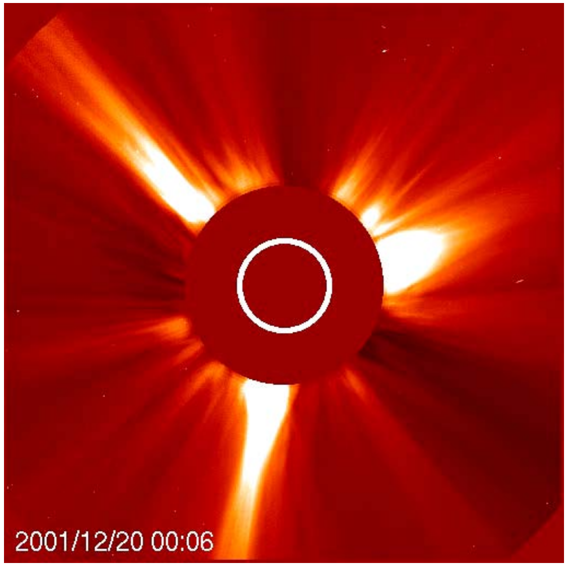


Coronal Mass Ejections as Key Players in Sun-Earth Connection

Nat Gopalswamy
NASA Goddard Space Flight Center
Greenbelt, MD 20771

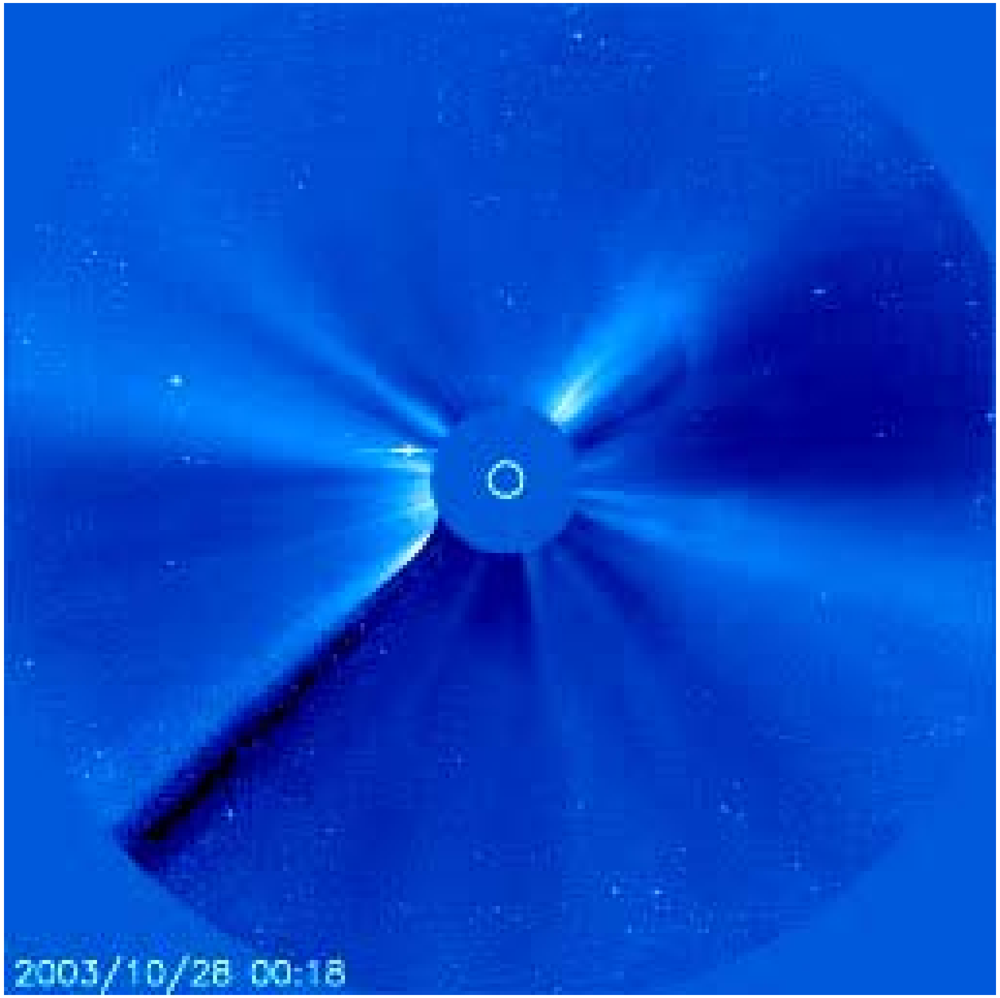
ISWI – Europe School on Space science, August 20-27, 2011 Tatranska Lomnica, Slovakia

High Energy Plasmas & Particles

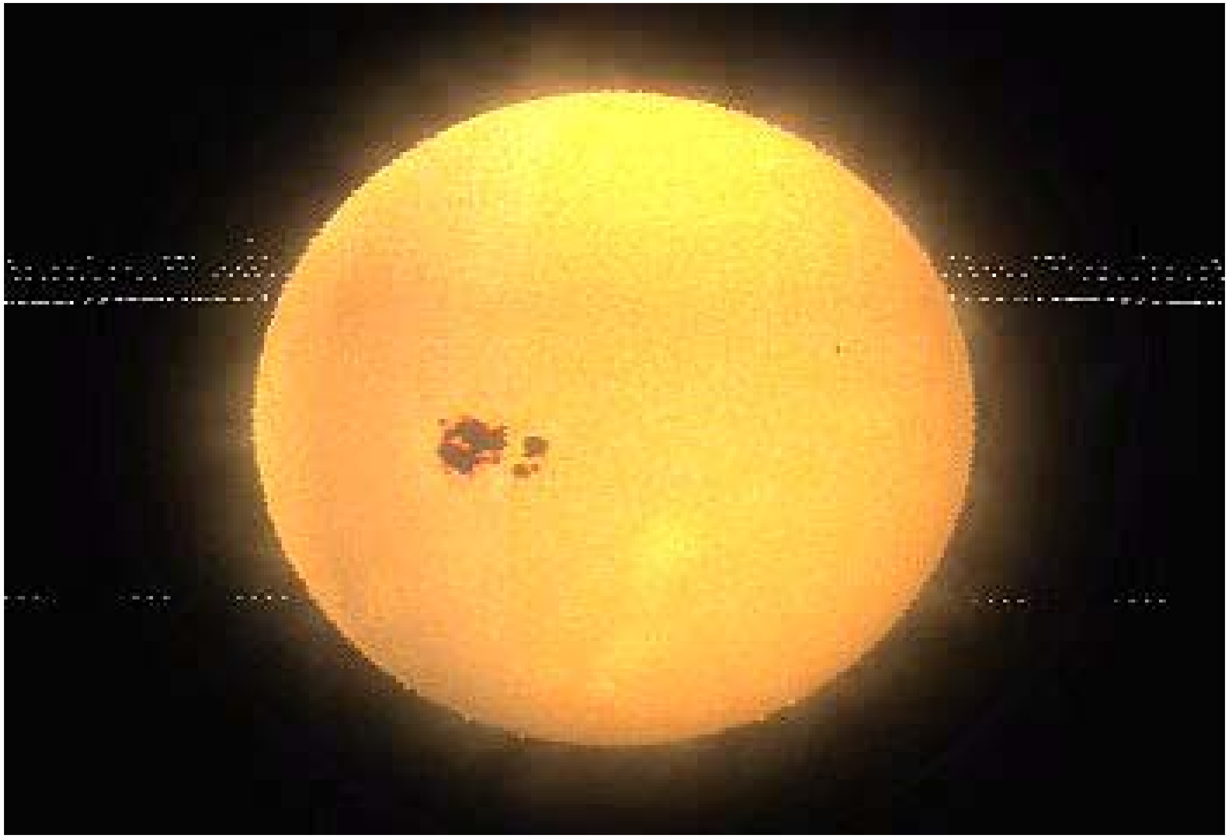
Solar Wind

Plasma Ejected from the Sun
(Coronal Mass Ejections – CMEs)

Energetic Particles



Animation of Halloween 2003 Events



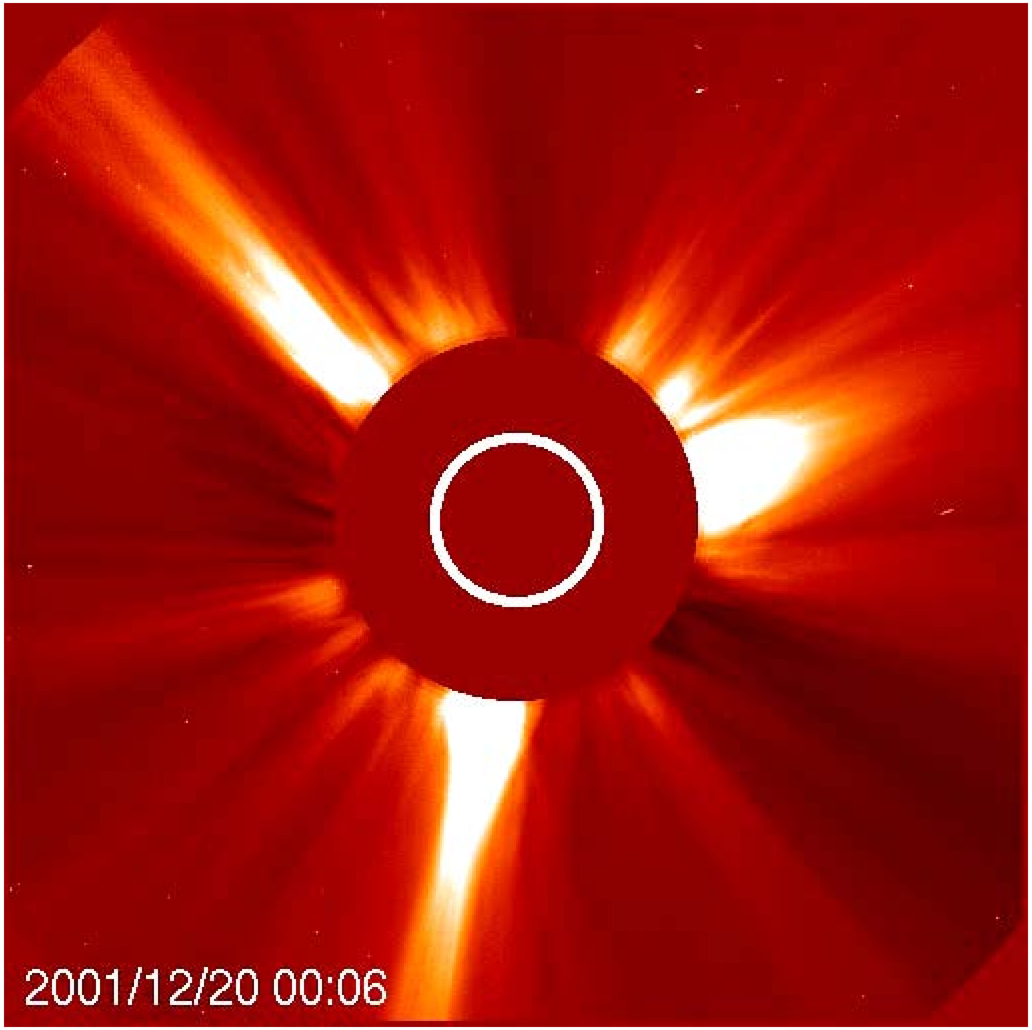
… to illustrate their heliospheric impact

What is a CME?

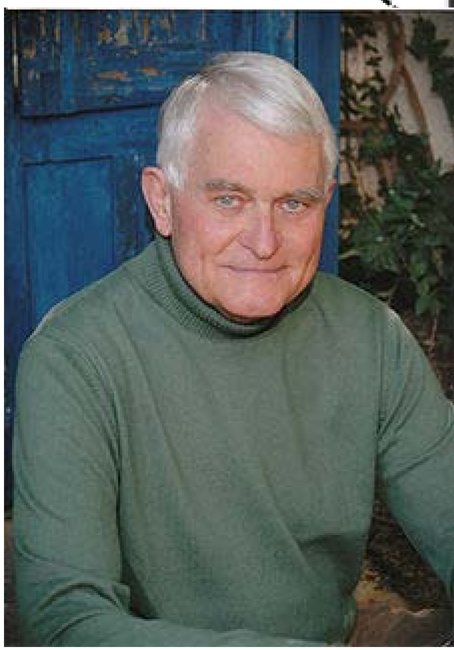
CME can be defined as the outward moving material in the solar corona which is distinct from the solar wind

This image shows three main CMEs from The solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph

Physical Properties
Statistical properties
morphology (eruption geometry)
energetics
in situ measurements
Plage and Sunspots



CME in Old Eclipse Pictures: 1860 July 18



J. A. Eddy (1931 – 2009)

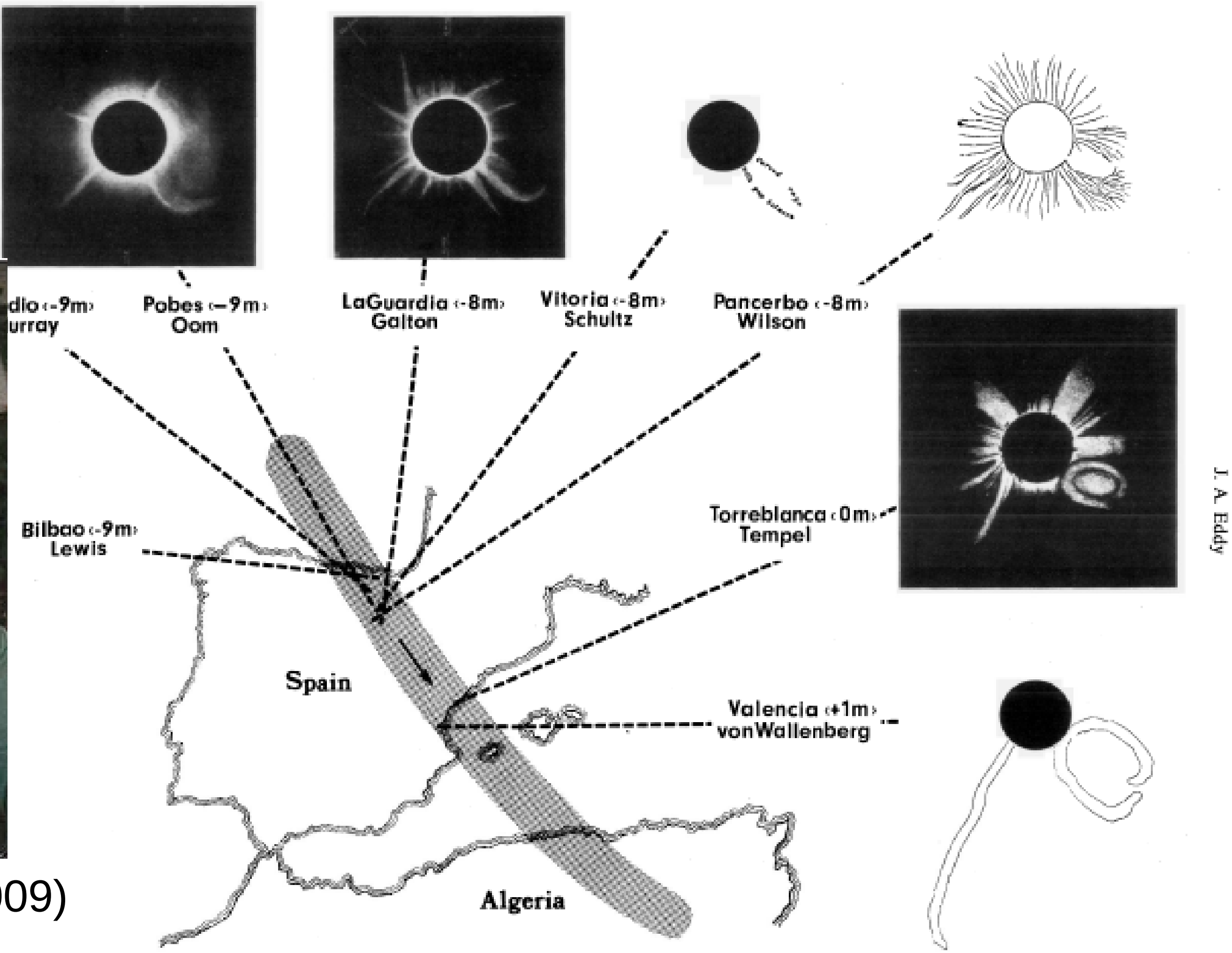


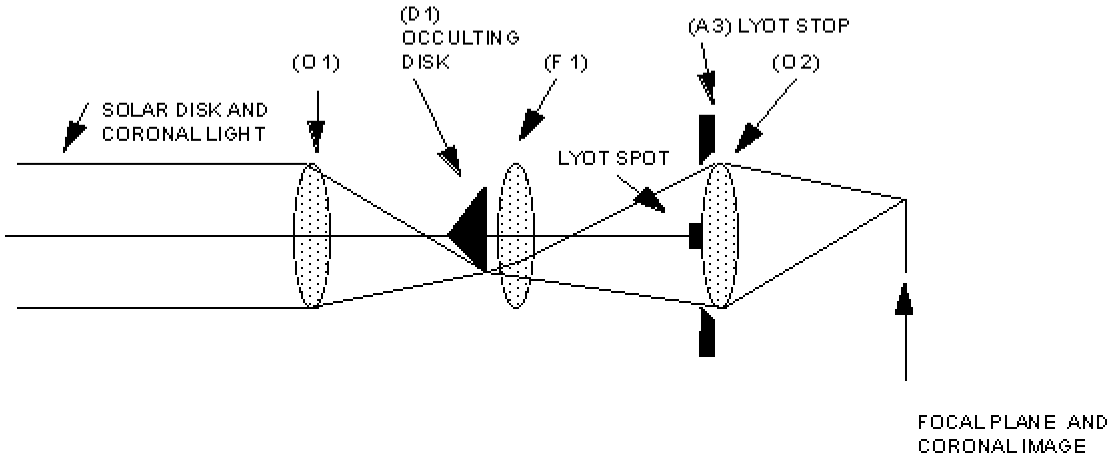
Fig. 4. Selected drawings of the corona (from Ranyard, 1879), made by different observers along the path of totality in Spain during the 1860 eclipse. Times are relative to mid-totality at Tempel's station at Torreblanca

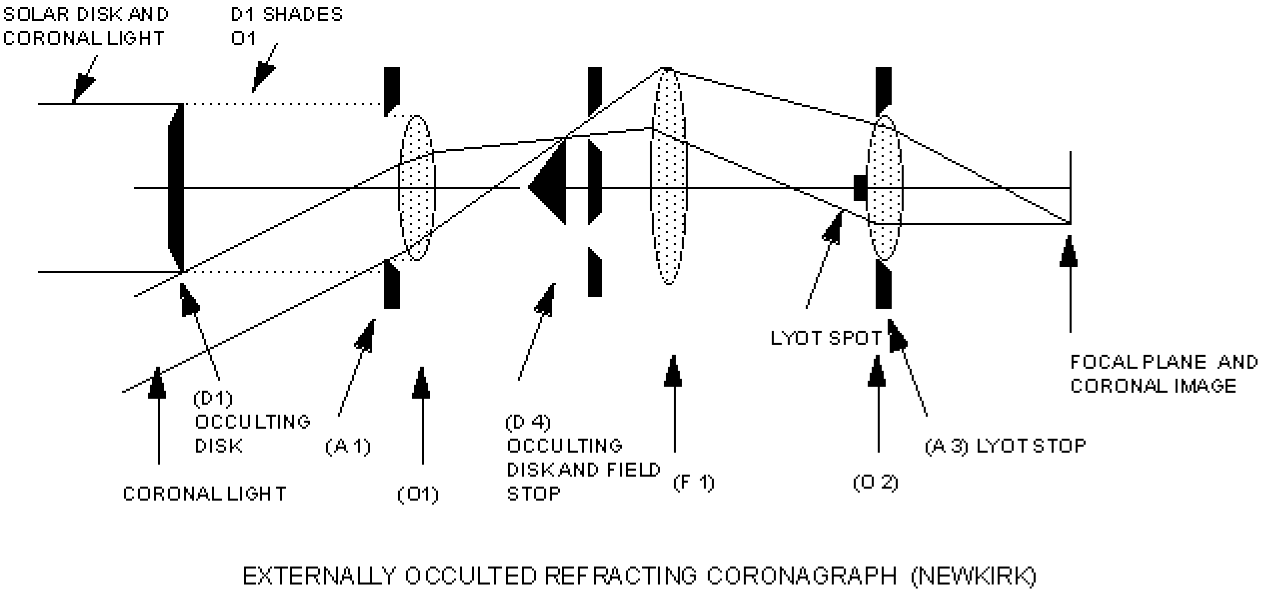
Eddy, 1974 estimated the CME speed to be 200-500 km/s

Coronagraphs

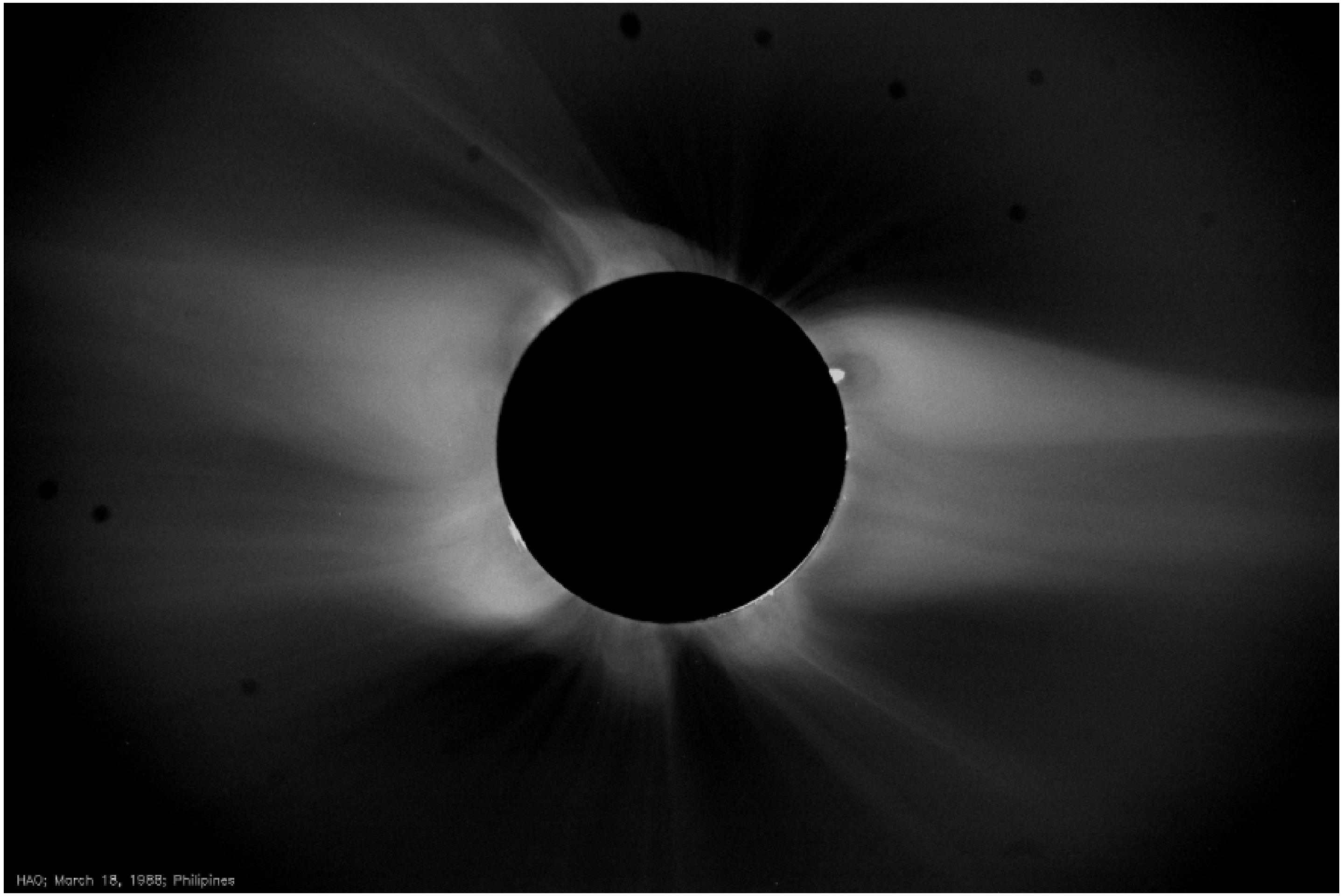
Bernard Lyot (1939)

extra occulting disk so direct photospheric light does not fall on the objective





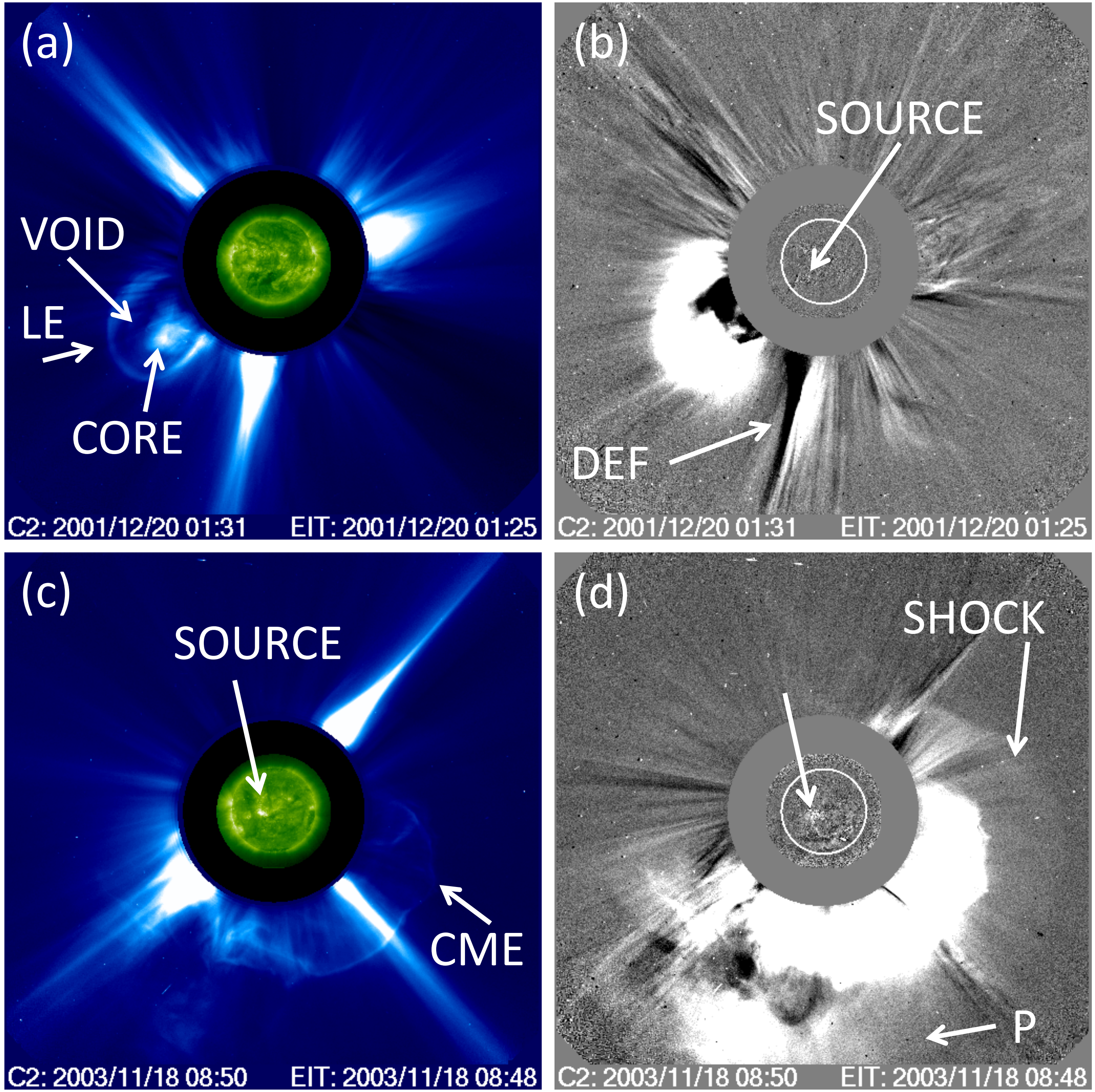
Moon is a natural occulting disk

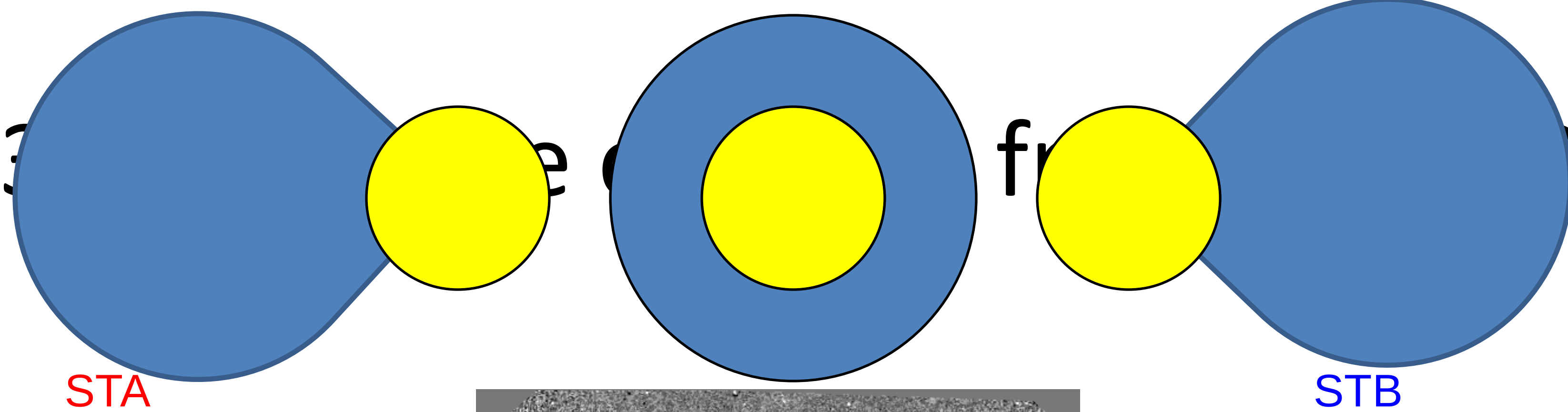


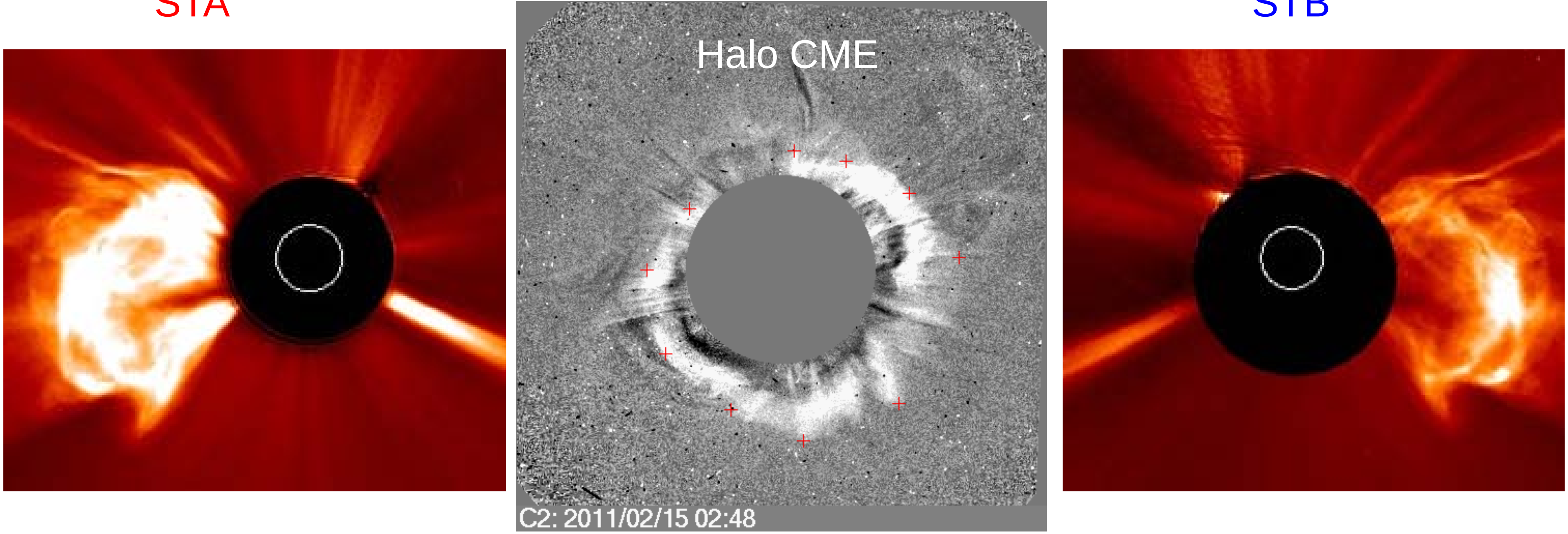
Courtesy: HAO

Prominence, coronal cavity and overlying streamer:
Look like a CME before taking off!

Morphological Properties



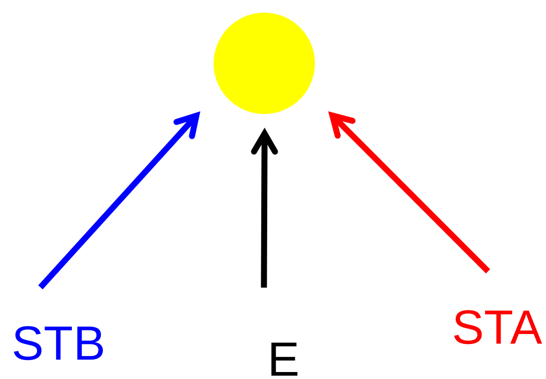




Limb CME

Limb CME

3-D Structure of CMEs



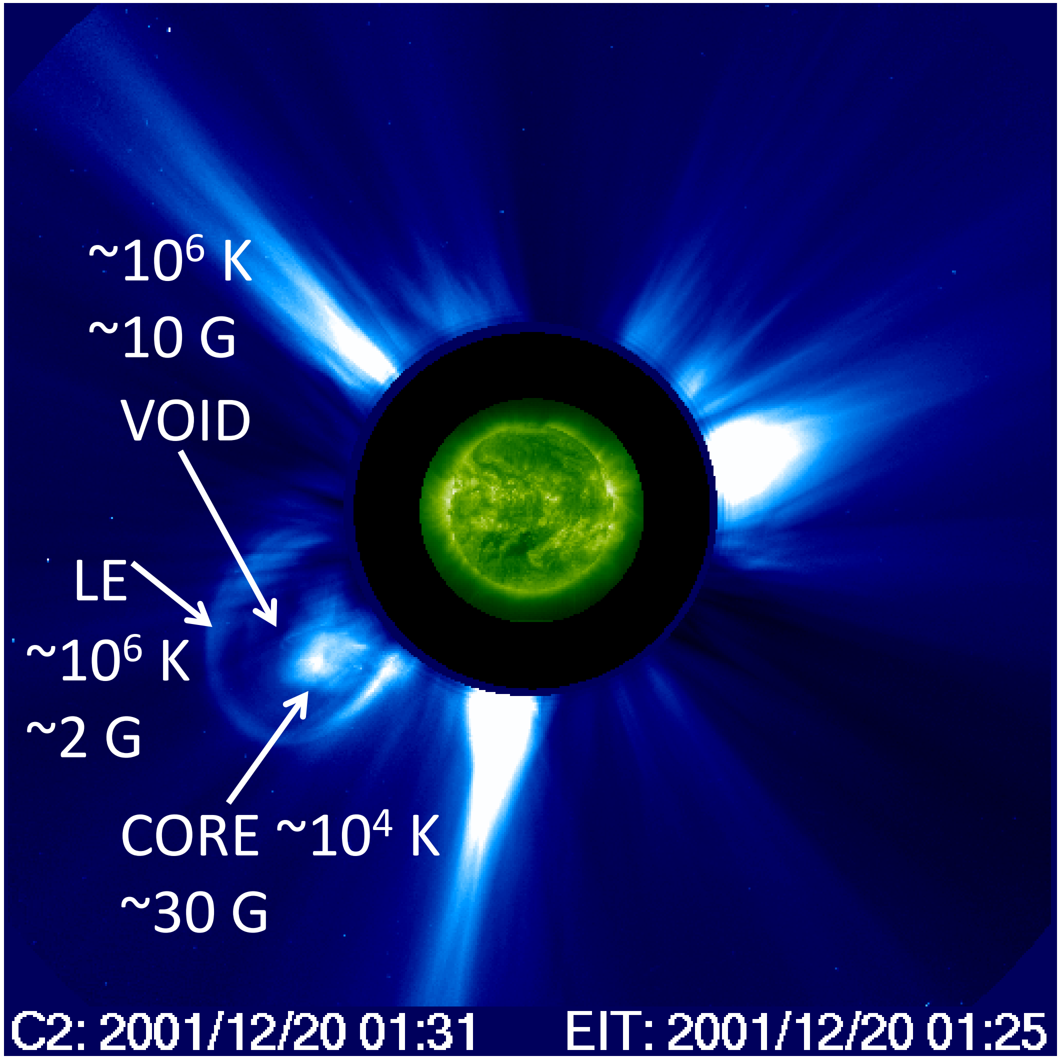
Physical Properties

Three-part structure
Illing & Hundhausen, 1986

Four-part structure when shock driving

Shock compression:
up to four times the upstream temperature (SOHO/UVCS)

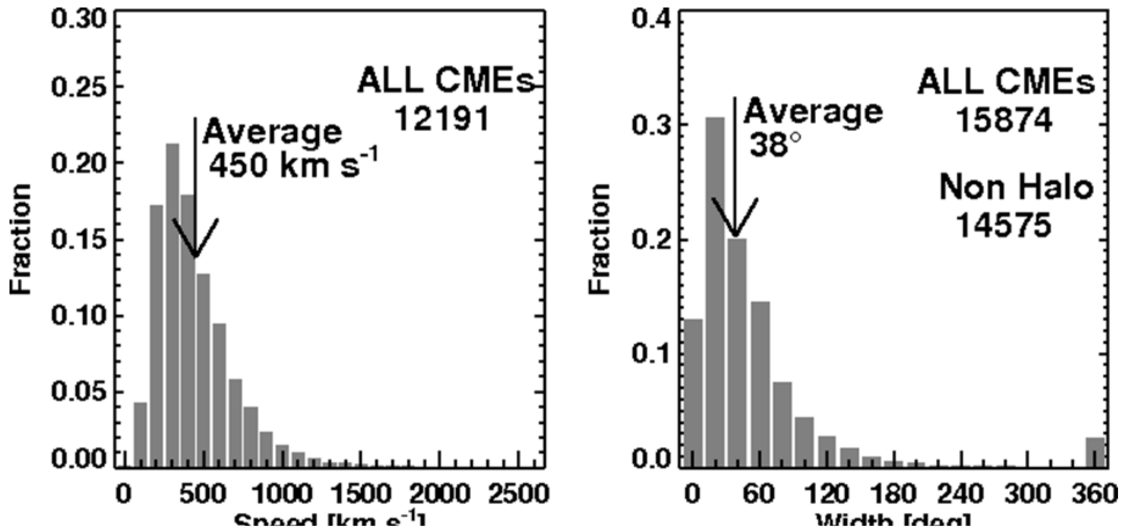
Flare plasma can reach ten of MK



CME Structures

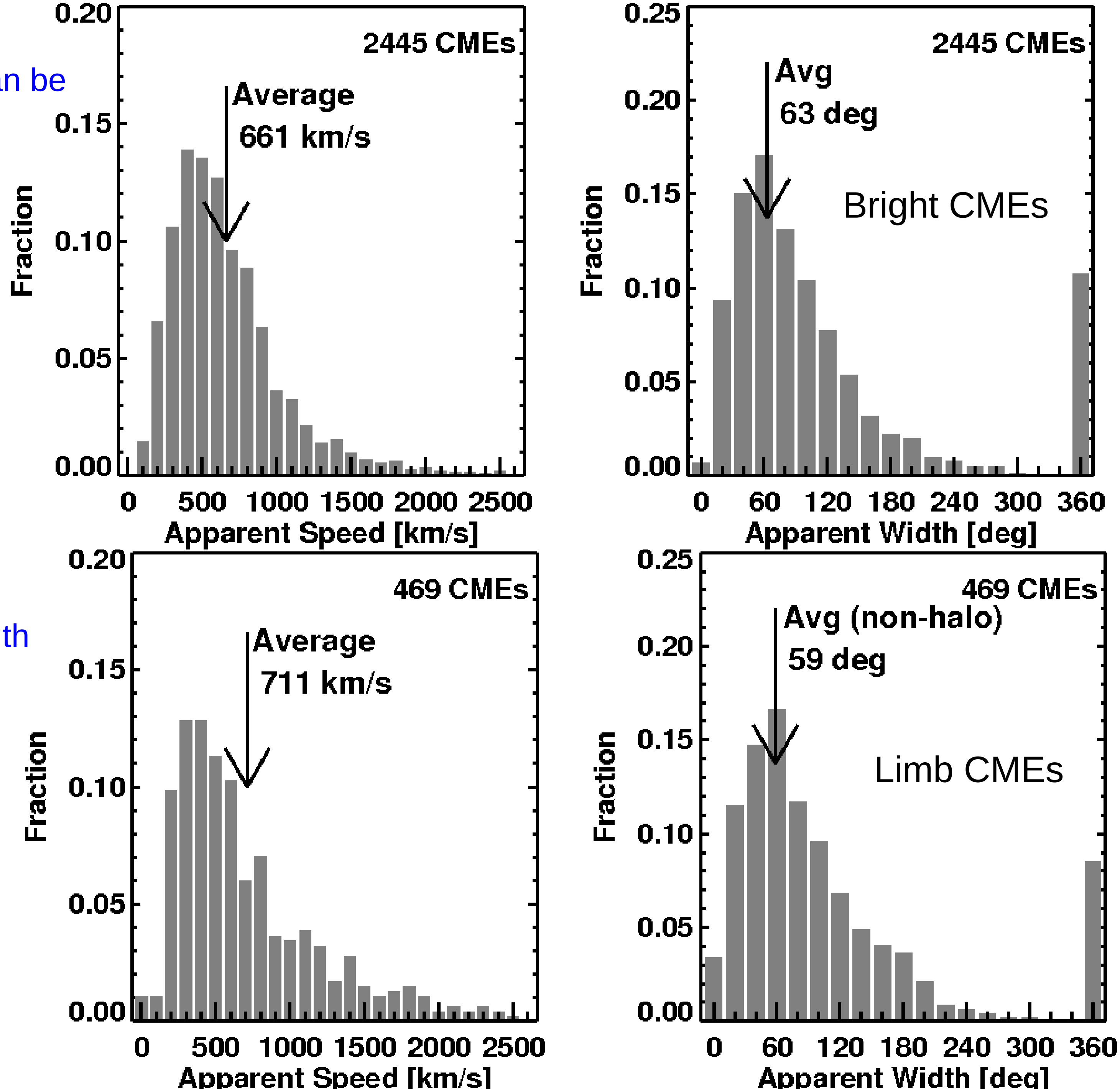
- Flare (energized loops stuck to the Sun)
- Filament/prominence
- flux rope/cavity (observed as magnetic cloud)
- shock

Statistical properties: Speed & Width

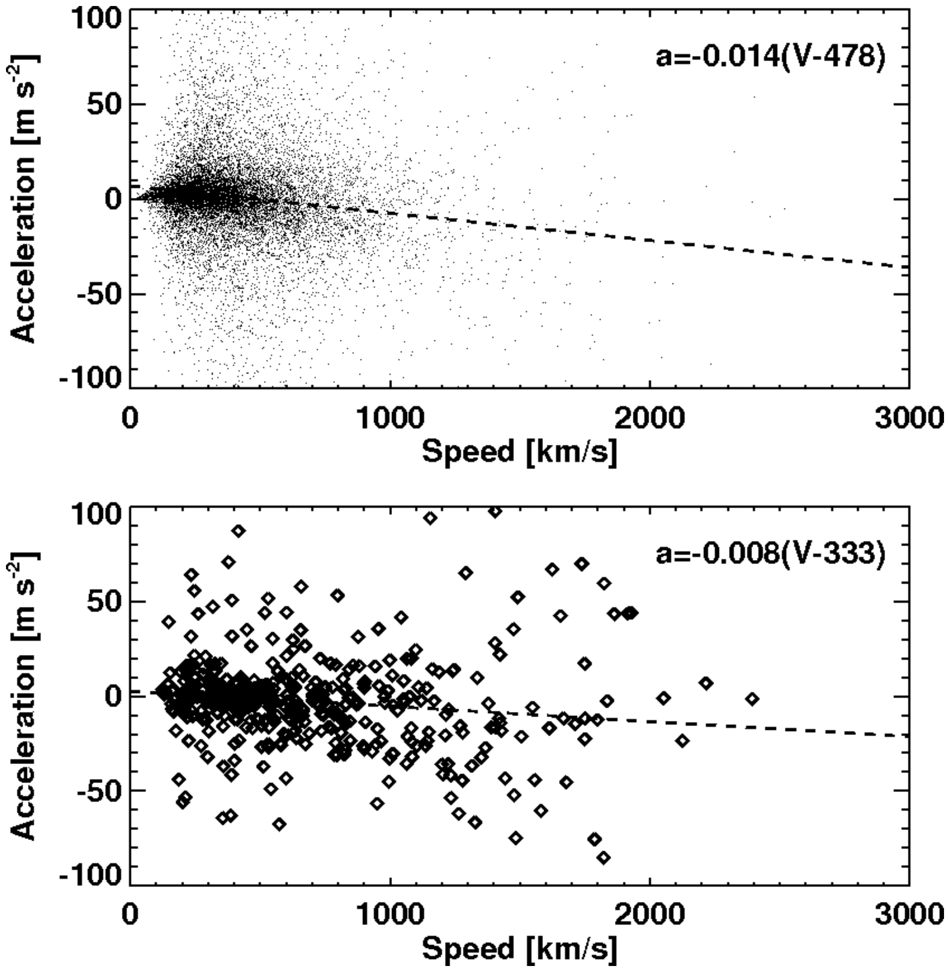


CMEs that can be Measured to >20 Rs

Limb CMEs associated with ≥C3.0 flare



Acceleration in LASCO C2/C3 FOV

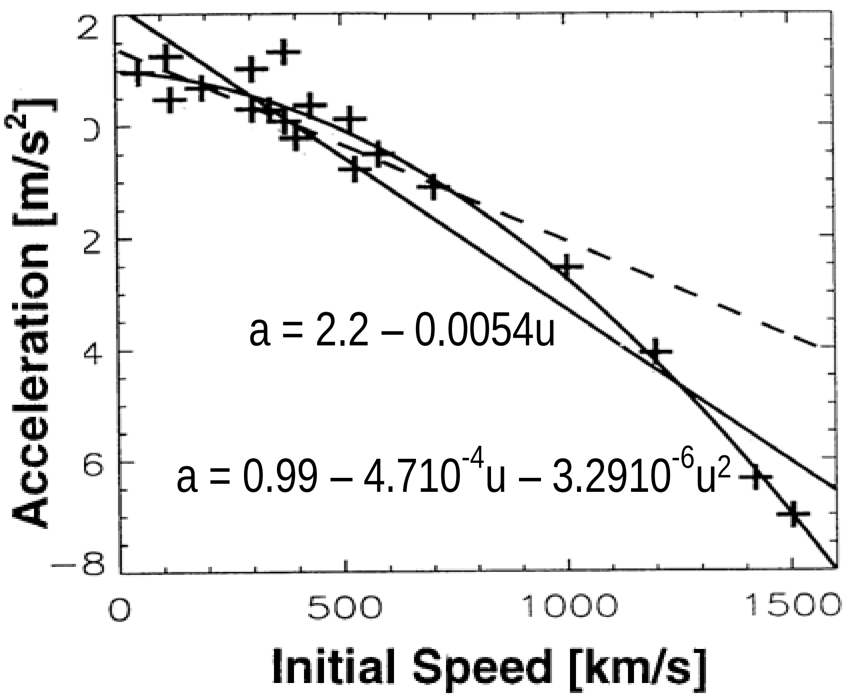


- $a = -a_d$

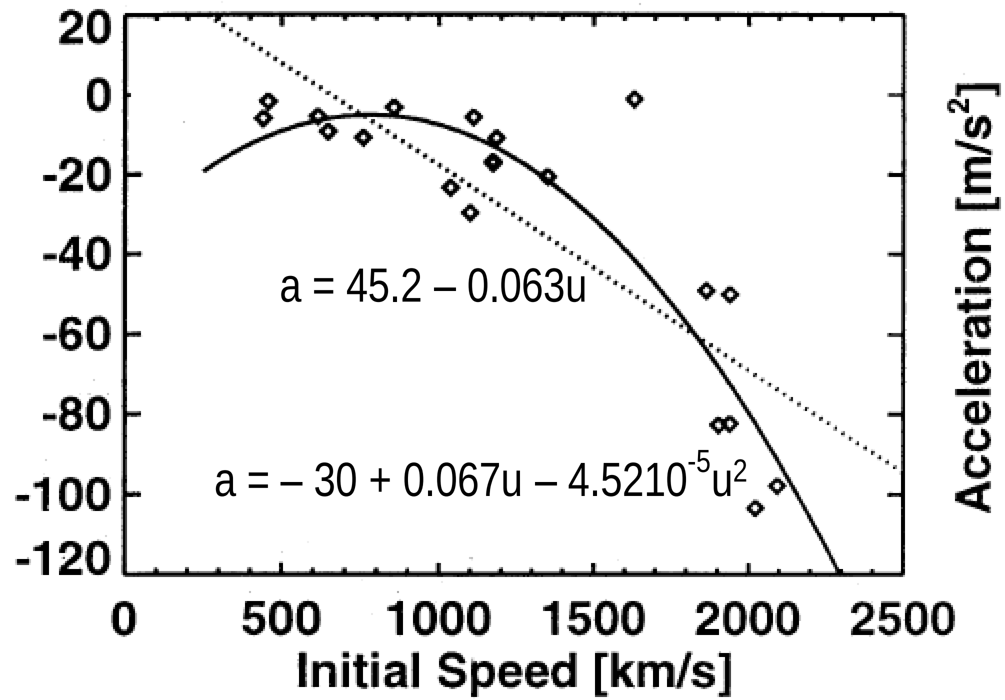
- $a = a_p - a_g - a_d$

IP Acceleration

(a) Helios/PVO Data



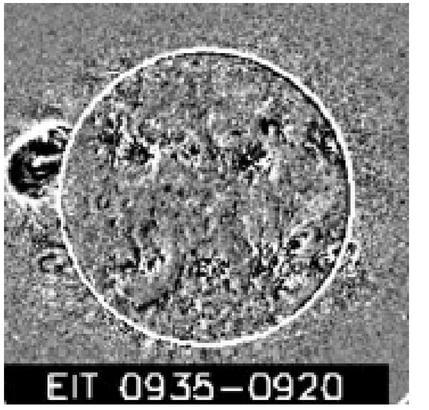
(b) SOHO/LASCO Limb CMEs



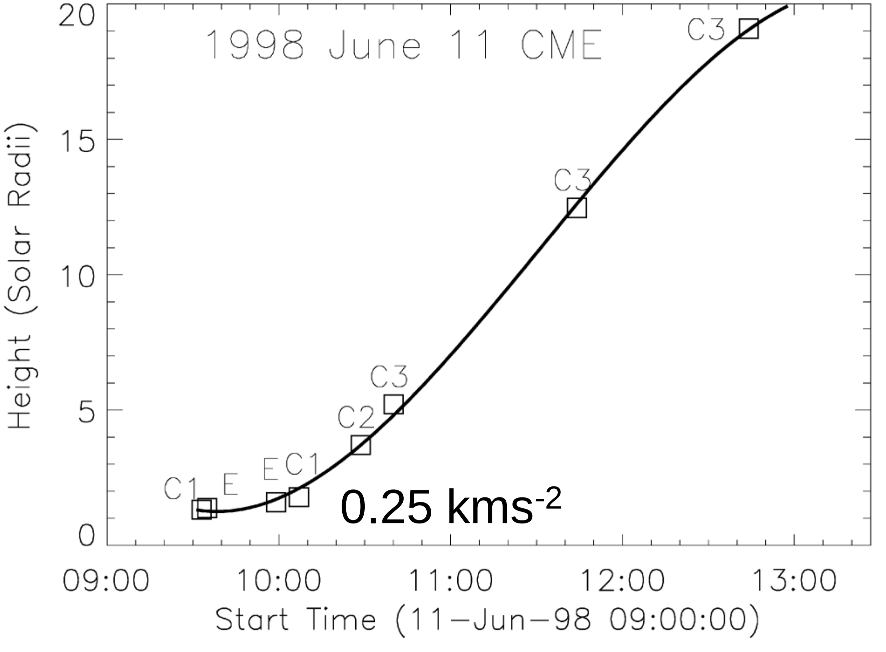
useful for predicting Sun-Earth travel time
of CMEs based on initial speed

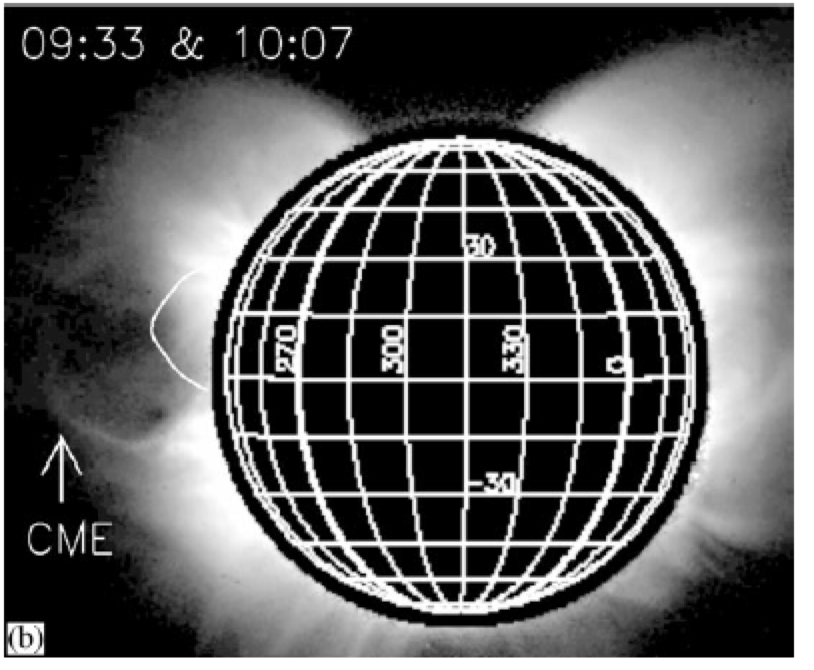
Gopalswamy et al., 2001

Acceleration from LASCO C1, EIT



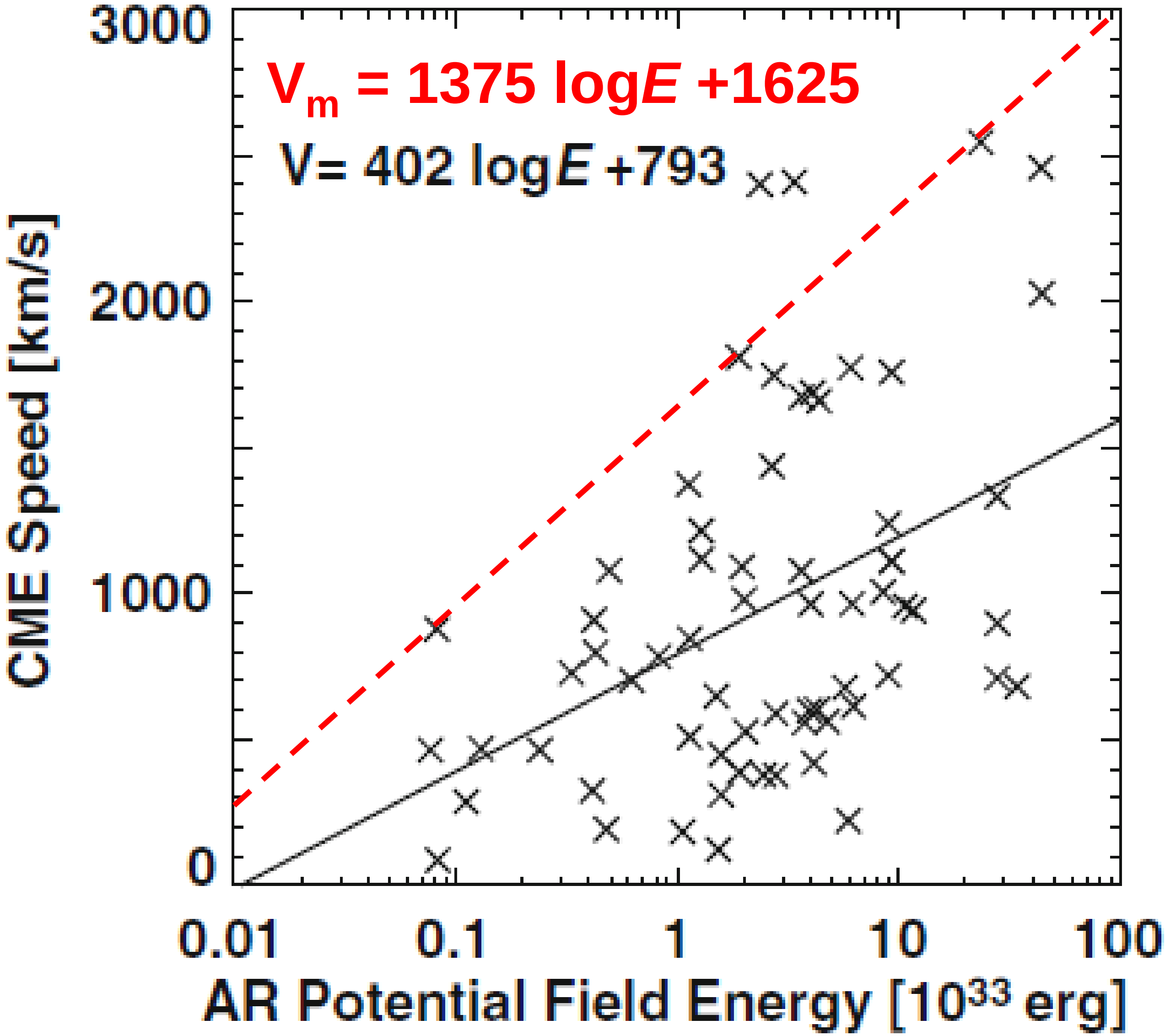
Gopalswamy & Thompson 2000





$$h = 3.1 - 0.1t + 1.5\text{x}10^{-3}t^2 - 3.4\text{x}10^{-6}t^3$$

Gopalswamy et al., 2010



Assume free energy ~ Potential field energy (McKay and Forbes 2000)

$E = 10^{36}$ erg

$E_{33} = 1000$

$V_{max} = 5750$

For

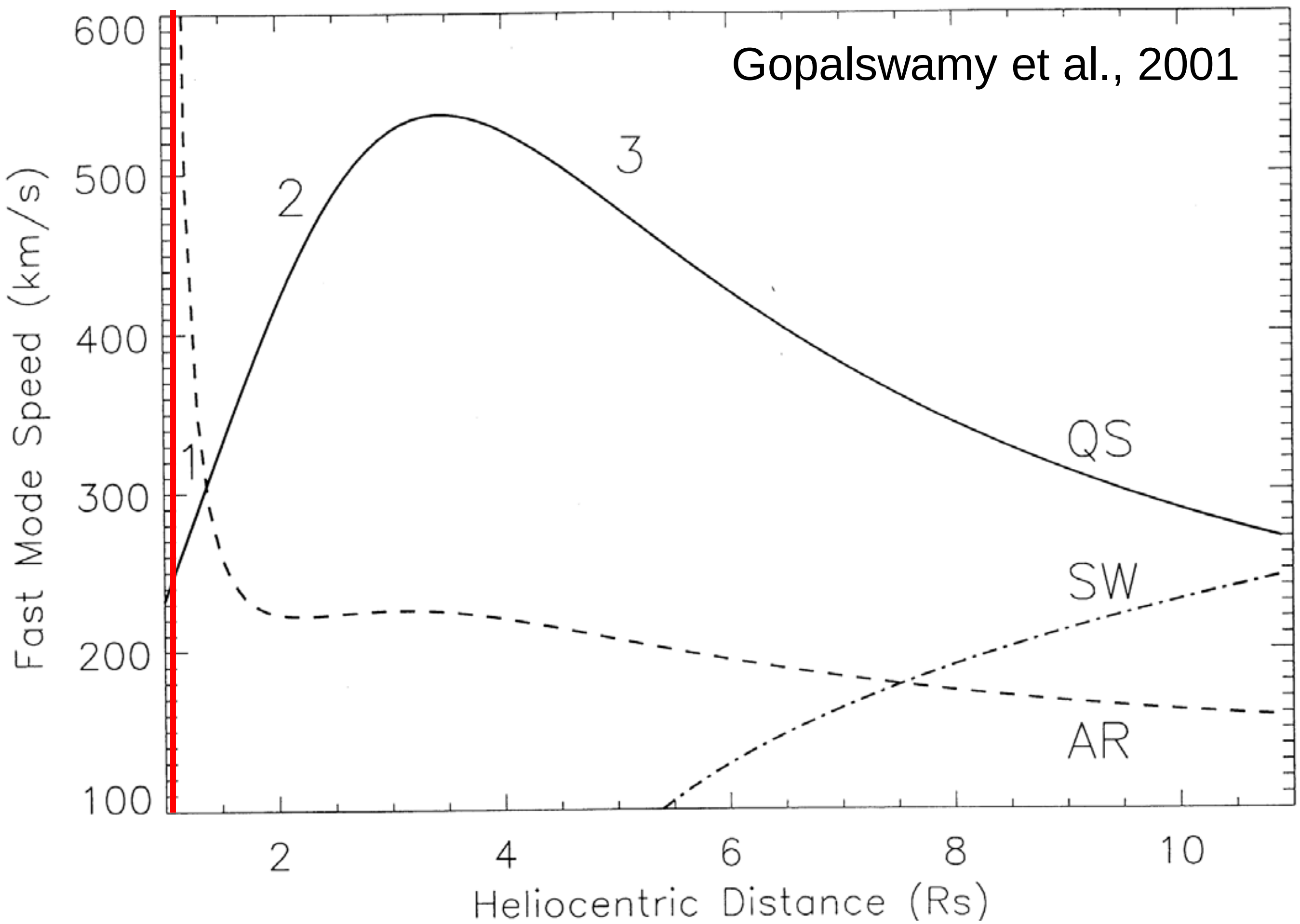
$n = 10^9\ cm^{-3}$

$B = 26$ G

$V_A = V_{max}$

$\frac{1}{2}\rho V^2 \leq B^2/8\pi \rightarrow V \leq V_A \rightarrow a \leq V_A/t_A = V_A^2/L$ (Vrsnak, 2008)

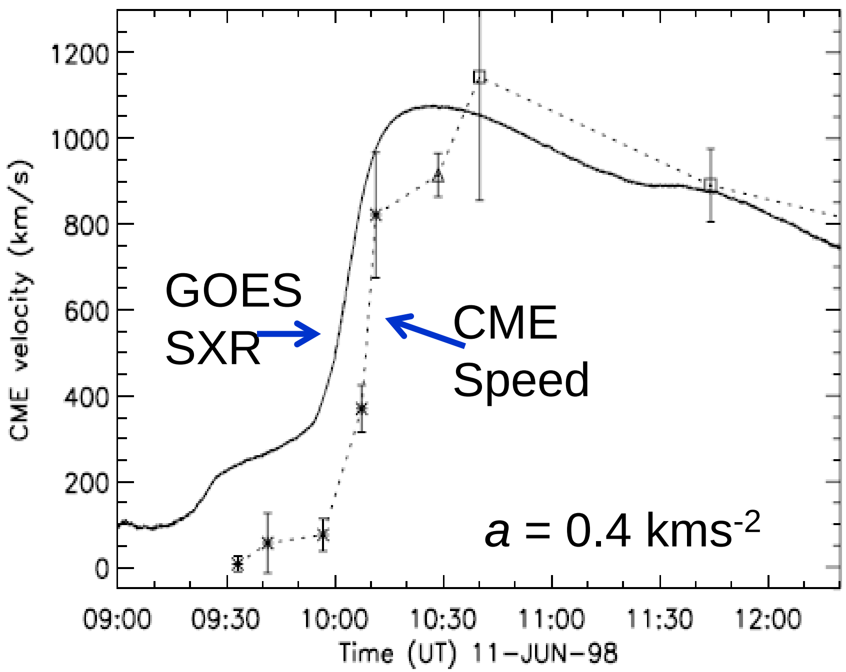
Alfven Speed in the Source Region



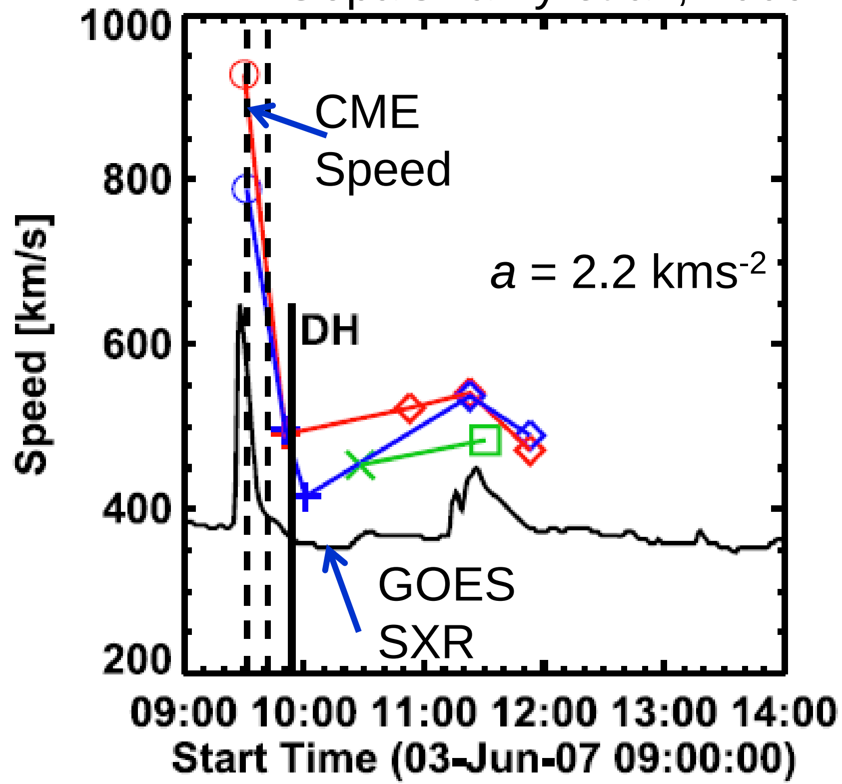
V_A = 1500 km/s; L ~175,000 km → a ≤ 13 kms^{-2}

CME speed max at Flare peak

Zhang et al., 2001



Gopalswamy et al., 2009

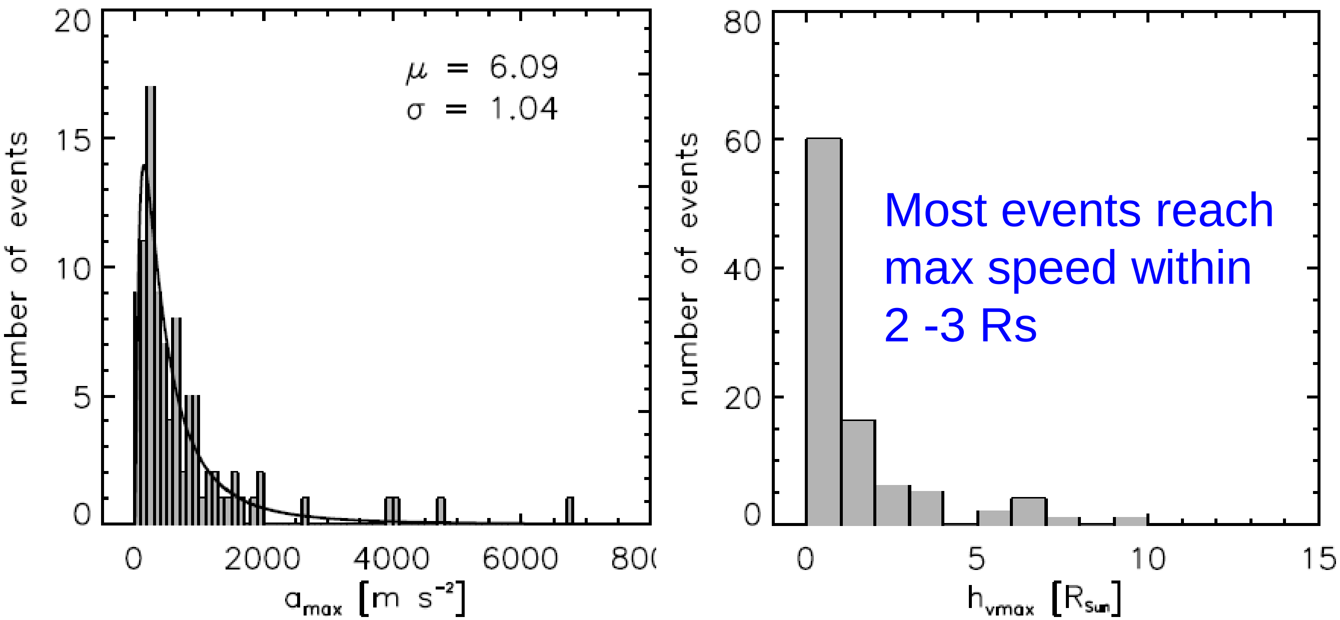


CME speed profile similar to the Flare soft X-ray profile

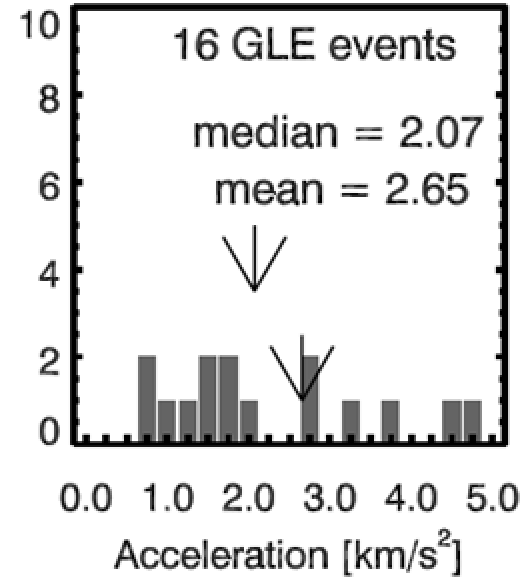
CME onset ~ Flare Onset

Initial Acceleration of CMEs

Bein et al., 2011



Gopalswamy et al. 2011



- STEREO/EUVI COR1
- 95 CMEs
- a_{max}: 0.02 to 6.8 kms^{-2}
- Height at Vmax: 1.17 to 11 Rs

- Ultrafast CMEs
- CME accel = Flare accel
- a: 0.5 to 7.5 kms^{-2}

CME Rate & Speed (Rotation Averaged)

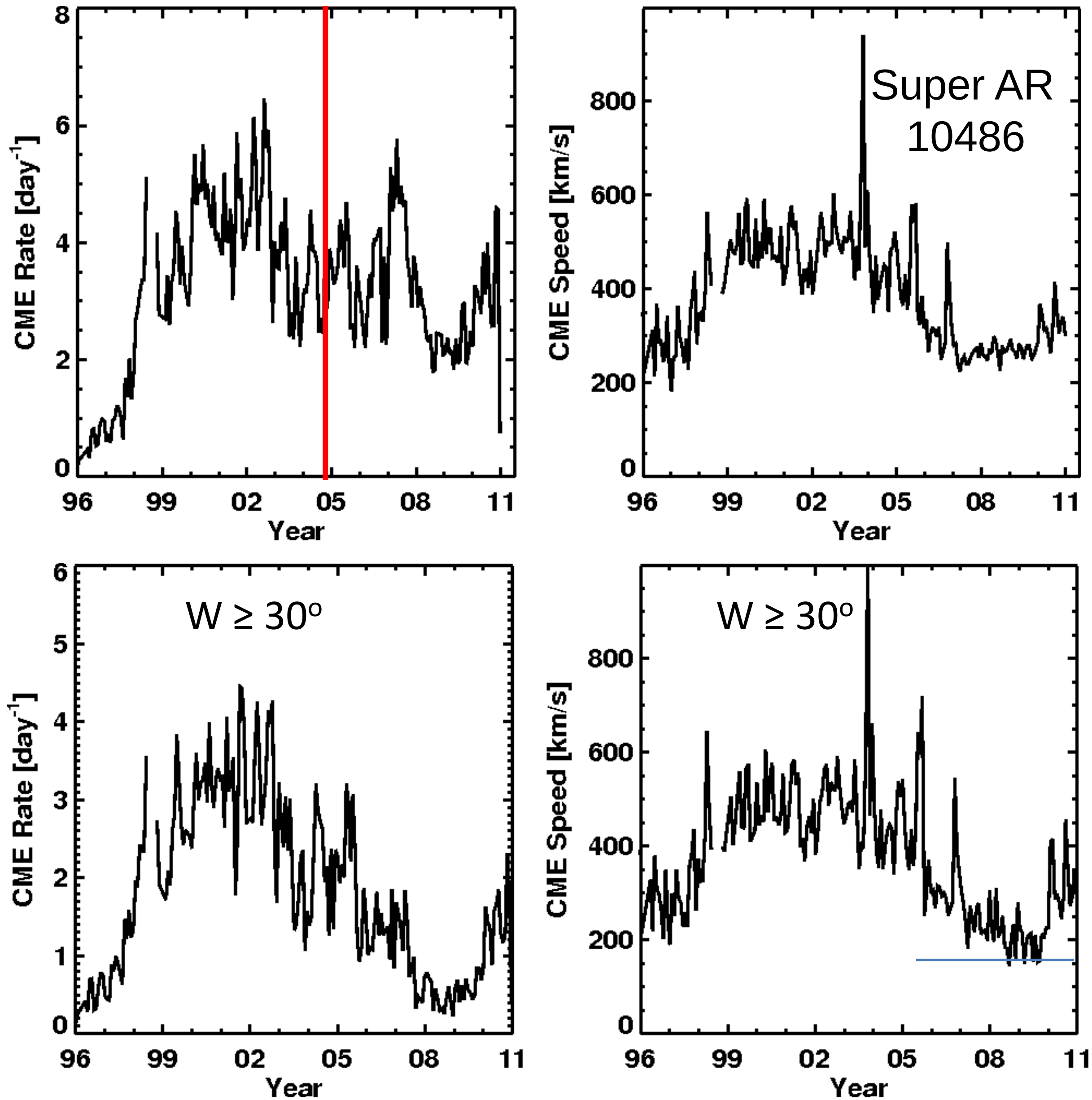
#CMEs per year
$\sim 10^3$

Mass per CME
$\sim 4\times10^{14}$ g

Mass loss due to CMEs
$\sim 4\times10^{14}$ kg.yr^{-1}
$= 2\times10^{-16}$ Ms. yr^{-1}

Solar wind mass loss:
$\sim 2\times10^{-14}$ Ms. yr^{-1}

During solar maximum,
CME mass loss up to
10% of solar wind flux

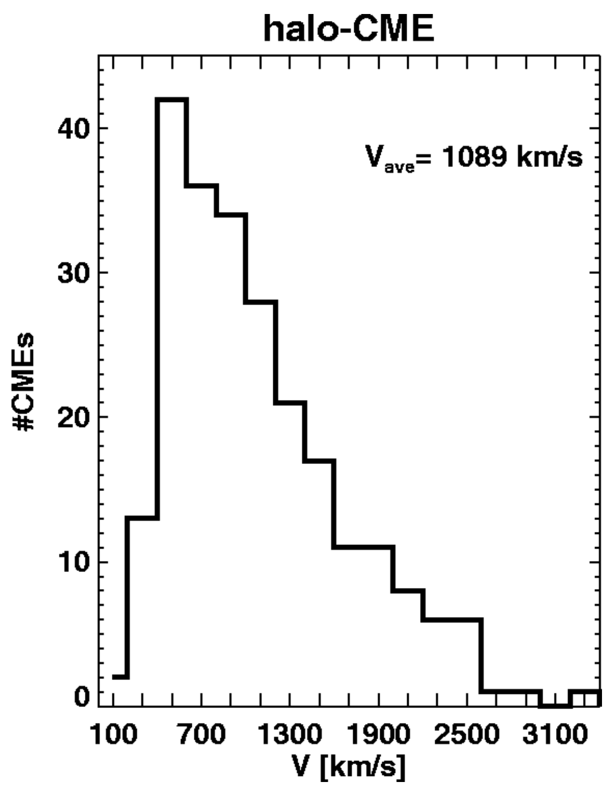


SOHO and Pre-SOHO CMEs

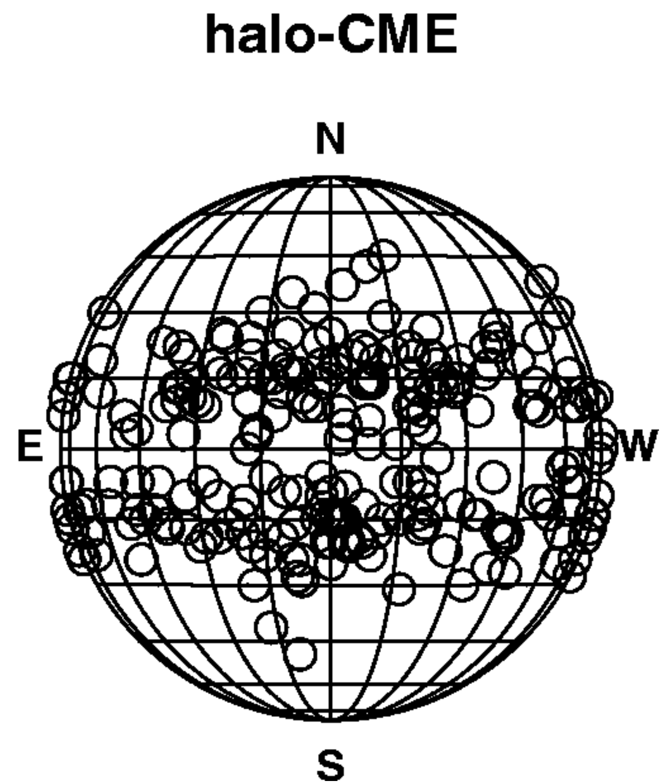
Coronagraph Epoch →	OSO-7 1971	Skylab 1973-74	Solwind 1979-85	SMM 1980,84-89	LASCO 1996-2010
FOV(Ro)	2.5-10	1.5 - 6	3 - 10	1.6 -6	1.2-32
#CMEs	27	115	1607	1206	15874
Mean V (km/s)	---	470	460	350	450
Mean W (deg.)	---	42	43	47	38
Mass (10^{15} g)	---	6.2	4.1	3.3	0.4
Reference	1	2	3	4	5

1 Tousey (1973)
2 MacQueen et al 1974
3 Michels et al 1980
4 Brueckner et al., 1995; Gopalswamy 2010 (updated)

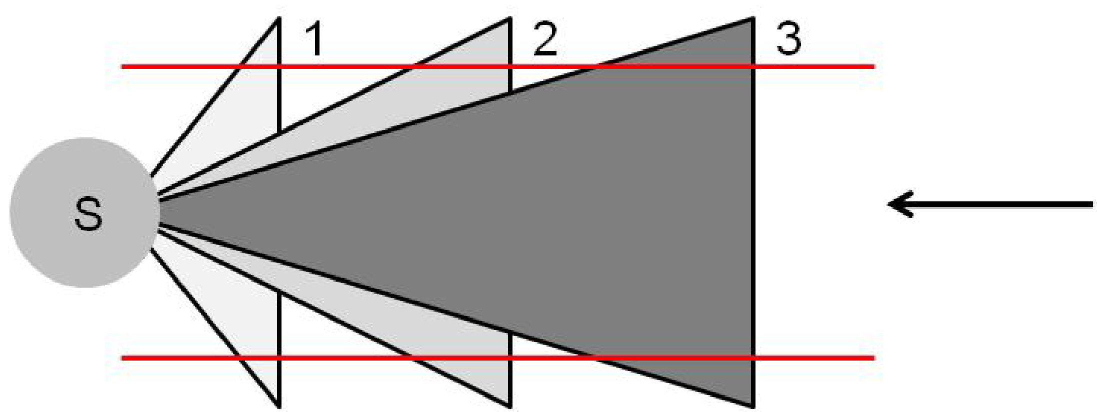
Halo CMEs



halo-CME
V_{ave}= 1089 km/s
#CMEs
0
10
20
30
40
100
700
1300
1900
2500
3100
V [km/s]

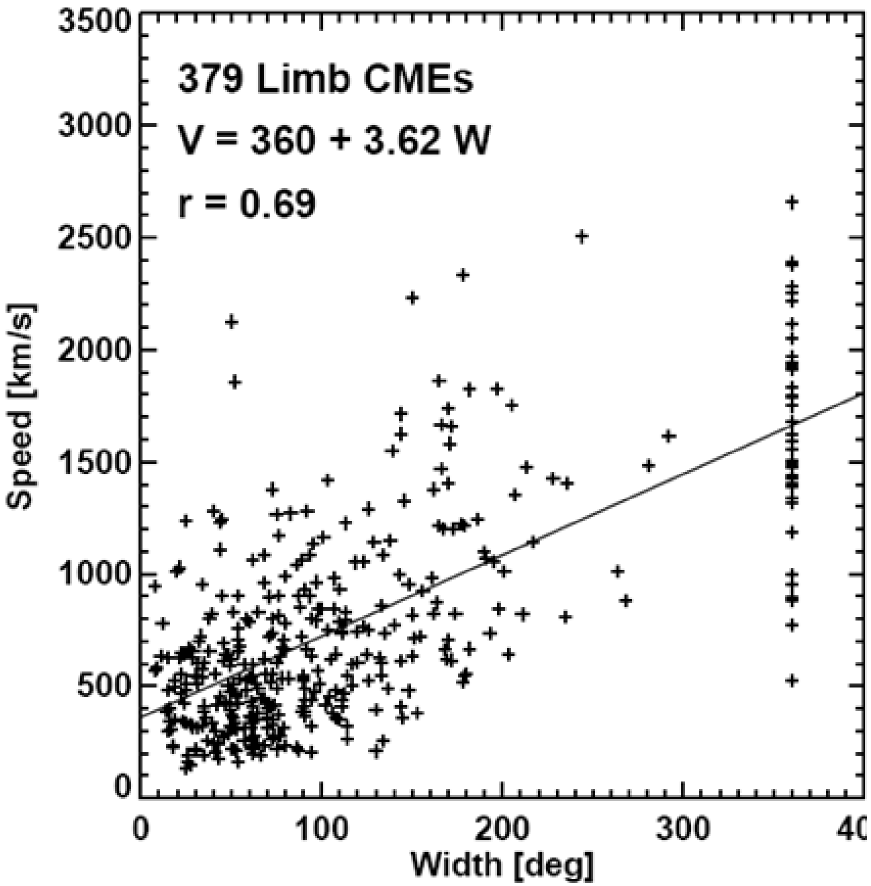


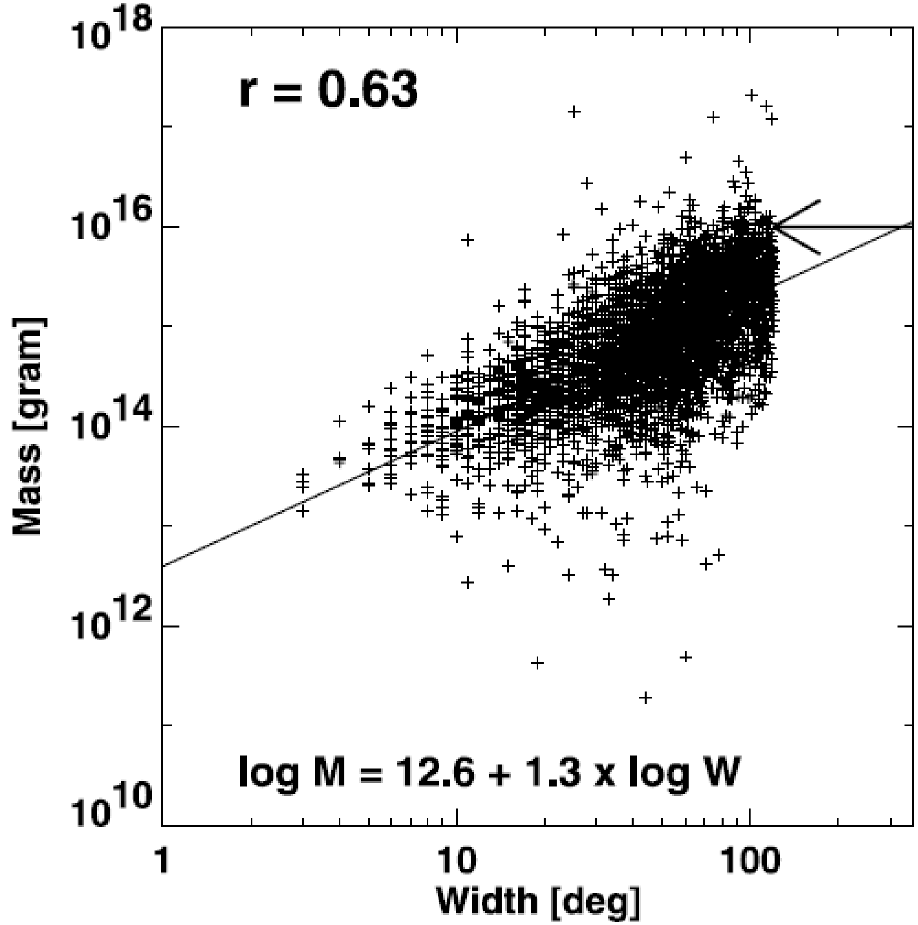
halo-CME
N
E
W
S



1
2
3
S

Faster and Wider CMEs are more Energetic



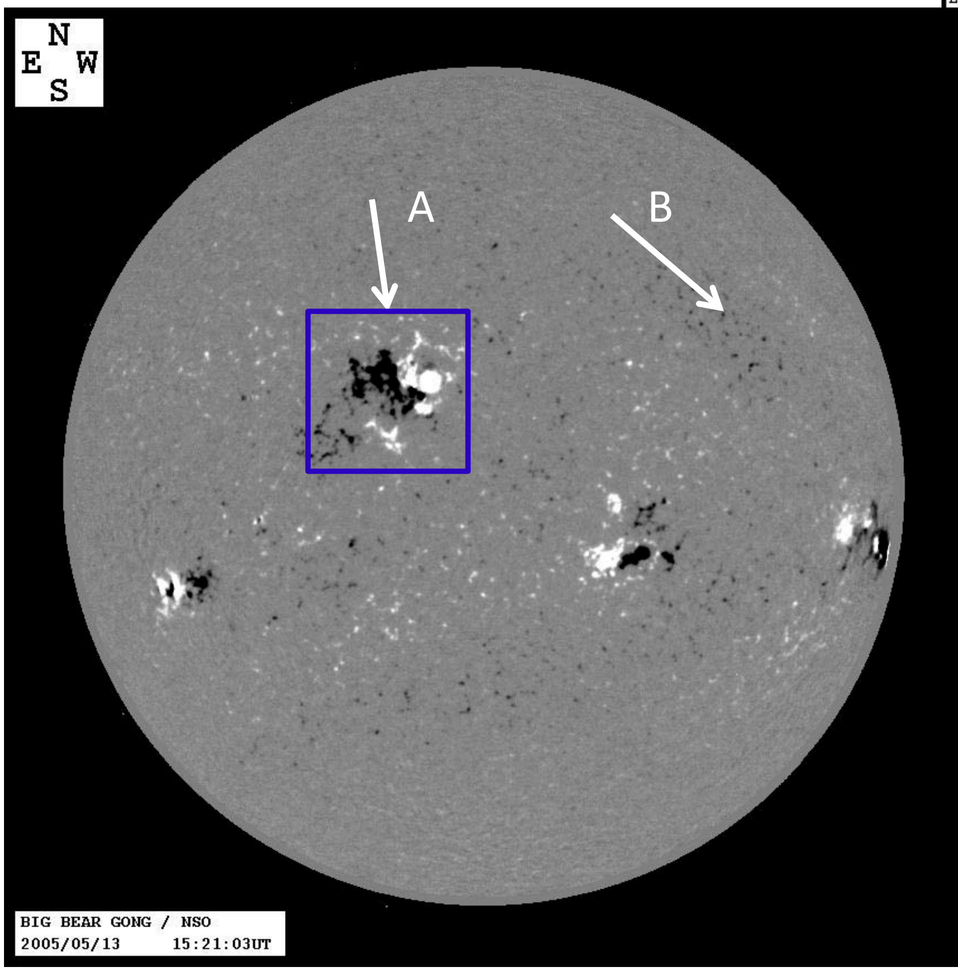


Halo CMEs are more energetic

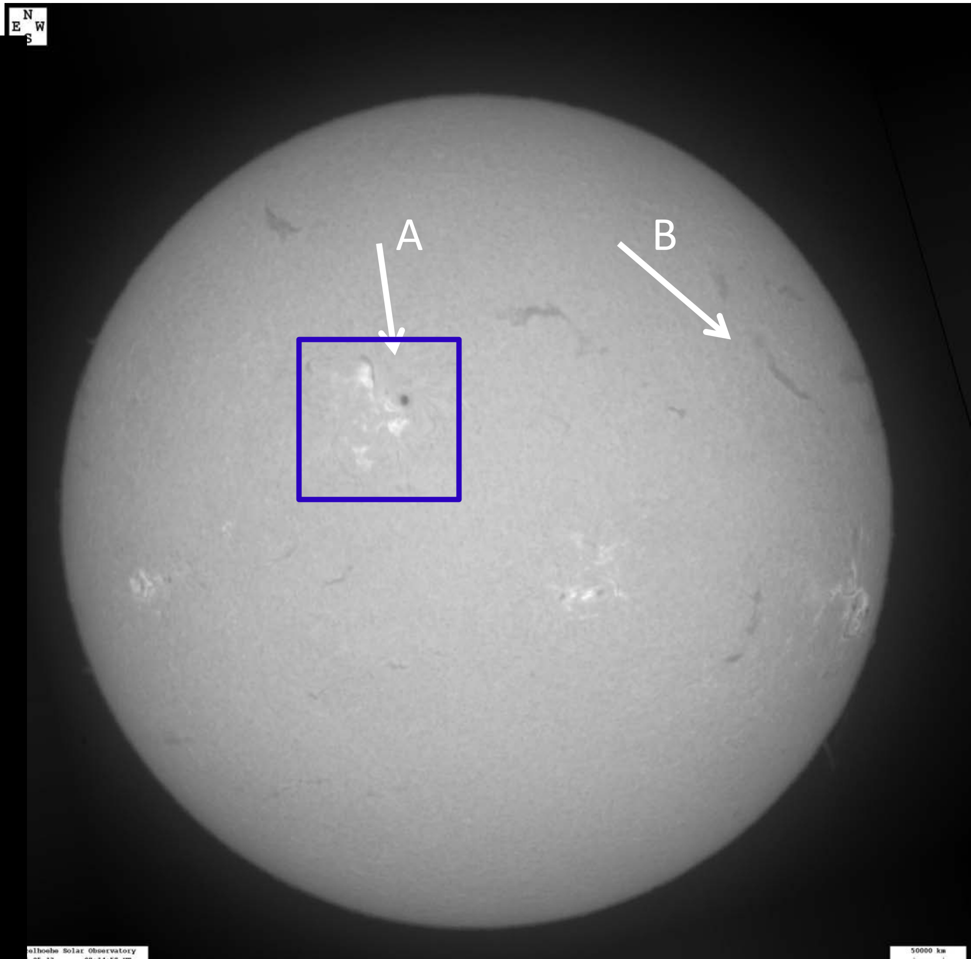
Fraction of halos is a measure of the energy of a CME population

An Eruption Region

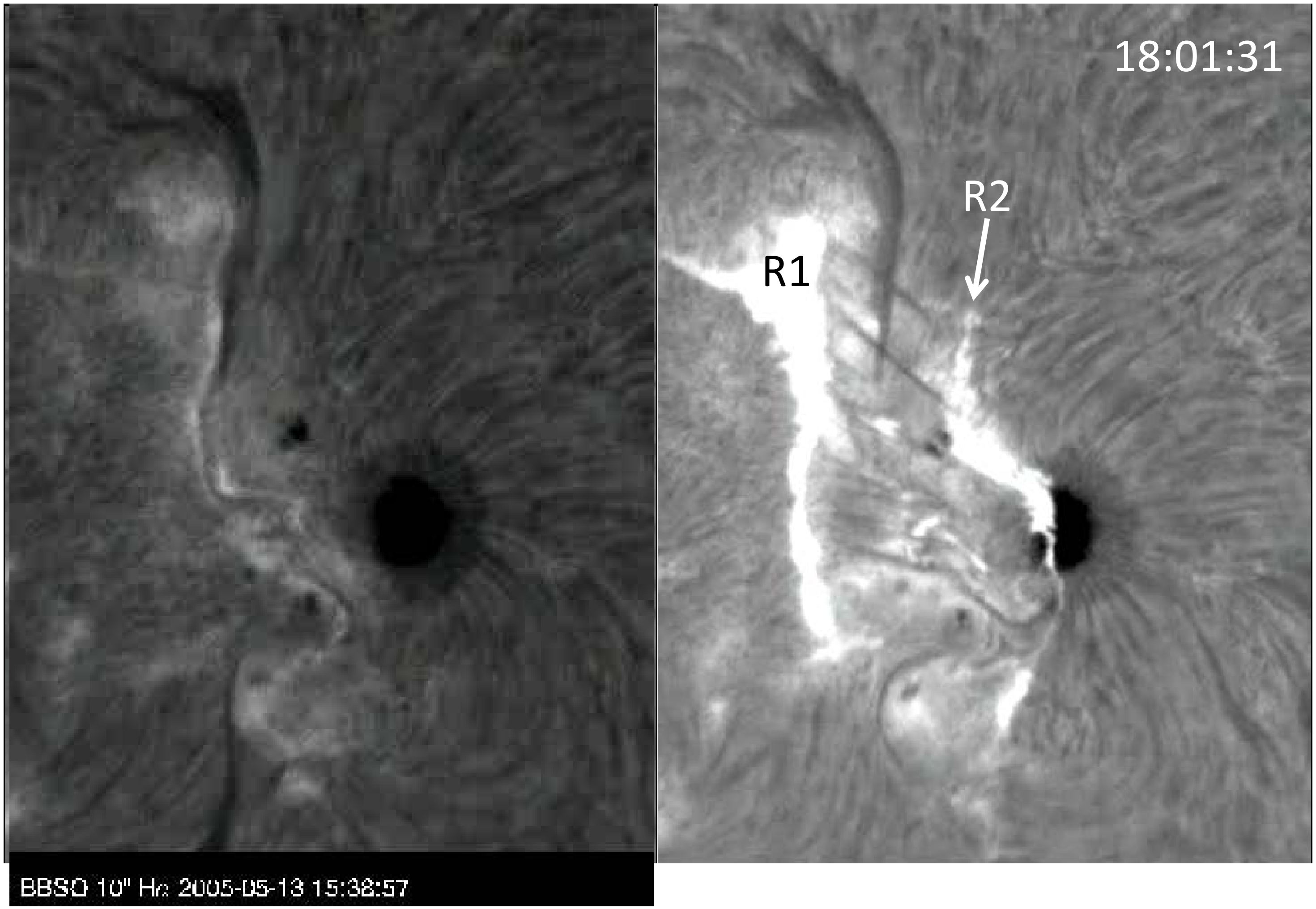
Photosphere



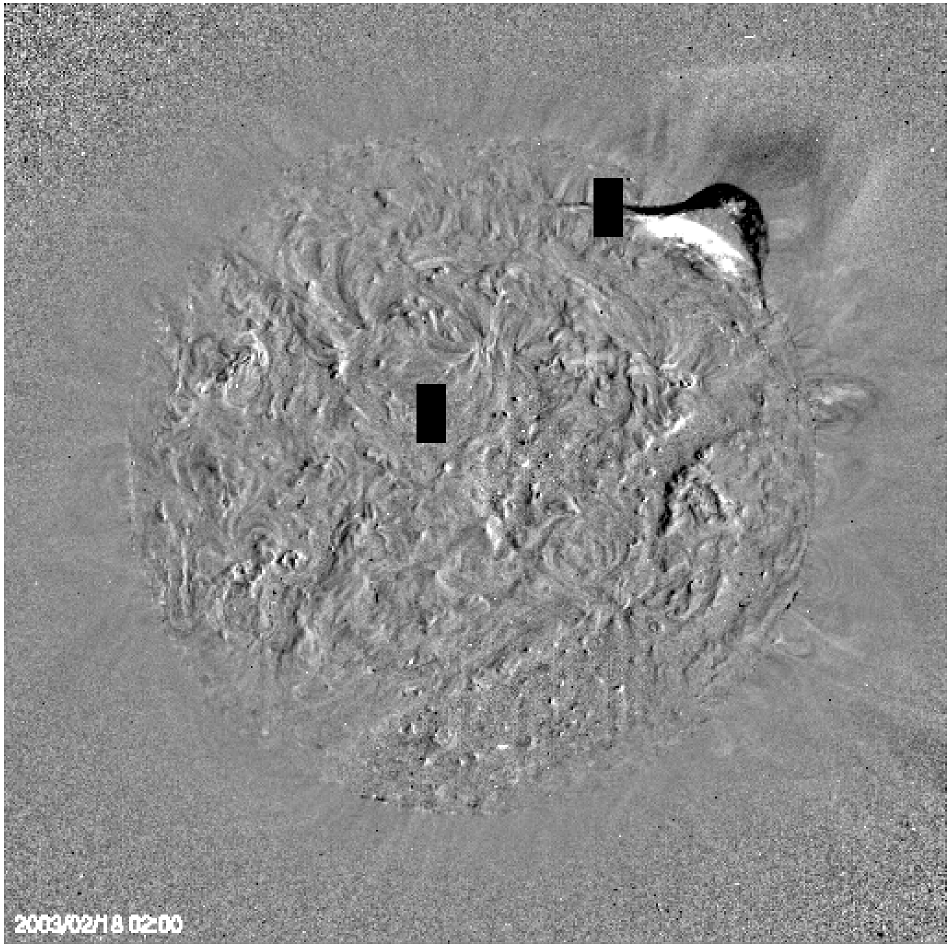
Chromosphere

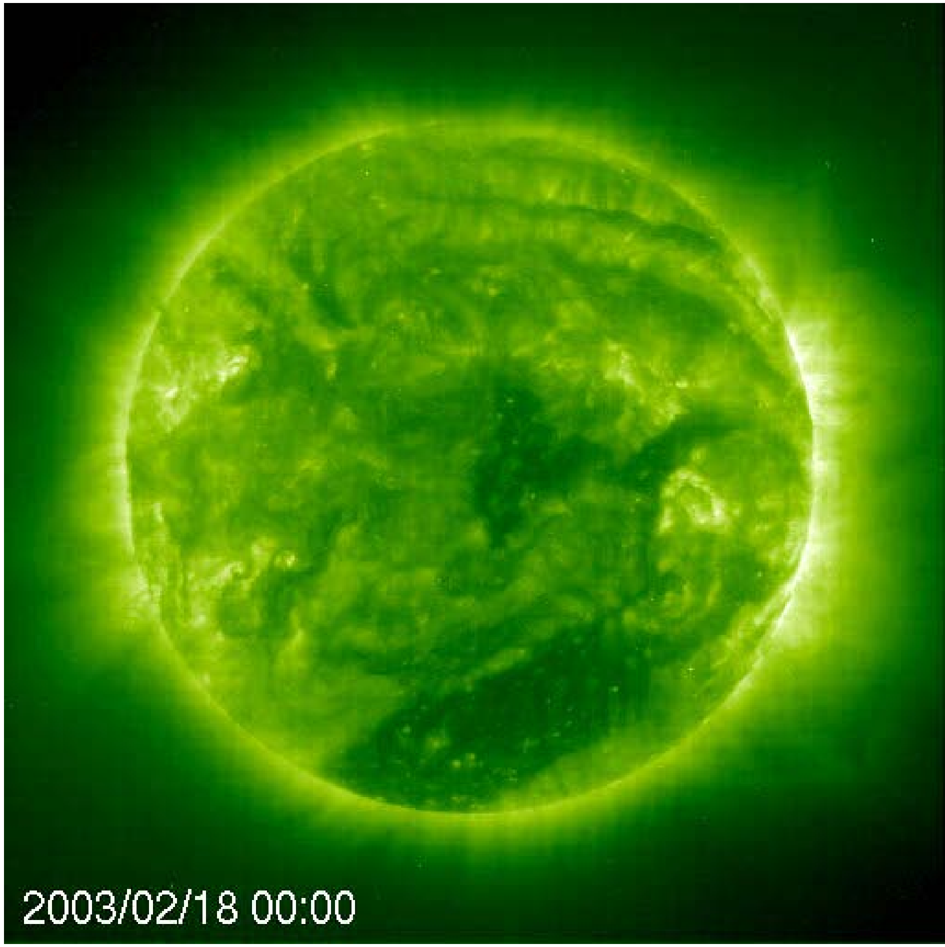


Chromospheric Change

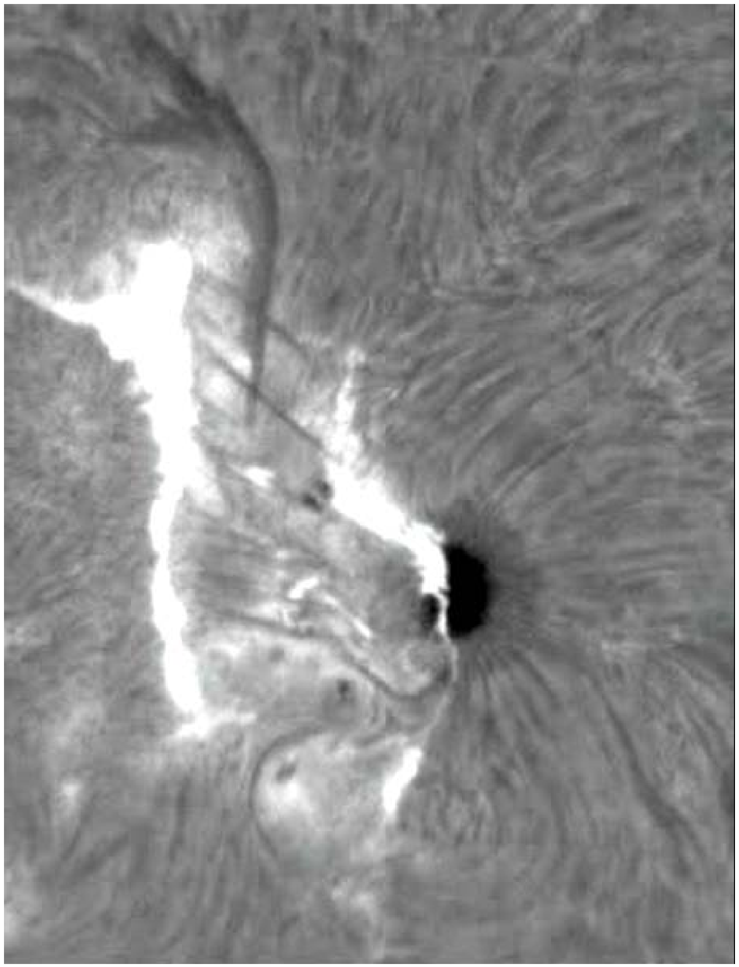


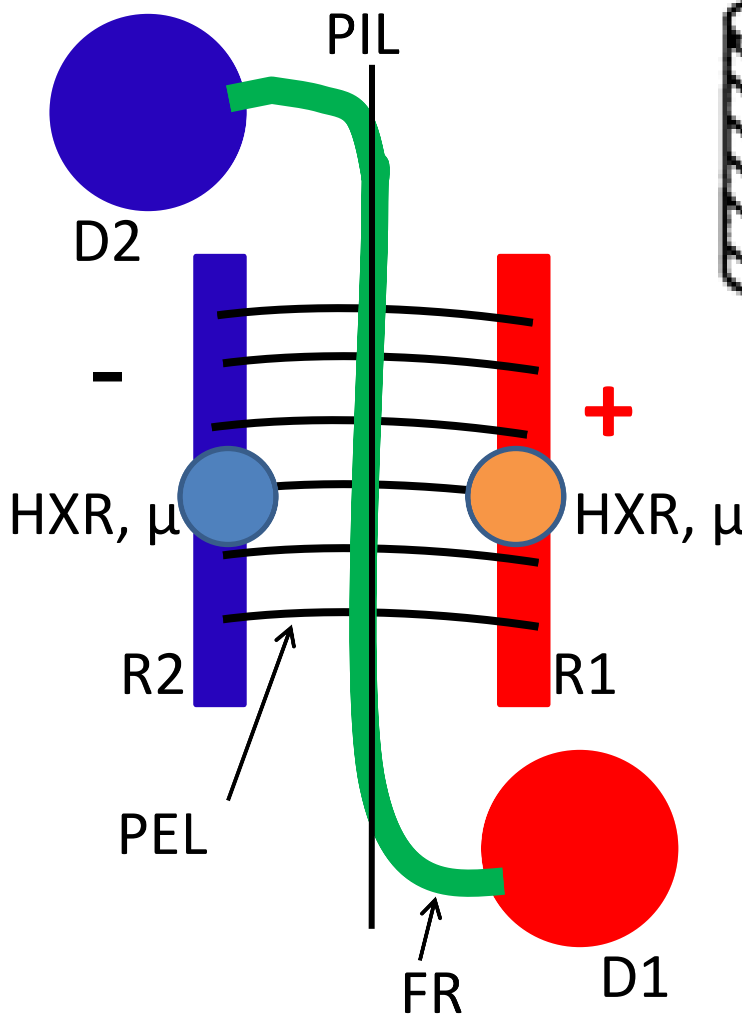
Filament eruption

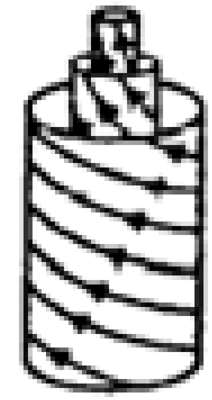




Eruption Geometry Tells About Flux Rope axis



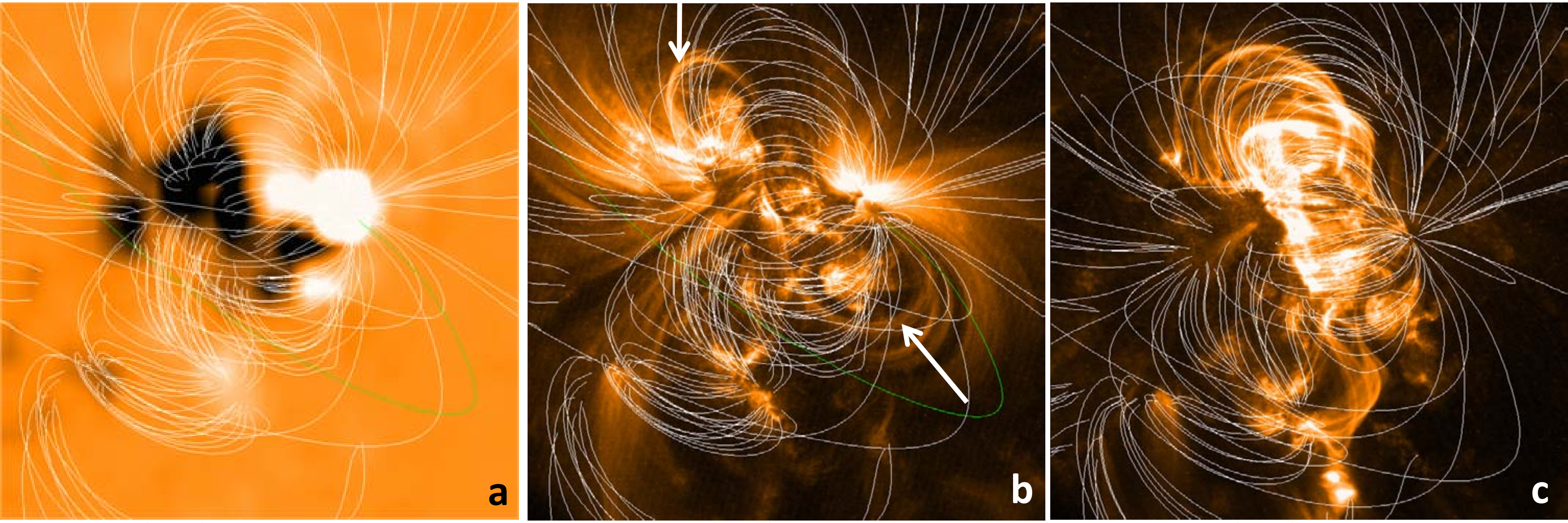




Fully North – No storm

Where does the energy come from?

Extrapolated field lines on TRACE coronal images



2005/05/13 14:56:00

2005/05/13 15:25:56

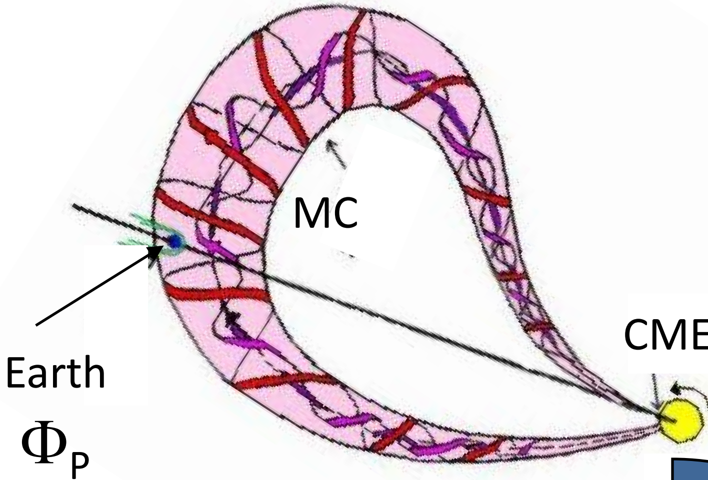
2005/05/13 21:26:36

Photospheric magnetogram with potential field extrapolation

Actual coronal structure is "distorted" from potential field → free energy (FE)

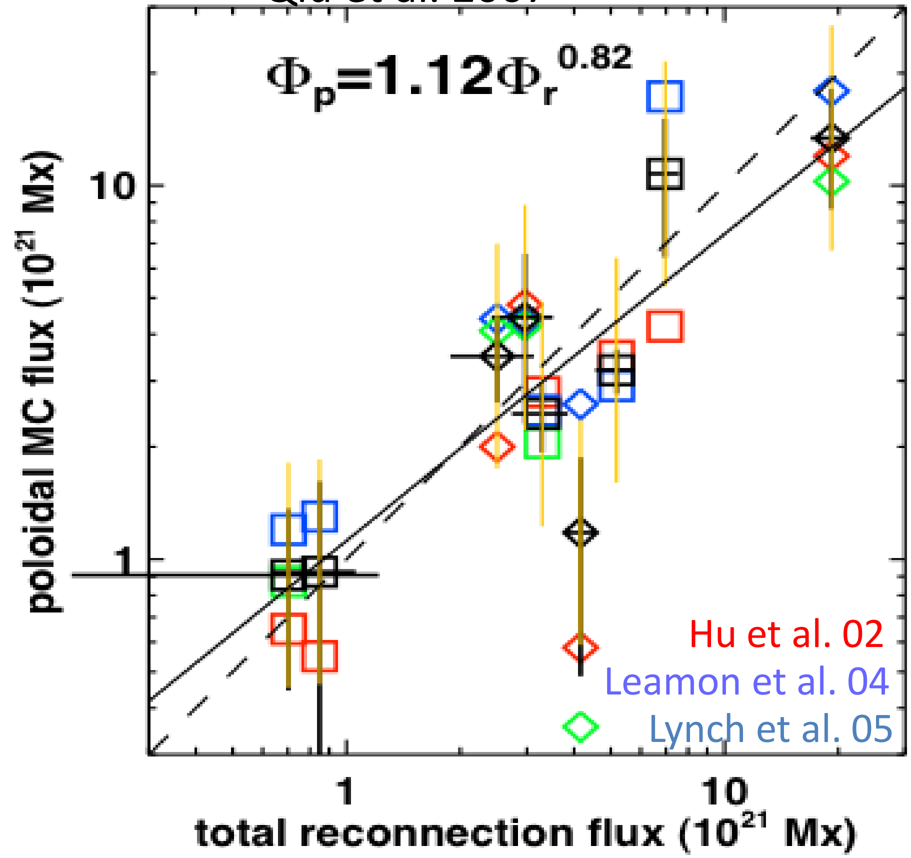
Free energy went into the CME kinetic energy
Arcade is potential

De Rosa & Schrijver

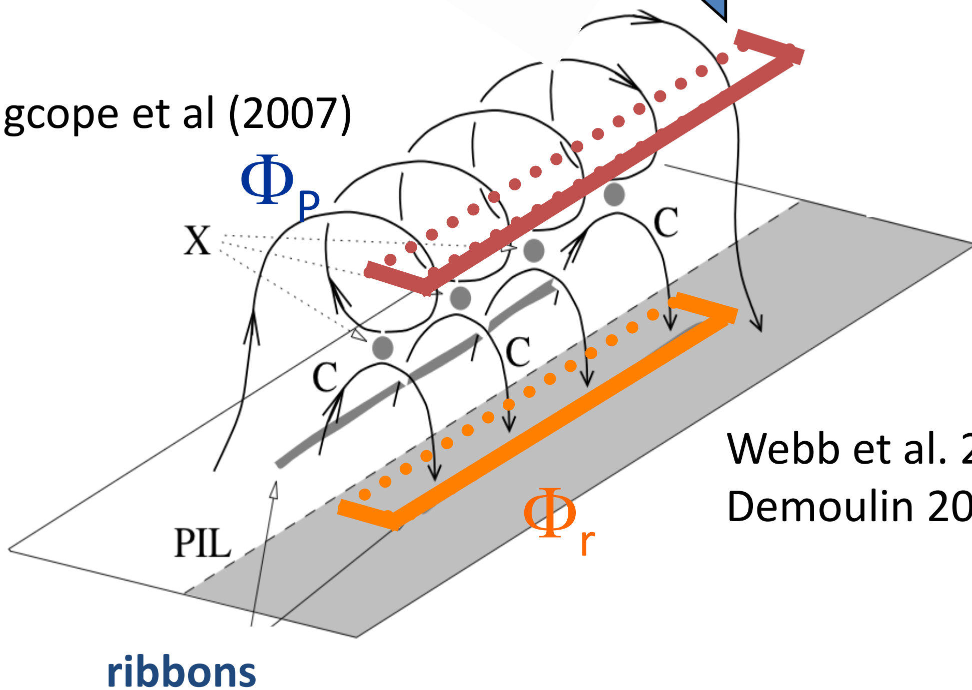


Marubashi 1997

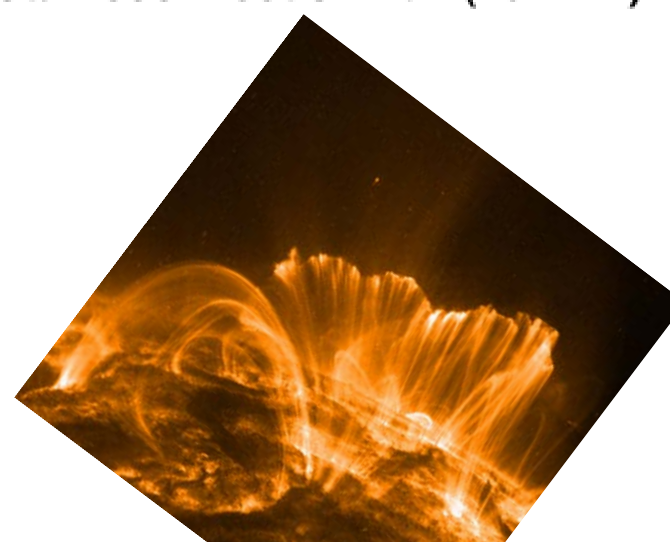
Qiu et al. 2007



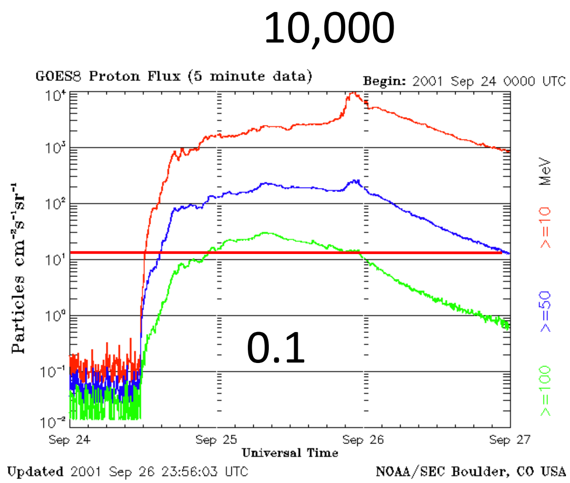
Longcope et al (2007)

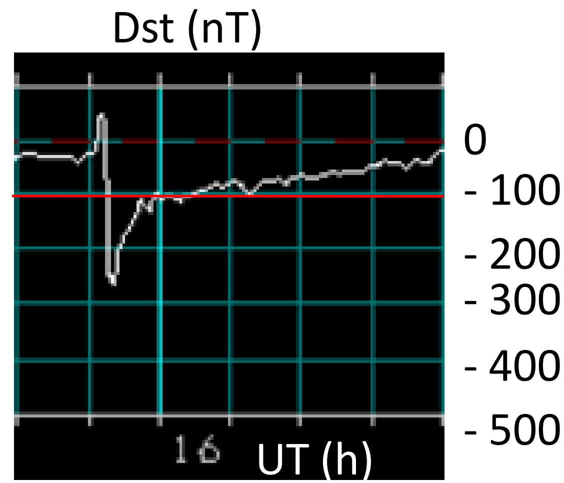


Webb et al. 2000
Demoulin 2008



CMEs & Space Weather





CMEs

On the way and upon arrival

SEPs

Shock-driving Capability is Crucial

$V_{CME} - V_{SW} > V_{MS}$

Space systems
Airplanes
atmosphere

Magnetic storms

Upon arrival at Earth

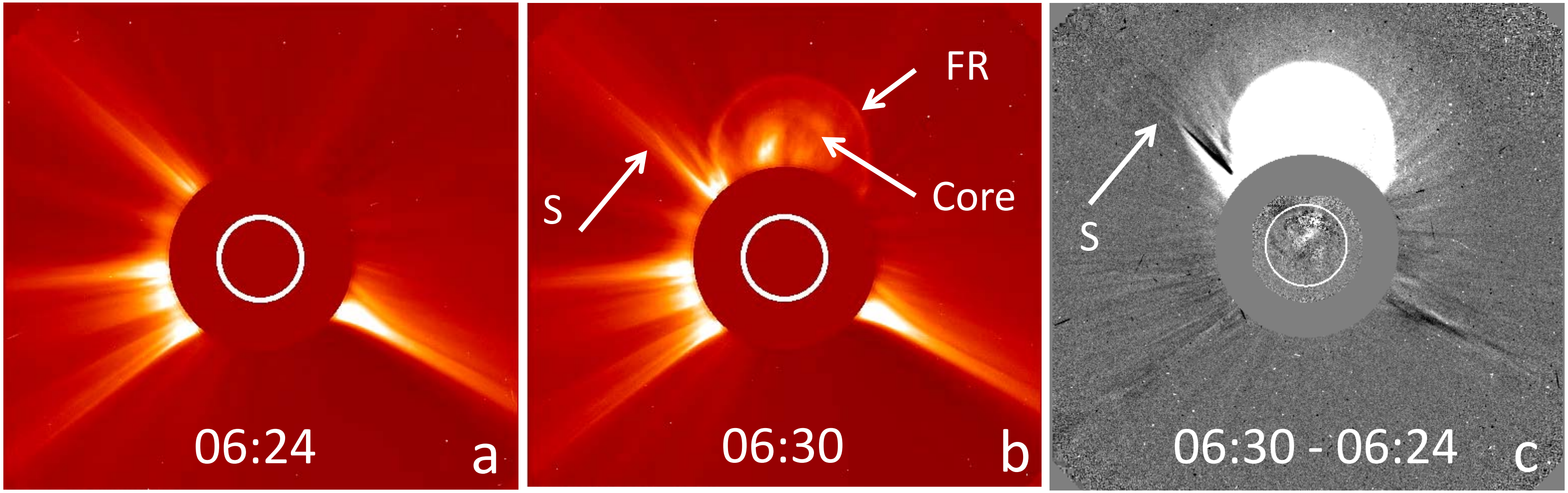
Space systems
Magnetosphere
Ionosphere
Atmosphere
Ground

CME's Magnetic Structure Is Crucial
(Bz <0)

CMEs & SEPs

Four-part Structure!

Shock Sheath in white light



White light CMEs were discovered in 1971
(Koomen, 1972; Brueckner, 1972, Tousey, 1973
But CME substructures were recognized for nearly
a century!

Gopalswamy, 2010 Springer book

Radio Bursts Reveal Matter Leaving the Sun

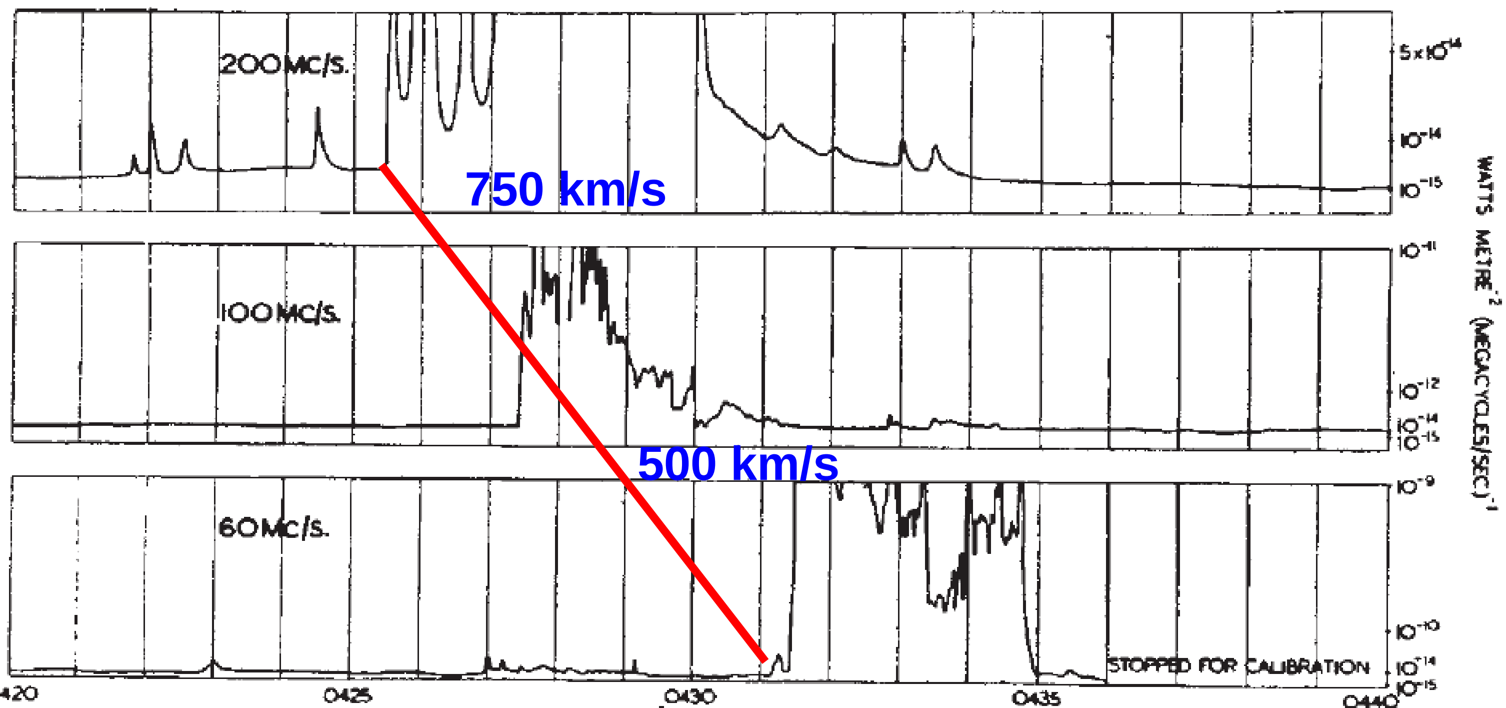
Ruby Payne-Scott
1912 – 1981

The whole pattern drifts;
140 MHz in 6 min
df/dt = 0.4 MHz/s

Plasma density
5.0×10^{8} cm^{-3}

1.2×10^{8} cm^{-3}

0.4×10^{8} cm^{-3}

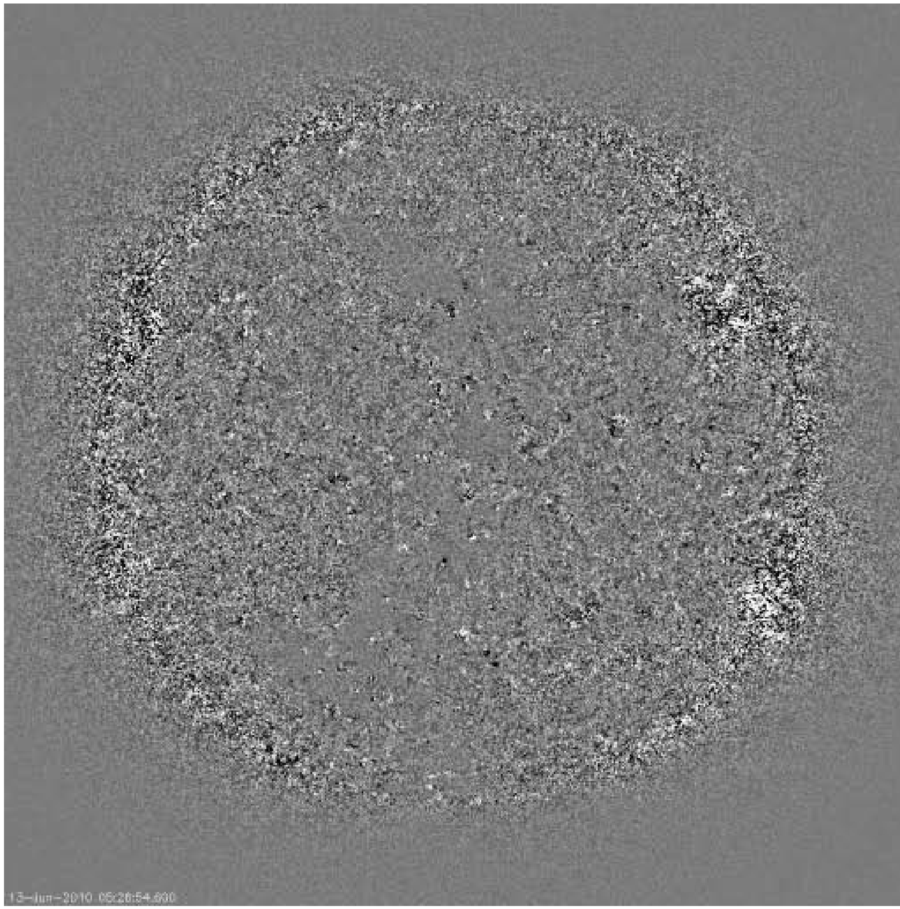


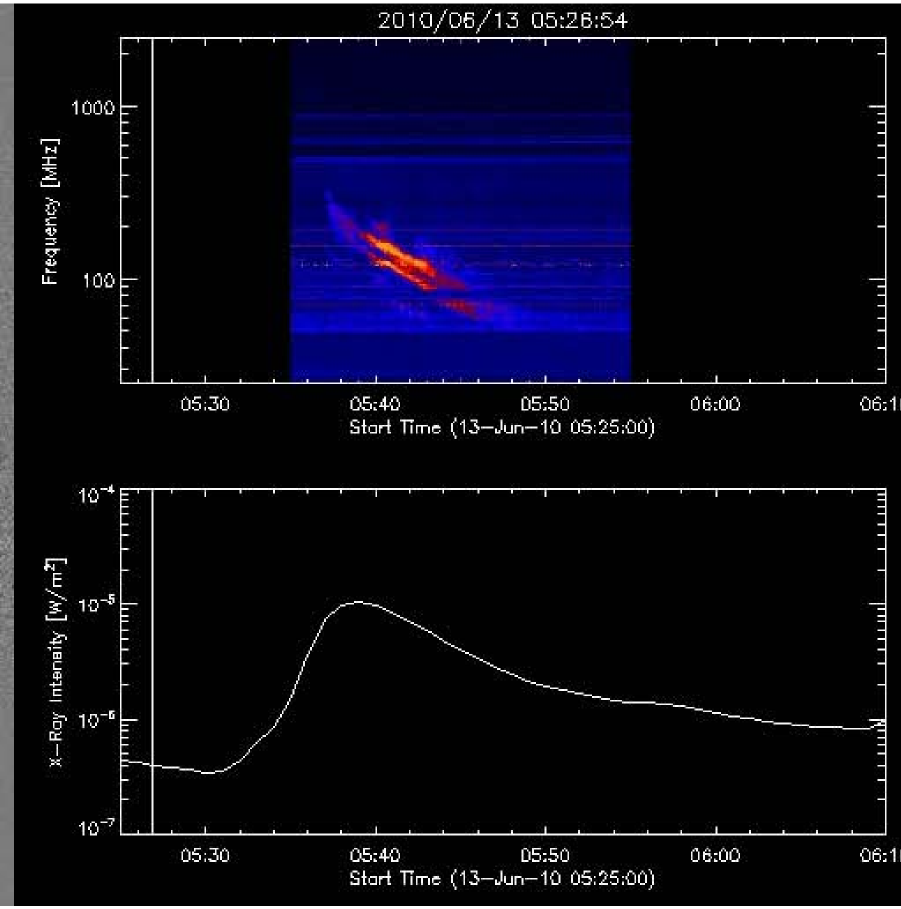
Nature 260, 256, 1947

LARGE OUTBURST OF MARCH 8, 1947

2010/06/13

f_p = 150 MHz → n_p =2.8x10^8 cm^{-3}





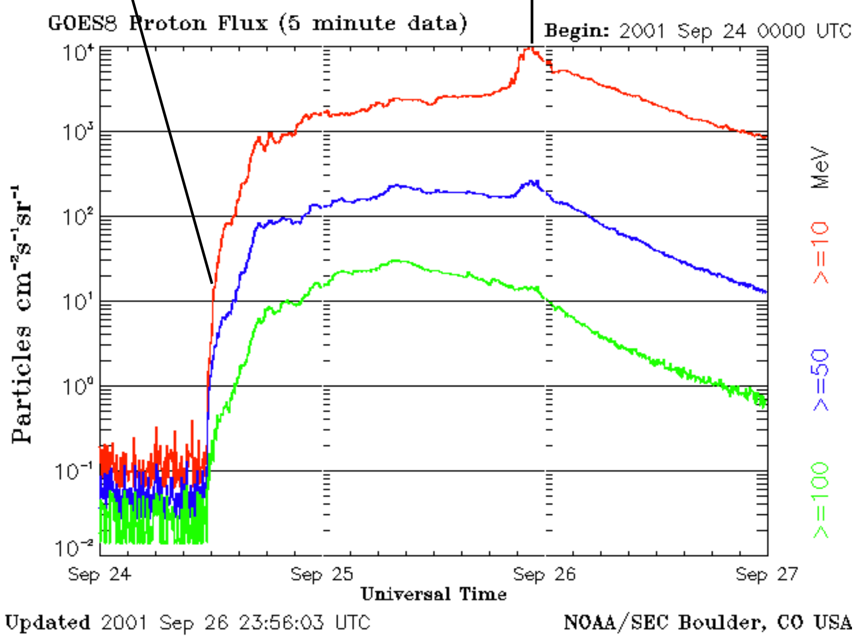
CME starts at 5:34 at 1.13 Rs; Type II starts at 5:36 when the CME at 1.17 Rs; shock 1.19 Rs

Radiation hazard is of primary concern for space missions

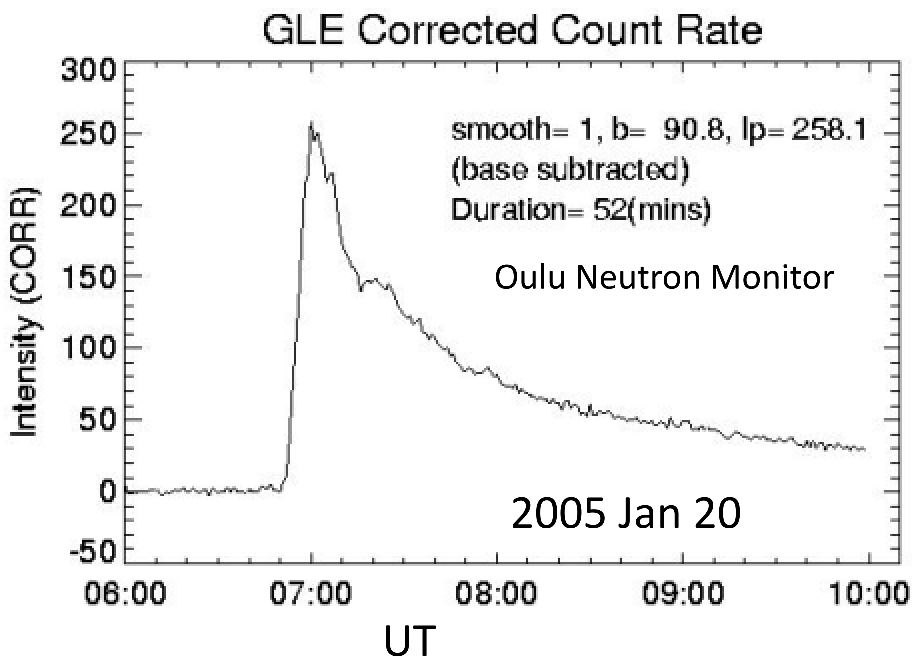
CME-related Energetic Particles

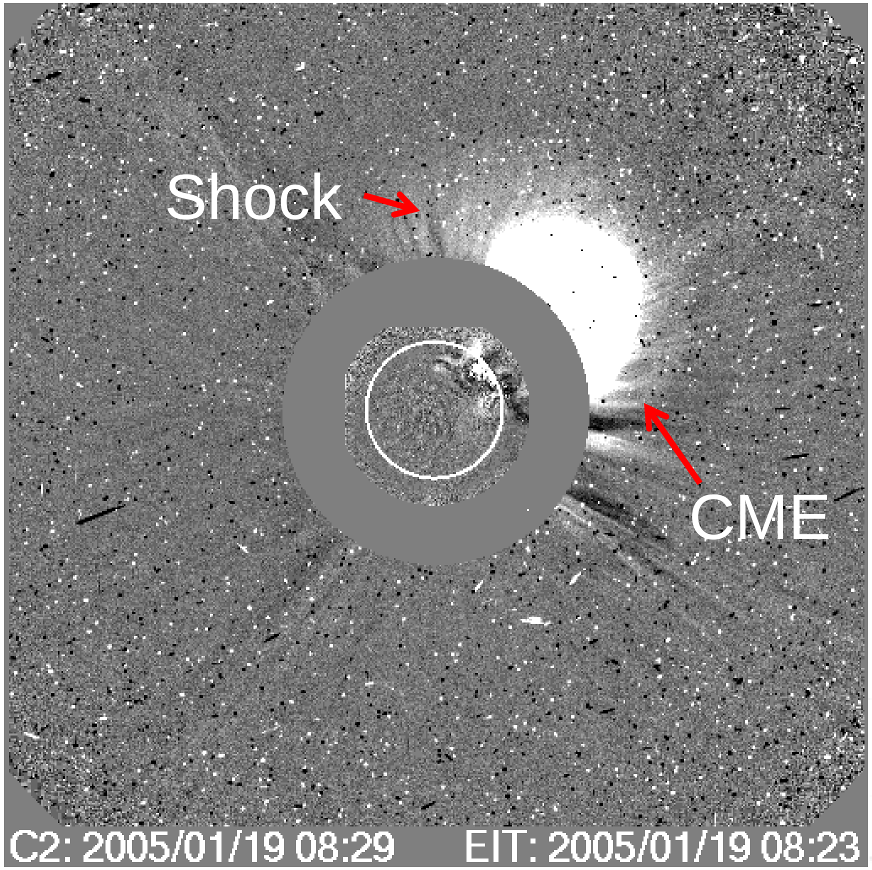
SEPs accelerated when the shock is far away from the detector

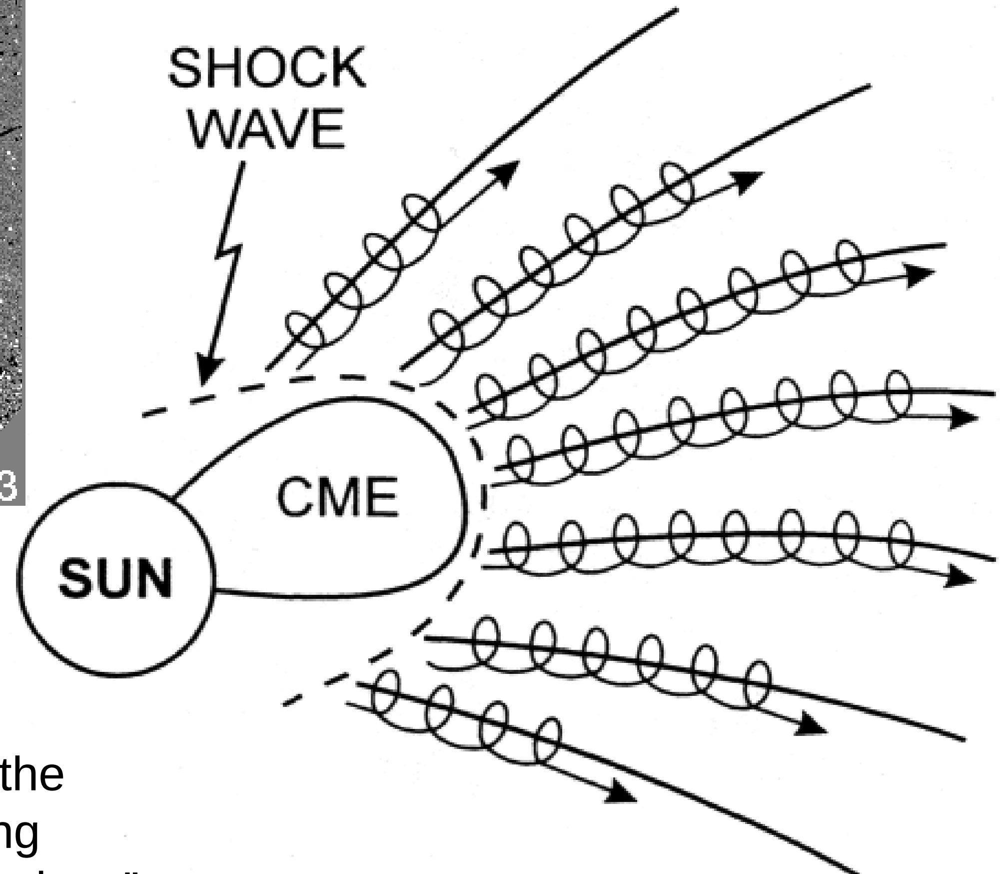
Energetic Storm Particle (ESP) events: acceleration when the shock is at the detector



SEPs with ground-level enhancements







“energetic protons are accelerated in the shock front just ahead of the expanding loop structures observed as mass ejections”
Kahler, Hildner, & Van Hollebeke (1978)

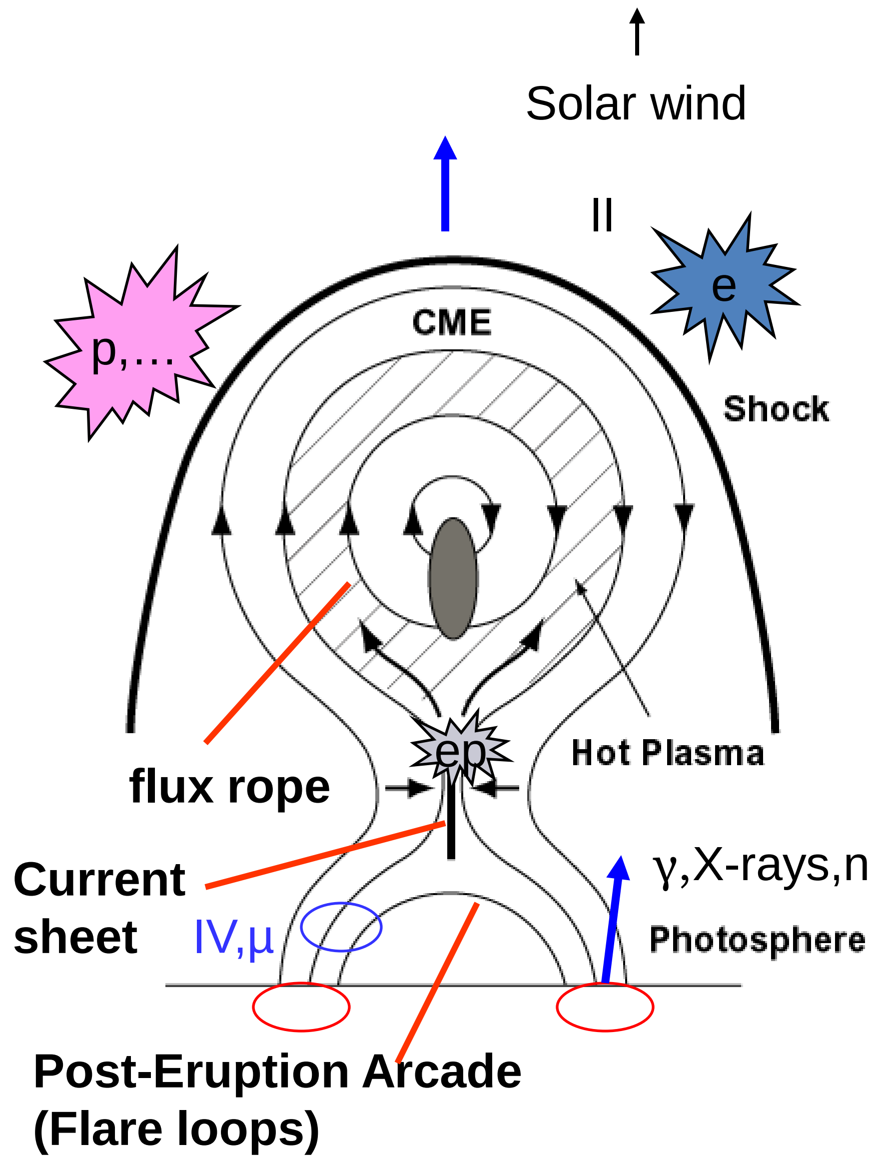
Two Processes for Particle Acceleration

Flare Reconnection
Shock

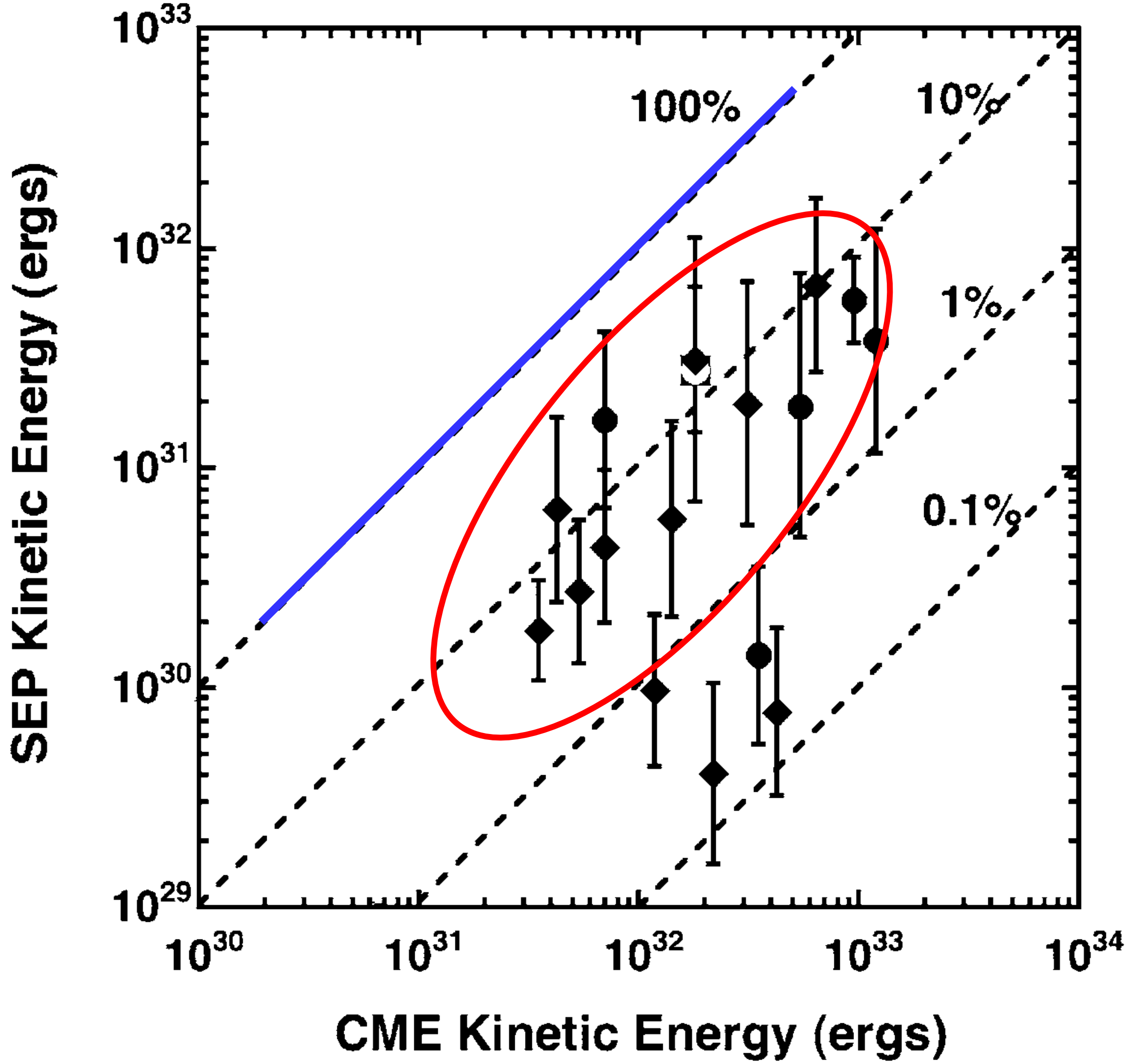
Shock: large SEP events
CME a must

Flare: impulsive SEP events,
Much smaller, high charge states
CME may or may not accompany

The relative contribution from
Flare & CME in a given event
under debate



CMEs are Efficient Accelerators

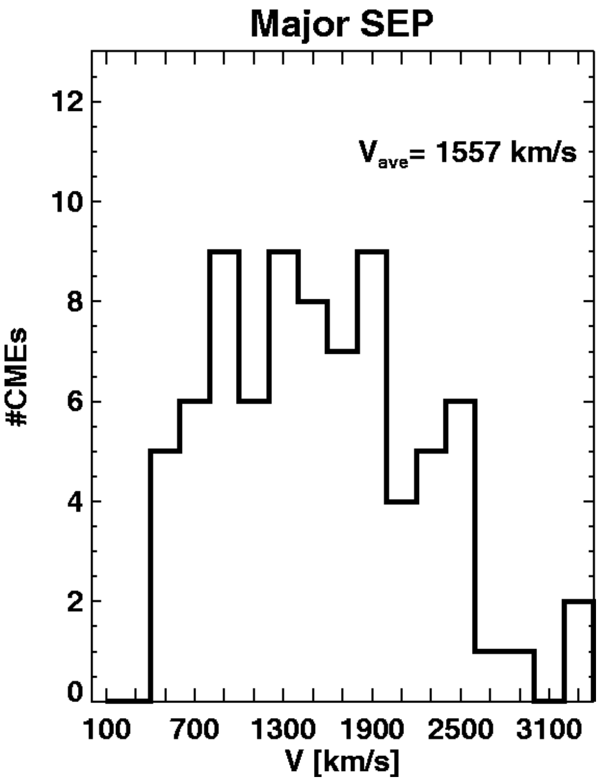


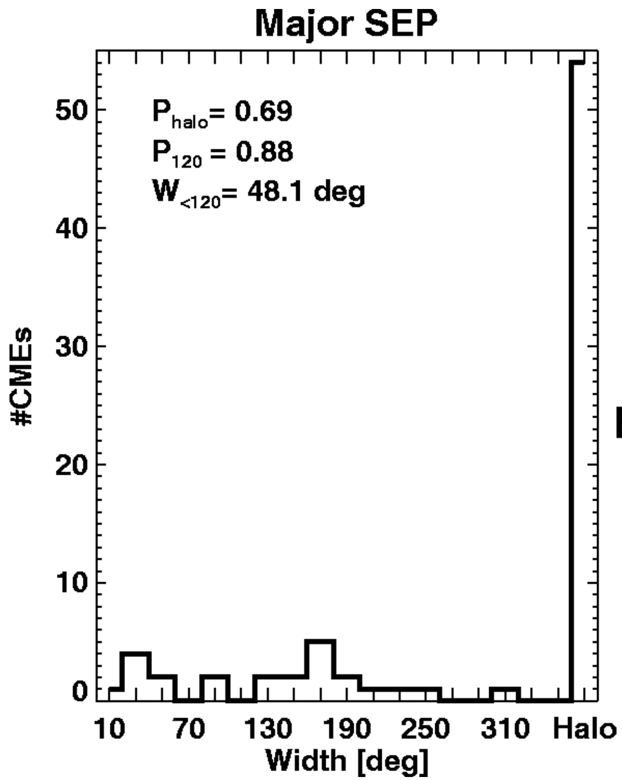
Typically about 10% of CME kinetic energy goes into SEPs

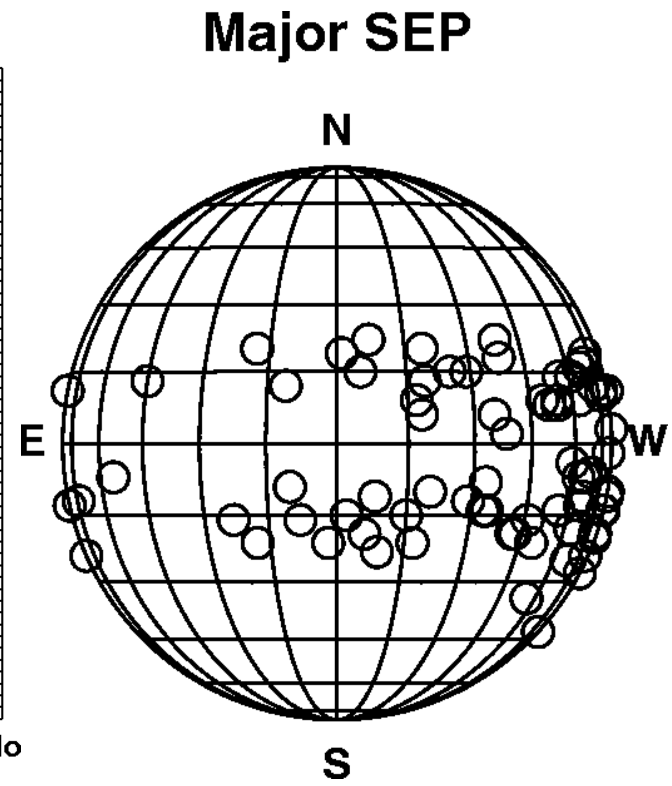
Expect GLEs to be associated with faster CMEs

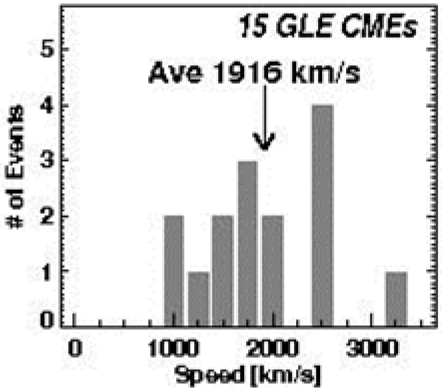
Mewaldt, 2006

SEP-Producing CMEs



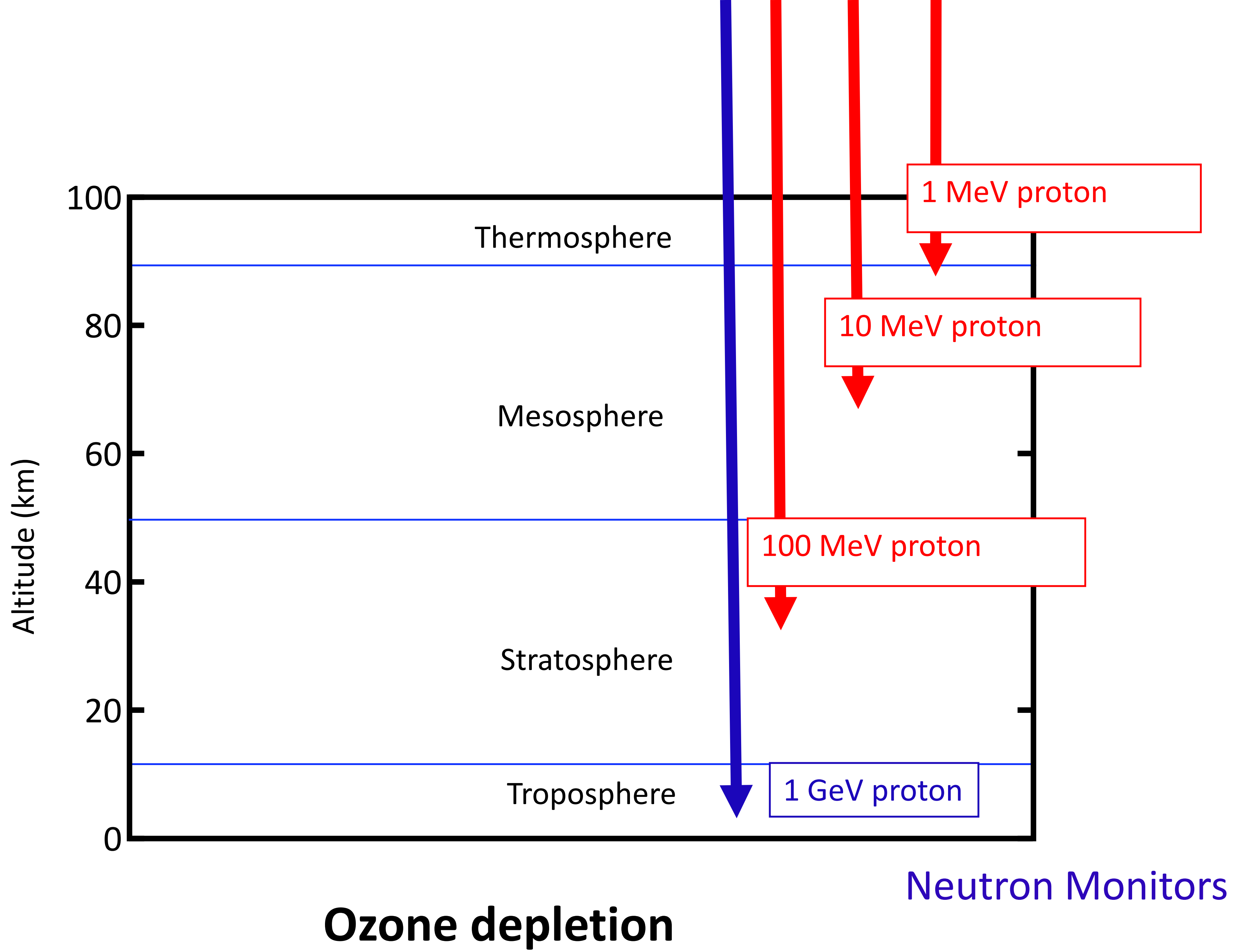






Fast and wide CMEs from mostly the western hemisphere

From the active region belt



1 MeV proton
10 MeV proton
100 MeV proton
1 GeV proton
100
80
60
40
20
0
Altitude (km)
Thermosphere
Mesosphere
Stratosphere
Troposphere
Neutron Monitors
Ozone depletion

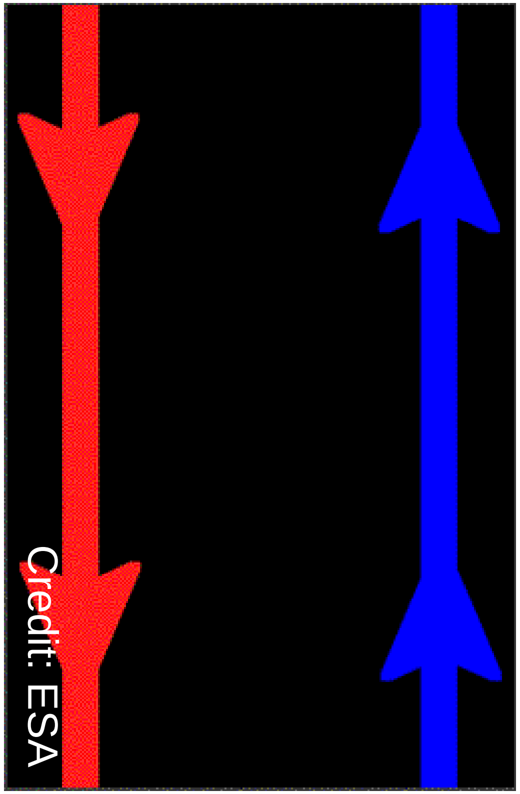
CMEs and Geomagnetic Storms

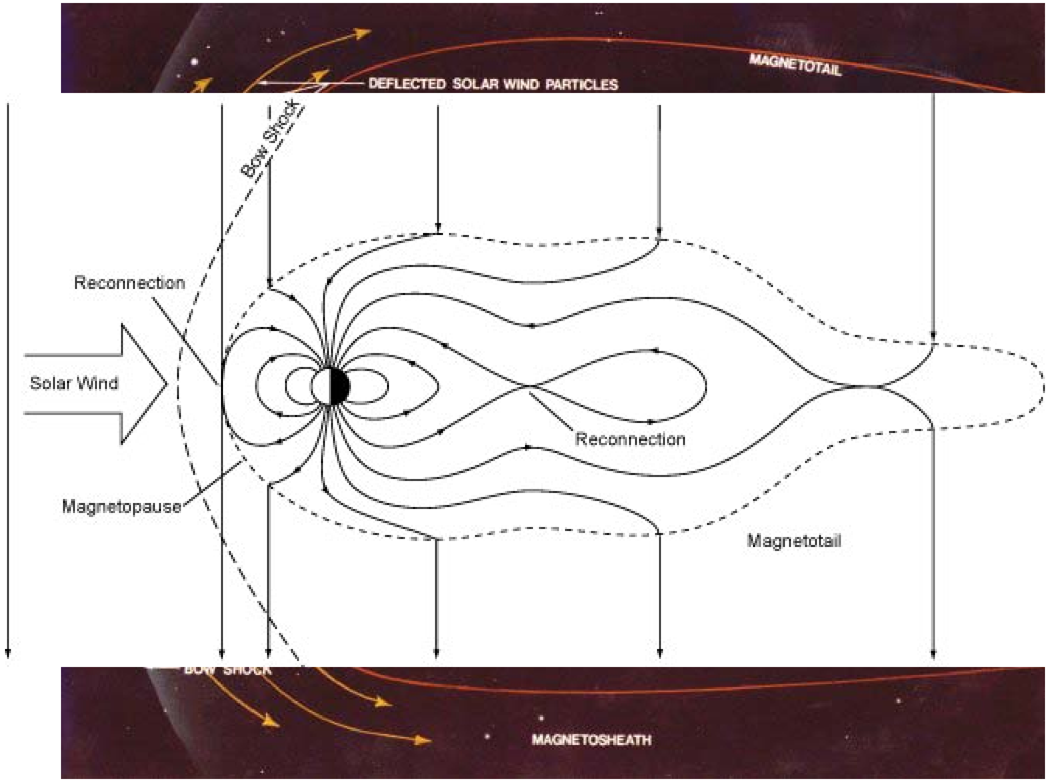
- Direct impact of CME plasma on Earth's magnetosphere
- Causes ring current enhancement
- Acceleration of electrons inside the magnetosphere
- Sudden commencement and exposure of geosync satellites to the interplanetary space
- …

magnetic reconnection: A key physical process

Reconnection leads to particle acceleration at the Sun
→ Flares

Reconnection between interplanetary and Earth's dayside magnetic fields is the basic process for magnetic storms. A second reconnection on the nightside pushes plasma towards Earth



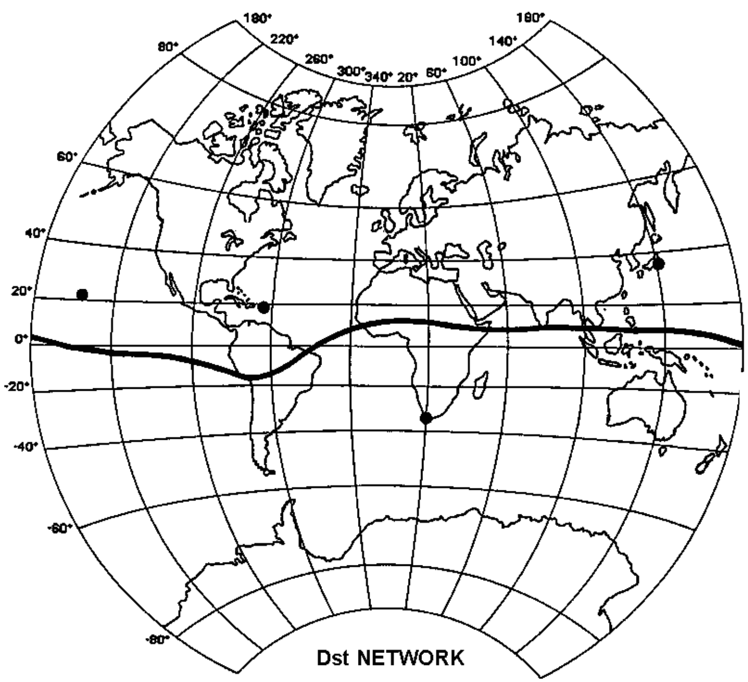


Dungey, 1962

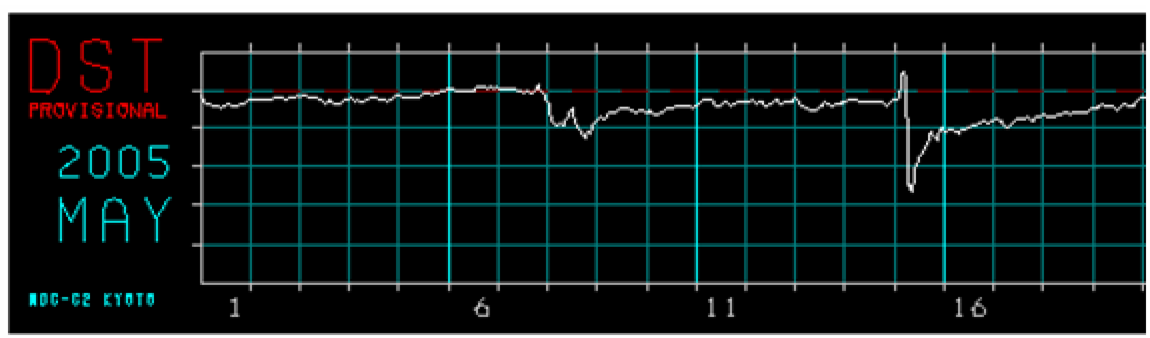
Dst Index

http://swdcwww.kugi.kyoto-u.ac.jp/dst2/onDstindex.html

- A geomagnetic index describing variations in the equatorial ring current.
- Positive: Sudden compression of the magnetosphere (e.g. IP shock)
- Negative: Ring current enhancement causing a decrease in horizontal B



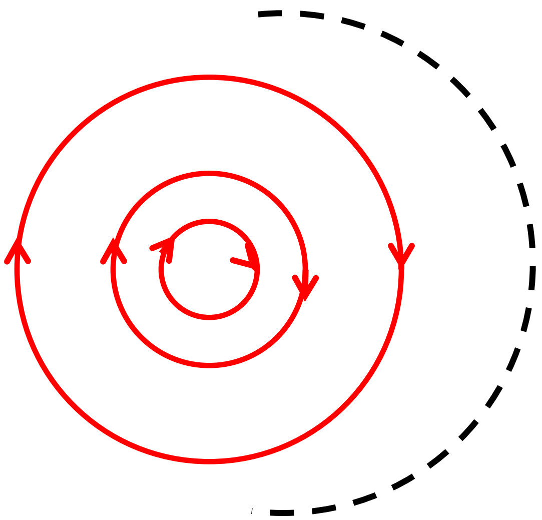
A CME (or any solar wind structure) is said to be Geoeffective if it results in Dst ≤ -50 nT.
Dst < -100 nT → intense storms

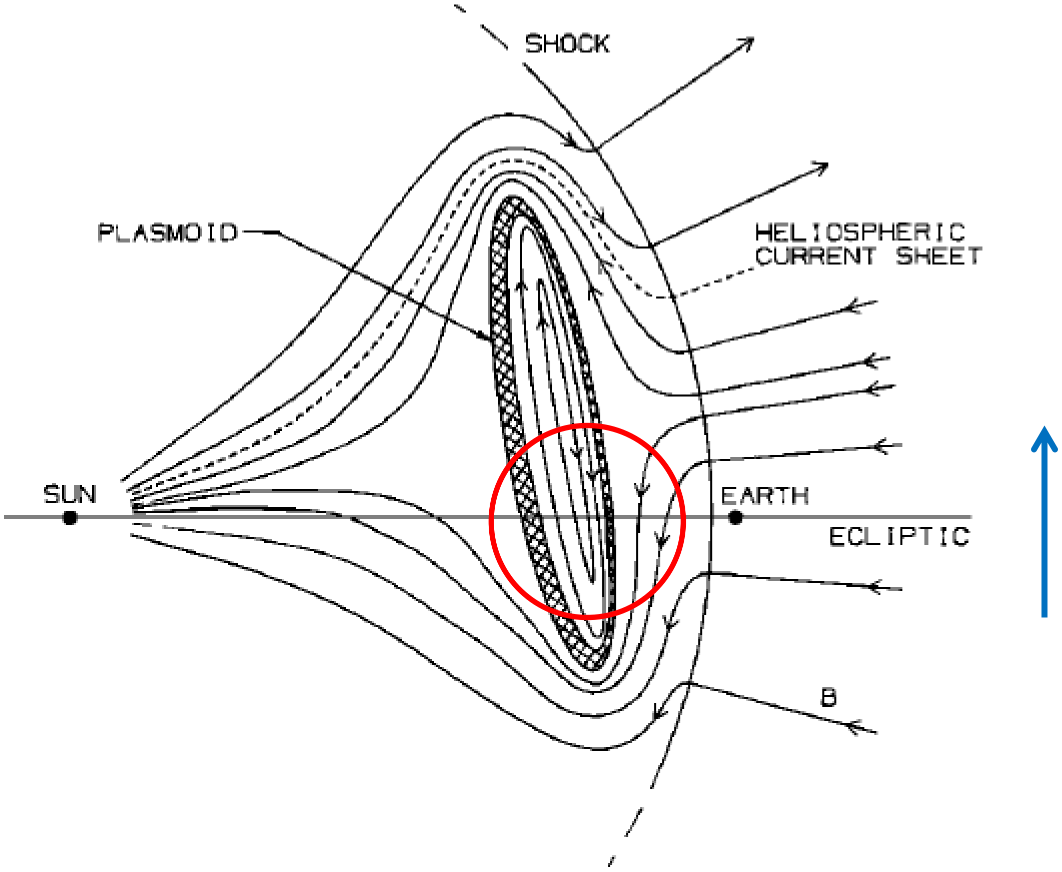


Out of the Ecliptic B from CMEs

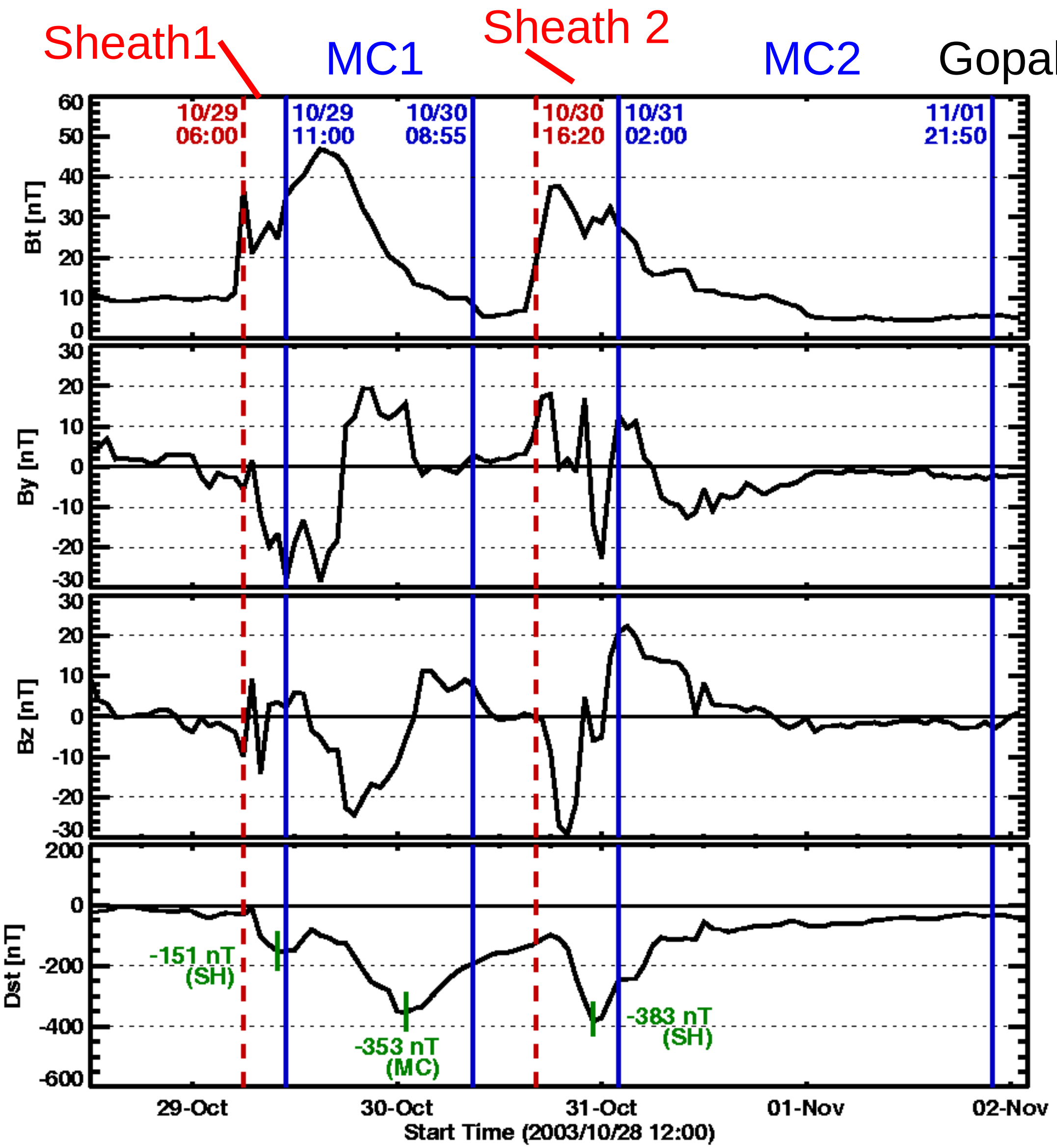
- Normal Parker-spiral field does not have a Bz component
- CMEs with flux rope structure (magnetic clouds) naturally produce the Bz component
- Magnetic field draping in the shock sheath can also cause Bz (Gosling & McComas, 1987; Tsurutani & Gonzalez, 1988)
- Corotating interaction regions
- Alfven waves

Out of the ecliptic B component due to the CME and draping



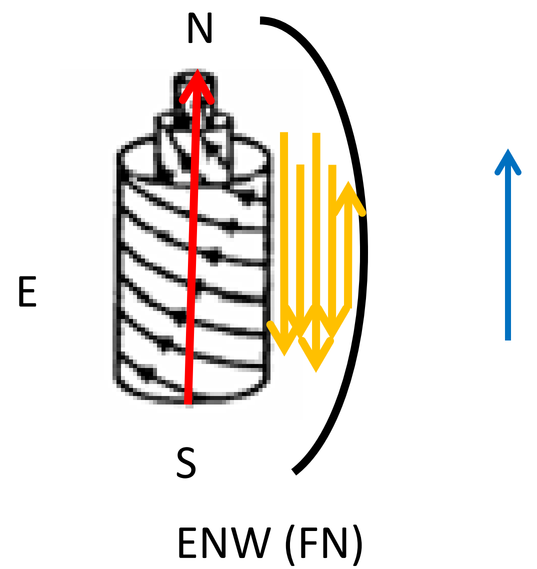


Gosling and McComas, 1987 GRL



Gopalswamy et al., 2008

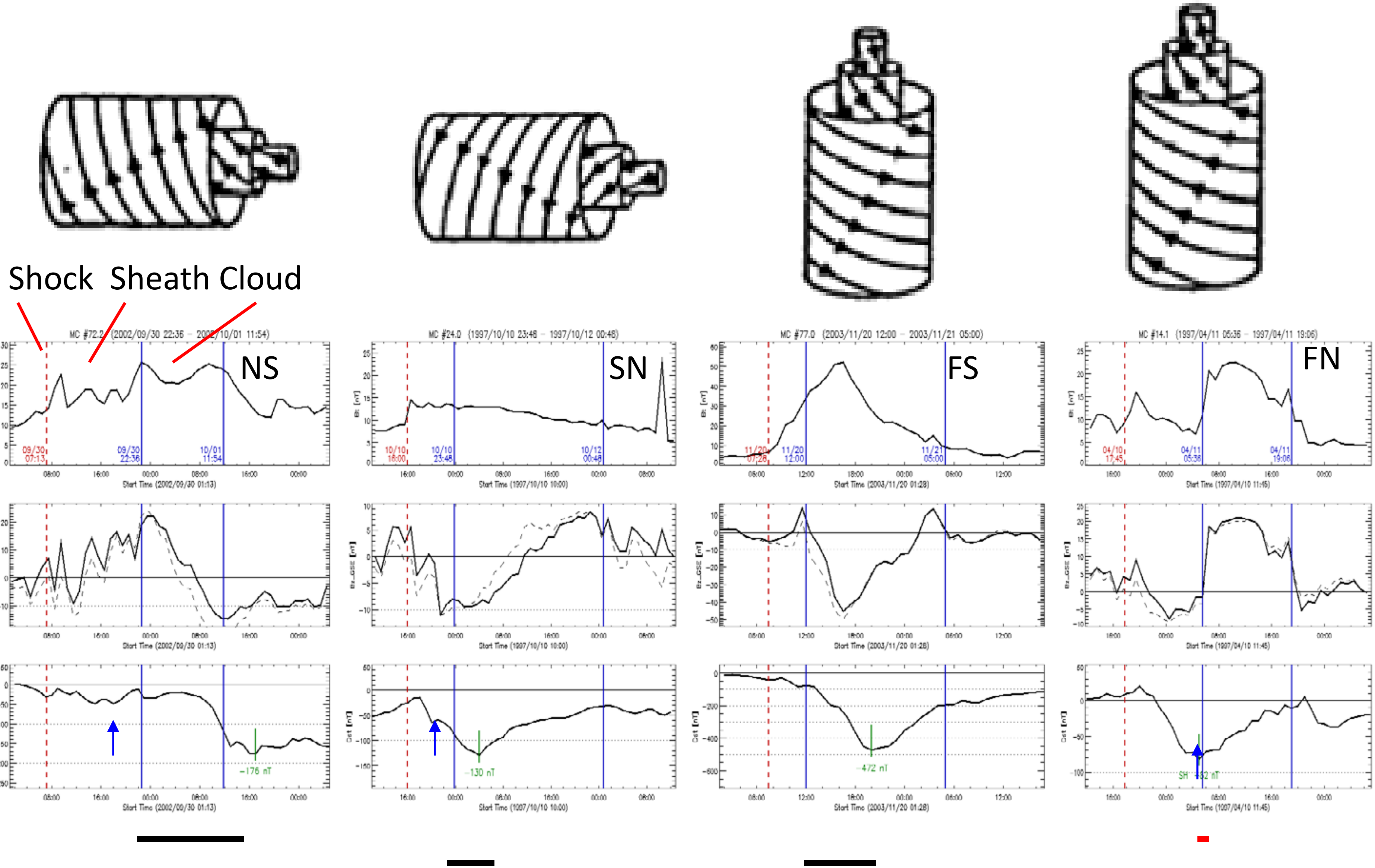
Sheath Superstorm



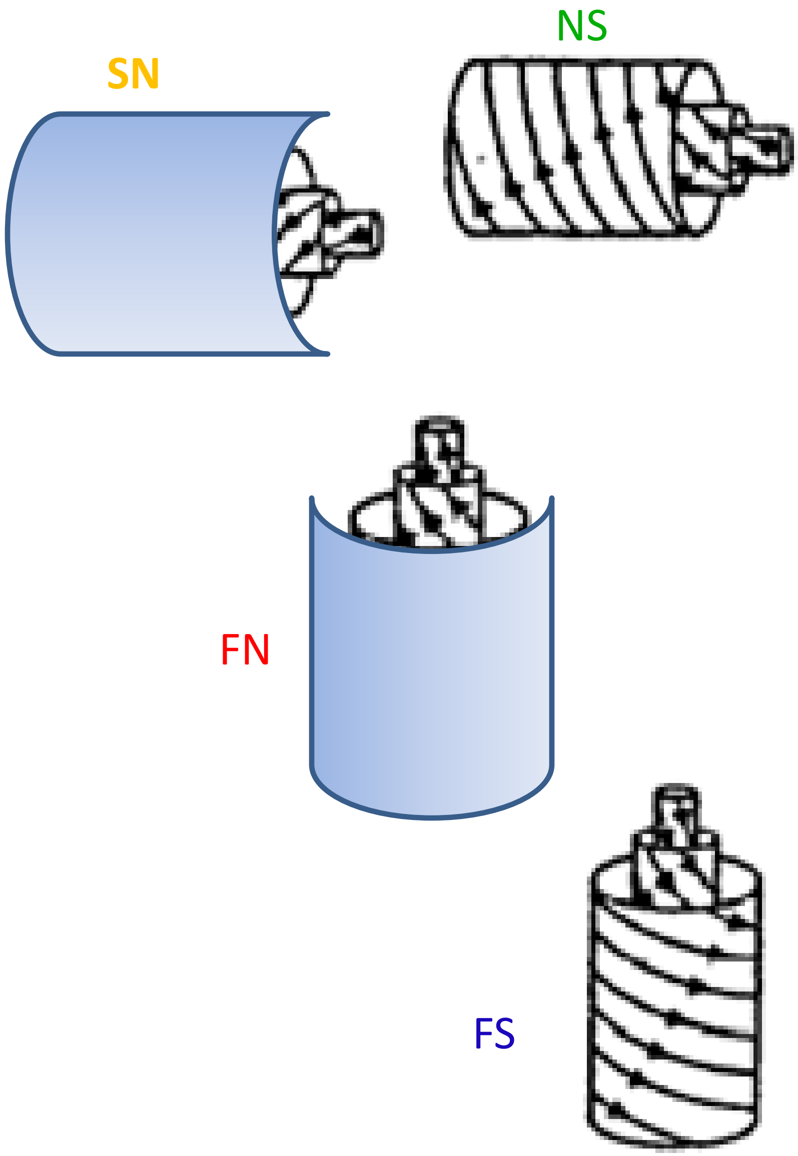
When MCs have high inclination the rotation is in the Y direction.
In the Z-direction, the field will be always to the north or south.
In this example, Bz is always north pointing so no storm. But there was a big storm due to the sheath consisting of intense south pointing Bz

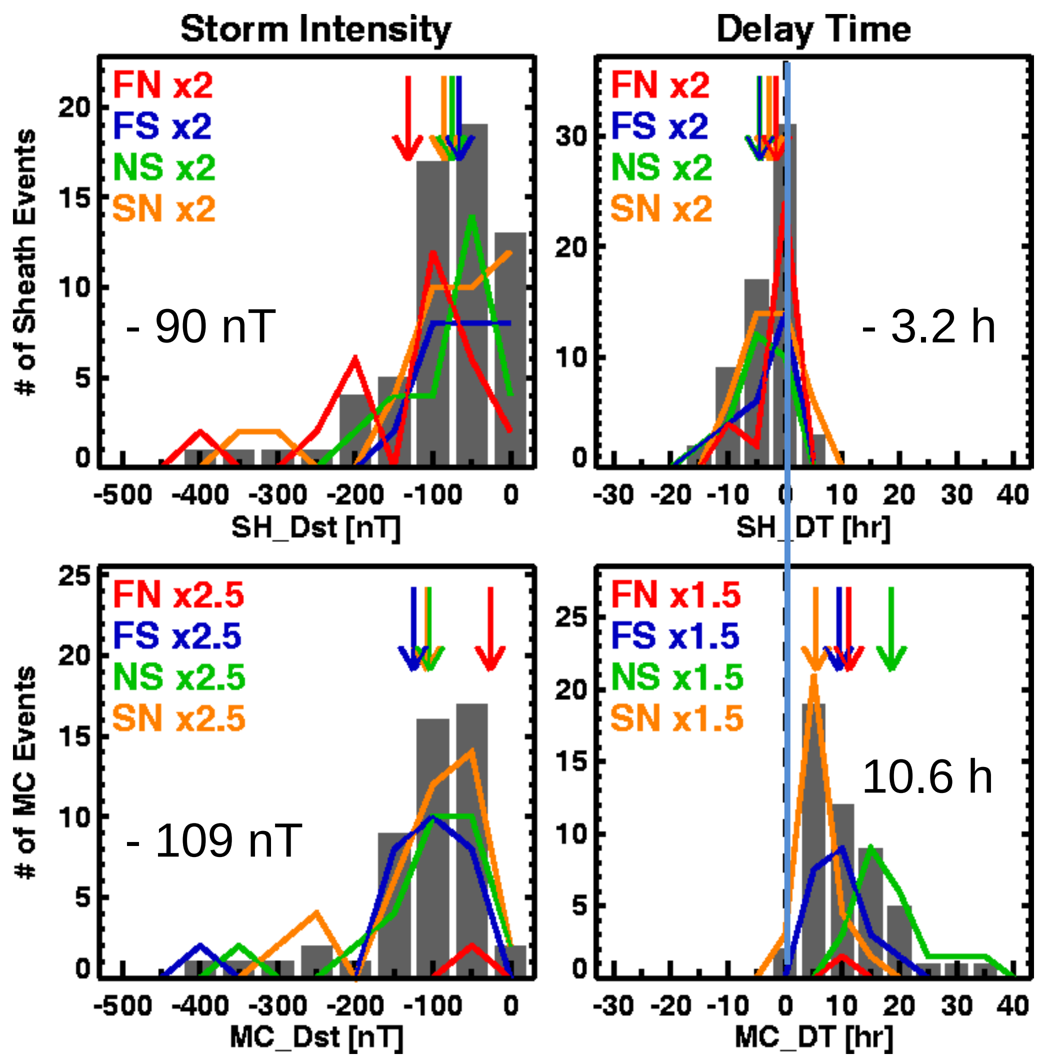
Gosling and McComas1987; Tsurutani et al 1988

Summary of MC Structure

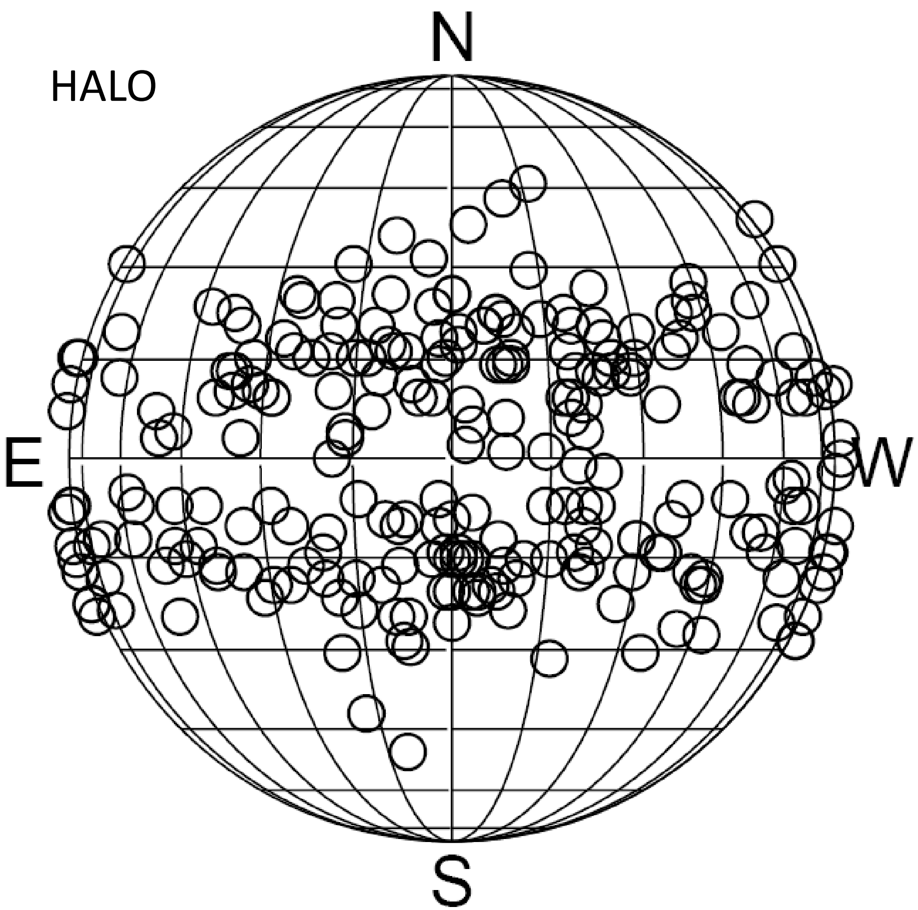


Cloud & Sheath Storms

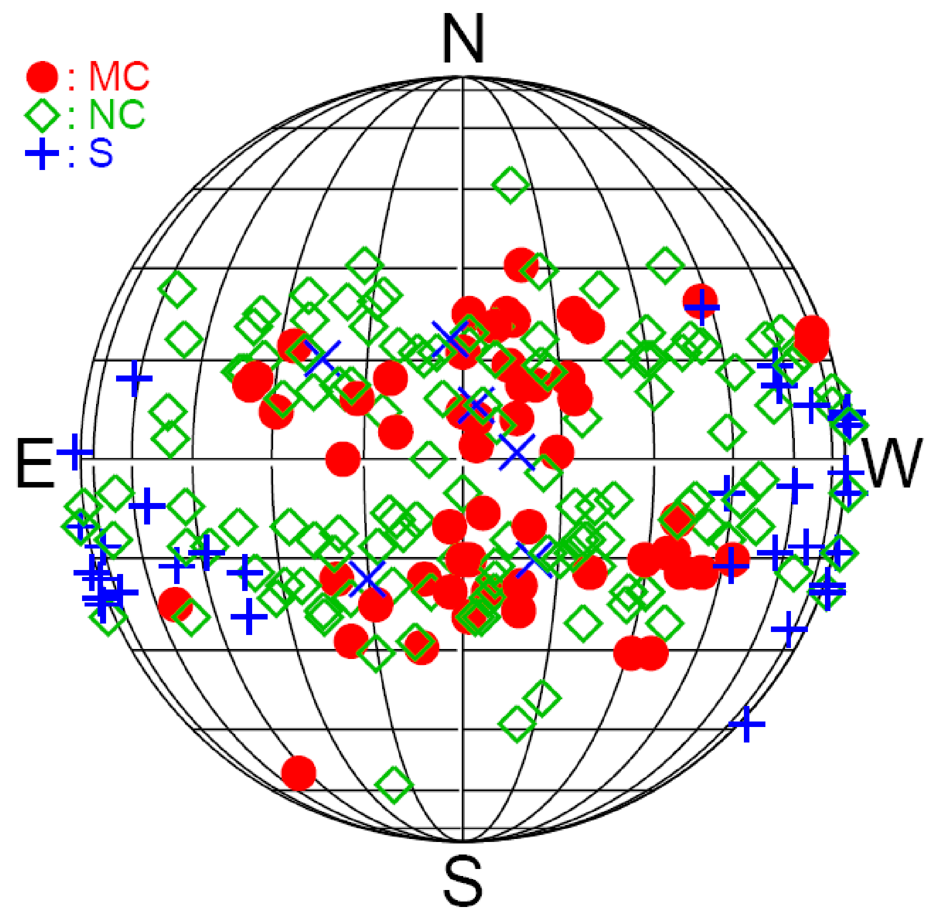




Most ICMEs are from Halo CMEs

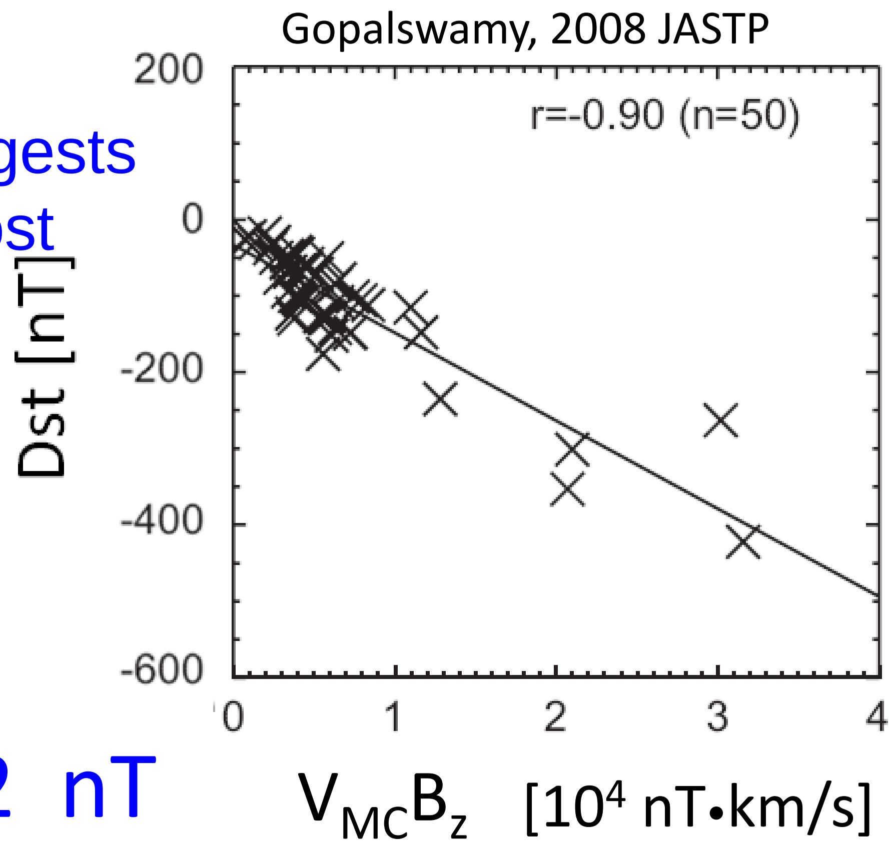


Exceptions: Propagation effects



Geomagnetic Storm and CME parameters

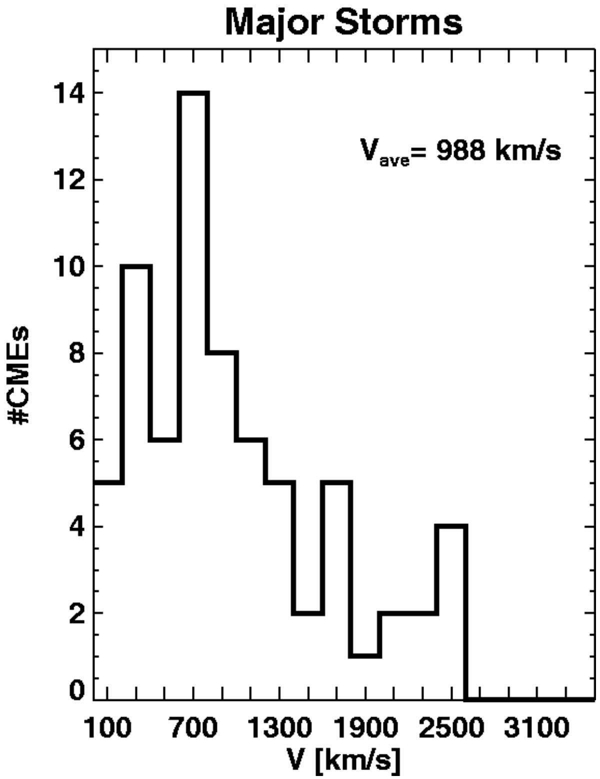
The high correlation suggests that V and Bz are the most important parameters decided by the source active regions

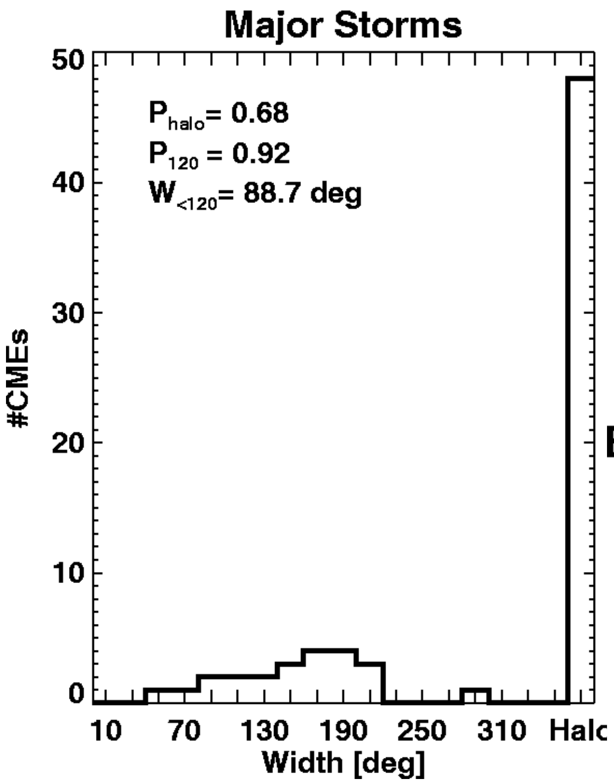


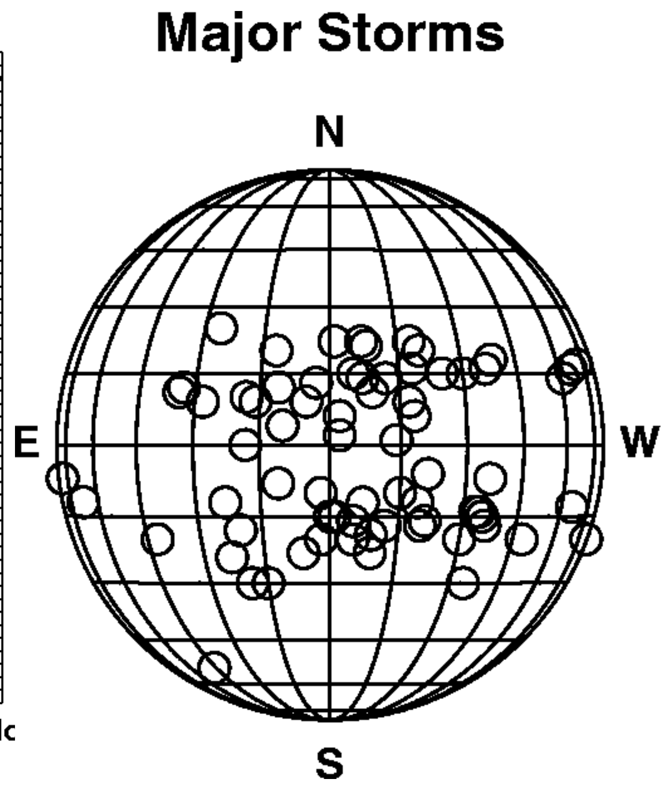
$$Dst = -0.01VB_z - 32\ \text{nT}$$

Dungey 1962; Akasofu, 1981; Tsurutani et al., 1990; Wu &Lepping, 2002; Yurchyshyn et al., 2004; Srivastava &Venkatakrishnan, 2004; Gopalswamy, 2008

Geoeffective CMEs

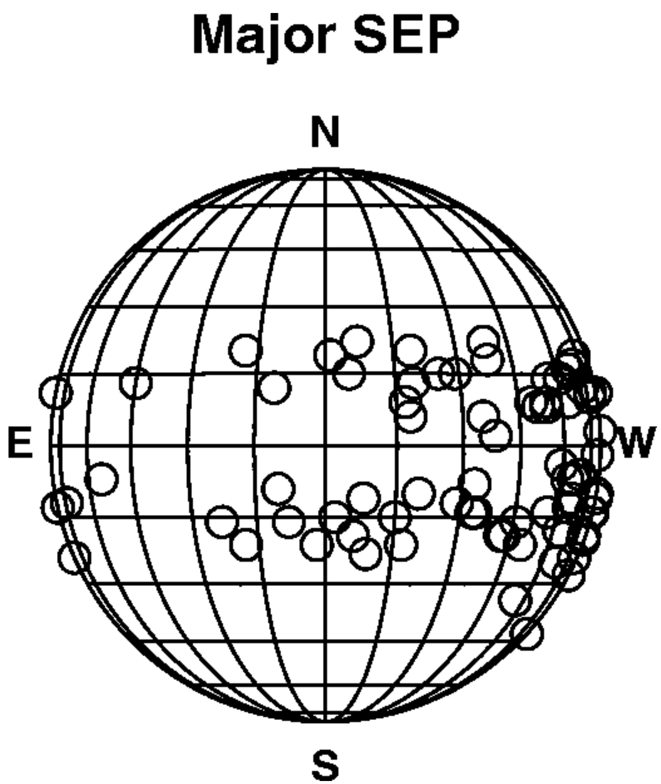




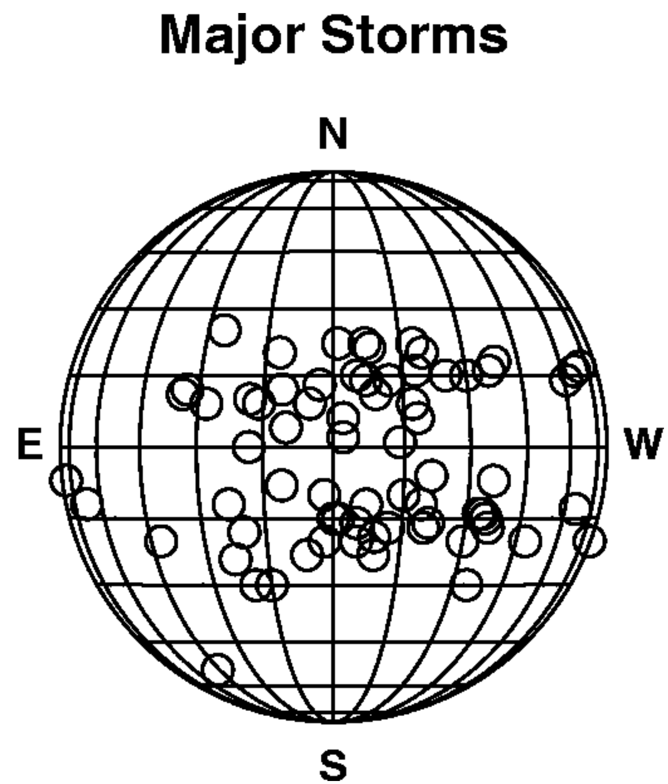


Fast and wide CMEs from mostly the disk center
From the active region belt

Different Source Distributions



Magnetic Connectivity

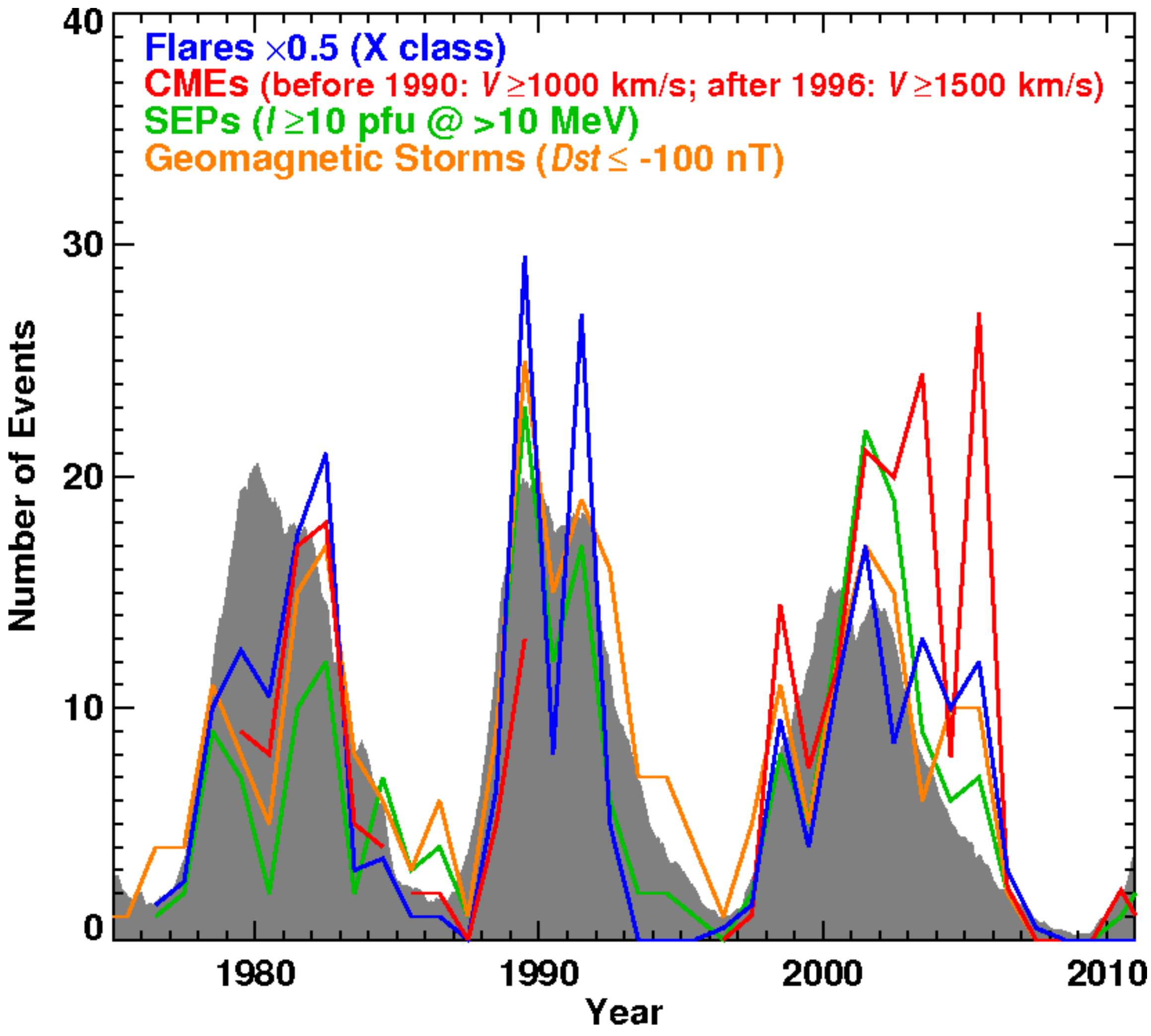


Direct Impact

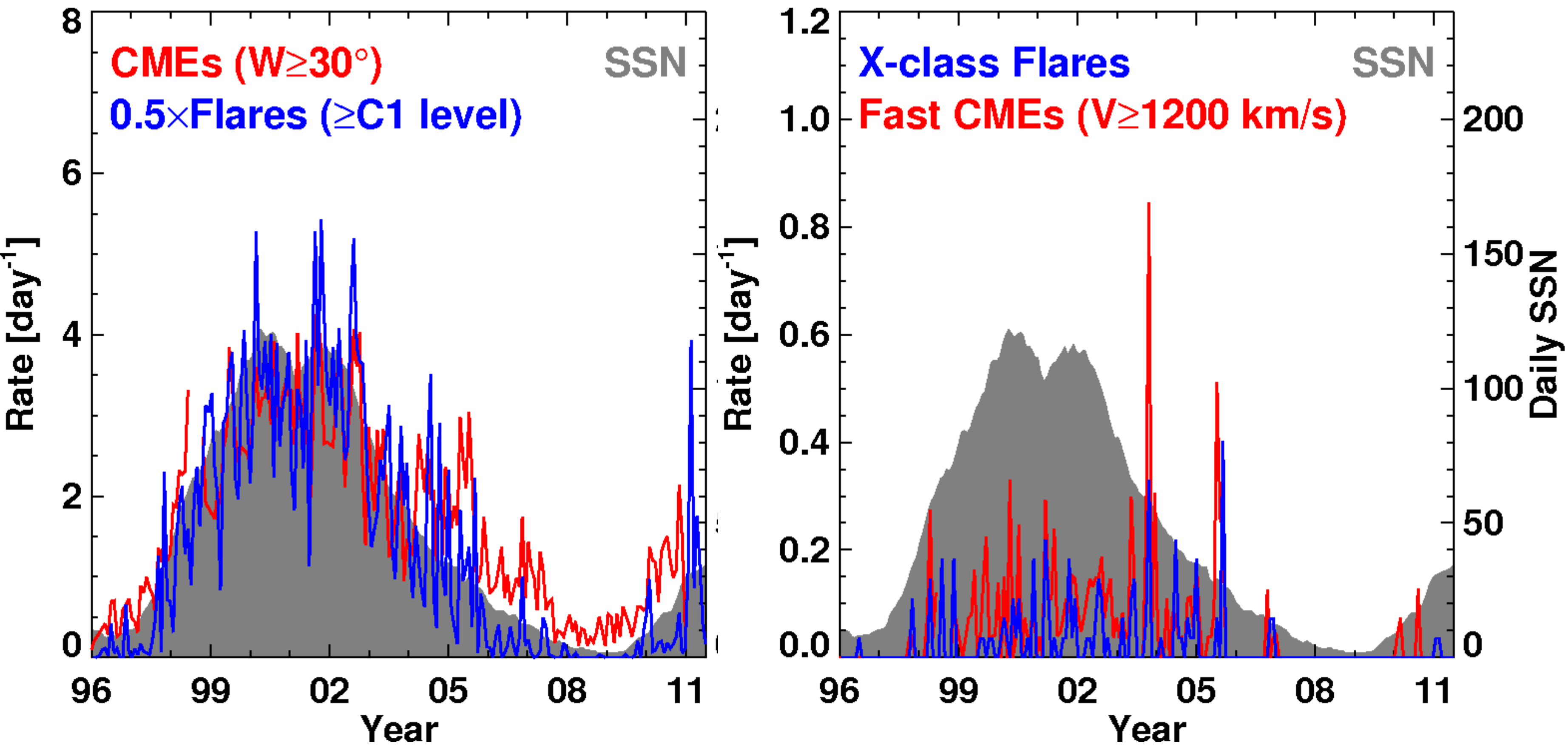
Requirement on Solar Storms to become Magnetic Storms and/or Particle Storms

Magnetic	Particle
CME plasma has to reach Earth's magnetosphere (Earth-directed CMEs)	SEPs need to arrive at Earth (Western CMEs)
CME magnetic filed needs to have southward component	Magnetic structure unimportant
CMEs need not drive shocks	CMEs have to drive shocks
Fast CMEs (~1000 km/s)	Ultra-fast (~1500 km/s)

Major Events Over Solar Cycle



Big events have poor solar-cycle dependence



Significant CMEs

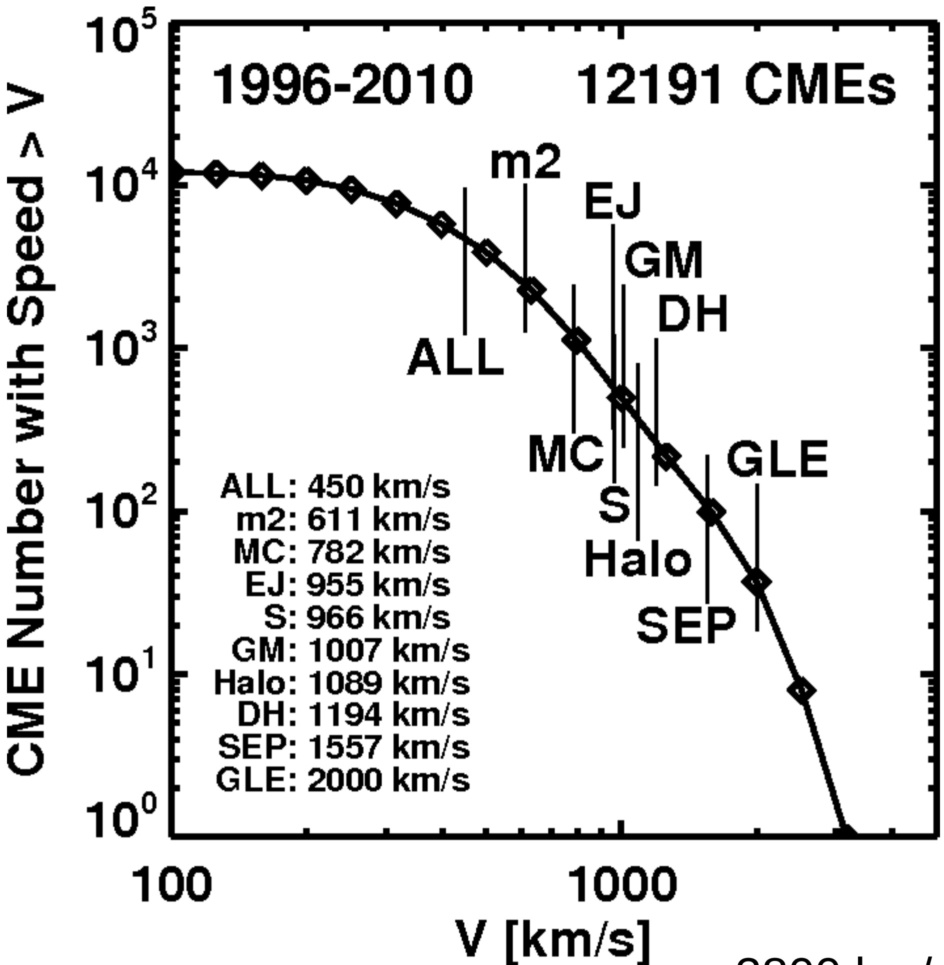
How fast can CMEs get?

Maximum area 5000 msh (Newton 1943)
Maximum sunspot field 6100 G
(Livingston et al., 2006)
Potential field energy ~10^{36} erg
Free energy ~ potential energy

If all energy goes into a 1018 g CME,
Vmax ~ 14,000 km/s (0.05c)

In reality many CMEs exhaust the free
energy (each CME carries 5 -25%.

Using 25%, Vmax = 7000 km/s



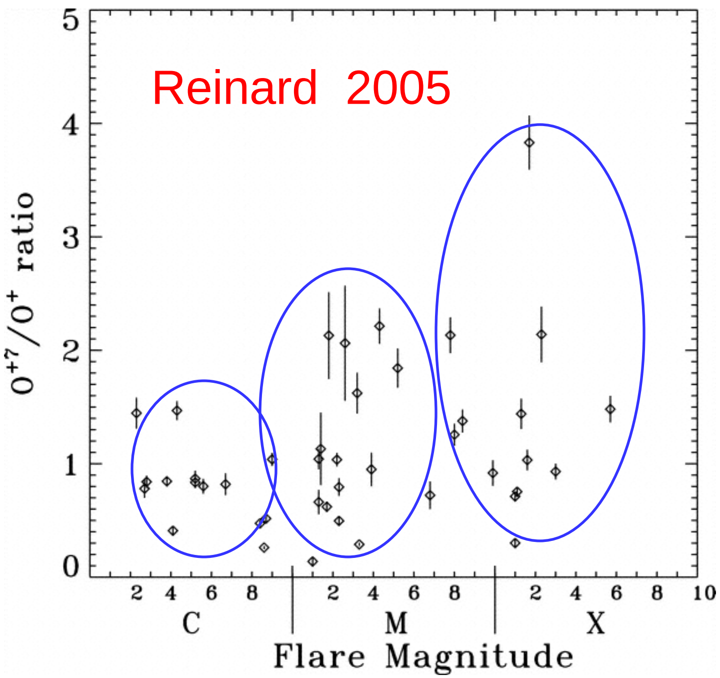
Such CMEs would travel to earth in 11.6 hours

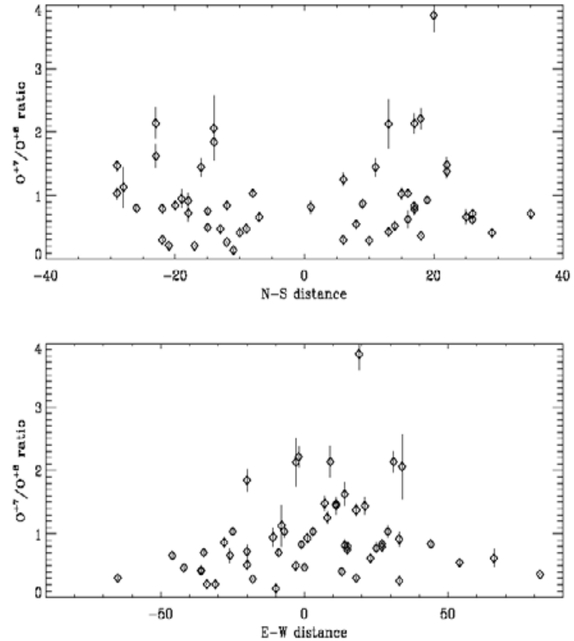
3800 km/s

Summary

- CMEs constitute the most energetic phenomenon in the heliosphere (10^{26} J)
- CMEs cause two primary space weather effects: SEPs and geomagnetic storms
- CMEs are produced in closed magnetic regions on the Sun known as active regions

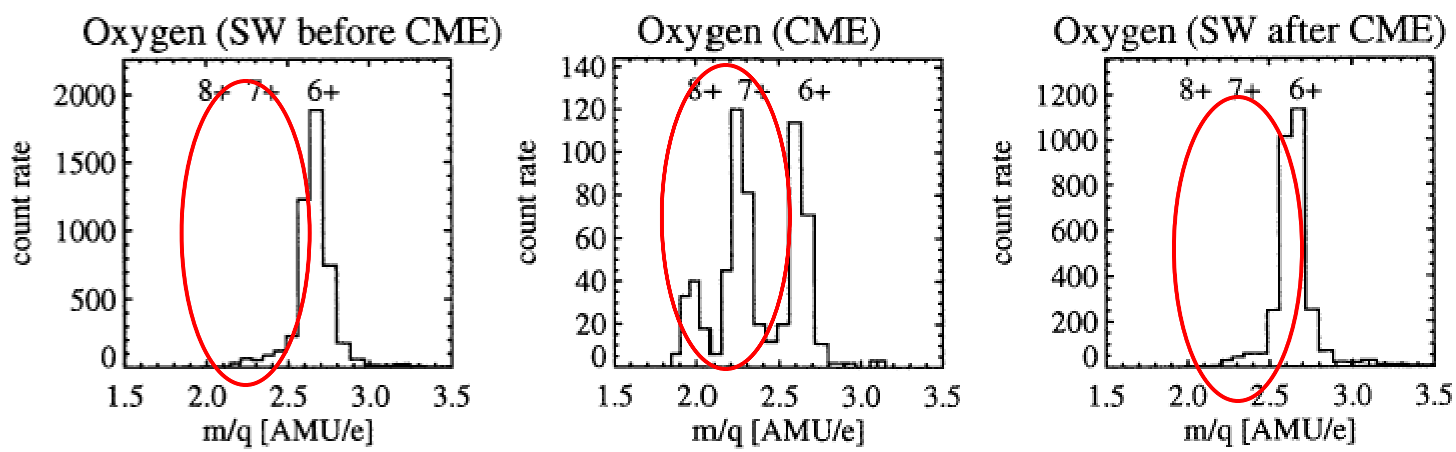
O7+/O6+





O7+/O6+ ratio is also good indicator of MCs. The ratio is higher for ICMEs associated with bigger flares and sun-center sources.
Both are consistent with MCs.

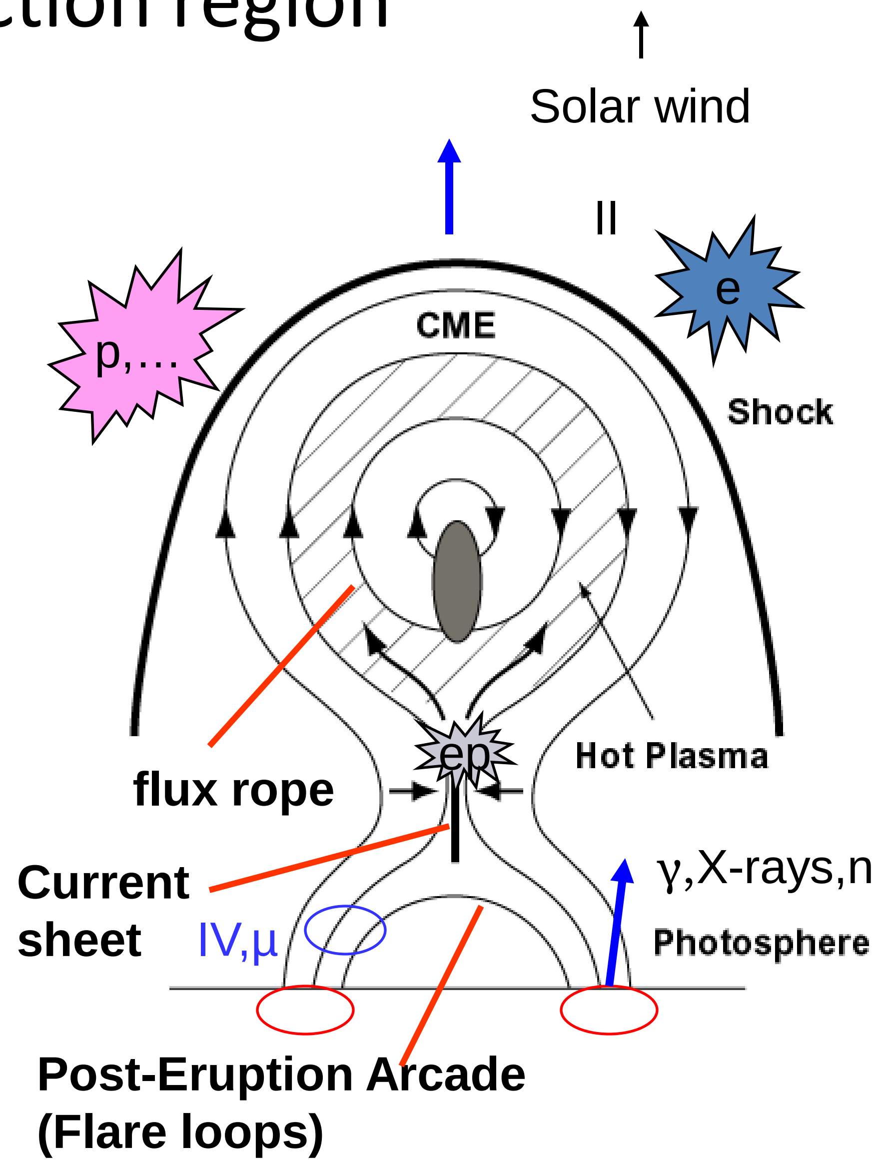
Henke et al. 2001

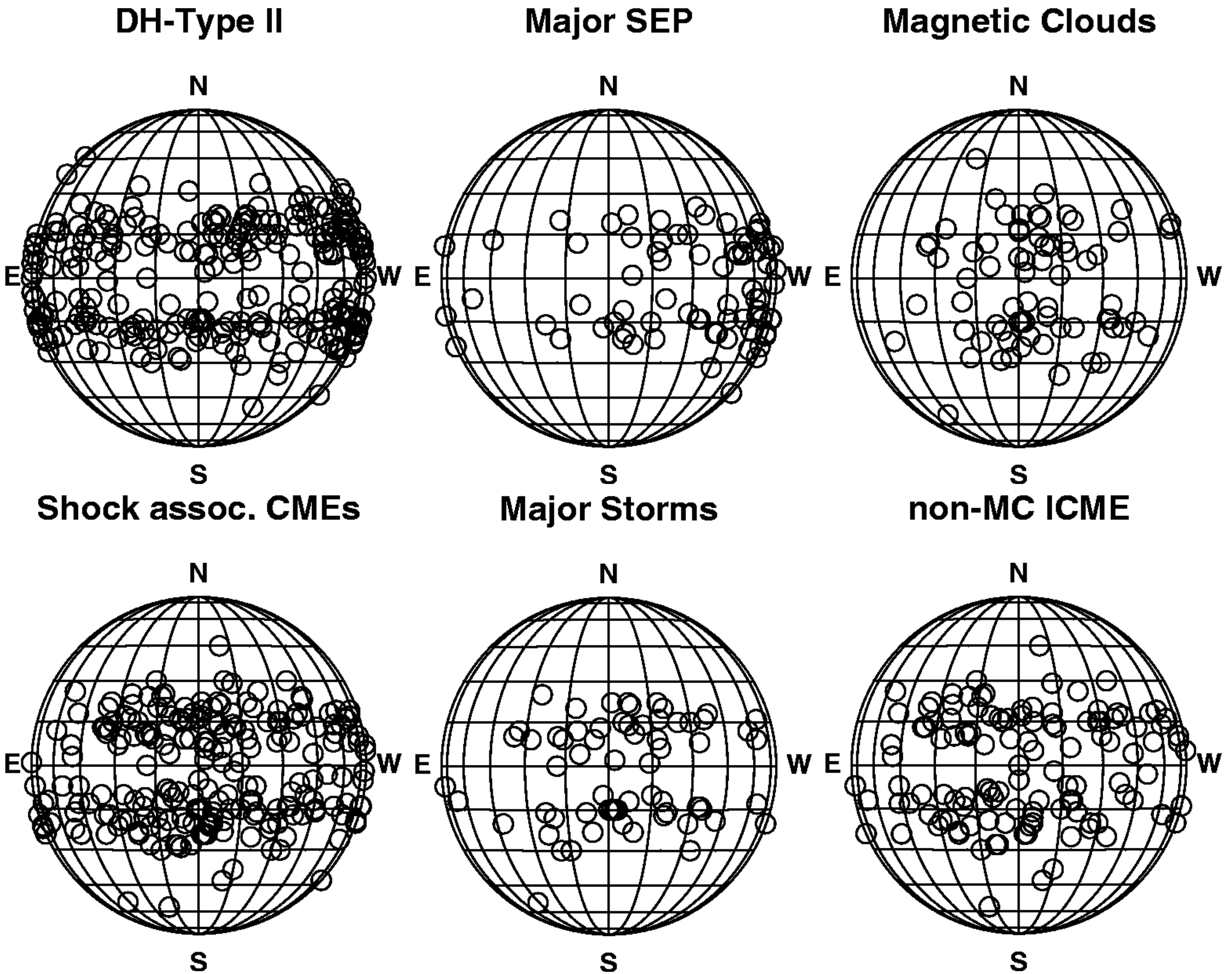


Temperature increase in the source: Reconnection at the time of eruption

Hot plasma enters the flux rope from the reconnection region

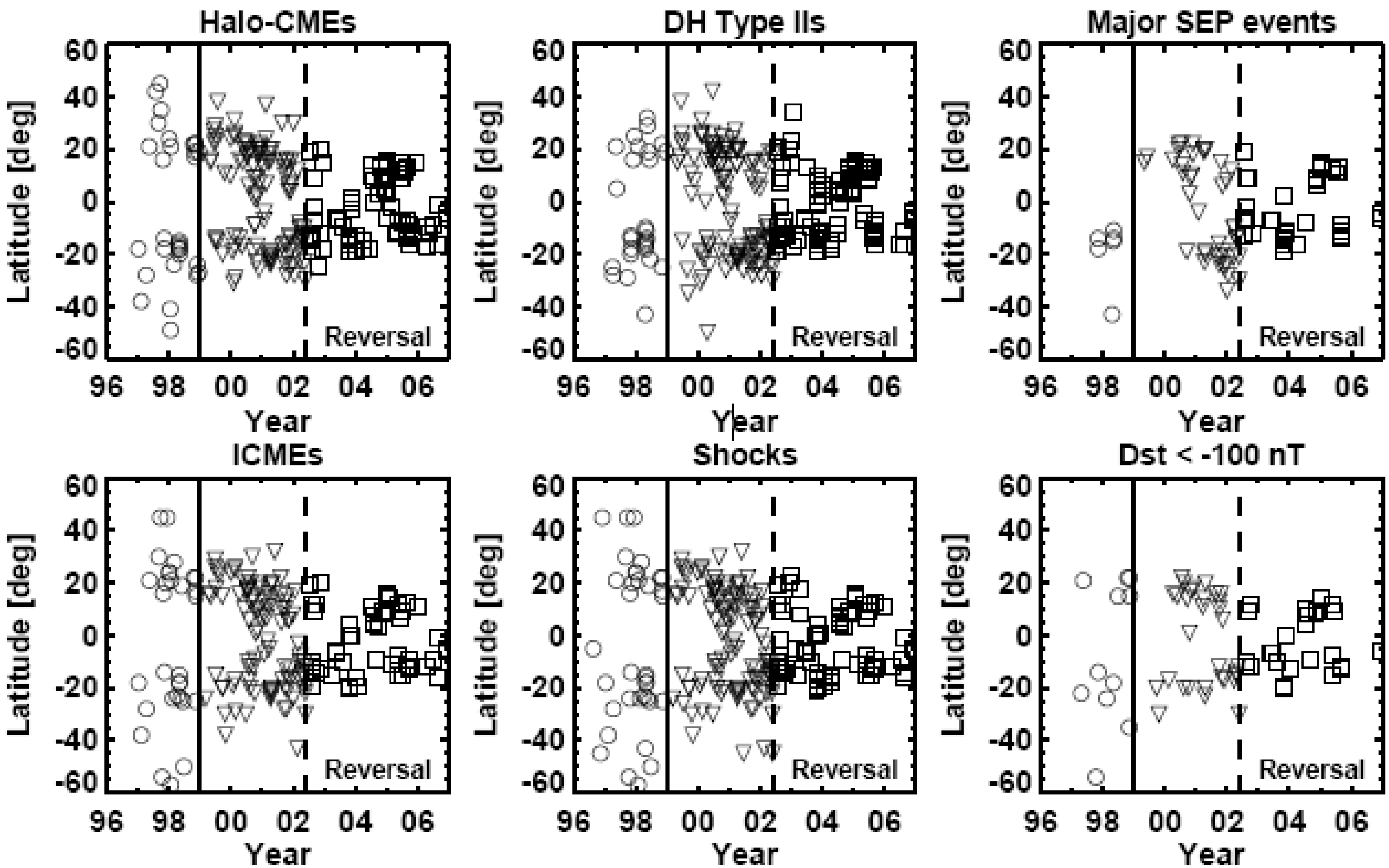
Hot plasma → high charge state





Special populations

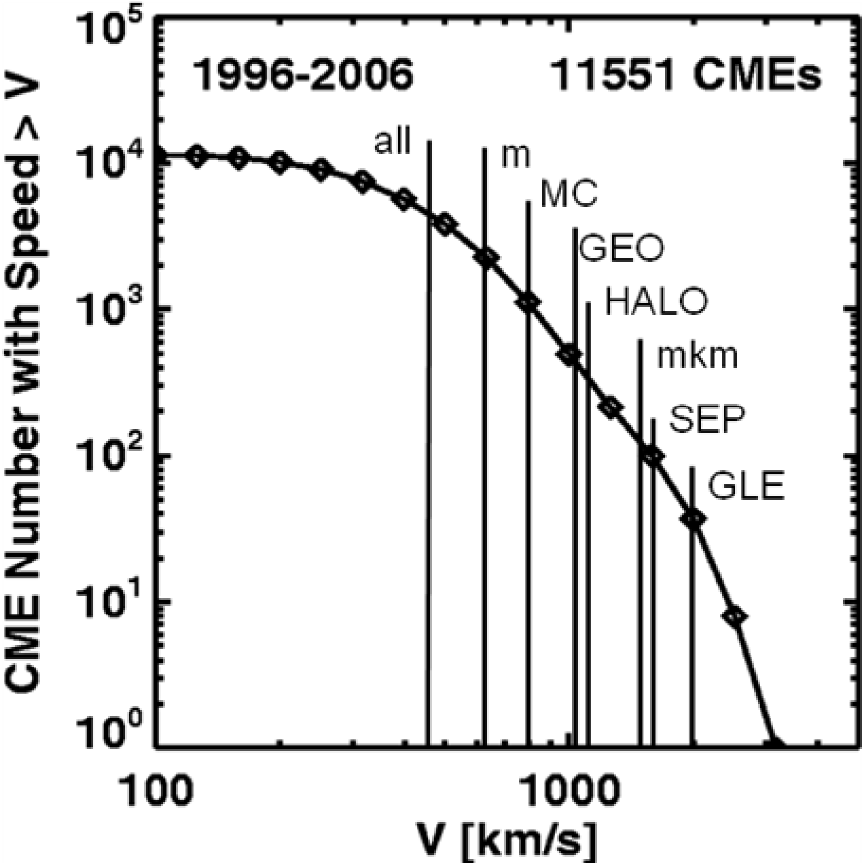
Solar Cycle Variation



The special populations originate from the active region belt

CMEs of Cycle 23

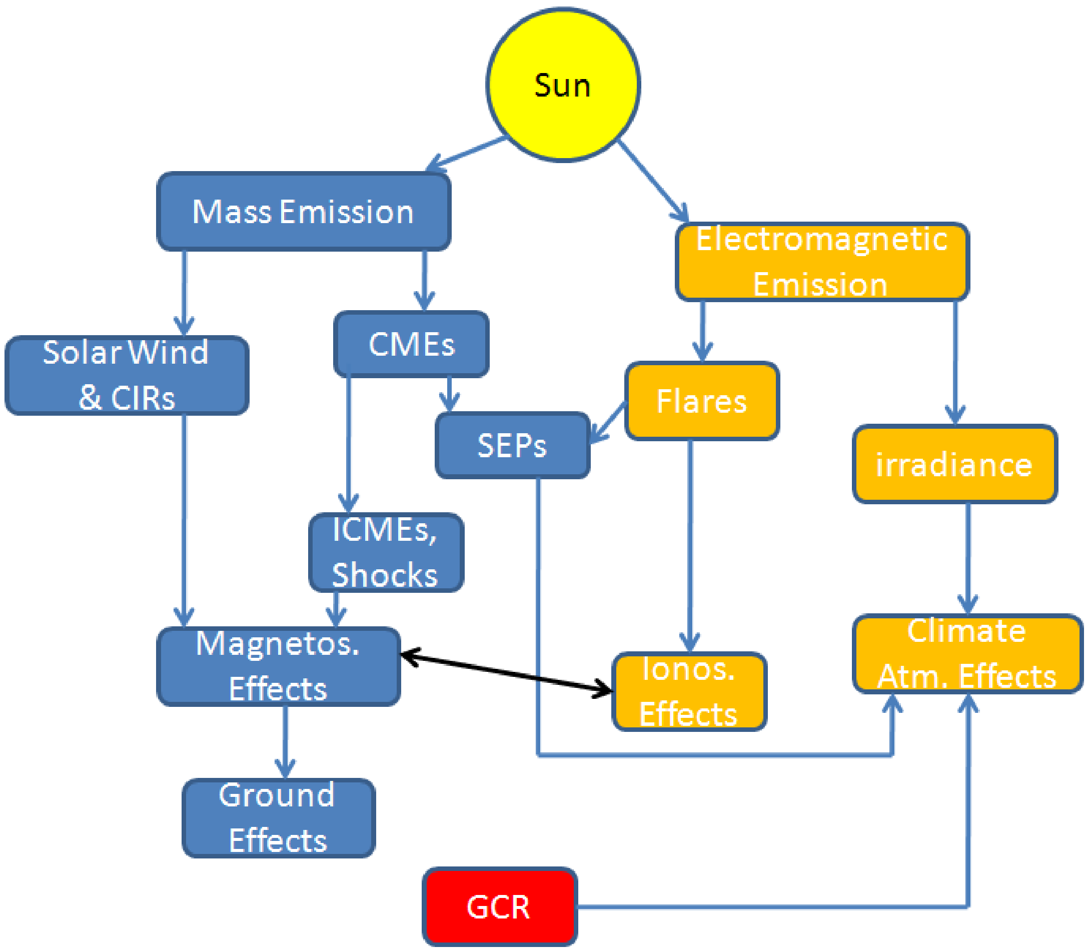
Gopalswamy, 2006



CME population	<V> km/s
All CMEs	471
metric II CMEs	610
MC CMEs	774
Geoeffective CMEs	1042
Halo CMEs	1052
mkm II CMEs	1500
SEP CMEs	1600
GLE CMEs	2000

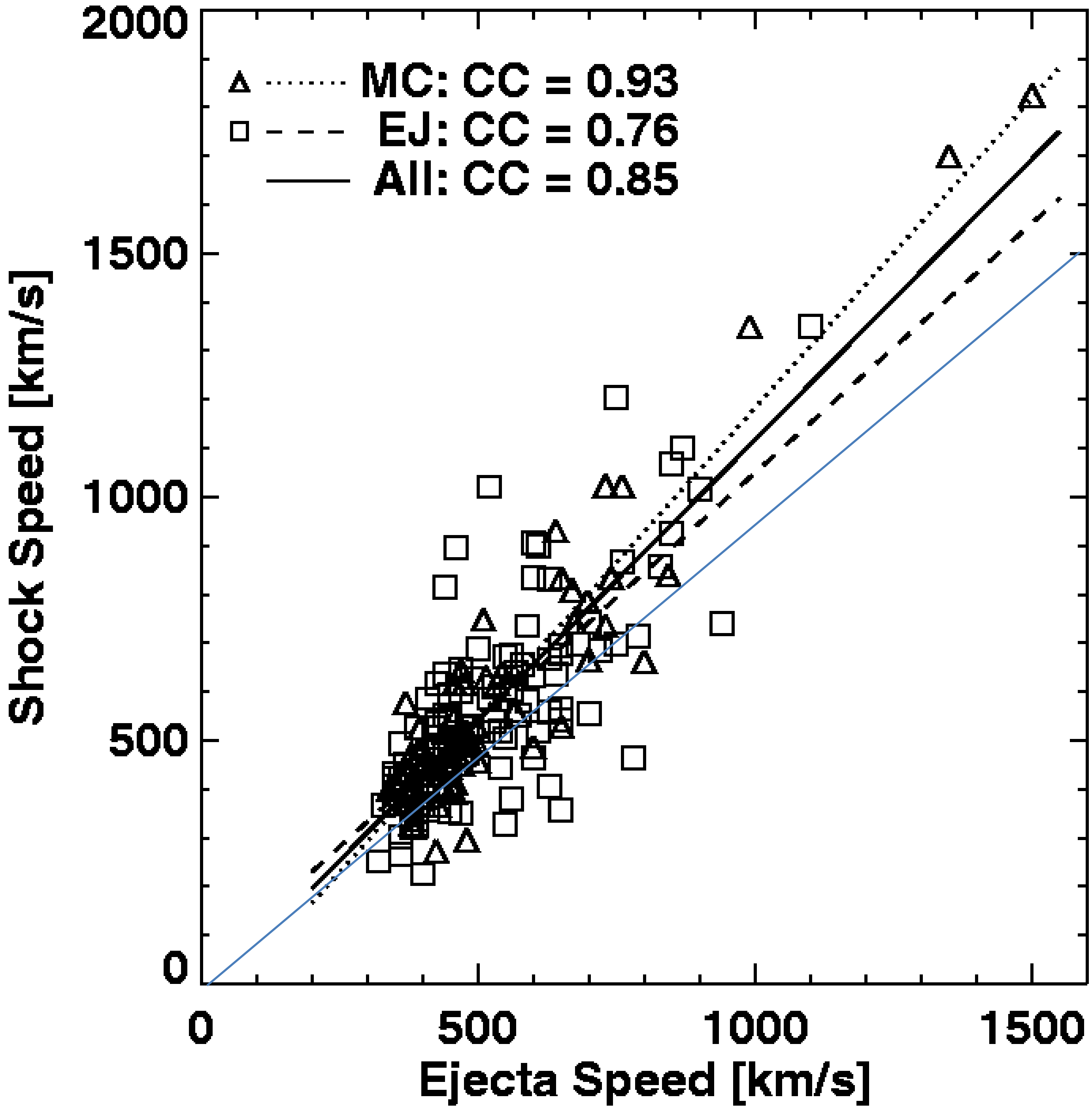
CME speed < ~4000 km/s → Limit to the Free energy available in active regions

11% of CMEs are wide (W ≥120°) ~1000
Fast and wide CMEs ~500
Halo CMEs ~500 (some are slower than 900 km/s
MCs ~100; intense storms ~100; SEPs ~100


Sun
Mass Emission
Electromagnetic Emission
Solar Wind & CIRs
CMEs
Flares
SEPs
irradiance
ICMEs, Shocks
Magnetos. Effects
Ionos. Effects
Climate Atm. Effects
Ground Effects
GCR

Summary

- Intense geomagnetic storms are caused by the out of the ecliptic component of the magnetic field in CMEs and/or their sheath.
- Large SEP events are due to fast and wide CMEs
- Shock-driving CMEs, ICME-associated CMEs, Type II producing CMEs, major storm producing CMEs are all energetic and have overlap and appear mostly as halo CMEs
- CMEs are the major players in Sun-Earth connection



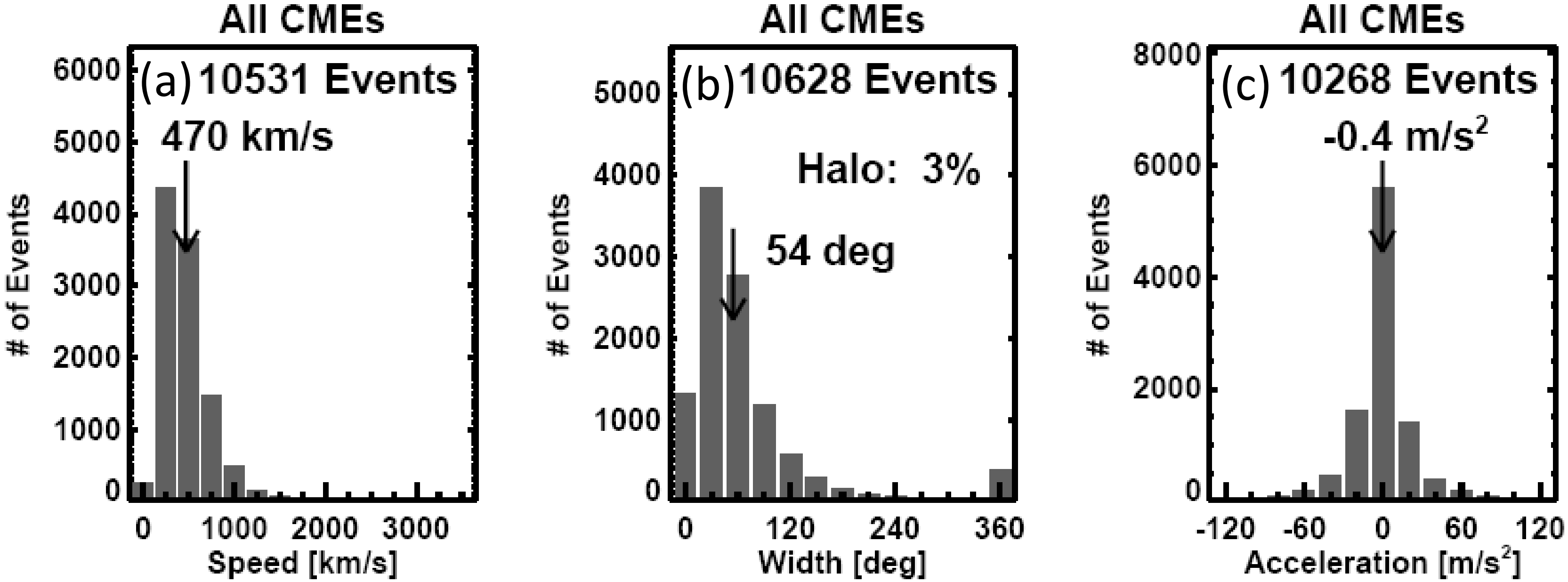
MC: CC = 0.93
EJ: CC = 0.76
All: CC = 0.85
Shock Speed [km/s]
Ejecta Speed [km/s]
0
500
1000
1500
2000

Pre-Coronagraphic CME Signatures

- Slow drift burst due to mass motion from the Sun (Payne-Scott, Yabsley & Bolton, 1947)
- Classification of solar radio bursts: Type I,II, III burst by Wild & McCready (1950)
- Due to an outrush of matter from flare … which, causes great magnetic storms and aurorae (Wild, 1955)
- Type II due to acoustic shocks at the front of flare plasma (Wild et al. 1954), Westfold, 1957
- Moving type IV bursts (Boishot, 1957)
- Type II due to hydromagnetic shocks Uchida (1960).
- Moreton waves (1964) identified with flare flash
- Theory based on flare blast (Uchida, 1968)

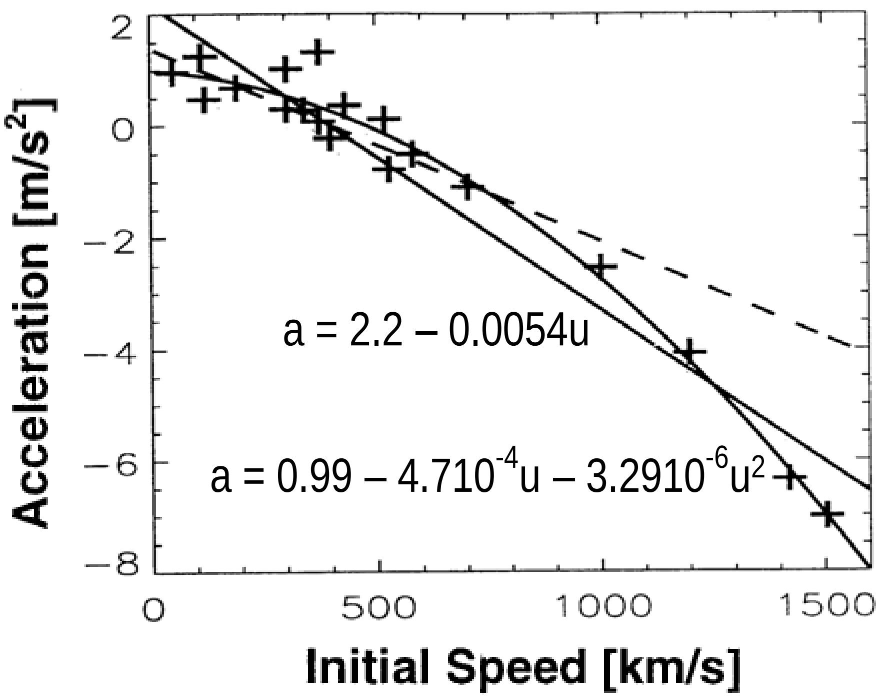
IP Shock history

- Type II Bursts discovered by Payne-Scott et al. (1947)
- Gold predicts IP shocks in 1955
- Type II bursts from shocks (Uchida, 1960)
- IP shocks by Mariner 2 in 1962 (Sonnet et al. 1964)
- ESP events from shocks (Rao et al., 1967)
- CME similar to Gold bottle (Koomen et al., 1974)
- SEPs from CME-driven shocks (Kahler et al., 1978)
- Shock sheath Magnetic cloud (Burlaga 1981)
- Type II bursts and CMEs (Robinson, 1985)
- CMEs and IP shocks (Sheeley et al., 1985)

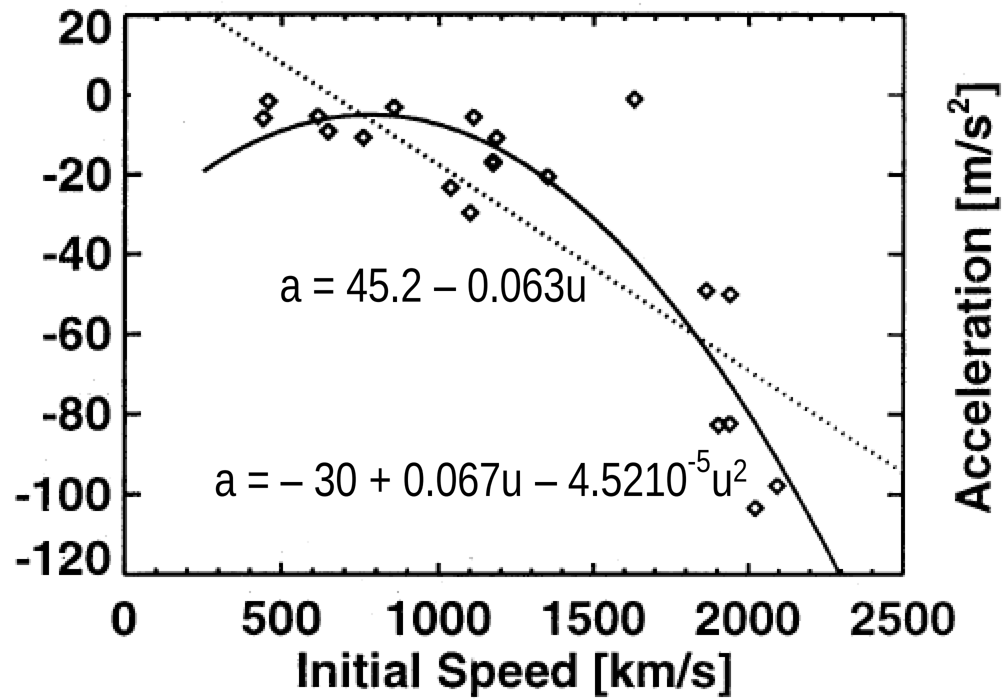

All CMEs
(a) 10531 Events
470 km/s
# of Events
Speed [km/s]
All CMEs
(b) 10628 Events
Halo: 3%
54 deg
# of Events
Width [deg]
All CMEs
(c) 10268 Events
-0.4 m/s2
# of Events
Acceleration [m/s2]

IP Acceleration

(a) Helios/PVO Data



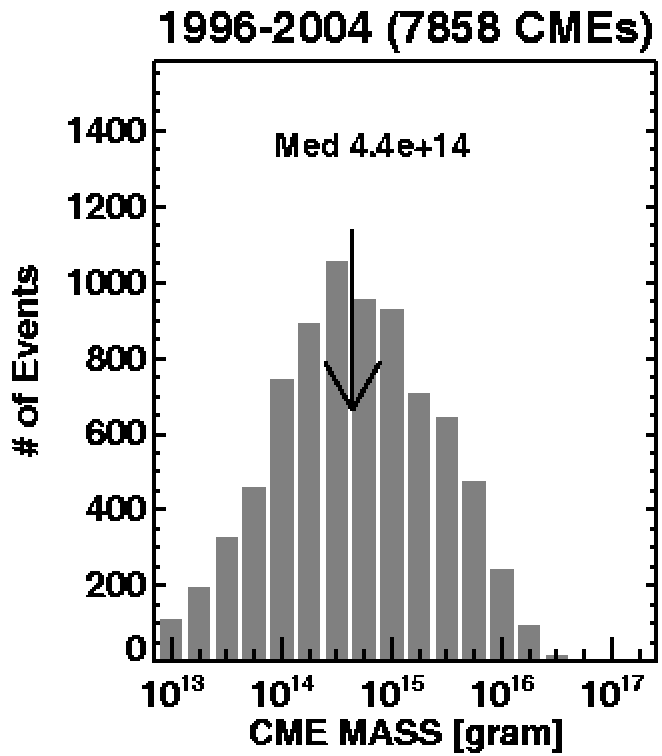
(b) SOHO/LASCO Limb CMEs

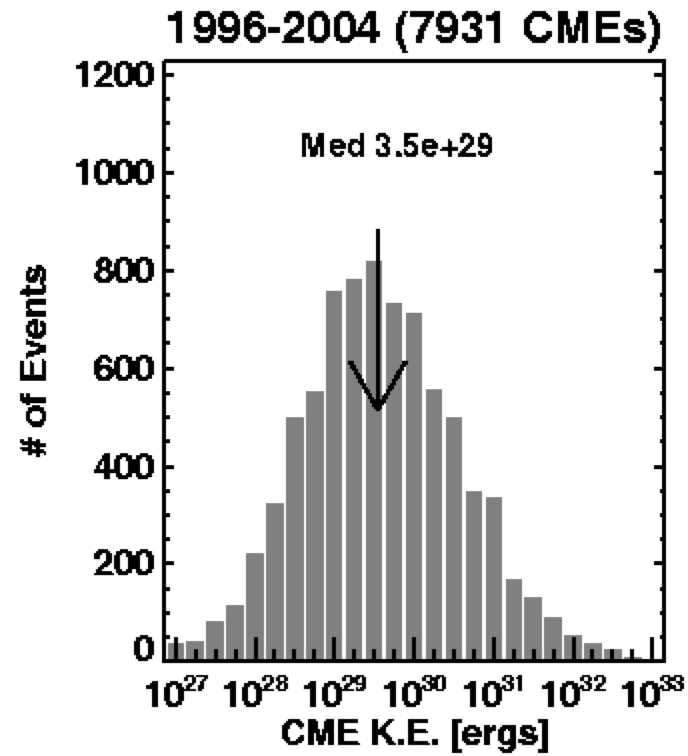


Gosling et al., 2001; Lindsay et al., 1999
Gopalswamy et al., 2000;2001

Gopalswamy et al., 2001

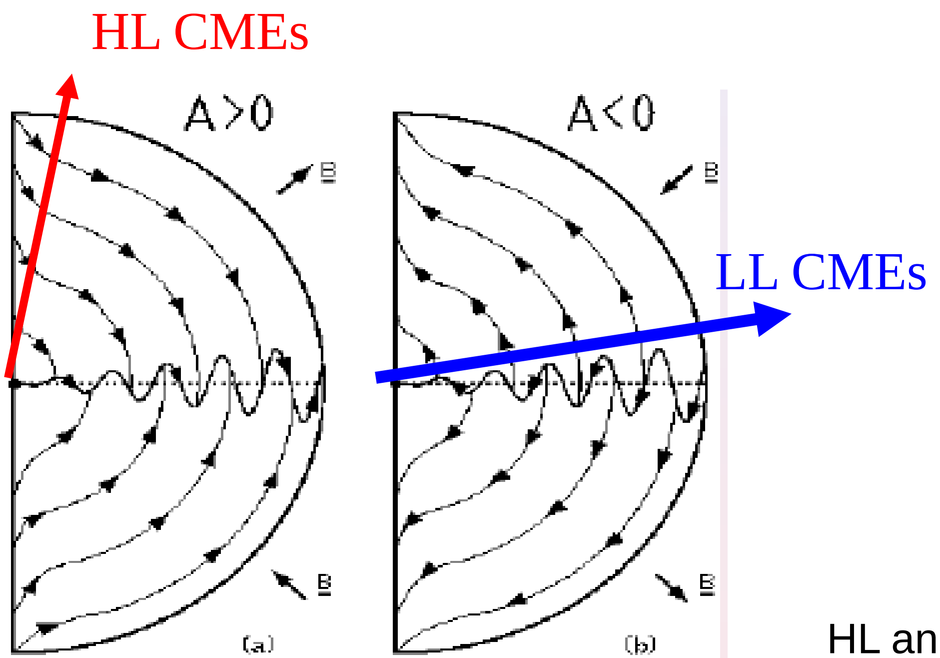
Mass and Kinetic Energy



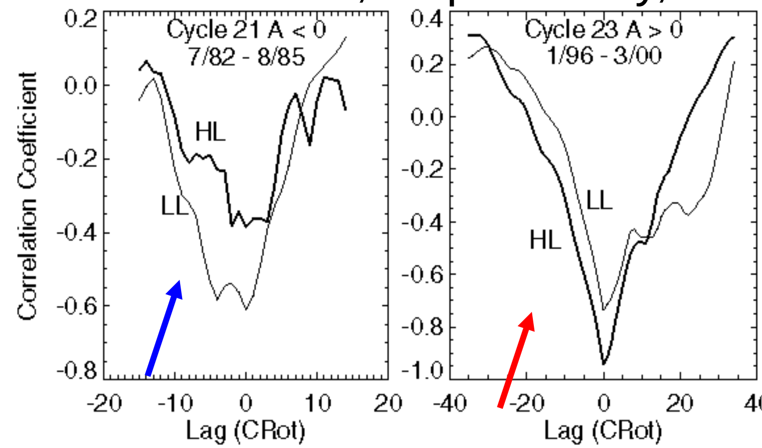


- The basic pre-eruption magnetic field is a magnetic arcade (closed bipole) in which the core field is strongly sheared (Moore et al., 1999)
- $B_{flr} = 1.4\ (\theta_{CME}/\theta_{flr})^2$ [Moore et al. 2007]

HL and LL CME Rates and GCR Intensity



Lara et al. 2005; Gopalswamy, 2004



HL and LL CMEs have different effects on GCR

CME rate high enough
Min to max variation high enough
Contribution from High-latitude CMEs
GMIRs did not form during the Oct-Nov 03 storms (Richardson et al. 2005)
See also Cliver et al. 2003
Gazis et al. 2006