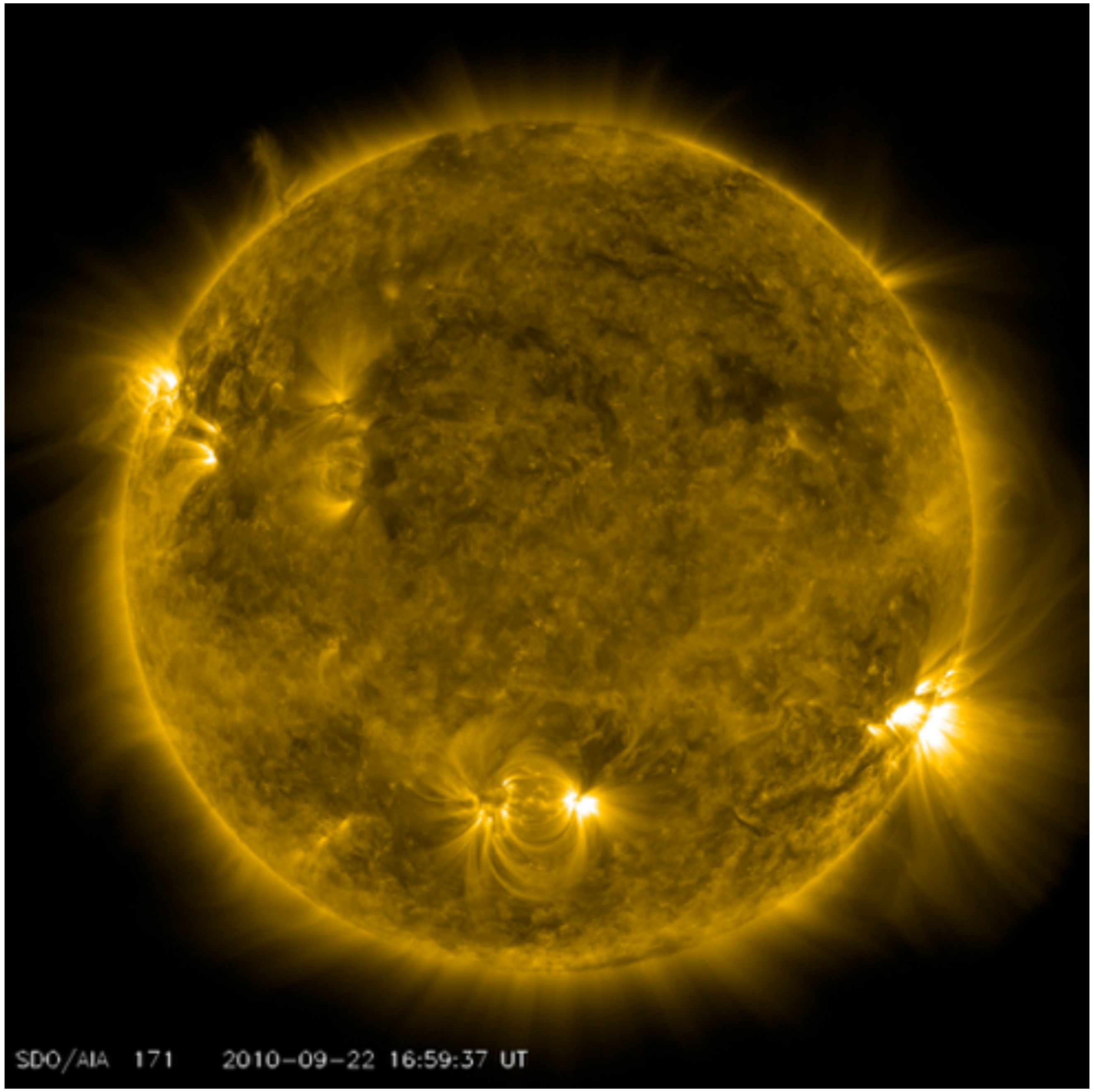
Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

# The Solar Atmosphere





**Mark Miesch**
HAO/NCAR

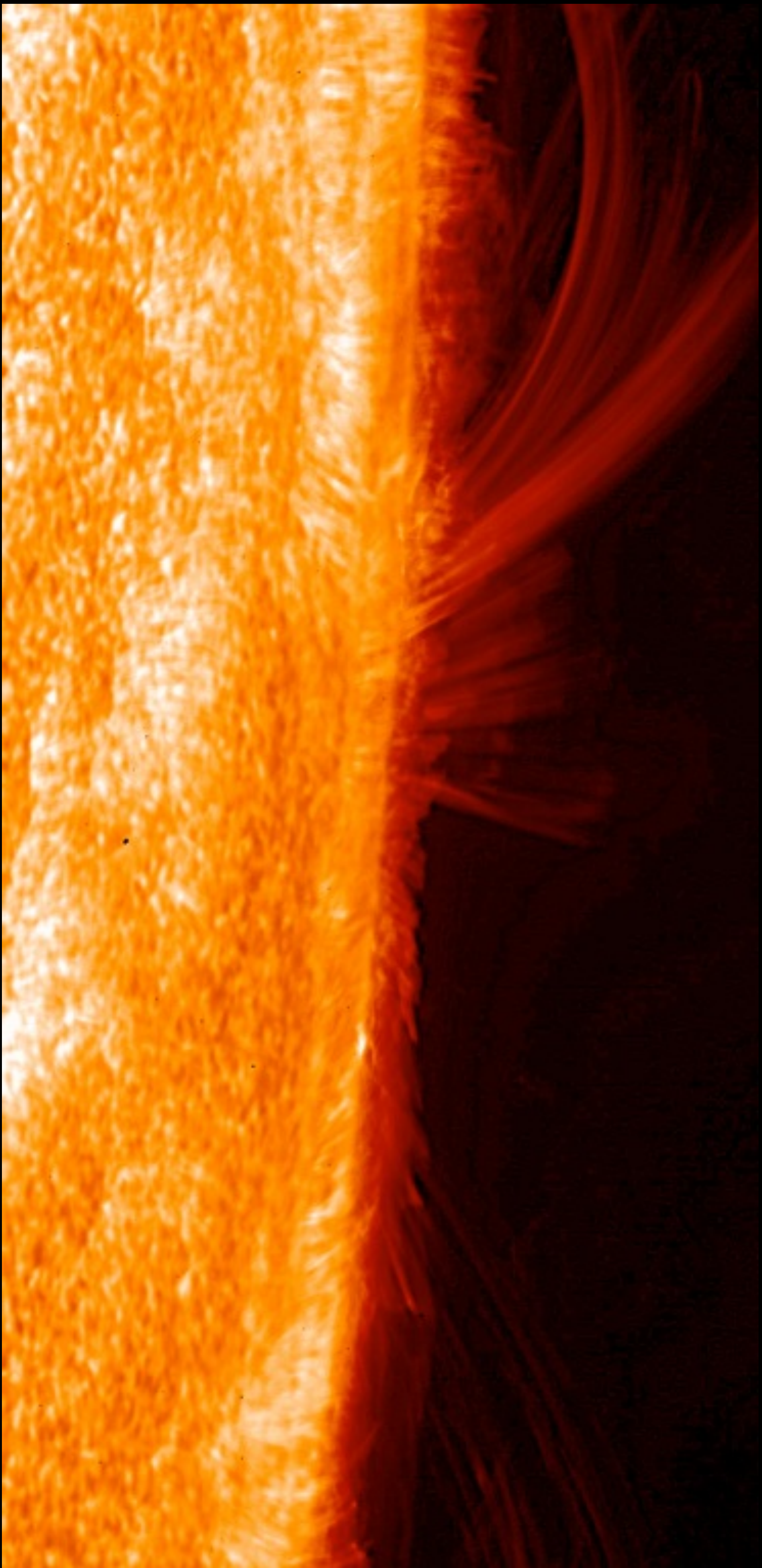

ISWI/SCOSTEP
School on Space Science

Lima, Peru
September, 2014





NCAR

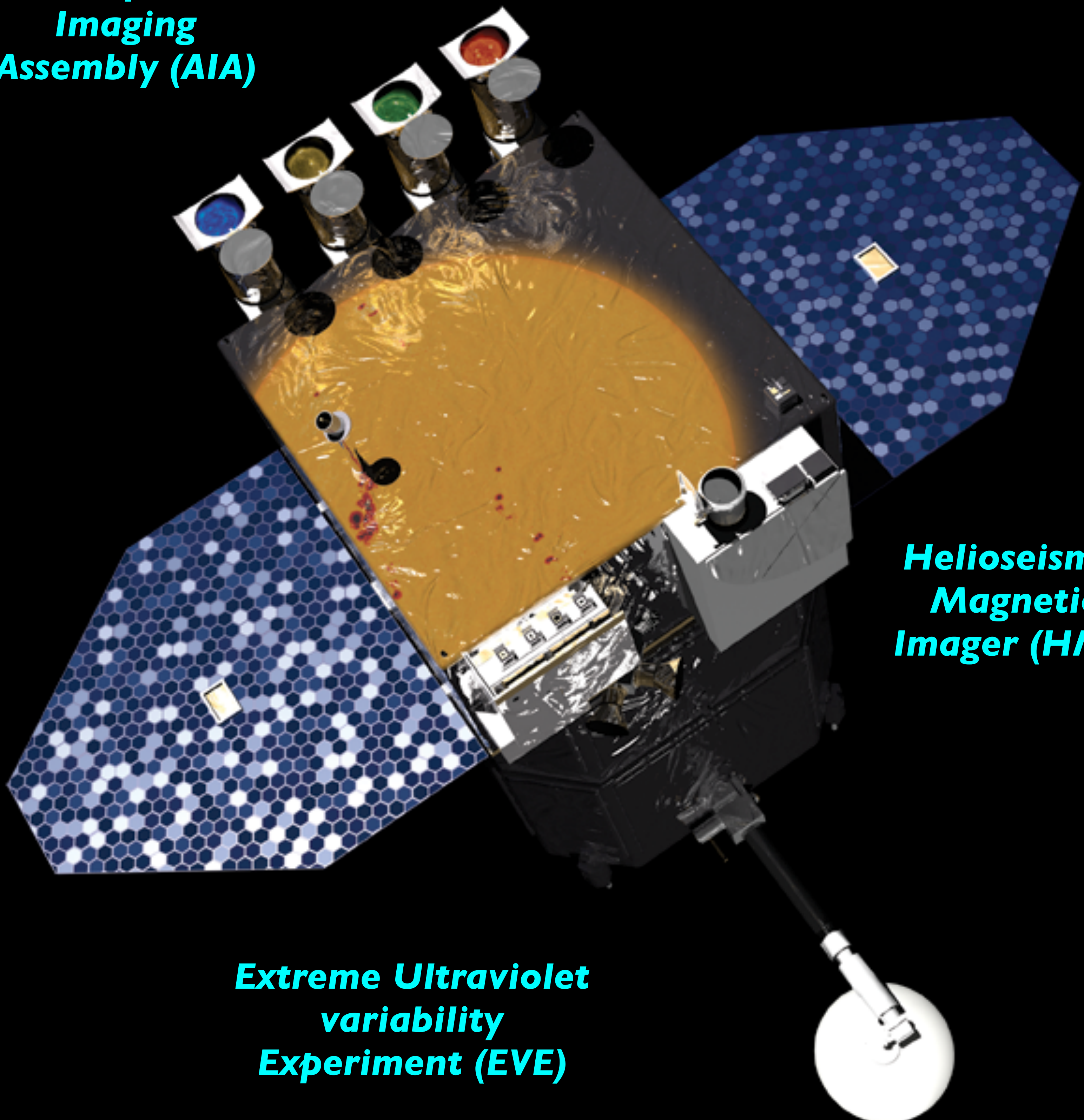


# Outline

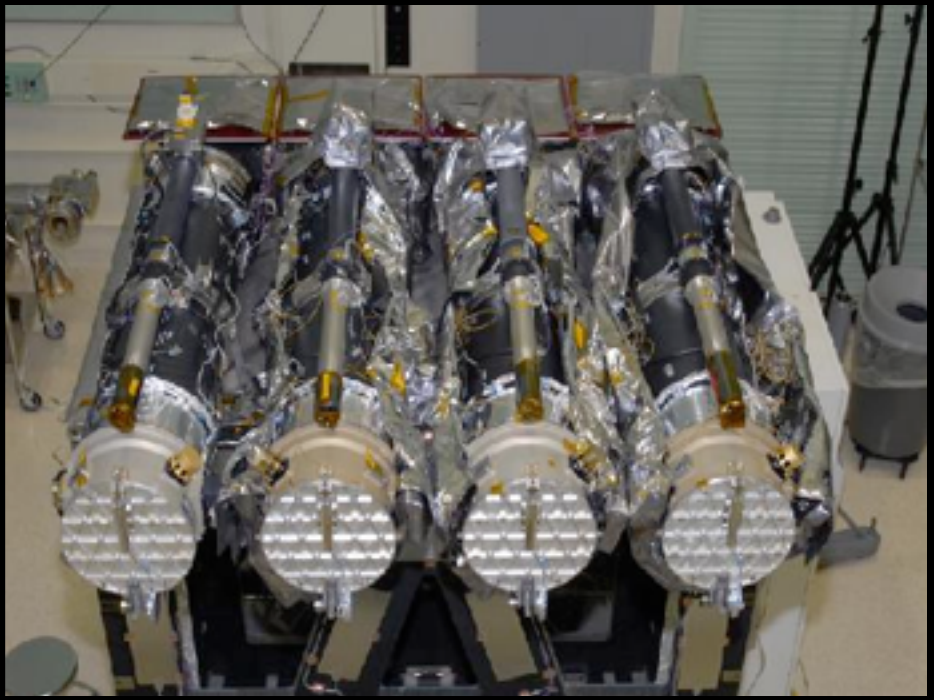
- **Observing the Sun with SDO**
  - *Illustrates the importance of multi-wavelength observations in solar physics*
  - *Demonstrates the layered nature of the solar atmosphere (while introducing some terminology)*
- **The Solar Photosphere**
  - *Transition from convective to radiative energy transport*
  - *Flux Emergence regulates solar origins of space weather*
- **Magnetic Coupling of the Solar Atmosphere**
  - *Field extrapolations*
  - *Coronal Heating*
  - *Flux Emergence*
- **The Solar Corona**
  - *Energy storage and release*

Observing the Sun with
Our newest toy

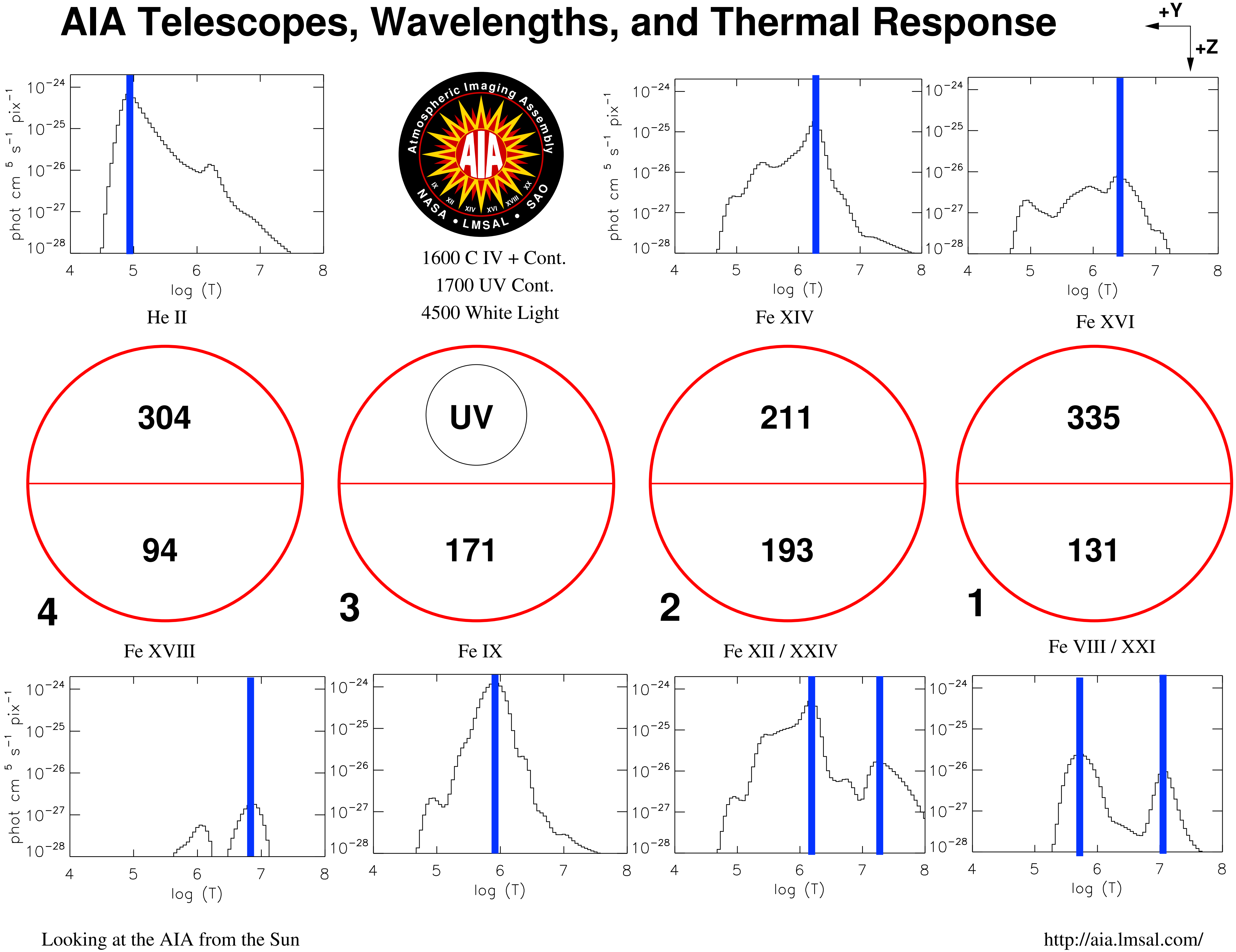
NASA's Solar Dynamics
Observatory (SDO)



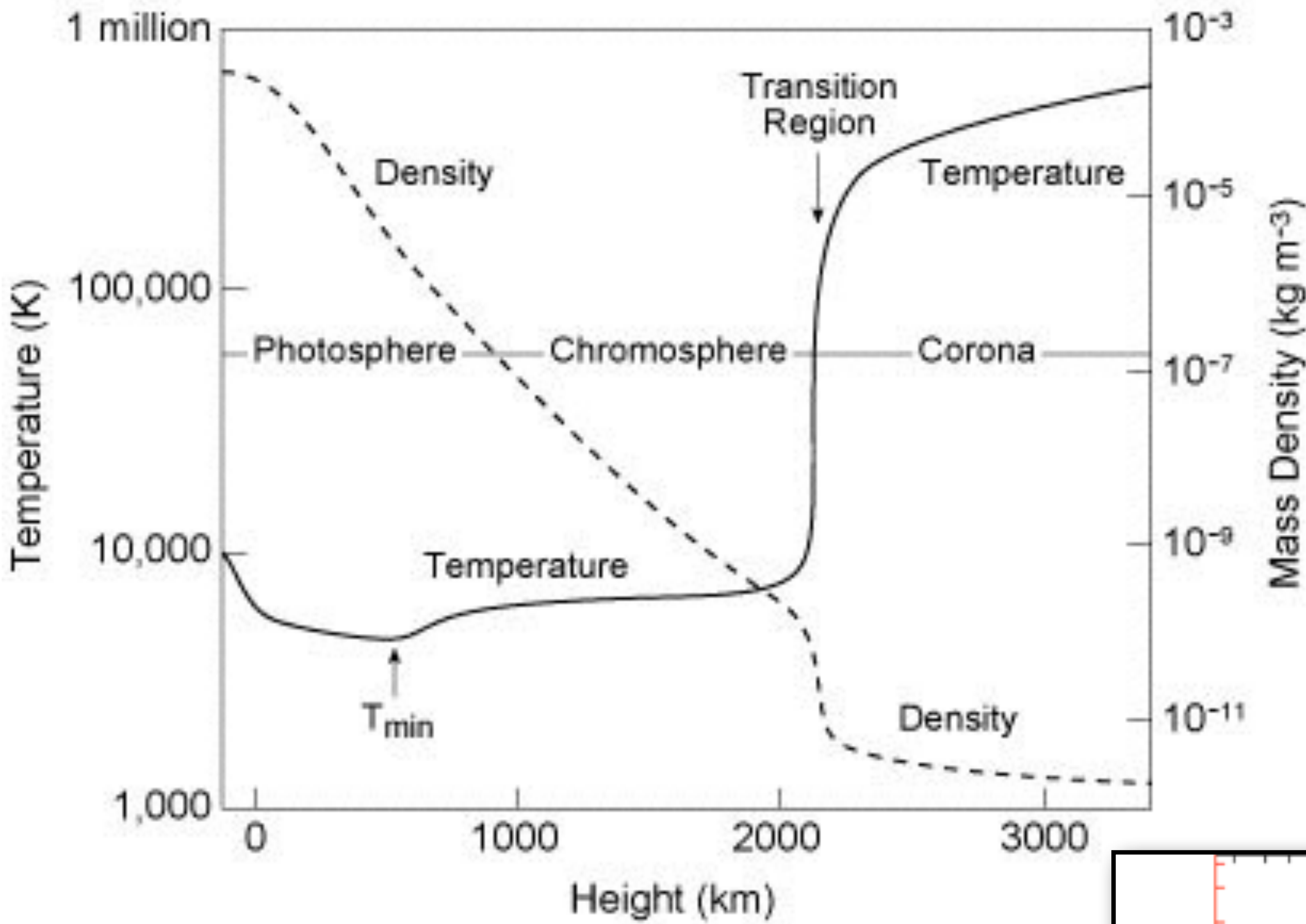

1.5 TB of data
per day!



# AIA Telescopes, Wavelengths, and Thermal Response

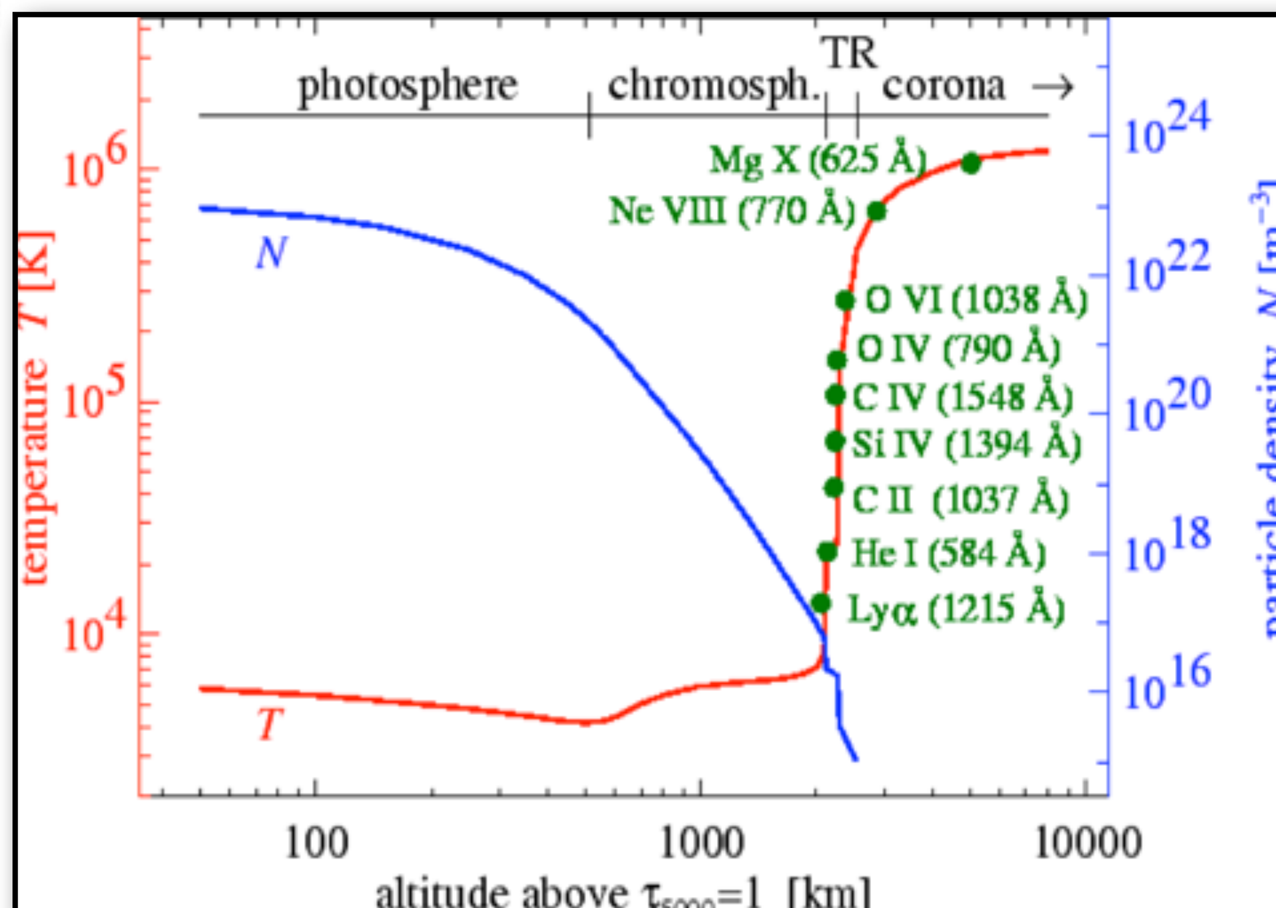



John Serafin (2011)




**_Why does the temperature increase outward?_**

**_Near the solar surface the temperature and density change rapidly: More than 2 orders of magnitude in less than 0.5% R_**



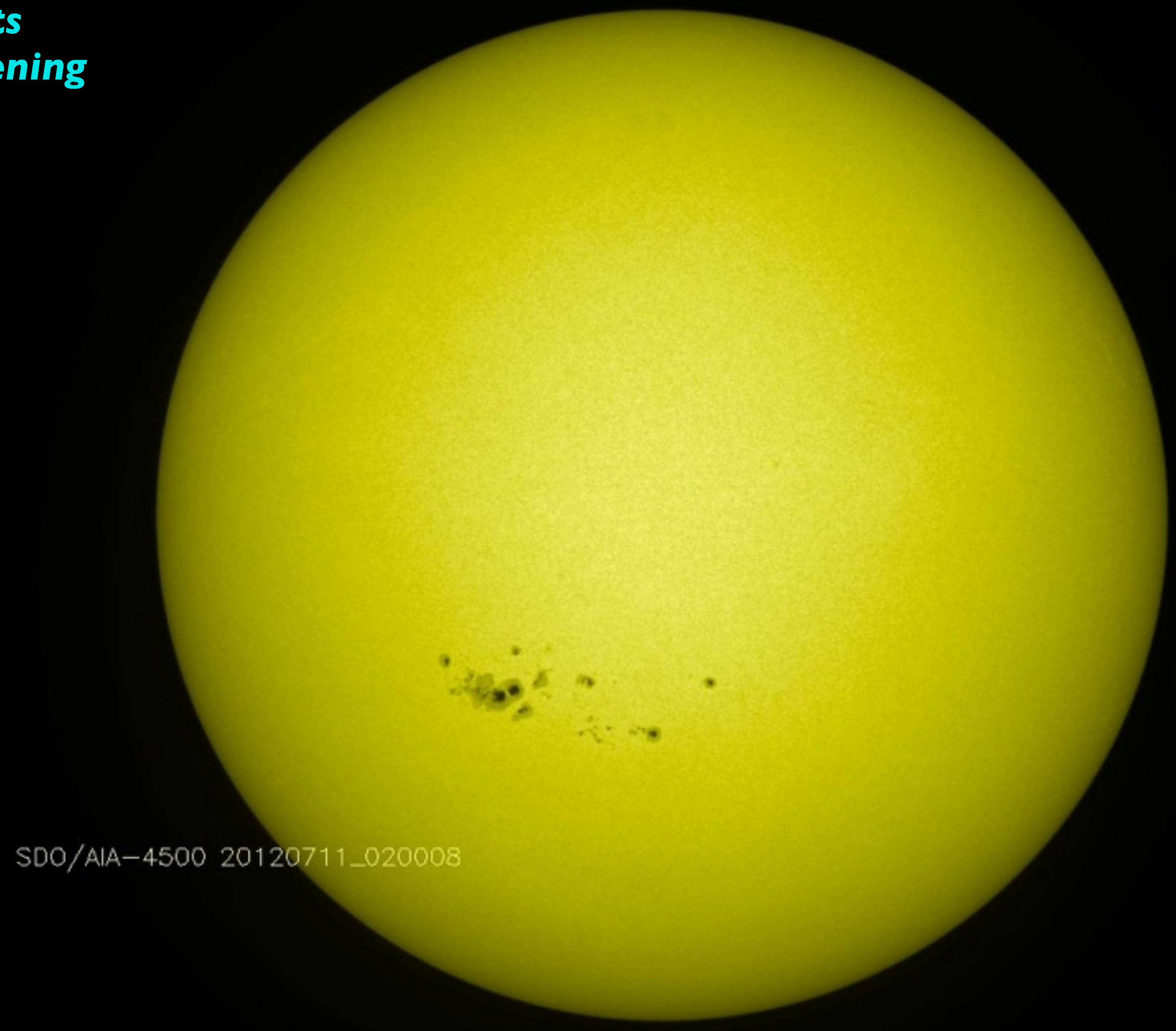

**_Temperature traces height!_**

**_Ion line emission traces Temperature!_**

***Note the***

***Sunspots***

***Limb darkening***

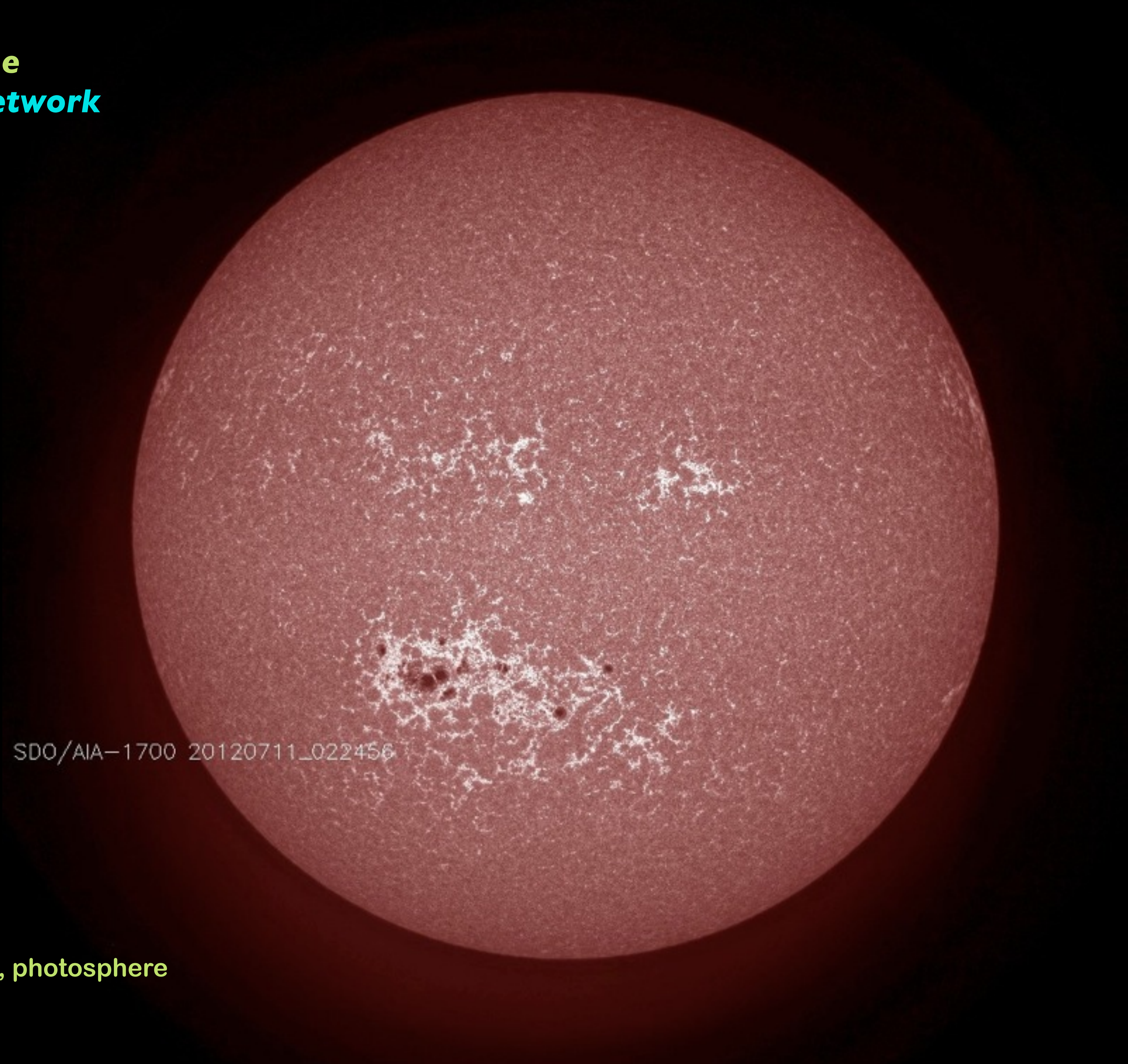



cont 4500
photosphere

Note the

Magnetic Network

Plages

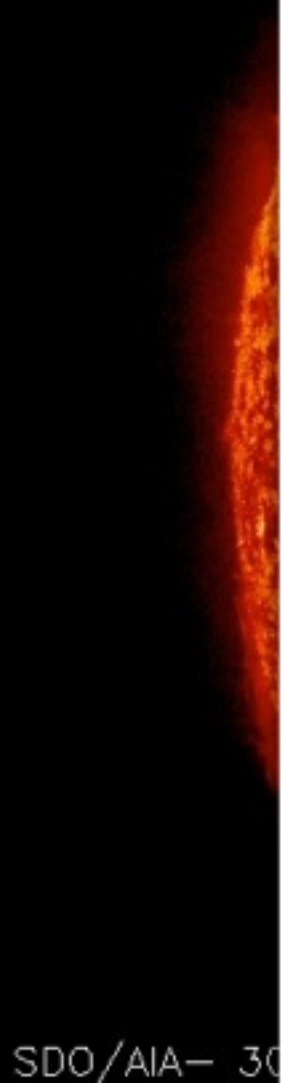


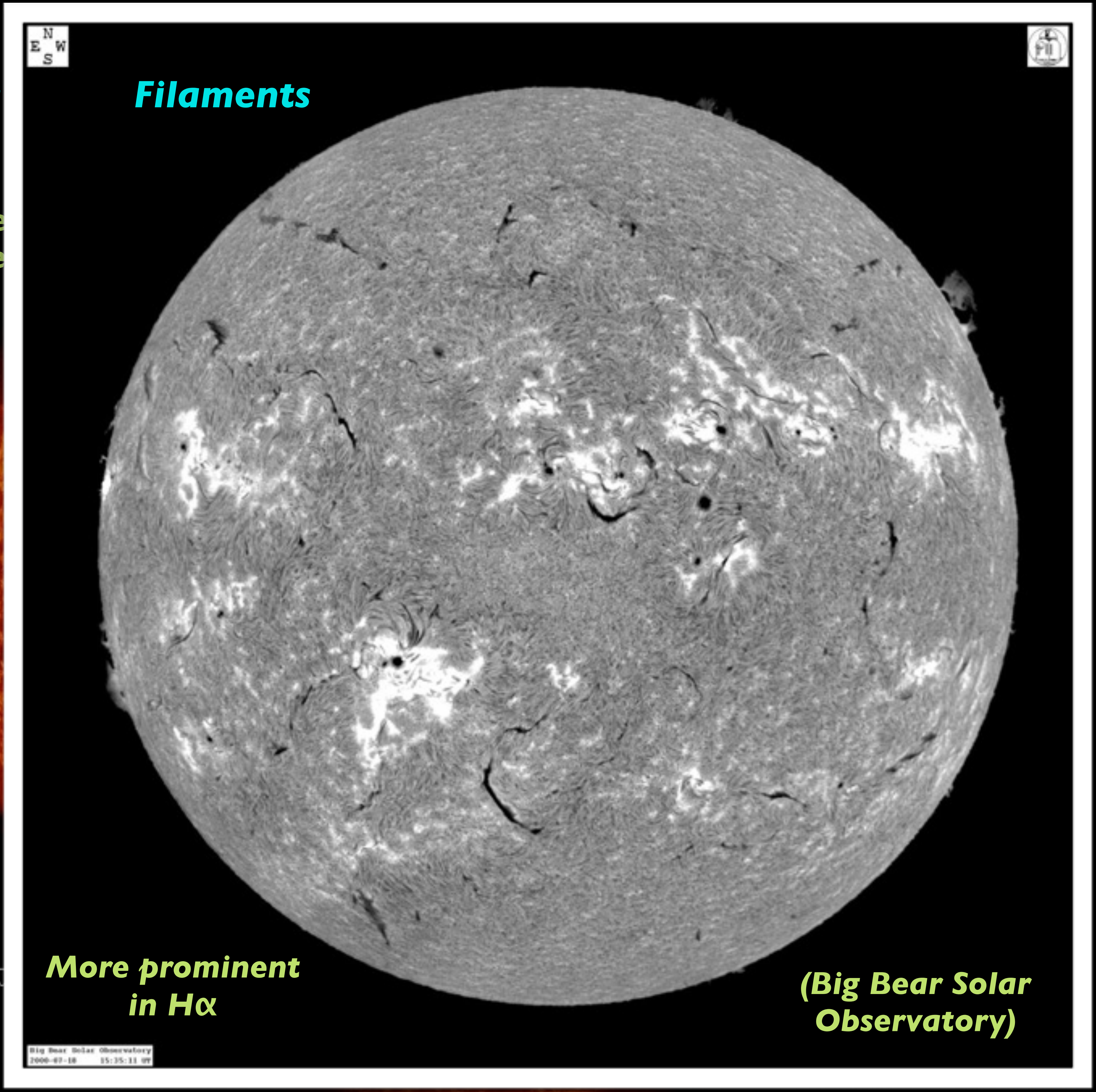

cont 1700

temperature minimum, photosphere

## Note the
## Prominences & Filaments

*(cool material suspended relatively high up;*
*same phenomena but the forme*
*is seen on the limb, against the*
*backdrop of space)*



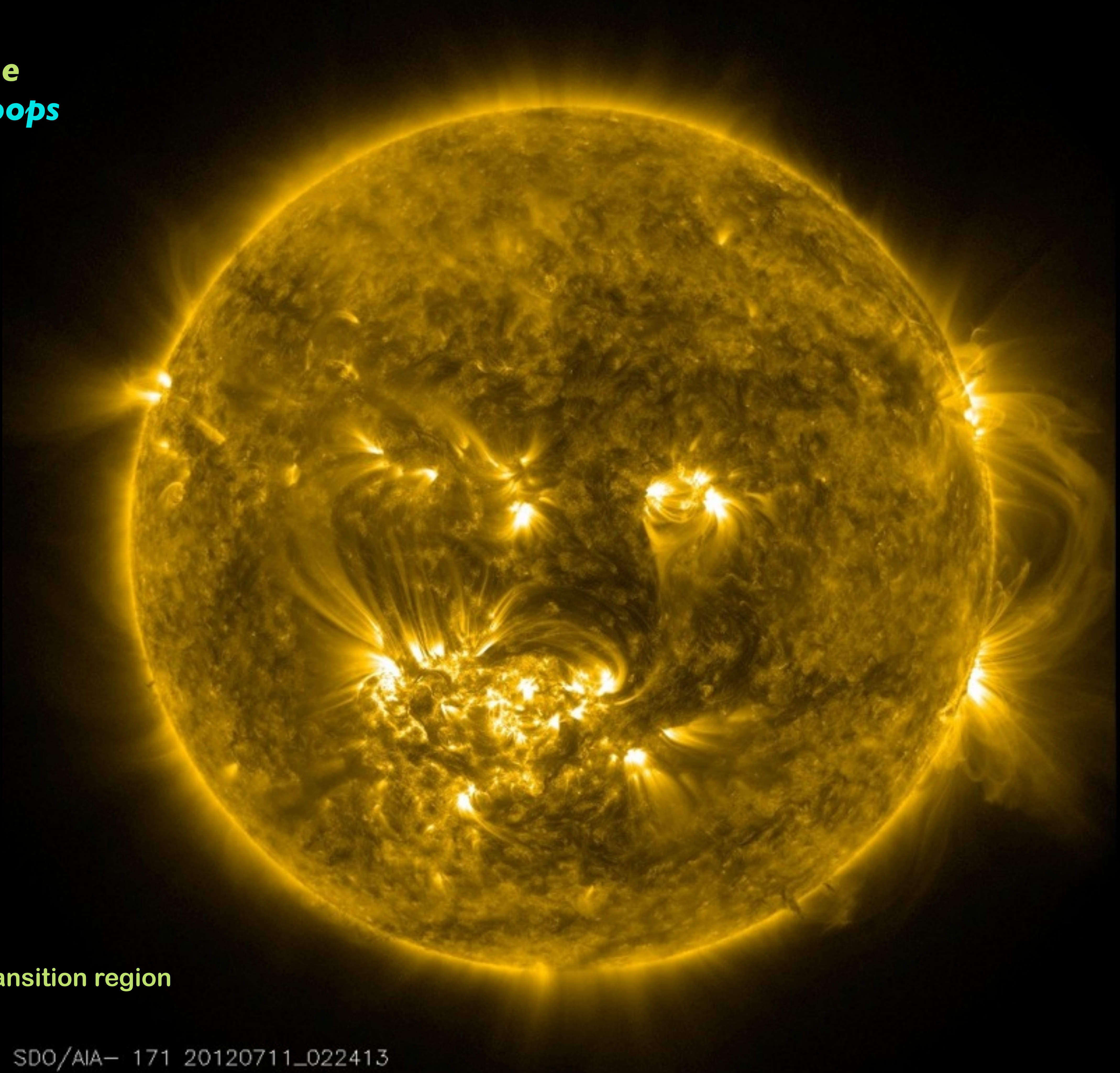

**Filaments**

**More prominent in Hα**

**(Big Bear Solar Observatory)**

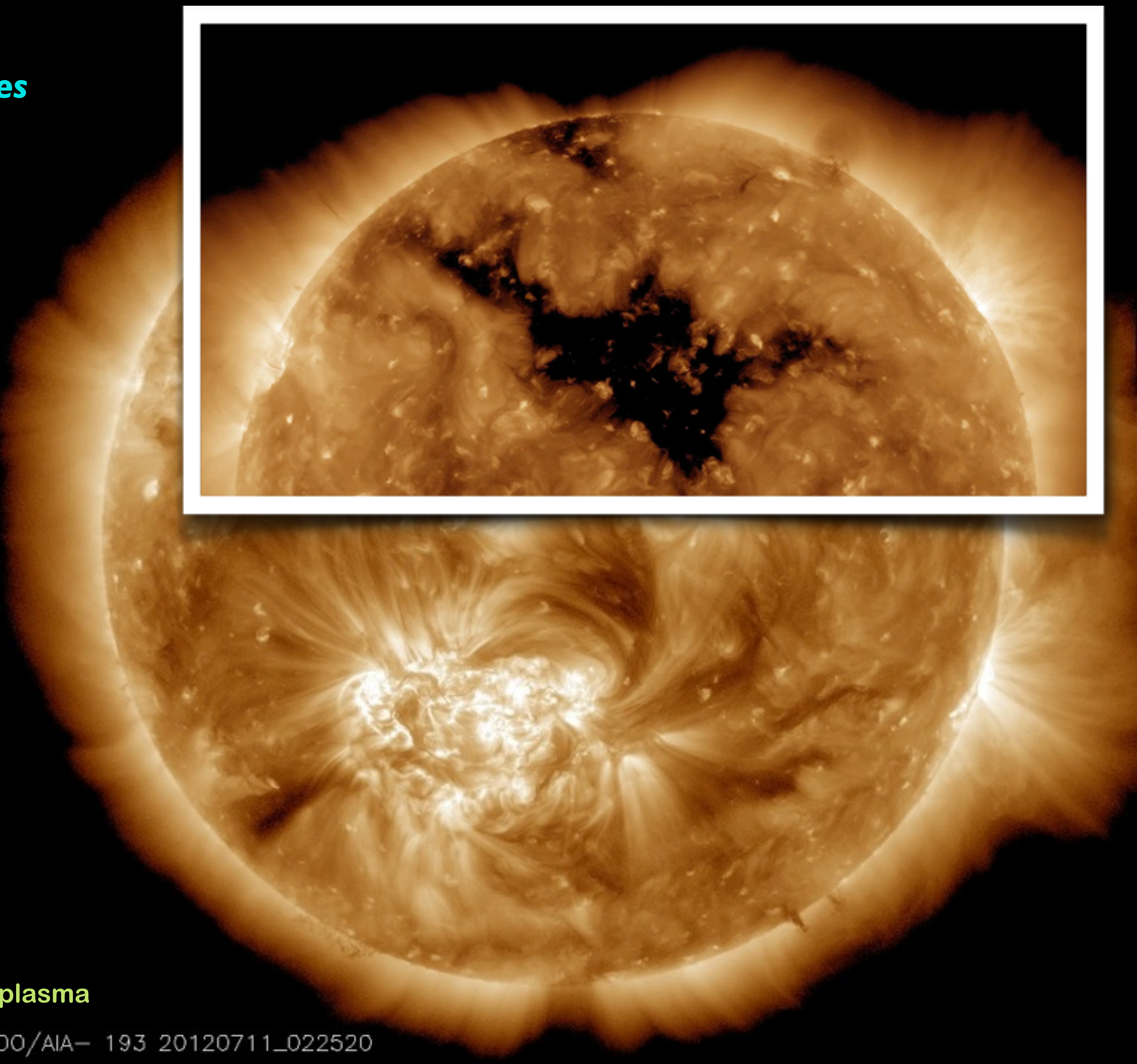
He II 304
chromosphere, transition region

*Note the*
*Coronal loops*



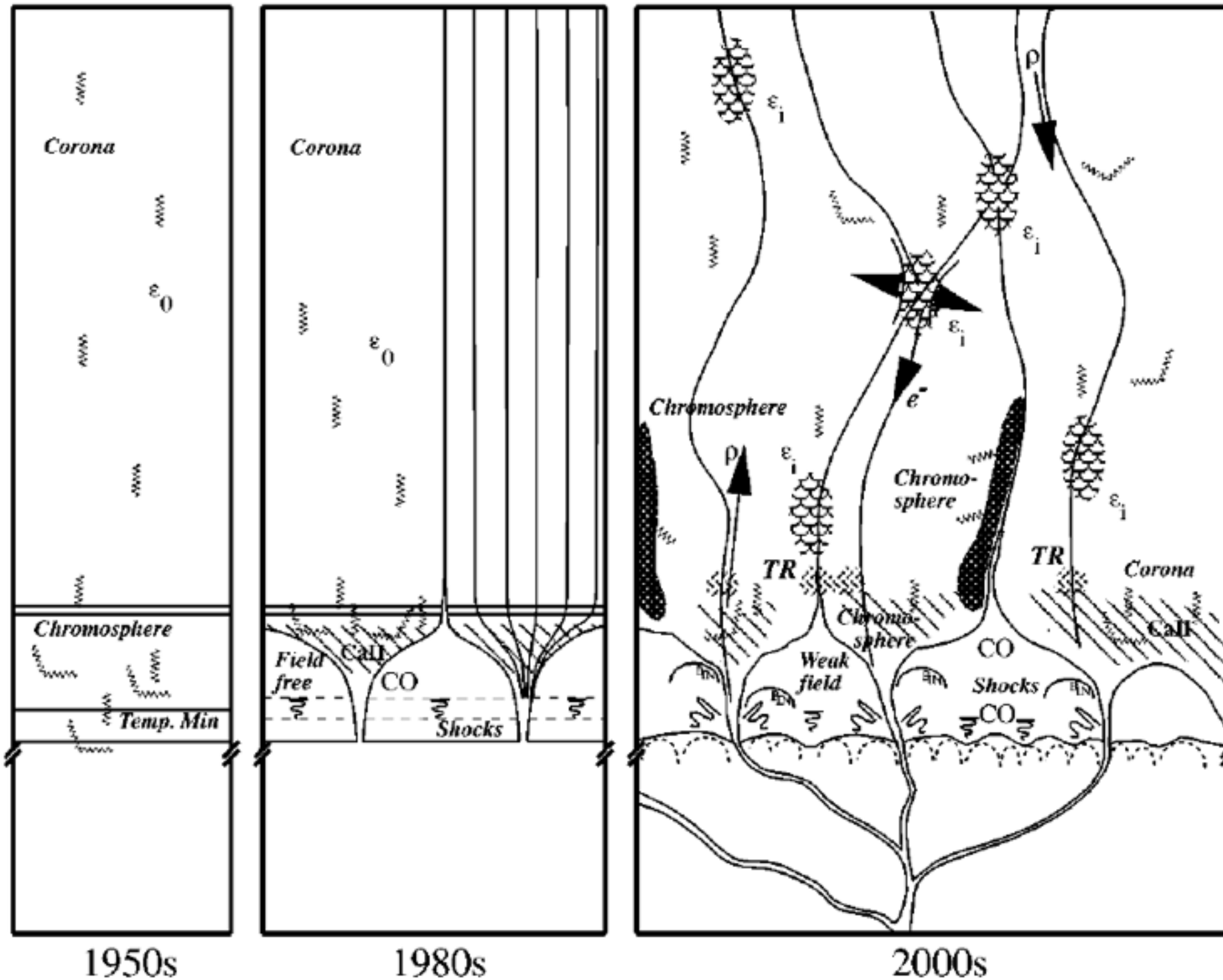

Fe IX 171
quiet corona, upper transition region

***Note the***
***Coronal holes***



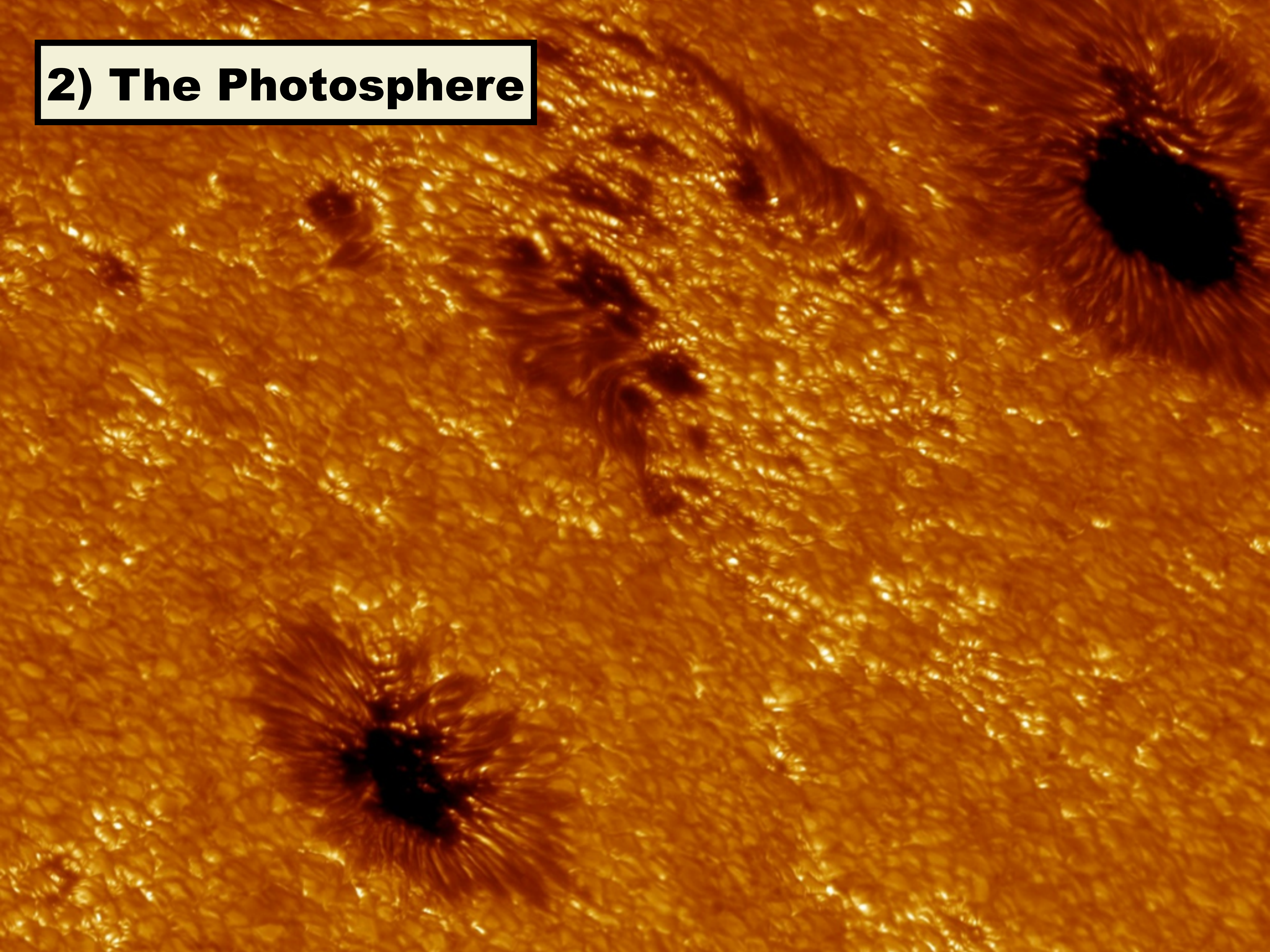

**Fe IX, XXIV 193**
**corona and hot flare plasma**

**_Don't be fooled by those 1D temperature plots: the Sun is 3D!_**
**_Magnetism shapes the structure & dynamics of the solar atmosphere_**

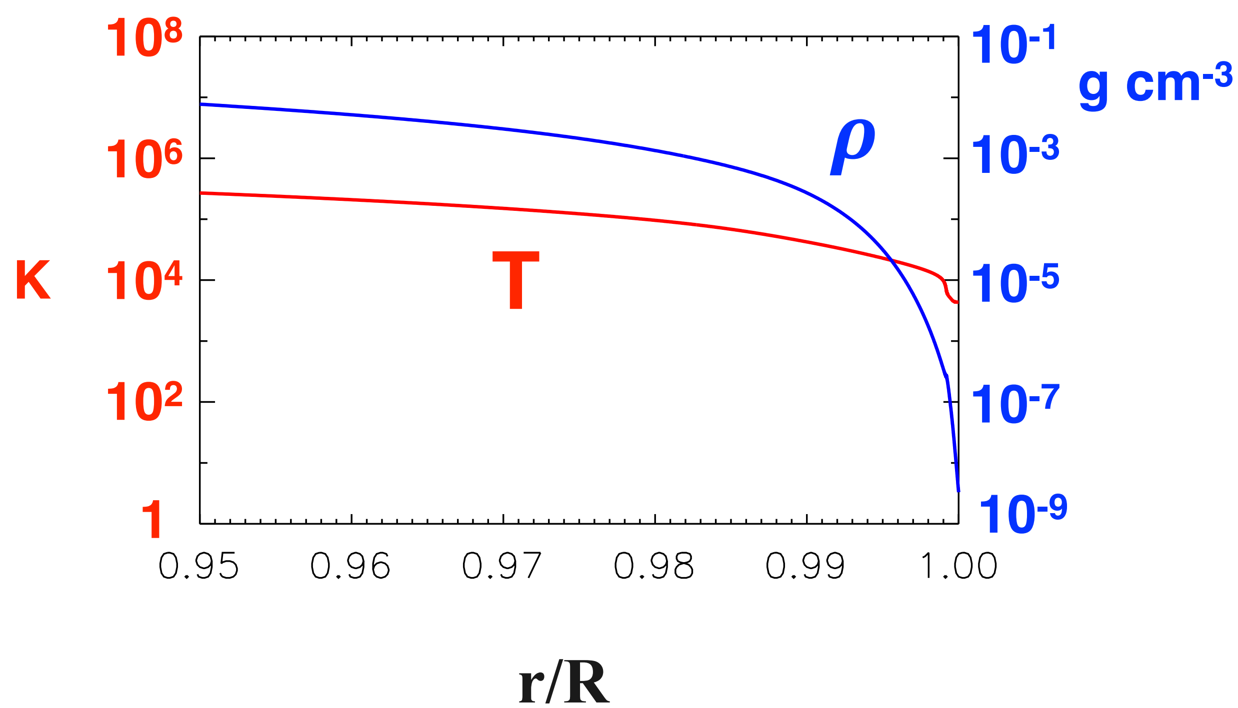



Aschwanden, Poland & Rabin (2001)

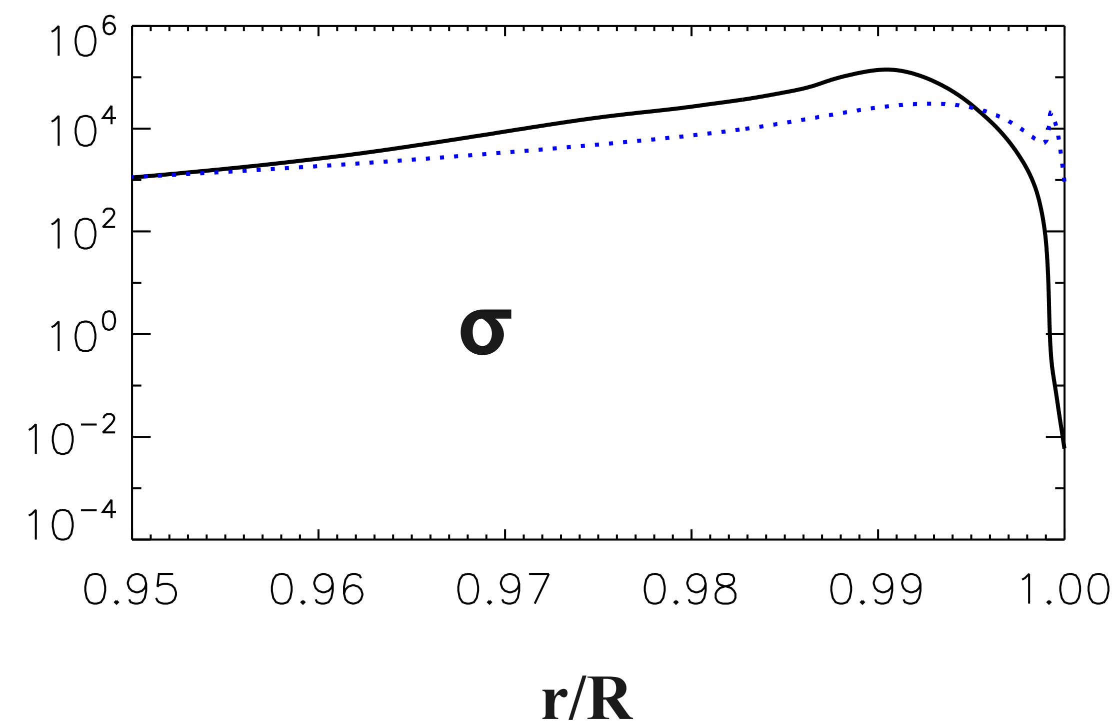
## 2) The Photosphere



# The Solar Surface




***As density and thus opacity drop, heat transport shifts from convection to radiation***




***Kramers Opacity***

***Free-free, bound-free, bound-bound***

$$\sigma \propto \rho T^{-3.5}$$

**$H^-$ *Opacity***

***Extra electron in a Hydrogen atom gets knocked off by a passing photon***

$$\sigma \propto \rho^{1/2} T^9$$

# The Solar Surface

***Basic radiative transfer equation***

**specific intensity** (J s$^{-1}$ m$^{-2}$ ster$^{-1}$ Hz$^{-1}$)

$$\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu$$

**path** (m)

**emission, absorption coefficients**

$$\alpha \propto \rho\sigma$$

**Optical depth!**

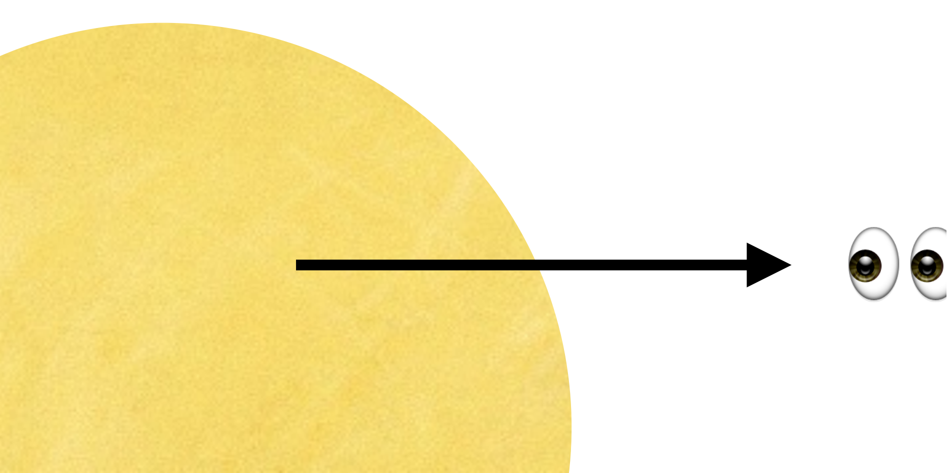
$$\tau = \int_{s_0}^{s} \alpha_\nu(s')ds'$$

$$\frac{dI_\nu}{d\tau} = S_\nu - I_\nu$$

$$S_\nu = \frac{j_\nu}{\alpha_\nu}$$

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)} S_\nu(\tau'_\nu)d\tau'$$

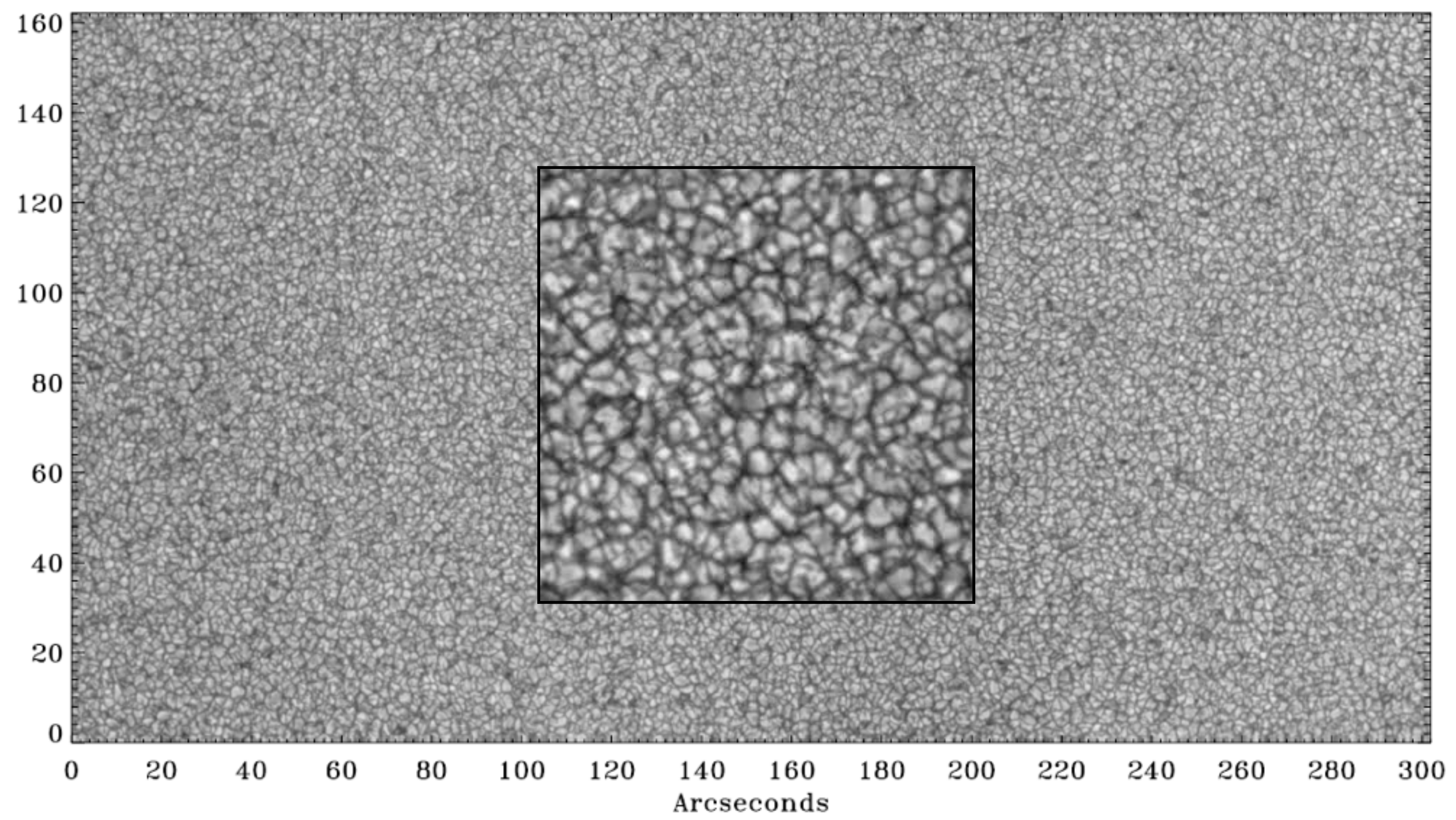
***Solar photosphere ("surface") is defined as where*** $\tau = 1$



***This is where the (visible) light that reaches our eyes comes from***

# Granulation in the Quiet Sun

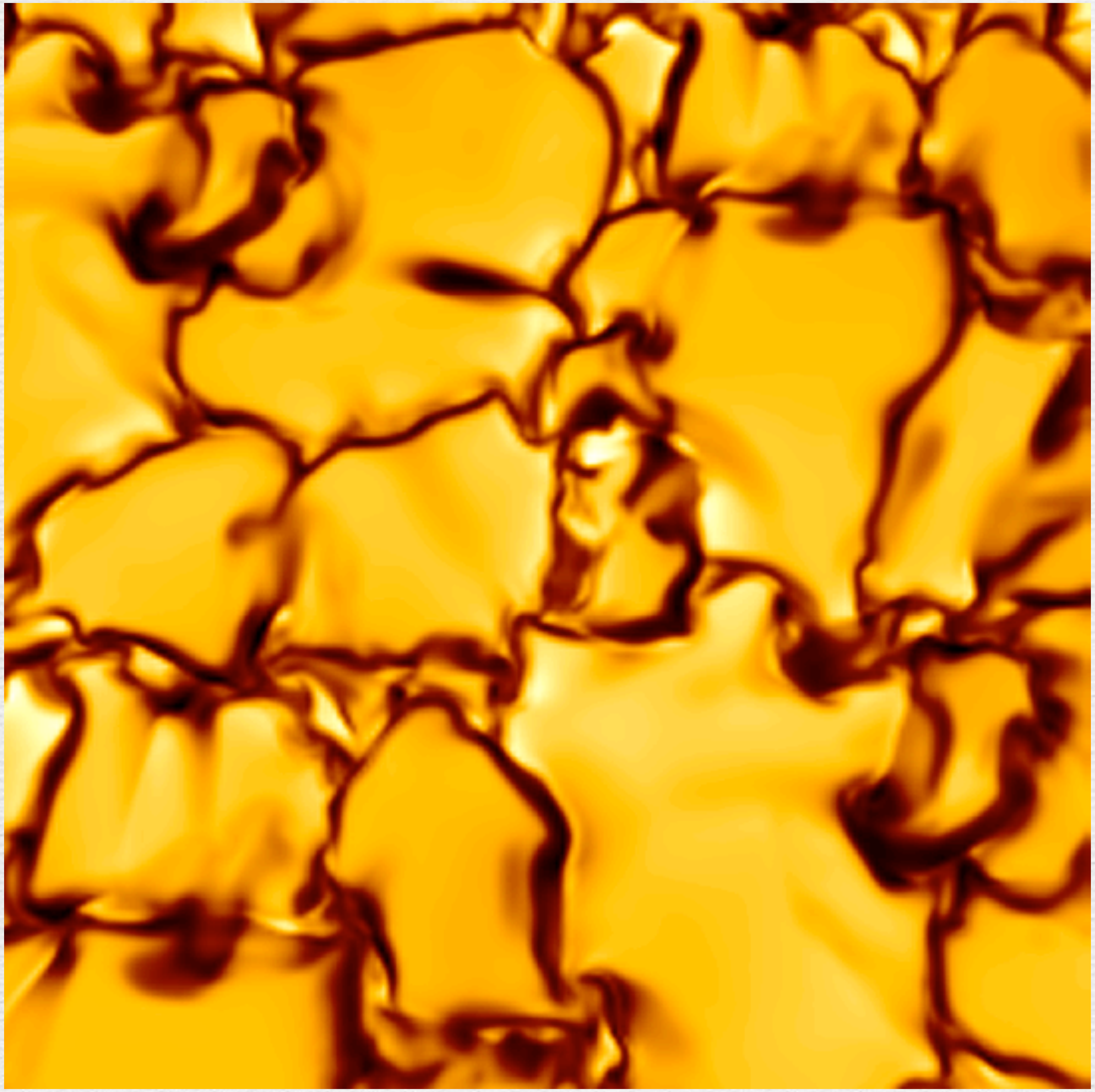
Lites et al (2008)



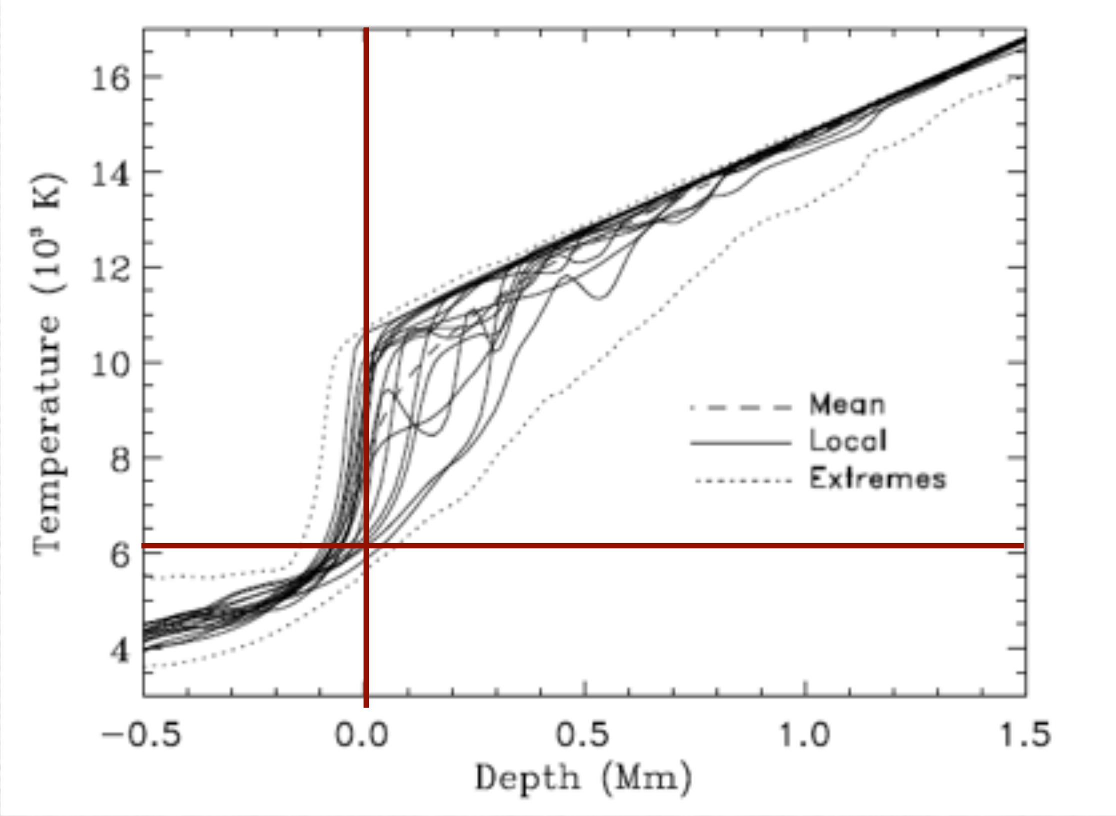

$L \sim$ 1-2 Mm
$U \sim$ 1 km s$^{-1}$
t ~ 10-15 min

***Dominant size scale of solar convection***

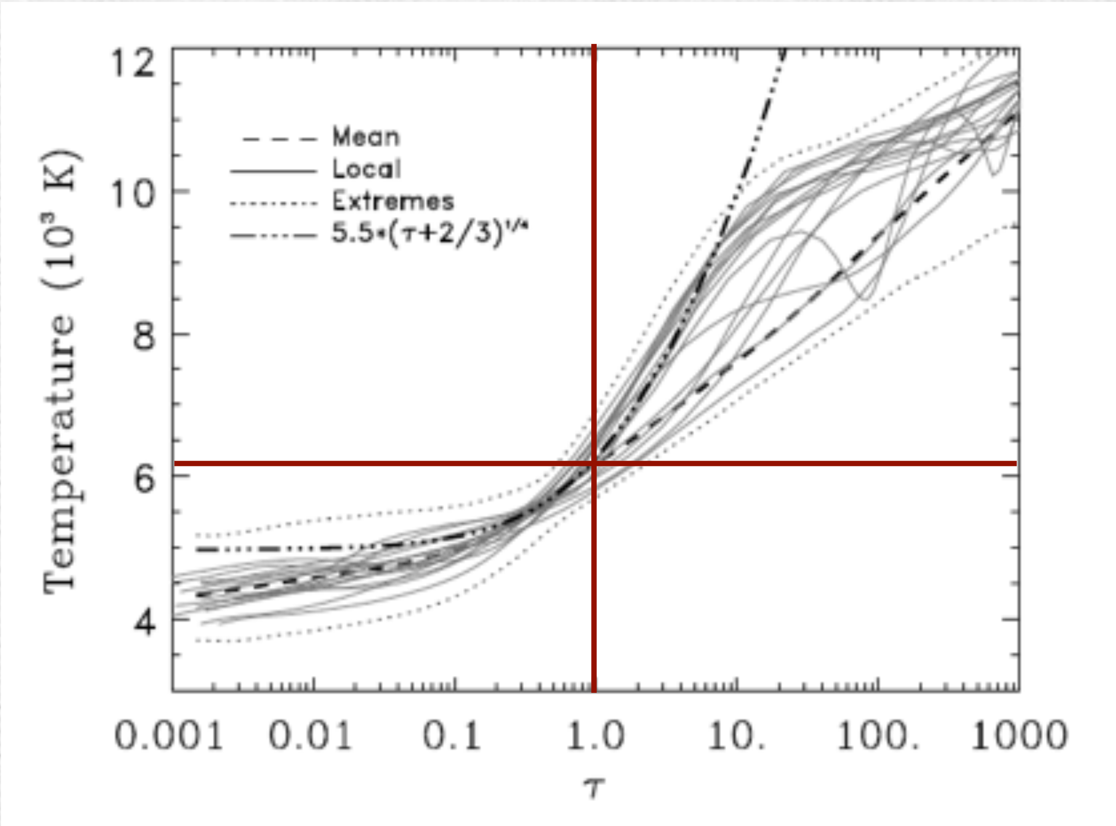
# The Surface of the Sun is Corregated!



Carlsson et al. (2004)




Stein & Nordlund (1998)



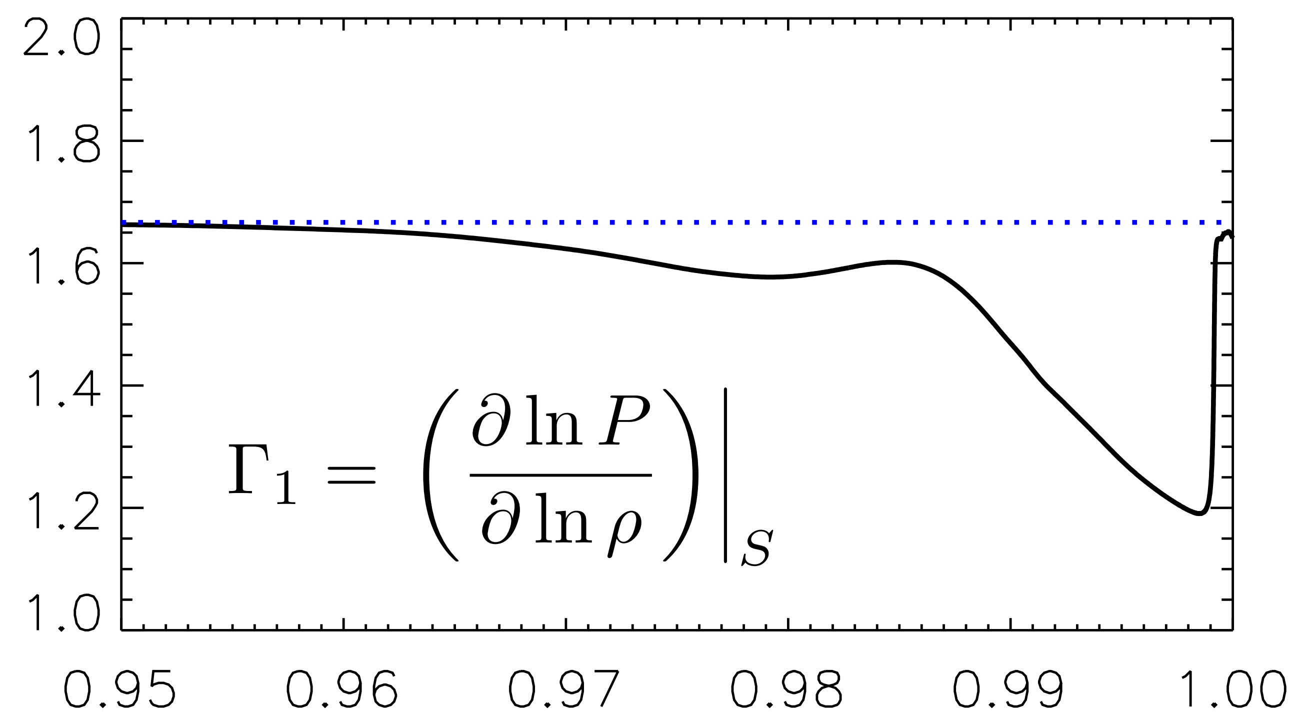

***Photosphere depressed in downflow lanes even without magnetism***
***Photospheric temperature variations relatively small***

***$H^-$ opacity ~ $T^9$***

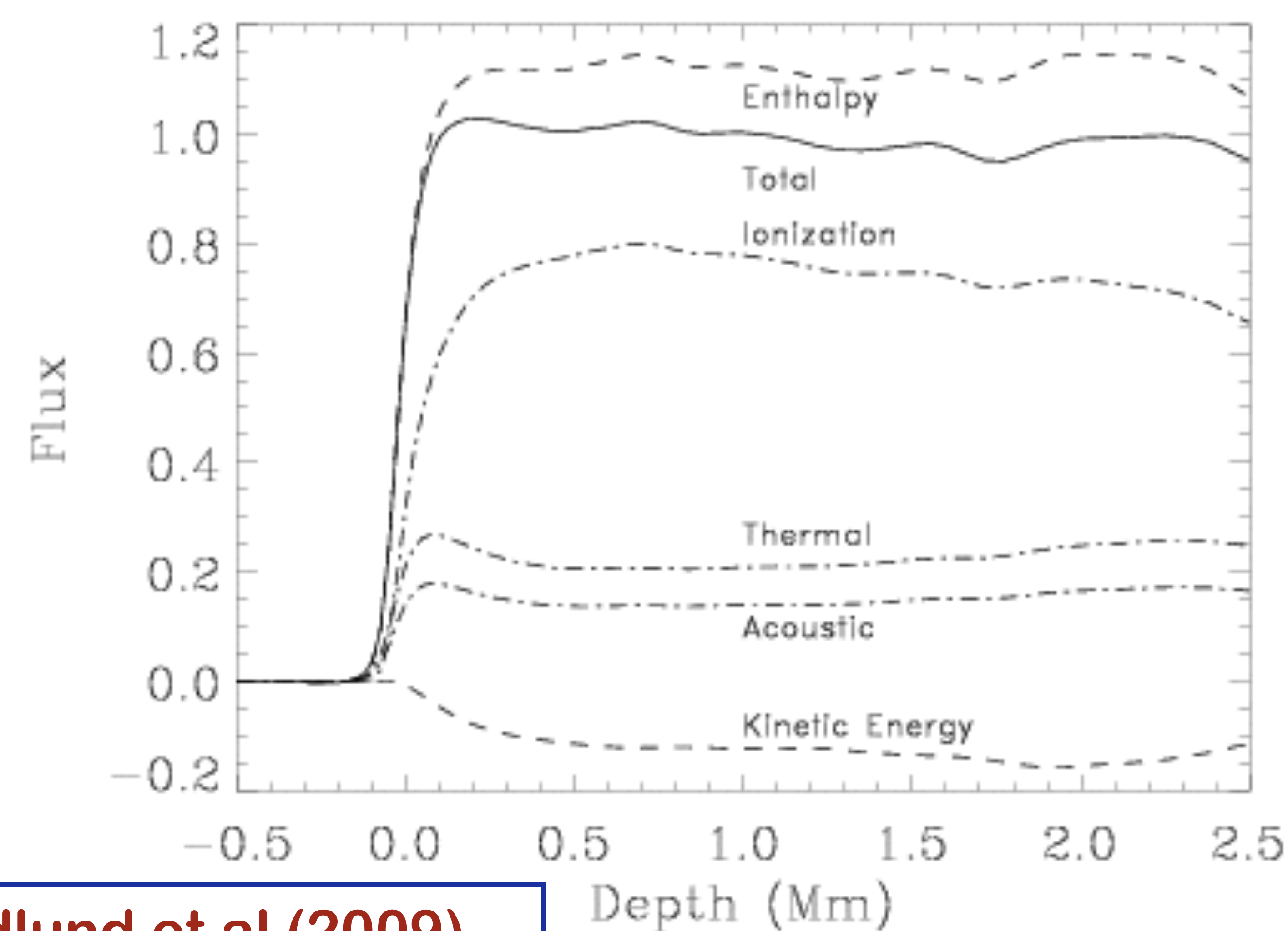
**Another consequence of lower T**

**Ions start to recombine!**

**Equation of state changes (no longer an ideal monatomic gas)**




**Latent heat contributes substantially to energy flux**




Nordlund et al (2009)

**Partial Ionization**

**Eventually leads to departures from ideal MHD in the chromosphere (ion-neutral friction)**

# Scale Selection: Why 1 Mm?

***Granulation is driven by strong radiative cooling in the photosphere***

***Downflows dominate buoyancy work***

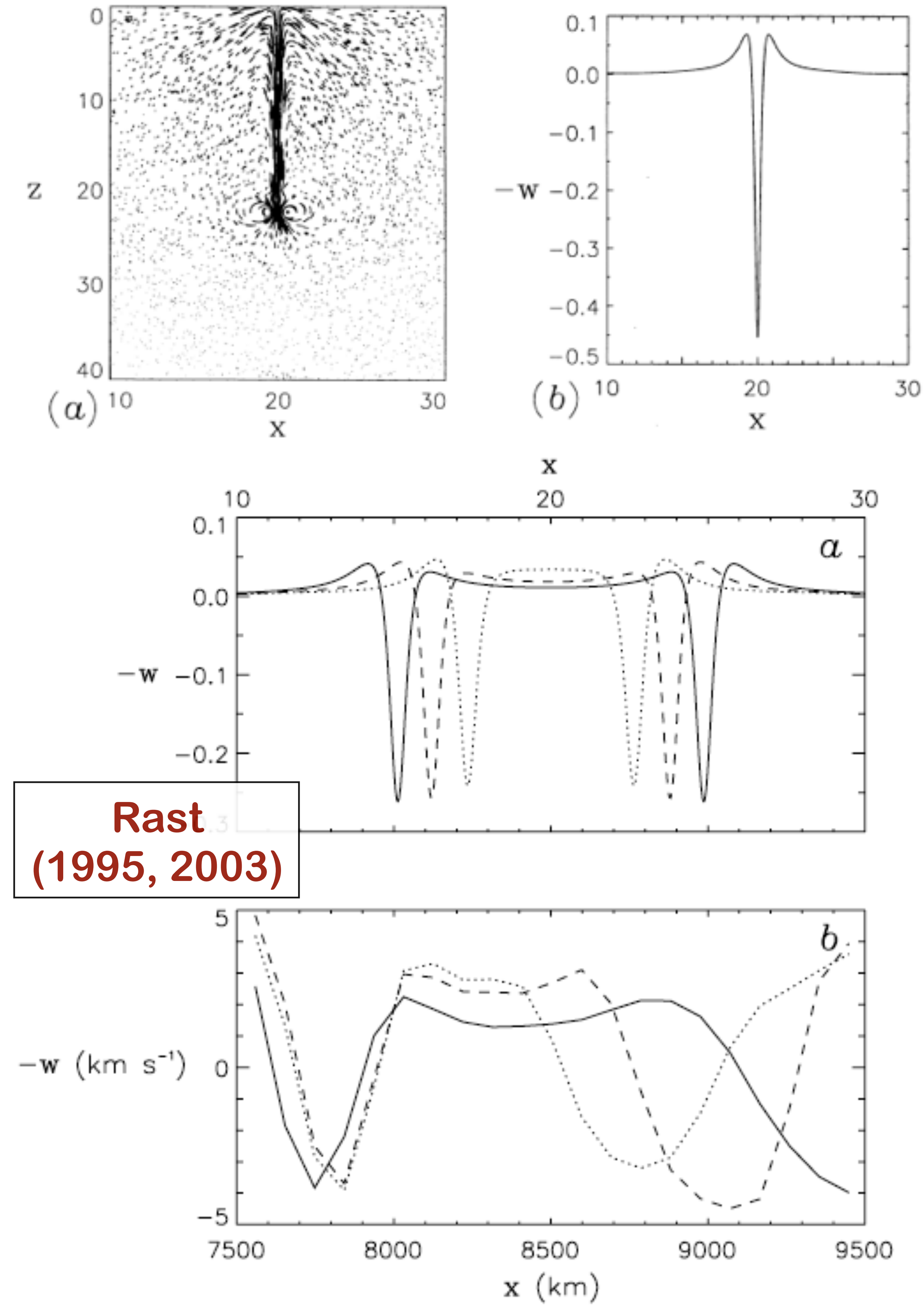
***Upflows are largely a passive response induced by horizontal pressure gradients; peak velocities occur adjacent to downflows***

***When granules get too wide, radiative cooling overcomes the convective flux coming up from below, reversing the buoyancy driving in the center of the granule***

***Upflow becomes downflow and the granule bisects***
***(exploding granules)***

$$\rho v_z y N_A \chi_H \gtrsim \sigma T^4$$

$$L \sim D \frac{v_h}{v_z} \qquad v_h \lesssim c_s \qquad D \sim H_\rho$$



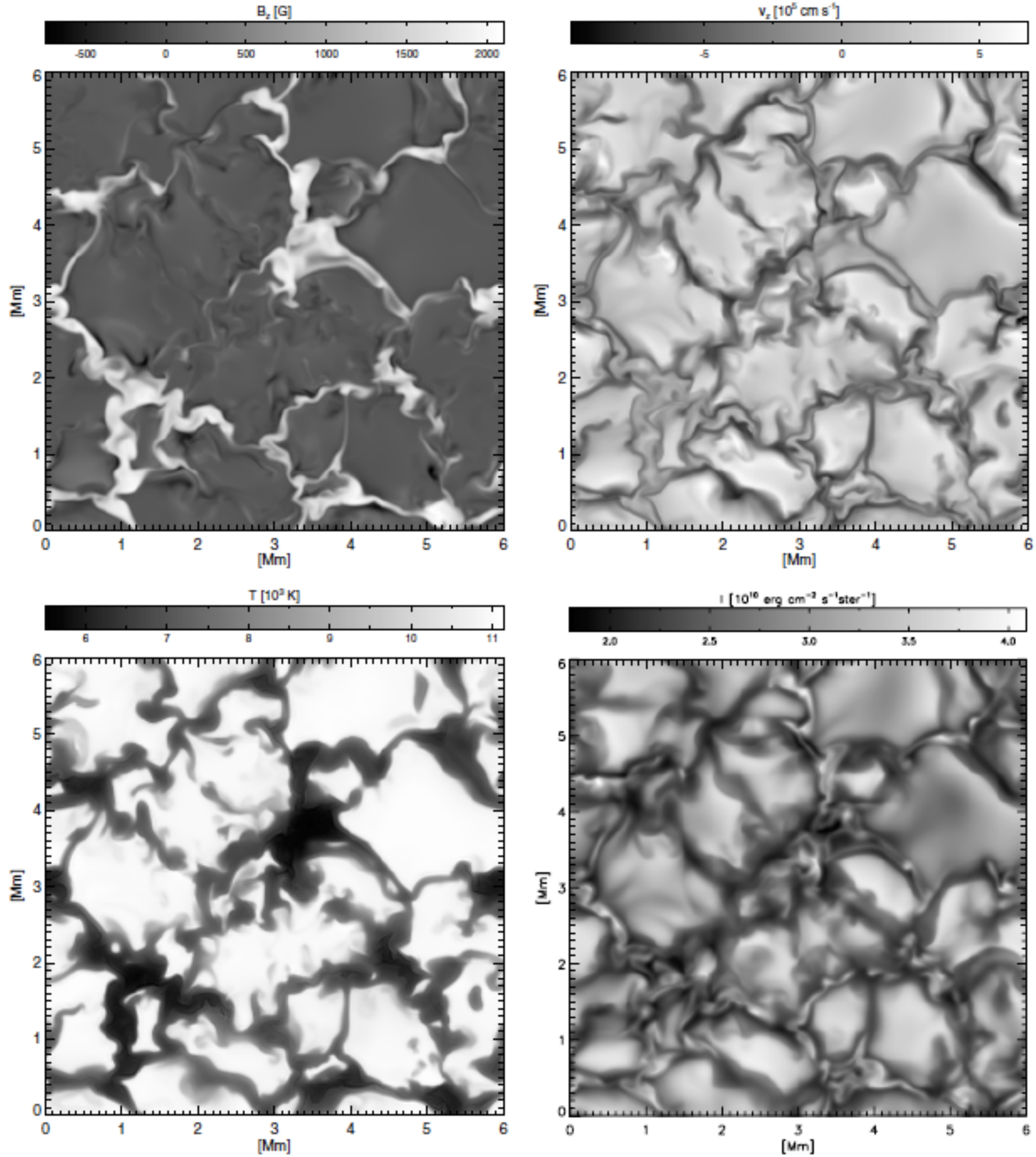
# Radiative MHD Simulations of Solar Granulation

***Upflows***
***warm, bright***

***Downflows***
***cool, dark***

***Vertical magnetic fields swept to downflow lanes by converging horizontal flows***

***Bright spots in downflow lanes attributed to magnetism***




Vogler et al. (2005)

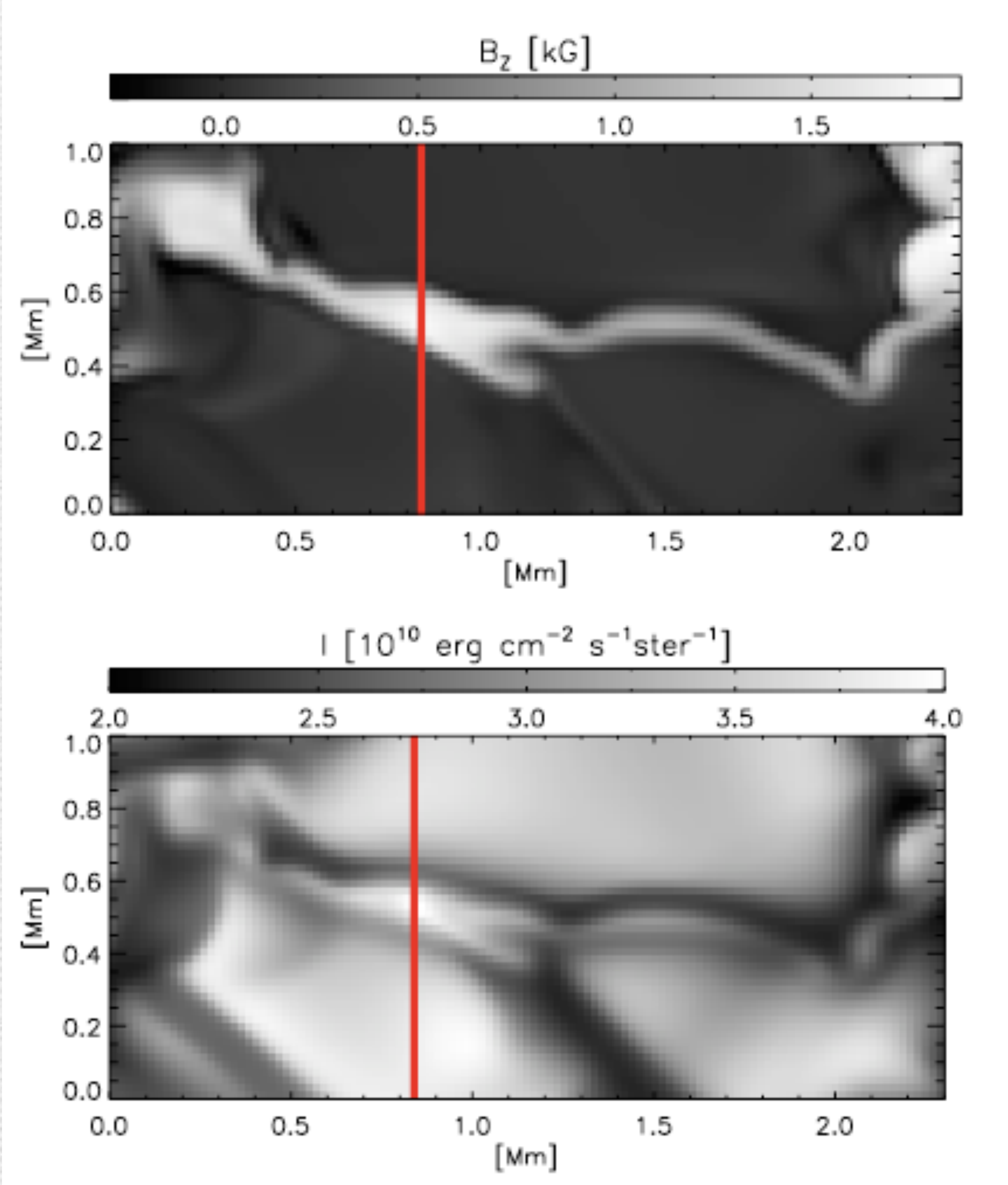
# Cool doesn't necessarily mean dark

***Channelling of radiation in magnetic flux concentrations ($B_z > 1$ kG)***

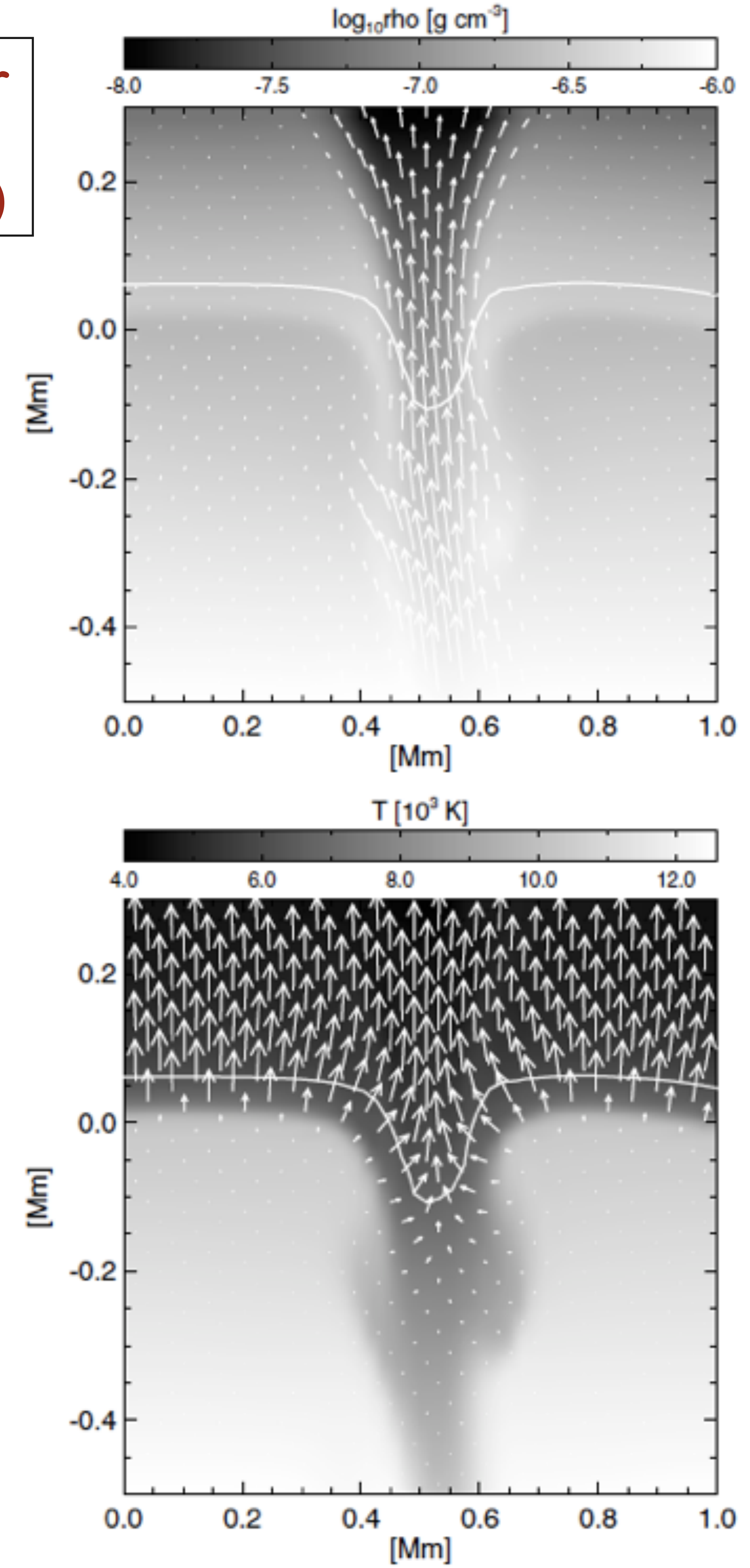
***Viewed at an angle they look brighter still***

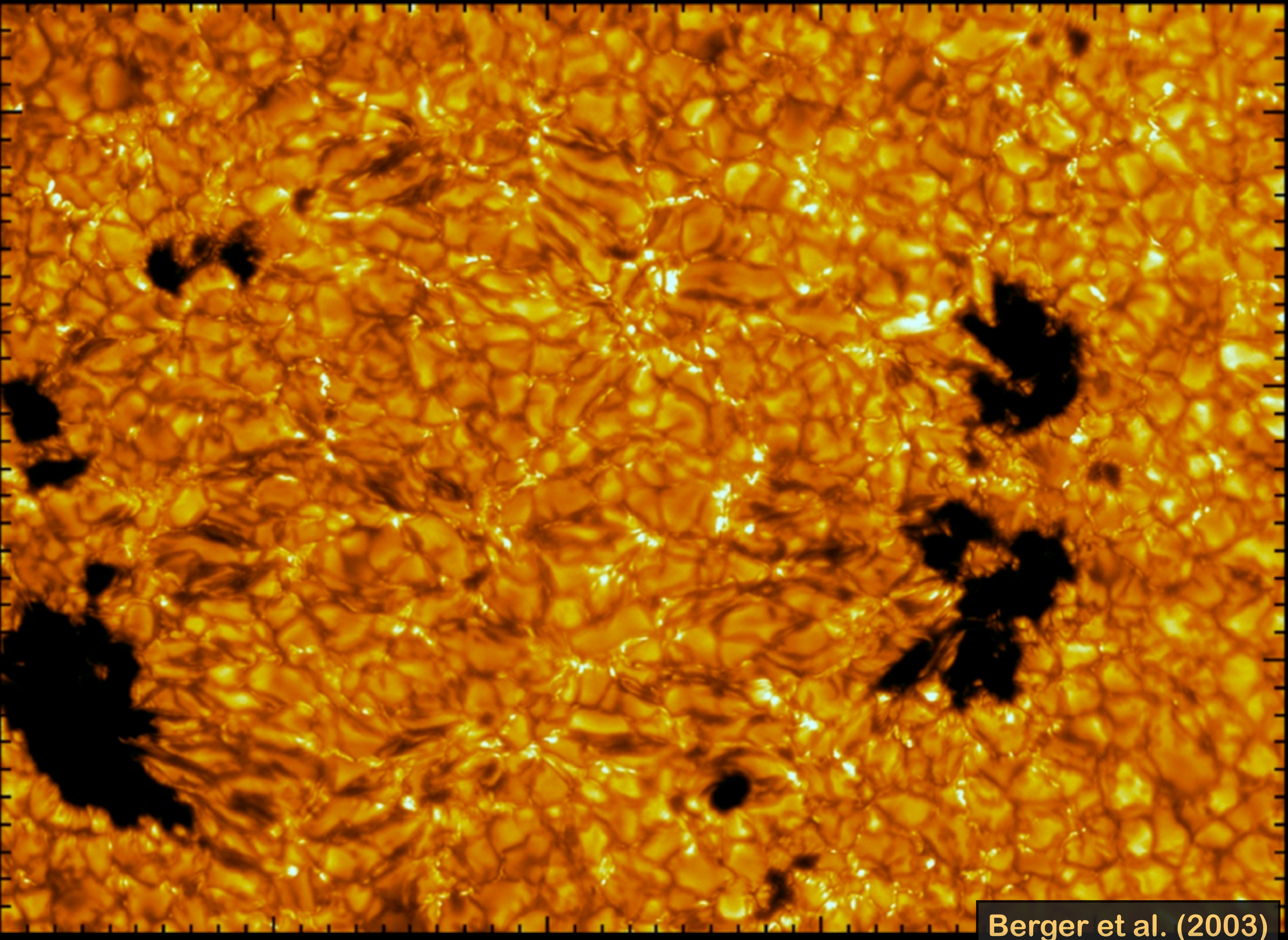
***Faculae***

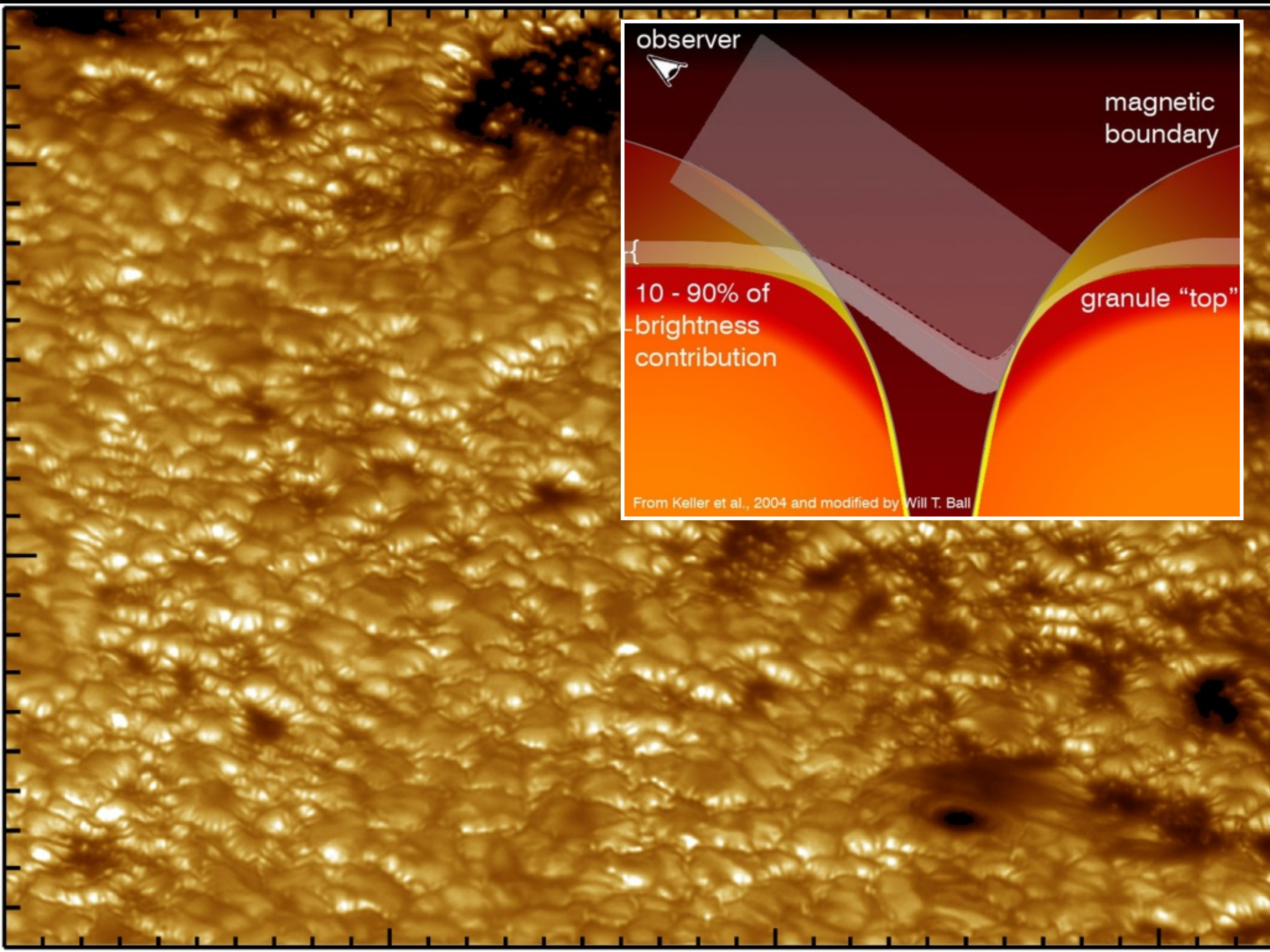
Keller et al (2004)




Vogler et al. (2005)




Berger et al. (2003)

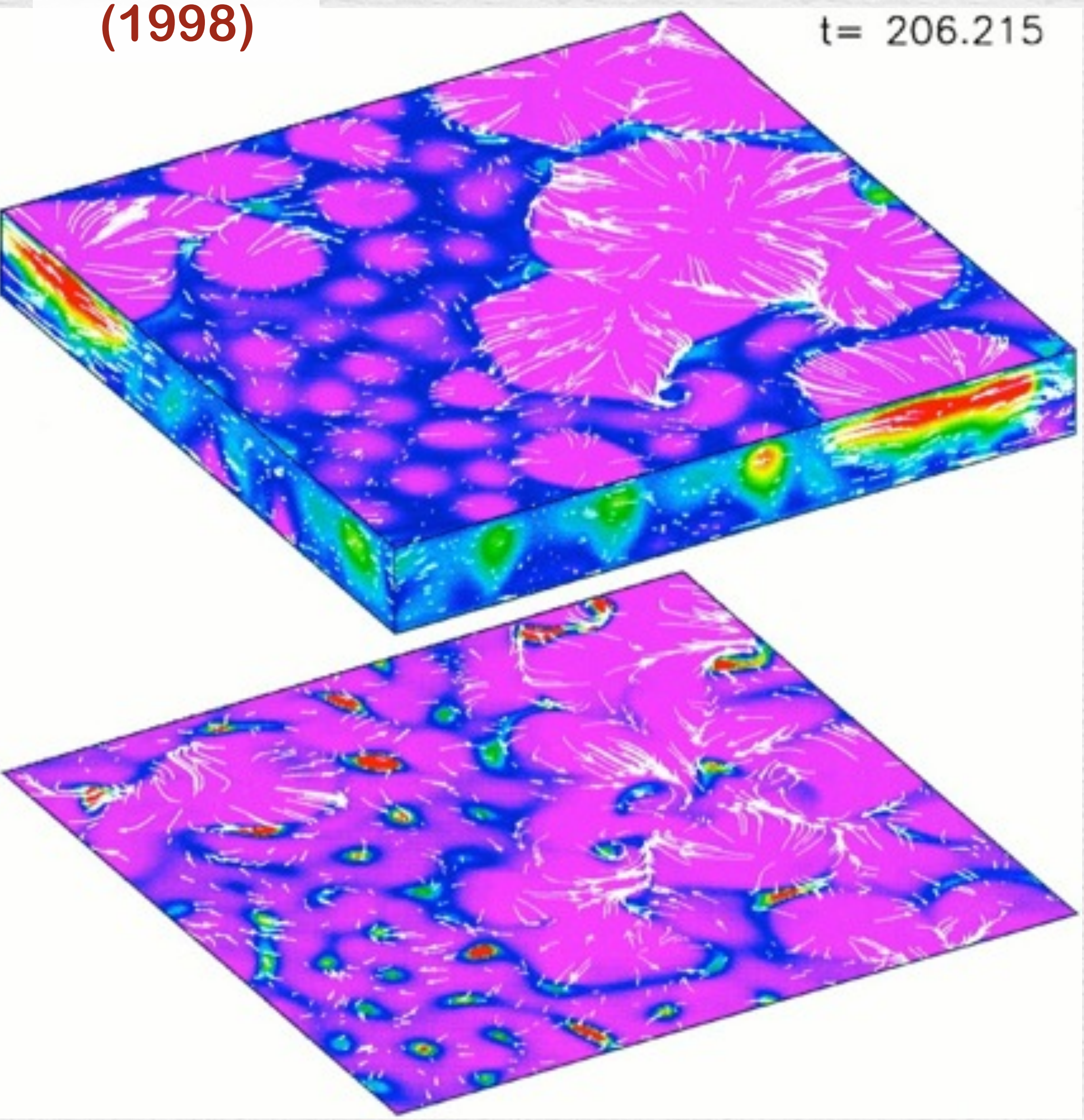

observer
magnetic
boundary
10 - 90% of
brightness
contribution
granule “top”
From Keller et al., 2004 and modified by Will T. Ball

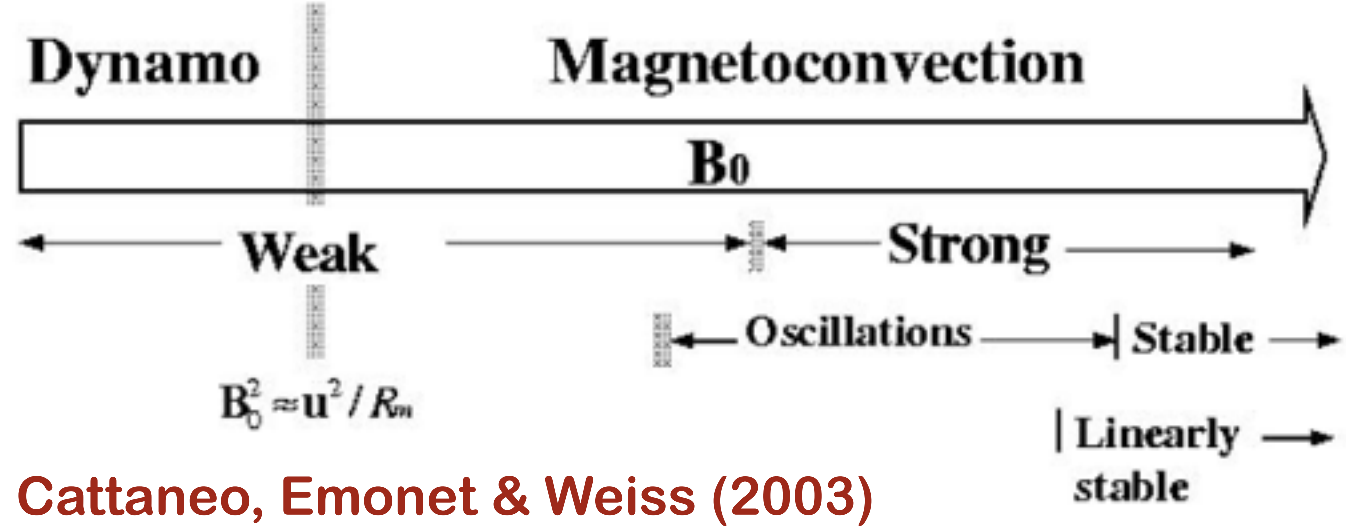
# Spots and Pores

***Larger flux concentrations suppress convection, look dark***

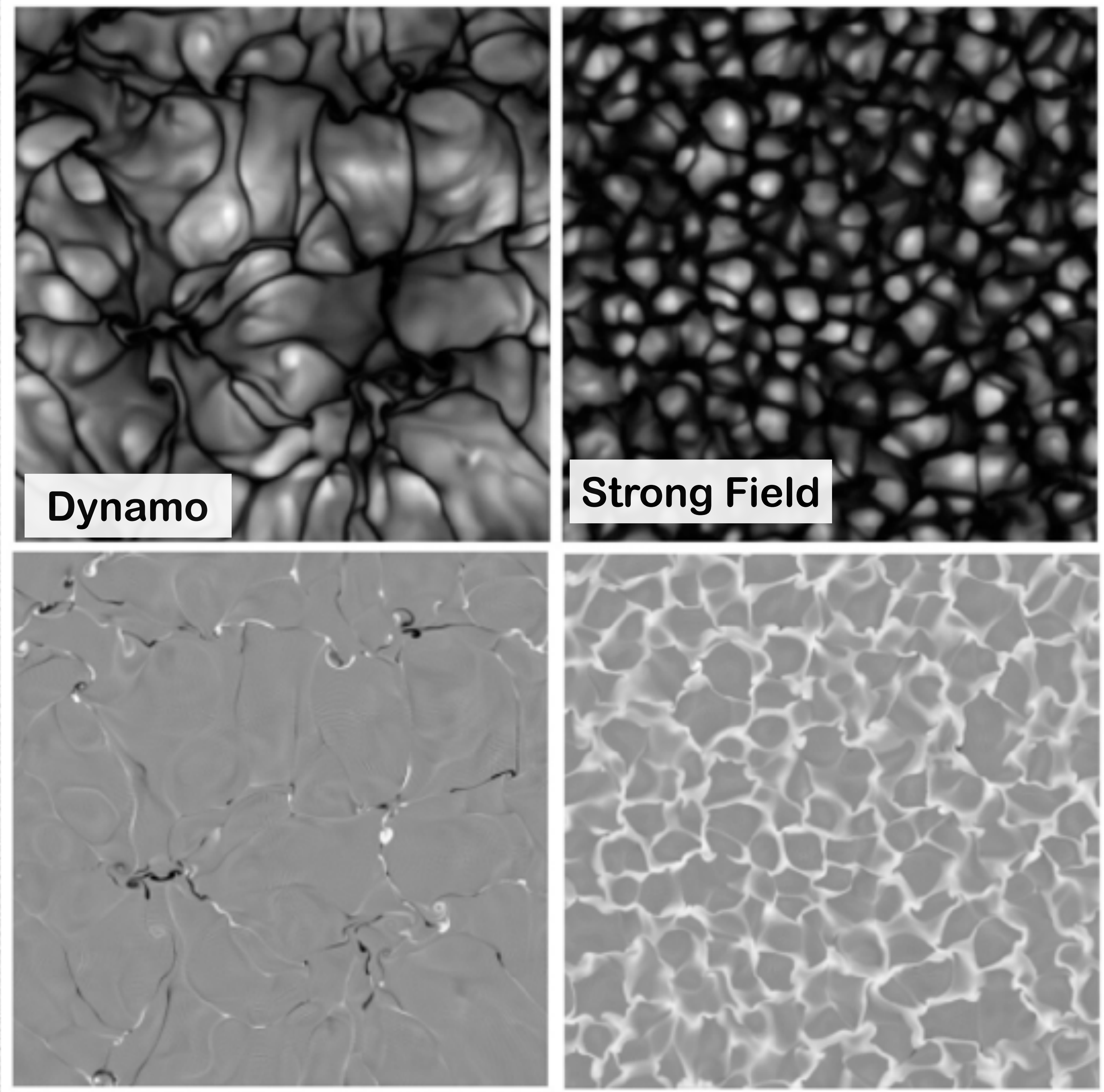
Flux Expulsion,
Turbulent Diamagnetism,
Subcritical instability

Tao et al. (1998)

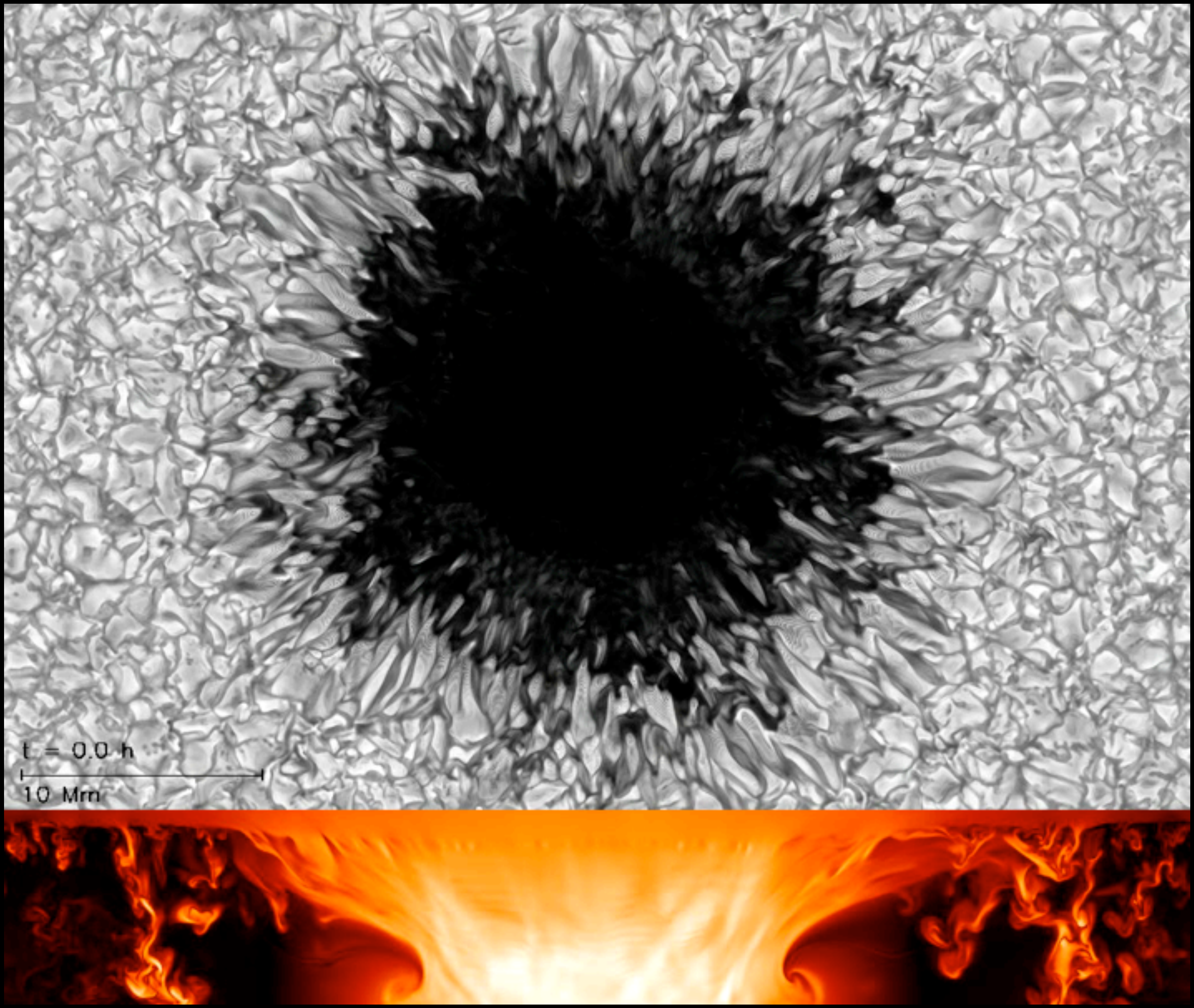



Cattaneo, Emonet & Weiss (2003)



## *Suppression of convection in a sunspot*




Rempel et al (2009)

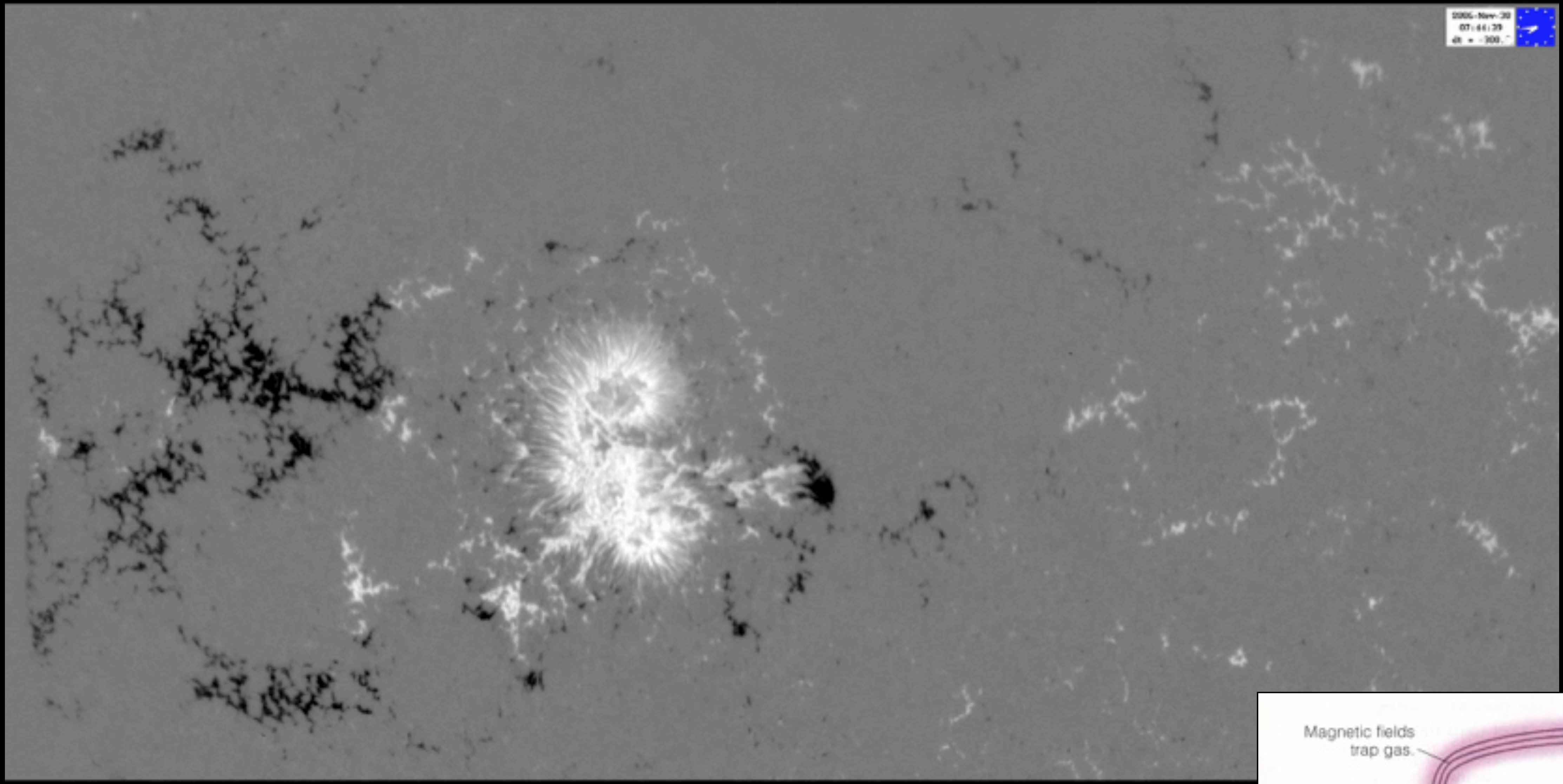
## *Enhanced cooling in flux concentrations can induce inflow positive feedback can help form flux concentrations*

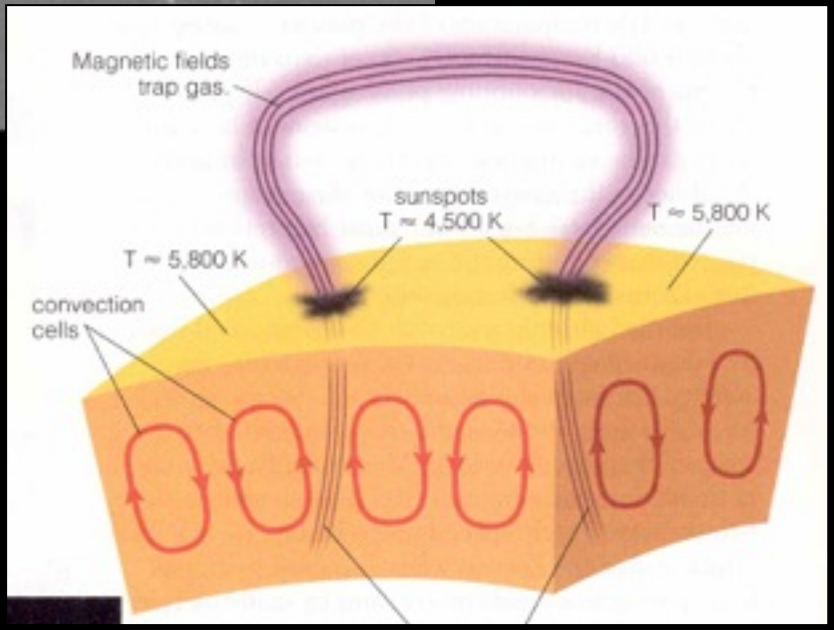
t= 0 hrs 00 mins

Cheung et al. (2010)

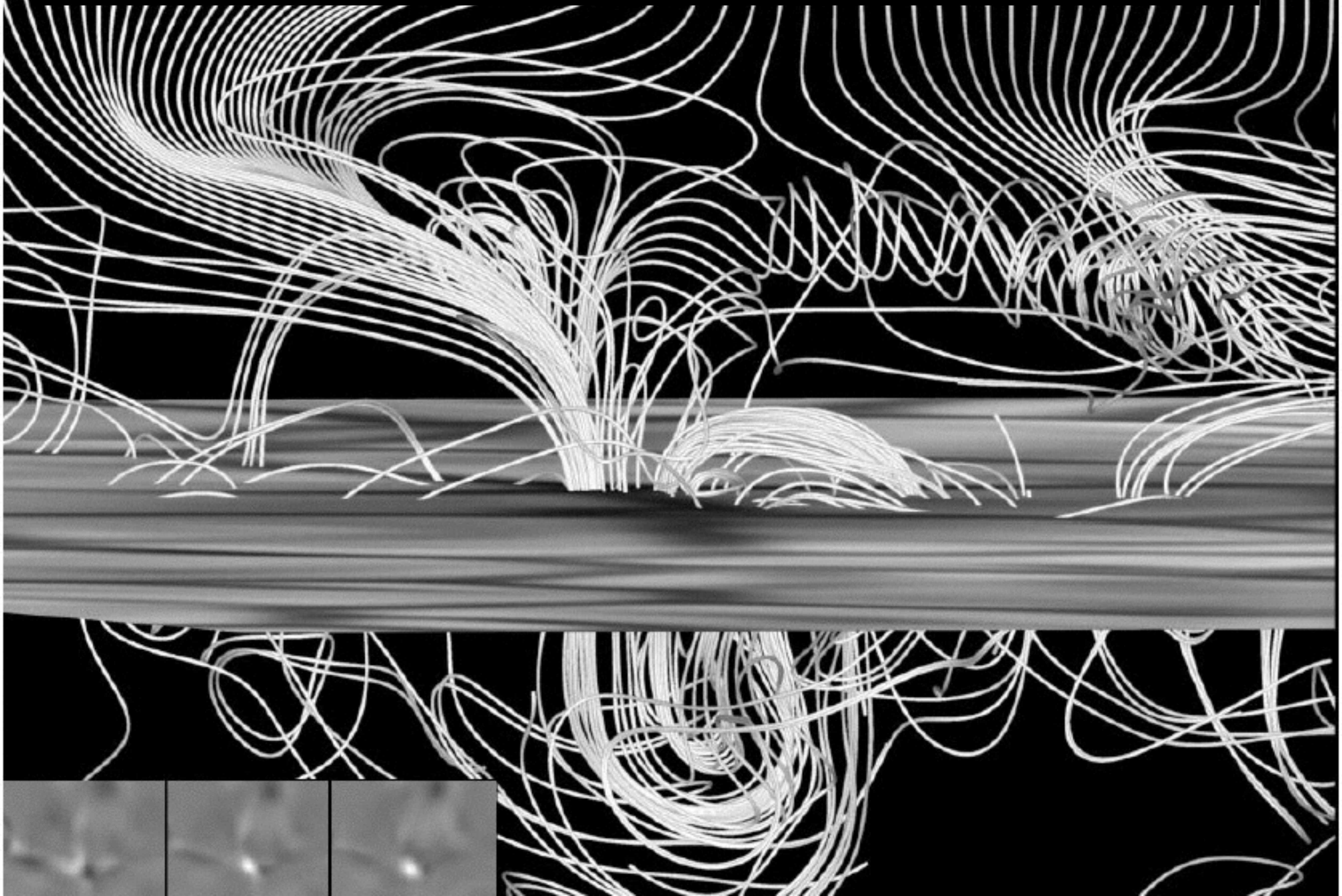
*Though surface processes contribute to organizing flux, it is clear that the flux ultimately comes from within*

***Flux Emergence***

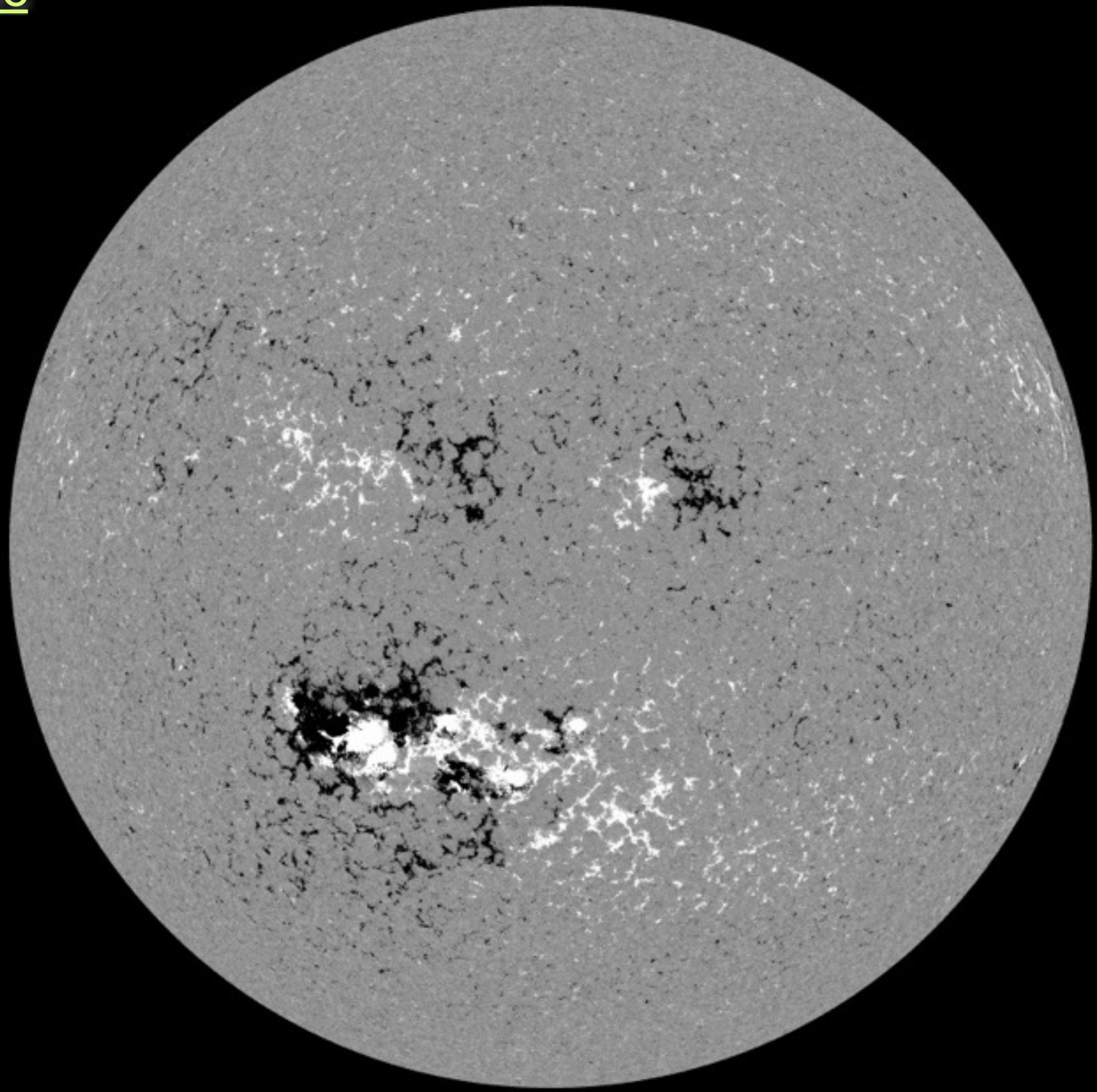




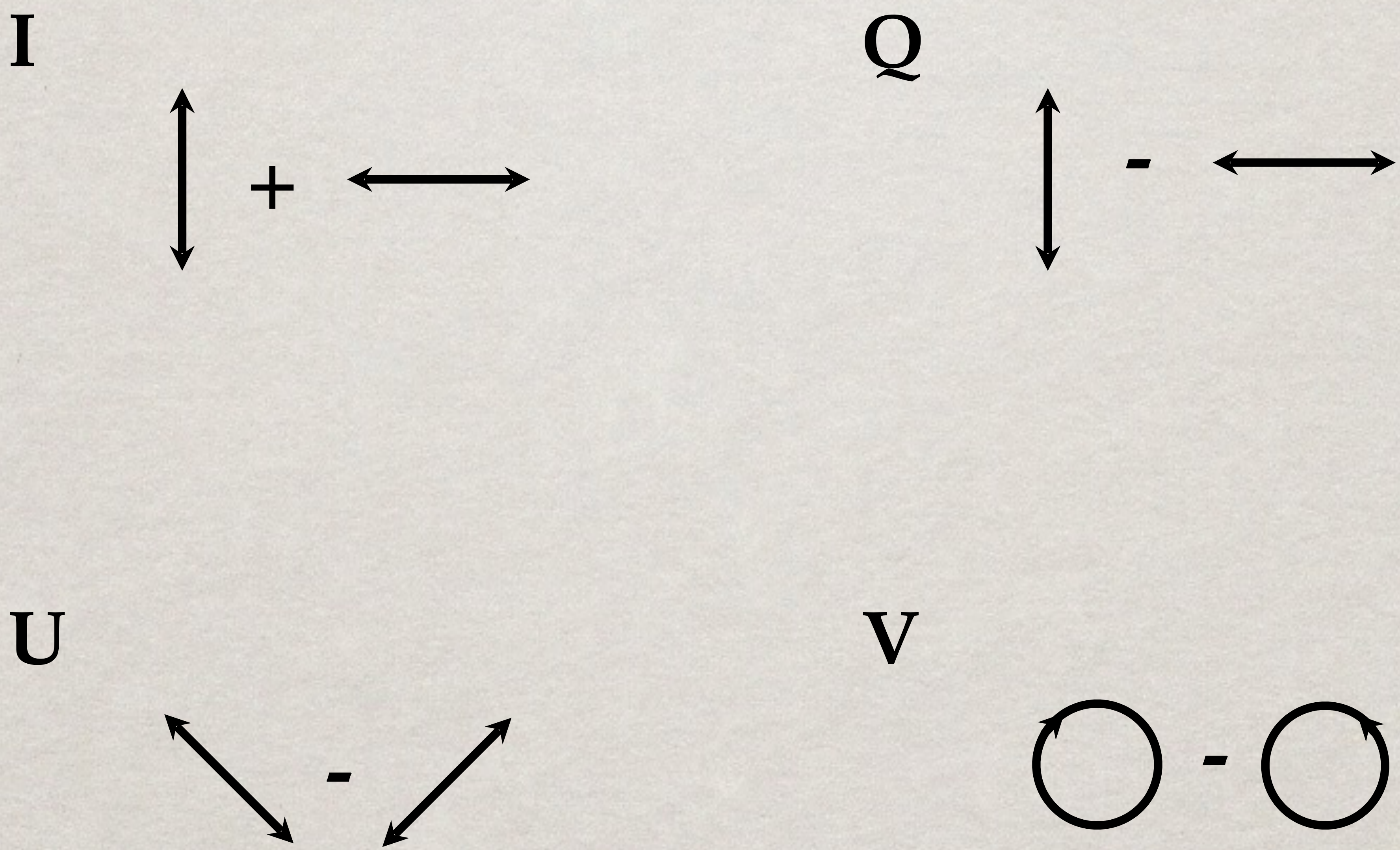
# 3) Magnetic Coupling of the solar atmosphere



# Measuring Magnetic Fields

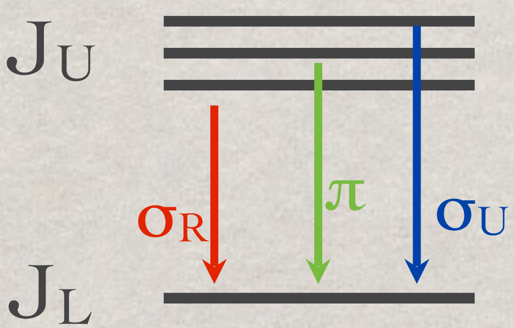


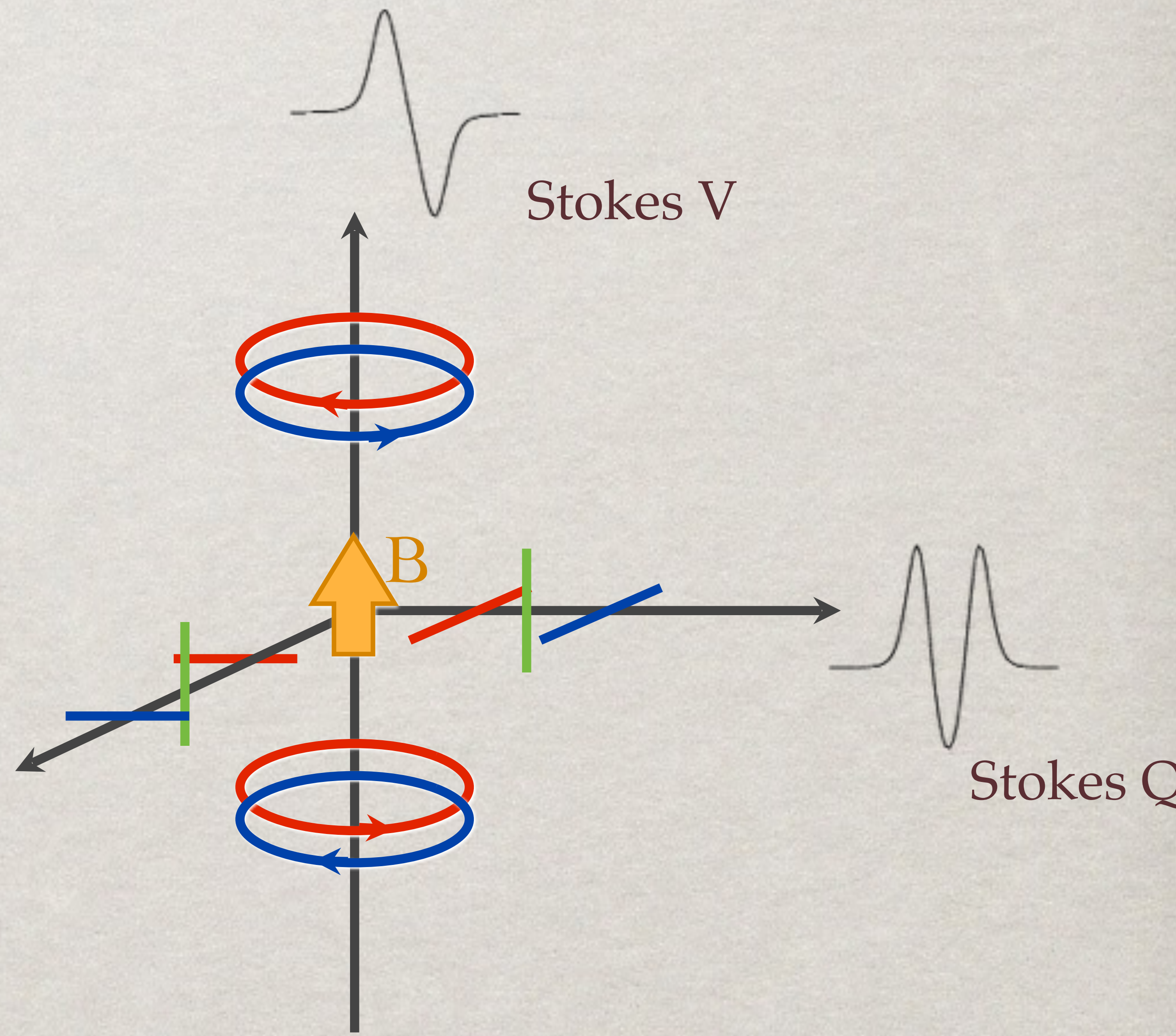
# Polarization of Light



# Zeeman Effect

Splitting of energy levels
of an atom:

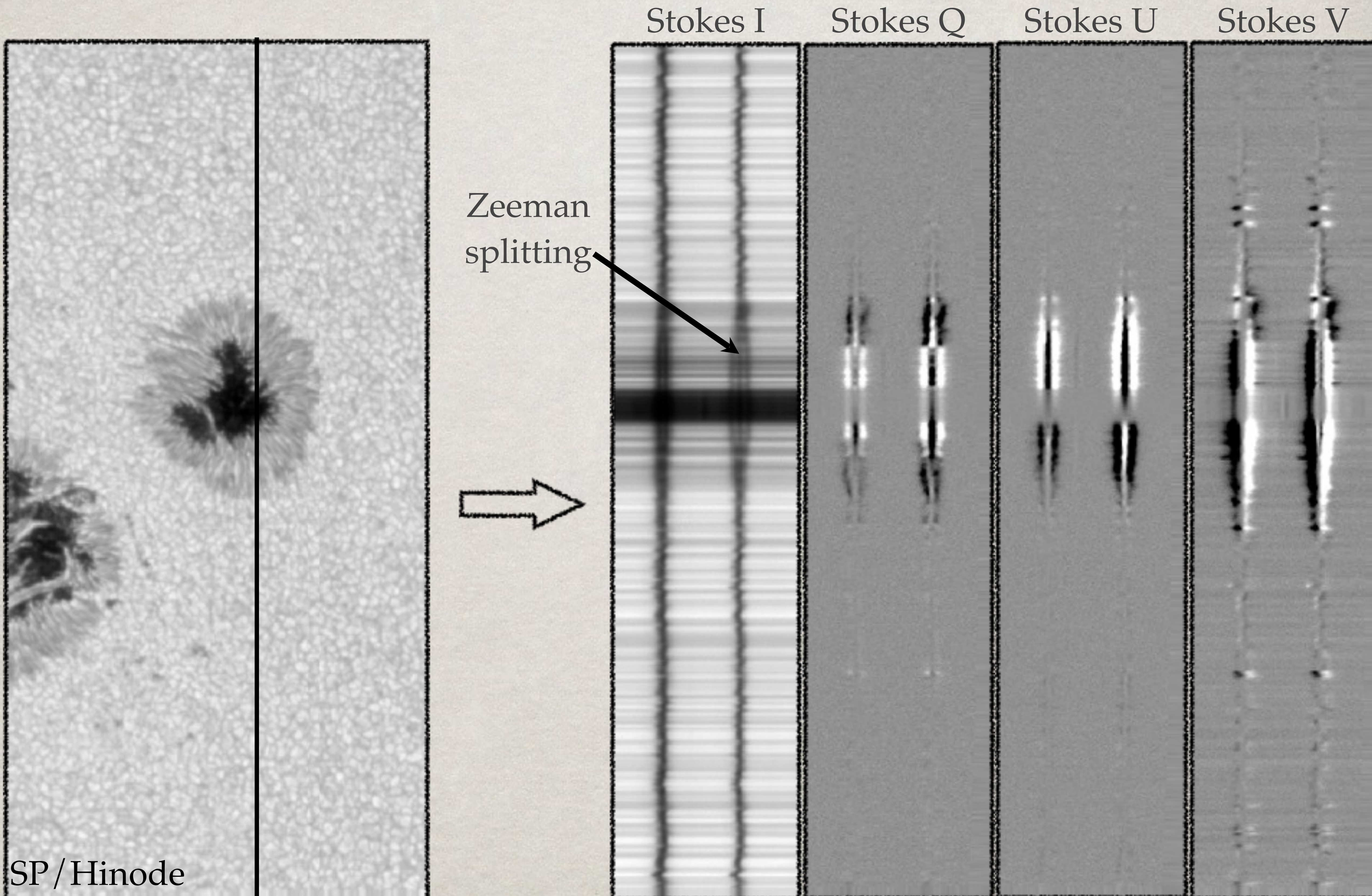



# In General...

- Intensity - FIELD STRENGTH
- Circular polarization - LONGITUDINAL (line-of-sight magnetograms)
- Linear polarization - TRANSVERSE

# Zeeman Effect



# Inversions

**Forward modeling:**

Set of physical parameters
(T, P, ρ, $v_{LOS}$, **B**..)

Reasonable assumptions
(LTE, Milne-Eddington, Zeeman...)

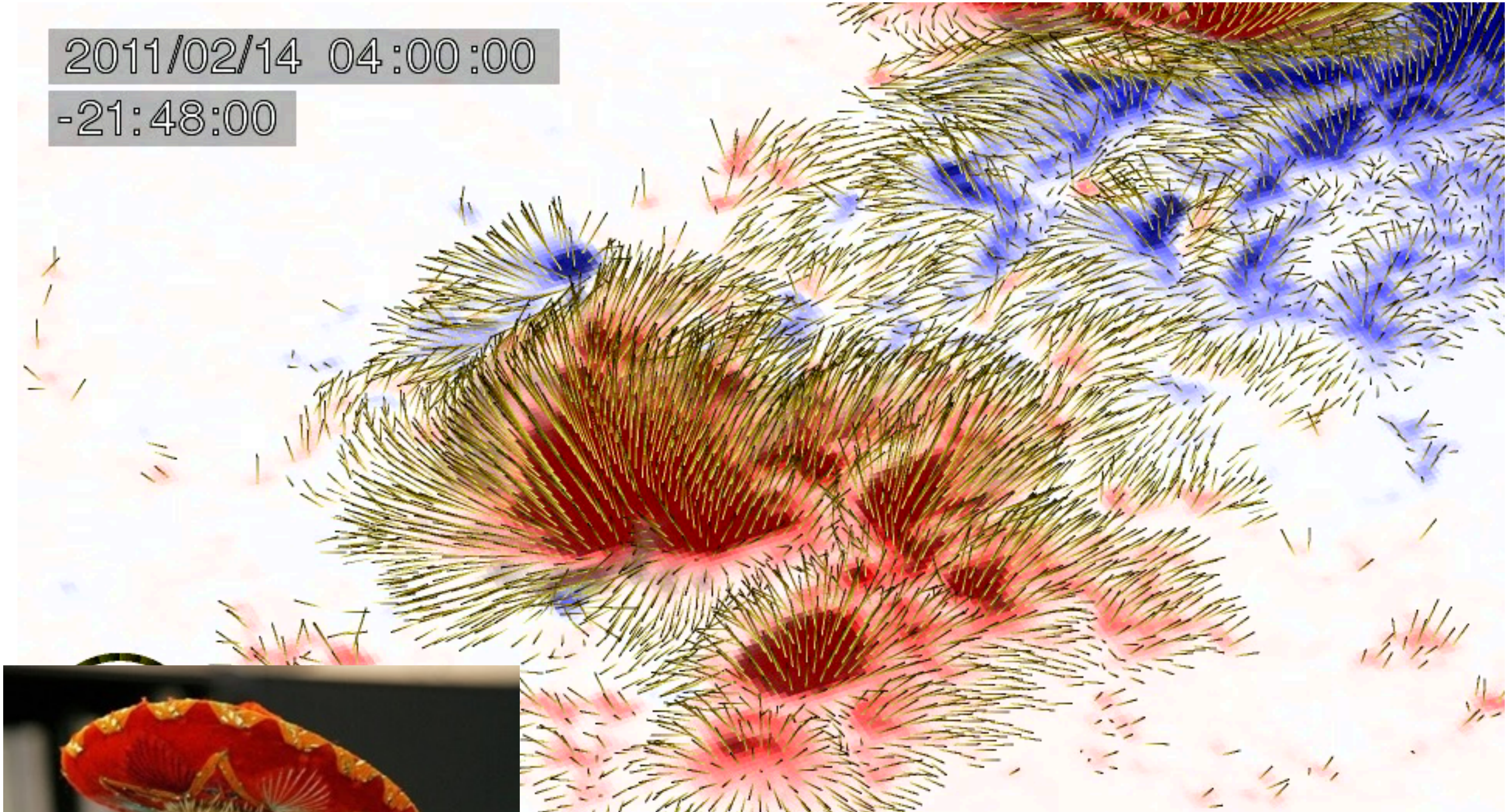
Solve Radiative Transfer Eq.

Model dependency

Stokes profiles
(I, Q, U, V)

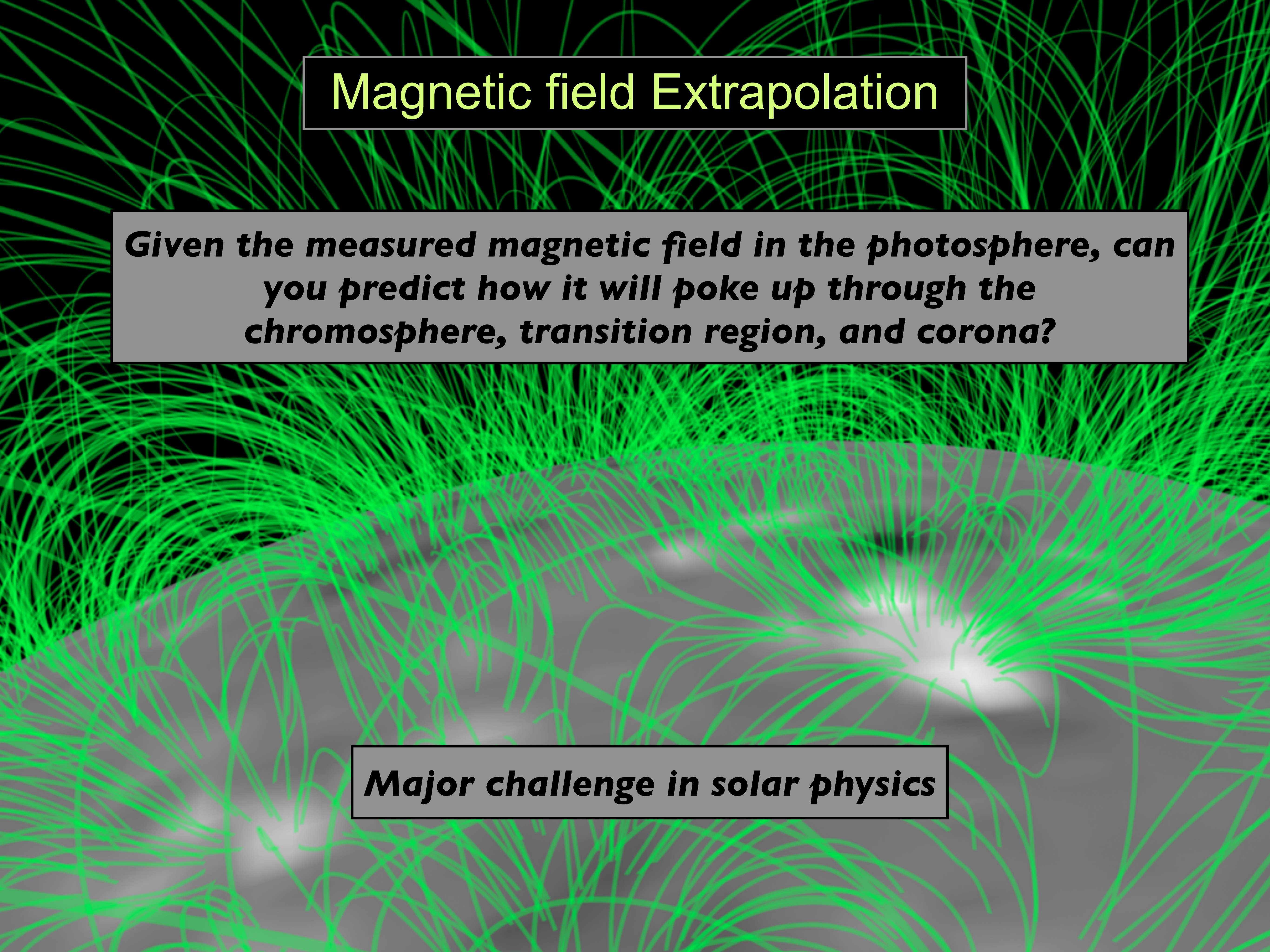
**Inverse problem:**
given a set of Stokes profiles (data!!),
what are the physical conditions in the atmosphere?

***vector magnetogram, courtesy of the SDO/HMI team***




***Hedgehog courtesy of the internet***

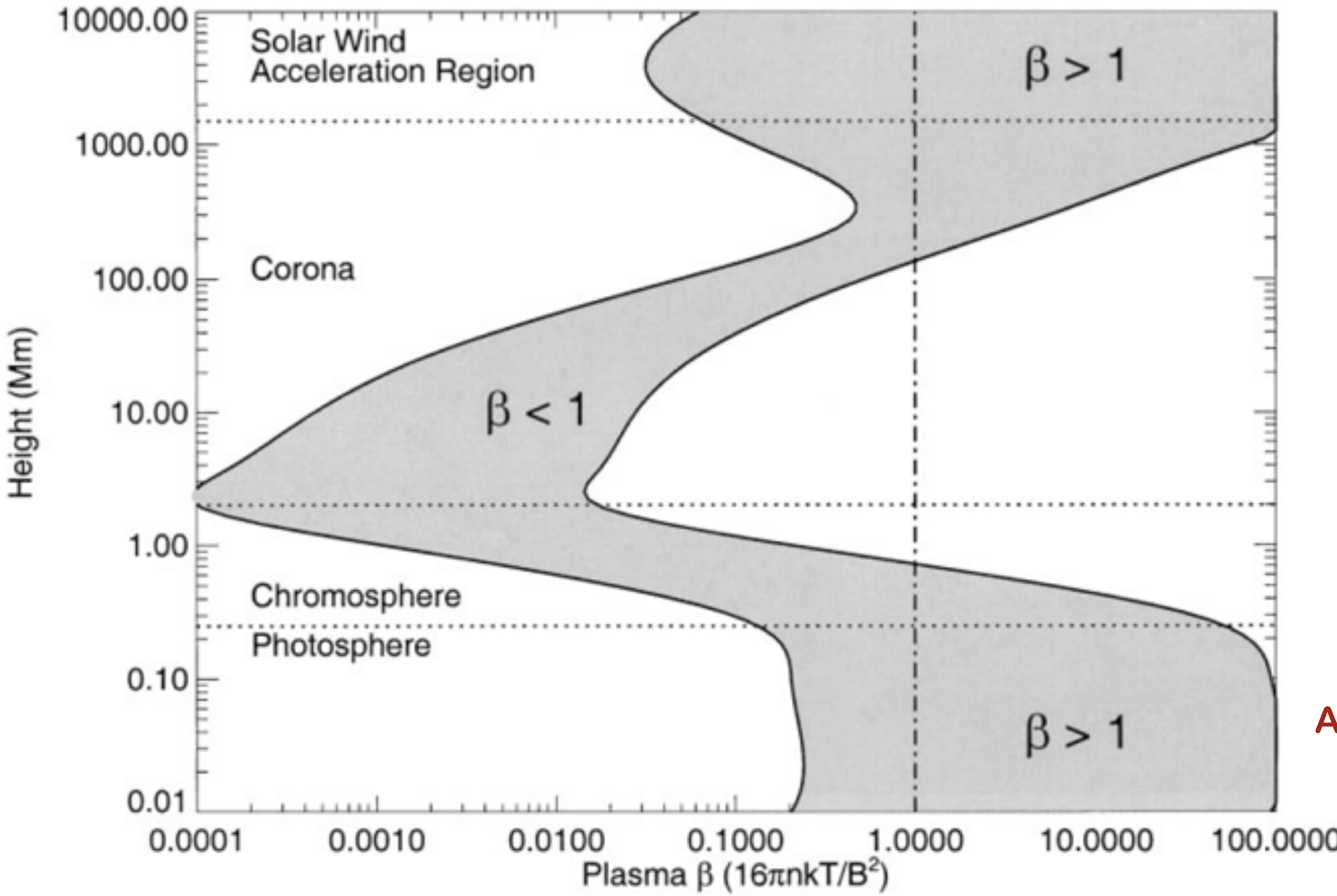
# Magnetic field Extrapolation



***Given the measured magnetic field in the photosphere, can you predict how it will poke up through the chromosphere, transition region, and corona?***

***Major challenge in solar physics***

## *Magnetism dominates the structure & evolution of the solar corona*




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

Aschwanden, Poland & Rabin (2001)

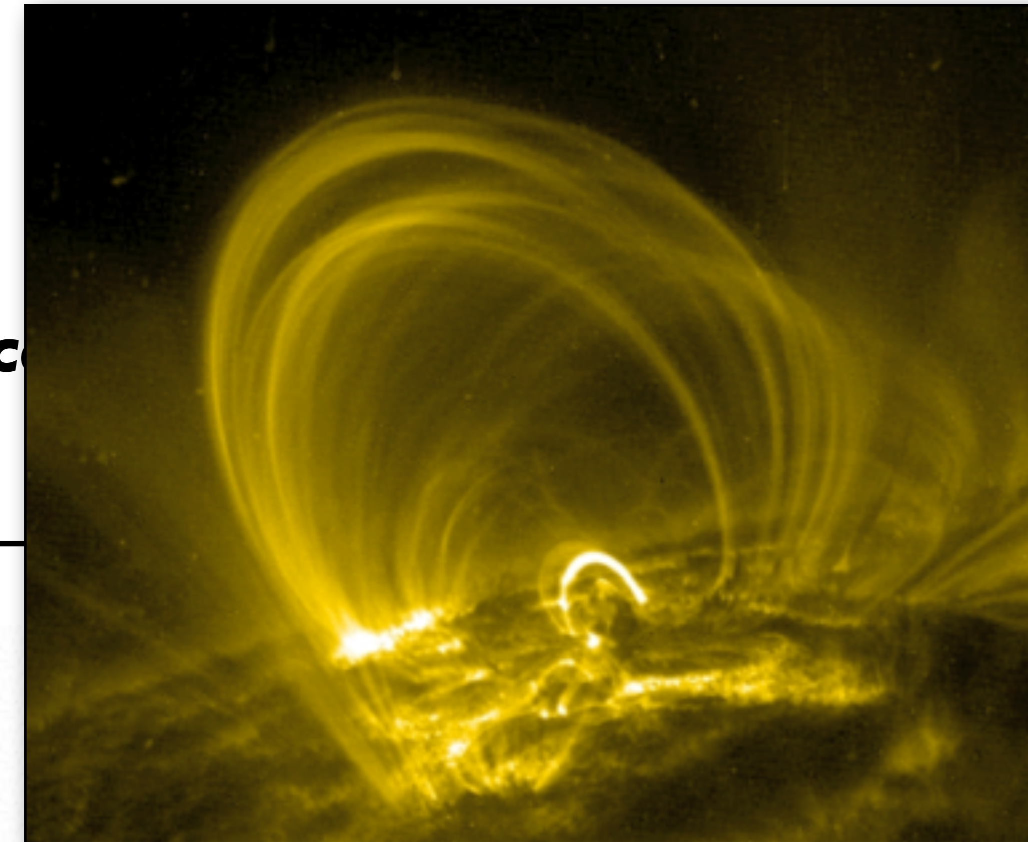
***In the Corona, the Lorentz force is so big it must be small!***

$$\rho\frac{\partial \mathbf{v}}{\partial t} + \rho\left(\mathbf{v}\cdot\boldsymbol{\nabla}\right)\mathbf{v} = -\boldsymbol{\nabla}P_g + \rho\mathbf{g} - 2\rho\boldsymbol{\Omega}\times\mathbf{v} - \rho\boldsymbol{\Omega}\times\left(\boldsymbol{\Omega}\times\boldsymbol{\lambda}\right) + c^{-1}\,\boldsymbol{J}\times\boldsymbol{B} + \boldsymbol{\nabla}\cdot\boldsymbol{\mathcal{D}}$$

**"Force free"** $\boldsymbol{J}\times\boldsymbol{B}\approx 0$

## *Alfven's Theorem (flux freezing)*

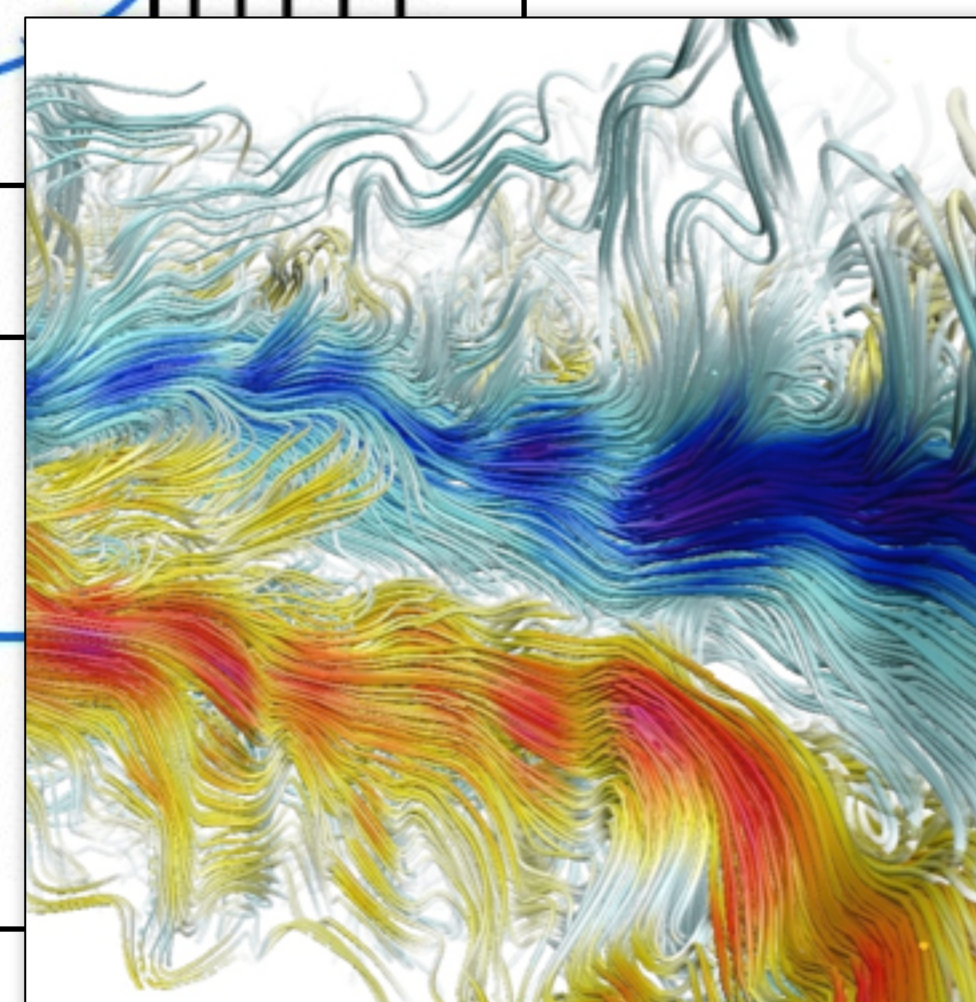
*In the perfectly conducting limit ($\eta = 0$), the flow c*



# Corona

*magnetic energy >> kinetic energy*

*flow follows field ⇒ coronal loops!*



# Convection Zone

*magnetic energy << kinetic energy*

*flow pushes field around ⇒ dynamo!*

## Magnetic field Extrapolation

***Simplest approximation that you can think of:***

$$J = \frac{c}{4\pi} \boldsymbol{\nabla} \times B = 0$$

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

$$\boldsymbol{\nabla} \cdot \mathbf{B} = \nabla^2 \Psi = 0$$

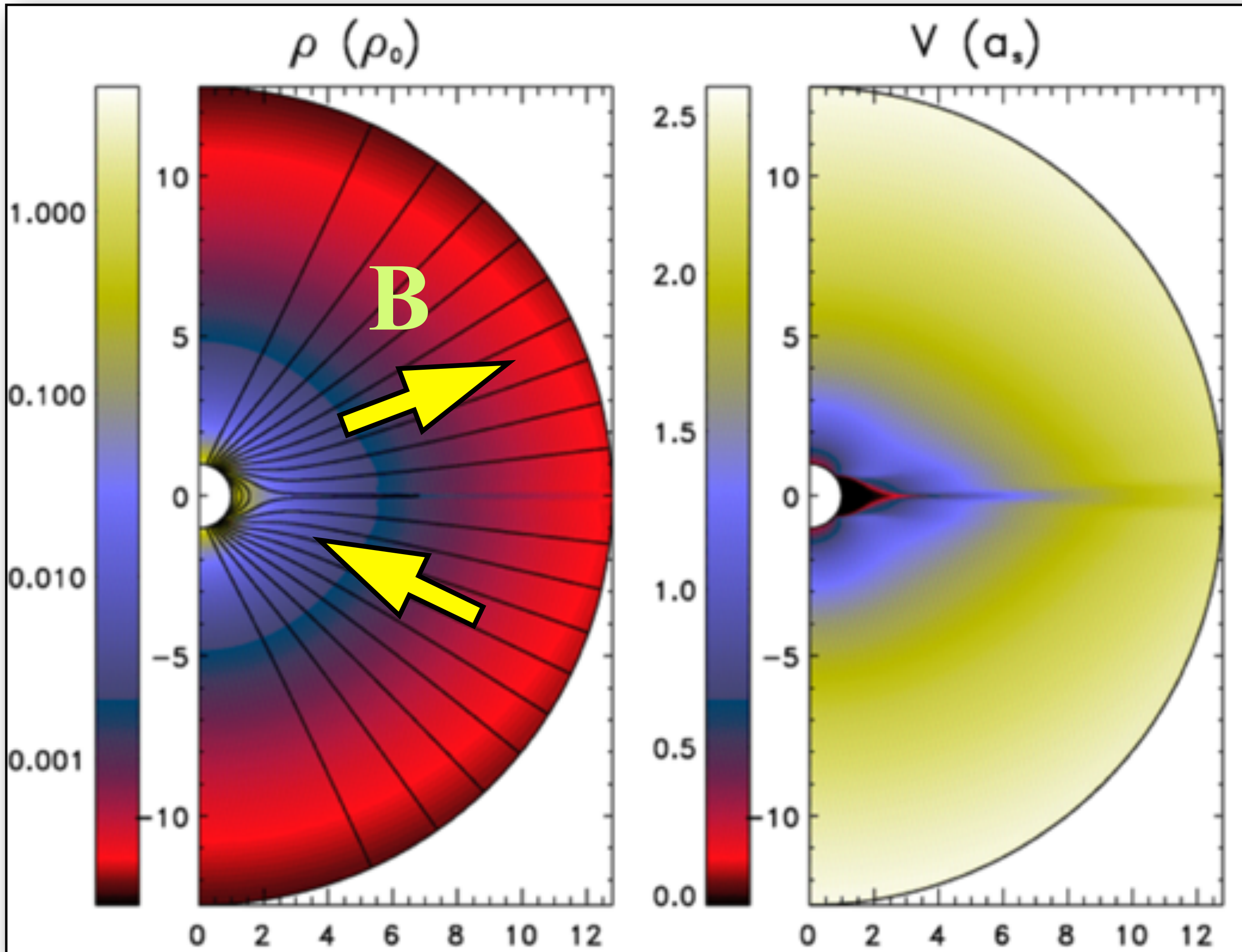
***Laplace's Equation***

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

***What should we use for boundary conditions?***

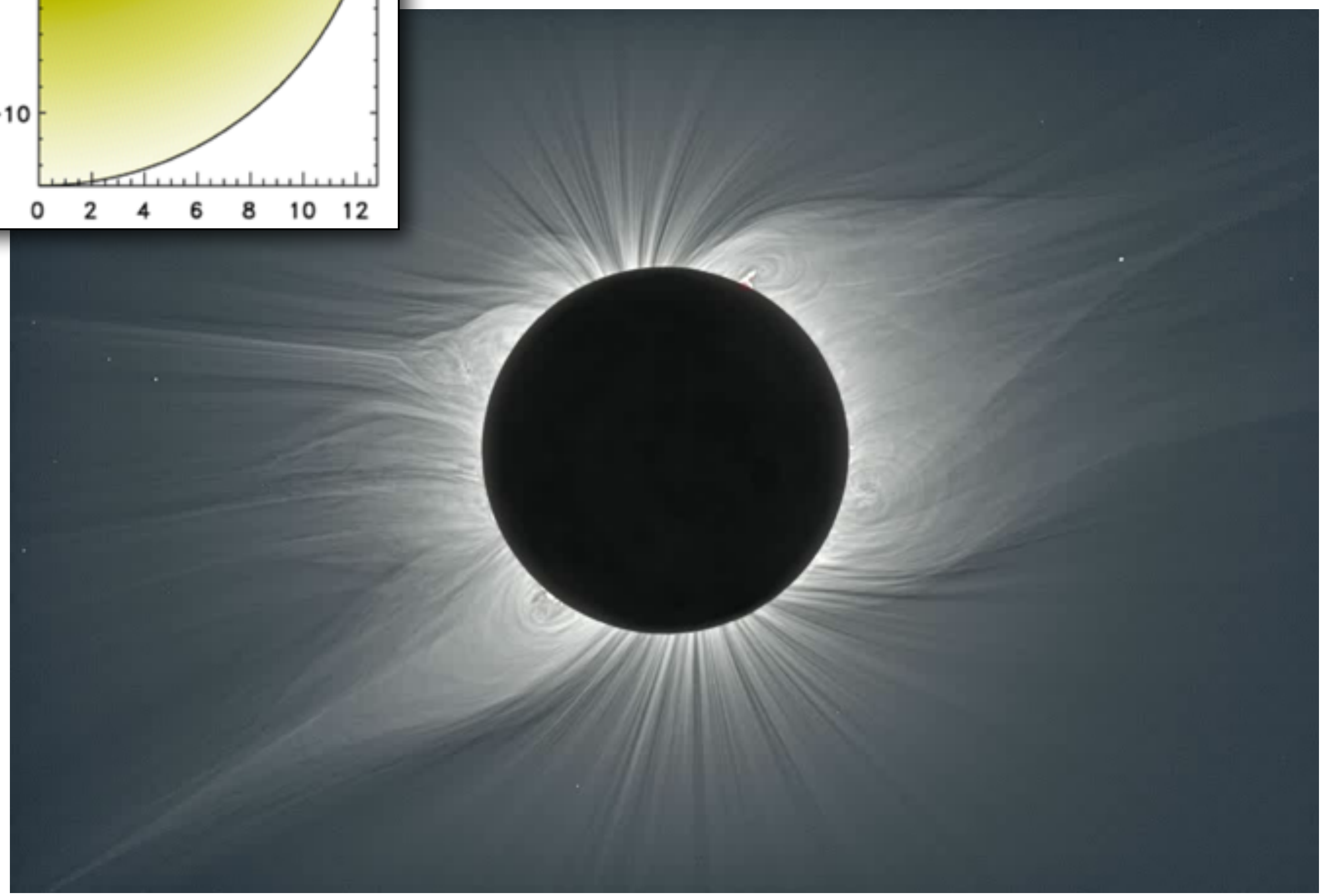
***General Solution***

$$\Psi = \sum_{\ell m} \left( a_{\ell m} \, r^{\ell} + b_{\ell m} \, r^{-(\ell+1)} \right) Y_{\ell m}(\theta, \phi)$$




***Solar wind pulls magnetic field lines out until they're nearly radial*** ***(remember flux freezing)***

***(solar rotation produces "Parker spiral" shape farther away from the Sun)***



***This forms***

***coronal streamers***

***and the***

***heliospheric current sheet***

# PFSS Extrapolation

***Potential Field***

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

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

***Boundary conditions***

$$B_r = B_s(\theta, \phi)$$ ***at*** $\mathbf{r = R}$

$$\Psi = 0$$ ***(radial field)*** ***at*** $\mathbf{r = R_s}$

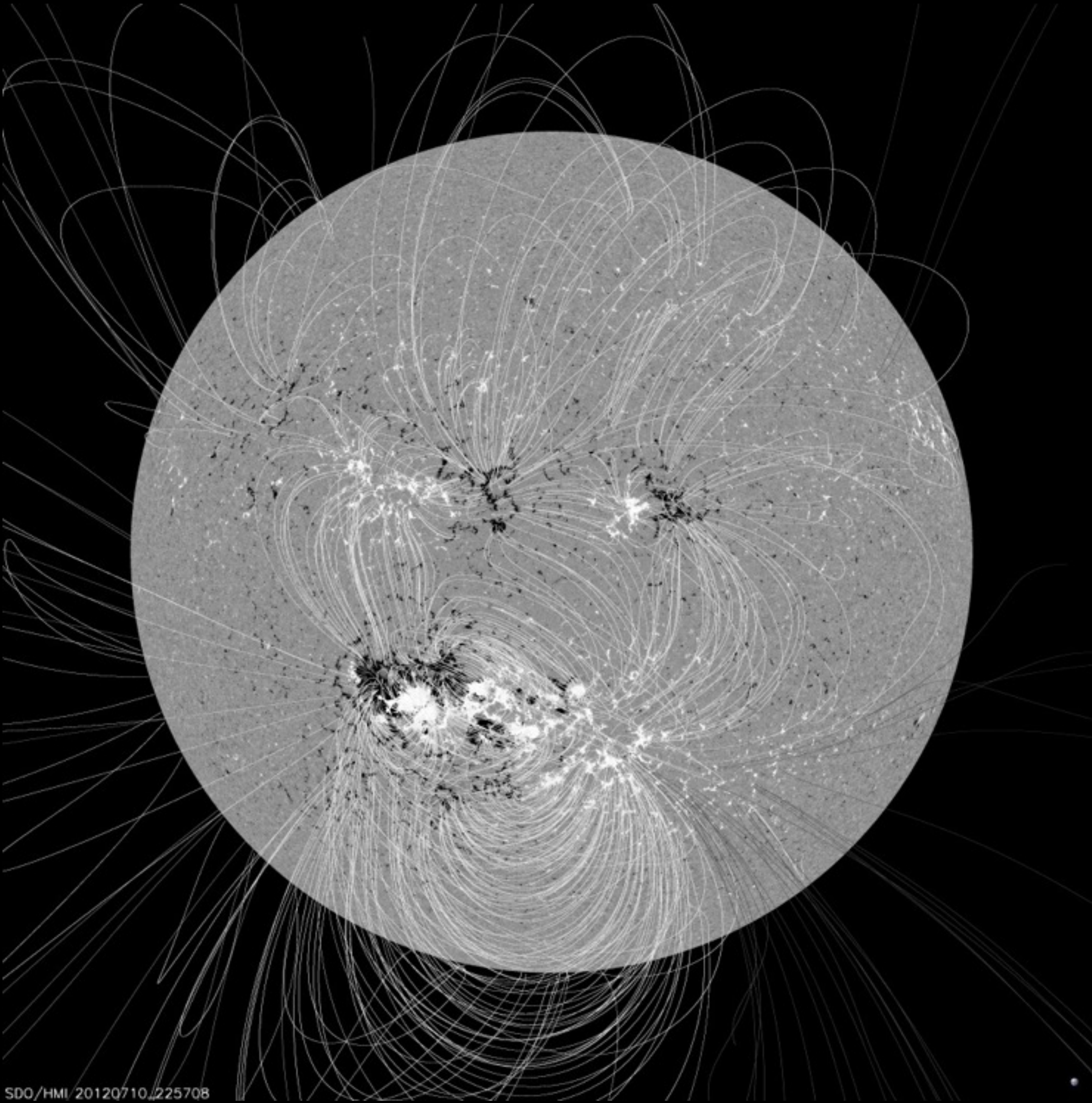
***Source Surface***

***$R_s$ often taken to be ~ 2-3 R***

Magnetogram (Zeeman effect)

+

PFSS extrapolation



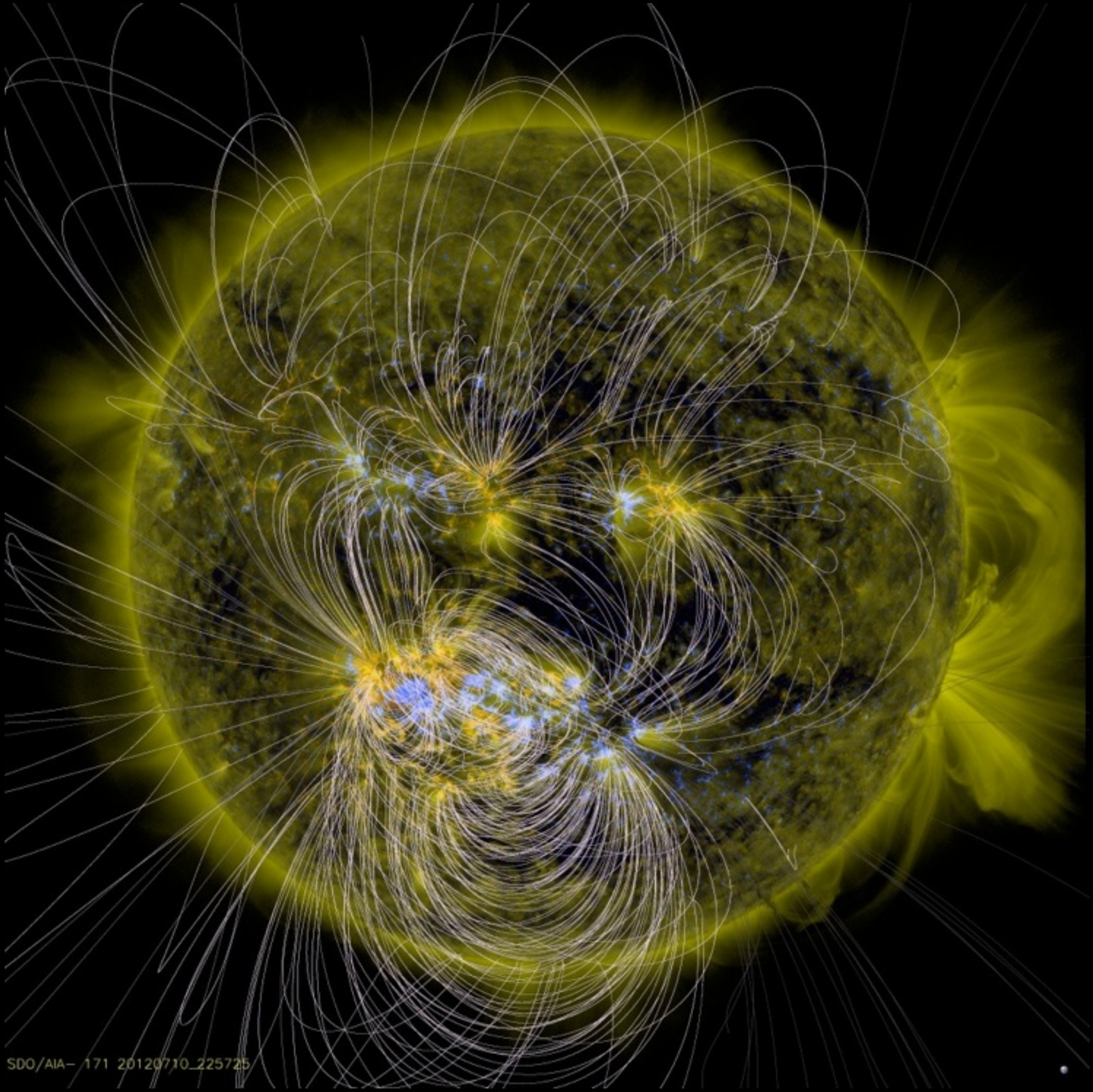
Magnetogram
(Zeeman
effect)

+

PFSS
extrapolation

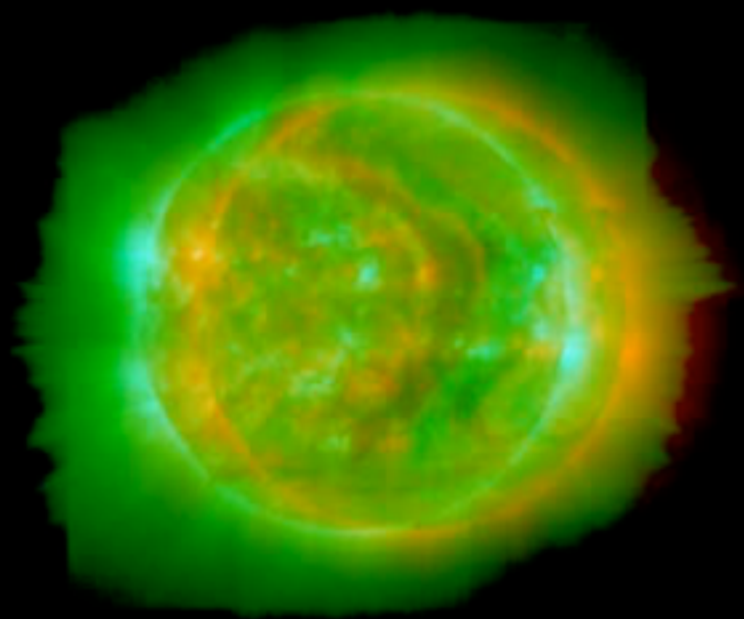
+

171



# Magnetic extrapolations

- ★ ***PFSS***
  - ***$J = 0$***
- ★ ***Force-free***
  - ***$J = \alpha B$***
  - ***Linear: $\alpha$ = constant***
  - ***Nonlinear: $\alpha(B)$***
- ★ ***Magneto-hydrostatic***
  - ***Include pressure & gravity***
  - ***Restricted to idealized circumstances***
- ★ ***Full MHD simulations***
  - ***Most realistic but, like any simulation, challenged by limited resolution***



# But Magnetic Coupling is Dynamic!

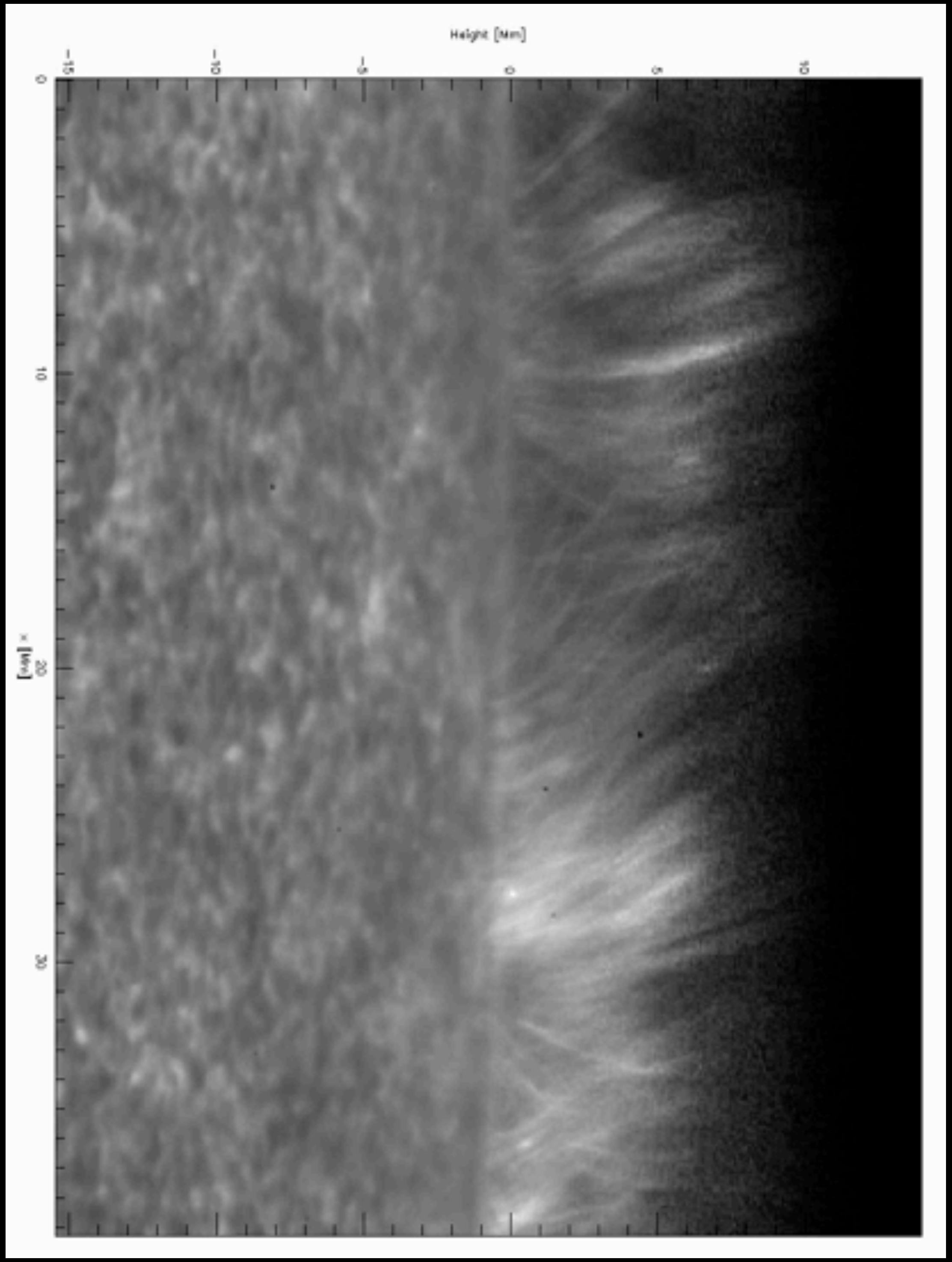
***Flux Emergence***

***MHD Waves***

***fast magneto-acoustic wave***
***slow magneto-acoustic wave***
***Alfven wave***

***Shocks***


SAO /NASA/JAXA/NAOJ




***Spicules***

***Jets***

# And Magnetic Coupling is Complex

## *The Chromosphere!*

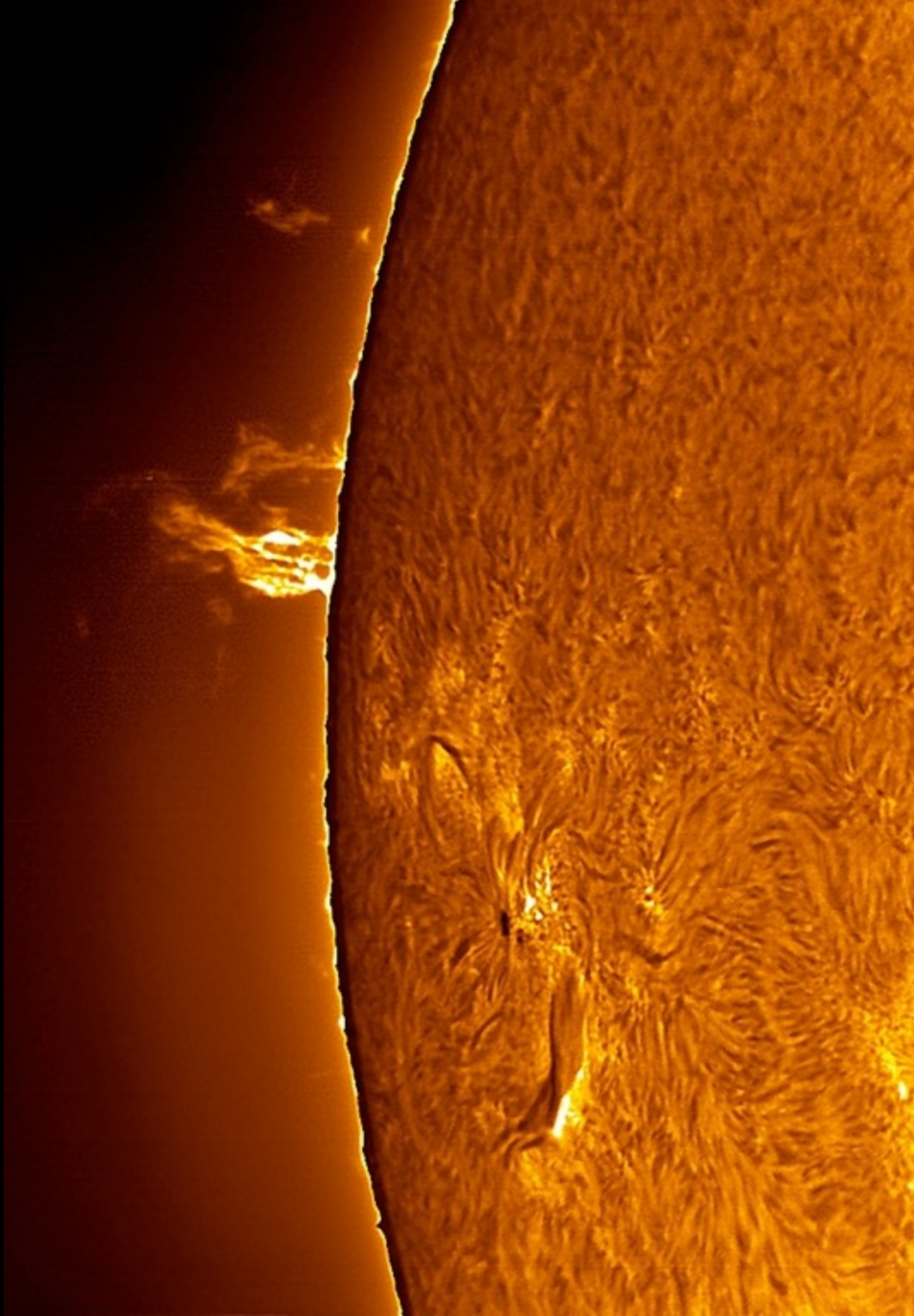
***Partial Ionization***

***Complex radiative transfer***

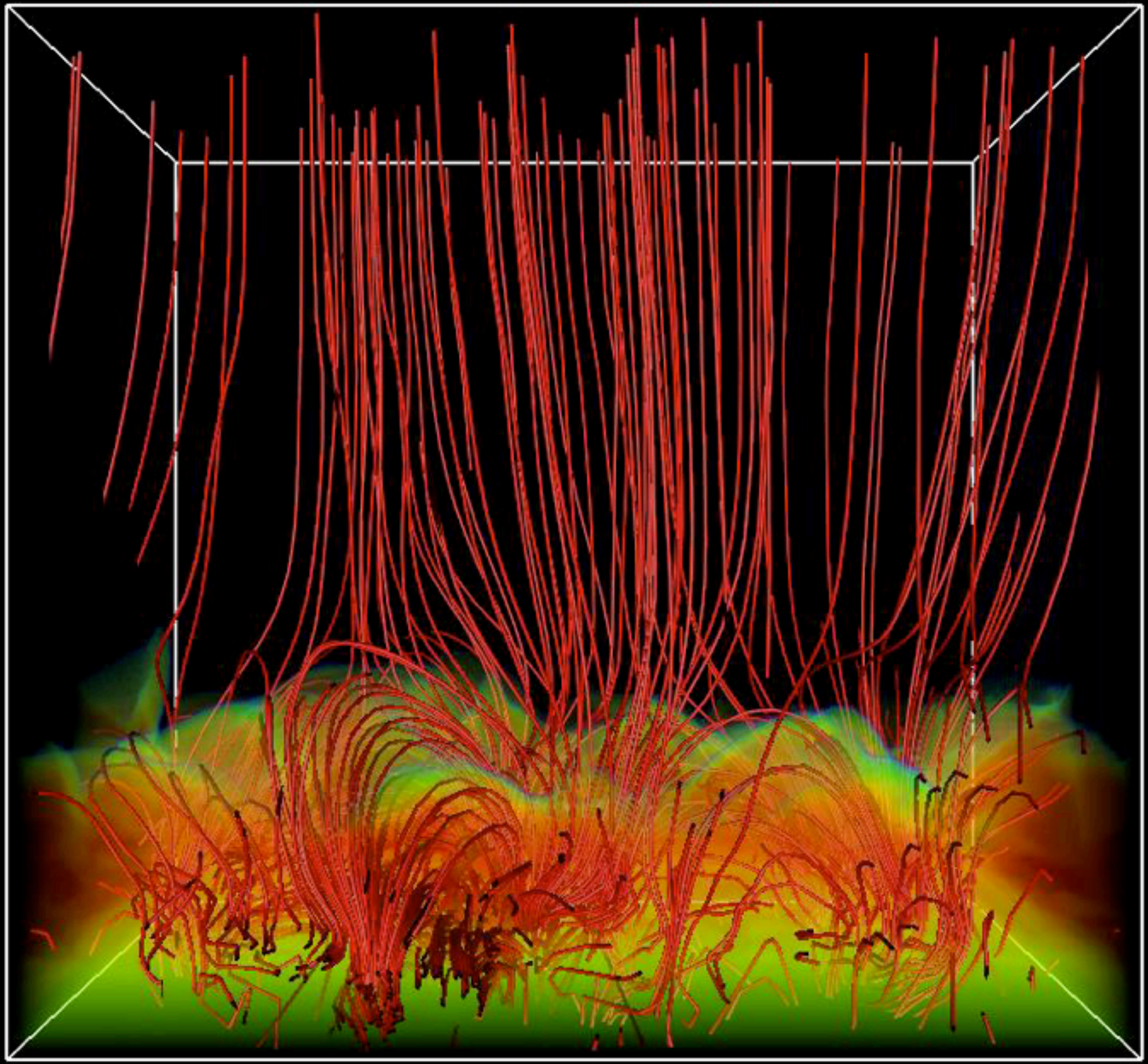
***Non-ideal MHD***

***Transition from high to low***

***…a formidable modeling challenge***



# Alfven Waves



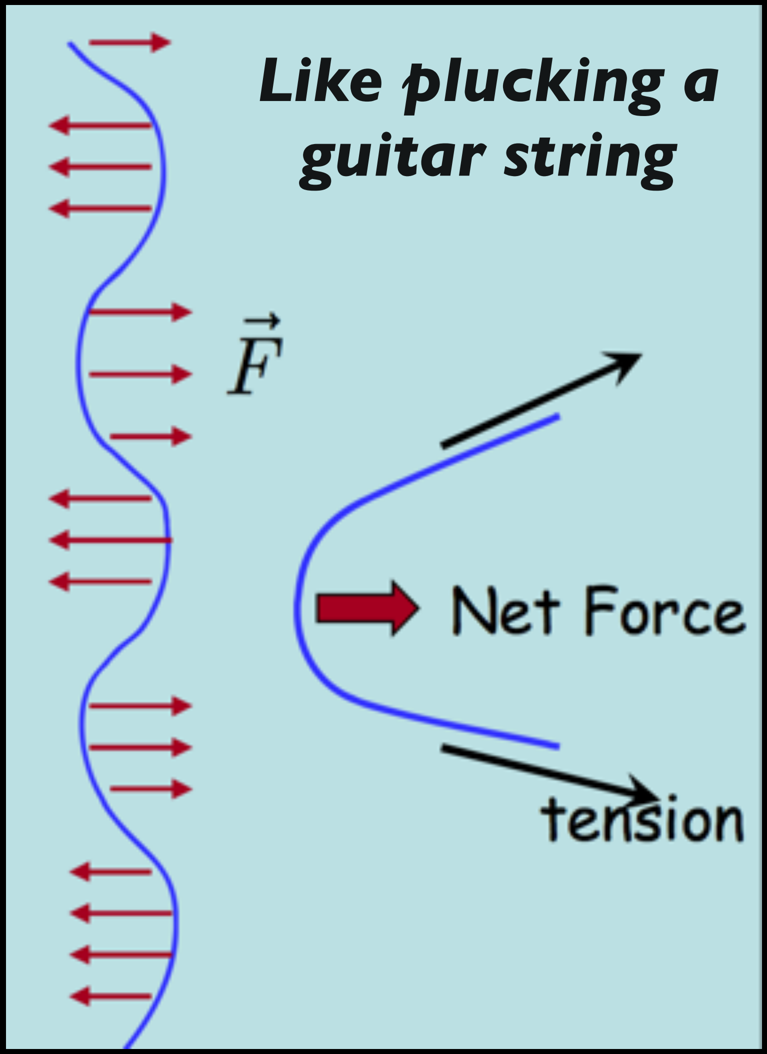
*Oslo group (M. Carlsson et al)*

***Restoring force***

**=**

***magnetic tension***

$$\frac{\partial \mathbf{B}}{\partial t} = (\mathbf{B}\cdot\nabla)\,\mathbf{B}$$



Alfven Waves propagate up into the corona

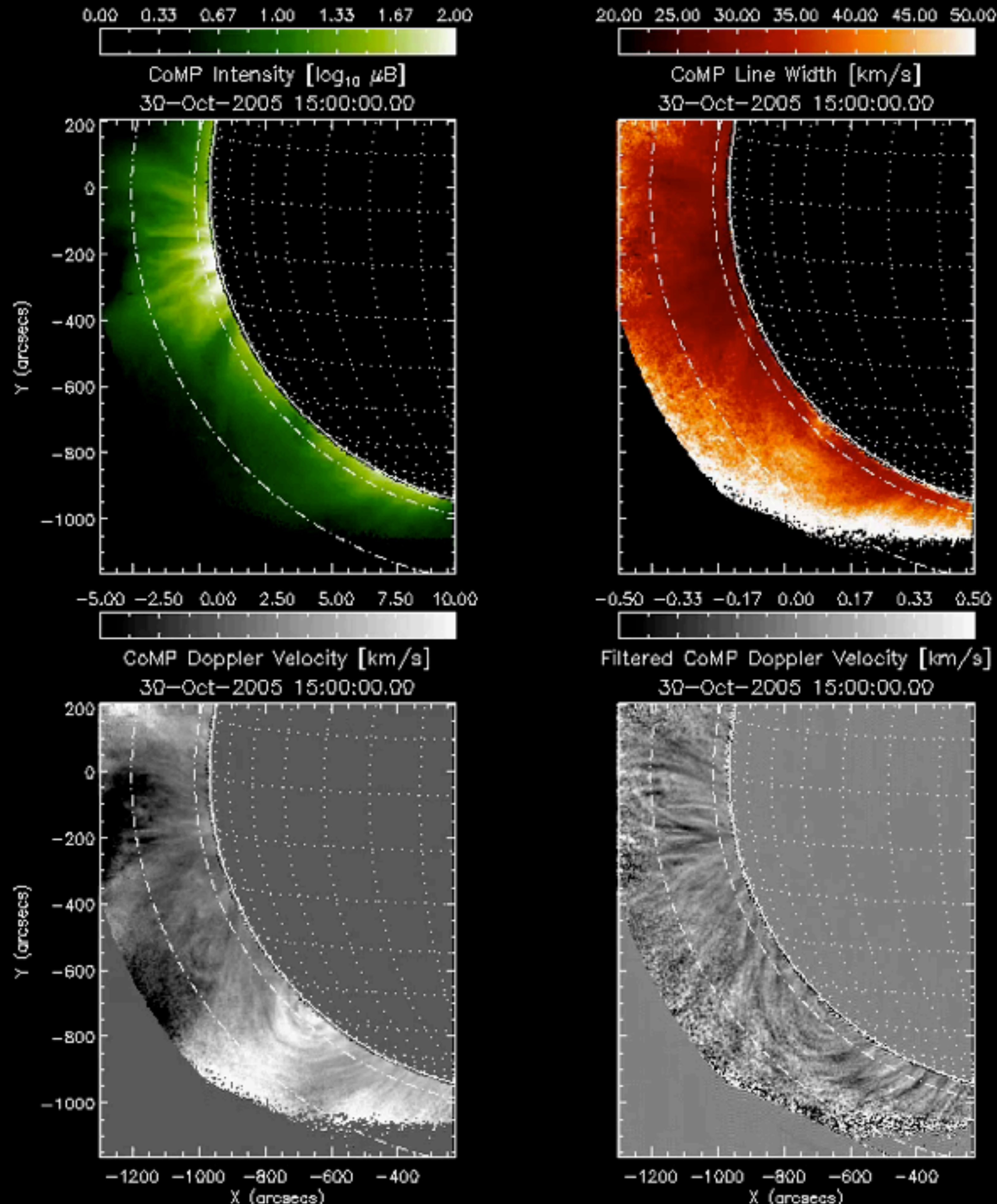
Likely contribute to coronal heating

But...

Alfven waves are non-compressive

This makes them hard to dissipate

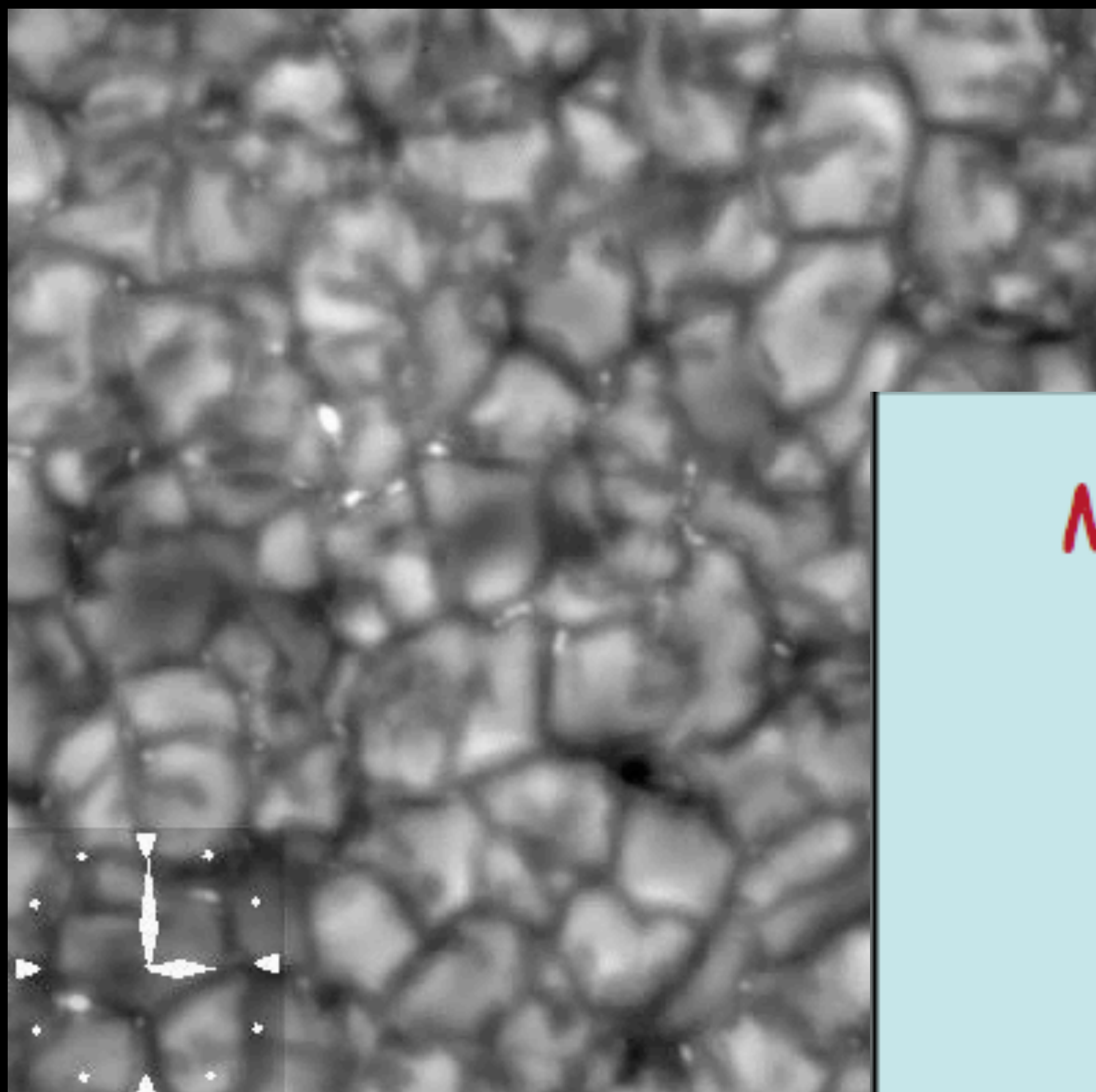
...and hard to detect

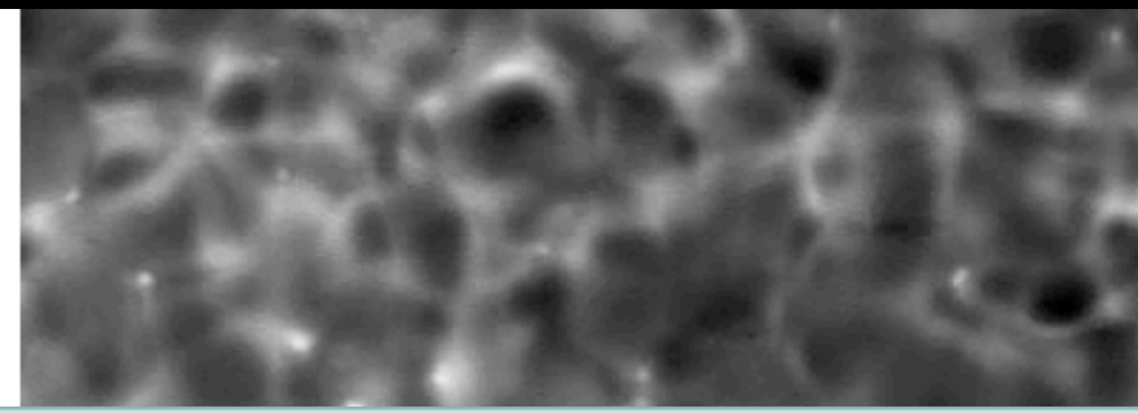


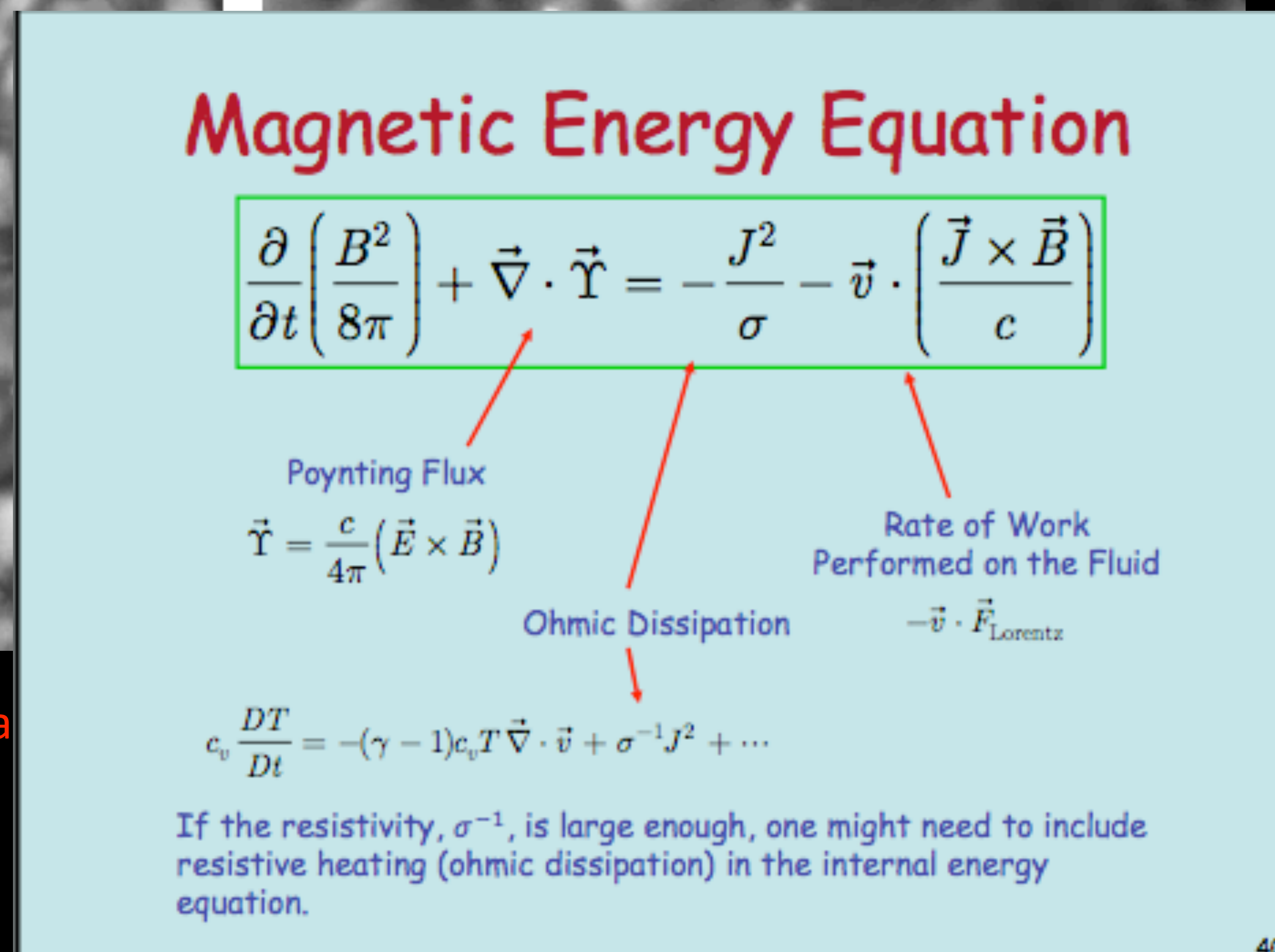
# 4) The Solar Corona

# Coronal energy source

Continuous flows and magnetic flux emergence through the solar surface

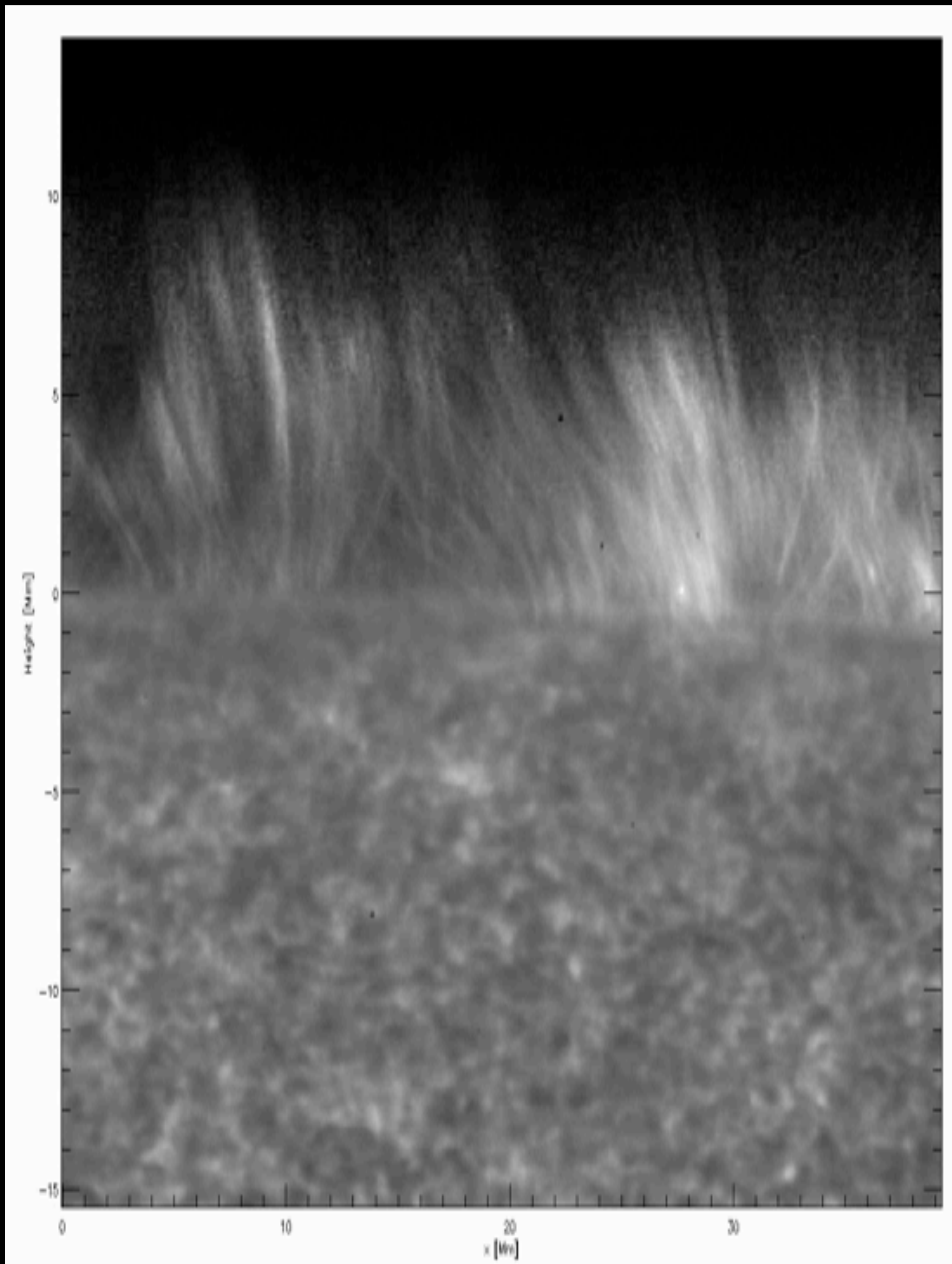






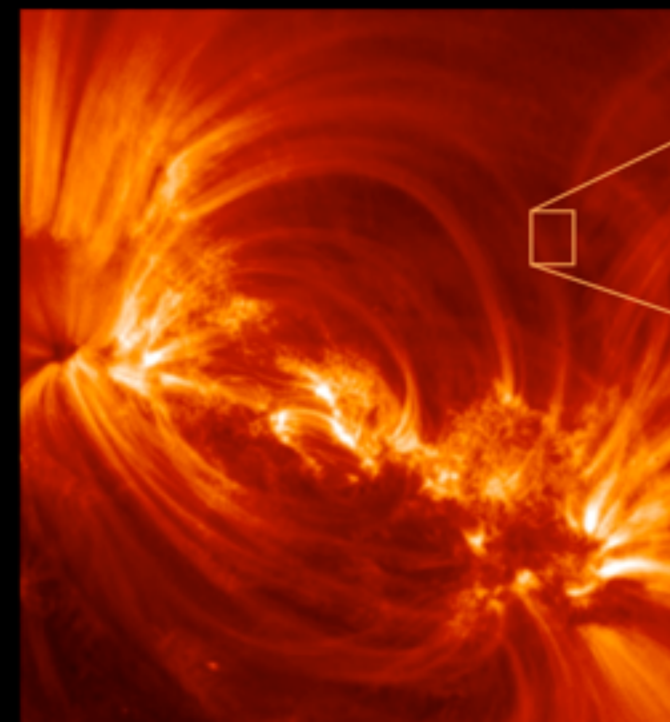

**Hinode SOT:** High resolution movies in G-ba
(430nm) and Ca II H (397nm) showing the
motion of granules and small magnetic flux

# Coronal heating



Short timescale (fast motions)

***Waves (AC)***



*Courtesy J. Klimchuk*

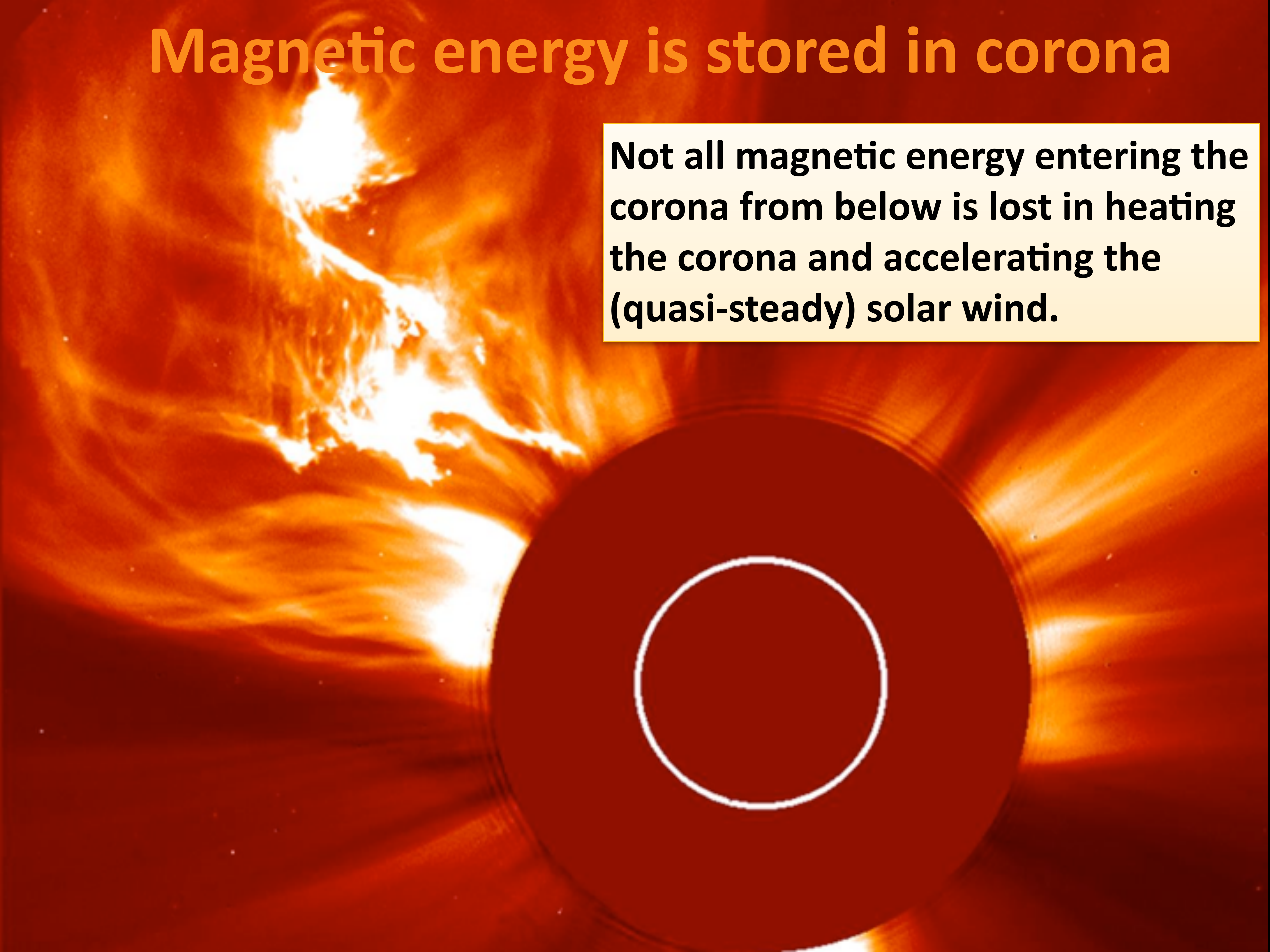
Long timescale (slow, quasi-static stressing of the field)

***Microflares (DC)***

*Parnell & de Moortel, 2012*

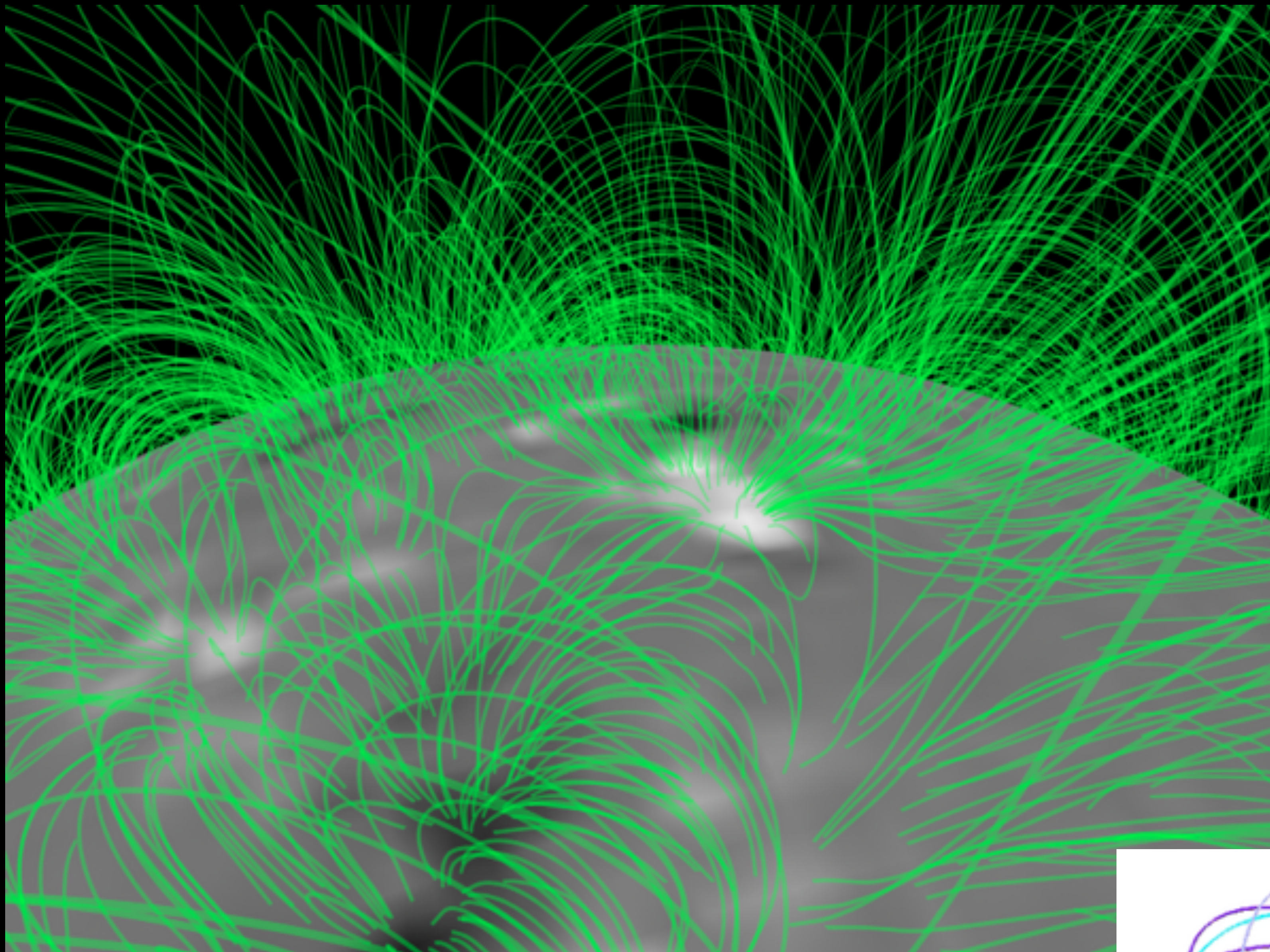
http://arxiv.org/abs/1206.6097

# Magnetic energy is stored in corona



Not all magnetic energy entering the corona from below is lost in heating the corona and accelerating the (quasi-steady) solar wind.

# Coronal magnetic fields



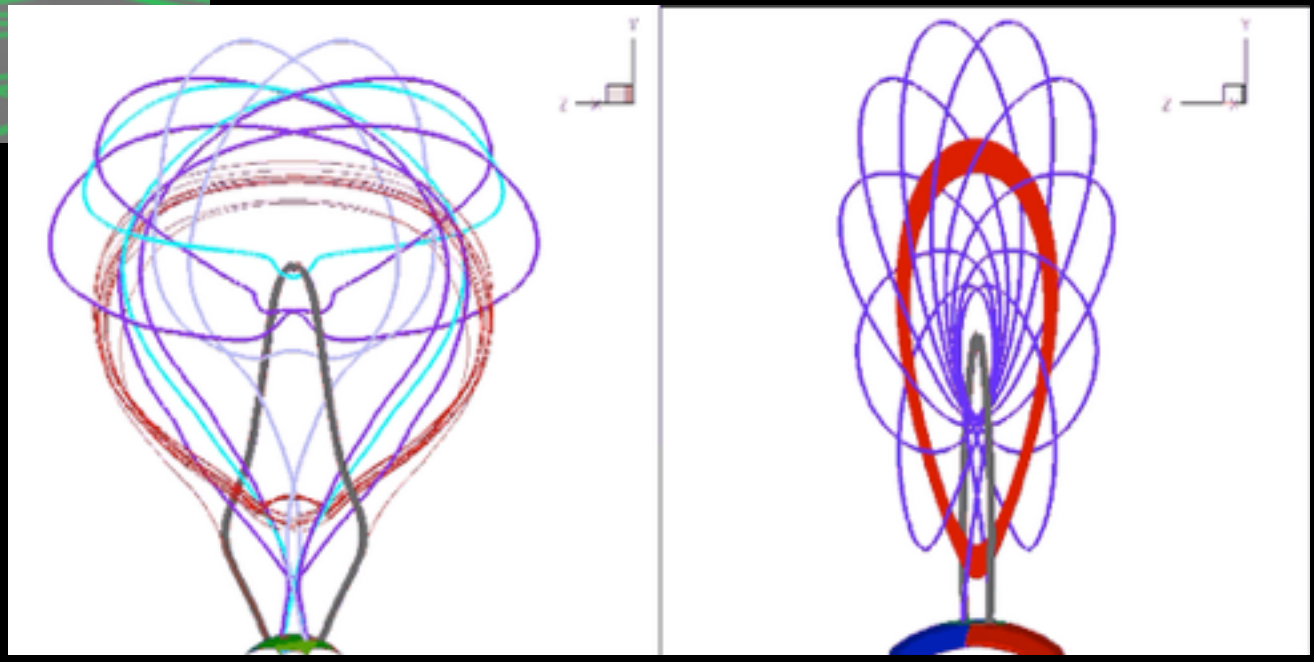
Free energy

Magnetic energy above that of potential field with the same boundary condition

$$F(\boldsymbol{B}) = E(\boldsymbol{B}) - E(\boldsymbol{B}_P)$$

$$E(\boldsymbol{B}) = \frac{1}{2\mu_0}\int_V B^2\, dV$$

Corona can store "free" magnetic energy in twisted (current-carrying) field



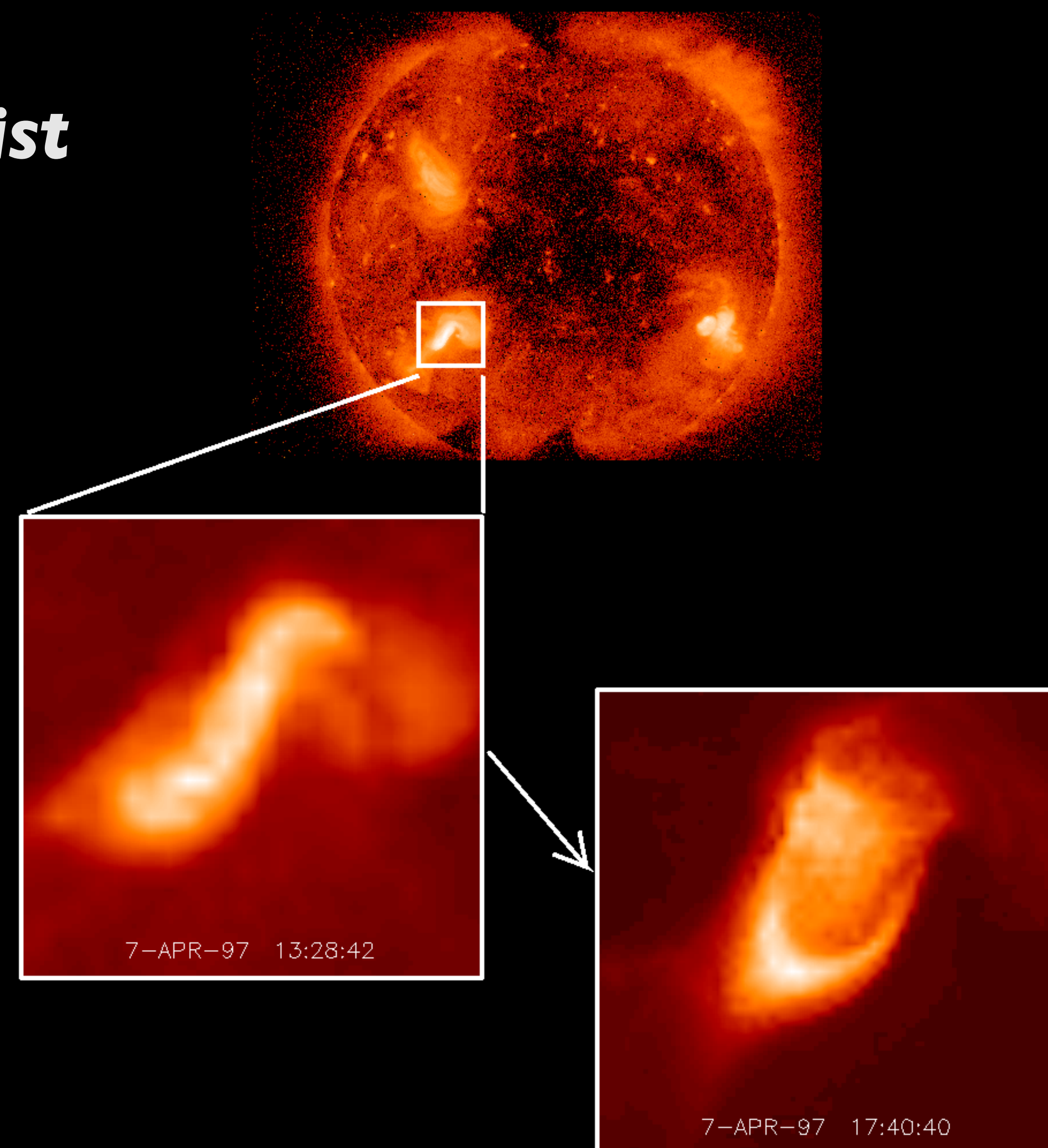
# Magnetic Helicity

***Free energy linked to twist in fields***

$$H_k = \langle \boldsymbol{\omega} \cdot \boldsymbol{v} \rangle$$
$$H_m = \langle \boldsymbol{A} \cdot \boldsymbol{B} \rangle$$
$$H_c = \langle \boldsymbol{J} \cdot \boldsymbol{B} \rangle$$

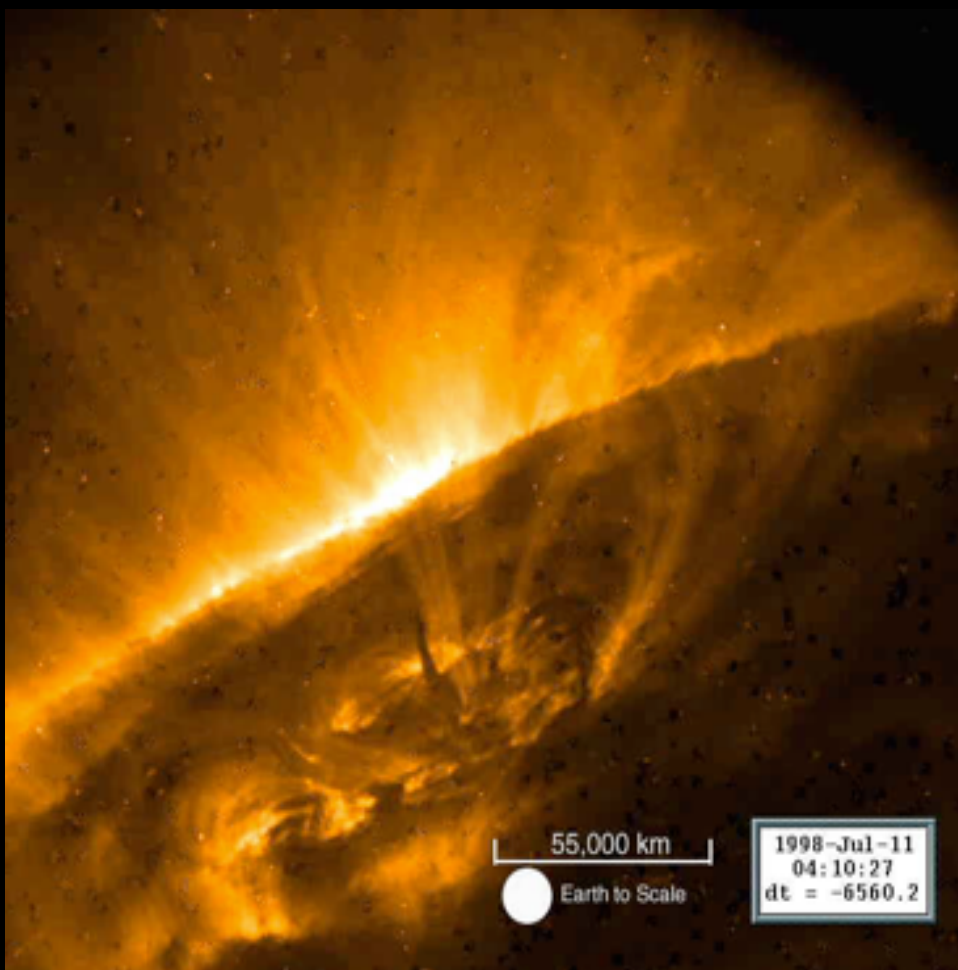
$$\boldsymbol{\omega} = \boldsymbol{\nabla} \times \boldsymbol{v}$$
$$\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A}$$
$$\boldsymbol{J} = \frac{c}{4\pi} \boldsymbol{\nabla} \times \boldsymbol{B}$$

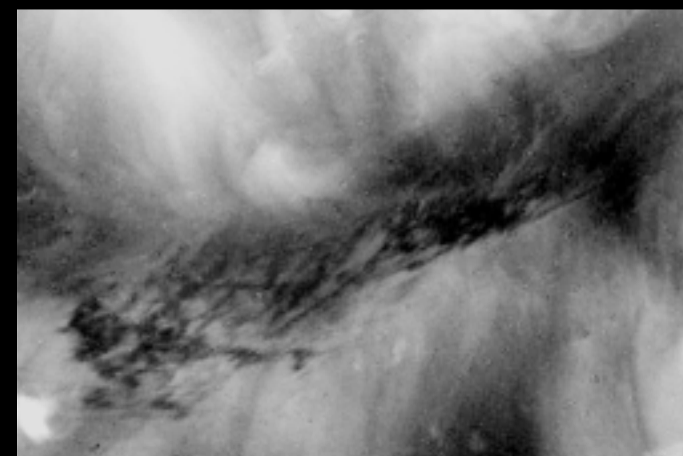
Sigmoids...

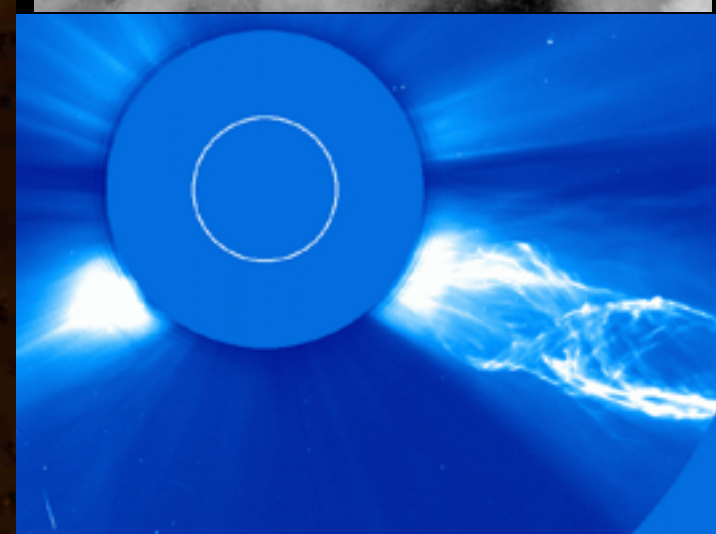


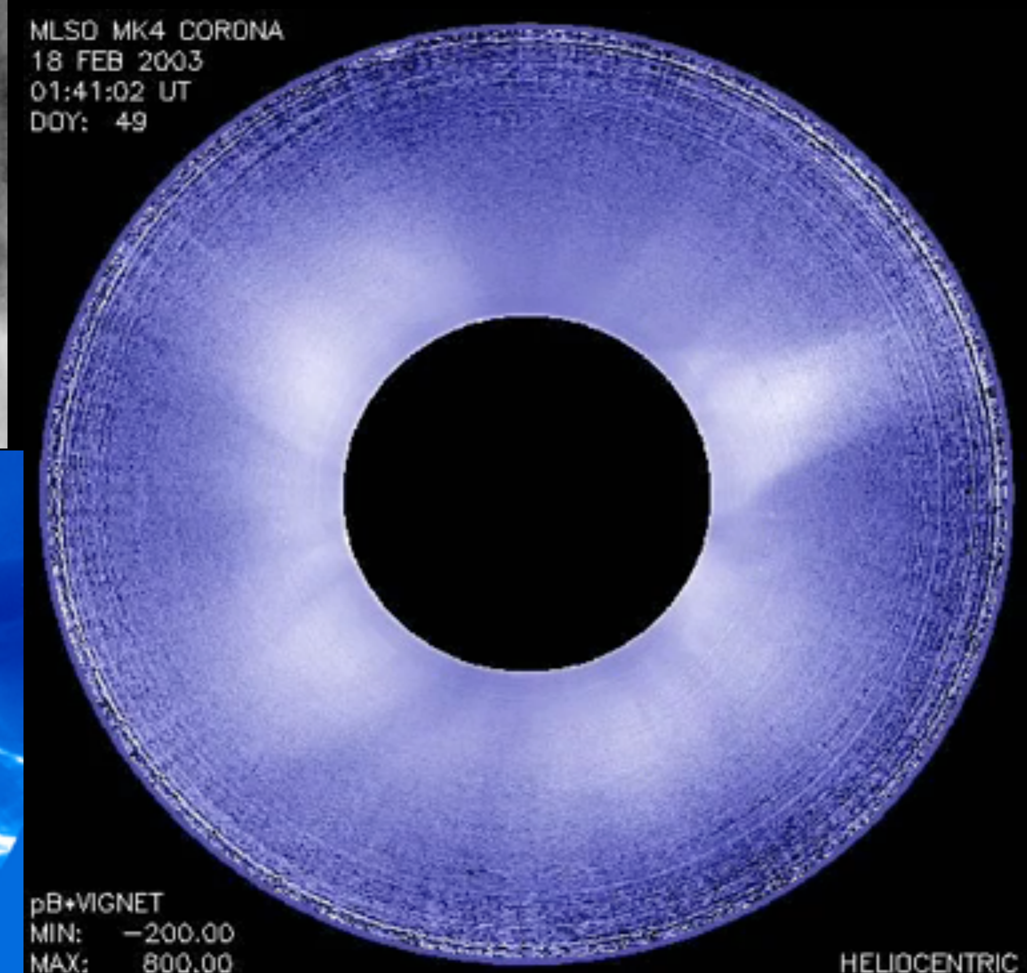

Active regions are significantly more likely to produce flares or CMEs when associated with sigmoid structures. (*Canfield et al., 1999*)
Such structures are especially well-defined at the onset of an eruption, but also **exist quiescently**

# Would we recognize twist if we saw it?



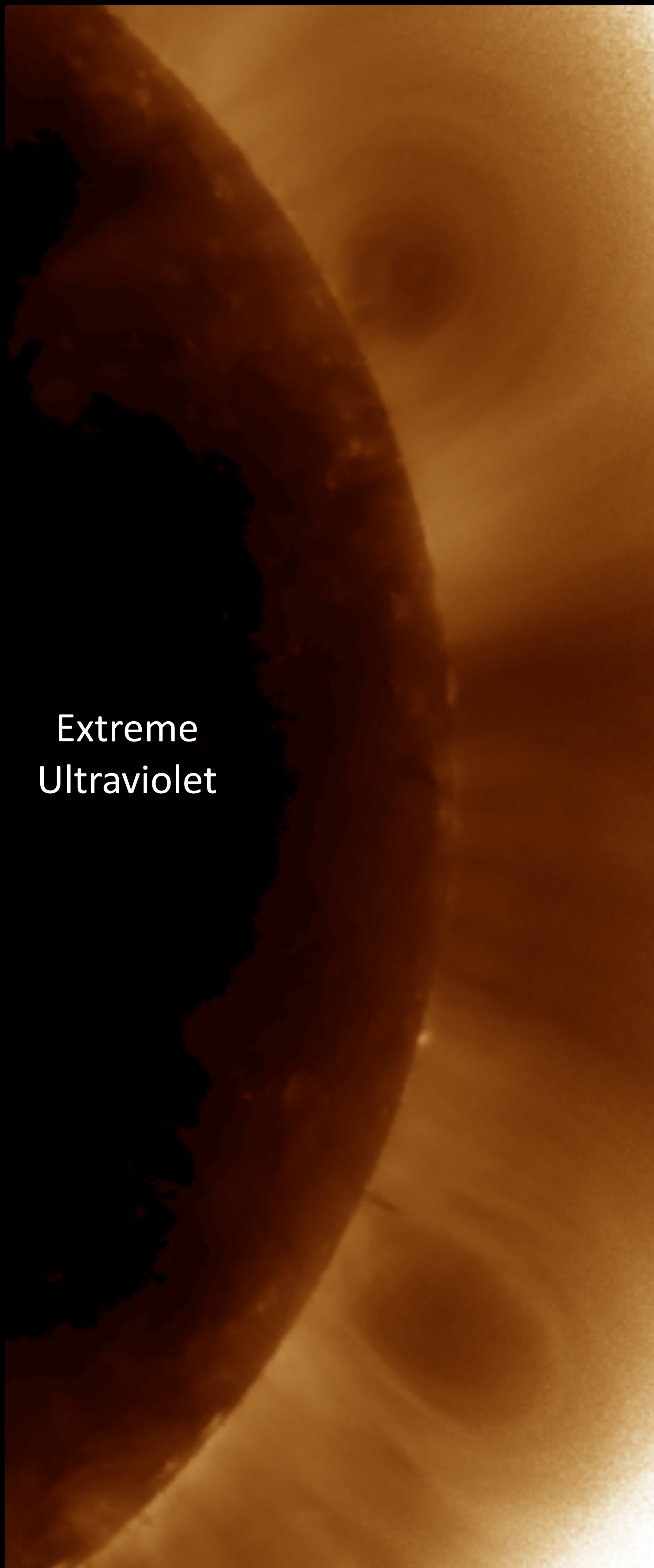


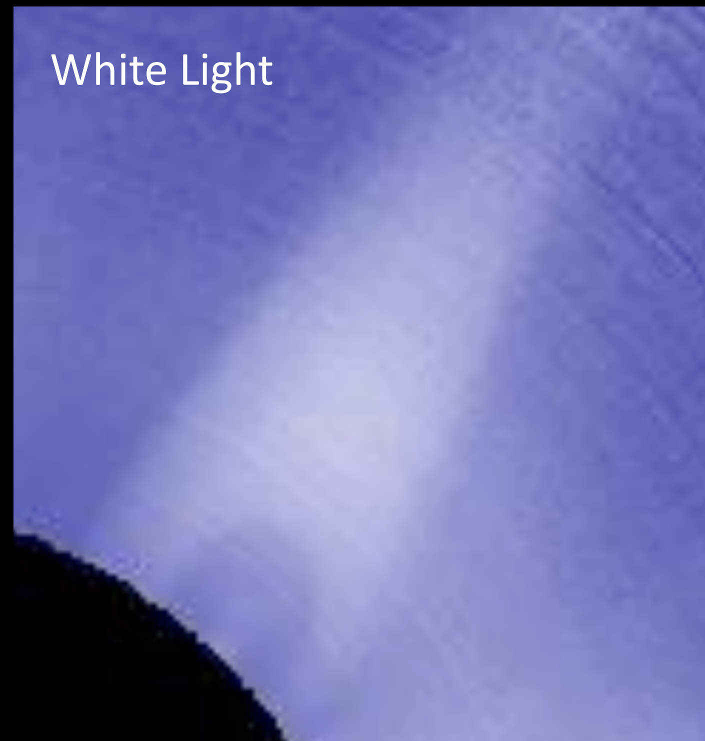


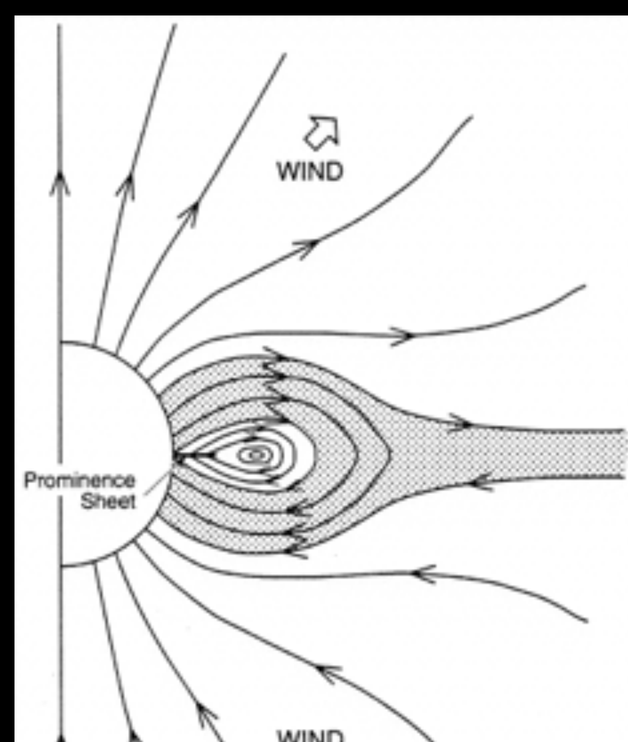

Maybe --

twisting motions, braided morphologies....

# Stored energy: prominence cavities



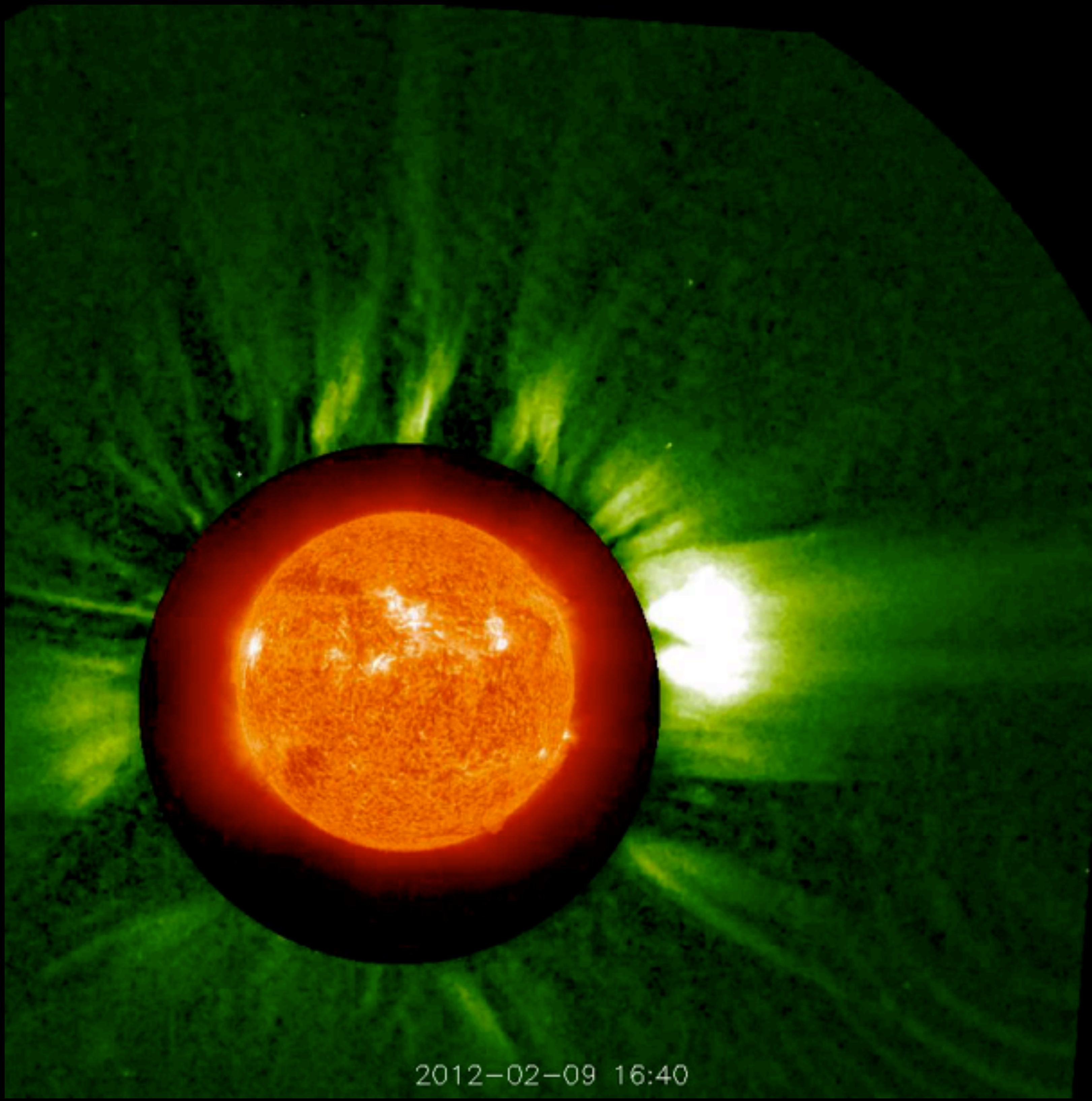




*Low & Hundhausen, 1995*

…Actually they are quite dynamic when you look close enough -- but on large-scale, they pretty much stay put….


*Li et al. 2012*

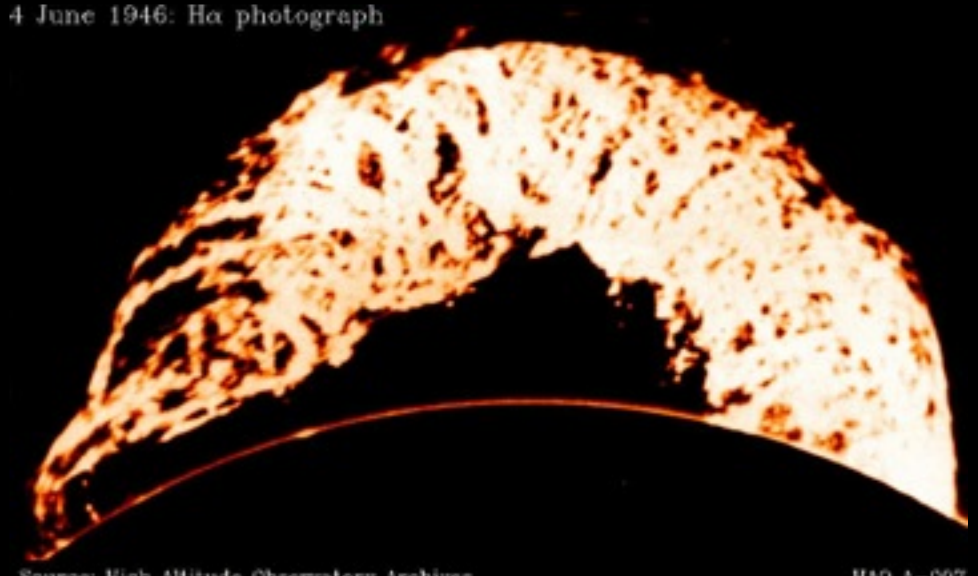
# Released energy: prominence cavities




…until BANG!!

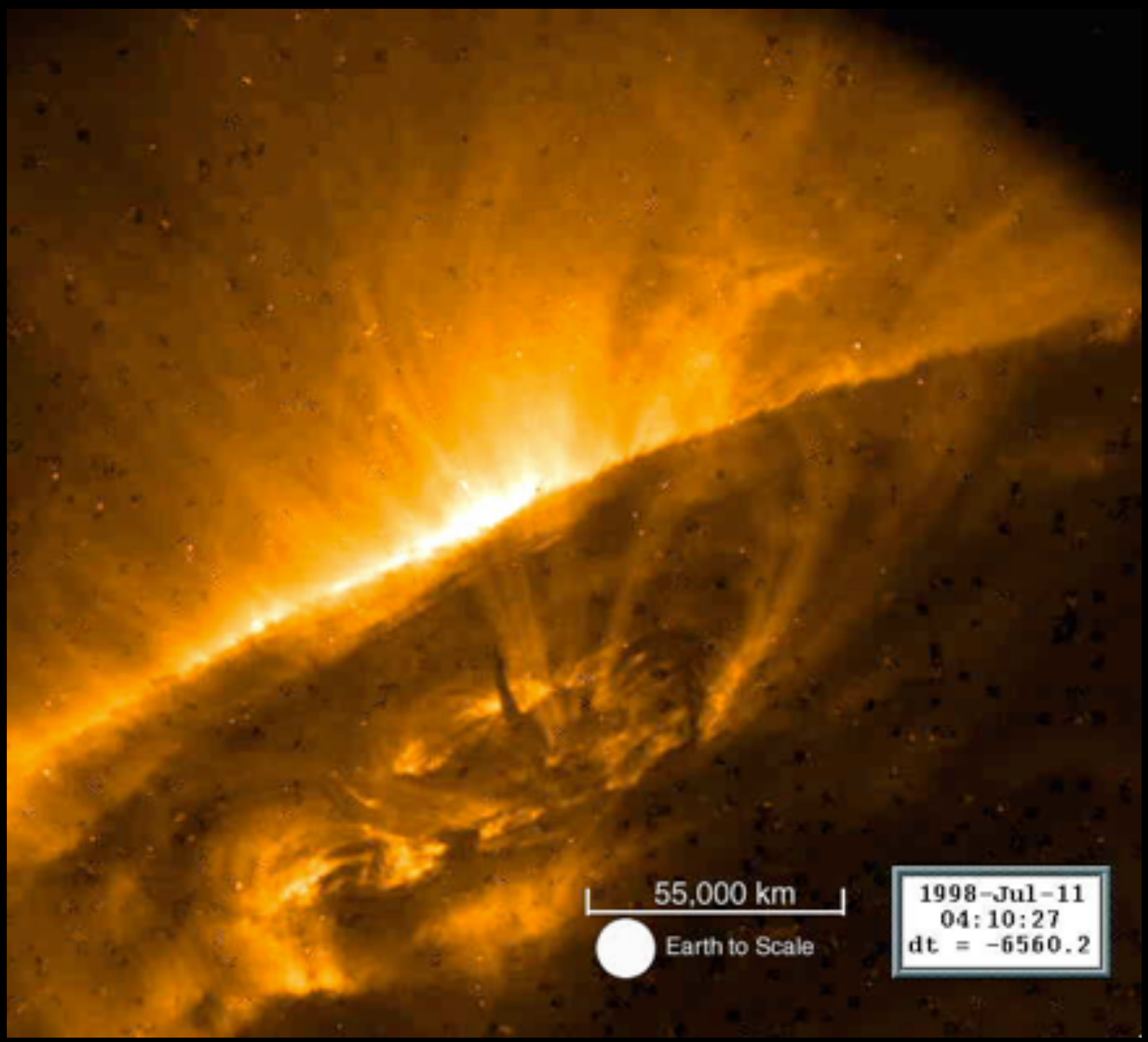
**Coronal Mass Ejection**

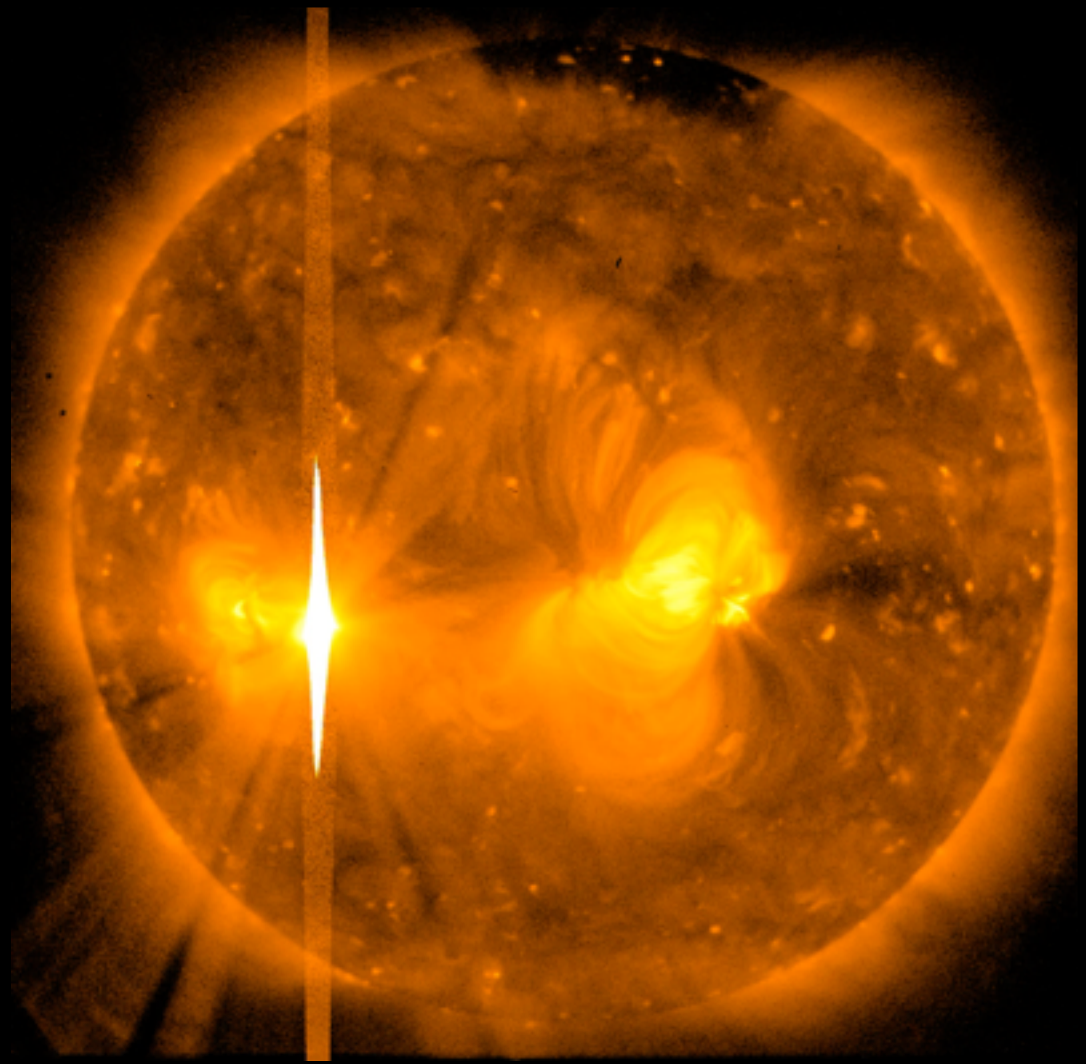
***Eruptions***
Fed by a release of magnetic energy, CMEs and solar flares send particles and radiation streaming into the *heliosphere*



# Eruptive Events

***Both are powered by the release of magnetic energy in the corona***



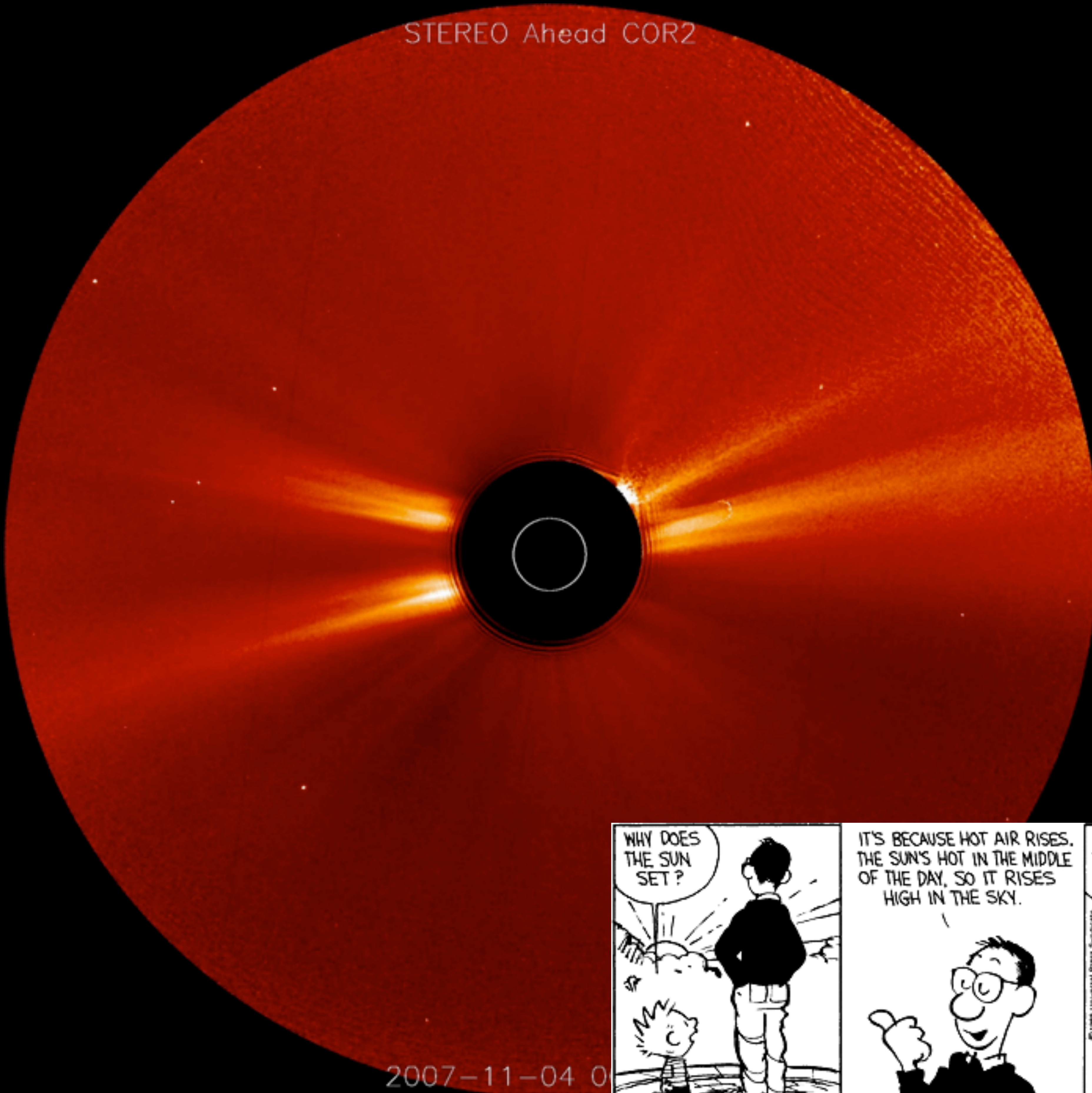



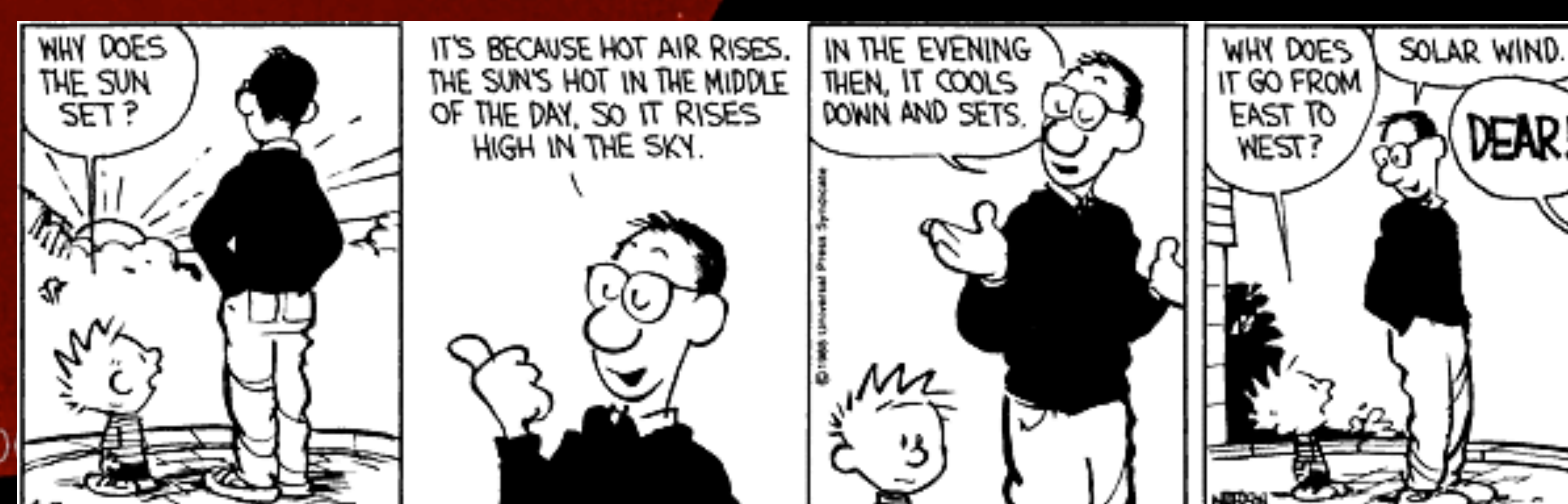
***Coronal Mass Ejections (CMEs)***

***Plasma is bodily lifted off the Sun and thrust into space***

***Solar flares***

***Associated mainly with x-ray radiation***
***...but other radiation too (e.g. white light)***
***and non-thermal partical acceleration***


STEREO Ahead COR2
2007-11-04


WHY DOES THE SUN SET?
IT'S BECAUSE HOT AIR RISES. THE SUN'S HOT IN THE MIDDLE OF THE DAY, SO IT RISES HIGH IN THE SKY.
IN THE EVENING THEN, IT COOLS DOWN AND SETS.
WHY DOES IT GO FROM EAST TO WEST?
SOLAR WIND.
DEAR!