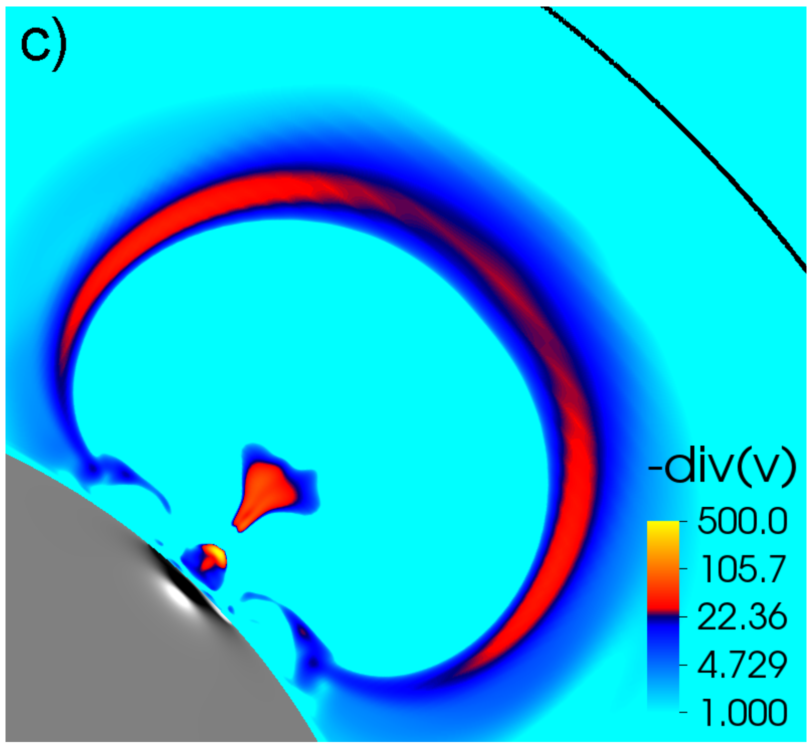
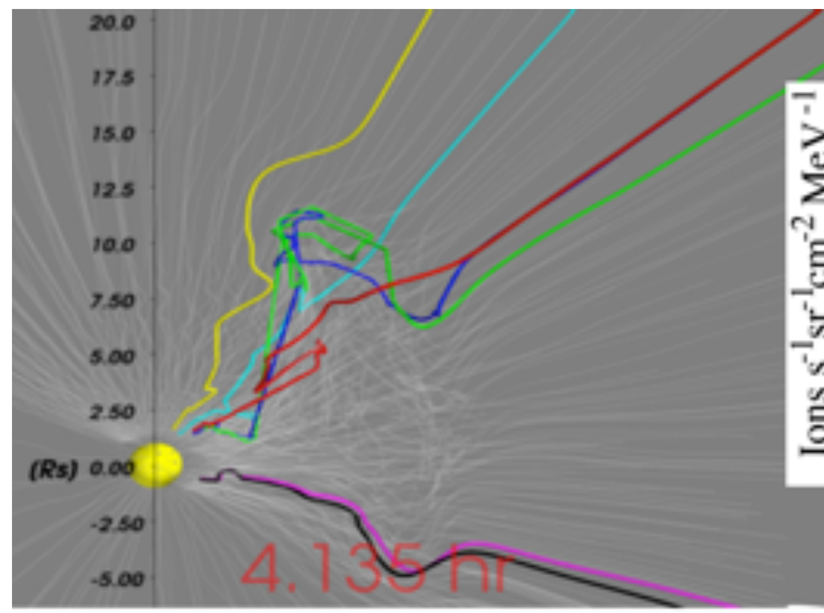
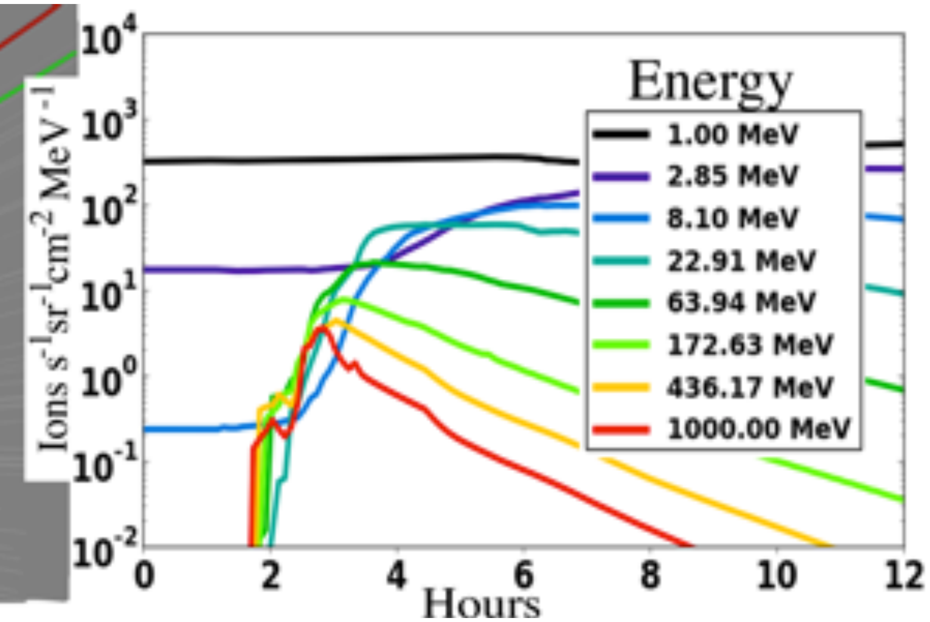
Modeling fast CMEs & related SEPs

Predictive Science, Inc.

University of New Hampshire



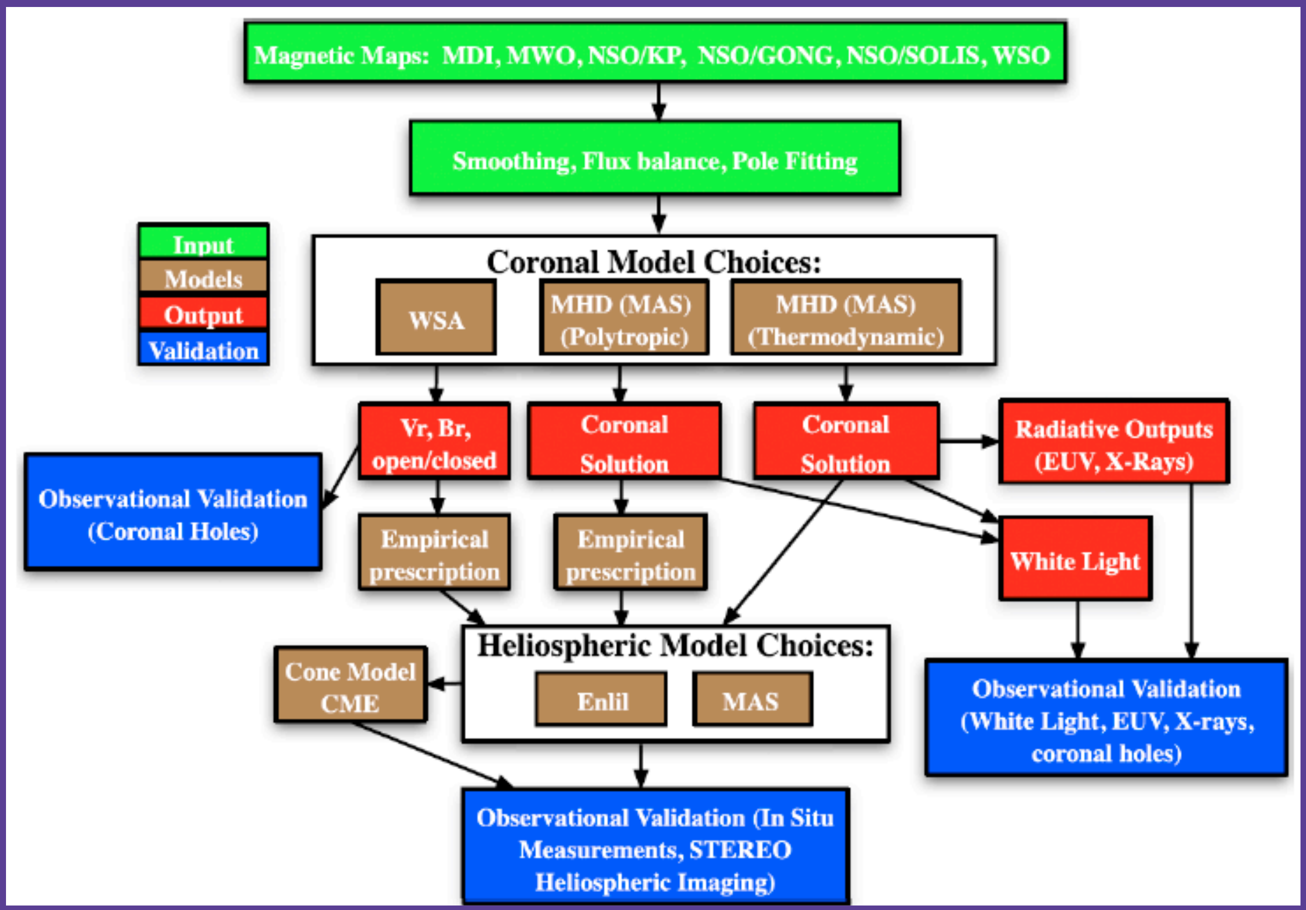




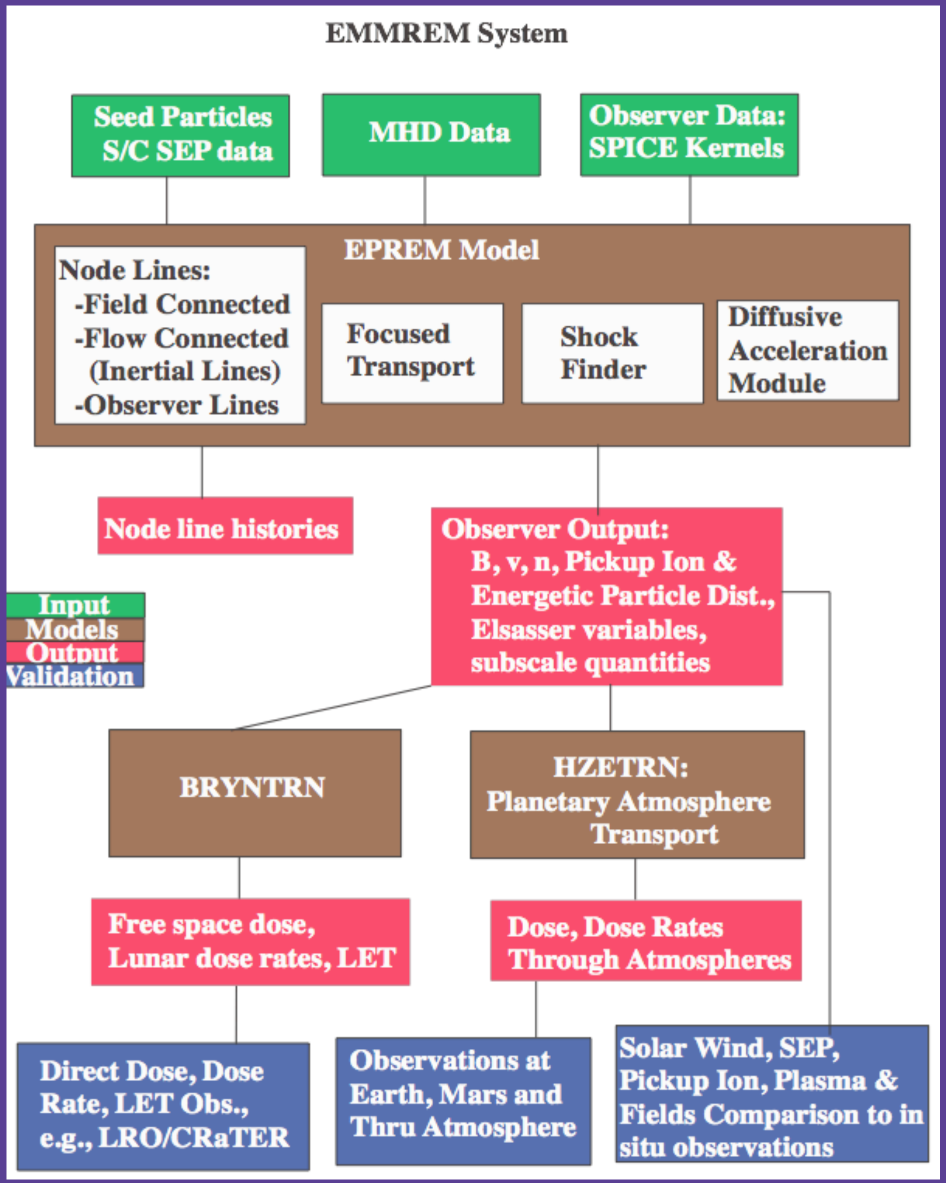
Tibor Török, Cooper Downs, Roberto Lionello, Slava Titov
Jon Linker, Zoran Mikić, Pete Riley, Matt Gorby, Nathan Schwadron

LWS-TIM meeting, 2014, May 20-22, NASA AMES center

C-SWEPA project



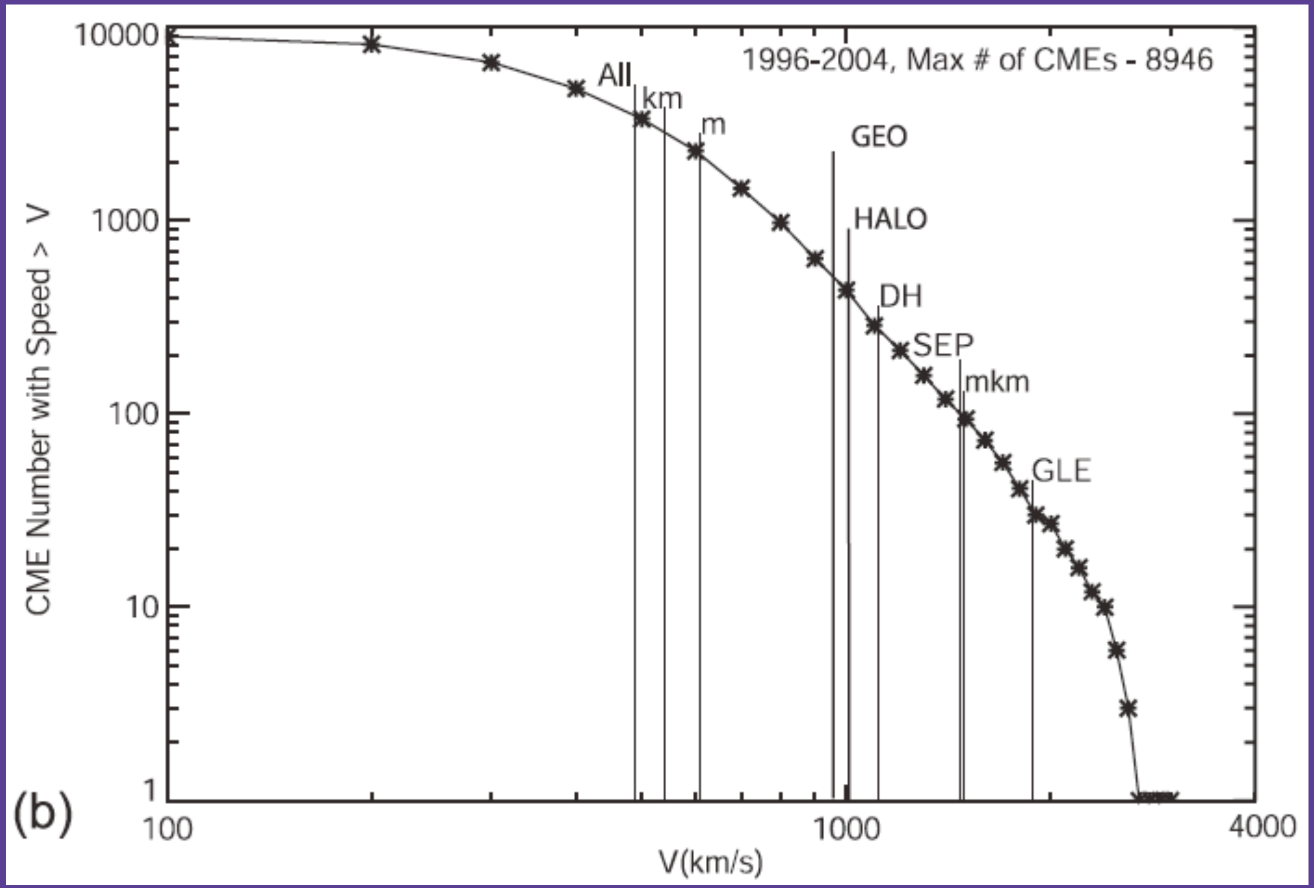
CORHEL (corona, solar wind, CMEs; PSI)



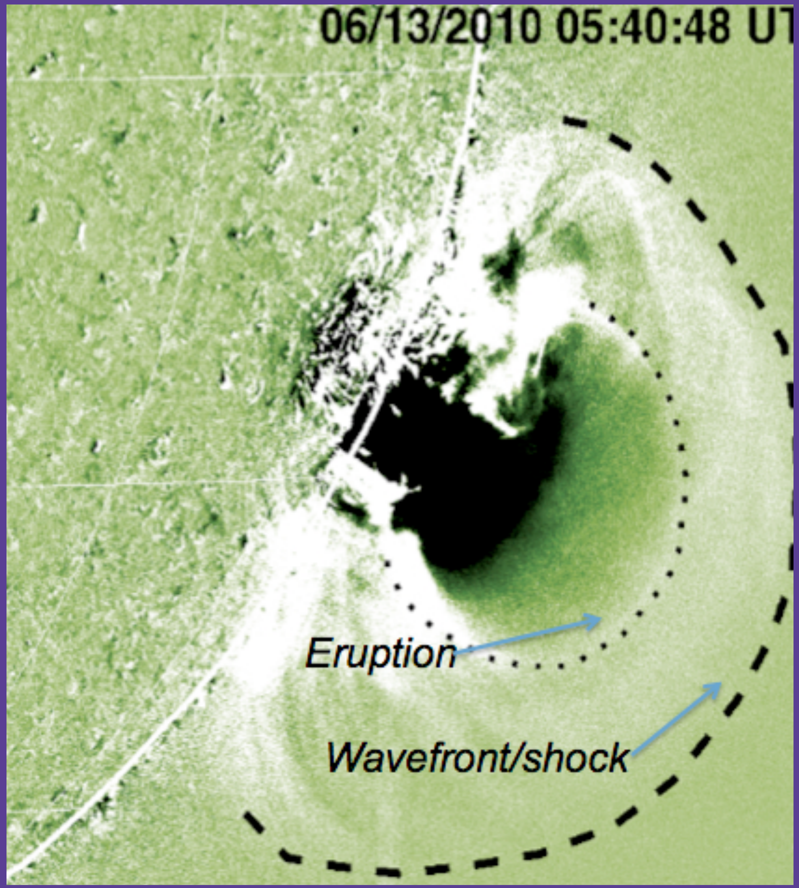
EMMREM (particles, radiation; UNH)

- objective: model and predict CME-driven SEPs & characterize their potential hazards
- combine two existing numerical sytems: CORHEL and EMMREM
- specifically: couple MAS & EPREM → compute SEP distributions from CME simulations

Solar Energetic Particles (SEPs)



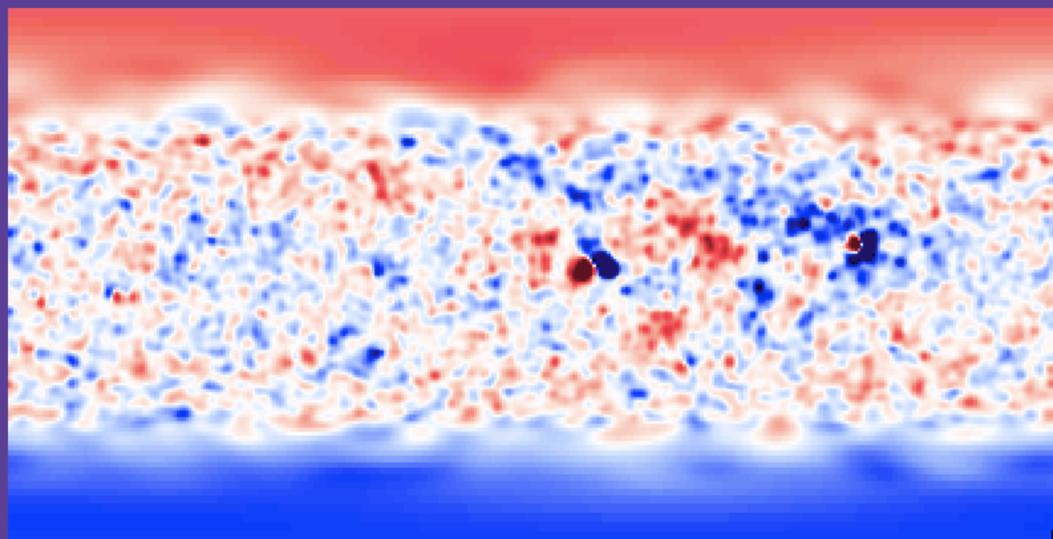
Gopalswamy (2006)



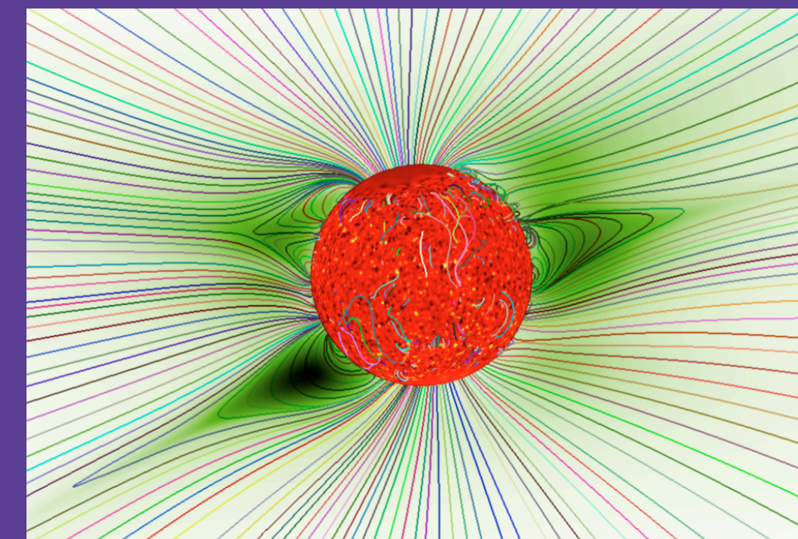
Kozarev *et al.* (2011)

- important space weather phenomena (satellite damage, hazardous for astronauts)
- primarily associated with fast CMEs → particles accelerated at CME-driven shocks
- shocks can form low in the corona (below 2 R_{sun})
- essential: accurate modeling of Alfvén speed and interplanetary magnetic field

"Thermodynamic" MHD modeling of the corona (MAS)

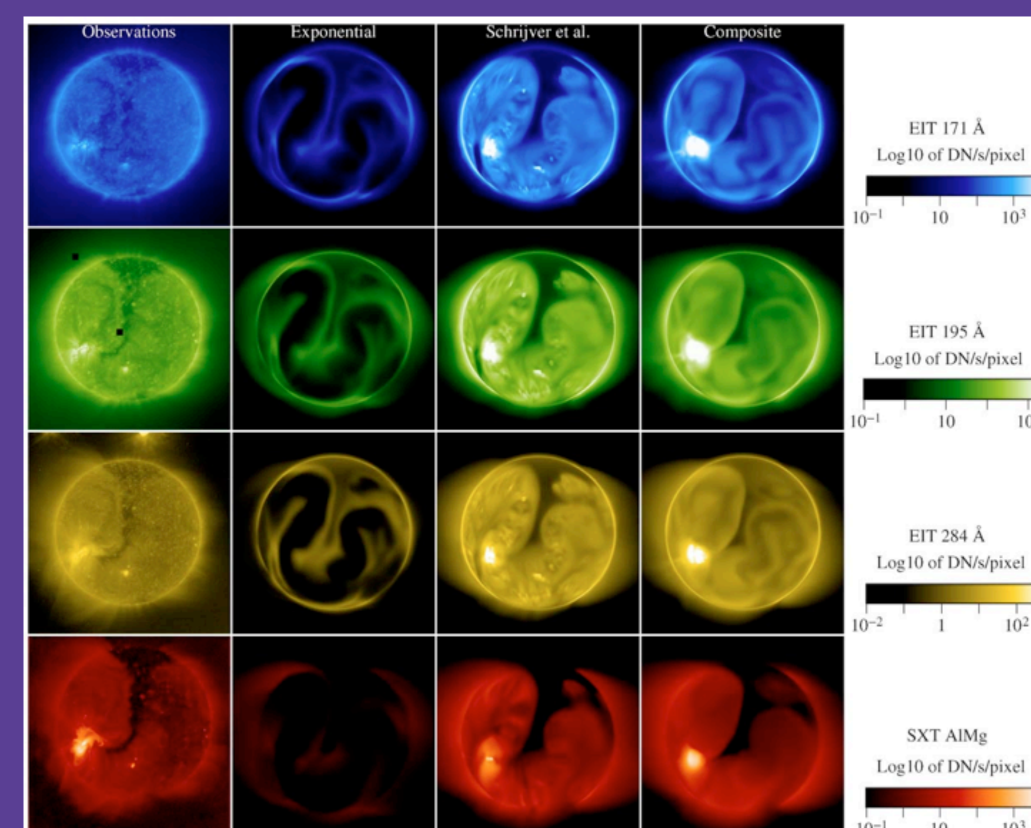


CR 2071 (June 9 - July 6, 2008)



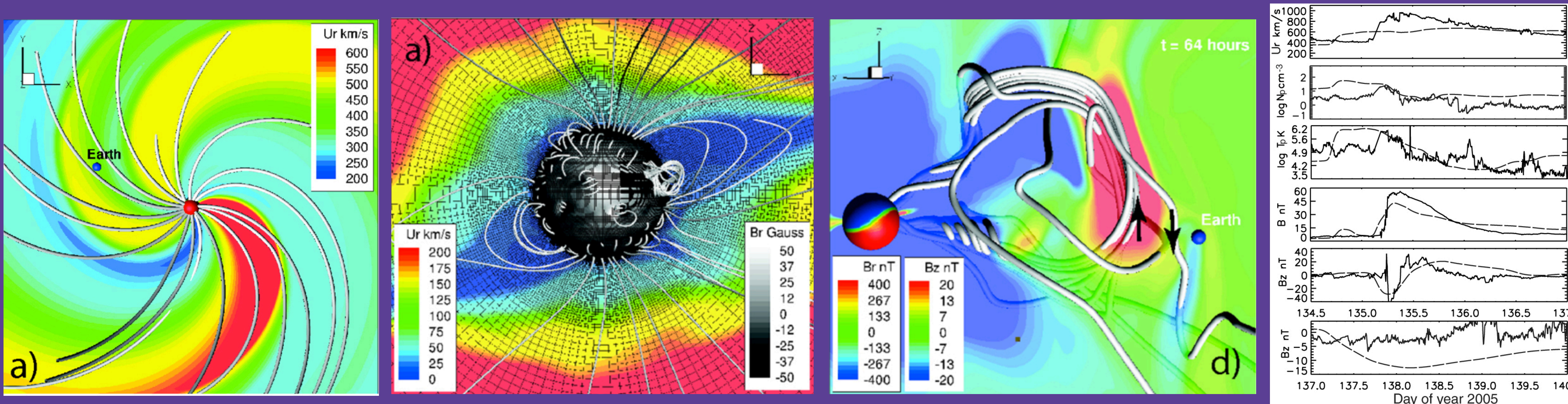
- potential field from (filtered) synoptic map
- relax to steady-state including solar wind
- MHD with advanced energy equation:
    - parallel thermal conduction
    - radiative losses
    - coronal heating (empirical)

→ realistic coronal density & temperature



Lionello et al. (2009)

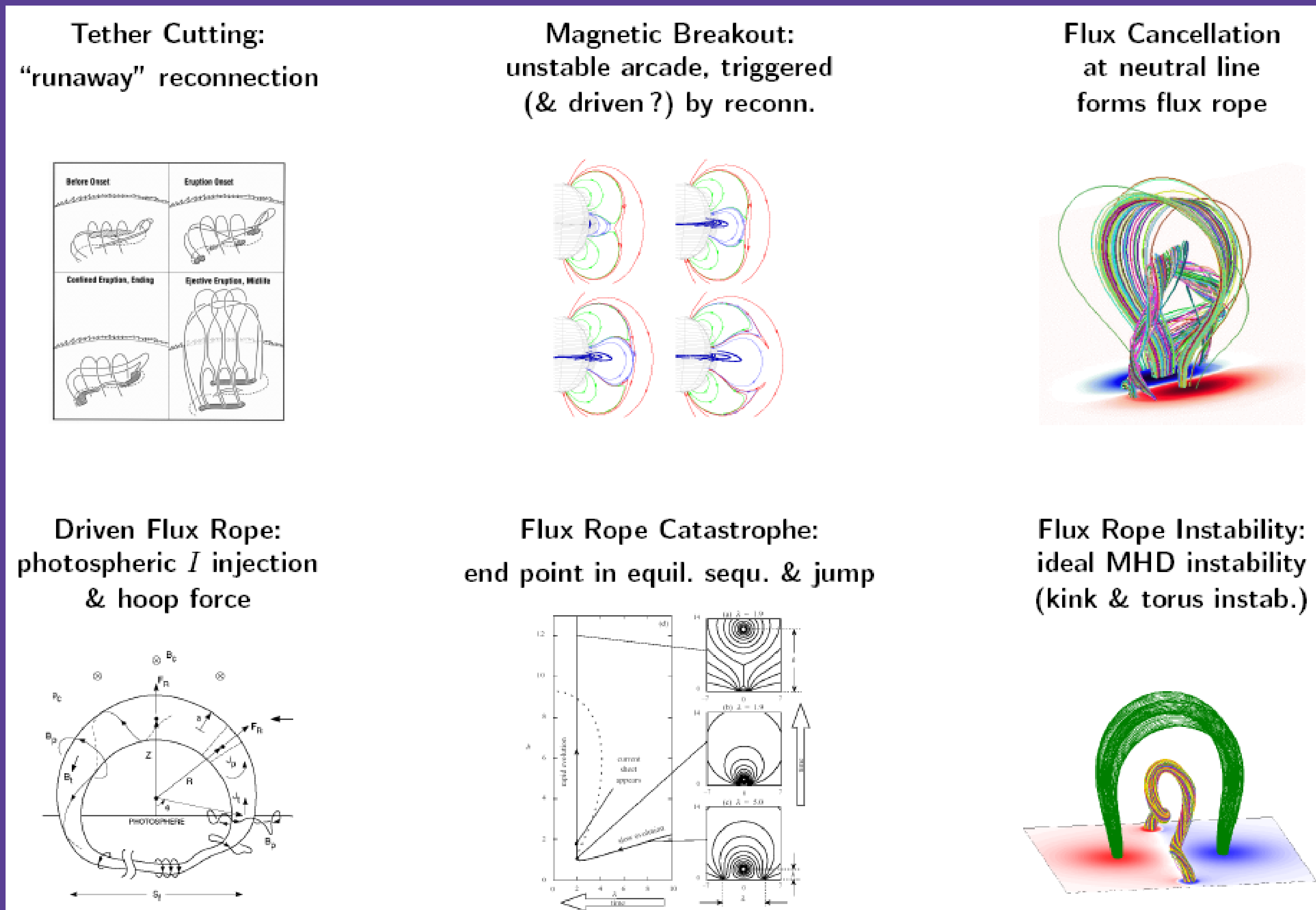
State-of-the-art CME simulations



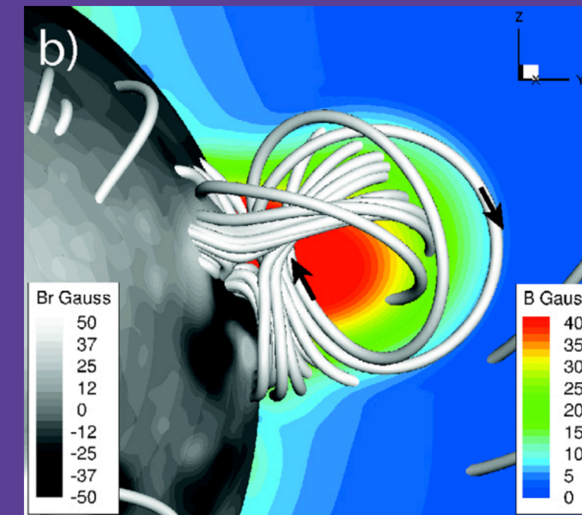
simulation of 2005 May 13 CME (Manchester *et al.* 2014)

- global configurations (up to 1 AU and beyond)
- magnetic field obtained from observed magnetograms
- realistic plasma distributions & solar wind (“thermodynamic MHD”)
- two-temperature model (protons and electrons)
- future: predictive capabilities (operational)

Still an issue: CME initiation

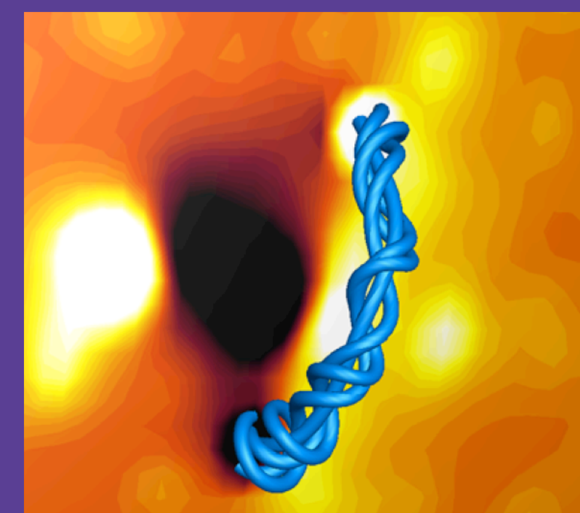


suggested CME initiation mechanisms



Gibson-Low flux rope out of equilibrium

(Manchester et al. 2014)



Titov-Démoulin flux rope out of equilibrium

(Lugaz et al. 2011)

solar eruptions start from magnetic equilibrium, but: model CMEs often triggered by out-of-equilibrium flux rope

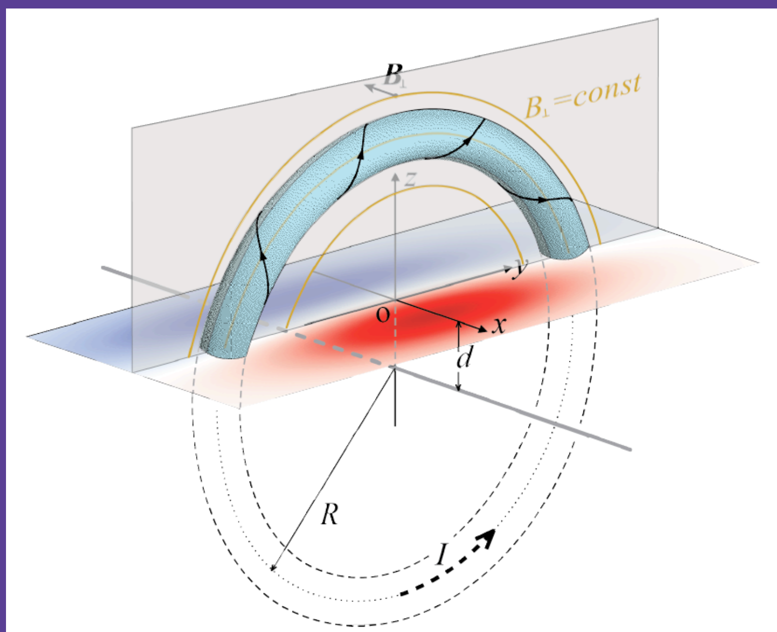
→ pre-eruptive model configuration cannot be verified by comparison to observations

→ magnetogram modified (flux rope footprints)

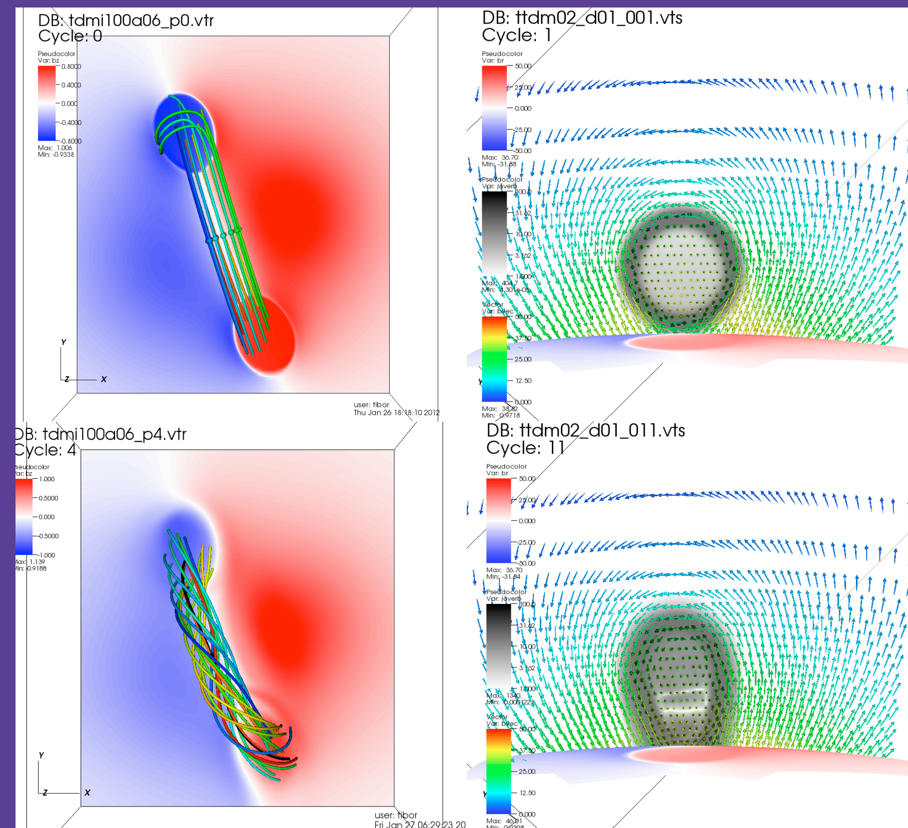
→ free magnetic energy (and magnetic field strength) likely overestimated

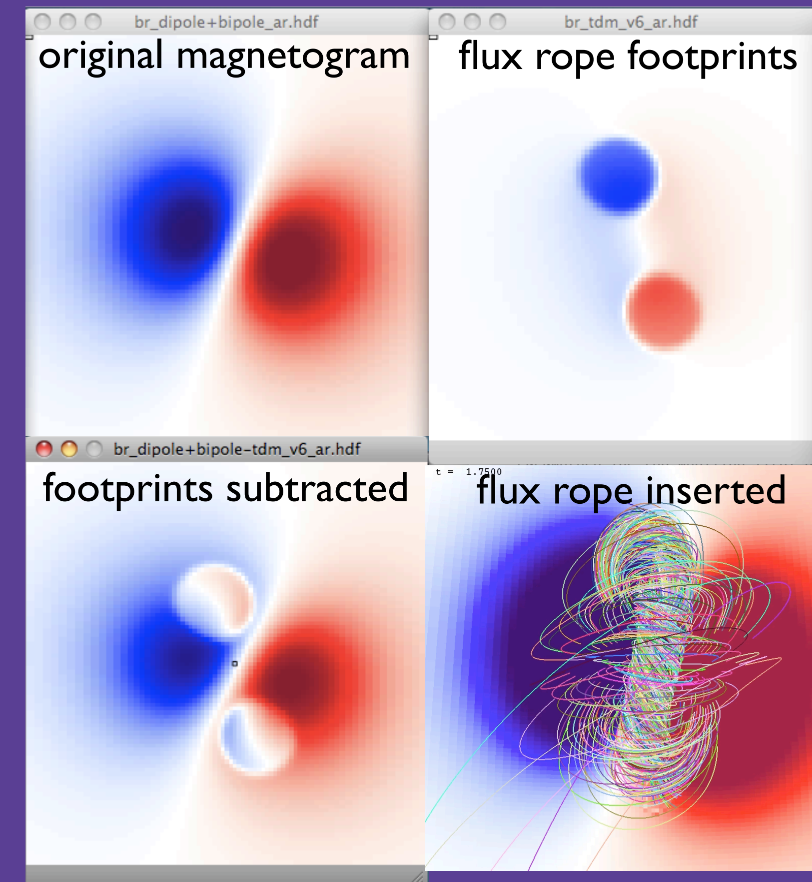
→ flux rope triggers unphysical perturbation (should propagate out of domain before CME starts)

New approach: pre-eruption configuration with stable flux rope



(Titov *et al.*, under revision)

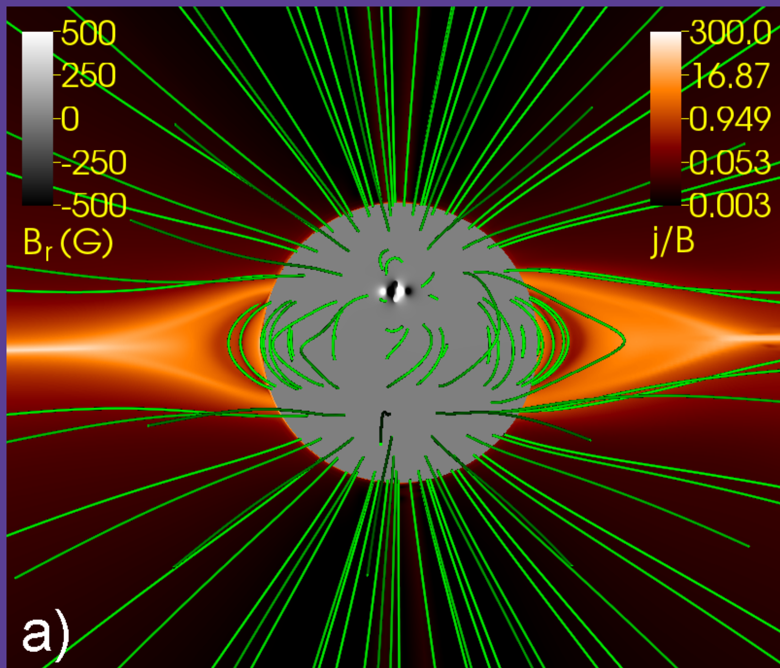




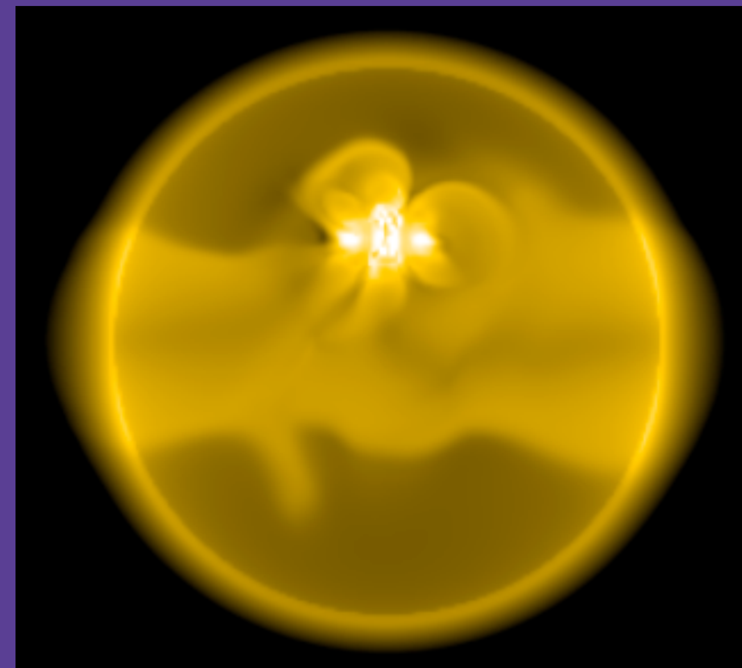
example: idealized bipolar active region

- use modified Titov-Démoulin (TDm) flux rope to energize eruption source region
- insert rope along contour of stabilizing ambient field & relax to numerical equilibrium
- preserve magnetogram by subtracting flux rope footprints before insertion
- trigger eruption by photospheric converging flows toward PIL

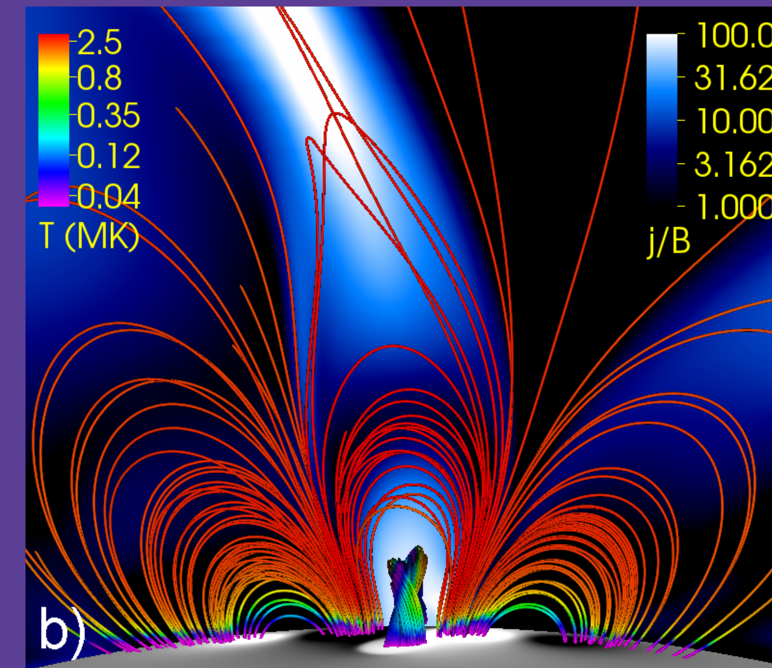
Modeling a fast CME



global configuration



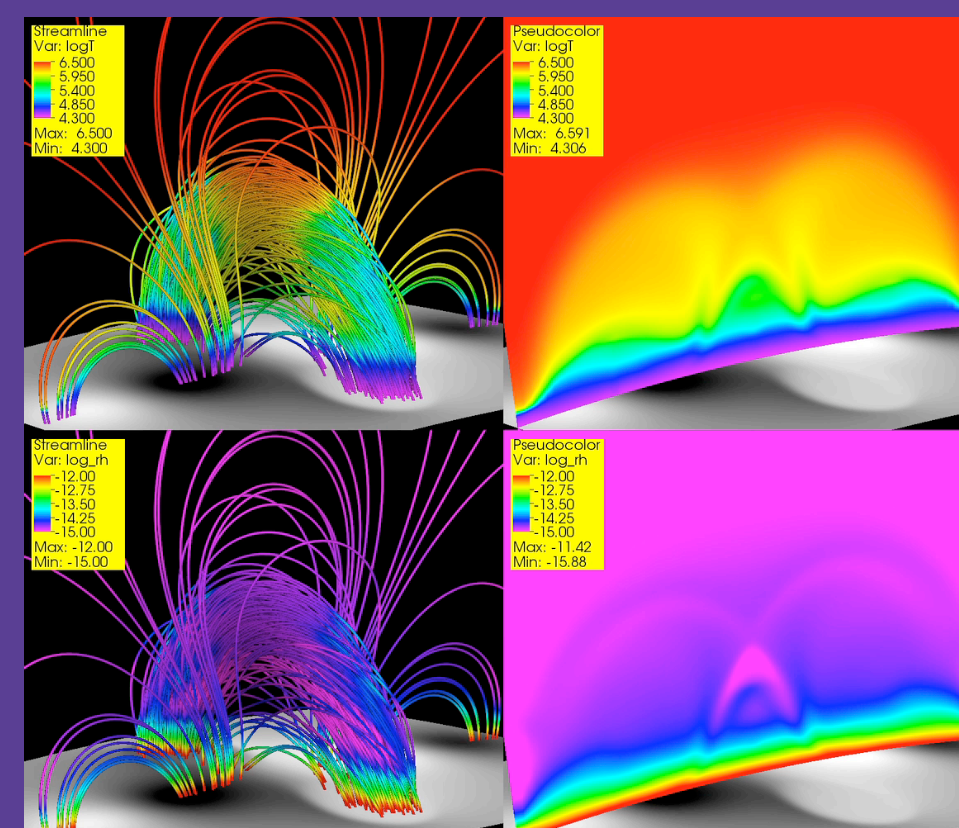
synthetic SDO/AIA 171 Å



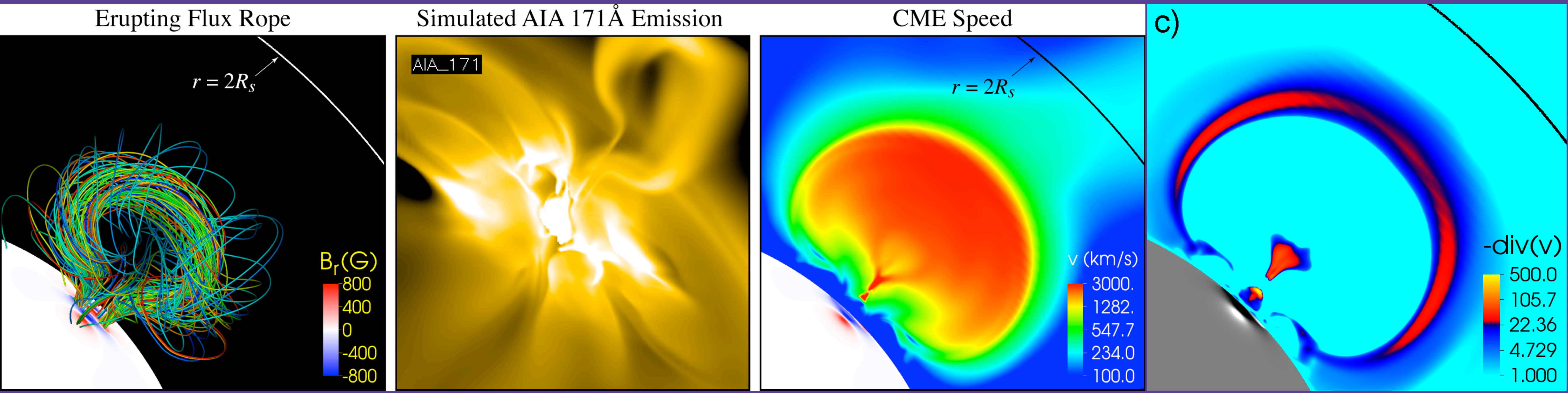
model active region

modeling fast CMEs from equilibrium with realistic coronal densities is challenging!

- idealized configuration: global dipole + quadrupolar AR
- stable flux rope (magnetogram not preserved)
- AR flux ≈ 7.5*10^{22} Mx; B_r_{max} = 1070 G; W_{free} ≈ 10^{33} ergs
- “prominence” formation (dense + cold plasma accumulation)



Flux rope eruption (low corona)



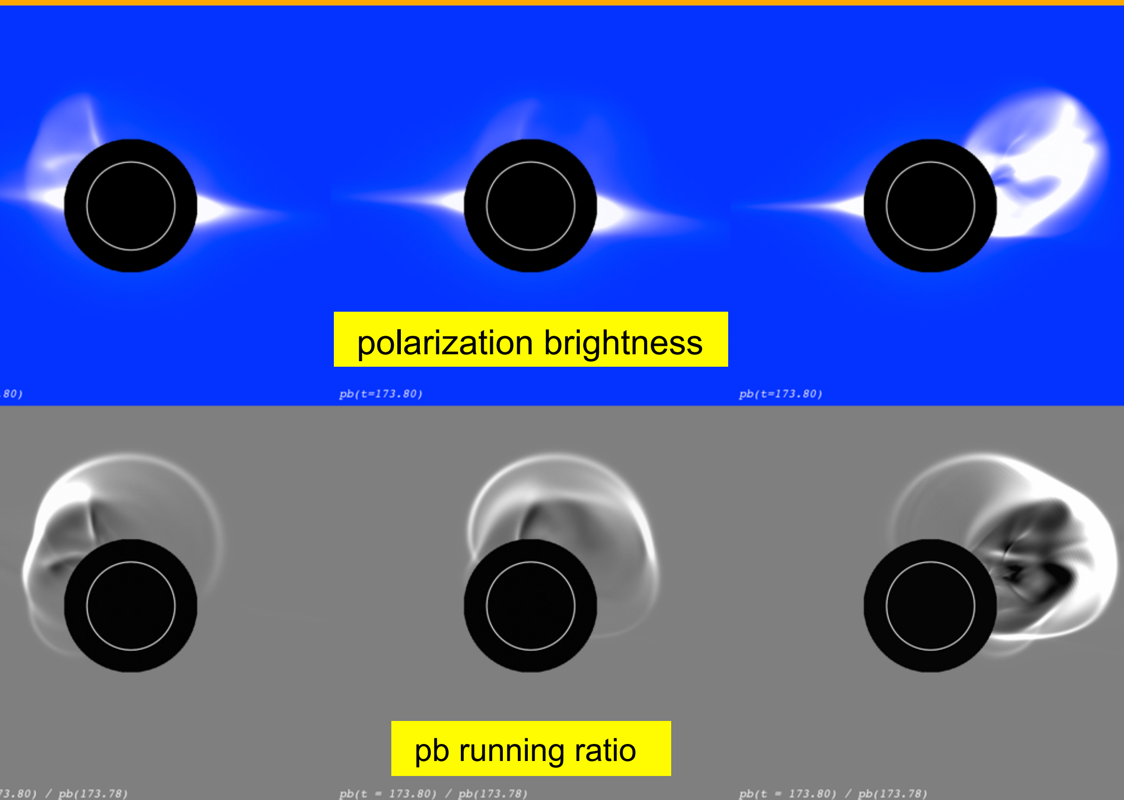
eruption triggered by converging toward main AR PIL

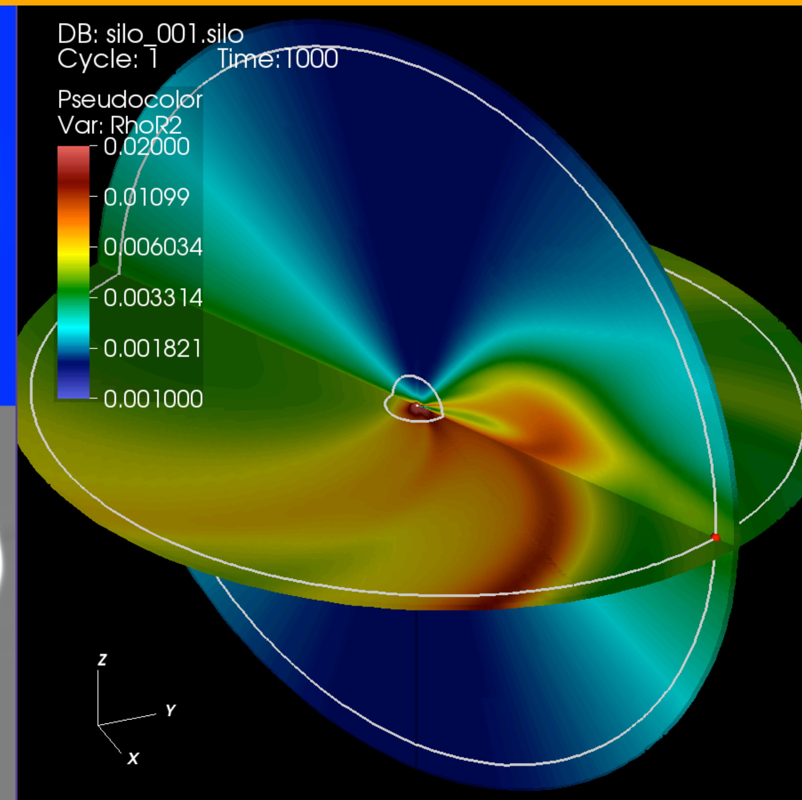
shock locations

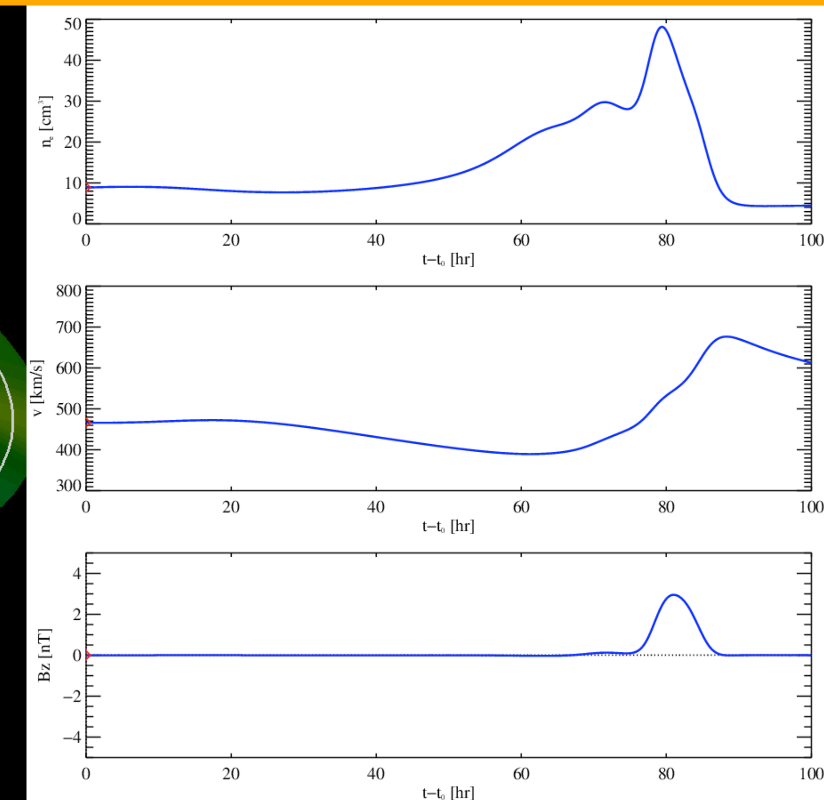
- initially very fast CME, produces shock low in the corona (≈ 1.4 R_{sun})
- max. speed > 3000 km/s, then strong deceleration to < 1000 km/s below 3 R_{sun}
- such extreme deceleration is not (rarely?) observed
- reason: unrealistically large reconnection jets (> 15,000 km/s)
  (jet speed very sensitive to plasma density in reconnection region)

but: low-corona evolution resembles a very fast CME

CME propagation





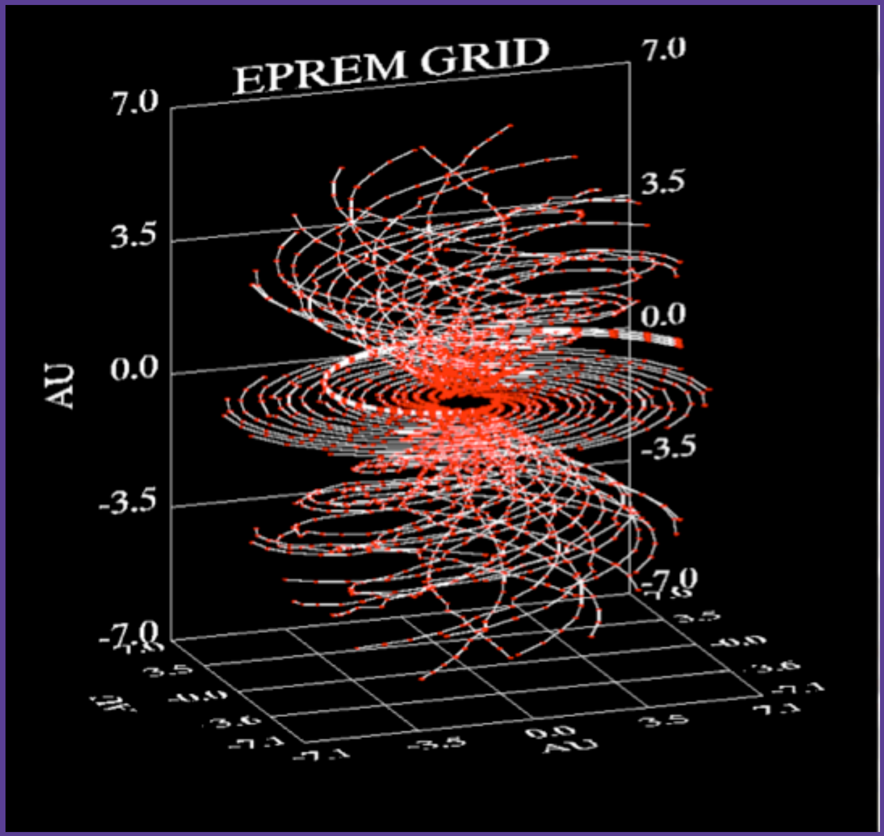


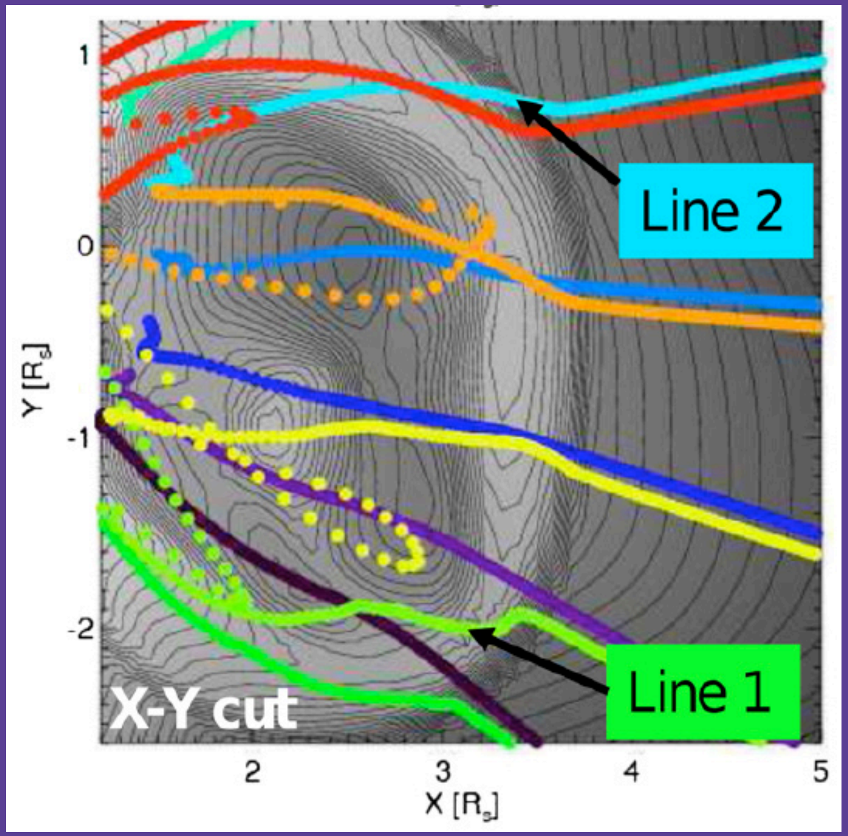
synthetic coronagraph images
(different viewing angles)

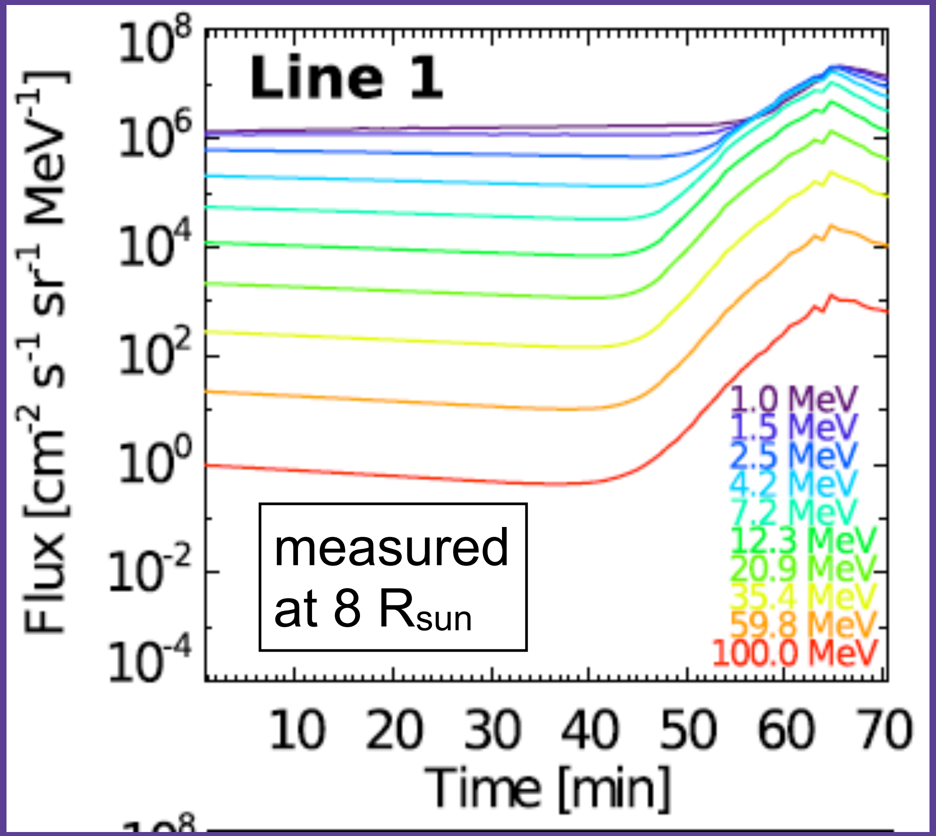
coupled coronal and heliospheric simulations
Lionello *et al.*, ApJ 777, 76 (2013)

- CME morphology and brightness depend strongly on viewing angle
- important for, e.g., CME mass and kinetic energy estimations
- couple coronal & new heliospheric MAS code at 20 R_{sun} (via boundary conditions)
- heliospheric calculation possible in inertial or rotating frame of reference

Coupling CME simulations to EPREM





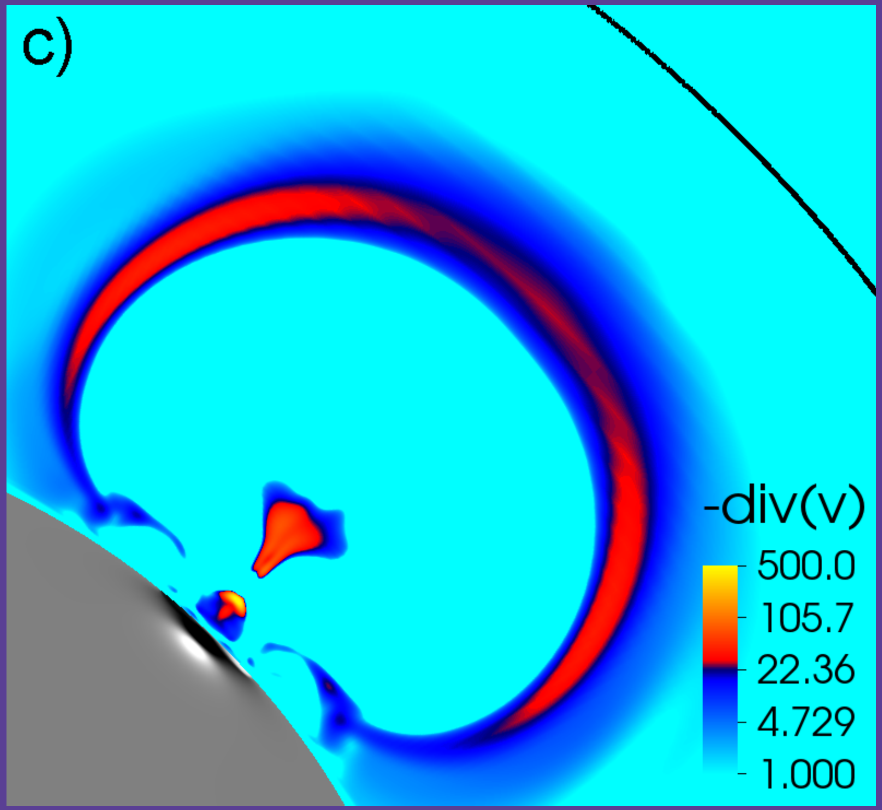


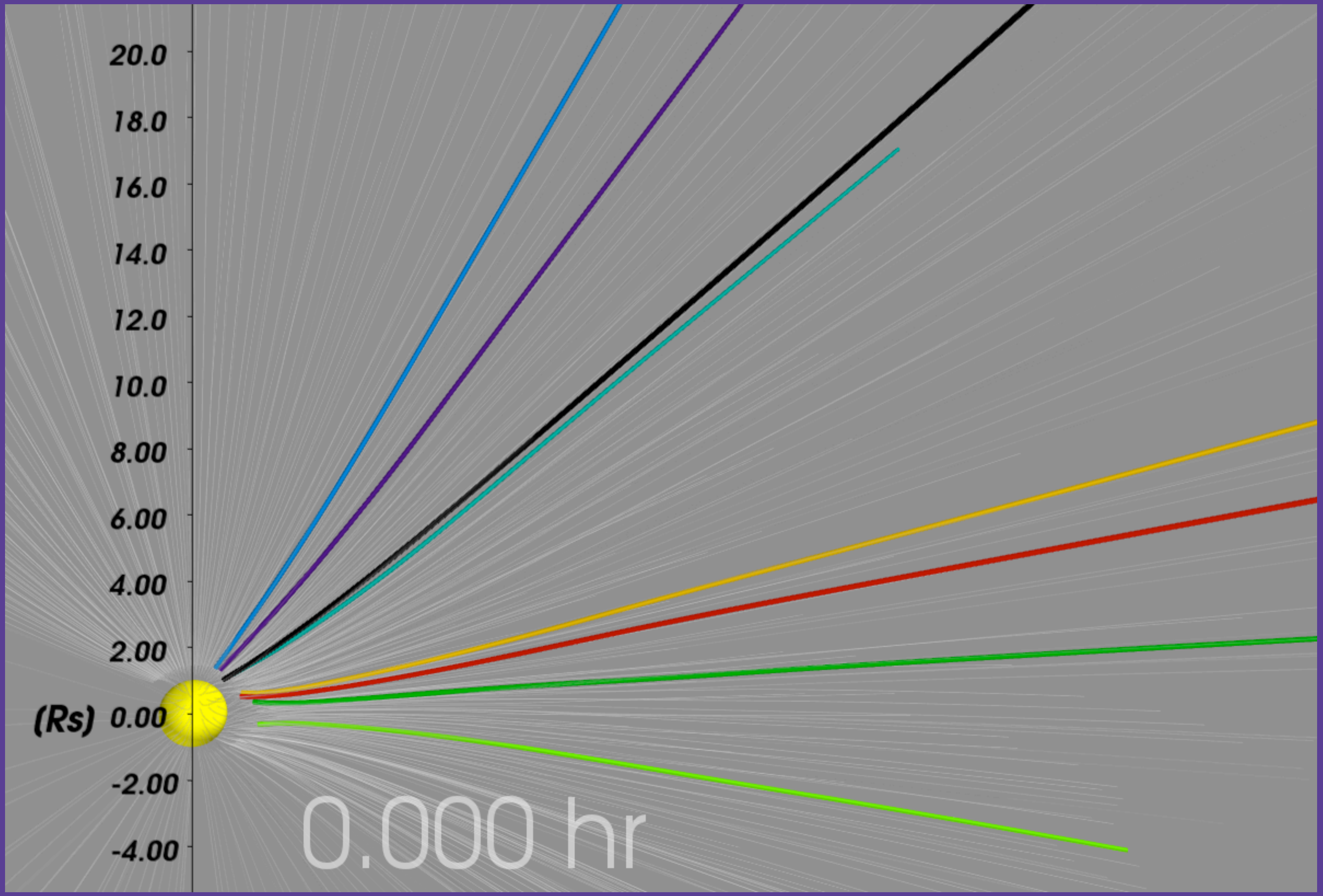
Schwadron *et al.* (2010)

Kozarev *et al.* (2013)
(simulation of 2005 May 13 CME)

- EPREM: Energetic Particle Radiation Environment Module
- models acceleration & propagation of energetic particles in inner heliosphere
- input: satellite observations or MHD simulations
- incorporates shock finder (via velocity perturbations along node lines)

Coupling MAS fast CME simulation to EPREM

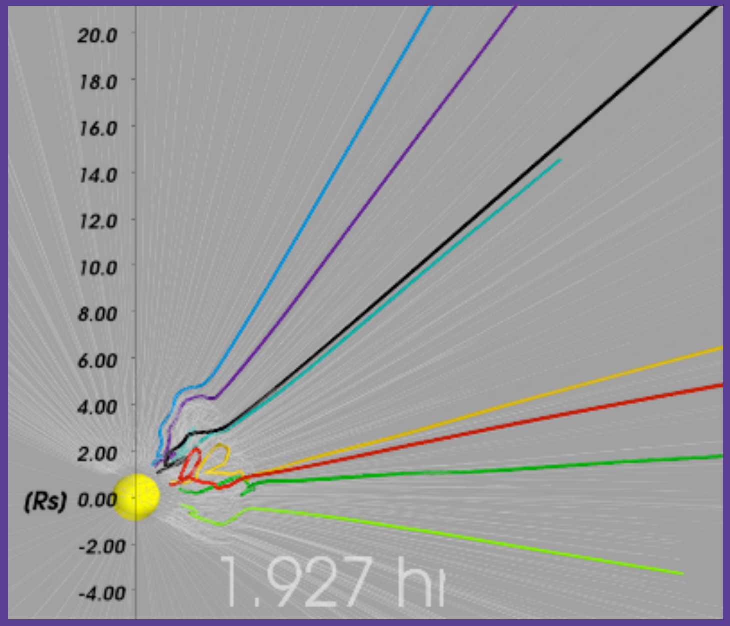


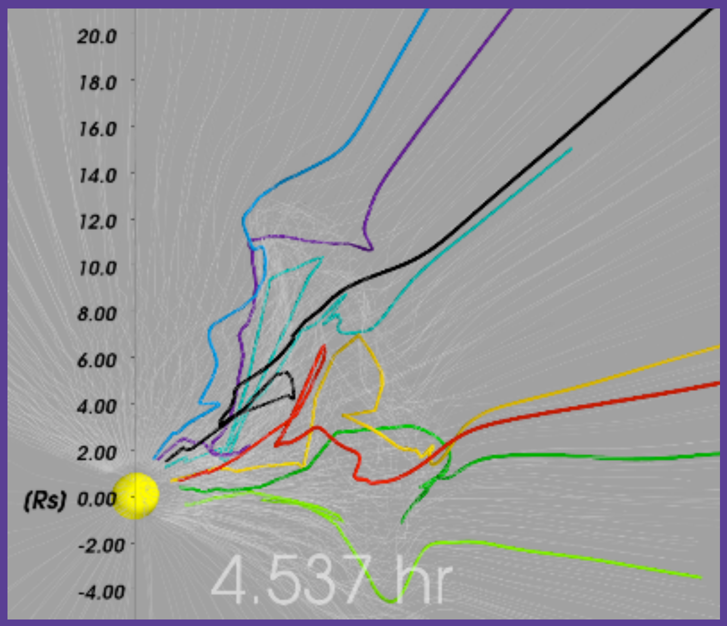


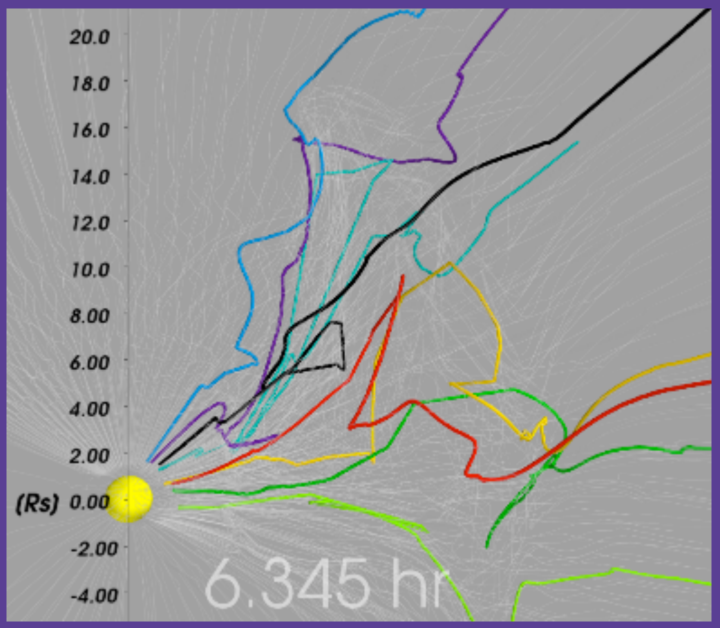
EPREM nodes lines distorted by expanding CME

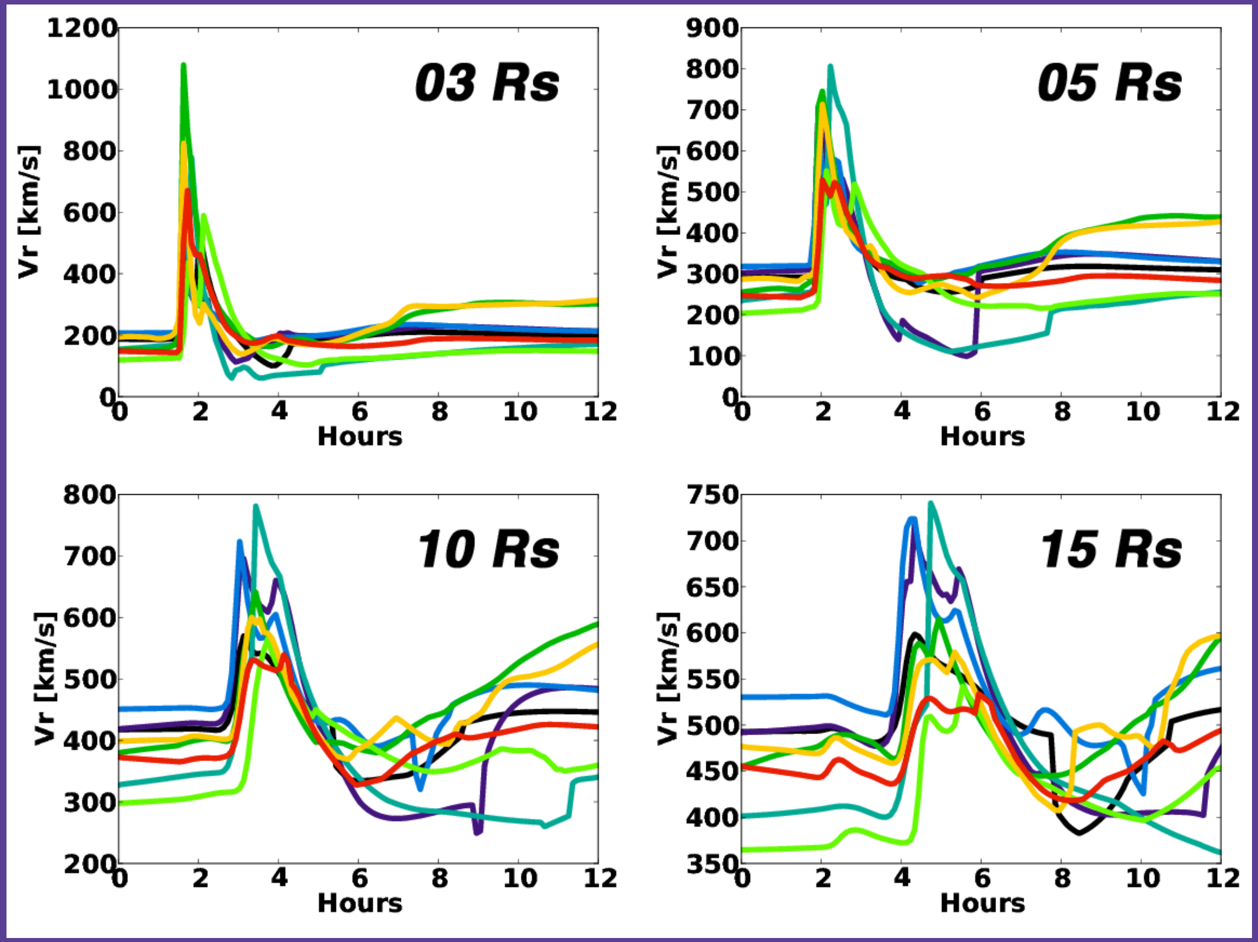
- EPREM grid: Lagrangian node-lines that propagate with the solar wind (connected nodes trace magnetic field lines)
- inner boundary at 1.8 R_{sun}
- EPREM runs on GPUs (thousands of field lines can be incorporated)

CME evolution on EPREM grid

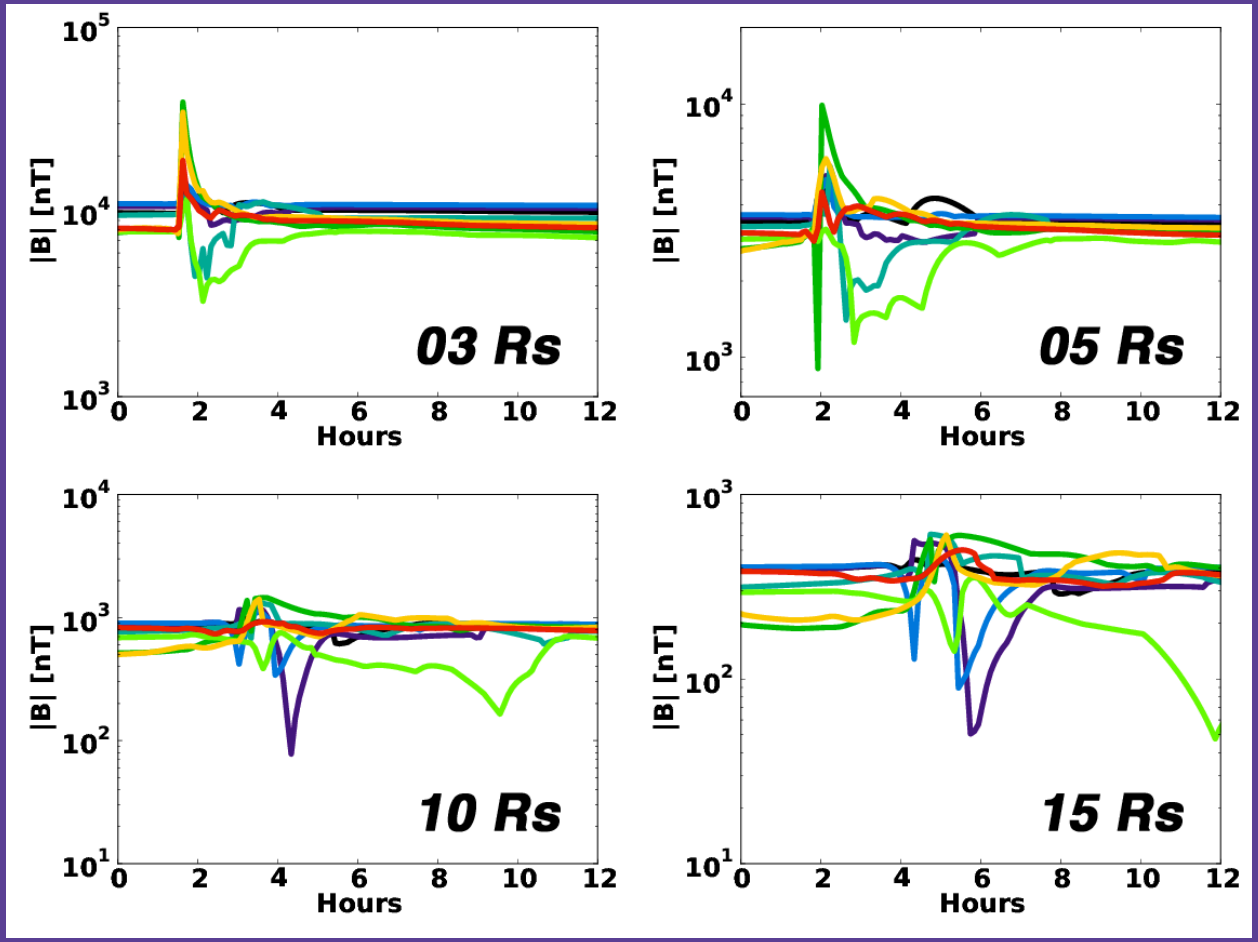








radial velocity



magnetic field strength

Particle acceleration and propagation

$$\left(1-\frac{(\vec{u}\cdot e_b)v\mu}{c^2}\right)\frac{df}{dt}+v\mu\frac{\partial f}{\partial z}+\frac{(1-\mu^2)}{2}\left[v\frac{\partial \ln B}{\partial z}-\frac{2}{v}e_b\cdot\frac{d\vec{u}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial \mu}+$$
$$\left[-\frac{\mu e_b}{v}\cdot\frac{d\vec{u}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial \ln p}=\frac{\partial}{\partial \mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial \mu}\right)+S$$

Focused Transport Equation on Lagrangian grid (Kota 2005, Schwadron *et al*. 2010)

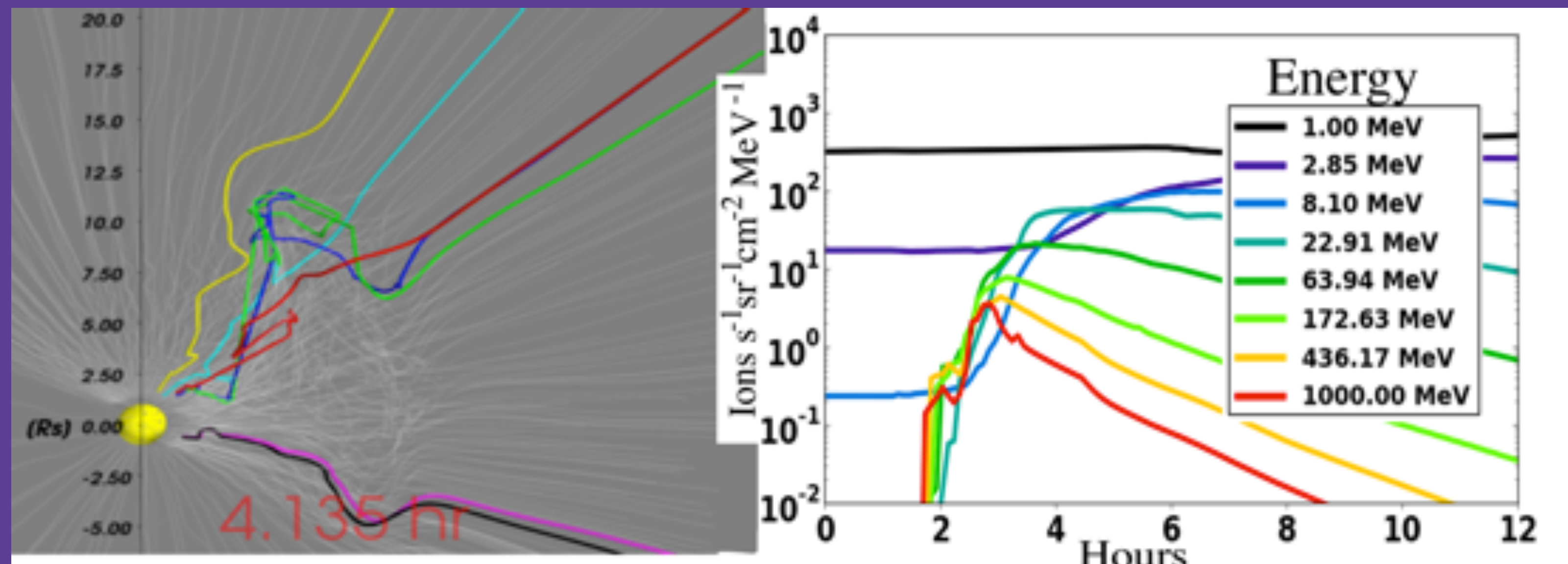
setup suprathermal pre-event spectrum:

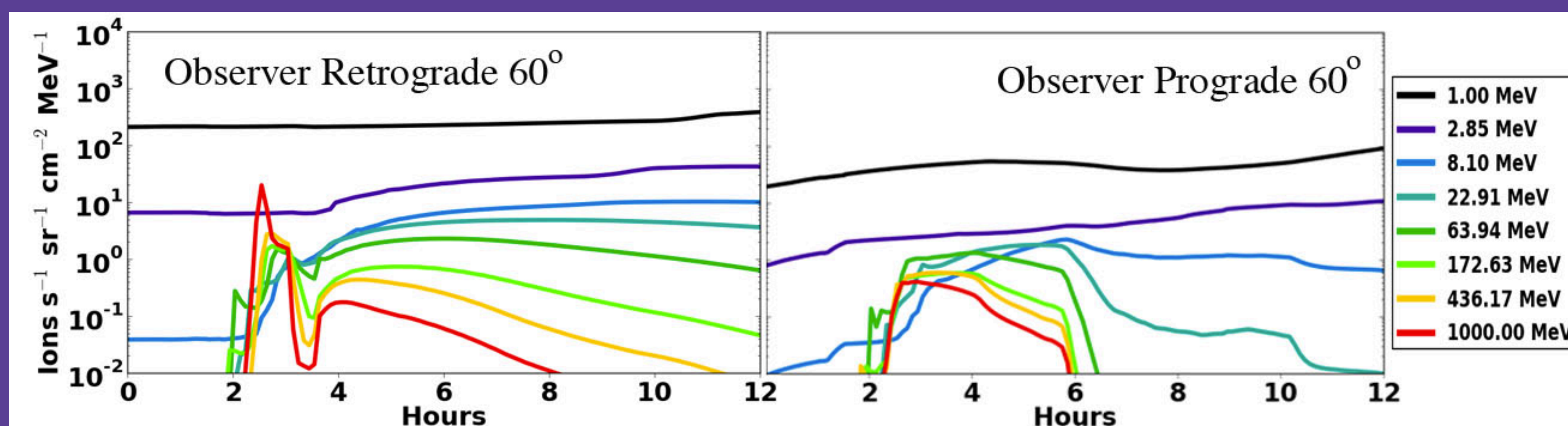
- use quiet-time ^{4}He ion (0.1-0.5 MeV/nuc) observations from ACE/ULEIS (Dayeh *et al.* 2009)
- convert spectrum to protons (assuming flux scales as r $^{-2}$ and He/H ratio of 10%)

some assumptions:

- characteristic parallel scattering mean free paths of 0.1-0.5 AU from 1-100 MeV at 1 AU
- fixed ratio perp/para diffusion= 0.01 (e.g., Giaclone & Jokipii 1999)

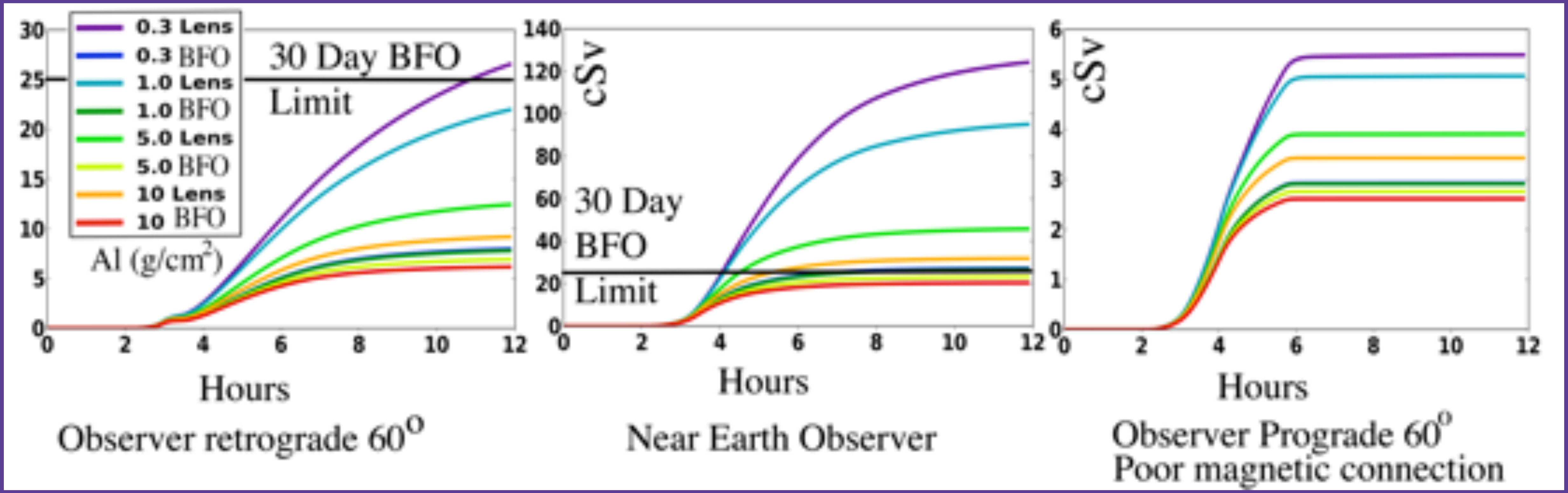
Proton fluxes at 1 AU





- EPREM simulation extended to 1 AU: particle fluxes for energies up to 1 GeV
- abrupt event (rapidly rising high-energy fluxes at 1AU formed within 2 hours)
- broad longitudinal distributions due to cross-field diffusion (even for low perp. diffusion)
- acceleration from compressions prior to CME shock formation (Giacalone 2002; 2005)

Potential hazard: radiation doses at 1 AU



time-dependent radiation exposure at 1 AU

- calculate integrated dose equivalents for Lens and Blood Forming Organs (BFO) for different levels of shielding at 1AU
- find 10's of cSv even for well-shielded (10 g/cm^2 Al) spacecraft
- indicates a radiation hazard that approaches 30-Day-Limit (25 cSv) in about 2 hours

Summary

- modeled idealized fast CME with MAS (CORHEL):
  - realistic plasma environment in background corona & solar wind
  - very strong initial acceleration (v > 3000 km/s)
  - strong field compressions & shock low in corona (≥ 1.4 R_{sun})

- modeled related strong SEP event & radiation doses with EPREM (EMMREM):
  - relatively high particle fluxes up to ≈ 1GeV at 1 AU
  - broad longitudinal extent of SEP event (even for low (1%) perp. diffusion)
  - large enough high-energy fluxes to approach 30-Day radiation limits
  - very abrupt event (high-energy fluxes formed within 2 hours)

demonstrates significant potential hazard for astronauts and spacecraft