ASTRO5010: The Sun's Atmosphere

Session 2024-25

Lecture 11: "Observing and interpreting solar magnetism"

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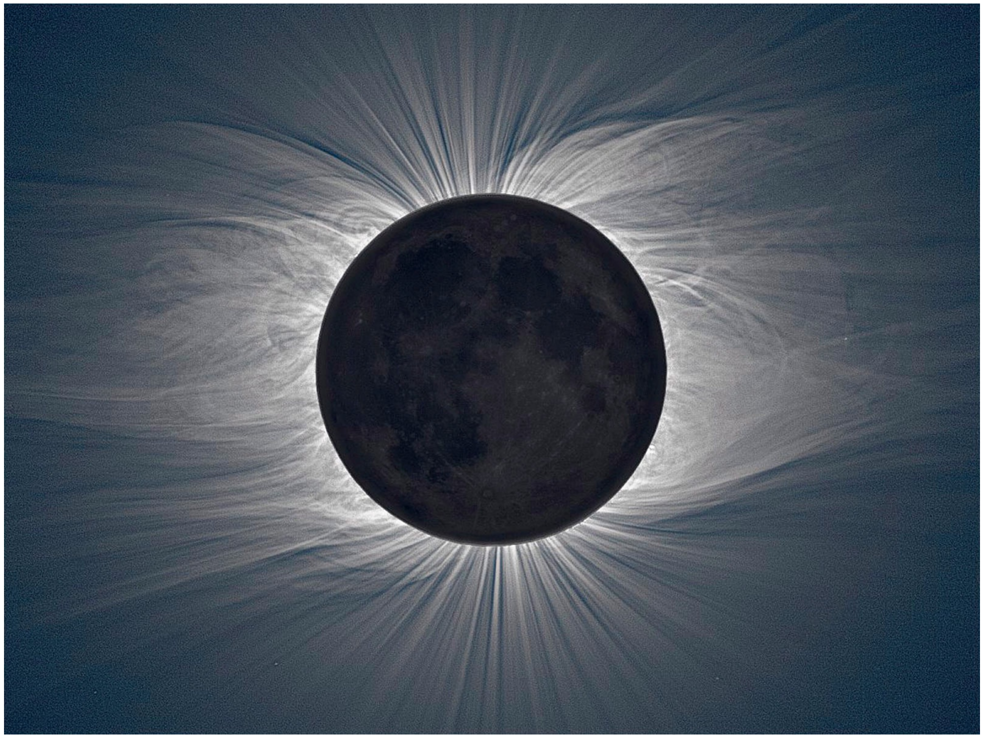
Useful homework questions based on this material

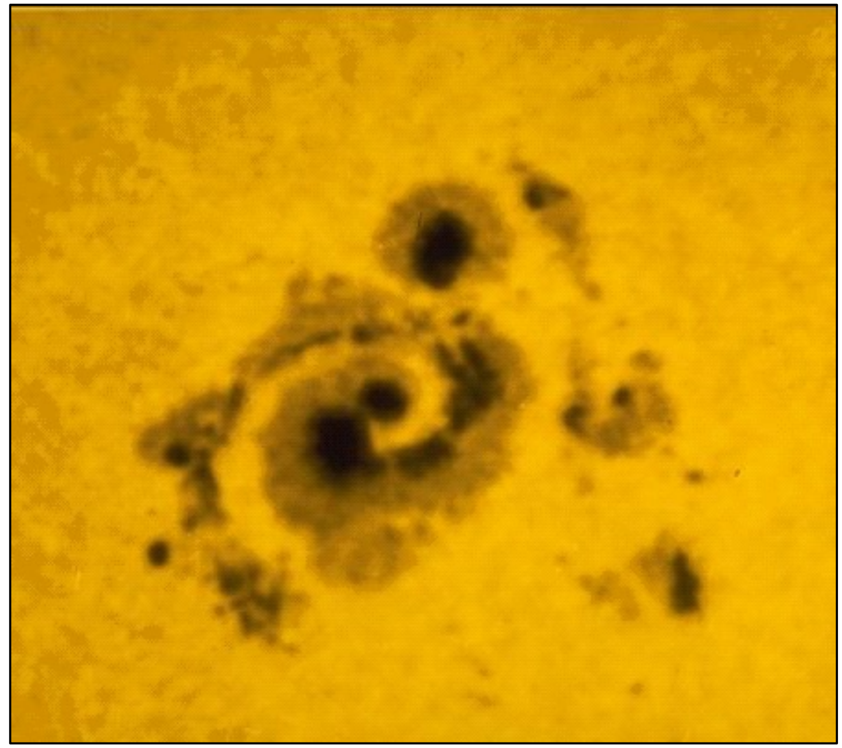
- What are the forces acting on plasma in a coronal magnetic loop, a rough quantitative estimate?
- For what value of B can a flux tube escape from the tachocline and emerge in one cycle?
- What is the electrical potential at the photosphere?
- At what stereoscopic angle can Stokes (I,V) do better than Stokes (I,Q,U,V) for the B vector?

These are questions to be answered by rough approximation, and the necessary facts should be here on the slides. I will post discussion of these items on Moodle and at

http://www.ssl.berkeley.edu/~hhudson/presentations/tsa.250303/

Solar magnetism



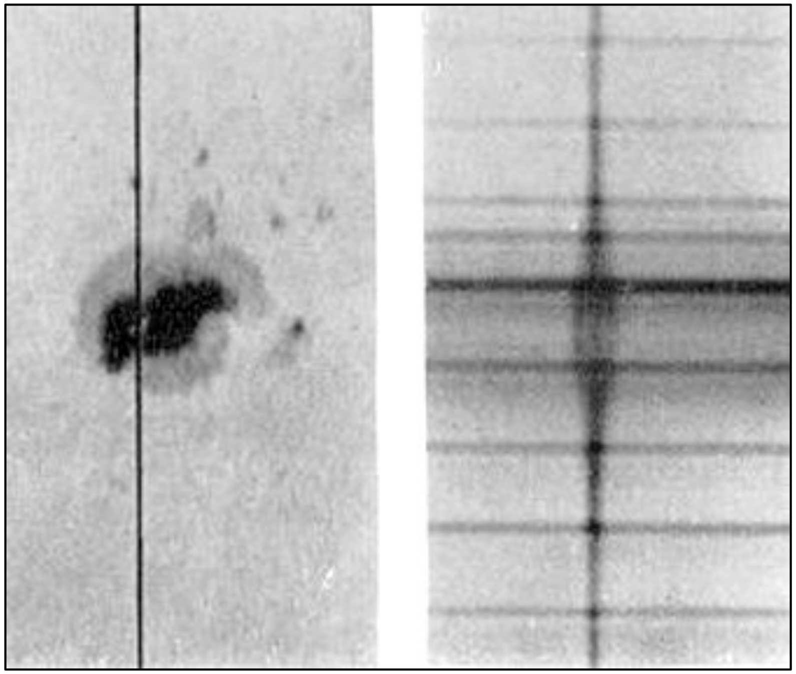


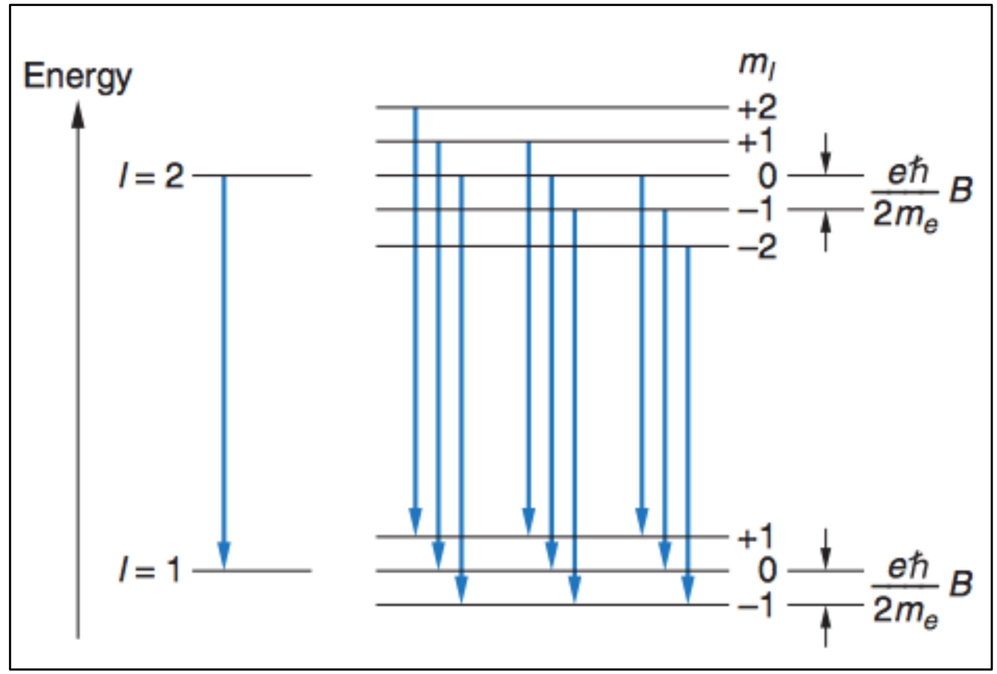
- The fine striations at the poles during an eclipse sure look like a dipole magnetic field.

- Sometimes sunspots have spiral patterns.

- Clues such as these led Hale to confirm the existence of solar magnetism via the Zeeman effect.

The Zeeman effect

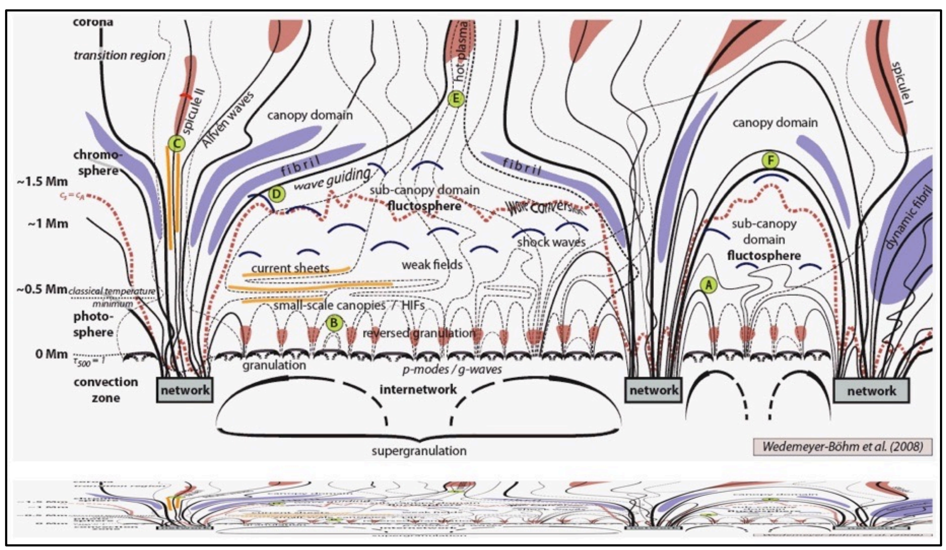




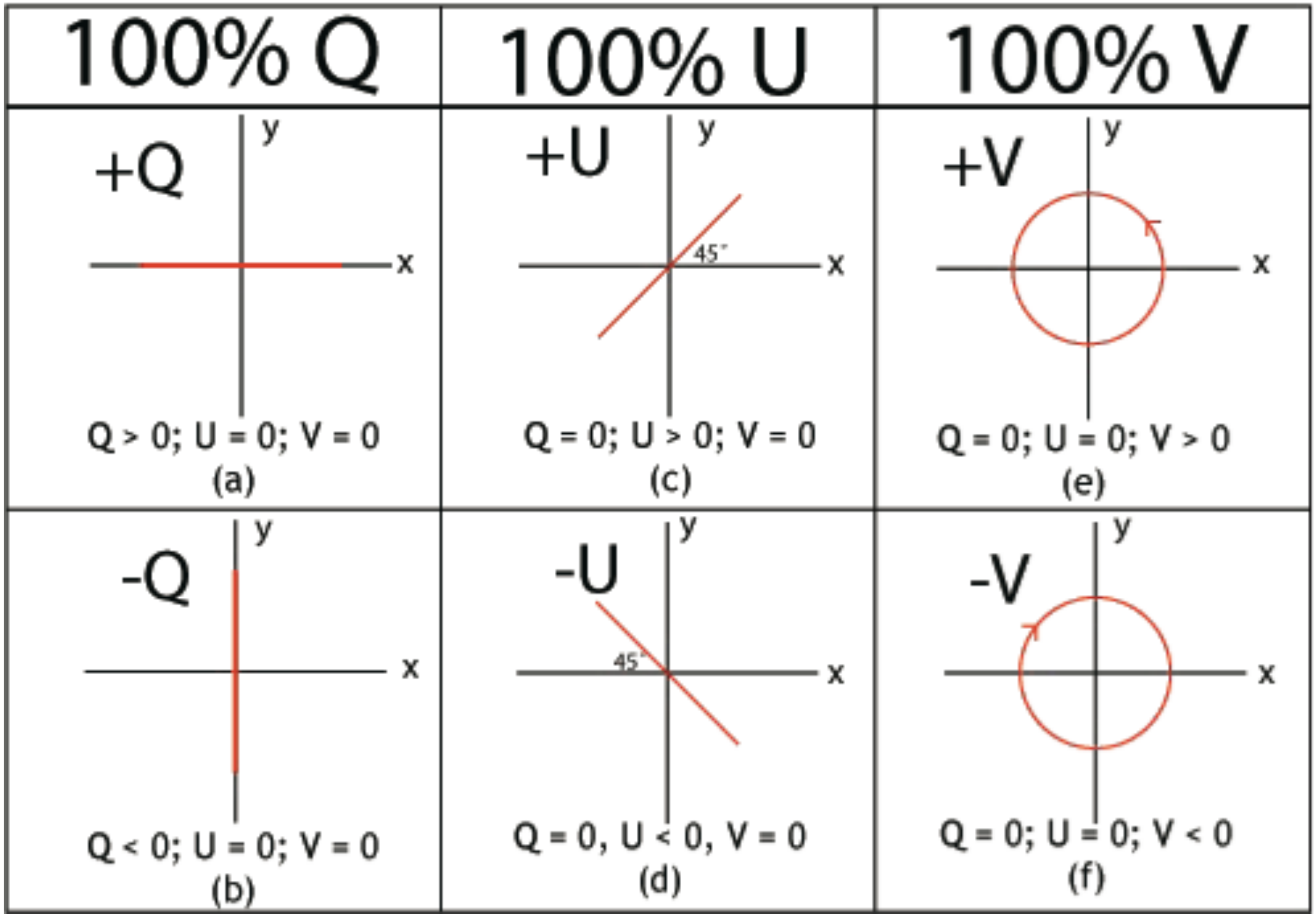
- Magnetic fields distort atomic energy levels in a polarized manner.
- For sunspot 0.1 T fields, the splitting is visible to the naked eye in a spectroscope. The "Bohr Magneton" is 5.788×10^{-5} ev/T.
- The splitting depends upon the angle <B, eye>: the σ components (linear polarization) reflect the perpendicular field, whereas the π components (circular) reflect the line-of-sight field.

How do we absorb this discovery?

- Hale showed that we can observe photospheric magnetism via Zeeman splitting
- Eclipse observations had already revealed “bar magnet” dipole light patterns
- How to link these phenomena?
  - Mathematical extrapolation (the dipole etc.)
  - New physical observations of the corona



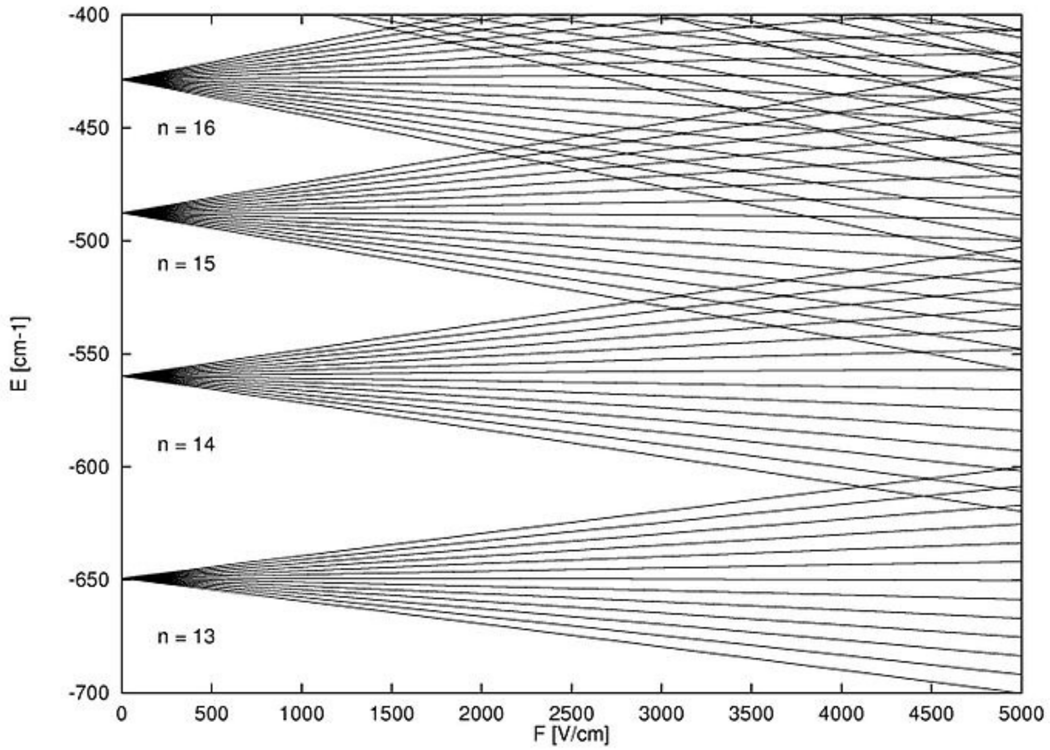
Three of the Stokes parameters



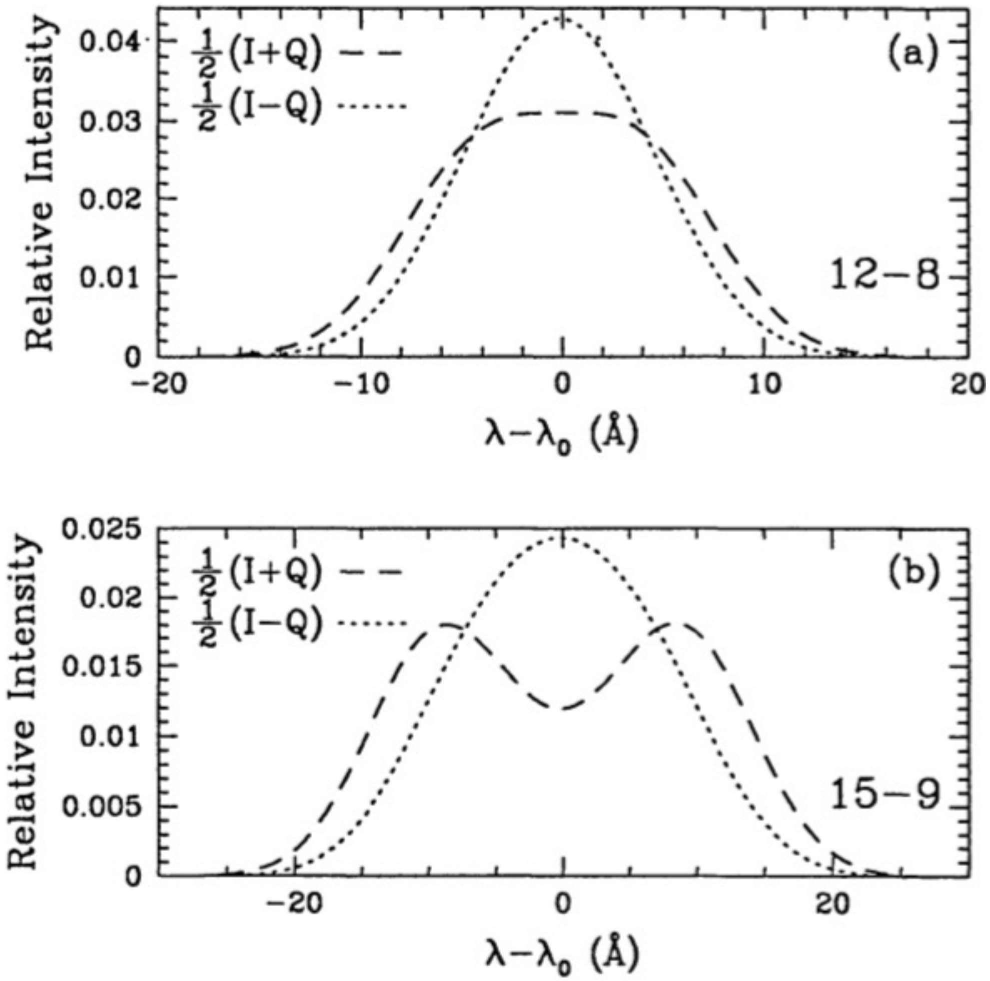
(the fourth Stokes parameter is just the intensity I)

The Electric Field

- The Stark effect results from level shifts due to the presence of an electric field (the generic term).
- Pressure broadening is the Stark effect at the atomic level in a dense plasma.



Stark Effect



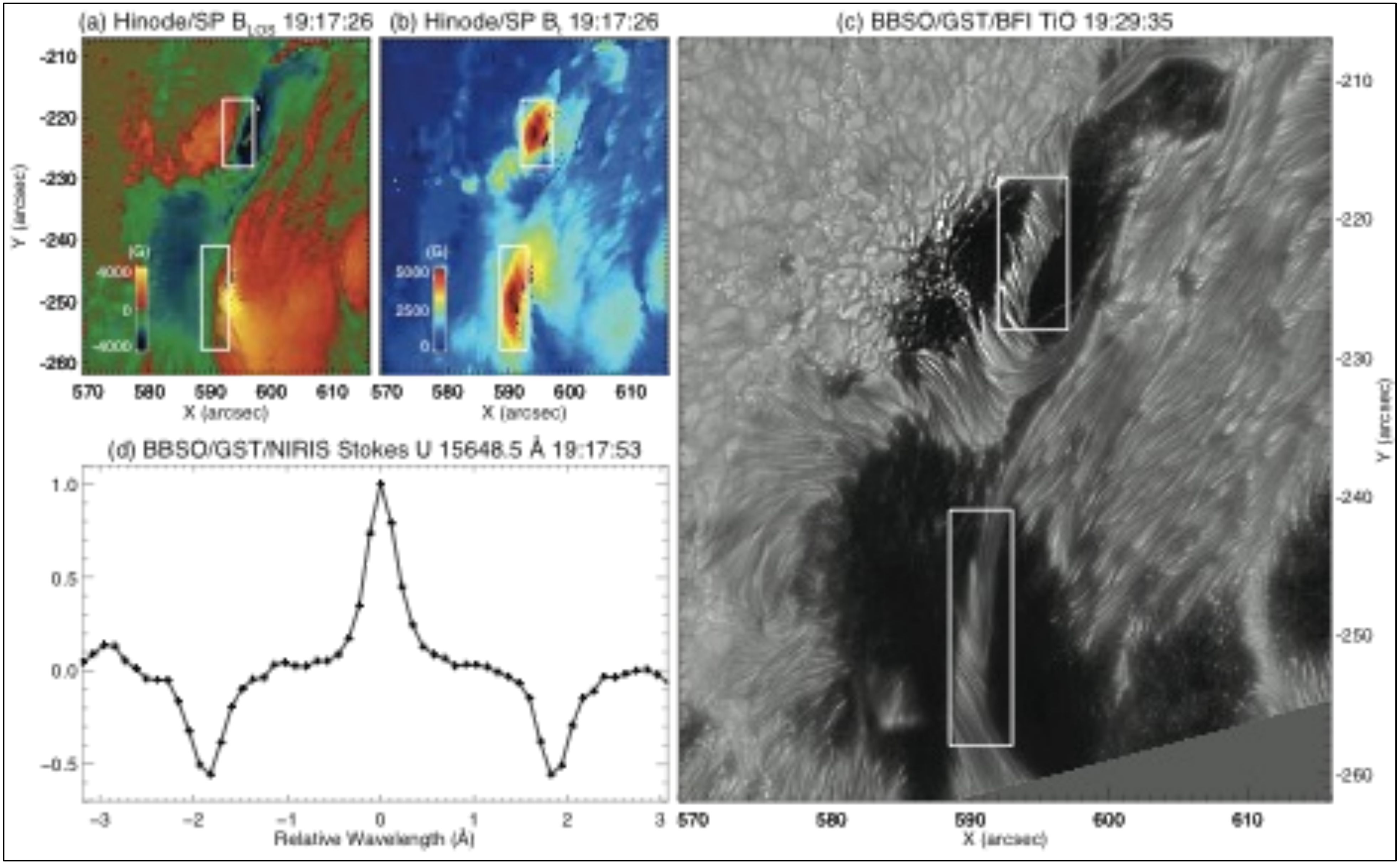
Casini-Foukal 1996

- The effect is strongest for "Rydberg" states (e.g., n = 20), hence ALMA?

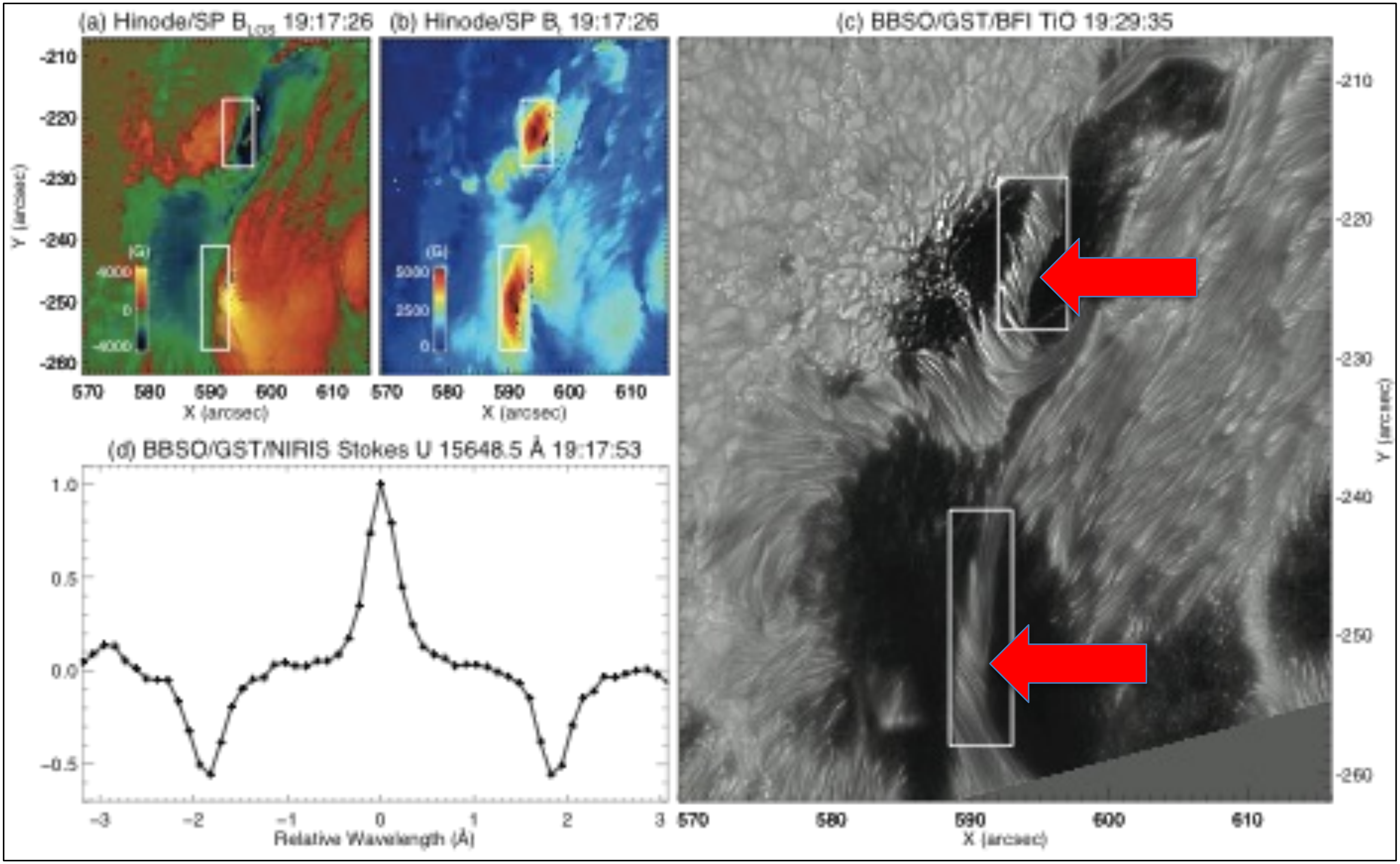
- Minimum detectable macroscopic fields may be of order 100 V/m.*

**This is not as crazy as it seems, since flare motions may cause huge electric fields*

An extreme case (H. Wang)

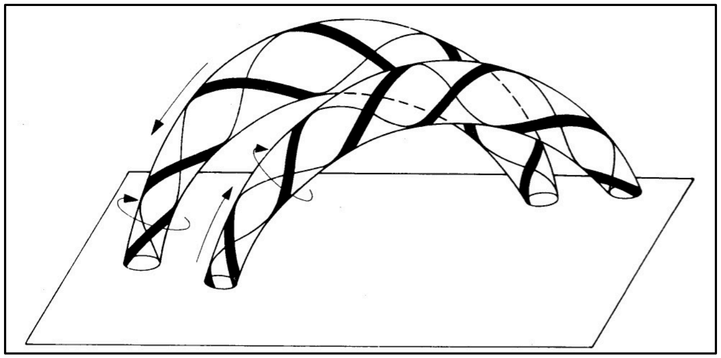


“Light bridges” in sunspots



Flux ropes

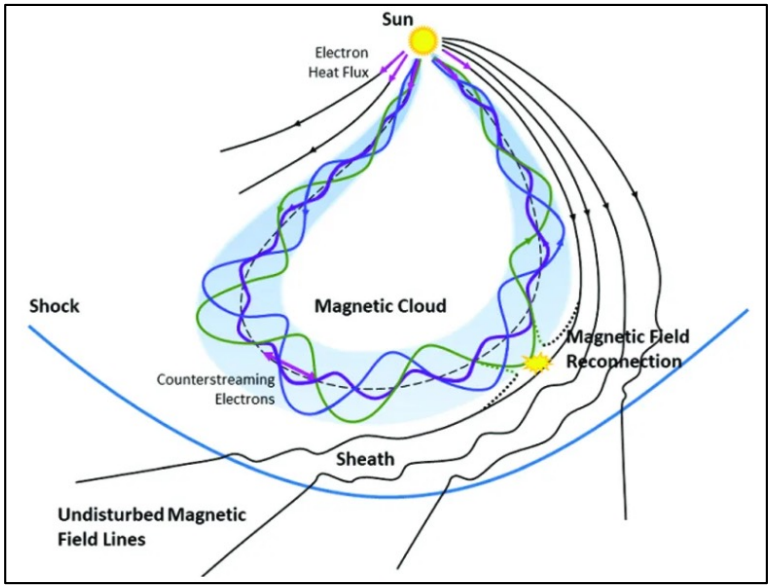
- In a magnetized plasma, the presence of velocity shearing naturally leads to helical structures ("flux ropes") via the Lorentz force. There are various mathematical representations.
- Related solar topics: filaments, filament channels, magnetic clouds



Gold-Hoyle flare model

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} I \int_C \frac{d\boldsymbol{\ell} \times \mathbf{r}'}{|\mathbf{r}'|^3}$$

Biot-Savart law (simple) relates currents and B



Generic coronal mass ejection (CME) structure

https://www.astro.gla.ac.uk/cartoons/index.html

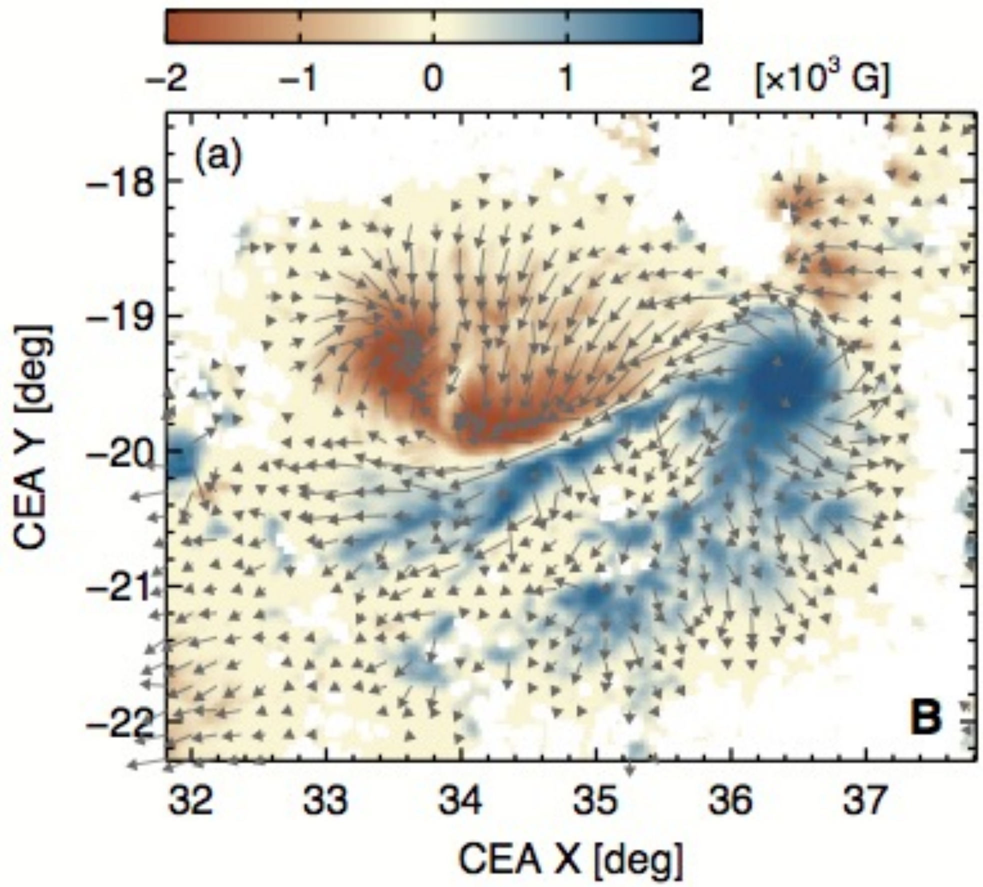
Maxwell and the EM field

What is it about the field that likes helices?

- Maxwell's EM equations unified earlier work (Faraday, Ampere, *etc*.)
- The synthesis allowed Maxwell to make a laboratory-based estimate of c
- The implication of this was the existence of a new physical object: the *field*
- The EM field requires the ***curl*** operator ∇

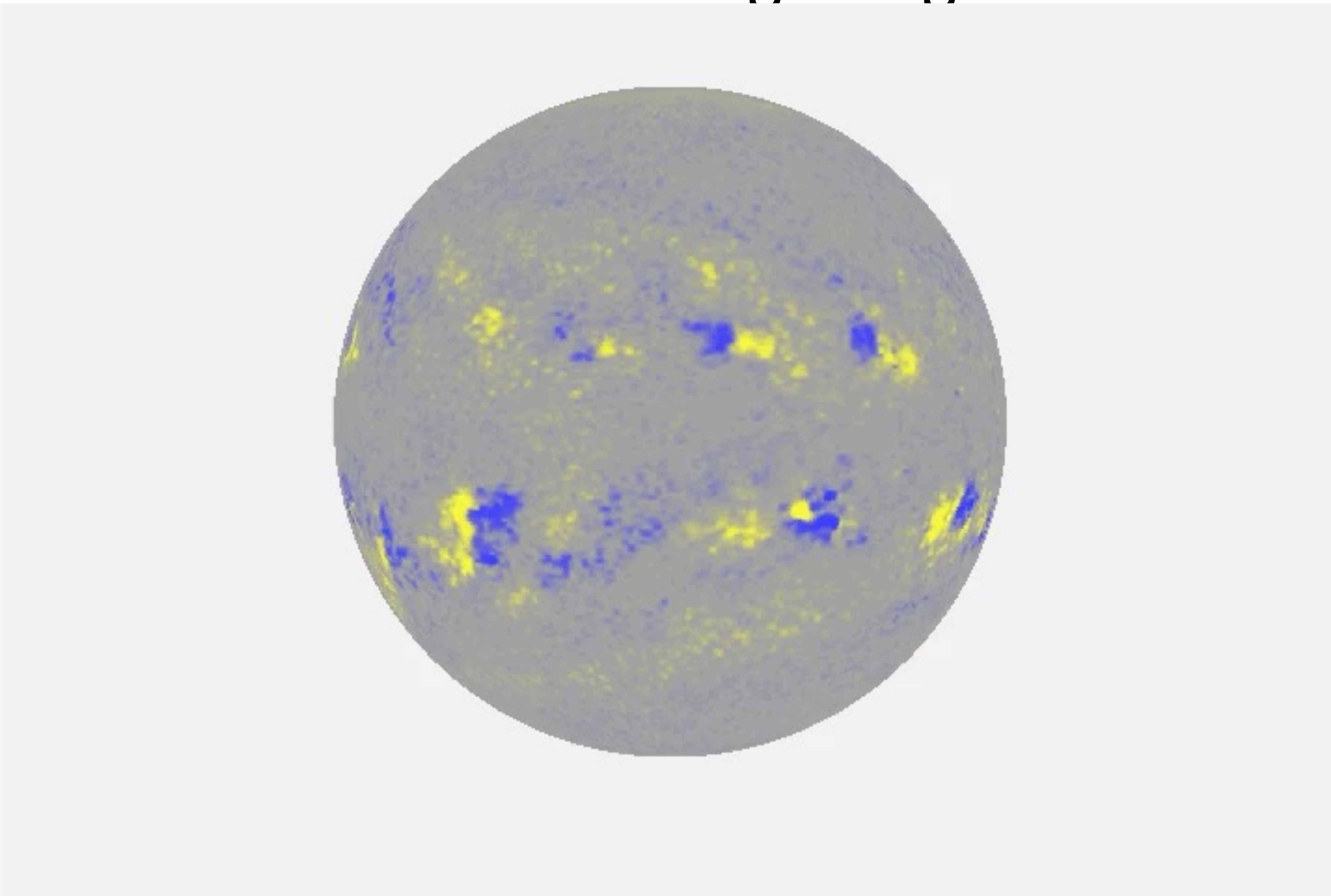
- Next historical step: Einstein and GR?

Vector field at photosphere

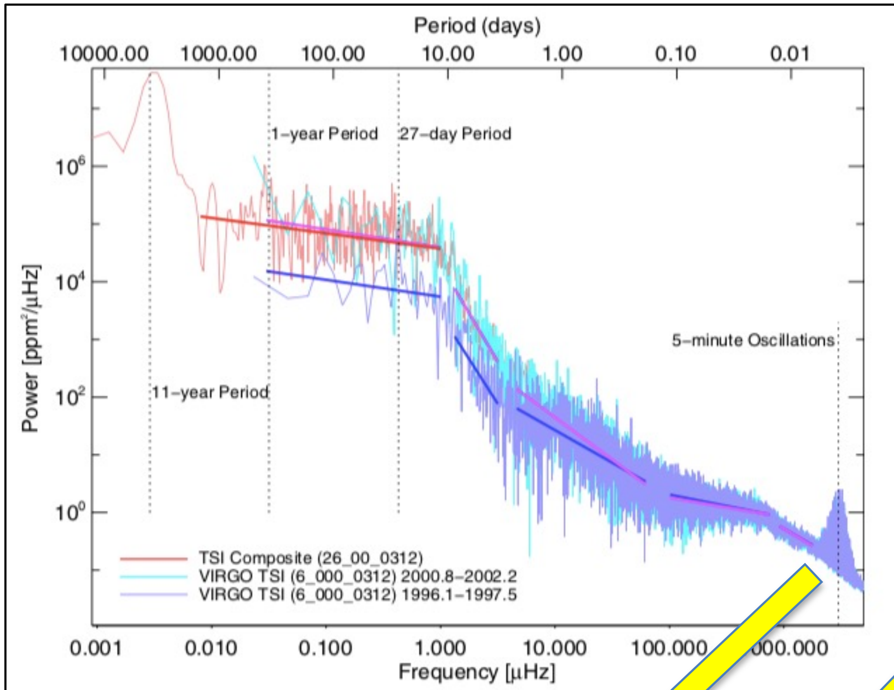


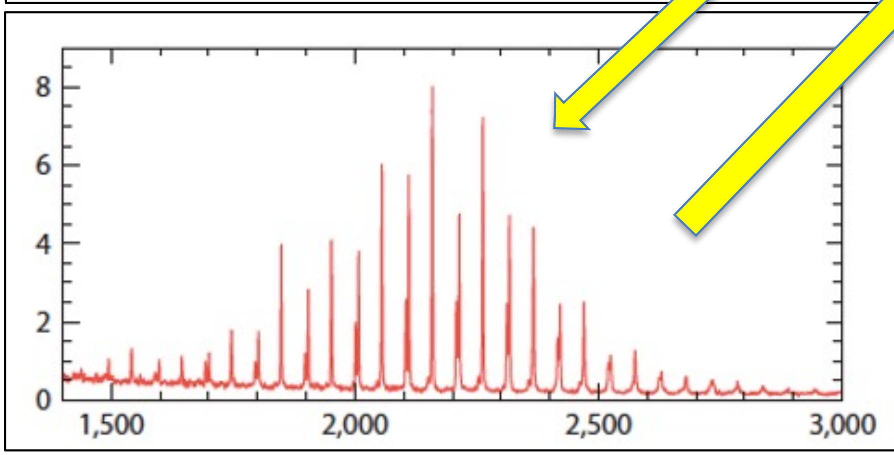
- With both parallel and perpendicular components, modulo a sign, one can infer the vector **B**.
- Note the "Polarity Inversion line" (PIL)
- This is also a "filament channel" with a strong horizontal current

Routine solar magnetograms

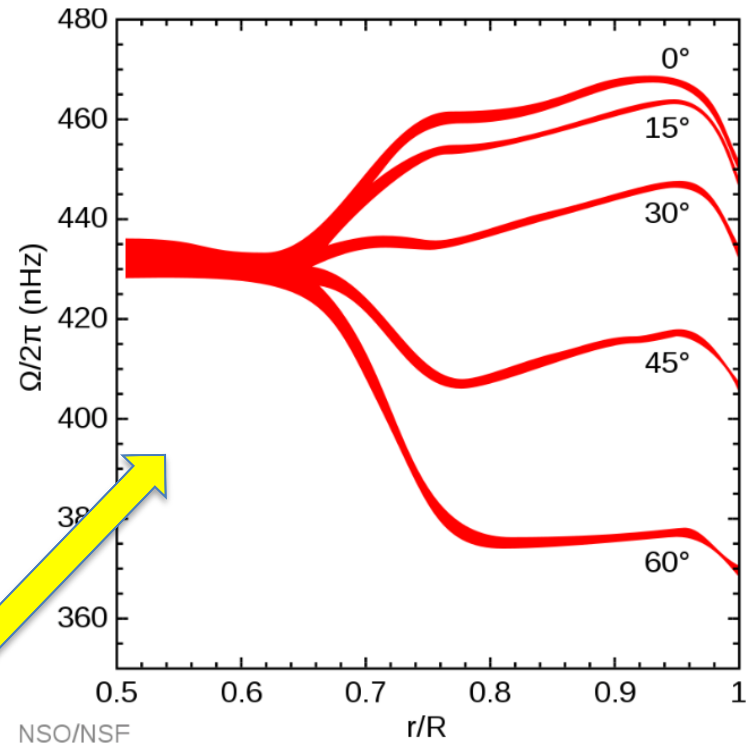


Helioseismology and the Tachocline





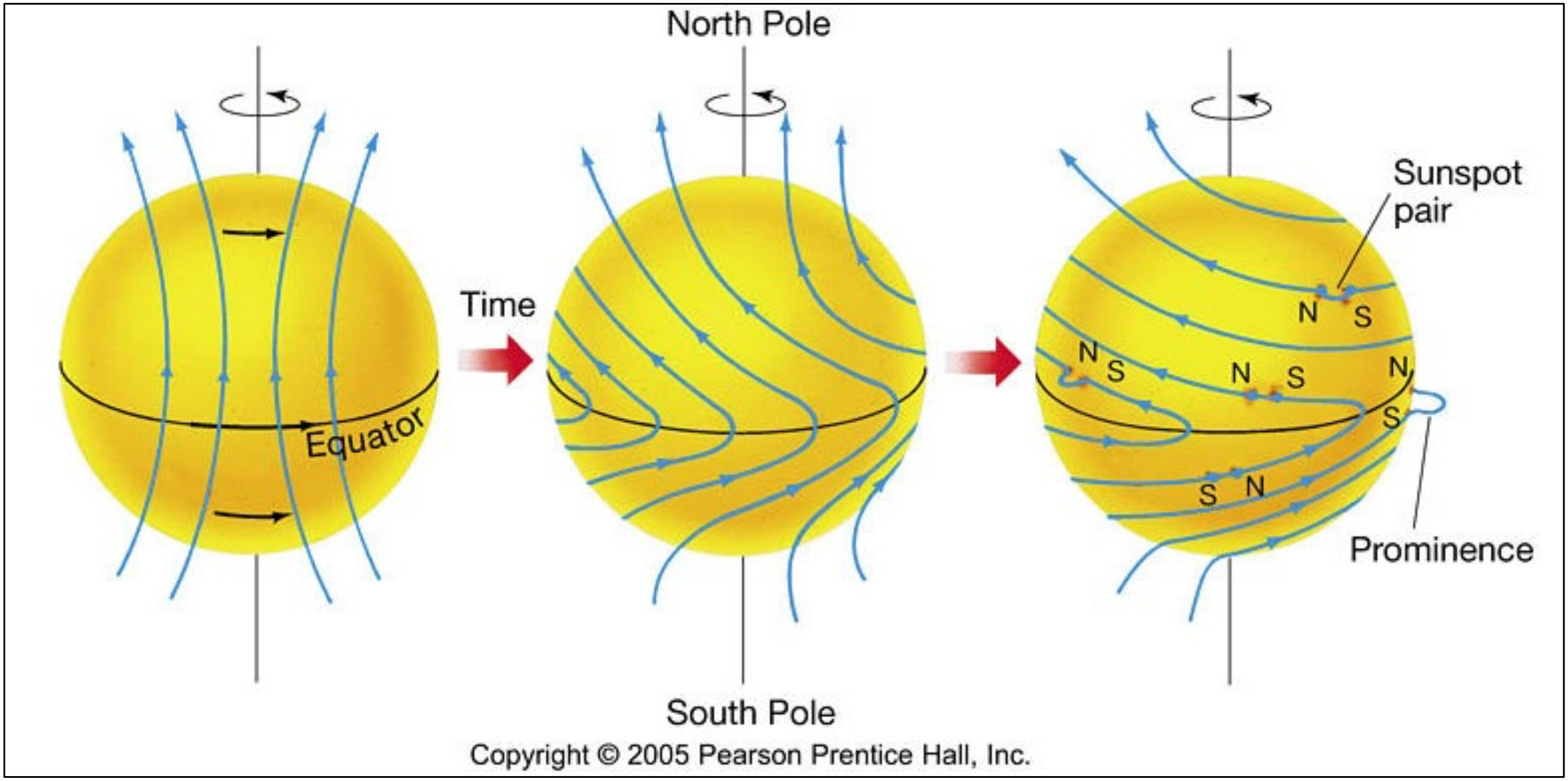
This example from a star, not the Sun!



- The solar resonances (“p-modes” or “5-min oscillations” allow us to locate the “tachocline”.

* This may be the site of the solar dynamo and magnetism.

Global: the Hale cycle



“Poloidal” fields amplify, due to differential rotation, and become “toroidal”

The problem of coronal magnetism

• We can use the Zeeman effect in the photosphere to determine the **B** (modulo symmetry-breaking) on a "surface," but the 3D field is required to understand energetics.

• Can we just *extrapolate* from the photospheric boundary into the corona? With full Stokes info, we know the vector **B** in the "plane" of the photosphere.

• Plasma "beta" ($\sim nkT/B^2$) dictates the effect of matter on magnetism: the corona is low-beta, $nkT \ll B^2$, but the chromosphere is not.

Extrapolating the photospheric field

i) Field derived from a scalar potential (∇ **x B** = 0)
ii) Linear force-free models, LFF (∇ **x B** = α **B**)
iii) Non-linear force-free models, NLFF:

$$\nabla \times \mathbf{B} = \alpha(x,y)\, \mathbf{B}$$

....

iv) MHD models: zero beta, "cold plasma"; $P_B >> P_g$

....

v) MHD models, multi-fluid MHD
vi) Non-MHD models: any dynamics, actually

Note that the solar corona is a near-fully ionized plasma, and so its electrical resistivity is very small (of order 10^{-7} Ohm-m).

Potential fields

- Extrapolation would be OK if there were no plasma in the corona, but if that were the case we couldn't see it!
- We could in principle ignore this basic fact and just plow ahead.
- In the absence of currents ($\nabla \times \mathbf{B} = 0$)*, one can uniquely extrapolate the coronal magnetic field via spherical harmonics.
- An example would be to represent the photospheric magnetic field as a set of *magnetic charges* from which a multipole expansion could determine the coronal field.
- In the popular "PFSS" model**, in which the Laplace's equation is solved inside a concentric spherical domain, outside of which the field is assumed to be radial.

* Thus, solutions of Laplace's equation: $\nabla^2\mathbf{B} = 0$

** "Potential Field Source Surface"

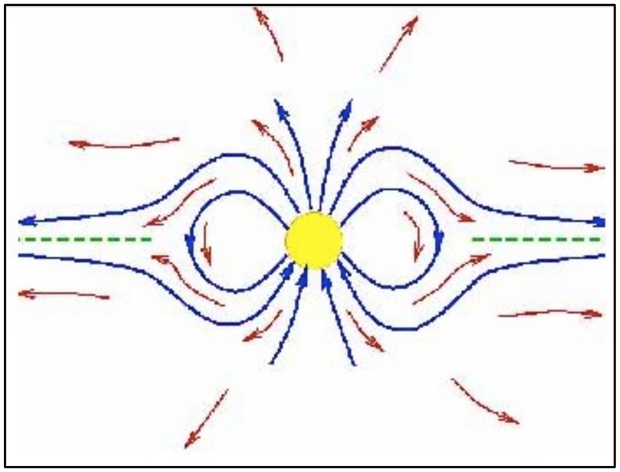
Limitations on mathematical extrapolations

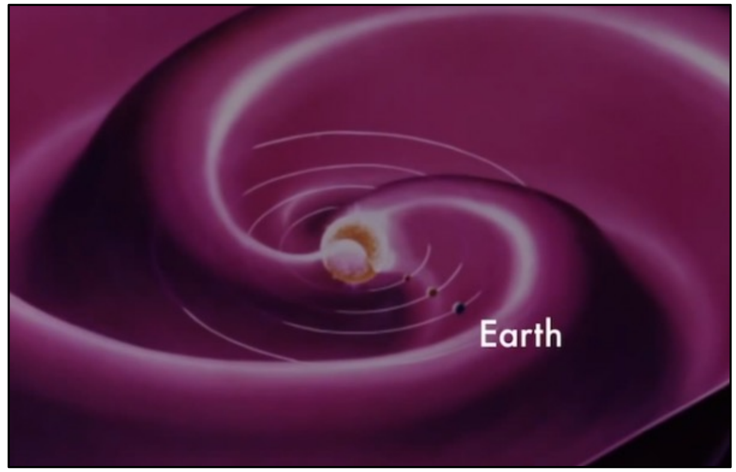
- The chromosphere is not force-free and not static
- Unbalanced currents penetrate the corona
- The base of the corona cannot be an equipotential surface
- The top of the corona (the base of the solar wind) is not low-β

Other ways to measure the coronal magnetic field

- The Hanle effect results from line depolarization when the collision frequency exceeds the Larmor frequency.
- Faraday rotation alters the polarization angle of a linearly polarized background source (e.g., a quasar).
- Image striations can be interpreted in terms of field direction: note that would be ~2/3 of the problem of measuring **B(r)**.
- Gyrosynchrotron radiation has natural circular polarization.
- Coronal coherent emissions contain many clues about coronal B.
- Birefringence effects polarize even thermal emission from magnetized plasmas.
- Magnetically induced transitions a new atomic spectroscopy tool.
- TeV cosmic-ray shadows a new technique, largely unused yet.
- *In situ* measurement (Parker Solar Probe).

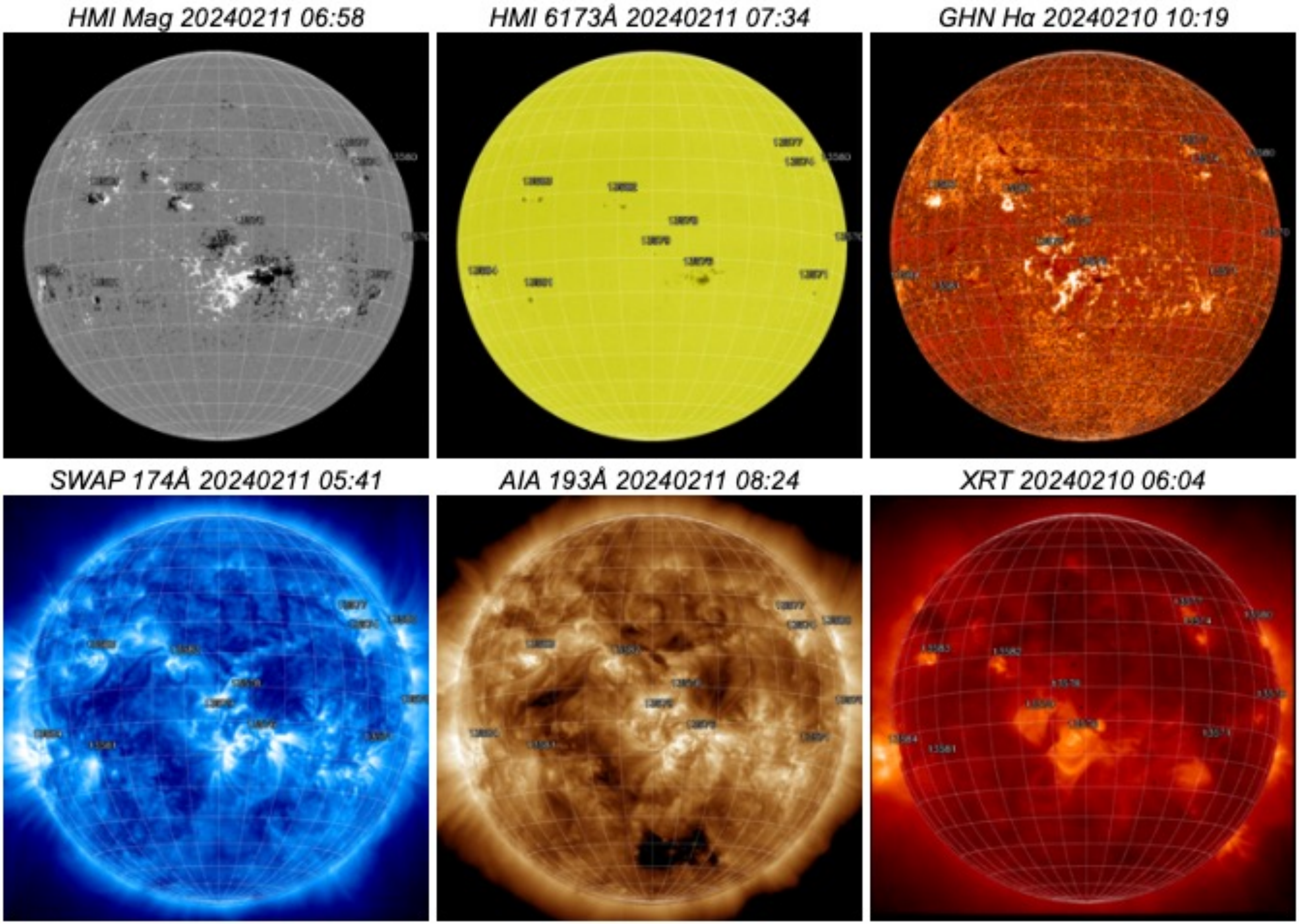
Heliospheric current sheet



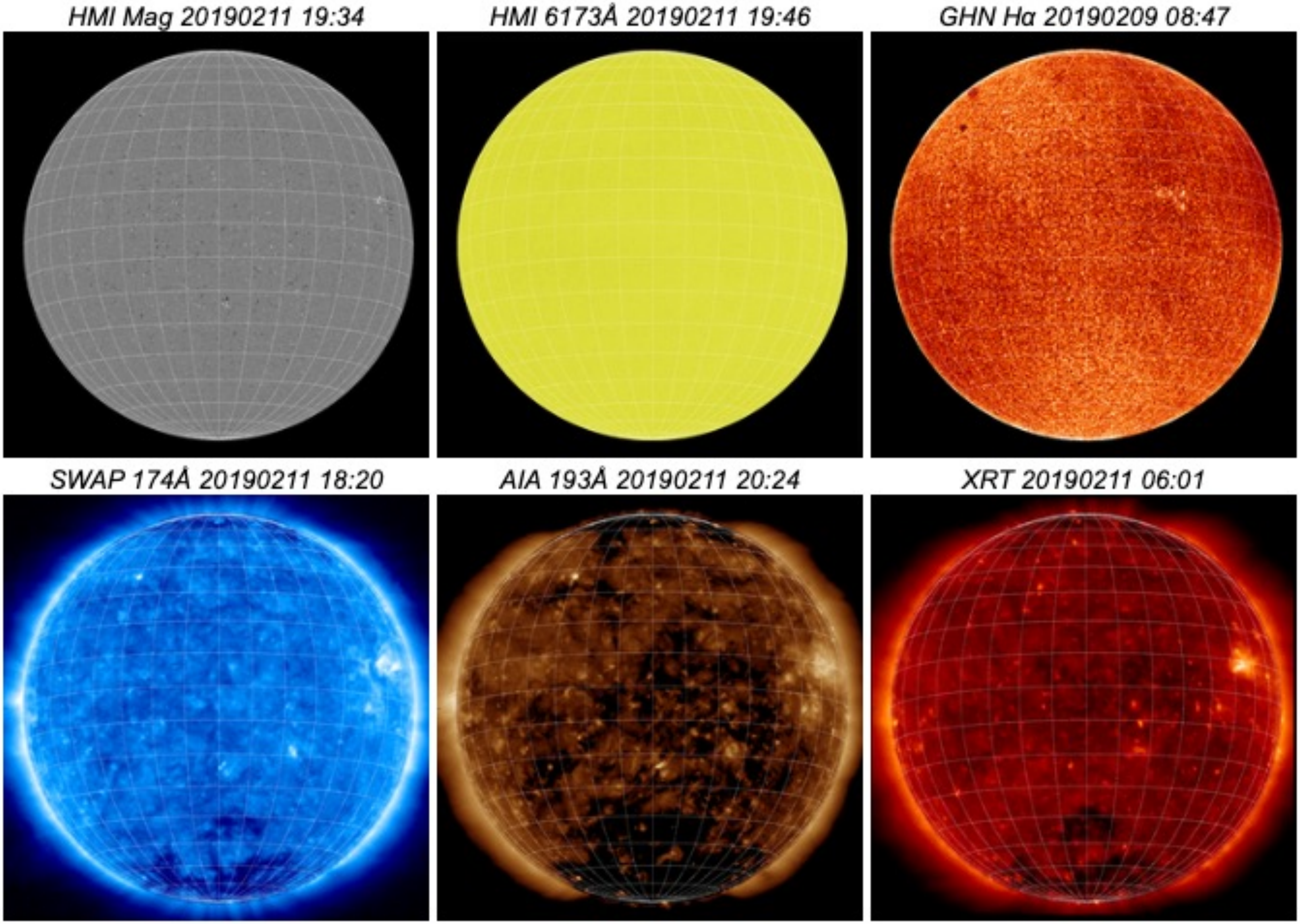


- A solar wind, with radial field, violates the potential-field concept of zero current.
- The rotation of the Sun induces a spiral pattern in the heliosphere due to the solar wind.
- Field asymmetry introduces warps (“sectors” at 1 AU) in the structure.

The Sun yesterday



The Sun five years ago



The stability of the coronal field

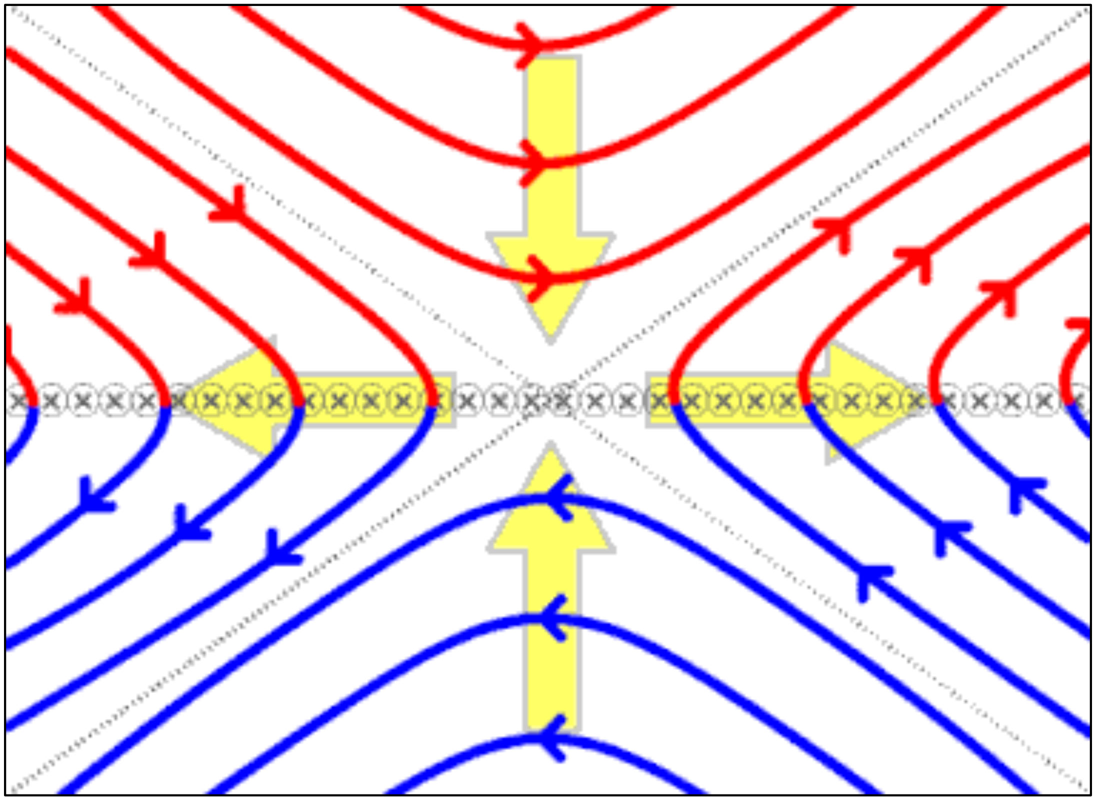
• A solar magnetic transient (flare or CME; coronal mass ejection) derives energy from the magnetic field: $\mathbf{B}^2/8\pi$ (in CGS units). It must become more potential-like as this happens.

• Large currents (10^{12} A) may flow in the corona, storing this energy inductively.

• Identifying the plasma instabilities that do this is an open problem now, and of course very important for flare prediction ("space weather").

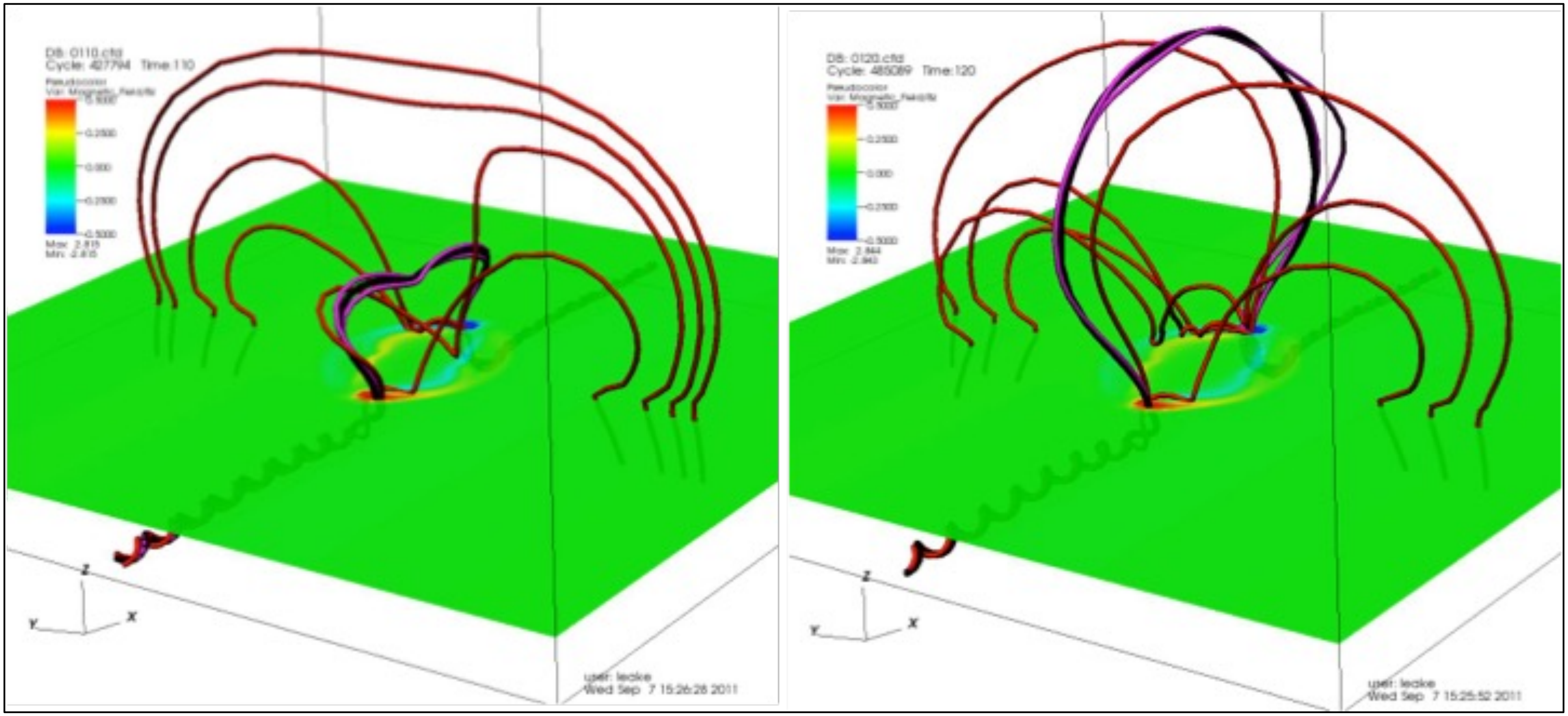
- Ideal MHD instability (no magnetic reconnection), such as the kink instability
- Resistive instabilities, such as the torus instability or the "tether-cutting" cartoon

“Magnetic reconnection” (flux transfer)



- This great Wikipedia graphic shows how magnetic field lines are thought to “reconnect,” and this is the key physics of many models of flares.
- Reconnection is often described as a mechanism for energy release, but here the magnetic energy is constant - it is a steady state.

The “torus instability”

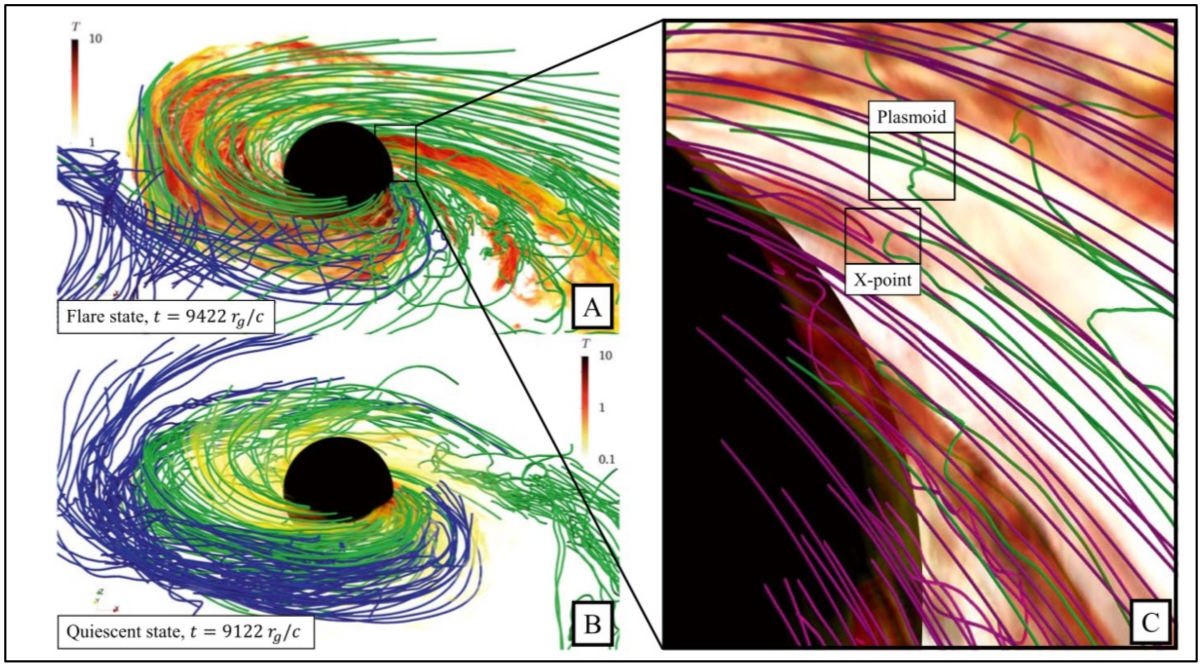


- A *flux rope* forms above a *photospheric inversion line.*
- This structure is held in place by overlying field.
- Torok & Kliem (2005) suggest that if this overlying field decreases in strength with height, the structure may blow.

Magnetic reconnection elsewhere

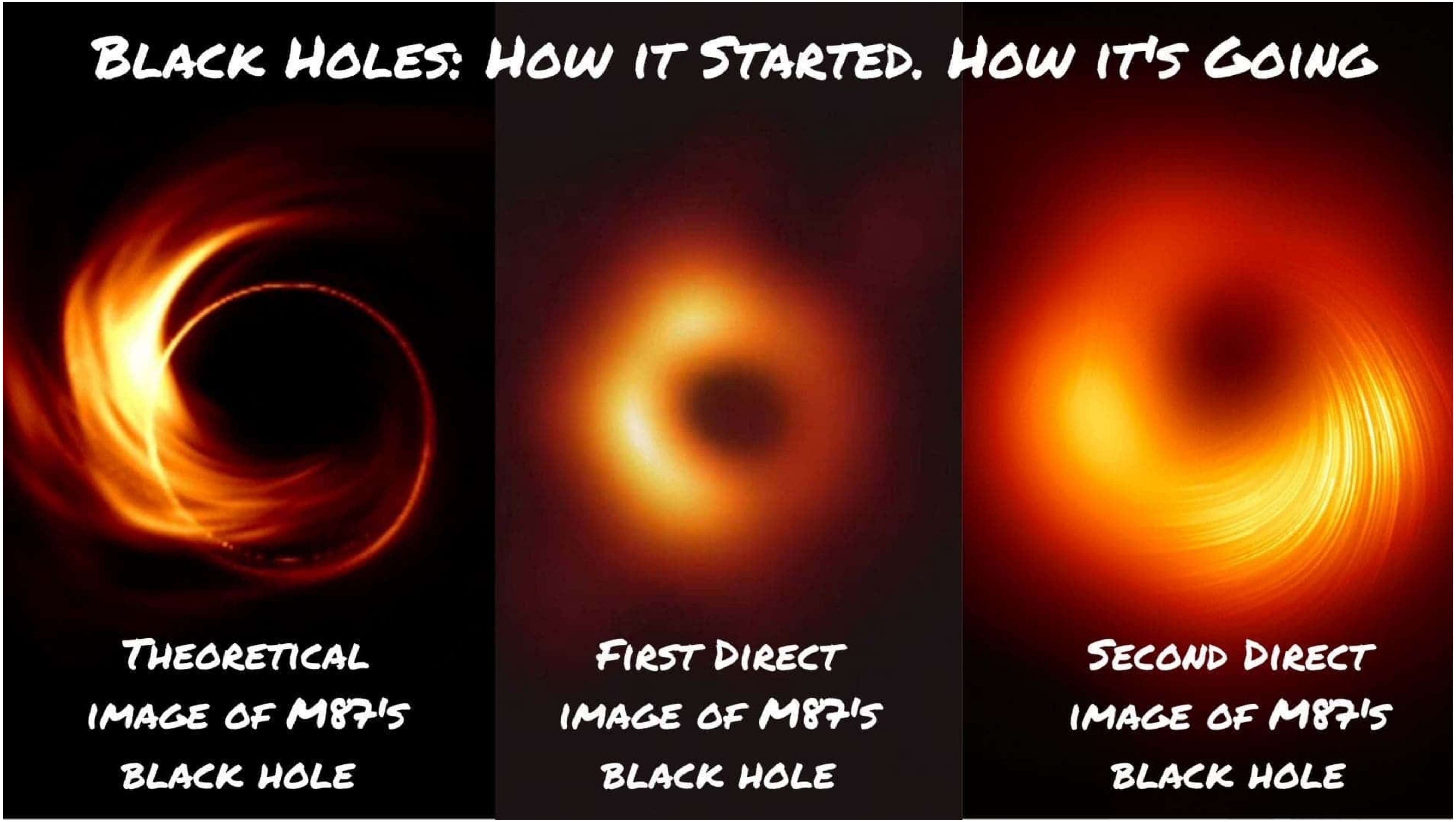
Black Hole Flares: Ejection of Accreted Magnetic Flux through 3D Plasmoid-mediated Reconnection

B. Ripperda[1,2,3,11], M. Liska[4,5,11], K. Chatterjee[6,7], G. Musoke[7], A. A. Philippov[1], S. B. Markoff[7,8], A. Tchekhovskoy[9], and Z. Younsi[10]



- Flaring activity occurs near black-hole horizons.
- One can explain it in the same way "standard models" explain solar flares, ie "plasmoid-driven" reconnection.

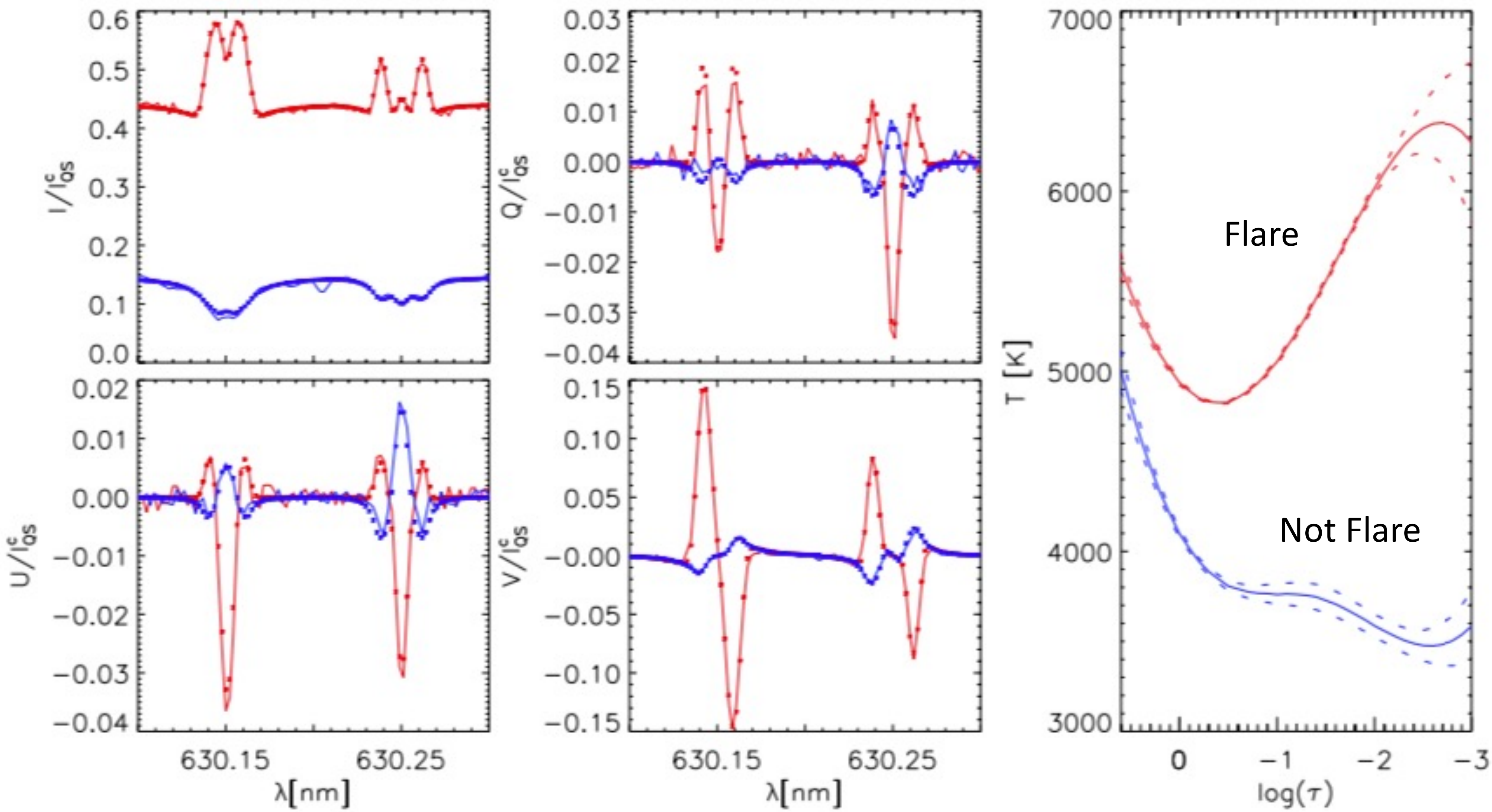
Imaging a black hole



Spectroscopic “inversions”

- Jurčák *et al.* 2018, “Heating of the solar photosphere during a white-light flare”
  - The behavior of an actual photospheric spectral line
  - “Line inversions” to obtain quasi-3D structure
  - What the Stokes parameters can tell you
  - How flares might work
- The ”SIR” Stokes Inversion code translates line profiles, “forward fitting” T to a coarse 1D map at 5 points over a four-decade range of optical depths: many assumptions!

Hinode line profiles and inversion for T



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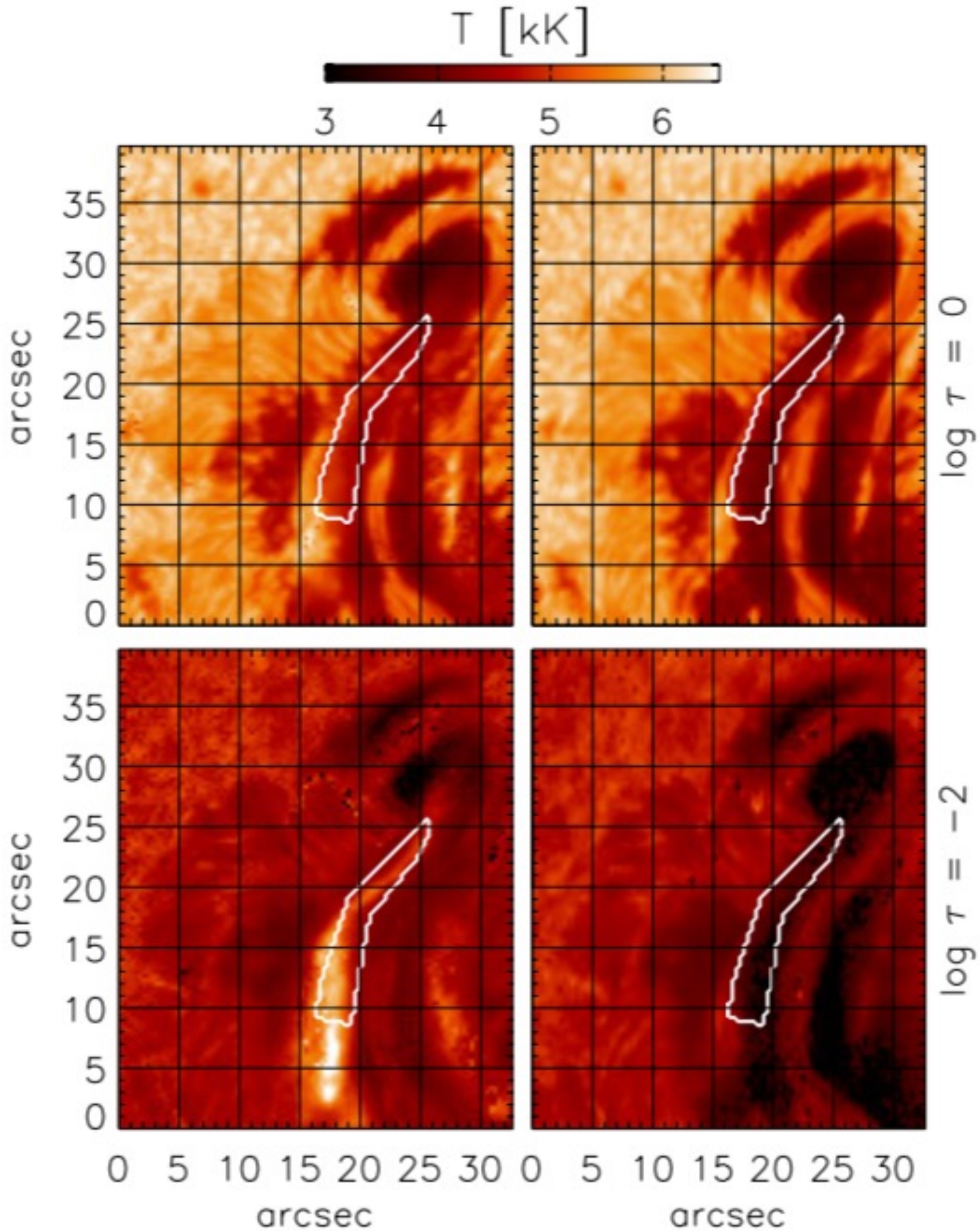
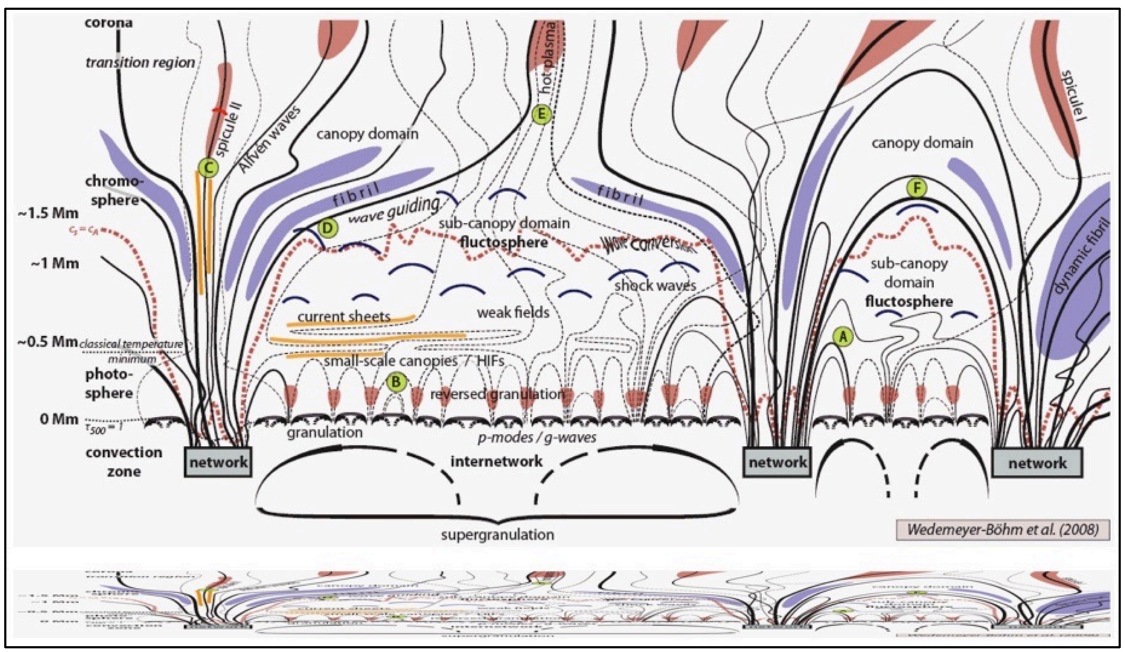


Photospheric level

~300 km higher

Conclusions

- Magnetism makes the solar atmosphere interesting from the point of view of plasma physics.
- ALMA; PSP, Hinode, Solar Orbiter (in space); ground-based DKIST, SST, BBSO, Gregor high-resolution *etc*.



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