Lateral Deformation of Two Coronal Mass Ejections in the Transition from Non-radial to Radial Propagation

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Spanish-German WE-Heraeus-Seminar on Interdisciplinary Physics of the Sun

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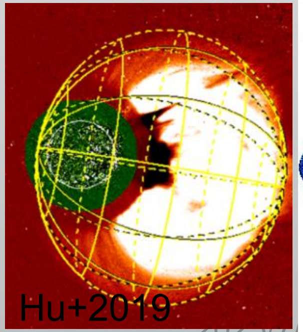
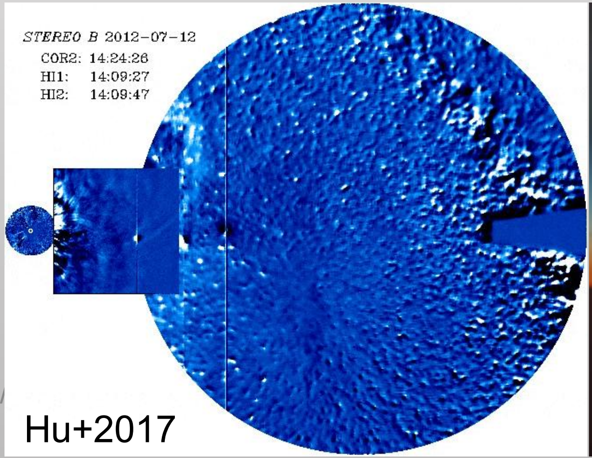
Physikzentrum Bad Honnef, Deutschland

Introduction

- **Coronal Mass Ejections (CMEs)**
  - Large-scale expulsions of plasma and magnetic fields from the solar corona
  - V: 20 – 3000 km/s; M: 10^8 – 10^{14} kg; E_k: 10^{18} –10^{26} J (Vourlidas+2010; Alobaid+2023)
  - CMEs are one major space-weather factor
- **Various processes during propagation from Sun to Earth**
  - Acceleration and deceleration; collision with other CMEs or solar wind structures; rotation about its propagation direction; change of propagation direction. (Gopalswamy+2000; Lugaz+2012; Savani+2010; Vourlidas+2011; MacQueen+1986)
  - These processes reshape CMEs' space-weather effects. (Liu+2014; Riley+2018)


Hu+2019

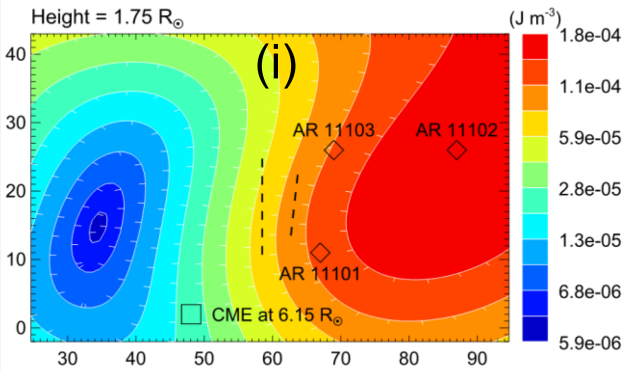


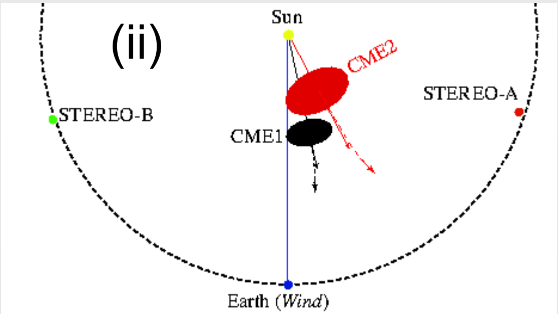
Hu+2017

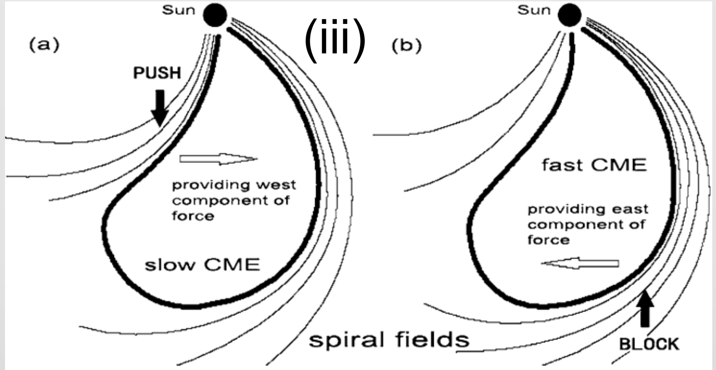

2024 May 11 on CA932

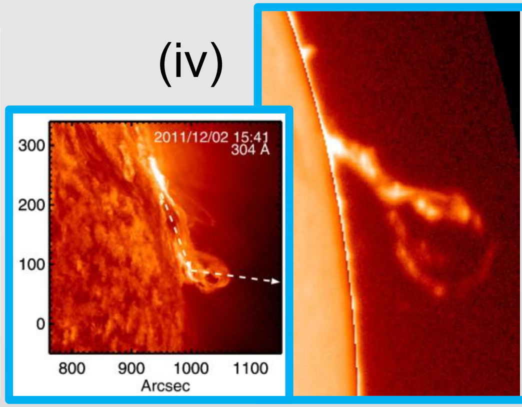
Introduction

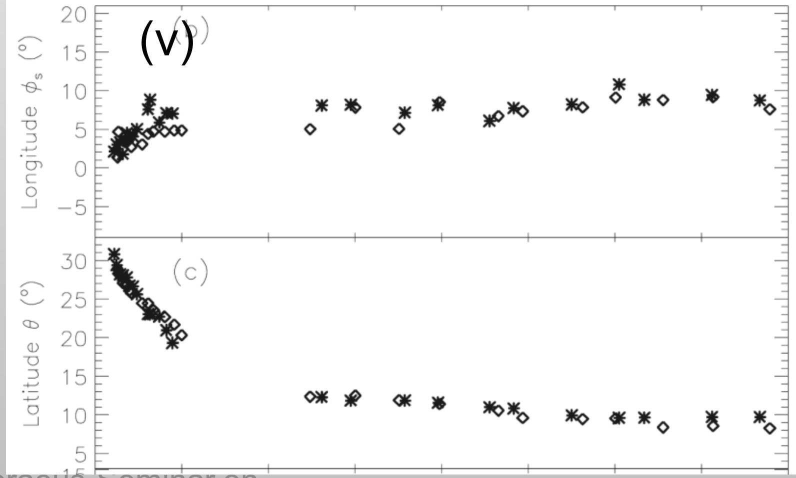
- CME propagation direction is a key factor that **determines space weather effects**
  - Whether or which part impacts Earth
- **Non-radial motion is not rare**
  - Gradient of magnetic pressure-(i)
  - Interaction with other CME(s)-(ii)
  - Moderated by solar wind-(iii)
  - Erupted (born) non-radially-(iv)
- Most eventually propagate in nearly **radial direction**-(iv--v)
- **What happens in the non-radial to radial transition?**









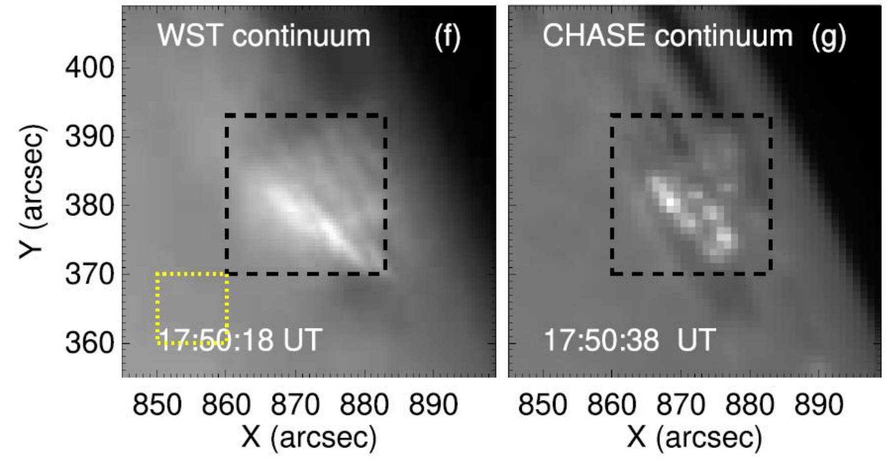


i. Hu+2017,
ii. Lugaz+2012,
iii. Wang+2004,
iv.a McCauley+2015,
iv.b Zhang+2022,
v. Gui+2011

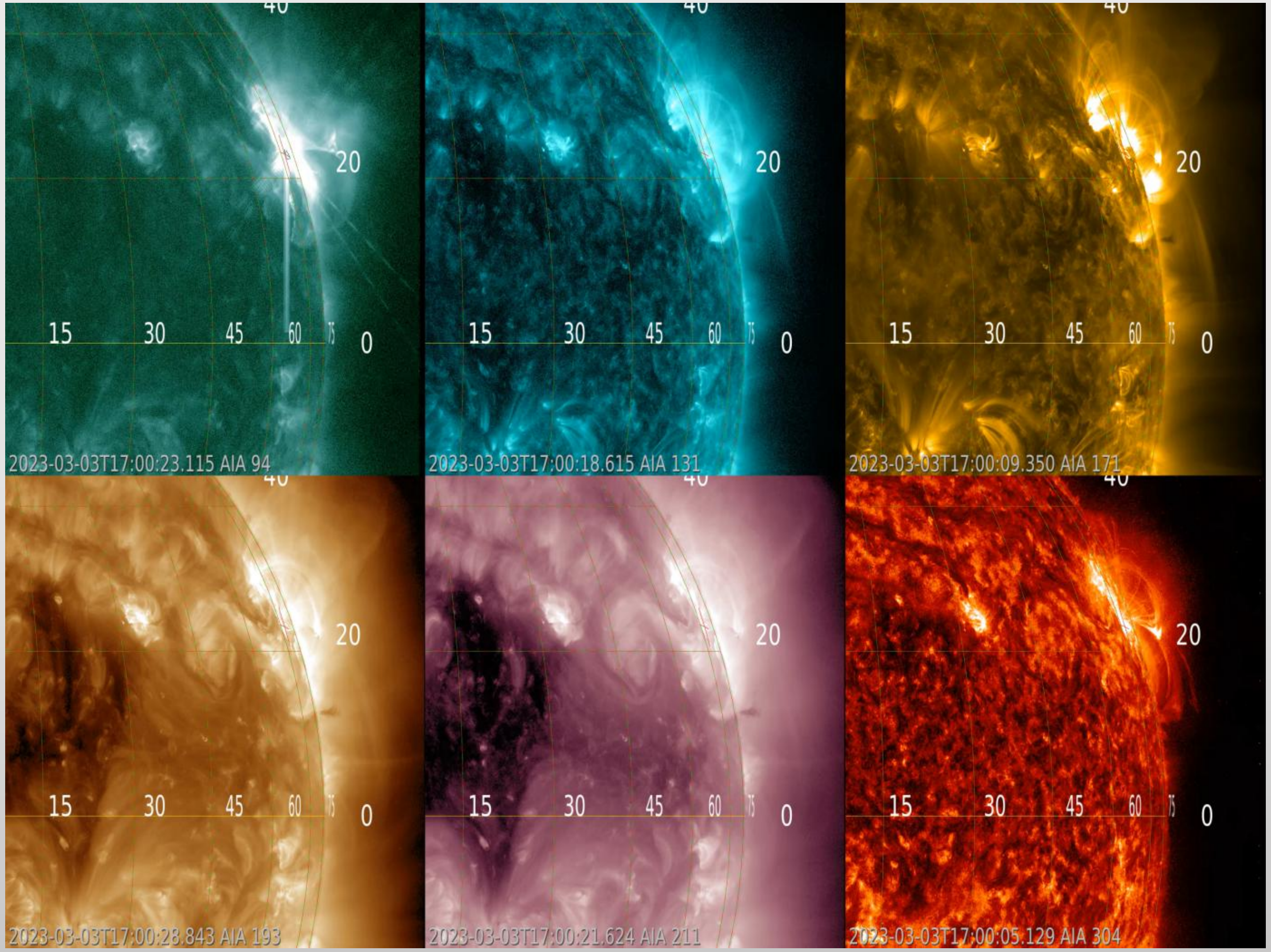
Two non-radial events:

CME 1: 2023 March 3

- NOAA AR 13234
- X2.1 flare (17:52; 78W23N)



White-light flare (Li Y.+2024),
Kink oscillations (Li D.+2024),
First Lyα wave (Zhou+2025, in prep.)



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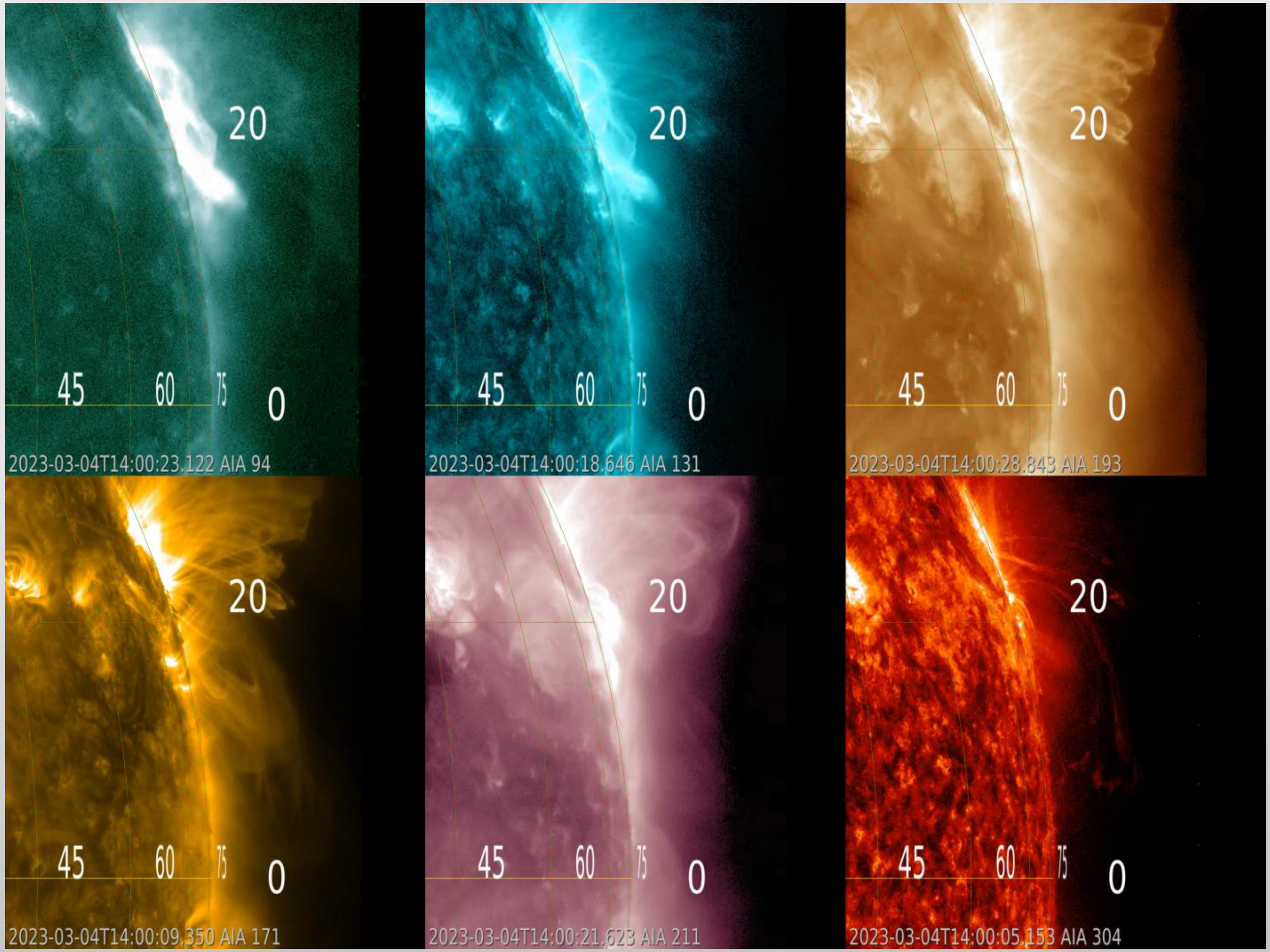
Two non-radial events:

CME 2: 2023 March 4

- NOAA AR 13234
- M5.2 flare (15:57; 90W23N)
- Exactly on solar limb
- “Hot channel” moves almost horizontally
- Edge-on flux rope
- Overlying loops above eruption site



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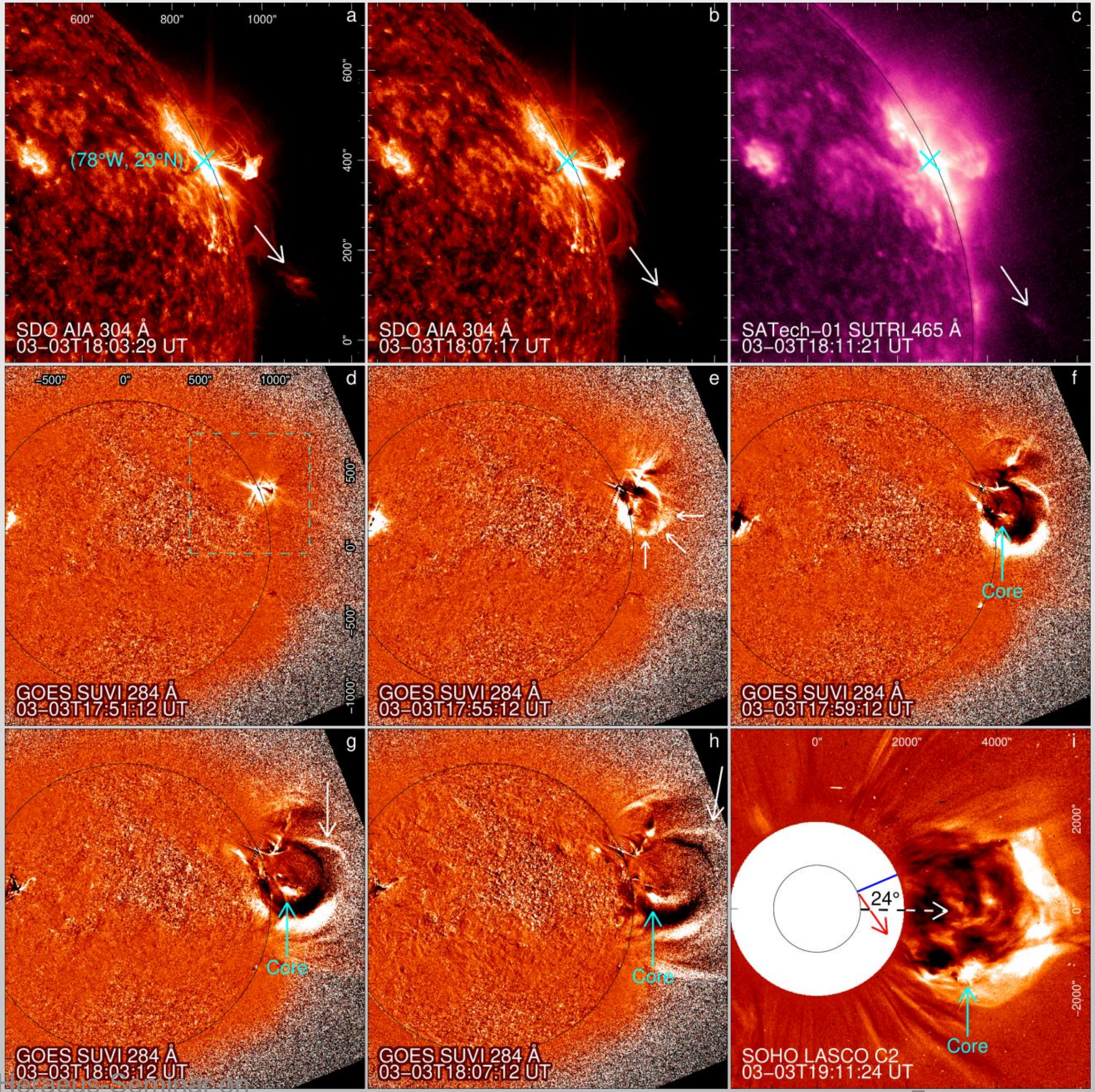
Observations and Methods

- **Instruments**
  - Solar Dynamics Observatory (SDO, Pesnell+2012)
    - SDO/AIA (Lemen+2012); track eruptions in the bottom corona
    - SDO/HMI (Scherrer+2012); locate magnetic polarity inversion lines for eruptions
  - Geostationary Operational Environmental Satellites (GOES) SUVI (Darnel+2022); track CMEs with its **large field of view (~1.6 $R_\odot$)**
  - Solar and Heliospheric Observatory (SOHO) LASCO C2 (Domingo+1995); track CMEs in the low corona **(~2 – ~6 $R_\odot$)**
  - Solar Upper Transition Region Imager (SUTRI) Ne VII 465 Å (Bai+2012); detect erupted material in the corona at a **different wavelength** band
- **Methods**
  - Graduated Cylindrical Shell model (GCS, Thernisien+2006)
  - Potential Field Source Surface (PFSS, Schatten+1969, Altschuler+Newkirk1969)
  - Decay index $n = -\frac{d \ln B_T}{d \ln h}$, B_T is the transverse magnetic field and h is the height above the photosphere (Kliem+Török2006)

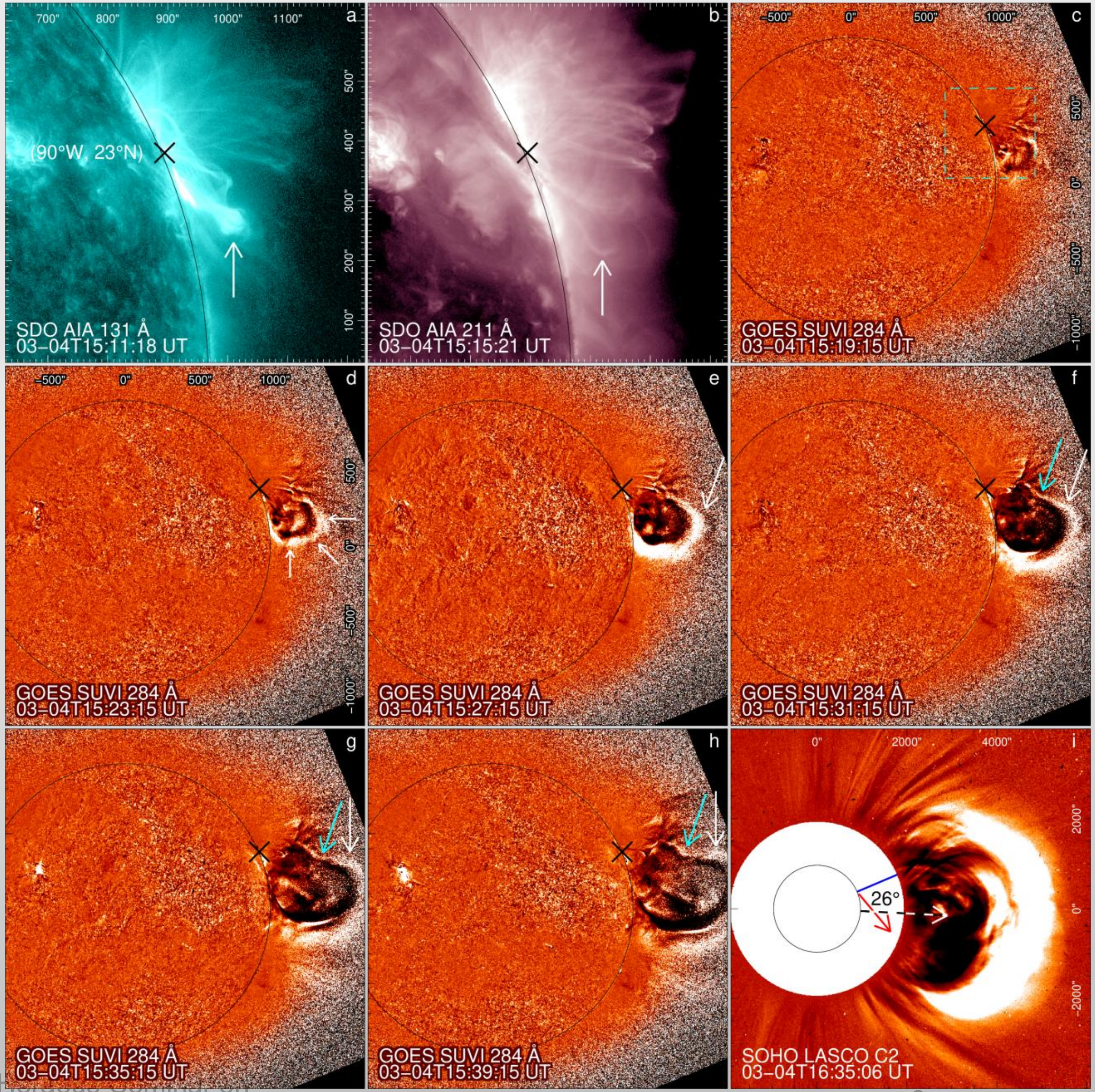
2023-03-03 CME 1

- Filament erupts non-radially (seen in 304 Å+465 Å)
- A southward non-radial (almost horizontal) CME
- Upper flank **bulges** resulting in **direction transition**
- CME turns from non-radial to radial, 24° offset in latitudes from the eruption site (by GCS based on LASCO C2)
- Core (filament) displaced to the southern part of the CME



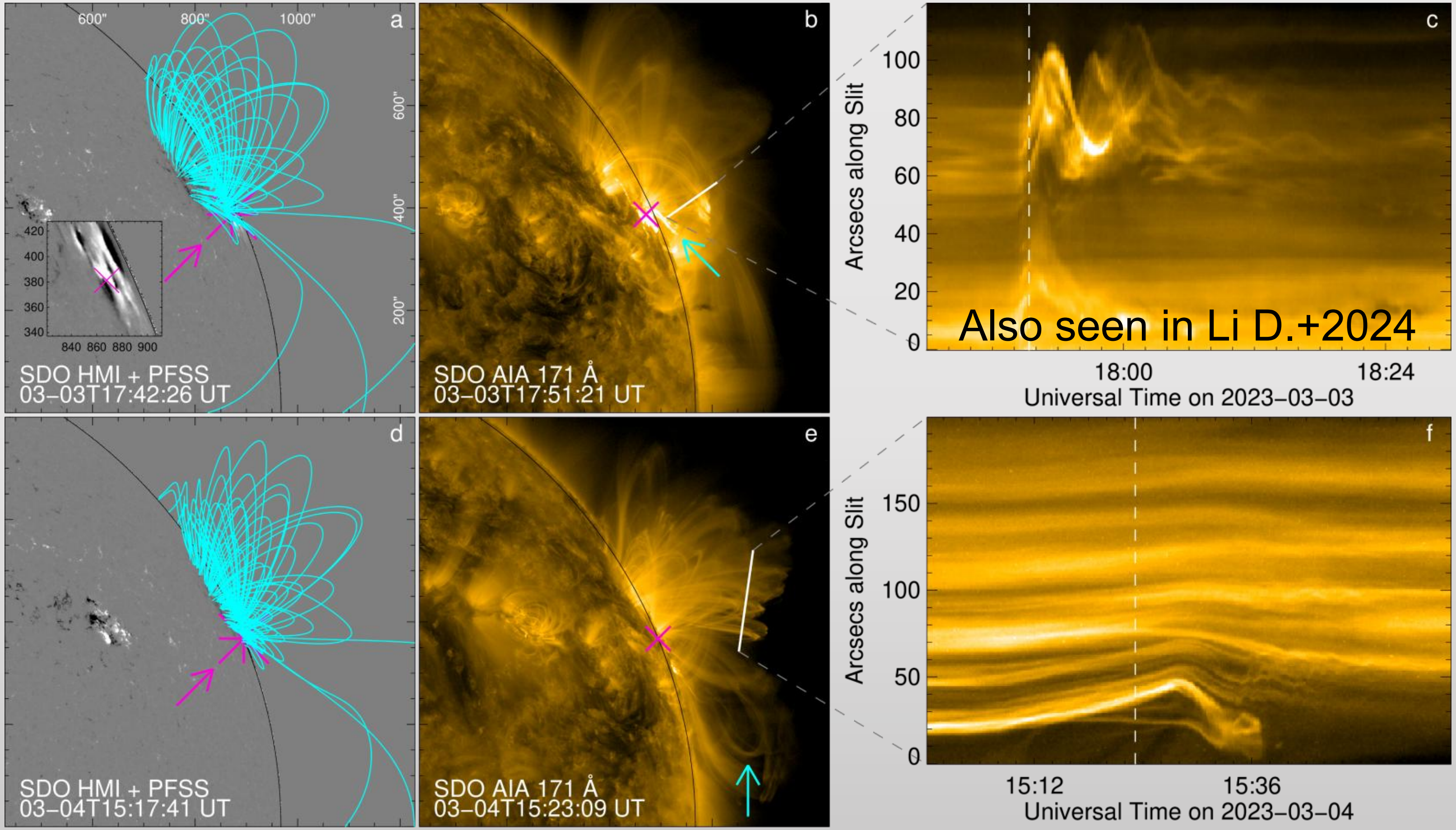
2023-03-04 CME 2

- Hot channel (flux rope) erupts non-radially
- In edge-on view (flux-rope axis parallel to line of sight)
- Upper flank also obviously bulges upward
- Upper flank becomes leading edge, after transitioning from non-radial to radial
- Eventually 26° offset from the eruption site
- Upper flank is partially **confined and indented**



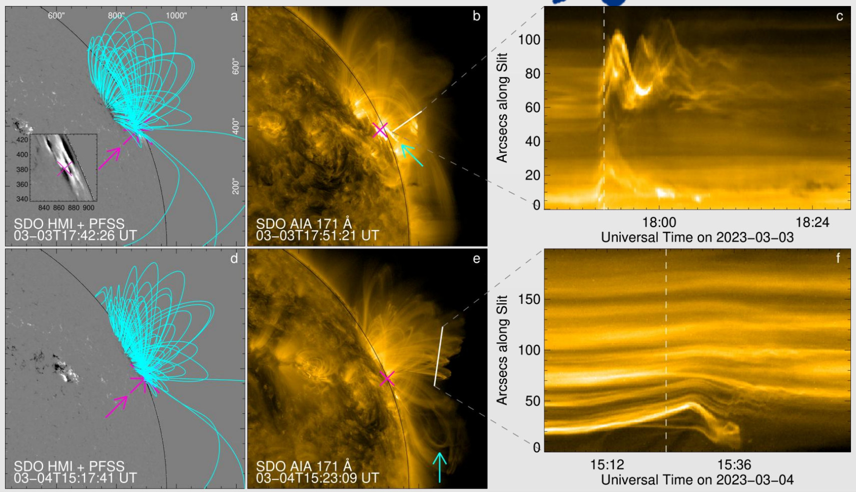
Environment magnetic fields

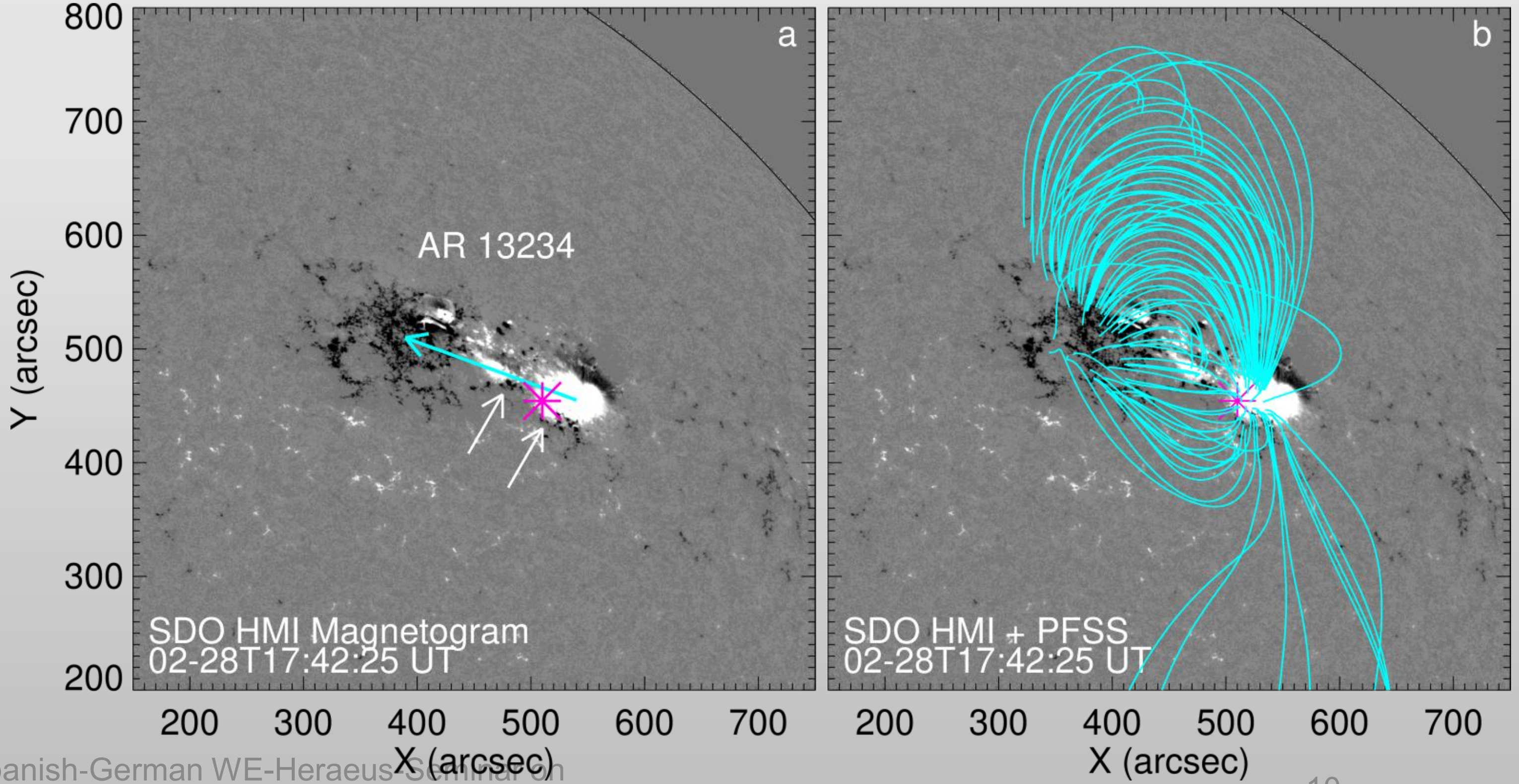
- Overlying loops
- Eruption site is beneath the loops
- Expanding CME interacts with the loops causing oscillations like plucking musical-instrument strings



Environment magnetic fields

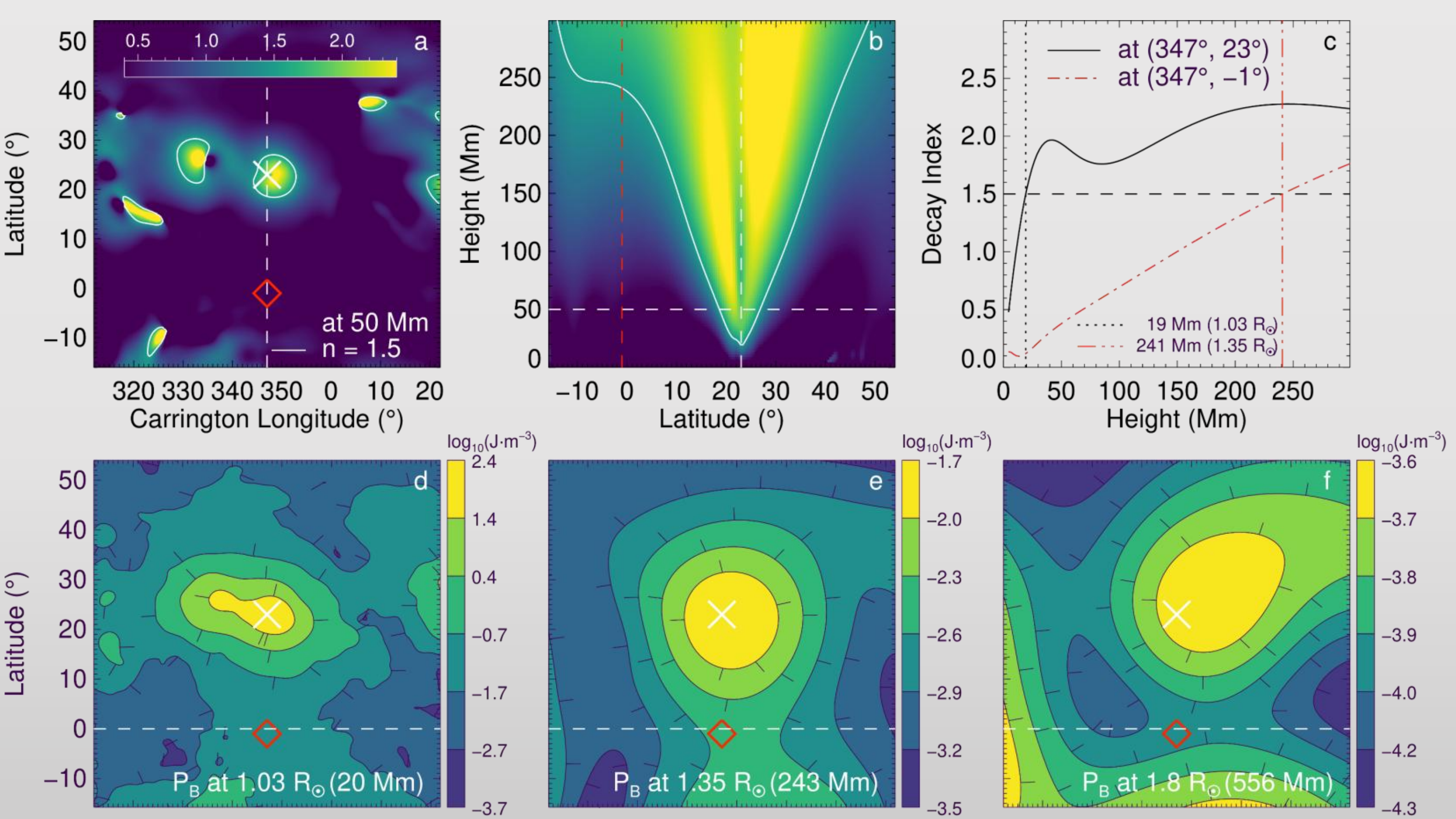
- Overlying loops
- Eruption site is beneath the loops
- Expanding CME interacts with the loops causing oscillations like plucking musical instrument strings
- **Overlying loops parallel to flux rope (not strapping)**





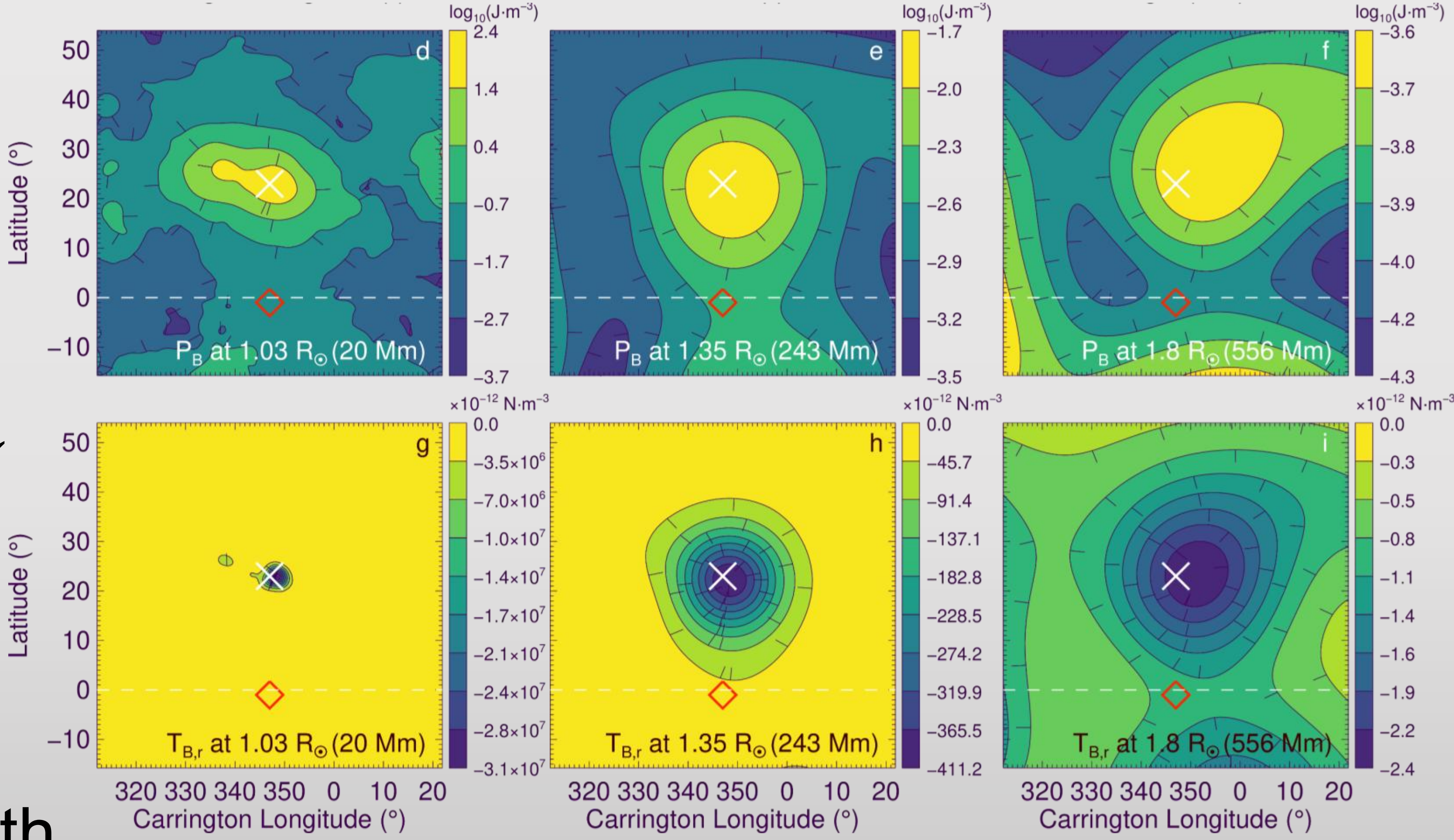
Environment magnetic fields

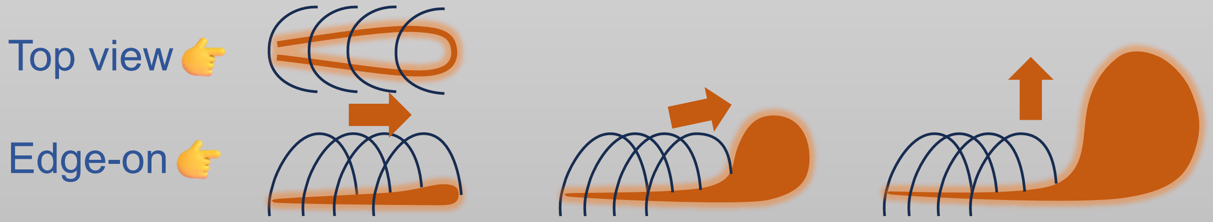
- Decay index $n = -\frac{d \ln B_T}{d \ln h}$ (B_T is **parallel** to rope)
- At eruption site, $n > 1.5$ at ~19 Mm, but the CME does not rise radially there
- At 1.8 $R_\odot$, low-pressure valley observed near the final CME direction
- Magnetic pressure is very high, **like a lid**; which consistent with the overlying loops



Environment magnetic fields

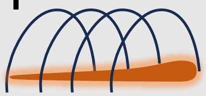
- Magnetic pressure can't explain constraint on radial expansion; $\mathbf{F}_{\mathrm{P,B}} = -\nabla \mathrm{P}_{\mathrm{B}}$:↑
- $\mathbf{T}_{\mathrm{B}} = (\mathbf{B}\cdot\nabla)\mathbf{B}/\mu_0$ → $\mathrm{T}_{\mathrm{B,r}}$:↓
- Tension force of the loops constrains the radial expansion in the non-radial propagation
- The CME moves beneath the loops like a bullet in a barrel



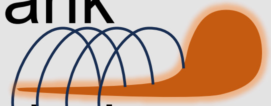


Summary

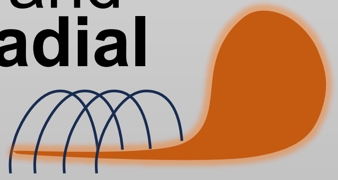
- Two large-scale CMEs erupted **non-radially** from an AR on the limb
  - Eruption site is covered by overlying loops roughly parallel to the flux rope
- First report of the lateral deformation of CME structure in the **transition from non-radial to radial** propagation in the low corona



  - In the non-radial phase, CMEs move like a bullet in a barrel
- During the transition, the CME bulges its upper flank, and the flank eventually becomes the leading edge in the radial phase



  - The expanding CME interacts with the overlying loops like plucking musical-instrument strings, and causes oscillations of the loops
- The filament of CME 1 is displaced from the center to southern part
  - A possible reason for missing filament signatures in *in situ* ICME observations
- The magnetic tension force of the loops above the eruption site constrains the radial expansion of the CME in the non-radial phase; After the CME leaves the loops, its upper flank bulges upward, and **this lateral deformation results in the transition from non-radial to radial propagation.**



THANK YOU!

Herzlichen Dank an
Wilhelm und Else Heraeus-Stiftung und
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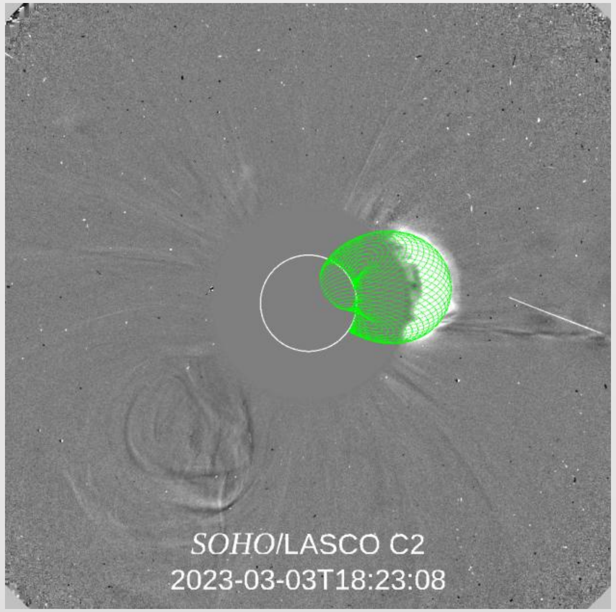
Information / Ankündigung

The third China-Europe Solar Physics Meeting
Sept 15-19, 2025
Beijing

Deadline for registration
30 July 2025

Citizens from 40+ countries **visa-free** to enter China
More details:
https://cespm2025.casconf.cn

A. GCS model obtains CME direction



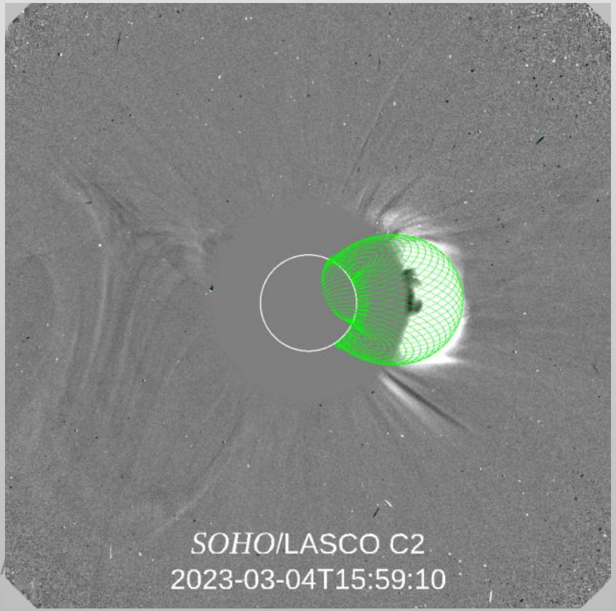


Table 1. GCS Parameters Based on LASCO C2 Observations

Time (UT)	Longitude (Carrington, °)	**Latitude**	Tilt Angle (°)	**Height** ($R_\odot$)	Ratio	Half Angle (°)
CME on 2023 March 3						
18:23	347	9	−20	3.0	0.5	30
18:35	347	5	−20	3.5	0.5	30
18:47	347	2	−20	4.2	0.5	30
18:59	347	0	−20	4.9	0.5	30
19:11	347	−1	−20	5.6	0.5	30
19:23	347	−1	−20	5.2	0.5	30
CME on 2023 March 4						
15:59	347	2	−20	3.2	0.6	35
16:11	347	2	−20	3.9	0.6	35
16:23	347	0	−20	4.7	0.6	35
16:35	347	−3	−20	5.4	0.6	35
16:47	347	−3	−20	6.1	0.6	35

NOTE—Only latitude and height are fitted for each time.