

COLLAGE 2019

Large-Scale Solar Magnetic Fields

Xudong Sun (UH/IfA)

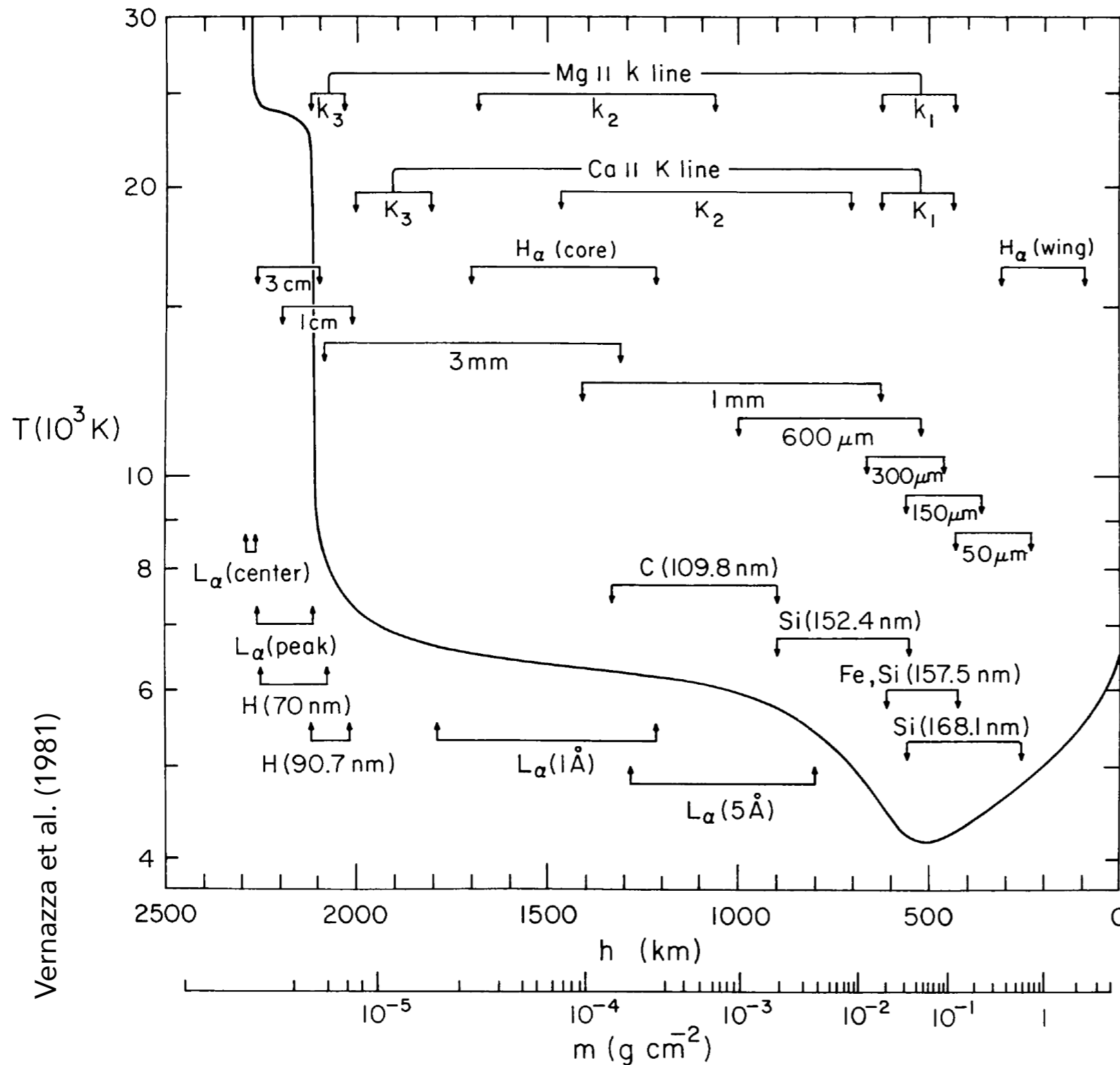
Apr 02 2019

Outline

- Solar features & magnetic origin
- Photospheric magnetic field maps
- Potential field model of quiescent corona

Solar Feature & Magnetic Origin

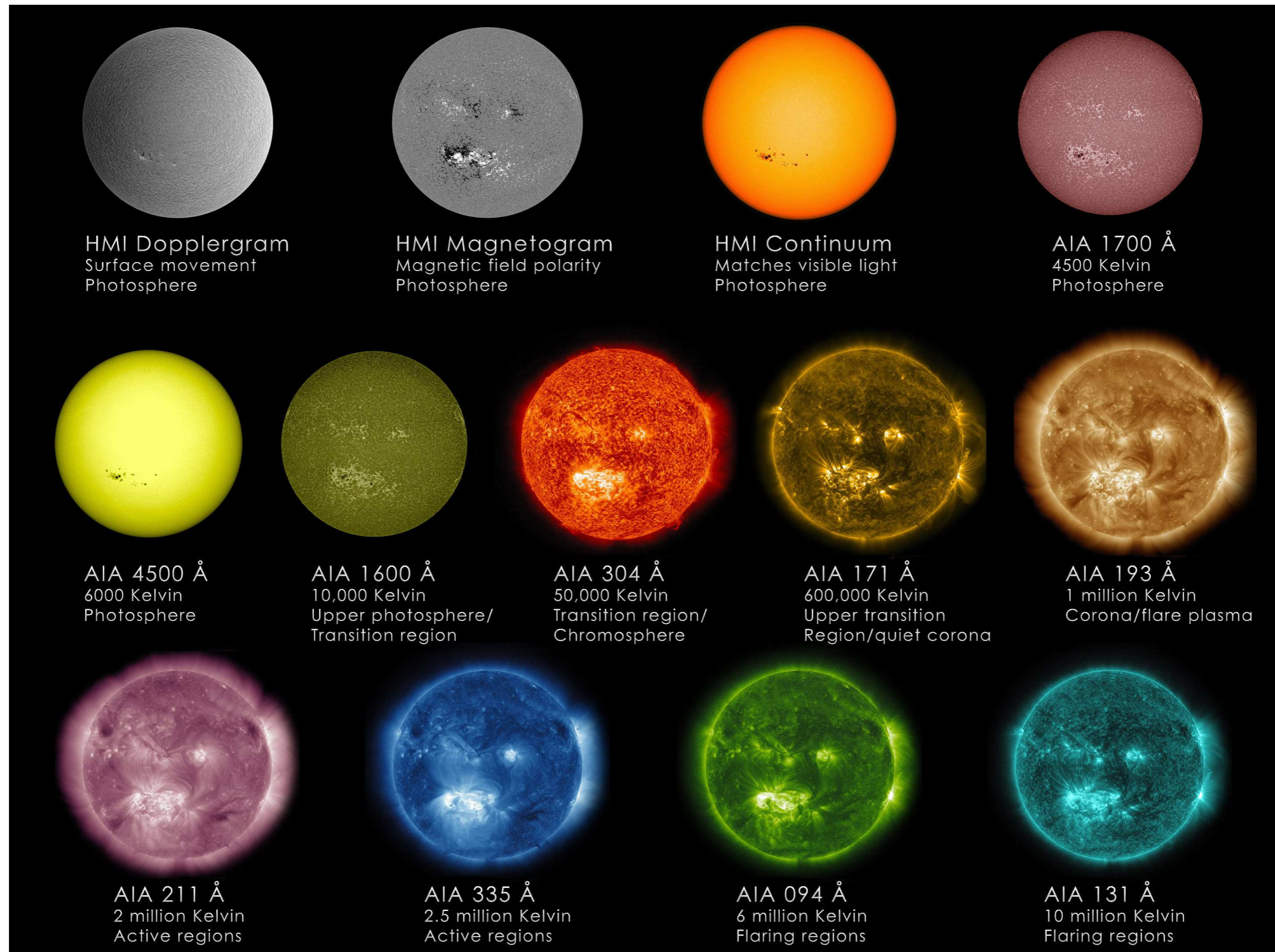
A Steep Stratification



Vernazza et al. (1981)

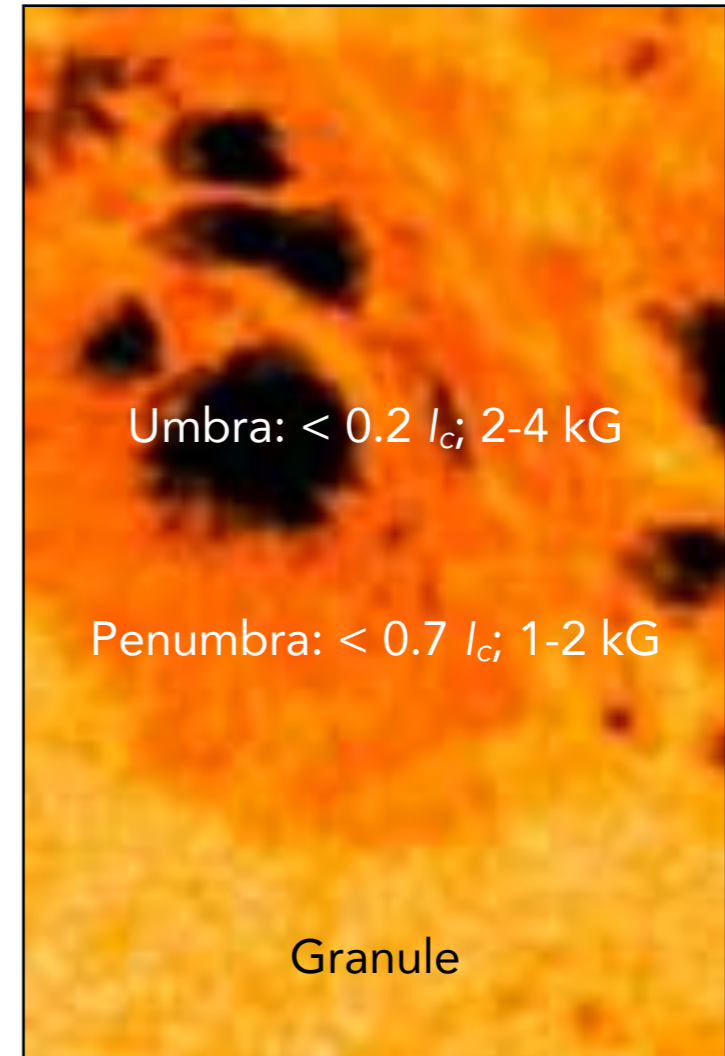
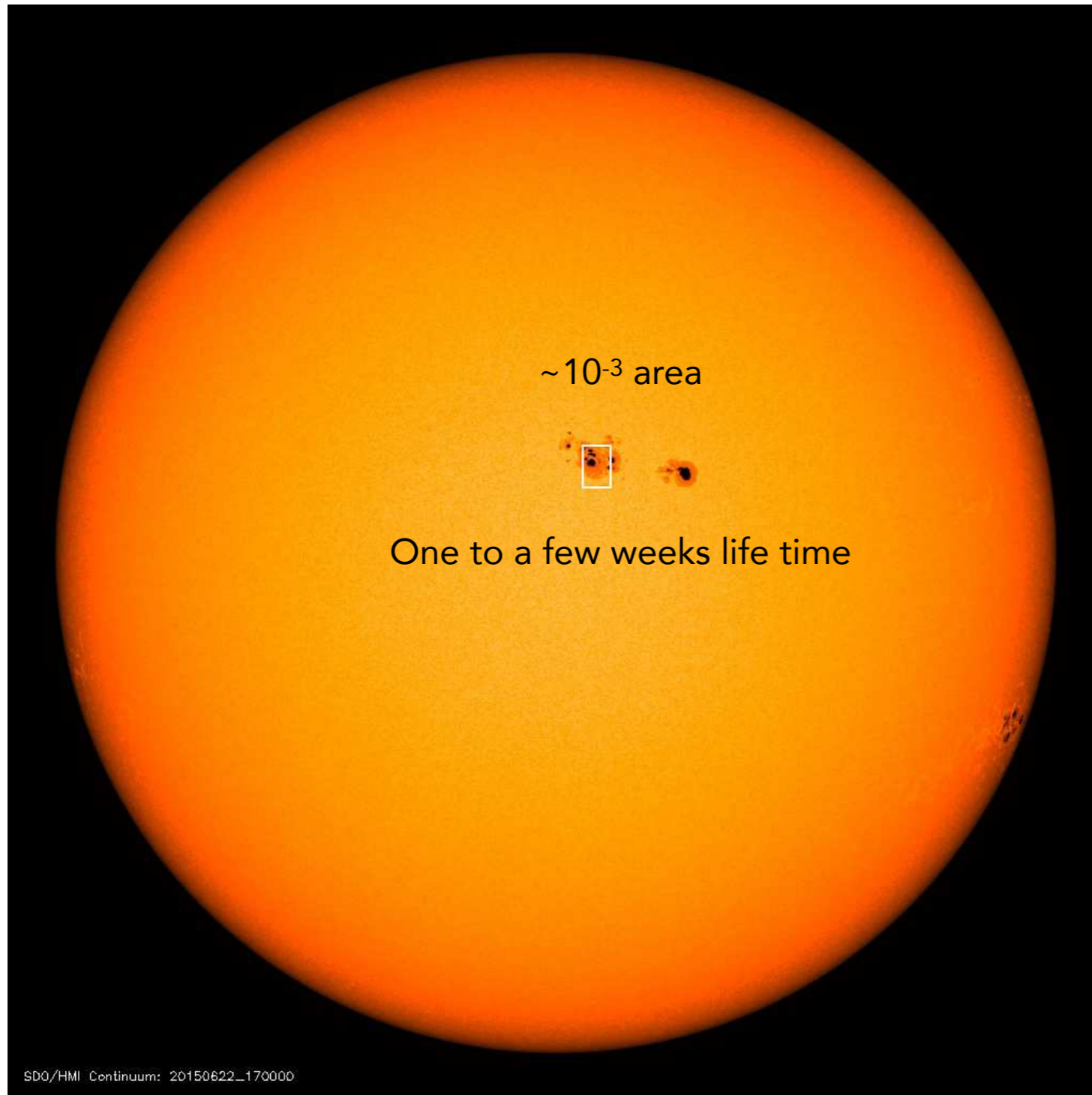
- Different spectral lines probe different “layers” of solar atmosphere
- Large contrast in spatial and temporal scales
- Rich information resides in spectro-polarization signals as well as emission morphology

The Multi-Wavelength Sun

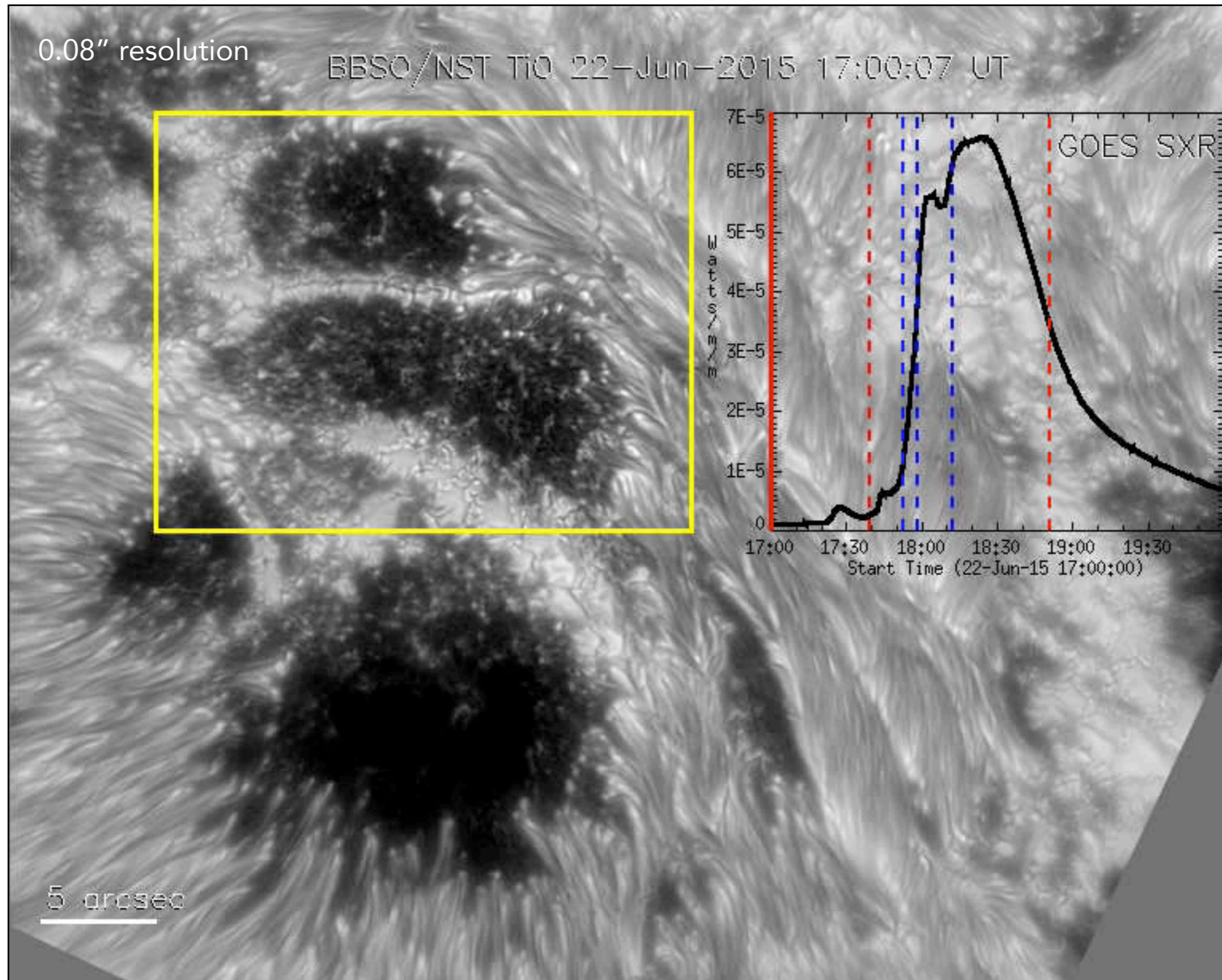


Photosphere: Full Disk View

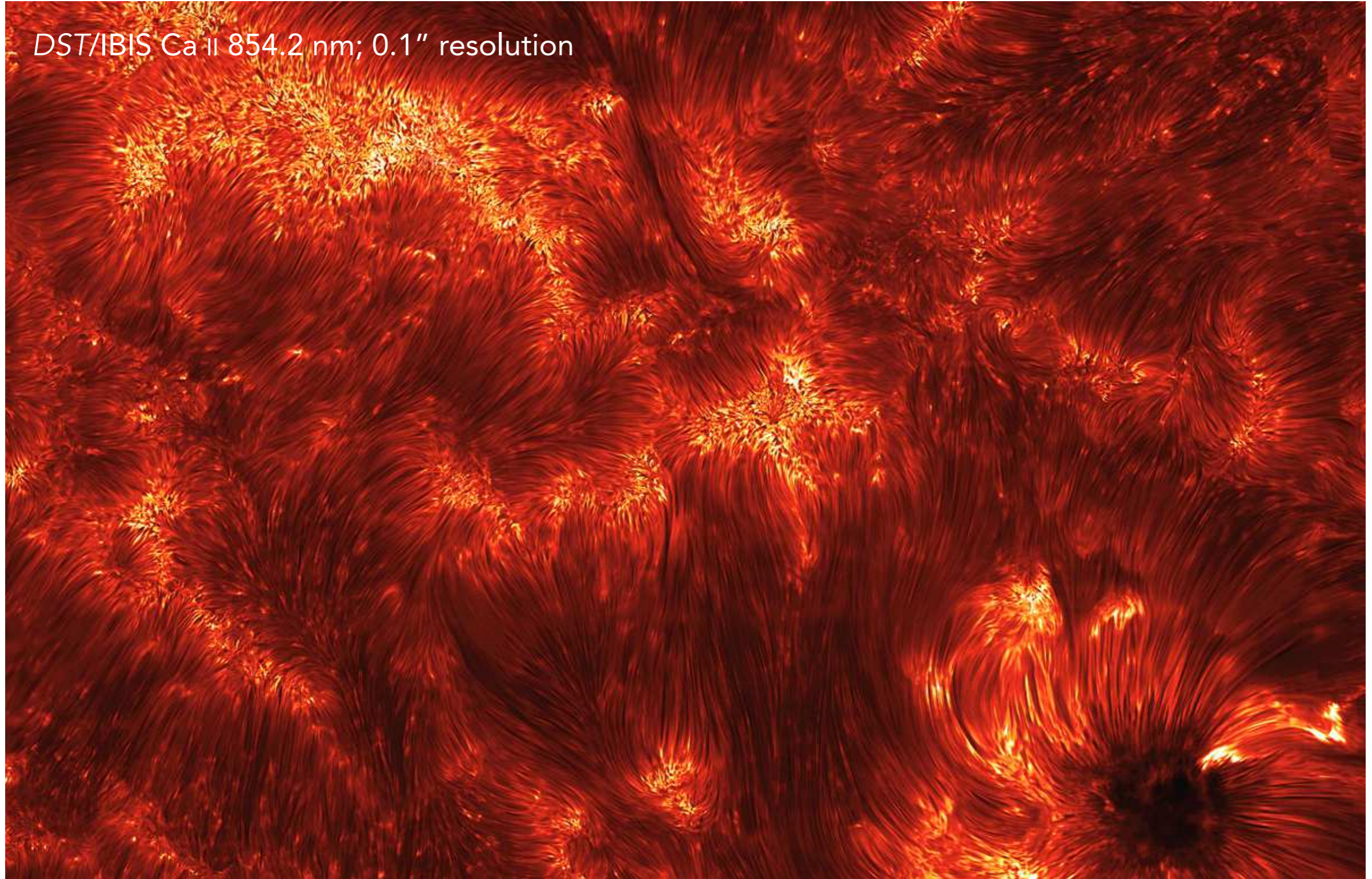
SDO/HMI Fe I 617.3 nm; 1" resolution



Photosphere: High Resolution

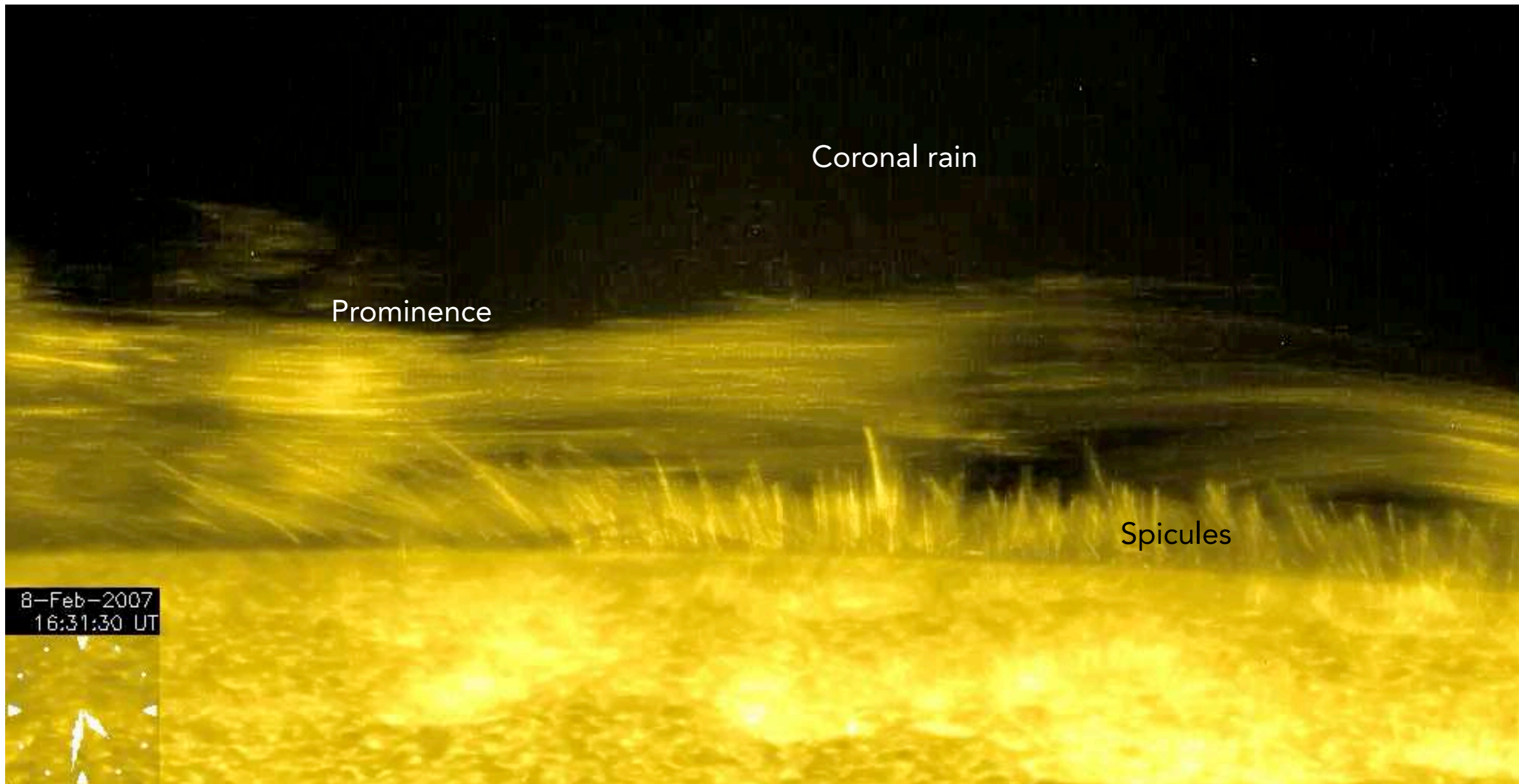


Chromosphere: On Disk

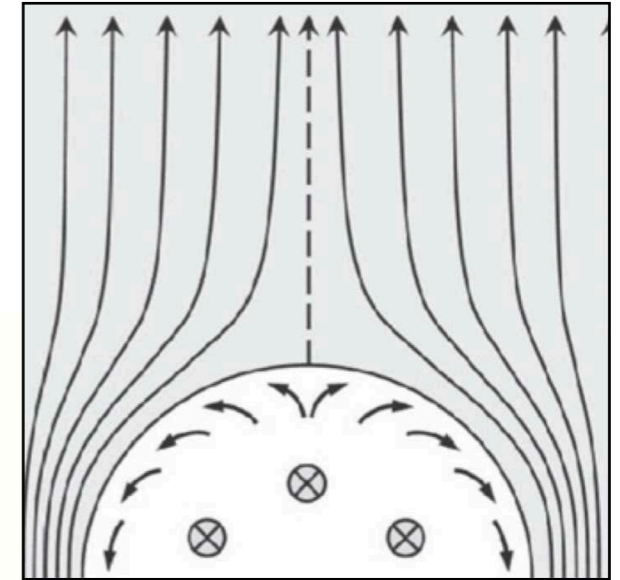
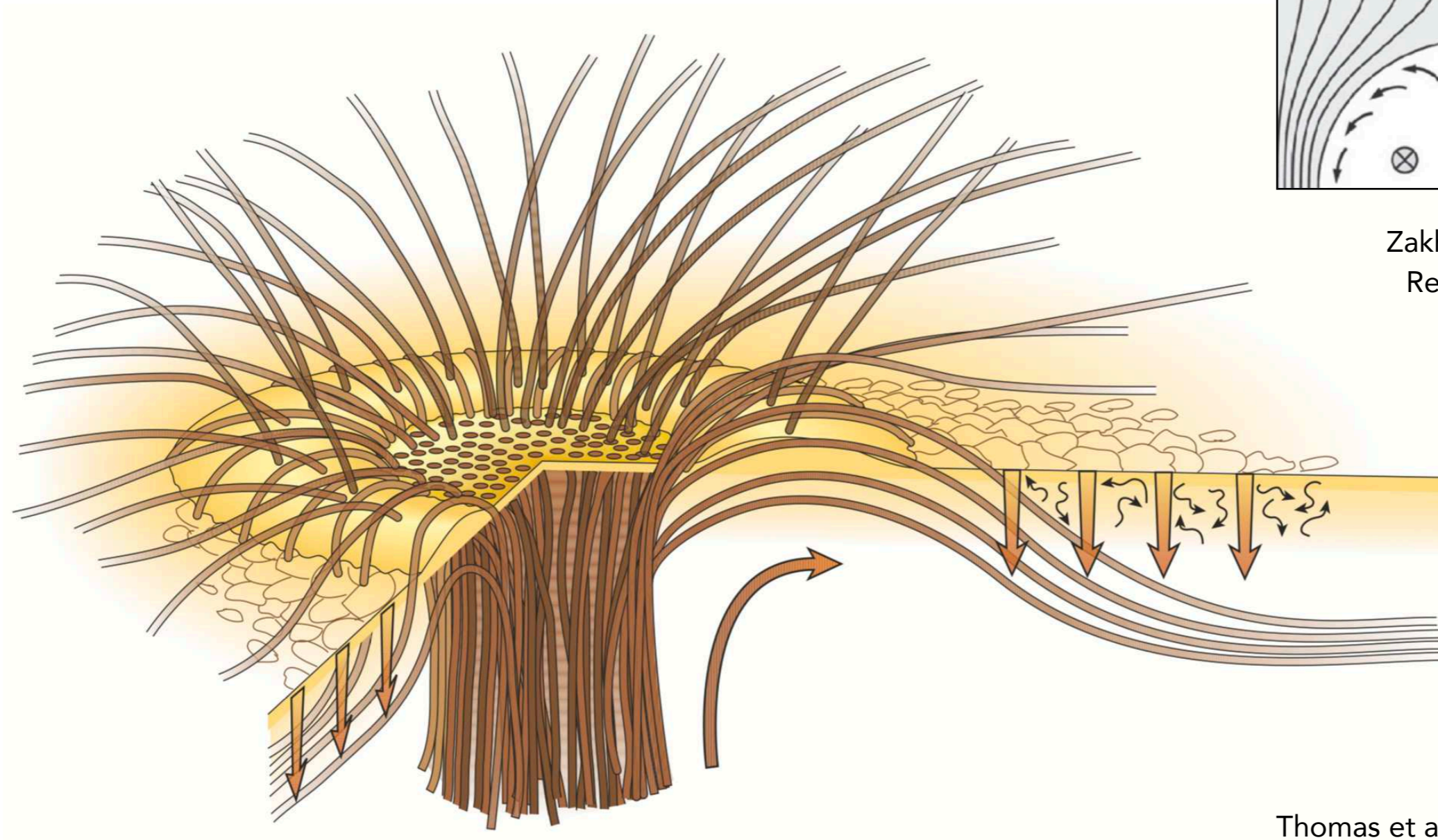


Chromosphere: Off Limb

Hinode/SOT Ca II H line 396.9 nm; 0.2" resolution



Magnetic Connectivity: Sunspot

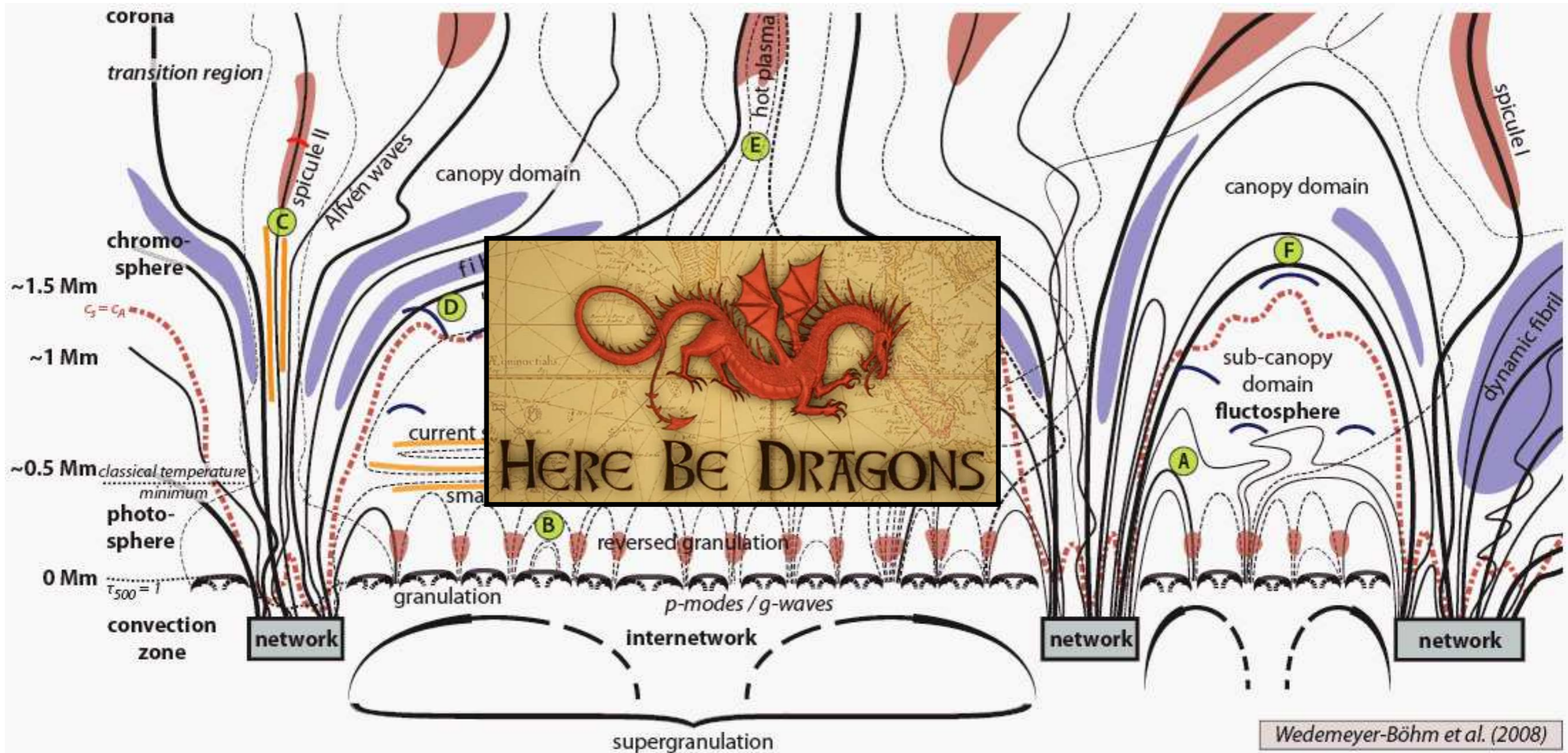


Zakharov et al. (2008)
Rempel et al. (2009)

Thomas et al. (2002)

Magnetic Connectivity: Quiet Sun

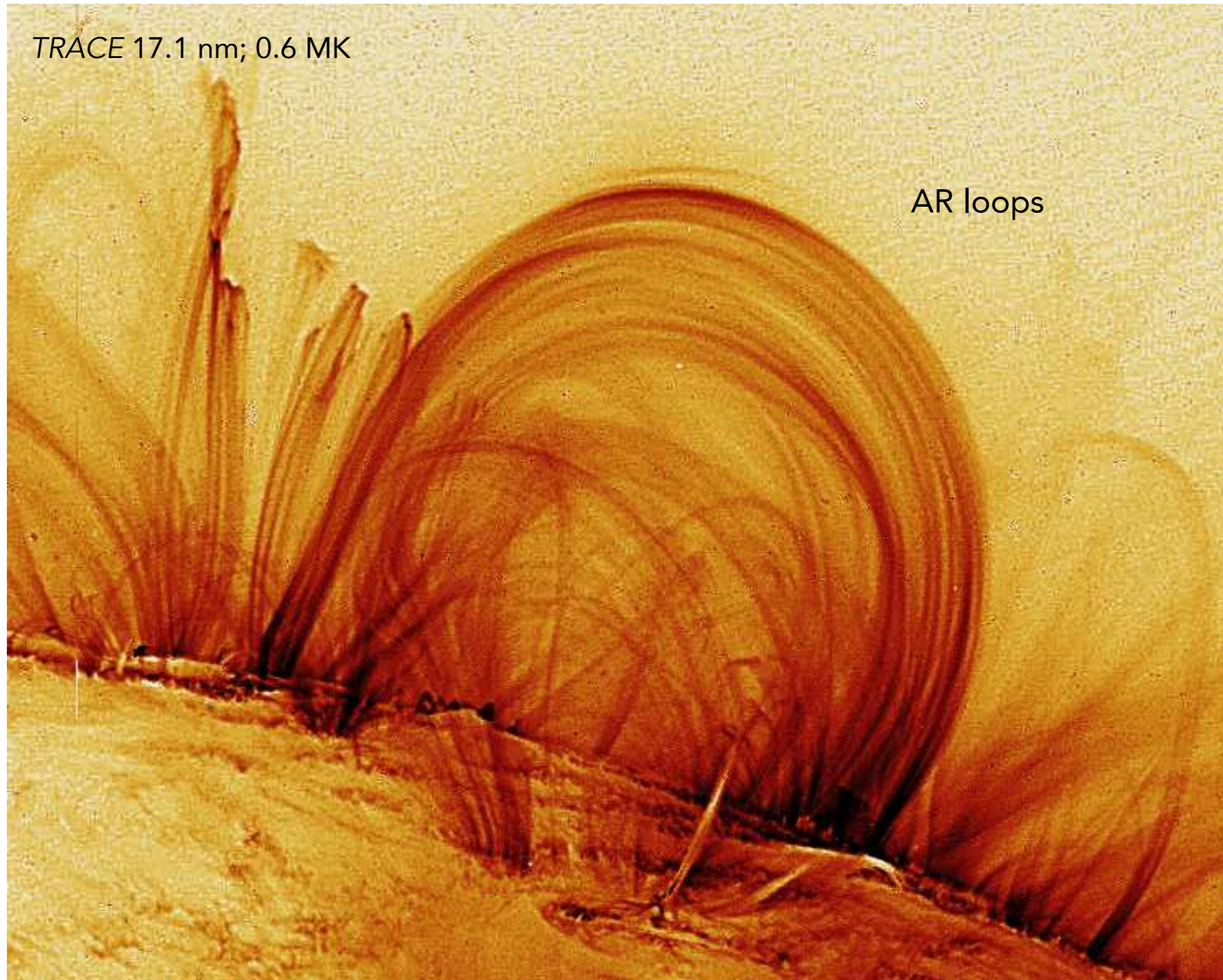
Wedemeyer-Böhm et al. (2008)



When drawn to scale



Corona: Active Region Loop



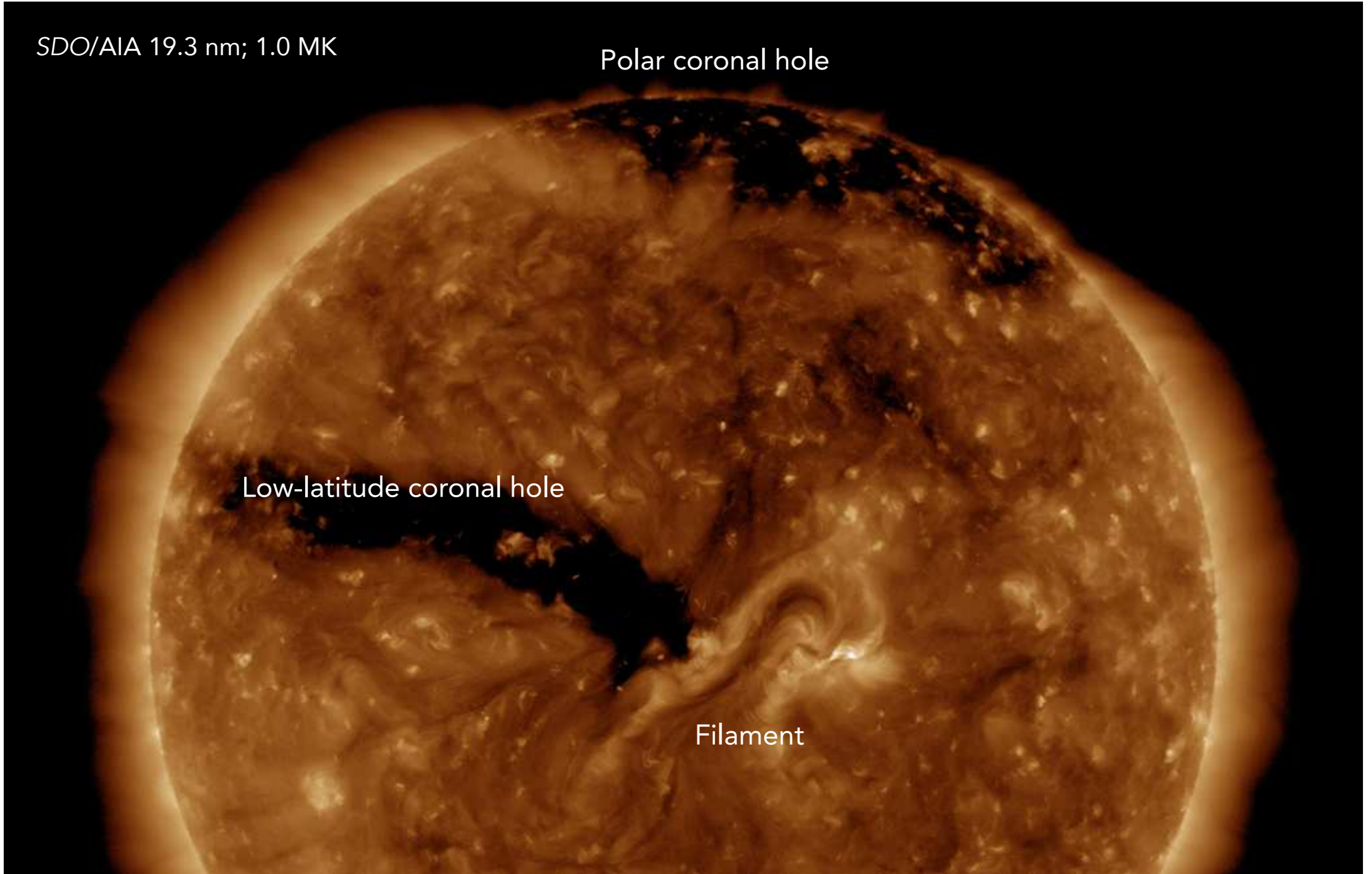
Corona: Coronal Hole

SDO/AIA 19.3 nm; 1.0 MK

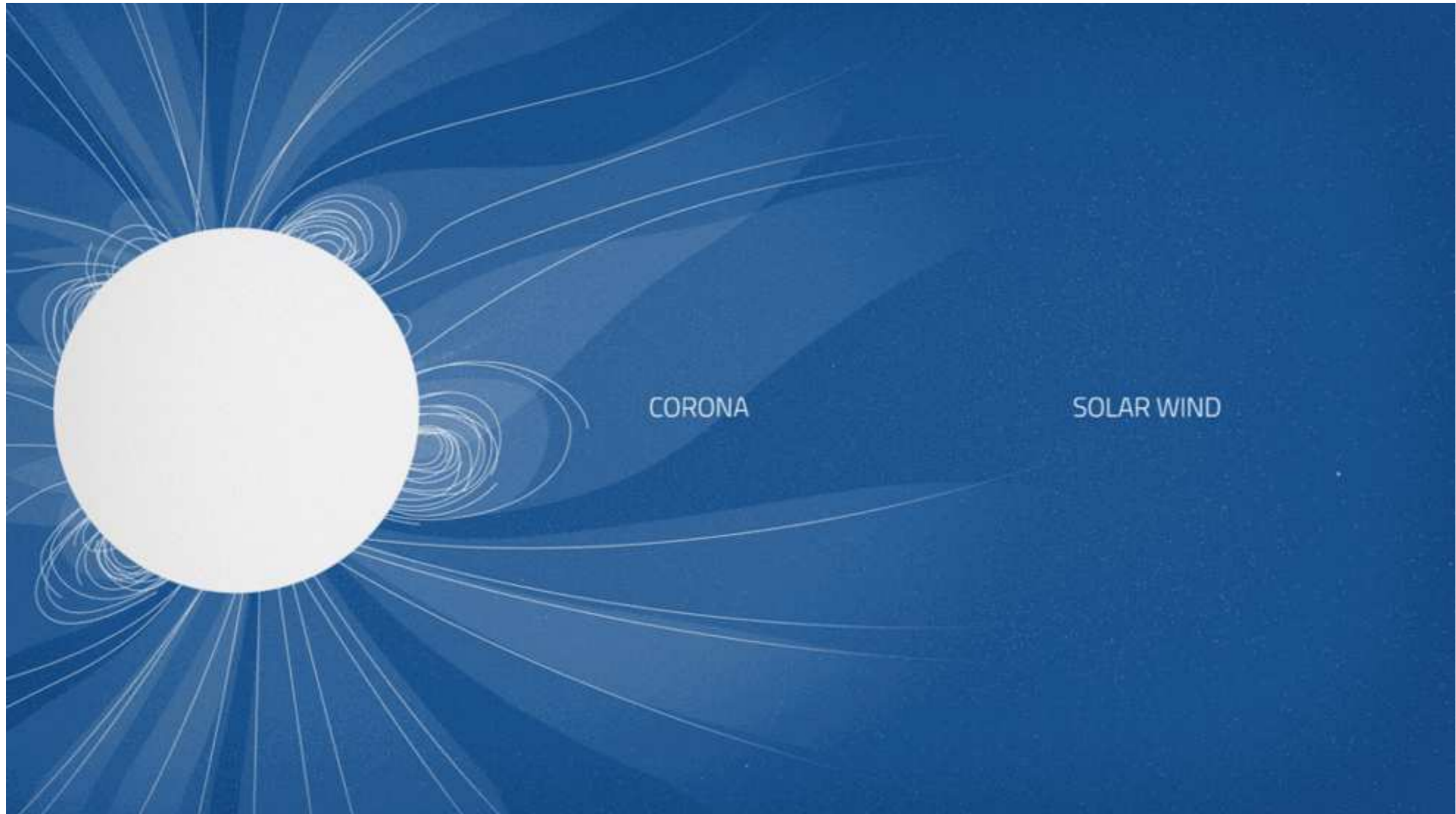
Polar coronal hole

Low-latitude coronal hole

Filament

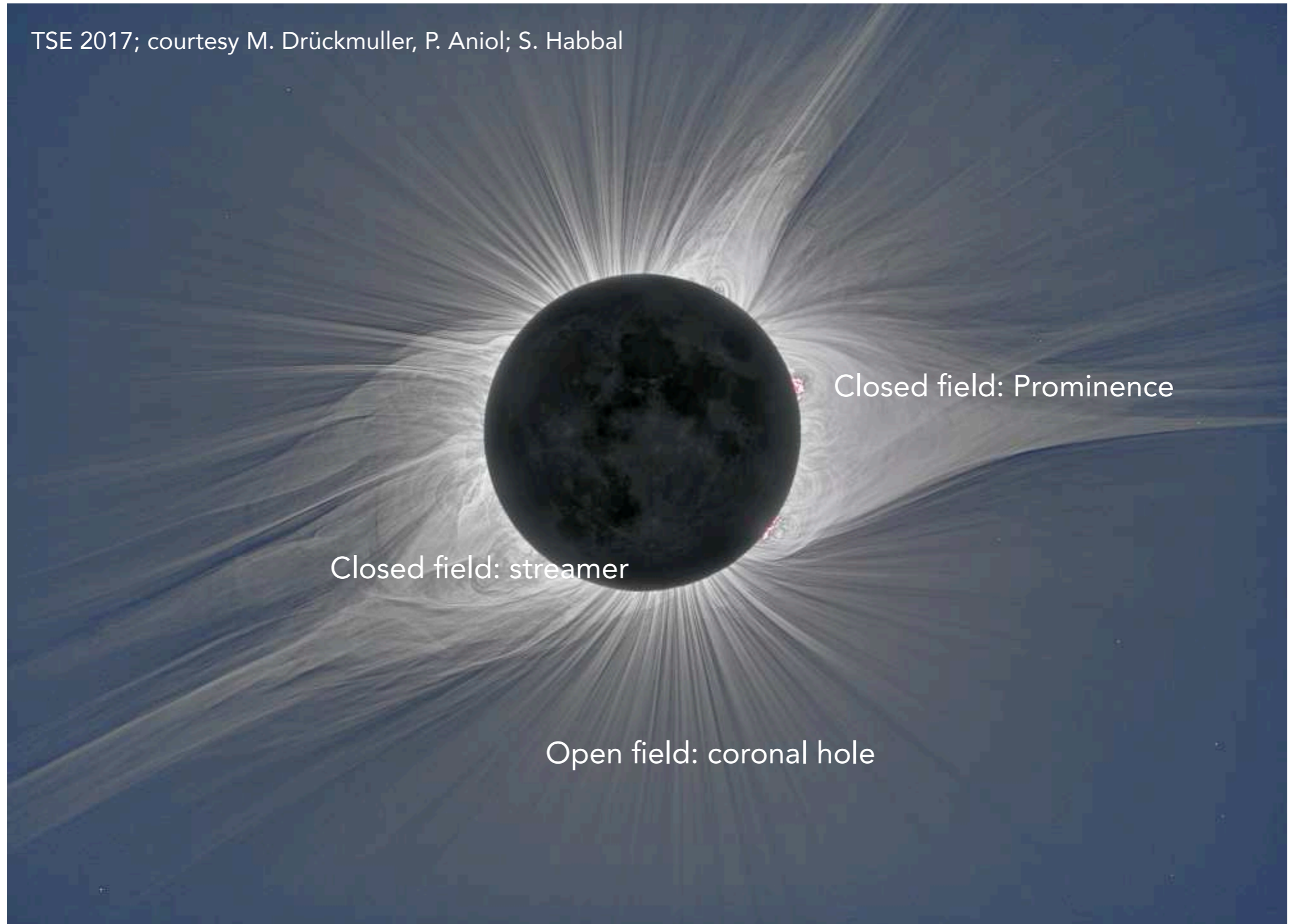


Magnetic Connectivity: Cartoon



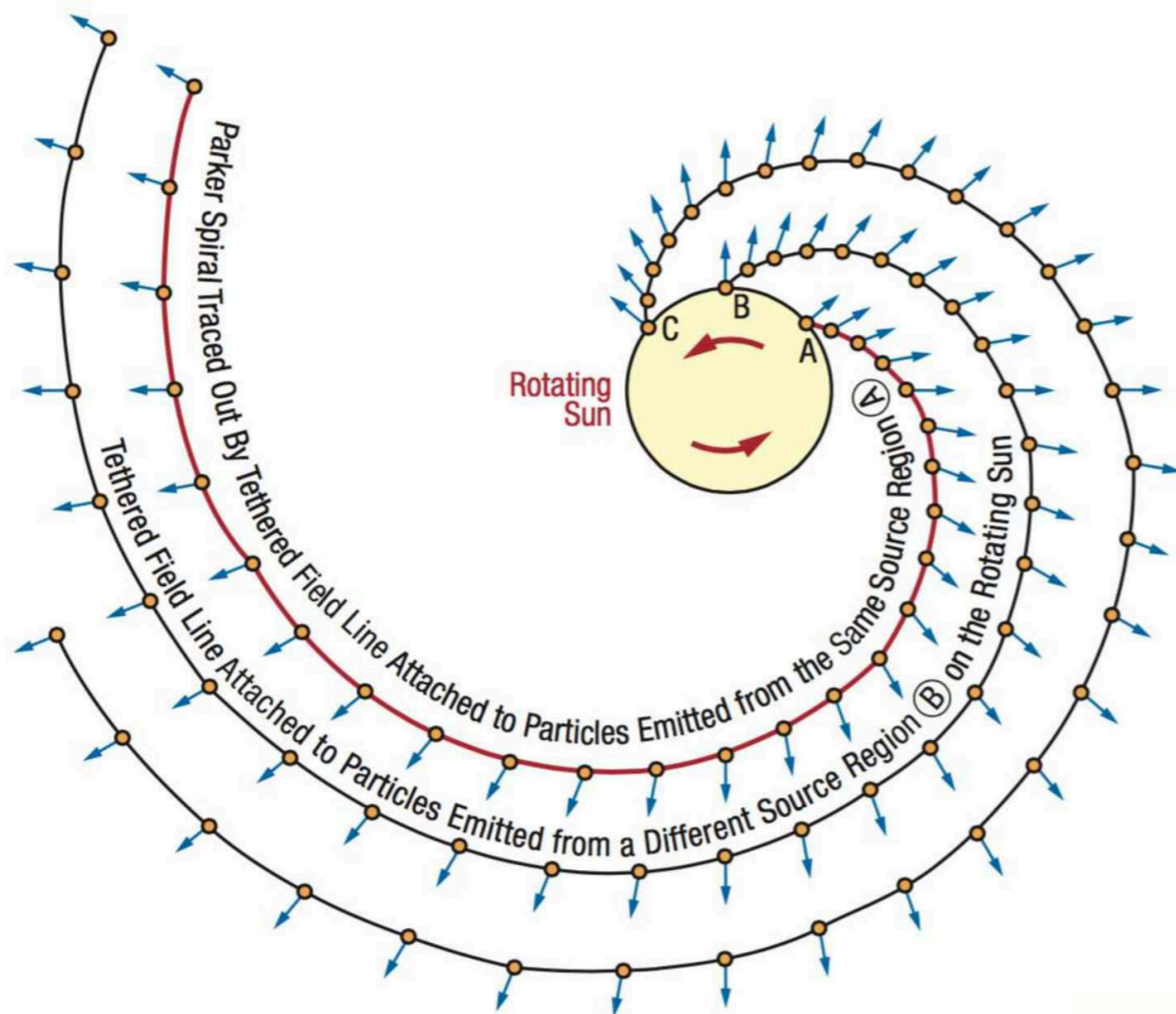
Magnetic Connectivity: Model

TSE 2017; courtesy M. Drückmüller, P. Aniol; S. Habbal



Magnetic Connectivity: Heliosphere

Parker spiral

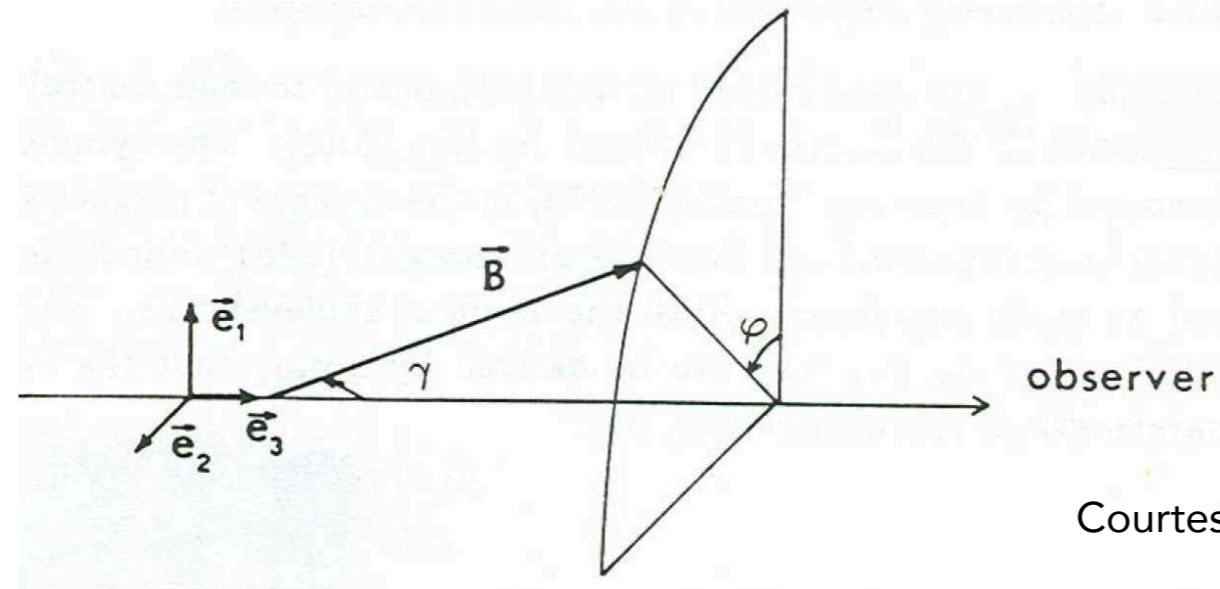


Heliospheric current sheet



Photospheric Magnetic Maps

Observing B with Zeeman Effect



Courtesy J. Borrero

- For weak fields, Stokes profiles depend on field geometry

$$Q \propto B^2 \sin^2 \gamma \cos 2\phi = B_t^2 \cos 2\phi$$

$$U \propto B^2 \sin^2 \gamma \sin 2\phi = B_t^2 \sin 2\phi$$

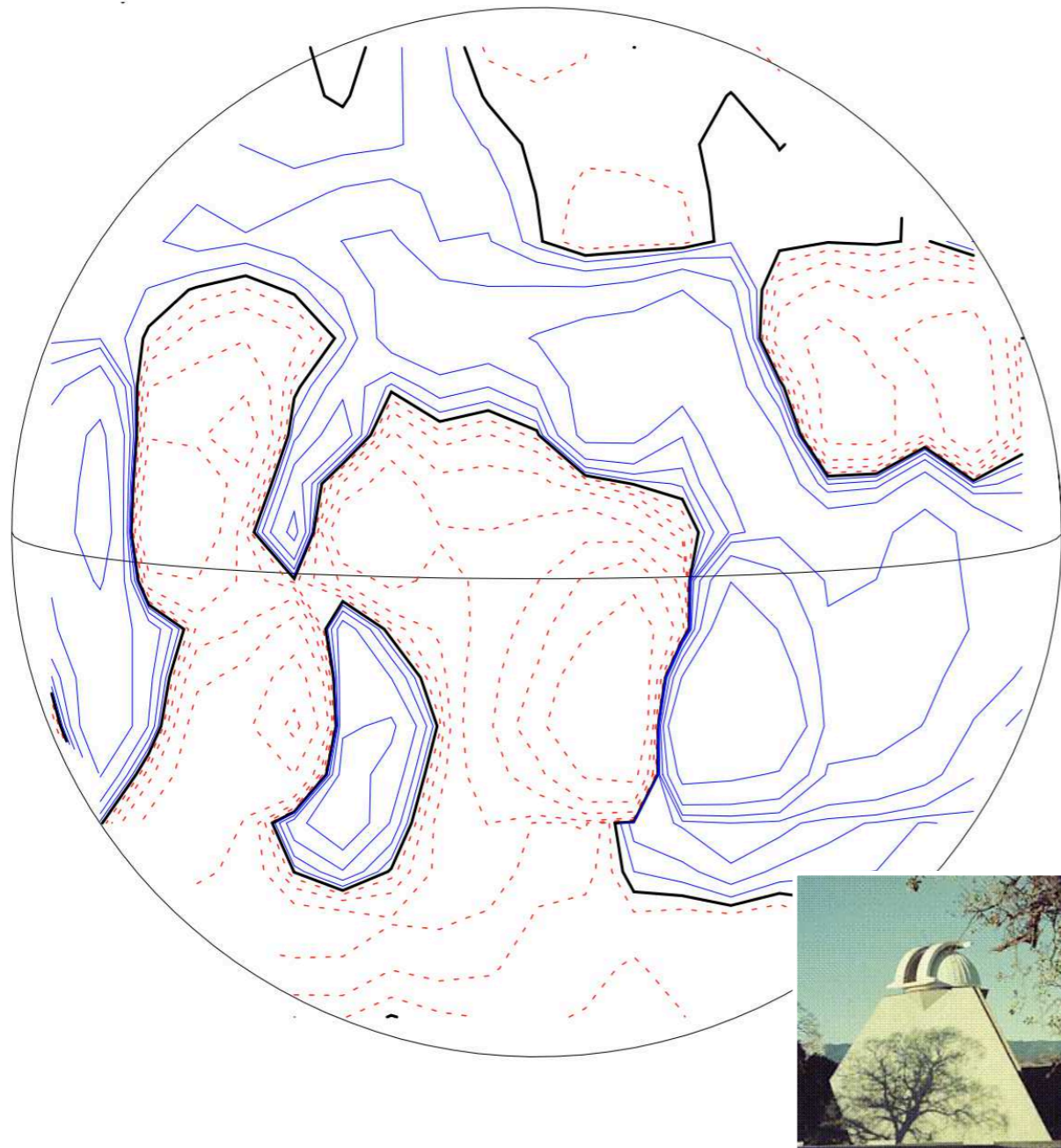
$$V \propto B \cos \gamma = B_l$$

- Sensitivity of transverse field (B_t) is lower than longitudinal field (B_l)

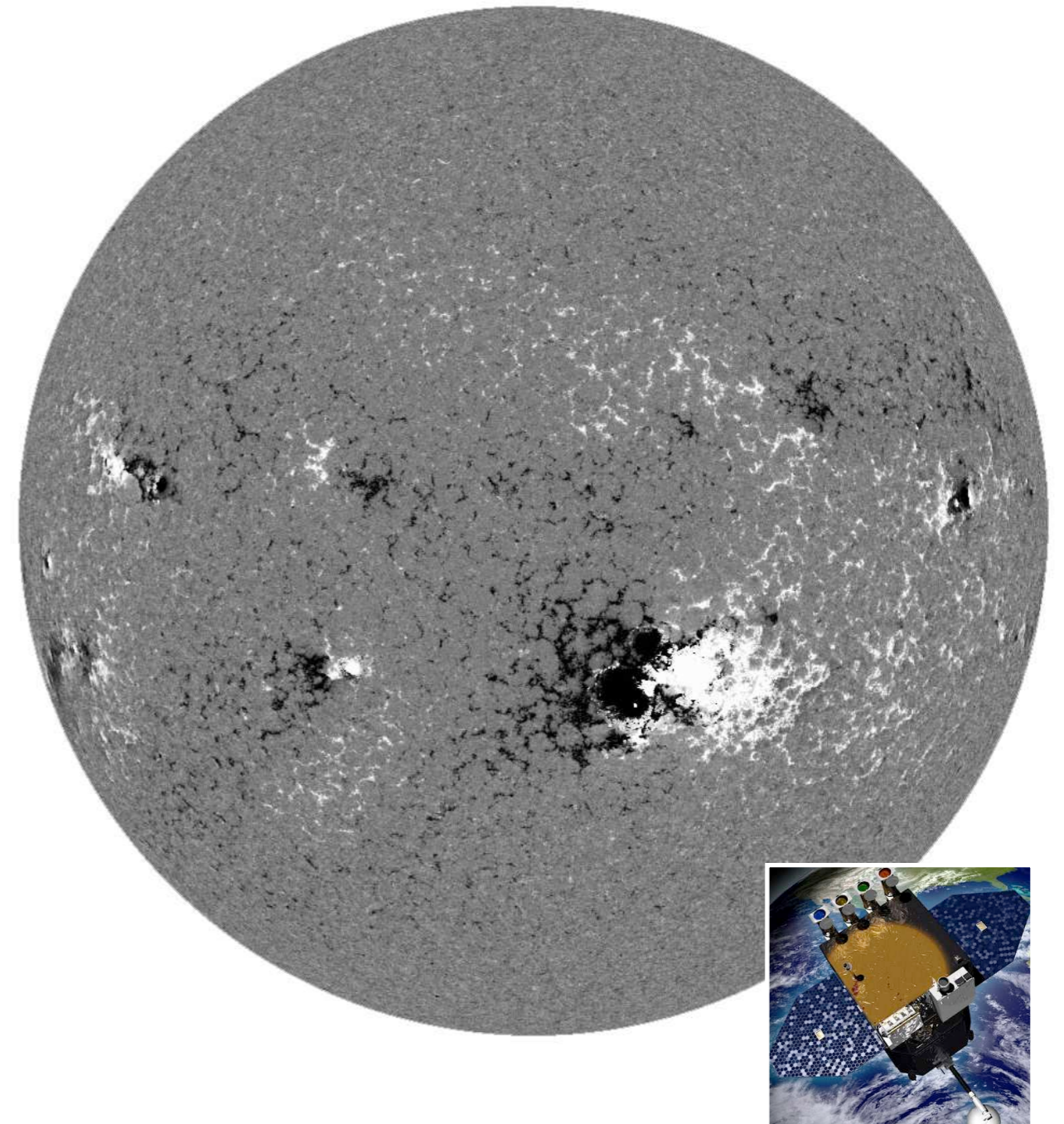
$$\frac{Q}{I} < \frac{V}{I}$$

Longitudinal Magnetograms

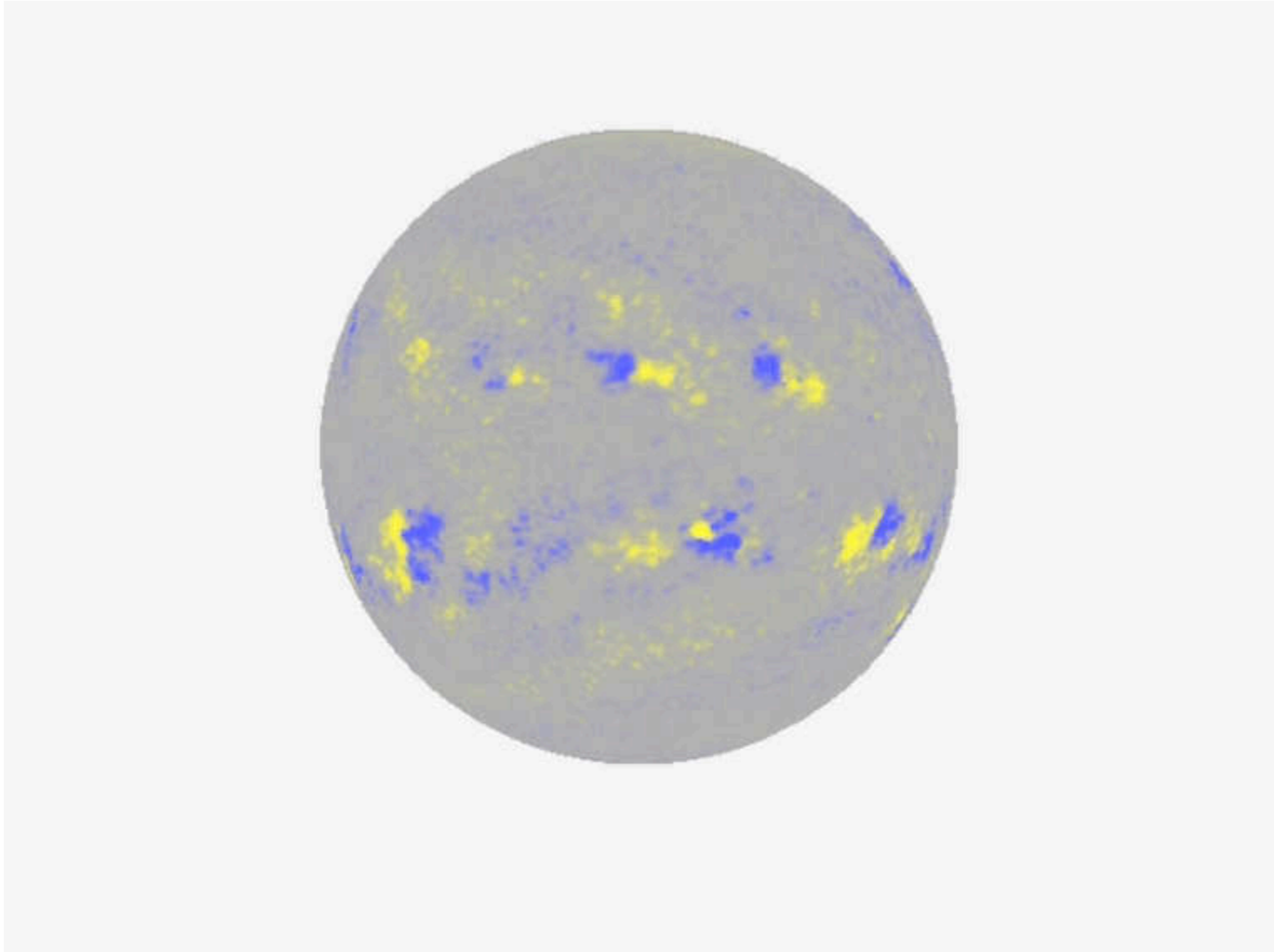
WSO; Fe I 525.0/524.7 nm; 3' resolution
22 × 11 pixels; 2 per day



HMI; Fe I 617.3 nm; 1'' resolution
4096 × 4096; 1920 per day

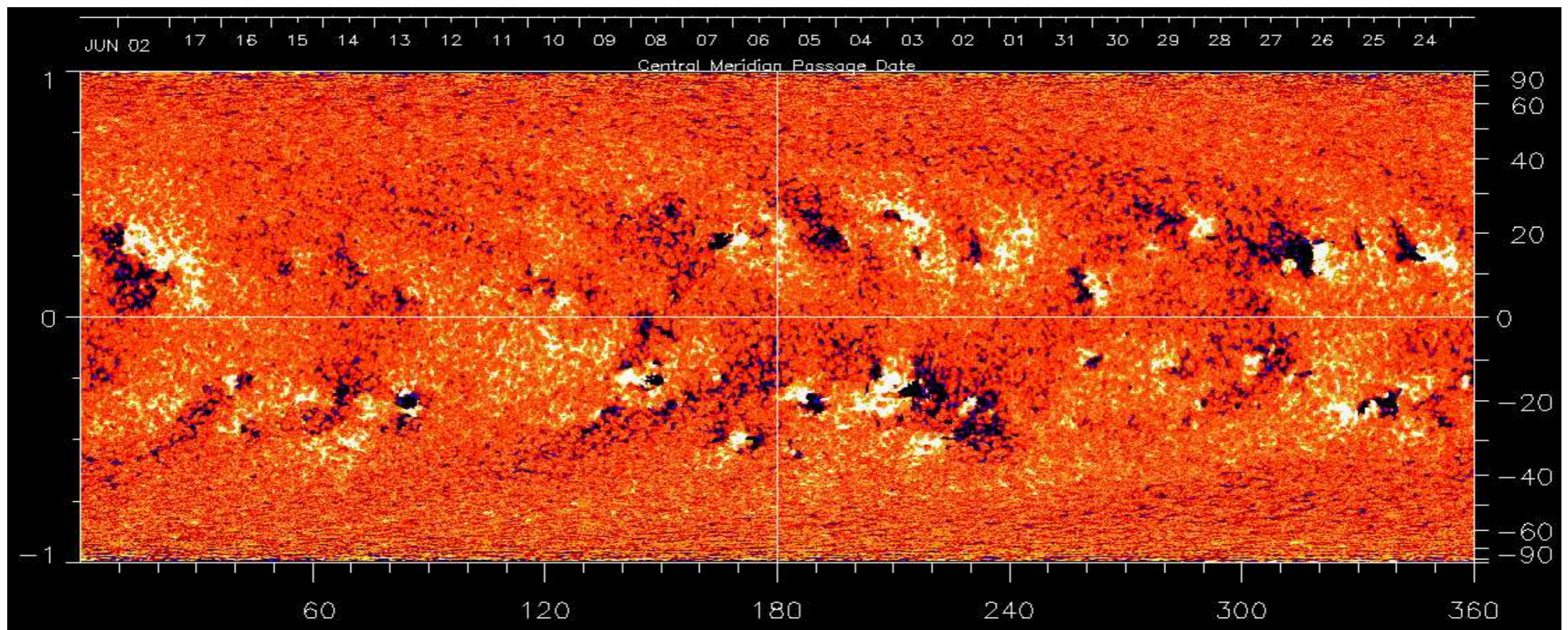
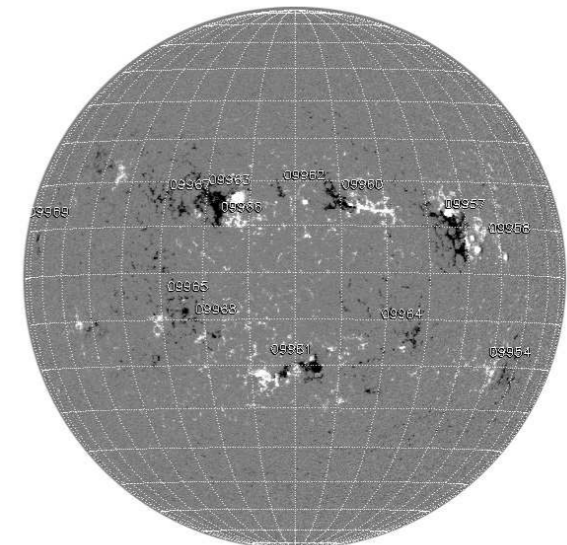
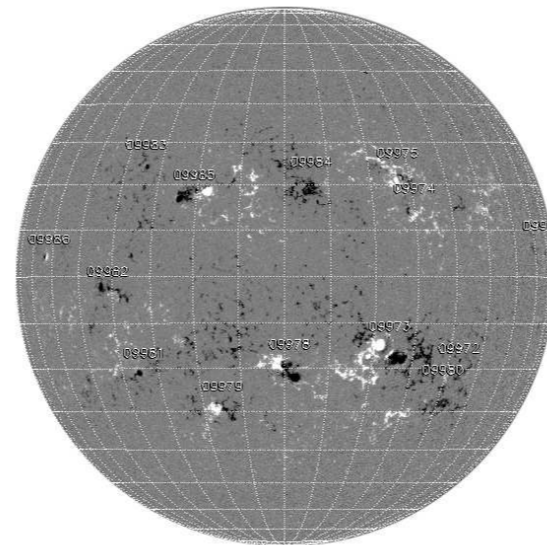
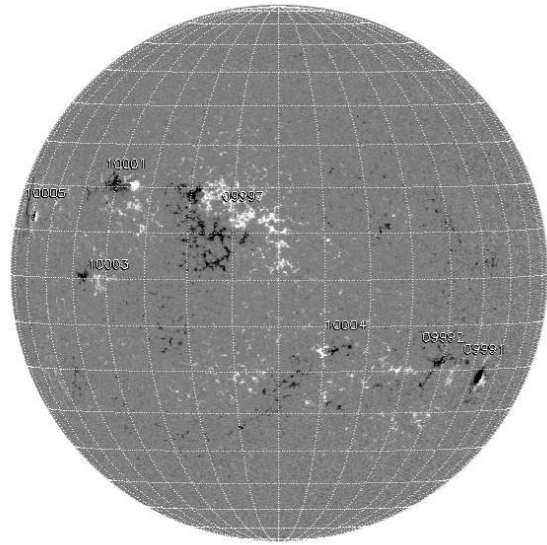


Synoptic Map



Synoptic Map & Heliographic Coord

$$B_r = B_l / \mu$$



Nuisances

Synoptic

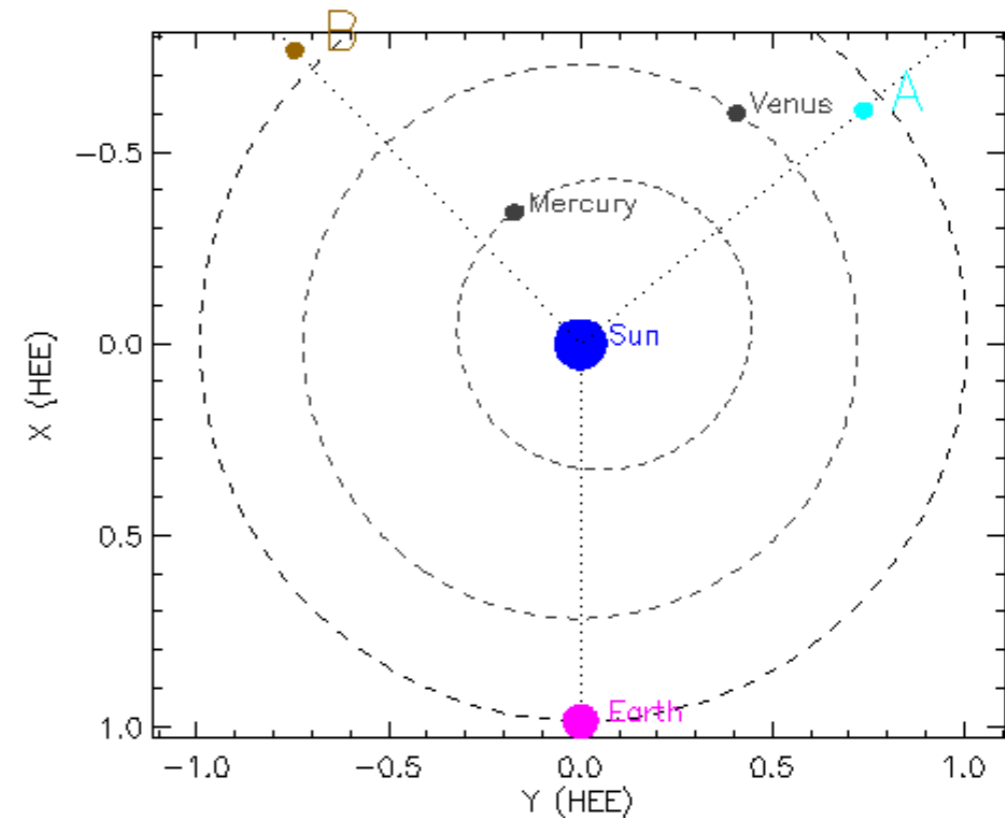
From Wikipedia, the free encyclopedia

Not to be confused with [synopsis \(disambiguation\)](#).

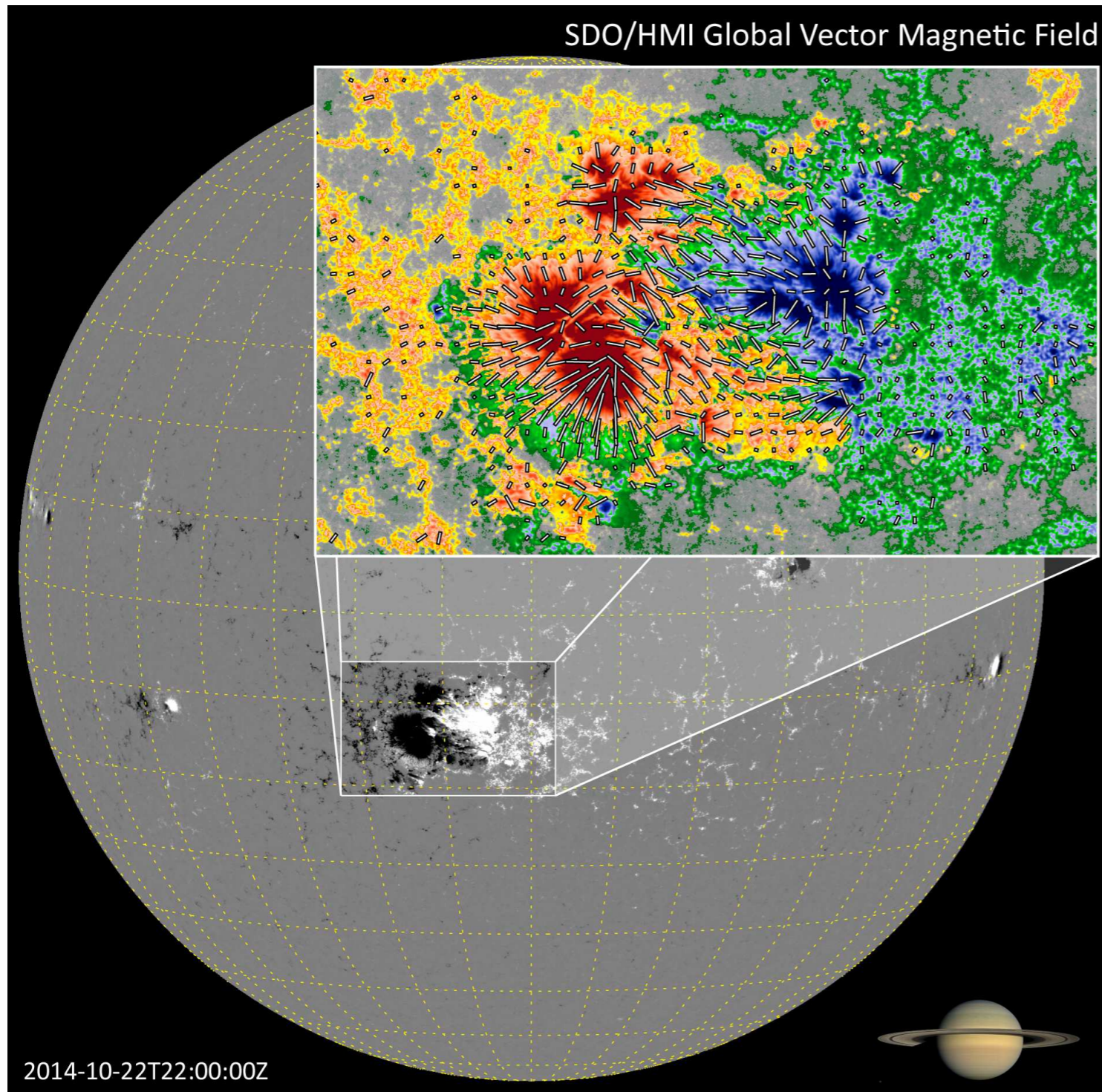
Synoptic is derived from the Greek words σύν (*syn*, "together") and ὄψις (*opsis*, "view"), and describes observations that give a broad view of a subject at a particular time. Specific uses include:

- Misnomer: not instantaneous snapshot
 - Different parts reflect conditions of different time
 - New emergence west of CMP not captured
 - Flux imbalance as half a bipole rotates on or off disc

STEREO doesn't have magnetograph...

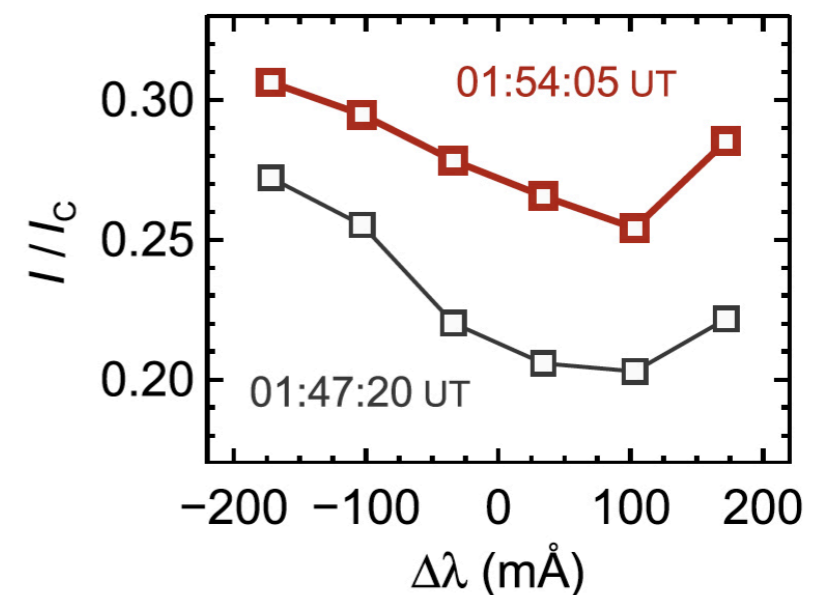


Vector Magnetograms



Choices, choices

- Cadence
- Field of view
- Duty cycle
- Spatial resolution
- Spectral resolution



Azimuthal Ambiguity

- 180-deg azimuthal ambiguity inherent to Zeeman effect

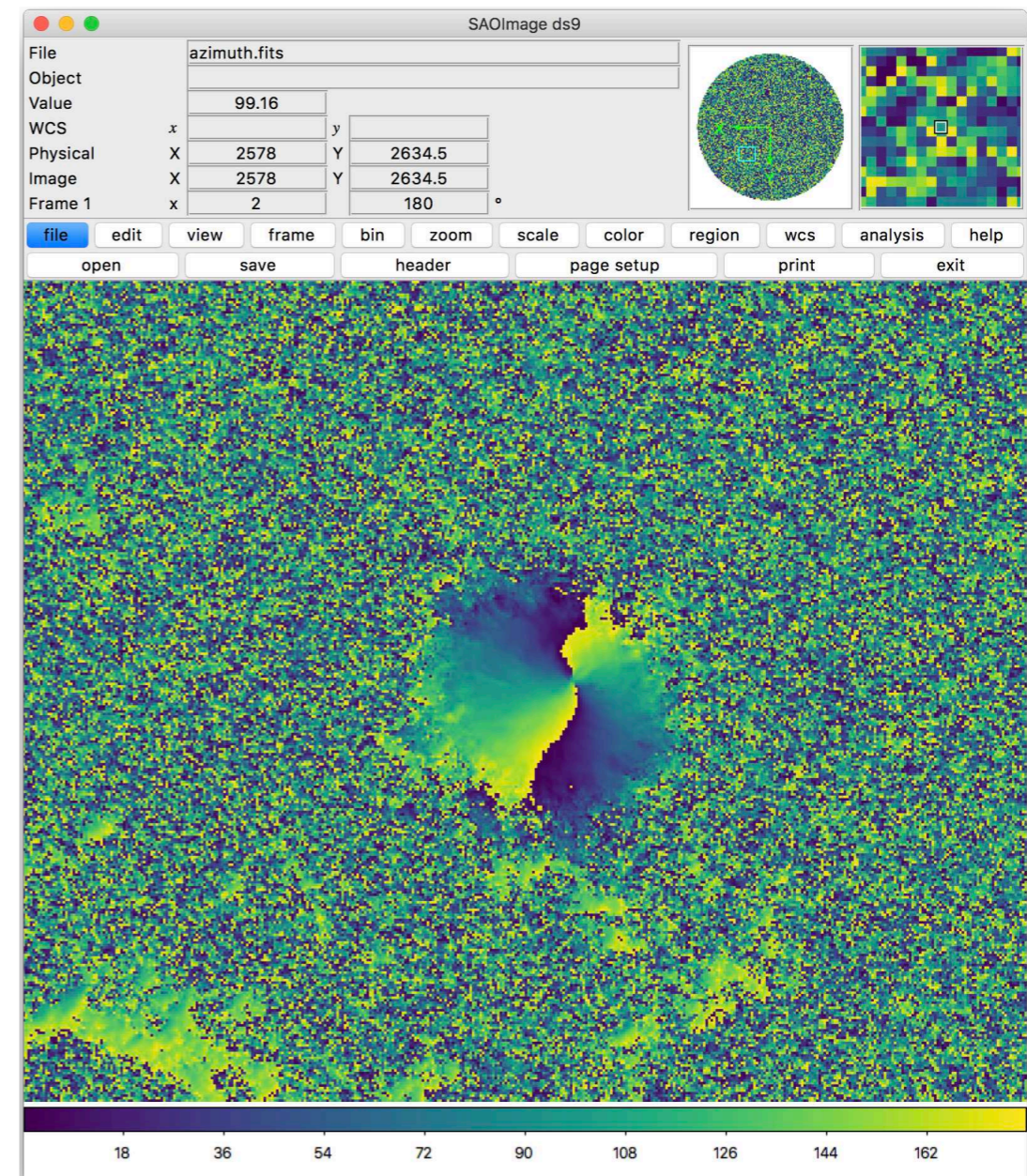
$$Q \propto B_t^2 \cos 2\phi = B_t^2 (\cos^2 \phi - \sin^2 \phi)$$

$$U \propto B_t^2 \sin 2\phi = 2B_t^2 \sin \phi \cos \phi$$

- Requires additional model, e.g. minimizing "energy" (Metcalf 1996):

$$E = \sum (\lambda_1 |J_z| + \lambda_2 |\nabla \cdot \mathbf{B}|)$$

- Weak field azimuth is noisy



Vector Projection

- Inversion provides longitudinal field (B_l) from V & transverse field (\mathbf{B}_t) from Q, U
- Usually we are more interested in radial (B_r) and horizontal (\mathbf{B}_h) components

$$\begin{pmatrix} B_r \\ B_\theta \\ B_\phi \end{pmatrix} = \begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix} \begin{pmatrix} B_\xi \\ B_\eta \\ B_\zeta \end{pmatrix},$$

- Relevant geometric parameters: p -angle, b -angle, longitude φ , latitude λ
- We are mixing signals with different noise characteristics (e.g., at poles)

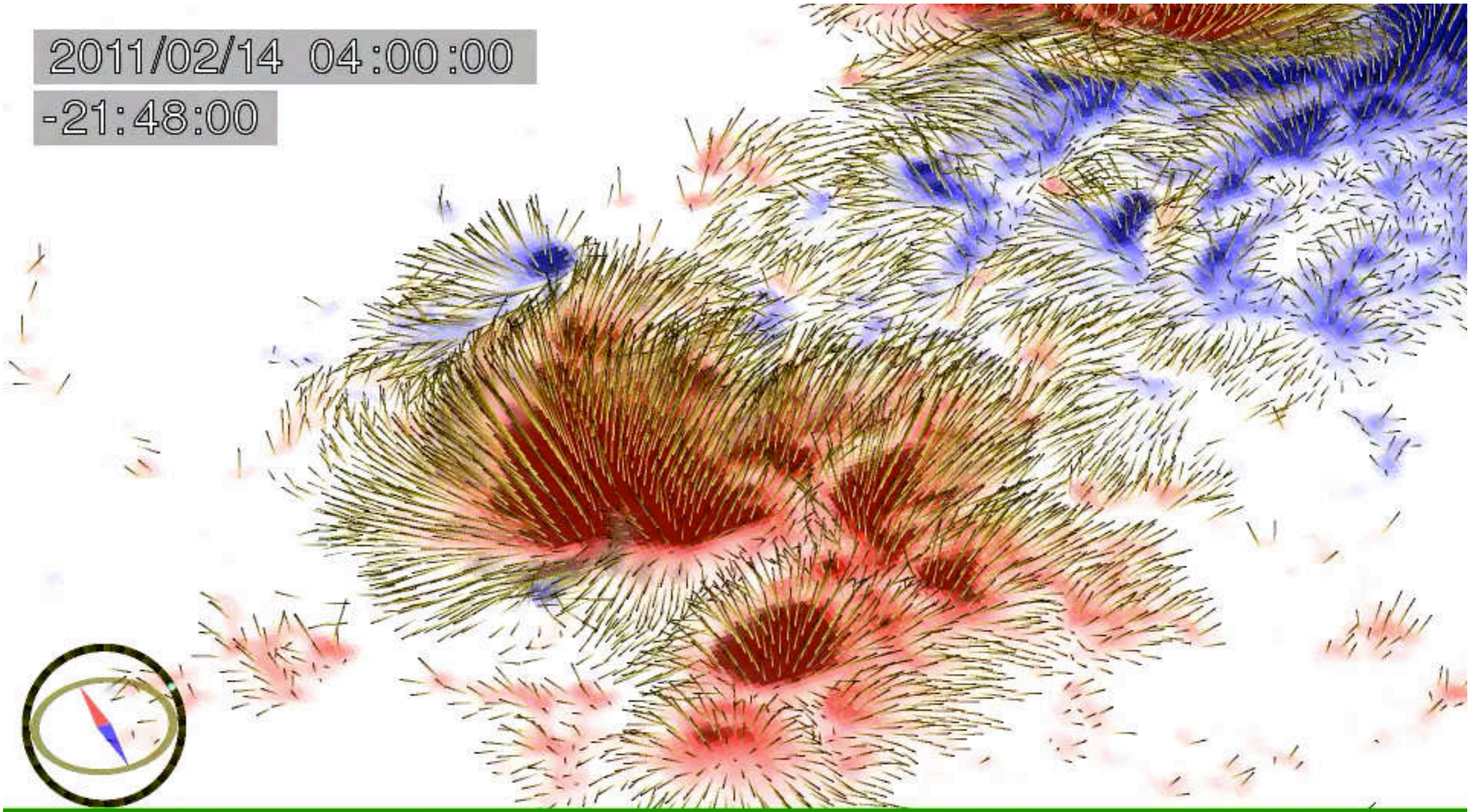
$$\begin{aligned} k_{11} &= \cos \lambda [\sin b \sin p \cos \phi + \cos p \sin \phi] - \sin \lambda [\cos b \sin p], \\ k_{12} &= -\cos \lambda [\sin b \cos p \cos \phi - \sin p \sin \phi] + \sin \lambda [\cos b \cos p], \\ k_{13} &= \cos \lambda \cos b \cos \phi + \sin \lambda \sin b, \\ k_{21} &= \sin \lambda [\sin b \sin p \cos \phi + \cos p \sin \phi] + \cos \lambda [\cos b \sin p], \\ k_{22} &= -\sin \lambda [\sin b \cos p \cos \phi - \sin p \sin \phi] - \cos \lambda [\cos b \cos p], \\ k_{23} &= \sin \lambda \cos b \cos \phi - \cos \lambda \sin b, \\ k_{31} &= -\sin b \sin p \sin \phi + \cos p \cos \phi, \\ k_{32} &= \sin b \cos p \sin \phi + \sin p \cos \phi, \\ k_{33} &= -\cos b \sin \phi. \end{aligned}$$

The "Hedgehog"

HMI vector field sequence

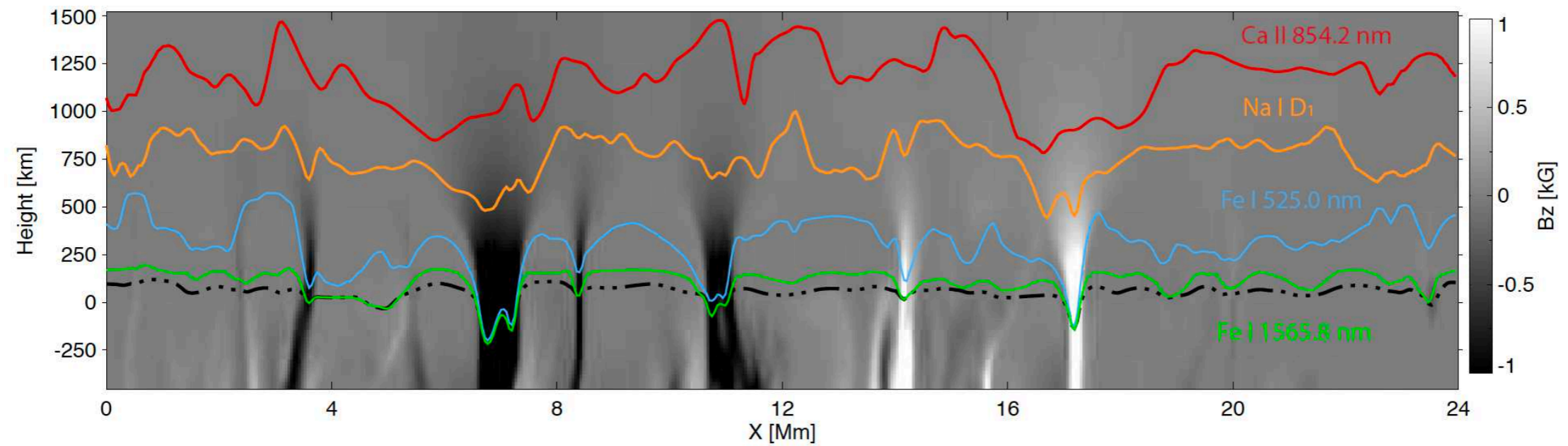
2011/02/14 04:00:00

-21:48:00



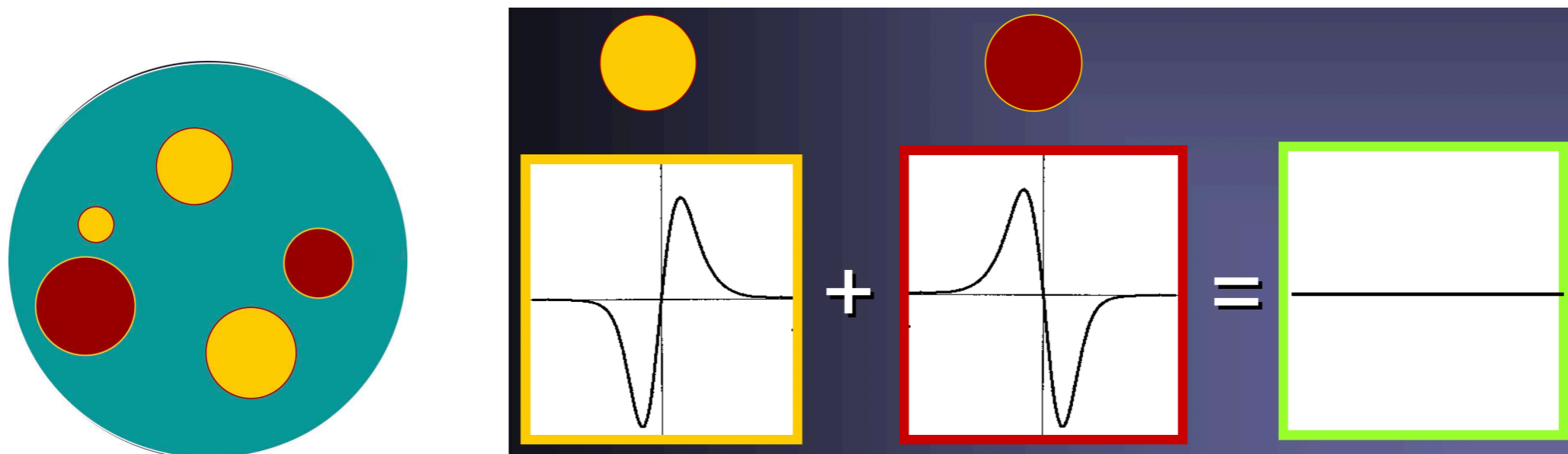
More Nuisances

Rugged "formation" height



Courtesy C. Quintero Noda

Magnetic "filling factor"



Courtesy S. Solanki

Potential Field of Quiescent Corona

Lorentz Force & Magnetic Pressure

- MHD momentum equation:

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \rho \mathbf{g} + \mathbf{j} \times \mathbf{B}$$

- Lorentz force: magnetic pressure gradient + tension force

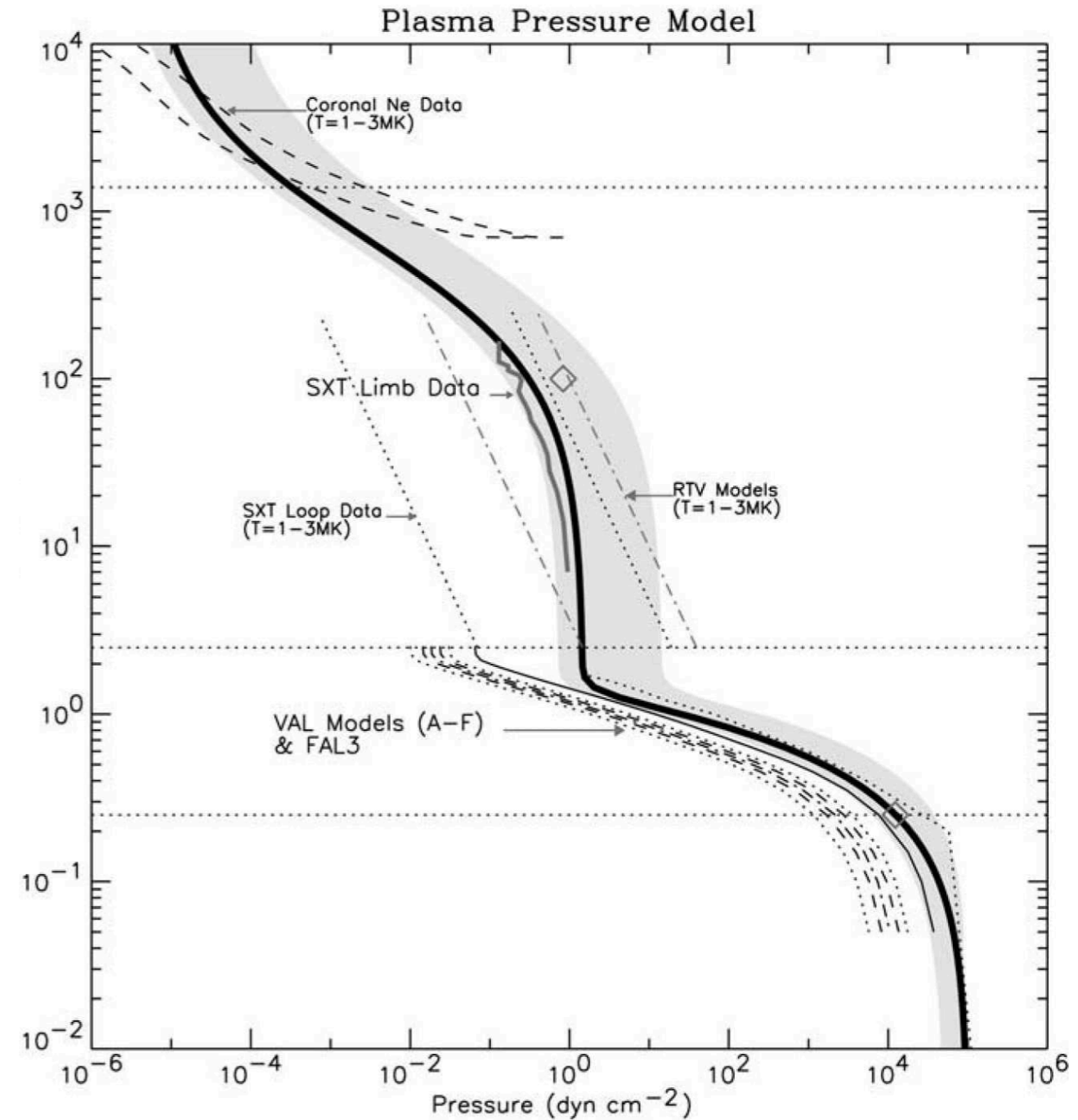
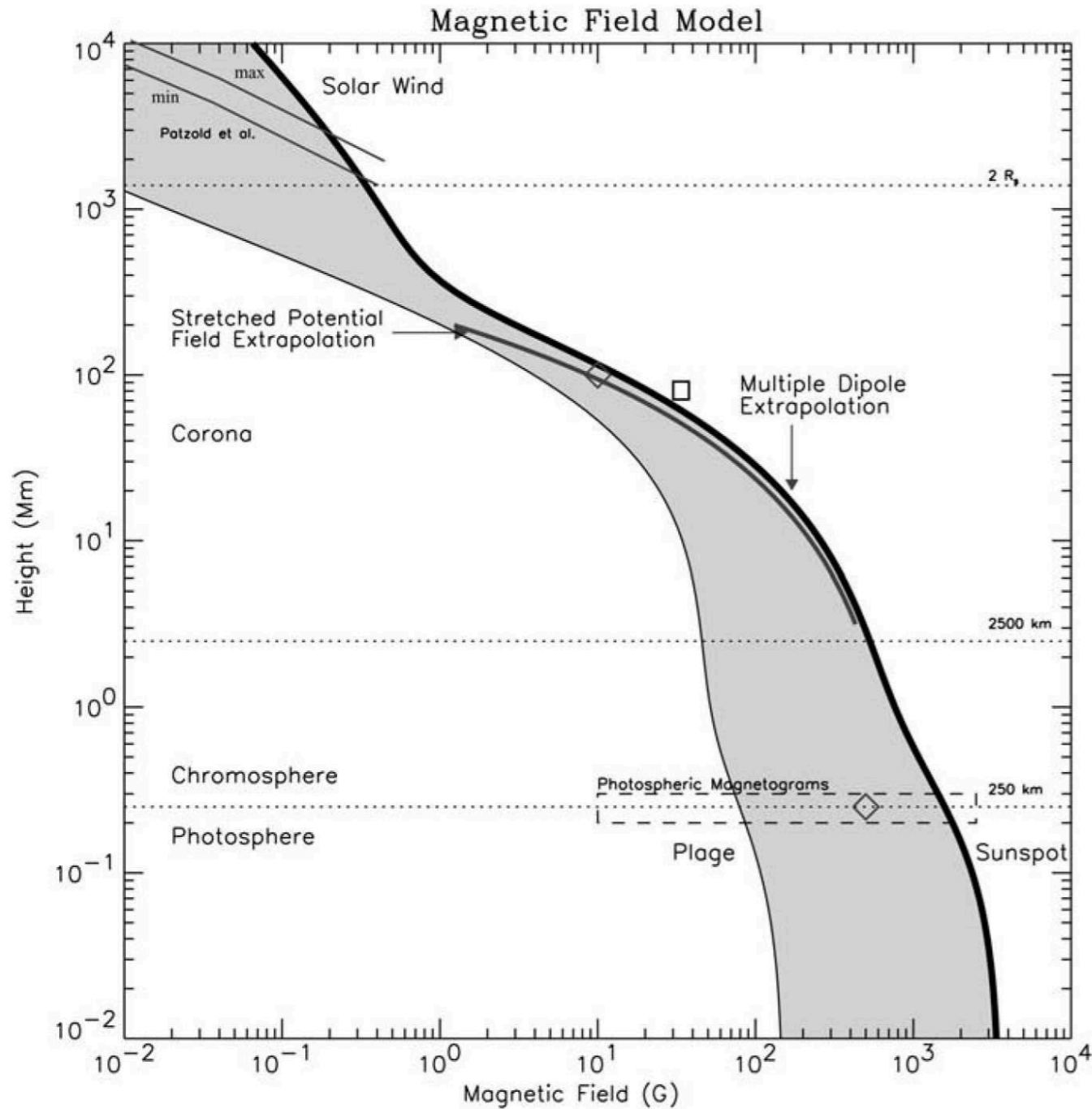
$$\frac{1}{c} \mathbf{j} \times \mathbf{B} = \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} = -\nabla \frac{B^2}{8\pi} + \frac{(\mathbf{B} \cdot \nabla) \mathbf{B}}{4\pi}$$

- Relative importance of plasma compared to field: plasma β

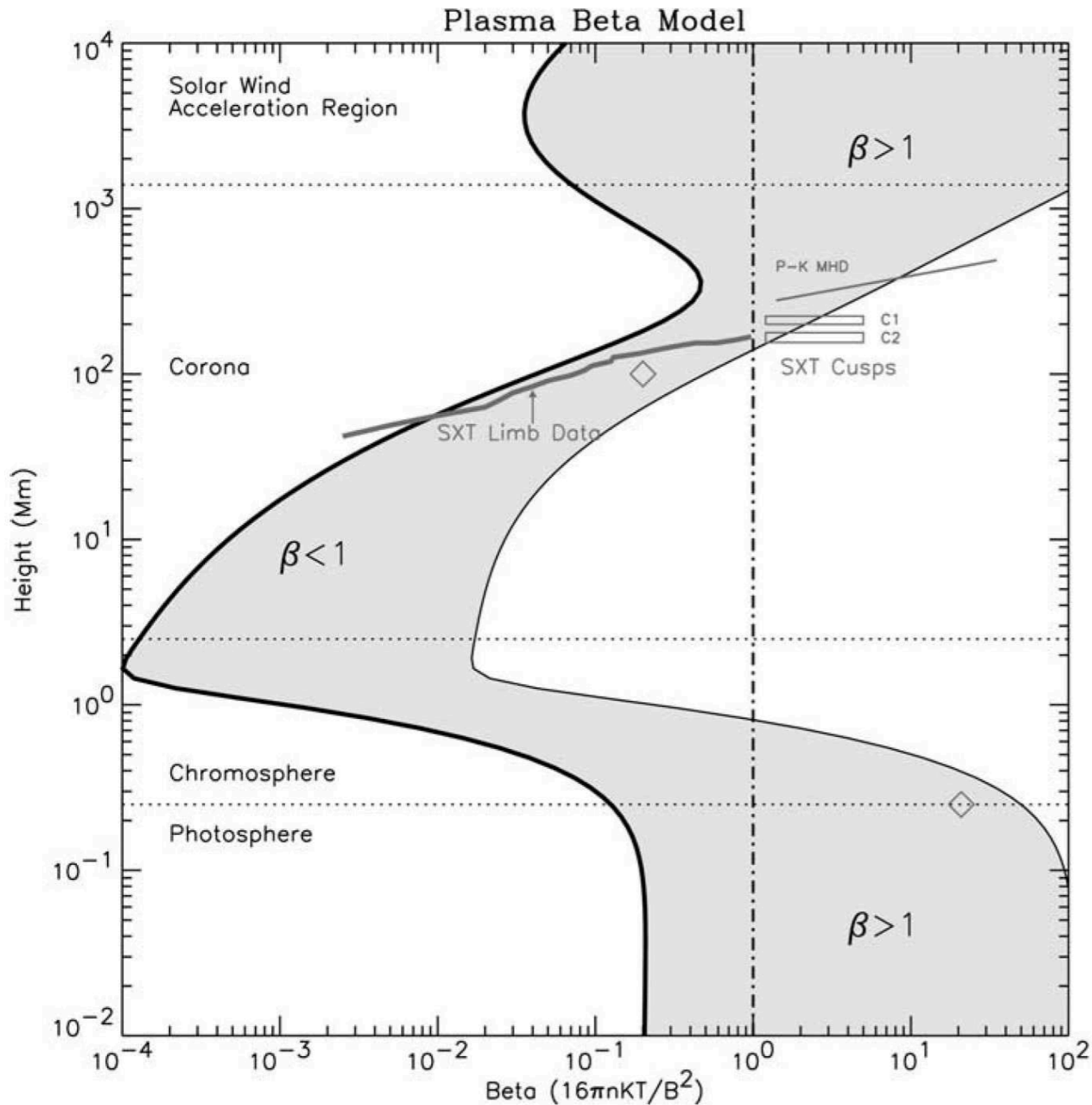
$$\beta = \frac{p}{p_{\text{mag}}} = \frac{p}{B^2/(8\pi)}$$

Reign of Magnetic Field: Plasma β

$$\beta = \frac{p}{B^2/(8\pi)}$$



Plasma β & Force-Free Field



- Quasi-static ($v \sim 0$); low β

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

or

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$$

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

current (anti-)parallel to field

- Potential field $\alpha = 0$; linear force-free field α is constant:

$$\nabla^2 \mathbf{B} + \alpha^2 \mathbf{B} = 0$$

- Lowest energy state

Gary (2001)

Electric Currents; Potential Field

- Electric currents exist as twist, shear, or discontinuity in \mathbf{B}

$$\int \mathbf{j} \cdot d\mathbf{S} \propto \int \nabla \times \mathbf{B} \cdot d\mathbf{S} = \oint \mathbf{B} \cdot d\mathbf{l}$$

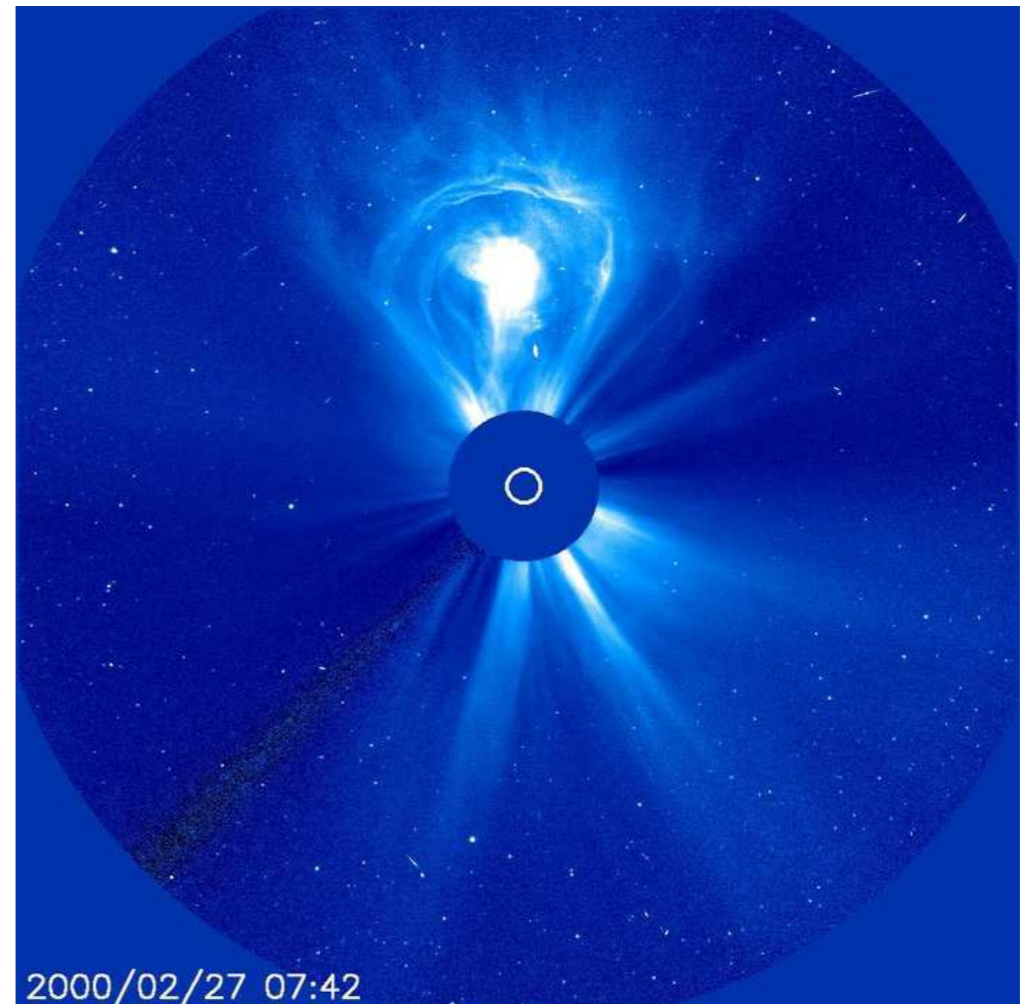
- Large-scale field is mostly current free, i.e. potential field (PF)

$$\nabla \times \mathbf{B}_p = 0$$

- Generally speaking, PF is the "lowest energy state"; "free" energy

$$E_f = \int \frac{B^2}{8\pi} - \frac{B_p^2}{8\pi} dV$$

Where's \mathbf{j} ?



SoHO/EIT C3

PFSS Model

- Assuming lower corona is current free, \mathbf{B} can be expressed as a scalar potential

$$\mathbf{B} = -\nabla\Psi$$

- \mathbf{B} vector in spherical coord

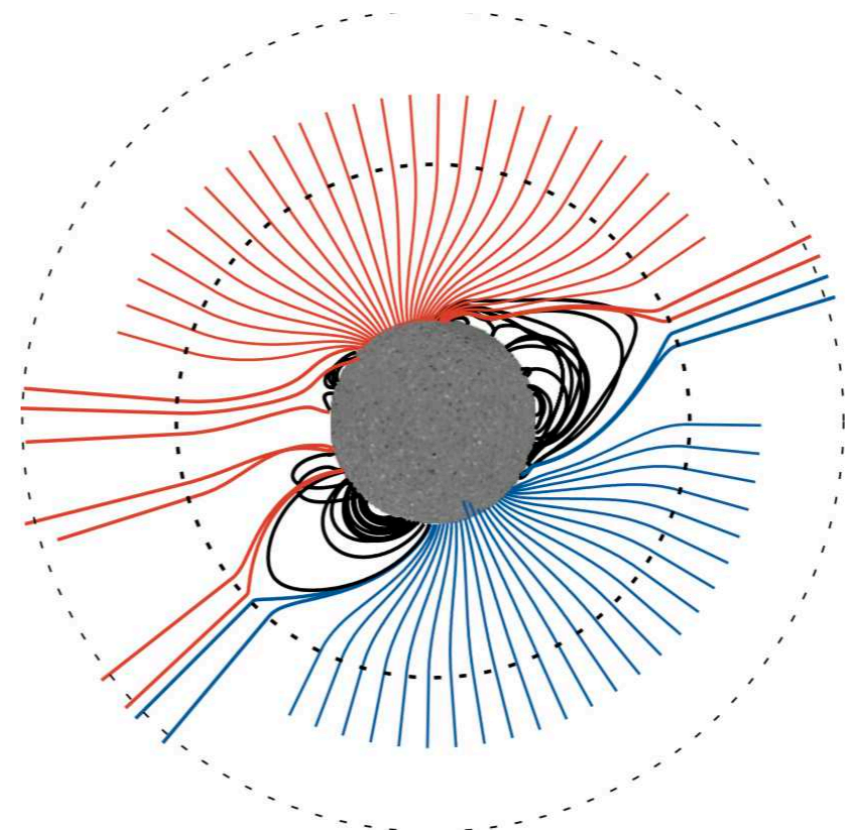
$$B_r = -\frac{\partial\Psi}{\partial r}$$

$$B_\theta = -\frac{1}{r}\frac{\partial\Psi}{\partial\theta}$$

$$B_\phi = -\frac{1}{r\sin\theta}\frac{\partial\Psi}{\partial\phi}$$

- Coronal field governed by Laplace eq.

$$\nabla^2\Psi = 0$$



Sun (2012)

PFSS Model

- Inner boundary: photosphere radial field

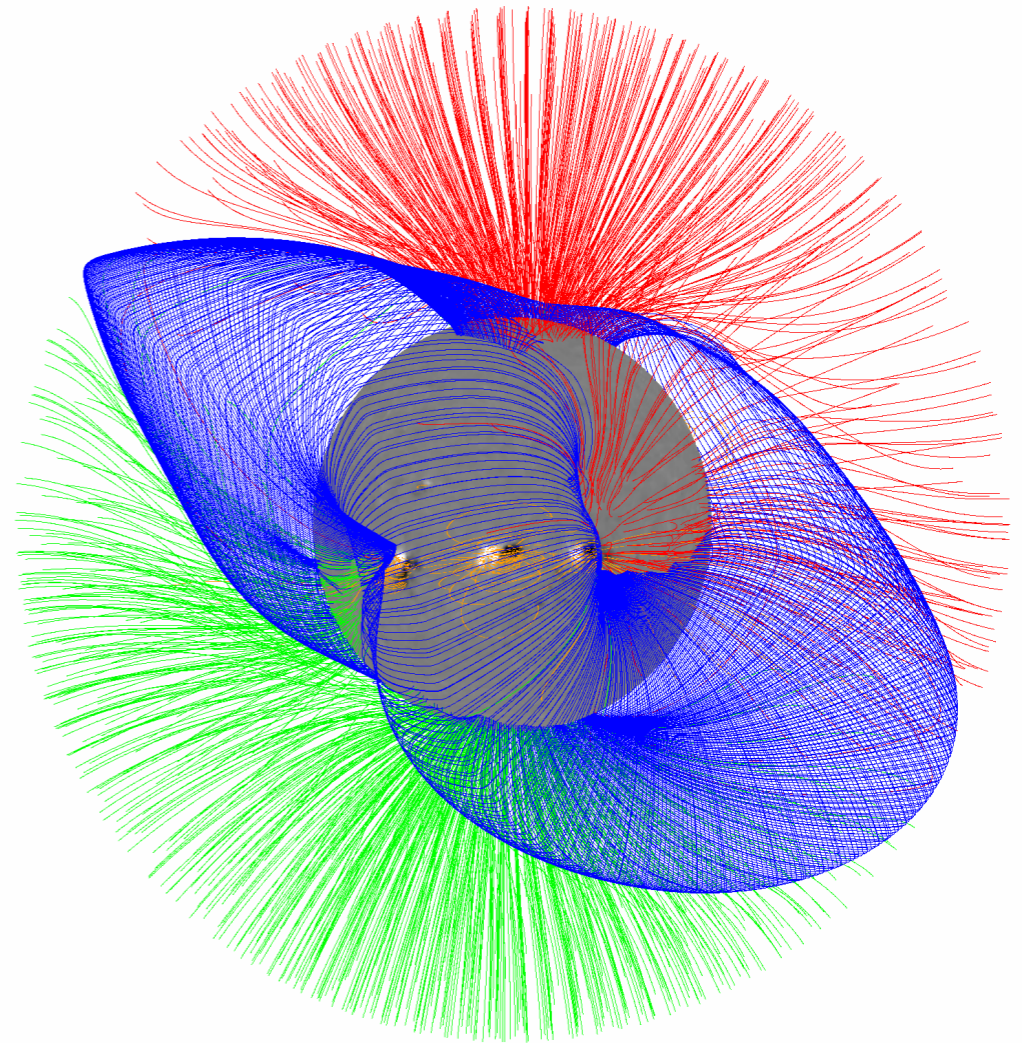
$$-\frac{\partial \Psi}{\partial r} \Big|_{r=R_{\odot}} = B_r(\text{obs})$$

- Outer boundary: source surface where field becomes radial and open

$$\Psi \Big|_{r=R_s} = 0$$
$$R_s = 2.5R_{\odot}$$

- General solution of Laplace equation:

$$\Psi = \sum_{l=0}^{\infty} r^{-(l+1)} \sum_{m=-l}^l a_{lm} Y_l^m(\theta, \phi) + \sum_{l=0}^{\infty} r^l \sum_{m=-l}^l b_{lm} Y_l^m(\theta, \phi)$$



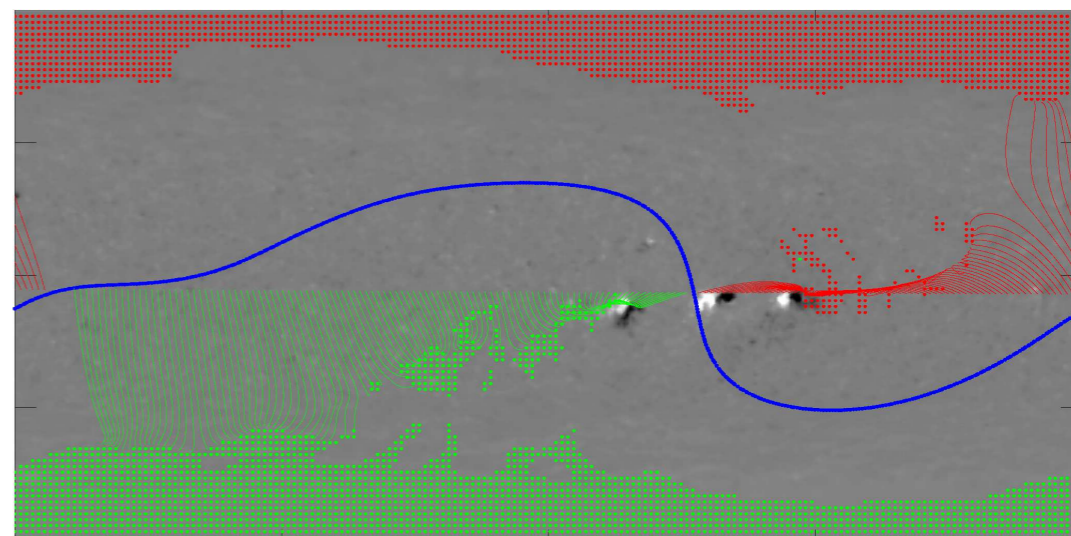
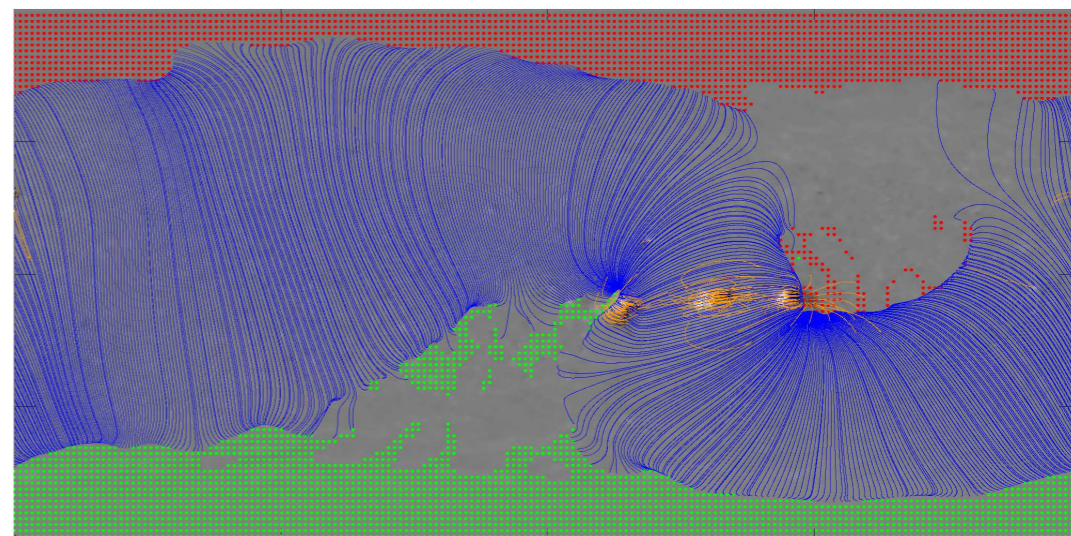
NSO/GONG

PFSS Model

- Coefficients can be obtained through spherical harmonics decomposition

$$k_{lm} \propto \int d\Omega Y_l^m(\theta, \phi) B_r \Big|_{r=R_\odot}$$

- Coefficients contain important information, e.g., dipole reverses sign
- Captures most topological features: current sheet location; streamer extent; coronal hole size/location
- Open field as solar wind sources



PFSS Widget

<https://tinyurl.com/pfss-wid>

Not Secure — spacephysics.ucla.edu

HOME Rotatable Potential Fields Rotatable Simple Source Surface Fields **Rotatable Realistic Source Surface Models** Realistic Source Surface Magnetic Map

Potential Field: Rotatable Realistic Source Surface Models

This module allows you to examine the magnetic topology of realistic potential field models.

Data set:
 Input values Minimum dipole Minimum tilted dipole
 Intermediate quadrupole Maximum case 1 Maximum case 2
 Maximum case 3

Dipole coefficients

g_{10}, g_{11} : Tm^3
 h_{11} : Tm^3

Quadrupole coefficients

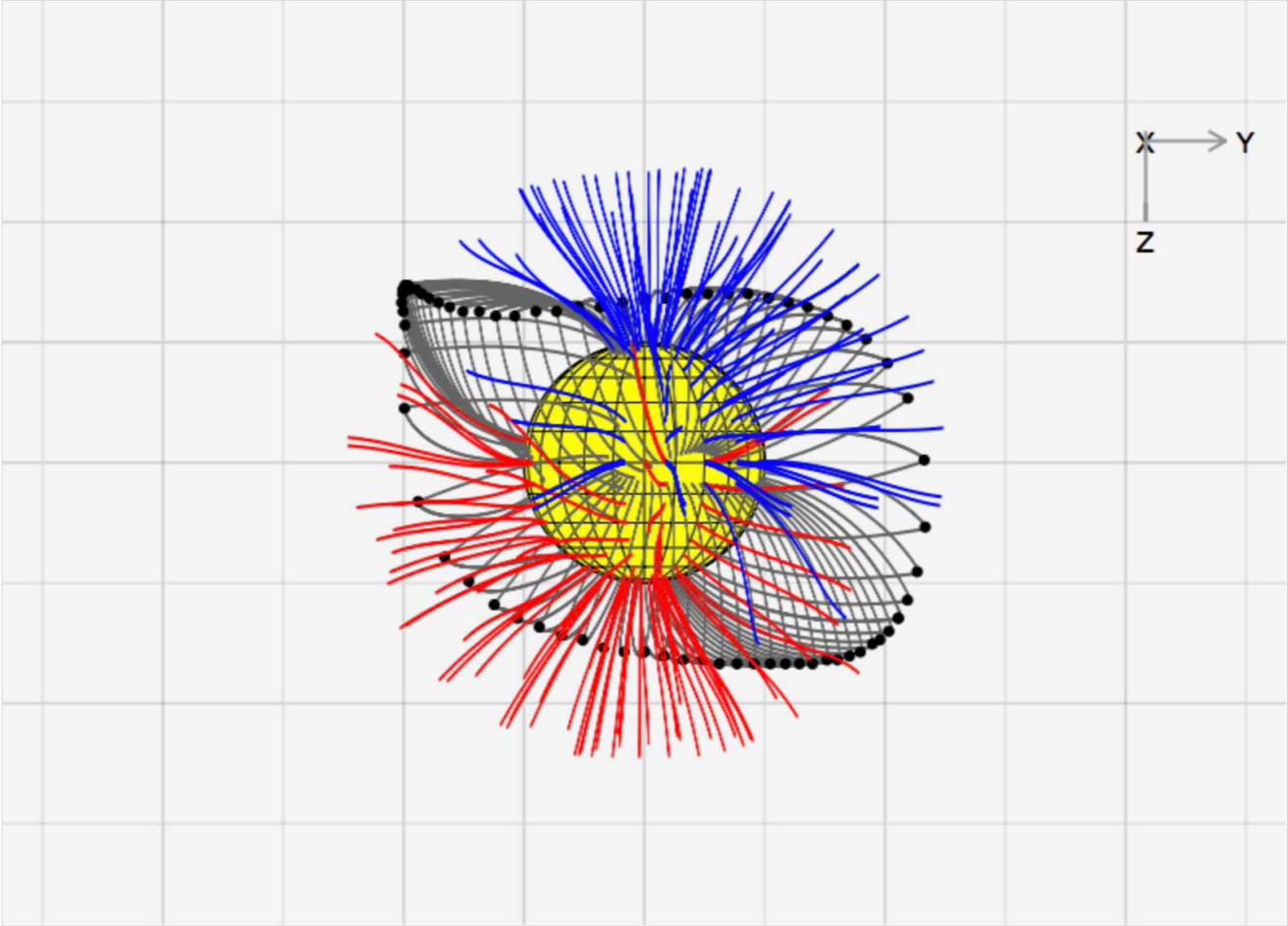
g_{20}, g_{21} : Tm^3
 g_{22} : Tm^3
 h_{21}, h_{22} : Tm^3

Octupole coefficients

g_{30}, g_{31} : Tm^3
 g_{32}, g_{33} : Tm^3
 h_{31}, h_{32} : Tm^3
 h_{33} : Tm^3

View configuration

Latitude: °
Longitude: °
View angle: °
Source surface radius: R_{\odot}



This option uses coefficients from the Wilcox Solar Observatory (WSO). You can fill in the WSO coefficients up to order 3. Select the **Input values** option to evaluate the data input by you, or one of the other six options to display a set of WSO coefficients for different solar configurations. The source surface around the Sun is an imaginary radius at which magnetic field lines go radial. Usually the source surface is taken to be in a range of 2 to 3 times the radius of the Sun, R_{\odot} . You can vary solar radii value from a minimum value of 1 to a maximum value of 6. In the display, gray lines are closed field lines, red lines are open field lines (inward), and blue lines are open field lines (outwards). Small black circles map out the neutral line on the source surface, dividing the outward radial fields there from the inward radial fields. Regions with neither closed nor open field lines plotted here are regions with closed field lines that do not reach the source surface.

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PFSS Model at Solar Min & Max

