Modeling Solar Eruptions

Judy Karpen, Spiro Antiochos, and Rick DeVore, NASA/GSFC

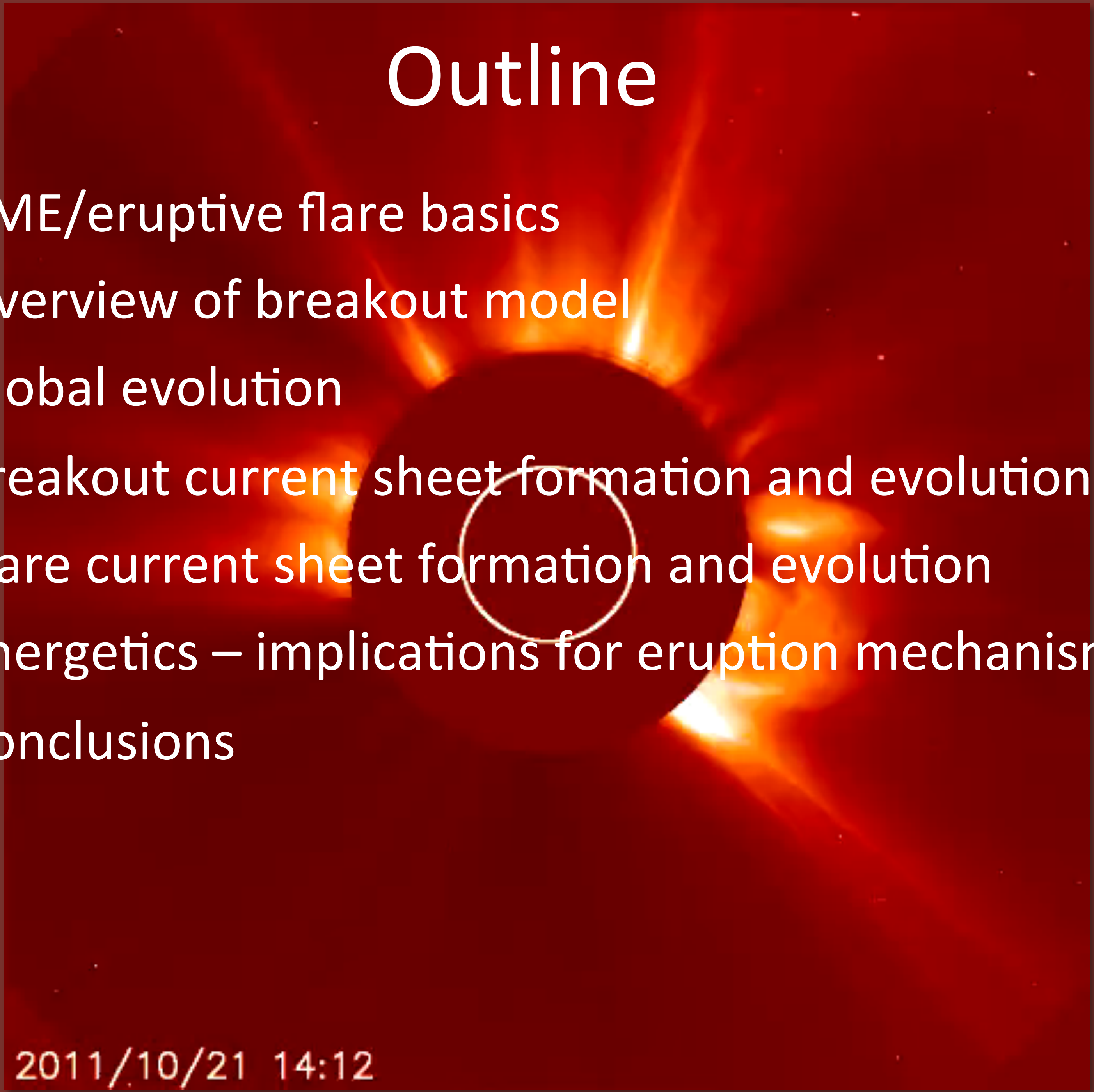
The big questions about solar eruptions:

- How is energy built up and stored?
- How is energy released so quickly?
- How are particles accelerated?
- How do they propagate into the heliosphere and affect humans and technology?

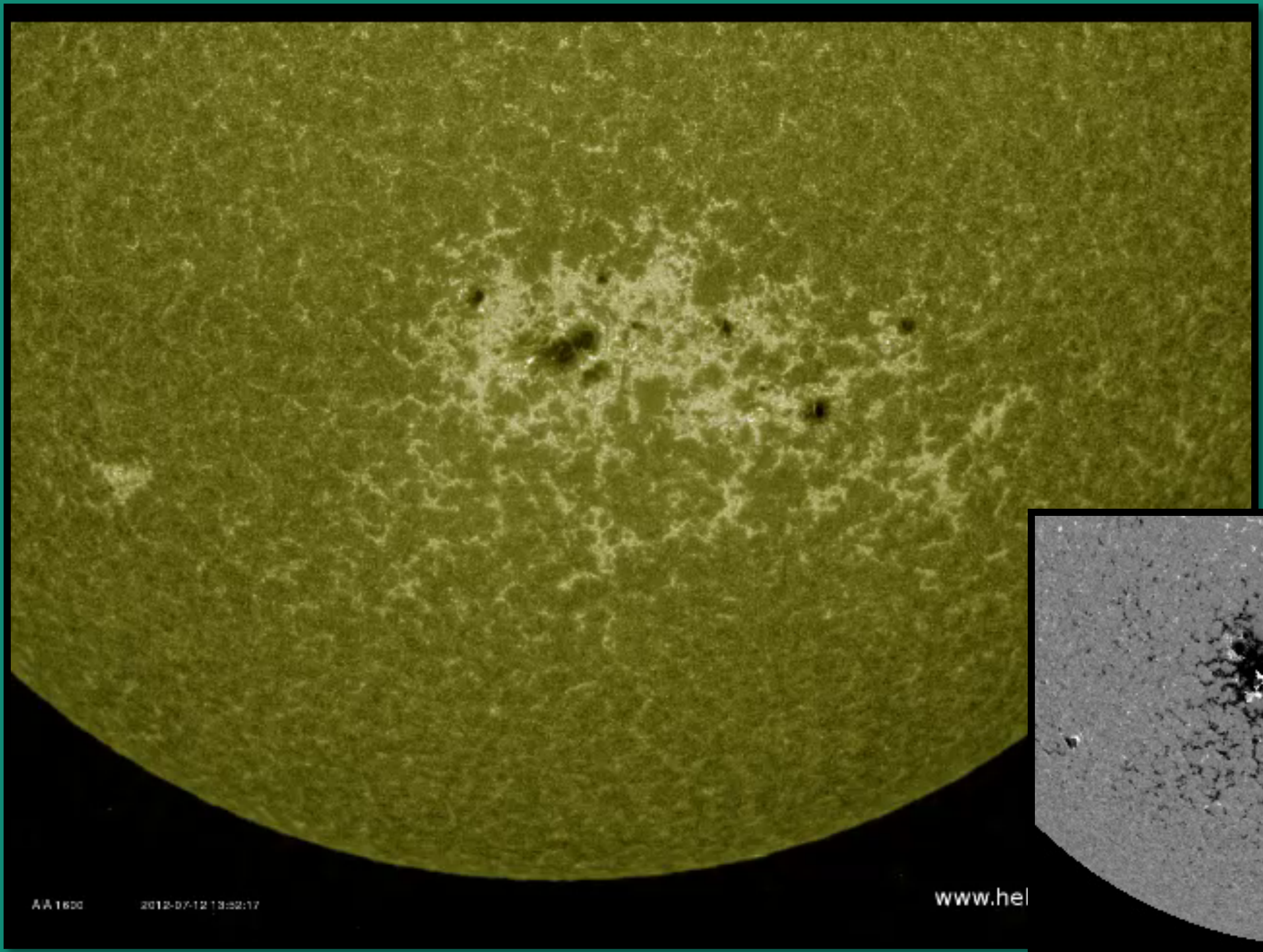
Can numerical simulations answer these questions? Of course!

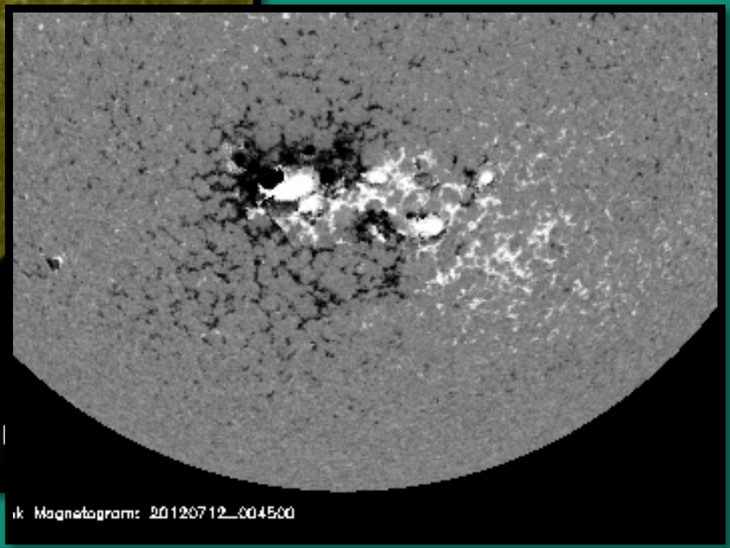
Outline

- CME/eruptive flare basics
- Overview of breakout model
- Global evolution
- Breakout current sheet formation and evolution
- Flare current sheet formation and evolution
- Energetics – implications for eruption mechanism
- Conclusions



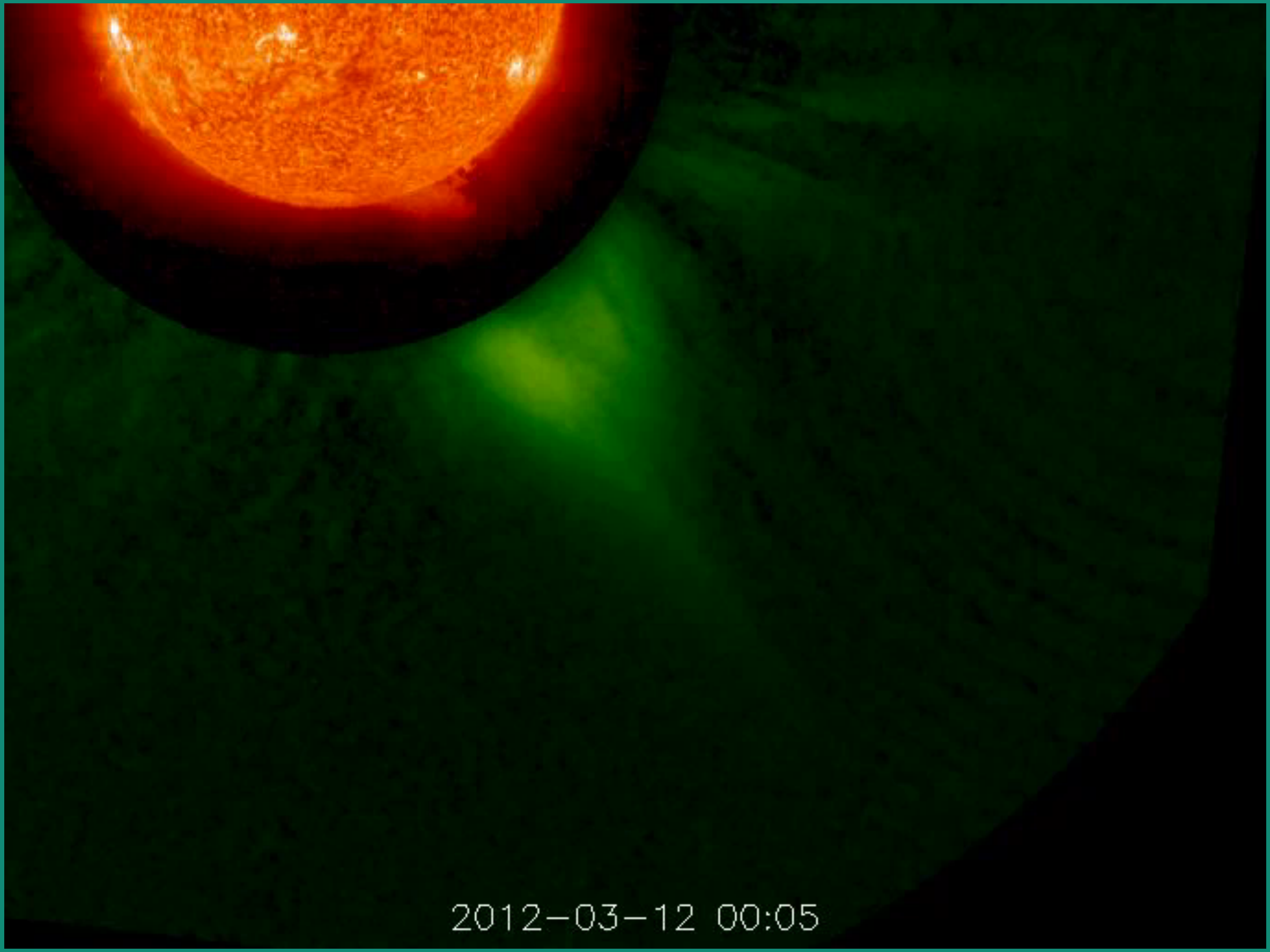
Sources of Solar Eruptions





SDO/AIA (1600Å) – line of sight along Earth-Sun line
T < 100,000K

Solar Eruptions = Flares + CMEs

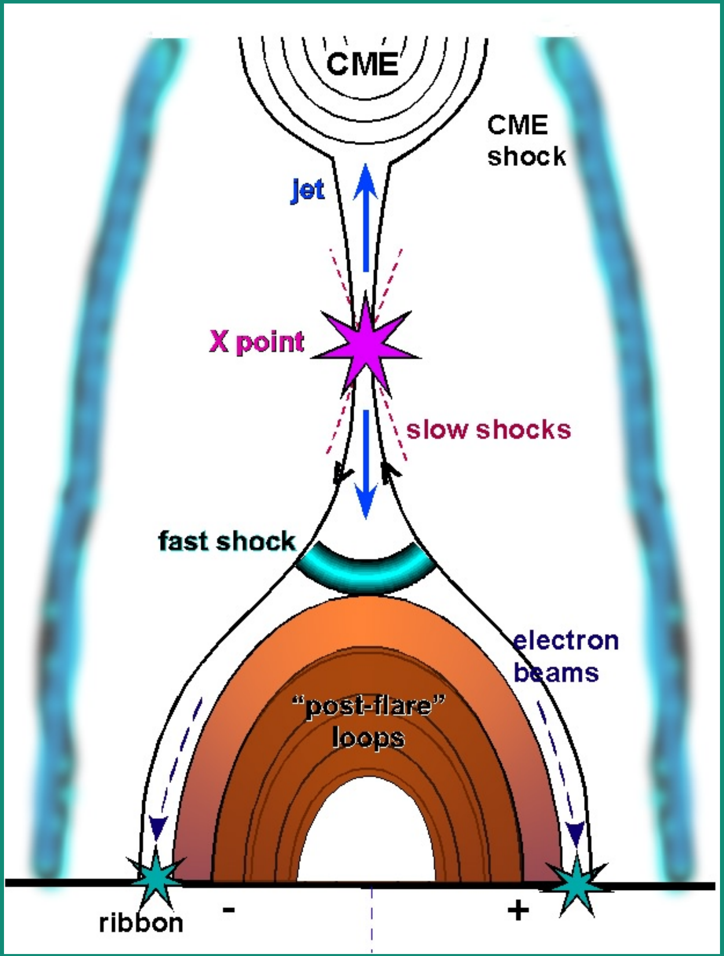


STEREO A 304A and coronagraph– line of sight perpendicular to Earth-Sun line, bright = dense

How can we understand the underlying physics?

- Propose a theory that meets the requirements set by observations and physical laws
- Test this theory by modeling simplest possible system with essential properties
- Compare simulation results with theoretical predictions and observations: CME speeds, energetics, timings, magnitude, etc.
- Test robustness: successful explanation of progressively more complex/realistic systems?

Updated "Standard" CME-Flare Cartoon



Observed to date

- Coronal mass ejection (CME)
- Current sheet (UVCS)
- Electron beams (HXR, μιχροwave, Type III emissions)
- Reconnection inflows & outflows
- Fast shock above post-eruption loops (standing Type II, superhot HXRs)?
- Flare ribbons (Hα, etc.)
- Post-eruption loops (newly formed, filling, and cooling)
- plasmoids in current sheet

Key Point: Need physical insight to develop theories *before* testing by numerical modeling and comparison with observations

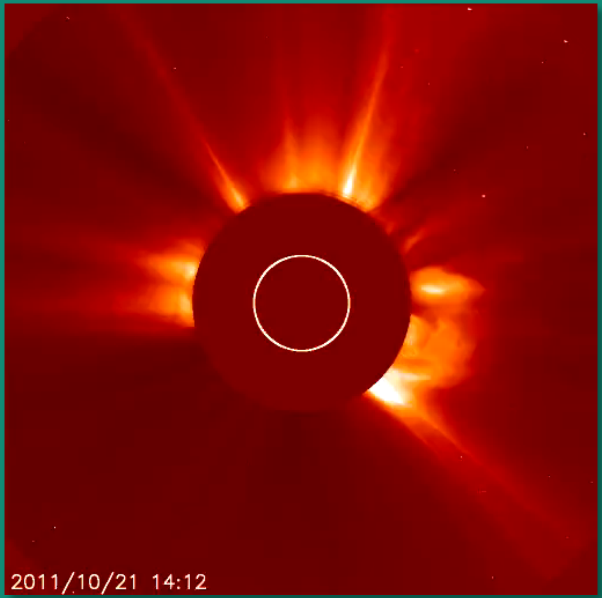
Fundamental Questions

- What is the pre-eruption magnetic configuration?
  - filament channel: sheared arcade or twisted flux rope
- How is free energy injected and stored?
  - photospheric motions: shearing, emergence
- How is energy suddenly released?
  - magnetic reconnection or ideal instability or …
- How is this energy partitioned and transported to yield observable signatures?

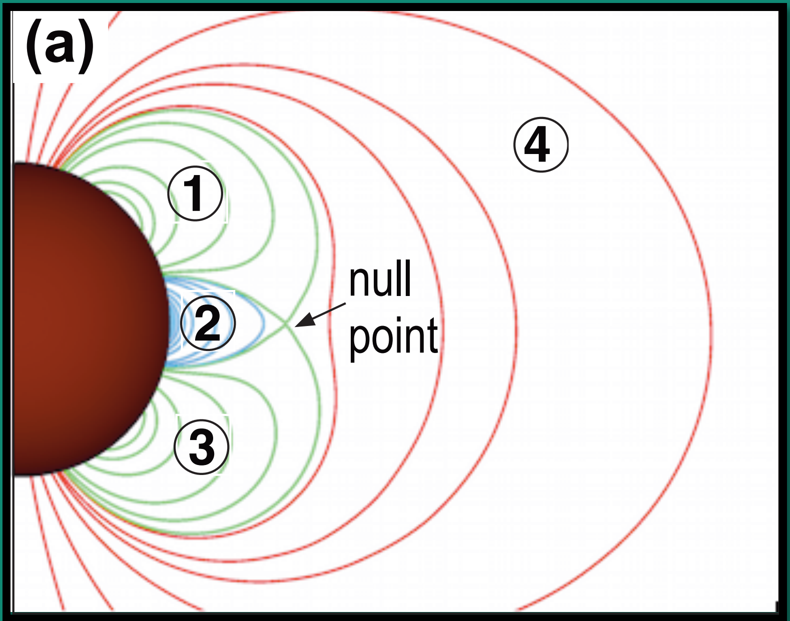
Solar Eruptions = Volcanoes?

- Energy storage: increasing pressure (rising magma) held back by overlying magnetic field (rock cap)
- Energy release can be gradual or <u>sudden</u>
- Intense eruptions can drive shock waves

But, volcanoes are not magnetically driven or released

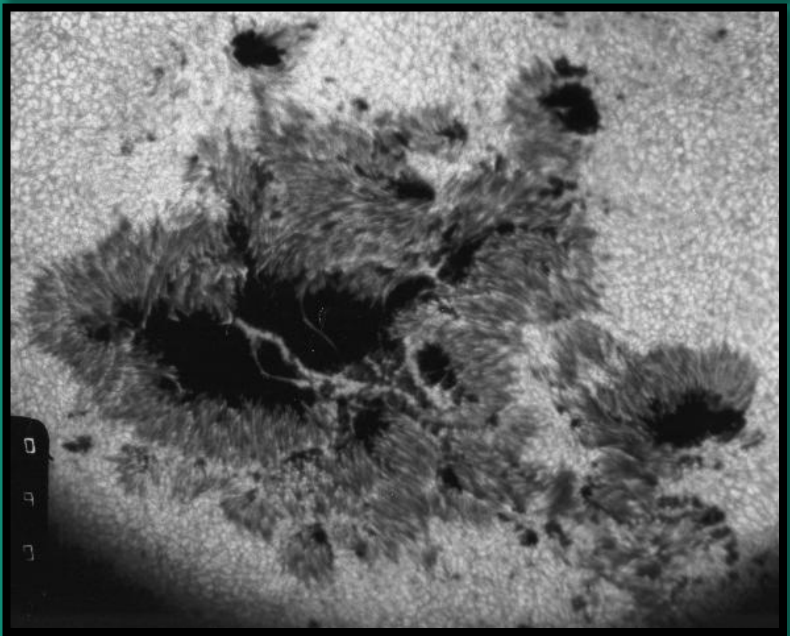


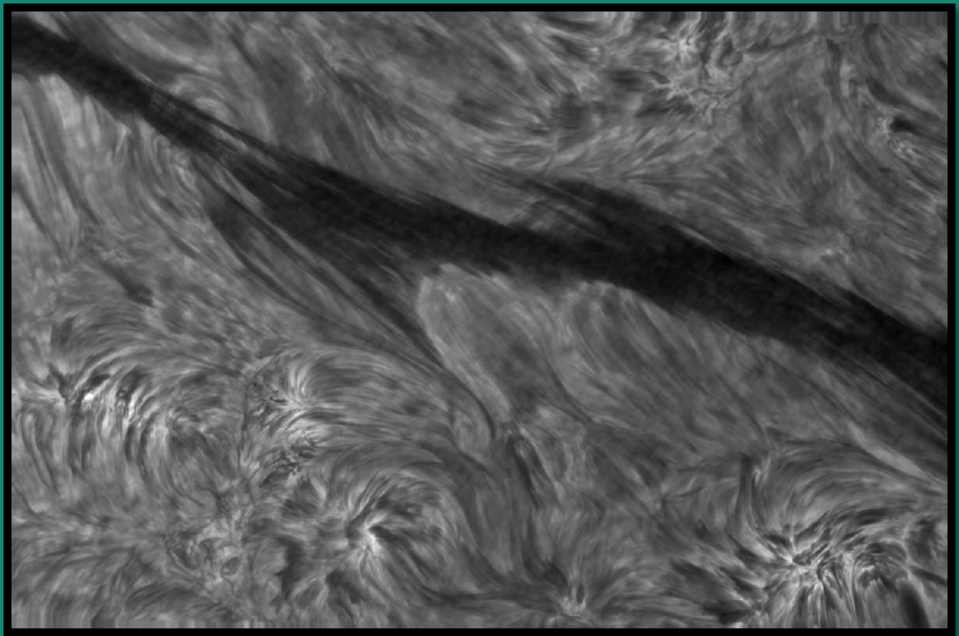
Breakout Model for Fast CME Initiation



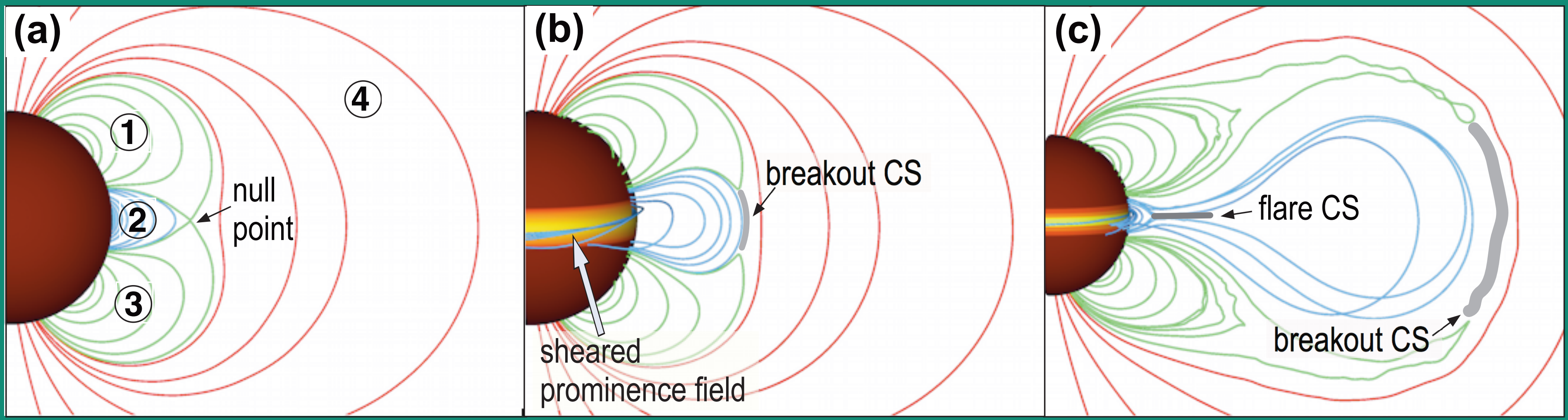
Three Simple Requirements:

- Multipolar topology
- Sheared filament channel (formation mechanism unimportant)
- Scale-dependent resistivity





Breakout Model Overview



- Initial field from two dipoles – *axisymmetric 4 flux system*
- Slow footpoint motions create *sheared filament channel*
- Outward expansion drives *breakout current sheet formation at the null, followed by reconnection (flux transfer)*
- Expanding sheared core field creates thinning flare current sheet
- *Flare reconnection in lower current sheet* forms CME flux rope
- Fast CME is launched, post-flare arcade builds up

Approach

2.5D numerical experiments with *ARMS* in spherical geometry.

- Adaptively refined
  - Refinement criteria: gradient in one or more J components exceeds specified value, in specified |B| range
  - Outer boundary at 125 R_{sun}
  - Filament channel formed by slow antiparallel photospheric motions around equatorial PIL
- Null finder subroutine identifies and tracks nulls (X and O points), and assesses their robustness

ARMS

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \rho \mathbf{v} = 0$$

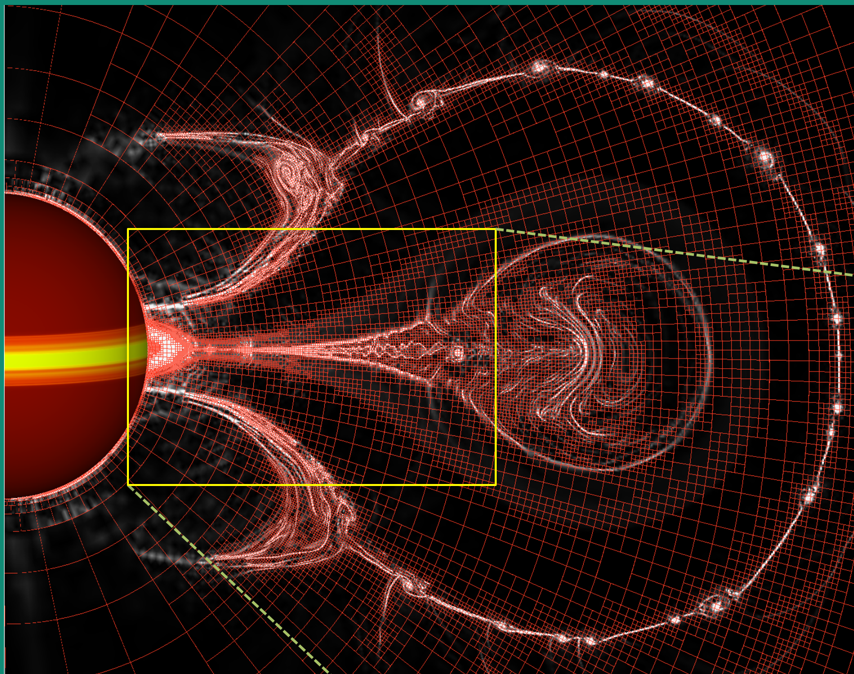
$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \bullet \rho \mathbf{v}\mathbf{v} = -\nabla P + \frac{1}{4\pi}\left(\nabla \times \mathbf{B}\right) \times \mathbf{B} + \rho \mathbf{g}$$

$$\frac{\partial T}{\partial t} + \nabla \bullet T\mathbf{v} = \left(2 - \gamma\right) T \nabla \bullet \mathbf{v}$$

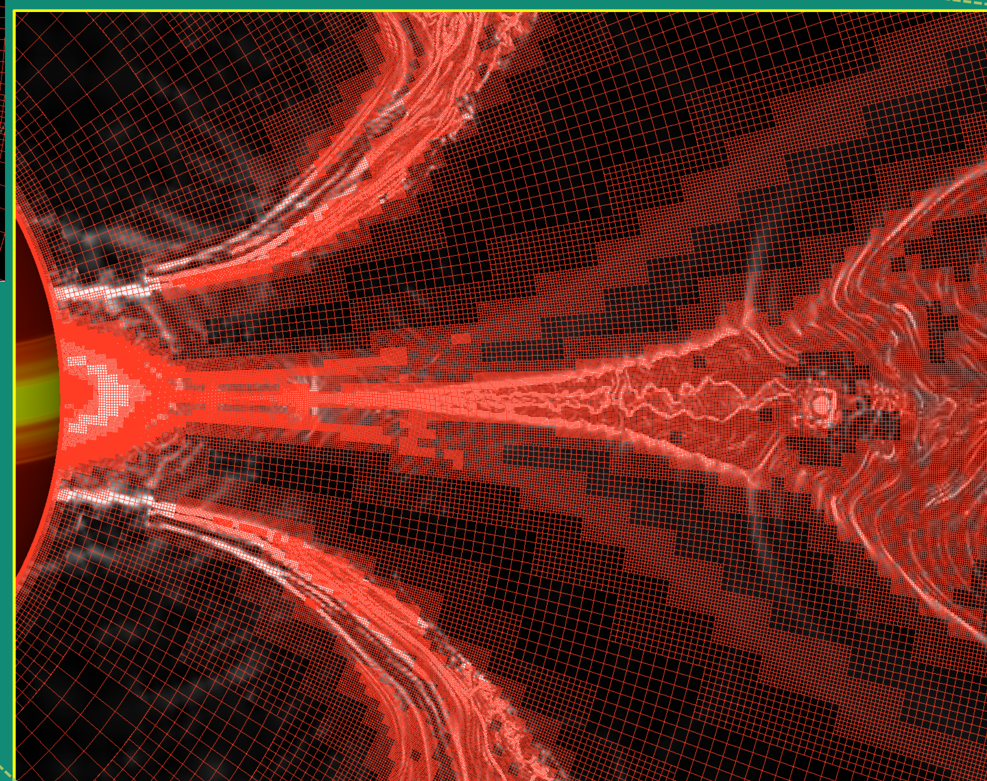
$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \left(\mathbf{v} \times \mathbf{B}\right) = 0$$

- Finite volume, Flux Corrected Transport-based solver
- Fixed and dynamically adaptive grids (PARAMESH)
- Refinement/derefinement criteria defined by user
- Initial conditions:
  - current-free multipolar field, hydrostatic atmosphere, spherical
- Boundary Conditions:
  - radial: line-tied, no-flow-through, with specified photospheric shear
  - open conditions at all other boundaries

Why AMR is Important



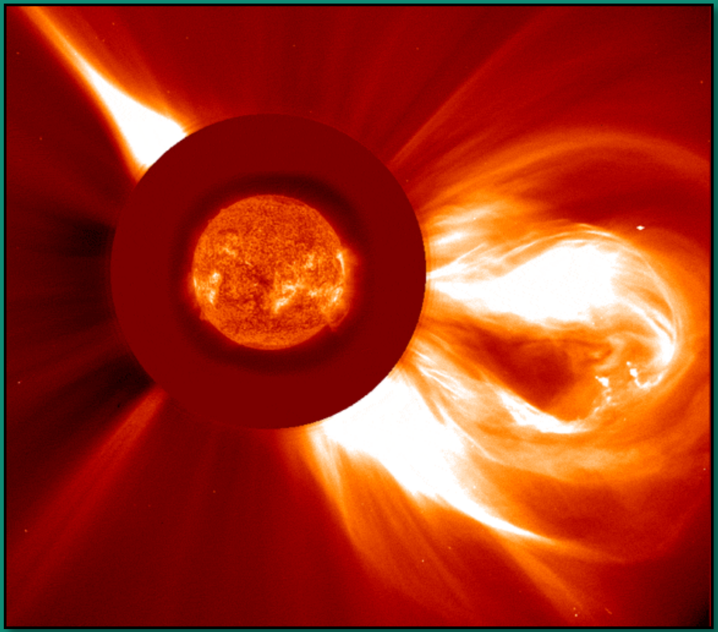
Currents and grid at 102500 s: *block* boundaries shown in global view at left; *cell* boundaries shown in closeup below

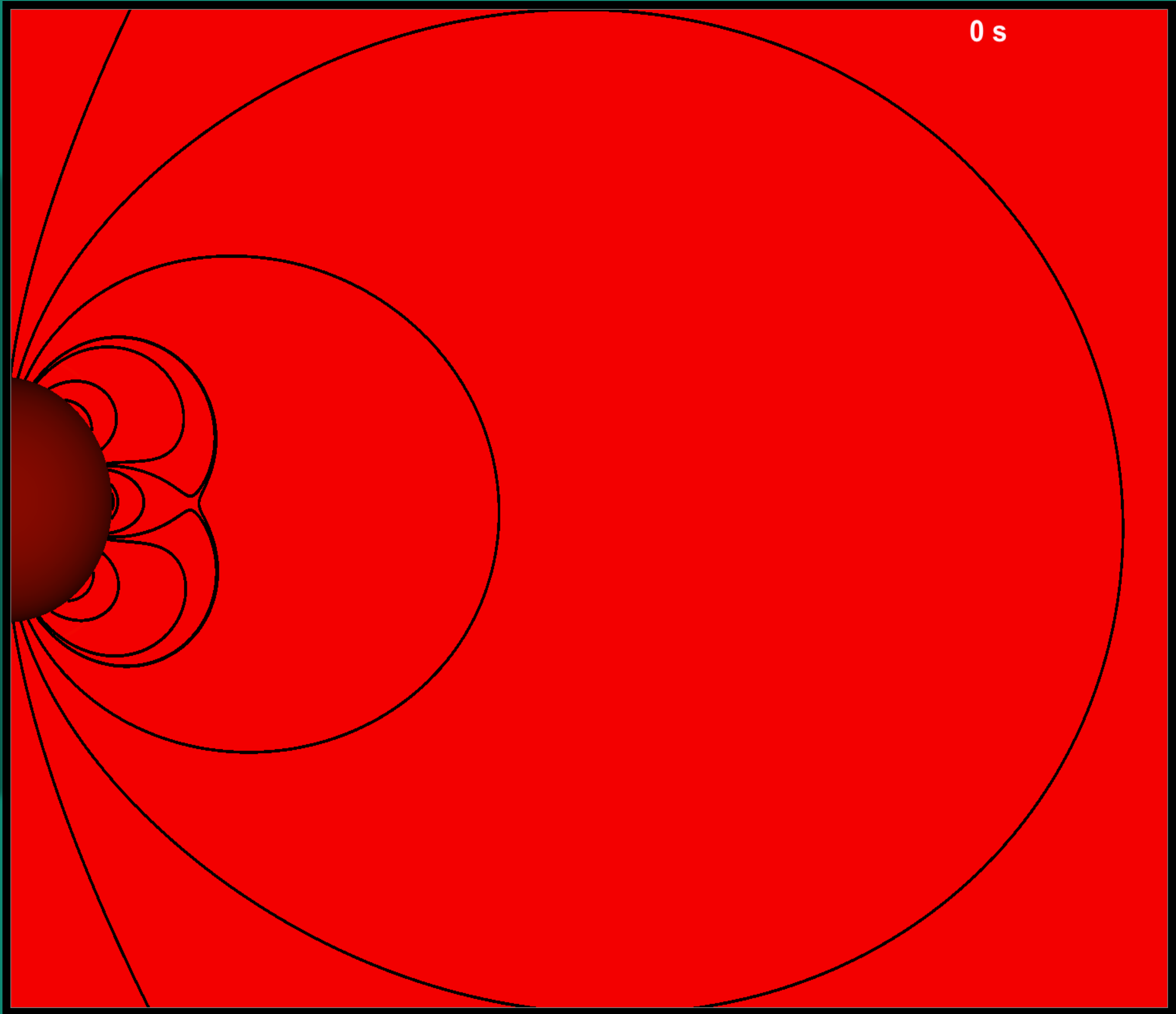


Numerical resistivity is scale dependent: smaller cells → higher R_m

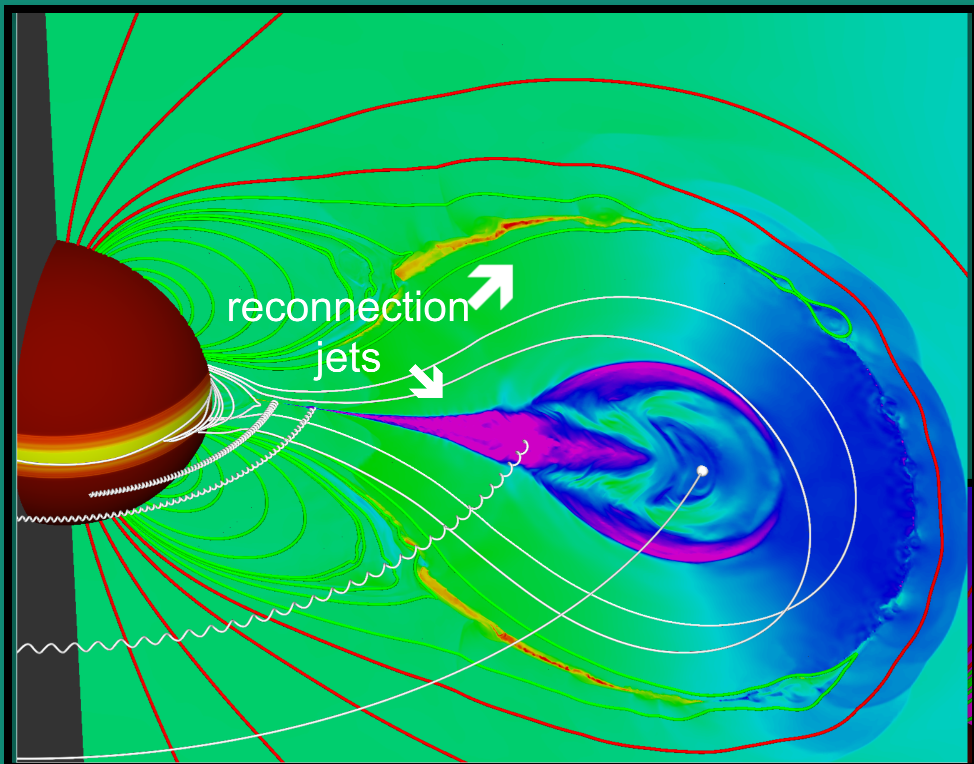
CME Buildup and Eruption

- Removal of overlying field
- Gradual rise of pre-CME field commonly observed
- Fast expulsion + flare



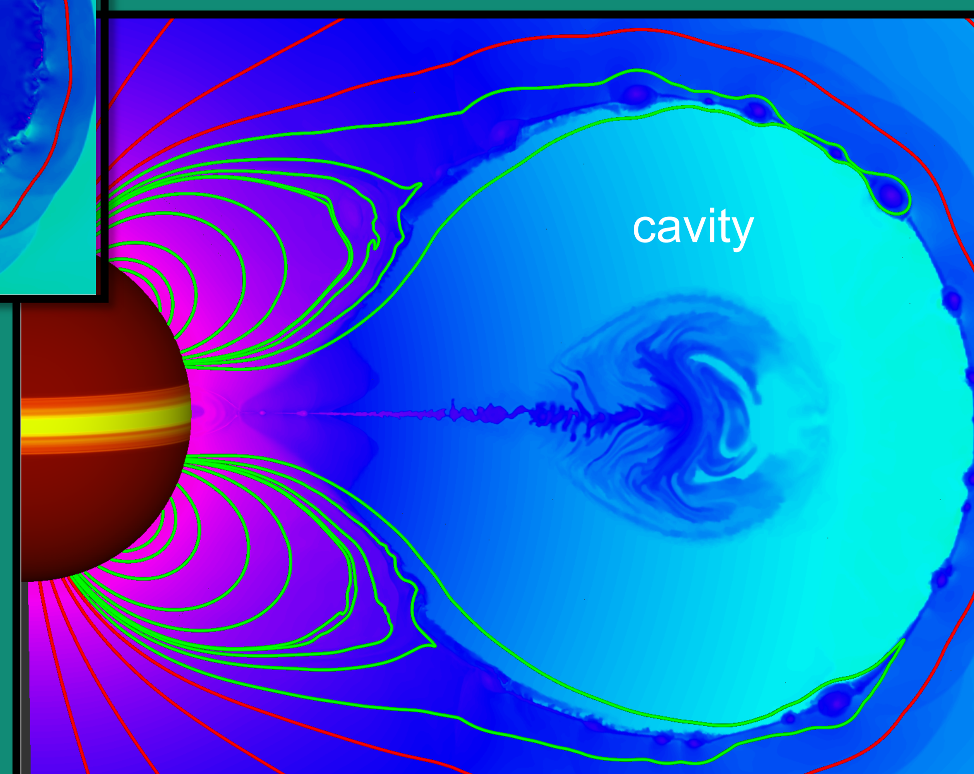


Radial Velocity and Density at 102500s



V_r in corona: magenta ≥ 500 km/s, red ≤ -500 km/s

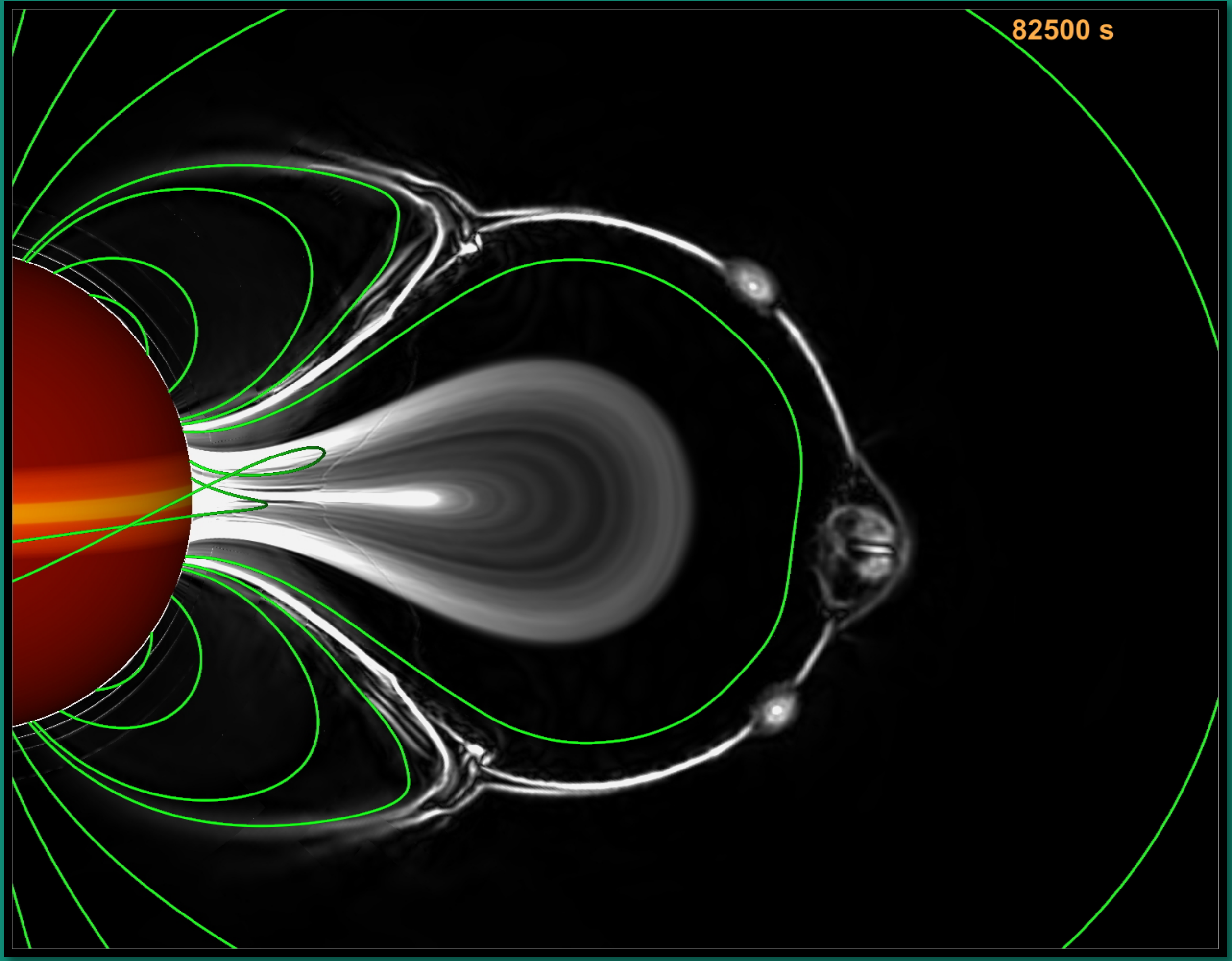
Log(ρ) in corona



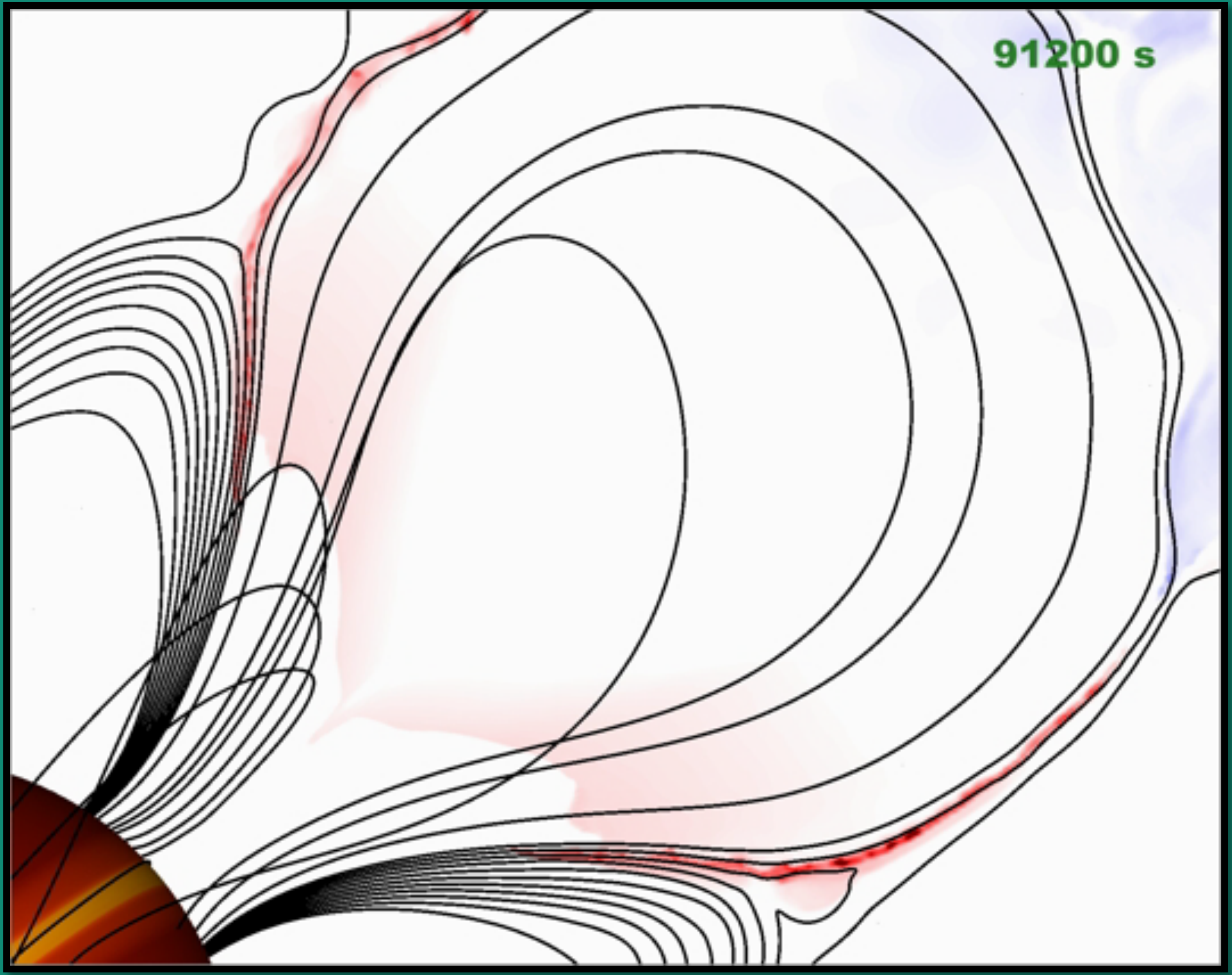
Flare Close-up

- Current sheet forms and thins
- Reconnection causes explosive dynamics
- Magnetic energy converted to motions, heating, etc.

- *Fine structure only* visible with AMR
- Now: investigating particle acceleration in flare plasmoids
- Future: simulate flare emission and compare with data

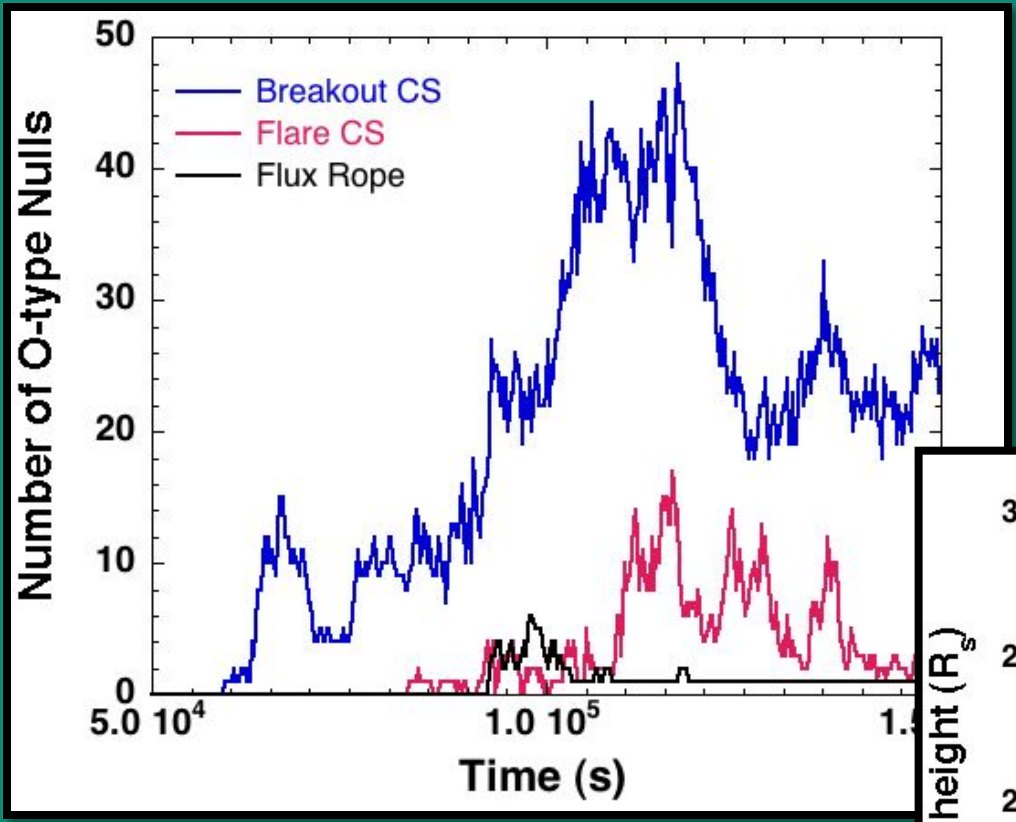


Flare Reconnection Jets

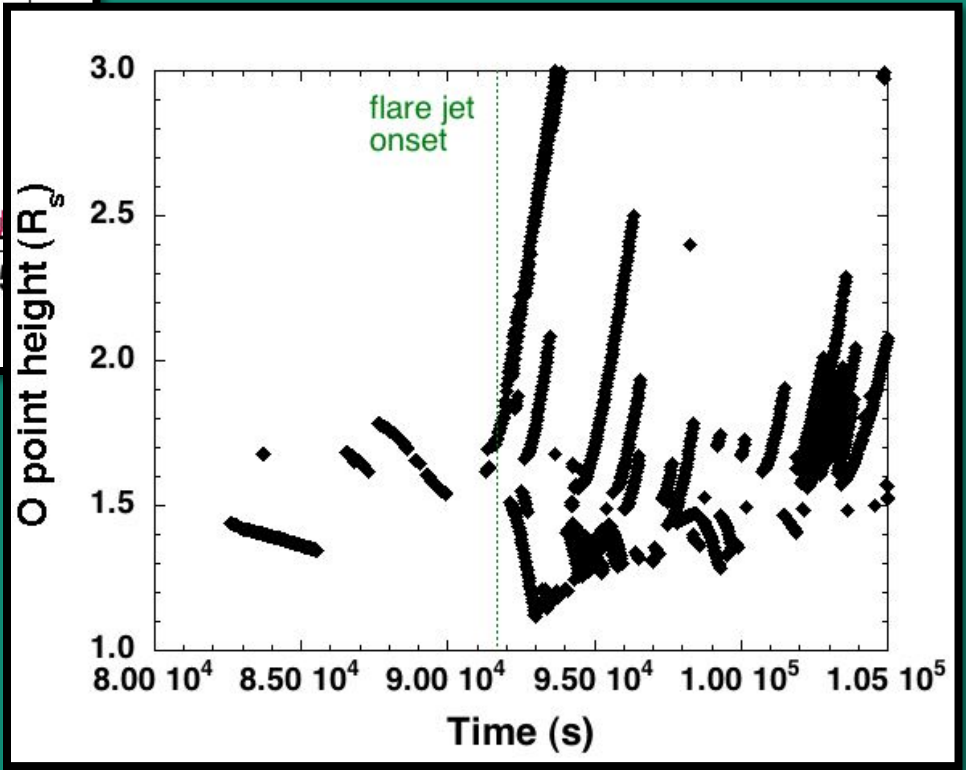


Black field lines (same in all frames); radial velocity (red < 0, blue > 0, max. V_r = 500 km/s)

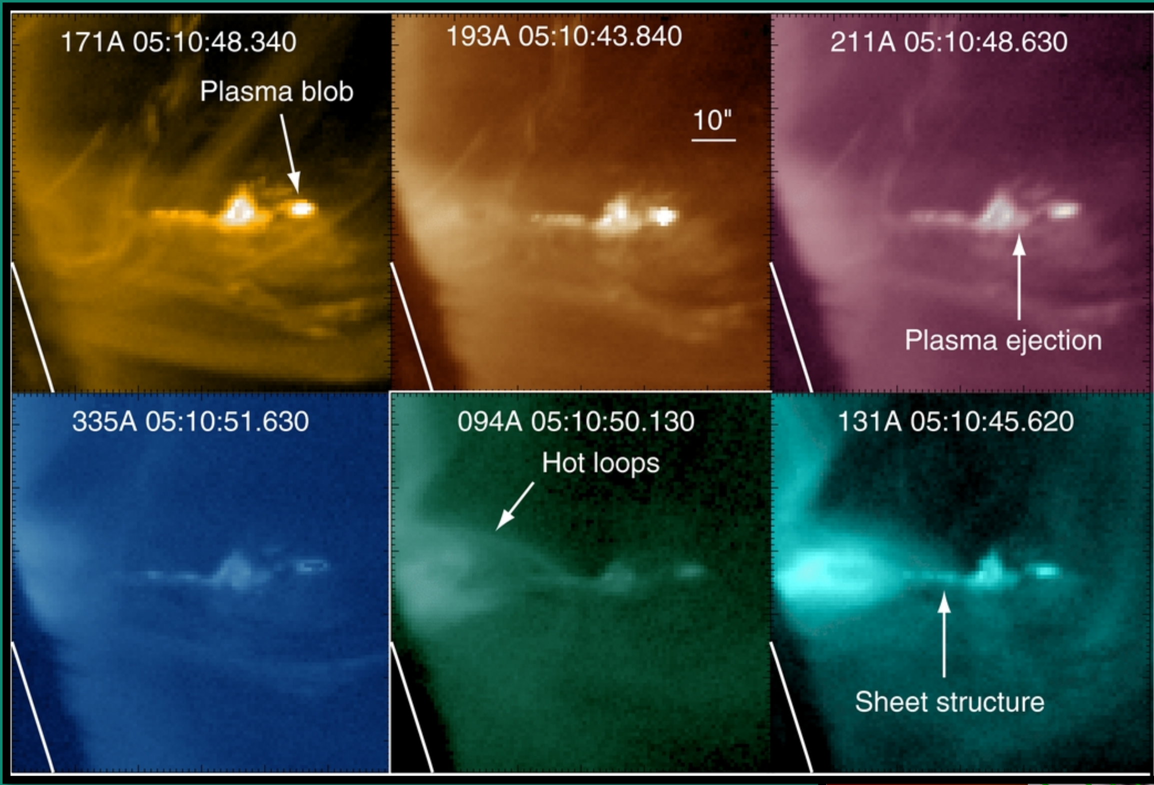
Dynamic Plasmoids



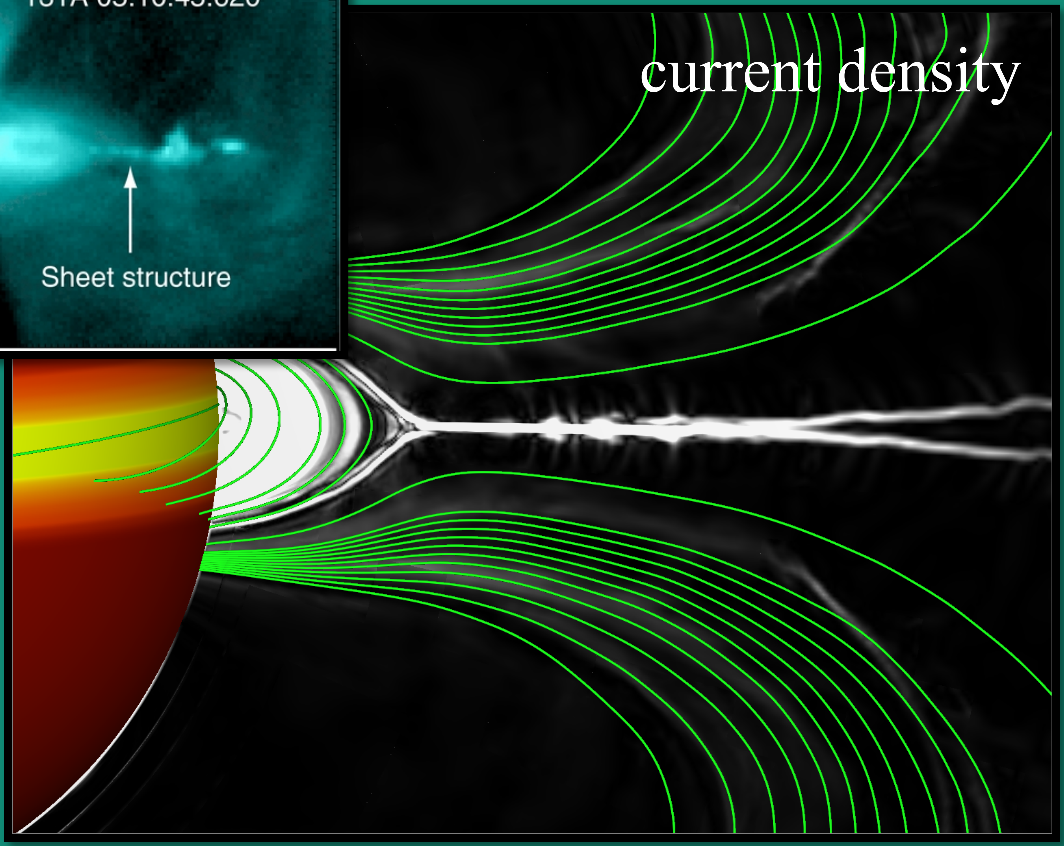
in flare sheet



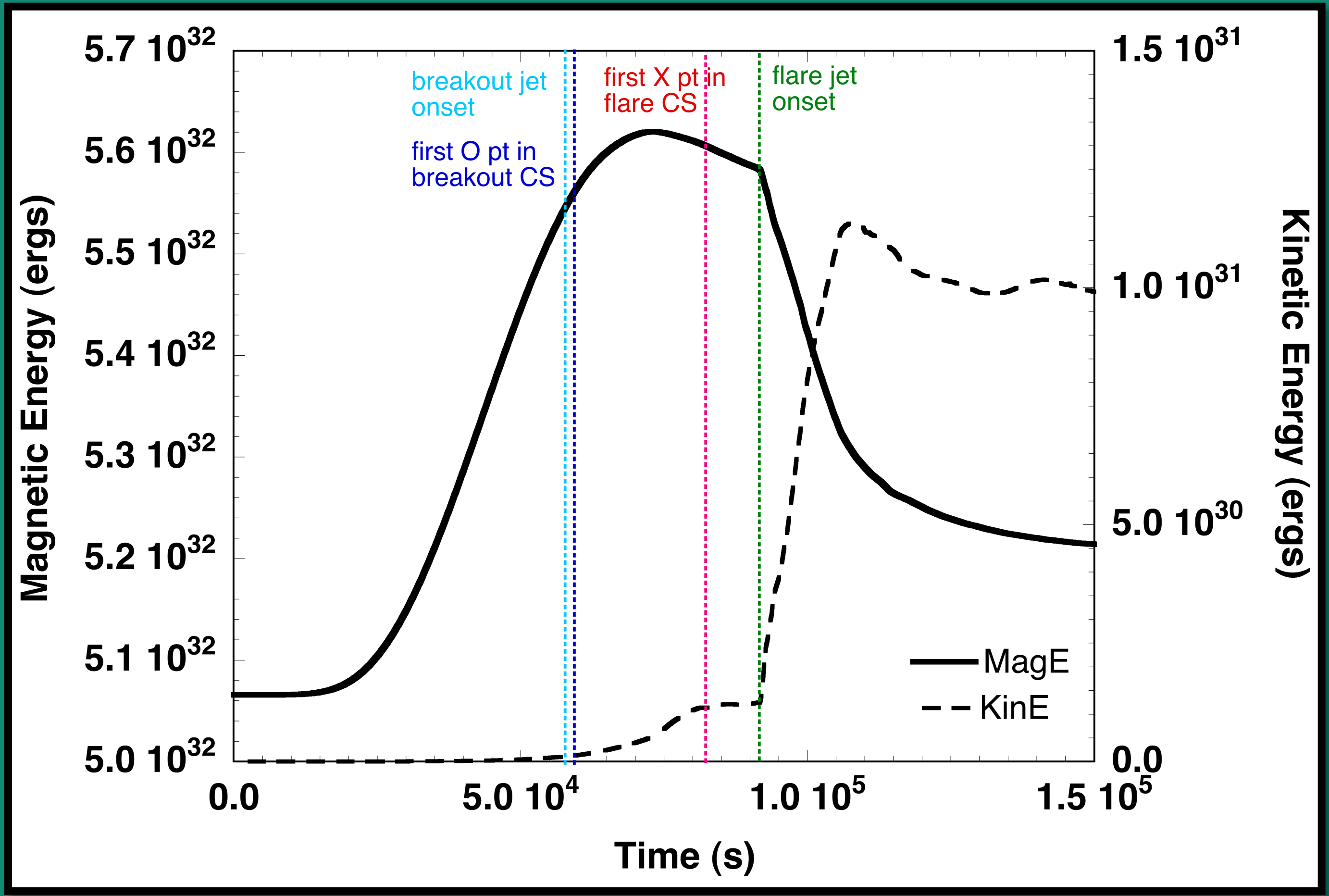
Observed vs. Simulated Islands



SDO/AIA images

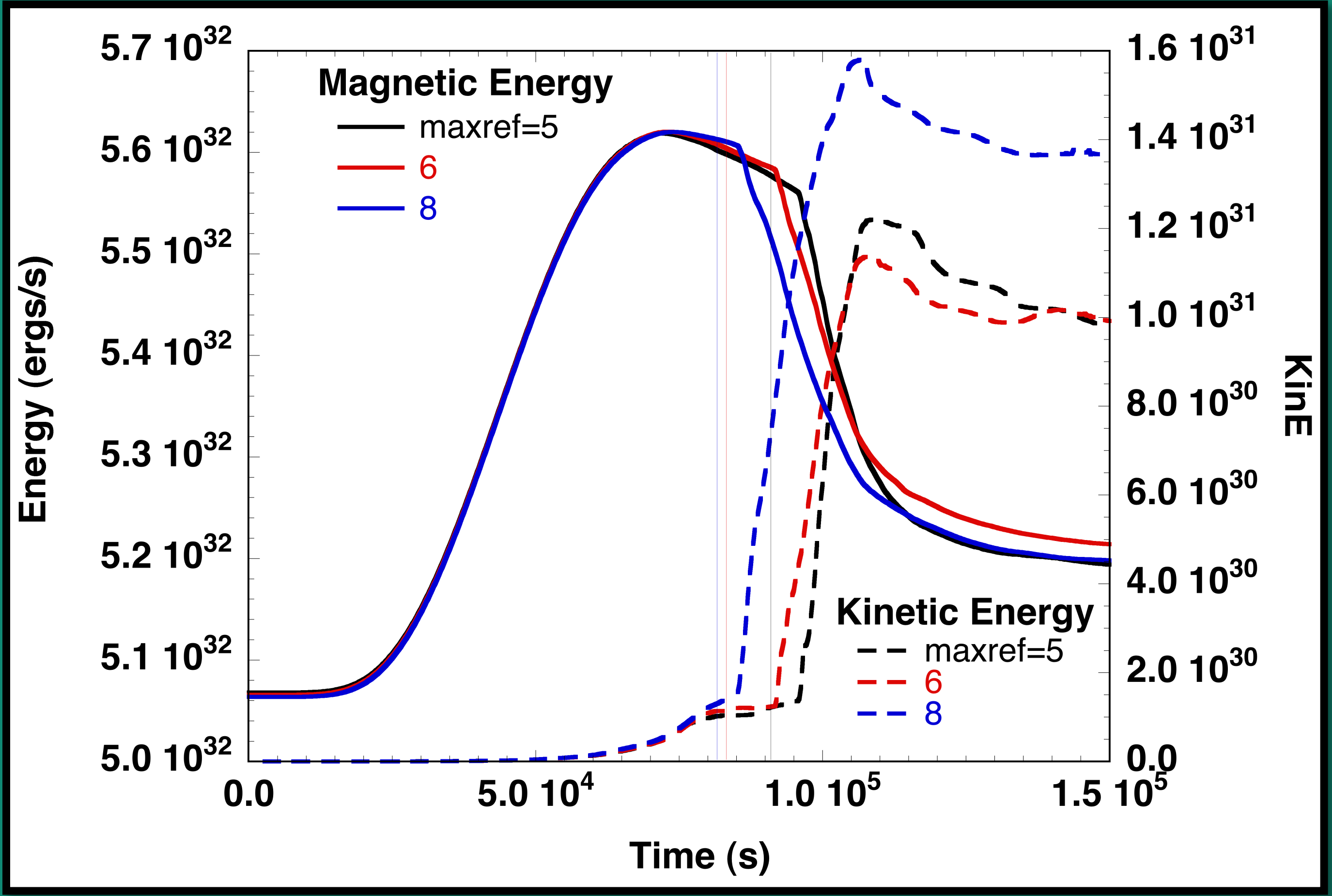


Energy Evolution



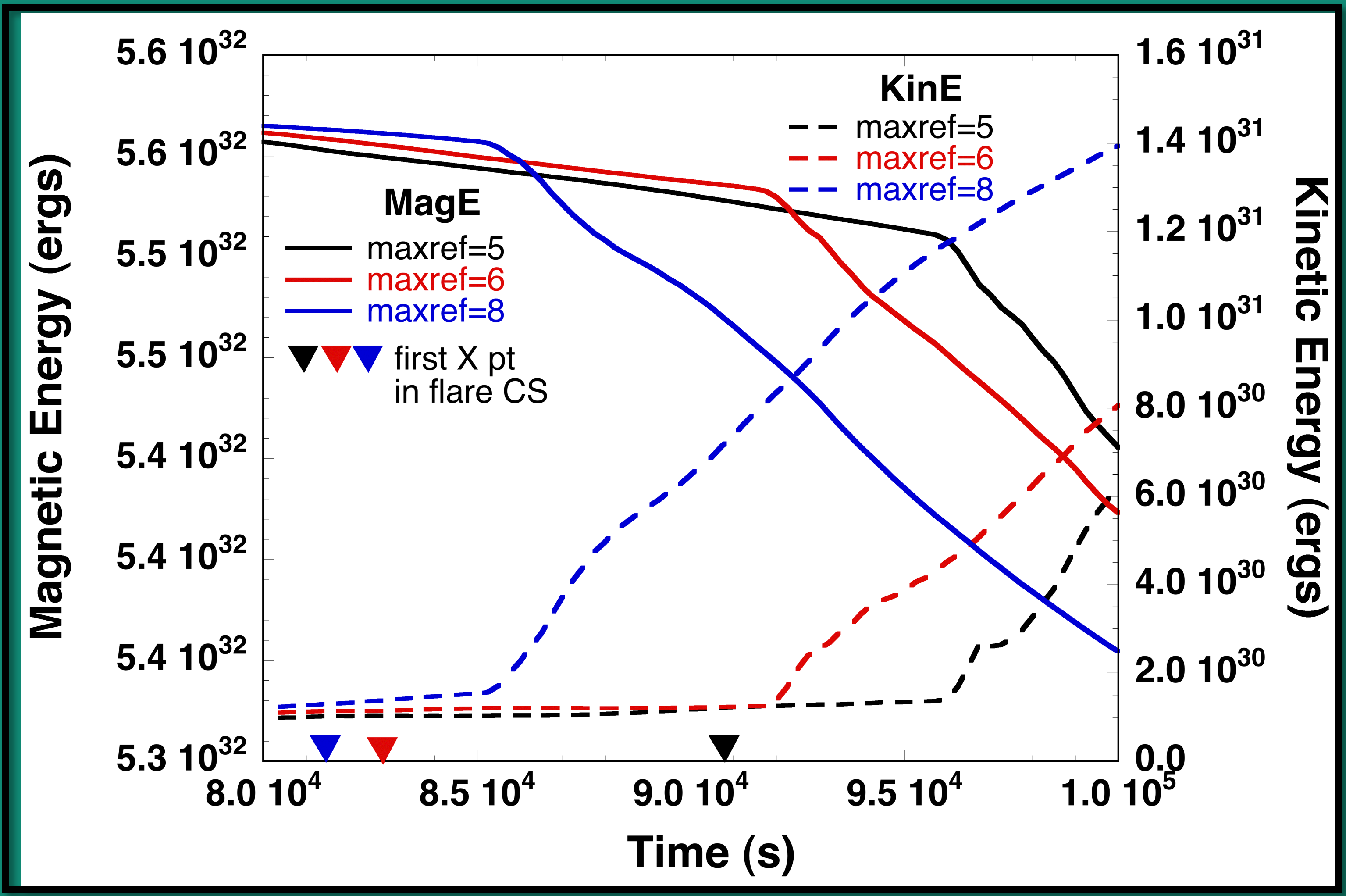
- Time history of magnetic and kinetic energies
  - CME onset corresponds to start of breakout reconnection
  - "Take-off" corresponds to start of fast flare reconnection

Scaling with S: Energy



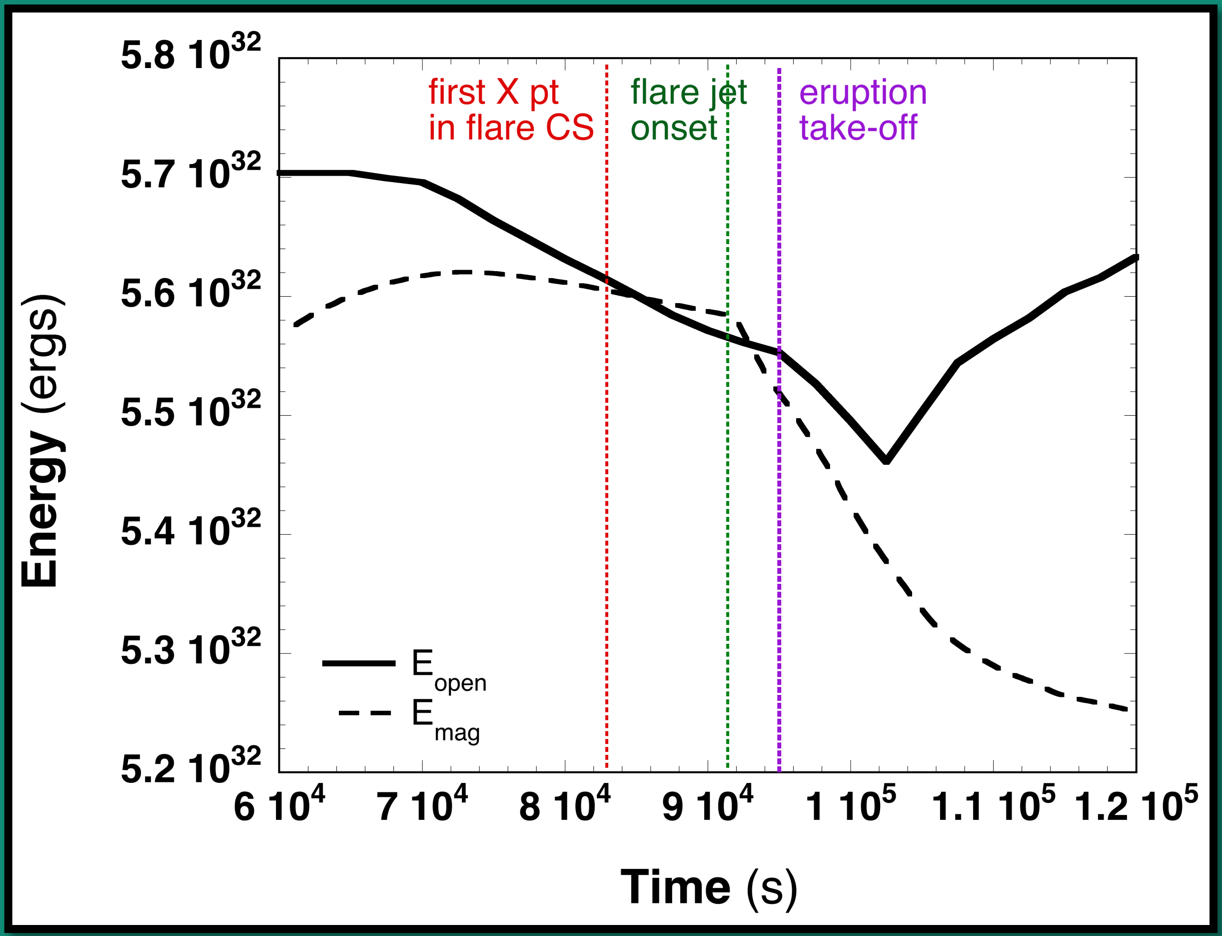
- Basic onset and take-off evolution insensitive to S
  - Weak energy dependence on S (refinement level x 2)
- Eruption dominated by MHD, E partitioning by kinetics

Effects of Resolution on Flare Onset



- First flare X point appears BEFORE sharp rise in Kinetic Energy (eruption)
- Higher resolution (higher S) → earlier eruption

Eruption Mechanism



- Magnetic energy vs energy of corresponding "open" state
  - No evidence for ideal instability/loss of equilibrium
  - Resistive instability

Roles of Reconnection

- **Initial breakout reconnection**
  - Removes overlying flux by transfer to adjacent system
  - Feedback loop between expanding core acceleration and reconnection rate (exponential growth)
- **Flare reconnection**
  - Forms flux rope and accelerates CME
  - Enables system to relax to lower energy state
  - Accelerates electrons via shocks, plasmoids, ?
- **Feedback between breakout and flare reconnection enhances <u>both</u> rates**

Comparison with Observations

- ✓ Fast (Alfvénic) eruption *(most important test)*
- ✓ Classic three-part structure: *shell, cavity, core*
- ✓ CME = flux rope
- ✓ Post-eruption loops form while CME lifts off
- ✓ Widening flare ribbons at base of post-eruption loops
- ✓ EUV and H-alpha remote brightenings from breakout reconnection (Sterling et al. 2001; SOHO)
- ✓ Prolific plasmoid formation
  - ✓ downward moving plasmoids in early impulsive phase (Sui, Holman & Dennis 2003; RHESSI)
  - ✓ plasma blobs in flare sheet (Takasao et al. 2011; SDO)
  - ✓ plasmoid shrinkage may accelerate electrons (Drake et al. 2005; Guidoni et al., in preparation)

Conclusions

- Breakout model explains many important features of fast CMEs/eruptive flares
- Fast reconnection dominated by plasmoid formation
  - Favors Drake mechanism for particle acceleration
- Self-consistent driving and formation of current sheets are crucial
- Next steps:
  - Scaling with magnetic Reynolds number S
  - Incorporate parametrized kinetic-scale flux breaking
  - extend to 3D
  - develop robust model driven by observed conditions
- **Need more observational tests!!**
  - **next-generation hard X-ray imager**
  - **next-generation coronagraph**

Summary: Scaling to Active Regions

$t_{sim}/t_{obs} \approx B_{obs}d_{sim} / B_{sim}d_{obs} \approx 950$

- **Temporal estimates**
  - interval between reconnection onsets in breakout and flare current sheets ≈ 25 s
  - interval between first X pt and jet onset in flare sheet ≈ 9 s
  - delay between jet onset and eruption take-off ≈ 3 s
  - impulsive phase lasts 7-34 s
- **Spatial estimates**
  - longest-lived preflare reconnection site moves down ~22 arcsec
  - comparable downward shift in main impulsive-phase X pt
  - top of flare arcade rises ~33 arcsec (≈ max. lower jet length) during peak impulsive phase