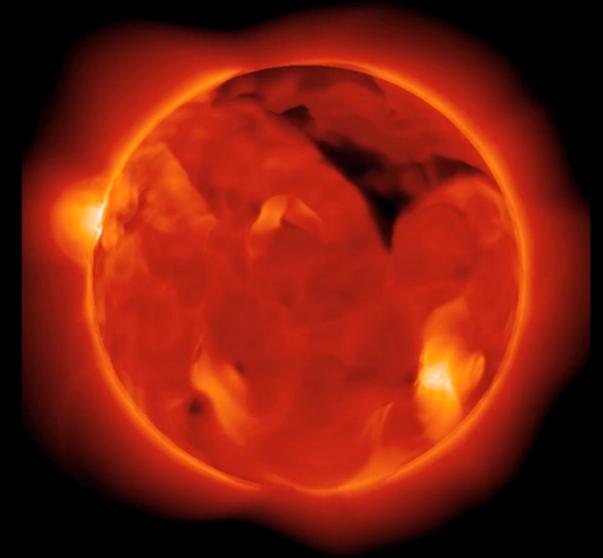
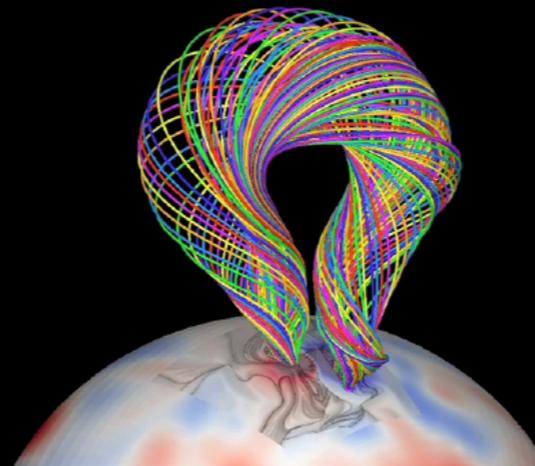
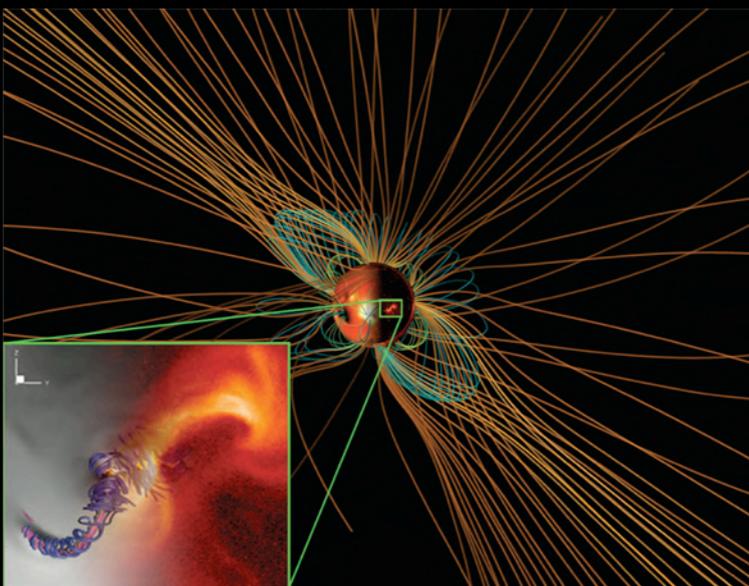
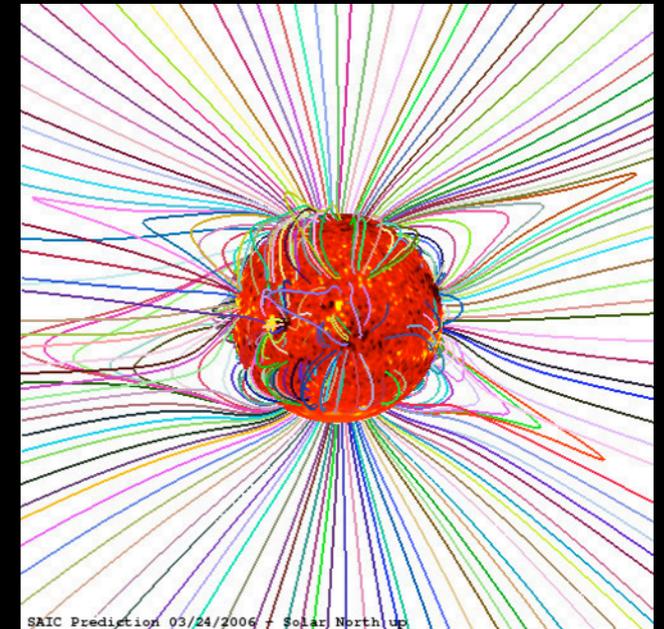
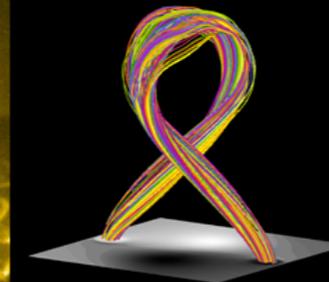
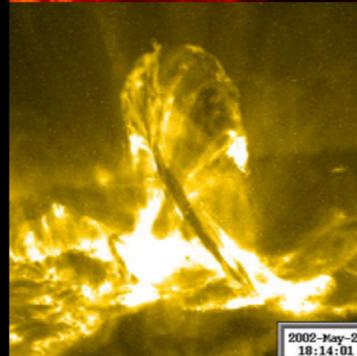
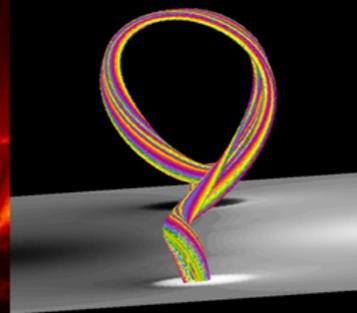
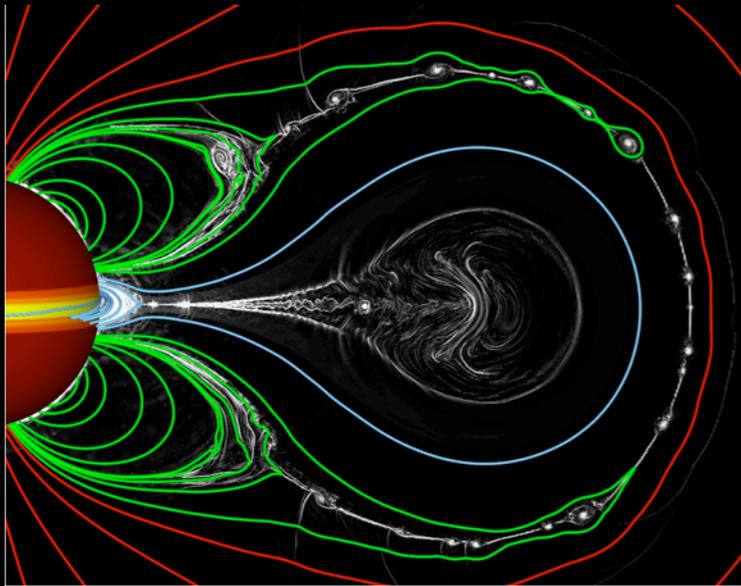


Modeling Solar Eruptions: Where Do We Stand?

Tibor Török



Predictive Science, Inc.



SPD meeting, 2013, July 8-11, Bozeman

Past...

2000-2003



AIP (Germany)

2003-2004



St. Andrews (UK)

2004-2007



MSSL (UK)

2007-2010



Meudon (France)



Bernhard Kliem



Thomas Neukirch

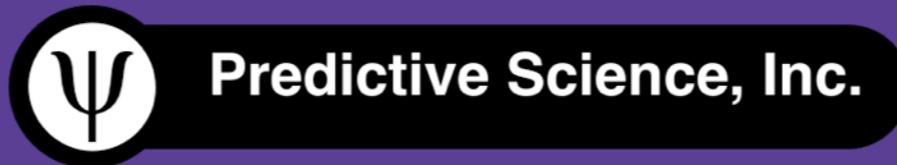


Lidia van
Driel-Gesztelyi



Guillaume
Aulanier

...and Present



Predictive Science, Inc.

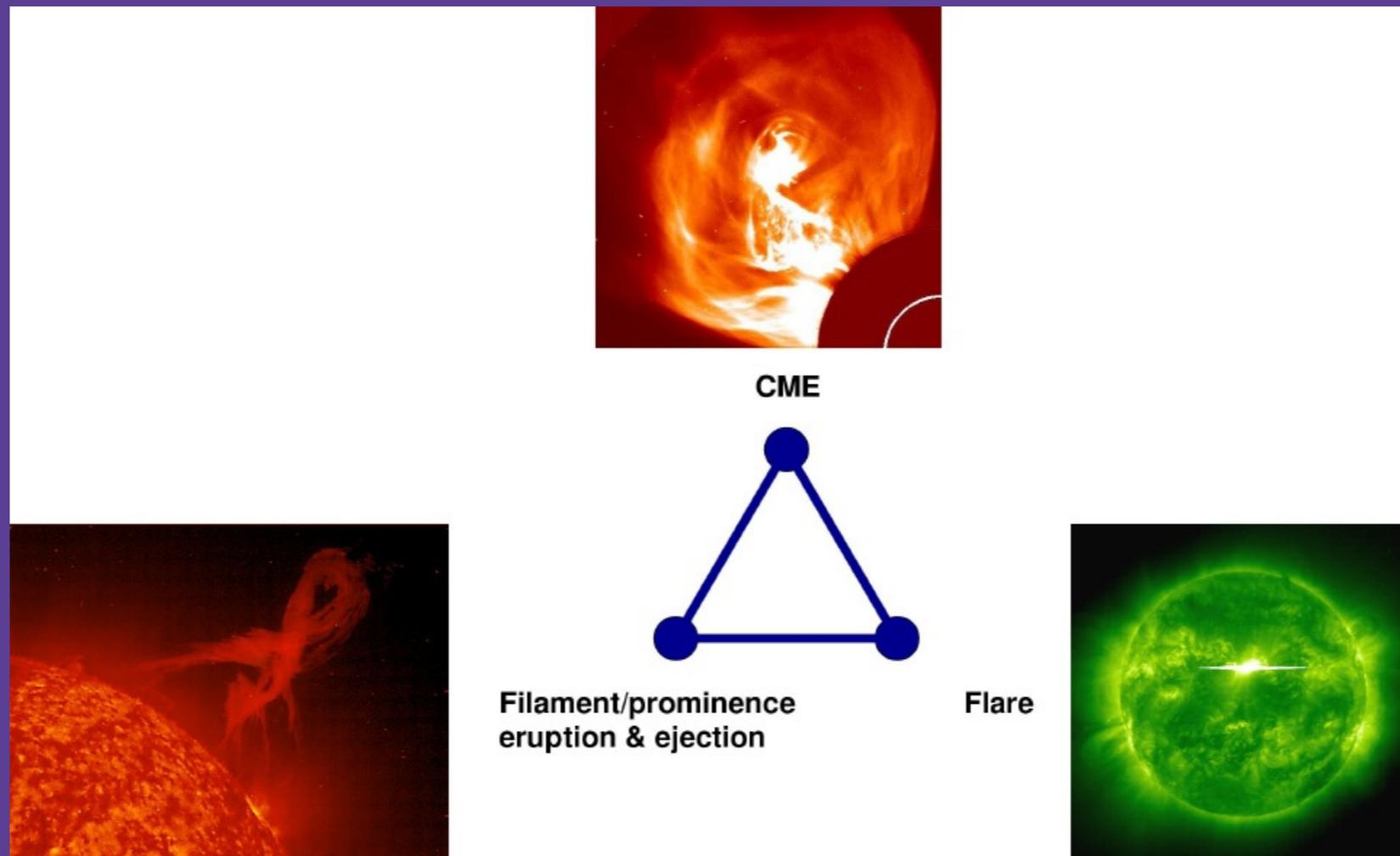
www.predsci.com



Outline

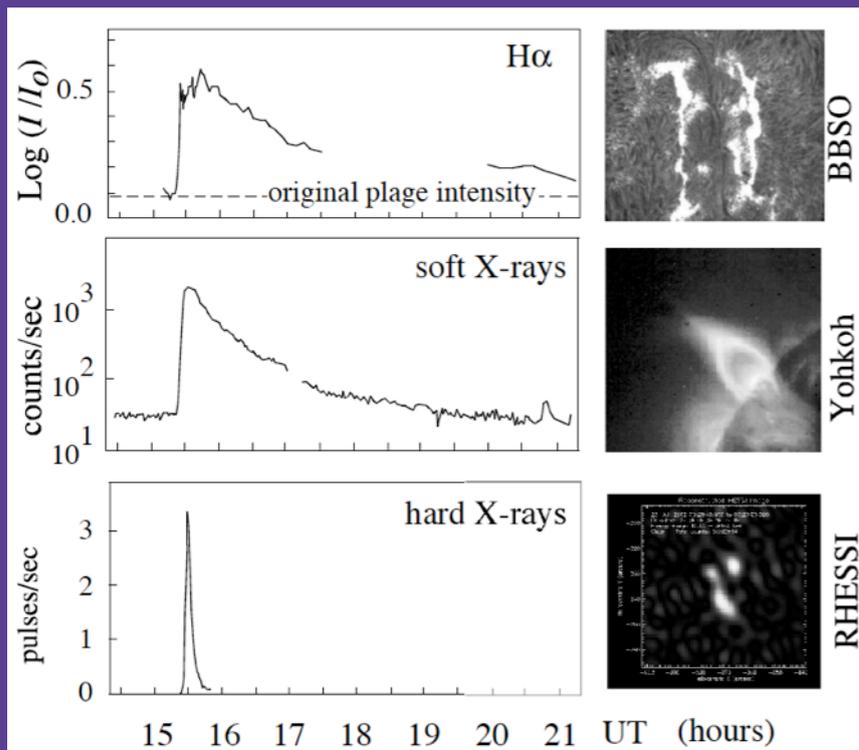
- Introduction
 - What are solar eruptions?
 - Modeling eruptions (constraints & methods)
- Two (still) open questions:
 1. How are eruptions triggered & driven?
 2. Are solar eruptions coupled?
- State-of-the-art: global & thermodynamic simulations
- Summary & Outlook

What are solar eruptions ?

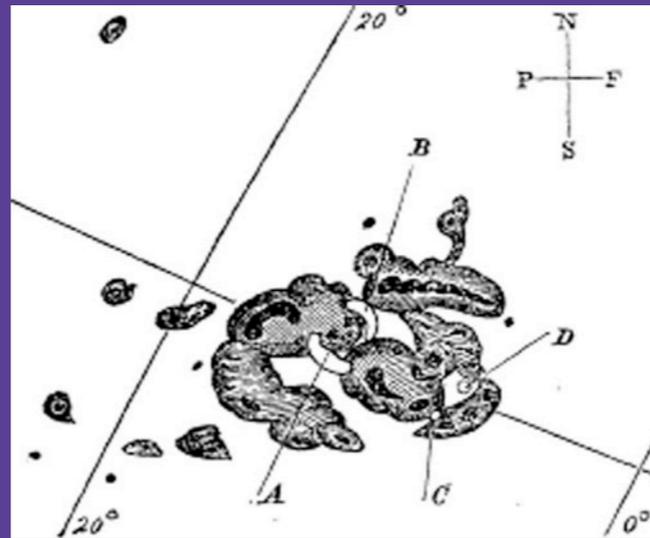


- Largest energy release events in the solar system: up to several 10^{25} J
(current annual world energy consumption: 5×10^{20} J)
- Occur in the solar atmosphere (corona)
- Three main types: flares, prominence eruptions, and CMEs

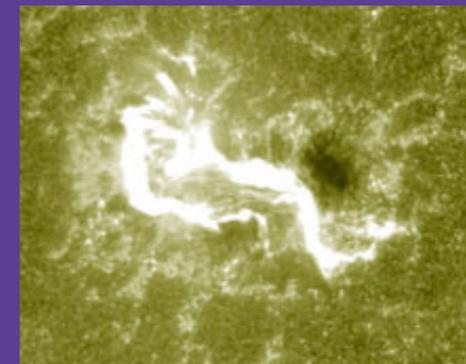
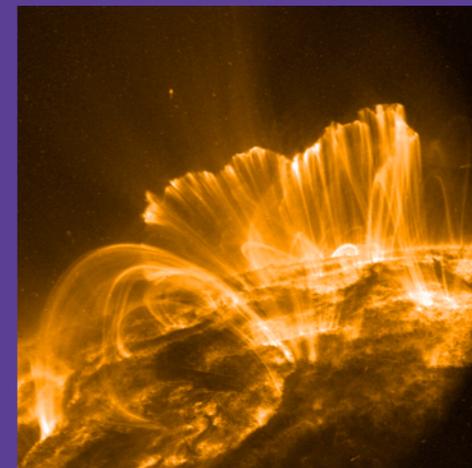
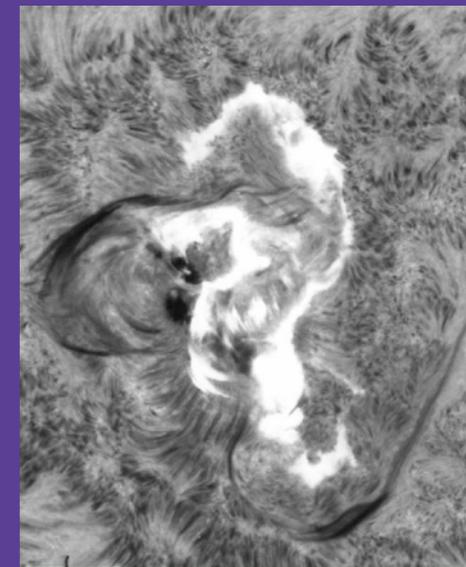
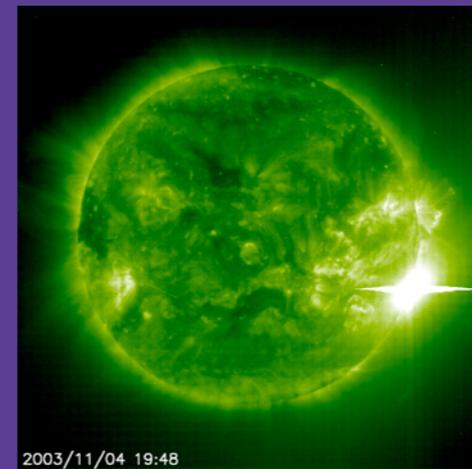
(Eruptive) Flares



courtesy of T. Forbes

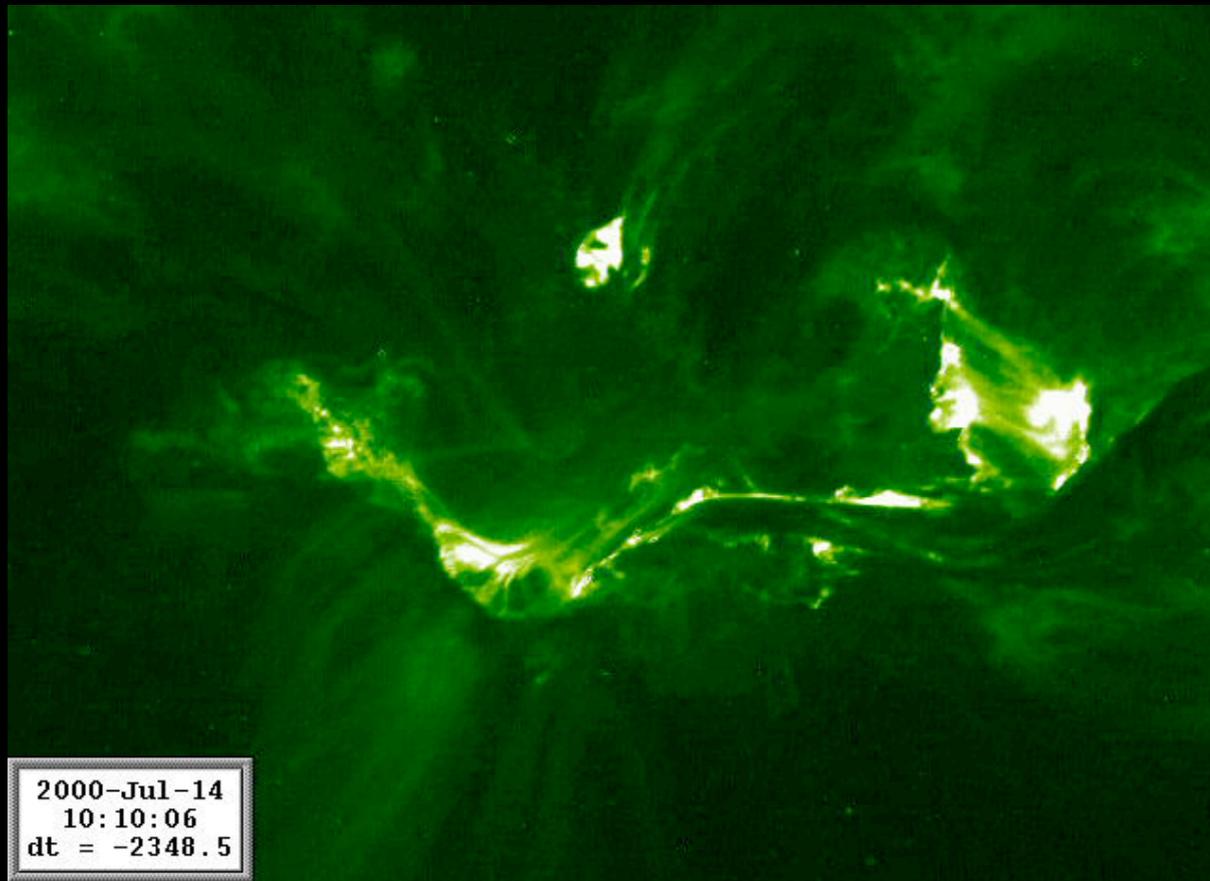


drawing by R.C. Carrington
(first recorded flare 1859)



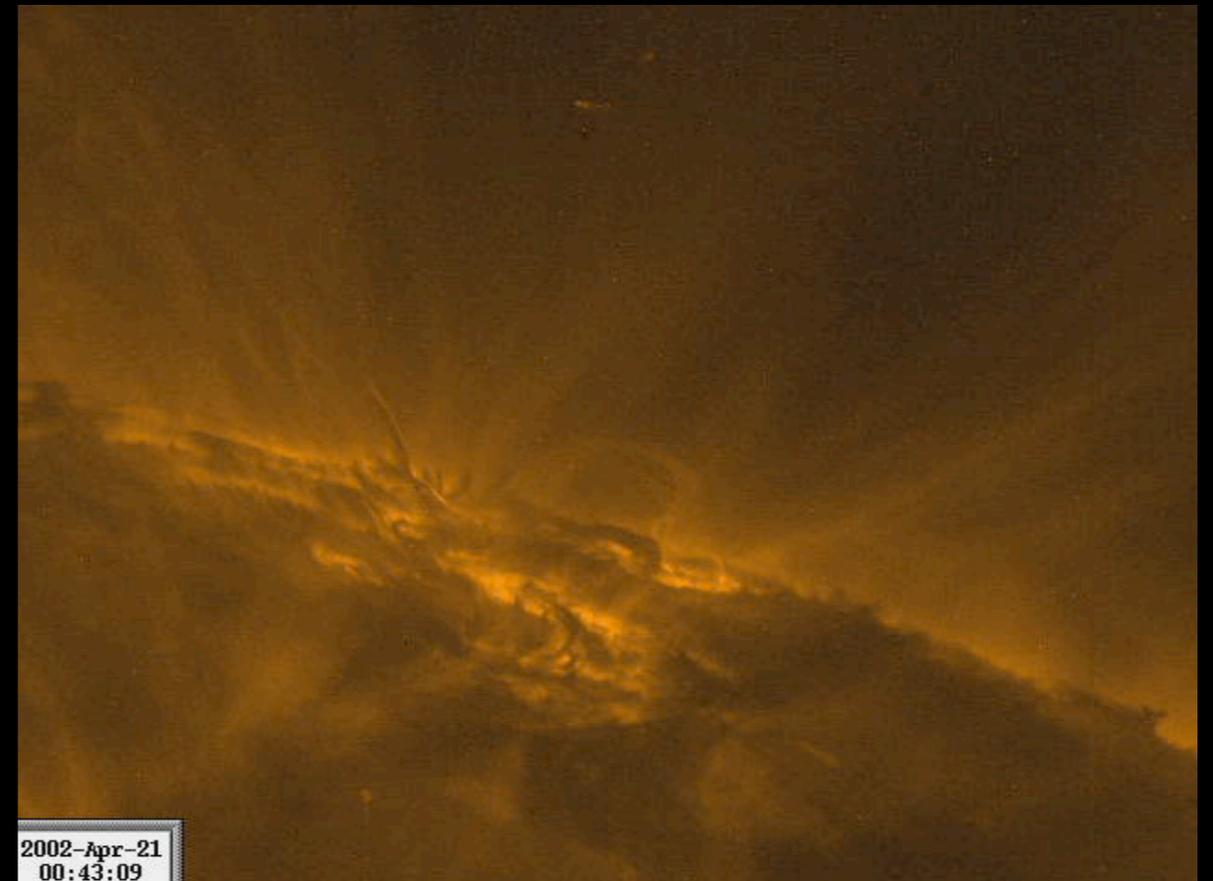
flare arcade & ribbons

- Sudden, localized increase of emission (mostly EUV & X-ray)
- First observed in the 19th century (in white-light)
- Produce two “ribbons” and “post-flare” arcade



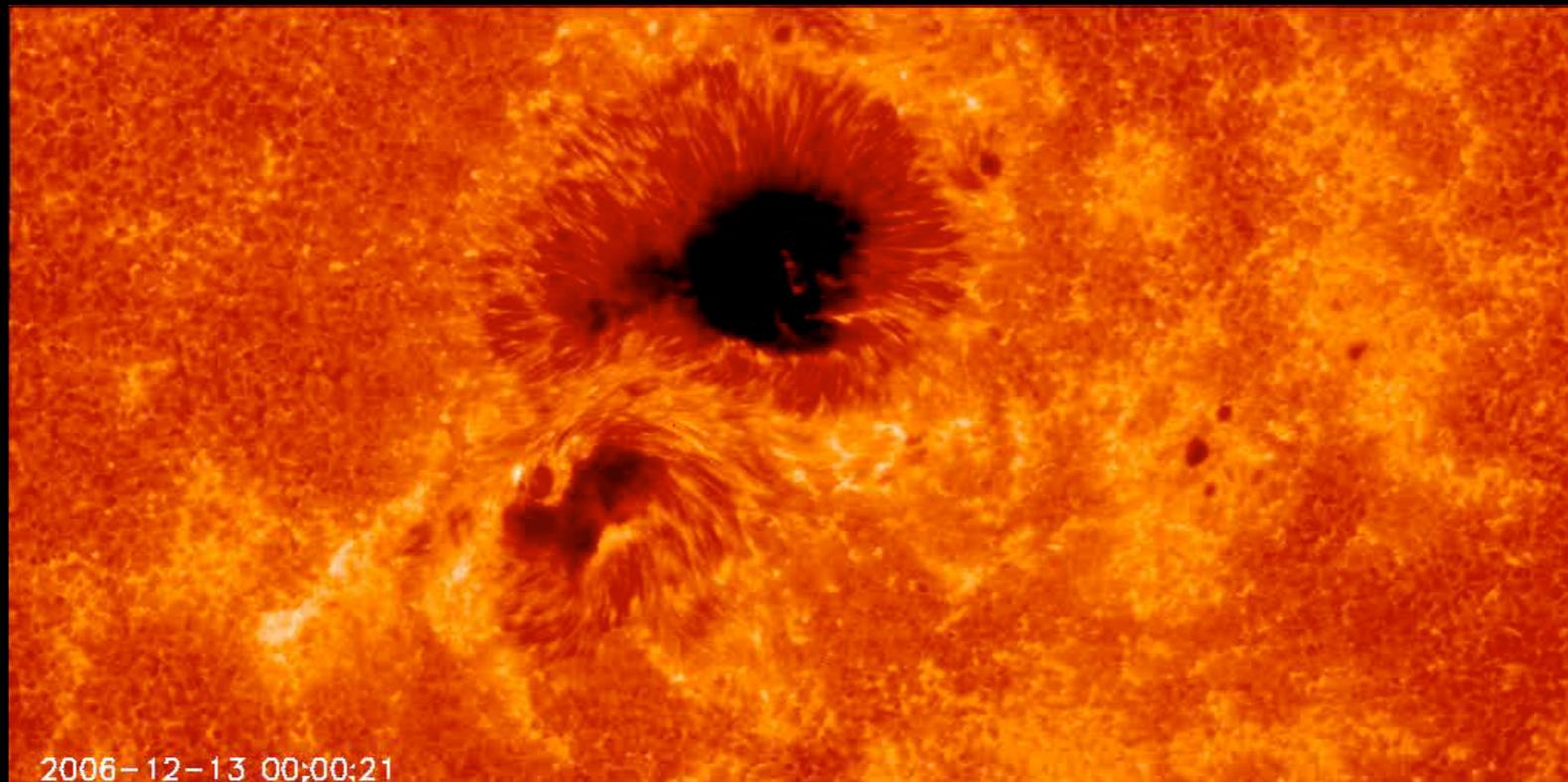
2000-Jul-14
10:10:06
dt = -2348.5

14 July 2000 ("Bastille Day Event")



2002-Apr-21
00:43:09

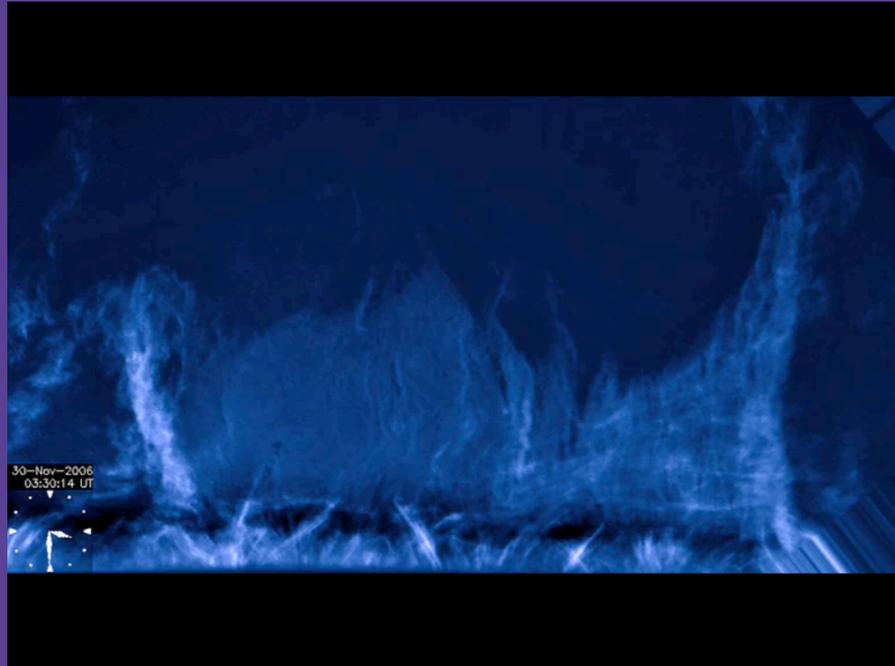
21 April 2002 (TRACE 195 Å)



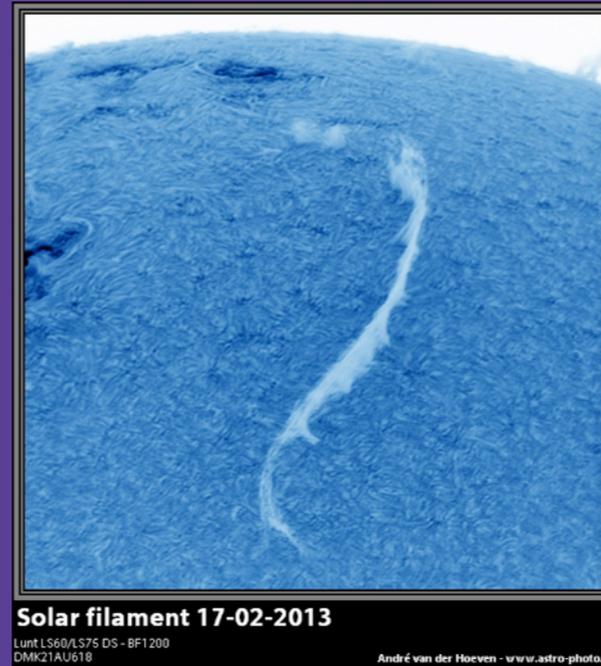
2006-12-13 00:00:21

13 December 2006 (Hinode/SOT)

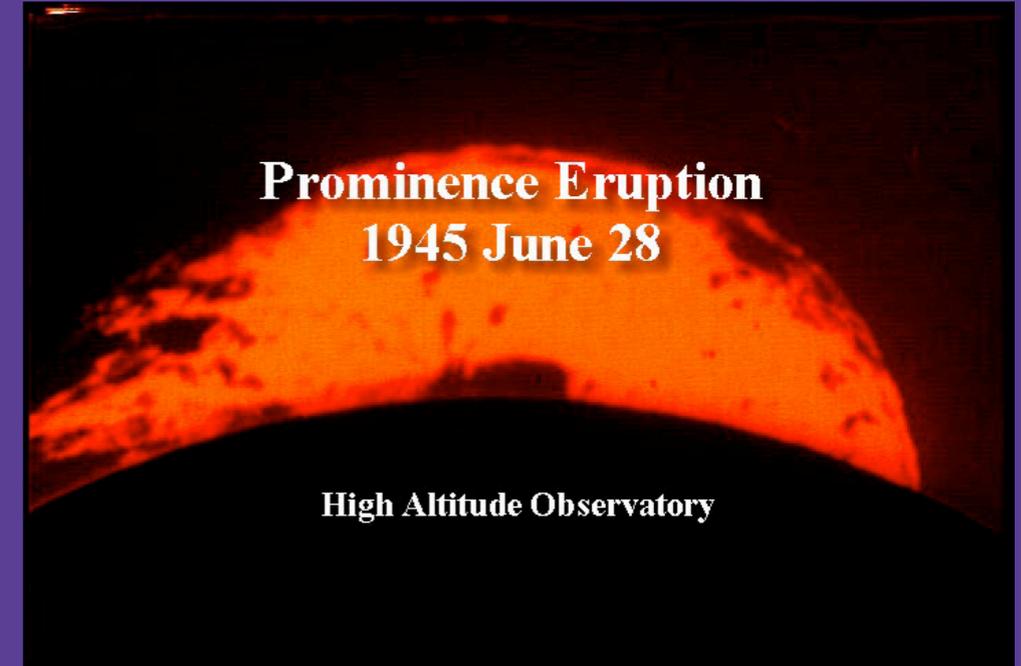
Prominence (filament) eruptions



solar prominence
(Hinode/SOT; courtesy of Tom Berger)



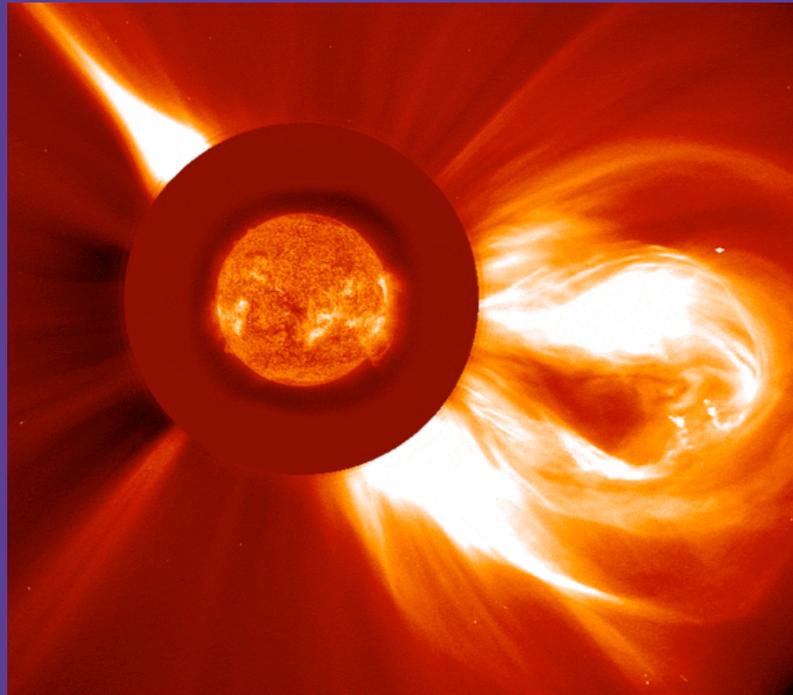
solar filament (courtesy
of André van der Hoeven)



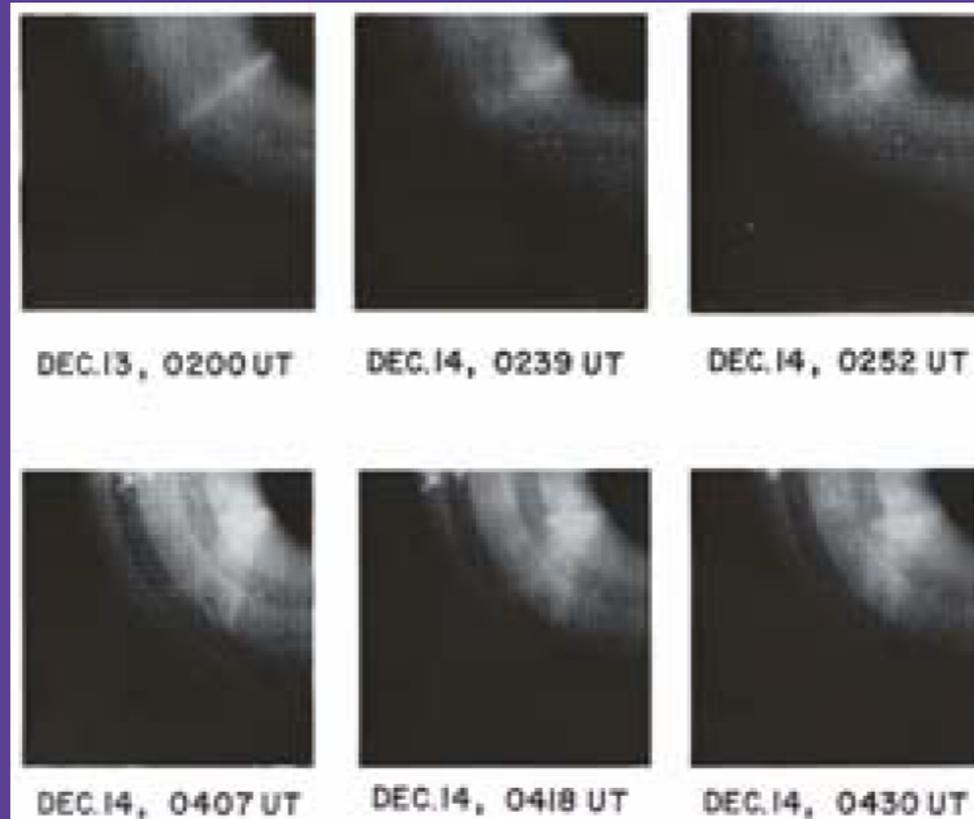
erupting prominence "Granddaddy"
(courtesy of HAO)

- Dense and cool (10^4 K) structures suspended in hot (10^6 K) corona
- Lengths up to several 100,000 km (smaller in active regions)
- Can exist for weeks or even months
- Most prominences/filaments eventually erupt

Coronal Mass Ejections (CMEs)



SOHO/LASCO C2 coronagraph

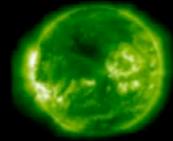


first white-light CME observation
(1971; OSO-7 coronagraph)



1860 ECLIPSE DRAWINGS
SHOWING POSSIBLE CME
drawing by G. Tempel
(during solar eclipse
over Spain)

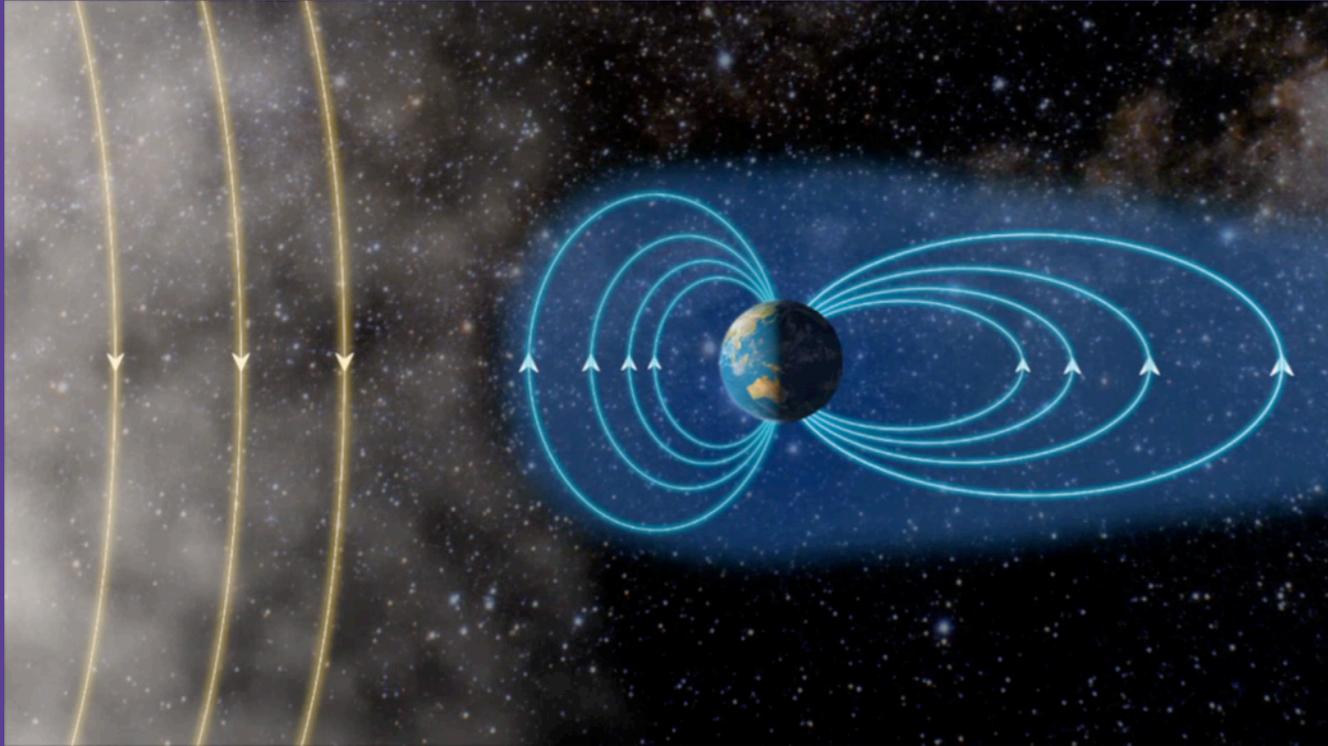
- Huge expulsions of plasma (and magnetic field) from the corona
- Masses up to $\approx 10^{16}$ g; speeds up to ≈ 3500 km/s
- Can occur several times a day (during maximum solar activity)
- Discovered only in the 1970s



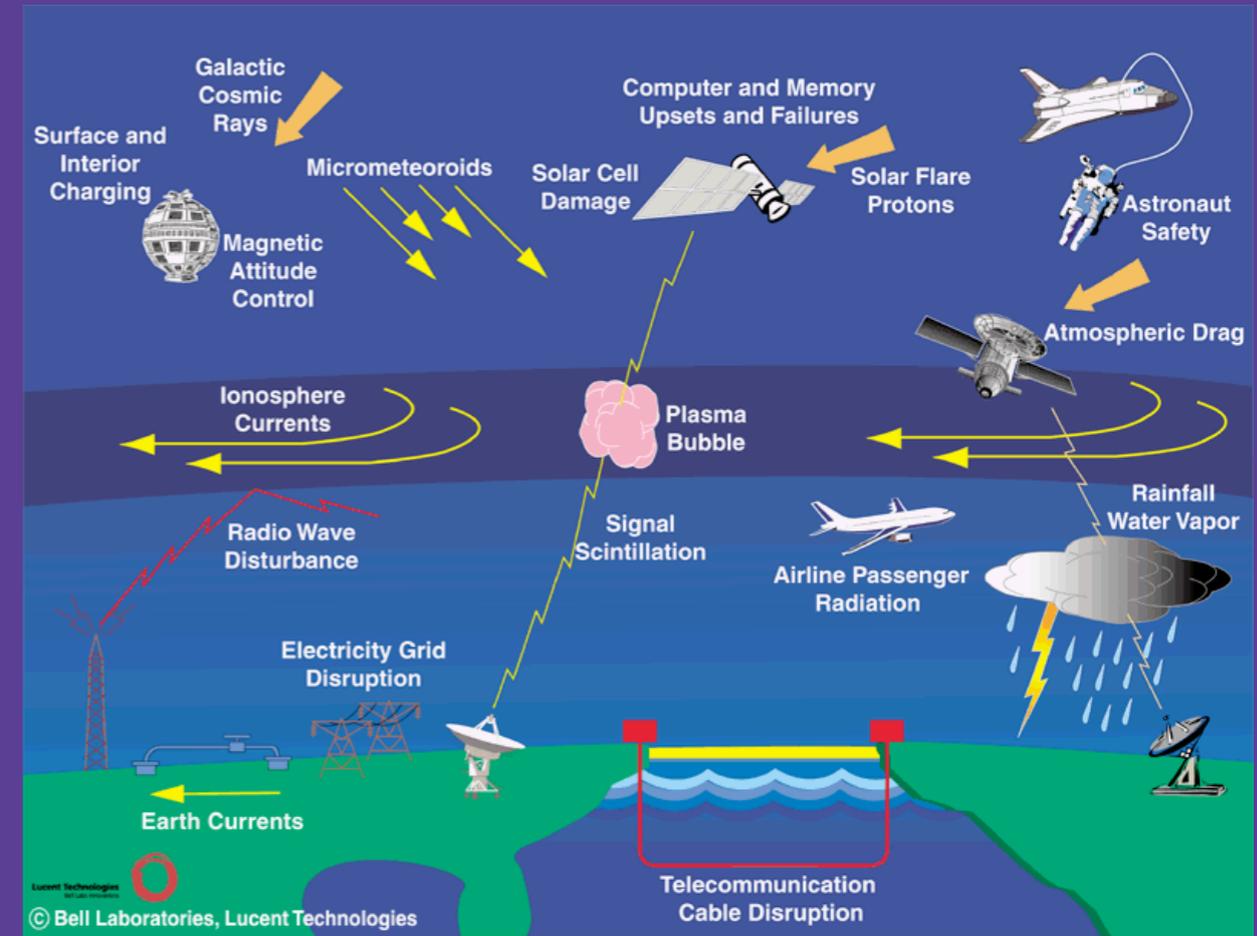
2003 Oct 25 00:00:12

“Halloween Events” (Oct/Nov 2003) observed by SOHO/LASCO coronagraph

Why do we care? ... space weather

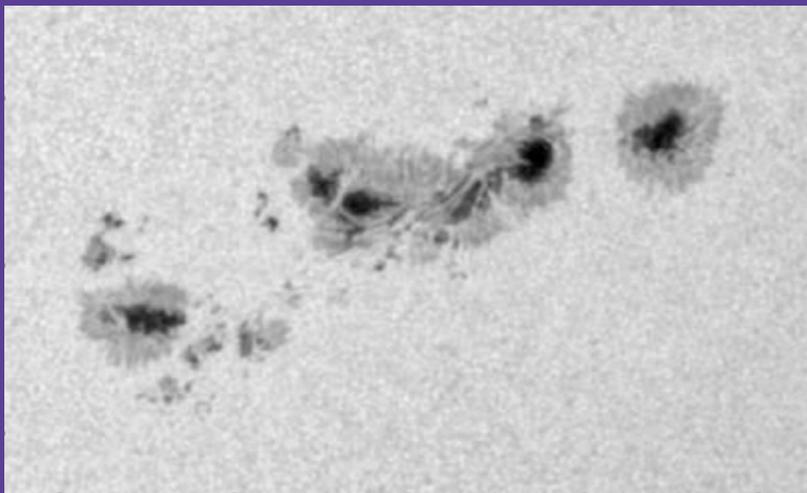
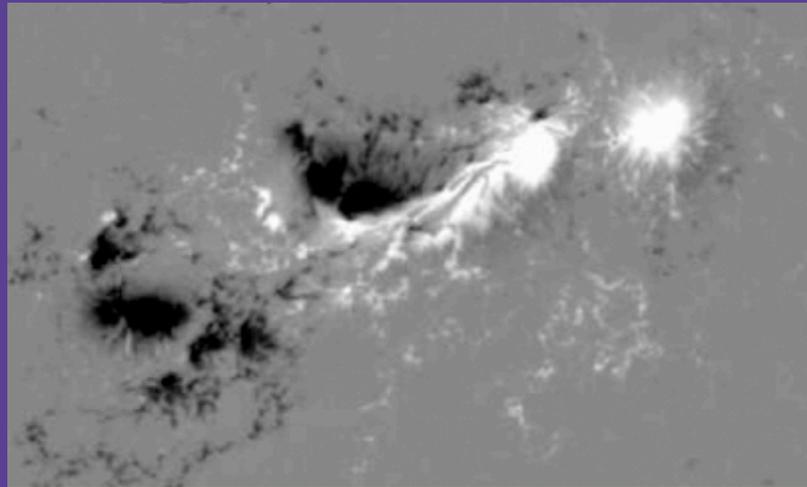


courtesy of University of Oslo (forskning.no)

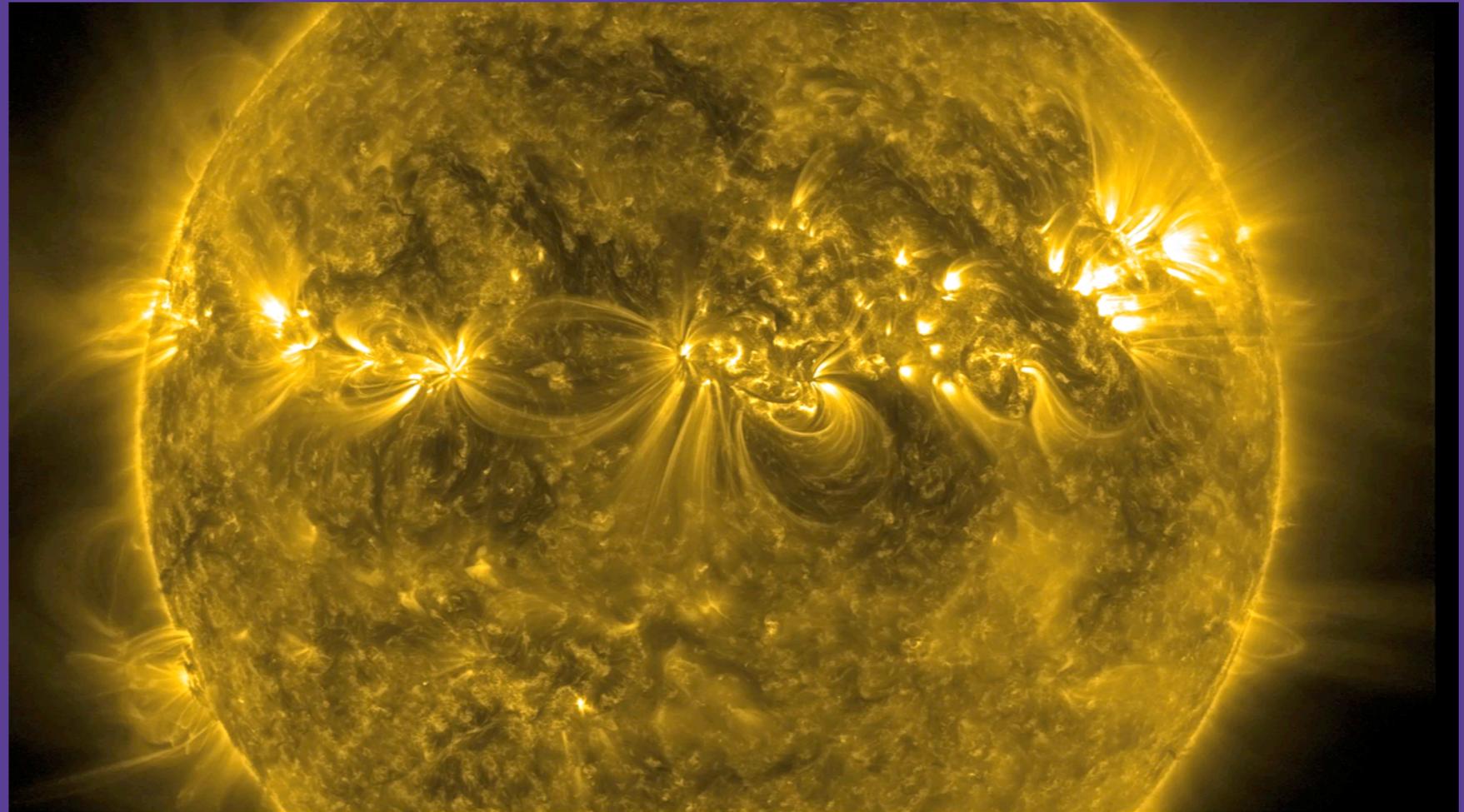


- CMEs can hit the Earth and cause “geomagnetic storms”
- CMEs & flares can destroy satellites, power grids, harm astronauts...
- One main research goal: forecast occurrence and impact of eruptions

Observational constraints: where do eruptions come from?

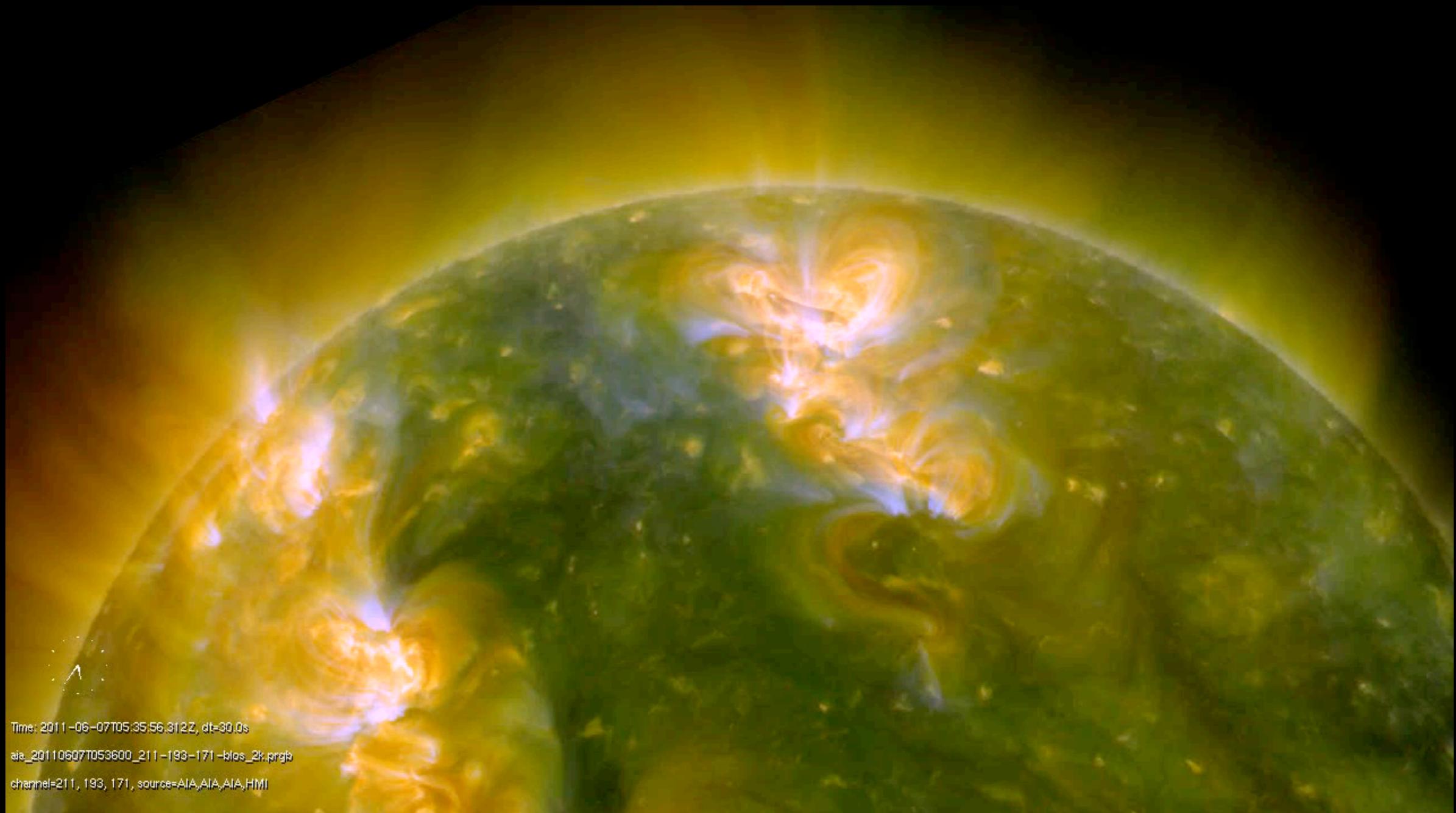


active region & sunspots
(2011, February 15)



EUV corona showing a belt of active regions (SDO/AIA 171 Å)

- Strongest events originate in large **active regions** (above sunspot groups)
- ... but also in dispersed regions (quiescent prominences)
- Always above (sheared) magnetic **polarity inversion lines**



eruption on 7 June 2011 observed by SDO/AIA (courtesy of C. Schrijver)

- Flares, PEs & CMEs **typically occur together** (especially in large events)
- Different observational manifestations of violent disruption of magnetic field?

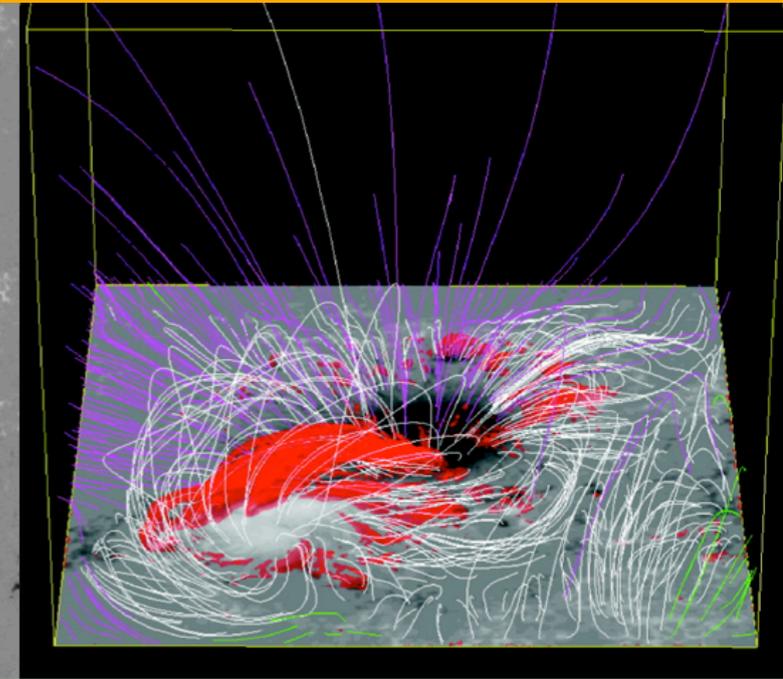
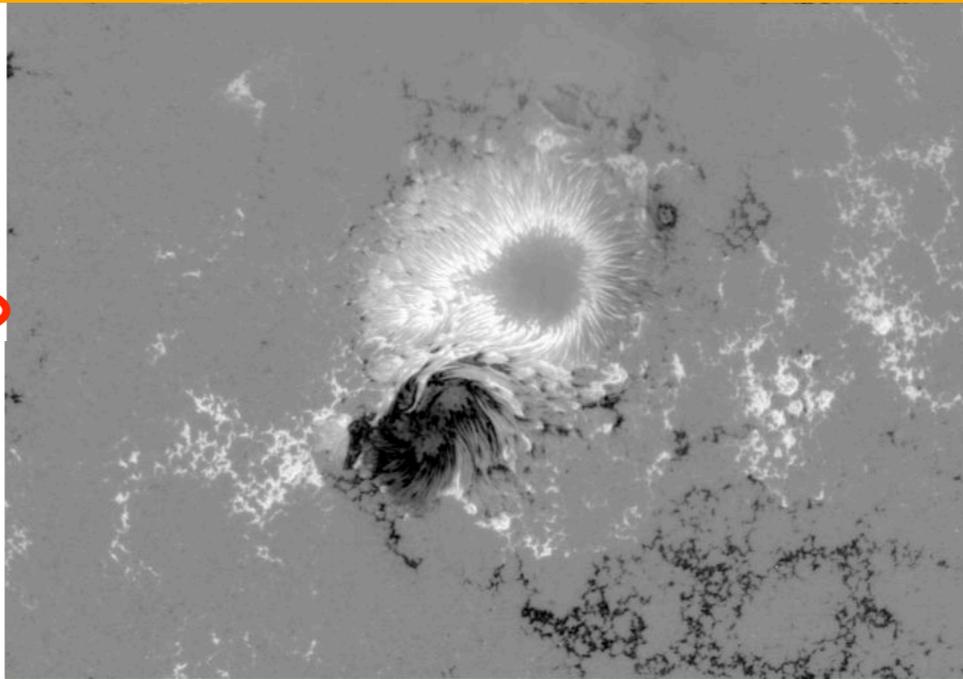
Further constraints

Table 1. Energy Requirements for a Moderately Large CME

Parameter	Value
Kinetic energy (CME, prominence, and shock)	10^{32} ergs
Heating and radiation	10^{32} ergs
Work done against gravity	10^{31} ergs
Volume involved	10^{30} cm ³
Energy density	100 ergs cm ⁻³

Table 2. Estimates of Coronal Energy Sources

Form of Energy	Observed Average Values	Energy Density ergs cm ⁻³
Kinetic ($(m_p n V^2)/2$)	$n = 10^9$ cm ⁻³ , $V = 1$ km s ⁻¹	10^{-5}
Thermal (nkT)	$T = 10^6$ K	0.1
Gravitational ($m_p n g h$)	$h = 10^5$ km	0.5
Magnetic ($B^2/8\pi$)	$B = 100$ G	400



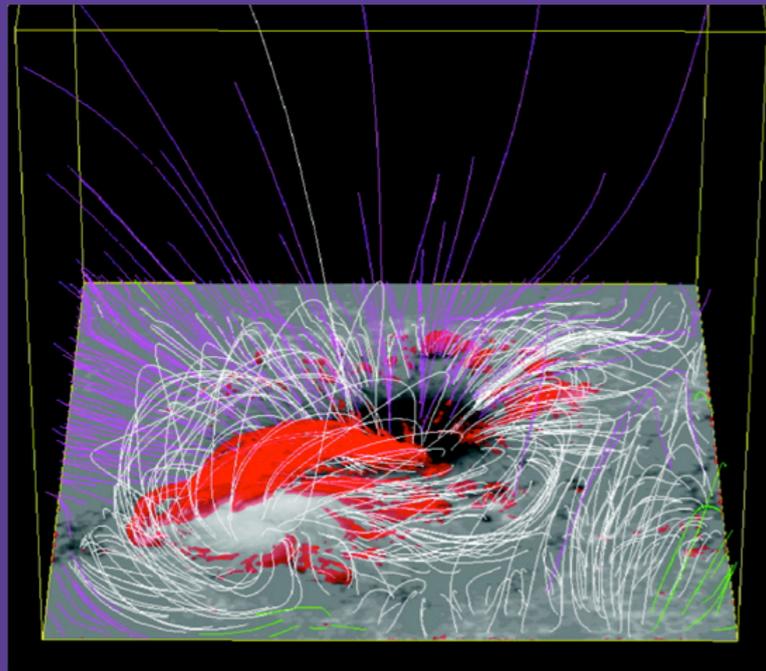
Forbes (2000)

surface magnetic field around
X-class flare on 13 Dec. 2006
(Hinode/SOT)

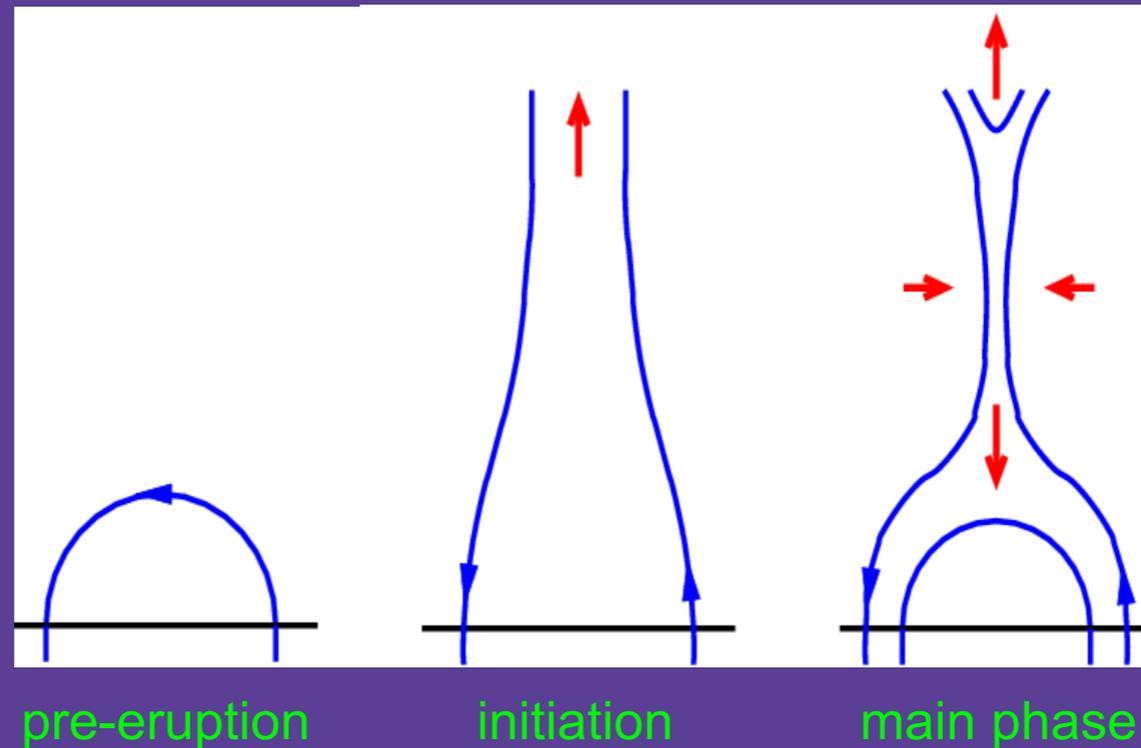
magnetic field extrapolation
of active region (13 Dec. 2006)
Schrijver et al. (2008)

- Eruptions originate in the low corona
 - plasma environment dominated by magnetic fields
 - eruptions are **magnetically driven** (non-magnetic models ruled out)
- Slow surface evolution of active regions not significantly affected by eruptions
 - foot-points of coronal field lines effectively stationary (“line-tied”)
- Required (“free”) energy stored in current-carrying, **sheared/twisted core field**
- Core field formed by flows/emergence & **stabilized by overlying potential fields**

Basic eruption scenario



magnetic field extrapolation
of active region (13 Dec. 2006)
Schrijver et al. (2008)



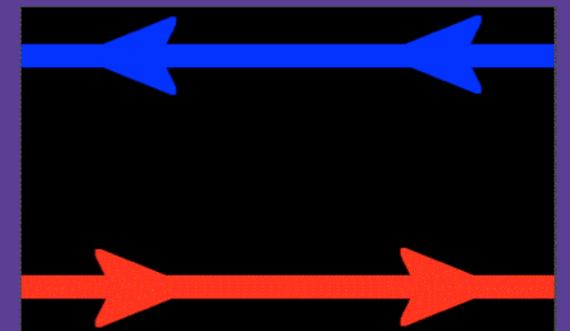
pre-eruption

initiation

main phase



Yokoyama et al. (2001)



magnetic reconnection

Pre-eruption phase: source region formed and energized by flows & flux emergence
→ current-carrying sheared core field stabilized by overlying field

Initiation phase: stress exceeds threshold → opening of closed field → CME (+ PE)

Main phase: - huge expansion + formation of vertical current sheet below eruption
→ re-configuration of coronal field by magnetic reconnection → flare

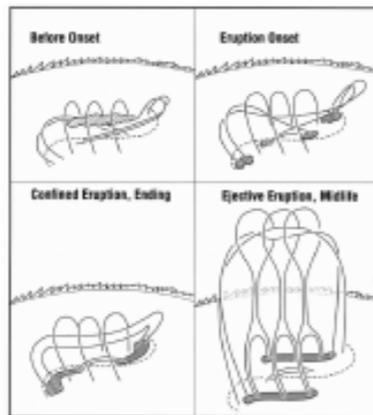
Solar eruption models (see Forbes 2001)

- Virtually all eruption models formulated as **initial boundary-value problems**:
 - System of **differential equations** (single-fluid MHD)
 - Set of **boundary conditions** (quite well constrained by observations)
 - **Initial state** (less well constrained)
- Limitations:
 - MHD approximation: → no kinetic physics (e.g. particle acceleration)
 - Coronal magnetic field not known → initial state more or less ad-hoc
 - Computer power limited → complexity & length scale range not covered

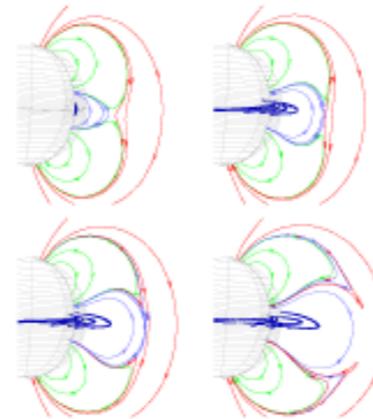
Models still valuable to test proposed physical mechanisms

1. How are eruptions triggered & driven? ...many models...

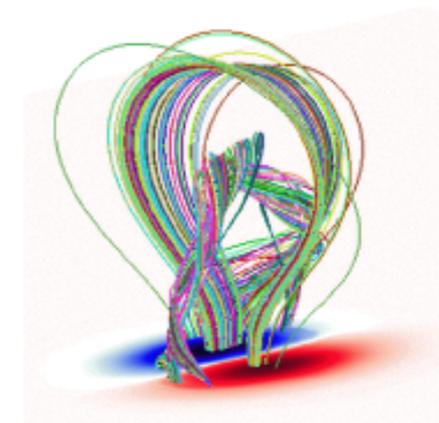
Tether Cutting:
“runaway” reconnection



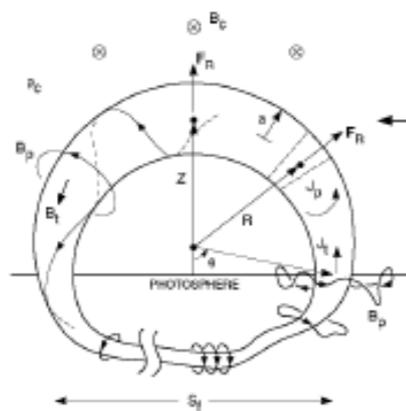
Magnetic Breakout:
unstable arcade, triggered (& driven?) by reconnection.



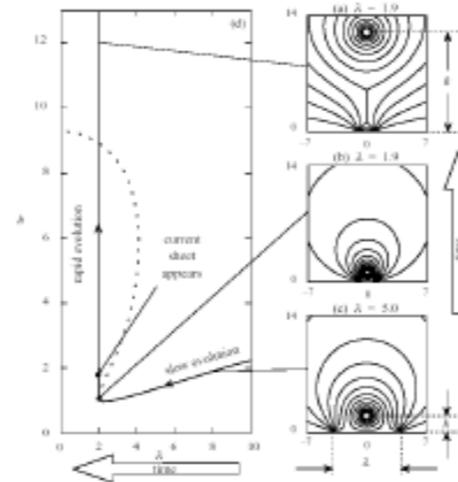
Flux Cancellation
at neutral line
forms flux rope



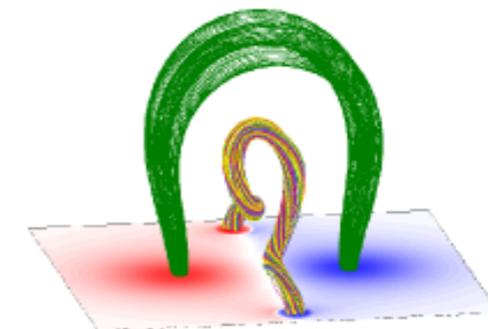
Driven Flux Rope:
photospheric I injection
& hoop force



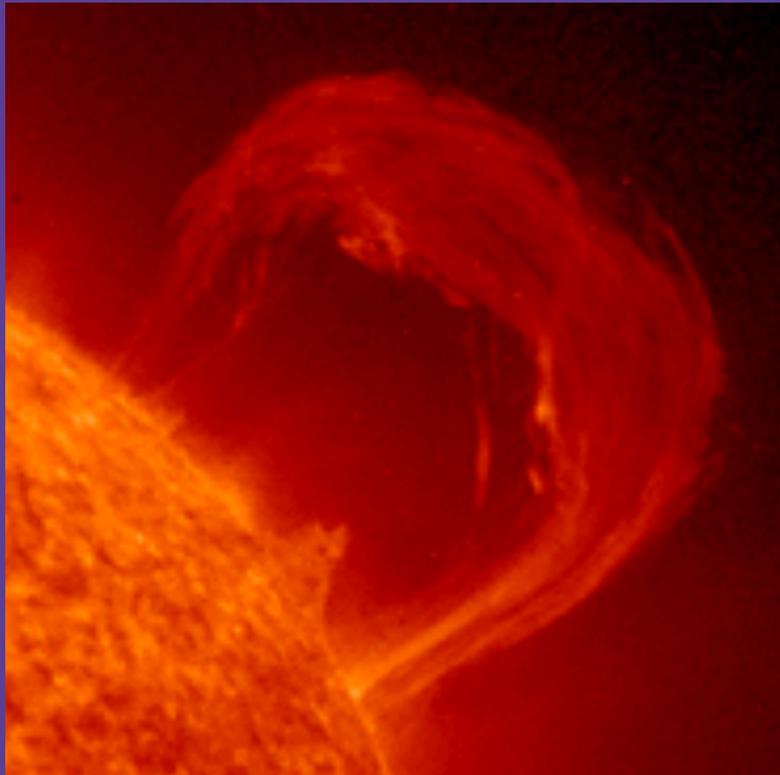
Flux Rope Catastrophe:
end point in equil. sequ. & jump



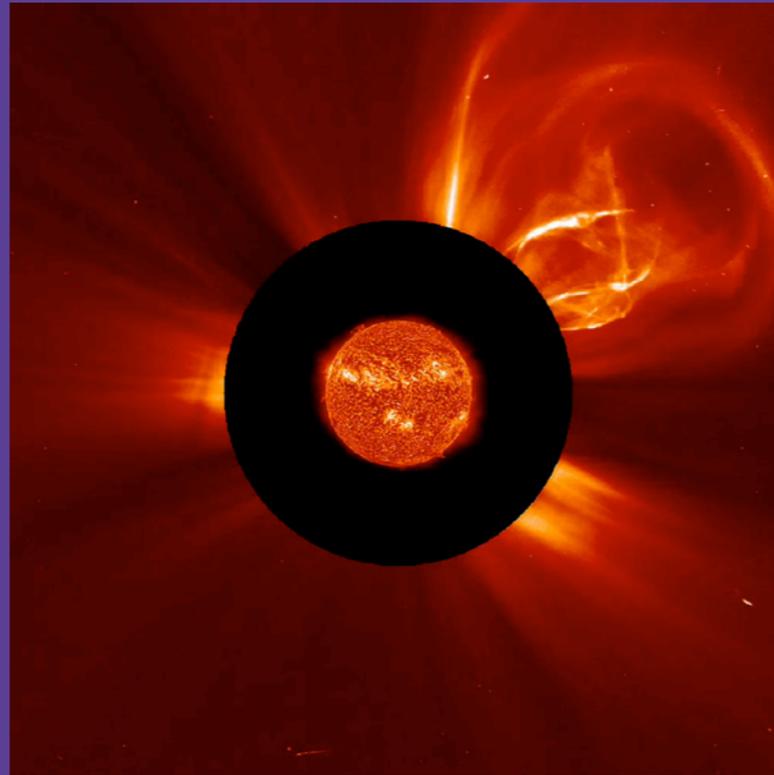
Flux Rope Instability:
ideal MHD instability
(kink & torus instab.)



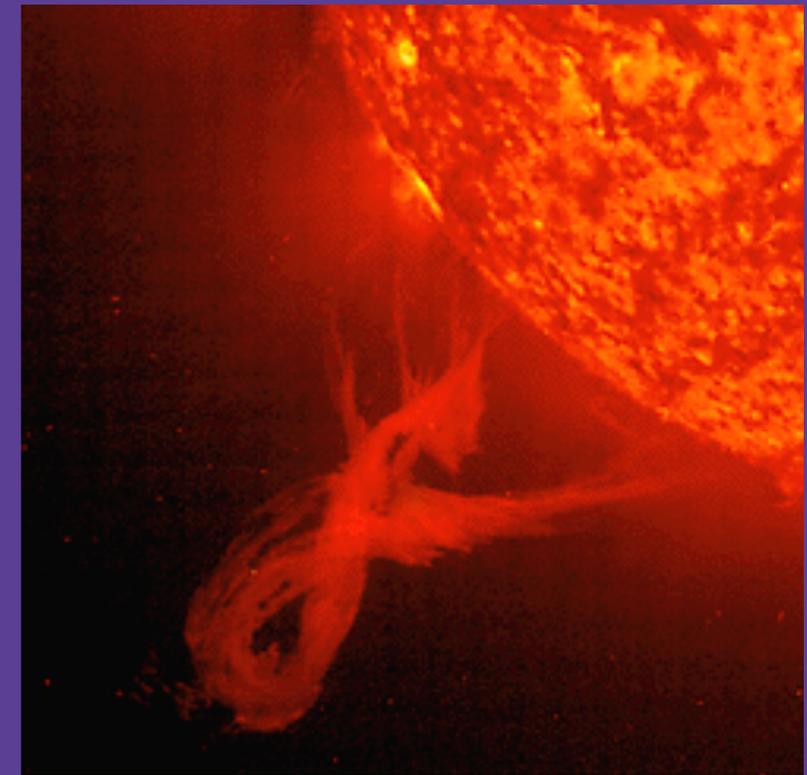
Flux rope instability models



loop-shaped prominence
(SOHO/EIT 304 Å)



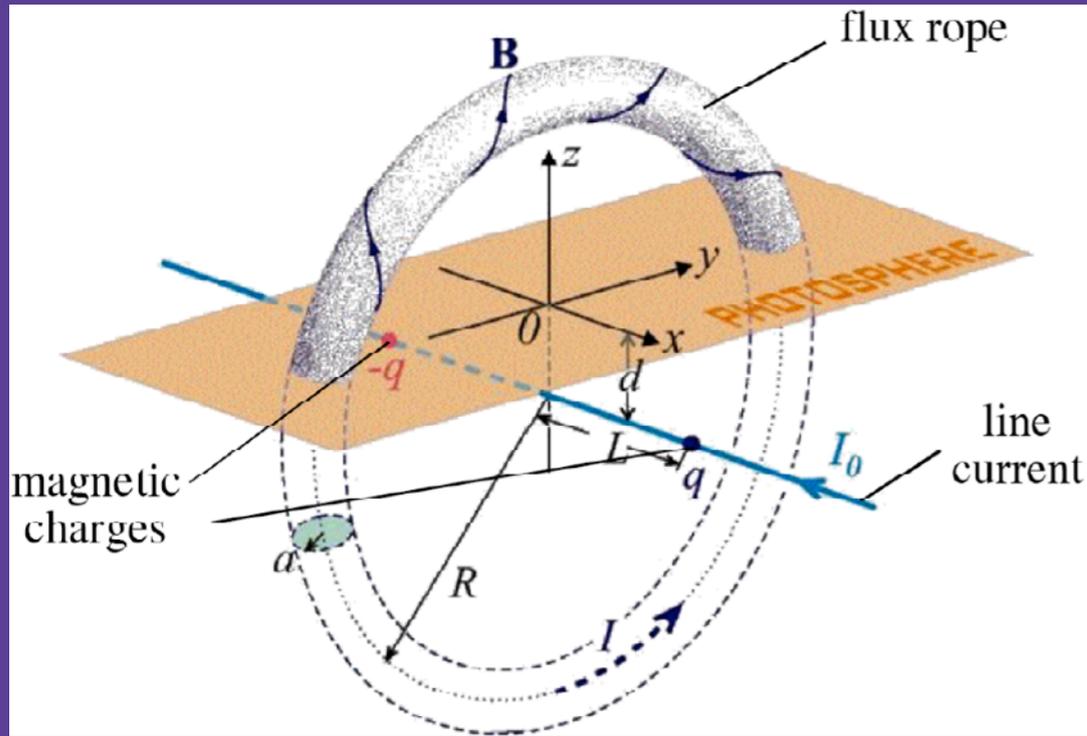
twist in CME core
(SOHO/LASCO)



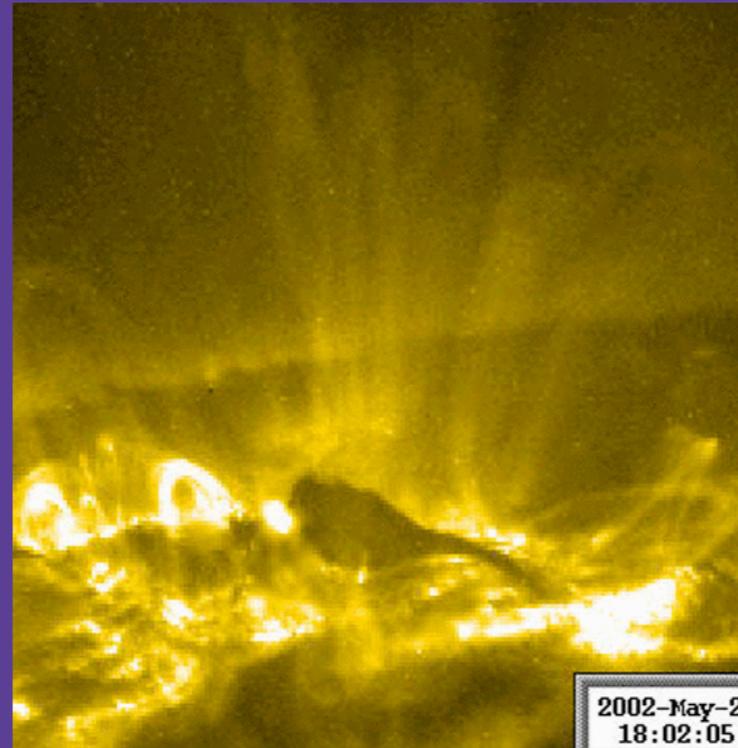
kinking eruptive prominence
(SOHO/EIT 304 Å)

- Eruptions often show:
 - single, loop-shaped structure
 - signatures of internal twist
 - helical deformation of rising loop
- Suggests **flux rope** geometry + occurrence of ideal MHD **kink instability** (occurs if flux rope twist exceeds threshold → helical deformation)

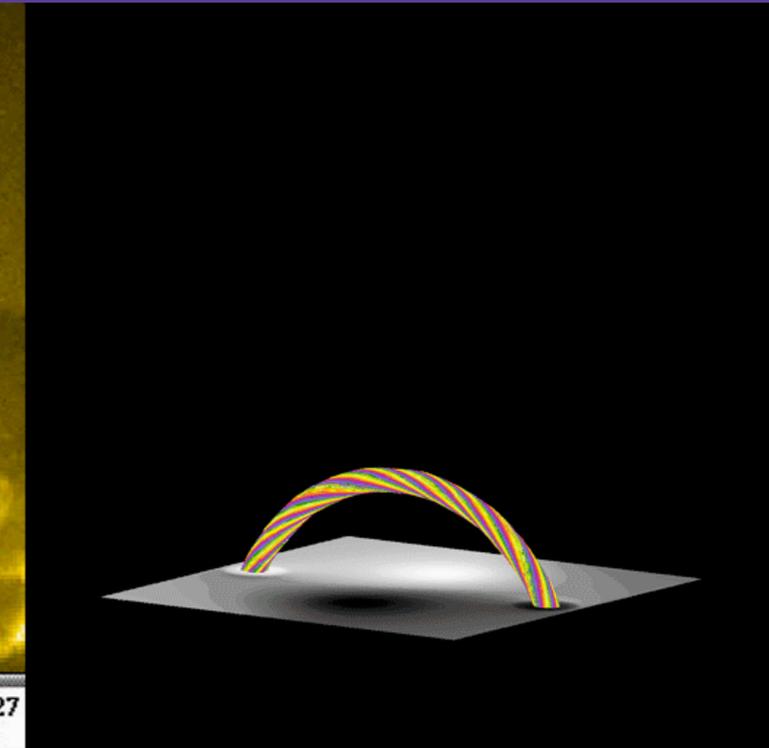
The helical kink instability (KI)



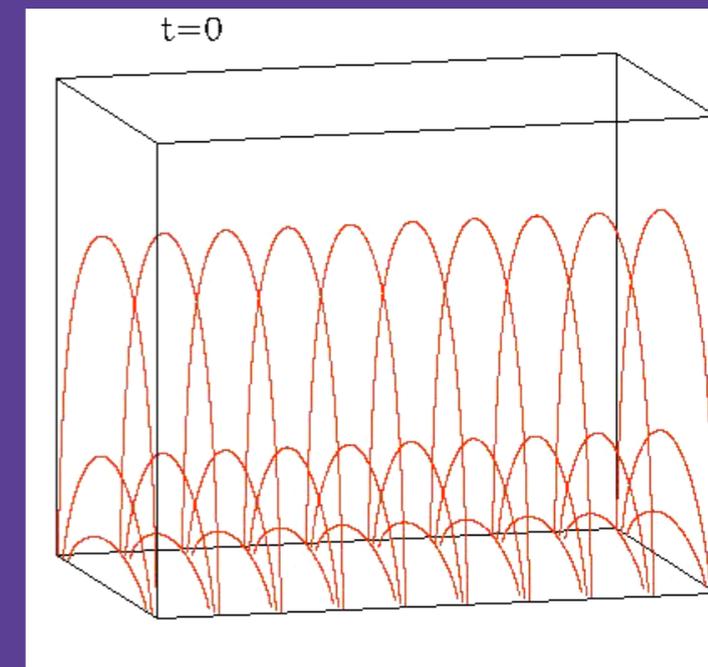
Titov & Démoulin (1999)



Török & Kliem (2005)

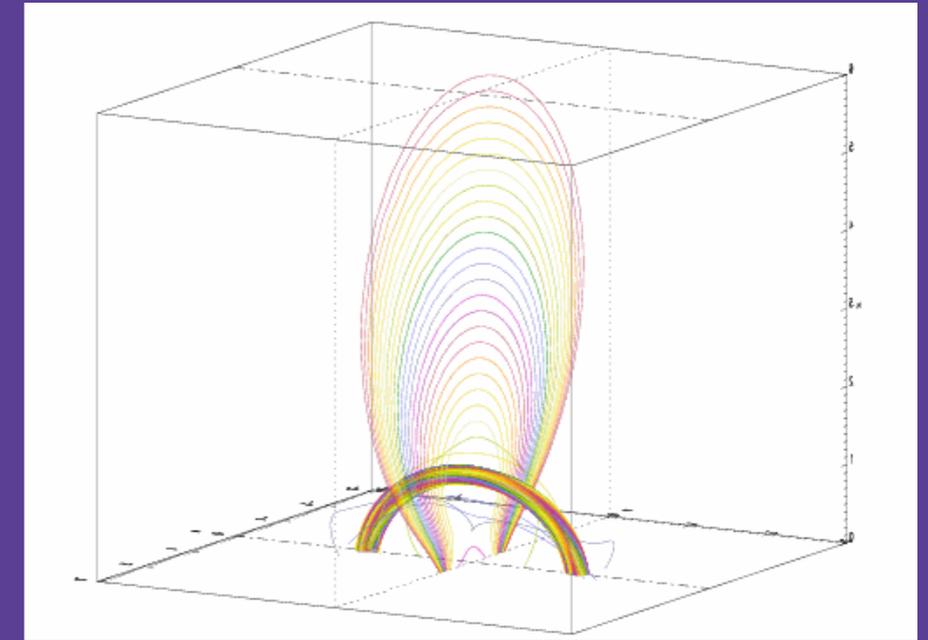
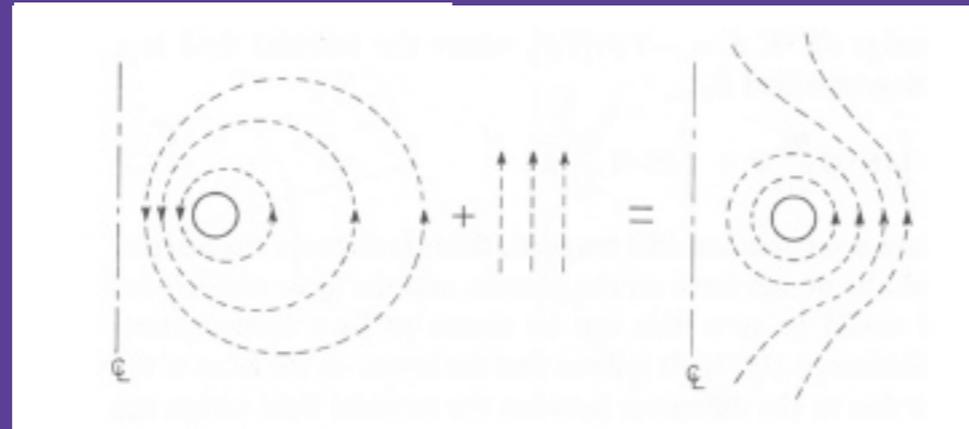
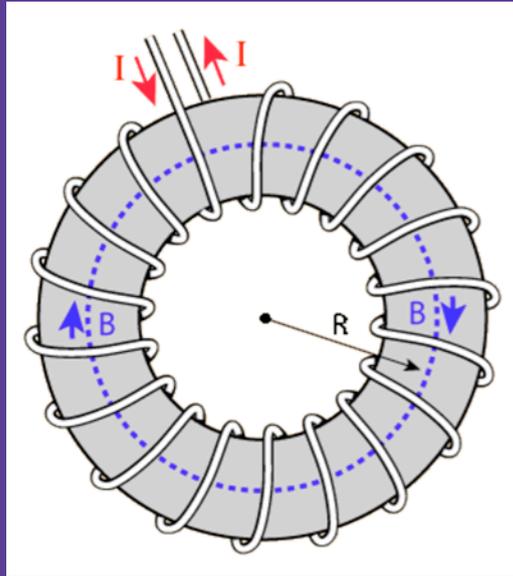


- Simulate KI using analytical coronal flux rope model
- Morphology & rise of kinking filament well reproduced
- Similar model at the same time by Fan & Gibson (HAO)
- However: flux rope does not fully erupt (no CME)



Fan & Gibson (2004)

Torus instability (TI)



Török & Kliem (2007)
(line-tied partial current ring)

- Current ring + external poloidal field:

$$f_I = \frac{I^2}{4\pi^2 a^2 R^2} (L + \mu_0 R/2)$$

“hoop force”



$$f_B = -\frac{I B_{\text{ex}}}{\pi a^2}$$

restoring force

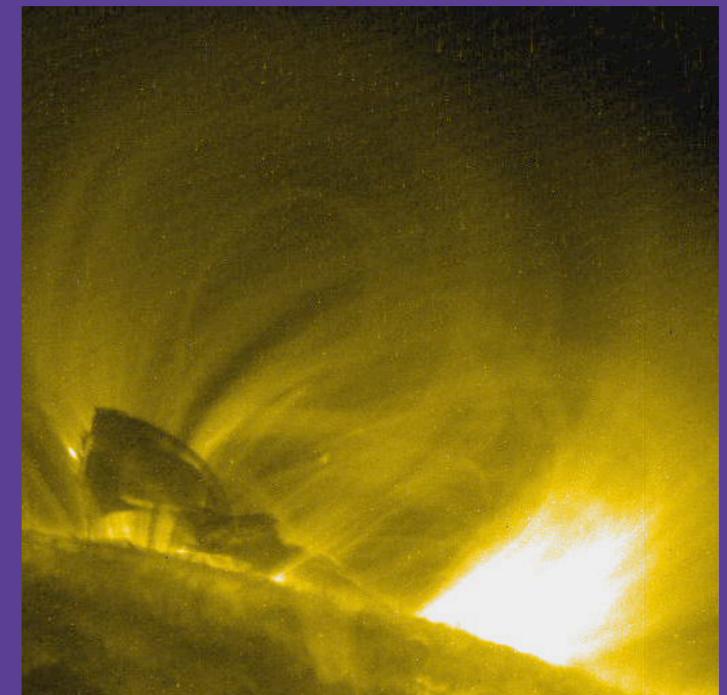
- TI occurs if restoring force **drops faster** than hoop force during expansion of the ring after perturbation in R

$$B_{\text{ext}}(R) = B_0 R^{-n}$$



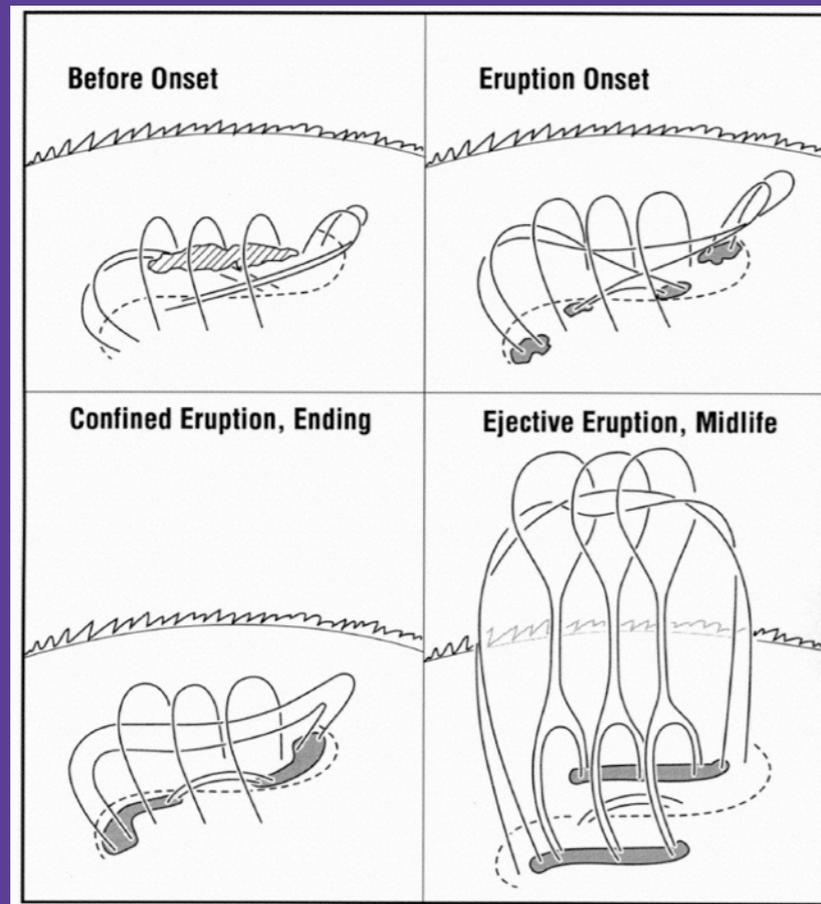
$$n_{\text{crit}} \approx 3/2$$

Bateman (1978); van Tend & Kuperus (1978); Kliem & Török (2006)

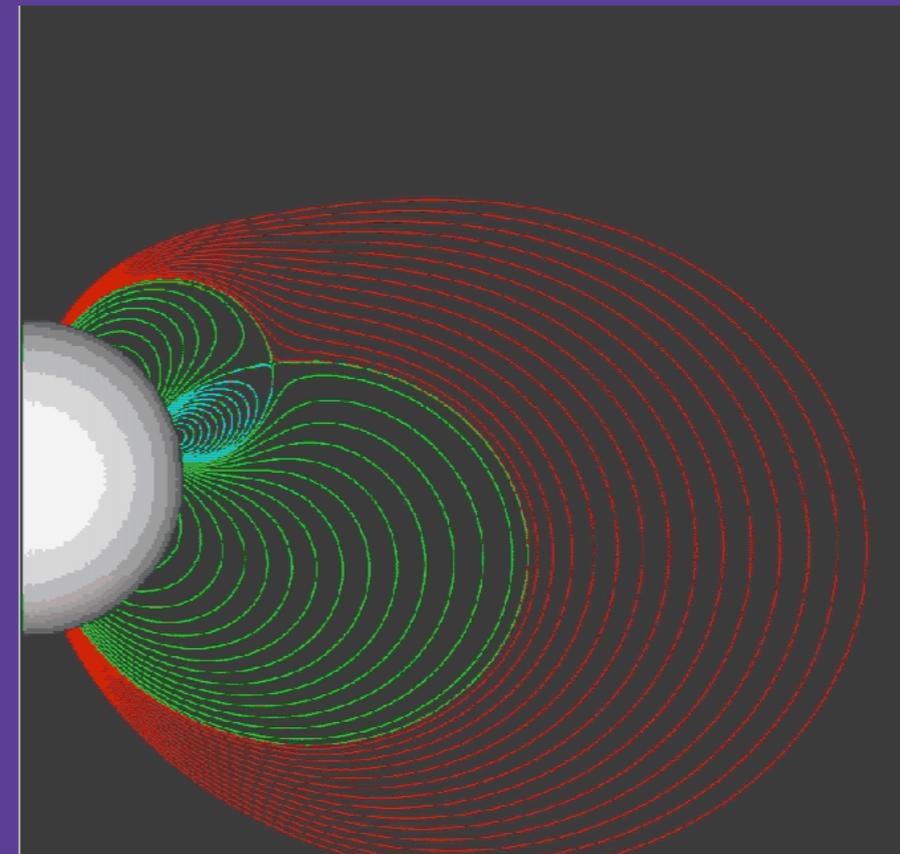


- On the sun: slowly rising flux rope (filament) has to reach height at which $n > n_{\text{crit}}$

That's just part of the story ... role of reconnection?



Moore et al. (2001)



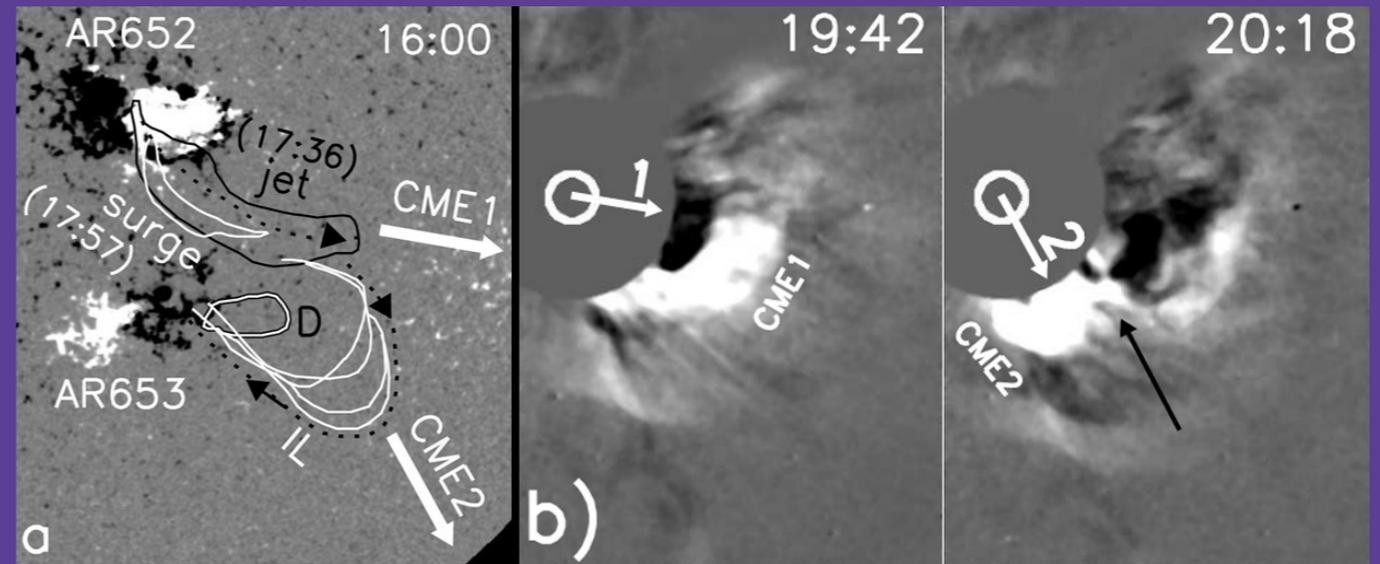
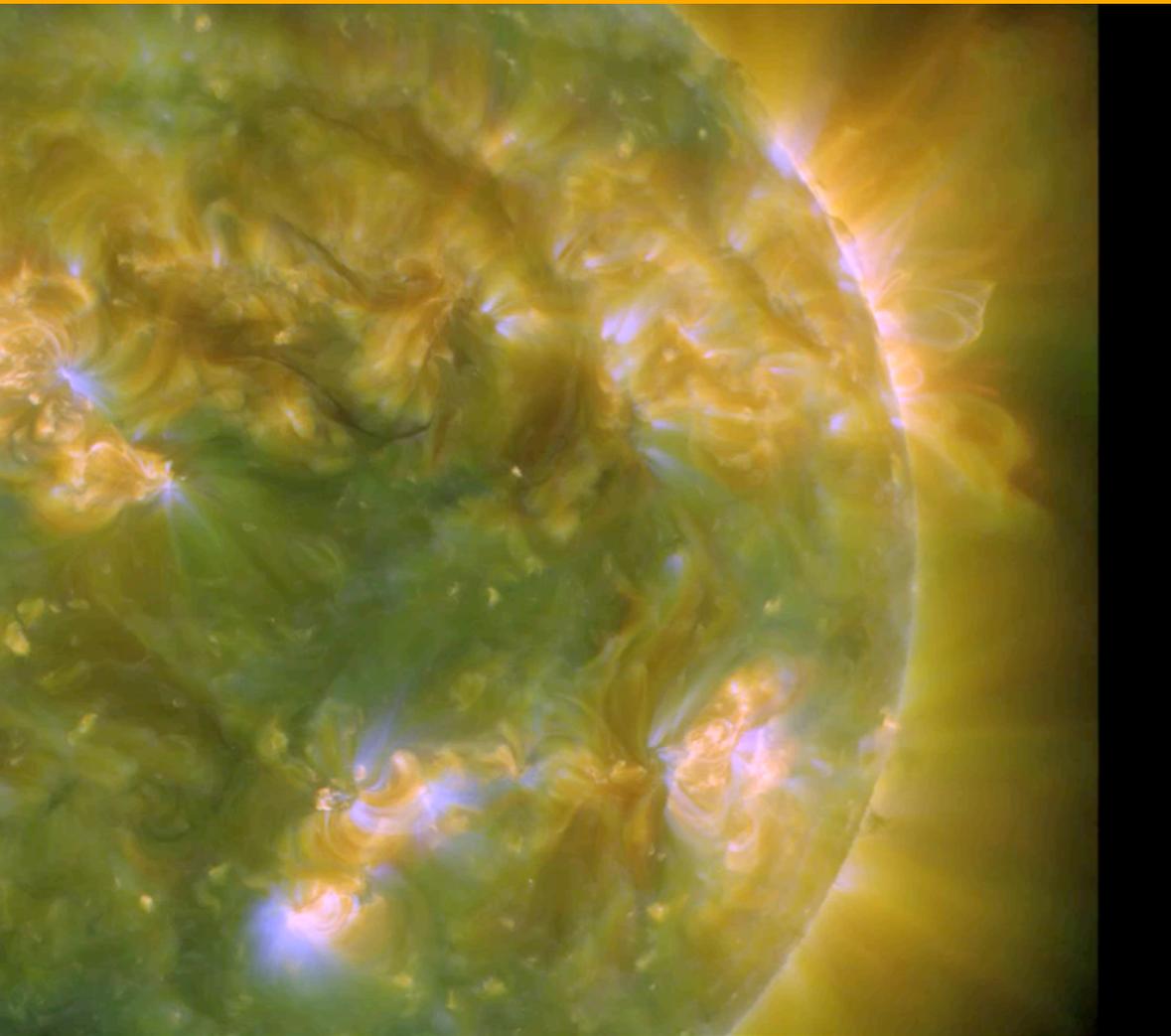
Lynch et al. (2008)

- **Within / below** core field (“tether cutting”):
 - slow: arcade-to-rope transition (slow rise phase)
 - fast: flare reconnection → eruption driver
- **Above** core field (“breakout”):
 - can trigger eruption
 - can speed it up significantly

these processes (and TI) work together in eruptions !

(which one dominates depends on the circumstances)

2. Are solar eruptions coupled (“sympathetic”) ?

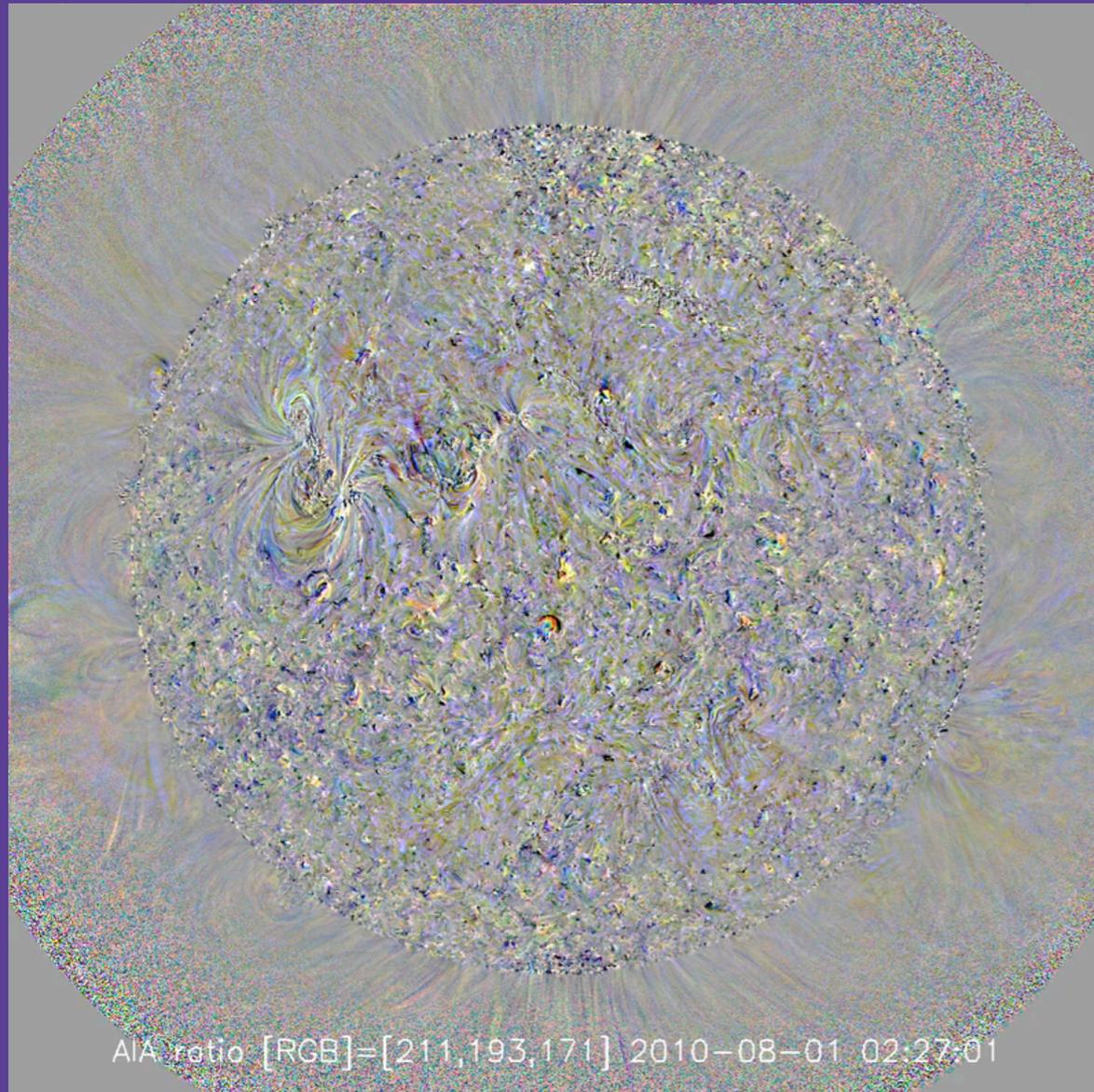


Jiang et al. (2008)

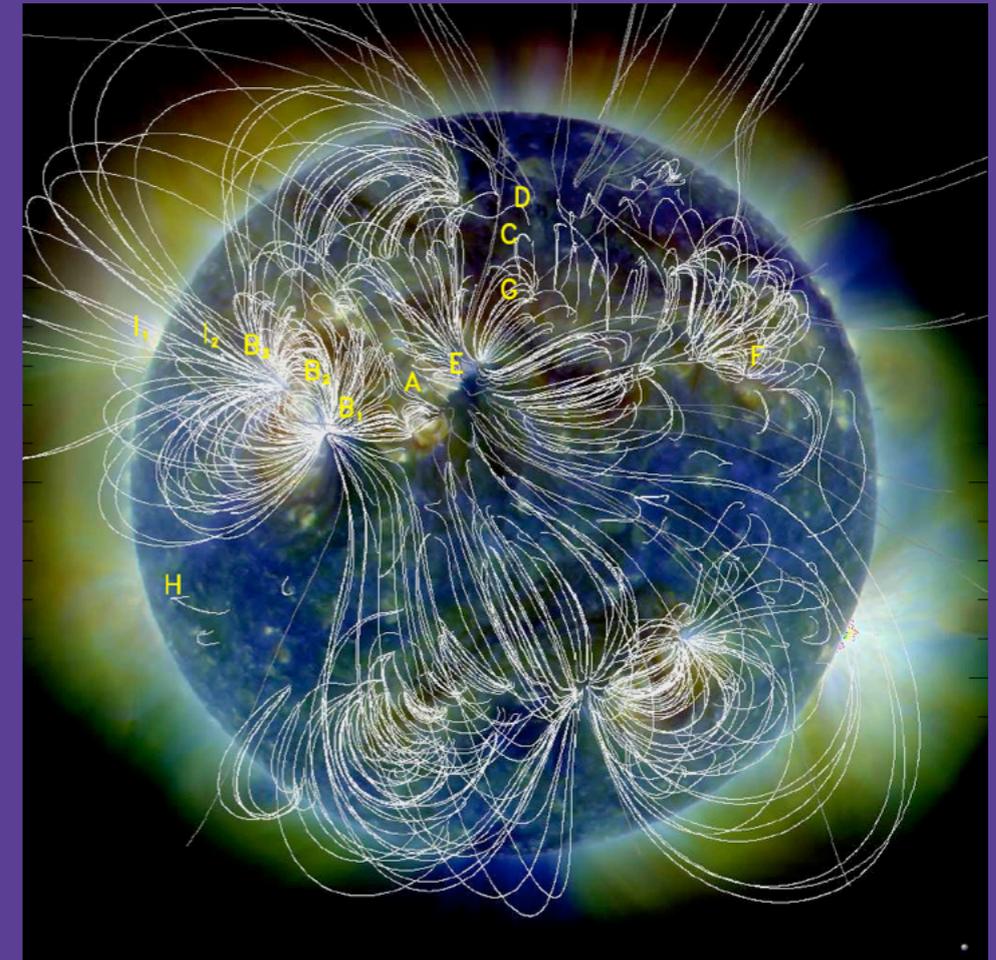
sympathetic eruptions on 25 December 2011
(courtesy of C. Schrijver)

- Near-simultaneous eruptions from different source regions
- Statistical studies indicate that such eruptions are sometimes **causally linked**
- Various linking mechanisms were suggested (waves, magnetic reconnection, surges, sub-surface connection...), but **no model** has been developed

The eruptions on 1-2 August 2010



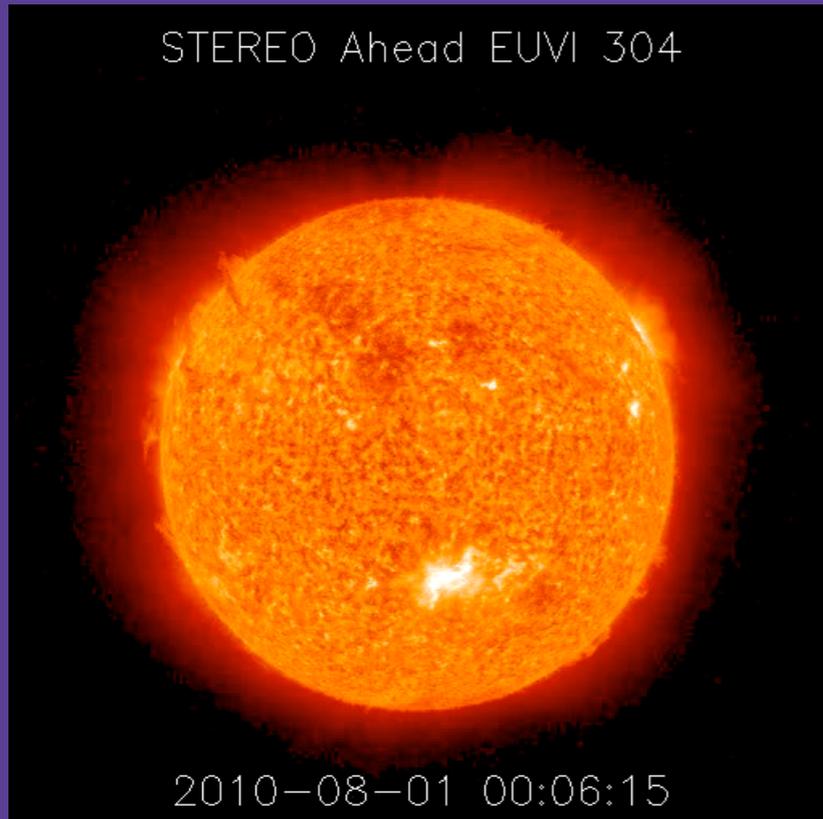
SDO/AIA 171+193+211 Å
Schrijver et al. (2013)



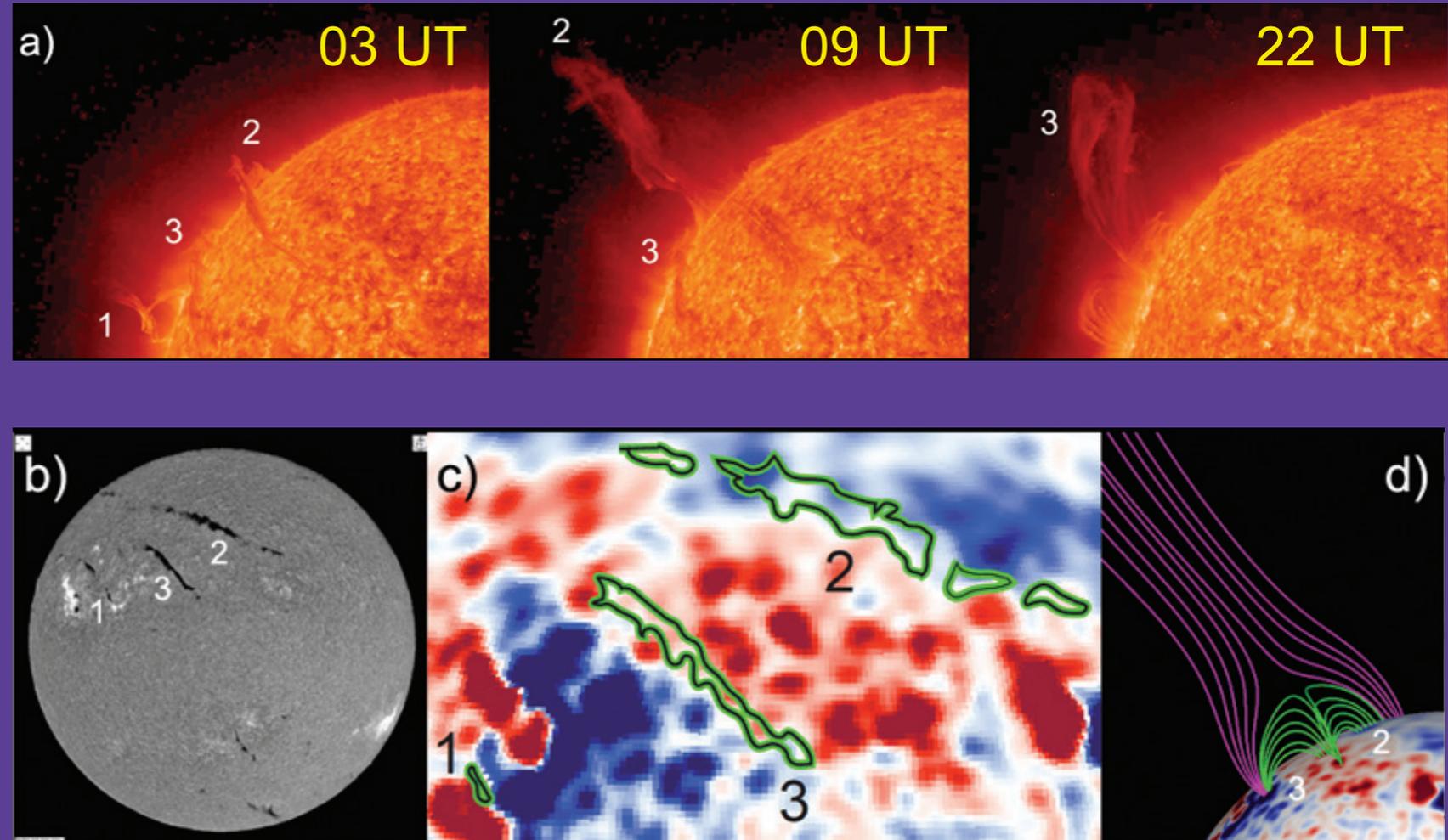
Schrijver & Title (2011)

- Global event; half a dozen individual eruptions involved
- All source regions appear to be magnetically connected

Modeling: subset of three eruptions

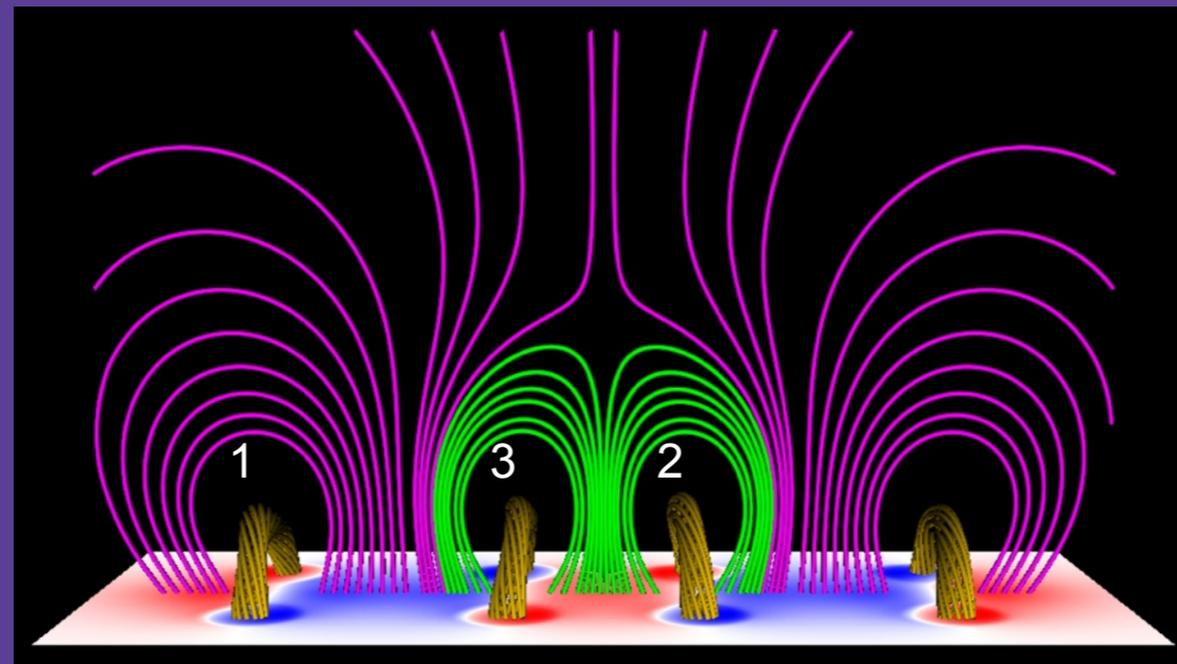
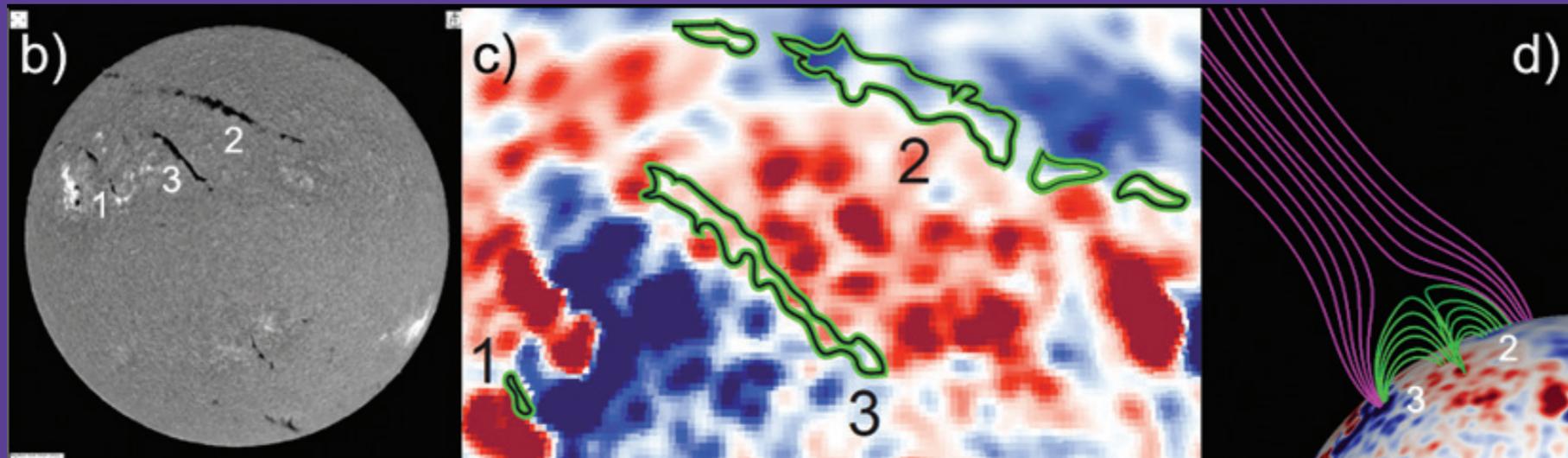


STEREO Ahead 304 Å



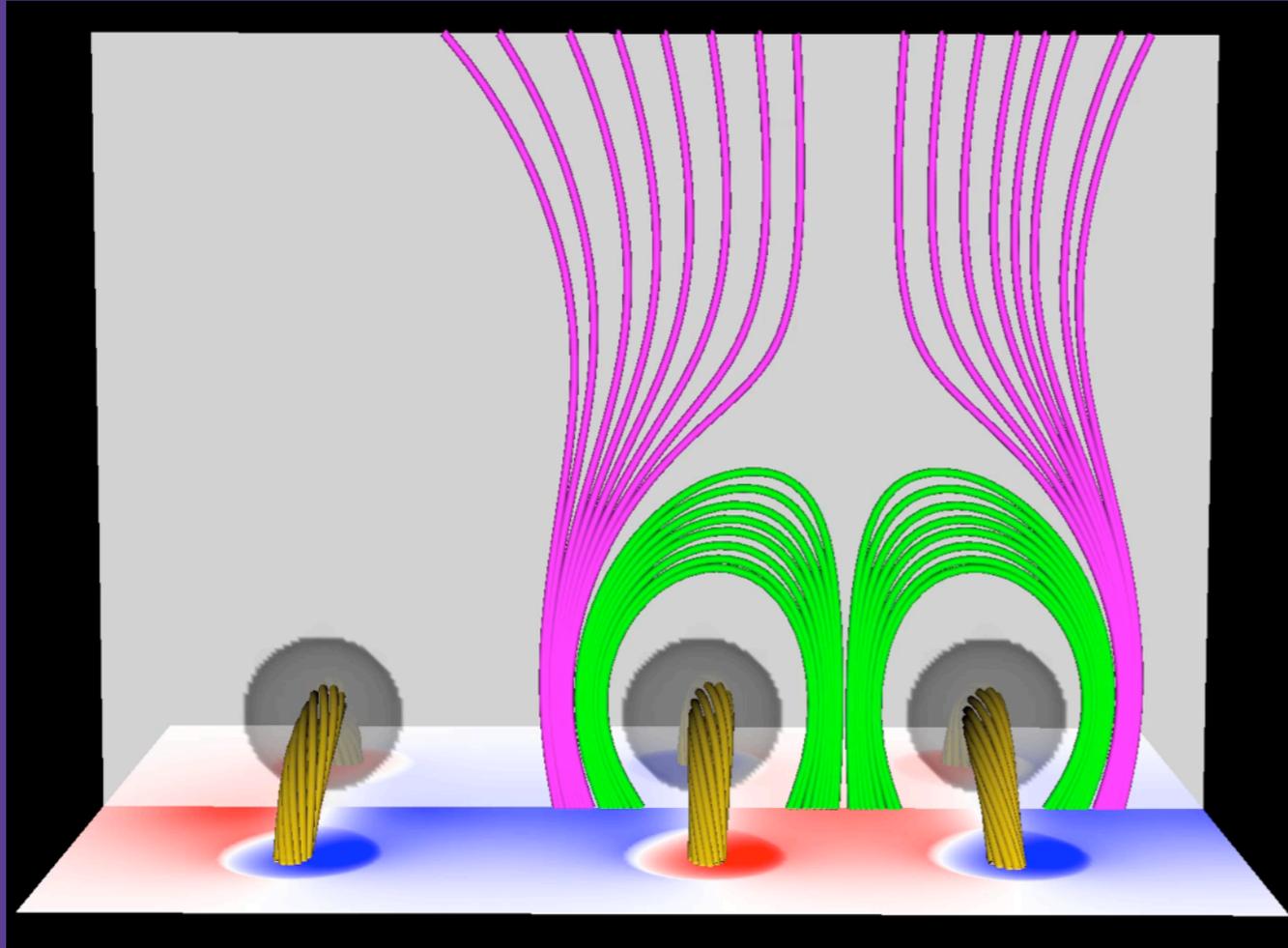
- Eruption sequence apparently triggered by eruption of filament 1
- Note: filament further away from 1 erupts first !
- Before eruptions: large filaments 2 and 3 located in pseudo-streamer

Numerical setup



- Idealized model: two TD flux ropes in pseudostreamer & two ropes next to it
- Ignore details like field asymmetries & different size of filaments
- $\beta = 0$ approximation & ideal MHD equations (reconnection due to num. diffusion)

Simulation results

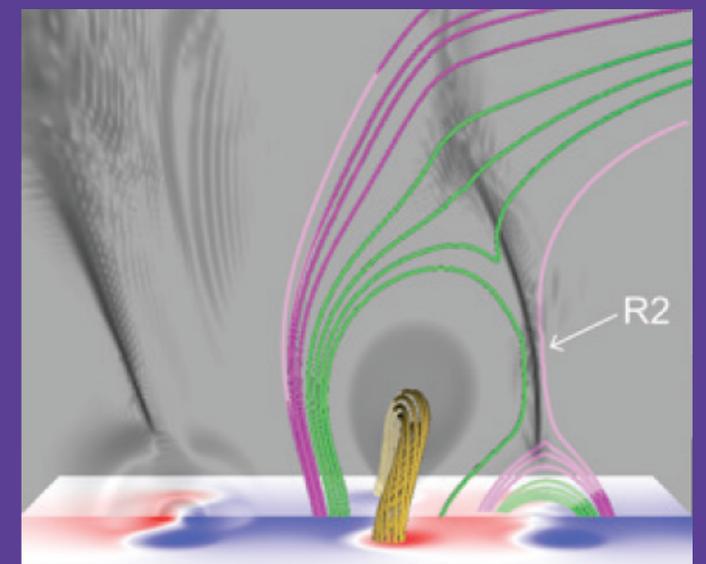
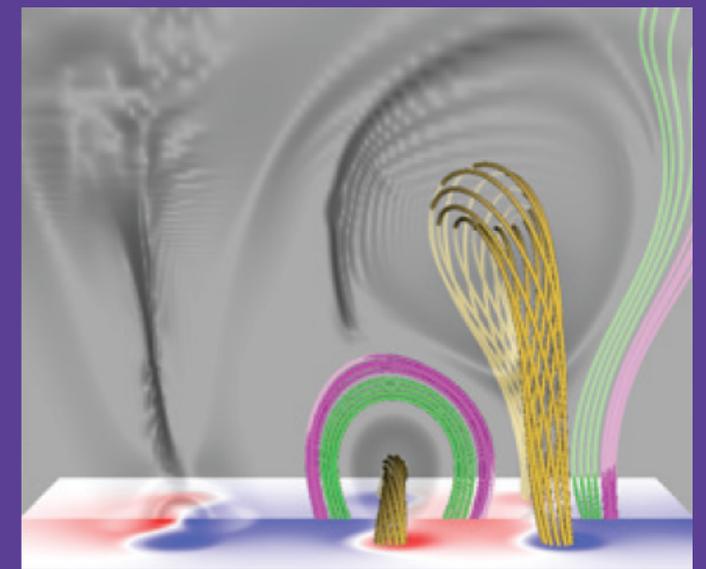
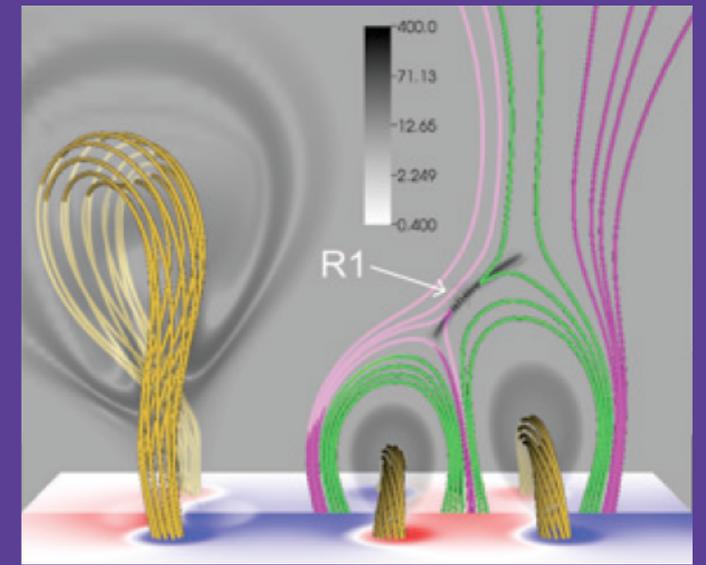


Török et al. (2011)

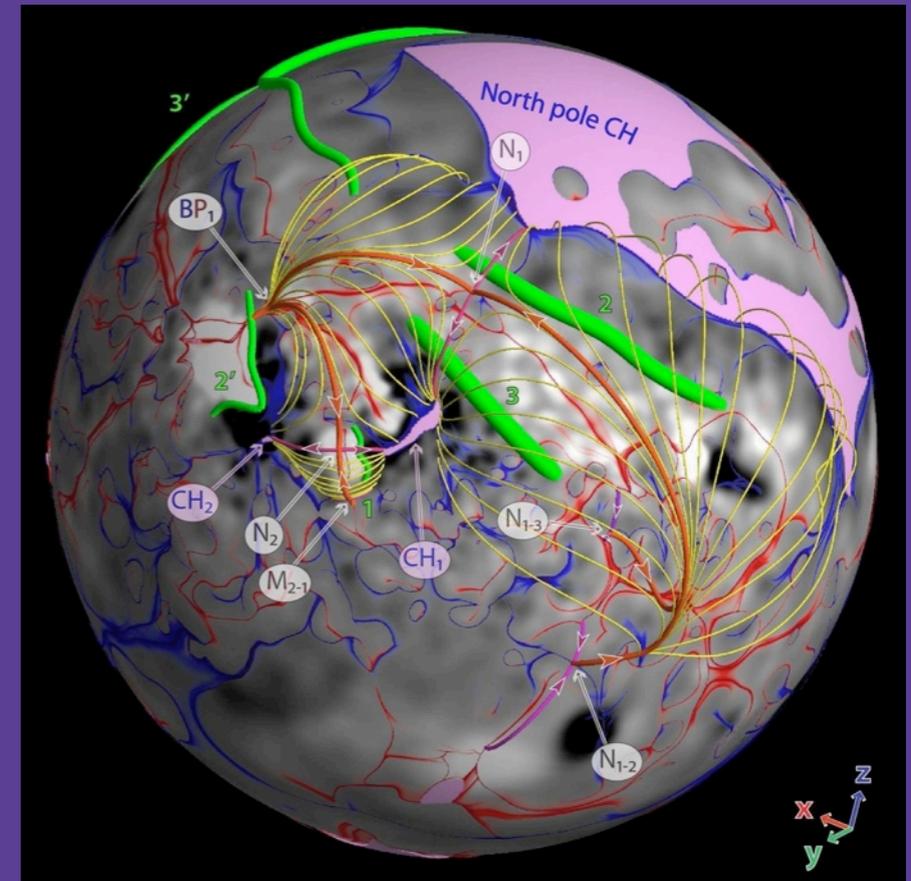
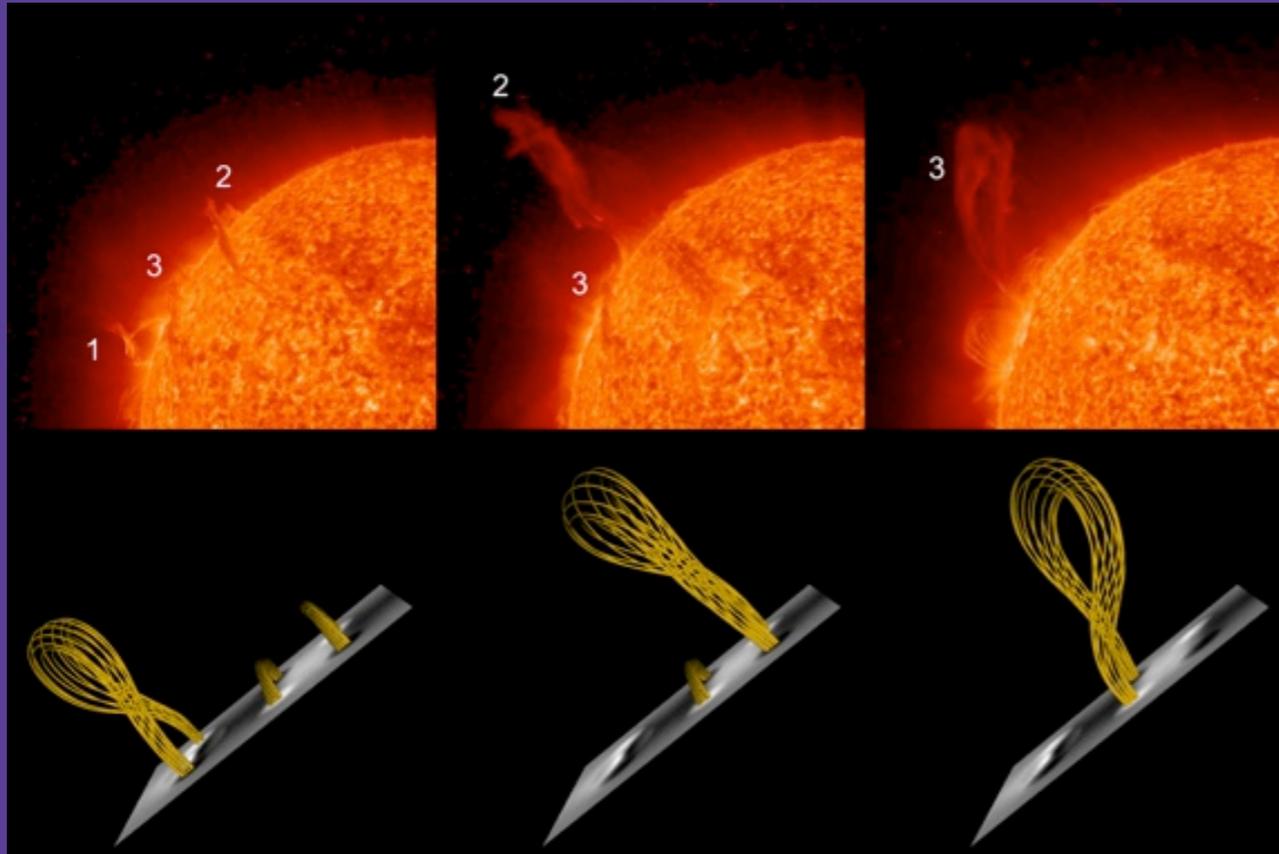
- Initiate eruption of flux rope 1 by converging flows (ad-hoc)
- Eruption leads to two consecutive reconnection events, each of which triggers a new eruption

R1: “breakout” reconnection at pseudostreamer separator

R2: “flare” reconnection in the wake of erupting FR 2



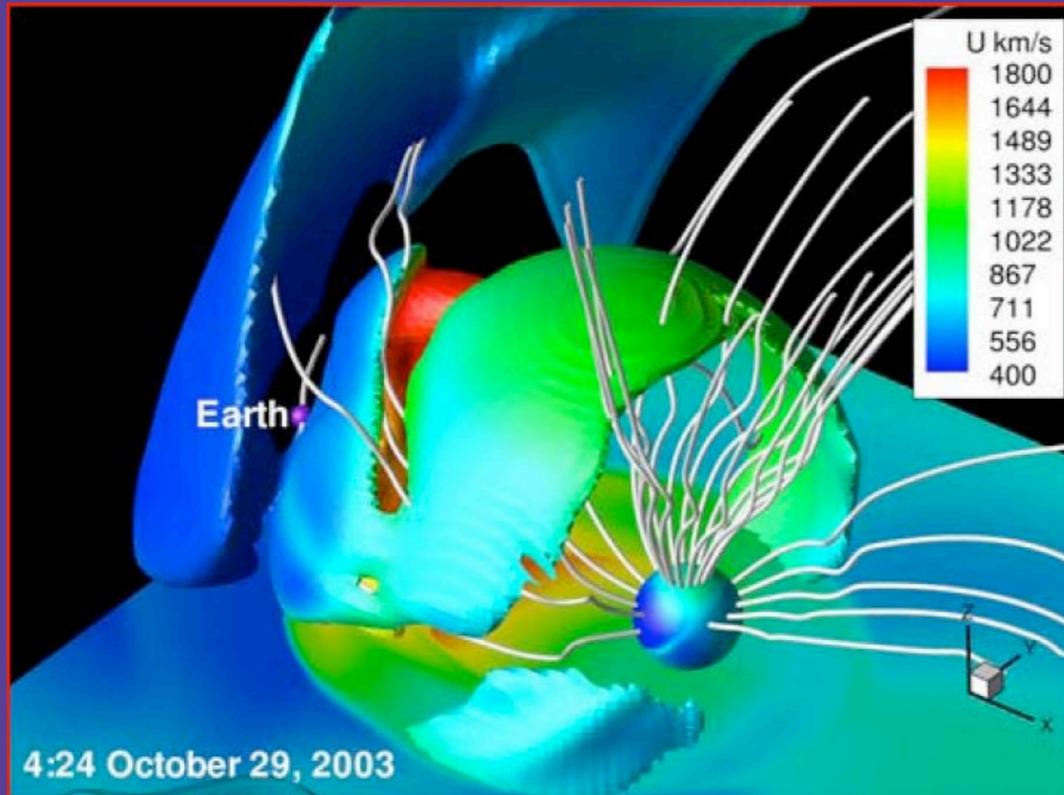
Validity of idealized model



Titov et al. (2012)

- Model: – suggests how one eruption can trigger subsequent eruptions
– reproduces correct order of eruptions
- However: **difficult to confirm** whether this happened in the real event
- Further support from data-based analysis of coronal **magnetic topology**
- More detailed, data-based simulations are needed

State-of-the-art: global & “thermodynamic” simulations



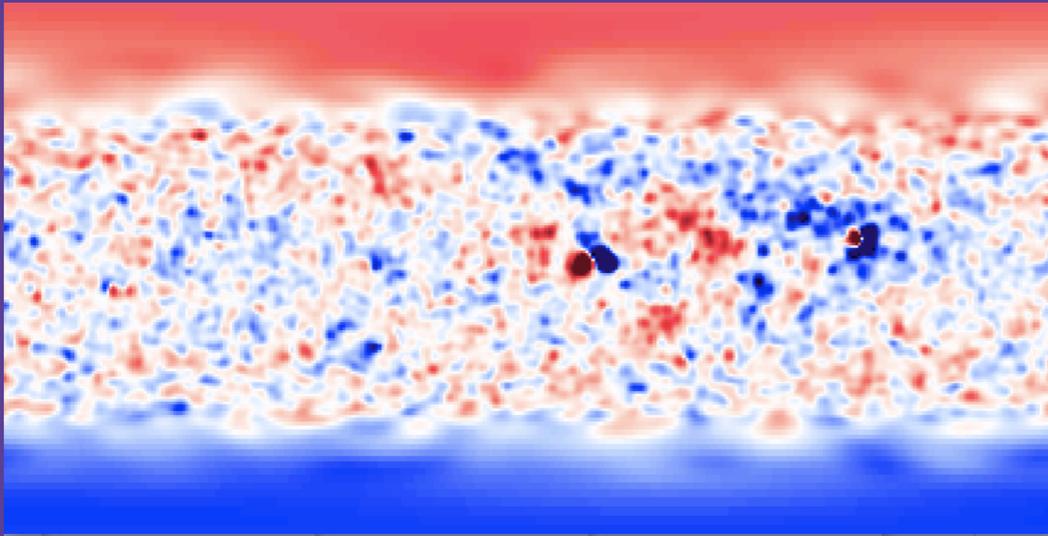
Tóth et al. (2007)



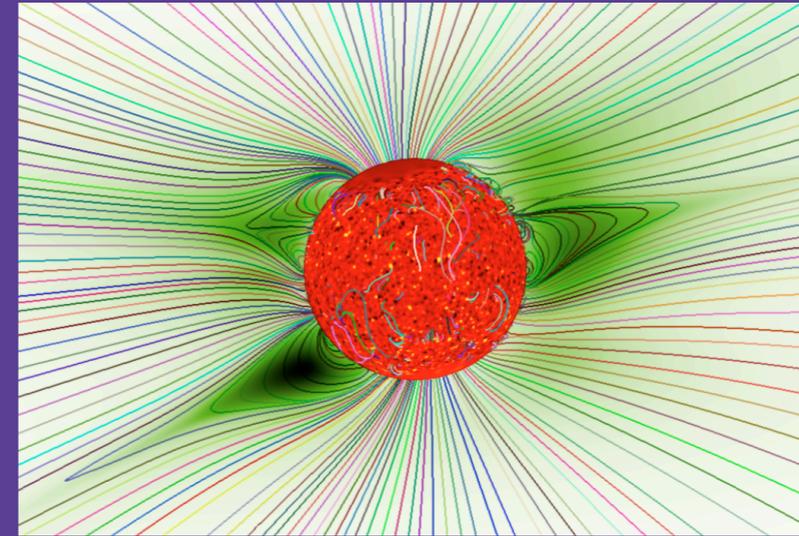
Mok et al. (2008, 2011)

- Idealized models computationally **inexpensive** → study & test basic physical mechanisms
- State-of-the-art models aim for **more realism** by using:
 - **large spherical domains** to model extended corona & solar wind
 - observed **photospheric magnetic fields** as boundary condition
 - **improved energy transport**: coronal heating, thermal conduction, radiation losses

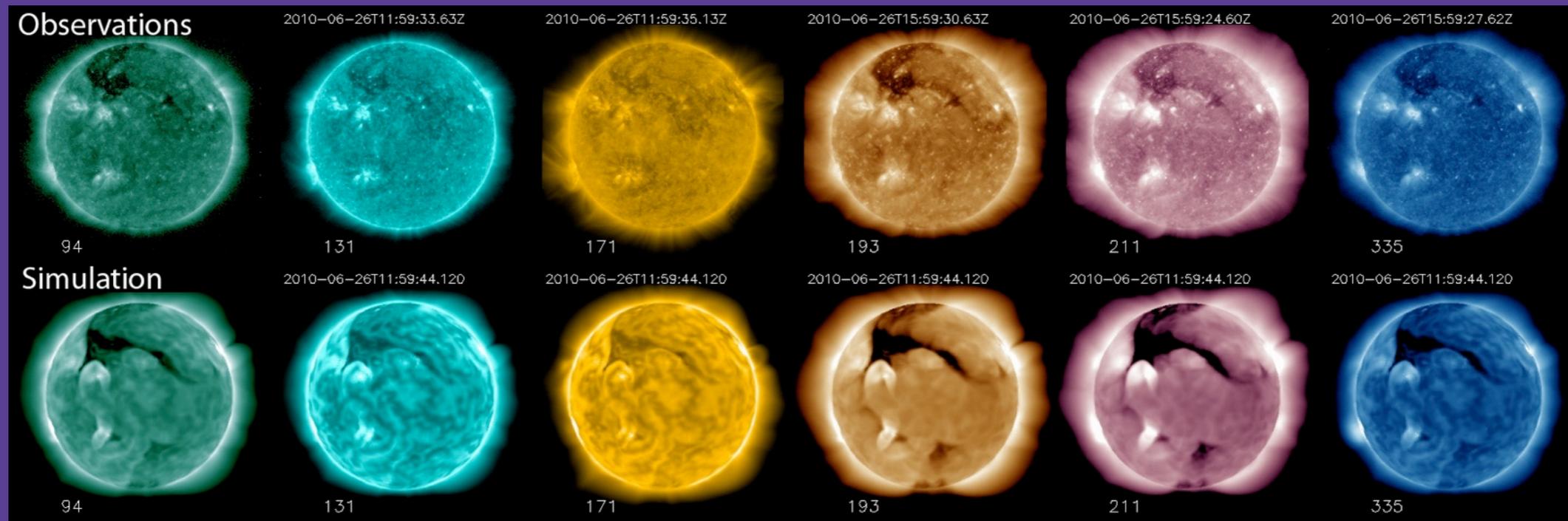
Thermodynamic modeling of the corona



synoptic (full-Sun) magnetogram

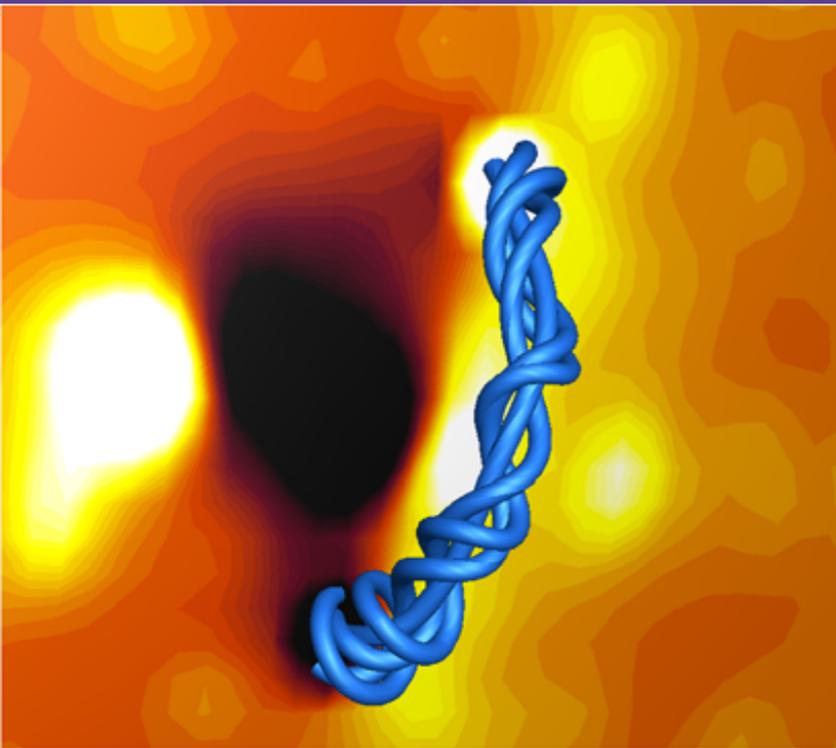


relaxed (partially open) coronal field

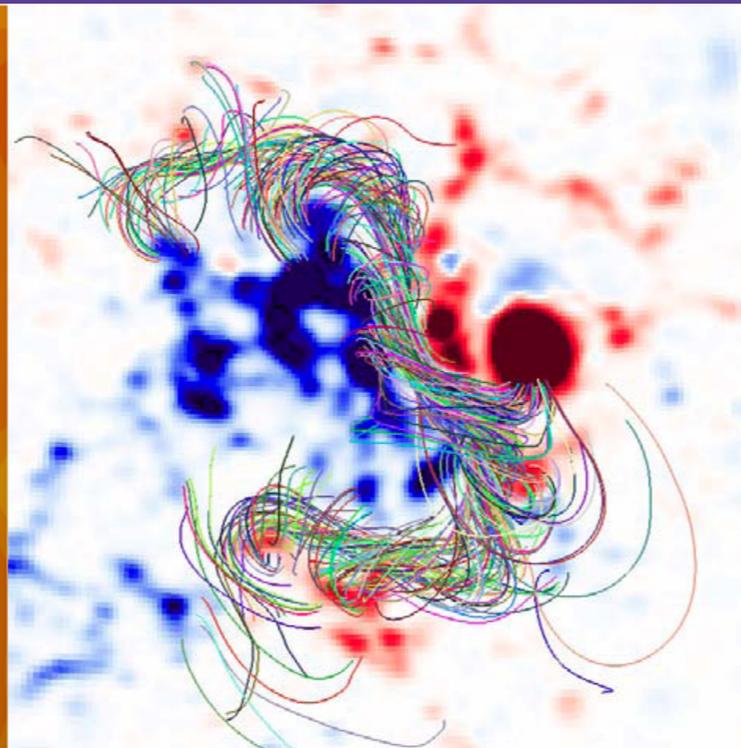


1. Extrapolate initial magnetic field from **synoptic** (1 month) photospheric **magnetogram**
2. Run thermodynamic simulation until **steady-state** (including solar wind) is reached
3. Produce **synthetic satellite images** (allows direct comparison to observations)

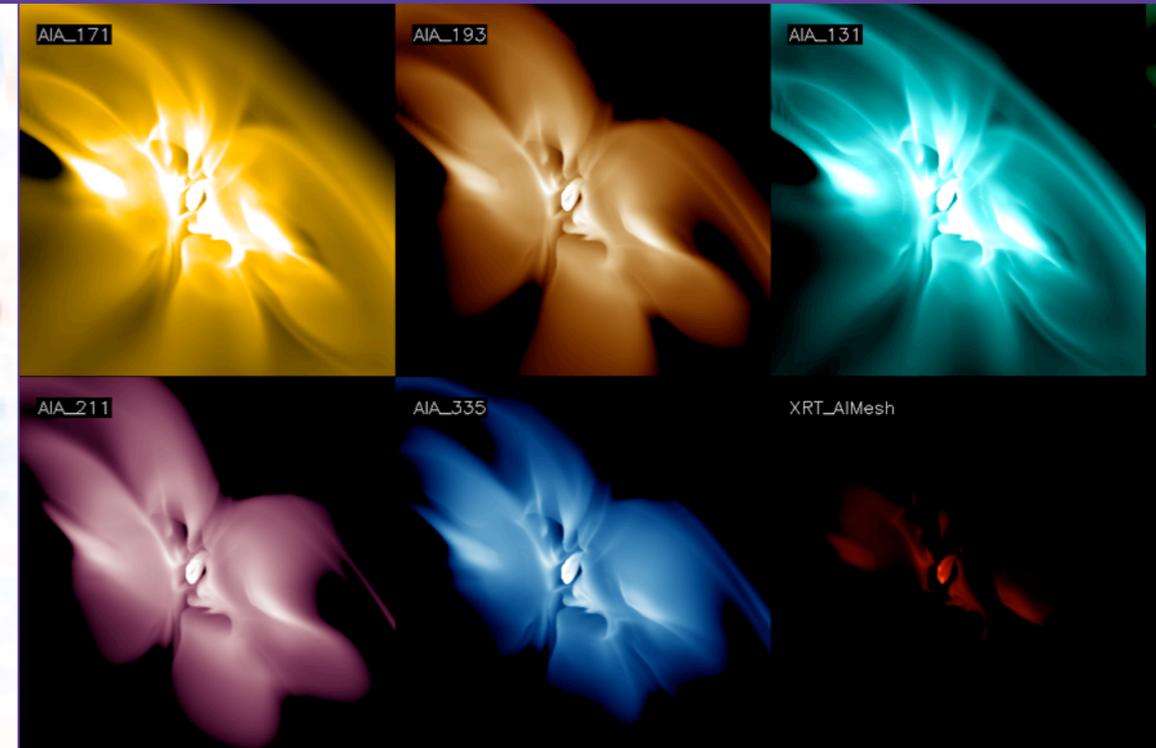
Thermodynamic CME simulations



TD flux rope (out of equilibrium)
Lugaz et al. (2011)



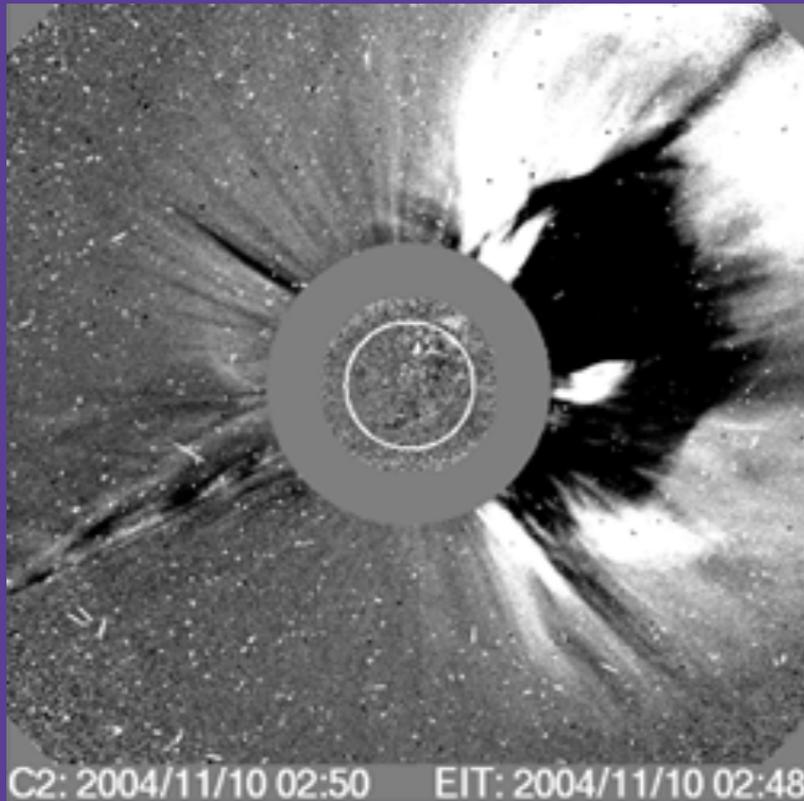
Stable flux rope 13 May 2005
PSI simulation



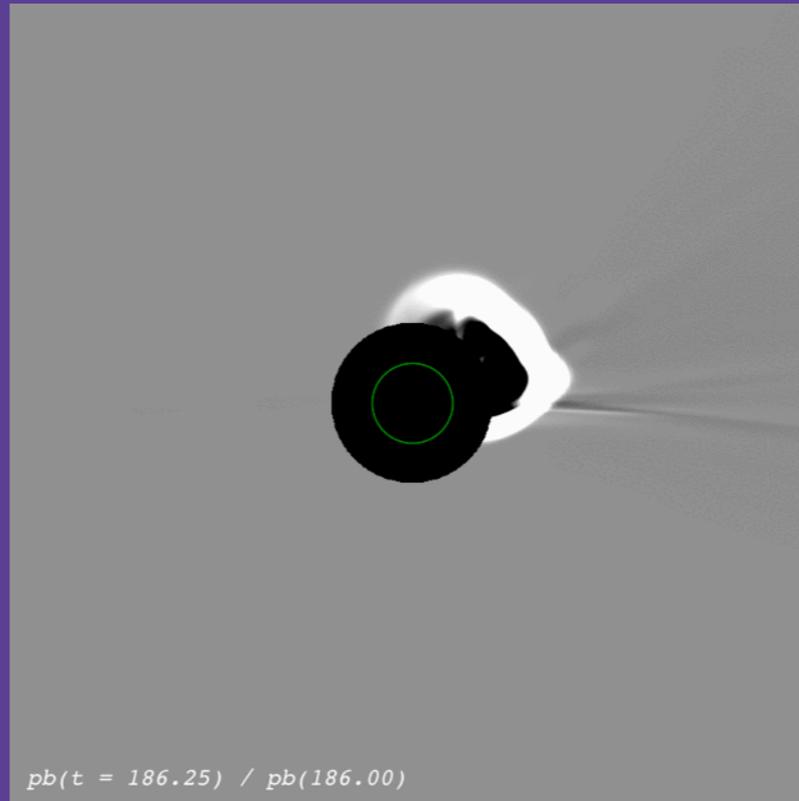
Synthetic SDO/AIA images
(idealized eruption)

- Energize eruption source region:
 - insert stable or unstable analytical flux rope
 - impose boundary evolution to create flux rope
- Trigger eruption by, e.g., converging flows toward source region neutral line

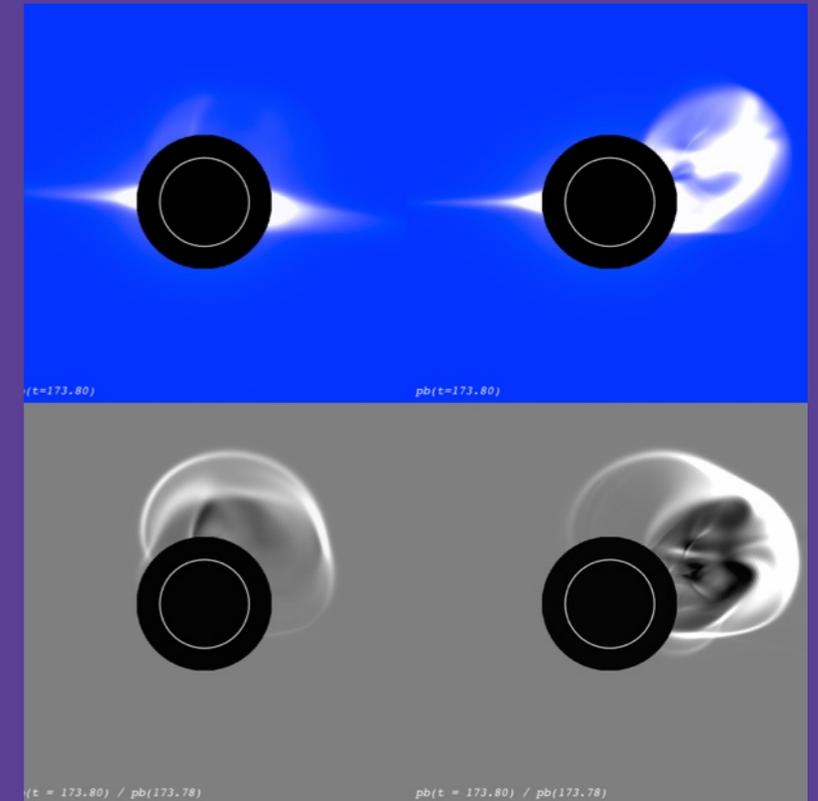
Comparison with white-light CME observations



CME observed by LASCO
(running ratio images)



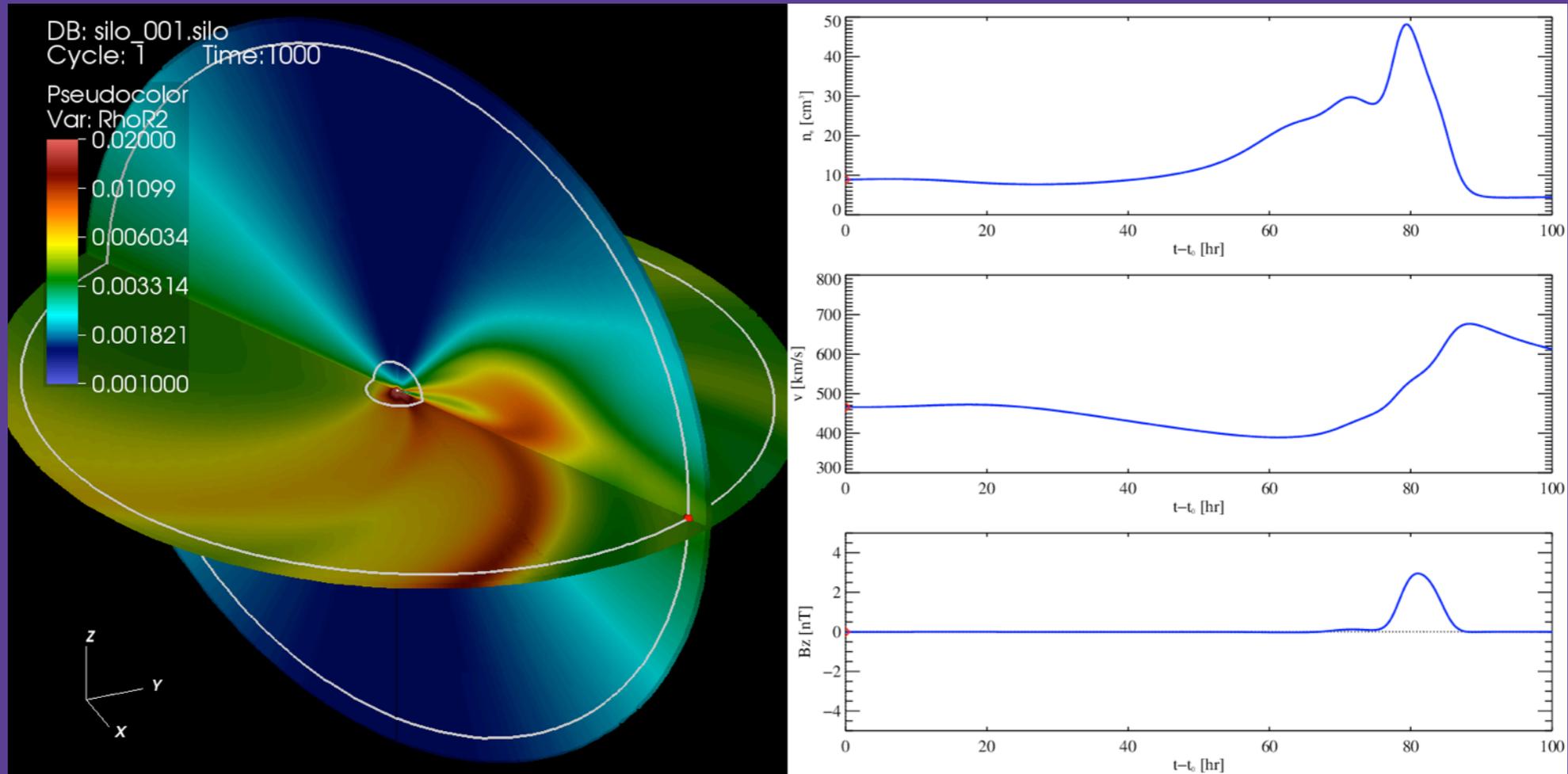
synthetic images from simulation



different viewing angles

- Compare synthetic polarization brightness images to observations
- Result depends strongly on viewing angle
- Important for estimations of CME mass & kinetic energy

Interplanetary CME propagation

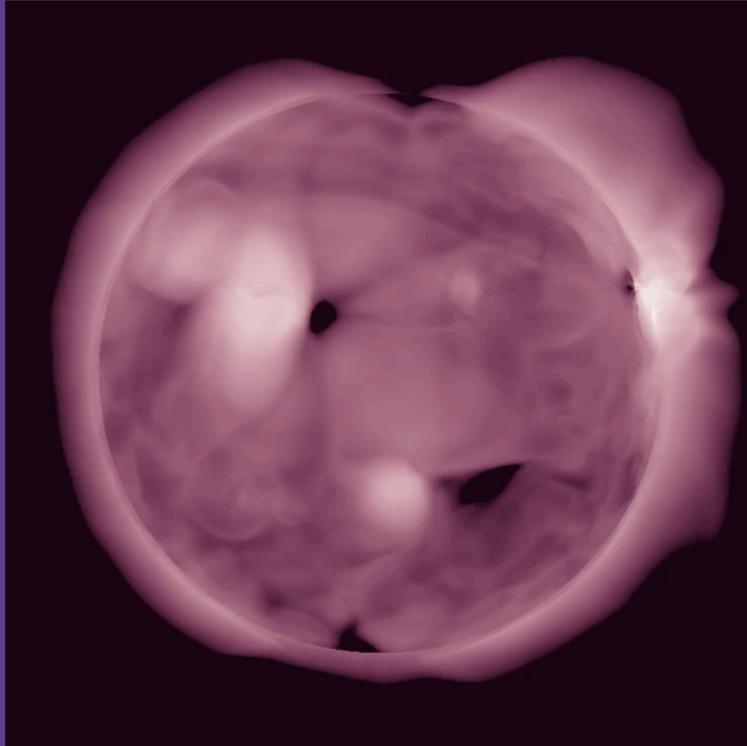


coupled CME simulation from Sun to Earth
Lionello et al., submitted

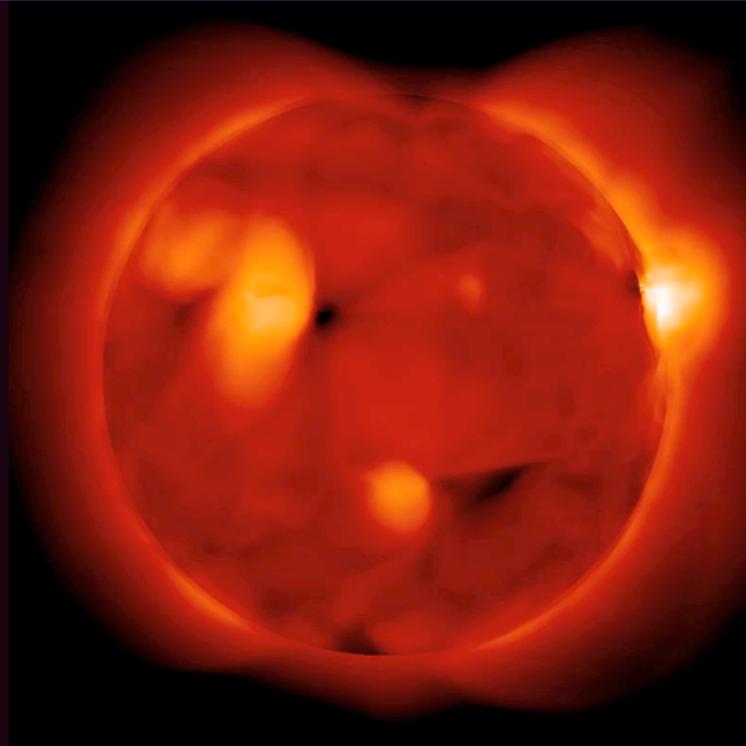
- Thermodynamic simulations are computationally very expensive
- Couple with heliospheric codes that use reduced set of equations
 - model CME propagation to Earth (and beyond)
 - produce synthetic in-situ measurements at 1 AU

Modeling observed eruptions

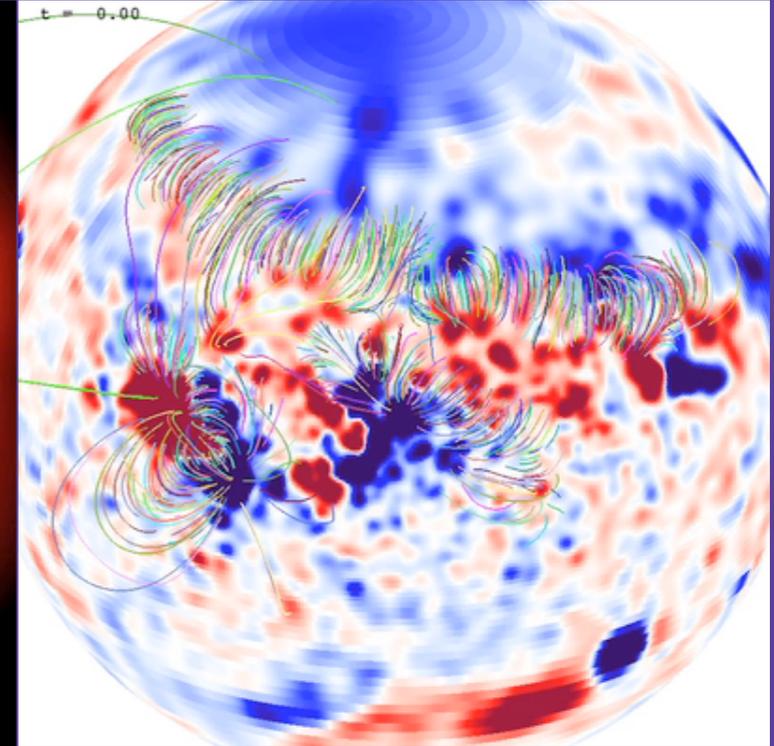
1-2 August 2010



AIA 211

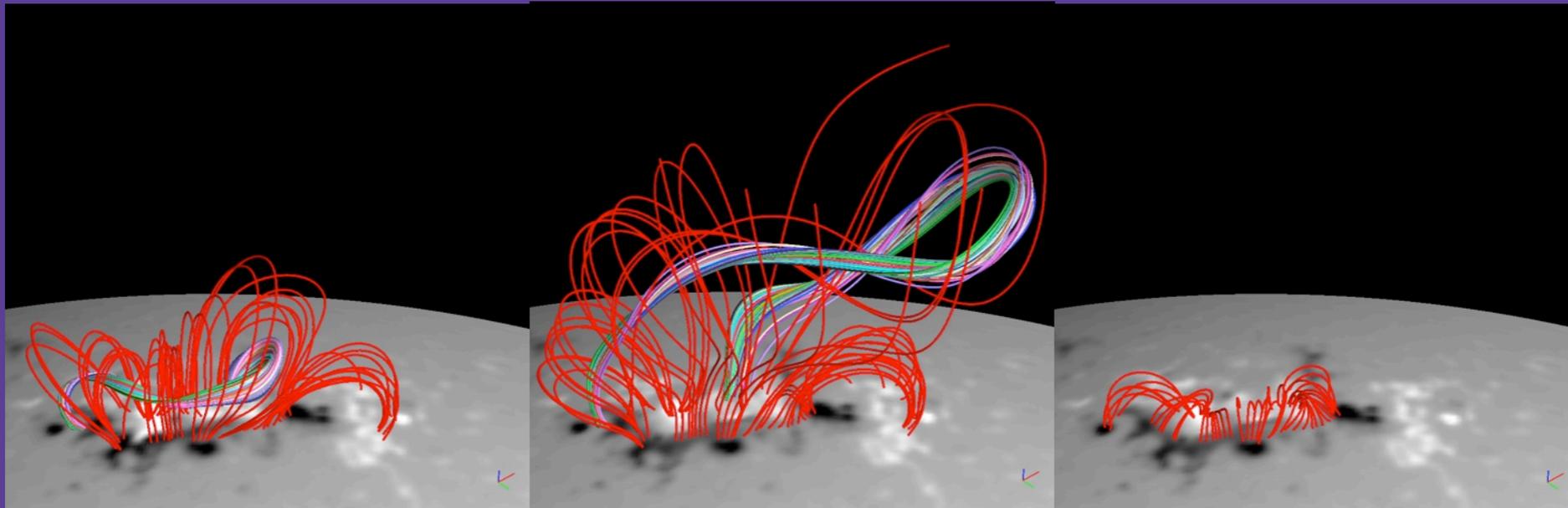


XRT Ti-poly



$\beta = 0$

14 July 2000 (Bastille Day event)

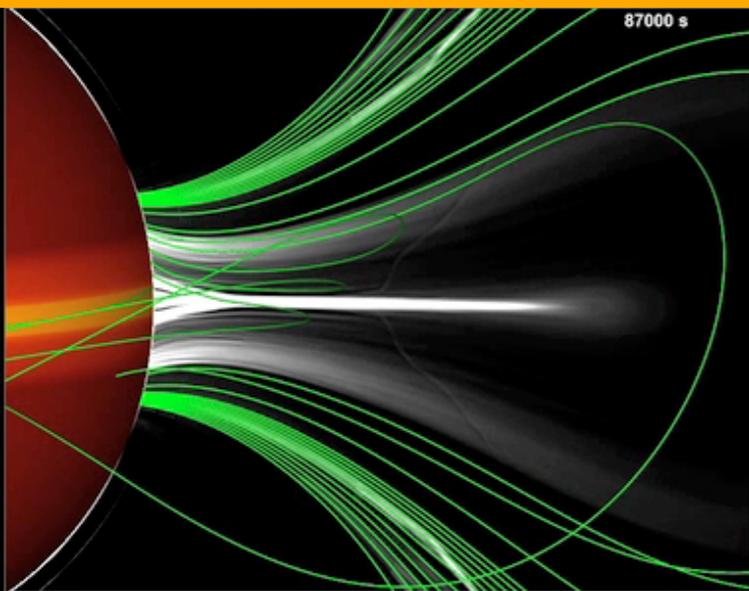


$\beta = 0$

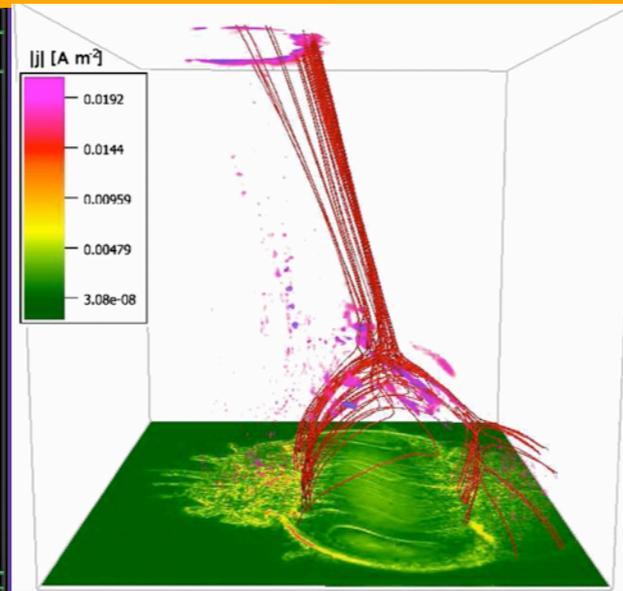
Summary

- **Idealized simulations** improve our understanding of physical mechanisms at work in solar eruptions → e.g initiation & driving of eruptions and coupling between eruptions
- **Global simulations** using real data & improved coronal plasma descriptions emerging → deeper insight & semi-realistic modeling of observed eruptions
- **Coupling of coronal & heliospheric models** will allow us soon to simulate observed events from Sun to Earth → important for understanding and predicting space weather
- Still, it will be many(?) years before we have models that:
 - resolve the enormous range of length scales present in solar eruptions
 - solve the complete set of plasma equations
 - use boundary & initial conditions that match reality

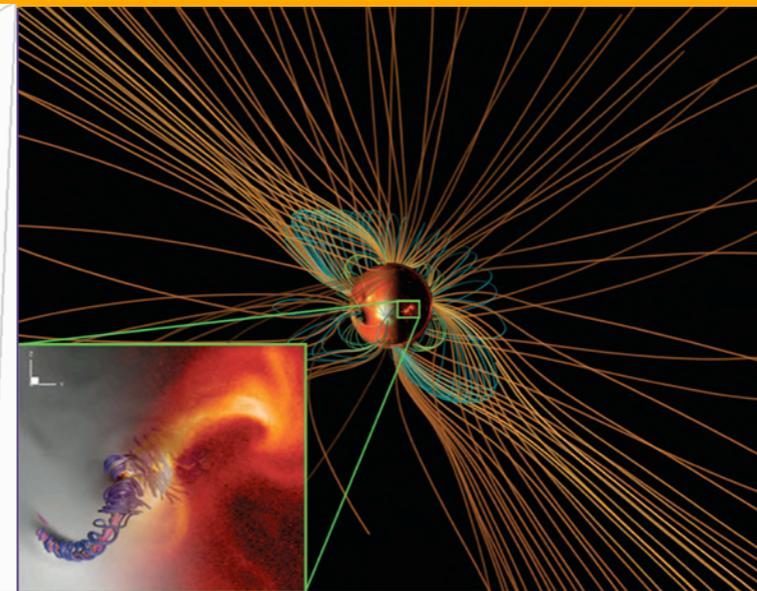
Outlook (some current & next steps)



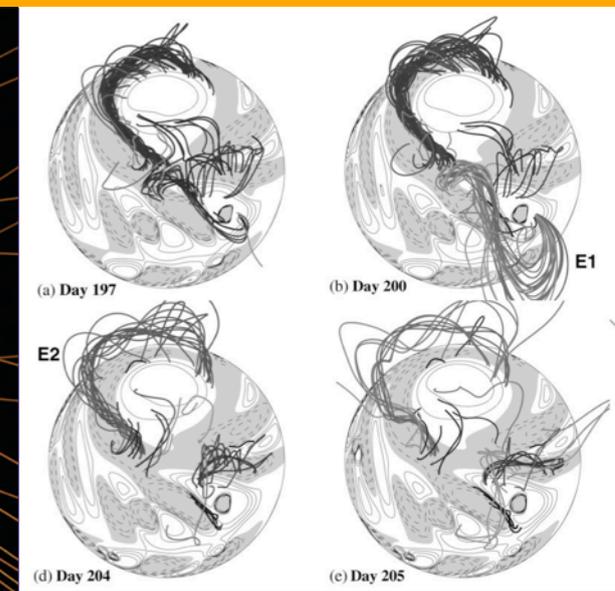
Karpen et al. (2012)



Baumann & Nordlund (2012)



Roussev et al. (2012)



Yeates & Mackay (2009)

- Adaptive mesh refinement → improve modeling of reconnection, shocks, etc.
- Couple MHD and PIC (kinetic) codes → modeling of particle acceleration
- Couple FE or NLFFF & CME models → more realistic pre-eruption configurations
- Develop evolutionary MHD models → overcome present “static” modeling of corona
→ simulate CMEs in real time

Many thanks to AAS/SPD

Thank you for your attention

