Probing the Puzzle of Fermi Long-Duration Gamma-Ray Flares by Data-driven Global MHD Simulations

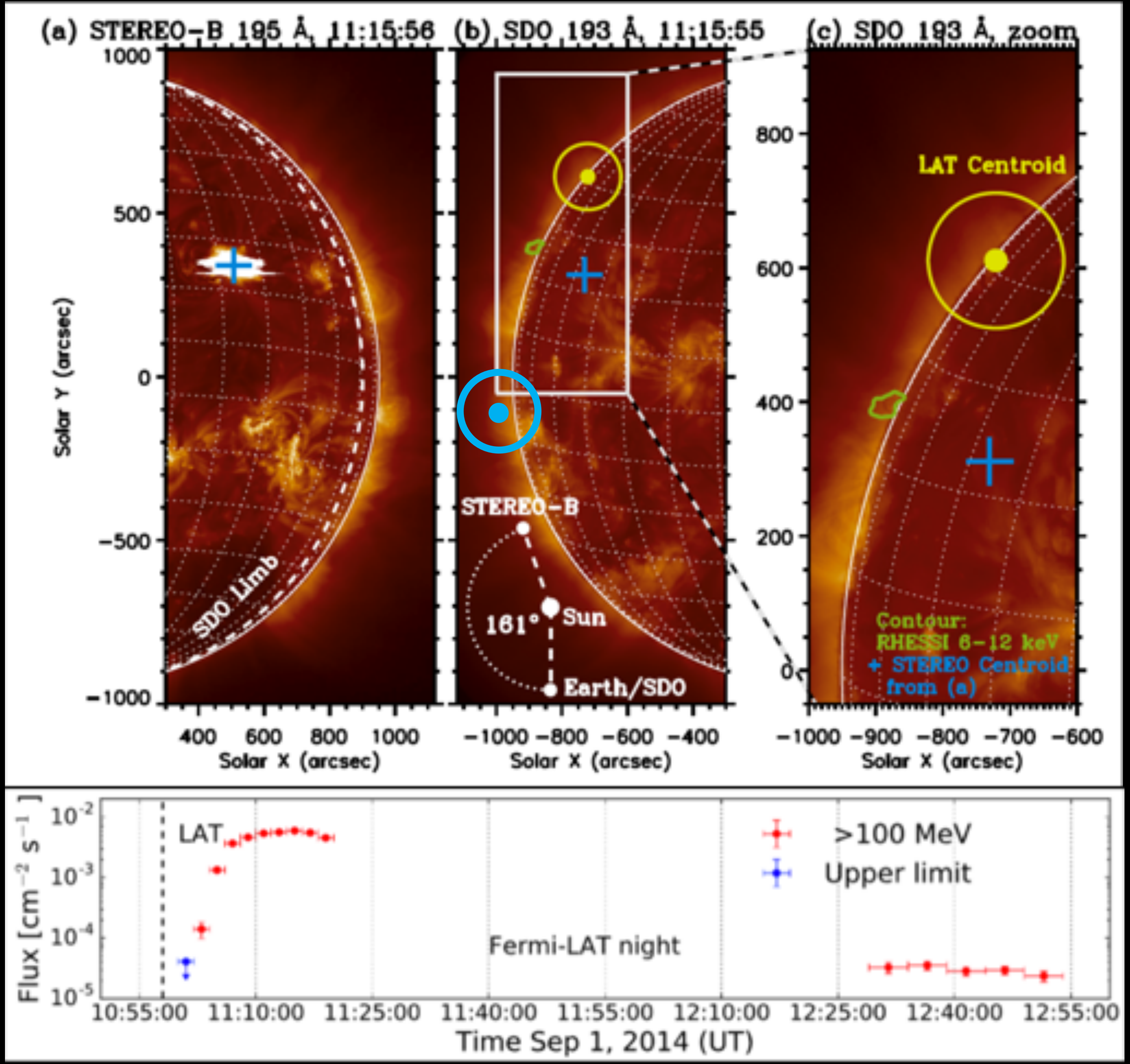
Meng Jin[1,2], Vahe Petrosian[3], Wei Liu[1,5], Nariaki Nitta[1], Nicola Omodei[3], Frederic Effenberger[4,5]
Gang Li[6], Melissa Pesce-Rollins[7], Alice Allafort[3], Ward Manchester[8]

[1]Lockheed Martin Solar and Astrophysics Lab (LMSAL), Palo Alto, CA, USA
[2]SETI Institute, Mountain View, CA 94043, USA
[3]Department of Physics, Stanford University, Stanford, CA, USA
[4]Helmholtz Centre Potsdam, GFZ, German Research Centre for Geosciences, Potsdam, Germany
[5]Bay Area Environmental Research Institute, NASA Research Park, Moffett Field, CA, USA
[6]University of Alabama in Huntsville, Huntsville, AL, USA
[7]Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Pisa, Italy
[8]Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA

Ninth International Fermi Symposium – April 12-17, 2021

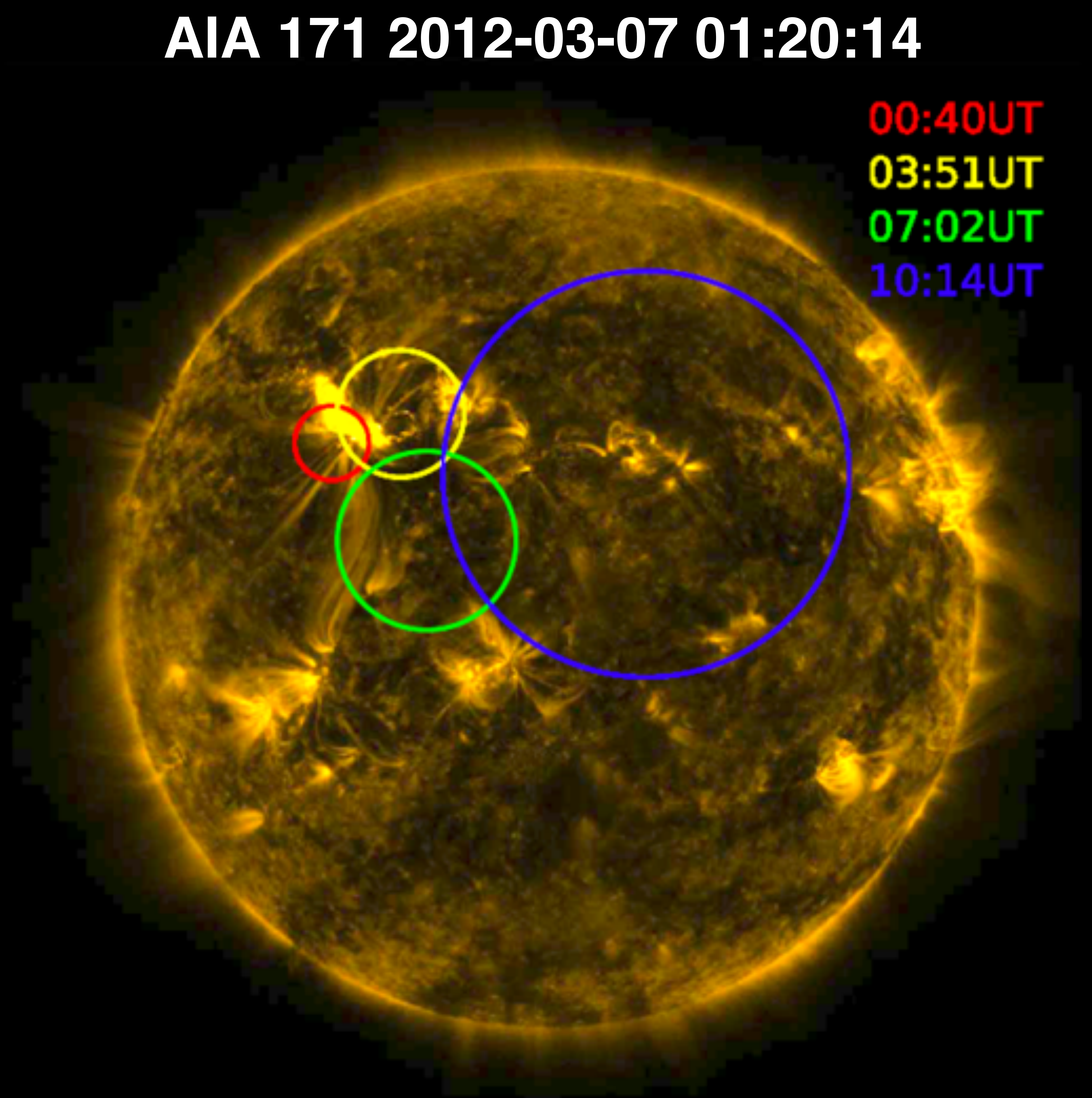
Long-duration >100 MeV Gamma-ray solar flares observed by *Fermi*/LAT pose a puzzle on particle acceleration/transport mechanisms.

Behind-the-Limb Flares (Ackermann et al. 2017)

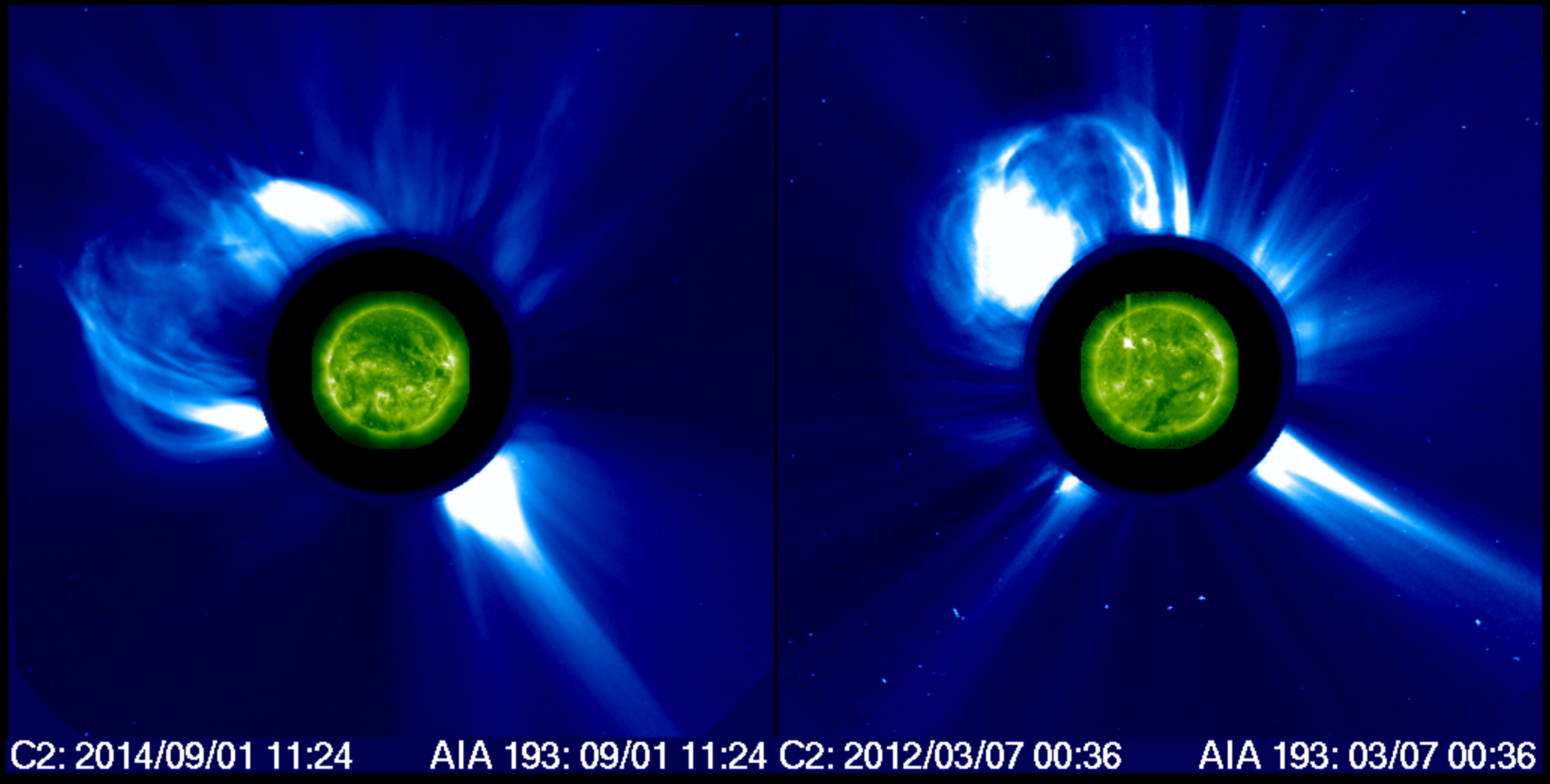


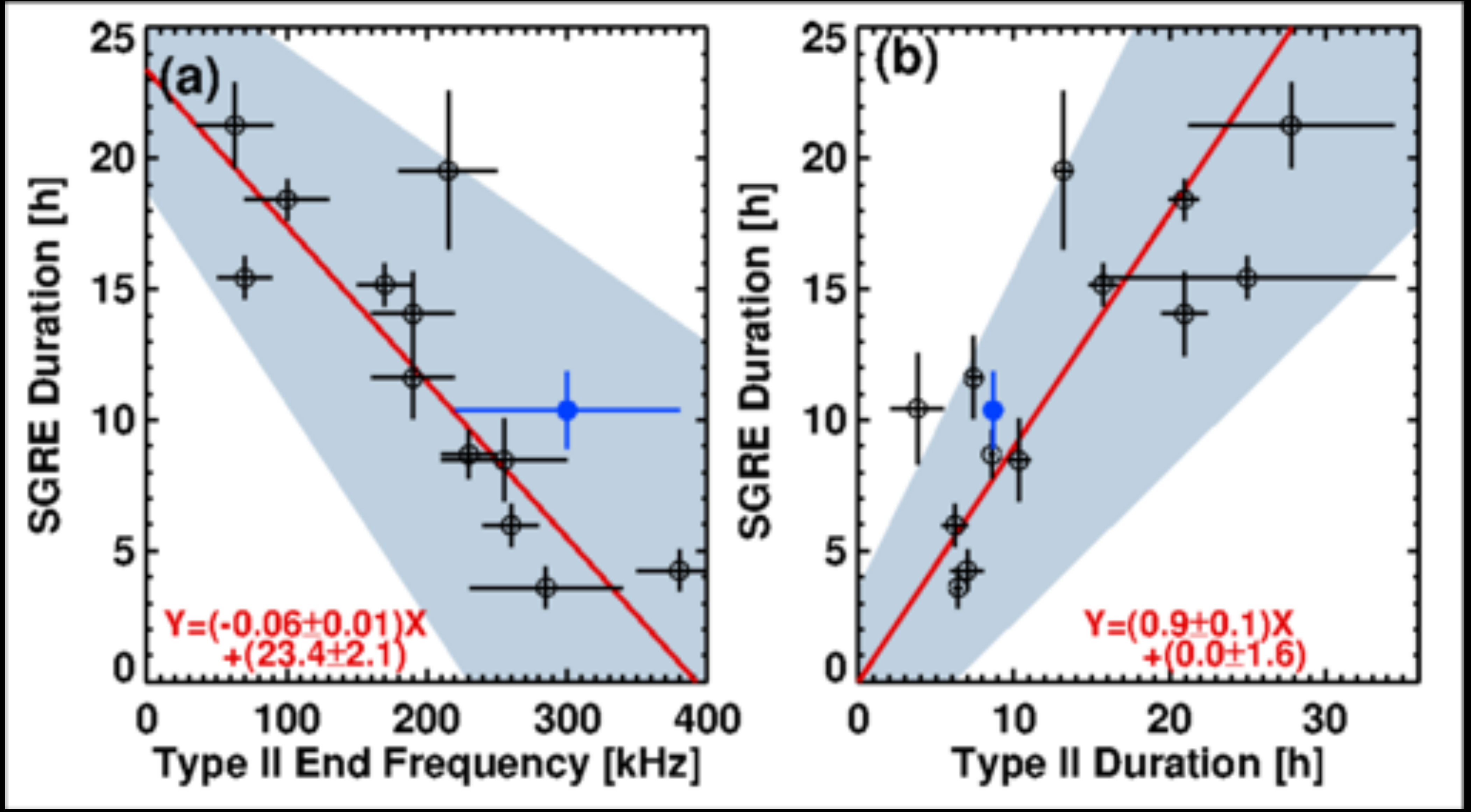
Blue: Updated centroid in Ajello et al. (2021)

Emission Centroid Migration (Ajello et al. 2021)



Most of the long-duration Gamma-ray events are associated with CMEs, which leads to a "CME-driven Shock" Scenario





- Cliver et al. (1993) first proposed that the BTL gamma-ray events are caused by particles that are accelerated at CME-driven shocks and then propagate back to the visible solar disk.

- In a recent study, Gopalswamy et al. (2018) found that the sustained/long-duration gamma-ray emission (SGRE) events and Type II bursts are highly correlated:

  - The ending frequency of type II bursts has an inverse linear relation with SGRE duration suggests that in the long-duration gamma-ray events, the IP shocks remaining strong over larger distances from the Sun.

  - The duration of type II bursts and SGRE have a linear relationship, suggesting that the same shock is responsible for accelerating both electrons and protons.

Data-driven Global MHD simulations can reconstruct the global corona and dynamic evolution of the CME-driven shock, which is a unique tool for probing the puzzles of long-duration gamma-ray events.

Alfvén Wave Solar Model (AWSOM)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right) + \nabla \left(p_p + p_e + \frac{w_+ + w_-}{2} + \frac{B^2}{8\pi} \right) = -\rho \frac{GM_\odot}{r^2} \mathbf{e}_r \tag{2}$$

$$\frac{\partial \left(\frac{p_e}{\gamma - 1} \right)}{\partial t} + \nabla \cdot \left(\frac{p_e}{\gamma - 1} \mathbf{u} \right) = -p_e \nabla \cdot \mathbf{u} + \frac{2}{\tau_{pe}} (p_p - p_e) - \nabla \cdot \mathbf{q}_e - Q_{rad} + \alpha Q_w \tag{3}$$

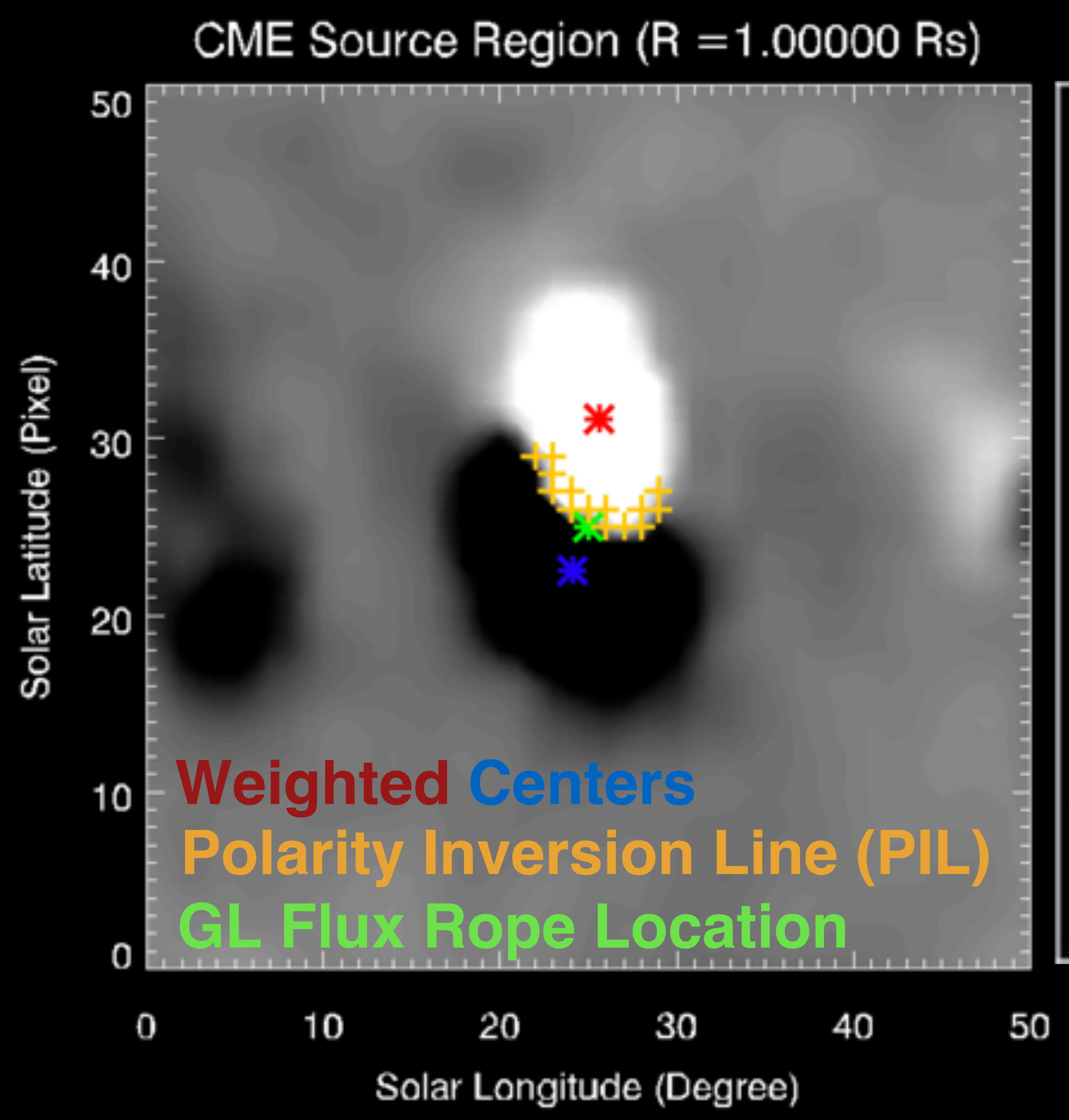
$$\frac{\partial \left(\frac{p_p}{\gamma - 1} \right)}{\partial t} + \nabla \cdot \left(\frac{p_p}{\gamma - 1} \mathbf{u} \right) = -p_p \nabla \cdot \mathbf{u} + \frac{2}{\tau_{pe}} (p_e - p_p) + (1 - \alpha) Q_w \tag{4}$$

$$\frac{\partial w_\pm}{\partial t} + \nabla \cdot [w_\pm (\mathbf{u} \pm \mathbf{u}_A)] = -\frac{w_\pm}{2} \nabla \cdot \mathbf{u} - \Gamma_\pm w_\pm \tag{5}$$

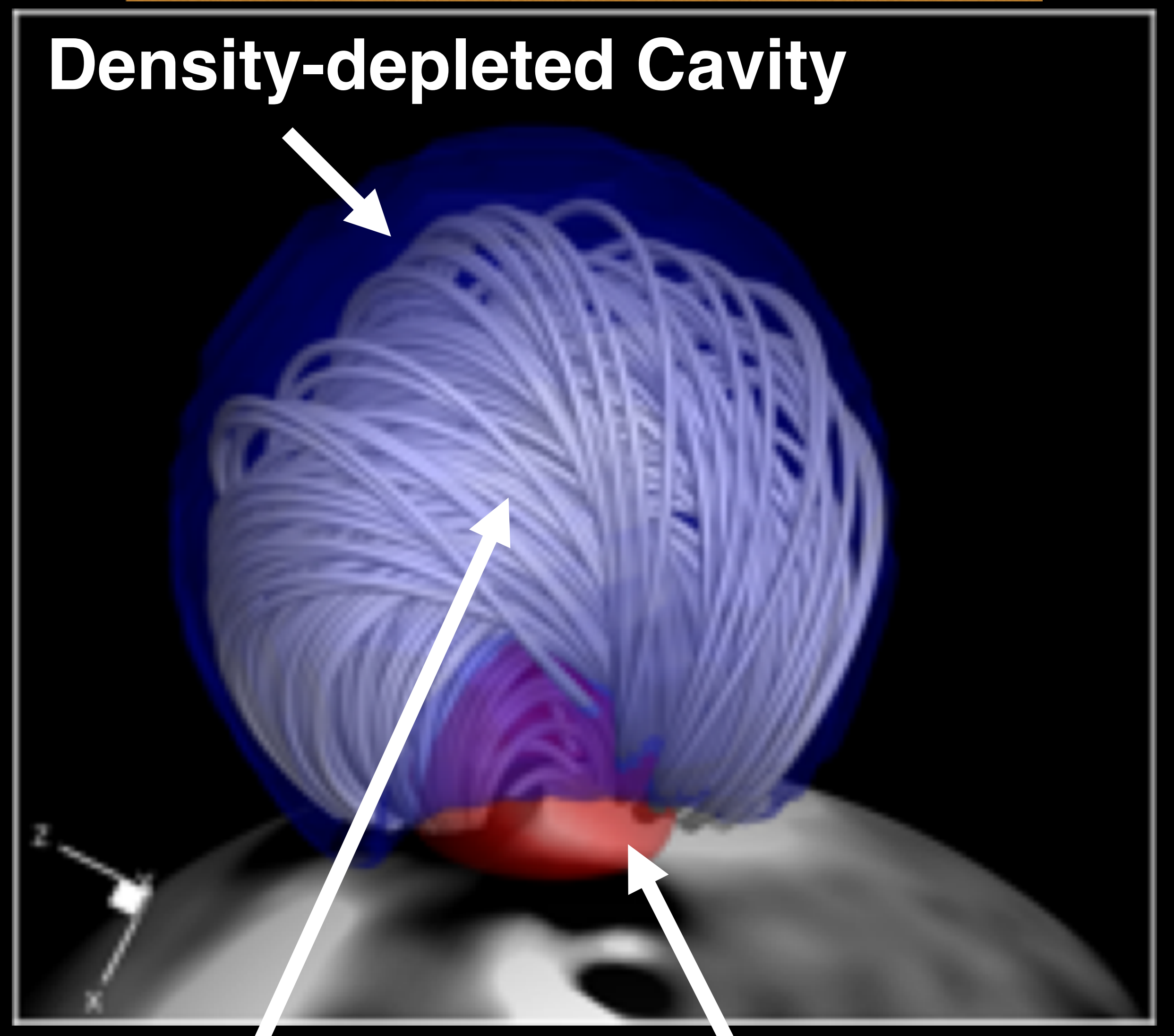
$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{u} \times \mathbf{B}) = 0 \tag{6}$$

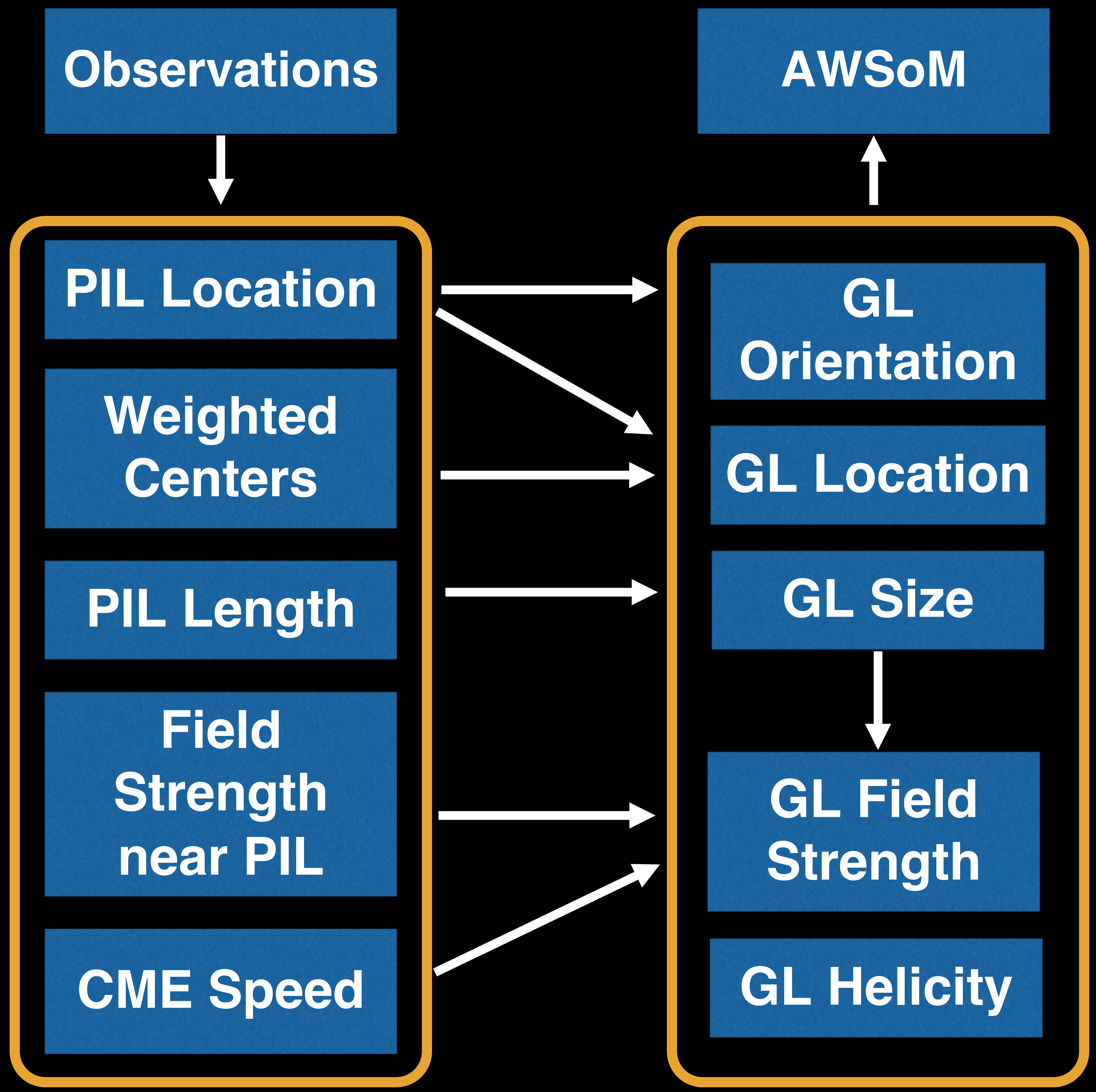
- Alfven Wave Solar Model (van der Holst et al. 2014), developed within Space Weather Modeling Framework (SWMF; Toth et al. 2012) at U of Michigan.
- Coronal heating and solar wind accelerating by Alfven waves. Physically consistent treatment of wave reflection, dissipation, and heat partitioning between the electrons and protons.
- Model starts from upper chromosphere including heat conduction (both collisional and collisionless) and radiative cooling.
- Adaptive mesh refinement (AMR) to resolve structures (e.g., current sheets, shocks).
- Data-driven boundary condition from synchronous magnetogram based on a flux transport model (*Schrijver & DeRosa 2003*).

EEGGL: Eruptive Event Generator (Gibson and Low)



GL 3D Configuration



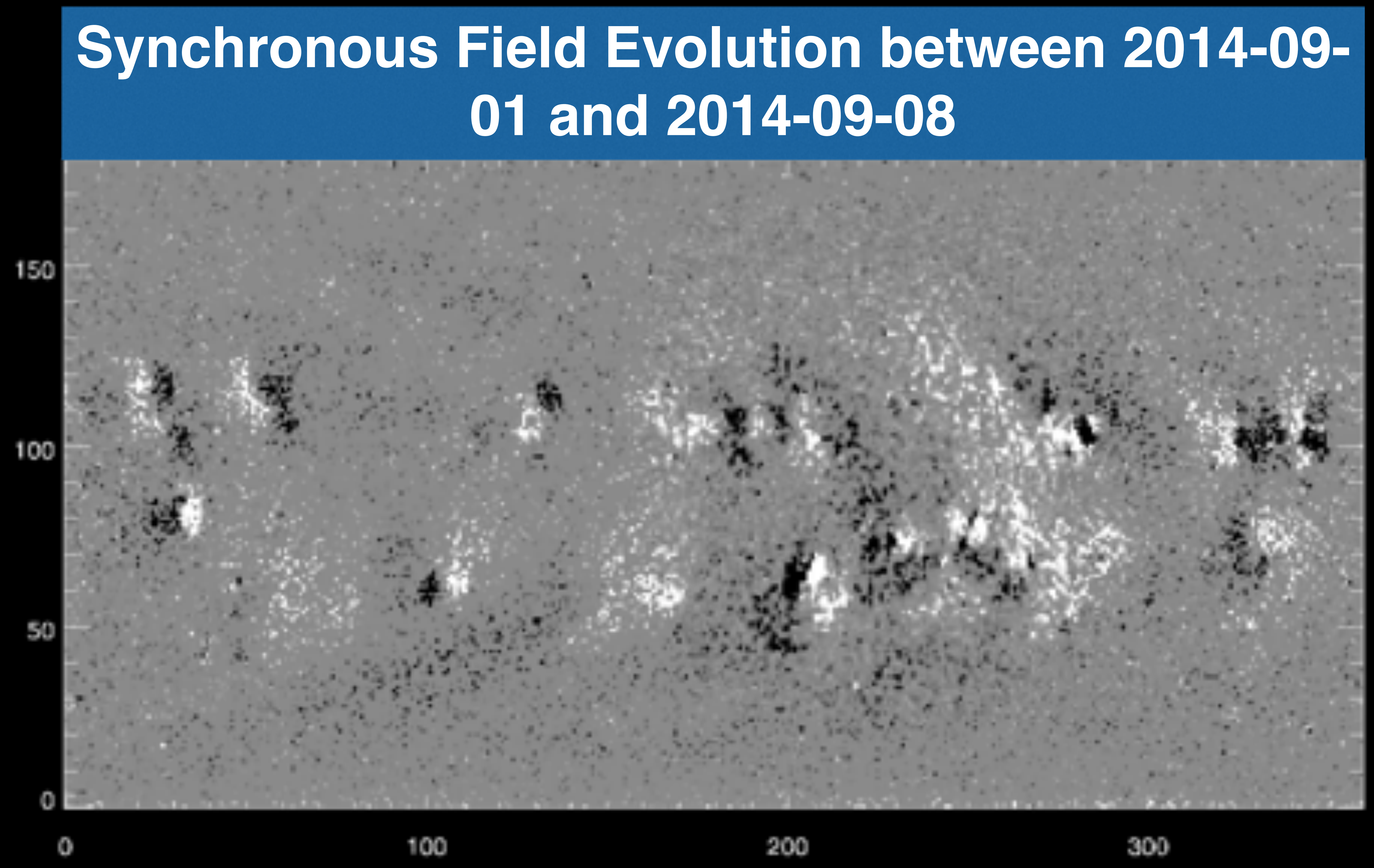


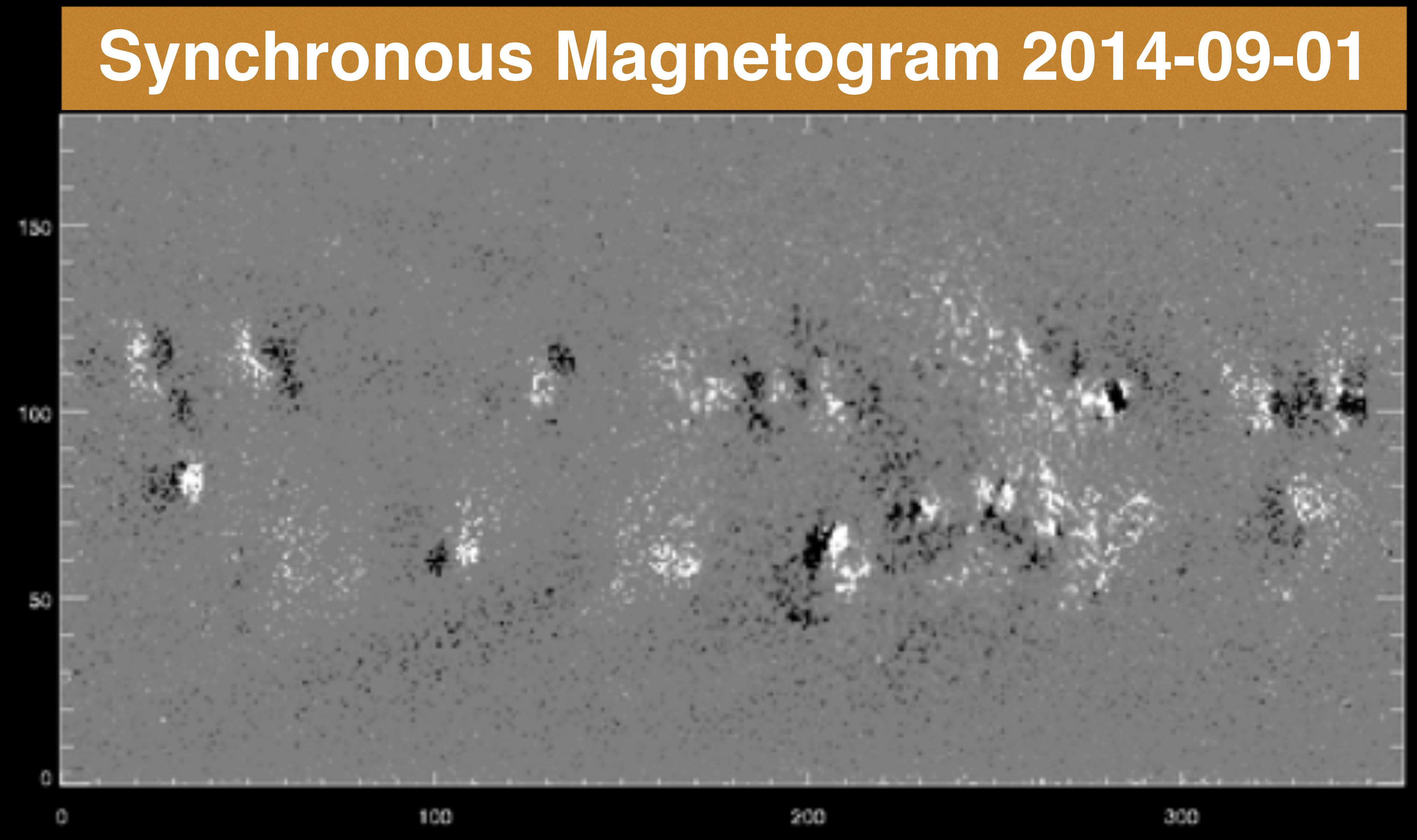
- **EEGGL uses observational data to specify input parameters for the Gibson-Low flux rope model (Gibson & Low 1998) so that it could approximately reproduce observed CME events.**

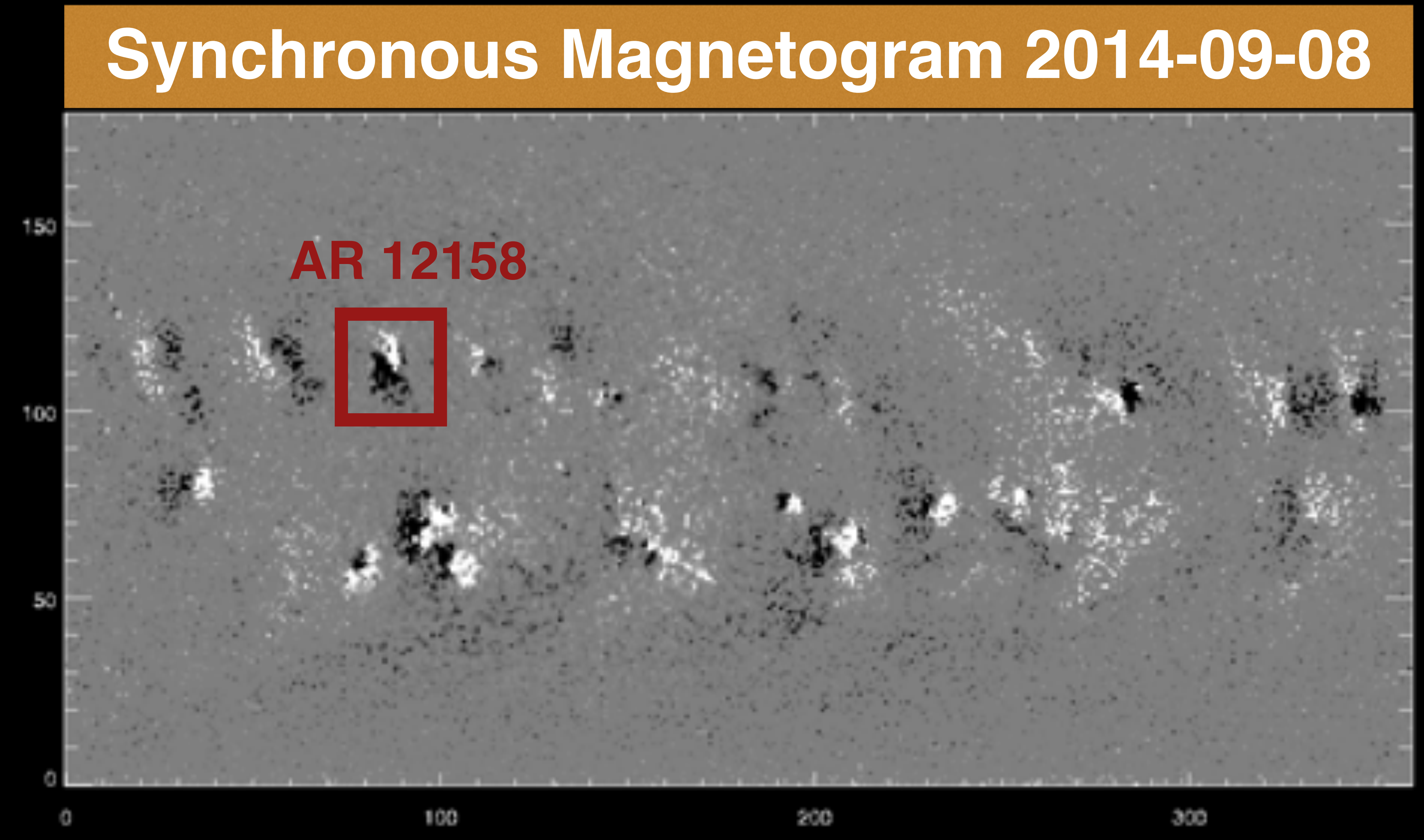
(Jin et al. 2017)

More information: https://ccmc.gsfc.nasa.gov/eeggl/

Choosing Input Magnetogram



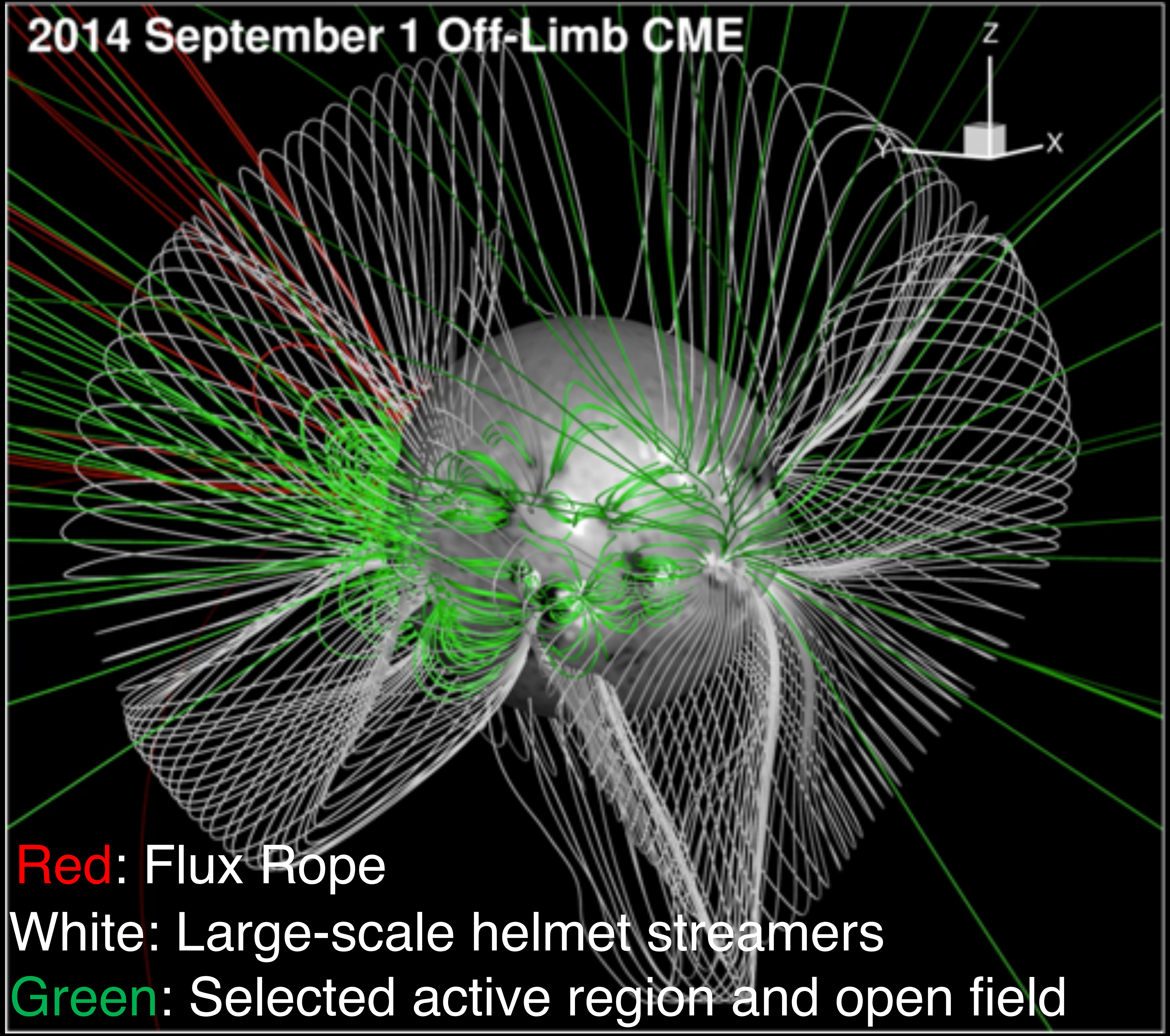




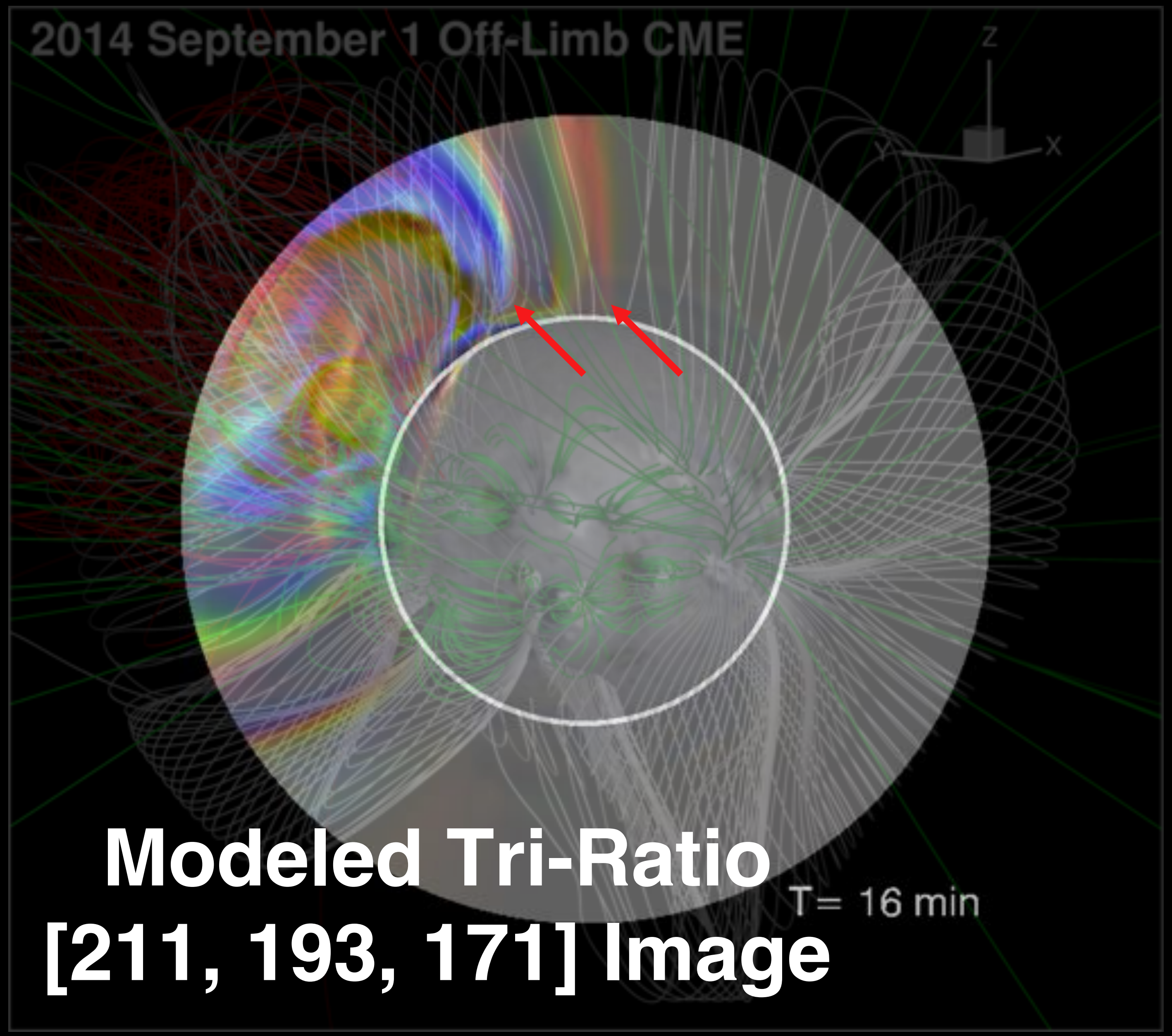
- New Observations within 60 degree from disk center are assimilated in a time-step of 6 hours.
- Since the flare region is behind the eastern limb, the magnetic field around the event time contains the most aged observation therefore a large amount of flux could be missing.
- The synchronous magnetogram on September 8 is a better representation of the magnetic field around the event time.

Corona Field Evolution in 1 Hour

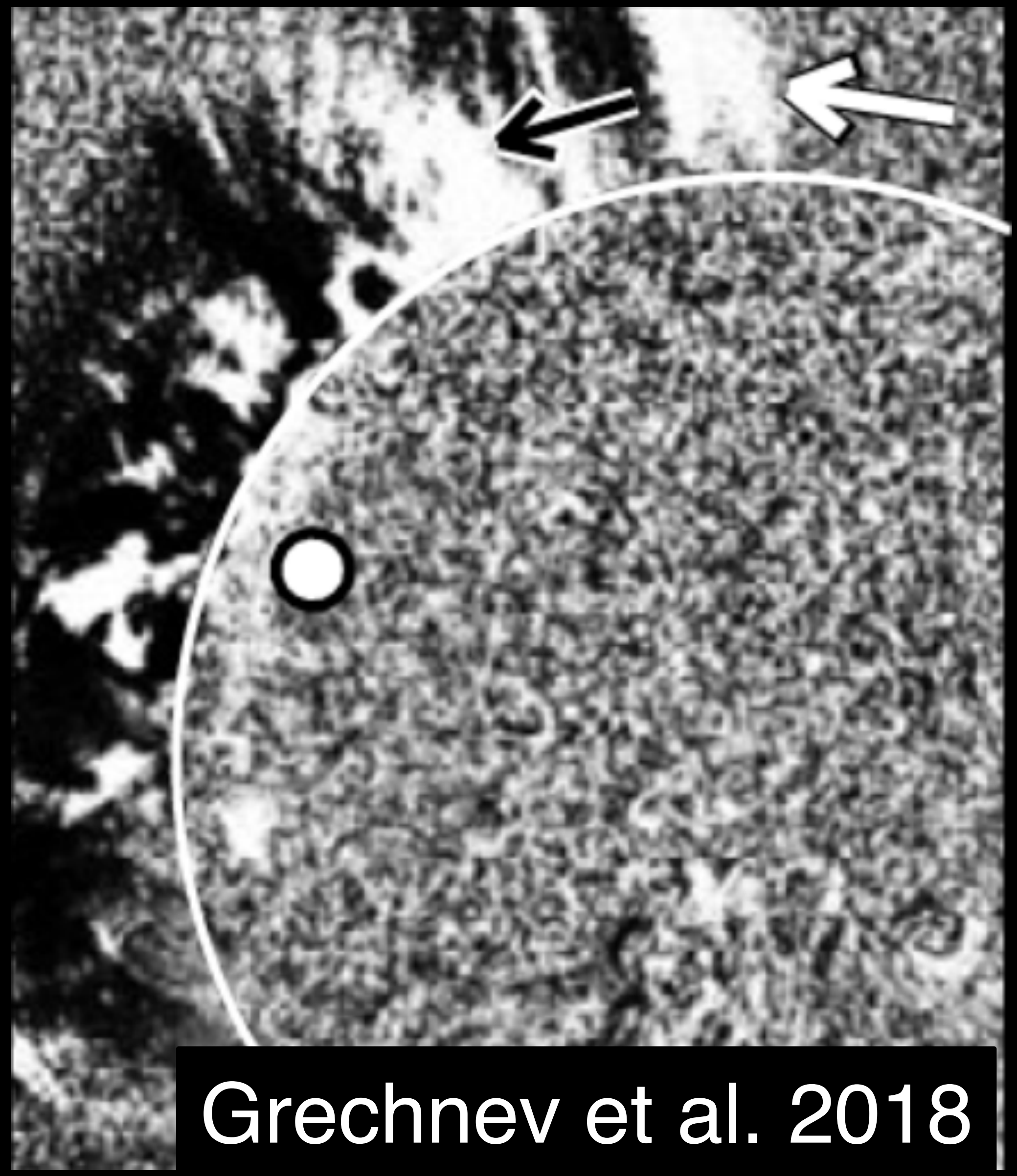
3D Field Evolution in 2014 Sep 1 Fermi BTL Event



Simulation t = 16 min

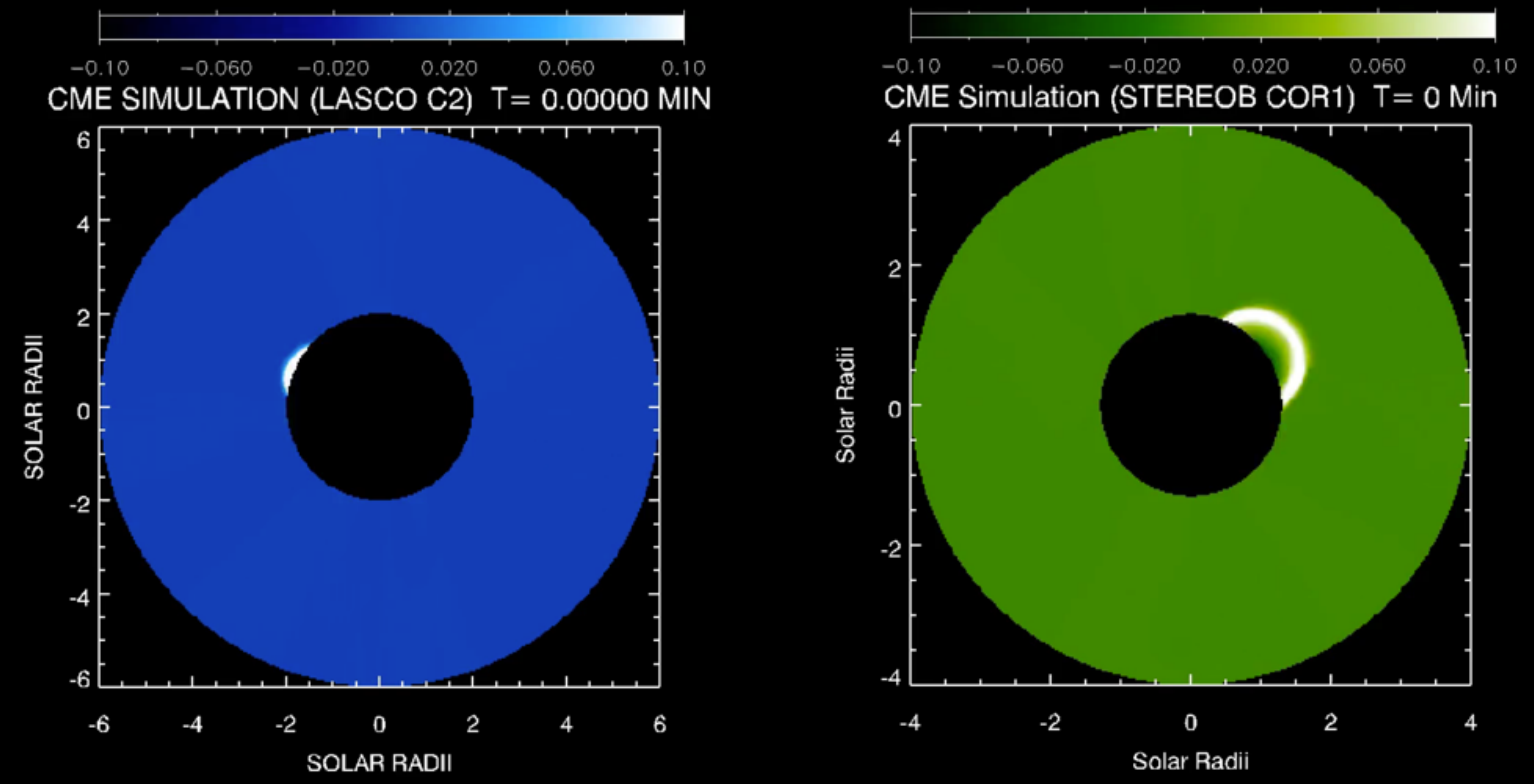


Observation

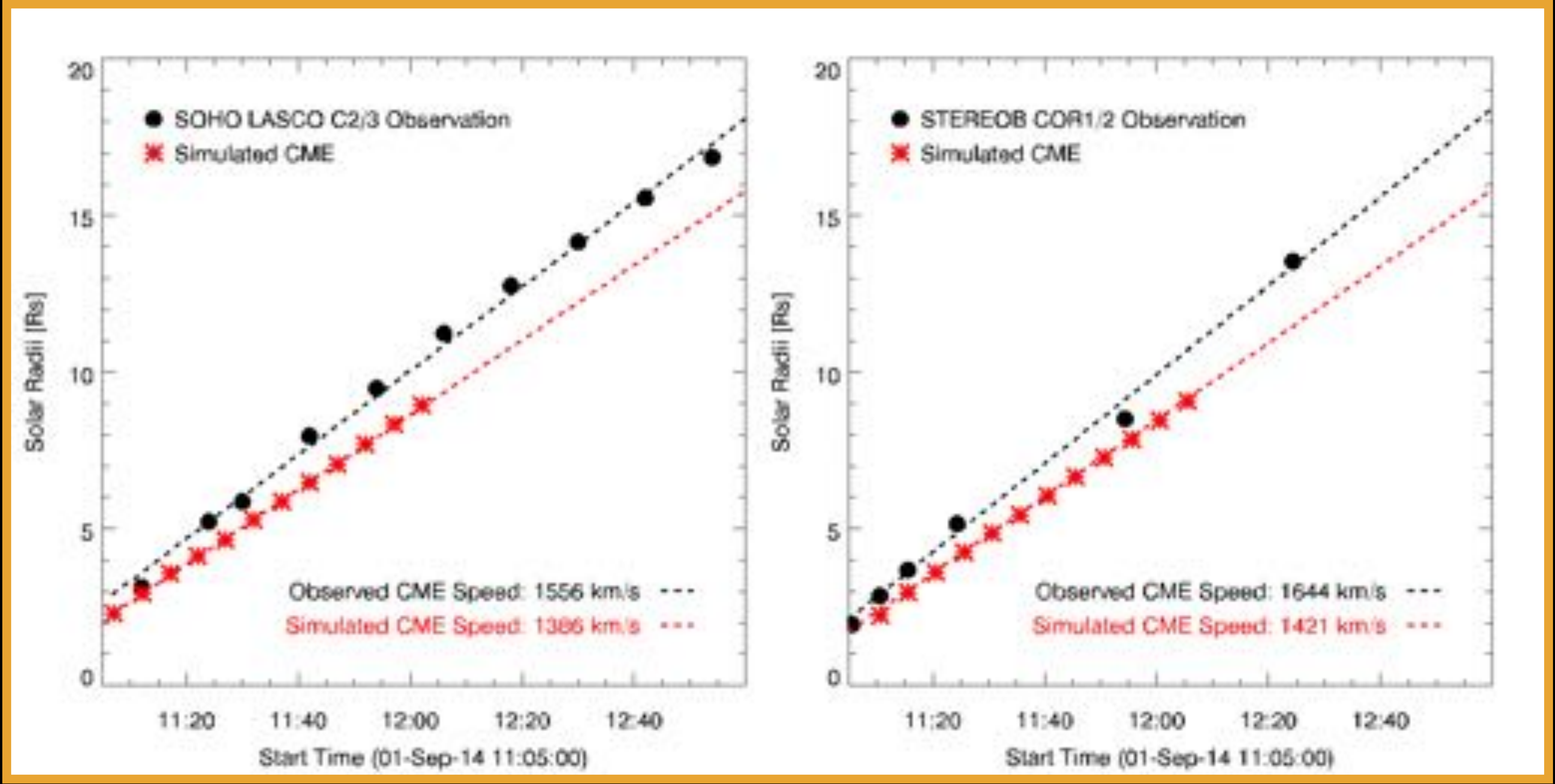


- **The simulation reproduced the two EUV wave fronts in the observation.**
- **The first wave front is the fast-mode wave/shock driven by the eruption. The second one is caused by the expending CME flux rope shell.**

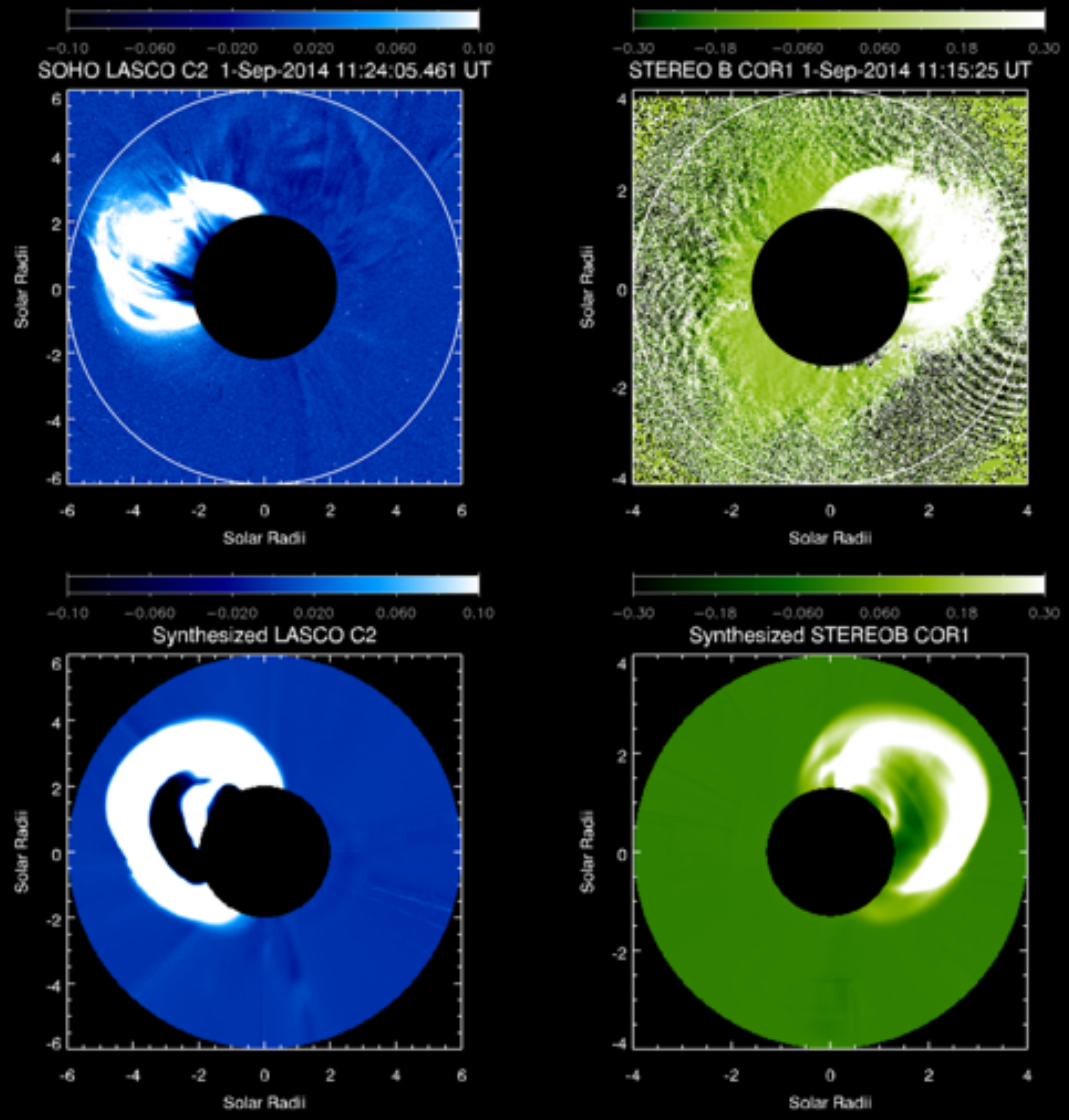
Synthesized White Light in LASCO & STEREOB



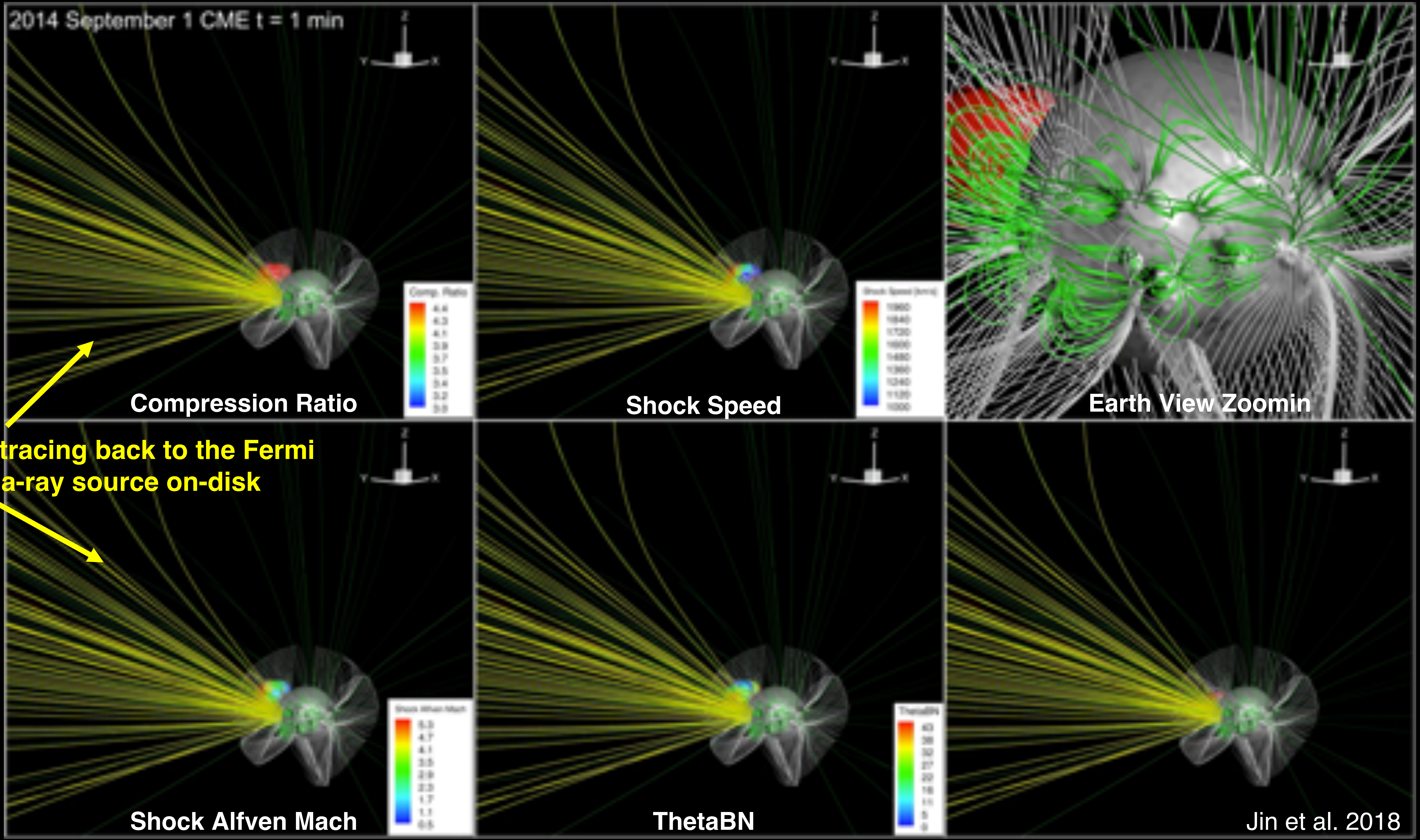
CME Height-Time Evolution



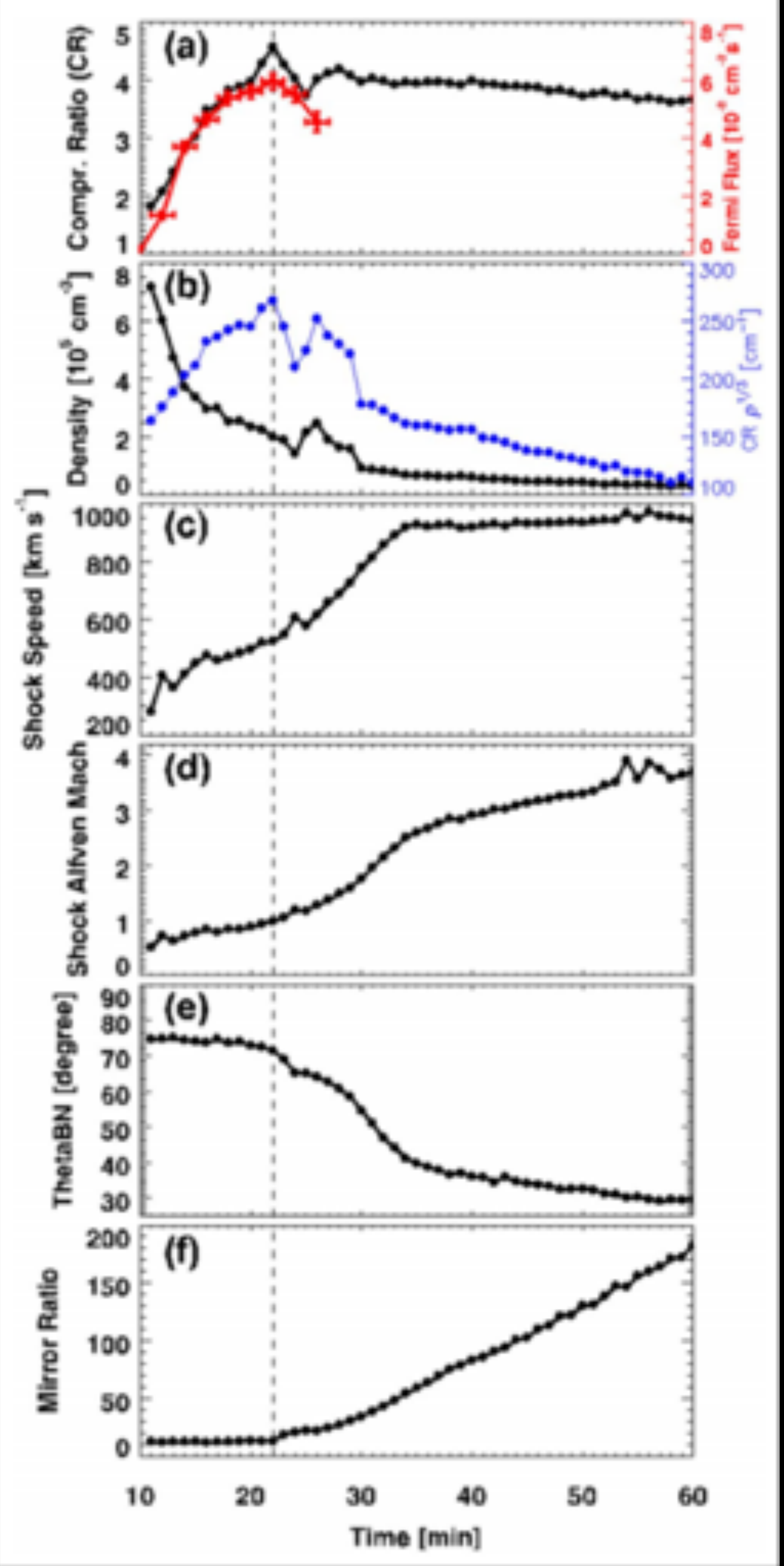
Comparison with Observations



CME-driven Shock Evolution (Earth View)



Field lines tracing back to the Fermi gamma-ray source on-disk



Shock Parameter Evolution

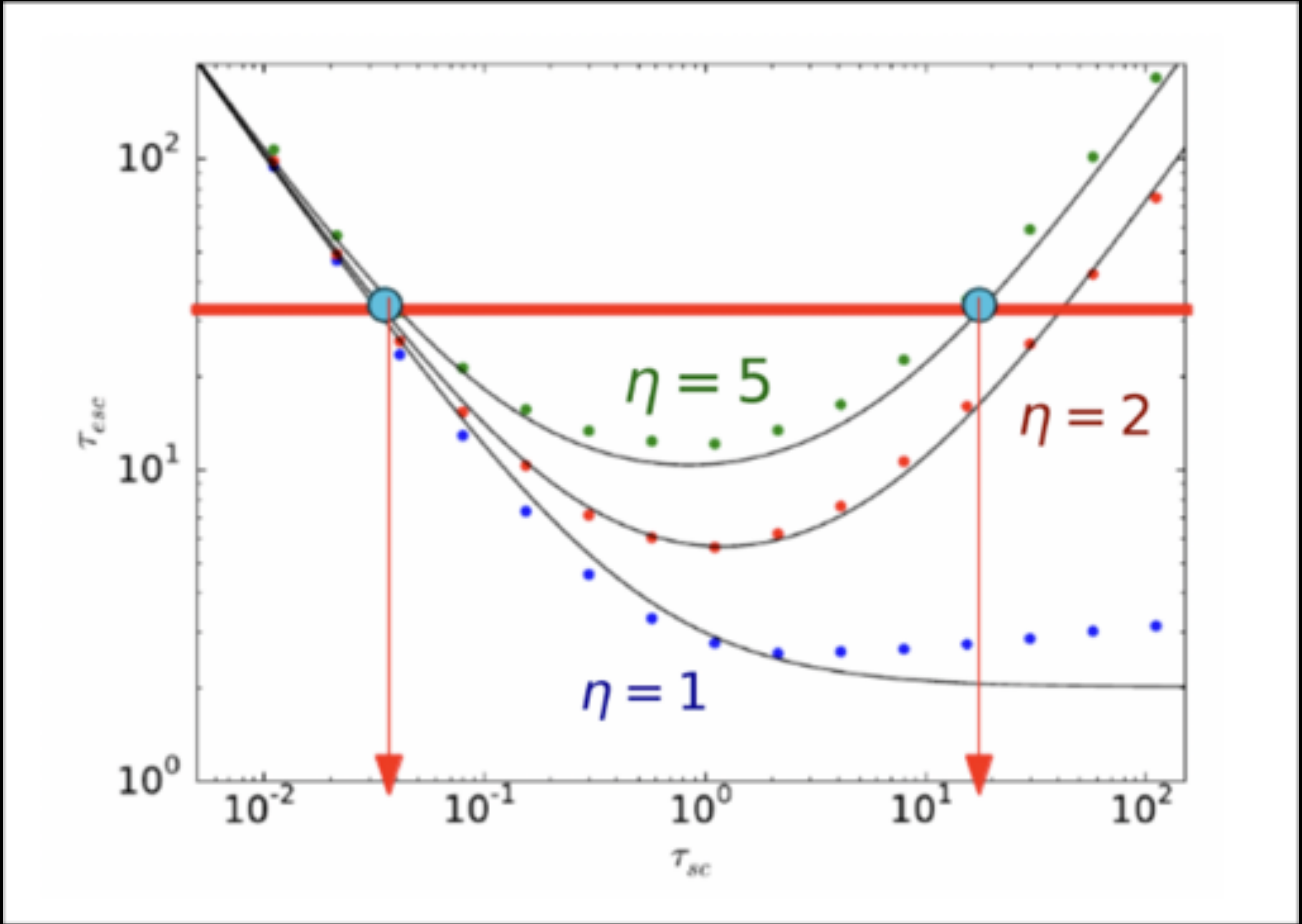
- Shock compression ratio increases rapidly from ~1.8 at 10 minutes to ~4.6 at 20 minutes and then gradually decreases to ~3.7 at 60 minutes. This evolution trend is similar to the Fermi/LAT gamma-ray intensity profile (Ackermann et al. 2017).

- The average local plasma density at the shock front could potentially explain the simultaneous decrease in the Fermi flux, even though the shock compression ratio and Mach number remain high.

- The shock changes from a quasi-perpendicular shock (before t= 30 minutes) to a quasi-parallel shock at t = 60 minutes, which is also consistent with the study by Plotnikov et al. (2017) for the same event.

- The mirror ratio increases from ~10 to ~100 during first hour in the simulation. With an approximate relationship between the escape time and mirror ratio (Malyshkin & Kulsrud 2001), the particle escaping time scale is smaller than the gamma-ray emission period.

Effect of Magnetic Mirroring



Variation of the escape time with scattering time for three different degrees of field convergence. Solid lines are based on the analytic approximation (Malyshkin & Kulsrud 2001) and symbols are from the simulations (Effenberger & Petrosian 2018).

- The shock downstream region is highly turbulent, rendering a sufficiently shorter scattering mean free path.
- For isotropic/pancake pitch-angle distribution: when mirror ratio (η) < 100, the escaping time (T_{esc}) is smaller than emission duration (ΔT):

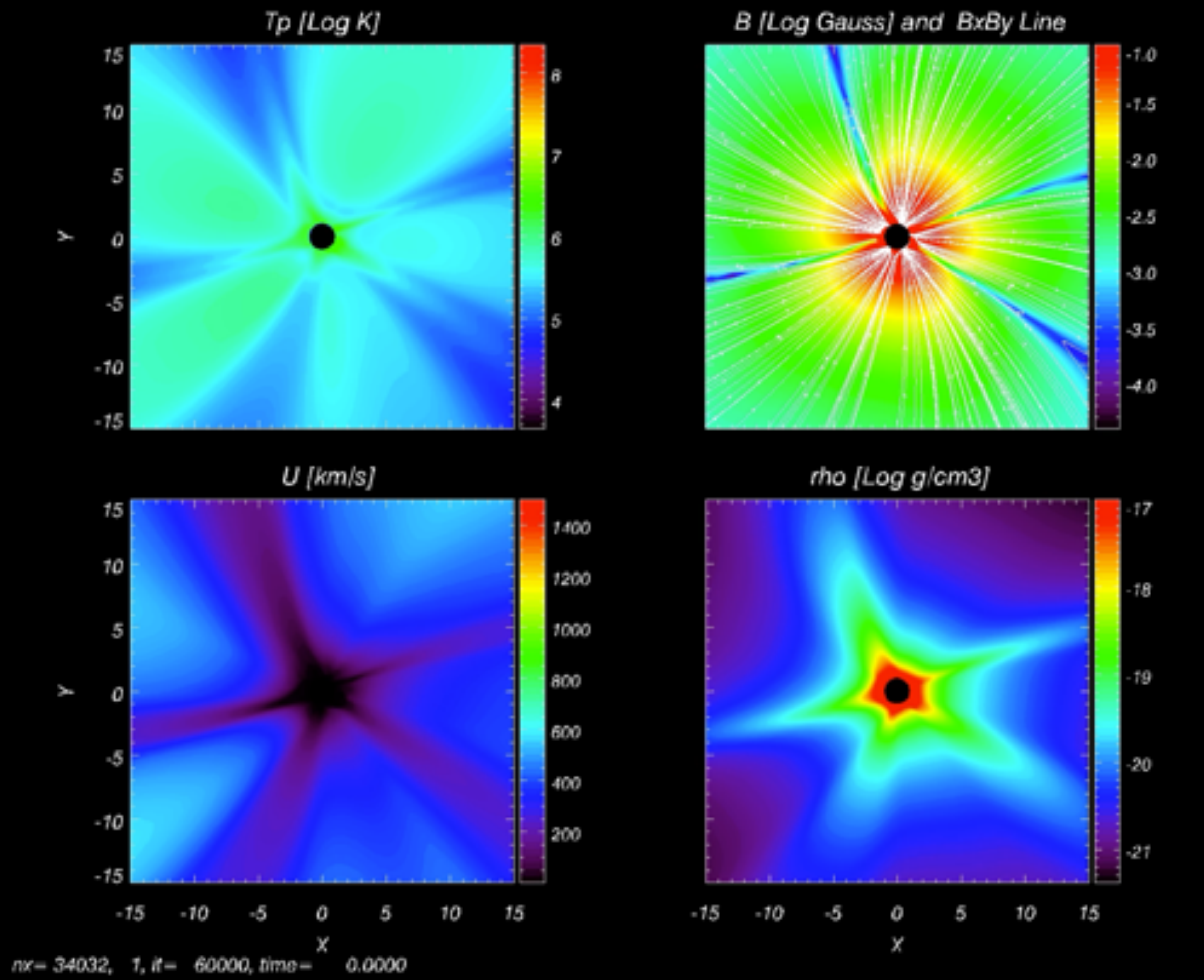
$$\frac{T_{esc}}{\Delta T} \sim \frac{2\eta v_{CME}}{c} \sim \frac{\eta}{100} \text{ for } v_{CME} \sim 1500 \text{ km/s}$$

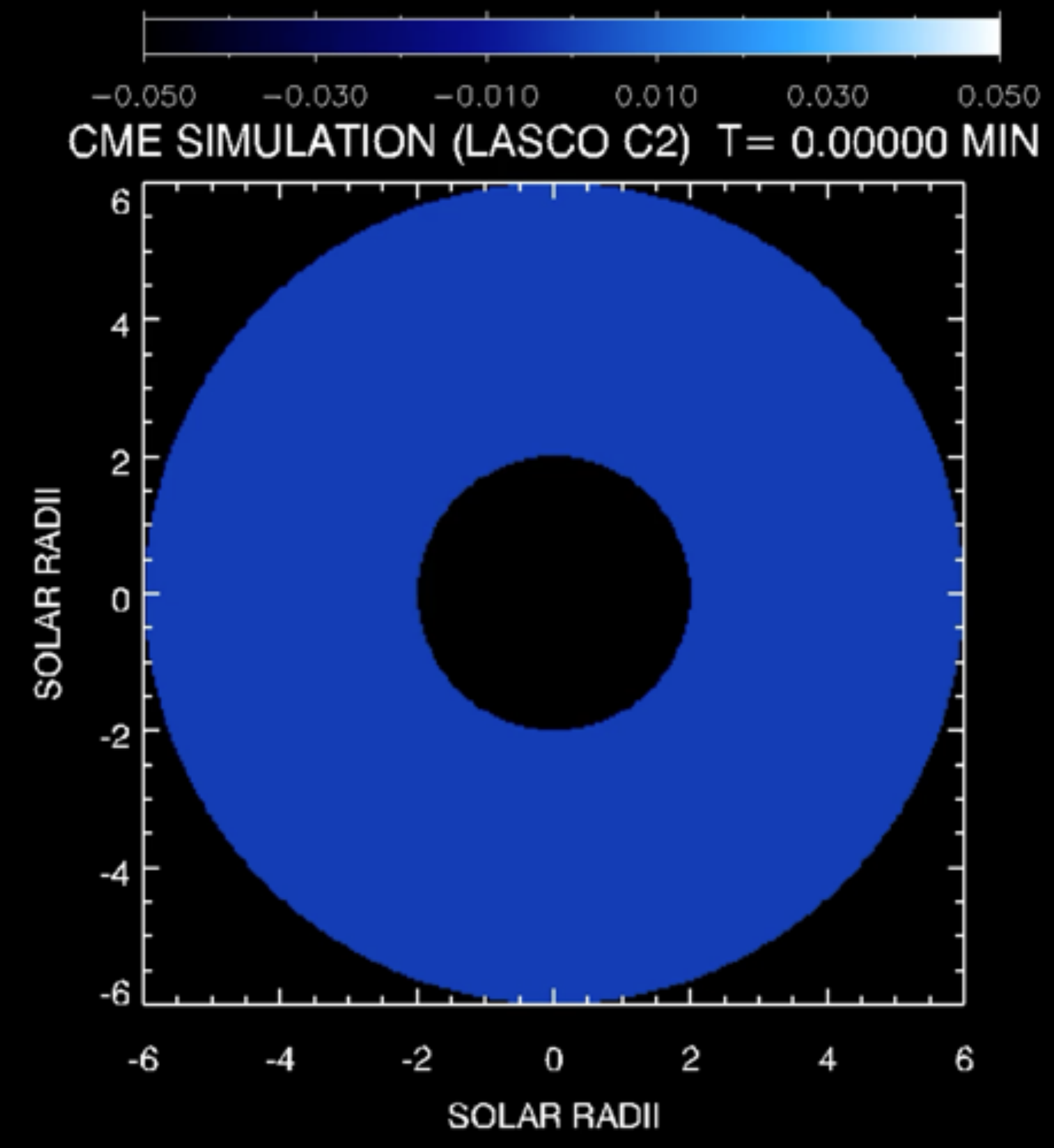
- For beamed distribution: the escape time will be shorter thus facilitate particle precipitation back to the Sun.

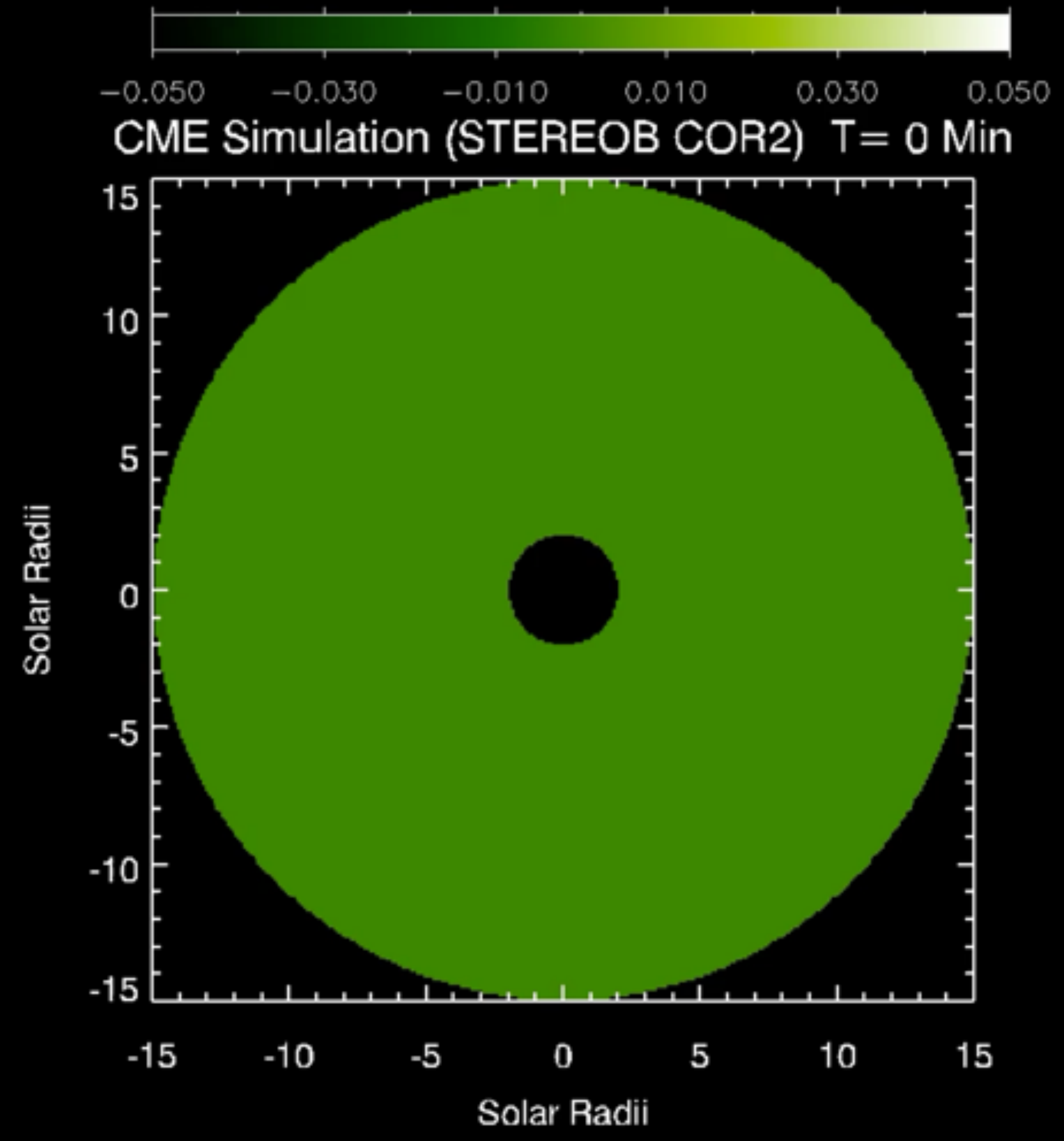
$$T_{\rm esc} = \tau_{\rm cross}\left(2\eta + \frac{\tau_{\rm cross}}{\tau_{\rm sc}} + \ln\eta \frac{\tau_{\rm sc}}{\tau_{\rm cross}}\right)$$

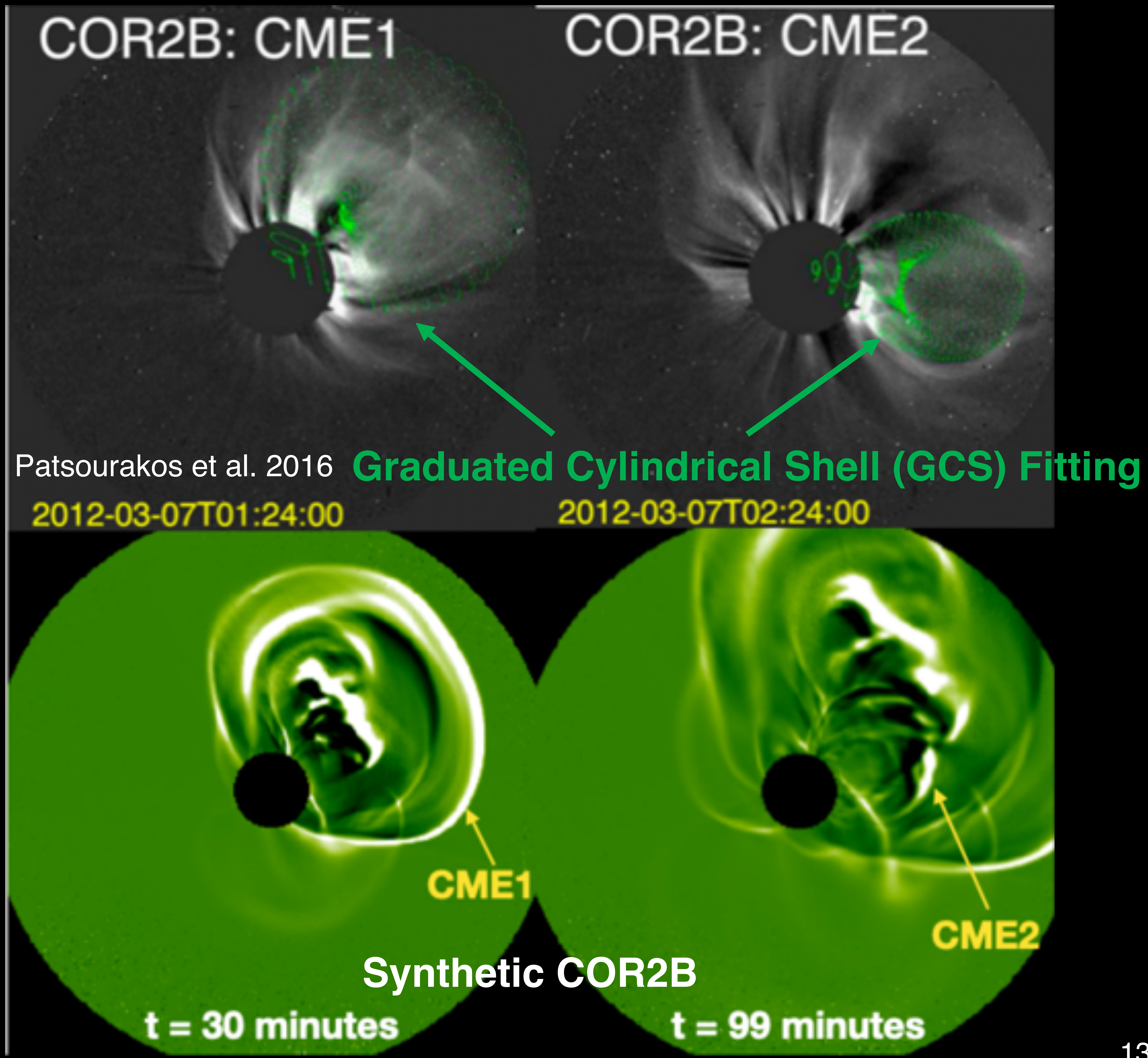
2012 March 7 Event

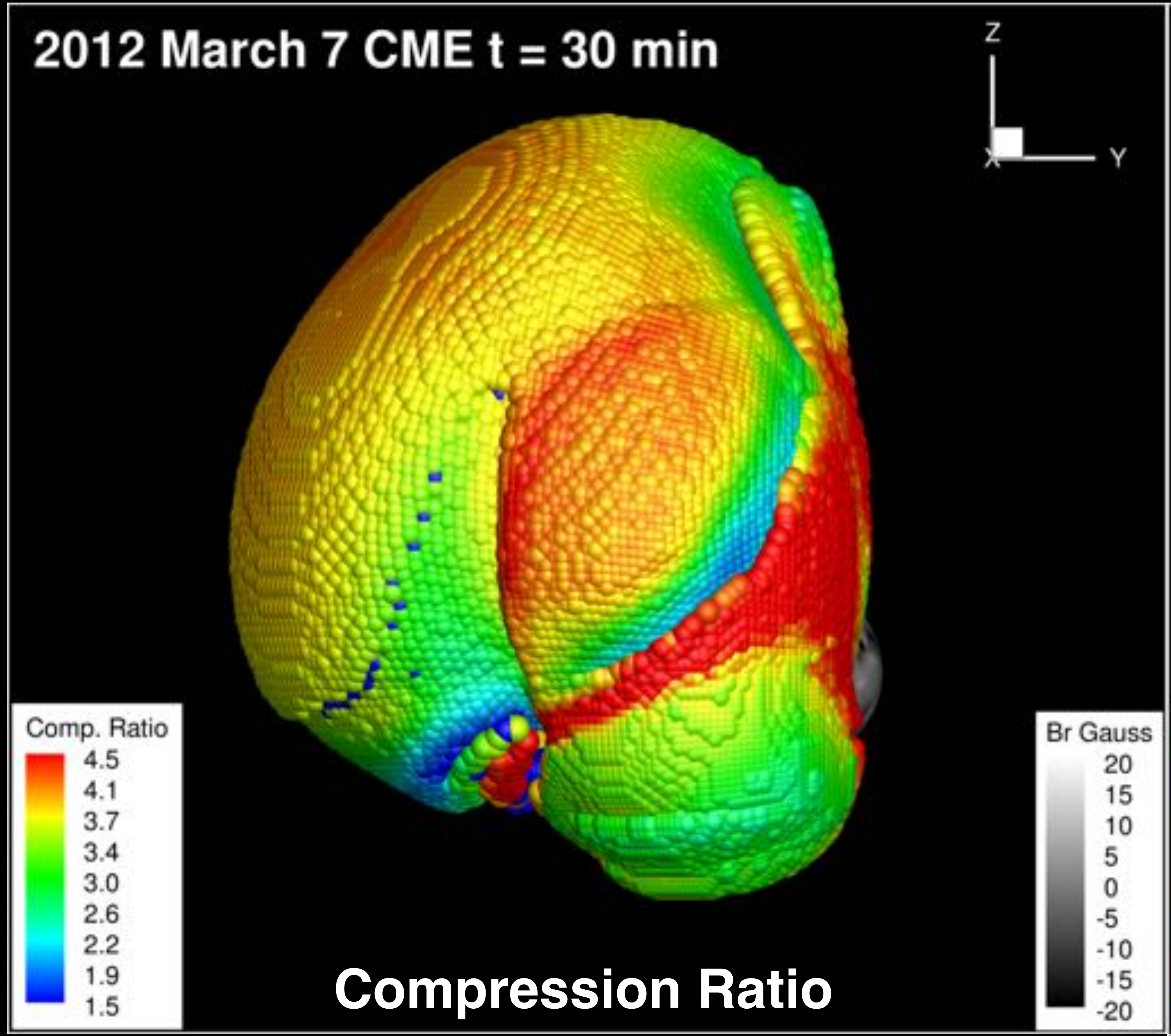
MHD Plasma Evolution (Double CME Eruption)

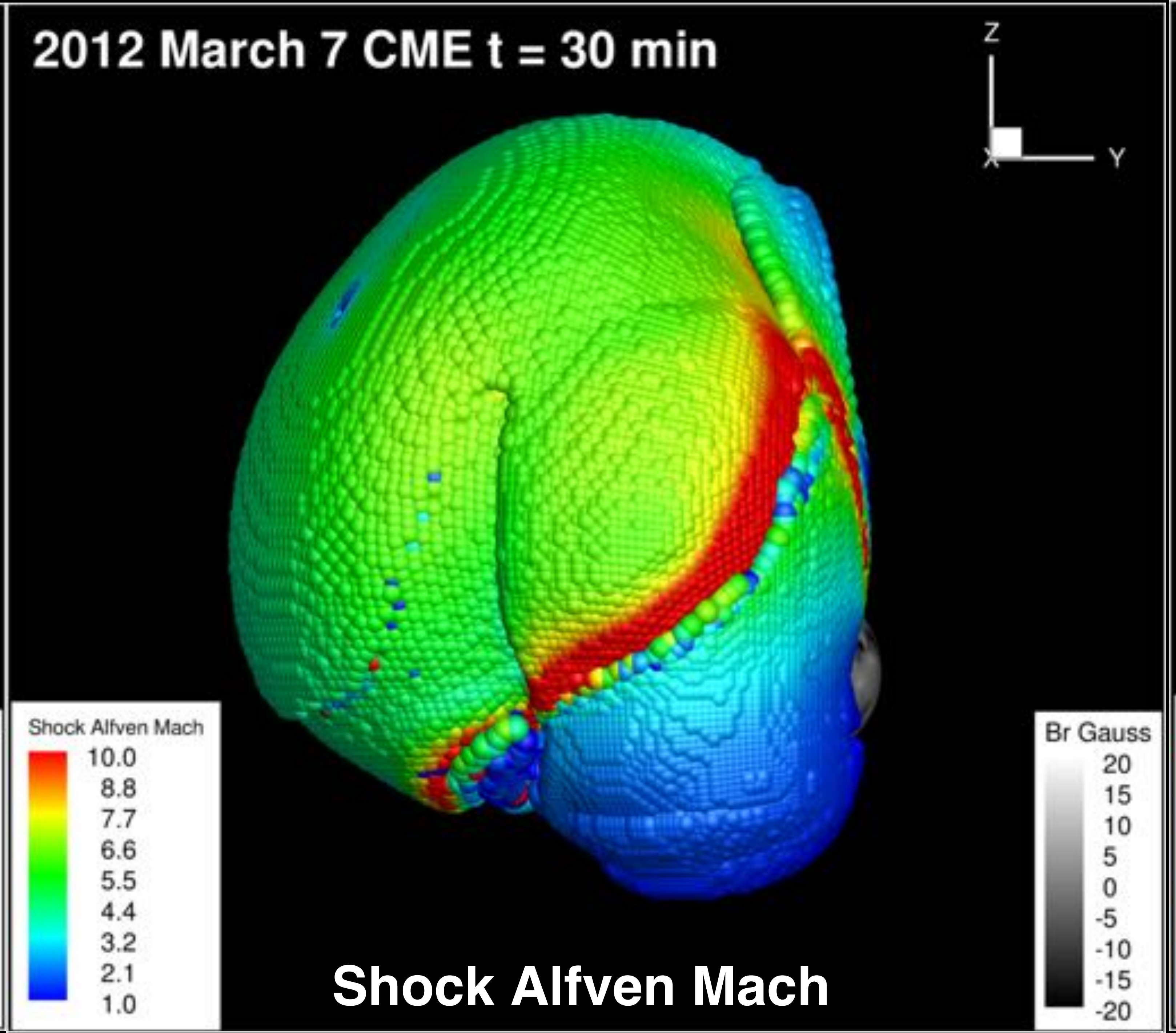


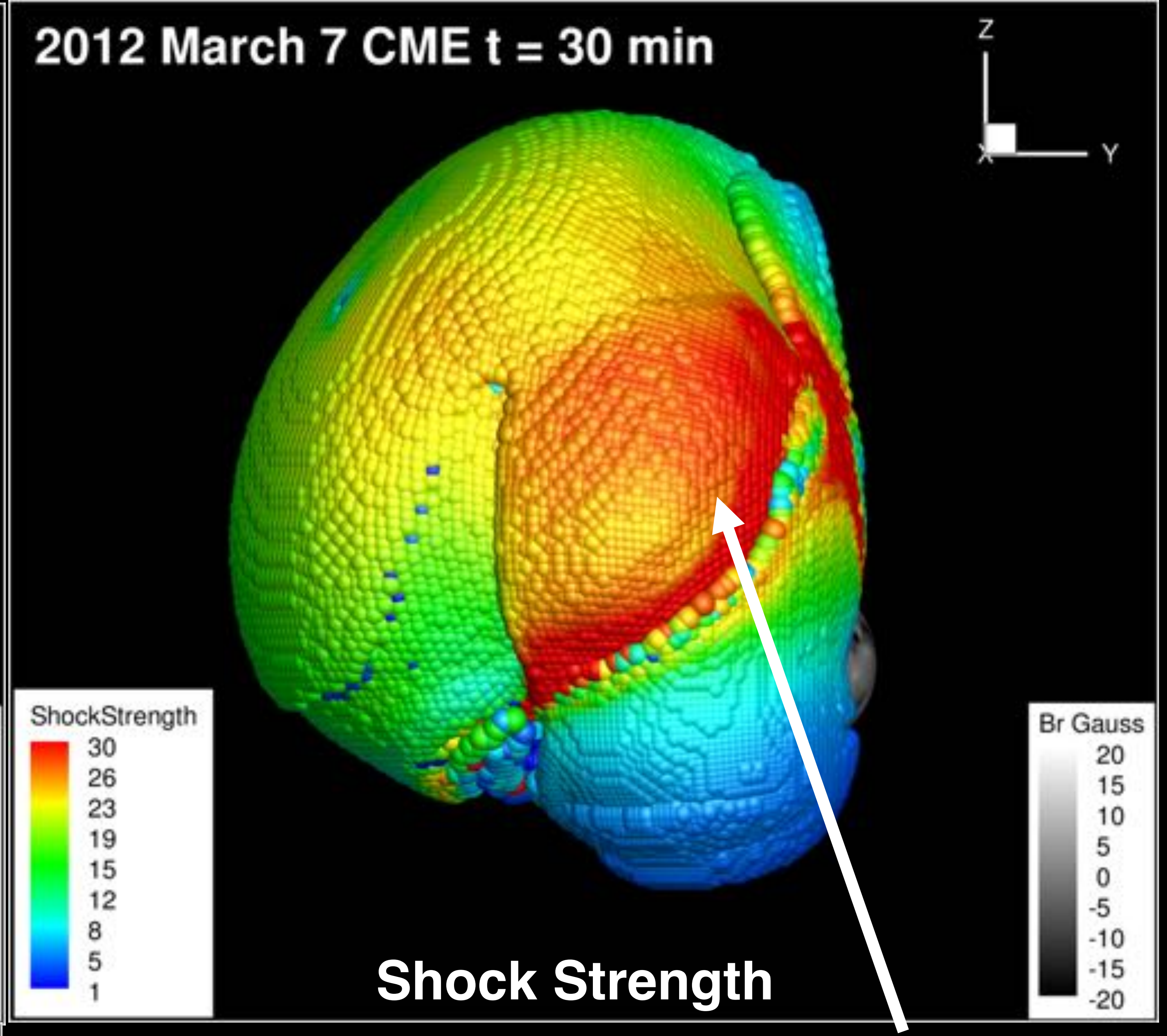

−0.050 −0.030 −0.010 0.010 0.030 0.050
CME SIMULATION (LASCO C2) T= 0.00000 MIN
SOLAR RADII
SOLAR RADII
6 4 2 0 -2 -4 -6
-6 -4 -2 0 2 4 6


−0.050 −0.030 −0.010 0.010 0.030 0.050
CME Simulation (STEREOB COR2) T= 0 Min
Solar Radii
Solar Radii
15 10 5 0 -5 -10 -15
-15 -10 -5 0 5 10 15

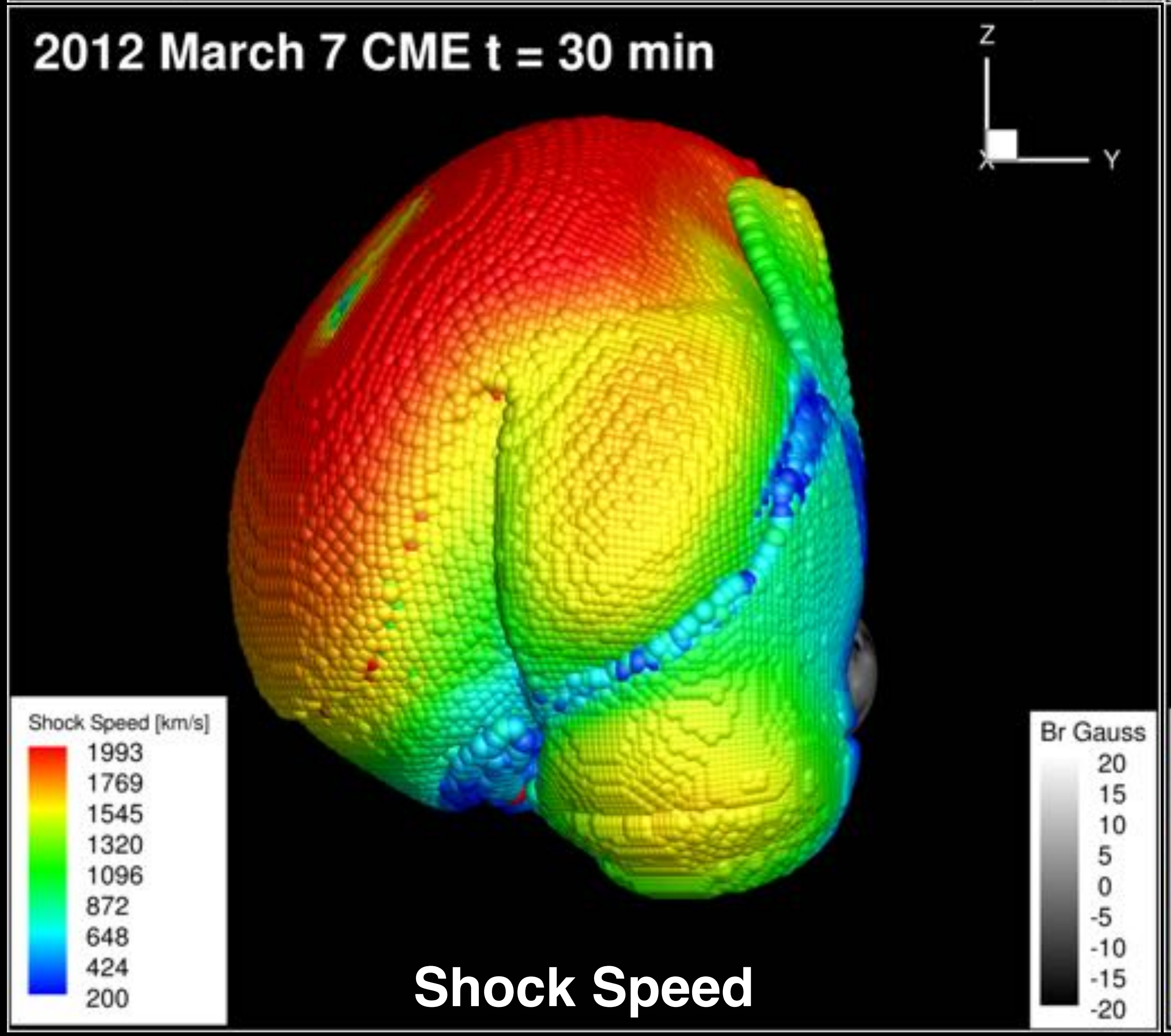

COR2B: CME1
COR2B: CME2
Patsourakos et al. 2016
Graduated Cylindrical Shell (GCS) Fitting
2012-03-07T01:24:00
2012-03-07T02:24:00
CME1
CME2
Synthetic COR2B
t = 30 minutes
t = 99 minutes

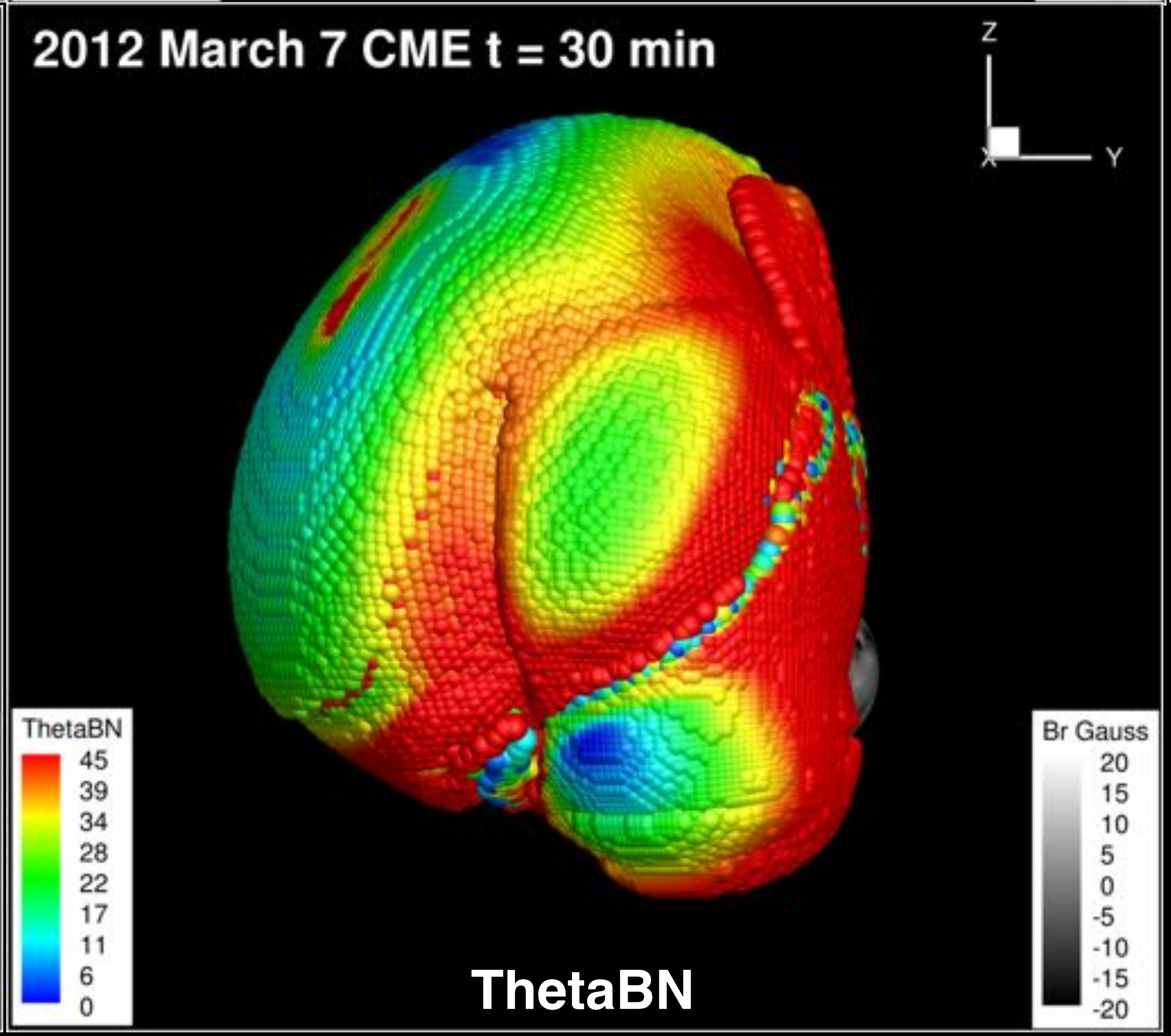






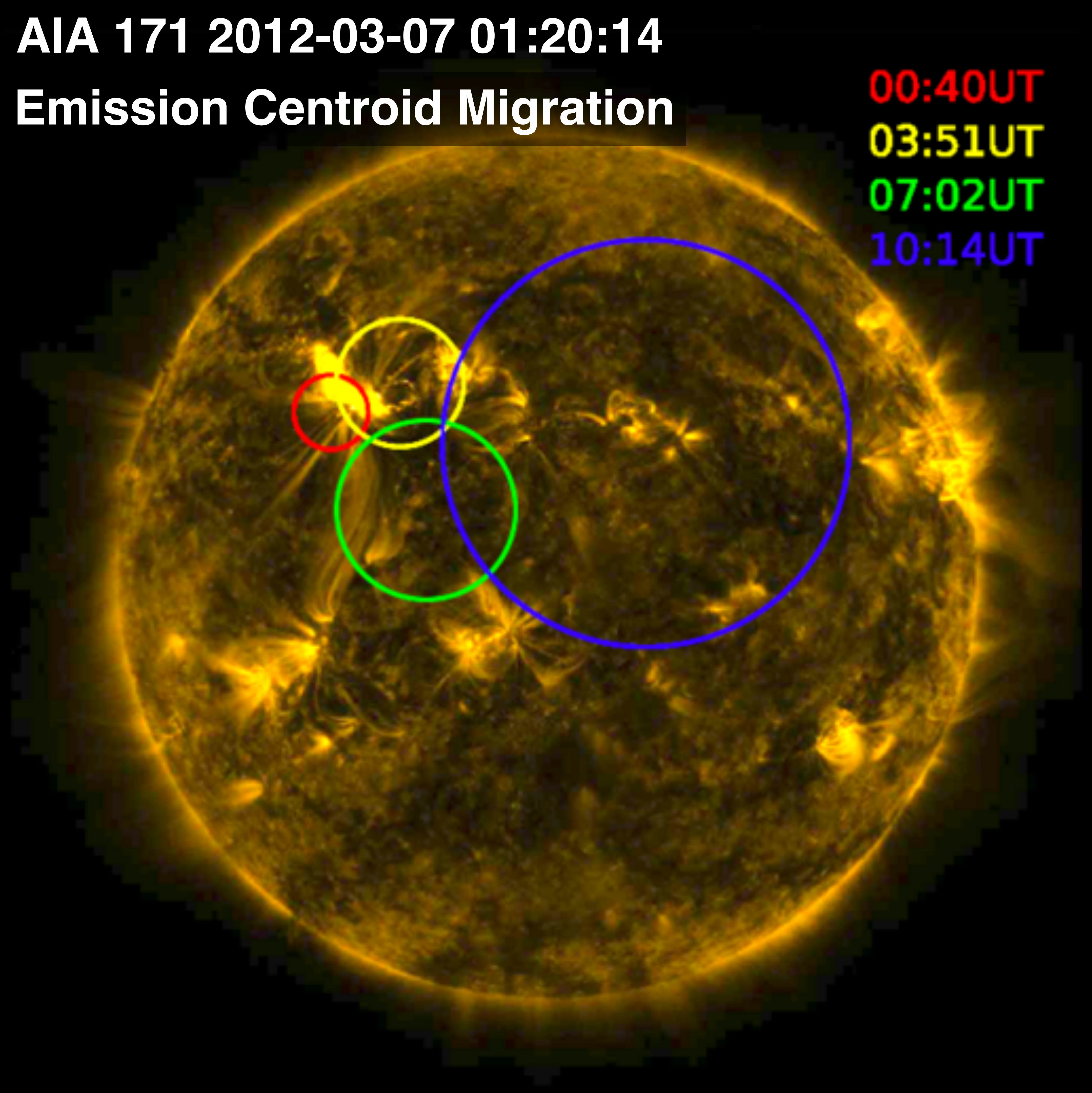
Strong Shock Location

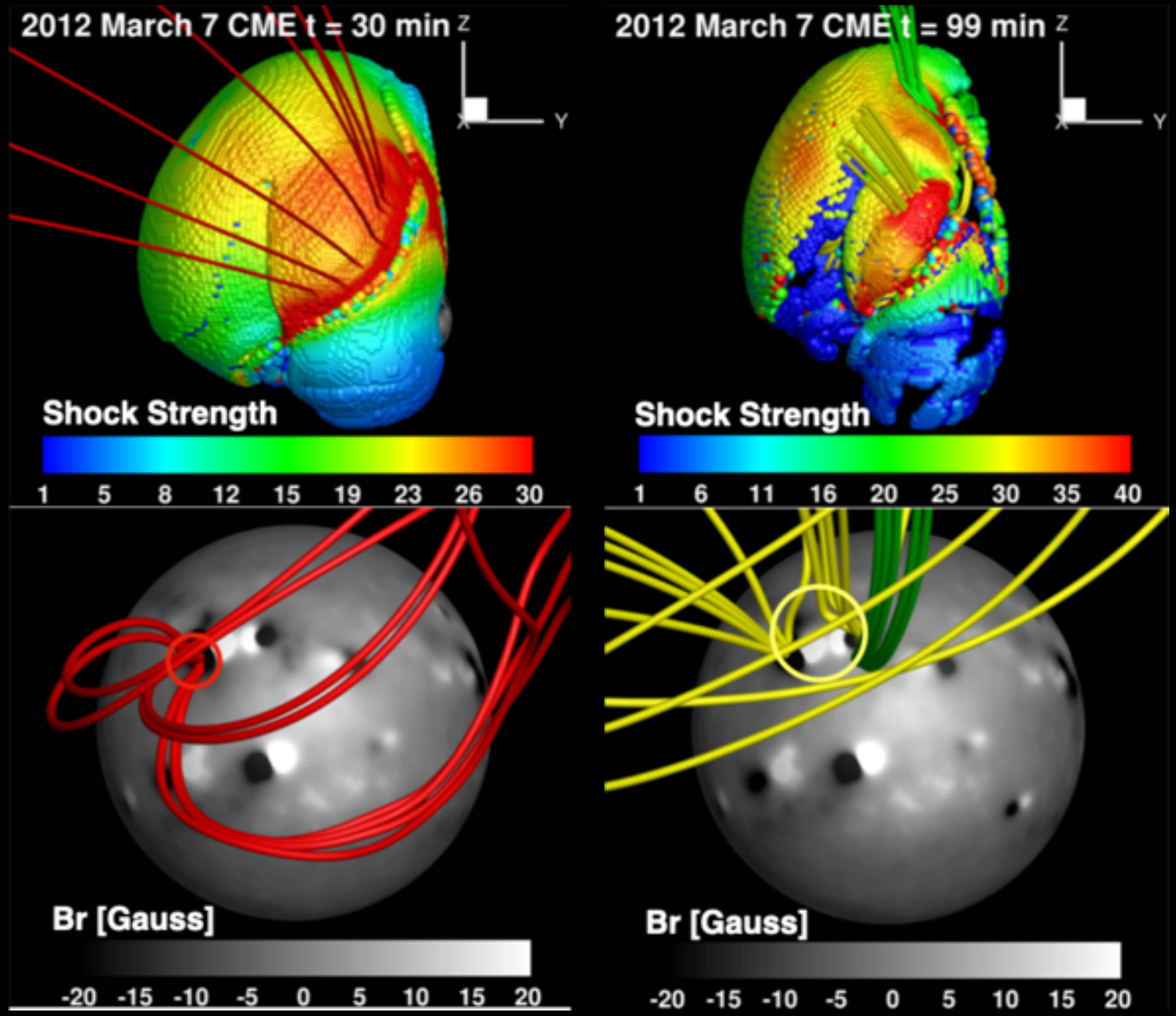




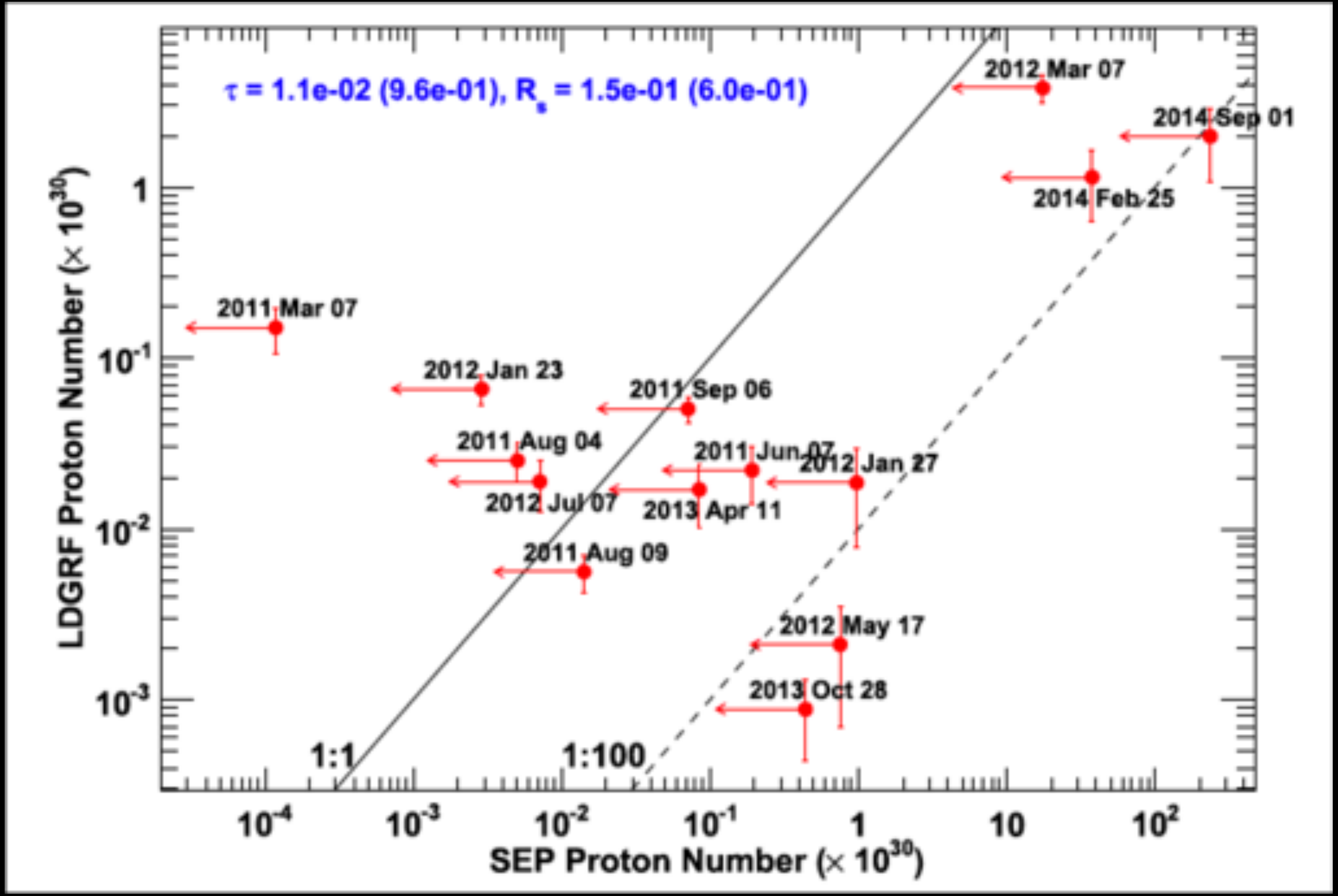
To get an estimation of strongest shock location among the shock surface, we define a new parameter: CR * Alfven Mach number as shock strength measure.

The temporal evolution of footpoints connecting to the strongest shock location agrees with the Fermi centroid migration in the first 100 minutes



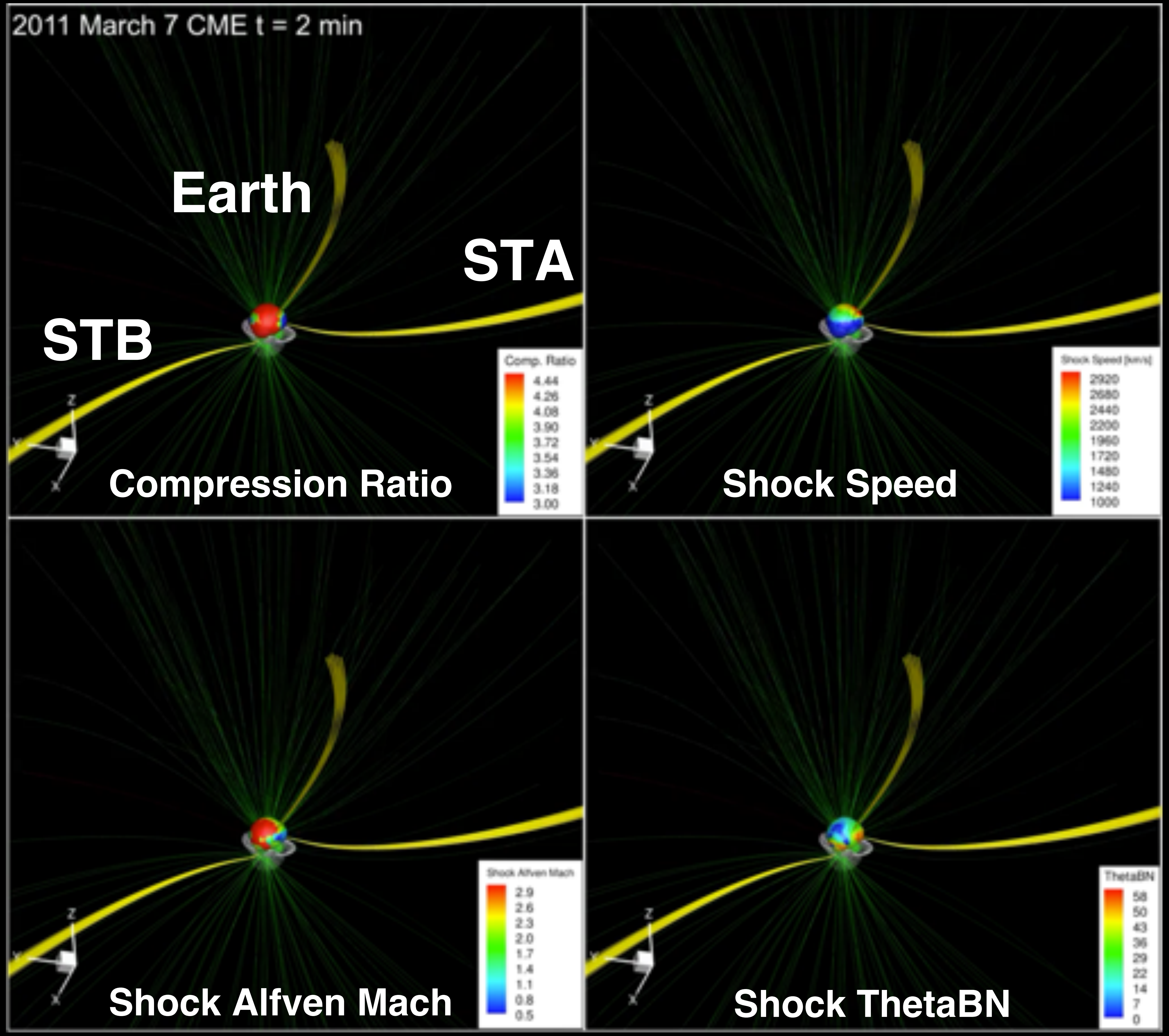


Gamma-Ray Producing Particles vs. Solar Energetic Particles



- De Nolfo et al. (2019) compared the particles interacting with the Sun from Fermi /LAT and SEP observed at 1 AU from PAMELA in 14 LDGRF events.
- The result suggests the two populations are poorly correlated.

3D shock Evolution in 2011 March 7 Event

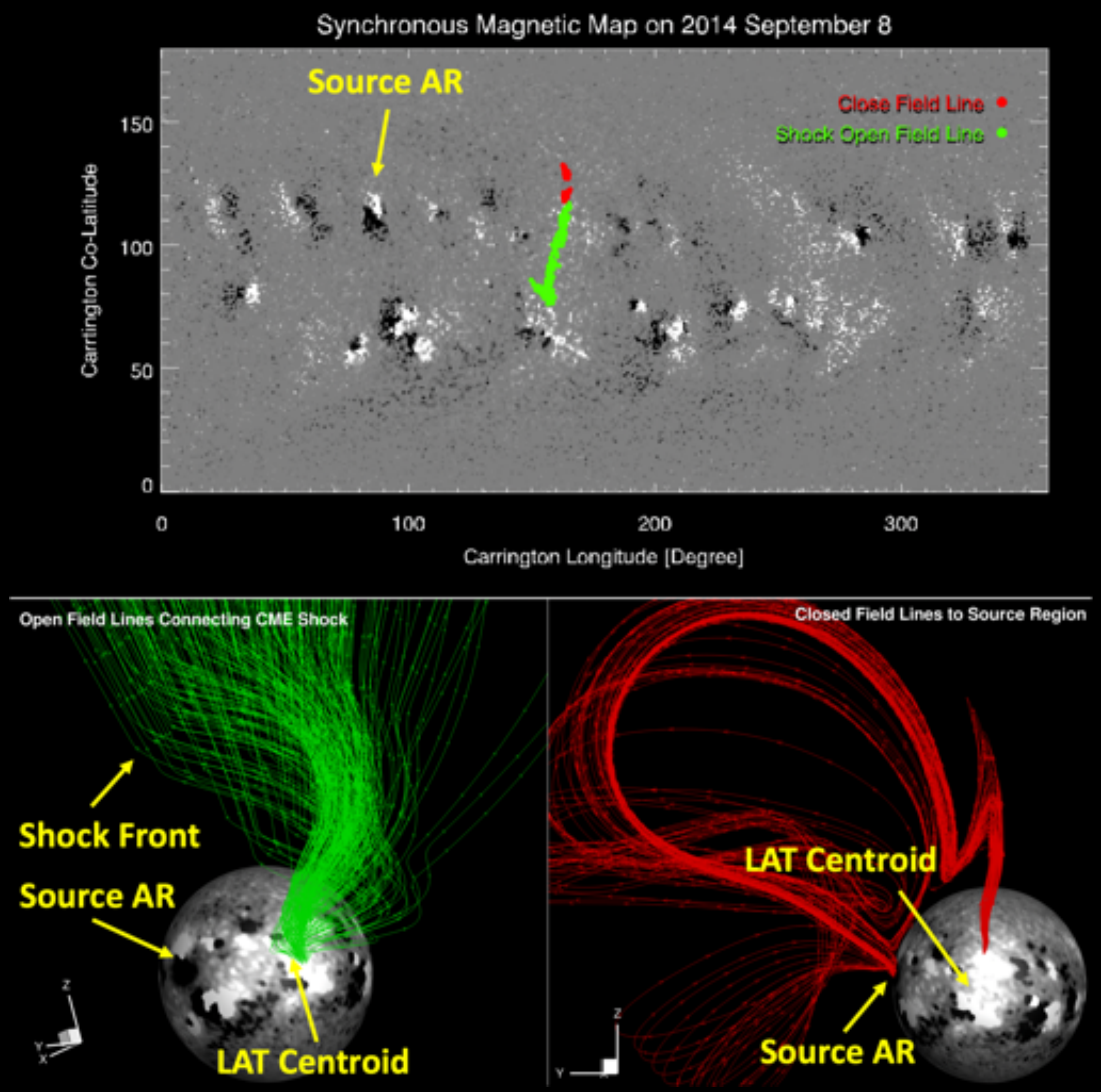


The shock connecting to Earth observer is not the strongest.

Alternative Scenarios

- Particles are accelerated via second-order Fermi mechanism and trapped locally within extended coronal loops (Ryan & Lee 1991, Hudson 2018).
- We found closed field lines connected to the source region due to the interaction between the flux rope magnetic field and global solar corona in the 2014 September 1 event.
- Most long-duration Fermi flares are associated with multiple CME events. What is the role of CME-CME interaction in generating the energetic particles (e.g., Li et al. 2012)?
- More information waiting to be explored in the simulations. And more advanced modeling is needed to better distinguish different scenarios.

2014 September 1 Event Simulation



Summary

- In this study, we perform global MHD simulations of CMEs associated with the long-duration gamma-ray flares. Our result shows promising evidence that CME shock-accelerated particles could travel back to the Sun to produce gamma-rays observed by Fermi.

- In 2014 September 1 (Behind-the-Limb) event, we found that the temporal evolution of the compression ratio and thus the shock particle production are closely correlated with the Fermi gamma-ray flux, suggestive of a causal relationship.

- In 2012 March 7 (Migrated Emission Centroid) event, our preliminary result shows that the temporal evolution of footpoints connecting to the strongest shock location agrees with the Fermi centroid migration. The migration of the footpoints in the simulation are caused both by the dynamic change of the shock parameters and by reconnection between the erupting flux rope and the ambient corona field.

- More detailed modeling and data analysis are needed to better understand the acceleration mechanisms behind the long-duration gamma-ray events: e.g., the role of twin-CMEs (Li et al. 2012), the relationship with in-situ SEP measurements (de Nolfo et al. 2019), and coupling with particle acceleration/transport models (e.g., M-FLAMPA, iPATH).