Interaction between multiple CMEs and its impact on space weather

Chenglong Shen, Yuming Wang, Rui Liu, Jiayi Liu,

Yutian Chi, Mengjiao Xu, STEP Group@USTC

School of Earth and space Science, Univ. Of Sci. & Tech. Of China, Hefei, Anhui, 230026, China

Email:clshen@ustc.edu.cn

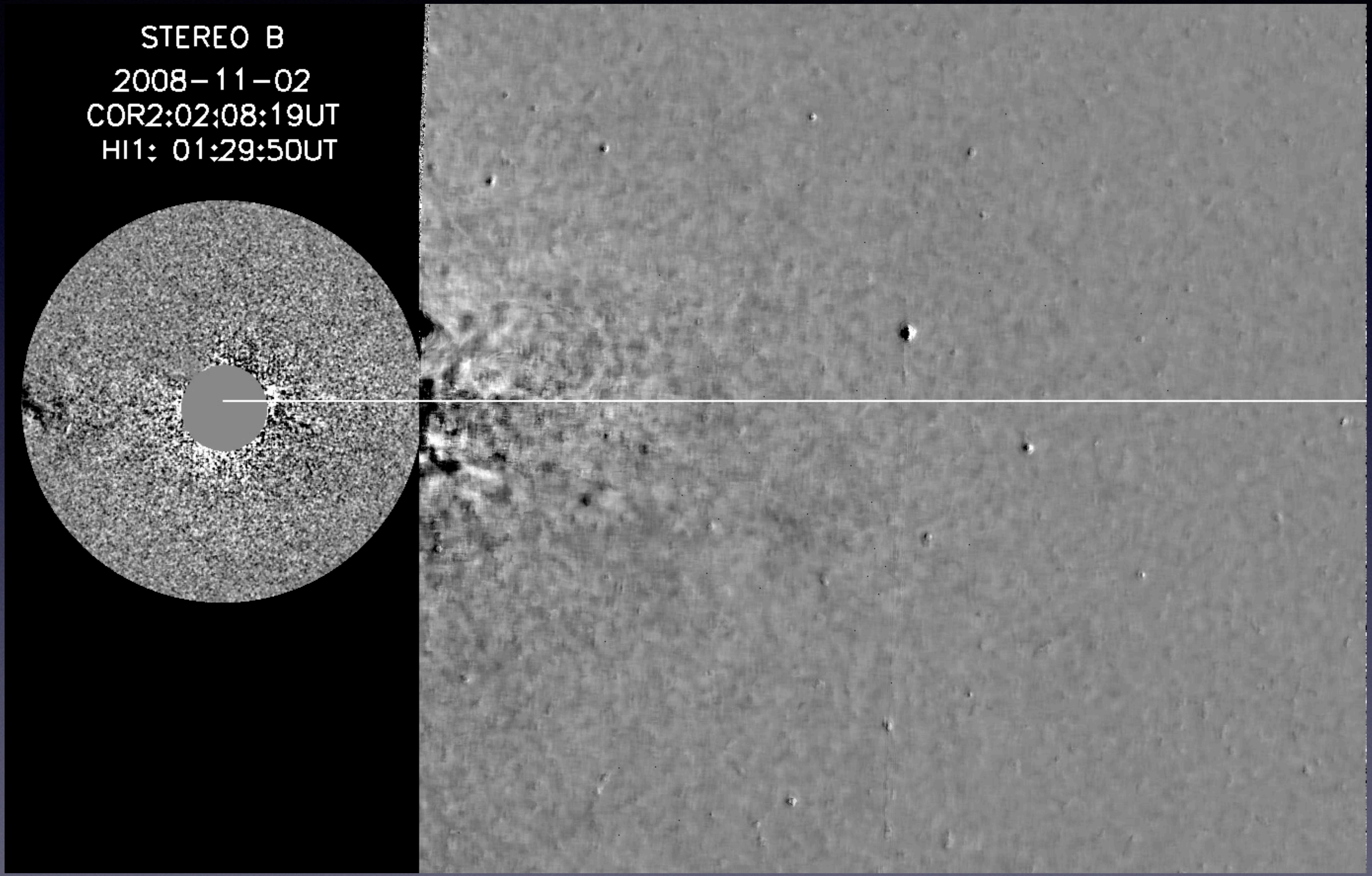
Outline

- Introduction
- Physical process of CME interaction
- Impact on geoeffectiveness
- Impact on SEP events
- Conclusions

Outline

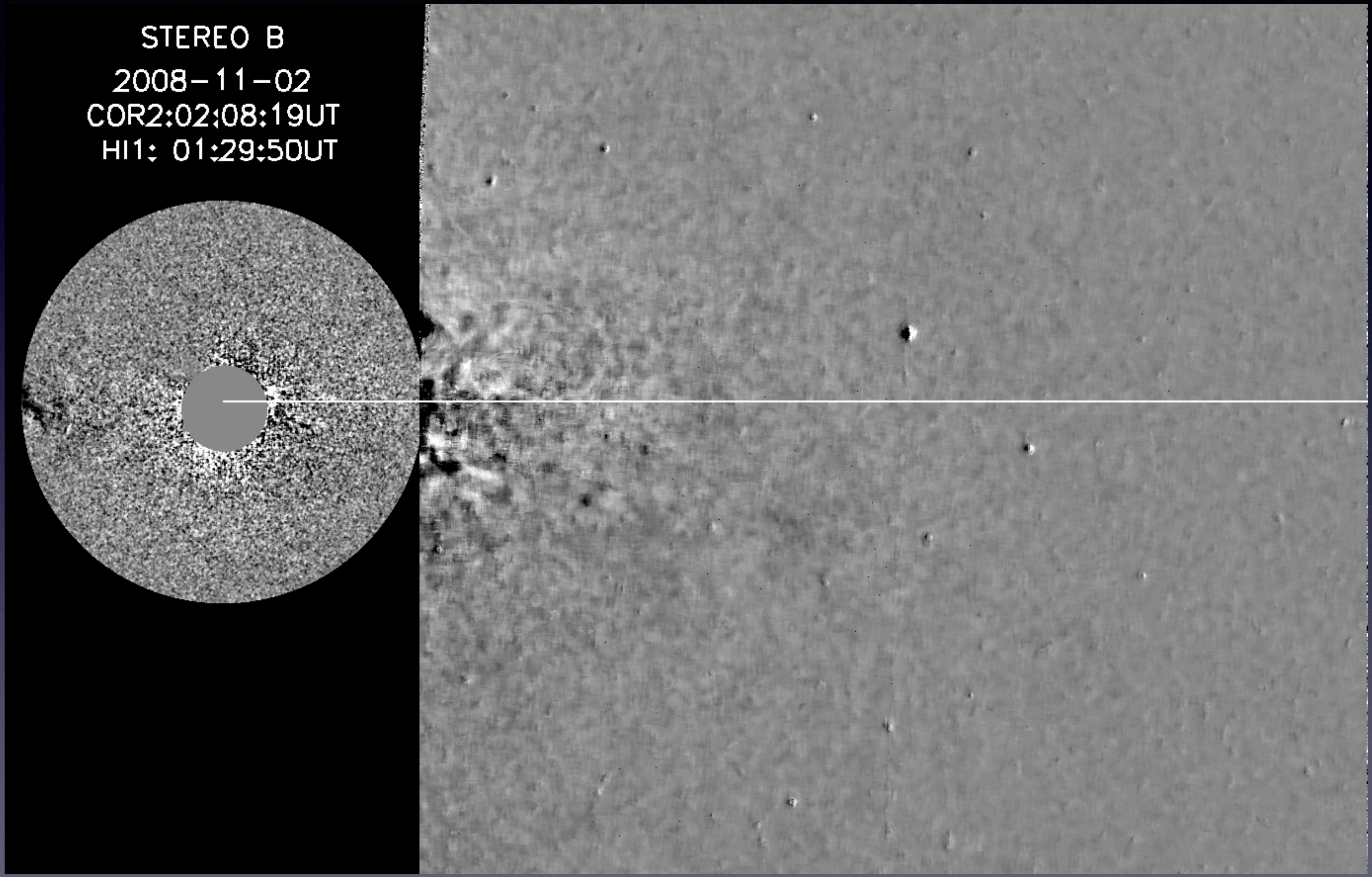
- Introduction
- Physical process of CME interaction
- Impact on geoeffectiveness
- Impact on SEP events
- Conclusions

CMEs' interaction in the heliosphere



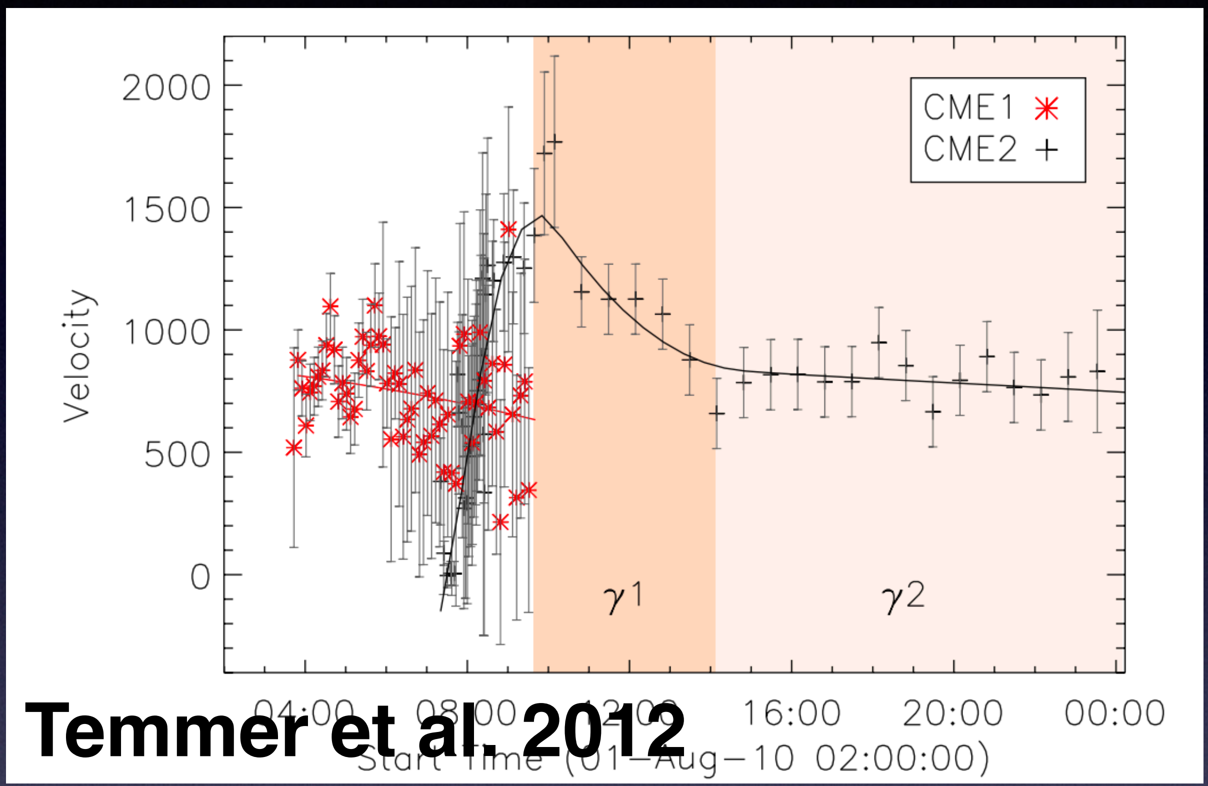
CMEs continuously erupted from the Sun and then may interacted in the heliosphere!

CMEs' interaction in the heliosphere

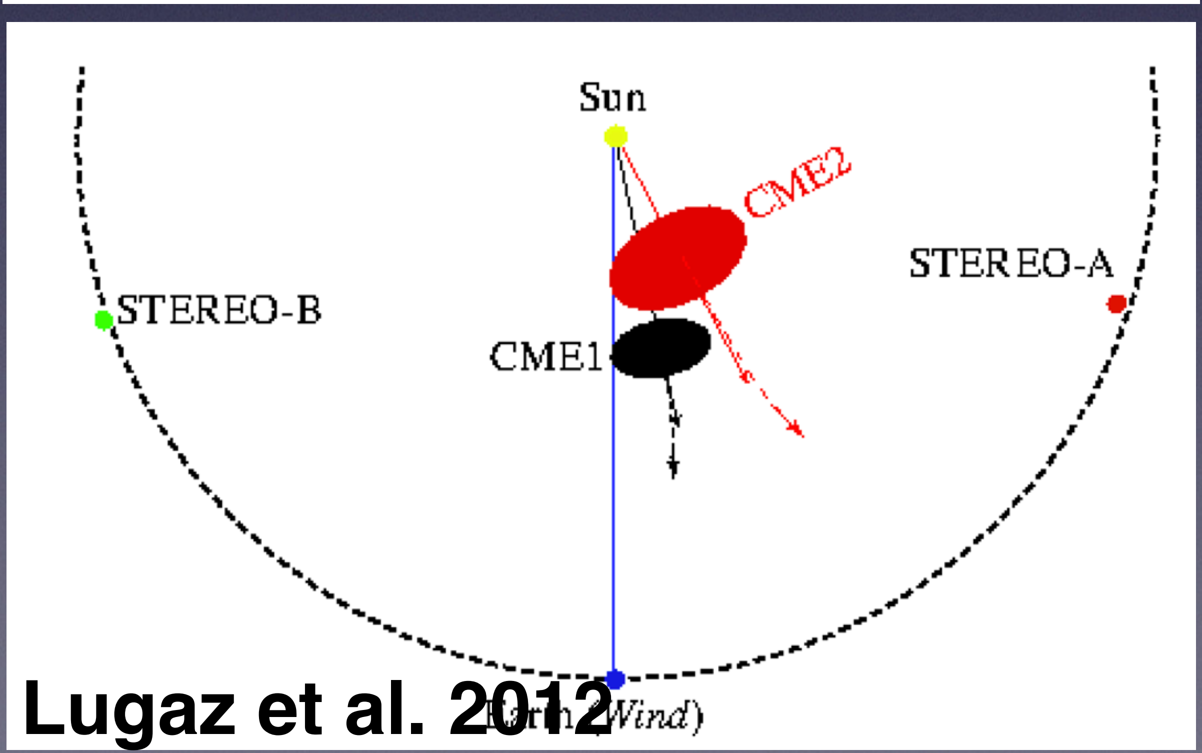


CMEs continuously erupted from the Sun and then may interacted in the heliosphere!

Kinematic evolution during the interaction



Temmer et al. 2012



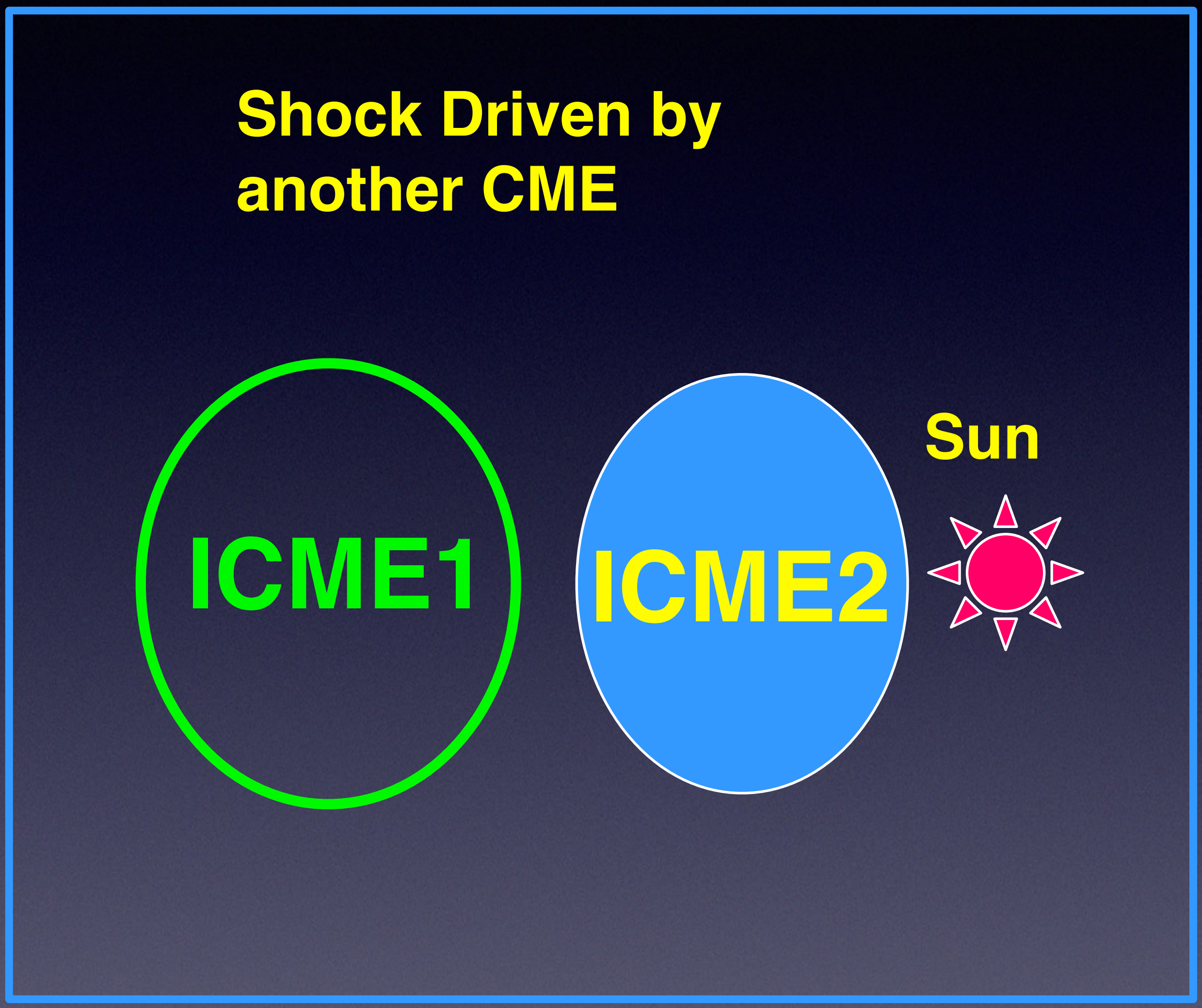
Lugaz et al. 2012

CMEs' interaction can change their propagation velocities and directions!

[e.g., Lugaz et al. 2012; Shen et al. 2012; Temmer et al., 2012; Liu et al. 2012, 2014a; Mishira et al., 2015,2017 Some review papers: Manchester et al., 2017; Shen F. et al., 2017; Lugaz et al., 2017]

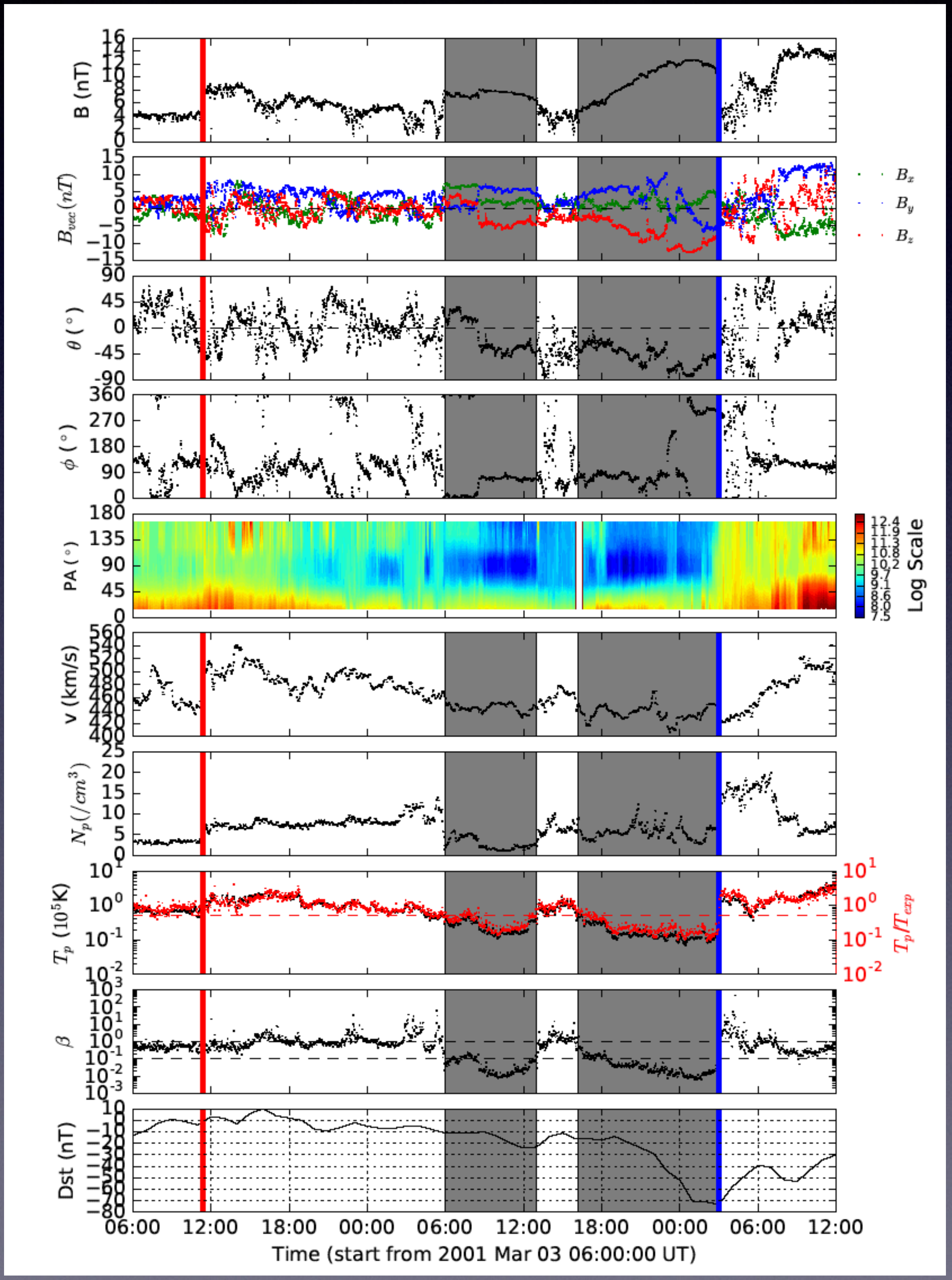
What is the physical process of CMEs' interaction?

Complex structures caused by CMEs' interaction

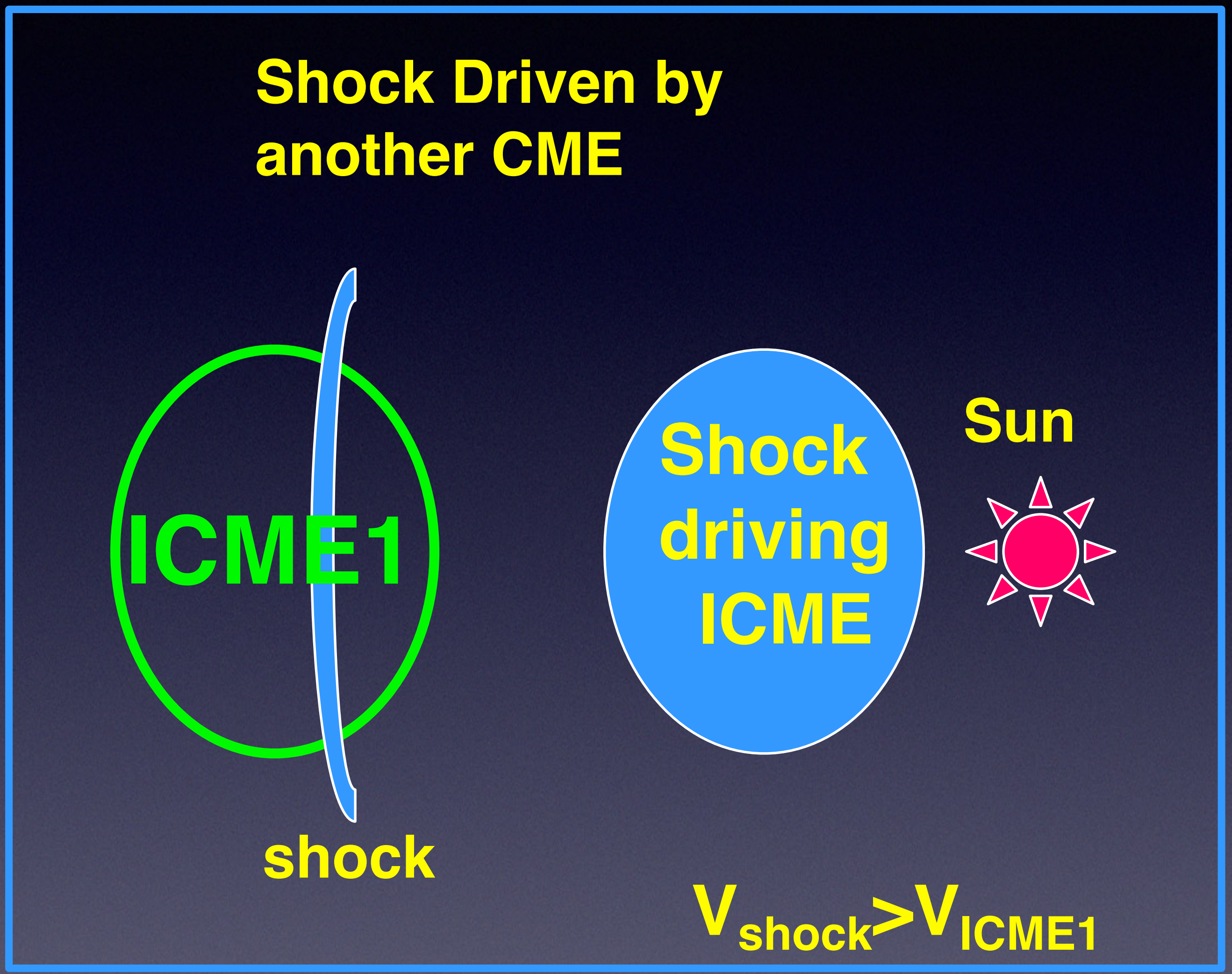


Multiple ICMEs

[e.g., Wang et al., 2003, 2003c, 2003a; Richardson andCane, 2004; Gopalswamy, 2006; Zhang et al., 2007; Richardson and Cane, 2010;]

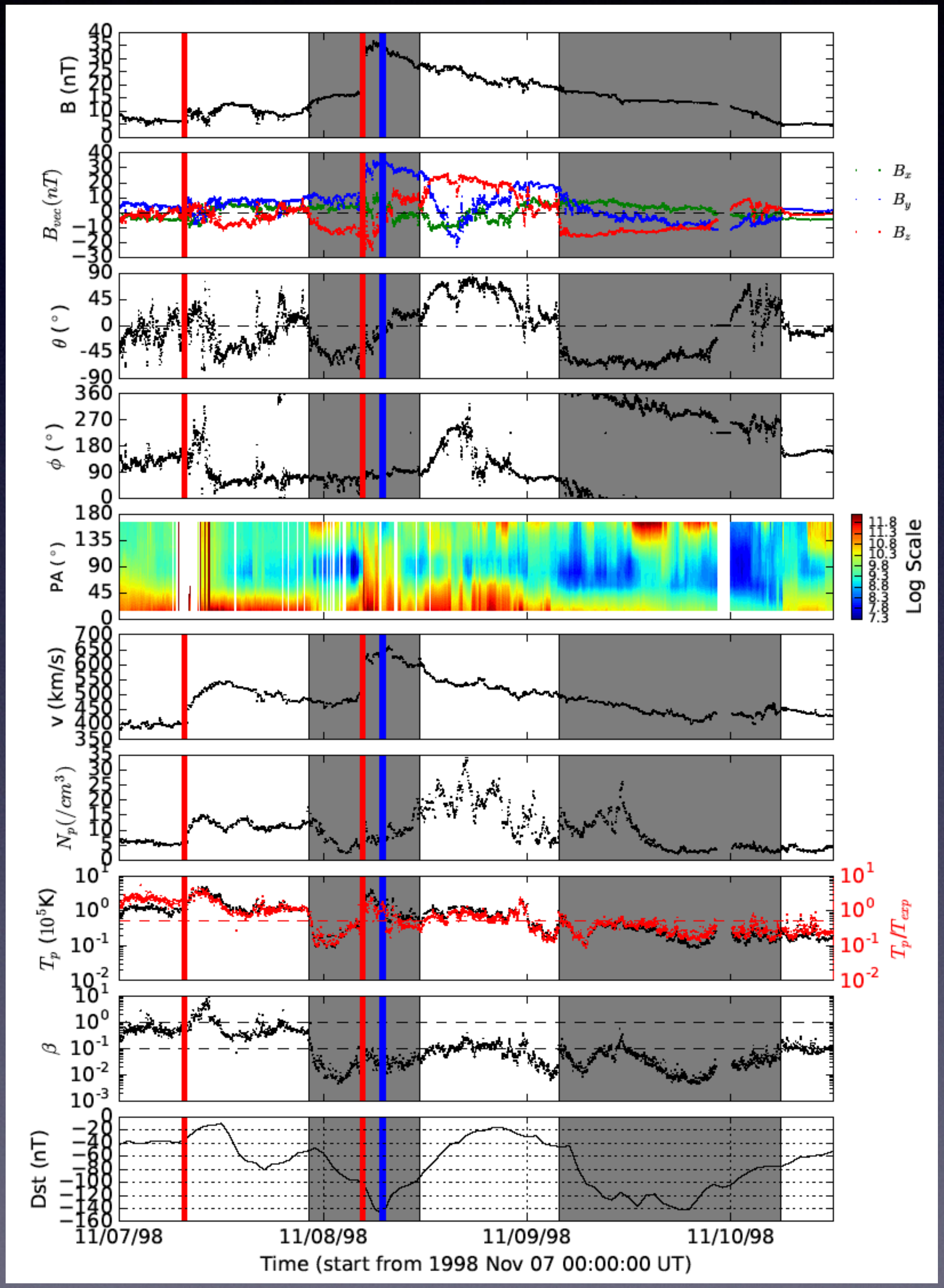


Complex structures caused by CMEs' interaction



Shock-ICMEs

[e.g., Ivanov, 1982; Lepping et al., 1997; Wang et al., 2003c; Shen et al., 2008; Lugazet al., 2015]

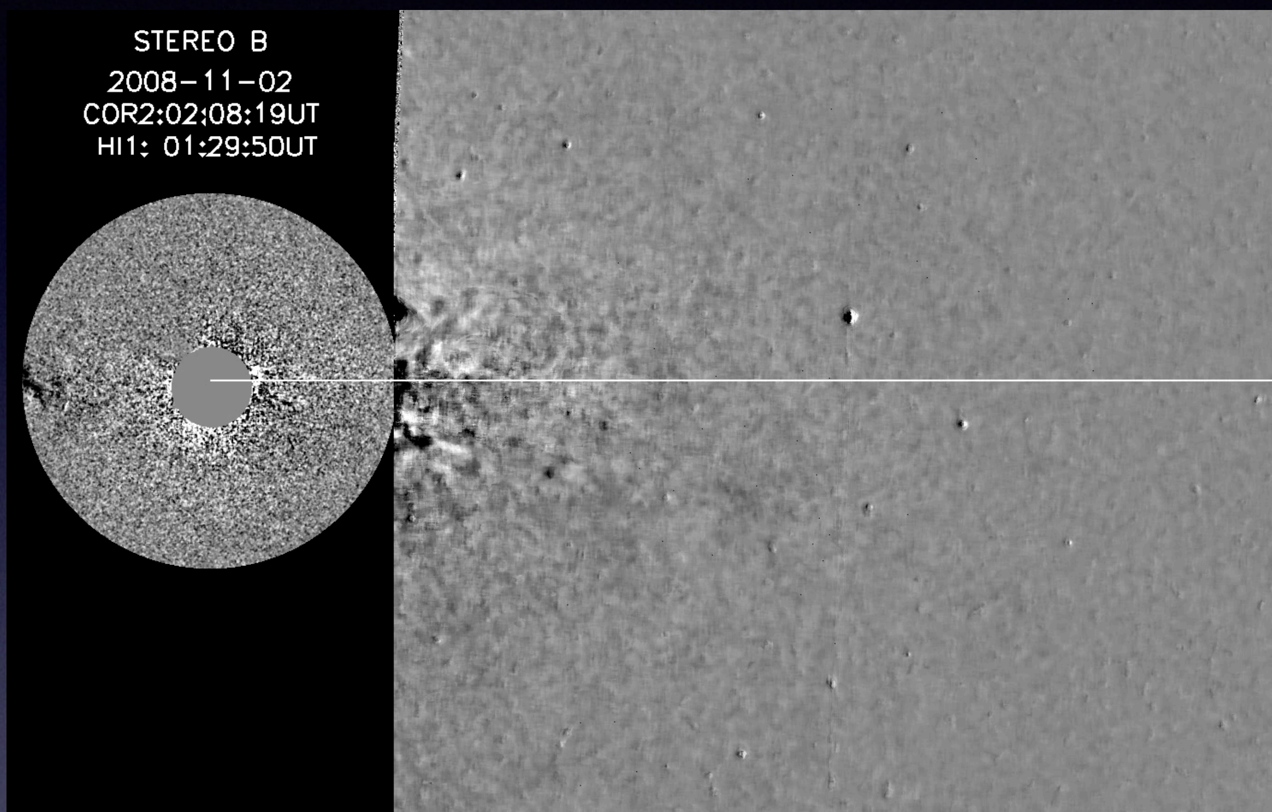


Shock-ICMEs

Outline

- Introduction
- **Physical process of CME interaction**
- Impact on geoeffectiveness
- Impact on SEP events
- Conclusions

Case study: 2008 Nov. CMEs



The interaction between two CMEs make the total kinematic energy enhanced!

[Shen et al., 2012, NP]

Table 1 | The parameters of the two CMEs before and after the collision.

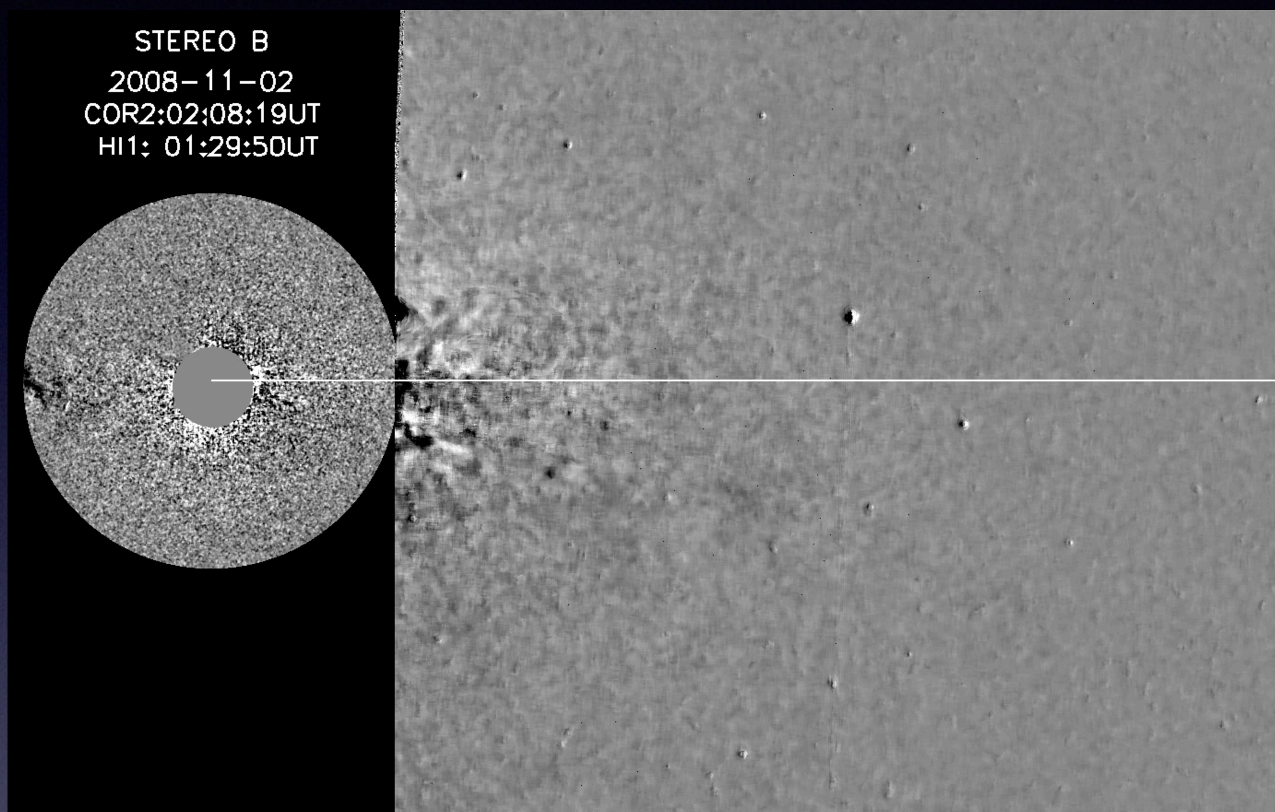
Parameters derived from observations

	θ	φ	v_c	v_e
CME1	6 ± 2	28 ± 10	243^{+25}_{-16}	43^{+16}_{-15}
CME2	16 ± 2	8 ± 10	407^{+102}_{-74}	74^{+65}_{-51}

Second-level derived parameters

	v_p	v_{ep}	θ_C	φ_C	$v_\perp$	$v_\parallel$	$v'_\parallel$	v'_c	v'_p	v'_{ep}	$\Delta\theta_v$	$\Delta\varphi_v$	$\Delta E/E$	$\Delta E_t/E_t$	e
CME1	241	36			130	205	288	316	316	41	−4	7	68%		
			−10	57										6.6%	5.4
CME2	392	26			332	237	116	351	325	N/A*	6	−16	−25%		

Case study: 2008 Nov. CMEs



The interaction between two CMEs make the total kinematic energy enhanced!

[Shen et al., 2012, NP]

Table 1 | The parameters of the two CMEs before and after the collision.

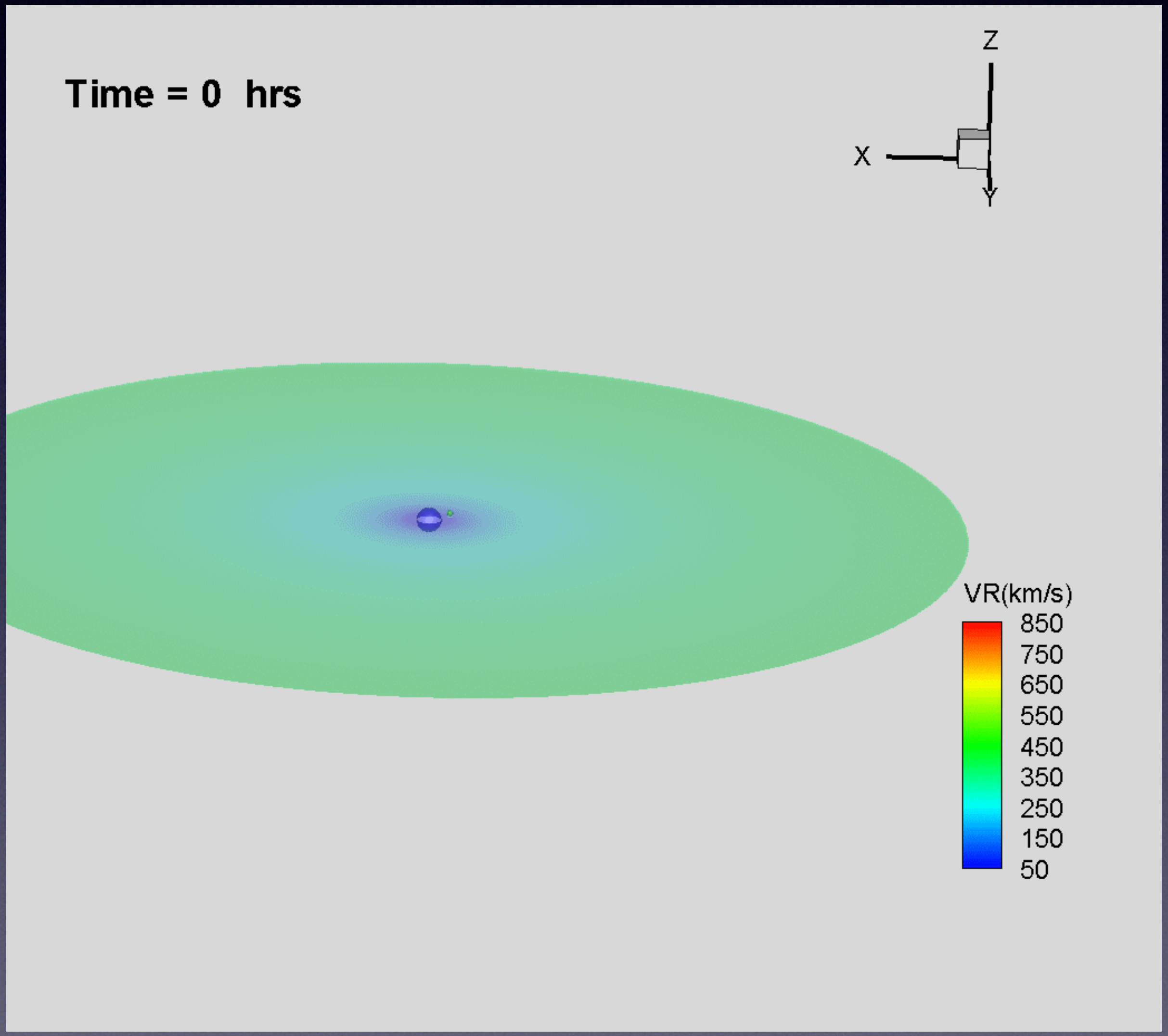
Parameters derived from observations

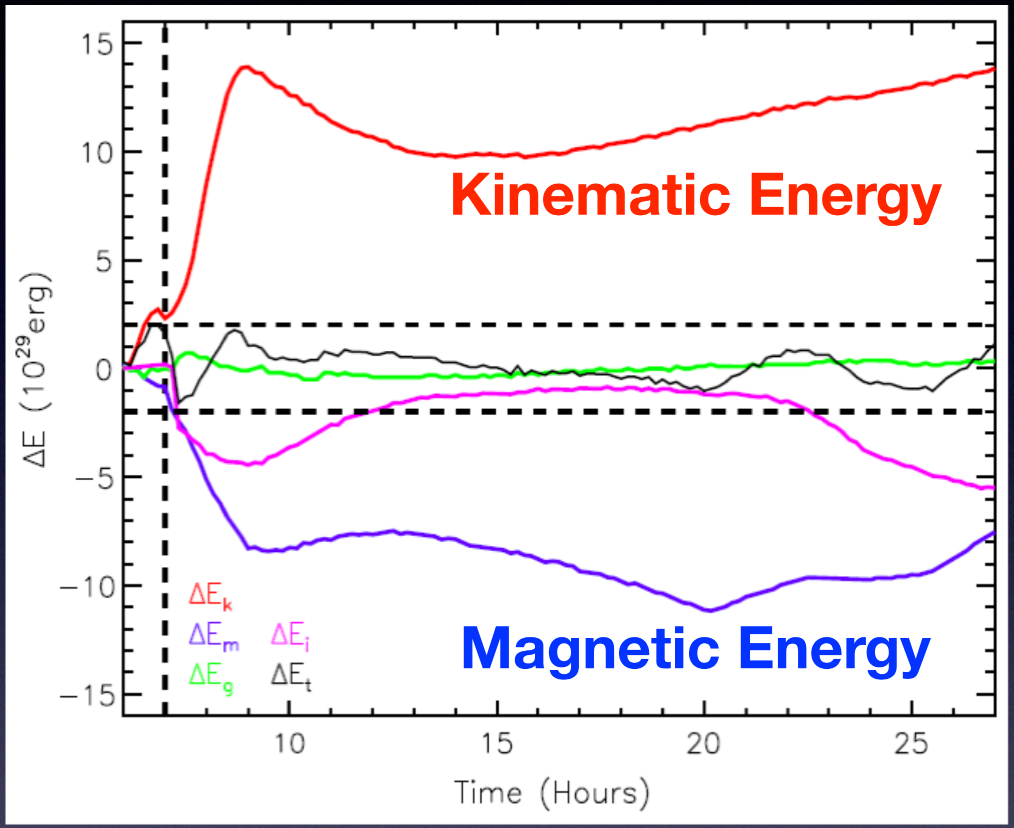
	θ	φ	v_c	v_e
CME1	6 ± 2	28 ± 10	243^{+25}_{-16}	43^{+16}_{-15}
CME2	16 ± 2	8 ± 10	407^{+102}_{-74}	74^{+65}_{-51}

Second-level derived parameters

	v_p	v_{ep}	θ_C	φ_C	$v_\perp$	$v_\parallel$	$v'_\parallel$	v'_c	v'_p	v'_{ep}	$\Delta\theta_v$	$\Delta\varphi_v$	$\Delta E/E$	$\Delta E_t/E_t$	e
CME1	241	36			130	205	288	316	316	41	−4	7	68%		
			−10	57										6.6%	5.4
CME2	392	26			332	237	116	351	325	N/A*	6	−16	−25%		

MHD simulation results: Single Case



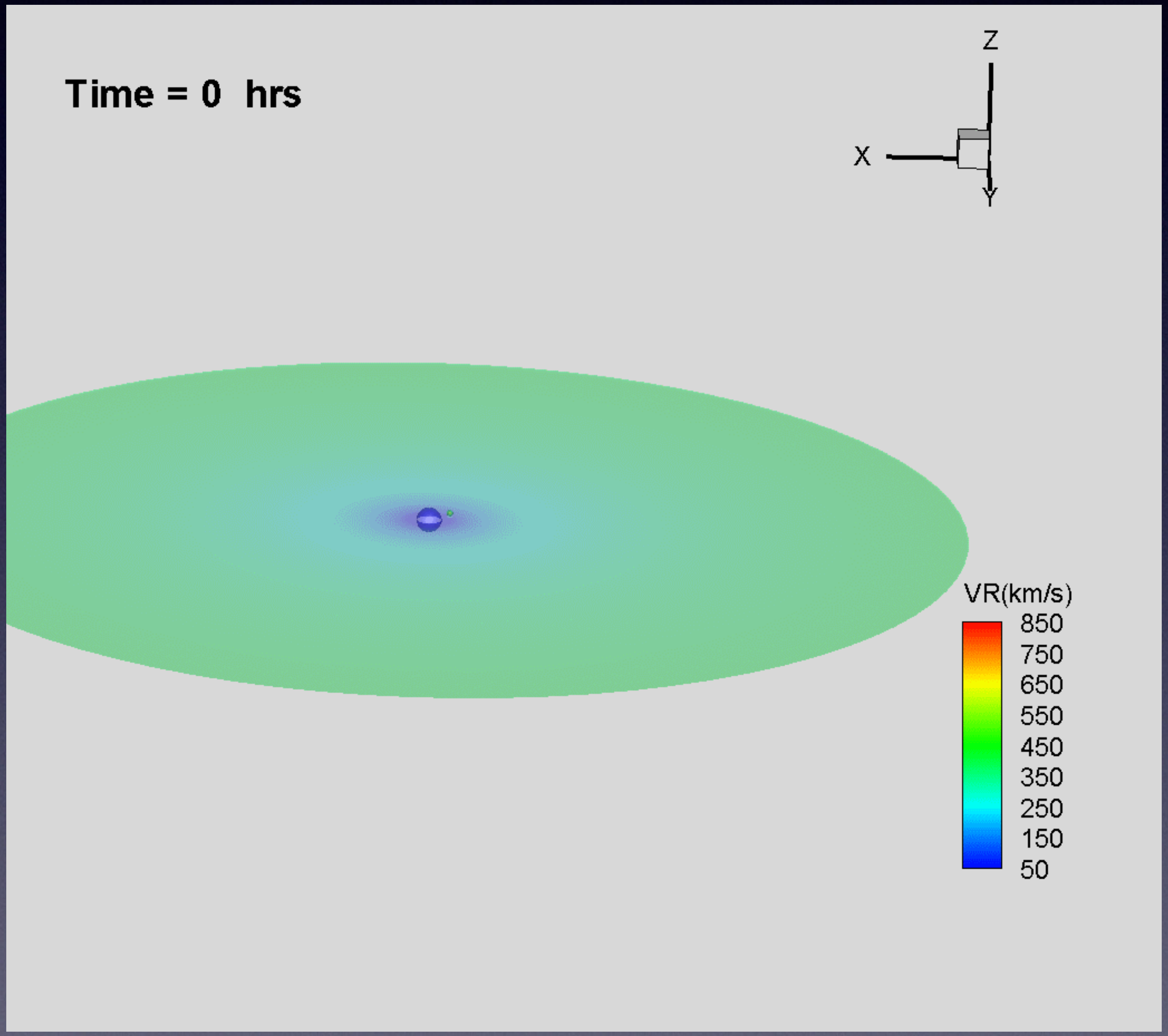


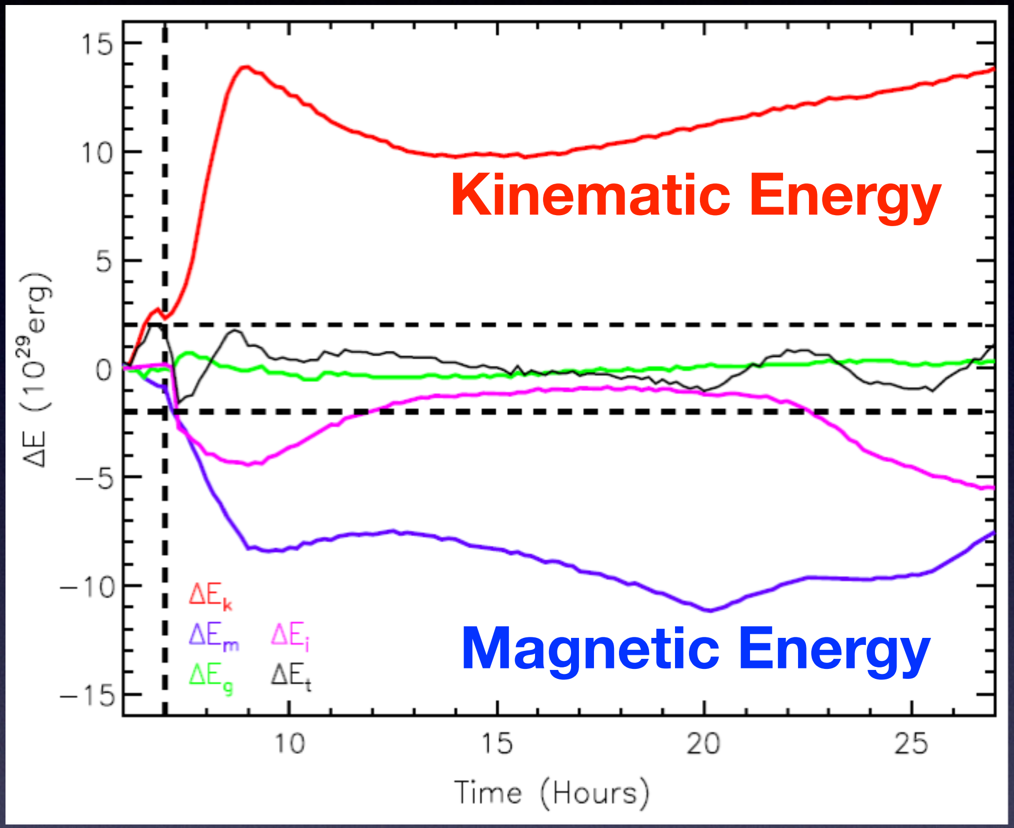
Magnetic Energy

Kinematic Energy

[Shen F. , 2013, GRL]

MHD simulation results: Single Case





Magnetic Energy

Kinematic Energy

[Shen F. , 2013, GRL]

Case study: Other works

$\Delta E>0$; $e>1$:

- e.g. Shen et al. 2012; Colaninno & Vourlidas 2015

$\Delta E<0$; $e<1$:

- e.g. Lugaz et al. 2012; Temmer et al. 2012; Mishra & Srivastava 2014; Mishra et al. 2015a, 2015b

Which parameters determine the physical process of the interaction between multiple CMEs?

MHD simulation results: Multiple Cases

	Direction	*R*	*B*	*n*	*T*	*Em*	*Ei*	*Eg*	*Vsw*	
Common par.	N11W18	R_S	$\times 10^5$ nT	$\times 10^7$ cm^{-3}	$\times 10^5$ K	$\times 10^{31}$ erg			km s^{-1}	
		0.5	1.47	4.0	5.0	1.50	1.37	−0.64	316 ~ 461	
Other par.	Case 1		Case 2		Case 3		Case 4		Case 5	
	CME1	CME2	CME1	CME2	CME1	CME2	CME1	CME2	CME1	CME2
V_{CME} (km s^{-1})	200	400	200	600	200	1000	600	800	1000	1200
E_k ($\times 10^{31}$ erg)	0.513	1.83	0.513	3.44	0.513	9.13	3.44	5.96	9.13	12.9
E_t ($\times 10^{31}$ erg)	2.74	4.06	2.74	5.67	2.74	11.36	5.67	8.19	11.36	15.13
t_s (hours)	7		8		10		4		3	

The relatively low approaching speed can cause the total energy enhanced during the interaction!

Lower v_2-v_1 → Collision coefficient e is more likely lager than 1!

[Shen F. , 2016, Sci. Rep.]

Statistical analysis results

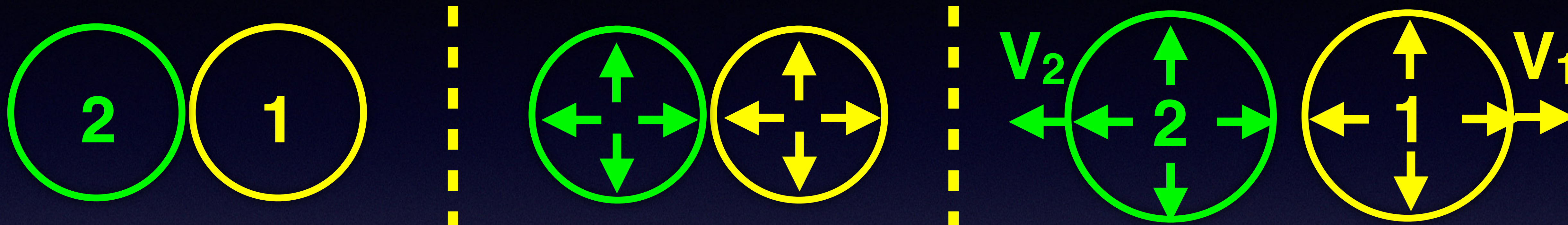
Table 1
Selected CME Events

Events	*STEREO* Observations	Collision Sites	Collision Phase	Accuracy
2011 Feb 14–15	Both A and B	24 $R_\odot$	Well identified	Highest
2012 Jun 13–14	Both A and B	100 $R_\odot$	Well identified	Highest
2010 May 23–24	Both A and B	42 $R_\odot$	End phase poorly identified	Moderate
2012 Mar 4–5	Both A and B	160 $R_\odot$	Well identified	Moderate
2012 Nov 9–10	Only A	30 $R_\odot$	Well identified	Moderate
2013 Oct 25	Only B	37 $R_\odot$	Well identified	Moderate
2011 Aug 3–4	Both A& B	145 $R_\odot$	End phase not identified	Lowest
2012 Sep 25–28	Only A	170 $R_\odot$	Well identified	Lowest

Lower approaching speed, expansion speed of the following CME higher than the preceding one, and a longer duration of the collision phase can enhance the possibility of super elastic collision!

[Wageesh et al., 2017, ApJS]

A Simple model



Phase 1

Two static balls are located close to each others!

Phase 2

These balls begin to expand!

Phase 3

These balls propagated far away from each others!

$E_k=0$ → $E_k>0$

A Simpel model: Two CMEs

Propagation direction →

Before interaction | **After interaction**

$V_2+V_{2e}>V_1-V_{1e}$

$V_{2`}+V_{2e}\leq V_{1`}-V_{1e}$

Assumptions: No reconnection! No shocks!

A Simpel mode: Two CMEs

Moment conservation: $m_1v_1+m_2v_2=m_1v_1`+m_2v_2`$

$V_{2`}+V_{2e}\leq V_{1`}-V_{1e}$ → $V_{1`}-V_{2`}\geq V_{2e}+V_{1e}$

$$V_1' = \frac{m_1v_1 + m_2V_2 + m_2(v_{1e} + V_{2e})}{m_1 + m_2}$$

$$V_2' = \frac{m_1v_1 + m_2V_2 - m_1(v_{1e} + V_{2e})}{m_1 + m_2}$$

$$e = \frac{V_{2e} + V_{1e}}{V_2 - V_1}$$

$$\Delta E = -\frac{m_1m_2[(V_2 - V_1)^2 - (V_{1e} + V_{2e})^2]}{2(m_1 + m_2)}$$

Higher $v_{e2}+v_{1e}$

Lower v_2-v_1

→ e is more likely lager than 1!

Application on observations

Events			Observation			Model	
			v (km/s)	v' (km/s)	e	e	v’(km/s)
Event 1	2 Nov. 2008	CME1	205	288	5.4	3.66	264.6
	2 Nov. 2008	CME2	237	116			147.6
Event 2	14 Feb. 2011	CME1	310.1	484.2-505.6	1.6-1.92	1.86	501.6
	15 Feb. 2011	CME2	452.4	256.5-236.9			236.9

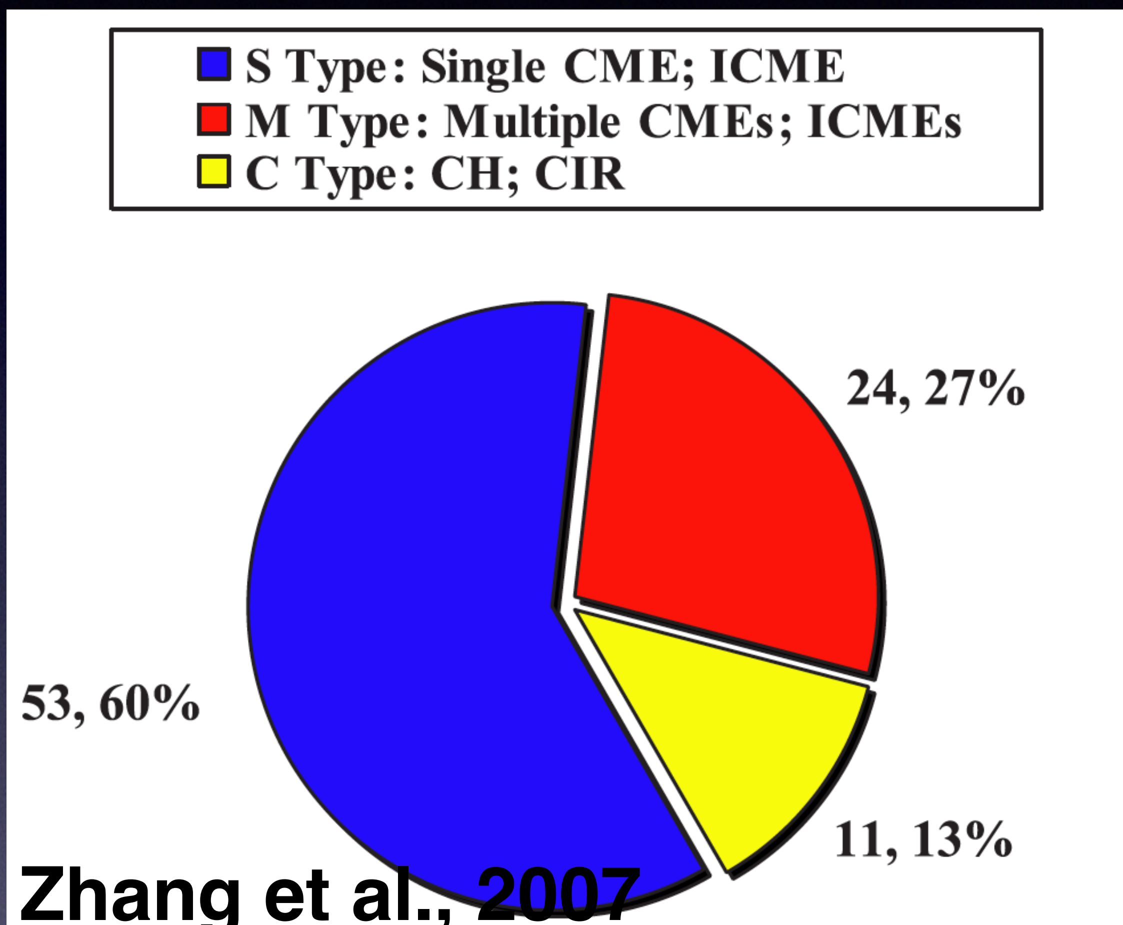
Can interaction between multiple CMEs be simply described?

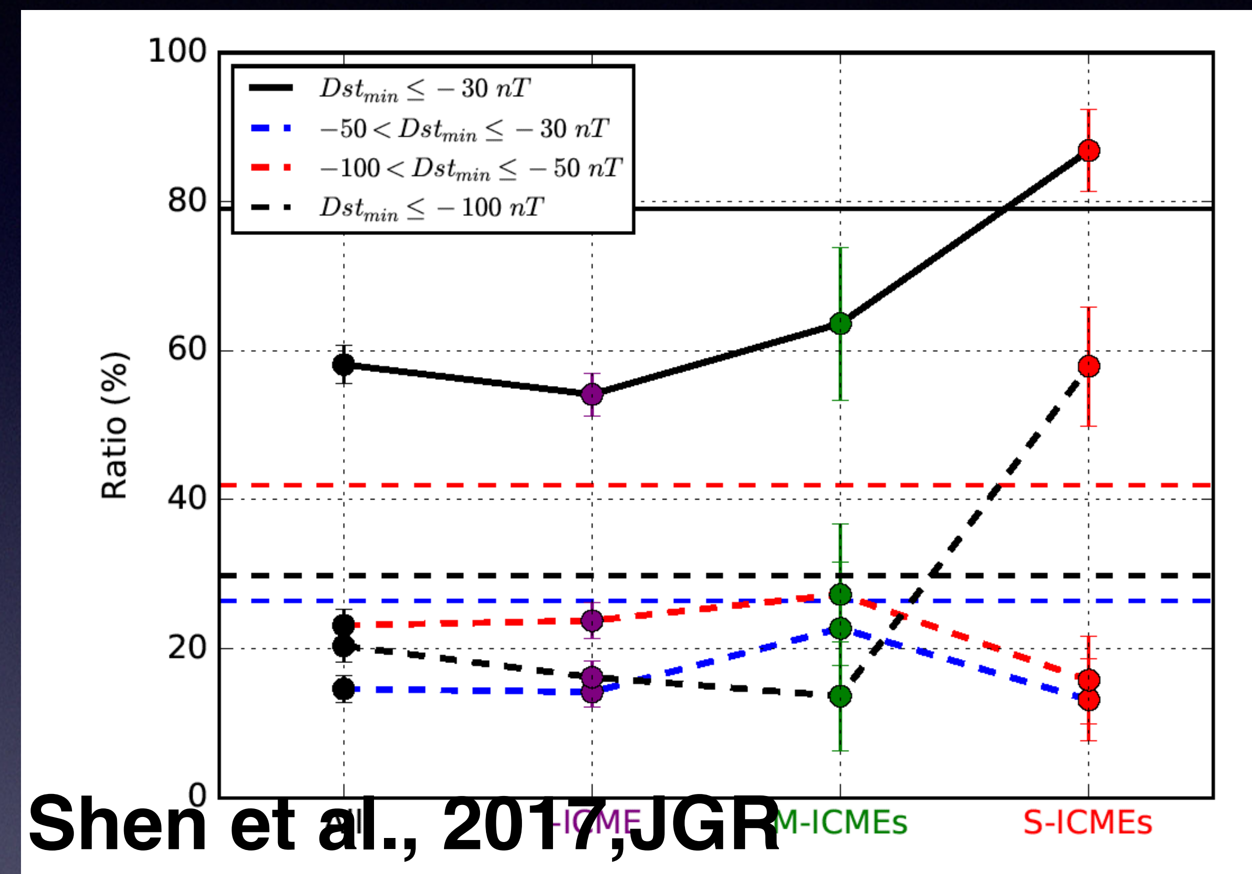
More events are being analyzed.

Outline

- Introduction
- Physical process of CME interaction
- Impact on geoeffectiveness
- Impact on SEP events
- Conclusions

Enhance the geoeffectiveness





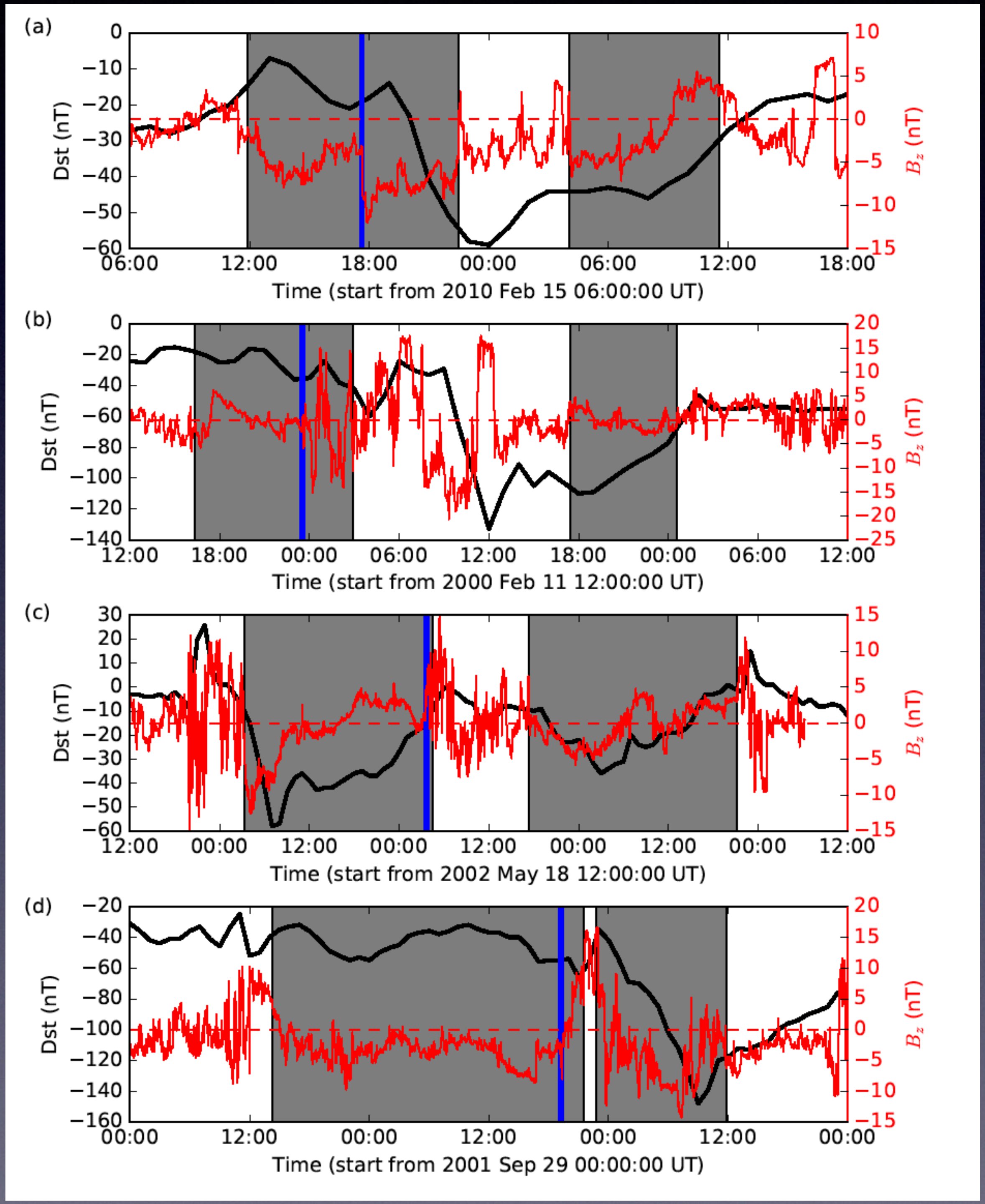
About 30% of intense geomagnetic storms were caused by CMEs interaction structures!

[e.g. Zhang et al., 2007, JGR; Shen et al., 2017,JGR]

The shock-ICME structures can caused the geomagnetic storms with higher possibility!

[e.g. Wang et al., 2003 a,b; Lugaz, et al.,2015a,b; Shen et al., 2017,JGR]

Physical Explanation for Shock-ICME



Shen et al., 2017

Shock propagated in to ICME

↓

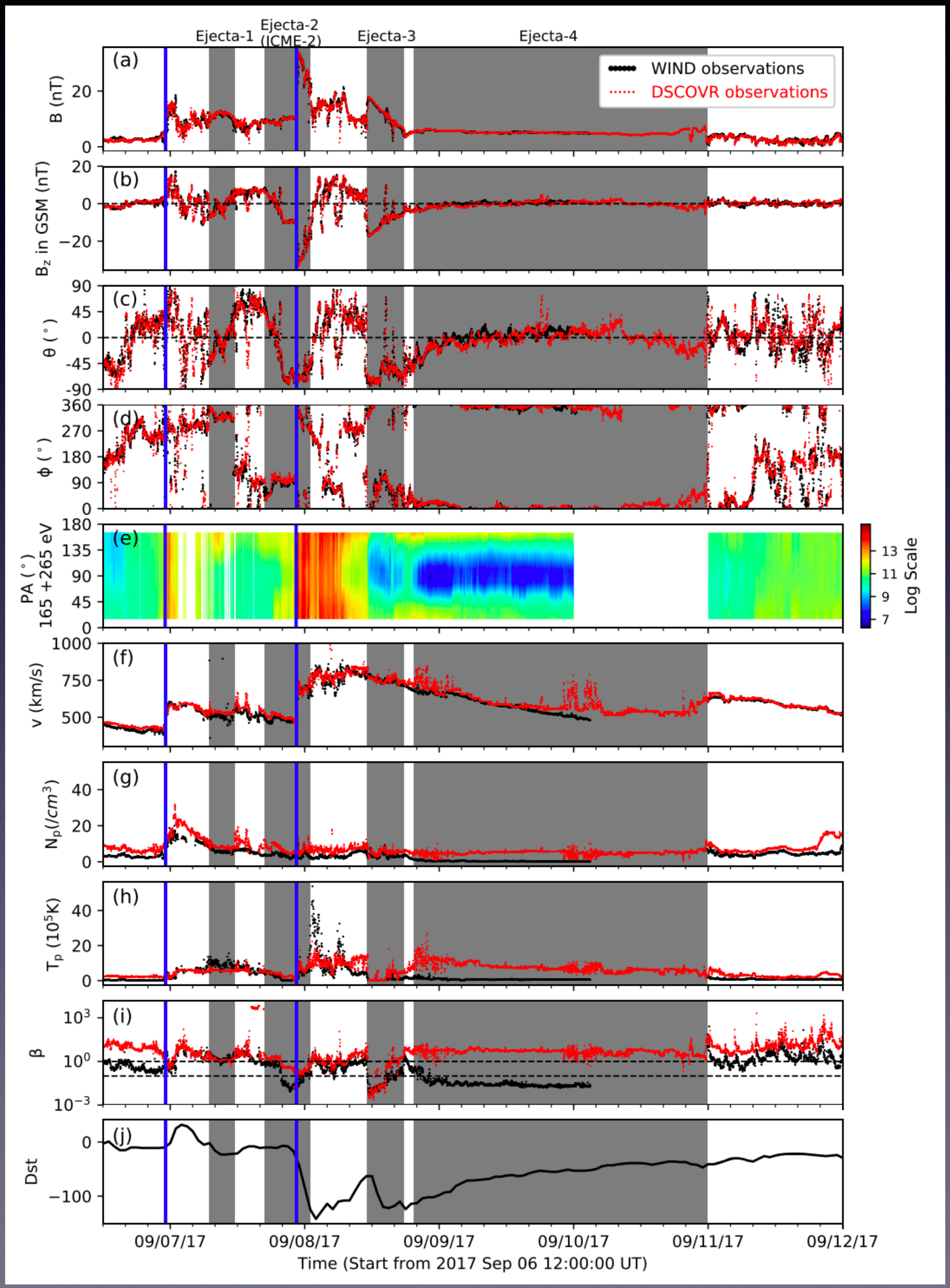
Compressed the Bs

↓

Enhanced the geoeffectiveness

- How Significant?
- What will happen without shock compression?

Case Study: 2017 September event

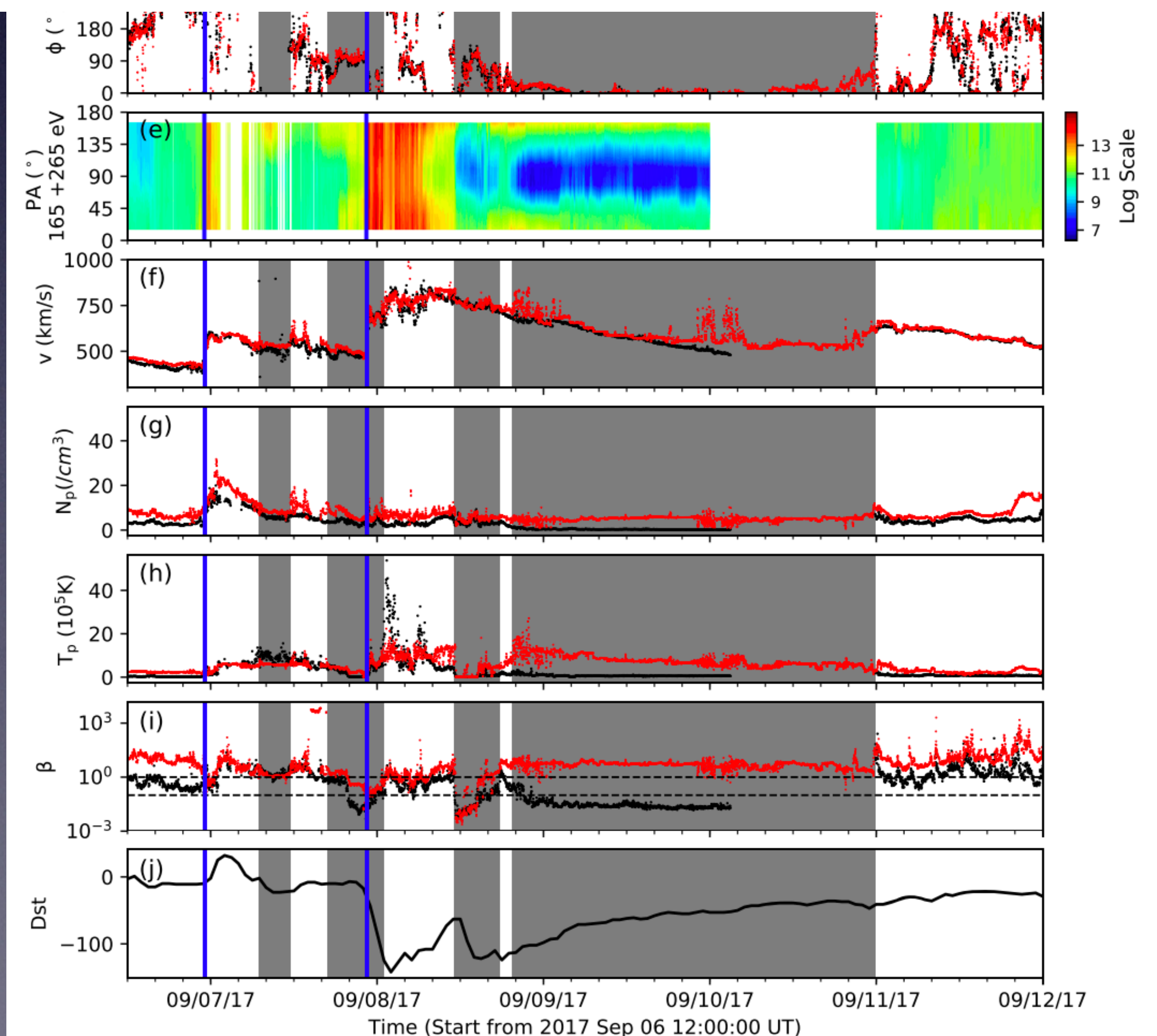


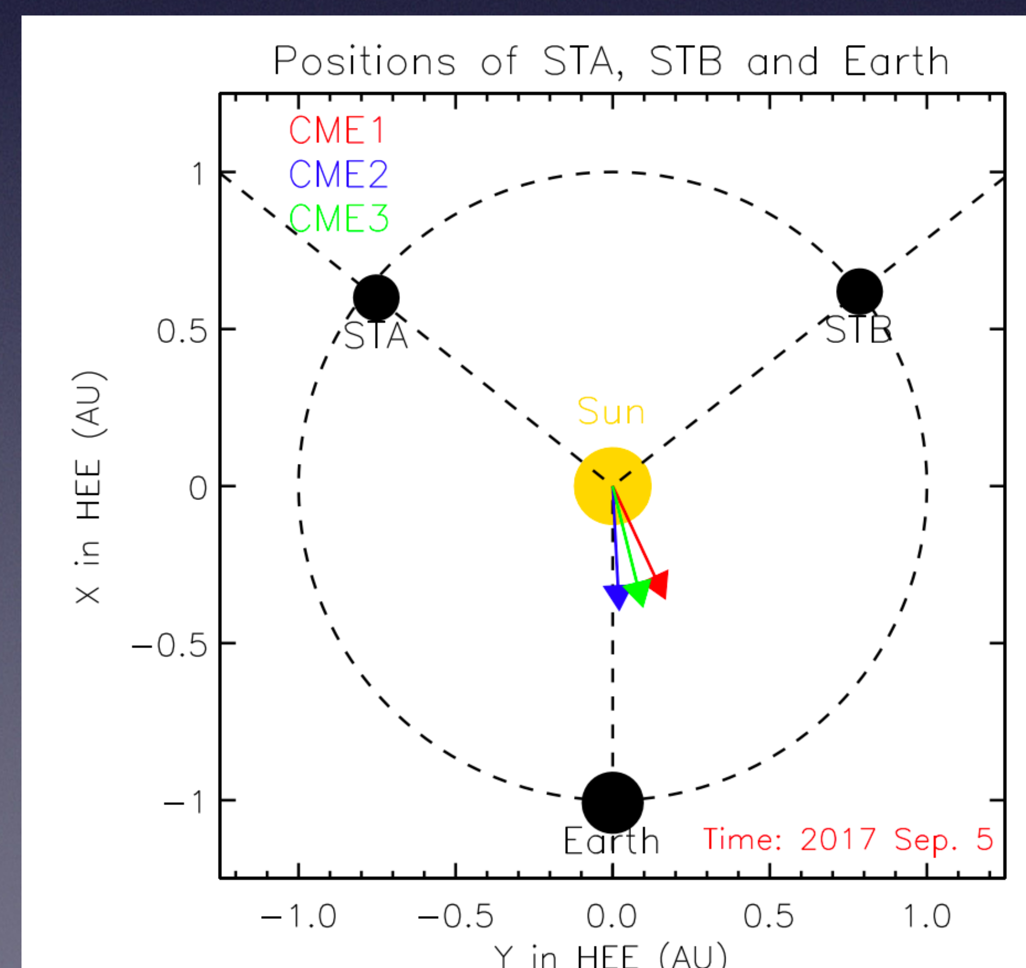
A campaign event of ISEST.

- ★ 4 ICMEs
- ★ 2 Shocks

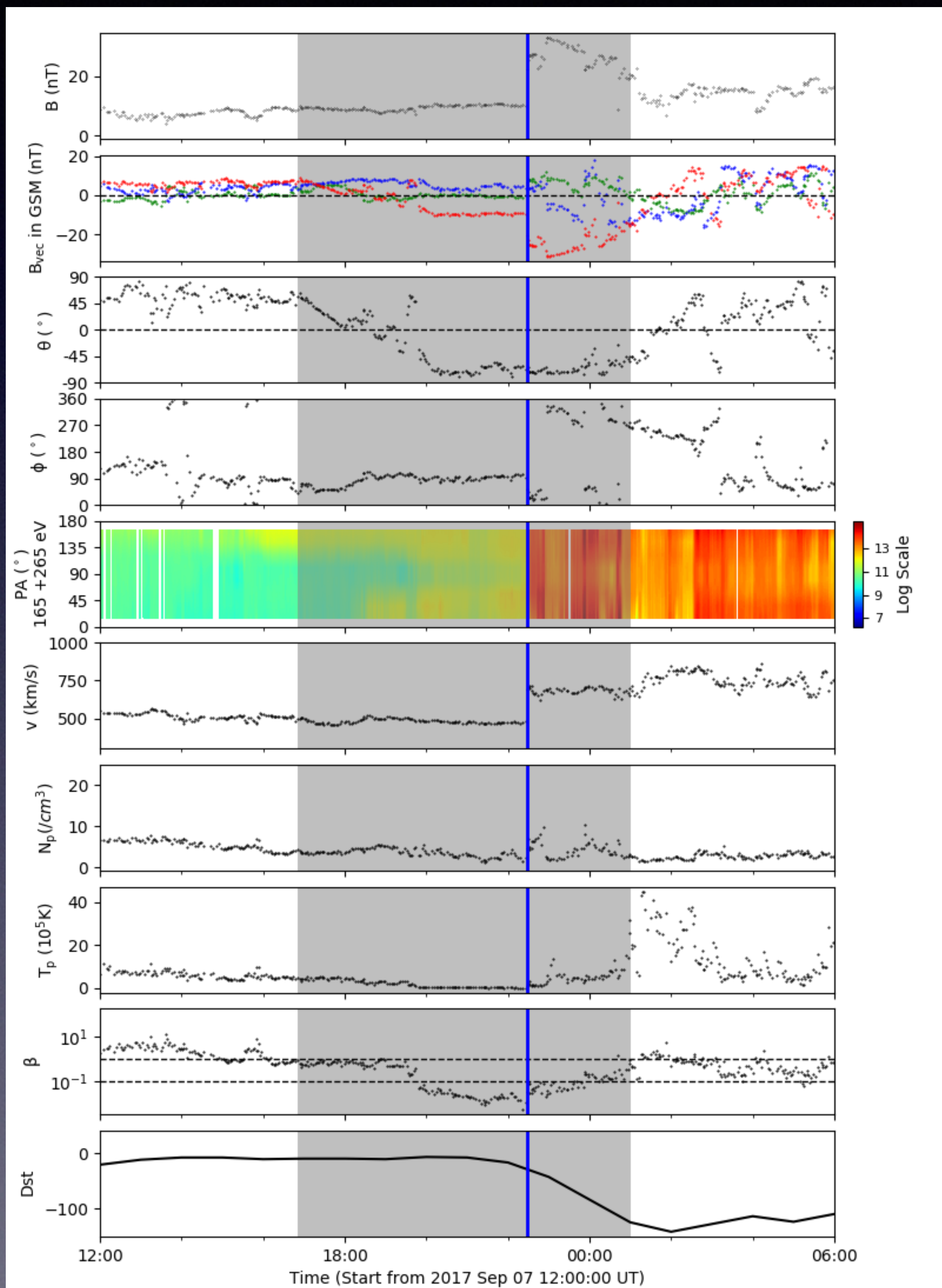
Case Study: 2017 September event

No	Shock Arrival (UT)	Begin (UT)	End (UT)	CME Time (UT)[a]	Propagation Direction	Velocity (km s^{-1})	Face-on Width (°)
1	Sep 6 23:06	Sep 7 06:50	Sep 7 11:30	Sep 4 19:00	S08W25	1005	73
2	···	Sep 7 16:50	Sep 8 01:00	Sep 4 20:24	S25W03	1766	75
3	···	Sep 8 11:05	Sep 8 17:38				
4	Sep 7 22:28	Sep 8 19:30	Sep 11 00:00	Sep 6 12:24	S18W14	1548	80





Case Study: 2017 September event



Dst_{peak}: -142 nT

Peak time: Sep 8 02:00 UT

ICME Begin: Sep 7 16:50 UT

ICME End: Sep 8 01:00 UT

Shock: Sep 7 22:28 UT

This geomagnetic storm was caused by a shock-ICME structure!

Without shock compression?

A method to get the uncompressed state based on RH relationship

[Wang et al., 2018,JGR]

$$\rho_1 = \frac{1}{r_c}\rho_2$$

$$\mathbf{B_{1n}} = \mathbf{B_{2n}}$$

$$\mathbf{B_{1\perp}} = \frac{v_{A2}^2 - u_2^2}{v_{A2}^2 - r_2 u_2^2}\mathbf{B_{2\perp}}$$

$$\mathbf{u_{1\perp}} = r_c \mathbf{u_{2\perp}}$$

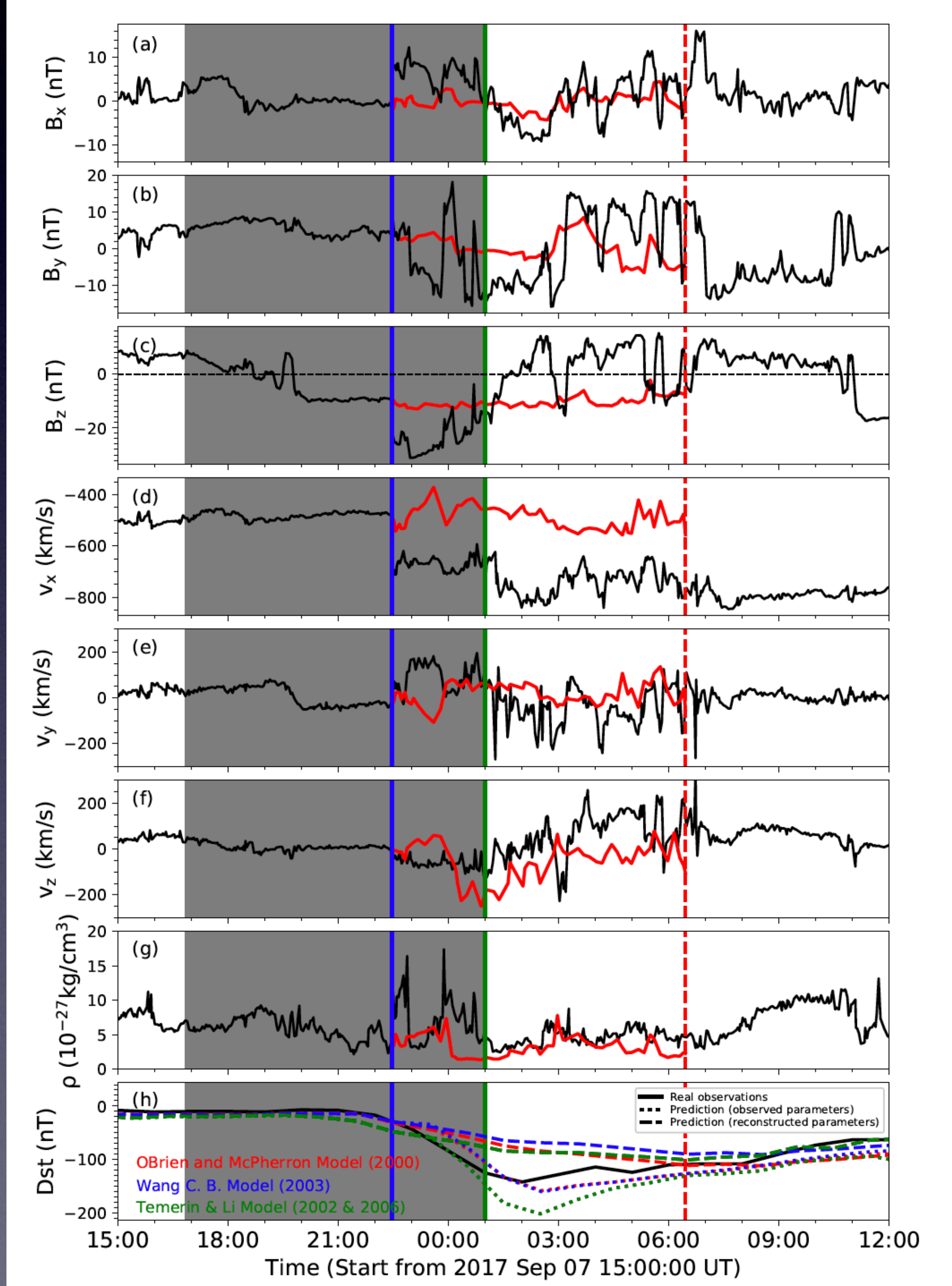
$$\mathbf{u_{1\perp}} = \frac{v_{A2}^2 - u_2^2}{v_{A2}^2 - r_2 u_2^2} r_c \mathbf{u_{2\perp}}$$

1: uncompressed state

2: compressed state

n: Normal direction

⊥: Perpendicular to the normal



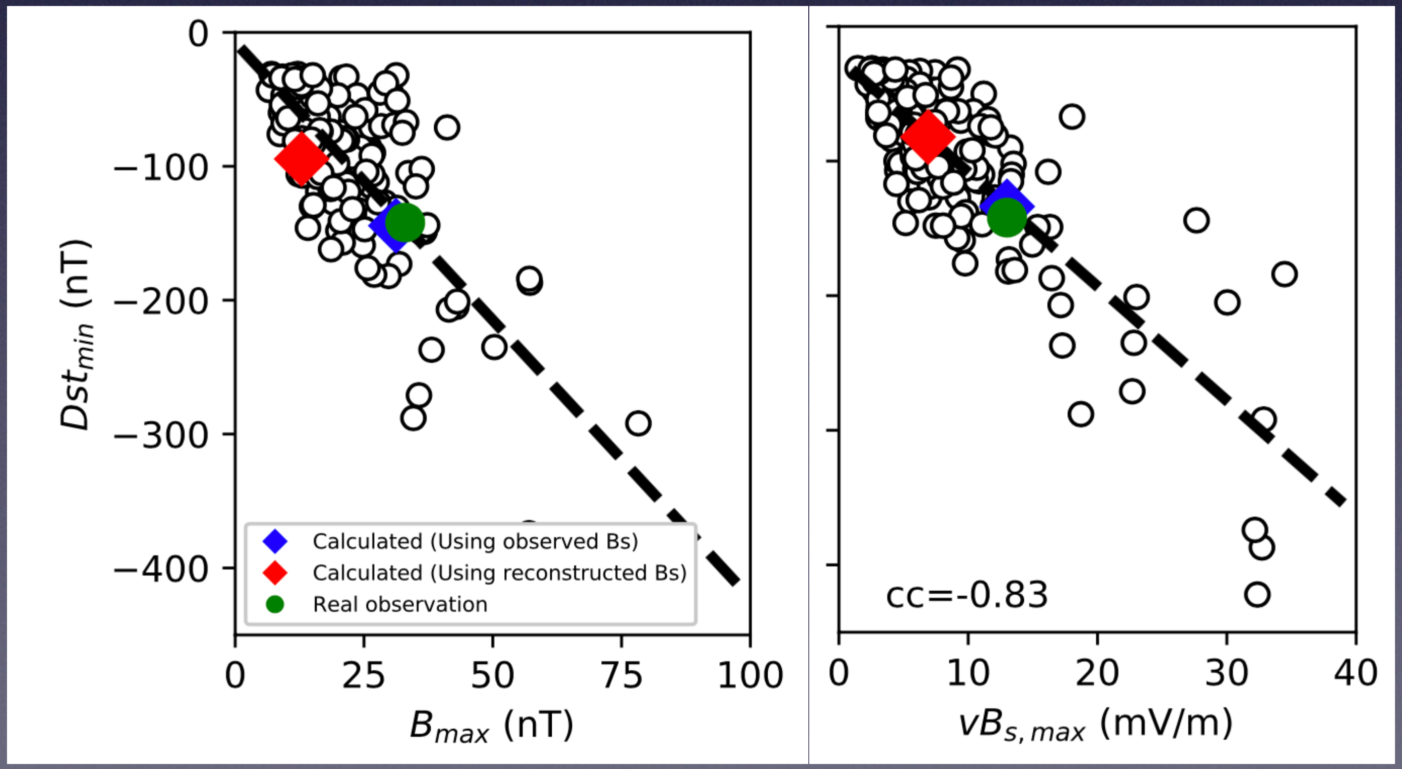
Red Lines: recovered structure

Assumption:

Shock parameter not changed

Without shock compression?

	Shen et al., 2017	OBrien and McPherron Model (2000)	Wang Model (2003)	Temerin & Li model (2002 & 2006)
Observation	-135 nT	-158 nT	-160 nT	-202 nT
Reconstructed	-79 nT	-122 nT	-91 nT	- 101 nT

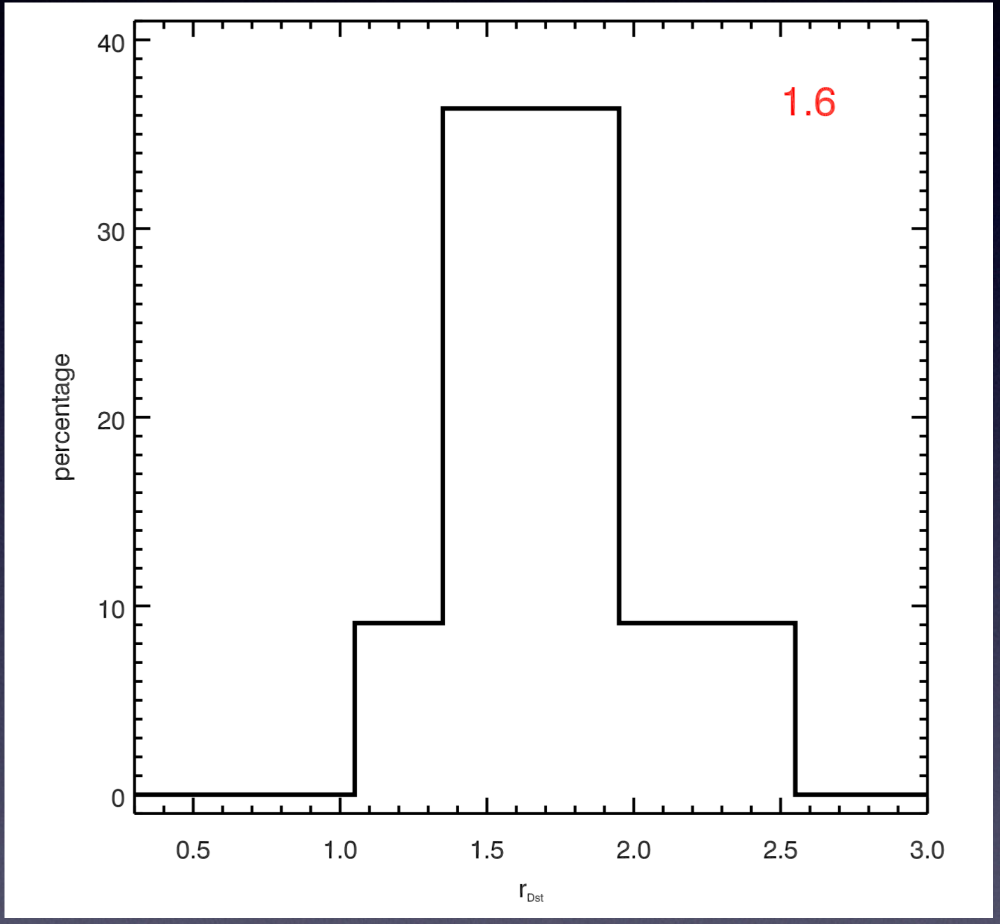


[Shen et al., 2018, ApJ]

- ⭐Shock compression enhanced the geoeffectiveness of this event ~2!
- ⭐Without shock compression, there would only be a moderate storm!

Statistical analysis

No.	ICME Information		Shock Parameters			
	$ICME_{stark}$ (UT)	Δt	Shock Arrival (UT)	n	V_{SH}	r_N
1	1995-03-04T11:42:51	12.4	1995-03-04T19:59	[-0.90,-0.18,0.39]	461	1.38
2	1998-08-06T01:25:00	9.8	1998-08-06T07:16	[-0.90,-0.12,0.41]	479	1.63
3	1999-02-17T12:22	22.1	1999-02-18T02:48	[-0.98,-0.18,0.02]	699	3.2
4	2000-04-24T04:25	9.2	2000-04-24T09:13	[-0.91,0.42,0.03]	562	1.6
5	2000-10-03T12:09	42.3	2000-10-05T03:28	[-0.99,0.09,0.13]	560	2.23
6	2002-08-19T18:53	50.9	2002-08-20T13:50	[-0.81,0.21,0.55]	494	1.20
7	2003-06-17T19:03	14.0	2003-06-18T04:42	[-0.72,-0.7,0.04]	496	1.40
8	2012-09-30T12:29	21.2	2012-09-30T22:18	[-0.91,0.42,0.03]	446	2.11
9	2014-02-18T14:43	19.0	2014-02-19T03:09	[-0.94,-0.06,-0.34]	603	1.68
10	2014-02-19T11:43	18.1	2014-02-20T02:42	[-0.89,-0.24,0.39]	760	2.19
11	2017-09-07T19:44	4.7	2017-09-07T22:28	[-0.85,0.34,-0.41]	744	2.04



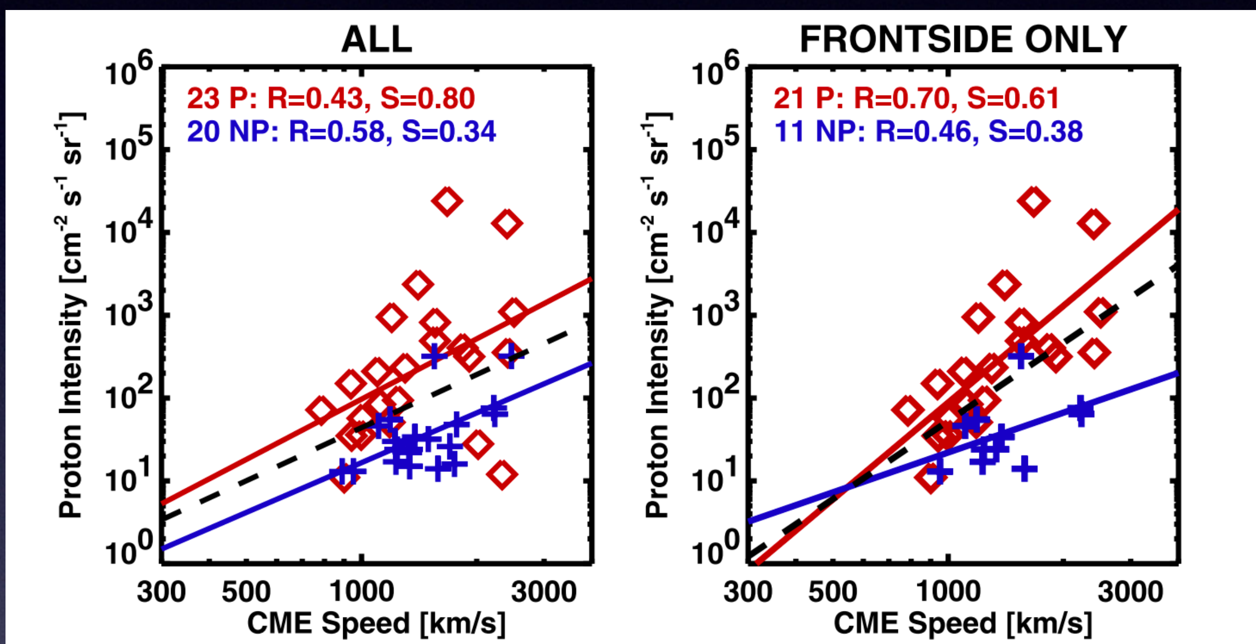
The shock compression can enhance the intensity of the geomagnetic storm by a factor of ~1.6!

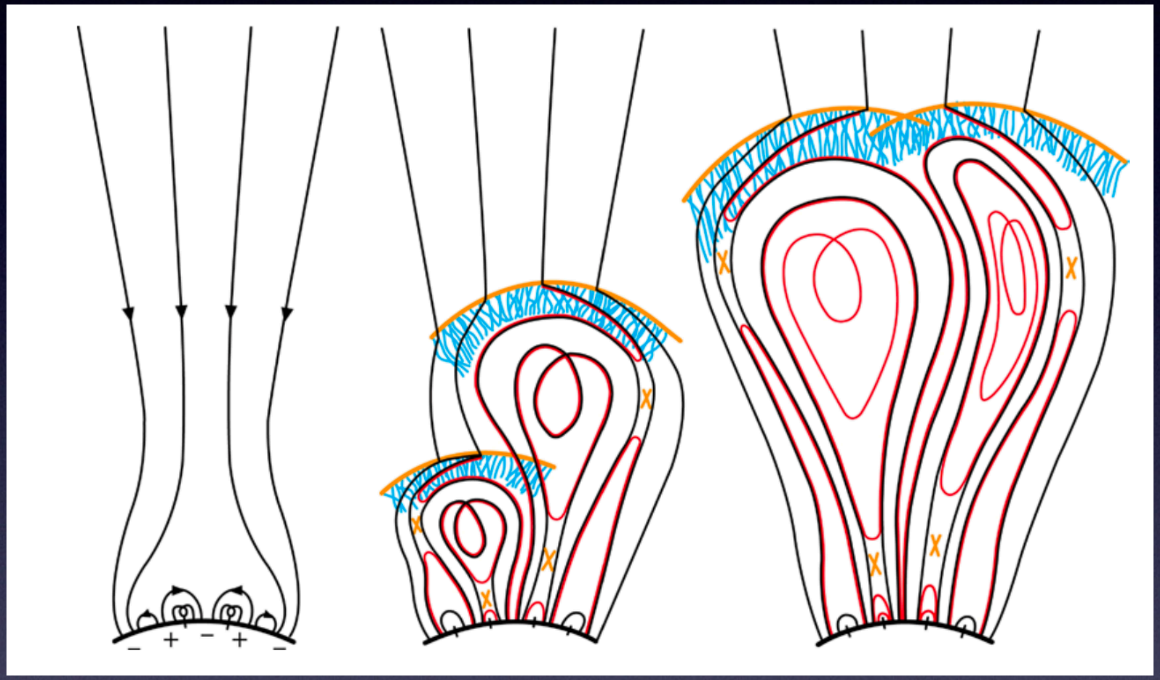
[Xu, et al., 2018, to be submitted]

Outline

- Introduction
- Physical process of CME interaction
- Impact on geoeffectiveness
- Impact on SEP events
- Conclusions

CME interaction impact on SEP production





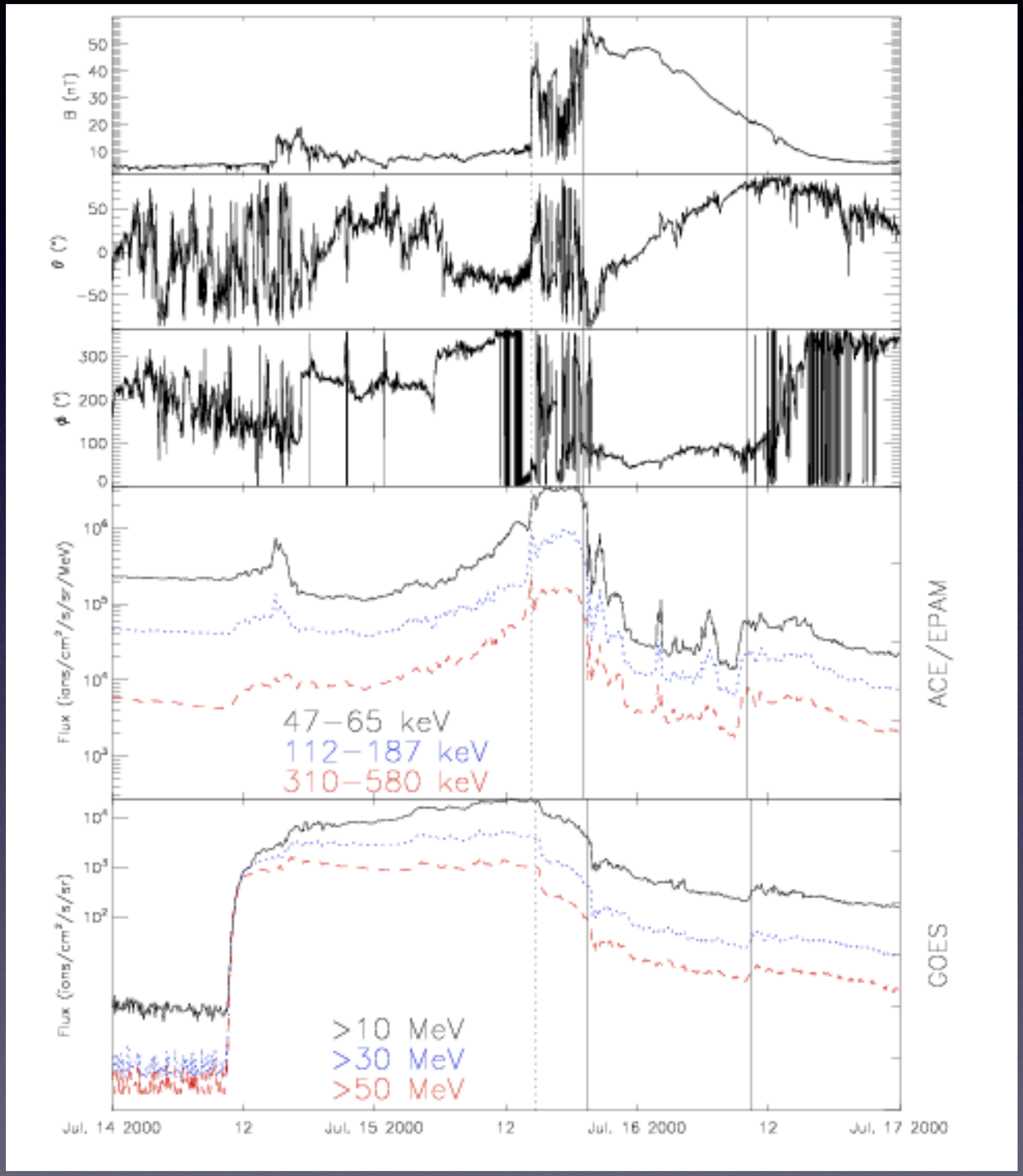
Gopalswamy et al., 2004

Li et al., 2012

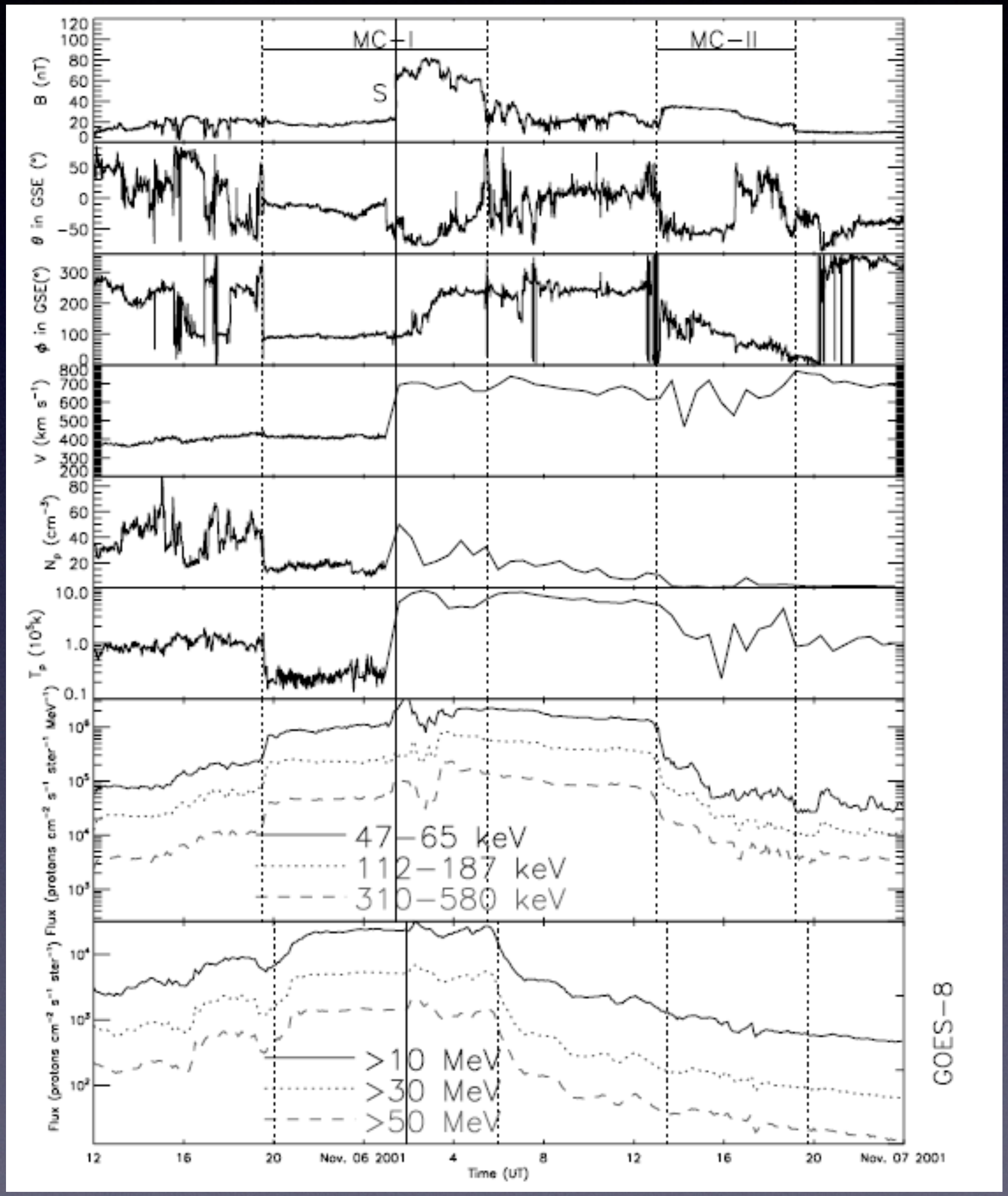
The interaction between multiple CMEs can produce the SEP events with higher possibilities!

[e.g. Gopalswamy, 2002, 2004; Li et al., 2012; Shen et al., 2013; Ding et al., 2013, 2014; Zhao et al., 2014,2016]

SEP signature of Shock-ICMEs: 2001 Nov. event



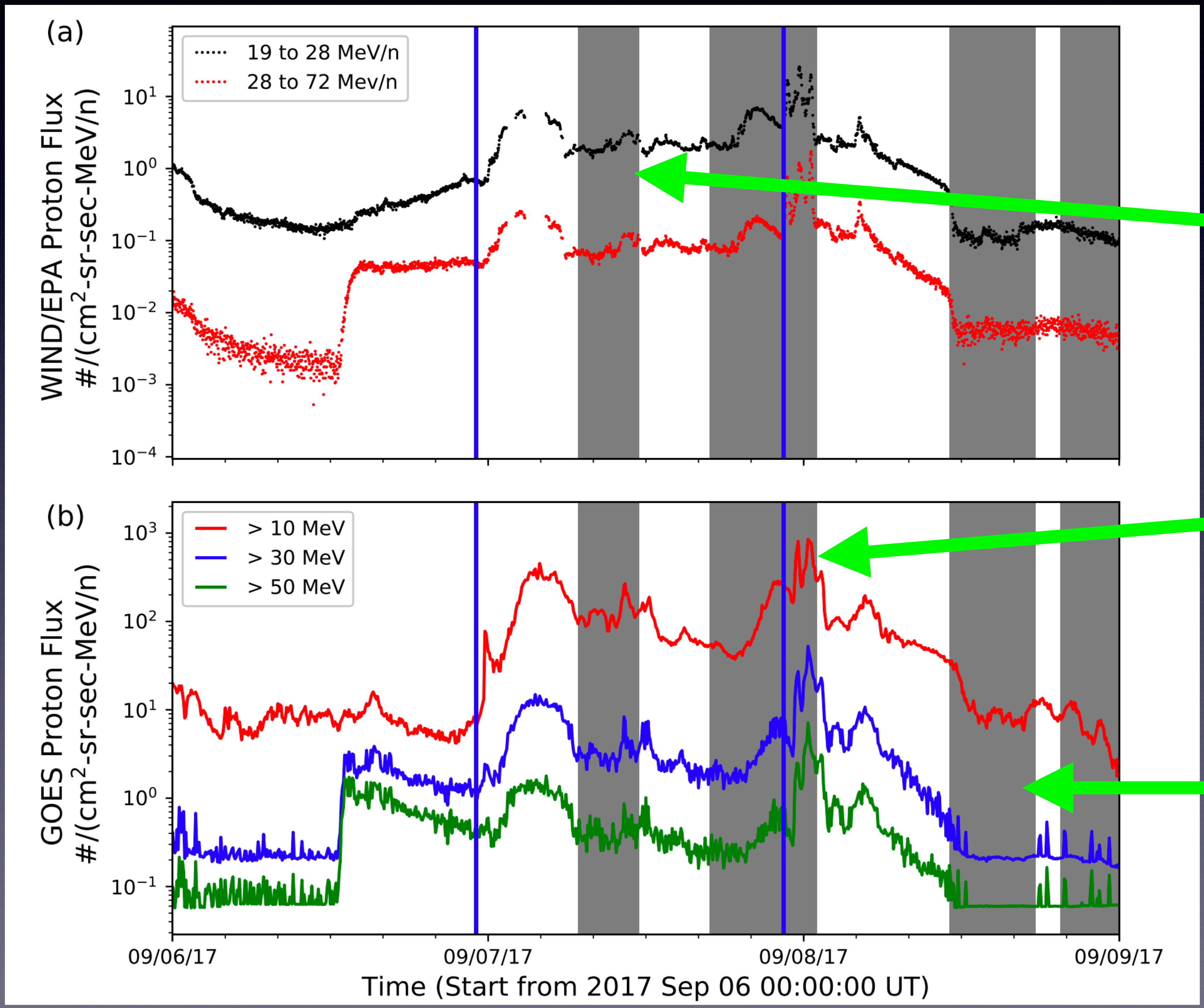
Typical Event: 2000 Bastille Day event



Shock-ICME：Nov. 5 2001 event

[Shen et al., 2008，Sol. Phys.]

SEP signature of Shock-ICMEs: 2017 Sep. event



Decrease

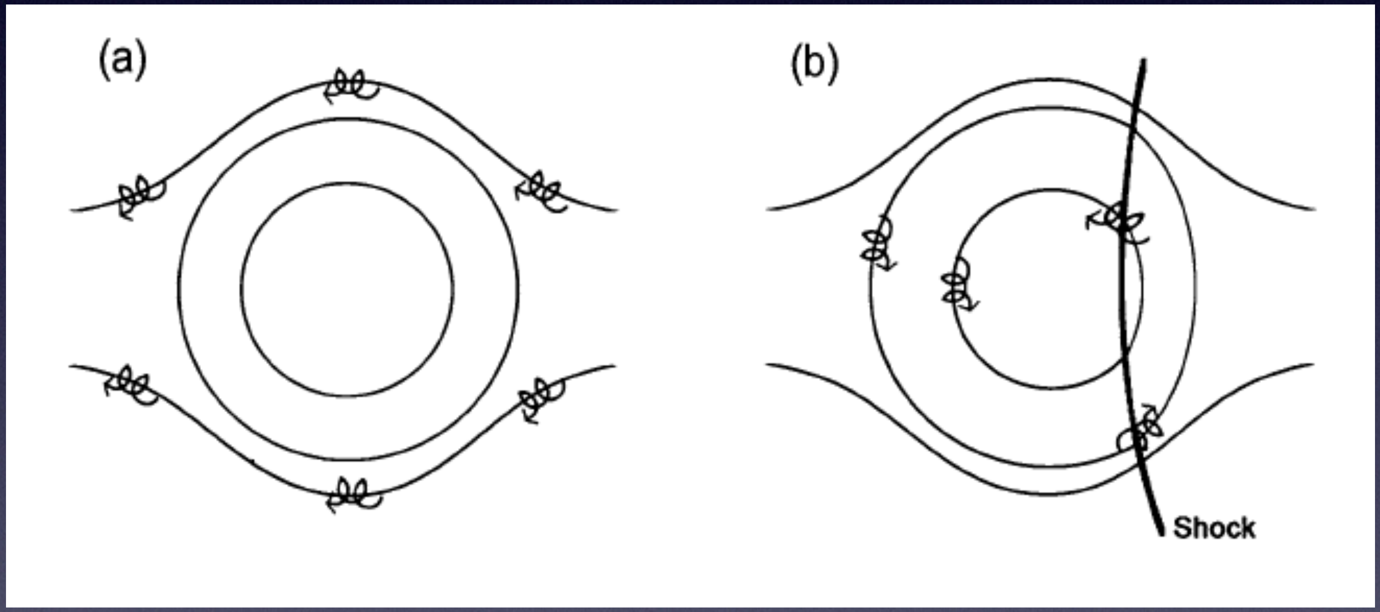
Increase

Decrease

[Shen et al., 2018, ApJ]

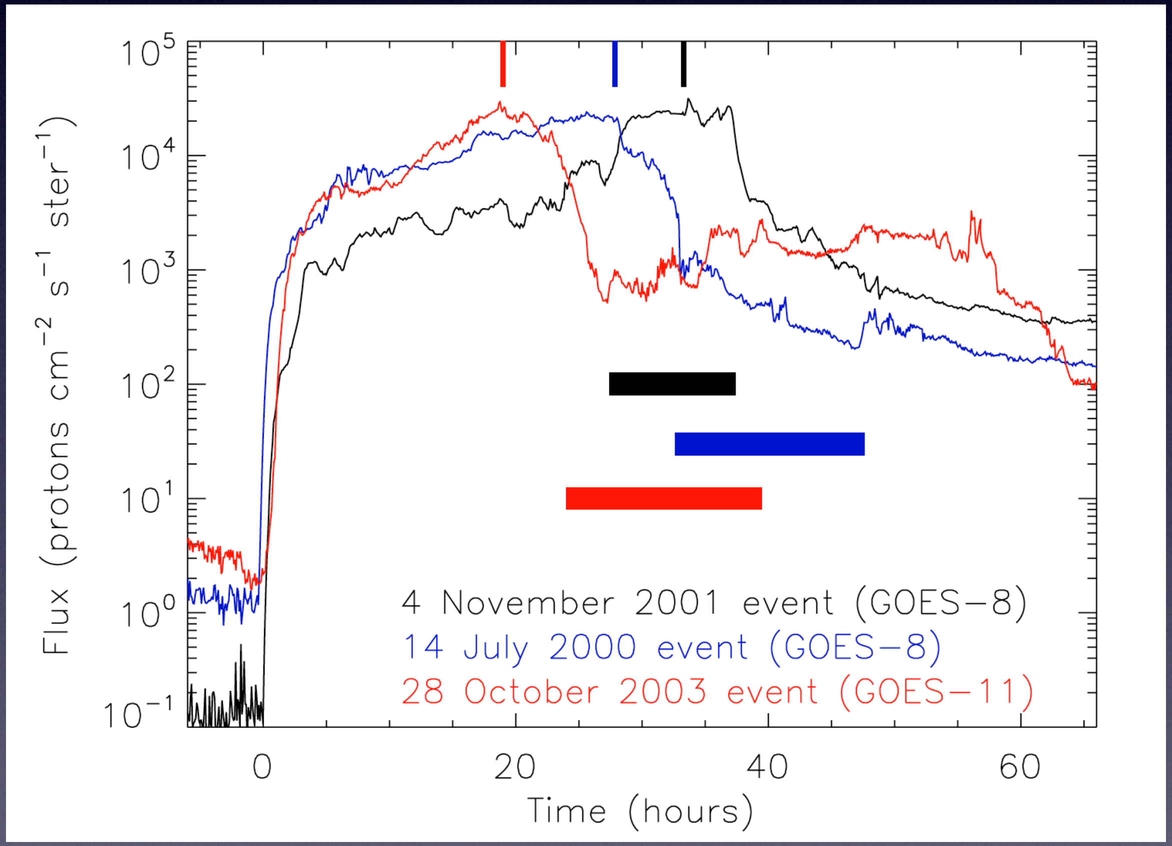
SEP signature of Shock-ICMEs

Physical Explanation



[Shen et al., 2008,Sol. Phys.]

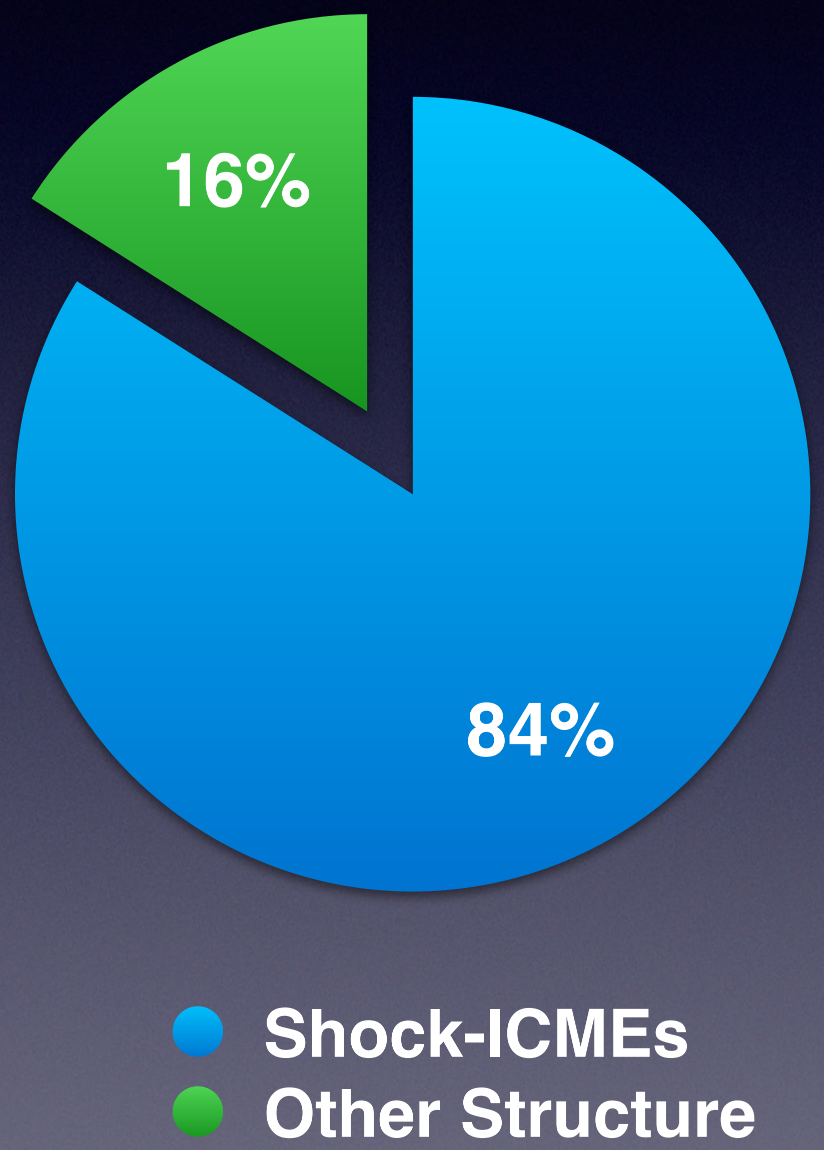
Significant influence



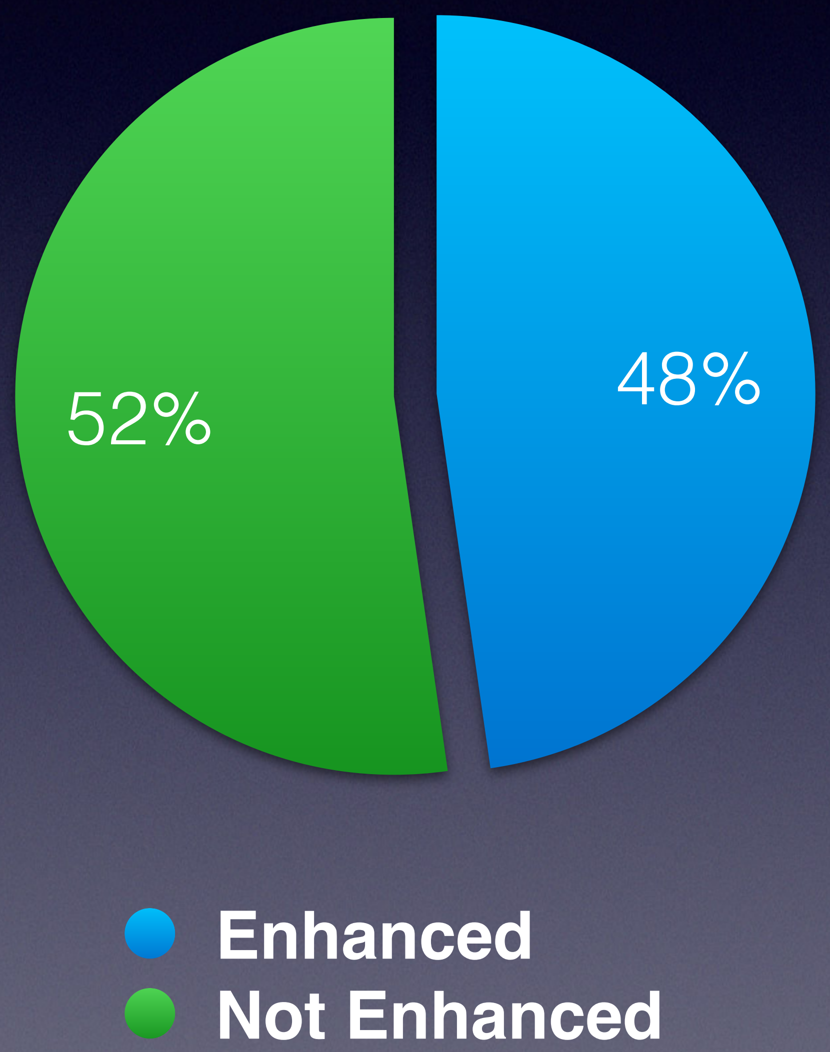
- ☐ Are all such enhancement caused by the S-ICMEs?
- ☐ Can all the S-ICMEs cause such enhancement?

SEP signature of Shock-ICMEs: Statistical result

All SEP enhanced ICMEs

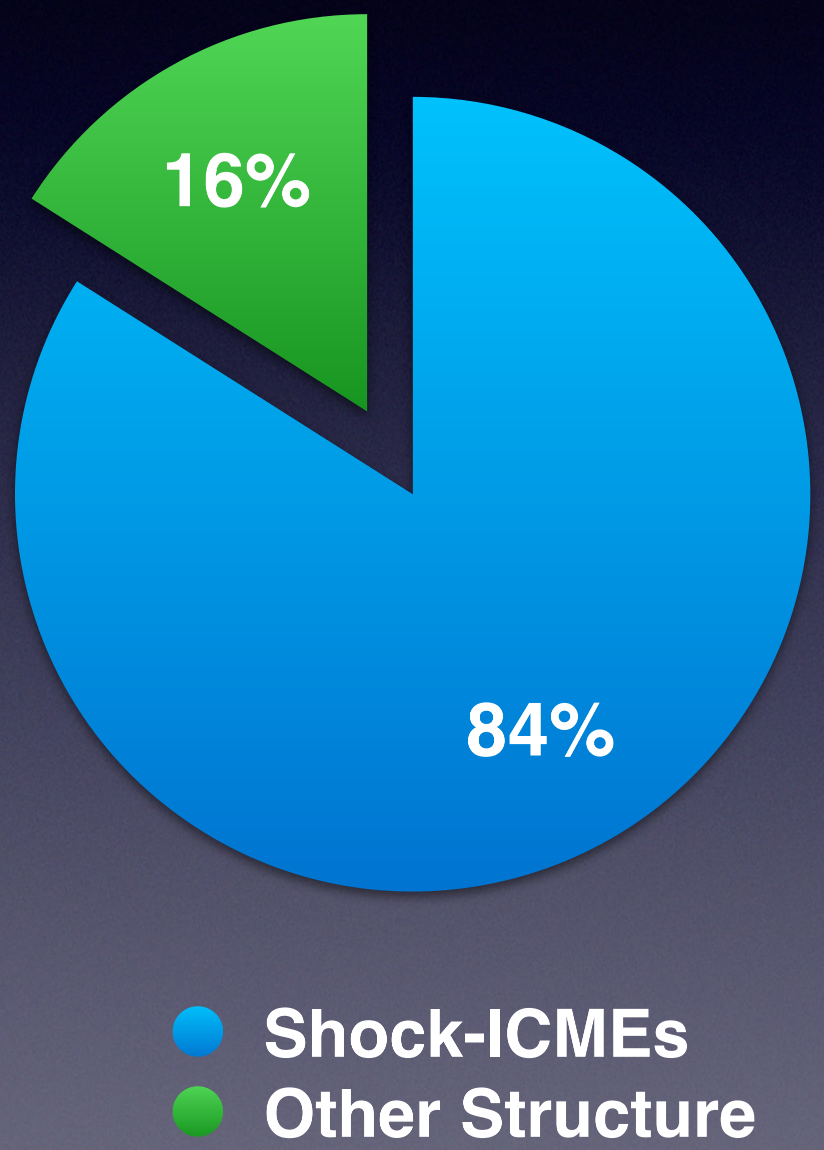


All Shock-ICMEs events

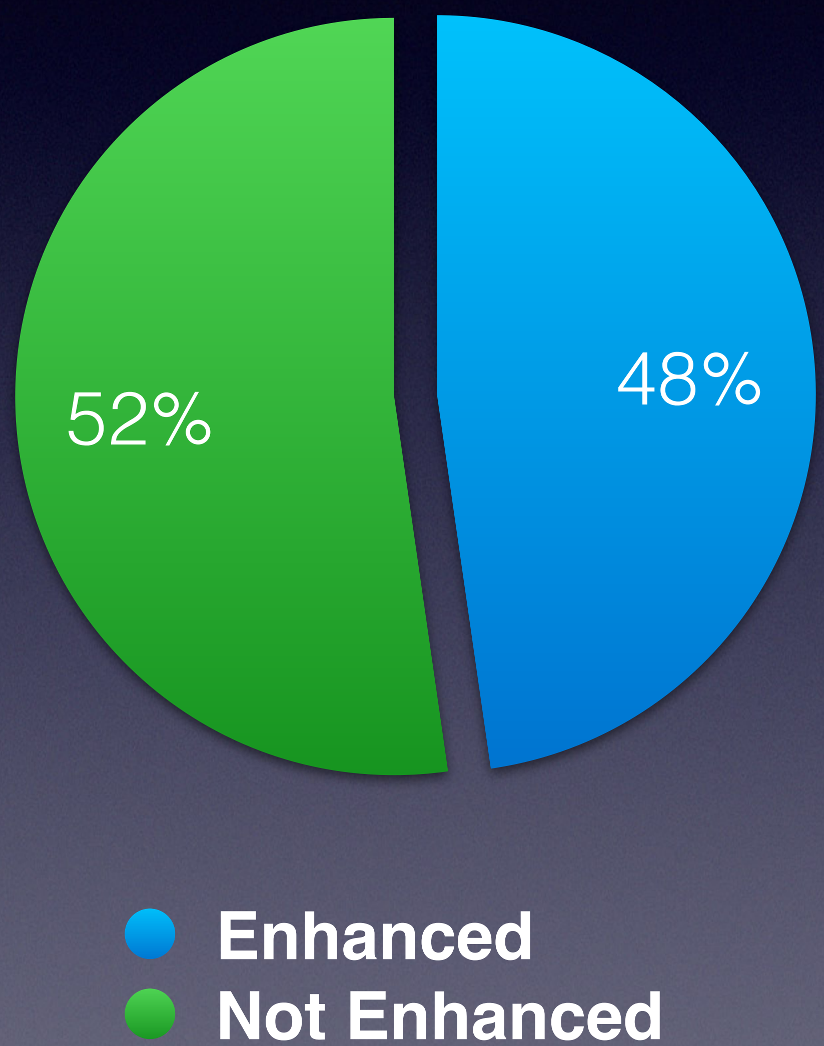


SEP signature of Shock-ICMEs: Statistical result

All SEP enhanced ICMEs



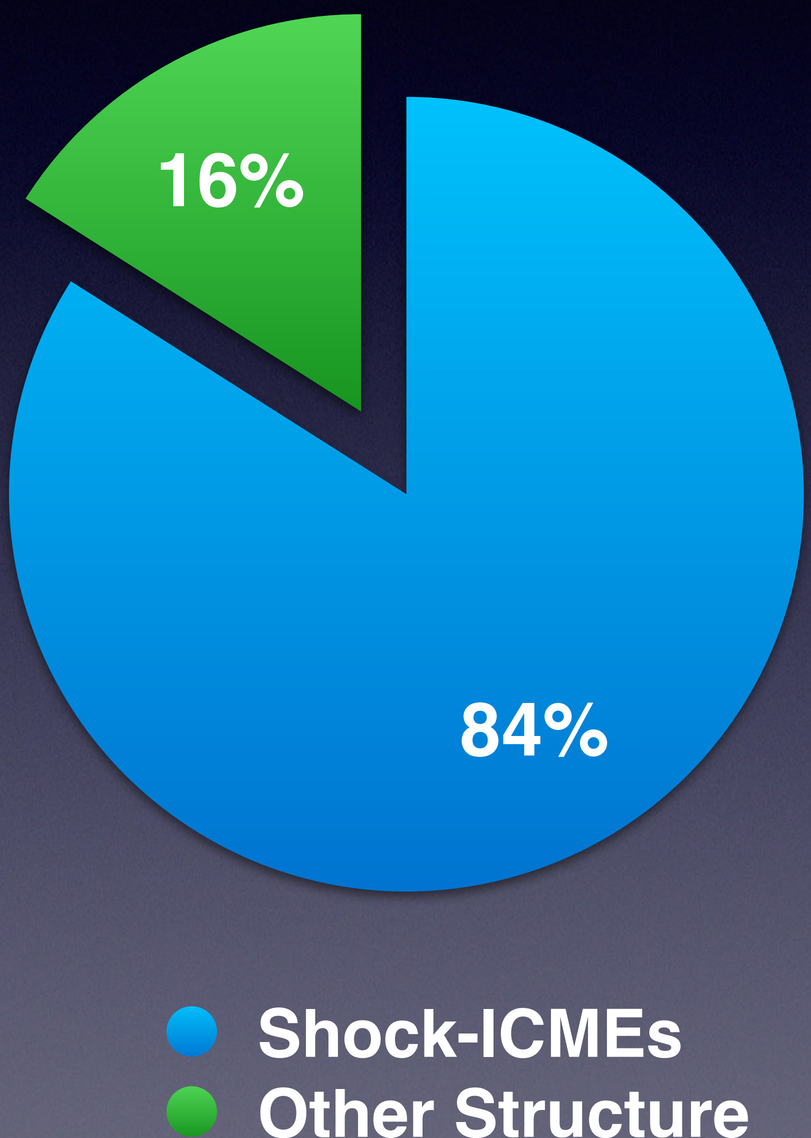
All Shock-ICMEs events



Not all, but large fraction!

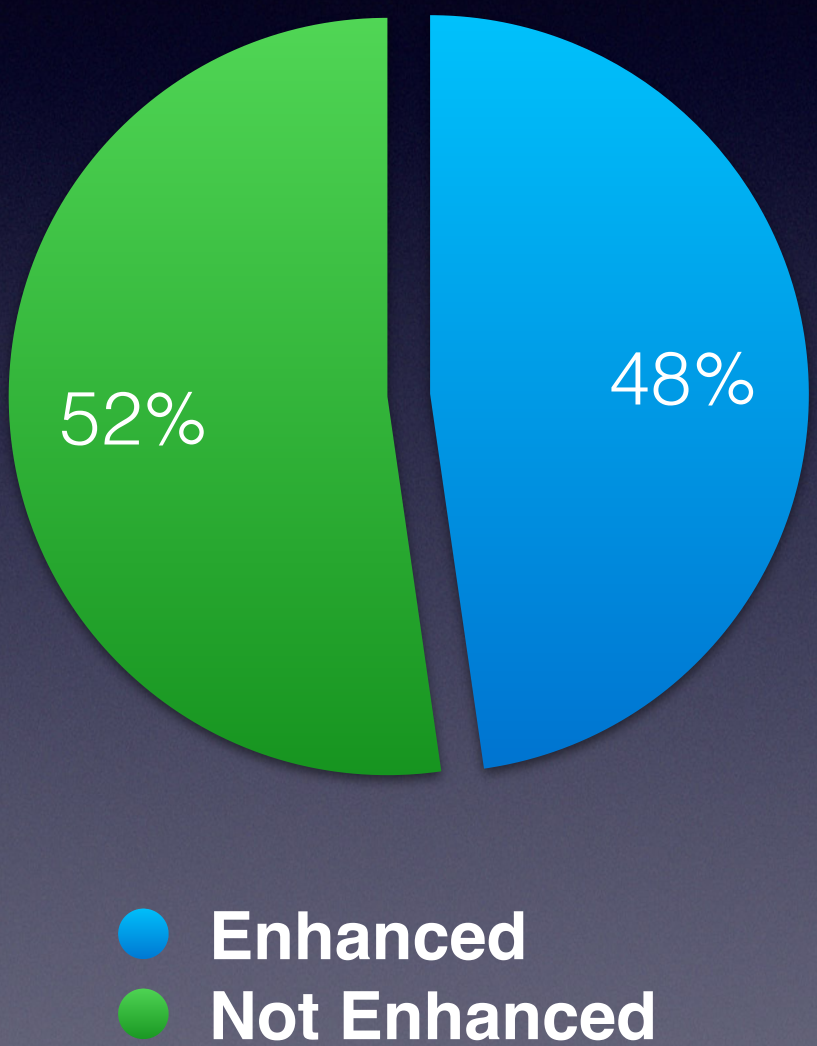
SEP signature of Shock-ICMEs: Statistical result

All SEP enhanced ICMEs



Not all, but large fraction!

All Shock-ICMEs events



About half!

Outline

- Introduction
- Physical process of CME interaction
- Impact on geoeffectiveness
- Impact on SEP events
- Conclusions

Conclusions

- CMEs interaction can change their kinematic parameters greatly!
  - Can CMEs' interaction be described by a simple model?
- Shock compression previous ICME can enhance the geoeffectiveness by a factor of ~1.6!
  - How can we forecast it?
- The SEP intensity would enhanced in the shock-ICME complex structure!
  - What is the physical mechanism?
  - What is the condition of the enhancemnt?

中国科学技术大学
University of Science and Technology of China

DREAMS

Data, REseArch & More in S

Color Scheme White/Black
Username
Password
Login

USTC-SPD | MCFitting | DIPS | SLIPCAT | CMELOC

中文版 Location: Homepage >> DREAMS

This server is maintained by the team of Solar-Terrestrial E

Online Models

- CME Deflection in Interplanetary Space (DIPS)
  Predict the CME trajectory in the ecliptic plane from the Sun
- Fitting Magnetic Clouds
  Velocity-modified cylindrical flux rope models for magnetic c

Data Products

- Interplanetary Causes of Geomagnetic Storms Since 2
  Interplanetary causes of moderate to intense geomagnetic st
- ICMEs recorded by WIND spacecraft Since 1996 (Wir
  Interplanetary coronal mass ejections (ICMEs) are identified
  storms are also listed. (launched on Apr 16, 2015)
- Full Halo CMEs (FHCMEs)
  A list of full halo CMEs viewed by SOHO/LASCO since 200
- Quasi-Homologous CMEs (QHCMEs)
  A list of quasi-homologous CMEs originating from the same
- CME Source Locations (CMELOC)
  CME's source locations on the visible solar disk manually ide
- Solar LImb Prominence CAtcher & Tracker (SLIPCAT
  Movies and catalogs of auto-detected solar limb prominence
- Events
  Events of interest. (launched on Mar 22, 2013)

http://space.ustc.edu.cn/dreams/

- ★ ICME catalogue from 1995 till now [Chi et al., 2017]
- ★ Front side halo CME catalogue with GCS model's parameters from 2005 to 2012 (will be updated soon)[Shen et al., 2013; 2014]
- ★ CMEs catalogues with their source regions from 1998 to 1999 [Wang et al., 2011]
- ★ SIR catalogues from 1995 till now (Extension of Jian's catalogue, will be online soon) [Chi et al., 2018]
- ★ …

Thanks!