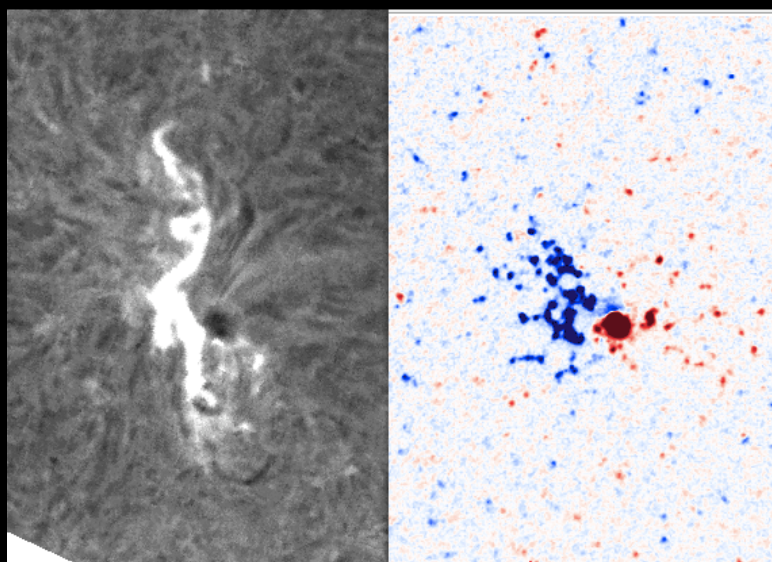
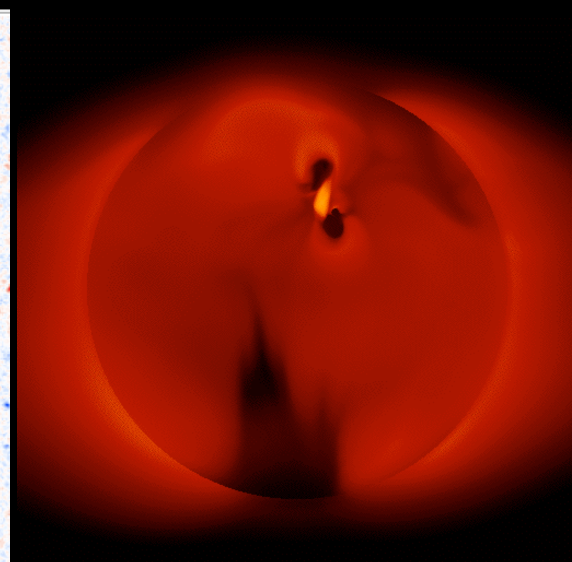
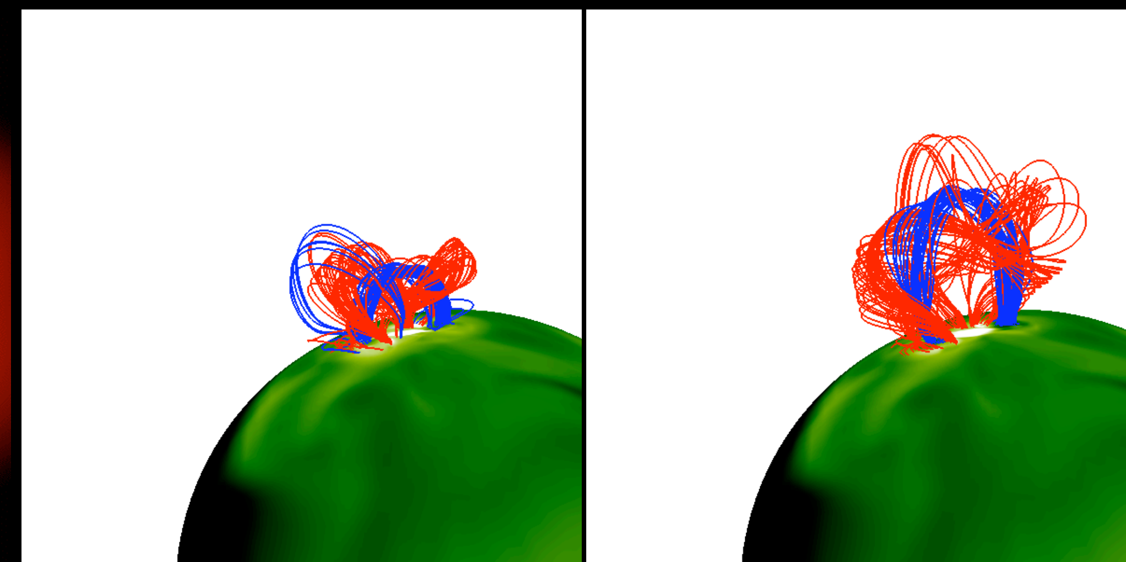
Understanding Eruptive Phenomena with Thermodynamic MHD Simulations

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Introduction

- Why is it so hard to understand and model CMEs?
- The structure and dynamics of the solar magnetic field is crucial.
- It is difficult to ascertain from observations what the pre-event magnetic field structure is, and how much free energy resides in the field.
- Models attempt to describe the magnetic field evolution with assumptions about the pre-event corona
- Discussion/debate often centers upon the interpretation and comparison of modeled magnetic field structure/evolution with features observed in emission.
- For a meaningful comparison, models should be able to produce emission so that they can be *directly* compared with observations.

Introduction (continued)

- Through innovations in the treatment of the transition region, we have been able to extend global 3D models of the corona to predict EUV/X-ray emission.
- I believe that this type of modeling can be used to obtain a deeper understanding of emission features.
- Example: What is the magnetic structure of dimming regions? (2nd part of talk)
- To look at this question, we needed to improve upon the initial simulation results
- The first part of the talk discusses how we obtained a better match to observational features

MHD Equations

(Improved Energy Equation Model)

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

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

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\,\mathbf{v}\right) = \frac{1}{c}\mathbf{J}\times\mathbf{B} - \nabla p - \boxed{\nabla p_w} + \rho\mathbf{g} + \nabla\cdot(\nu\rho\nabla\mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla\cdot(p\mathbf{v}) = (\gamma - 1)\left(-p\nabla\cdot\mathbf{v}\;\boxed{-\nabla\cdot\mathbf{q} - n_e n_p Q(T) + H}\right)$$

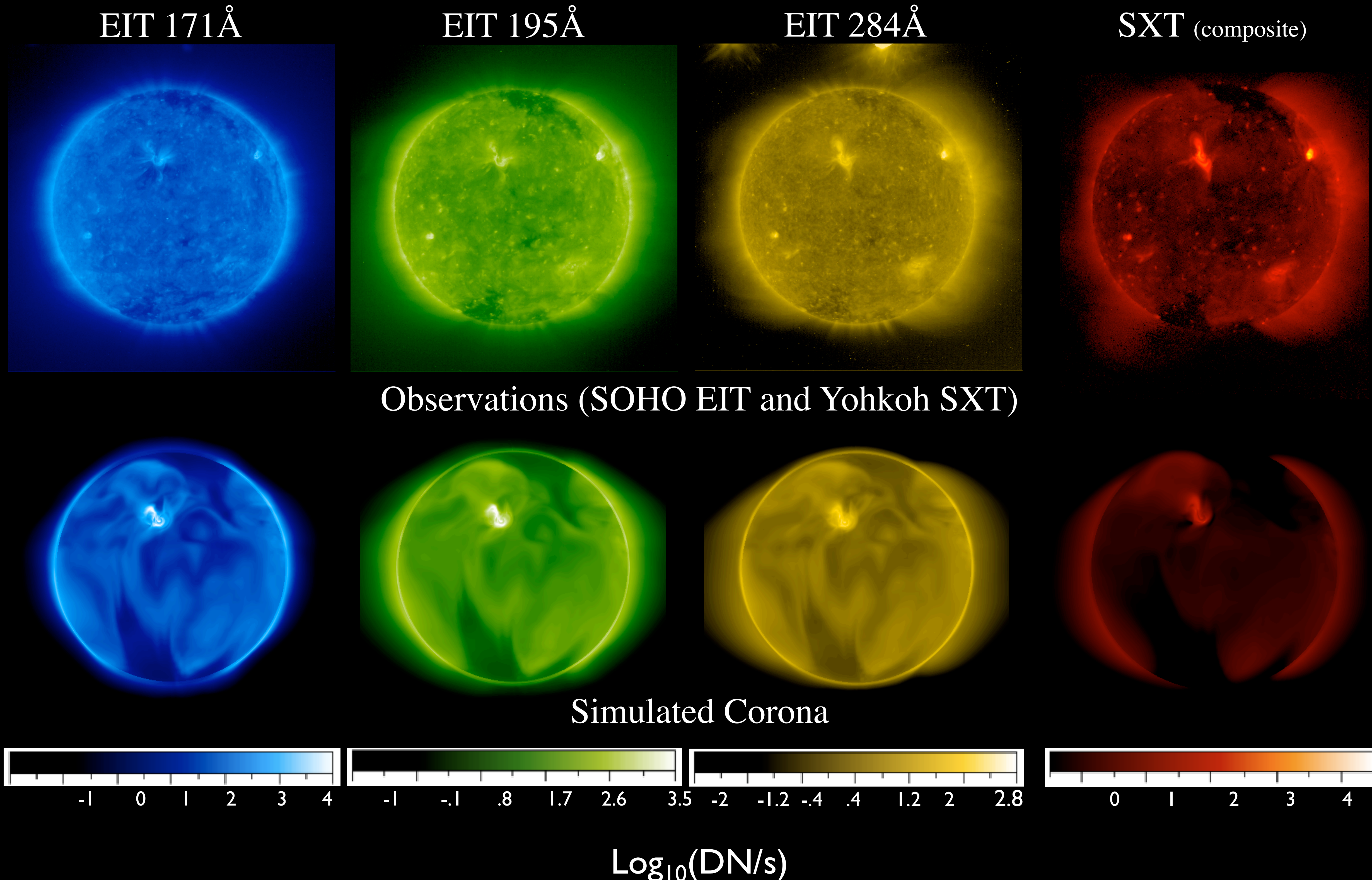
$$\gamma = 5/3$$

$$\mathbf{q} = -\kappa_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\nabla T \qquad \text{(Close to the Sun, } r \lesssim 10R_S\text{)}$$

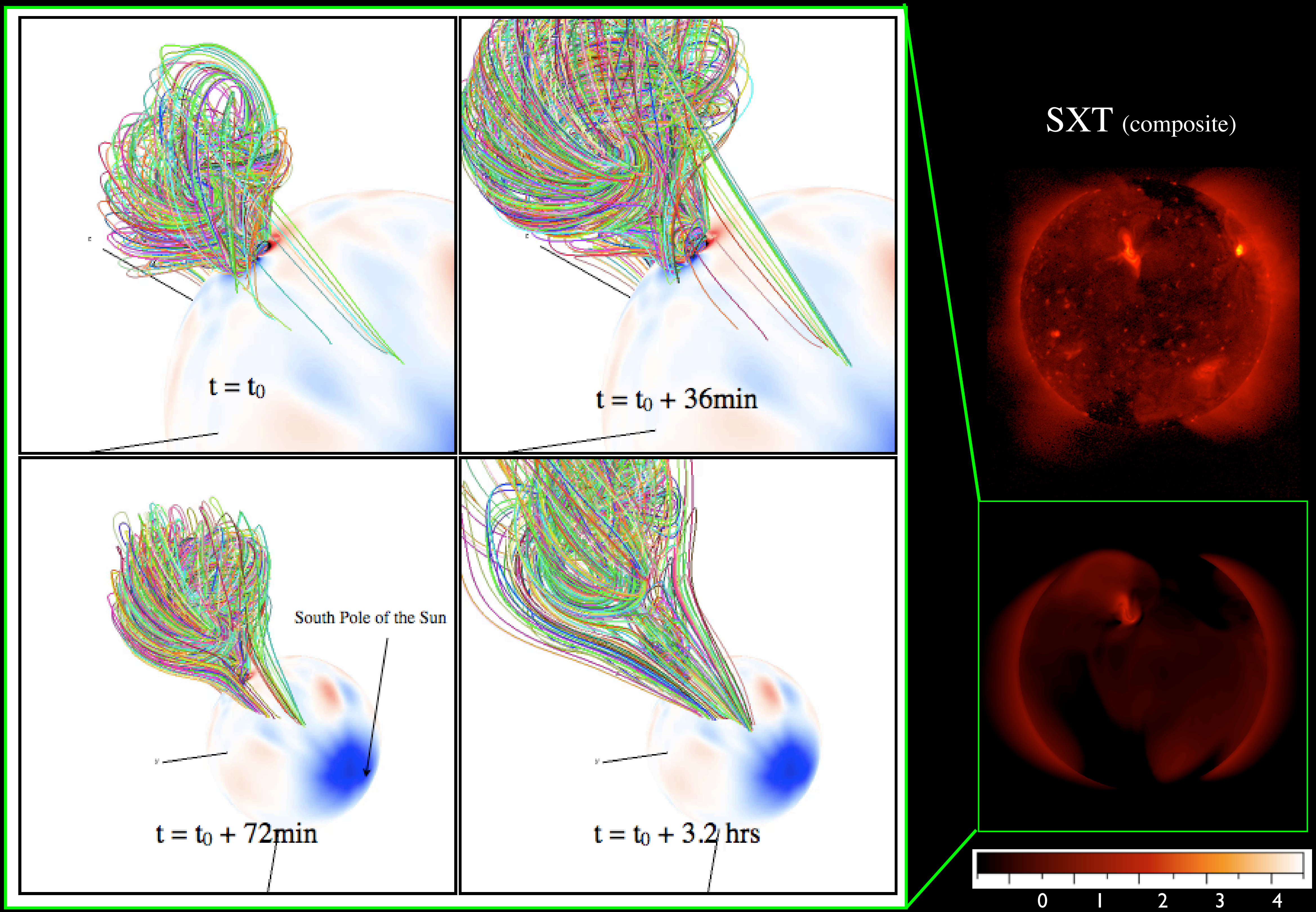
$$\mathbf{q} = 2\alpha n_e T\,\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\mathbf{v}/(\gamma - 1) \qquad \text{(Far from the Sun, } r \gtrsim 10R_S\text{)}$$

+ WKB equations for Alfvén wave pressure p_w evolution

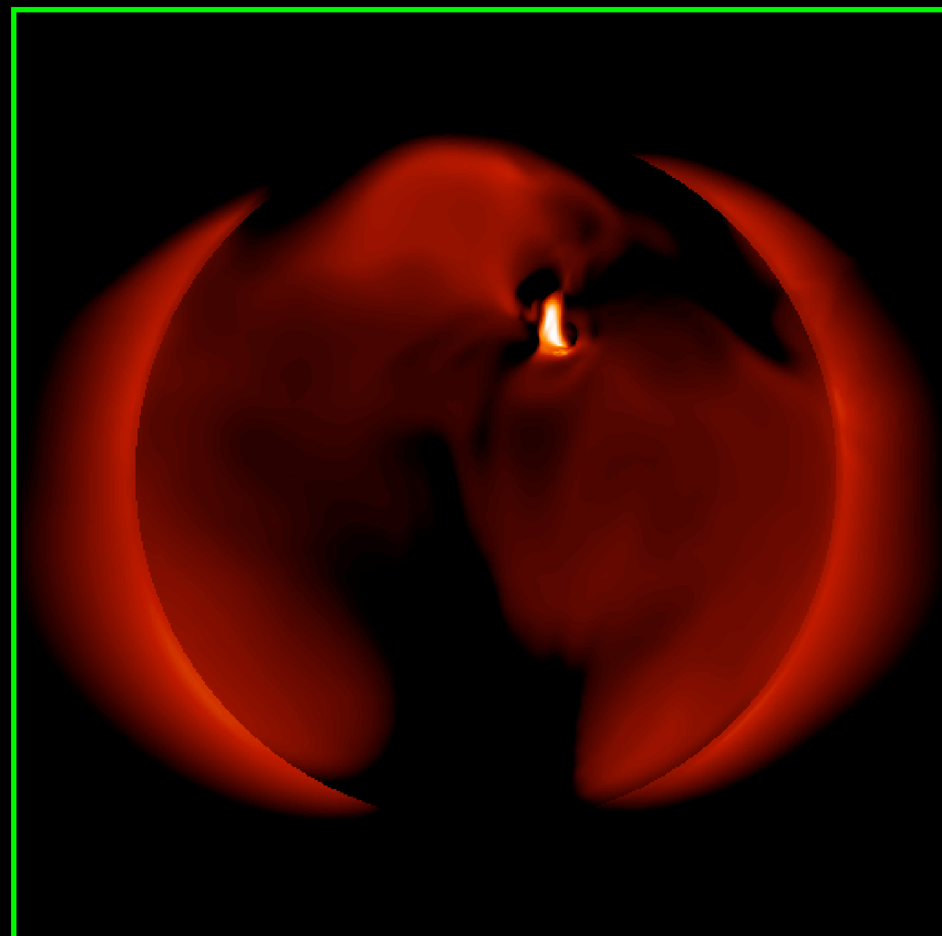
May 12, 1997 CME: Comparison of the Simulated Pre-event Corona with Observations



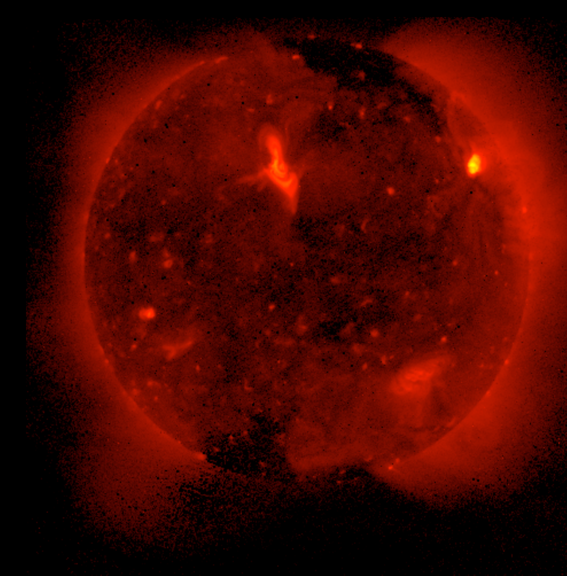
Magnetic Field Evolution in a CME Simulation: CME fluxrope propagates outward from the Sun

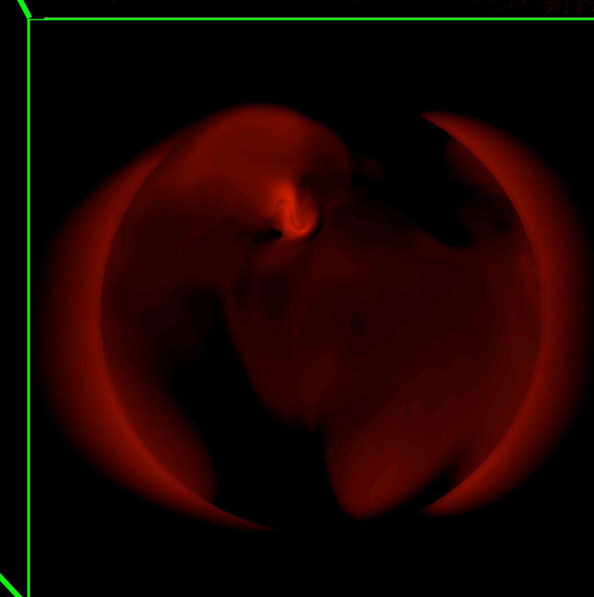


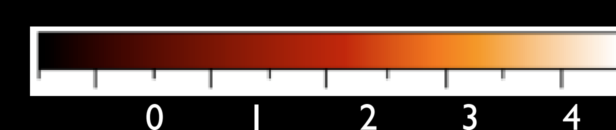
Simulated X-ray emission: Dimming regions and post-CME loops



SXT (composite)





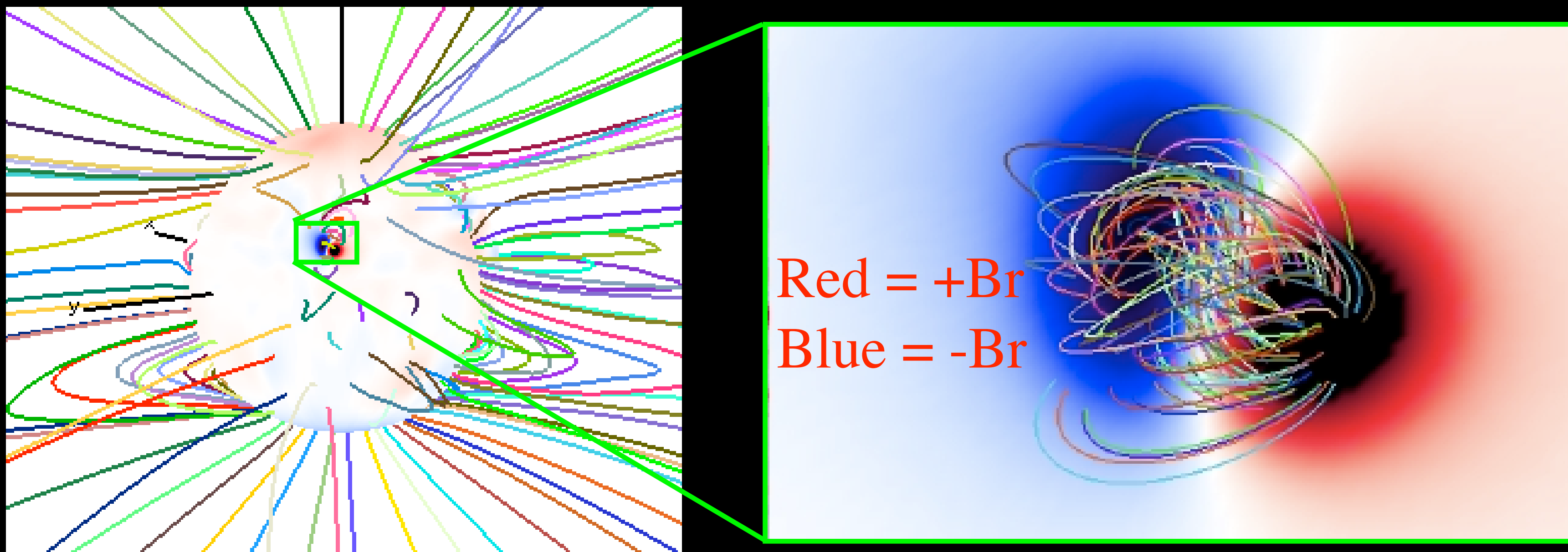


- Simulation shows dimming region, postflare loops, EIT waves, flux rope at 1 AU
- But ...
- Eruption is too weak
- Dimming primarily in the north

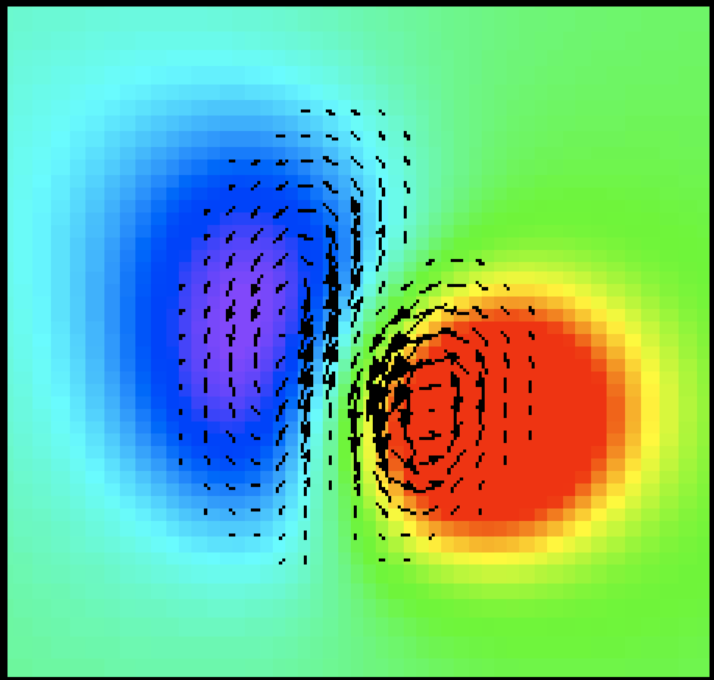
Shear Introduced by Flux-Preserving Flows

Global View

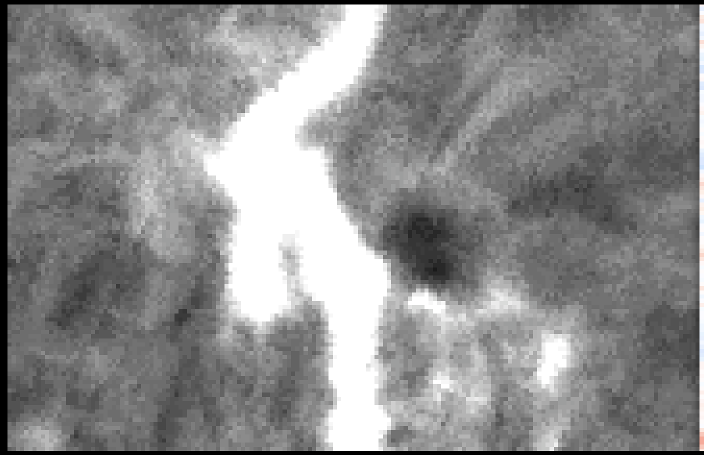
Sheared/twisted Field in AR



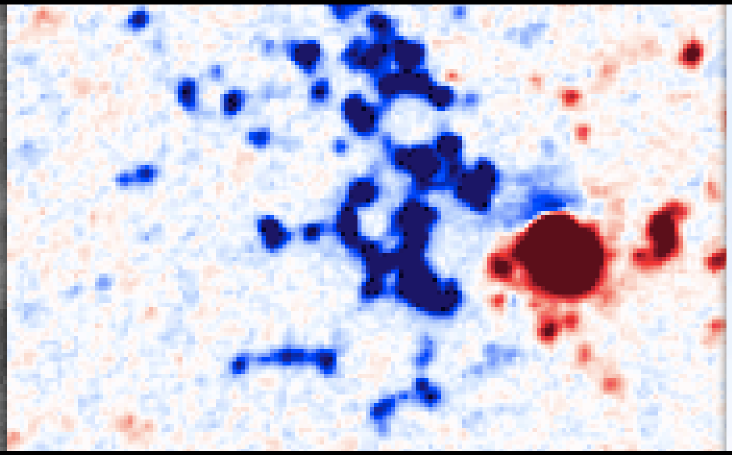
Vortical flows used for Shear



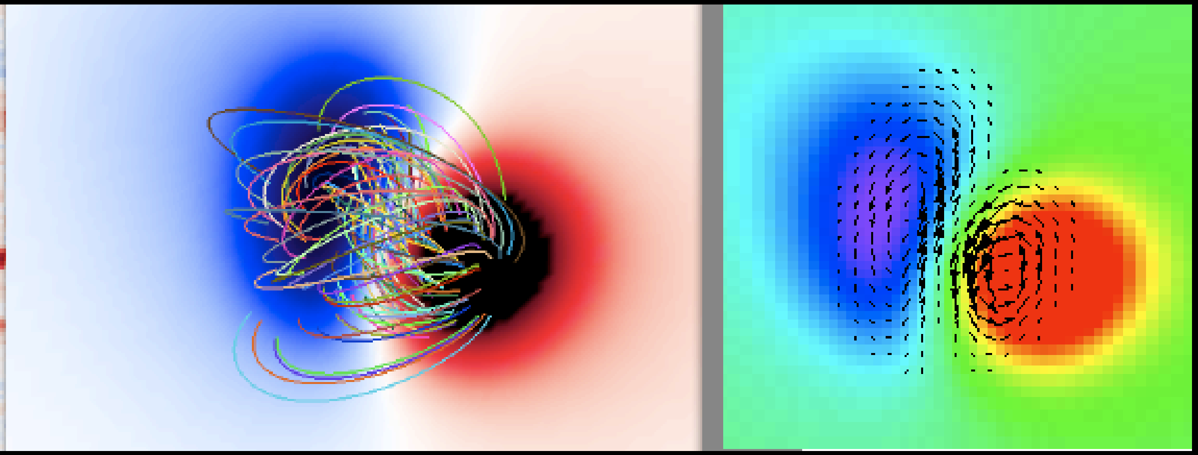
Filament channel & flare (SOON Hα)



NSOKP magnetogram

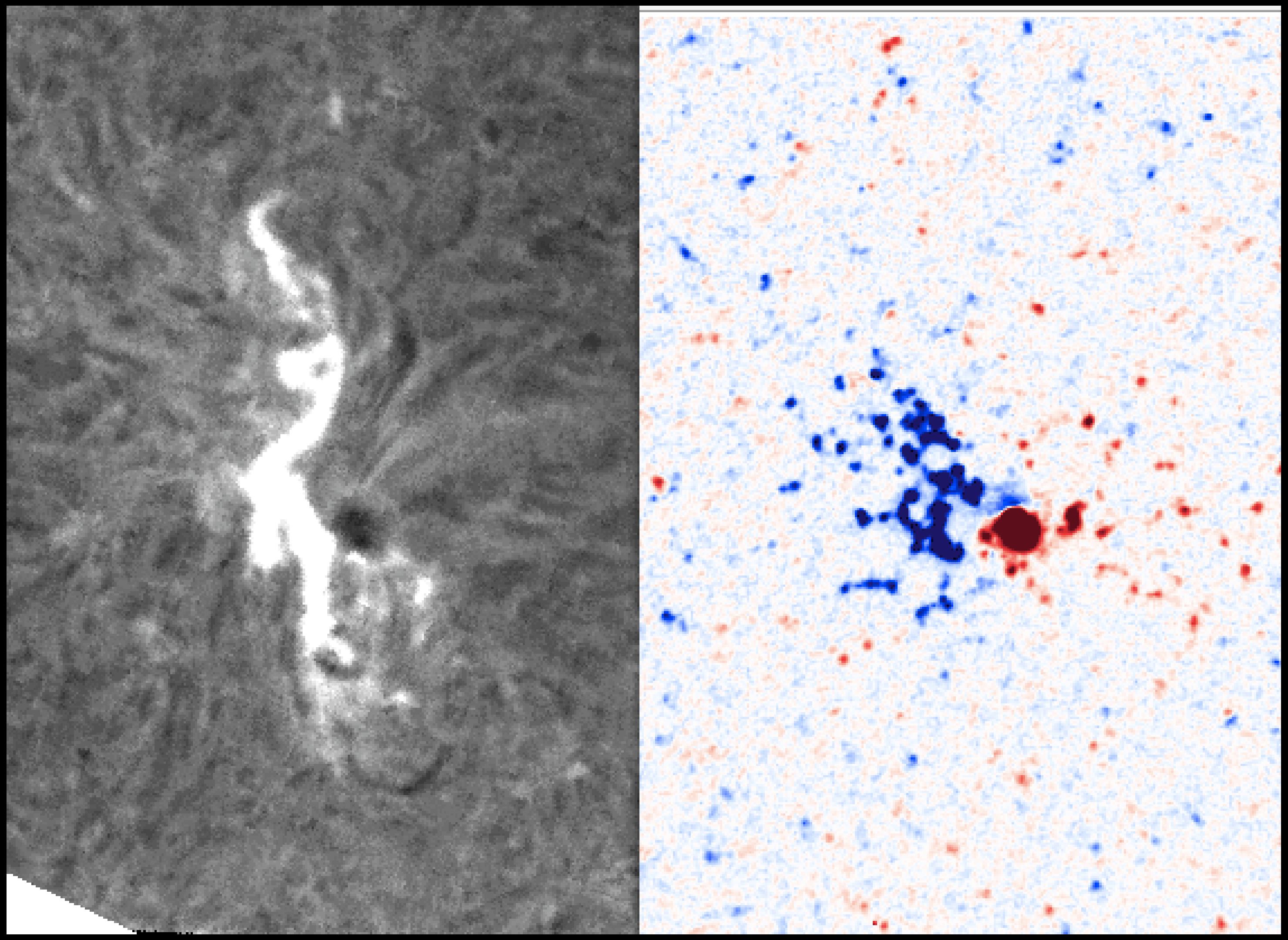


Smoothed Map



- Shear introduced in the vicinity of large B_r only - not parallel to PIL
- In real case, filament channel (and shear) are much longer and aligned with PIL

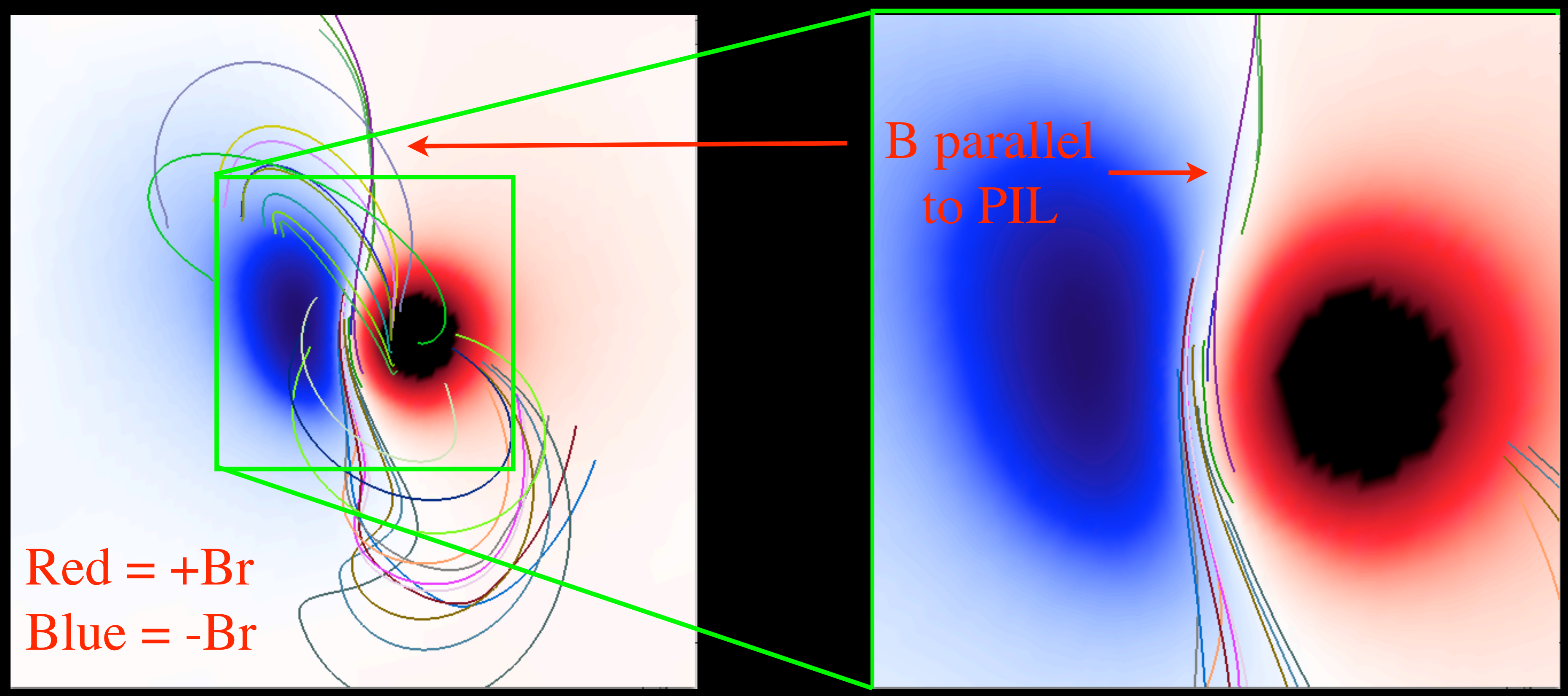
Filament Channel & Resulting Eruption



- The filament channel and the resulting flare extend well outside the center of the active region
- Flows in the active region will never create this shear
- How do we deal with this?

Introducing Shear Parallel to the Polarity Inversion Line

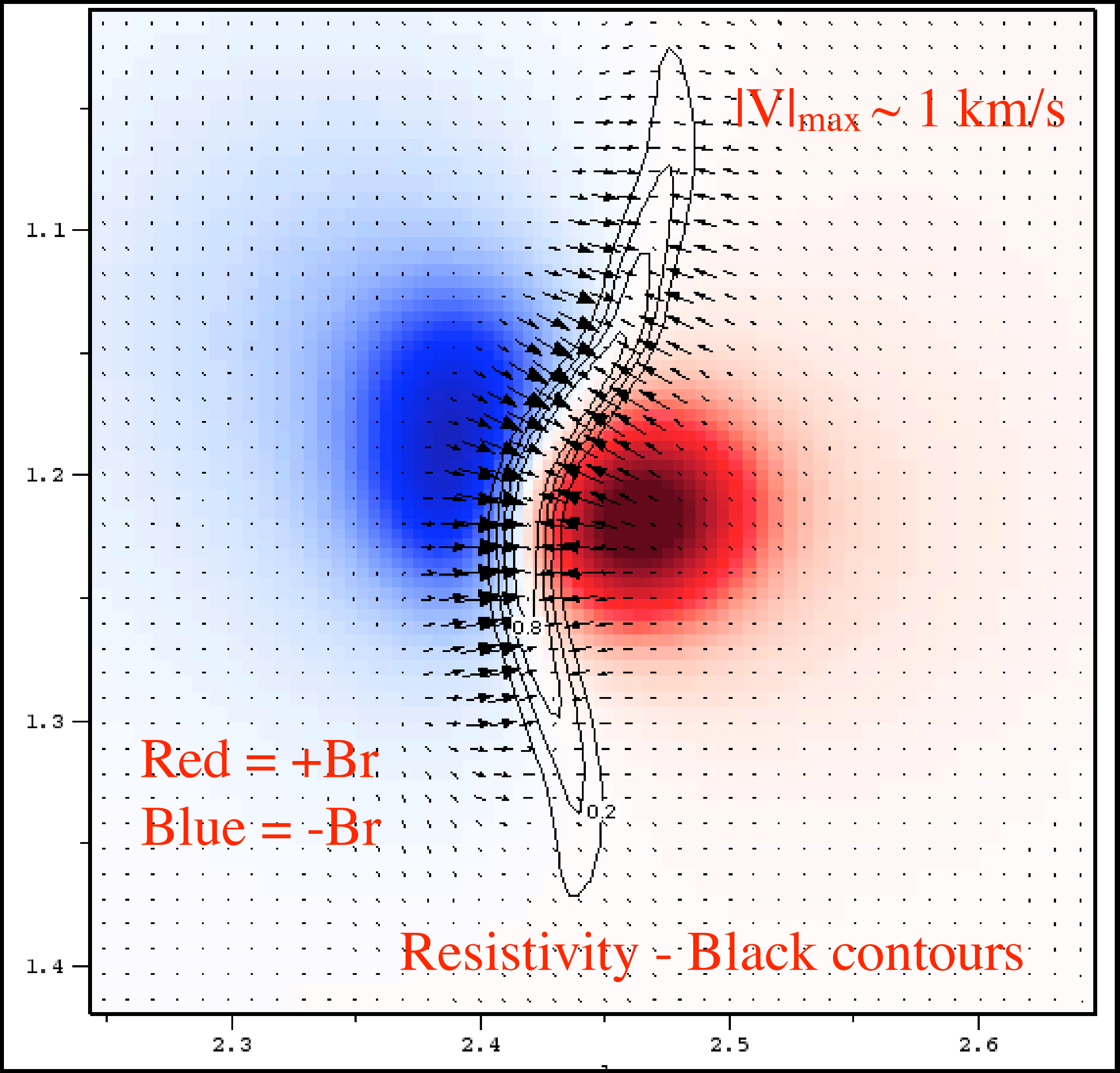
- Filament channels have magnetic fields nearly parallel to the polarity inversion line (PIL)
- It is difficult to develop such magnetic fields with flows
- We noticed that in applying our technique for matching vector magnetograms, the algorithm emerged shear along the PIL
- We apply an $\mathbf{E}_{\mathbf{tangential}}$ at the boundary that emerges sheared $\mathbf{B}$ parallel to the PIL



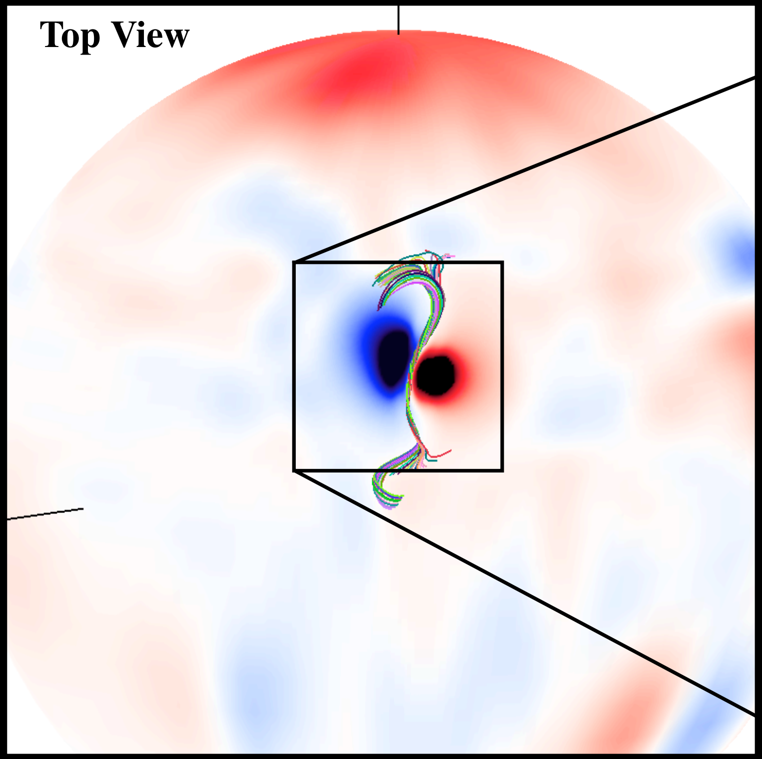
- No flux rope forms (yet)

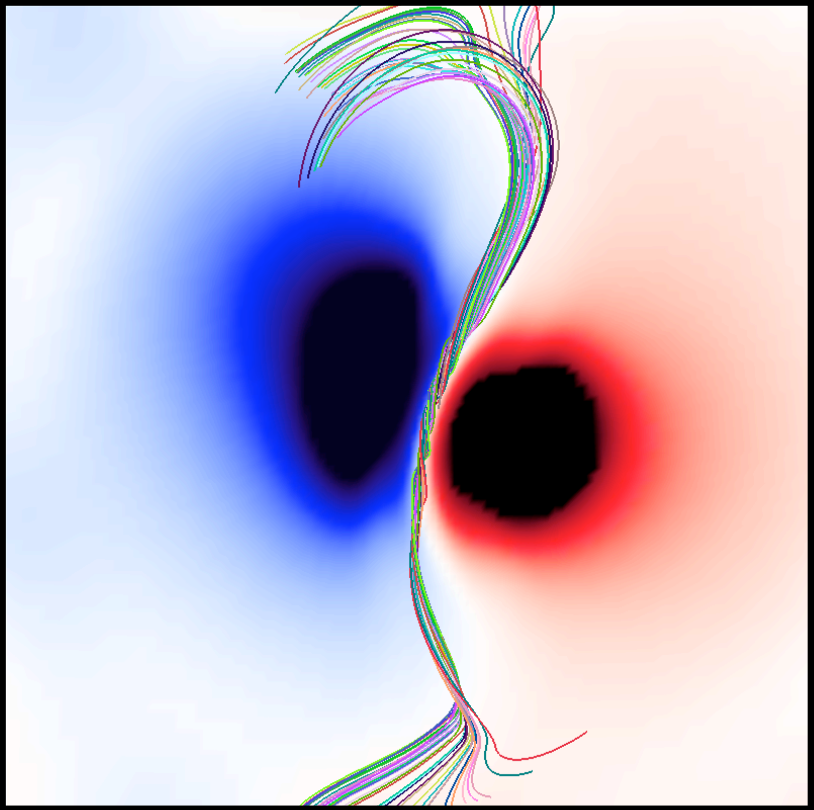
Converging Flows and Flux Cancellation

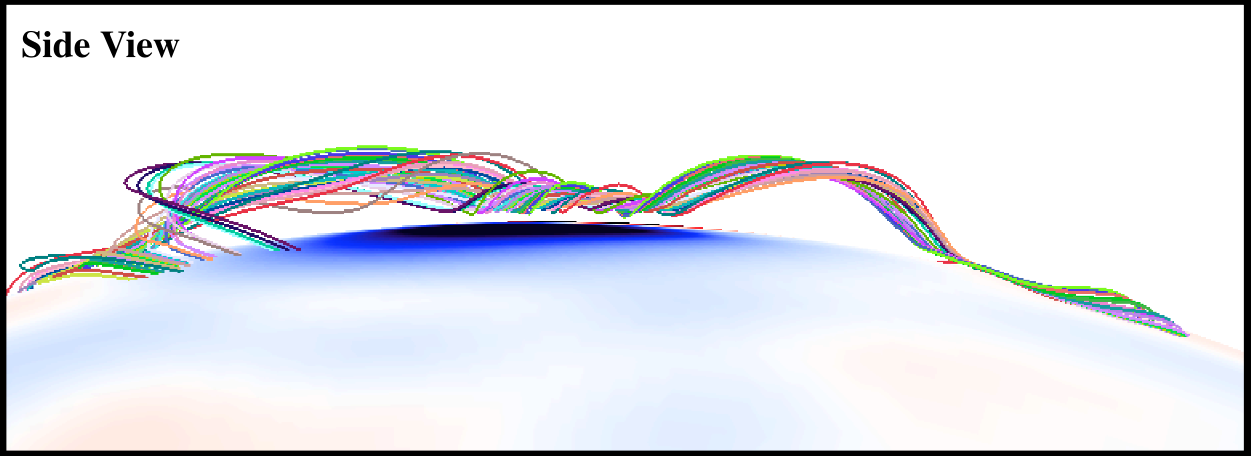
- Flux cancellation was observed prior to (and during) the May 12, 1997 CME
- To cancel flux, we apply converging flows perpendicular to the polarity inversion line (PIL)
- Enhanced resistivity is introduced at the PIL at the boundary only (similar to van Ballegooijen et al.)



Flux Cancellation Leads to Flux Rope Formation



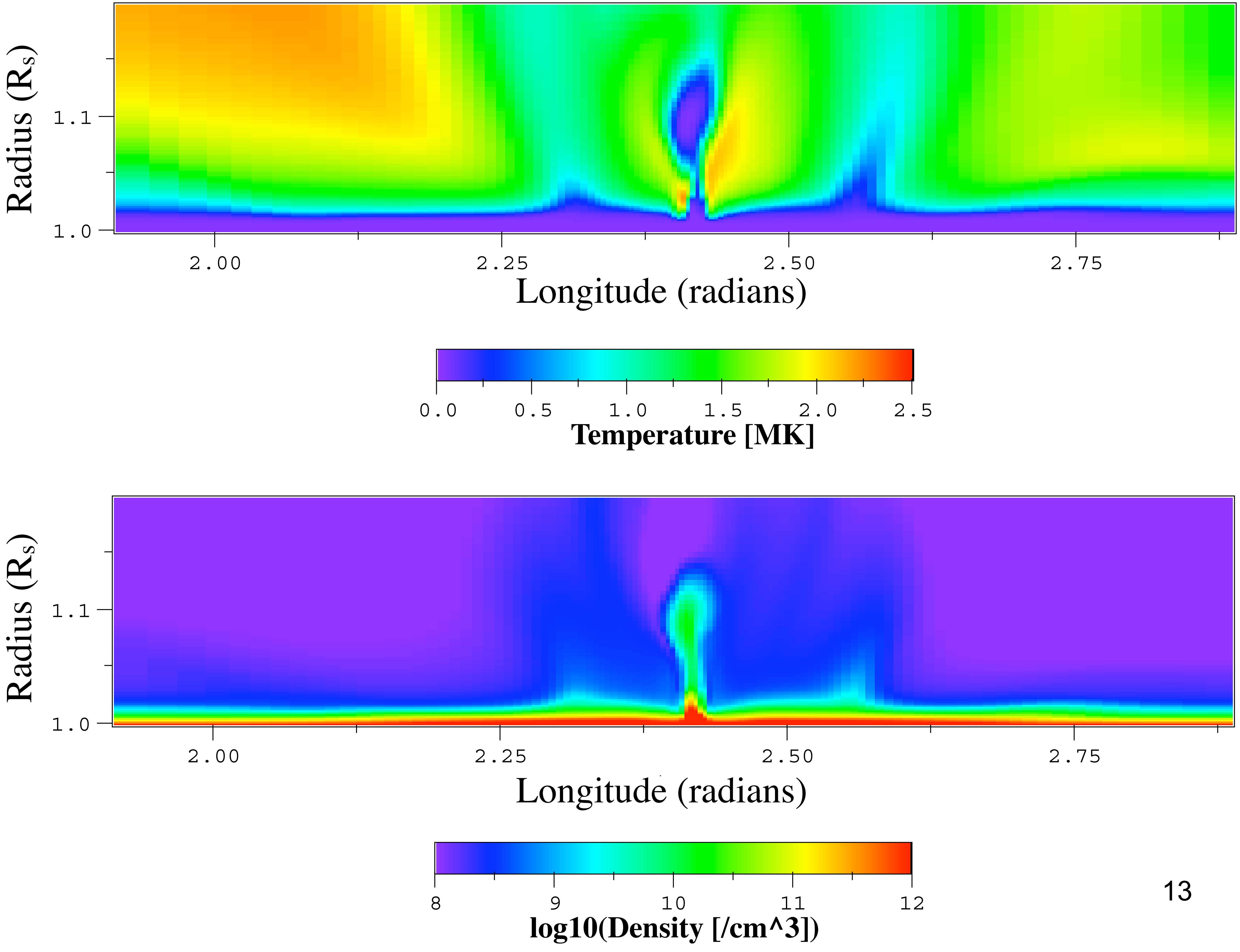




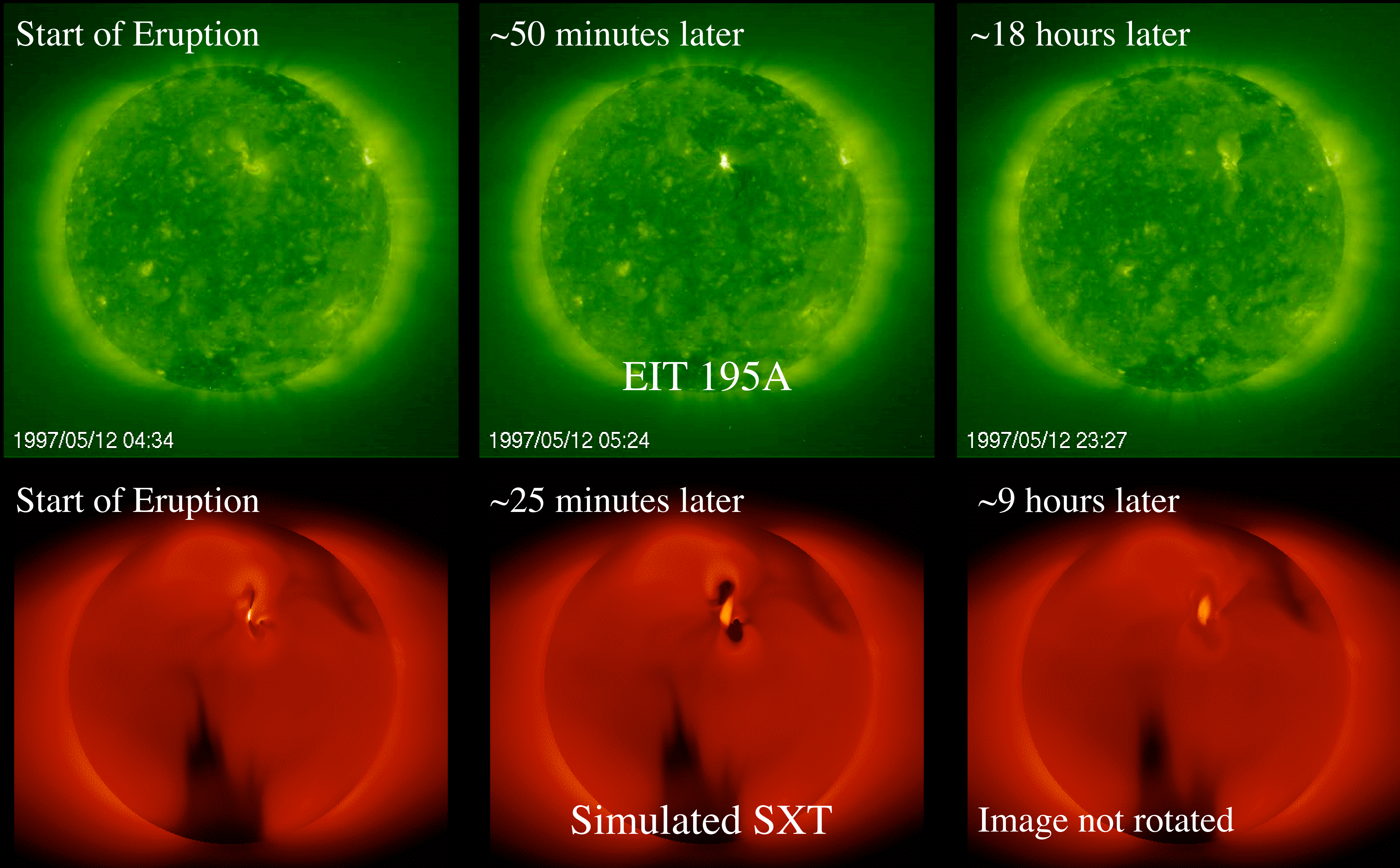
- Prominence-like structure forms along the PIL
- Cold, dense plasma (4 x10^4 K, 10^{10} #/cm^3) is lifted into the corona
- With continued cancellation, the structure erupts

Formation of a "Prominence" by Flux Cancellation

- A cut in co-latitude, of Density and Temperature (Eruption starting)

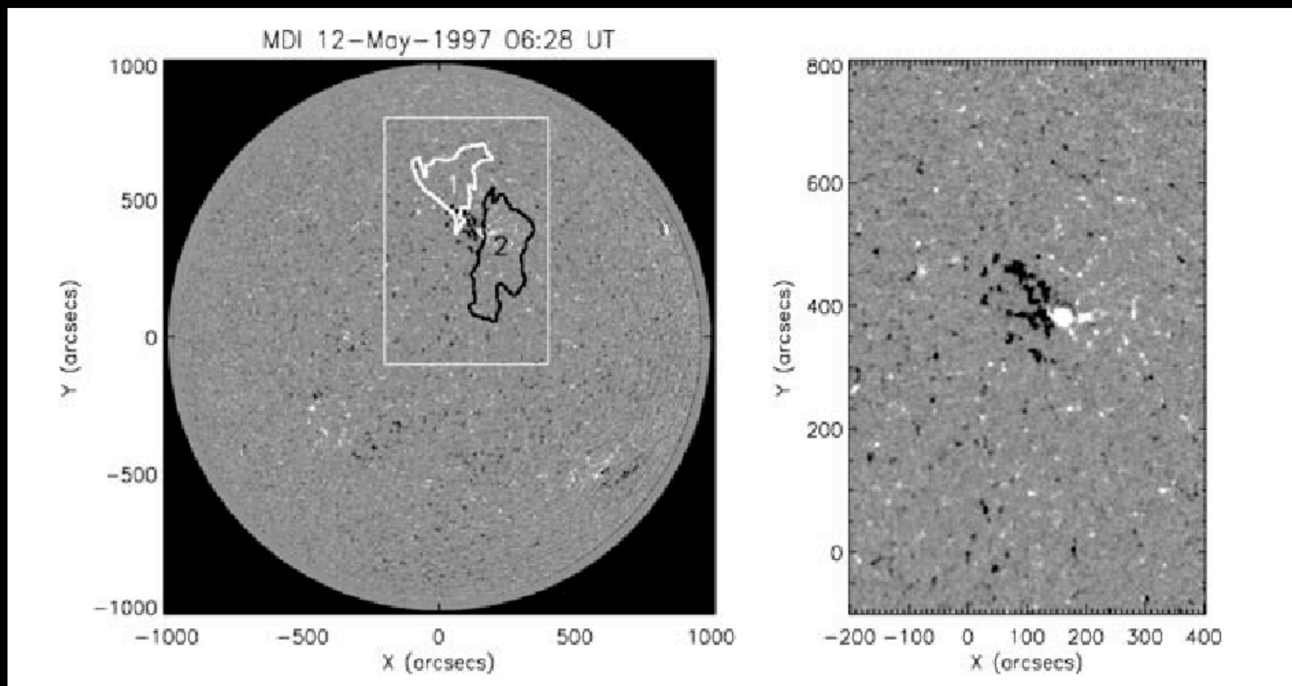


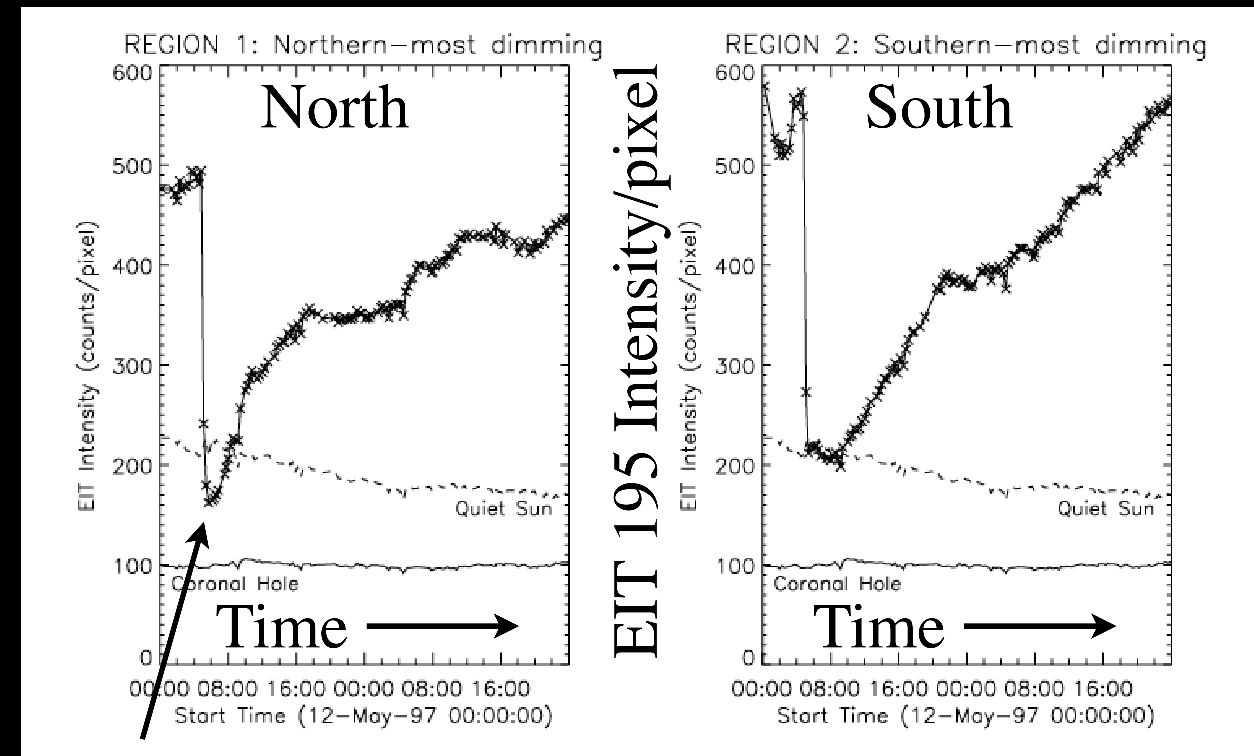
Comparison of Dimming Regions in New Simulation

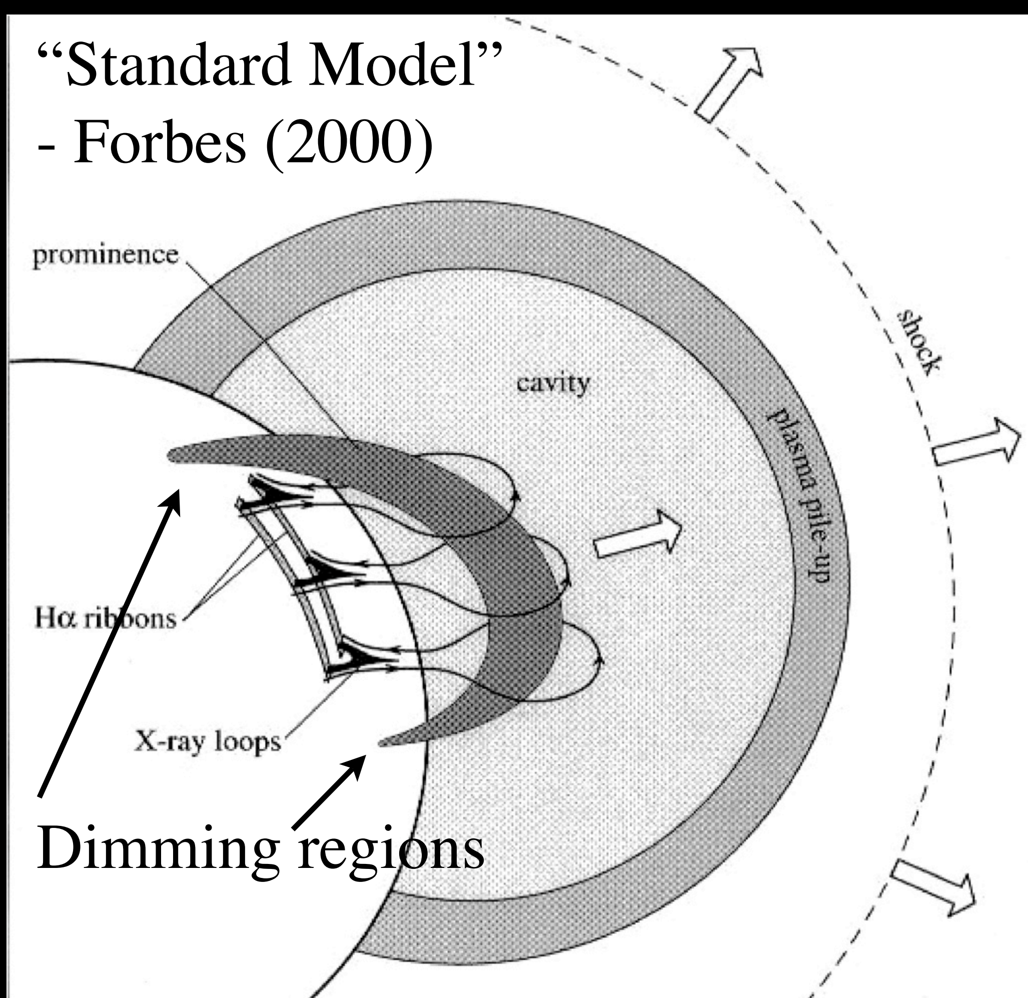


- Both North and South Dimmings now well developed in the simulation
- Shape and location still differs

Analysis of Dimmings - Attrill et al. (2006)



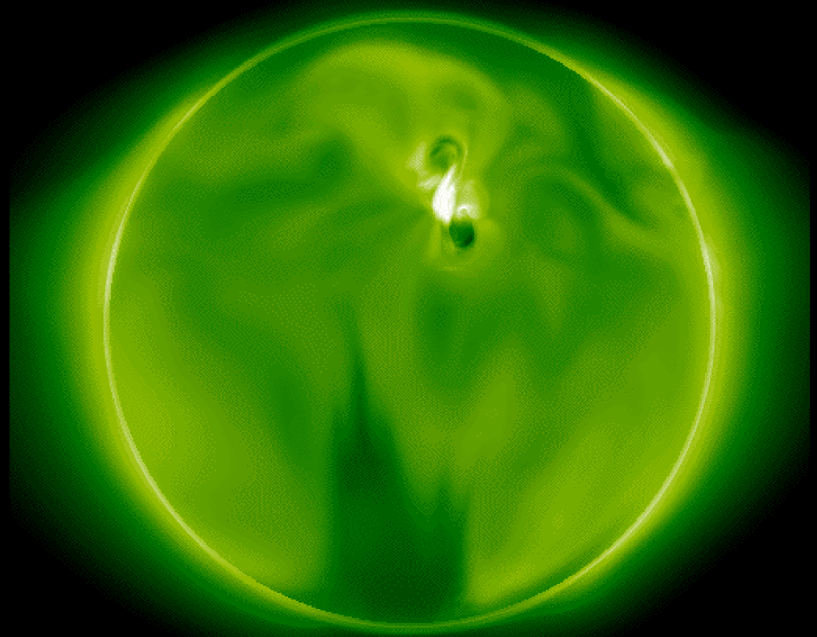




- Computed counts/pixel in dimming regions
- Images differenced from base image prior to eruption
- Dimmings can be seen for ~2 days
- Correlated flux in dimmings with flux in magnetic cloud at 1 AU
- Concluded that cloud was connected to southern dimming

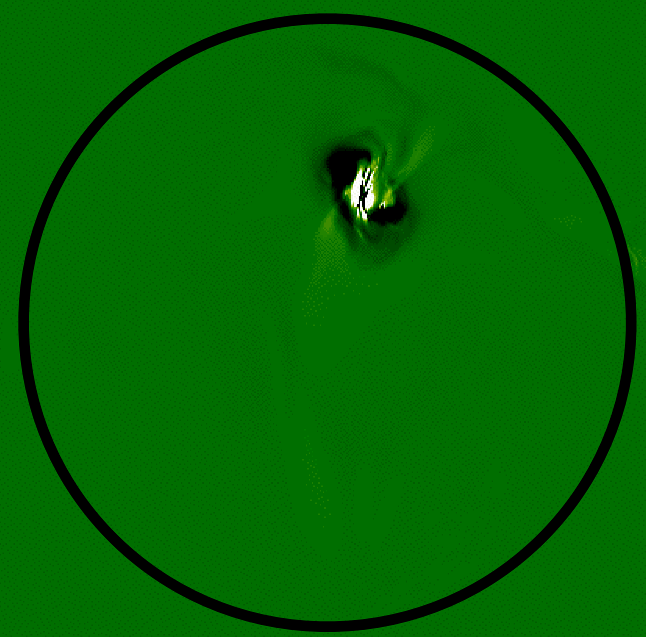
Analysis of Dimming Regions - Simulation

~25 minutes after CME starts

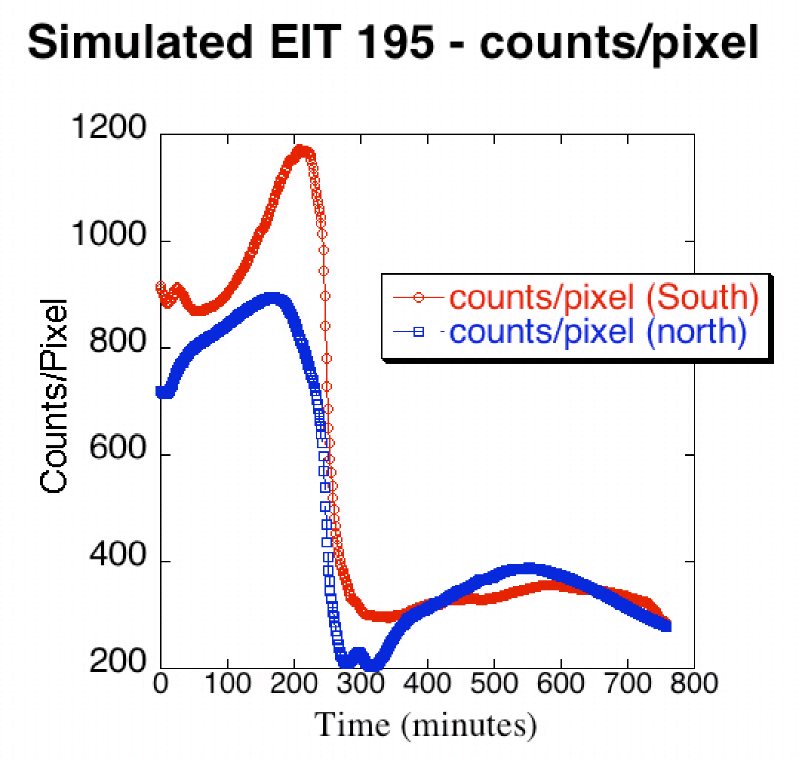


Simulated EIT 195A

~9 hours after CME starts

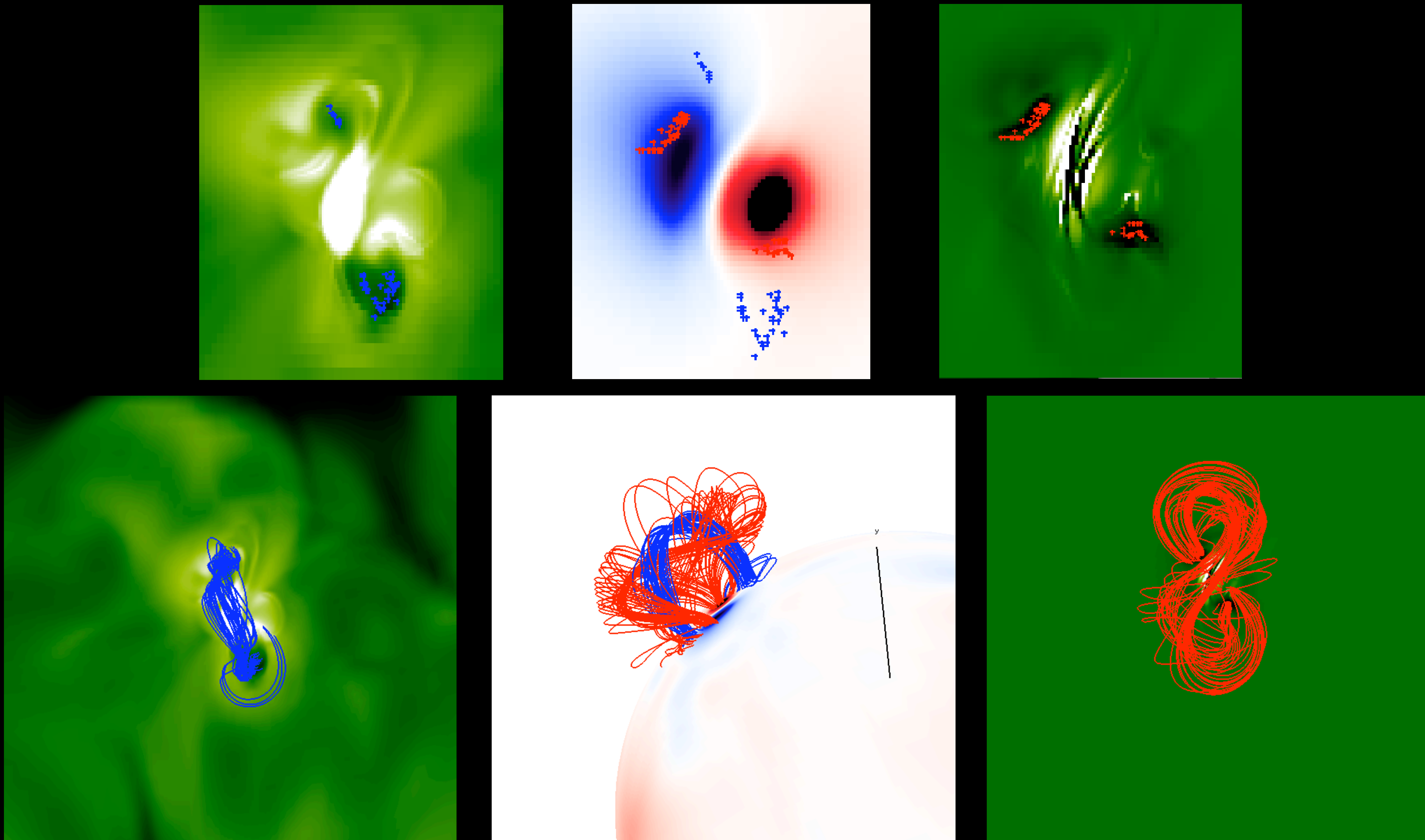


Differenced image - EIT 195A



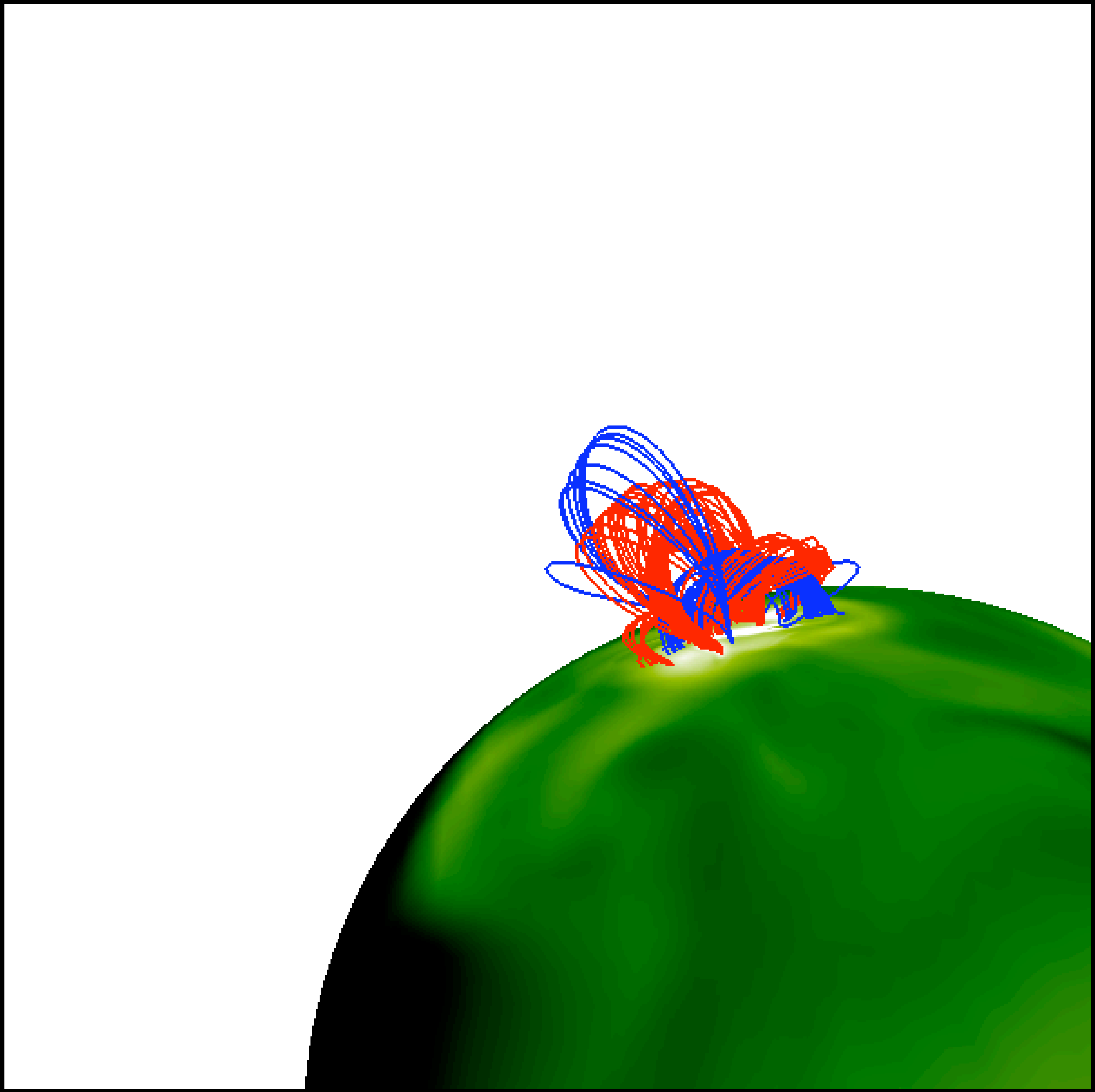
- Dimmings in the simulated images have recovered ~4 hours after CME starts
- Analyzed simulated dimmings in the same way as Attrill et al.
- Dimmings present all 9 hours when analyzed with difference images
- Counts/pixel behavior similar to the observations
- Maximum dimming not exactly co-located with visual image
- What is the magnetic structure of the simulated dimmings?

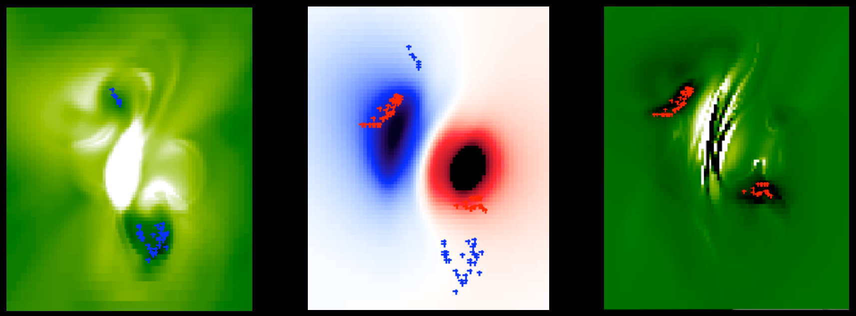
Trace Magnetic Field Lines from Dimming Locations



- Blue footpoints - largest dimming from visual inspection
- Red footpoints - largest dimming from subtracting base image

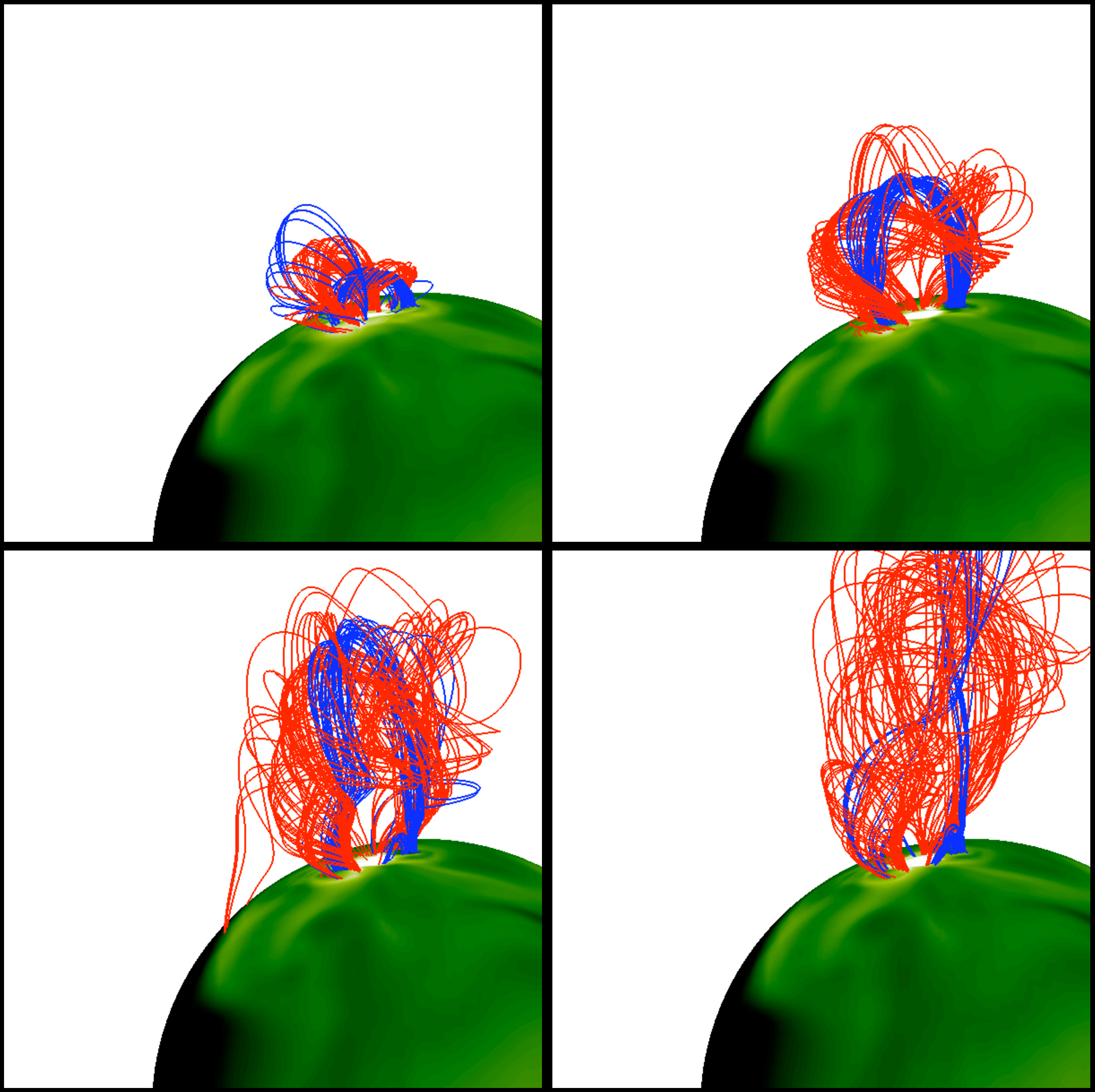
Magnetic Field Lines & Simulated Emission



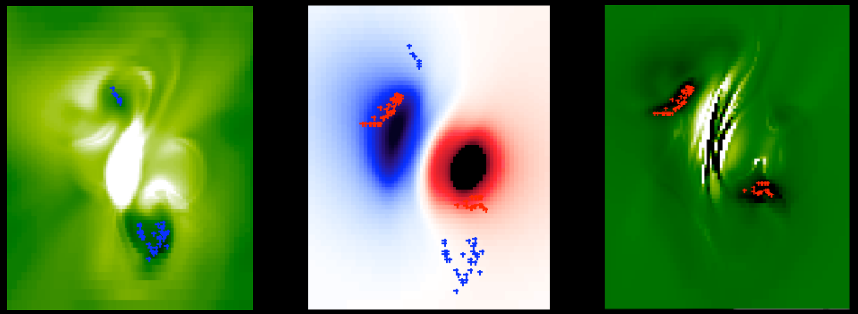


- Blue field lines form the dimmings - but they come from weak flux!
- Red field lines rooted in stronger AR fields
- Blue fields are dragged out by erupting rope
- All fields closed after 9 hours!

Magnetic Field Lines & Simulated Emission



- Not the same as the standard paradigm!
- Caution: Perhaps not directly applicable to May event
- However, real solar fields are even more complicated



Summary

- MHD thermodynamic simulations can be used to understand what magnetic structures underlie observed emission
- The nature of the shear/energization is an important aspect of CME event simulations
  - Results were improved by incorporating sheared field similar to observed filament
  - A prominence-like structure was formed and erupted
- The magnetic structure of the dimmings in the simulation is different than the standard model
  - Field lines originating from the dimmings overlie the erupting flux rope
- Higher fidelity of the magnetogram structure must be retained for more detailed comparisons