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# Deriving CME volume and density from remote sensing data

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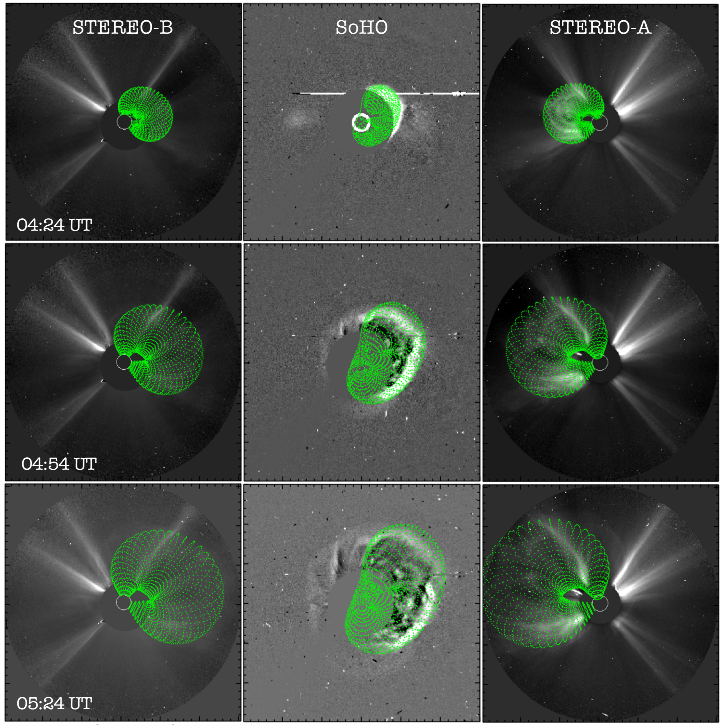
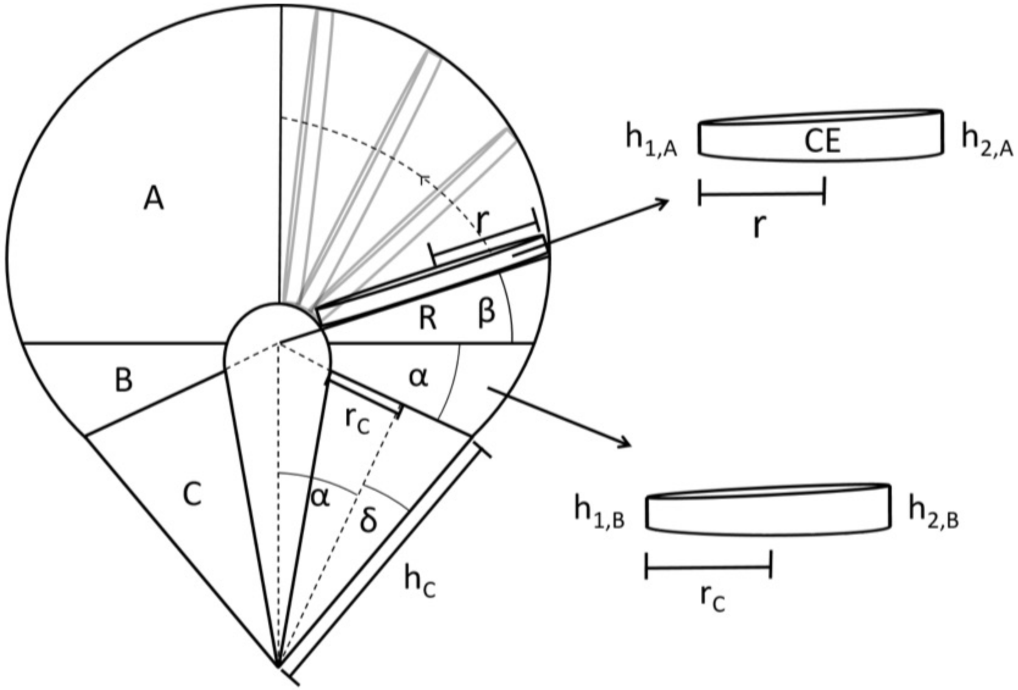
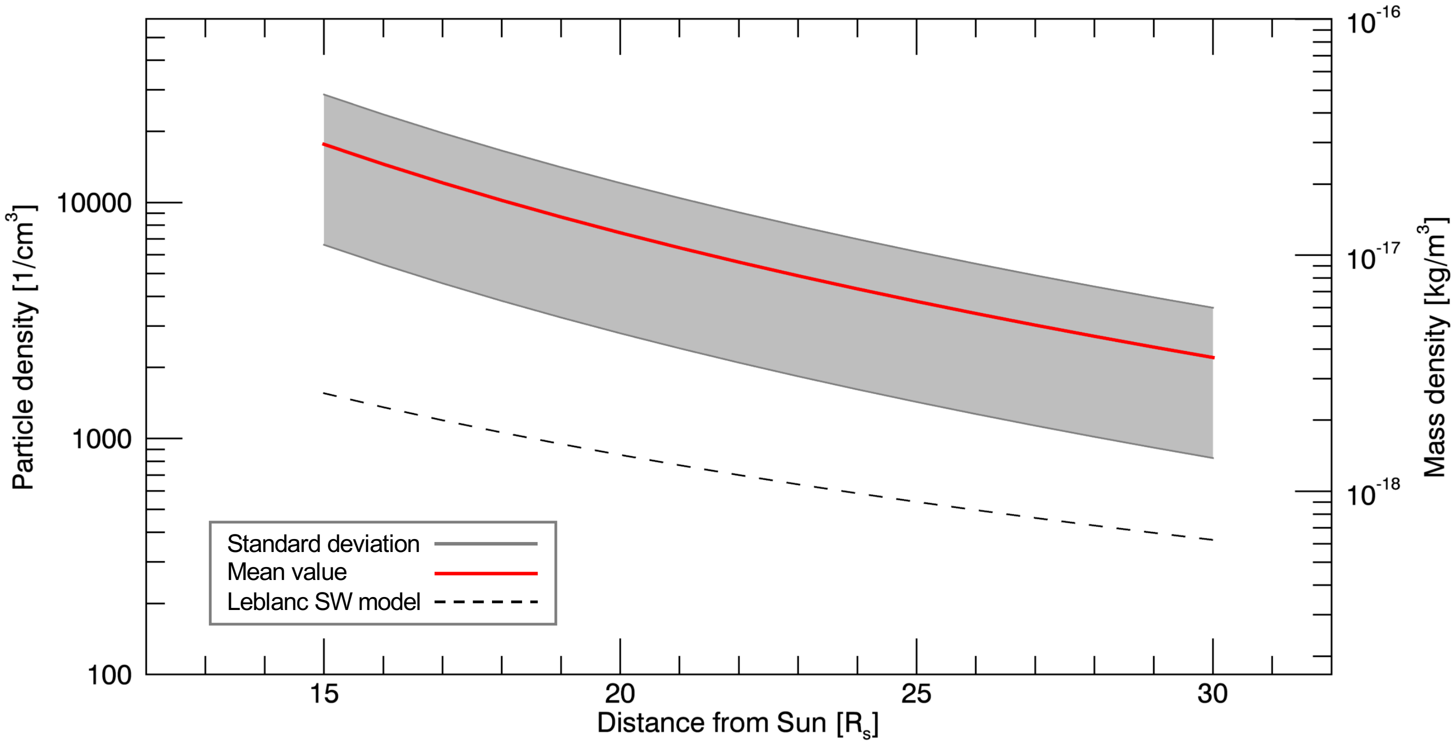
# CME volume, mass and density using multiple s/c




We first perform a GCS reconstruction (Thernisien et al., 2006; 2009) using SoHO and STEREO white-light data. The CME volume is calculated as function of height/distance using the derived parameters α (angular half-width) and κ (aspect ratio) as described in Holzknecht et al. (2018). The CME deprojected mass is calculated for a distance of about 15Rs by using STEREO data as described by Colaninno & Vourlidas (2009) and Bein et al., (2013).

# CME density profile over the distance range 15-30 Rs

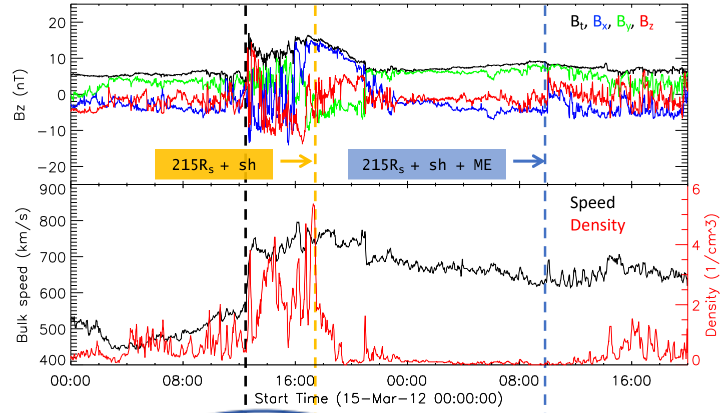



For a sample of 29 events the mean distance-density profile (red line) together with its standard deviation (black lines) is given. We assume that the CME flux rope expands in a self-similar manner and the CME mass is constant over that distance. As comparison we plot the density profile from the empirical SW model by Leblanc et al. (1998).

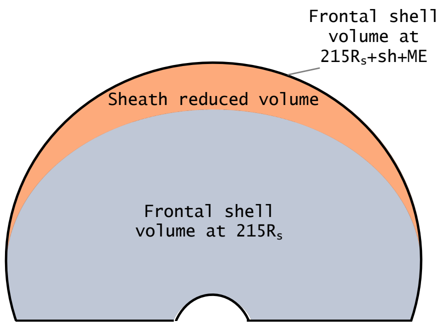
The ratio between CME and solar wind density decreases from ~11 at *h* = 15 Rs to ~6 at *h* = 30 Rs.

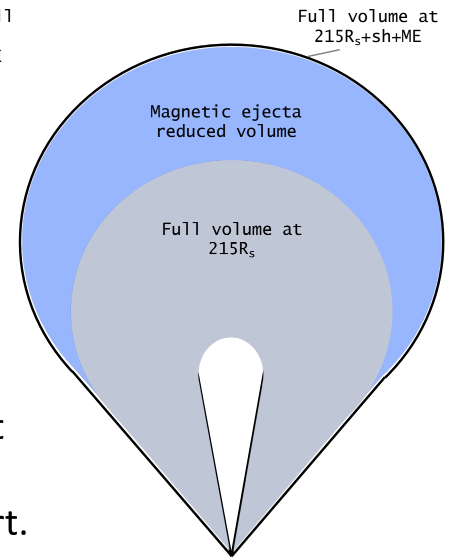
# CME volume in IP space

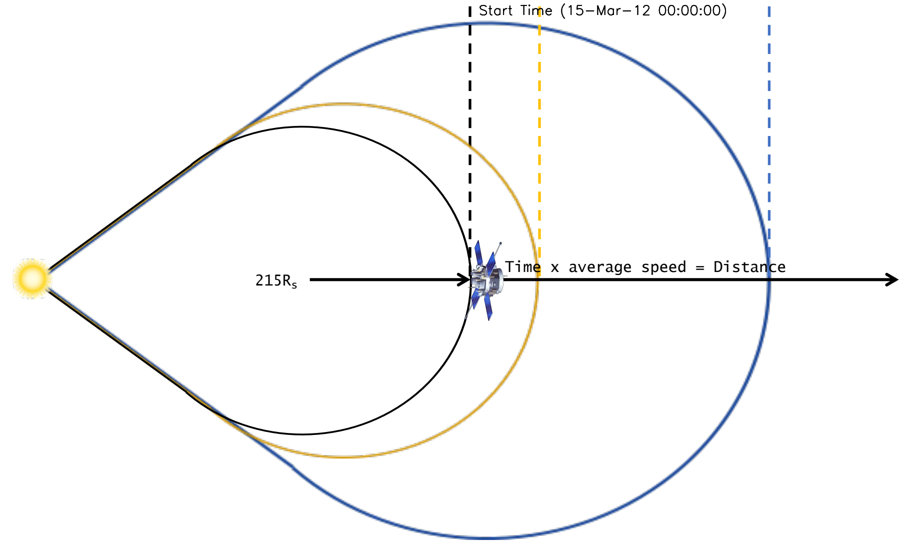
The volume is derived by assuming a self similar expansion with different expansion factors (see e.g., Bothmer & Schwenn 1998; Demoulin+2008). In contrast to near-Sun distance, the volume is now calculated separately (*reduced volumes* - see below) for the ICME structures *sheath* and *magnetic ejecta* (ME).




The deprojected mass (at 15Rs) is assumed to stay constant within the ME. For the sheath region, an extra mass of similar amount as the deprojected mass is used for deriving the density at 1AU.

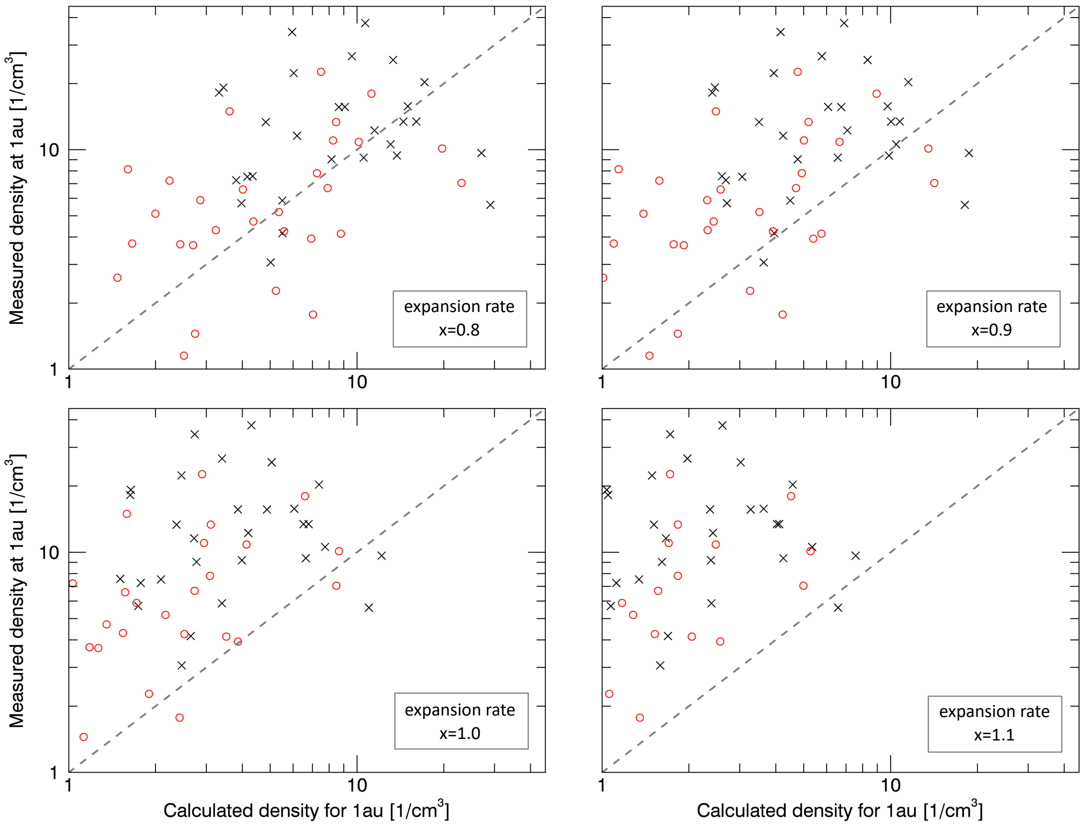



*Reduced volumes* (colored) used for density calculation at 1AU “simulating“ the sheath pile-up region and the ME part.

# Comparison to 1AU in-situ density measurements



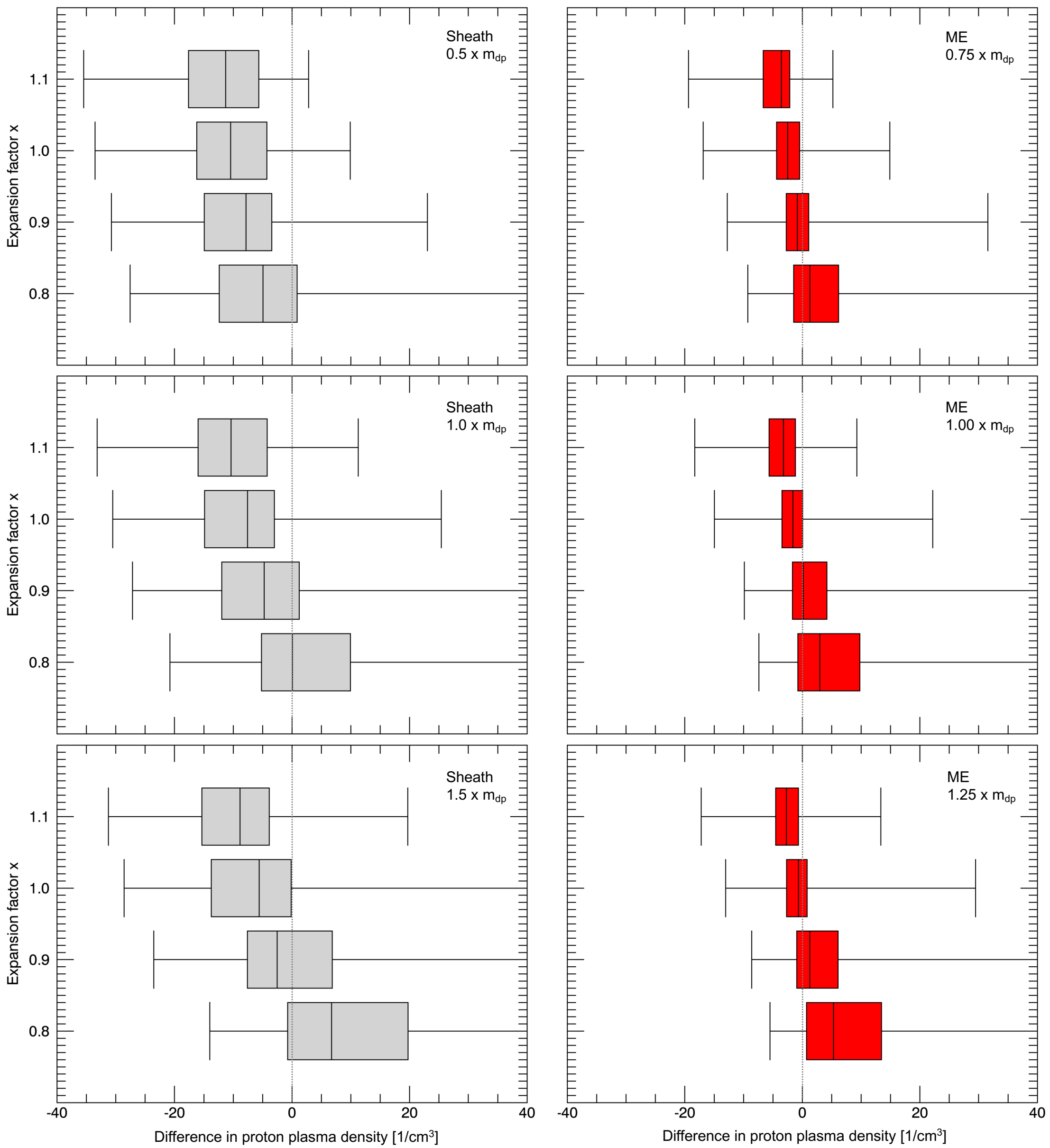

Calculated versus measured density (red circles: magnetic ejecta region, black crosses: sheath region).

The deprojected CME mass (presuming this is the mass within the magnetic ejecta region) is assumed to stay constant.

For the mass sheath region we apply the same amount as the deprojected CME mass.

*These findings support that the CME geometry / volume derivation and mass calculation, based on remote sensing image data, are physically meaningful.*

# Comparison to 1AU in-situ density

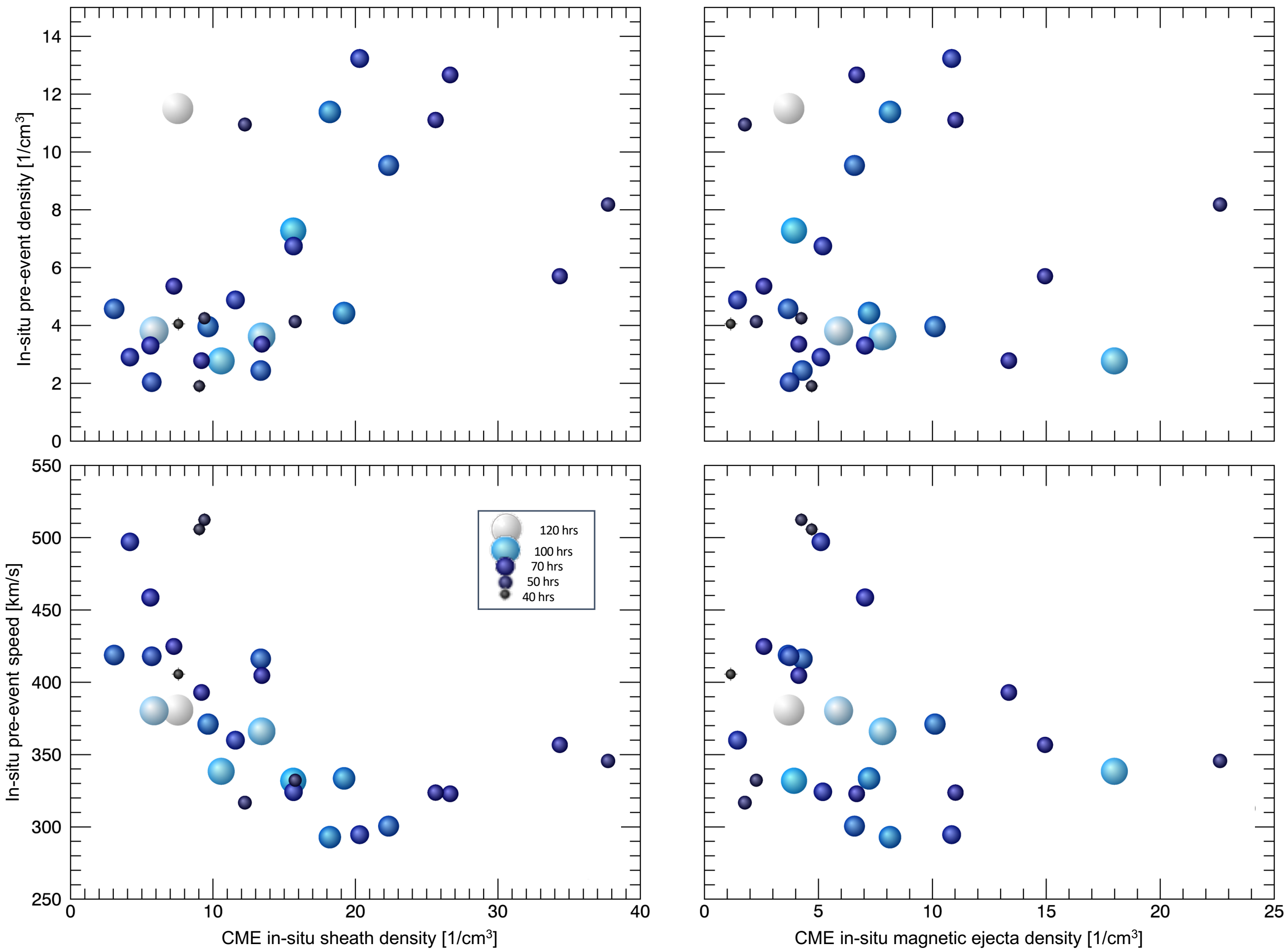



Boxplots showing the differences between calculated and observed proton plasma density (left panel sheath; right panel ME region). The whiskers give the minimum and maximum values, and the box itself is confined by the lower and upper quartile, with the vertical line within marking the median.

We use different expansion factors and different multiples of the derived deprojected mass (see axis and plot legends) to calculate from the reduced volume the proton plasma density separately for the sheath and ME region.

We obtain:
sheath region: cc ≈ 0.26
ME structure: cc ≈ 0.56 – 0.59

# Solar wind properties ahead of the (I)CME




1AU in-situ measured solar wind properties 24 hours prior to CME shock arrival ($SW_{24}$).

Top: $SW_{24}$ density versus average density of the sheath (left) and magnetic ejecta (right). Bottom: $SW_{24}$ speed versus in-situ measured average density of the sheath (left) and ME (right).

Sheath density vs. $SW_{24}$ speed/density:
cc = –0.73/0.56
ME density vs. $SW_{24}$ speed/density:
cc = –0.30/0.08

Sheath shows high (anti-)correlation with $SW_{24}$ speed and density independent of CME transit time!

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# Conclusions

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- CME volume and mass can be calculated from remote sensing data; using that in comparison to in-situ data, we derive important information on CME expansion behavior and sheath generation in IP space

From that we find:

- The CME *magnetic structure* covers the major part of the CME mass as measured from remote sensing white-light data
    - mass conservation within the ME as it propagates in IP space; some mass exchange with the ambient solar wind might be possible (ca +/-25%).
    - measured in-situ densities within the ME could be explained by a volume expanding in a self-similar manner with $x \approx 0.9 - 1.0$
- The CME *sheath region* forms and consists of piled-up interplanetary solar wind material
    - strongly deviates from an idealized flux rope structure
    - the amount of piled-up mass depends on (1) the prevailing density and solar wind flow speed in IP space ahead of the CME, and (2) the CME size (wider CMEs act as piston leading to a stronger mass pile-up compared to narrow CMEs acting like a bow shock where plasma can more easily flow around)
    - no relation between sheath density and CME speed in IP space (transit time) is found