Extreme CME Events from the Sun

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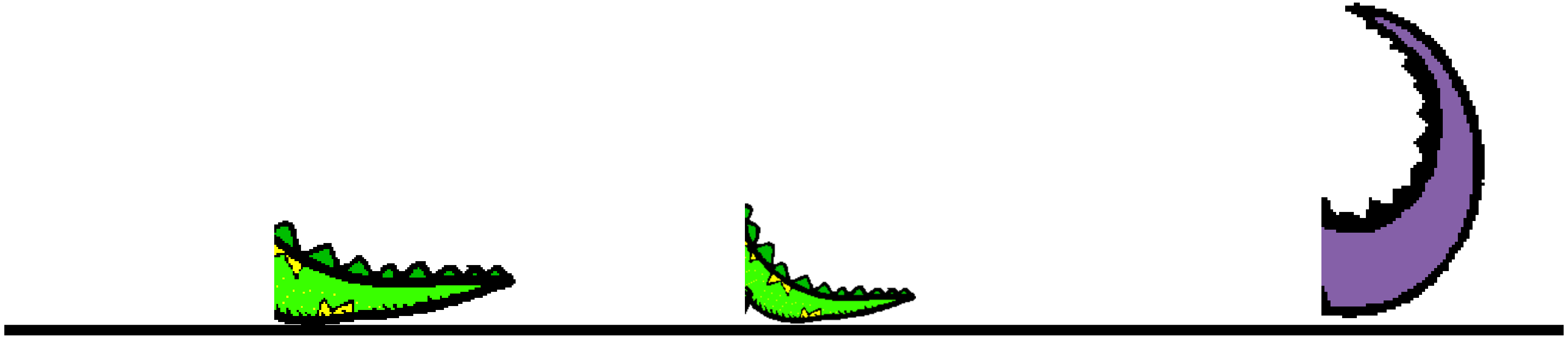
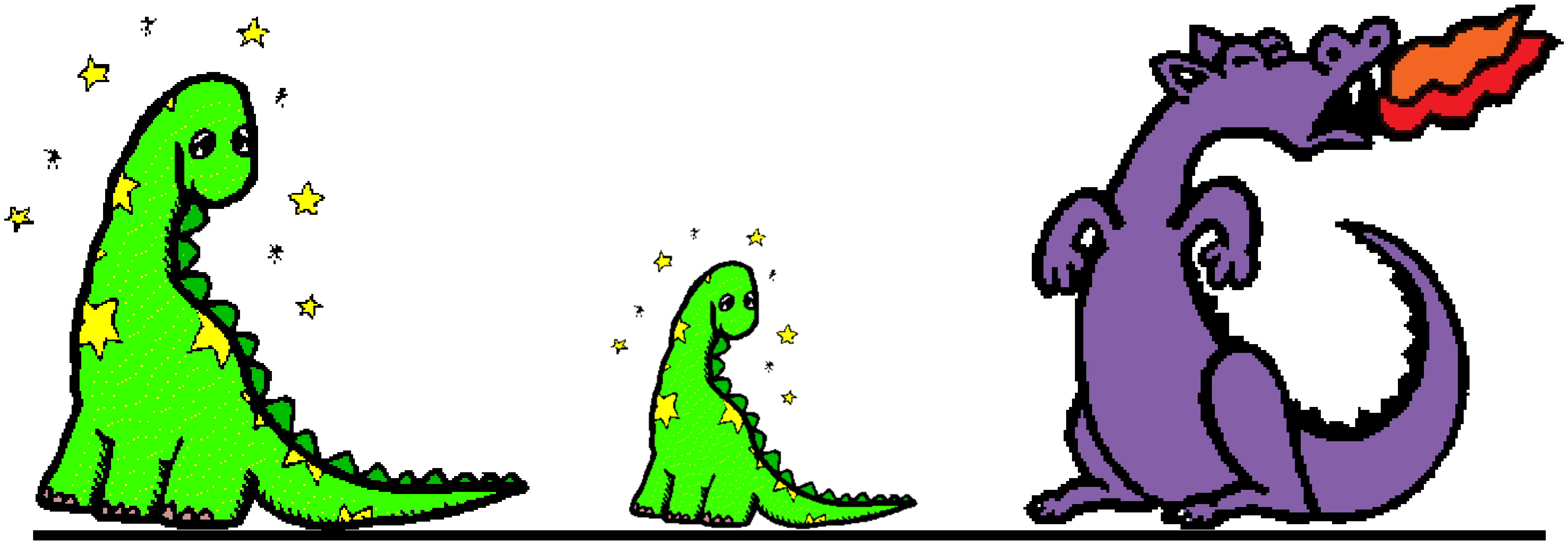
An Extreme Event

- Event on the tail of the distribution of interest
- An occurrence singularly unique either in the occurrence itself or in terms of its consequences
- Occurrence: CME
- Consequences: SEP events (GLEs), Magnetic storms

What can we learn from the study of tails (caudology?) …



… about the whole animal?



PDF = Probable Dinosaur Function ??

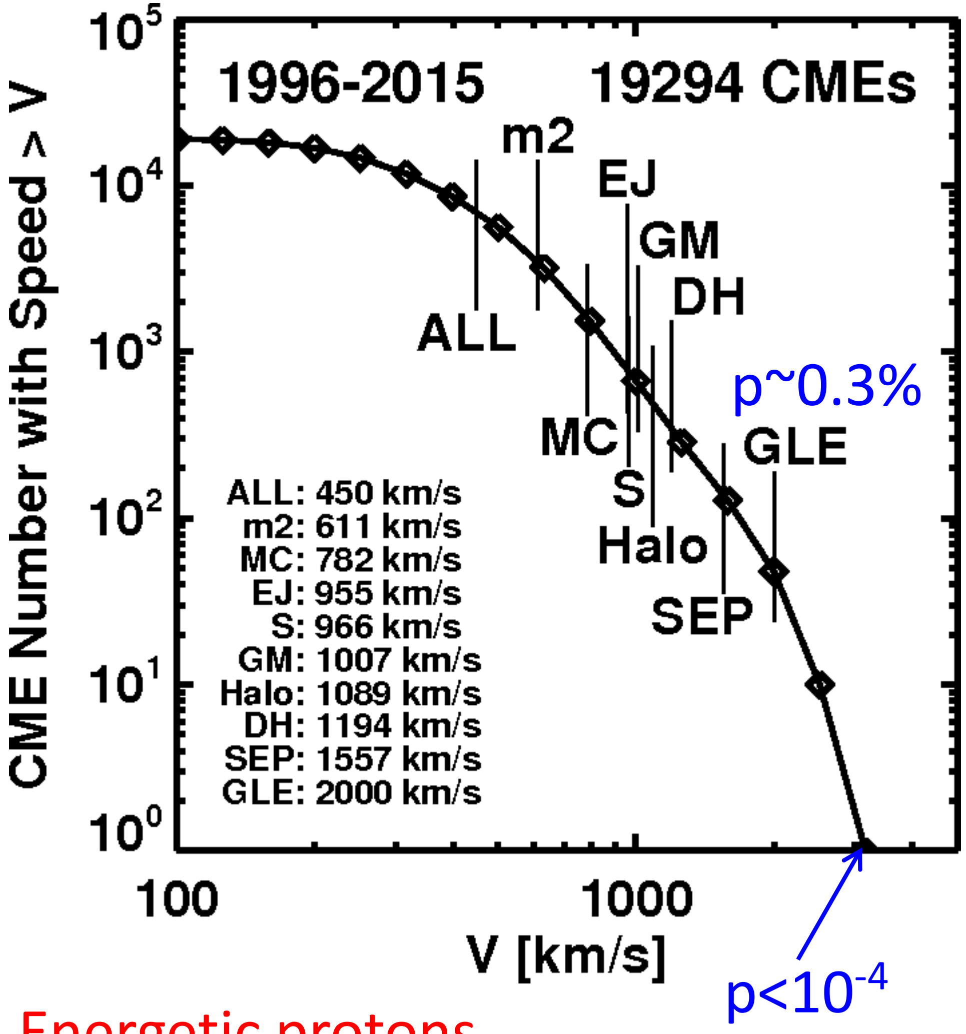
David B. Stephenson 2005

Significant CMEs & their Consequences

Cycle 23 – 24 CMEs from SOHO/LASCO

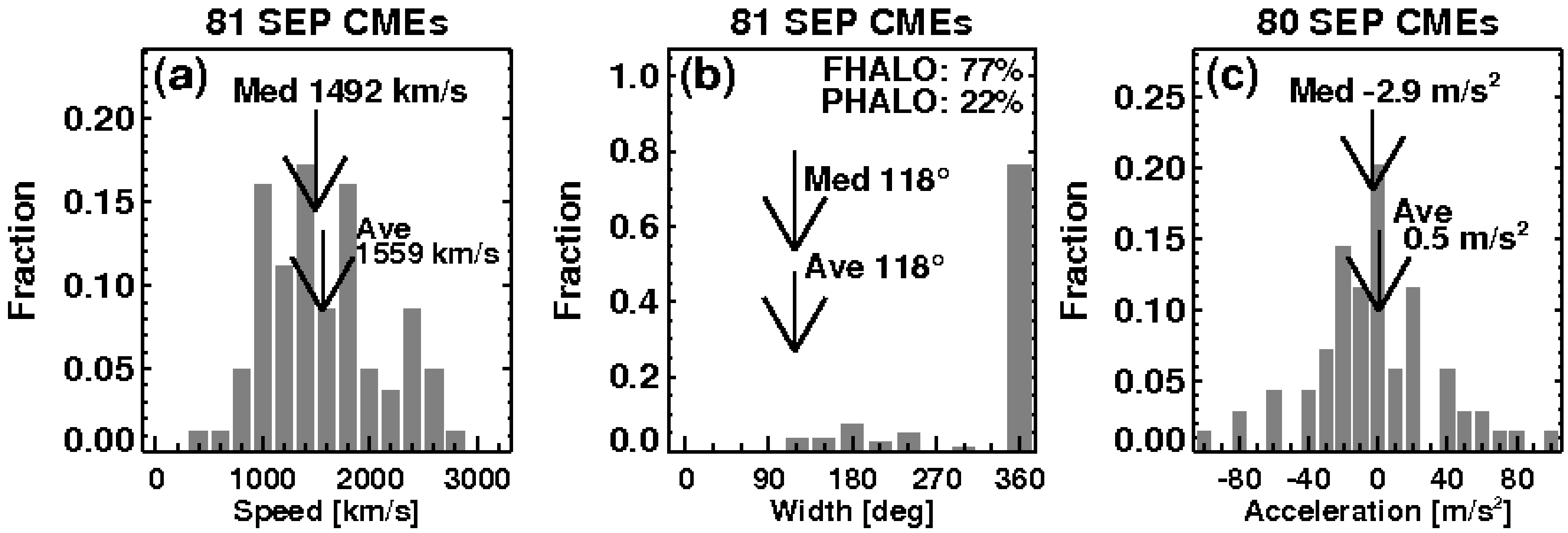
m2 – Metric type II
MC – Magnetic Cloud
EJ – Ejecta
S – Interplanetary shock
GM – Geomagnetic storm
Halo – Halo CMEs
DH – Type II at λ 10-100 meters
SEP – Solar Energetic Particles
GLE – Ground Level Enhancement

Gopalswamy, 2006; 2010



Plasma impact   Energetic electrons   Energetic protons

SEP Producing CMEs

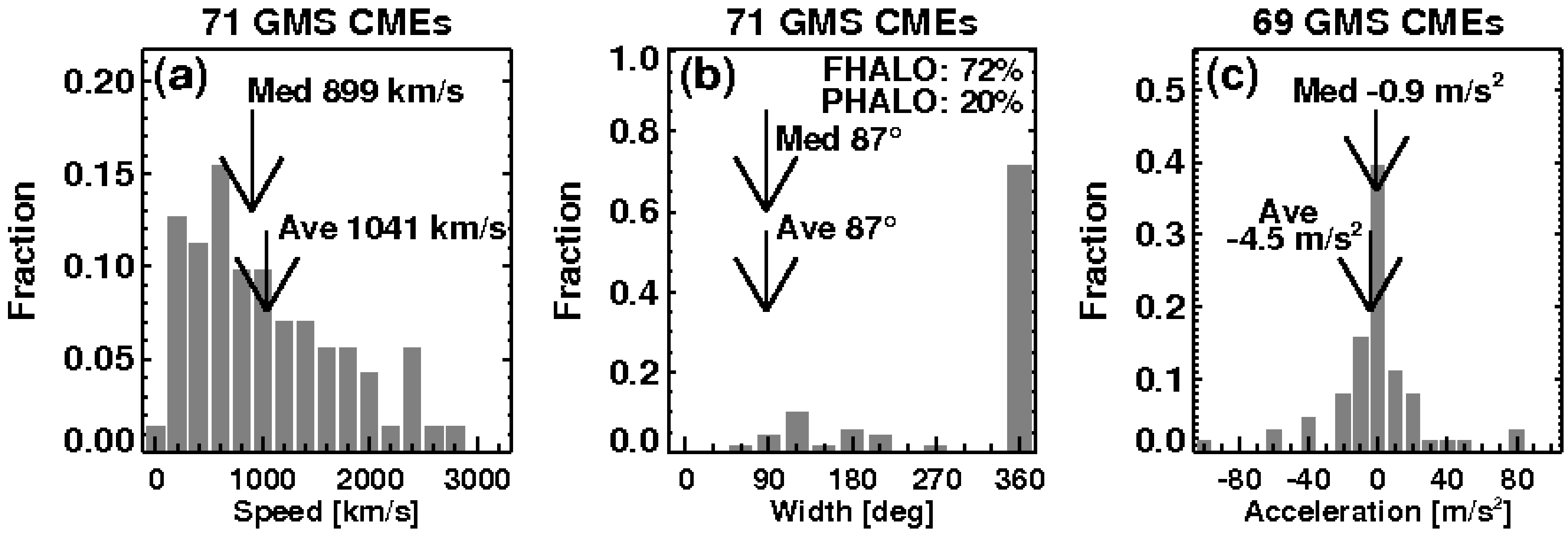


The CMEs are very fast

Almost all CMEs are halos or partial halos

Halo CMEs are generally wide

CMEs Producing Magnetic Storms



The CMEs are very fast (projected speed ~1041 km/s)
Almost all CMEs are halos or partial halos (92%)

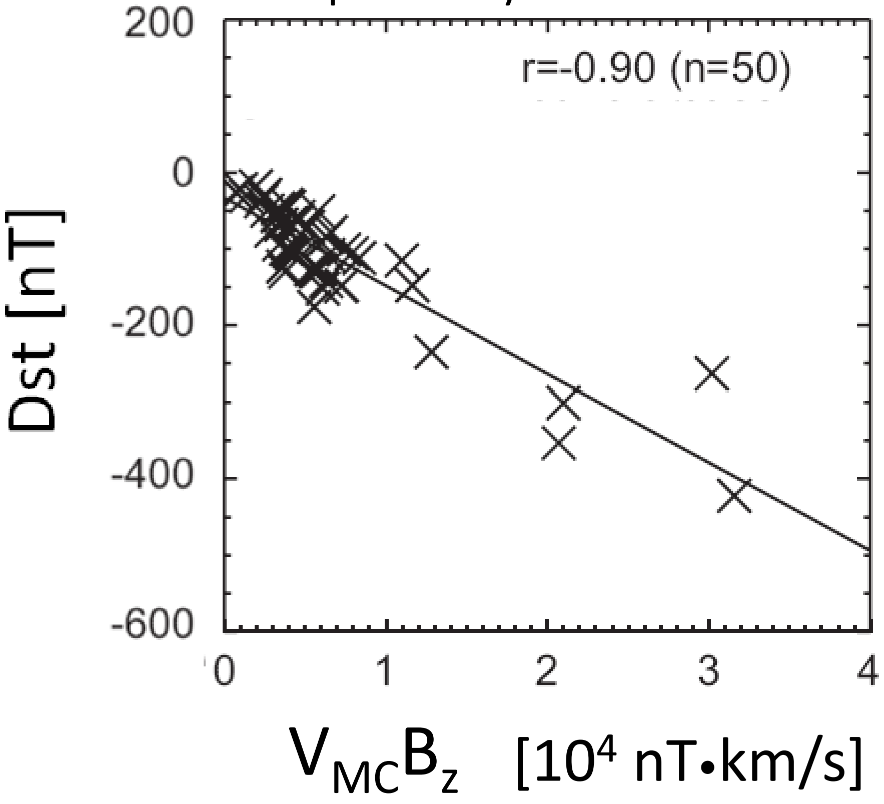
Geomagnetic Storm and CME parameters

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

The high correlation suggests
That V and Bz are the most
Important parameters
(- Bz is absolutely necessary)

V and Bz in the IP medium are
related to the CME speed and
magnetic content

Gopalswamy 2008



Carrington Event: VBz = 1.6 10^5 nT•km/s

V = 2000 km/s, Dst = -1650 nT → Bz = -81 nT

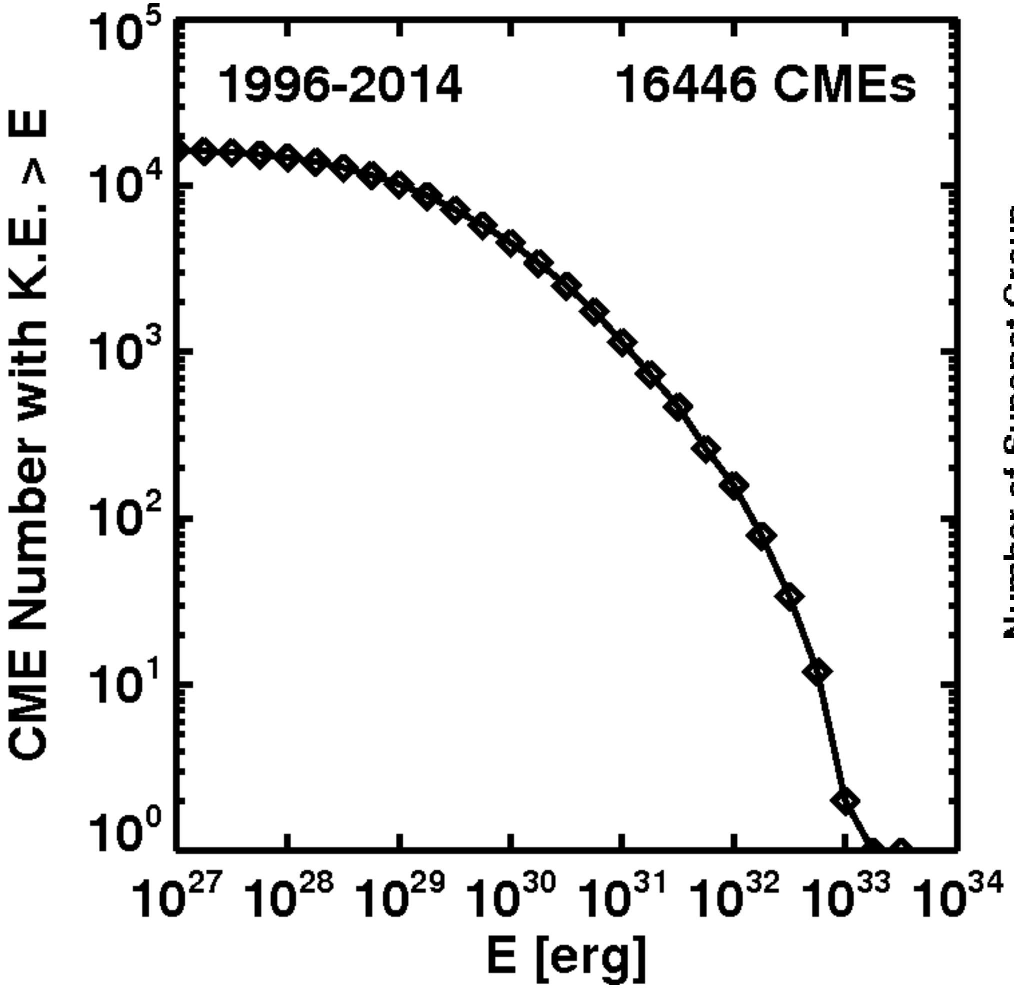
Tsurutani et al. 2003

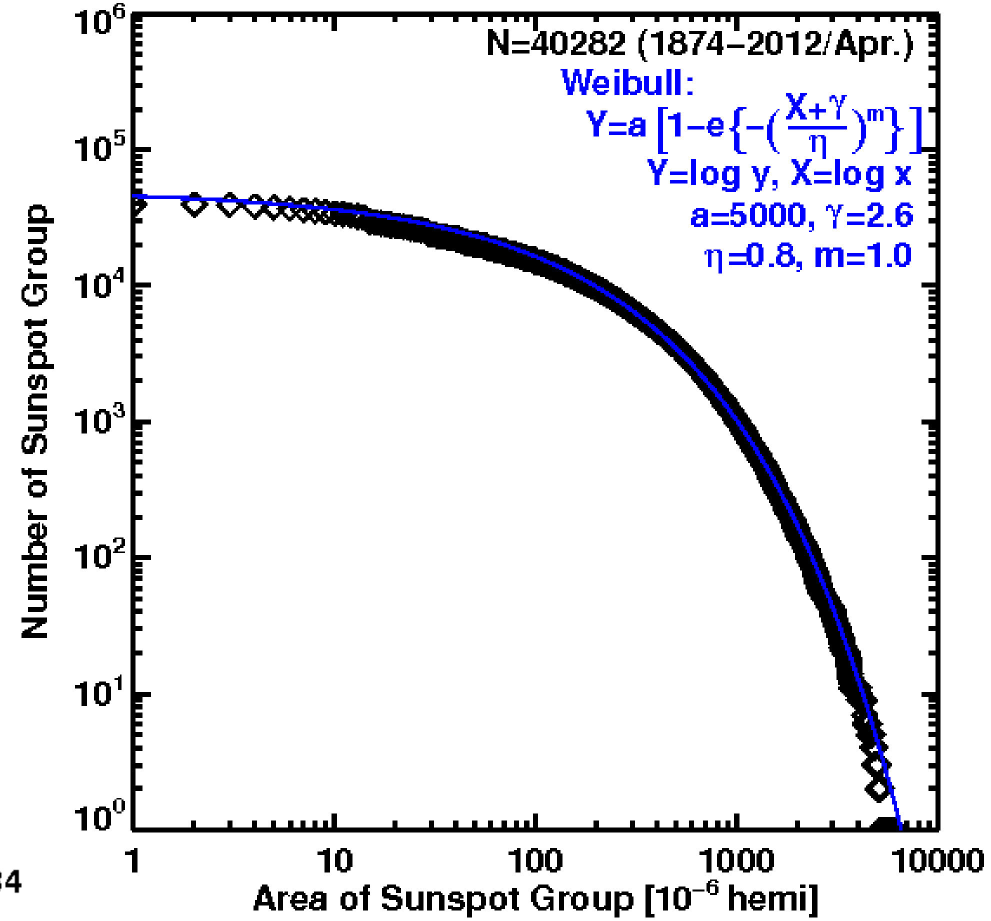
Tail of the CME Distribution (1/1996 – 7/2015)

Category	Number of CMEs
All identified CMEs	25161
# CMEs with V ≥ 1000 km/s	667
# CMEs with V ≥ 1500 km/s	151
# CMEs with V ≥ 2000 km/s	47
# CMEs with V ≥ 2500 km/s	12
# CMEs with V ≥ 3000 km/s	2*
# CMEs with V ≥ 3500 km/s	1*
# CMEs with V ≥ 4000 km/s	0

*Including the 2005 Jan 20 event with an estimated speed of ~3675 km/s

There is a reason why power law may not be appropriate





AR Potential Field Energy ~ Free Energy

Free Energy ~ Magnetic Potential energy (Mackay et al., 1997)

Free energy is > Mag PE

by a factor 3-4 (Metcalf et al. 2005)

Max potential energy during cycle 23 ~ 4 x 10^{34} erg

Max CME KE observed ~ 1.2 x 10^{33} erg

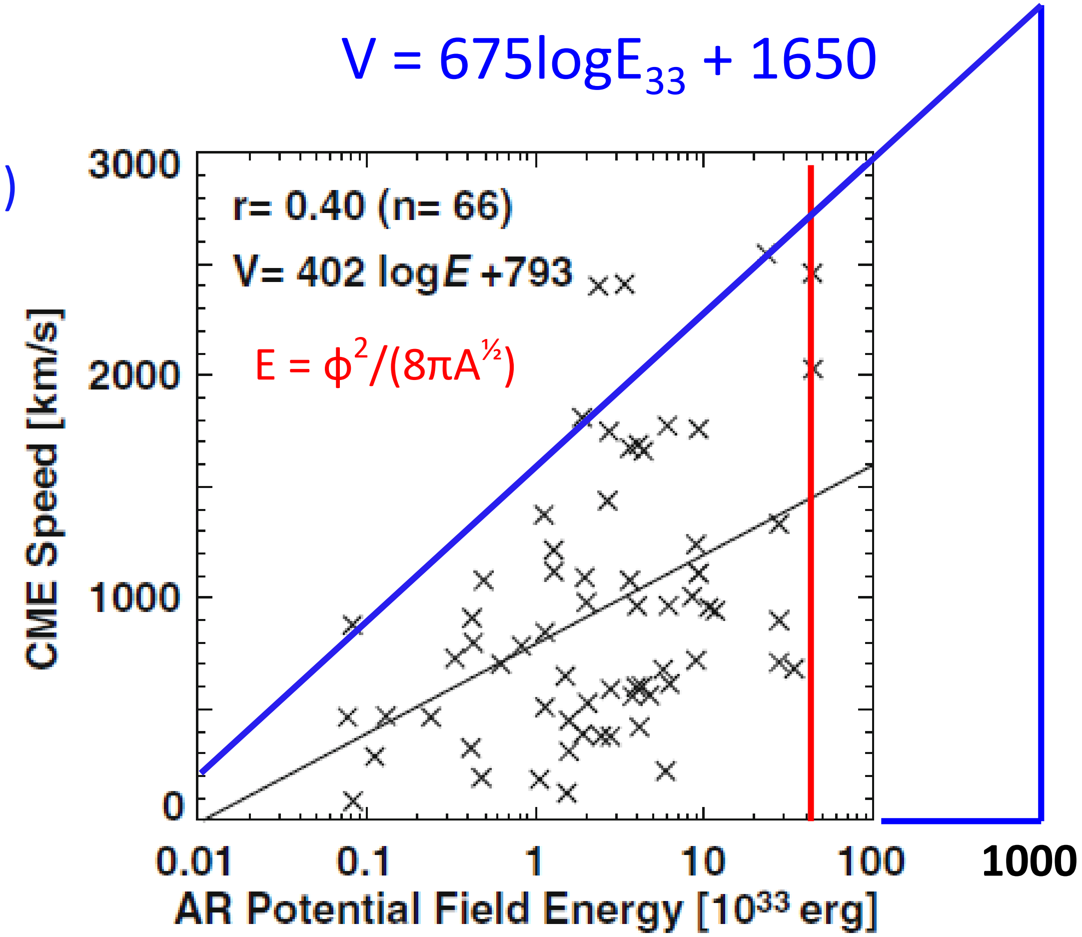
CME Speed limit → maximum energy that can be stored depending on A, B

B < 6100 G; A < 5000 msh

→ E ~ 10^{36} erg

(1000, 3675)

$V = 675 \log E_{33} + 1650$



ϕ = AR flux; A = AR area; E = AR Potential energy

Livingston et al. 2006; Newton, 1955

Gopalswamy et al., 2010; Shibata 2013

Max speed from mag PE

- $V = 675 \log E_{33} + 1650$; $E = \phi^2/(8\pi A^{½})$ $\phi = BA$
- $E \sim 10^{36}$ or $E_{33} = 10^3 \rightarrow V = 3675$ km/s
- Transit time = 11.3 h
- But there is the solar wind → longer transit time ~12.6 h (2005 Jan 20 CME had this speed; transit time was 34 h because the source was at W60)

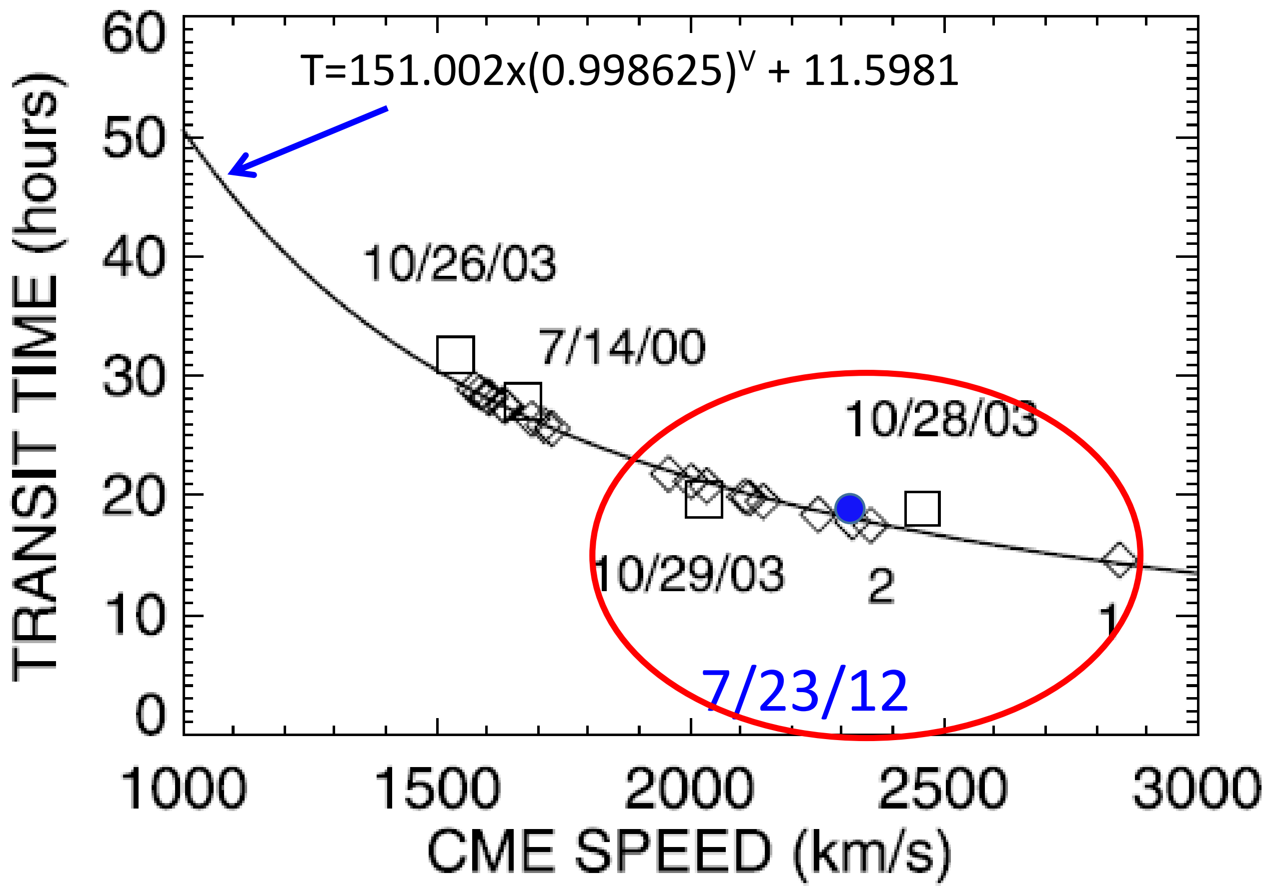
Historical Fast Transit Events

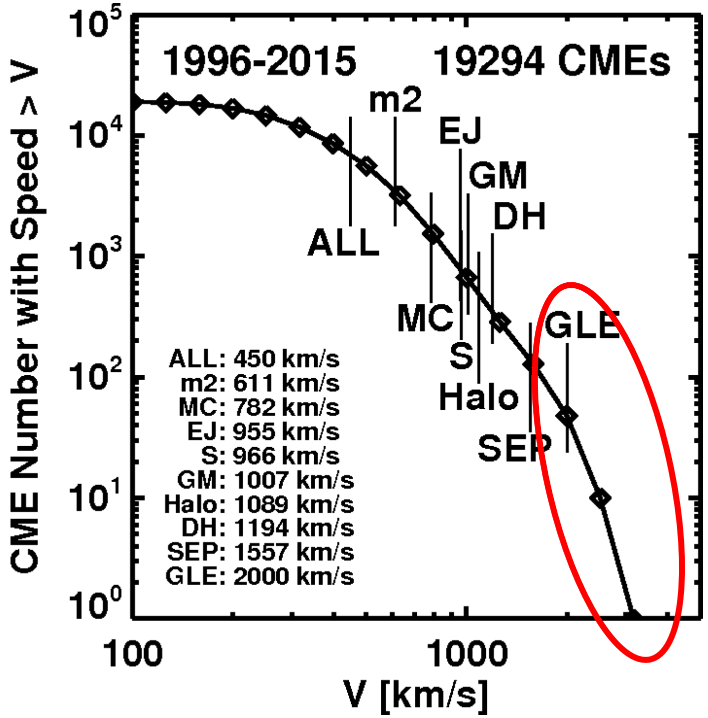
Table 3. Historical Fast Transit Shocks Compared With Those of the October–November 2003 Period

Number	Flare Date	UT	Location	Area	SC Date	SC UT	T	V_{inf}	Ref.[h]
01	1 Sep 1859	1118	N20W12	2300	2 Sep	0448	17.5	2356	N
02	15 Jul 1892	1700	S31E32	829	16 Jul	1230[e]	19.5	2144	H,N
03	10 Sep 1908	0536	S21W22	494	11 Sep	0947	28.2	1605	H
04	24 Sep 1909	1006	S05W08	605	25 Sep	1143	25.6	1728	H,N
05	10 Nov 1916	1542	N24E18[c]	142	11 Nov	1912	27.5	1636	N
06	14 Feb 1917	1606	S23E44[c]	110	15 Feb	1200	19.9	2108	N
07	25 Jan 1926	2000	N21W17	3285	26 Jan	1648[f]	20.8	2033	N
08	31 Jul 1937	1642	N24E67[d]	634	1 Aug	2136	28.9	1575	N
09	16 Jan 1938	0040	N17E31	3179	16 Jan	2235	21.8	1958	CS,N,Ca
10	15 Apr 1938	0830	N27W12	1098	16 Apr	0542	21.2	2002	Cb
11	28 Feb 1941	0930[a]	N12W14	683	1 Mar	0354	18.4	2253	CS,Ca,N1
12	17 Sep 1941	0836	N11W09	1896	18 Sep	0448	19.8	2117	N,CS,Ca
13	28 Feb 1942	1242	N07E03	1865	1 Mar	0812	19.5	2144	N, Ca
14	6 Feb 1946	1628	N27W19	4799	7 Feb	1018	17.8	2320	Ca,Cb
15	25 Jul 1946	1504	N21E16	4279	26 Jul	1842	27.6	1631	Cb,NGDC
16	20 Jan 1957	1100	S30W18	557	21 Jan	1254	25.9	1712	Cb,NGDC
17	9 Feb 1958	2108	S12w14	756	11 Feb	0124	28.3	1600	Cb,NGDC
18	10 May 1959	2102	N18E47	1552	11 May	2324	26.4	1688	Cb,NGDC
19	14 Jul 1959	0325	N17E04	1314	15 Jul	0800	28.6	1587	Cb,NGDC
20	16 Jul 1959	2114	N16W31	1981	17 Jul	1642	19.5	2144	Cb,NGDC
21	12 Nov 1960	1315	N28W01	1740	13 Nov	1023	21.2	2002	CS,Ca,E
22	4 Aug 1972	0620	N04E08	1140	4 Aug	2054	14.6	2847	Ca,Cb
23	14 Jul 2000	1024[b]	N22W07	490	15 Jul	1417	27.9	1670[g]	G,NGDC
24	26 Oct 2003	1741[b]	N04W43	1420	28 Oct	0130	31.8	1537[g]	T,NGDC
25	28 Oct 2003	1106[b]	S20E02	2110	29 Oct	0600	18.9	2459[g]	T,NGDC
26	29 Oct 2003	2041[b]	S19W09	2680	30 Oct	1620	19.7	2029[g]	T,NGDC
27	23 Jul 2012	01:50	S17W141	????			18.6	2330	

Cliver et al., 1990; Gopalswamy et al., 2005

Transit Time – Event on the tail





1 Aug 4, 1972 14.6 h

V=2854 km/s

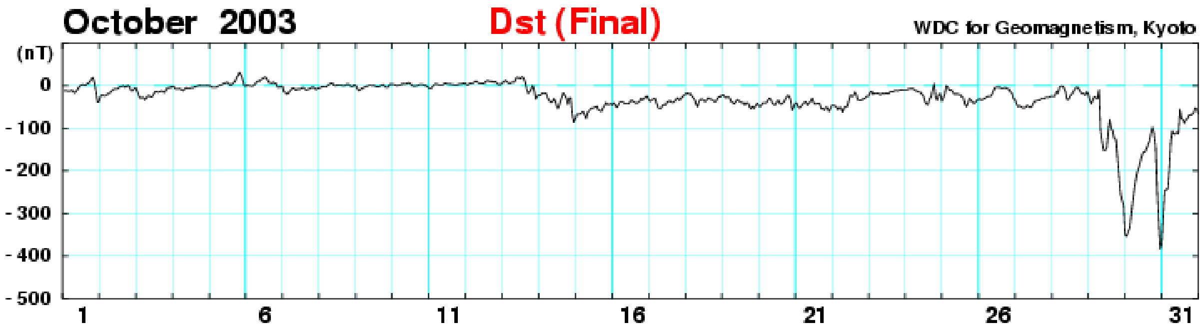
2 Sep 1, 1859 17.5 h

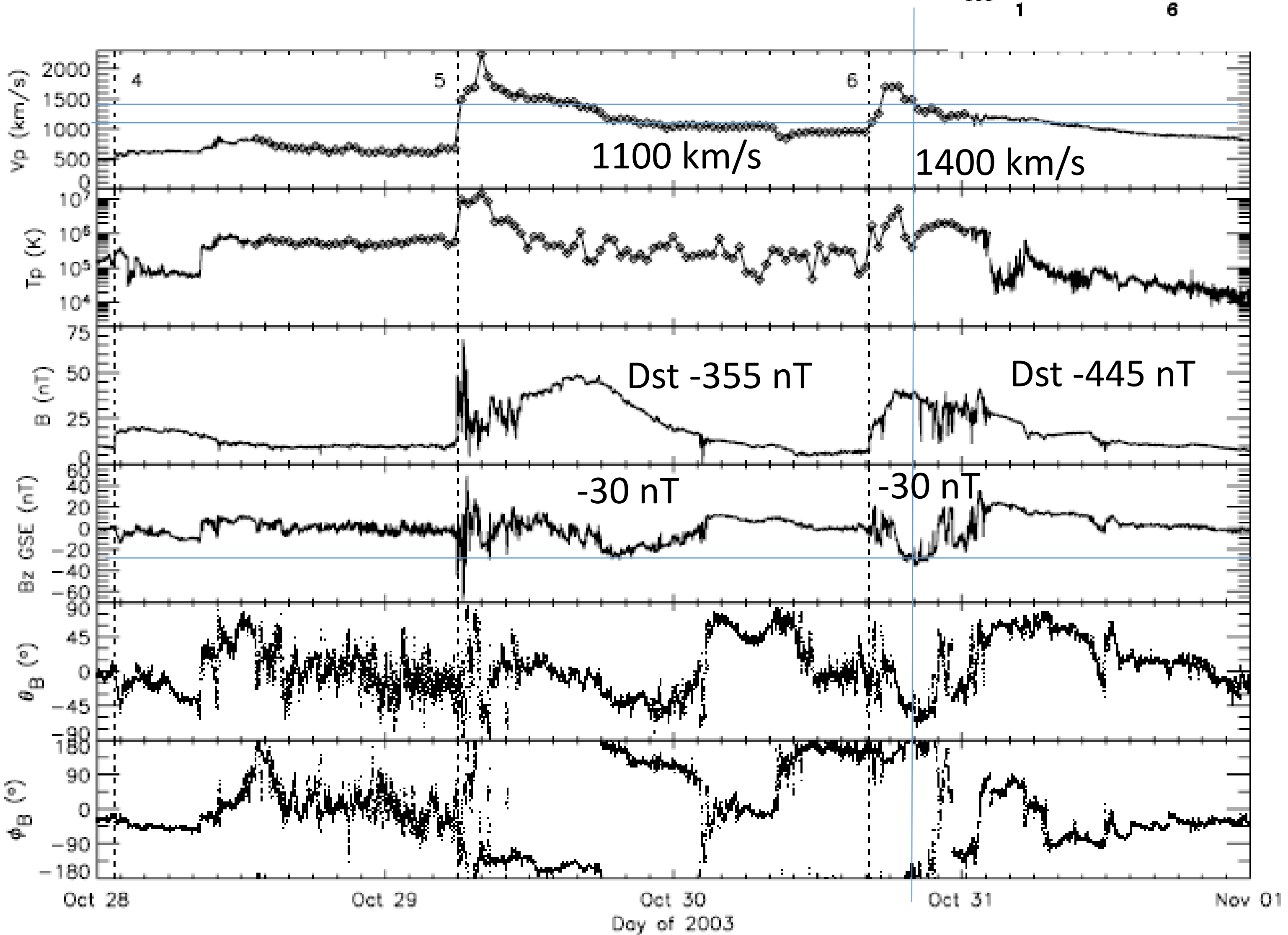
V = 2356 km/s

CME/shock transit time: 1-4 days

~15 events since 1859 had transit times < 1 day (Cliver et al. 1990; Gopalswamy et al. 2005)

Halloween Events





- Location of Bz important
- Bz ~-30 nT
- Speeds: 1100 km/s & 1400 km/s
- Dst computed: 355 nT & -445 nT
- - similar to observed
- 10/29: Cloud storm
- 10/30: Sheath storm (FN cloud)
- Shock speed of the 10/29 event ~2000 km/s – similar to Jul 24 2012 shock

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

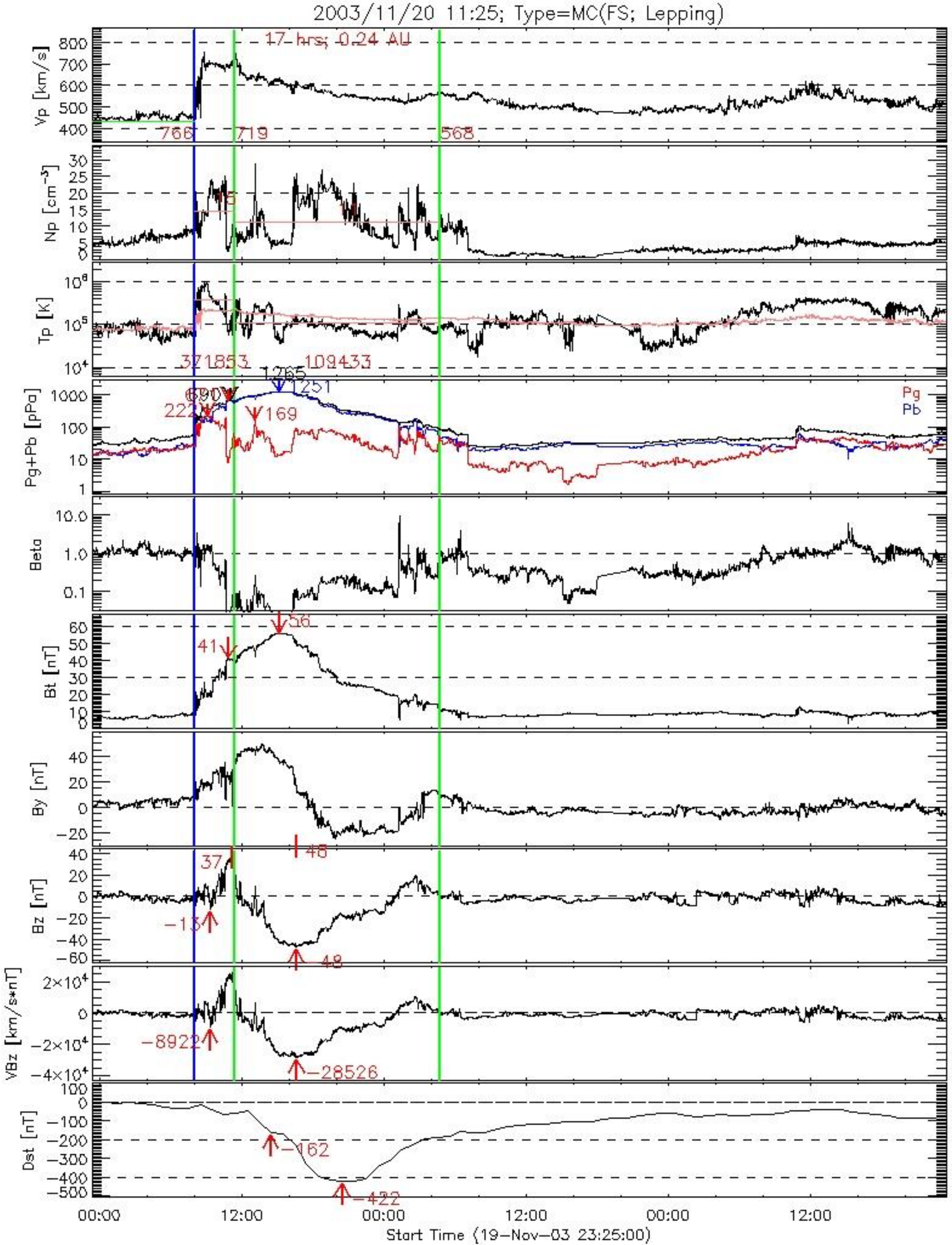
The Largest Storm of Cycle 23: 11/20/2003

V = 600 km/s
Bz = -48 nT
VBz = - 28526 km/s.nT

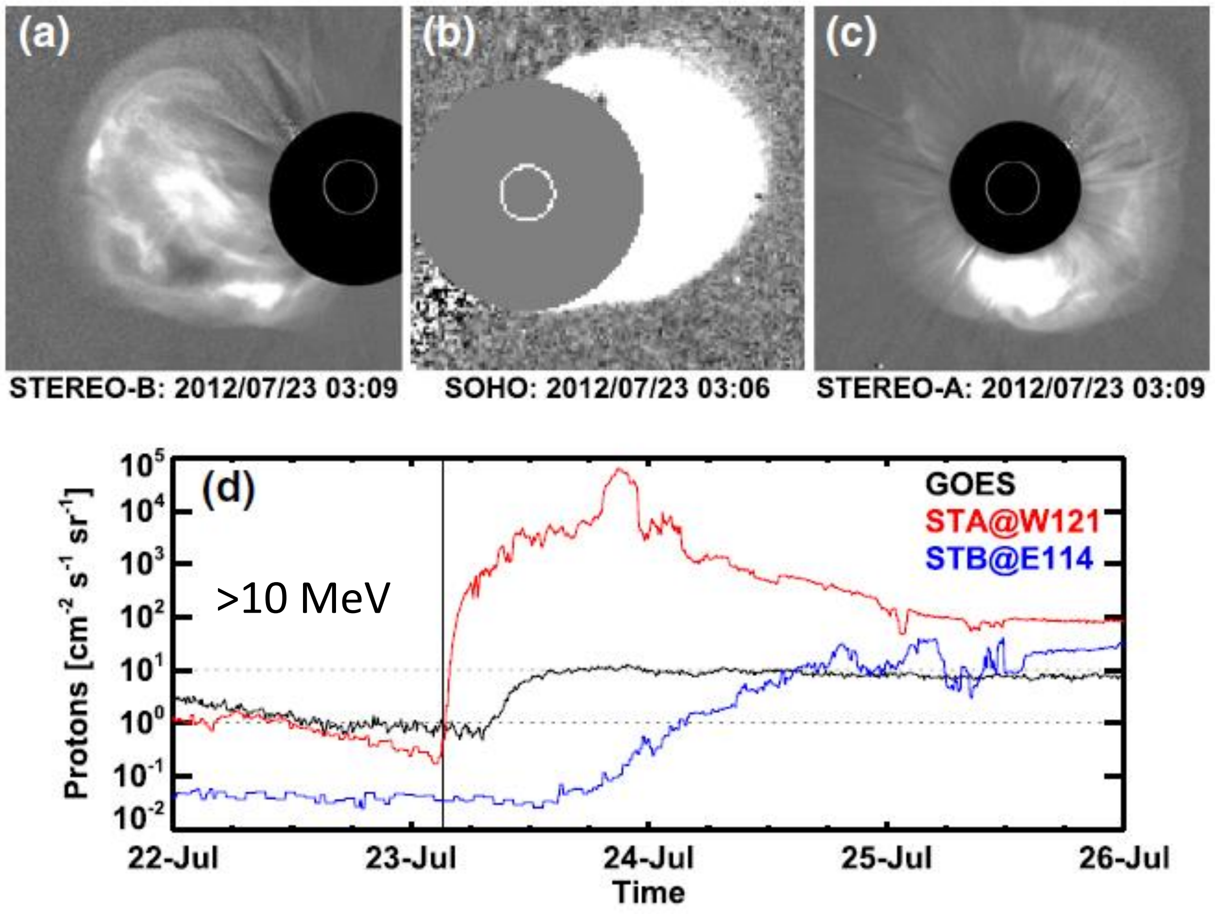
Dst = - 312 nT

Much slower than the Halloween events but had higher Bz (FS cloud)

Gopalswamy et al. 2005 GRL

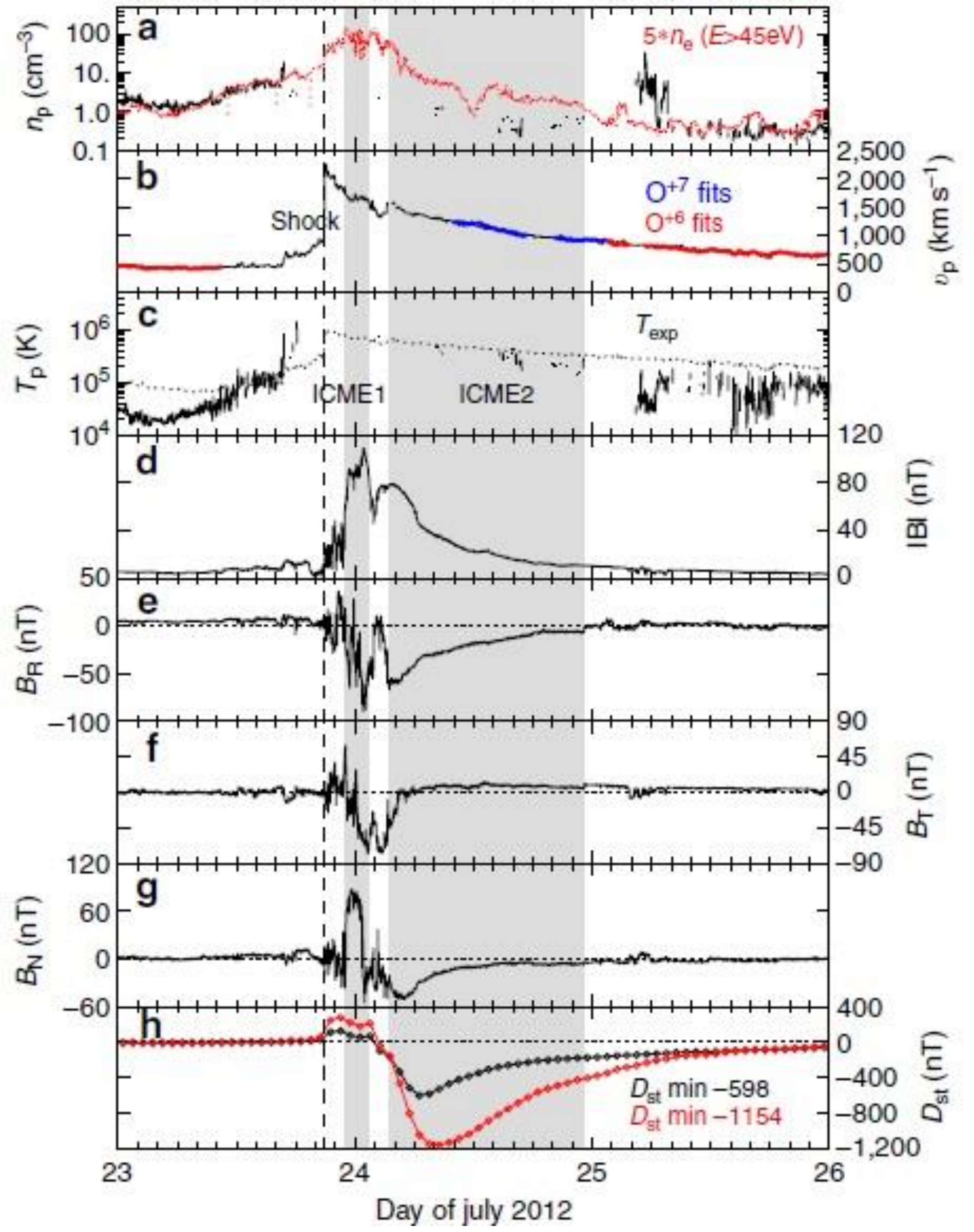


The July 23 2012 CME



Backside event (S17W141)
 heading toward STREO A
Peak speed: 2631 km/s
Average speed 2230 km/s in coronagraph FOV
>10 MeV flex: 5000 (SEP), 65000 (ESP)
Larger than the Halloween event!

Shock transit time ~18.5 h → historical event



Carringtonesque?
2012 July 24 ICME

ICME speed = 1100 km/s (avg)

ICME speed Peak = 1500 km/s

Expansion speed ~ 250 km/s

Shock speed ~2000 km/s

Bmax = 60 nT

Bz = -52 nT

Dst = $-0.01VB_z - 32$ nT

→ -812 nT

(Liu et al. : -1150 to -600 nT)

Carrington Dst: -850 nT

(Siscoe et al. 2006; Cliver& Dietrich 2013)

Tsurutani et al. 2003: -1600 nT

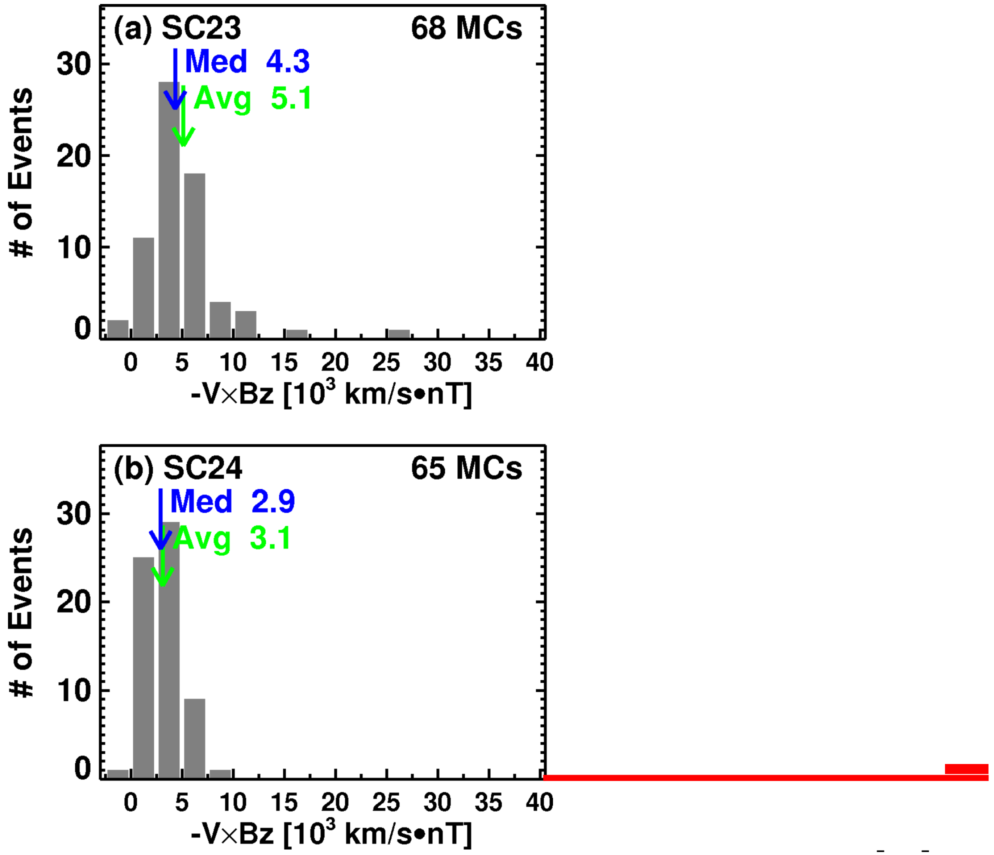
VBz = 1.6 10^5 nT•km/s

V = 1500 km/s → Bz = -106.6 nT

Russell et al. 2013; Baker et al. 2013; Liu et al. 2014

2012 July 23

- Cycle 23
- Dst = 0.01 VBz - 25 nT
- Bz = -52 nT; V = 1500 km/s
- VBz = - 7.8 × 10^4 nT.kms^{-1}



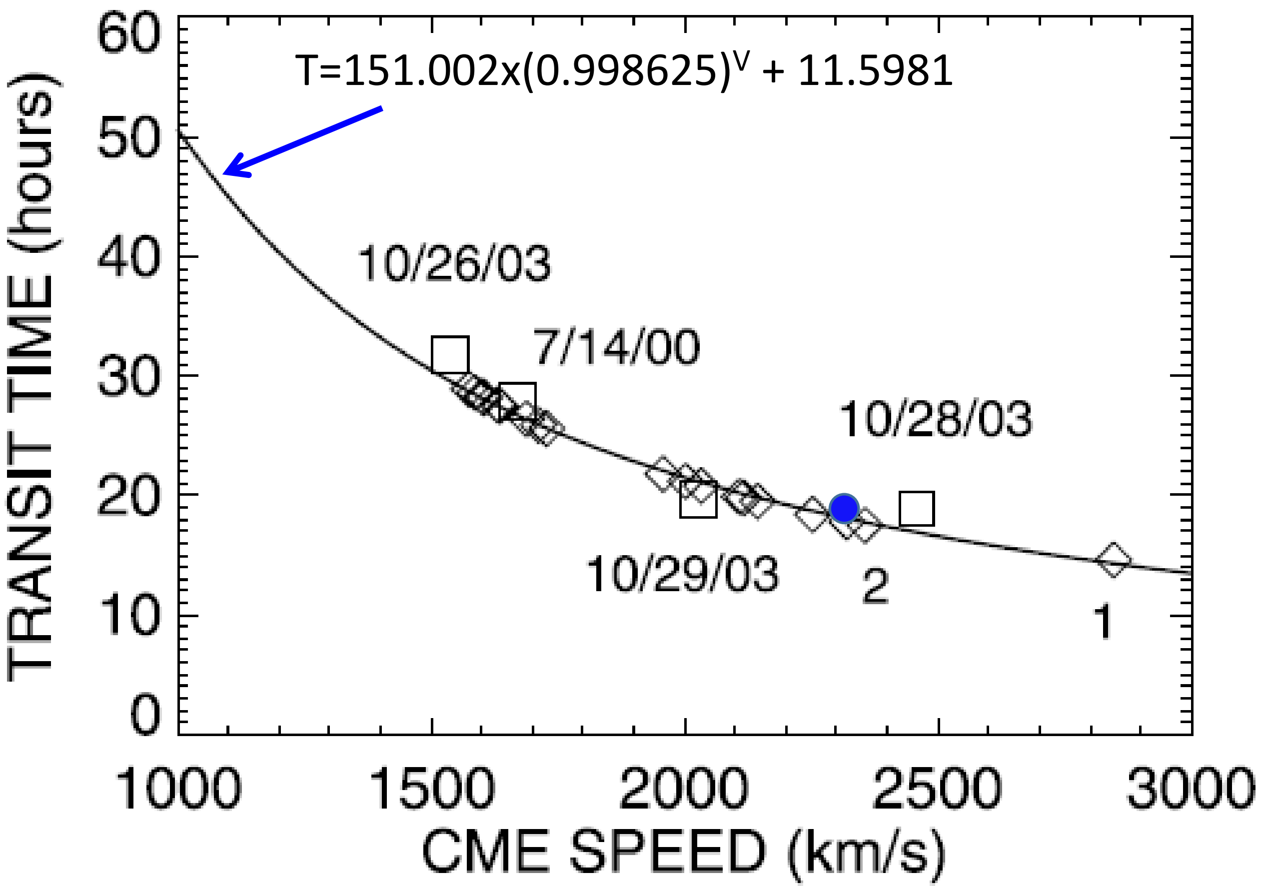
- Cycle 24
- Dst =0.017 VBz + 16 nT
- Dst = -1300 nT

VBz fits the extreme event description

Gopalswamy et al. 2015 JGR

Transit Time

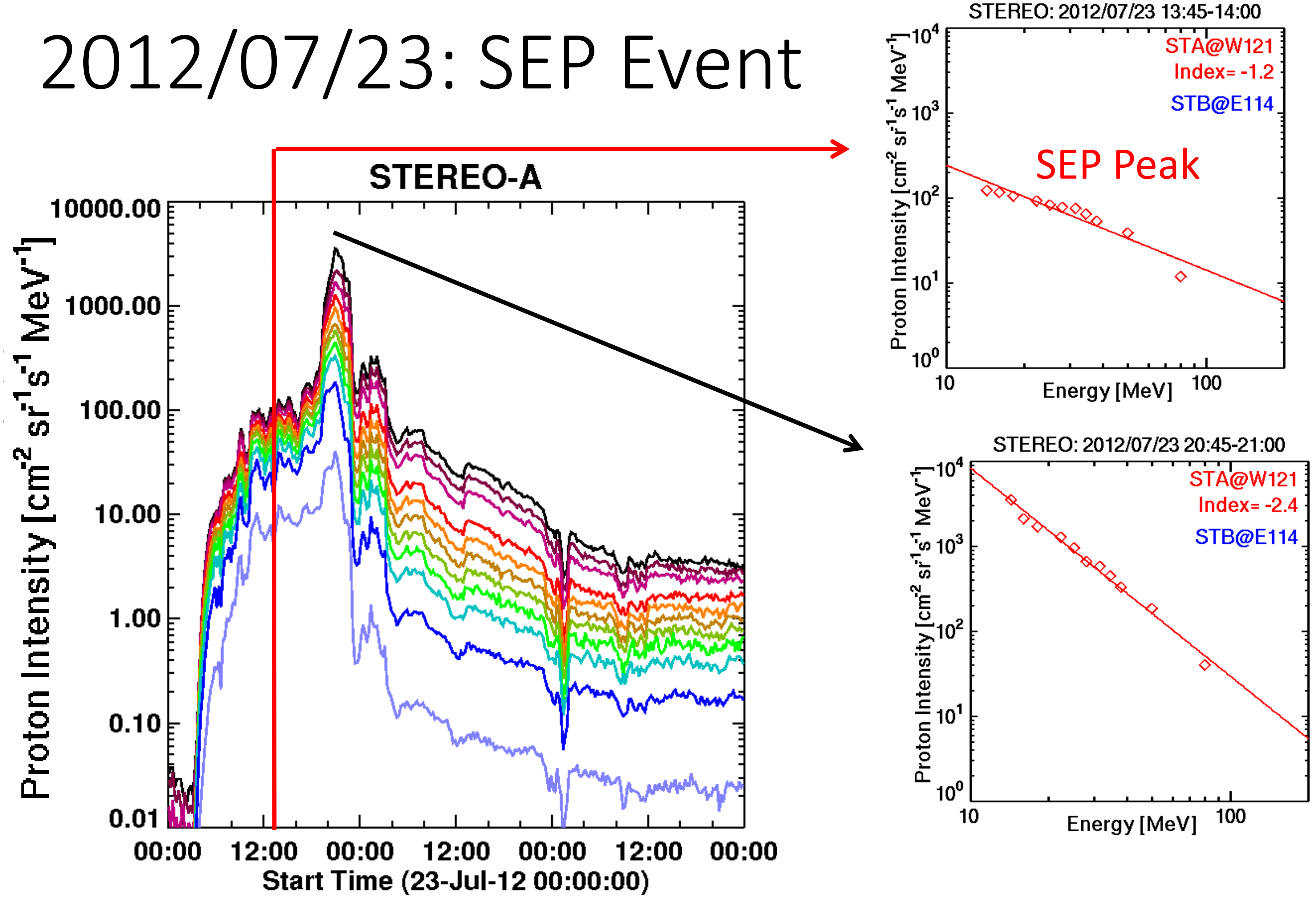
$F_d \sim C_d \rho A(u-u_c)^2$



CME speed: 2330 km/s (STEREO)
1-AU speed: 1500 km/s
CME transit time: 24.5 h
Observed deceleration: -8.3 m/s^2
Decelerates similar to what is expected from empirical relation
$a = -0.0054\ (u-u_c)$
$u_c = 406$ km/s
$a = -10.4$ m/s^2
Nothing unusual about deceleration
Also from the ESA model
<V> = 2330 km/s
T = 17.7 h
vs. 18.6 h observed

The transit time is larger than the August 1972 event and similar to the Carrington event

2012/07/23: SEP Event

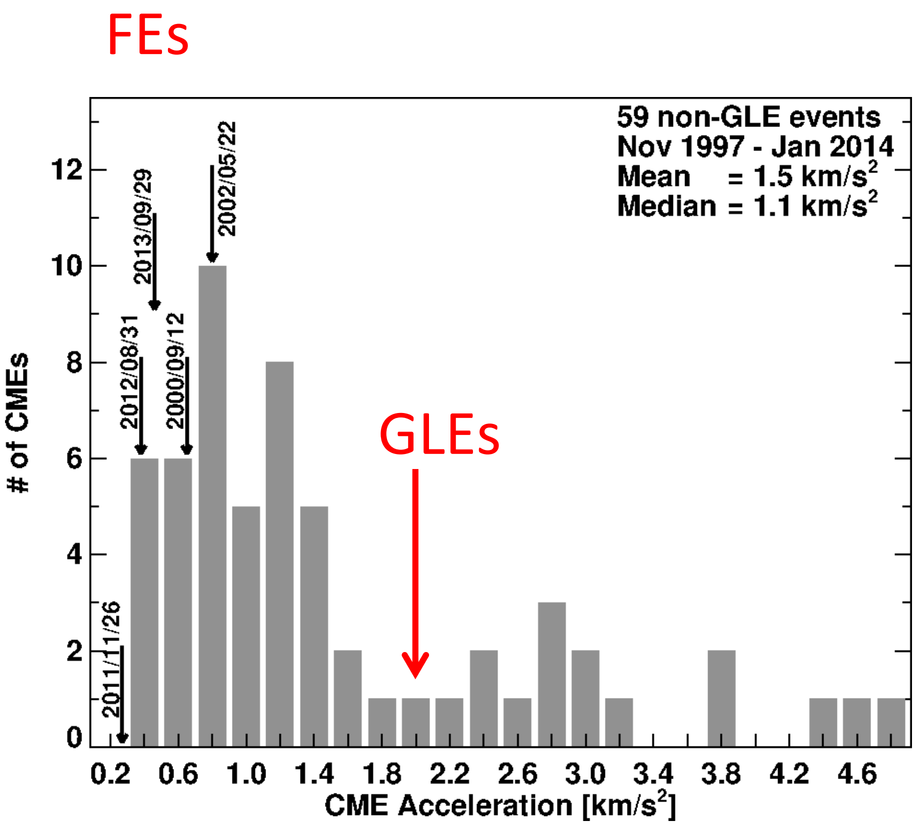


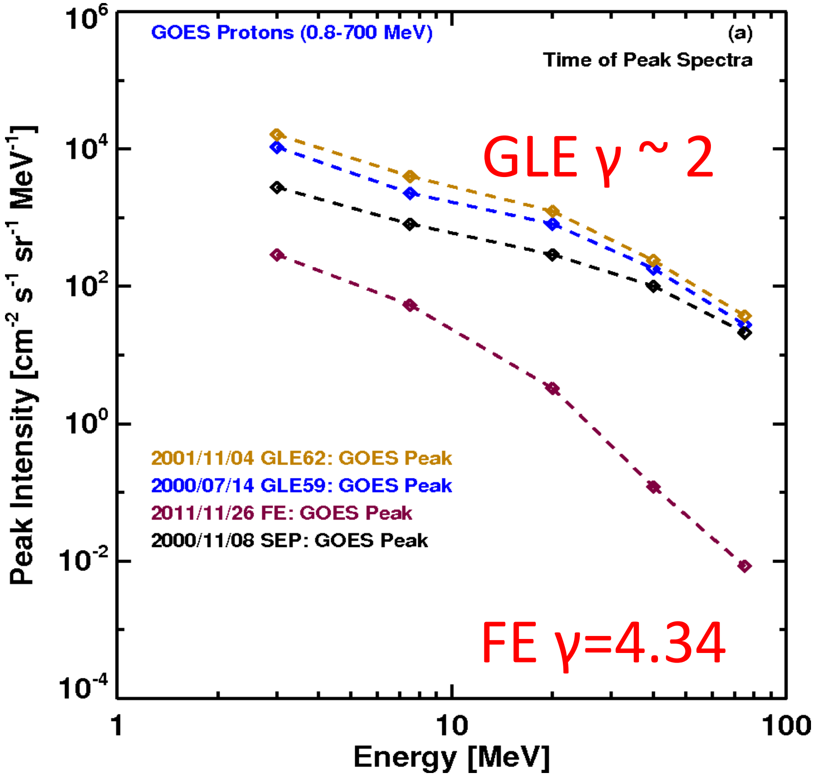
Hard spectrum consistent with a GLE-type event

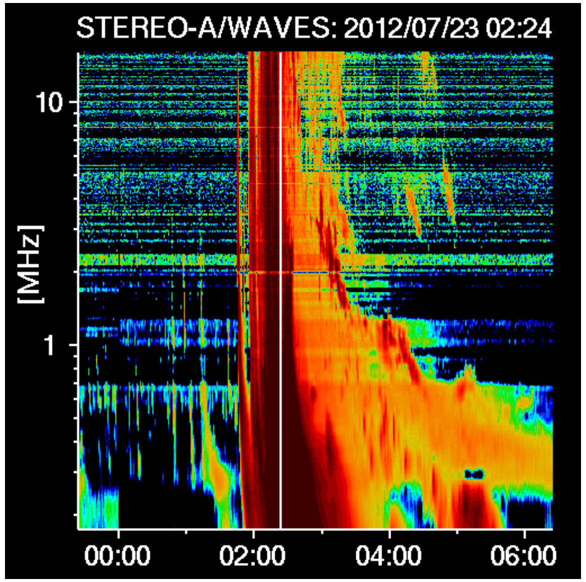
Also CME acceleration is high ~1.6 km/s^2
- typical of GLE events

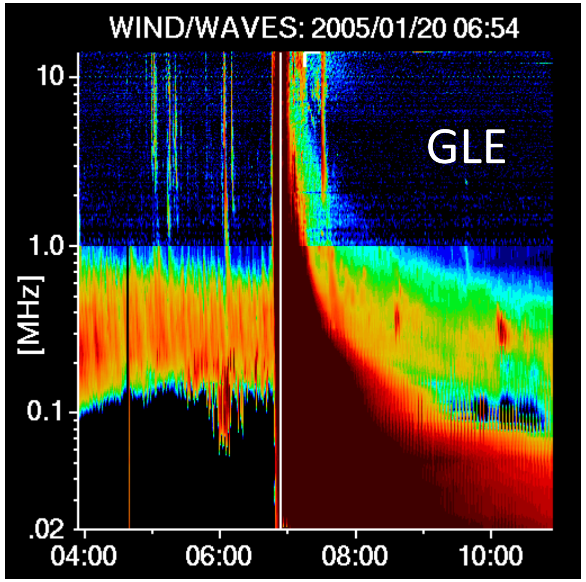
Russell et al. 2013
Mewaldt et al. 2013

Shock Formation Height, CME Accel. & Spectral Index









slow acceleration → large shock formation heights

GLE events: <1.5 Rs

FE SEP events: >3 Rs

GLEs and FEs correspond to the extreme ends

Steep spectrum

FE γ >4

GLE γ ≤2

Mäkelä et al. 2015; Gopalswamy et al. 2015

Summary

- CMEs with speed > 2000 km/s can be extreme events
- The "CME speed limit" stems from the maximum energy that the Sun can store in its magnetic pockets
- 1-AU transit time <24 h is a good sign of an extreme event (although the extreme consequences depend on the magnetic structure – e.g., the Aug 1972 event with an FN cloud)
- The July 23, 2012 is an important contribution from the weak cycle 24 to the list of bench-mark events