiation ≈ 10 % of energy input

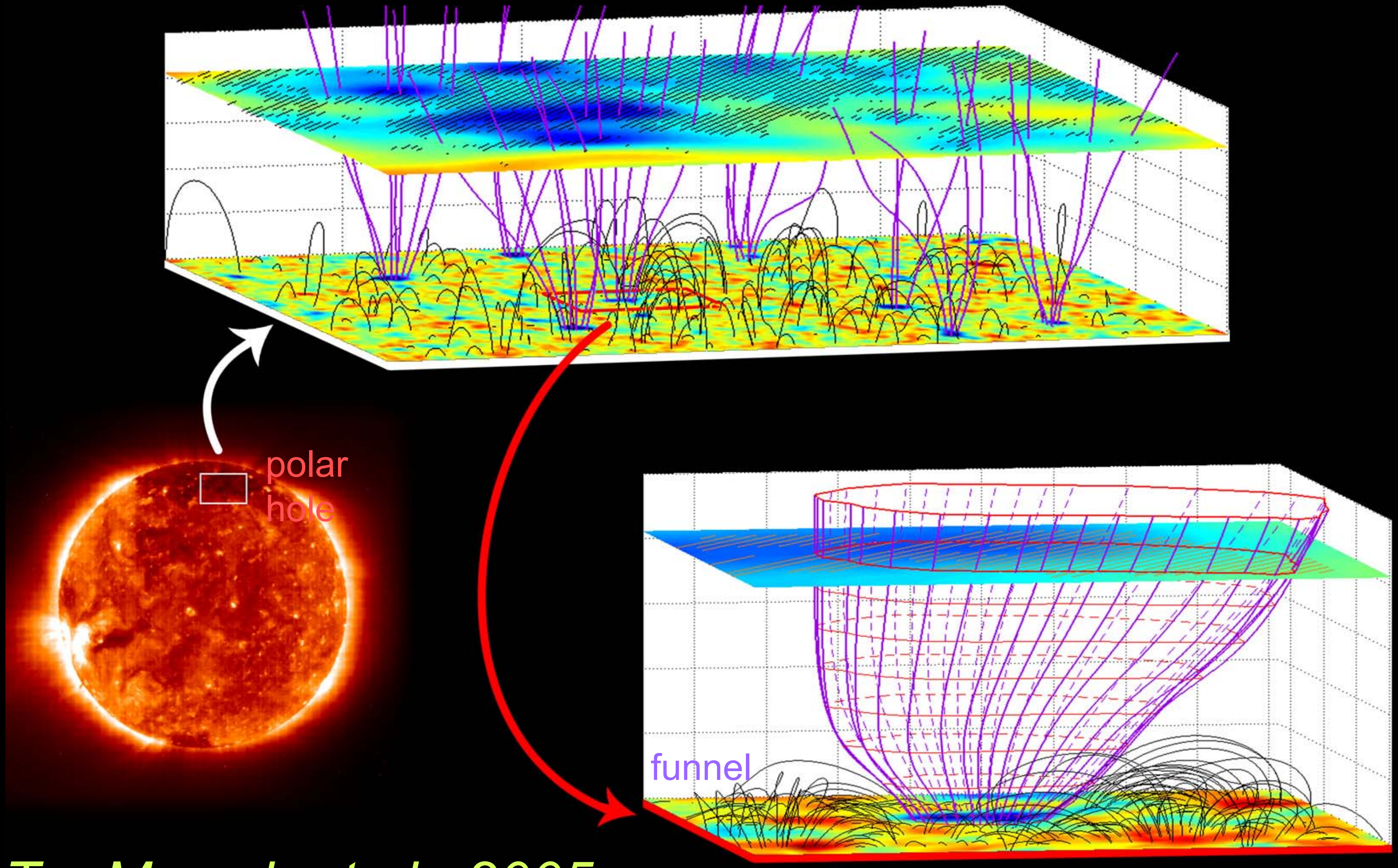
F_H = Energy flux heating the gas; F_q = Conductive energy flux; F_{SW} = Solar wind flux

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) !

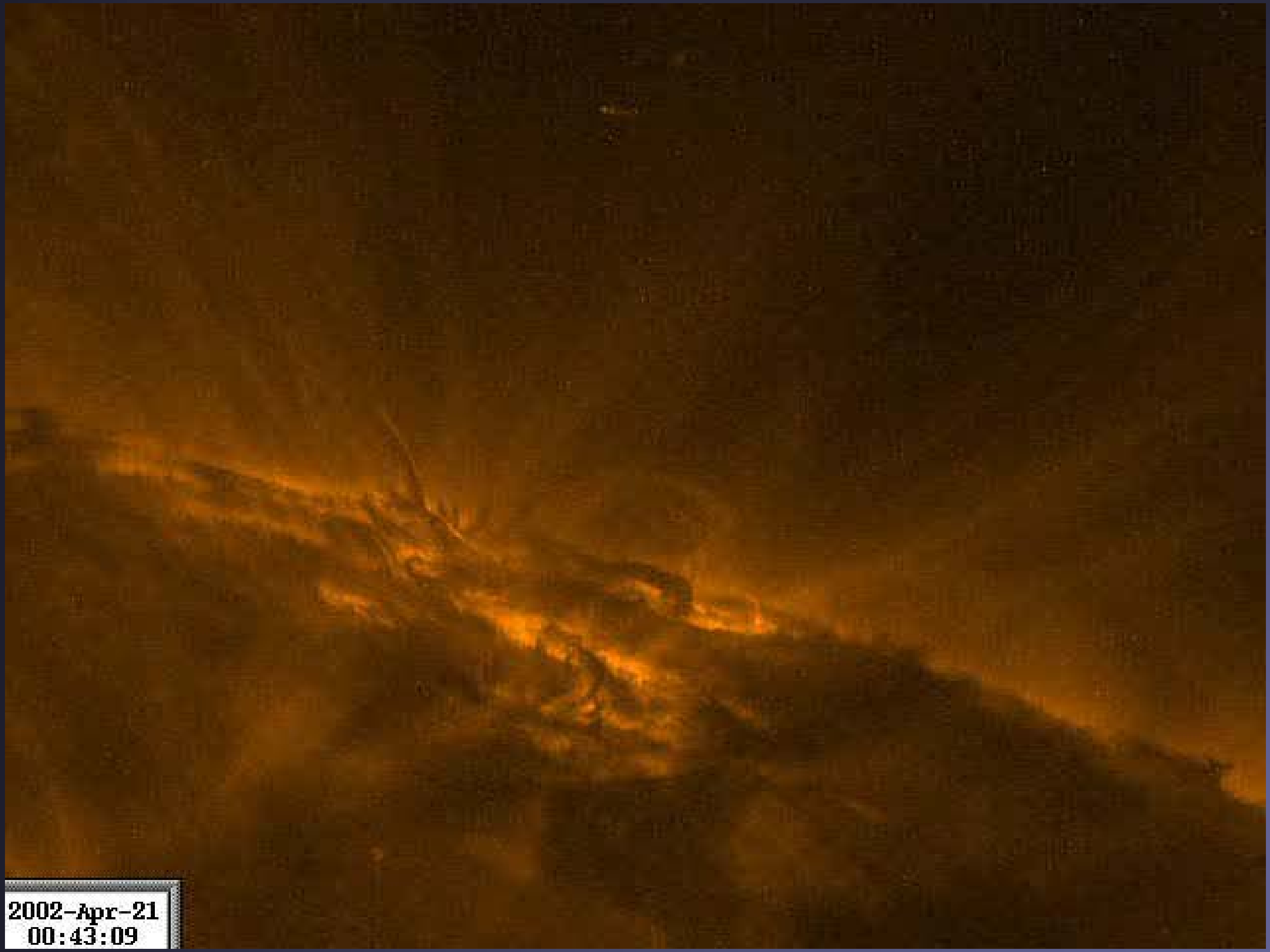
kindly provided by Hardi Peter

Sources of solar wind: fast wind

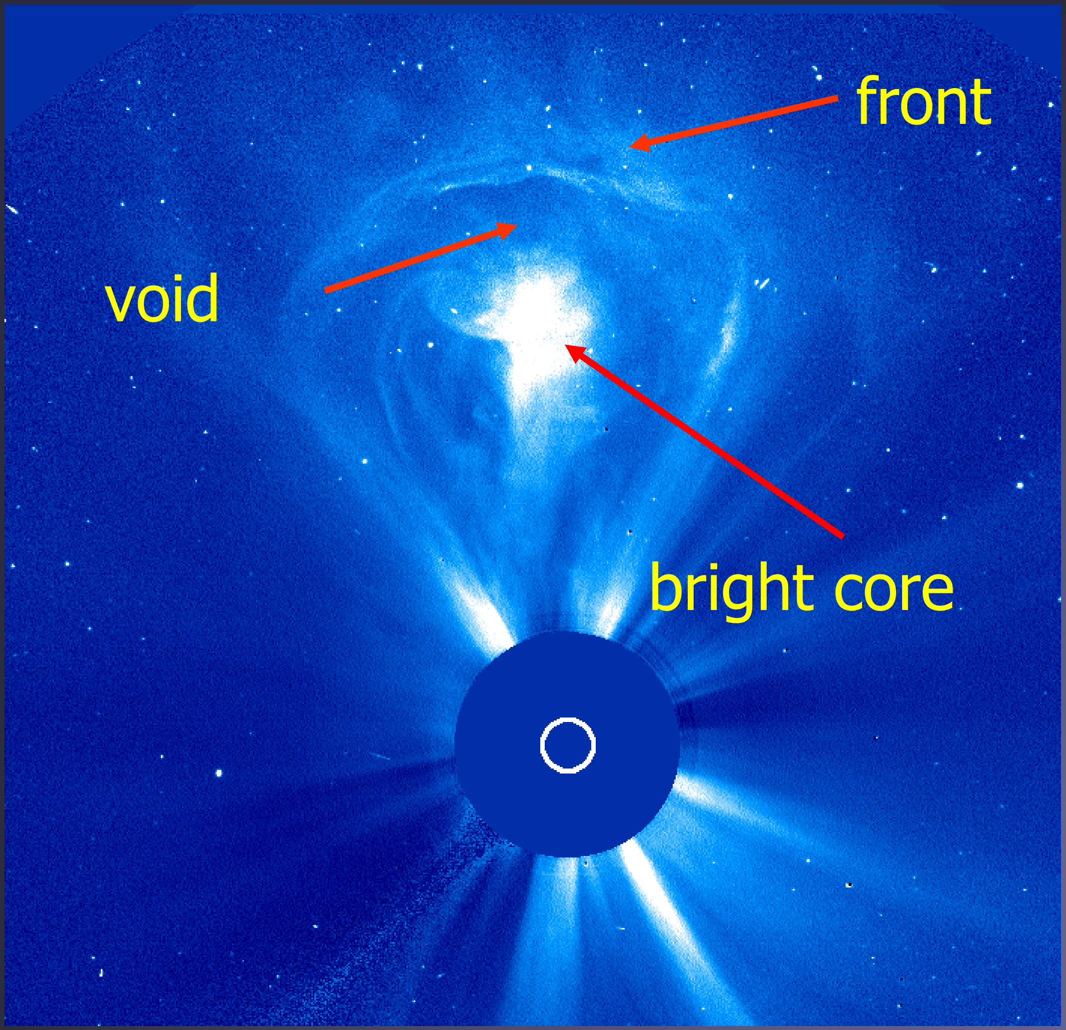


Tu, Marsch et al., 2005

TRACE 171Å observations of flare and post flare arcade near limb



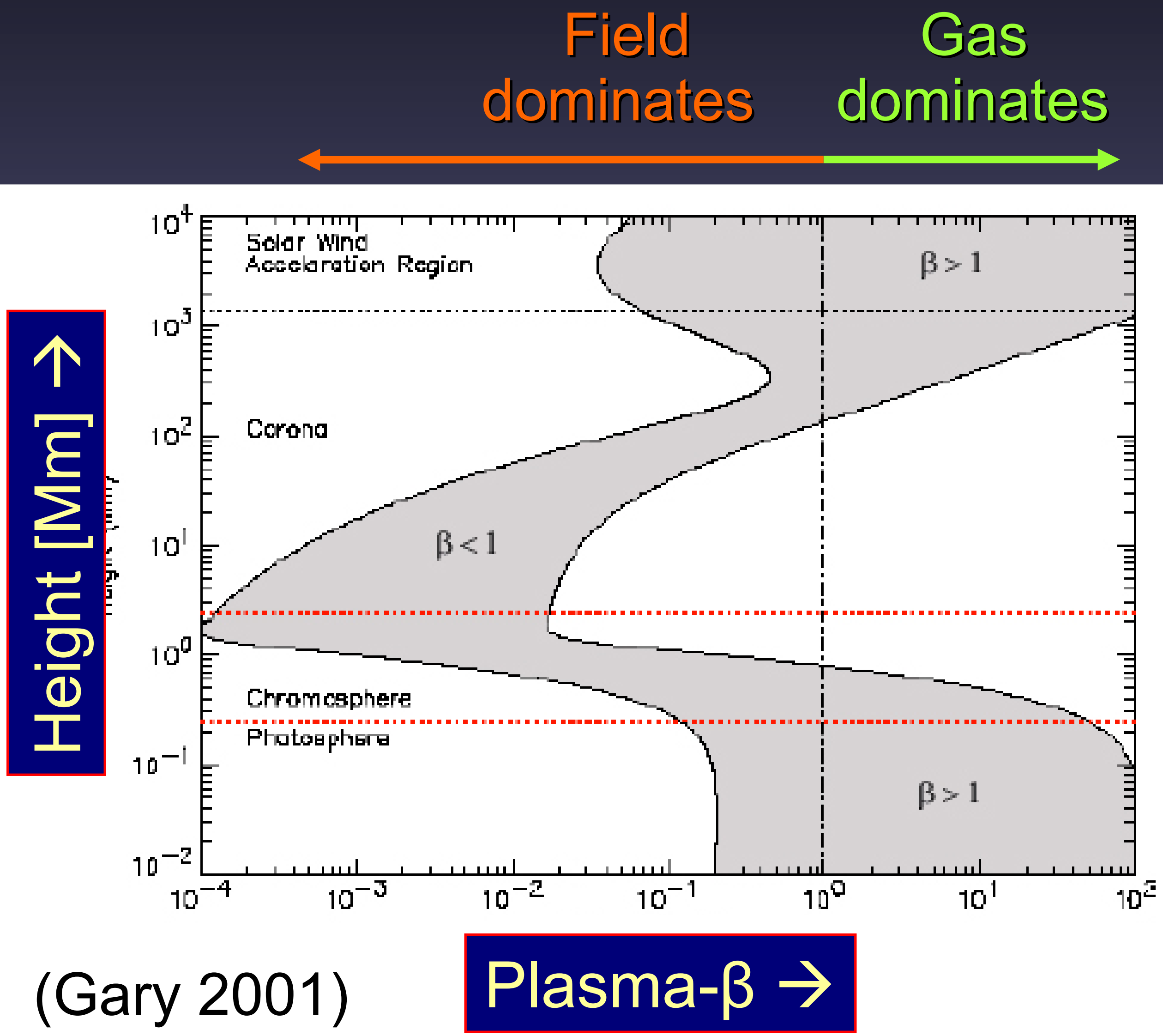
Coronal mass ejection (CME)



Plasma β vs. height in solar atmosphere

Plasma *β:* ratio of thermal to magnetic energy density:

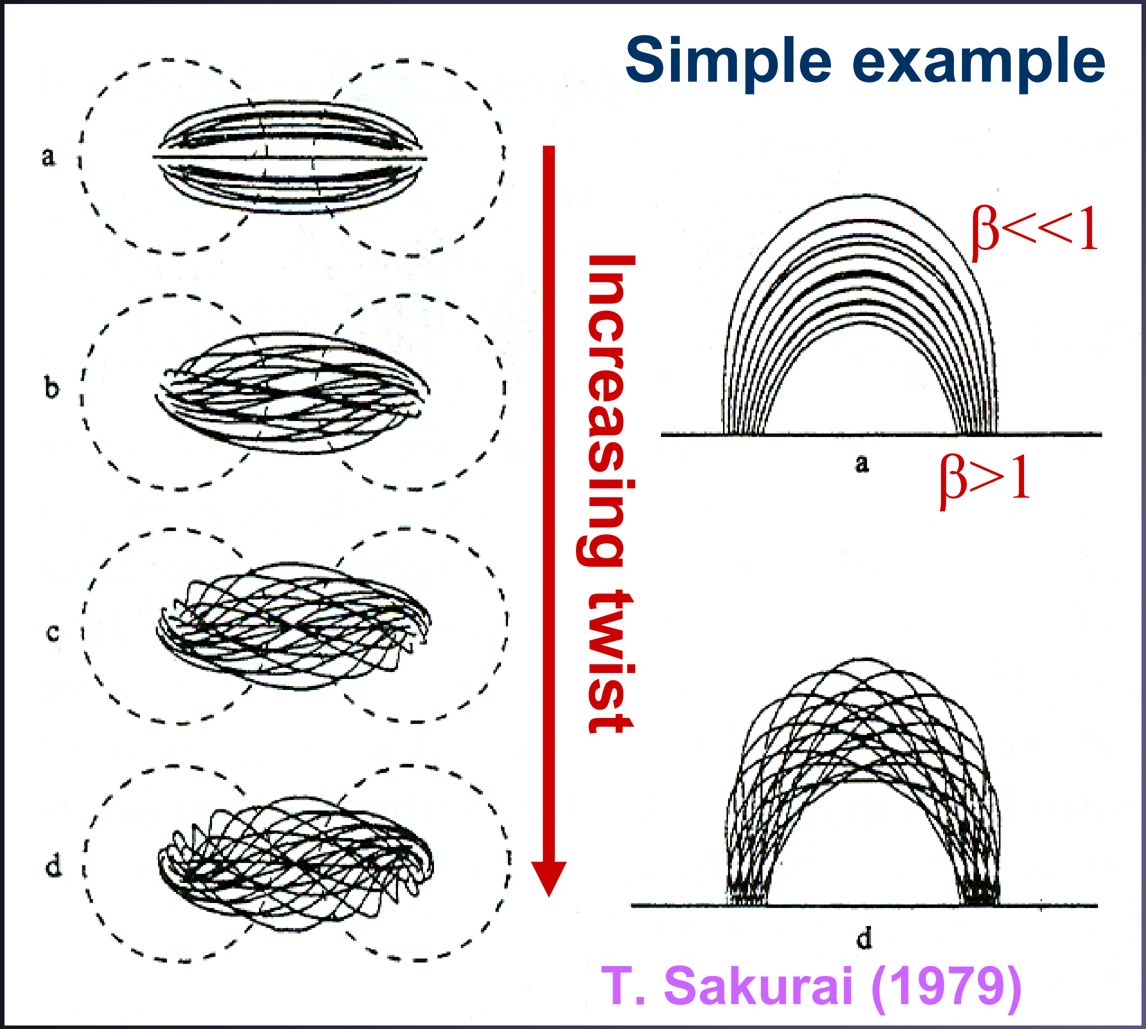
$$\beta = \frac{8\pi P}{B^2}$$



(Gary 2001)

Energy input into corona

Random footpoint motions of a loop will lead to a braiding of the field (first proposed by Parker 1983)



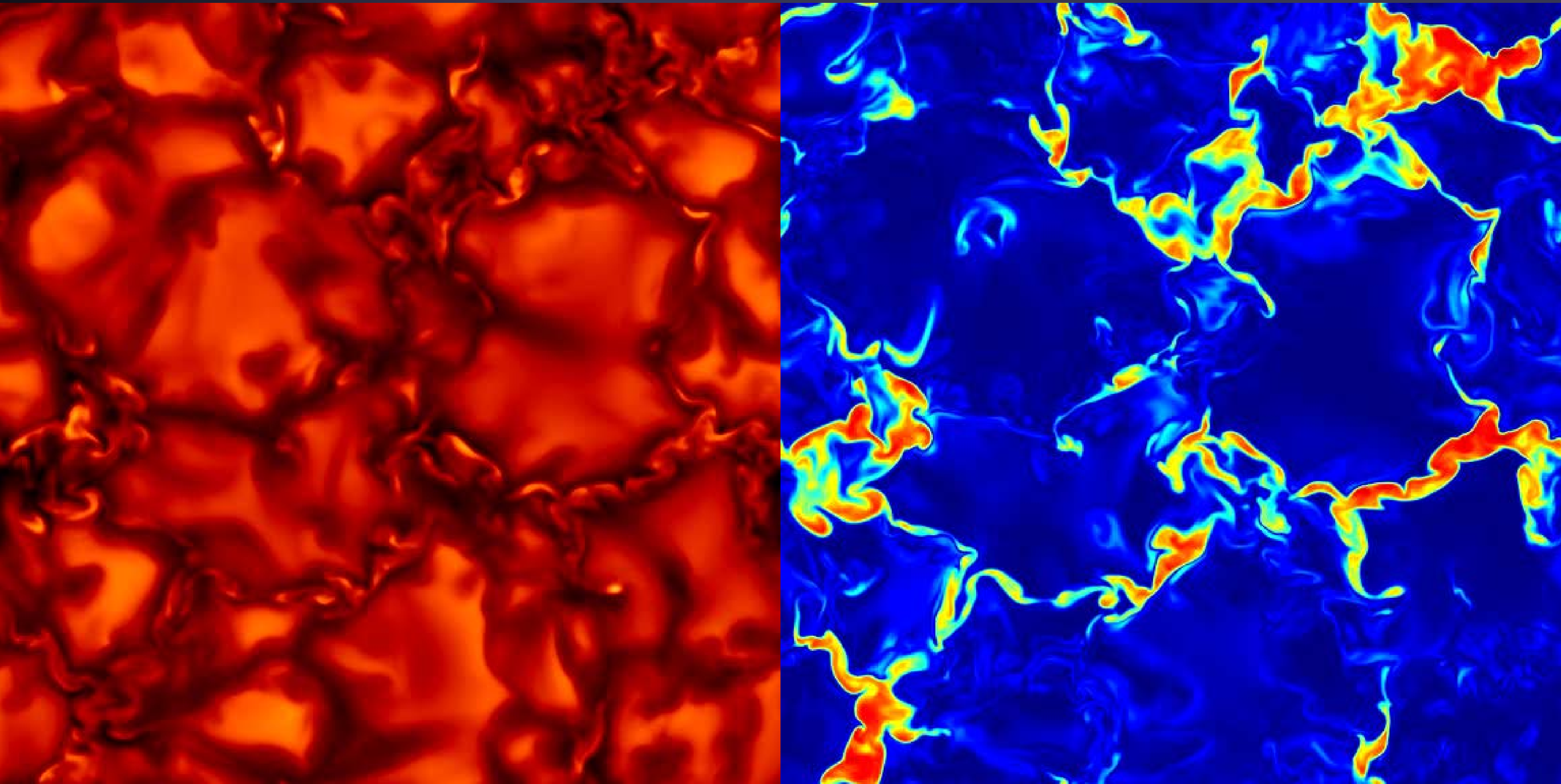
Starting from loop-like potential field, i.e. lowest energy configuration, energy in field can be increased by moving the loop footpoints

Source of footpoint motion: magneto-convection

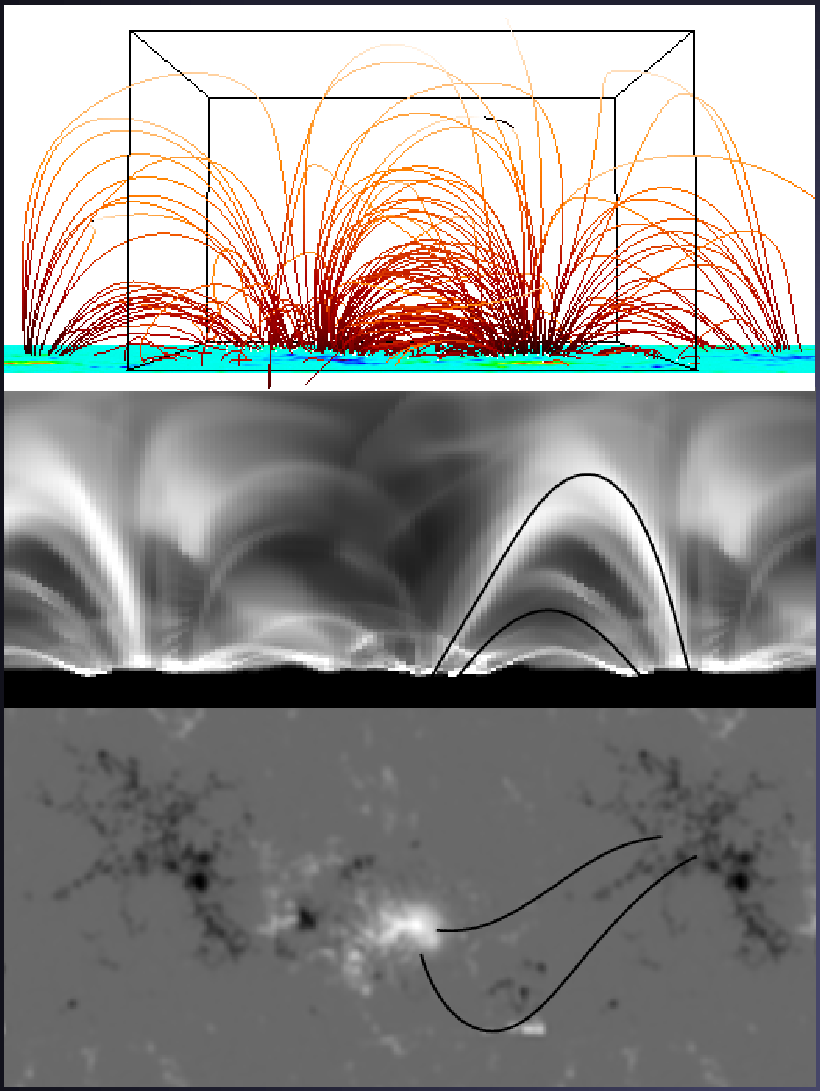
Structure and dynamics at small spatial scales

Radiation-MHD Simulations of small-scale magnetic fields

Intensity Vögler et al. Magnetic field



Magnetic coupling & coronal heating



Gudiksen & Nordlund (2002)

Coronal loops maintained at MK temperatures by current dissipation

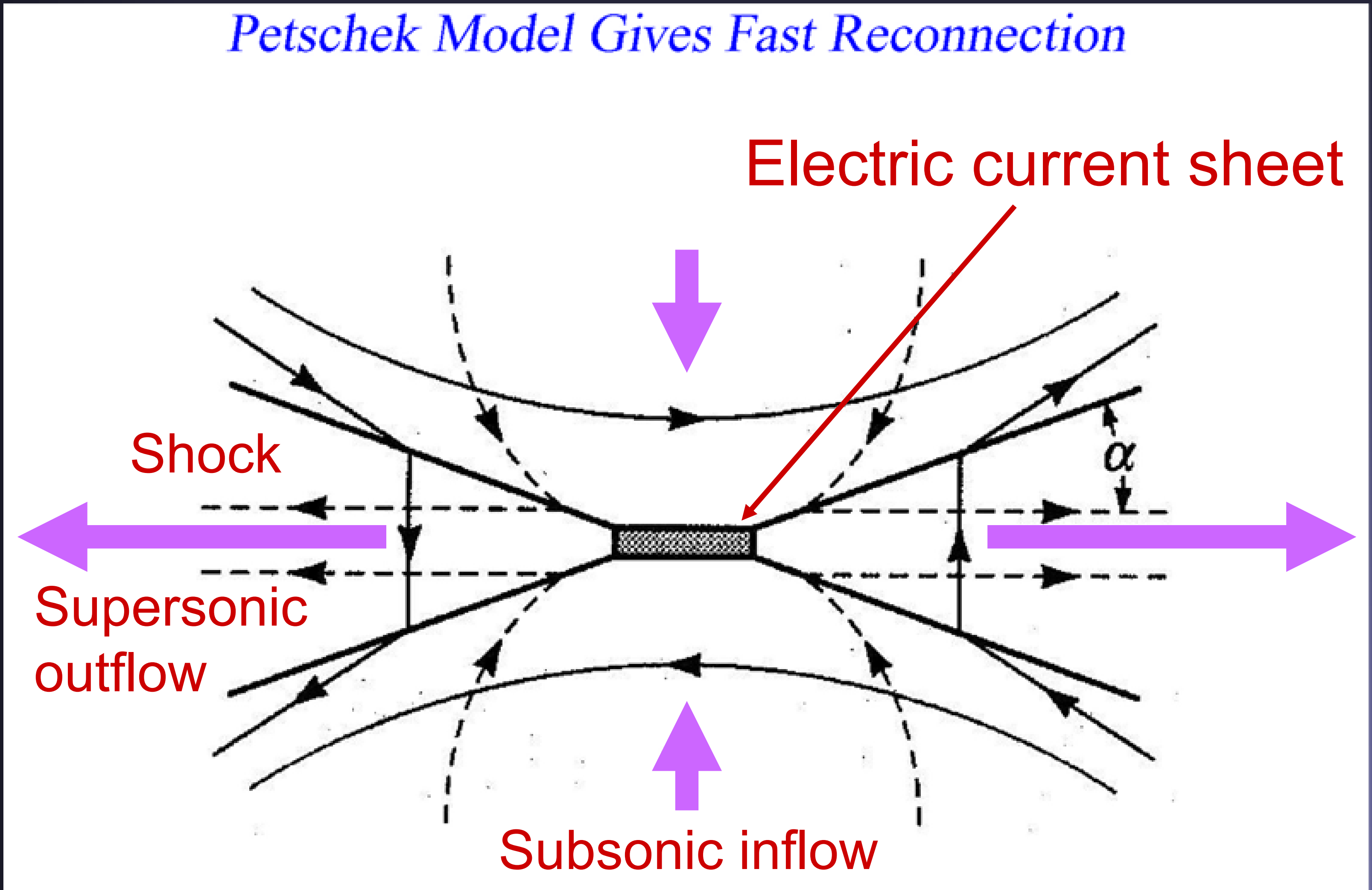
↑

Braiding of coronal magnetic field lines

↑

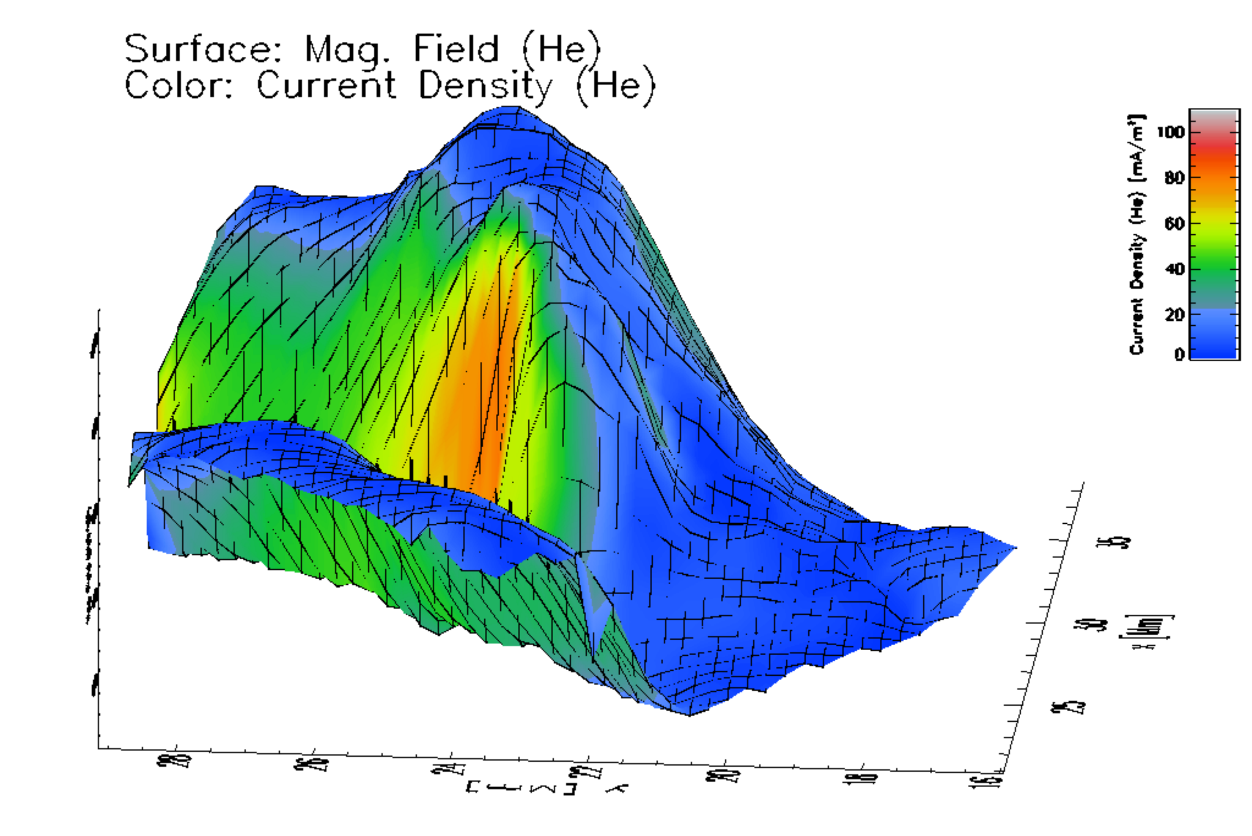
Emergence of new flux and interaction with convection: Magnetic footpoint motions

Magnetic reconnection (2-D)



Electric Current Sheet at Coronal Base

He I 10830 Å reveals electric current sheet (tangential discontinuity of magnetic vector) at coronal base



Observed in emerging flux region

Surface: magnetic field strength (note the valley)

Colour: current density

Solanki et al. 2003, Animation: A. Lagg

Explosive events: evidence for reconnection