What do coronal dimmings tell us about magnetic connectivity and reconfiguration during the early stage of a solar eruption?

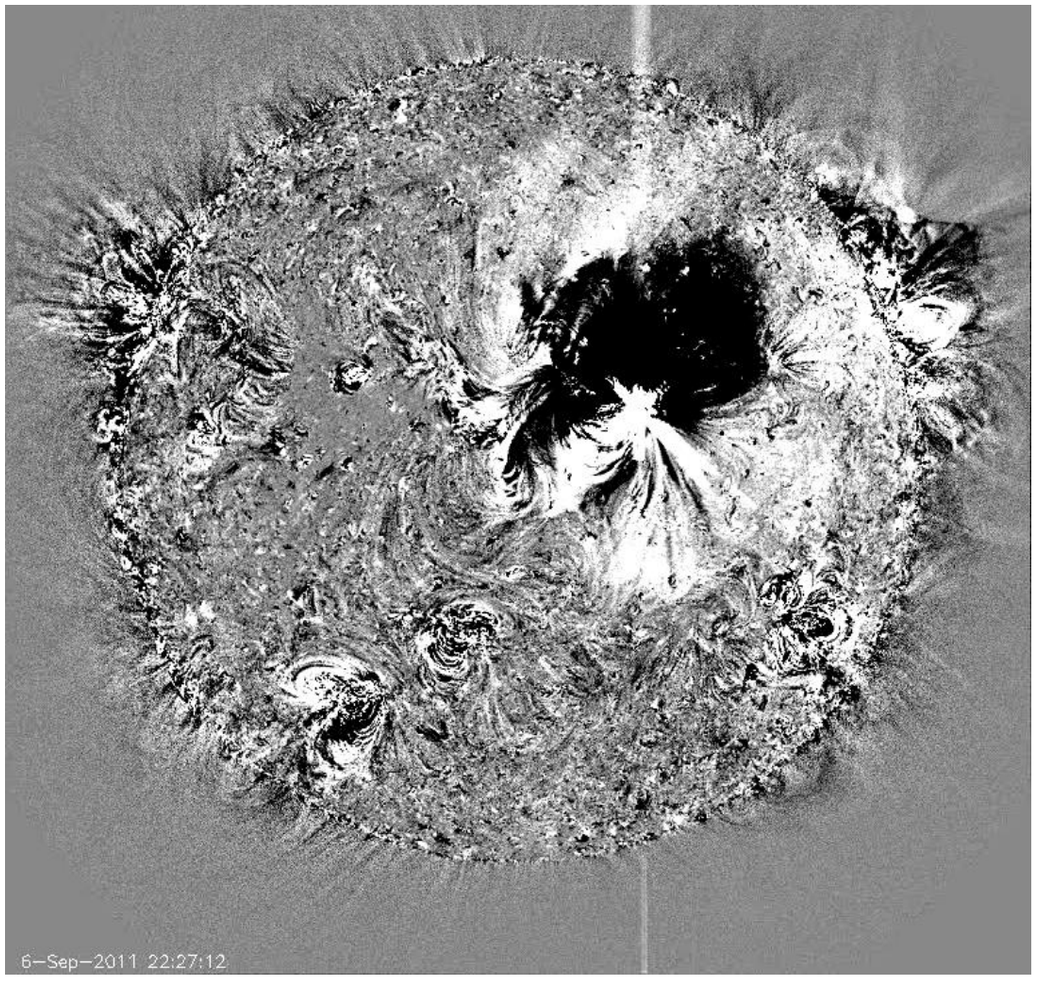
K. Dissauer[1,2], A. Prasad[3], Q. Hu[3,4], R. Bhattacharyya[5], A. M. Veronig[2,6], S. Kumar[7], B. Joshi[5]

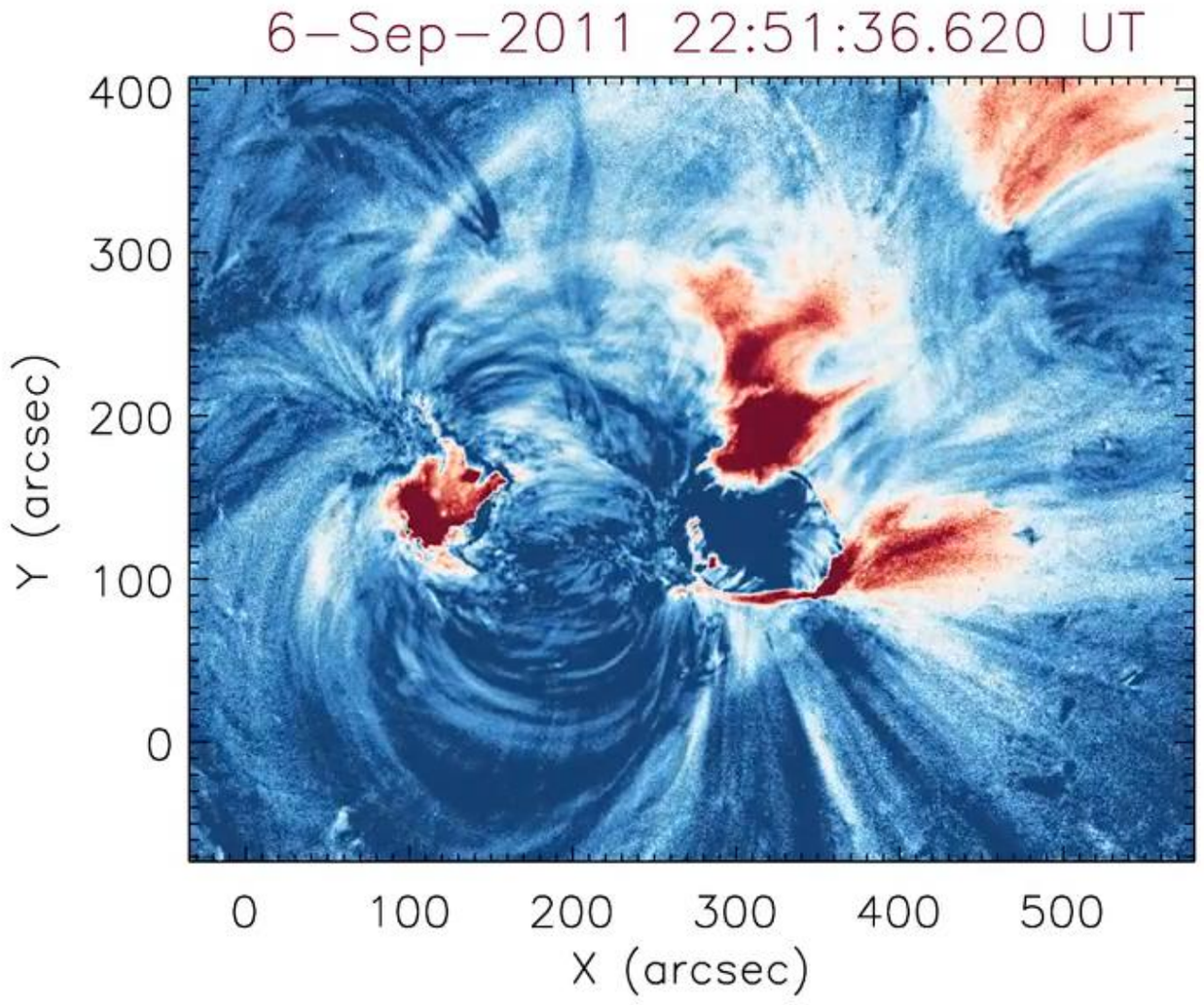
[1] NorthWest Research Associates, Boulder, Colorado, USA
[2] Institute of Physics, University of Graz, Austria
[3] Center for Space Plasma & Aeronomic Research, The University of Alabama in Huntsville, Huntsville, Alabama, USA
[4] Department of Space Science, The University of Alabama in Huntsville, Huntsville, Alabama, USA
[5] Udaipur Solar Observatory, Physical Research Laboratory, Udaipur, India
[6] Kanzelhoehe Observatory/Institute of Physics, University of Graz, Austria

HIGHLIGHTS:

- MHD simulation of X2.1 flare/CME event on 6-Sep-2011 in NOAA AR 11283 is performed to gain insight into observational features of coronal dimmings related to flare reconnection.
- Pre-flare dimmings, observed ~30 min before the flare onset, form due to the rise of the outer envelope of the flux rope and reconnection of those field lines at a pre-existing 3D null point.
- Ring-shaped dimming close to the main flare site is formed due to reconnection at the 3D null transforming closed inner spine field lines to open field lines of the outer spine.
- Plasma loss along open field lines can potentially explain dimming regions of strongest intensity decrease.
- Remote dimming formation could not be explained by the current simulation, although field lines connect to regions close to the dome and 3D null point.

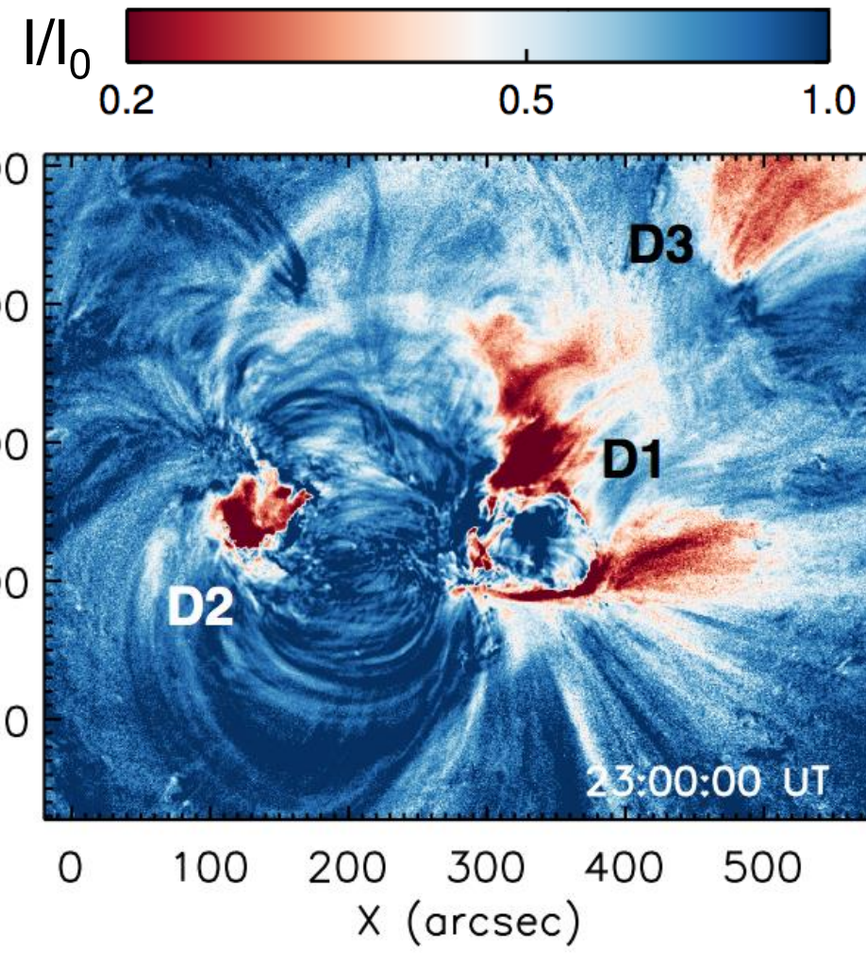
Introduction – coronal dimmings





- Temporary regions of strongly reduced emission in EUV and soft X-rays caused by expansion and evacuation of plasma associated with CMEs in the low corona (e.g. Hudson et al. 1996, Thompson et al. 1998, Dissauer et al. 2019)
- We study „famous“ X2.1 flare/CME event on September 6, 2011 (e.g. Jiang et al. 2013, 2014, 2016, 2018; Janvier et al. 2016, …) in combination with simulations to gain insight into observational features of coronal dimmings related to flare reconnection

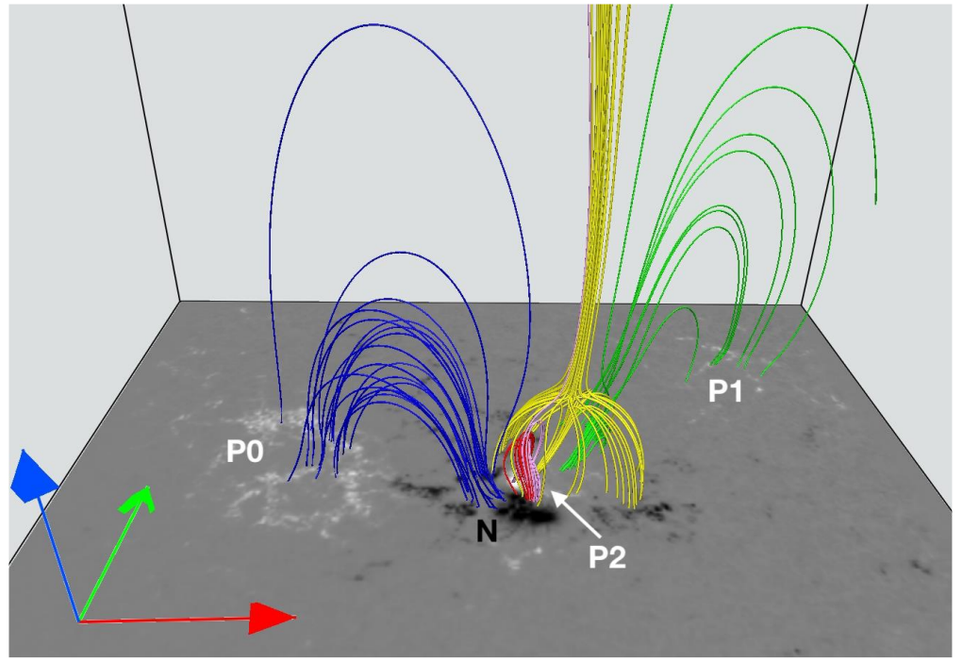
Coronal dimming evolution

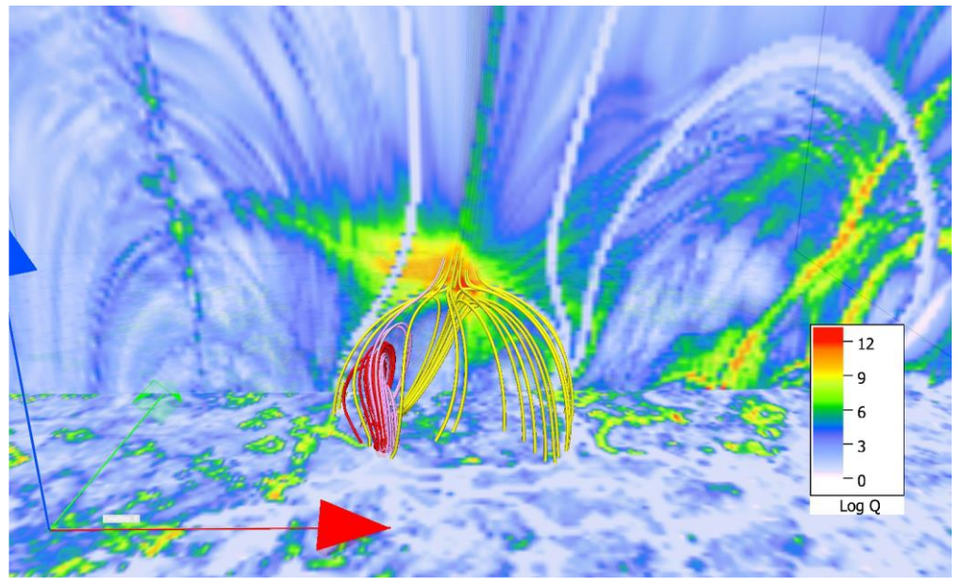


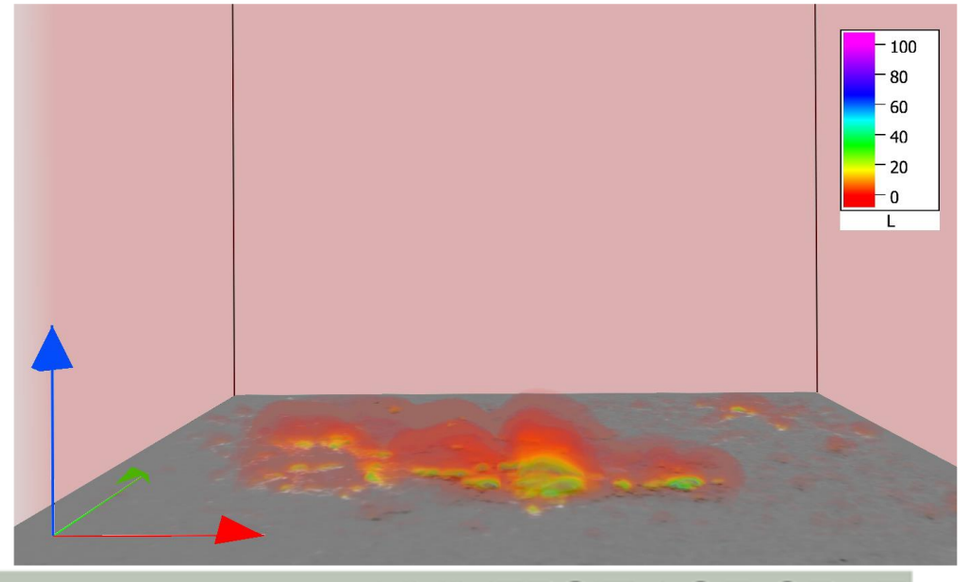
- Coronal dimmings are detected based on a thresholding method using logarithmic base-ratio images (Dissauer et al. 2018a) → resolve fine structure
- Regions in dark red represent locations of maximal intensity decrease
- Formation of pre-flare dimmings, ring-shaped dimming before the main eruption
- Regions of interest: ring-shaped dimming close to the main flare site D1, circular dimming region D2, and remote dimming region D3

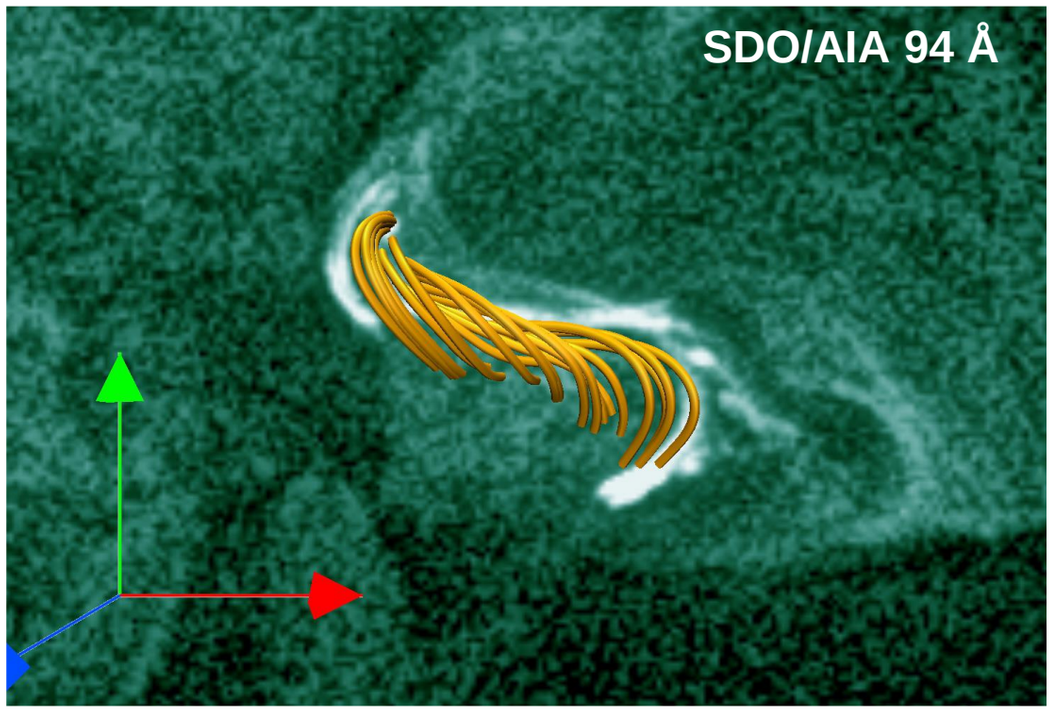
Numerical setup

- MHD simulation initiated by non-force-free magnetic field extrapolated from SDO/HMI photospheric vector magnetograms
  - Non-force-free magnetic field extrapolations obtained following Hu & Dasgupta 2008, Hu et al. 2008, 2010
  - Dynamical evolution is studied using incompressible Navier-Stokes MHD equations (Bhattacharyya et al. 2010, Kumar et al. 2014, 2015)
  - EULAG-MHD numerical model used to solve them (Smolarkiewicz & Charbonneau 2013)





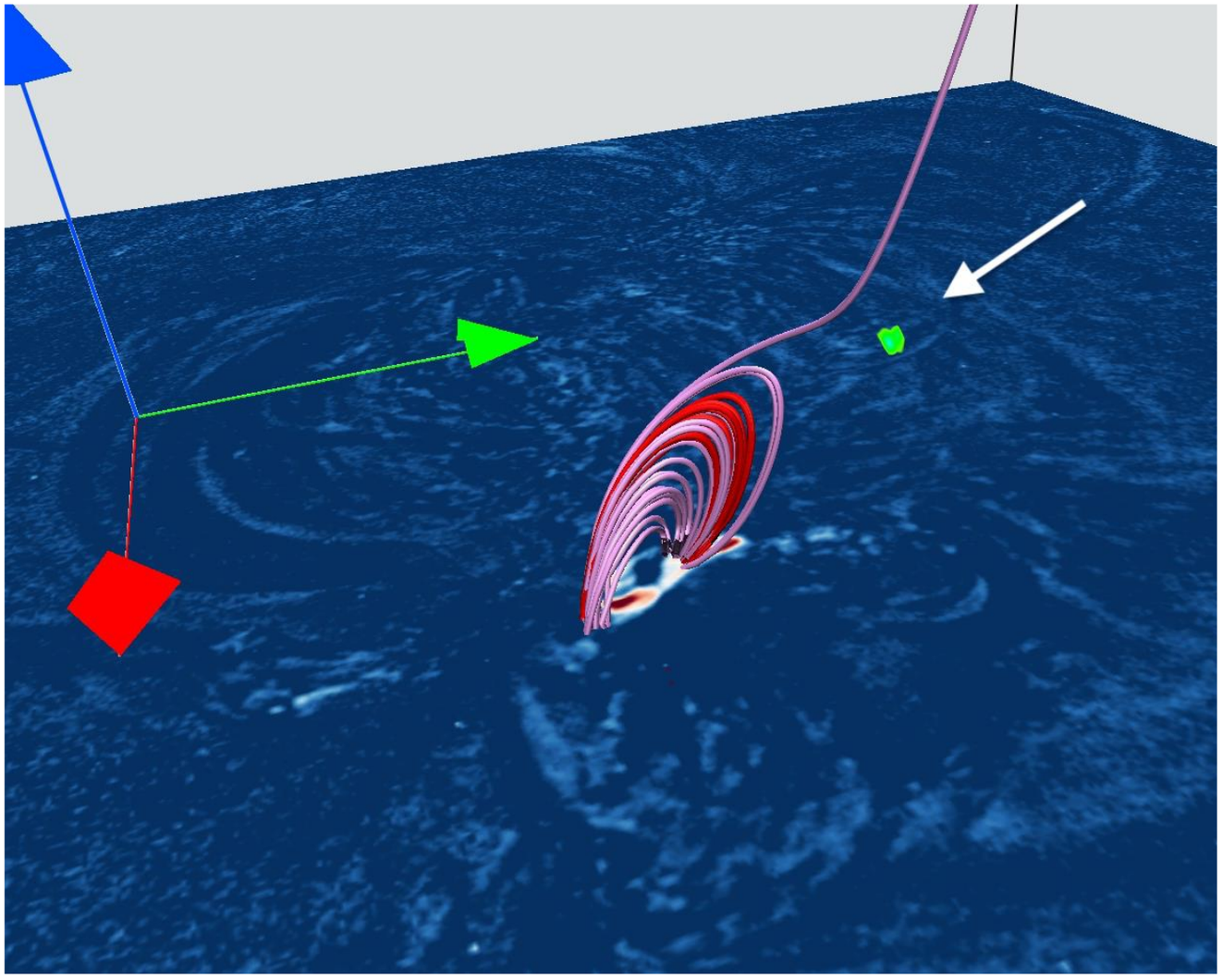


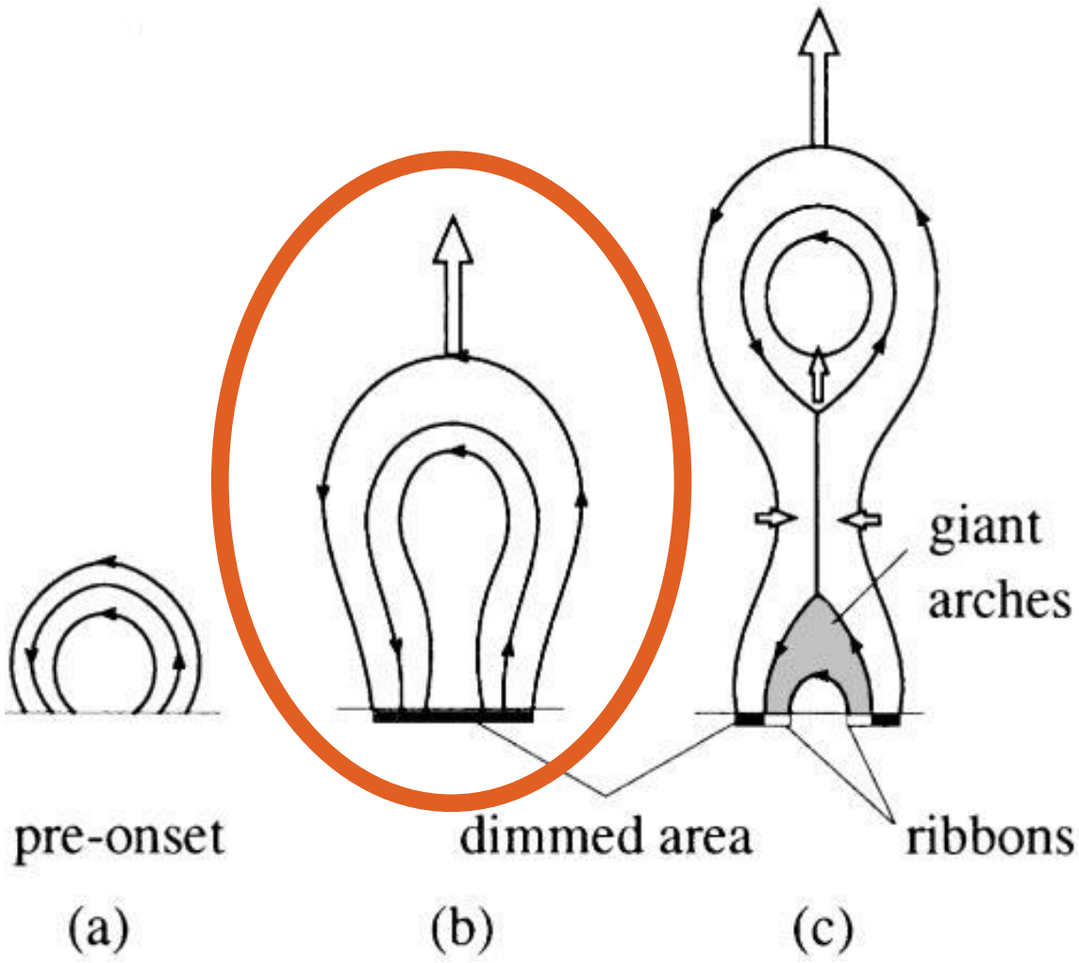


Pre-flare stage – simulation vs. observations

- Small-scale, bipolar pre-flare dimmings (Qiu & Cheng et al. 2017, Zhang et al. 2017) are formed ~30 min before the start of the flare

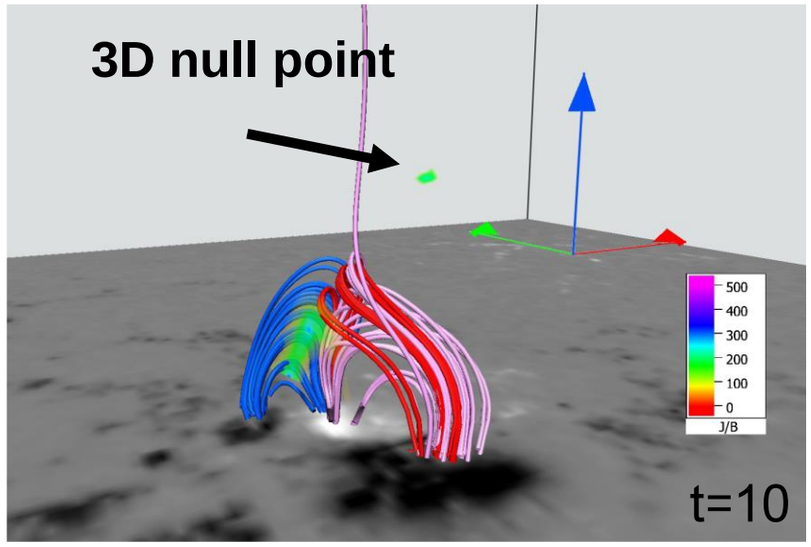
- Formation→ combination of (i) rising of the outer envelope of the flux rope and (ii) magnetic reconnection at the pre-existing 3D null point

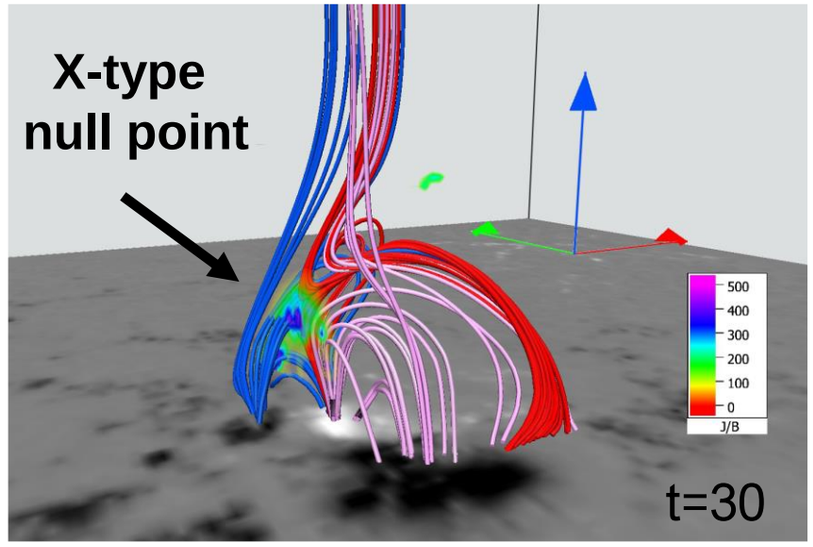


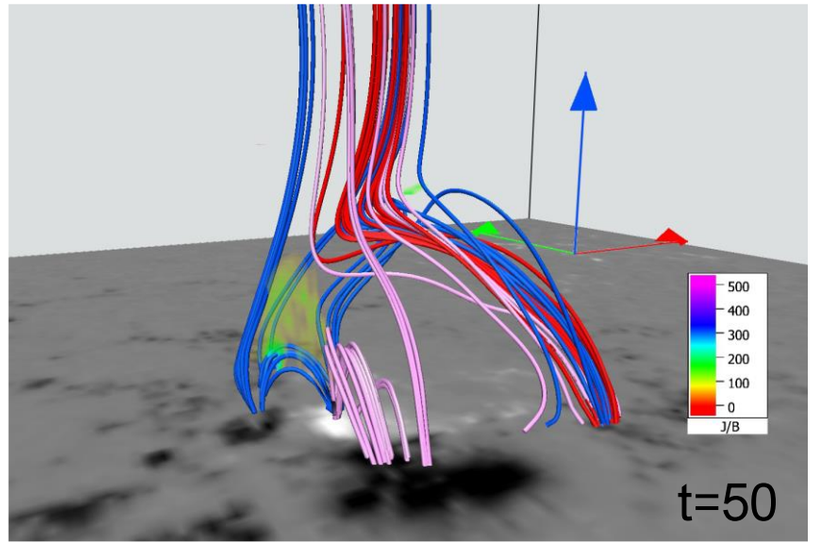


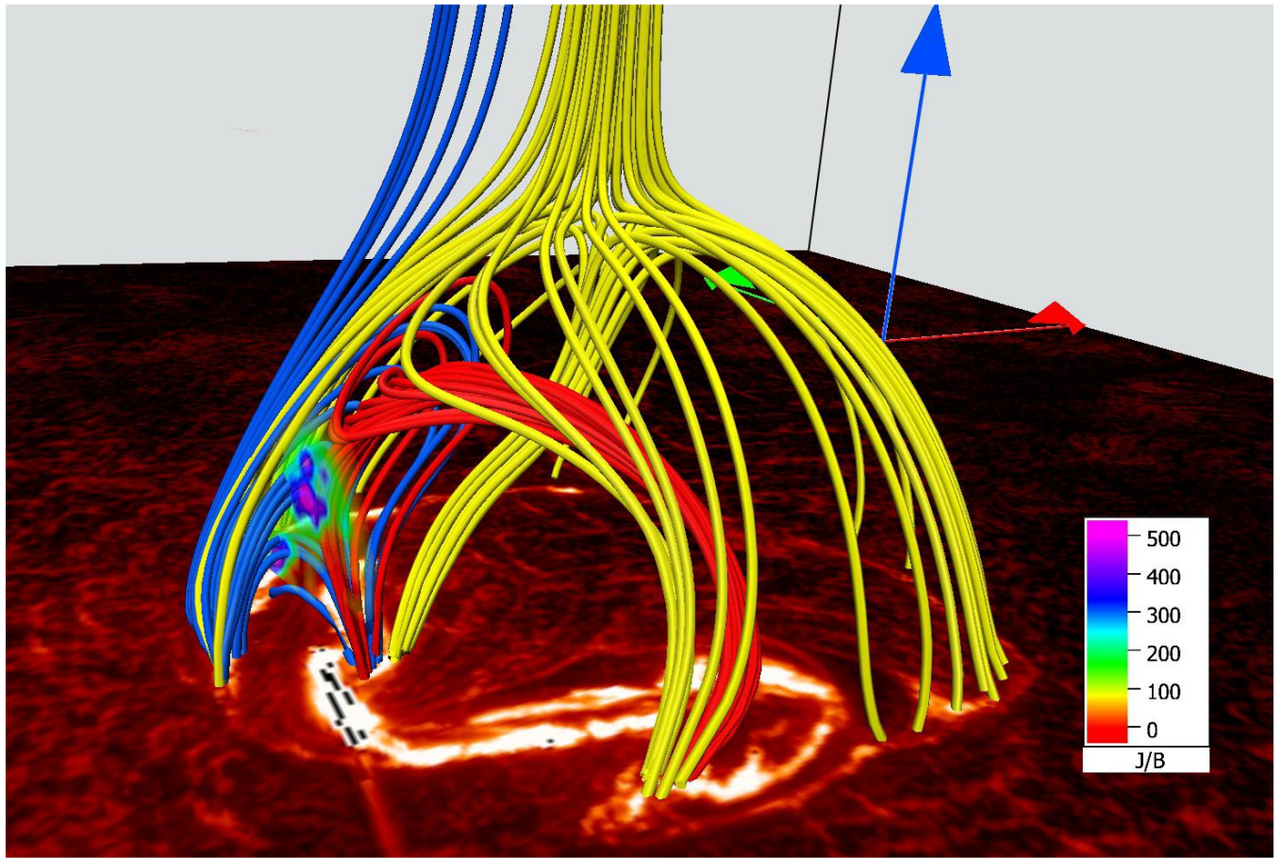
Theory: Forbes & Lin 2000, Lin et al. 2004;
Observations: e.g. Qiu & Cheng 2017

Flaring stage – simulation vs. observations



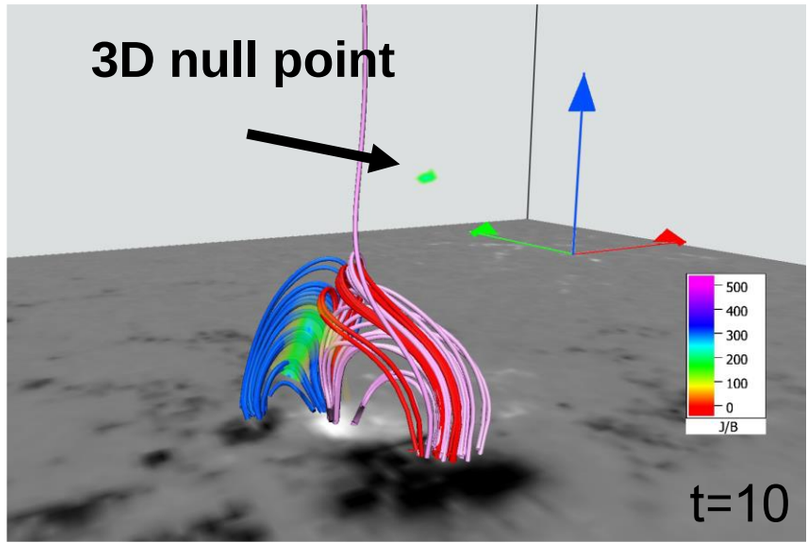


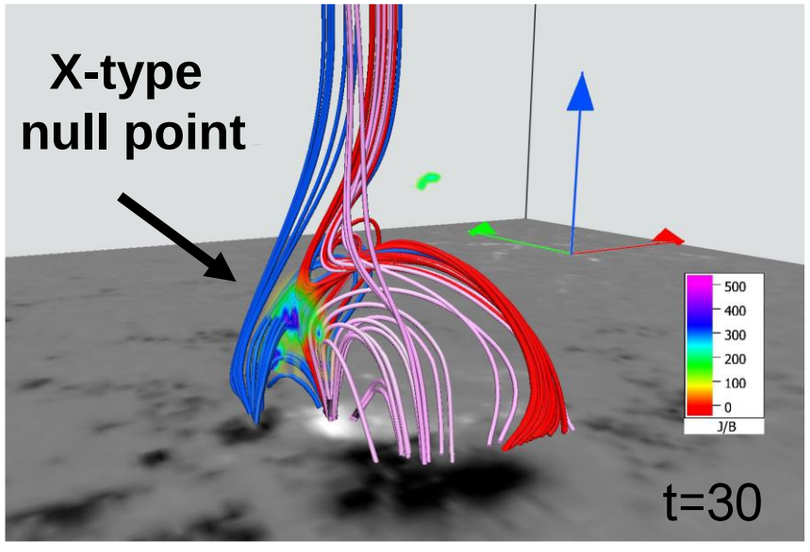


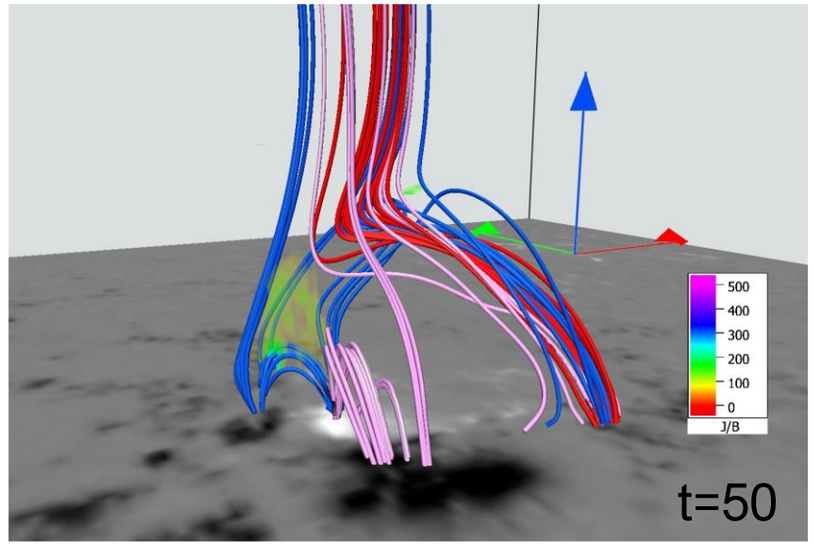


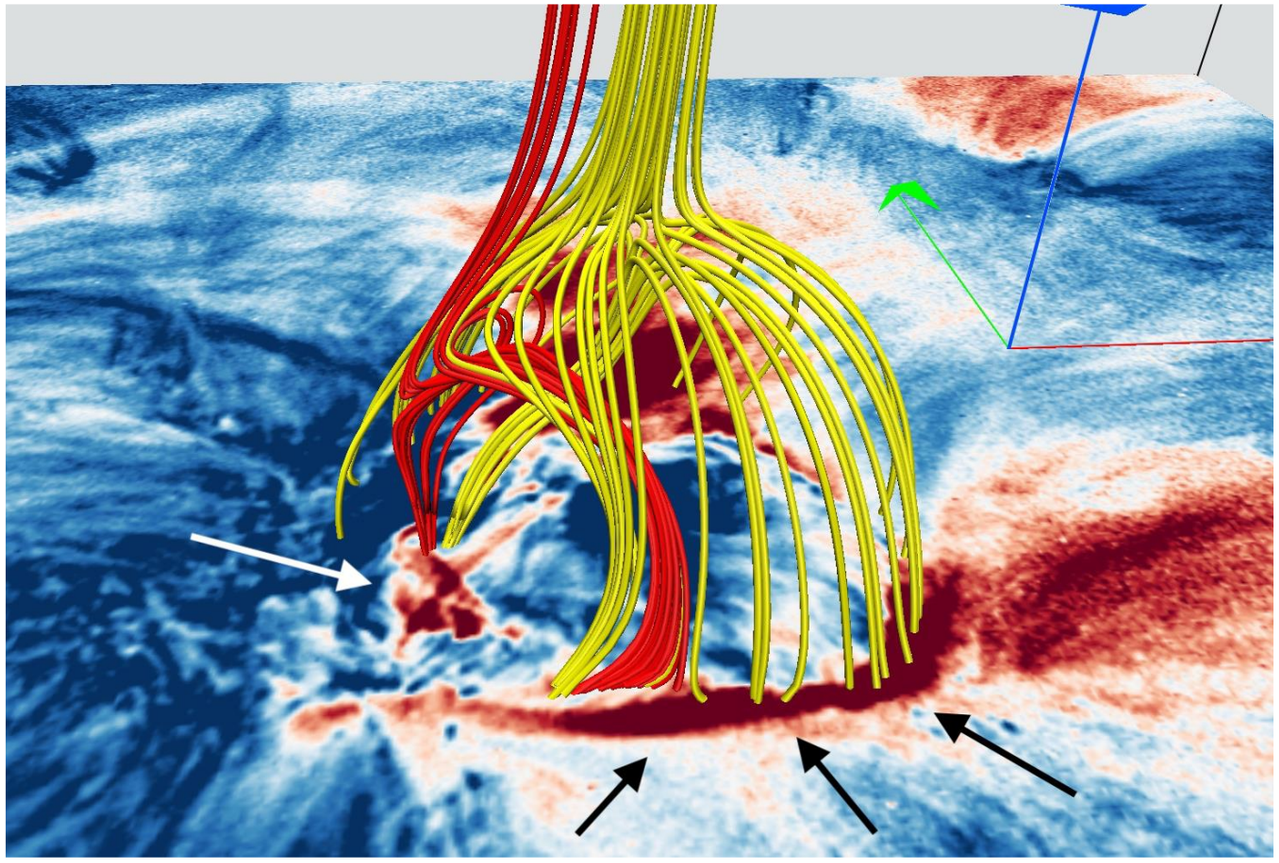
- Outer envelope of the flux rope is rising (purple) and reconnecting at the pre-existing 3D null point
- Development of X-type null point between flux rope (red) and nearby loops (blue)
- Simultaneous reconnection at the 3D null and X-type null point
- → Combined formation of circular flare ribbon and standard parallel flare ribbons

Dimming formation D1 – simulation vs. observations



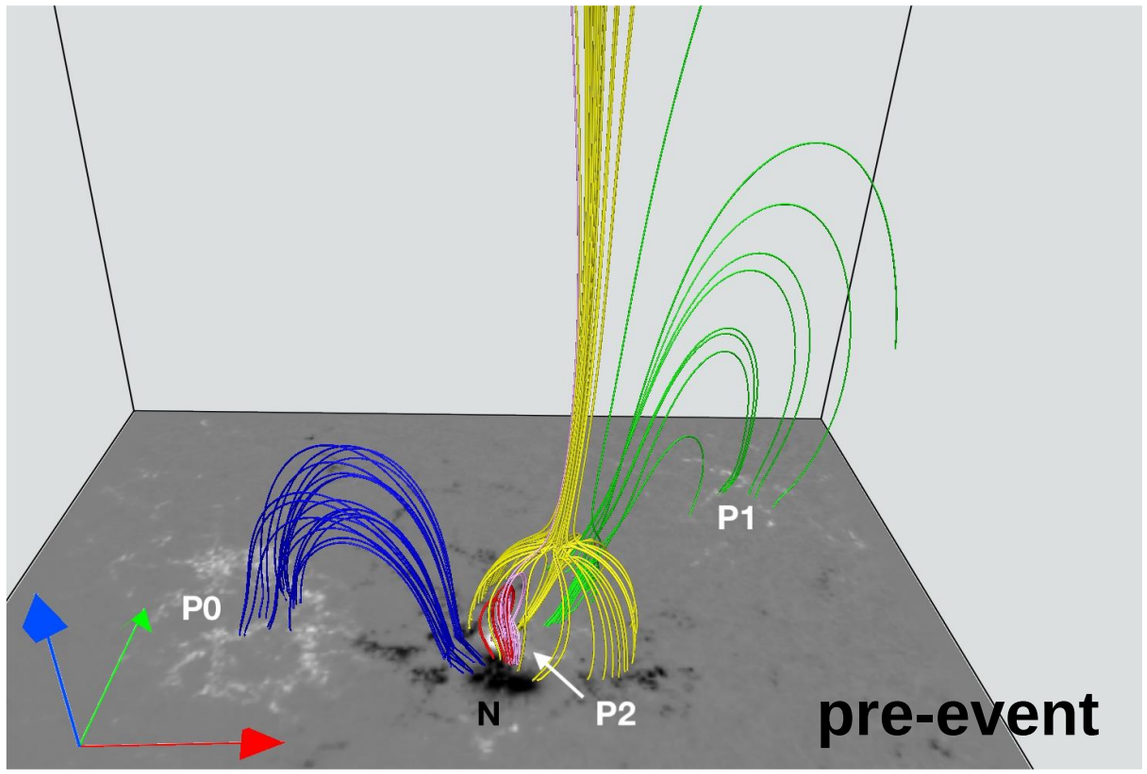


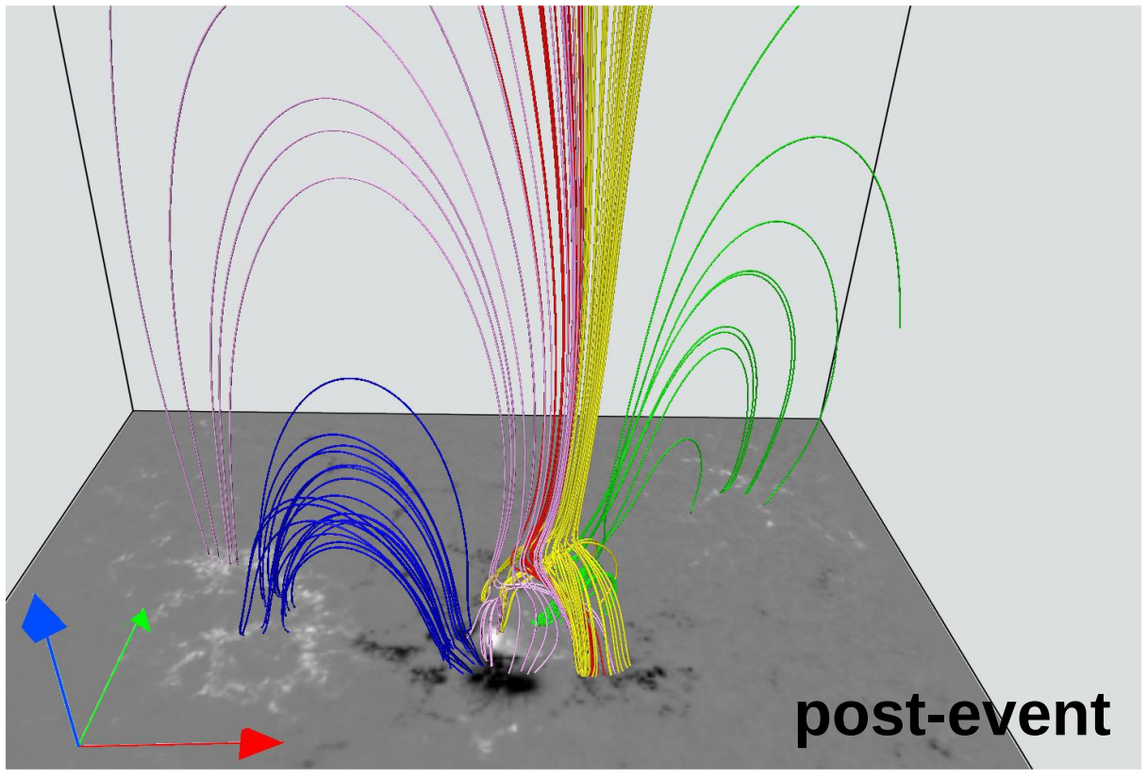


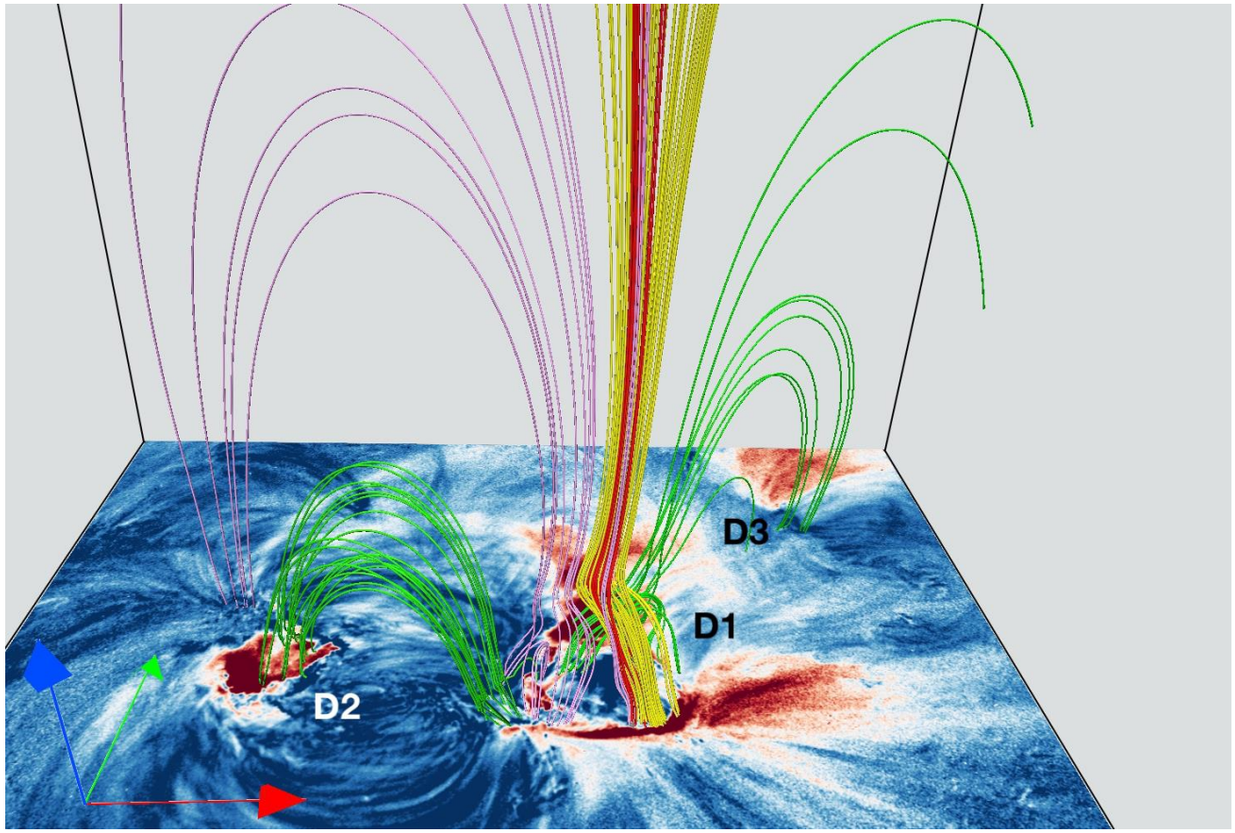


- Outer envelope of the flux rope is rising (purple) and reconnecting at the pre-existing 3D null point
- Transformation of closed field of the inner spine to outer spine field lines which are open
- Regions of strongest intensity decrease correspond to footpoints of open magnetic field lines in simulation

Dimming formation D2 & D3 – simulation vs. observations







- Blue and green field lines that originally connect to D2 and D3 are not changing during the simulation
- No explanation for the formation of those dimming regions from the simulation
- Absence of eruption → due to viscous dissipation (fast depletion of free magnetic energy)
- Field lines connect to regions close to the dome and 3D null point, match positions of remote flare ribbons

Summary

- For the case of the X2.1 flare in the AR 11283, we find a 3D null topology and a sigmoid close to the location of the flare in the initial extrapolated NFFF.
- In the MHD evolution we find reconnections occurring close to the location of the 3D null leading to formation of a X-type null that can explain the trigger for the flare, circular flare brightening and coronal dimmings as inferred from the AIA images.
- Pre-flare dimmings represent the outer envelope of the rising flux rope before the eruption → in agreement with Forbes & Lin 2000, Qiu & Cheng et al. 2017.
- Regions of strongest decrease within the dimming region map magnetic field lines that open during the eruption.
- In combination with flare ribbons, coronal dimmings provide a powerful tool for magnetic connectivity analysis.
- This study is published in: A. Prasad, K. Dissauer, Q. Hu, R. Bhattacharyya, A.M. Veronig, S. Kumar, B. Joshi, *Magnetohydrodynamic Simulation of Magnetic Null-point Reconnections and Coronal Dimmings during the X2.1 flare in NOAA AR 11283*, ApJ, 903, 129, 2020.