Physical Origin of the Drivers of Space Weather at the Sun

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This talk discusses recent progress in developing such tool for focused studies of CMEs and related phenomena.

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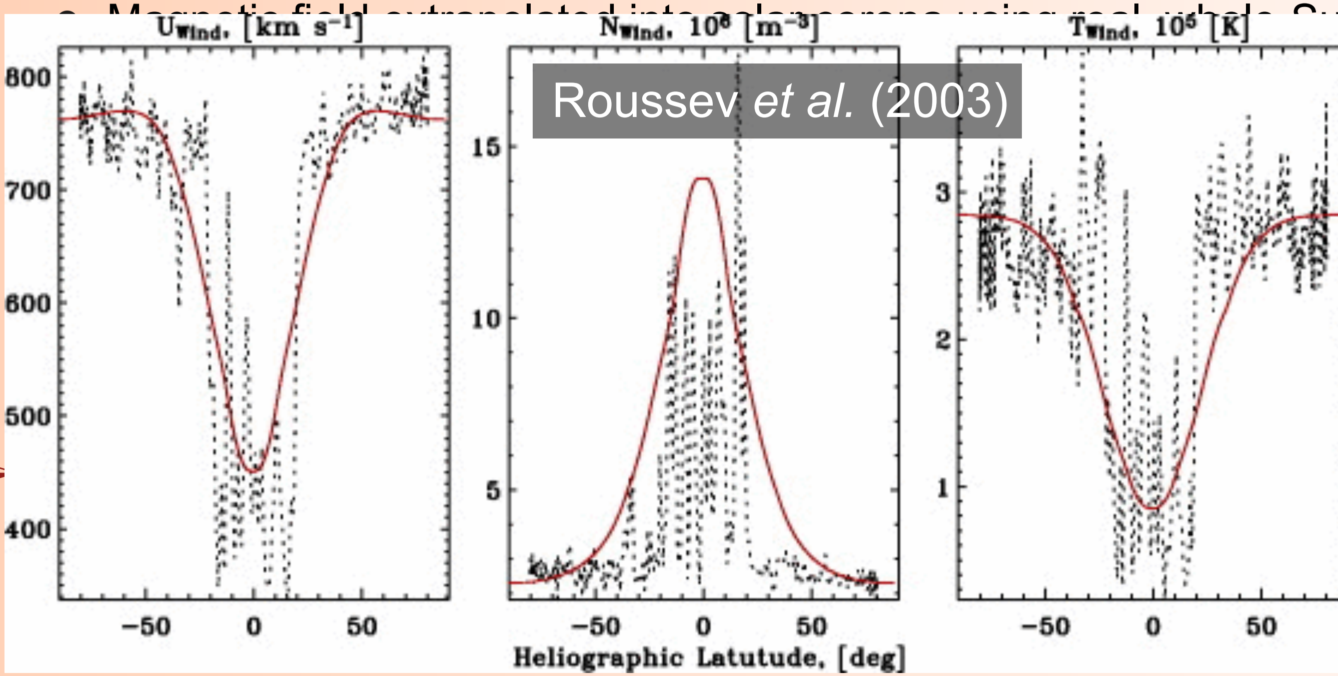

- In-situ observations at 1 AU and elsewhere (ACE, Ulysses, *etc.*).

![NSF logo]

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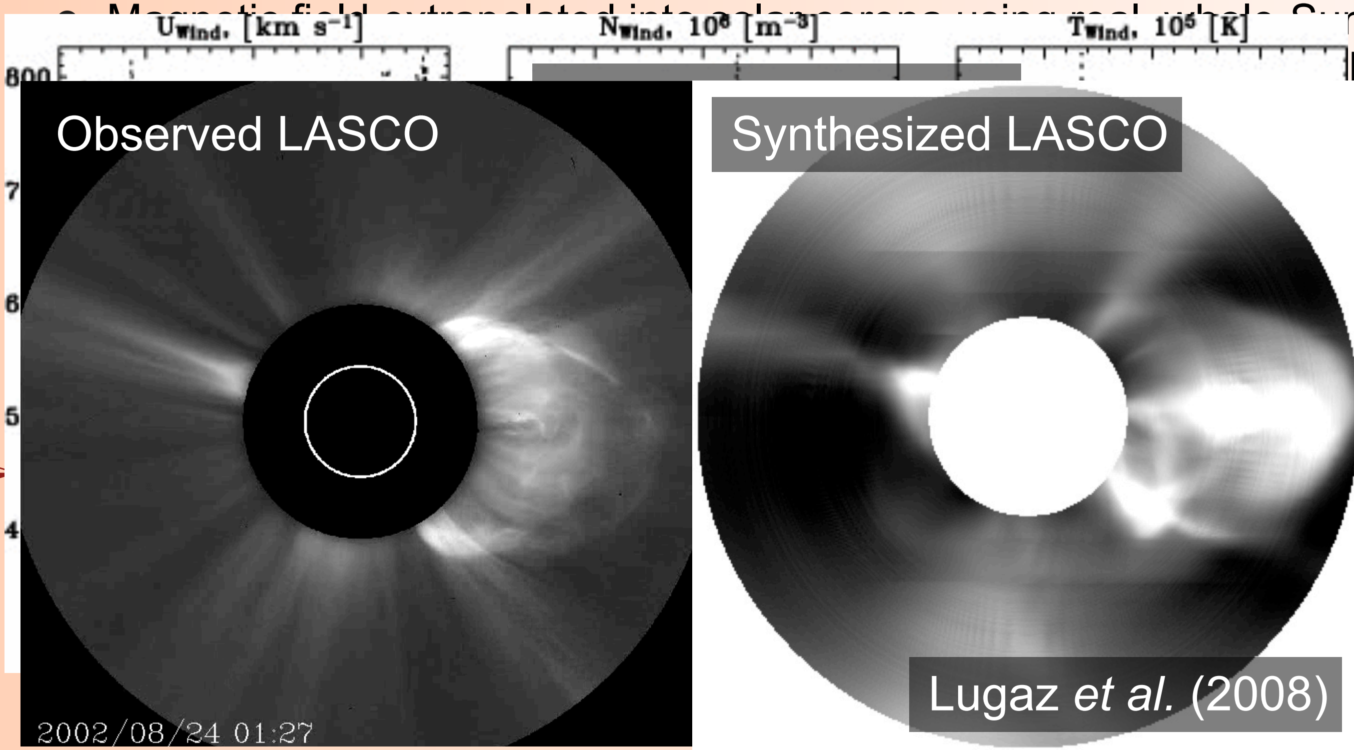

  - Thomson-scattered white-light observations of solar corona (SoHO/LASCO).

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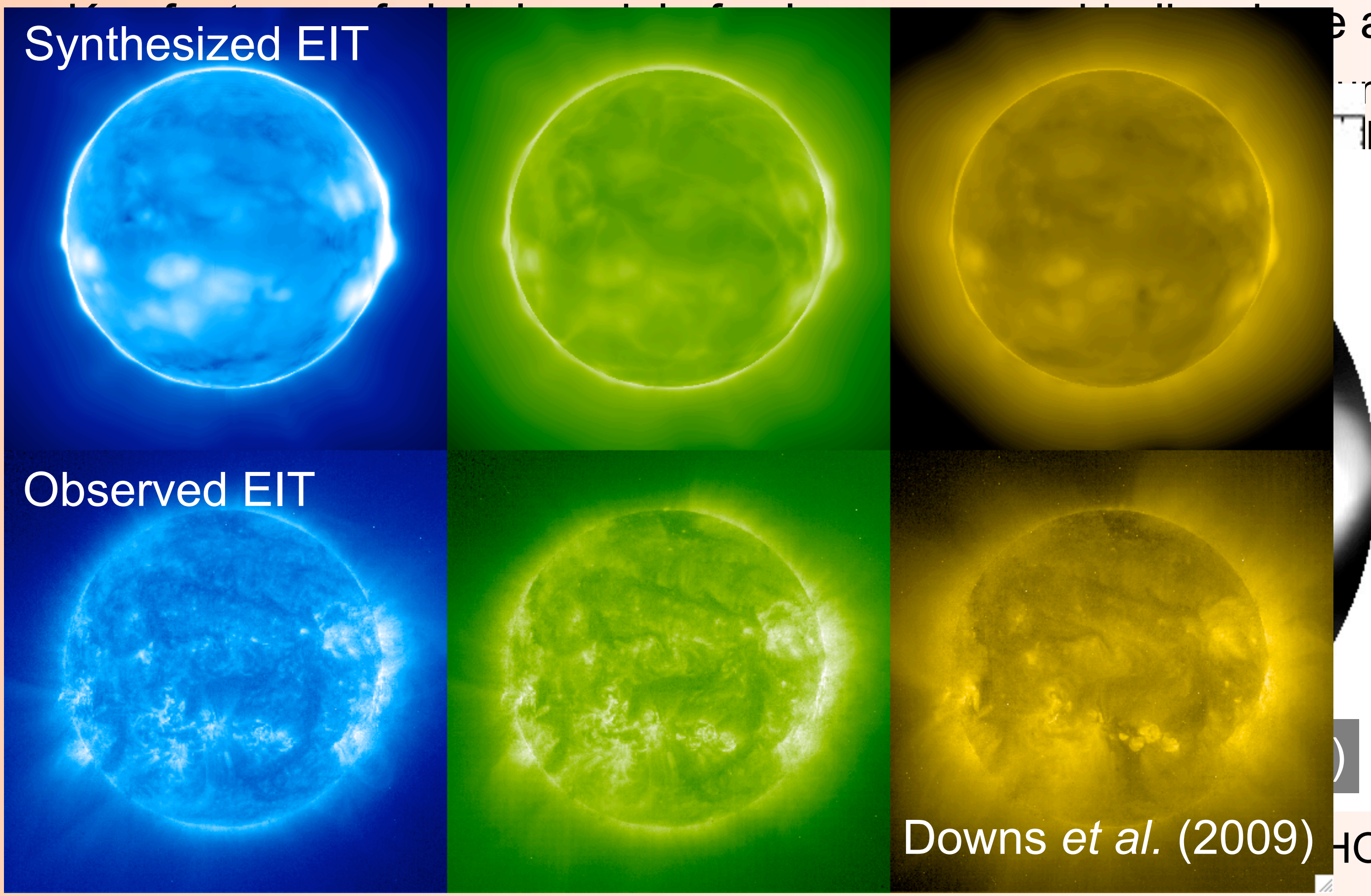
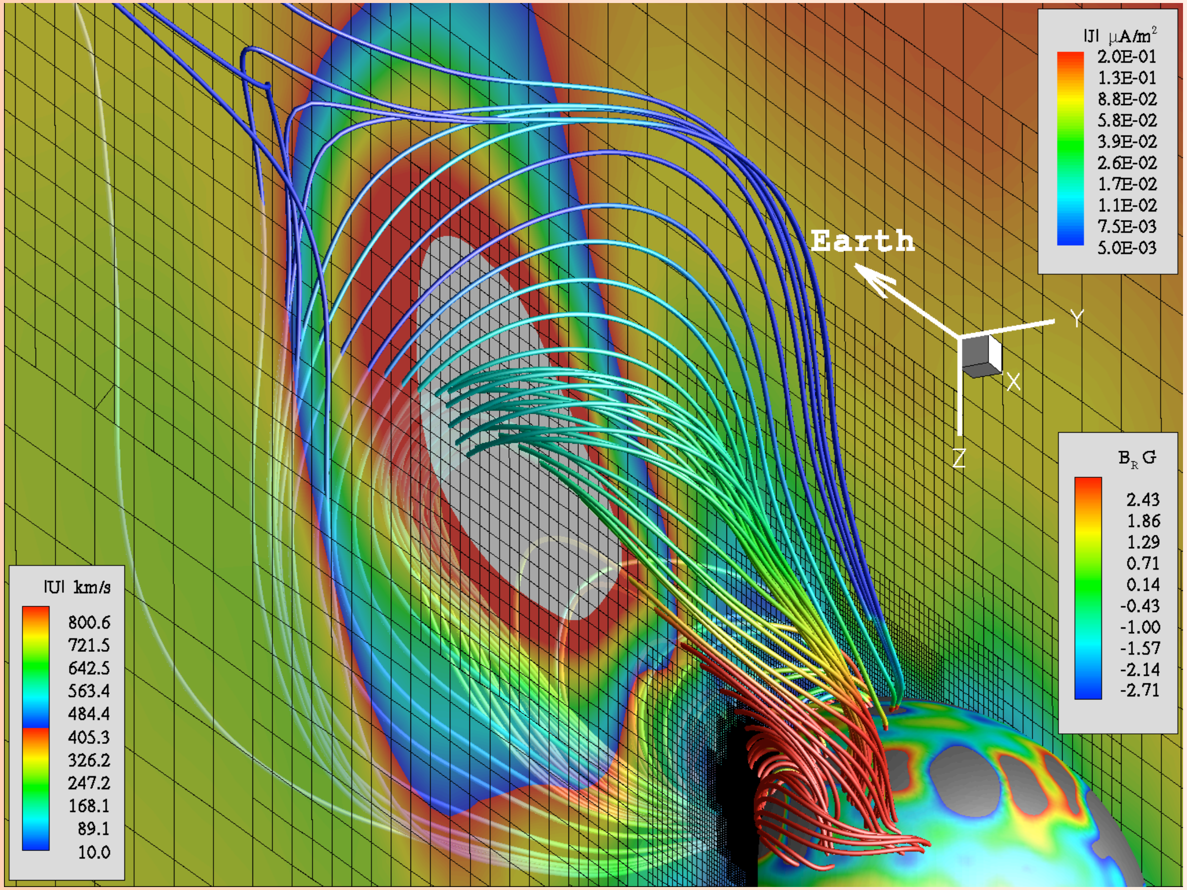


HO/LASCO).

- Solar observation in Extreme UV (SoHO, STEREO, and SDO).

Data-Driven Models of CMEs

Model of 1998 May 2 CME Event



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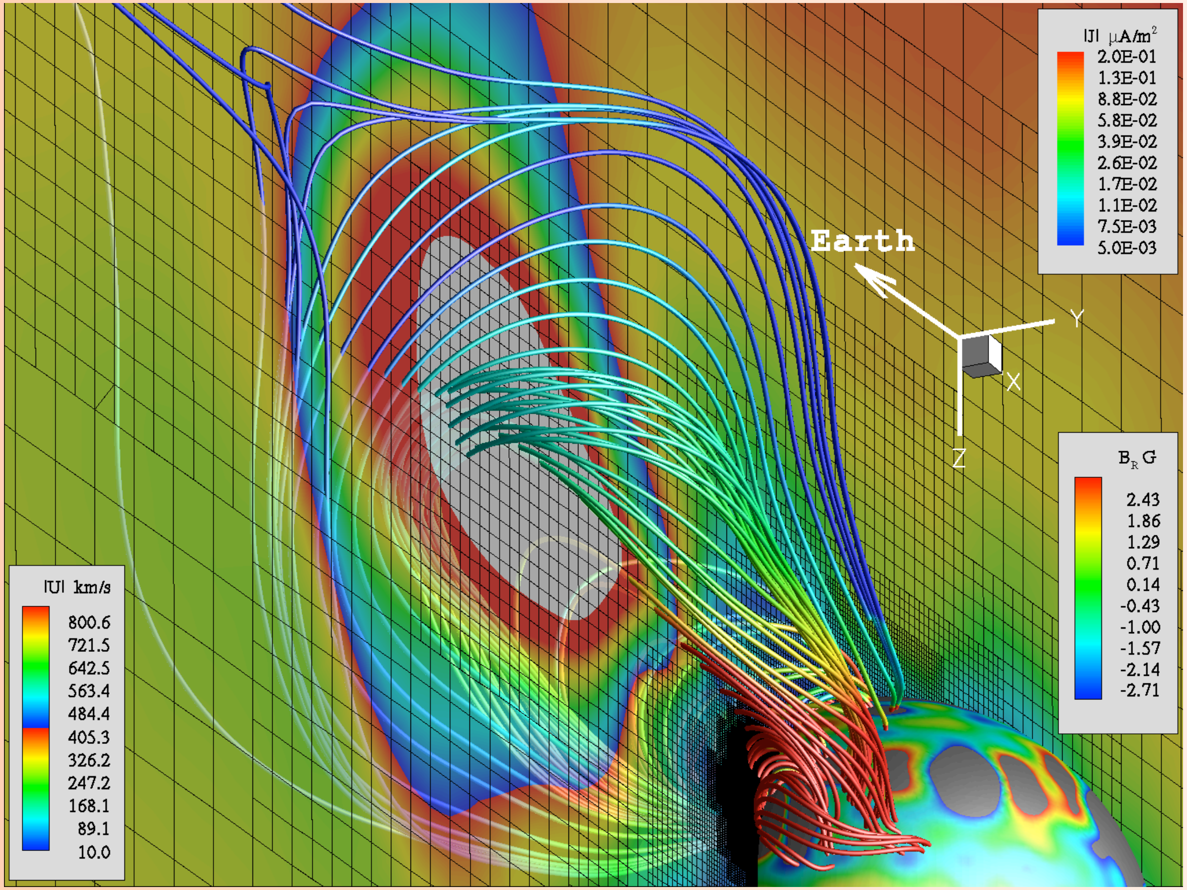
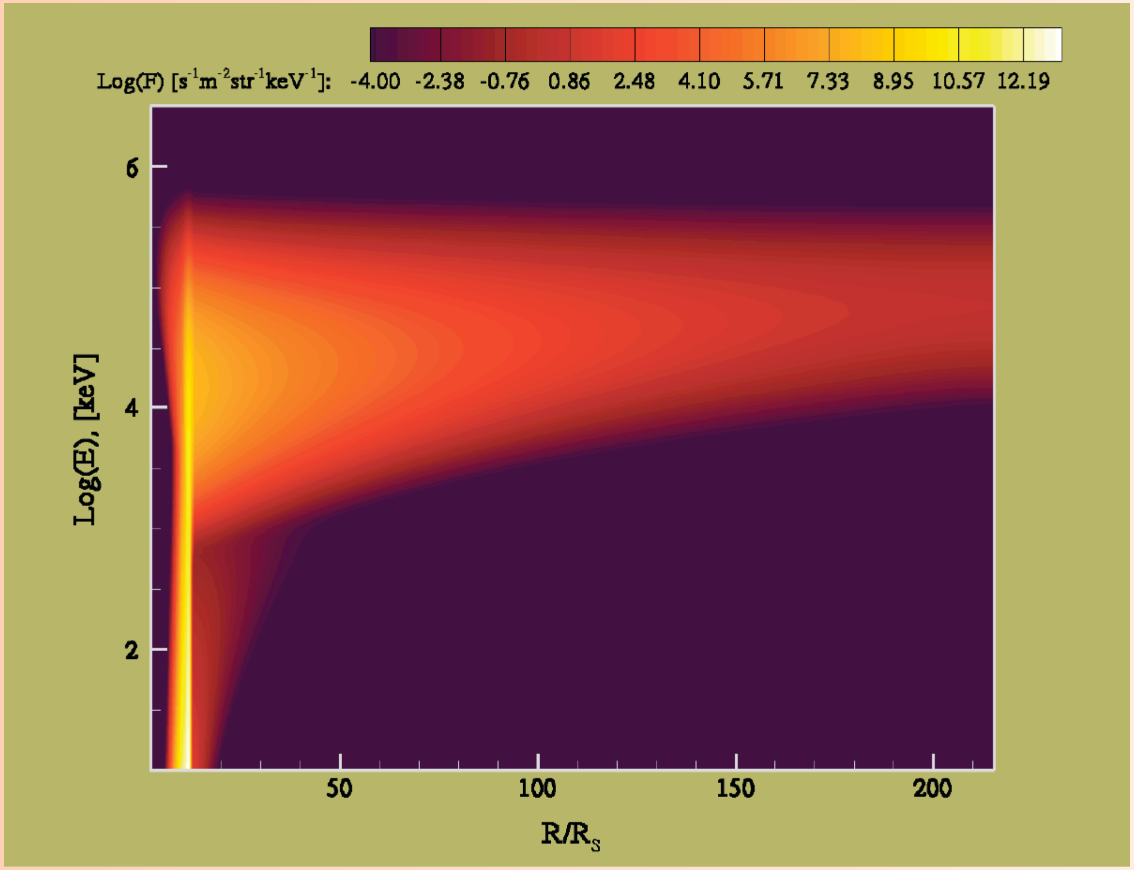


- Physical mechanisms leading to occurrence of CMEs have been debated by solar community for 40+ years now.
- Answering fundamental questions concerning energy build-up, CME trigger, evolution of background magnetic field & coronal plasma, shock formation & evolution, *etc*., requires event studies.
- By studying 1998 May 2 event, we have demonstrated that strong CME-driven shock can develop relatively close to Sun (Roussev *et al*., *ApJ Lett*., ***605***, *L73*, 2004).

Data-Driven Modeling of SEPs

Model of 1998 May 2 SEP Event



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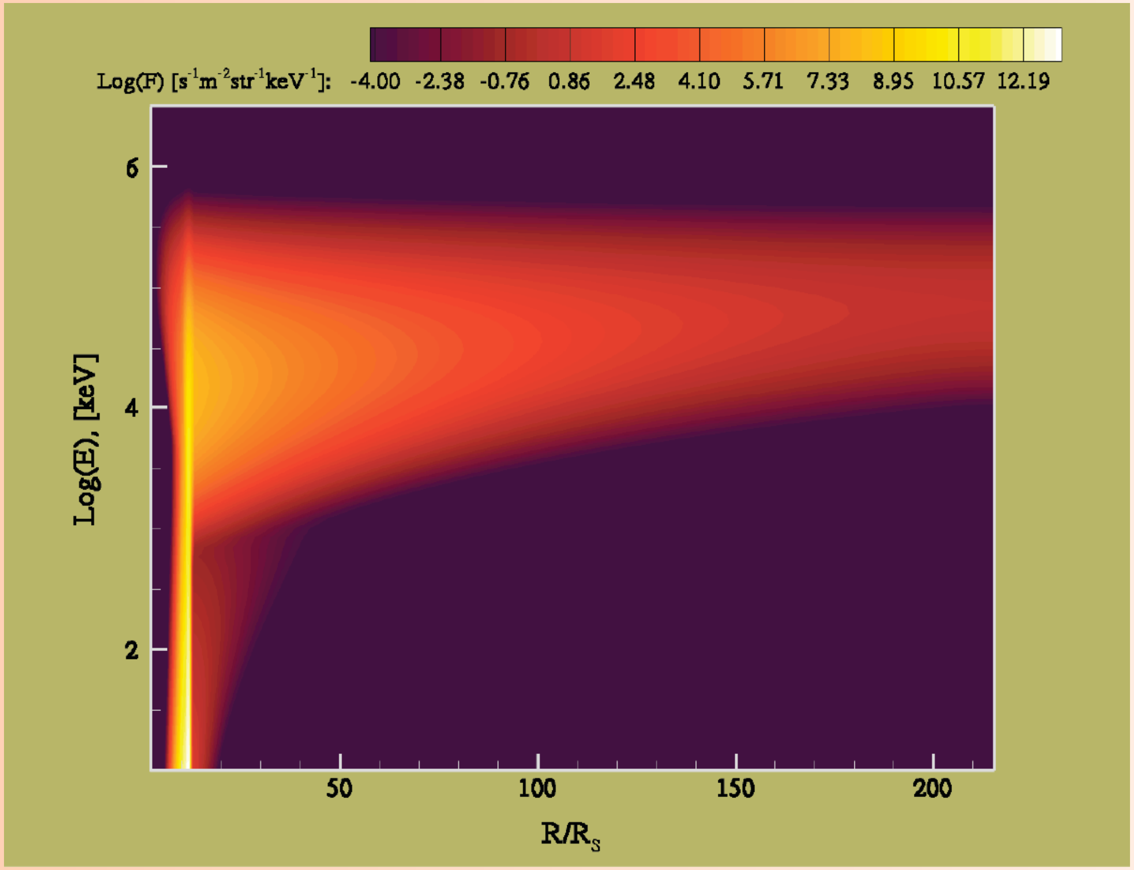
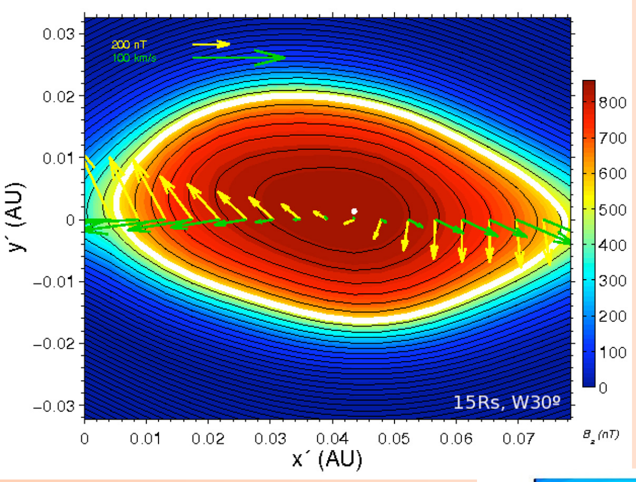
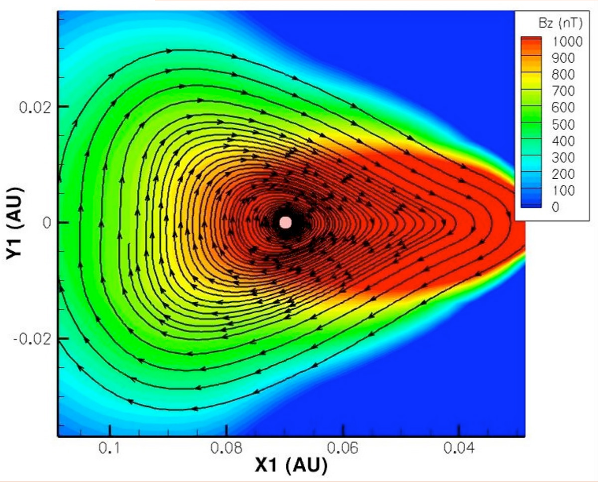


- Production of SEPs at CME-driven shocks is long-standing problem, because little is known from observations about properties of shock waves, level of IP turbulence, strength & geometry of IP magnetic field, *etc*.
- By having "realistic" model of CME-shock evolution, as for 1998 May 2 CME event, we can address the issue of SEP production at CME shocks more self-consistently.
- Simulated proton fluxes for 1998 May 2 SEP event are found to be in good agreement with *GOES-8* data (Sokolov *et al*., *ApJ Lett.*, ***616***, *L171*, 2004).

Model of ICMEs and Magnetic Clouds

Comparison of 3-D ICME Model with MC Reconstruction





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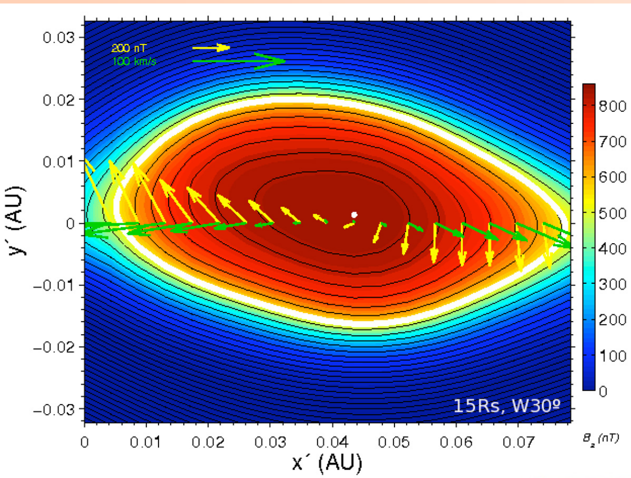
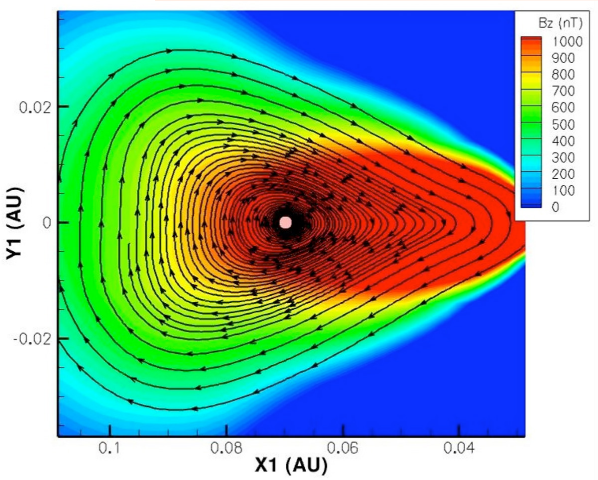
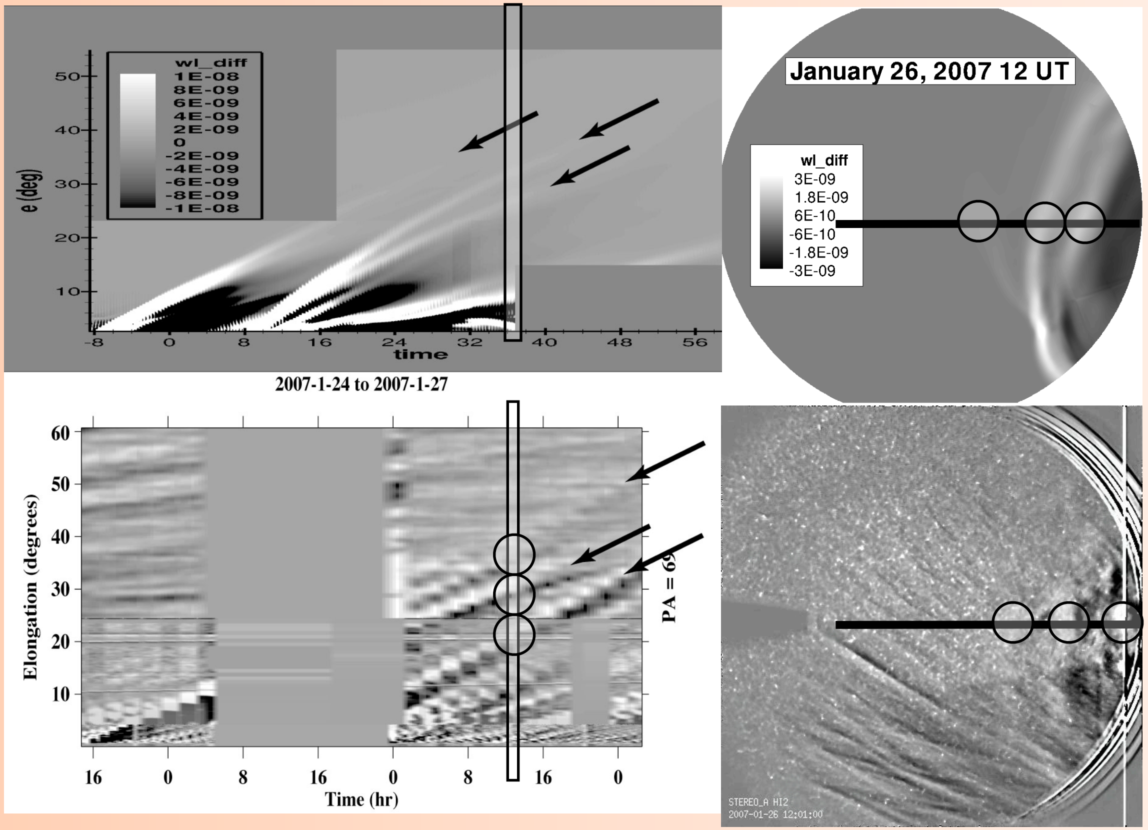
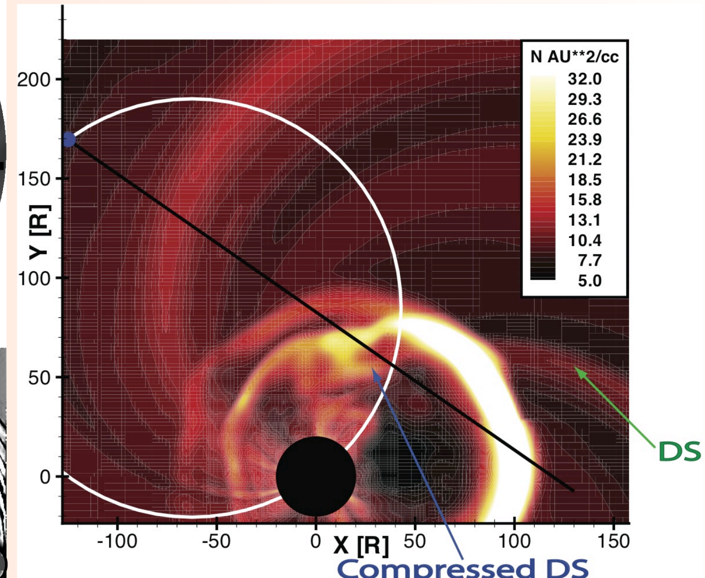




- ➢ Magnetic fields inside ICMEs are most often modeled as twisted flux ropes.
- ➢ Different interpretation of magnetic field structure of MCs is possible if writhe is also considered.
- ➢ We created a simulated ICME with limited twist but significant writhe.
- ➢ We were able to reconstruct MC structure (left) and to compare with 3-D simulation (right) in a way that would be interpreted as typical twisted flux rope.
- ➢ This result challenges accepted paradigm that ICMEs are always twisted magnetic flux ropes (Al-Haddad *et al*., *ApJ Lett., **738**, L18*, 2011).

Filling Data Gaps in STEREO Observations



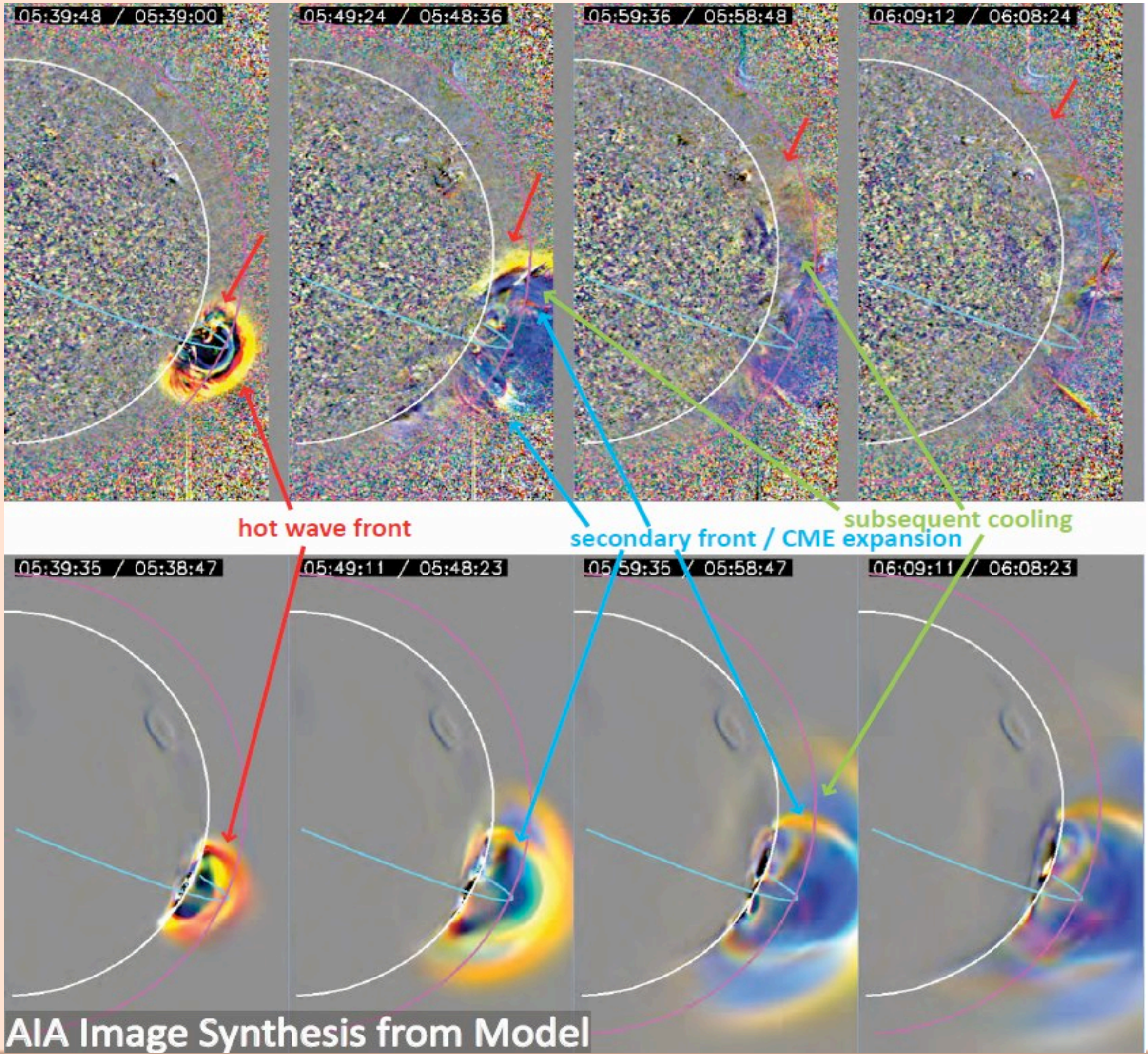


Lugaz *et al.*, *ApJL* (2008)

Time (from 01/25) - elongation plots for PA 69.

J-maps: see Sheeley *et al.* (1999) and Davies *et al.* (2009).

Tri-Color Running Ratio Analysis for 2010 Jun 13 EUV Wave



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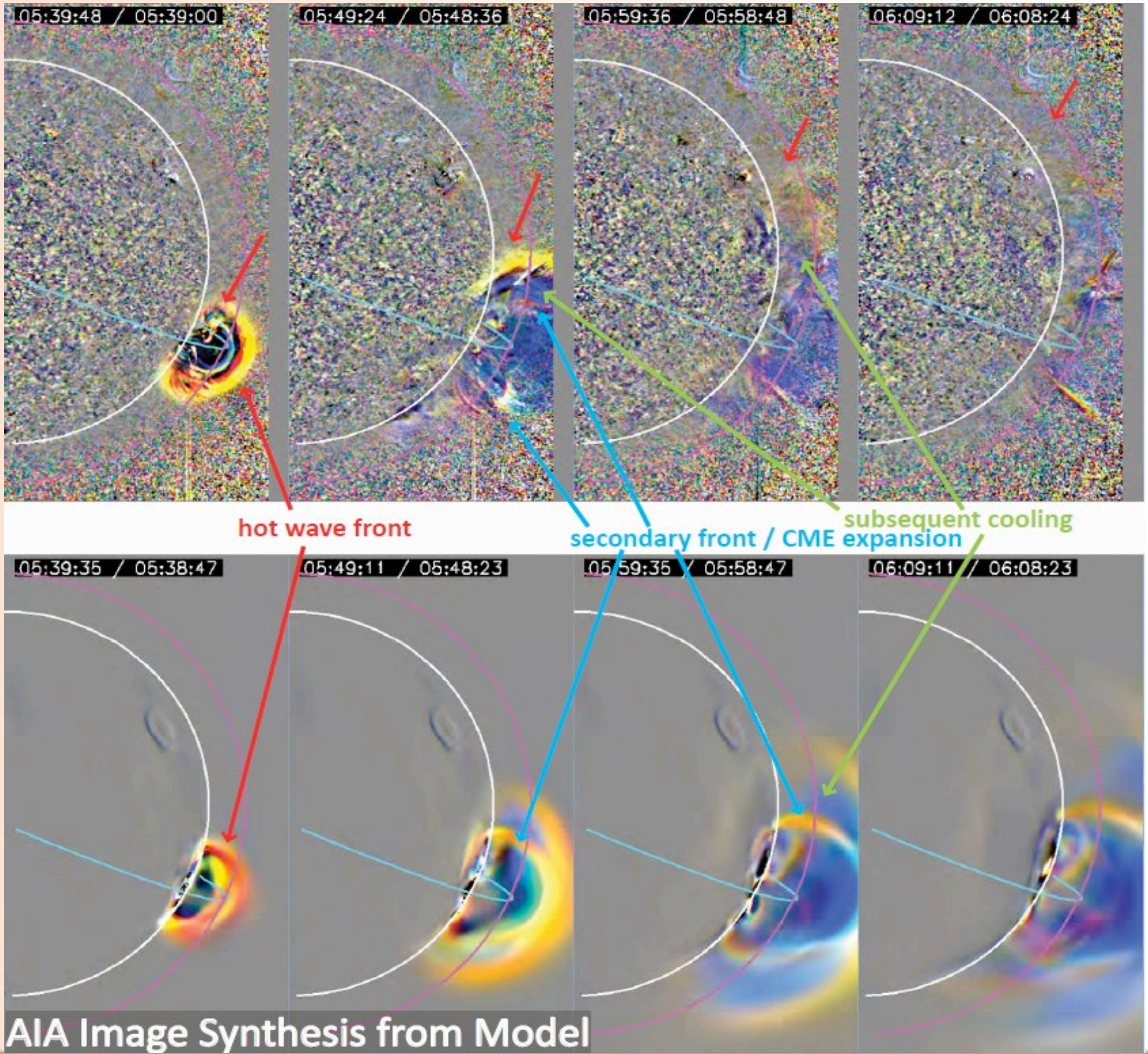
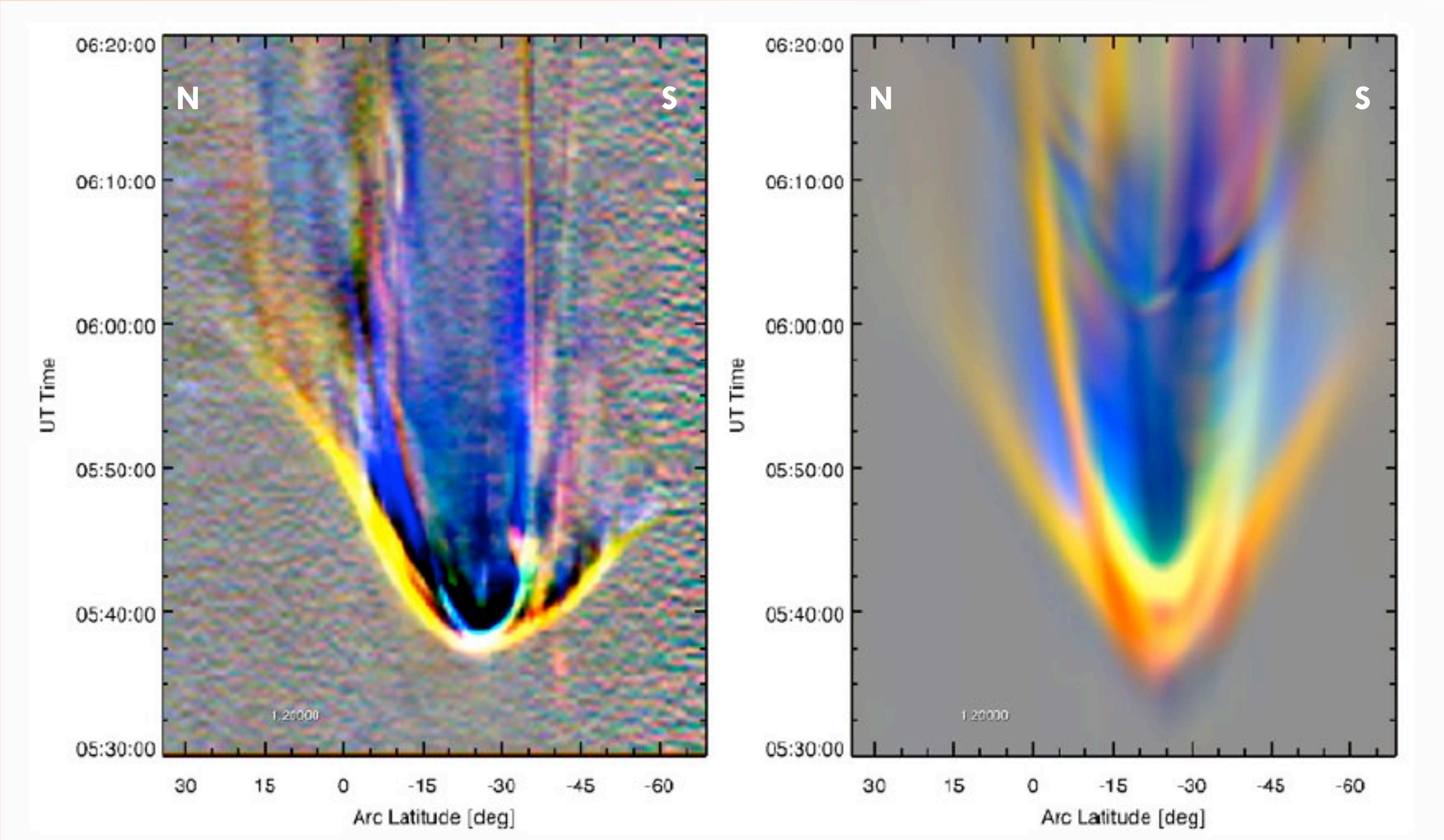
Tri-Color Running Ratio Analysis for 2010 Jun 13 EUV Wave

- 3-D MHD simulation of 2010 Jun 13 EUV wave produces similar thermodynamic perturbation as reflected in relevant EUV observations (Downs *et al*., *ApJ*, ***750***, *134*, 2012).
  - Here three tri-color channels are SDO/AIA 171 Å (blue), 193 Å (green), and 211 Å (red), with 48 s running ratios.
- Wave heats up plasma as it passes through (red).
- CME depletes coronal material and it cools down solar plasma near source region (blue).



Tri-Color Time-Distance Diagram for 2010 Jun 13 EUV Wave



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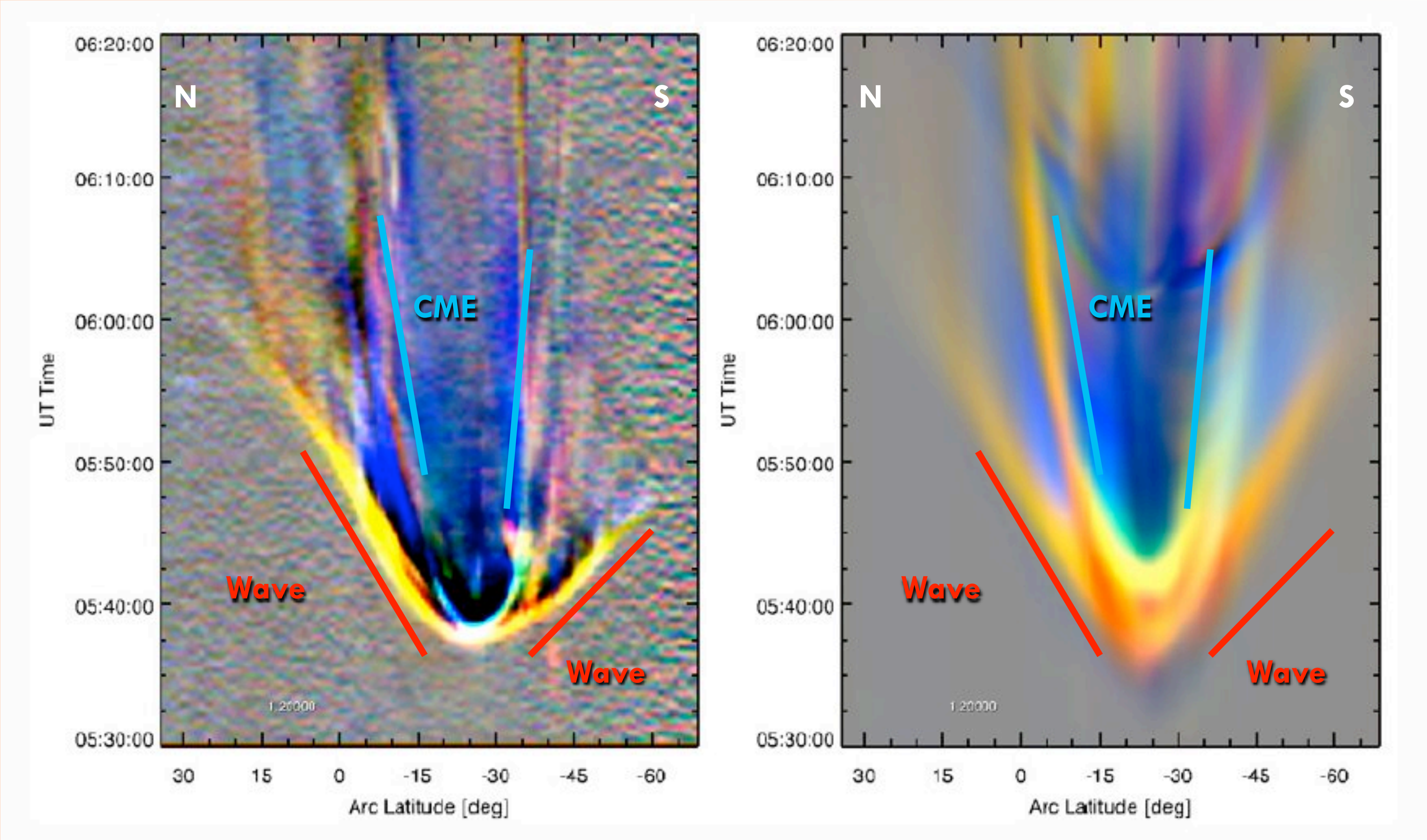

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Flux Emergence as CME Driver

Modeling FE from Convection Zone (CZ) to Solar Corona (SC)

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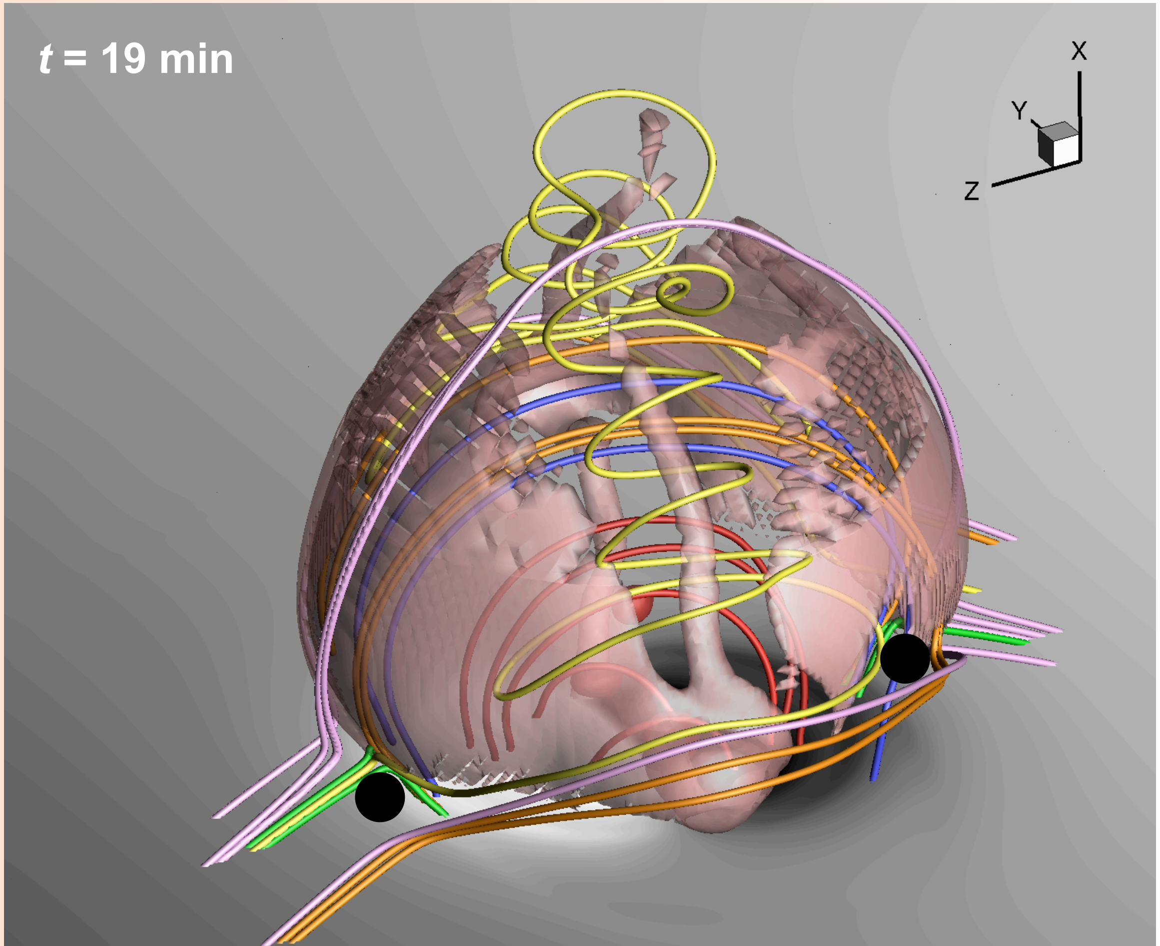
- Even if achieved, this is not a practical solution as far as space weather forecast is concerned.
  - It requires vast computational resources to resolve small-scale structures present in CZ that are miniscule in comparison to large-scale structures in SC.

Global 3-D Model of Magnetic Flux Emergence

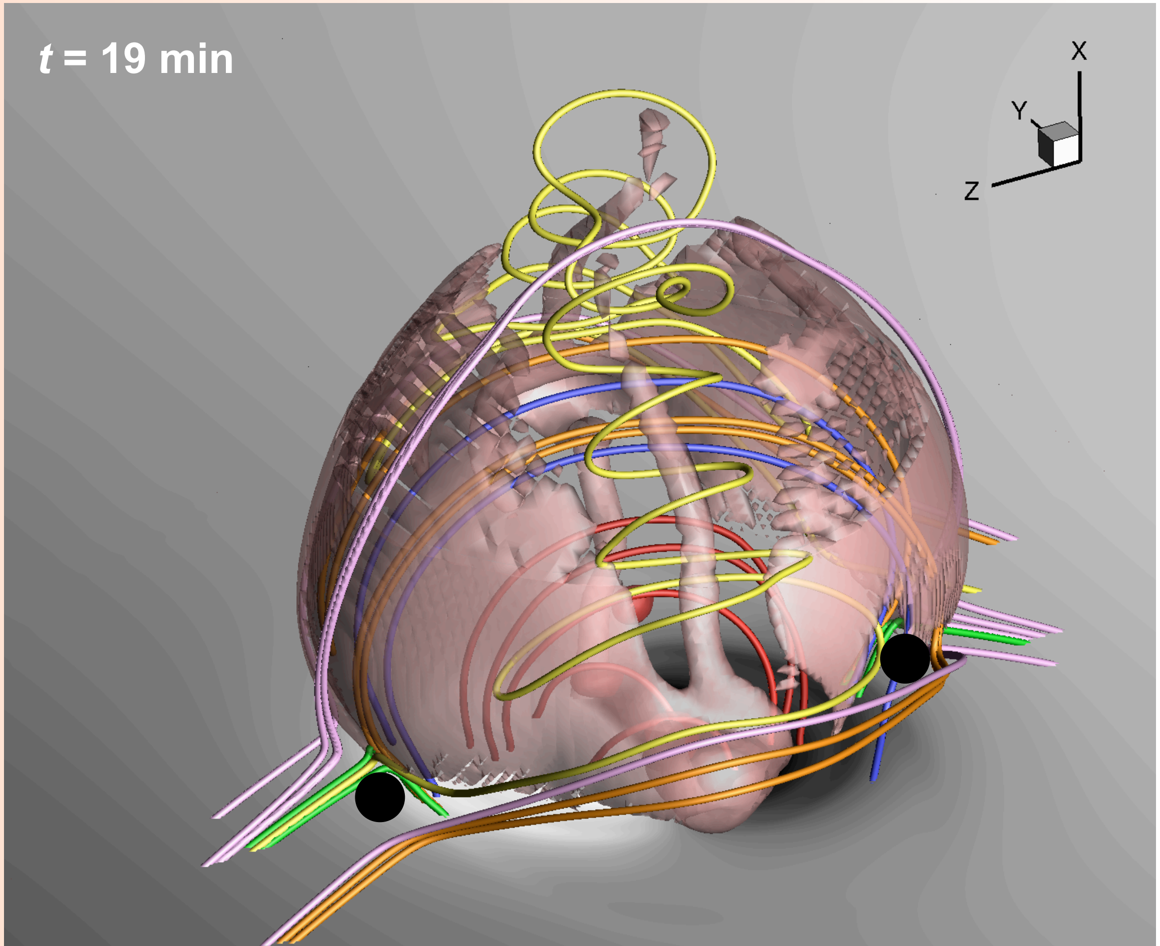


Roussev *et al.*, *Nat. Phys.*, ***8(11)***, 2012

Global 3-D Model of Magnetic Flux Emergence

Model Features

- ➢ Local flux-emergence model of Archontis *et al.* (2004) coupled with global 3-D MHD model of solar corona and solar wind using SWMF.
- ➢ Multi-polar magnetic field is produced by:
  - Global, dipolar-type magnetic field resembling Sun at solar minimum.
  - Emerging twisted flux rope along solar equator (*y*-axis).
- ➢ Flux-emergence model provides *self-consistent* time-dependent evolution of electric field, ***E***, at solar boundary!



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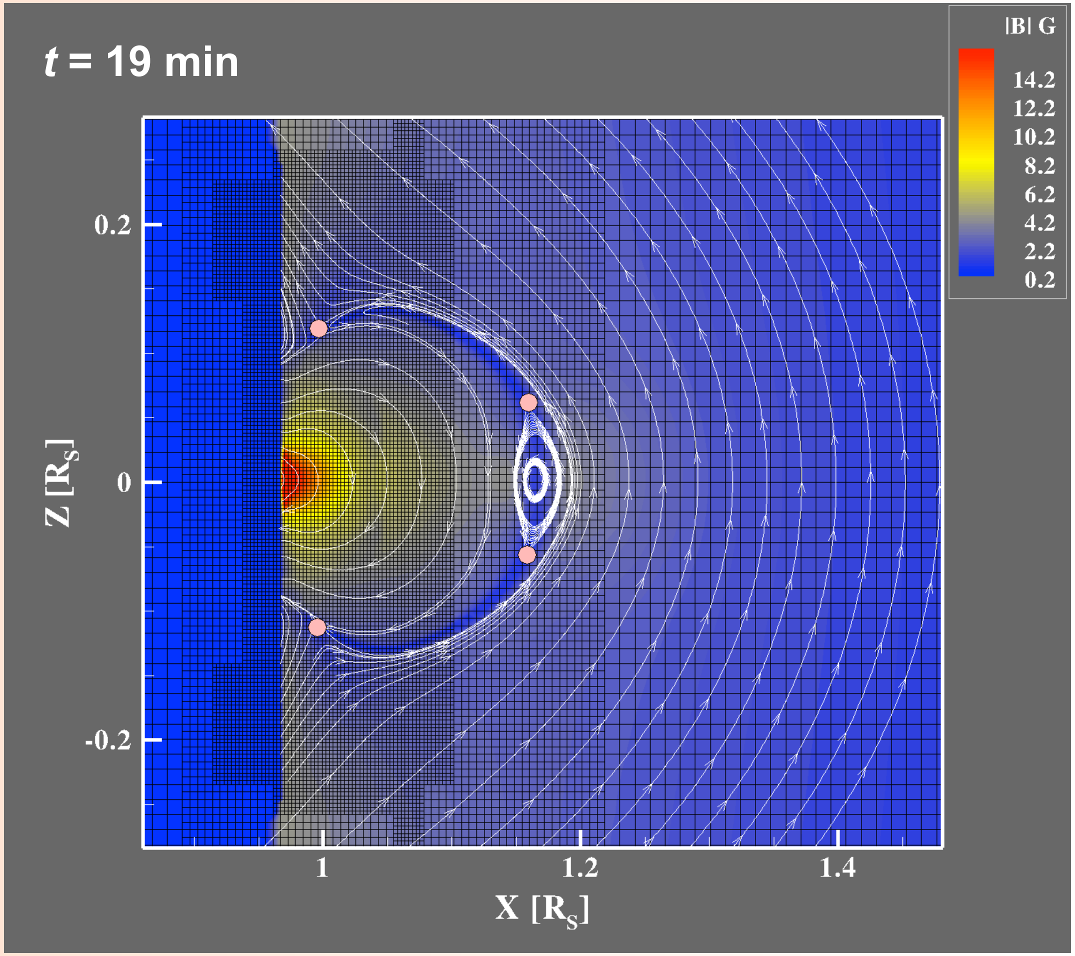
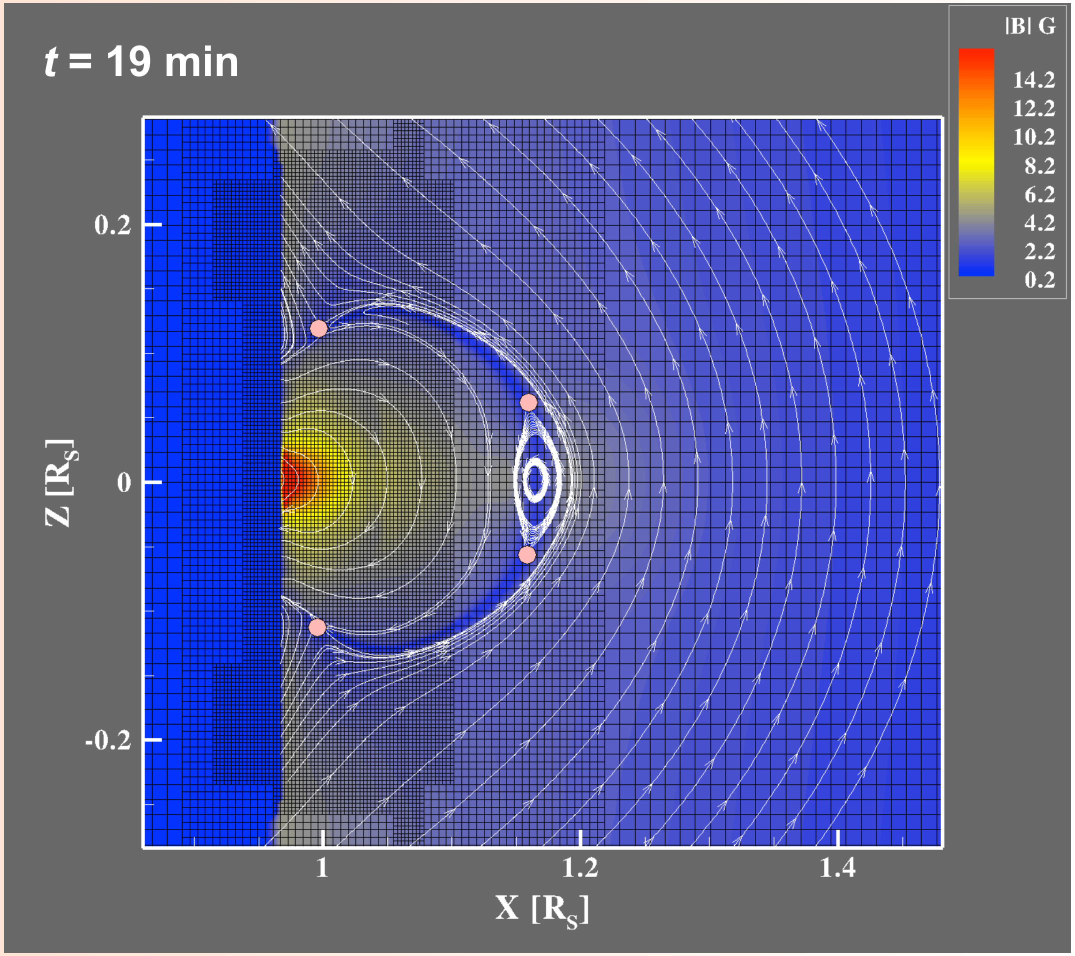
Model Coupling, Grids, etc.

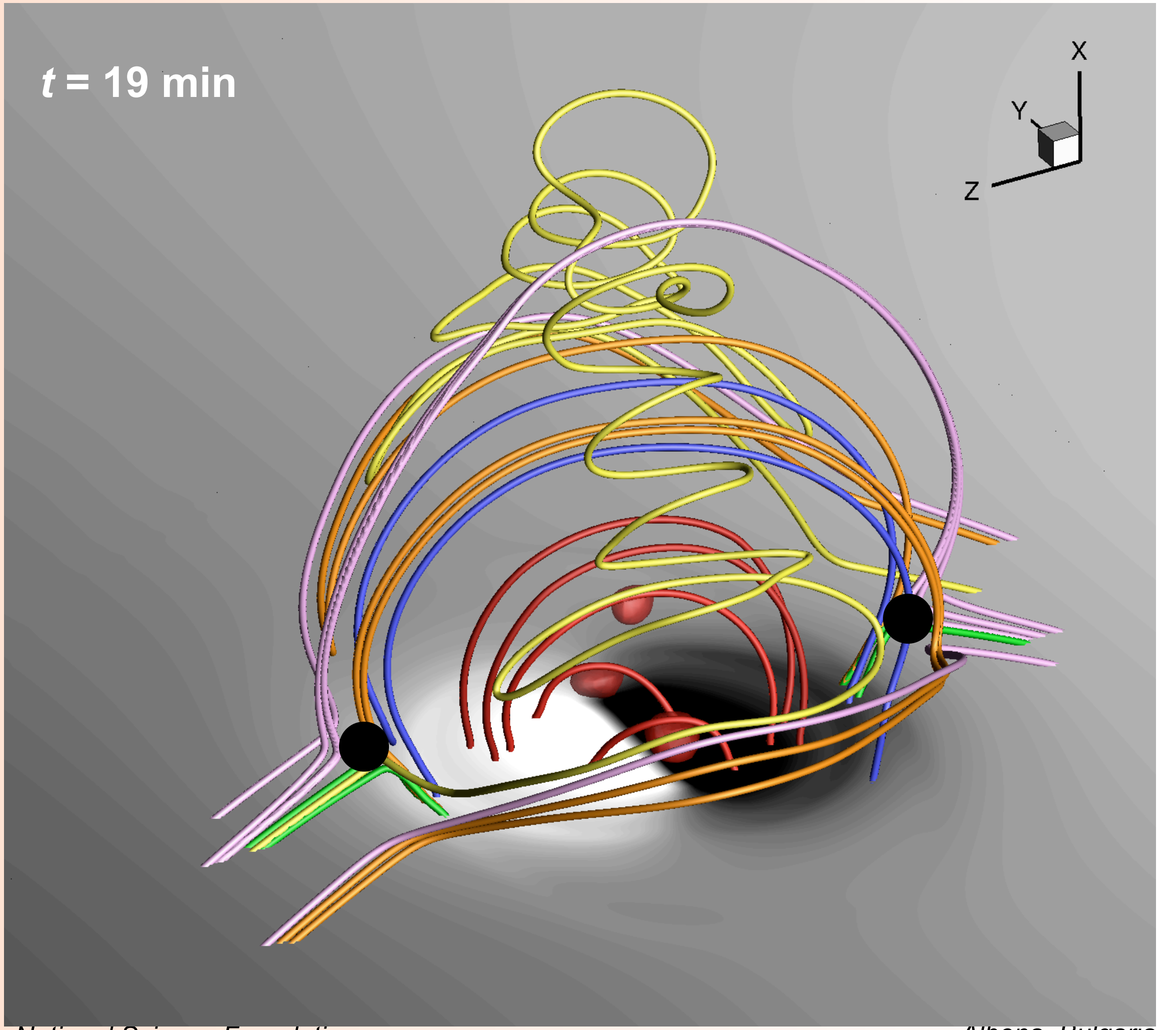


Model Coupling, Grids, etc.

- Grid refined in region where flux emergence occurs (3 extra levels of refinement).
- Boundary data from FEM interpolated in space and time to fit numerical grid and simulation time of global model.
- Region of FE enlarged by factor of 10.
- MHD variables from FEM scaled from photospheric values to coronal values to match inner boundary conditions of global model.

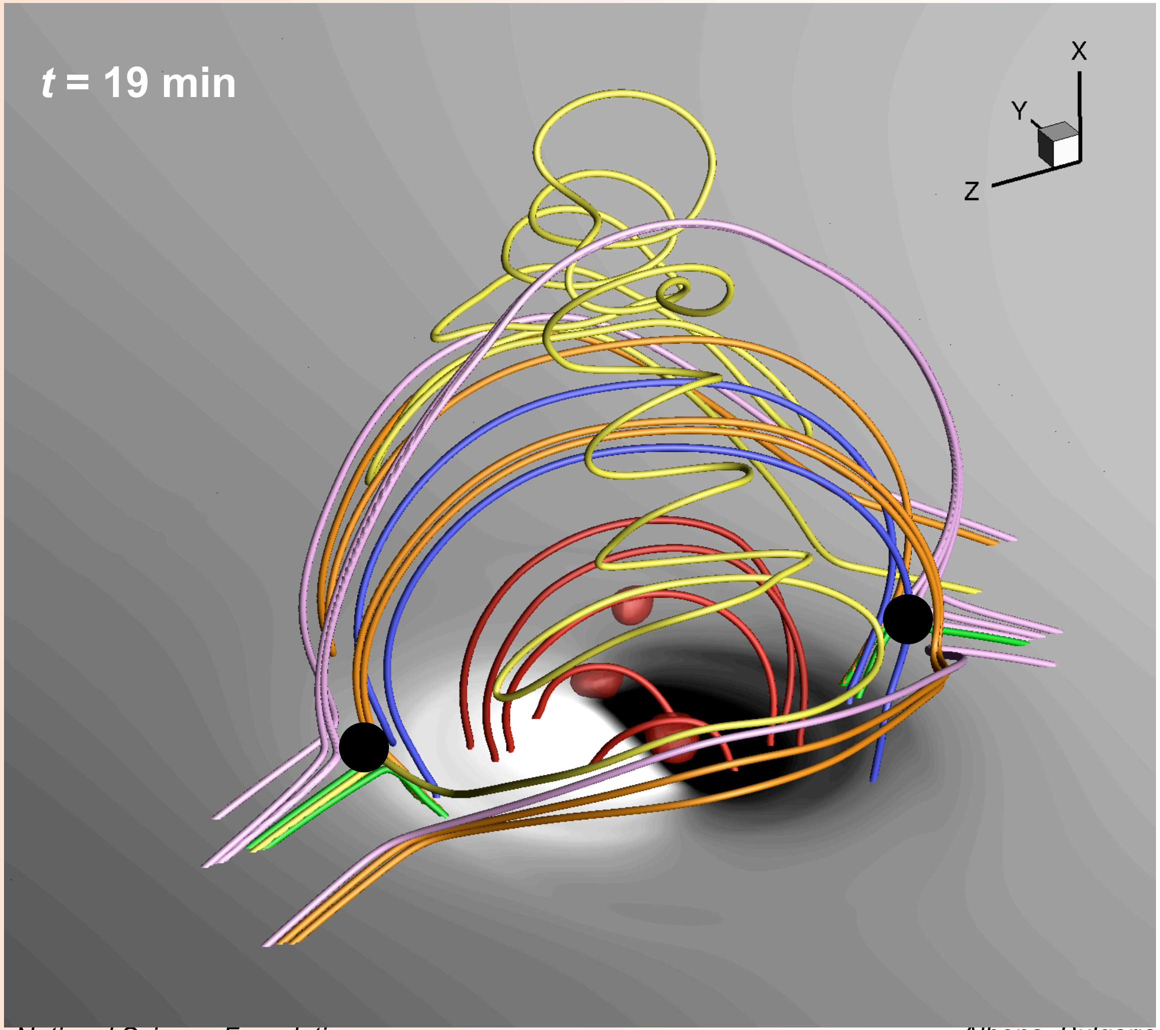


Magnetic Field Geometry at Early Times



Magnetic Field Geometry at Early Times

- Overlying global field of Sun reconnects with expanding field of emerging flux rope through SLs.
- Two 3-D null points form in solar corona (see black circles).
- Removal of overlying field sideways enables rapid acceleration outwards of expanding field (red lines) of emerging region.
- CME follows…



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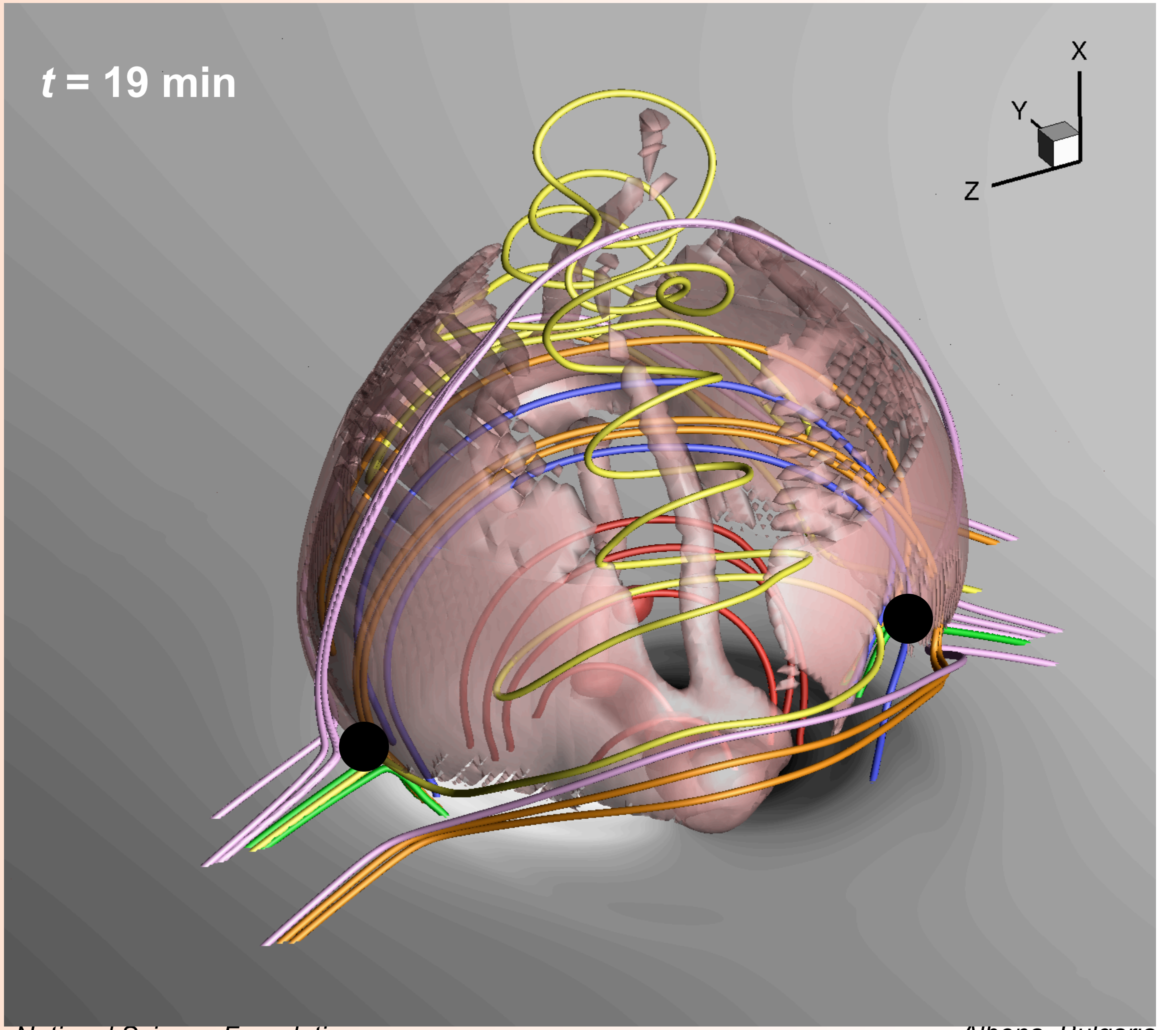
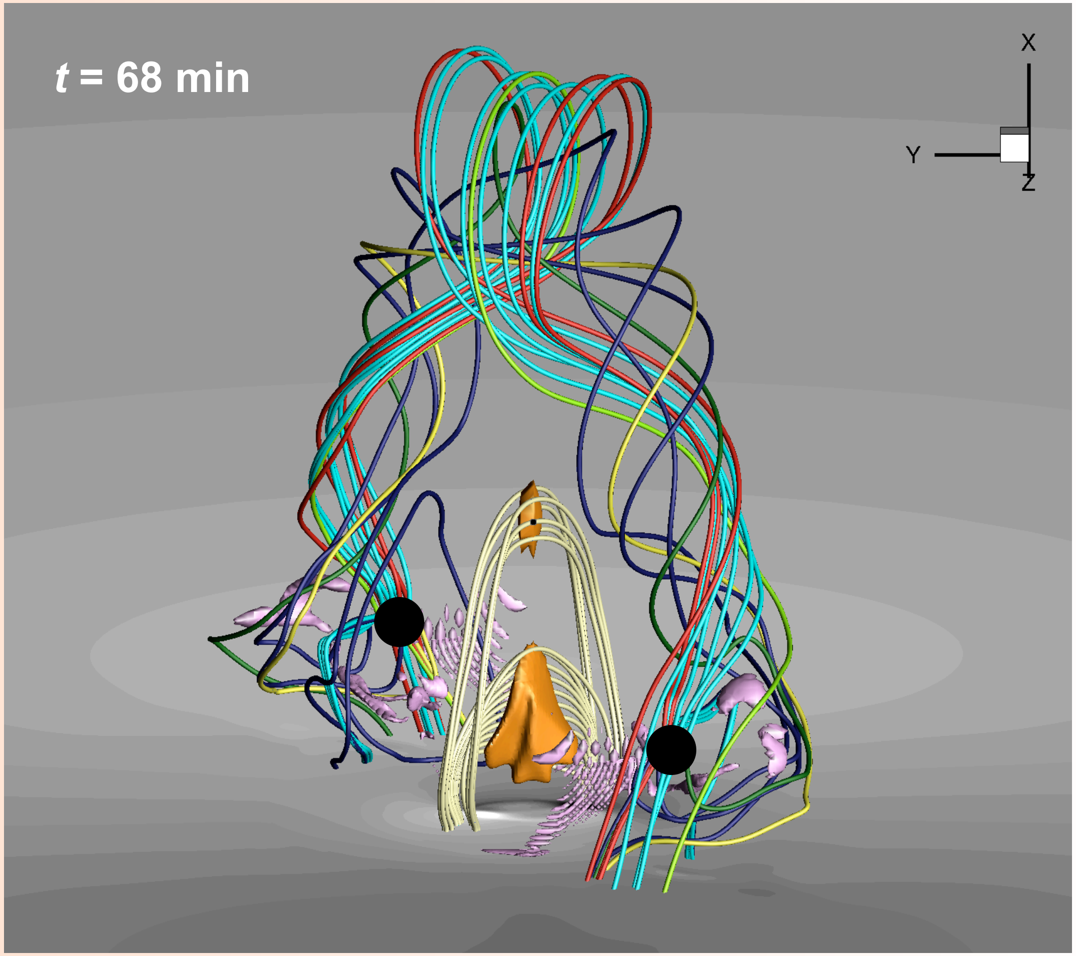
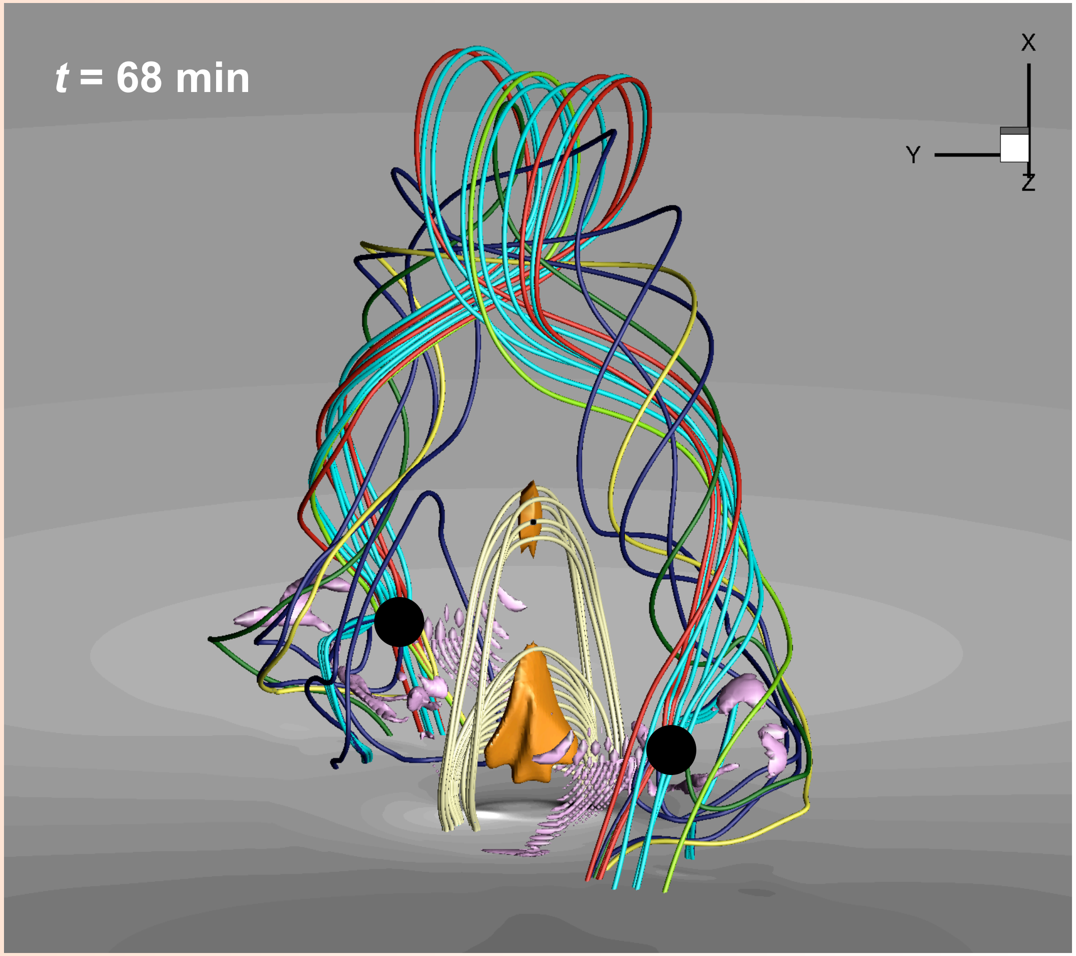


Magnetic Field Geometry at Early Times (t = 68 min)

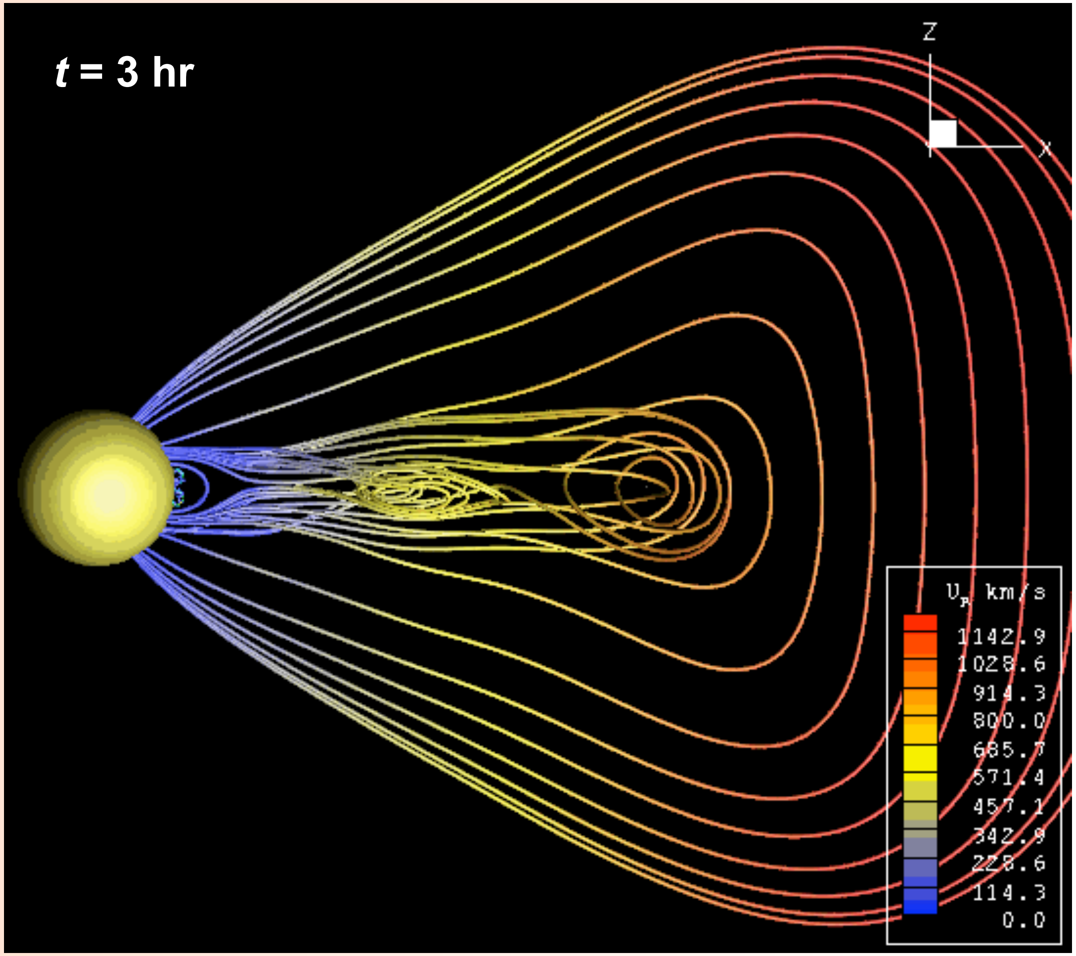


Magnetic Field Geometry at Early Times (*t* = 68 min)

- Reconnection becomes increasingly complicated as flux rope emergence proceeds.
- Magnetic flux and helicity continuously leave the flux emergence region via sequence of reconnection events.
- Newly formed field lines posses fair amount of twist and writhe due to transfer of mutual helicity (prior to reconnection) to self-helicity (after reconnection).

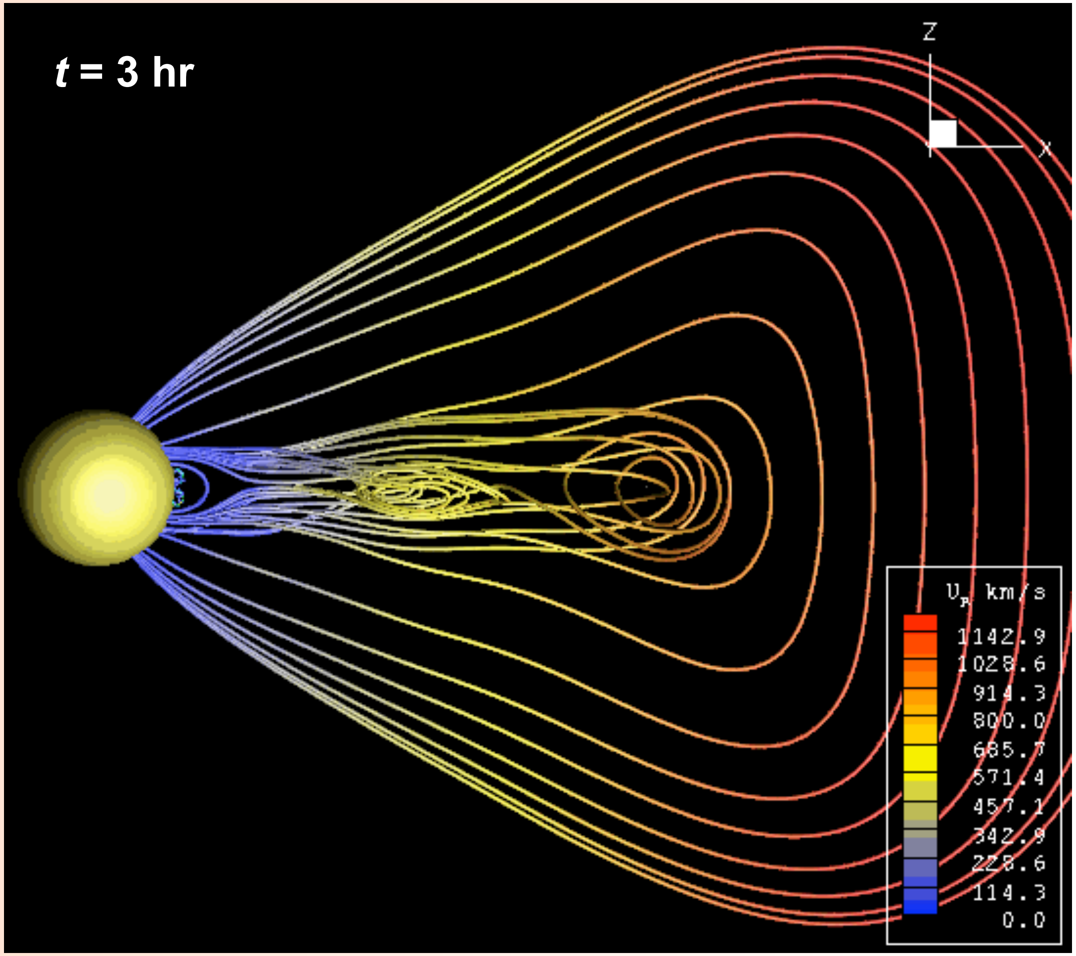


Magnetic Field Geometry at Later Times (t = 3 hr)

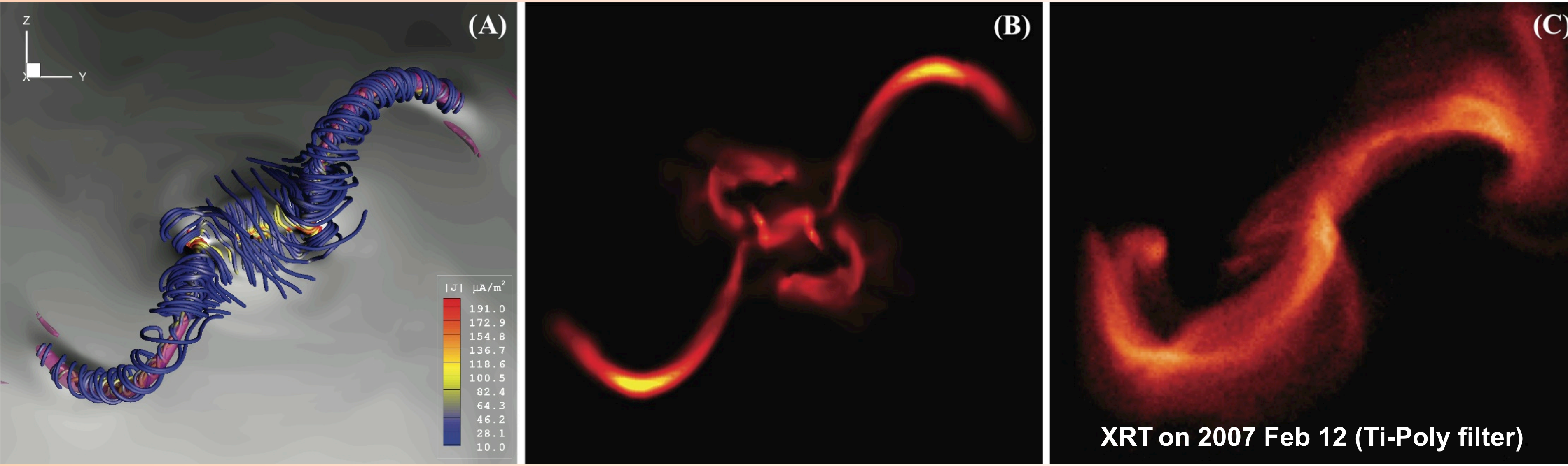


Magnetic Field Geometry at Later Times (t = 3 hr)

- Fast CME in progress (>1,200 km/s).
- Footprints of CME well outside flux emergence region (due to reconnection).
- Two confined flux ropes left behind in low corona.
- Original coherent flux rope emerging from convection zone is gone: post-emergence coronal field looks totally different!



Realistic Modeling of X-ray Sigmoids



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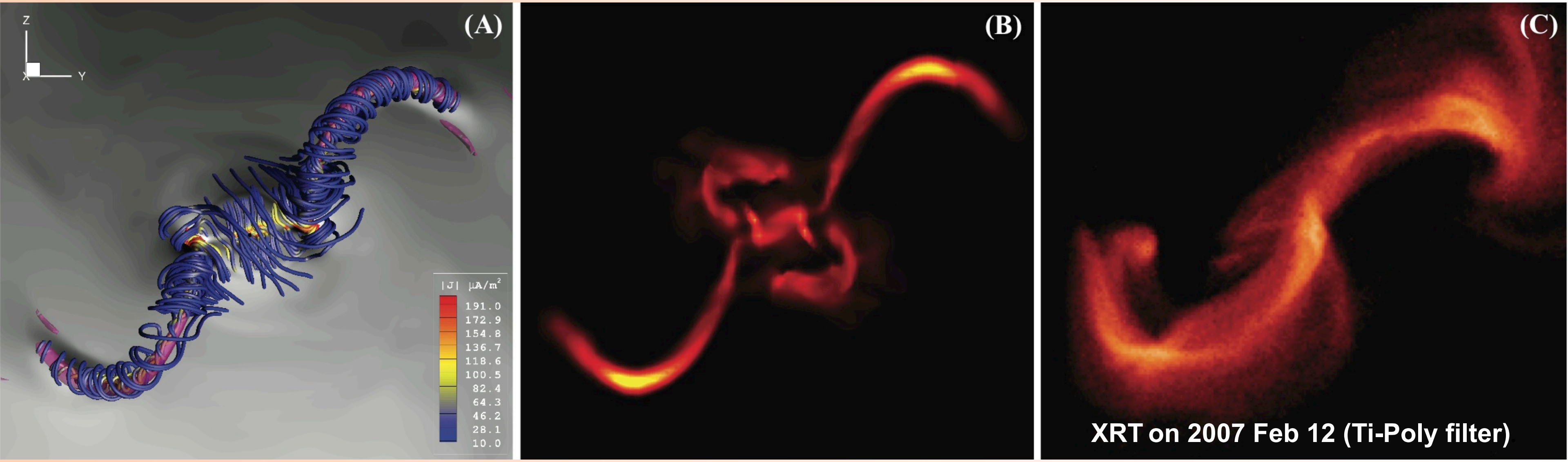

- With this improved low-solar-corona model, we have performed 3-D MHD computer simulation that captures fundamental connection between emergence of magnetic flux into solar atmosphere and origin of CMEs.
- Simulation provides evidence for formation of: (i) fast CME that is independent of emerging flux tube, (ii) two confined flux ropes in low corona (left image), and (ii) hot X-ray sigmoid (middle image).
- With realistic treatment of electric field at photosphere, we gain new insight on how magnetic flux and helicity injection lead to reorganization of solar corona.

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  - Footprints of erupting magnetic field do *not* remain stationary as CME evolves: one or both legs of CME migrate along solar surface.

Thank you!