Assessing the collision nature of coronal mass ejections in the inner heliosphere

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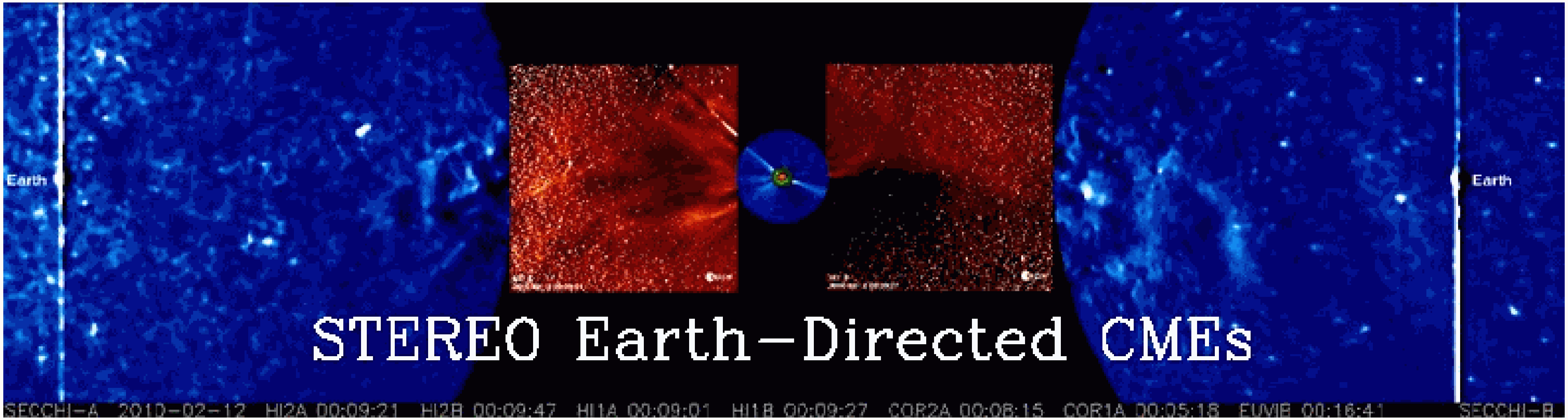

International Study of Earth-Affecting Solar Transients (ISEST) workshop-2017

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- Observed nature of collision
- Effect of uncertainties

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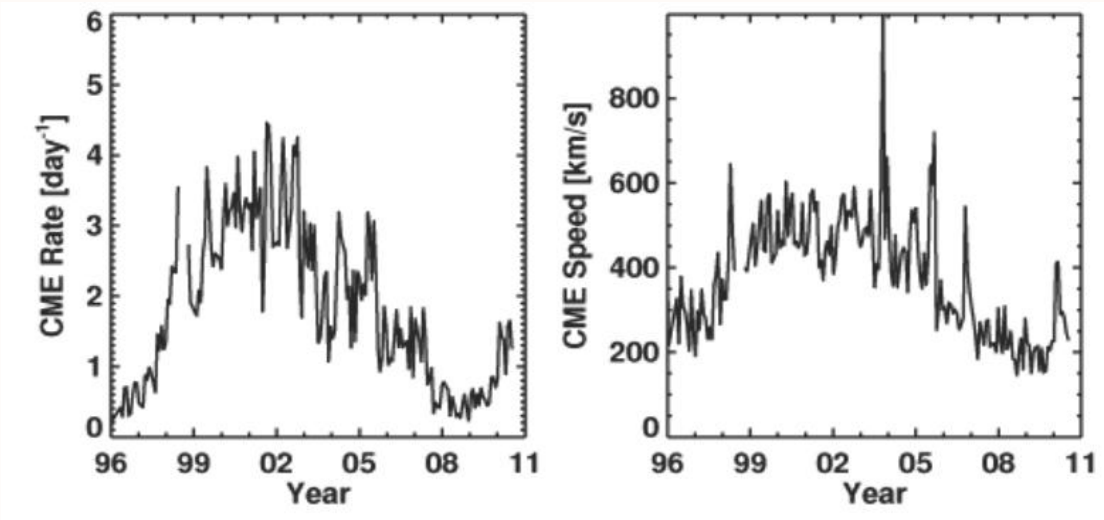
Introduction

- Coronal Mass Ejections(CMEs) occurrence rate:

(Gopalswamy et al. 2010)

~ 0.3 per day (minimum)

~ 4-5 per day (maximum)



- Travel time to Earth:

1 to 4 days

- CME-CME interaction: Prediction of arrival becomes difficult
- Successive CMEs may merge, form complex ejecta and lead to strong geomagnetic storms *(Wang et al. 2003, Farrugia et al. 2006 etc.)*

- Radio enhancements and SEPs *(Gopalswamy et al. 2001, Kahler and Vourlidas, 2014)*

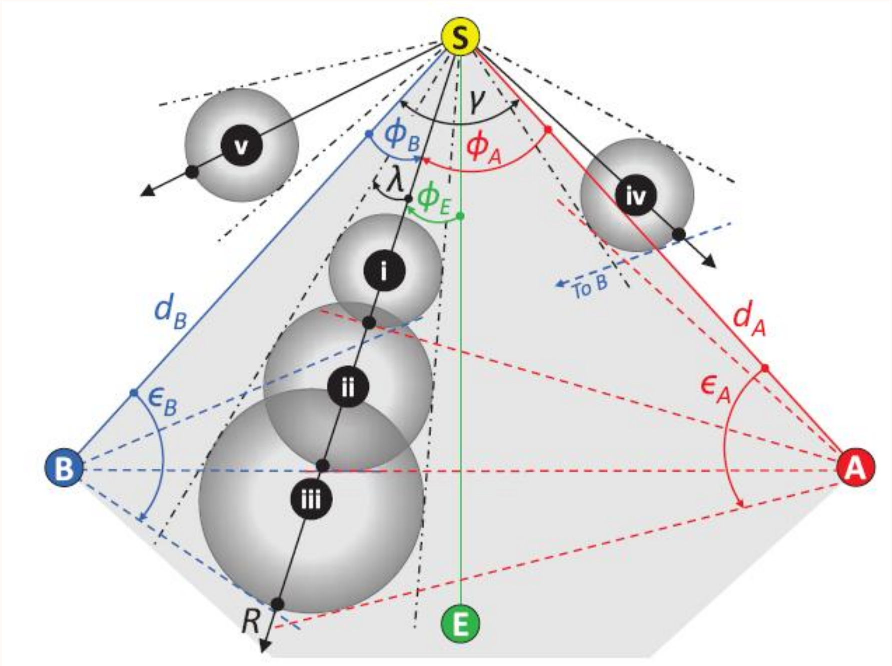
SOHO era: mainly MHD simulation

Kinematics, plasma parameters , arrival time, geoeffectiveness , shock-CME and CME-CME interaction

STEREO era: several observational studies

3D kinematics: Extremely Important

(Thernisien et al. 2009, Mierla et al. 2009,
Wood et al. 2009, Rouillard et al. 2008, Liu et al. 2010,
Lugaz et al. 2010,   Davies et al. 2012, 2013 etc)



CME-CME interaction: Collision nature

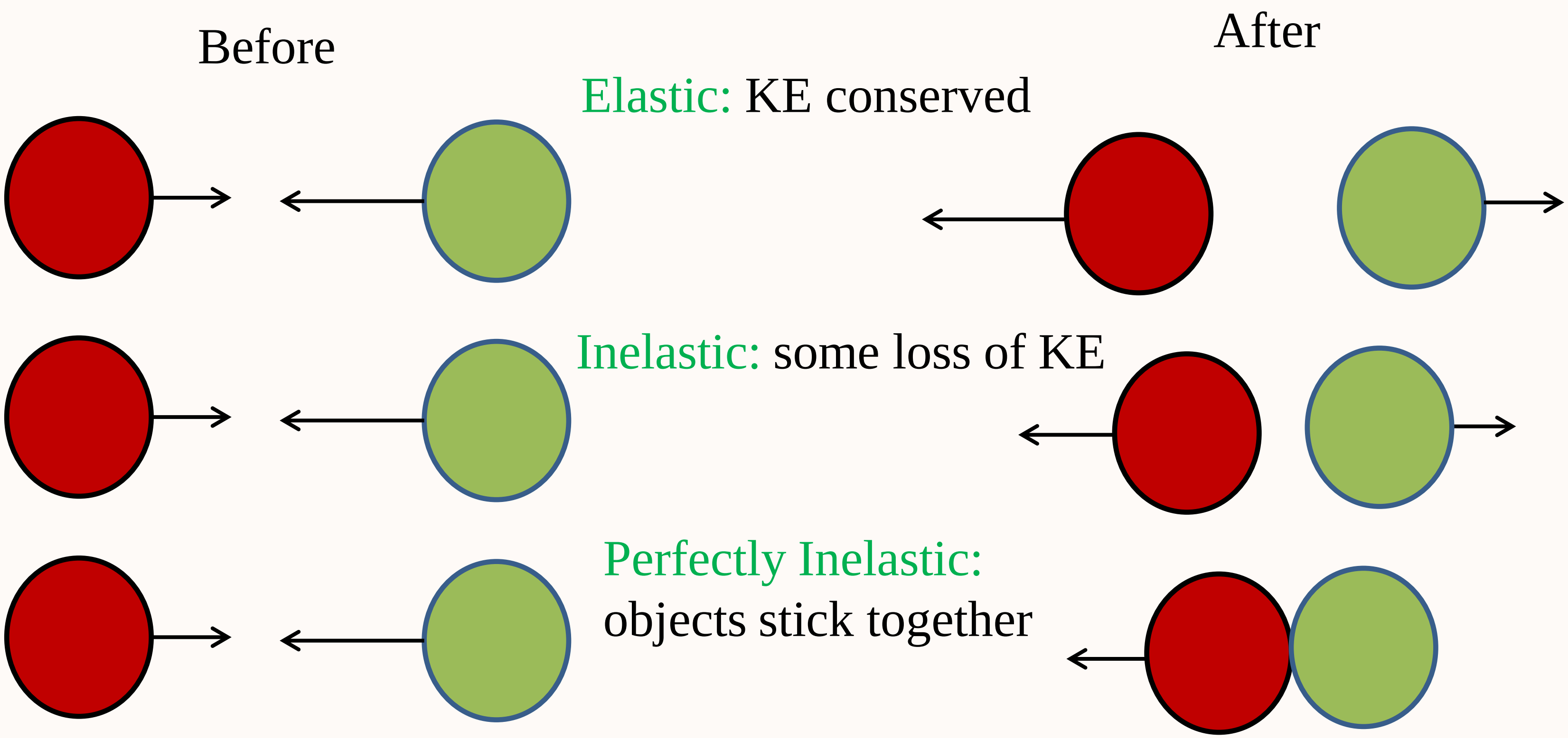
Shen et al. (2012), Harrison et al. (2012),
Temmer et al. (2012), Mostl et. al. (2012),
Mishra and Srivastava (2014), Colaninno and Vourlidas (2015), etc.

CME mass:

Projections effect play crucial role. *(Vourlidas et al. 2000)*
For deriving total mass two viewpoints are necessary.

(Colaninno and Vouridas, 2009)

Nature of collision



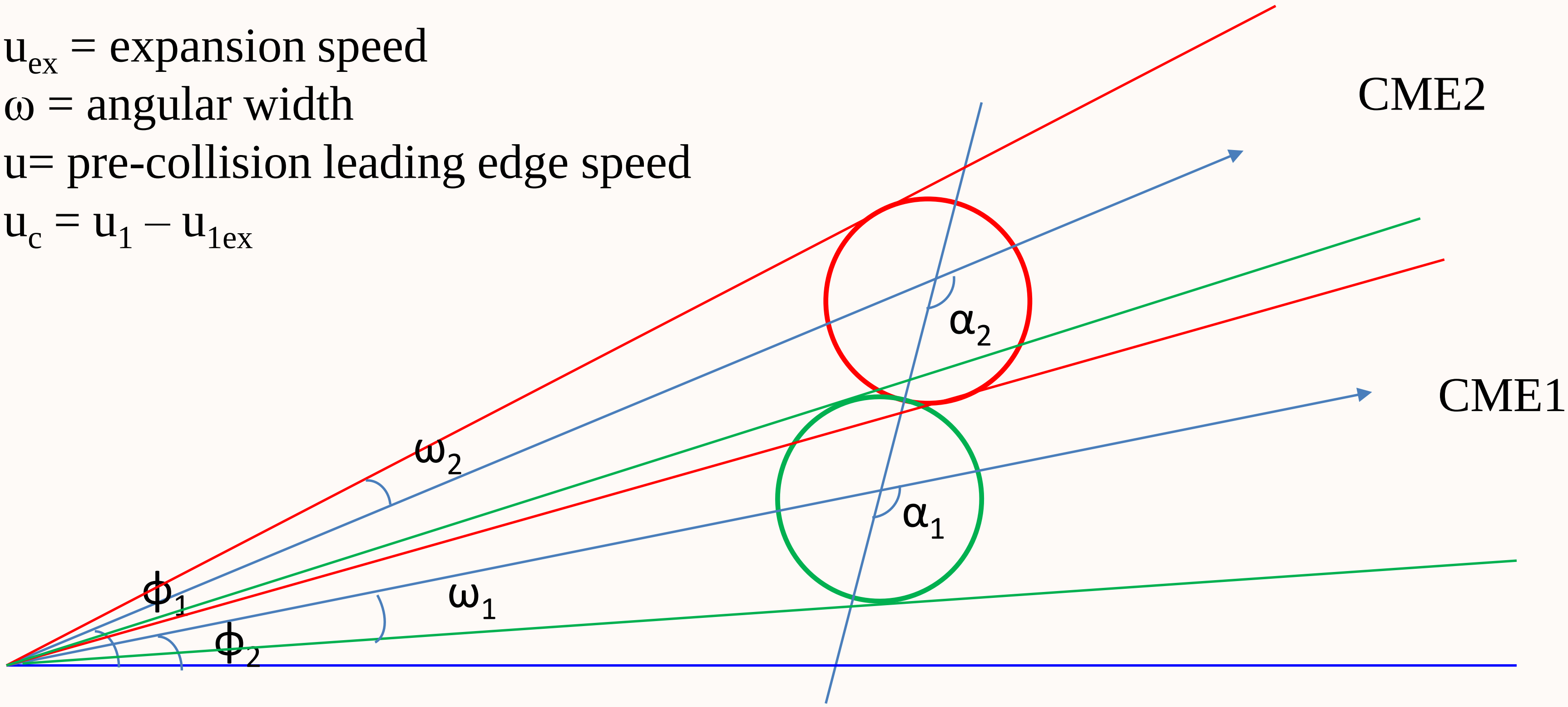
It may be helpful in arrival time prediction of the CMEs.

Earlier studies: Mostly in 1D having no account for CME expansion

STEREO observations: 3D kinematics from GCS, SSE or SSSE.
Mass using Colaninno and Vourlidas (2009) and Mishra and Srivastava (2014).

CME as an expanding sphere: oblique collision

u_{ex} = expansion speed
ω = angular width
u= pre-collision leading edge speed
$u_c = u_1 - u_{1ex}$



Observed post-collision speed may have large errors, therefore we find modified post-collision speeds values (v_{th}) for satisfying the conservation of momentum.

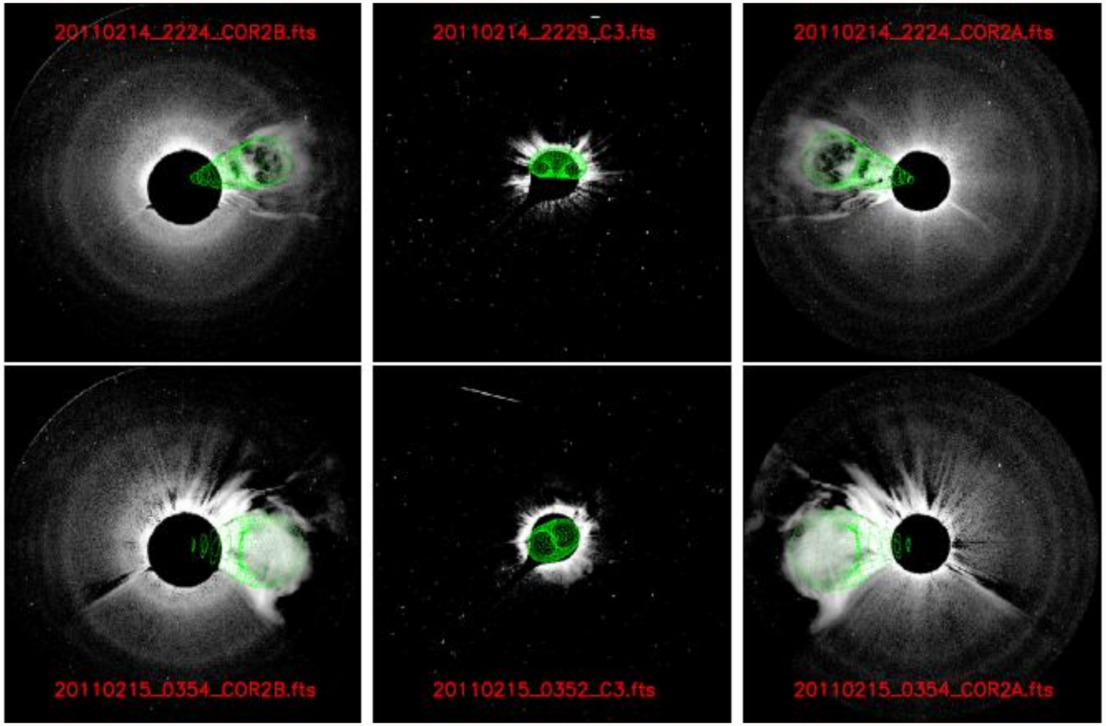
We define deviation $\sigma = \sqrt{[(v_{1th} - v_1)^2 + (v_{2th} - v_2)^2]/2}$

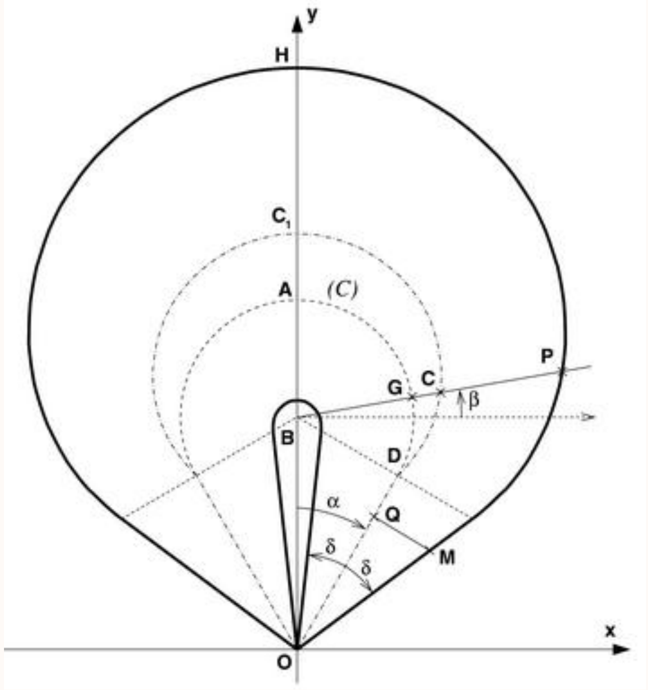
Large σ means unreliable value of “e”.

Selection of events based on the three criterion

Events	**STEREO observations**	**Collision sites**	**Collision phase**	**Accuracy**
2011 Feb 14-15	A & B	24 Rs	Well identified	Highest
2012 Jun 13-14	A & B	100 Rs	Well identified	Highest
2010 May 23-24	A & B	42 Rs	End phase poorly identified	Moderate
2012 Mar 4-5	A & B	160 Rs	Well identified	Moderate
2012 Nov 9-10	Only A	30 Rs	Well identified	Moderate
2013 Oct 25	Only B	37 Rs	Well identified	Moderate
2011 Aug 3-4	A & B	145 Rs	End phase not identified	Lowest
2012 Sep 25-28	Only A	170 Rs	Well identified	Lowest

CMEs of 2011 Feb 14-15: Graduated Cylindrical Shell model





CME1 (top panel) at 10 Rs: GCS parameters

Longitude=6°

Latitude=4°

Aspect ratio (κ)=0.28

Half angle (α)=32°

tilt angle (γ)=-8°

Speed = 420 km/s

CME2 (bottom panel) at 11 Rs: GCS parameters

Longitude=-3°

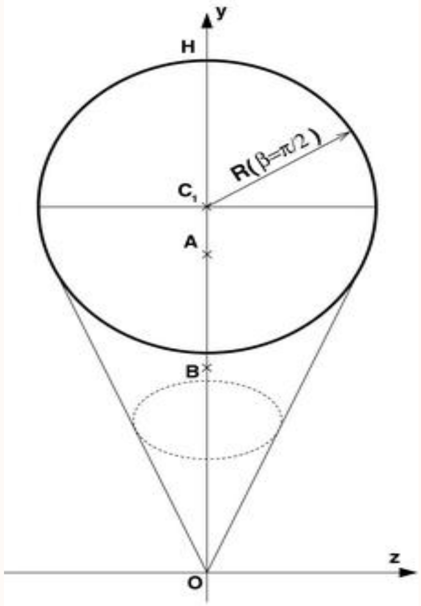
Latitude=-11°

κ=0.37

α=18°

γ=25°

Speed = 580 km/s

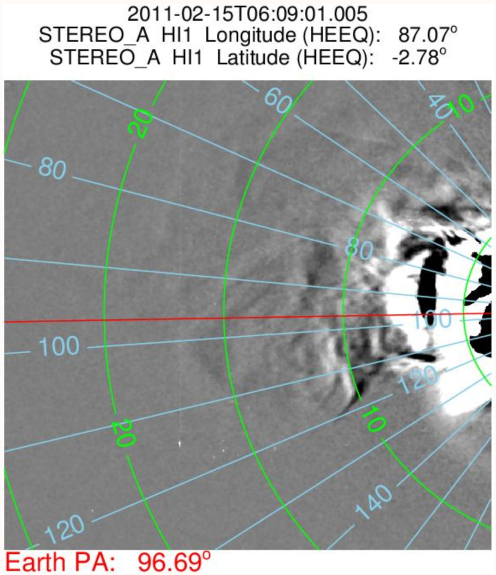


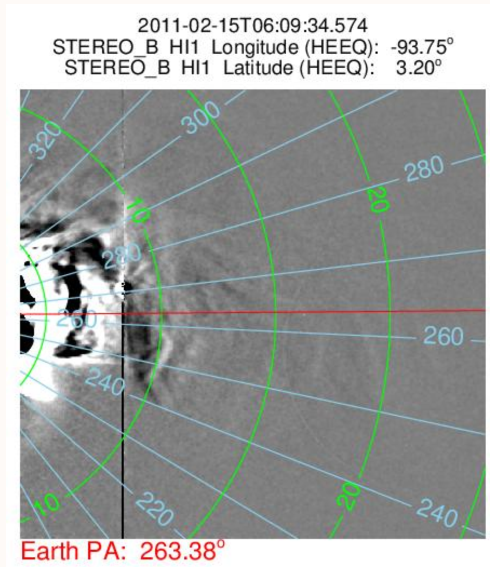
GCS parameters suggest for possible collision

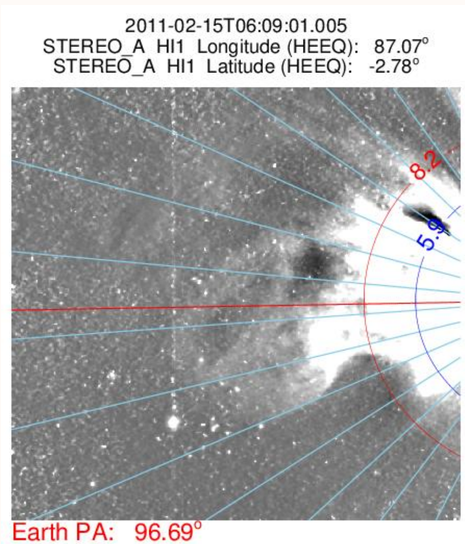
Events	Φ (^{0})	θ (^{0})	h (Rs)	$\omega_{eo}/2$ (^{0})	u (km/s)
Feb 14 at 18:24 UT	6	4	10	16	420
Feb 15 at 02:24 UT	-3	-11	11	22	580
Jun 13 at 13:25 UT	-15	-26	13.5	33	560
Jun 14 at 14:12 UT	-2	-31	14.2	37	900
May 23 at 18:30 UT	12	6	16.3	15	450
May 24 at 14:06 UT	26	-5	14.5	22	650
Mar 4 at 11:00 UT	-55	23	16.5	37	1025
Mar 5 at 04:00 UT	-40	41	10.7	44	1300
Nov 9 at 15:12 UT	2	-14	9.6	31	620
Nov 10 at 05:12 UT	6	-25	8.2	11	910
Oct 25 at 8:15 UT	-70	3	11.5	23	485
Oct 25 at 15:15 UT	-65	3	12.5	36	1000
Aug 3 at 14:00 UT	14	14	13	30	1100
Aug 4 at 04:12 UT	19	16	13	28	1700
Sep 25 at 11:24 UT	19	-11	15	20	500
Sep 28 at 00:12 UT	25	13	13	31	1200

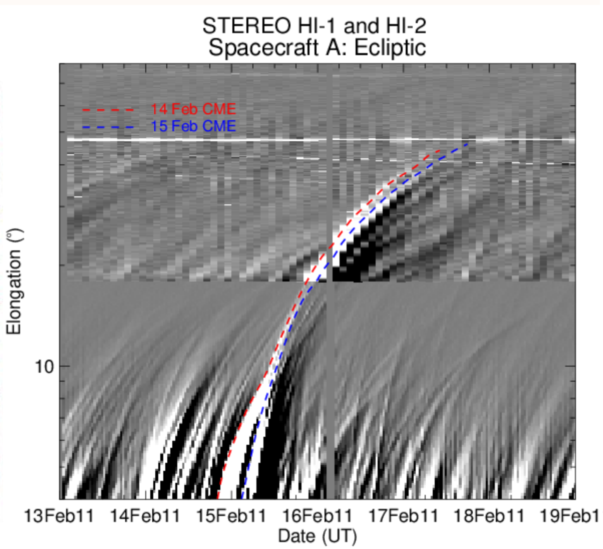
2011 Feb 14-15 CMEs in heliospheric imagers (HIs) field of view

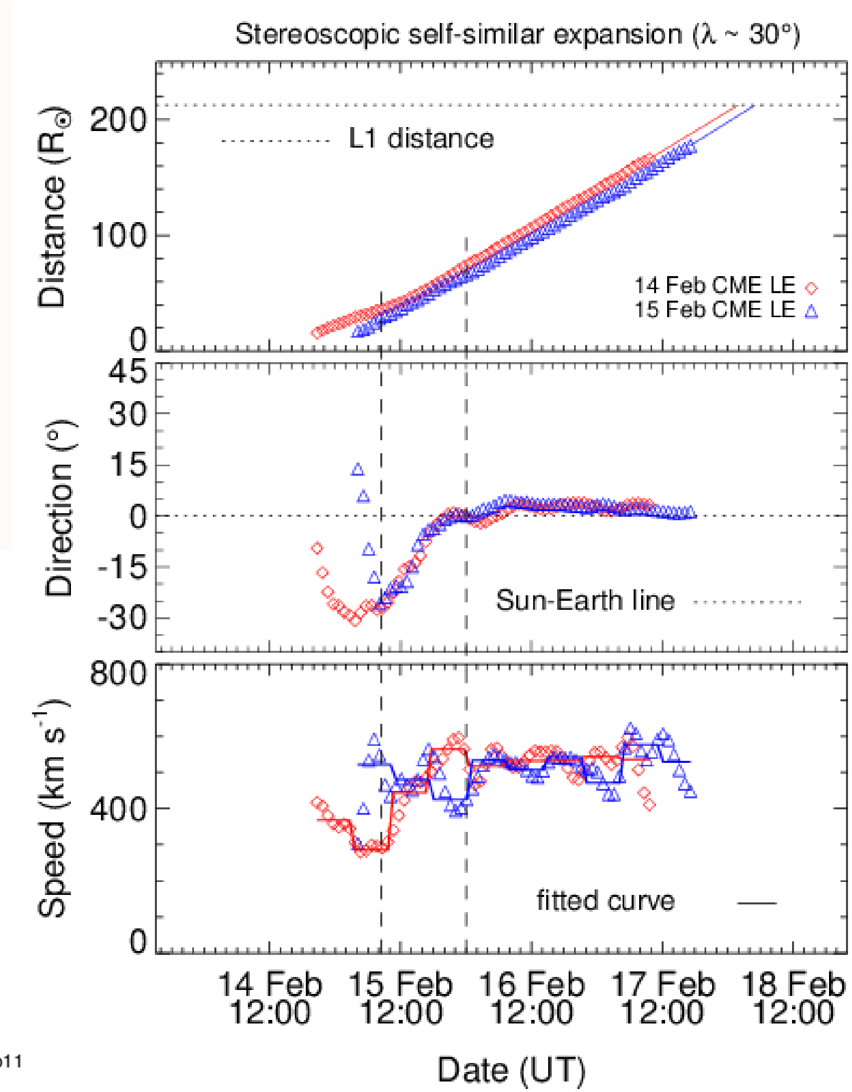
Davies et al. (2013)



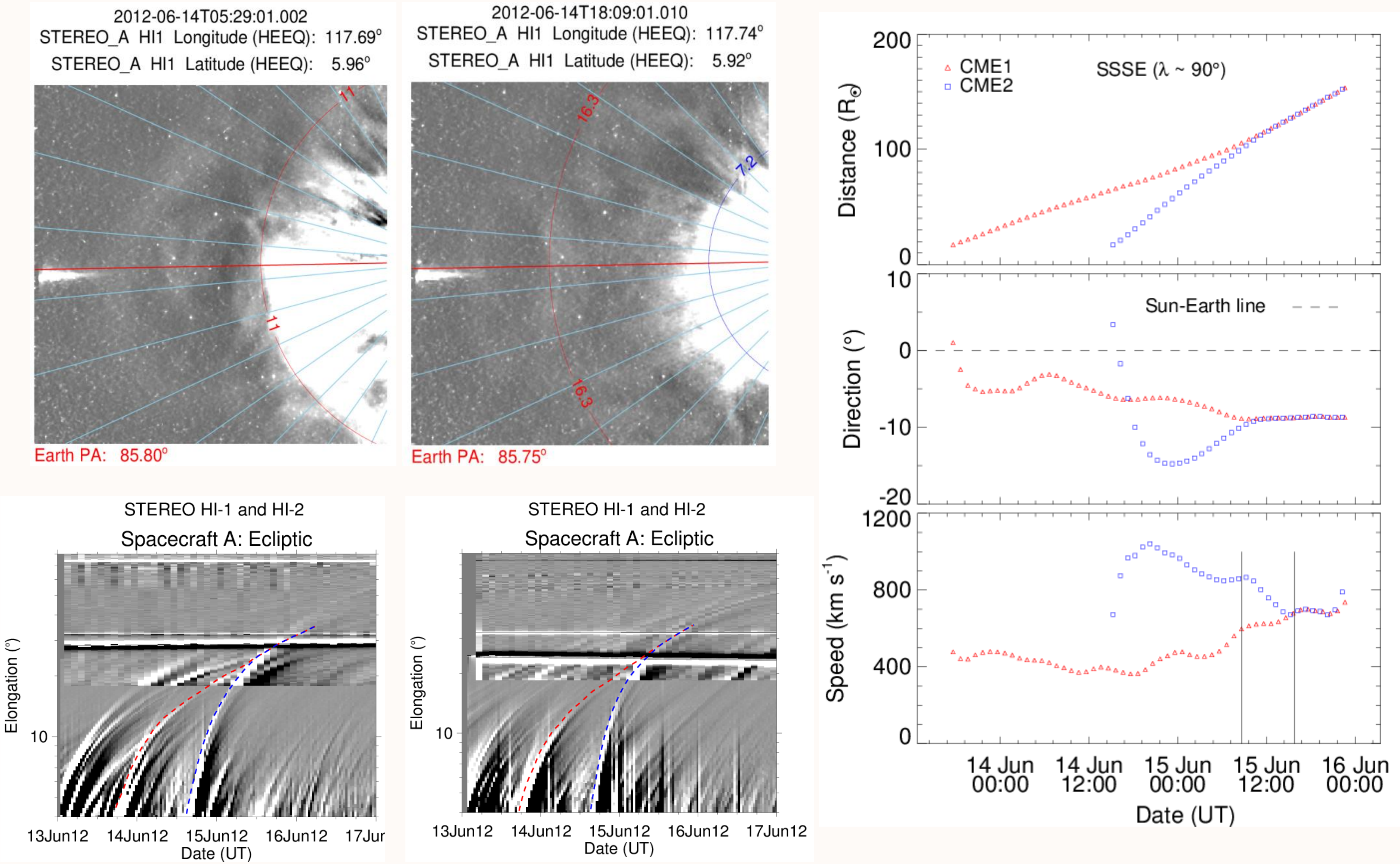








2012 June 13-14 CMEs in heliospheric imagers (HIs) field of view



CMEs parameters under oblique collision: all the cases

Events	e_{3D}	Ψ (^{0})	ΔT (hr)	R (Rs)	e_{1D}
2011 Feb 14-15	1.65	3.6	18	24	0.9
2012 Jun 13-14	0.35	21.9	7.2	100	0
2010 May 23-24	1.4	6.6	2.5	45	0.25
2012 Mar 4-5	0	12.3	4.8	160	0
2012 Nov 9-10	0	0.5	5.8	30	0.1
2013 Oct 25	1.0	7.9	7.0	37	0.45
2011 Aug 3-4	0.1	6.6	obscure	145	0
2012 Sep 25-28	2.0	9.7	16.8	170	0.8

- Direction of impact (Ψ) is the angle between the line connecting the centroids of two colliding CMEs and the propagation direction of CME2 relative to CME1.

- No clear dependence on direction of impact, distance of collision site and mass ratio for a particular nature of collision.

Super-elastic
Elastic
Inelastic
Perfectly inelastic

Sum of expansion speed

Ratio of expansion speed

Relative approaching speed

Relative separation speed

Ratio of mass

Events	e	u_{12exs} (km/s)	u_{2ex}/u_{1ex}	u_{12cjr} (km/s)	v_{21cjr} (km/s)	m_2/m_1
2011 Feb 14-15	1.65	208	2.2	130	230	0.8
2012 Jun 13-14	0.35	533	1.56	135	45	1.1
2010 May 23-24	1.4	237	2.2	100	135	0.5
2012 Mar 4-5	0	551	2.0	210	-10	2.9
2012 Nov 9-10	0	224	0.8	280	-60	0.48
2013 Oct 25	1.0	378	2.2	130	140	1.24
2011 Aug 3-4	0.1	341	1.4	145	-5.0	1.37
2012 Sep 25-28	2.0	305	2.1	110	250	5.53

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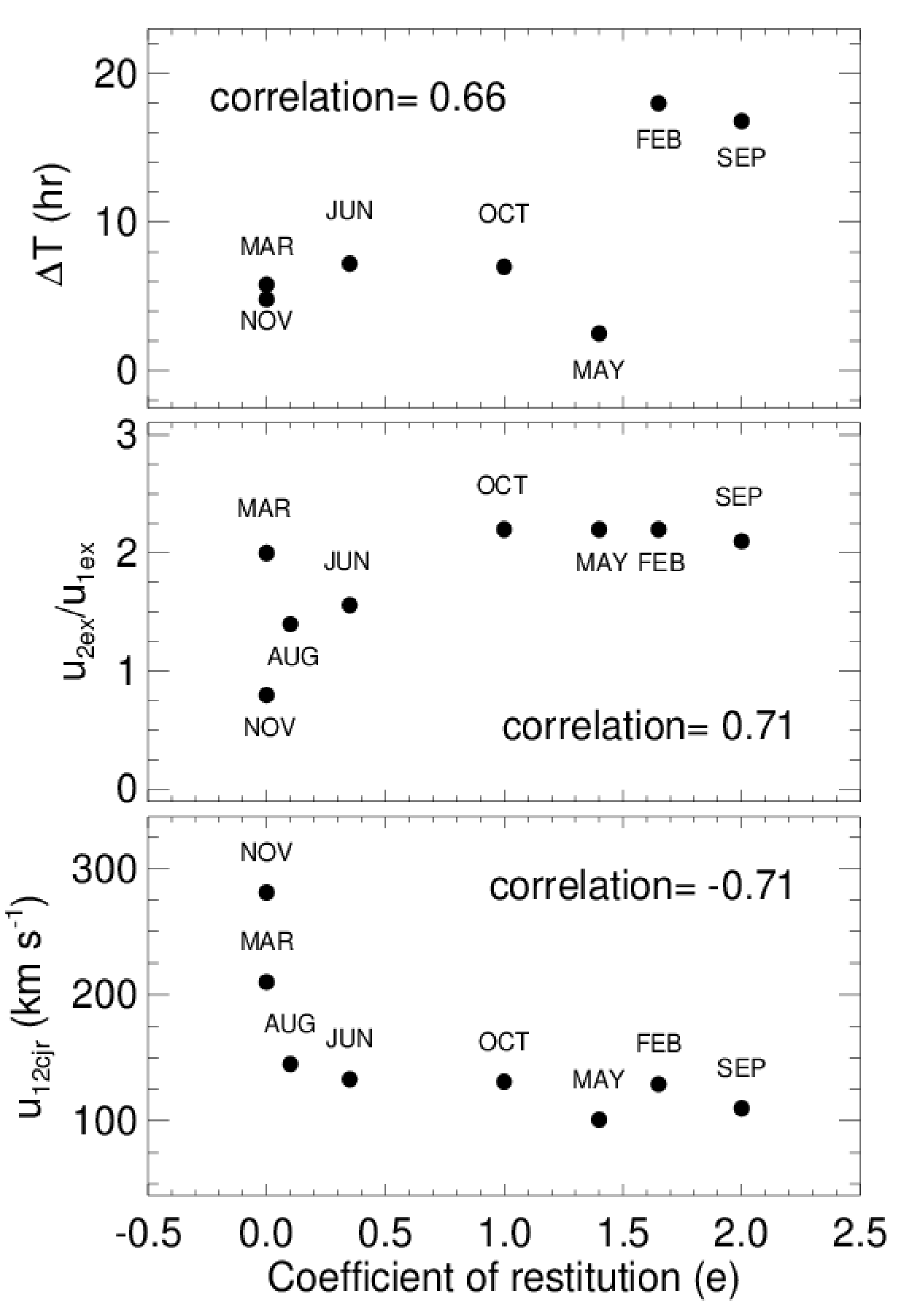


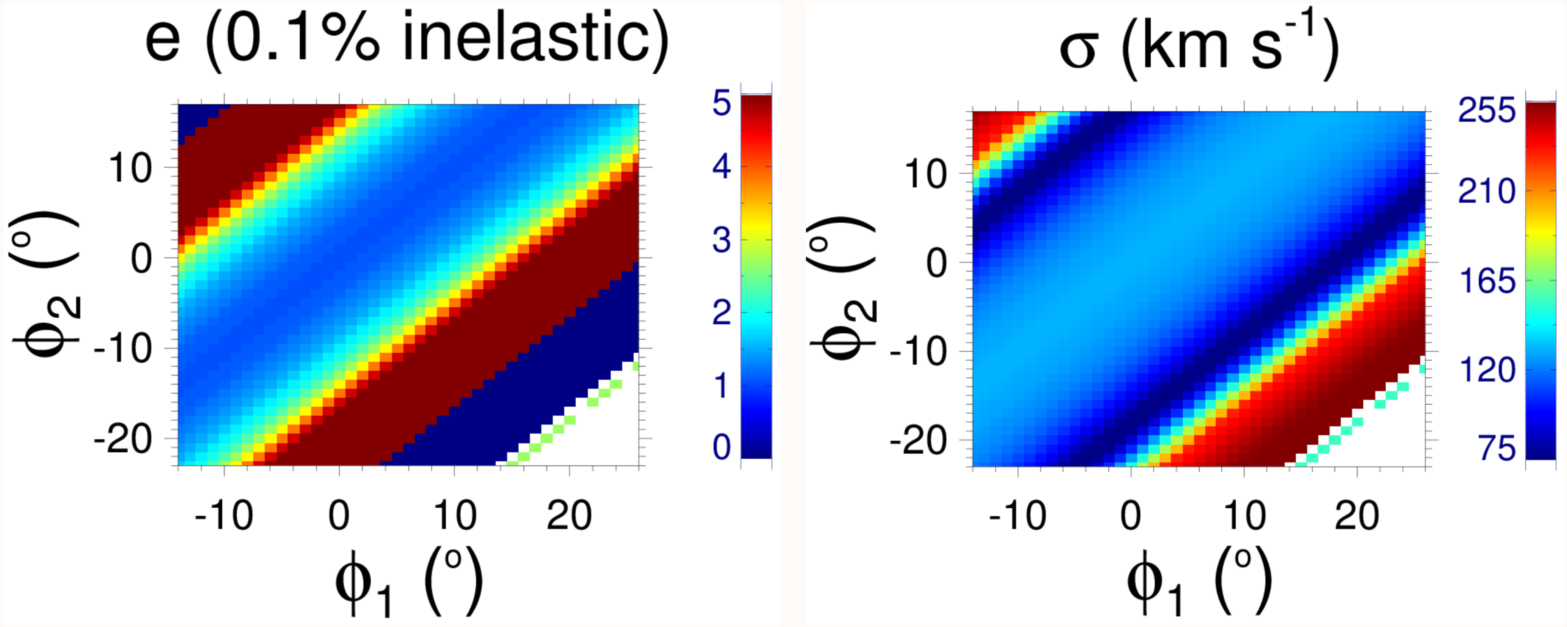
- 2 cases (Mar & Nov): perfectly inelastic,
- 2 cases (Jun & Aug) inelastic,
- 1 case (Oct) elastic
- 3 cases (Feb, May and Sept) super-elastic

- Smaller approaching speed and simultaneously larger value of ratio of CME2 to CME1 expansion speed leads to larger value of "e".

- May 23-24 CMEs have large errors for collision duration.
- Mar 4-5 CMEs have large errors for speeds.

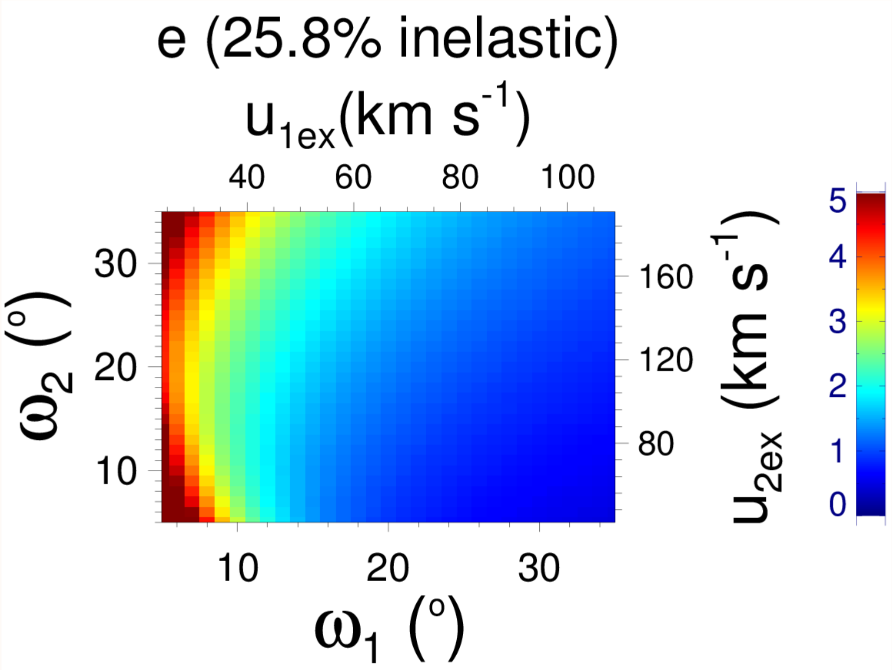
Mishra, W., Wang, Y., Srivastava, N., Shen, C., ApJ Supplement Series, (2017) Observed physical nature of collision is super-elastic for 2011 Feb 14-15 CMEs

Role of ± 20 degree uncertainties in the propagation direction



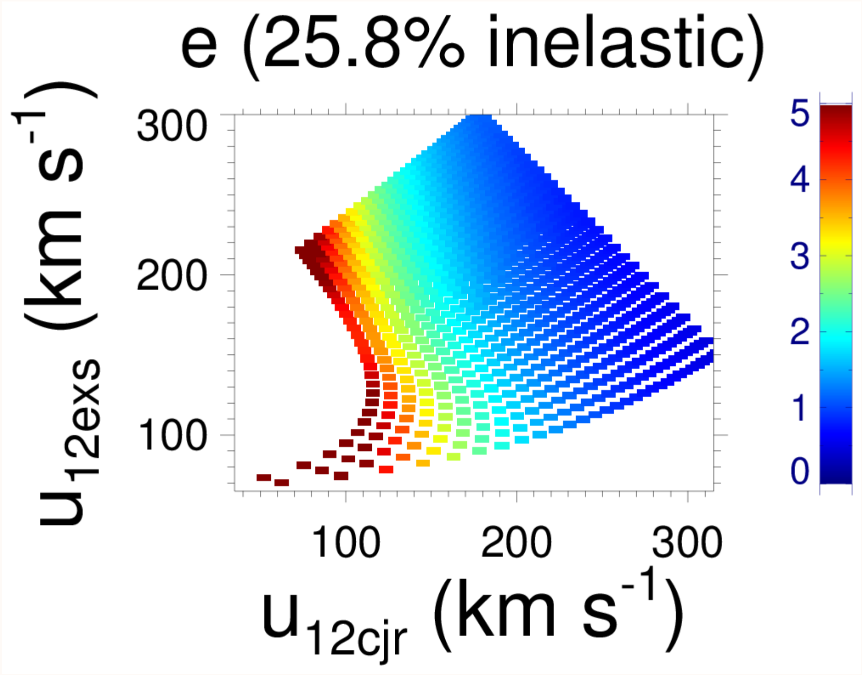
- Decrease in probability of super-elastic collision from 100% to 87.7%.
- 12.2% data points having e=0 violate the momentum exchange condition.
- "e" value for large value "σ" is unreliable and overlooking of which may be deceptive.

Effect of variation in half-angular width from 5 to 35 deg : 2011 Feb 14-15 CMEs



- Probability of super-elastic collision reduces to 73.2%.
- Super-elastic collision is more probable for larger value of ratio of CME2 to CME1 expansion speed

Collision nature with approaching speed and sum of expansion speed



- Low approaching speed favors for super-elastic collision.
- ±100 km/s uncertainties in the speed also shows the same rsults.

Effect of uncertainties: all the selected cases

Events	Nature of collision observed	Probability (%) due to uncertainties			
		Direction	**Width**	**Speed**	**Total**
2011 Feb 14-15	Super-elastic	87.7	73.2	88.8	~ 89-73
2012 Jun 13-14	Inelastic	65.1	50.4	93.8	~ 94-50
2010 May 23-24	Super-elastic	39.5	43.6	60.7	~ 61-44
2012 Mar 4-5	Perfectly inelastic	61.8	65	97.9	~ 98-62
2012 Nov 9-10	Perfectly inelastic	48.3	40.7	100	~ 100-41
2013 Oct 25	Elastic	15.1 (inelastic)	74.9 (inelastic)	49.6 (inelastic)	~ 75-15
2011 Aug 3-4	Inelastic	76.6	53.1	84.3	~ 84-53
2012 Sep 25-28	Super-elastic	89.2	60.2	48.8	~ 89-49

Effect of uncertainties: all the selected cases

Events	Nature of collision observed	Probability (%) due to uncertainties			
		Direction	Width	Speed	Total
2011 Feb 14-15	Super-elastic	87.7	73.2	88.8	~ 89-73
2012 Jun 13-14	Inelastic	65.1	50.4	93.8	~ 94-50
2010 May 23-24	Super-elastic	39.5	43.6	60.7	~ 61-44
2012 Mar 4-5	Perfectly inelastic	61.8	65	97.9	~ 98-62
2012 Nov 9-10	Perfectly inelastic	48.3	40.7	100	~ 100-41
2013 Oct 25	Elastic	15.1 (inelastic)	74.9 (inelastic)	49.6 (inelastic)	~ 75-15
2011 Aug 3-4	Inelastic	76.6	53.1	84.3	~ 84-53
2012 Sep 25-28	Super-elastic	89.2	60.2	48.8	~ 89-49

On taking into account the uncertainties, the nature of collision of three cases of CMEs (May, October and September) could not be assessed decisively.

Effect of relative expansion speeds and approaching speed (due uncertainties in angular width)

Ratio of CME2 to CME1 expansion speed for

Super-elastic   Inelastic

Events	u_{2ex}/u_{1ex} for e>1	u_{2ex}/u_{1ex} for 0<e<1	e>1 among $(u_{12exs}/u_{12cjr})>1$ (%)	e>1 among $(u_{12exs}/u_{12cjr})>2$ (%)
2011 Feb 14-15	0.6-7.9	0.38-1.54	84.7	100
2012 Jun 13-14	0.64-4.8	0.44-2.0	31.6	42.8
2010 May 23-24	0.56-7.6	0.36-2.8	48.9	64
2012 Mar 4-5	0.89-8.7	0.74-5.6	11.1	24.7
2012 Nov 9-10	5.6-7.8	0.75-6.8	2	5.8
2013 Oct 25	1.6-7.5	0.39-2.7	32.1	57.9
2011 Aug 3-4	2.8-6.8	0.89-4.4	11.8	21.2
2012 Sep 25-28	0.94-7.2	0.35-1.44	74.1	99.7

Larger the ratio of CME2 to CME1 expansion speed: super-elastic (column 2nd)

Larger ratio of sum of expansion speed to approaching speed

↓

Probability for Super-elastic

Events	**u_{2ex}/u_{1ex} for e>1**	**u_{2ex}/u_{1ex} for 0<e<1**	**e>1 among $(u_{12exs}/u_{12cjr})>1$ (%)**	**e>1 among $(u_{12exs}/u_{12cjr})>2$ (%)**
2011 Feb 14-15	0.6-7.9	0.38-1.54	84.7	100
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Decrease in approaching speed favors for super-elastic collision (col. 4^{th} and 5^{th})

Conclusions

- The crucial pre-collision parameters of the CMEs responsible for increasing the probability of a super-elastic collision are, in descending order of priority, their lower approaching speed, expansion speed of the following CME higher than the preceding one, and a longer duration of the collision phase.

- The expansion speed of the CMEs plays a greater role than any other parameters.

- The change in direction indirectly may alter the relative contributions of expansion speeds in the approaching speeds of the CMEs centroids.

- The direction of impact, distance of a collision site from the Sun, and mass ratio of the CMEs do not favor for a particular nature of collision.

- In head-on (1D) collision assumption, the value of “e” is underestimated.

- Nature of collision of the CMEs should only be determined with a finite probability for a specific nature.

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Discussion

- Large expansion speed => large internal pressure (harder the CMEs? physical nature ?)

- Snow plough effect for the mass. Does the total mass participate?
- Difficult to know the error in kinematics: deceleration, acceleration, deflection and over-expansion before reaching to L1
- Speeds are overestimated from SSE or SSSE => overestimation of “e” value.

- Remote interaction probably begins before the collision is observed.
- The marked start of collision is postponed => overestimation of “e” value
- Ignored contribution of CME2 driven shock => underestimation “e” value
- Complex collision: different time scales for compression, subsequent expansion and exchange of momentum.

- No consideration of rotation and deflection: Only linear speeds of centroids
- No consideration of effect of solar wind
- J-maps are along the ecliptic

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- Large expansion speed => large internal pressure (harder the CMEs? physical nature ?)

- Snow plough effect for the mass. Does the total mass participate?
- Difficult to know the error in kinematics: deceleration, acceleration, deflection and over-expansion before reaching to L1
- Speeds are overestimated from SSE or SSSE => overestimation of "e" value.

- Remote interaction probably begins before the collision is observed.
- The marked start of collision is postponed => overestimation of "e" value
- Ignored contribution of CME2 driven shock => underestimation "e" value
- Complex collision: different time scales for compression, subsequent expansion and exchange of momentum.

- No consideration of rotation and deflection: Only linear speeds of centroids
- No consideration of effect of solar wind
- J-maps are along the ecliptic

THANKING YOU !