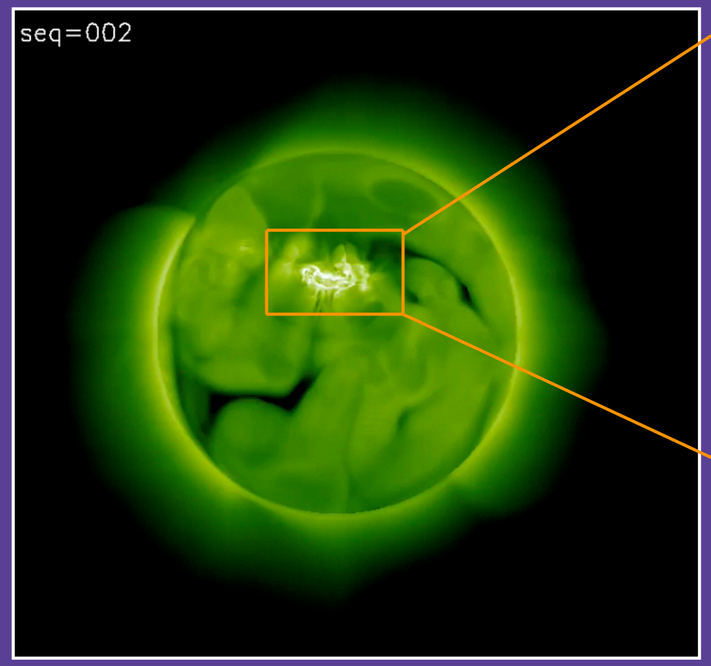
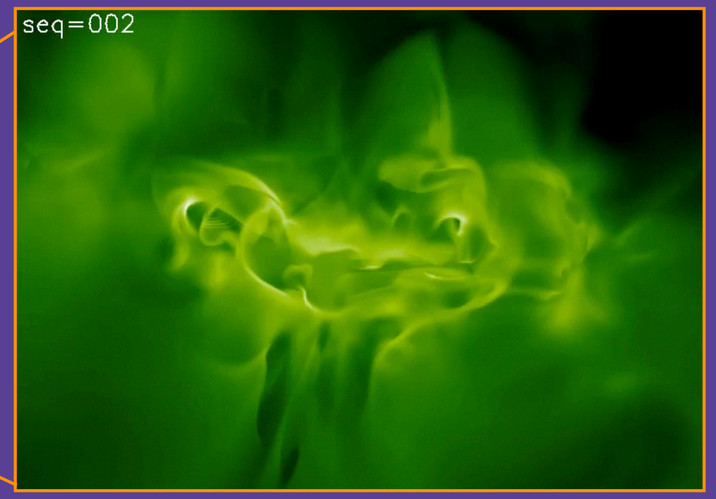
WG3: Simulations

- Level of collaboration: (very) low
- <u>One important caveat</u>:
  - relatively simple simulations starting in the heliosphere (ENLIL) are now run in real-time.
  - more realistic simulations with simplified CME “initiation” mechanisms can be run few months after an event (H3DMHD, SWMF or MAS w/ out-of-equilibrium FRs).
  - for the most advanced simulations, where realistic initiation mechanisms and realistic physics are important, most researchers are still focusing on events from SC23.
- Thanks to T. Török (PSI), W. Manchester (UMich) and F. Shen (CAS) for input.
- Lack of involvement from European groups focusing on simulations (Leuven, St Andrews, Paris)
- <u>Some potential solutions</u>: agreeing with SHINE on a reviving of 2-3 campaign events (should not be more) with clear rationale; better collaborations with European groups with somewhat similar goals (FP7: AFFECTS, HELCATS, ESA ITT: VSWMC)

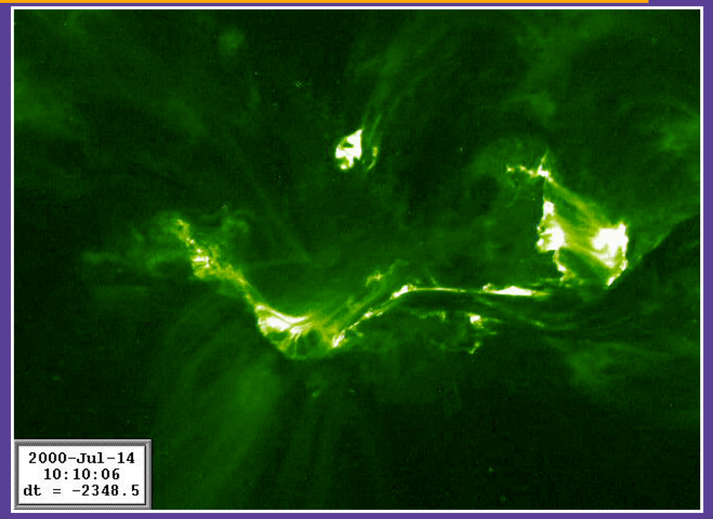
Thermodynamic MHD simulation of the Bastille Day event



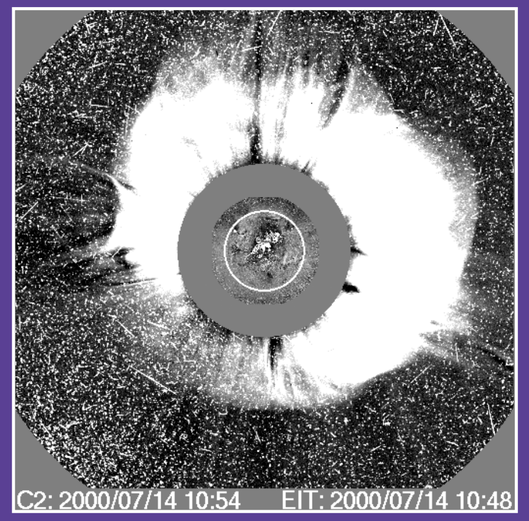
SOHO/EIT 195 Å
(synthetic emission)



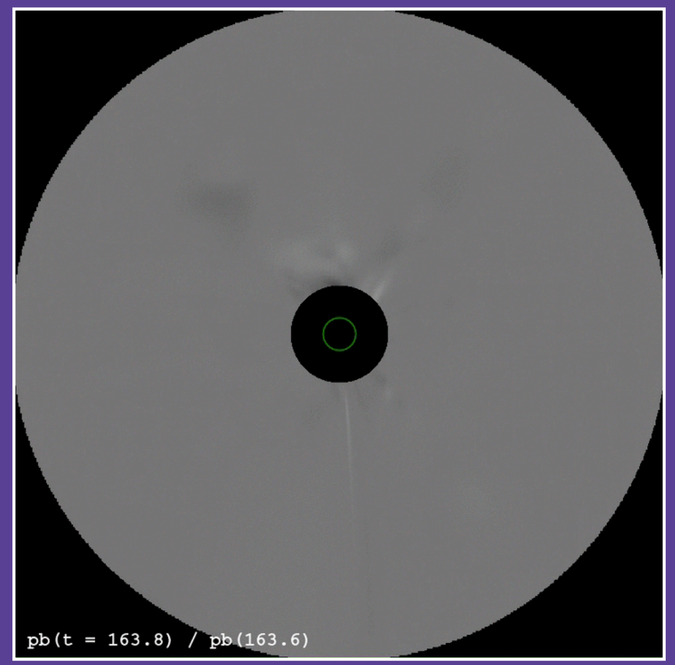
synthetic SOHO/EIT 195 Å



TRACE 195 Å



SOHO/LASCO C2

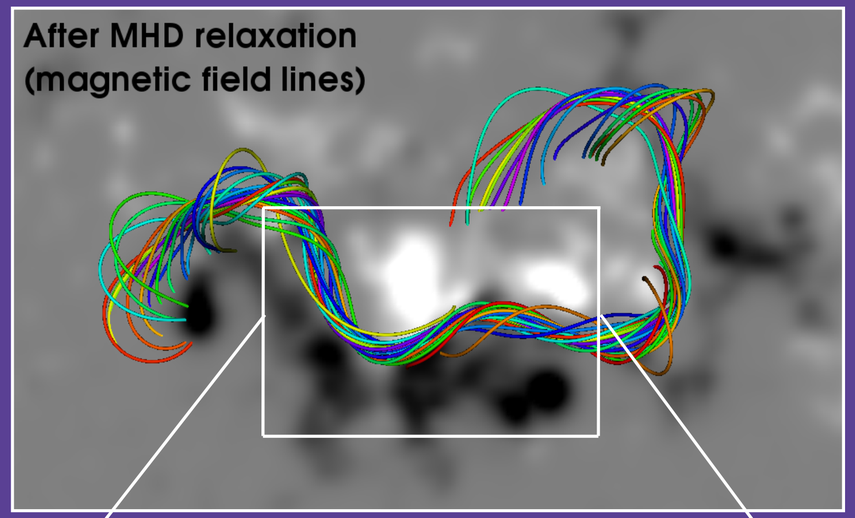


polarization brightness
running ratio
(synthetic emission;
3-20 solar radii)

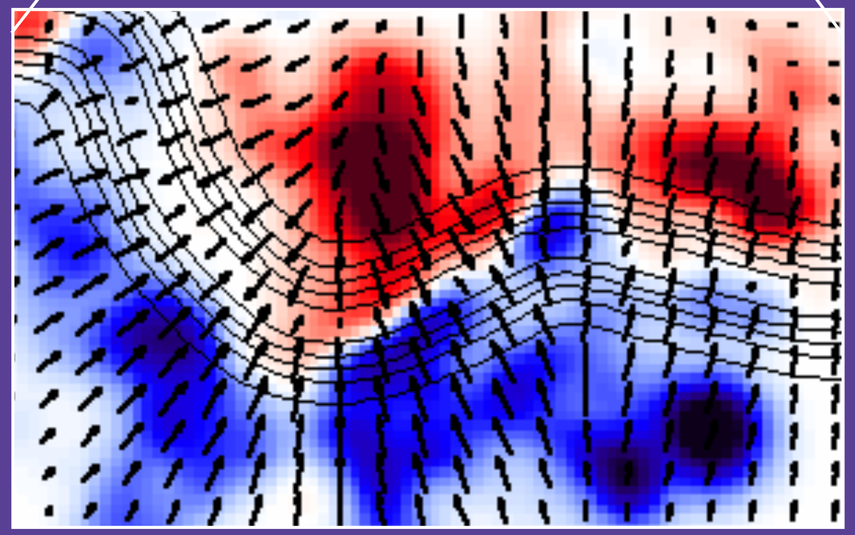
- synthetic satellite images allow direct comparison with observations
- flare arcade and halo-CME morphologies qualitatively reproduced
- CME speed ≈ 1500 km/s & kinetic energy ≈ 4 x 10^{32} ergs

provides quantities that cannot be observed directly (e.g. 3D magnetic field)

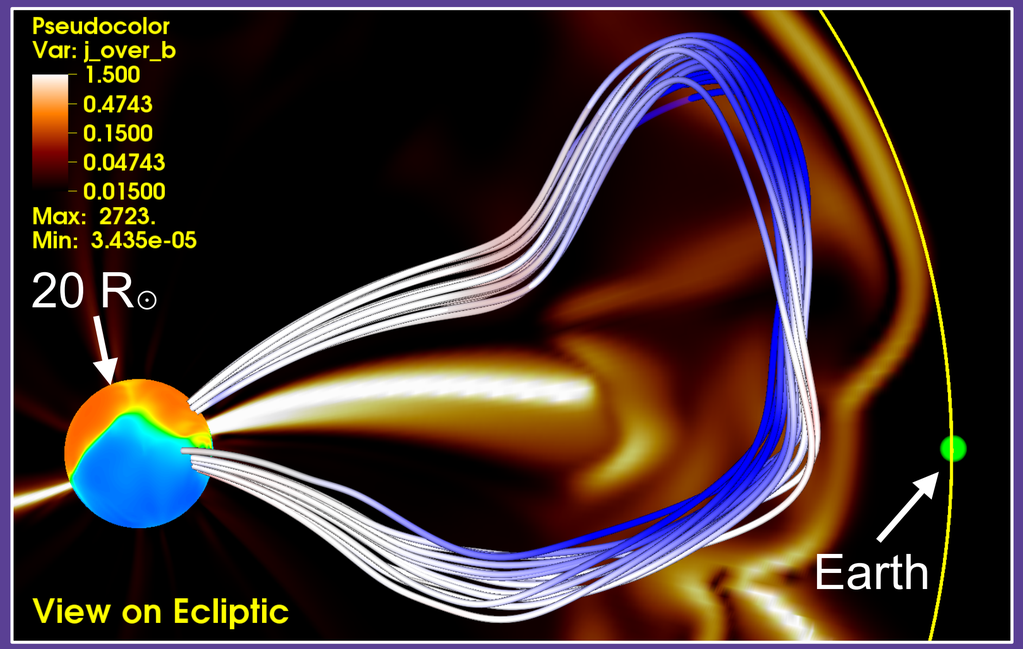
Heliospheric simulation of the Bastille Day event



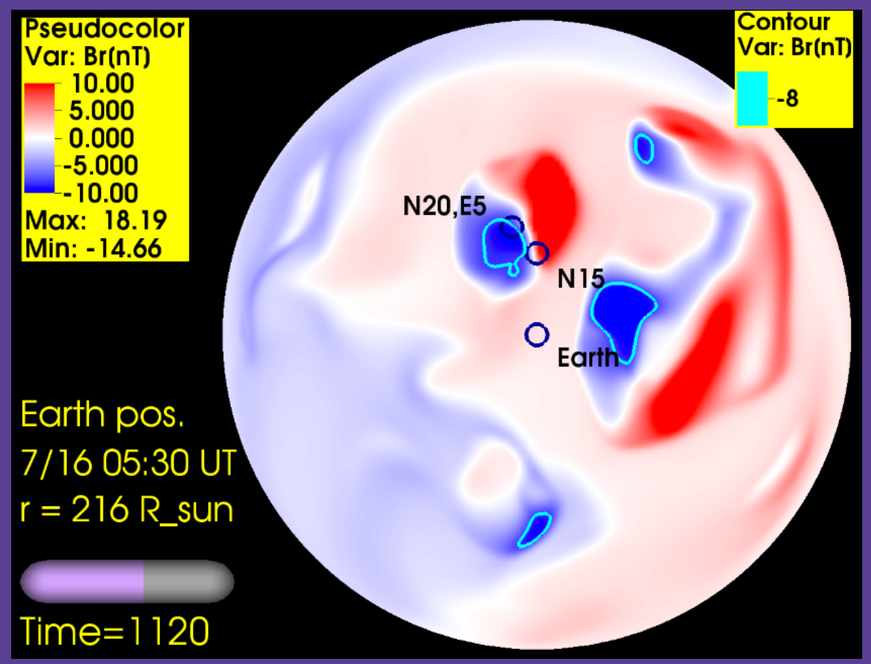
inserted flux rope



converging flows



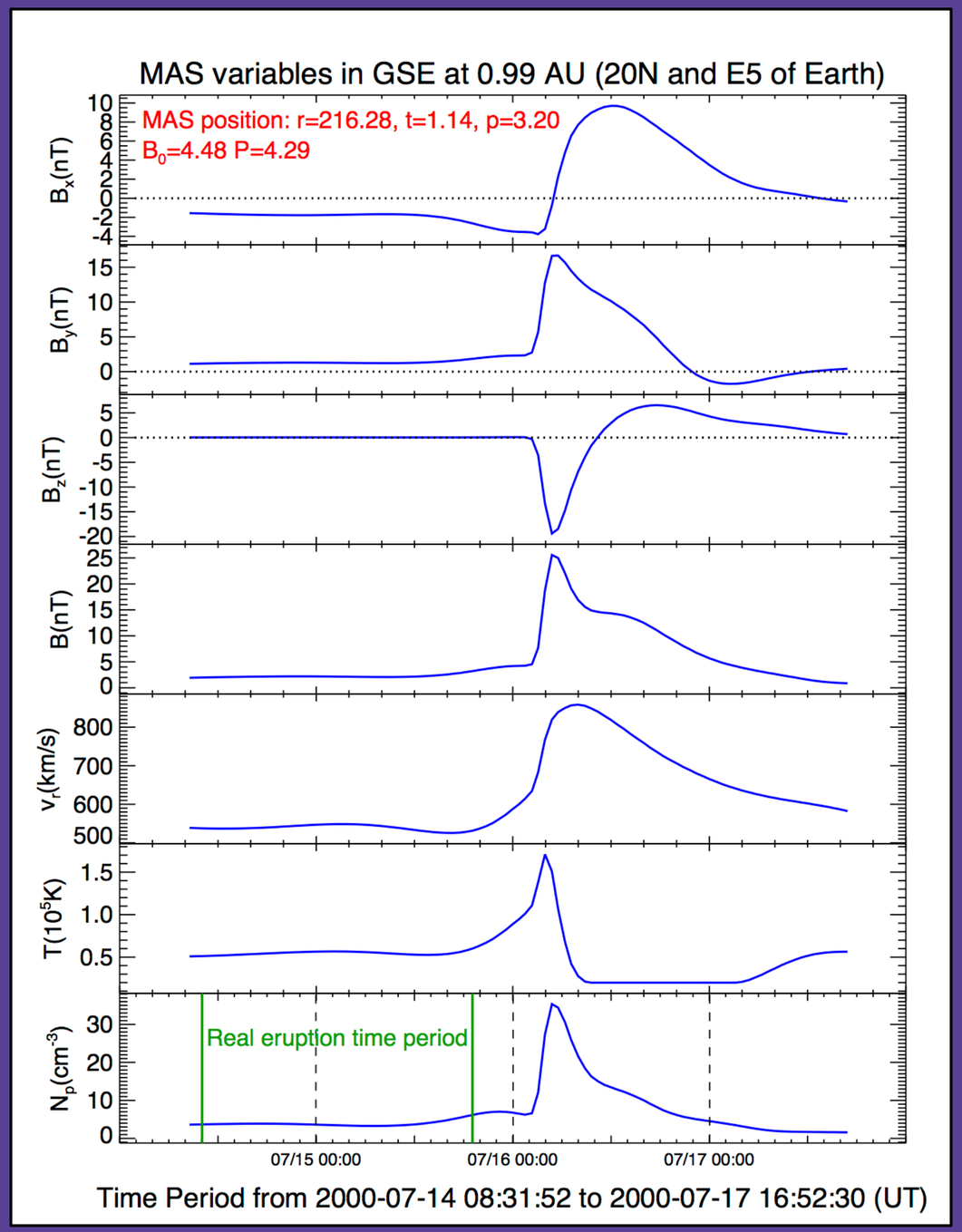
model ICME core & electric currents in ecliptic plane



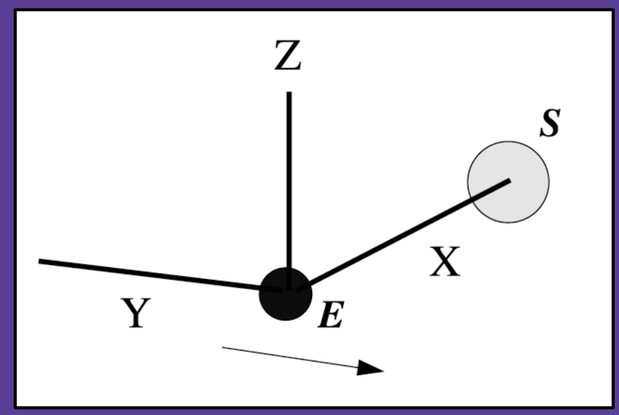
radial magnetic field at 1 AU

- flux-rope core structure preserved at 1 AU (still connected to surface)
- ICME arrives with rather scattered shape
- area of -Bz relatively small → difficult to match/predict

Heliospheric simulation of the Bastille Day event



simulation data at 1 AU

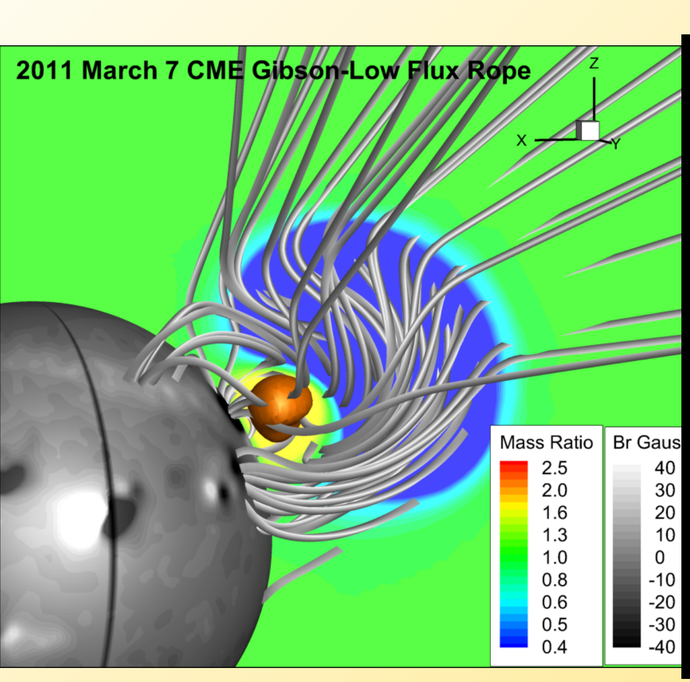


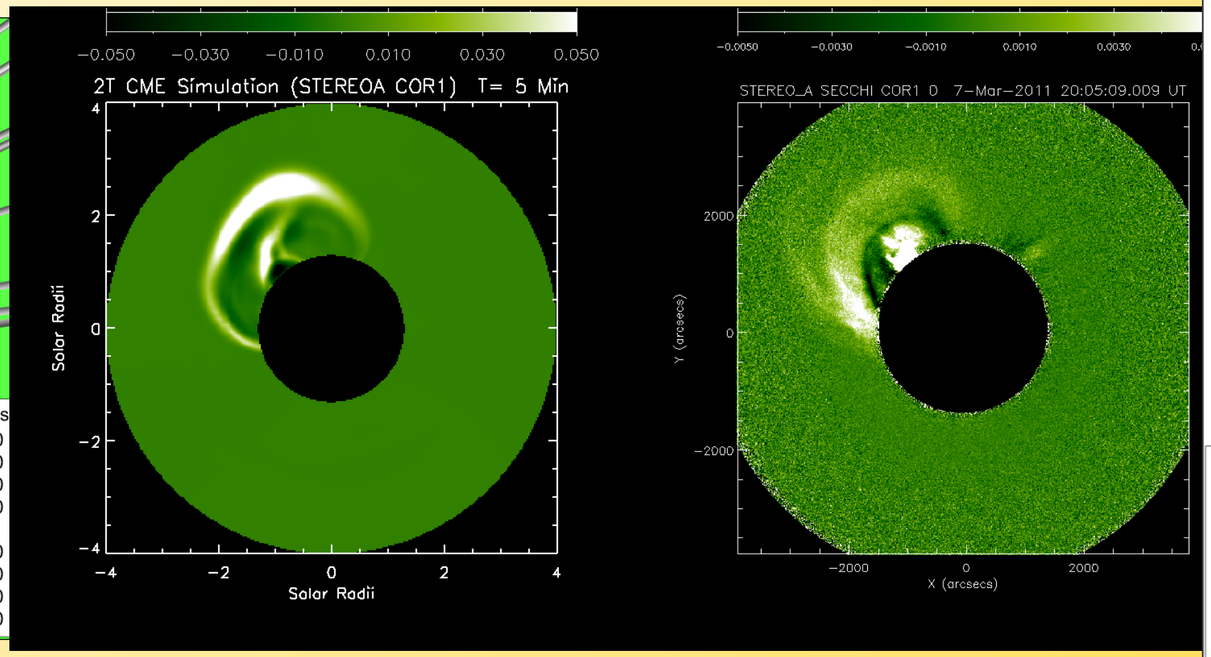
GSE coordinate system

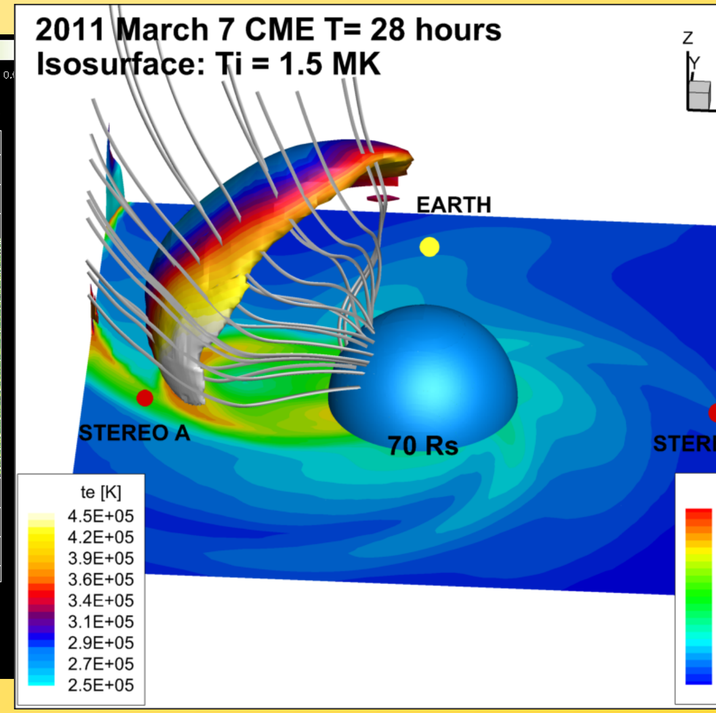
- flux rope qualitatively reproduced
  (but: 15-20 degrees north of Earth!)
- B field strength too low (≈ factor 2)
- ICME too slow (≈ 6-8 h delay)

quantities at Earth very difficult to match with present models?

Recent results from Michigan group



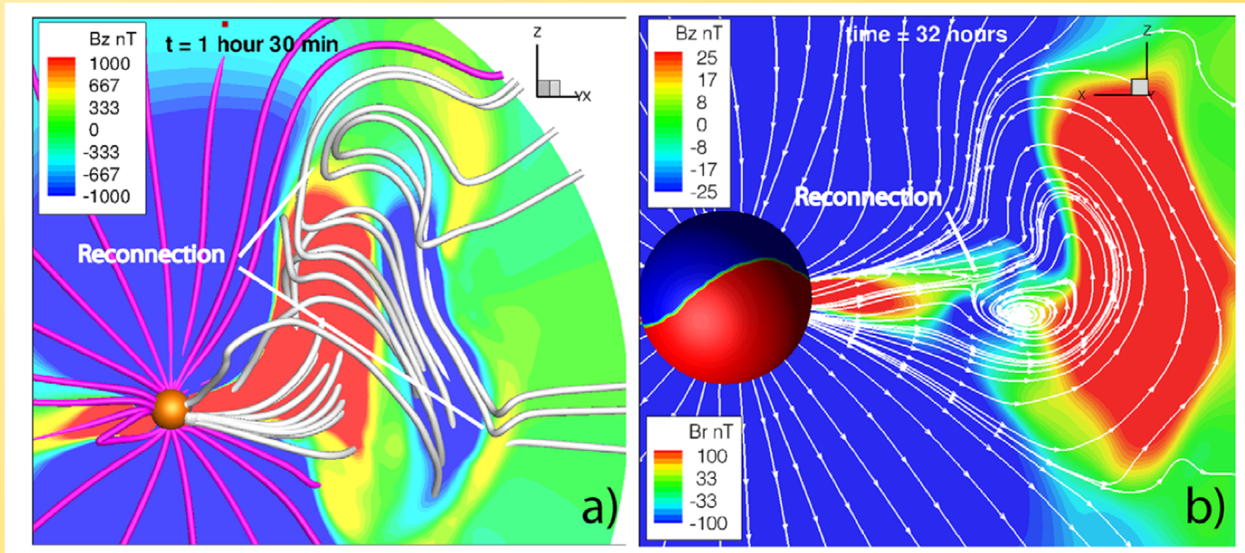


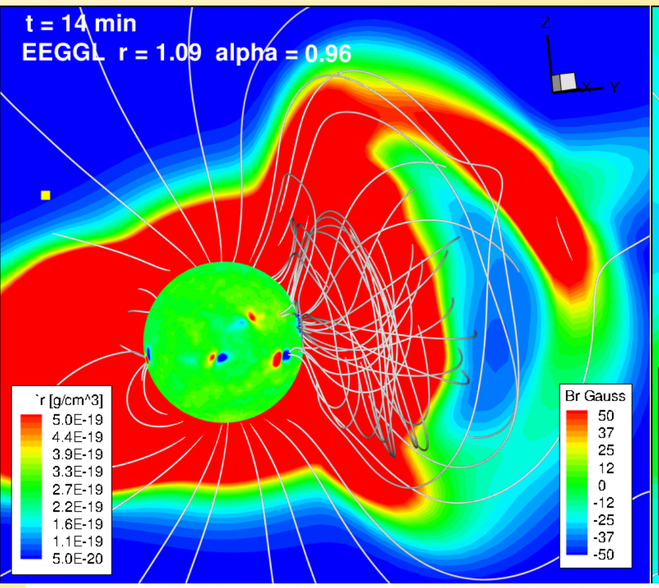


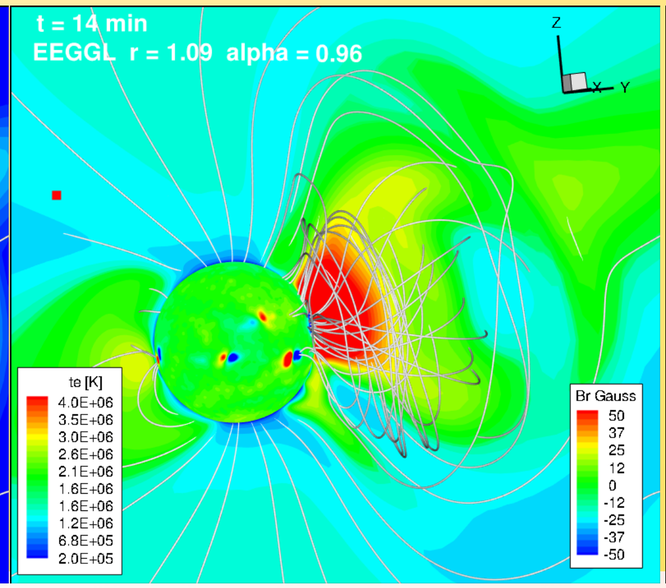
- Meng Jin *et al.* (ApJ, 2013): 2-T, thermodynamic simulation of the 2011 March 7 CME.
- 2-T required to get shock structure right (and results in a higher Mach number) and to get a realistic compression ratio.

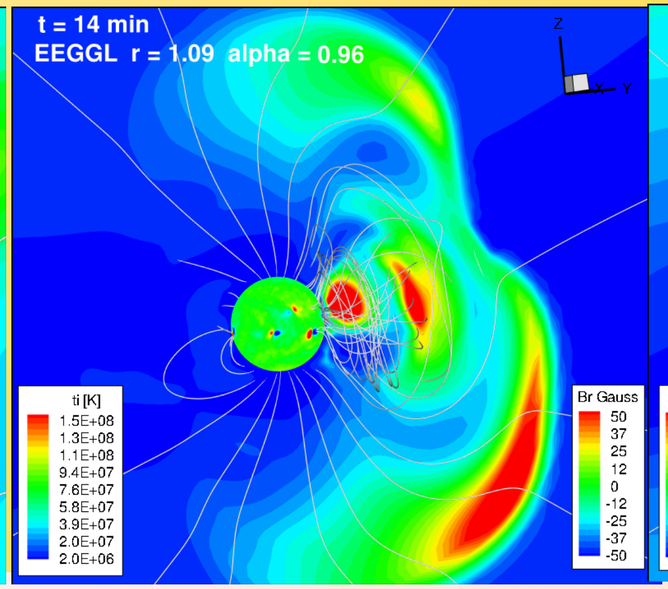
Recent results from Michigan group

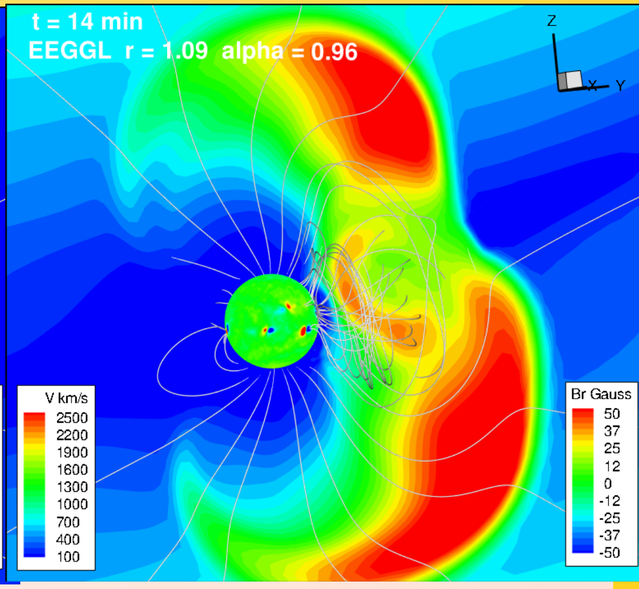
- Manchester *et al.* (PPCF, 2014): new simulation of the May 2005 CME.
- Strong reconnection of the initial flux rope results in the formation of a new flux rope with a different "orientation"
  - Possible scenario to explain some "observed" CME rotations?





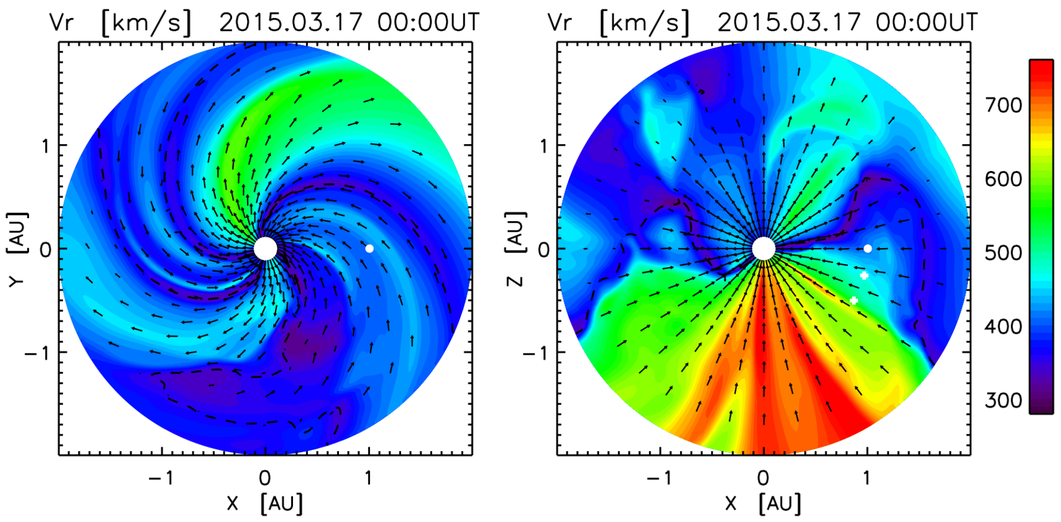




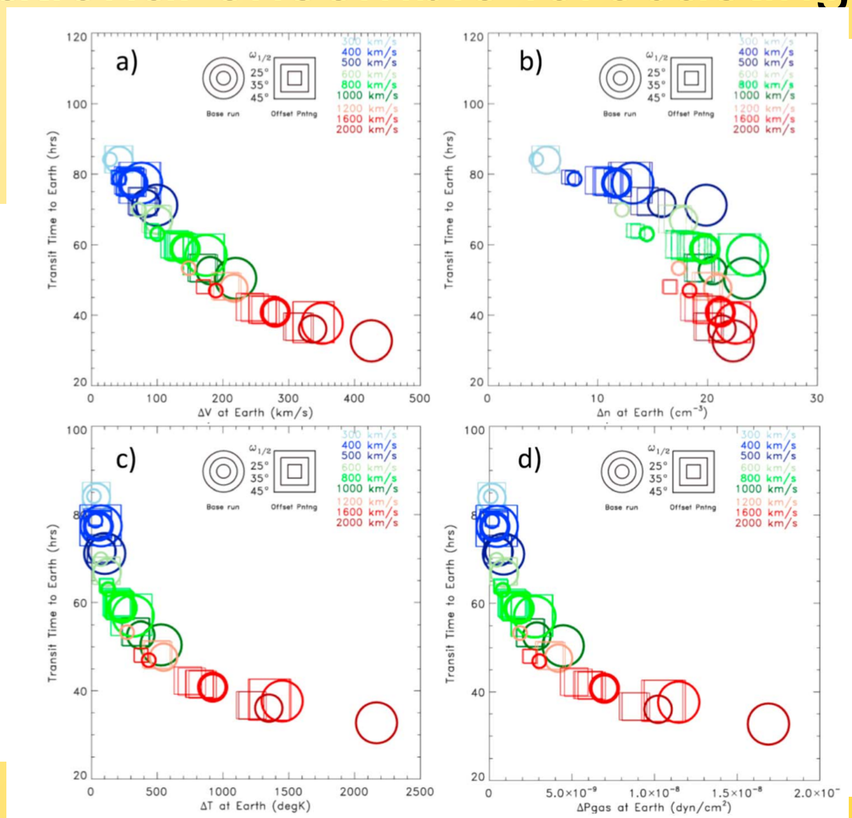


Simulations in support of real event analyses (*in situ*)

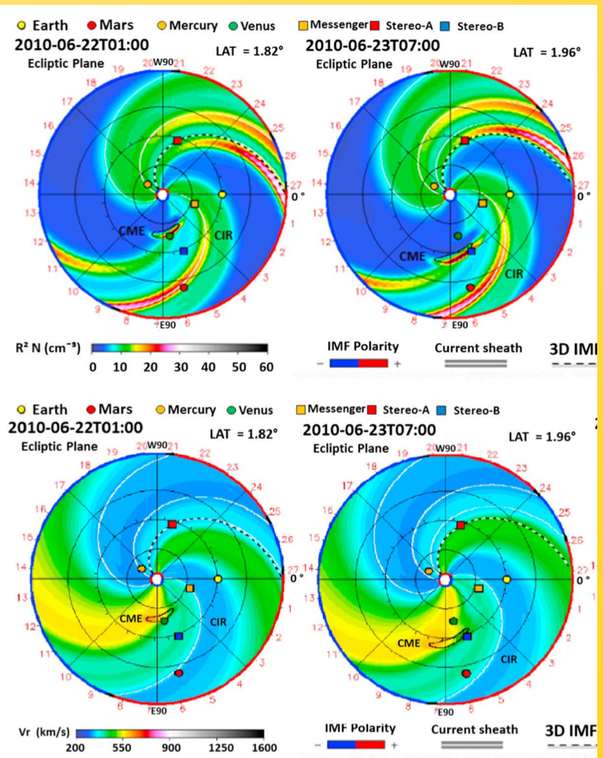
- ENLIL background solar wind (steady-state) and/or cone model now routinely used to get insight on the conditions into which CMEs propagate.
- Same possibility with other codes. Example: Kataoka *et al.* (2015) for the March 2015 CME.
- ENLIL use moving towards operational ensemble forecasting (see: Pizzo *et al.*, Space Weather, 2015).



Kataoka *et al.* (2015)



Pizzo *et al.* (2015)

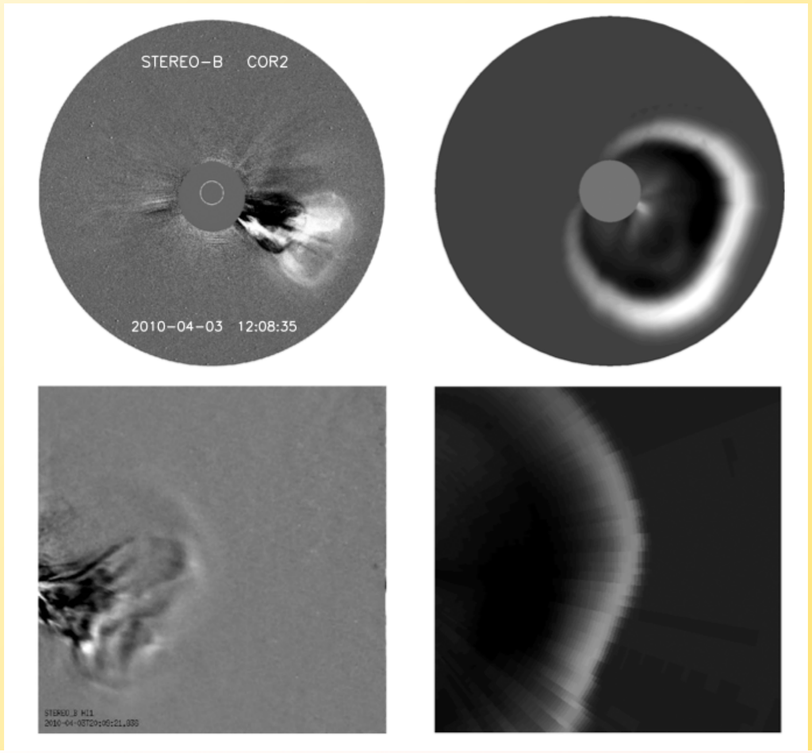


Prise *et al.* (2015)

Simulations in support of real event analyses (remote)

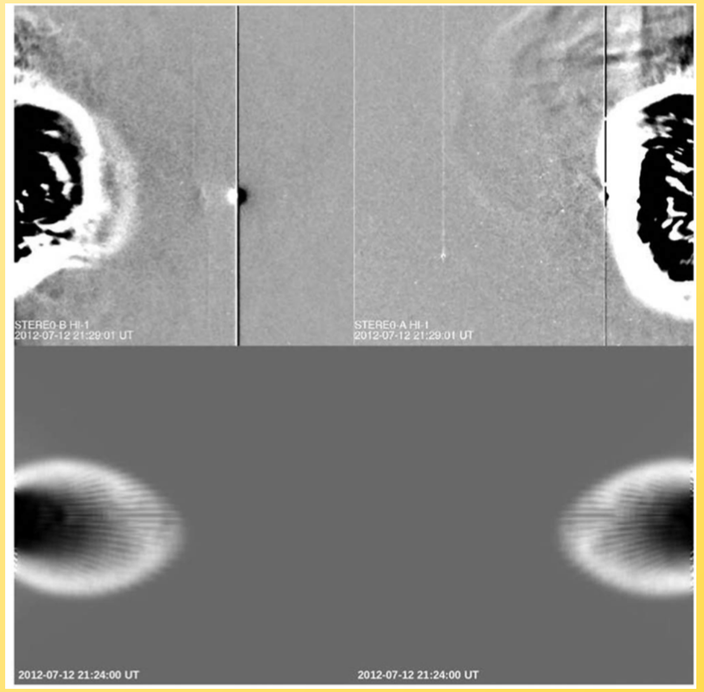
- Work by PSI group, Manchester *et al.* on coronagraphs/eclipse in the early 2000s.
- Work on STEREO synthetic observations by Lugaz *et al.* (2005, 2008, 2009), Odstrcil *et al.* (2009) in mid-to-late 2000s.
- More recent work by C.-C. Wu *et al.*, Zhou *et al.;* Shen Fang *et al.* among others

April 3, 2010 CME



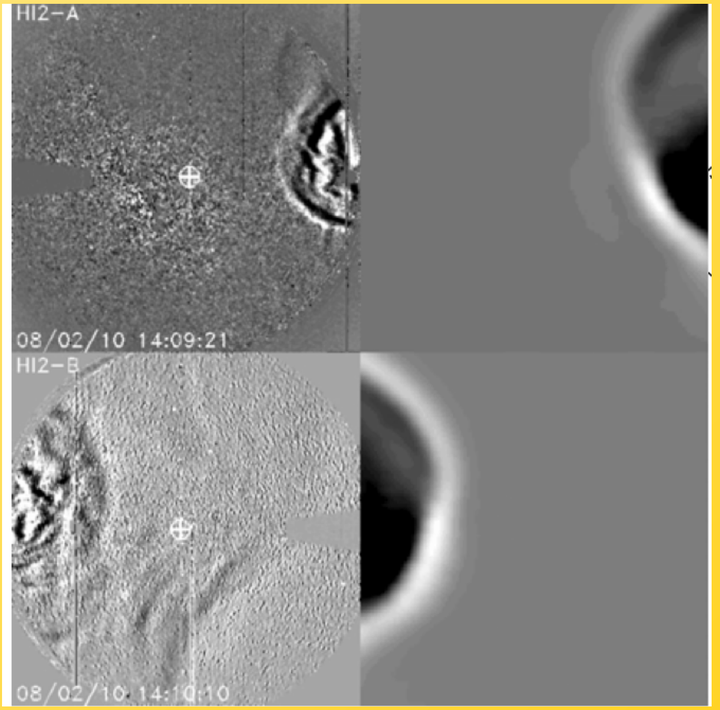
Zhou *et al.* (2014)

July 12, 2012 CME



F. Shen *et al.* (2014)

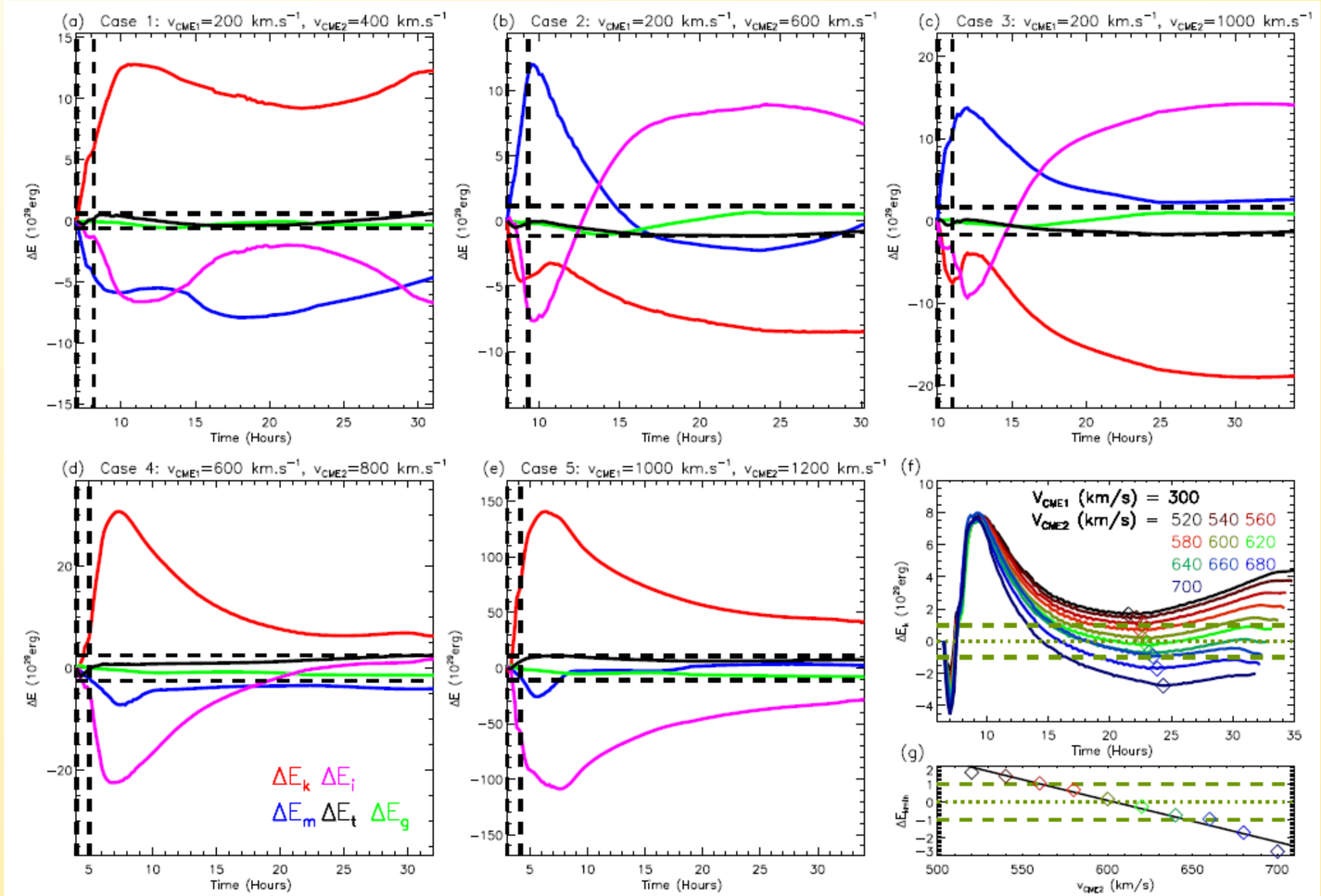
Aug. 1, 2010 CME



C.-C. Wu *et al.* (2010)

Simulations of multiple/interacting CMEs

- Topic of renewed importance in the past few years.

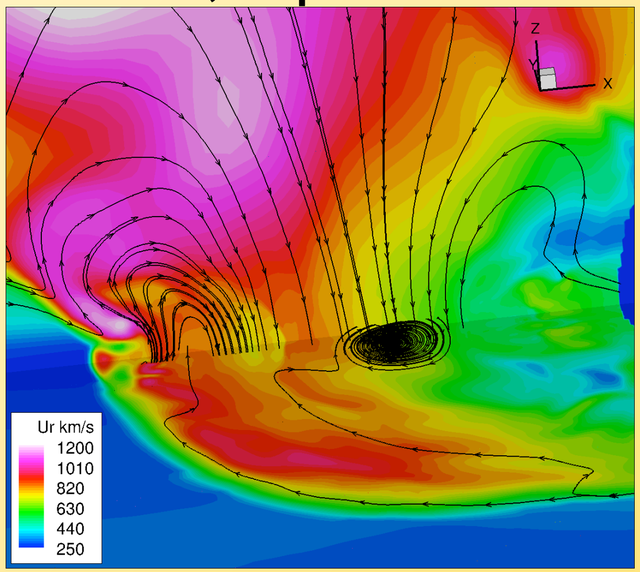


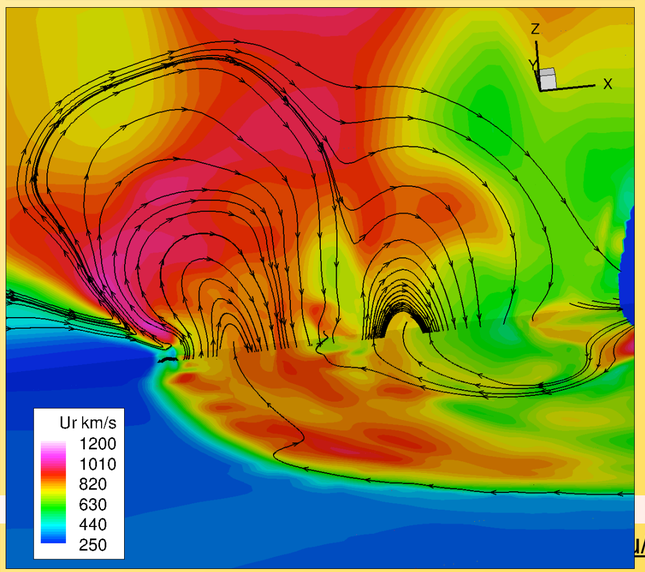
- What are the changes in CME properties during interaction?
- What is the influence of different CME initial parameters (speed, orientation)?
- What makes some collisions super-elastic while others aren't?
- Work in parallel with analyses of remote observations (see talks Tuesday 16-17:30)

see talk by F. Shen (given by Y. Wang)

Changes in CME properties during CME-CME interaction

- The overtaking shock, if present, is essential to **homogenize the speeds** between the two ejecta.
- First CME gets compressed;expansion after the inter





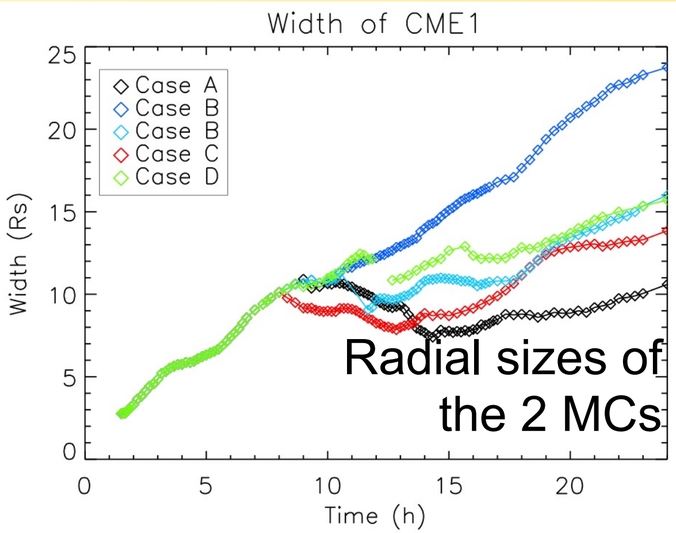
B_z = -20 n

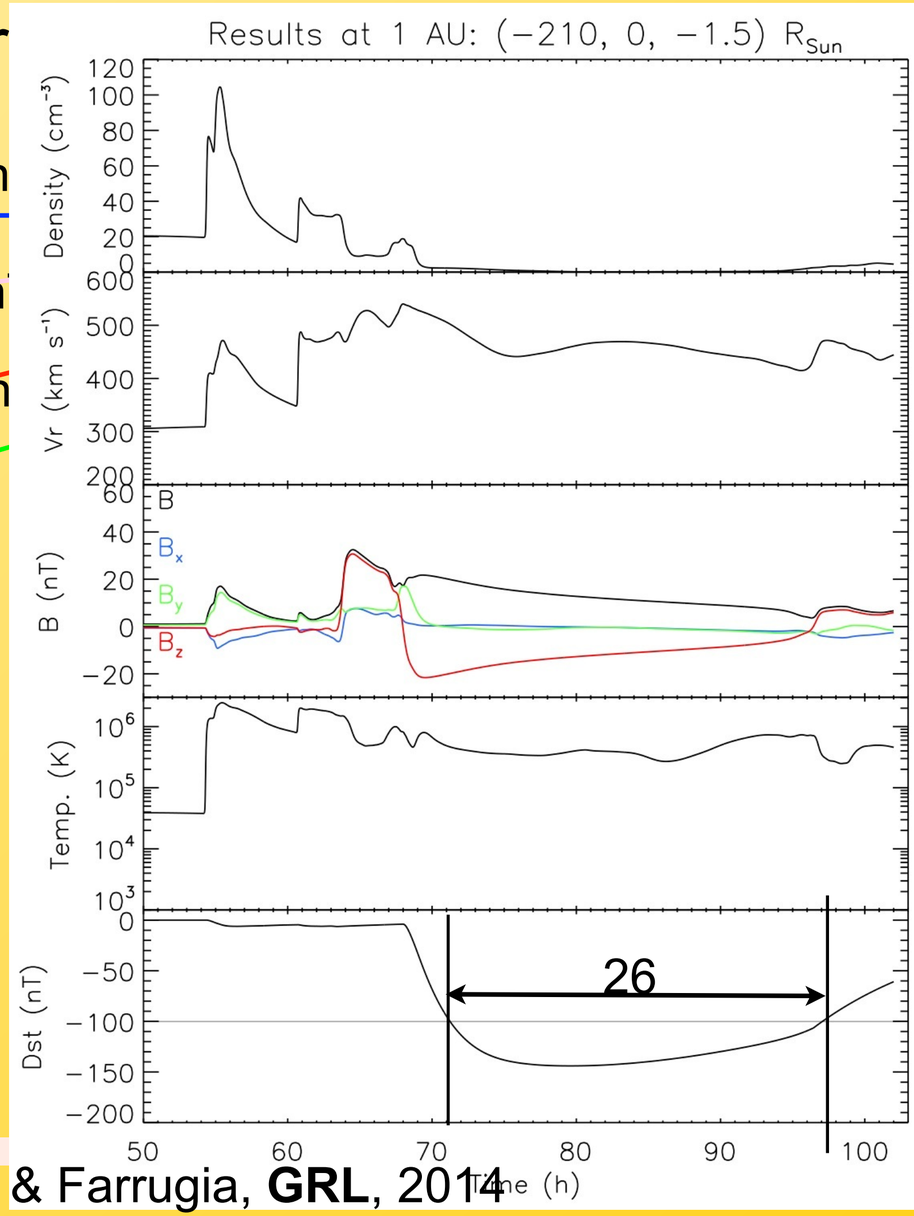
B_y = 20 n

B_z = 20 n

"Earth"

Lugaz *et al.*, **ApJ**, 2013





Lugaz & Farrugia, **GRL**, 2014

Conclusions

- Simulations have really reached the point where very different simulations are used for different goals:
  - Real-time forecasting: ENLIL, moving towards ensemble-forecasting. Still no internal magnetic field (soon?) but useful for arrival time and interaction with solar wind structures. Some European effort in this direction.
  - Providing environment for analyses of real events: Synthetic remote and in-situ observations are needed - eventually will merge with forecasting? (useful for code validation but not so much new physics learnt).
  - Understanding causes of eruption: complex initiation mechanism, as much realistic physics as possible. Eventually might lead to simplified/ad hoc prediction models (what makes an AR erupt? what causes a CME to be fast?)
  - Understanding complex physical processes: need for realistic CME models (but not necessarily realistic initiations) and as much physics as possible. Better understanding of physics around CME: energy exchange during interaction, shock formation and properties, nature of dimming/EUV waves, particle acceleration, reconnection between CMEs, with solar wind, etc…)
- Is there something ISEST wants to focus on?