

Data-driven **MHD simulation** of coronal mass ejection (CME) originating from Sun and its propagation to Earth

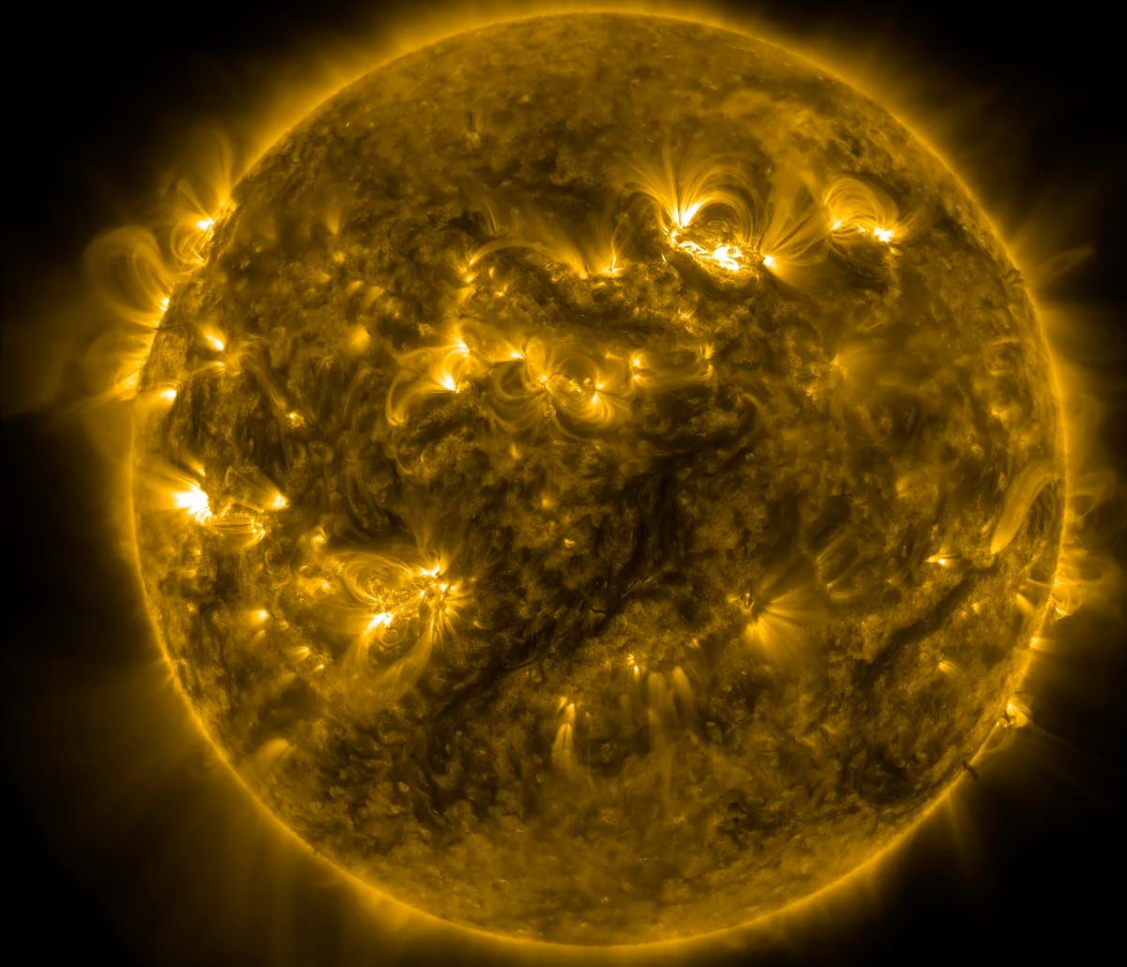
Chaowei Jiang (江朝伟)

Harbin Institute of Technology, Shenzhen

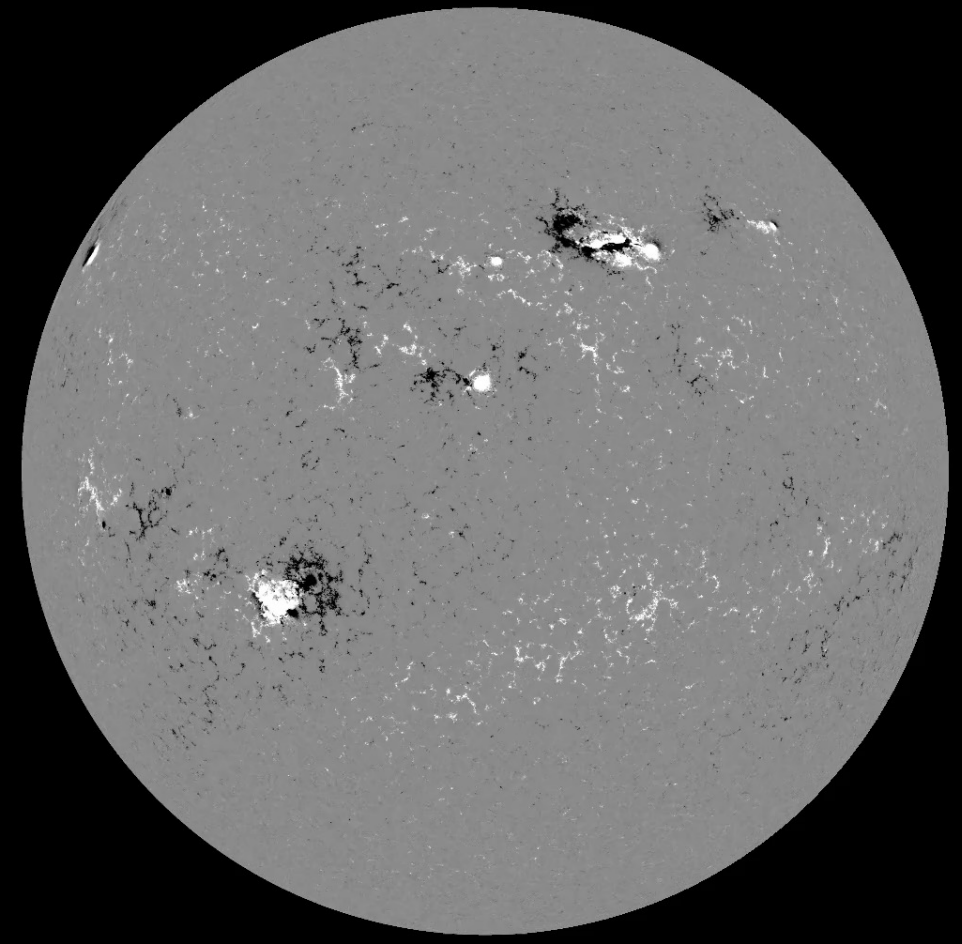
chaowei@hit.edu.cn

2025-09-17, Jeju

Ceaseless evolutions of magnetic fields drive activities and eruptions in the solar corona

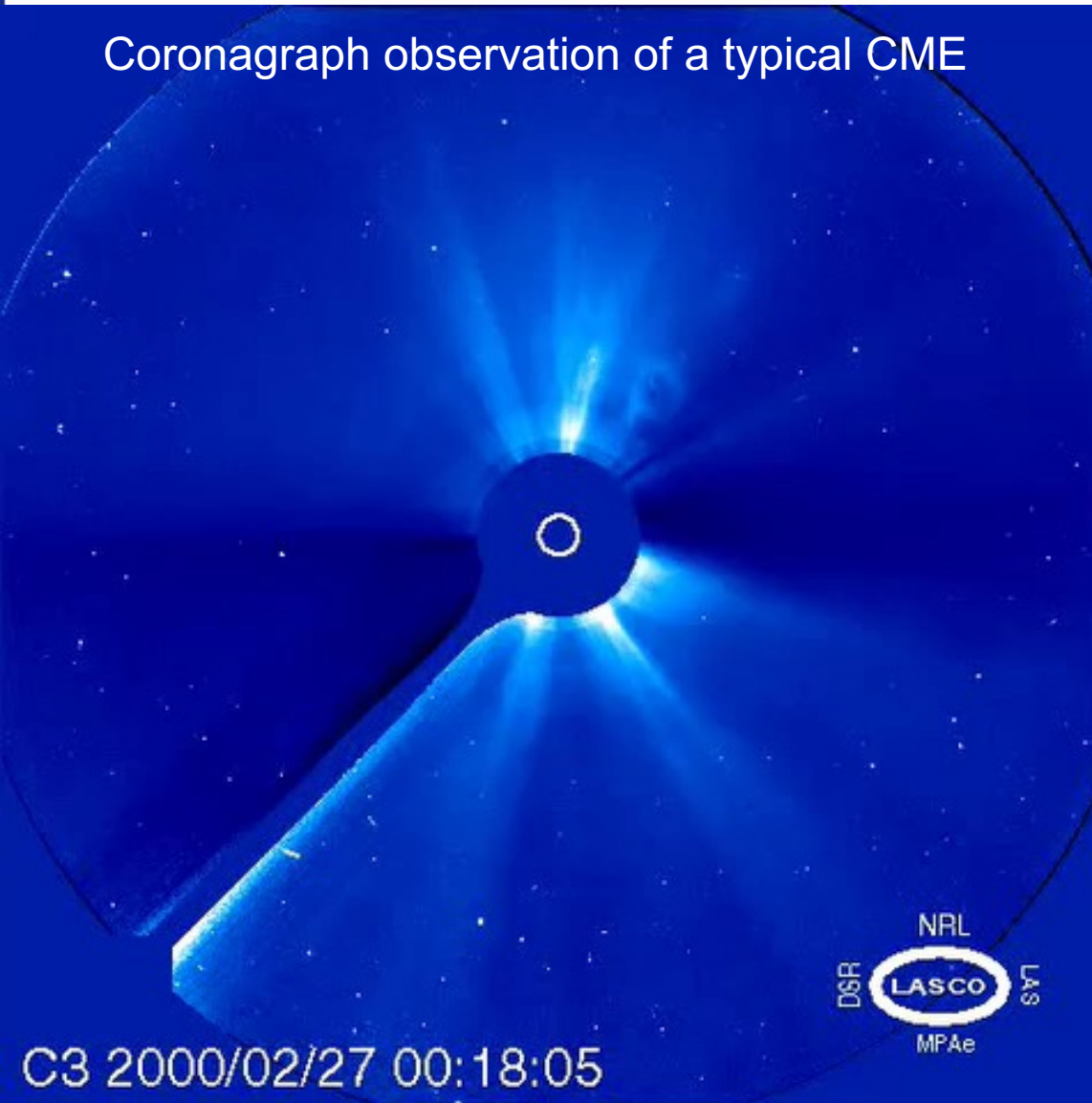


Solar atmosphere (corona) EUV images

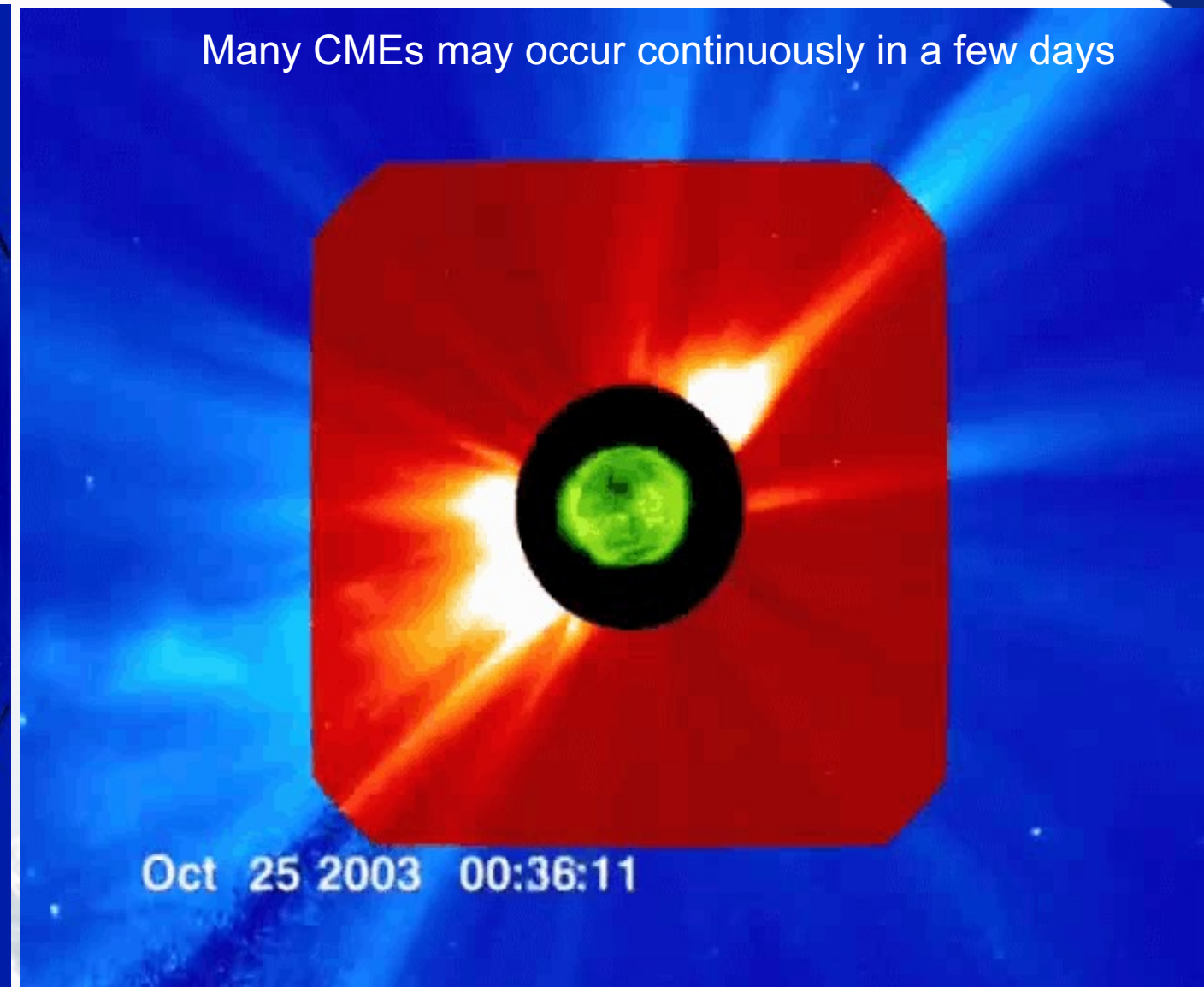


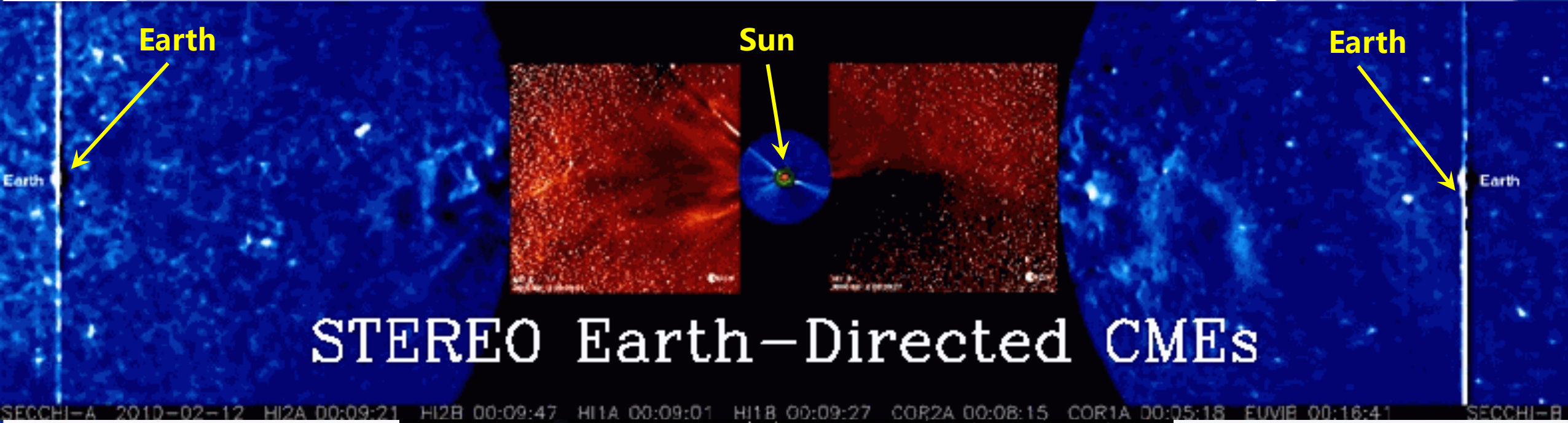
Solar surface (photosphere) magnetogram

Coronagraph observation of a typical CME

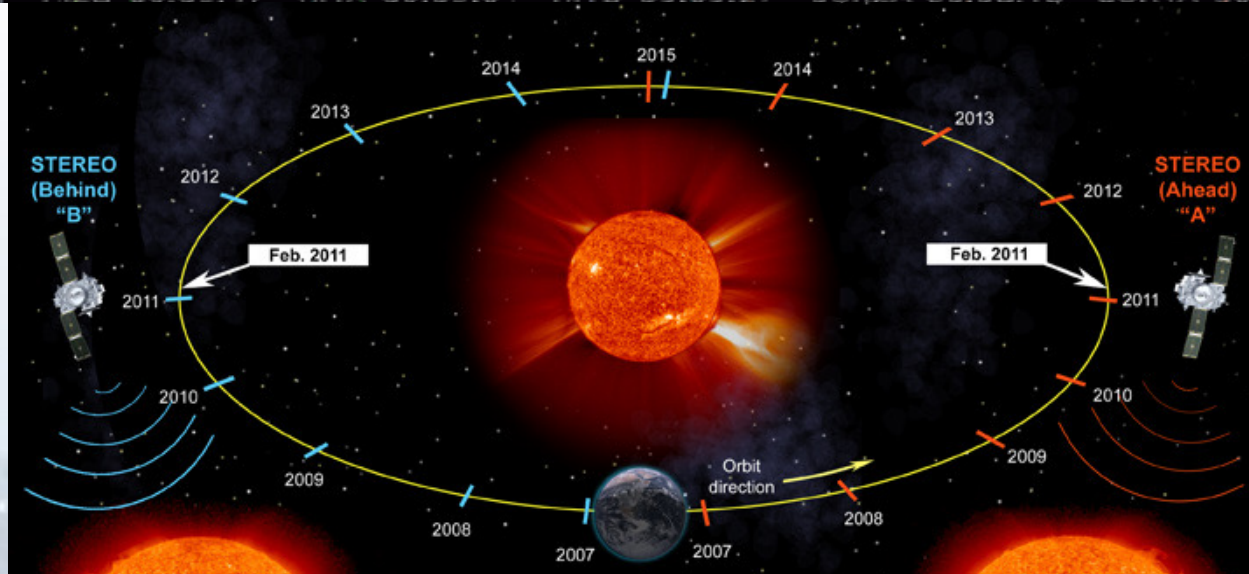


Many CMEs may occur continuously in a few days





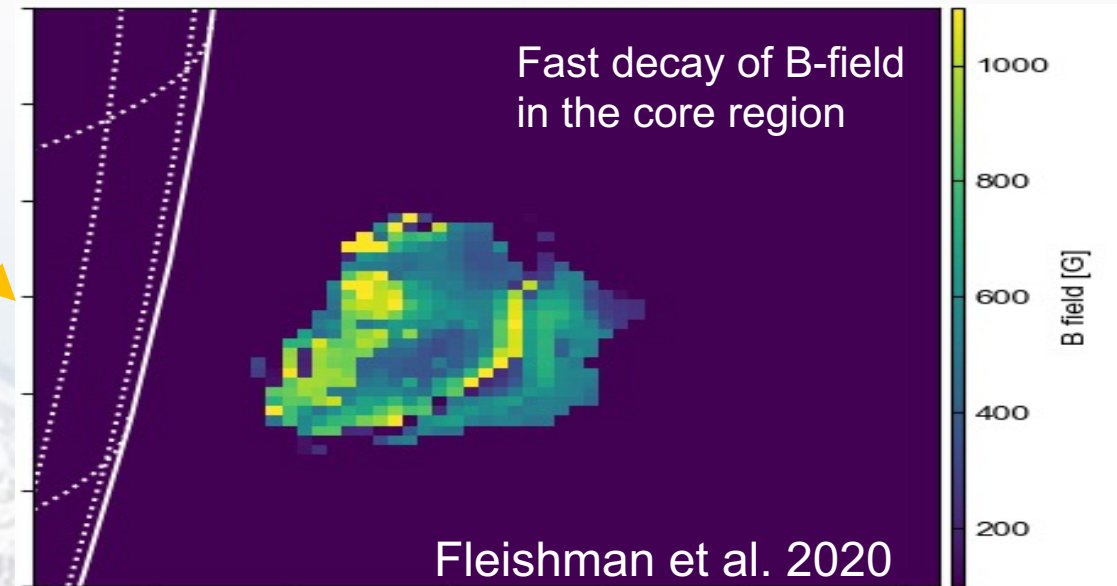
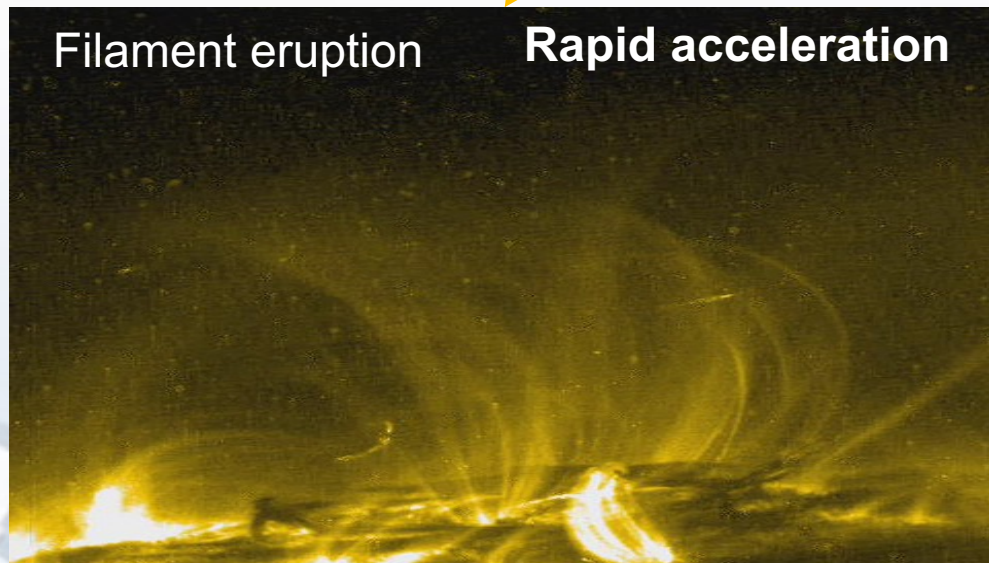
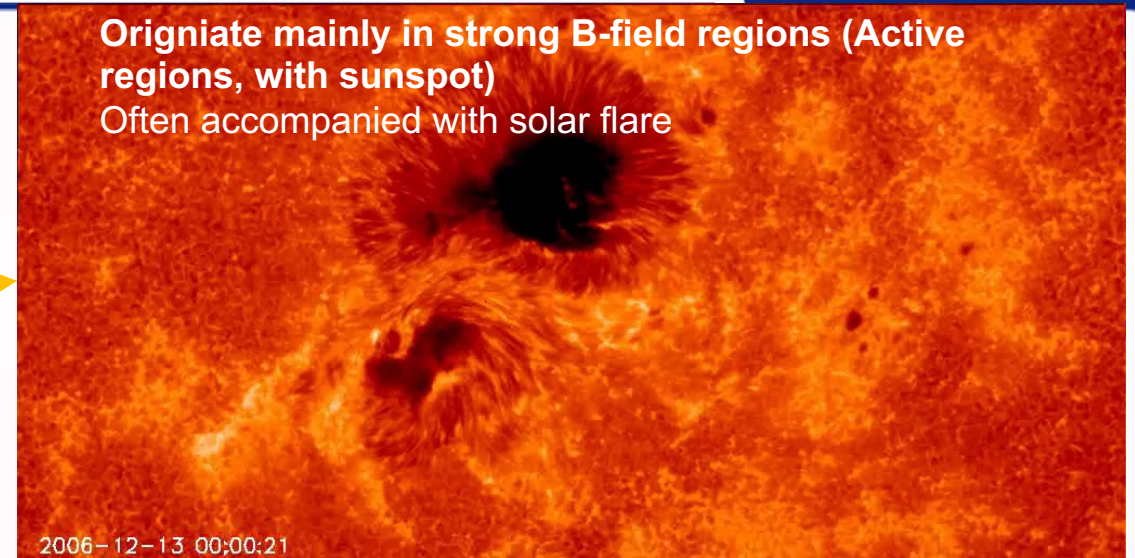
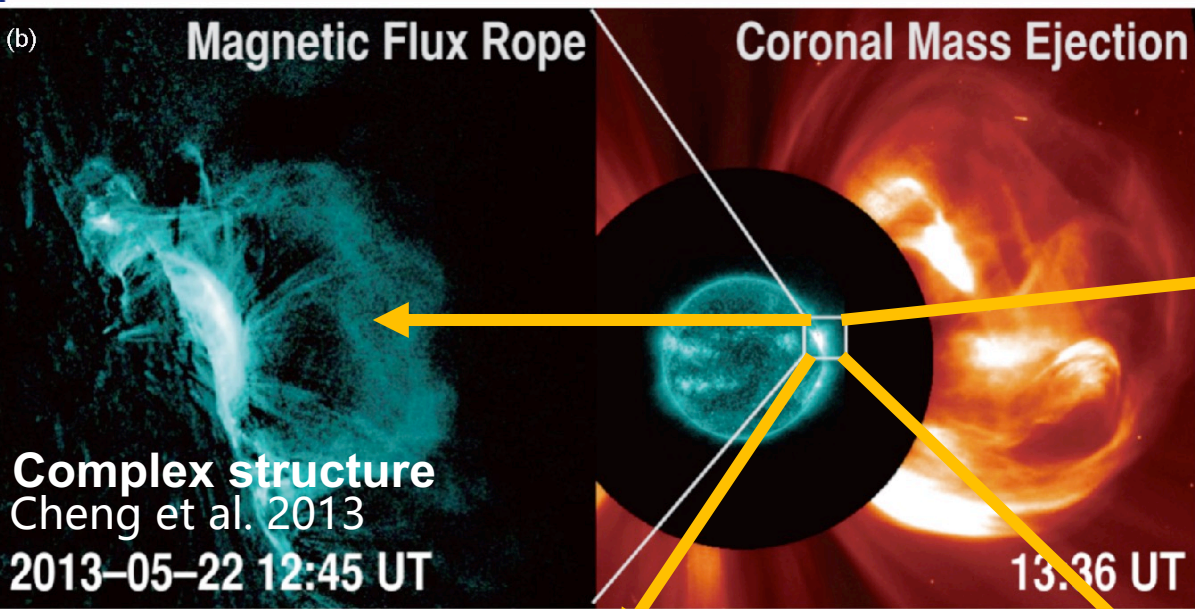
STEREO A & B: Large-scale image with two different view angles



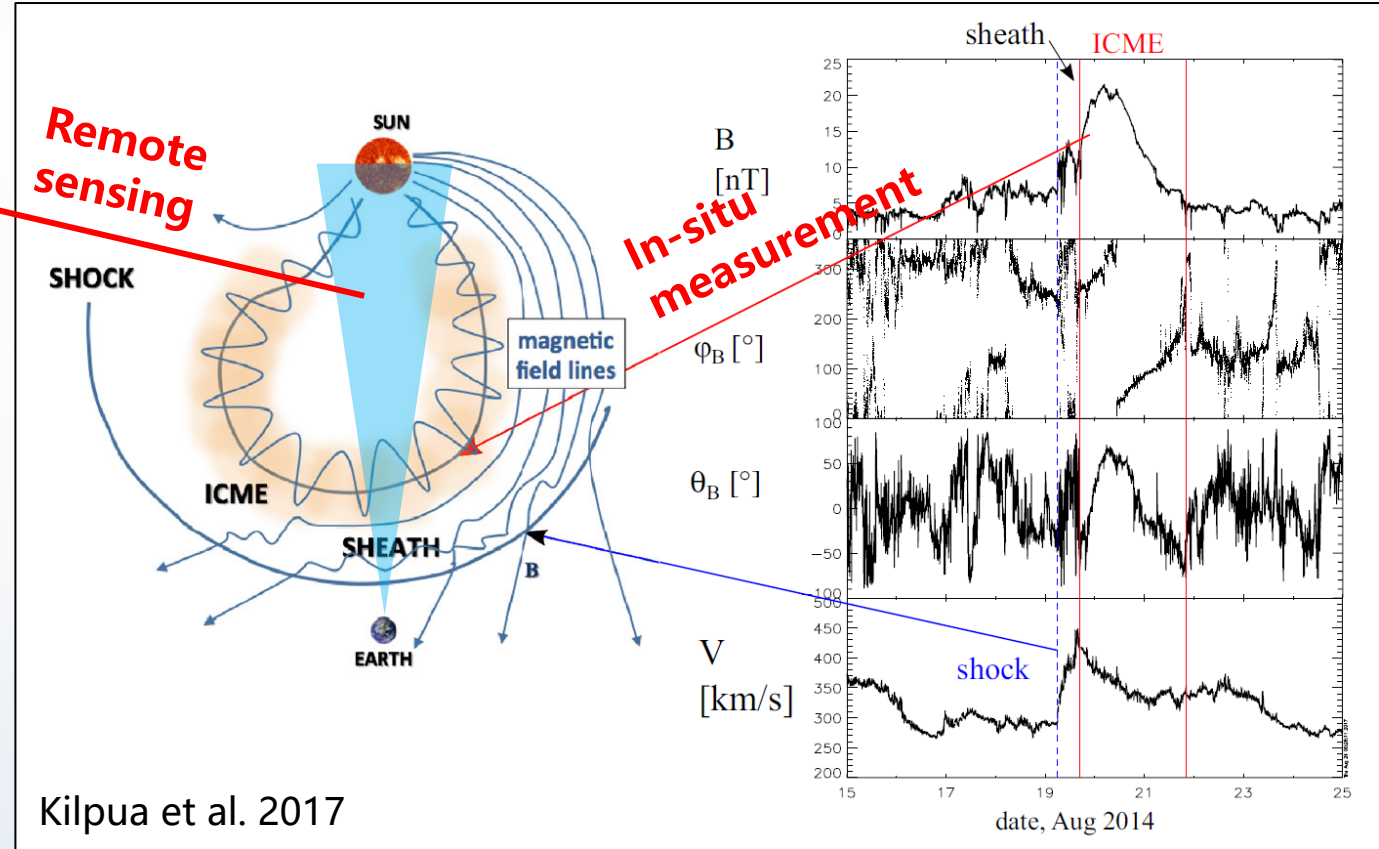
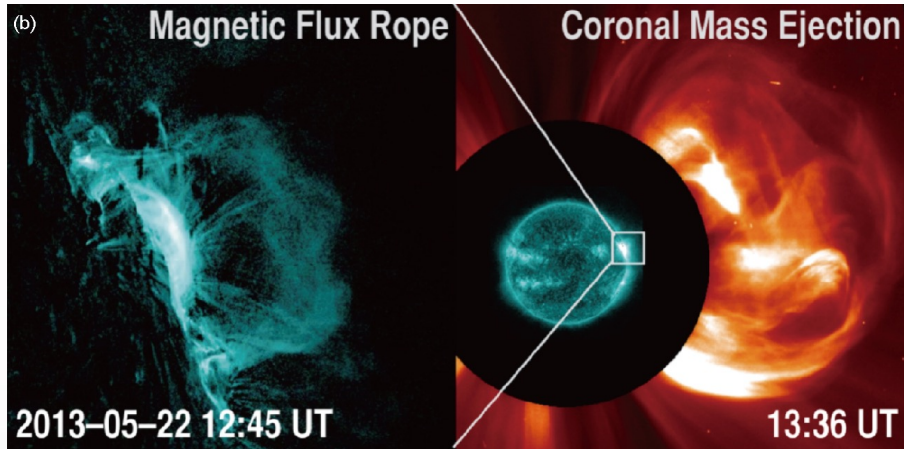
CMEs carry huge amounts of plasma and energy
They hit Earth's magnetosphere and cause geomagnetic storms.
These storms can trigger **space weather disasters.**
Need to understand **How CMEs are produced and **How they propagate**, and predict them**



CMEs origin: Magnetic explosions in solar corona



- To understand the origin and propagation of CMEs, we must characterize their 3D structure and evolution, especially the key physical quantity: **the magnetic field**.



Kilpua et al. 2017

Remote sensing

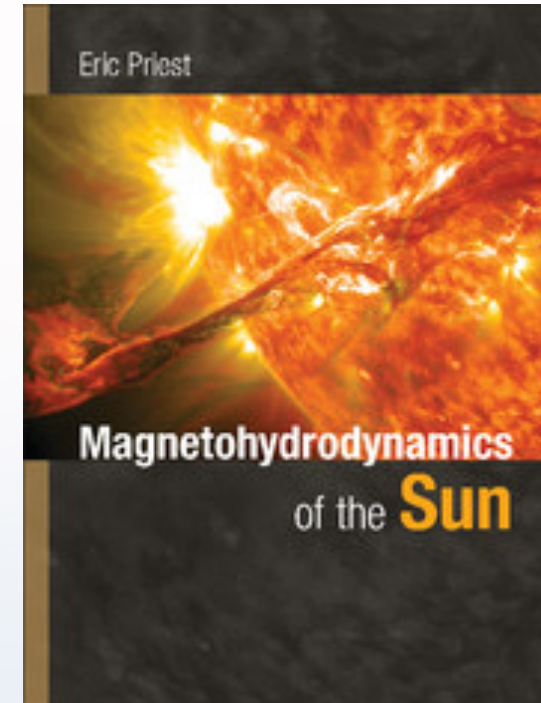
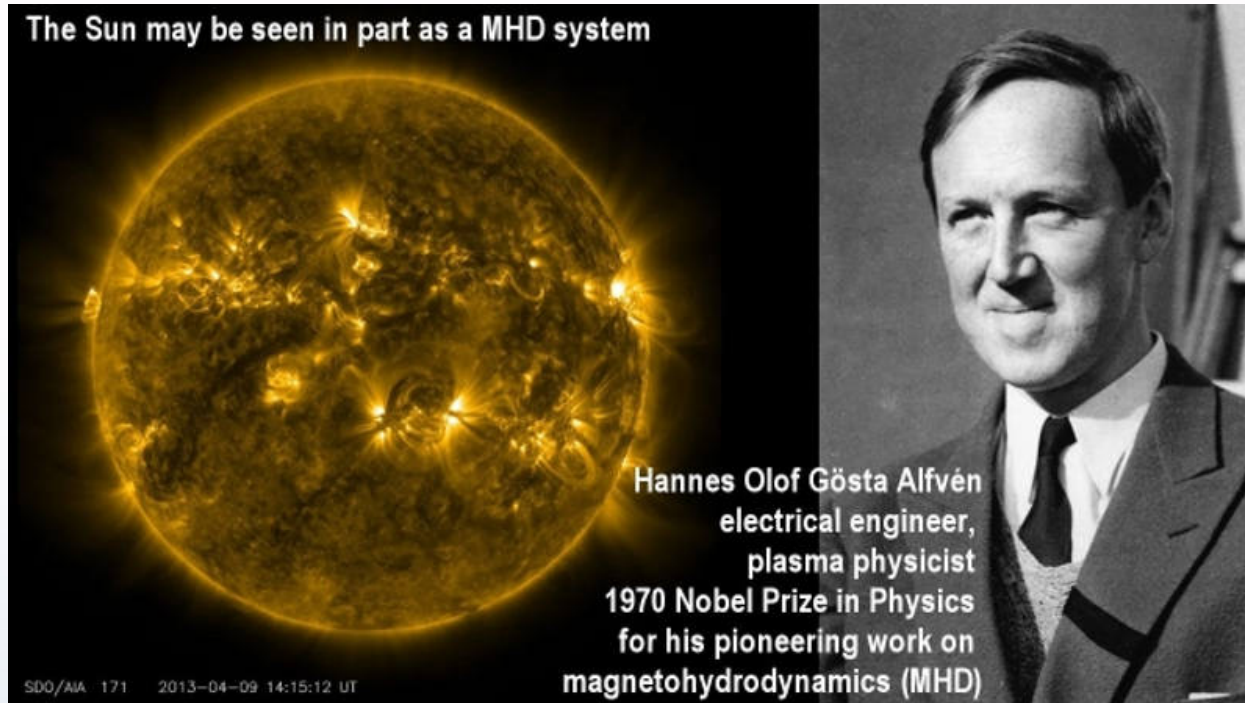
- Integrates along the line of sight — hard to reveal 3D structures.
- Cannot measure the coronal magnetic field
- Like viewing through fog (雾里看花) — blurred and indirect.

In-situ measurement

- Primarily conducted near Earth.
- Provides data at only single (or a few) points — fails to capture the full picture.
- Like the blind men touching an elephant (盲人摸象) — limited and fragmented.

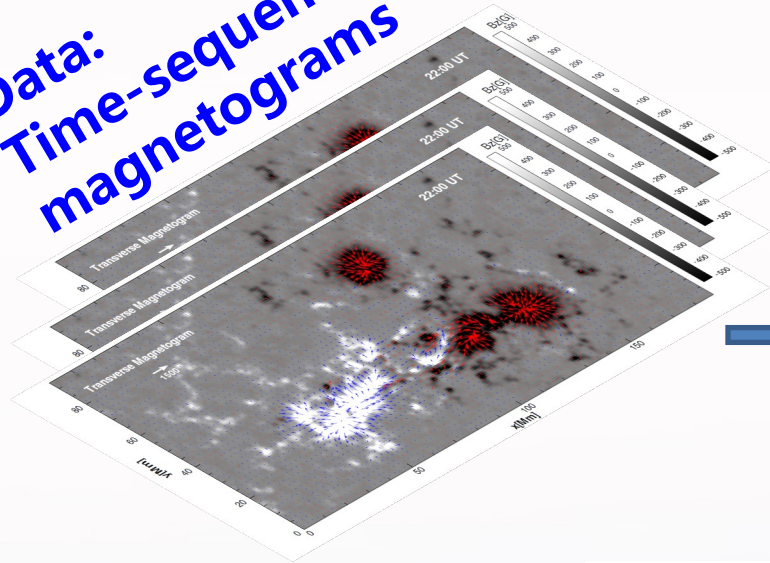
So, we do numerical simulations

- Solar (stellar) corona consists of plasma which can be described by MHD.
- Numerical simulations based on the MHD equations are a fundamental tool for studying macroscopic dynamics in the solar atmosphere.

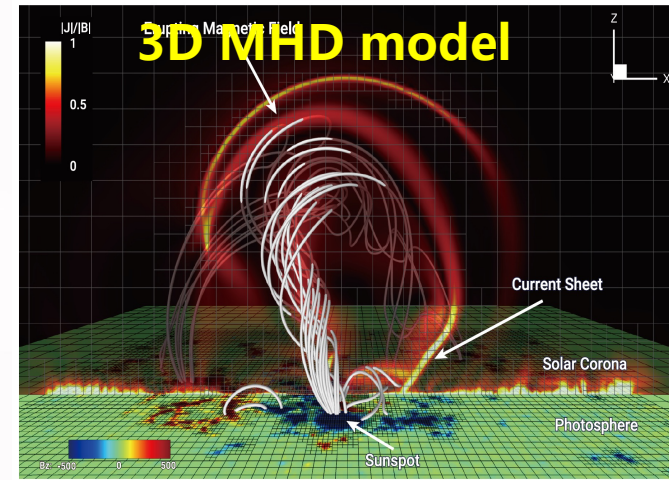


- We further employ observational data as key constraints in doing simulations: we use it directly to drive the simulations: **data-driven simulations**.

Data:
Time-sequence
magnetograms



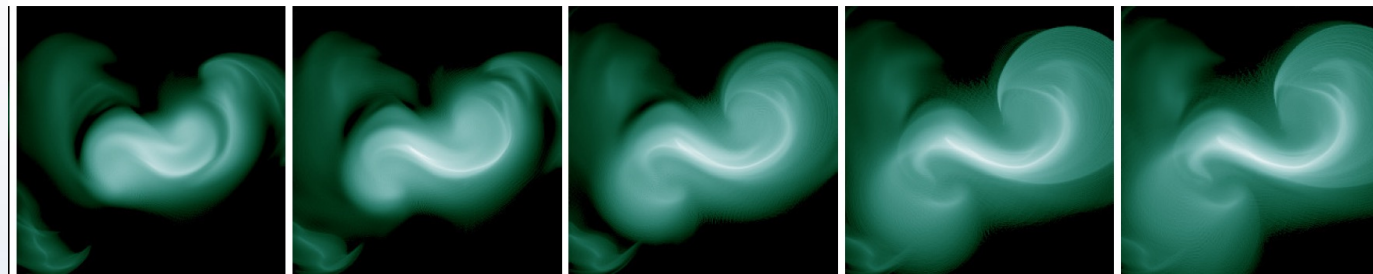
Driving as
bottom BCs



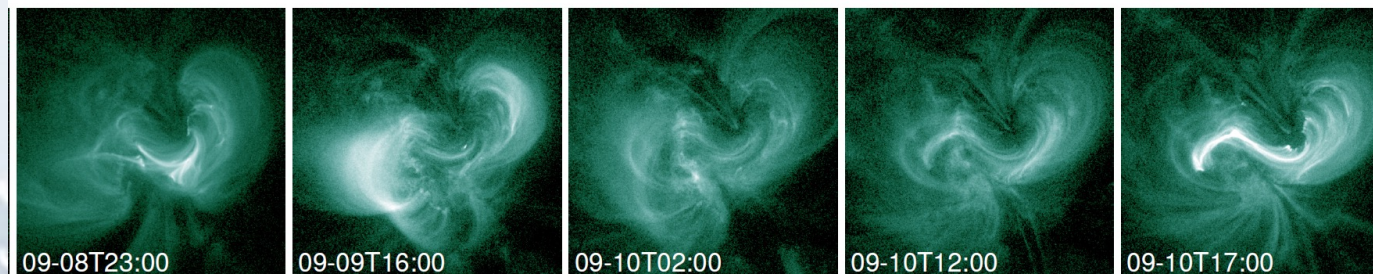
Output

- Localized box with size of ARs
- Solving full MHD equations
- High resolution with AMR
- High-accuracy scheme
- Using typical coronal ρ and T
- Self-consistent BCs
- ...

**Synthetic images
based on simulation**



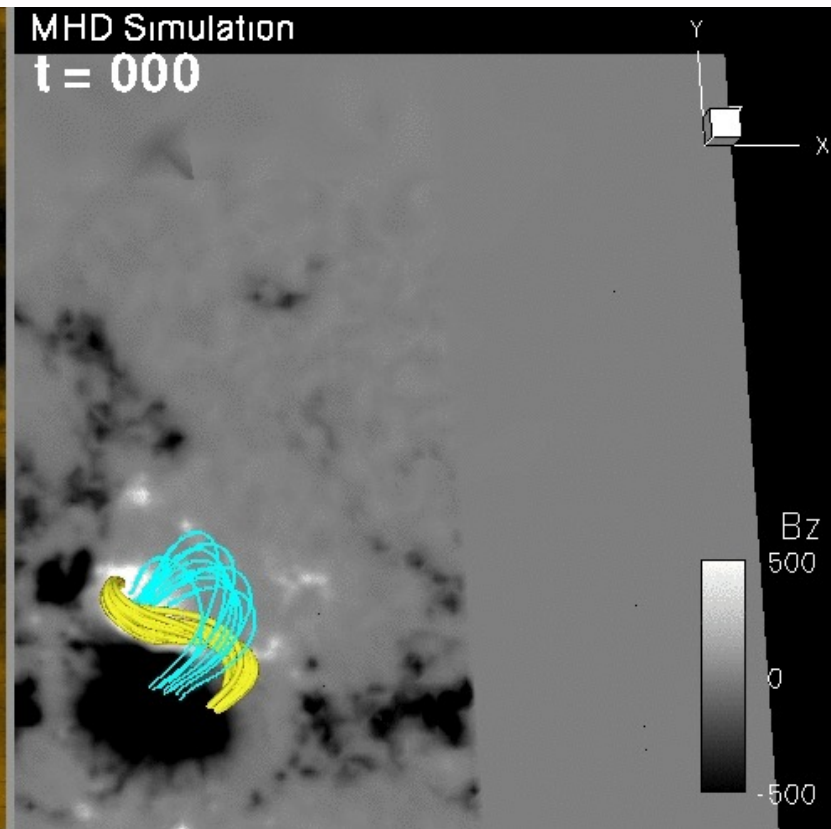
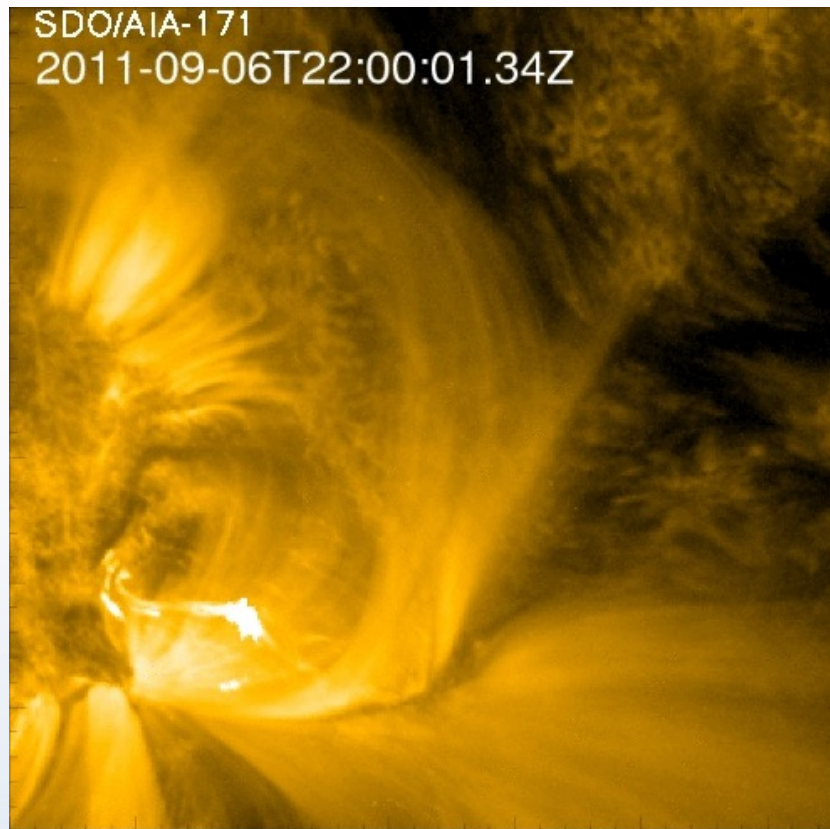
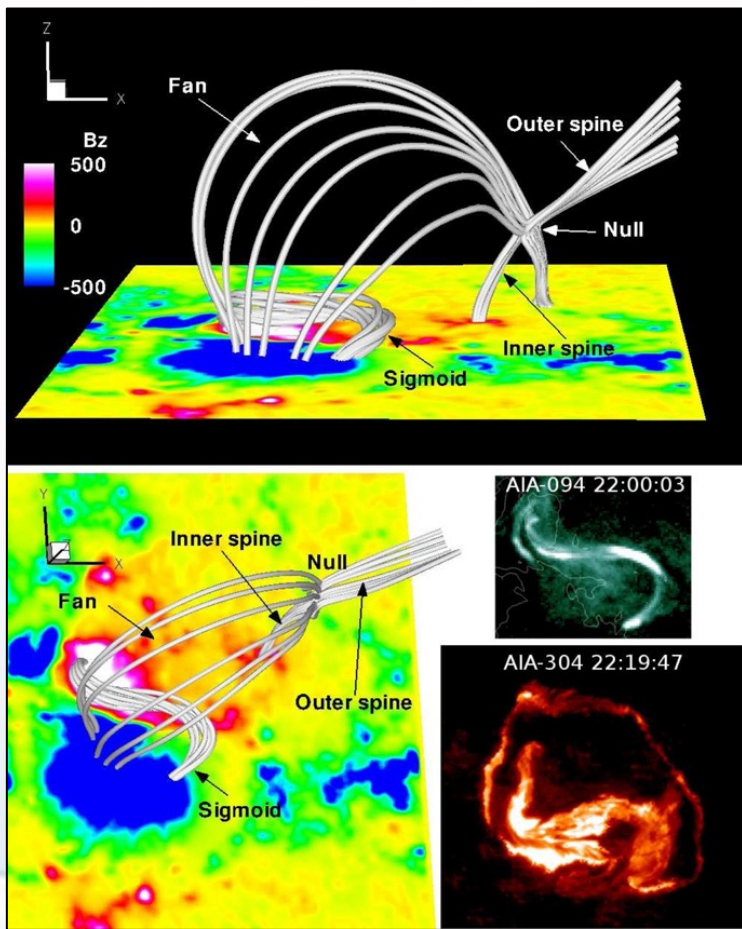
EUV observations



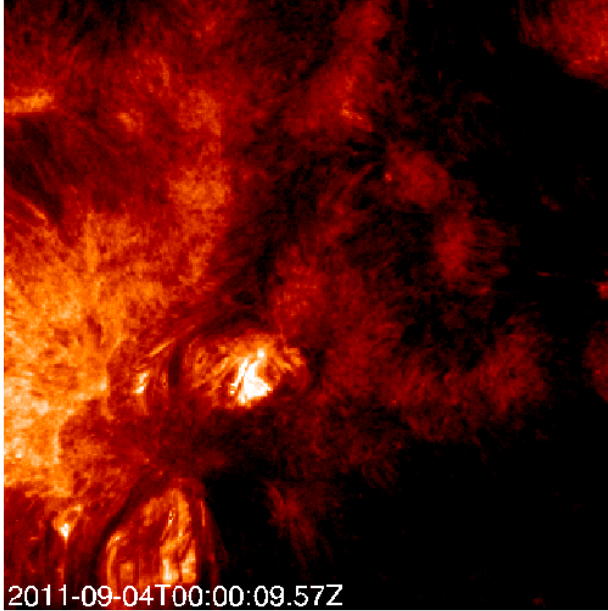
Jiang et al. ApJL 2013, ApJ 2014, NatCo 2016, ...

**Compare &
validate**

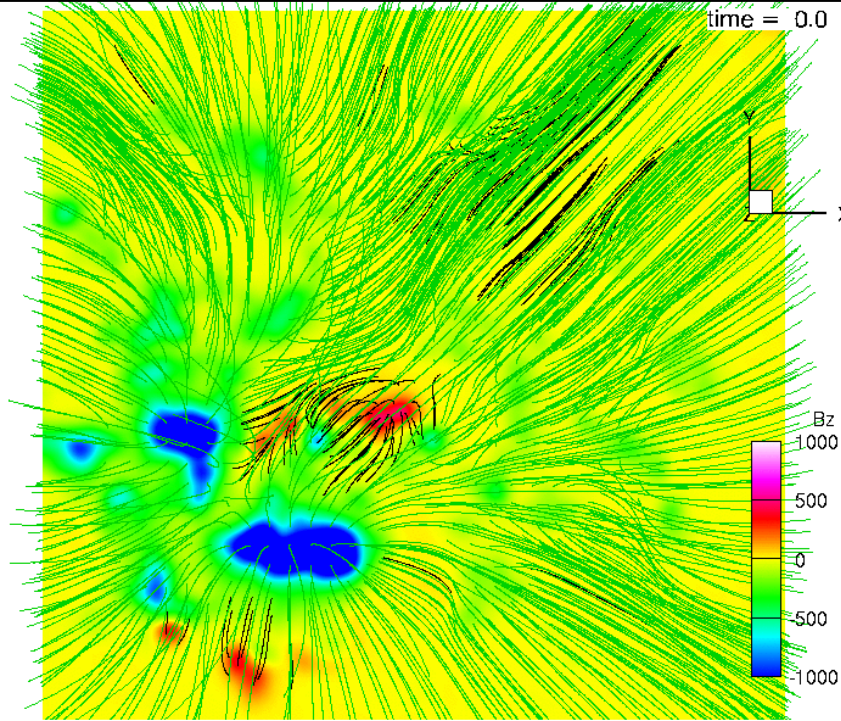
- Eruption of an unstable MFR that contains a filament



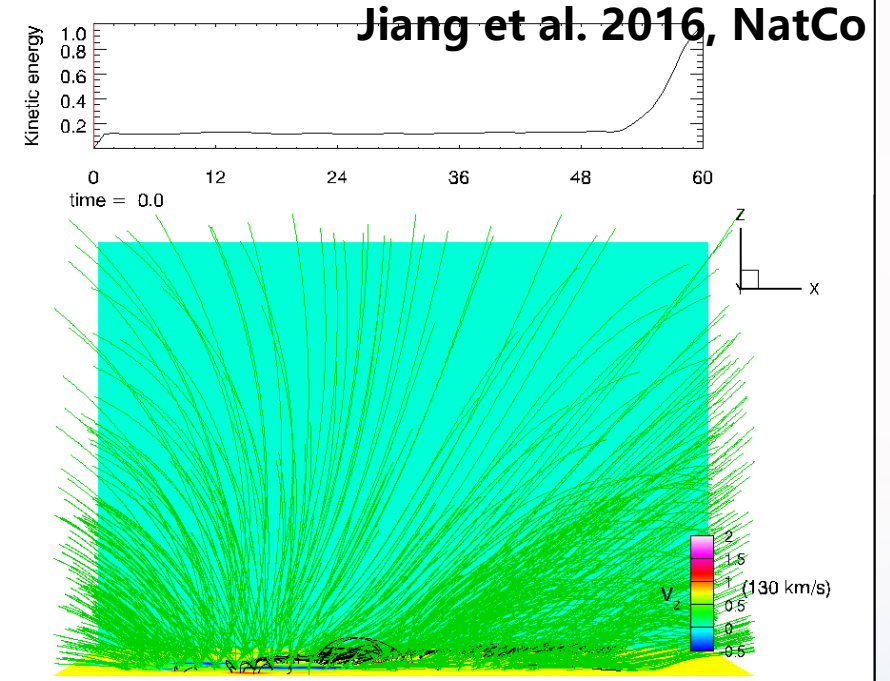
SDO/AIA-304 Observation



SDO/AIA-304

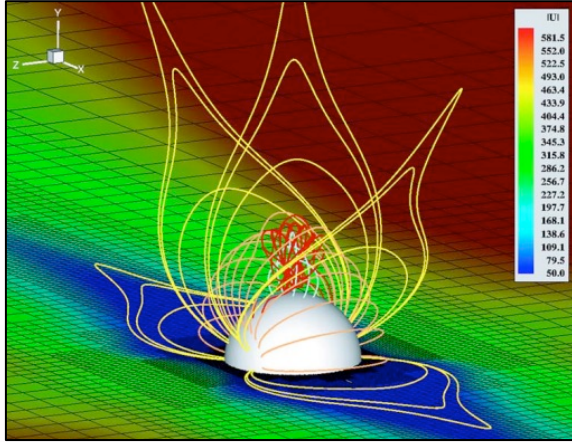


Simulation B

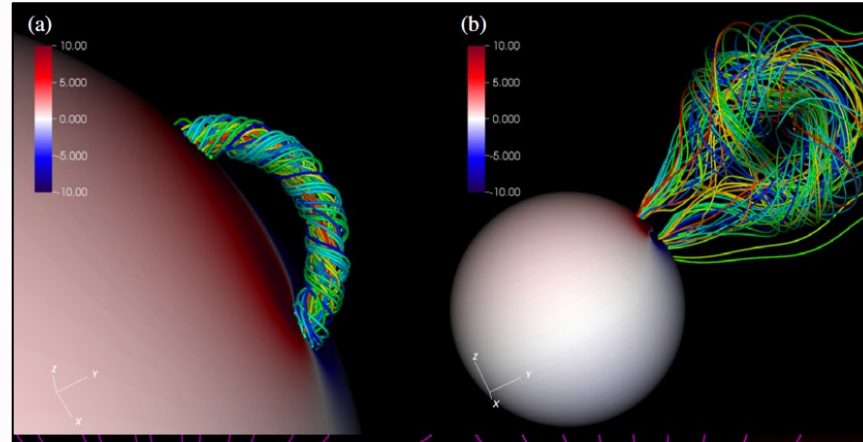


Simulation B+V

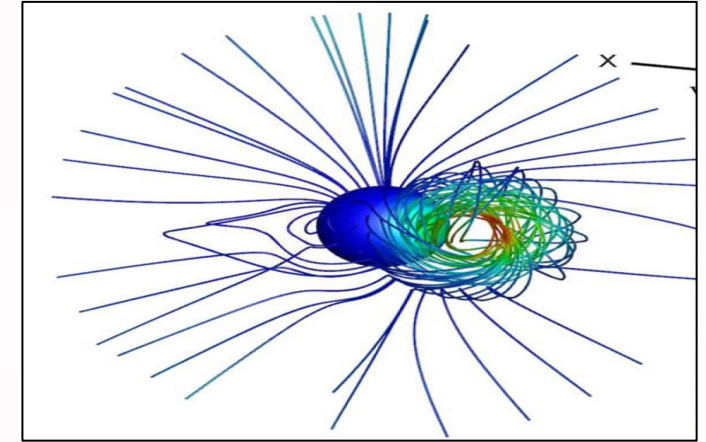
- A flux emergence event of over 3 days that finally leads to an eruption in a topology-complex AR.
- Simulation aligns with observations in both spatial structure and temporal evolution: the eruption timing closely matches the observed flare time.
- **However, these simulations are local model (limited to the active region scale) and cannot follow CME propagation.**



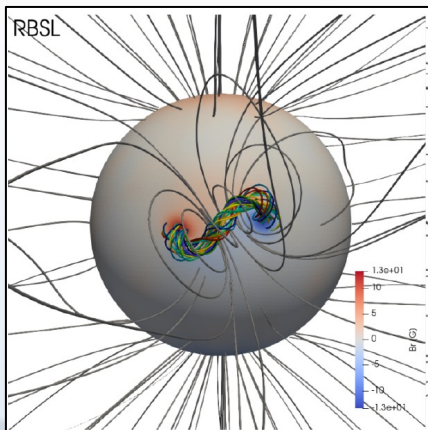
Gibson-Low flux rope,
Manchester et al. 2004, Jin et al. 2017, ...



Titov-Demoulin flux rope
(Lionello et al. 2013)



Spheromak flux rope,
Kataoka et al 2009; Shiota & Kataok 2016
Yang et al. 2021

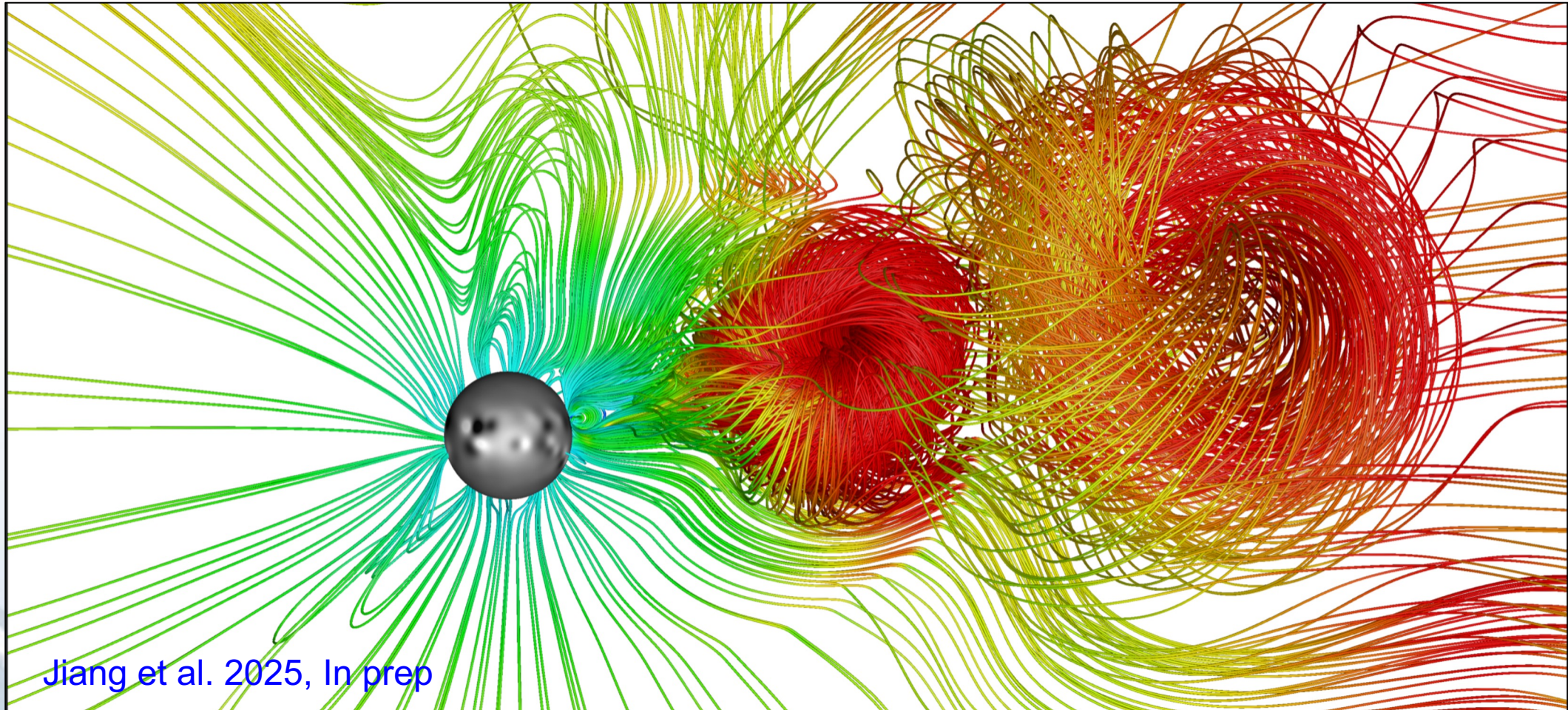


TDm, RBSL, Torok et al. 2018, Linan et al. 2024, Guo et al. 2024

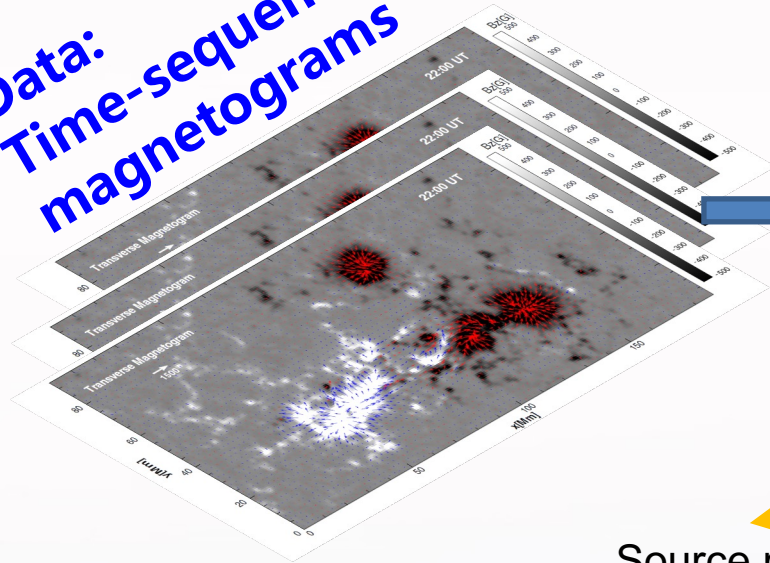
- Current global CME simulations use assumed MFR models as input, which fails to capture the true triggering mechanism and realistic evolution process of a CME!

Newly developed data-driven CME (DCME) model

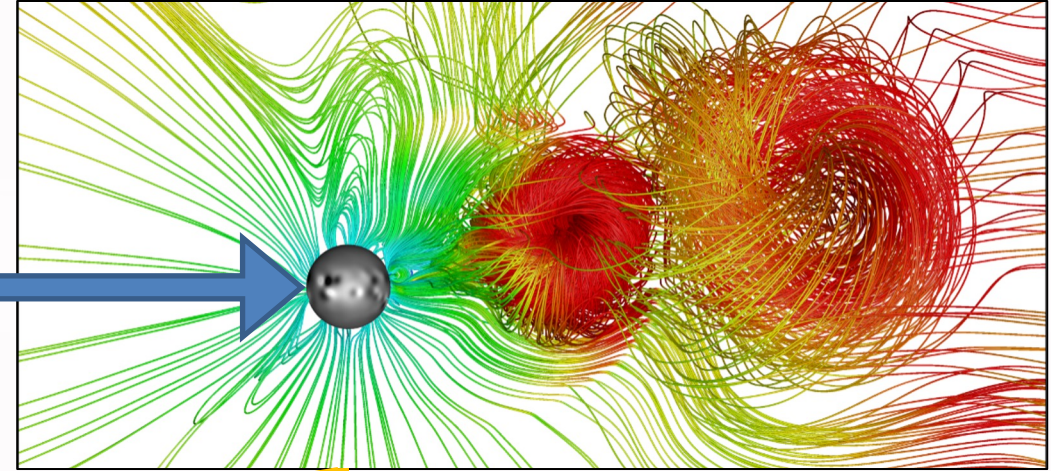
- Include both source region of CME and the background solar wind
- Full-scale simulation of the complete CME evolution process — from pre-event conditions, initiation, near-Sun evolution, to its propagation until to Earth.



Data:
Time-sequence
magnetograms



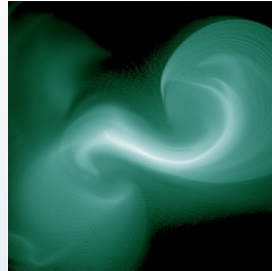
Driving as
inner BCs



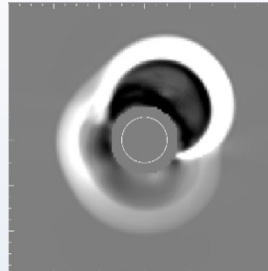
Output

Simulation results

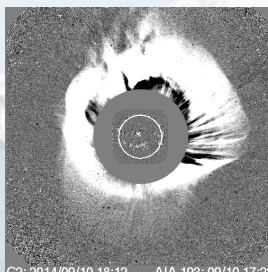
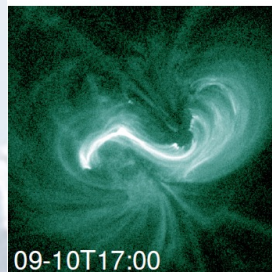
Source region



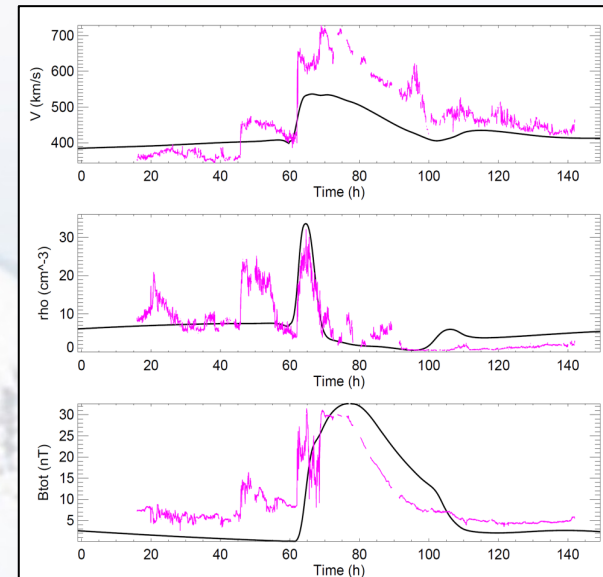
Near-Sun



Observations



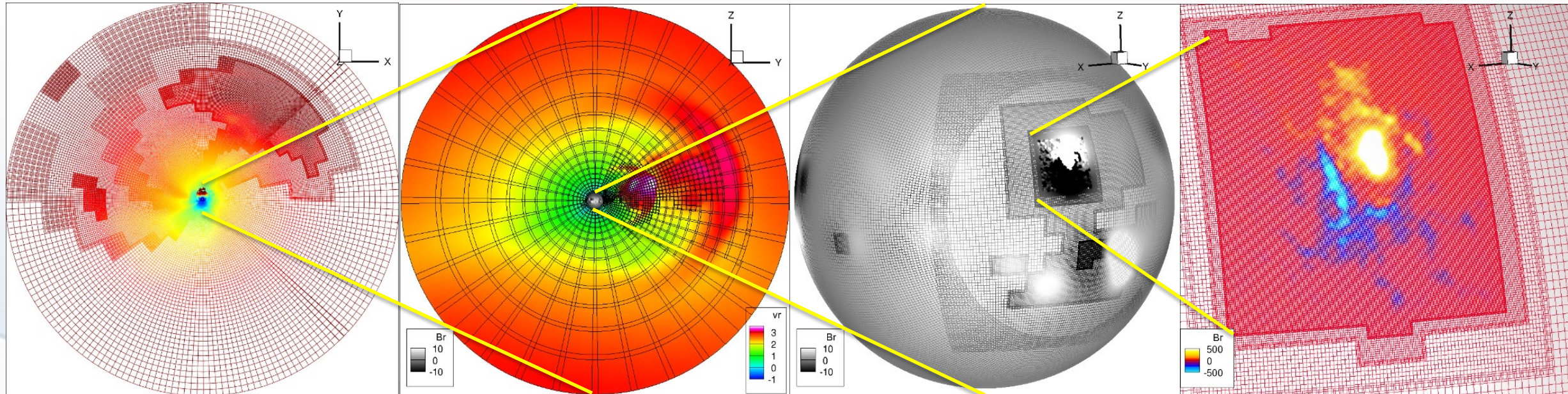
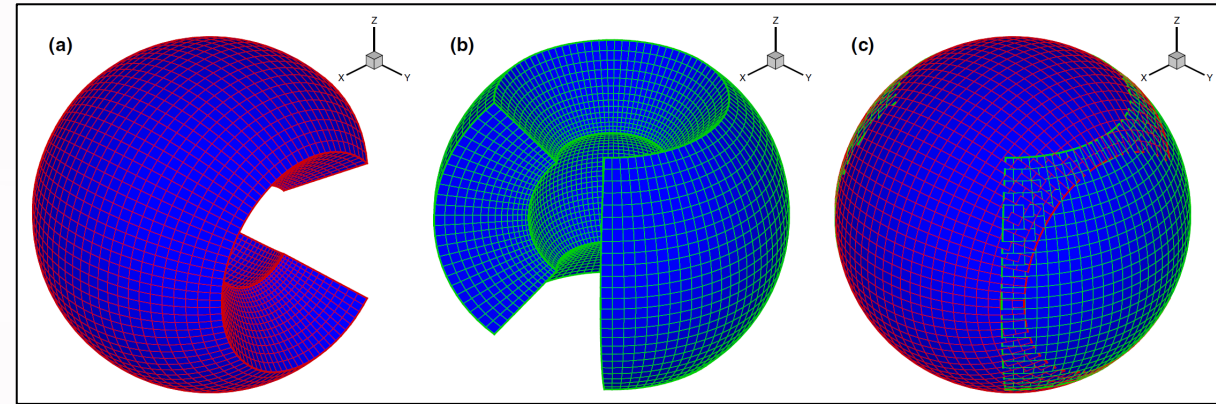
1au



Compare &
validate

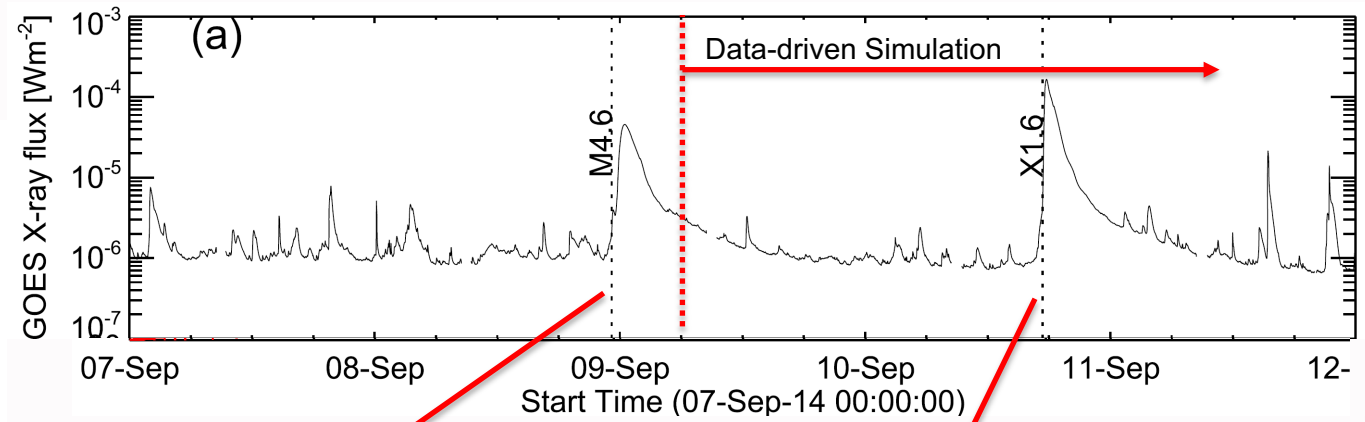
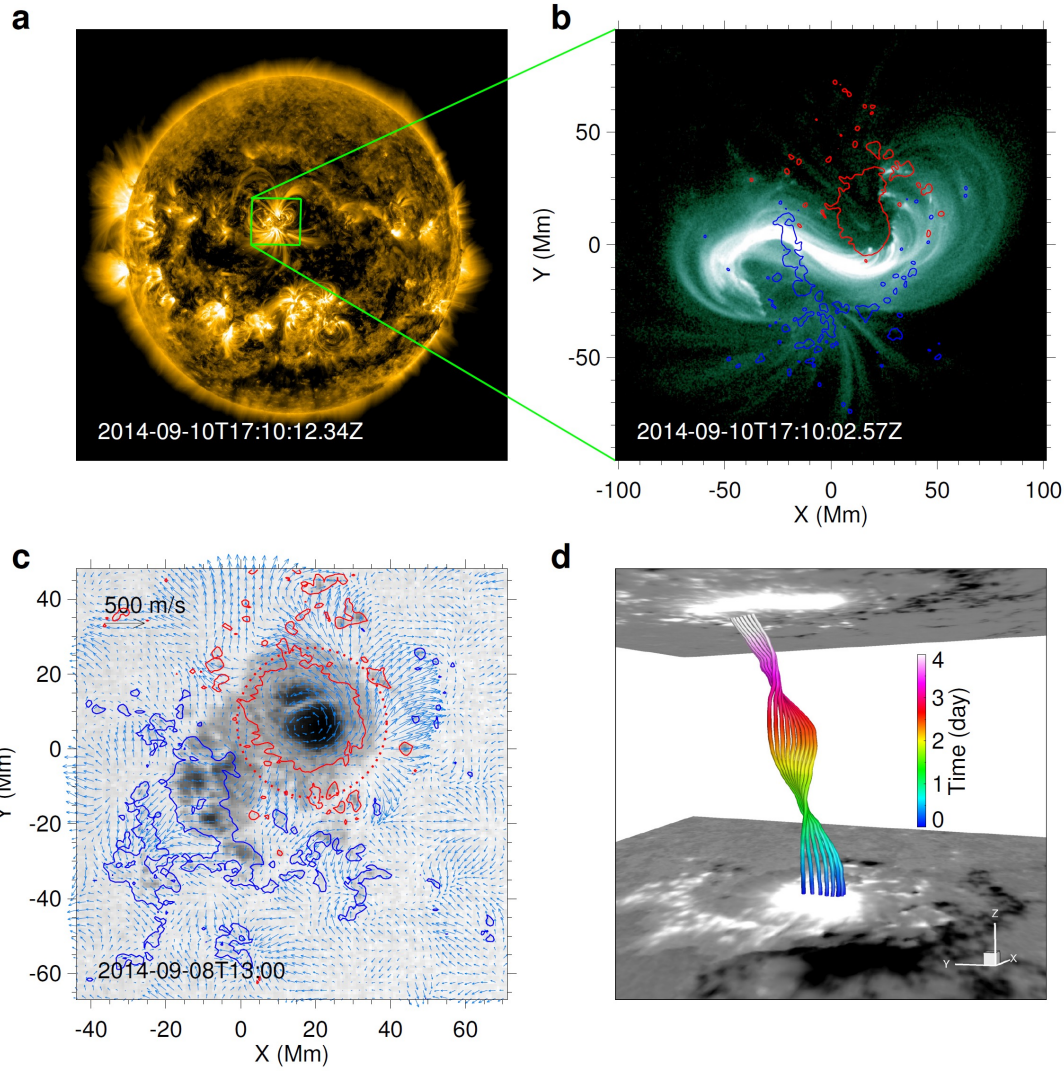
Jiang et al. 2025, In prep

- A Yin-Yang grid cover the full sphere from solar surface to 1.5 au
- AMR with lowest resolution of 2° and highest resolution of 0.06° (1arcsec \sim 700km $\sim 10^{-3}R_s$ near the solar surface)
- Driven by vector magnetograms (VMs) from SDO/HMI

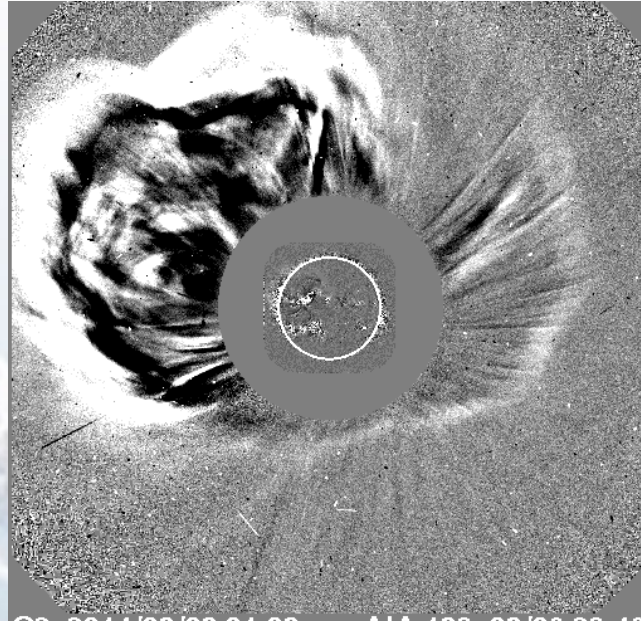


The studied event

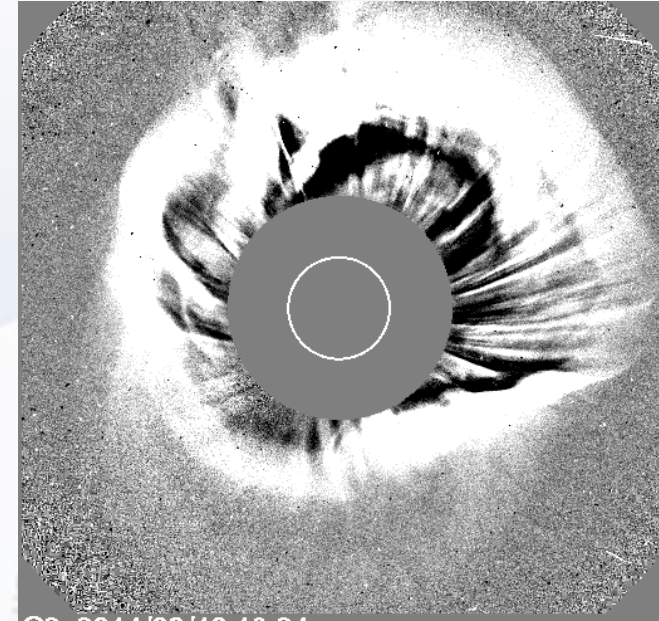
AR12158: A fast sunspot-rotating region producing CMEs



CME#1



CME#2

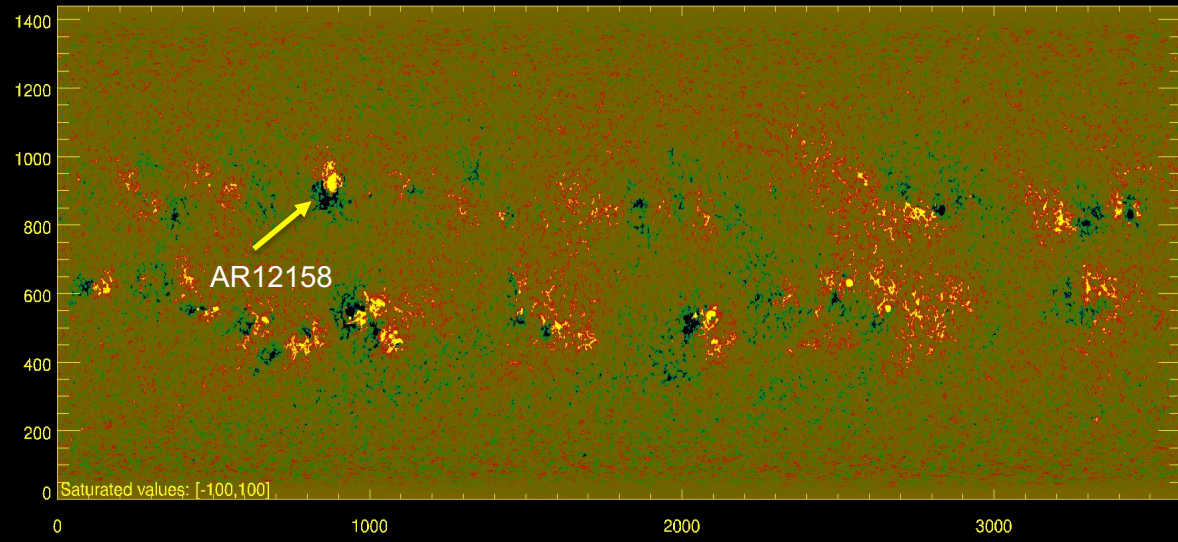


Recipe of simulations

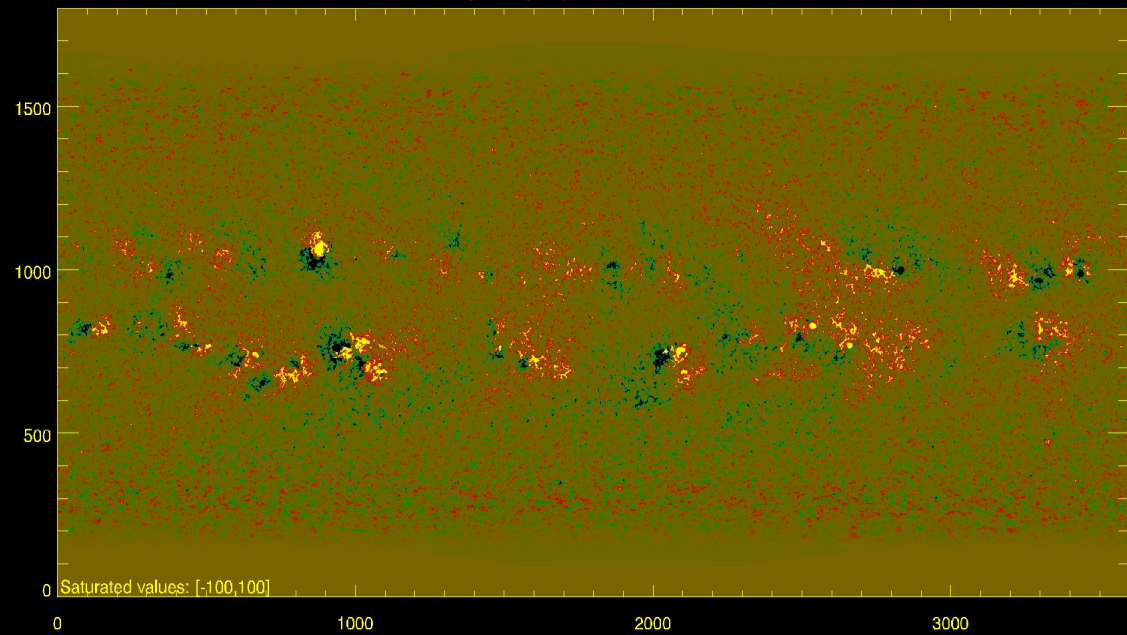
- **Step0**. Compute a background steady-state solar wind based on the HMI synoptic map (i.e., magnetogram covering the full solar surface, for Carrington rotation (CR) number 2154)
- **Step1**. Construct an initial MHD equilibrium for the active region at the time of starting simulation (here AR 12158, based on VM of 2014-09-09 06:00 UT) along with the solar wind
- **Step2**. Drive the system to evolve with a time sequence of HMI VMs until an eruption is initiated, then see how the CME evolves and propagates

Step0: prepare synoptic magnetogram of CR2154

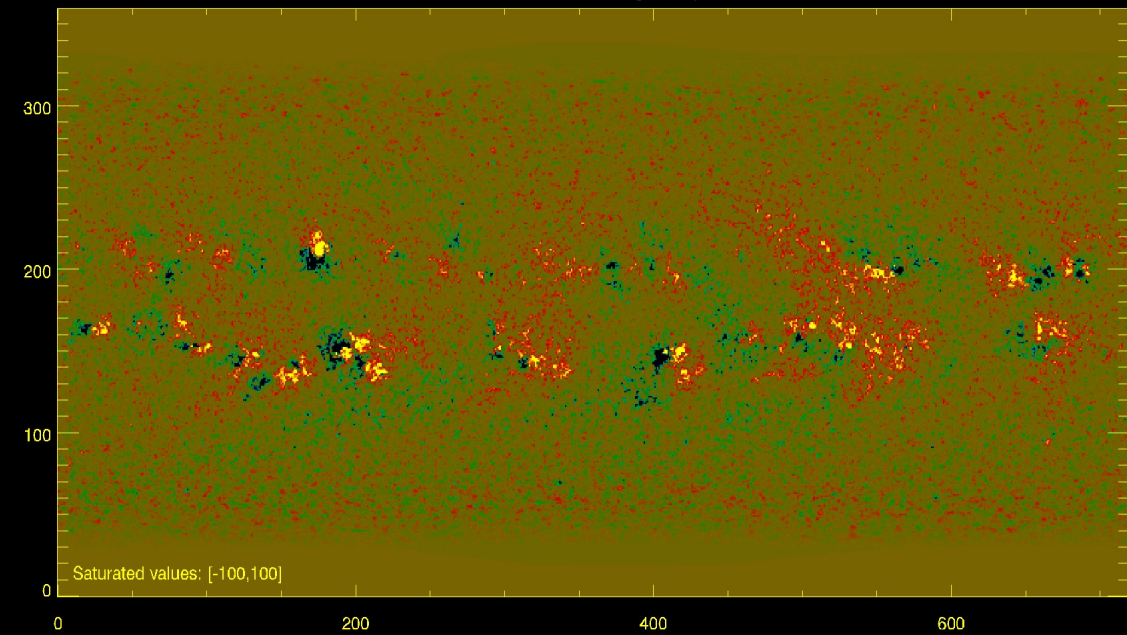
0:Original HMI synoptic



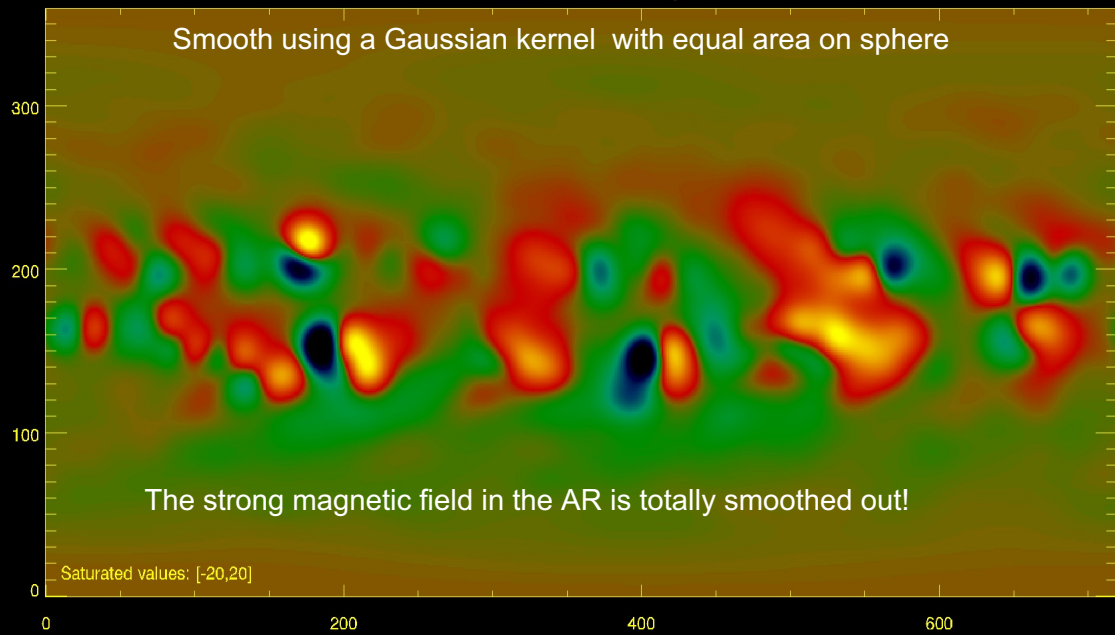
1:Original synoptic in uniform latitude



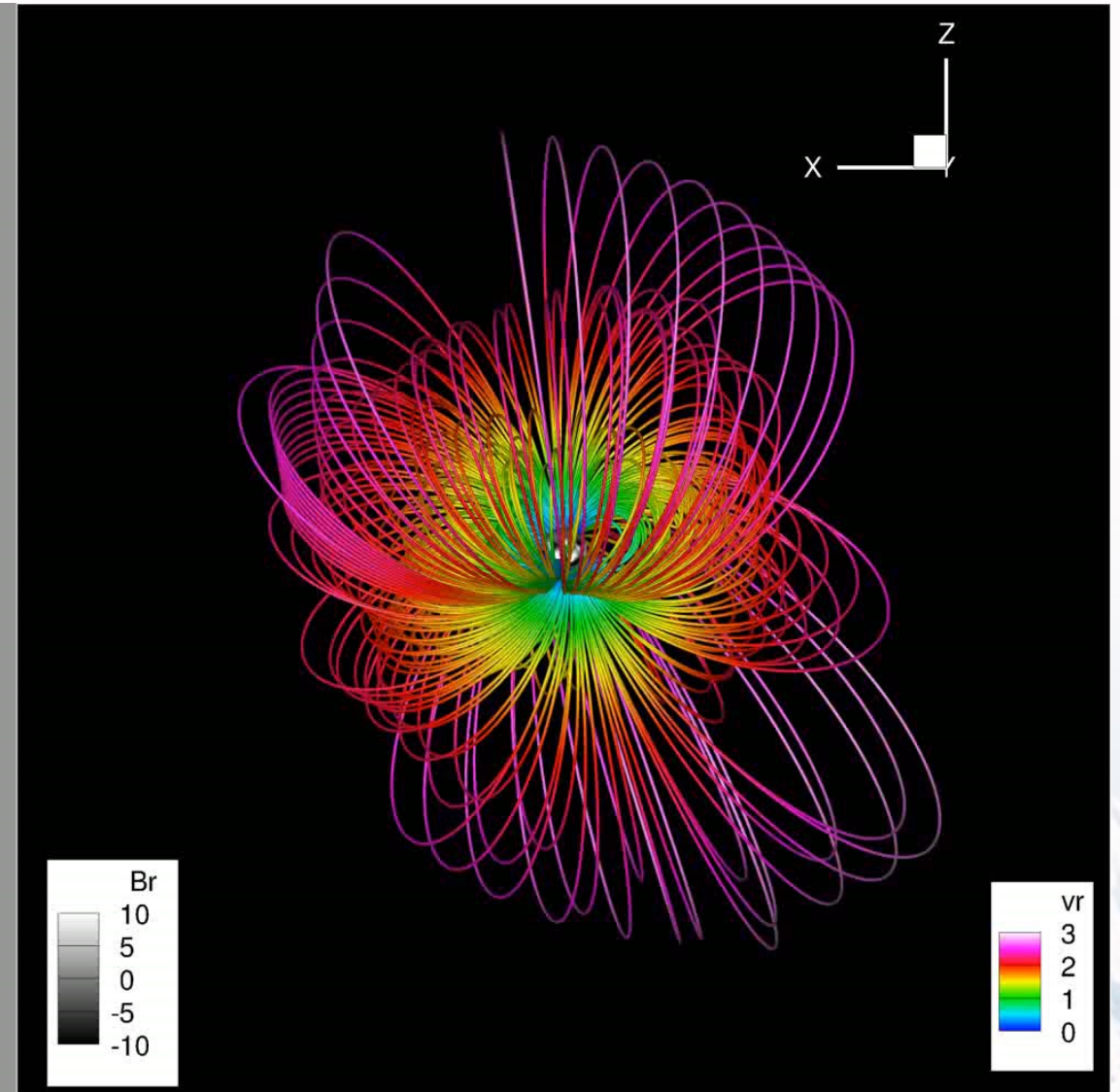
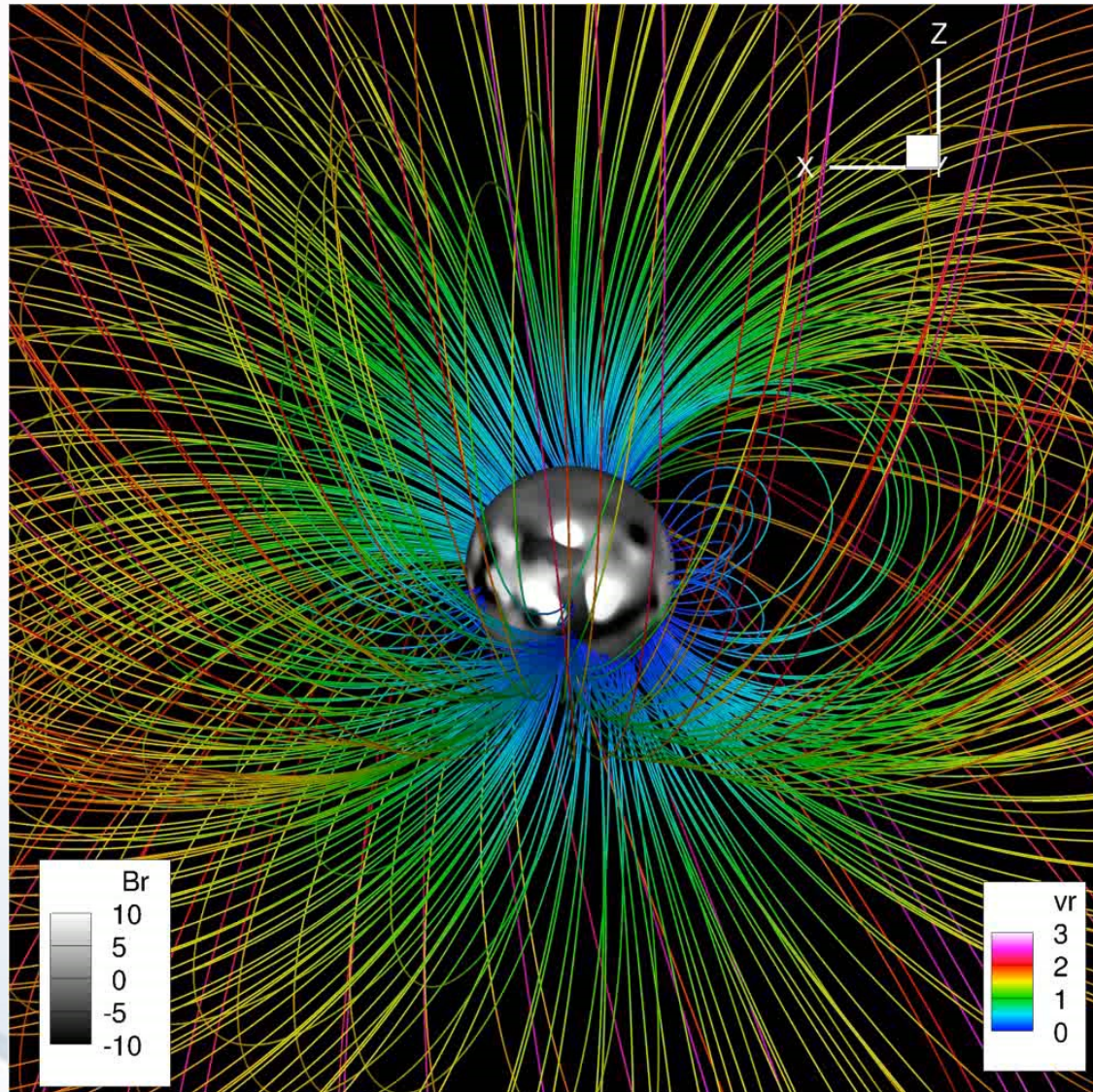
2:Rebined to 0.5 degree / pixel



3:Final smoothed Map



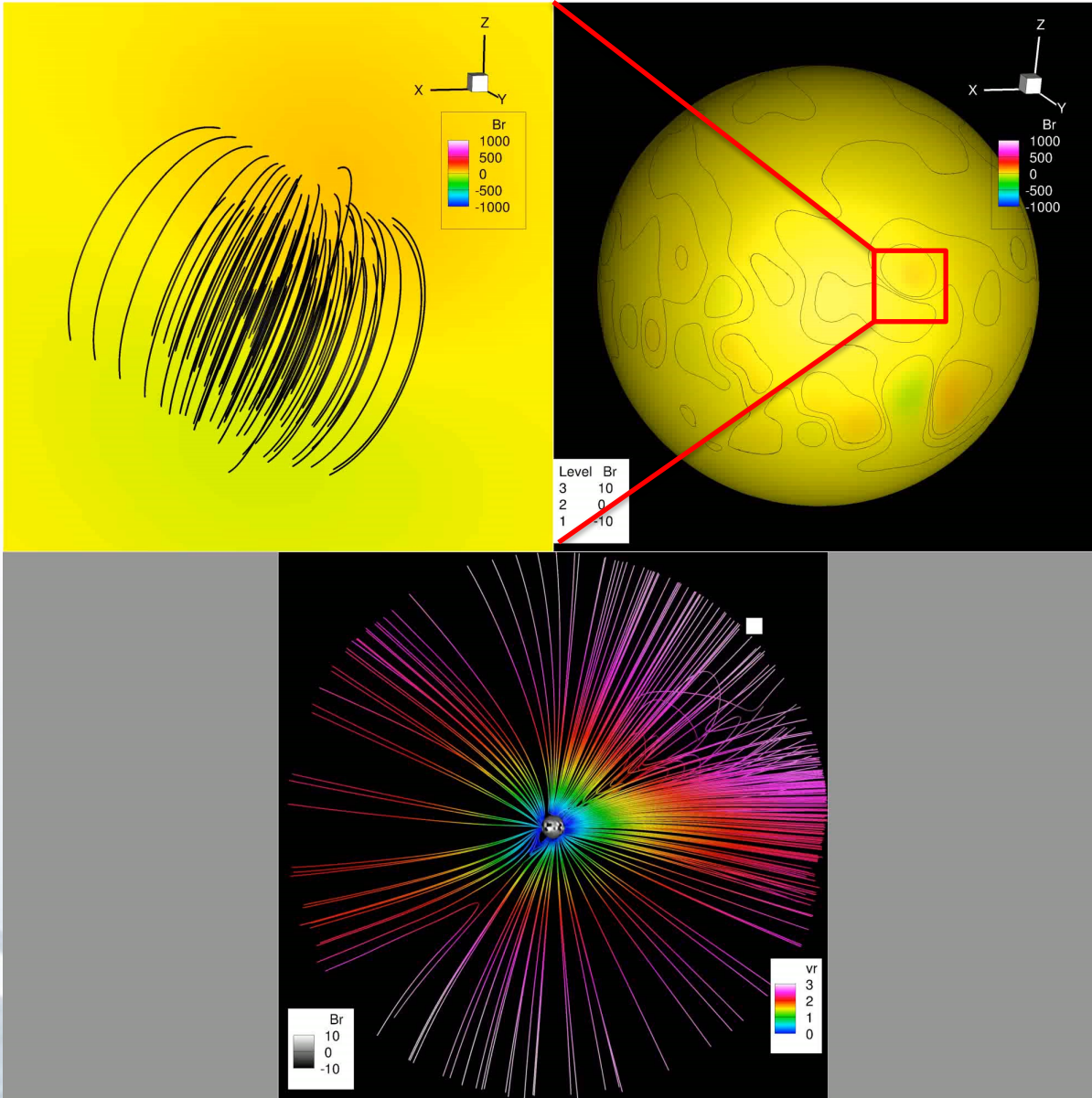
Step0: modeling the solar wind



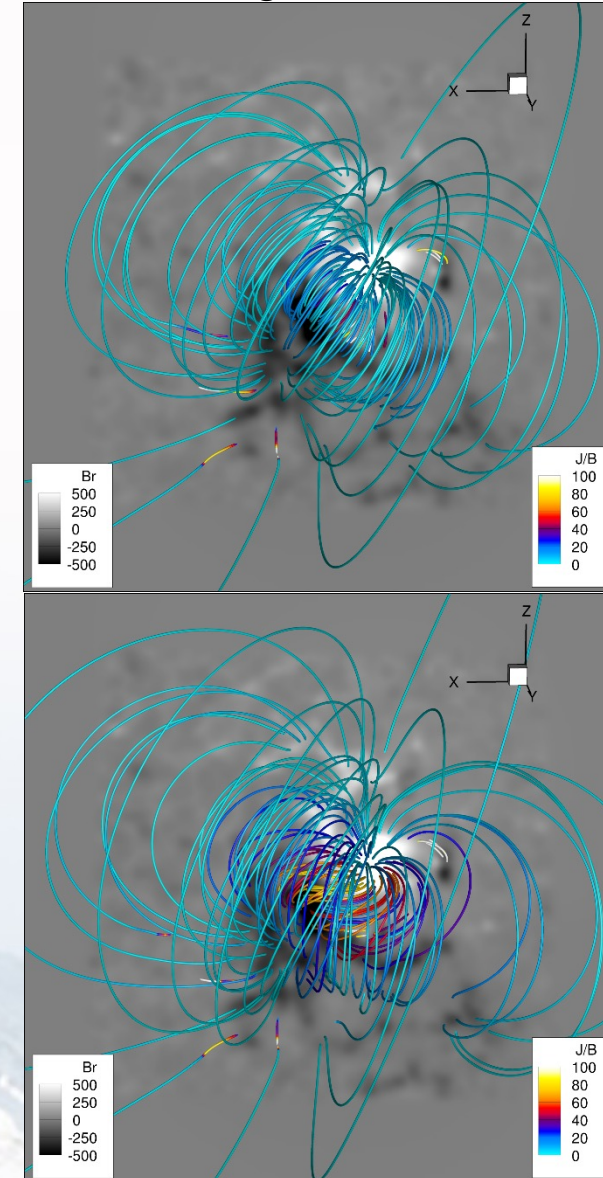
Relaxation of potential field + Parker's analytic solution

Step1: Construction of the initial MHD equilibrium with AR

1. A pseudo emergence of the AR magnetic flux



2. A pseudo emergence of the AR current

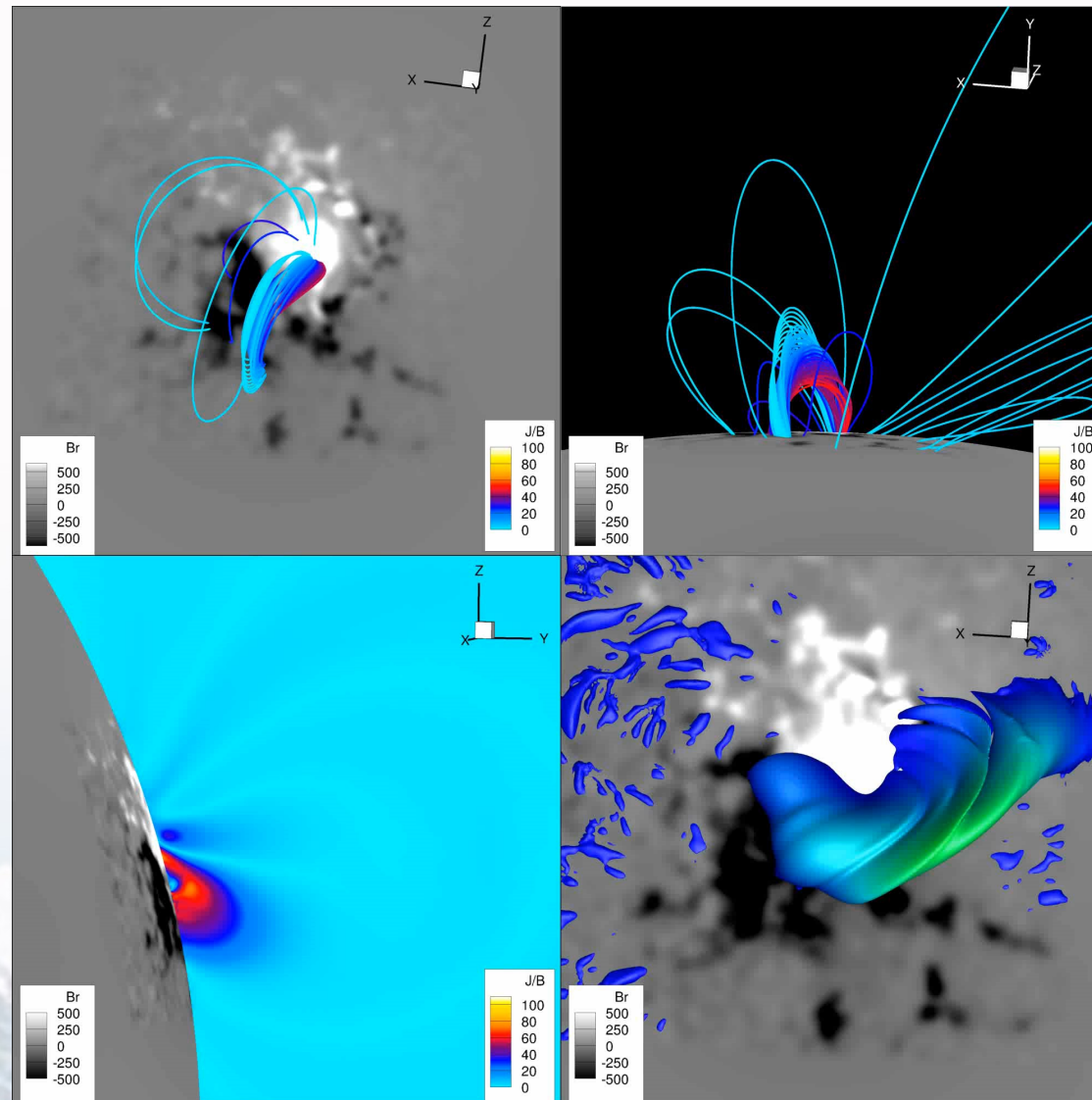
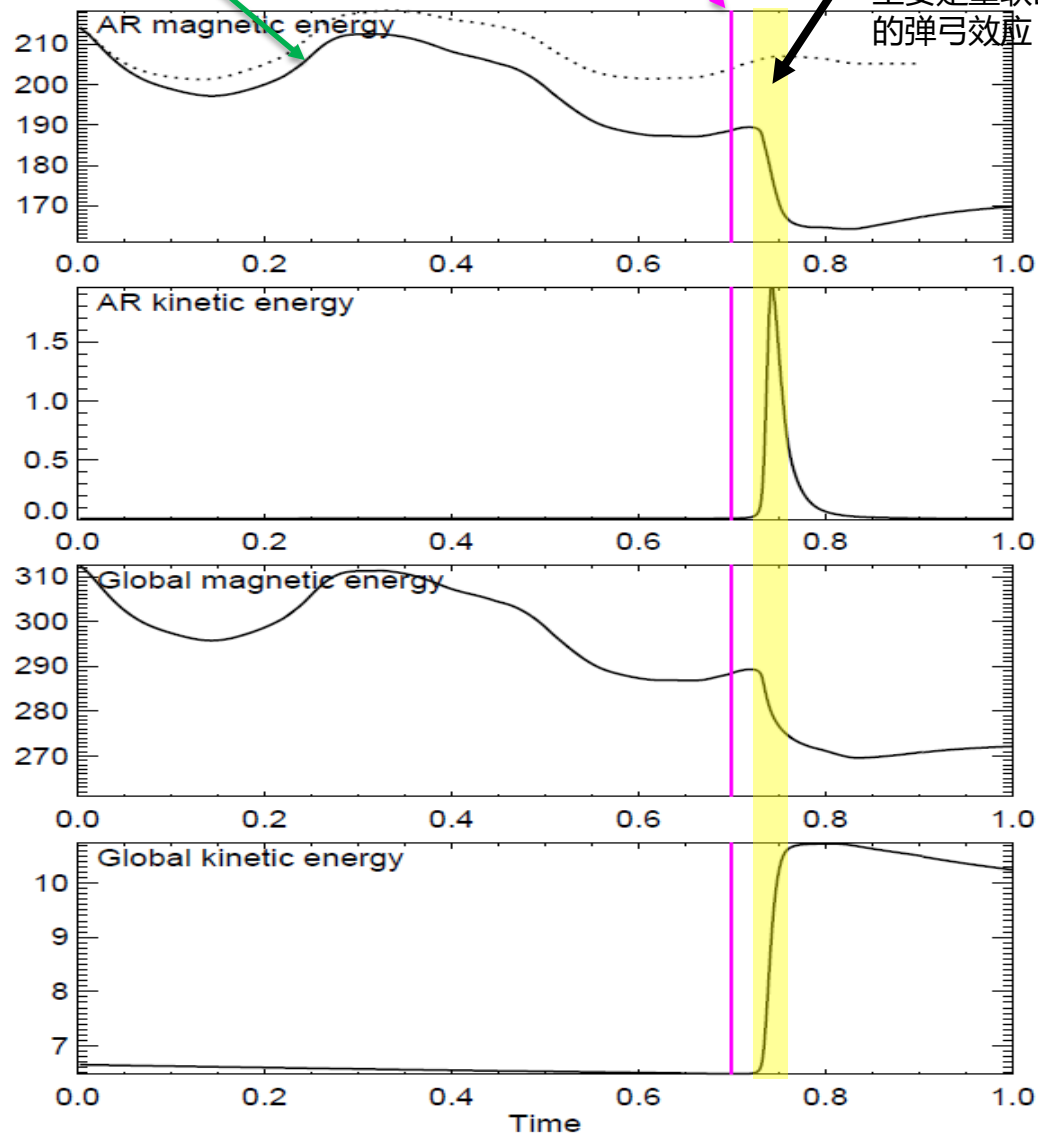


Step2. Data-driven evolution to eruption

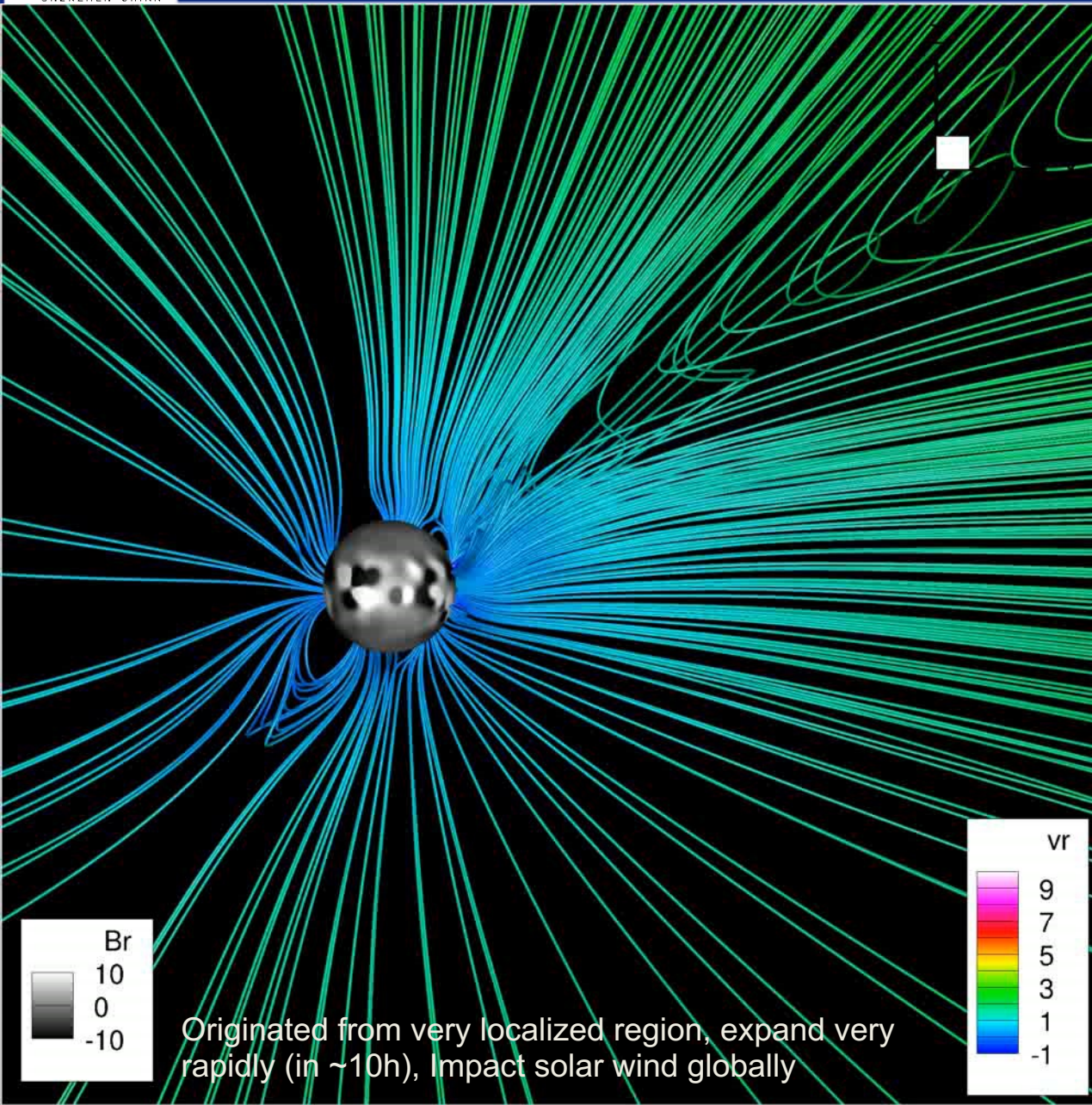
energy injection by Poynting flux

Onset time of X1.6 flare

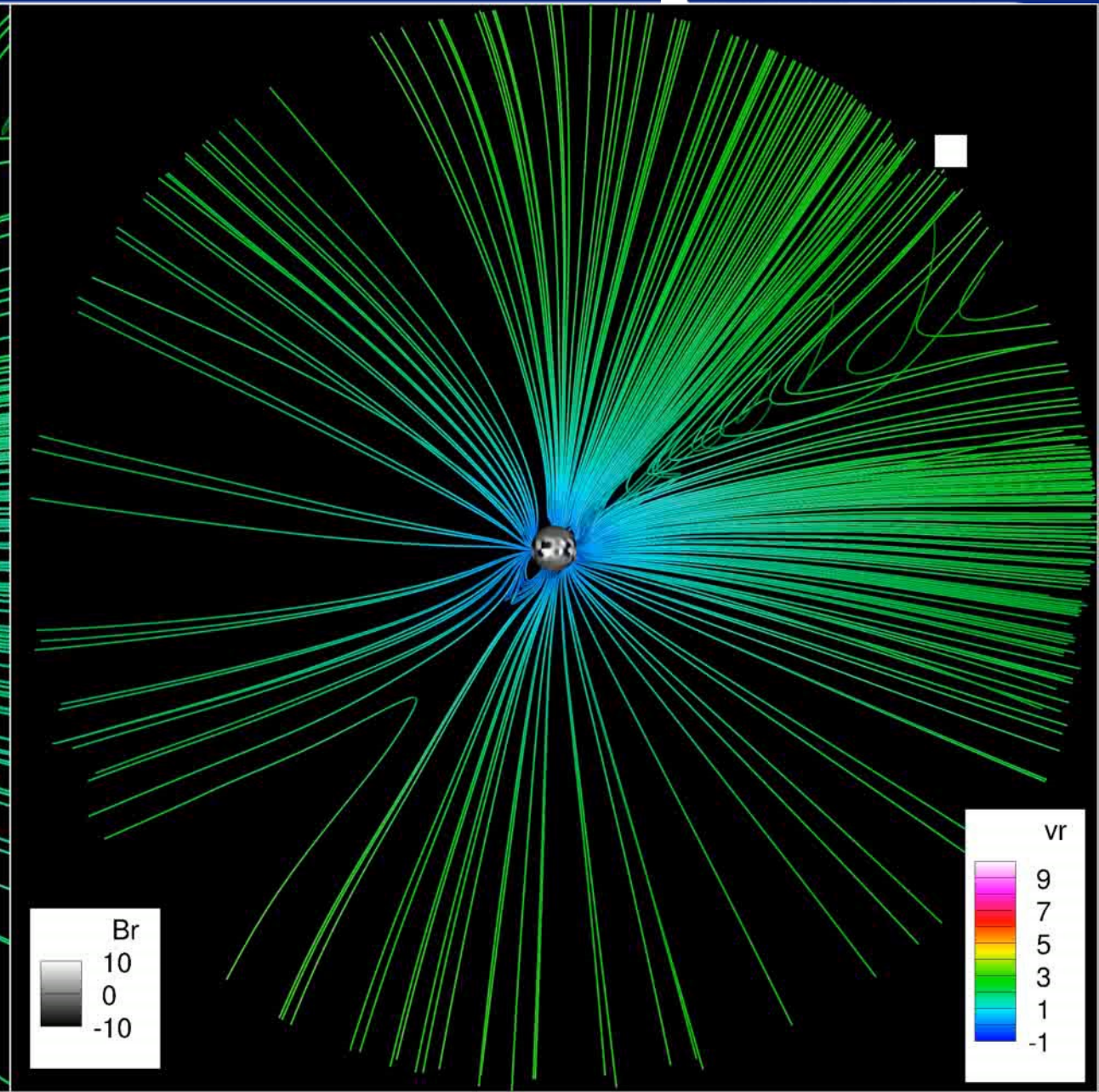
CME加速阶段仅为4.5min, 加速机制主要是重联出流区的弹弓效应

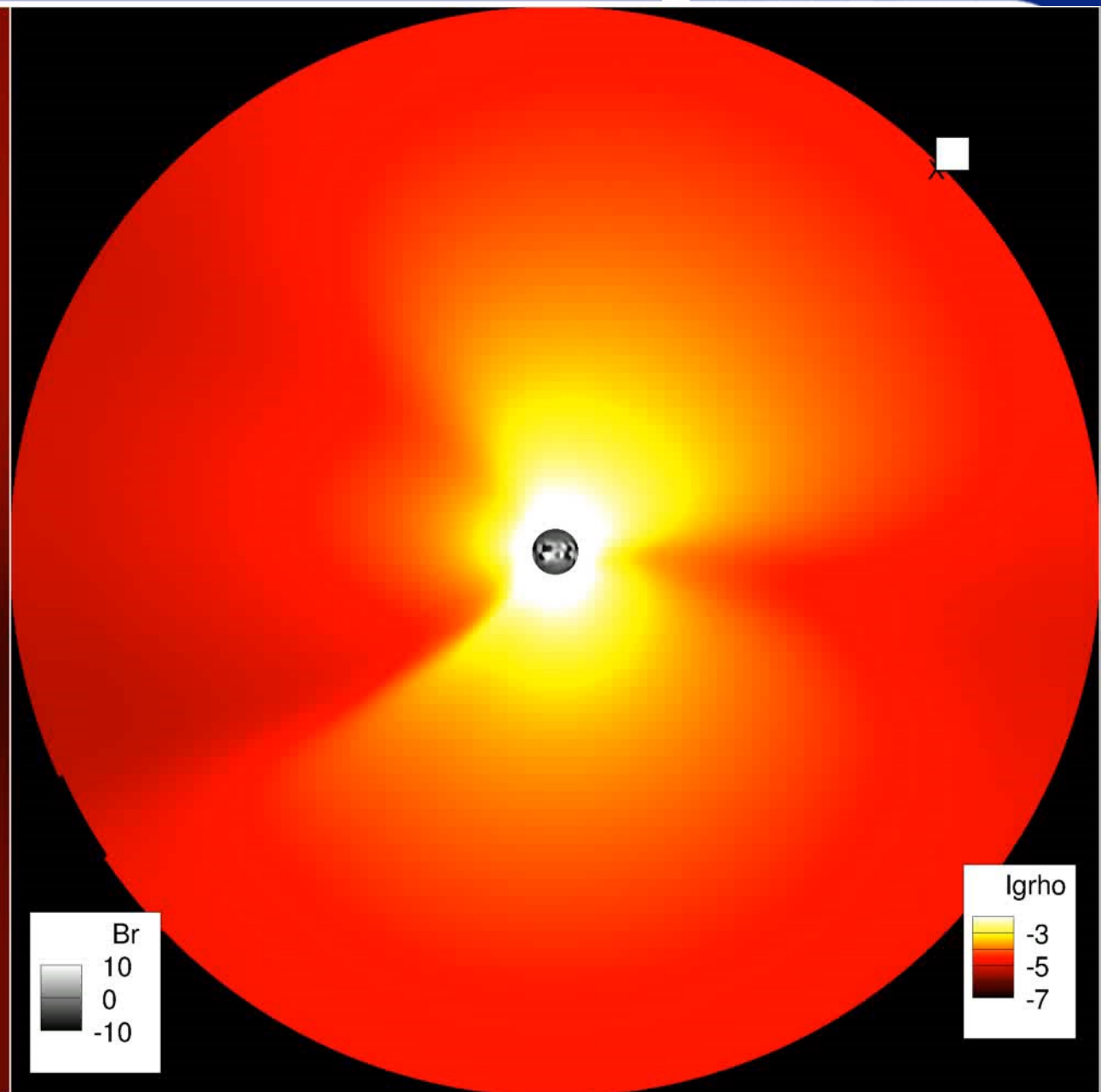
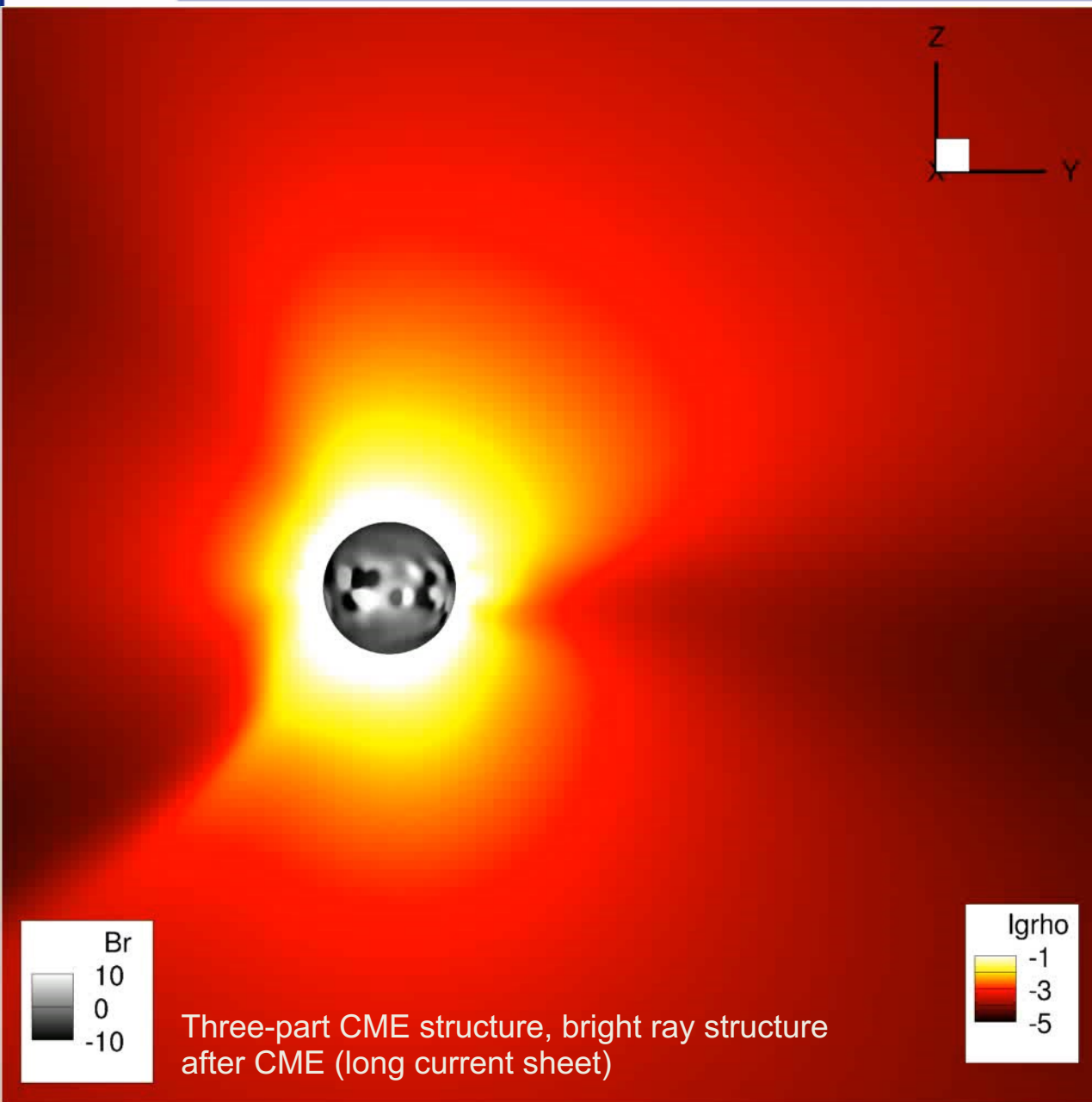


爆发前形成电流片, 重联触发爆发 (机制类似于Jiang et al. 2021, Nat Astro)

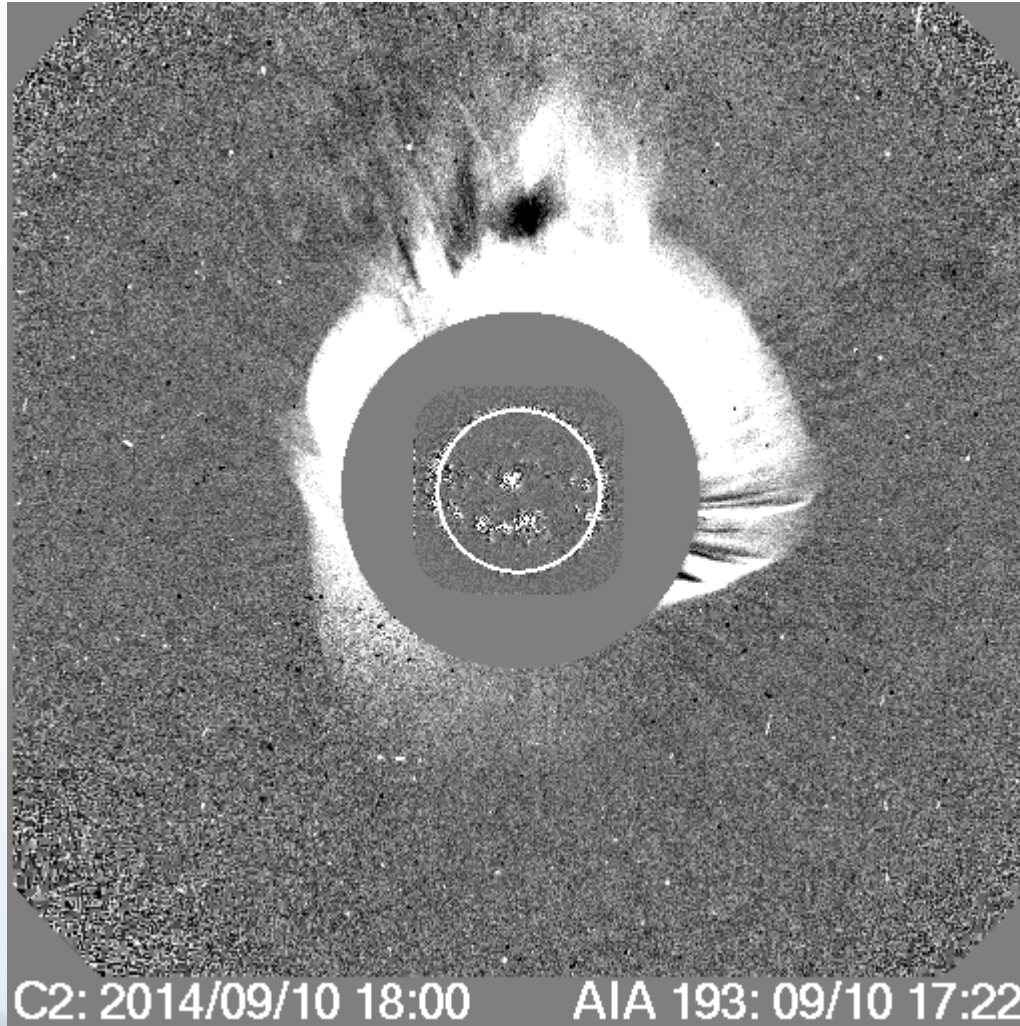


Originated from very localized region, expand very rapidly (in ~10h), Impact solar wind globally



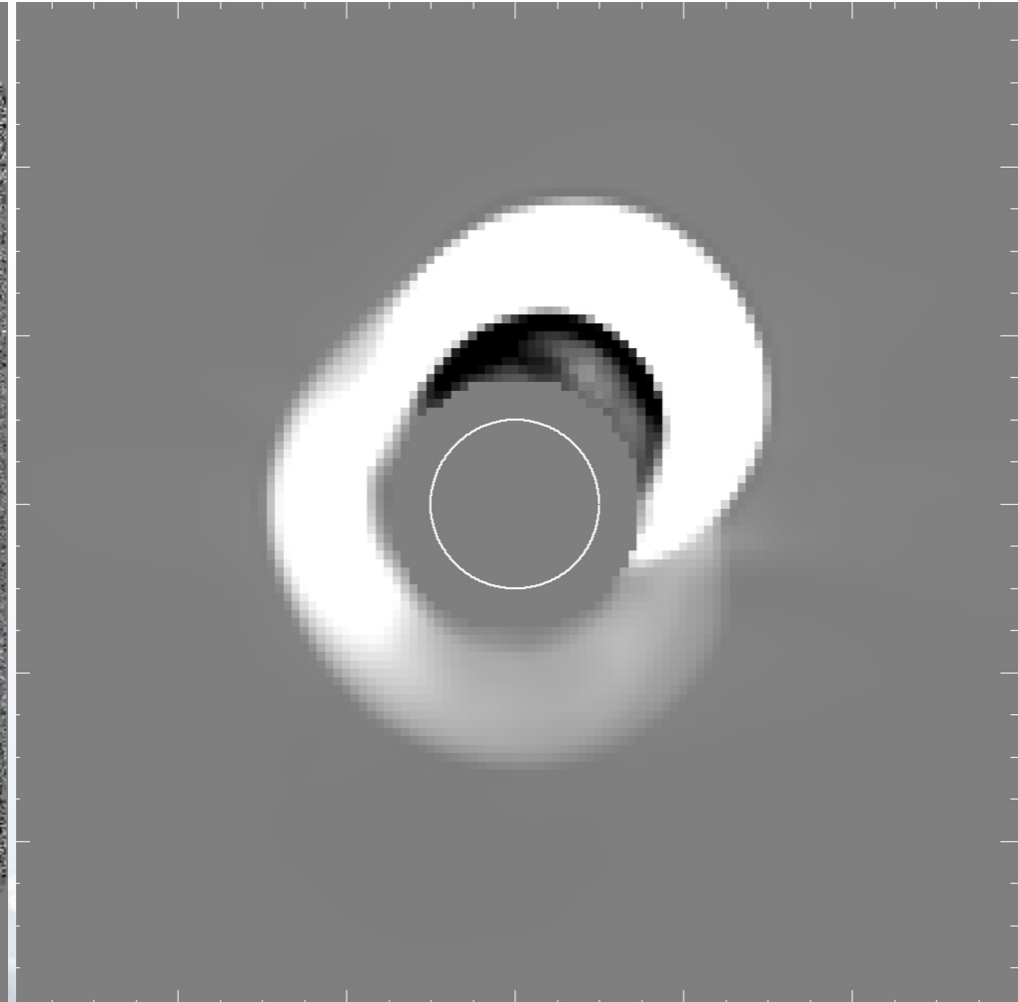


Preliminary comparison with Coronagraph observations

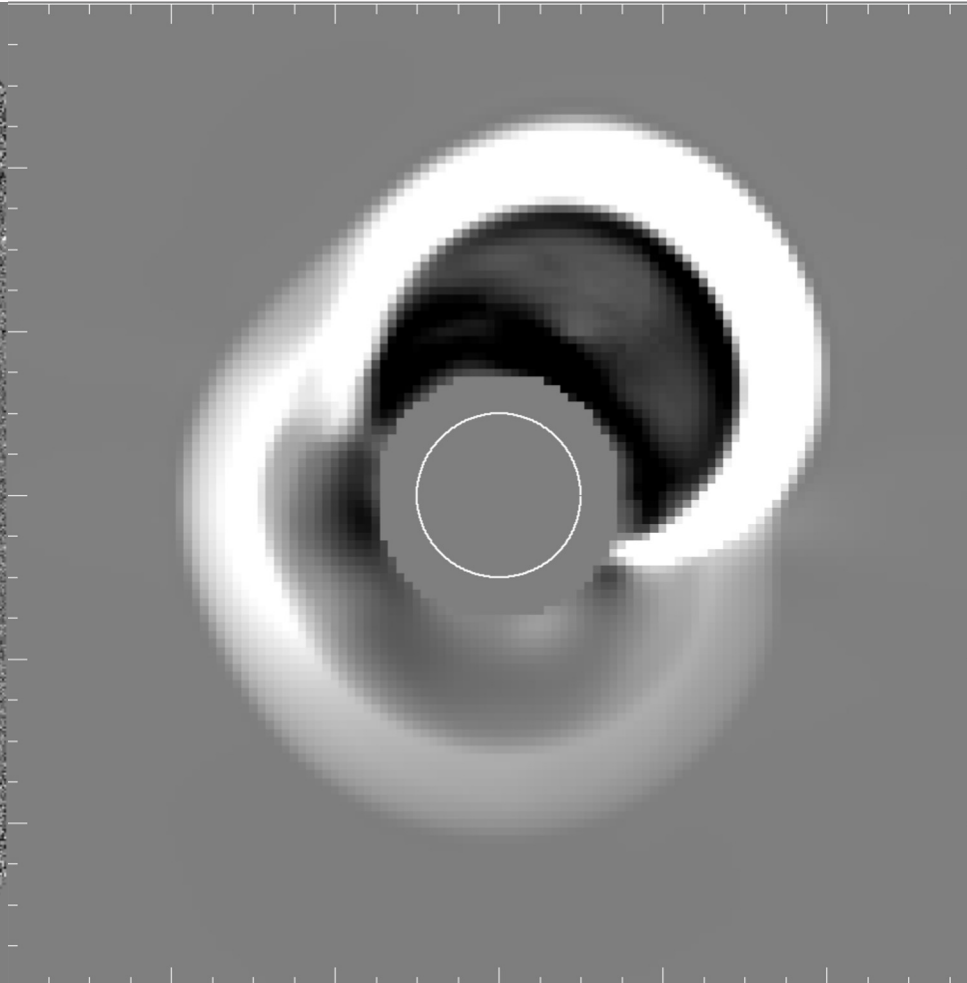
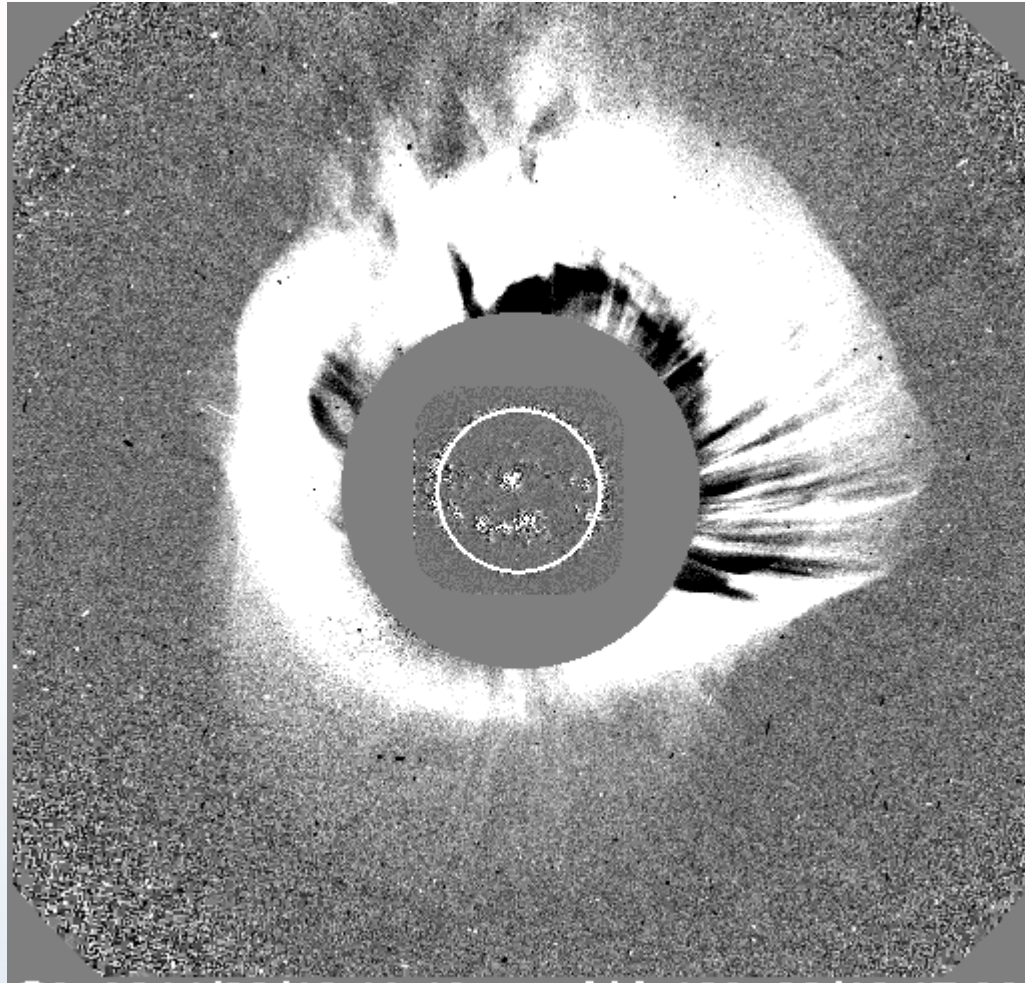


LASCO C2 Observations

CME propagates heading directly toward Earth: full halo CME



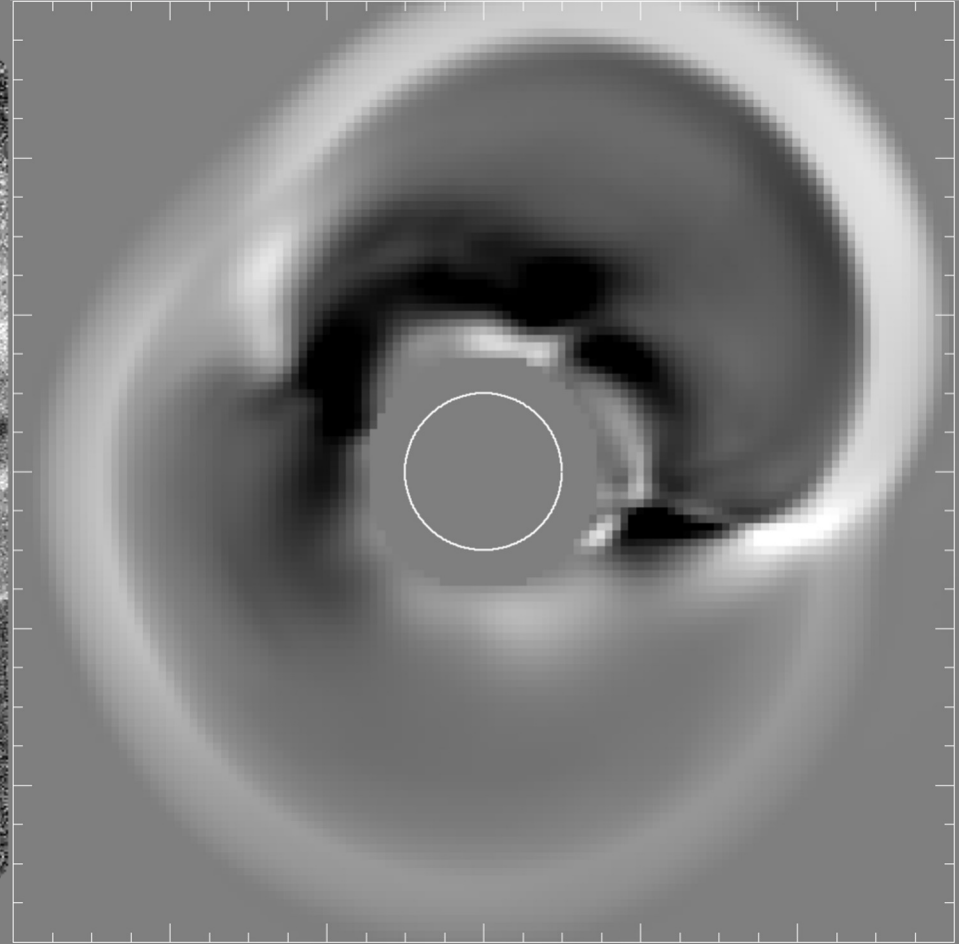
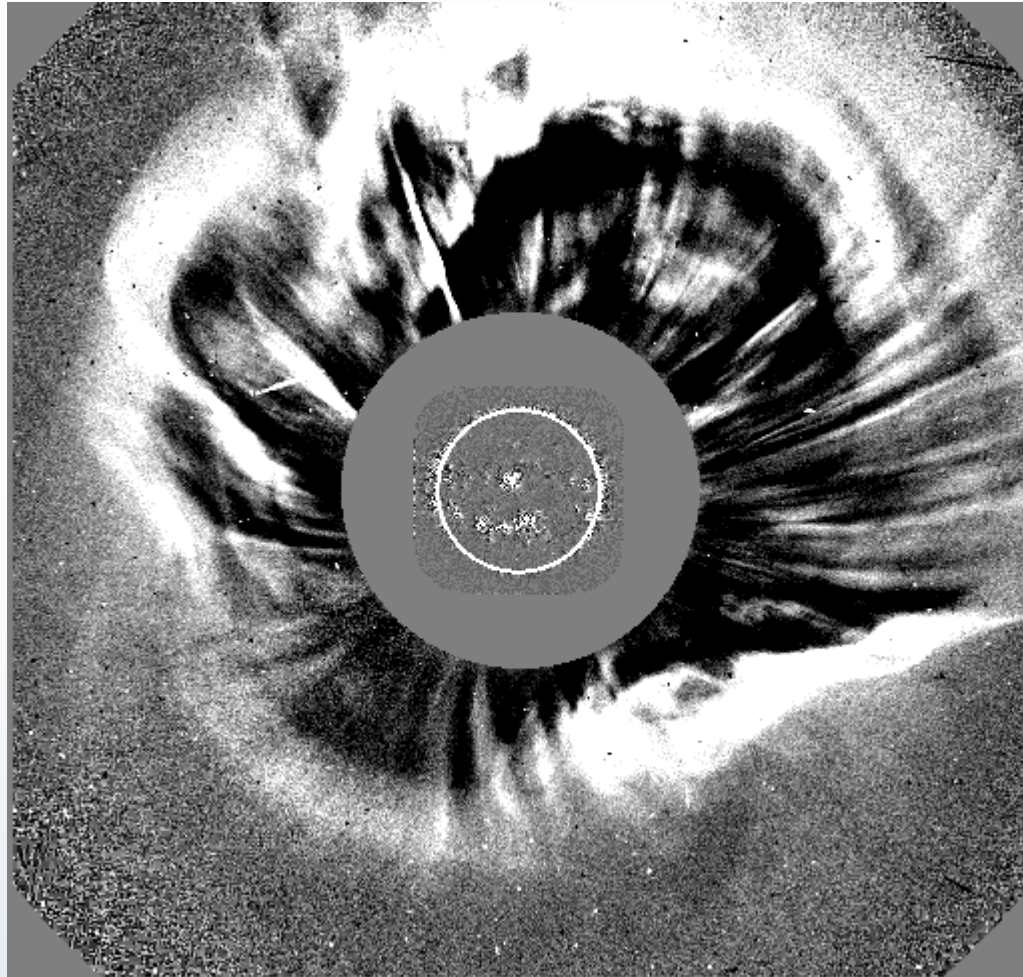
Simulation



C2: 2014/09/10 18:12

AIA 193: 09/10 17:22

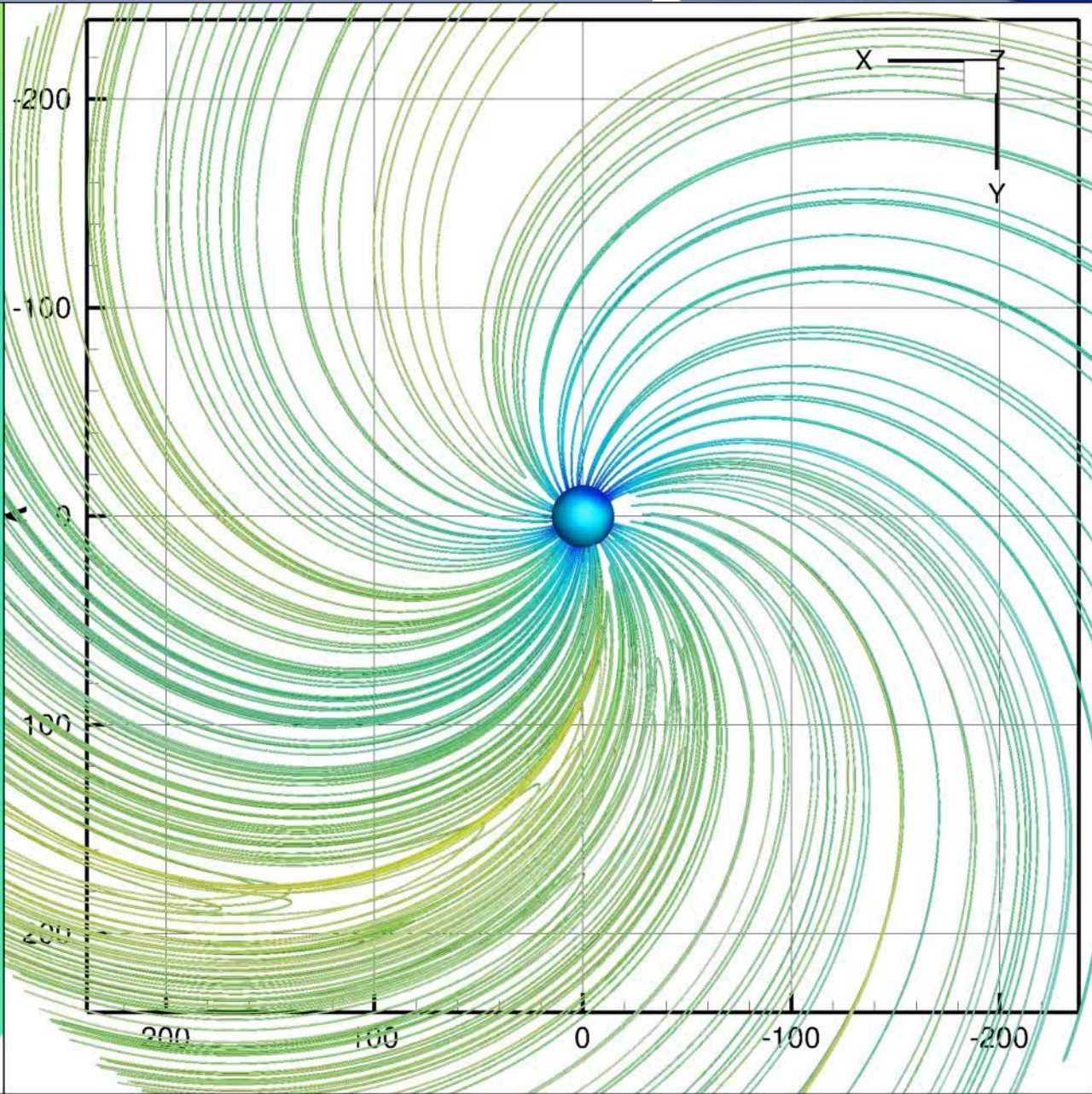
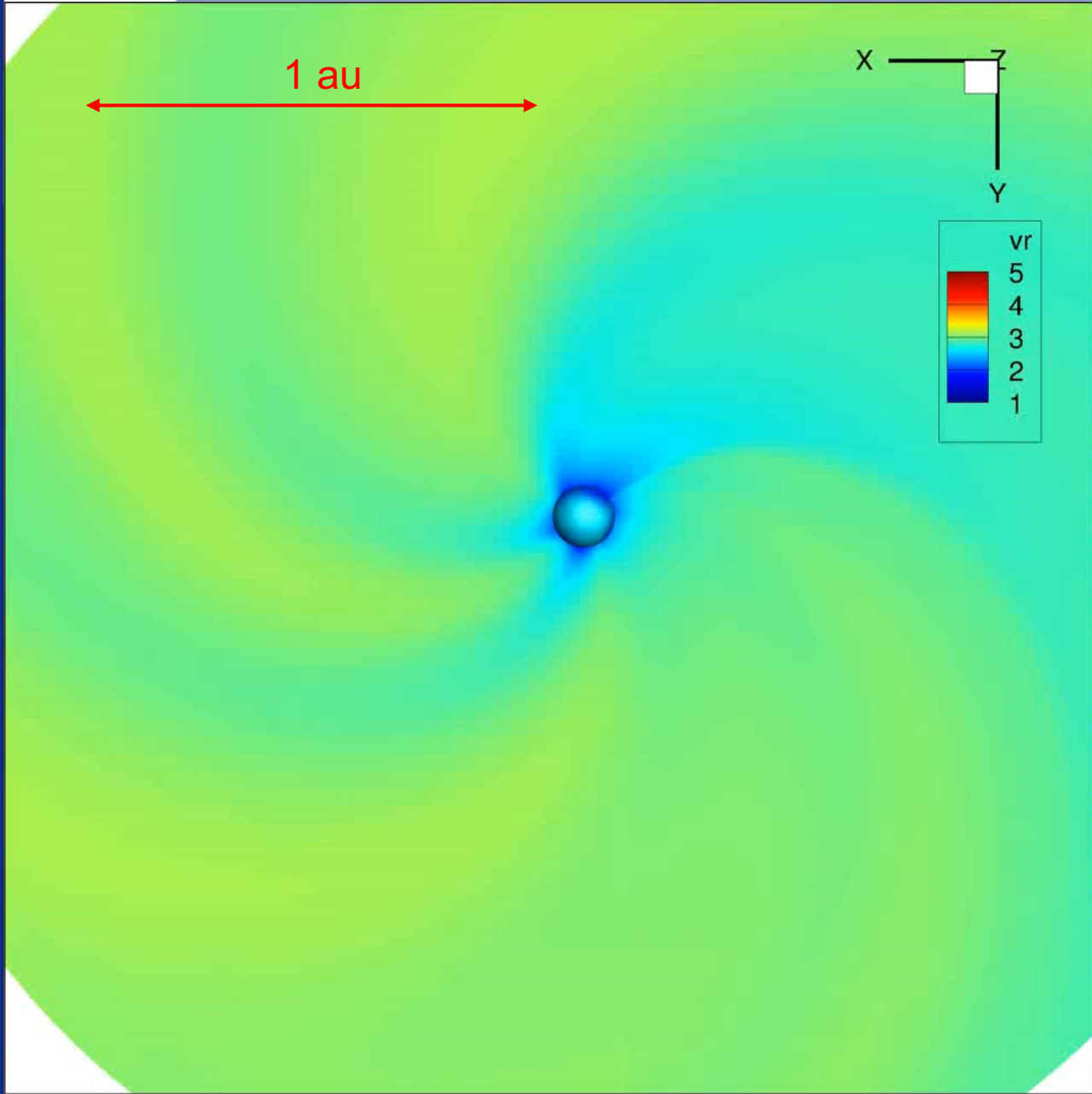
Preliminary comparison with Coronagraph observations



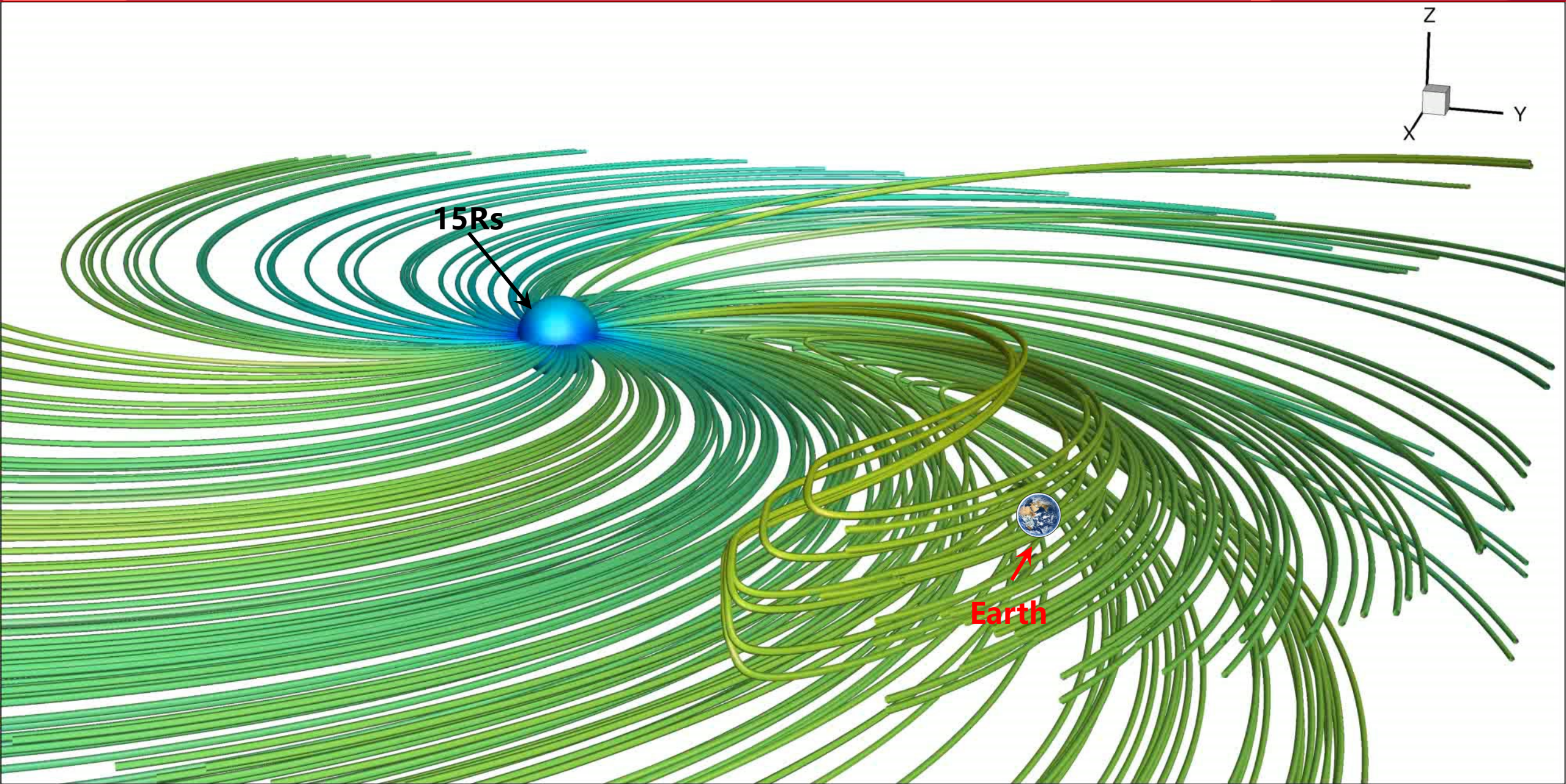
C2: 2014/09/10 18:36

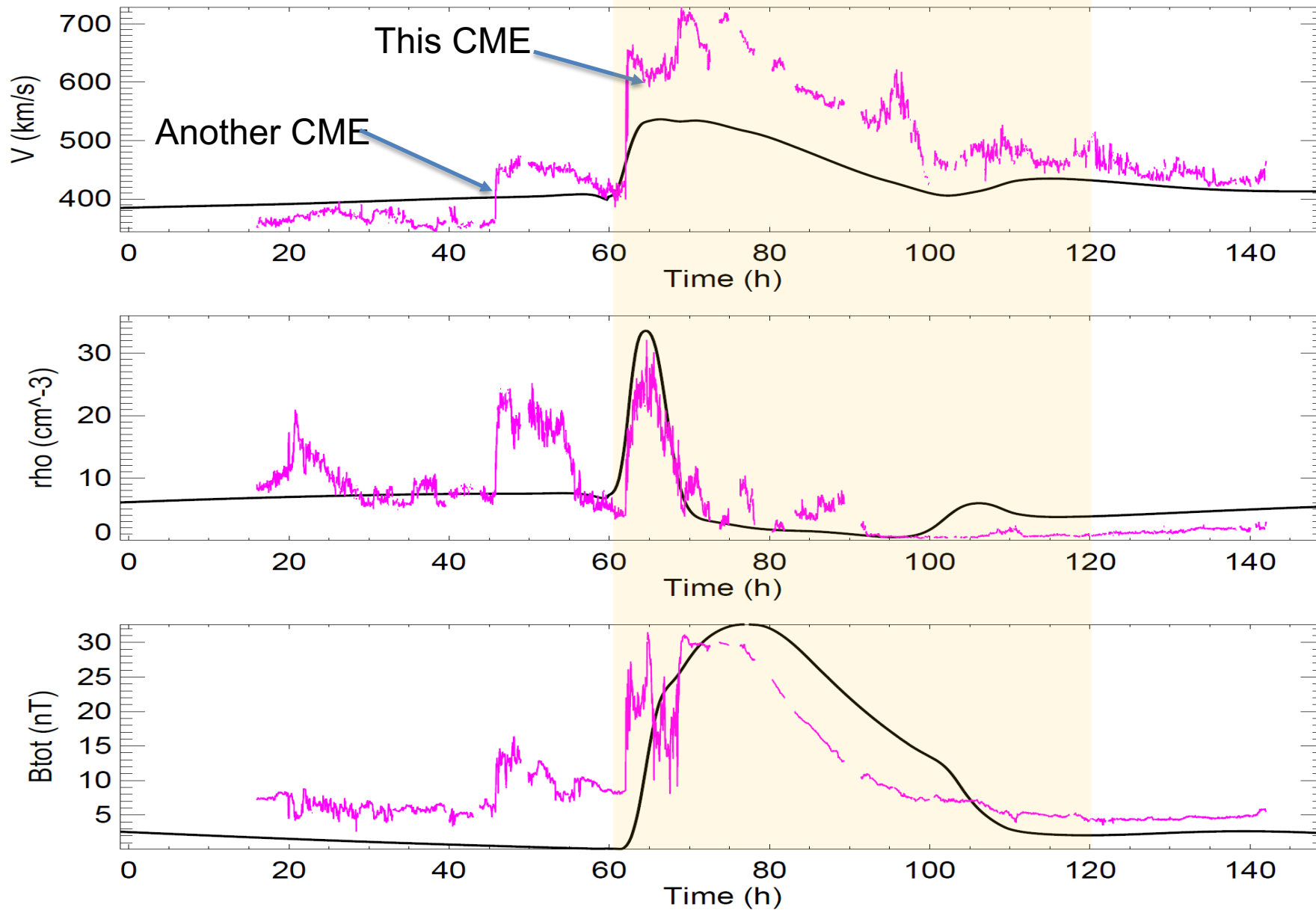
AIA 193: 09/10 17:22

CME propagation to 1au



CME propagation to 1au





Summary

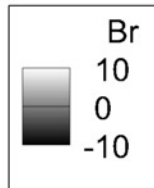
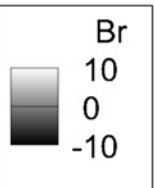
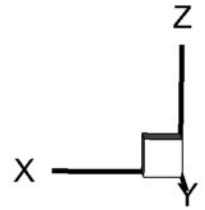
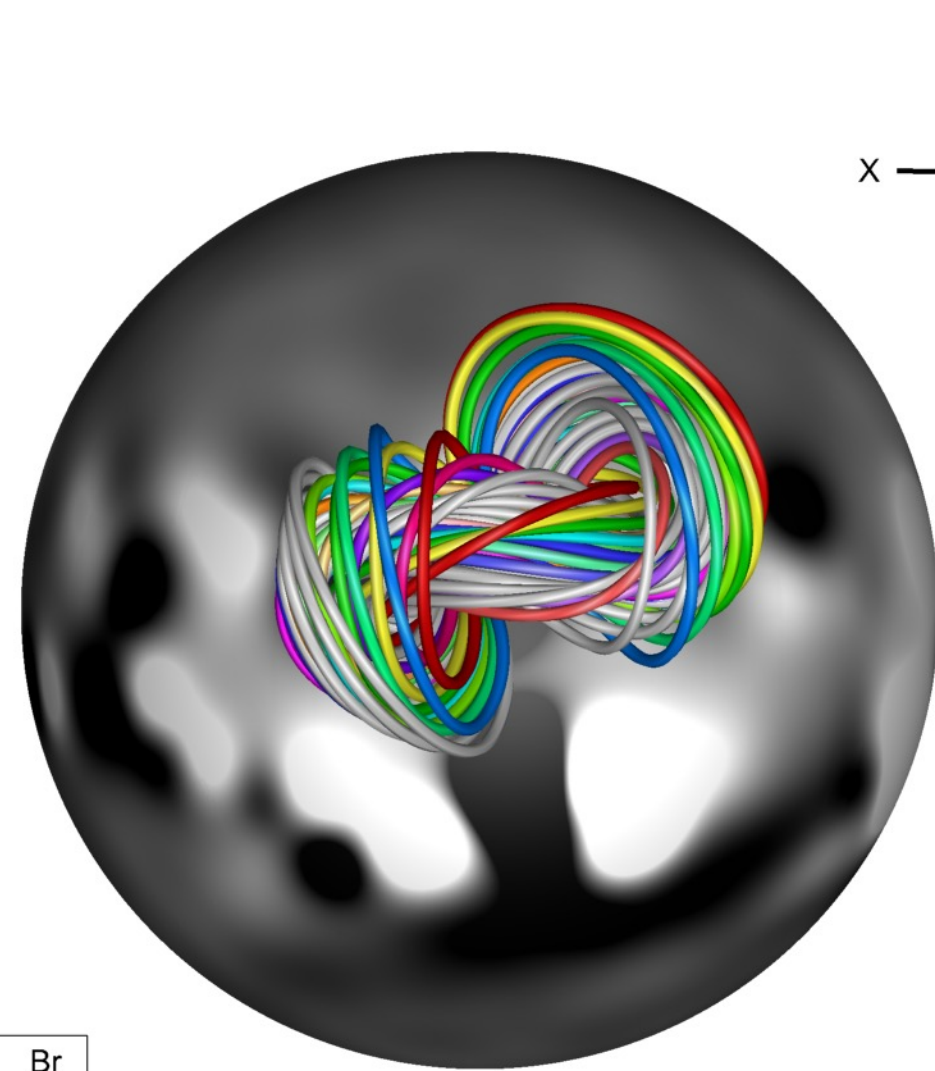
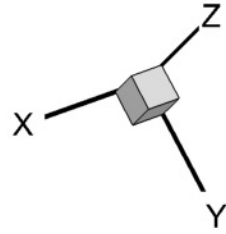
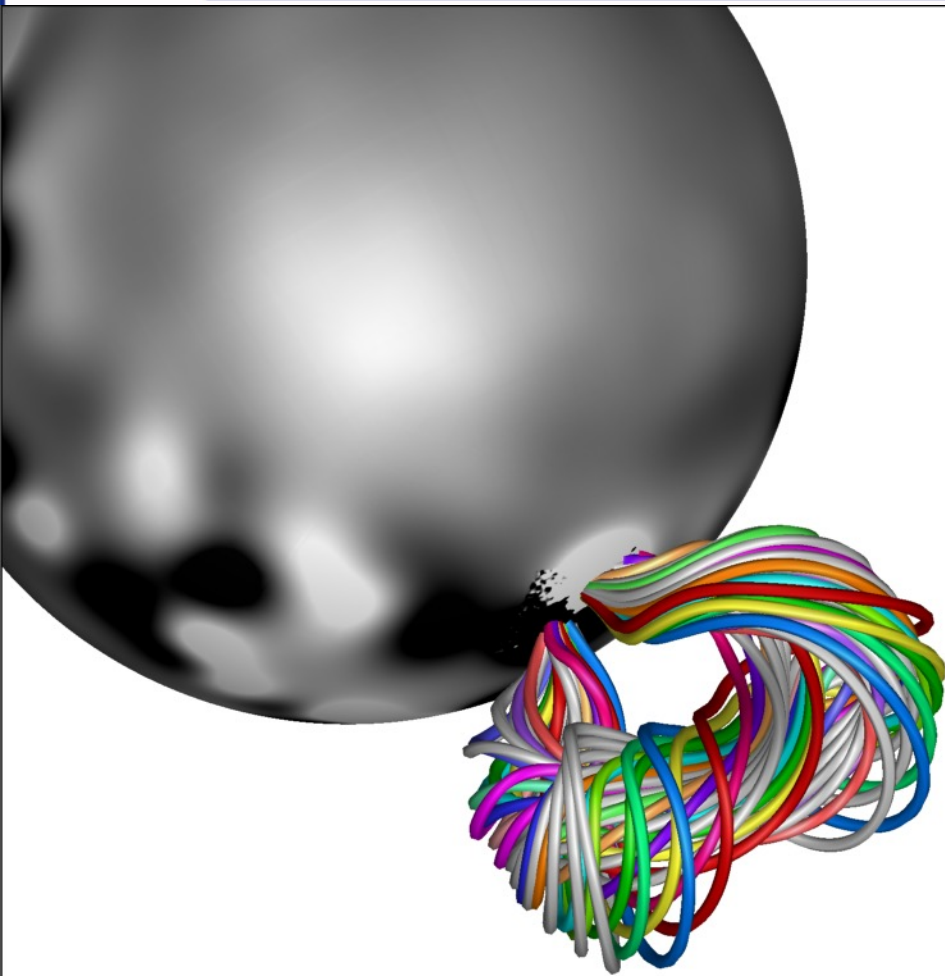
- We have developed the first data-driven MHD model that can follow CME origination from the Sun and its propagation to 1.5 au
- The simulation reproduced the magnetic evolution in both the source region and the 1 au in-situ observation (in large-scale)
- The model can potentially be applied for space-weather prediction

Thanks!
chaowei@hit.edu.cn





3D magnetic structure of CME, early phase ($<2R_s$)



3D magnetic structure of CME: 20Rs(0.1au)



Br

10

0

-10

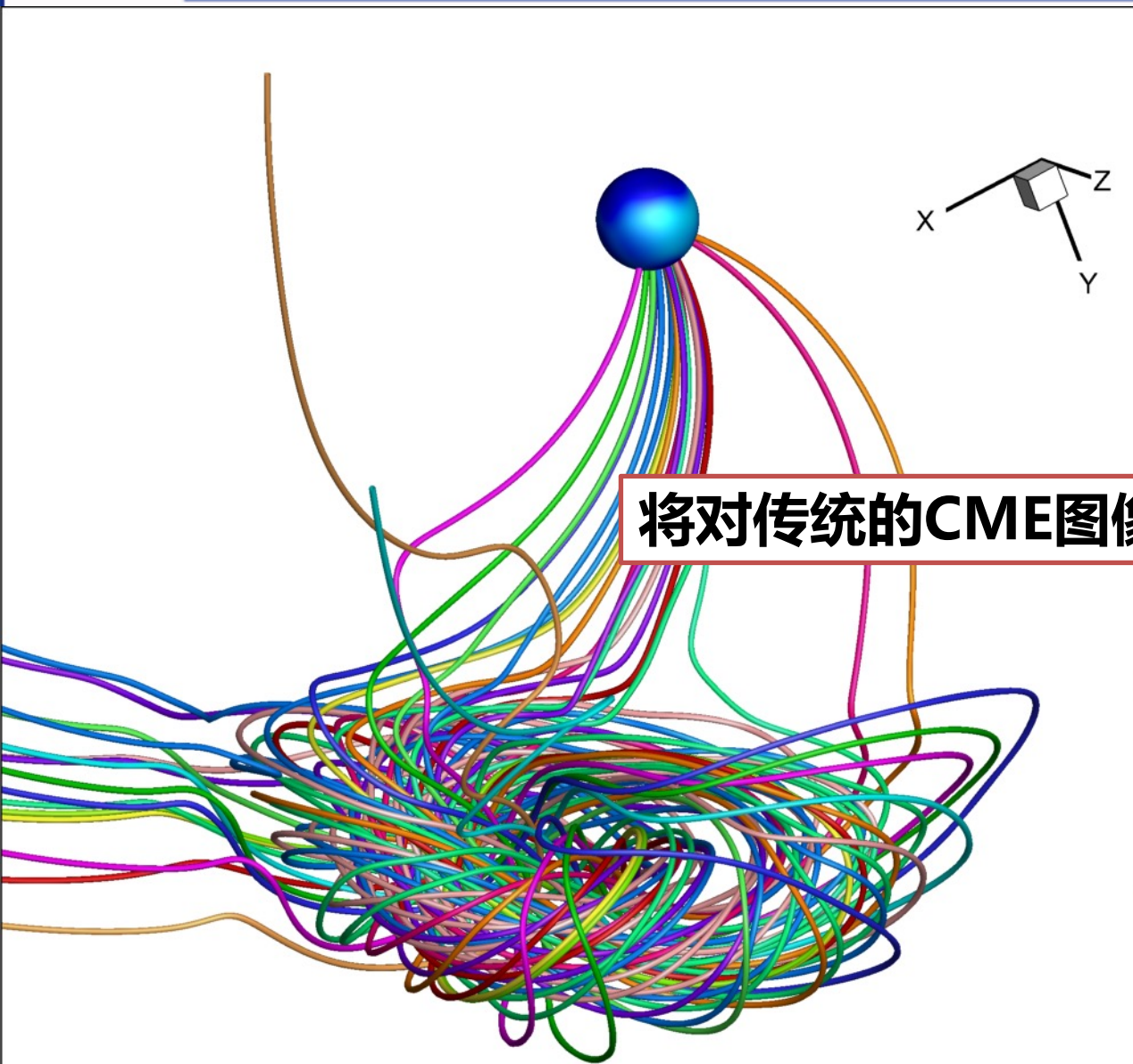
Br

10

0

-10

3D magnetic structure of CME: 1au



将对传统的CME图像有一个重要的更新!

