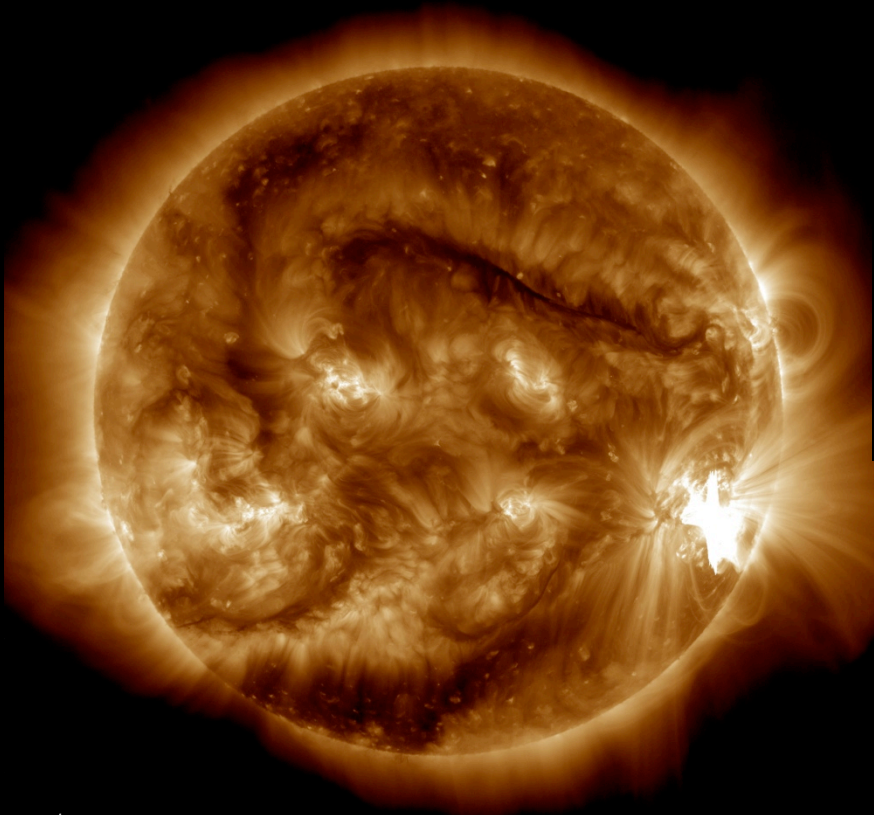


OBSERVATOIRE DE PARIS
COMPAS/DASOP-LPSH
SPECTROHELIOGRAPH
1999 OCT 15
12h37mn UT
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The Structure and Dynamics of Solar Prominences



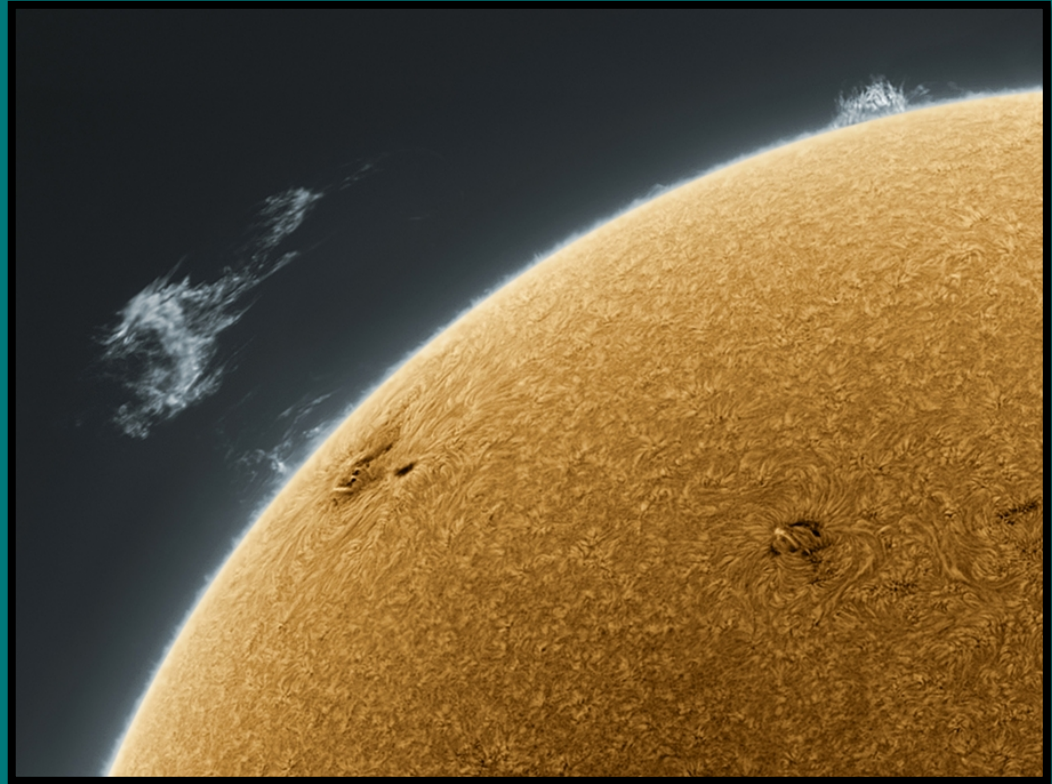
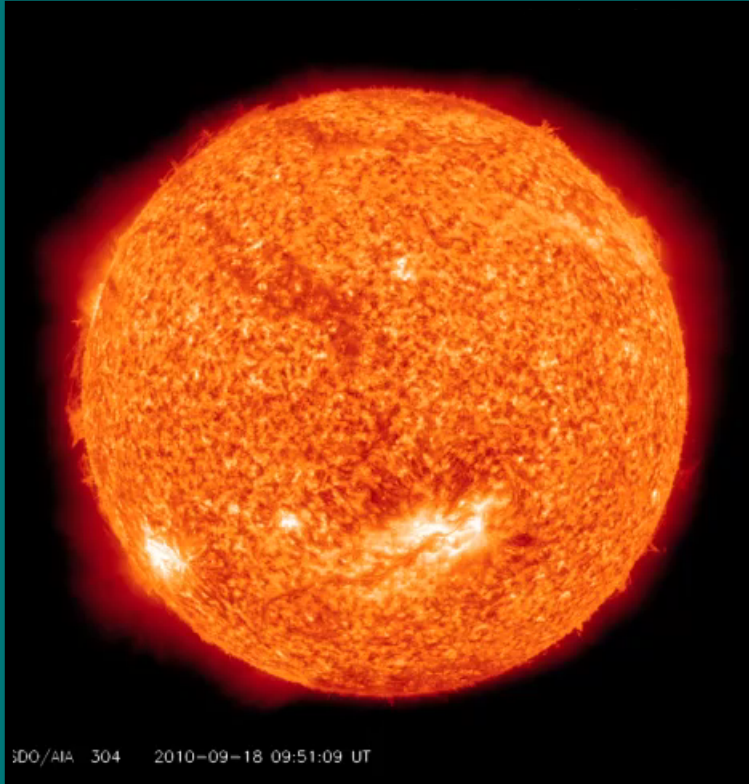
Judy Karpen
NASA GSFC
Coupling and Dynamics of the
Solar Atmosphere
IUCAA, Pune
10-14 November 2014

Outline



- **What are prominences/filaments?**
- **Fundamental questions**
- **Magnetic structure theories**
- **Plasma structure theories**
- **Have all questions been answered?**

What are Prominences?

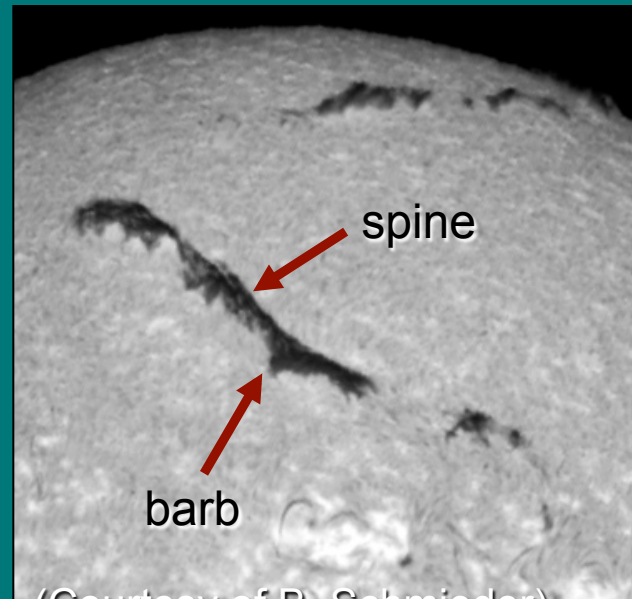
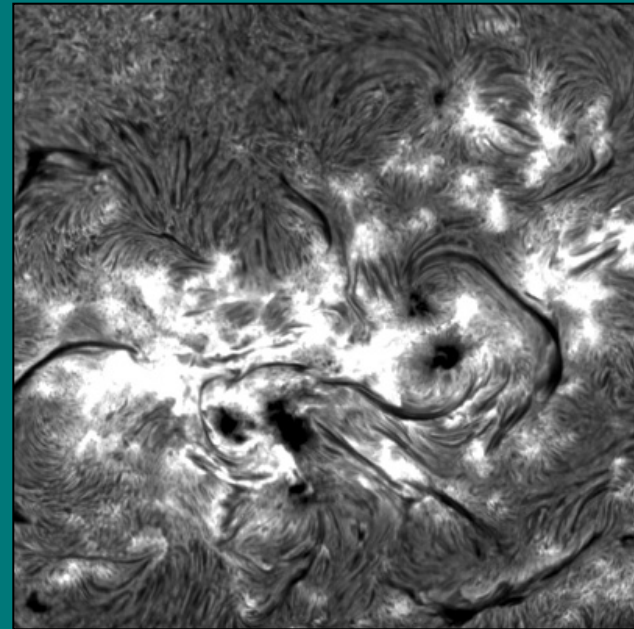


Working definition: cool dense gas in the hot corona

Reviews: Martin 1998, Labrosse et al. 2010, Mackay et al. 2010,
Solar Prominences (new book in press, eds. Vial and Engvold)

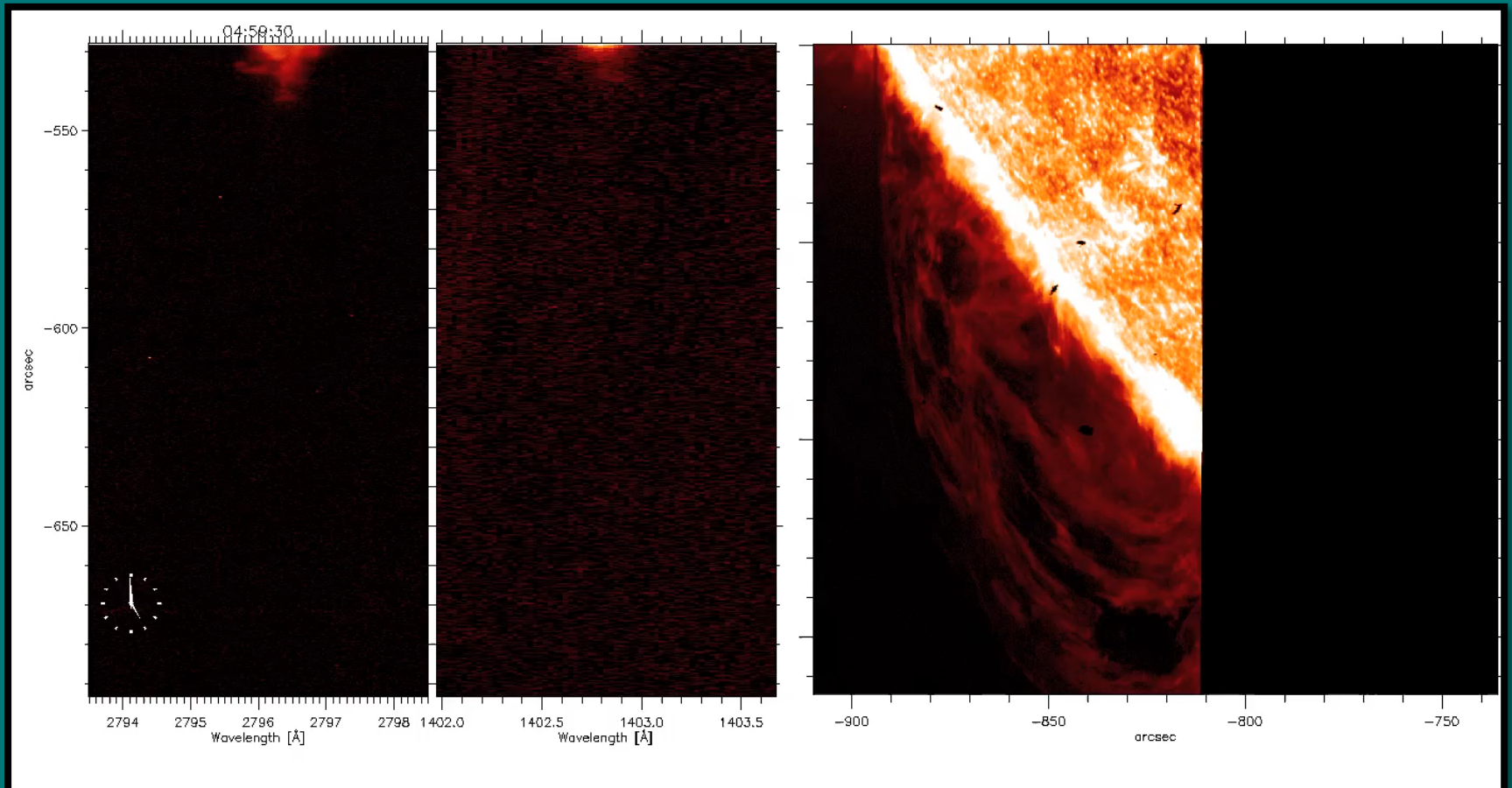
Types of Prominences

- **Active Region**
 - Short, low
 - Fast evolution
 - Highly dynamic, short-lived
- **Quiescent/Intermediate**
 - Long, high
 - At edges of active regions, under helmet streamers
 - Dynamic, slower evolution
- **Quiescent/Polar Crown**
 - Longest, highest
 - At edge of coronal hole, under helmet streamers
 - Dynamic, long-lived



(Courtesy of B. Schmieder)

Intermediate Prominence



IRIS Si IV ($\sim 80,000$ K)
courtesy of Bart de Pontieu

Coronal Funnel



courtesy of W. Liu

- observed for decades but neglected until recently
- seem to condense at cusps and drain

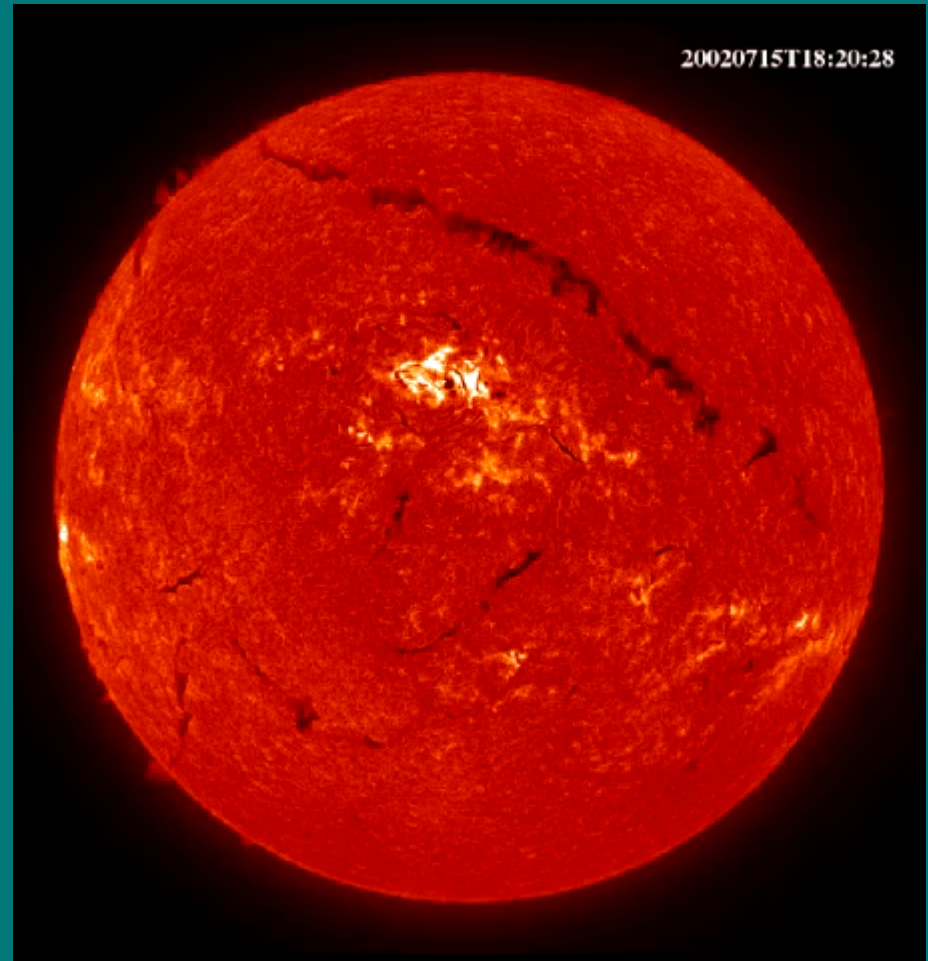
Polar Crown “Hedgerow”



- vertical upflows and downflows, rotation, bubbles, and plumes
- vertical structure \gg scale height of cool plasma

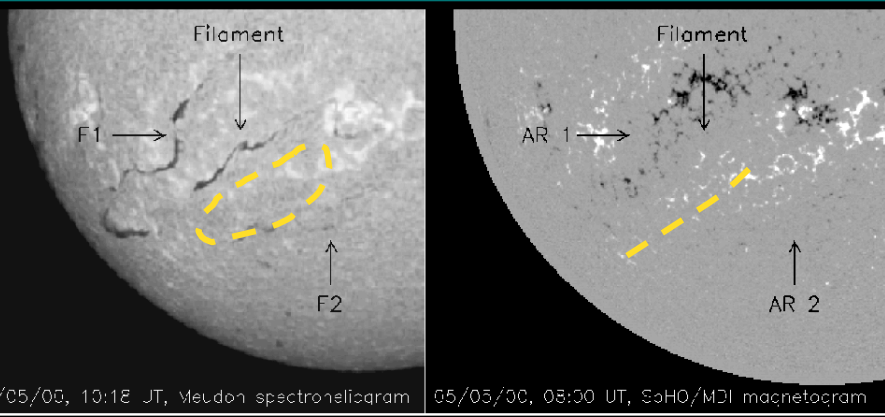
Important Magnetic Properties

- Found above magnetic polarity inversion lines (PILs), in filament channels
- Located at all latitudes from active belts to polar crown
- Remarkably stable despite constant turnover at base and eruptions
- Capable of shielding and supporting cool mass in hot corona



BBSO H α
analyzed by Anderson & Martin 2005

Filament Channels



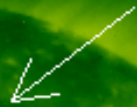
05/05/00, 10:18 UT, Meudon spectroheliogram

05/05/00, 08:00 UT, SoHO/MDI magnetogram

(from Aulanier & Schmieder 2002)

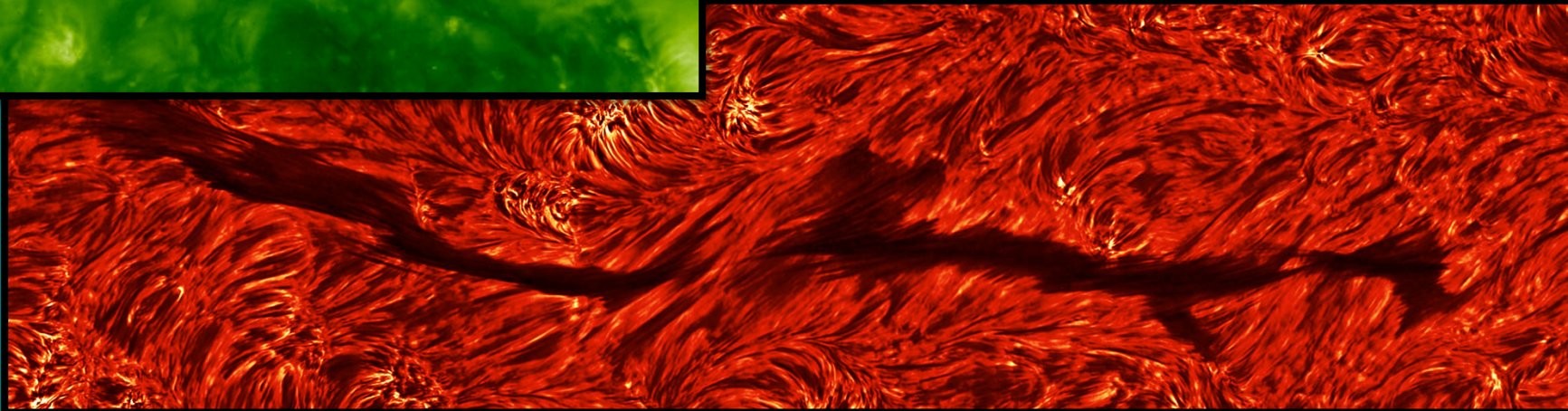
SOHO/EIT 195A

Filament Channel



Only place on Sun where field is highly nonpotential!

- Core B // PIL (fibril pattern)
- Overlying $B \perp$ PIL
- Exist before, after, and without visible filaments
- Persist through many eruptions
- Encompass filament and coronal cavity (≤ 60 Mm wide)



Fundamental Questions

- How do filament channels form?
- What is the magnetic field structure in filament channels?
- How does the prominence mass collect and evolve in these channels?

Challenges to Understanding Magnetic Structure

- Few good observations of coronal magnetic field – recent advances (e.g., THEMIS, IBIS, CoMP) are improving this situation
- Cool plasma occupies a small fraction of FC
- Tracing field with cool plasma only works if plasma is moving and well-resolved
- Hard to observe connections to the chromosphere due to foreground activity

Numerical simulations can fill in these gaps
and test theories

Flux Rope Models: Motivation

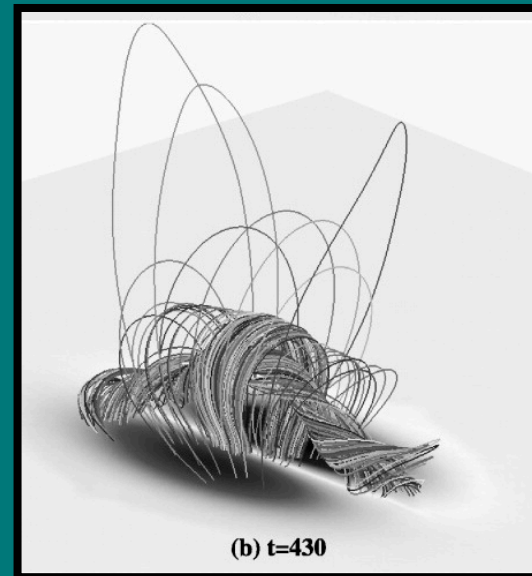
Observational

- Flux ropes in solar interior, form ARs
- Inverse polarity
- Twisted erupting prominences, CMEs, IP magnetic clouds
- Sharp boundary between cavity and overlying corona

Theoretical

- Dips support mass
- Free energy storage
- Analytically tractable
- Fits into instability/loss-of-equilibrium models for eruption

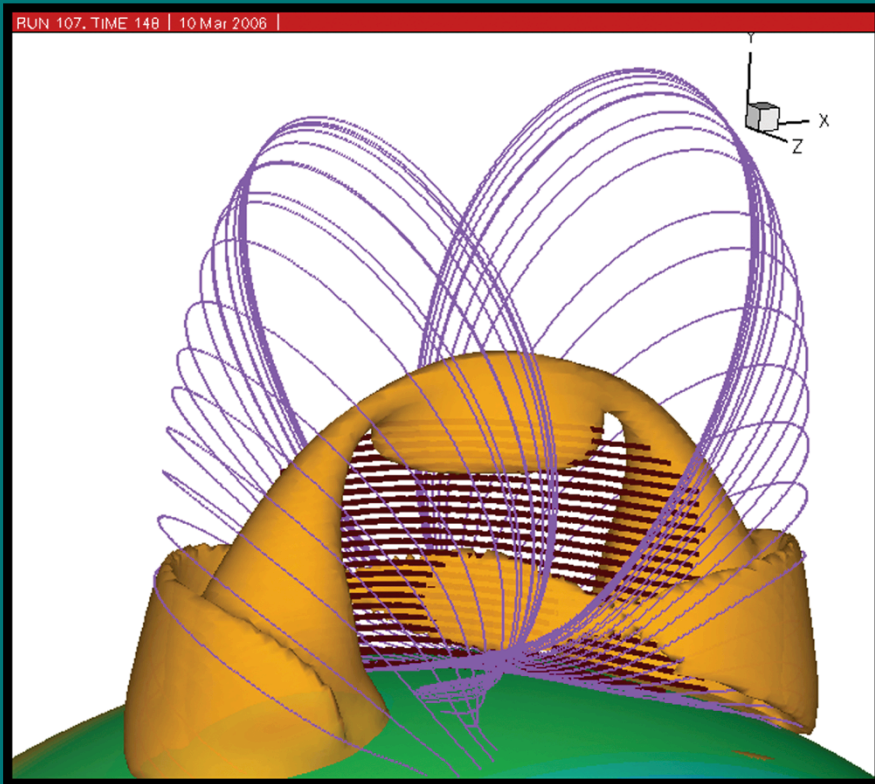
References: Rust & Kumar 1994, Low 1996, Titov & Démoulin 1999, Gibson & Low 2001, van Ballegooijen 2004, Fan & Gibson 2006, Guo et al. 2010, Yelles Chaouche et al. 2012



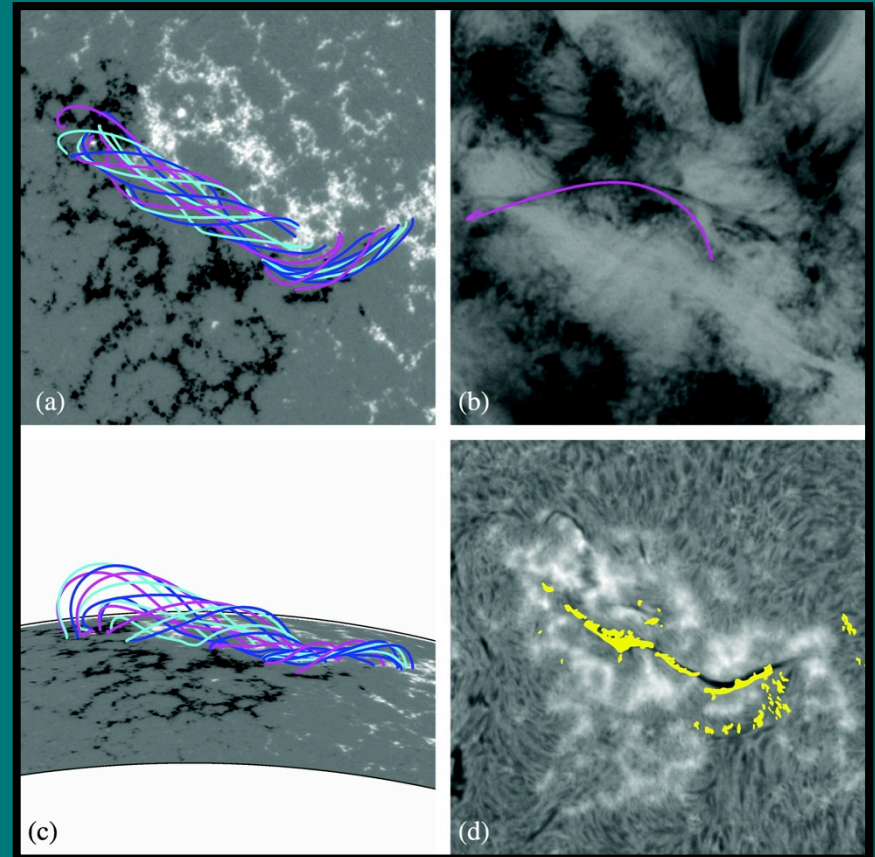
*Amari et al.
2000*

Flux Rope Filament Simulations

- Filament sits in dips of magnetic field lines (brown)
- Filament is sheet-like, aligned at a small angle to PIL



Fan & Gibson 2006

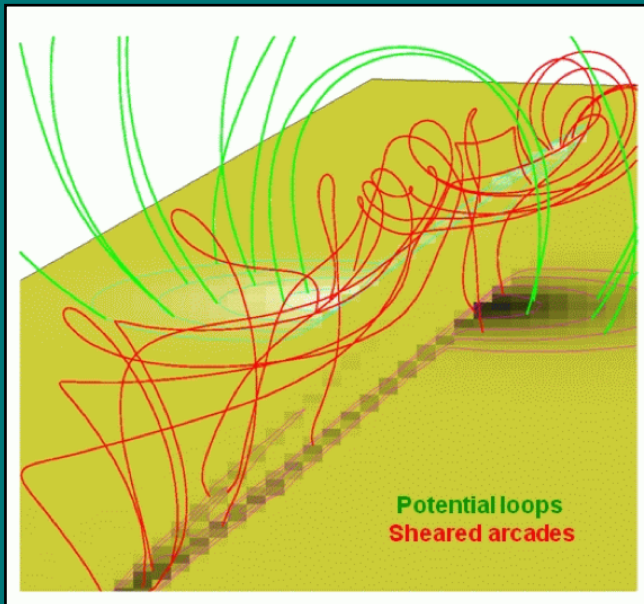


- Inserted flux rope
- Weak twist yields best fit
- Mass assumed to sit in dips
(*Bobra et al. 2008*)

Sheared Arcade Model: Motivation

Observational

- Strong shear near PIL
- Lack of pre-eruption twist
- Mixed polarity
- Footpoint motions



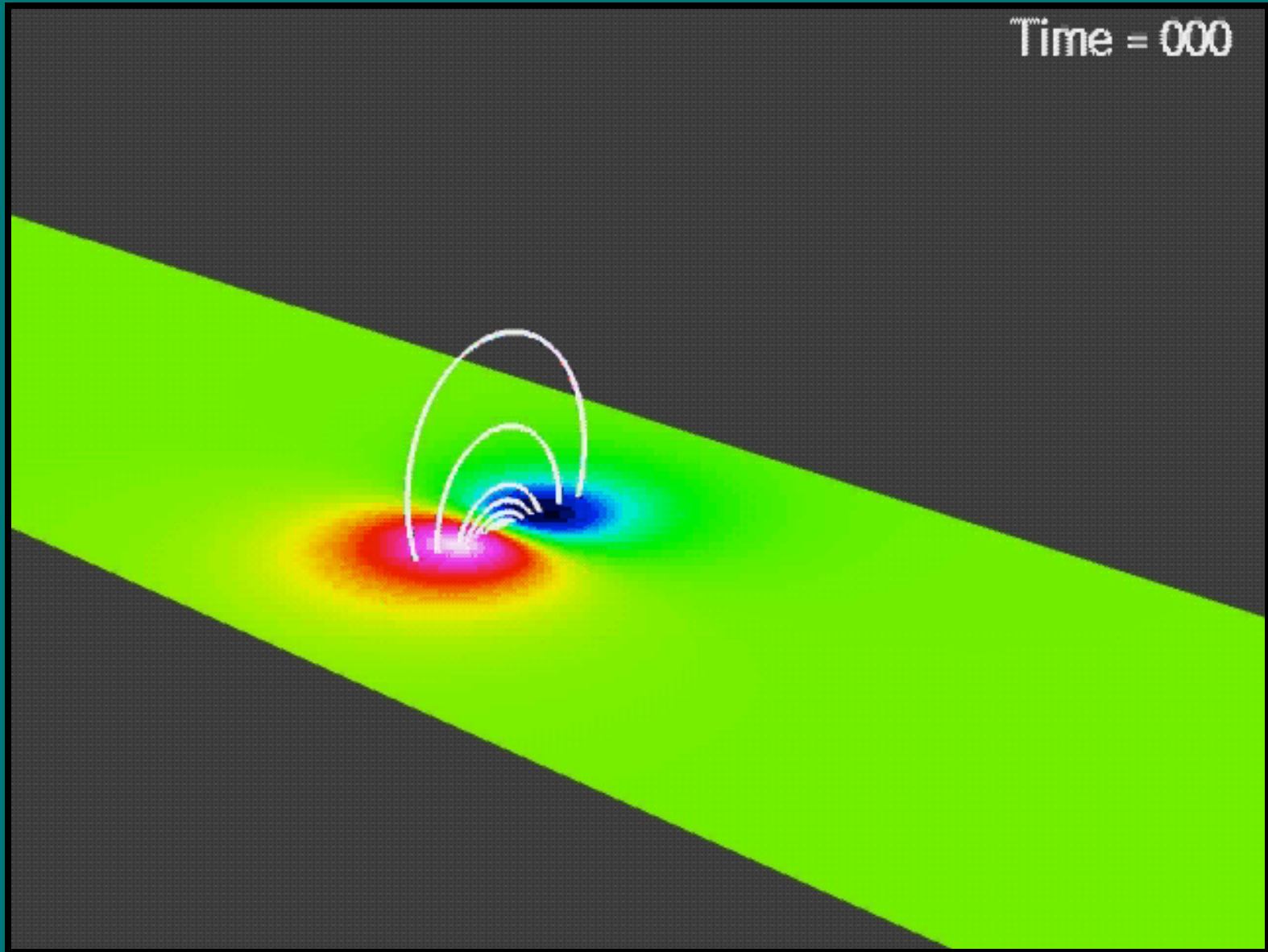
Aulanier et al. 2006

Theoretical

- Shallow dips not caused by mass loading (low β)
- Free energy storage
- Inherently 3D
- Partial flux emergence
- Fits into breakout model for eruptions

References: Antiochos et al. 1994; DeVore & Antiochos 2000; DeVore et al. 2005; Aulanier et al. 2002, 2006; Luna et al. 2012

Sheared Arcade Simulation



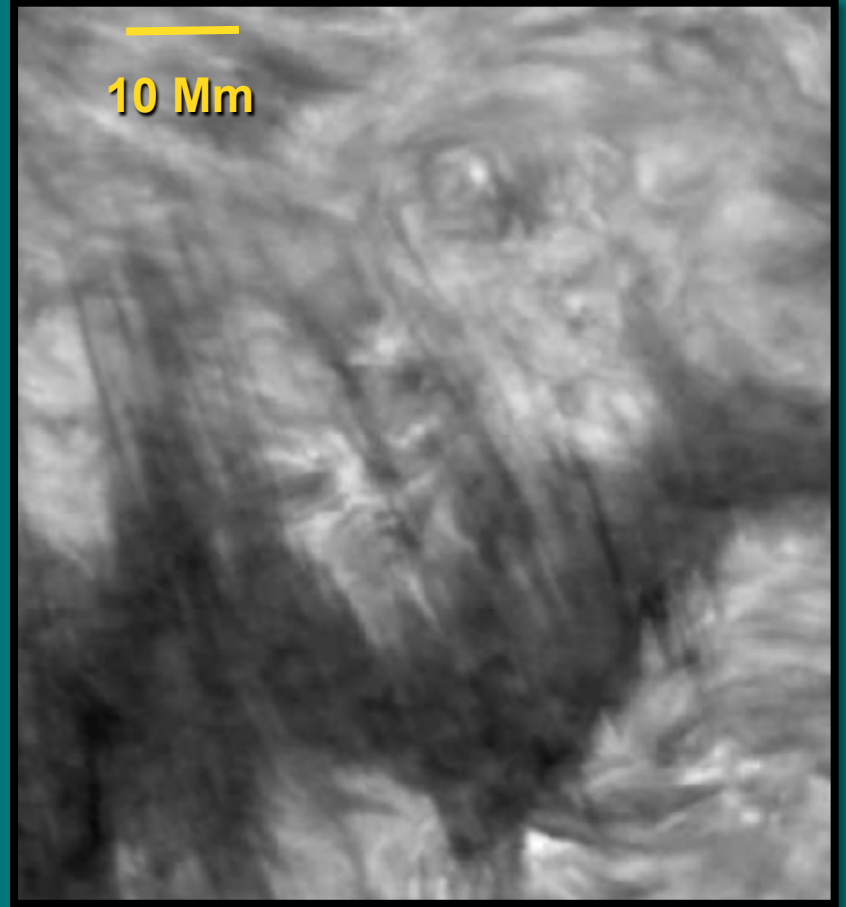
Summary: Magnetic Structure Models

Both flux rope and sheared arcade models explain some key observed features. But....

- **Challenges for flux rope model**
 - full emergence not generally seen in simulations
 - little evidence for upward concavities or helical flows (high twist)
 - reproduce observed mass distribution
- **Challenges for sheared arcade model**
 - realistic source of shear (beyond real-time footpoint motions)
 - distinct prominence-cavity and cavity-streamer interfaces
 - shear concentration
- **Neither model explains hedgerow prominences!**
- **Demonstrate self-consistent path to eruption**

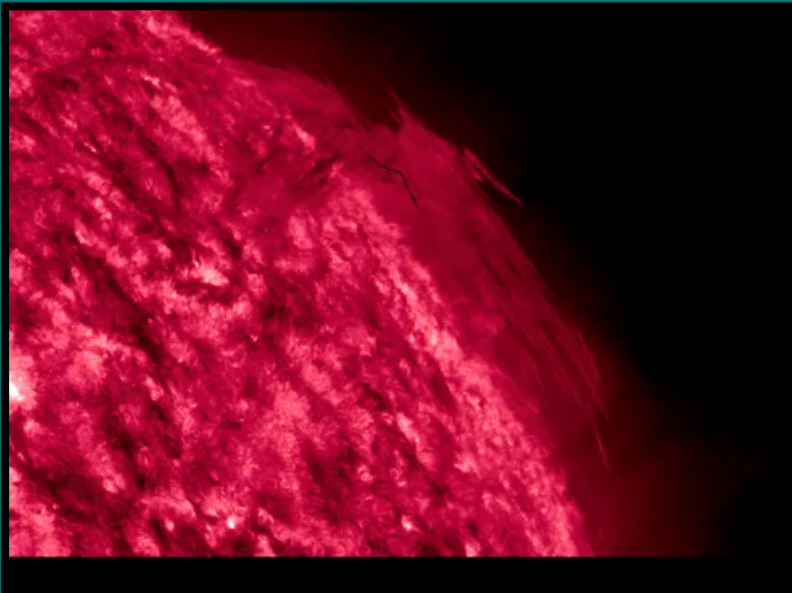
Important Plasma Properties

- Covers 10-60% of PIL
- Filamentary
- Knots and threads
- Appearance varies with T
- **HIGHLY DYNAMIC**



SVST, courtesy of Y. Lin

SDO AIA 304Å



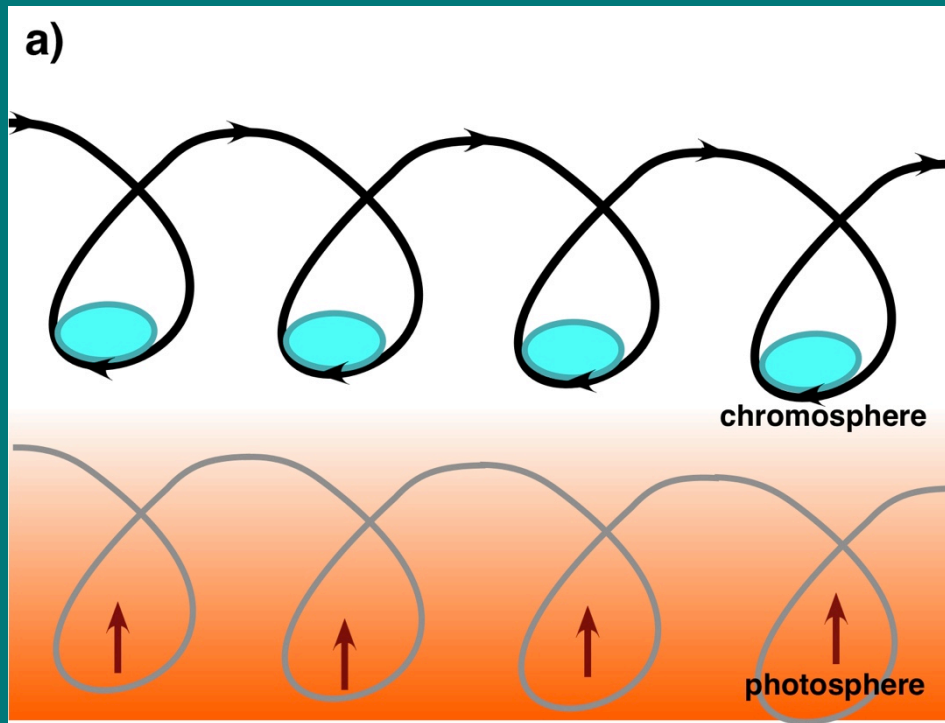
Plasma Model Constraints

- Mass comes from *chromosphere*
- Mass generally traces magnetic structure (frozen in)
 - ionization fraction 0.2-0.9, neutrals not frozen in
- Field-aligned thermal conduction dominates ($\kappa_{\parallel} \gg \kappa_{\perp}$)
- Pressure scale height $H_g \sim 500$ km
- chromospheric T and ρ
- NOT STATIONARY

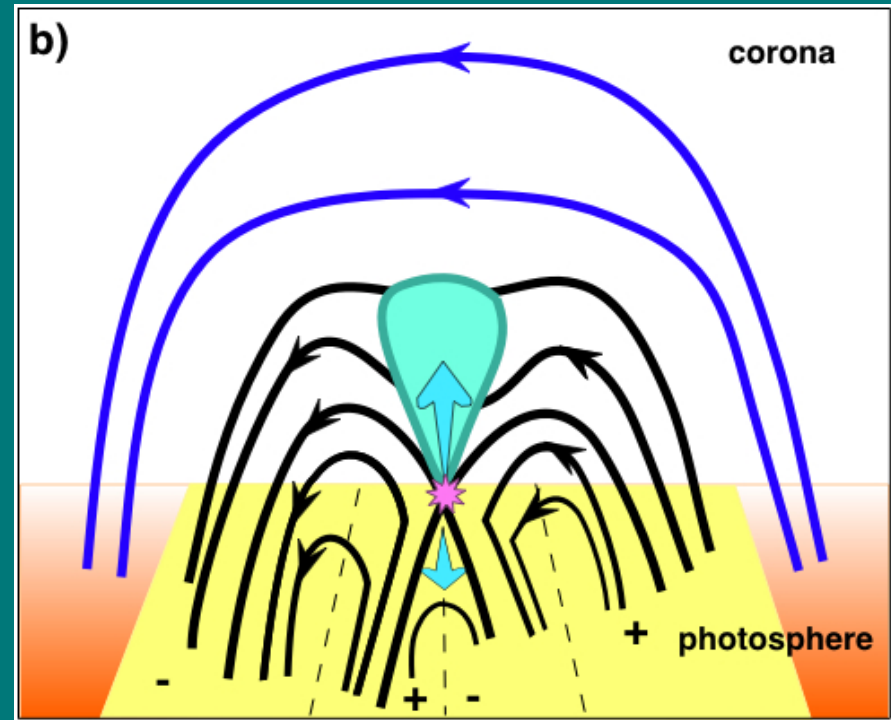
Mass Transport Mechanisms

- **Cool plasma moves from chromosphere to corona**
 - **Levitation:** *cool* plasma is lifted into the corona
 - **Injection:** *cool* plasma is driven into the corona
- **Hot plasma condenses in corona**
 - **Evaporation-condensation:** chromospheric plasma heated to coronal temperatures *evaporates* and *condenses*
 - **Magneto-thermal convection:** cycle of heating, magnetic buoyancy, condensation, and instability (*Berger et al. 2011, Low et al. 2012*)

Levitation



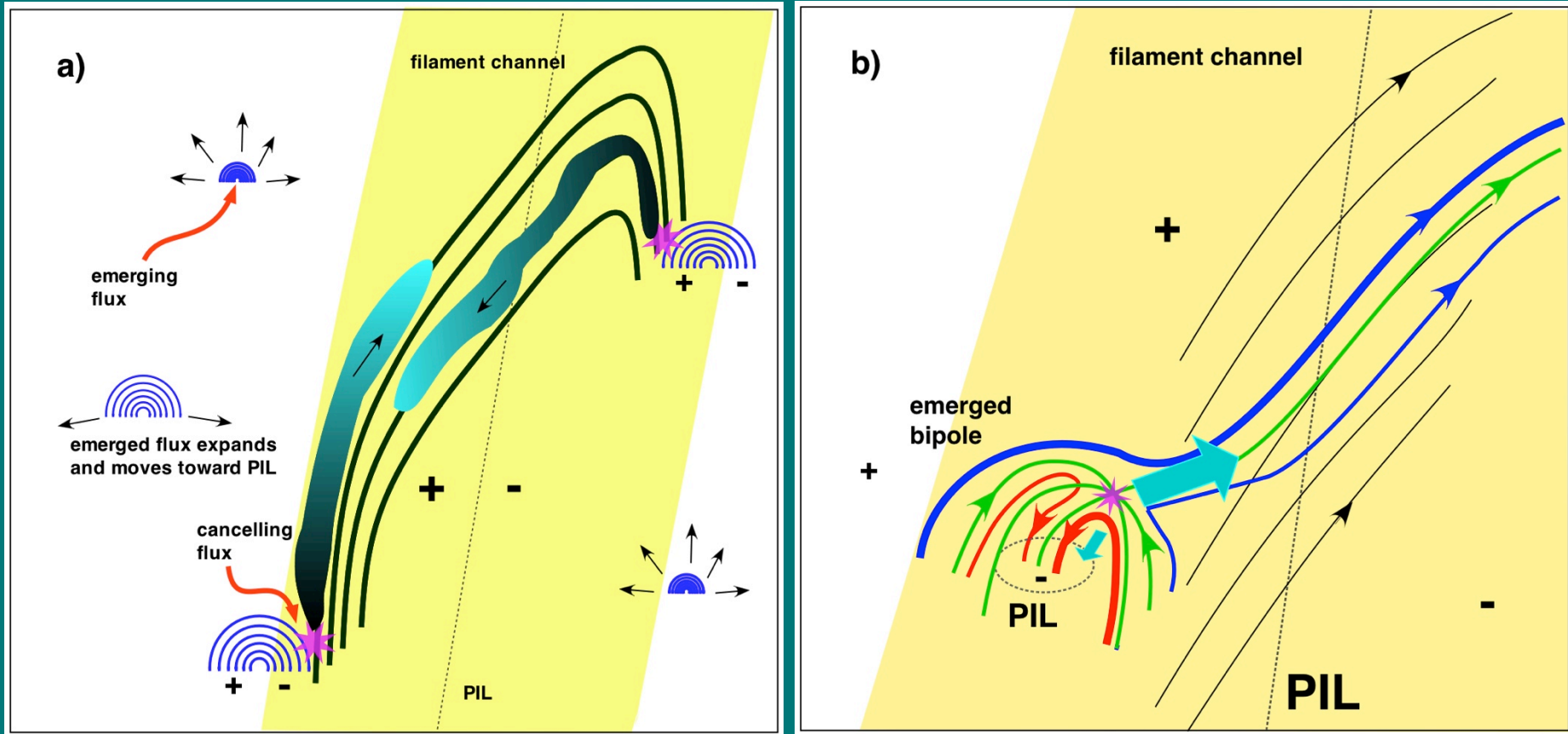
flux emergence



reconnecting bipoles

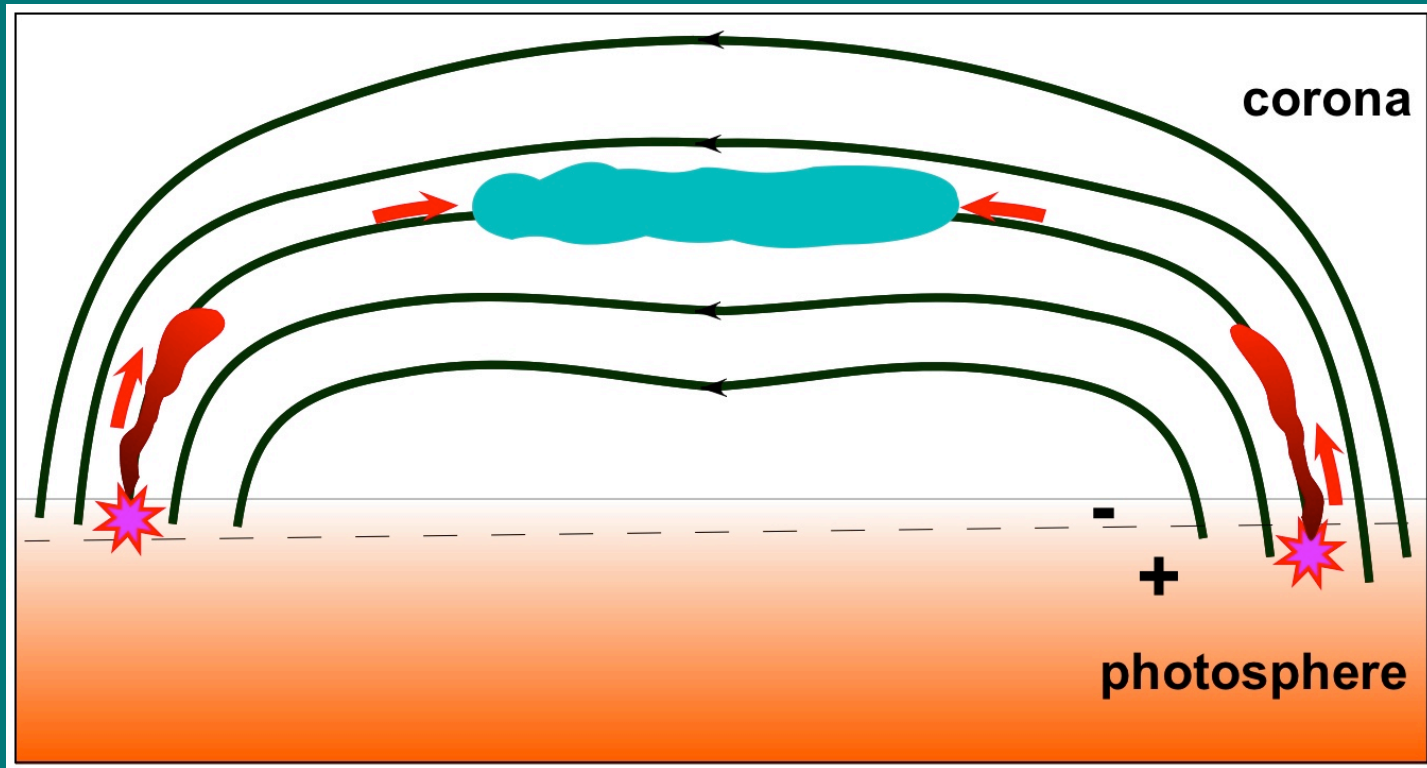
Cool chromospheric plasma is lifted into the corona by emerging flux rope (e.g., Kuckein et al. 2012) or field lines reconnected by flux cancellation (e.g., Welsch et al. 2005)

Injection



Photospheric reconnection between arcade and cancelling bipole drives cool, field-aligned jets (e.g., Wang 1999)

Evaporation-Condensation



- Optically thin radiative loss function peaks $\sim 10^5$ K and emissivity depends on n_e^2
- Adding heat increases coronal density while decreasing the chromospheric mass slightly (evaporation)

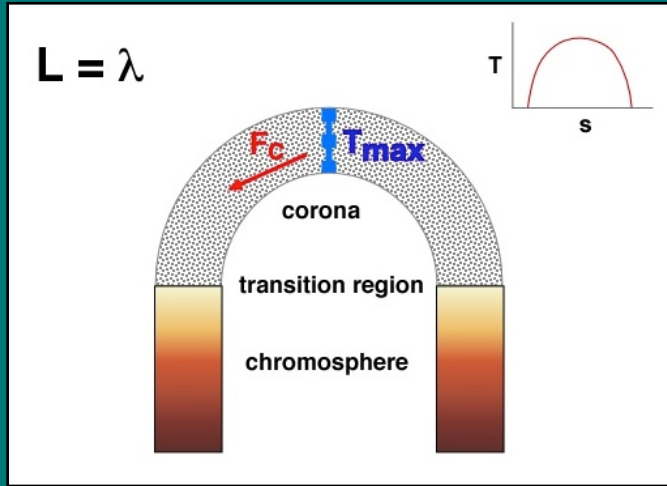
Evaporation-Condensation

- **Thermal Nonequilibrium Model**

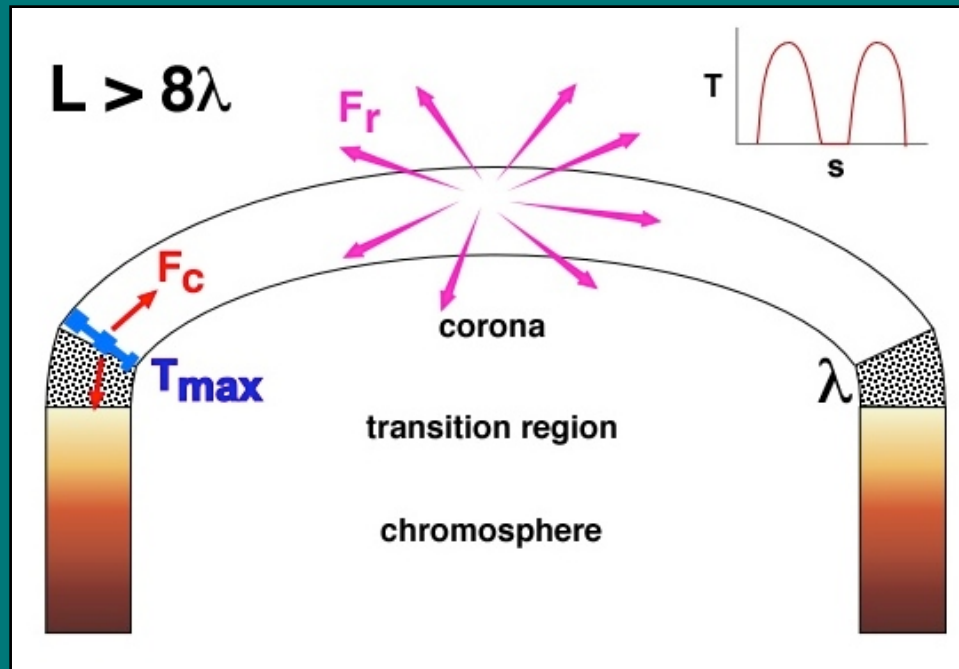
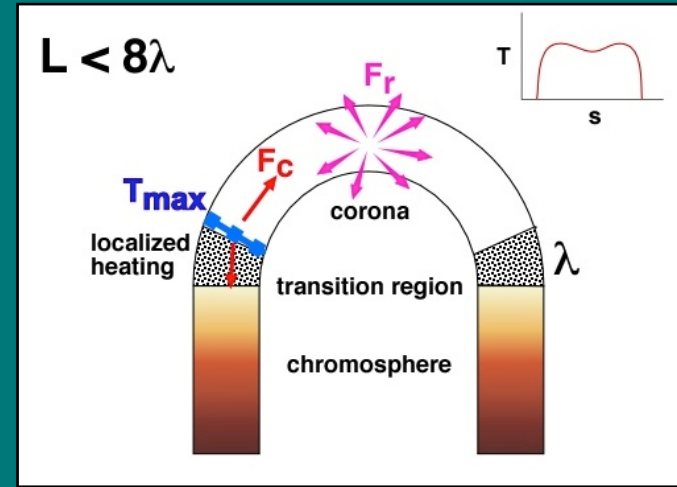
- *condensations* are caused by normal coronal heating, localized above footpoints of long, low-lying field lines, with heating scale $\lambda \ll L$ (*Mok et al. 1990*)
- symmetric heating and geometry yields single condensation at midpoint
- condensations become *dynamic* due to force imbalance from unequal heating and/or asymmetric geometry

References: Antiochos & Klimchuk 1991; Dahlburg et al. 1998; Antiochos et al. 1999, 2000; Karpen et al. 2001, 2003, 2005, 2006, 2008; Luna et al. 2012a,b,c; Xia et al. 2012; Zhang et al. 2013

Uniform Heating

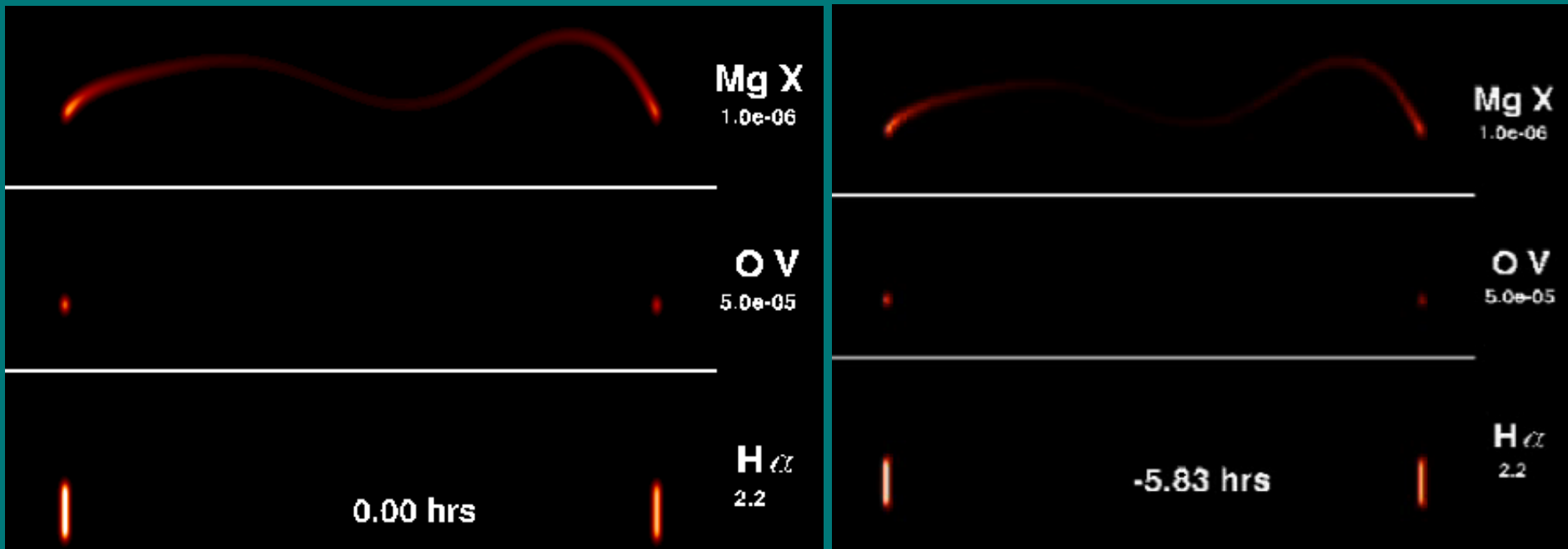


Symmetric footpoint heating



Symmetric footpoint heating

Thermal Nonequilibrium Simulations



t = 26.58 hrs

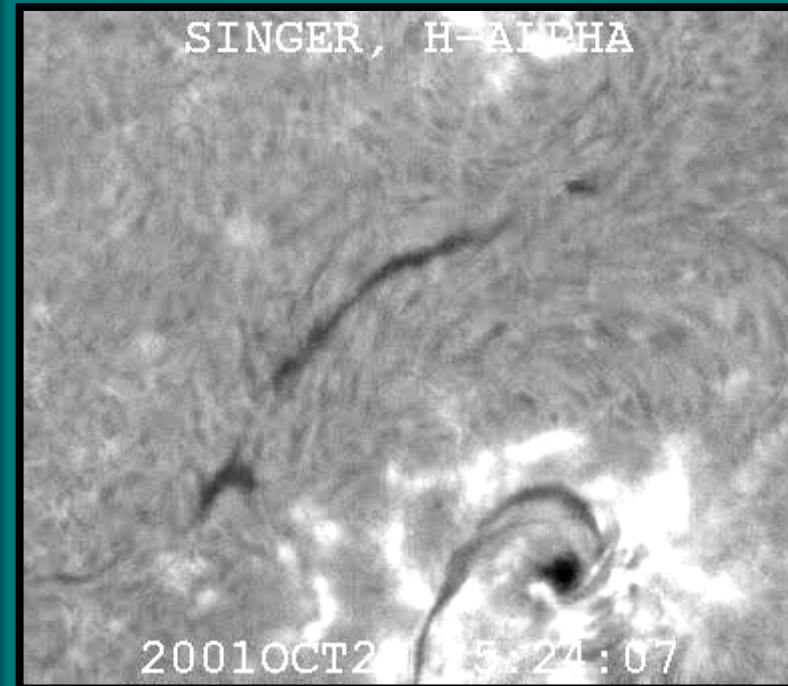
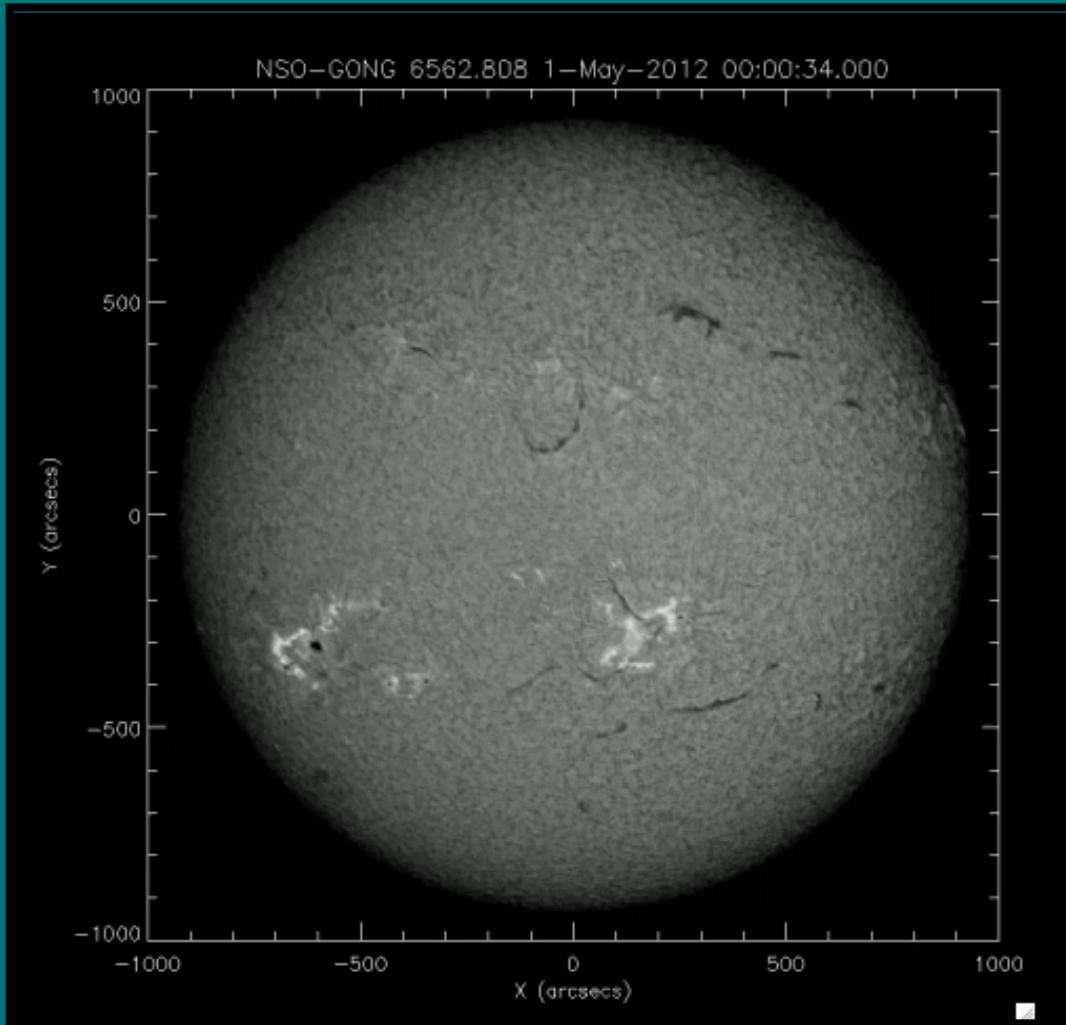


sheared arcade, top view

Summary: Plasma Structure Models

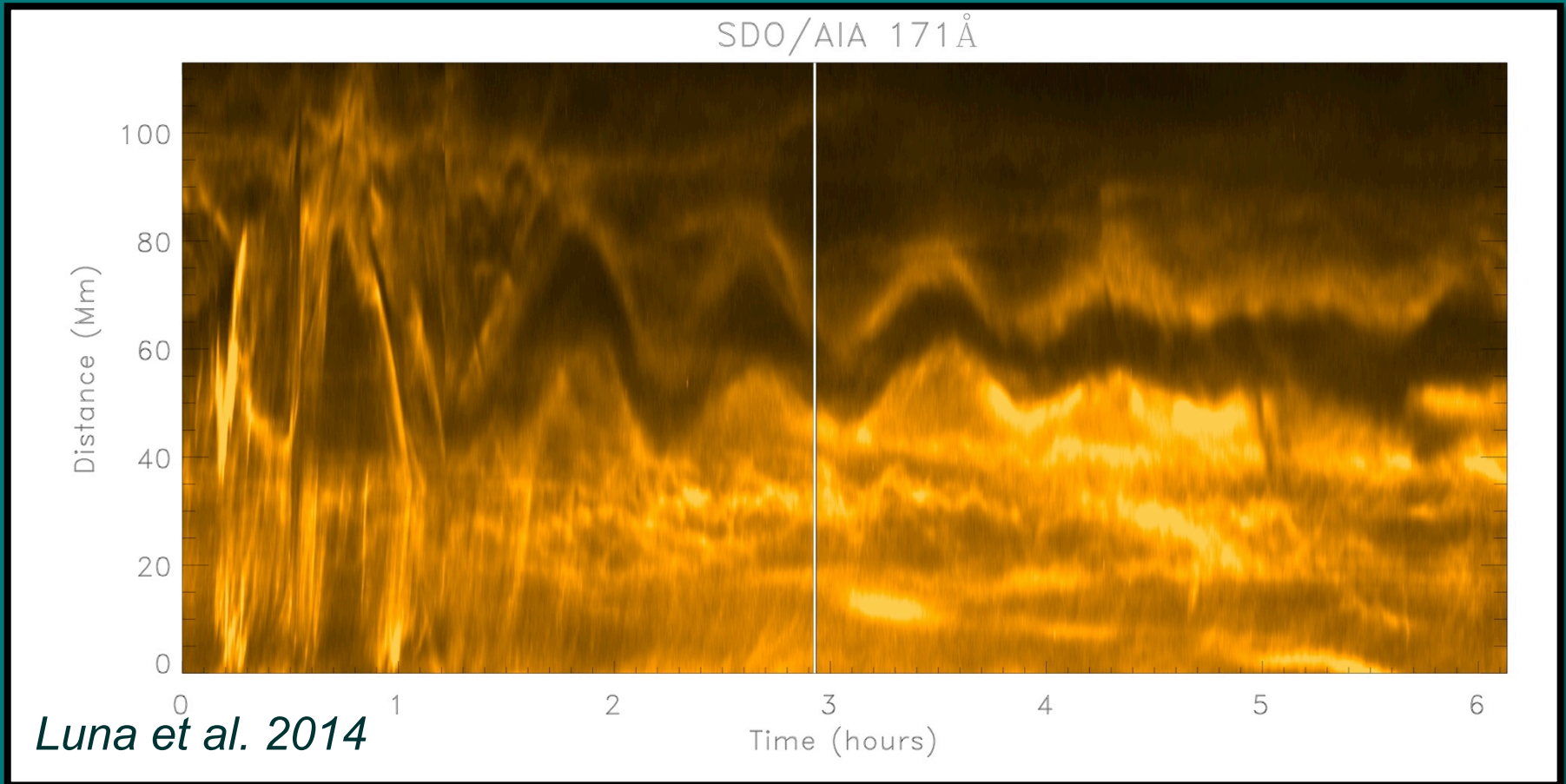
- **Levitation and Injection**
 - can't explain *in situ* appearance of cool plasma
 - most applicable to “fountains” or AR filaments
 - require photospheric or chromospheric reconnection
 - more realistic modeling needed
- **Evaporation-condensation**
 - thermal nonequilibrium explains *in situ* threads and knots, counterstreaming, downflows in legs
 - requires coronal heating localized at footpoints
 - comprehensive 3D modeling needed (e.g., Xia et al. 2012)
- **Magneto-thermal convection**
 - possible explanation for polar-crown prominences and funnels
 - more observations and 3D modeling needed

Longitudinal oscillations are everywhere



from Jing et al. 2003

Longitudinal Oscillations: 20 Aug 2010



- Triggered by jet emanating from same filament channel
- Note bright ends of dark thread, as predicted by TNE
- Behaves like a damped harmonic oscillator

Lessons Learned from Longitudinal Oscillations

- **Excellent fit to observed periods and damping**
 - restoring force is gravity, damping by mass accretion
 - large radius of curvature (~ 50 Mm) \rightarrow must have dips
 - no evidence of helical or vertical structure!
- **Lower limit on magnetic field strength (~ 30 G)**
- **Implied limits on impulse from nearby event**
 - too little \rightarrow no motion
 - too much \rightarrow no oscillation (mass falls to chromosphere)
 - energy consistent with typical microflare ($\sim 10^{24-27}$ erg)

Have We Answered the Fundamental Questions?

- **What is the magnetic field structure in filament channels?**
 - flux rope or sheared arcade
- **How does the prominence mass collect and evolve in these channels?**
 - thermal nonequilibrium in quiescent filaments, funnels, some AR filaments
 - levitation in fountains, levitation and injection in some AR filaments?
 - magneto-thermal convection in funnels and polar-crown prominences?

Magnetic Structure: Outstanding Problems

- **Filament channel formation** – roles of flux emergence, cancellation, helicity condensation
- **Self-consistent path to eruption** – lifecycle
- **Connection to interior processes (convection, flux emergence) and solar cycle** – does longevity = deep roots?
- **Structure of barbs** – vertical, horizontal, ?

More observations and modeling needed!

Plasma Structure: Outstanding Problems

- **Origin of fine structure** – heating inhomogeneity in space and time, Rayleigh-Taylor instability?
- **Link to coronal heating mechanism(s)** – are filament channels different?
- **Physics of active-region prominence plasma** – short heating scale, levitation, injection?
- **Physics of hedgerow prominence plasma** – magneto-thermal convection, Rayleigh-Taylor instability, tangled field?

More observations and modeling needed!

Acknowledgements

Pioneers: Arvind Bhatnagar, Vic Gaizauskas, B. C. Low, Sara Martin, Eric Priest, Dave Rust

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