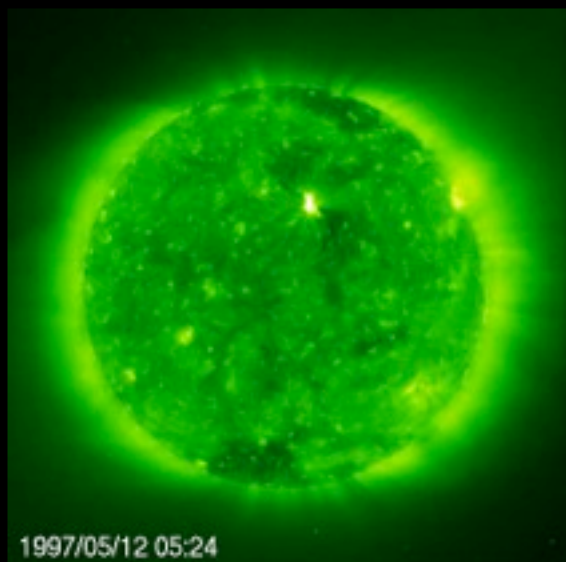
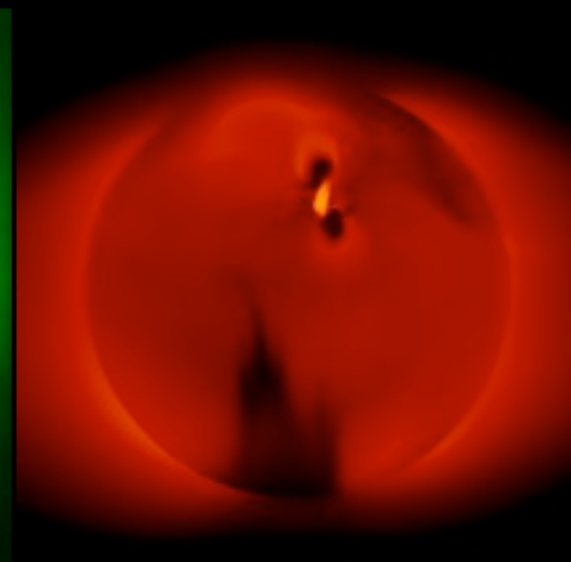
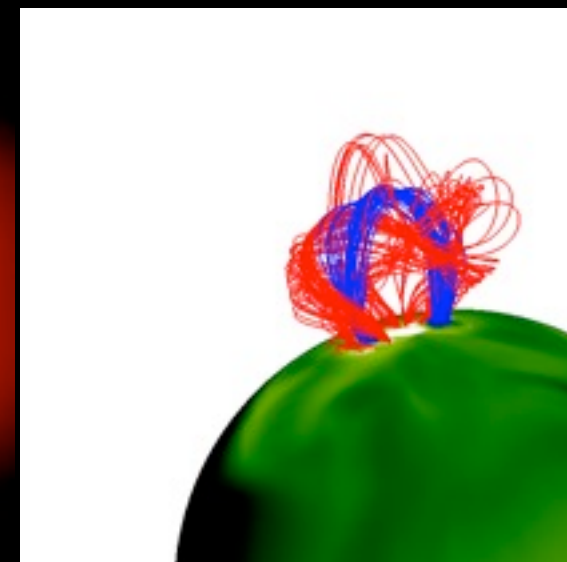
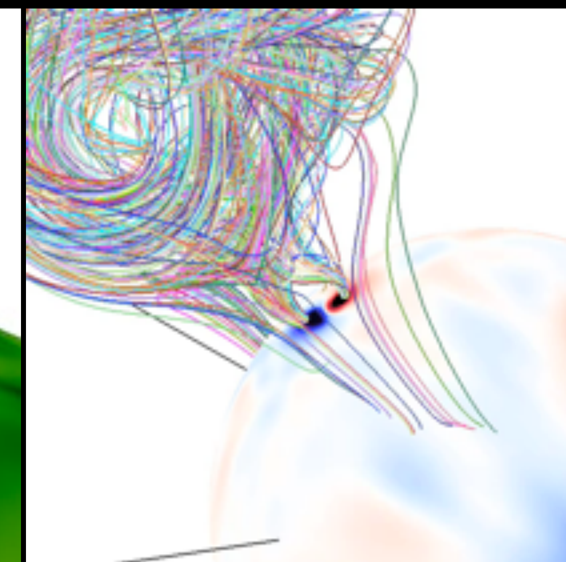
How Can We Understand the Causes and Consequences of Extreme CME Events?



Jon Linker, for Predictive Science Inc., San Diego, CA

http://www.predsci.com

Key Questions

- How are the fastest CME initiated?
  - Does only one mechanism produce very fast CMEs?
- Are there special characteristics of the active region and corona for extreme CMEs?
  - Fall-off of |B|?
  - Multipolar topology or complexity?
  - Energization, as deduced from proxies?
- Is connectivity to the flaring region a crucial aspect of extreme SEP events, or do you just need shocks low in the corona?
- Is the three-dimensional structure of the shock (low in the corona) important for SEP production?

Approach

- Answering many of these questions requires modeling CMEs in the context of a realistic model of the corona
- An advantage of this type of model is that observable quantities such as emission can be simulated.
- Quantities from the models can be *directly* compared with observations, as opposed to debating what field lines from a model would “look like”
- In practice, it is far more difficult to model CMEs in this manner, because of the complexity of the structures and computational resource requirements.
- Ultimately, to know if a mechanism can produce CMEs with huge speeds, as well as the evolution, shock formation, etc., requires this approach

MHD Equations
(Improved Energy Equation Model)

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

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

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

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

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

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

$$\gamma = 5/3$$

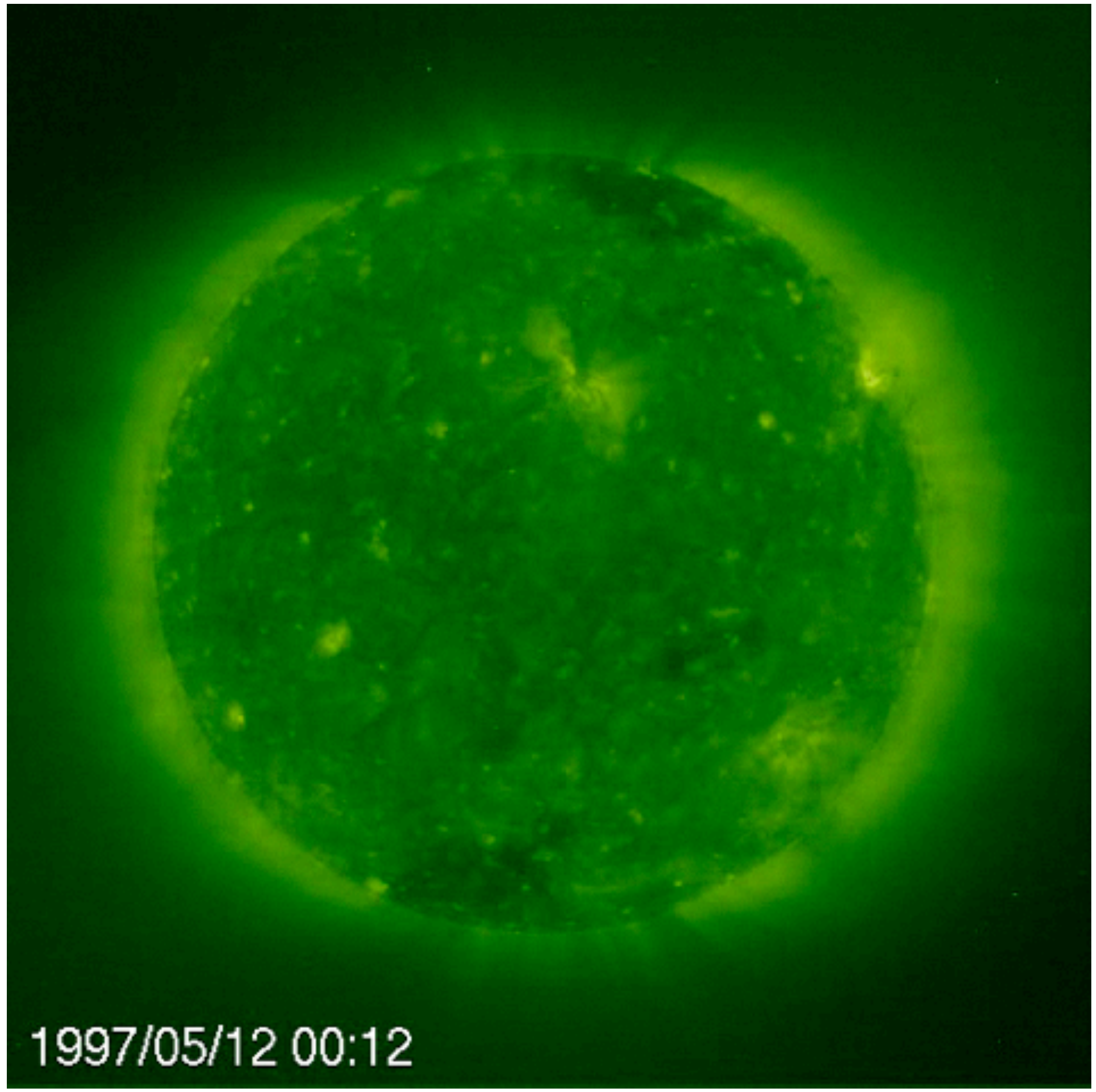
$$\mathbf{q} = -\kappa_{\parallel}\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\nabla T \qquad \text{(Close to the Sun, } r \lesssim 10R_S\text{)}$$

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

+ WKB equations for Alfvén wave pressure p_w evolution

May 12, 1997 CME

- Not an extreme event



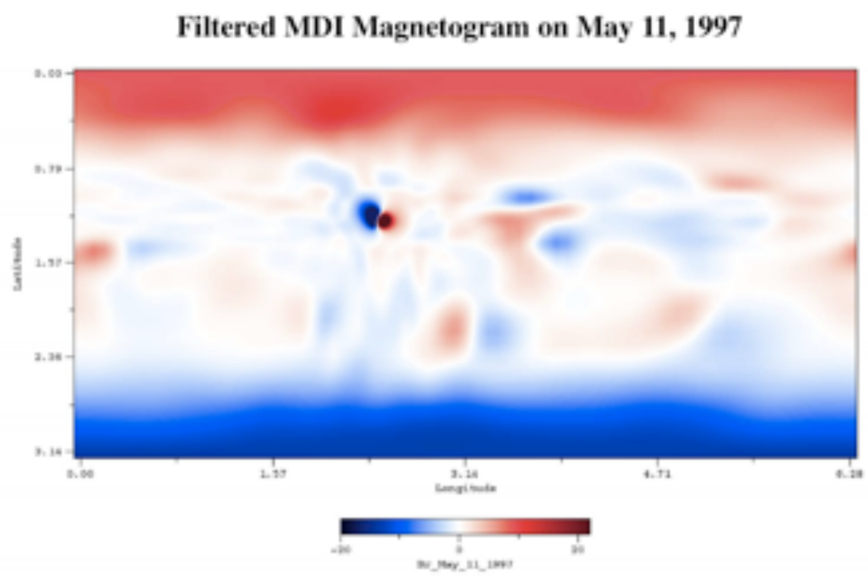
- Very well studied.
- Classic “Dimming” regions observed

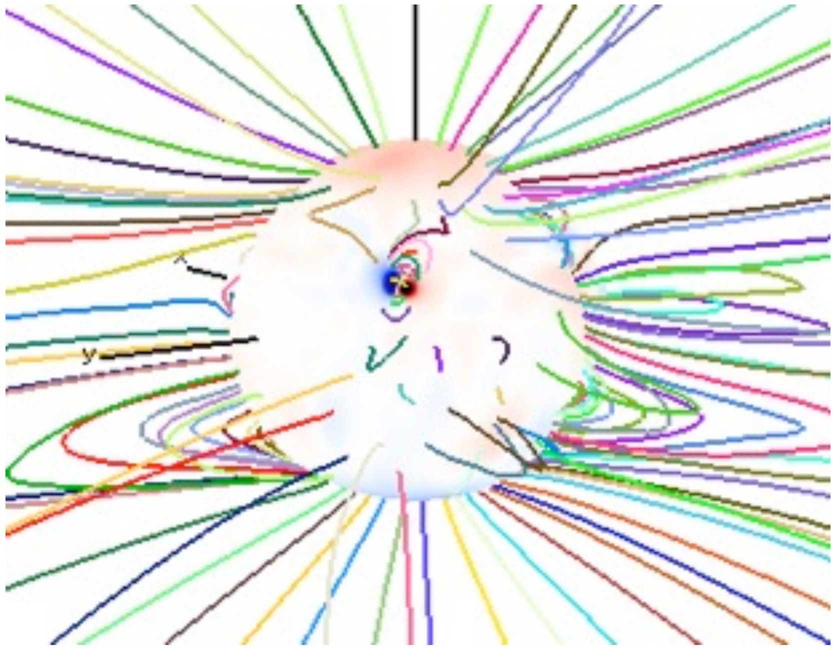
May 12, 1997 CME

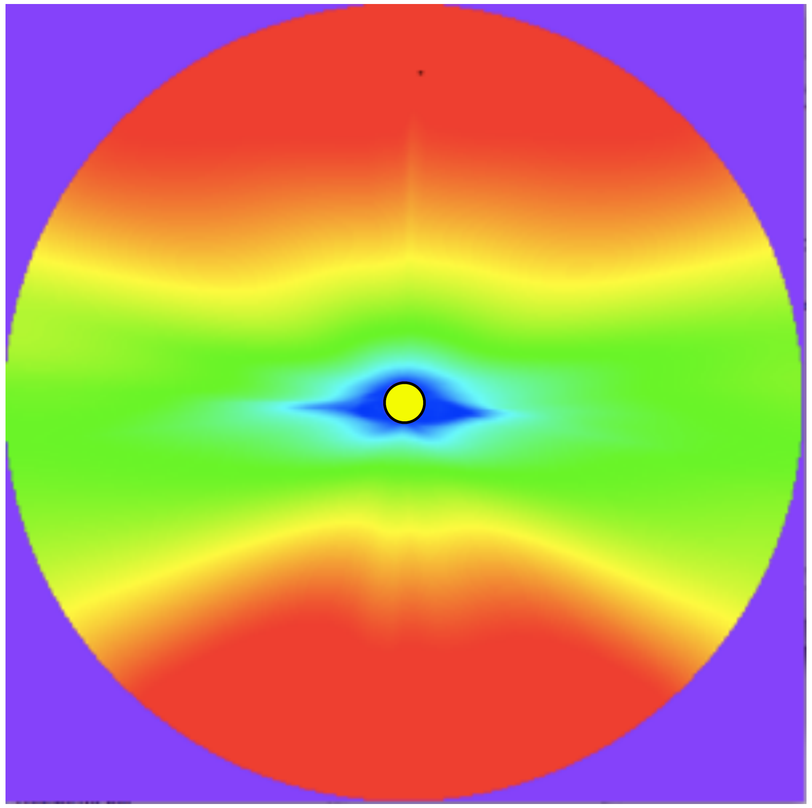
- Not an extreme event

- Very well studied.
- Classic “Dimming” regions observed

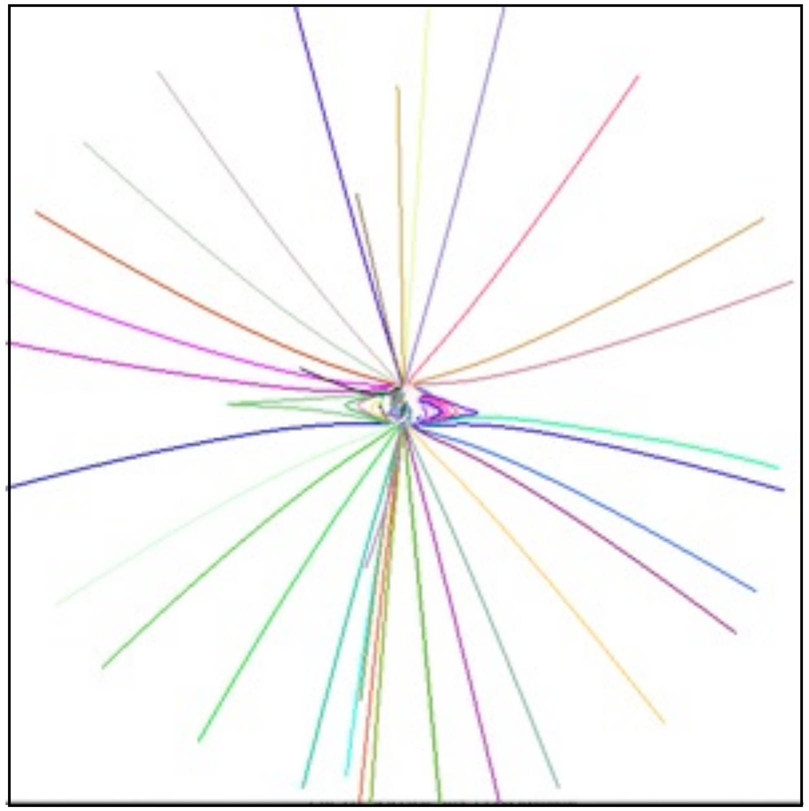
Global Coronal Solution to 20 R_S





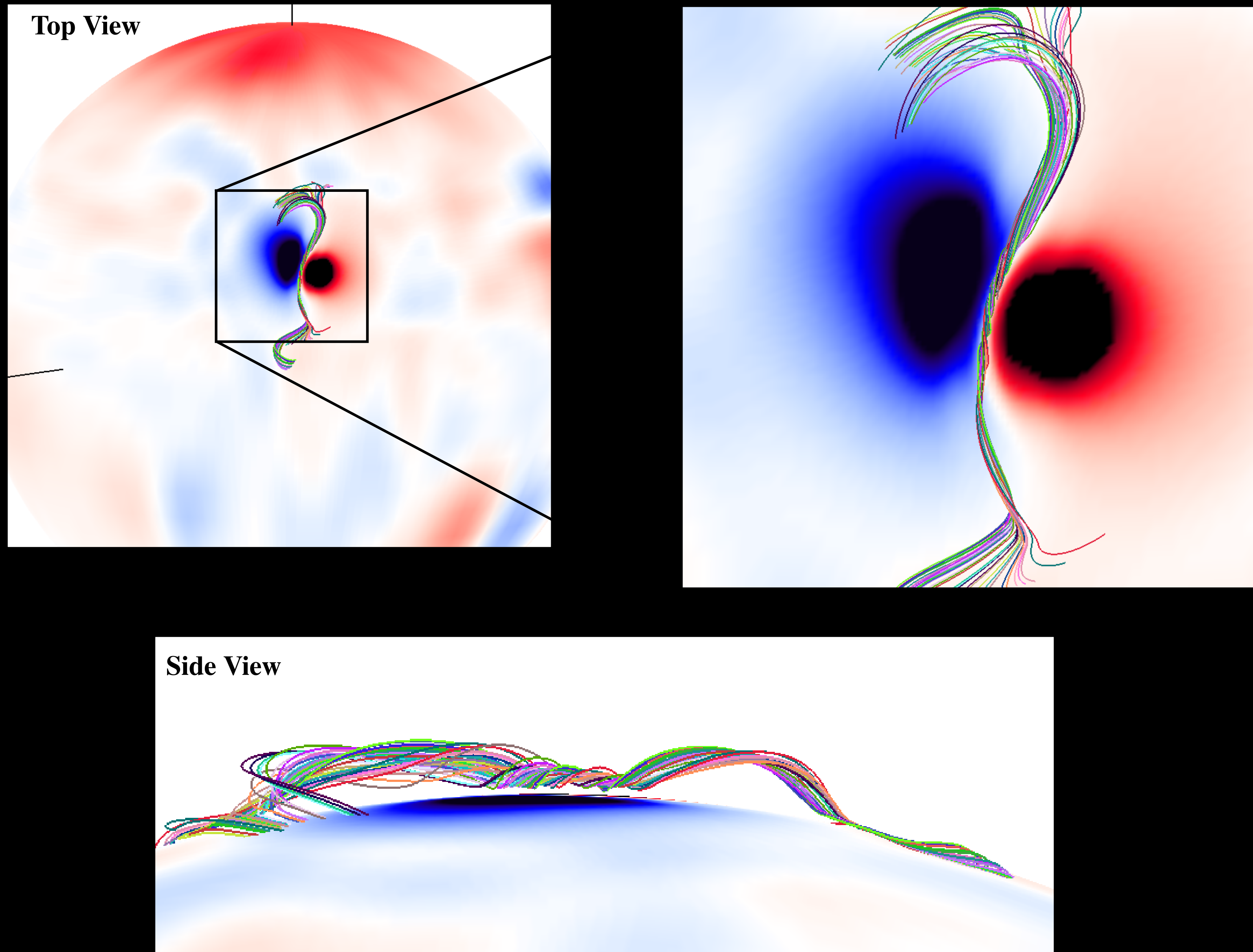


Vr (max ~ 750 km/s)



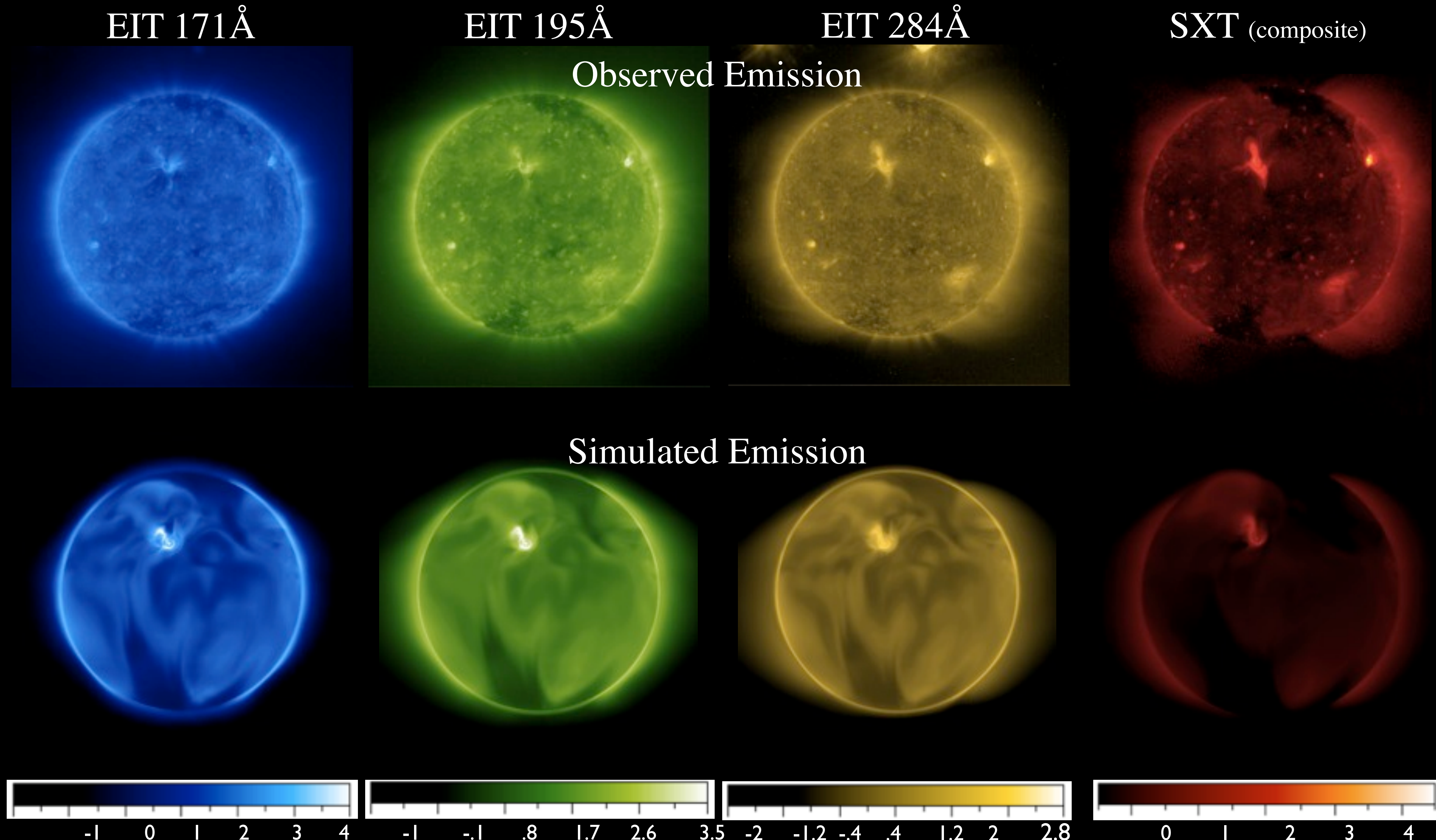
Magnetic Field Lines

Flux Cancellation Leads to Flux Rope Formation



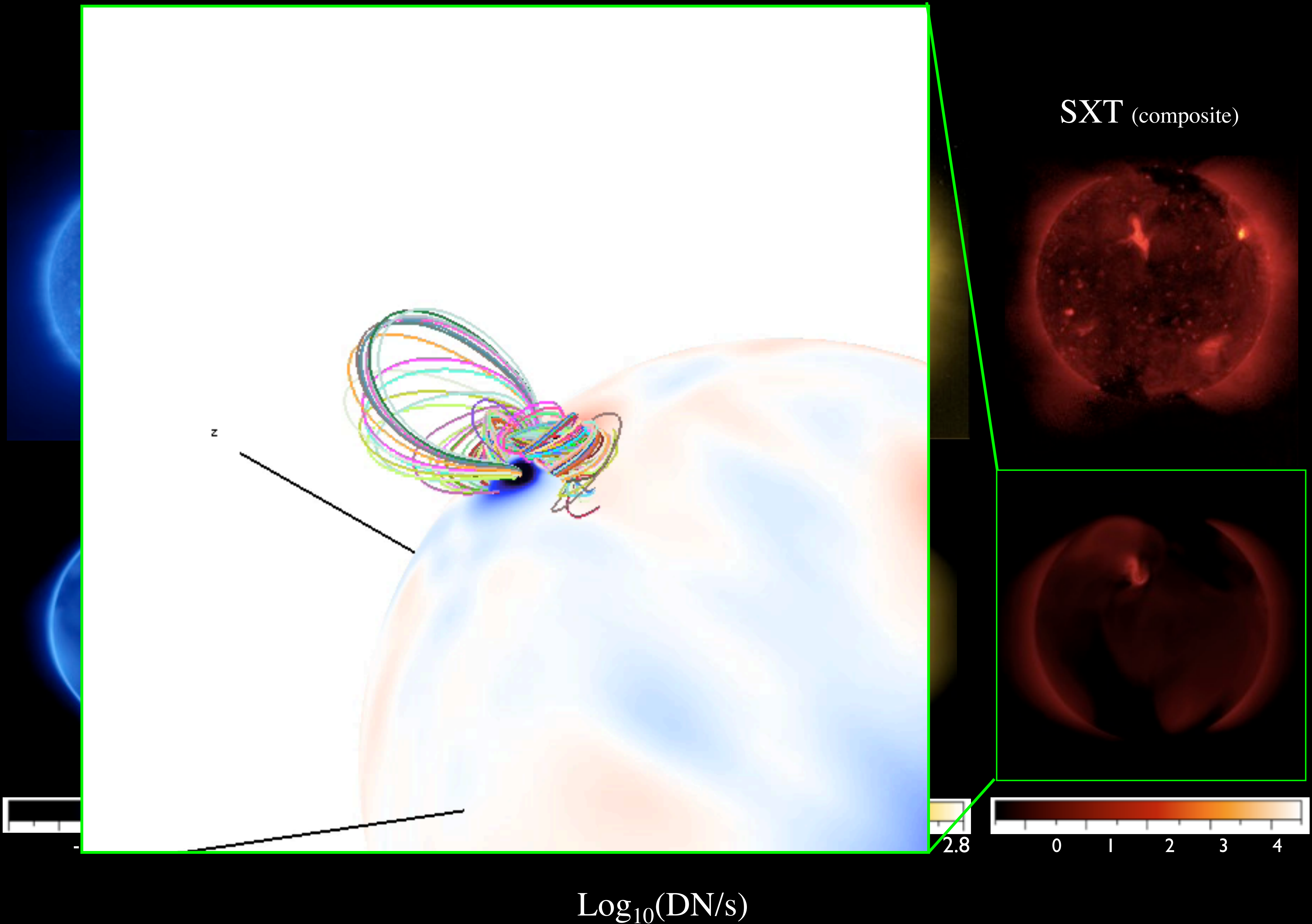
- Prominence-like structure forms along the PIL
- Cold, dense plasma (4×10^4 K, 10^{10} #/cm^3) is lifted into the corona
- With continued cancellation, the structure erupts

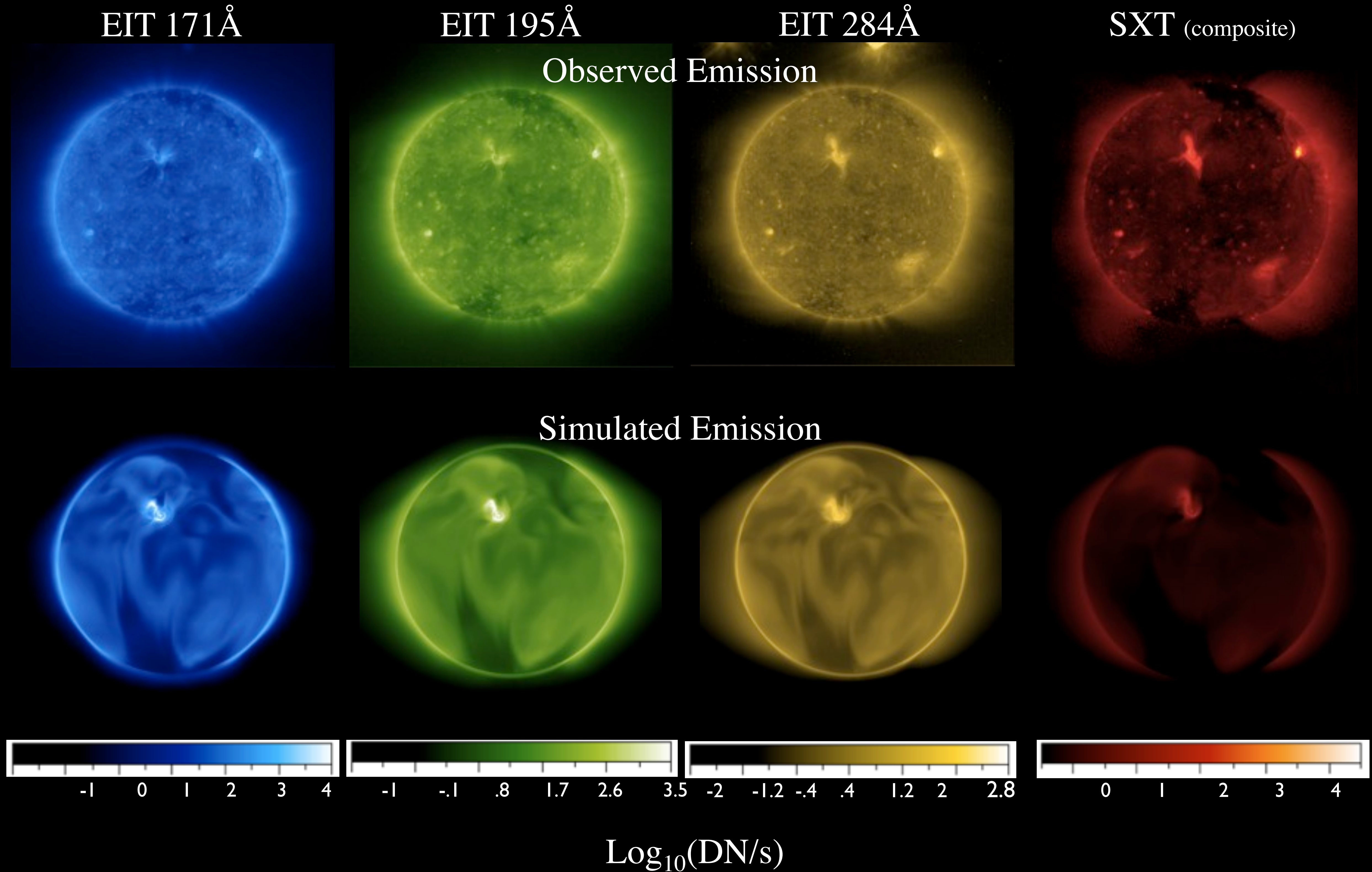
Simulated Corona Prior to May 12, 1997: Quantitative Comparison with Emission



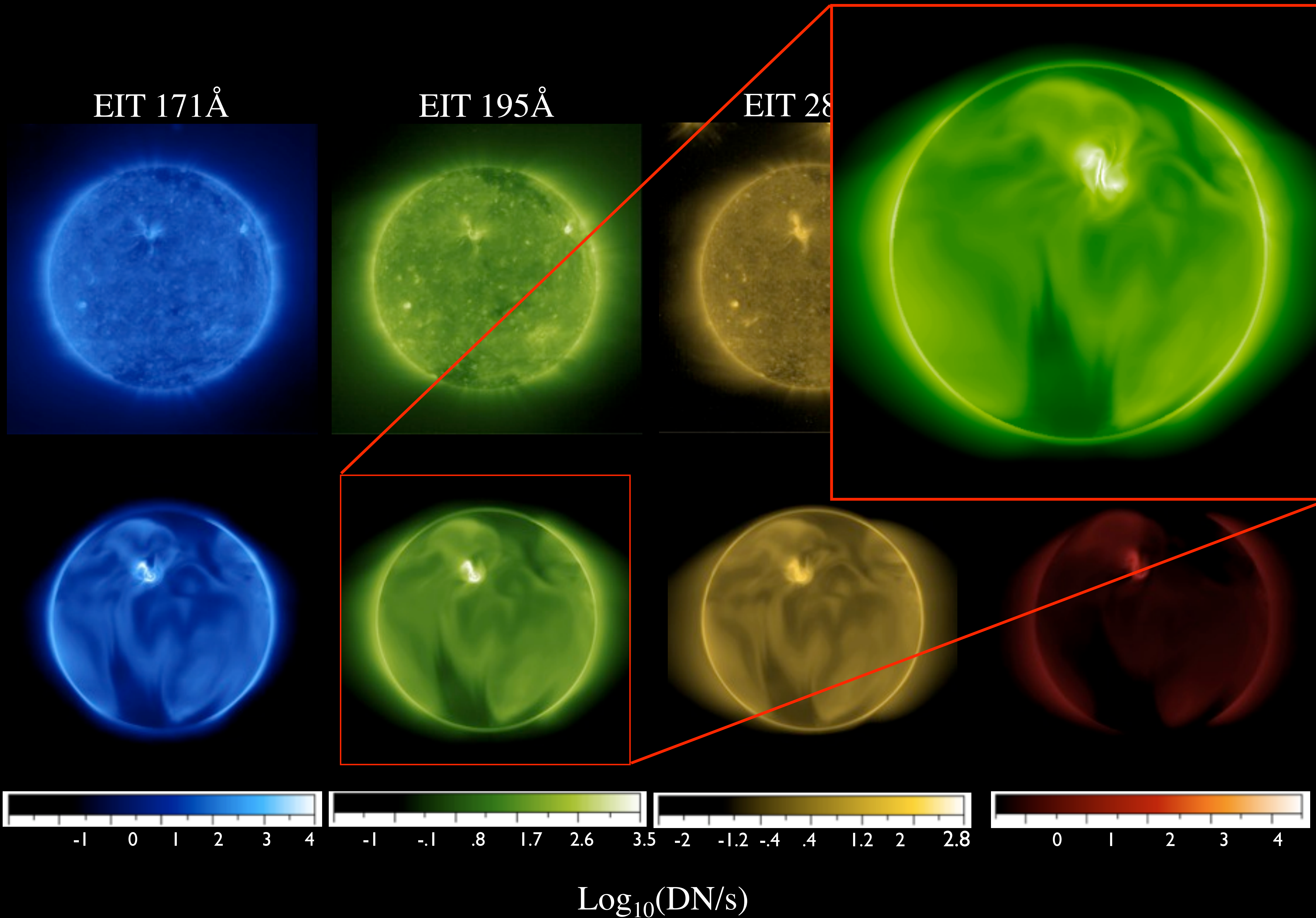
$Log_{10}(DN/s)$

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

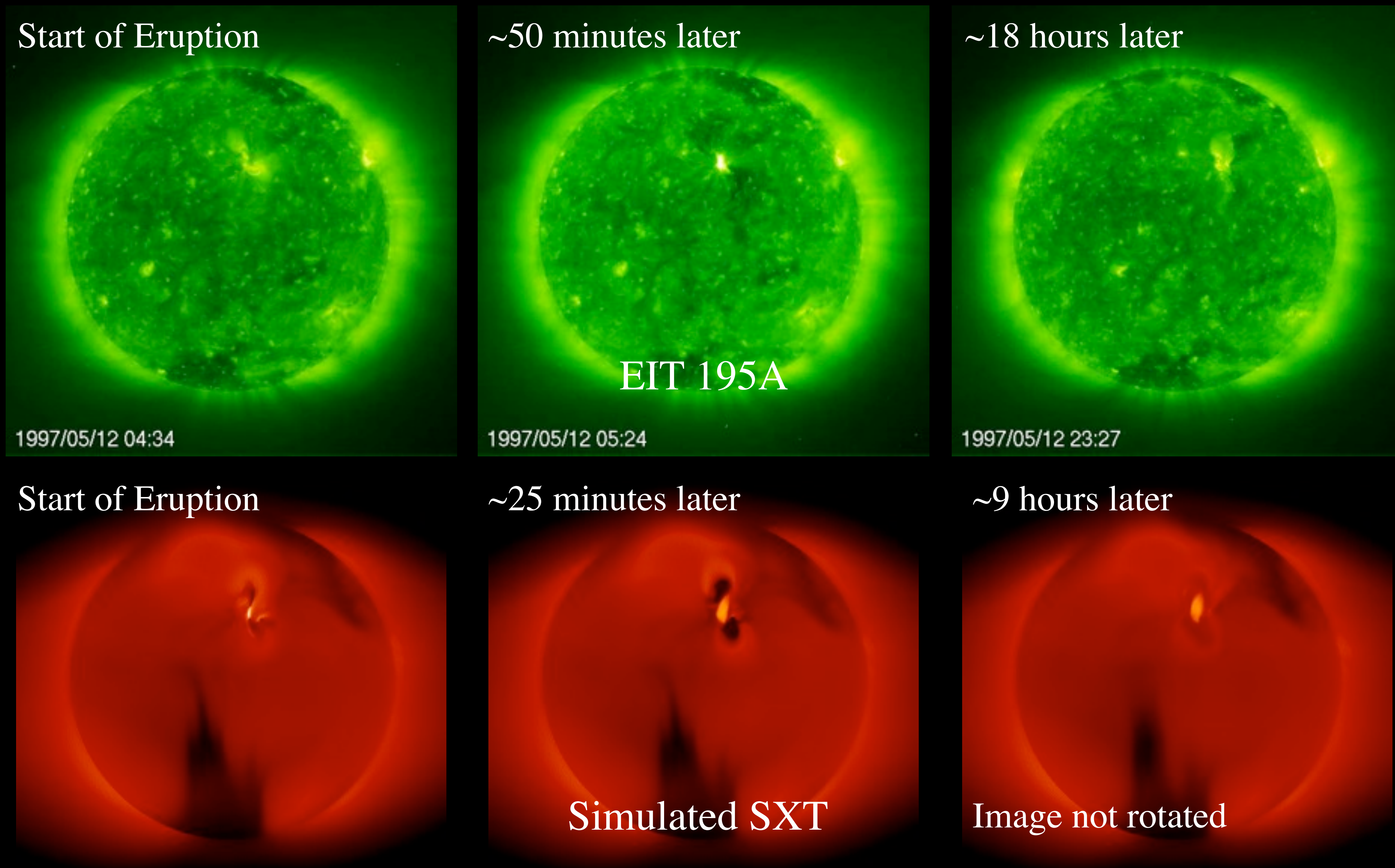



EIT 171Å
EIT 195Å
EIT 284Å
SXT (composite)
Observed Emission
Simulated Emission
-1 0 1 2 3 4
-1 -.1 .8 1.7 2.6 3.5
-2 -1.2 -.4 .4 1.2 2 2.8
0 1 2 3 4
Log10(DN/s)

Simulated EIT 195 emission:
Dimming regions and post-flare loops



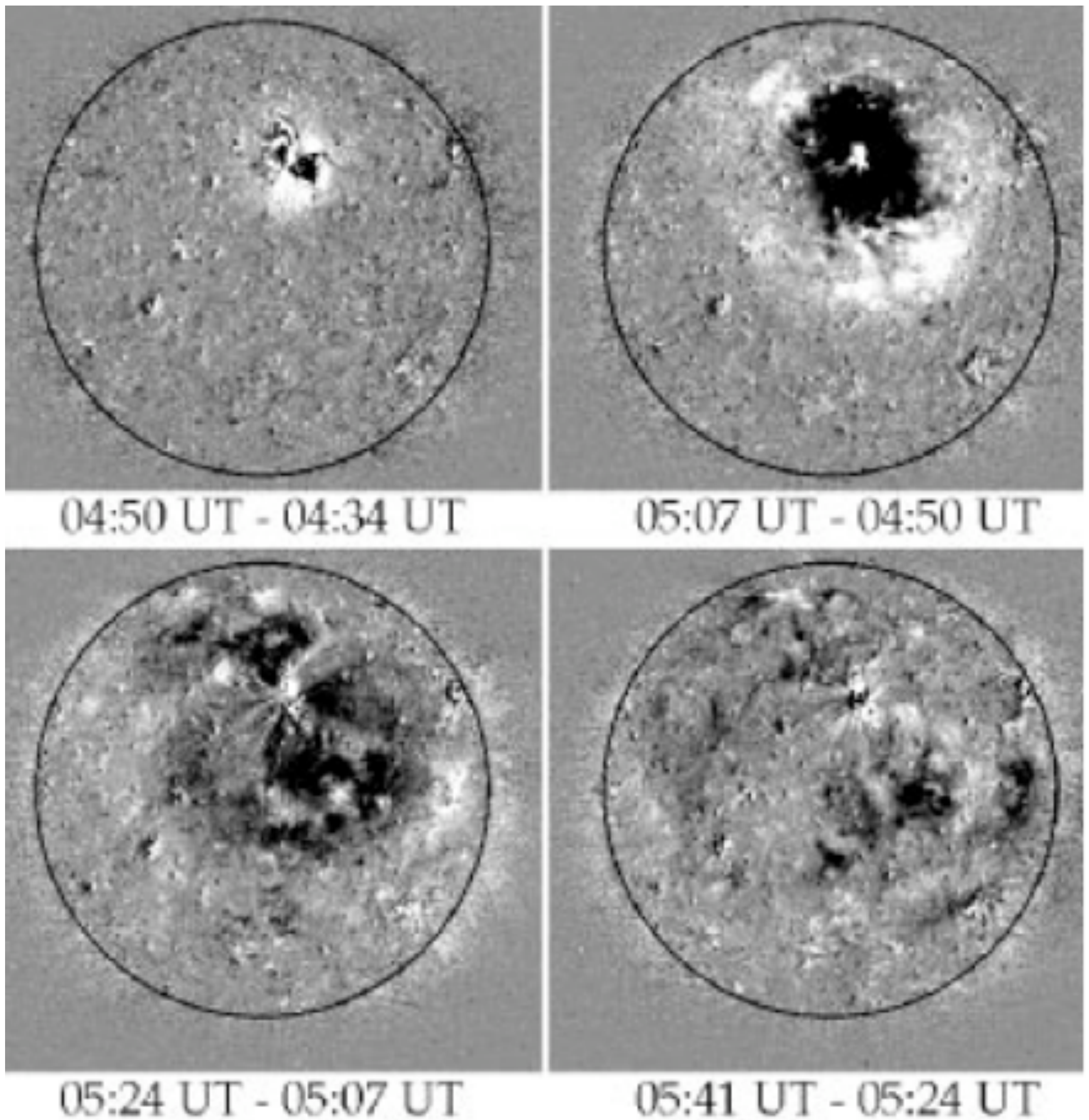
Comparison of Dimming Regions in the Simulation



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

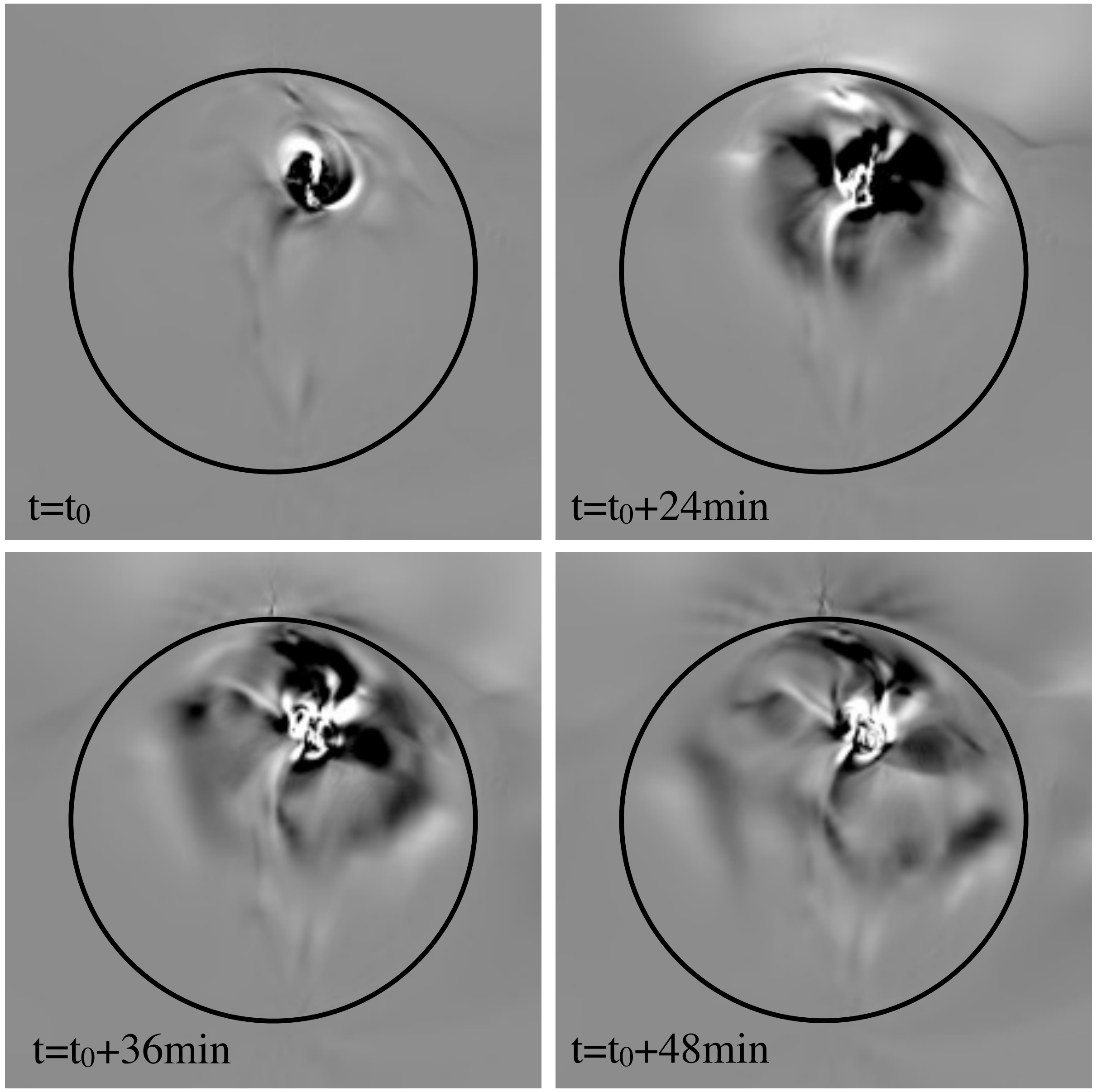
Simulated EIT Wave

Observed Difference Images (EIT 195Å)



From Thompson et al. (1998)
Inferred V_{wave} ~ 245km/s

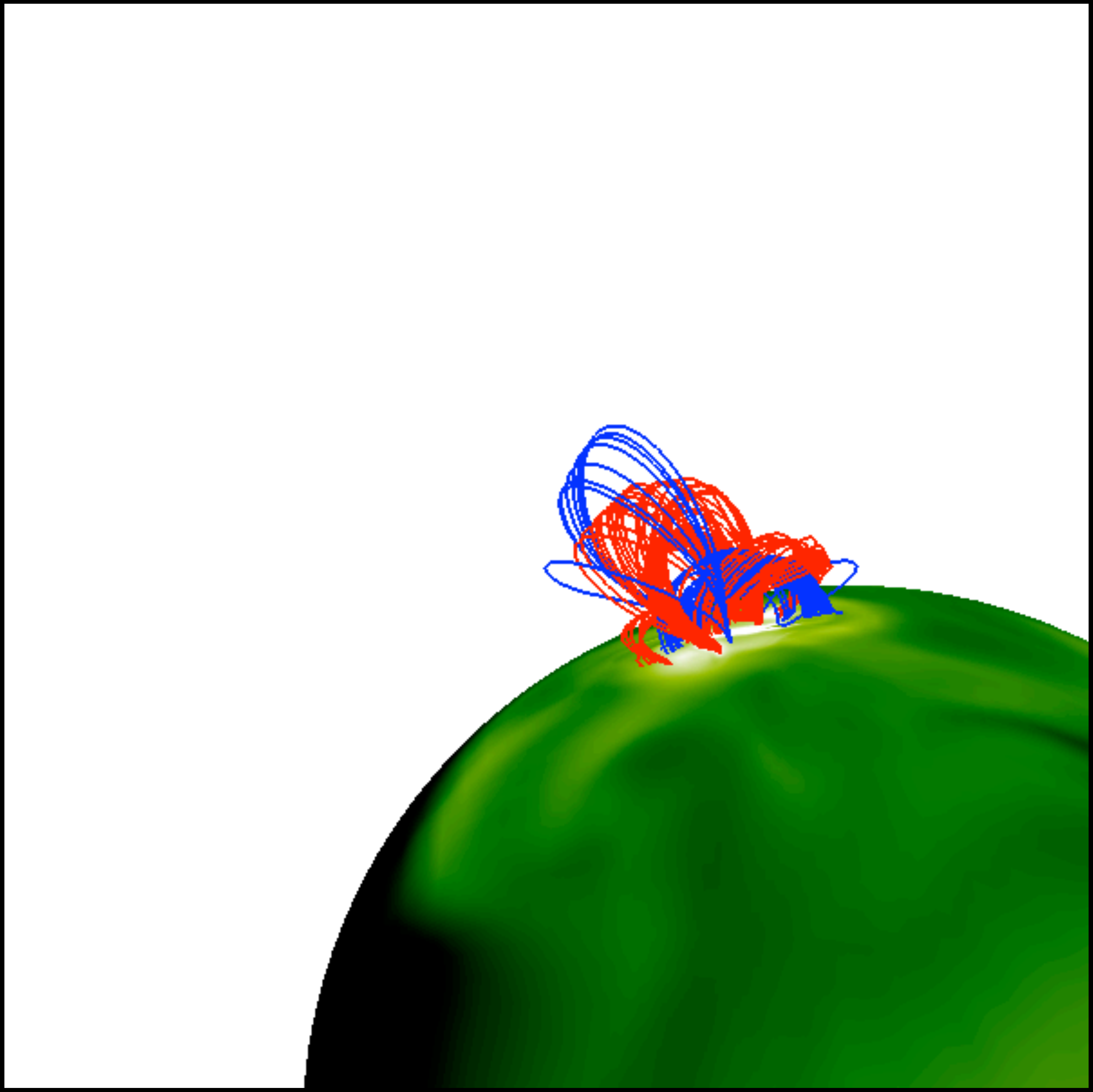
Simulated Difference Images (EIT 195Å)

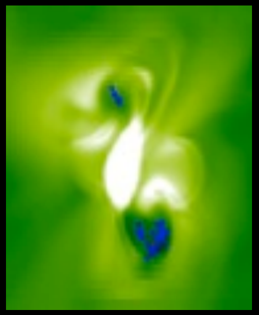


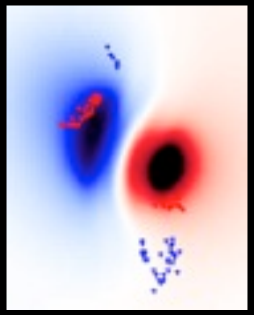
Estimate of V_{wave} from difference images ~ 250 ± 50 km/s,

Magnetic Field Lines & Simulated Emission

Magnetic Field Lines & Simulated Emission

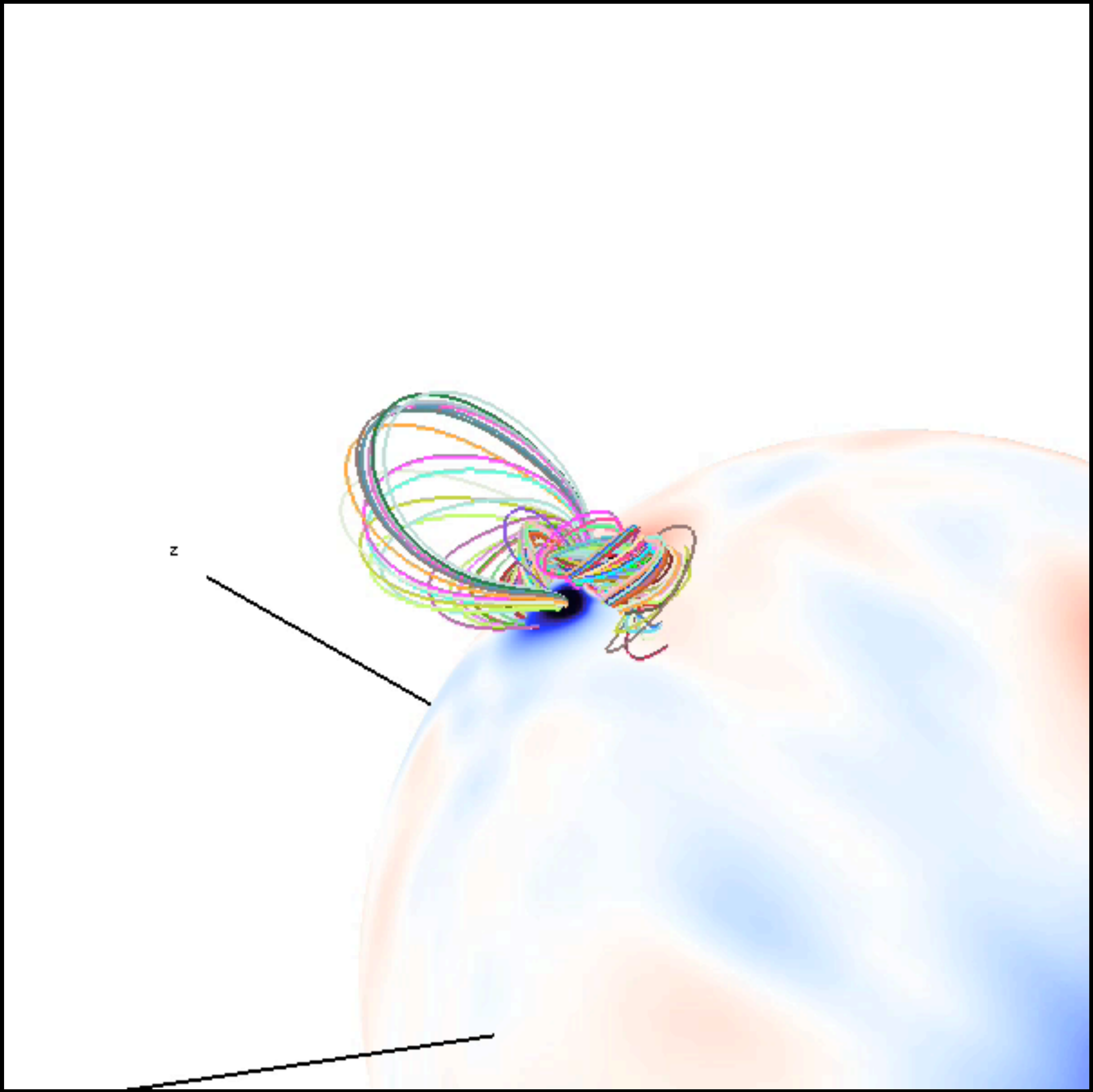






- Blue field lines form the dimmings - but they come from weak flux!
- Red field lines rooted in stronger AR fields
- Blue fields are dragged out by erupting rope
- All fields closed after 9 hours!

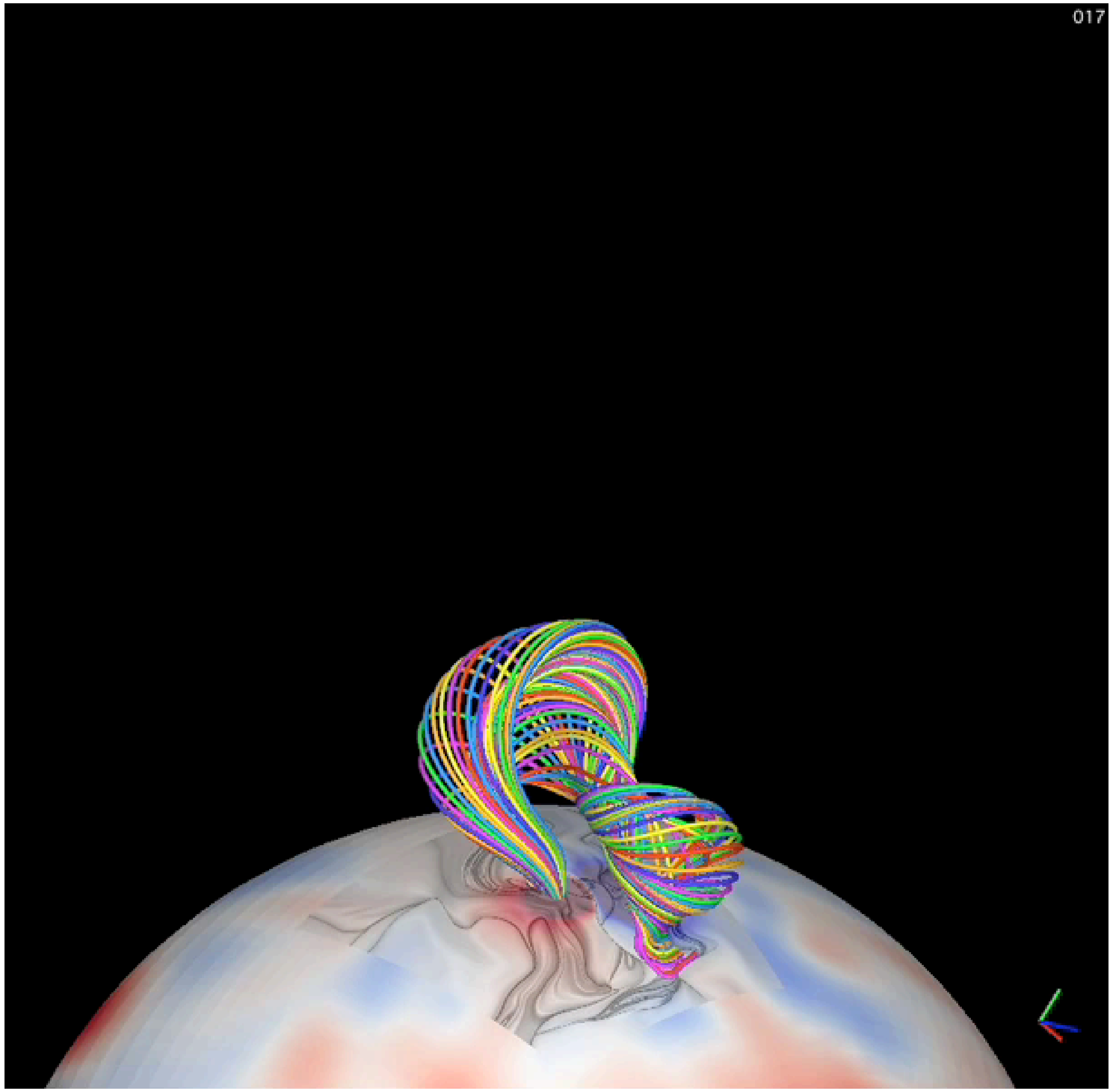
Magnetic Field Lines & Simulated Emission



- As eruption proceeds, flux rope field lines reconnect with open flux ("interchange reconnection")
- Eventually, flux rope is connected to edges of coronal holes
- Flux rope in interplanetary space is a combination of original flux rope and overlying fields

Topological Analysis of the Field Identifies the Flux Rope

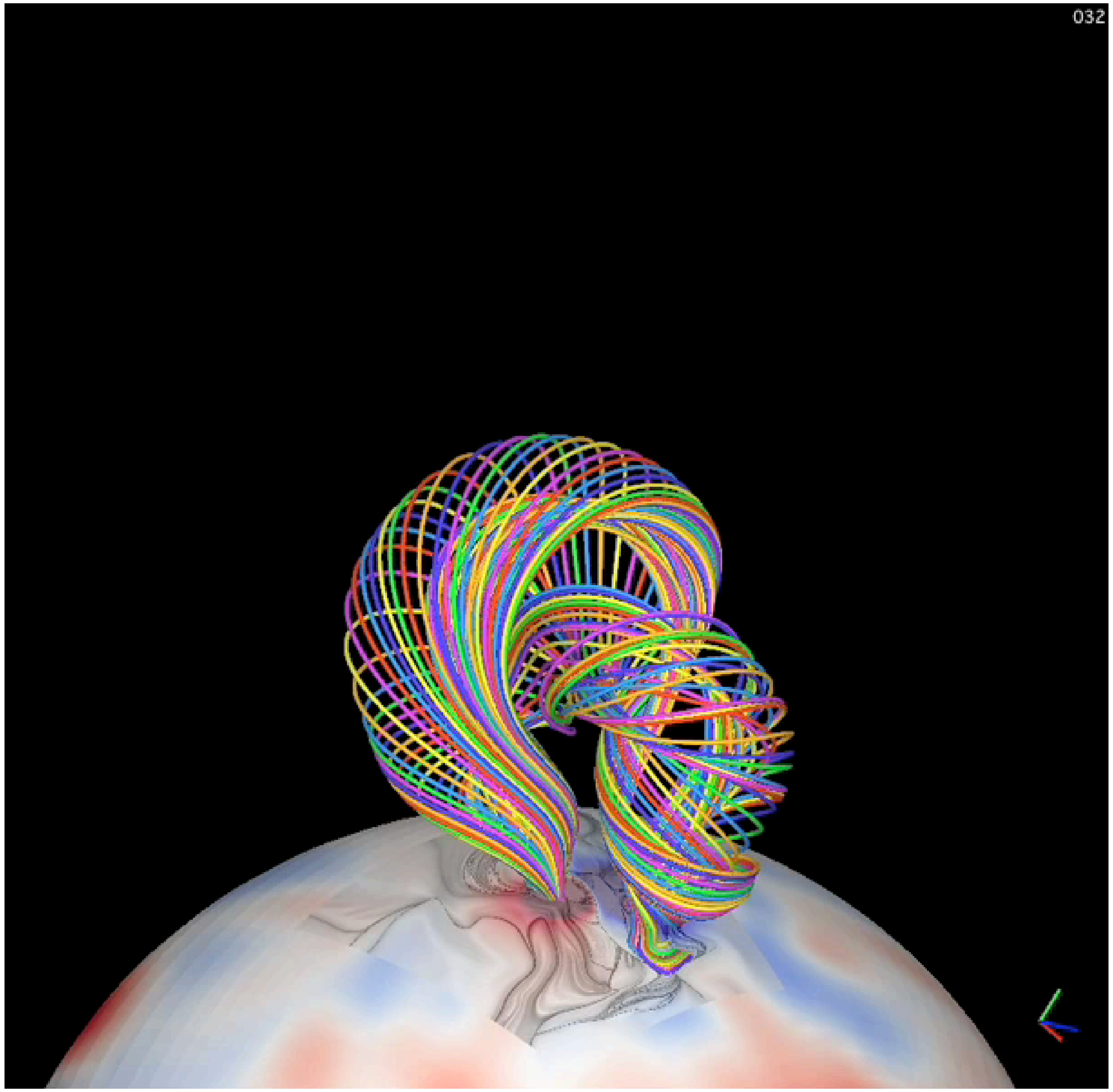
~ 20 minutes after eruption



Topological Analysis of the Magnetic Field Identifies the Flux Rope (Slava Titov)

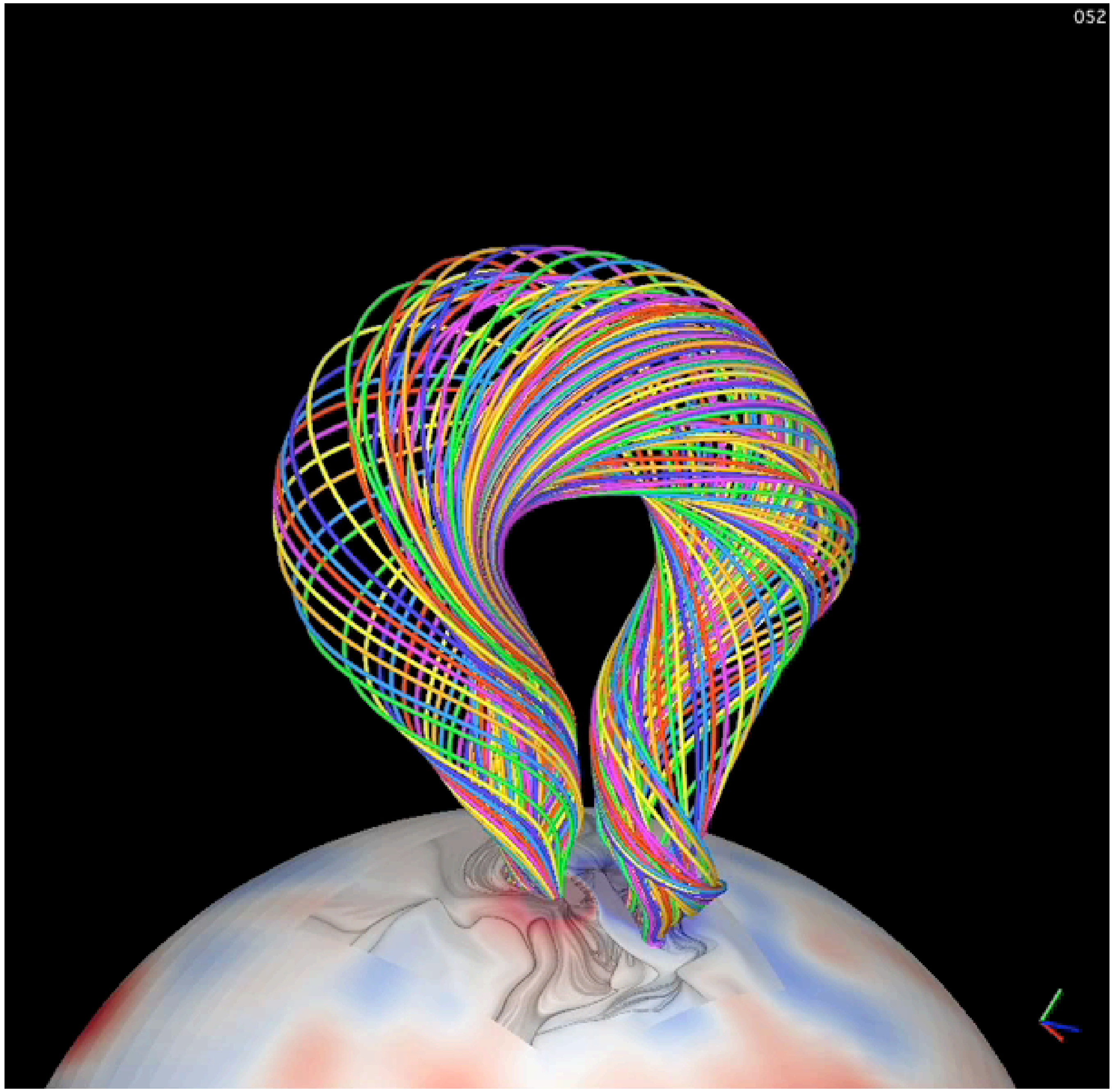
Topological Analysis of the Magnetic Field Identifies the Flux Rope (Slava Titov)

~ 38 minutes after eruption



Topological Analysis of the Field Identifies the Flux Rope

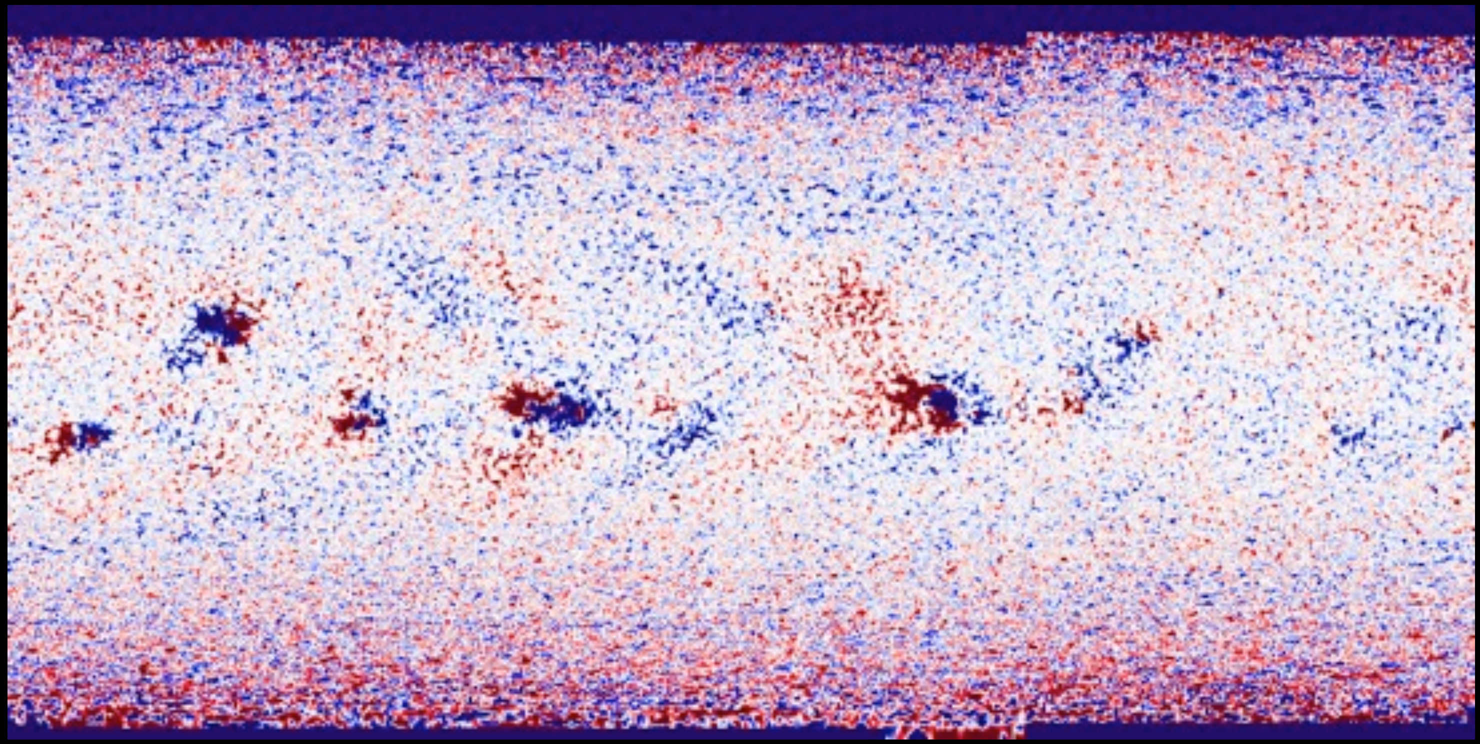
~ 62 minutes after eruption



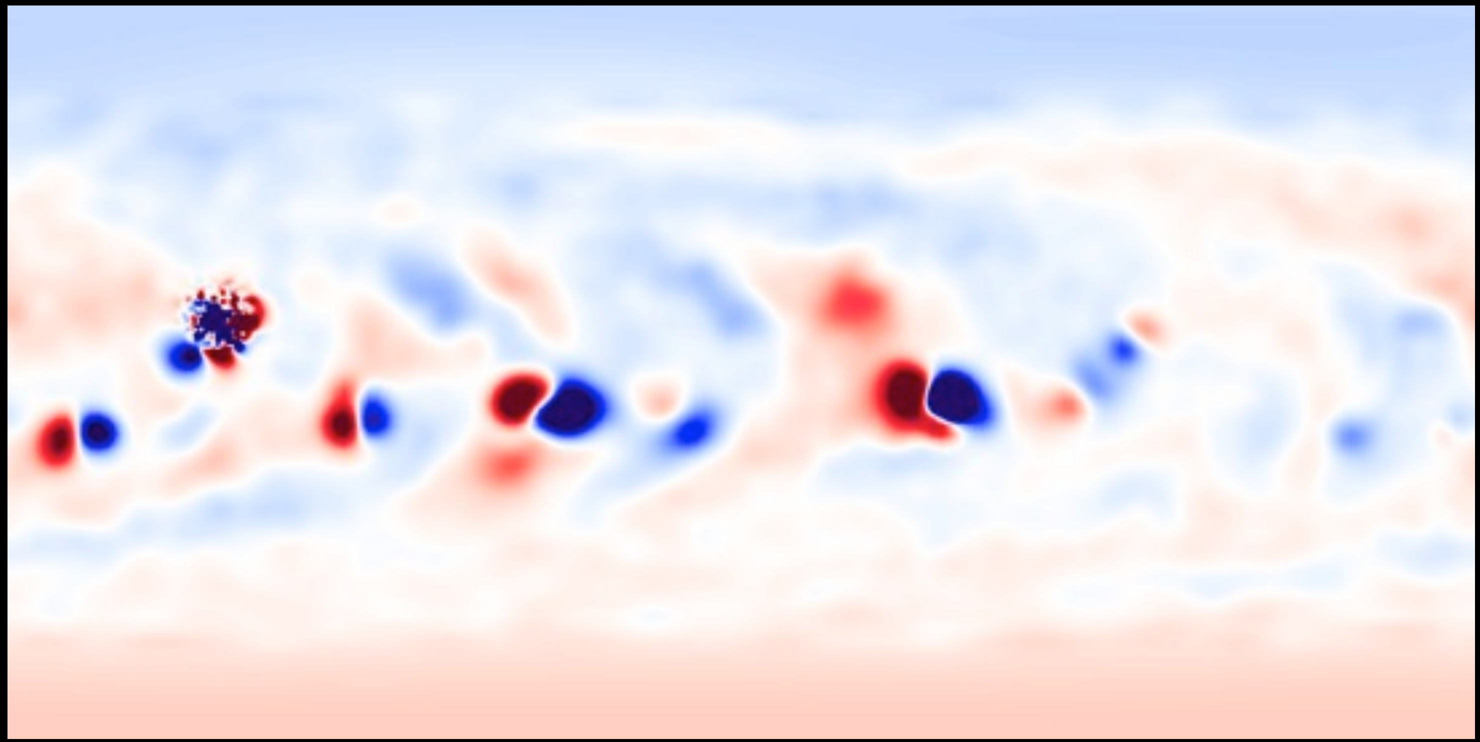
CME Propagation:
Alfven Speed in the Corona

May 13, 2005 CME

MDI synoptic magnetic map

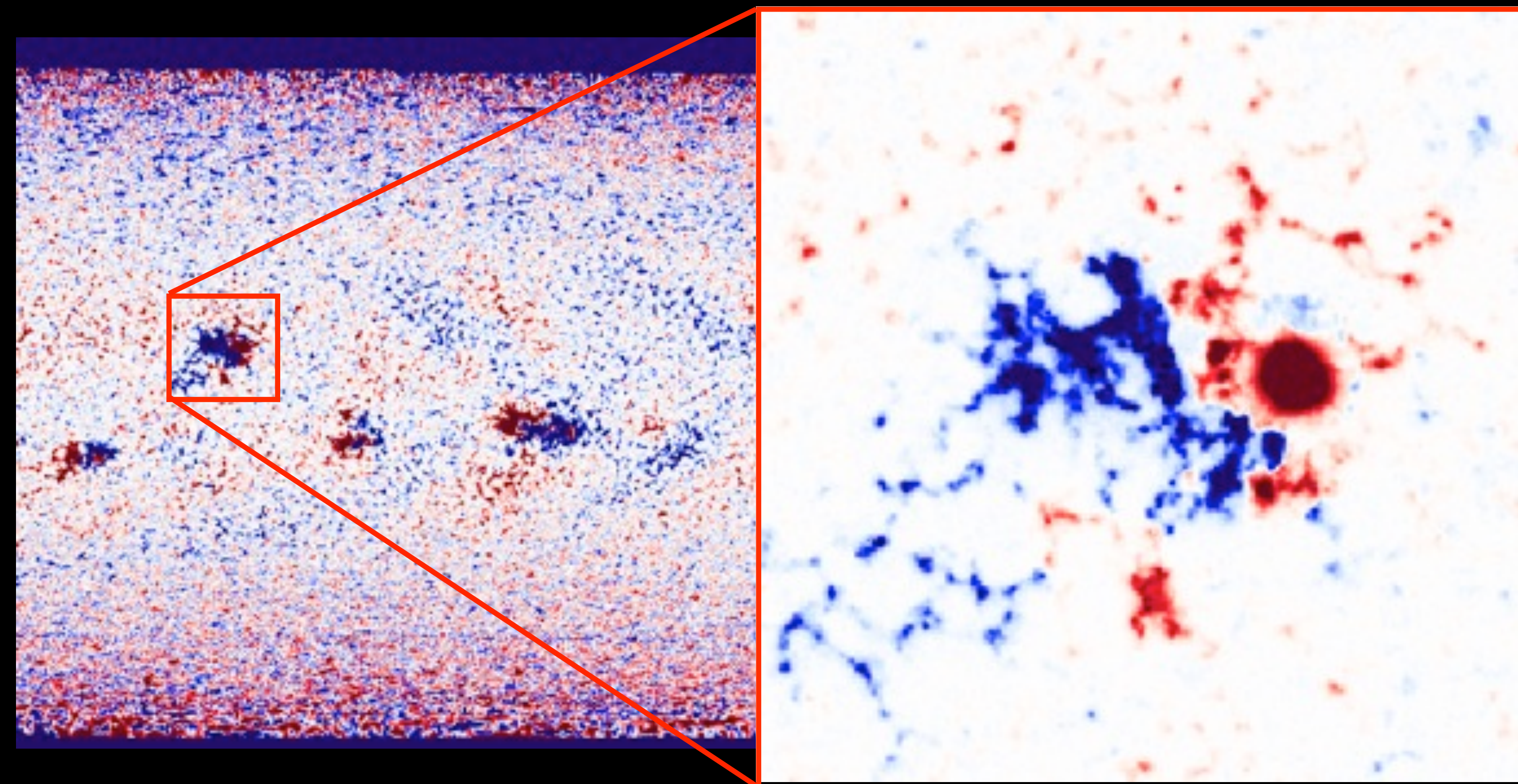


Smoothed version suitable for
MHD Calculation.
We are applying less smoothing to
the data than in the May 97 case.



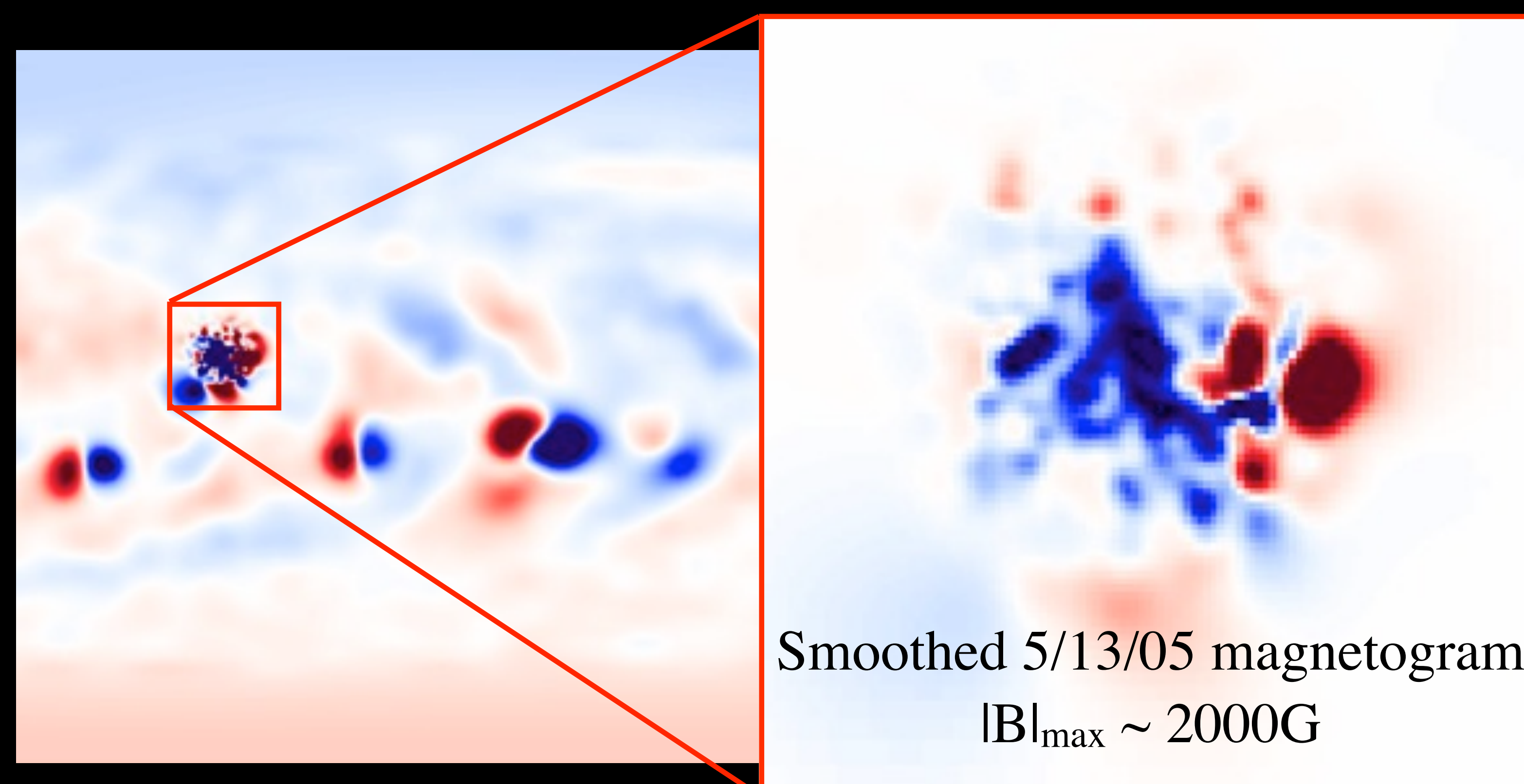
May 13, 2005 CME

MDI synoptic magnetic map

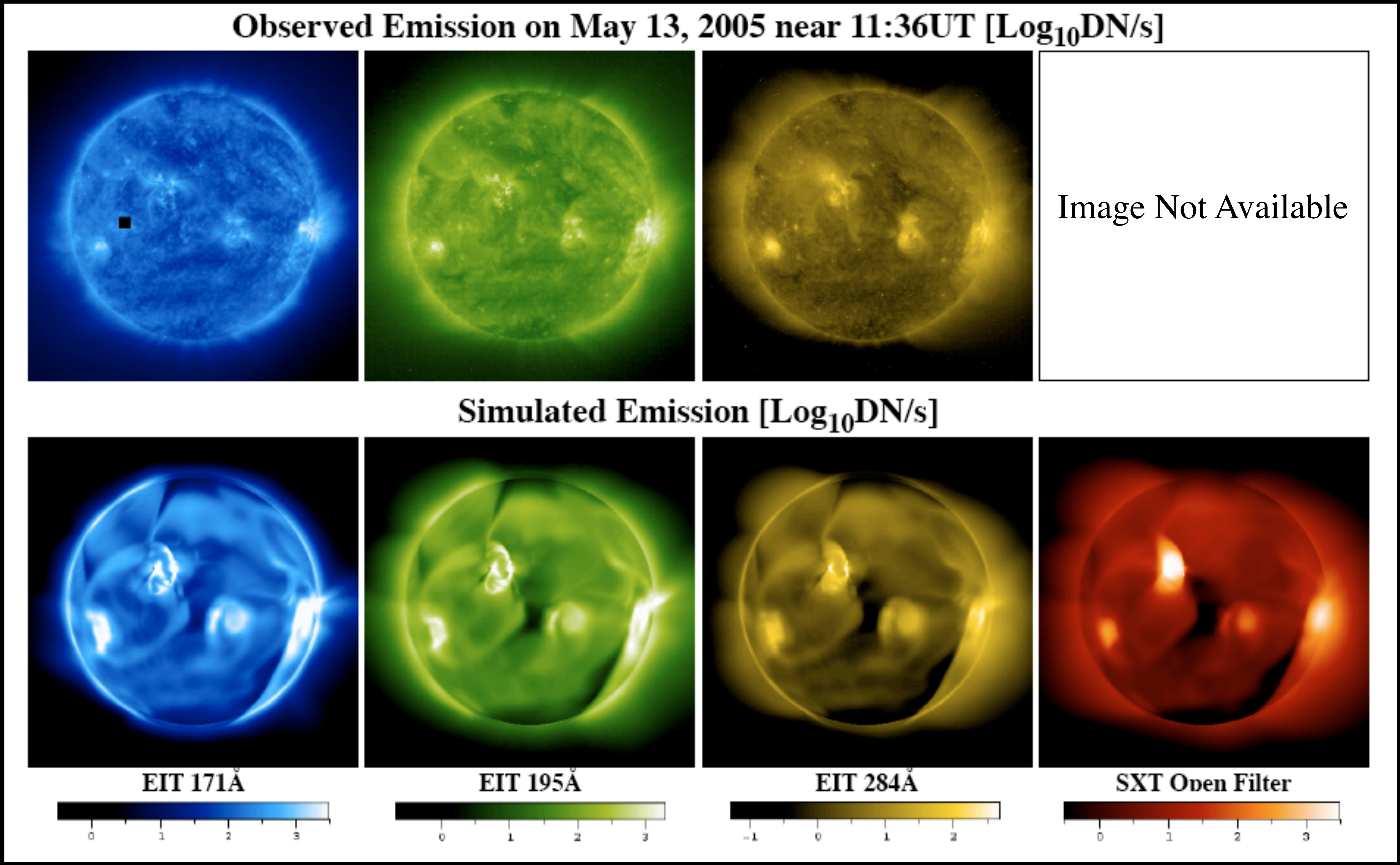


A very fast CME (~1700 km/s) originated from this Active Region

Smoothed version suitable for MHD Calculation.
We are applying less smoothing to the data than in the May 97 case.

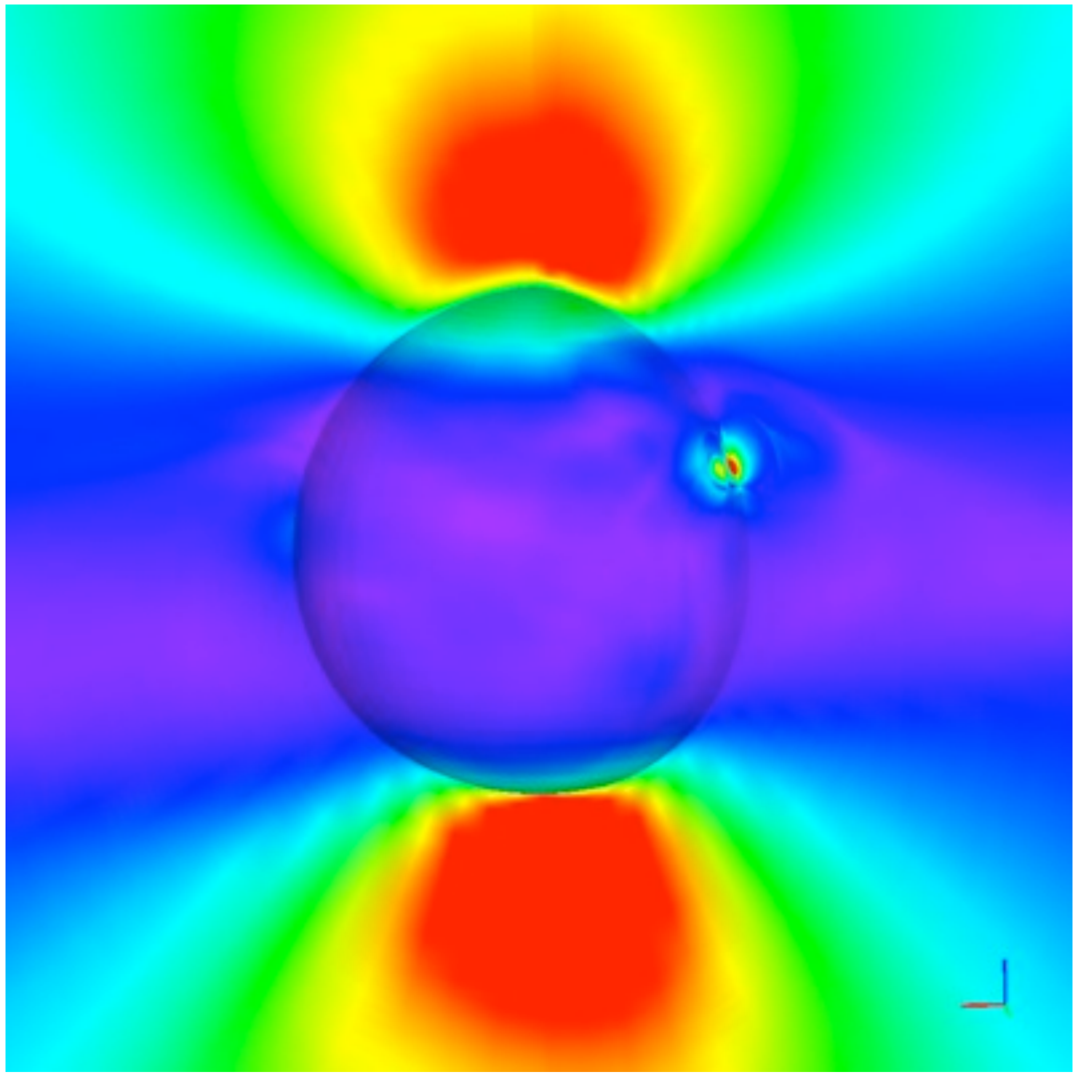


A Preliminary Simulation of the Background Corona

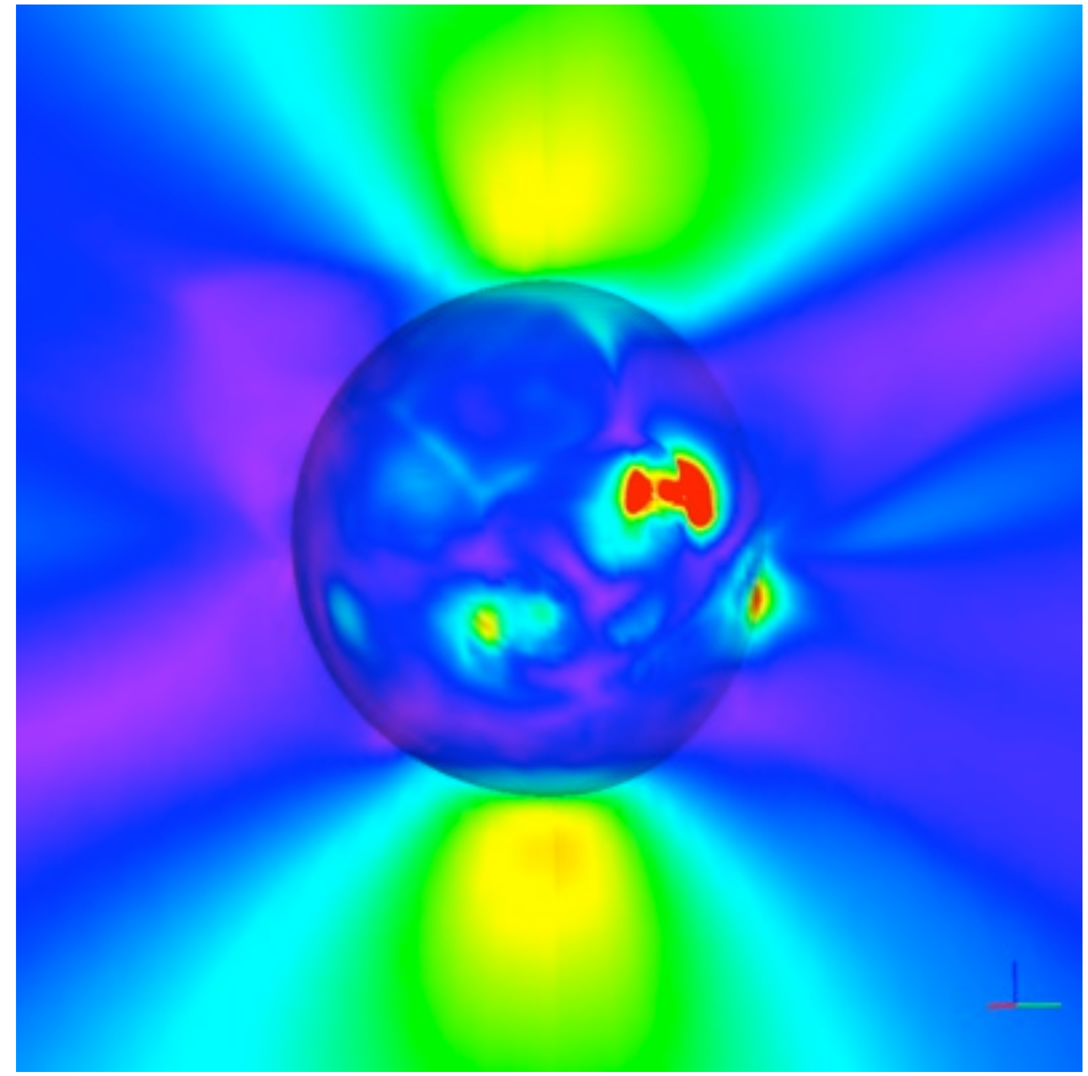


Alfven Speed in the Corona

May 12, 1997 CME

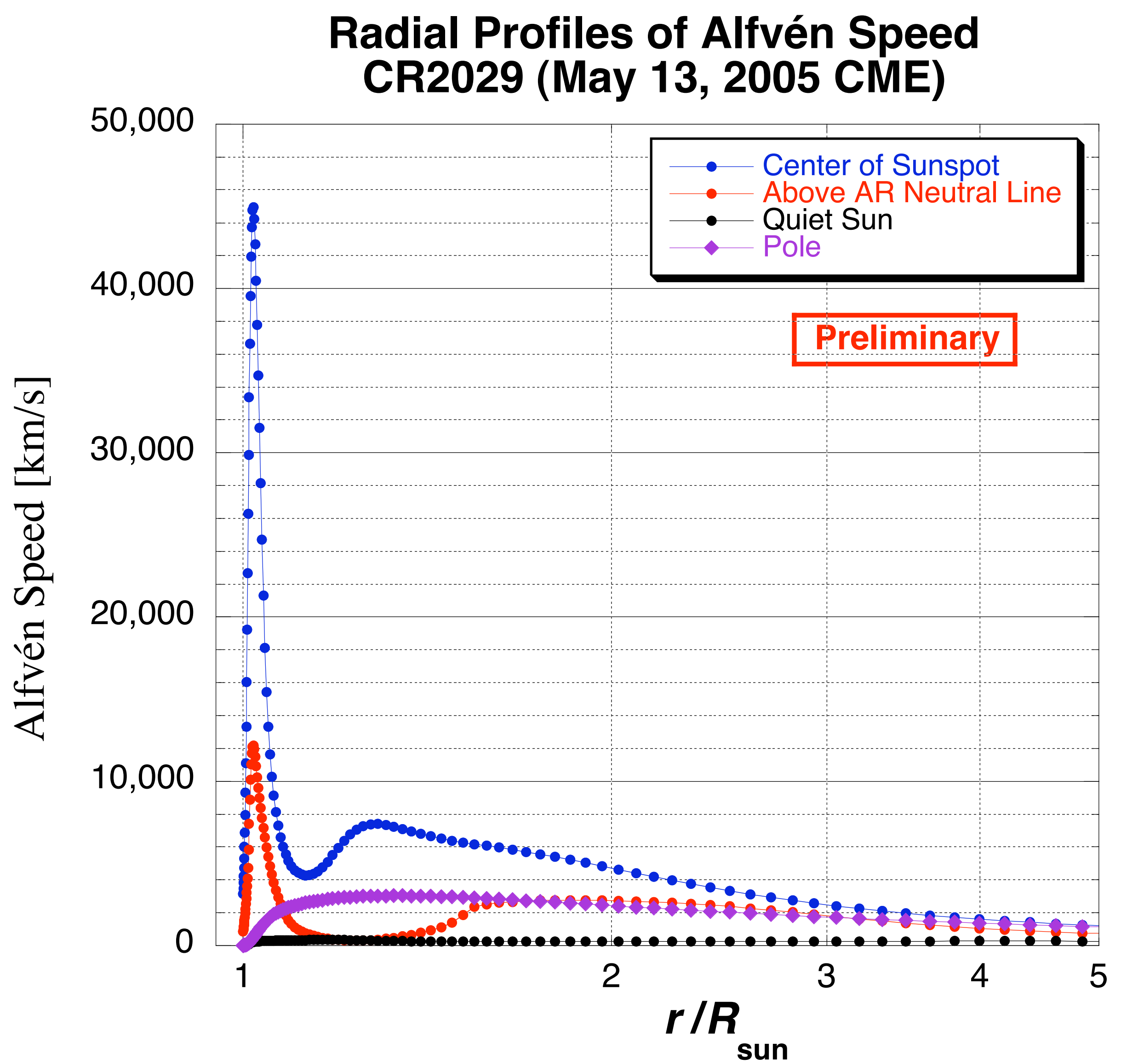


May 13, 2005 CME



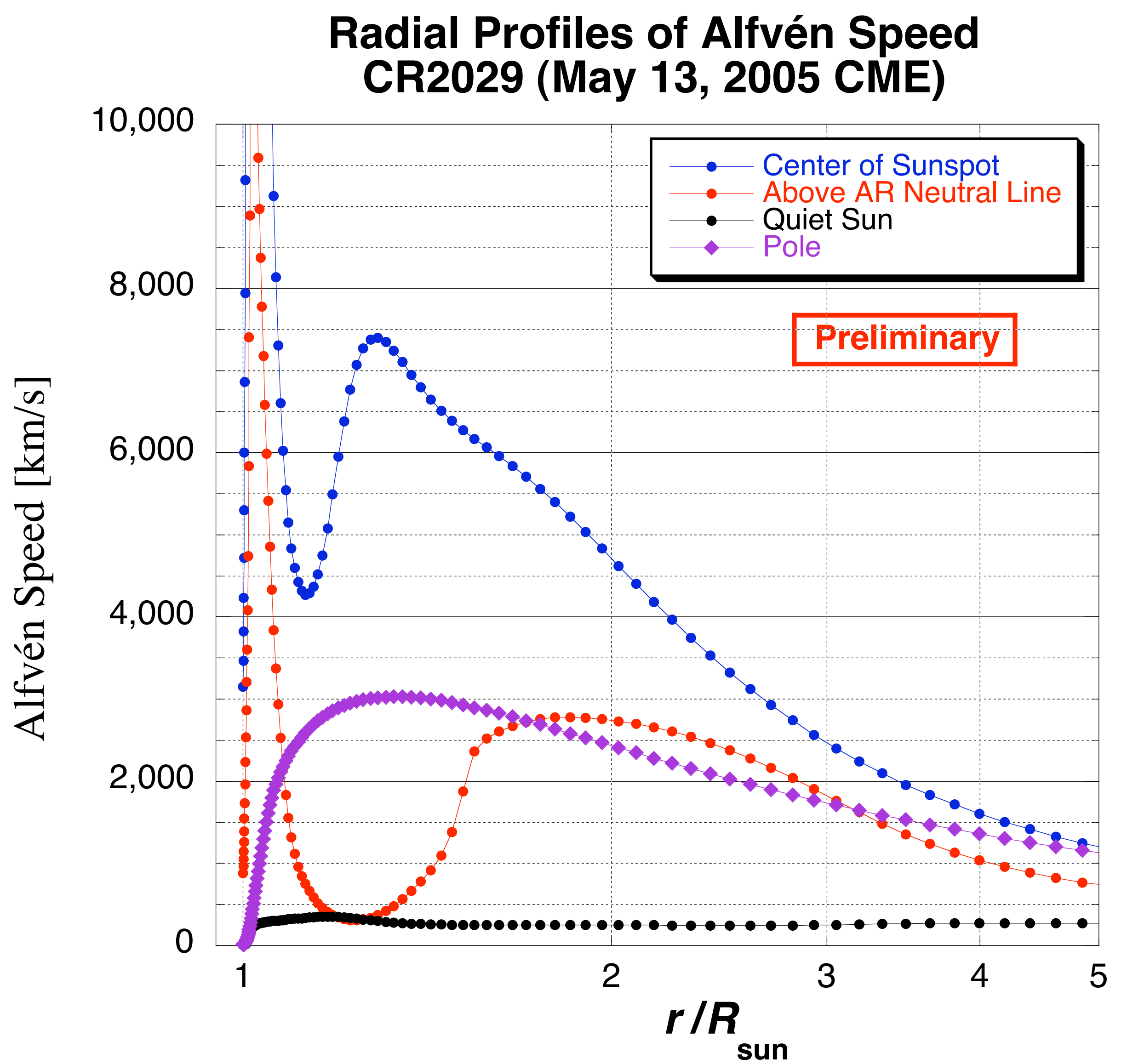
V_A is greatly oversaturated in May 13 case

Alfven Speed in the Corona: Radial Profiles



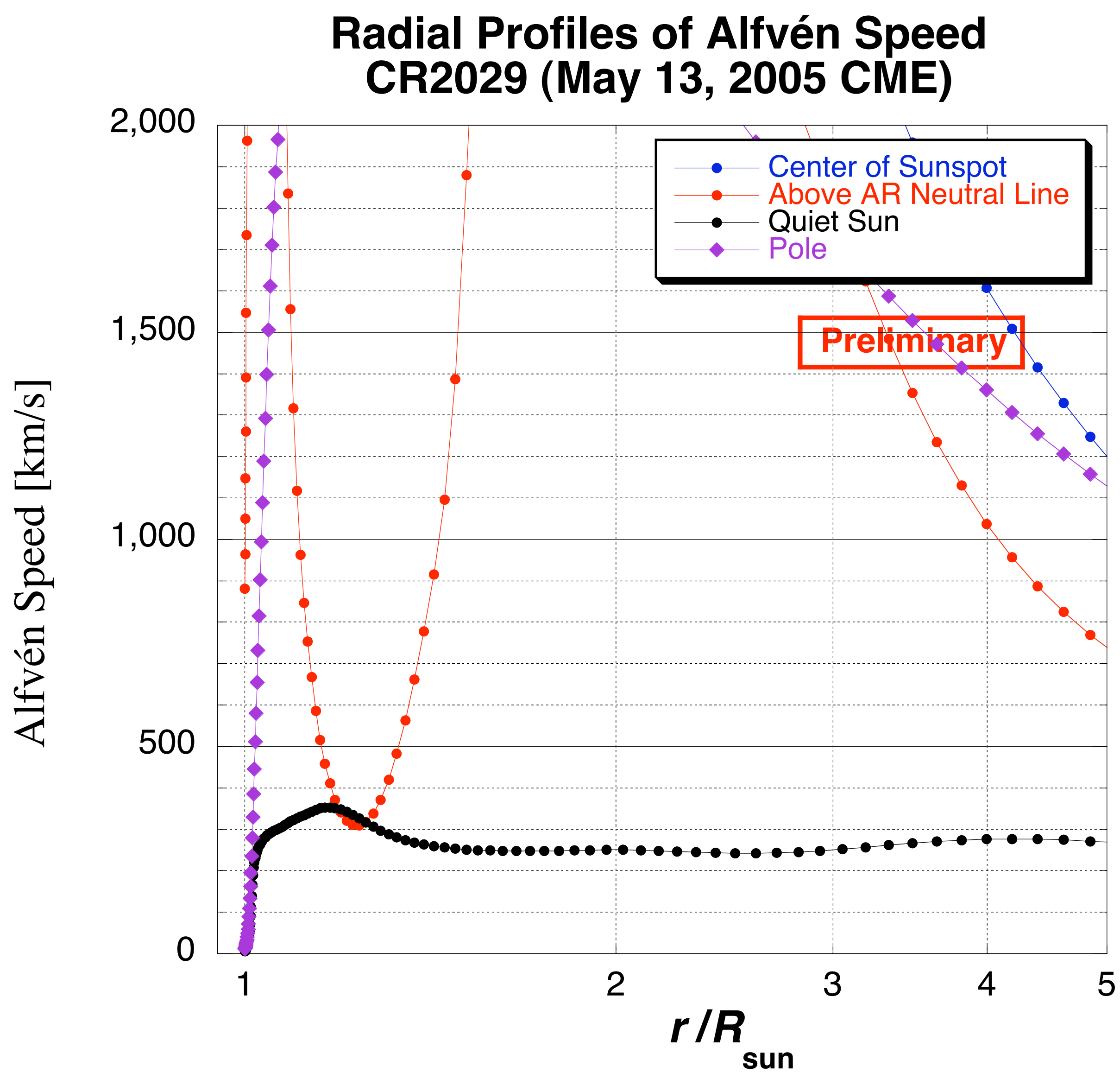
may05_21c [037]

Alfven Speed in the Corona: Radial Profiles



may05_21c [037]

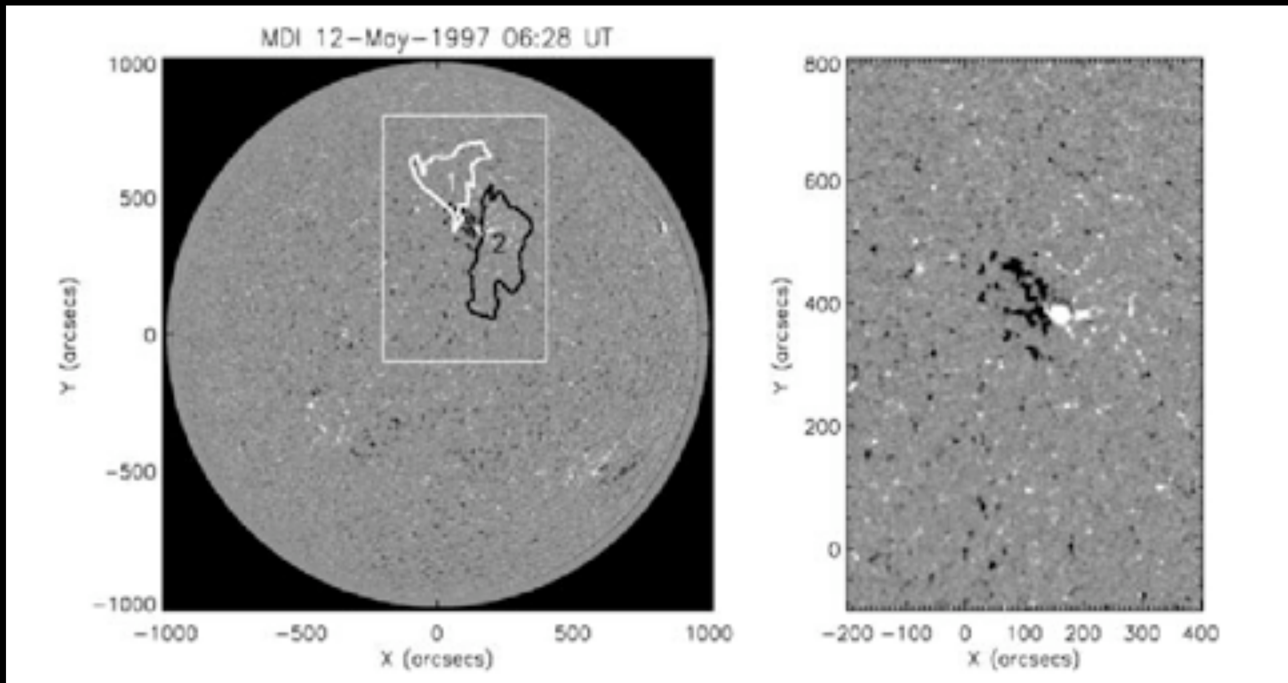
Alfven Speed in the Corona: Radial Profiles

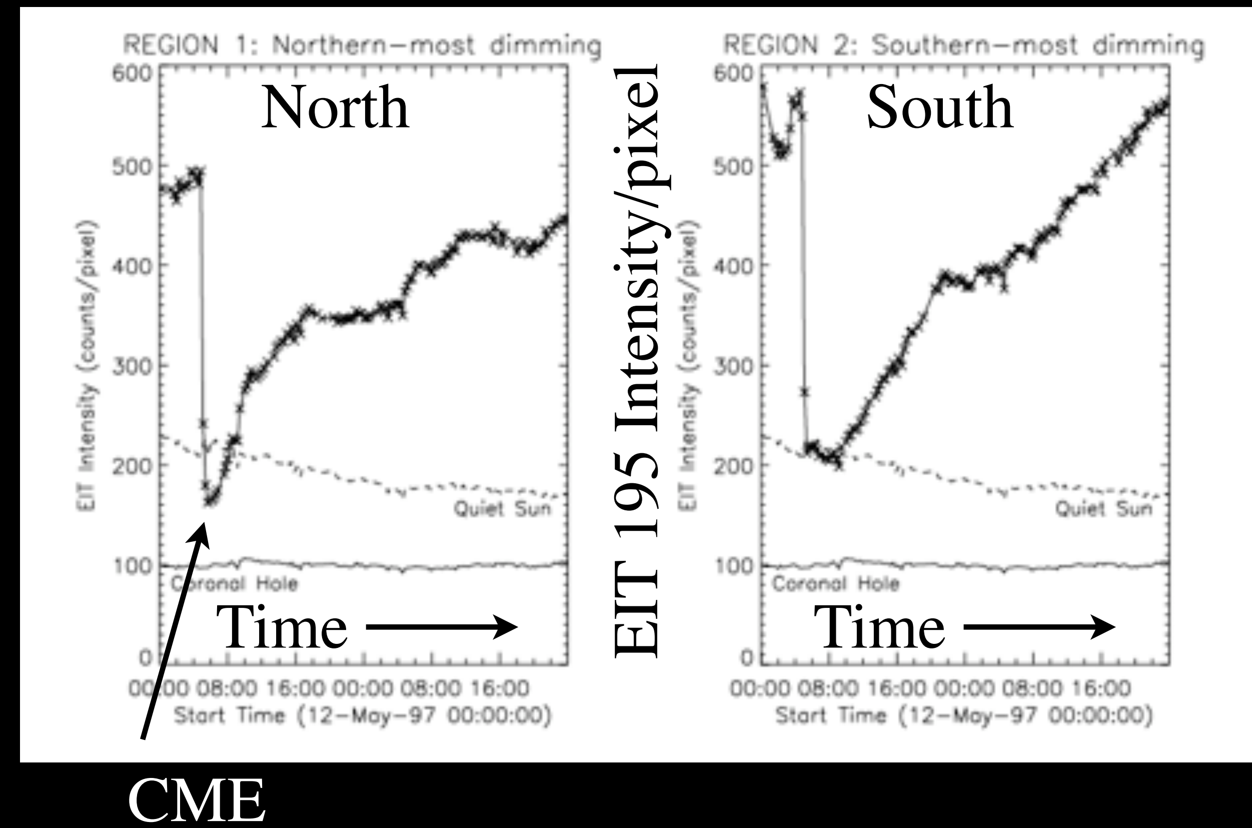


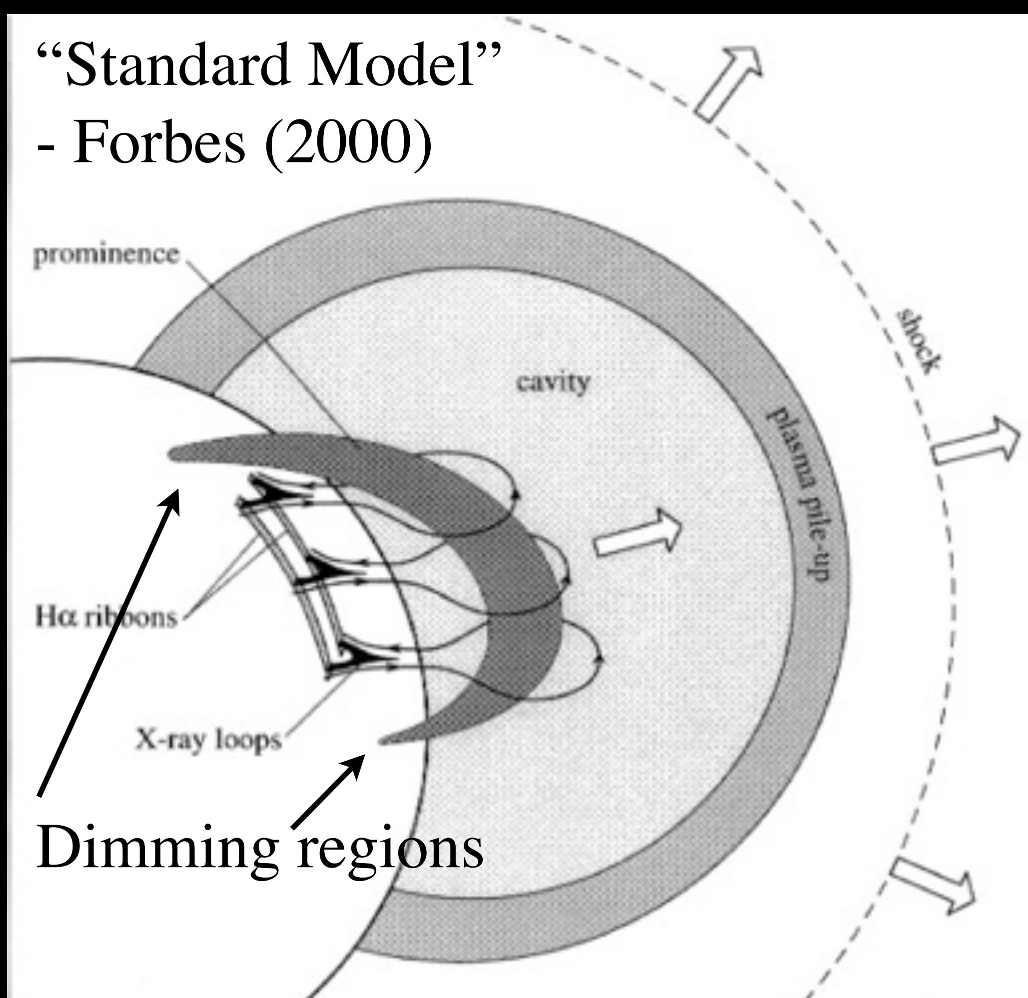
may05_21c [037]

Extra Slides

Analysis of Dimmings - Attrill et al. (2006)



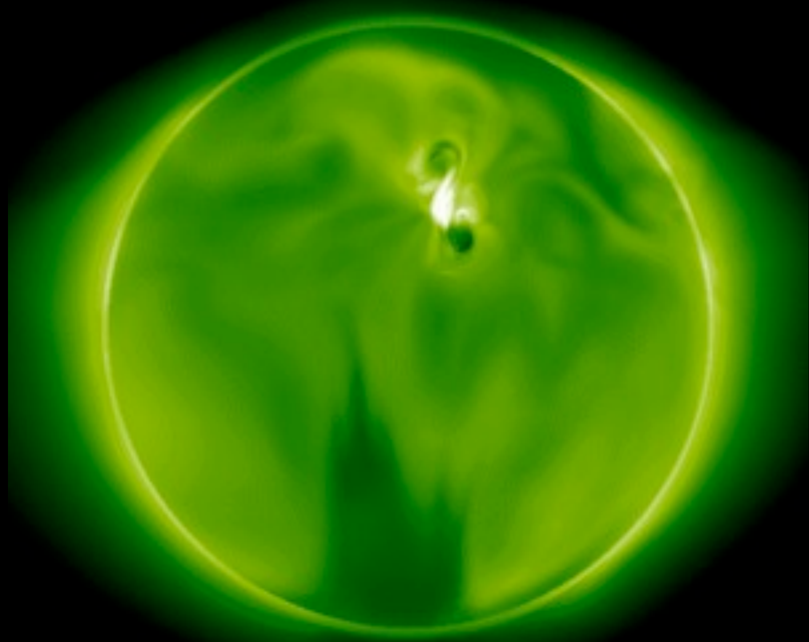




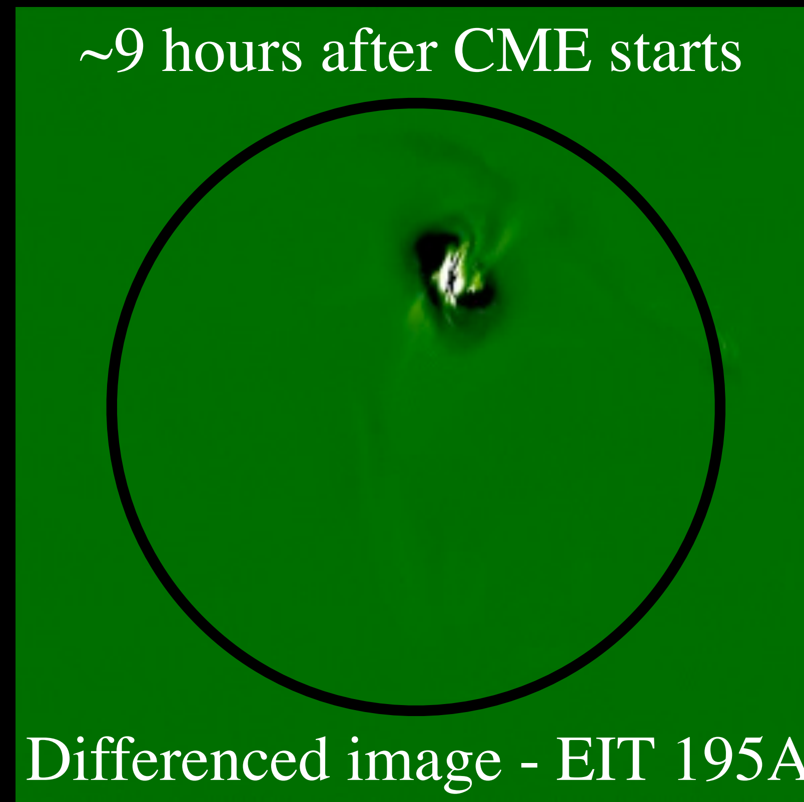
- Computed counts/pixel in dimming regions
- Images differenced from base image prior to eruption
- Dimmings can be seen for ~2 days
- Correlated flux in dimmings with flux in magnetic cloud at 1 AU
- Concluded that cloud was connected to southern dimming

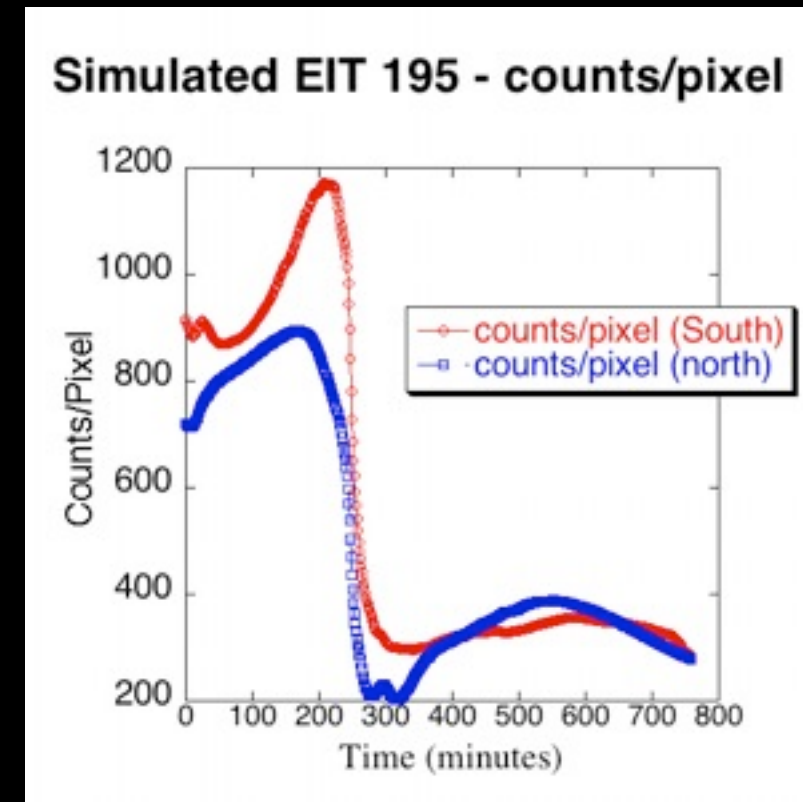
Analysis of Dimming Regions - Simulation

~25 minutes after CME starts



Simulated EIT 195A





- 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?

MHD Equations
(Improved Energy Equation Model)

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

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

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

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

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

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

$$\gamma = 5/3$$

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

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

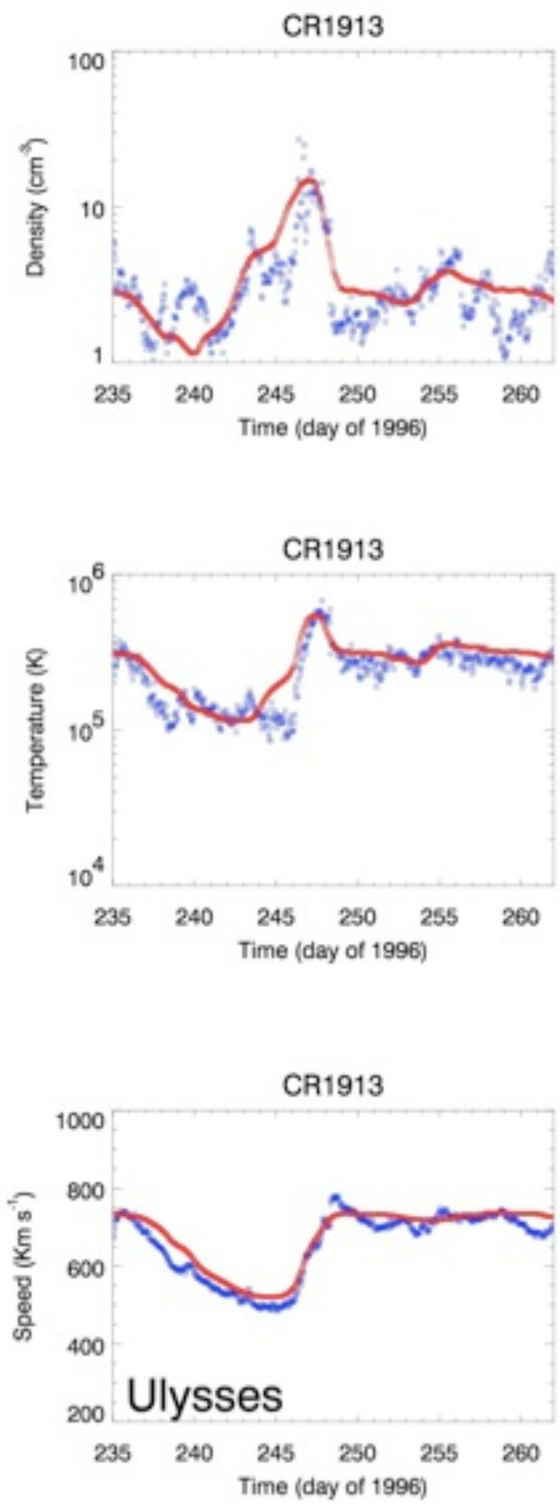
+ WKB equations for Alfvén wave pressure p_w evolution

Summary

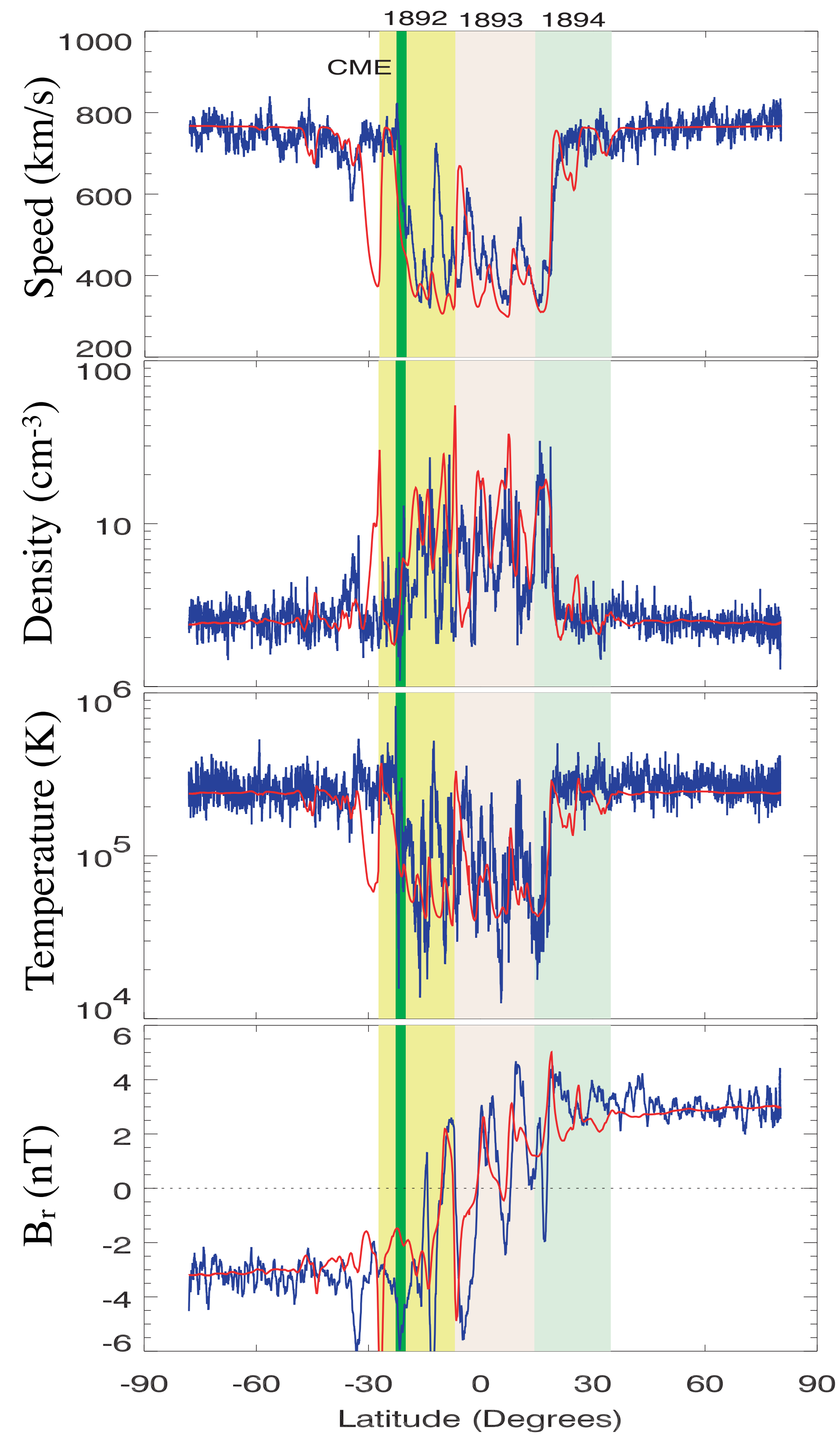
- MHD "thermodynamic" simulations can be used to understand what magnetic structures underly observed emission
- We have applied this technique to the May 12, 1997 CME and investigated dimming regions (transient coronal holes)
- The magnetic structure of the dimmings in the simulation is different than the simple picture many people use
  - Field lines originating from the dimmings overlie the erupting flux rope
  - Erupting flux rope reconnects with overlying fields as the structures propagate outward
  - Interplanetary flux rope combines these fields, is eventually connected back to coronal holes
- Will this occur in more energetic CMEs? We have begun to investigate the May 13, 2005 CME

Comparison of MHD Models with Ulysses Measurements

Whole Sun Month



Fast Latitude Scan

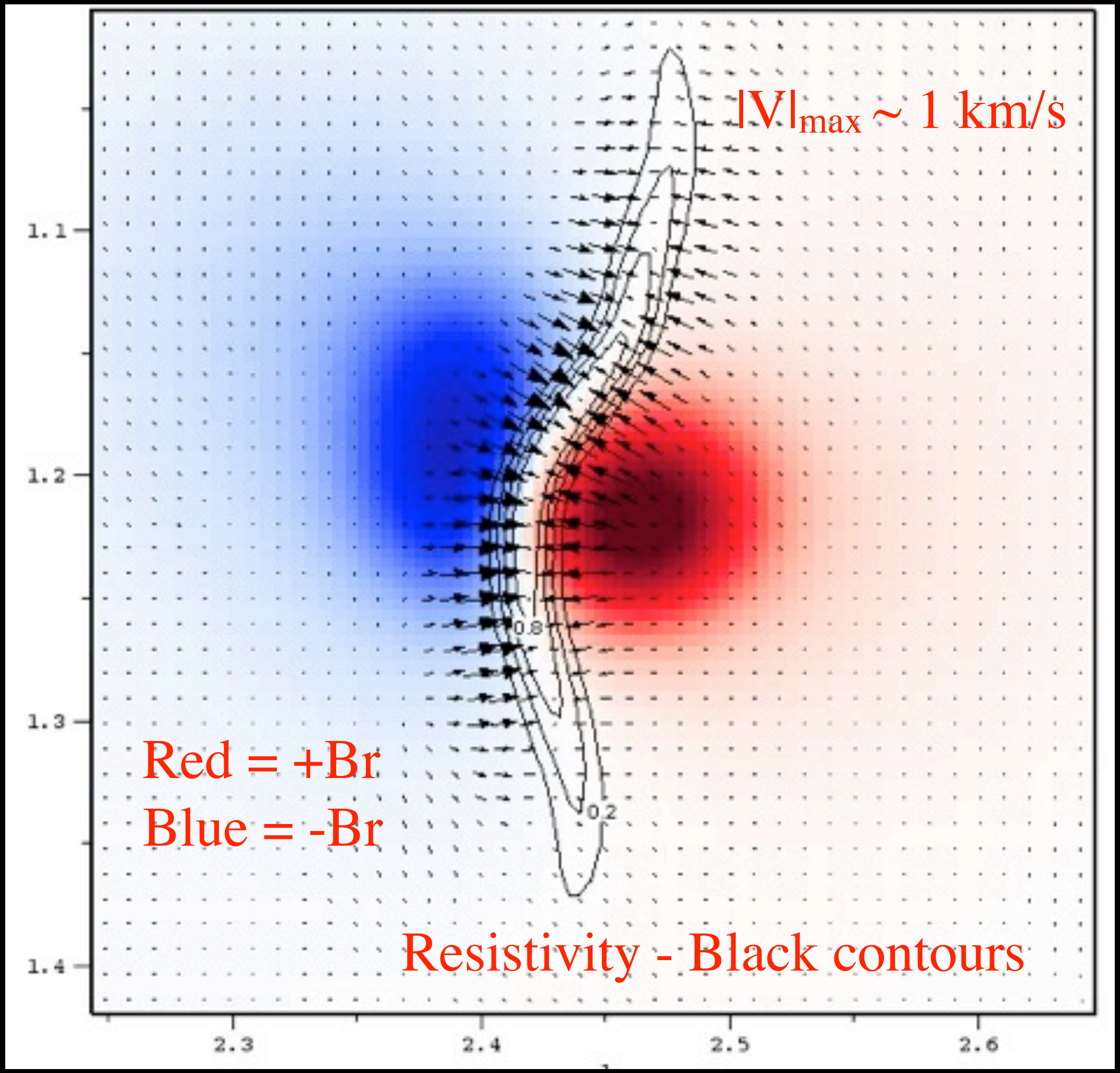


Riley et al. 2001

Predictive Science, Inc.

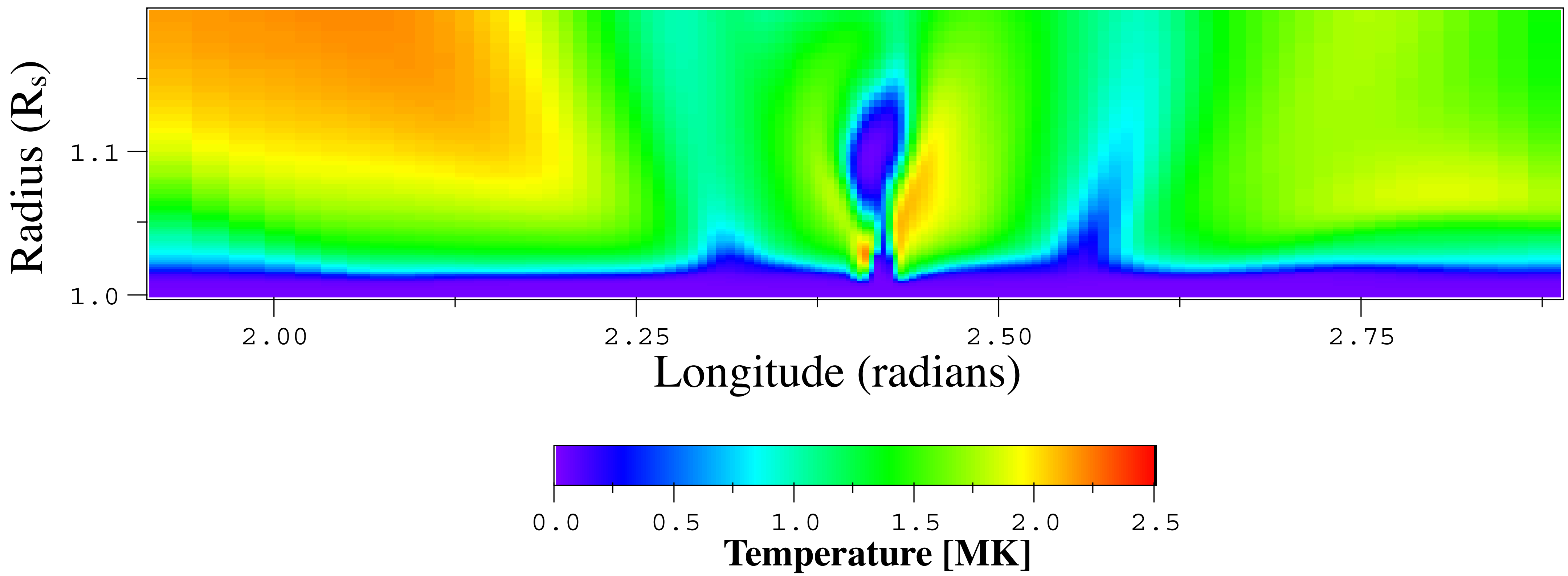
Converging Flows and Flux Cancellation

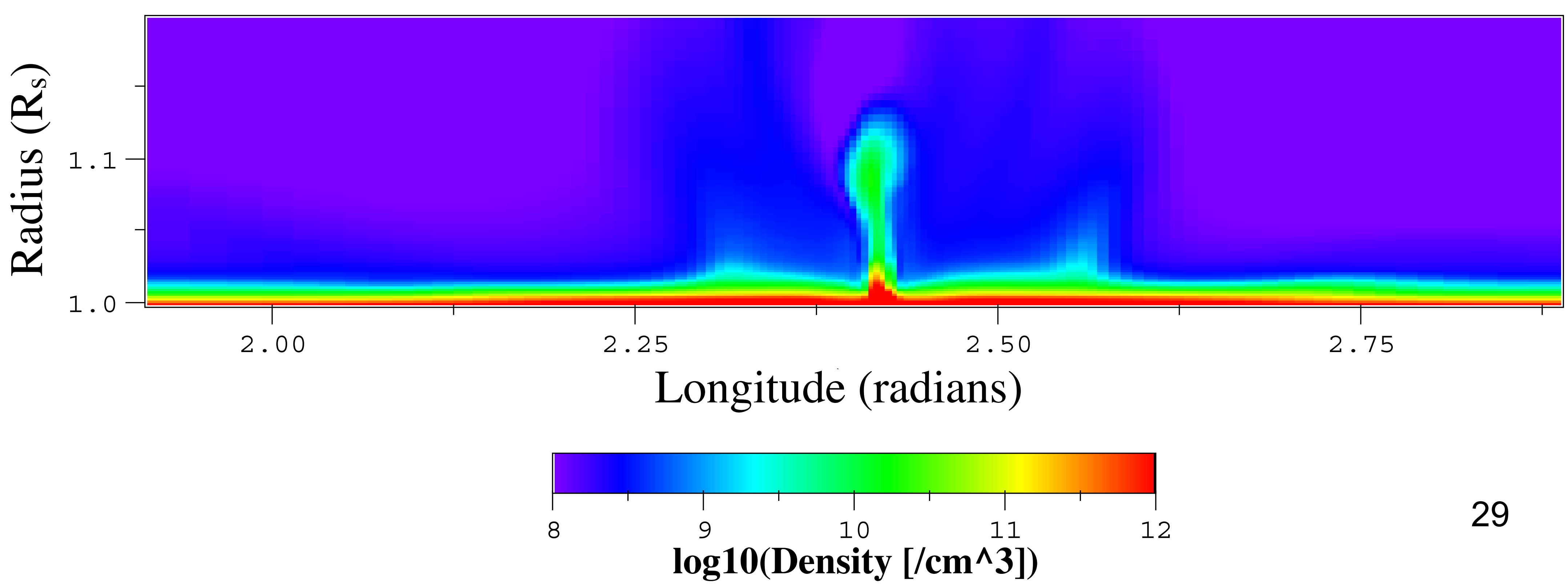
- Flux cancellation was observed prior to (and during) the May 12, 1997 CME
- To cancel flux, we apply converging flows perpendicular to the polarity inversion line (PIL)
- Enhanced resistivity is introduced at the PIL at the boundary only (similar to van Ballegooijen et al.)



Formation of a “Prominence” by Flux Cancellation

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





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)

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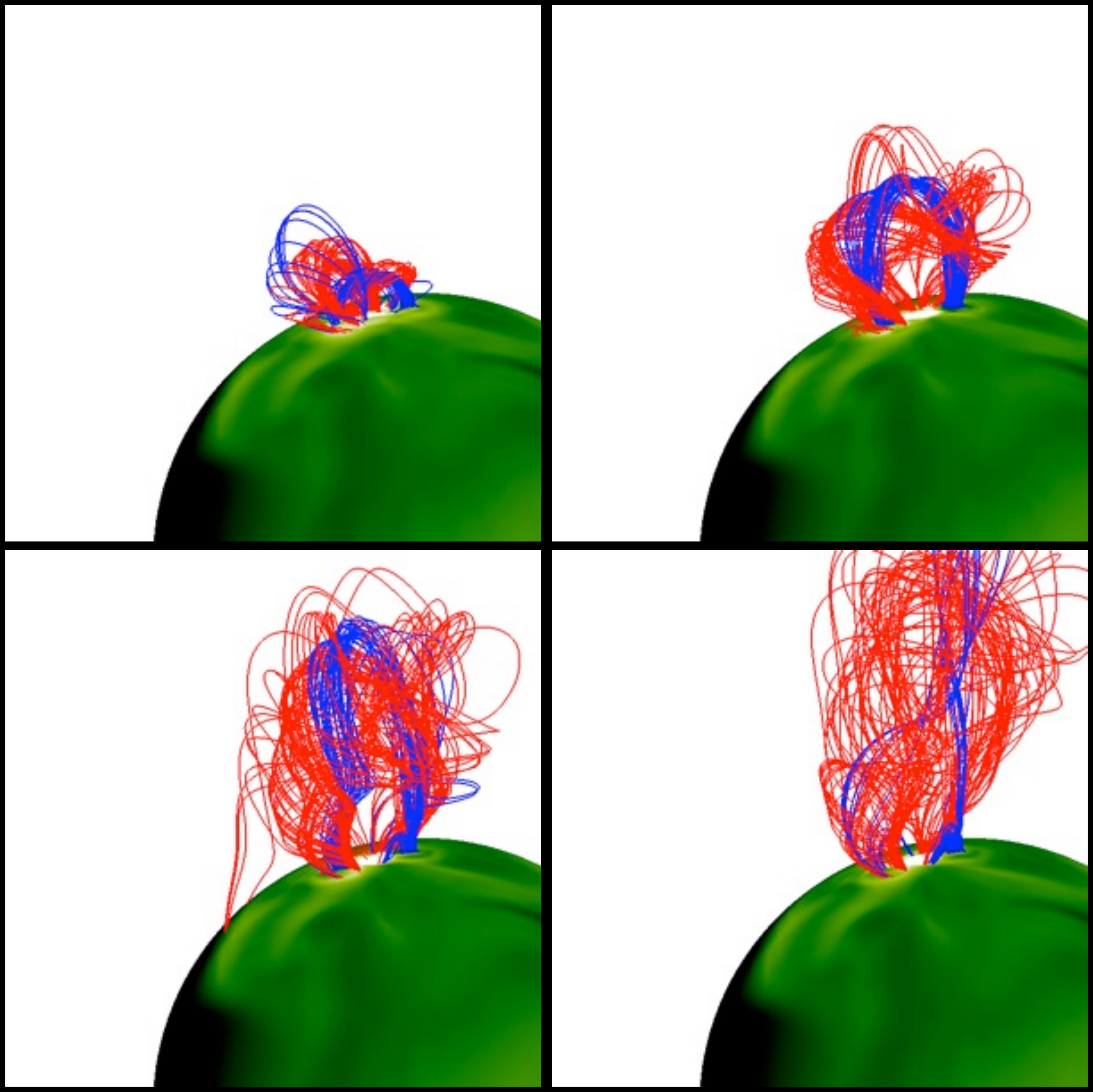
+ WKB equations for Alfvén wave pressure p_w evolution

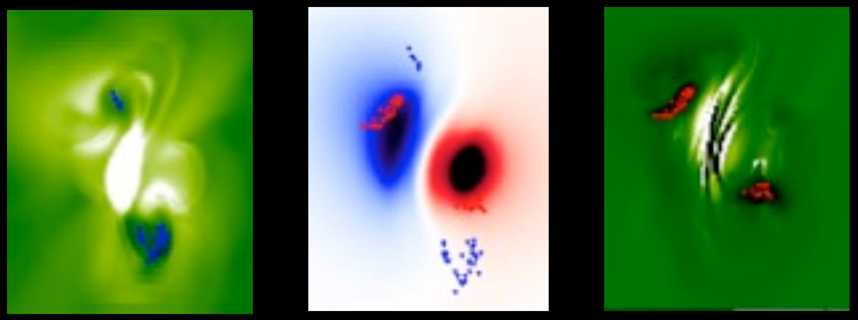
Our Result Differs from the Simple Picture

- Our result explains how CMEs can still be connected to the Sun even after dimmed regions have returned to background levels
- Flux rope in interplanetary space combines erupting flux rope and overlying fields
- How general is this result?
  - May 12, 1997 CME was not very fast (~600 km/s)
  - Active region did not have that much flux
- What happens in fast CMEs from larger active regions?

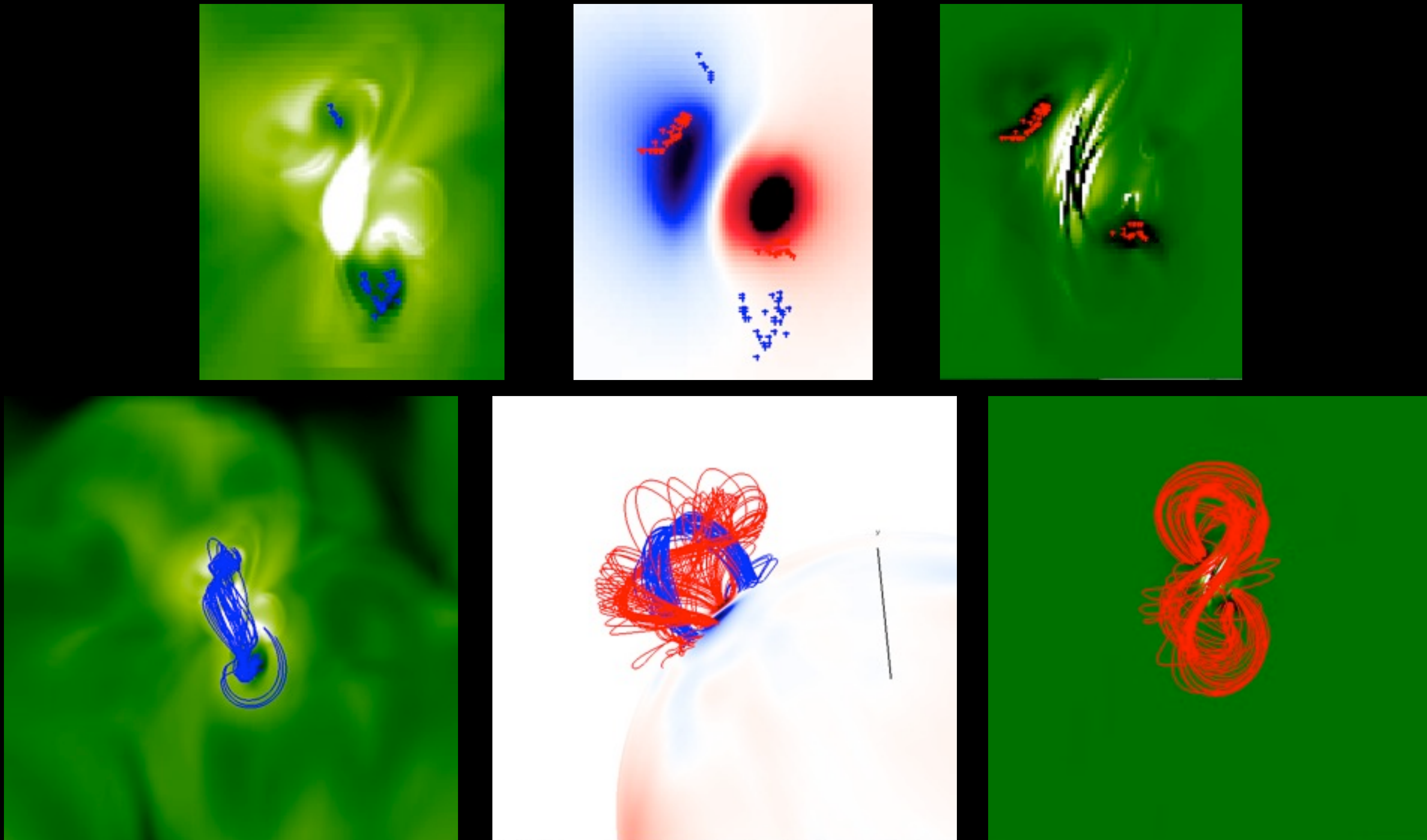
Magnetic Field Lines & Simulated Emission



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



Trace Magnetic Field Lines from Dimming Locations

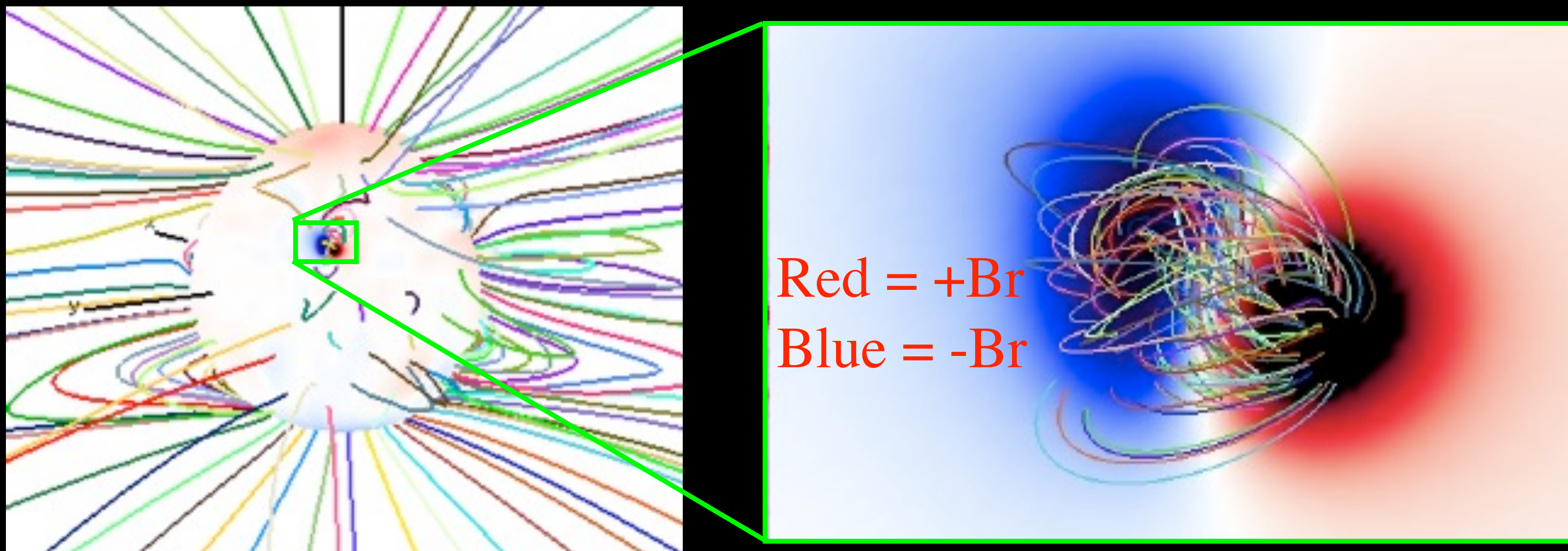


- Blue footpoints - largest dimming from visual inspection
- Red footpoints - largest dimming from subtracting base image

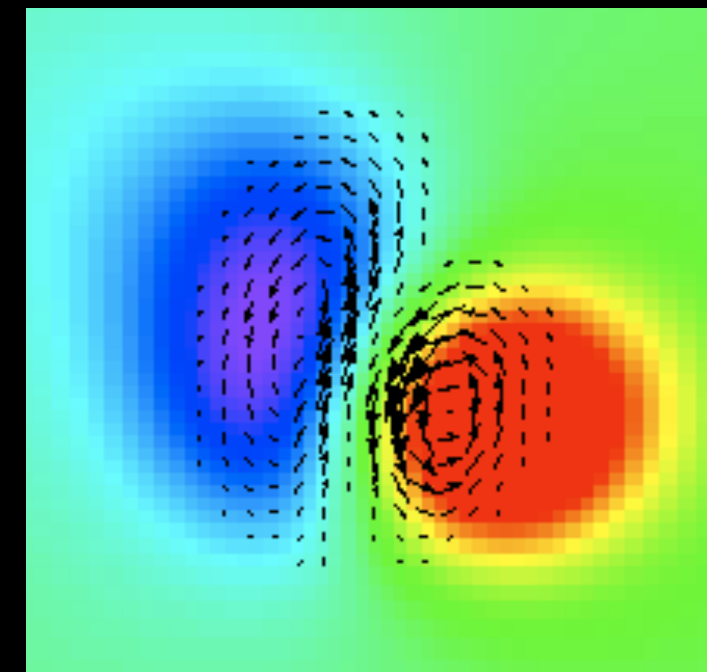
Shear Introduced by Flux-Preserving Flows

Global View

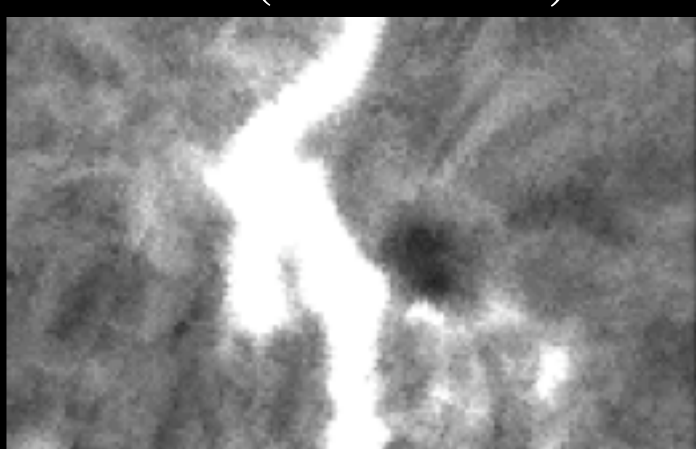
Sheared/twisted Field in AR



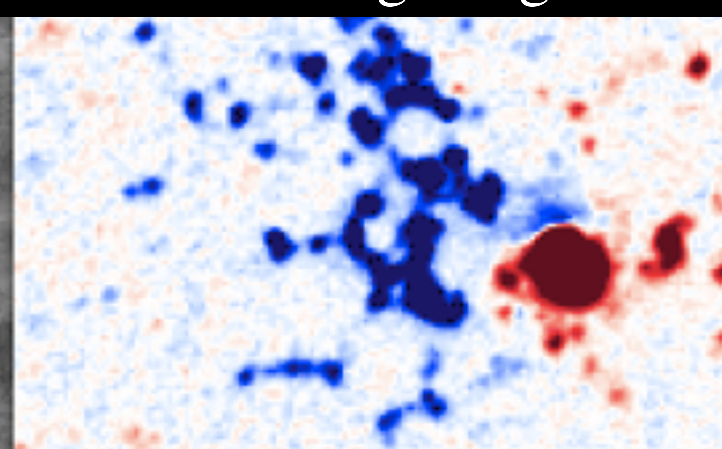
Vortical flows used for Shear



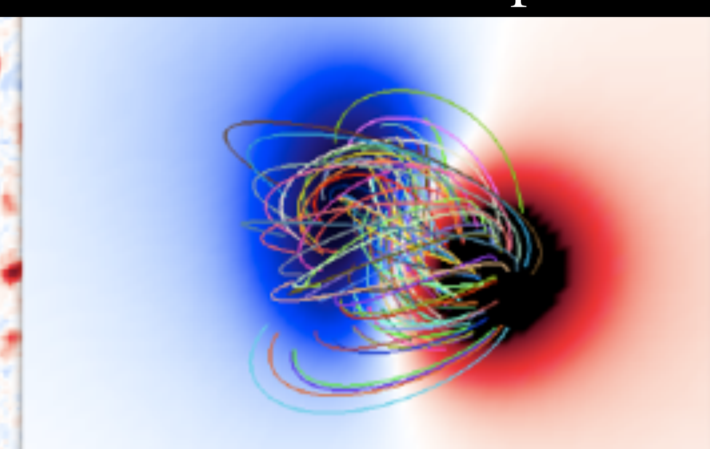
Filament channel & flare (SOON Hα)

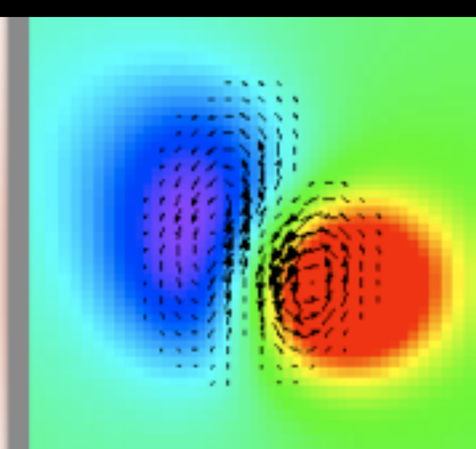


NSOKP magnetogram



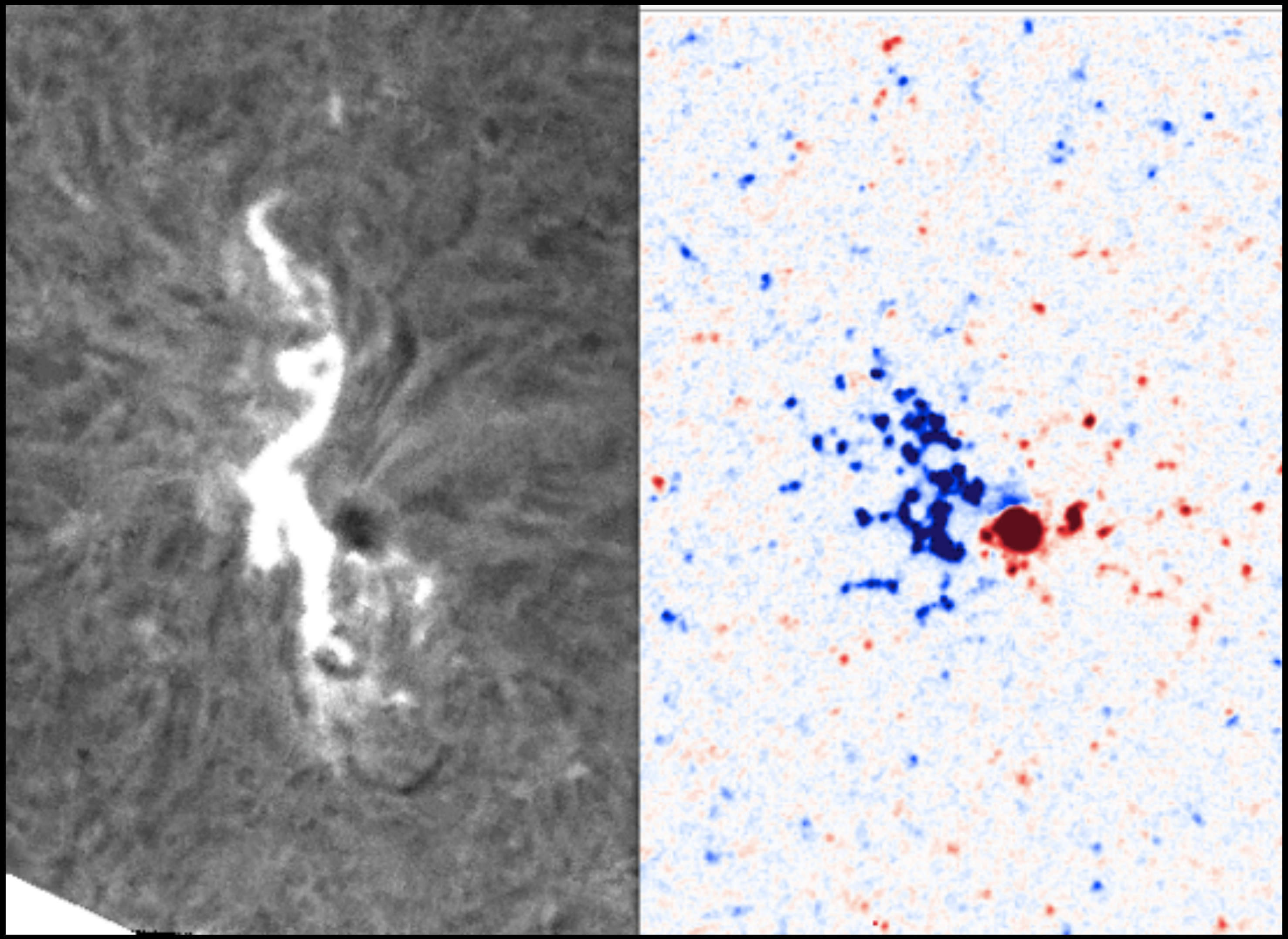
Smoothed Map





- 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

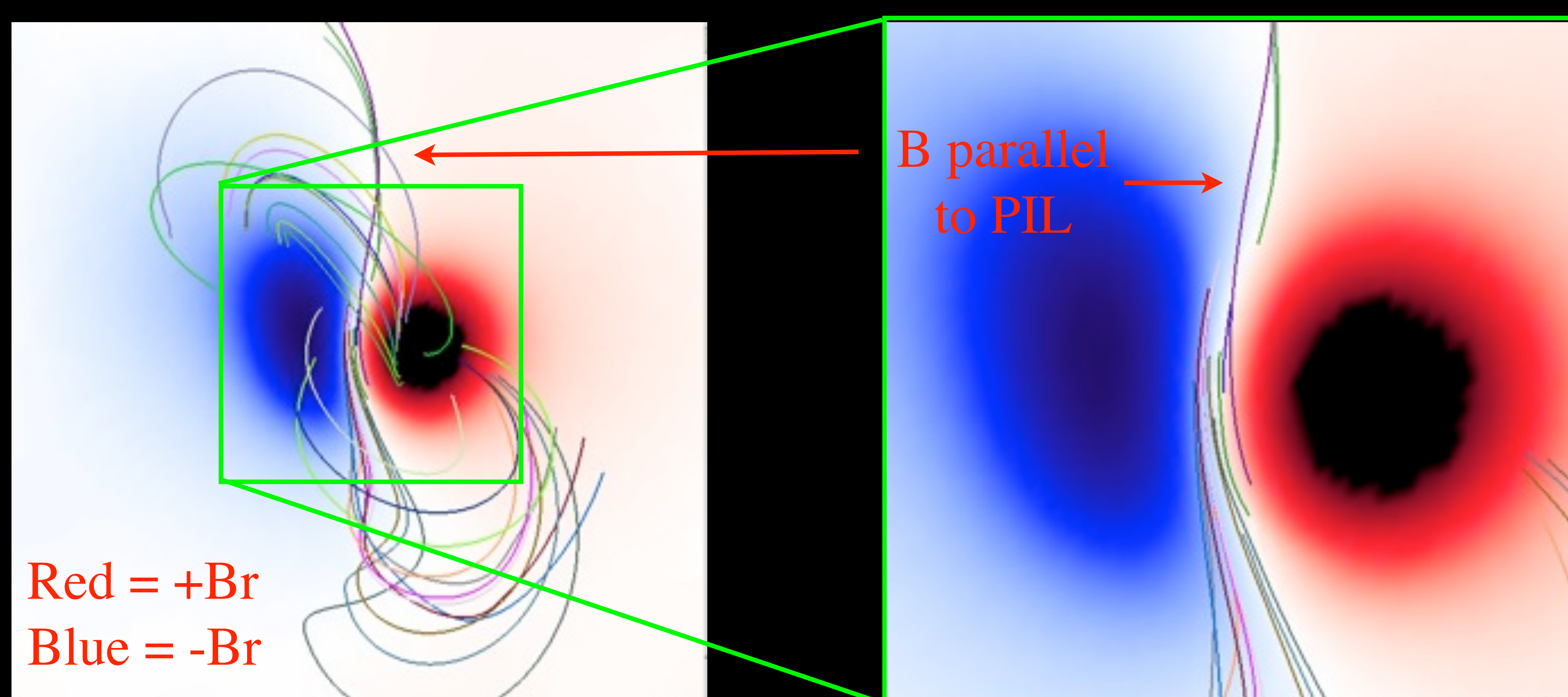
Filament Channel & Resulting Eruption



- 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 **B** parallel to the PIL

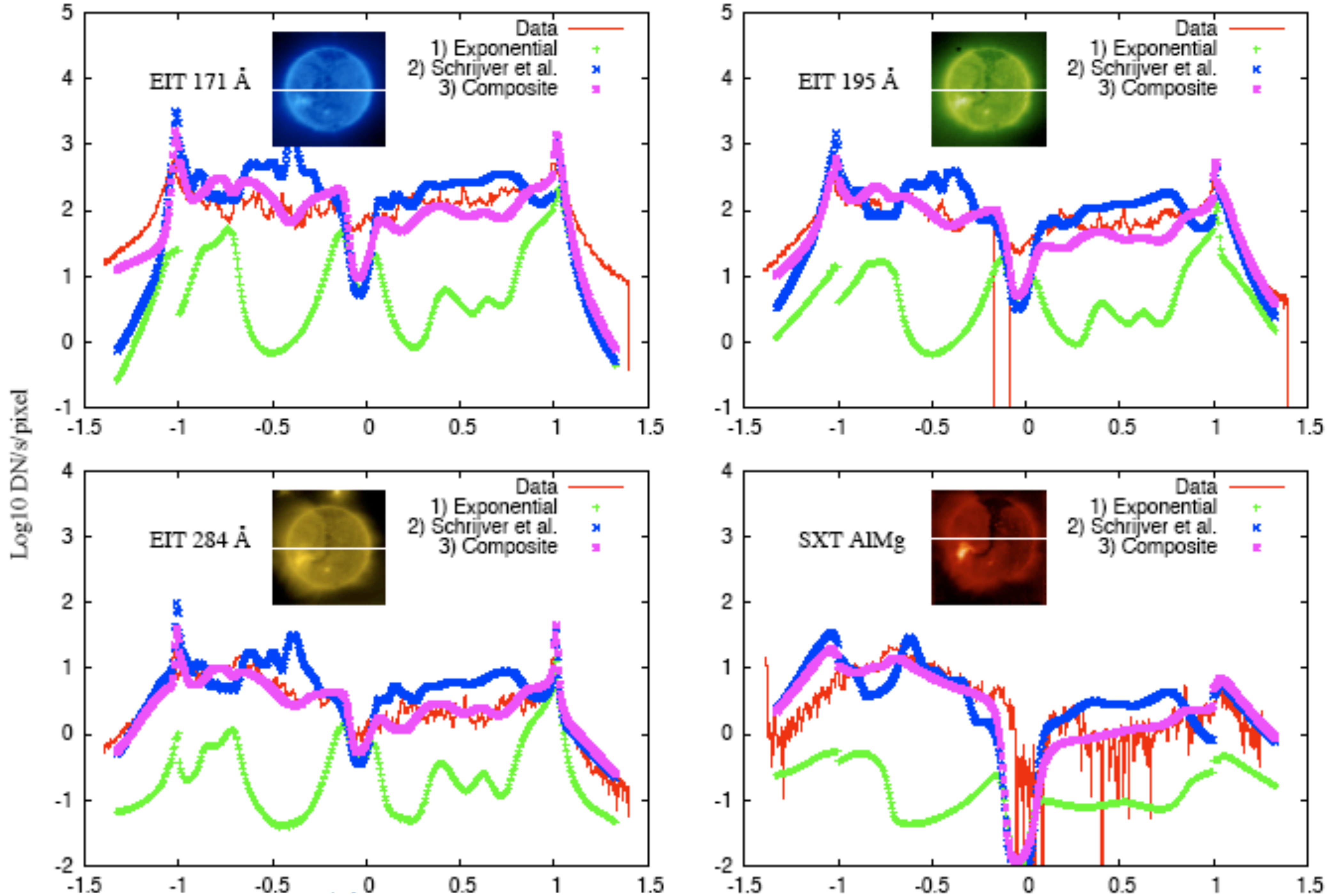


- No flux rope forms (yet)

Is the Standard Paradigm for Dimmings Correct?

- Two Problems:
  - Magnetic flux in dimming is weak. How was strong active region magnetic flux opened?
  - Bi-directional heat flux in CMEs → CME connected to the Sun at 1-5 A.U. (propagation 4-20 days). Dimmings typically last < 2 days. What's going on?
- Addressing this question requires a model that can reproduce emission.
- We solve the time-dependent MHD equations, including radiative losses, parallel thermal conduction, coronal heating (empirical), and solar wind acceleration (WKB description of Alfven waves).
- Advantage of this approach: Self-consistently describe plasma & magnetic field, compare with observed emission
- We have investigated the May 12, 1997 CME. We are beginning studies of May 13, 2005 CME.

August 1996 Emission: Equatorial Cut



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