# Coronal Mass Ejections and Extreme Events of Solar Cycle 23

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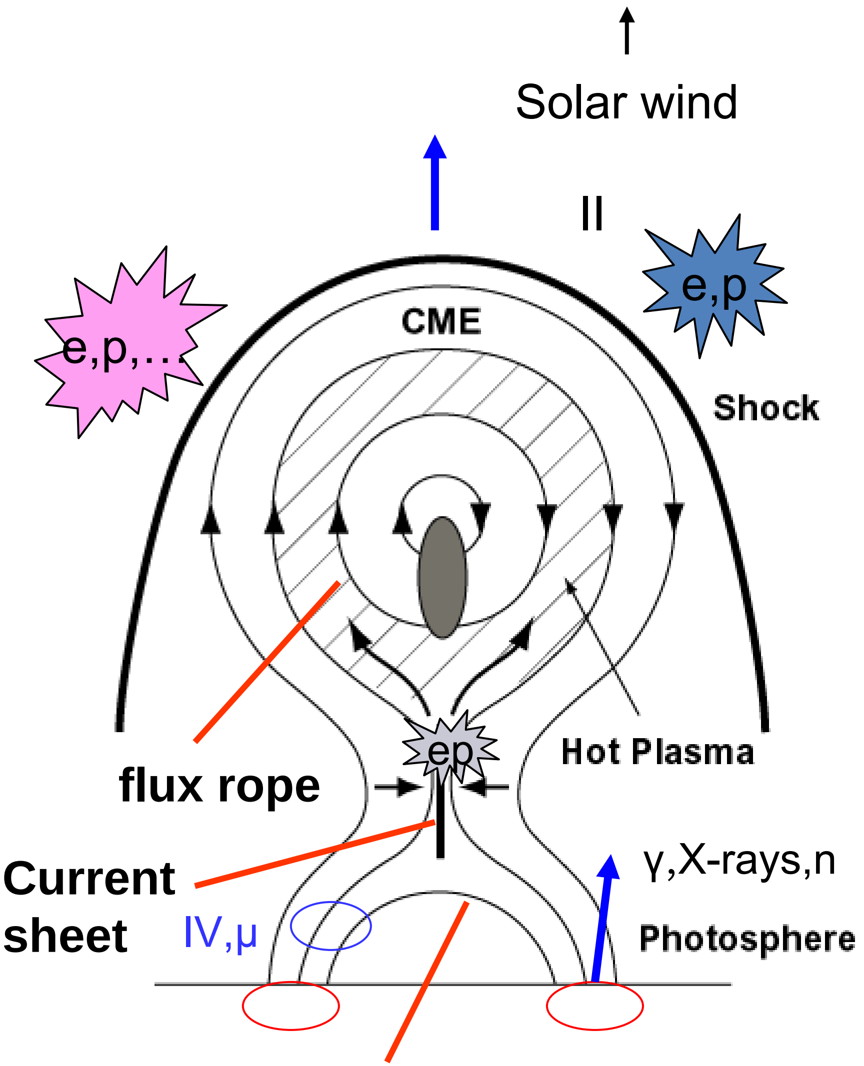
# Generic Eruption




Adapted from Martens and Kuin 1986

Two sources of particle acceleration : shock & flare

Injection of hot plasma into the CME structure,
resulting in higher charge states in magnetic clouds

The prominence material is cool occasionally observed at 1 AU as low charge state interval.

# Extreme Events

Extremeness of an event
in the source
and/or in its consequences

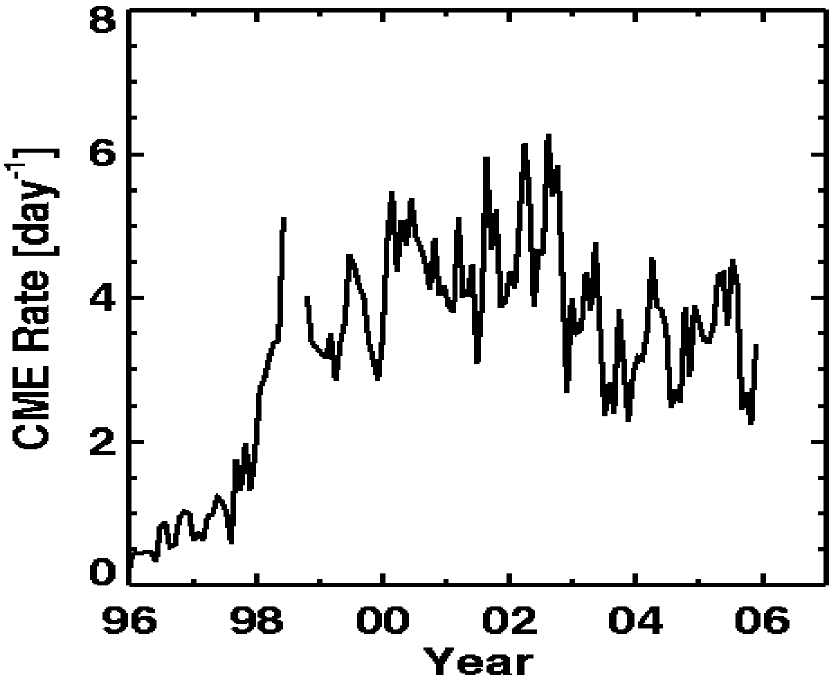
- Super Active regions (high B, sunspot area)
- Energetic CMEs
- Major flares

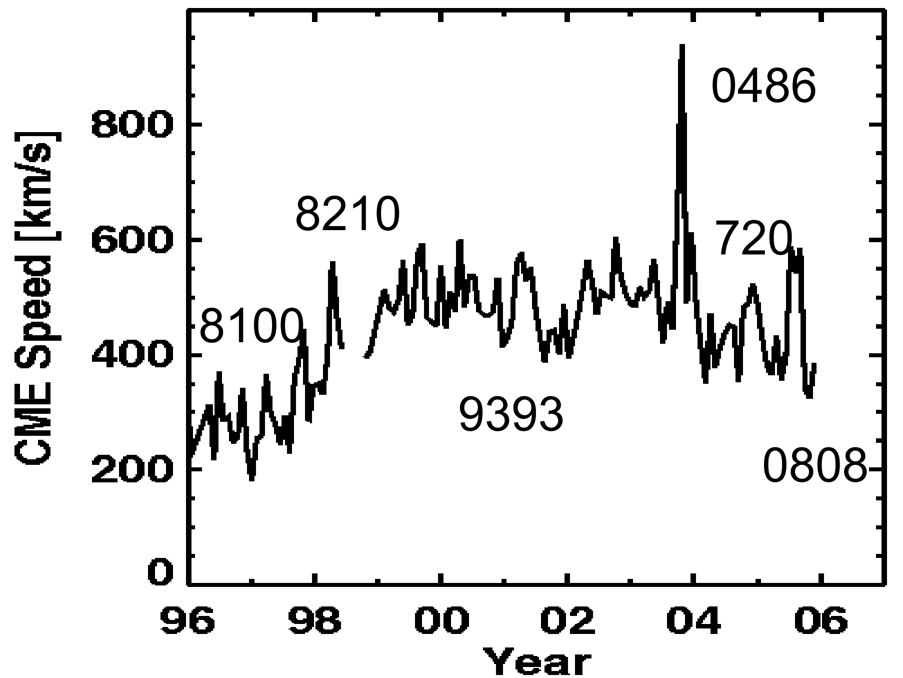
SOURCE

Consequences

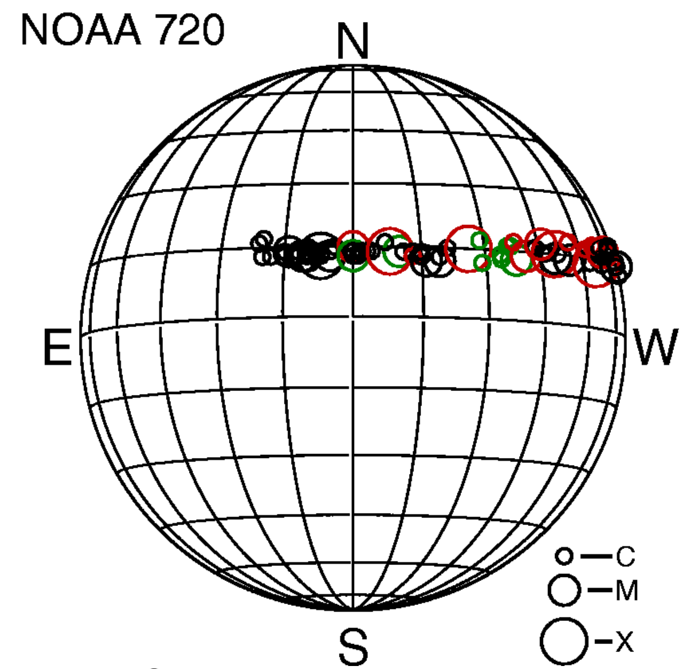
- Large SEP events & GLEs
- Major geomagnetic storms

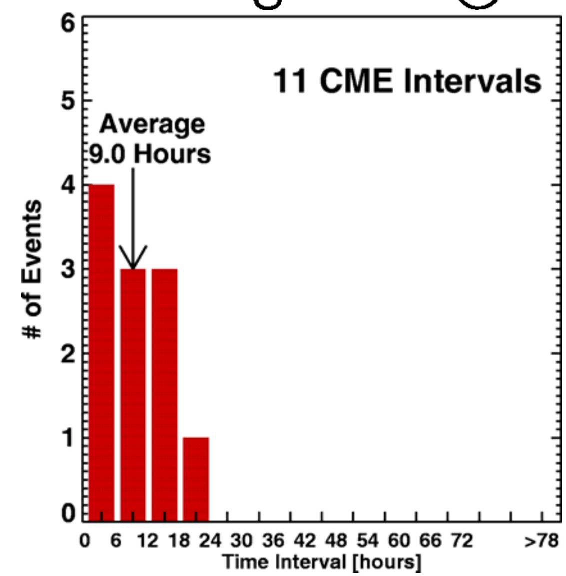
# Super AR → High Speed CMEs



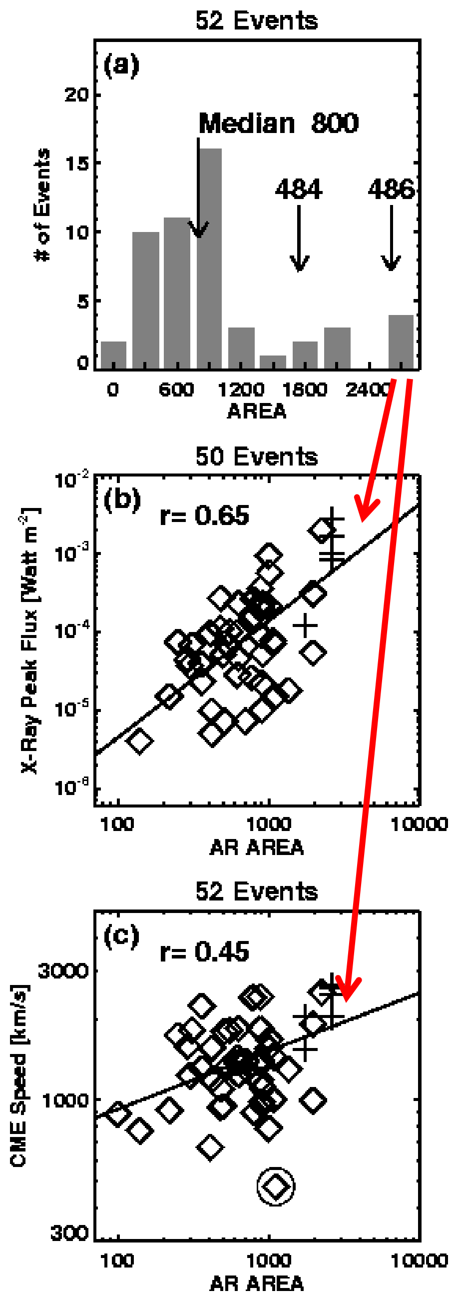
# Super Active Regions




- At least one Large SEP event (≥ 10 pfu in the GOES >10 MeV channel) during disk passage. Consequences:
- High CME and Flare recurrence
- Cause Geomagnetic storms
- Important for Space Weather

# Active Region Area vs. Flares & CMEs (SEP associated ARs)




Halloween events

$$\log X = -8.34 + 1.50 \log A$$

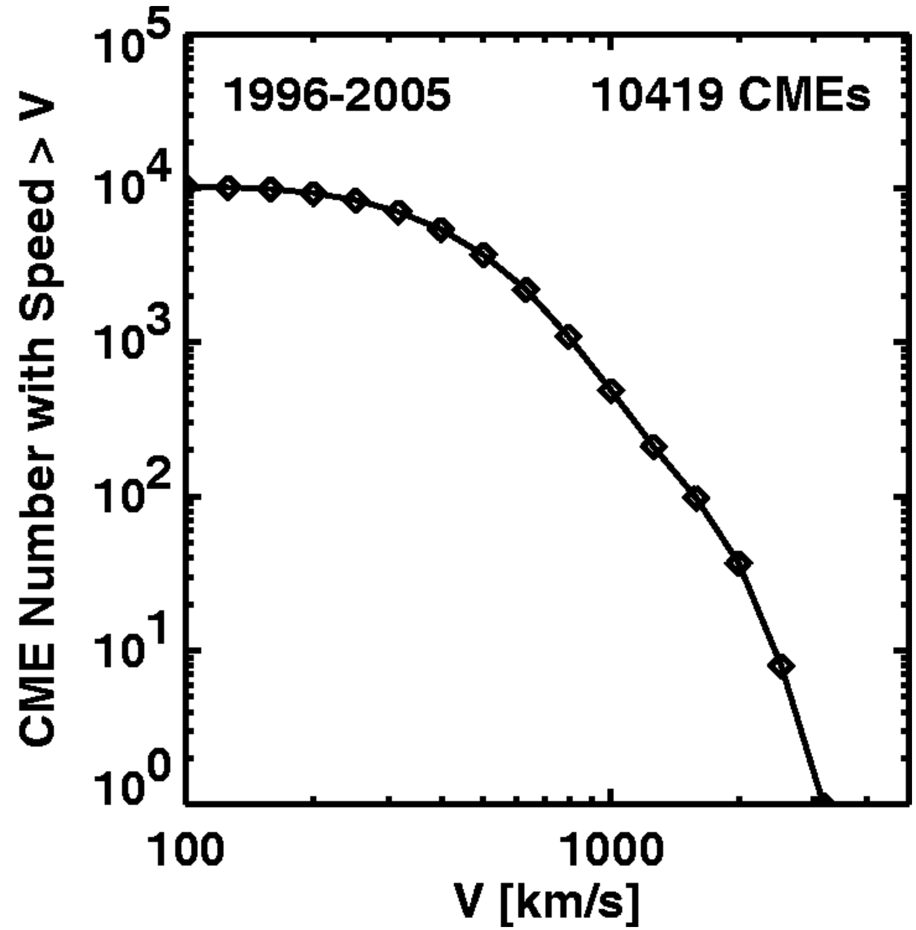
log (Volume)

$$\log V = 2.54 + 0.22 \log A$$

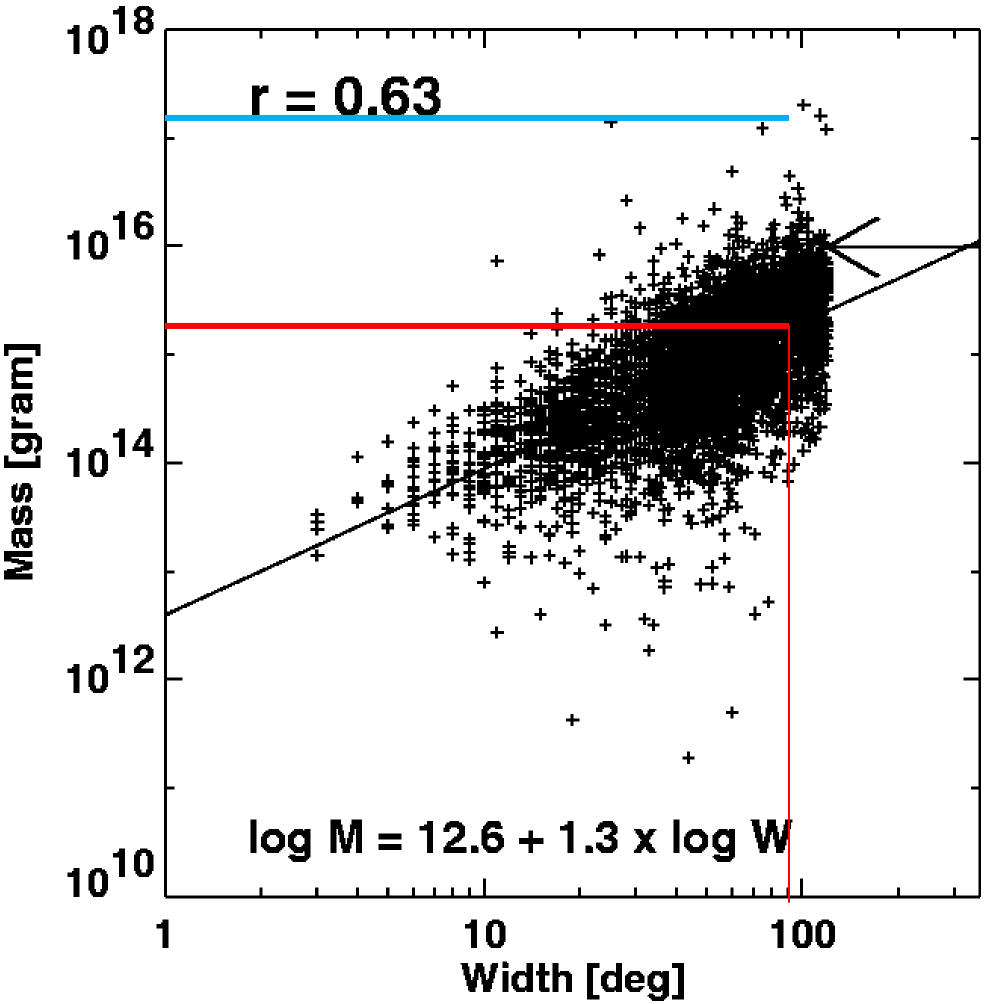
# CME speed limit: Free energy limit?

Free Energy ~ Total Energy – Potential Energy

~ Potential Energy



# Mass & Kinetic Energy

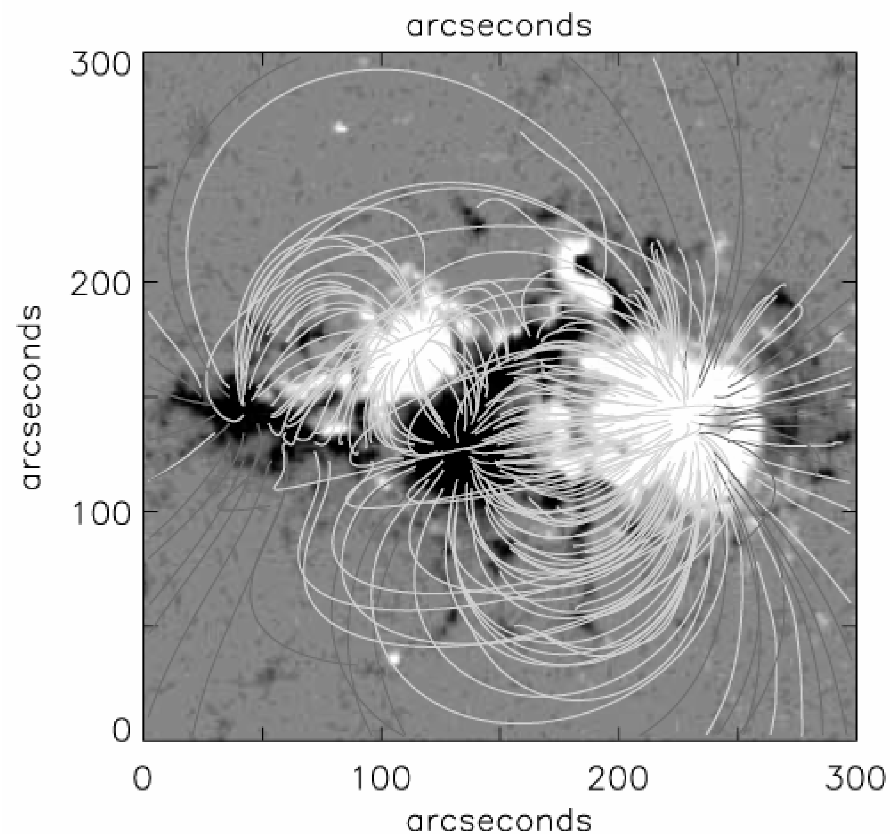



- Mass ~$10^{17}$ g
- Speed ~3500 km/s
- KE ~$6 \times 10^{33}$ erg
- $VB^2/8\pi \geq$ KE
- V ~ $10^{31}$ $cm^{-3}$
- B ~ 122 G

# AR Potential Energy & CME Kinetic Energy

- AR 486: Volume ~ $10^{31}$ $cm^3$
(300 x 300 x 300 $arcsec^3$)
- Potential Energy ~ $2x10^{33}$ erg
(<B> ~ 70 G)
- Total Magnetic Energy ~ 2 x PE ~ $4x10^{33}$ erg
- Free energy ~ $2x10^{33}$ erg
- CME Kinetic Energy ~ $1.2x10^{33}$ erg
- ~1/2 of free energy goes into CME KE

AR 486 potential field



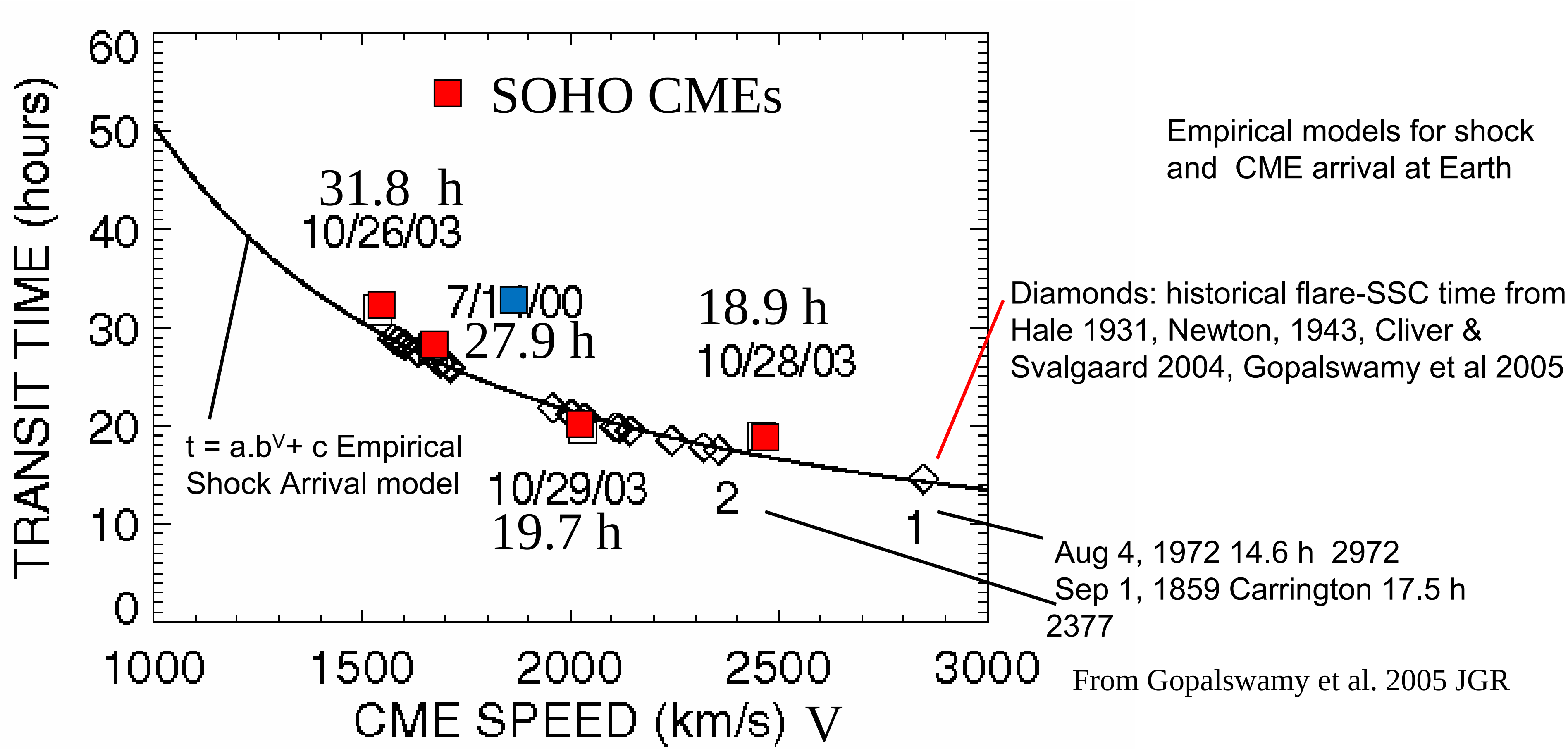

Gopalswamy et al 2005 JGR

# Recent Super ARs

| AR # | 486 | 696 | 720 | 808 | 930 |
|---|---|---|---|---|---|
| Interval | 10/18-11/7 03 | 11/2 – 11/13 04 | 01/11 - 01/23 05 | 09/05-09/19 05 | |
| Area (msh) | 2610 | 910 | 1630 | 1430 | 680 |
| X/M flare | 7/23 | 2/13 | 5/19 | 11/20 | |
| Full Halos | 7 | 7 | 8 | 7 | |
| Fast CMEs | 14 (5) | 6(2) | 7 (6) | 8 (2) | |
| < -100 nT | 3 events | 2 events | 2 events | 1 event | 1 event |
| Dst (-nT) | 363, 401 | 373, 289 | 121, 105 | 123 | 180 |
| >10 pfu | 13 days | 6 days | 7 days | 8 days | 3 days |
| SEP pfu | 33,600 | 495 | 5040 | 1880 | 500 |
| IP Shock | 7 | 5 | 1 | 3 | |

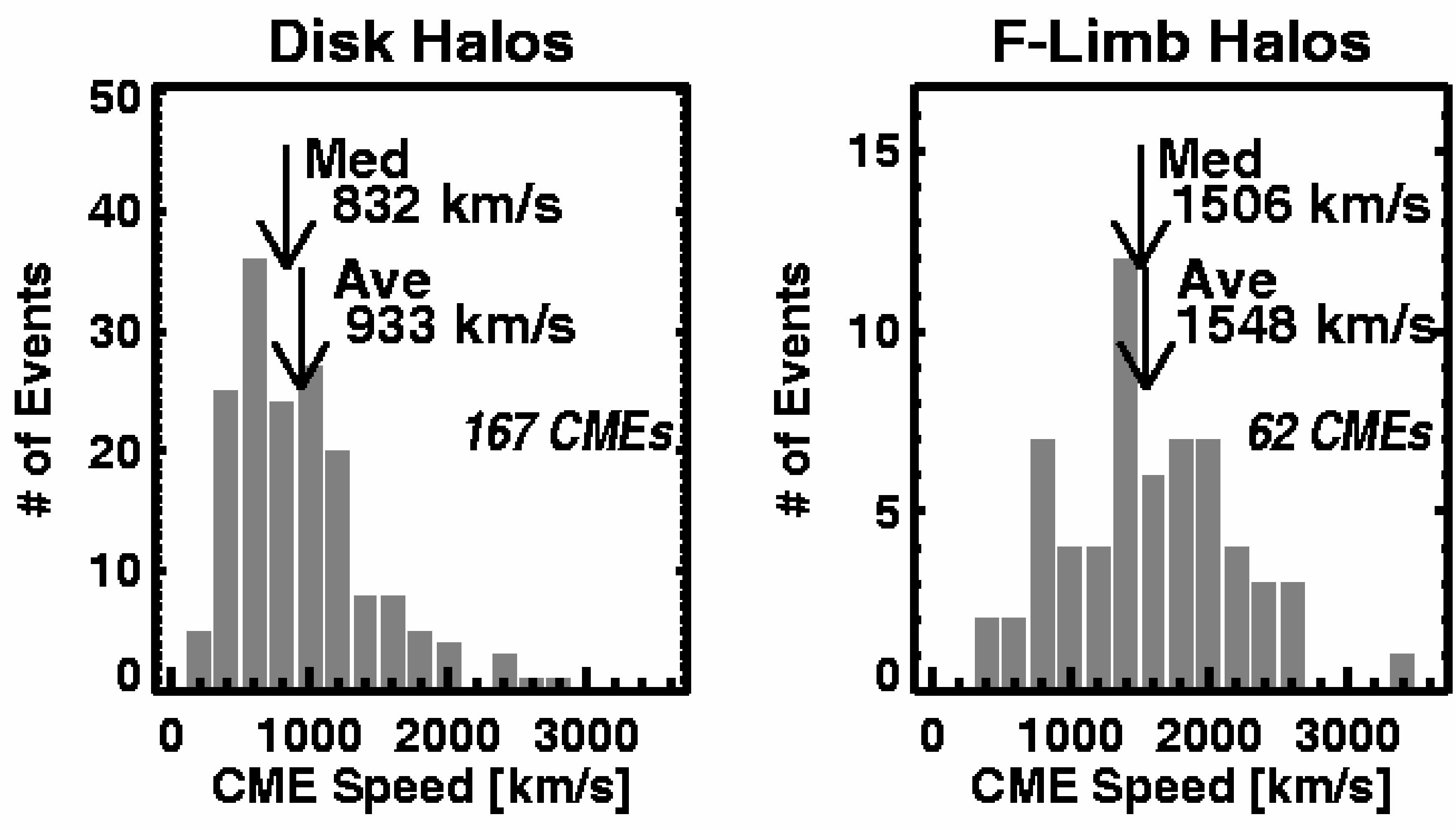
# Transit Time of Shocks & CMEs

Speed limit implies a limit on the shock arrival time – at least half a day




From Gopalswamy et al. 2005 JGR

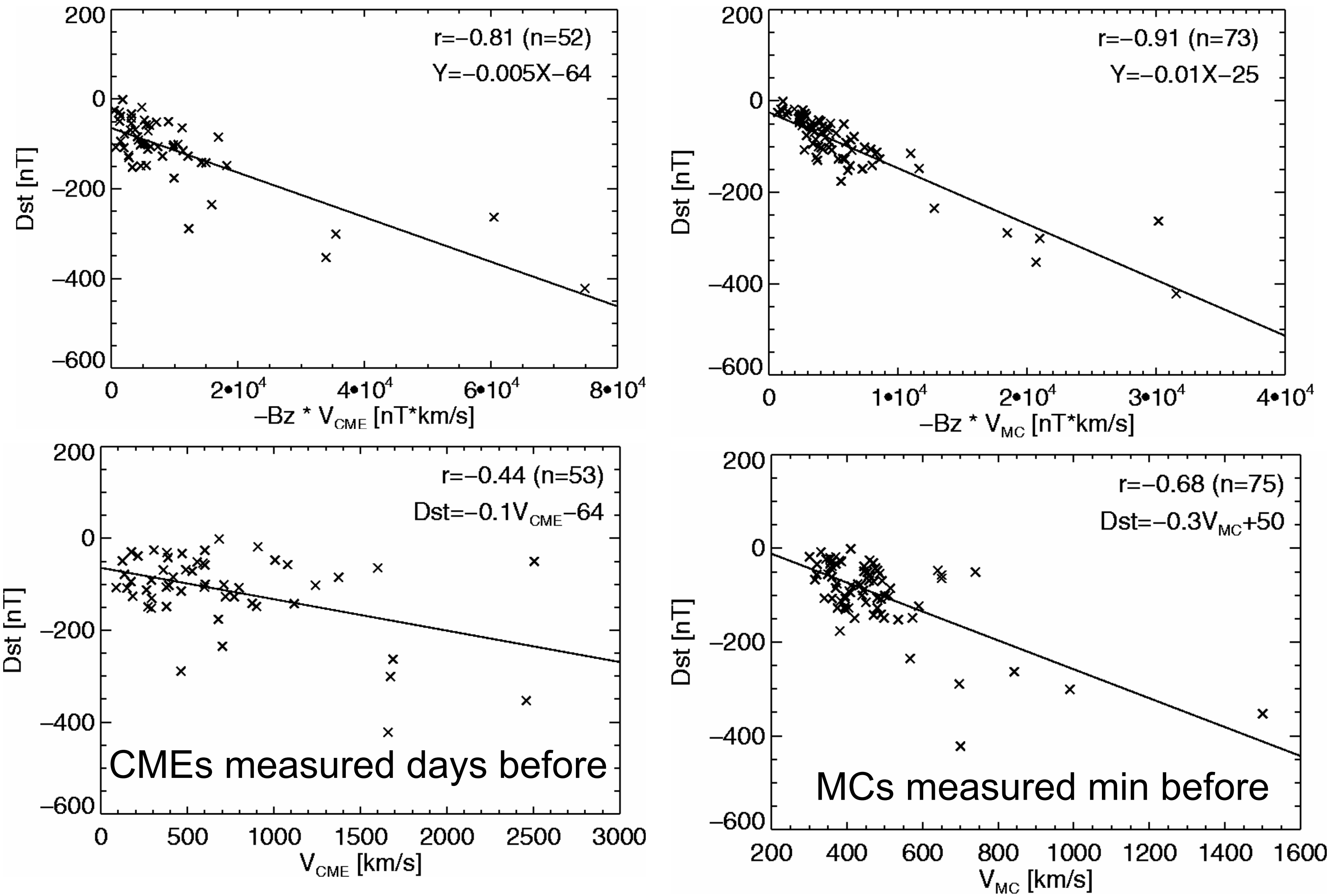
# Halo & MC Speeds

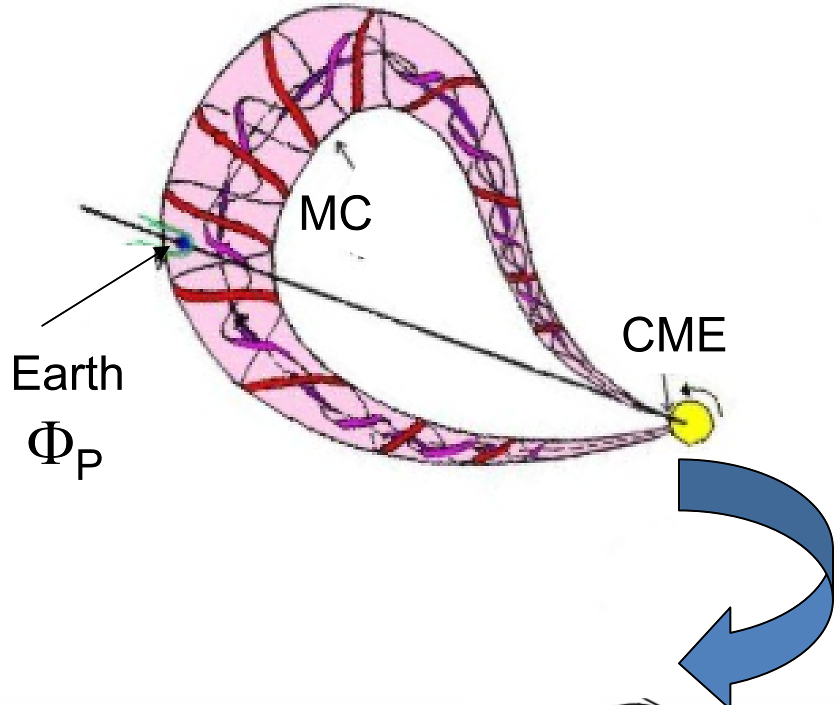


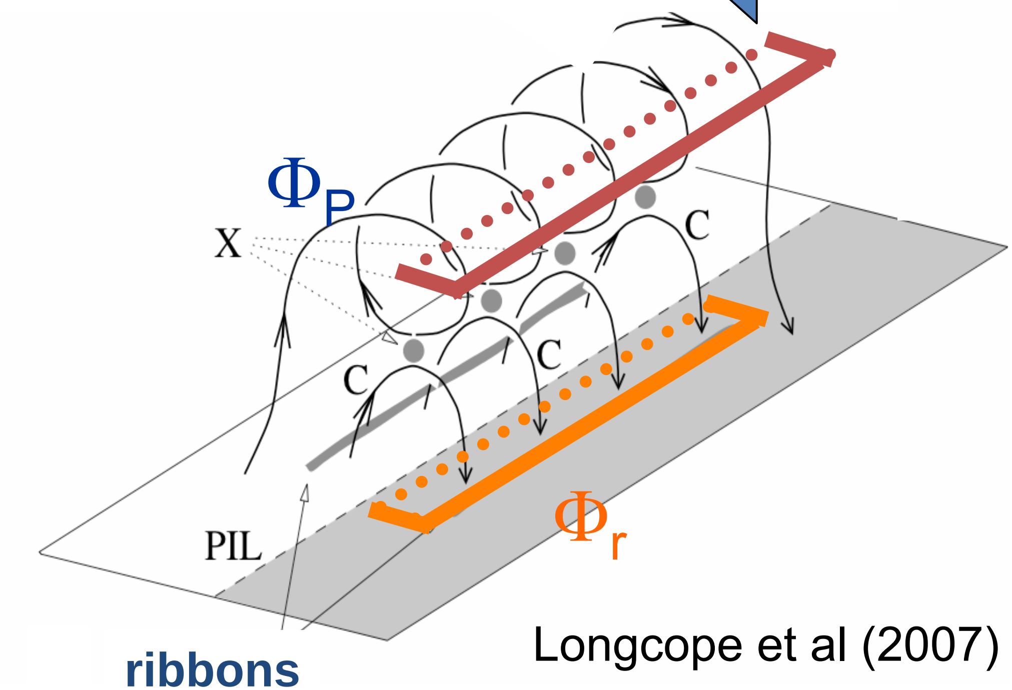

MCs result from energetic CMEs at the Sun

# Dst Dependence on V and B

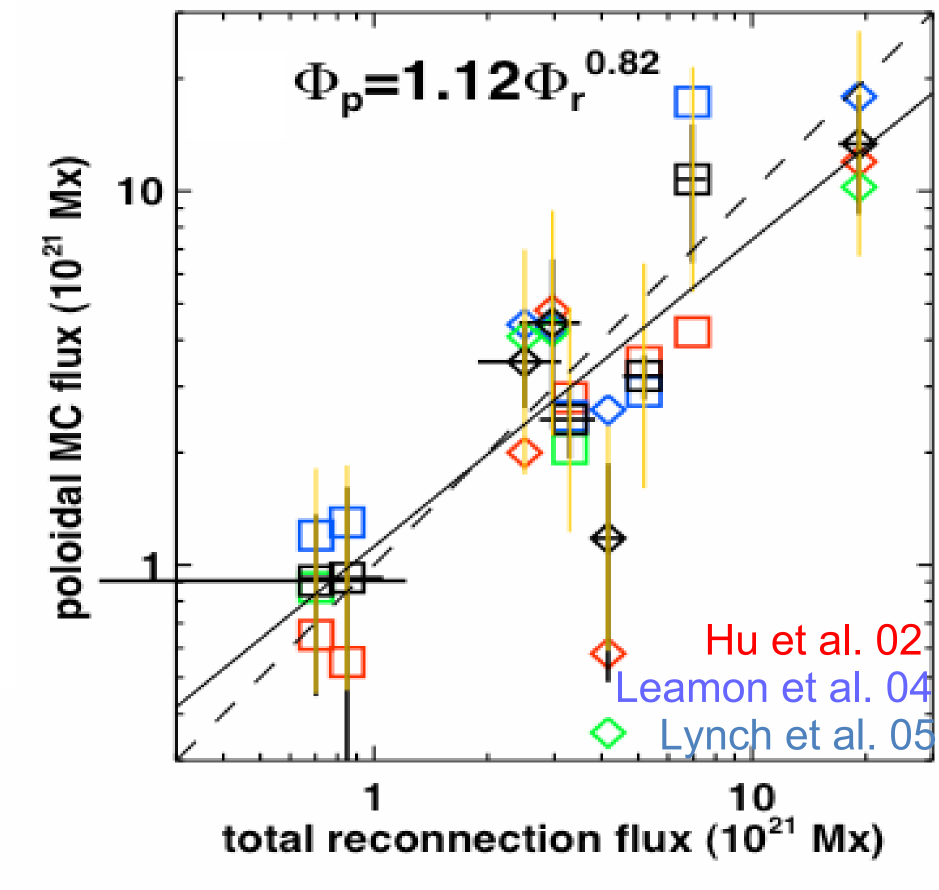
Gonzalez et al., Yurchyshyn et al., Zhang et al…….






Longcope et al (2007)

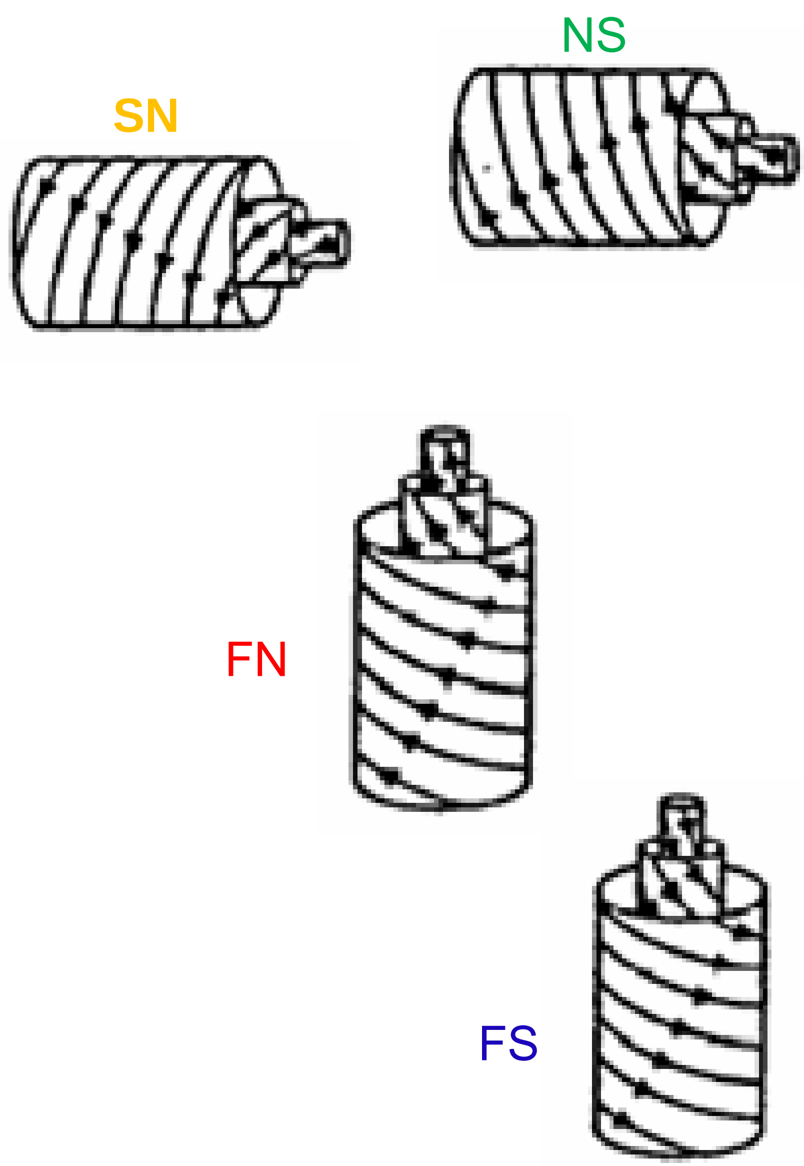


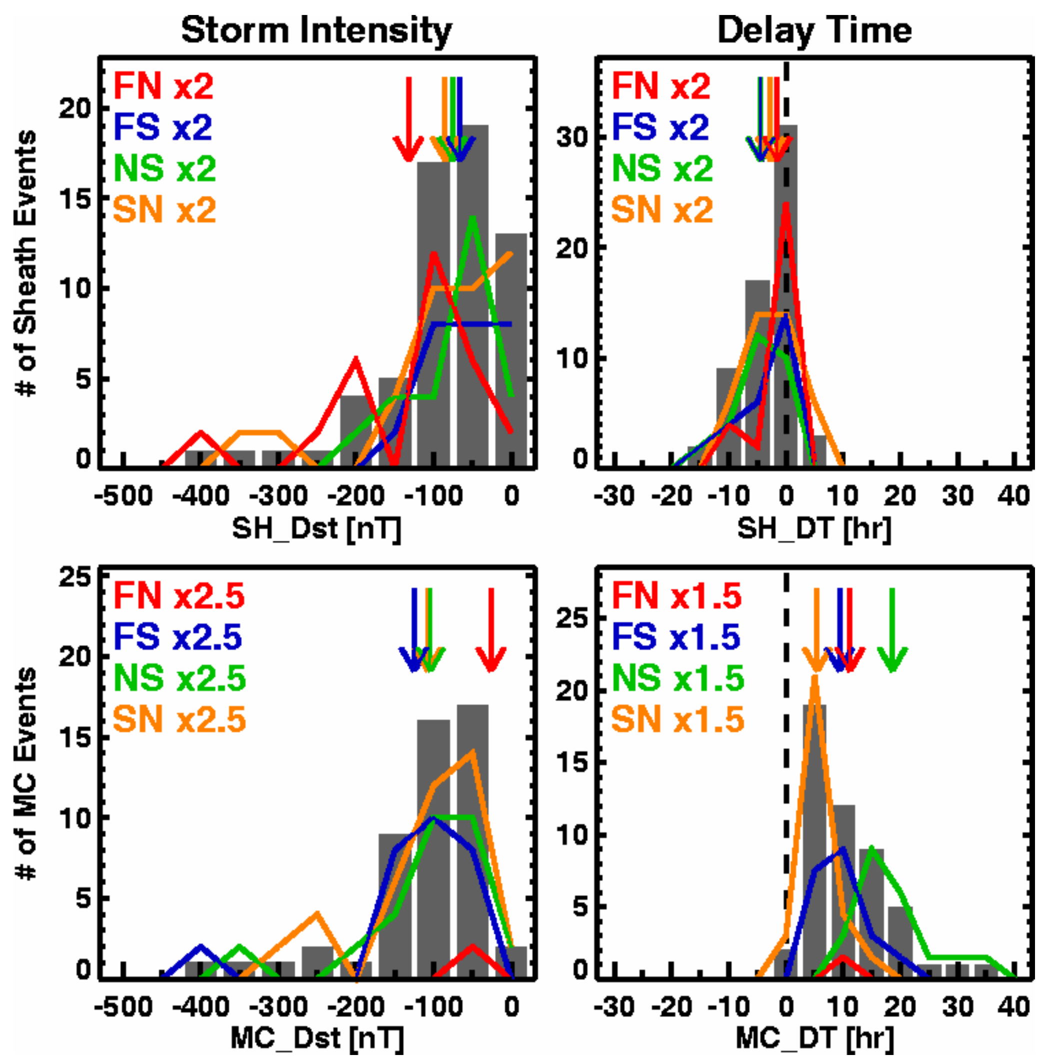

Qiu et al. 2007

# Storm Intensity Depends on

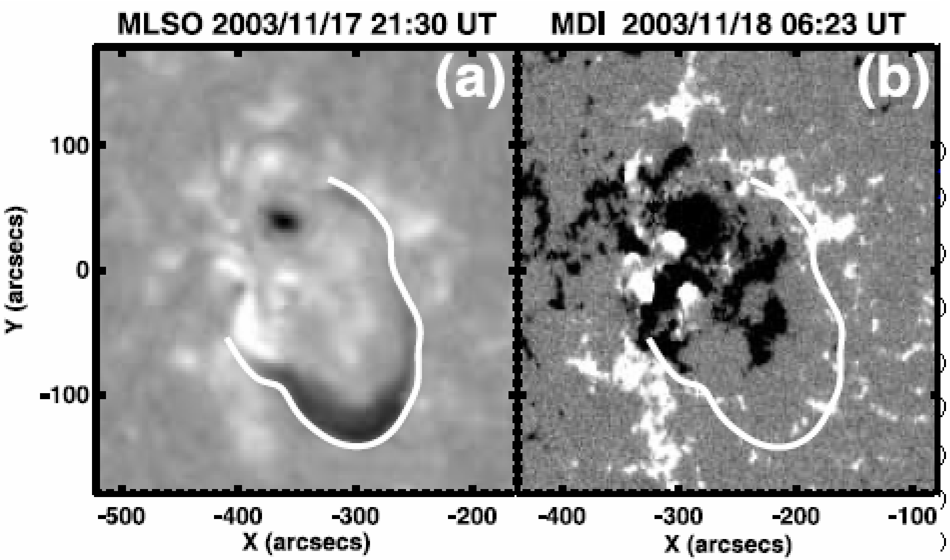
- CME speed
- BzS
- Topology of magnetic cloud
- Propagation conditions
- Geometry
- It is somewhat difficult to characterize the extremeness based on geoeffectiveness

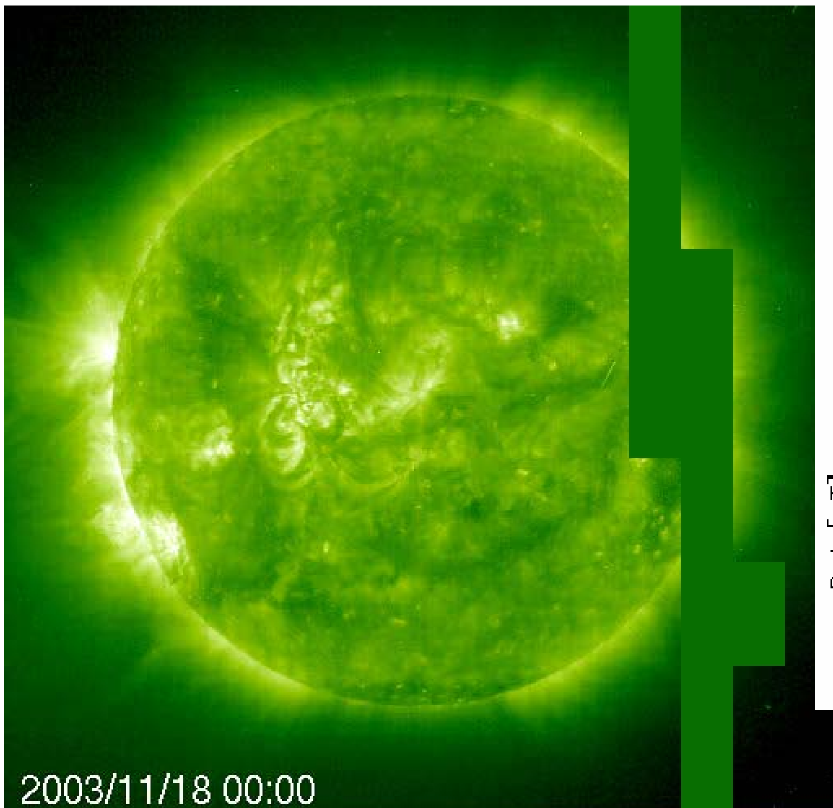
# Cloud & Sheath Storms

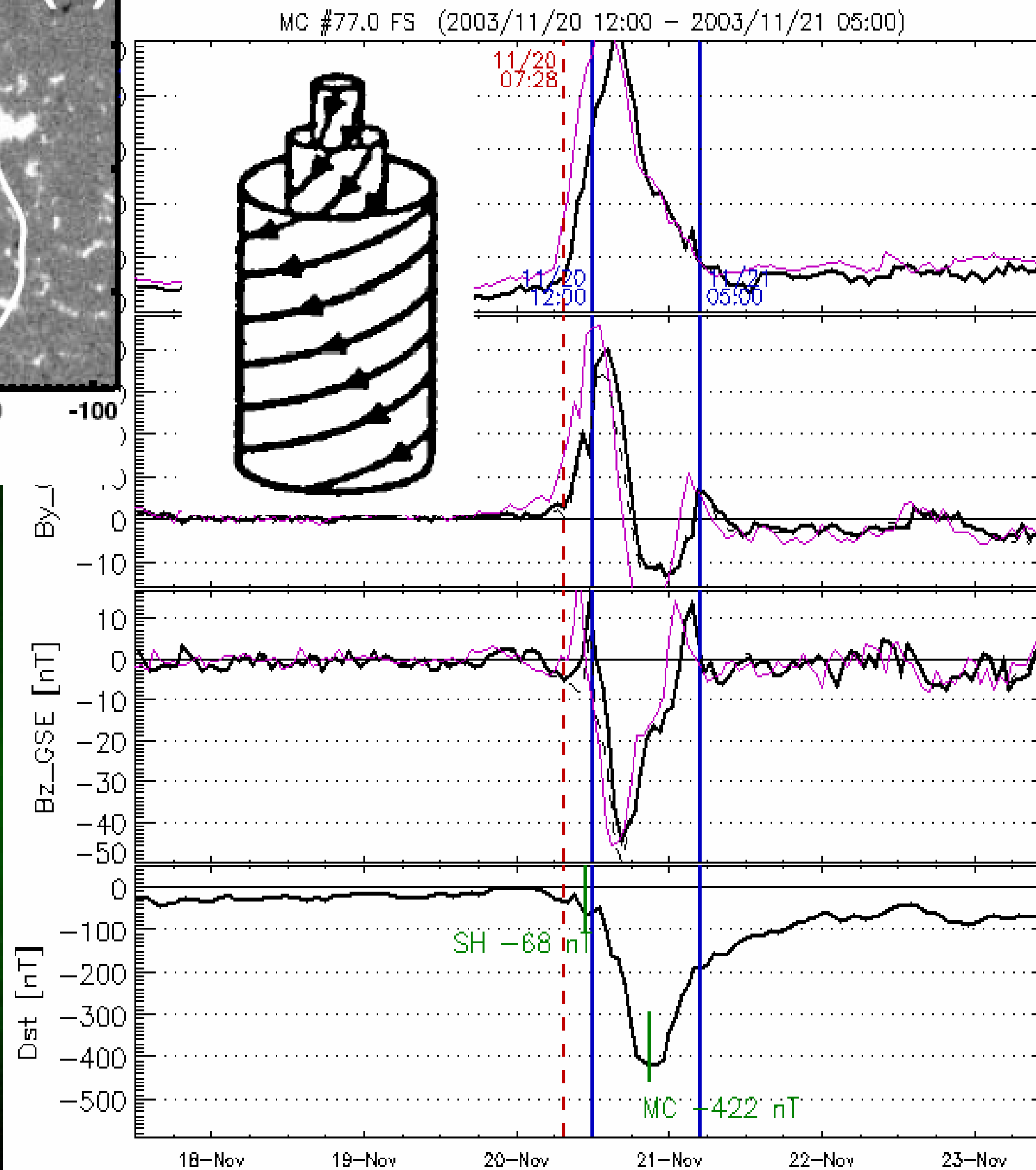


# Largest Dst in cycle23



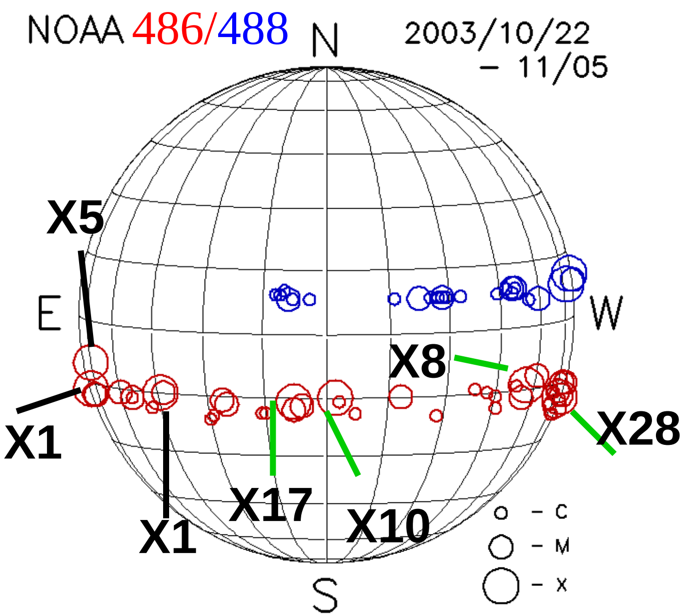



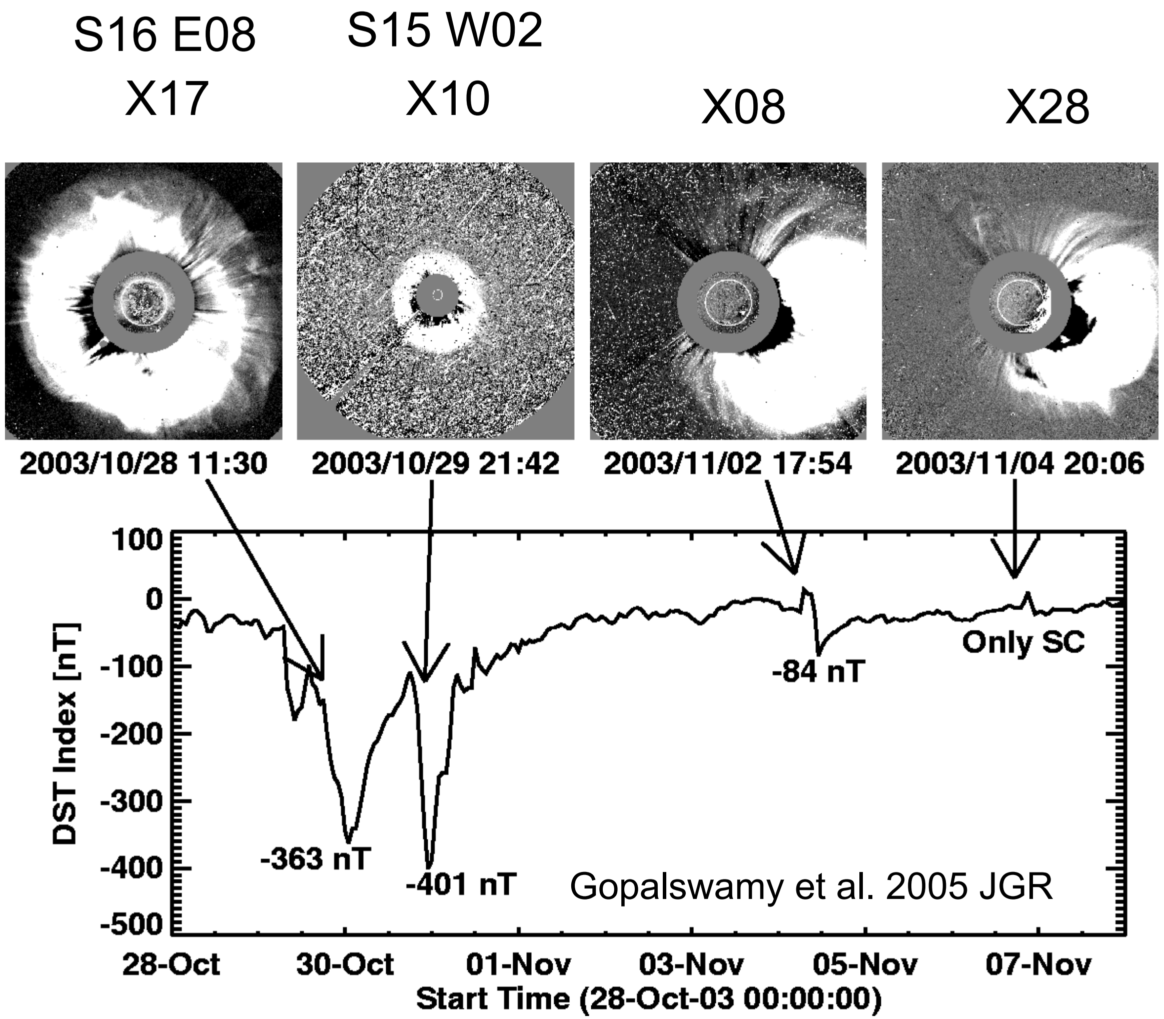

ESW MC

Vcme _1660 km/s

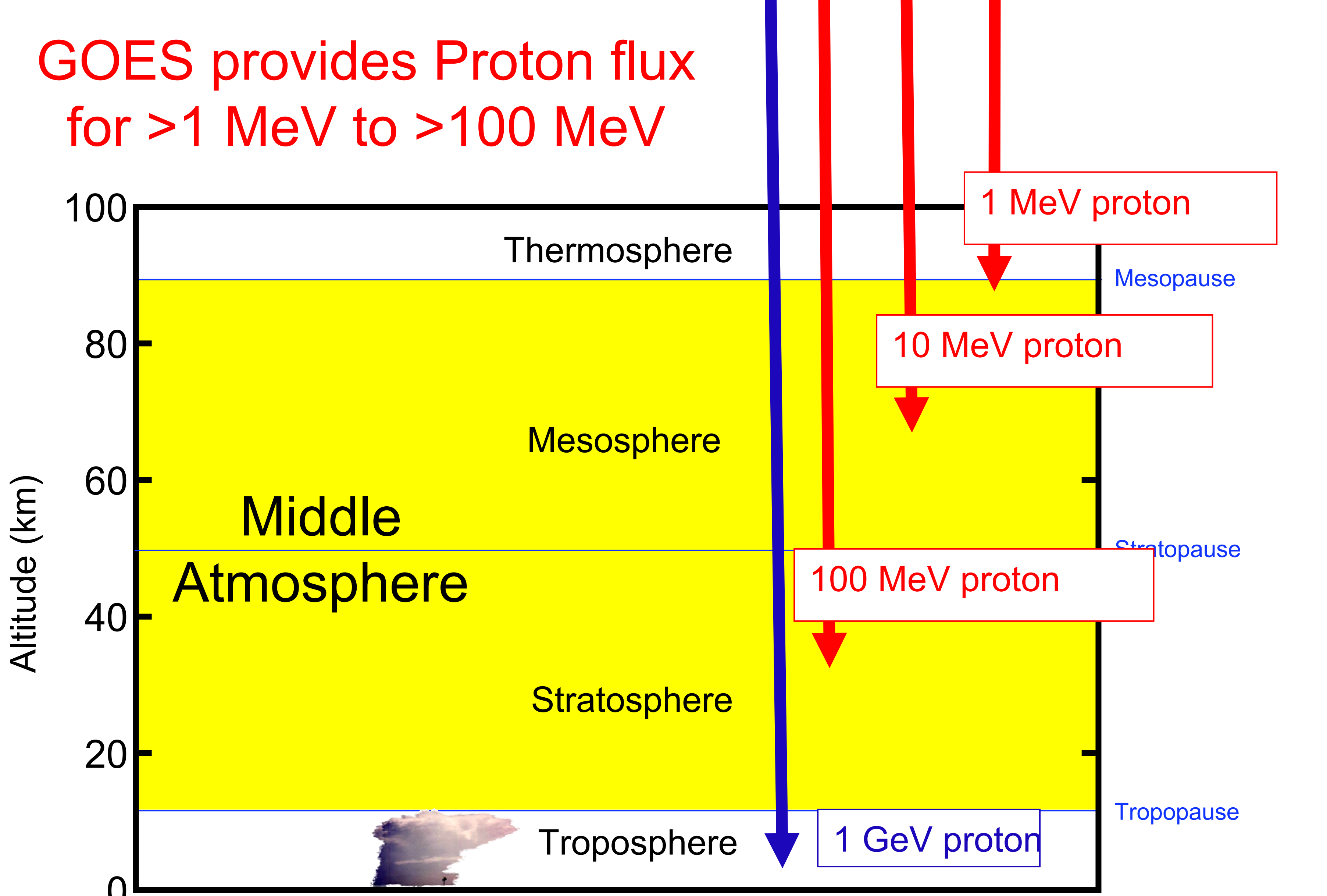
# Solar Source location important for geoeffectiveness




Heliographic coordinates of the associated flare is used as the source location.

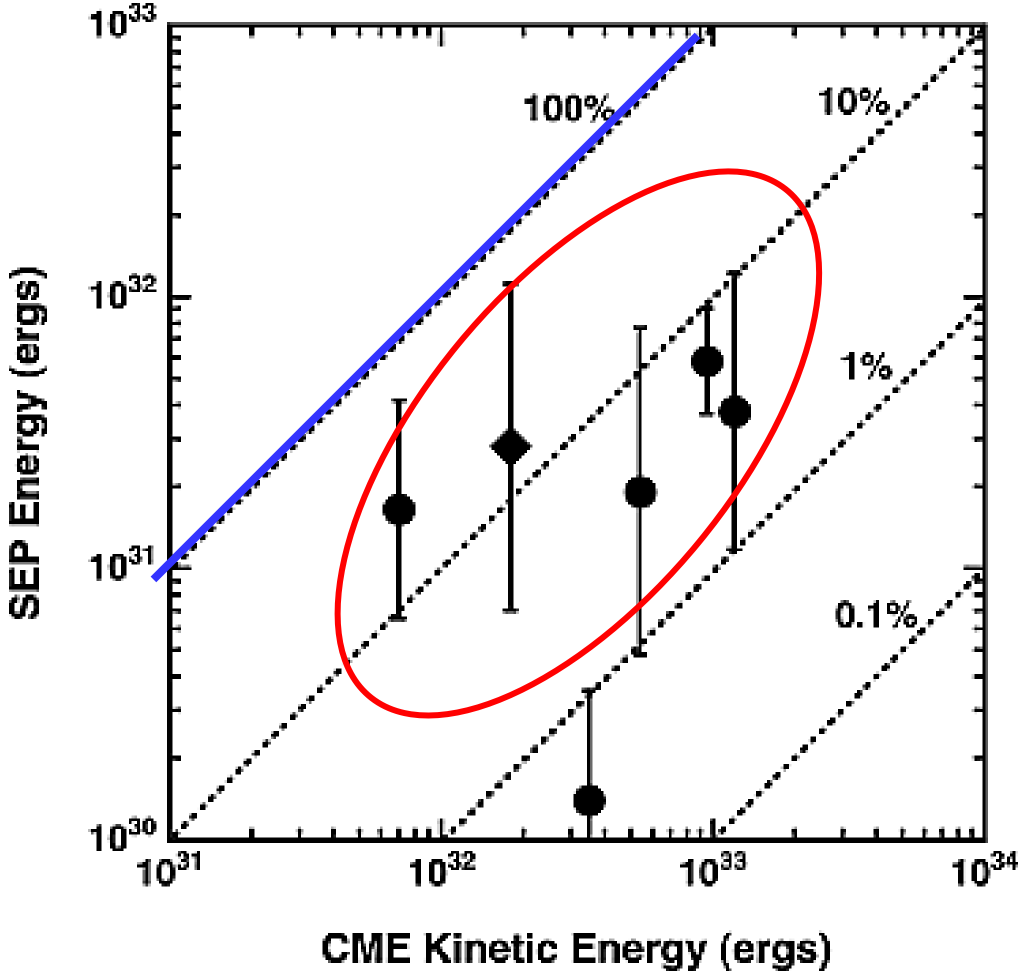


# GOES provides Proton flux for >1 MeV to >100 MeV




**GLEs: Extreme SEP Events?**

# CMEs are Efficient Accelerators

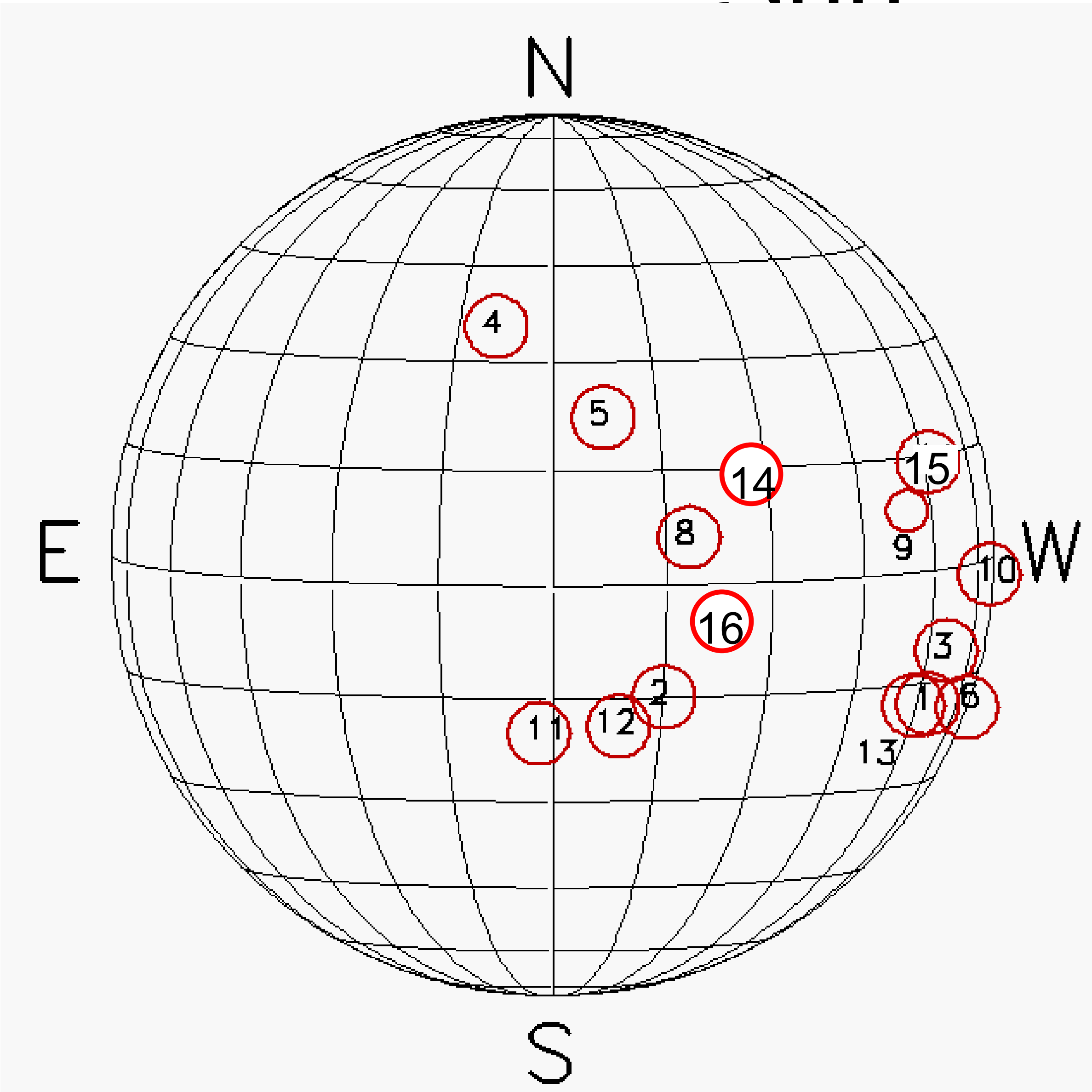



Typically about 10% of CME kinetic energy goes into SEPs

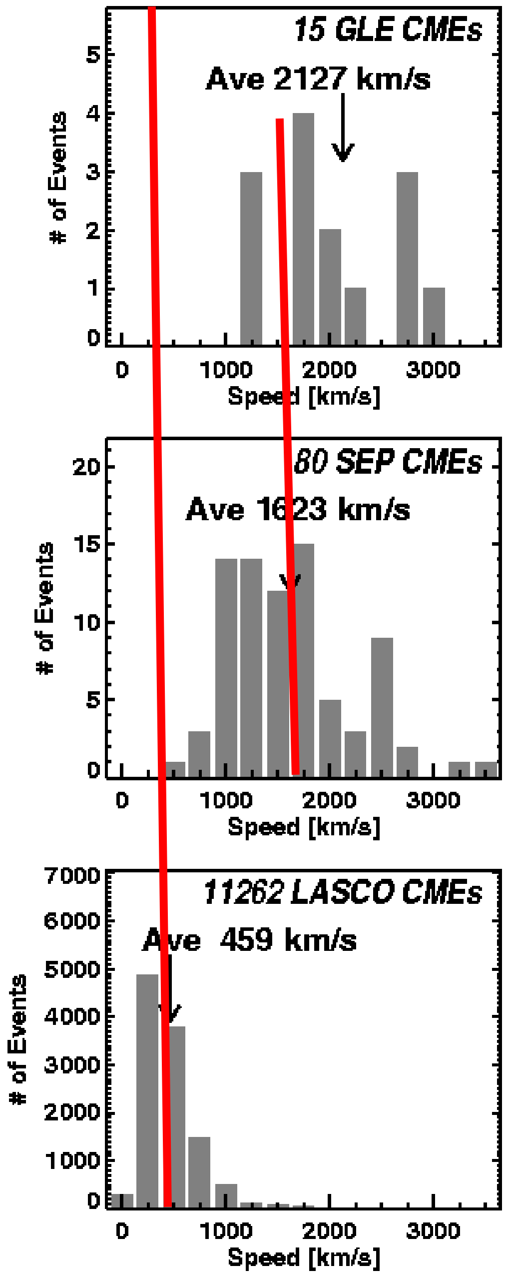
Expect GLEs to be associated with faster CMEs

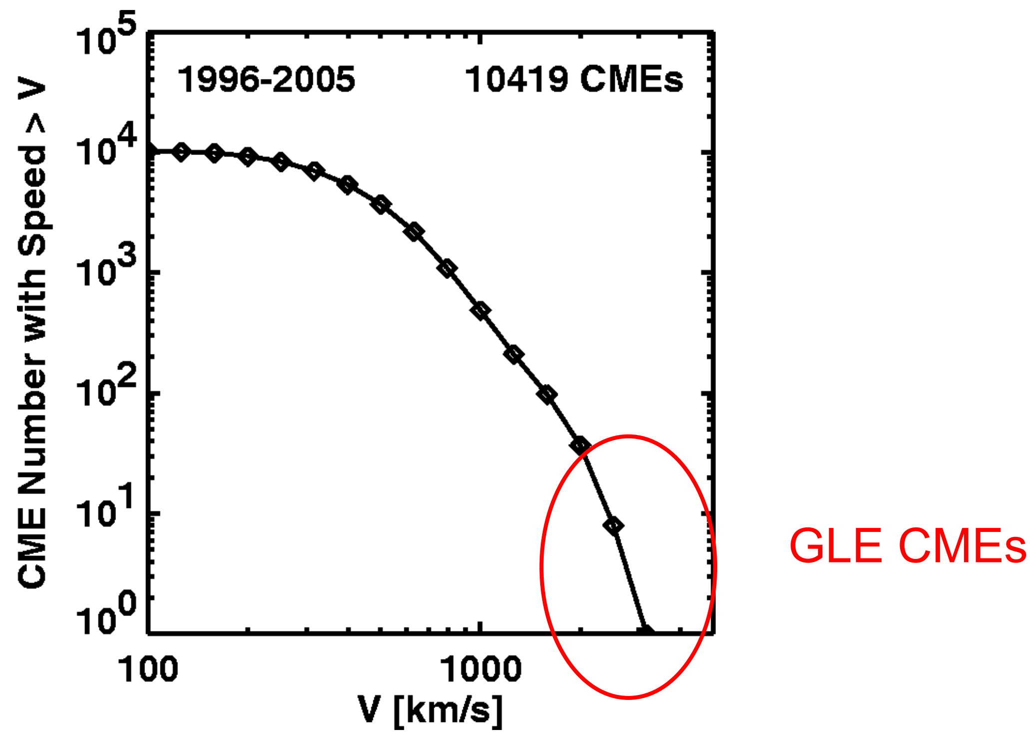
Mewaldt, 2005

# Cycle 23 GLE Sources on the Sun




| # | Date | % |
|---|---|---|
| 01 | 1997/11/06 | 11.3 |
| 02 | 1998/05/02 | 6.8 |
| 03 | 1998/05/06 | 4.2 |
| 04 | 1998/08/24 | 3.3 |
| 05 | 2000/07/14 | 29.3 |
| 06 | 2001/04/15 | 56.7 |
| 07 | 2001/04/18 | 13.8 |
| 08 | 2001/11/04 | 3.3 |
| 09 | 2001/12/26 | 7.2 |
| 10 | 2002/08/24 | 5. 1 |
| 11 | 2003/10/28 | 12.4 |
| 12 | 2003/10/29 | 8.1 |
| 13 | 2003/11/02 | 7.0 |
| 14 | 2005/01/20 | 3.0 |
| 15 | 2005/01/17 | 277.3 |
| 16 | 2006/12/13 | 92.3 |

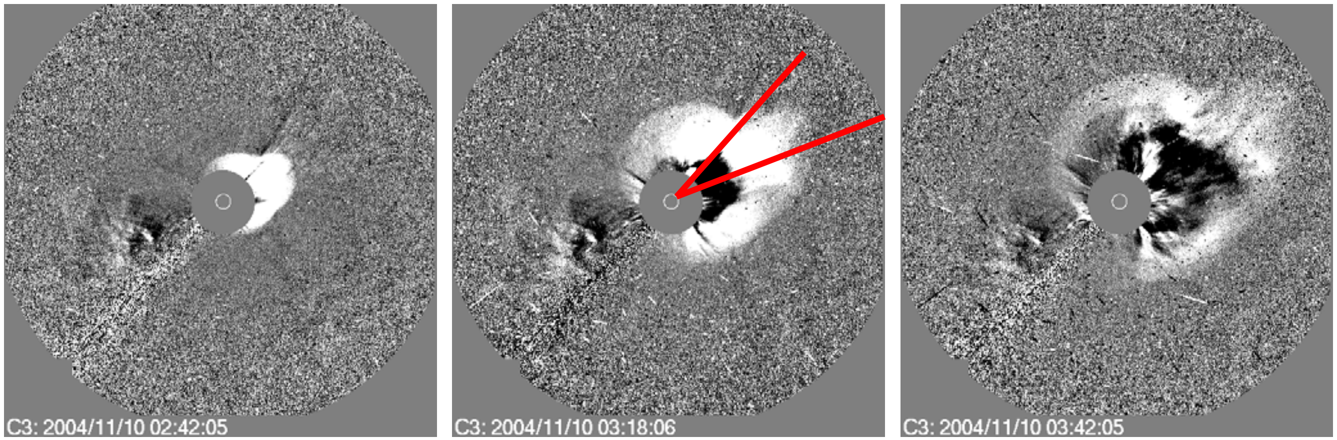


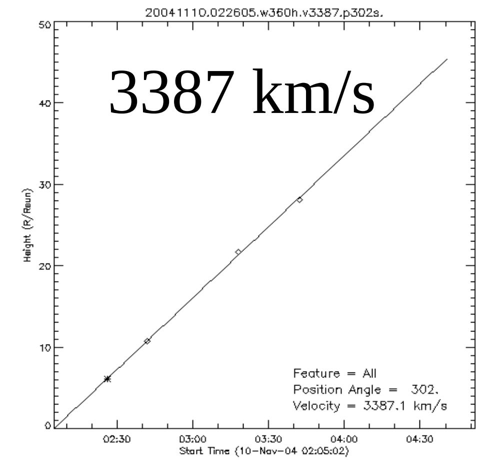



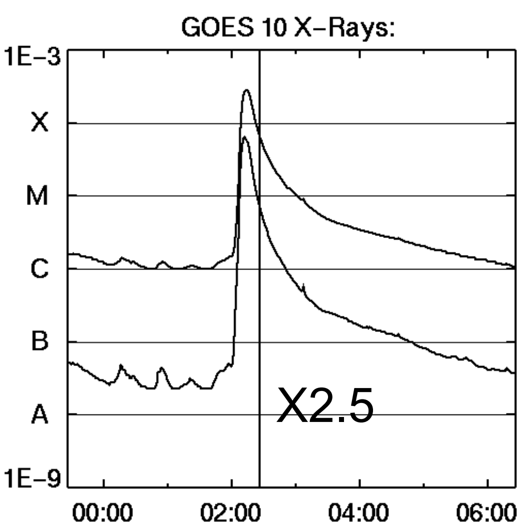

- Avg Sky-plane speed ~1960 km/s
- Avg space speed ~2130 km/s
- Avg speed of SEP CMEs ~1620 km/s
- GLE-associated CMEs constitute the fastest population

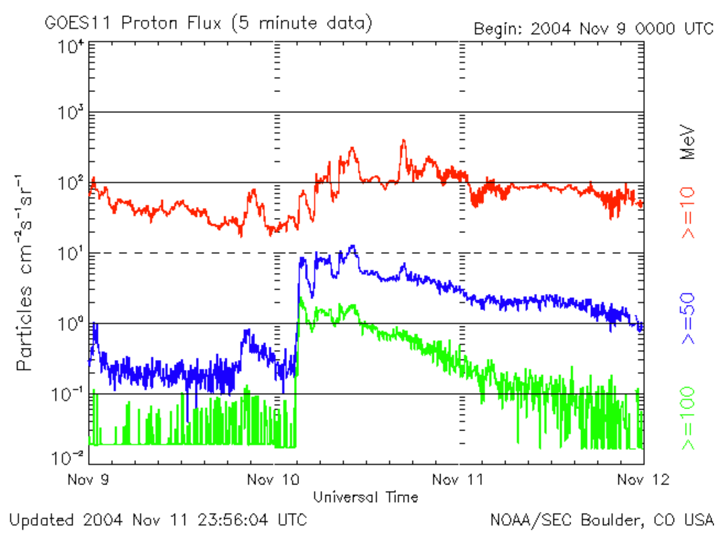
# Fastest CME of cycle 23: No GLE

2004 Nov 10




The CME is peculiar: the fastest section is only 30 deg wide → low KE

Possibility of two events: two type II bursts

Gopalswamy 2005 JGR

# Summary

- CME speed (KE) seems to be an important parameter characterizing extreme events
- The free energy available from the Sun depends on the size of the active region magnetic field
- To characterize CMEs as extreme events based on geomagnetic storms, propagation & geometry need to be considered
- GLEs can be regarded as extreme SEP

- Typical enhancement is < 10%
- Rare occurrence: 15 in 11 y → 1.3/y

- Solar cycle: [4,5,7] min, rise, max
- Rare occurrence: 16 in 11 y → 1.4/y

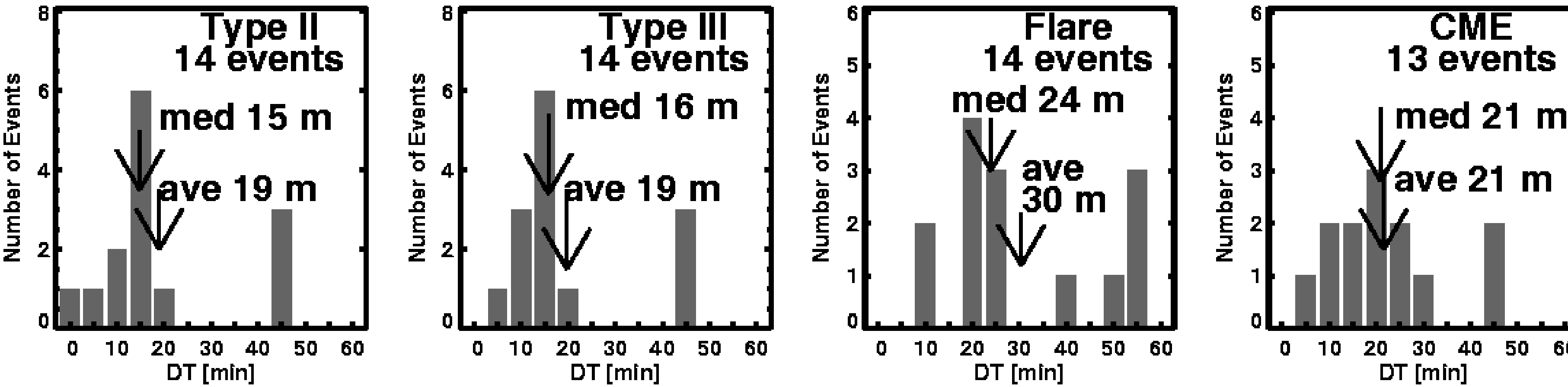
SOLAR CYCLE 23 GLE EVENTS

| GLE event Date | GLE Onset (Obs) | GLE Onset (Inf) | Peak time ($T_{pk}$) (UT) | GLE Intensity (%) | Type II Onset | Type III Onset (UT) | Flare onset (UT) | Flare Class /Location | CME onset (UT) | CME height (Rs) | CME speed (km/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1997Nov06 | 12:10 | 12:07 | 14:00 | 11.3 | 11:53 | 11:52 | 11:49 | X9.4/S18W63 | 11:39 | 5.2 | 1726 |
| 1998May02 | 13:55 | 13:52 | 14:05 | 6.8 | 13:41 | 13:35 | 13:31 | X1.1S15W15 | 13:32 | 3.3 | 1332 |
| 1998May06 | 08:25 | 08:22 | 09:30 | 4.2 | 08:03 | 08:01 | 07:58 | X2.7/S11W65 | 07:55 | 3.8 | 1208 |
| 1998Aug24 | 22:50 | 22:47 | 02:05 | 3.3 | 22:02 | 22:04 | 21:50 | X1.0/N35E09 | DG | DG | DG |
| 2000Jul14 | 10:30 | 10:27 | 11:00 | 29.3 | 10:28 | 10:18 | 10:03 | X5.7/N22W07 | 10:25 | 1.4 | 1741 |
| 2001Apr15 | 14:00 | 13:57 | 14:35 | 56.7 | 13:47 | 13:49 | 13:19 | X14/S20W85 | 13:35 | 3.3 | 1203 |
| 2001Apr18 | 02:35 | 02:32 | 03:10 | 13.8 | 02:17 | 02:15 | 02:11 | ?/S23W117 | 02:11 | 5.9 | 2712 |
| 2001Nov04 | 17:00 | 16:57 | 17:20 | 3.3 | 16:10 | 16:13 | 16:03 | X1.0/N06W18 | 16:13 | 8.0 | 1846 |
| 2001Dec26 | 05:30 | 05:27 | 06:10 | 7.2 | 05:12 | 05:13 | 04:32 | M7.1/N08W54 | 05:06 | 4.2 | 1779 |
| 2002Aug24 | 01:18 | 01:15 | 01:35 | 5.1 | 01:01 | 01:01 | 00:49 | X3.1/S02W81 | 00:59 | 3.6 | 1937 |
| 2003Oct28 | 11:22 | 11:19 | 11:51 | 12.4 | 11:02 | 11:03 | 11:00 | X17/S20E02 | 11:07 | 3.9 | 2754 |
| 2003Oct29 | 21:30 | 21:27 | 00:42 | 8.1 | 20:42 | 20:41 | 20:37 | X10/S19W09 | 20:43 | 8.7 | 2049 |
| 2003Nov02 | 17:30 | 17:27 | 17:55 | 7.0 | 17:14 | 17:16 | 17:18 | X8.3/S18W59 | 17:19 | 3.0 | 2981 |
| 2005Jan17 | 09:55 | 09:52 | 09:59 | 3.0 | 09:43 | 09:41 | 09:52 | X3.8/N14W25 | 09:43 | 3.2 | 2802 |
| 2005Jan20 | 06:51 | 06:48 | 07:00 | 277.3 | 06:44 | 06:45 | 06:39 | X7.1/N14W61 | 06:33 | 4.0 | 3675 |
| 2006Dec13 | 02:45 | 02:42 | 03:05 | 92.3 | 02:26 | 02:24 | 02:17 | X3.4/S06W23 | 02:25 | 4.2 | 2164 |

Normalized wrt to the arrival of Electromagnetic signals at Earth

CME height at GLE release

# GLE delay with respect to type II, Type III, Flare & CME

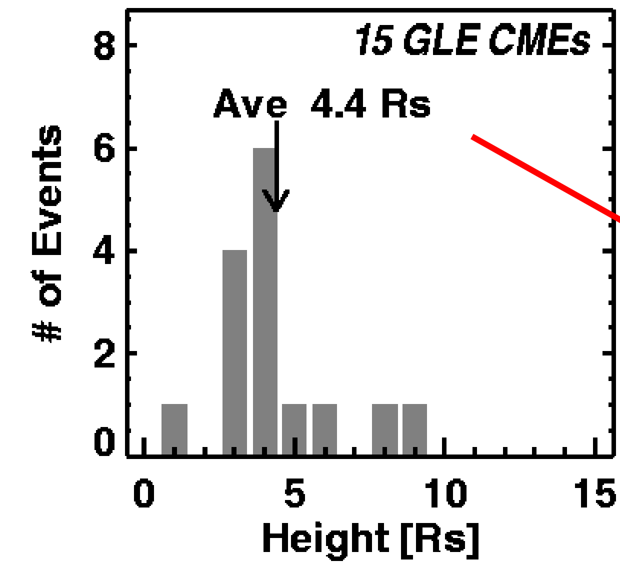


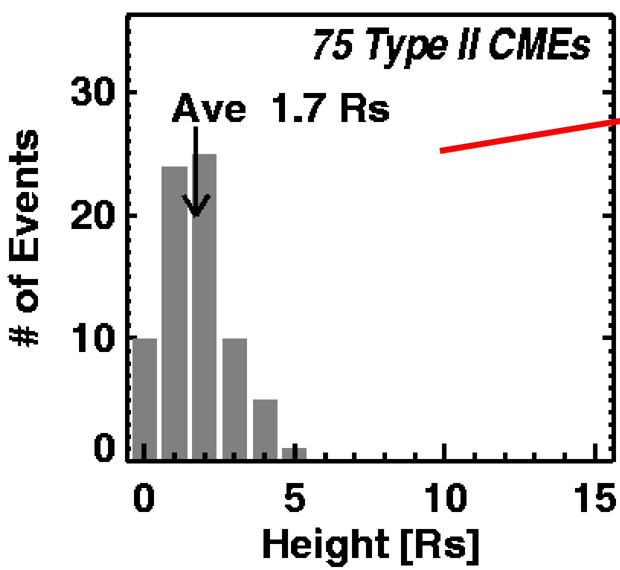

GLE onset is delayed with respect to all indicators of solar activity

Shortest delay for metric type II bursts

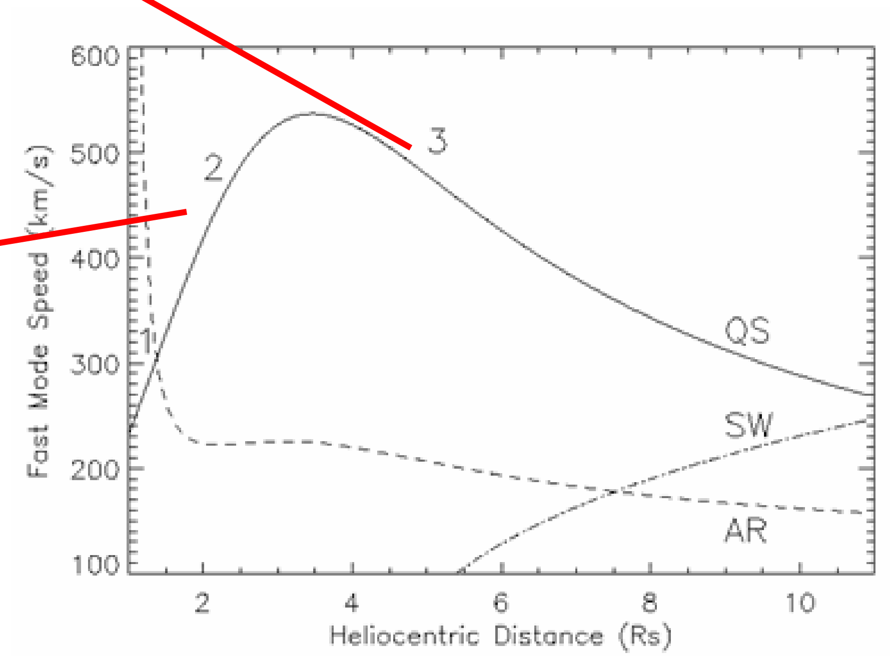
Longest delay for GOES soft X-ray flares

# CME Height at GLE Onset



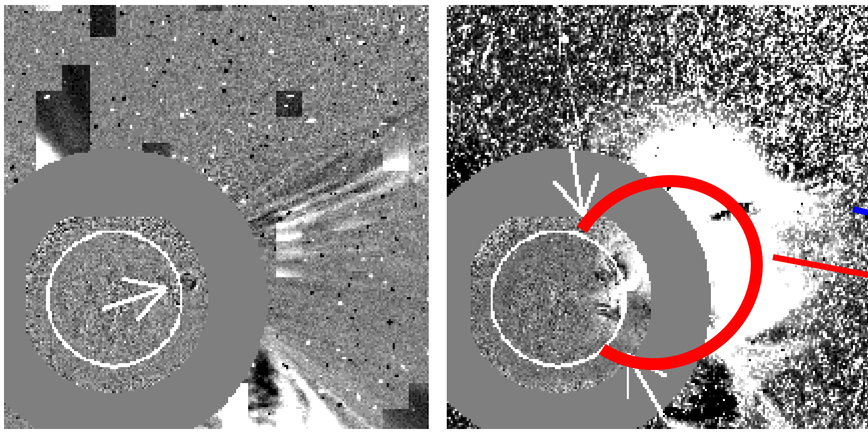




Shock is likely to be the strongest at GLE release:
- CMEs finish accelerating
- Local Alfven speed starts falling

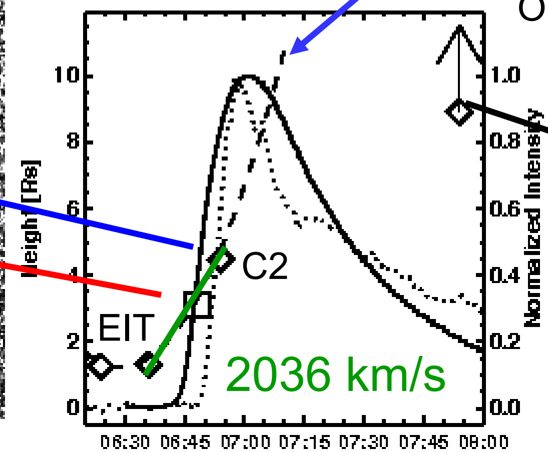


# The Largest cycle-23 Ground Level Enhancement of Solar protons

h = 6.052 -0.3361t + 0.0057t$^2$
(t min from 06:00 UT)
t =54 → dh/dt = 0.28 Ro/min
Or 3242km/s



C2: 06:30  EIT: 06:36  C2: 06:54  EIT: 06:48




C3
Rapid deceleration or the height underestimated due to snowstorm

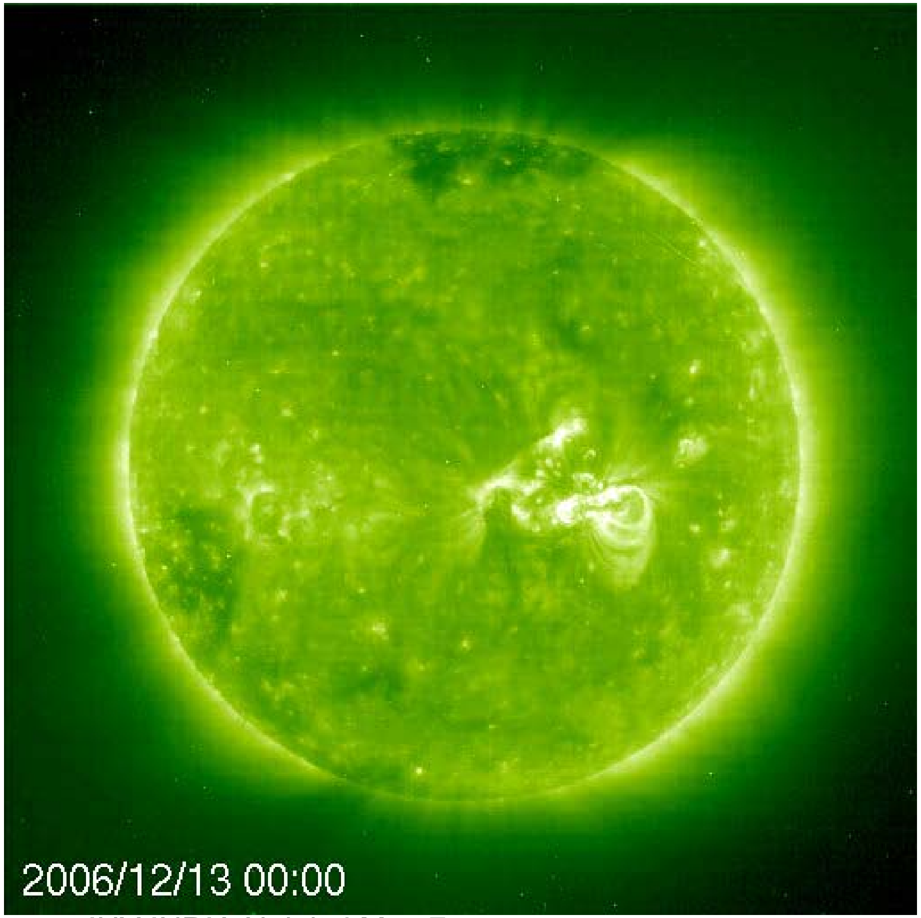
**January 20 2005 Event**

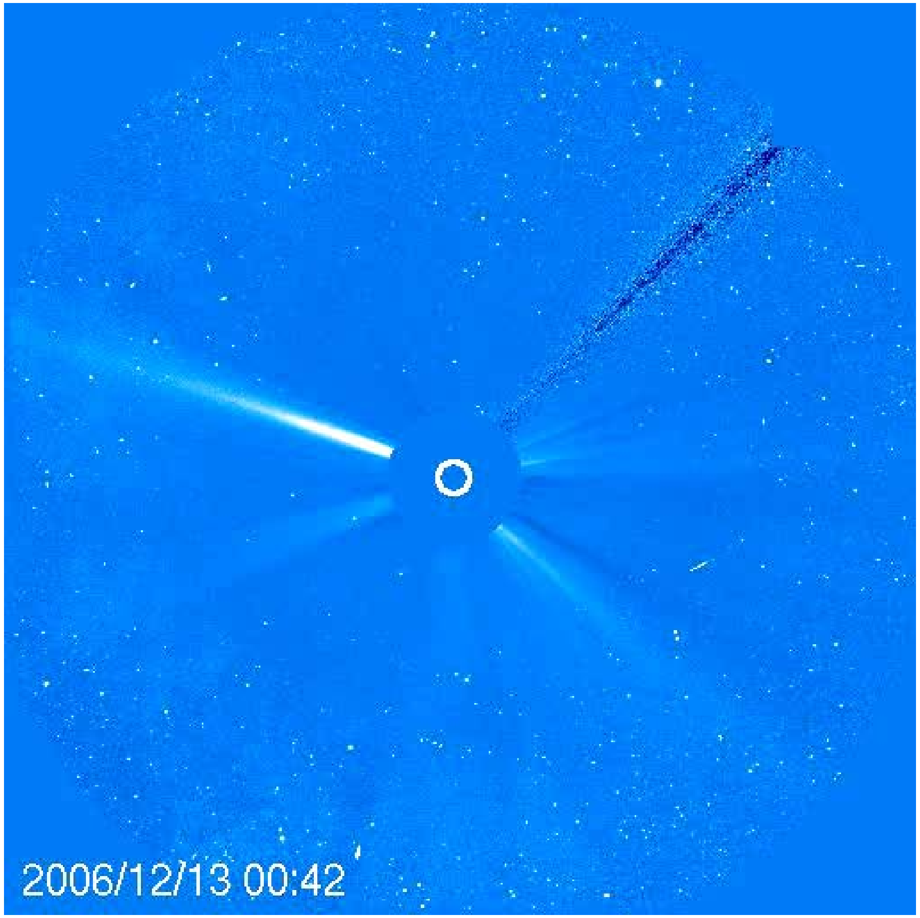
- Snow-storm at first appearance → Particles reached in < 16 min
- CME speed ~ 3200 km/s (sky-plane)
  ~3600 km/s (cone-model)
- Rapid deceleration
- Consistent with GLE acceleration by CME-driven shocks

Is the January 20 2005 GLE event a new kind of storm?

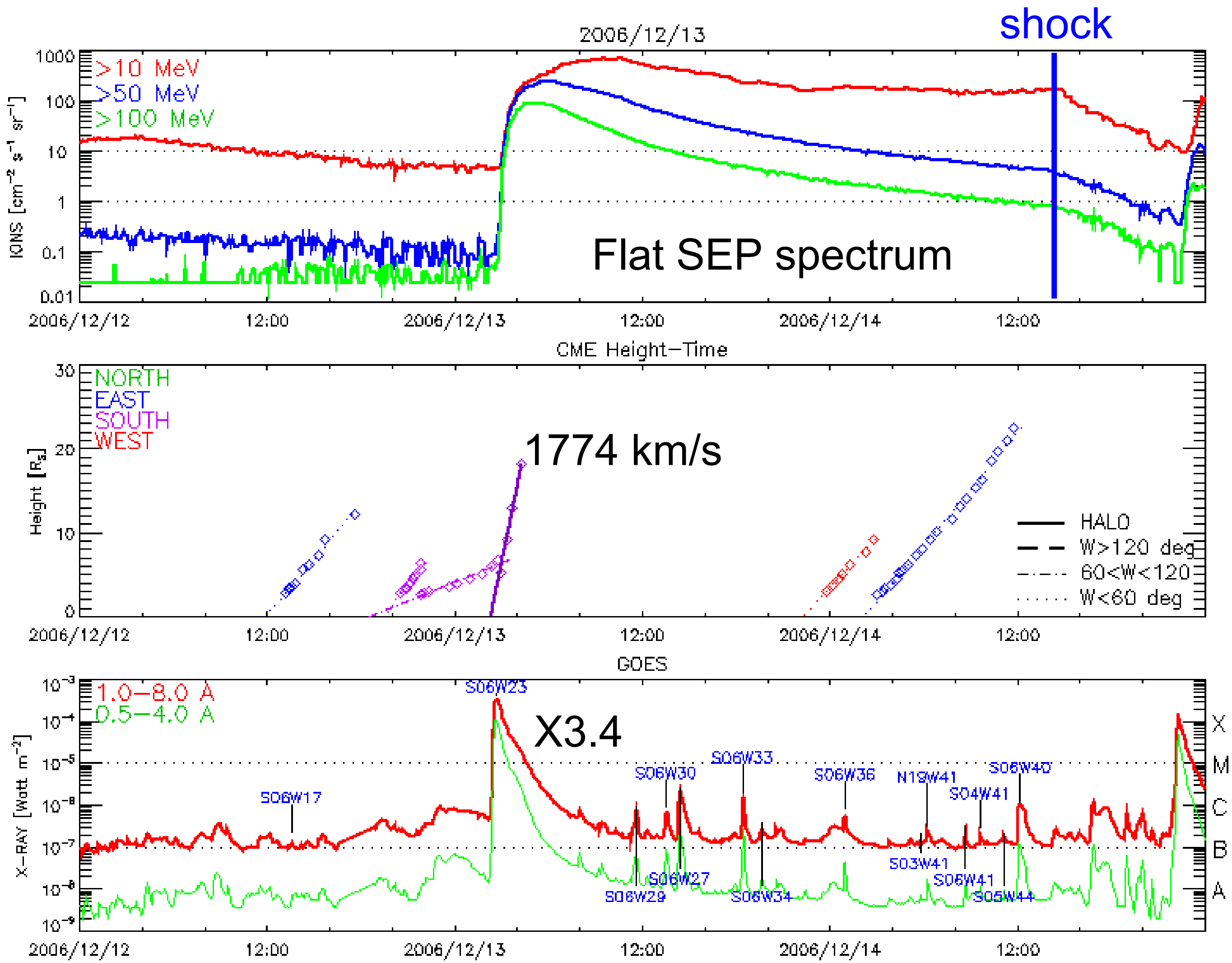
No. It is similar to other GLE events in their CME association

# Second Largest GLE

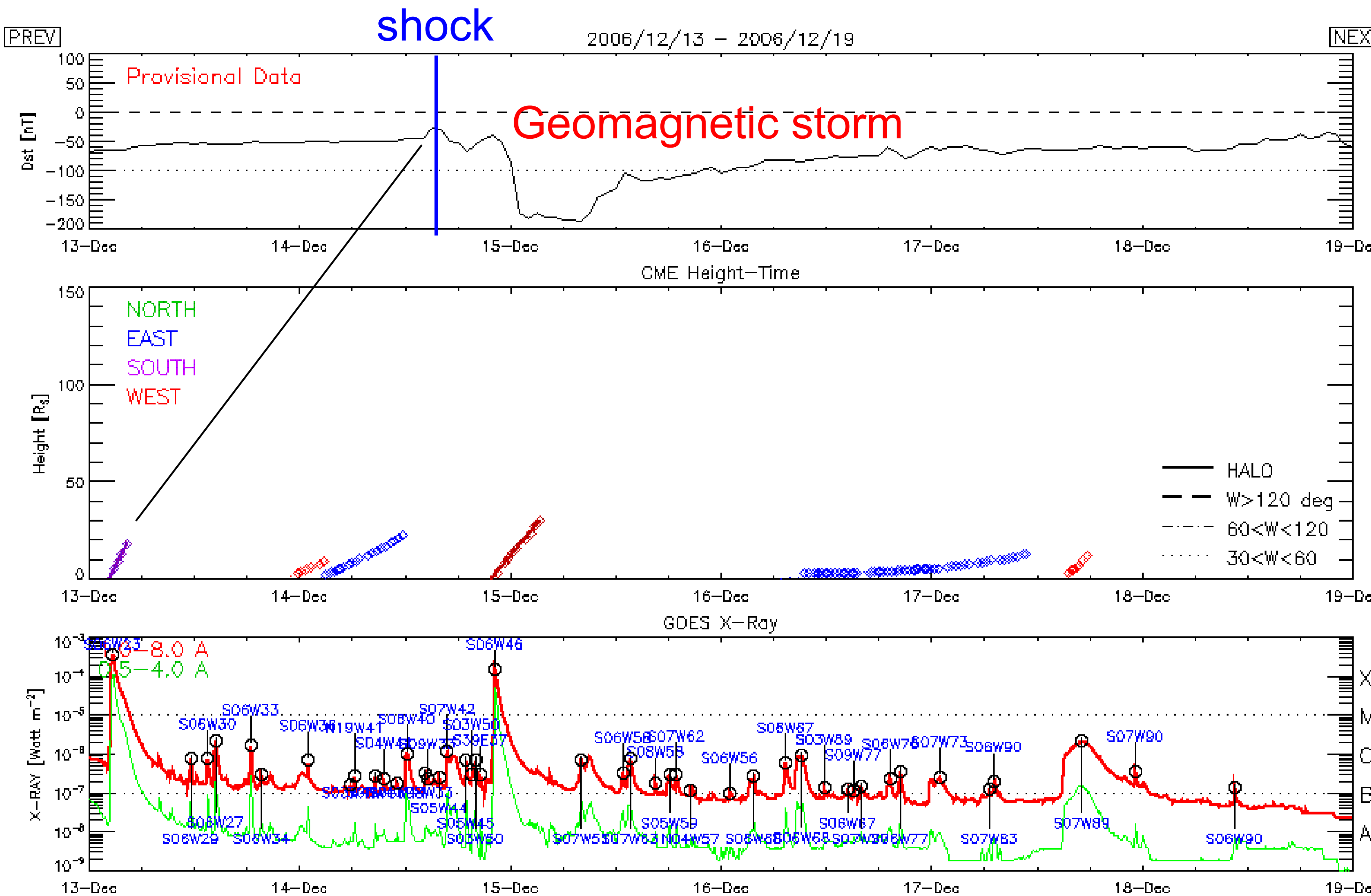


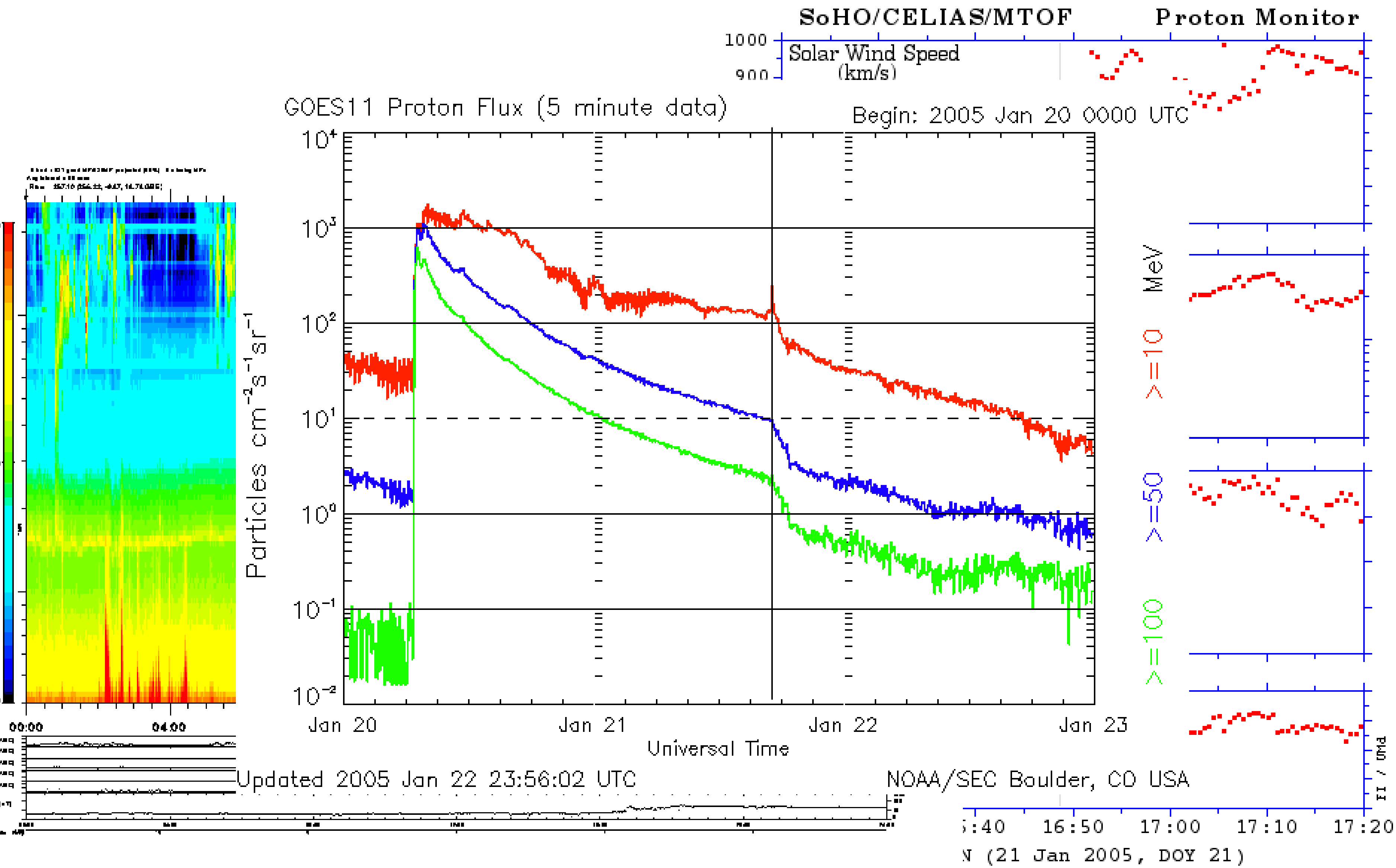
# 2006 12 13 Event (AR 0930)



# Geospace Impact

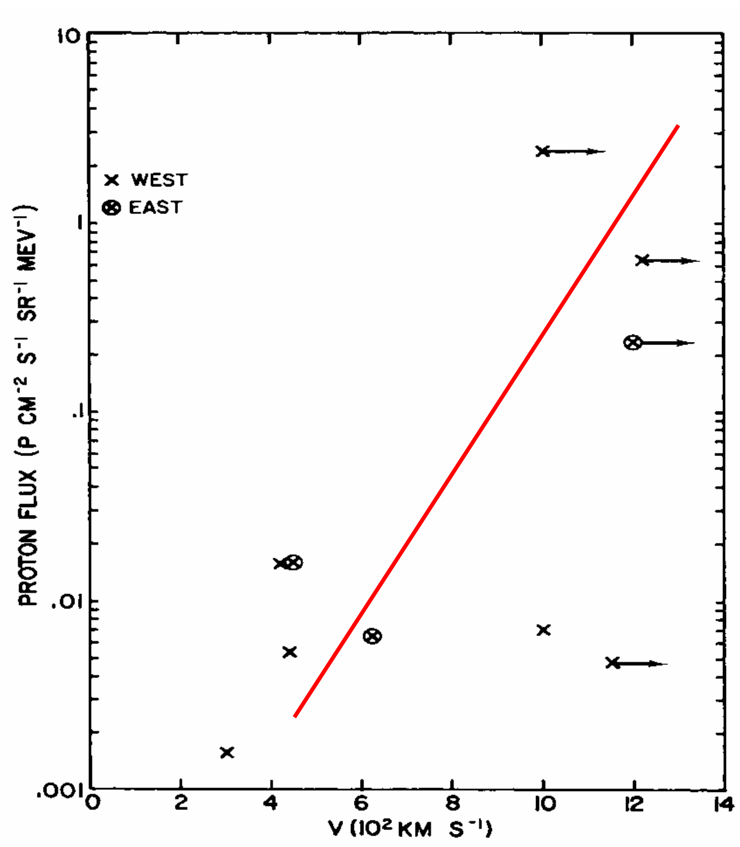



Perfect Storm: SEPs, GLEs, fast CME, Intense flare, IP shock, ICME, magnetic storm

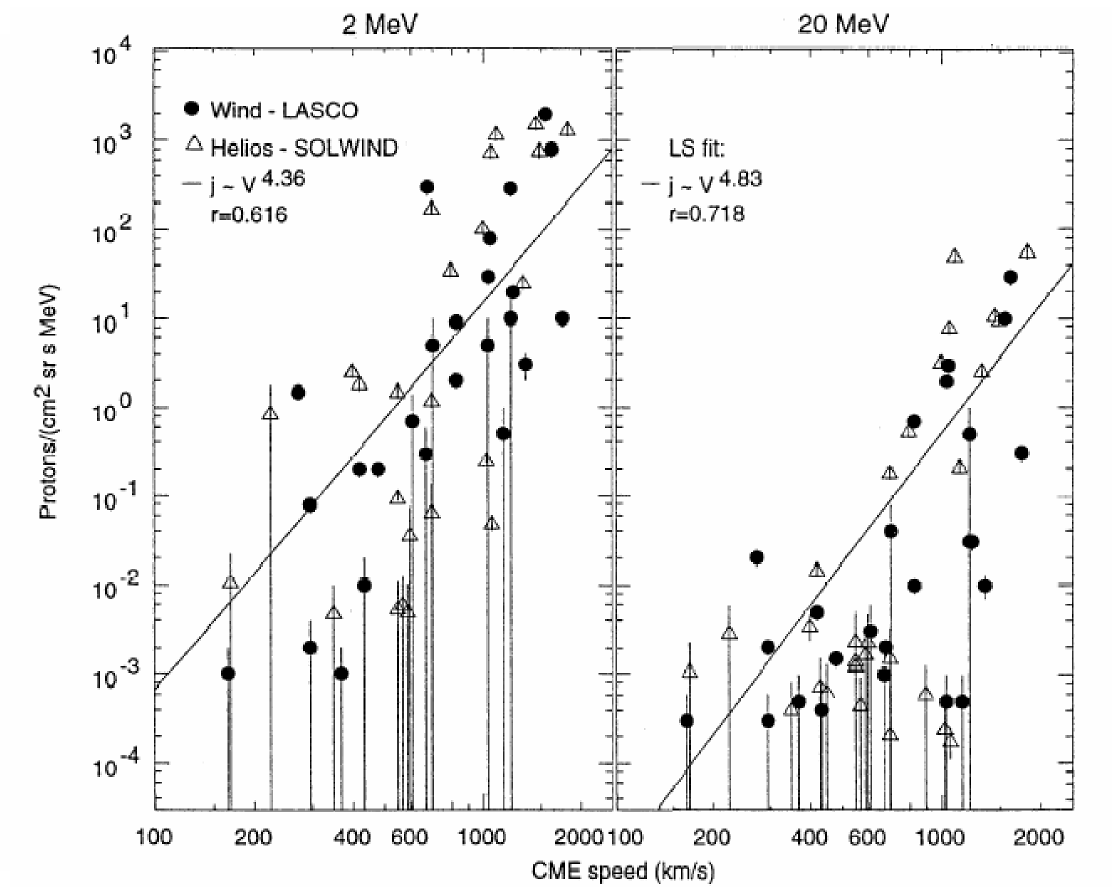


SoHO/CELIAS/MTOF
Proton Monitor
Solar Wind Speed (km/s)
1000
900
GOES11 Proton Flux (5 minute data)
Begin: 2005 Jan 20 0000 UTC
Particles cm$^{-2}$s$^{-1}$sr$^{-1}$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
MeV
>=10
>=50
>=100
Jan 20
Jan 21
Jan 22
Jan 23
Universal Time
Updated 2005 Jan 22 23:56:02 UTC
NOAA/SEC Boulder, CO USA
00:00
04:00
16:50
17:00
17:10
17:20
(21 Jan 2005, DOY 21)

# CMEs & Large SEPs




Kahler 1978



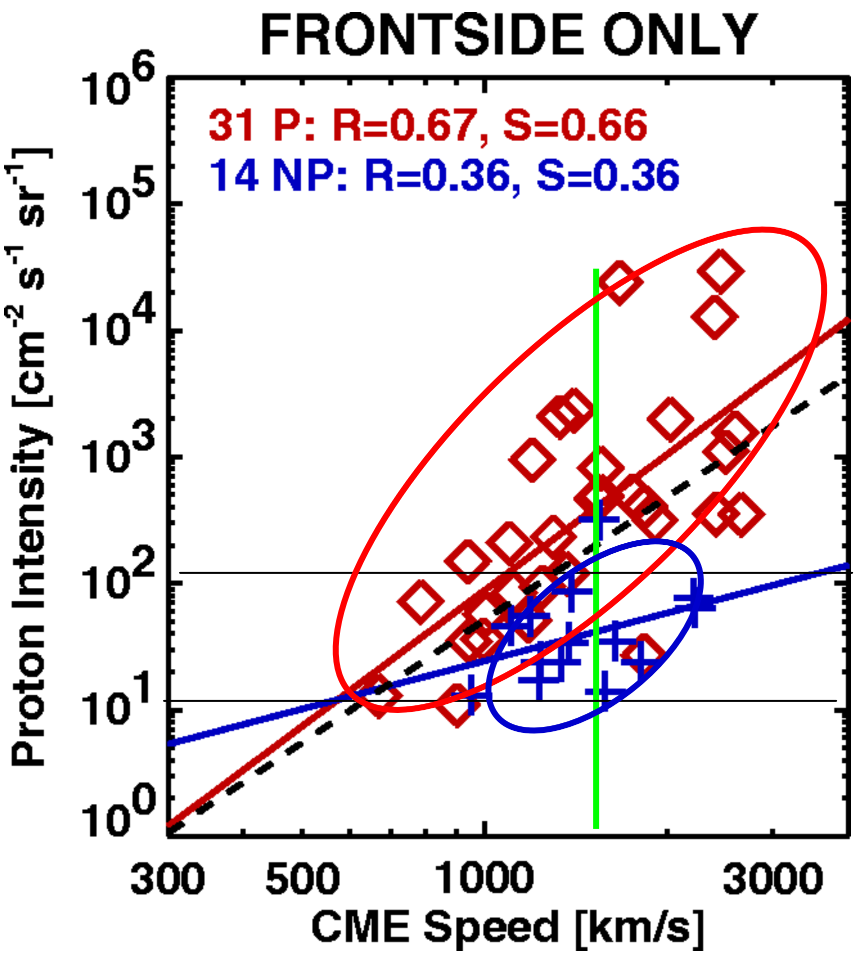

Kahler 2001

# P and NP Events – Another Source of Vcme –Ip Scatter

CME interaction accounts for at least one order of magnitude of scatter

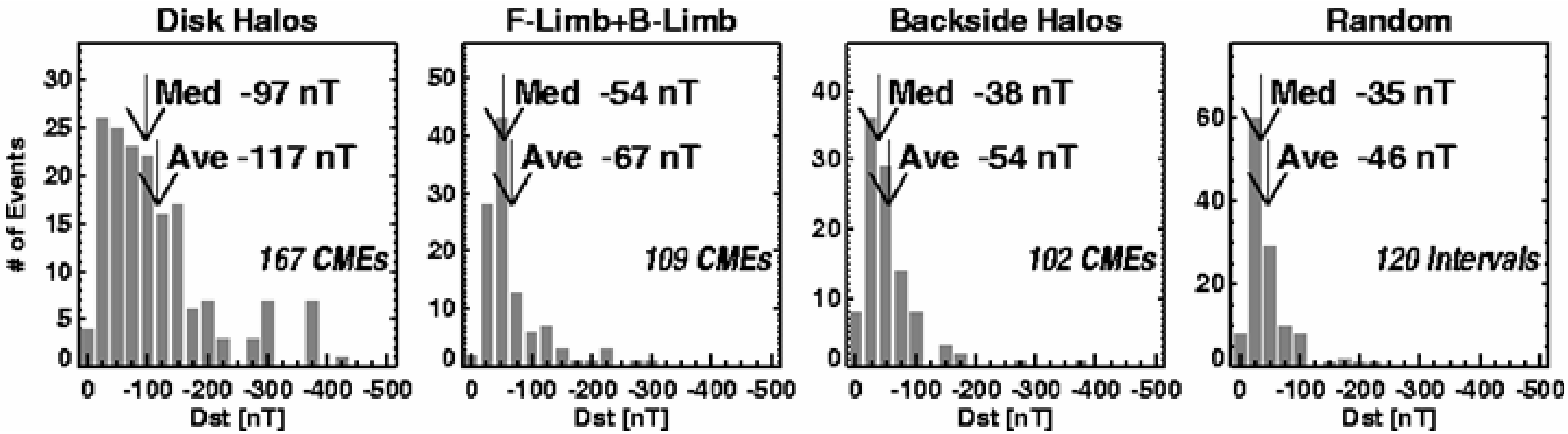
P – SEP producing CMEs with preceding CMEs within a day

NP – SEP producing CMEs with no preceding CMEs




Influence of the ambient medium

# Geoeffectiveness of Halo CMEs




St. Cyr et al. 2000
Yermolaev and Yermolaev 2006
Zhao and Webb 2003
Kim et al. 2005
Michalek et al. 2006
Gopalswamy et al. 2007

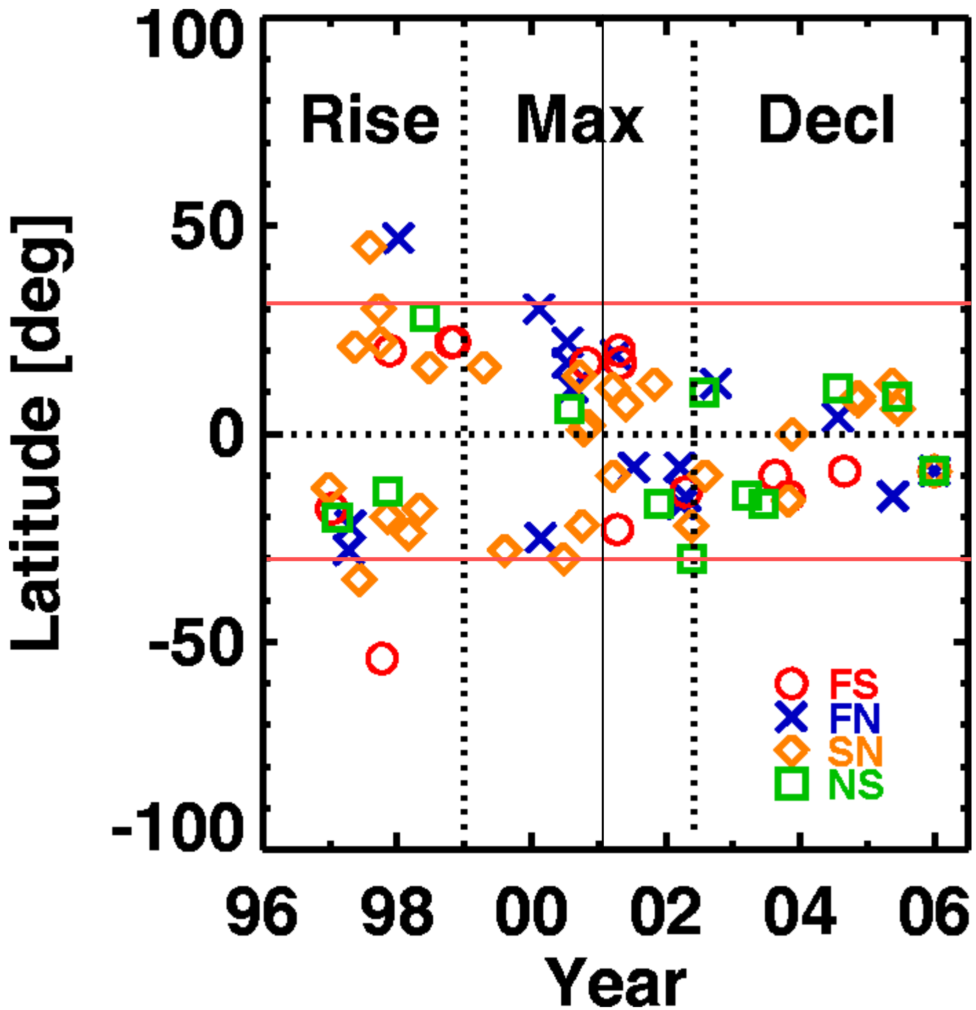
75% of the disk halos and 60% of limb halos are geoeffective

71% of the frontside halos are Geoeffective

The nongeoeffective halos generally have lower speed, predominantly originate from the eastern hemisphere, and have a greater central meridian distance

There is no significant difference between the flares associated with geoeffective and

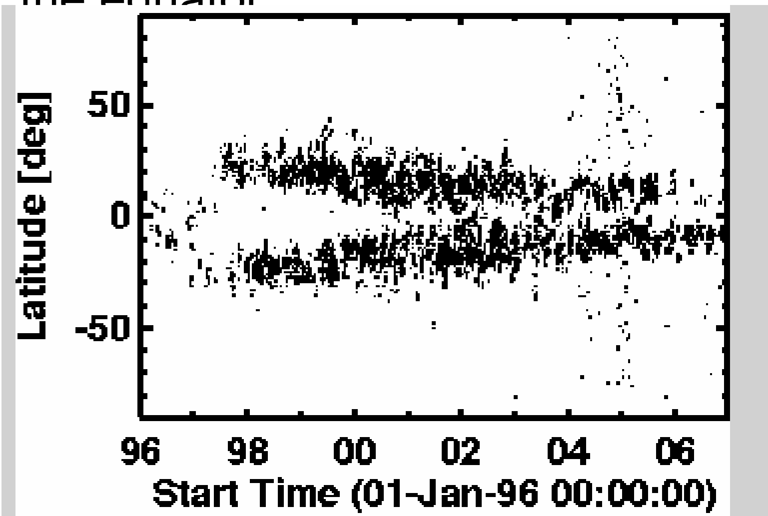
# Magnetic Clouds: CME Sources



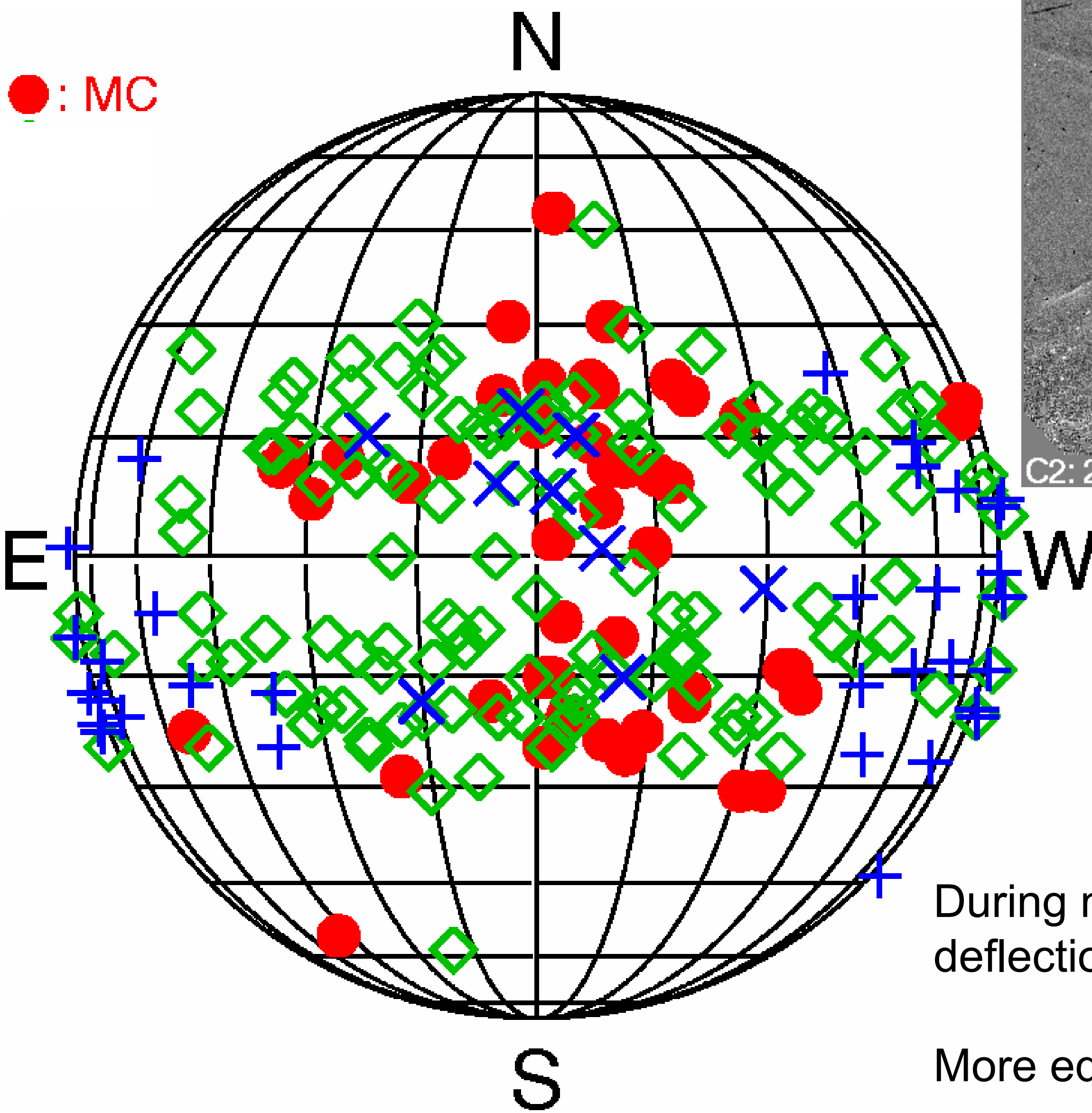

During Solar minimum, the solar source is relatively far from the equator.

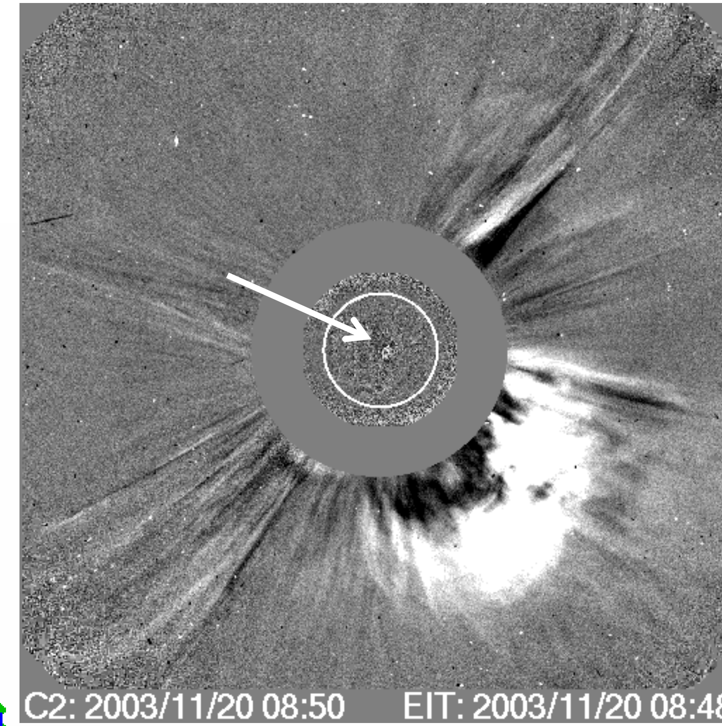
This is offset by the strong influence of the global dipolar field of the Sun

During solar max and declining phases, the global field is weak. Active regions also originate closer to the equator



# Reality




During max: more CME collisions → deflections are common

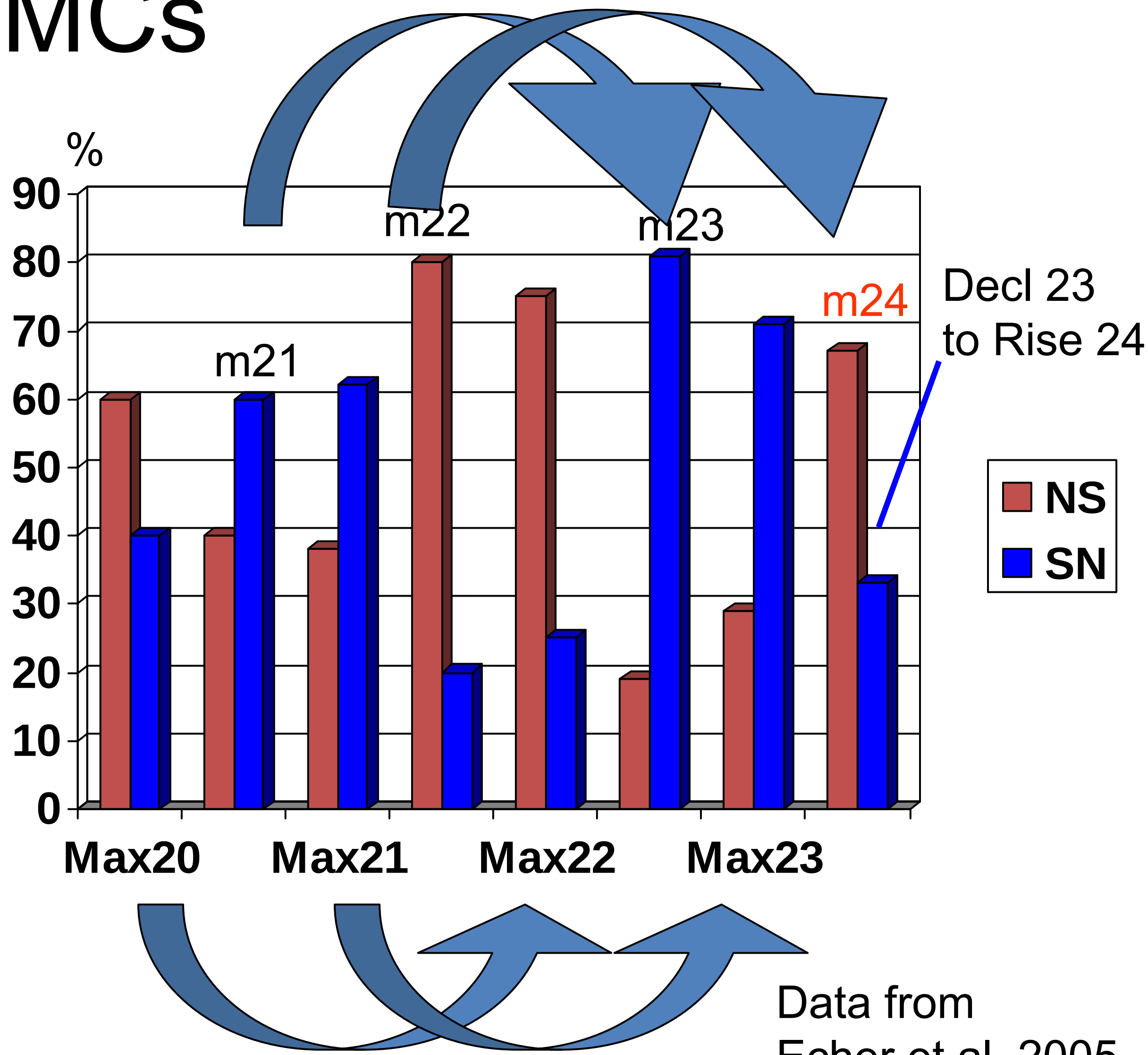
More equatorial coronal holes

# Bipolar MCs

Bipolar MCs follow the 22 year magnetic cycle of solar global field

Odd cycles have southward global solar field (up to max)

Cycle 23 MCs are consistent with the 22-yr pattern (SN and NS MCs dominate during odd and even cycles, respectively – consistent with the global solar field

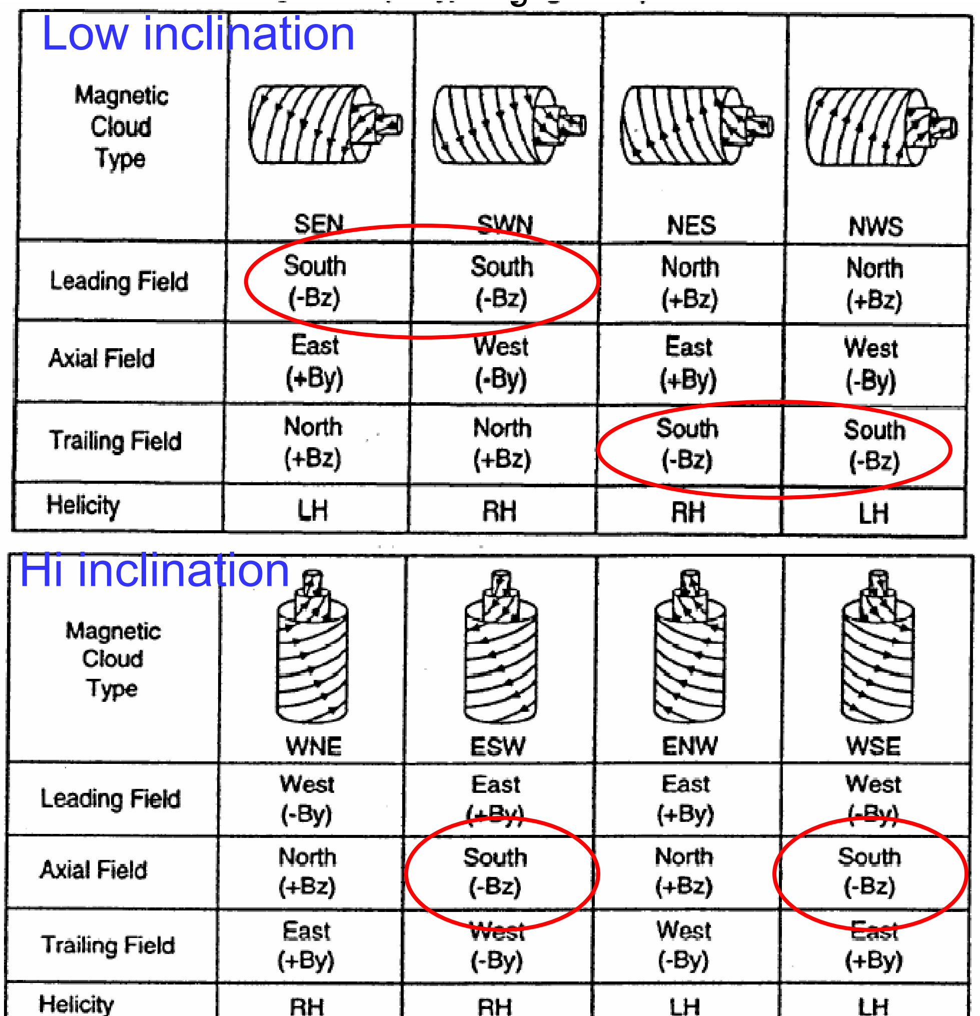



Data from Echer et al. 2005

Bothmer & Schwenn, 1998; Mulligan et al. 1998; Li & Luhmann 2004; Huttunen et al. 2005

# Topology: also unipolar MCs

Mulligan et al. 1998



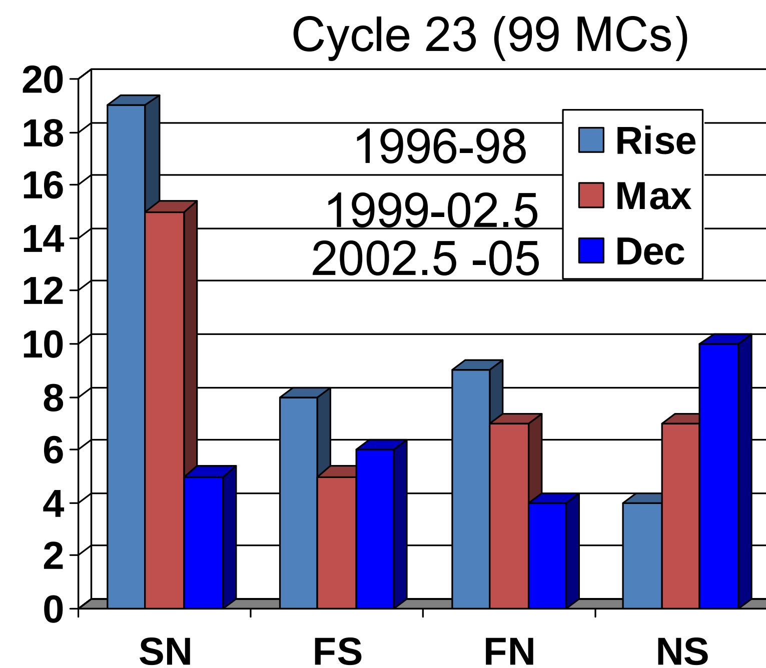
Low inclination

| Magnetic Cloud Type | SEN | SWN | NES | NWS |
|---|---|---|---|---|
| Leading Field | South (-Bz) | South (-Bz) | North (+Bz) | North (+Bz) |
| Axial Field | East (+By) | West (-By) | East (+By) | West (-By) |
| Trailing Field | North (+Bz) | North (+Bz) | South (-Bz) | South (-Bz) |
| Helicity | LH | RH | RH | LH |

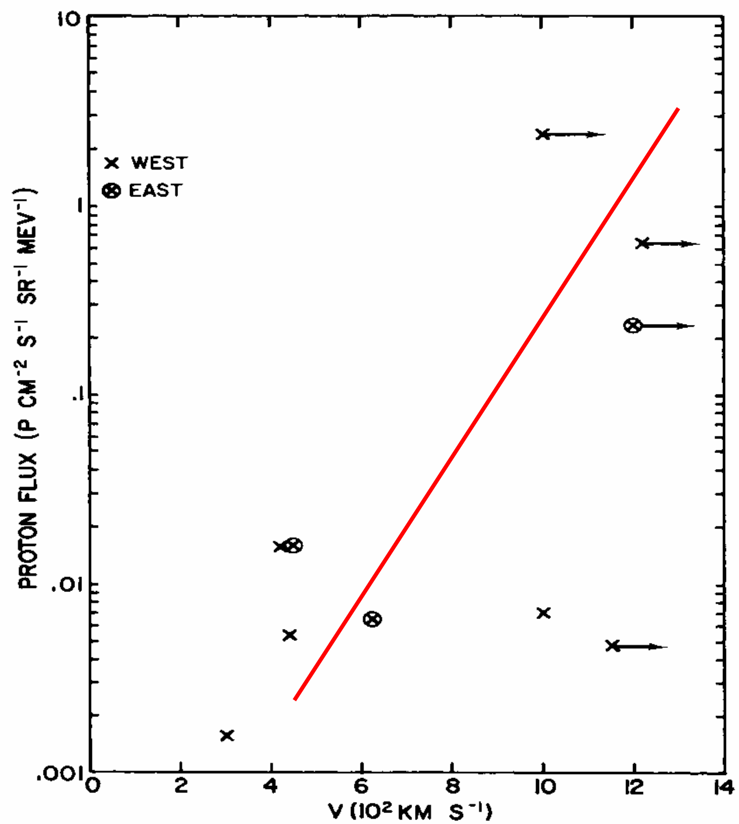
Hi inclination

| Magnetic Cloud Type | WNE | ESW | ENW | WSE |
|---|---|---|---|---|
| Leading Field | West (-By) | East (+By) | East (+By) | West (-By) |
| Axial Field | North (+Bz) | South (-Bz) | North (+Bz) | South (-Bz) |
| Trailing Field | East (+By) | West (-By) | West (-By) | East (+By) |
| Helicity | RH | RH | LH | LH |

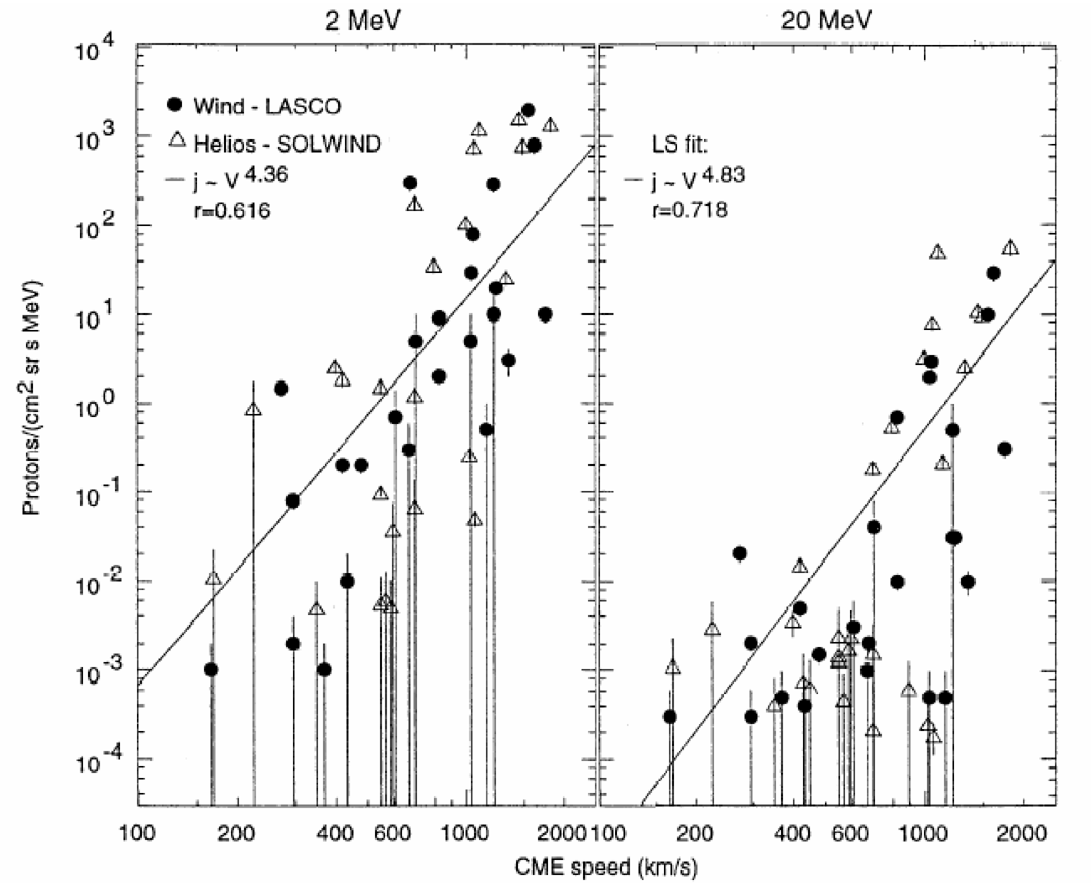
- A significant fraction of high Inclination clouds
- Axial field is N or S ("unipolar")
- Azimuthal filed has EW rotation
- FN or FS MCs



# CMEs & Large SEPs




Kahler 1978



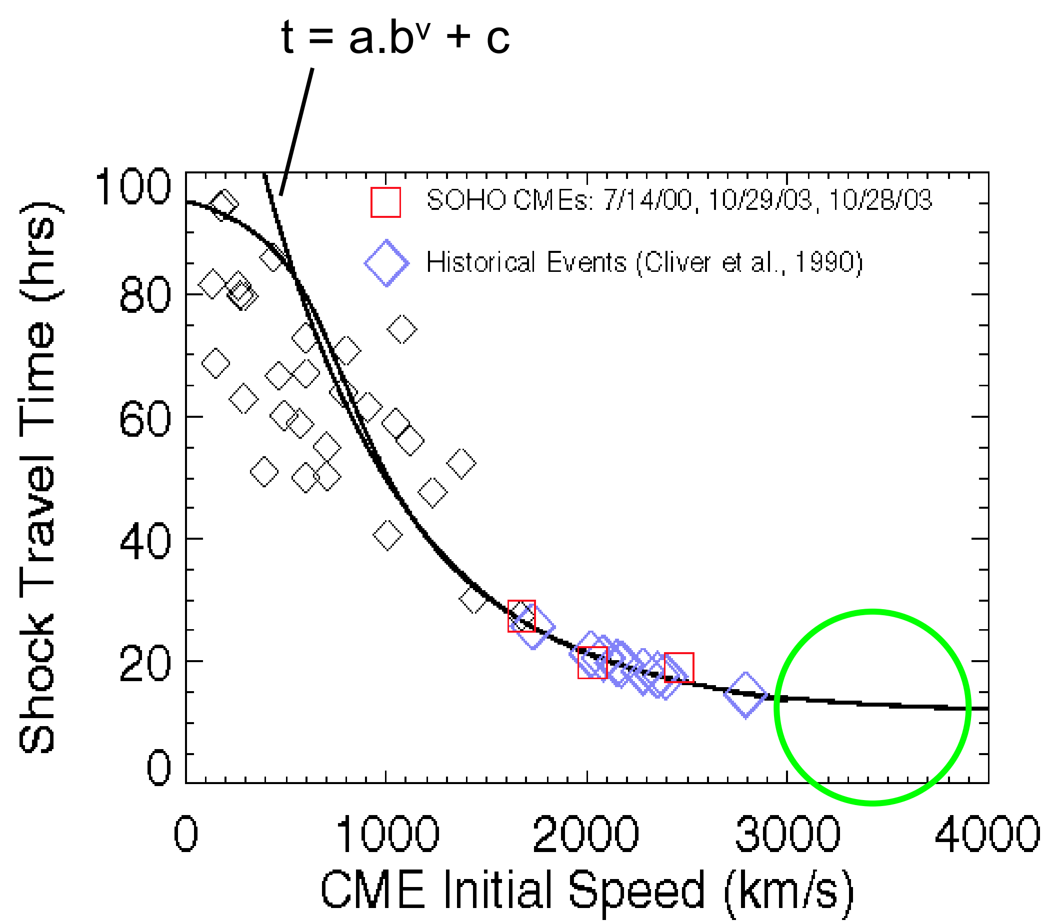

Kahler 2001

# Compute for the above vol and 1000 G

- What Mach numbers?
- Vcme 3500 km/s
- $V_A$ ~500 -1500 km/s
- $M_A$ ~ 2-7
- Need $M_A$ >1.5 for efficient particle acceleration
- Avg speed for 14.6 h transit time: 2972 km/s
- Avg transit speed for 12h transit: 3467 km/s (near-Sun speed expected to be higher)
- Minimum warning time ~12 h

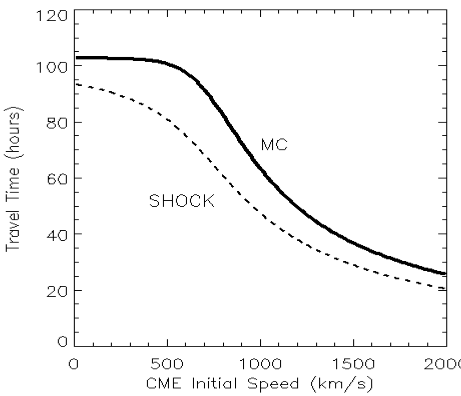
# Worst-Case Scenario

- There were only 25 of the 8000 CMEs had speed > 2000 km/s; only 4 with speed > 2500km/s
- Inferred speeds of historical events is < 2800 km/s
- CMEs have a speed limit not too different from ~ 3000 km/s
- This limit arises from the maximum energy extractable from an active region ($<10^{34}$ erg)
- The Sun-Earth Travel time of shocks has a limit of ~ half a day



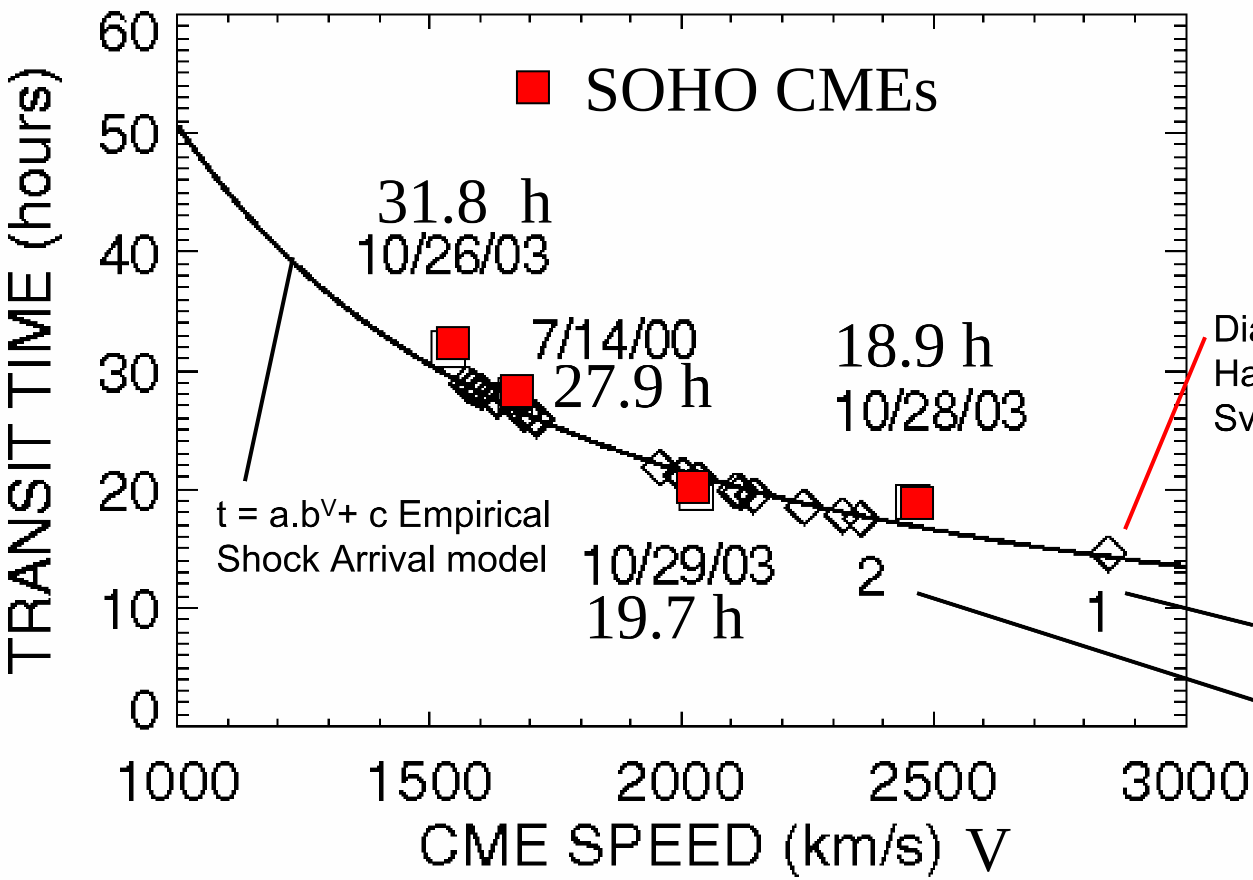
# Transit Time of Shocks & CMEs

The IP acceleration can be used to estimate the CME transit time to Earth. The shock transit time can be obtained from the CME transit time by estimating the standoff distance.




Empirical models for shock and CME arrival at Earth

SOHO contributed 2 events to the historical fast transit events compared with a simplified formula for the shock transit time.



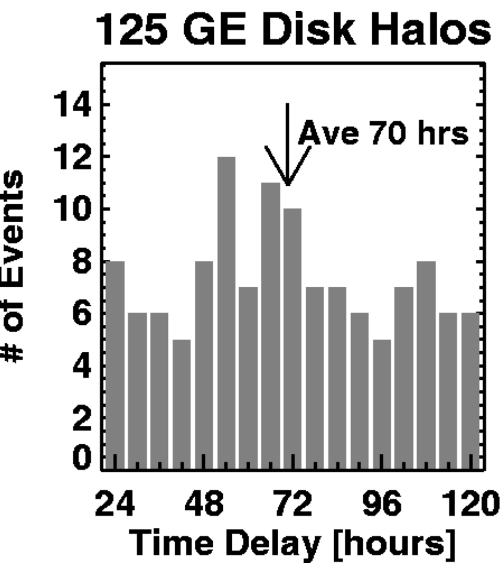

Diamonds: historical flare-SSC time from Hale 1931, Newton, 1943, Cliver & Svalgaard 2004, Gopalswamy et al 2005

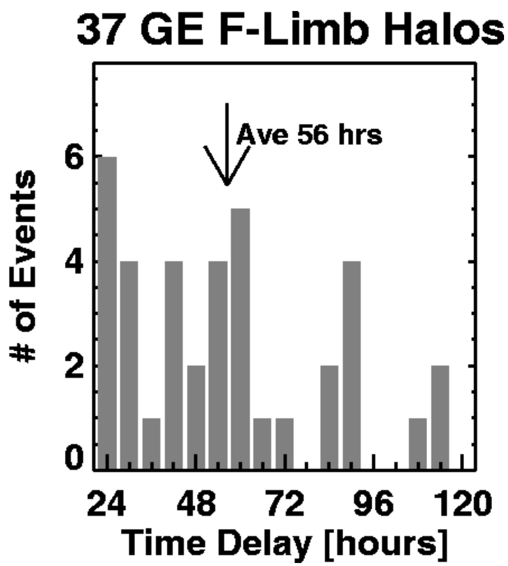
Aug 4, 1972

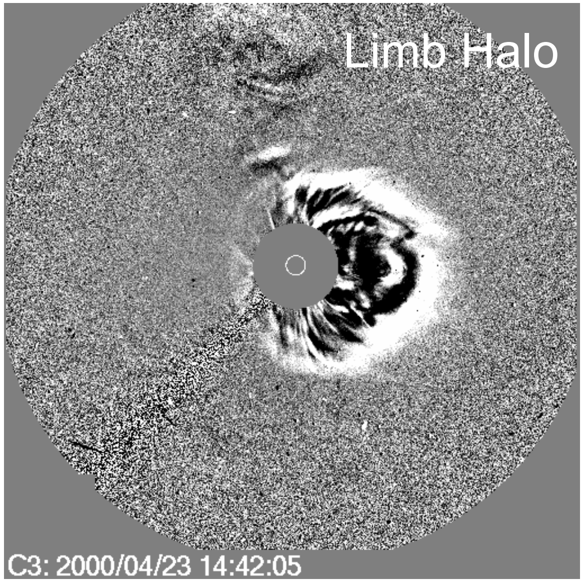
Sep 1, 1859 Carrington

From Gopalswamy et al. 2005 JGR

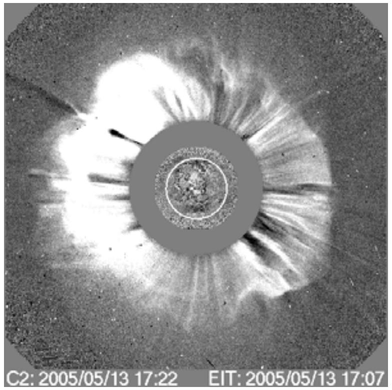
# CME-Dst Delay Time



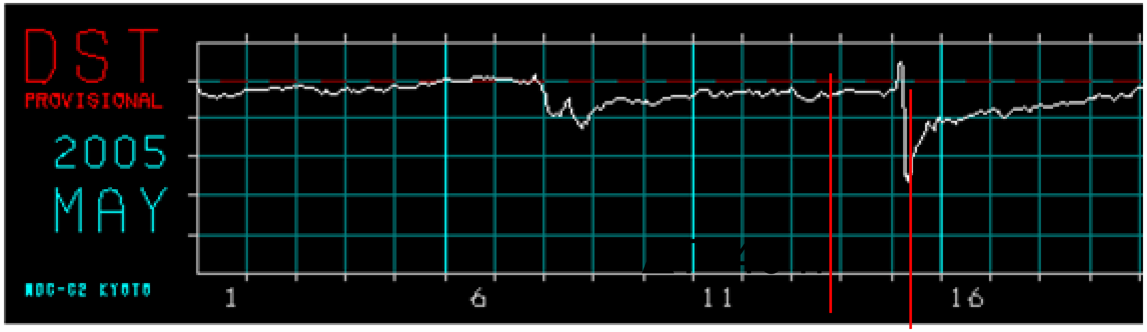




Limb halos are geoeffective (GE) because of BzS in Sheath (Sheath comes first)




Disk Halo




Gopalswamy et al. 2007 JGR