Turn on the super-elastic collision nature of CMEs through low approaching speed

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Type of collision nature

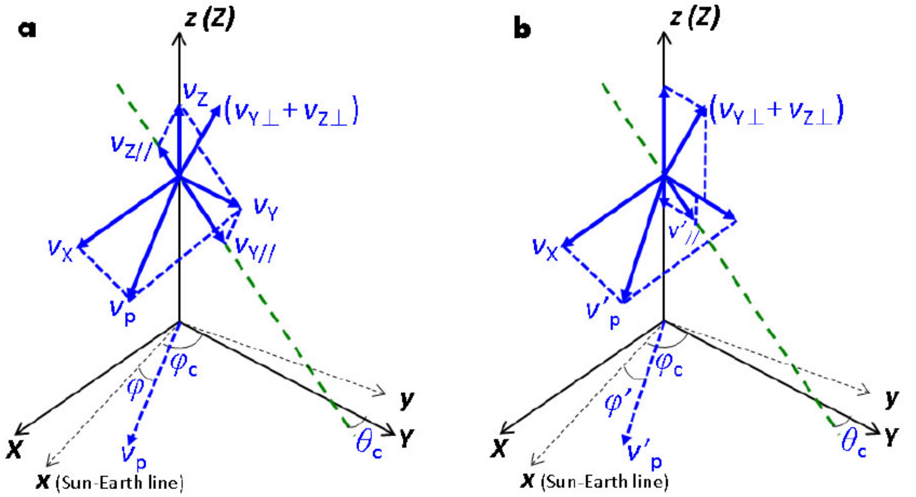
Type	e	Total kinetic energy
Merging	-1<e<0	Decrease
Perfectly inelastic	e=0	Decrease
Inelastic	0<e<1	Decrease
Elastic	e=1	Conserved
Super-elastic	|e|> 1	Increase

Two measures

- Coefficient of restitution

  $$e = (v'_2 - v'_1)/(v_1 - v_2)$$

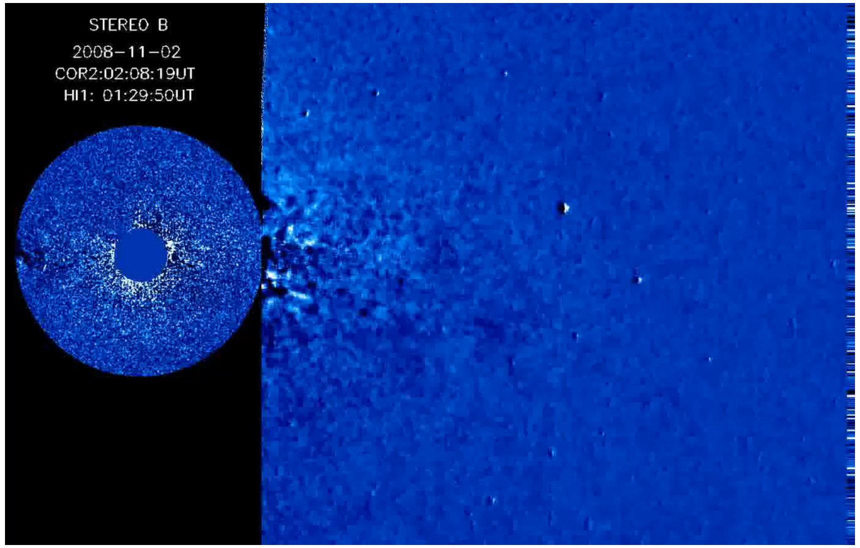
- Total kinetic energy

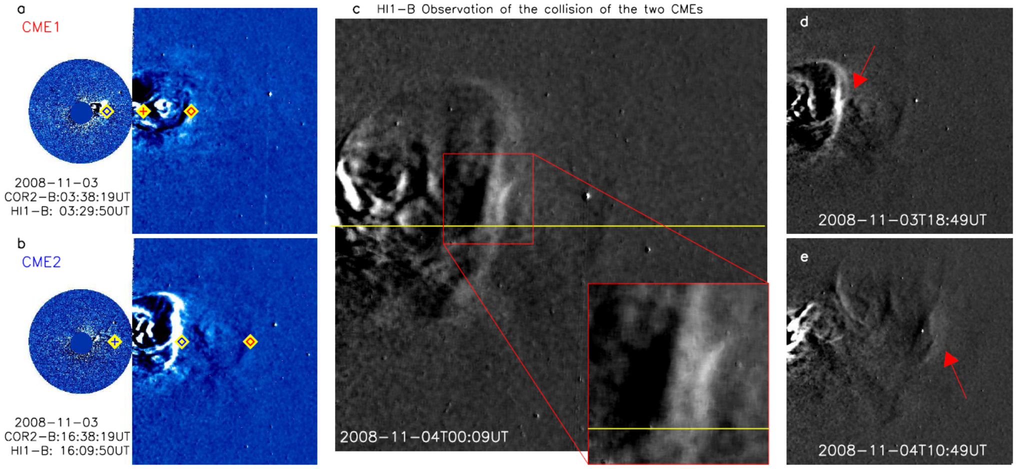


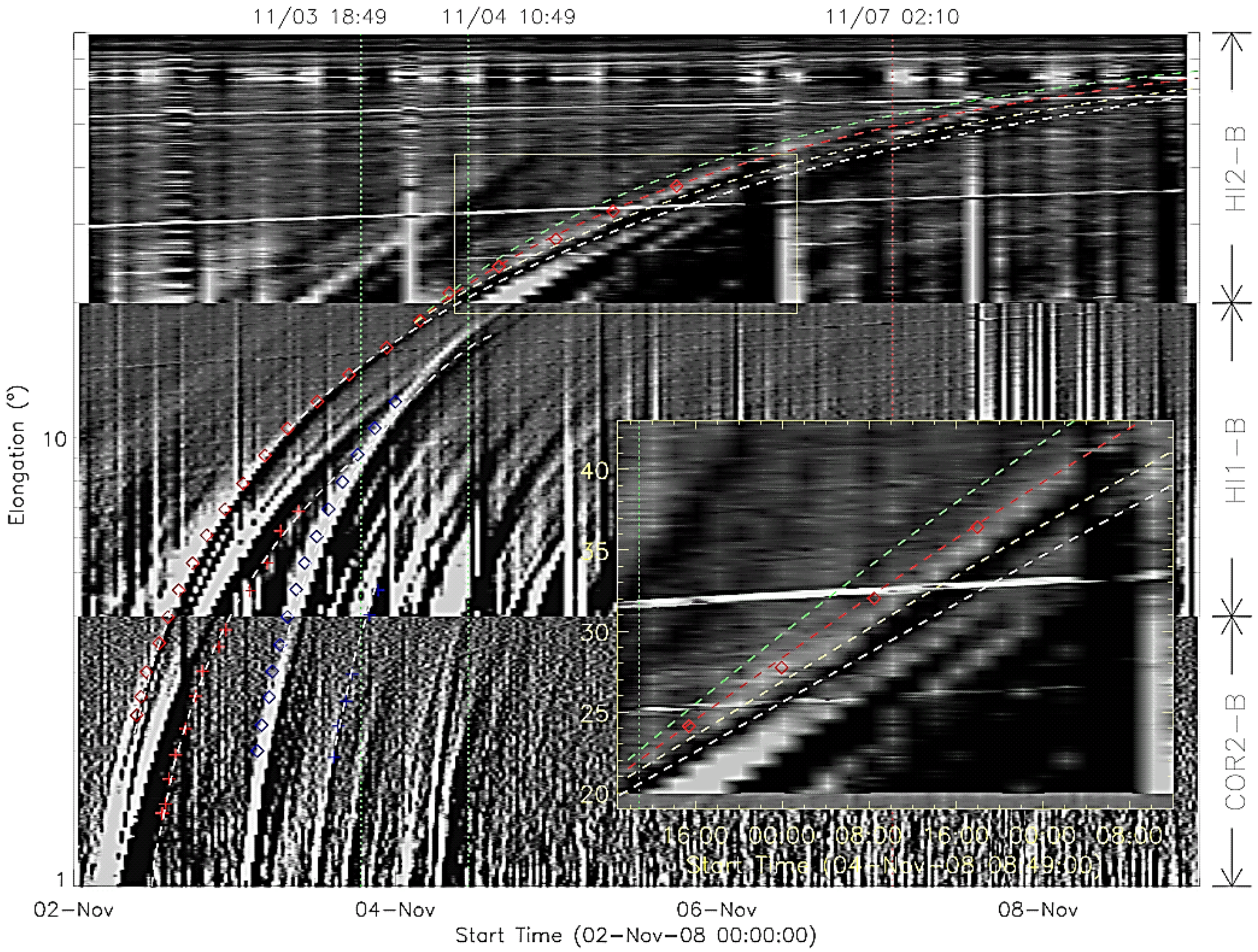
Supplement in Shen et al., NatPhys, 2012

Propose the possibility of super-elastic collision between CMEs

(Shen C., et al., Nat. Phys., 2012)

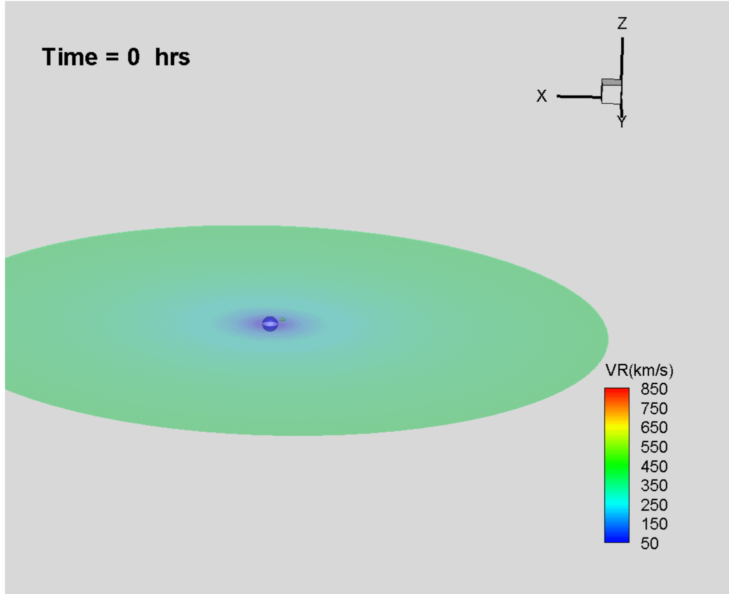


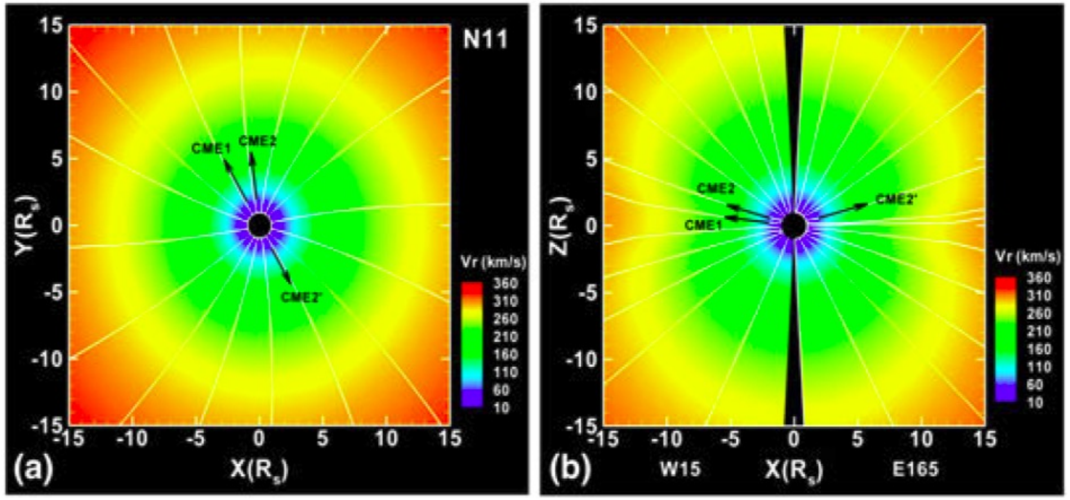


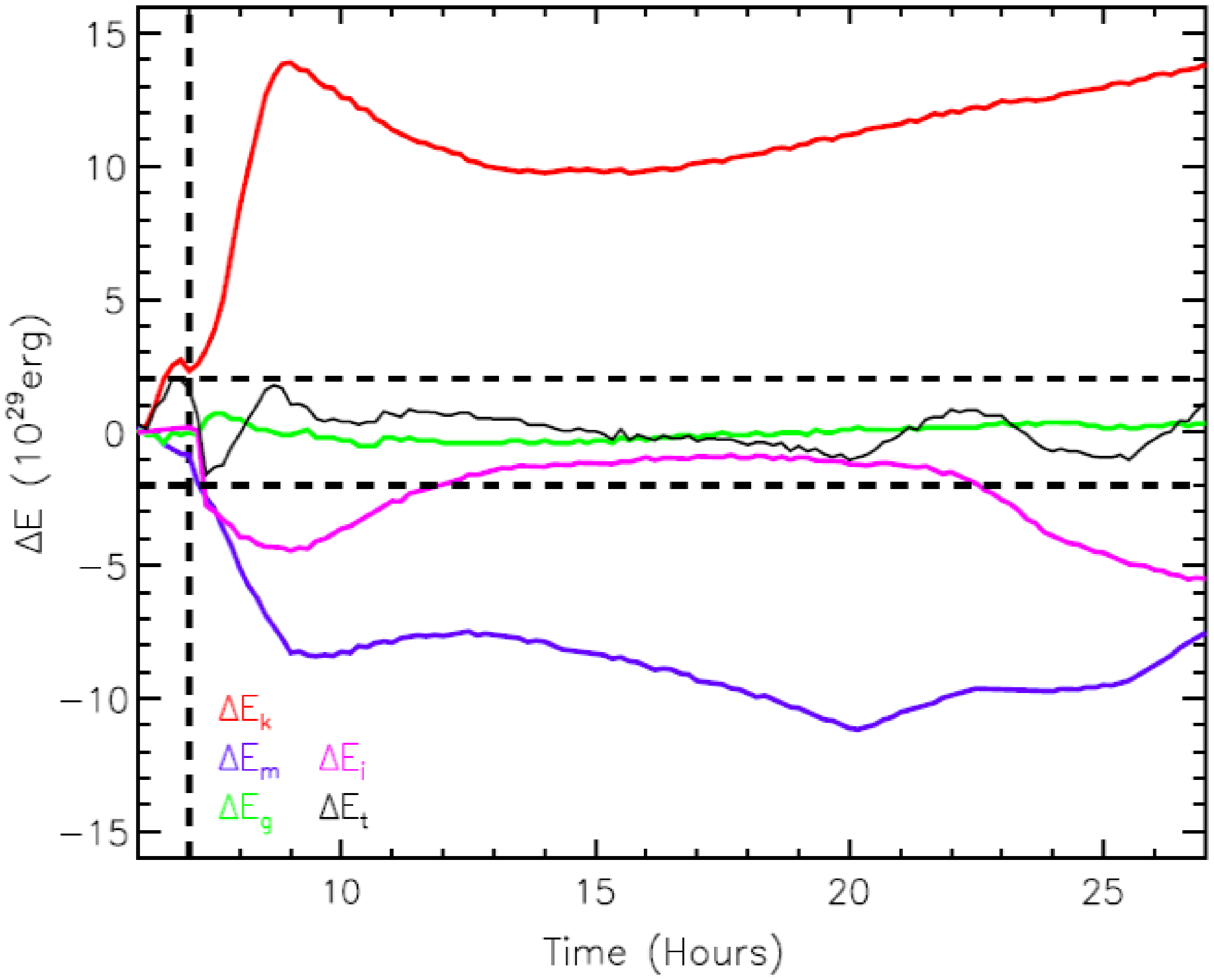


Verified with 3D MHD numerical simulations

(Shen F., et al., GRL, 2013)



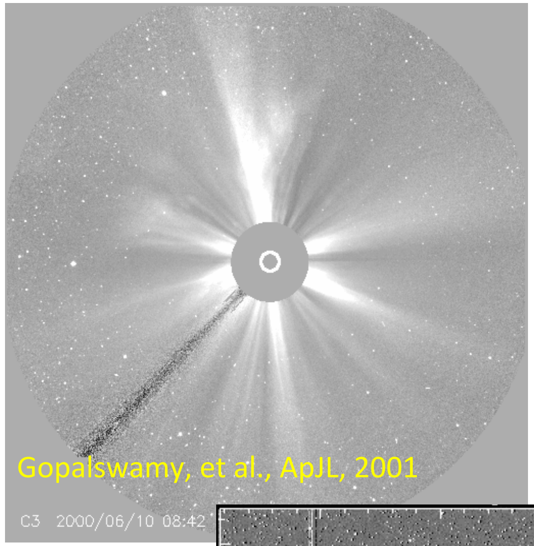


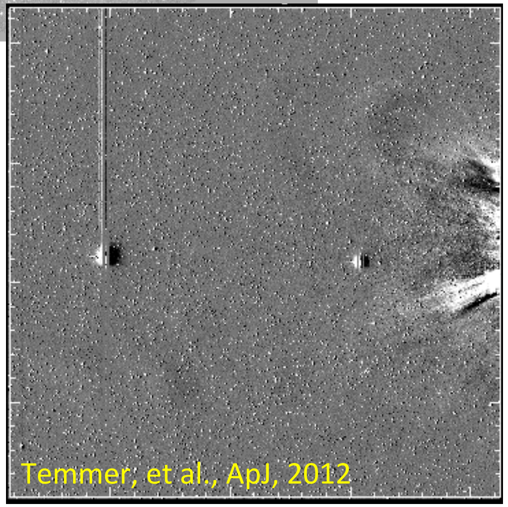


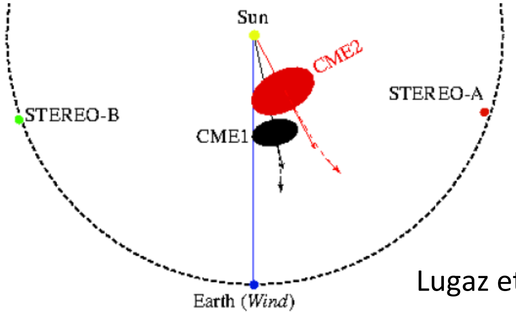
However ……

- Gopalswamy et al., 2001, ApJL: Cannibalism of two CMEs --- merging?
- Lugaz et al., 2009, AG: Vcme1: 600 → 850 – 900 km/s, Vcme2: 1200 – 1300 → 800 km/s --- possibilities of perfectly inelastic, elastic and shock effect were discussed
- Temmer et al., 2012, ApJ: before collision, Vcme1 ~ 600 km/s and Vcme2 ~ 1400 km/s; after collision, merged feature ~ 800 km/s --- “super” inelastic → merging?
- Lugaz et al., 2012, ApJ: Vcme1 increases a little, Vcme2: 600 → 380 km/s --- perfectly inelastic
- Lugaz et al., 2013, ApJ: Simulation Case B, minimum reconnection; Vcme1: 600 → 650 km/s, Vcme2: 1000 → 650 km/s --- “super” inelastic → merging?
- Temmer et al., 2014, ApJ: Vcme1: 400 → 700 km/s Vcme2: 1300 → 600 km/s --- “super” inelastic → merging?
- Mishra et al., 2015, SoPh: Vcme1: 365 → 450 km/s, Vcme2: 625 → 430 km/s --- inelastic
- Colaninno & Vourlidas, 2015: super-elastic
- Shen et al., 2012, NP: Vcme1: 240 → 320 km/s, Vcme2: 410 → 350 km/s --- super-elastic

Approaching speed might play a important role



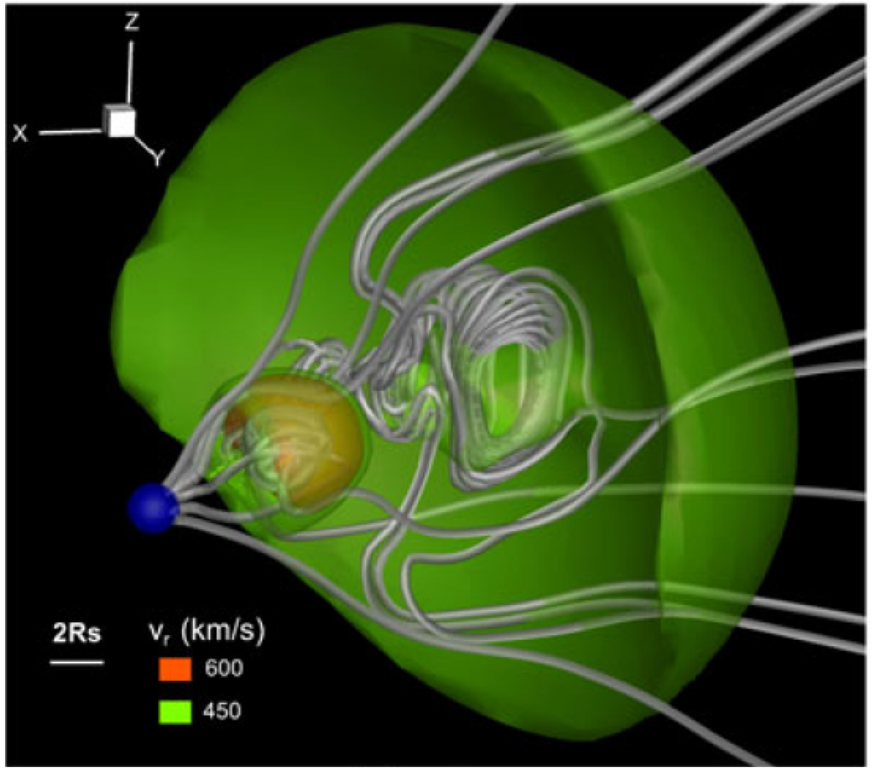




Lugaz et al., ApJ, 2012

Numerical experiments

- MHD Model
  - 3-D corona-interplanetary total variation diminishing (COIN- TVD) scheme in a Sun-centered spherical coordinate system
  - Non-reflecting Boundary Conditions at lower boundary
- CME Initiation
  - A high-density, -velocity, -temperature, and magnetized plasma blob is superposed on the background solar wind model



Five test cases --- Setup

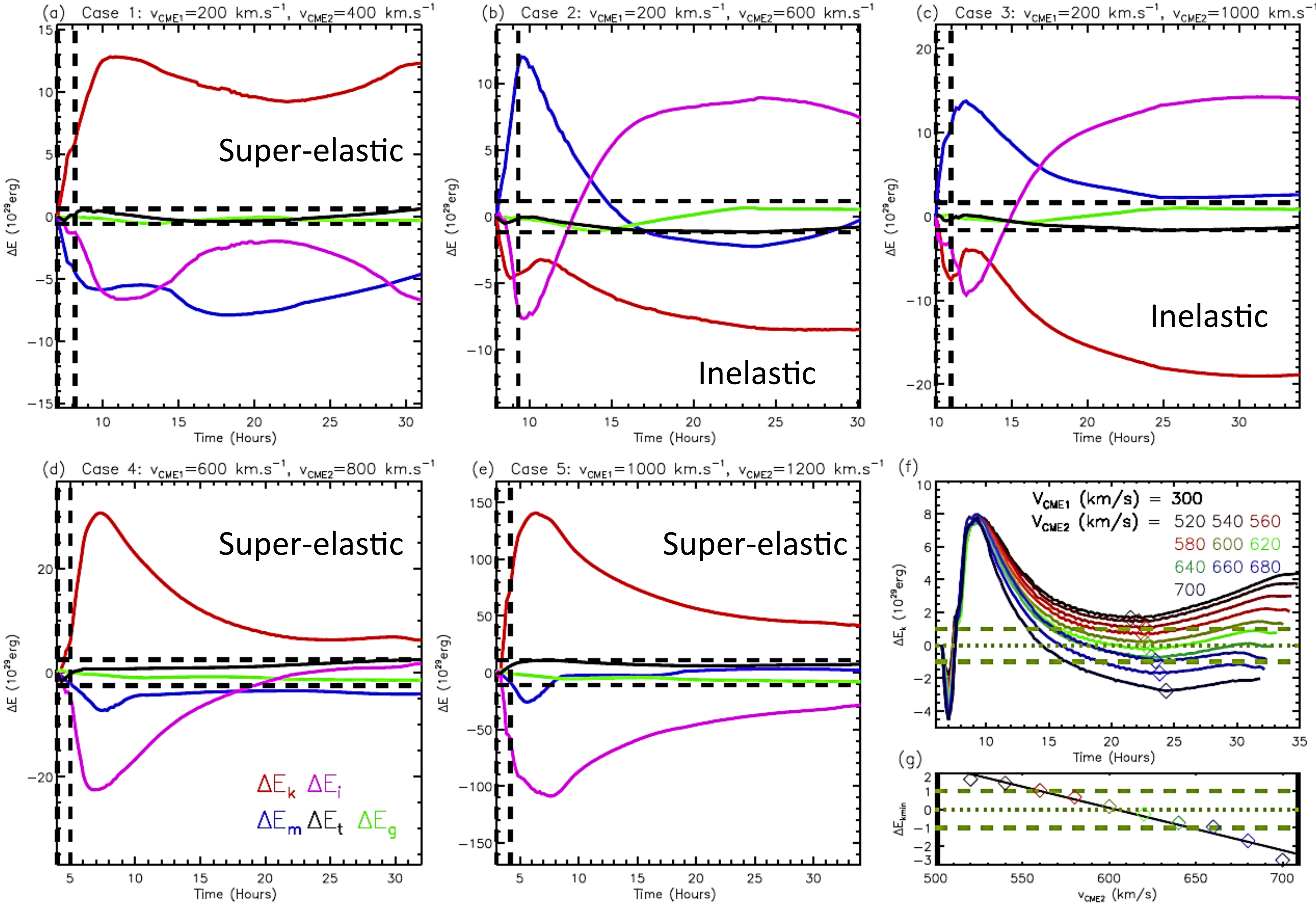
Common par.	Direction	R	B	n	T	E_m	E_i	E_g	V_{sw}
		R_s	$\times 10^5$ nT	$\times 10^7$ cm^{-3}	$\times 10^5$ K	$\times 10^{31}$ erg			km s^{-1}
	N11W18	0.5	1.47	4.0	5.0	1.50	1.37	-0.64	$316 \sim 461$

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	

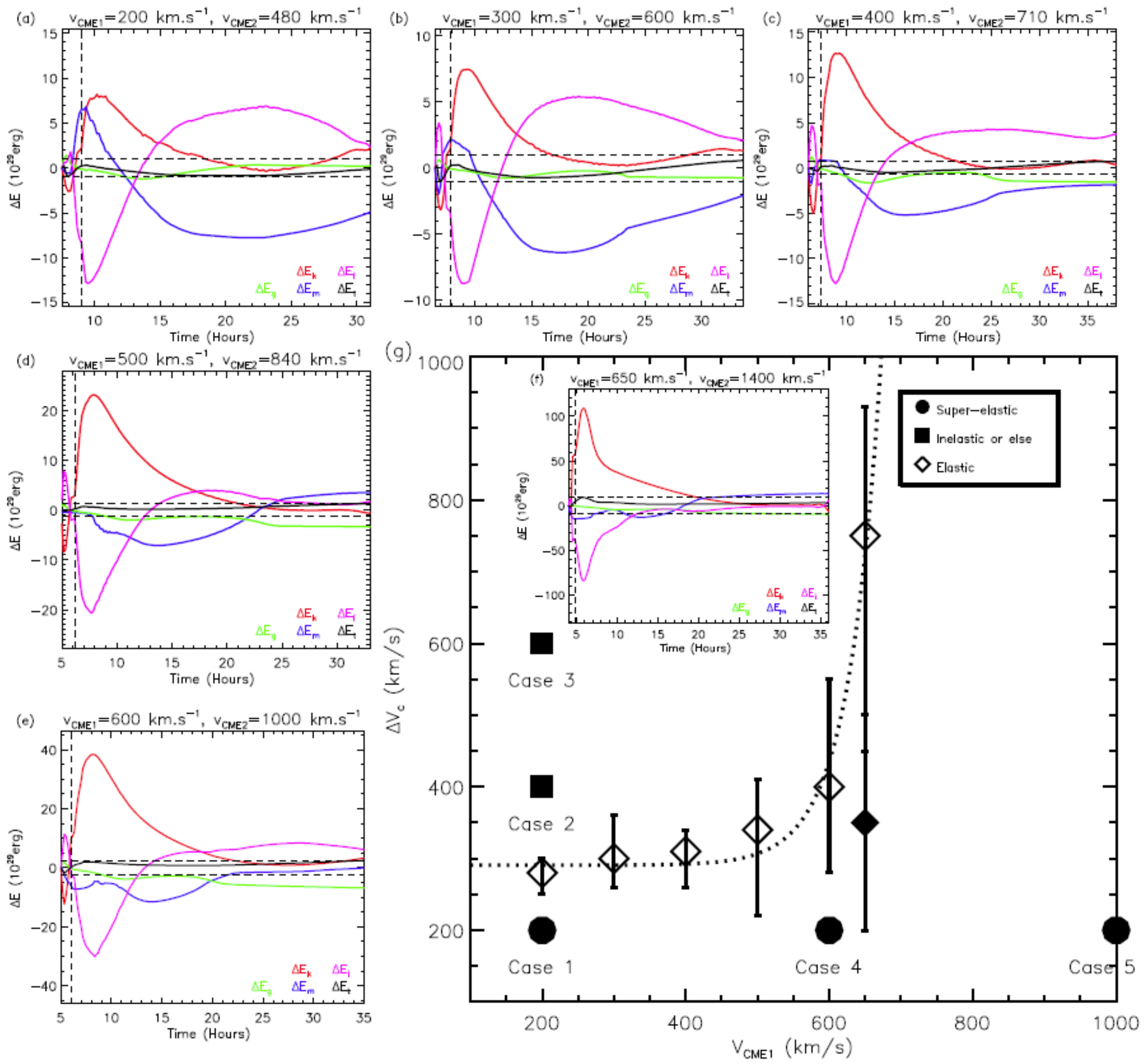
Same V_{cme1}, different ΔV

Different V_{cme1}, same ΔV

Five test cases --- Results



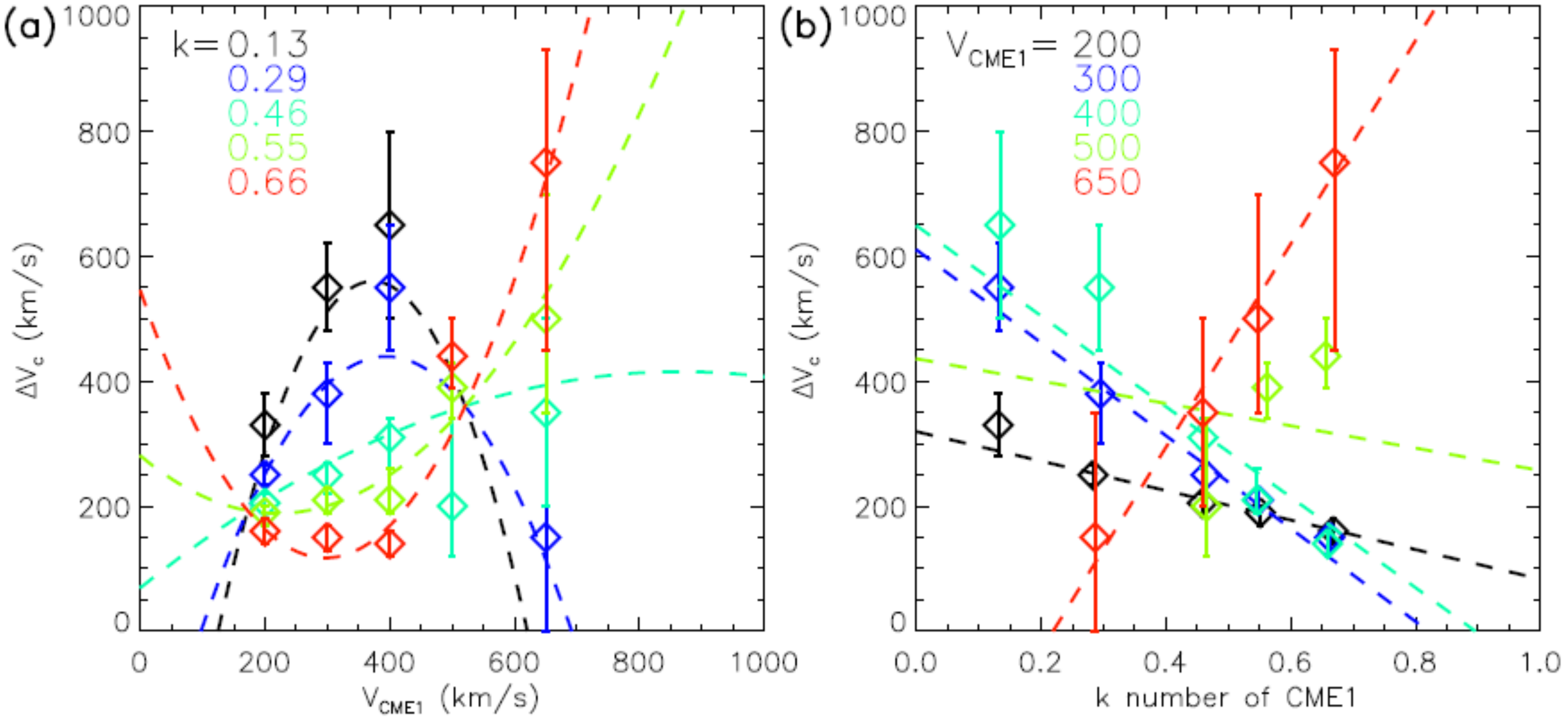
Search the boundary between the super-elastic and inelastic nature



Critical value of the approaching speed ΔV

- Dependent on CME speed, e.g., V_{cme1}
- Dependent on the ratio of CME kinetic energy to the total energy, defined as k-number
  - ✓ k > 0.5 means kinetic energy is dominant, otherwise kinetic energy is a minor one.

Relationship of the approaching speed with V_{cme1} and k-number



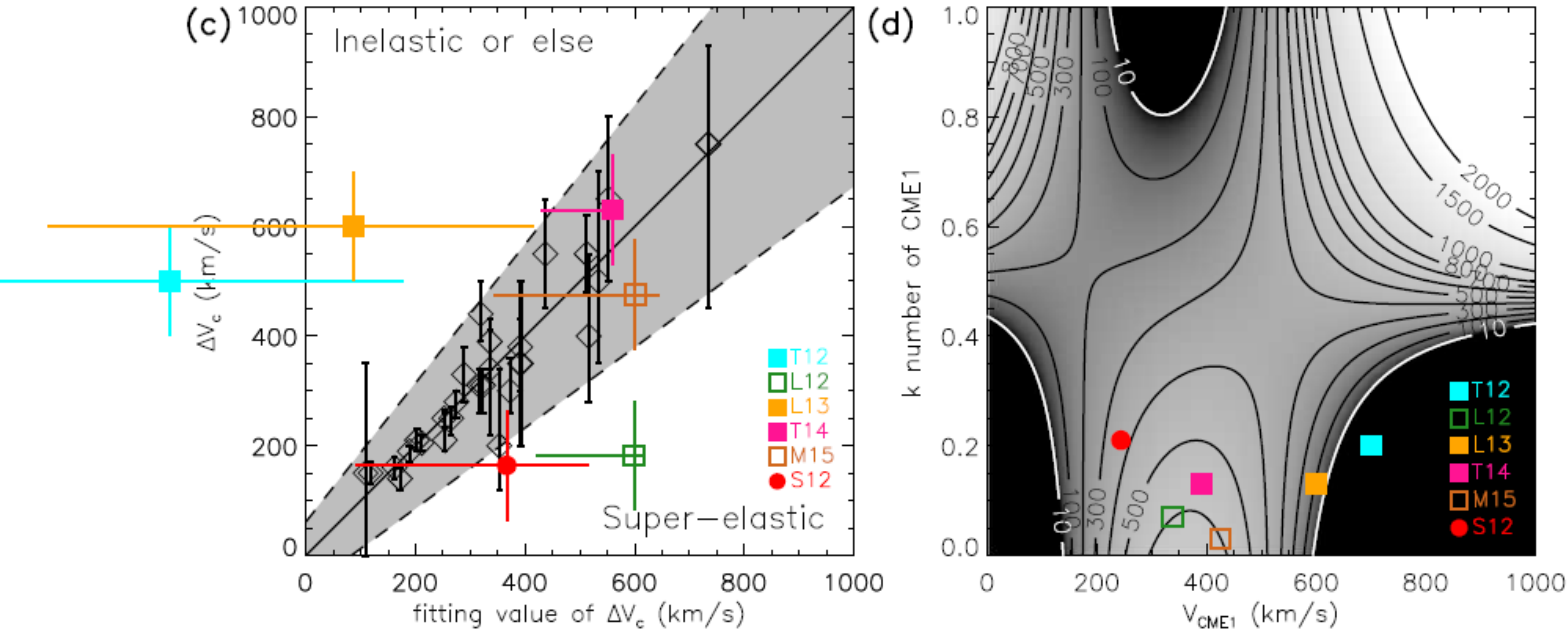
parabolic

linear

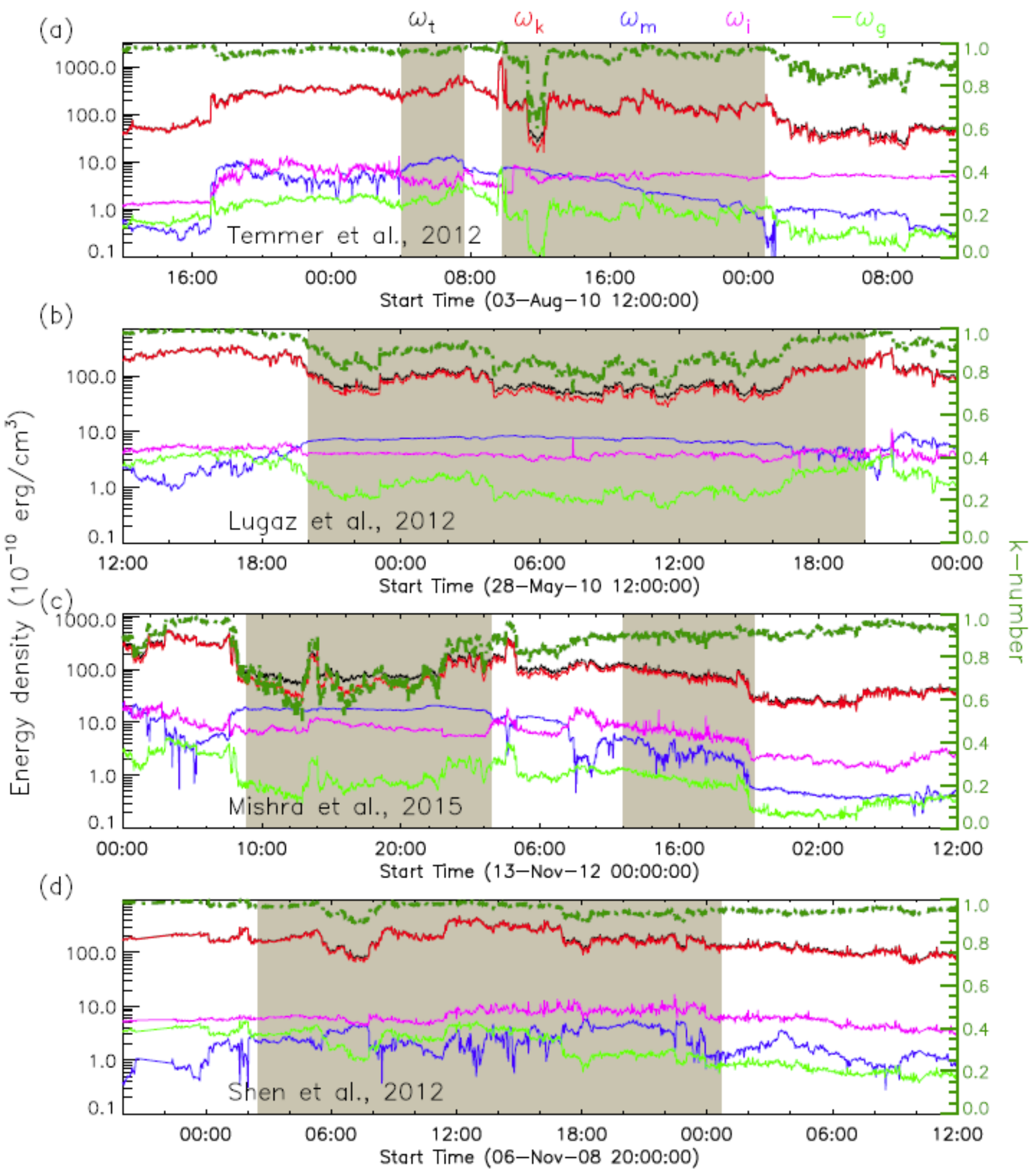
$$\Delta V_c = (0.026k - 0.013)V_{CME1}^2 - (18k - 9.2)V_{CME1} + (2360k - 1019) \quad (\mathrm{km\ s^{-1}})$$

or $$\Delta V_c = (0.026V_{CME1}^2 - 18V_{CME1} + 2360)k - (0.013V_{CME1}^2 - 9.2V_{CME1} + 1019) \quad (\mathrm{km\ s^{-1}})$$

Diagram of the collision nature



Derive the k-number from in-situ data



Energy density

$$\omega_k = \frac{1}{2}(m_p n_p v_p^2 + m_e n_e v_e^2)$$

$$\omega_m = \frac{B^2}{2\mu}$$

$$\omega_i = \frac{n_p k T_p + n_e k T_e}{\gamma - 1} = \frac{p_p + p_e}{\gamma - 1}$$

$$\omega_g = -\frac{G M_s}{r}(m_p n_p + m_e n_e)$$

Scaling law

$$\omega_k \propto r^{-3}$$

$$\omega_m \propto r^{-4}$$

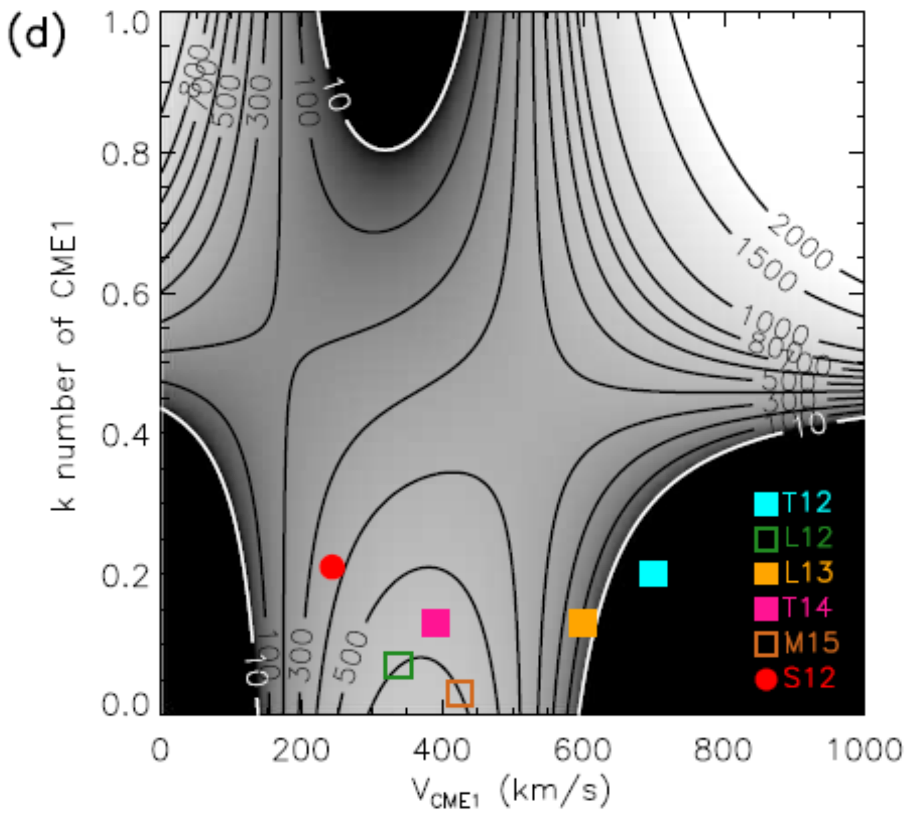
$$\omega_i \propto r^{-4}$$

$$\omega_g \propto r^{-4}$$

Average k-number of the events is 0.13

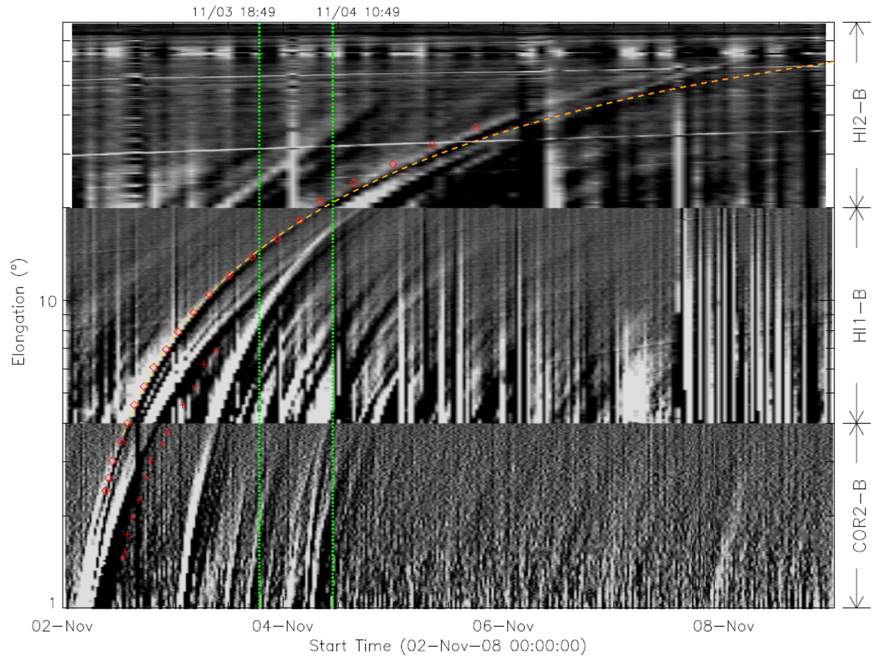
Summary

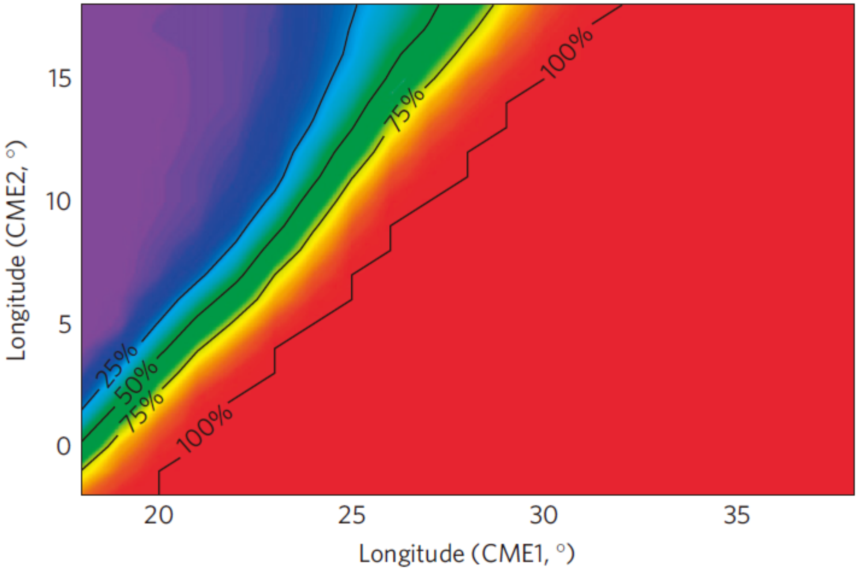
- A smaller approaching speed is more favorable for a super-elastic collision.
- The critical approaching speed is linearly correlated with the k-number and roughly quadratically correlated with the first CME's speed.
- A diagram is inferred. It is particularly useful in roughly estimating the collision nature as long as we know the values of the CMEs' speeds and the k-number, which are all possibly obtainable from observations.
- For a super-elastic collision, the extra kinetic energy gain could be from CME's magnetic energy and/or thermal energy.



Discussion

- Many influence factors are ignored, such as the magnetic field reconnection, shock, the approaching angle, the collision distance, background solar wind, CME mass change, etc.
  - ➢ The solar wind efficiency in acceleration CME is about 6.5% of the collision efficiency
  - ➢ Mass ratio of the two CMEs is not sensitive to the collision nature
  - ➢ The approaching angle does influence the results significantly --- simple 1D collision model is not appropriate
  - ➢ Expansion speed may also influence the results significantly --- a model of expanding elastic balls in 3D is more appropriate





Shen et al., NatPhys, 2012

Thanks for your attention!

Test the effects of background solar wind