S2I kick-off meeting
Nov. 3rd, 2011

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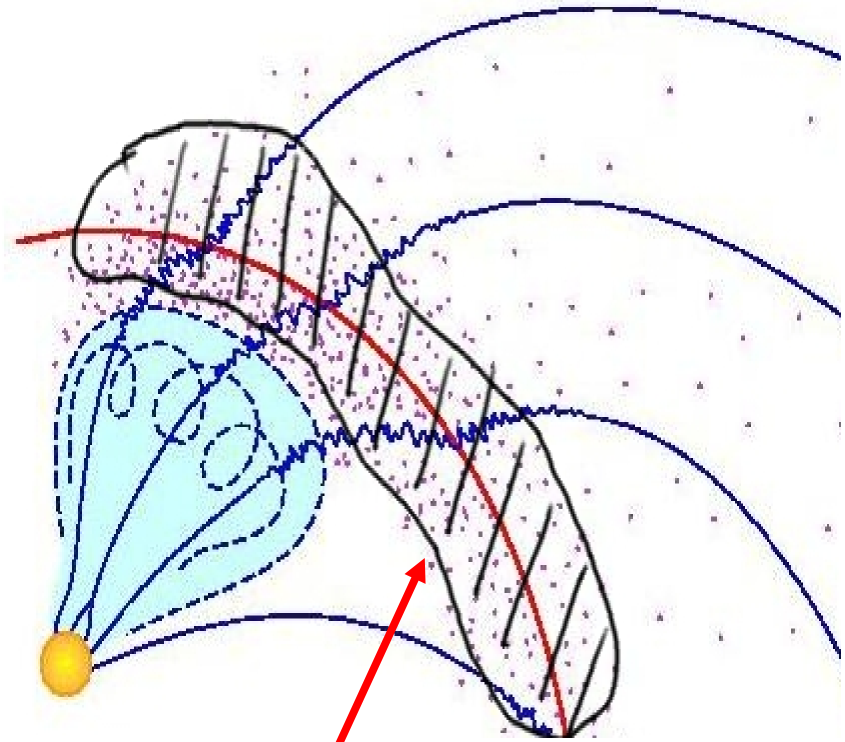
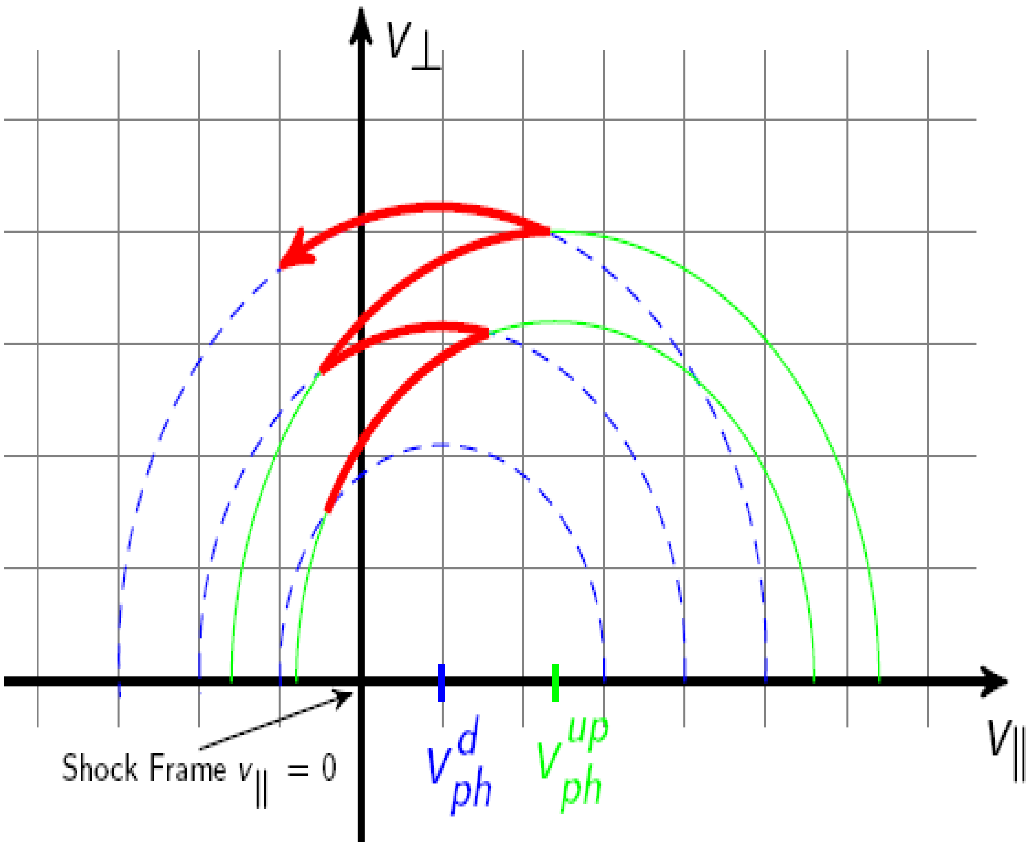
Diffusive shock acceleration
(a microscopic point of view)





The acceleration region

Sugiyama & Terasawa, 1999

Diffusive Shock acceleration-- the standard theory

Parker's transport equation: Near isotropic dist.

$$\frac{\partial f}{\partial t} = -V_{w,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\kappa_{ij}\frac{\partial f}{\partial x_j} - V_{D,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p} + Q$$

advection *diffusion* *drift* *energy change*

Effect of turbulence on particle

In conservation form:

$$\frac{\partial f}{\partial t} + \nabla \cdot S + \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 J) = 0$$

$$\mathbf{S} = -\frac{p}{3}\mathbf{u}\frac{\partial f}{\partial p} - \kappa \nabla f$$

S: current in r space

$$J = \frac{p}{3}u \cdot \nabla f$$

J: current in p space

Gleeson-Axford 1967

Steady state solution is

$$f(p) \sim p^{-3s/s-1}$$

Acceleration time scale and shock geometry

- the highest energy is decided by the acceleration time scale.

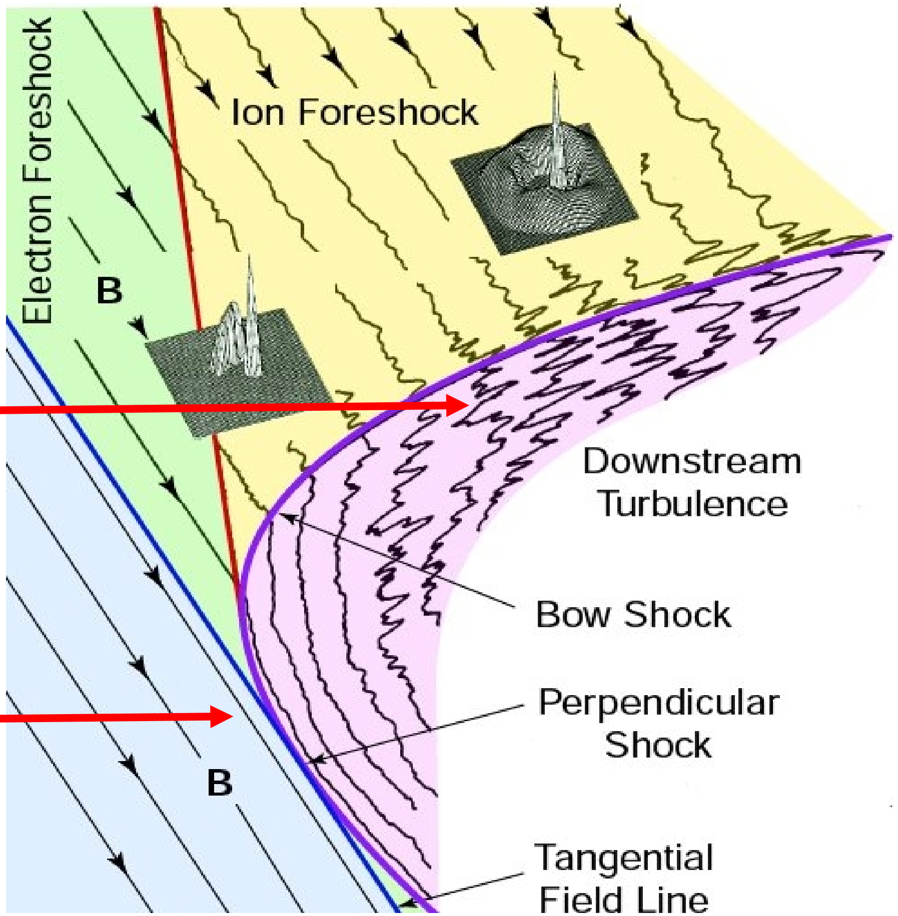
$$\Delta t = \frac{3s}{s-1}\frac{\kappa(p)}{u_{sh}^2}\frac{\Delta p}{p}$$ Drury (1983)

smaller κ lead to higher energy

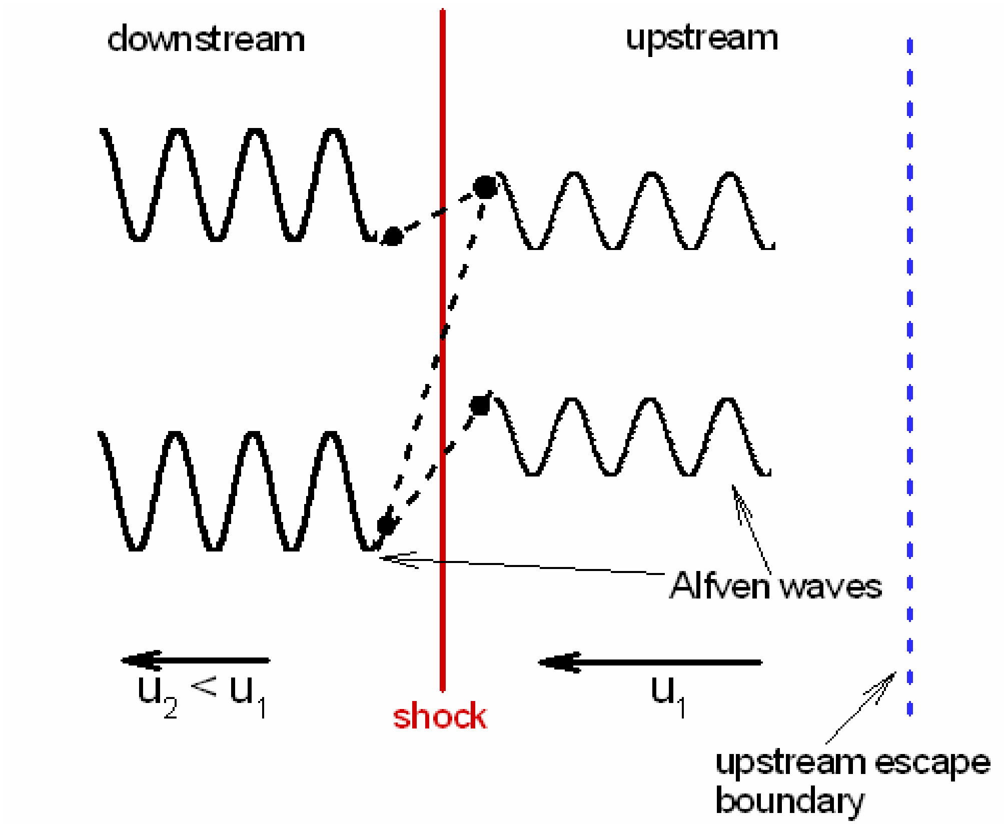
How to obtain a small κ?

1)self-excited wave by streaming protons at a quasi-parallel shock

2) particle acceleration at a perp. shock – particles are difficult to diffuse cross field (κ_perp < κ_parallel)



Wave amplification at a parallel shock



$$\frac{\partial A}{\partial t} + u\frac{\partial A}{\partial r} = \Gamma A - \gamma A,$$

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial r} - \frac{p}{3}\frac{\partial u}{\partial r}\frac{\partial f}{\partial p} = \frac{\partial}{\partial r}\left(\kappa\frac{\partial f}{\partial r}\right),$$

$$\kappa(p) = \frac{\kappa_0}{A(k)}\frac{B_0}{B}\frac{(p/p_0)^2}{\sqrt{(m_p c/p_0)^2 + (p/p_0)^2}},$$

A

$$I_+(|k| < \gamma m|\Omega|/p_o) = \frac{q|\Omega|NV_A p_o^{q-3}cos\psi}{4(q-4)(q-2)V'^2}\frac{1}{k^2}\left|\frac{\gamma m\Omega}{k}\right|^{4-q} + I_+^o(k)$$

Seed population

Ground Level Events (GLEs)

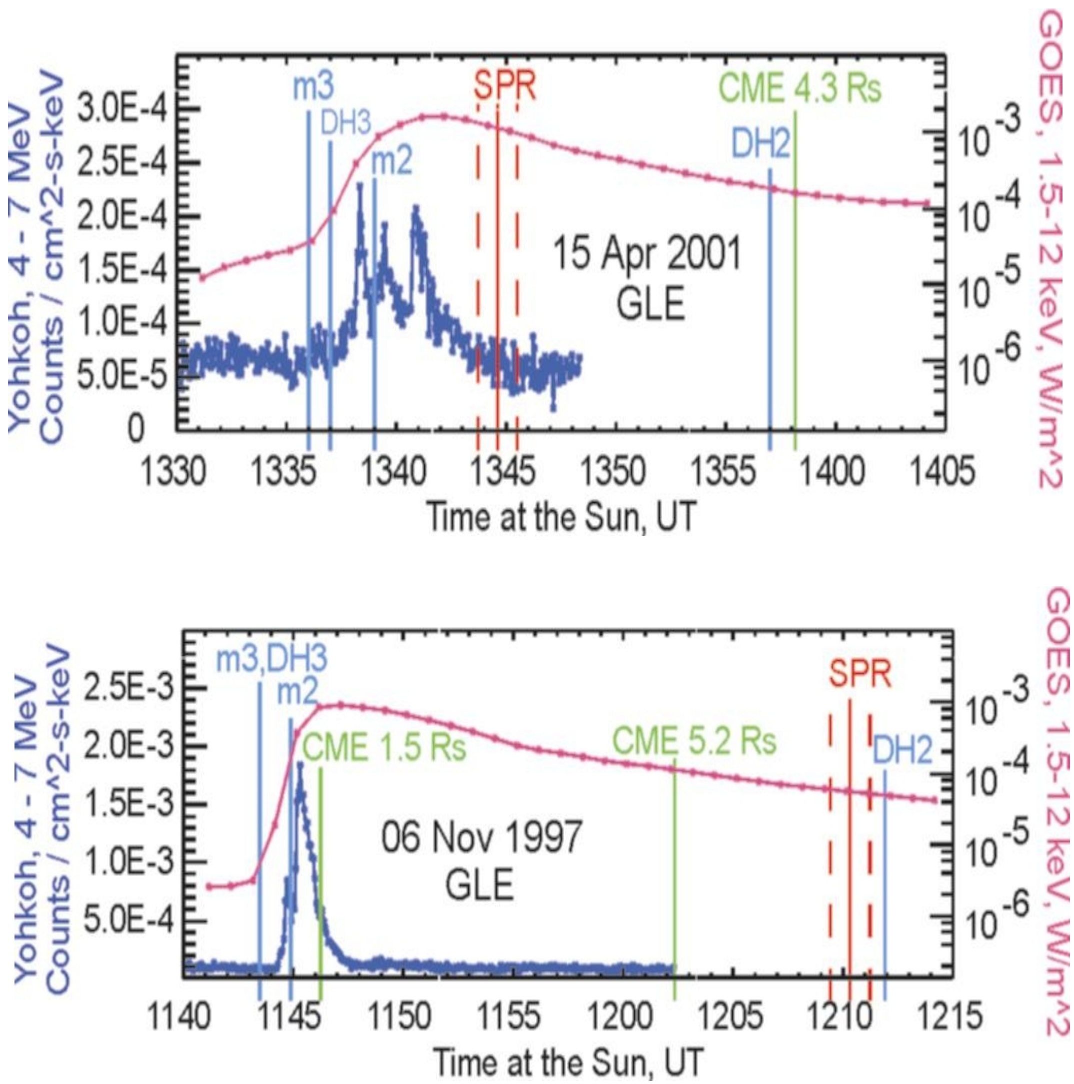
GLEs are rare: only 16 in solar cycle 23.

- GLEs are very energetic particle events that have high intensity and reach high energy.

- Because their numbers are few, they offer a good opportunity for detailed examination of the underlying diffusive shock acceleration theory.

In particular, its applicability and limits.

Constraints on the acceleration height



Tylka et al (2005)

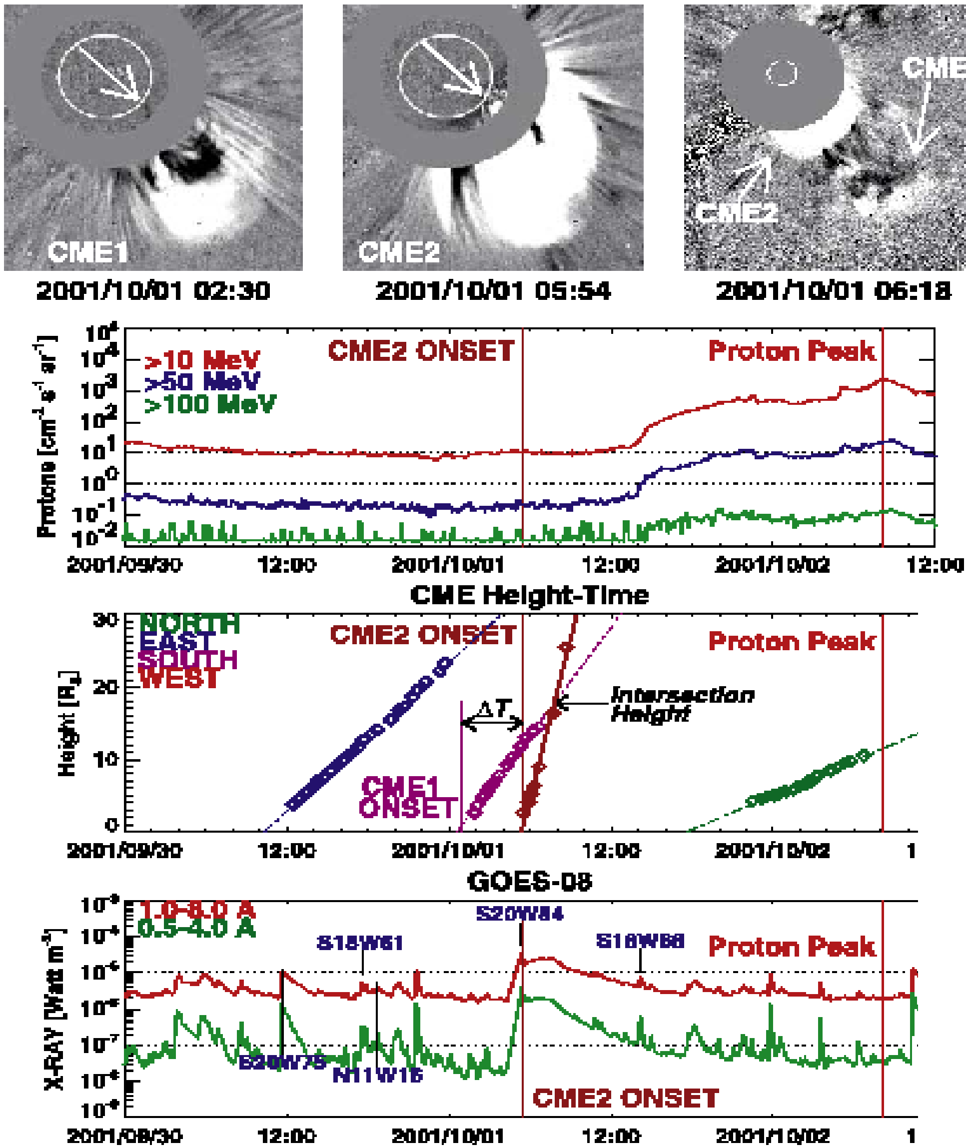
Event #	GLE event date	GLE onset (Obs)	GLE onset (Inf)	CME ht, Rs
1	06 Nov 1997	12:10	12:07	5.3
2	02 May 1998	13:55	13:52	3.9
3	06 May 1998	08:25	08:22	3.8
4	24 Aug 1998	22:50	22:47	DG
5	14 Jul 2000	10:30	10:27	2.0
6	15 Apr 2001	14:00	13:57	3.4
7	18 Apr 2001	02:35	02:32	6.6
8	04 Nov 2001	17:00	16:57	8.8
9	26 Dec 2001	05:30	05:27	4.4
10	24 Aug 2002	01:18	01:15	4.0
11	28 Oct 2003	11:22	11:19	4.5
12	29 Oct 2003	21:30	21:27	9.4
13	02 Nov 2003	17:30	17:27	3.0
14	17 Jan 2005	09:55	09:52	3.4
15	20 Jan 2005	06:51	06:48	3.2
16	13 Dec 2006	02:45	02:42	4.9

Gopalswamy et al (2010)

Presence of preceding CMEs

GLE number/date	AR number/loc	FC/Onset time[a]	CME time	Δt^b	CME speed	CPA	AW	database	Ne/O	Mg/O	Si/O	Fe/O
–	8100	C1.9/3:12	04:20	8	307	263	59	CDAW	–	–	–	
55/1997.11.6	8100/S18W63	X9.4/11:49	12:10	–	1556	Halo	360	CDAW	0.26	0.202	0.169	0.650
–	8210	C5.4/4:48	05:31	8.5	352	228	80	SEEDS	–	–	–	
56/1998.5.2	8210/S15W15	X1.1/13.31	14:06	–	958	298	91	CDAW	0.33	0.298	0.203	0.636
–	8210	M2.5/23:27[p]	00:02	8.0	786	274	110	CDAW	–	–	–	
57/1998.5.6	8210/S11W65	X2.7/07:58	08:29	–	1099	309	190	CDAW	0.32	0.249	0.157	0.502
–	8210	X2.7/07:58	09:32	-1.0	792	328	248	CDAW	–	–	–	
58/1998.8.24	8307	X1.0(07:58)	–	–	–	–	–	CDAW	–	–	–	
–	9077	C7.1/6:52	08:30	2.4	395	245	12	SEEDS	–	–	–	
59/2000.7.14	9077/N22W07	X5.7/10:03	10:54	–	1674	Halo	360	CDAW	0.16	0.219	0.149	0.09
–	9415	C7.7(08:26)	09:30	4.5	403	267	16	CDAW	–	–	–	
–	9415	C5.3(10:56)	11:18	2.8	511	199	70	CDAW	–	–	–	
60/2001.4.15	9415/S20W85	X14(13:19)	14:06	–	1199	245	167	CDAW	0.18	0.231	0.196	0.42
–	9415[c]	–	18:54[p]	7.5	606	250	10	SEEDS	–	–	–	
61/2001.4.18	9415/S23W117	west limb	02:30	–	2465	Halo	360	CDAW	0.17	0.293	0.188	0.16
–	9684[d]	–	13:20	3.1	308	266	6	SEEDS	–	–	–	
62/2001.11.4	9684/N06W18	X1.0(16:03)	16:35	–	1810	Halo	360	CDAW	0.13	0.195	0.134	0.07
–	9742	[e]	02:06	3.4	800	283	21	CDAW	–	–	–	
63/2001.12.26	9742/N08W54	M7.1(05:03)	05:30	–	1446	281	>212	CDAW	0.13	0.199	0.208	0.37
–	10069	C4.3/20:33	20:50[p]	4.7	861	262	131	CDAW/CACT	–	–	–	
64/2002.8.24	10069/S02W81	X3.1/00:49	01:30	–	Halo	360	1913	CDAW	0.15	0.208	0.138	0.19
–	10486	C9.0/06:13	06:30	5.0	684	110	35	SEEDS[g]	–	–	–	
65/2003.10.28	10486/S20E02	X17/11:00[f]	11:30	–	–	–	–	CDAW	0.11	0.201	0.164	0.04
–	10486	C8.1/16:49	17:36	3.1	567	217	7	CACT/SEEDS[m]	–	–	–	
66/2003.10.29	10486/S19W09	X10/20:37	20:54	–	–	–	–	CDAW	0.24	0.241	0.172	0.14
–	10486	M1.3/8:39?[h]	9:30	8.0	2036	310	326	CDAW/CACT	–	–	–	
–	10486	[h]	11:30	6.0	826	224	33	CDAW	–	–	–	
67/2003.11.02	10486/S18W59	X8.3/17:03	17:30	–	2598	Halo	360	CDAW	0.13	0.193	0.119	0.04
–	10720	X2.2/9:06	09:30	0.4	2094	Halo	360	CDAW	–	–	–	
68/2005.1.17	10720/N14W25	X3.8/9:38[f]	09:54	–	2547	Halo	360	CDAW	0.18	0.185	0.114	0.04
–	10720	C4.8/3:21	04:06	2.8	503	301	18	CDAW	–	–	–	
69/2005.1.20	10720/N14W61	X7.1/6:39	06:54	–	3242	Halo	360	CDAW	0.23	0.231	0.162	0.17
–	10930	[l]	20:28	6.2	474	193	50	CDAW	–	–	–	
70/2006.12.13	10930/S06W23	X3.4/2:17	02:45	–	1774	–	–	CDAW	0.205	0.21	0.20	0.778

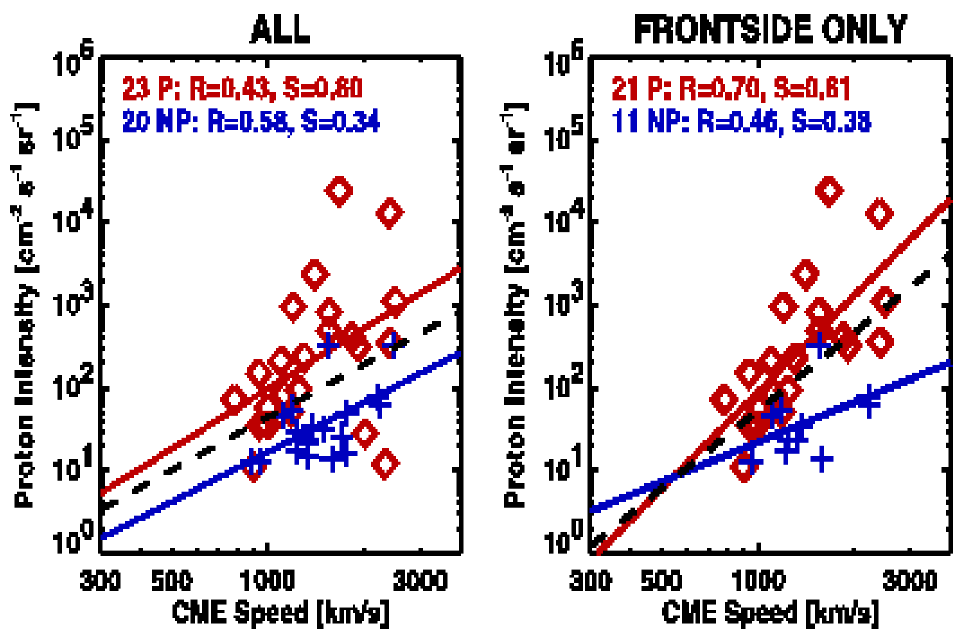
Early survey on Large SEPs



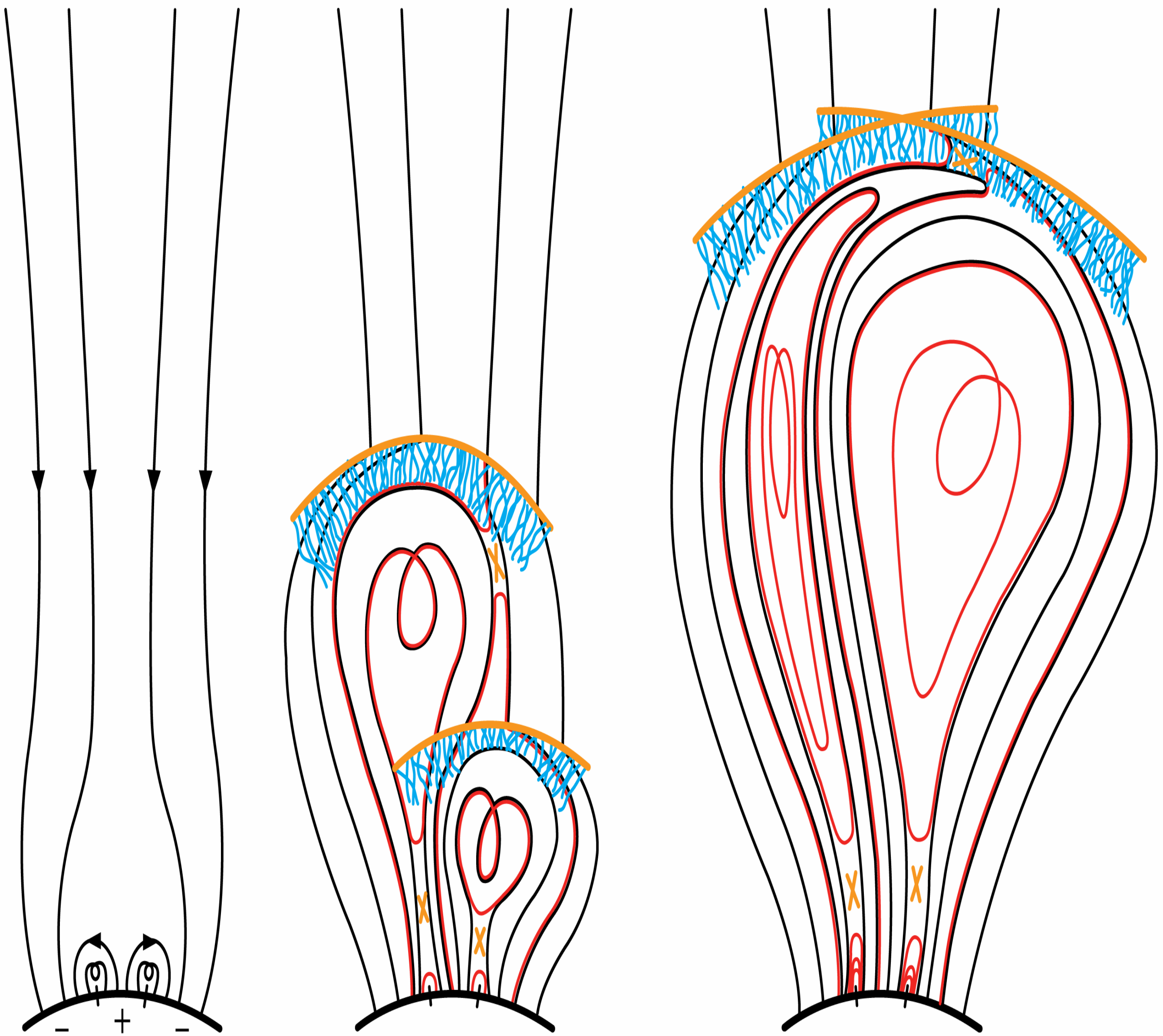
Gopalswamy et al. JGR, 2004

57 events between 1996-2002 are selected, with intensity > 10 pfu (proton cm-2 s-1sr-1) at >10 MeV channel.

23 with preceding CMEs (within 1 day), 20 without preceding CMEs



A twin-CME proposal



Li et al. 2011

Pre-eruption:
B field orientation ==>
Pseudo-streamer

Eruption:

two (or multiple) CMEs erupt in sequence within a time difference of ~ 8 hours

first CME/shock provides both the seed population and a strong background turbulence

second CME plumbs into the turbulence-enhanced region behind the 1st CME for an efficient shock acc

How about "normal" large SEP events?

Definition of large: at > 10 MeV/n, intensity > 10 pfu.

Group I: "twin-CMEs" that lead to large SEP

Group II: "twin-CMEs" that do not lead to large SEP

Group III: "fast single CME"

Are preceding CMEs necessary?

No.	Date	CME onset time	CPA	WD	Speed	AR	loc.	FC	Flare onset time	TypeII	Comment
			(deg)	(deg)	(km/s)						
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
12	2000/01/28	20:12	halo	360	1177	8841	S31W17	C4.7	19:45	n	
13	2000/04/23	12:54	halo	360	1187	-	>NW90	-	-	n	bs
14	2000/05/05	15:50	halo	360	1594	8976	S12W88	M1.5	15:18	n	
15	2000/06/28	19:31	270	134	1198	?	N30W60	-	-	18:57	o
16	2000/08/11	07:31	273	70	1071	-	>NW90	-	-	n	bs
17	2000/09/16	05:18	halo	360	1215	9165	N15W07	M2.1	05:04	04:11	
18	2000/12/13	16:26	halo	360	1067	9267	N08E11	-	-	n	
19	2001/03/20	08:06	226	112	1130	-	>SW90	-	-	n	bs
20	2001/04/09	15:54	halo	360	1192	9415	S21W04	M7.9	15:20	15:26	
21	2001/04/11	13:31	halo	360	1103	9415	S23W32	M2.3	12:56	13:17	
22	2001/05/10	01:31	246	198	1056	9445	N25W80	C5.6	01:04	n	
23	2001/06/20	19:54	halo	360	1407	9504	N08W17	C2.3	19:00	n	
24	2001/06/24	07:31	halo	360	1094	9511	N10E11	C3.9	06:31	n	
25	2001/07/19	10:30	275	166	1668	9537	S08W62	M1.8	09:52	n	
26	2002/05/07	00:06	287	100	1222	9929	N22W66	C6.4	23:52	n	
27	2002/05/30	05:06	271	144	1625	-	>NW90	-	-	n	bs
28	2002/06/05	19:54	300	82	1175	-	>NW90	-	-	n	bs
29	2002/07/18	08:06	halo	360	1099	10030	N19W30	X1.8	07:24	07:42	hb
30	2002/08/06	18:25	218	134	1098	?	S30W30	-	-	n	o
31	2002/10/14	14:54	halo	360	1694	-	>NE90	-	-	14:20	bs
32	2002/10/23	02:50	306	119	1052	-	>NW90	-	-	n	bs
33	2002/11/24	20:30	halo	360	1077	?	N30E55	-	-	20:06	o
34	2002/12/21	02:30	2	225	1072	?	N40E20	-	-	n	o
35	2002/12/22	03:30	328	272	1071	10223	N23W42	M1.1	02:14	n	
36	2003/01/05	10:37	353	67	1183	?	N40E05	-	-	10:01	o
37	2003/01/23	18:06	307	60	1236	10263	S12W68	-	-	n	
38	2003/01/27	22:23	205	267	1053	10267	S17W23	-	-	22:11	
39	2003/03/17	19:54	291	96	1020	10314	S14W39	X1.5	18:49	n	
40	2003/06/02	00:30	265	172	1656	10365	S07W91	M6.5	00:07	00:19	
41	2003/06/05	20:06	230	239	1458	-	>SW90	-	-	20:02	bs
42	2003/11/07	15:54	halo	360	2237	10495	S21W89	-	-	n	
43	2003/11/11	13:54	halo	360	1315	10498	S04W63	M1.6	13:21	13:33	
44	2003/11/15	17:50	245	148	1375	-	-	-	-	n	bs
45	2004/07/31	05:54	259	197	1192	10652	N05W89	-	-	n	
46	2004/11/09	17:26	halo	360	2000	10696	N08W51	M8.9	16:59	17:18	
47	2004/12/03	00:26	halo	360	1216	10708	N08W02	M1.5	23:44	23:52	
48	2005/01/04	09:30	288	102	1087	?	N15W60	-	-	n	o
49	2005/01/19	08:29	halo	360	2020	10720	N15W51	X1.5	08:03	08:11	
50	2005/02/17	00:06	halo	360	1135	10734	S03W24	-	-	n	
51	2005/07/09	22:30	halo	360	1540	10786	N12W28	M2.8	21:47	21:59	

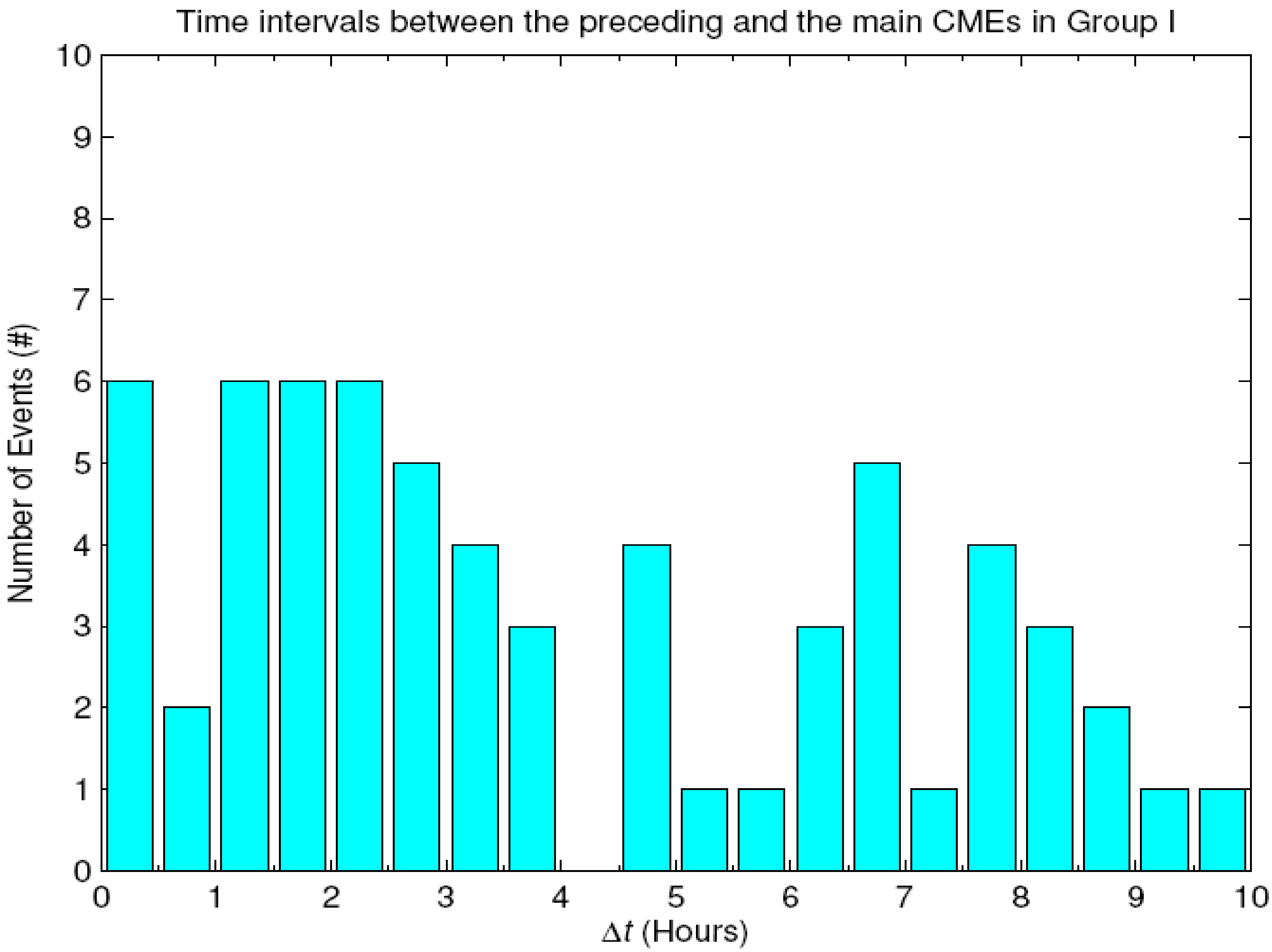
Fast single CMEs with V> 100 km/s.

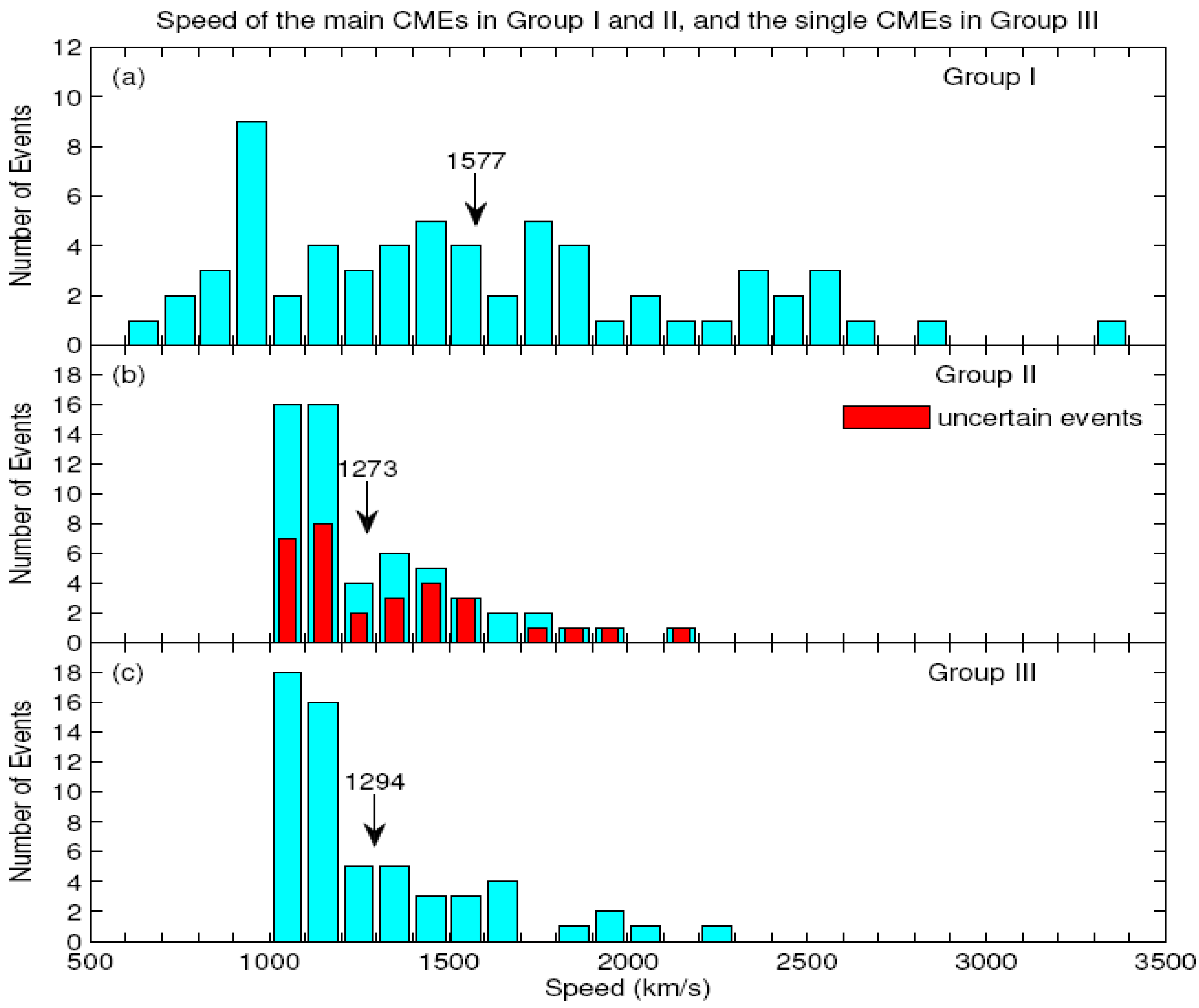
Some have X-flares, type II radio bursts, connection is good.

However ***<u>NONE</u>*** of these lead to large SEPs!

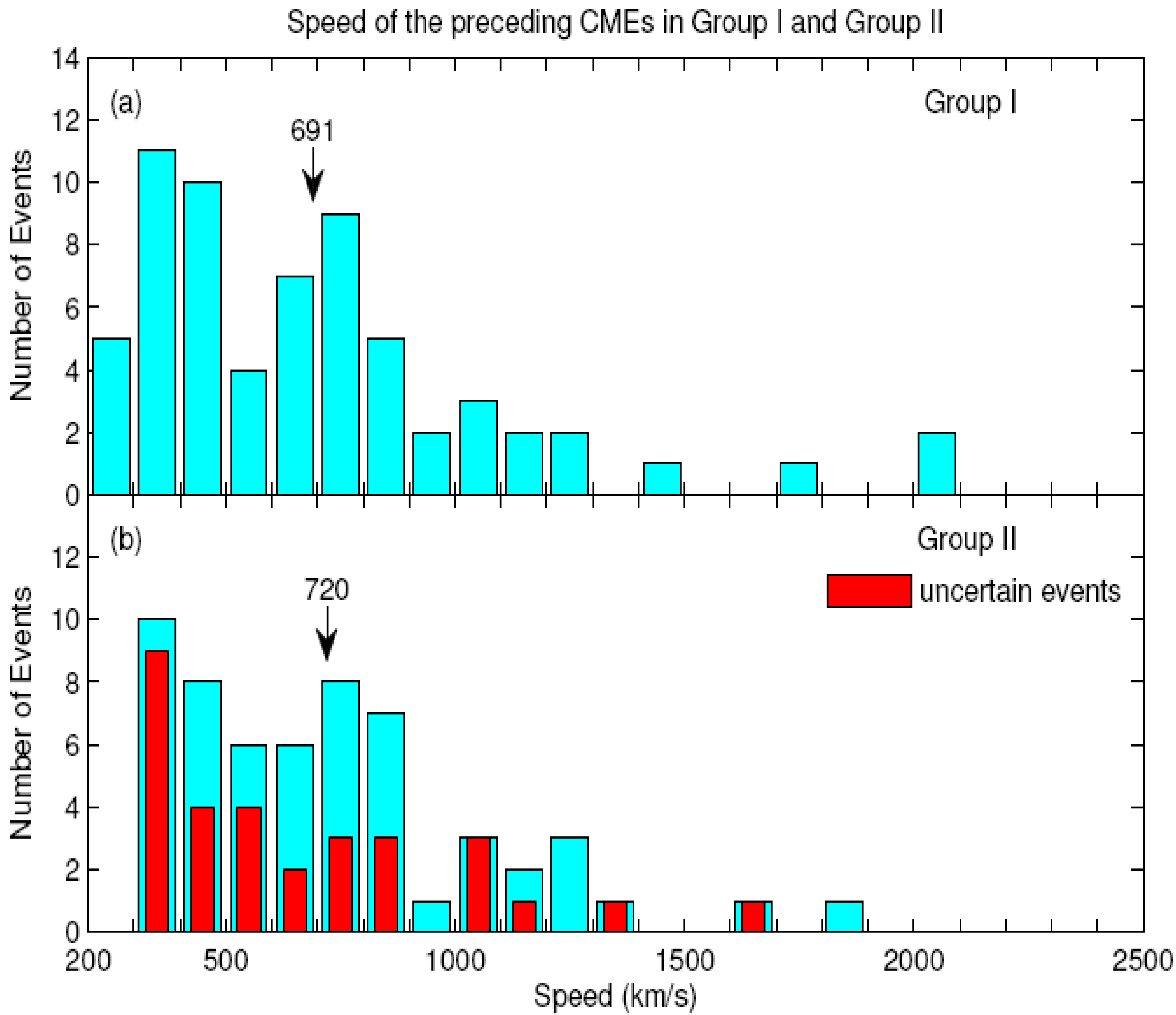
Ding et al, 2011

Large SEP events in solar cycle 23

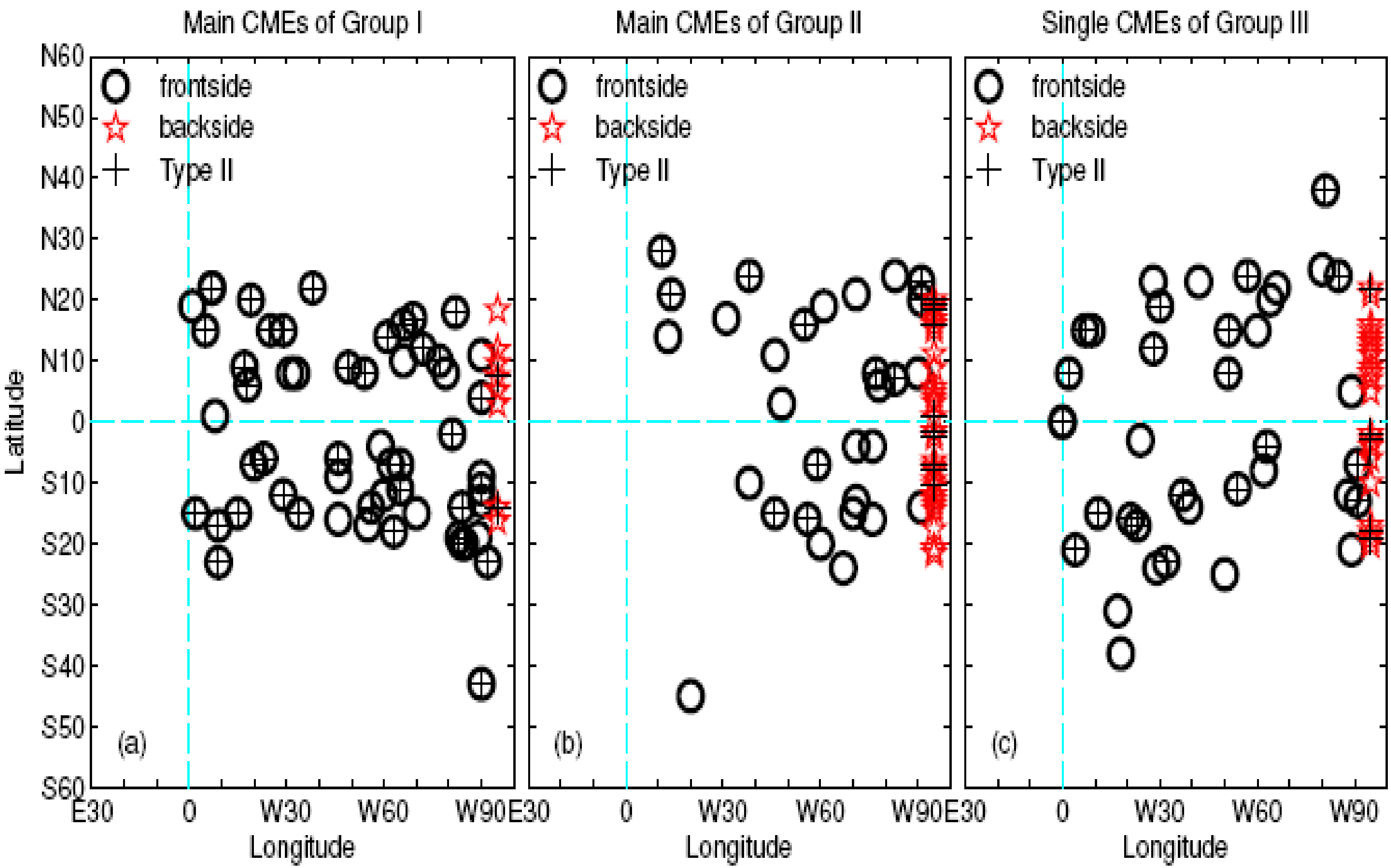




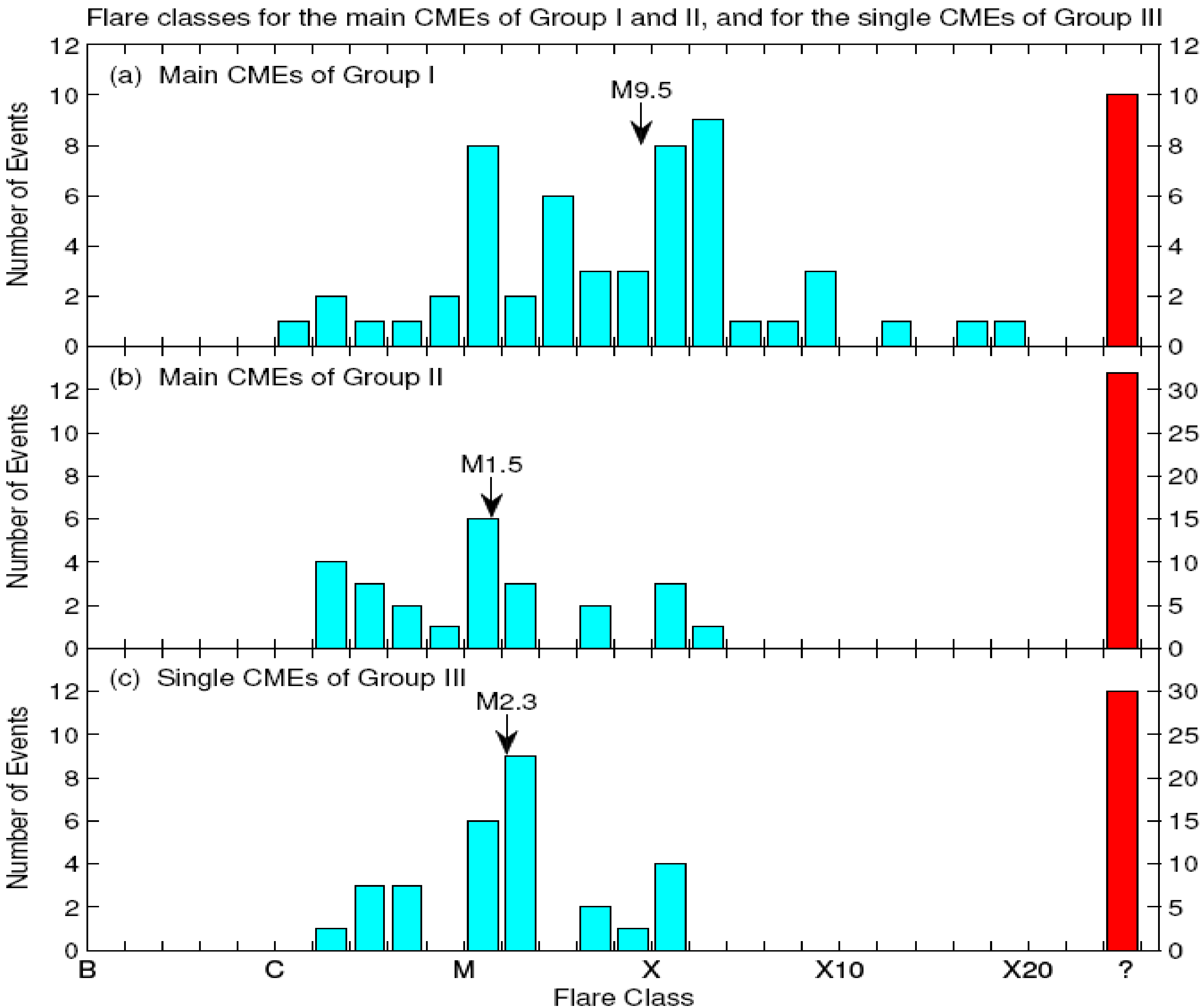
Speed of the main CMEs in Group I and II, and the single CMEs in Group III
(a)
Group I
1577
(b)
Group II
uncertain events
1273
(c)
Group III
1294
Number of Events
Speed (km/s)



Speed of the preceding CMEs in Group I and Group II
(a)
Group I
691
(b)
Group II
uncertain events
720
Number of Events
Speed (km/s)
0
2
4
6
8
10
12
14
200
500
1000
1500
2000
2500



Main CMEs of Group I
Main CMEs of Group II
Single CMEs of Group III
frontside
backside
Type II
N60
N50
N40
N30
N20
N10
0
S10
S20
S30
S40
S50
S60
Latitude
(a)
(b)
(c)
E30
0
W30
W60
W90
Longitude



Flare classes for the main CMEs of Group I and II, and for the single CMEs of Group III
(a) Main CMEs of Group I
M9.5
(b) Main CMEs of Group II
M1.5
(c) Single CMEs of Group III
M2.3
Number of Events
B
C
M
X
X10
X20
?
Flare Class

Effect of shock obliquity

Consider 5 shocks with theta_BN = 5, 25, 45, 65 and 85 degrees and prton, O^6+ and Fe^14 three species

kappa_parallel from the enhanced wave intensity due to streaming protons

$$\kappa_{||} = \frac{v^2}{8}\int_{-1}^{+1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}} = \frac{vp^2c^2}{8\pi Q^2 e^2}\frac{1}{I(k=\Omega/v)}\frac{8}{(\beta-2)(\beta-4)}.$$

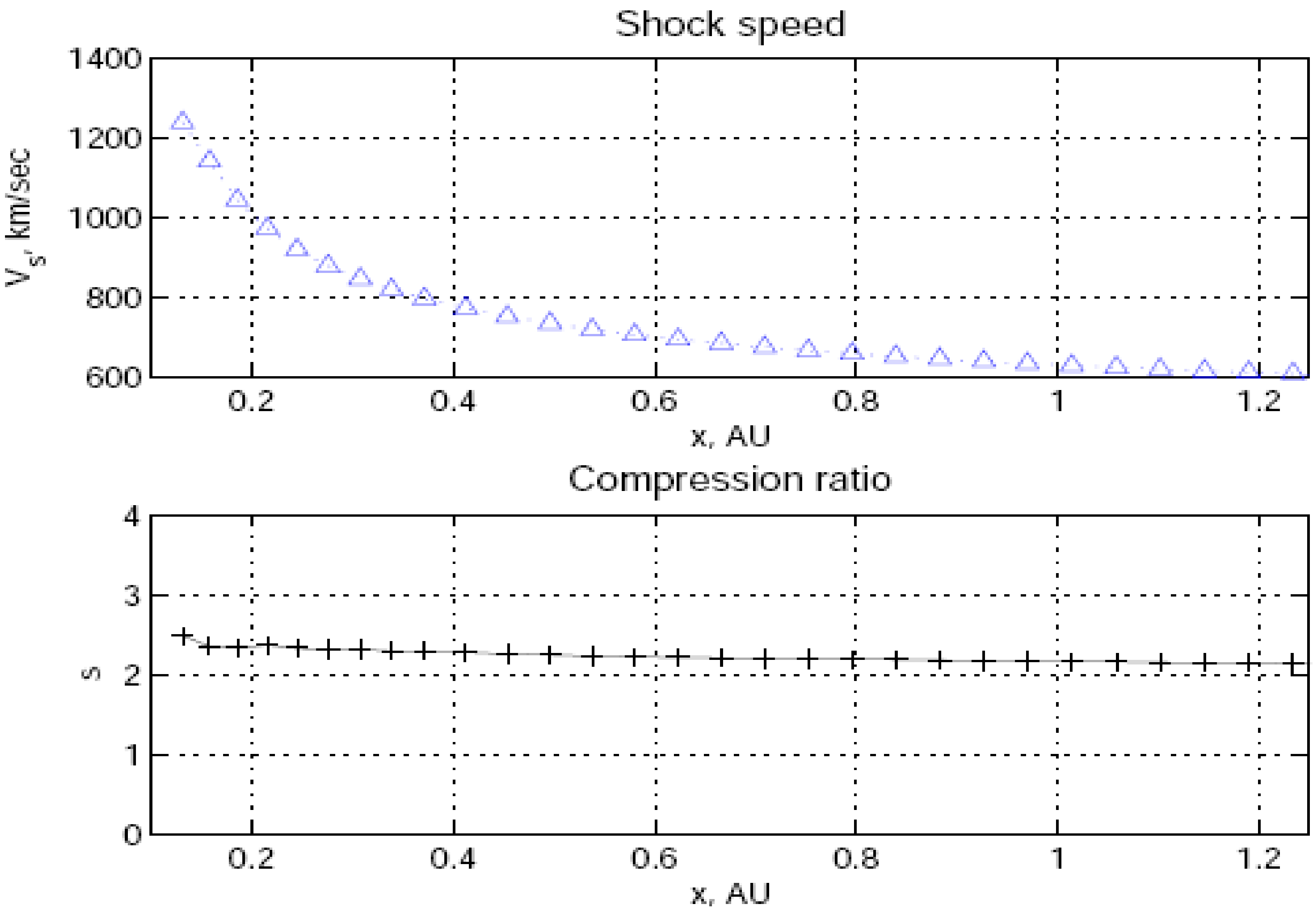
$$I(|k|<\gamma m|\Omega|/p_o) = I^e(k)+I^o(k) = 2\pi\frac{\beta|\Omega|\epsilon n V_A p_o^{\beta-3} cos\theta_{BN}}{(\beta-4)(\beta-2)u_{up}}\frac{1}{k^2}\left|\frac{\gamma m\Omega}{k}\right|^{4-\beta}+I^o(k),$$

kappa_perp from the NLGC (Non-Linear-Guiding-Center) theory (need kappa_parallel as an input)

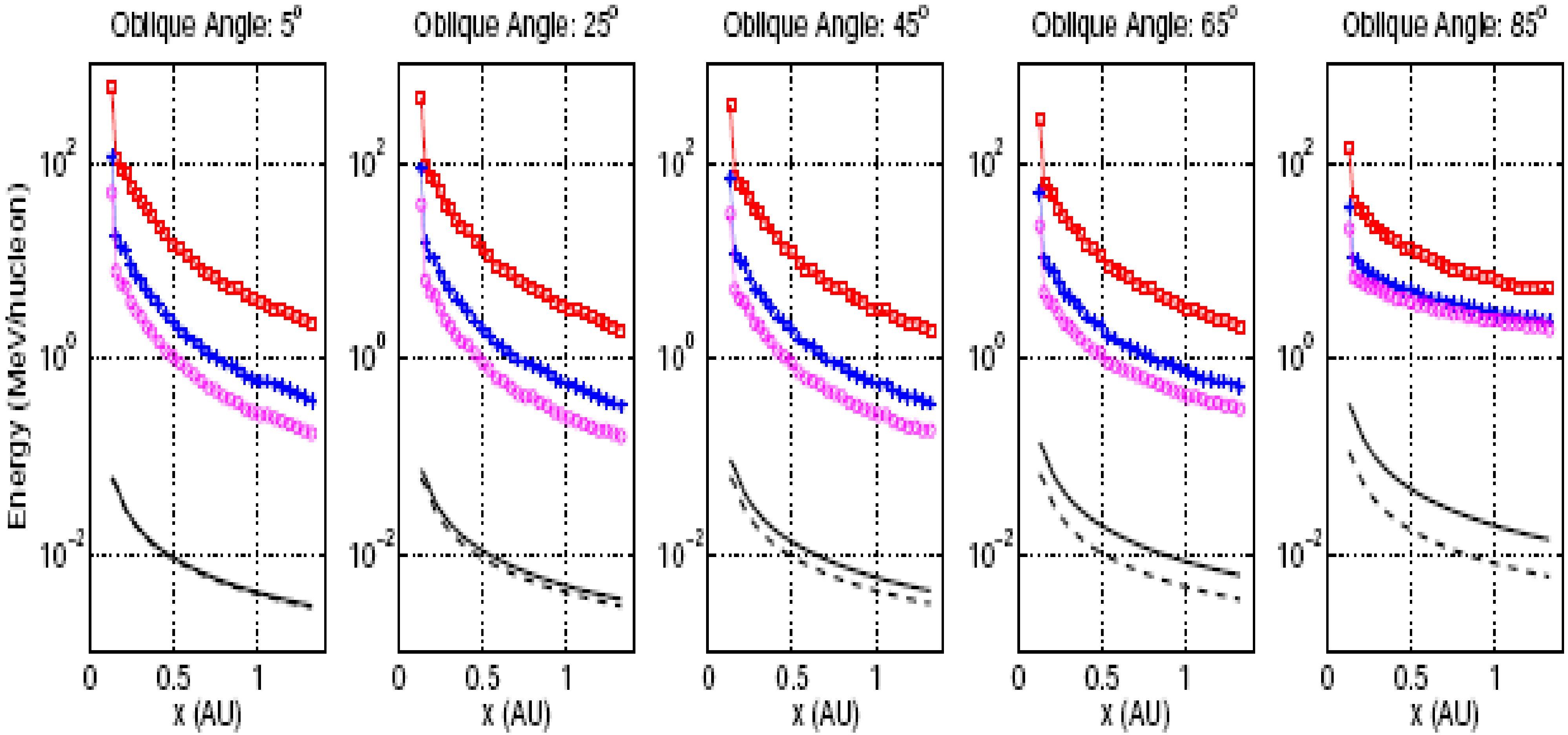
$$\kappa_\perp = [\sqrt{3}a^2\pi\frac{\Gamma(5/6)v}{2\sqrt{\pi}\Gamma(1/3)}\frac{\delta B_{2D}^2}{B_0^2}l_{2D}]^{2/3}\kappa_{||}^{\frac{1}{3}}, \quad \kappa_\perp\kappa_{||}/\mathrm{v}^2 > 3\mathrm{l}_{2D}^2$$

$$\kappa_\perp = \frac{a^2}{2}\frac{\delta B_{2D}^2}{B_0^2}\kappa_{||}, \quad \kappa_\perp\kappa_{||}/\mathrm{v}^2 < 3\mathrm{l}_{2D}^2$$

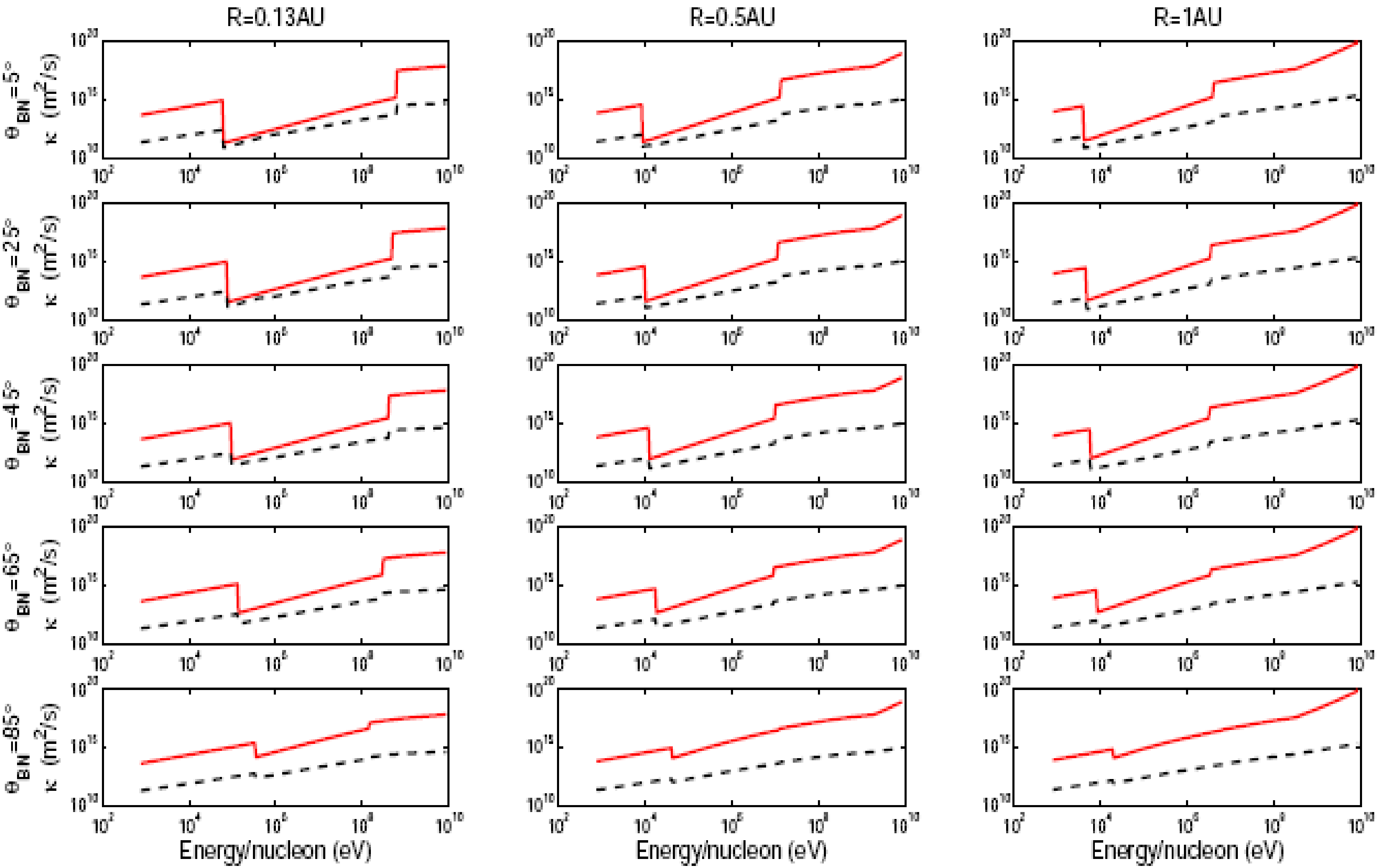
Shock evolution from ZEUS MHD



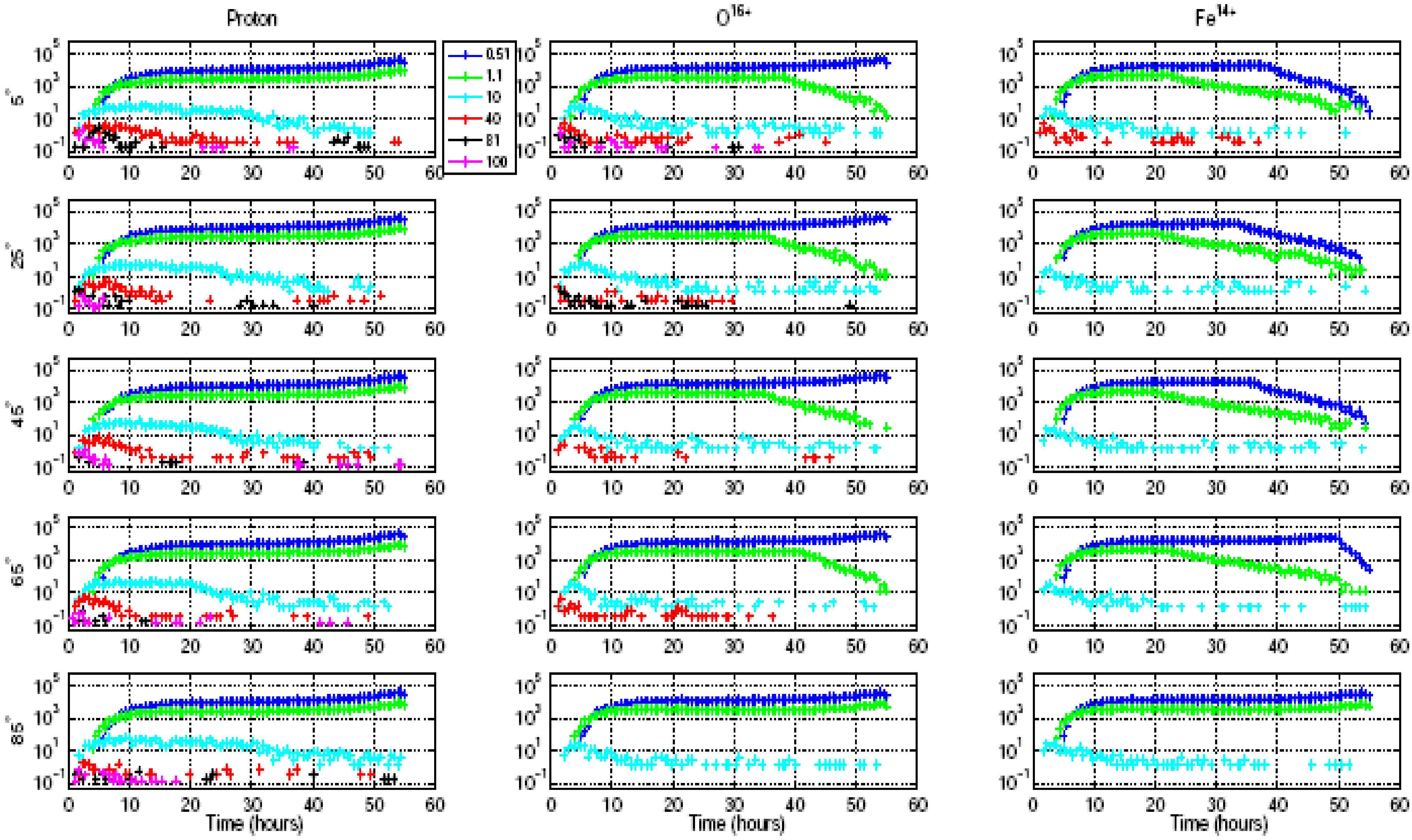
Need better/realistic CME/shock model from Predictive Science group!


Oblique Angle: 5°
Oblique Angle: 25°
Oblique Angle: 45°
Oblique Angle: 65°
Oblique Angle: 85°
Energy (MeV/nucleon)
10^2
10^0
10^{-2}
0
0.5
1
x (AU)

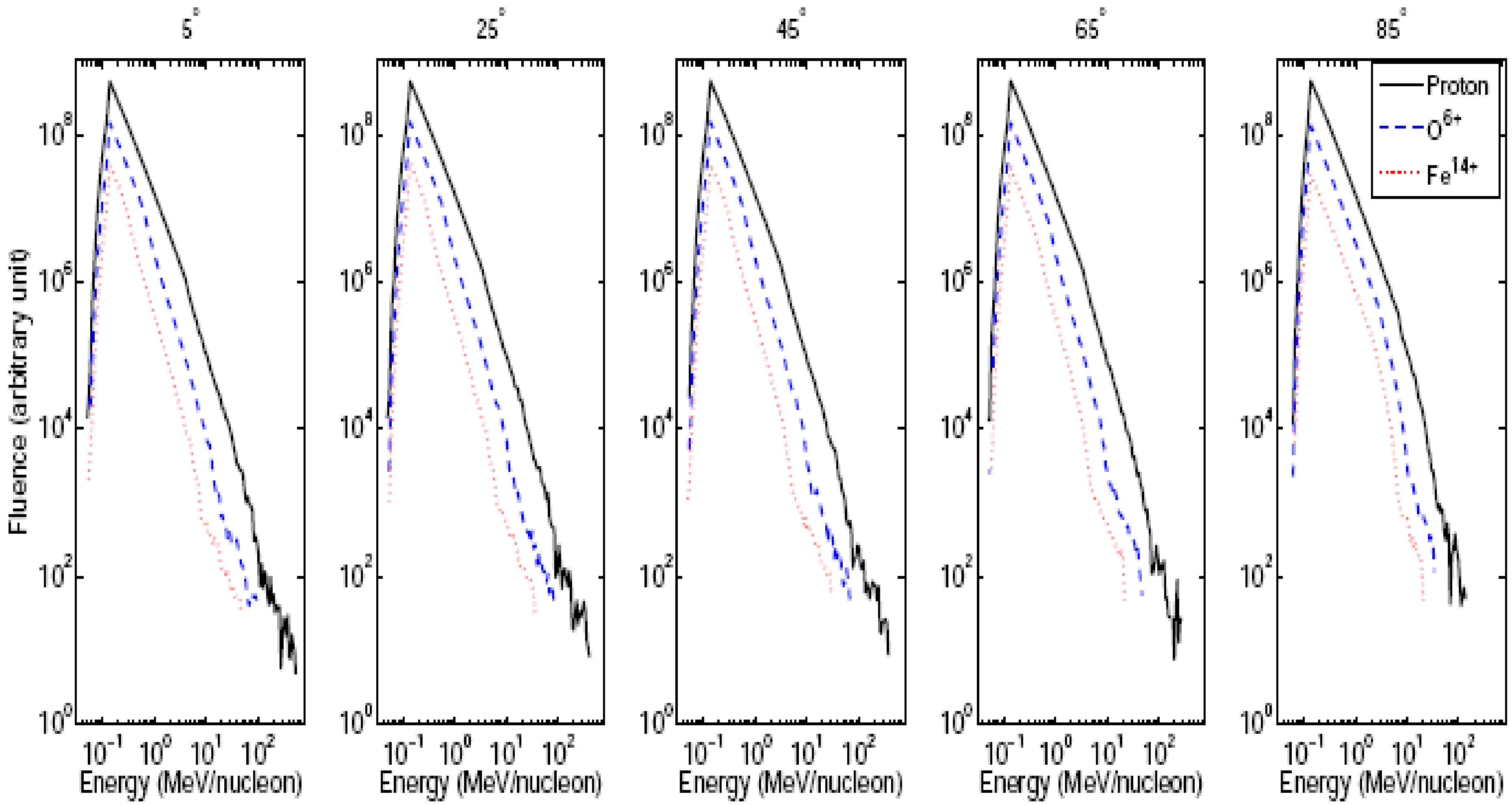
kappa_parallel and kappa_perp



Time intensity profiles



Fluence



5°
25°
45°
65°
85°
Proton
O^{6+}
Fe^{14+}
Fluence (arbitrary unit)
Energy (MeV/nucleon)

What is next?

1) Observationally, understand/confirm the role of upstream wave in accelerating particles at quasi-parallel shock for ESP events (with M. Desai).

2) Need better CME/shock model to yield shock parameters as input to the acceleration module of PATH (with P. Riley).

3) coupling to EMMREM, which has a Lagrangian grid to follow particle transport along and perp. to a field line by implementing the focused transport equation using a stochastic different equation method (with N. Schwadron).

4)understand the effect of shock ripples using test particle simulations and compare with hybrid ones (with J. Giacalone)