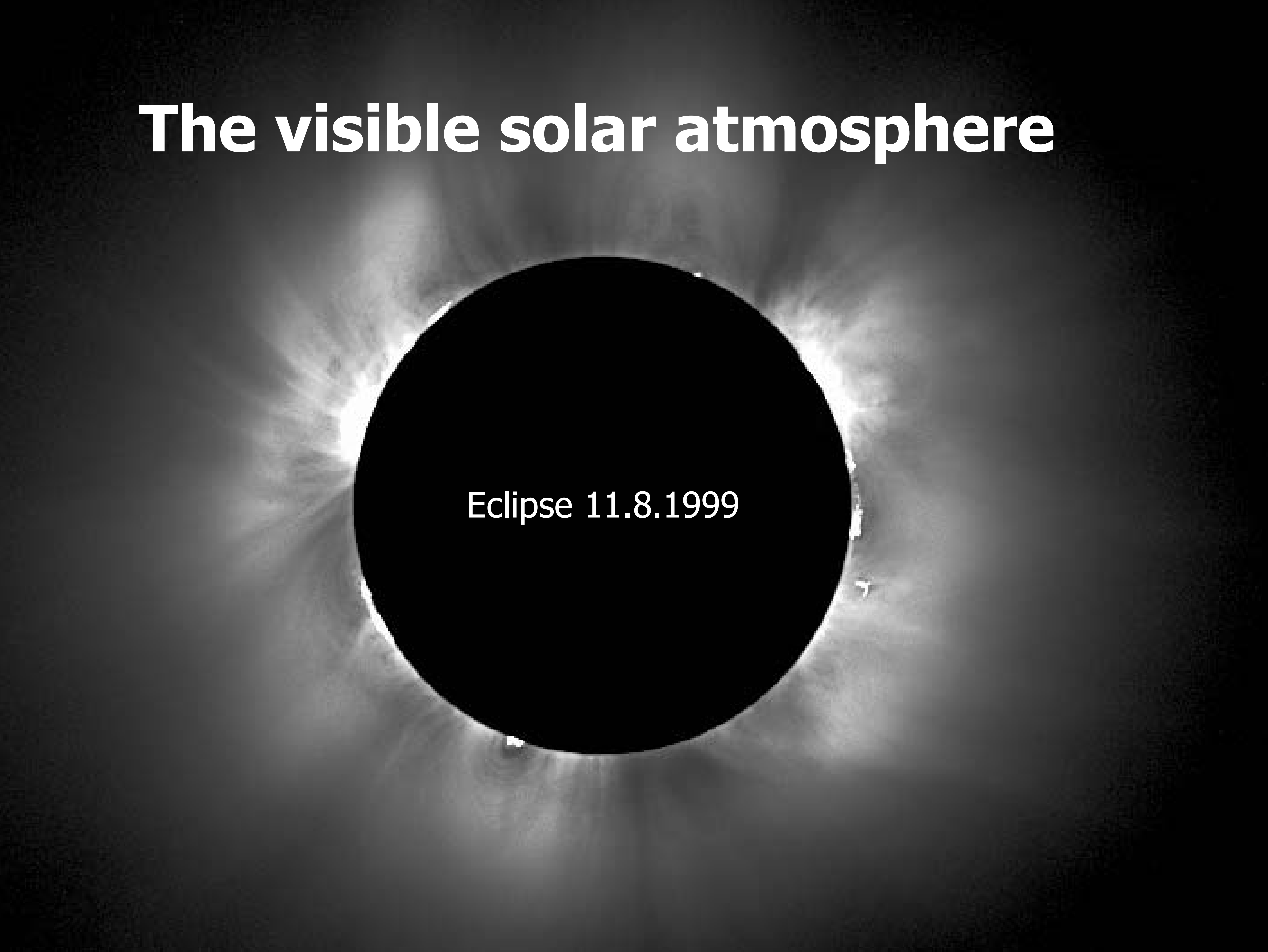
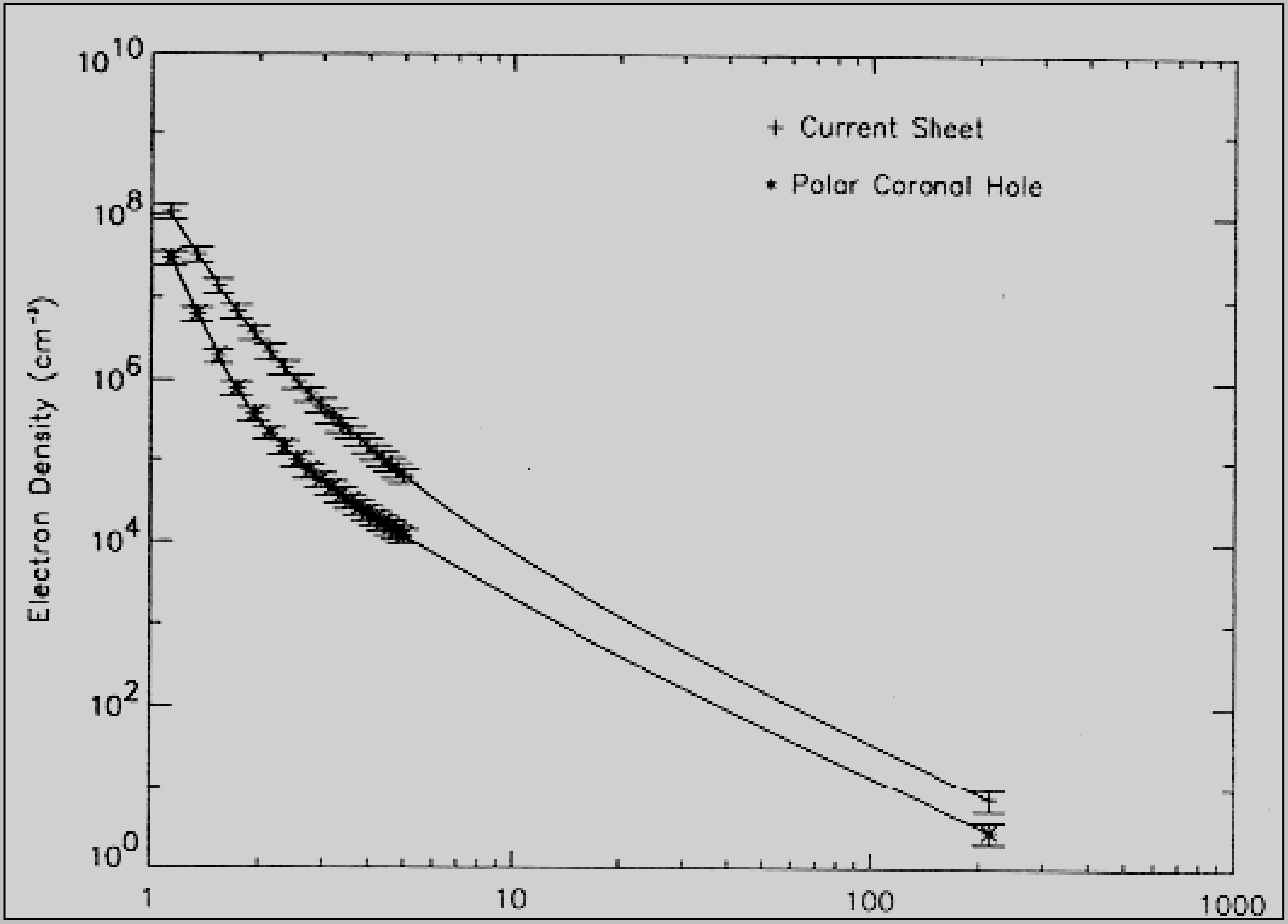
The solar atmosphere and magnetic field

- The Sun's corona and magnetic field
- The magnetic network
- EUV radiation of the corona
- Doppler spectroscopy in EUV
- Small-scale dynamics and turbulence
- Ion temperatures in the corona

The visible solar atmosphere



Electron density in the corona



Heliocentric distance / R_S

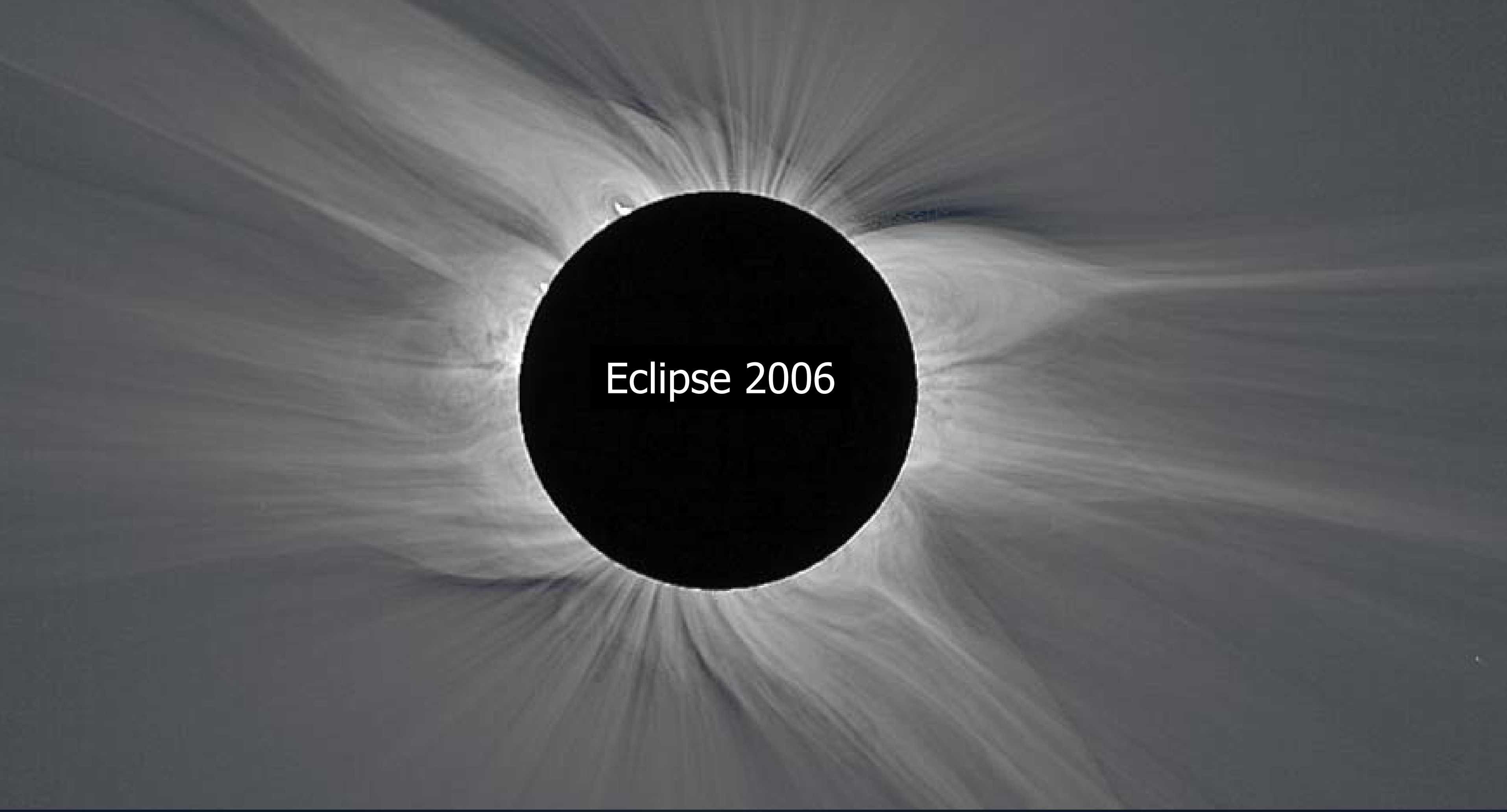
+ Current sheet and streamer belt, closed

• Polar coronal hole, open magnetically

Guhathakurta and Sittler, 1999, Ap.J., **523**, 812

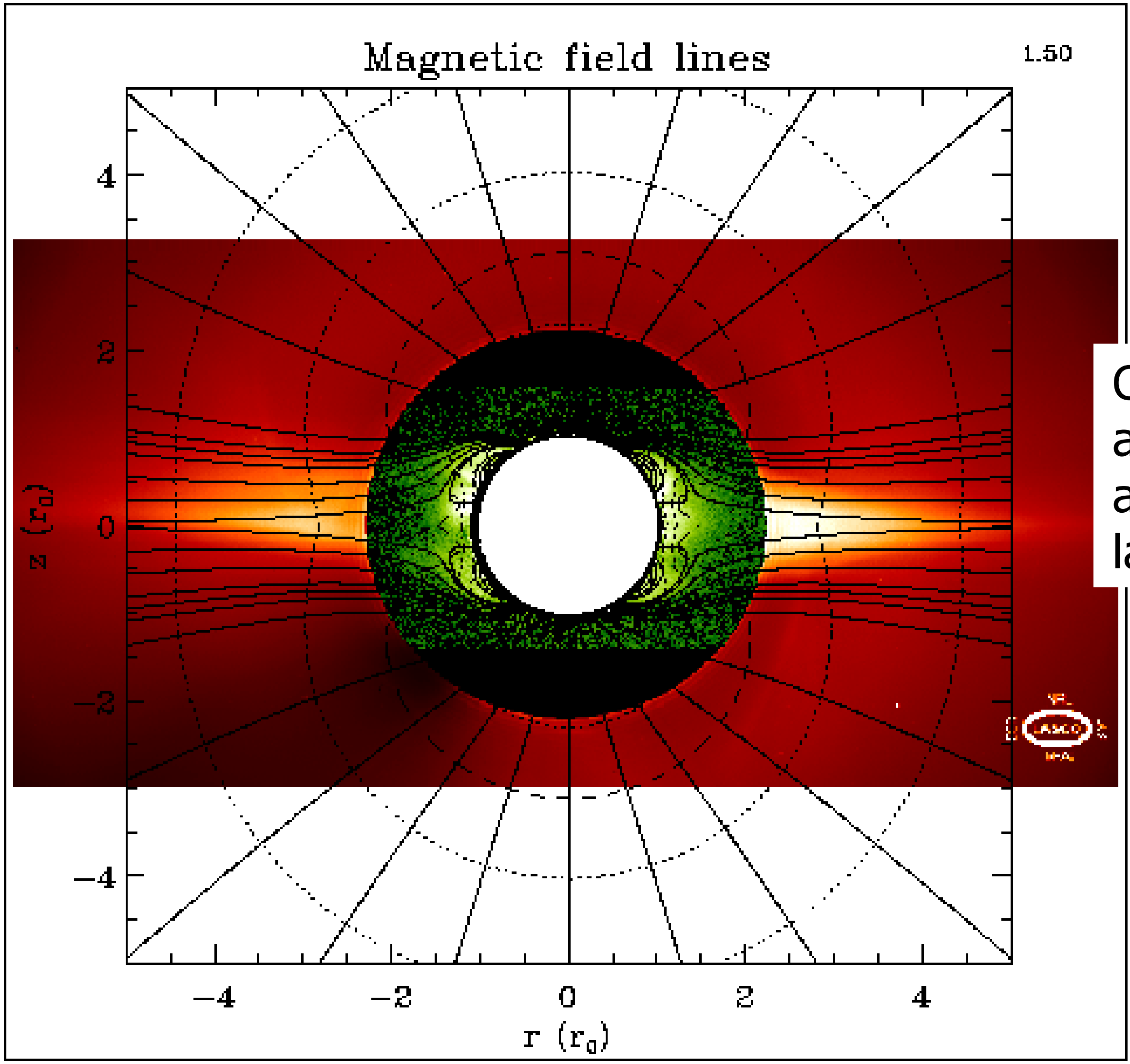
Skylab coronagraph/Ulysses in-situ

The highly structured corona



Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions



Polar field: B = 12 G

Current sheet is a symmetric disk anchored at high latitudes

Banaszkiewicz et al., 1998;

Schwenn et al., 1997

LASCO C1/C2 images (SOHO)

Plasma beta I

Starting from the MHD equation for a plasma at rest in steady quasineutral state, we obtain the simple force balance:

$$\nabla \cdot \mathrm{P} = -\frac{1}{\mu_0}\mathrm{B} \times (\nabla \times \mathrm{B})$$

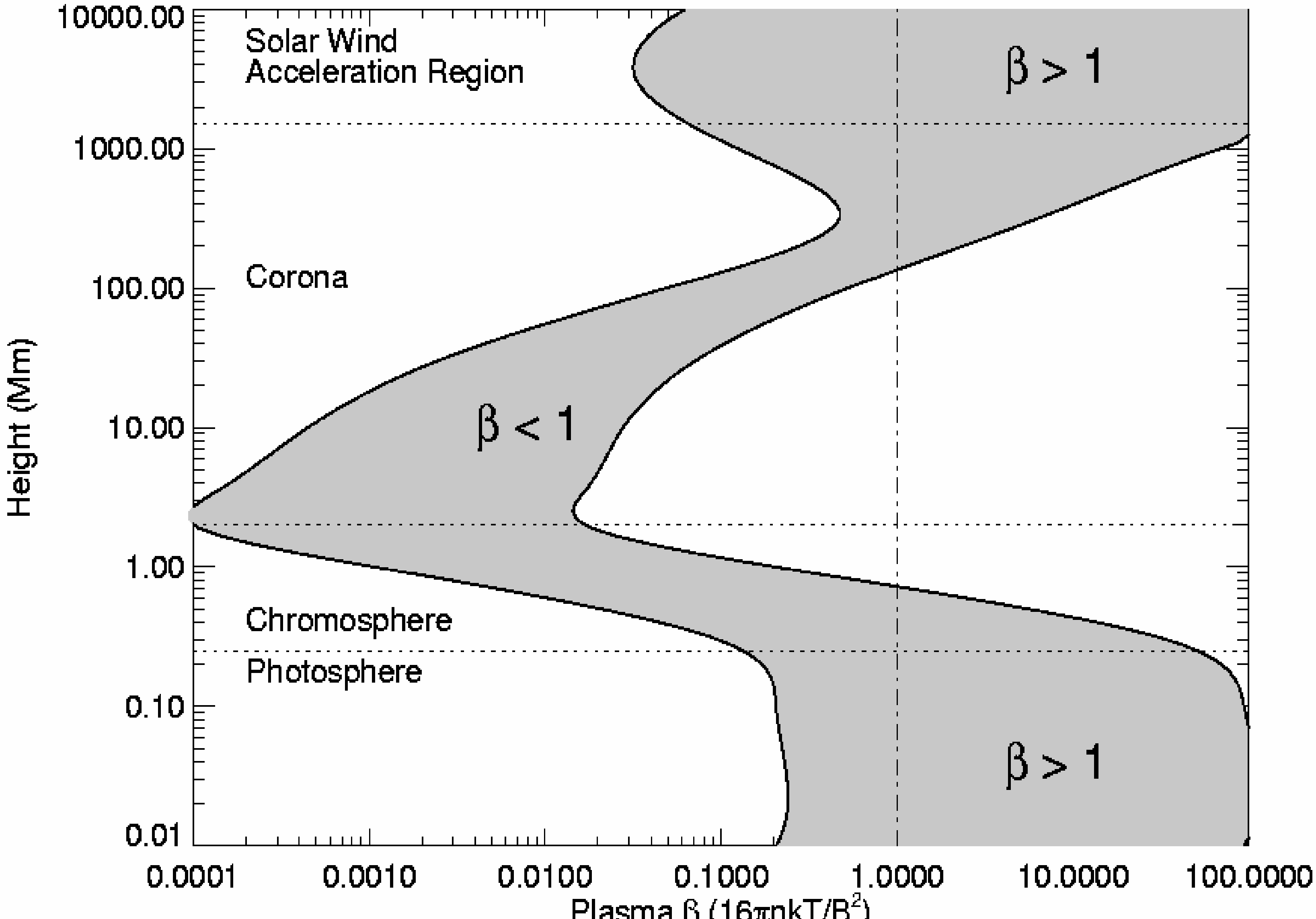
which expresses **magnetohydrostatic equilibrium**, in which thermal pressure balances magnetic tension. If the particle pressure is nearly isotropic and the field uniform, this leads to the total pressure being constant:

$$\nabla \left(p + \frac{B^2}{2\mu_0} \right) = 0$$

The ratio of these two terms is called the **plasma beta**:

$$\beta = \frac{2\mu_0 p}{B^2}$$

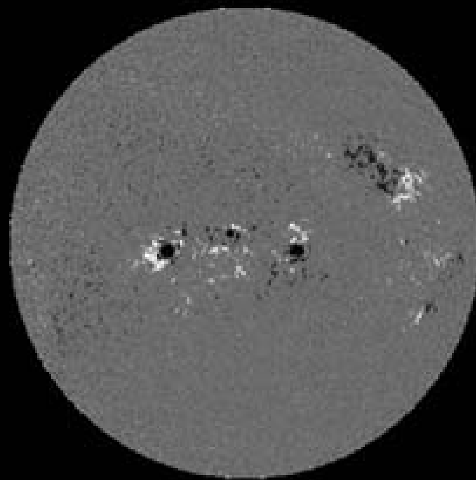
Plasma beta II



Aschwanden, 2004

Sun in different light

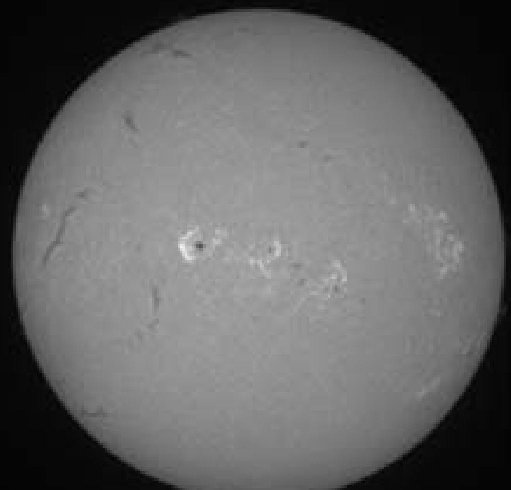
Na I 589 nm



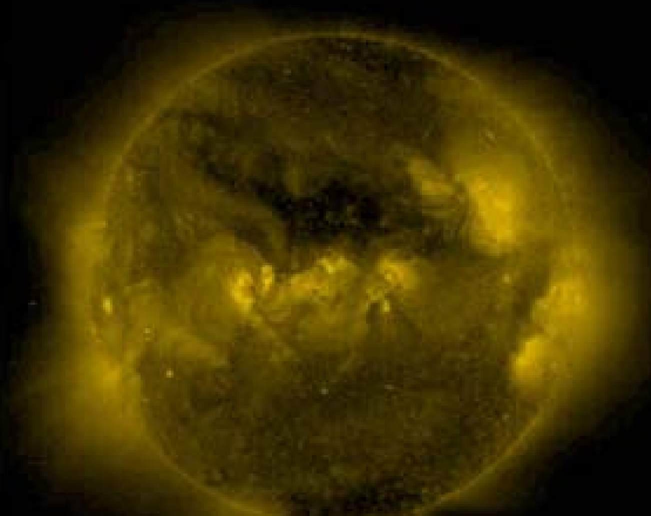
Ni I 676.8 magnetogram

Fe XII 195 nm

He II 30.4 nm

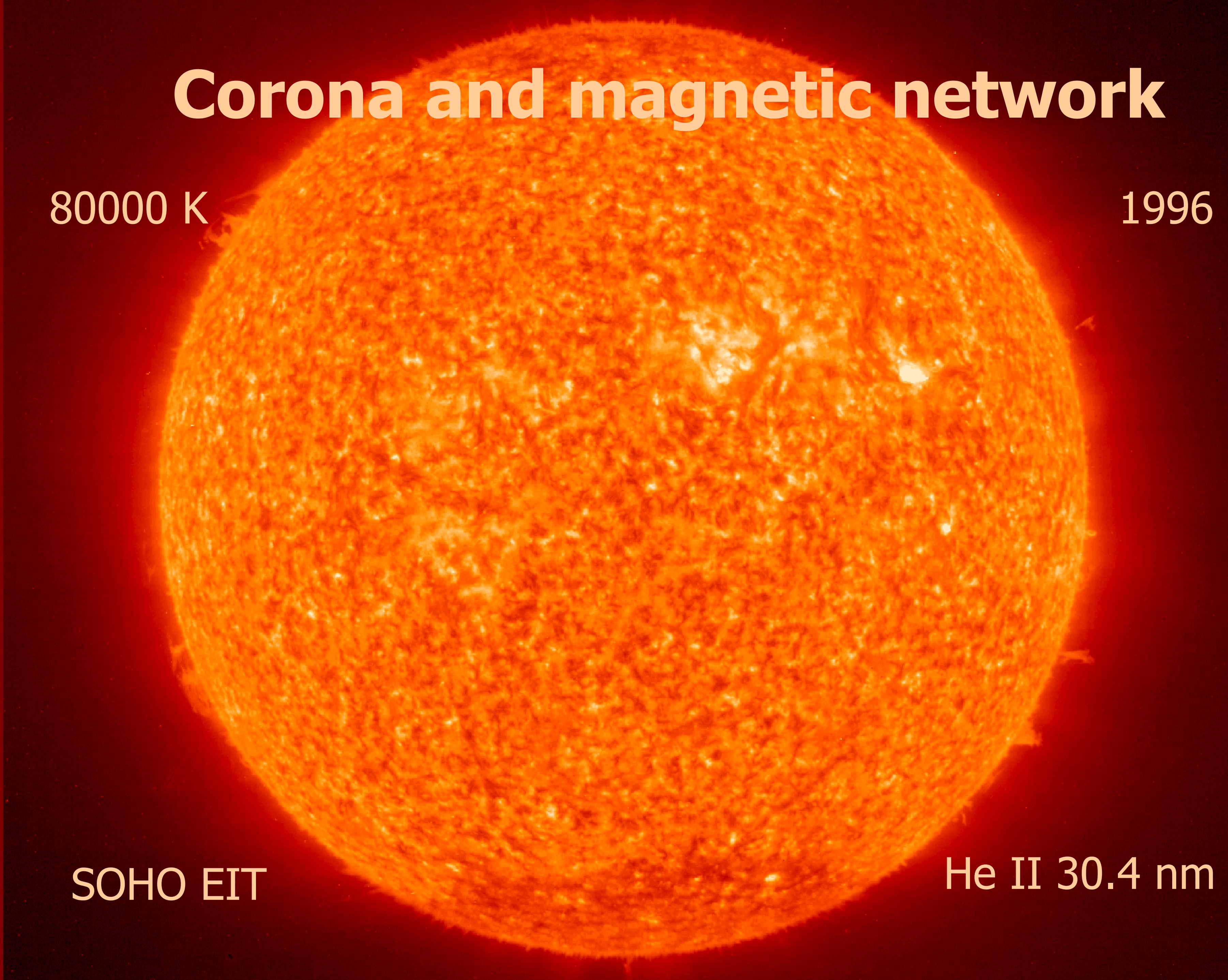


H_α 656.3 nm

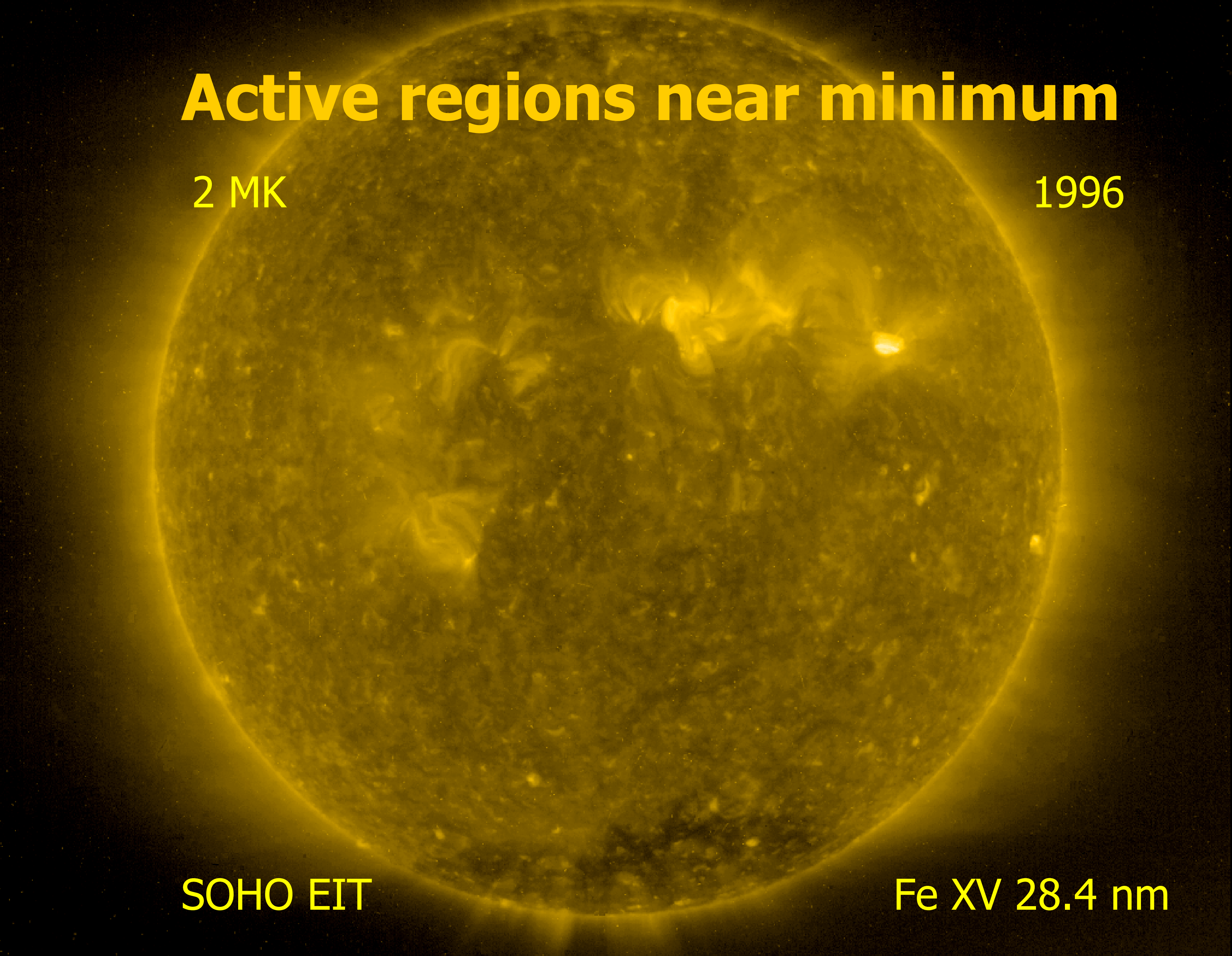


Fe XV 284 nm

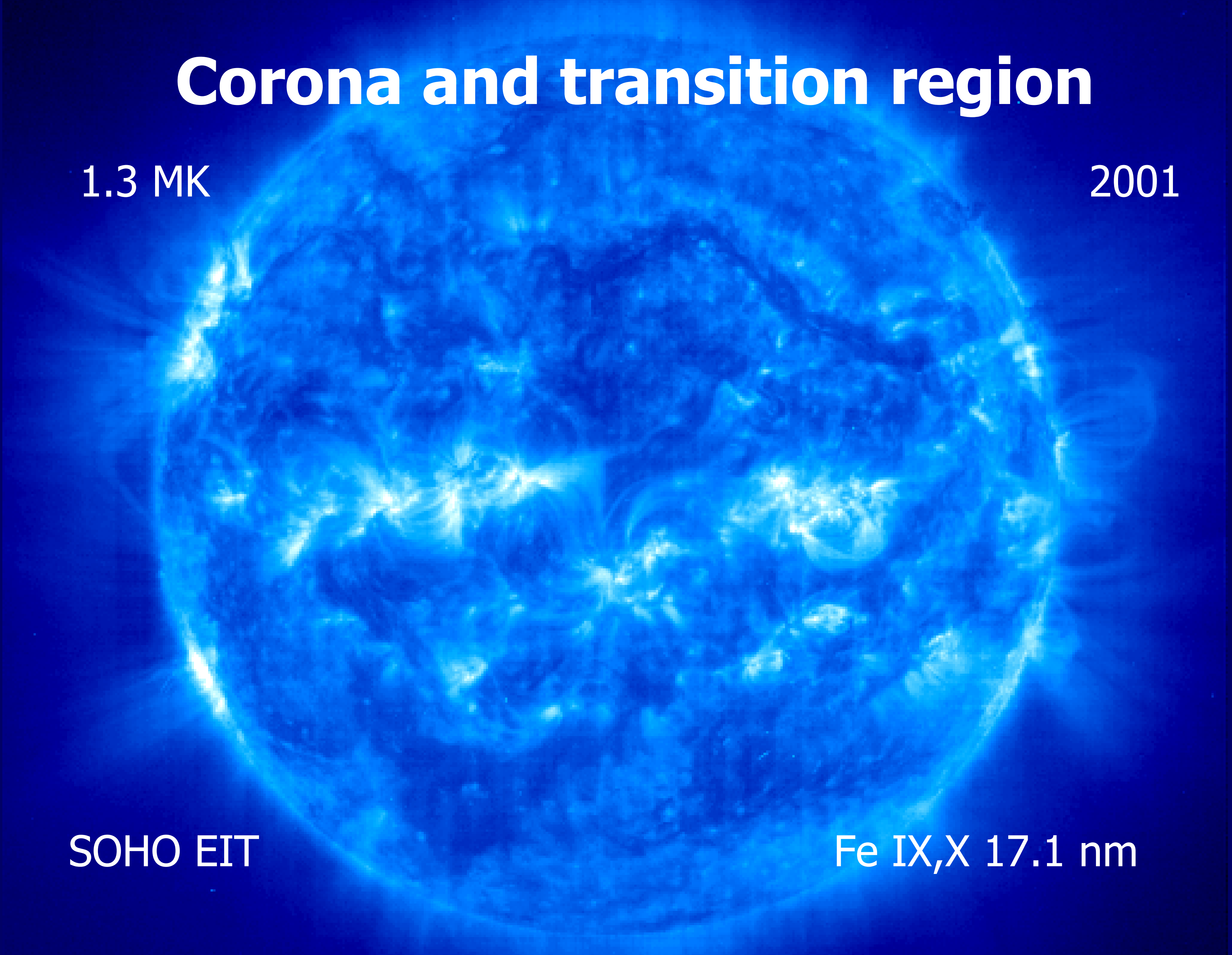
Corona and magnetic network



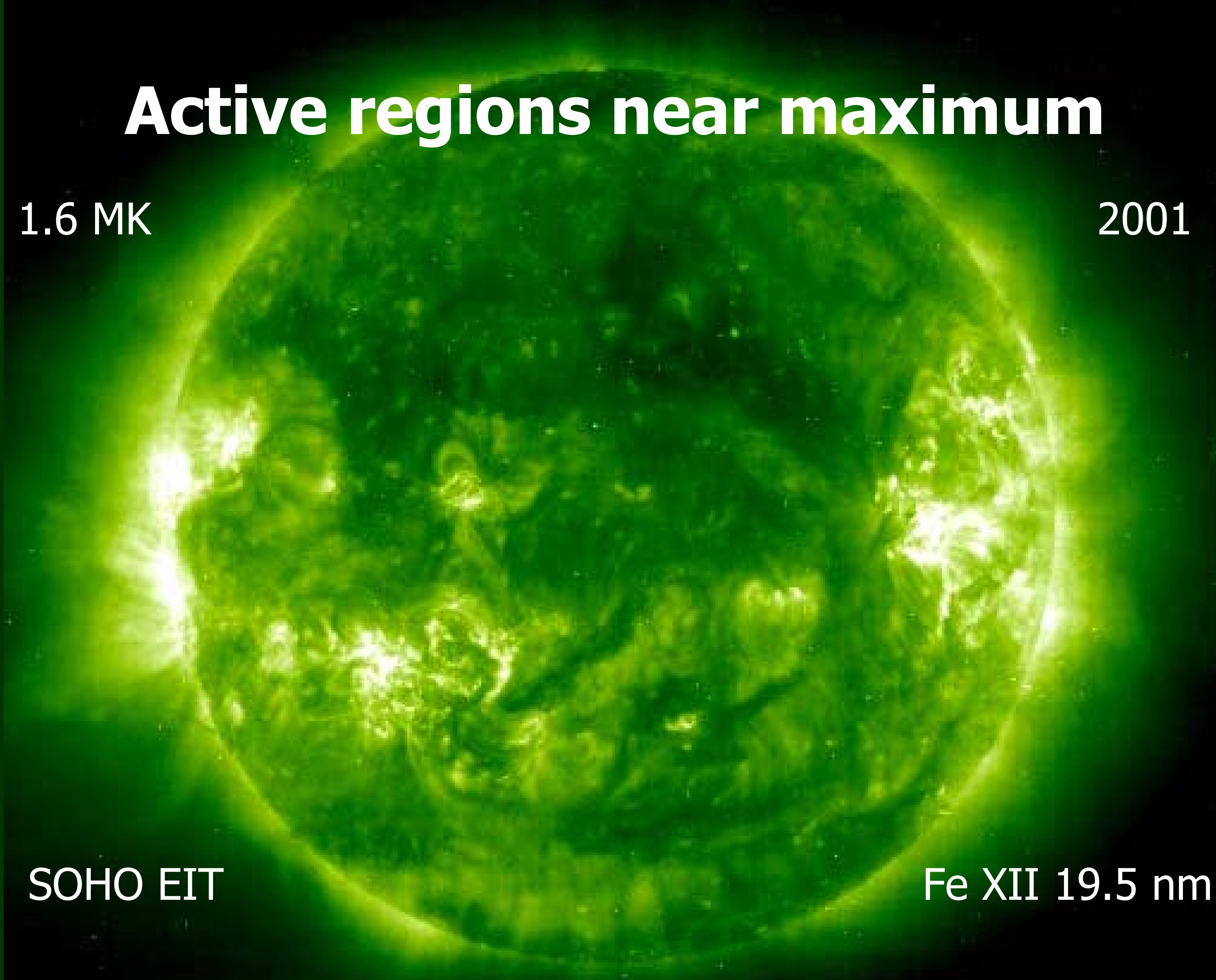
Active regions near minimum

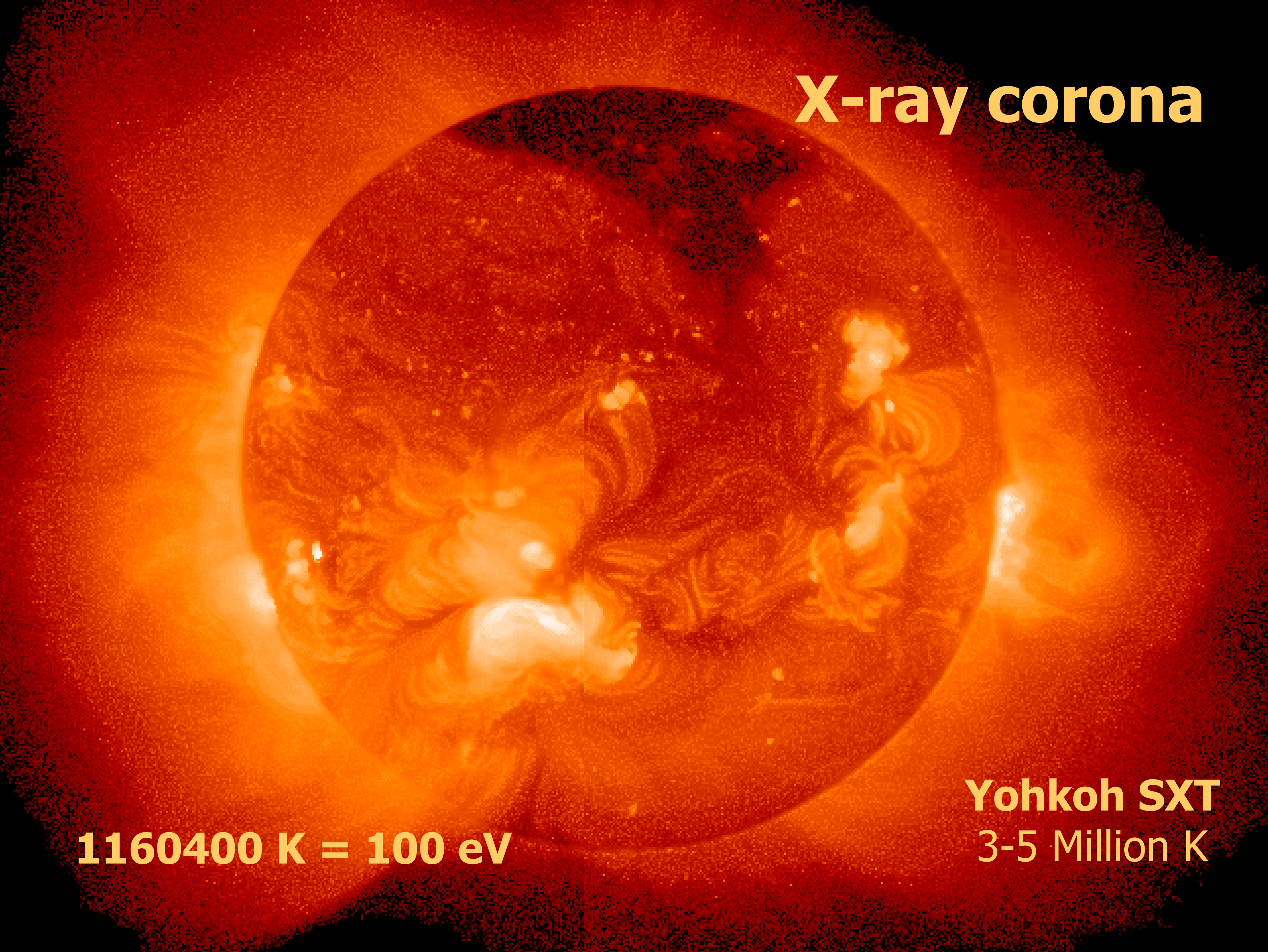


Corona and transition region

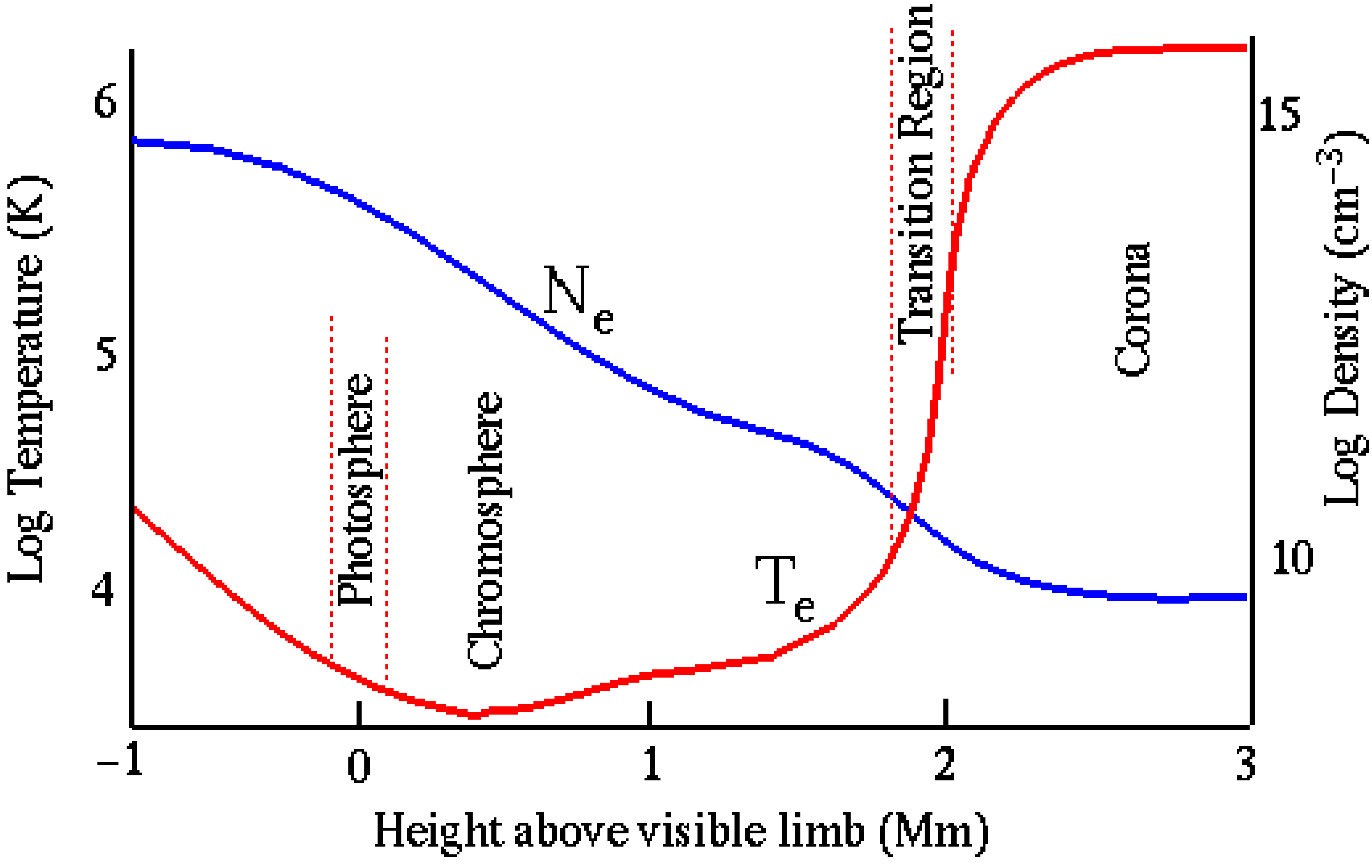


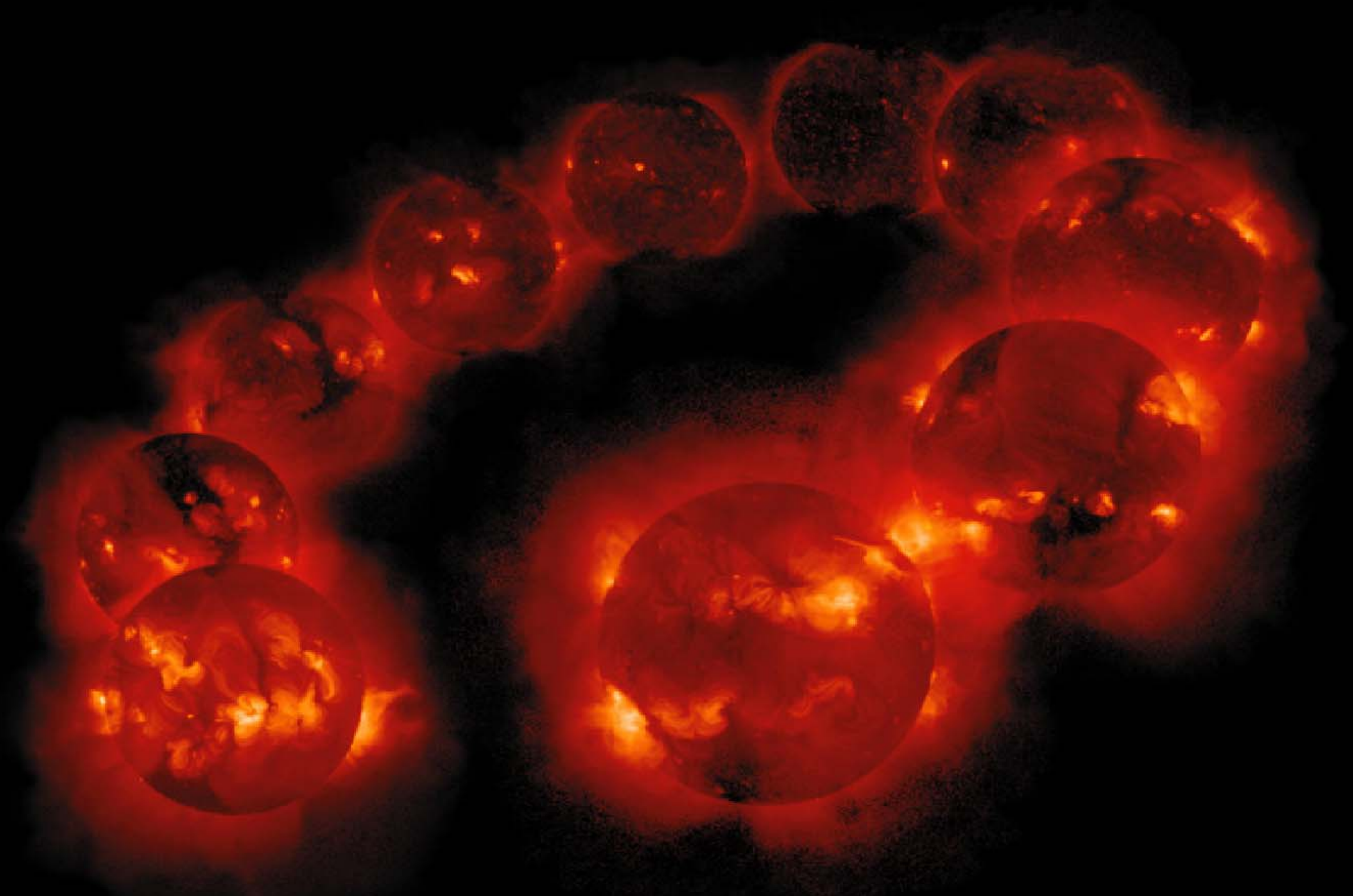
Active regions near maximum



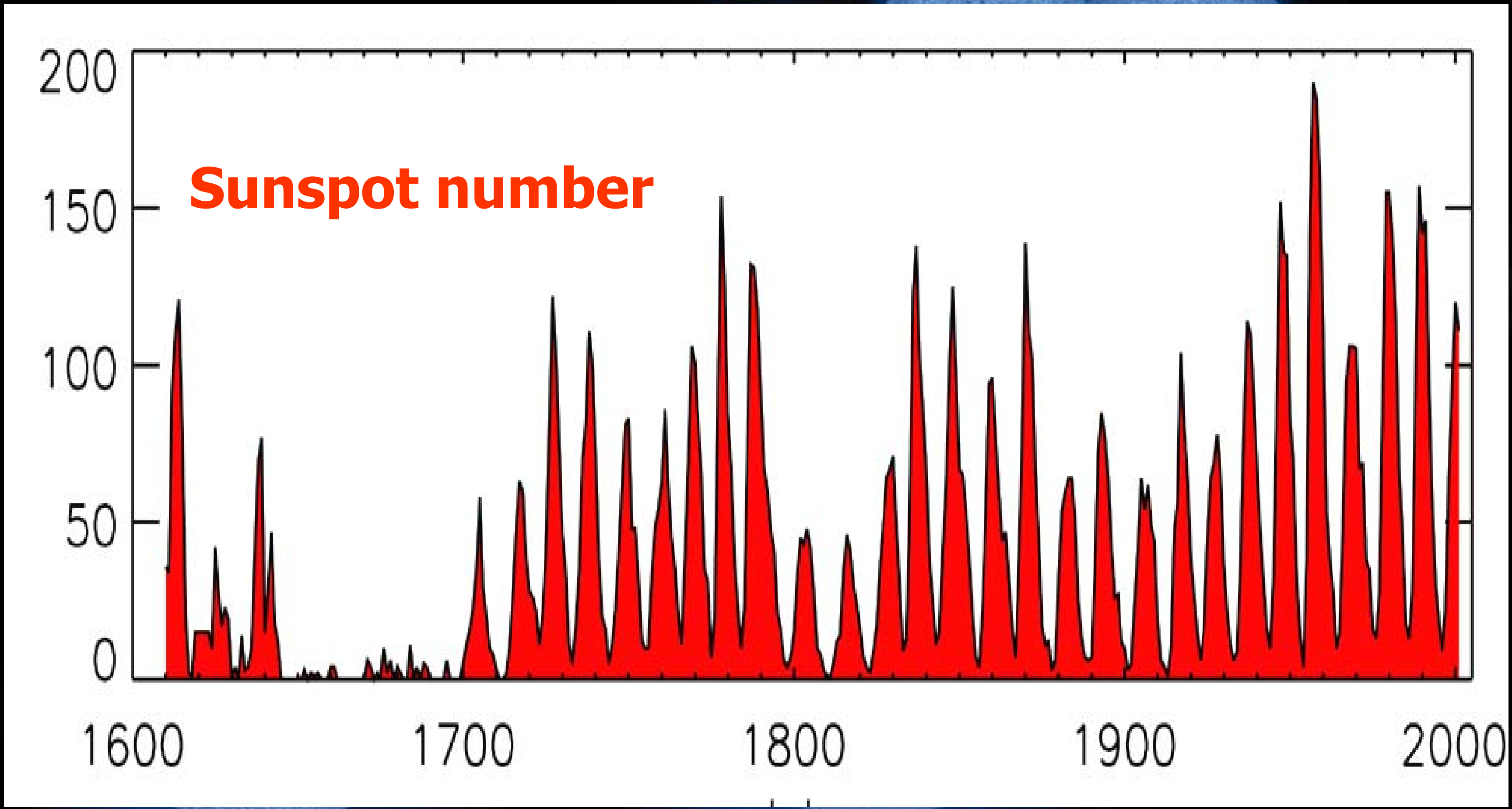

X-ray corona
Yohkoh SXT
3-5 Million K
1160400 K = 100 eV

How is the solar corona heated?



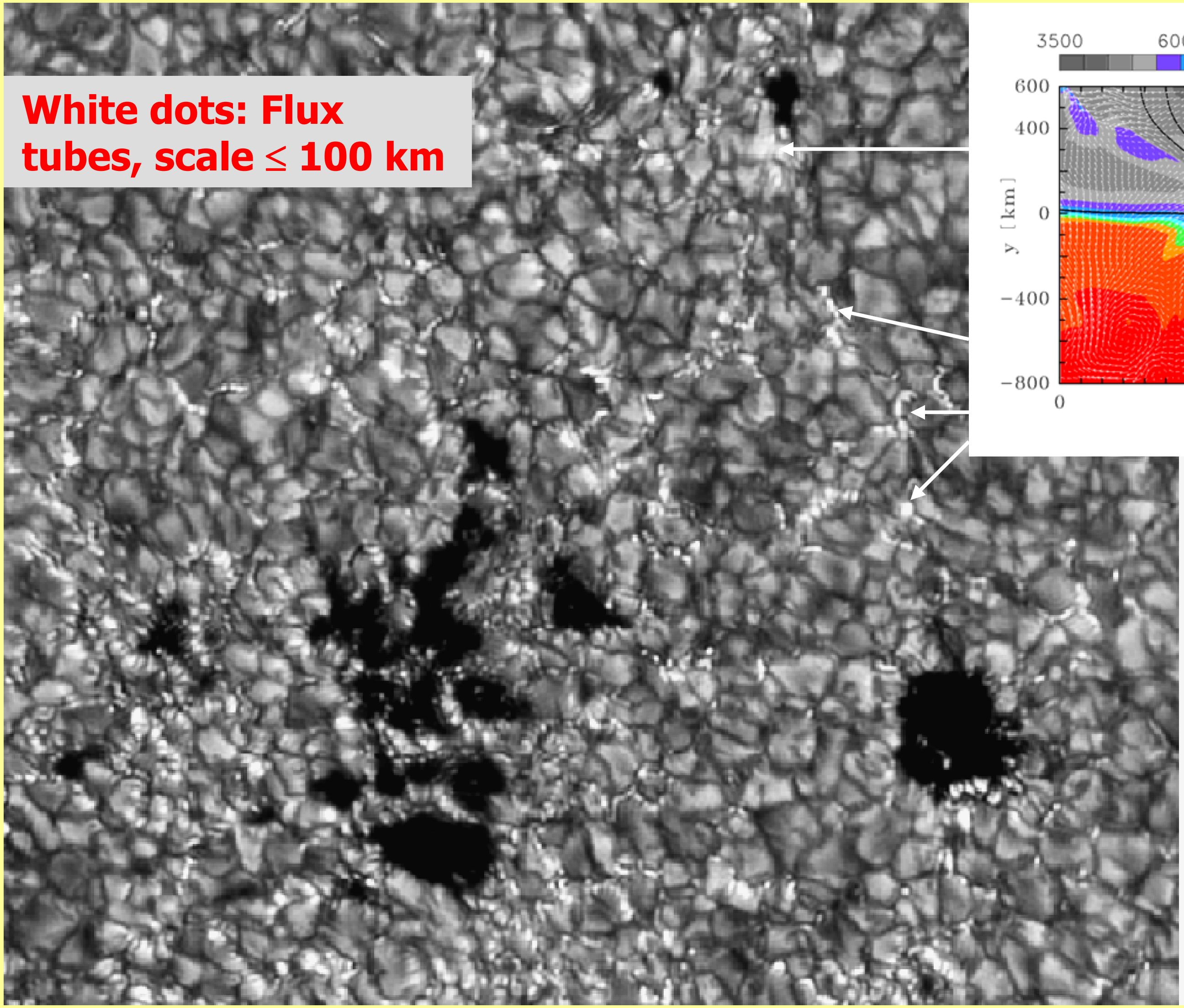


Yohkoh SXT: The changing corona

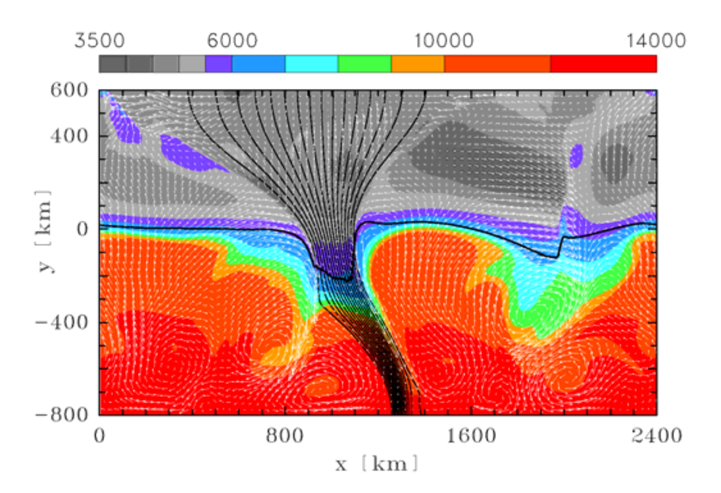


Ten photospheric magnetograms:
The solar cycle 1992 - 1999 (NSO)

Small magnetic flux tubes and photospheric granulation



White dots: Flux tubes, scale ≤ 100 km

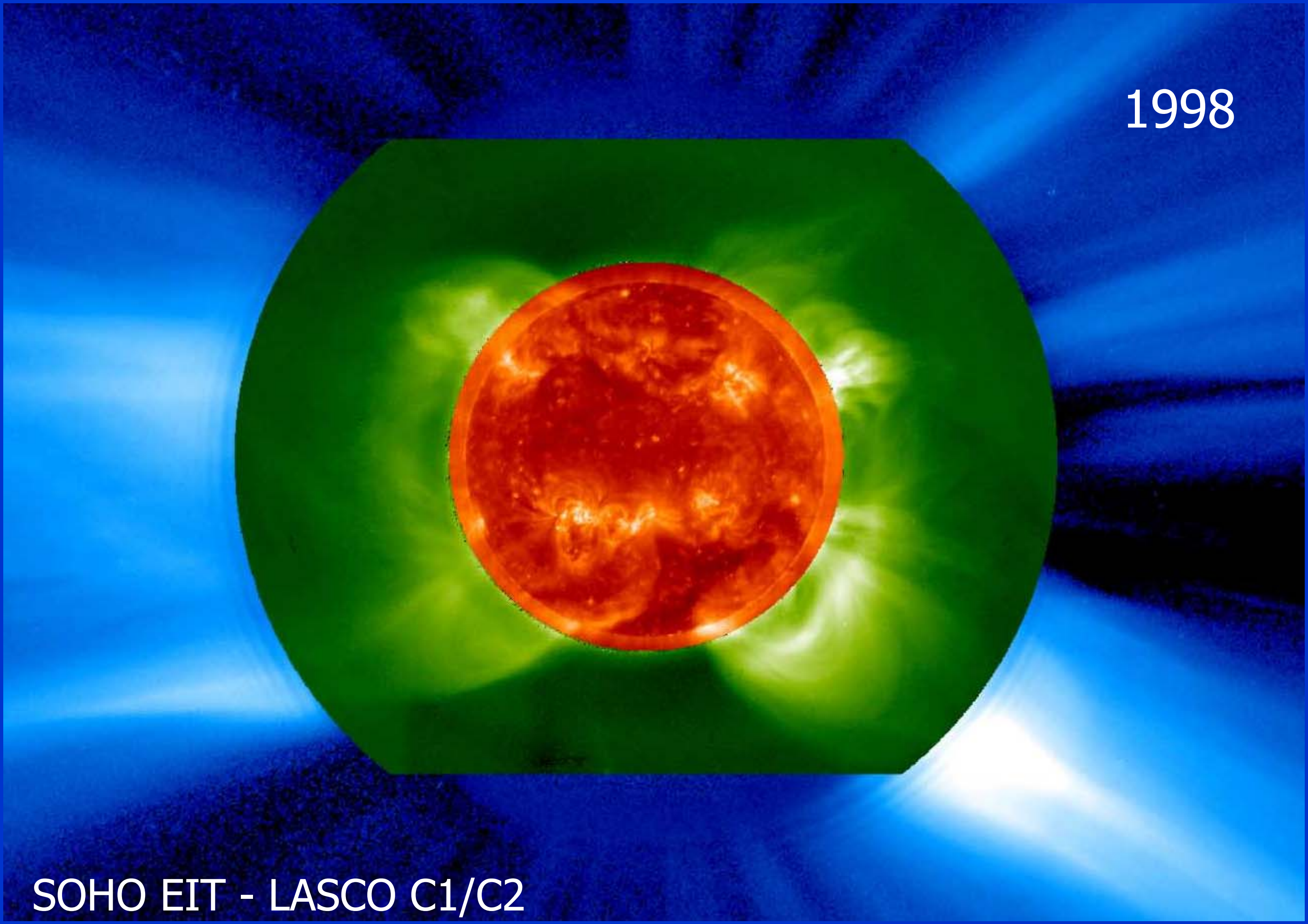


35 Mm x 40 Mm

Magnetic regions (seen in G-band near 430 nm) between granules

Scharmer, 1993

Corona of the active Sun



North coronal hole in various lines

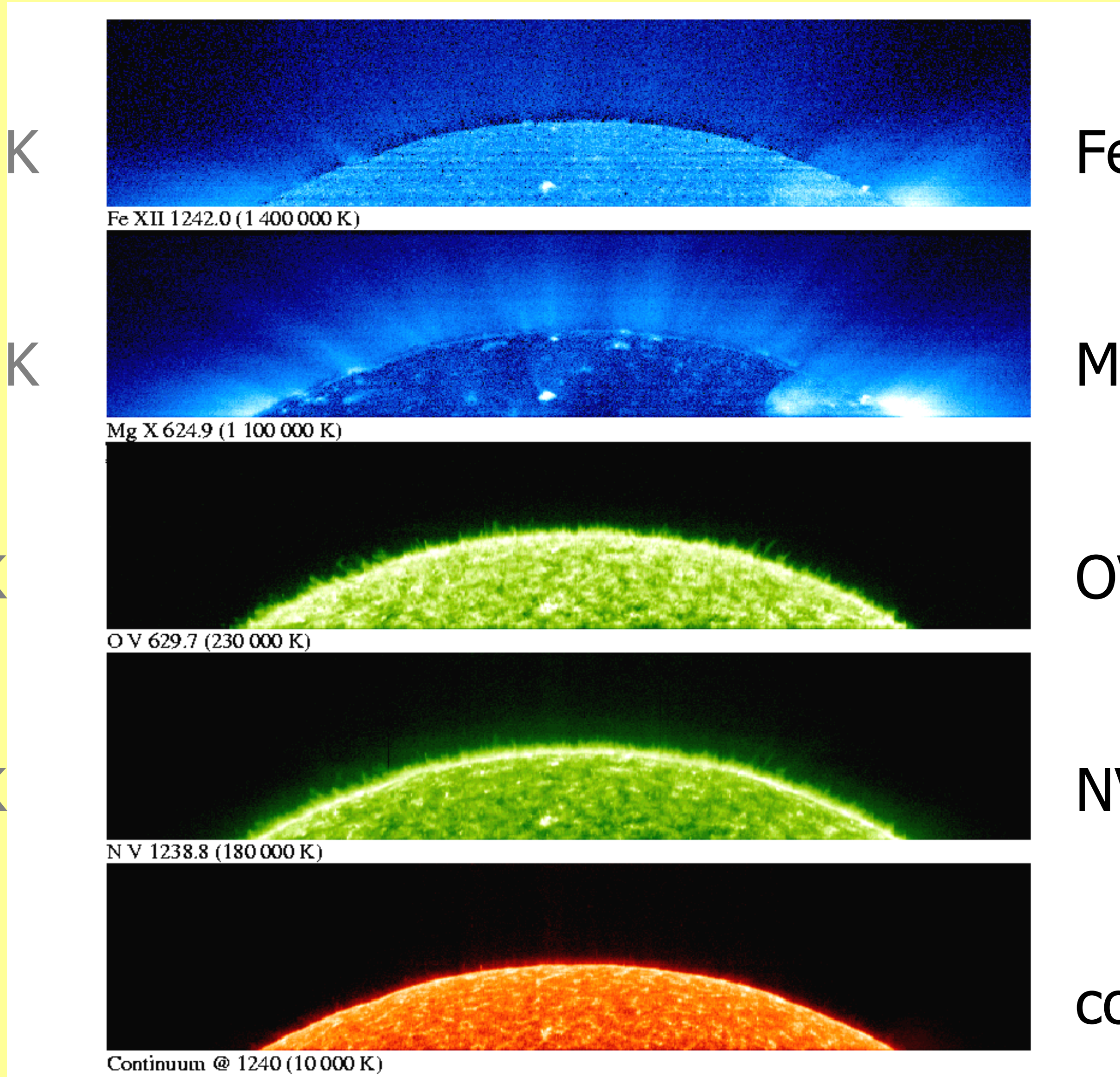
1400000 K — FeXII 1242 Å

1100000 K — MgX 624.9 Å

230000 K — OV 629.7 Å

180000 K — NV 1238.8 Å

10000 K — cont. 1240 Å



Forsyth & Marsch, Space Sci. Rev., **89**, 7, 1999

SUMER/SOHO 10 August 1996

EUV line excitation processes

- *Collisional excitation of atom or ion, A, followed by a radiative decay:*

$A + e^- \text{ --> } A^* + e^-$ ($n_e > 10^8$ cm^{-3})

$A^* \text{ --> } A + h\nu$ **Line radiance: $L_\lambda \sim n_e^2$**

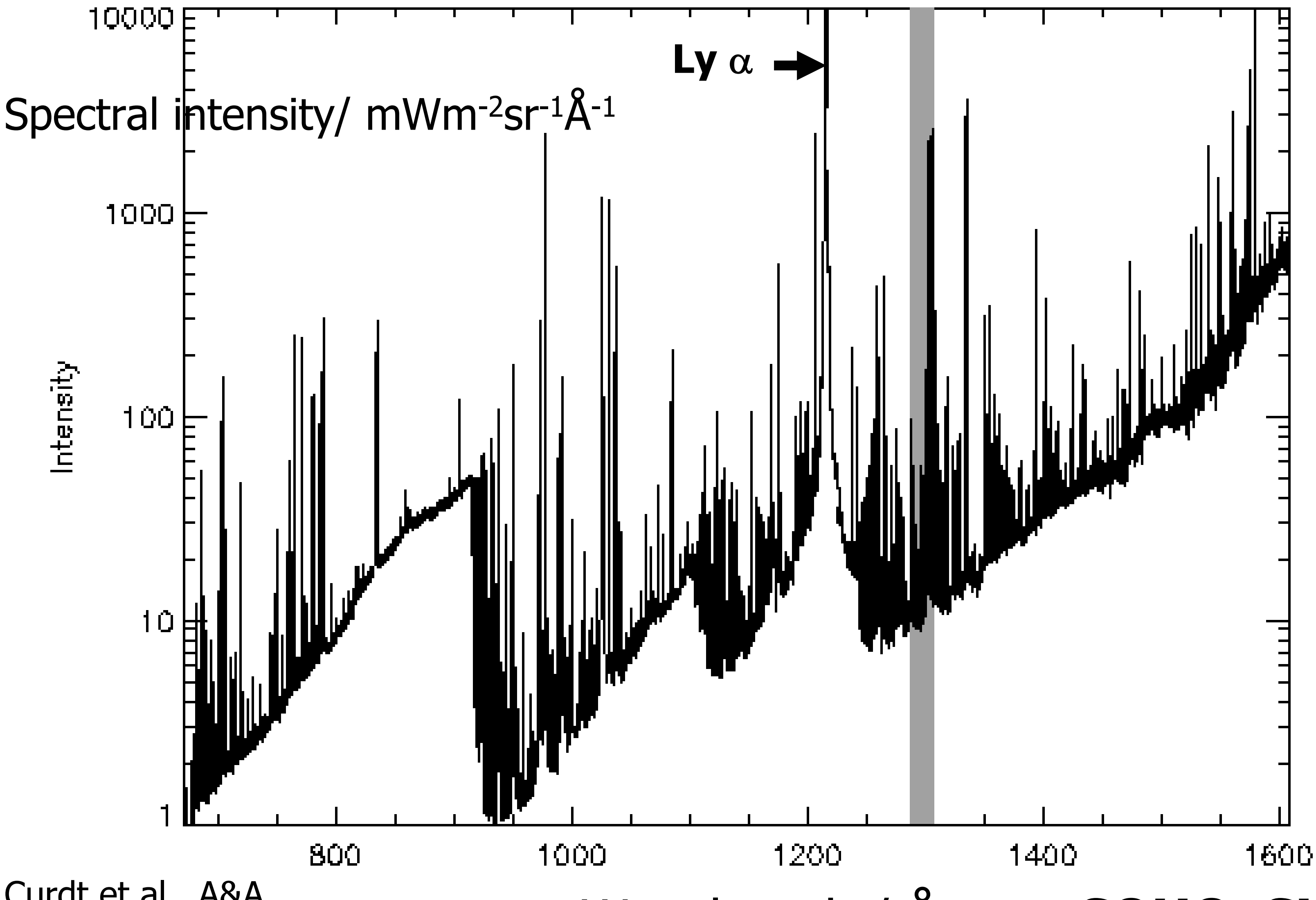
- *Resonant scattering (fluorescence):*

$A + h\nu \text{ --> } A^* \text{ --> } A + h\nu$ **Line radiance: $L_\lambda \sim n_e$**

- *Radiative recombination:*

$A^{+z} + e^- \text{ --> } A^{+(z-1)*} \text{ --> } A^{+z-1} + h\nu$

Solar EUV emission spectrum



Curdt et al., A&A
375, 591, 2001

SOHO SUMER

Elementary radiation theory I

Coronal model approximation:
collisional excitation and radiative decay

$$N_g(X^{+m})\, n_e\, C_{g,j} \;=\; N_j\, A_{j,g}$$

$C_{g,j}$ [$cm^3 s^{-1}$] collisional excitation rate

$A_{j,g}$ [s^{-1}] atomic spontaneous emission coefficient ($\approx 10^{10} s^{-1}$)

Emissivity (power per unit volume):

$$P(\lambda_{g,j}) = N_j(X^{+m})\, A_{j,g}\, \Delta E_{j,g} \qquad [\mathrm{erg\ cm^{-3}\ s^{-1}}]$$

$\Delta E_{g,j} = E_j - E_g$ photon energy

$N_g(X^{+m})$ number density of ground state of ion X^{+m}

Elementary radiation theory II

Occupation number density of level j of an ion (m-fold ionized atom) of the element X:

$N_j(X^{+m})/n_e$ =

$N_j(X^{+m})/N(X^{+m}) \bullet N(X^{+m})/N(X) \bullet N(X)/n(H) \bullet n(H)/n_e$

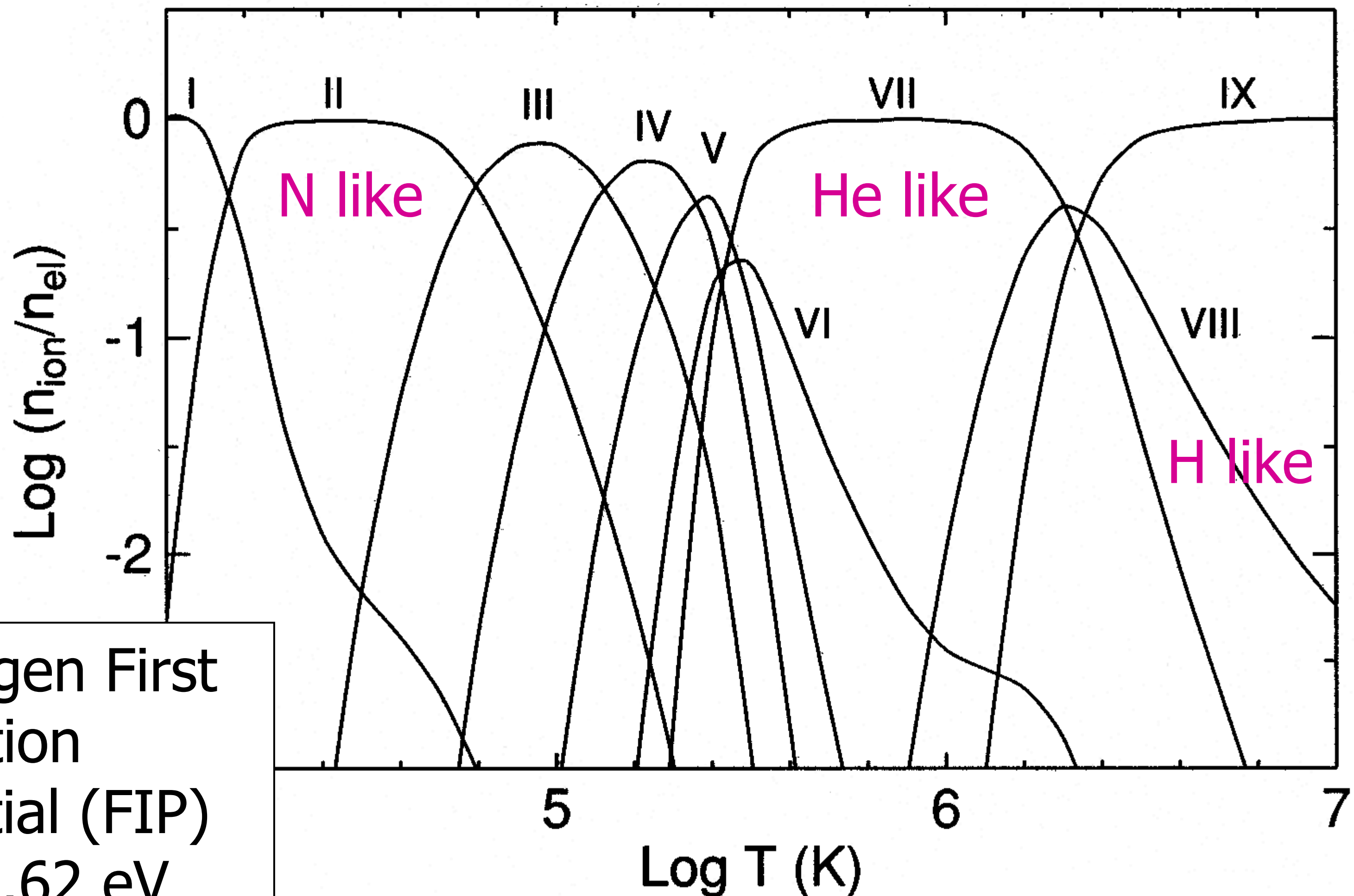
excitation level — ionic fraction — abundance — n(H) [cm^3] hydrogen

Collisonal excitation rate (Maxwellian electrons):

$C_{i,j} \sim 1/T_e^{1/2} \exp\{ \Delta E_{i,j} /(k_B T_e) \}$

Boltzmann factor

Oxygen ionization balance

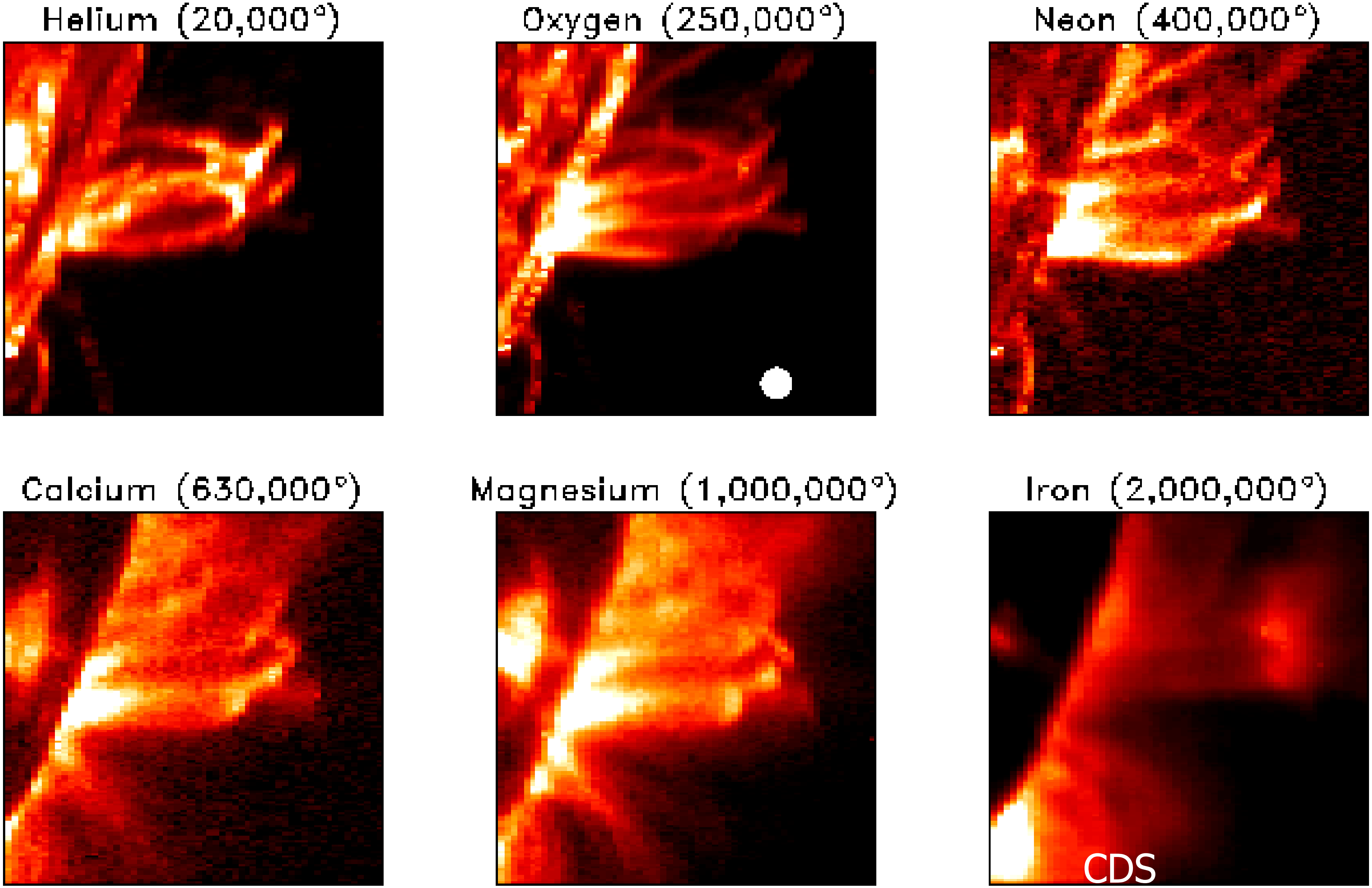


Hydrogen First ionization potential (FIP)
$I = 13.62$ eV

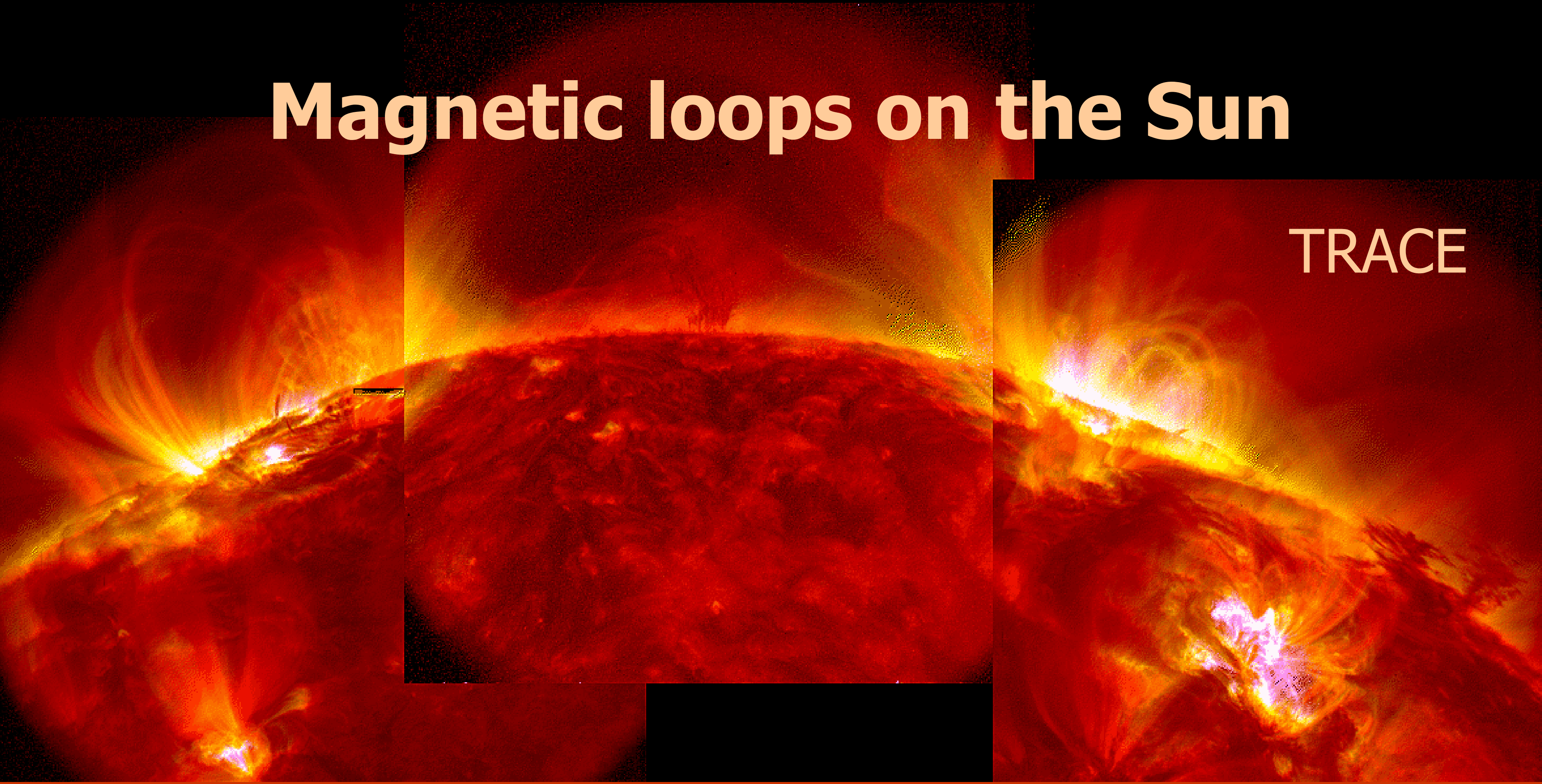
Shull and van Steenberg, ApJ. Suppl. **48**, 95; **49**, 351, 1982

LTE -> $N(X^{+m})/N(X)$ follows from Saha's equation; $\sim \exp(-I/k_B T_e)$

Loops near the solar limb



Magnetic loops on the Sun



- **Thin strands, intrinsically dynamic and continously evolving,**
- **Intermittent heating (in minutes), primarily within 10-20 Mm,**
- **Meandering of hot strings through coronal volume,**
- **Pulsed injection of cool material from chromosphere below,**
- **Variable brightenings, by braiding-induced current dissipation?**

Force-free magnetic field

A special equilibrium of ideal MHD occurs if the beta is low, such that the pressure gradient can be neglected. The stationary plasma becomes ***force free***, if the Lorentz force vanishes:

$$\mathbf{j} \times \mathbf{B} = 0$$

This is guaranteed if the current flows along the field and obeys:

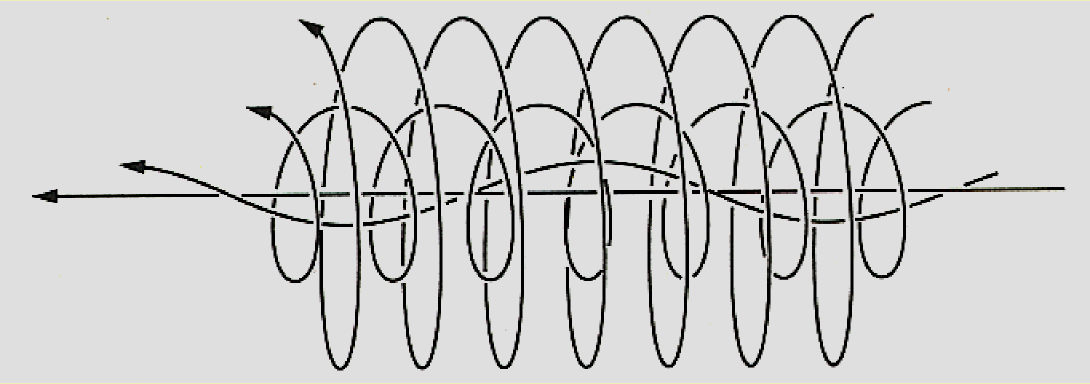
$$\mu_0 \mathbf{j} = \alpha_L \mathbf{B}$$

The proportionality factor $\alpha_L(\mathbf{x})$ is called *lapse field*. Ampère's law yields:

$$\nabla \times \mathbf{B} = \alpha_L \mathbf{B}$$

By taking the divergence, one finds that $\alpha_L(\mathbf{x})$ is constant along field lines:

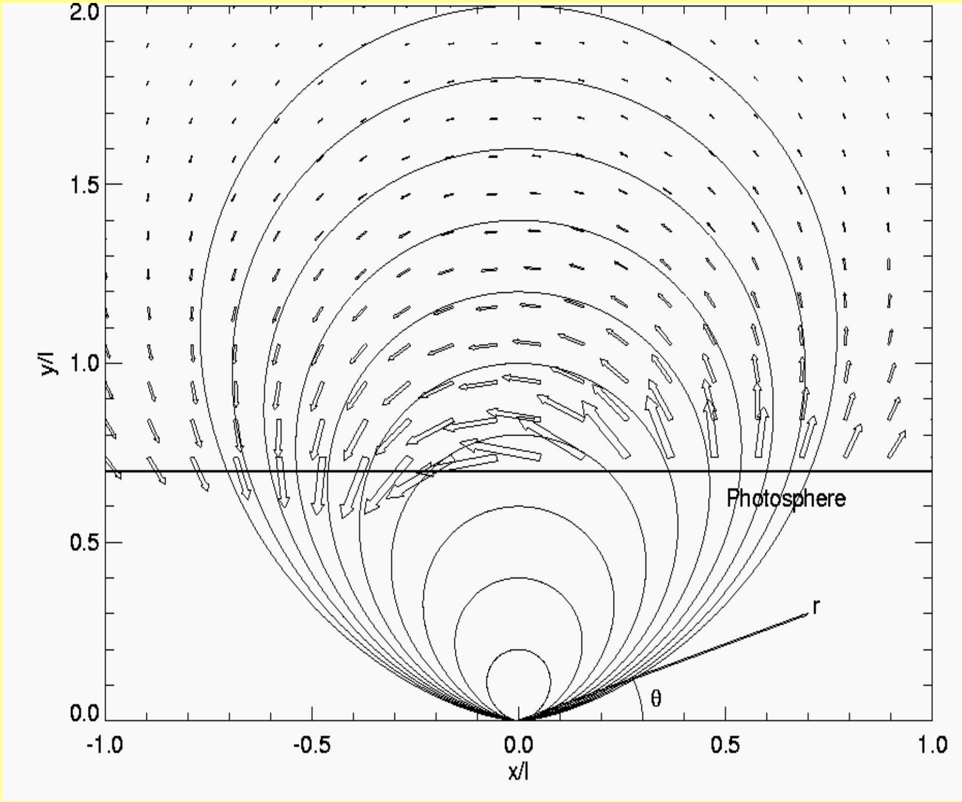
$$\mathbf{B} \cdot \nabla \alpha_L = 0$$



Loop structures

Dipole (potential) field

$$\varphi(r, \theta) = -m \cos\theta / r^2 \quad (m = \pi a^2 I / c)$$

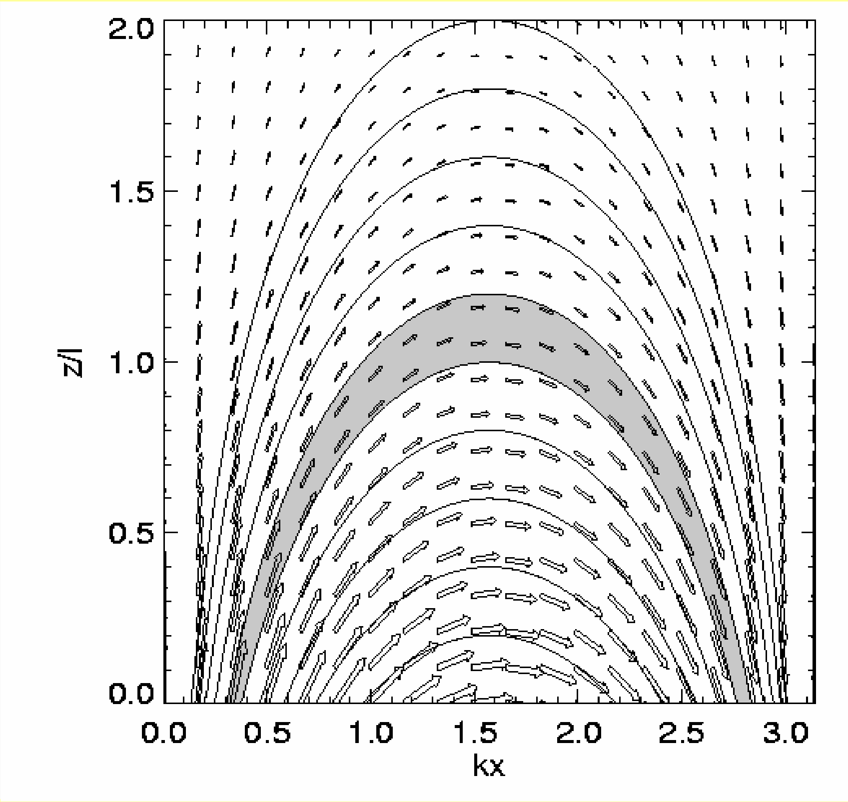


Aschwanden, 2004

$B = \text{grad}\ \varphi$

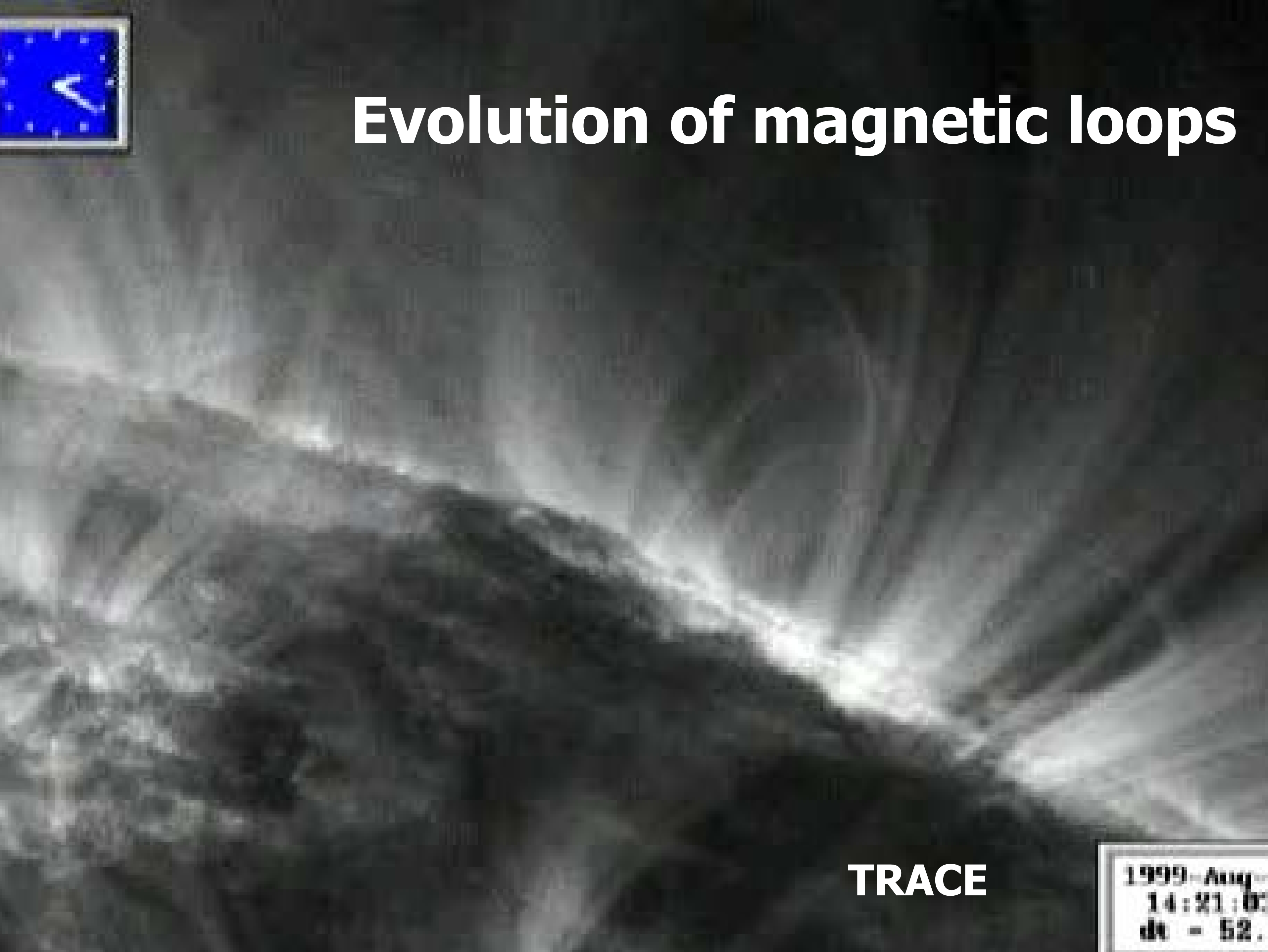
Sheared (force-free) arcade

$$\Delta \mathbf{B} + \alpha^2 \mathbf{B} = 0 \quad (\tan\theta = \alpha / l)$$

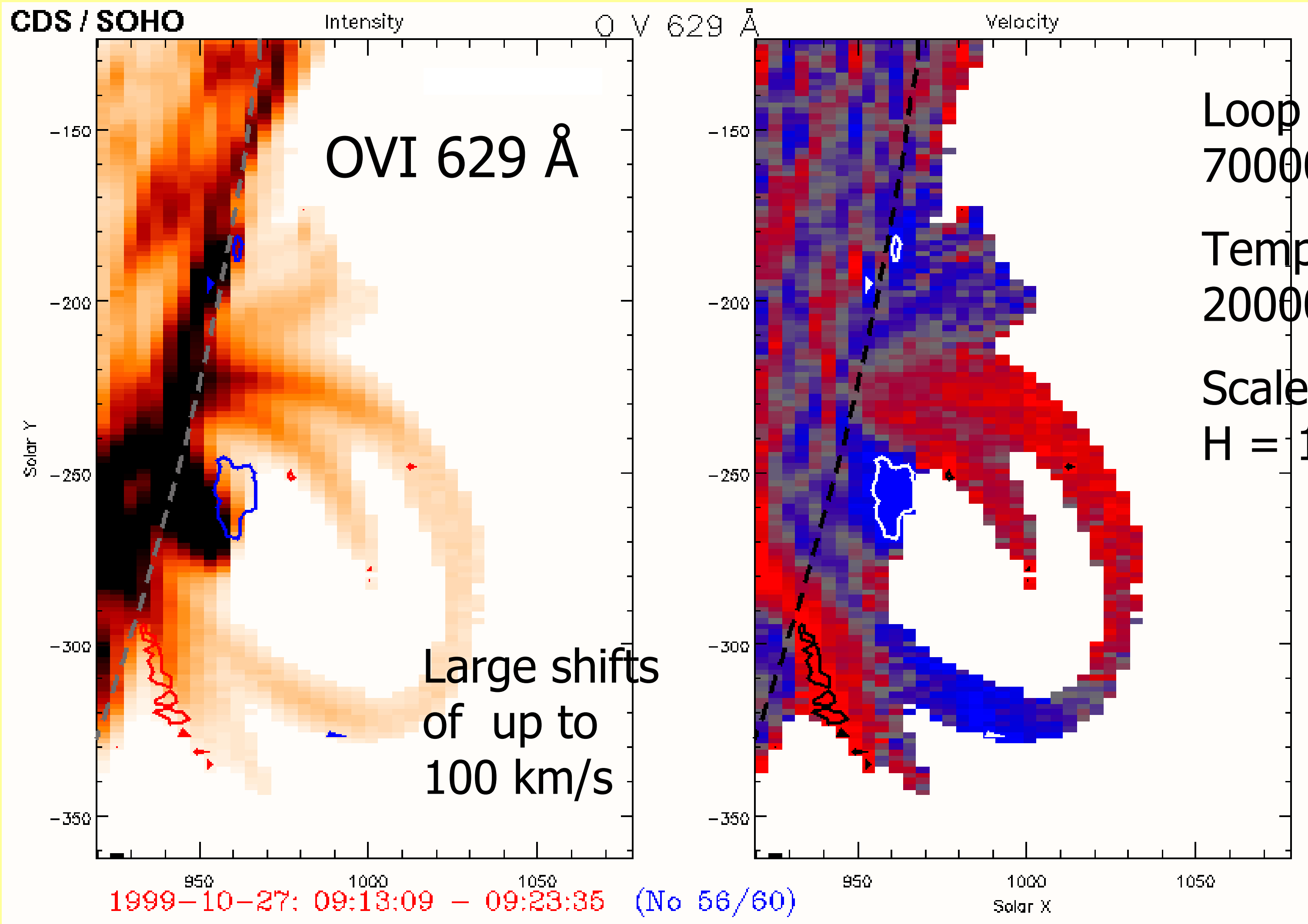


$B_x = B_{x0} \sin(kx) \exp(-lz)$

Evolution of magnetic loops



Cool loop in transition region



OVI 629 Å

Large shifts of up to 100 km/s

Loop height: 70000 km

Temperature: 200000 K

Scale height: H = 10000 km

CDS/SOHO web page

How can cool material reach this height?

Doppler spectroscopy

- **Line shift** by Doppler effect (bulk motion)

$$v_i = c(\lambda-\lambda_0)/\lambda_0 = c\Delta\lambda_D/\lambda \quad (+, \text{red shift}, - \text{blue})$$

v_i line of sight velocity of atom or ion; c speed of light in vacuo

λ_0 nominal (rest) wave length; λ observed wave length

$\varepsilon = h\nu = hc/\lambda = 12345$ eV/λ[Å] ; 1 eV = 11604 K

- **Line broadening** (thermal and/or turbulent motions)

$$T_{eff} = T_i + m_i\xi^2/(2k_B) = m_i c^2\{(\Delta\lambda_D)^2 - (\Delta\lambda_I)^2\}/(2k_B\lambda^2)$$

$\Delta\lambda_D$ ($\Delta\lambda_I$) Doppler (instrumental) width of spectral line; T_i ion temperature

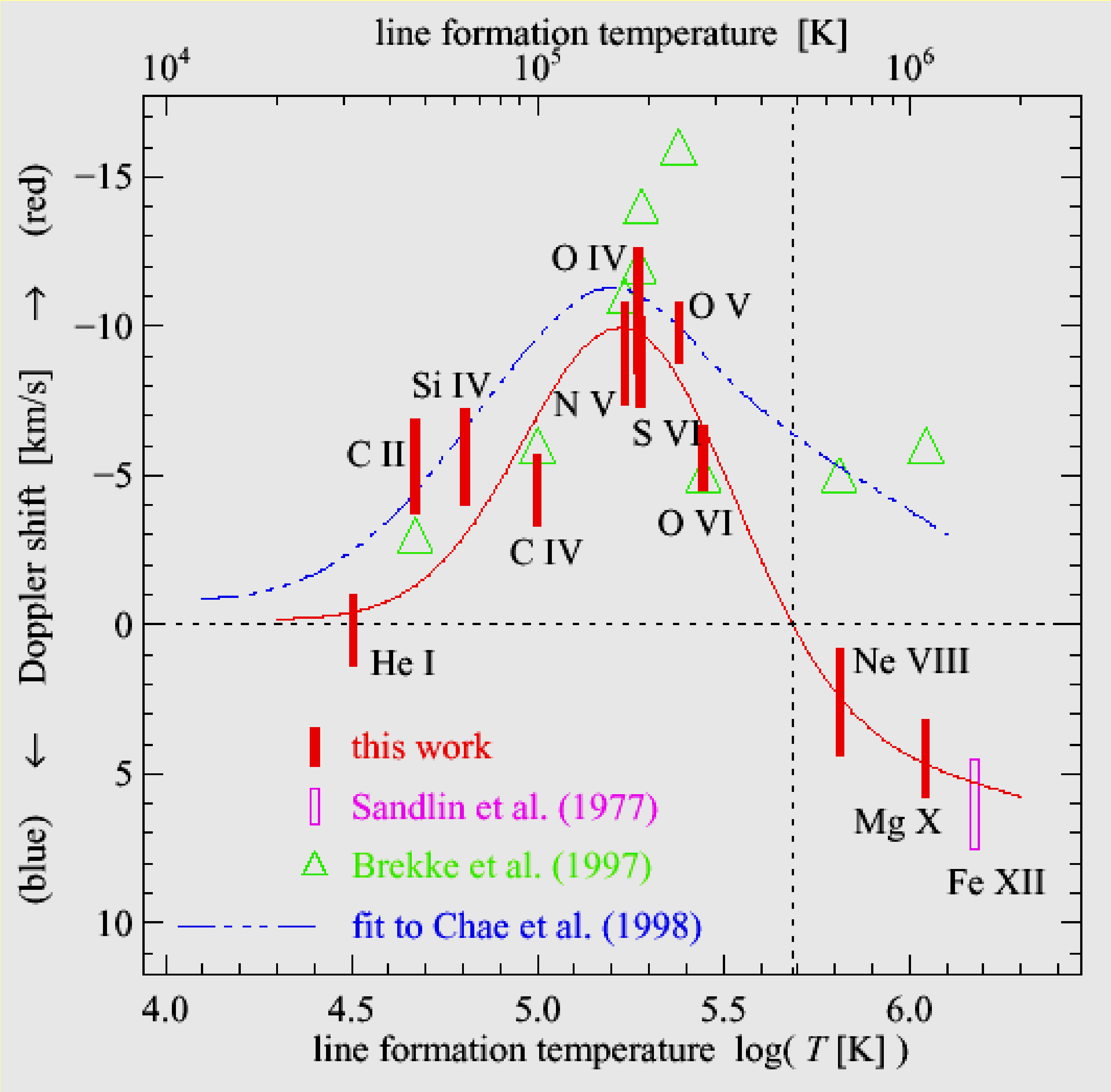
ξ amplitude of unresolved waves/turbulence; m_i ion mass

For optically thin emission and Gaussian line profile; $\Delta\lambda_I \approx$ 6 pm for SUMER

Doppler shift versus temperature

Dopplershifts (SUMER) in the transition region (TR) of the „quiet" sun

- Blueshifts in lower corona (MgX and NeVIII line), outflow
- Redshifts in upper TR, plasma confined



Peter & Judge, ApJ. **522,** 1148, 1999

Heavy ion heating by cyclotron resonance

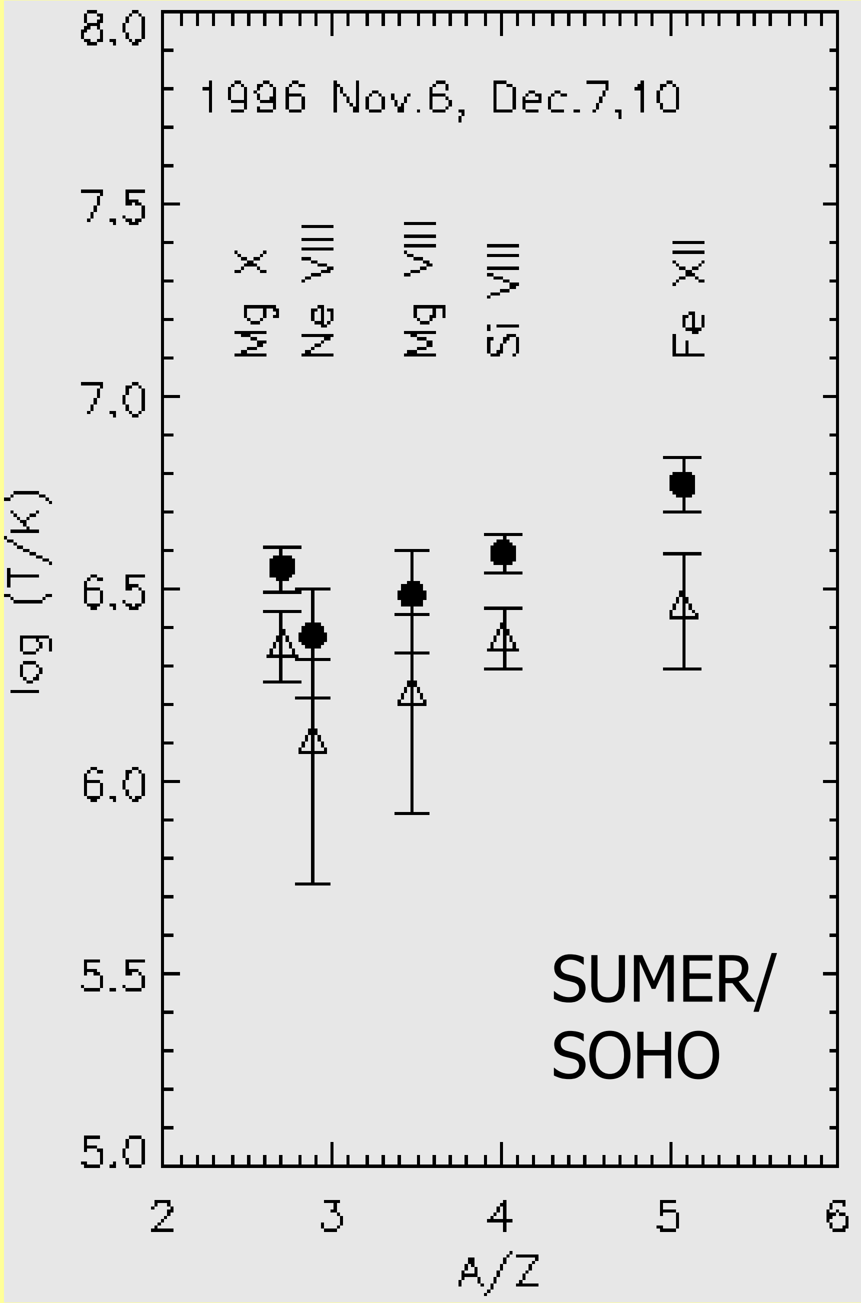
$\Omega \sim Z/A$

Heavy ion temperature

T=(2-6) MK

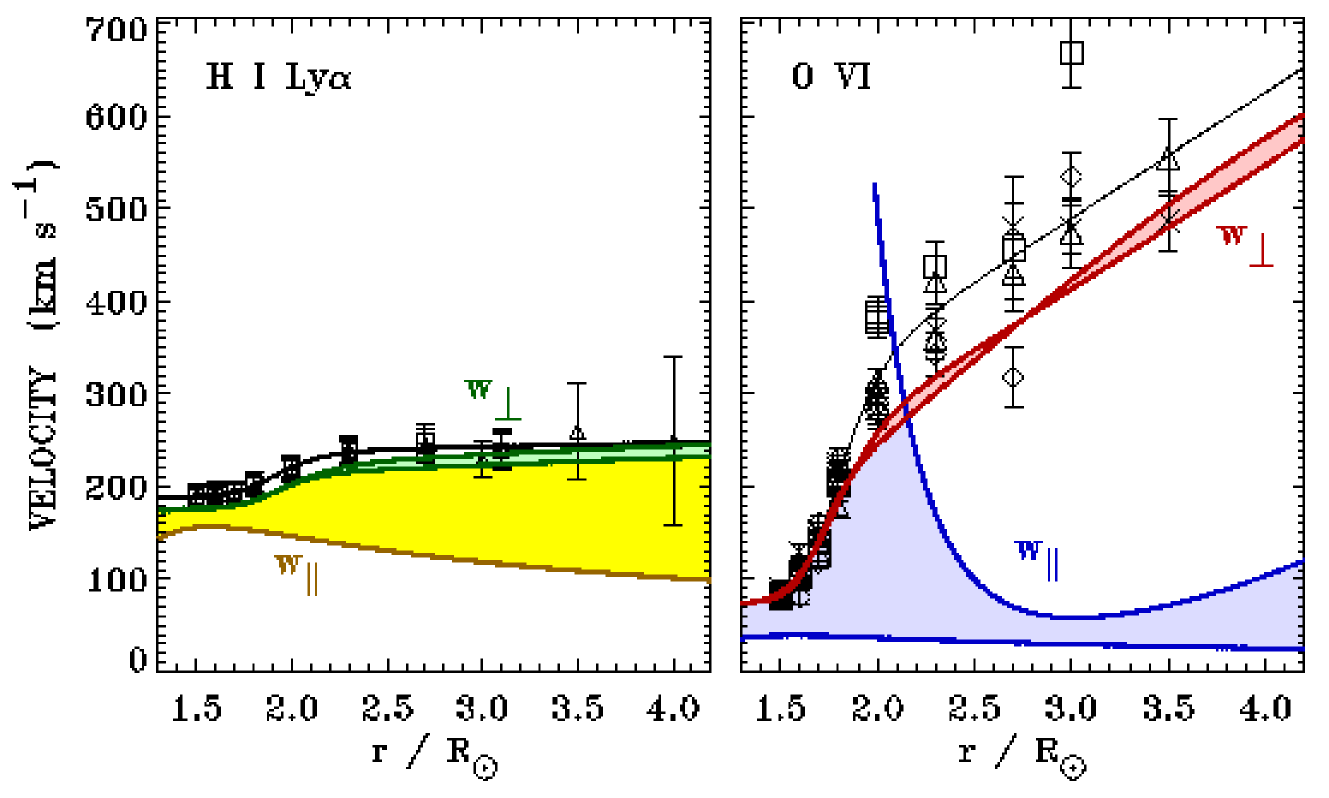
r = 1.15 R_S

- **Magnetic mirror in coronal funnel/hole**
- **Cyclotron resonance $\Rightarrow$ increase of μ**



Tu et al., Space Sci. Rev., **87**, 331, 1999

Oxygen and hydrogen thermal speeds in coronal holes

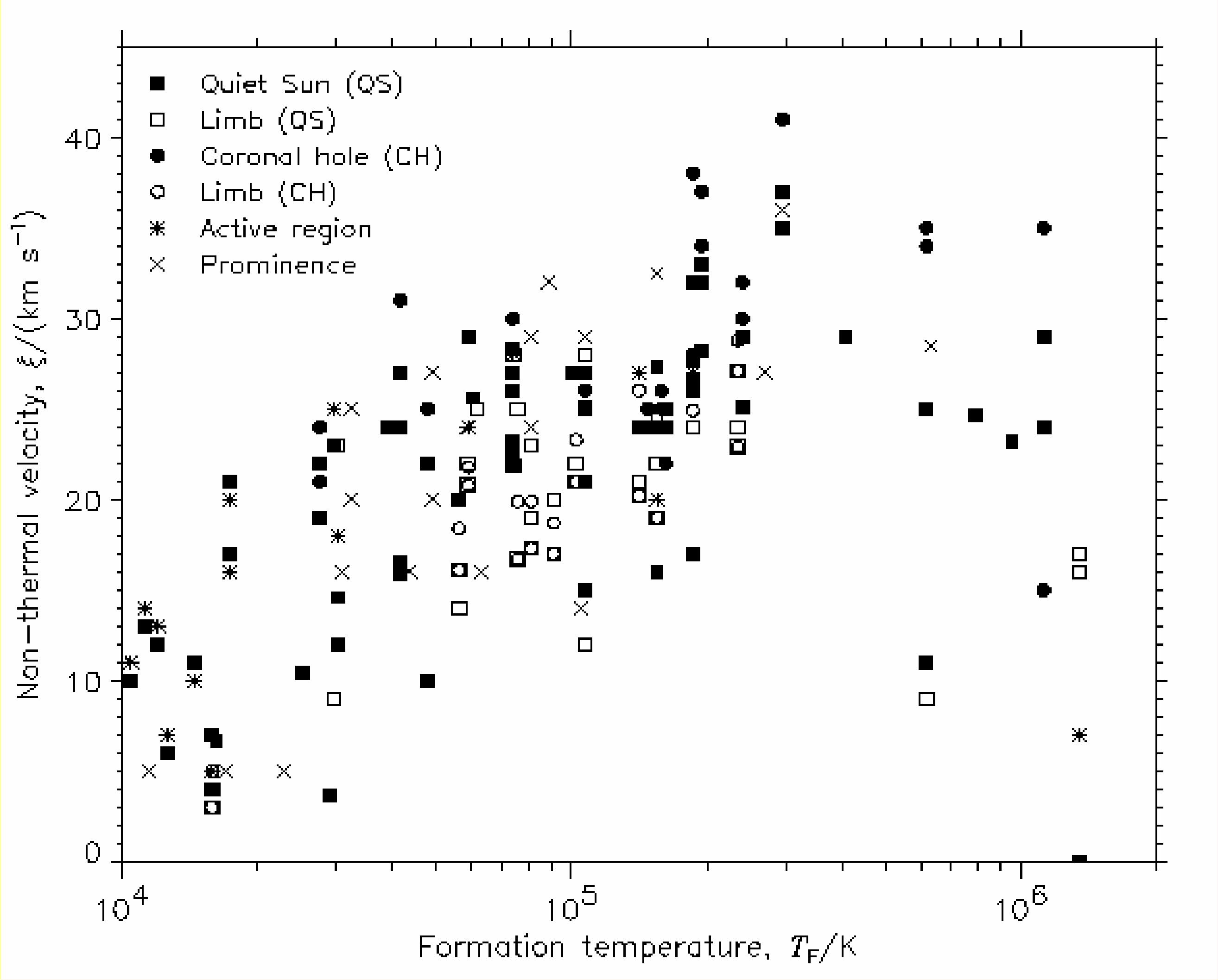


Very Strong perpendicular heating of Oxygen !

Cranmer et al., Ap. J., **511**, 481, 1998

Large anisotropy: $T_{O\perp}/T_{O||} \geq 10$

Coronal line broadenings



Limits on Alfvén wave amplitude

δv: 10 – 30 km/s

in solar transition region and corona

Wilhelm, Marsch, Dwivedi, Feldman, Space Sci. Rev., 2008

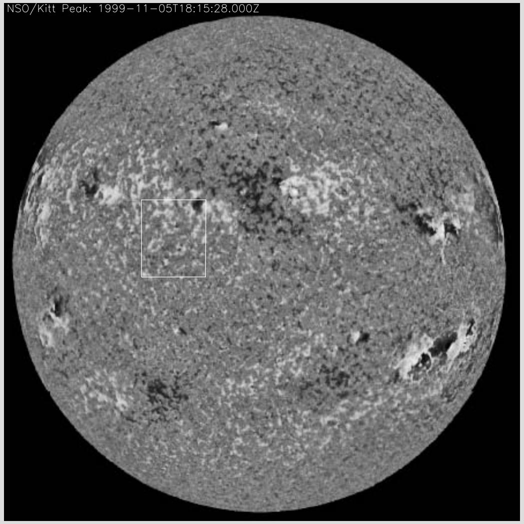
Force-free field extrapolation

$$\mathbf{j} = \alpha \mathbf{B}$$

$$B_x = \sum_{m,n=1}^{\infty} \frac{C_{mn}}{\lambda_{mn}} \exp\left(-r_{mn} z\right) \cdot \left[\alpha \frac{\pi n}{L_y} \sin\left(\frac{\pi m x}{L_x}\right) \cos\left(\frac{\pi n y}{L_y}\right) - -r_{mn} \frac{\pi m}{L_x} \cos\left(\frac{\pi m x}{L_x}\right) \sin\left(\frac{\pi n y}{L_y}\right)\right] \quad (1)$$

$$B_y = -\sum_{m,n=1}^{\infty} \frac{C_{mn}}{\lambda_{mn}} \exp\left(-r_{mn} z\right) \cdot \left[\alpha \frac{\pi m}{L_x} \cos\left(\frac{\pi m x}{L_x}\right) \sin\left(\frac{\pi n y}{L_y}\right) + +r_{mn} \frac{\pi n}{L_y} \sin\left(\frac{\pi m x}{L_x}\right) \cos\left(\frac{\pi n y}{L_y}\right)\right] \quad (2)$$

$$B_z = \sum_{m,n=1}^{\infty} C_{mn} \exp\left(-r_{mn} z\right) \cdot \sin\left(\frac{\pi m x}{L_x}\right) \sin\left(\frac{\pi n y}{L_y}\right) \quad (3)$$



$$r_{mn} = \sqrt{\lambda_{mn} - \alpha^2}.$$

$$\lambda_{mn} = \pi^2 (m^2 / L_x^2 + n^2 / L_y^2)$$

$$2/L^2 = (1/L_x^2 + 1/L_y^2)$$

definitions

symmetry

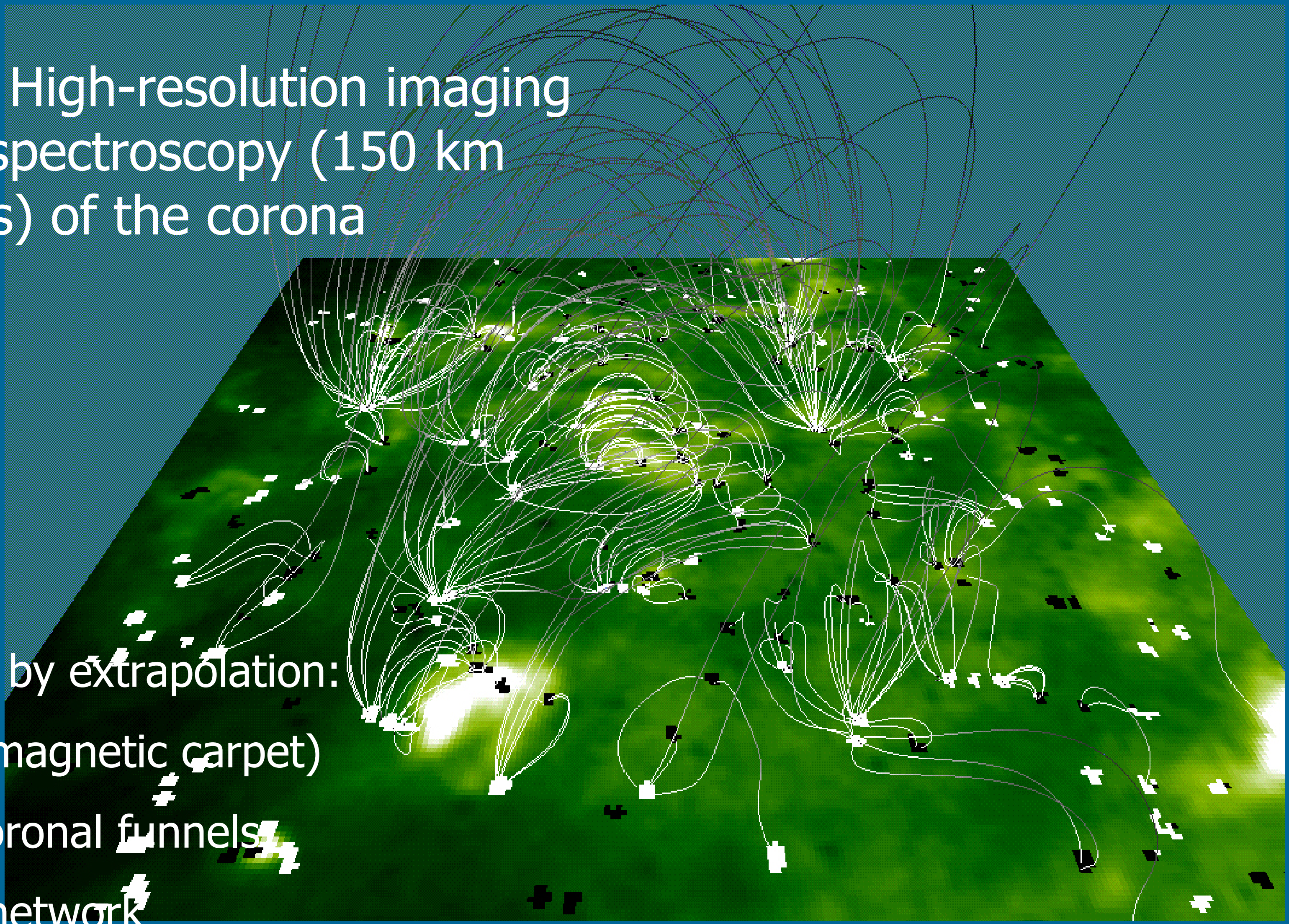
$$B_z(-x, y) = -B_z(x, y)$$

$$B_z(x, -y) = -B_z(x, y)$$

Seehafer, Solar Physics **58**, 215, 1978

The elusive coronal magnetic field

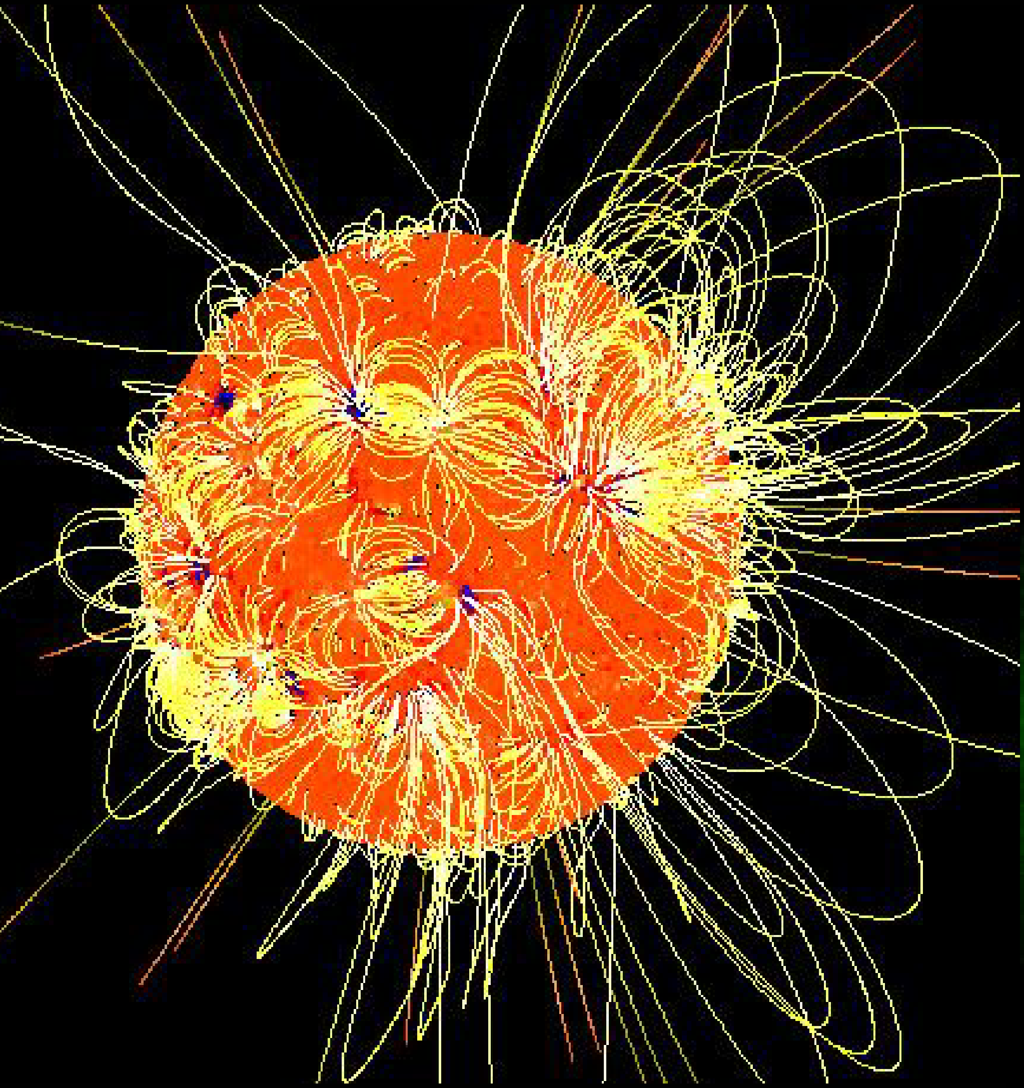
Future: High-resolution imaging and spectroscopy (150 km pixels) of the corona



Modelling by extrapolation:

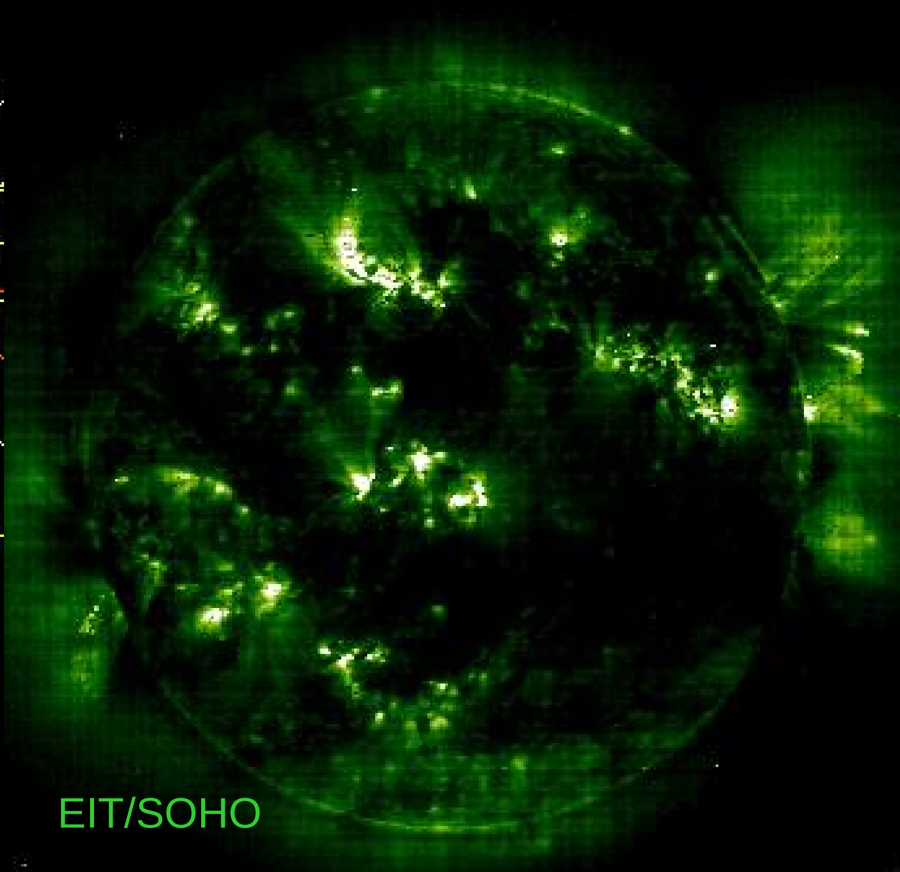
- Loops (magnetic carpet)
- Open coronal funnels
- Closed network

Coronal magnetic field extrapolation

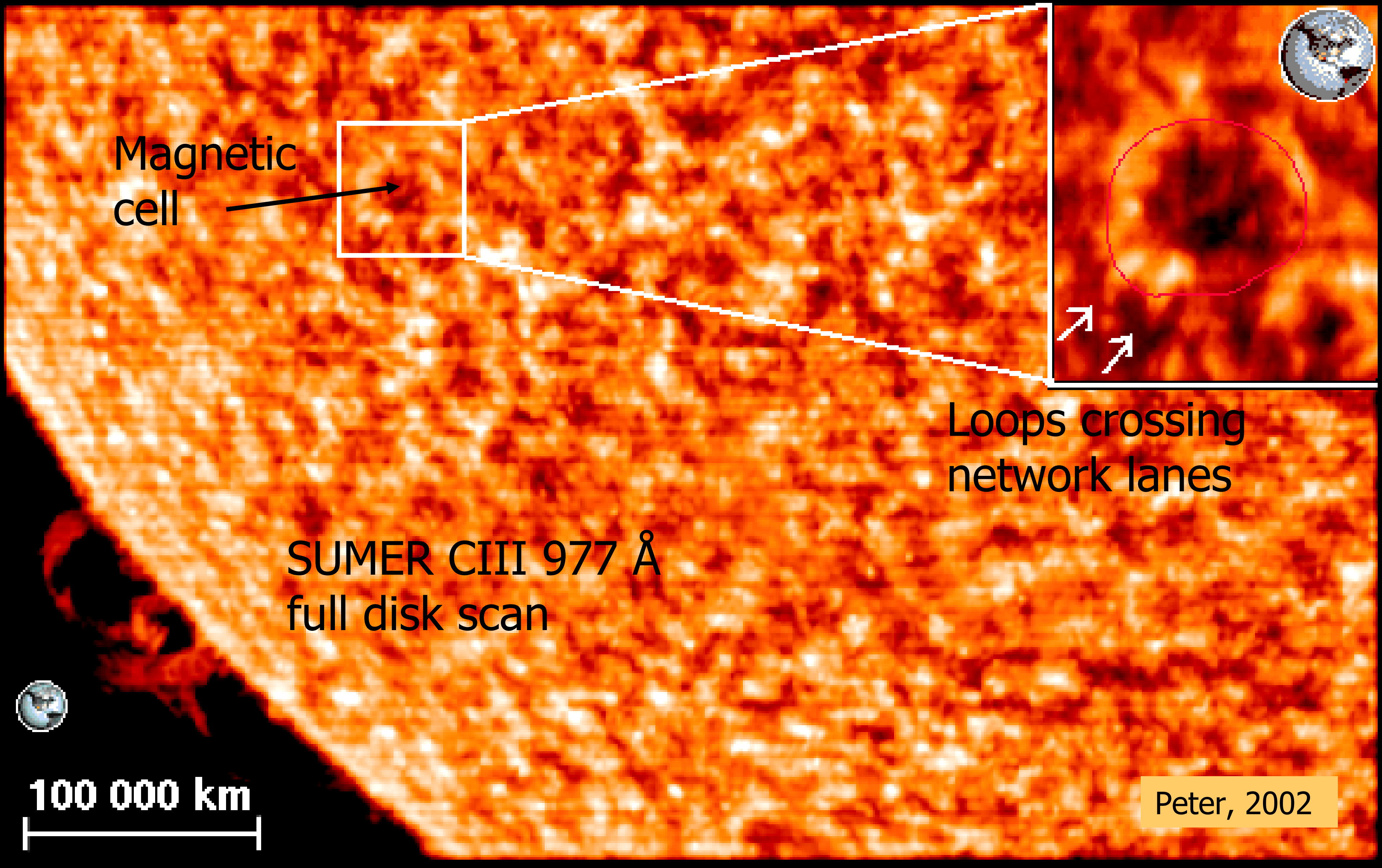


Wiegelmann and Solanki, 2005

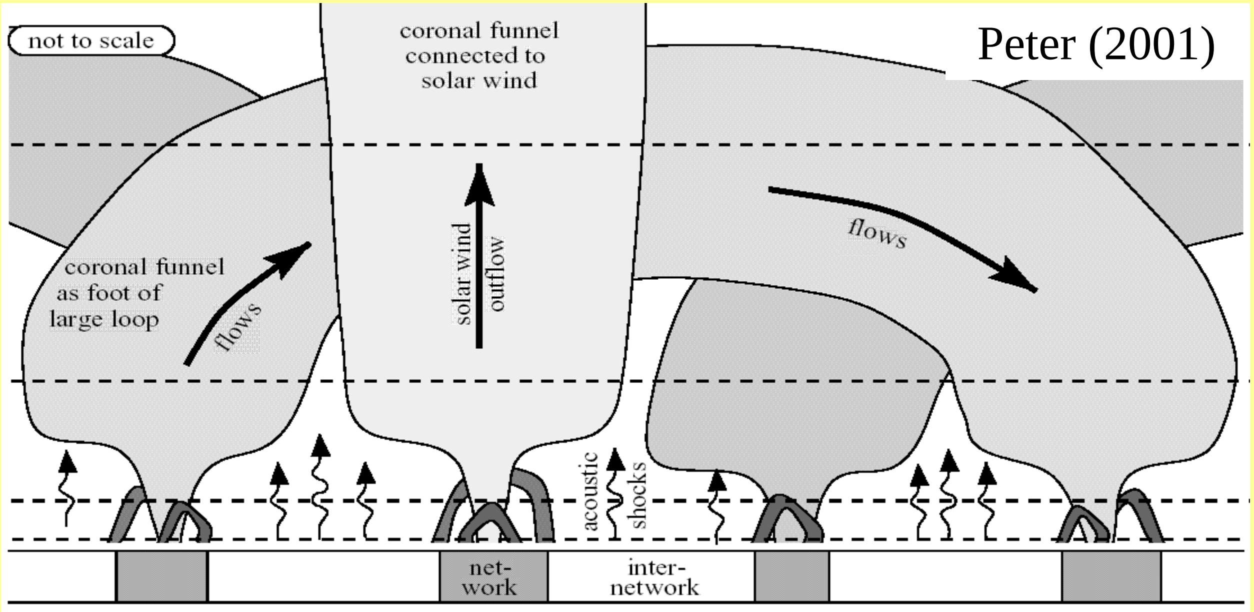
Active regions mainly consist of closed magnetic loops, in which plasma is confined and causes bright emission. The large-scale magnetic field is open in coronal holes, from which plasma escapes on open field lines as solar wind, and where the line emission is strongly reduced.



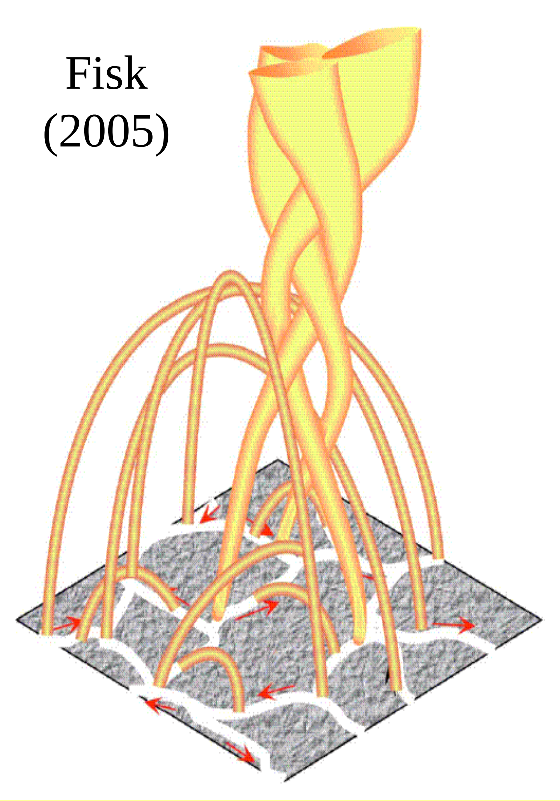
Magnetic network with loops



Funnel-type field expansion

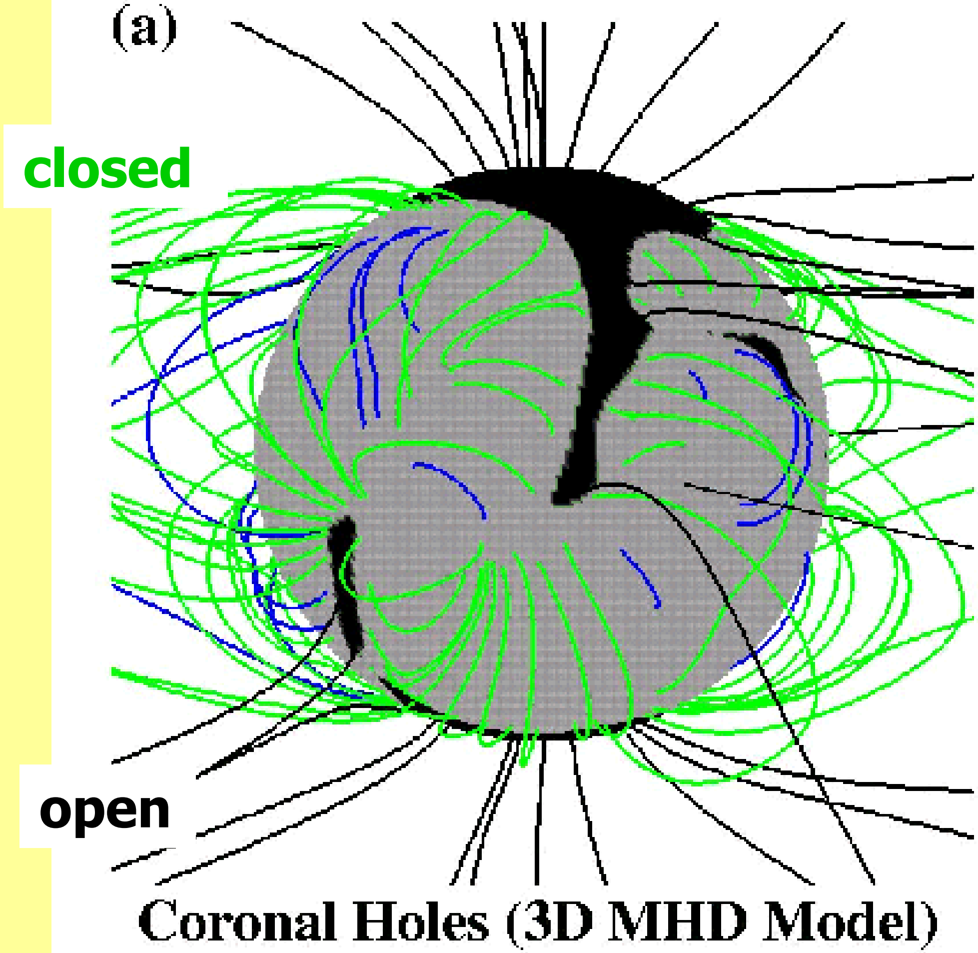


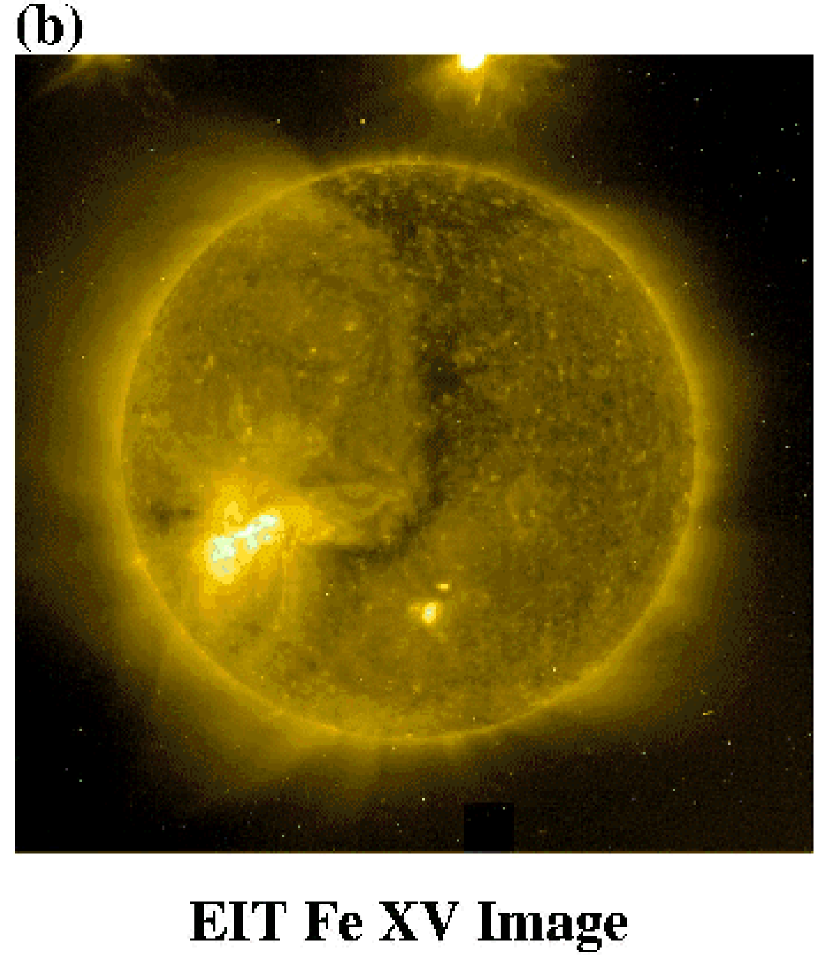
Παντα ρει !



- Empirical models of the open field from the "magnetic carpet" demand **superradial expansion** in low corona.
- UV Doppler blue-shifts are consistent with funnel flows (Byhring et al. 2008; Tu et al. 2005; Marsch et al. 2008).

MHD model of coronal magnetic field

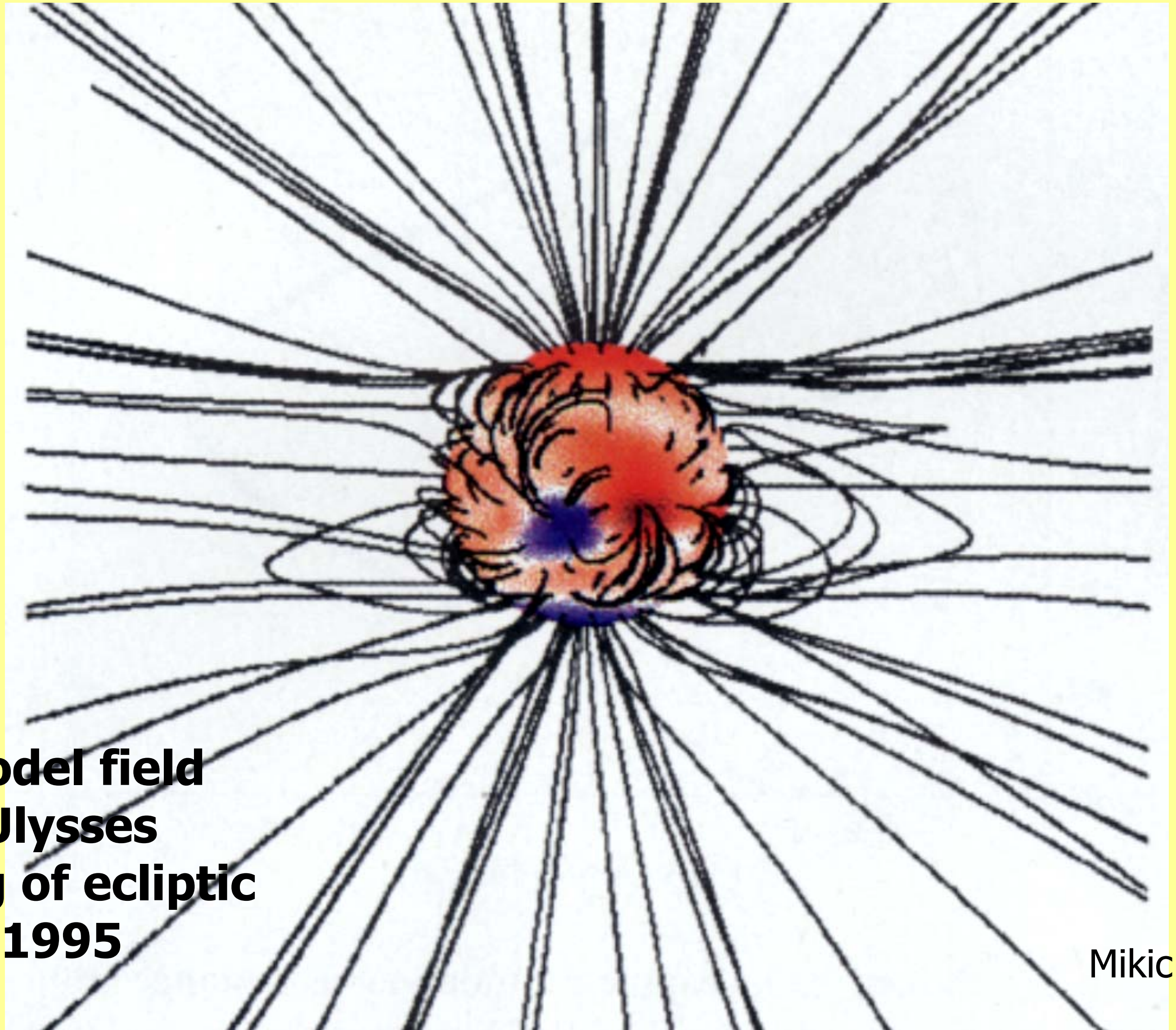




Linker et al., JGR, **104**, 9809, 1999

„Elephants trunk“ coronal hole

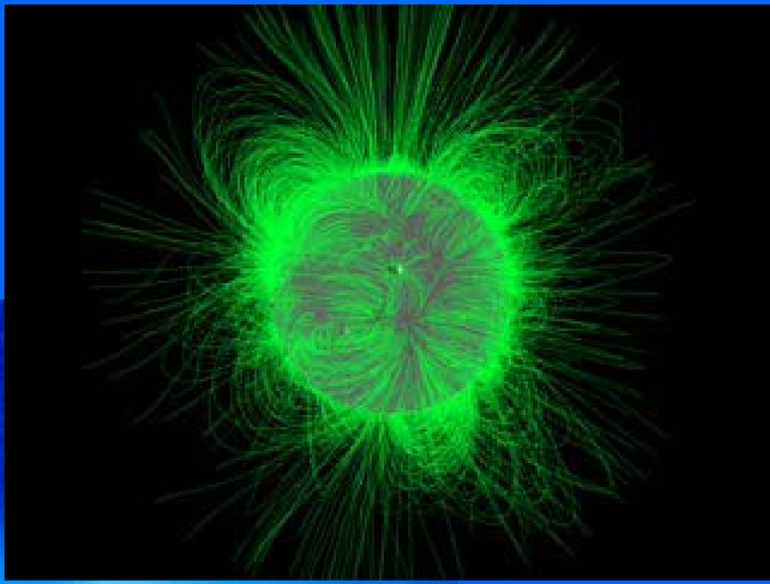
The Sun` open magnetic field evolves into the heliospheric field

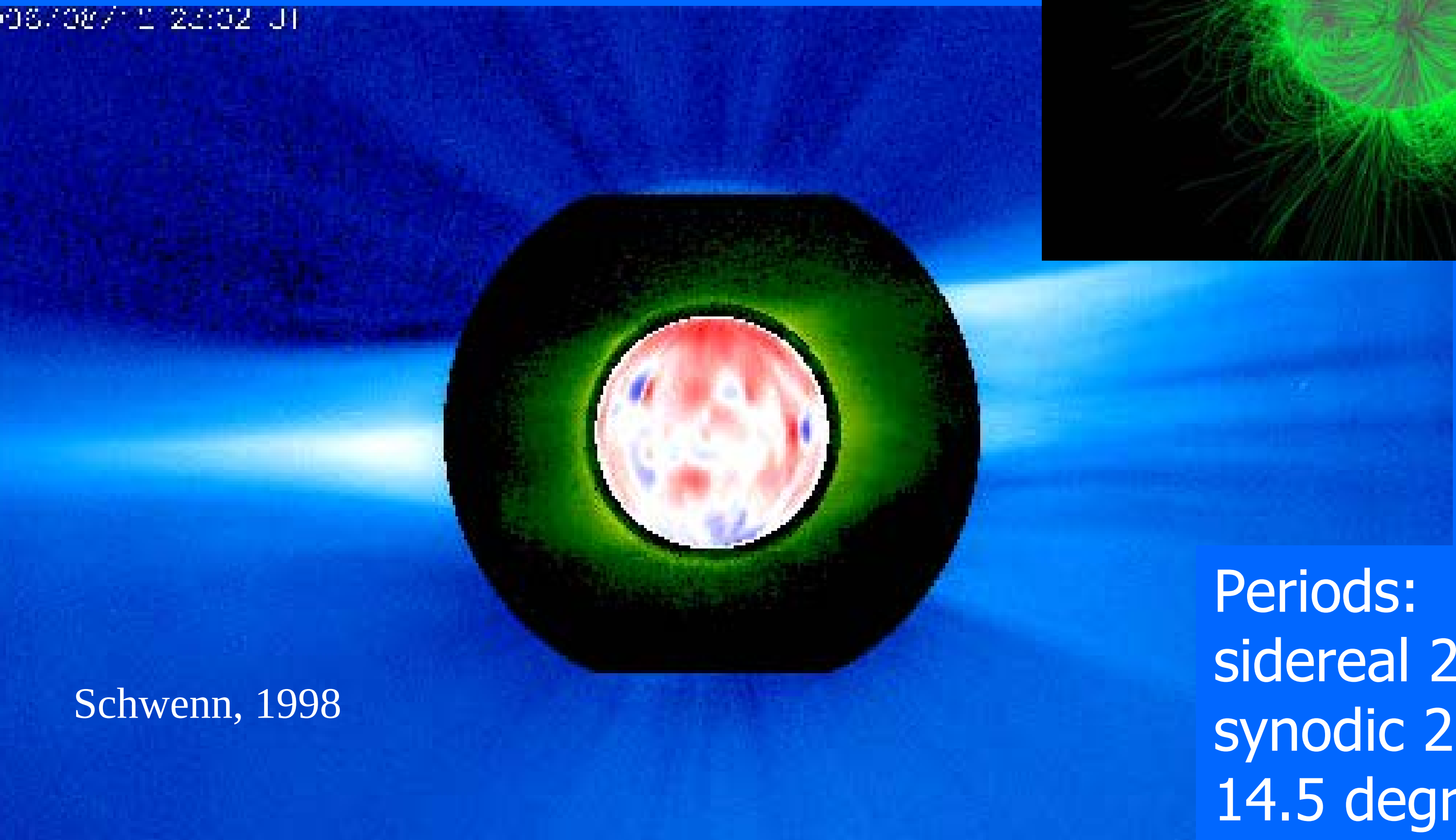


MHD model field during Ulysses crossing of ecliptic in early 1995

Mikic & Linker, 1999

Rigid rotation of corona with Sun

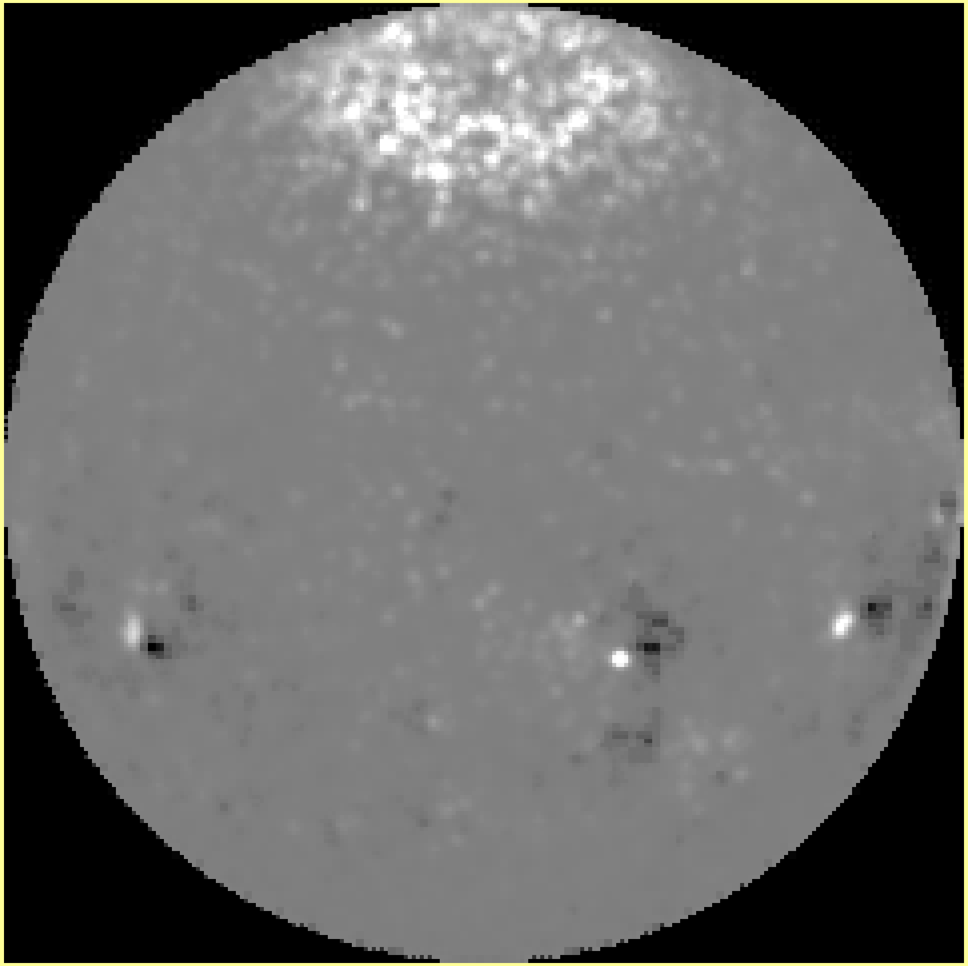




Schwenn, 1998

Periods:
sidereal 25.4 days
synodic 27.3 days
14.5 degrees/day

Measuring the polar magnetic field



View of the sun from 30° northern latitude

Solar Orbiter will allow us to study the:

- **magnetic structure and evolution of the polar regions,**
- **detailed flow patterns in the polar regions,**
- **development of magnetic structures, using local-area helioseismology at high latitudes.**

Model magnetogram of the simulated solar cycle (courtesy Schrijver).

Summary

- The Sun's corona is highly structured and varies
- The magnetic field consists of loops and funnels
- EUV radiation of the corona is highly structured
- Doppler spectroscopy in EUV enables plasma diagnostics via line shifts, widths and radiances
- The magnetic network is very dynamic
- Small-scale motions and turbulence prevail
- Temperatures indicate strong minor ion heating