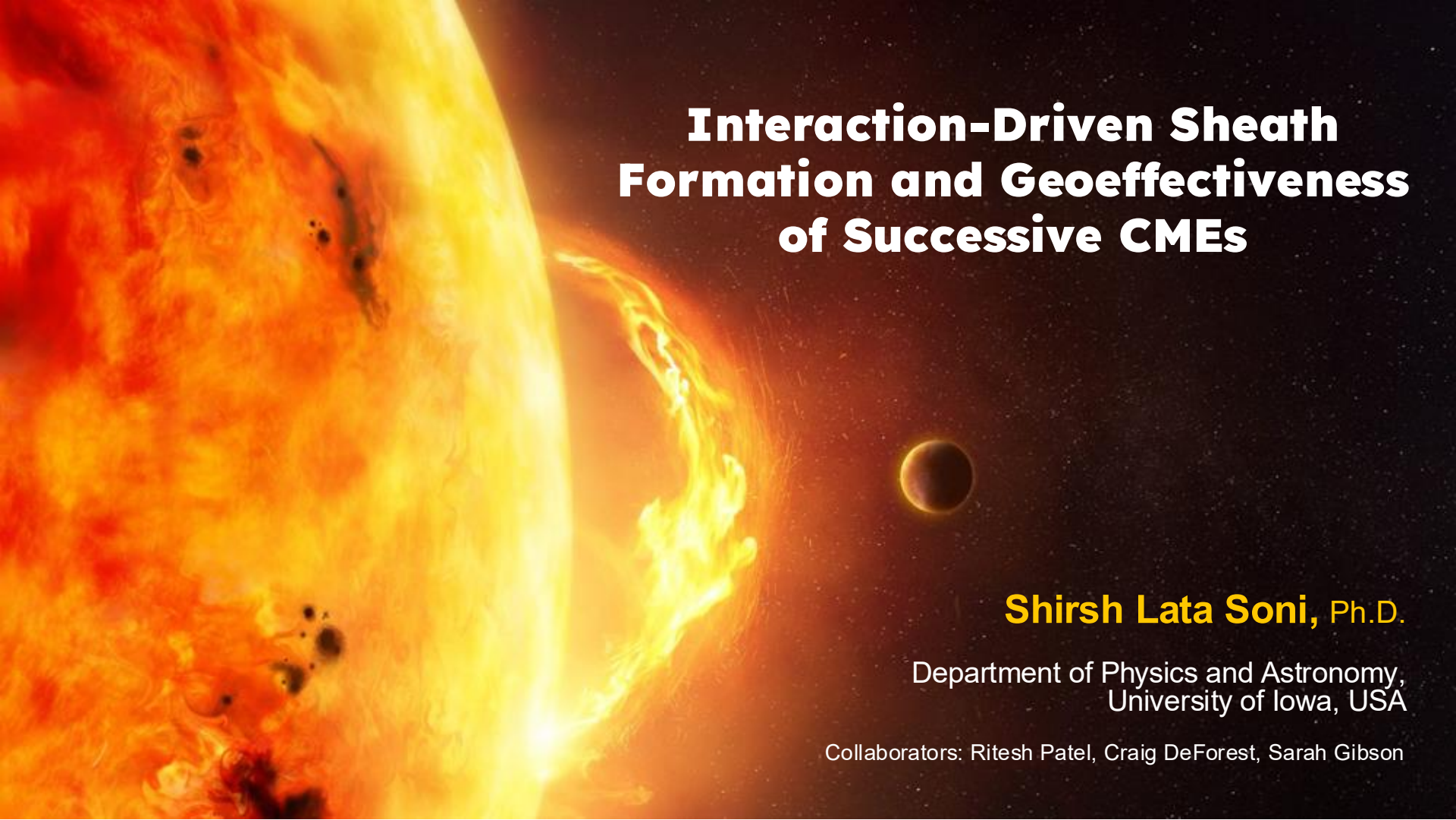


Interaction-Driven Sheath Formation and Geoeffectiveness of Successive CMEs

Shirsh Lata Soni, Ph.D.

Department of Physics and Astronomy,
University of Iowa, USA

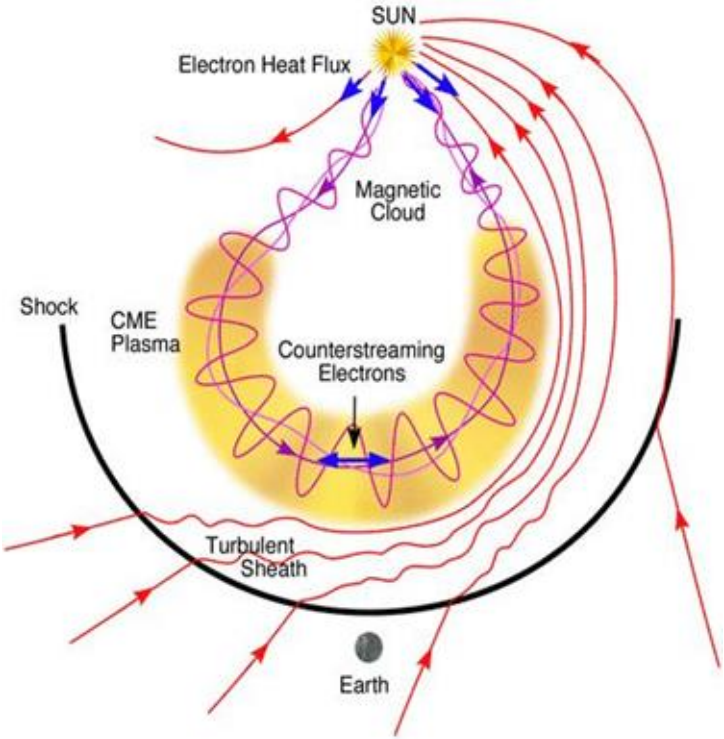
Collaborators: Ritesh Patel, Craig DeForest, Sarah Gibson

1. CME-CME Interaction

- CMEs accompanied by their associated interplanetary components (such as CME-driven shocks, sheaths, and magnetic ejecta:
  - Identified as the leading cause of up to 90% of severe geomagnetic storms (Dst index below -100 nT).

- The genesis of these intense storms primarily results from a combination of factors, including
  - Extended durations (typically exceeding 3 hours) of strongly southward-directed (negative Bz) interplanetary magnetic fields.
  - Elevated dynamic pressure within magnetic ejecta.

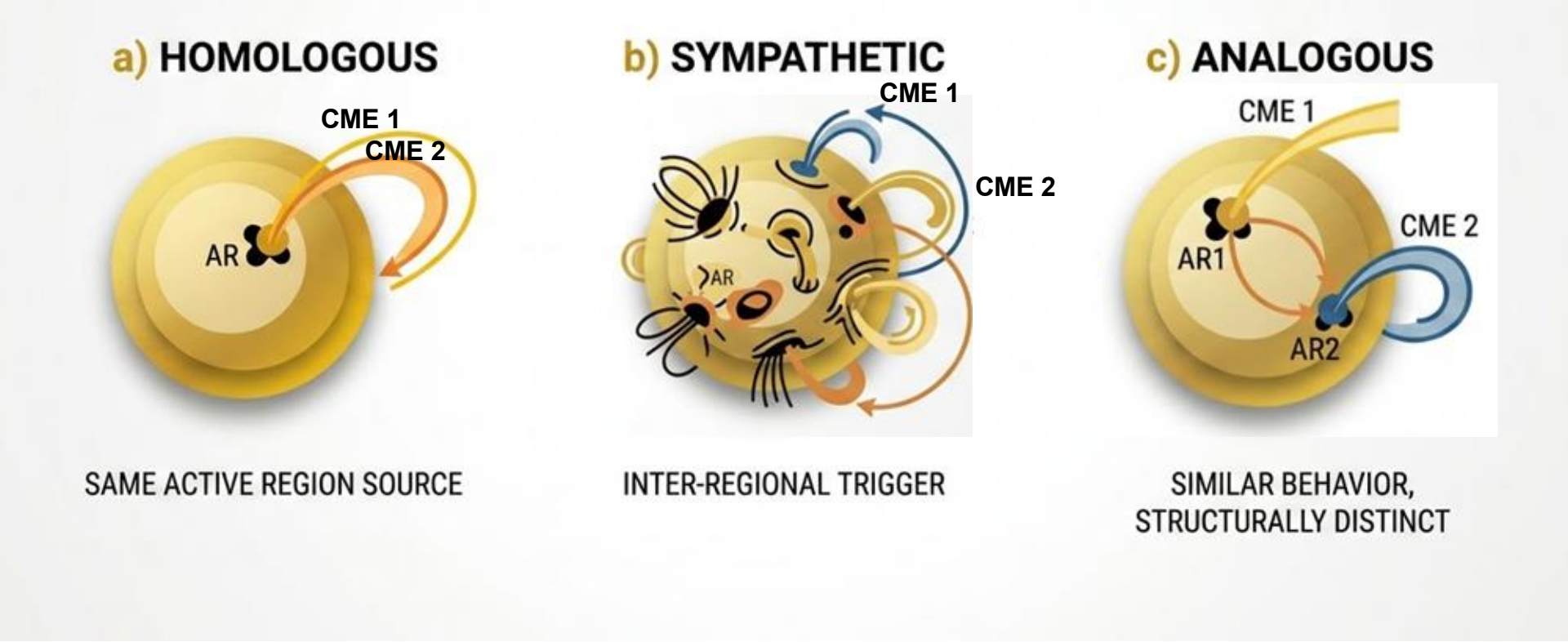
- A majority of these severe storms can be attributed to single CME events (approximately 60%),
  - Complex CMEs: ~27%
  - Individual CMEs and Other transient phenomena, including other CMEs and regions of stream interaction.



Nearly one-third of CMEs are complex CMEs.

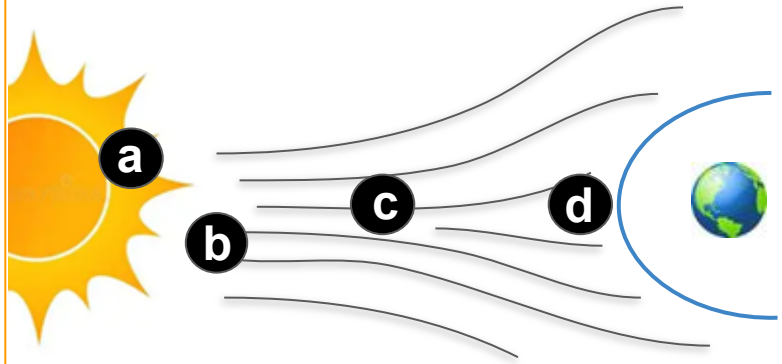
2. Types of Interacting CMEs

Interacting CMEs can be classified into three solar source regions:



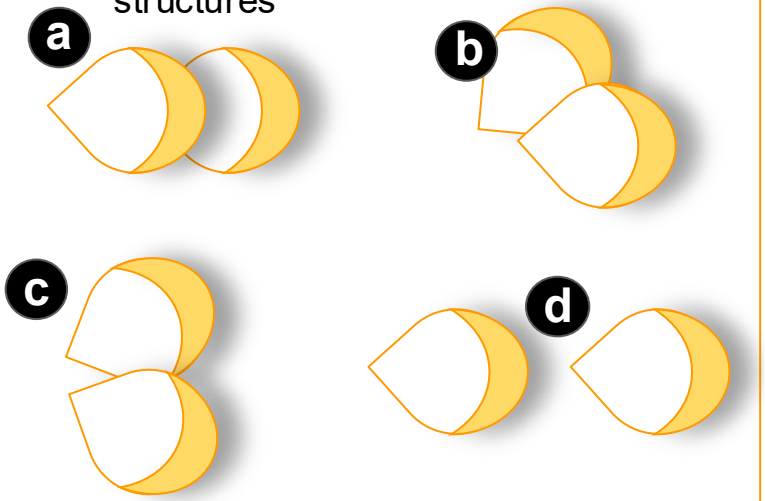
Location of Interaction

a. Within Solar Corona
b. Near Sun
c. In Between Sun-Earth Line
d. Near Earth (1 AU)



CME Interaction Type

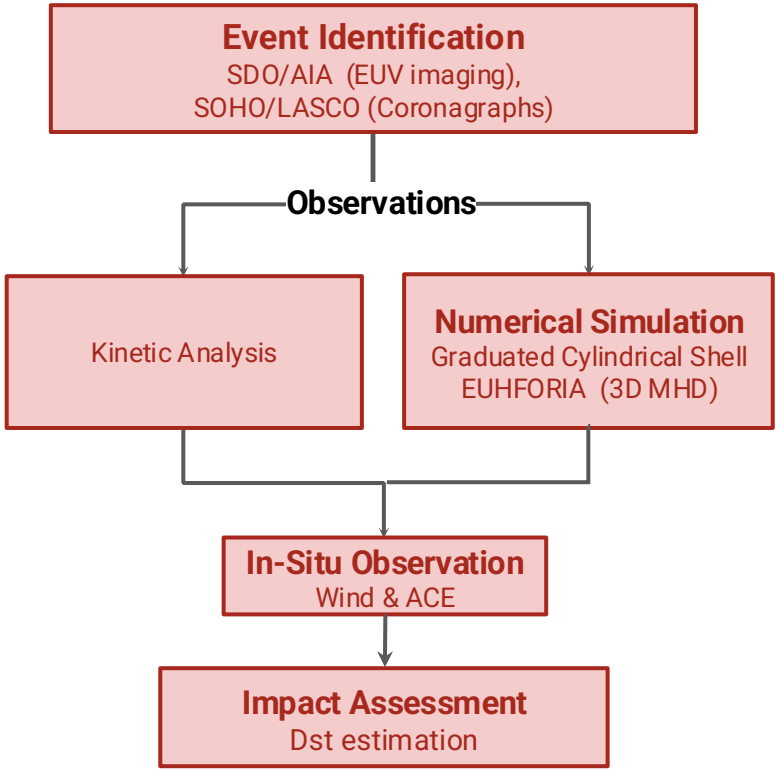
a. Back to Nose
b. Nose to Flank
c. Flank to Flank
d. Interaction with successive structures



Soni et al., 2023

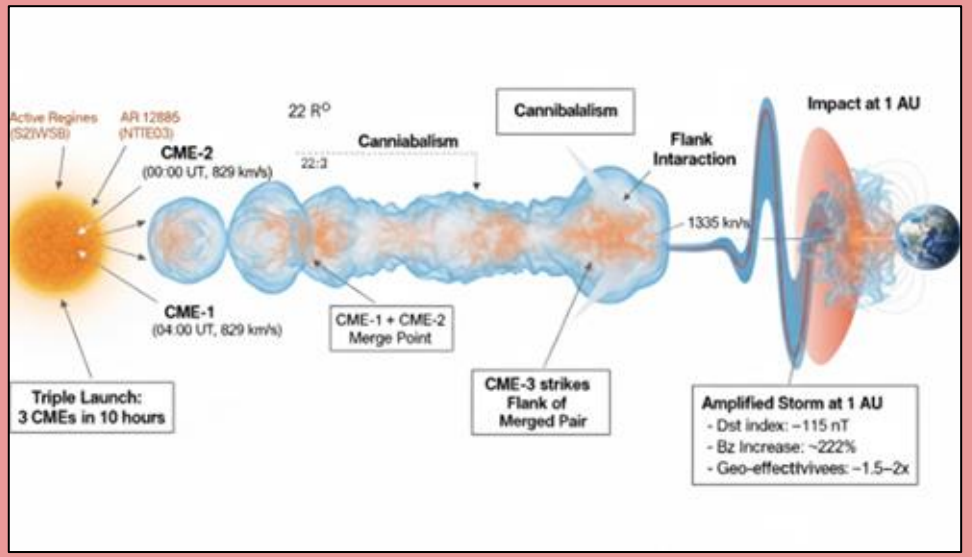
CMEs evolve in the interplanetary medium to double their predicted geo-effectiveness

METHOD



Conclusion

The interaction and cannibalism between multiple CMEs in November 2021 led to a significant compression of magnetic structures, doubling their predicted geo-effectiveness upon reaching Earth.



Takeaway Message: RD-type switchbacks relax upon generation and heat the solar corona by dissipating

Soni et al., 2023

CMEs evolve in the interplanetary medium to double their predicted geo-effectiveness

METHOD

Event
SD
SOH

Kinetic Analysis

Numerical Simulation
Graduated Cylindrical Shell
EUHFORIA (3D MHD)

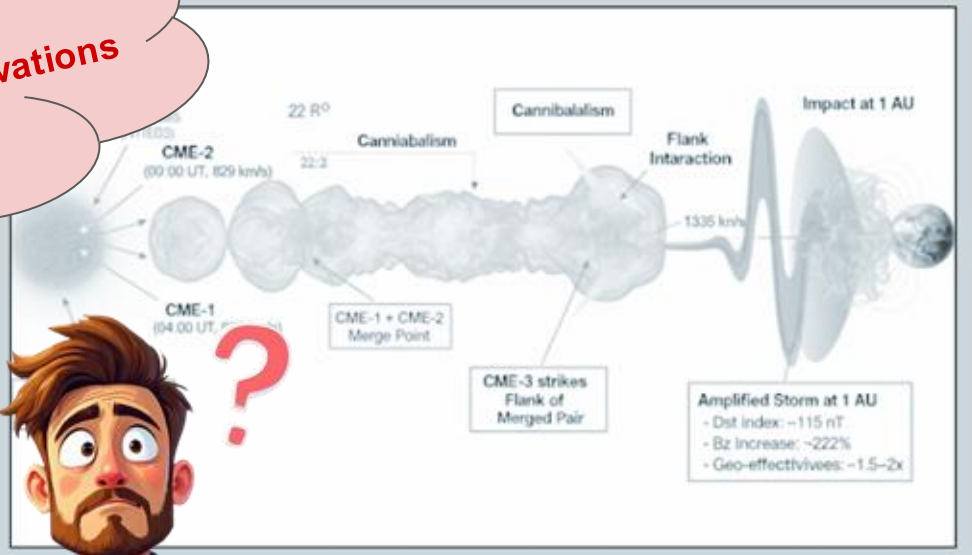
In-Situ Observation
Wind & ACE

Impact Assessment
Dst estimation

Limitation:
Required Multiview point Observations

Conclusion

The interaction and cannibalism between multiple CMEs in November 2021 led to a significant compression of magnetic structures, doubling their predicted geo-effectiveness upon ing Earth.



ge: RD-type switchbacks relax upon generation
eat the solar corona by dissipating

Soni et al., 2026

Comprehensive MHD modelling of ten successive CMEs driving a historic geomagnetic storm - The 2024 Mother's Day event

METHOD

Event Identification
Compile timeline of solar eruptions, flares, filaments, and CME launches

Analysis

Multi-Point Obs.
SDO, SOHO/LASCO, STEREO
Kinetic Analysis

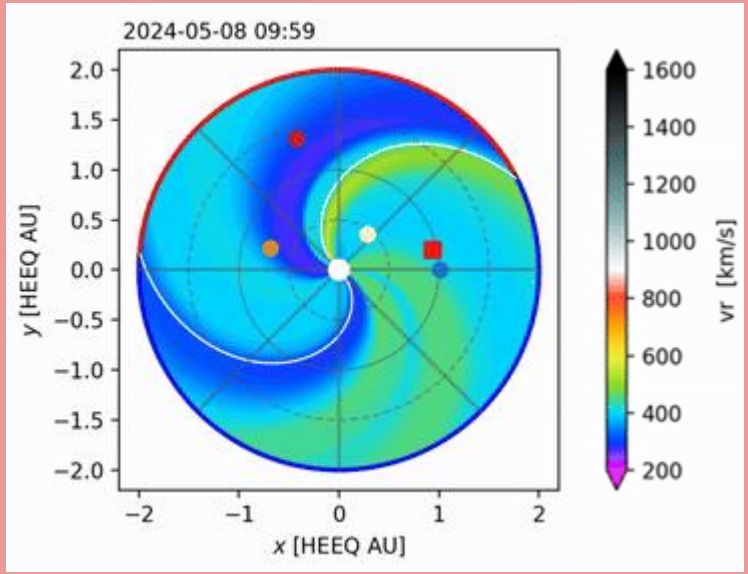
3D Reconstruction
Graduated Cylindrical Shell
EUHFORIA (3D MHD)

Model-Observation Comparison

Geoeffectiveness Assessment

Conclusion

1. A sequence of interacting CMEs whose combined evolution in the heliosphere substantially enhanced storm intensity compared to any single CME scenario.
2. 3D MHD modeling that includes all interacting CMEs reproduced the storm arrival time within ~2 hours and captured ~70% of the observed storm strength, highlighting the critical role of accurate CME identification and parameterization.



Takeaway Message: Extreme space-weather events cannot be predicted reliably without explicitly modeling CME–CME interactions using physics-based heliospheric simulations.

Soni et al., 2026

Comprehensive MHD modelling of ten successive CMEs driving a historic geomagnetic storm - The 2024 Mother's Day event

METHOD

Event
Compile timeline

Limitation:
Correct Speed Estimation

Multi-Point Obs.
SDO, SOHO/LASCO
Kinetic Analysis

3D Reconstruction
Graduated Cylindrical Shell
EUHFORIA (3D MHD)

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Conclusion

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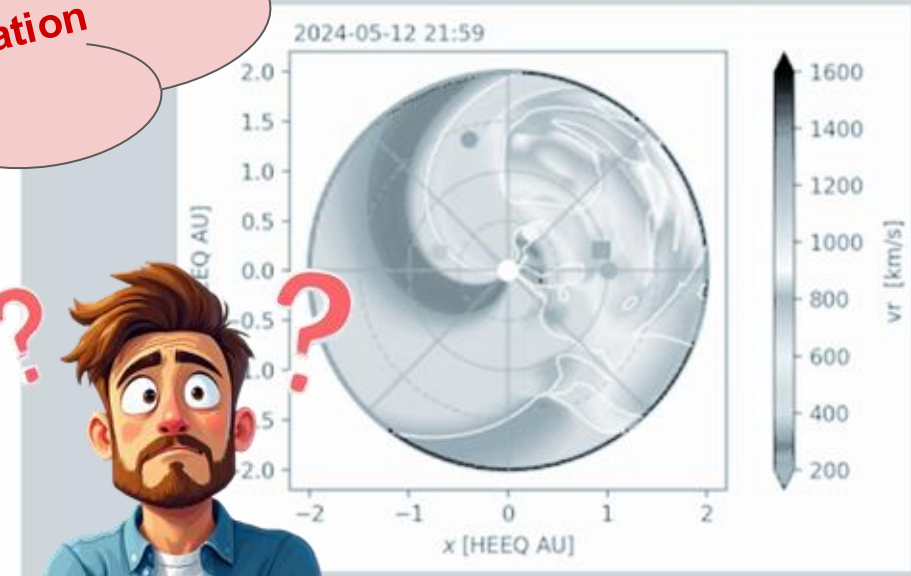


: Extreme space-weather events cannot be predicted explicitly modeling CME–CME interactions using sics-based heliospheric simulations.

Novelty with PUNCH Observations

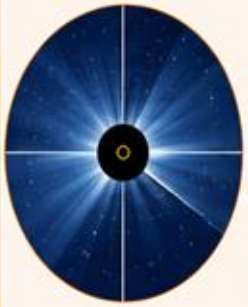
PUNCH

First continuous imaging-based tracking of CME-CME interaction from near-Sun to 180 Rs, rather than reconstructing it indirectly.

A physically connected, multi-scale description of CME interaction evolution across heliocentric distance.

Observational constraints on *when and where* geo-effectiveness amplification emerges

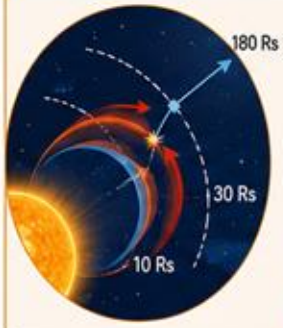
Continuous white-light imaging of the inner heliosphere



You can directly observe:

- Onset of interaction
- Compression region formation
- Shock merging or distortion
- Evolution of CME morphology

Identify where interaction begins

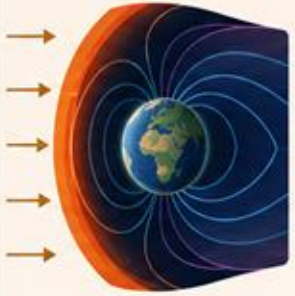


Quantify:

- Compression strength
- Density pile-up
- Shock-shock interaction

Observe kinematic changes in real time

You can directly test:

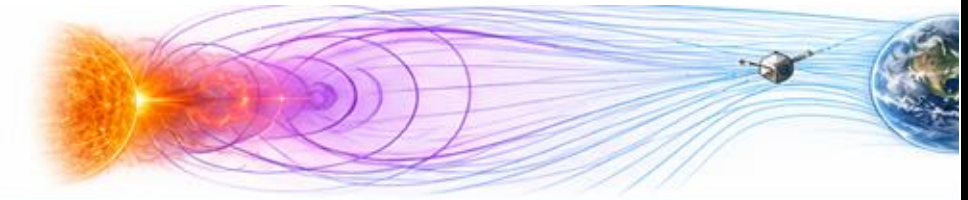


- Magnetic field amplification
- Dynamic pressure enhancement
- Shock strengthening
- $B_z\downarrow$ Southward Bz persistence

This study provides the first continuous, multi-point observational characterization of CME-CME interaction by combining PUNCH heliospheric imaging with in-situ measurements, enabling direct tracking of interaction onset, evolution, and its role in amplifying space-weather impacts.

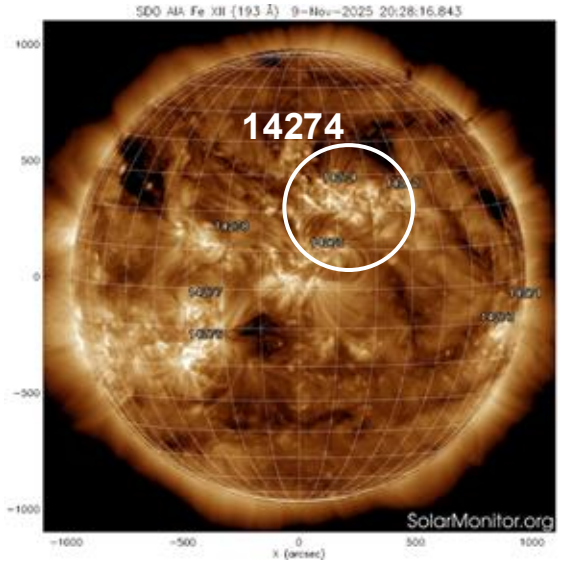
Complex CME events during PUNCH era

November 2025



Timeline

#	Date/Time	Speed (km/s)	Flare	Source
CME-1	2025/11/09 07:36	792	X1.7	14274
CME-2	2025/11/10 09:36	947	X1.2	14274
CME-3	2025/11/11 10:24	1772	X5.1	14274

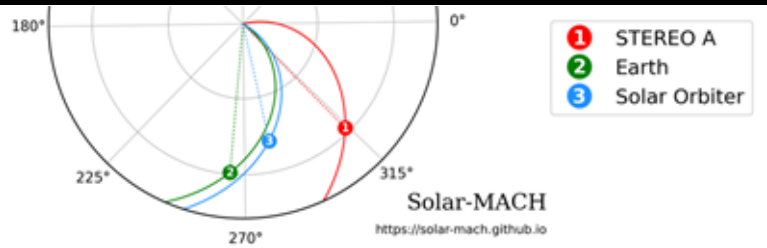


It's a Homologous Interacting Event

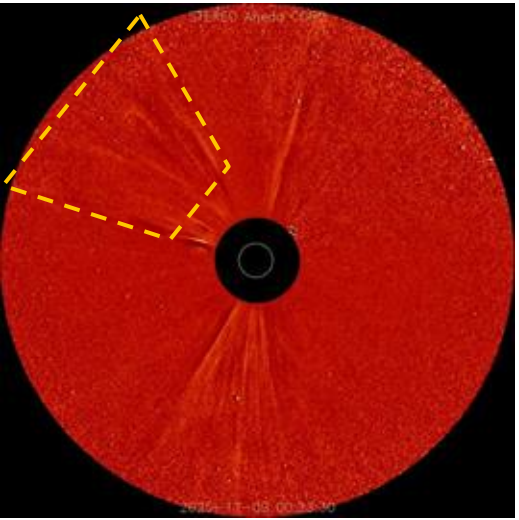
STEREO Observation

STEREO observations provide:

- Independent tracking of CME evolution,
- Additional propagation geometry,
- Validation of interaction timing.

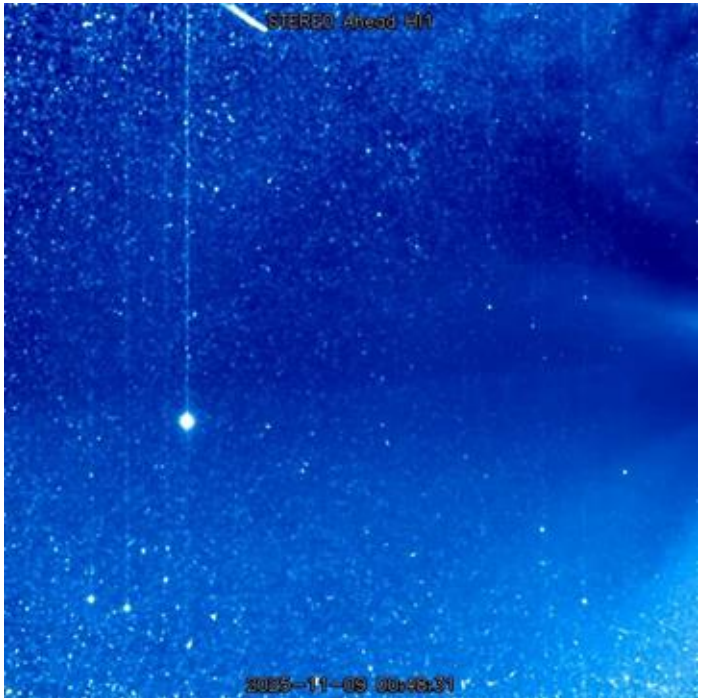


COR2

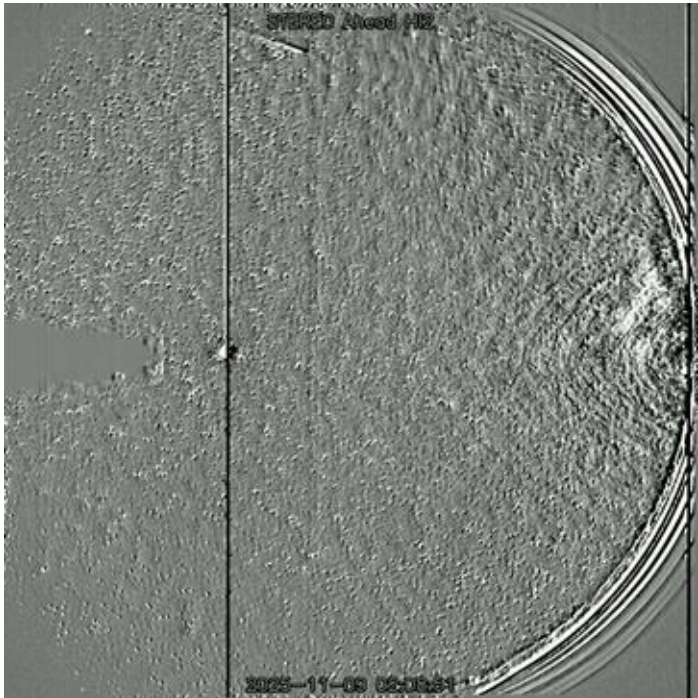


Importance: Multi-viewpoint observations reduce projection uncertainties.

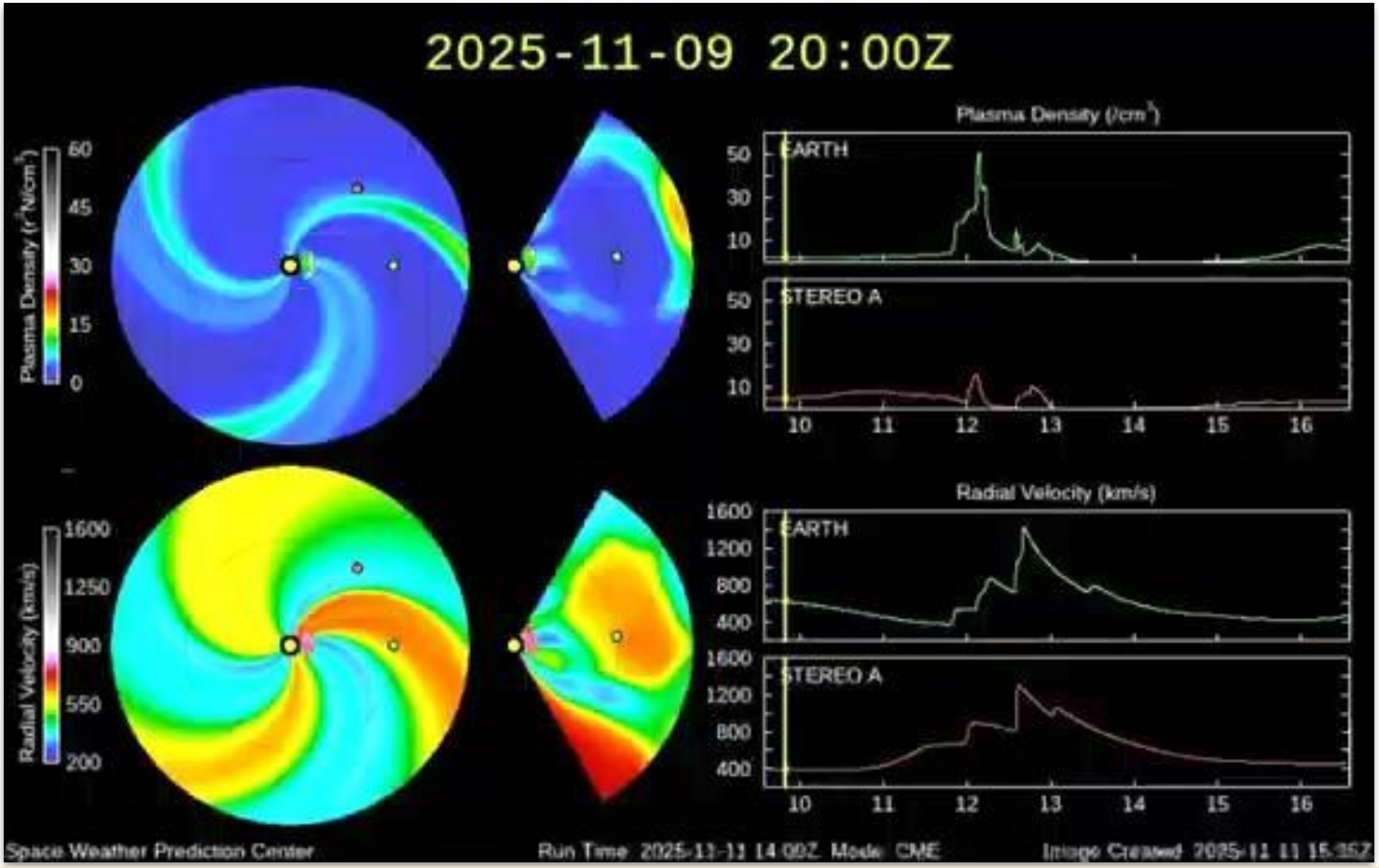
STEREO-HI1



STEREO-HI2



WSA-ENLIL Simulation Result



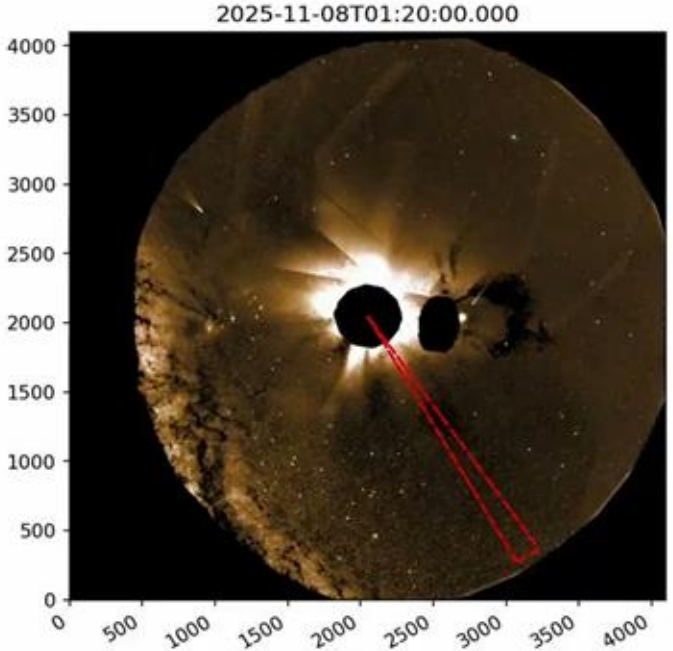
PUNCH Initial Observation

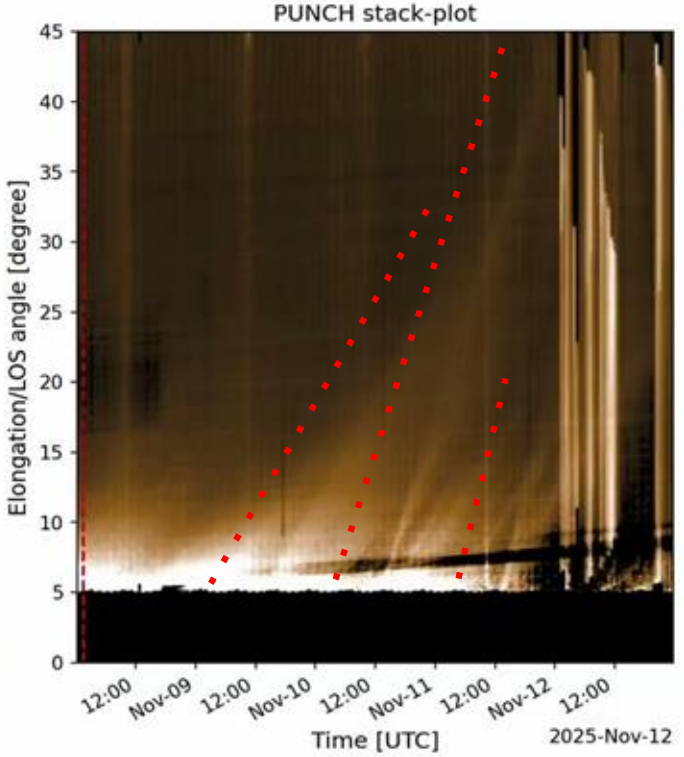
PUNCH White-Light Imaging

- Directly tracks CME propagation.
- Elongation-time stack plots reveal:
  - Multiple propagating fronts,
  - Converging trajectories,
  - Possible overtaking behavior.

Initial Evidence of Interaction

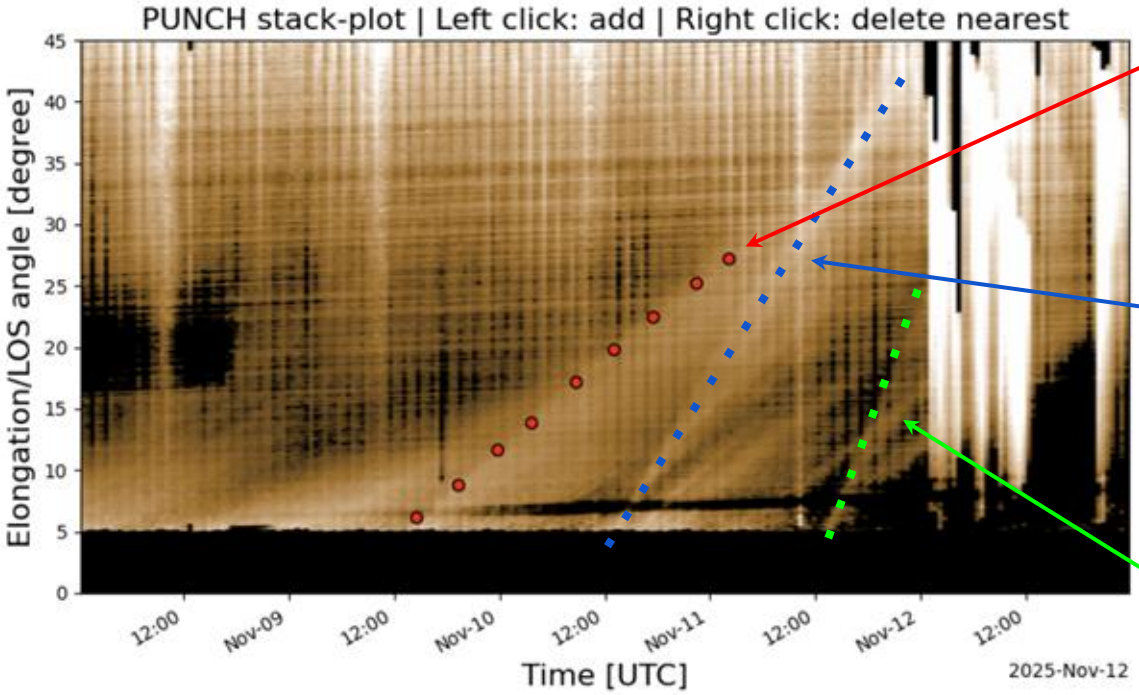
- Faster CME catches preceding ejecta.
- Brightness enhancement may indicate:
  - Compression region,
  - Density pile-up,
  - Early sheath development.

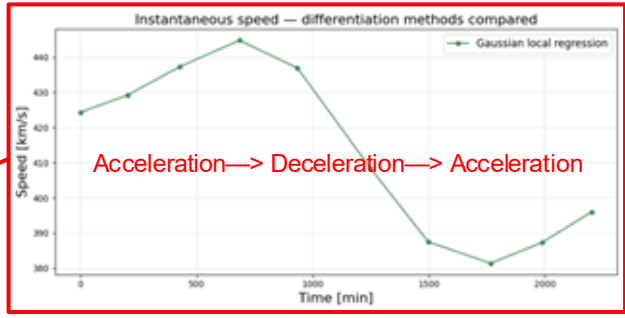


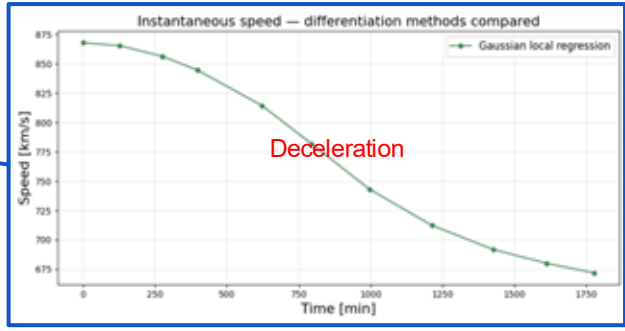


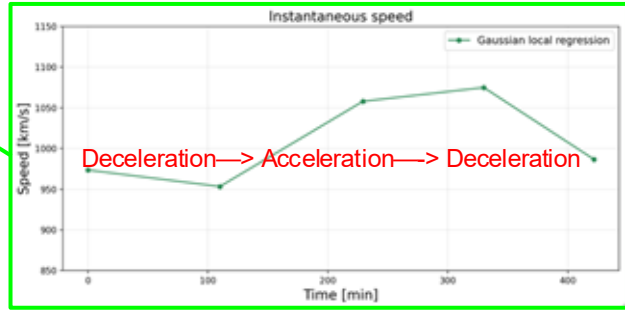
PUNCH enables continuous tracking of interaction evolution in the heliosphere.

J-map Observation









In-situ Observation @ Wind

In-Situ Signatures at 1 AU

Observed:

- Shock arrival,
- Multiple ICME intervals,
- Enhanced magnetic field strength,
- Elevated density and temperature,
- Increased solar wind speed.

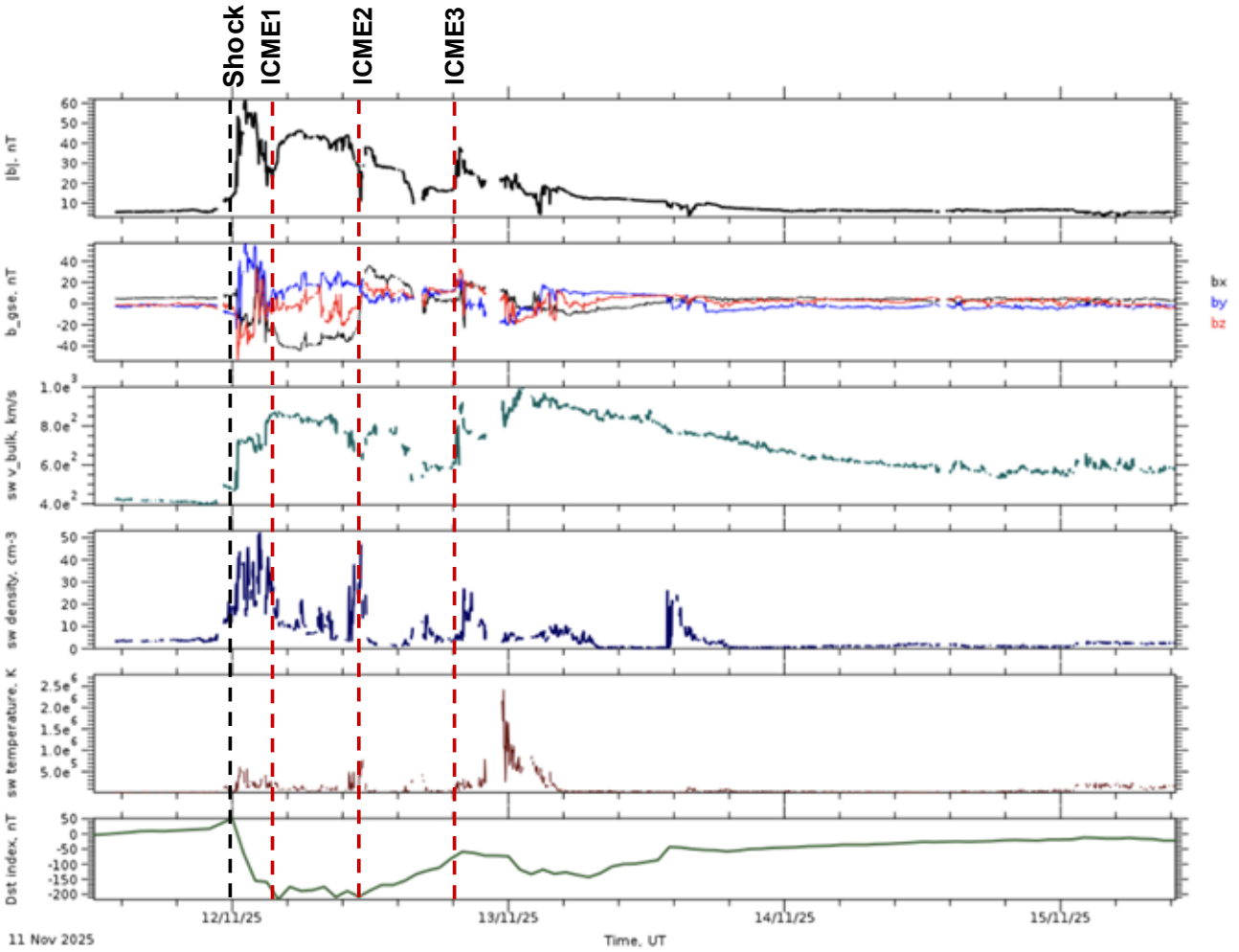
Possible Evidence for Sheath Formation

- Strong compression between shock and ejecta.
- Magnetic field enhancement.
- Elevated dynamic pressure.

Geomagnetic Response

- Significant Dst depression suggests:
  - Enhanced geoeffectiveness,
  - Possible interaction-driven amplification.

Key Question: Was storm enhancement caused by interaction-induced sheath compression or something else?



Future work

Ongoing Tasks

1. PUNCH Polarimetry

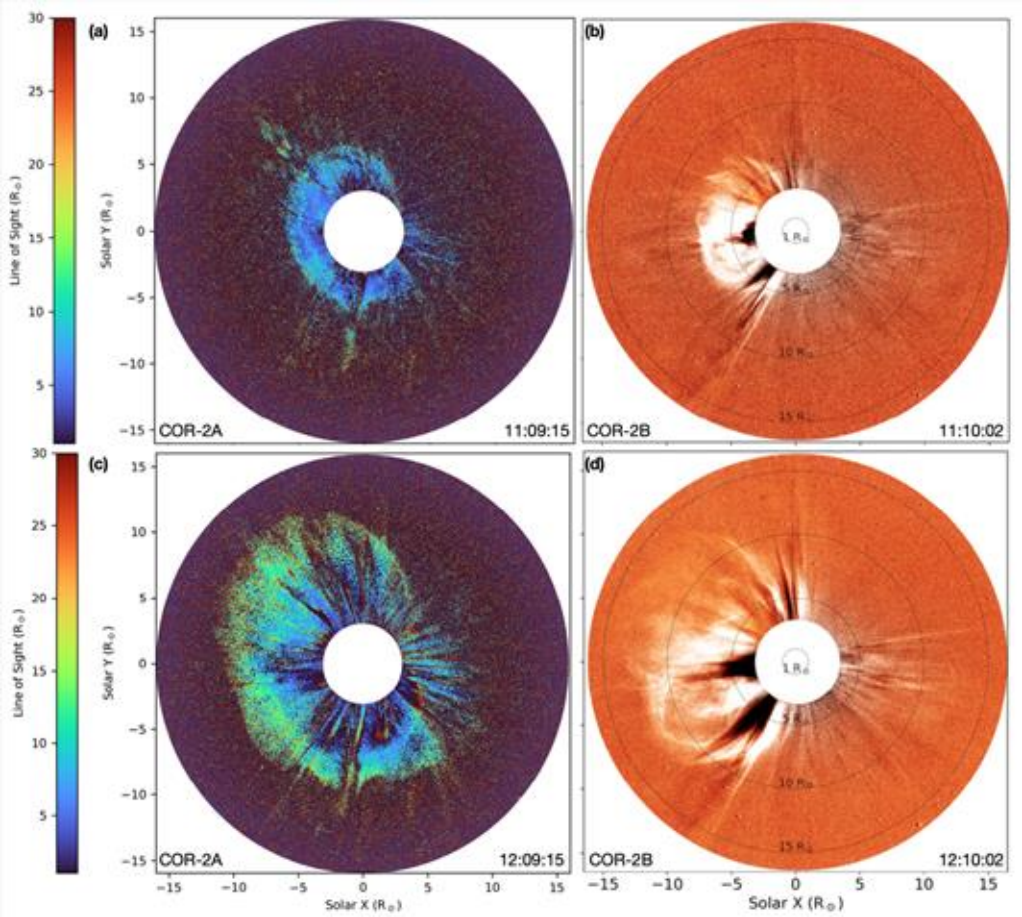
- Estimate:
  - 3D structure,
  - CME location,
  - Density distribution,
  - Interaction geometry.

2. 3D MHD Simulations (MS-FLUKSS)

- Reconstruct interaction physics.
- Quantify:
  - Shock evolution,
  - Sheath formation,
  - Compression enhancement.

3. Geoeffectiveness Assessment

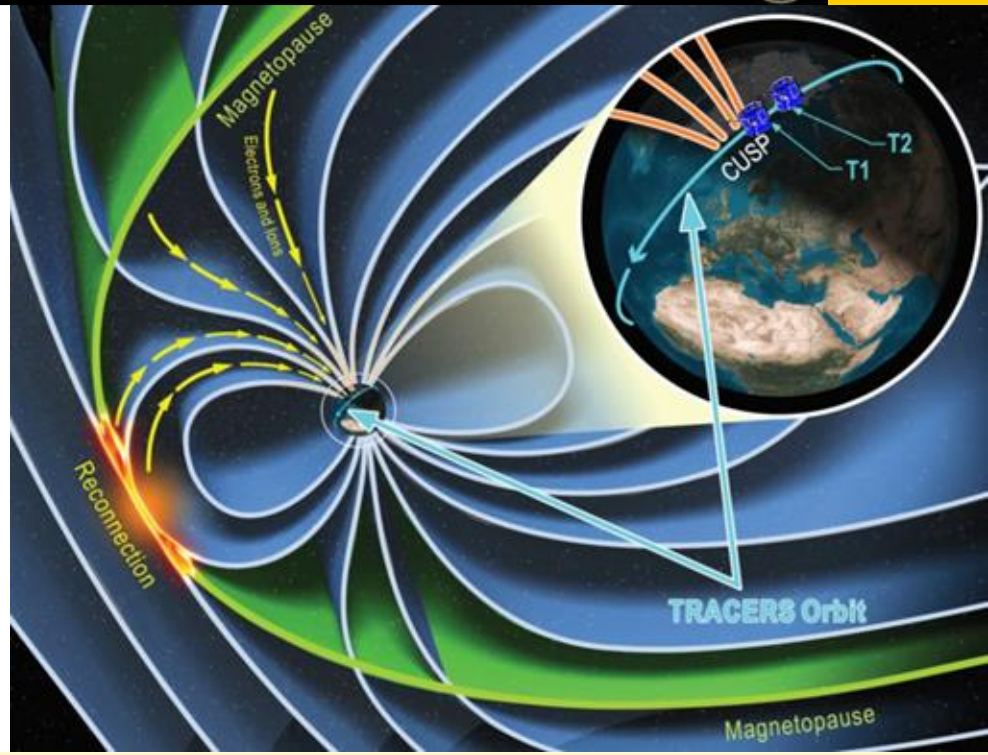
- Compare isolated vs interacting CME scenario.
- Determine amplification due to interaction.



Reference work with STEREO obs

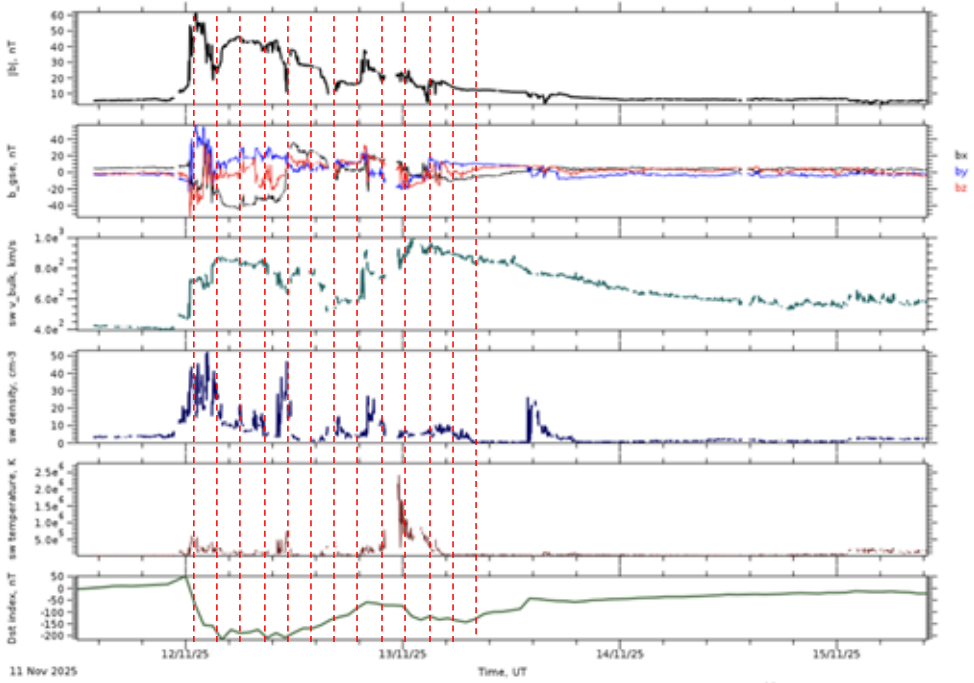
TRACERS Mission

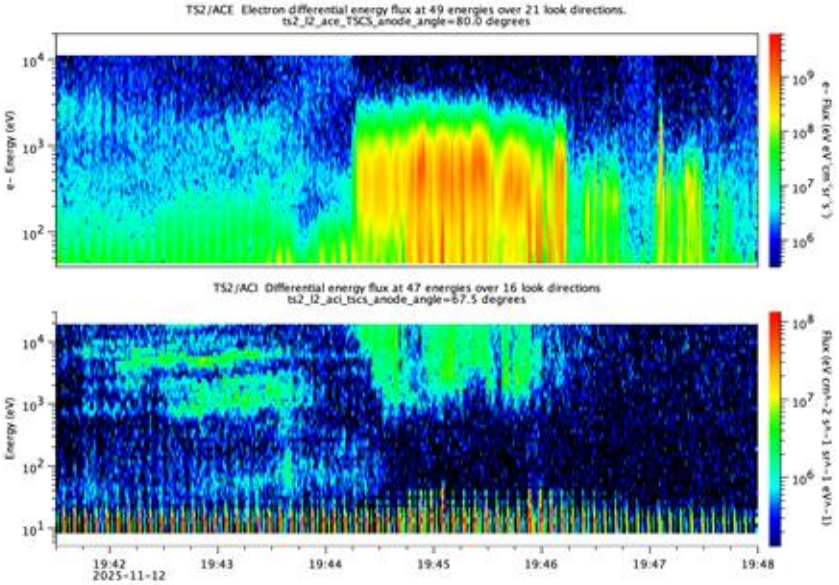
- Two identical satellites (~30 sec separation)
- ~590 km sun-sync orbit Orbital plane
- Intersects the Crossing northern Cusp/Southern Cusp every after 90 mins
- Observe: Ions, Electrons, waves, mag



Additional Study

TRACERS cusp crossing during ICME and geo-magnetic storm

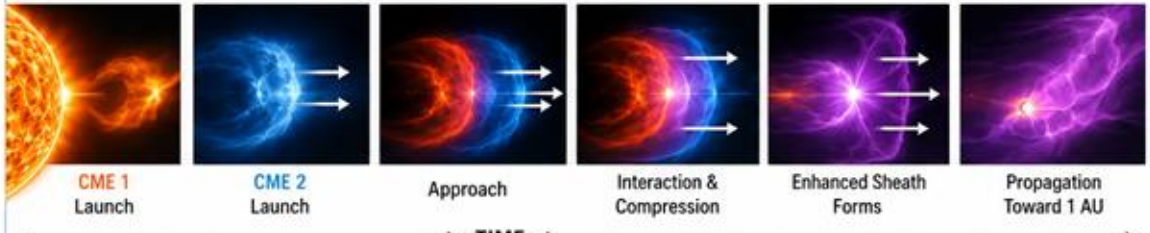




PUNCH REVEALS THE STORY OF CME–CME INTERACTIONS

A multi-view perspective across the inner heliosphere

1 A SEQUENCE OF SUCCESSIVE CMES UNDERGO INTERACTION



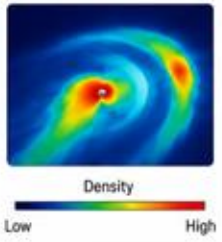
EVIDENCE FROM MULTIPLE PERSPECTIVES

PUNCH IMAGING
Wide-field views reveal morphological evolution

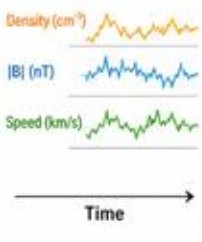
STEREO OBSERVATIONS
Multiple vantage points track 3D structure

CORONAGRAPH OBSERVATIONS
Coronagraph observations relevant to CME tracking

SIMULATIONS
MHD models reproduce compression and sheath enhancement



IN-SITU MEASUREMENTS
Increased density, |B|, and speed before ICME arrival



2 PUNCH ENABLES CONTINUOUS MONITORING OF CME–CME INTERACTION

We can identify interaction timing, propagation changes, and evolving morphology in the inner heliosphere.

3 INTERACTION–ENHANCED SHEATH REGION FORMS

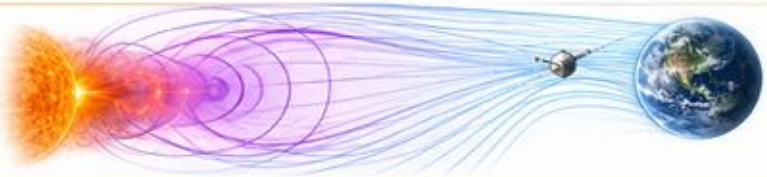
Elevated density, magnetic field compression, and enhanced solar wind speed occur prior to ICME arrival, potentially increasing geoeffectiveness.

4 IMPLICATION FOR SPACE-WEATHER FORECASTING

Accounting for CME–CME interactions is essential for reliable prediction of severe space-weather events.

TAKEAWAY MESSAGE:

PUNCH offers the first opportunity to continuously observe the onset, evolution, and consequences of CME–CME interactions across the inner heliosphere.



sheersh171@gmail.com

Thank you!