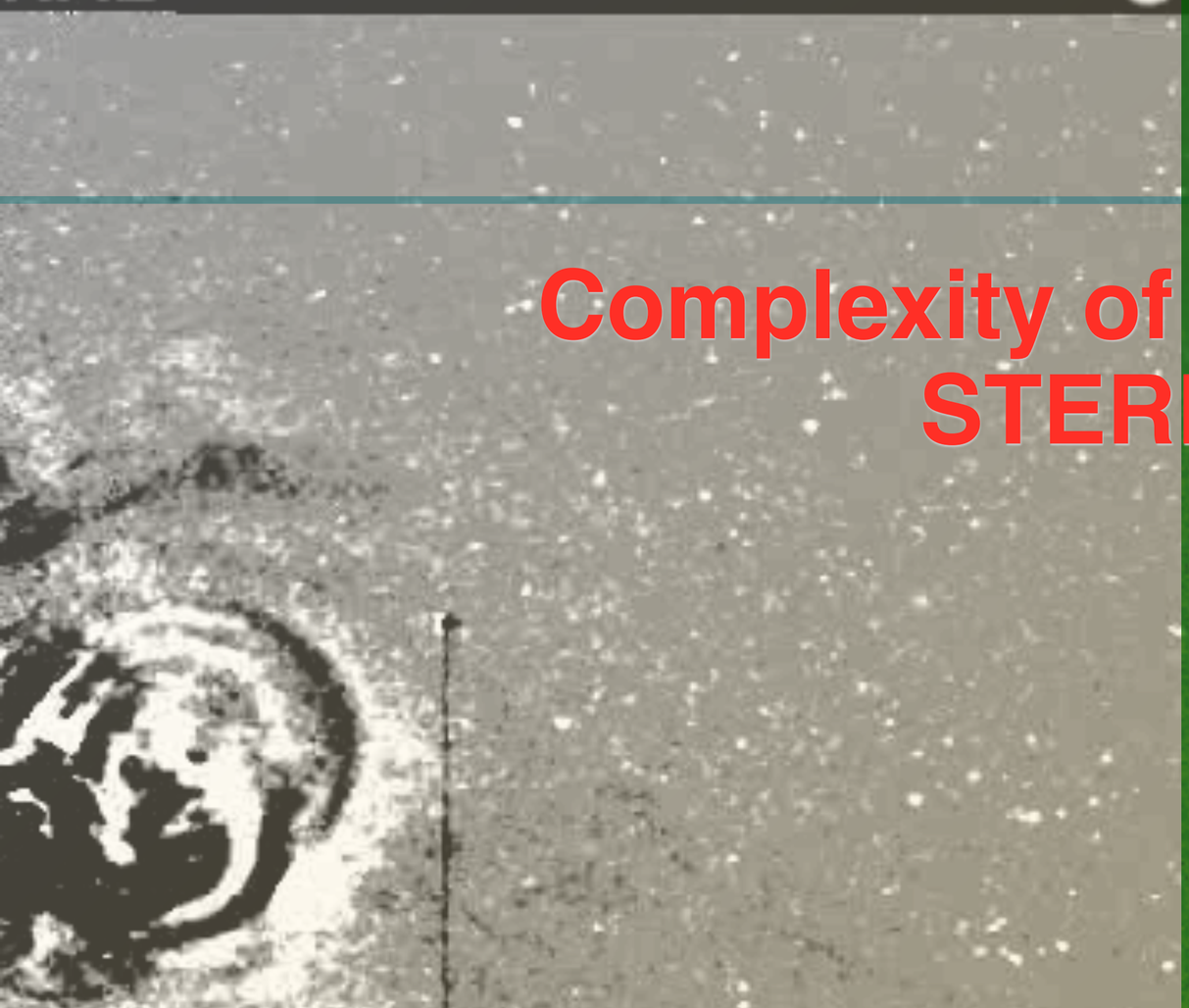
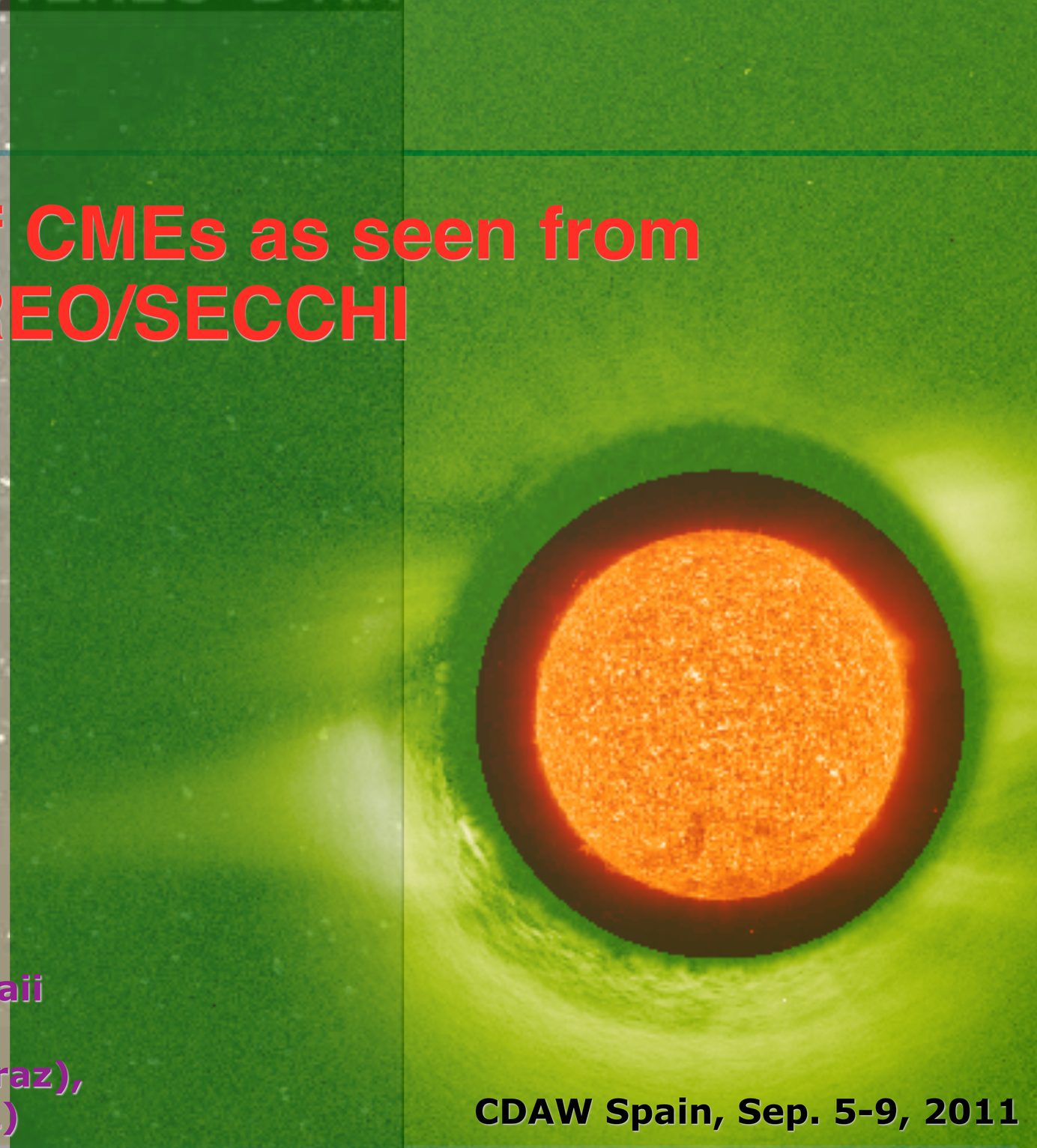
Complexity of CMEs as seen from STEREO/SECCHI





Noé Lugaz

Institute for Astronomy - University of Hawaii

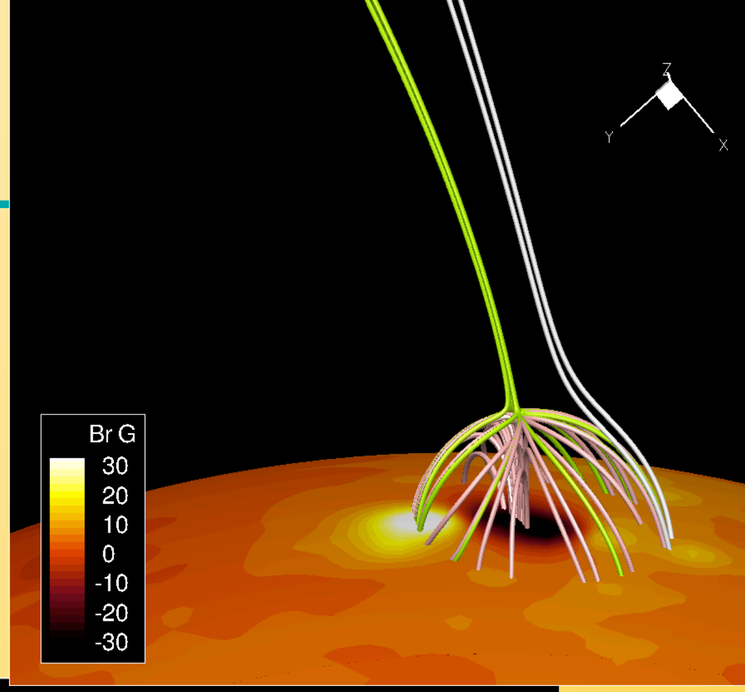
with the help of

P. Kintner (REU, U. Rochester), C. Möstl (U. Graz), I. Roussev (IfA), C. Davis & J. Davies (RAL)

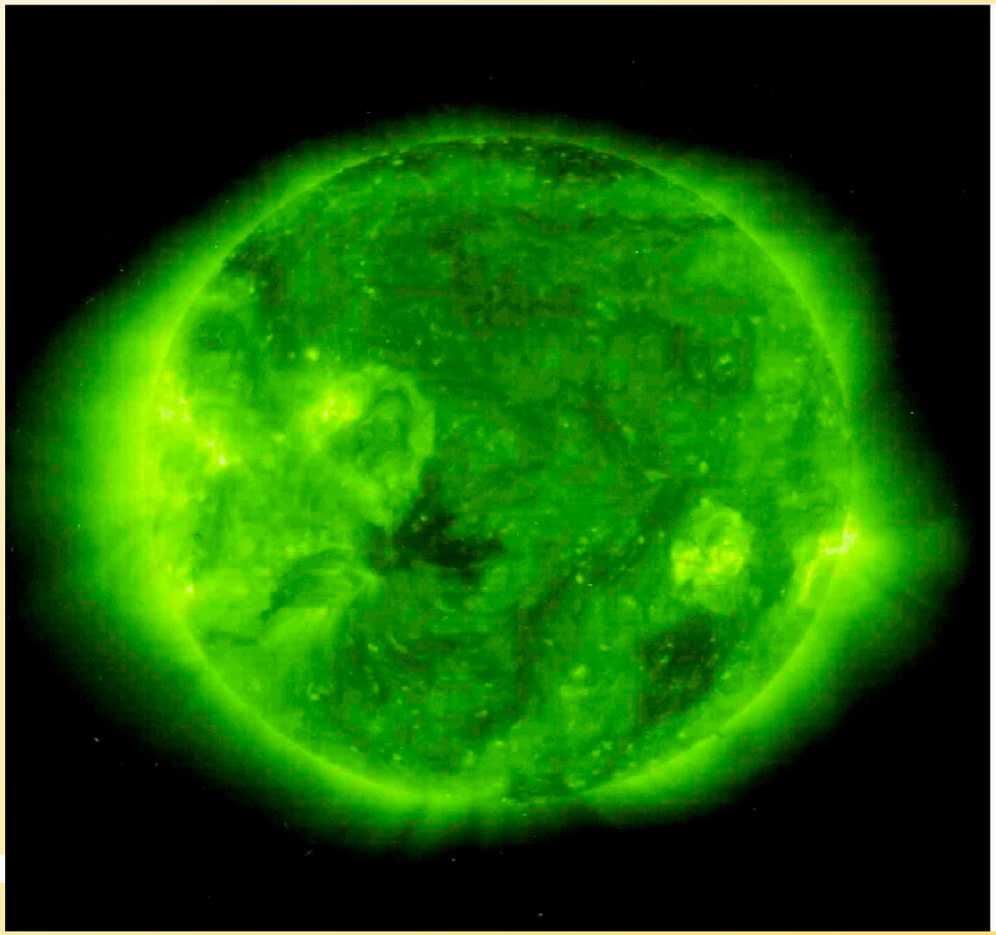
CDAW Spain, Sep. 5-9, 2011

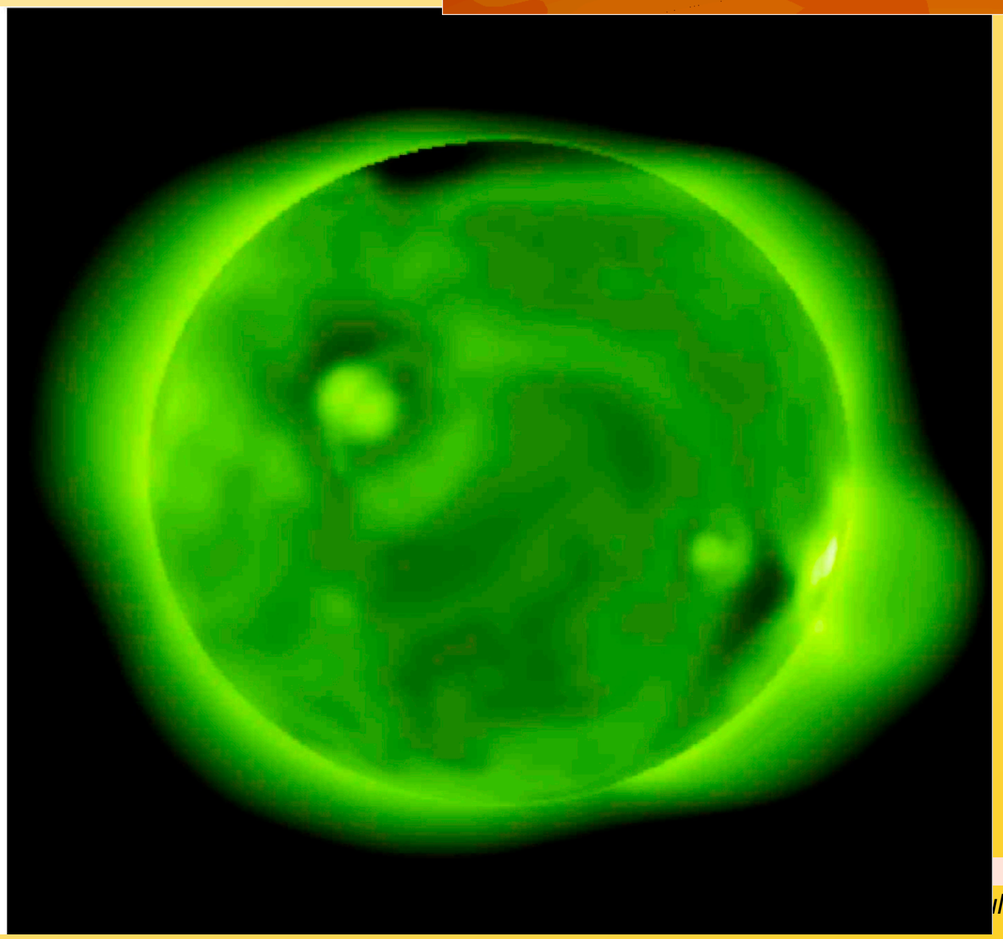
Deflection from CH

CME from anemone active region (inside a CH) published in Lugaz et al., **ApJ**, 2011



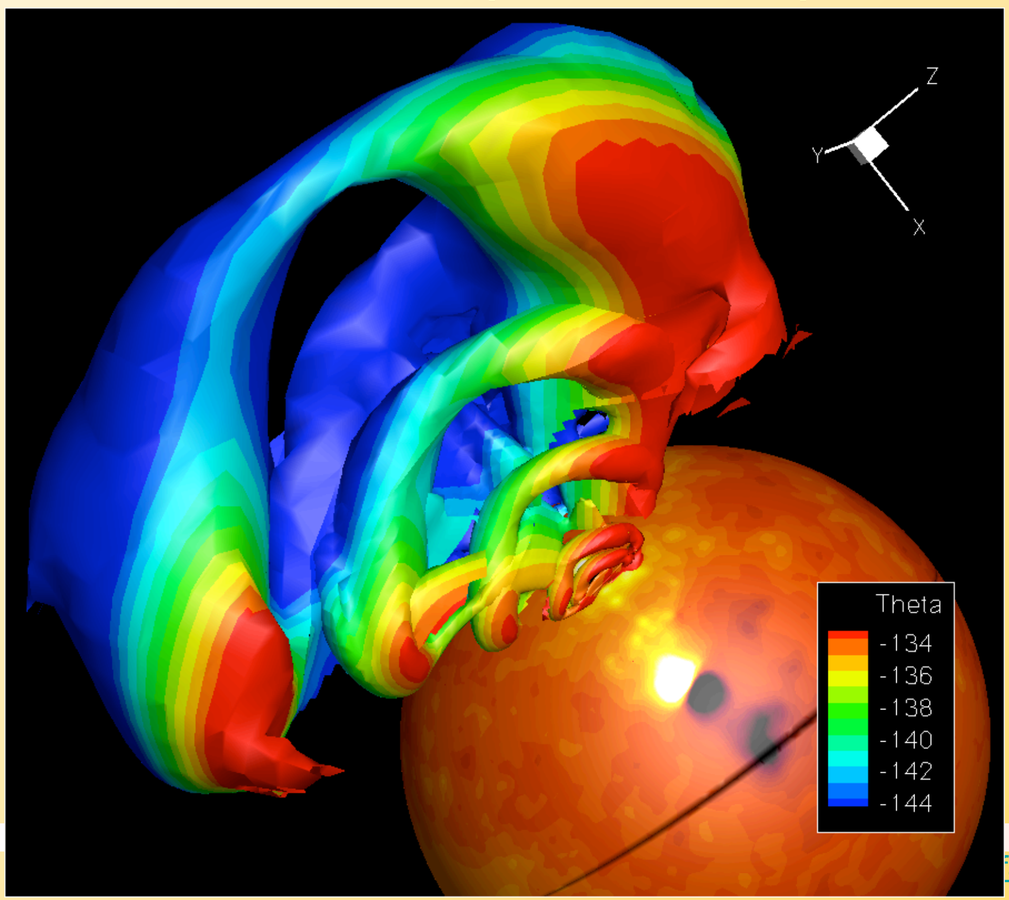
2005 August 22 (Asai et al., **JGR**, 2009)

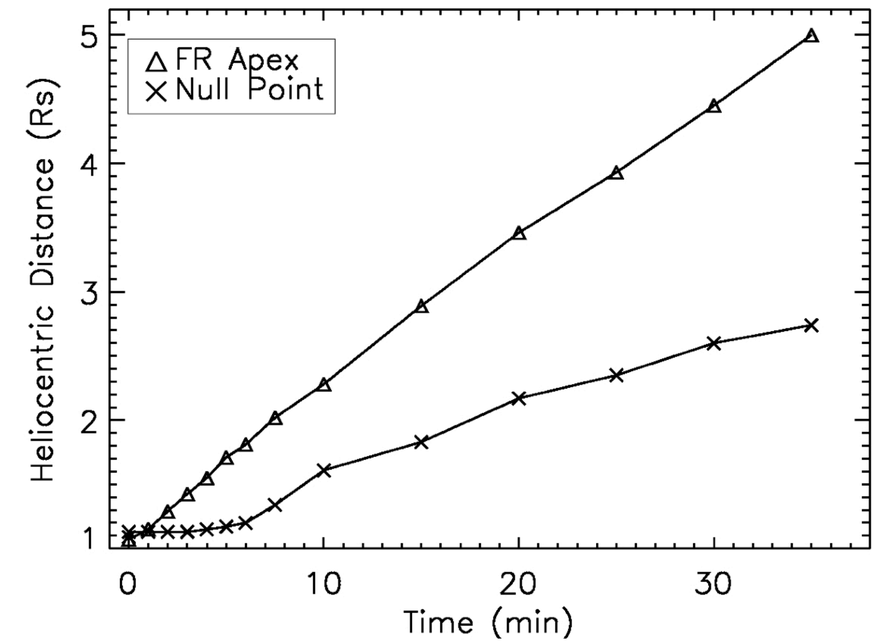


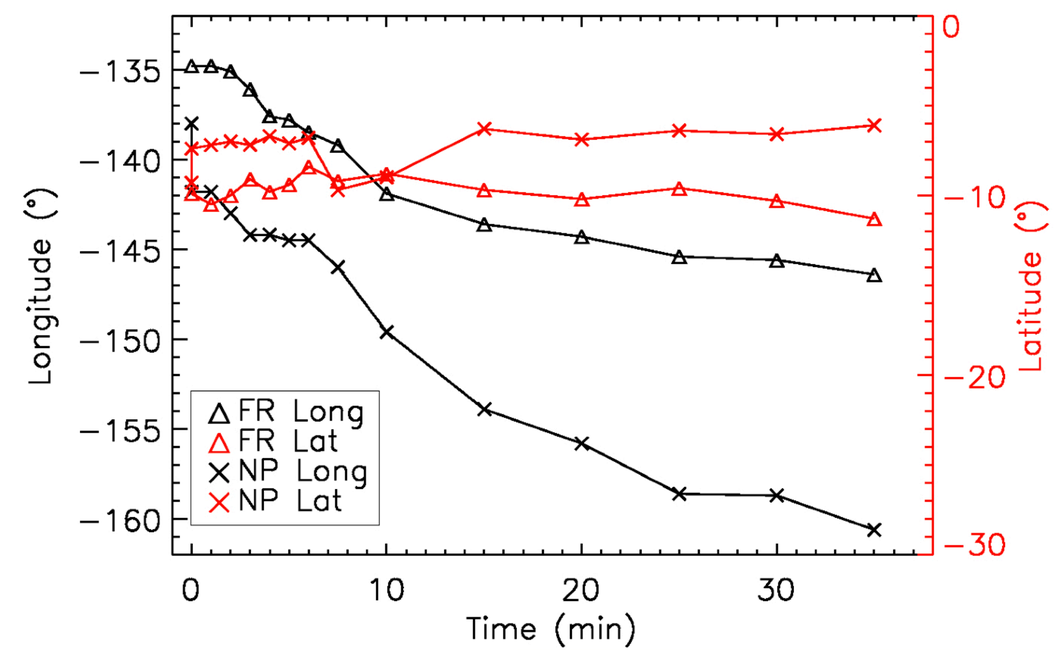


Deflection

- The FR is deflected by about 10° during the first 10 R_{sun} of propagation.
- East deflection is consistent with the Lorentz force between the south current and the positive open field.







Deflection (movie)

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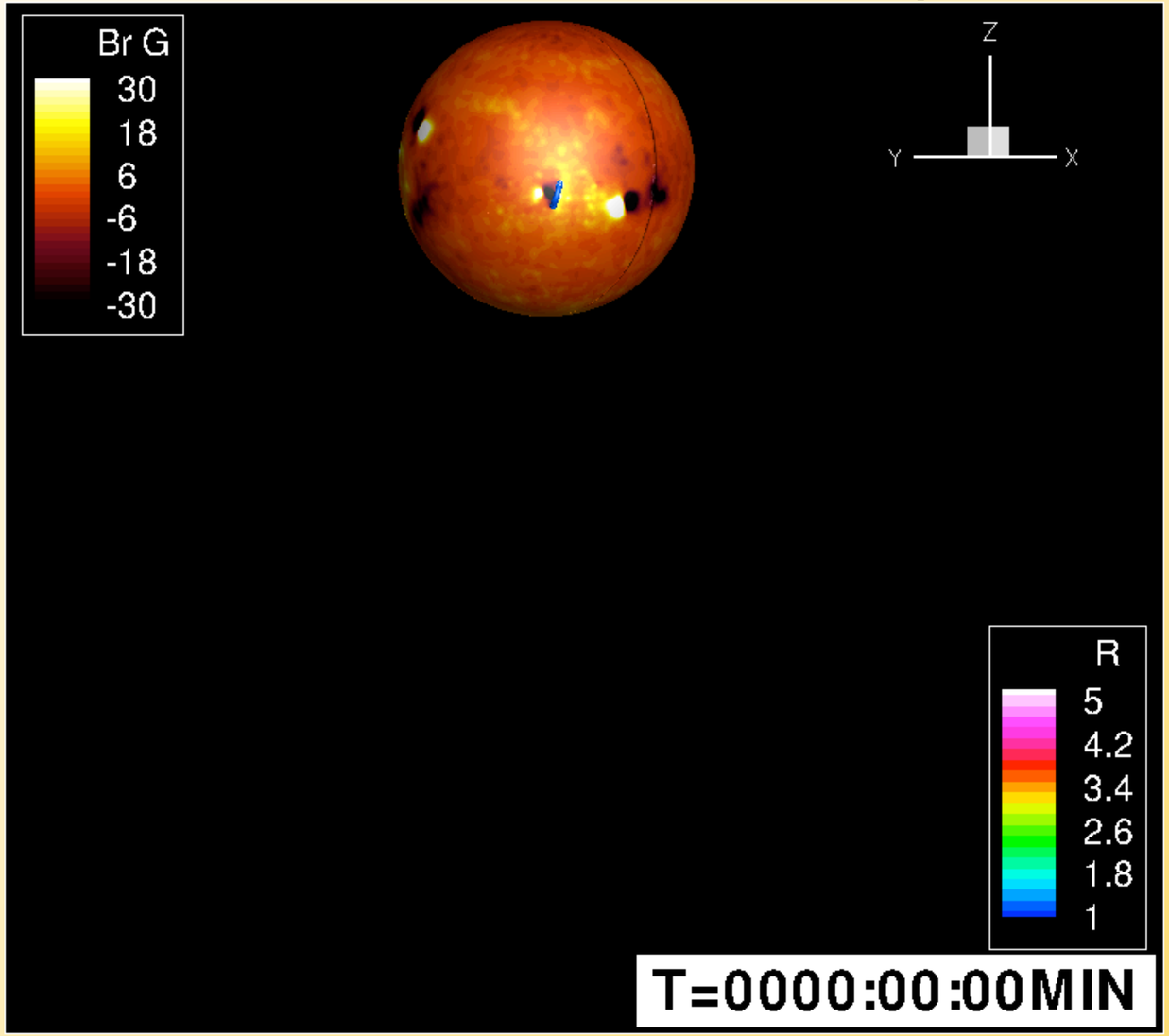

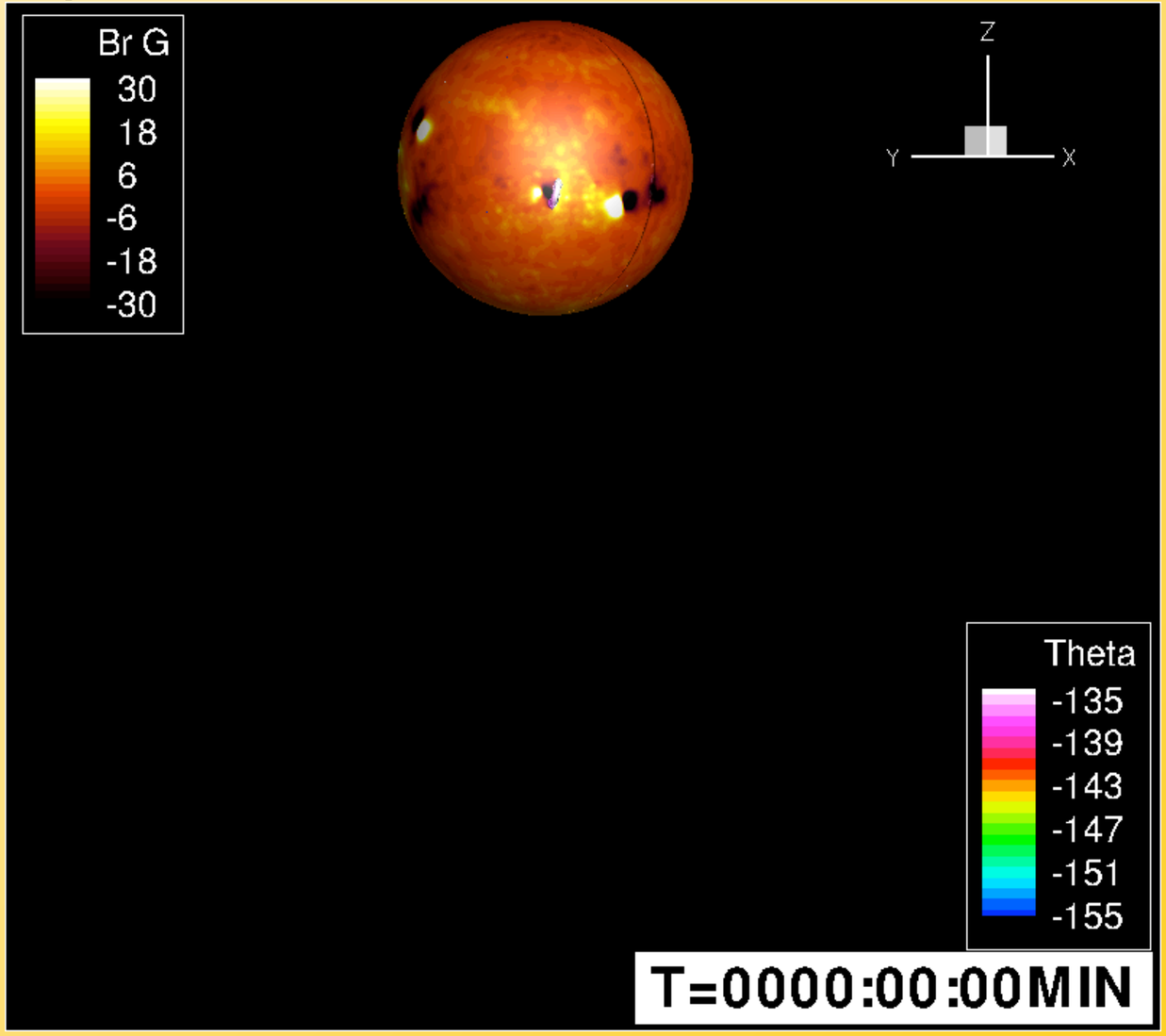

CME Tracking at Large Angular Separation

- How long will we be able to image Earth-directed CMEs with SECCHI?
- Let's look at STEREO-directed CMEs observed by STEREO/SECCHI:
- Example: Dec. 4, 2009 CME observed remotely by ST- B and in situ by ST-A; **A-B separation 130º**, similar to ST-Earth separation in Dec. 2012.

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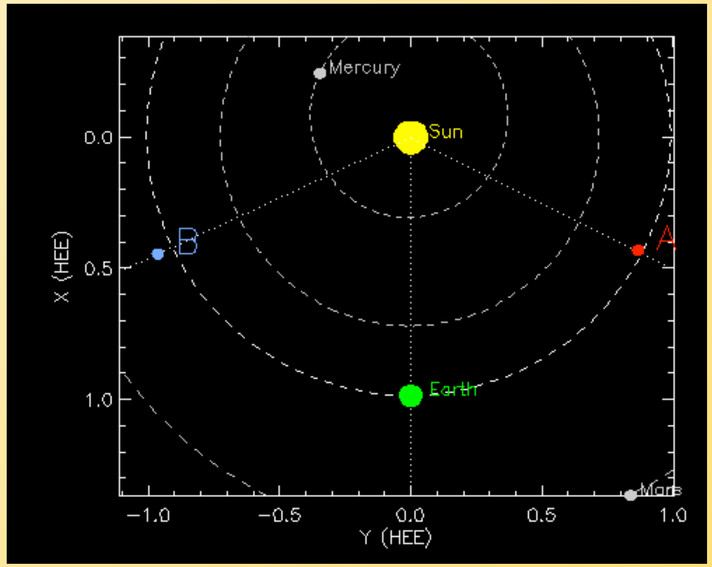

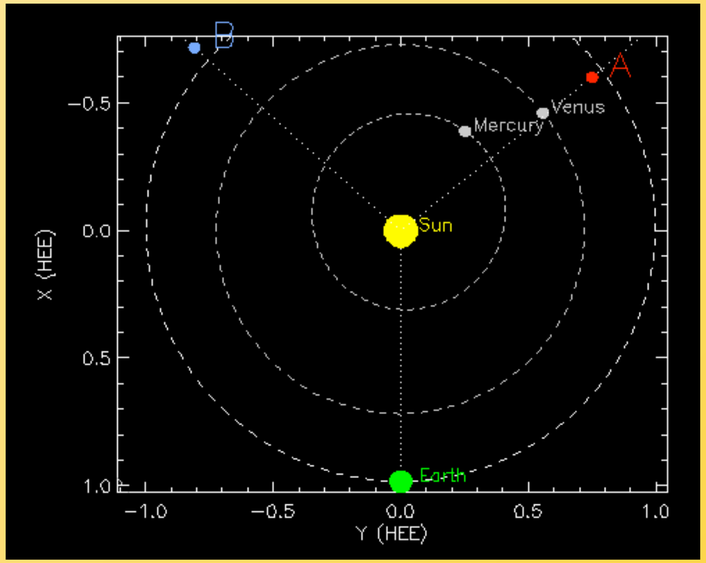

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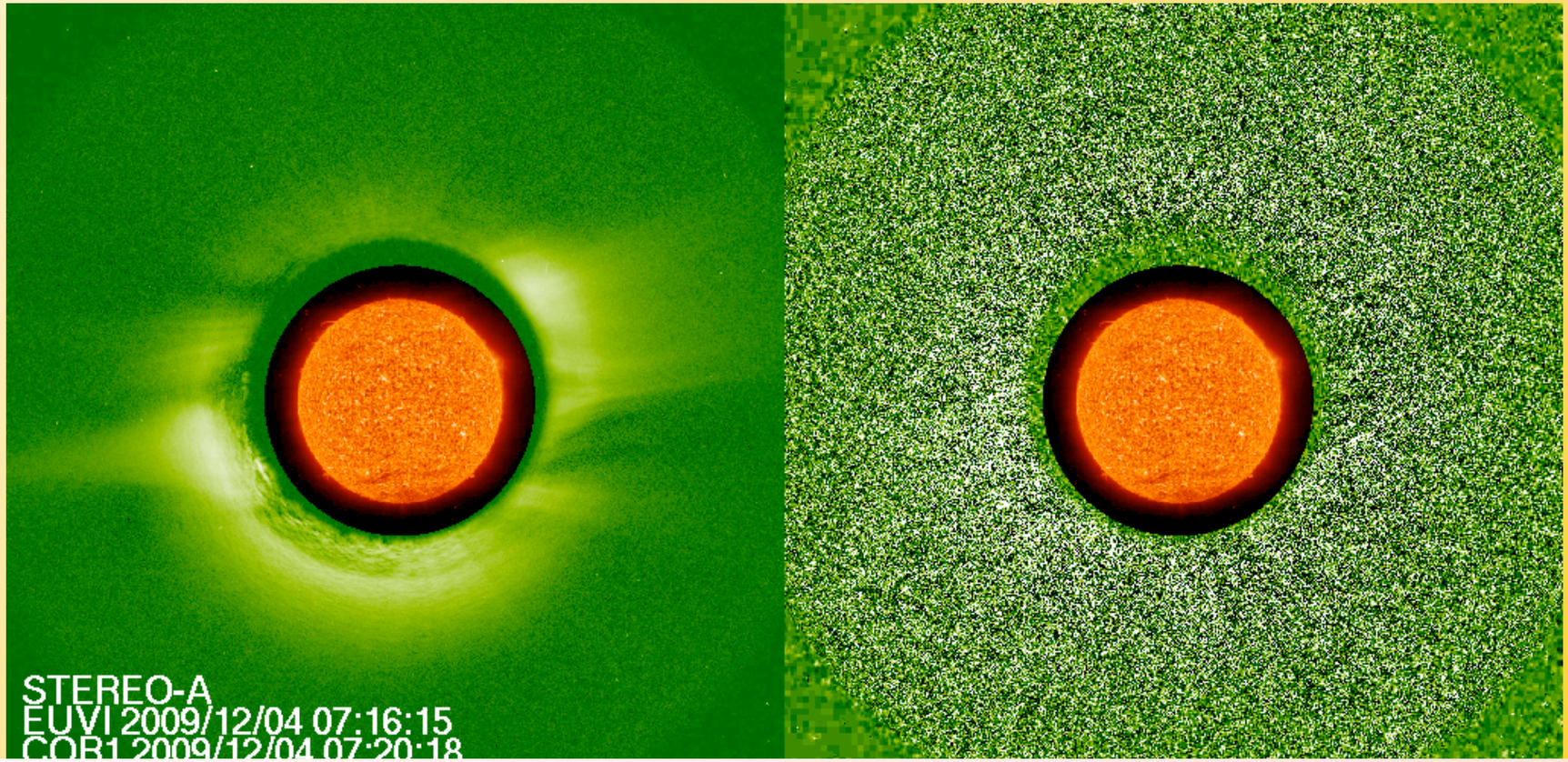

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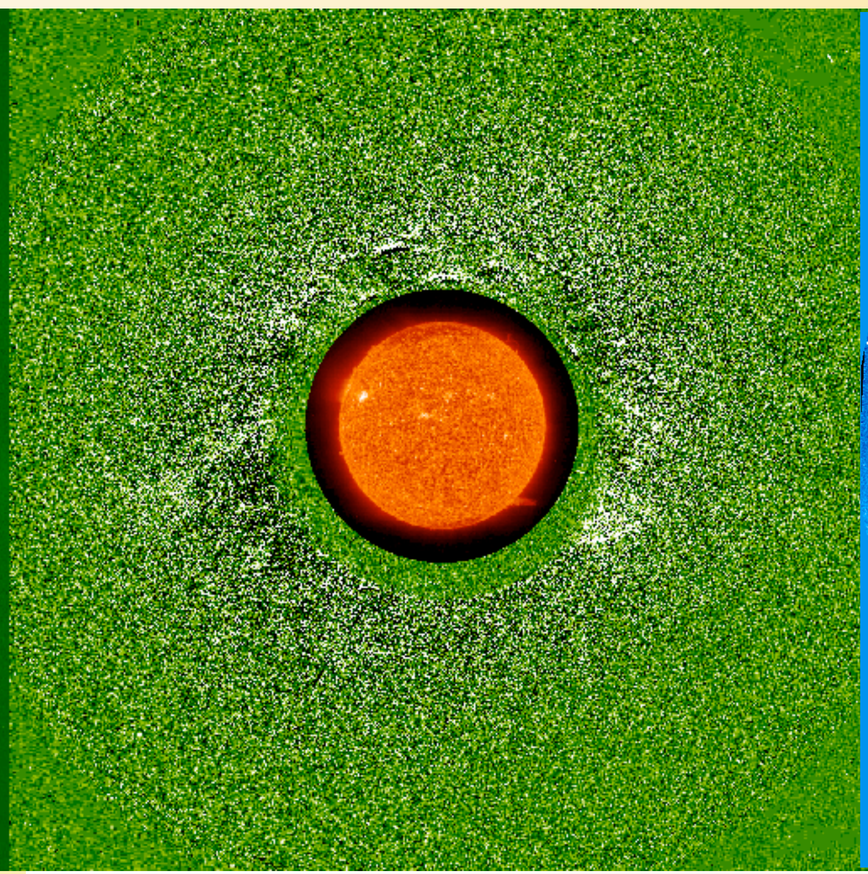
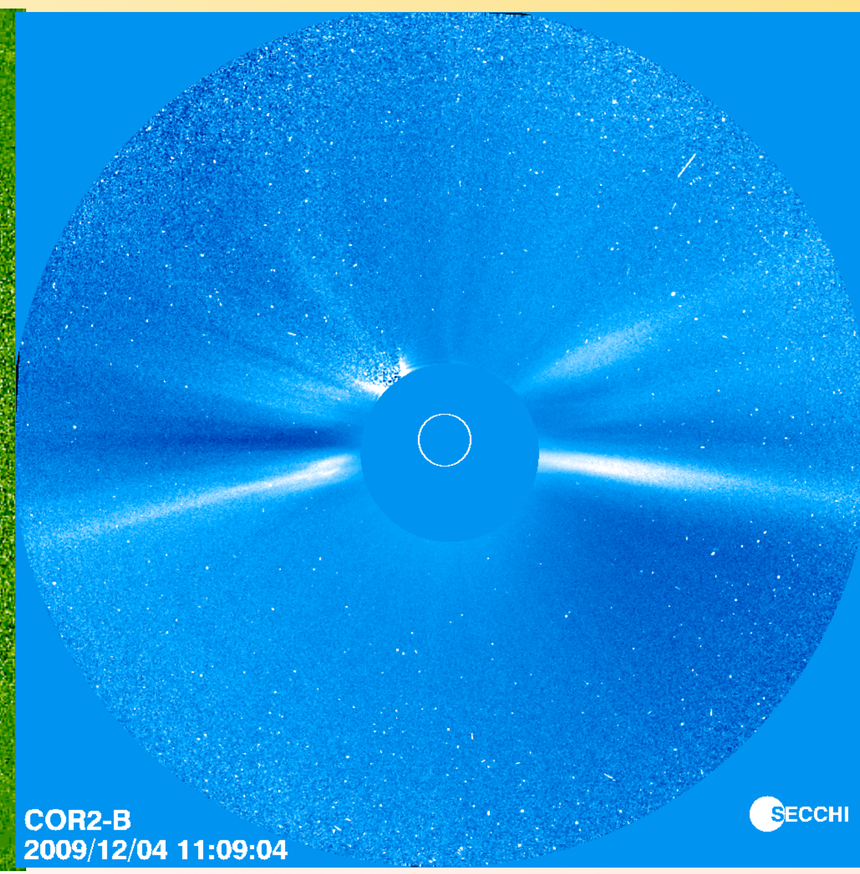
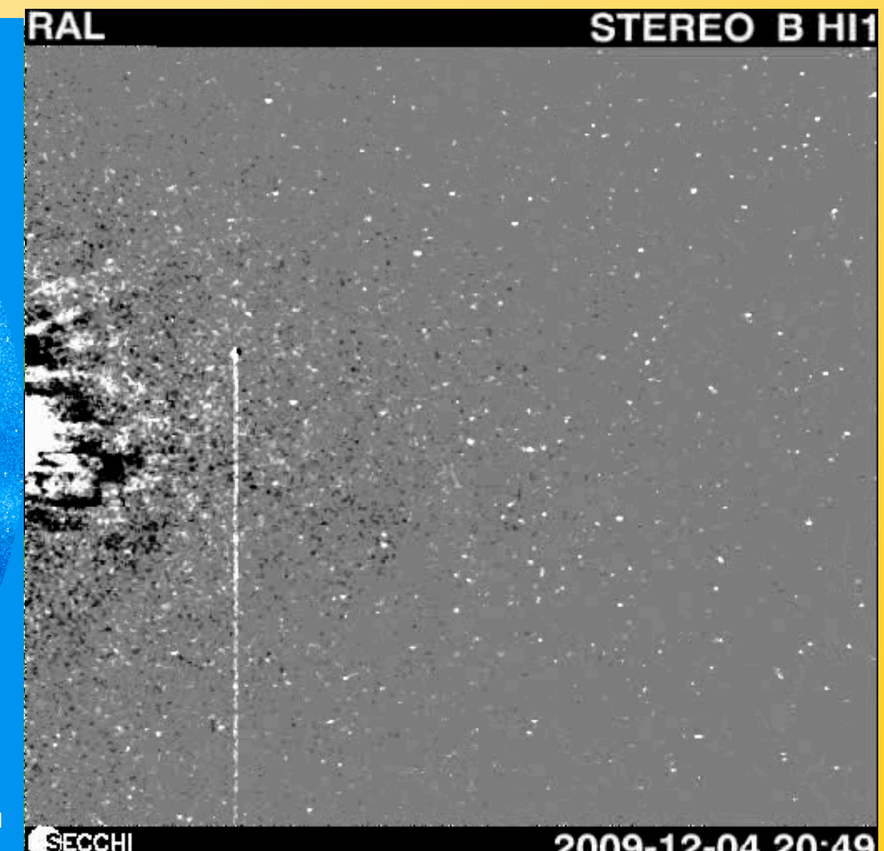
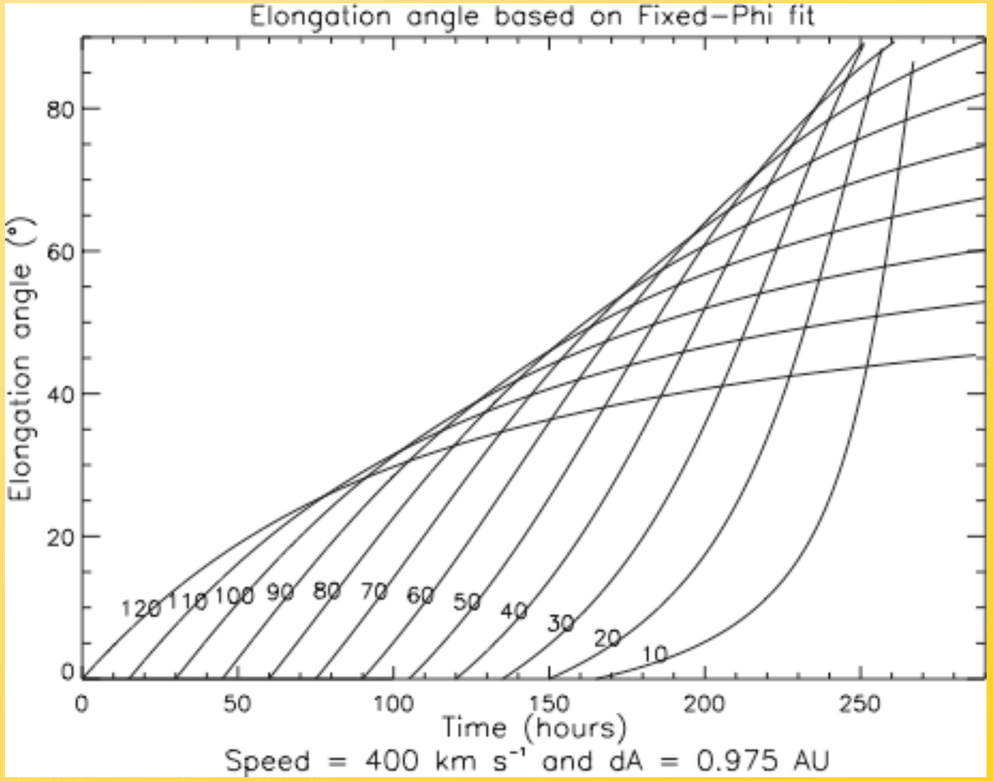






Fitting Methods

- Idea of fitting methods is that CMEs with a constant linear speed have different angular acceleration depending on their direction.
- Angle vs time profiles can be fitted to analytical formula assuming constant speed, constant direction.
- In addition, this is based on the Fixed-Phi approximation, i.e. the same part of the CME is imaged at all times.
- Harmonic Mean (HM) method of Lugaz et al. (2009) takes into account that the same part of the CME is not observed at all times.
- A fitting method based on the HM method was devised in Lugaz (2010).

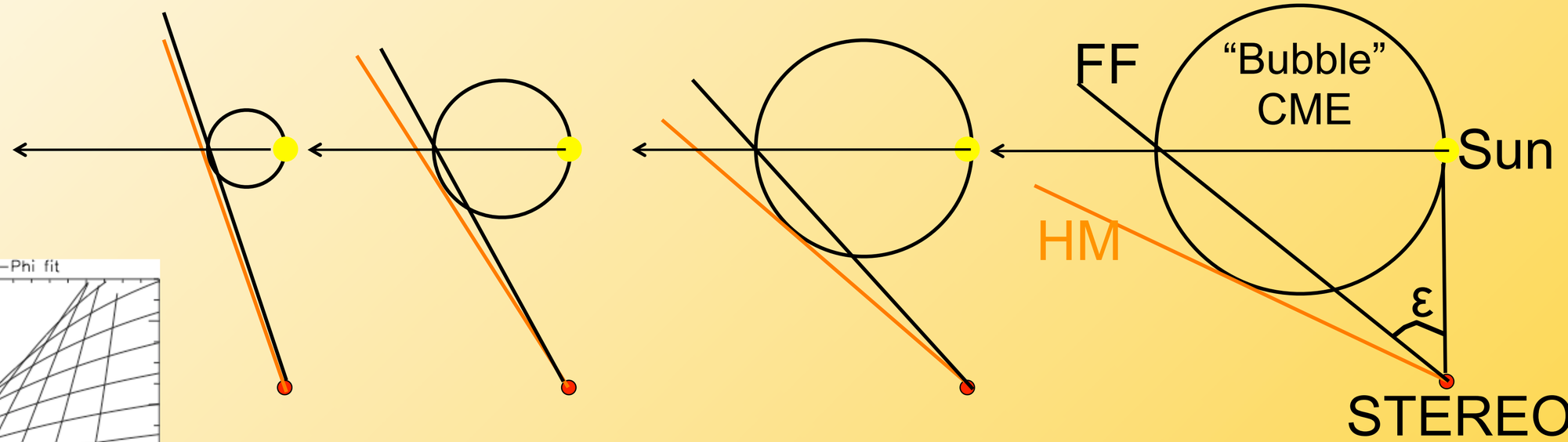


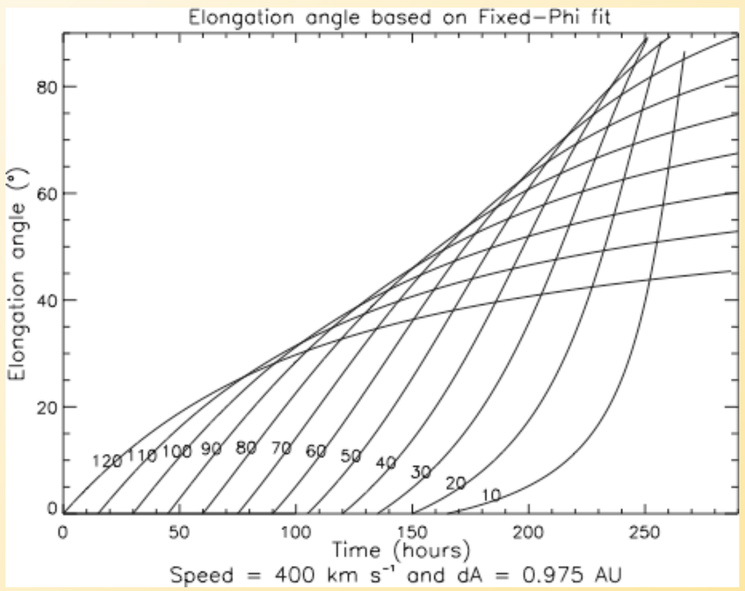
"Classical" fit (Sheeley *et al.*, Rouillard *et al.*)

Elongation Angle vs. Distance

HM: Less geometrical deceleration

Limb





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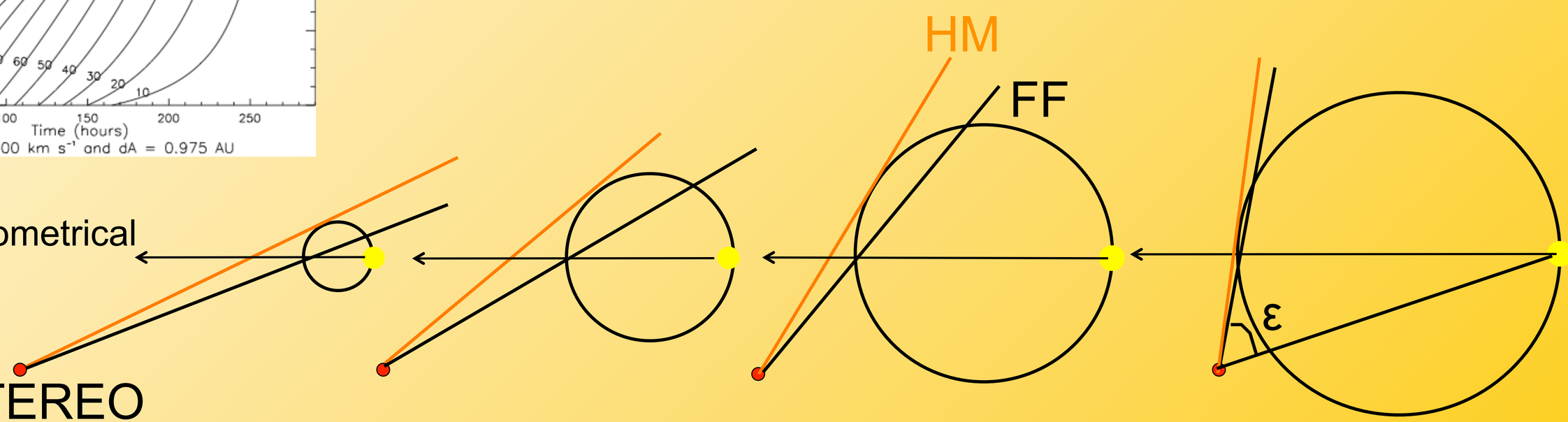
Halo



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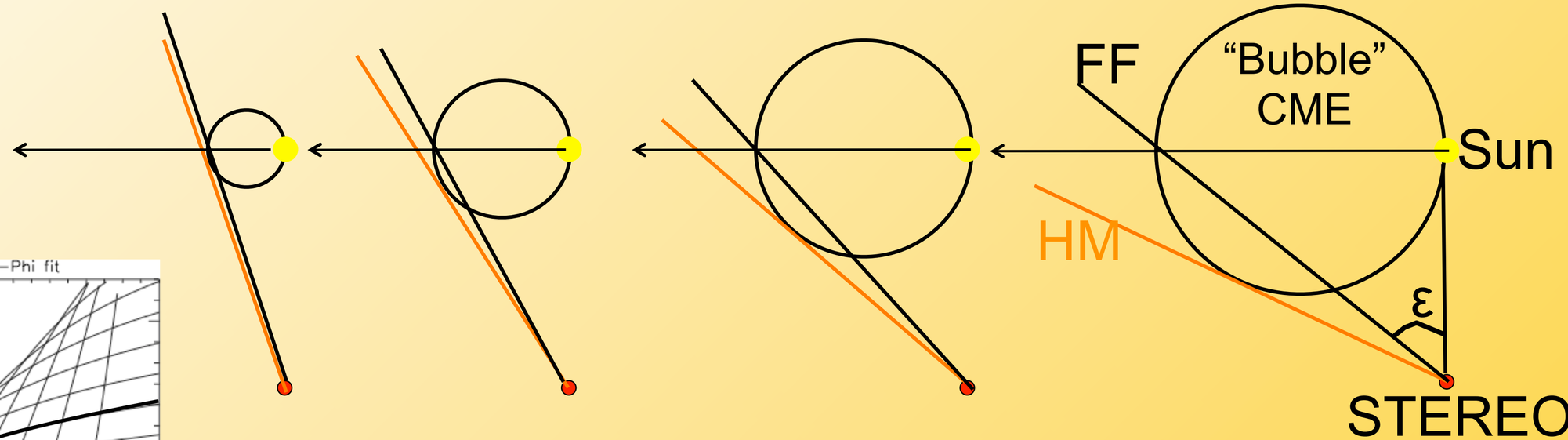

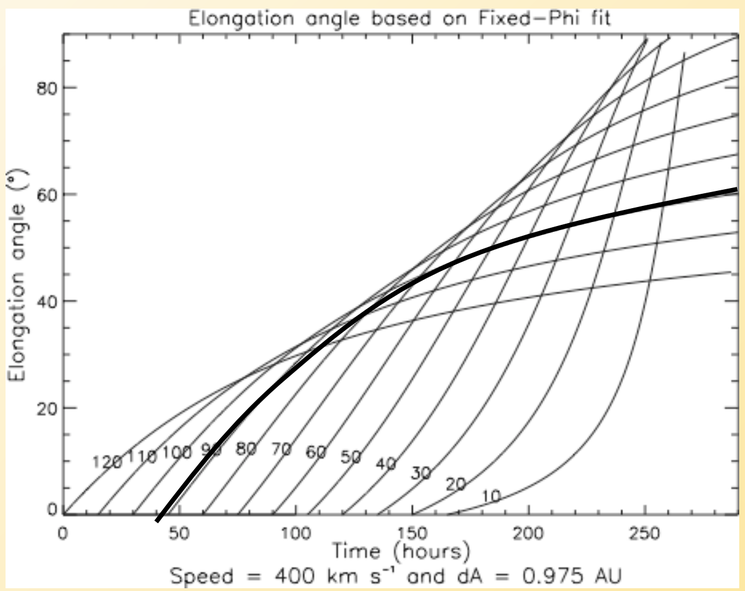

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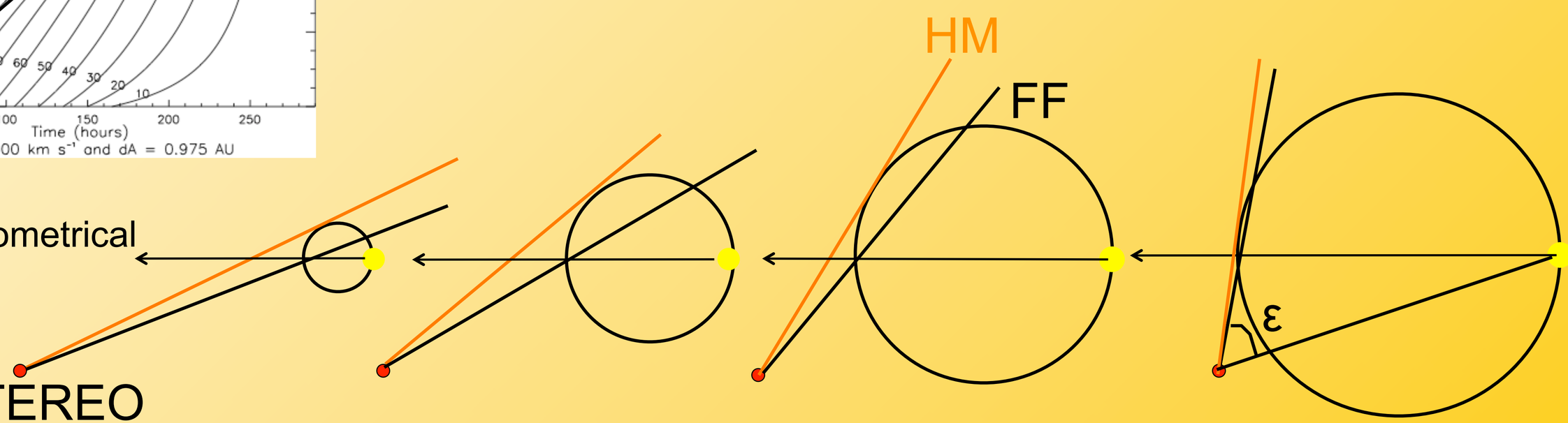

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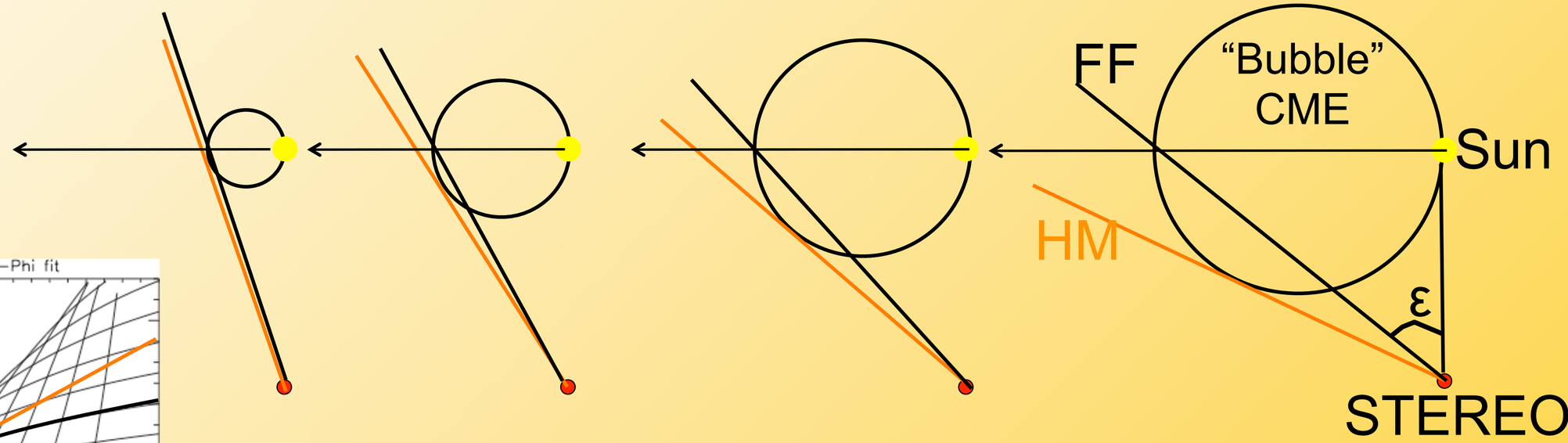

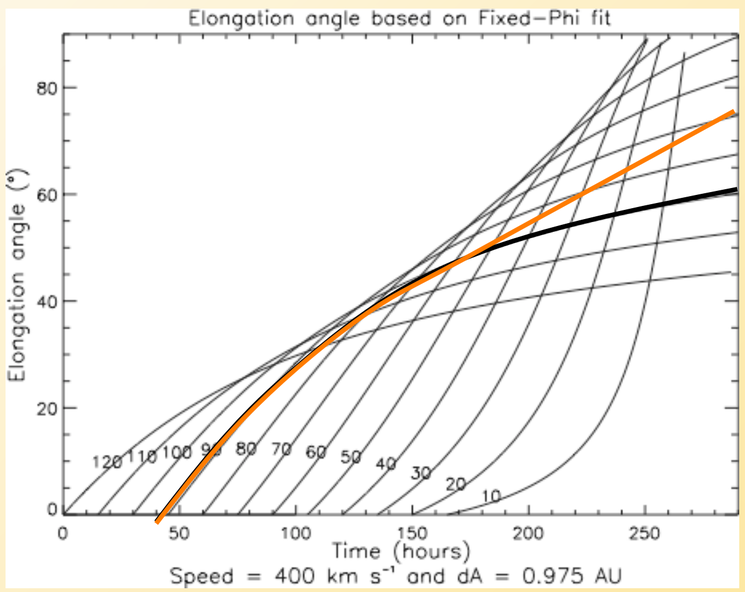

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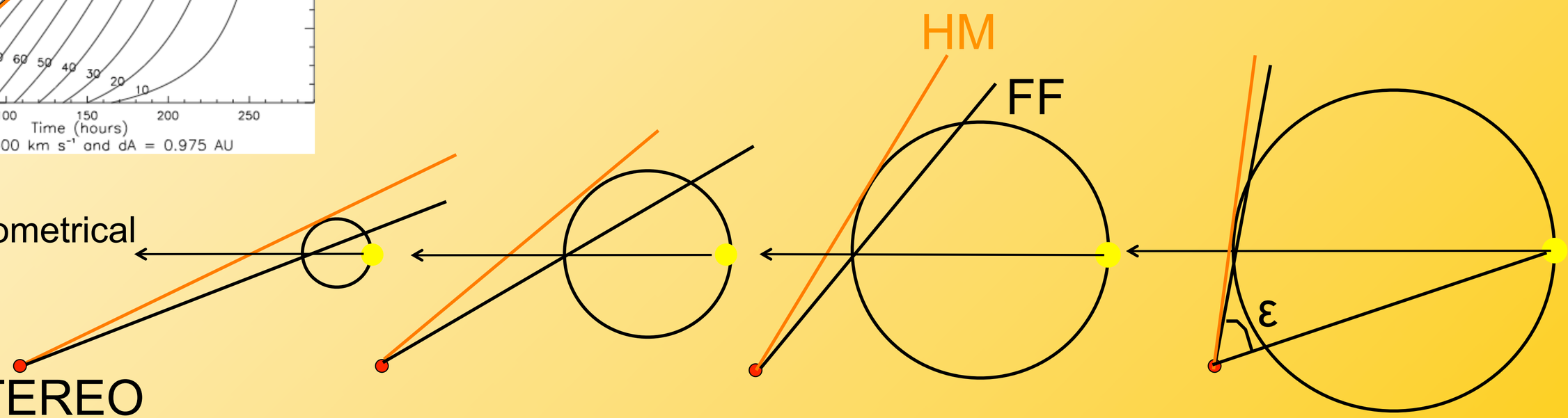

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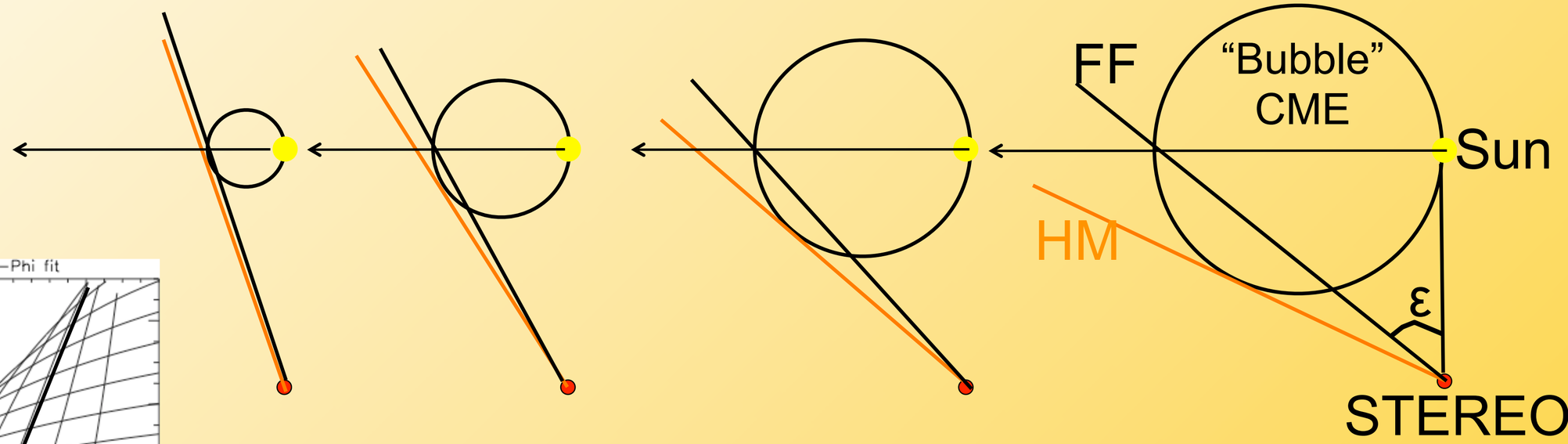

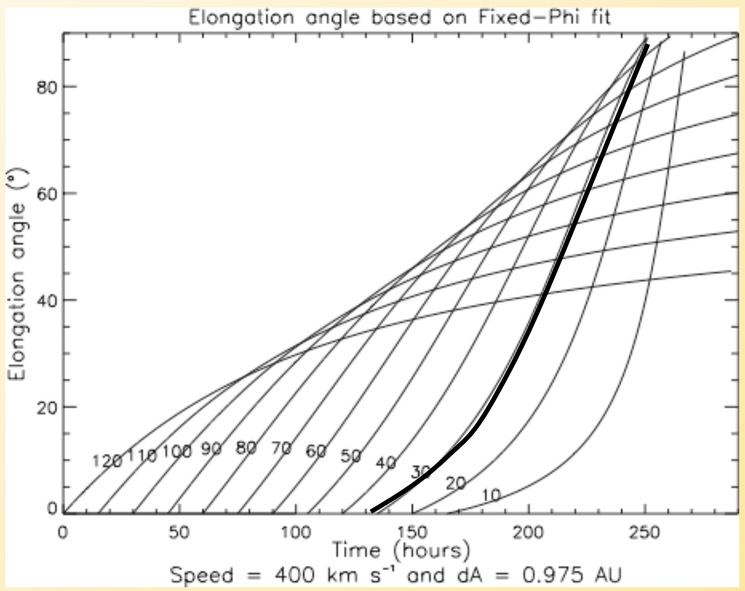

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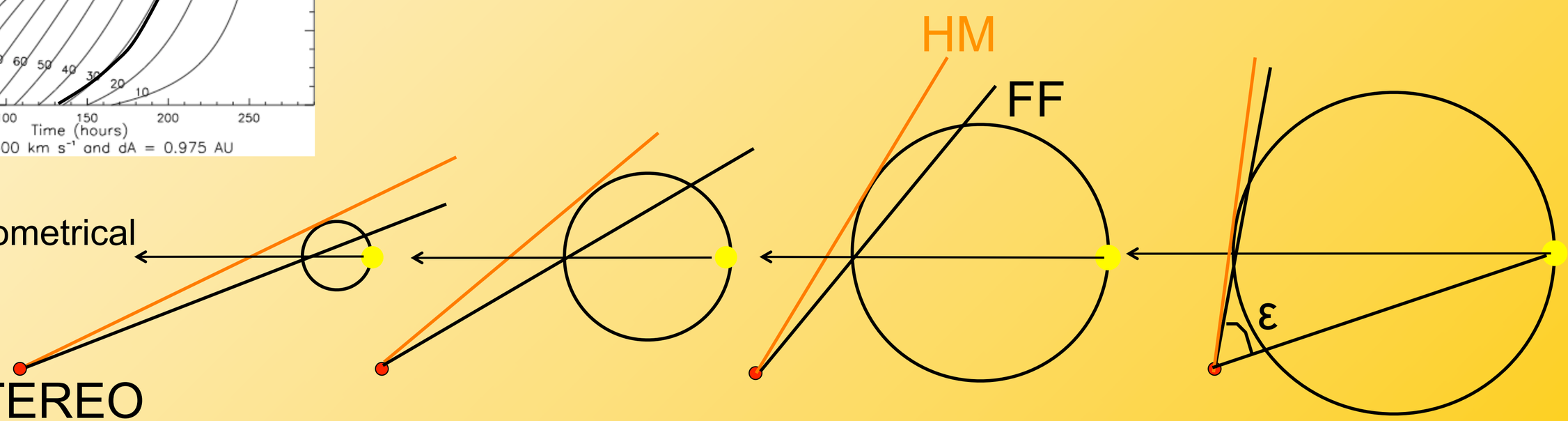

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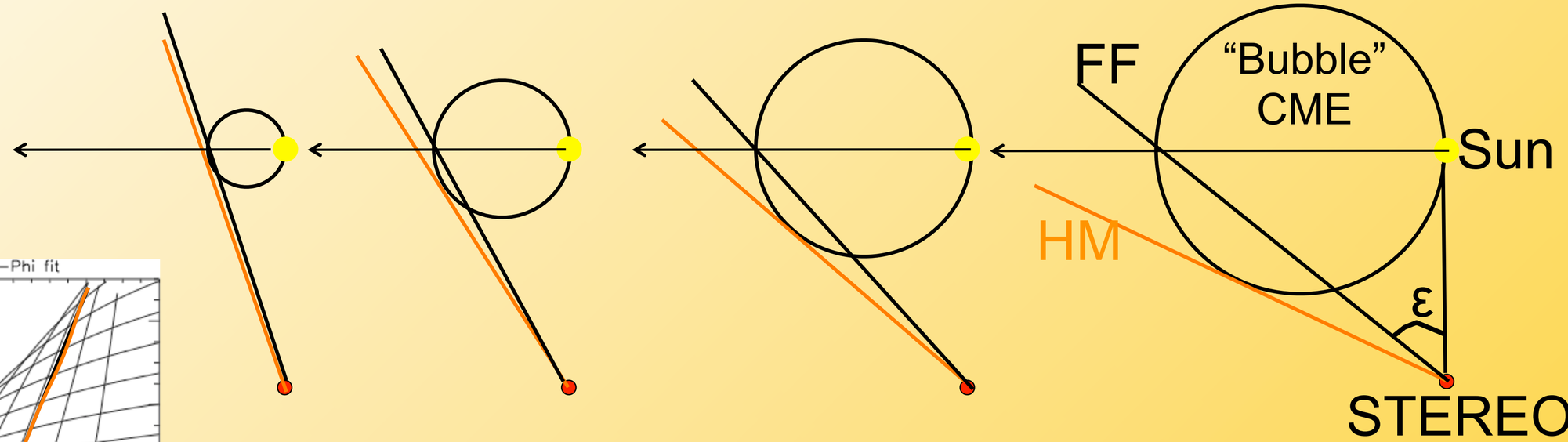

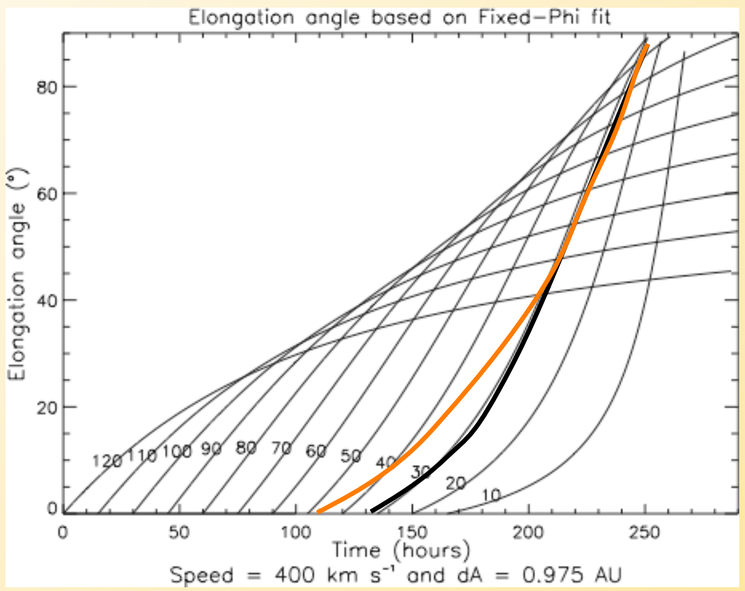

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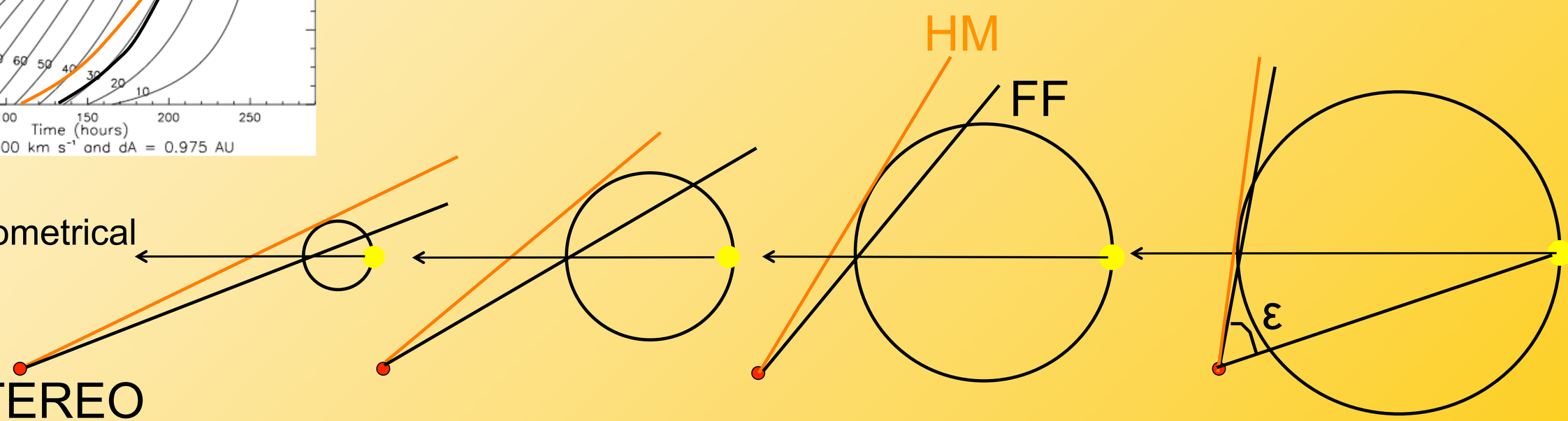
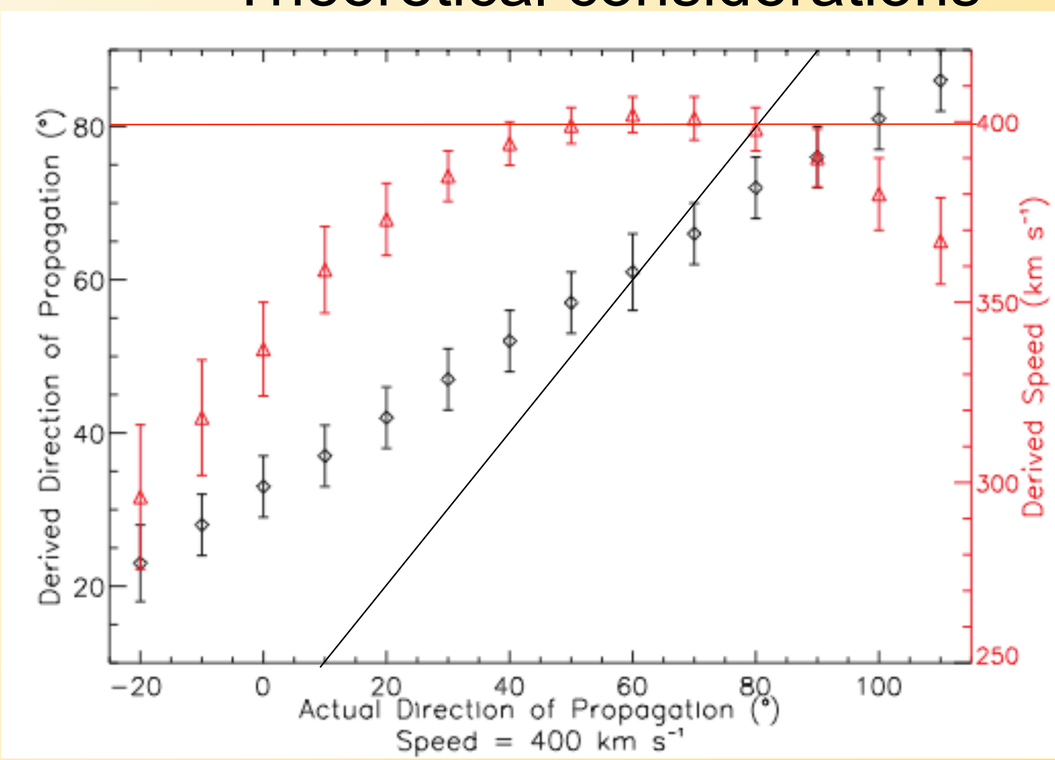


Differences between fits

- **Both methods give the same results for CME going 30º-70º away from the Sun-spacecraft line.** Most of what we observed so far.
- New fit best adapted to halo and behind the limb CMEs as seen from STEREO.

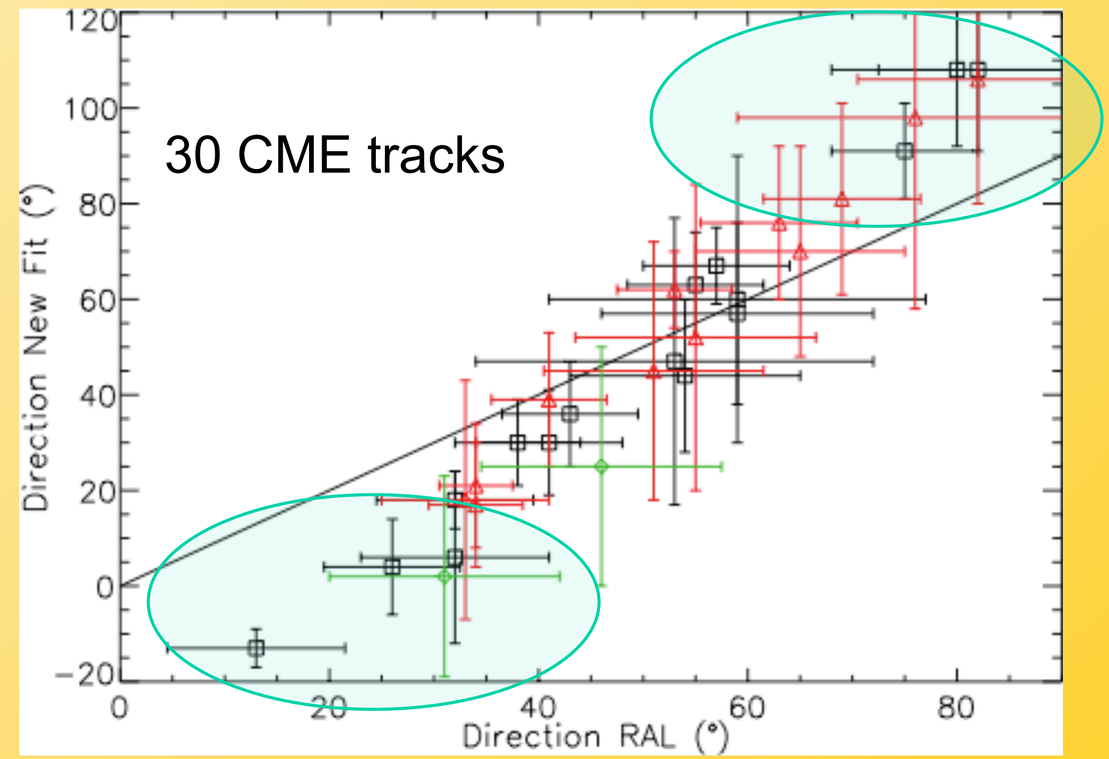
Theoretical considerations



Position given by HM, fitted by "classical" fit

Real CMEs

Lugaz, **Sol. Phys.**, 2010



New fit direction vs. classical fit direction

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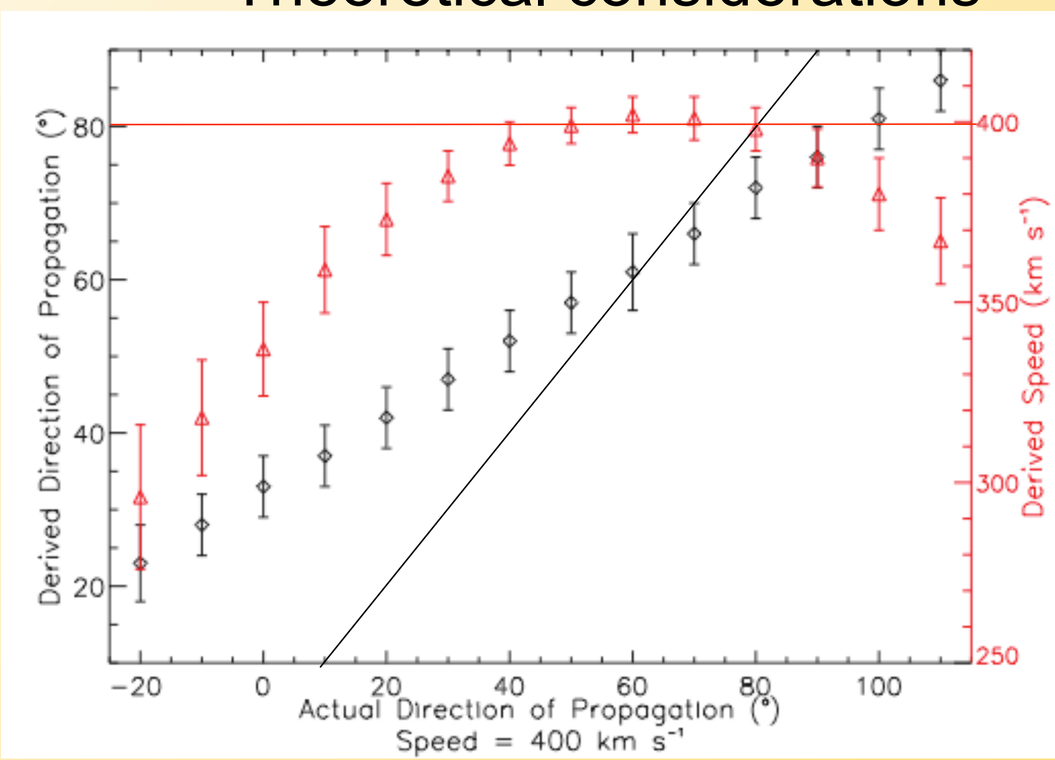

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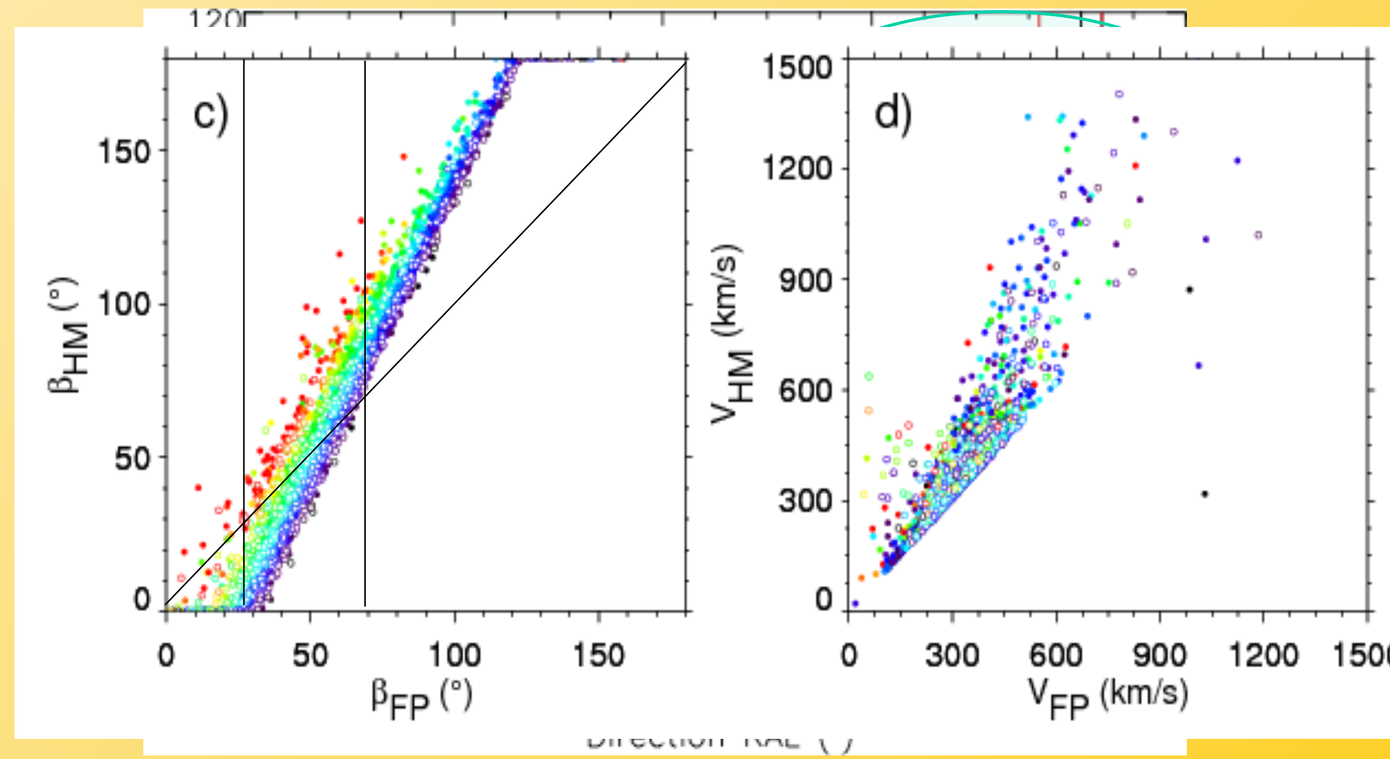
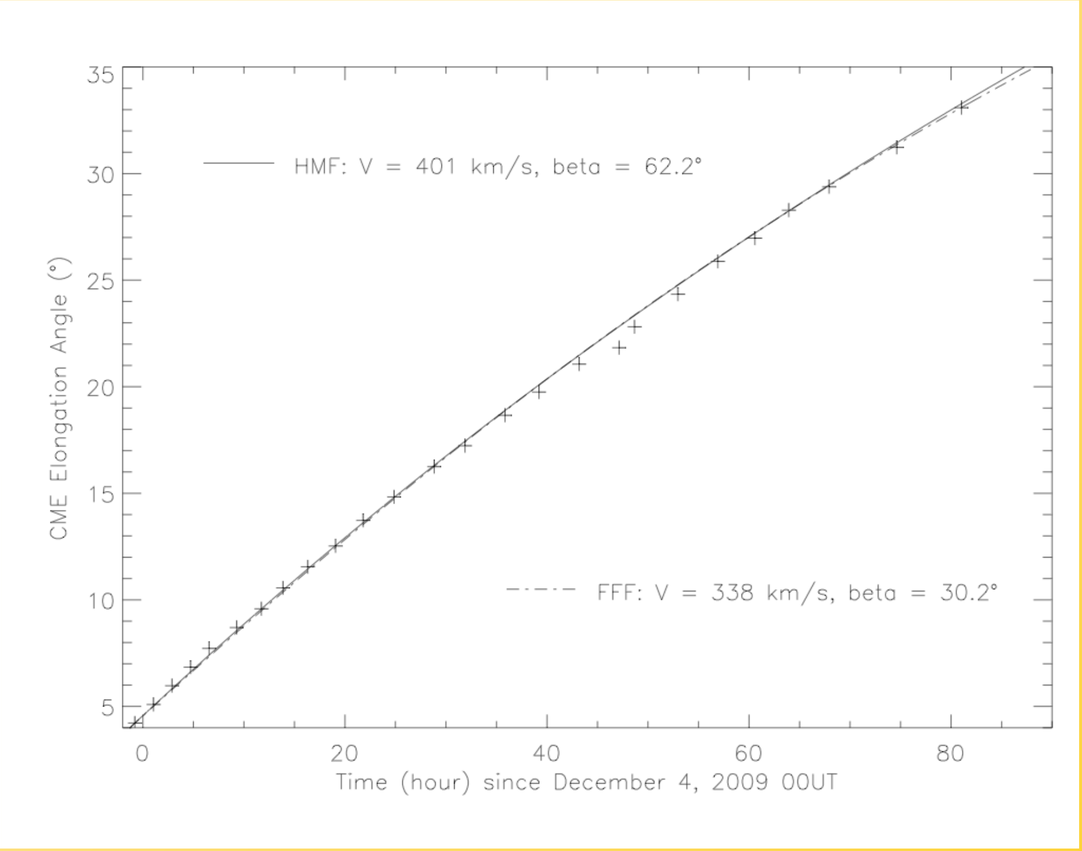


New fit direction vs. classical fit direction

Back on the 2009 December 4 CME

- Best fit:
  - FFF: 338 ± 63 km/s and 30.2° ± 14.5°
  - HMF: 401 ± 48.5 km/s and 62.2° ± 14°
- Arrival time at STEREO-A:
  - FFF: Assuming arrival time at 0.97 AU is the same for all parts of e fronts.
  - **FFF: 12/09/2009 12:30** - Very glancing blow (**33° away**).
  - HMF: Correction taking into account curvature of the front (Möstl *et al.*, 2011).
  - **HMF: 12/08/2009 18:20** - Direct hit (**1.5° away**).



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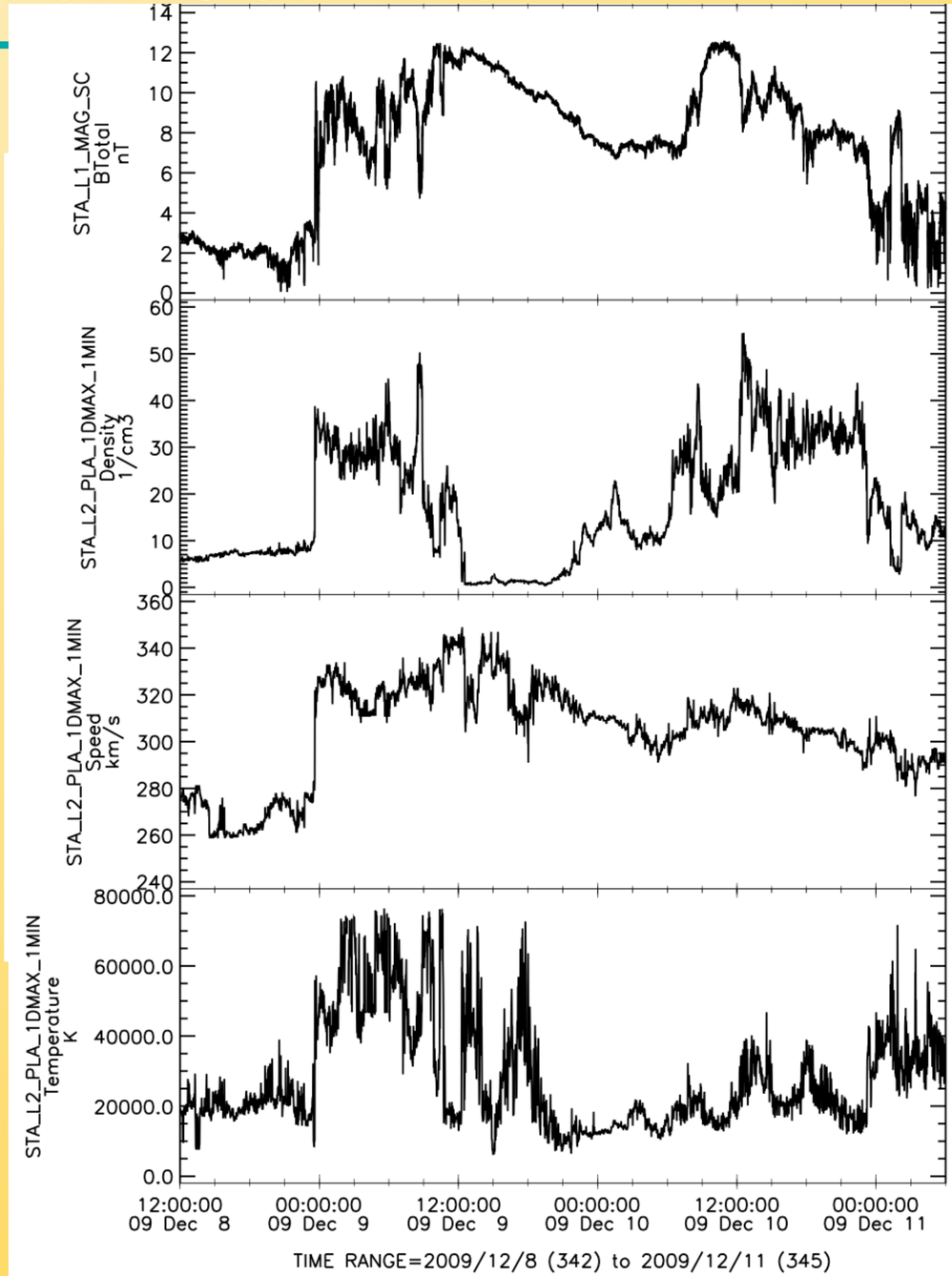
- Shock arrival at ST-A: 23:40 on 12/08.
- CME speed: 340 km/s



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- Best fit:
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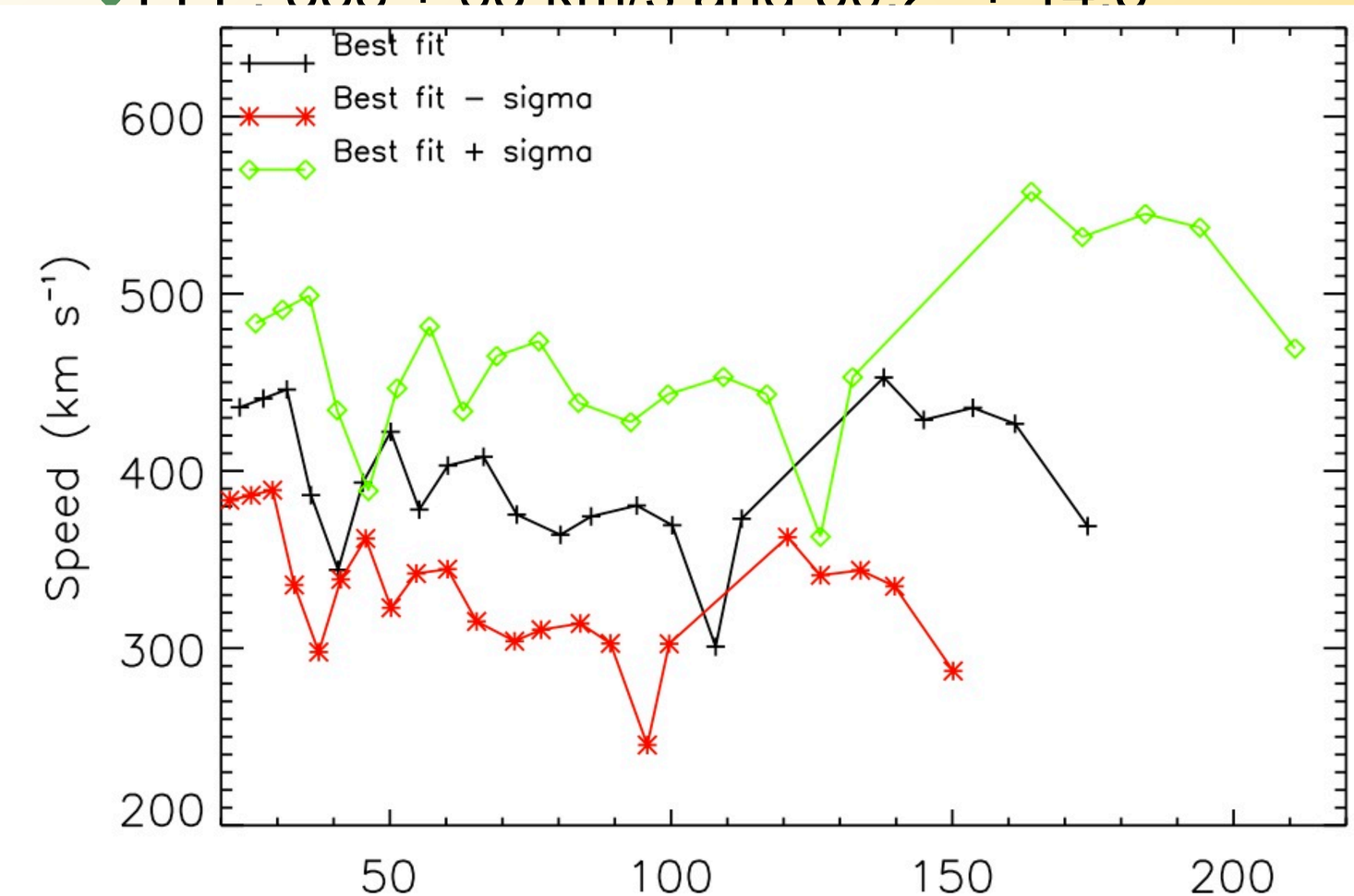
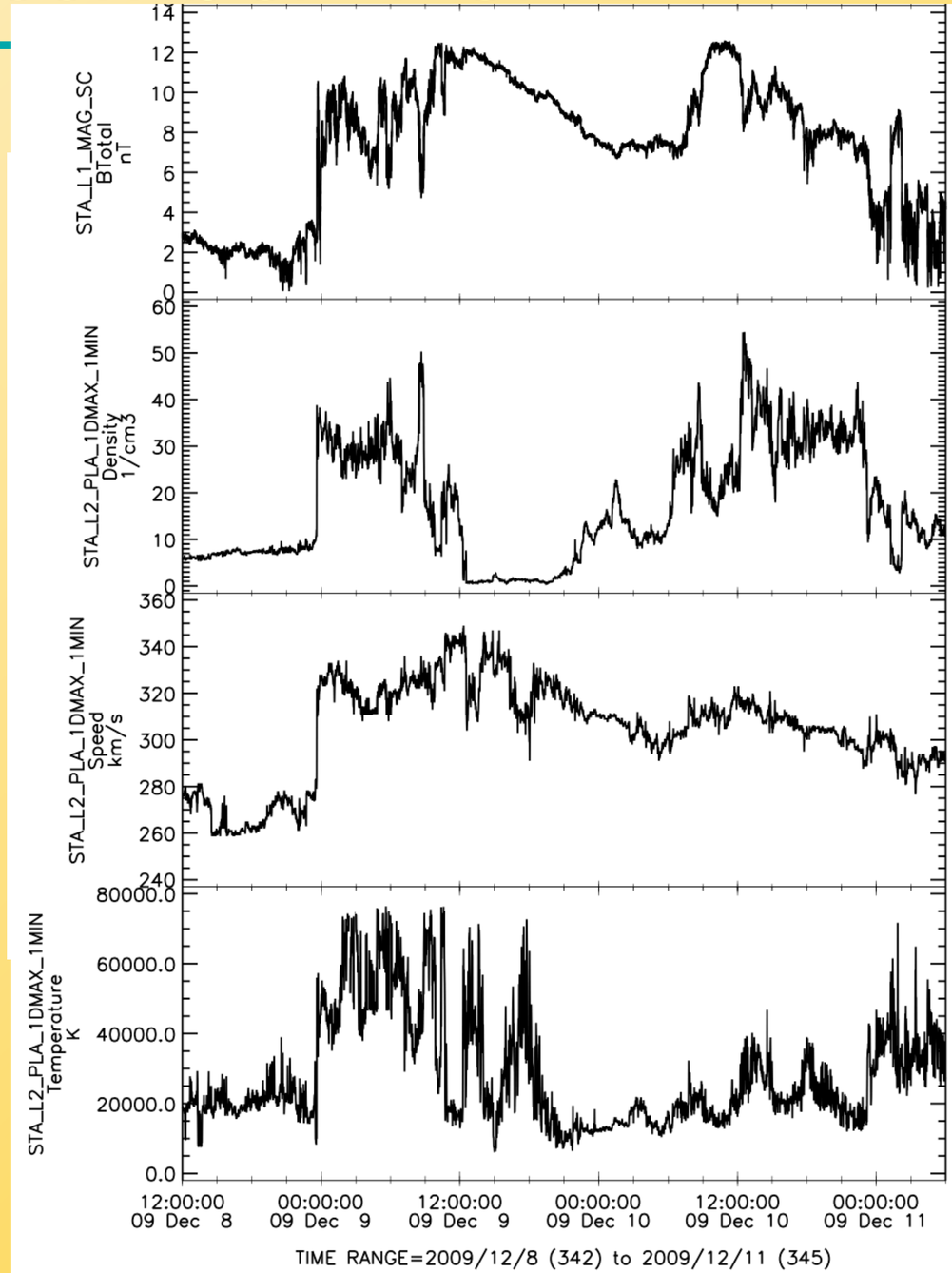


- Shock arrival at STA: 20:10 on 12/08.
- CME speed: 340 km/s



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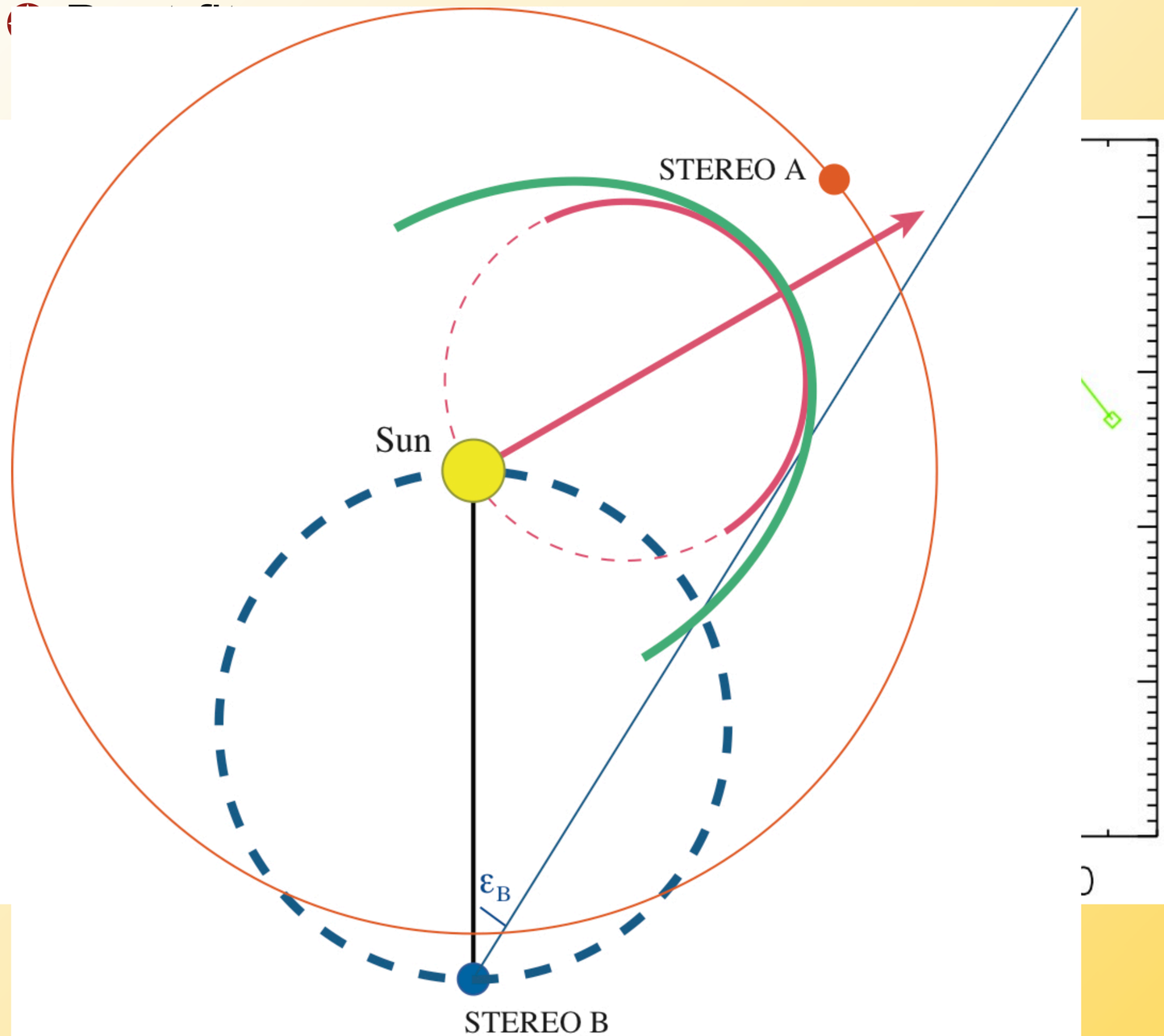

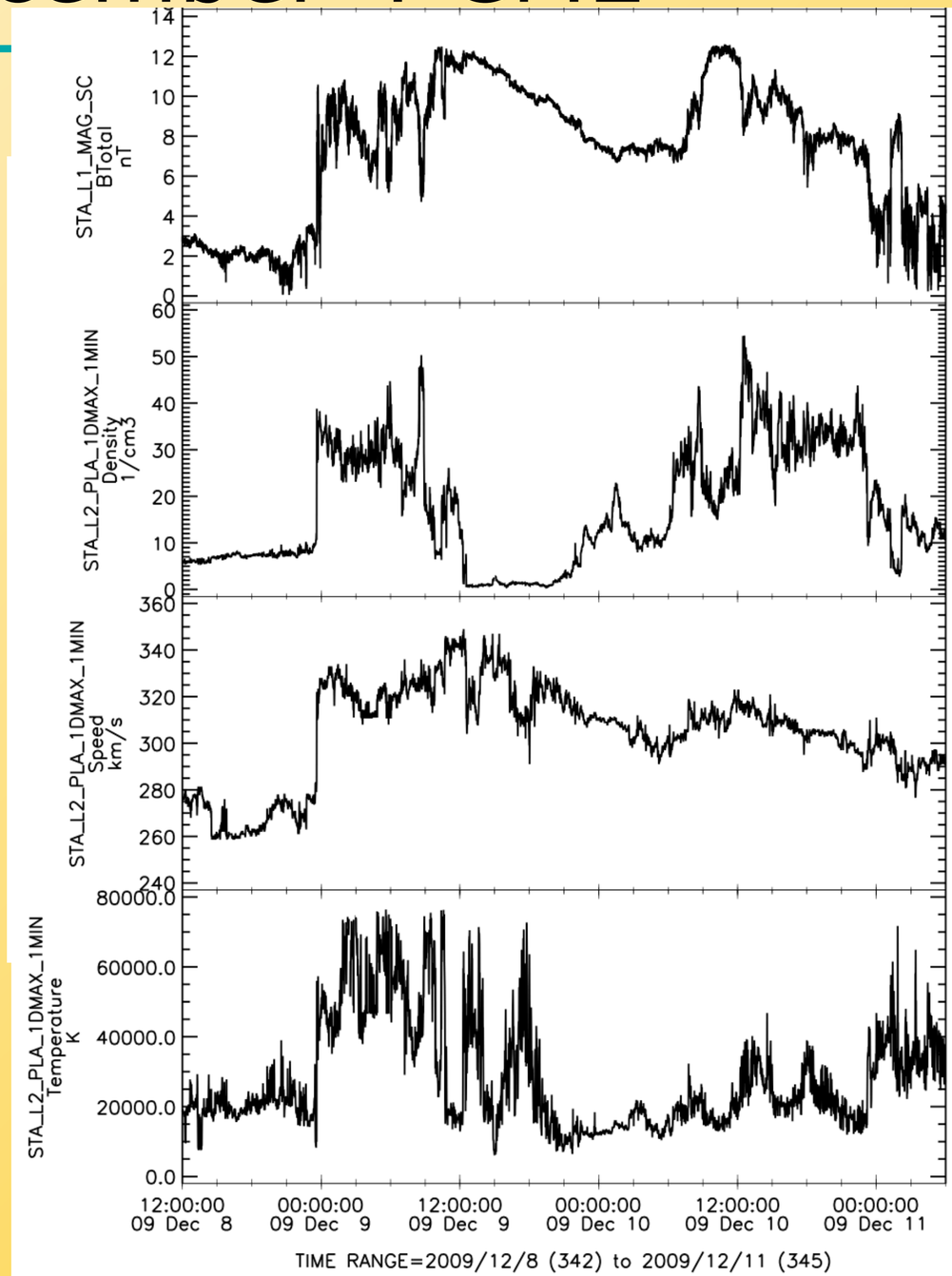

http://www.ifa.hawaii.edu/~nlugaz/

Dedicated study

- STEREO-impacting CMEs:
  - Started from Lan Jian's STEREO ICME list from 2008 to 2010.
  - Look for counterpart in SECCHI using RAL list.
  - Compare the 2 fitting methods for arrival time and hit/miss "prediction".
- Results: 20 ICMEs found:
  - 2008 (45 to 90 deg): 10/14 ICMEs found with counterpart.
  - 2009 (90 to 130 deg): 9/21 ICMEs found.
  - Until July 2010 (> 130 deg): 1/12 ICMEs found.
  - None since.
  - Some misses are due to data - gaps in SECCHI coverage.
- Comments:
  - 6 out of 9 CMEs observed with direction > 90 degrees are EPs.
  - If extrapolated to Earth-directed CMEs, some CMEs should be observed until early 2013.

Weblist

- http://ifa.hawaii.edu/~nlugaz/website/table.html

Event #	First Detection			RAL		IMPACT					Separation		FF						HM					
	Date	Time	Instrument	Track	Movie	Number	Date	Time	Type	Speed	Total	In situ	Speed	Direction	Hit/Miss	Arrival Day	Arrival Time	Arrival Speed	Speed	Direction	Hit/Miss	Arrival Day	Arrival Time	Arrival Speed
1	2008/01/31	N/A	COR-2	327A	HI1-A	7B	2008/02/05	20:30	irr.	385	45.3	-23.6	304 ± 13.5 km/s	-28.2° ± 14.5°	H	2008/02/06	15:50	304	316 ± 17.5 km/s	-30.2° ± 25.5°	H	2008/02/06	14:50	314
2	2008/04/26	14:25	COR-1	399A	HI1-A	9B	2008/04/29	14:10	1	490	49.8	-25.8	544 ± 44 km/s	-33.2° ± 18°	H	2008/04/29	19:30	544	548± 30.5 km/s	-33.2° ± 30.5°	H	2008/04/29	20:25	541
3	2008/05/07	N/A	COR-2	172B	HI1-B	2A	2008/05/01	06:30	1	350	51	24.3	368 ± 17 km/s	34.7° ± 12.5°	H	2008/05/11	11:25	368	373± 27 km/s	36.7° ± 27°	H	2008/05/11	12:30	367
4	2008/06/01	10:25	COR-1	428A	HI1-A	11B	2008/06/06	15:40	2	430	54.8	-29.2	371 ± 13 km/s	-23.8° ± 5.5°	H	2008/06/07	01:30	371	379± 27.5 km/s	-33.8° ± 15°	H	2008/06/07	01:30	375
5	2008/06/30	N/A	COR-2	214B	HI1-B	3A	2008/07/05	00:50	2	360	58.3	27.2	314 ± 5.5 km/s	11.8° ± 6.5°	H	2008/07/05	11:20	314	330± 13 km/s	-0.2° ± 17°	M	2008/07/05	18:30	282
6	2008/08/10	N/A	COR-2	514A	HI1-A	12B	2008/08/15	12:00	2	365	67.2	-36.2	325 ± 17 km/s	-24.8° ± 11°	H	2008/08/16	05:50	325	329± 18.5 km/s	-30.8° ± 16°	H	2008/08/16	4:50	329
7	2008/08/30	16:05	COR-1	247B	HI1-B	4A	2008/09/04	13:30	2	385	71.3	33.3	350 ± 8.5 km/s	33.7° ± 10.5°	H	2008/09/04	22:00	350	353± 14.5 km/s	36.7° ± 27°	H	2008/09/04	21:30	353
8	2008/10/26	N/A	COR-1	270B	HI1-B	5A	2008/10/31	12:20	2	400	81.3	40.1	358 ± 40 km/s	38.9° ± 17.5°	H	2008/10/31	16:00	358	369± 78 km/s	52.9° ± 37°	H	2008/10/31	15:20	361
9	2008/11/23	11:25	COR-1	290B	HI1-B	6A	2008/11/28	21:50	2	380	85.2	43.2	411 ± 111 km/s	32.8° ± 26.5°	H	2008/11/28	16:50	411	436± 168 km/s	49.8° ± 49.5°	H	2008/11/28	12:30	432
10	2008/12/27	02:25	COR-1	595A	HI1-B	14B	2008/12/31	02:00	irr	460	88.4	-42.6	425 ± 56.5 km/s	-11.4° ± 17.5°	H*	2008/12/31	10:20	425	431± 37.5 km/s	-19.4° ± 16.5°	H*	2008/12/31	21:30	386
11	2009/01/08	~04:00	COR-1	611A	HI1-A	10B	2009/01/13	05:20	irr	400	89.3	-46.6	351 ± 62.5 km/s	-33.2° ± 17°	H	2009/01/14	01:40	351	379± 35 km/s	-55.2° ± 35°	H	2009/01/13	18:40	375
12	2009/01/21	16:45	COR-1	328B	HI1-B	1A	2009/01/25	18:20	2	400	90.	43	376 ± 12.5 km/s	20.9° ± 6.5°	H	2009/01/26	07:50	376	386± 41 km/s	33.9° ± 20.5°	H	2009/01/26	07:10	381
13	2009/07/10	N/A	COR-1	762A	HI1-A	12B	2009/07/16	17:10	2	330	104.1	-55.2	286 ± 19 km/s	-46° ± 8°	H	2009/07/17	06:10	286	323± 58 km/s	-74° ± 12.5°	H	2009/07/16	20:30	306
14	2009/07/26	11:35	COR-2	771A	HI1-A	13B	2009/07/31	02:20	2	460	106.5	-50.1	407 ± 114 km/s	-39.4° ± 17.5°	H	2009/07/31	00:00	407	505± 174 km/s	-75.4° ± 27°	M	2009/07/30	12:40	456
15	2009/09/26	11:35	COR-2	818A	HI1-A	18B	2009/10/02	17:20	1	360	106.5	-57	454 ± 205 km/s	-64.6° ± 27°	H	2009/10/01	09:40	454	699± 201 km/s	-113.6° ± 109°	M	2009/10/02	03:30	385
16	2009/11/05	08:05	COR-1	858A	HI1-A	19B	2009/11/10	18:50	1	370	127.9	-64.4	283 ± 138 km/s	-56.6° ± 21°	H	2009/11/12	01:50	283	455± 198 km/s	-107.6° ± 32.5°	M	2009/11/12	01:50	332
17	2009/11/08	05:25	COR-1	466B	HI1-B	7A	2009/11/14	08:00	2	340	125.8	63.1	339 ± 61 km/s	32.3° ± 15°	M	2009/11/14	10:05	339	390± 66 km/s	61.3° ± 20.5°	H	2009/11/13	19:00	390
18	2009/11/22	N/A	COR-2	881A	2nd CME	20B	2009/11/27	12:40	2	400	127.9	-64.4	269 ± 26 km/s	-24.5° ± 52°	M	2009/11/28	18:10	269	306± 66.5 km/s	-52.5° ± 20.5°	H	2009/11/28	02:10	345

Are all flux ropes CMEs?

- 4/14 ICMEs from 2008 have no counterpart in SECCHI (11B - 2A):
  - 06/03 (B) 46 deg
  - 21/03 (A) 47 deg - maybe?
    - (23/03 @ 05:00UT, speed 280 km/s)
  - 15/05 (B) 51.5 deg
  - 19/10 (B) 79.4 deg

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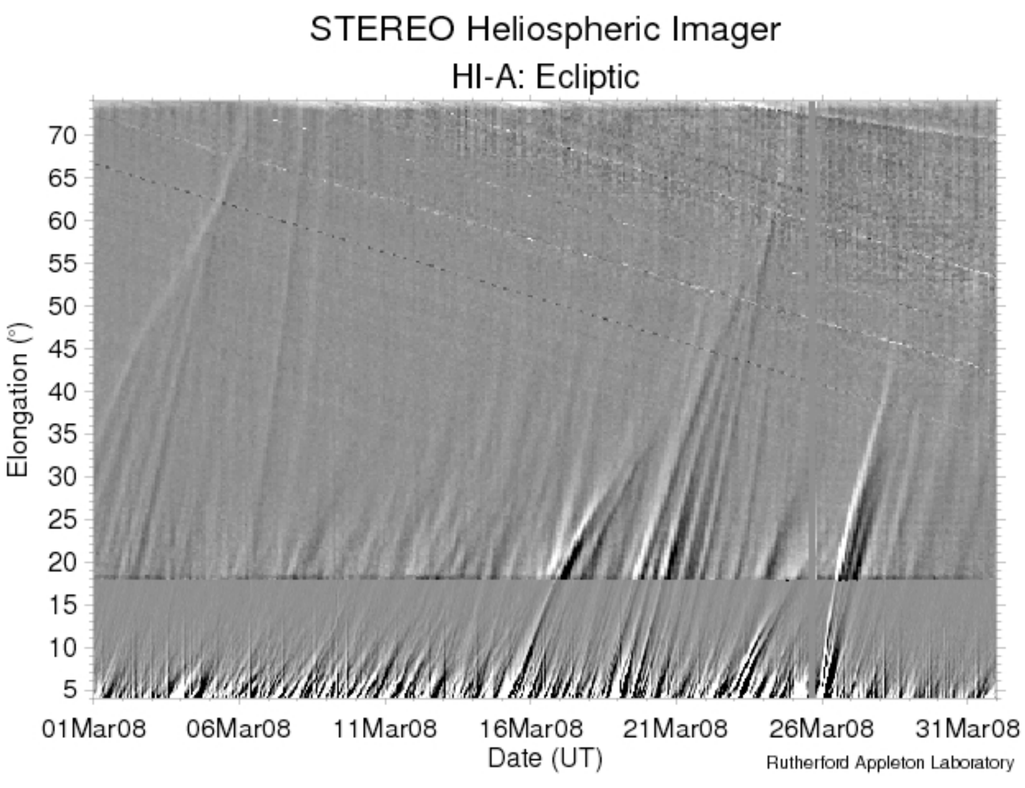

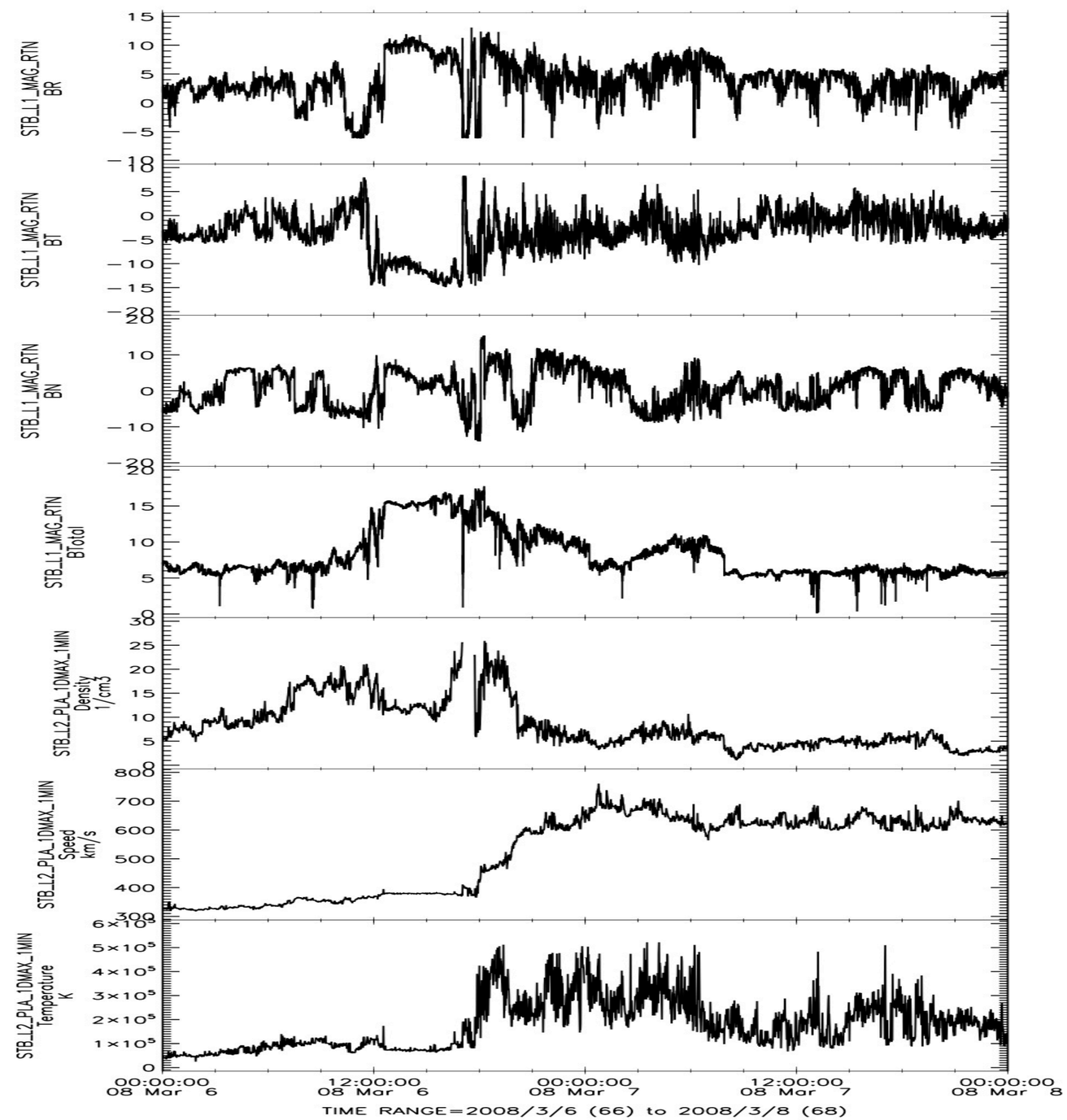

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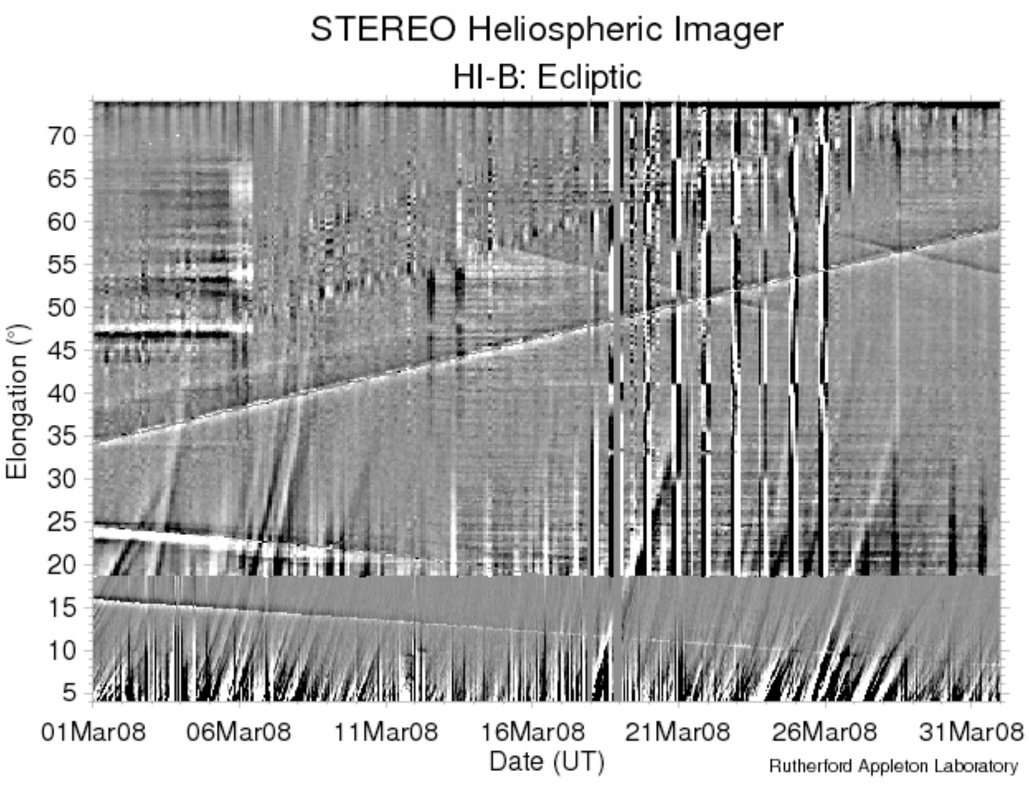

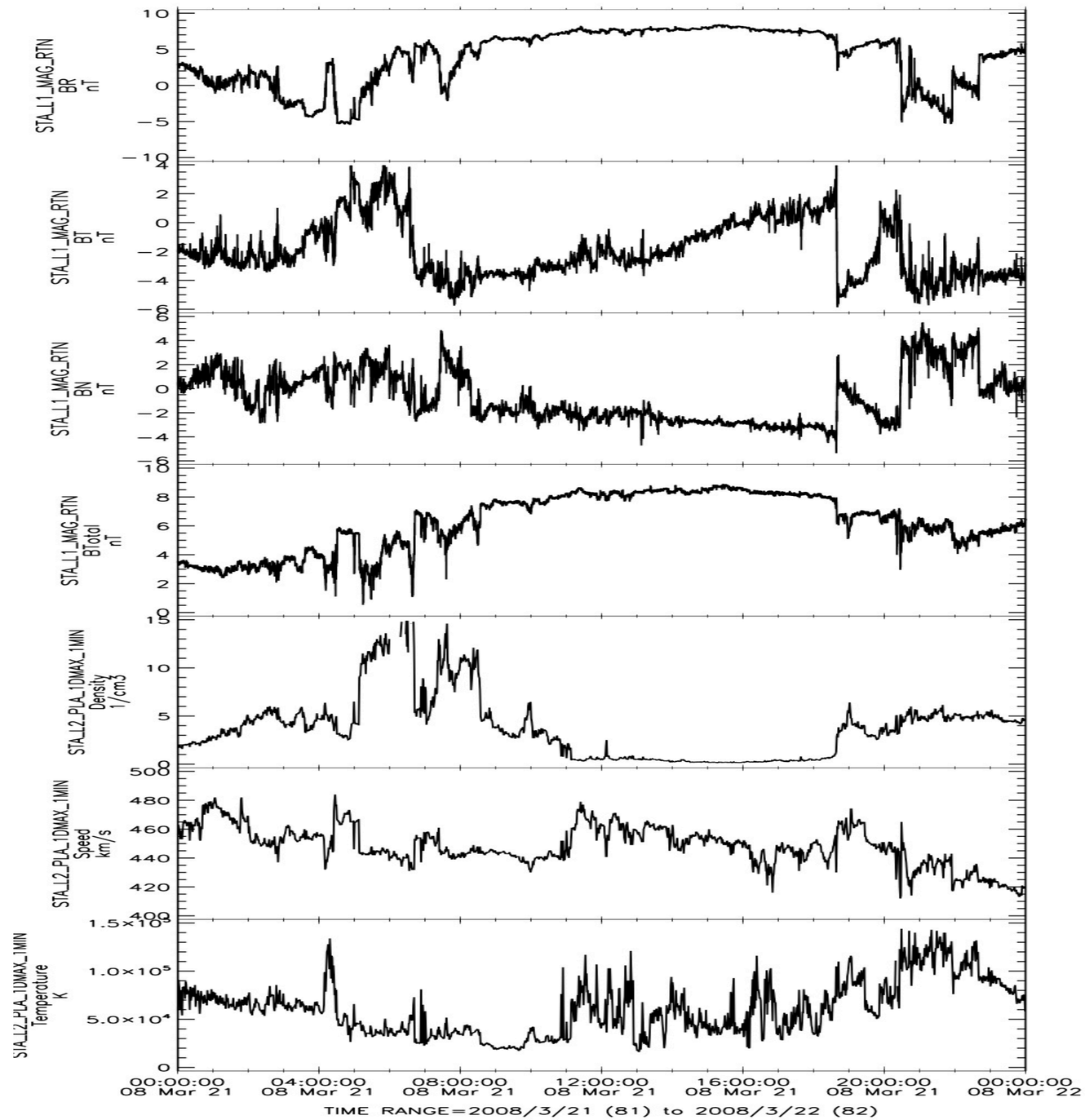

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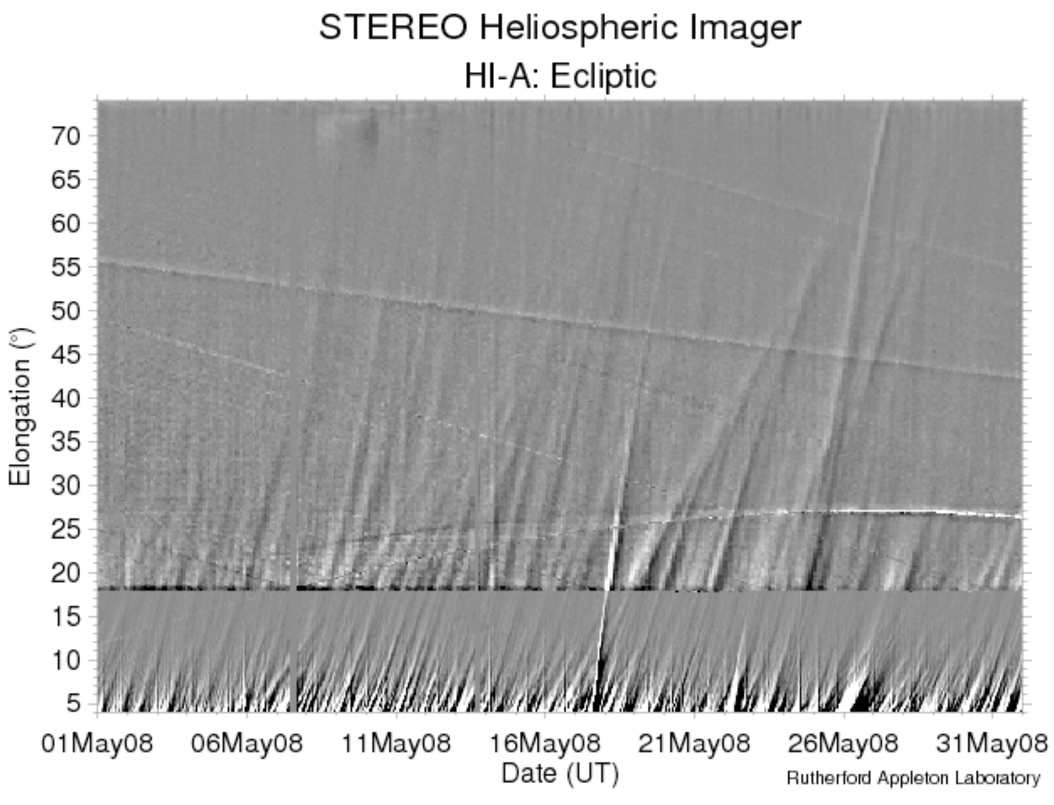

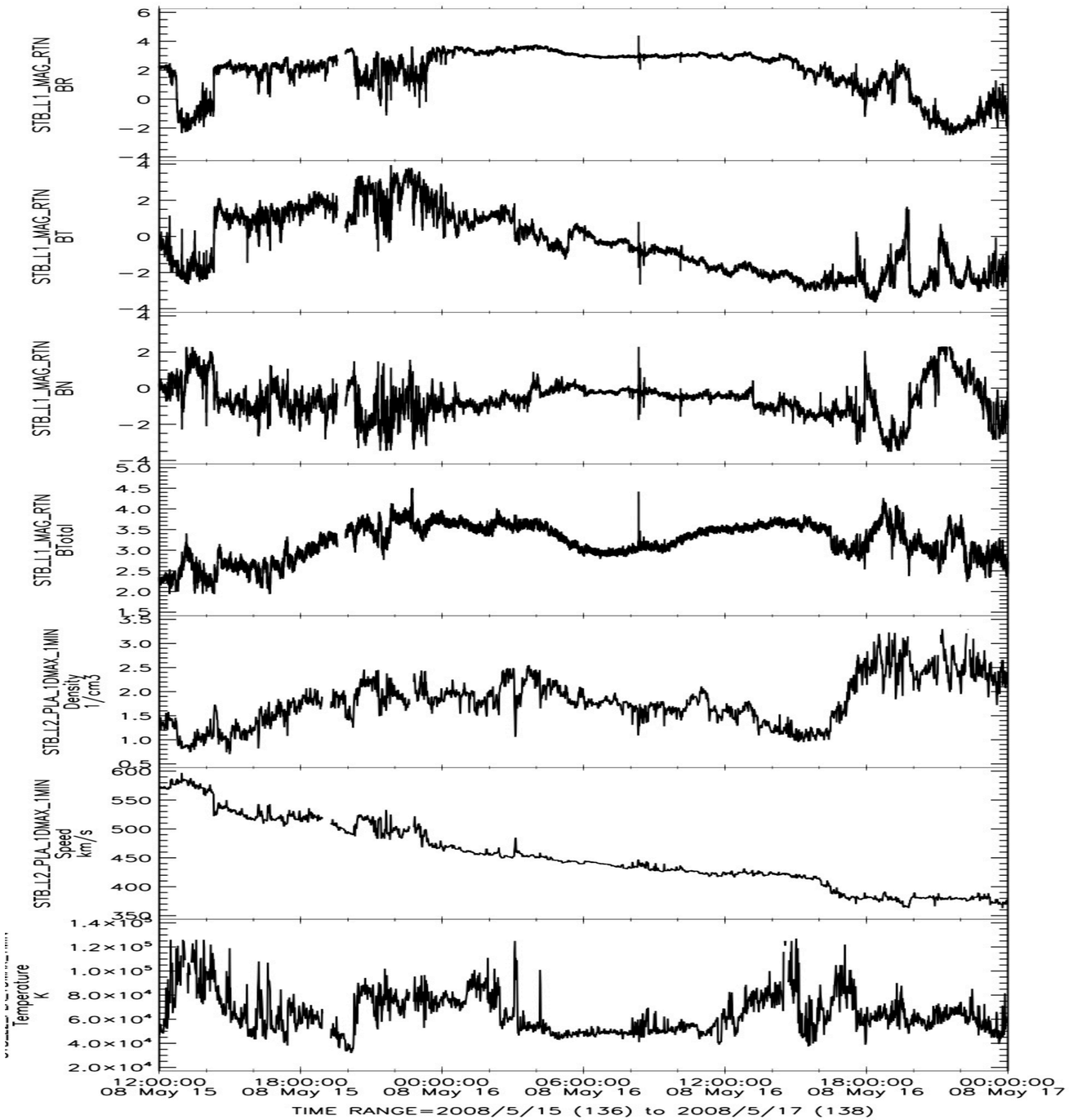

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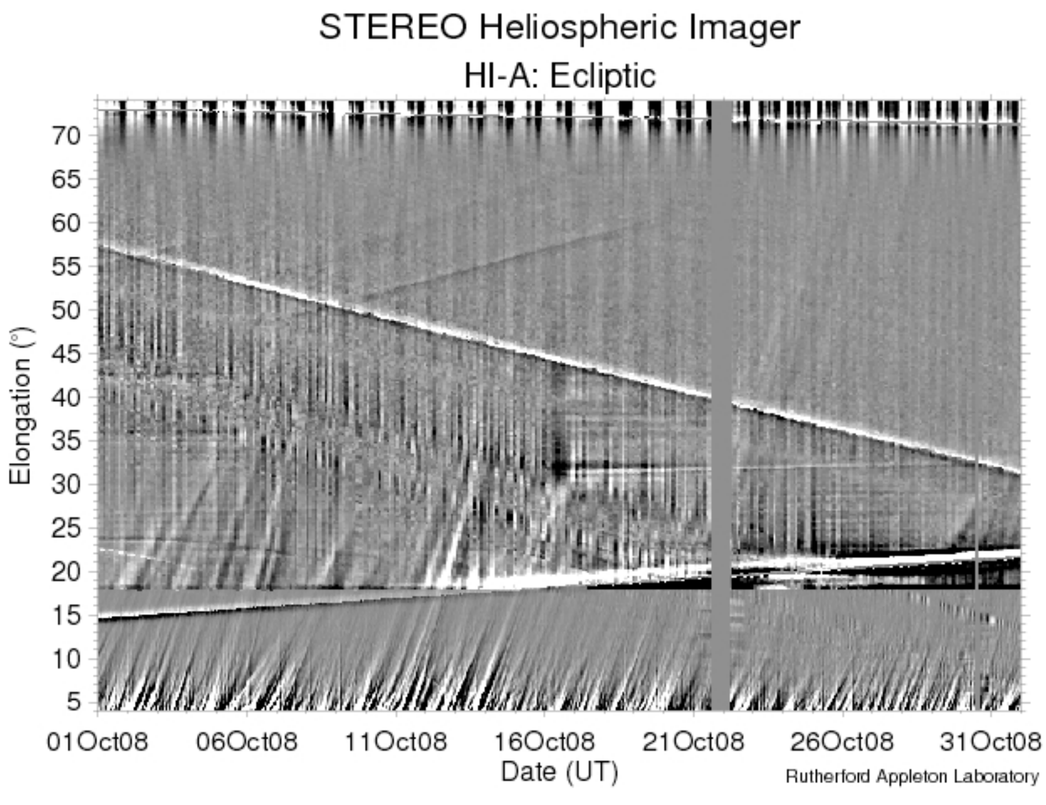
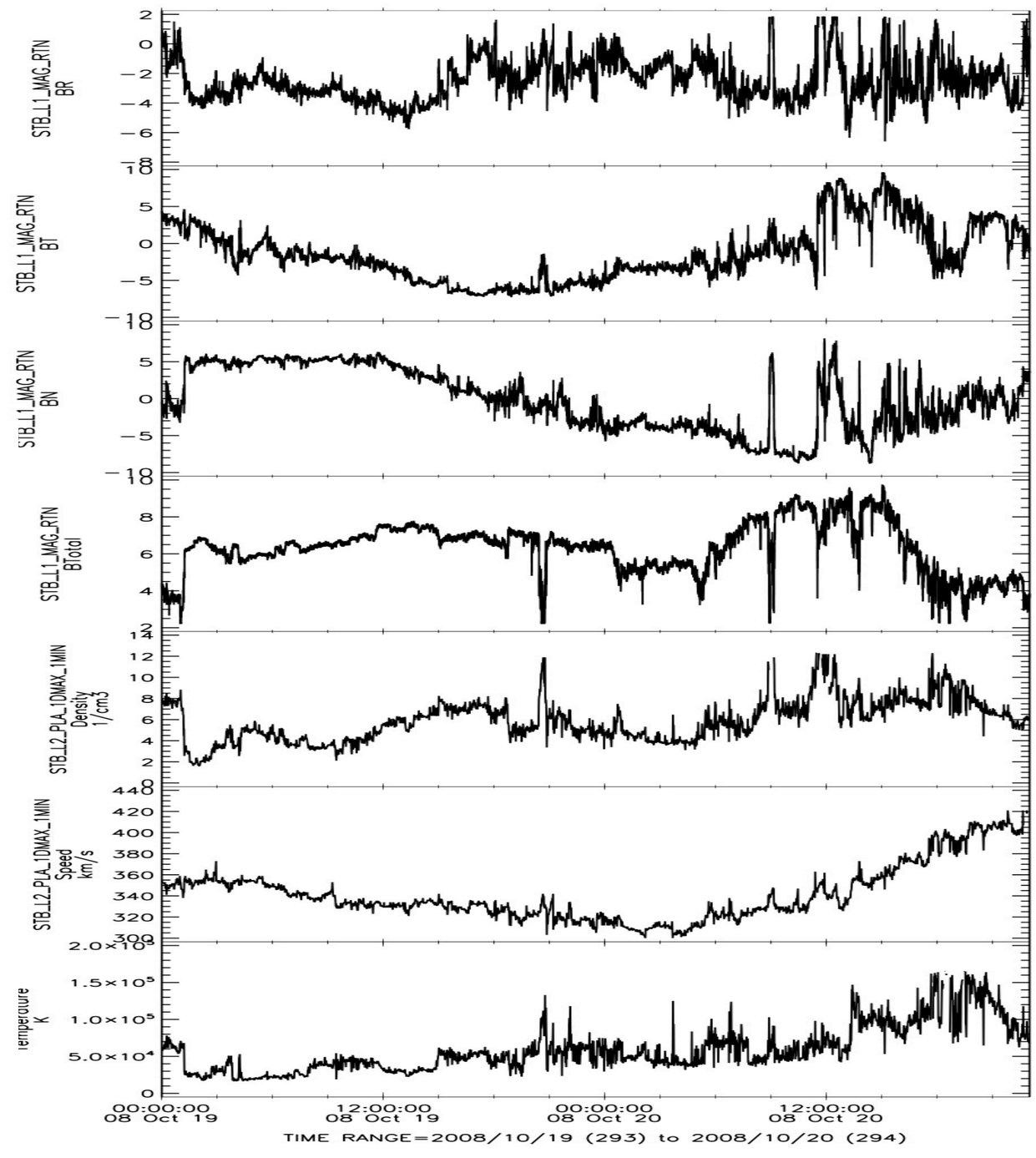
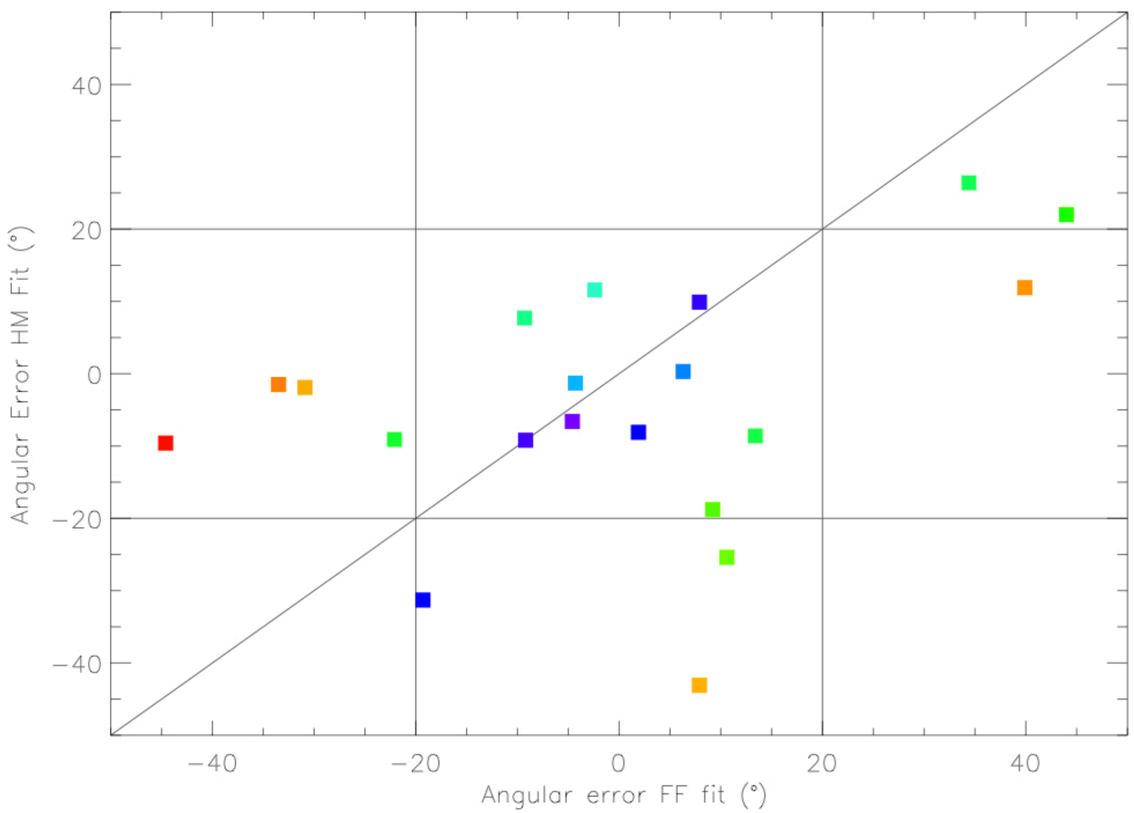




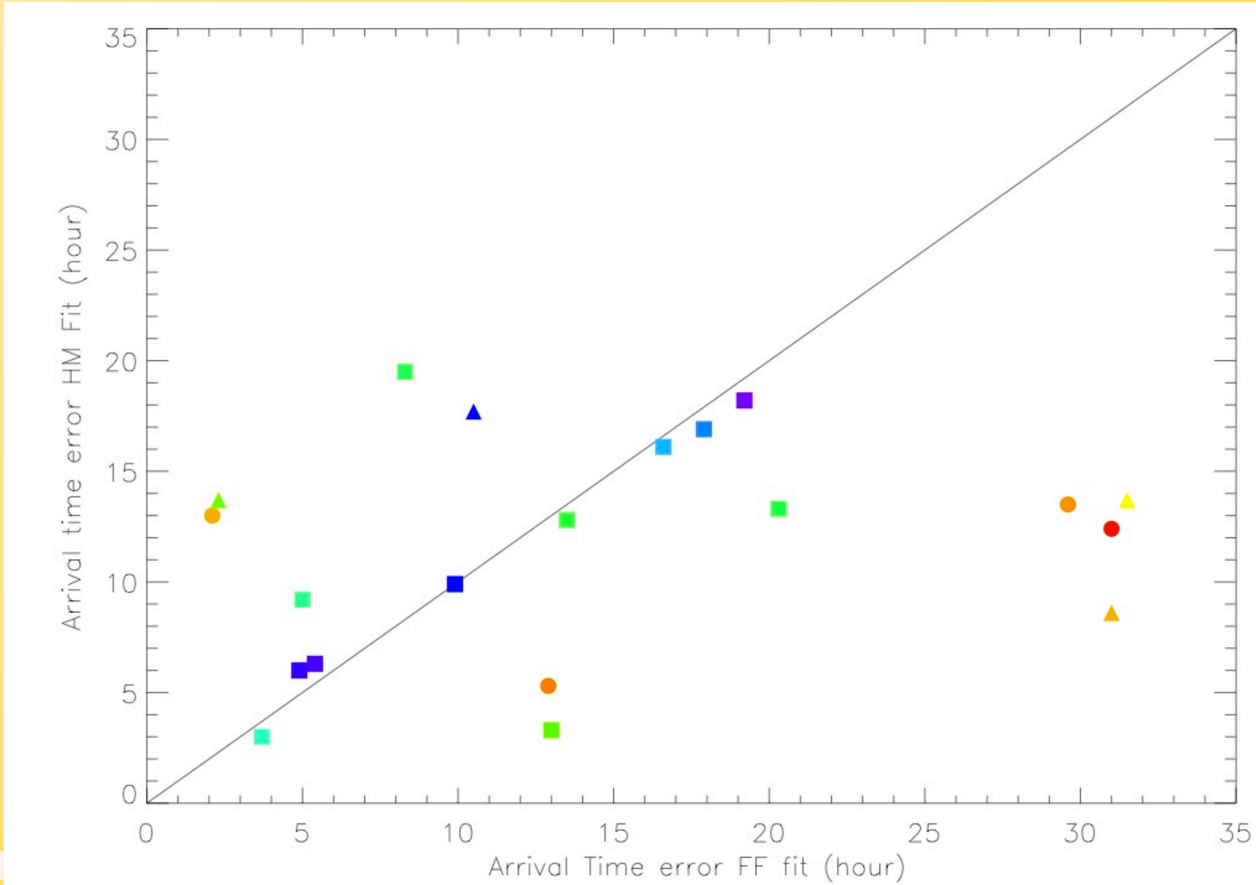
Comparing the methods

- For small (< 95°), two methods give pretty much the same predictions.
- For larger angles, 2 phenomena:
  - HM fit works better in general (due to assumption of width),
  - But HM is more sensitive to physical acceleration than FF fit.

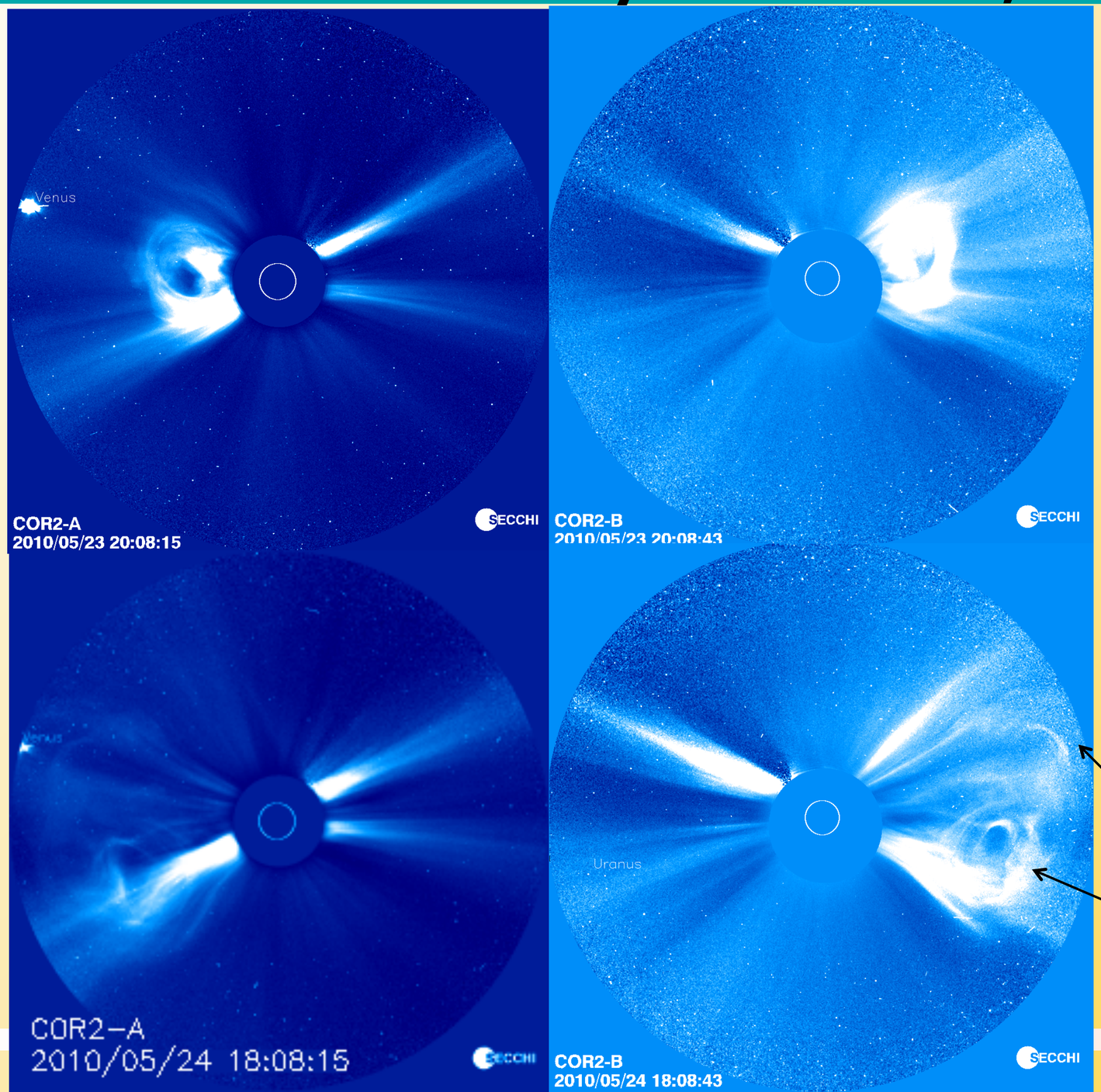
Angle "error"



Arrival time error

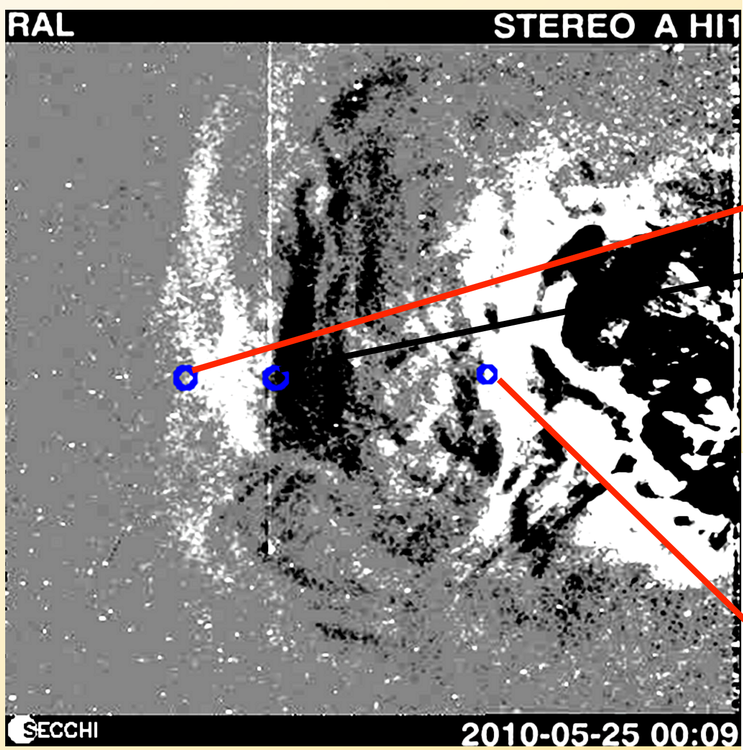


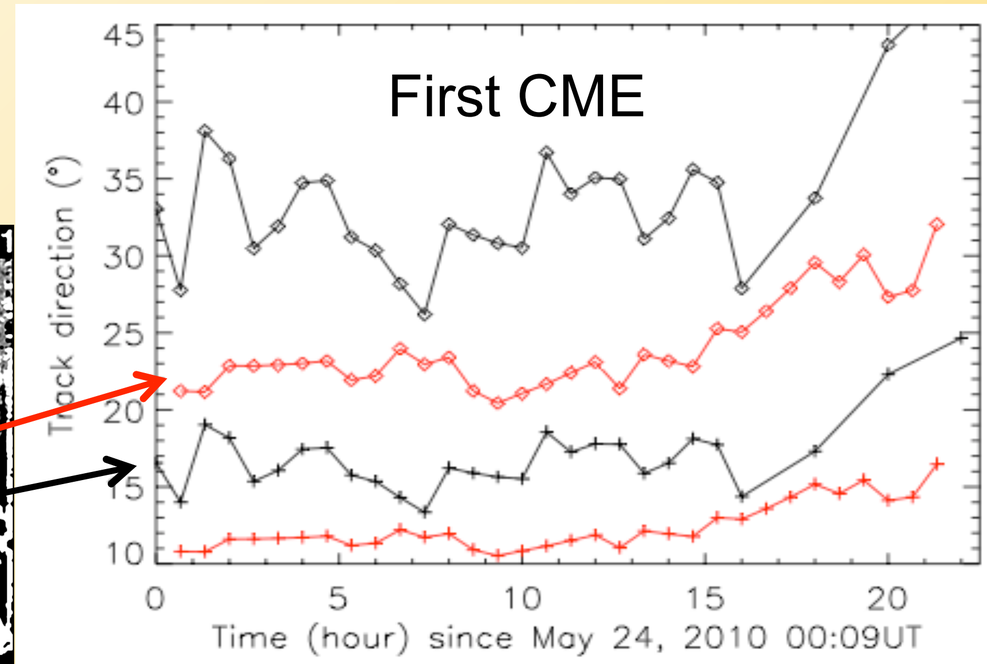
May 23-24, 2010 CMEs

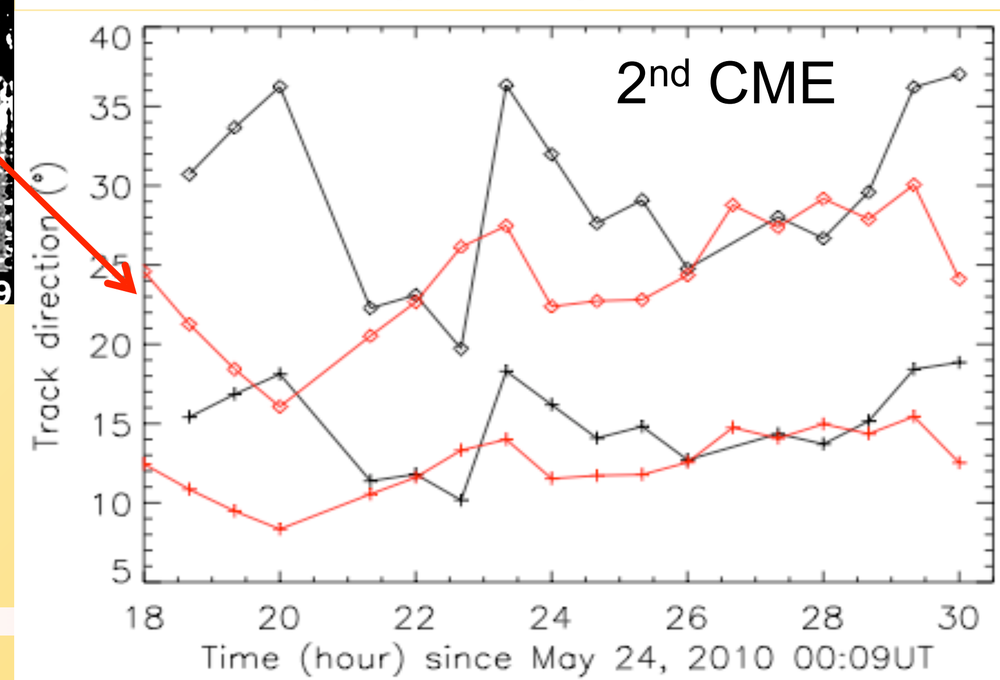


- 2 CMEs observed by A and B about 21 hours apart.
- **First CME:**
  - Flare: N19W12.
  - Deflected to the south.
  - Core only: 380 km/s
- **Second CME:**
  - Flare: N15W32
  - Deflected to the south.
  - Wider front: 650 km/s
  - Core:520 km/s

Direction of the CMEs







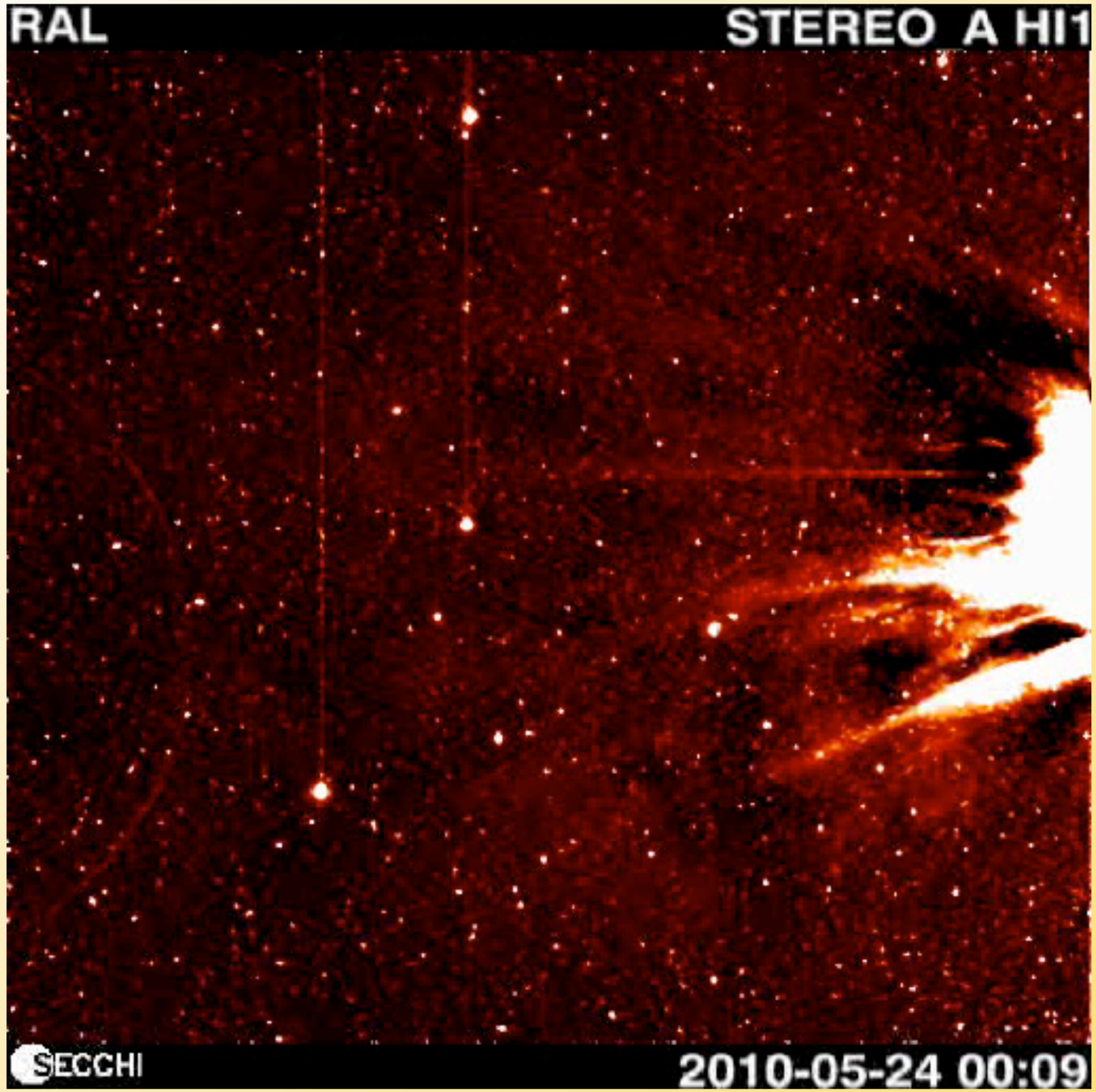
Tangent-to-a-sphere
(Lugaz *et al.*, **ApJ**, 2010)
W 23

Triangulation
(Liu *et al.*, **ApJ**, 2010)
W 10

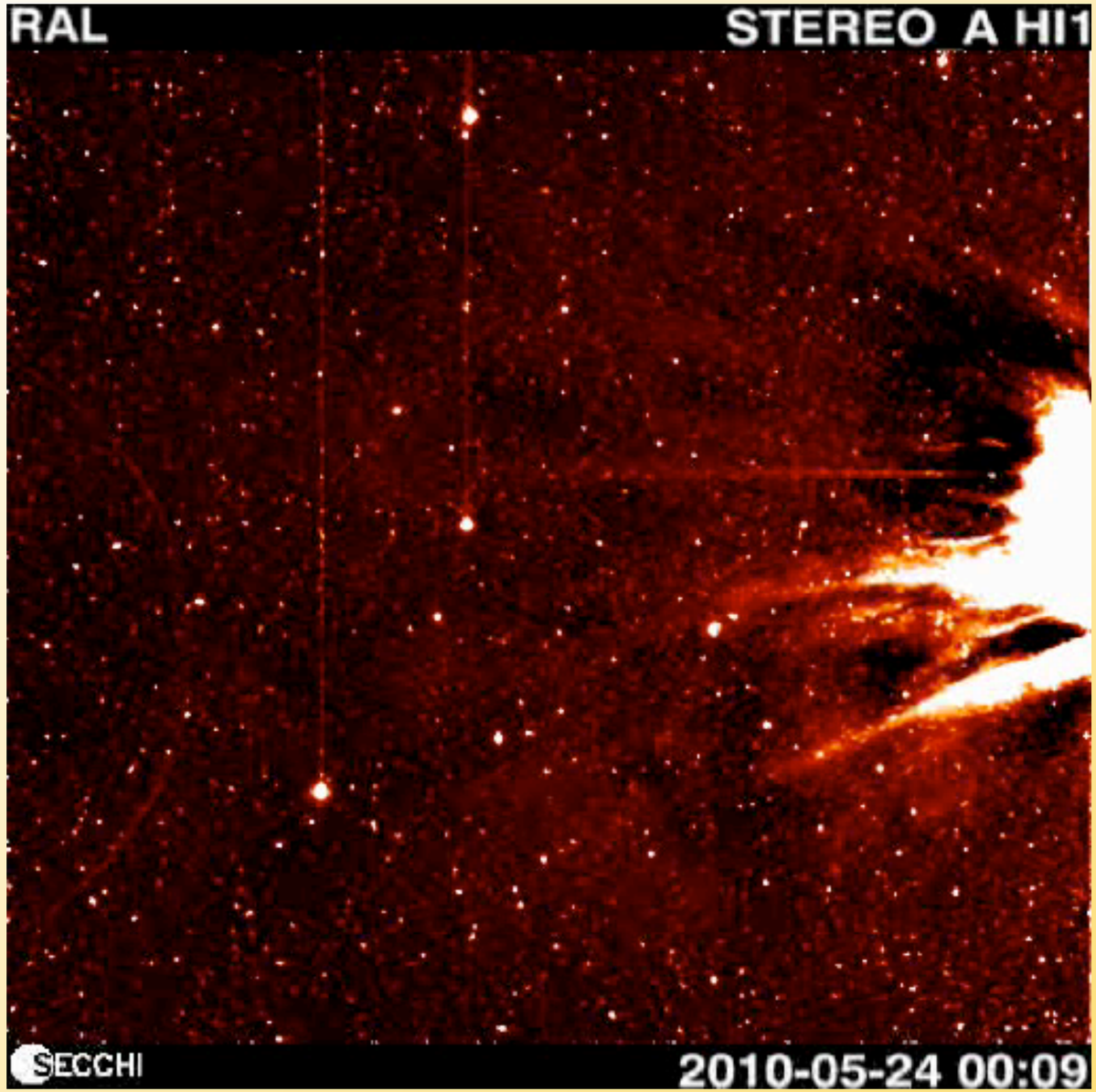
Tangent-to-a-sphere
W 27

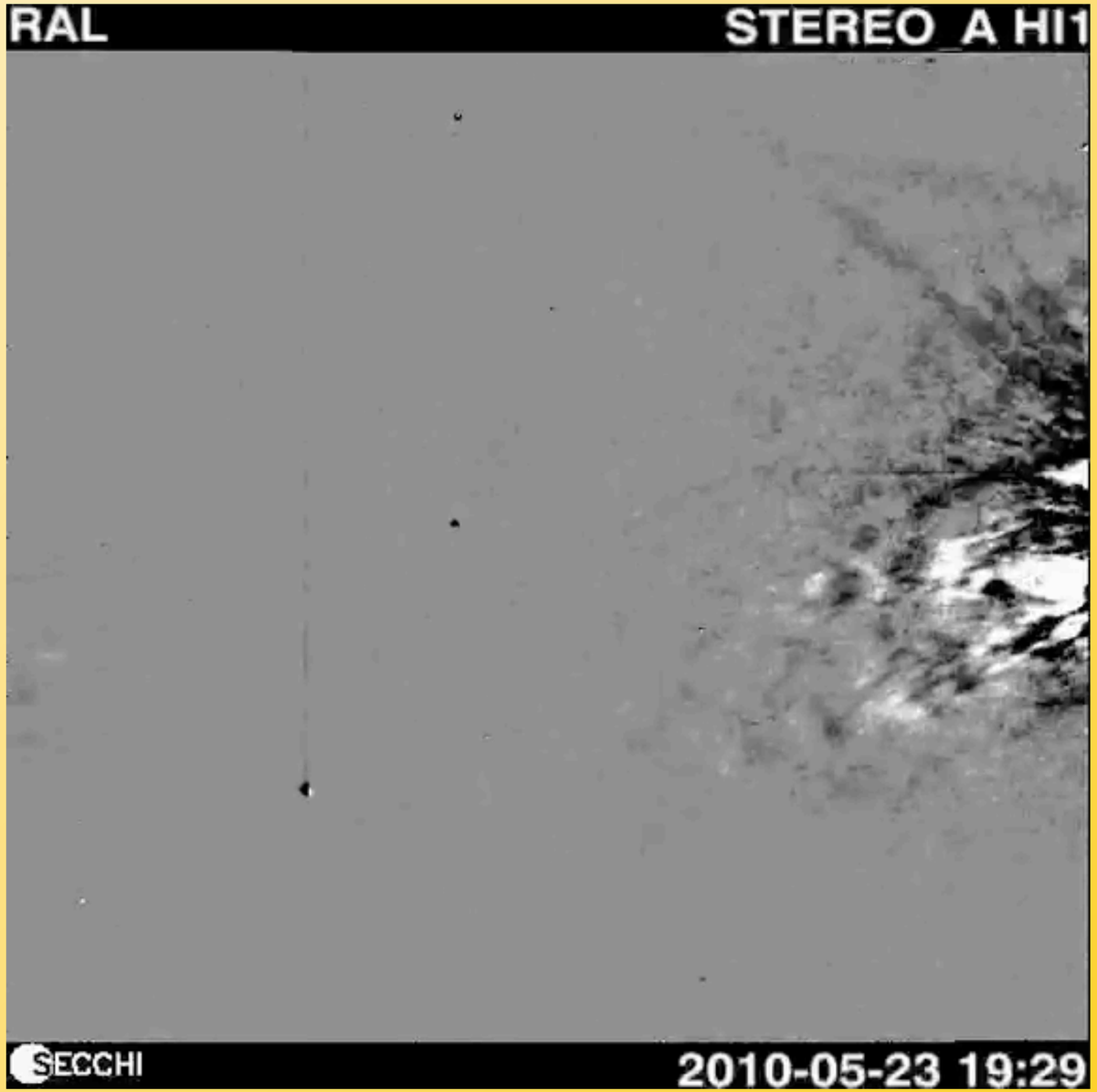
Triangulation
W 13

Observations

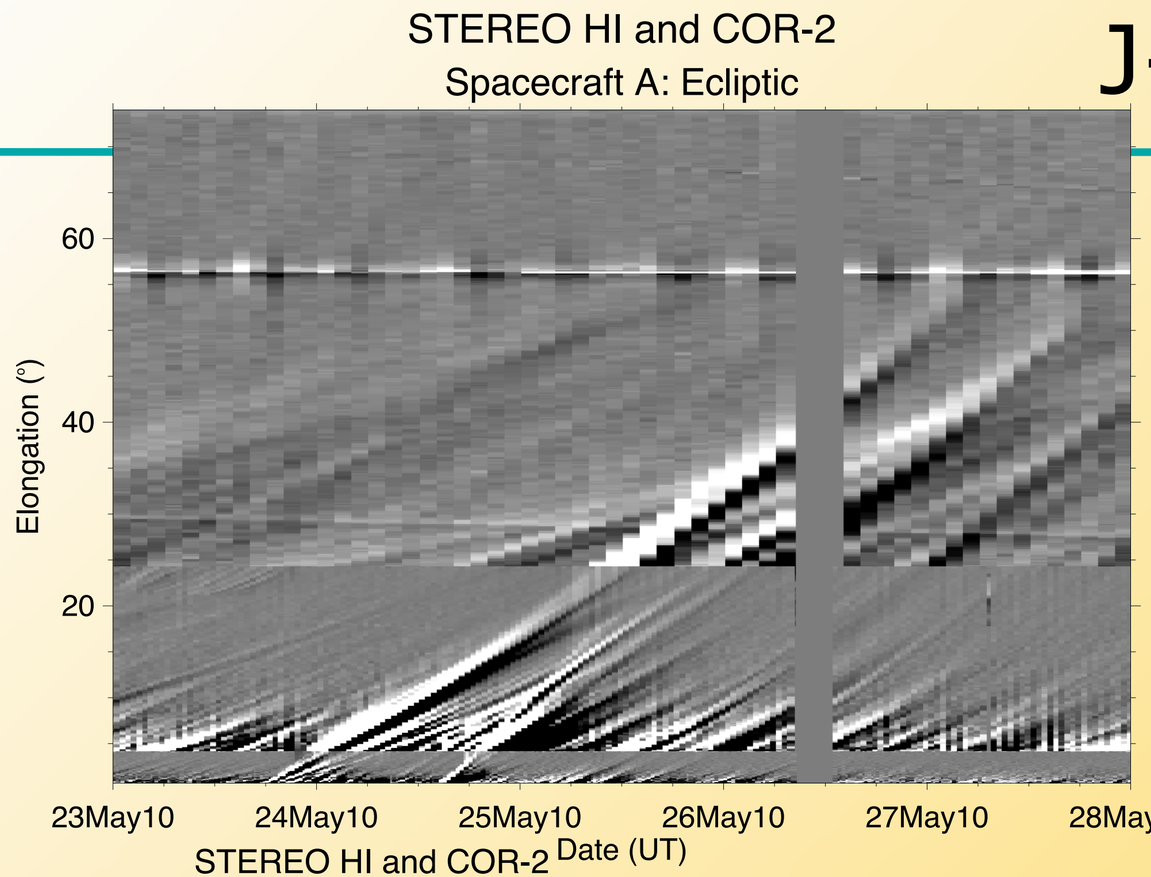


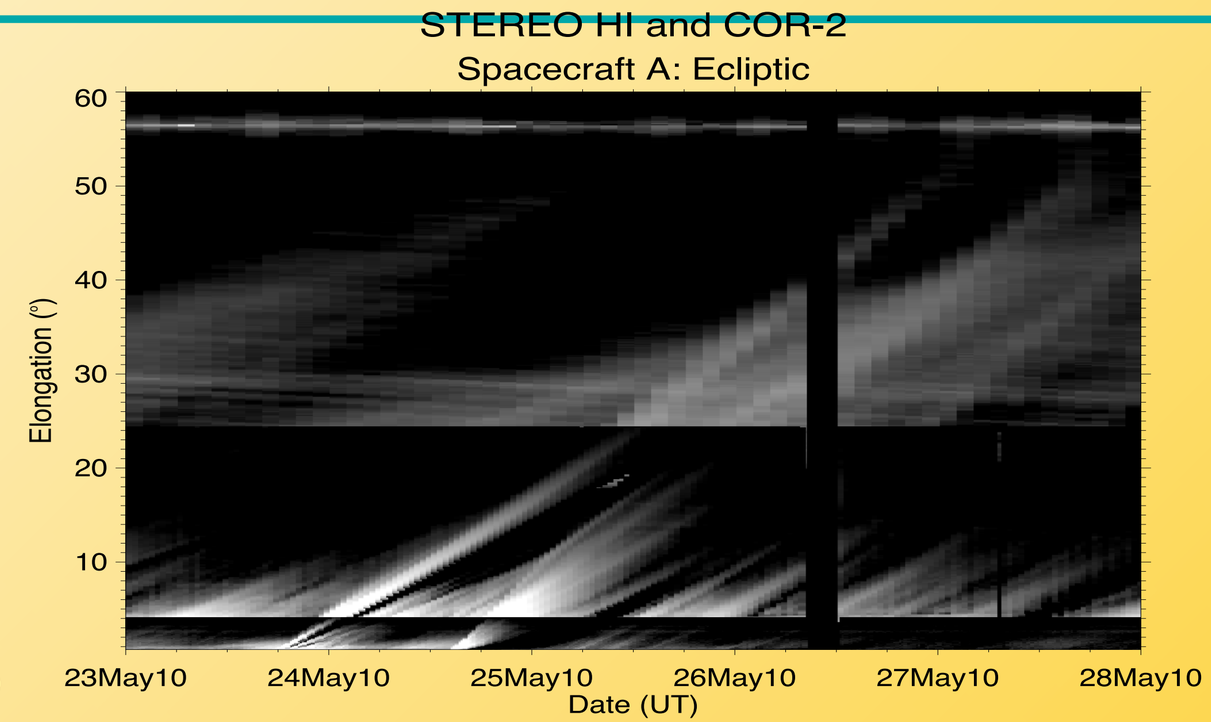
Observations





J-maps


STEREO HI and COR-2
Spacecraft A: Ecliptic
Elongation (°)
60
40
20
23May10
24May10
25May10
26May10
27May10
28May10
Date (UT)


STEREO HI and COR-2
Spacecraft A: Ecliptic
Elongation (°)
60
50
40
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10
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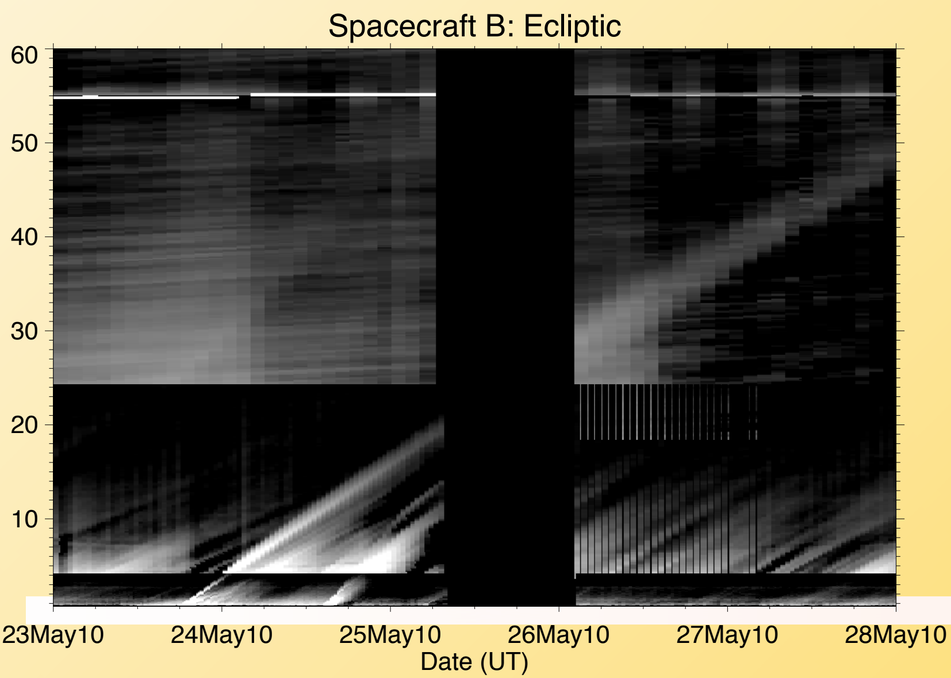
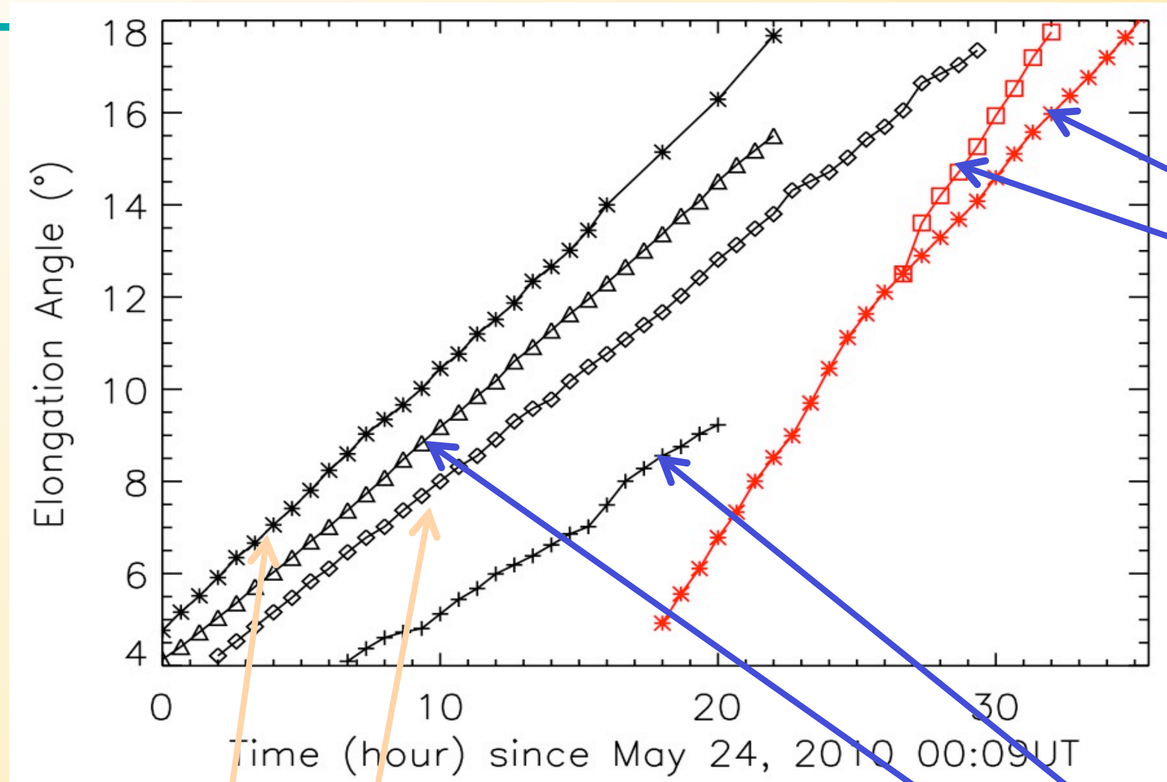
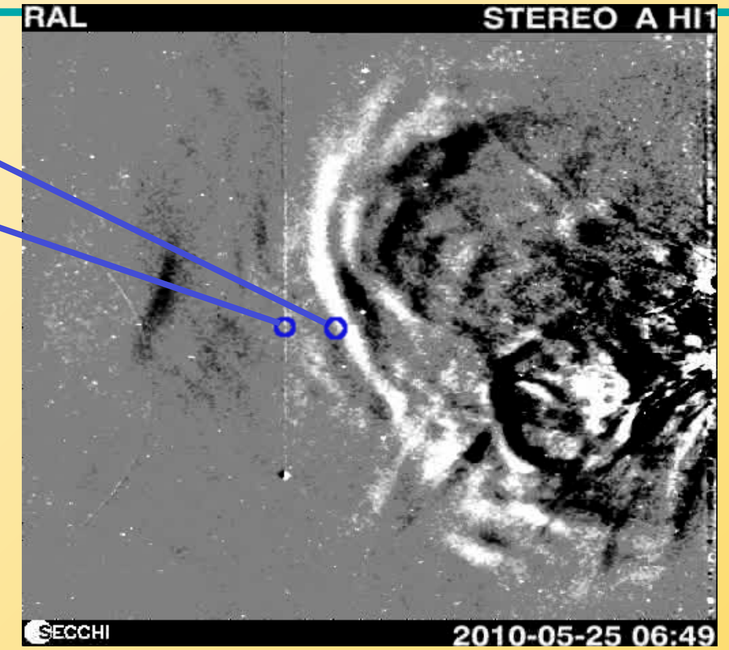
28May10
Date (UT)

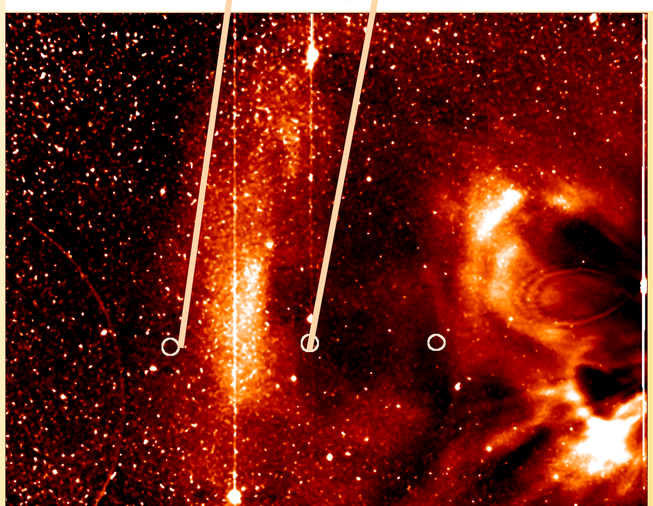

STEREO HI and COR-2
Spacecraft B: Ecliptic
60
50
40
30
20
10
23May10
24May10
25May10
26May10
27May10
28May10
Date (UT)

Observations

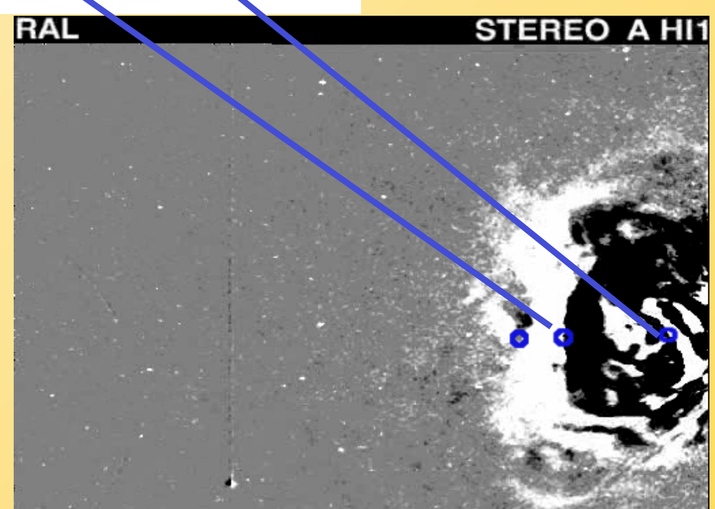




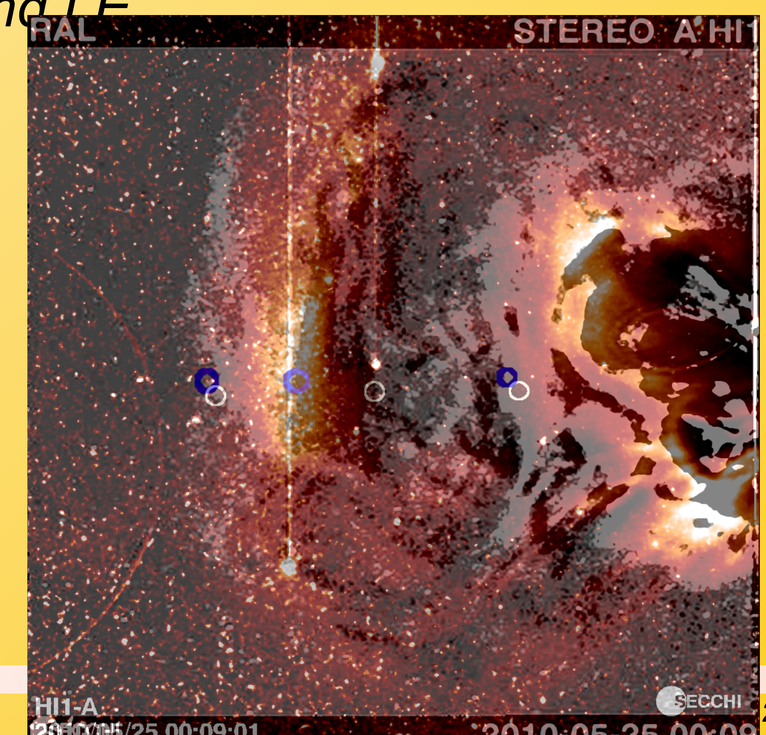
CME2 shock and LE



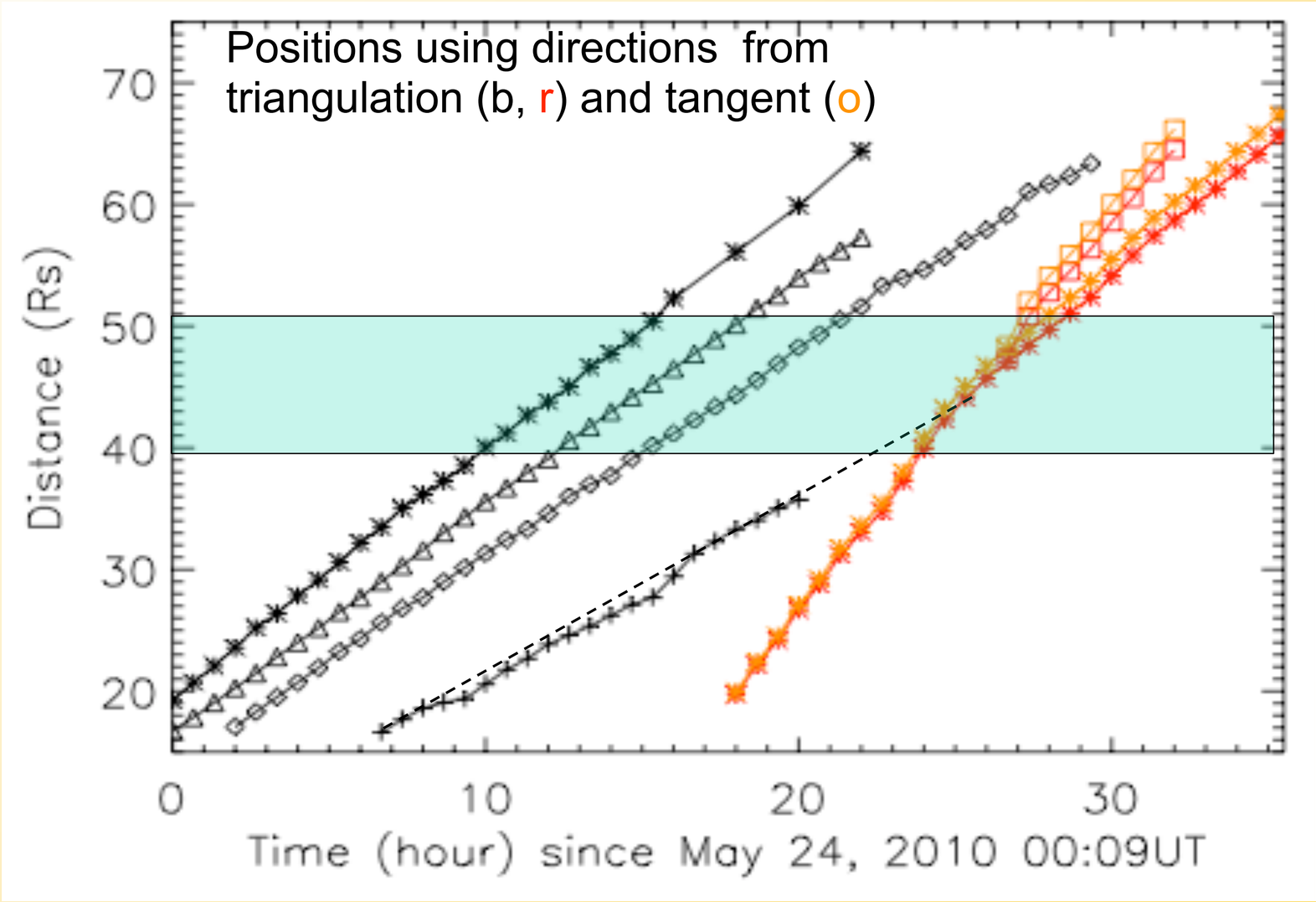
CME1 leading edge (LE) back and front

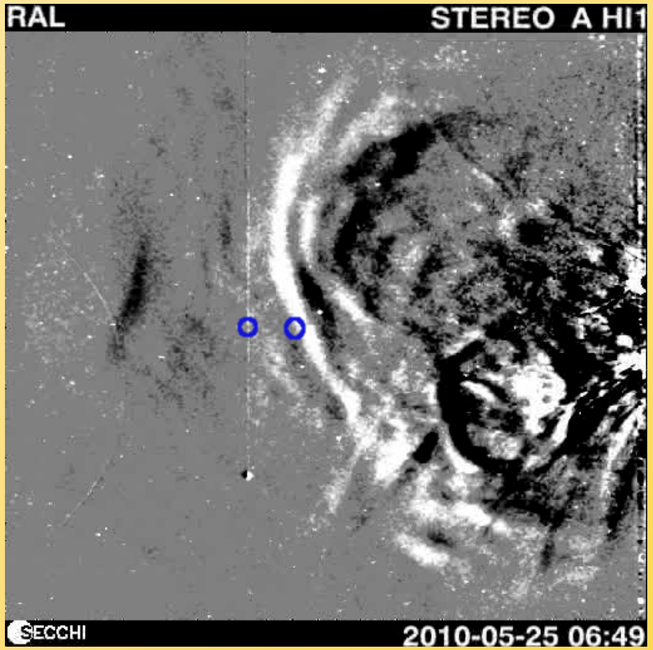


CME1 "black" edge and back of CME1



Position

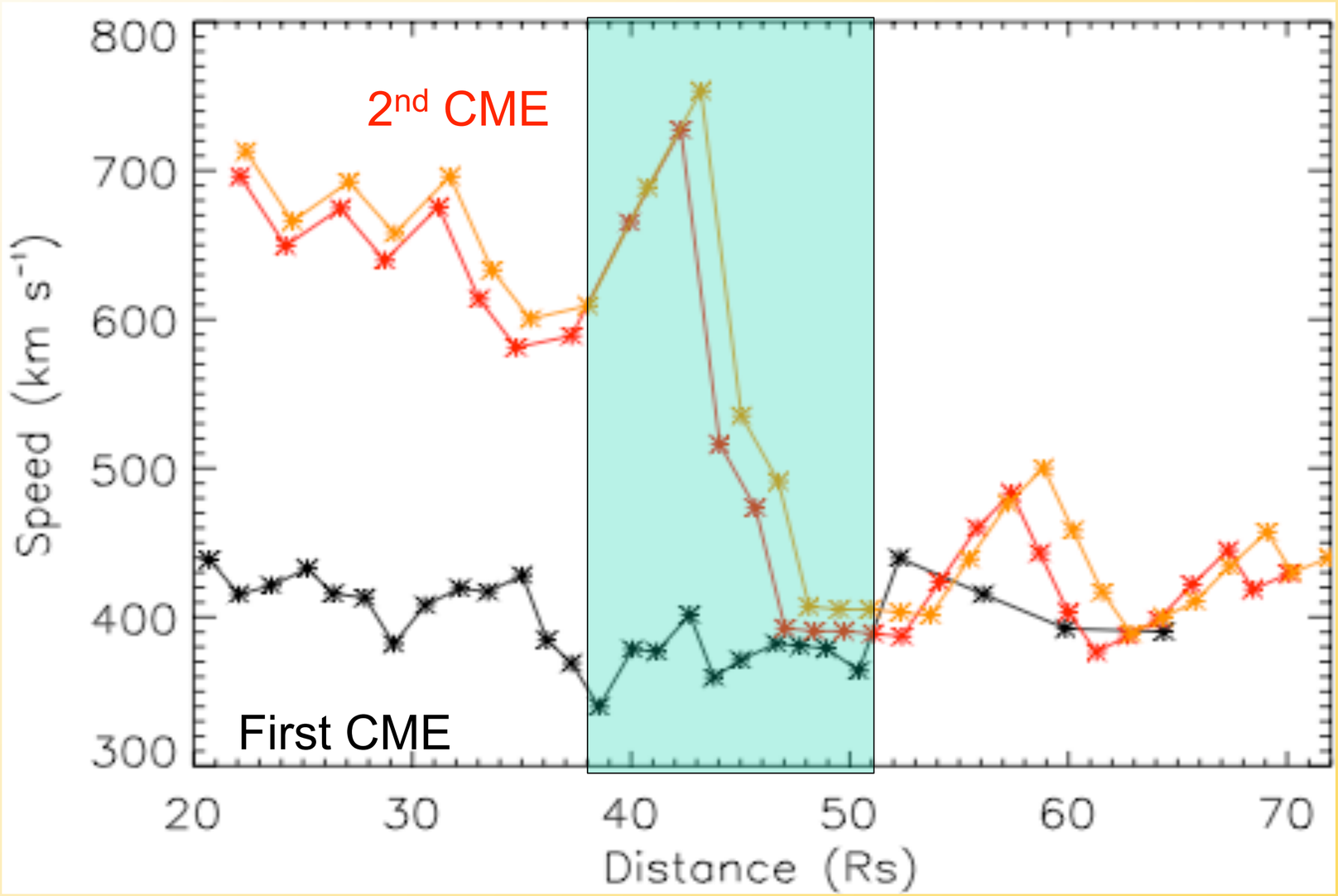




Shock/compression wave ahead of CME2

- A compression/shock wave forms and travels with a speed of 550-600 km/s.
- It is formed more or less when the 2nd CME “hits” the first CME.

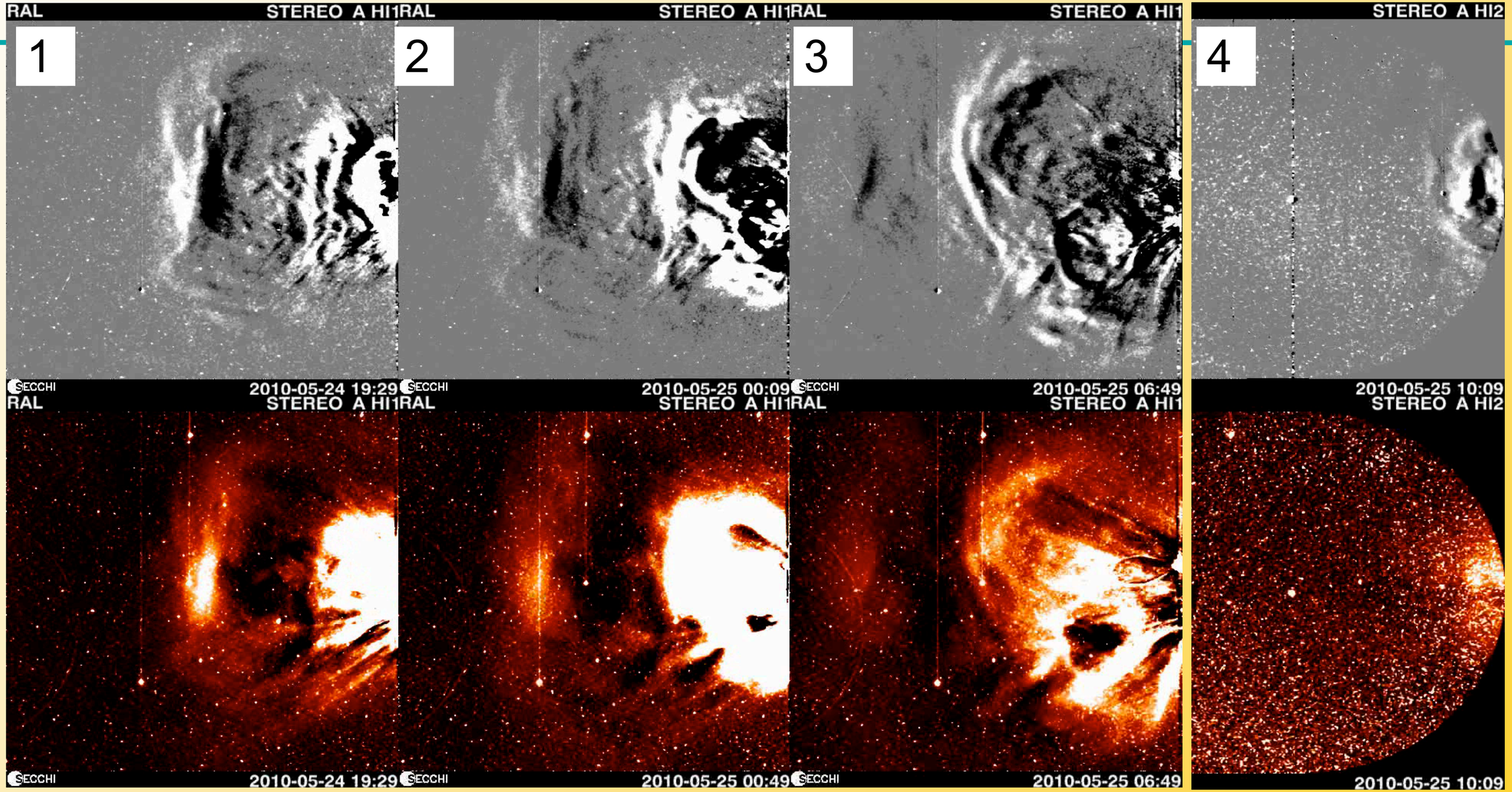
Speed



Speed of the leading edges as derived from the position using triangulation (b and r) and tangent-to-a-sphere (o) directions.

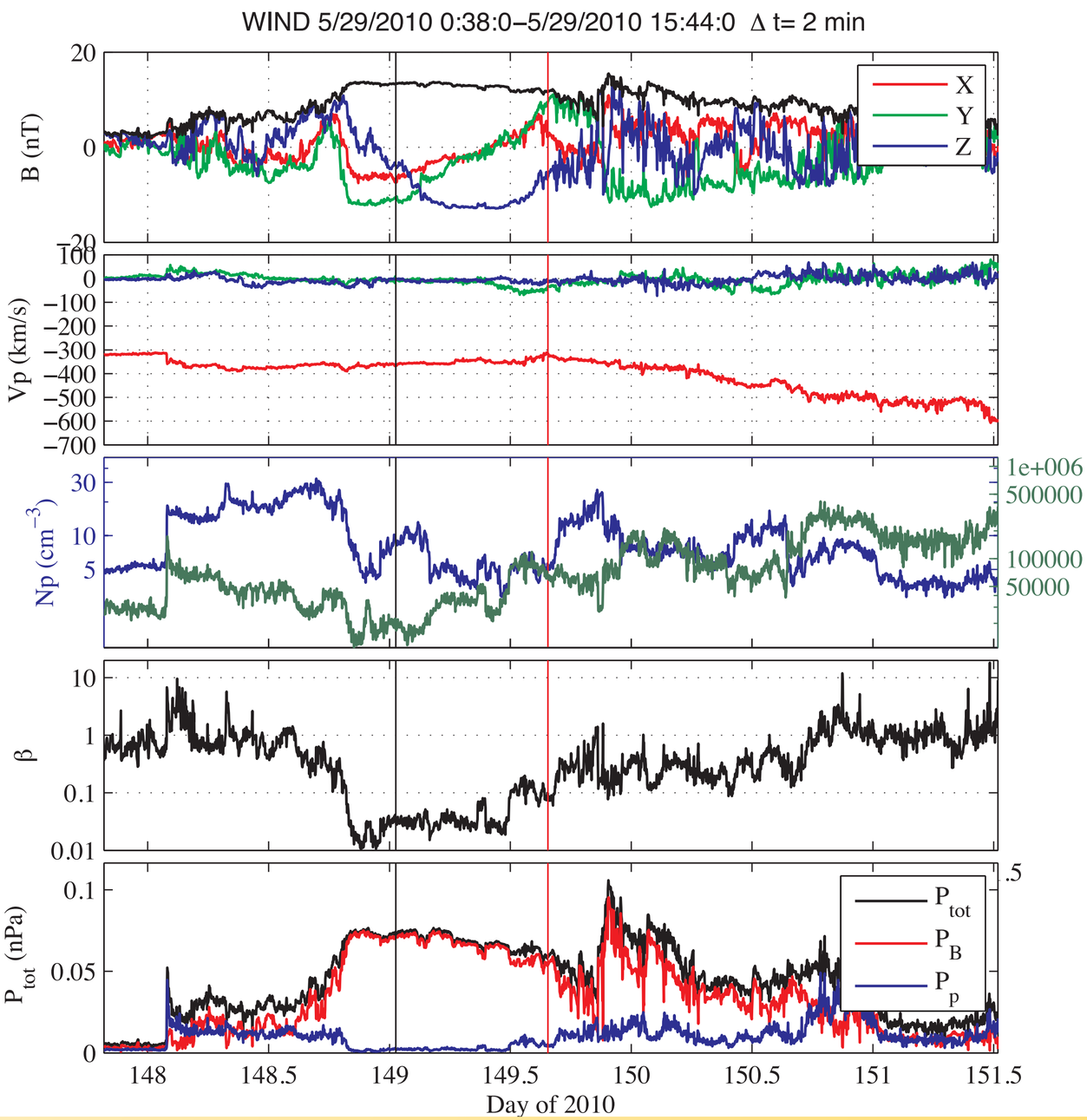
- There is a clear deceleration of the second CME at the time it hits the first CME.
- The speed of CME2 is constrained by that of the slower CME1.

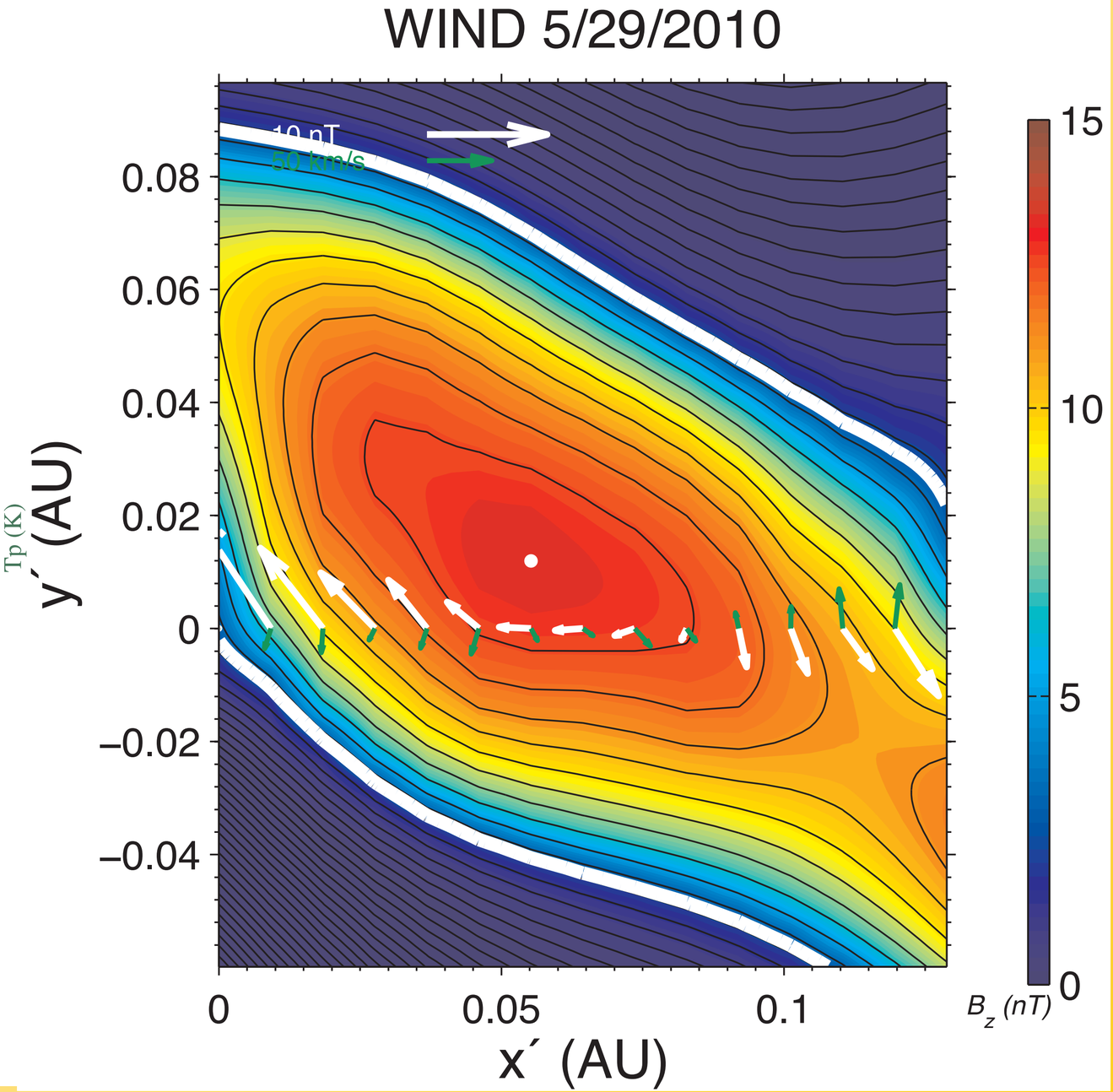
Scenario

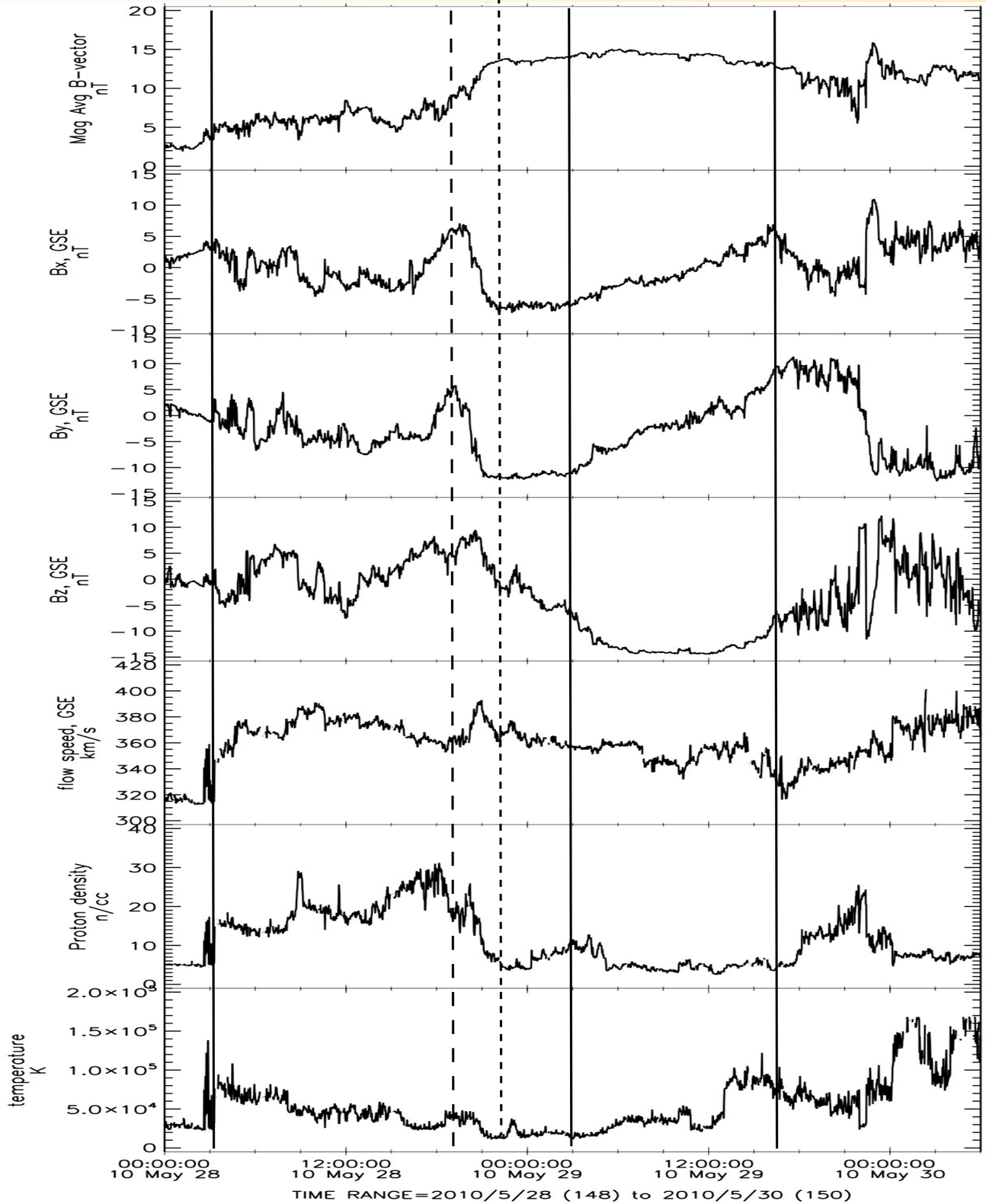


Proposed scenario: CME2 overtakes CME1 (1), collides with the back of the magnetic ejecta of CME1 (2), a shock wave forms (3) and overtakes the leading edge of CME1 (4).

Grad-Shafranov reconstruction





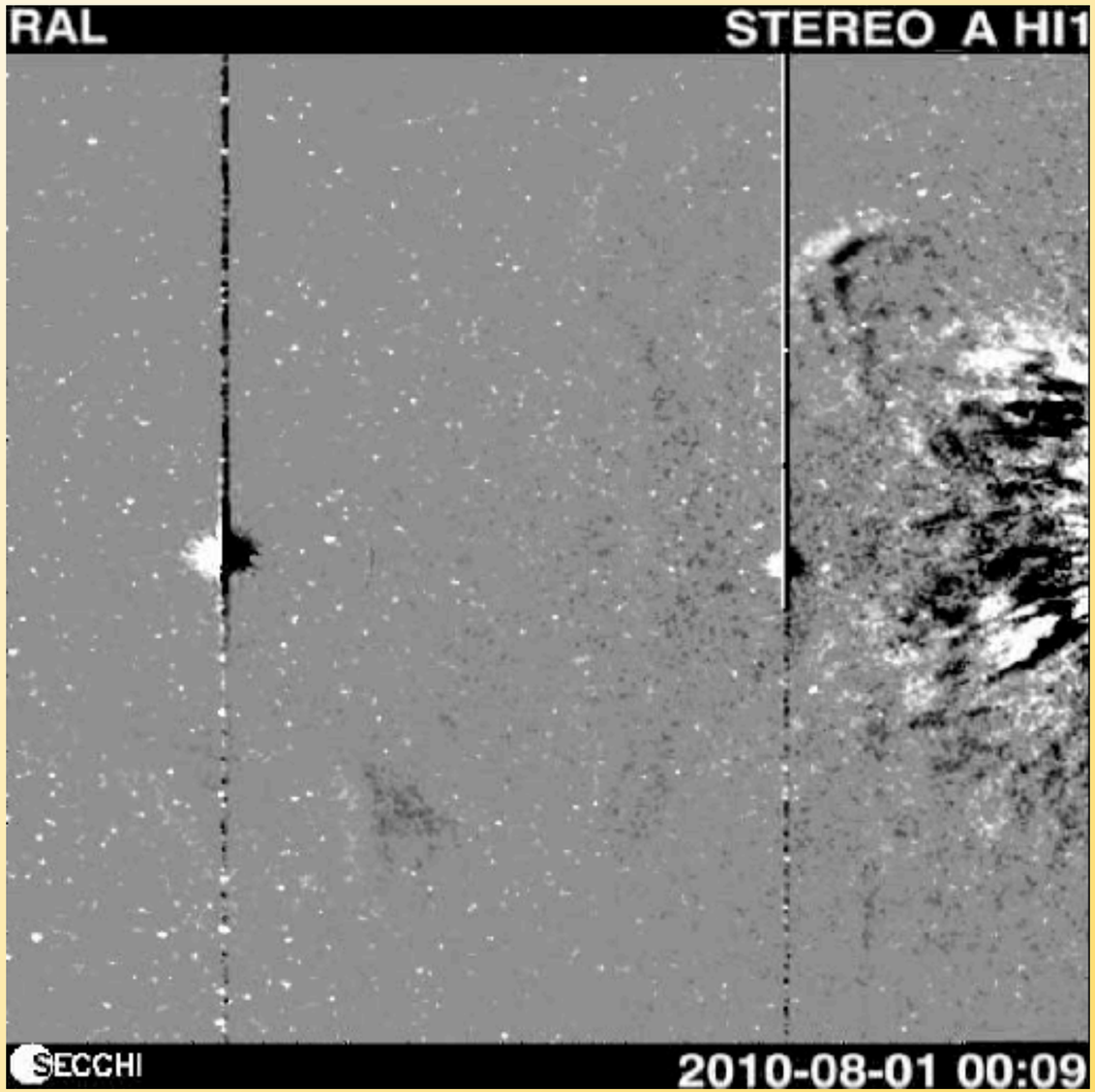


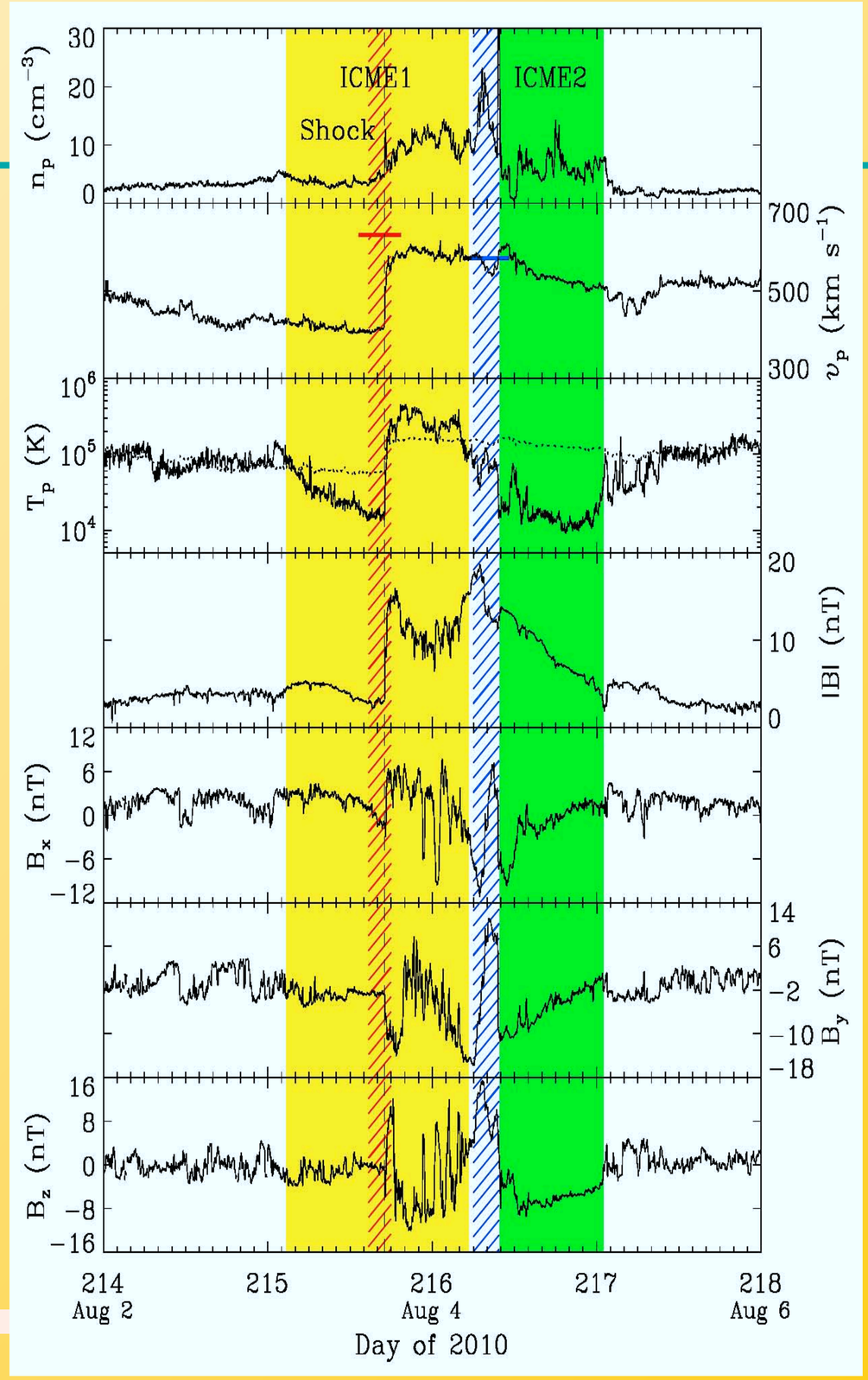
Results at 1 AU

- Shock + extended sheath (~18 hours) corresponds to the first HI-2 front.
- Secondary density peak at the back of the sheath.
- We propose that the back of the sheath corresponds to the merged sub front and second HI-2 front. It is associated with the remnant of CME1.
- Predicted arrival time of first front using constant speed past 60°:
  - FF (13): 10UT on 05/27, speed 520 km/s.
  - HM (26): 09UT on 05/28, speed 430 km/s.
- Predicted arrival time of second front using constant speed past 60°:
  - FF: 08UT on 05/28, speed 420 km/s.
  - HM (13): 18UT on 05/28, speed 380 km/s.
  - HM (27): 12UT on 05/29, speed 330 km/s.

2010 August 1

from Ying Liu (UCB/SSL)





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2010 August 1

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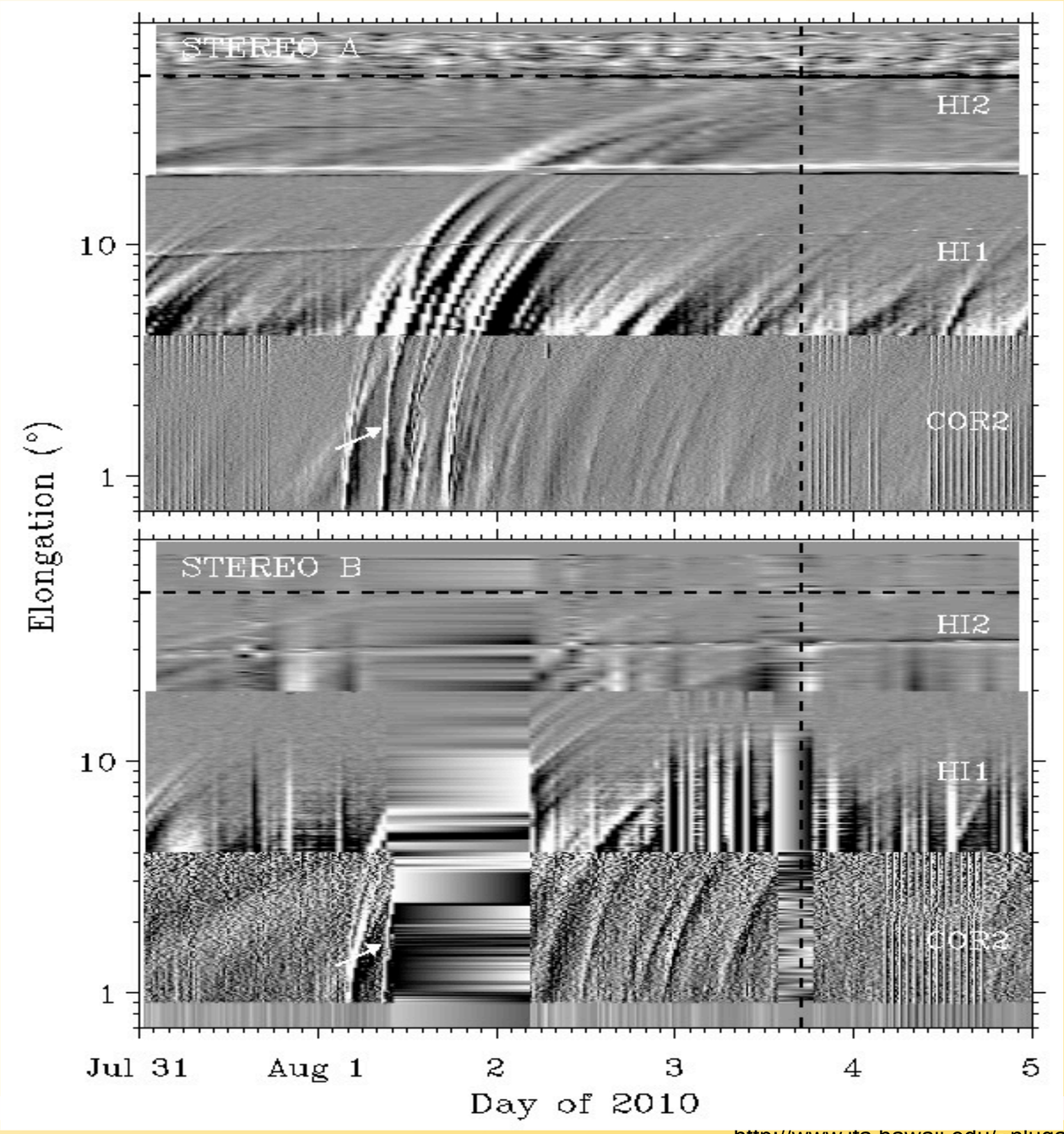

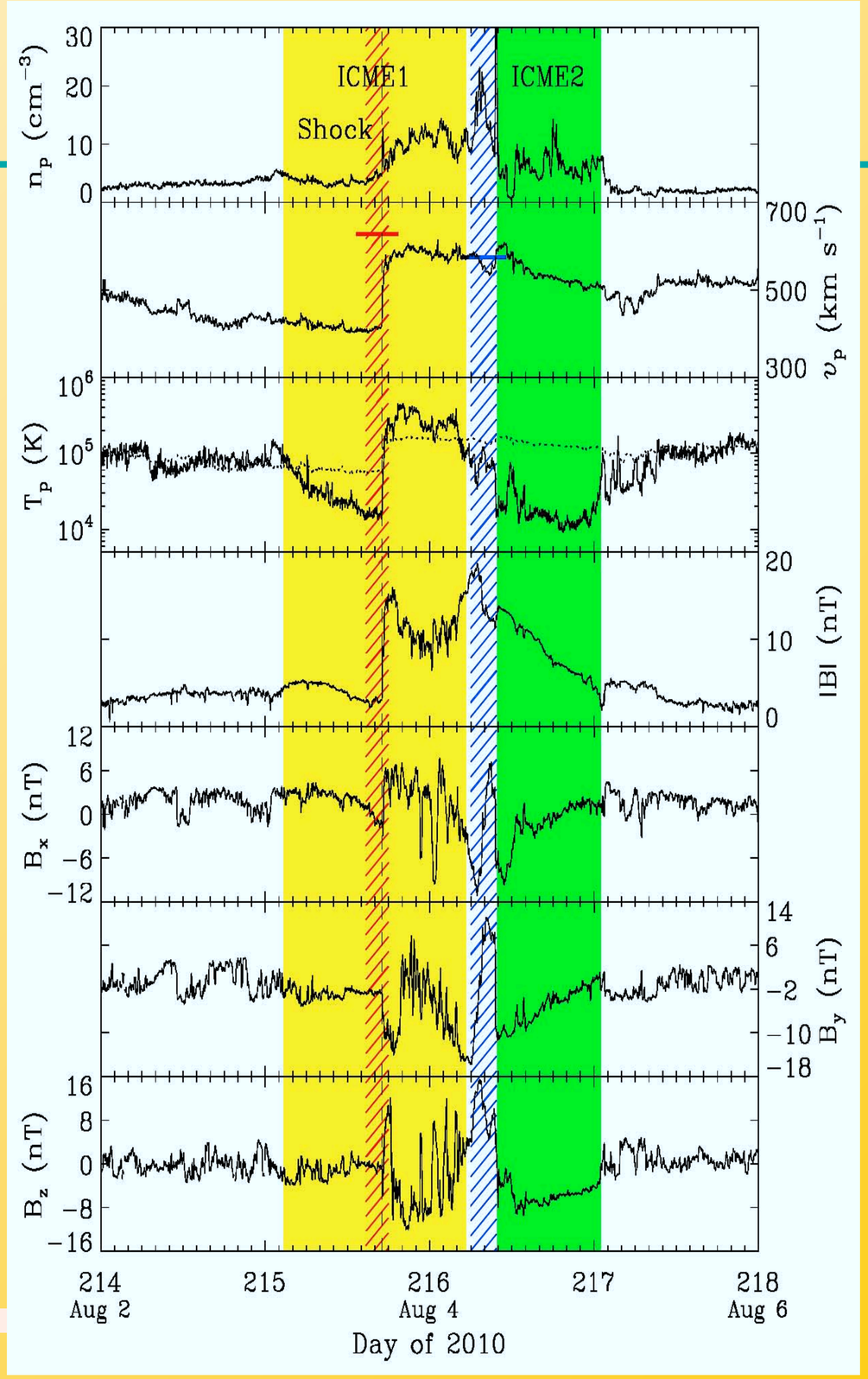

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