Science of Coronal Mass Ejections (CME)

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1. Observations
   - Physical properties
   - Quantitative properties
2. Underlying Physics
3. Theories/Models

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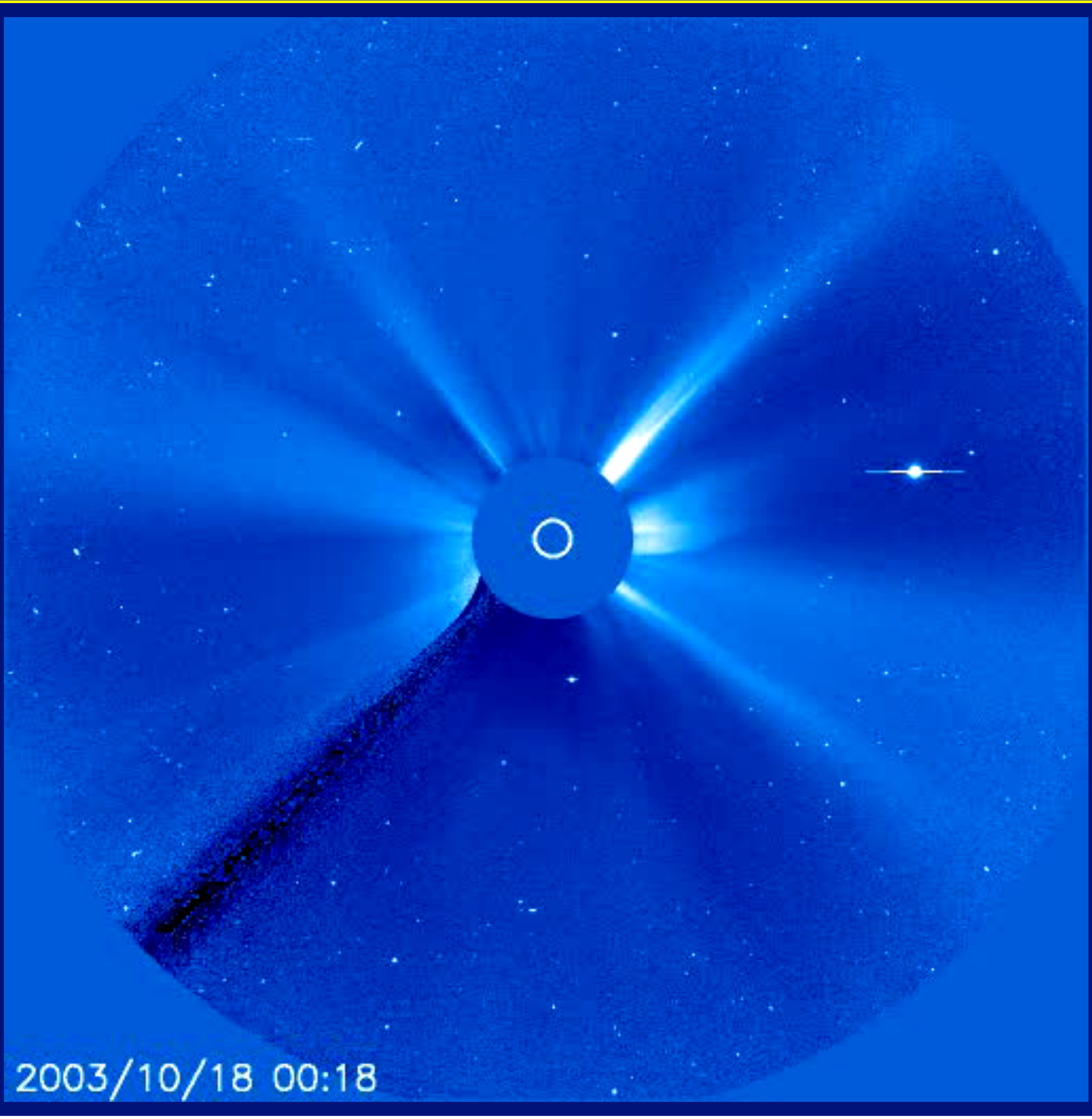
- Rules of the Seminar Road
  – Do Tailgate!
  – Do Backseat Drive!

LASCO C3 Observations of Outer Corona

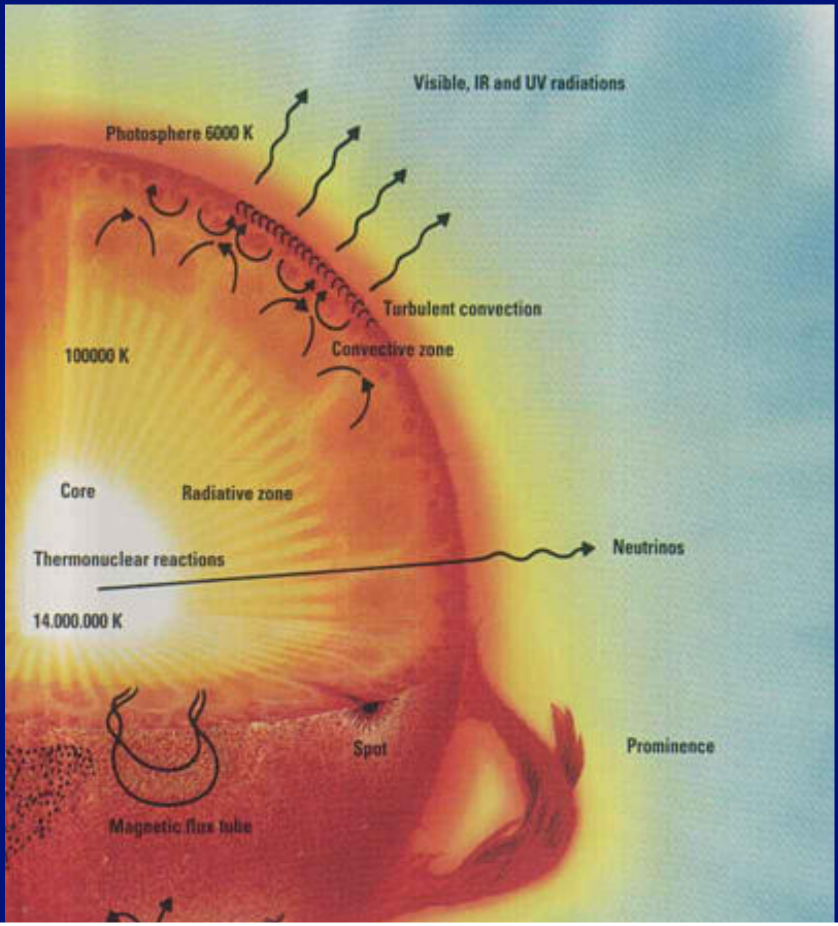


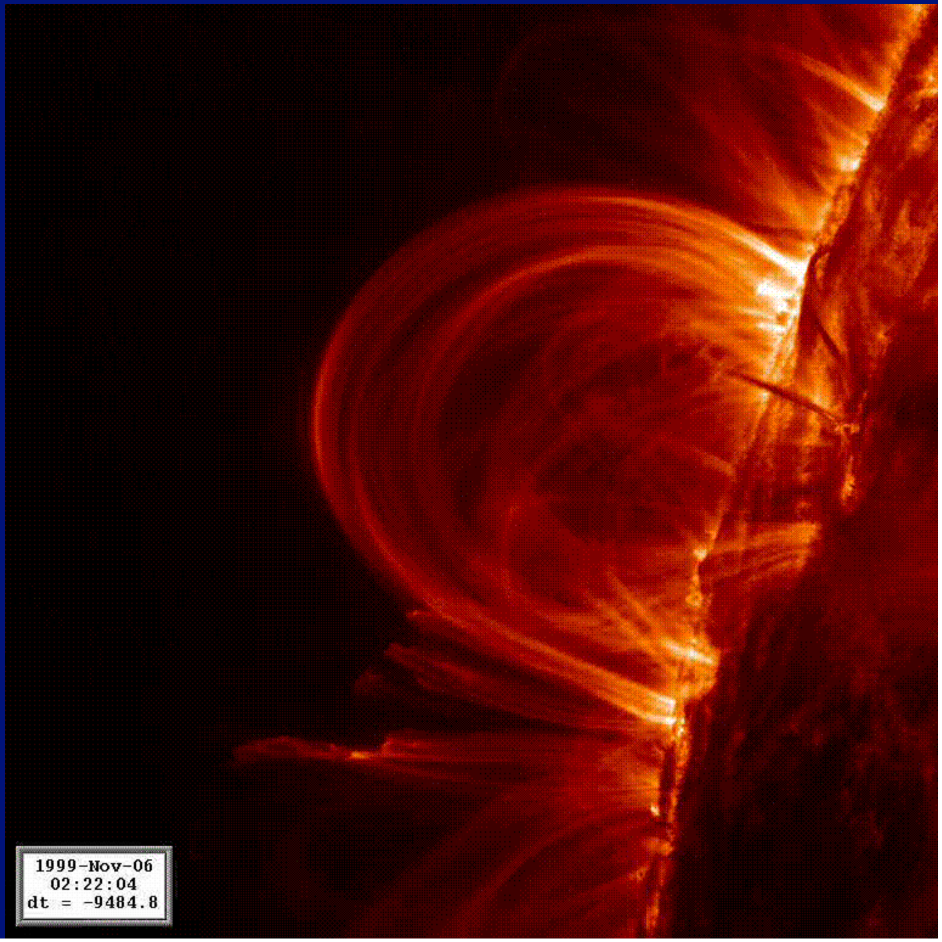
LASCO C3 Observations of Outer Corona

- Coronagraph: 5 – 30 R_s FOV, Cadence ~ 1 hour
- Thomson scattering of photospheric white light
  - $I \sim \int n_e \, dl$
- Observe solar wind structures
  - V ~ 400 km/s
- ~ 3 CMEs/day
  - Some with V > 1,000 km/s
  - $C_s \sim 10^{4.2} T^{1/2} \sim 100$km/s
  - $V_A \sim 10^{11.3} B n^{-1/2} \sim 100$km/s
  - Therefore, must have Interplanetary shock
  - Produces intense Solar Energetic Particle bursts
- Need to see coronal origins

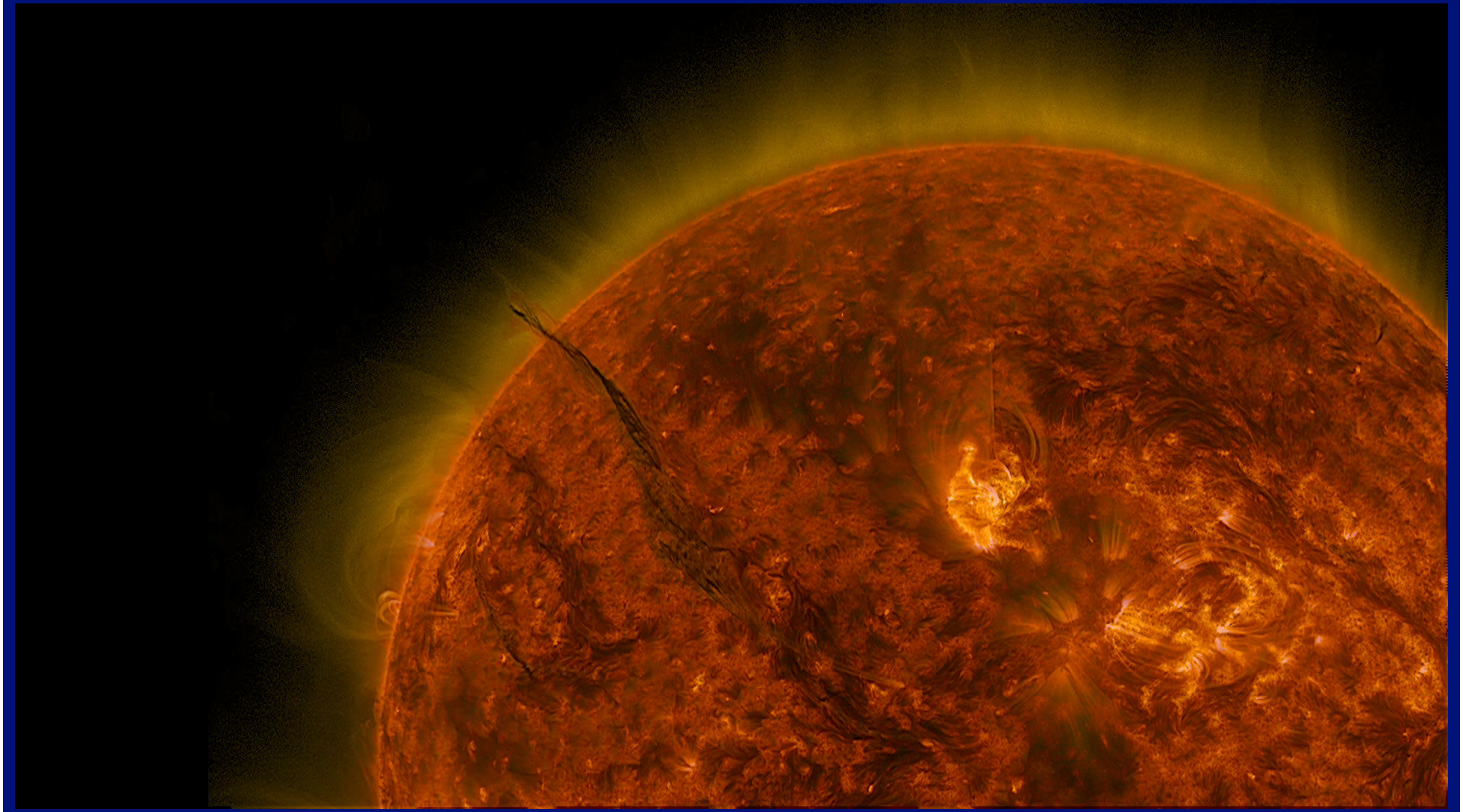
Origins of All Solar Activity

- B-field lines act ~ as material lines, $\tau \sim L^2/\eta >> 10^6$ years
- Couples corona to slow ($<< V_A$) photosphere flows
  - Provides both free energy and topological complexity
  - Drives both large and small events





Solar Origins of CMEs



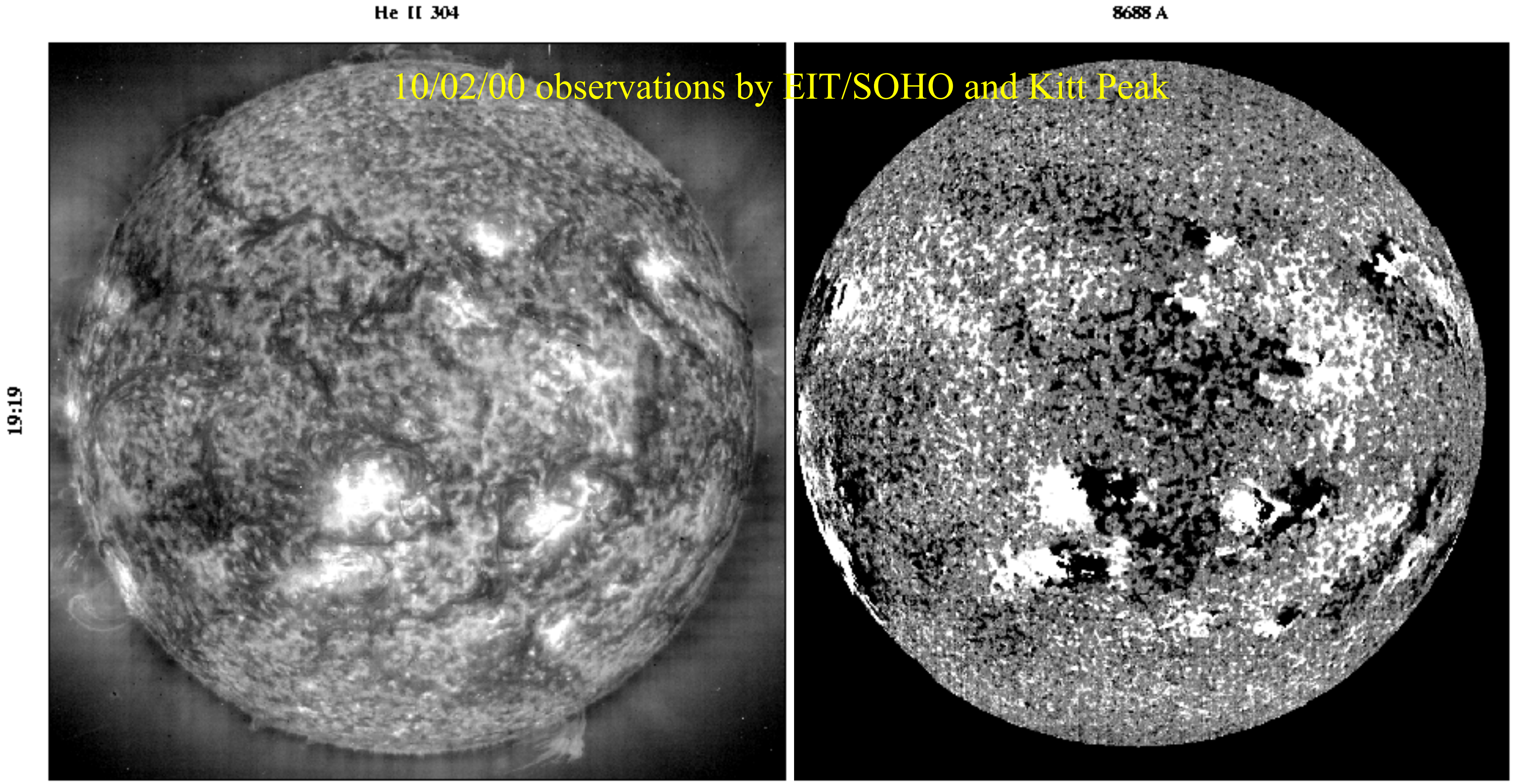
- SDO HE 304, ~ 80,000 K + LASCO C3
- Dark implies cool and dense – prominence/filament

Filament Ejection and Flare

Solar Origins of CMEs

- TRACE (EUV telescope) observations of 06/16/2005 event
  - Observe Fe XIX 171A line formed at T ~ 1.0 MK
  - Very high cadence < 1 m, and resolution ~ 700 km
- Cool (< .01 MK) dense prominence/filament lying below coronal loops (seen in absorption)
  - Loop height ~ 50 Mm, filament height < 5 Mm
  - But note, grav. scale height $H_g \sim 10^{3.7}$ T cm
  - Loop plasma supported by its internal pressure, but prominence plasma must be supported by magnetic field
- Coronal loops open and reform during ejection
- **All CMEs/flares associated with filament magnetic structure**

Filament Properties



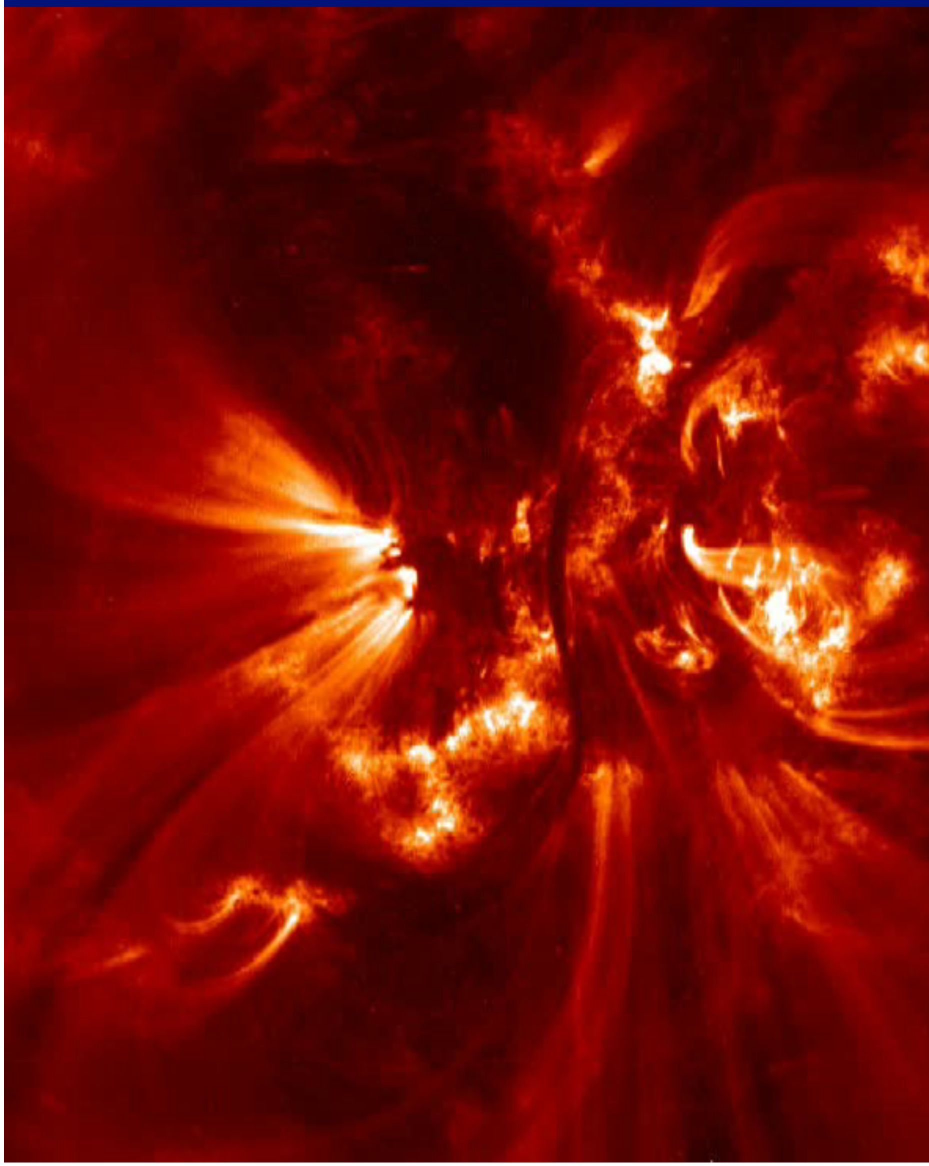
10/02/00 observations by EIT/SOHO and Kitt Peak

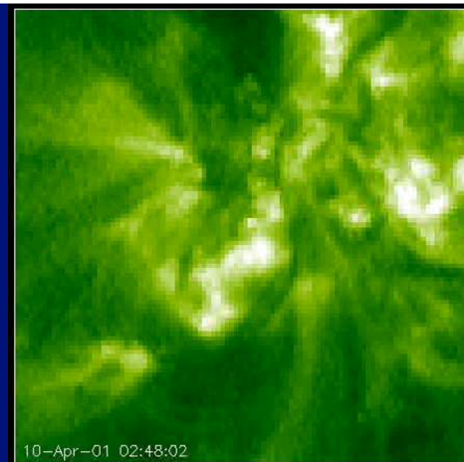
- Always lie above photospheric polarity inversion line
- Fairly common, ~ 50 % coverage, both active & quiet
- Origin is one of the outstanding problems in solar physics

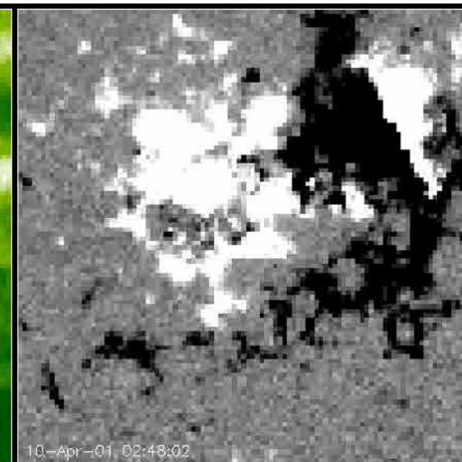
Recap of CME Properties

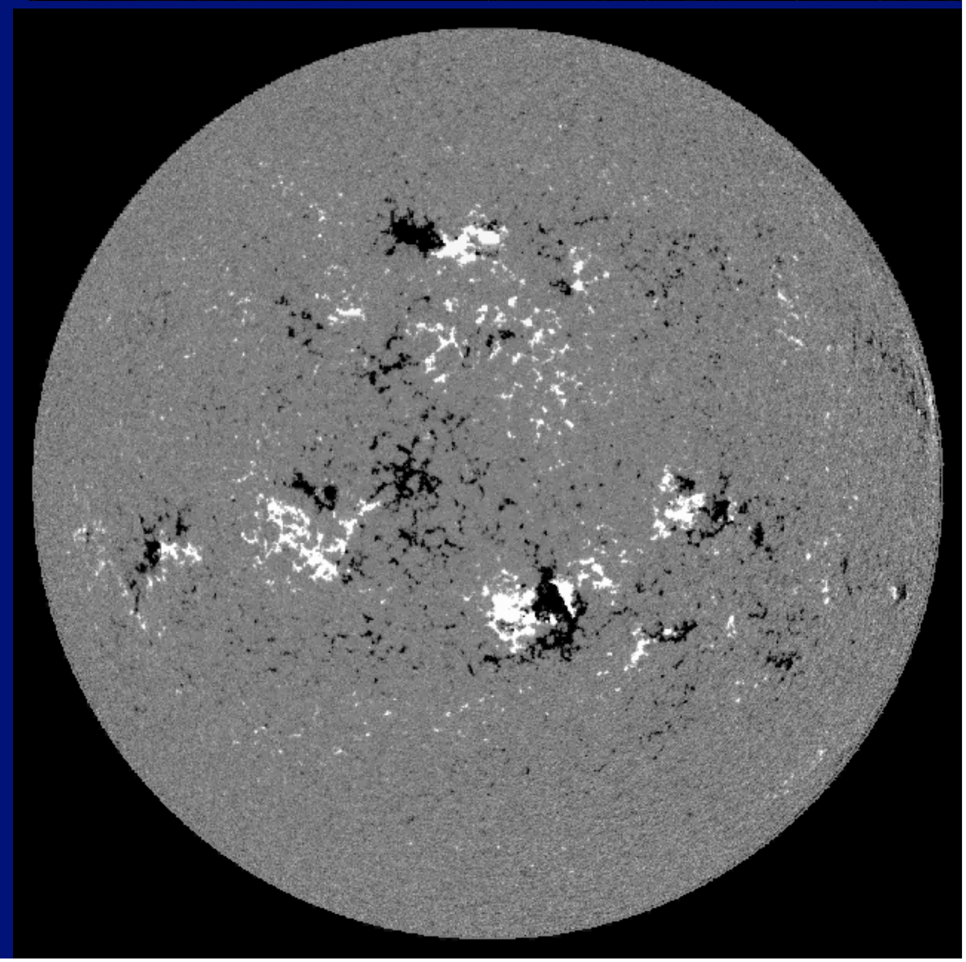
- "Typical" event consists of 3 components:
  - Ejection of filament/prominence field and mass
  - Ejection of coronal magnetic field and mass
  - Heating of > 10MK flare coronal loops and acceleration of flare particles
- Strength of each component can vary between events, but all are present to some degree
  - How are they related?
- What is role of photosphere?

Role of Photosphere









Role of Photosphere

- Filament overlies polarity inversion line (PIL) – low lying
- Filament field strongly non-potential (large free energy)
  - **Only place in corona where field observed to have high stress!**
- Photospheric B-field does not evolve during eruption
- Energy buildup slow compared to eruption – 1 km/s

CME Quantitative Properties

- For large event: M ~ 10^{16} gm, V ~ 1,000 km
  - E ~ 10^{32} ergs, t ~ 10^{3} s, Power ~ 10^{29} ergs/s
  - L ~ 10^{10} cm, W ~ 10^{9} cm, F ~ 10^{10} ergs/cm^2/s
  - note that F ~ 10^{3} active region heating – also much larger than chromospheric heating

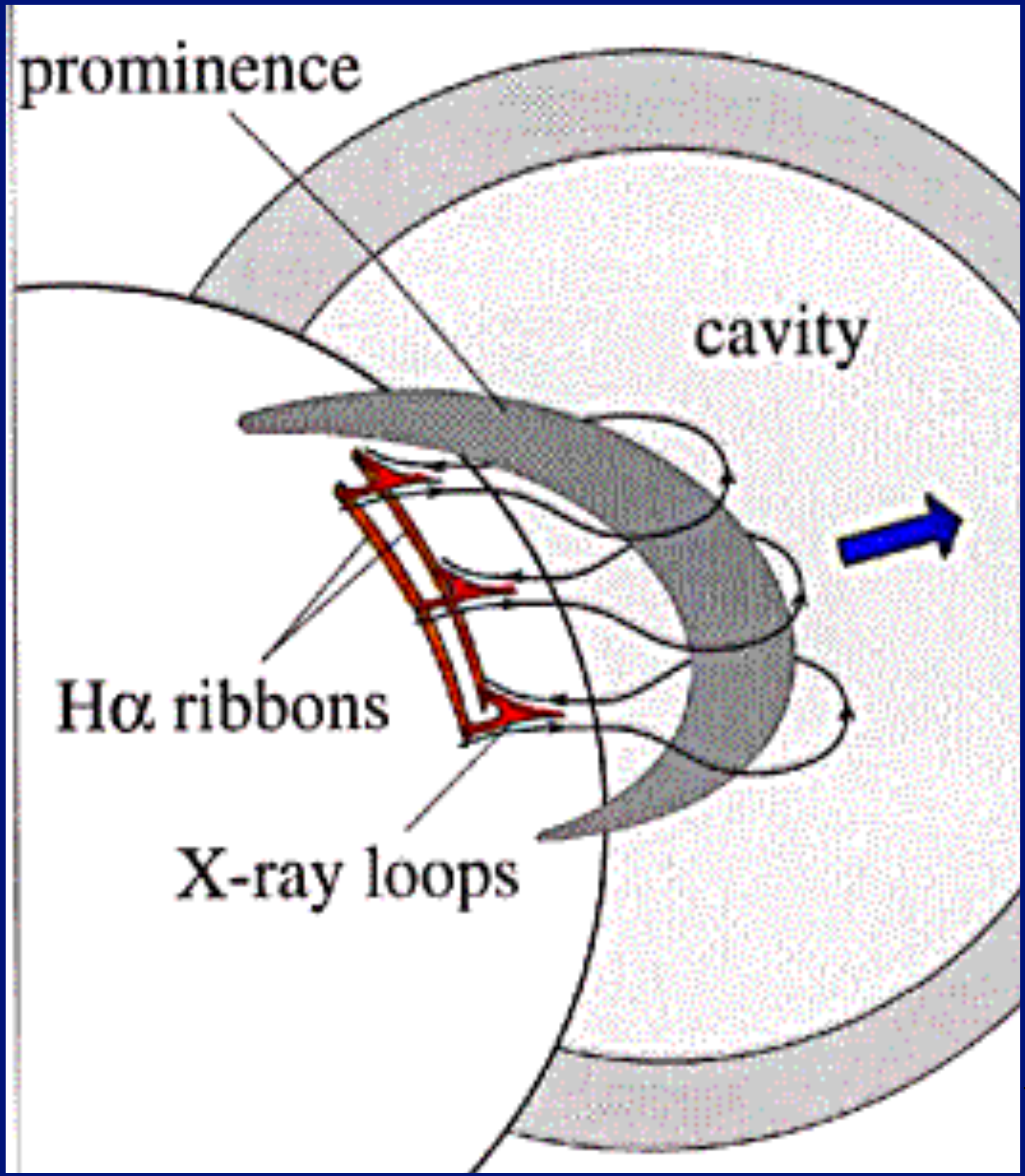
- Plasma plays negligible role in energetics
  - *active region:* T ~ $10^{6.5}$ K, N ~ $10^{10.5}$ /cm^3, E_G ~ 10 ergs/cm^3
  - B ~ $10^{2.5}$ G, E_B ~ $10^{3.5}$ ergs/cm^3
  - also gravitational potential energy, M g_{sun} H ~ E_G << E_B

Basic CME Scenario

- CME/eruptive flare due to explosive release of magnetic energy stored in corona

1. Magnetic shear continually builds up low down over PILs creating pre-CME equilibrium
2. Equilibrium disrupts and whole system expands outward at Alfvenic speeds
3. Closing and relaxation of opening field lines produces flare heating and particle acceleration
4. Rapid drop-off of V_A with height produces IP shock, $V \sim r^{-3}$

Basic CME Cartoon



(Courtesy, T. Forbes)

Underlying CME Physics

- Closest terrestrial analogy is volcano
  - Disruption of force balance between upward push and downward pull
  - Fast removal of downward pull results in supersonic expansion

- On the Sun, this must all be done with smoke and magnetism
  - Filament channel field provides upward push and free energy
  - Overlying coronal field provides downward pull
  - But field lines cannot break!!

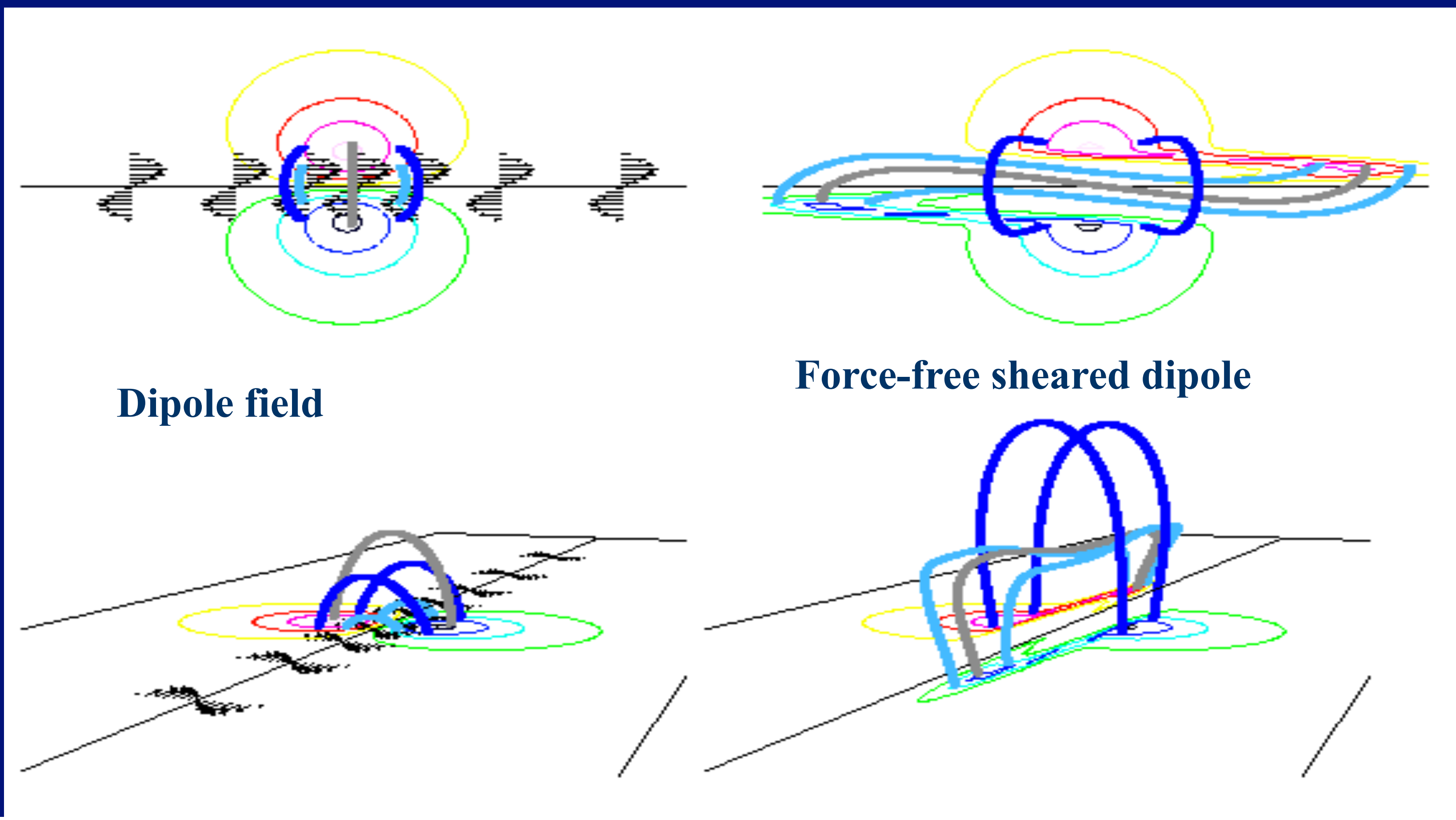
Pre-CME Force Balance

Consider Lorentz force of filament channel and overlying field:

$$J \times B = (\nabla \times B) \times B = -\nabla(B^2/2) + (B \cdot \nabla) B$$

$$= -\nabla_\perp (B^2/2) + B^2 (i_B \cdot \nabla) i_B$$

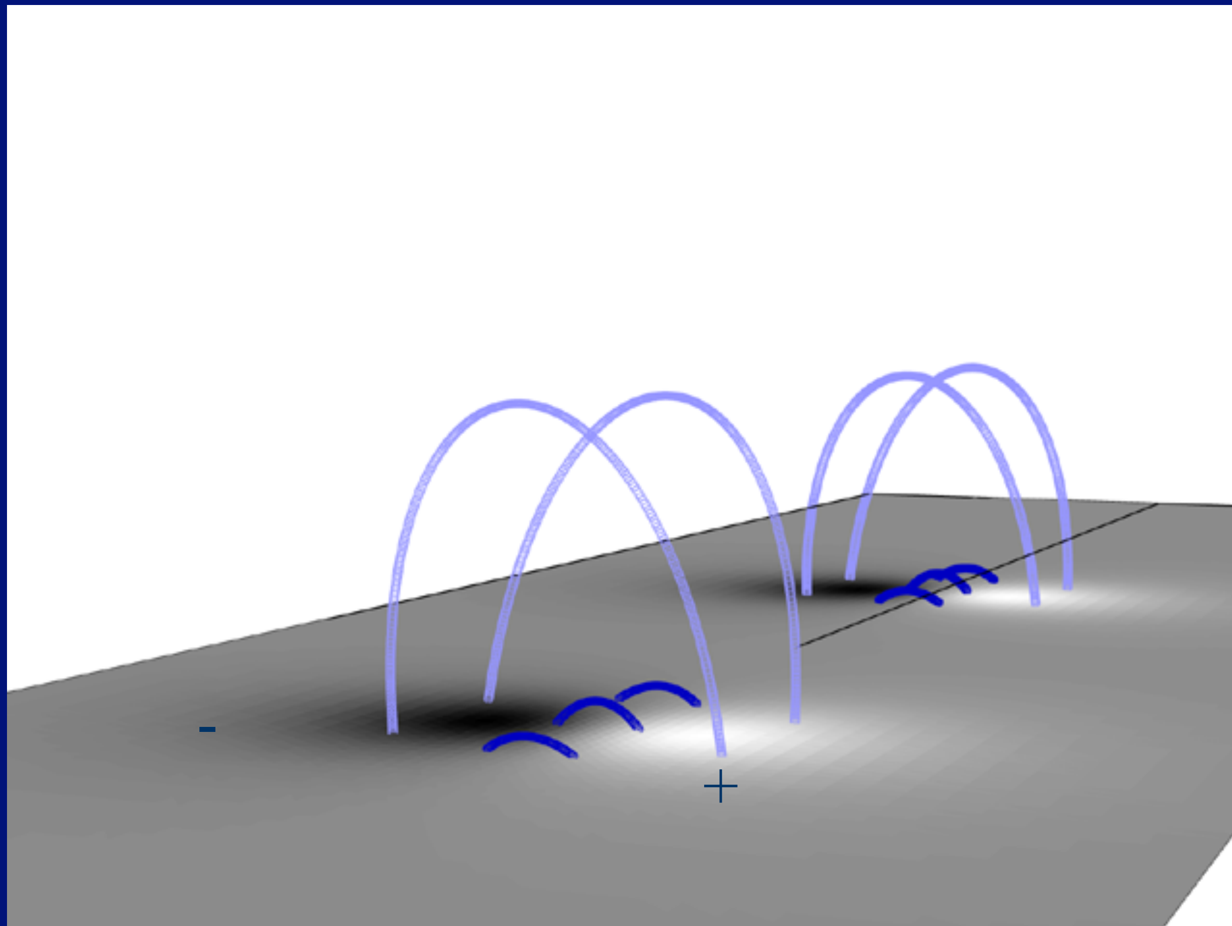
magnetic pressure — magnetic tension



Recap of CME Physics

- For some reason magnetic shear concentrates at PILs producing filament channels
  - Exact topology unclear (especially twist)
- Filament field held down by overlying non-sheared coronal field
  - Need some mechanism to disrupt force balance catastrophically
  - Must find mechanism for rapidly removing overlying field
  - Simply continuing the shearing does not do it! As shown by many simulations

Demonstration of Non-Eruption



(from, DeVore et al, 2005; Aulanier et al, 2005)

- Bipolar (one polarity inversion line) initial magnetic field
- Filament-field formation by shearing and reconnection
- See pronounced expansion & kinking – but no eruption

Non-Eruption

Underlying physics:

- Corona has no lid
- Magnetic field lines can stretch indefinitely without breaking
  - Free to open slowly in response to photospheric stress and gas pressure (rather than erupt as CME)
- Slow opening (not associated with filament channels) observed to occur continuously in large-scale corona

Theories for Eruption

- Non-ideal evolution
  - Magnetic field line topology changes due to reconnection
  - Small change in topology permits large rearrangement of field
  - Removes overlying field
- Ideal instability
  - Twisted field lines can “kink” or “buckle”
  - Separate or push overlying field out of way

- Both appear to “work” in numerical simulations

NUMERICAL SIMULATIONS

- Solve 3D or 2.5D ideal/dissipative MHD with variety of numerical schemes
  - Both explicit and implicit
  - Both fixed and fully amr grids
  - Both Cartesian and spherical grids
- Initial conditions:
  - Usually equilibrium with varying degree of complexity
  - Simple dipole to observed photospheric fields with solar wind
- Boundary Conditions:
  - Open conditions at outer boundaries
  - Photospheric conditions main discriminator between models
  - Simple shear to incomprehensible contortions

NUMERICAL SIMULATIONS

- Term “simulation” is misnomer
- Simply method for obtaining approximate solutions to standard equations
- Drastic change in theory techniques, but still comes down to physical insight
- Numerical simulation slowly turning into user-friendly community tools

ARMS NUMERICAL SIMULATIONS

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \frac{1}{c} \vec{J} \times \vec{B} - \rho \vec{g}$$

$$\frac{\partial U}{\partial t} + \vec{\nabla} \cdot (U \vec{v}) = -P(\vec{\nabla} \cdot \vec{v})$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{v} \times \vec{B}) = 0$$

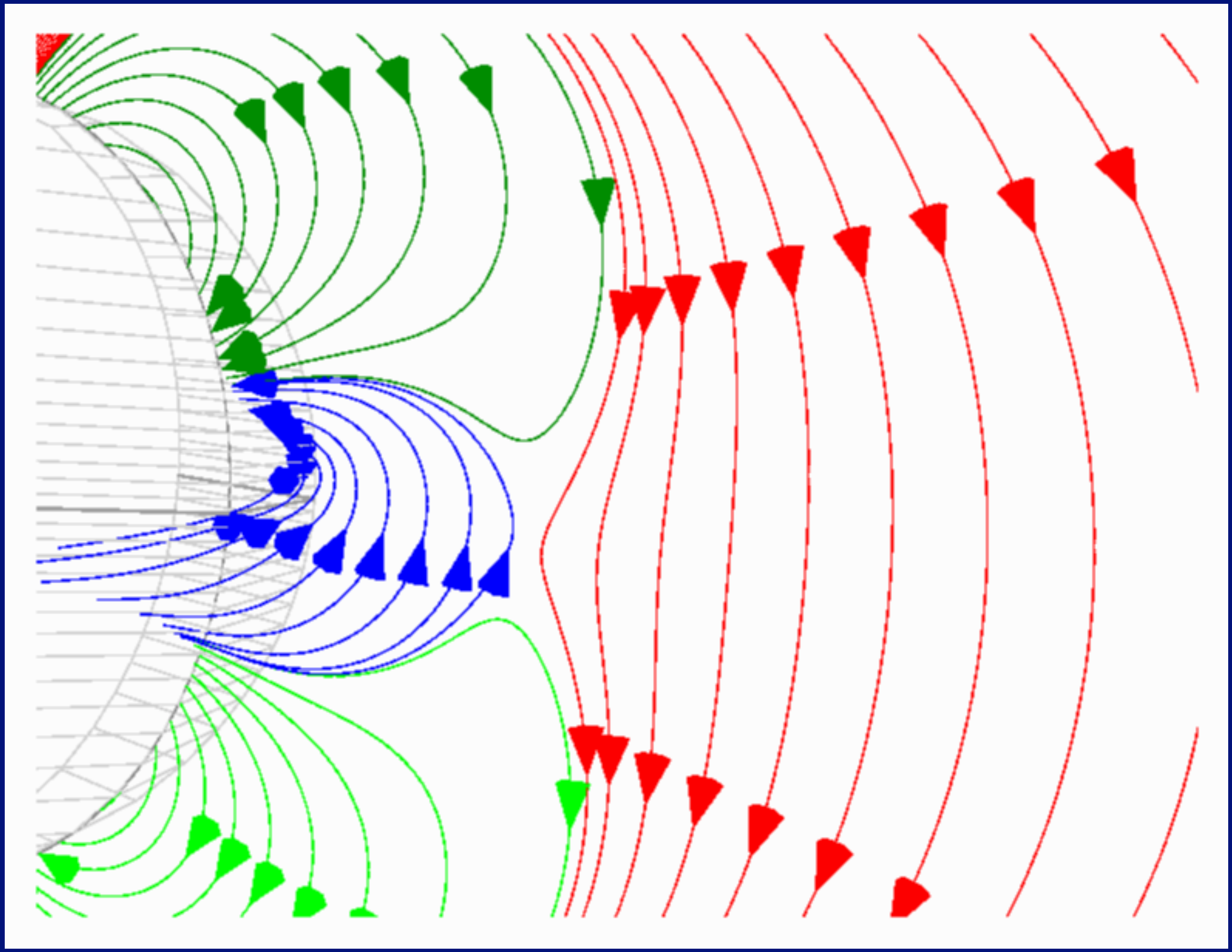
- Ideal MHD eqtns. (but numerical resistivity)
  - Use non-conservative energy equation for low-beta systems
  - Spherical grid with adaptive mesh refinement

Reconnection-Driven CME Models

- Breakout:
  - Magnetic reconnection removes overlying field, decreasing downward pull
  - Need topologically complex field
    - More than 1 dipole
    - Generally present on Sun

Non-Dipole Coronal Topology

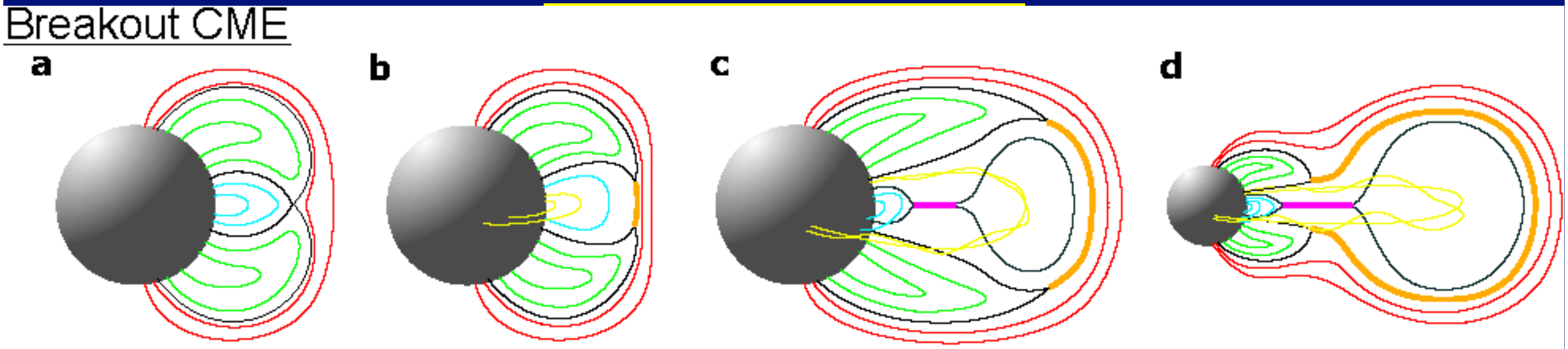
- Field of two dipoles – axi-symmetric
  - Large global at Sun center, weaker near surface
  - Produces 4-flux system with separatrix bdys, and null

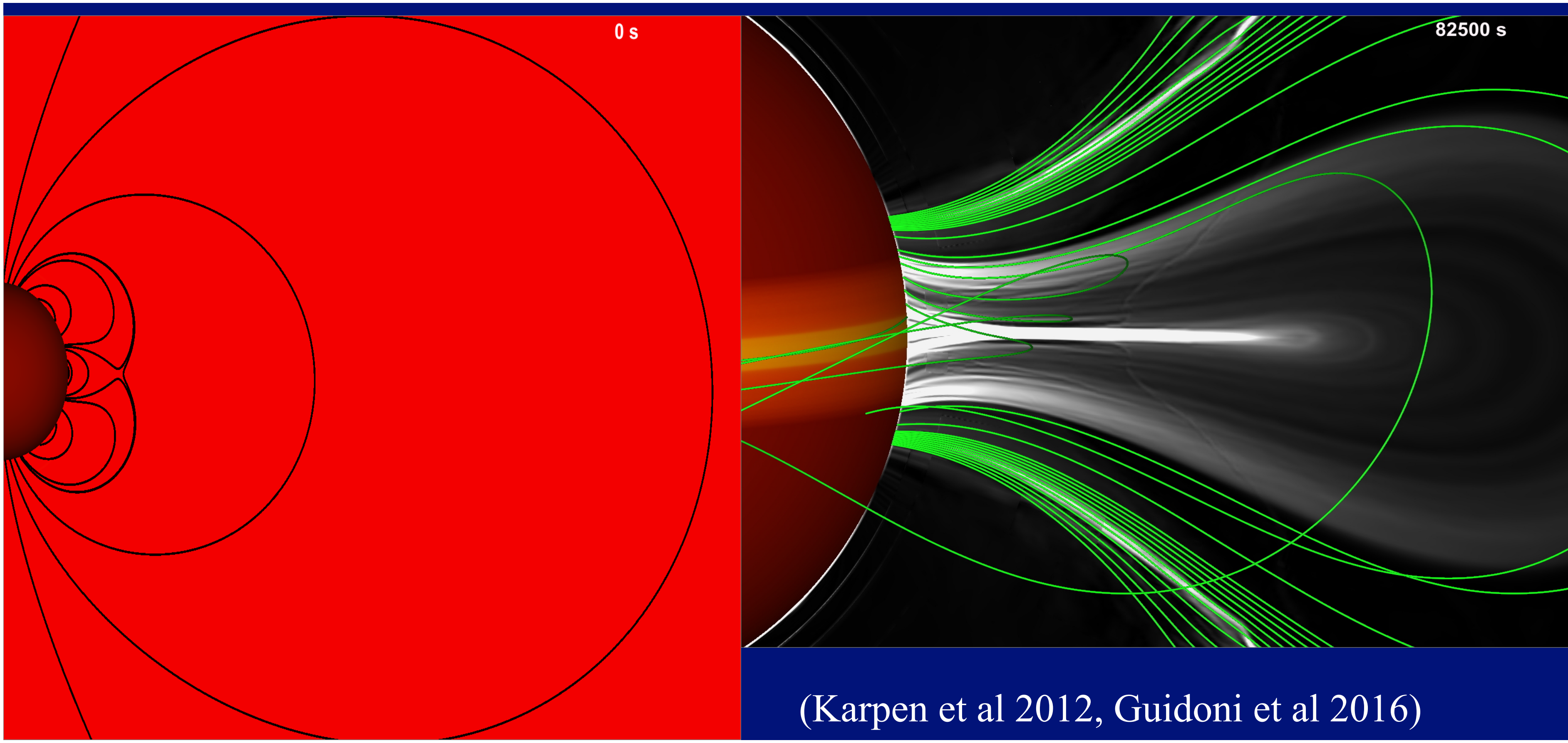


Magnetic Reconnection

- Frozen-in condition:
  - B-field lines ~ constants of the motion
  - Produces topological complexity and all solar activity
- Even in corona have finite diffusion, $t \sim L^2 / \eta \gg 10^6$ years, for L ~ 1 Mm
  - If L sufficiently small, field lines lose identity and can "reconnect" on short time scales, but only over localized region
  - Need to develop quasi-singular magnetic gradients for reconnection to be effective
  - Magnetic topology plays critical role

Breakout Model

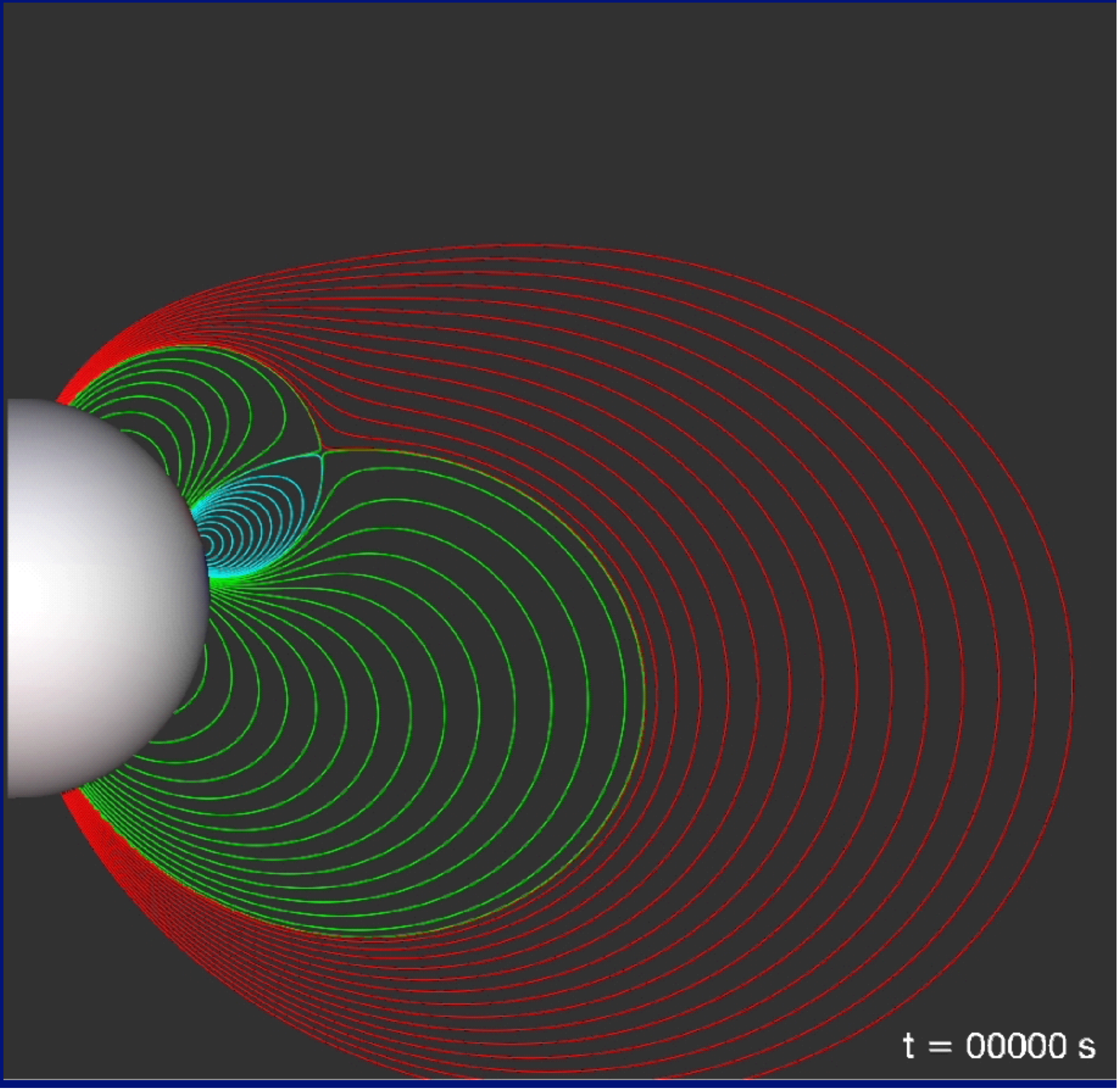




(Karpen et al 2012, Guidoni et al 2016)

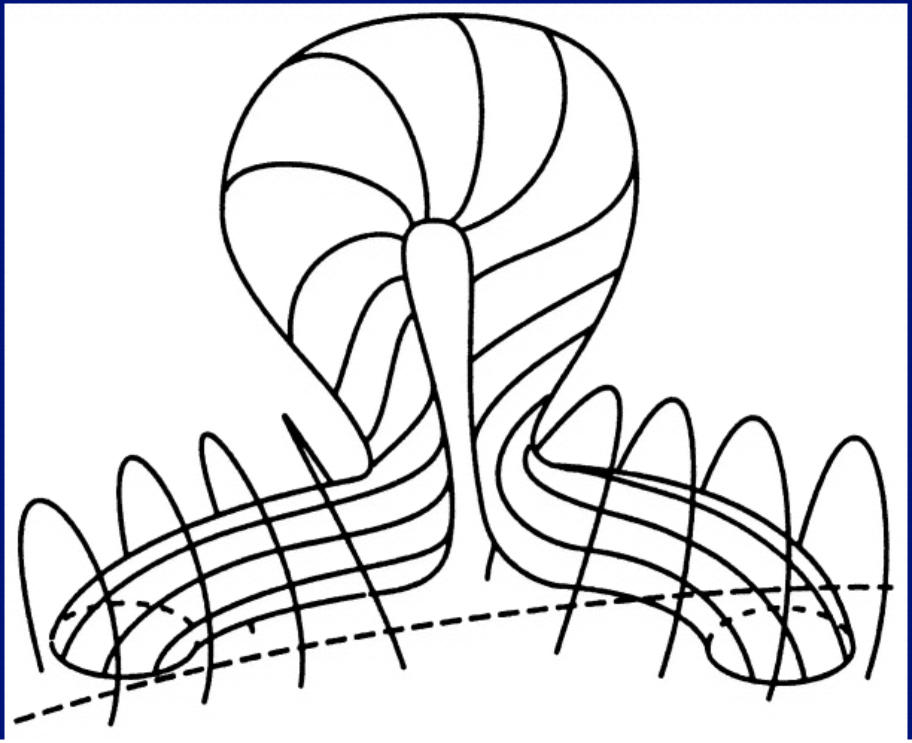
Breakout Model

- 3D simulation using 3D AMR code Lynch et al
- “Create” prominence by simple boundary flows
- Reproduces standard features of CMEs/flares



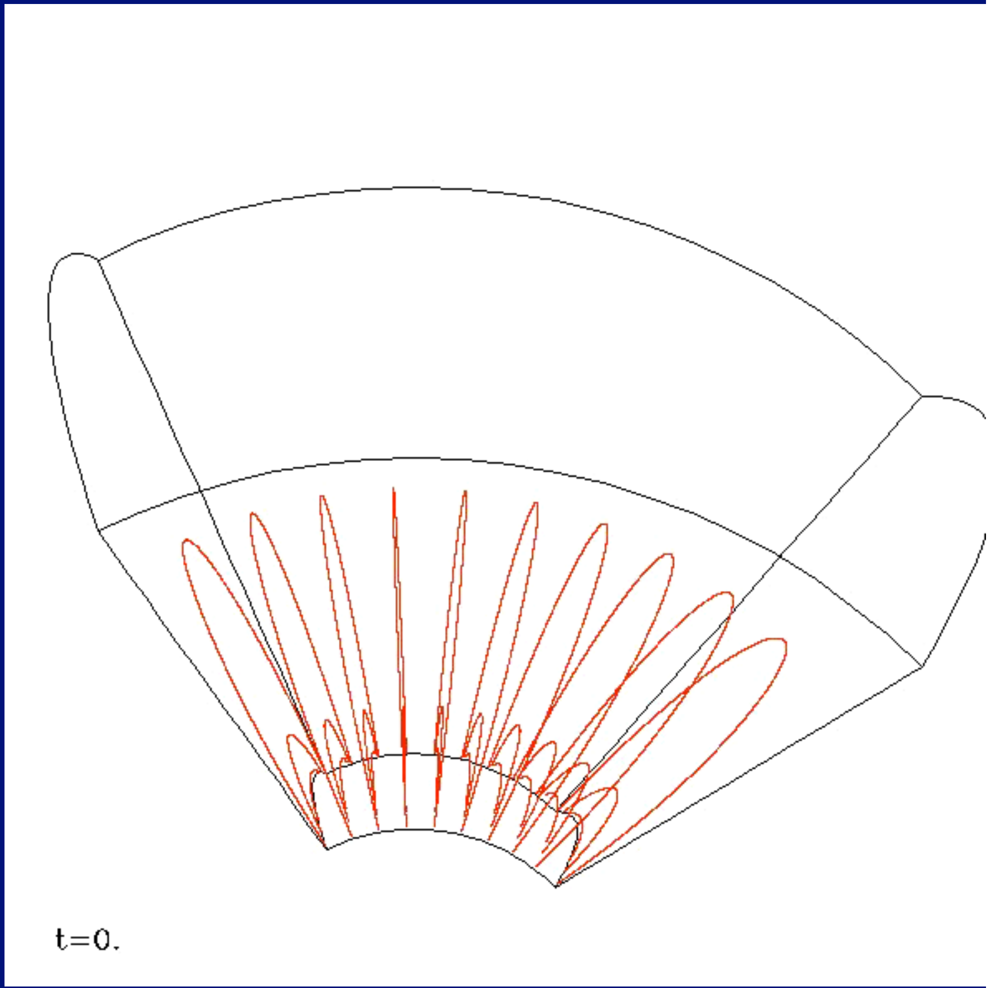
Ideal Instability/Loss of Equilibrium

- Either kink or torus instability
- Part rather than remove overlying field
- Need twisted flux rope
  - Sturrock, Fan, Kliem, …



Aneurism Model

- 3D simulation by Fan et al.
- System driven only by flux "emergence"
- Kink or torus instability depending on overlying field
- Must assume initial magnetic twist structure

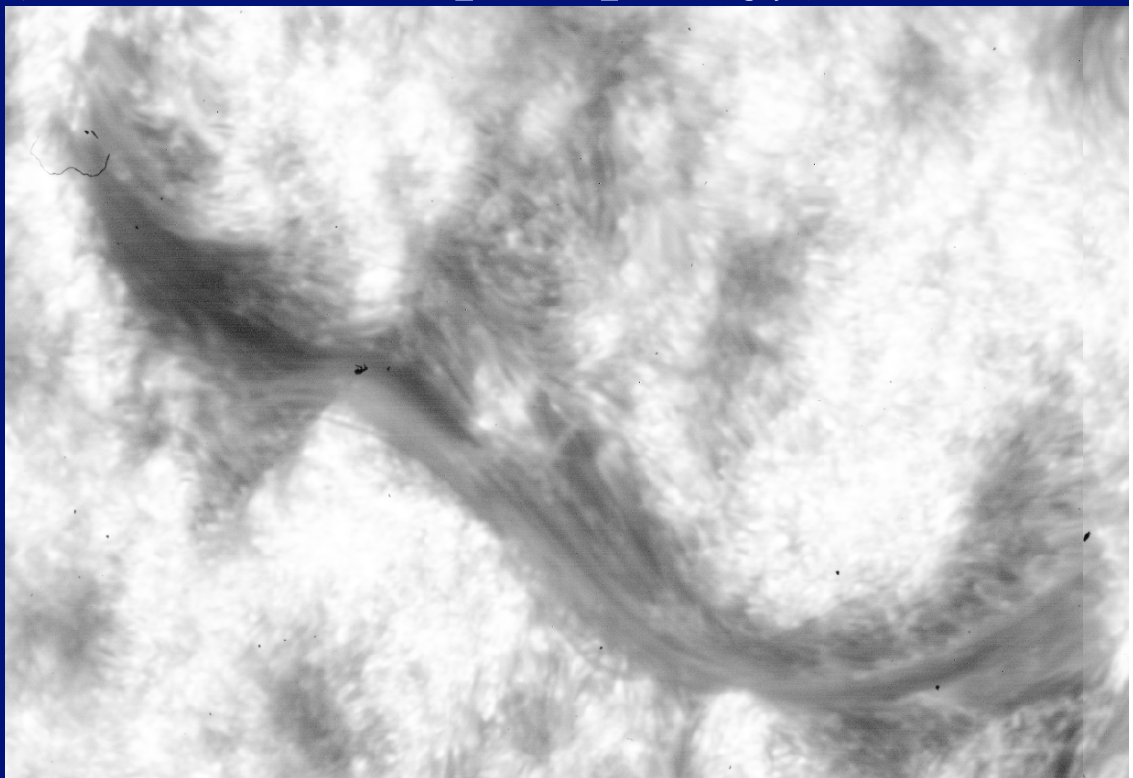


Models for CME Initiation

- Apparently have two mechanisms that can produce explosive CMEs in 3D simulations:
  - Reconnection (Breakout), ideal instability/loss-of-equilibrium
- Both require sheared prominence field
- Both produce twisted flux rope as a result of eruption
  - Flare evolution similar for both
- Ideal instability requires twisted flux rope before eruption

64K Question

- What is the pre-eruption structure of the prominence field?
  - Clearly has strong shear
  - Does it have twist (twisted flux rope topology)



- NRL VAULT image of 06/16/02, 20K material, spatial resolution < 200 km

- Little evidence for twist in either structure or motions, but exact topology still unclear