Coronal Mass Ejections
Basic observational facts & outstanding questions

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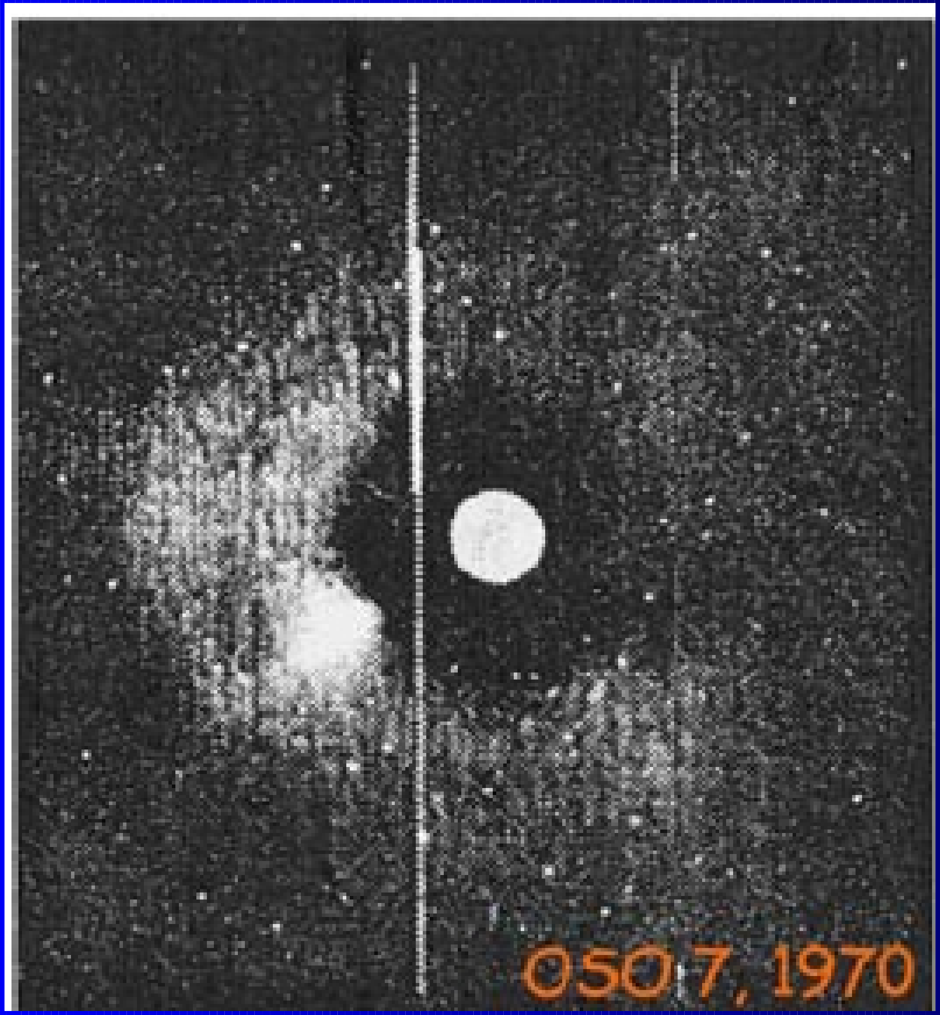
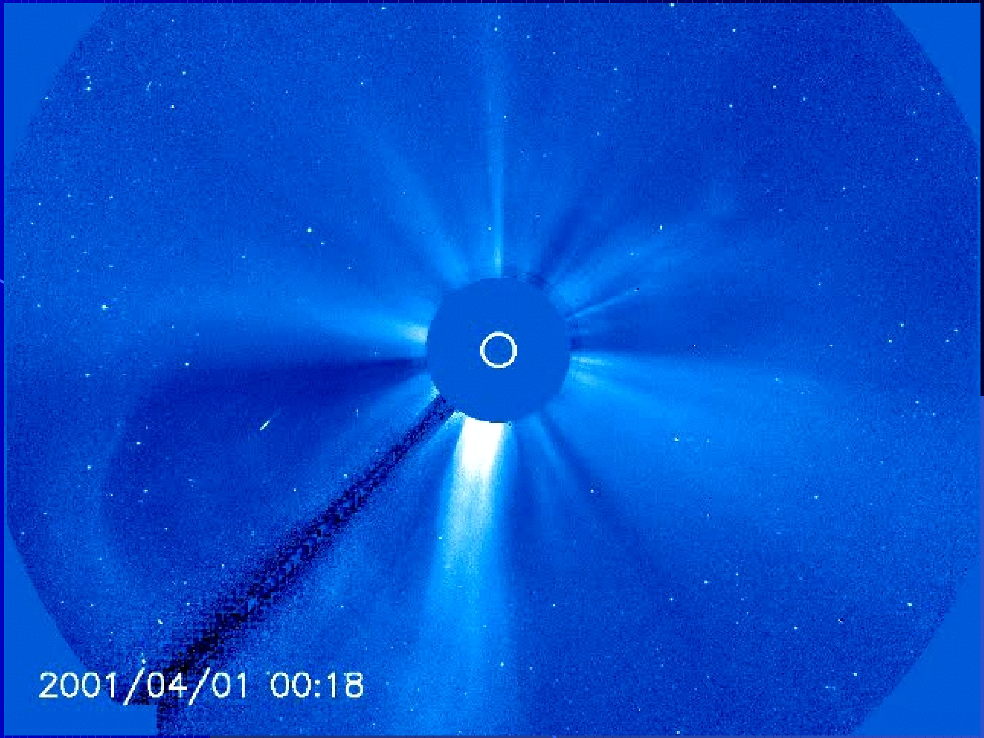
How it all started



Brueckner et al. 1972
Toussey et al. 1972

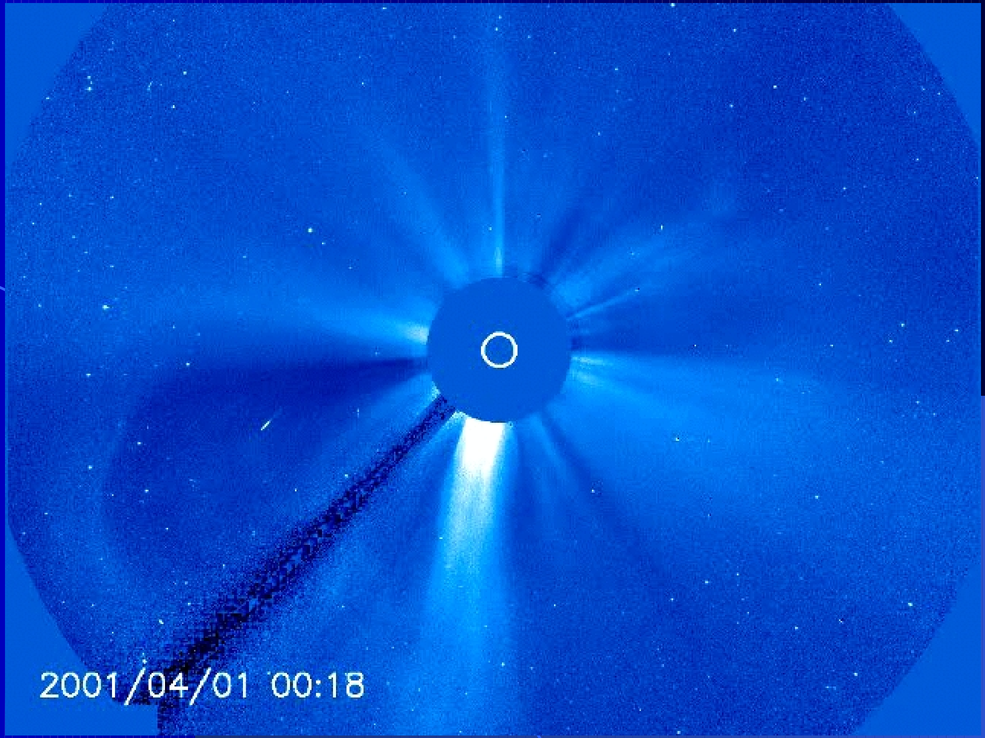
What is a CME?



The 80's- early 90's picture *(transient expulsion of coronal mass & frozen-in b-field into the IP medium*): **Hundhausen et al . 1984**

(Hund-hausen *et al.*, 1984), as expressed in Schwenn (2006): "*We define a CME to be an observable change in coronal structure that 1) occurs on a time scale of a few minutes and several hours and 2) involves the appearance (and outward motion) of a new, discrete, bright, white light feature in the coronagraph field of view.*"

What is a CME?



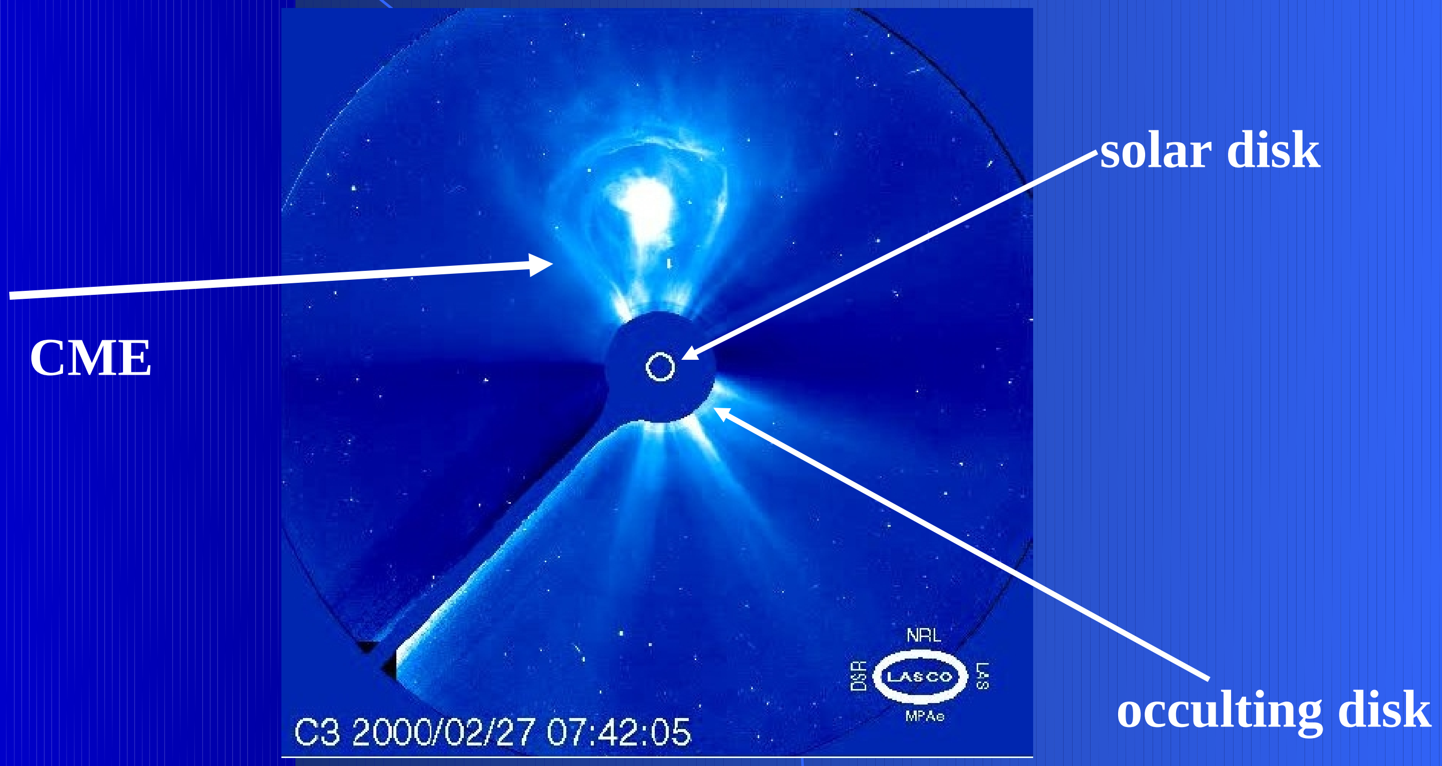
The current picture (add FR topology & width):

Vourlidas et al . 2013

We define an FR-CME to be the eruption of a coherent magnetic, twist-carrying coronal structure with angular width of at least 40° and able to reach beyond 10 $R_\odot$ which occurs on a time scale of a few minutes to several hours.

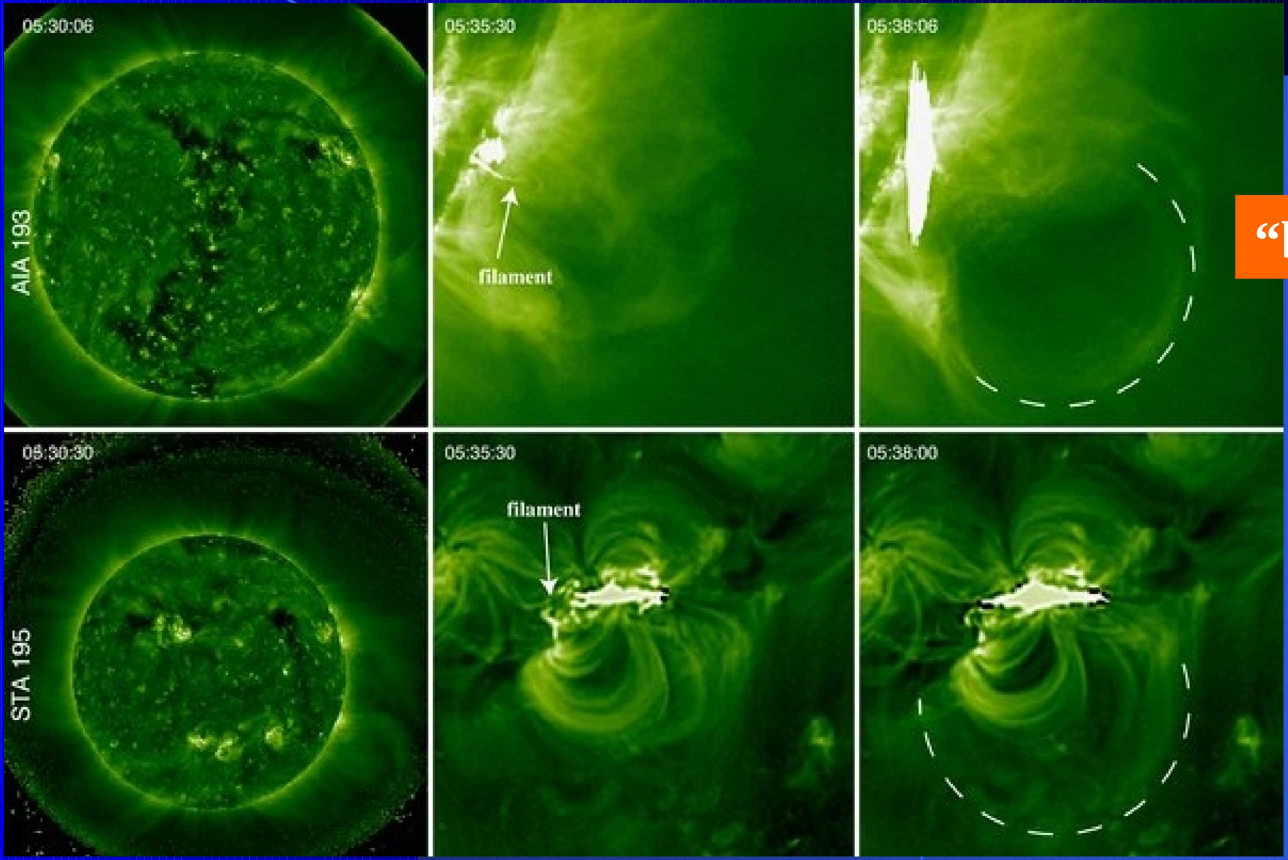
How do we observe CMEs?

- WL observations → photospheric light scattered by free coronal electrons ~ n
- Coronagraphs SOHO/LASCO C1-C2, STEREO/COR1,2 → 1.1-30 Rs
- Heliospheric imagers HI1,HI2 (on STEREO)→ 15-330 Rs
- Future (SoloHI; WISPR; A. Vourlidas lecture)
- Future (ASPIICS; as low as 1.05 Rs K. Tsinganos lecture)



How do we observe CMEs?

- EUV/SXR line emissions ~ n^2 * F(T)
- Disk imagers SOHO/EIT, EUVI/STEREO, SDO/AIA → (0-1.4 Rs)
- Disk (Hinode/EIS) & coronal (SOHO/UVCS) spectrometers



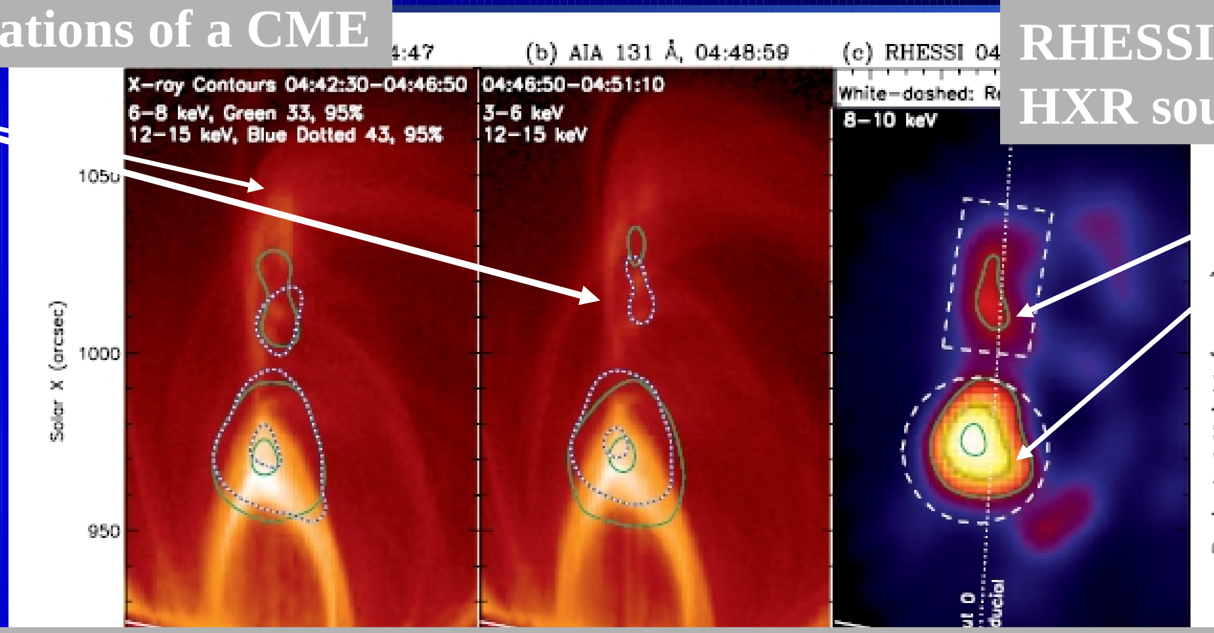
"baby"-CME

How do we observe CMEs?

- Non-thermal emissions in the HXRs and radio domains (RHESSI, NRH, WIND/WAVES, ARTEMIS) → sites of particle acceleration & shocks (0.0-215) Rs (M. Mathioudakis & E. Kontar's lectures)

EUV observations of a CME

RHESSI observations HXR sources



Liu et al. 2013

No routine observations of CME magnetic fields in the corona!

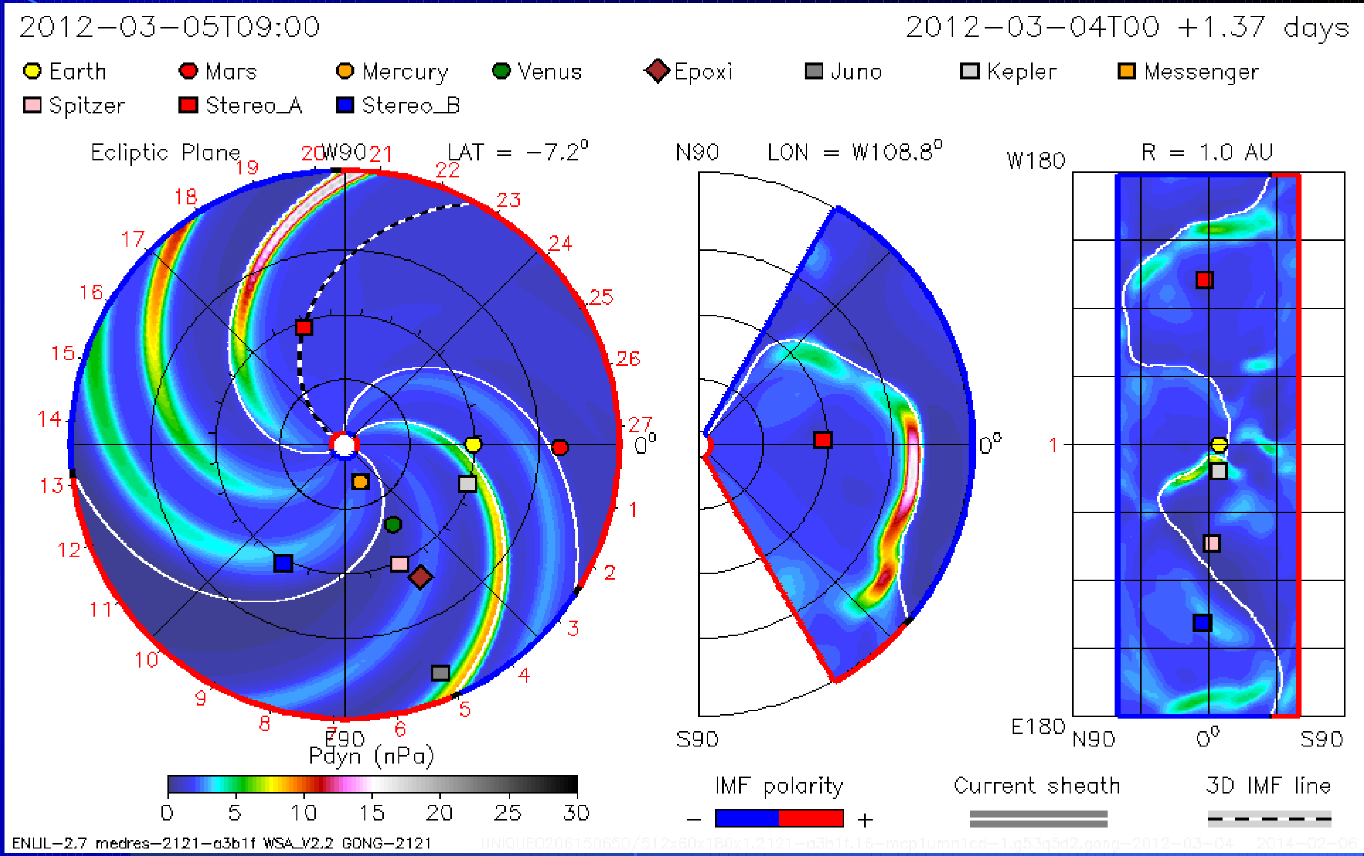
But check Tun & Vourlidas 2013 for one such determination @ ~ 1.2 Rs

CMEs are a major driver of Space Weather

Earth-dicteded & south Bz → geomagnetic storms (Bothmer & Daglis 2007)
fast CMEs → shocks → gradual SEP events (Reames 1990)

NASA/CCMC simulation of a CME propagation in the heliosphere

squares → spacecraft
circles → planets



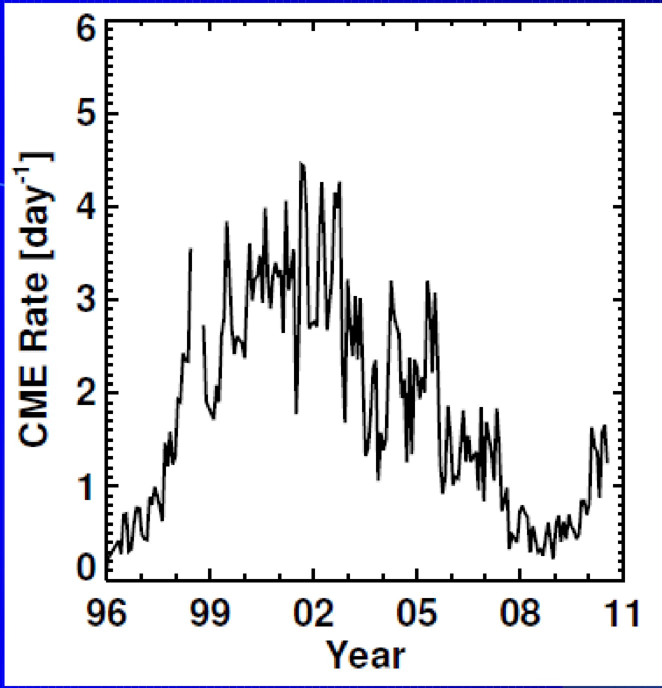
Major boosts of CME observations in the last 20 years

***SOHO** 1996-now* almost continuous observations of CMEs on disk and in the corona for two solar cycles → **unprecedented statistics & basic understanding**

***STEREO** 2006-now* multi-viewpoint observations of CMEs from the Sun to 1 AU → **reveal the 3D structure & evolution of CMEs; connect imaging w/ in-situ**

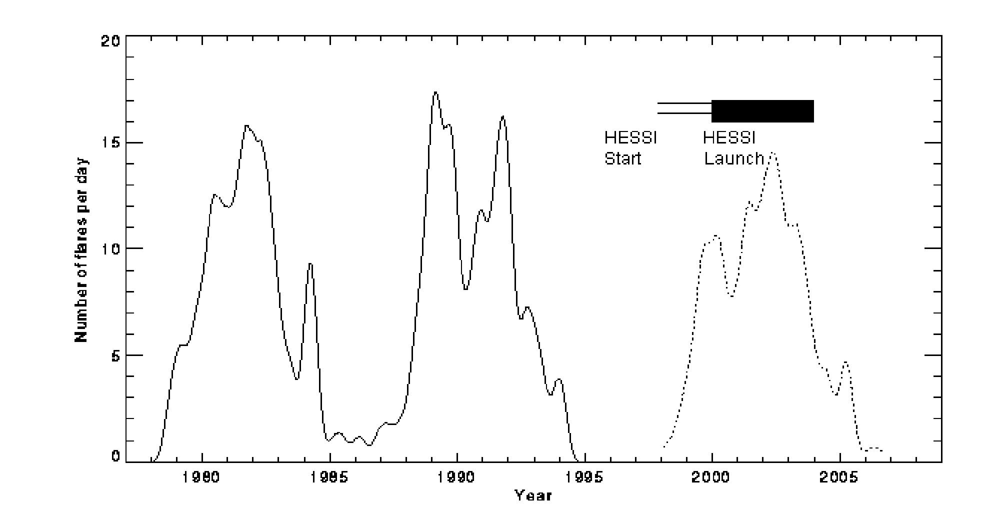
***SDO** 2008-now* high cadence, multi-temperature observations of CME onsets & FD photospheric b-field
→ **pre-eruptive configurations; tracking of ultra-fast events**

CME occurrence rates



# of CMEs roughly follows the solar cycle 0.5 CMEs/day → 4 CMEs/day

Gopalswamy et al. 2010

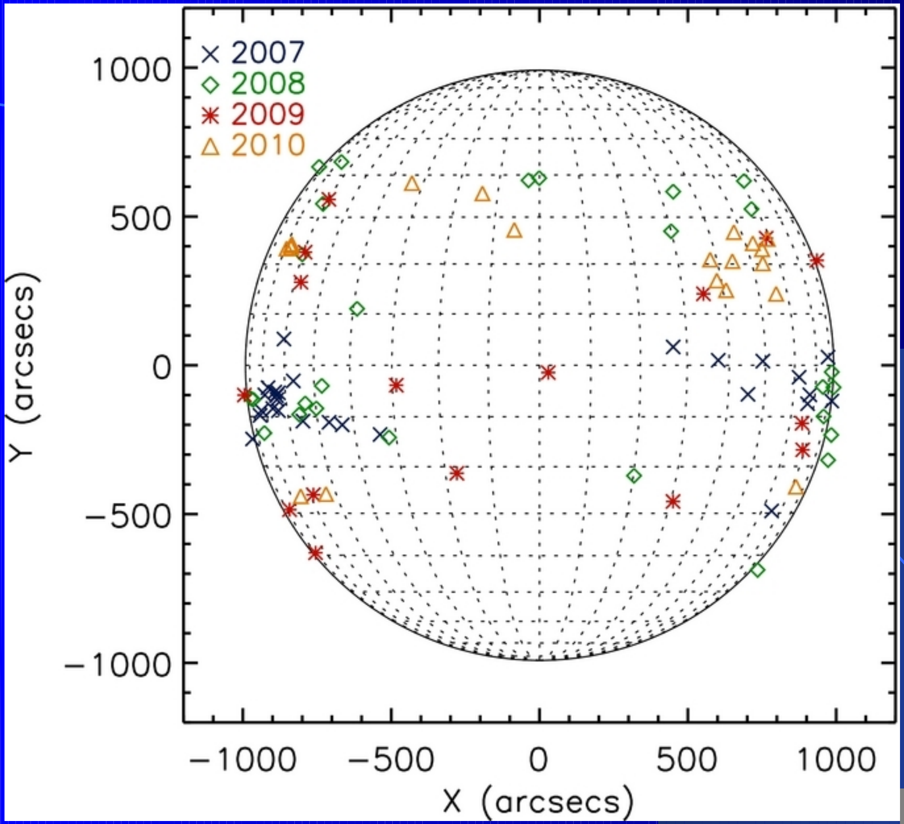


More flares than CMEs →

more “difficult” to make a CME than a flare?

RHESSI web-site

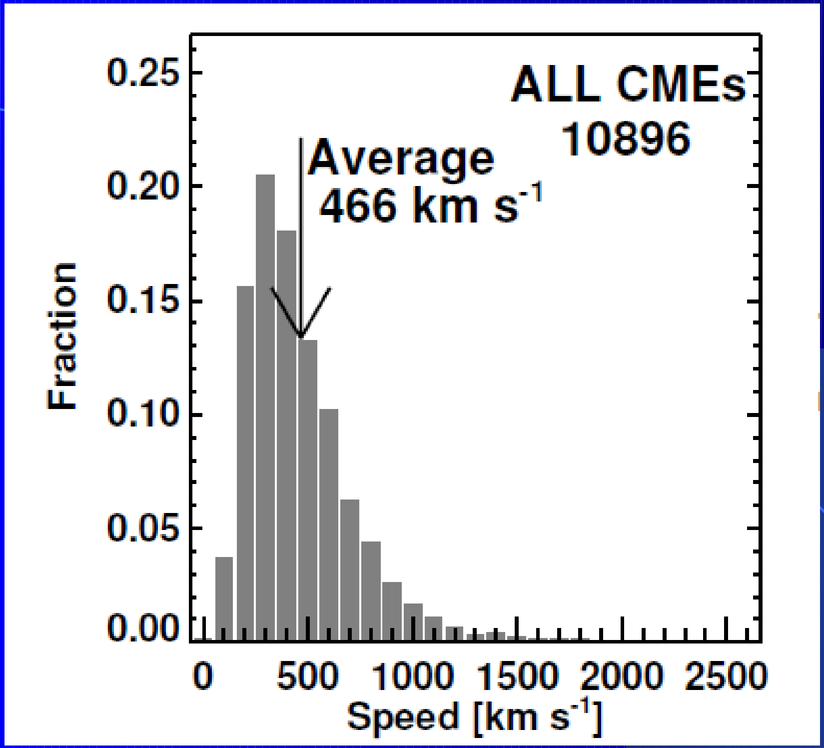
Source regions of CMEs

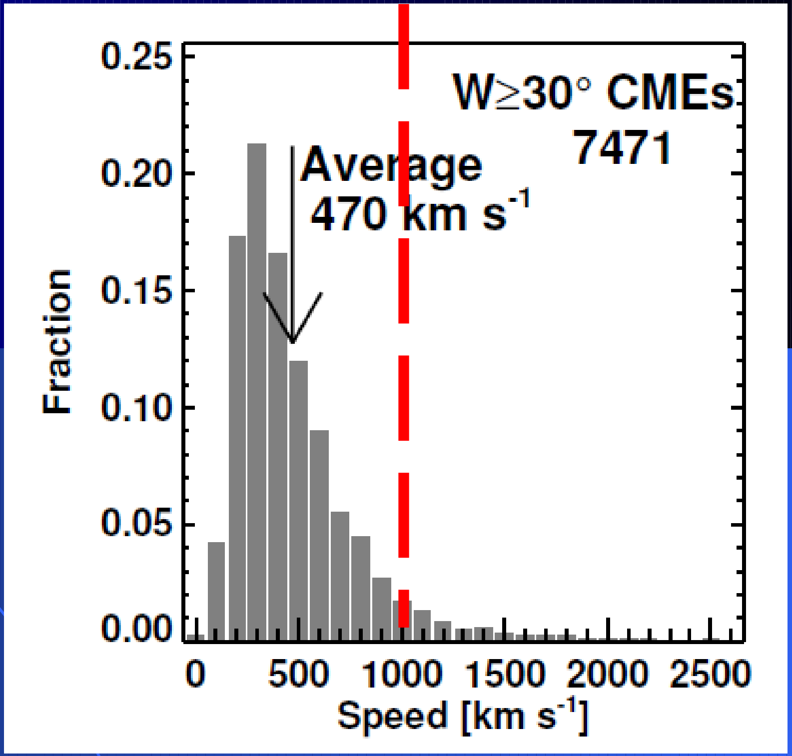


Solar source regions of 49 CMEs from STEREO observations Bein et al. 2012

CMEs can originate from :
Quiet Sun regions → no flare
Active regions → possibly a flare

CME crucial stats I

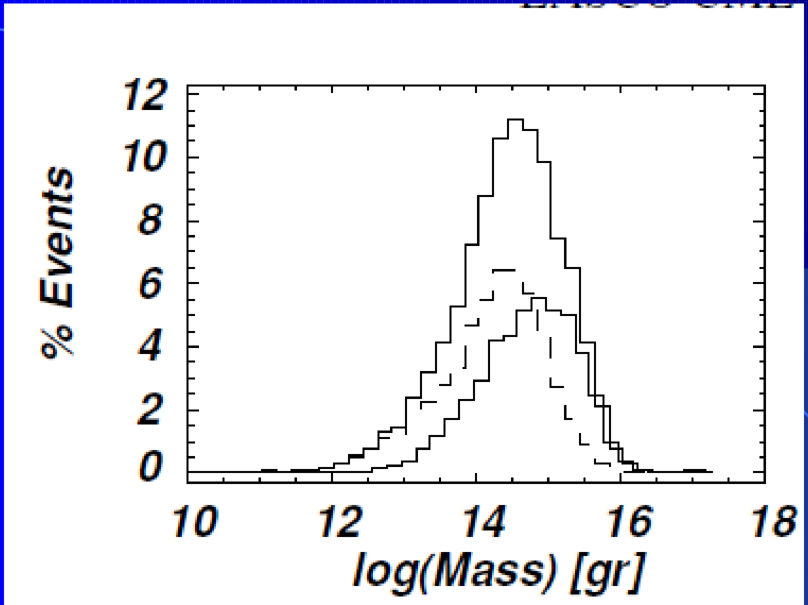


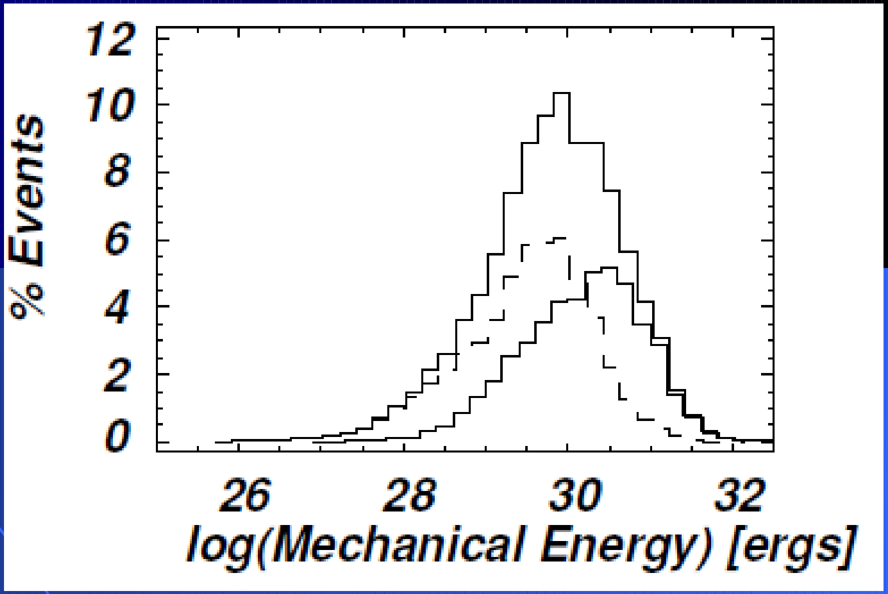


Gopalswamy et al. 2010

Speeds in the range ~ 300—2000 km/s
Few events w/ > 1000 km/s → shocks

CME crucial stats II





Vourlidas et al. 2010

Masses ~ 10^15 gr : 1/10^15 of solar mass lost by CMEs per year
Mechanical energy ~ 10^31 ergs --- compare w/ flare energy
(e.g., M. Mathioudakis & E. Kontar lectures)

CME crucial stats III

CME-filament eruptions associations: tight

60% of CMEs associated w/ filament eruptions (Subramanian & Dere 2001)
72% of filament eruptions associated w/ CMEs (Gopalswamy et al. 2003)

CME-flare associations: the bigger the flare the more possible there is an associated CME

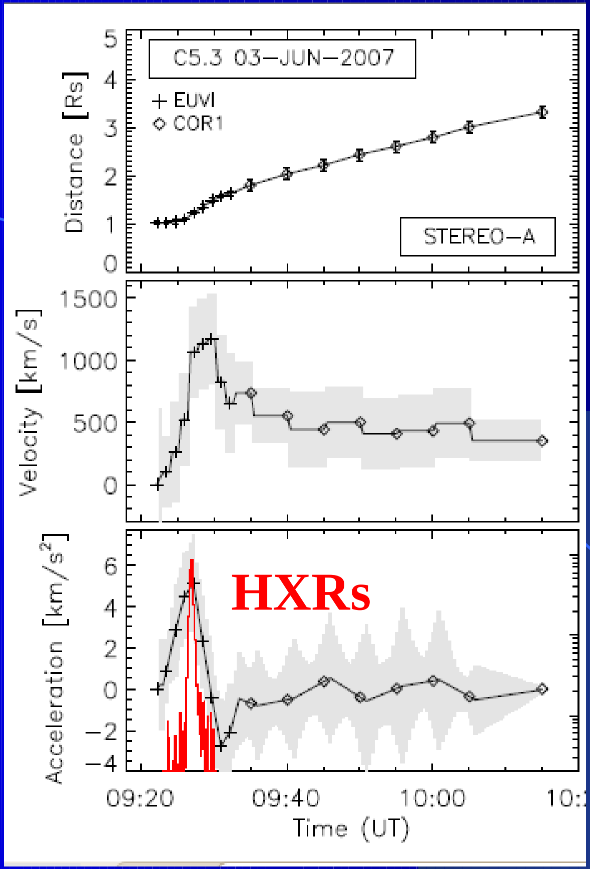
55 % of M-class flares have associated CMEs
100% of X-class flares have associated CMEs (Harisson 1995;Andrews 2003)

Temporal relationships between flares & CMEs

Height

Velocity

acceleration



Temmer et al. 2010

Zhang et al. 2001
Bein et al. 2012
close synchronization between HXRs (flare energy release) & CME acceleration

CMEs and flares are different facets of a common process (more later on the school)

What is the source of the CME energy ?

Table 1. Energy Requirements for a Moderately Large CME

Parameter	Value
Kinetic energy (CME, prominence, and shock)	10^{32} ergs
Heating and radiation	10^{32} ergs
Work done against gravity	10^{31} ergs
Volume involved	10^{30} cm^3
Energy density	100 ergs cm^{-3}

Forbes 2000

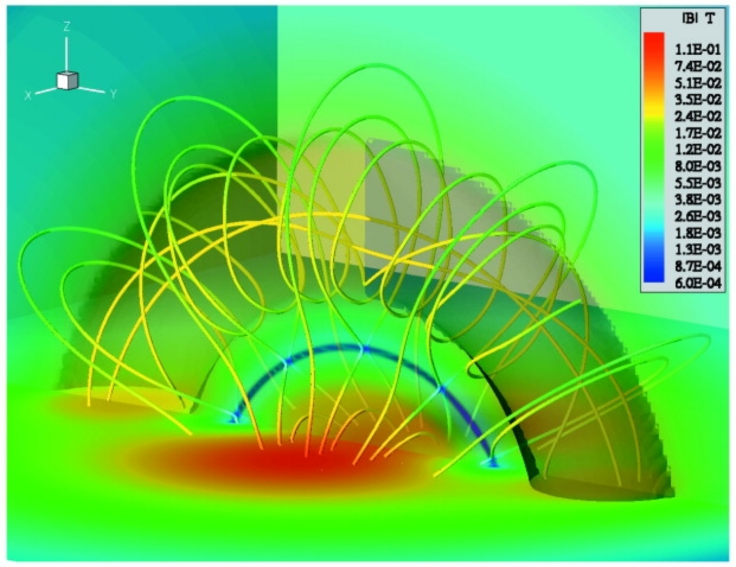
Table 2. Estimates of Coronal Energy Sources

Form of Energy	Observed Average Values	Energy Density ergs cm^{-3}
Kinetic ($(m_p n V^2)/2$)	$n = 10^9$ cm^{-3}, $V = 1$ km s^{-1}	10^{-5}
Thermal (nkT)	$T = 10^6$ K	0.1
Gravitational ($m_p n g h$)	$h = 10^5$ km	0.5
Magnetic ($B^2/8\pi$)	$B = 100$ G	400

CME energy comes from coronal magnetic energy

Important definitions

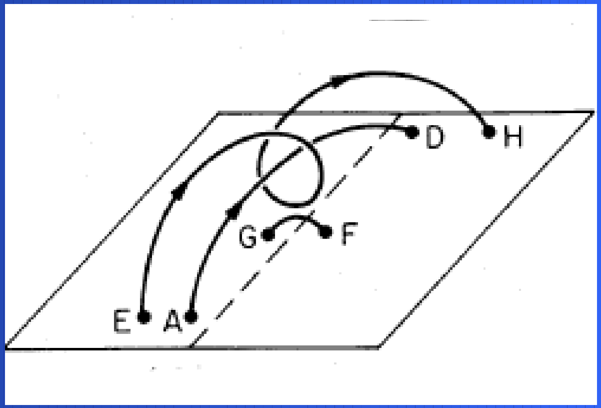
Magnetic flux rope =
a coherent toroidal magnetic structure with field-lines twisted around its major axis (e.g., Chen 1989)
check out for compexity in b-field in L. Vlahos's lecture



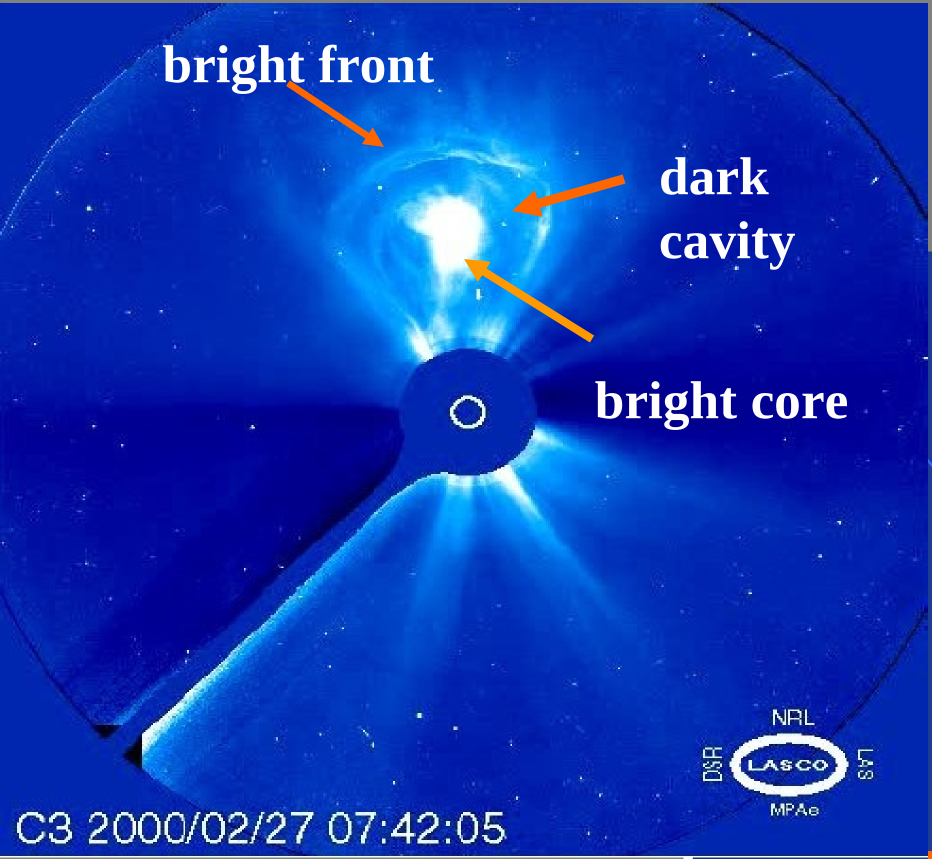
Manchester et al. 2004

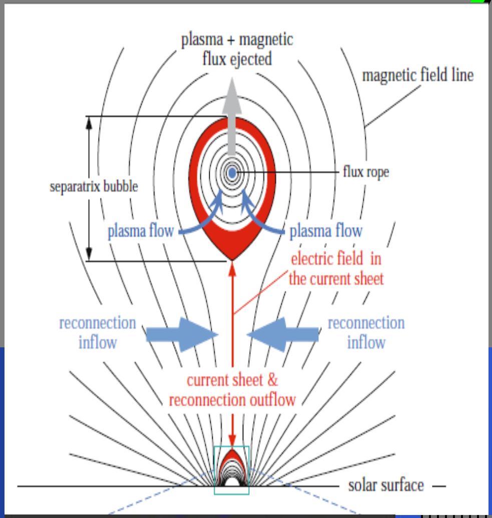
Magnetic Arcade =
an array of magnetic loops following magnetic neutral lines (=*a flux rope that has not fully emerged into the solar atmosphere*)

shearing an arcade → flux rope w/ hot plasma
van Ballegooijen & Martens 1989
proccess recovered by MHD models

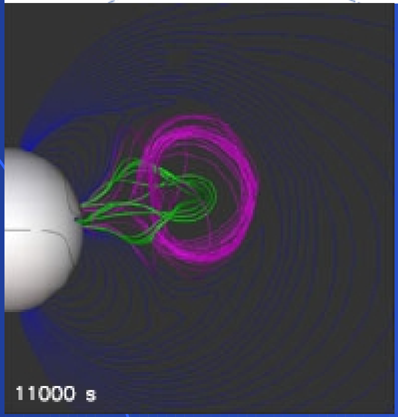


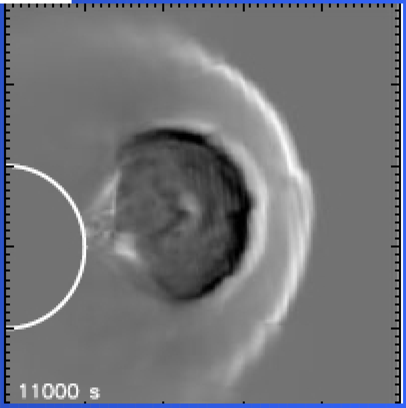
CME morphology from coronagraphs: 3-part structure (limb events)





Example of flux rope model (Lin 2004)



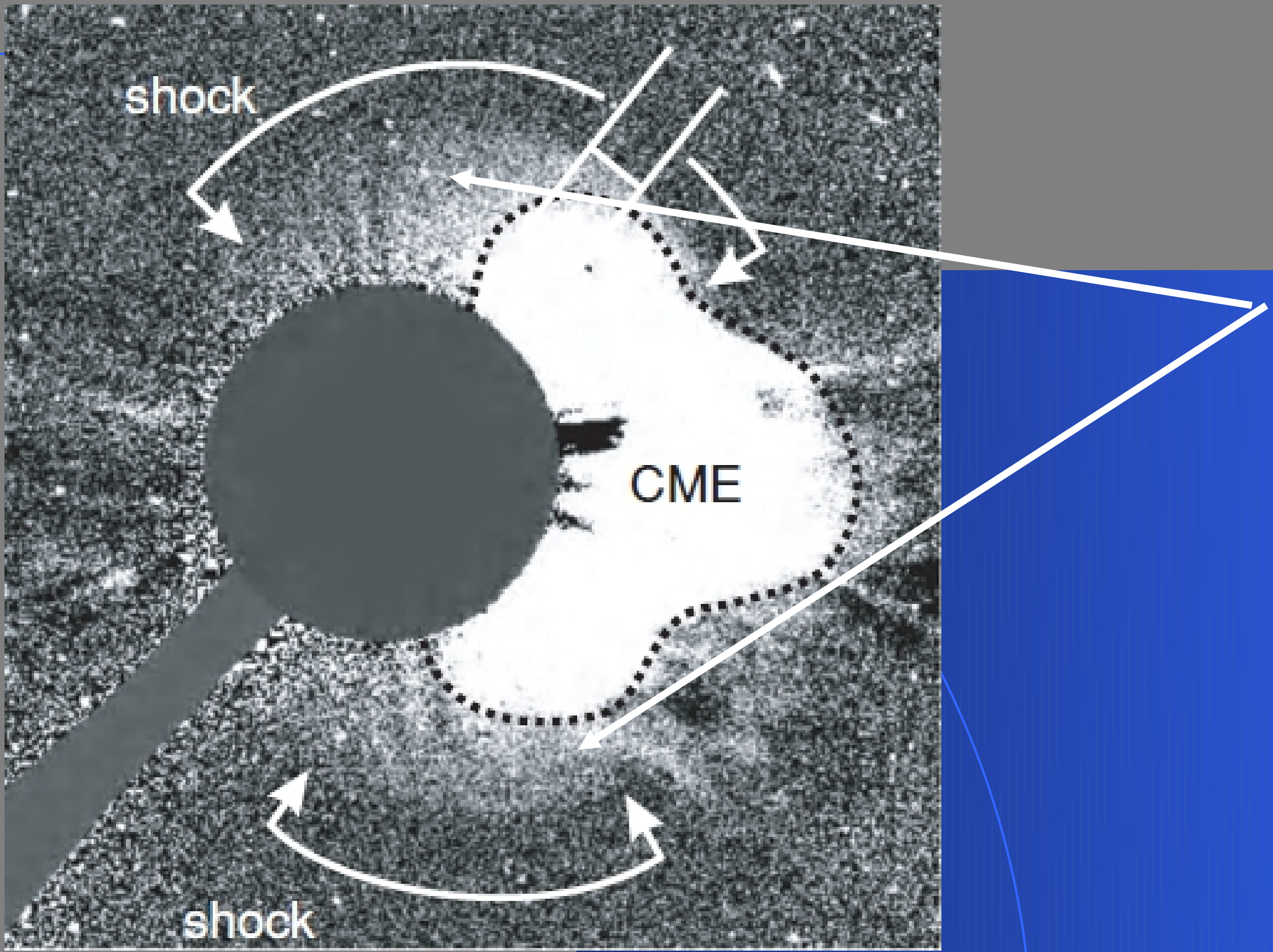


b-field from CME MHD simulation

synthetic WL image Vourlidas et al. 2013

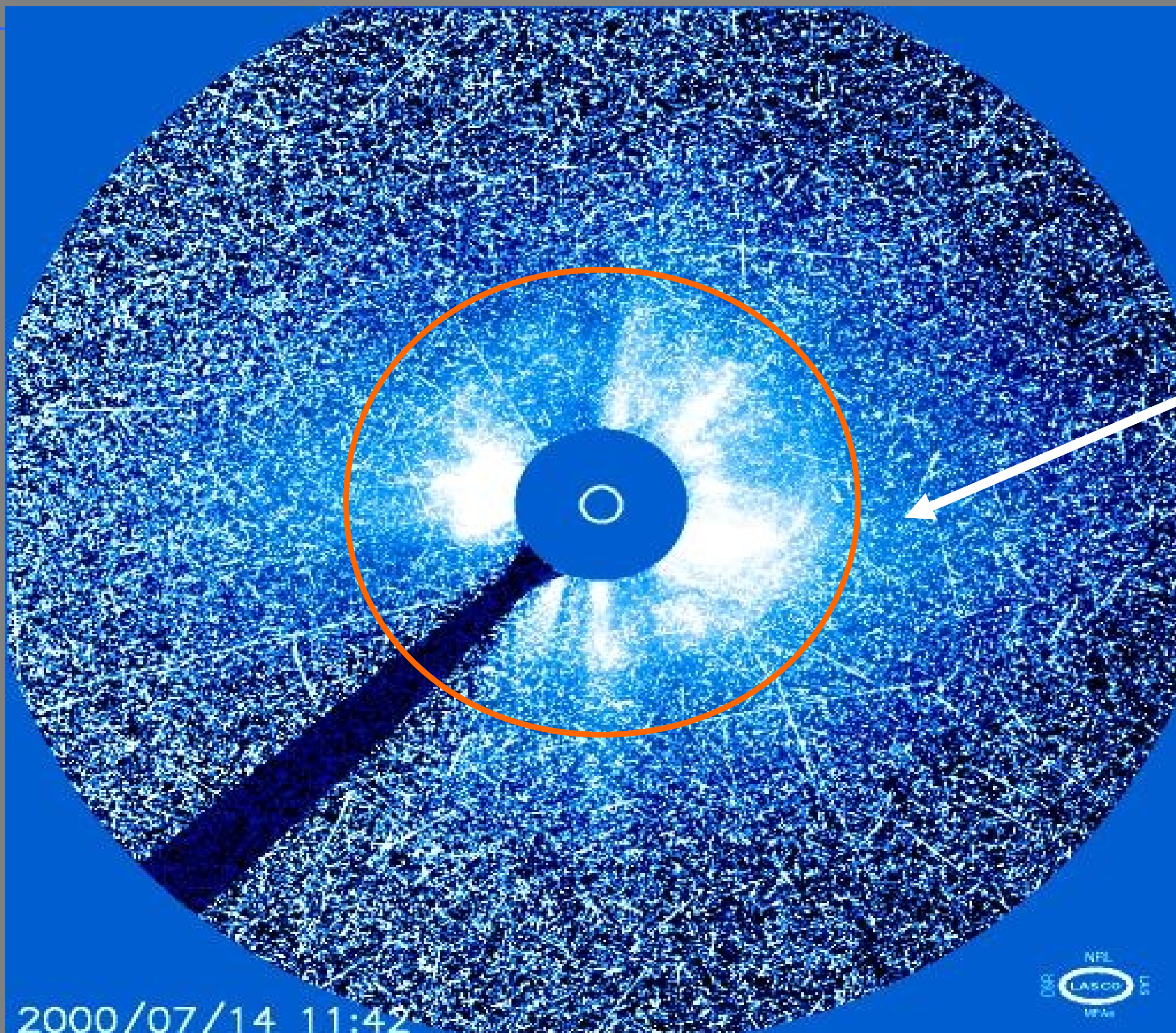
3-part morphology suggests the existence of a flux rope

CME morphology from coronagraphs: 5-part (+shock)



Ontiveros & Vourlidas 2009

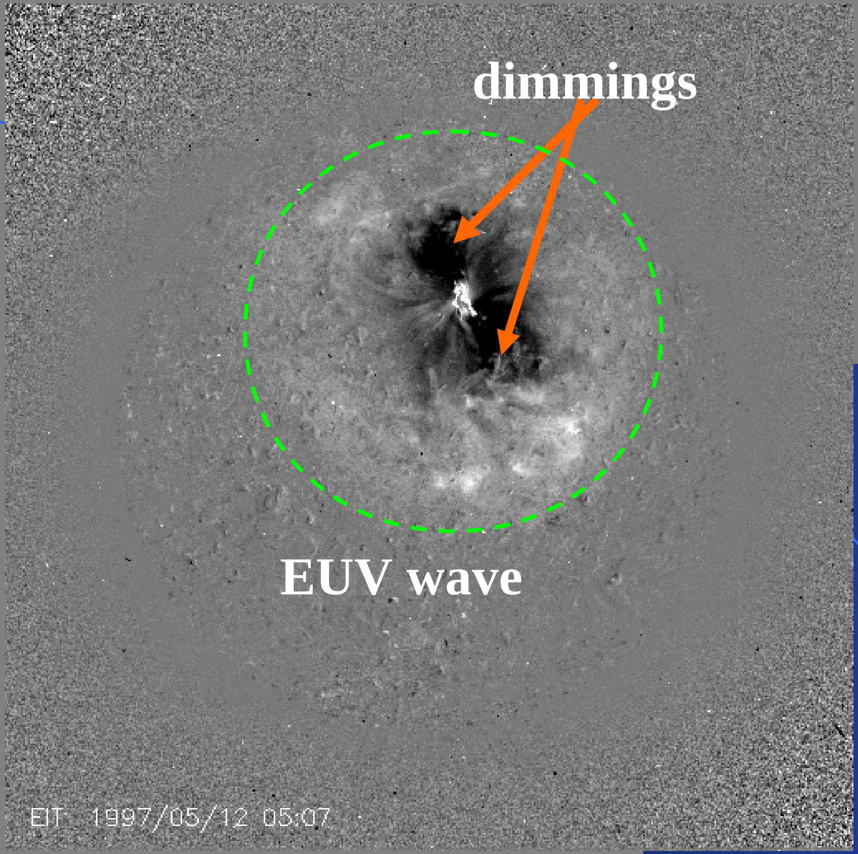
CME morphology from coronagraphs: halo CMEs

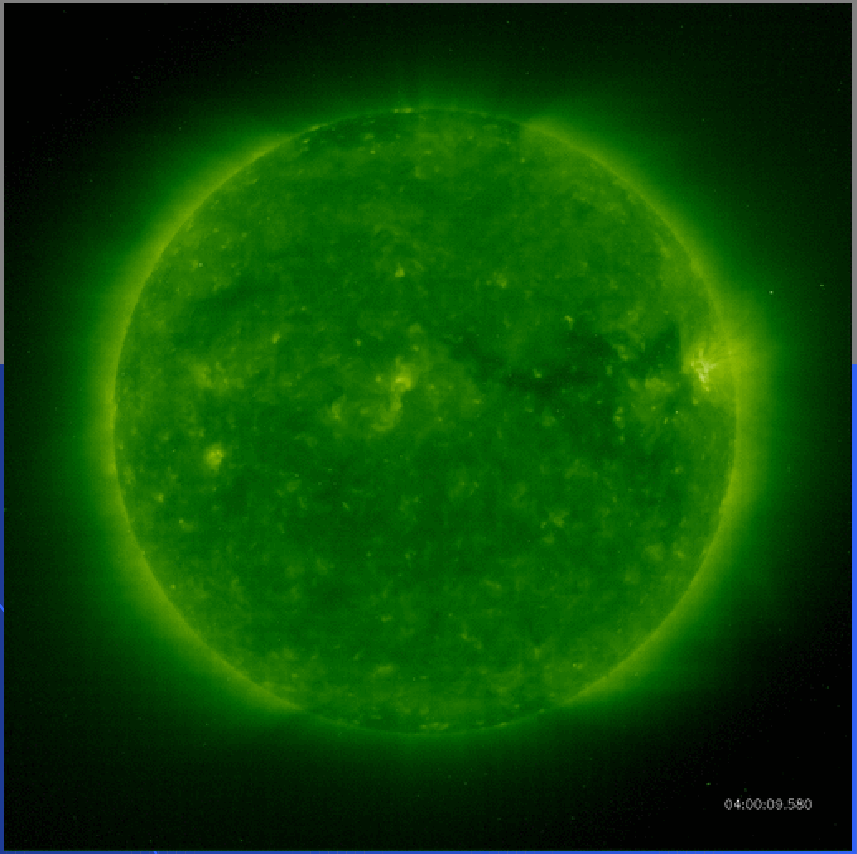


halo

"snow"→ relativ protons reaching L1

CME onset on disk





Observations of dimmings/EUV waves close to disk center suggest an Earth-directed CME (e.g., Thompson et al. 2001) but this in not always the case (more later on during the school)

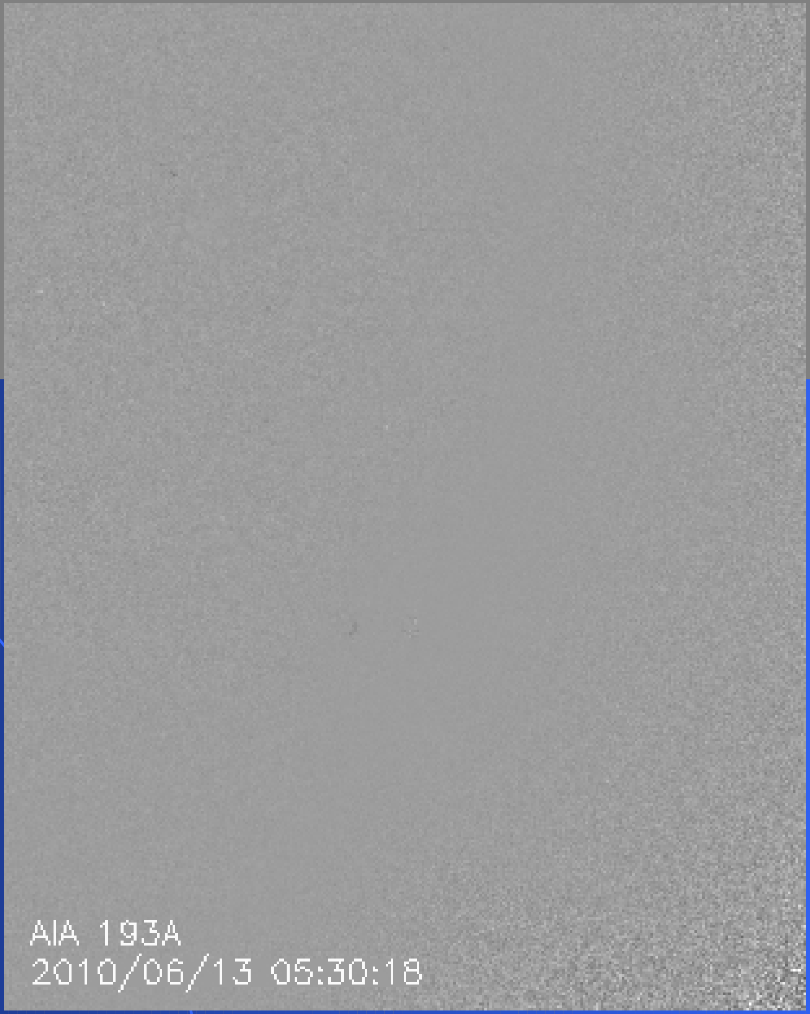
CME onset at the limb

Time, distance

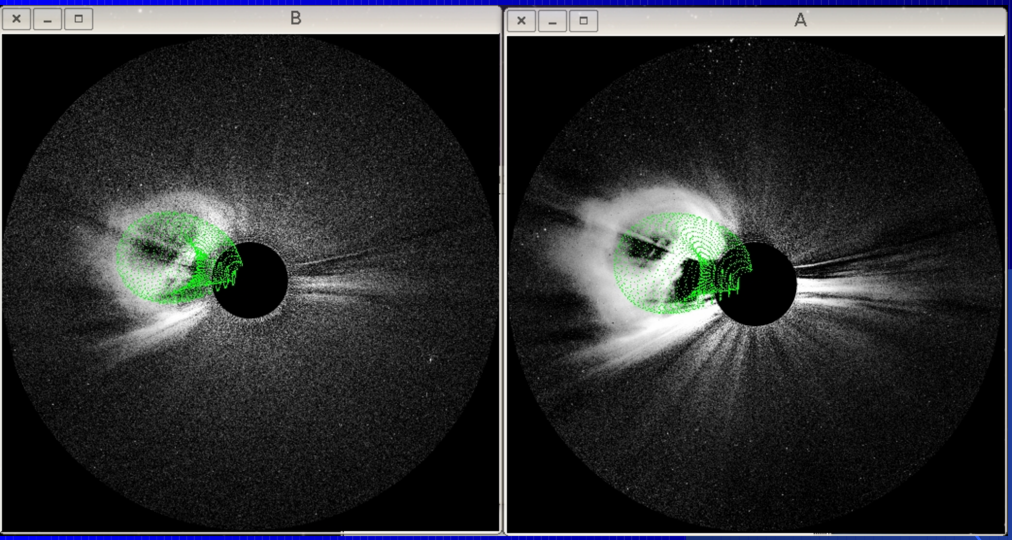
Expanding loops → cavity

Dimming

EUV Wave



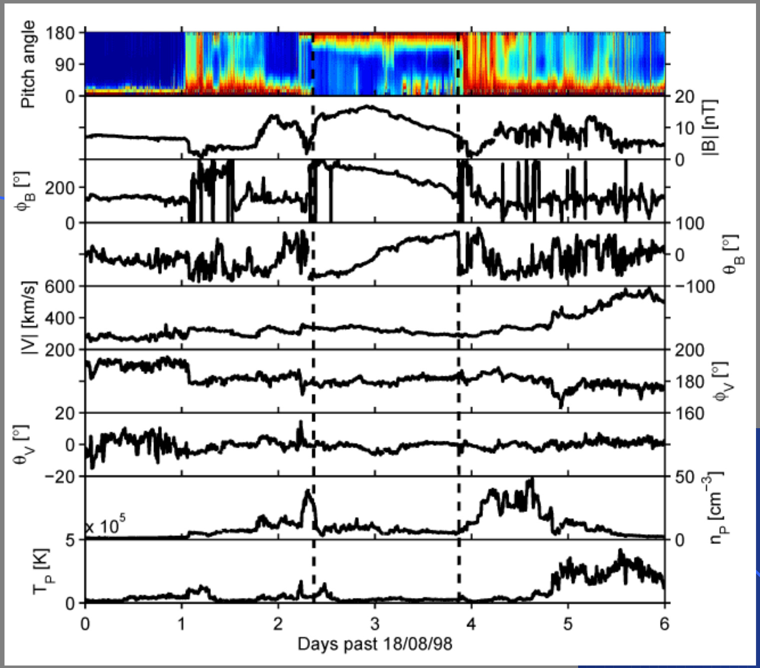
How common is the FR topology in CMEs observed with coronagraphs ?

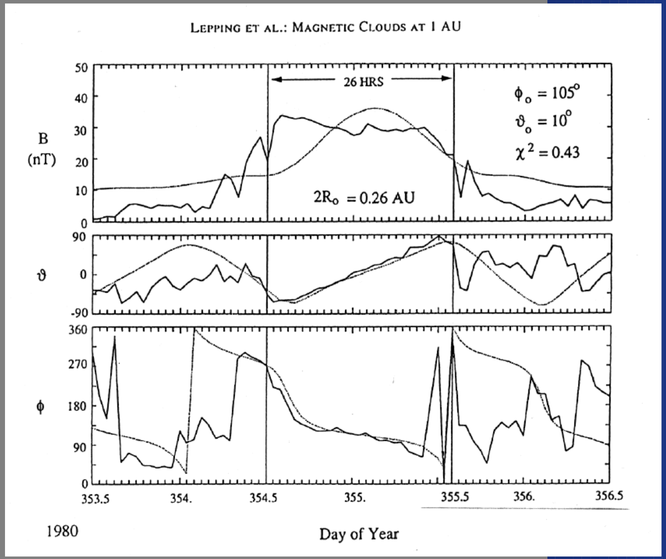


Flux-rope geometrical model simultaneously fits STEREO CME observations from multiple viewpoints *Thernisien et al. 2009*

at least 40% of > 10000 CMEs observed by LASCO In coronagraph FoV are FRs *Vourlidas et al. 2013*

In-situ observations of CMEs





In-situ observations of CMEs show that are are often ~ 30% (*Richardson & Cane 2010*) magnetic clouds (MCs)

: high B

: smooth b-field rotation

: low- β plasma

The magnetic field in MCs is consistent with flux rope models *Lepping et al. 1991*

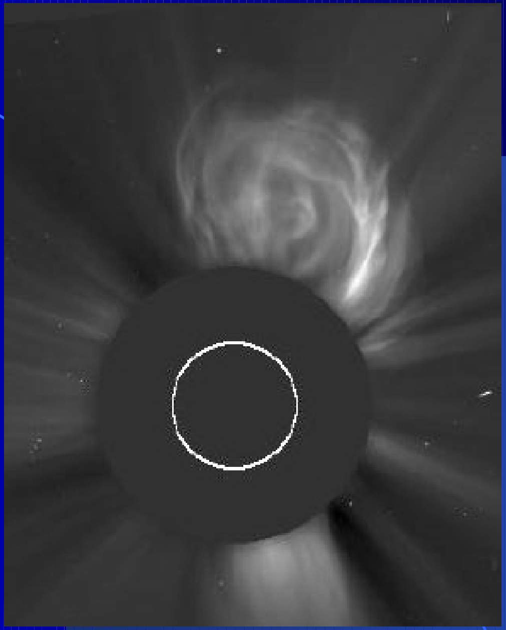
Magnetic flux ropes (FRs) : a major element of Sun-Earth Connections

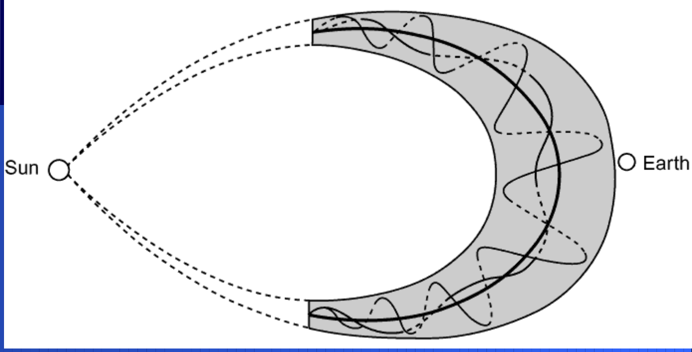
Sun ????

coronagraphs

1 AU

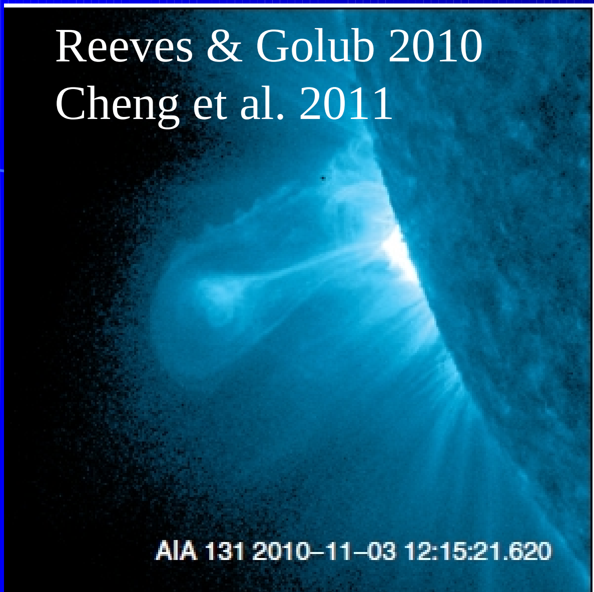
Do FRs pre-exist or do they form on the fly?
How are they formed?
Almost ALL CME models involve FRs at some stage

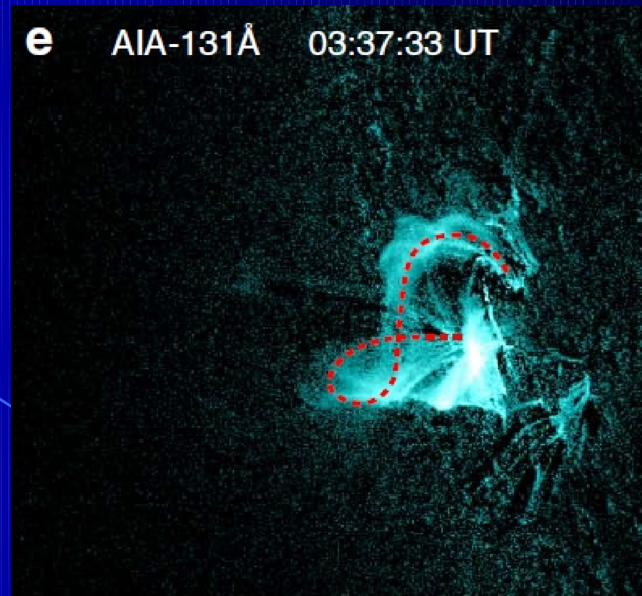




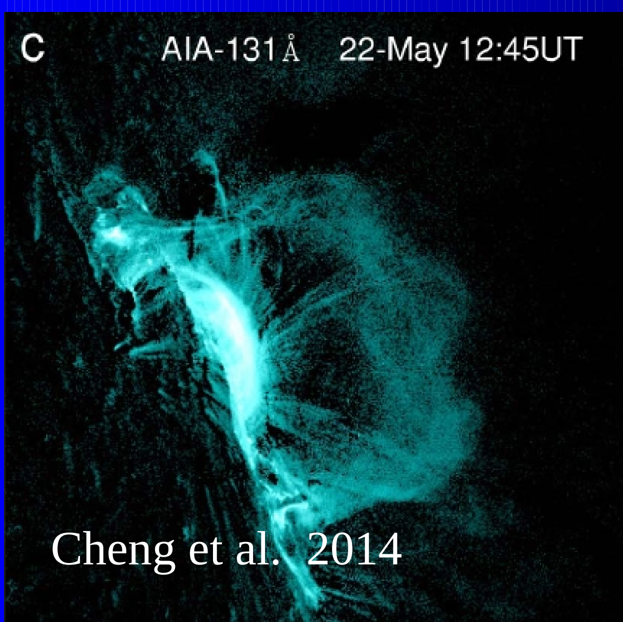
magnetic clouds

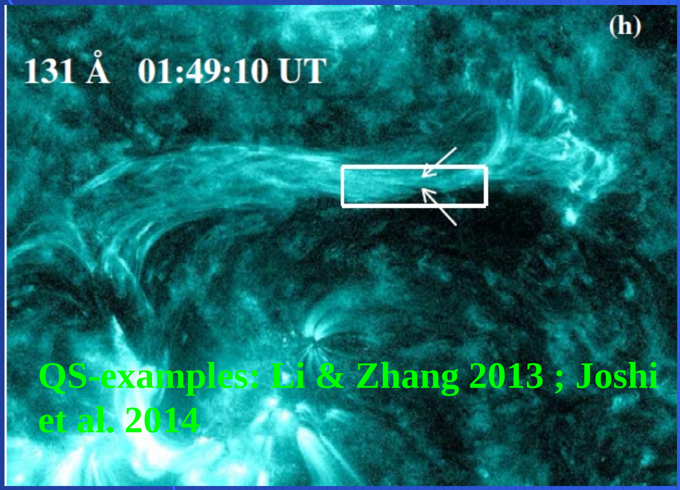
Hot FRs observed around CME onsets



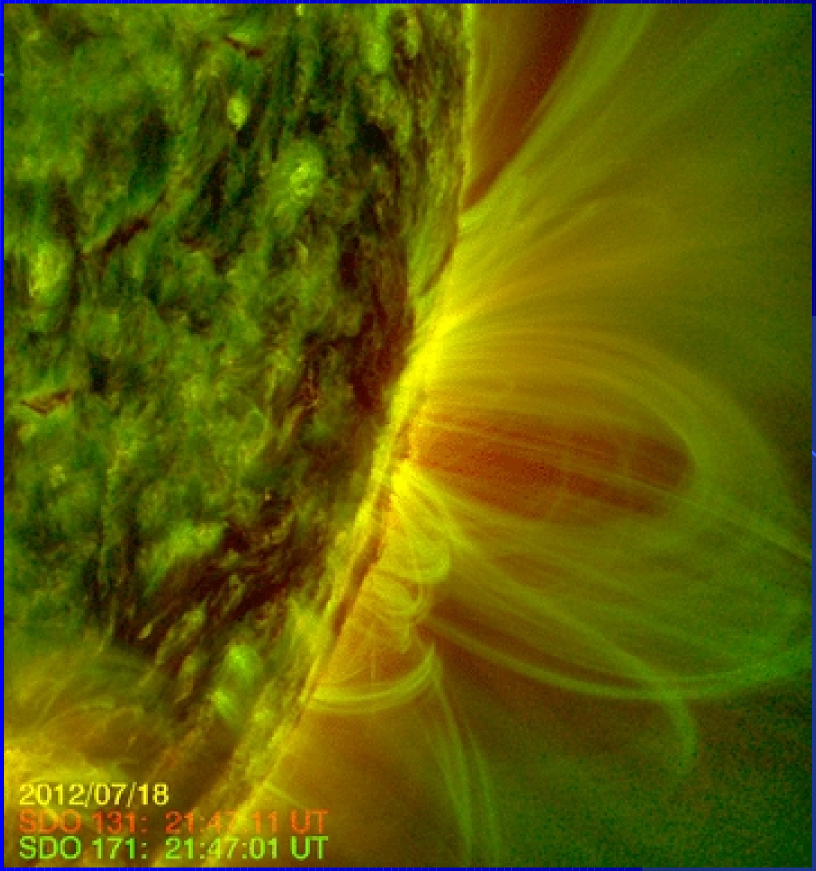


Zhang et al. 2012

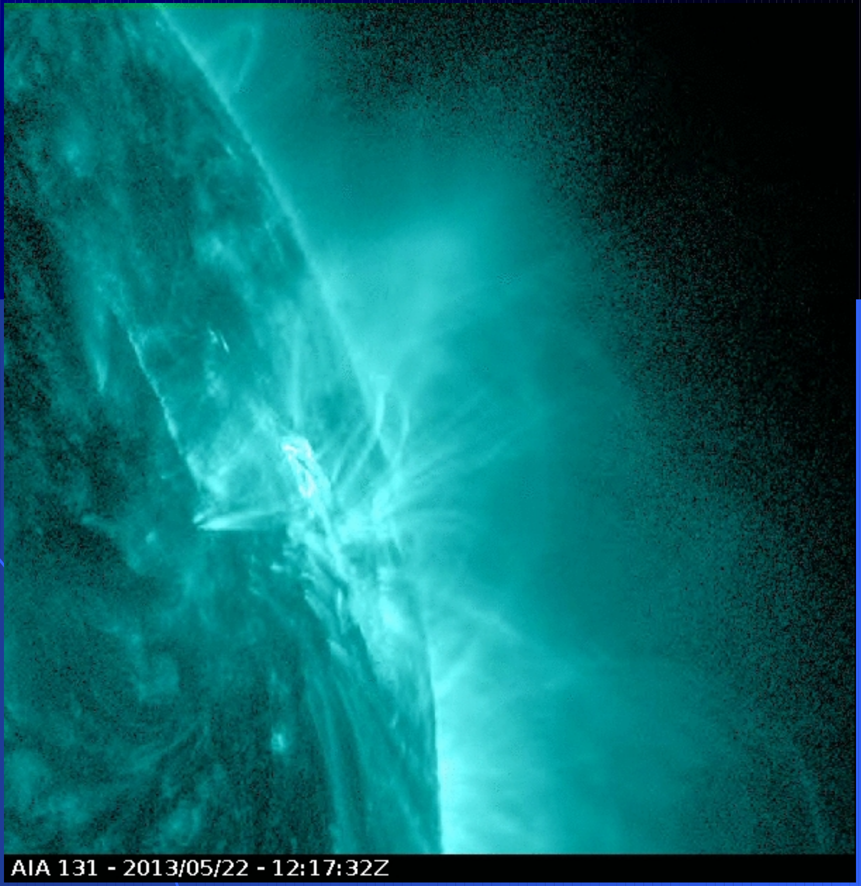




Sample movies of hot FRs

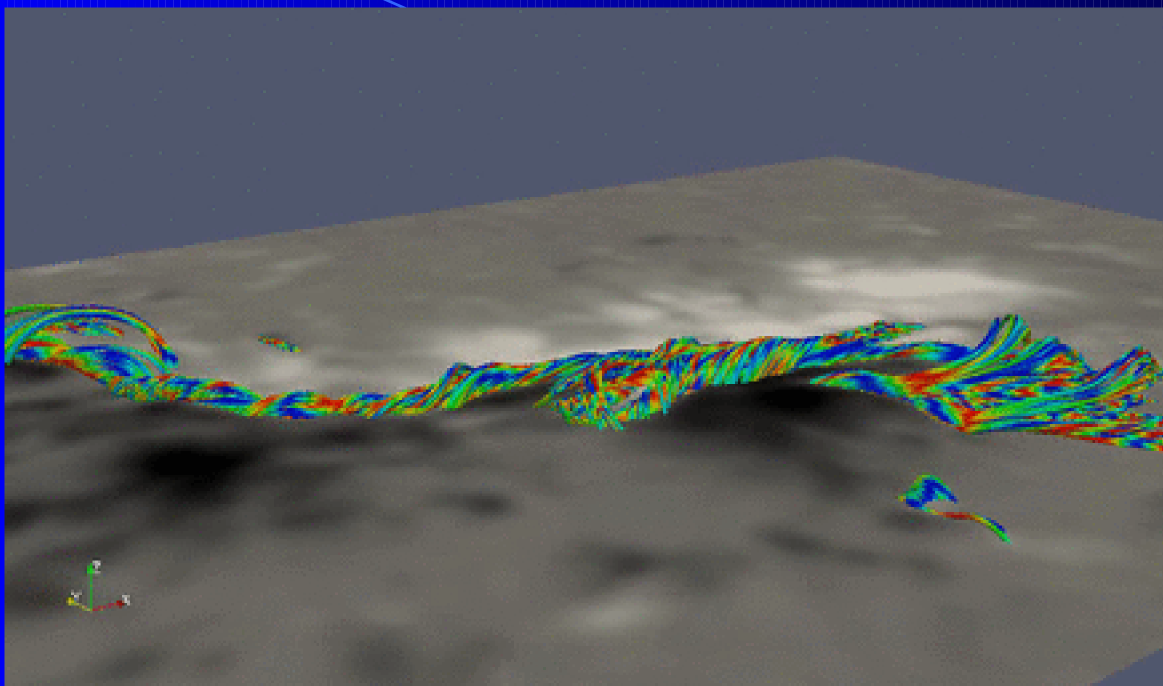


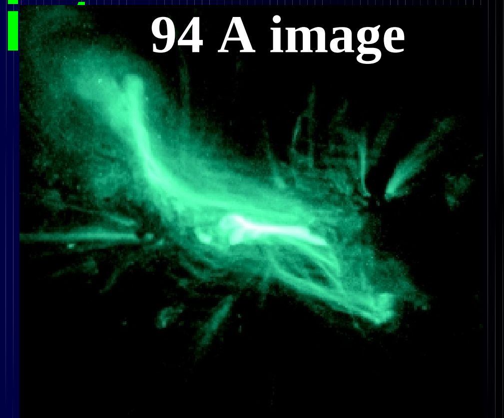
Edge-on view
Patsourakos et al. 2013

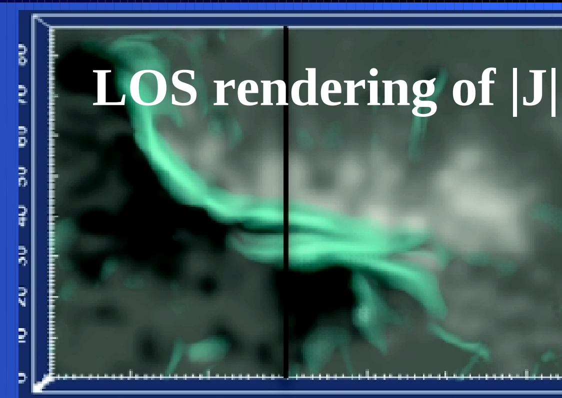


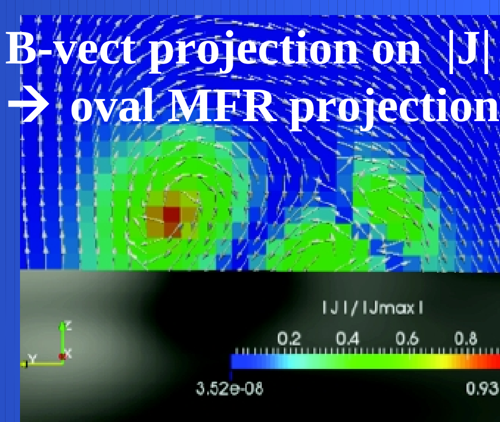
face-on view
Cheng et al. 2014

Magnetic field extrapolations in the corona show FRs









Chintzoglou et al. 2014

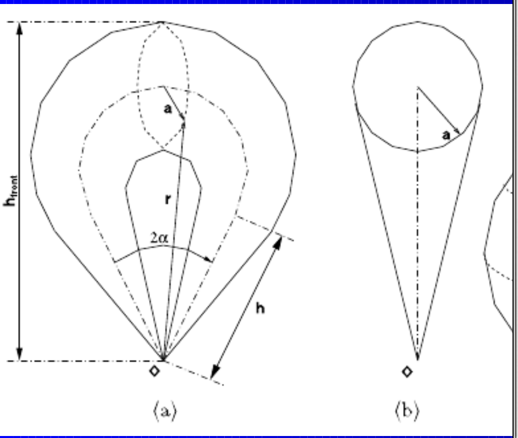
Propagation of CMEs: The STEREO era

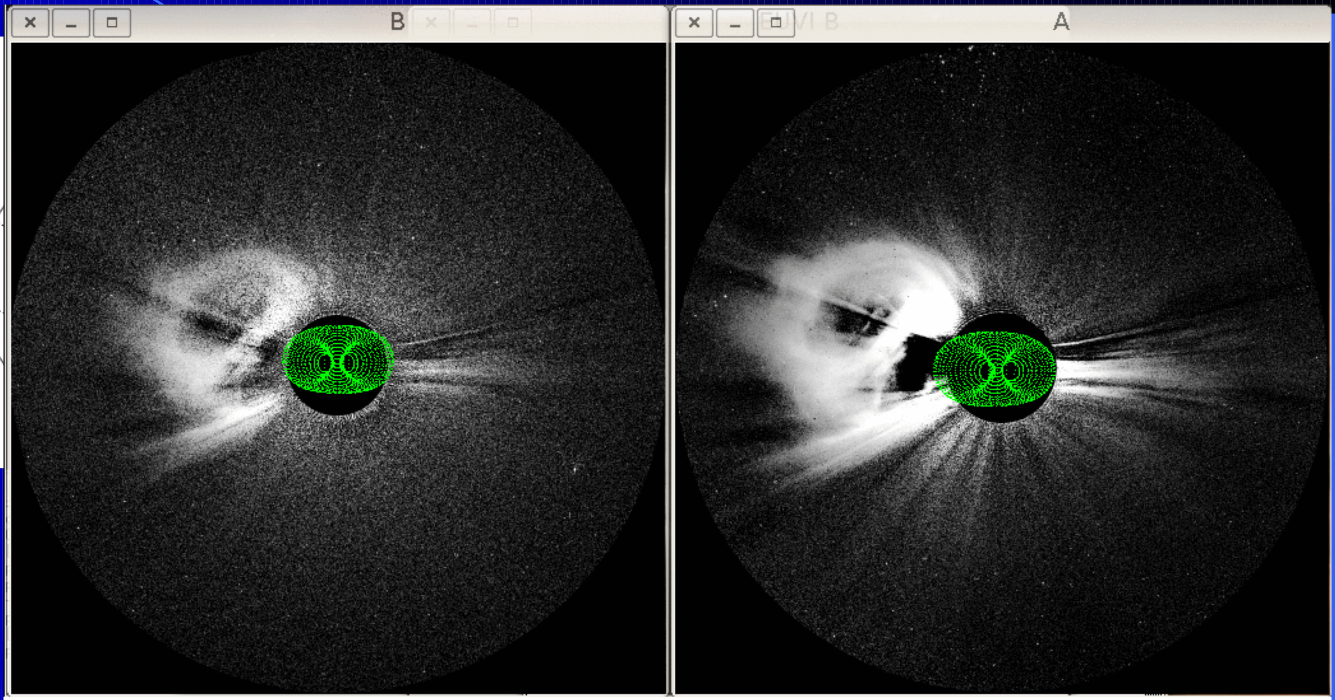
Track & characterize CMEs all way from the Sun to Earth & connect w/ in-situ

w/out proper multi-viewpoint analysis
one could get issues (e.g. confuse rotation w/ expansion)
e.g., Nieves-Chinchilla **2013**

Tools to analyze CMEs with STEREO I

Forward geometrical modeling: Thernisien et al. 2009
fits the CME envelope & gives CME ***height,size,direction,tilt***
rather robust to changes in most of its parameters (few degrees) not internal stucture of CME

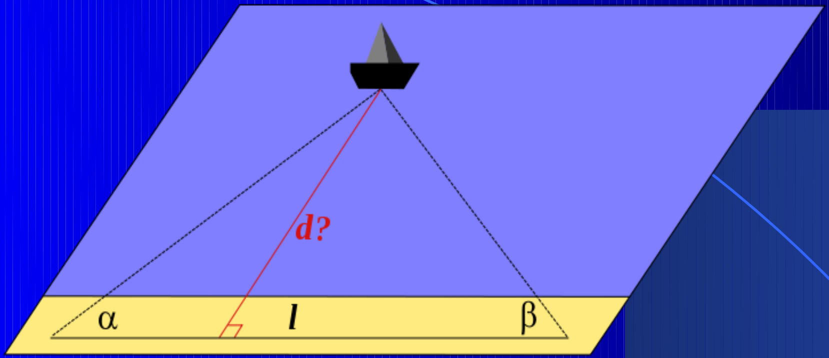


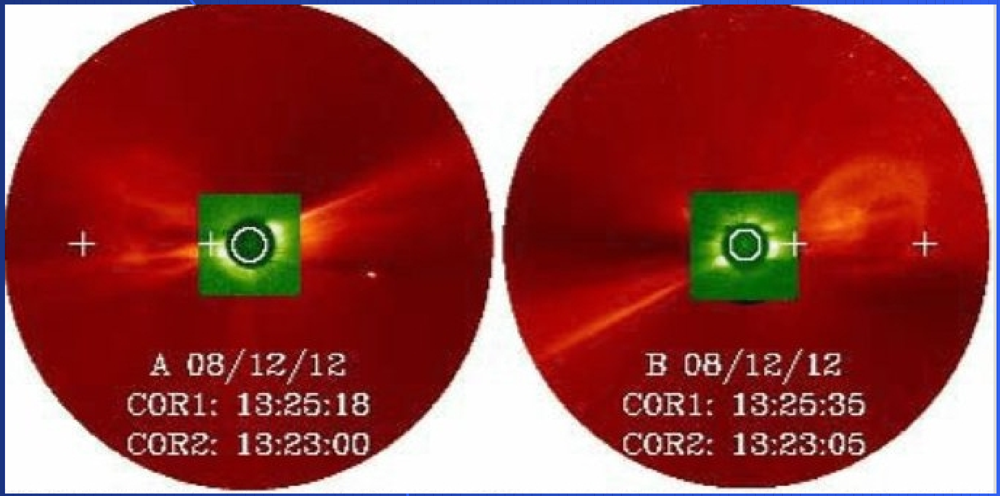


http://secchi.nrl.navy.mil/wiki/pmwiki.php?n=Main.DataProcessingAndAnalysis

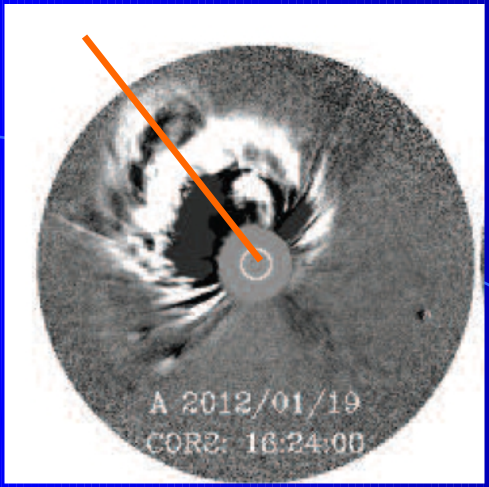
Tools to analyze CMEs with STEREO

Triagulation: **Inhester 2006; Aschwanden 2001**
pick up the same feature in a STEREO pair → "true" height

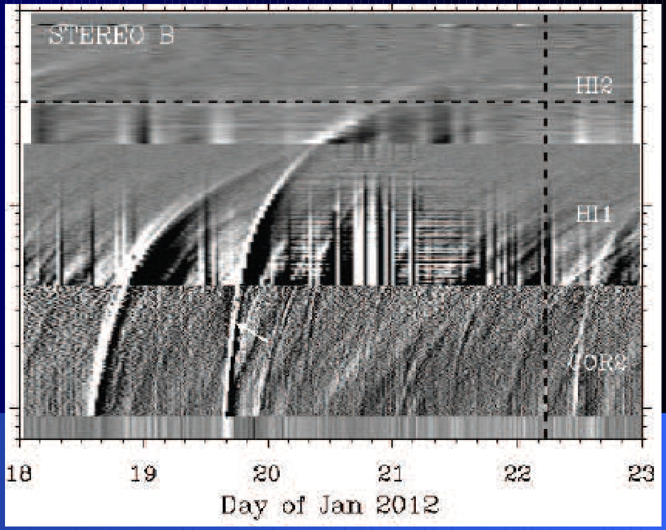




Tools to analyze CMEs with STEREO



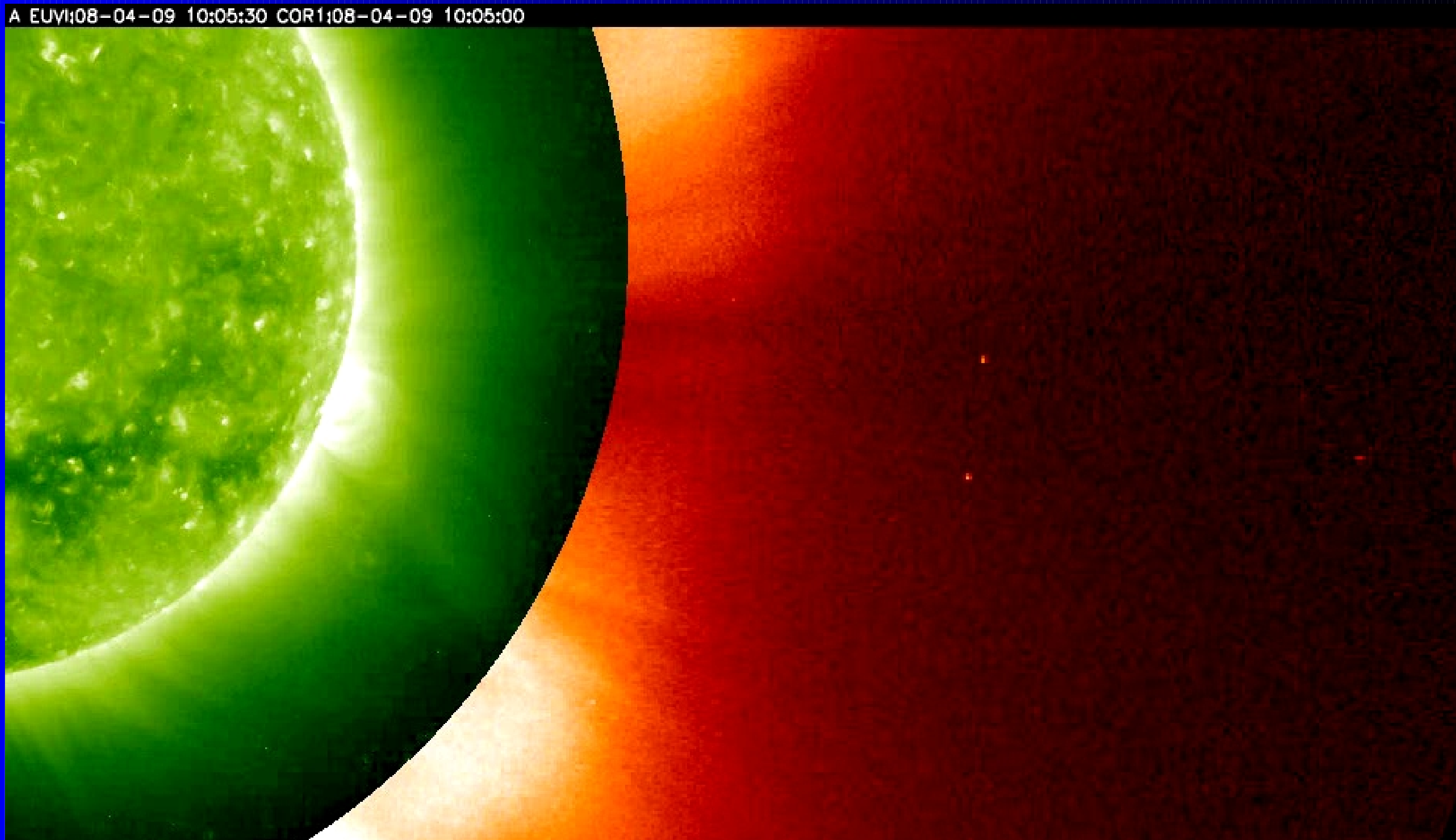
stacking of slit images



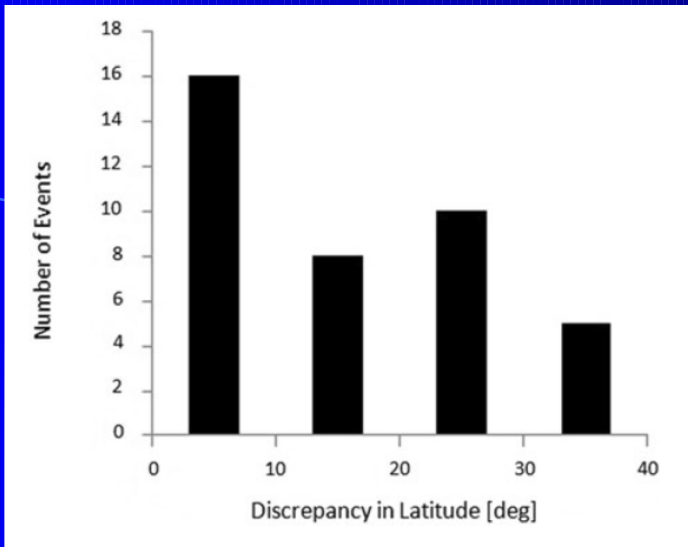
J-maps: make assumption regarding the
CME shape & sometimes its speed (constant) &
propagation direction (constant)
→ CME speed & direction
(Sheeley et al. 1999; Lugaz et al. 2010; Davies et al. 2012)

fast (one plot to analyze) but need to be first to be sure on what feature we select

CME deflections I

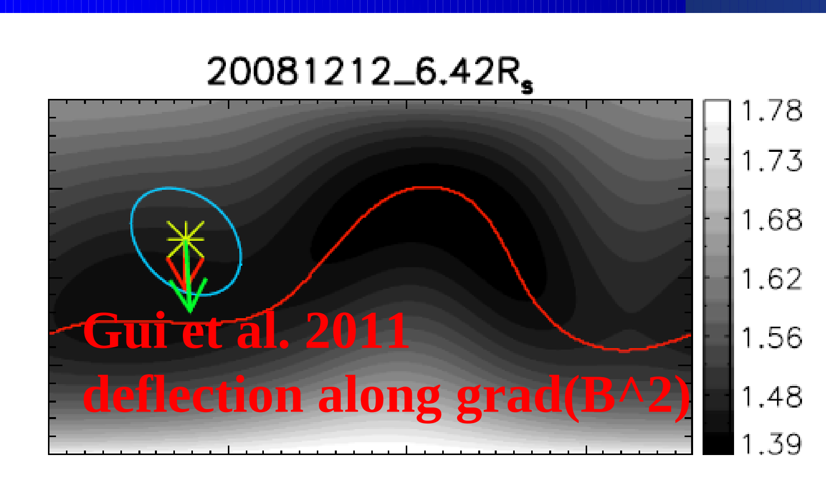


CME deflections II



CME lat offset from SR

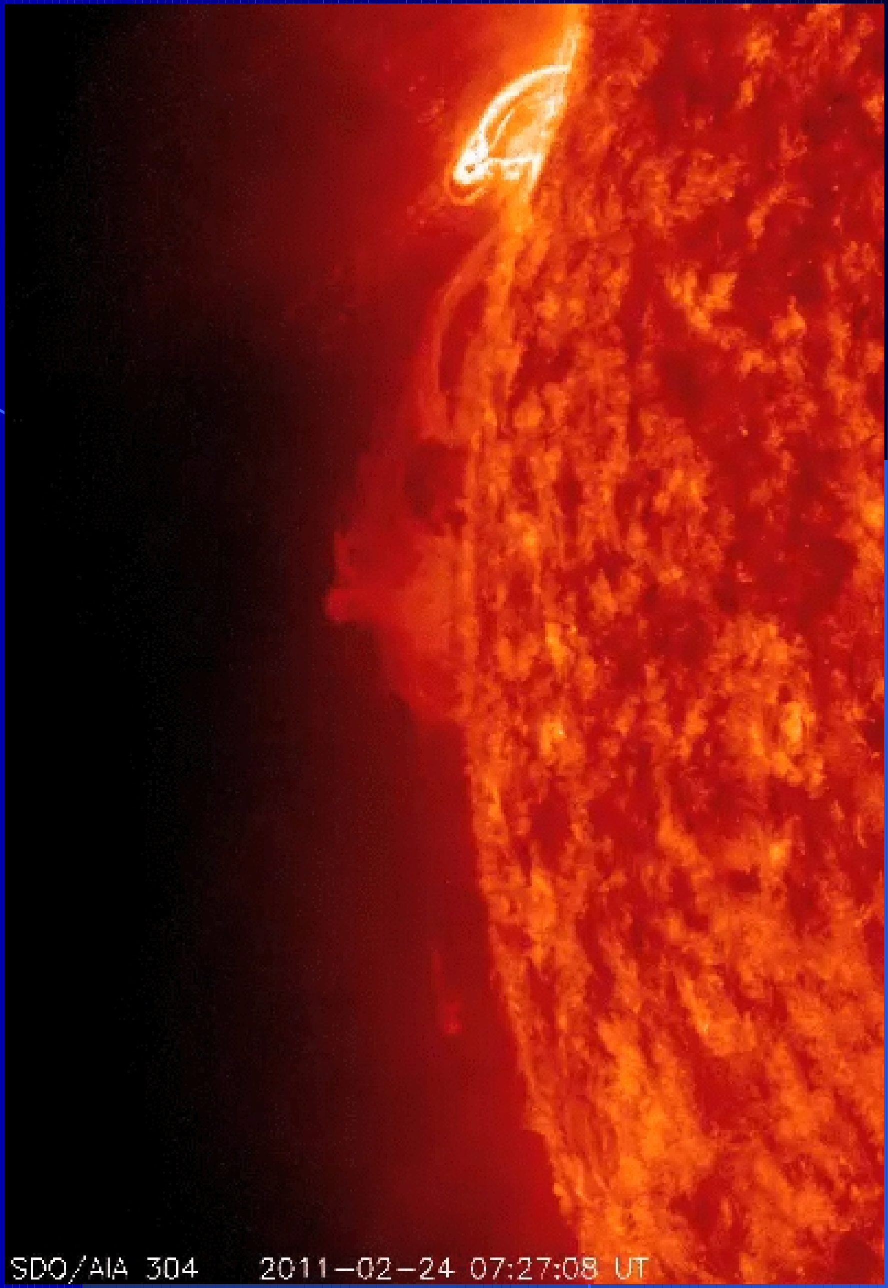
Bosman et al. 2012
39 CME in 2010
deflections~ [5,60] deg
from SR to 20 Rs
coverging towards equator



Gui et al. 2011
deflection along grad(B^2)

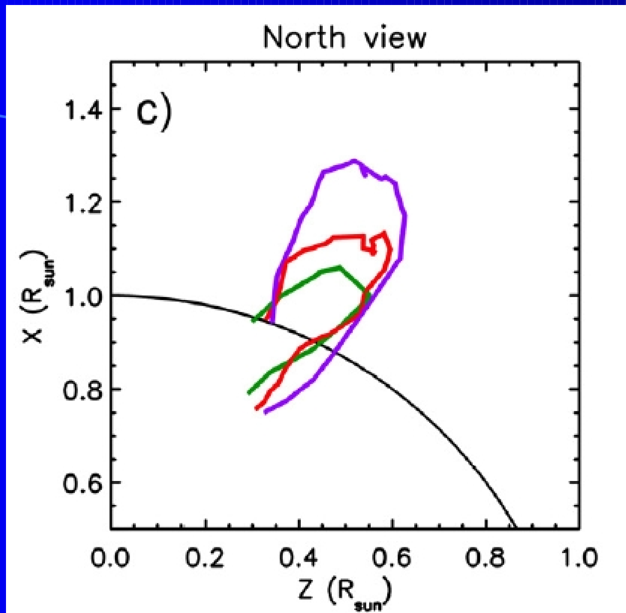
<u>deflections → magnetic field gradients</u>
(strong → weak)
Cremades, Bothmer, Tripathi 2006
Gopalswamy et al. 2010
Panasenco et al. 2011

CME rotate close to Sun 1.1-5 Rs

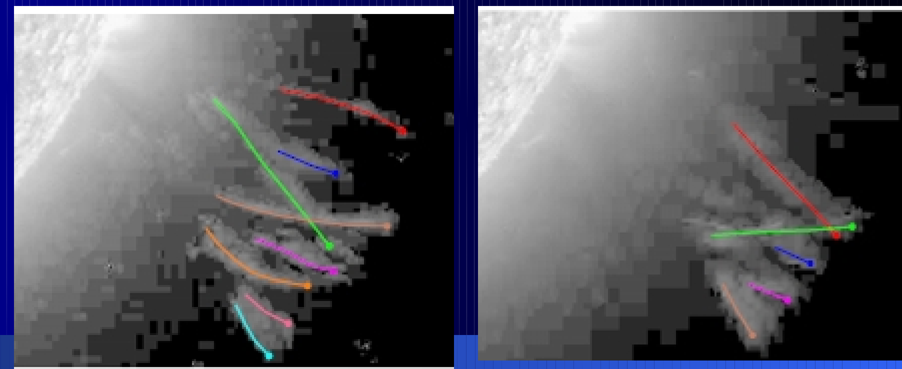


CME rotate close to Sun 1.1-5 Rs

3D reconstructions of prominence rotations

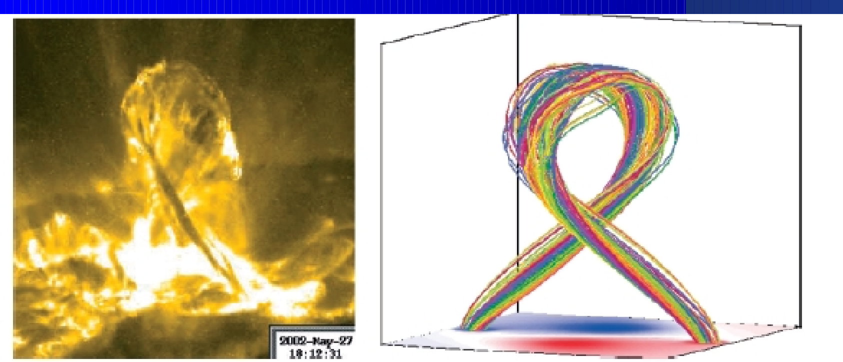


Bemporad, Mierla, Tripathi 2011



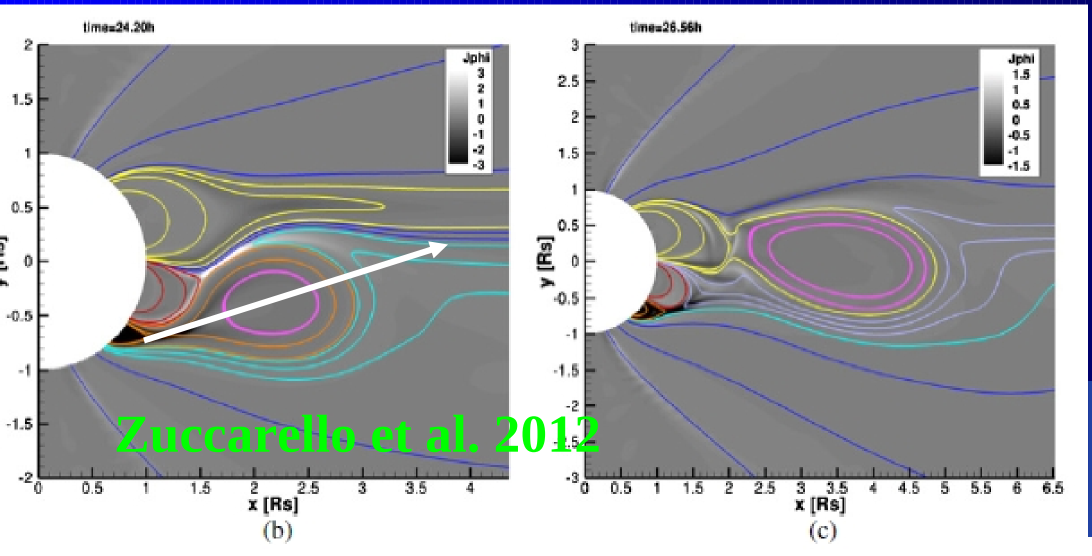
Thompson, Kliem, Torok 2012

rotations ~ [30,90] deg



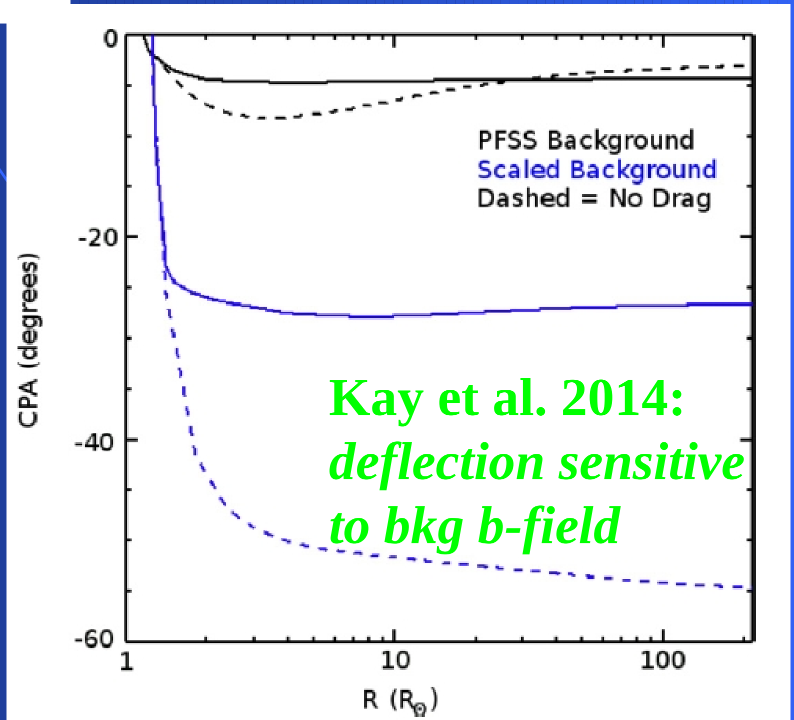
cause of rotation?
kink instability of twisted FRs
twist → writhe convertion
Torok & Kliem 2005

CME deflections close to the Sun: Modeling



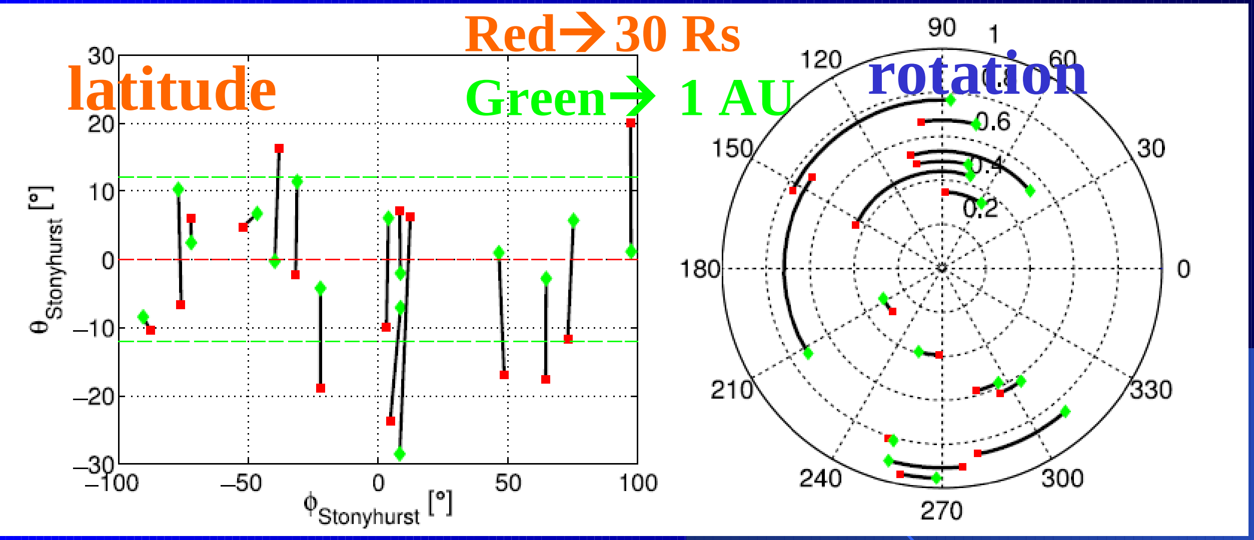
Zuccarello et al. 2012

central position angle of CME



Kay et al. 2014: ***deflection sensitive to bkg b-field***

CME deflection & rotation from 30 Rs → 1 AU

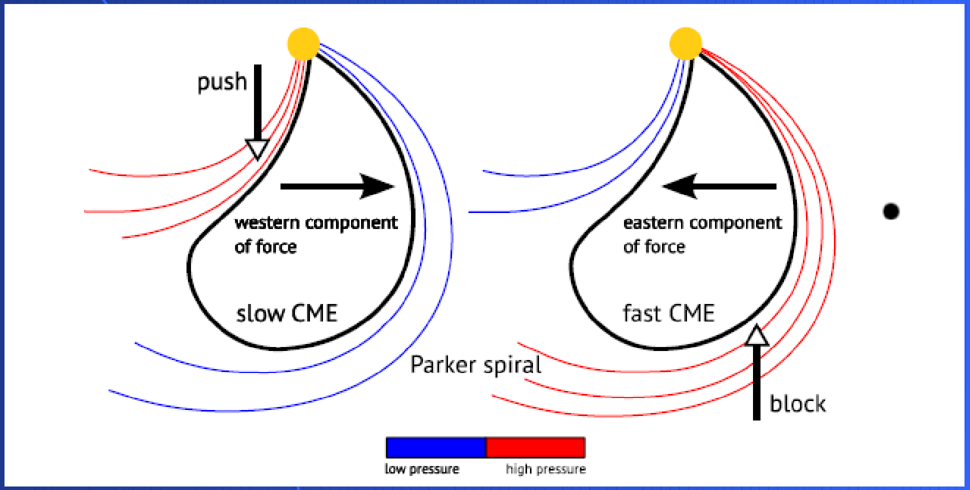


longitude

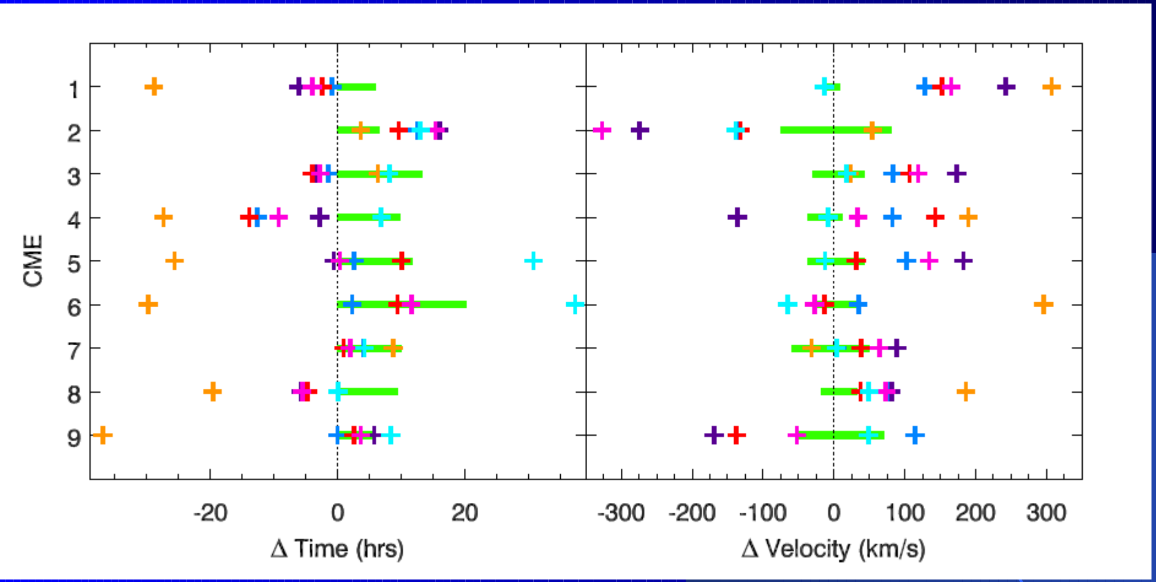
Isavnin, Vourlidas, Kilpua
2013,2014
15 CMEs 2008-2010
deflection ~ 2-30 deg
rotation ~ 2-80 deg
60% of variation in the first 30 Rs

Interaction of CME with Parker spiral
Wang et al. 2004

Weak CME b-field; how about solar-max CMEs?



Sun-to-Earth transit of CMEs



Colannino et al. 2013

Statistical studies of CME trajectories
from observations 30-120 deg away from Sun-Earth line

Colaninno, Vourlidas, Wu 2013
Mostl et al. 2014

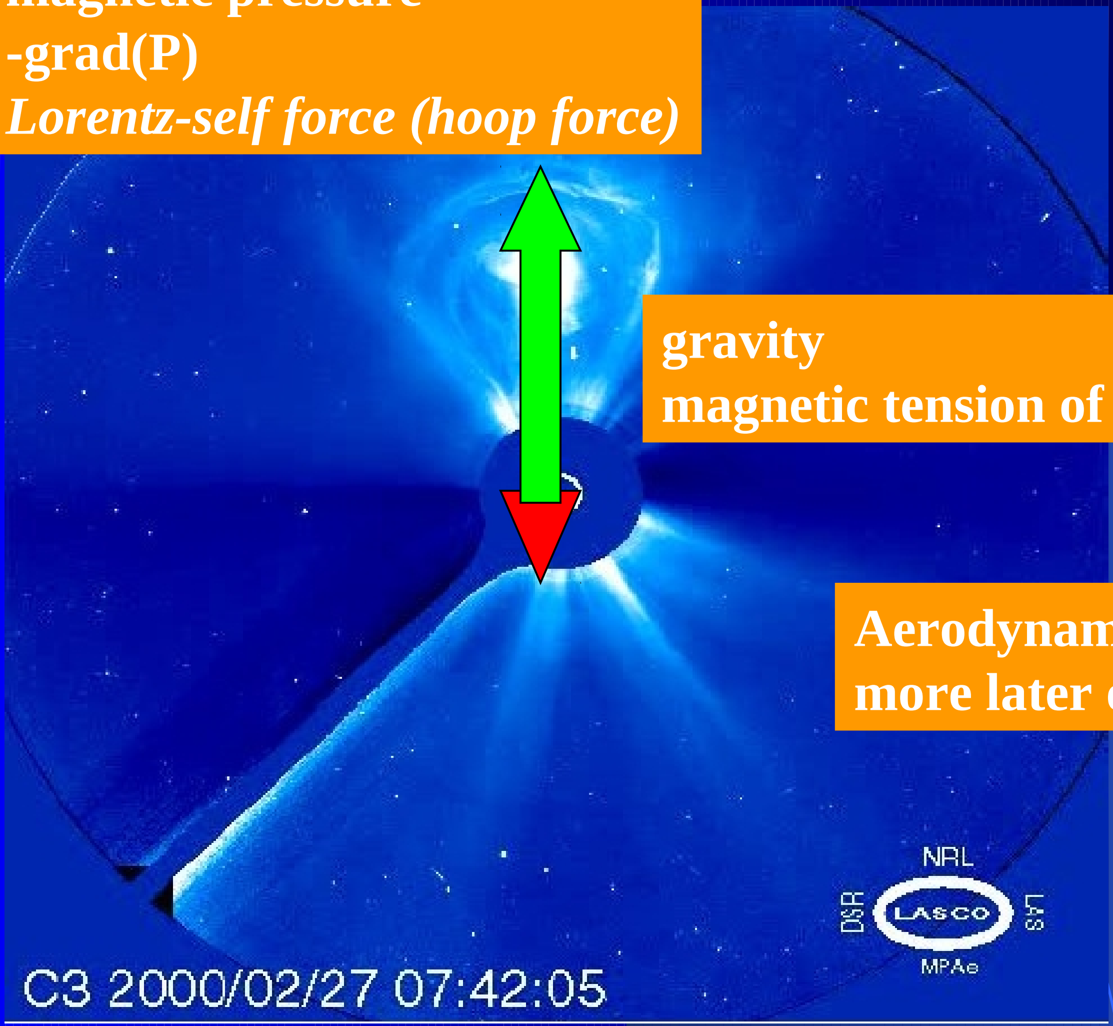
Arrival times ~ +- 6 hours
Arrival speeds ~ +- 150 km/s

Obs along Sun-Earth line give +- 15 hours (Gopalswamy et al. 2001)

Observations away from Sun-Earth line improve predictions of
arrival times/speeds of CMEs

Forces on CMEs

magnetic pressure
-grad(P)
Lorentz-self force (hoop force)

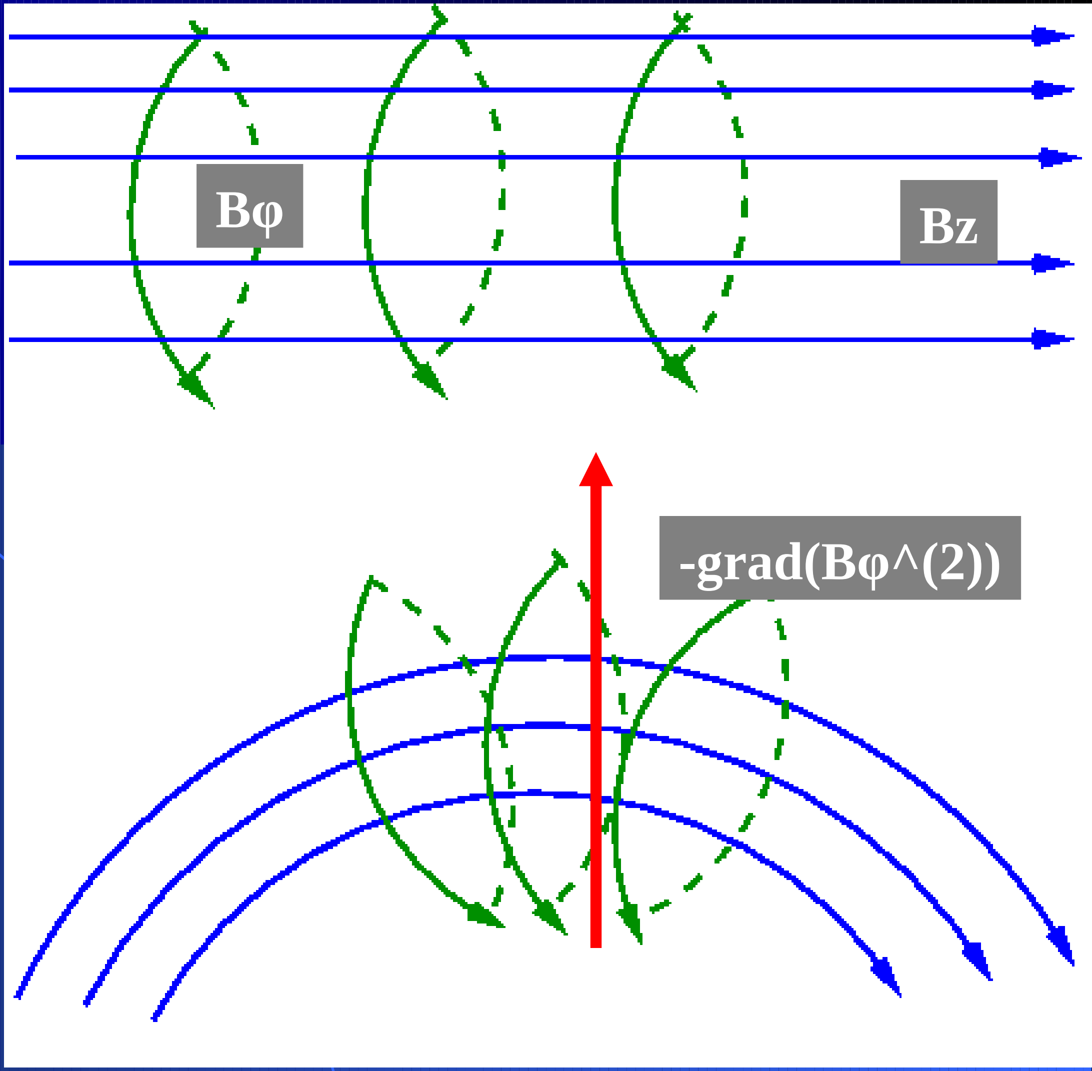


gravity
magnetic tension of overlying b-field

Aerodynamic force may be up or down
more later on the school

e.g., Chen 1989

Self-Lorentz (hoop force)



It is a toroidal force on a current-carrying loop

e.g., Chen 1989, Vrsnak 2008

Summary & Outlook

Flux-ropes are commonly found in CMEs observed with coronagraphs and in-situ @ 1 AU. Whether FRs pre-exist CME onsets
and how they are formed is open.

Statistics of FRs in hot emissions (AIA; Solar Orbiter/Fe XVII G. Zouganelis lecture ; ASPIICS in Ca XV? K. Tsinganos lecture) combined with detailed magnetic

All these problems require an extensive theory&modeling

CMEs are exciting&important phenomena & their comprehensive
study requires a new generation of scientists with solid foundations on solar, IP and magnetospheric physics

Velli & A. Vourlidas lectures) &
above the ecliptic (Solar Orbiter) are required.