OBSERVATION-BASED MODELLING OF MAGNETISED CORONAL MASS EJECTIONS WITH EUHFORIA

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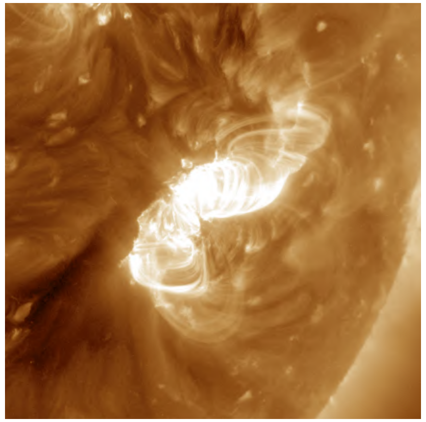

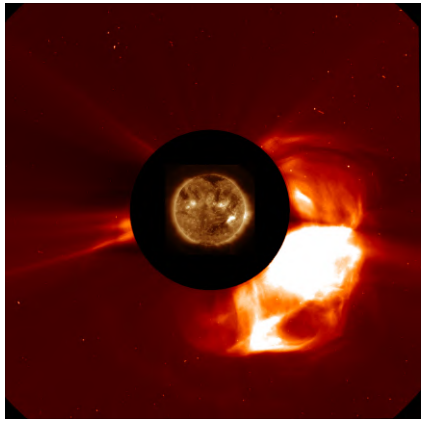

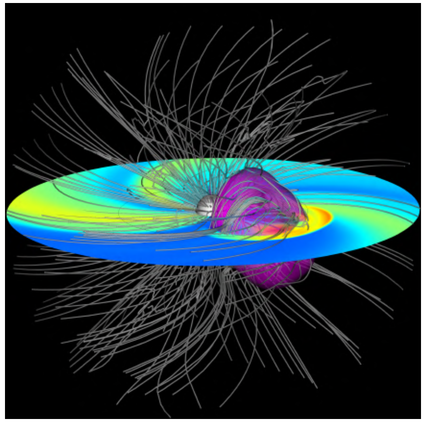

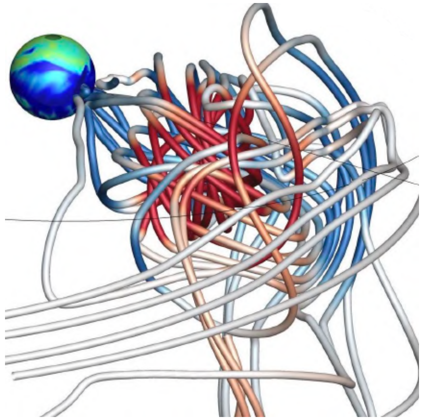

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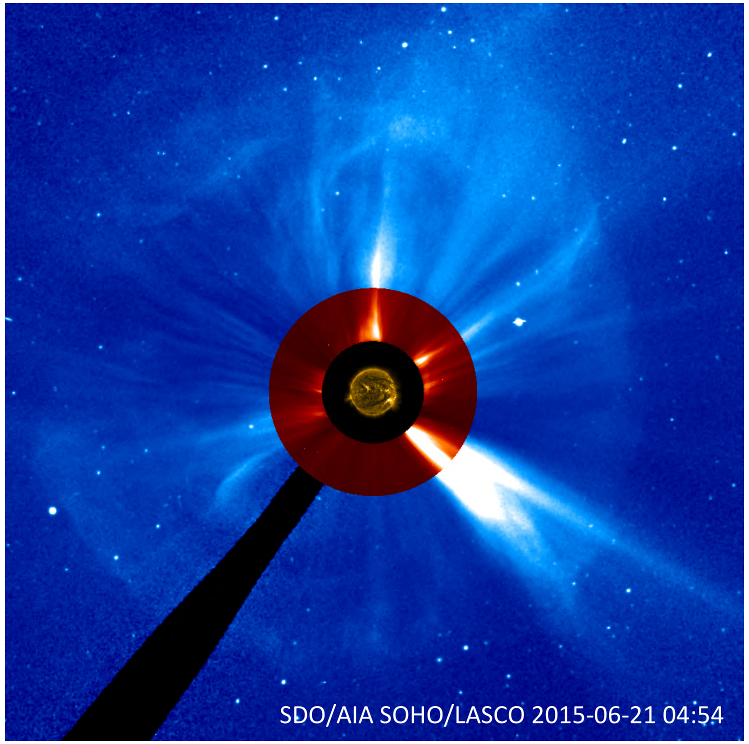
Opening new horizons

Introduction and goals

- **Coronal Mass Ejections (CMEs)** are gigantic eruptions of magnetised plasma from the Sun -- primary **cause of intense space weather disturbances** at Earth
- **Reliable predictions of their impact** at our planet and other target locations are the key to taking prompt protective measures



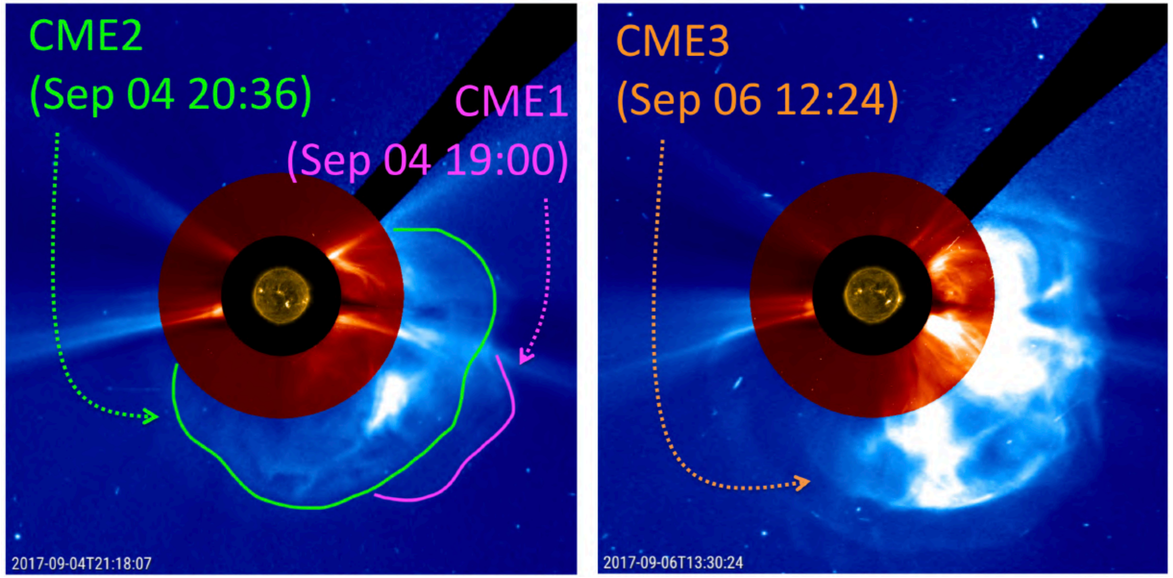
ULTIMATE GOALS

- Better understanding the role of CMEs as space weather drivers throughout the heliosphere
- Improve current predictive capabilities (e.g. B_z at 1 AU) for such kind of events
- Modelling tool: euhforia

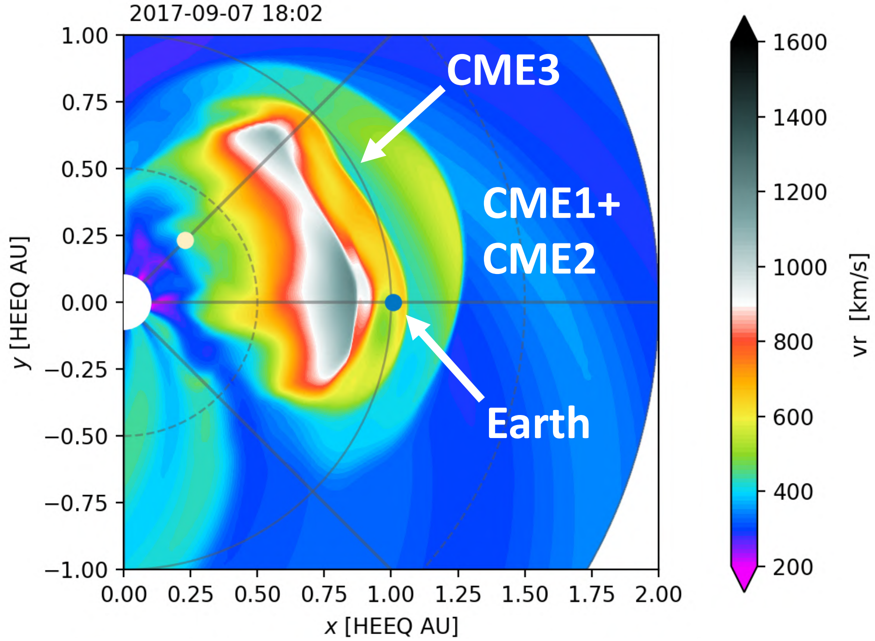
The 4-6 September 2017 CMEs

- Two successive CMEs on 4 September (19:00 UT and 20:36 UT) followed by a faster CME on 6 September (12:24 UT)
- CME1 and CME2 merged in the corona (CME1+CME2)
- Interaction of CME3 with CME1+CME2 during propagation triggered a major geomagnetic storm

SOHO/LASCO observations

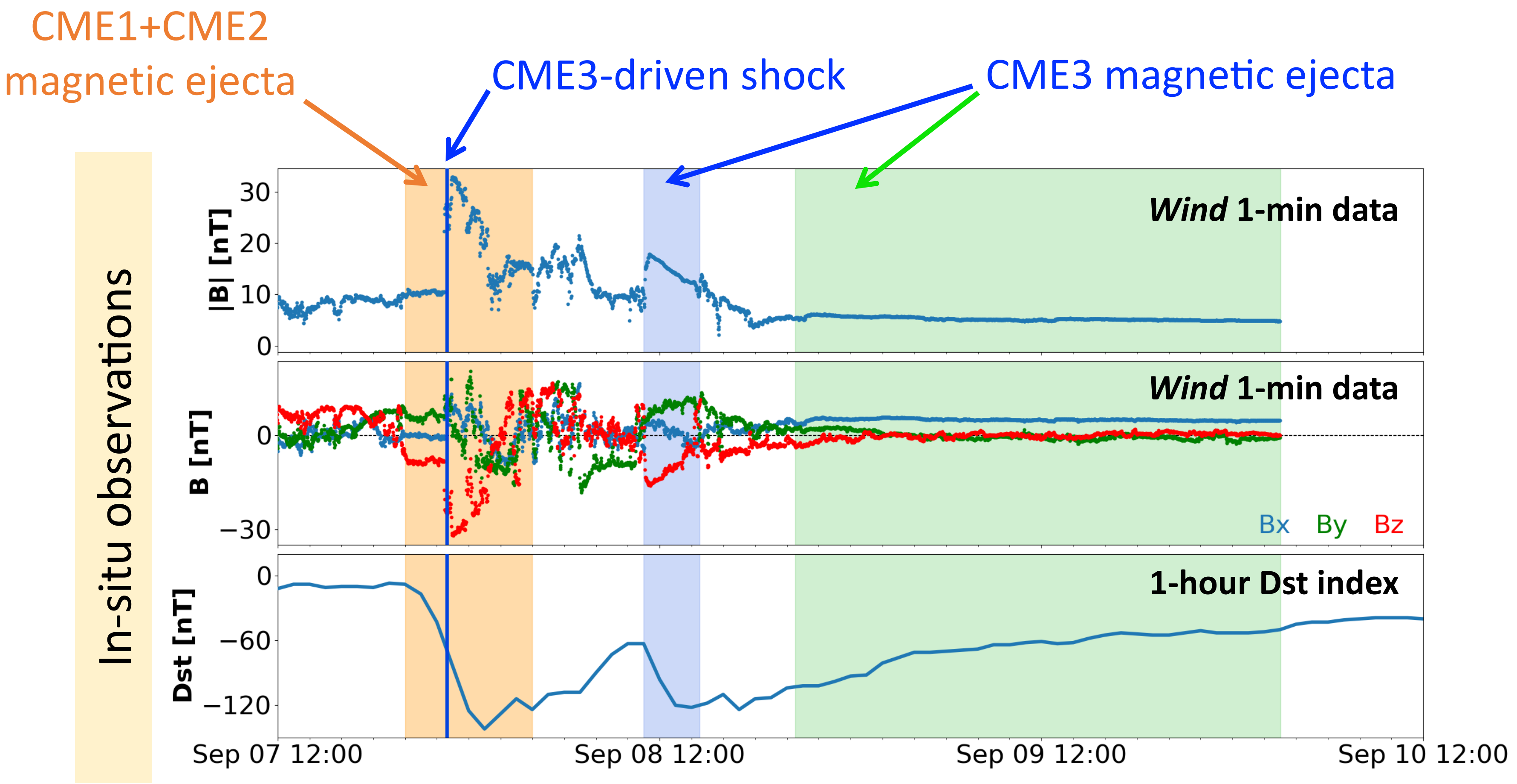


EUHFORIA simulation (equatorial plane)



The 4-6 September 2017 CMEs at Earth

- Interaction of CME3 with CME1+CME2 at 1 AU amplified the geo-effectiveness of this structure by a factor ~2 (shock embedded in preceding ejecta; Lugaz+2005,2016; Shen+2018)



Science questions: complex CME events

- Interaction of CME3 with CME1+CME2 at 1 AU amplified the geo-effectiveness of this structure by a factor ~2 (shock embedded in preceding ejecta; Lugaz+2005,2016; Shen+2018)

Q1 How did this amplification evolve in space and time as the CMEs propagated from the Sun to the Earth (i.e. as a function of the interaction phase)?

Q2 Is there a range of radial distances where interacting CMEs are more likely to trigger strong space weather disturbances (i.e. a characteristic ''helio-effectiveness amplification zone'')?

Terminology throughout this presentation:

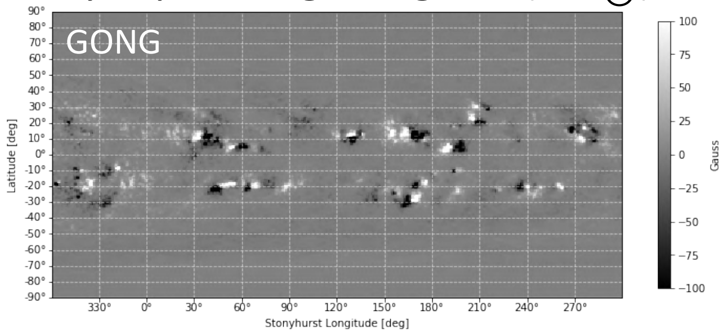
Geo-effective ⇔ impact at Earth (1 AU)

Helio-effective ⇔ potential impact at a generic heliocentric distance

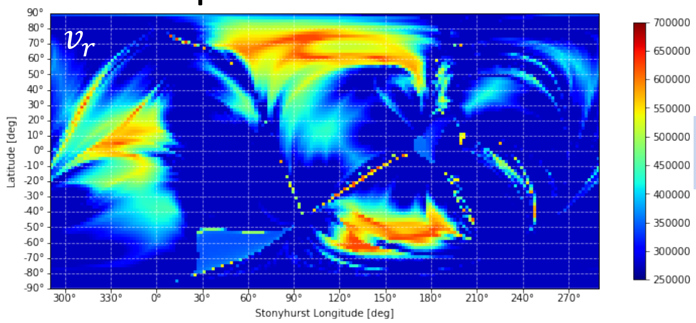
Ambient solar wind in euhforia

CORONA: semi-empirical WSA model

Synoptic magnetogram (1 $R_\odot$)



Empirical relations:
MHD parameters at 0.1 AU



PFSS model (1 to 2.6 $R_\odot$)

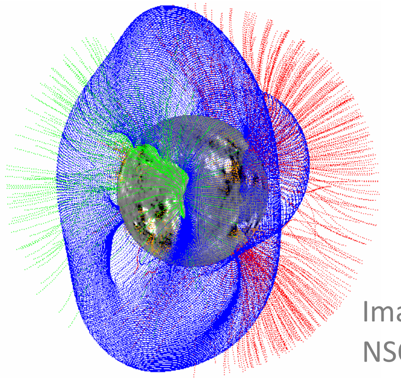
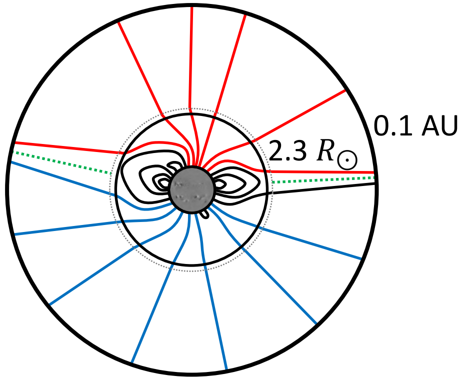


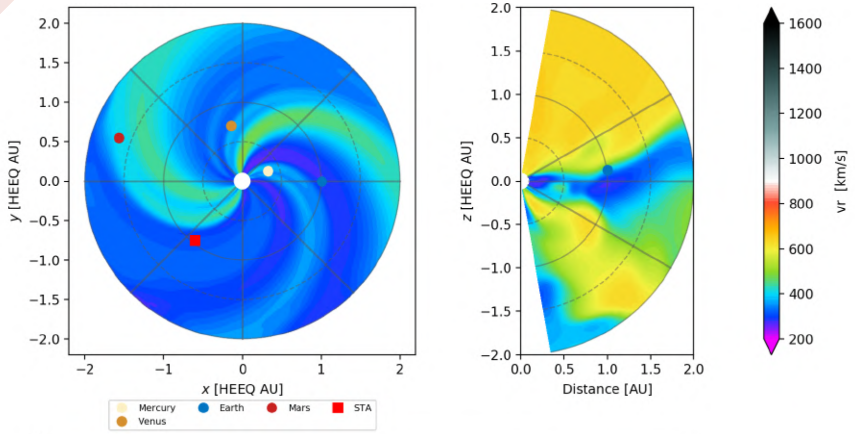
Image credit:
NSO/GONG

SCS model (2.3 $R_\odot$ to 0.1 AU)



HELIOSPHERE: time-dependent ideal MHD model

$\boldsymbol{v}, \boldsymbol{B}, n, T$ in the inner heliosphere (0.1 to 2.0 AU)

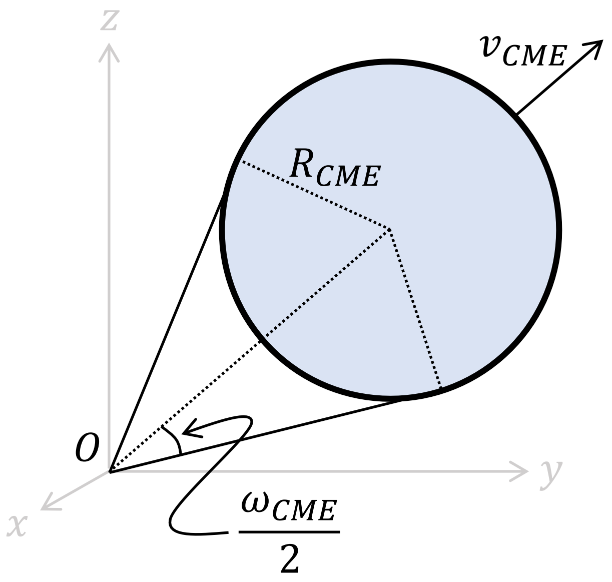


Pomoell & Poedts (2018), *Journal of Space Weather and Space Climate*, https://doi.org/10.1051/swsc/2018020

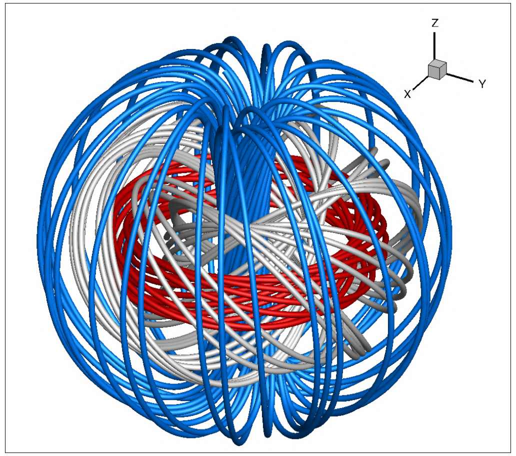
CME models in euhforia

- CMEs inserted as time-dependent inner boundary conditions at 0.1 AU
  - Cone-like model (unmagnetised) ⇢ Pomoell&Poedts2018; Scolini+2018,2020
  - Spheromak model (flux rope) ⇢ Verbeke+2019 ⇠ Used in this work
  - Fri3D, toroidal, Gibson-Low models (coming soon) ⇢ Isavnin+2016; Pomoell+2020 (*in prep*)

Ice-cream cone model



Spheromak model



Toroidal model

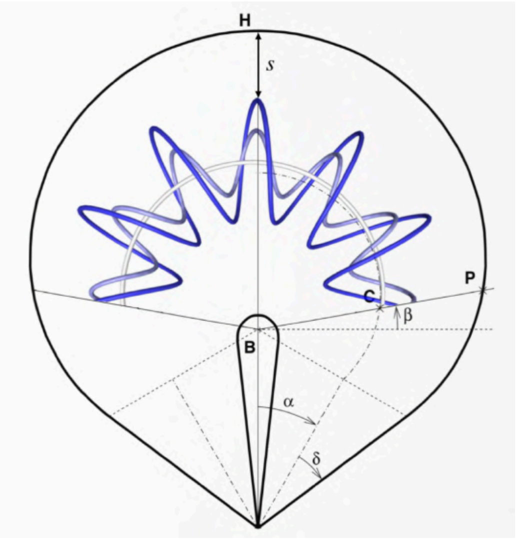


Image courtesy of J. Pomoell

CME initial parameters at 0.1 AU

How to determine the parameters of the CMEs to inject?

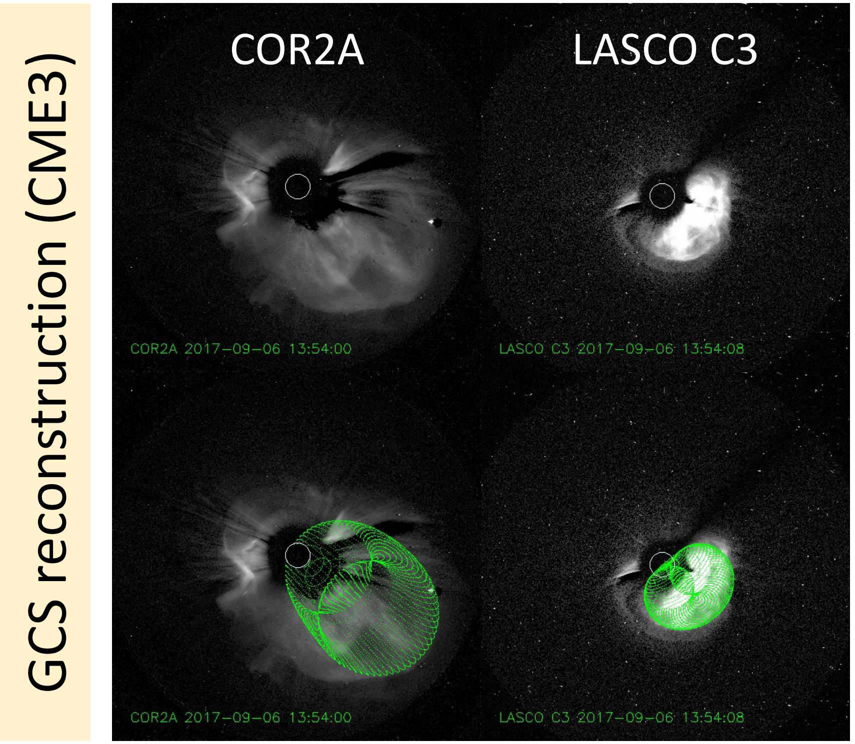
Forecasting perspective
⇢ they need to be determined from observations near the Sun

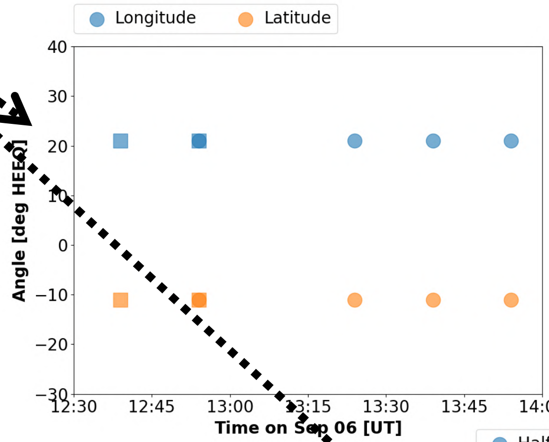
- **CME kinematics/geometry:** from coronagraphic images (ideally close to 0.1 AU)
- **CME magnetic structure:** need to look closer to the Sun

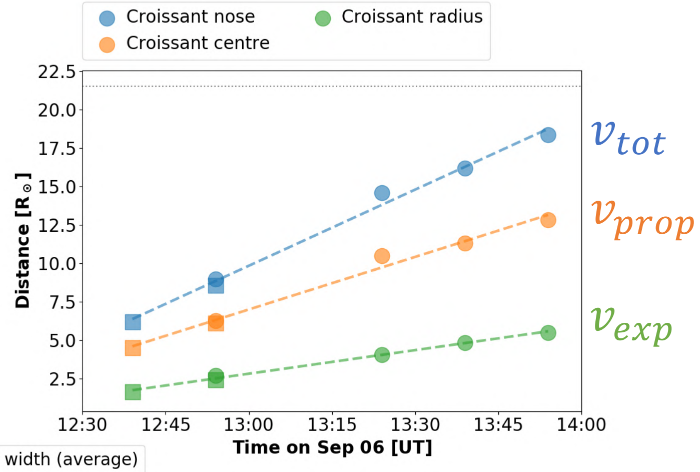
1. **Chirality**: inferred from low-coronal proxies (Palmerio+2017)
2. **Axis orientation**: inferred from photospheric and/or low-coronal proxies
3. **Axial magnetic flux**: based on reconnected flux given by area covered by low-coronal proxies: post-eruptive arcades (Gopalswamy+2017), flare ribbons (Kazachenko+2017), coronal dimmings (Dissauer+2018a,b)
4. Others (e.g. twist) -- note: the spheromak model assumes constant, uniform twist

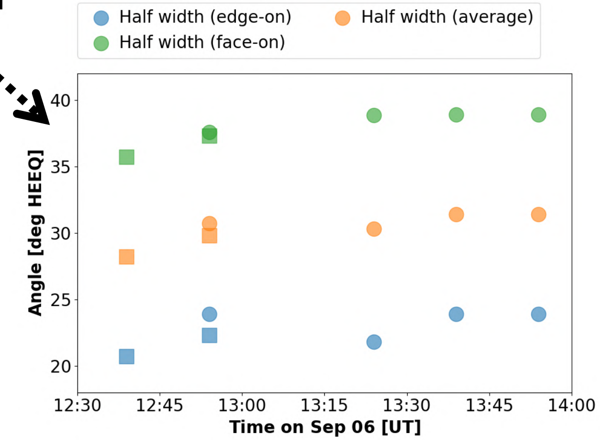
Kinematic/geometric parameters

- **CME direction, width, propagation speed** in the corona estimated by applying the Graduated Cylindrical Shell (GCS) model (Thernisien+2006,2009) to SOHO/LASCO and STEREO/COR2A images
- Extrapolation to 0.1 AU assuming self-similar expansion and no deflections -- good approximation for the particular CMEs under study







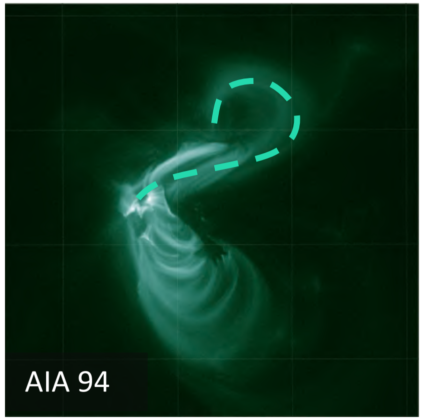


Chirality and orientation

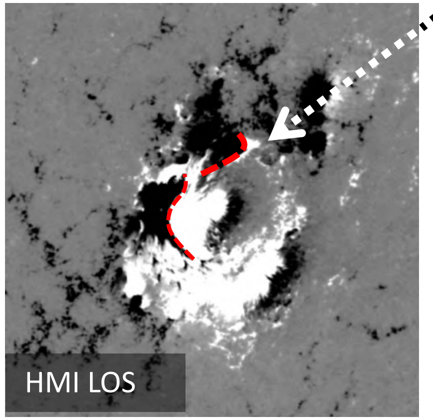
- **EUV sigmoids** provide an estimate of the AR chirality (Demoulin&Pariat2009; Palmerio+2017) – in most cases this is consistent with the **chirality of the erupted flux rope** (Bothmer&Schwenn1998; Palmerio+2018) – notable exceptions reported (e.g. Chandra+2010; Romano+2010; Zuccarello+2010)
- **PIL orientation** used as a signature for the **flux-rope axis orientation** -- neglects rotations in the corona (Vourlidas+2011; Kay+2015), difficult to univocally estimate for irregular PILs (as in the case of the CMEs under study)

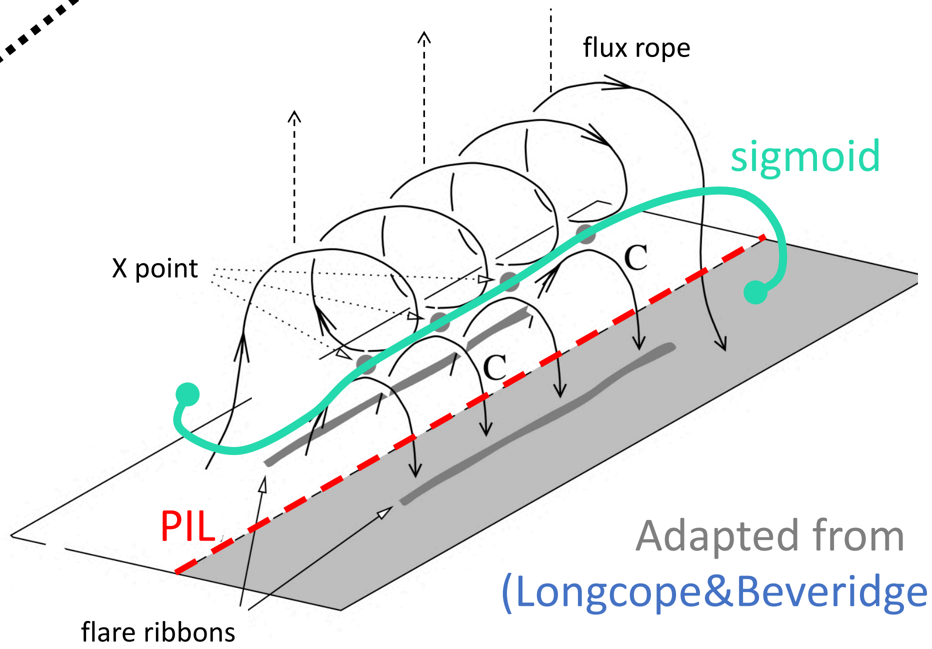
CME3

EUV sigmoid



PIL orientation





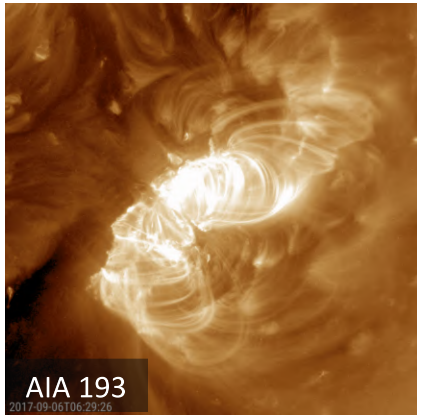
Adapted from (Longcope&Beveridge2007)

Reconnected flux

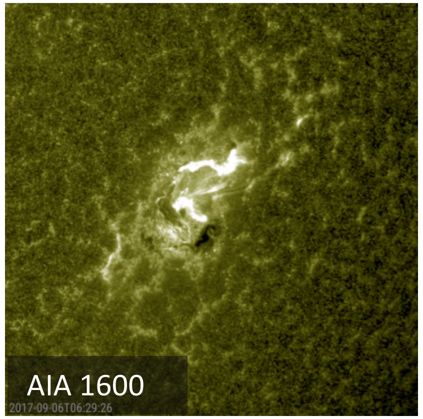
- **Axial magnetic flux $\boldsymbol{\varphi_t}$** estimated from the amount of **reconnected flux $\boldsymbol{\varphi_{\mathrm{RC}}}$** during an eruption
- (Signed) reconnected flux: $\varphi_{\mathrm{RC}} = \frac{1}{2}\int_A |B_{\mathrm{LOS}}|\, dA$ where A = area of observational proxy
- **Different observational proxies** map different regions in the photosphere ⇢ provide different estimates of φ_{RC} -- consistency to be assessed in the particular event studied
- Comparison with results from **statistical relations** (more forecasting "friendly") (Kazachenko+2017; Tschernitz+2018; Dissauer+2018a,b,2019; Pal+2018)

CME3

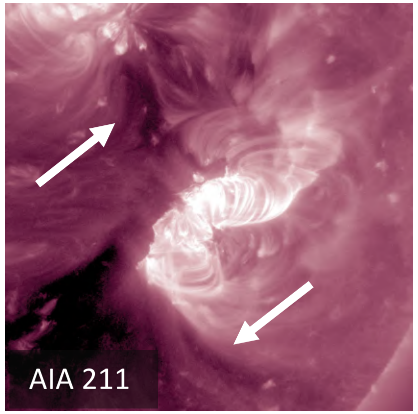
PEA area

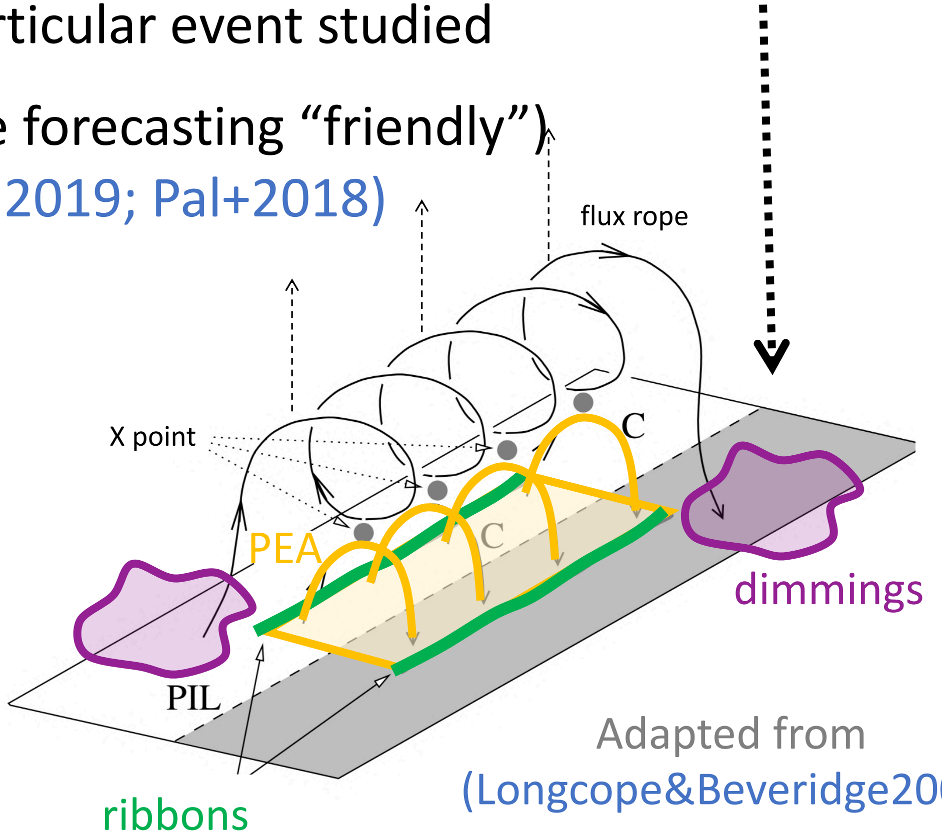


Ribbon area



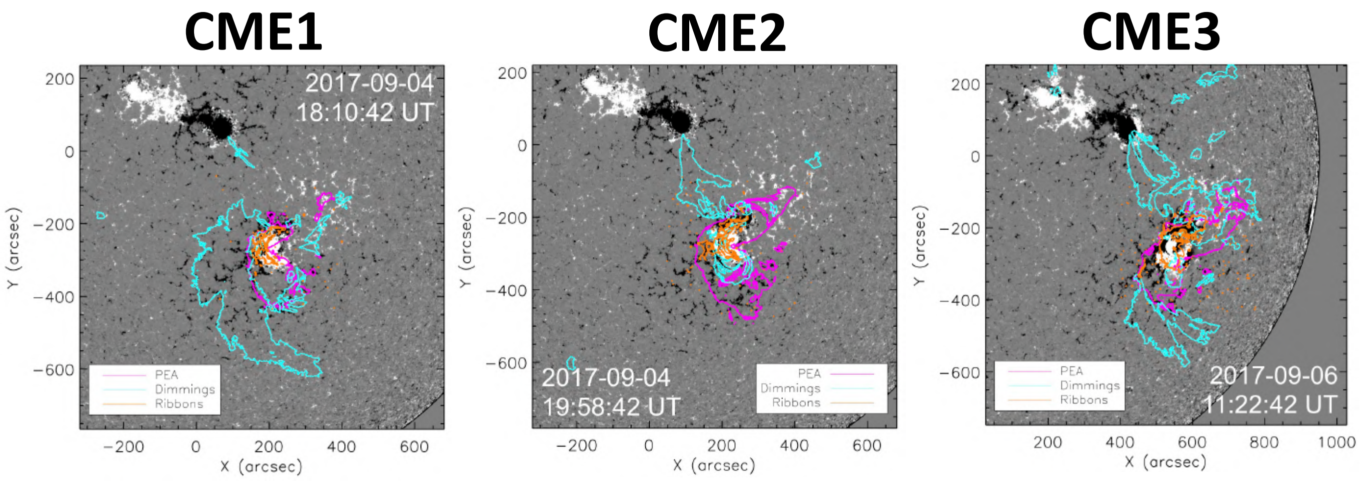
Dimming area





Adapted from (Longcope&Beveridge2007)

Results: reconnected flux estimates



Different proxies cover different areas
⇢ φ_{RC} ranges over 1 order of magnitude

Uncertainties expected to be up to $\pm 50\%$ of the estimated φ_{RC} values ⇢ estimates from different proxies are actually consistent; provide an order of magnitude for φ_{RC}

Parameter (in units of 10^{21} Mx)	**CME1**	**CME2**	**CME3**	
φ_{RC} (based on Kazachenko et al., 2017)	2.3	4.9	30	
φ_{RC} (based on Tschernitz et al., 2018)	2.8	5.5	28	
φ_{RC} (based on Dissauer et al., 2018b)	1.9	3.1	9.9	statistical
φ_{RC} (based on Pal et al., 2018)	4.8	9.9	13	
φ_{RC} (average)	**3.0**	**5.9**	**17**	
φ_{RC} (based on Kazachenko et al., 2017)	0.81	0.78	3.9	
φ_{RC} (based on Dissauer et al., 2018b)	4.9	3.4	7.6	
φ_{RC} (based on Gopalswamy et al., 2017)	8.2	8.7	10	single-event
φ_{RC} (average)	**4.6**	**4.3**	**7.2**	

Good agreement with estimates from statistical relations based on flare peak intensity; these could be potentially employed for operational forecasting

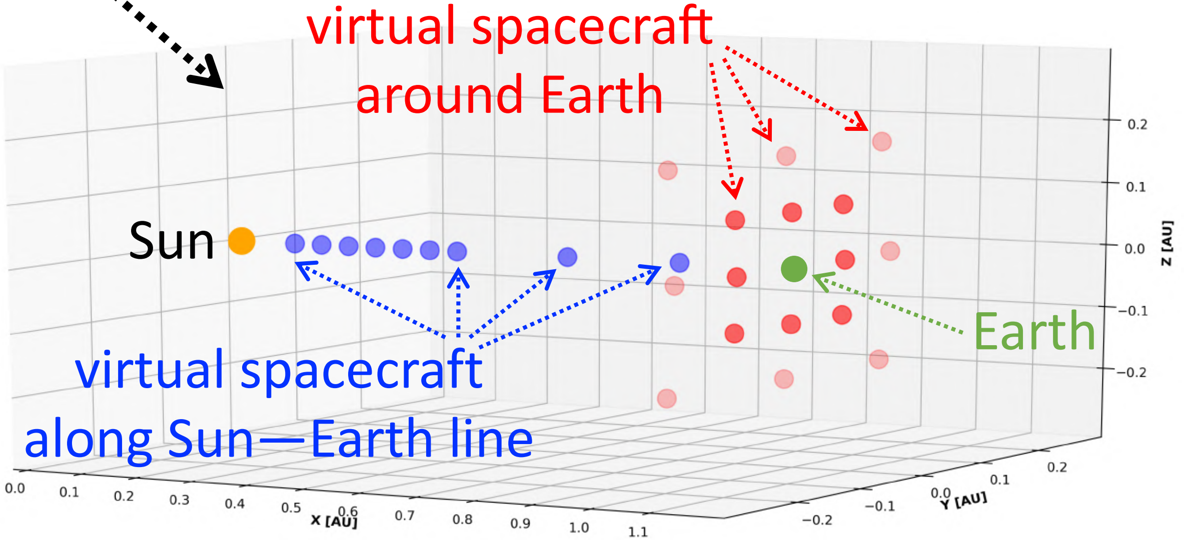
EUHFORIA simulations

- To assess the role of interactions on the helio- and geo-effectiveness of CME1, CME2 and CME3 we run a total of 5 simulations: 1 for the ambient solar, 3 ”block runs” progressively adding individual CMEs to the chain (from CME1 to CME3), 1 simulation with only CME3
- Best prediction can be slightly offset wrt Earth location (Verbeke+2019; Scolini+2019); uncertainty on initial CME direction reconstructed from GCS model around $\pm 10°$ (Thernisien+2009) ⇢ virtual spacecraft placed at 1 AU around Earth to assess spatial sensitivity of model results

Summary of EUHFORIA simulations

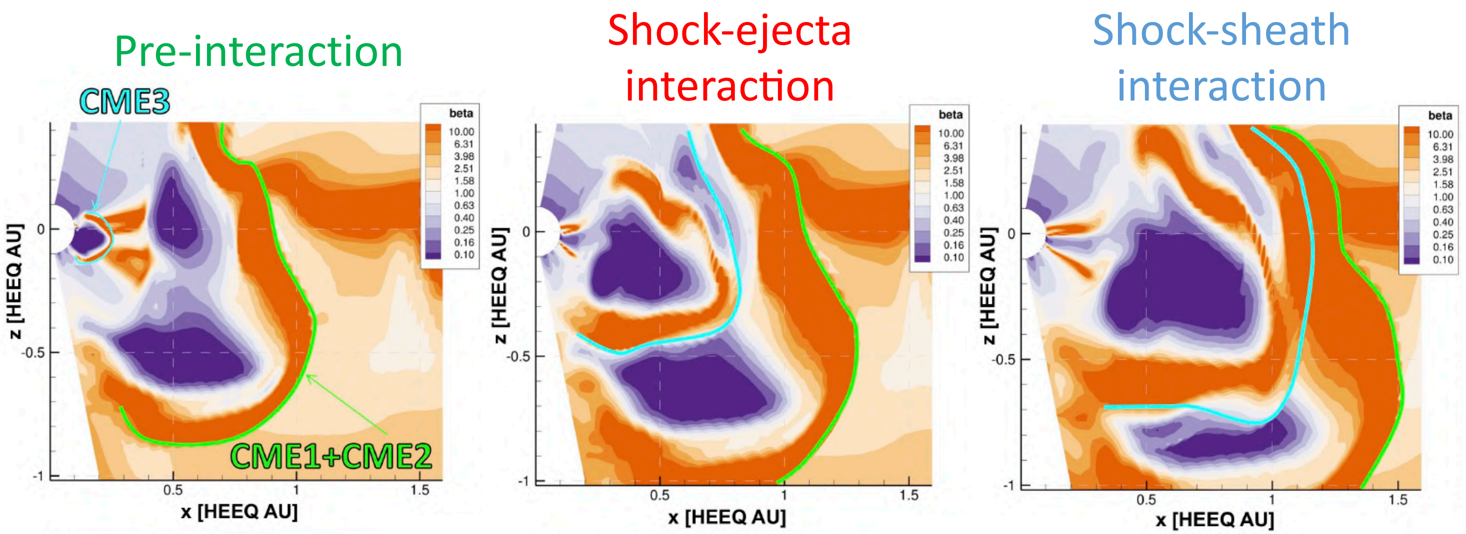
Run number	CME1	CME2	CME3
00-00-00	–	–	–
01-00-00	spheromak	–	–
01-01-00	spheromak	spheromak	–
01-01-01	spheromak	spheromak	spheromak
00-00-01	–	–	spheromak

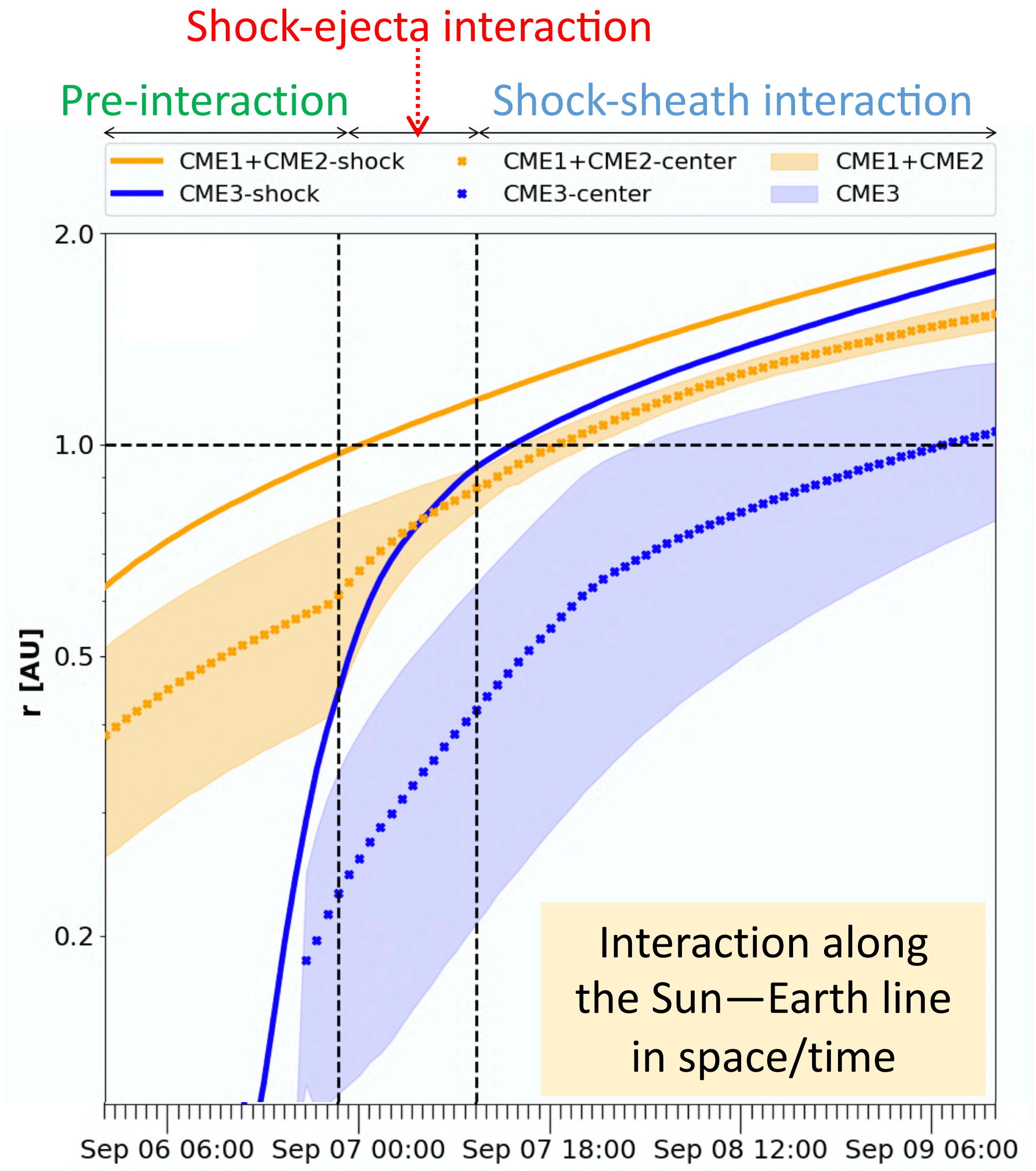
with CME initial parameters based on observational methods (see previous slides) except for the spheromak axial orientation



Results: CME-CME interactions

- CME-CME interactions are not point-like phenomena; their treatment require a description of the magnetic field inside magnetic ejecta ⇢ use of magnetised CME models needed (e.g. Lugaz+2005,2017)
- We characterise the interaction of CME1+CME2 with CME3 in space/time with particular focus on the evolution along the Sun—Earth line



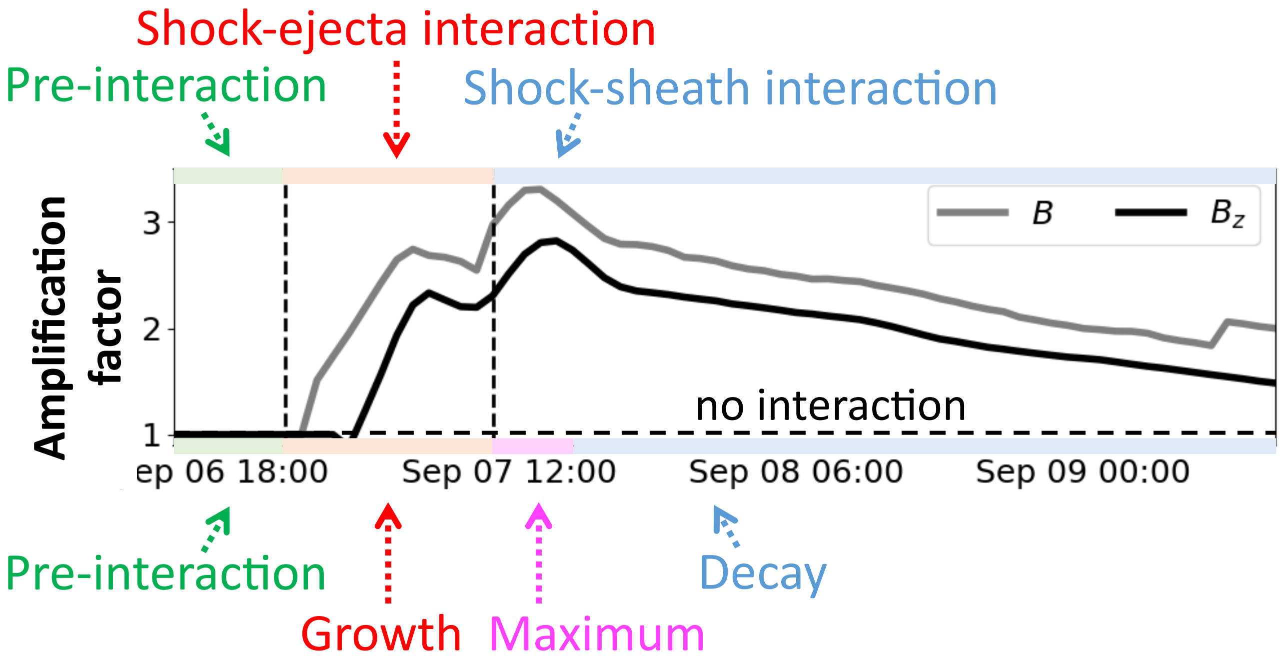


Results: helio-effectiveness amplification

- Amplification of helio-effectiveness of CME1+CME2 caused by CME3 calculated along the Sun—Earth line at various times in our simulations, as

$$A_{Bz} = \frac{\min(B_z)\text{ in run }010101}{\min(B_z)\text{ in run }010100} \quad \text{and} \quad A_B = \frac{\max(B)\text{ in run }010101}{\max(B)\text{ in run }010100}$$

CME1+CME2 helio-effectiveness amplification

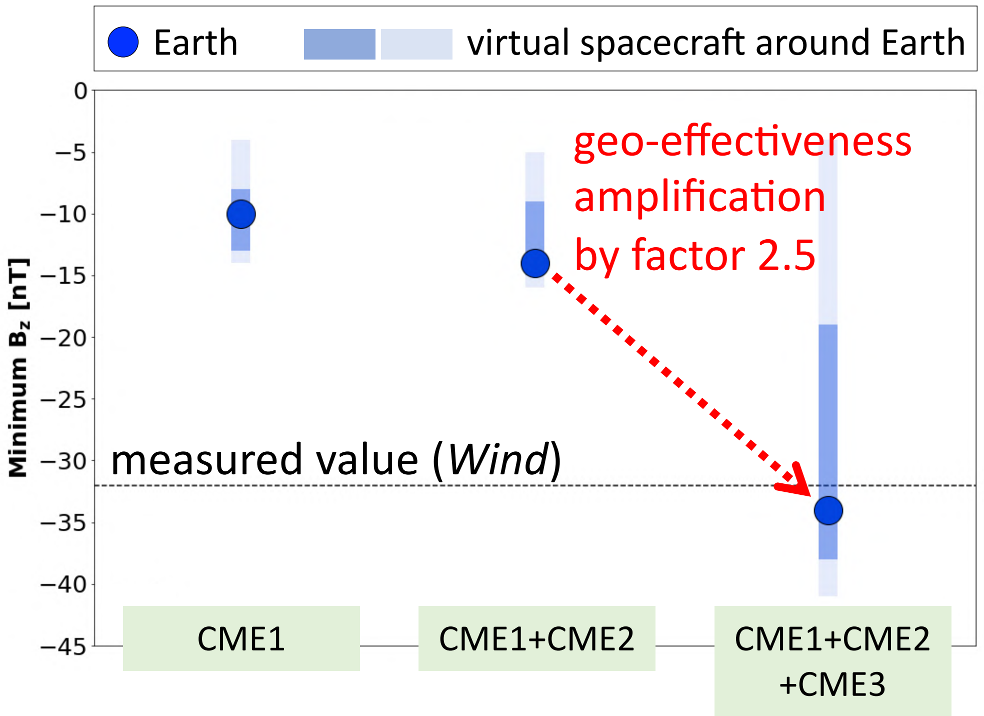


- Close correlation between interaction phase and amplification of potential helio-effectiveness of the preceding CME(s)
- Existence of **maximum amplification phase** hints to existence of a characteristic **"helio-effectiveness amplification zone"**
- Maximum amplification around 0.9 AU
  ⇢ **intense storm at Earth caused by impact during maximum amplification phase**

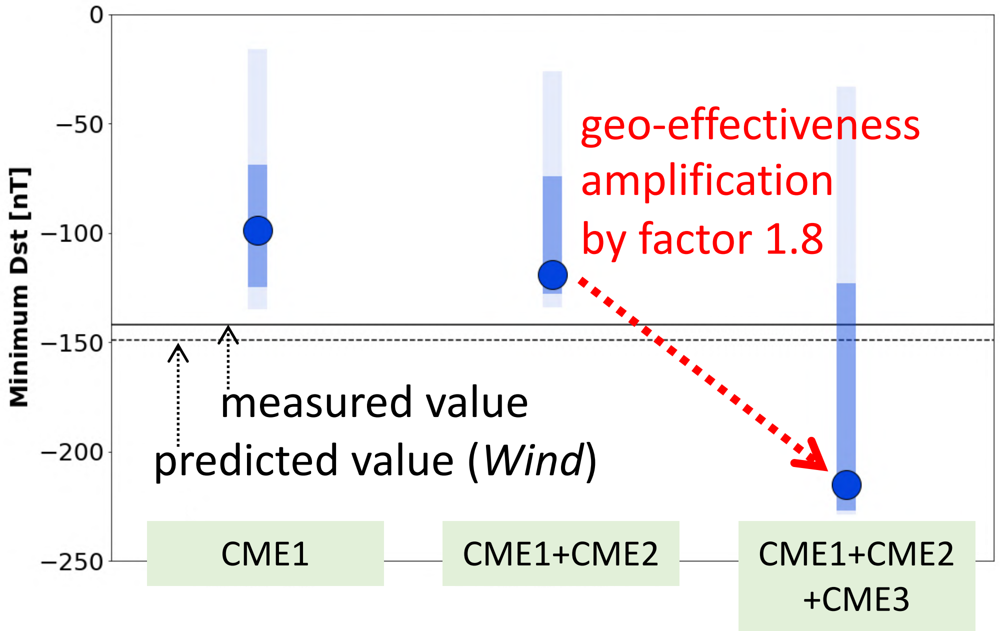
Results: geo-effectiveness amplification

- Simulations estimate the **geo-effectiveness of CME1+CME2** was **amplified by a factor 1.8 -- 2.5** due to interaction with following CME3 -- results are consistent with previous observation-based estimates by Shen+2018

Minimum B_z from EUHFORIA



Minimum Dst index from EUHFORIA + coupling function (O'Brien&McPherron2000)



Summary and conclusions

- In this study: we use EUHFORIA to investigate a series of geo-effective CMEs in September 2017
- Questions addressed: what is the role of CME-CME interactions in amplifying the helio- and geo-effectiveness of individual CMEs? How does it evolve in space and time?

→ **Reconnected fluxes from different low-coronal proxies** are **consistent** with results from **statistical relations**, which are faster and easy to apply ⇢ need to further investigate their potential for operational forecasting

→ Analysis of CME helio-effectiveness in space/time from simulations indicates a **maximum amplification is reached at the end of the shock-ejecta interaction phase** ⇢ hints to existence of a **characteristic ''helio-effectiveness amplification zone''** for each pair of interacting CMEs

- For the events under study: **intense geomagnetic storm caused by impact during maximum amplification phase** – amplification by a factor of 2.5 in B_z (1.8 in Dst)

→ More case studies + parametric studies required to build a statistical picture

Thank you for your interest!

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The results presented in this work have been recently published in the *Astrophysical Journal Supplement Series* as Scolini et al. (2020), DOI: 10.3847/1538-4365/ab6216

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