



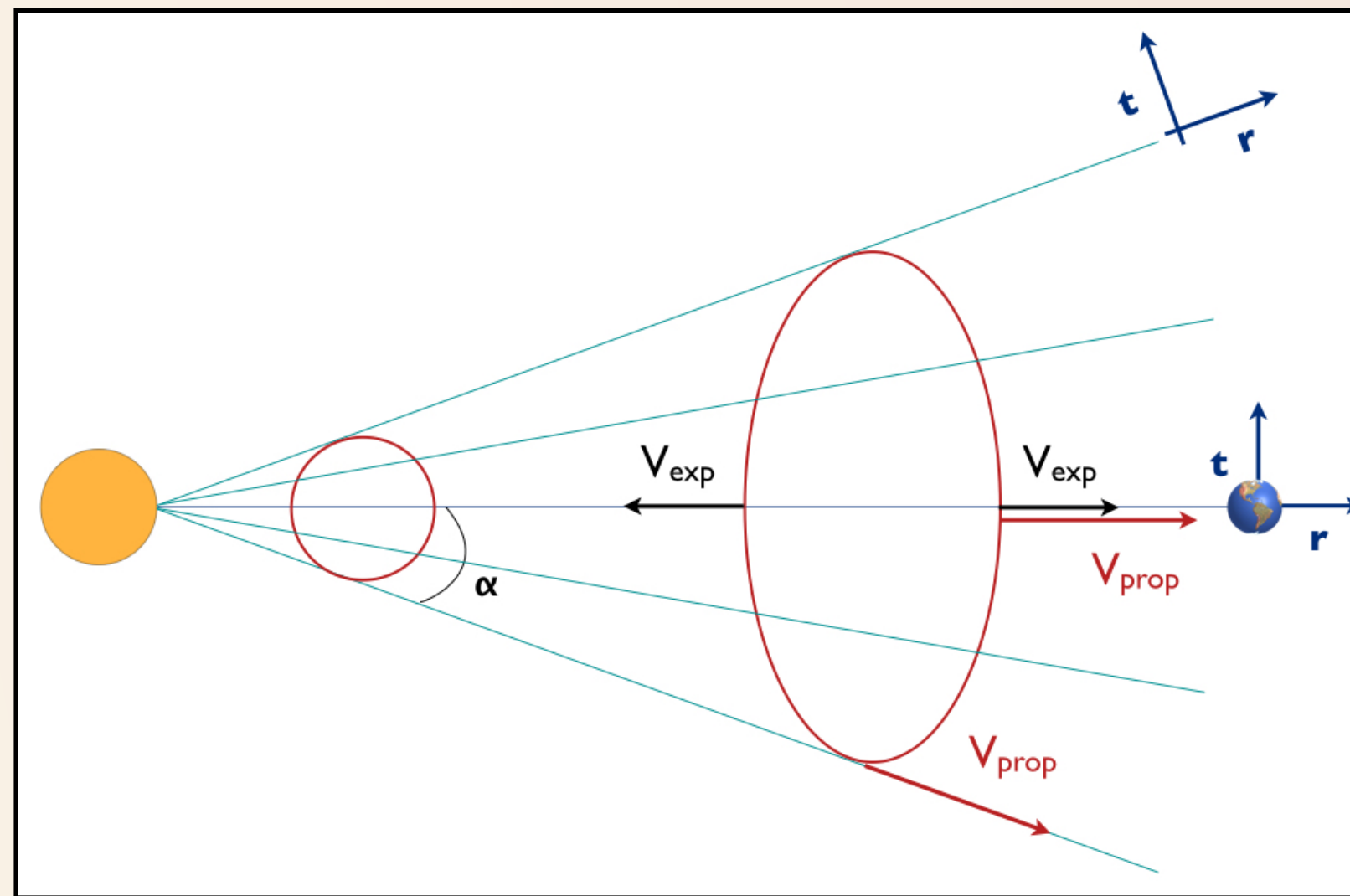
## Introduction

The solar wind, when measured close to 1 AU, is found to flow mostly radially outward. There are, however, periods when the flow makes angles up to  $15^\circ$  away from the radial direction, both in the east-west and north-south directions. Stream interaction regions (SIRs) are a common cause of east-west flow deflection. Coronal mass ejections (CMEs) may be associated with non-radial flows in at least two different ways: 1) the deflection of the solar wind in the sheath region 2) the expansion of the magnetic ejecta may include a non-radial component which should be easily measured when the ejecta is crossed away from its central axis. In this work, we present several studies of the solar wind flows as measured by STEREO/PLASTIC throughout the first 14 years of the mission. General statistics on the non-radial flows, solar cycle variation, and few case studies on the larger deflection flow angles and their associated phenomena are discussed. We find no clear evidence of strongly deflected flows, as would be expected with large deflection around the magnetic ejecta or elliptical cross-sections with large eccentricities. This study is available in Al-Haddad et al. 2021 (ApJ, *accepted*).

## Nonradial Flows: Model-Dependent Expectations

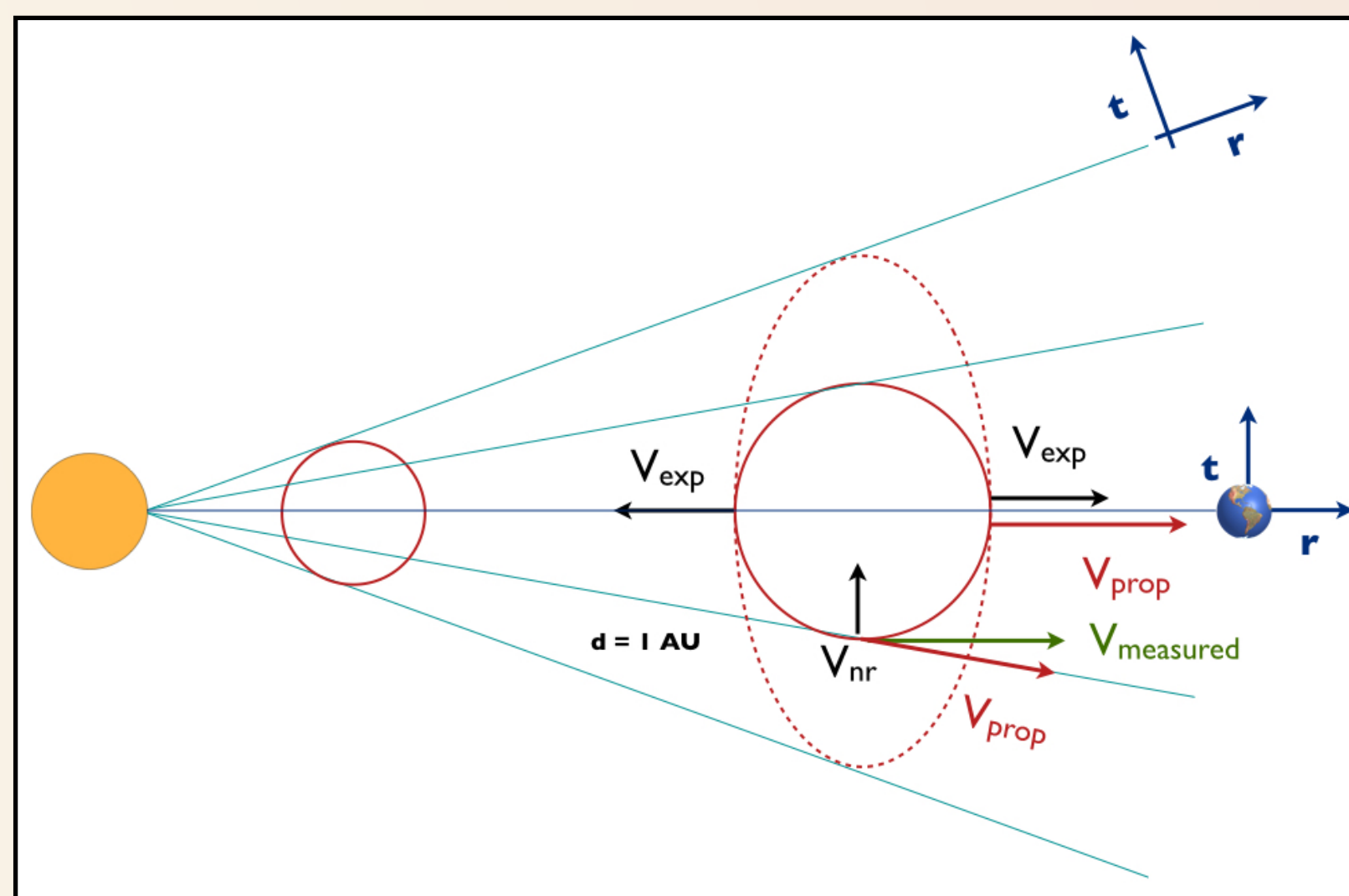
### Scenario#1: Pure radial flows:

As the CME lateral expansion is purely kinematic, it is not associated with bulk plasma motion away from the CME axis. However, radial expansion and flows are well attested, therefore this scenario needs to explain why no expansion flows are measured in the non-radial direction. If the CME magnetic tension force acts in a way that hinders expansion in the non-radial direction, then since the solar wind is radially structured, the expansion in the radial direction should be even more. Therefore, this possibility is unlikely. Another possibility would be: in order for the CME to maintain its angular width, non-radial expansion is required. This means that the non-radial flow velocity would have to be the exact value needed to balance out the physical mechanisms that compress the CME angular width. This is also highly unlikely as only one value of the non-radial expansion is possible to maintain the flow exactly radial. From the examination of these two possibilities, we conclude that non-radial flows are very likely to be present inside MEs as they propagate.



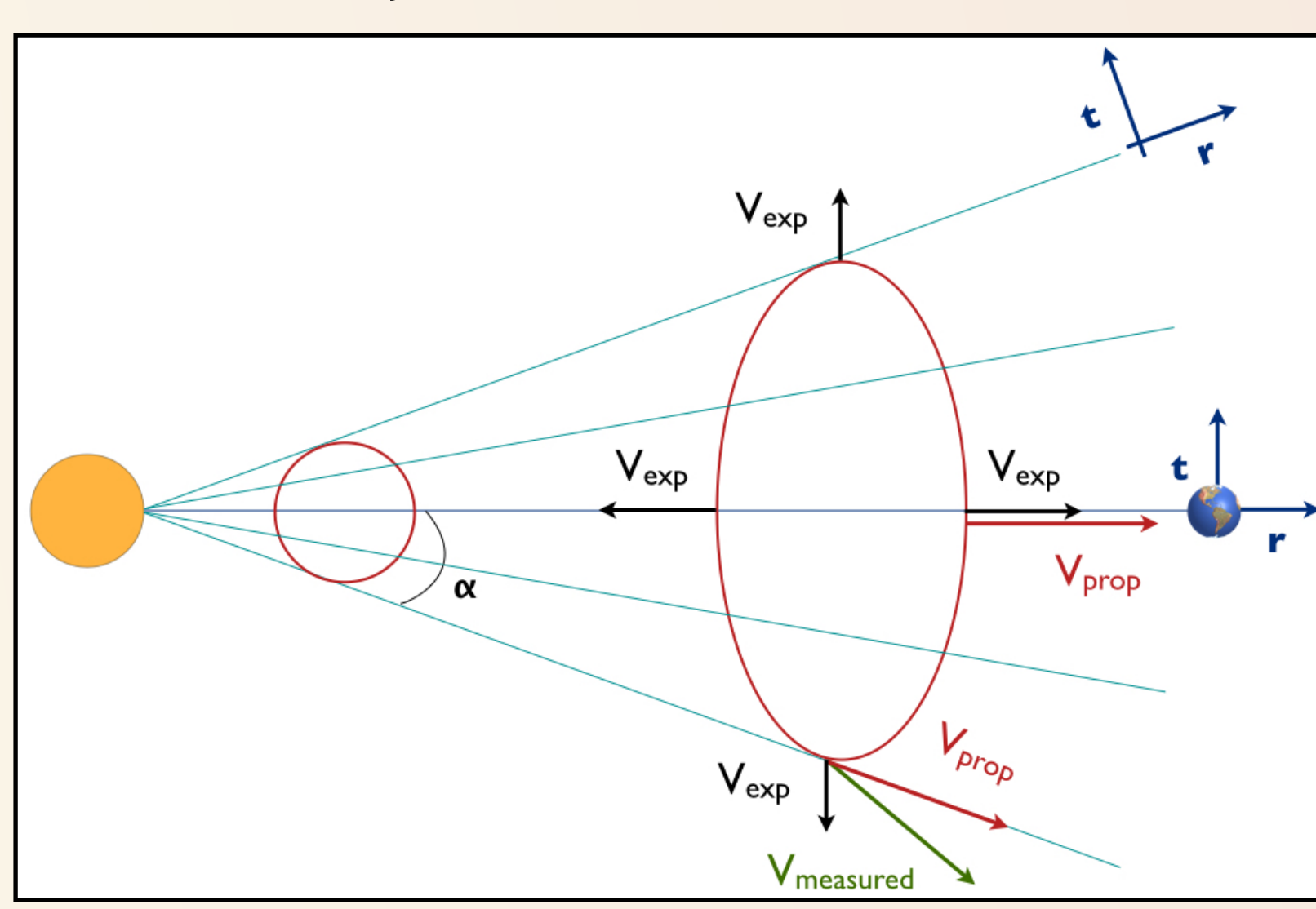
### Scenario#2: Elliptical cross-section with large eccentricity:

Radial expansion will make CME cross-section more circular, unless there is non-radial expansion, because radial expansion partially compensates the kinematically-driven lateral expansion. However, radial expansion should be associated with non-radial expansion of at least similar magnitude. Because the solar wind plasma is radially stratified, the non-radial expansion might be of larger magnitude than the radial expansion, as there is no strong pressure gradient force hindering it. Under this scenario, there should be non-radial flows measured in situ when the CME is crossed away from its center. These non-radial flows are associated with the CME expansion, have a magnitude of  $V_{exp}$ , and are directed away from the CME center. The net effect of the non-radial expansion combined with the kinematic expansion is to make the CME cross-section highly elliptical.



### Scenario#3: Elliptical cross-section with small eccentricity or circular cross-section:

If MEs have a circular cross-section near 1 au, there should be non-radial flows towards the ejecta center to maintain this circular cross-section, and to compensate for the kinematic distortion of the MEs and most likely associated with the magnetic tension force as discussed first by (Suess: 1988). These non-radial flows should only be measured when CMEs are crossed far from their center. They don't truly correspond to expansion but result from the difference between the expected radial propagation of all points within a CME and the measured velocity needed to keep the cross-section circular.

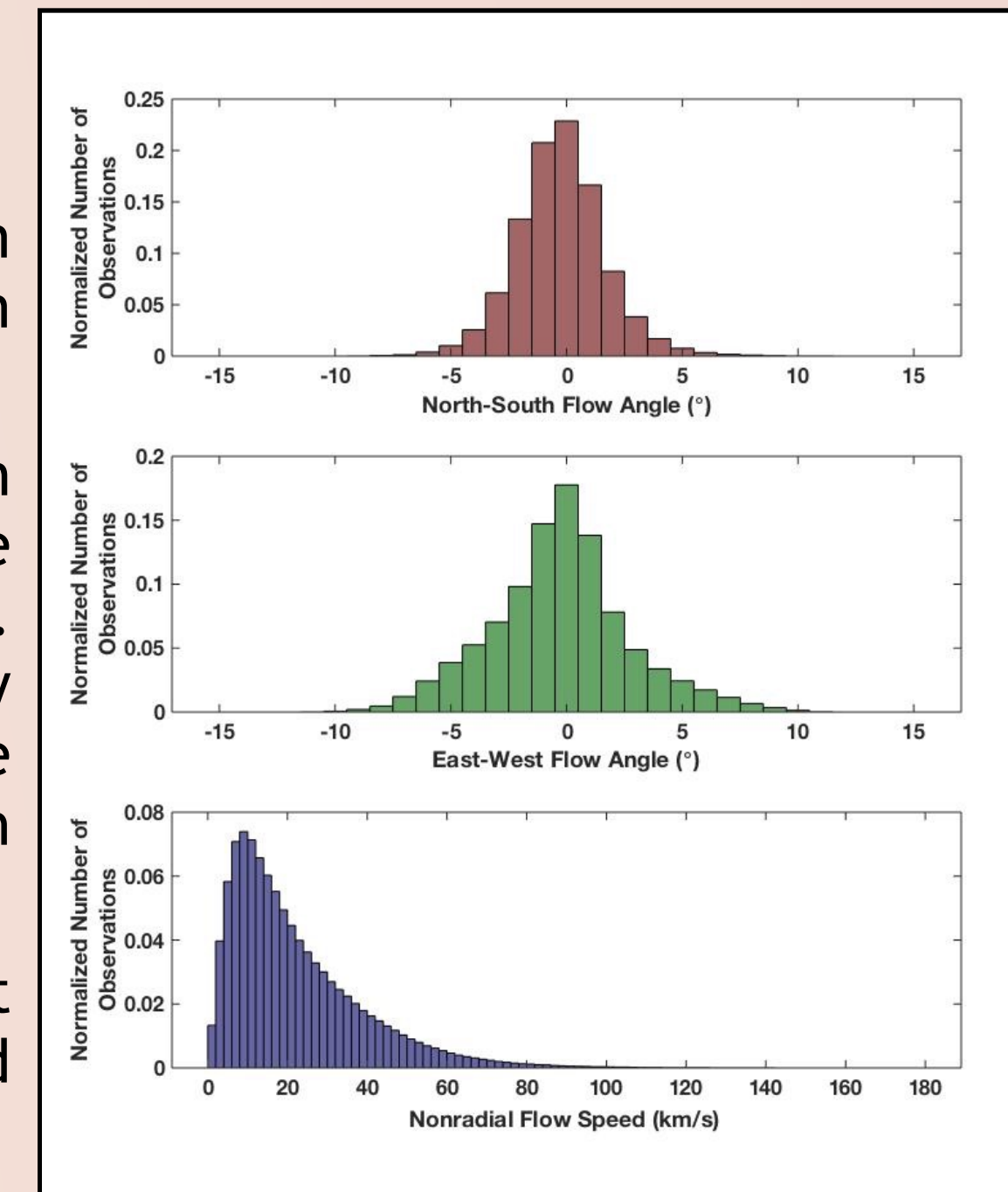


## Statistics

We used plasma data at 10-minute resolution from STEREO-A obtaining: the maximum and minimum flow angles and non-radial flow speeds.

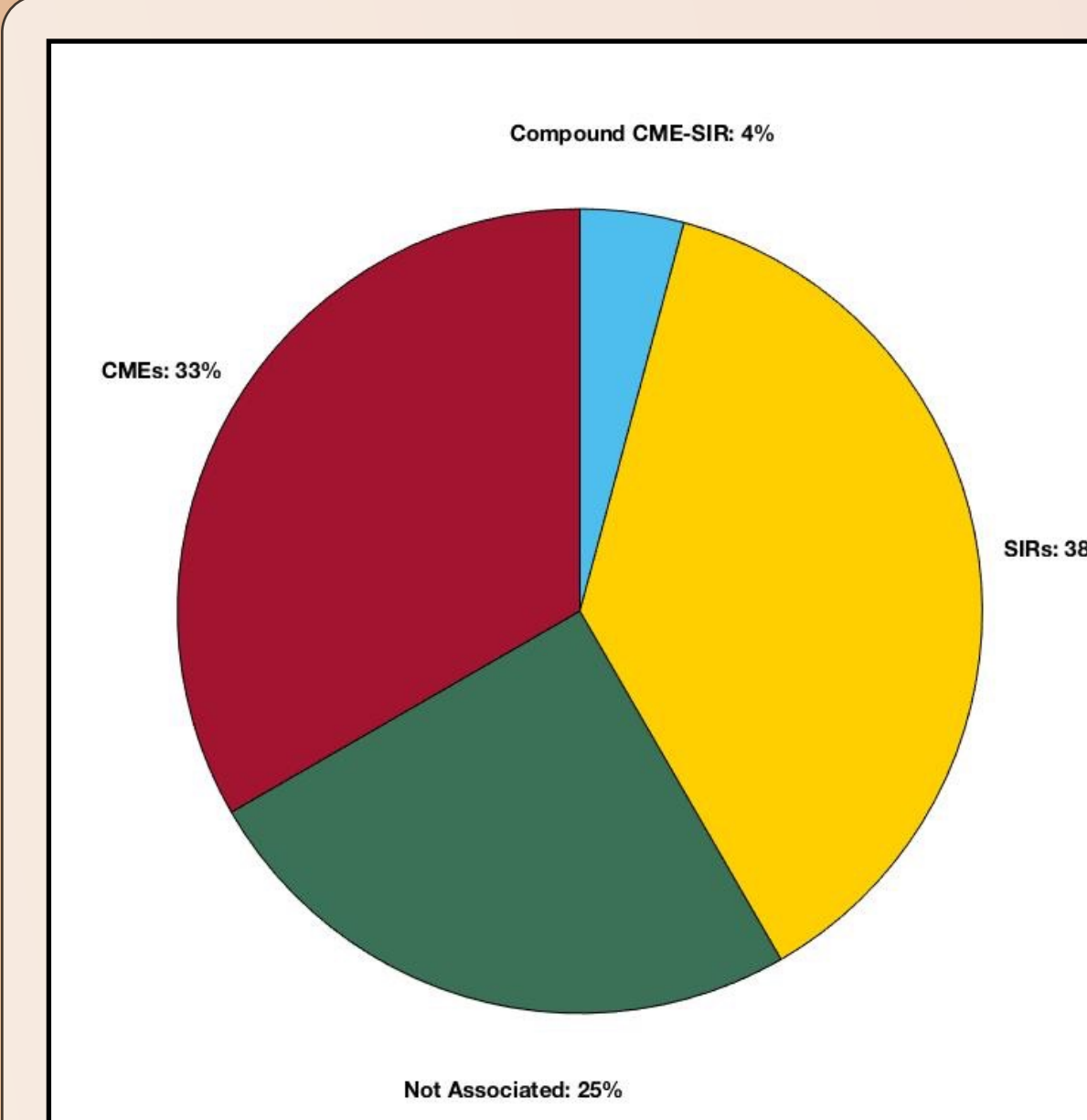
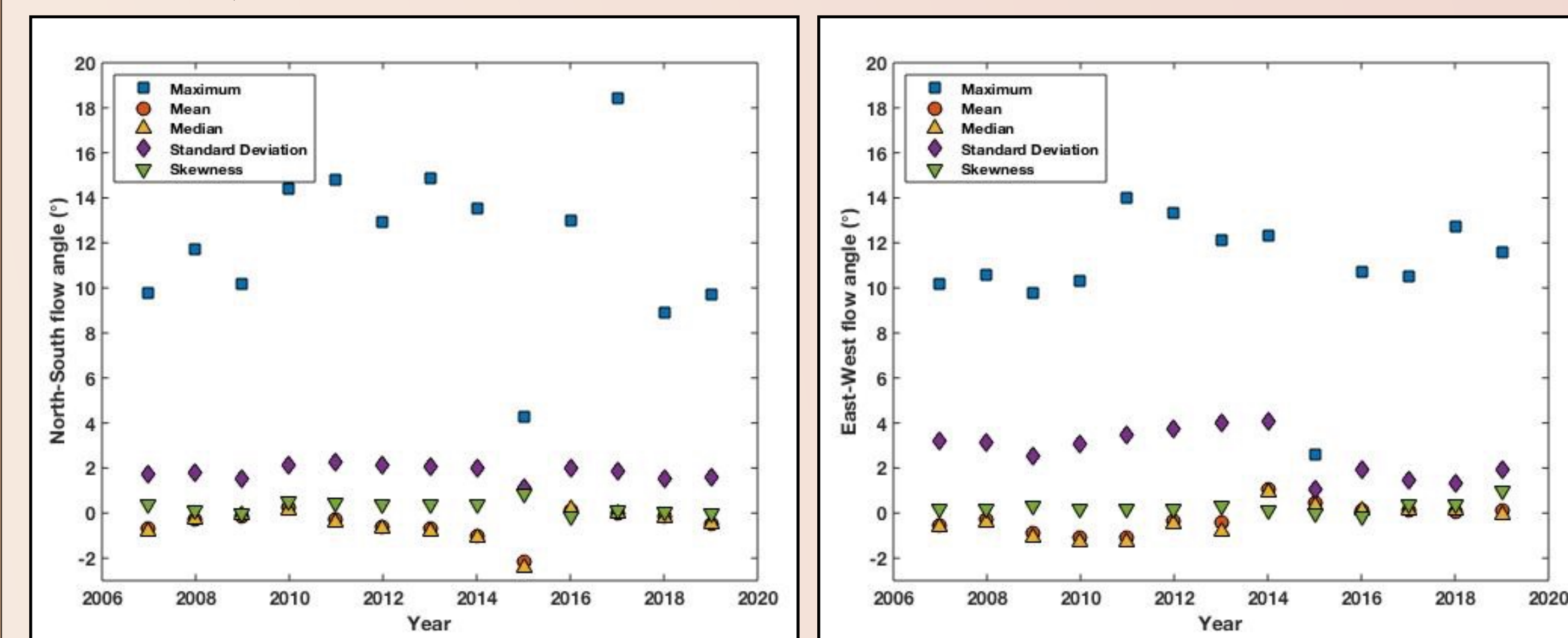
The vast majority of measurements are made within  $5^\circ$  of the radial direction and there is no preference for a specific direction (overall symmetric profiles). This indicates that the solar wind flows primarily radially outward. There are, however, some deflected flows as high as  $15^\circ$  away from radial both in the east-west and north-south directions.

Overall, this initial statistical survey indicates that relatively large non-radial flows are indeed measured.



## Solar Cycle Variation

There is a clear solar cycle dependency in the maximum deflection flow angle measured every year. The maximum deflection flow angles are larger close to solar maximum (2011-2015) than in solar minimum and the rising/declining phase of the cycle (2007-2009, 2018-2019). 2010 and 2017 represent the two transition years between large sunspot number (and CMEs) in solar maximum and low numbers (average yearly sunspot number less than 10) in solar minimum.



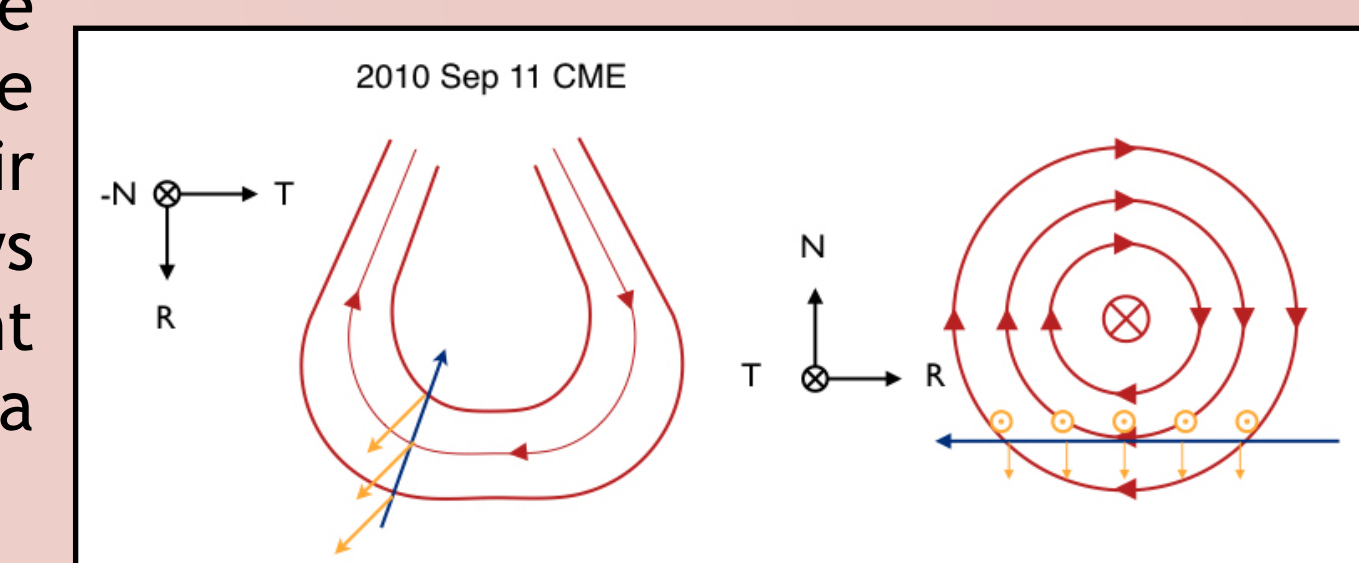
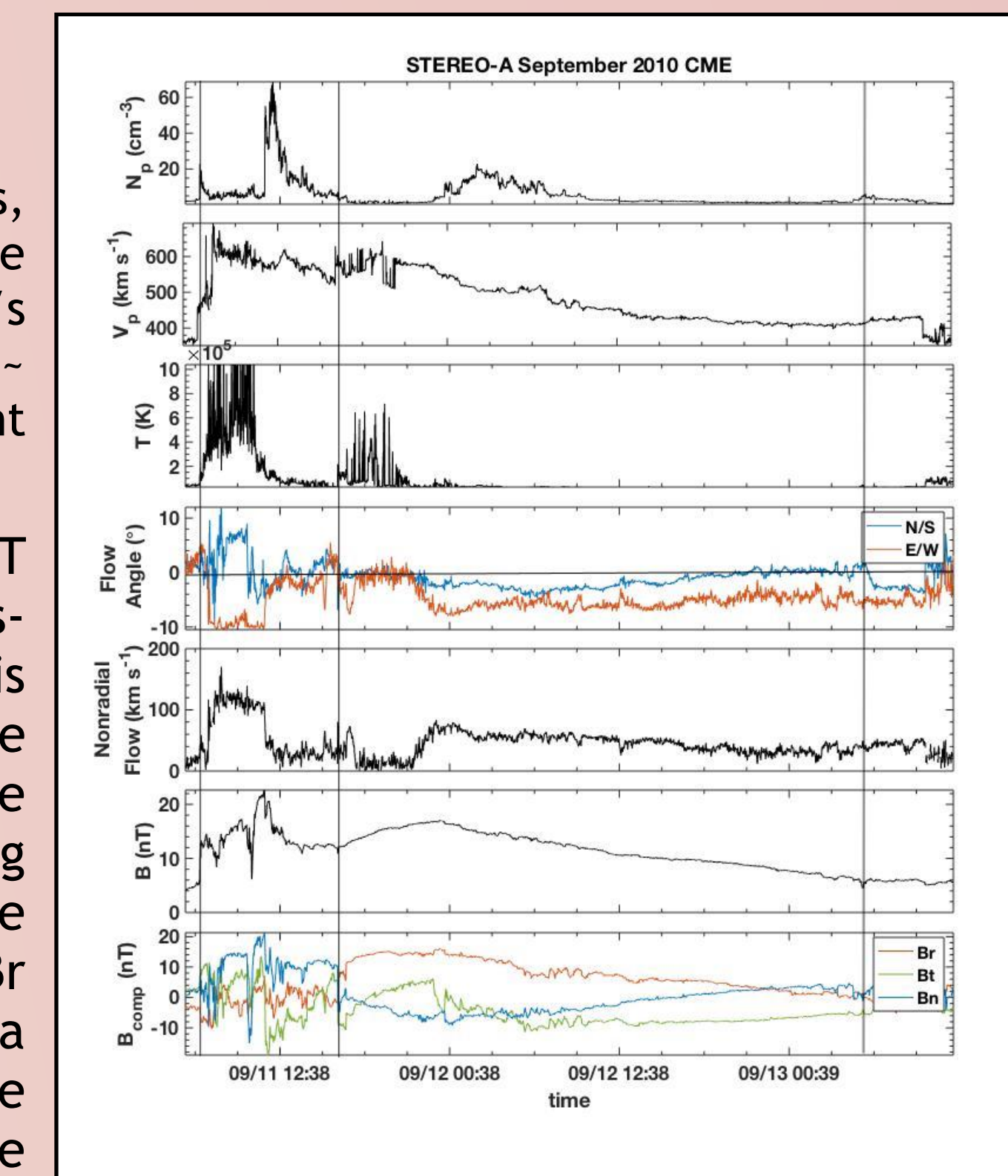
## Causes of Large Deflection Flows

We identify the origin of all large non-radial flows in terms of associated structures (SIRs, CMEs or others). We focus on the 24 events for which the 10-minute flow angle is greater than  $12^\circ$  either in the E-W or N-S direction for STEREO-A. We use the CMEs and SIRs database of (Jian:2018,2019) to determine the association of these flows with specific structures. The proportion of the different categories are shown.

## 2010 September 11 CME

The average of the non-radial flows inside the ejecta are  $\sim 40$  km/s, primarily in the east direction (-T) but with a component in the south direction (-N) in the center of the ejecta (peak of  $\sim 30$  km/s around 07:00 UT on September 12). These non-radial flows reach  $\sim 75$  km/s in the front half of the ejecta (note that the very front part of the ejecta has almost zero non-radial flows).

Fitting the ejecta in the period from September 11 16:45 UT to September 13 05:55 UT with the force-free circular cross-section model of Lepping et al. (1990), the orientation is found to be low-inclined with  $(\theta, \varphi) = (-23^\circ, 254^\circ)$ , the latitude and longitude angles of the flux rope axis with a negative chirality. As such, this is a south-west-north cloud (Bn varying from negative to positive, while Bt remains negative). The impact parameter is confirmed to be high at 0.75 with Br positive especially in the front part of the ejecta. For such a low-inclined ejecta crossed at high impact parameter, the non-radial flows associated with the ejecta cross-section are expected to occur in the north-south direction (see the bottom figure). The south-directed non-radial flows are consistent with these and following scenario-2, but their magnitude are only up to 25% of the radial expansion flows even though the impact parameter is large. The dominant non-radial flows in the -T direction could be associated with a global expansion of the CME axis (not its cross-section).

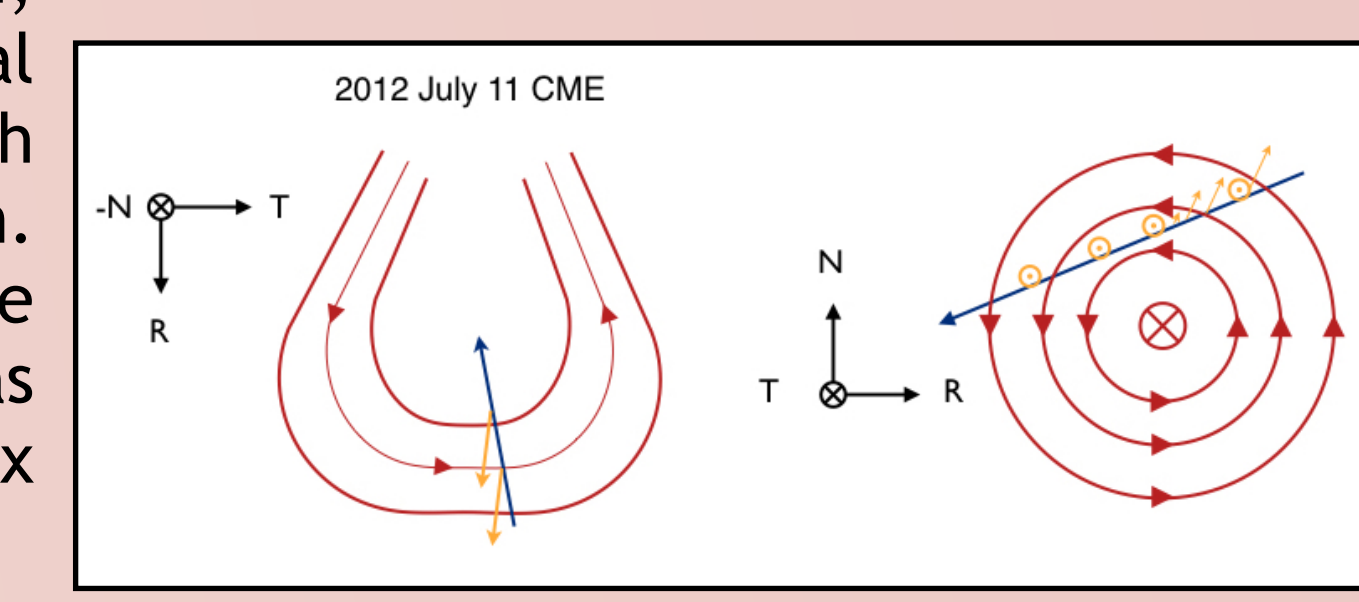
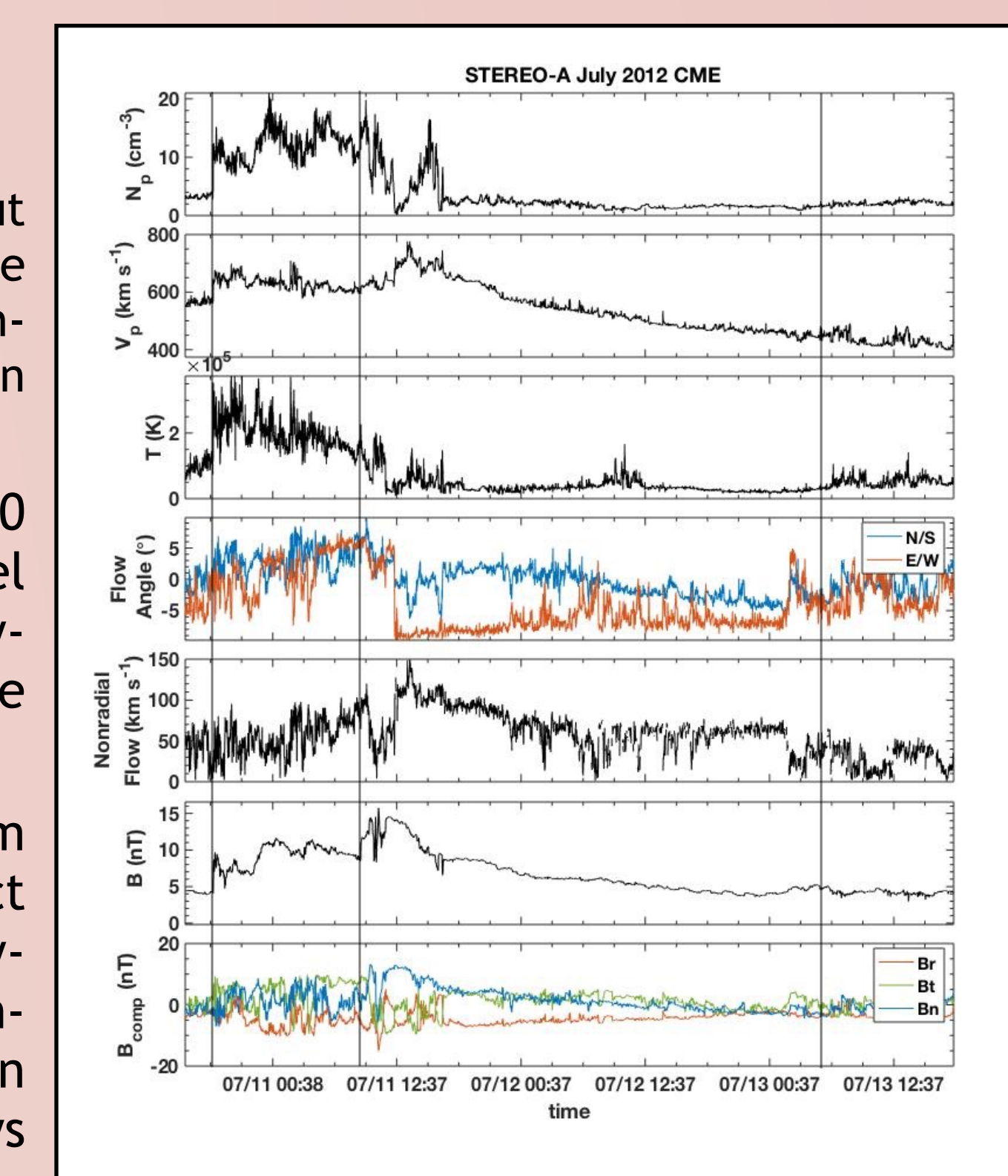


## 2012 July 11 CME

The flow makes an angle of  $8-10^\circ$  in the east direction throughout the ME with an additional deflection by  $3^\circ$  towards the north in the early part of the ejecta. Taken together, this corresponds to non-radial speeds reaching above 120 km/s, which are comparable in magnitude to the radial expansion of the ejecta.

Fitting the ejecta in the period 17:00 UT on July 11 to 06:00 UT on July 13 with the force-free circular cross-section model of Lepping et al. (1990), the orientation is found to be low-inclined with  $(\theta, \varphi) = (20^\circ, 94^\circ)$ , the latitude and longitude angles of the flux rope axis with a negative chirality.

As such, this is a north-east-south cloud (Bn varying from positive to negative, while Bt remains positive). The impact parameter is confirmed to be high at 0.79. For such a low-inclined ejecta crossed at high impact parameter, the non-radial flows are expected to occur in the north-south direction (bottom right panel). Since Br is large at first, the initial flows in the northern direction indicate flows away from the center, consistent with scenario 2. However, even with a large radial expansion and a large impact parameter, the north-south flows are only a small fraction ( $\sim 20\%$ ) of the radial expansion. The non-radial flows in the -T direction cannot easily be understood except as a general deflection of the ejecta, or as a sign that the CME magnetic morphology is more complex than one with invariance along a central axis.



## Discussion & Conclusions

Our expectations are that there should be significant  $> 5^\circ$  non-radial flows measured in association with the crossing of CME ejecta away from their center (high impact parameters). These flows should occur in all the following cases: (a) if the CME expansion, which is measured in the radial direction, is isotropic, (b) if the CME expansion occurs faster in the non-radial direction, (c) if the magnetic field tension force keeps the cross-section circular.

A surprising result of this investigation is that there are no steady large non-radial flows inside CME ejecta, as would be expected from uniform expansion or the effect of the magnetic tension force. This can only be understood if the radial expansion is not associated with an expansion in the non-radial direction and if the CME cross-section becomes highly elliptical due to kinematic effects. Alternatively, the entire paradigm of flux rope with an axial invariance might be too limited (see past discussion in Al-Haddad et al., 2011). Multi-spacecraft measurements that include plasma measurements may provide an opportunity to further investigate this problem. They will be more likely in the near future as STEREO returns to the vicinity of the Sun-Earth line while solar activity picks up. However, such multi-spacecraft measurements may not always be able to help distinguish between different CME structures (Al-Haddad et al. 2019).

## Acknowledgement

This research was supported by NASA grants 80NSSC21K0463, 80NSSC20K0431, 80NSSC17K0556, 80NSSC21K0463, and NSF grants AGS1954983.