Combining Heliospheric Imaging and in situ observations to constrain CME evolution

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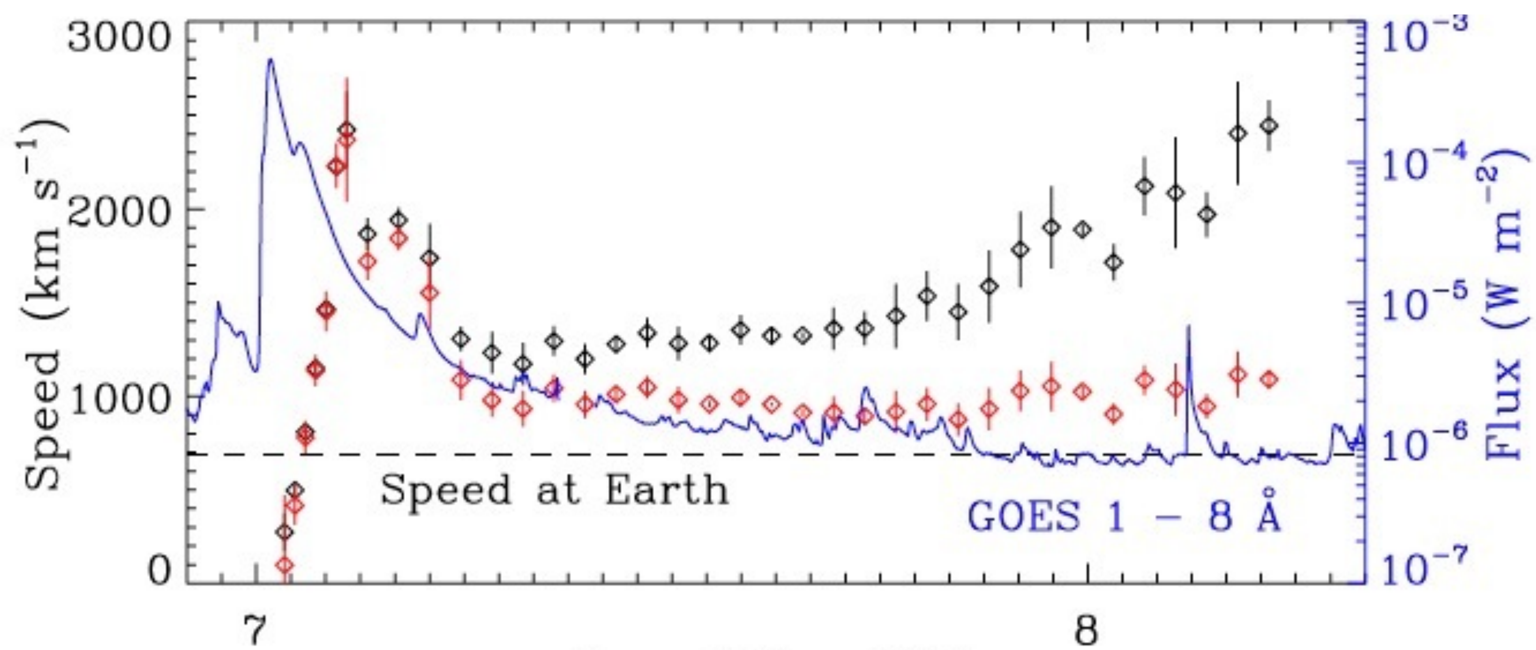
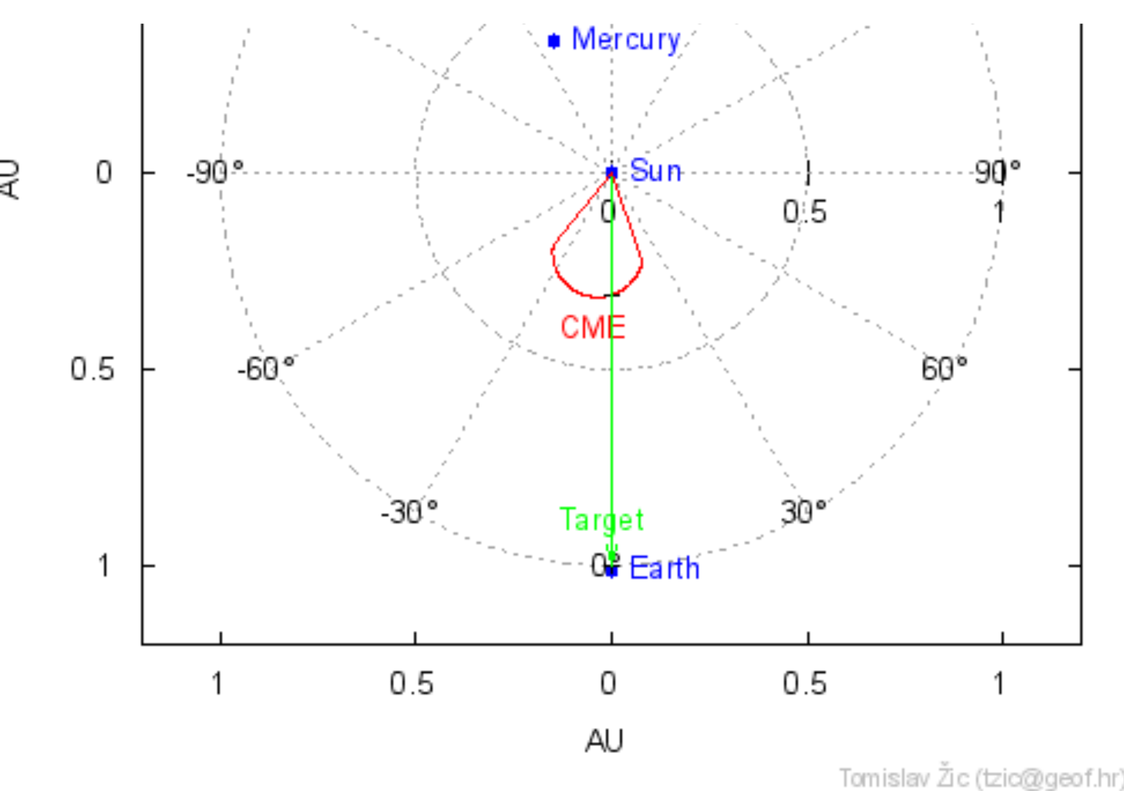
Physics of CME propagation and evolution

Propagation speed +direction

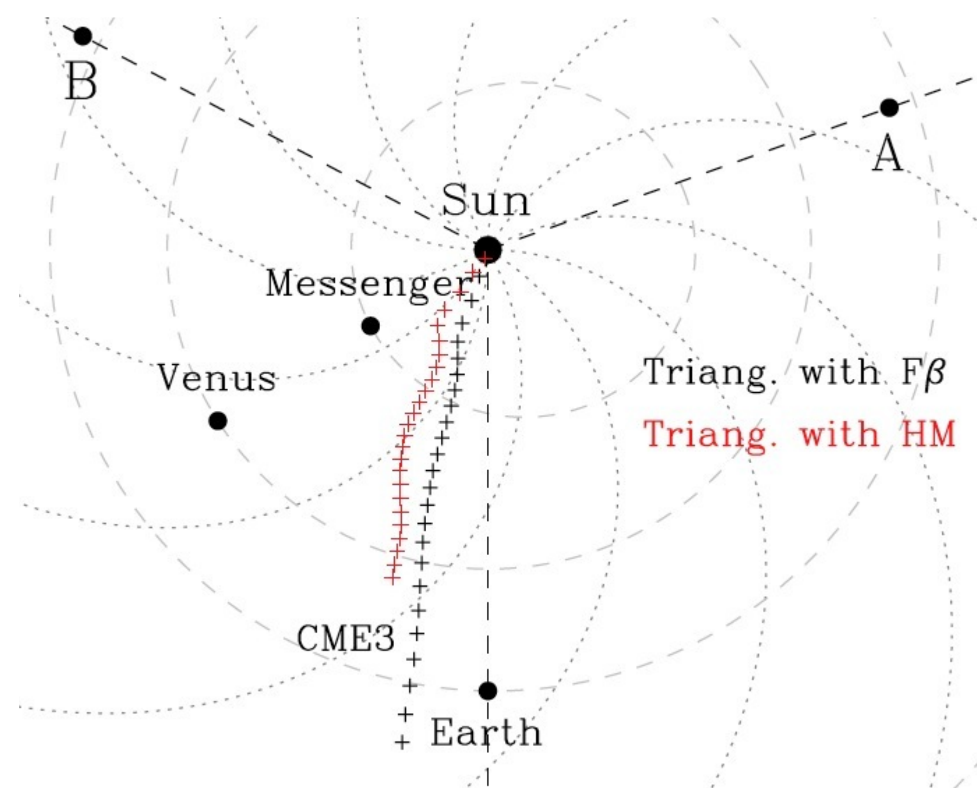
- Early, **impulsive acceleration** phase followed by **gradual deceleration, and constant propagation**
  Gopalswamy et al. 2001, Zhang et al. 2001 …. Byrne et al. 2010, Liu et al. 2013, …
- CMEs slower than the background wind (~400 km/s) become gradually accelerated to the solar wind speed
  “stealth“ CMEs, Robbrecht et al. 2009
- Propagation of CMEs can be described with equations of **aerodynamic drag** - Cargill et al., Vrsnak et al.



Liu et al., 2013 ApJ



Vrsnak et al., 2013 Sol. Phys.

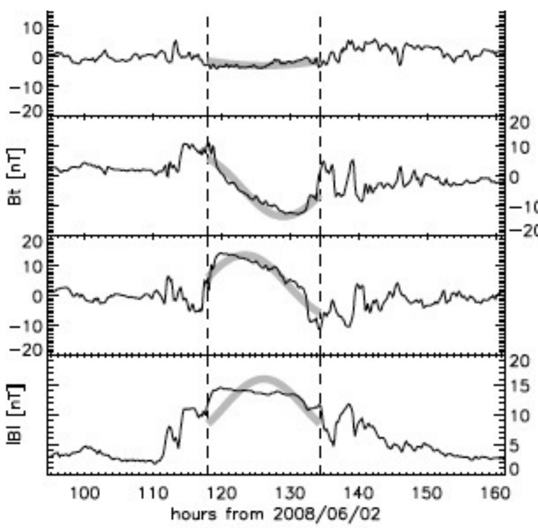


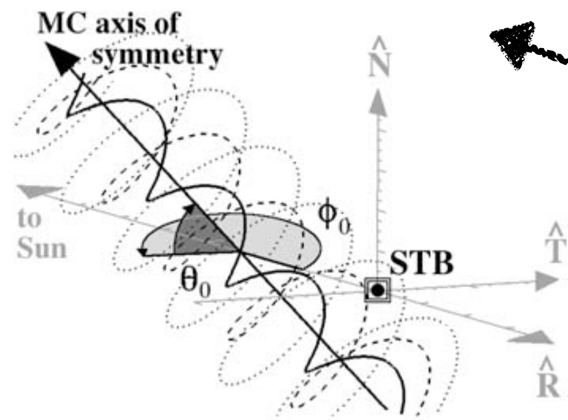
- Most CMEs seem to propagate radially away from the Sun in longitude; exception: interacting CMEs Lugaz et al., 2012 ApJ

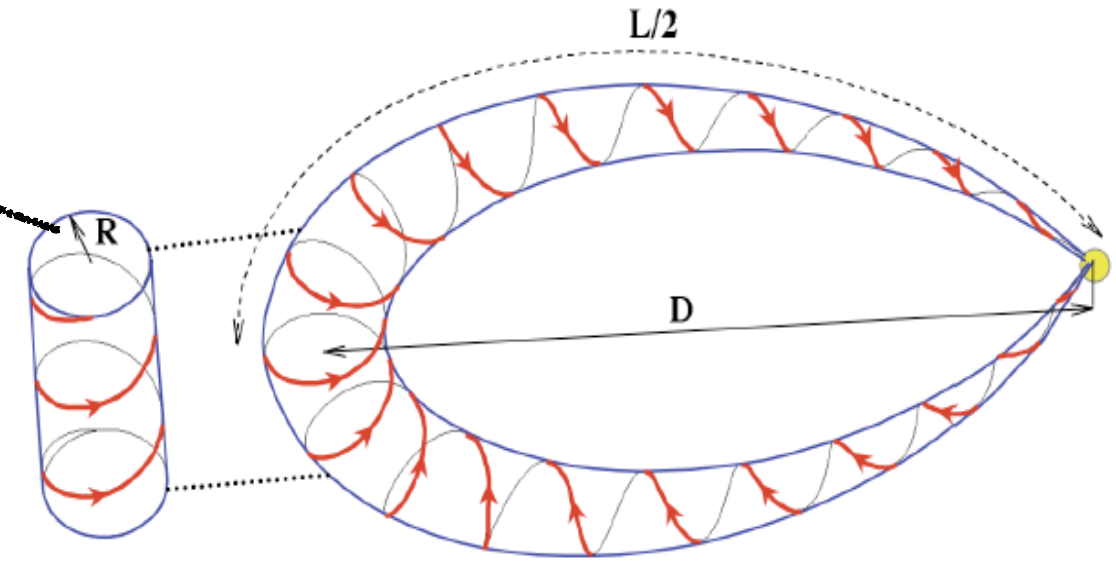
ICME magnetic structure

High twist force free modeling

P. Demoulin & S. Dasso



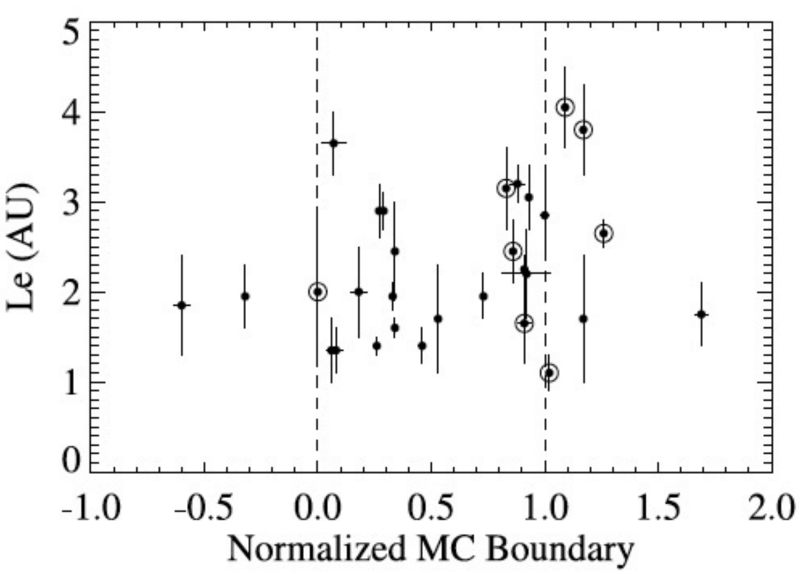




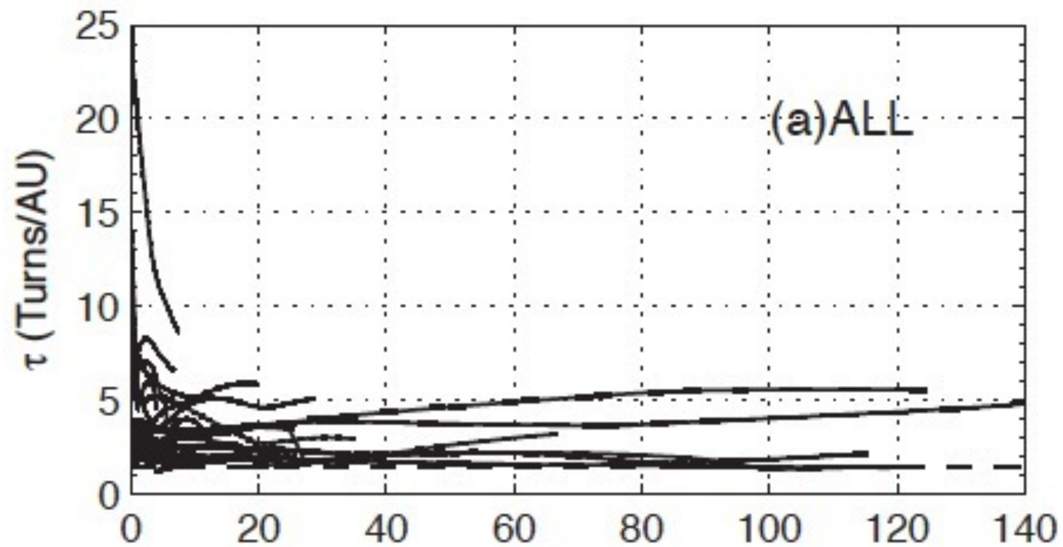
Lepping et al. 1990; ….. Leitner et al. 2007; Lynch et al. 2010

Low twist GS modeling

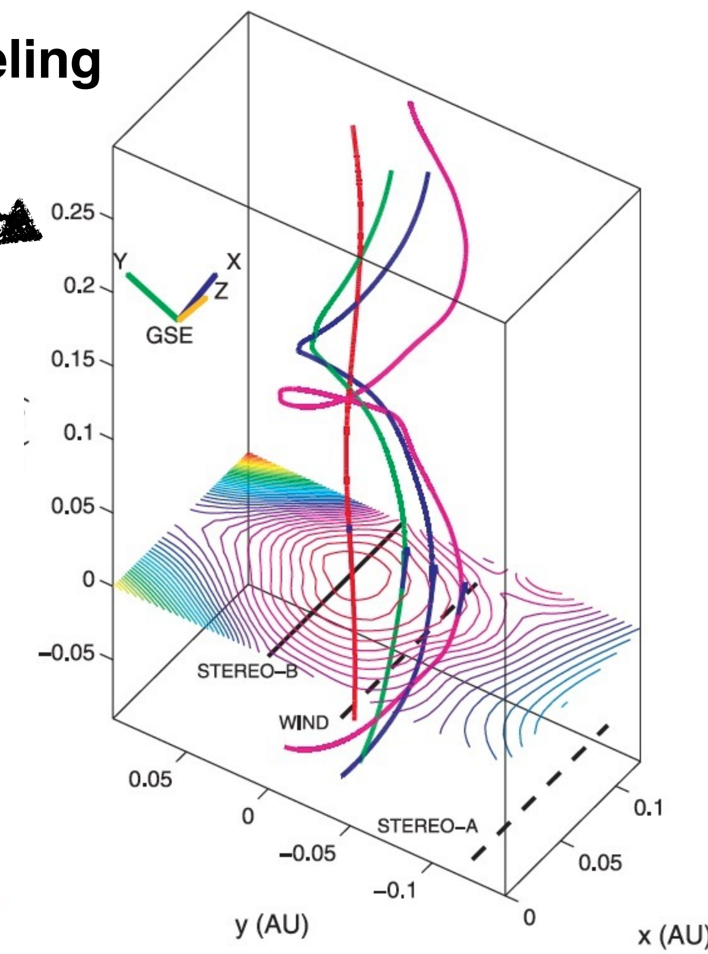
Electron flight times along field lines point to low-twist MCs



Kahler et al. 2011



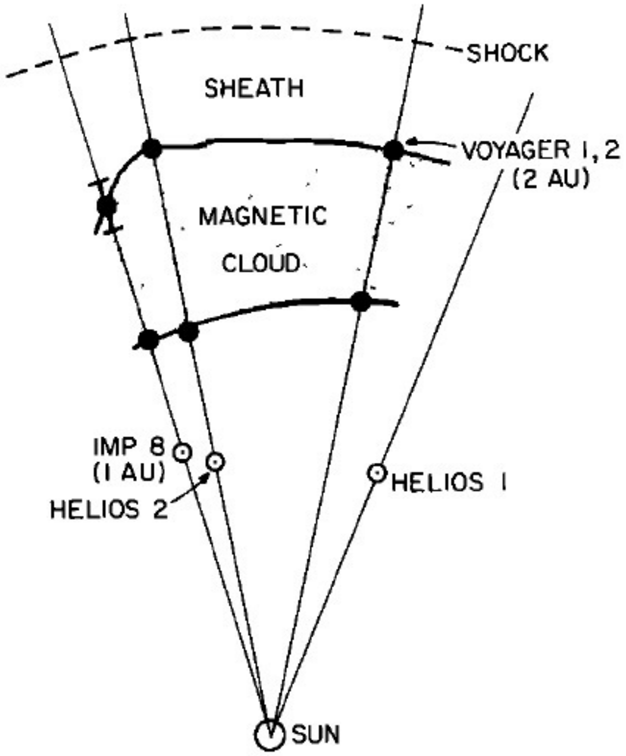
Hu et al. 2014, ApJ (arXiv)



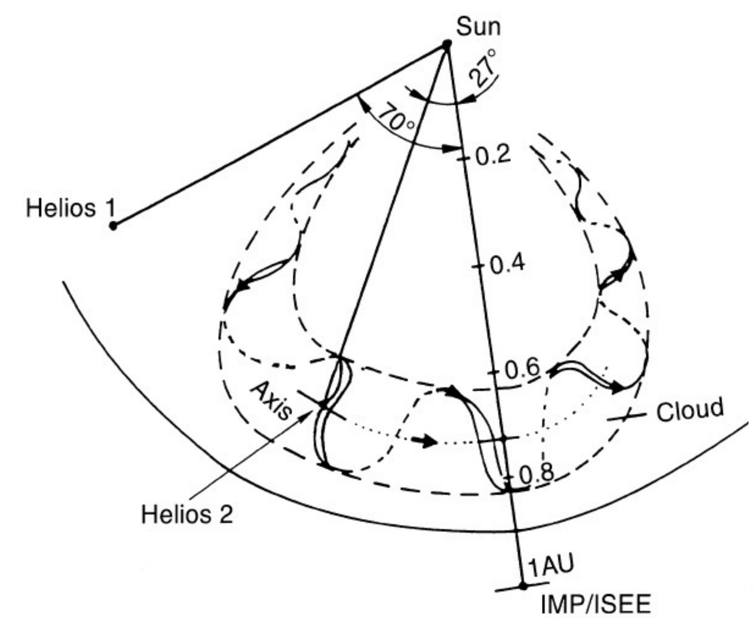
Möstl et al., 2009 JGR

Global shape

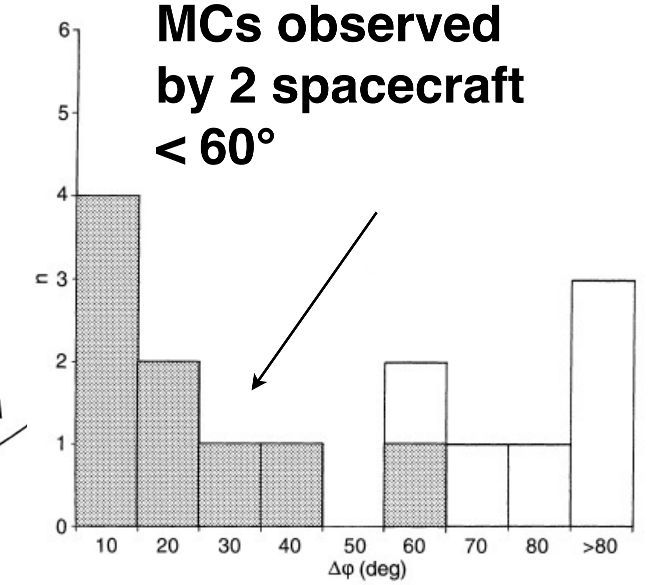
First multipoint observations



Burlaga et al. 1981 JGR

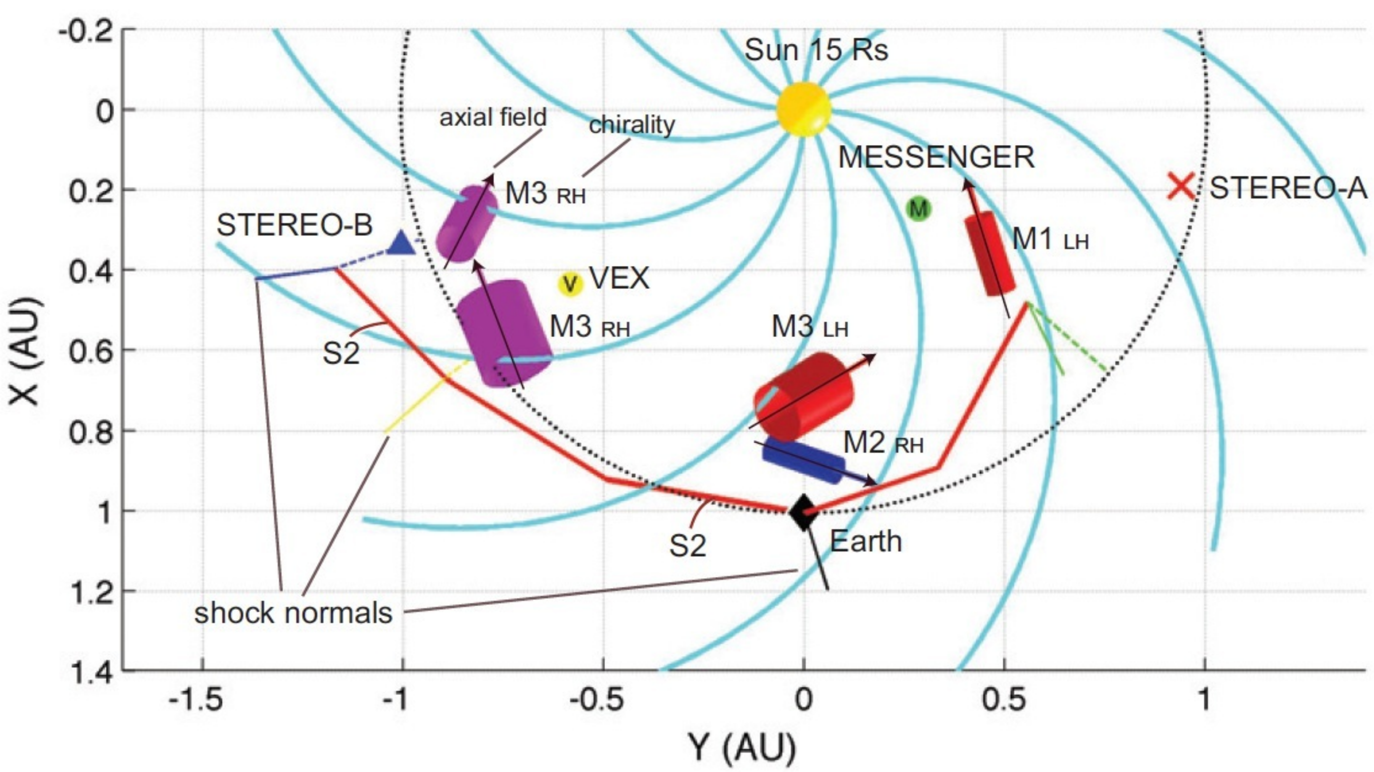


MCs observed by 2 spacecraft < 60°



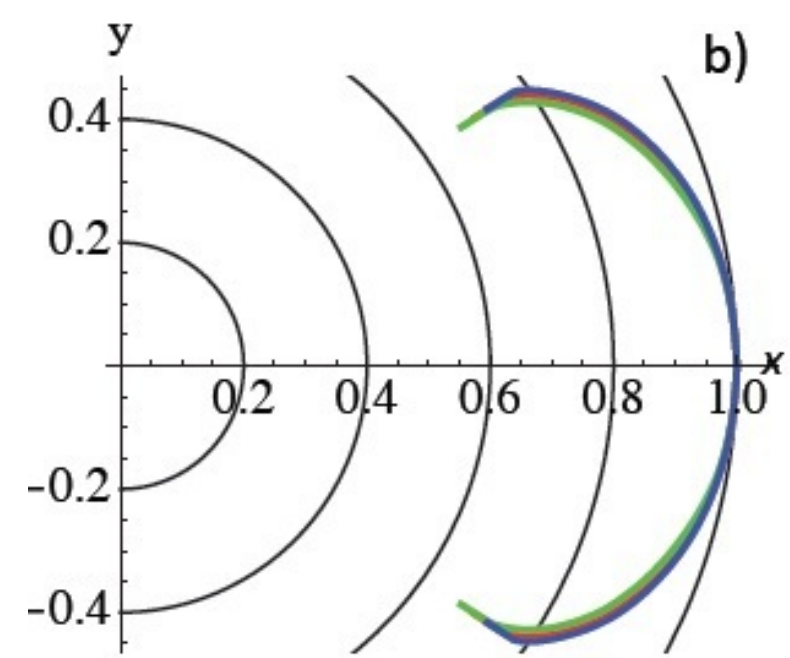
Bothmer & Schwenn 1998 Ann. Geophys.

Global configuration of interacting CMEs



Möstl et al. 2012 ApJ

Mean shape of ICME shocks at 1 AU

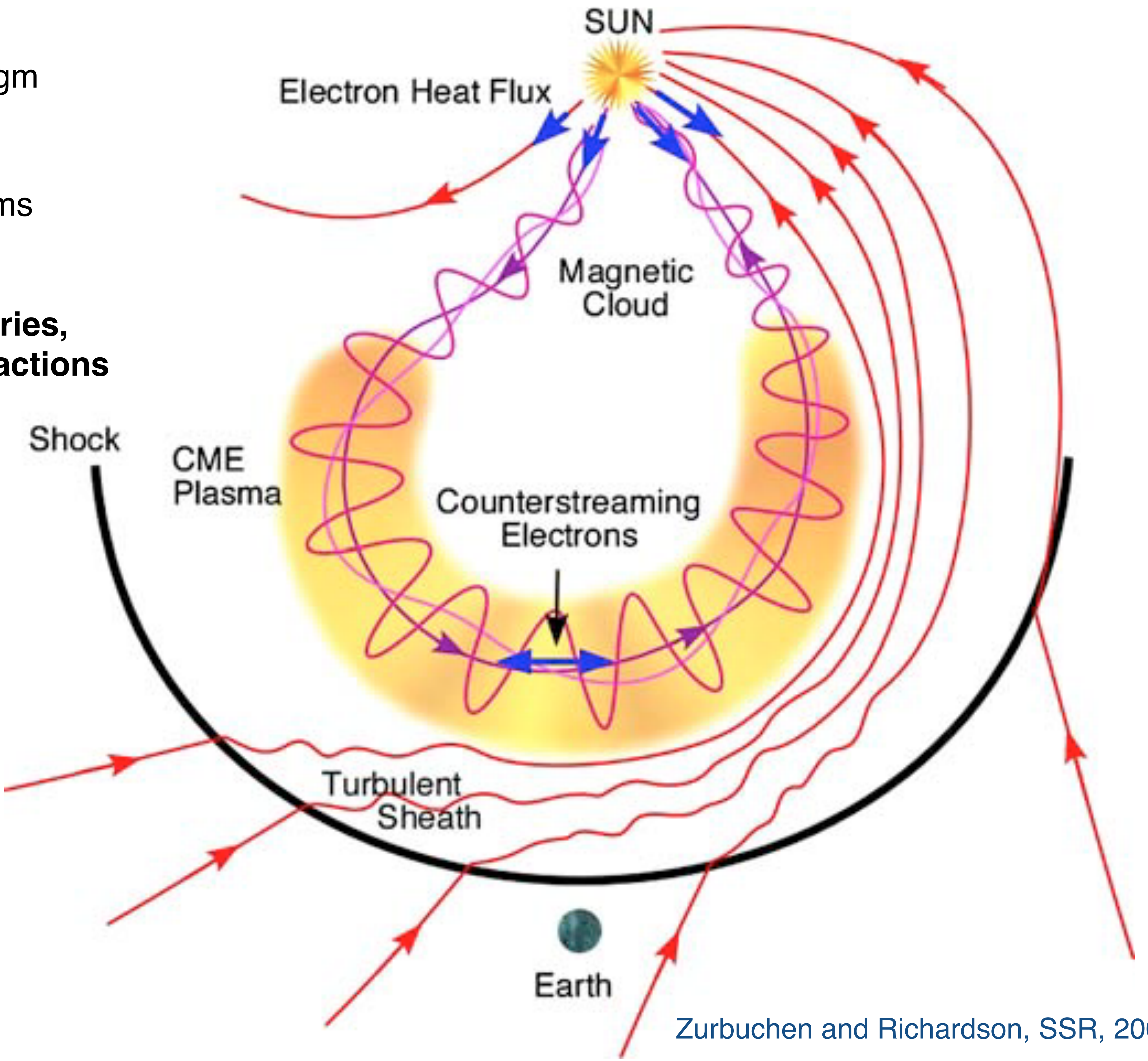


Janvier, Demoulin & Dasso 2014, A&A

ICMEs

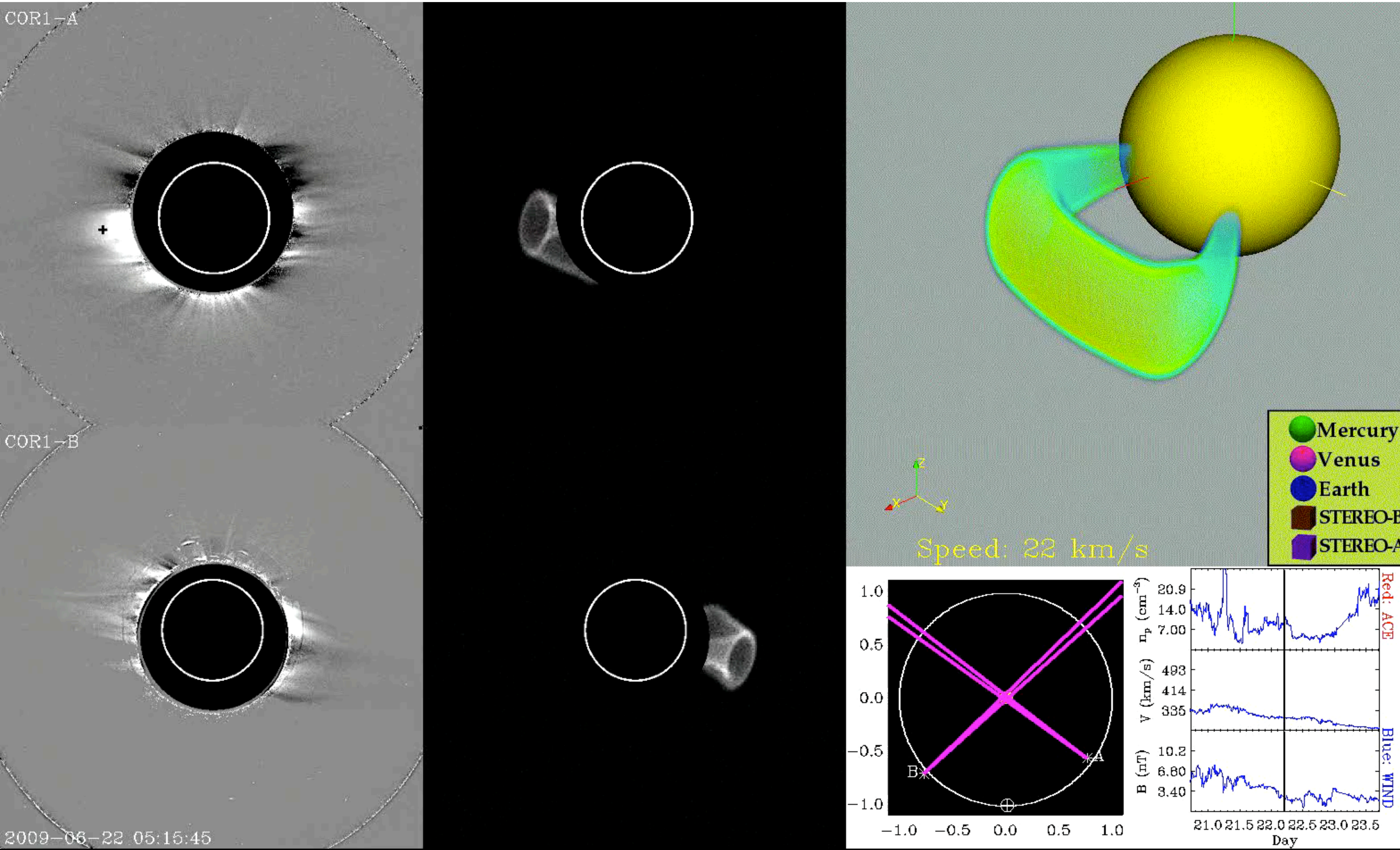
Pre-STEREO paradigm
is still accepted.

However, it now seems
that we need to
make **modifications**
in terms of **asymmetries,**
deformations, interactions



Zurbuchen and Richardson, SSR, 2006

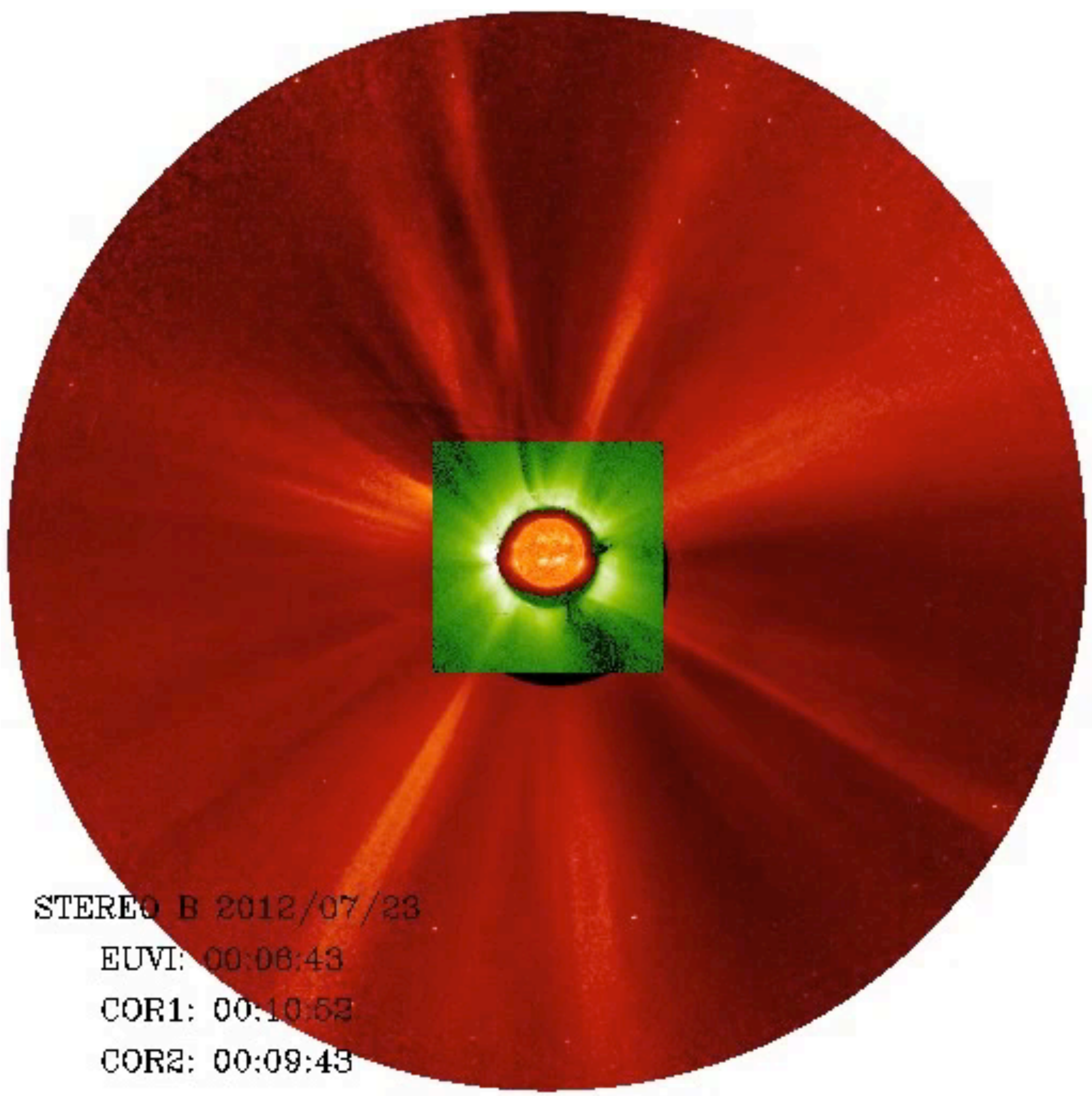
Evolution of global shape

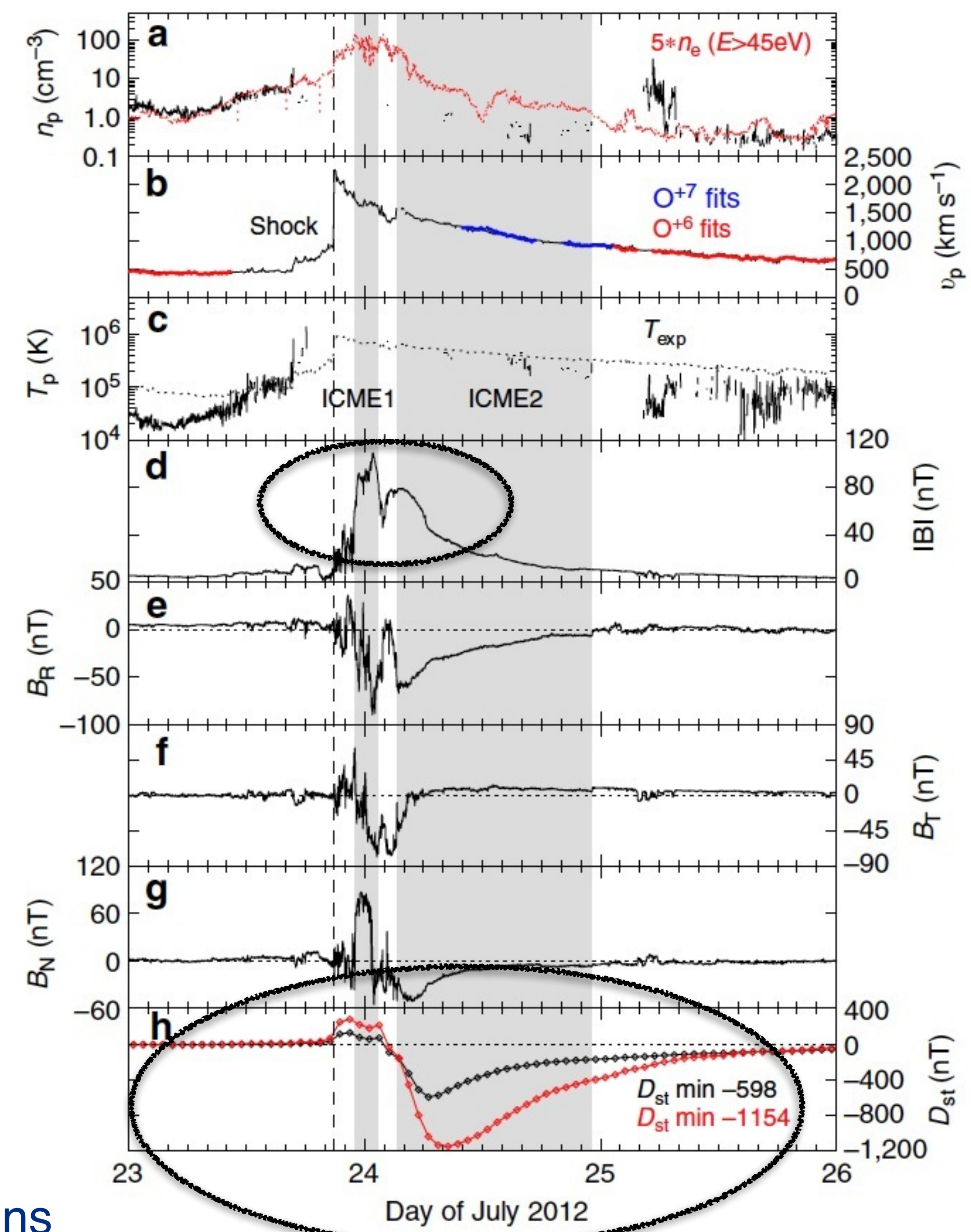


Wood et al. 2012 Sol. Phys.

CME–CME interaction

- Interaction of CMEs lead to momentum transfer. Farrugia & Berdichevsky 2004, Lugaz et al. 2009 observations: Shen et al. 2012 (super-elastic), Temmer et al. 2012, ApJ (super-inelastic)
- First multipoint observations of an extreme CME on 23 July 2012. Very early interaction of 2 CMEs leads to > 100 nT magnetic field at 0.96 AU (expansion inhibited)



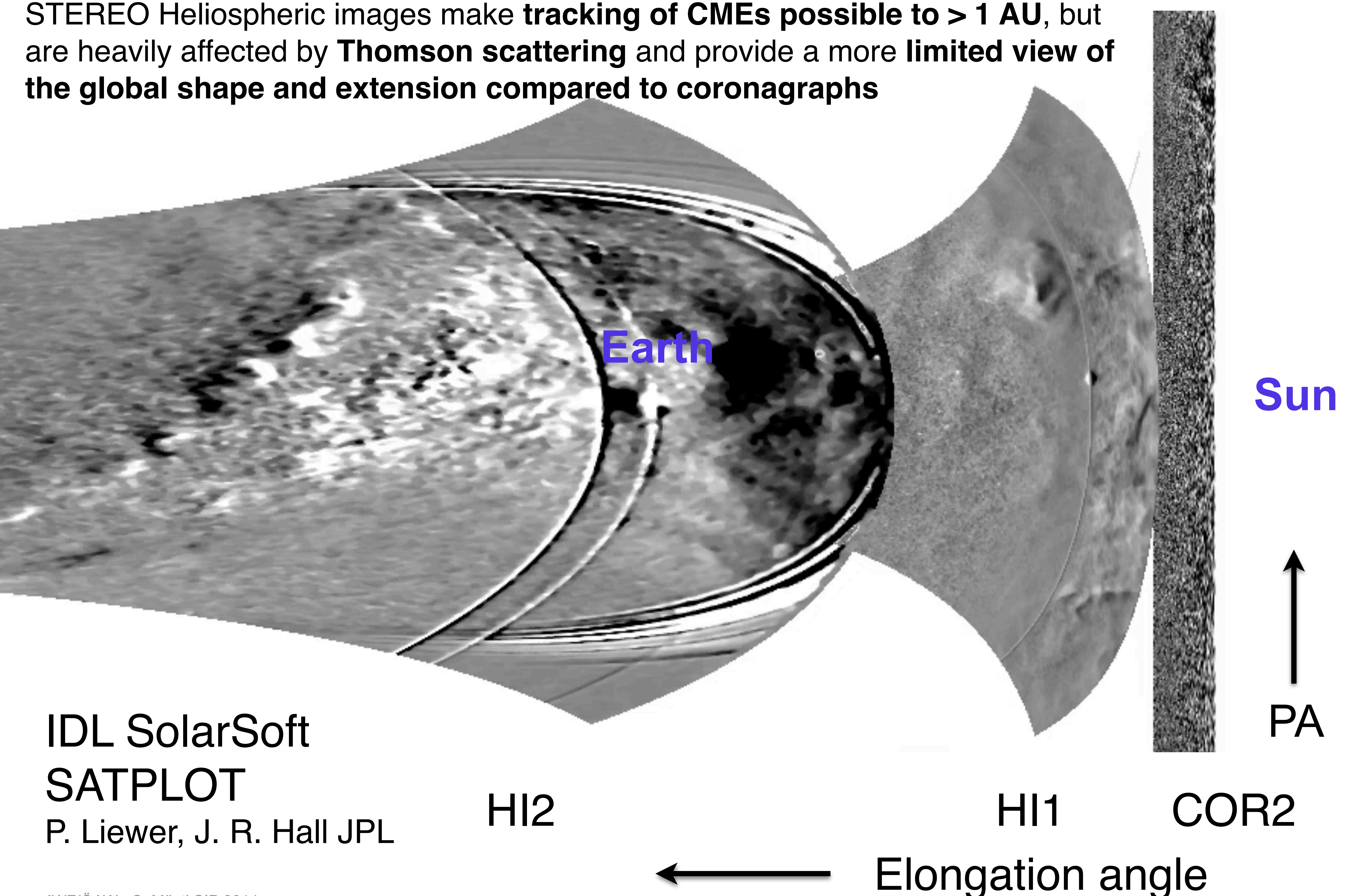


Liu et al., 2014, Nature Communications

Methods which predict CME parameters from HI, validated with comparison to in situ

Heliospheric Imaging (July 2012)

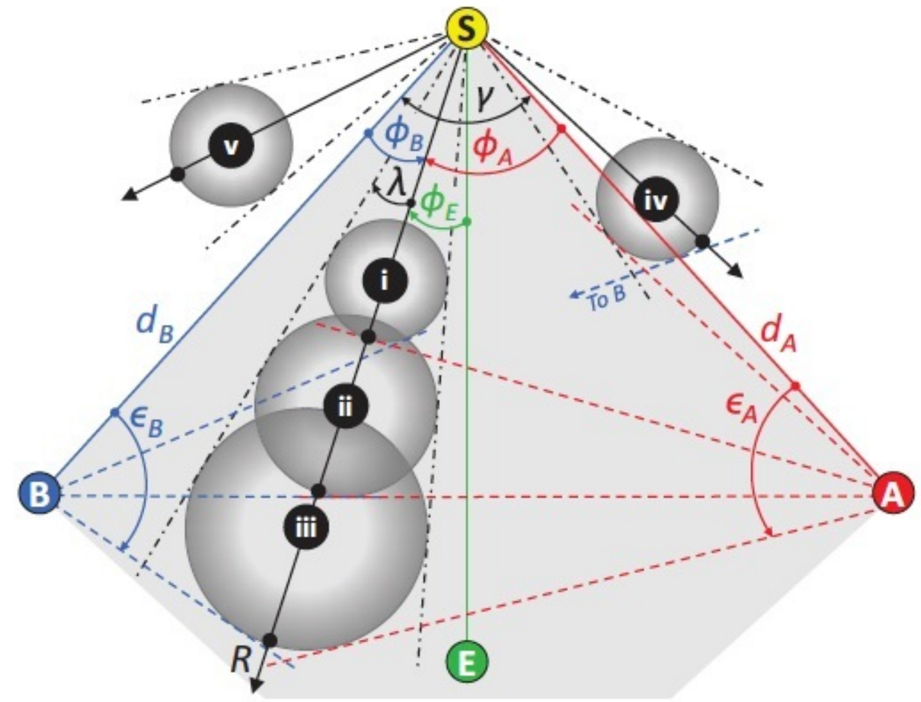
STEREO Heliospheric images make **tracking of CMEs possible to > 1 AU**, but are heavily affected by **Thomson scattering** and provide a more **limited view of the global shape and extension compared to coronagraphs**



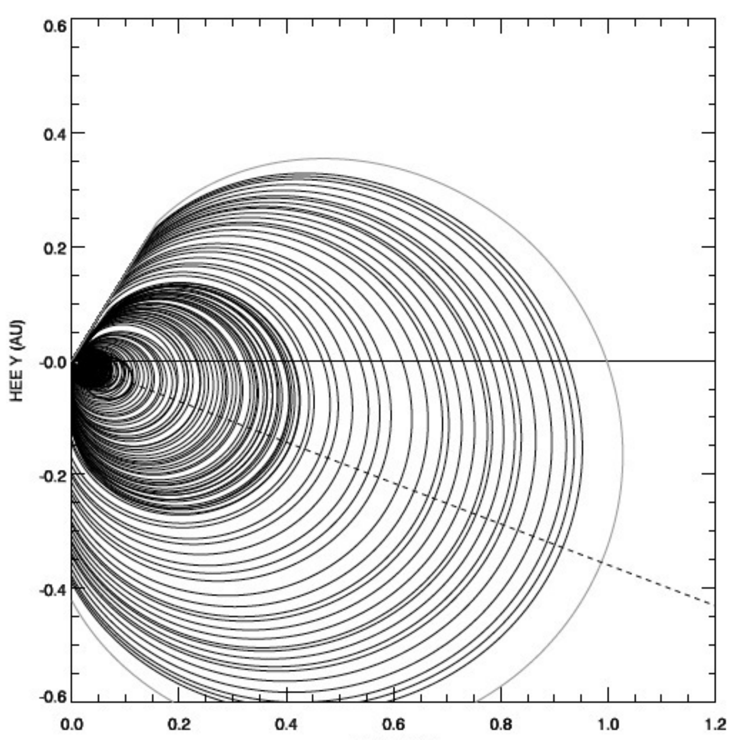
IDL SolarSoft
SATPLOT
P. Liewer, J. R. Hall JPL

CMEs in Heliospheric Imagers

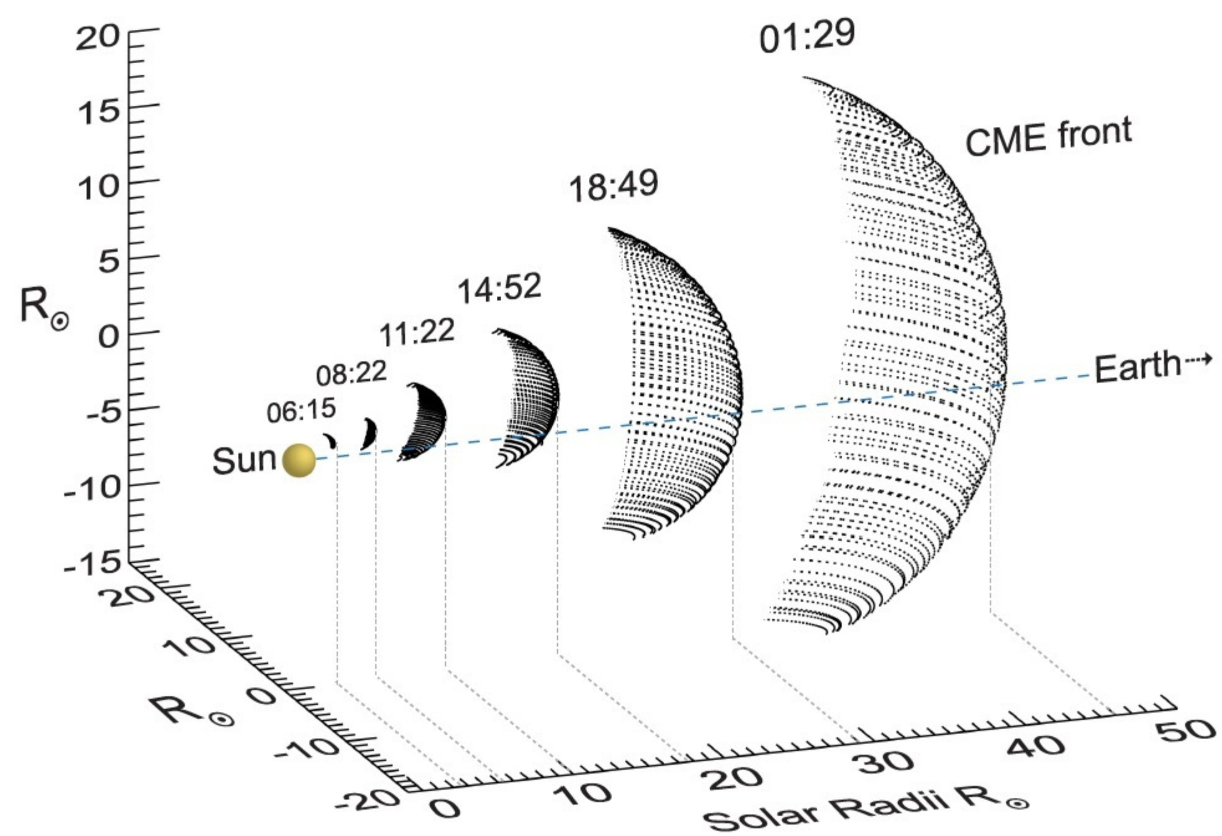
- Kahler and Webb, 2007, JGR (SMEI, fixed-phi)
- Tappin and Howard, 2009, SSR (T-H model)
- Wood et al. 2009/2010, ApJ (forward model)
- Byrne et al. 2010, Nat. Comm. (tie-pointing)
- Liu et al. 2010 ApJL (triangulation, FP)
- Lugaz et al. 2010 ApJ (triangulation, HM)
- Feng et al., 2012, ApJ (shape not predefined)
- Davies et al. 2013 ApJ (triangulation, SSE circle)
- Mishra & Srivastava 2013, 2014 ApJ (triangulation, drag model, comparison 1/2 HI)
- Colaninno, Vourlidas & Wu 2013 JGR (forward modeling for HI)



Davies et al., 2013 ApJ

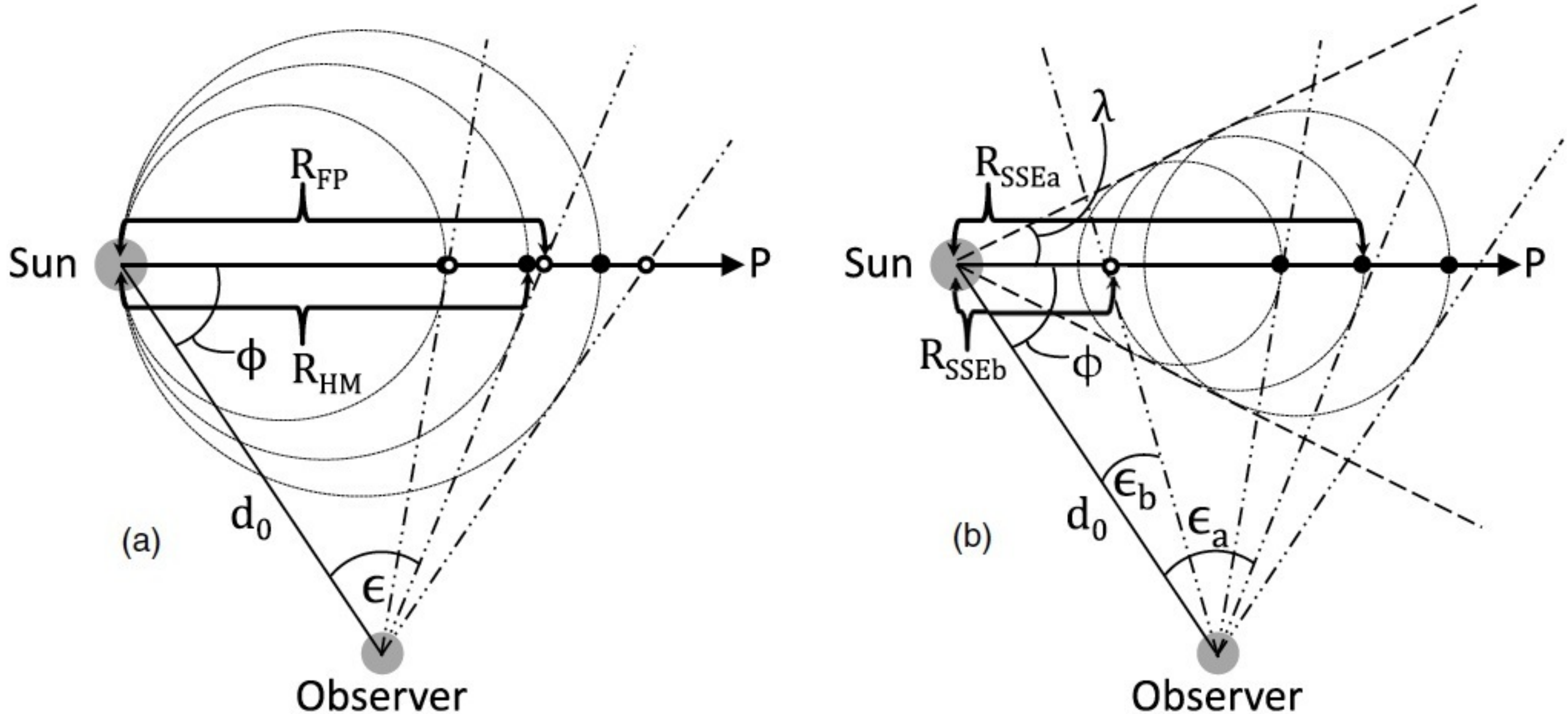


Colaninno, Vourlidas and Wu, 2013 JGR



Byrne et al., 2010 Nature Comm.

Elongation to distance conversion

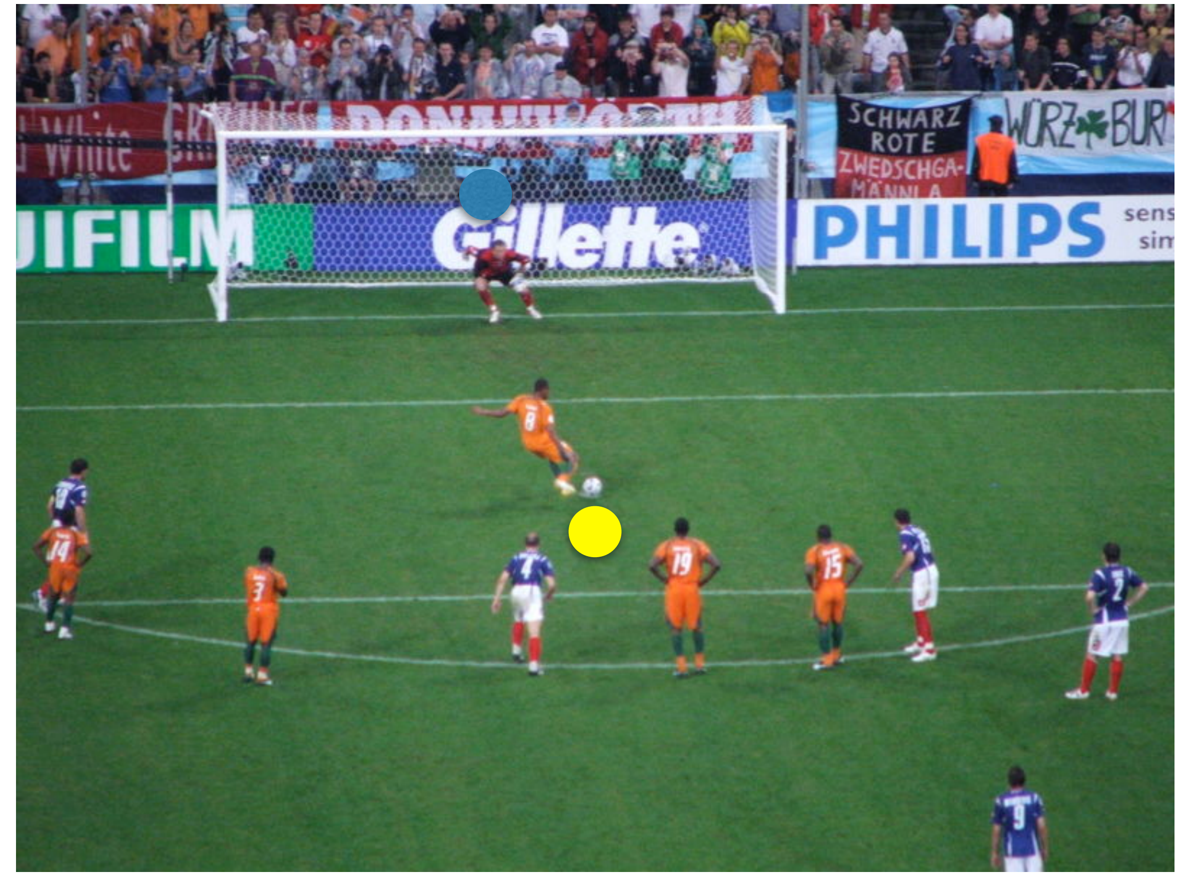


FP = Fixed - Phi: point like
HM = Harmonic Mean: wide circle, attached to the Sun
SSE = Self-similar expansion: circle with given width

In HI, **elongation** of a feature of a CME is observed, so to get its **distance** from the Sun the **direction and global shape** of the feature needs to be **known or assumed.**

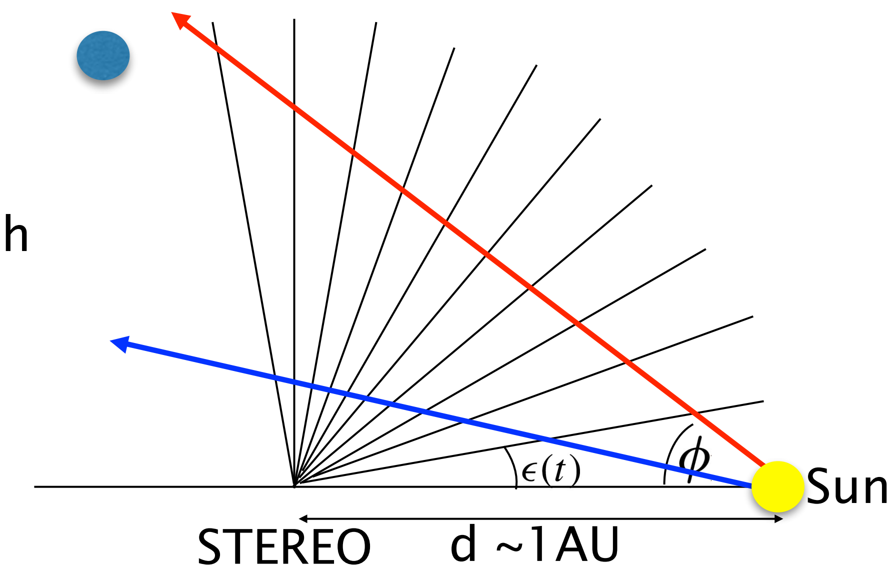
elongation-to-distance conversion:
observation -> model -> R(t), V(t)

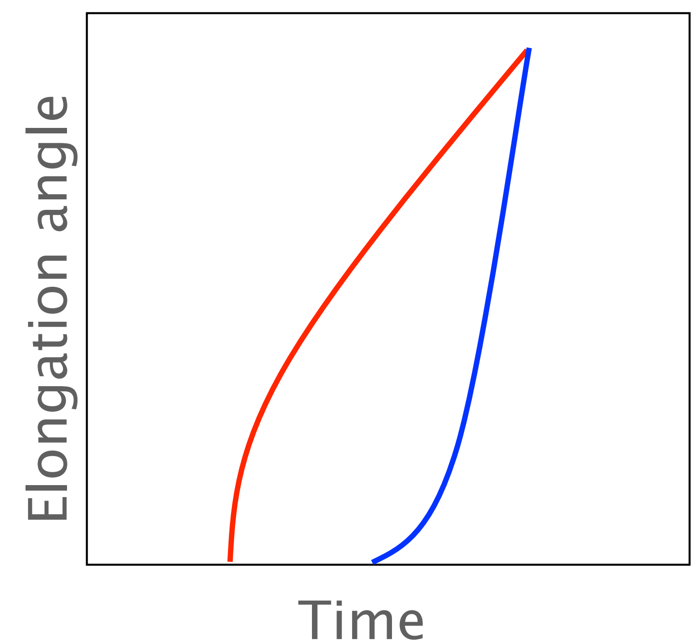
Single HI: speed and direction



stereoscopic methods which need two HIs:
direction and V are a function of time,
but suitable for future missions?

single-spacecraft HI:
direction and V are constant



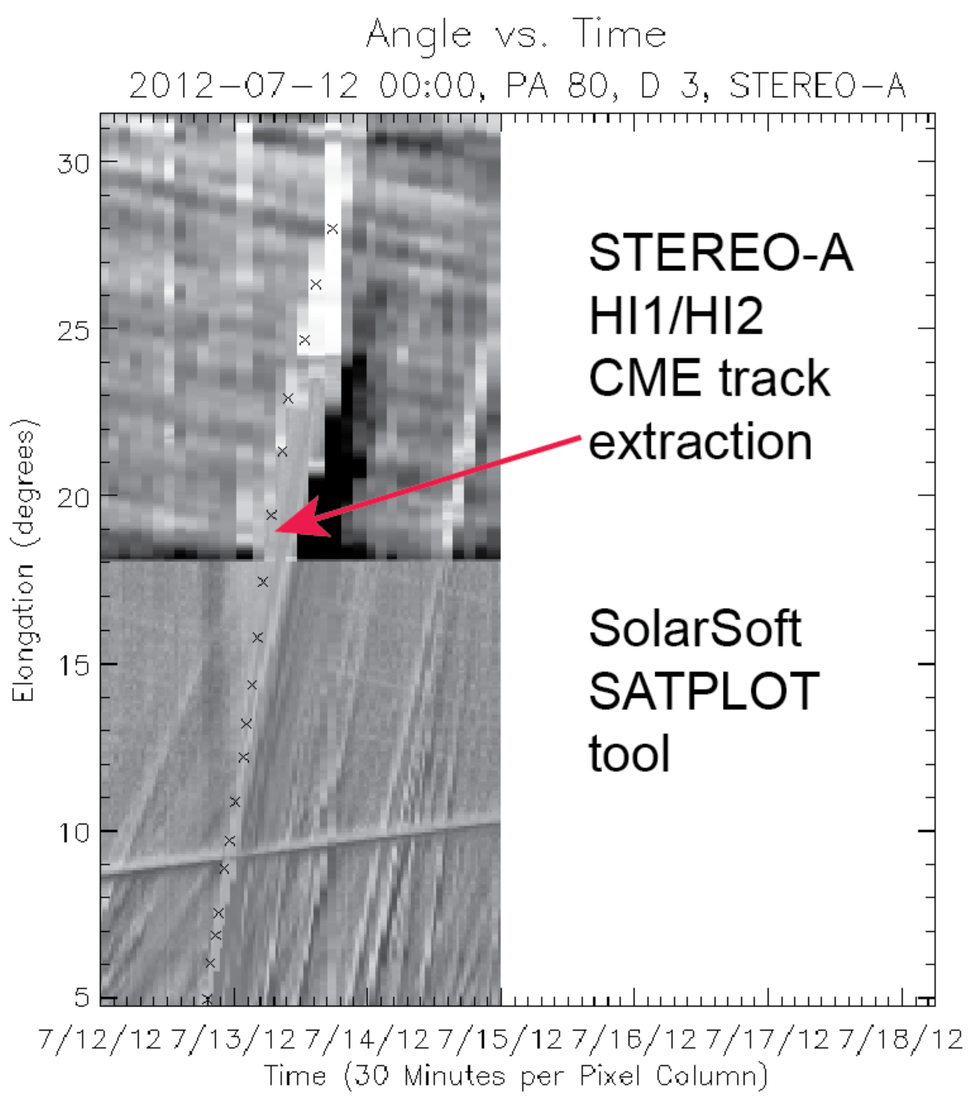


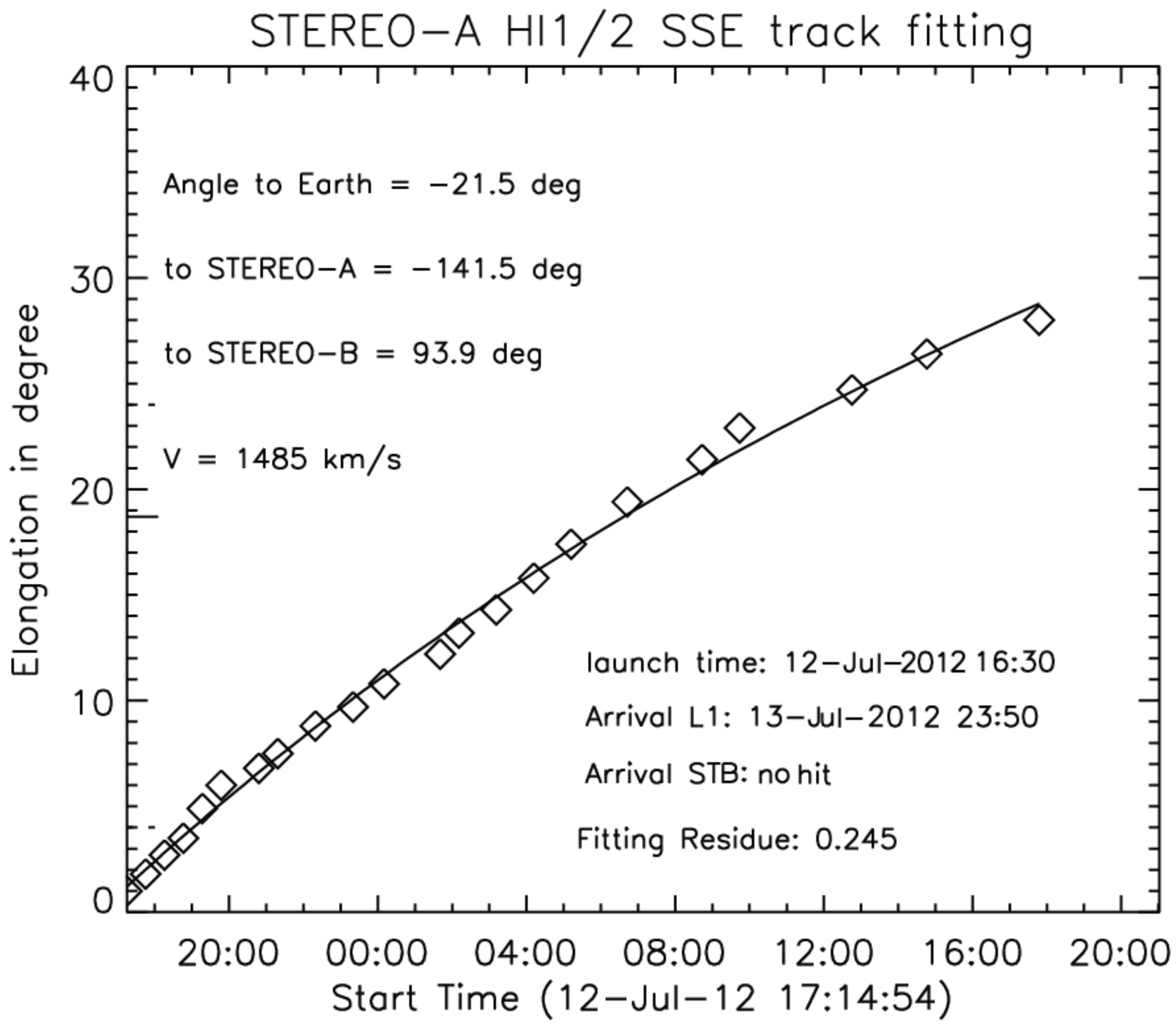
“apparent acceleration“
Sheeley et al. 1999, JGR

Single HI: speed and direction

“Geometrical Modeling“ we know the theoretical time-elongation profile, fit this to the observations: **model-> observation-> V, direction**

“tracking“ of a CME is done for the high density sheath region





SATPLOT authors: J.R. Hall, Paulett Liewer (Caltech/JPL Pasadena)

Single HI: speed and direction

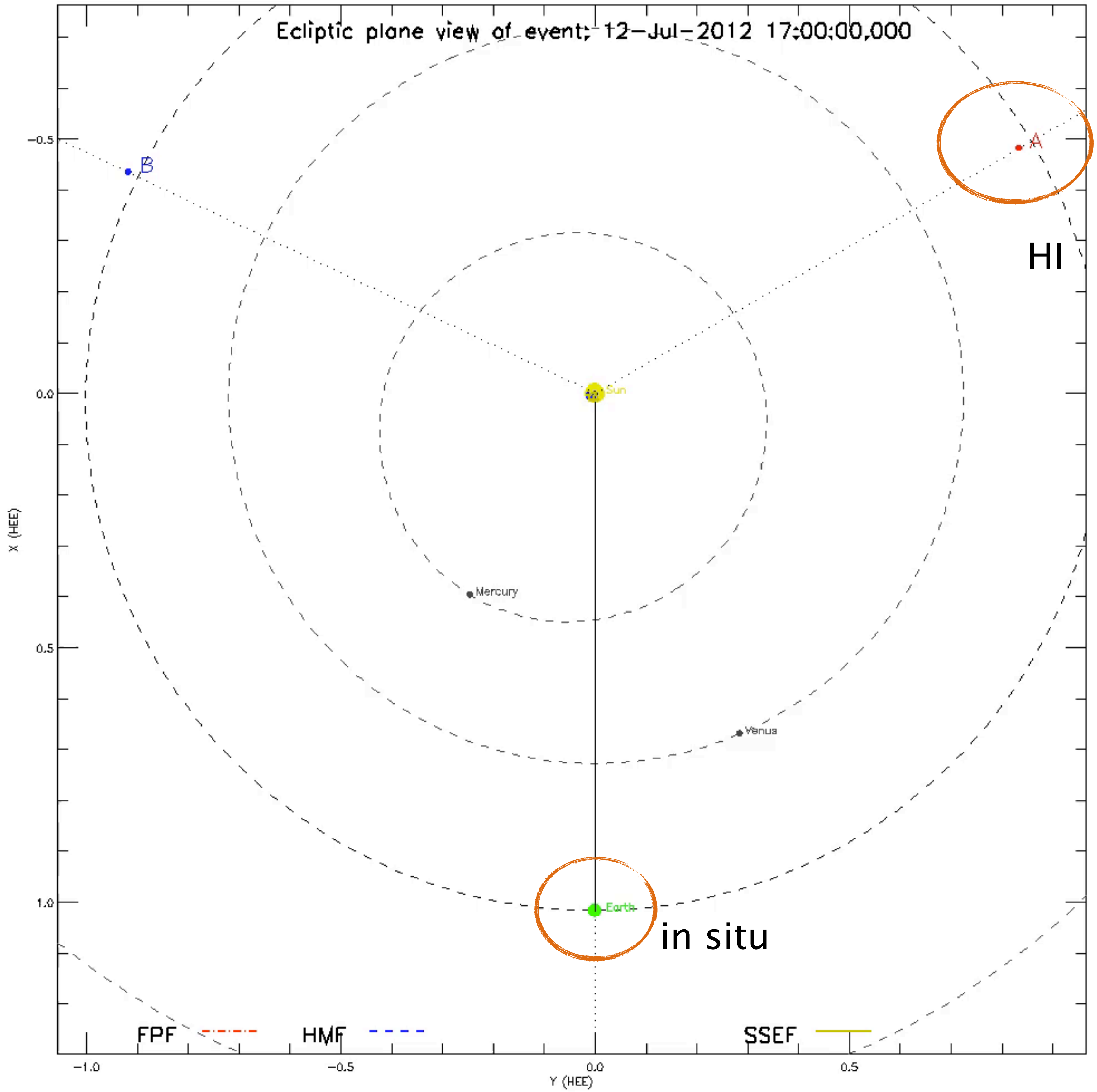
FPF: Rouillard et al. 2008 GRL

HMF: Lugaz, 2010 Sol. Phys.

SSEF: Davies et al., 2012 ApJ

Möstl and Davies, 2013
Sol. Phys.

application to many events:
Lugaz et al. 2012 Sol. Phys.
Möstl et al. 2014 ApJ



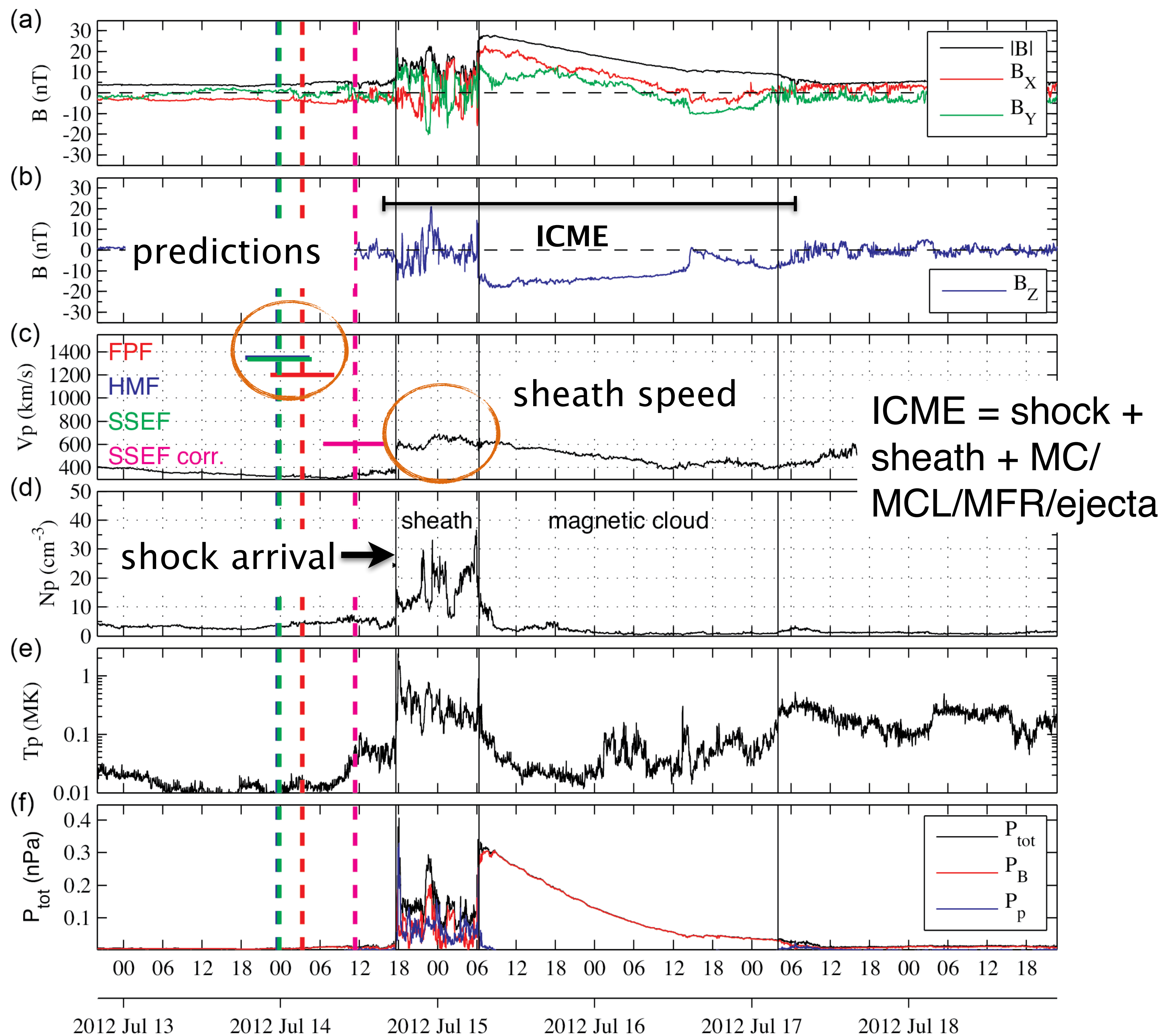
Single HI: speed and direction

In situ data show in **great detail + accuracy** the interplanetary CME magnetic field and plasma parameters and their **timing**, but are limited to a **one-dimensional trajectory.**

e.g. Wind at L1

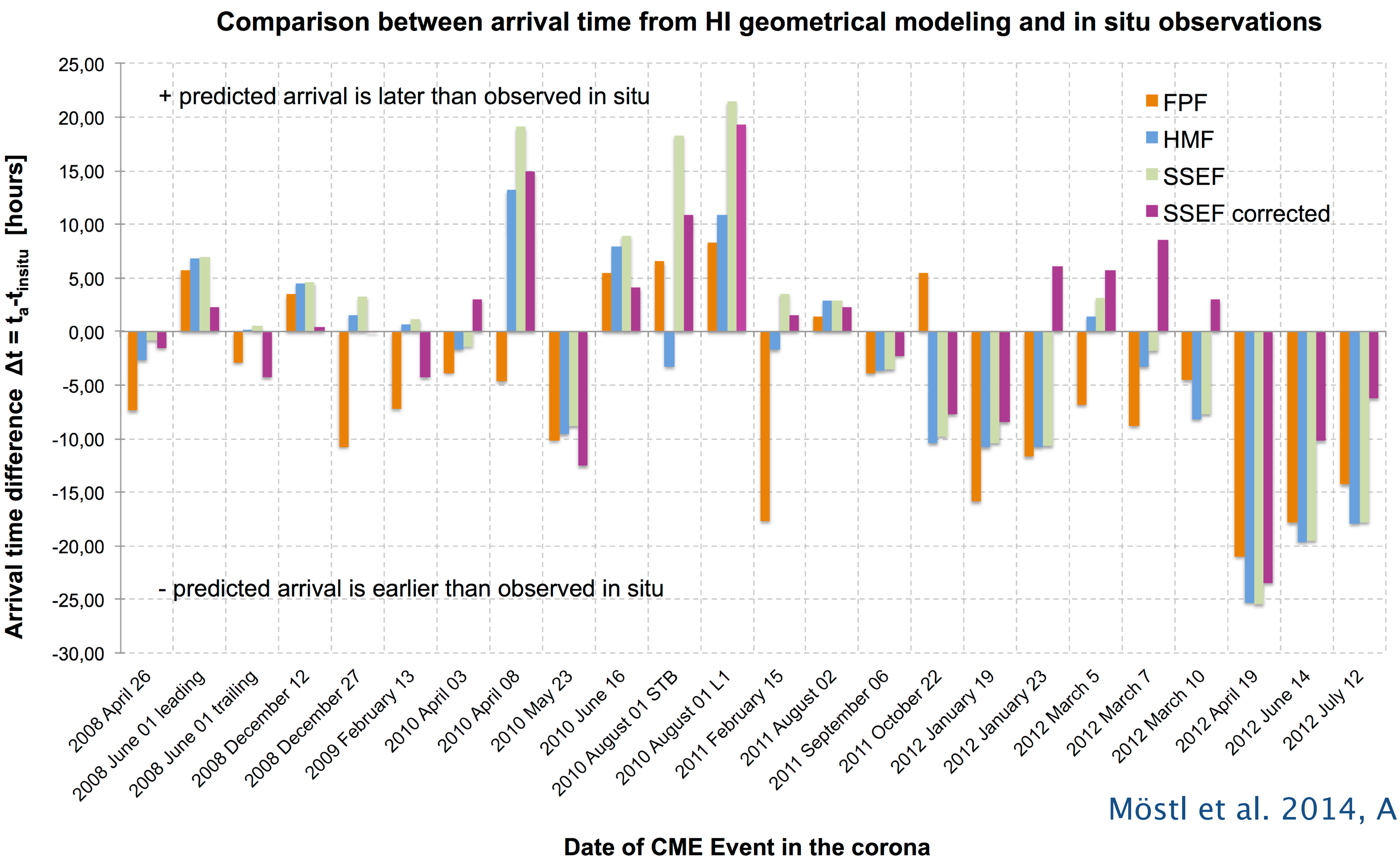
ACE, MESSENGER, VEX, STEREO-A/B

main link between in situ and imaging -> density!



Möstl et al. 2014, ApJ

Arrival time

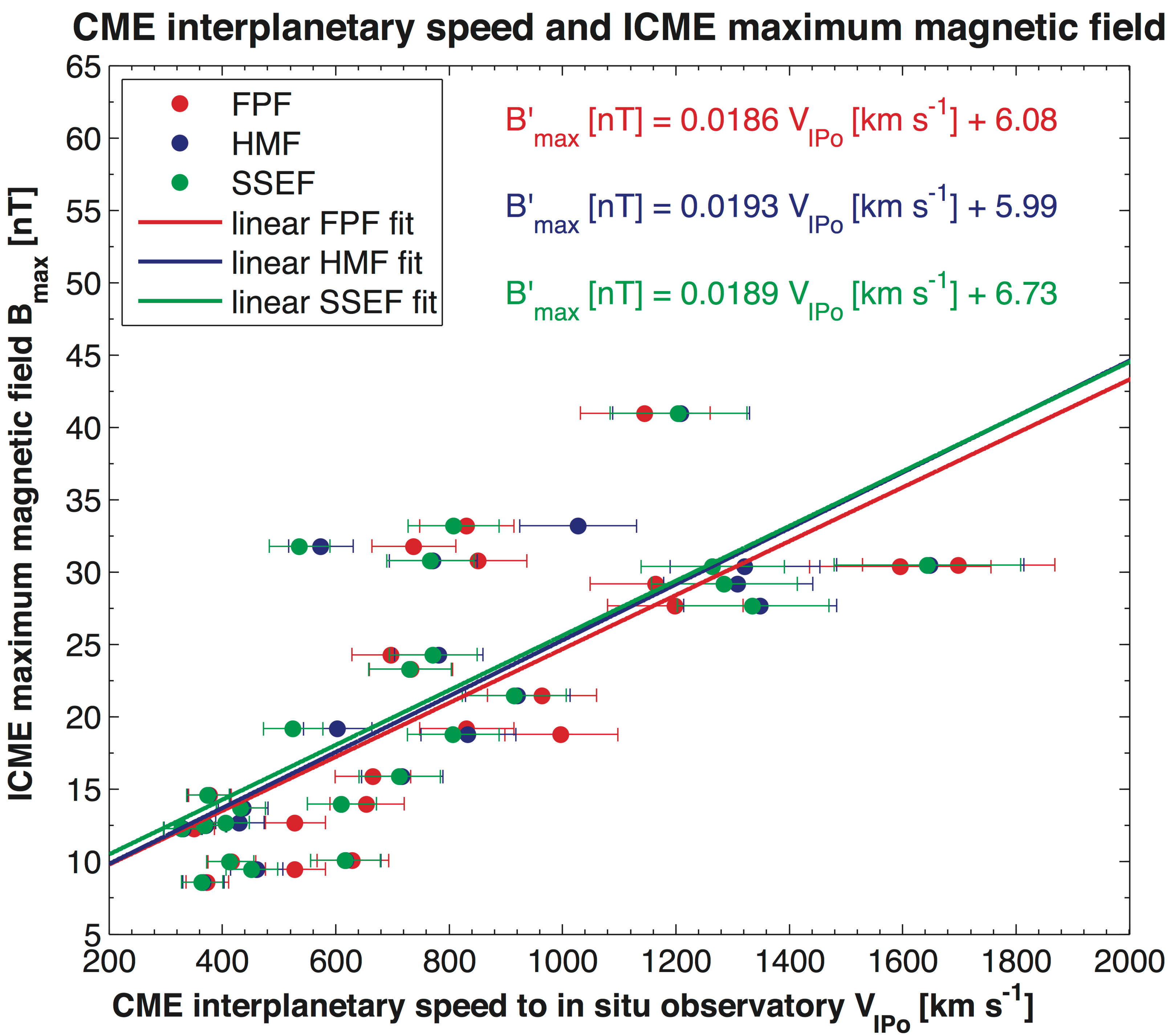


Möstl et al. 2014, ApJ

Simple metrics are used for evaluation!

Magnetic field

Link between speed from **HI** and **in situ** magnetic field - **prediction of total B?**



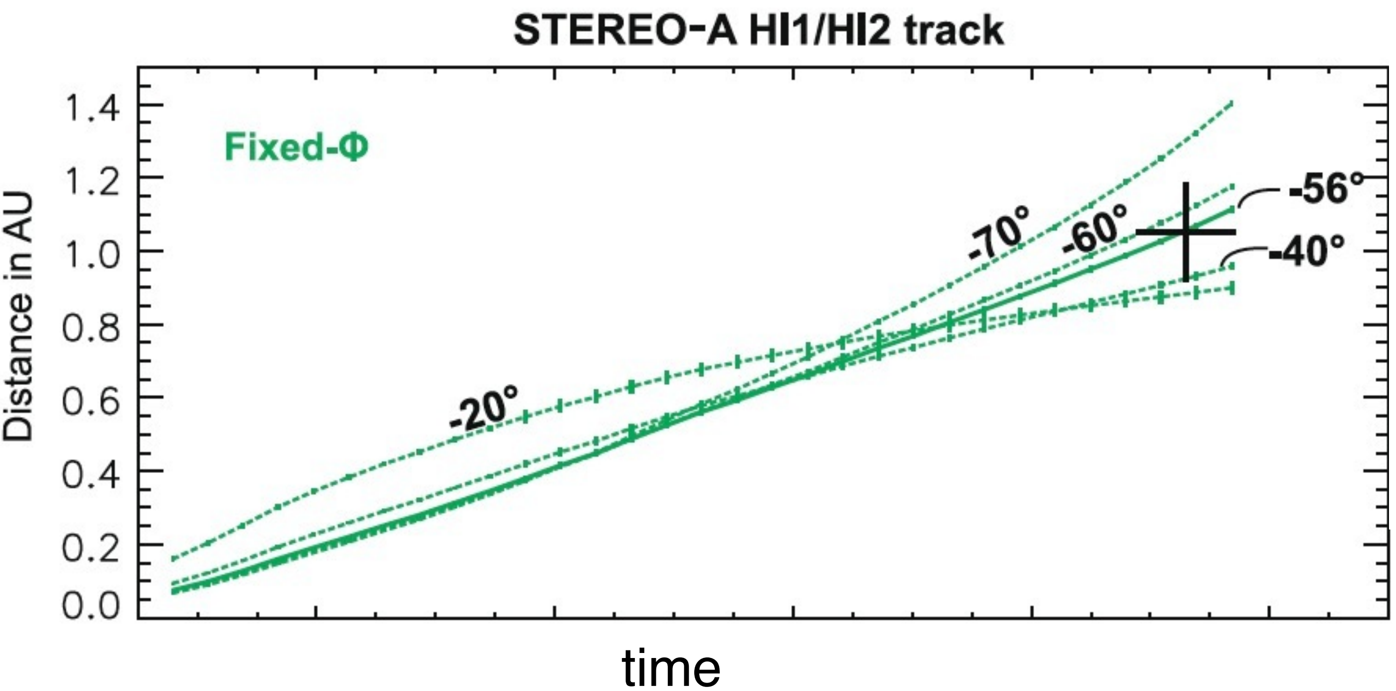
Möstl et al. 2014, ApJ

A method which uses combined HI and in situ data as input

Combining HI and in situ

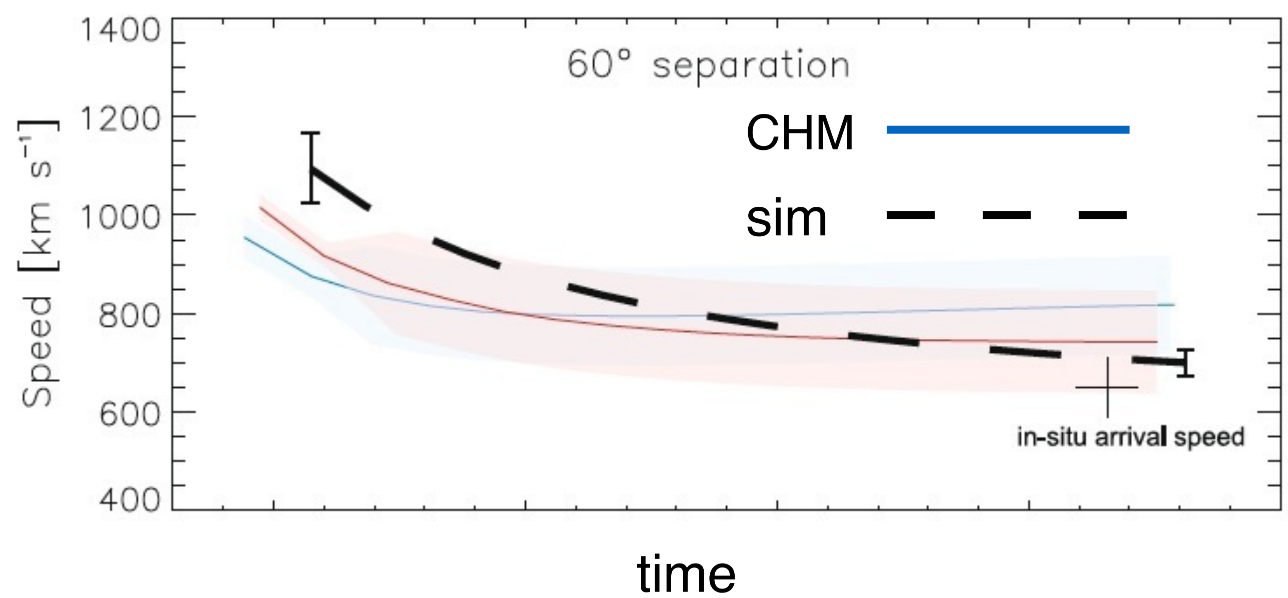
- Rollett et al. (2012, 2013, 2014) introduced a new method which **combines heliospheric imaging (single observer) and in situ data** as a starting point, using the assumptions on the CME front (=shock) global shape (FP, HM, SSE), which then lead to strongly constrained results on the kinematics of CMEs.
- crucial are the in situ arrival time and (if available) the plasma speed of the ICME sheath
- CFP/CHM/CSSE method - **C**onstrained **F**ixed **P**hi, ….

Find direction that matches best with in situ arrival time/speed



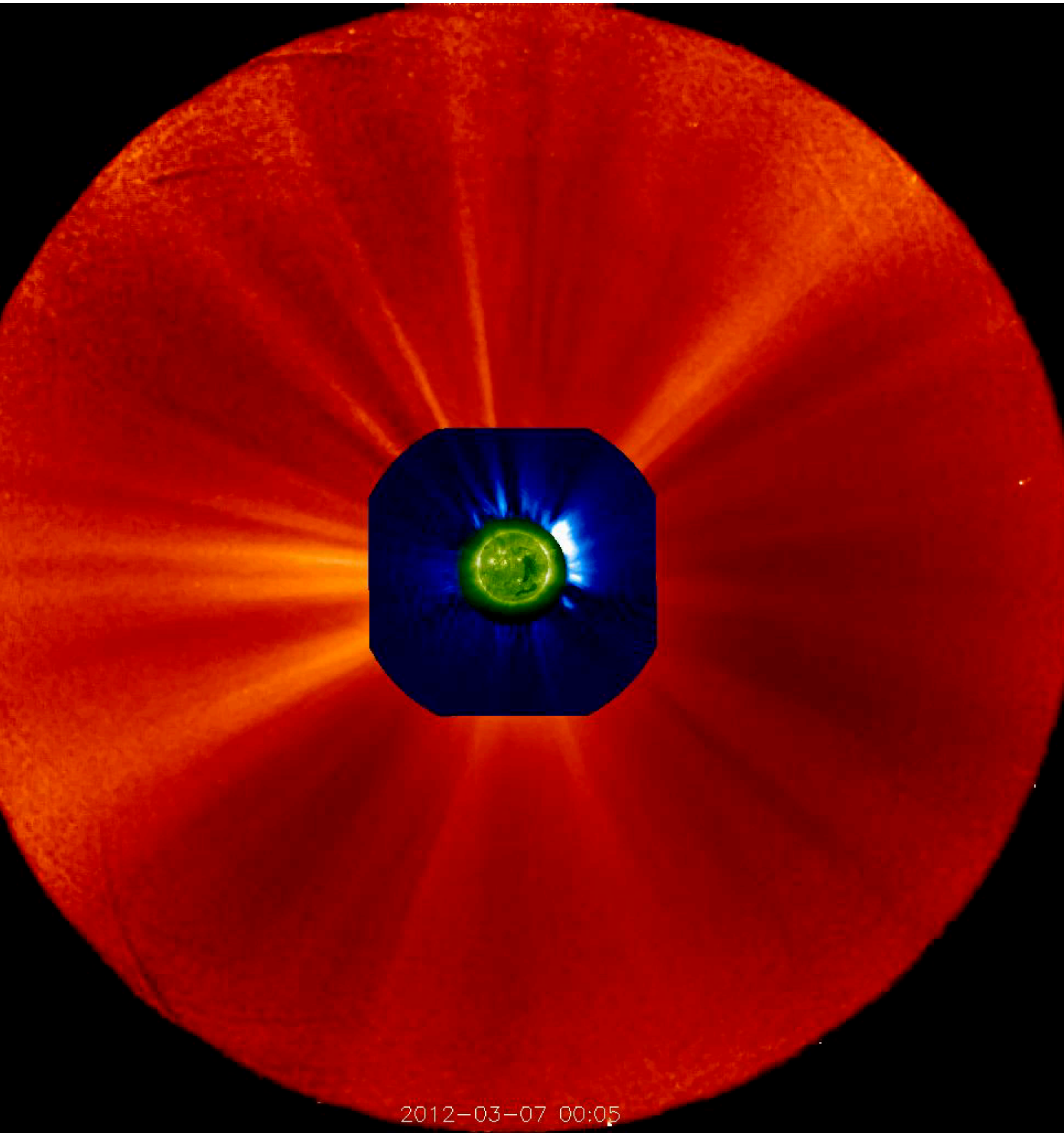
Rollett et al. 2012 Sol. Phys.

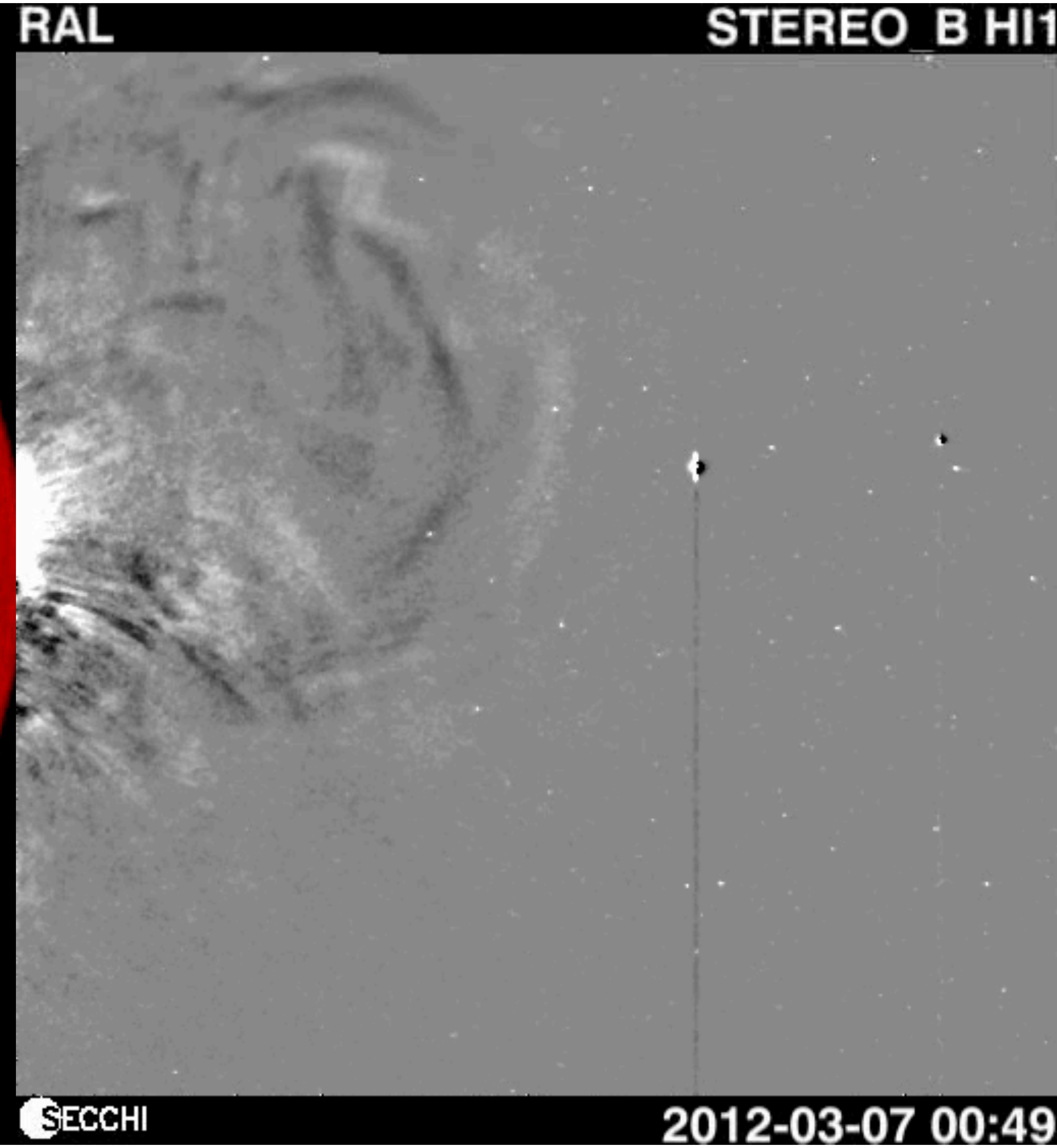
Comparison of result V(t) with simulation



Rollett et al. 2013 Sol. Phys.

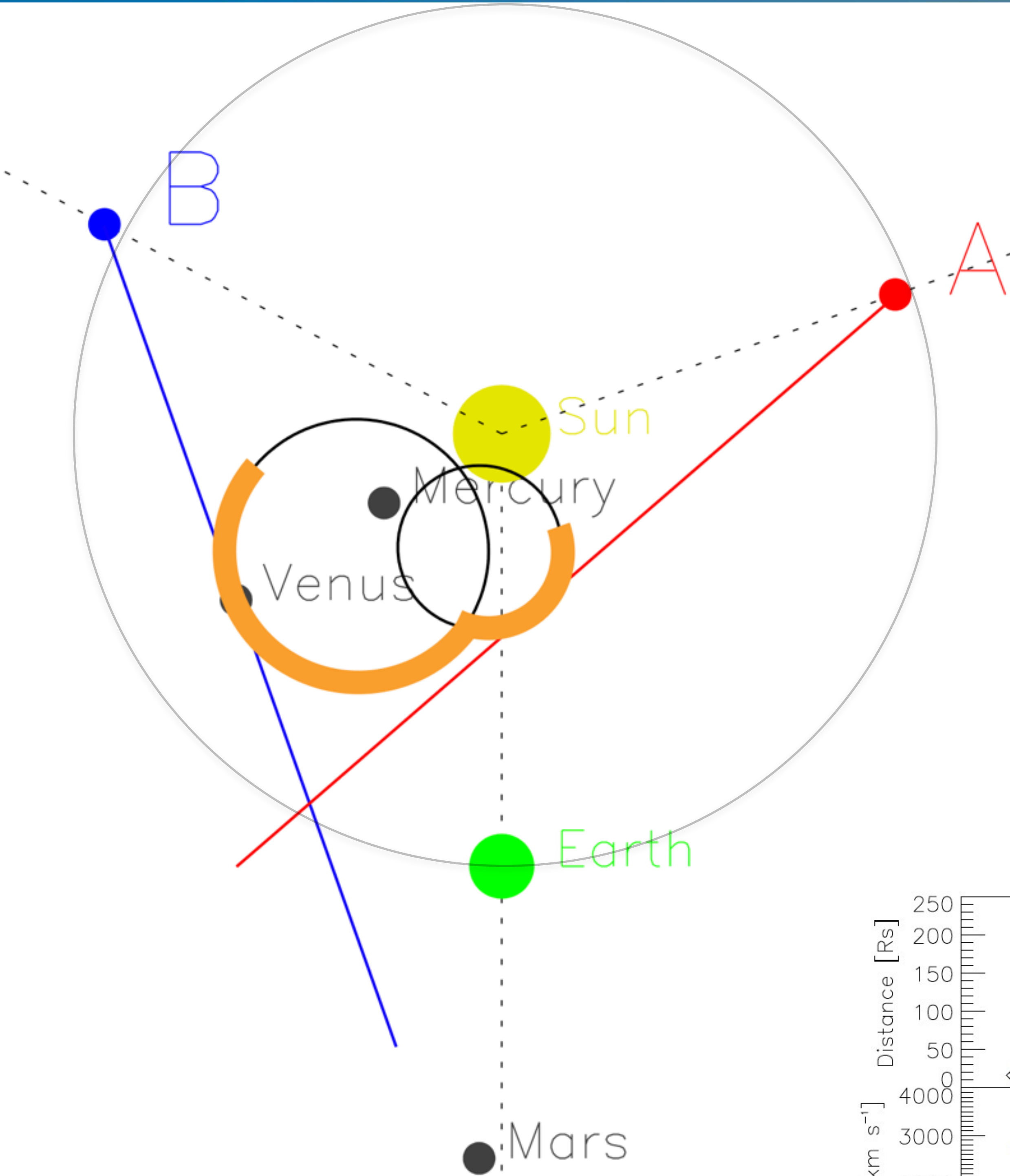
Combining HI and in situ

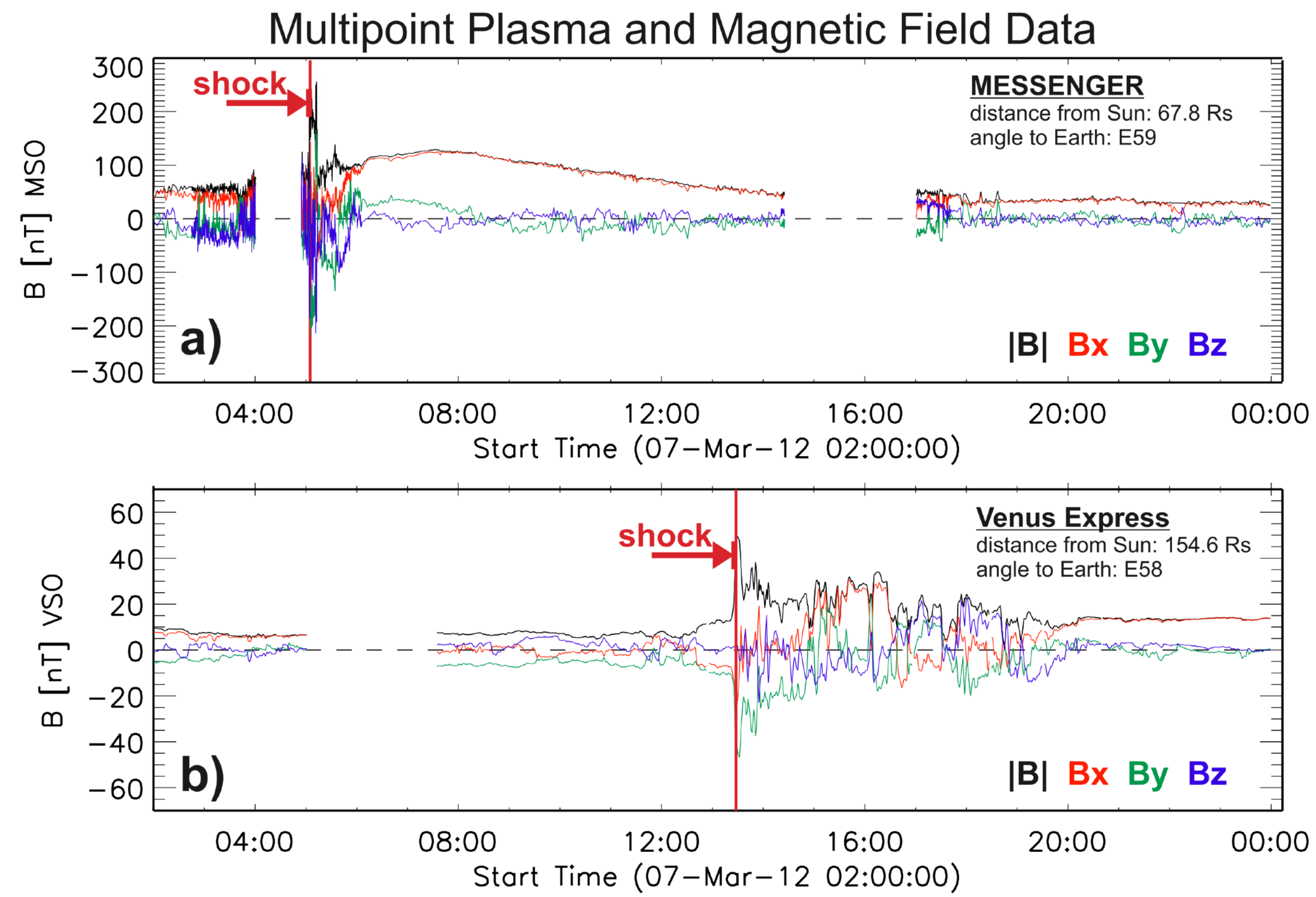


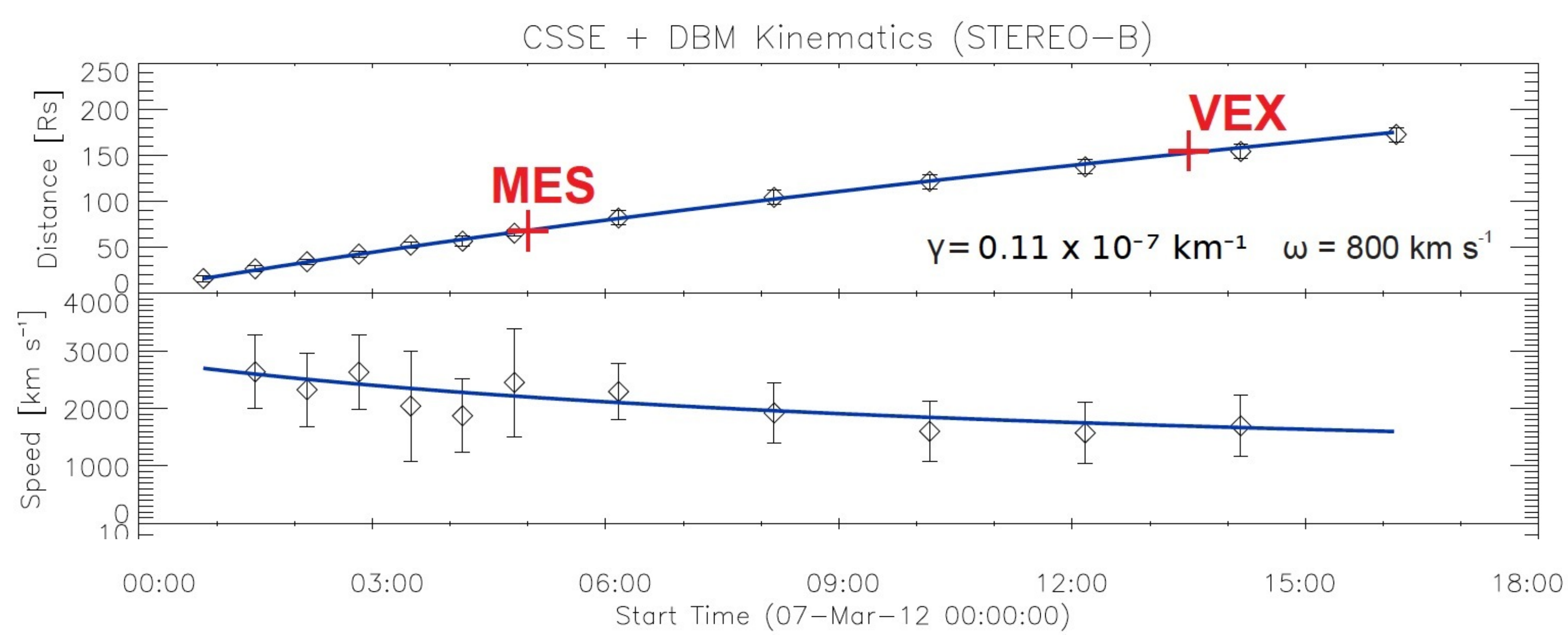


March 7 2012, X5.4 flare (2nd in SC24), Dst = −133 nT (1st in SC24), NOAA scale: G3

Combining HI and in situ

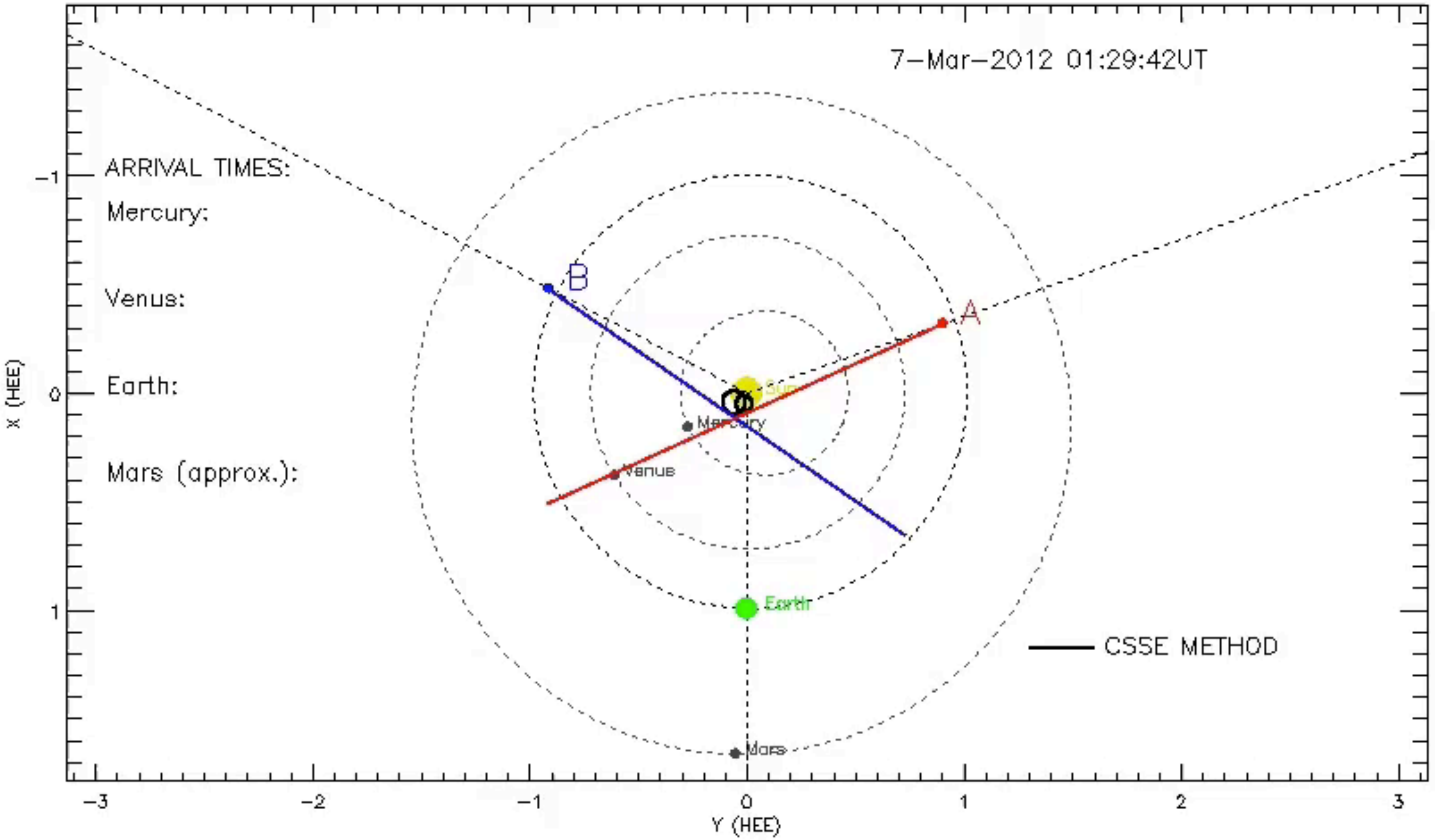






Rollett et al. 2014, ApJL

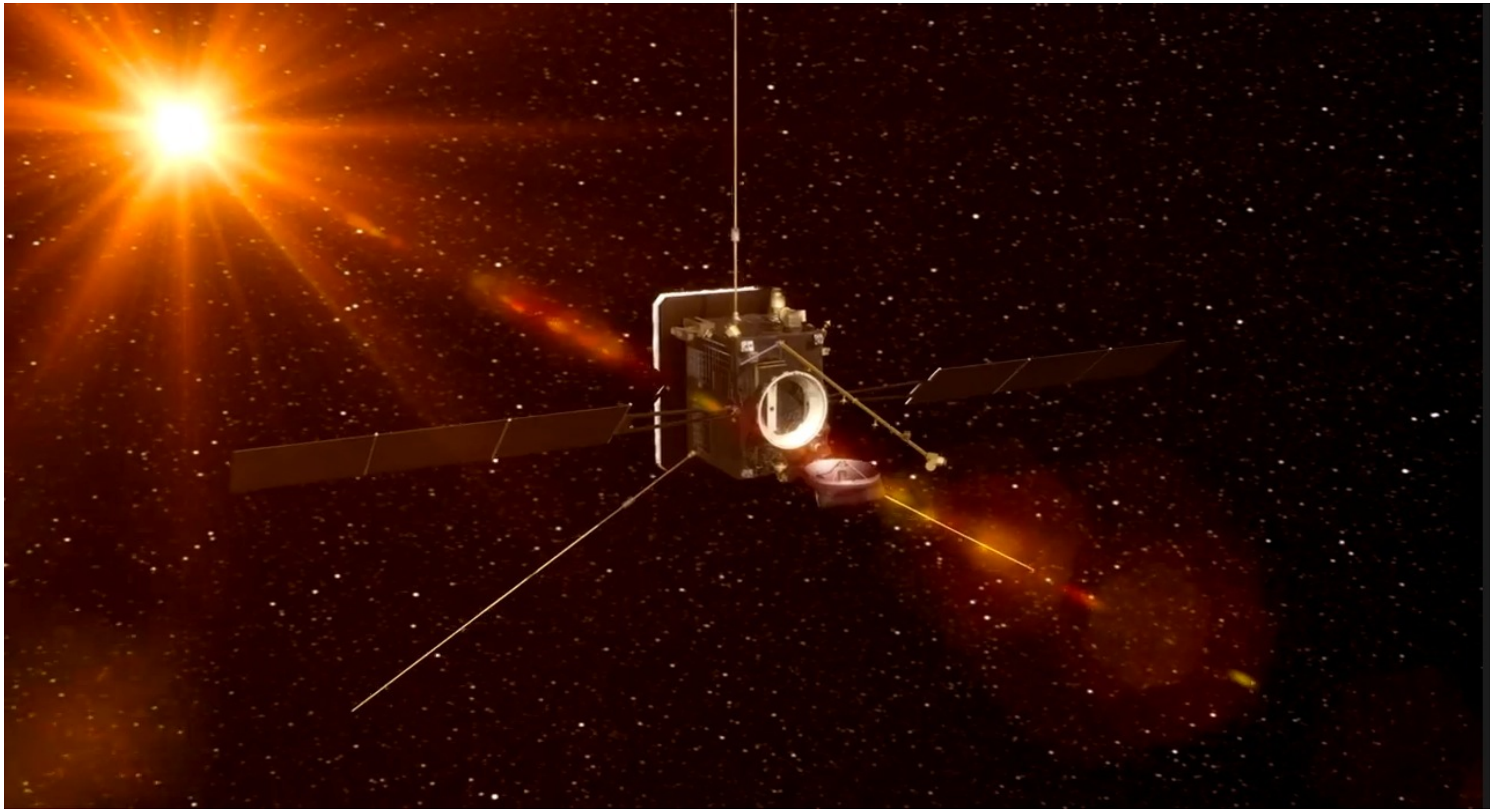
Combining HI and in situ



Rollett et al. 2014, ApJL

Arrival time at 1 AU east - west: 13h difference

Future combined observations



Solar Orbiter and Solar Probe Plus

- *Solar Orbiter* 2017- , 0.28 AU
  SoloHI imager
  plasma and magnetic fields in situ

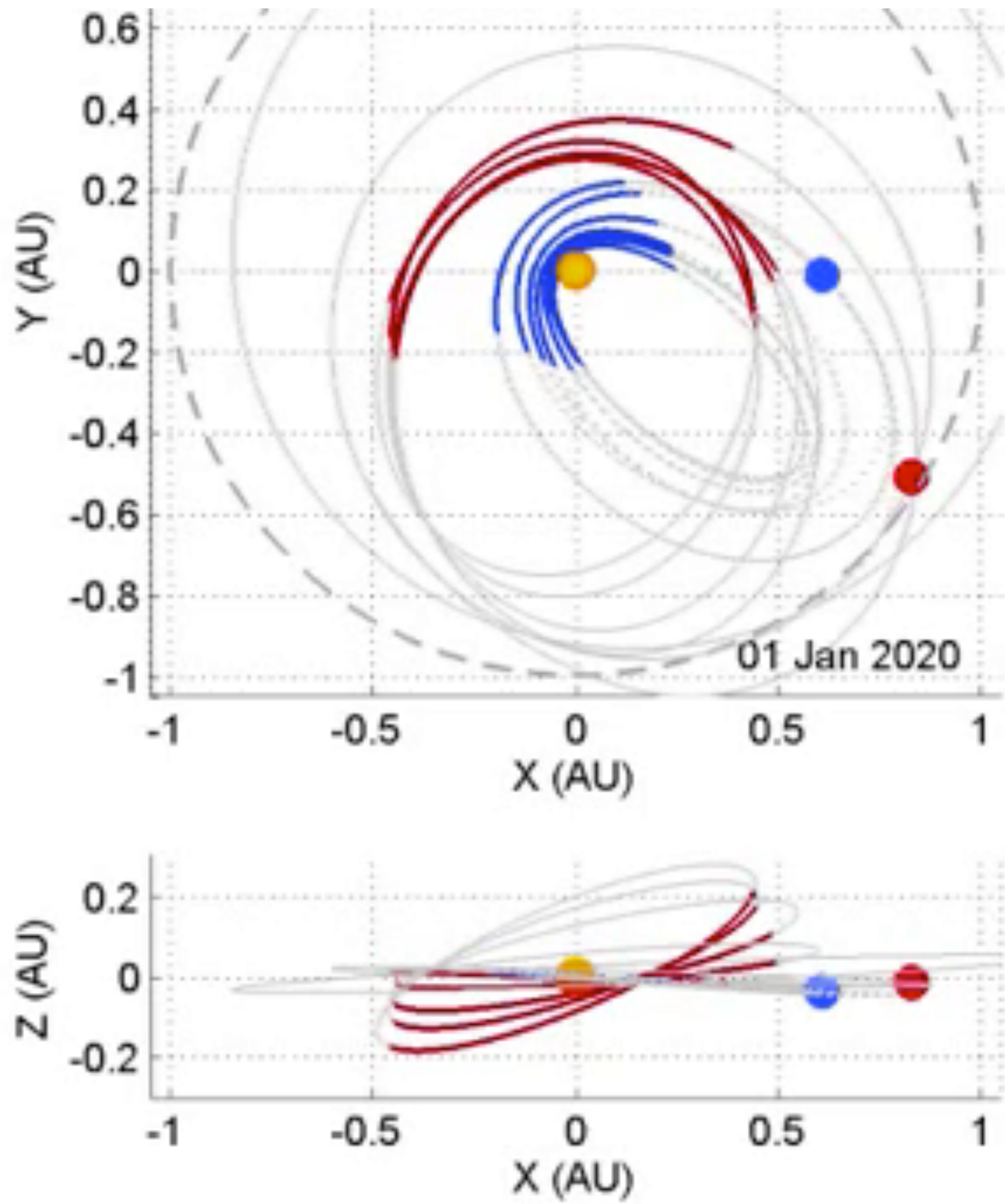
  Müller et al. (2013)

- *Solar Probe Plus* 2018- , 8.5 Rs
  WISPR imager
  plasma and magnetic fields in situ

- combining remote (SolOb) and in situ (SPP) observations will give answers and open new questions on CME flux rope and shock formation, the role of prominences, SEPs generation, ….

- single spacecraft HI methods for SoloHI
- but STEREO could still be here!

- special times: e.g. Nov 2021



Neel Savani, NRL: viewing angles of wide angle cameras when in operation, 2020 – 2021

Summary

Combining heliospheric imaging and in situ data

- **New methods combining these datasets put strong constraints on the global shape and kinematics of CMEs, seamlessly from the Sun to 1 AU**
- **Many models** have been developed to **extract CME parameters from HI images**, some have been tested for their capability for space weather forecasting with in situ observations
- For predicting CMEs, **no method seems to perform significantly better than any other** - however, tracking a CME longer with HI makes predictions more accurate, but lead times shorter

Upcoming research trends

- **Pre-conditioning** of the background wind (CIRs, HPS, other CMEs) for CME propagation seems to be very important, influencing the global shape (asymmetries), expansion, and kinematics.
- **Combining models:** triangulation and single spacecraft HI observations with empirical drag models, Enlil synthetic Jmaps with HI, …?
- **Missing link** in space weather forecasting: how to predict in situ magnetic field structure from remote images?

Future missions

- Single spacecraft HI - methods, and combination of HI + in situ that we have developed for STEREO can also be used for Solar Orbiter and Solar Probe Plus
- **Going closer to the Sun *and* combining in situ and HI data** will reveal many aspects of the **origin of CMEs,** their internal structures (solving the missing link?) and their effects on the heliosphere

HELCATS

- EU Project May 2014 – April 2017, led by RAL Space, UK (PI: Richard Harrison)
  Heliospheric Cataloguing, Analysis and Techniques Service
  Goal is to fully exploit STEREO heliospheric imaging + various in situ data of CMEs
- results of catalogued datasets will be accessible to all researchers
- **see poster by Rodriguez et al.**

CME Facts

- discovered by OSO-7 coronagraph (Tousey, 1973)
  Hundhausen et al. (1984, JGR): “*observable change in coronal structure that occurs on a time scale between a few minutes and several hours and involves the appearance of a new, discrete, bright, white-light feature in the coronagraph field of view*“

- **Size (radial)**
  close to Sun: ~ 1 solar radii (~100 earth radii)
  1 AU: ~ 0.2 AU (~5 000 earth radii)

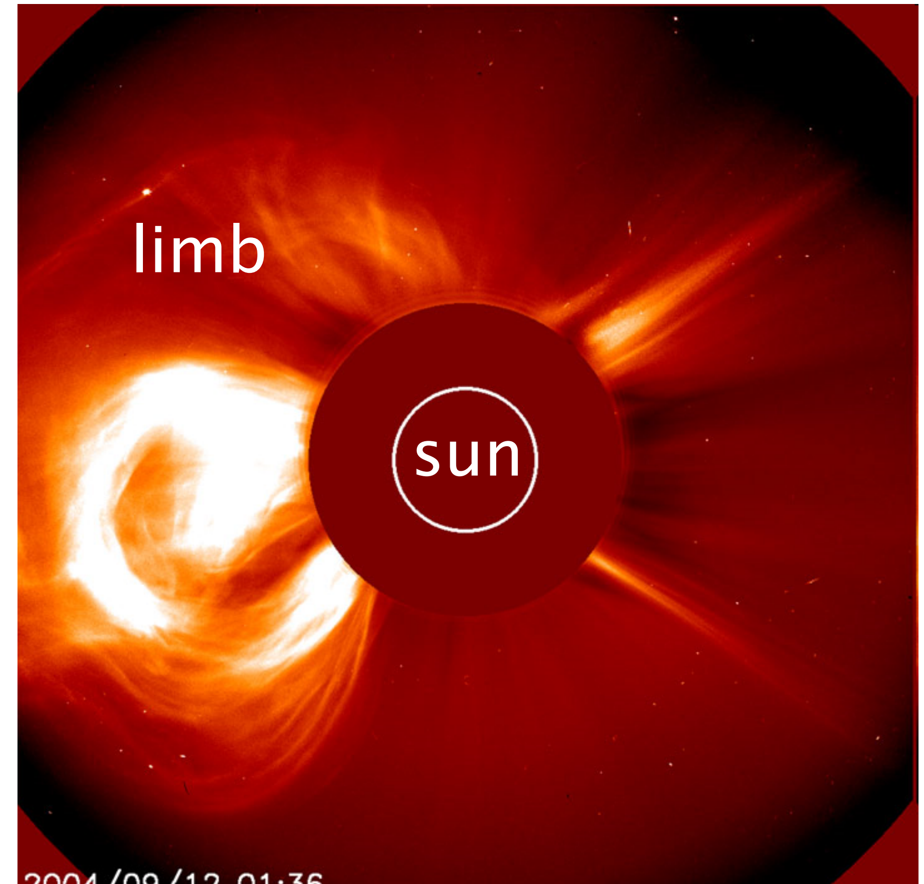
- **Mass** ~10^{12} kg = mass of a small mountain

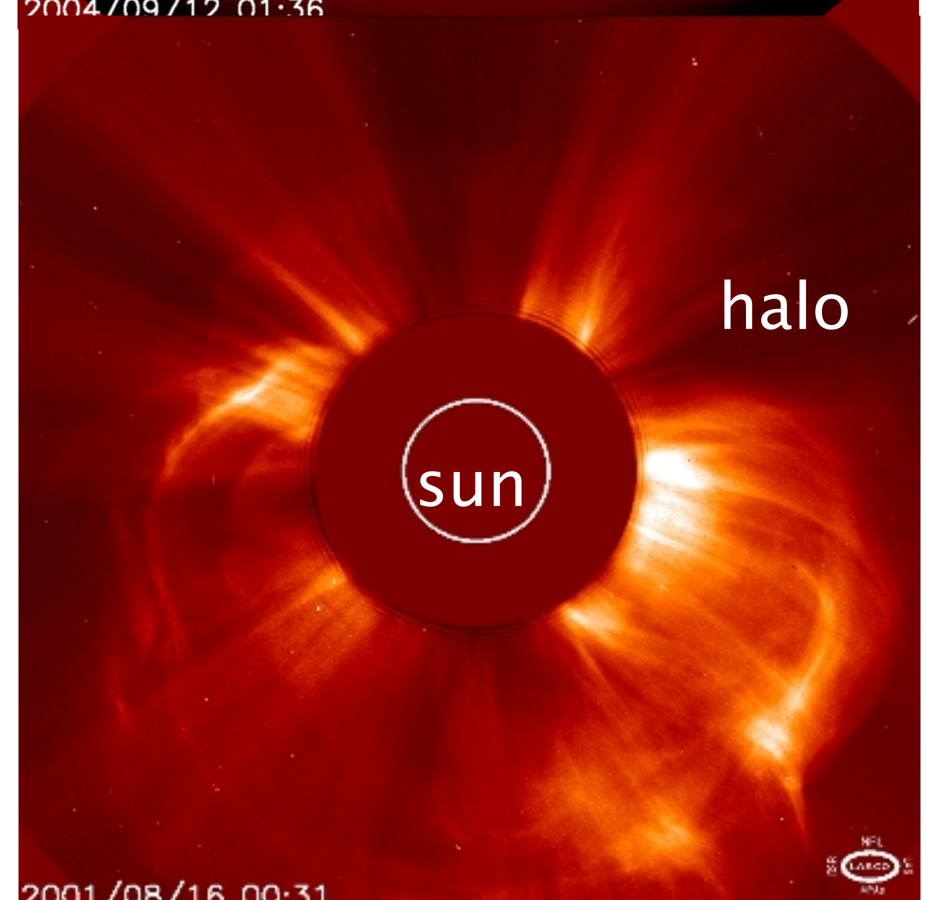
- **Energy**: up to 10^{25} J
  ~ 1/10 total solar irradiance / sec
  Hurricanes on Earth 10^{19} J / day

- **Magnetic field at 1 AU**: average 20 nT, up to 100 nT.

- **Speed:** 200 – 3500 km/s (*millions* km/h)
  Sun-to-Earth propagation: 14 h – 5 days

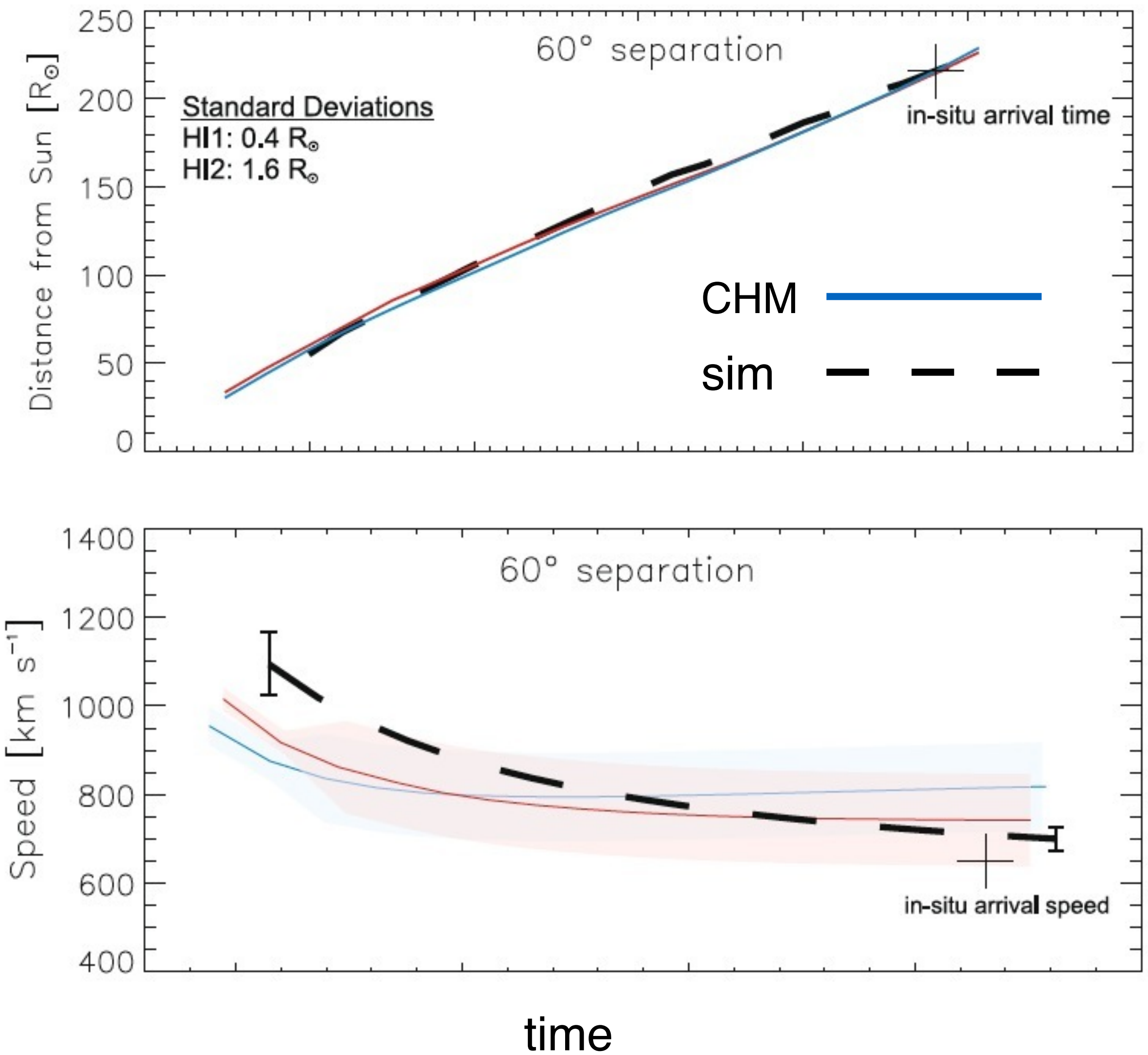
- CMEs are strong **particle accelerators**
  energetic particles may have up to 10% of CME energy

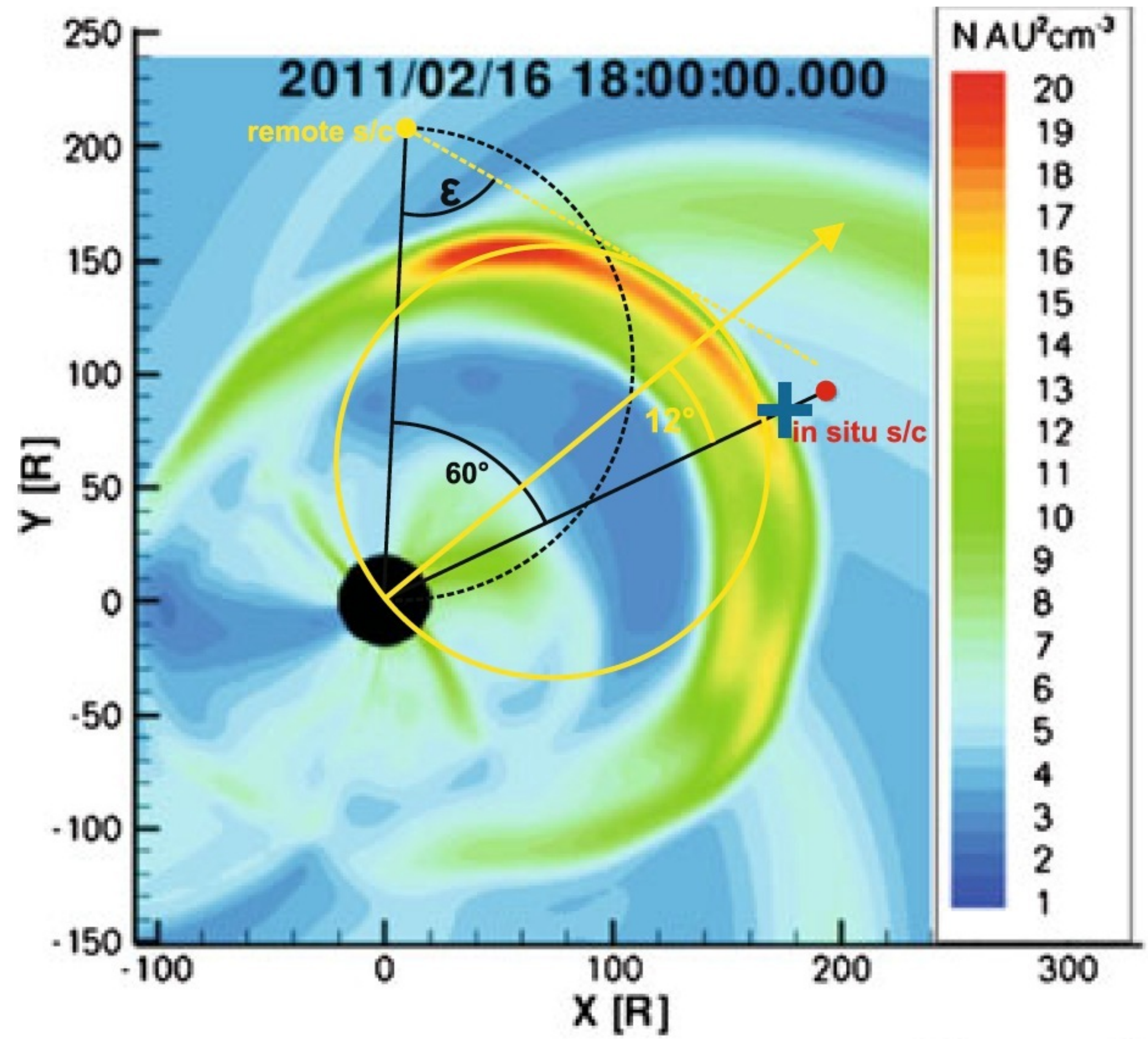




Combining HI and in situ

Method tested with numerical simulation - advantage: CME direction and global shape is known
Three HI observers: 30°, 60°, 90° to CME apex   in situ at 0°

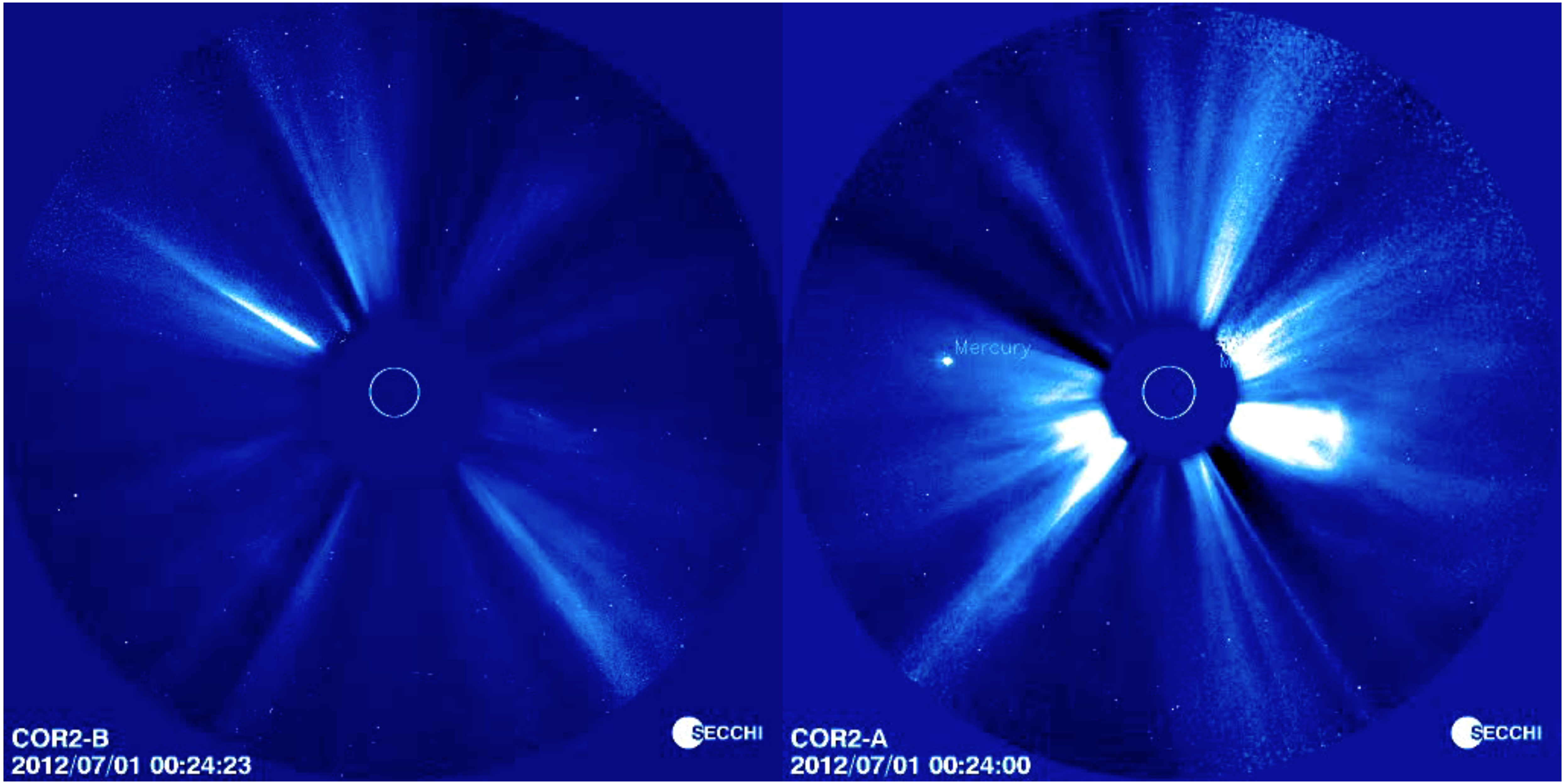




Direction obtained W7-W15, true dir: W0   **(residual) arrival speed diff. to in situ: -50 to 125 km/s**

Rollett et al. 2013 Sol. Phys.

Remote CME observations



movie NRL

Coronagraph images give a good global, even multipoint overview of initial general CME parameters, but lack information on the CME's magnetic structure

Rodriguez et al. (2011, Sol. Phys.) showed that predicting if a CME is detected as an ICME by a spacecraft works very good (90 % correct predictions) with COR2 forward modeling.