Complexity of Solar Eruptions

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Topics to be discussed

ï CME-CME interactions

ï Radio Signatures (Energetic Electrons)

ï Solar Energetic Particles

More details: ApJ, 548, L91, 2001

ApJ, 572, L103, 2002

GRL 29(8), 106-1, 2002

SW10 Proceedings

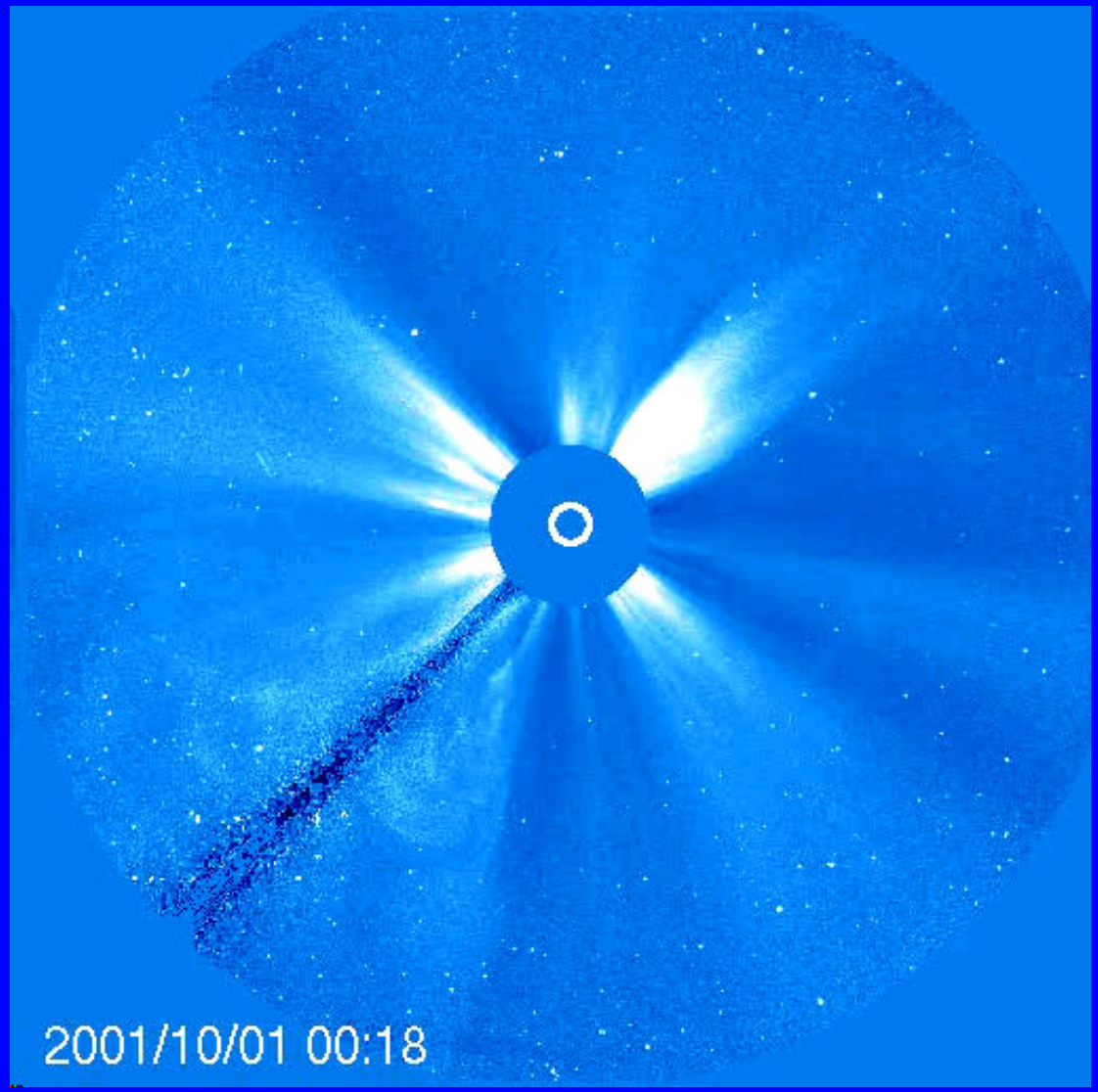
http://cdaw.gsfc.nasa.gov/LWS/

CME interaction: CMEs in the SW & NW are overtaken by a larger CME

→ CME1 at 01:54 and CME2 at 05:30 originated from the same region (S20W90) confirmed from SOHO/EIT and Nobeyama images.

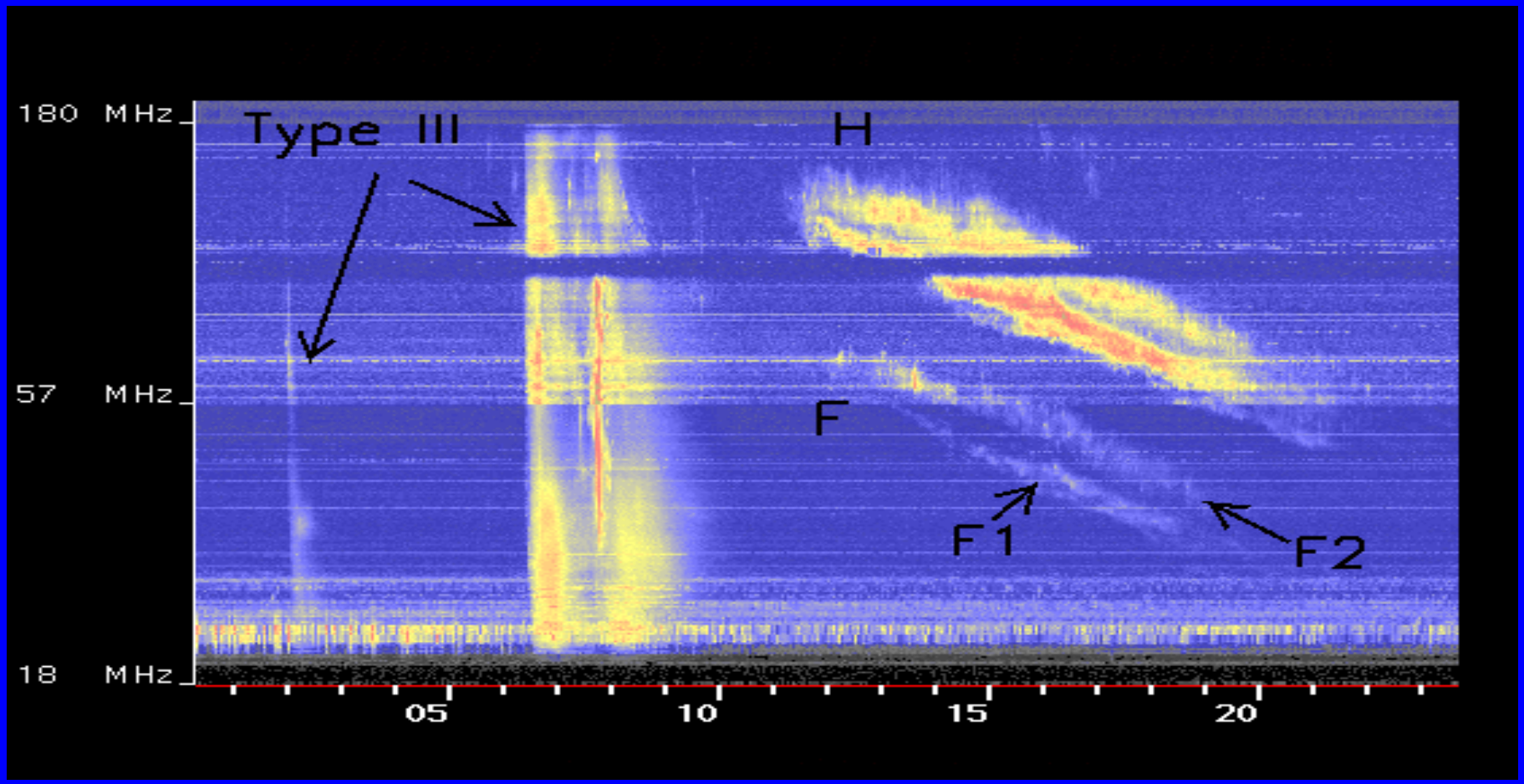
→ Note also that the streamer in the NW is pushed away by the eruption.

→ The ëSnow Stormí in LASCO images is due To SEPs reaching SOHO Detectors

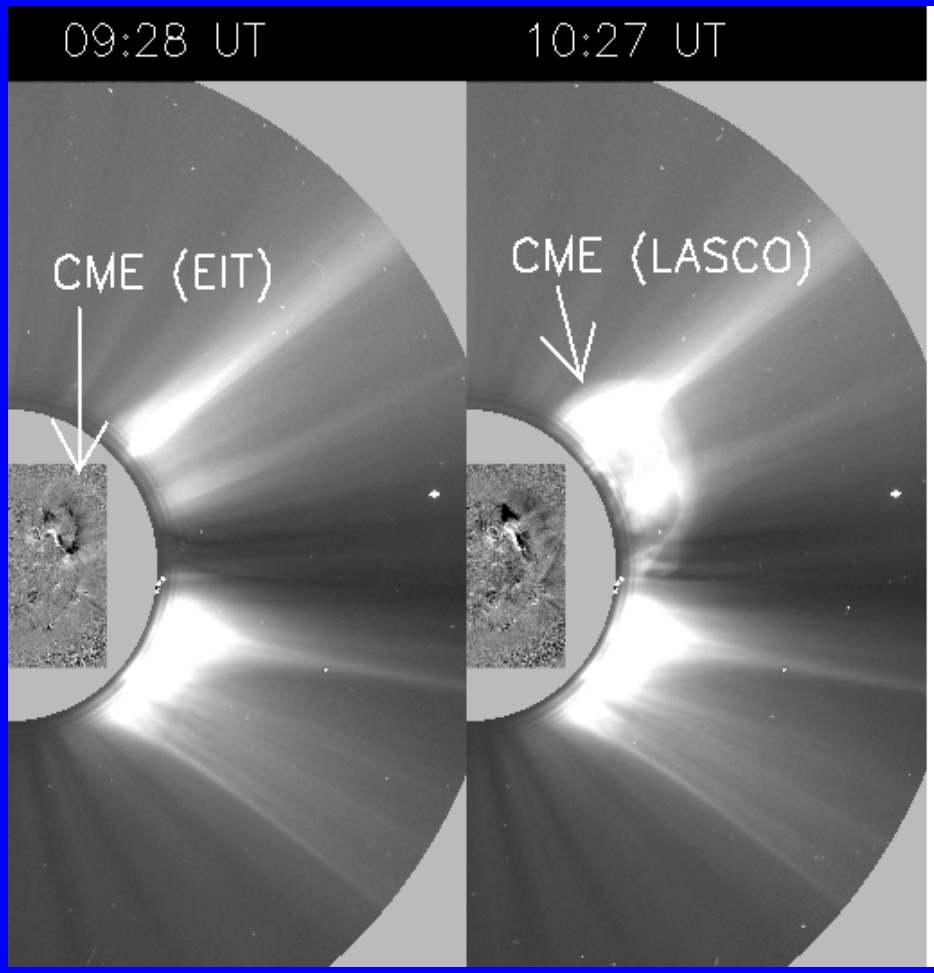


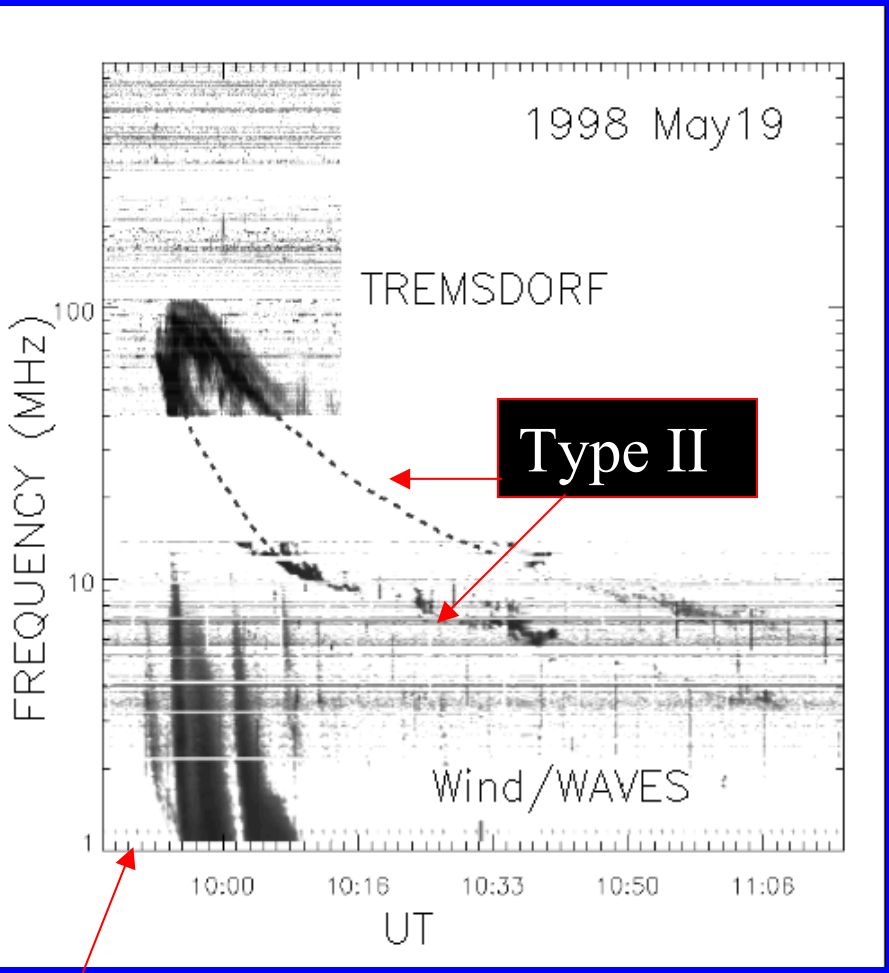
A Type II Radio Burst

Type III (e beams)v = 0.3 c, Type II (shocks) v 1000 km/s



Radio: Decameter-Hectometer (DH: 1-14 MHz)



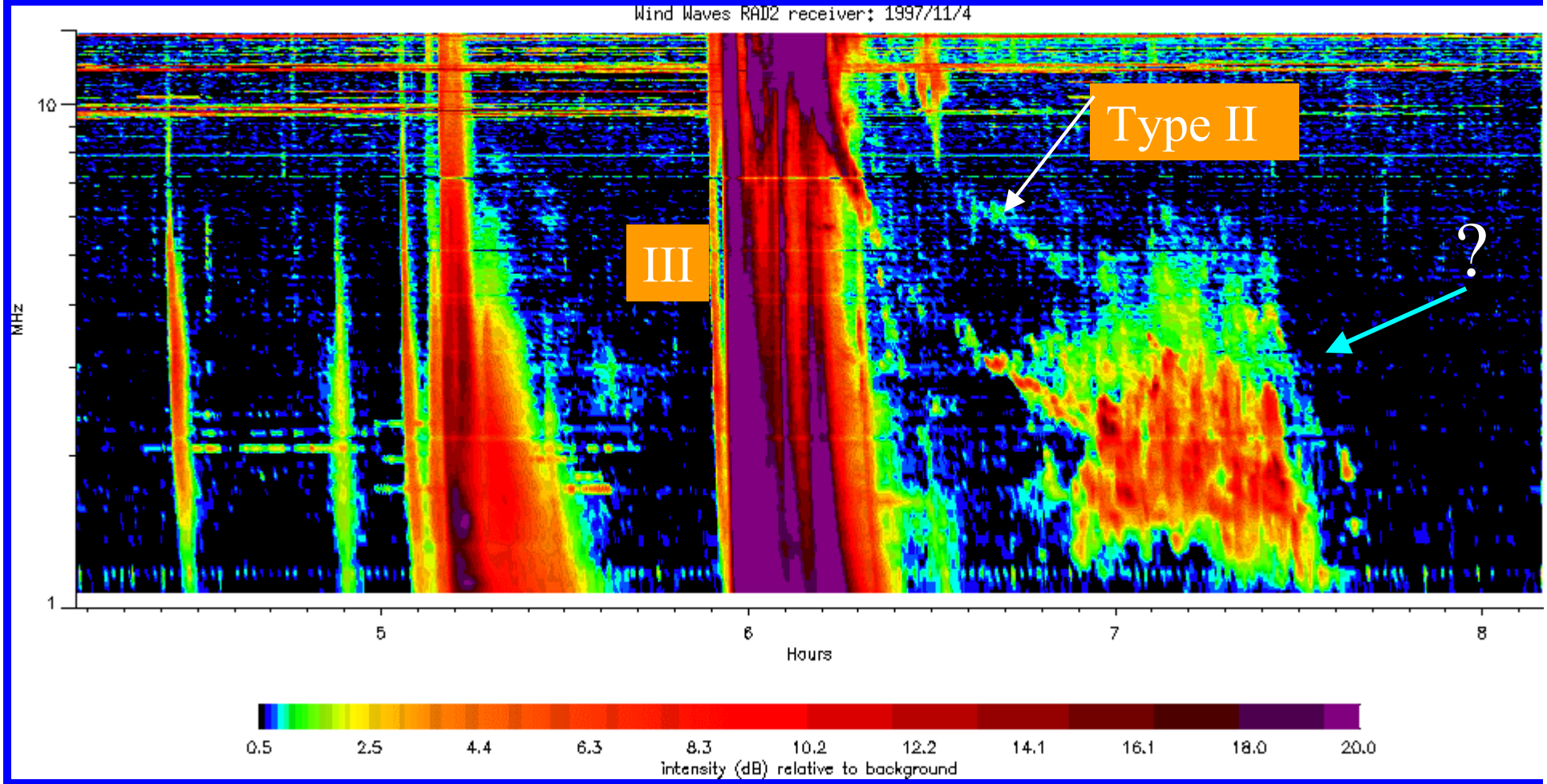


Gopalswamy, 2000 AGU Monogr.

SA Event (Type III Bursts)

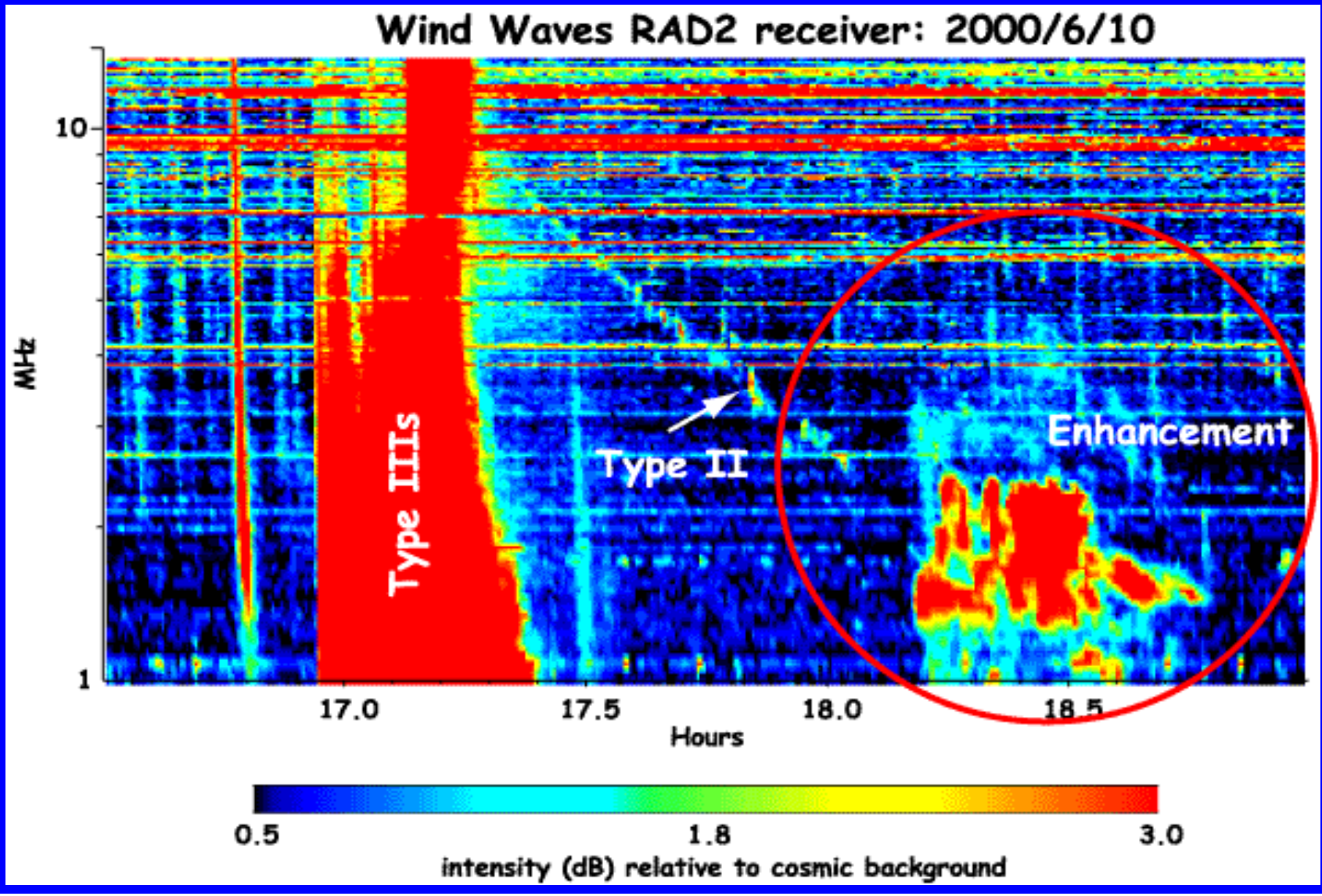
Something after the type II!

CME1 CME2

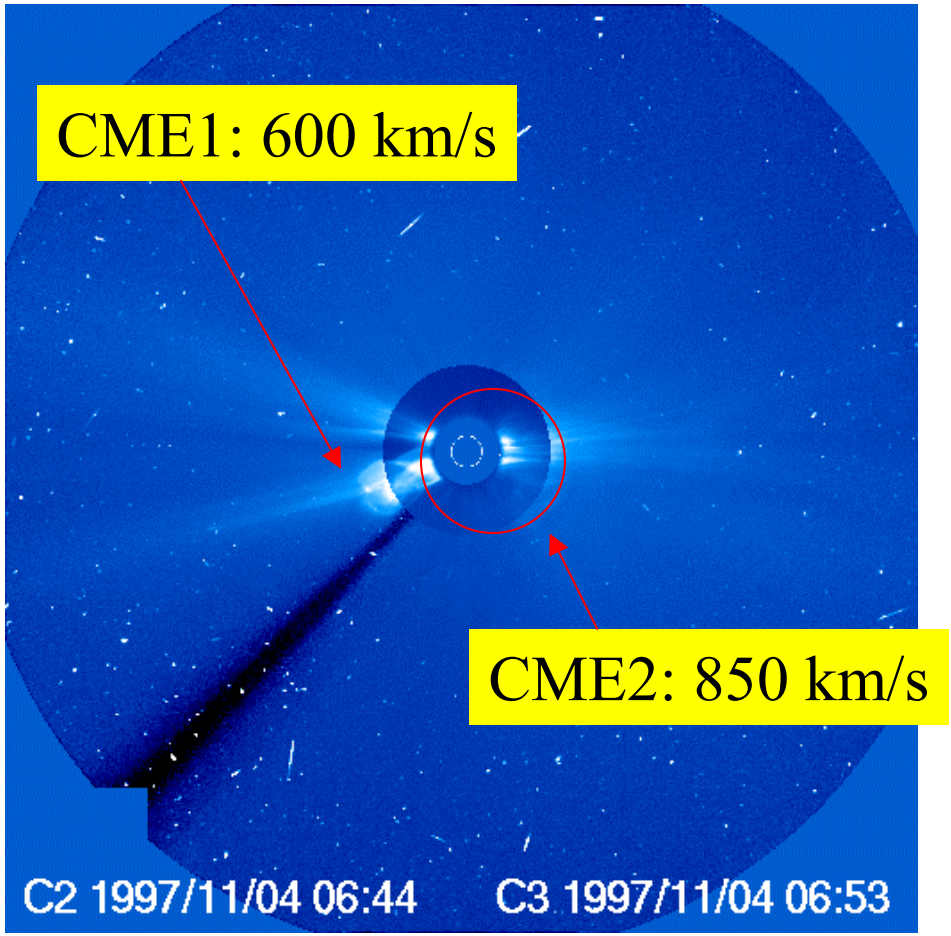


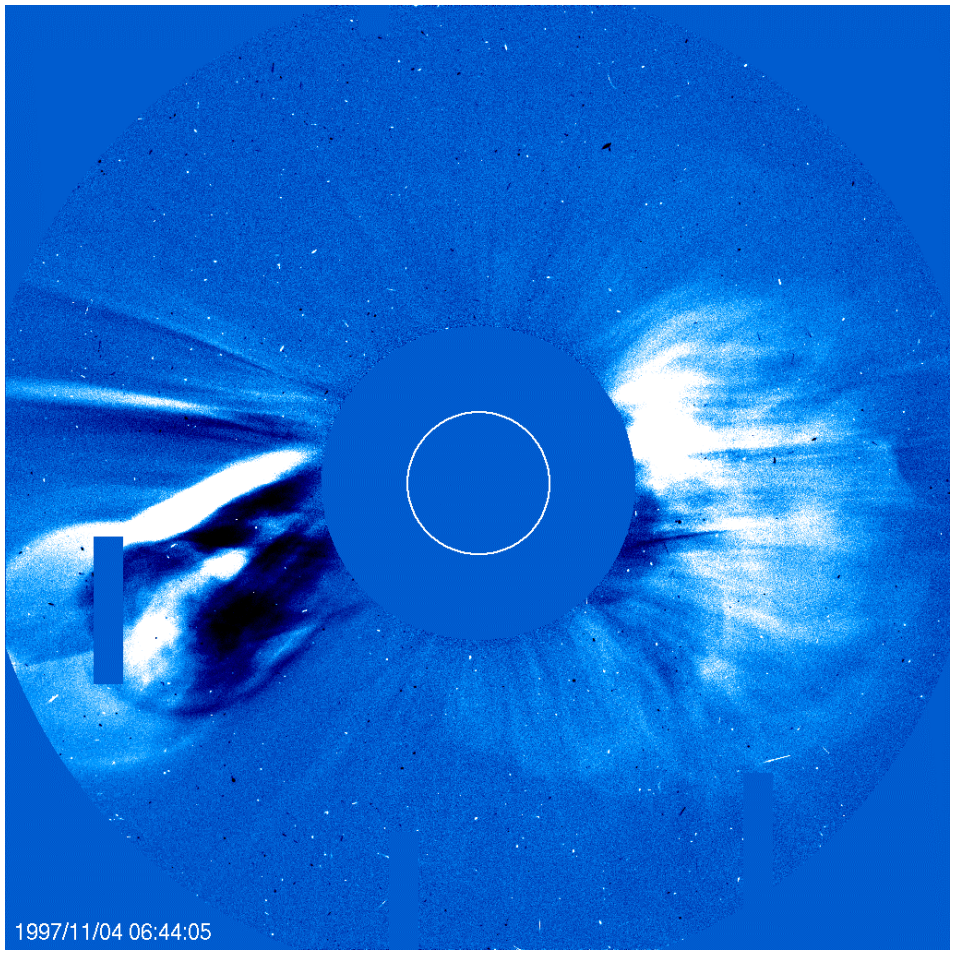
Another Strange Feature: 00/06/10

Gopalswamy et al. 2001, ApJ, 548, L91



Two Fast CMEs, 100 deg Apart

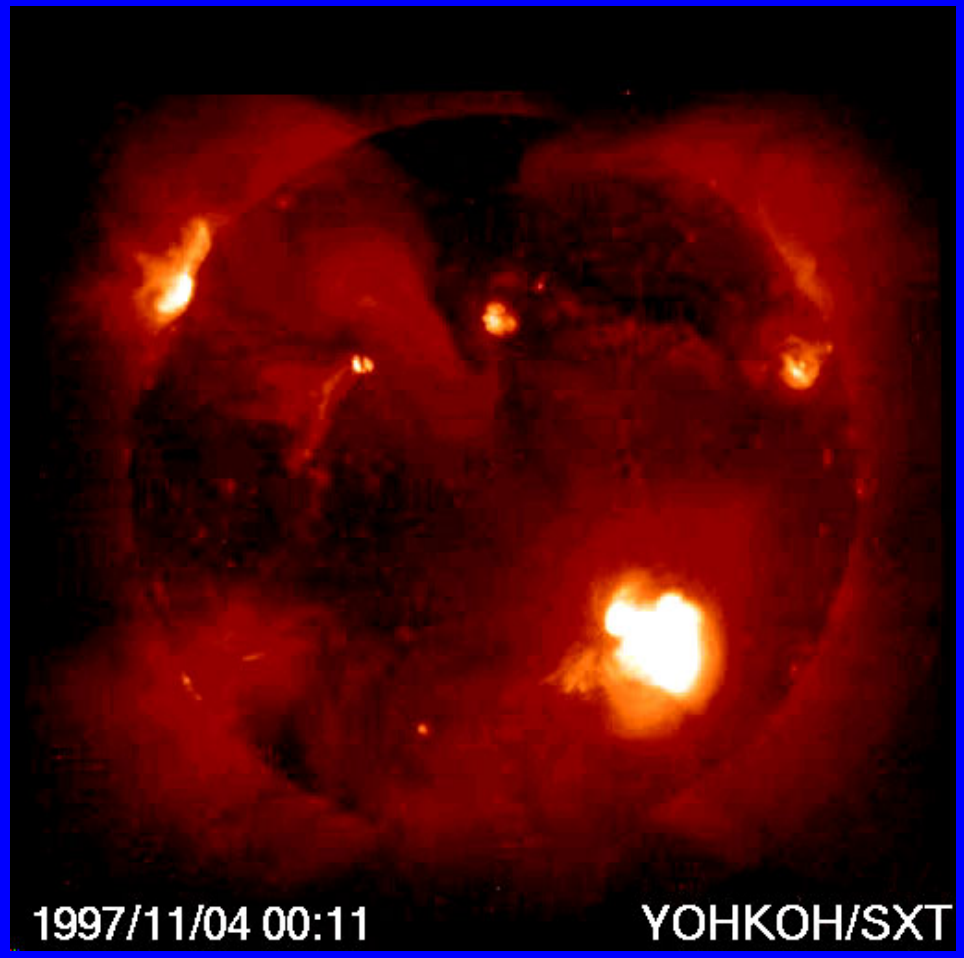




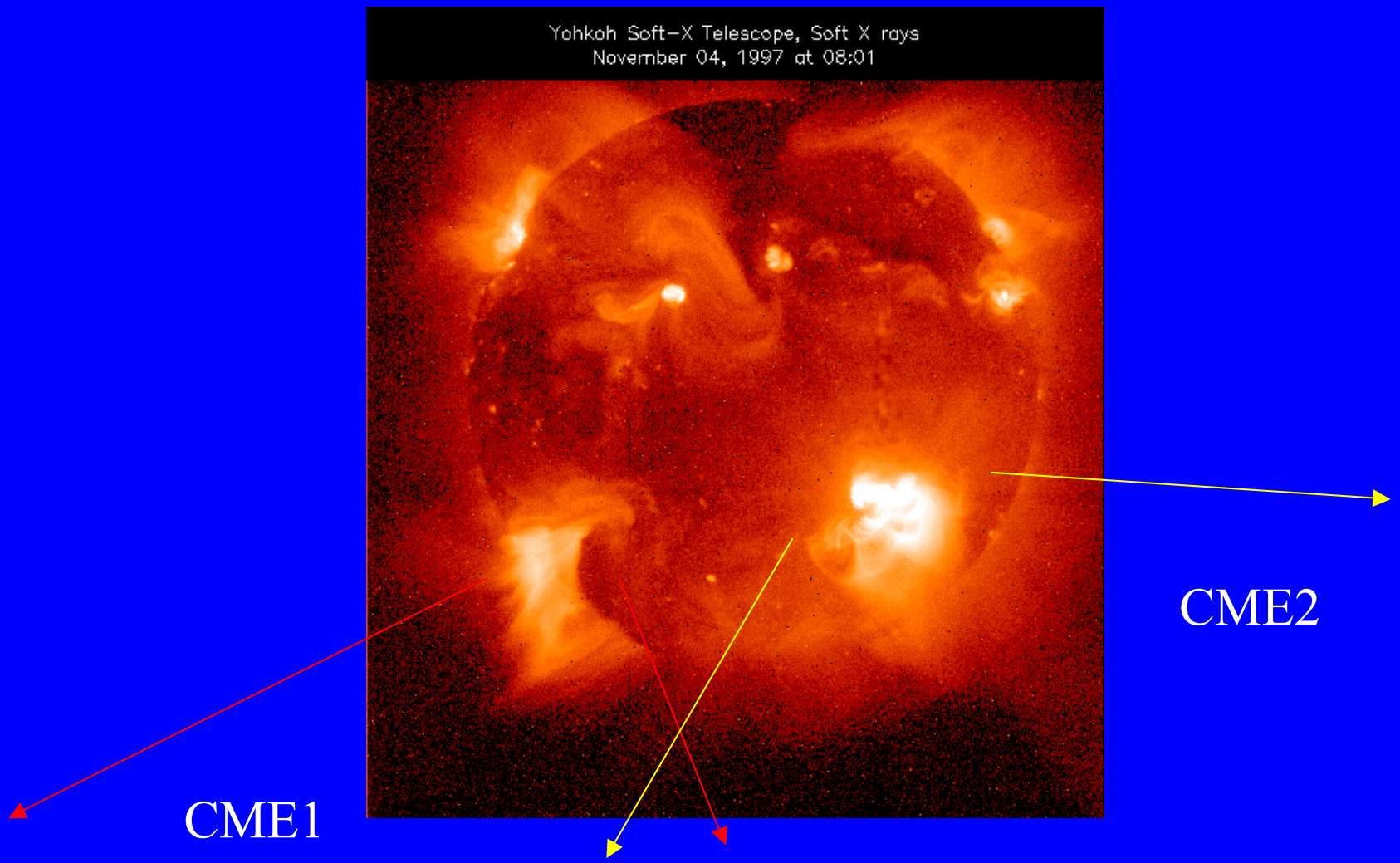
Shock ahead of CME2 passes through CME1

Solar Sources of Interacting CMEs

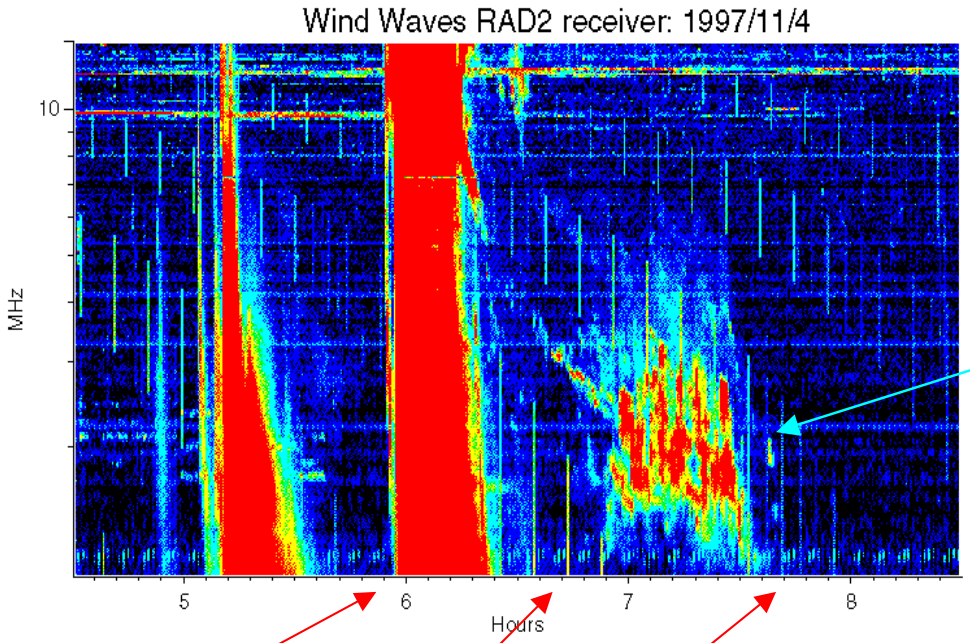
- Yohkoh/SXT movie shows that the CMEs originate from far away regions

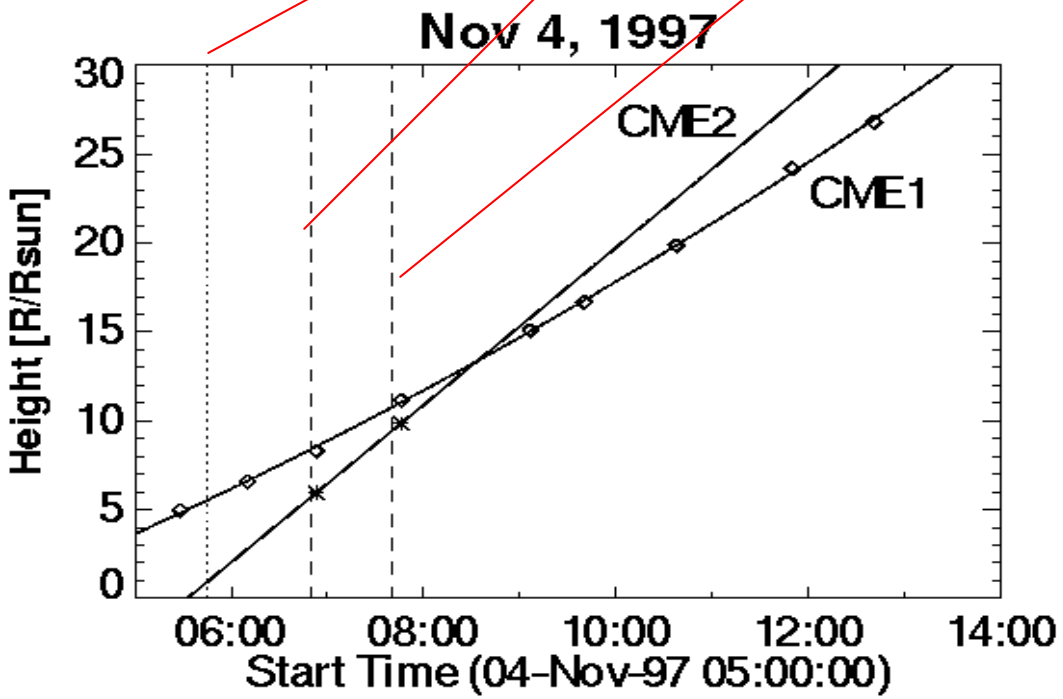


Source Regions of 1997 11 04 CMEs: Yohkoh/SXT



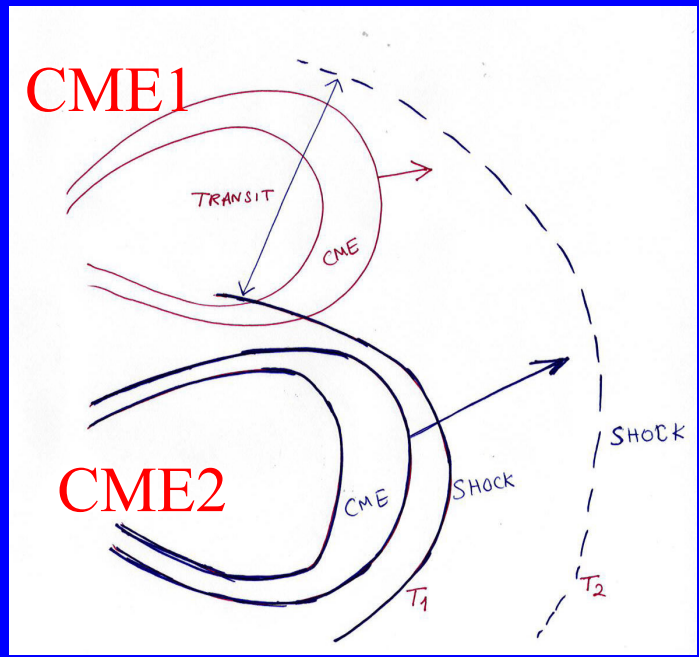
Shock Passing Through a CME



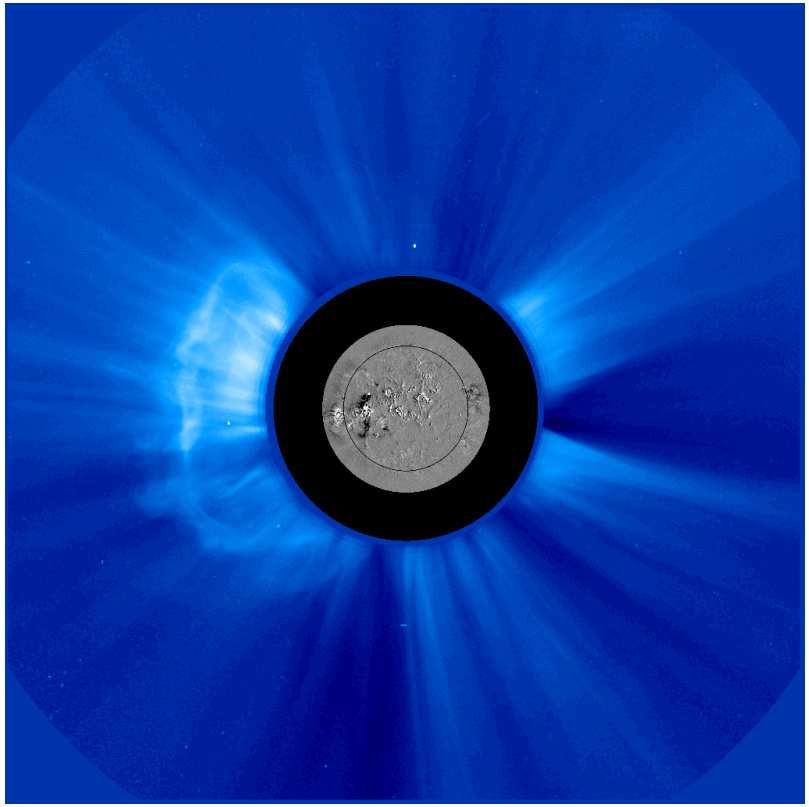


Radio emission due to CME1-shock2 interaction

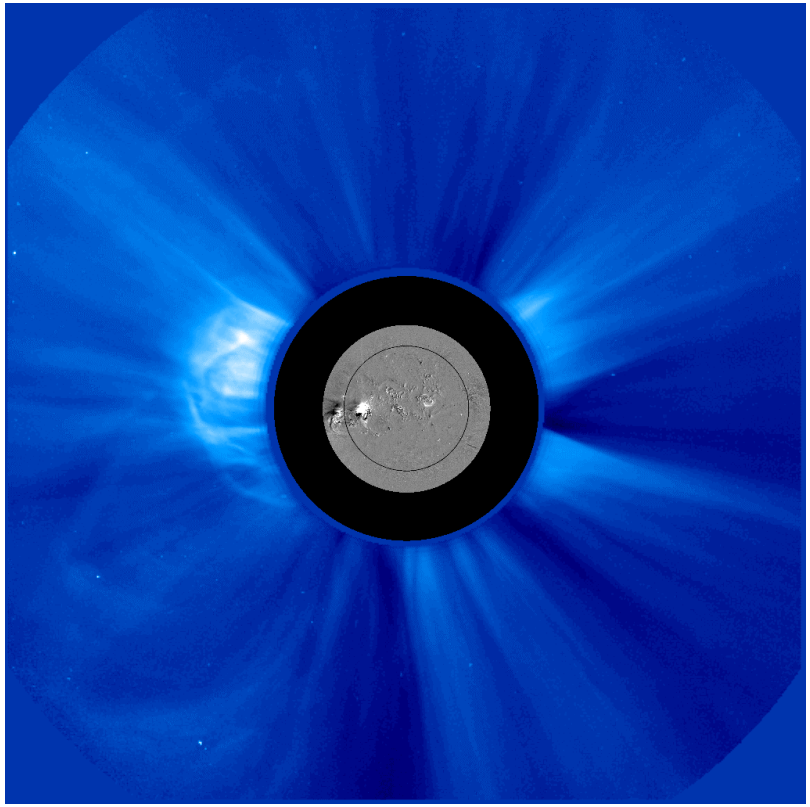
Caution: Not all interactions will produce the same type of radio signature



Two Fast CMEs: EIT Diff. & LASCO C2 images

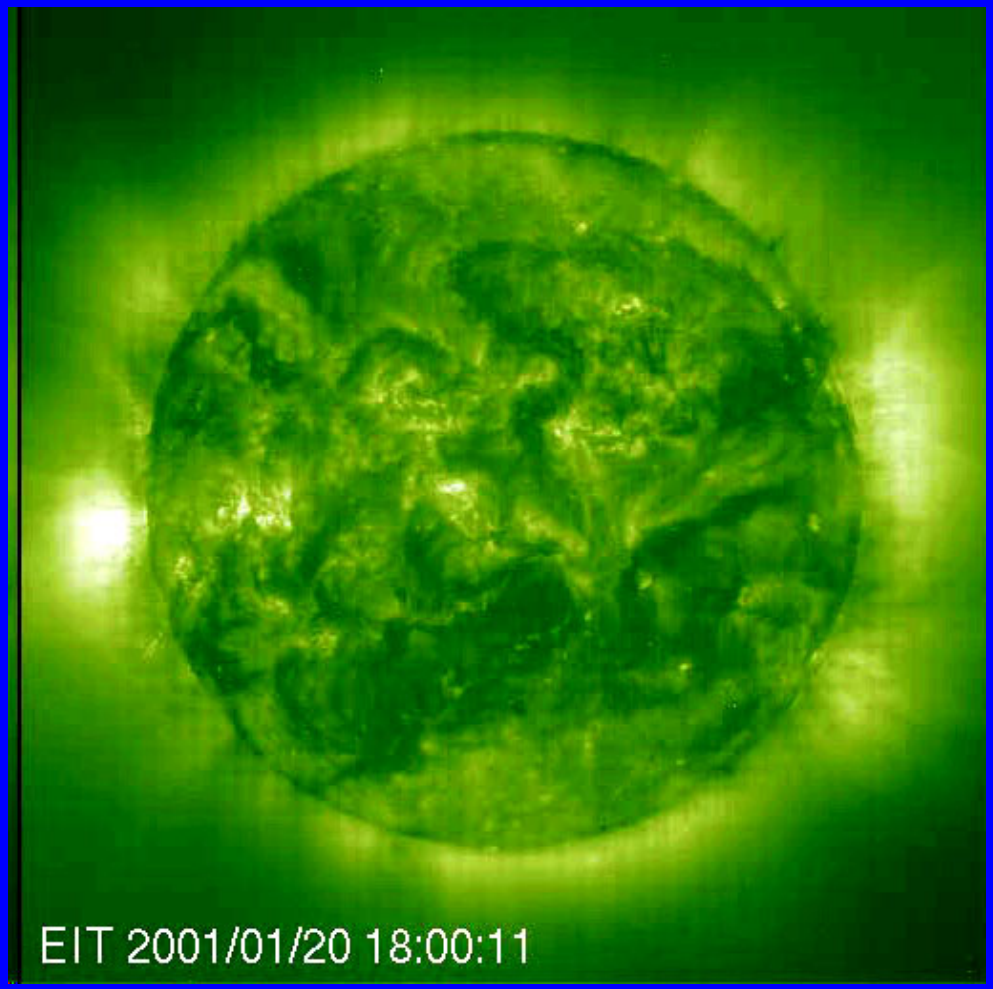


22:30 UT



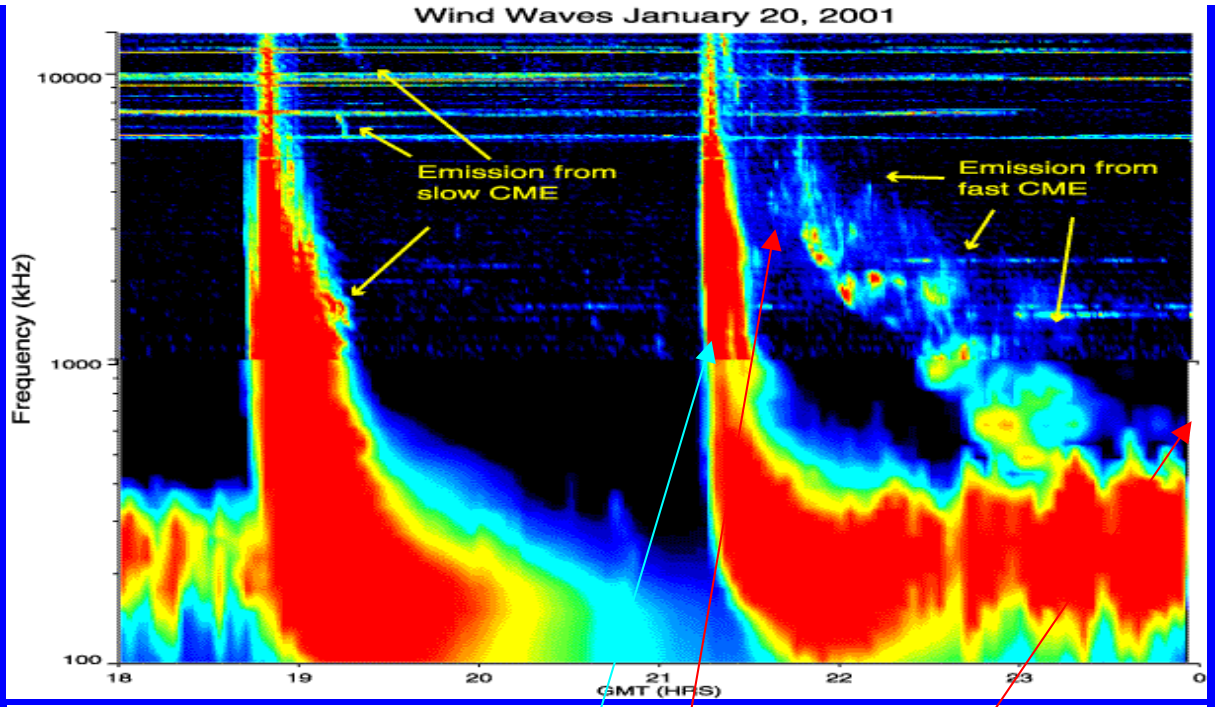
23:54 UT

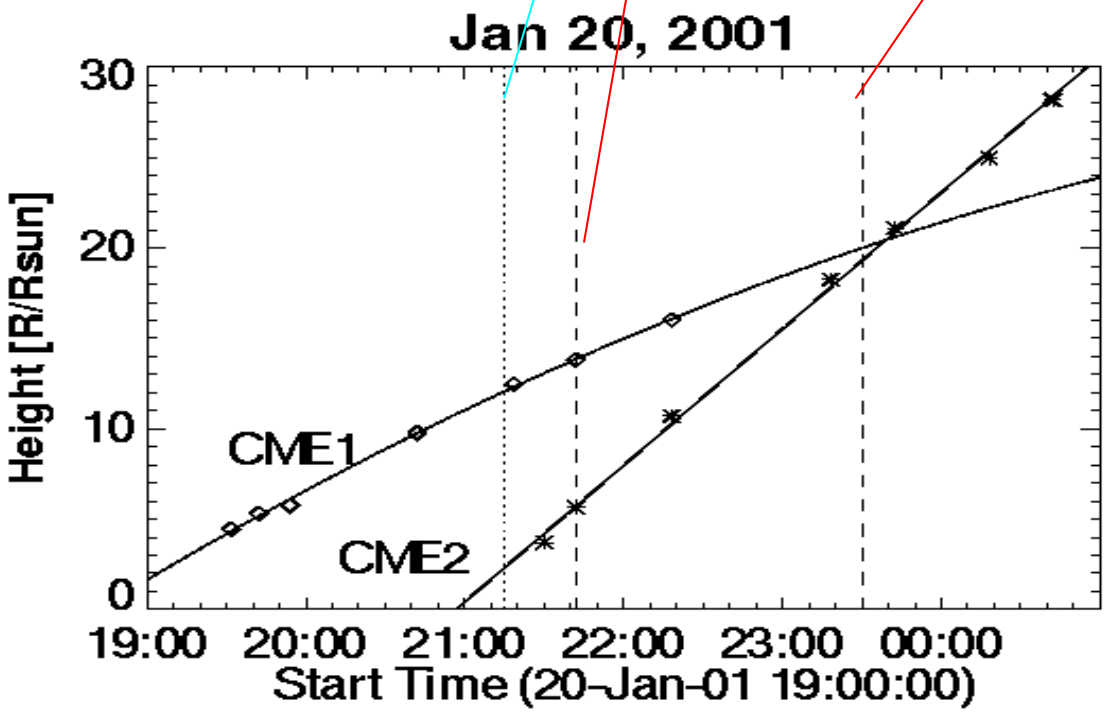
20010120 CMEs



- Two fast CMEs from the same region, two hours apart
- Both driving shocks
- Intense radio emission following the second
- The second CME ì seesî a different corona, viz, the first CME

EIT 195 movie showing the source of the two fast CMEs

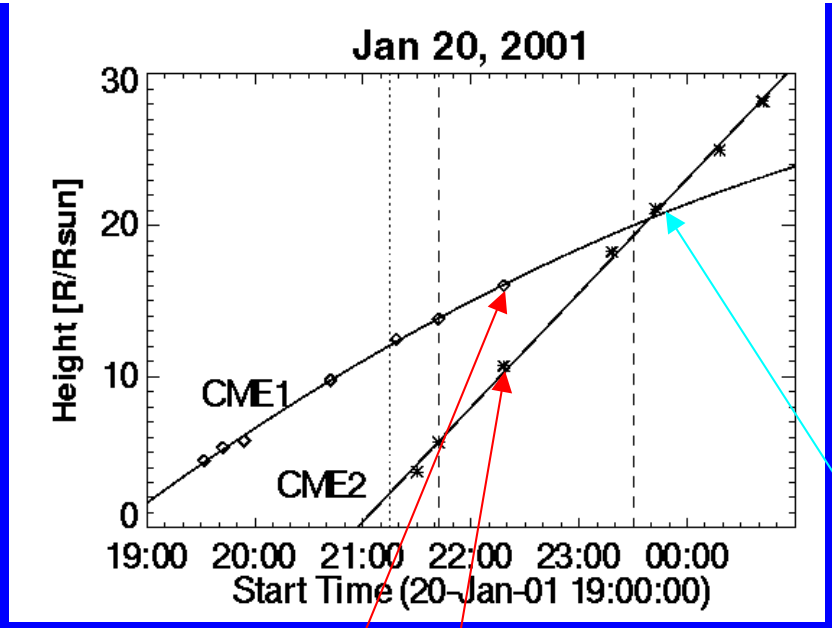




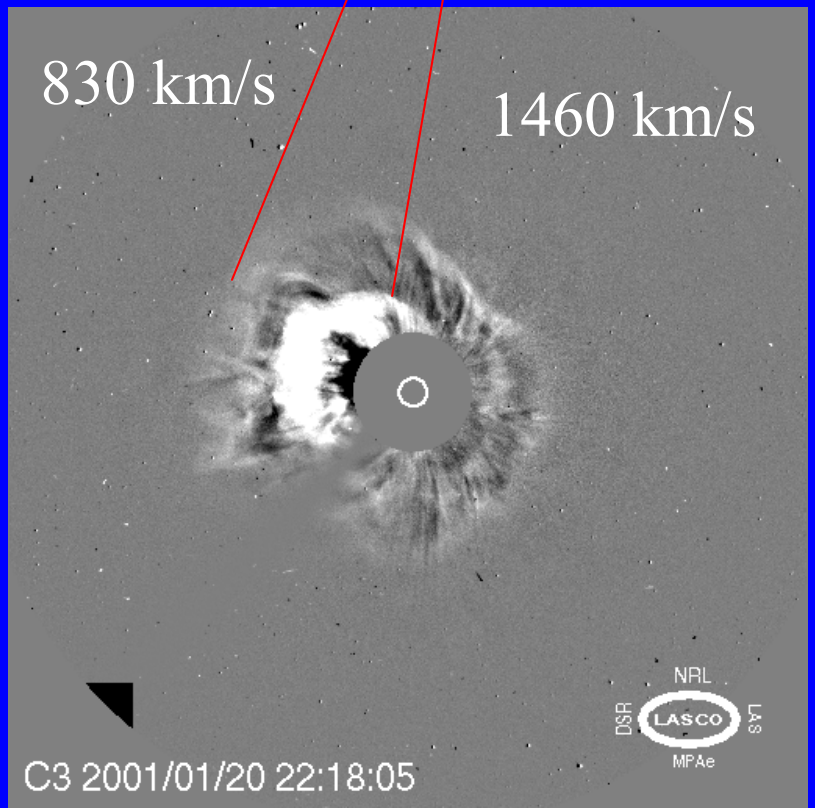
Wind/ WAVES Radio Burst

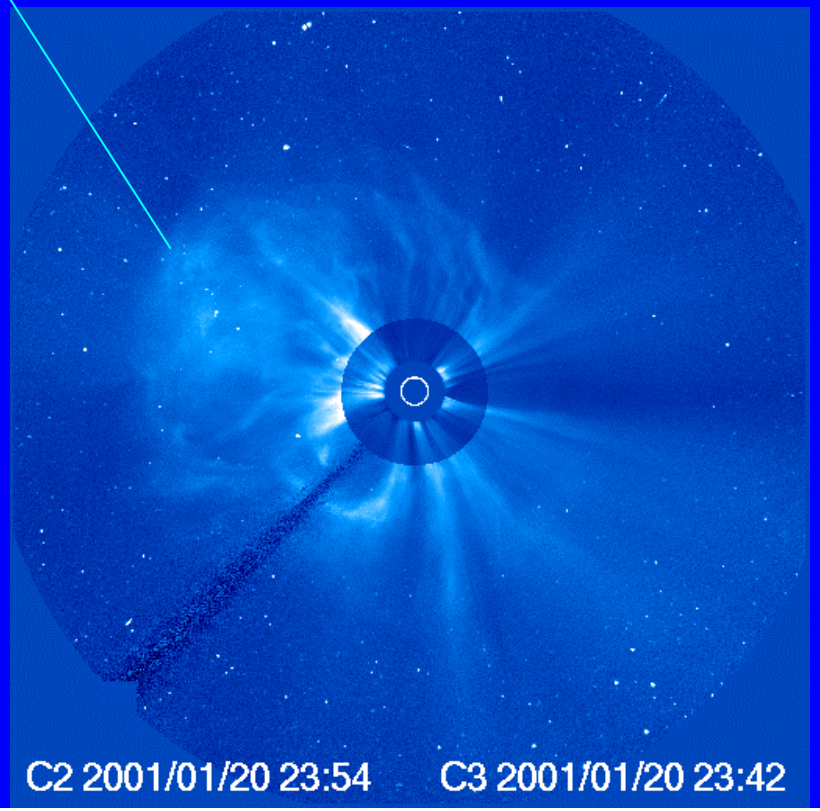
SOHO/LASCO Trajectories

CME1: 830 km/s
CME2: 1460 km/s
Shocks ì seeî different environments



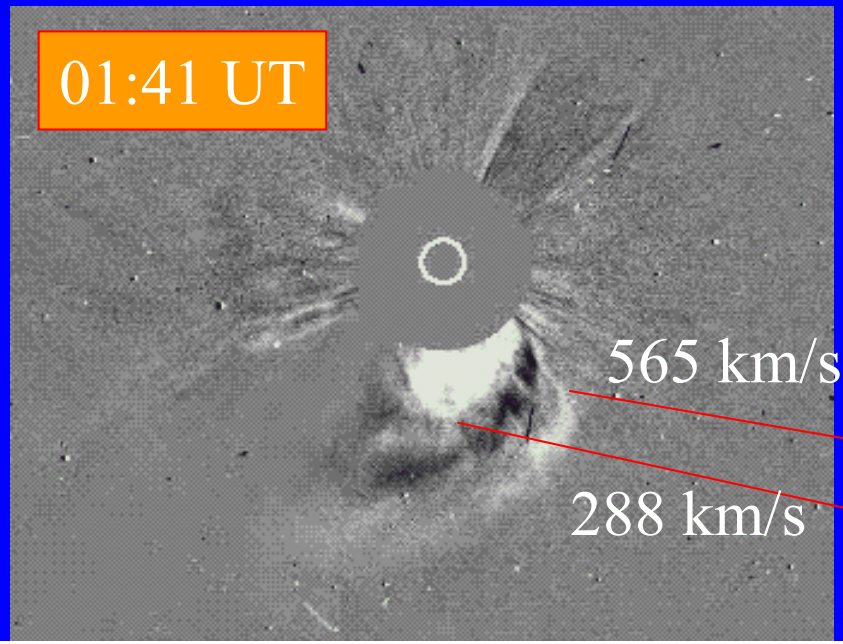
The two CMEs are indistinguishable at 23:42 UT (Cannibalism)

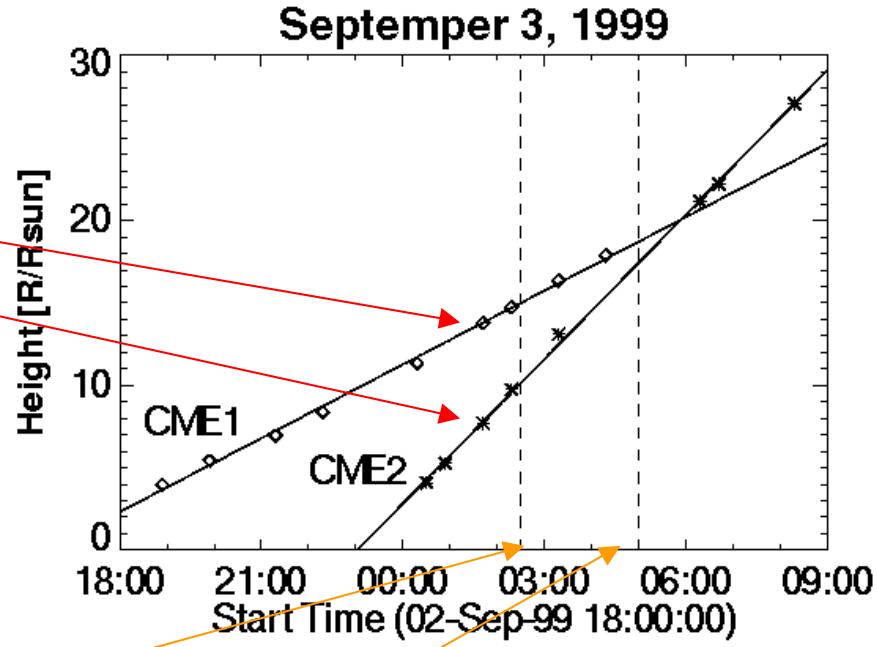


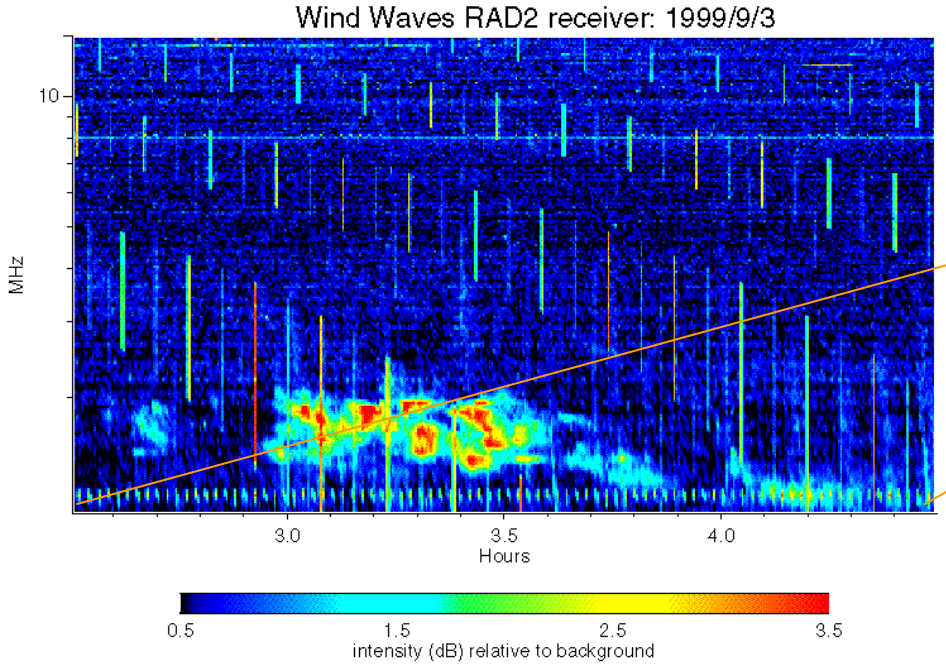


99/09/03 CMEs

GRL 29(8), 106-1, 2002



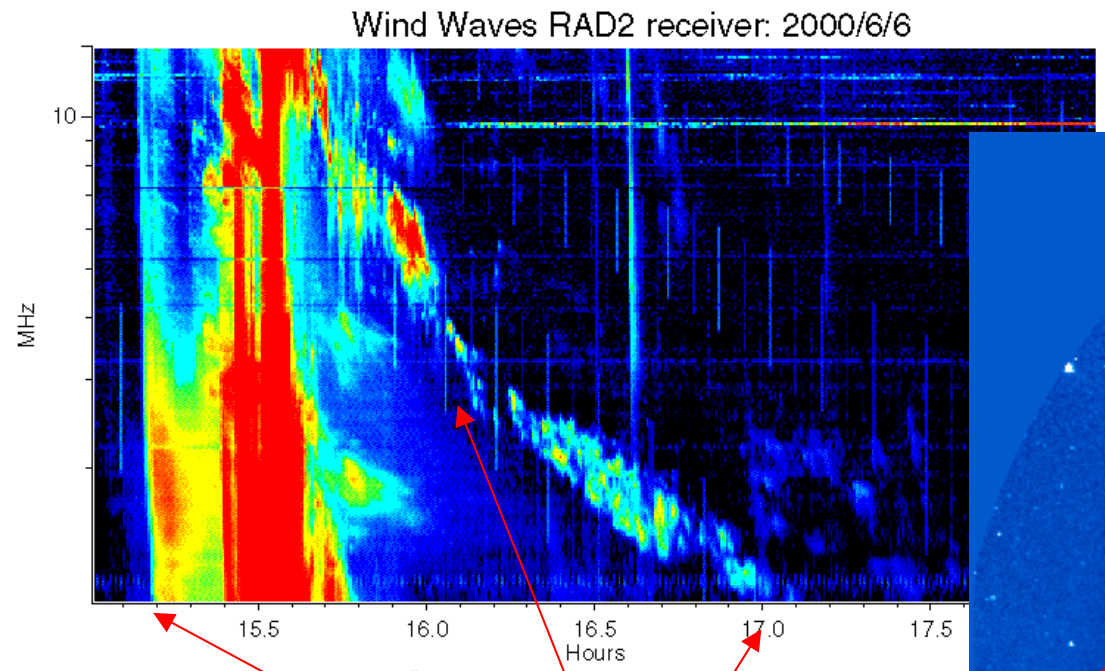


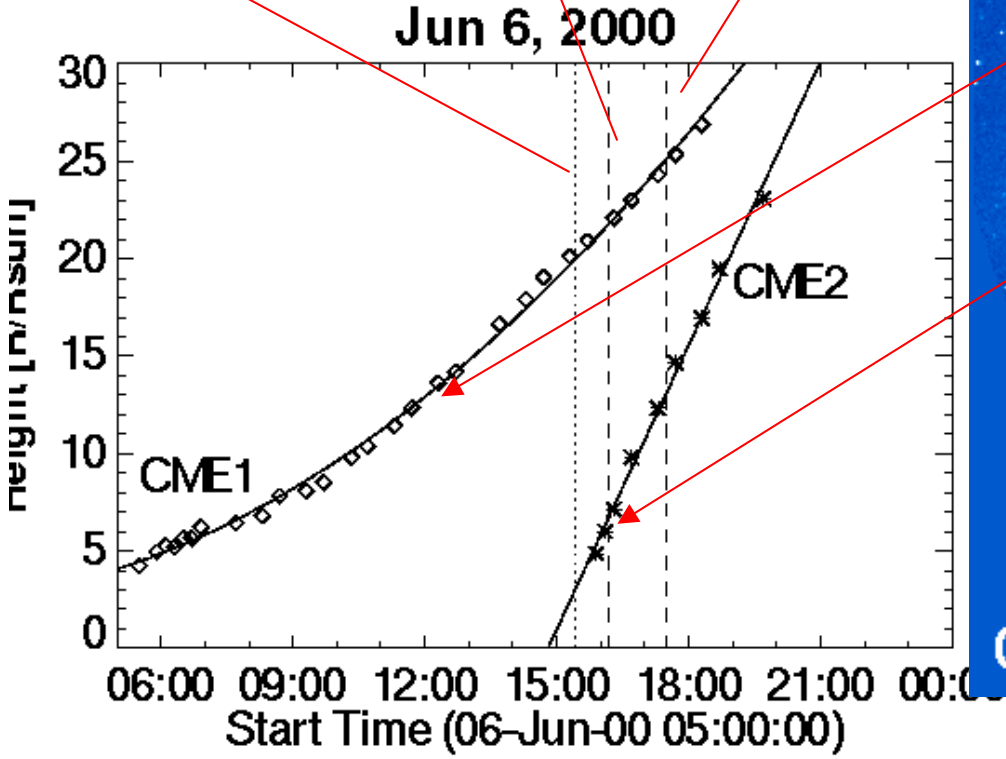


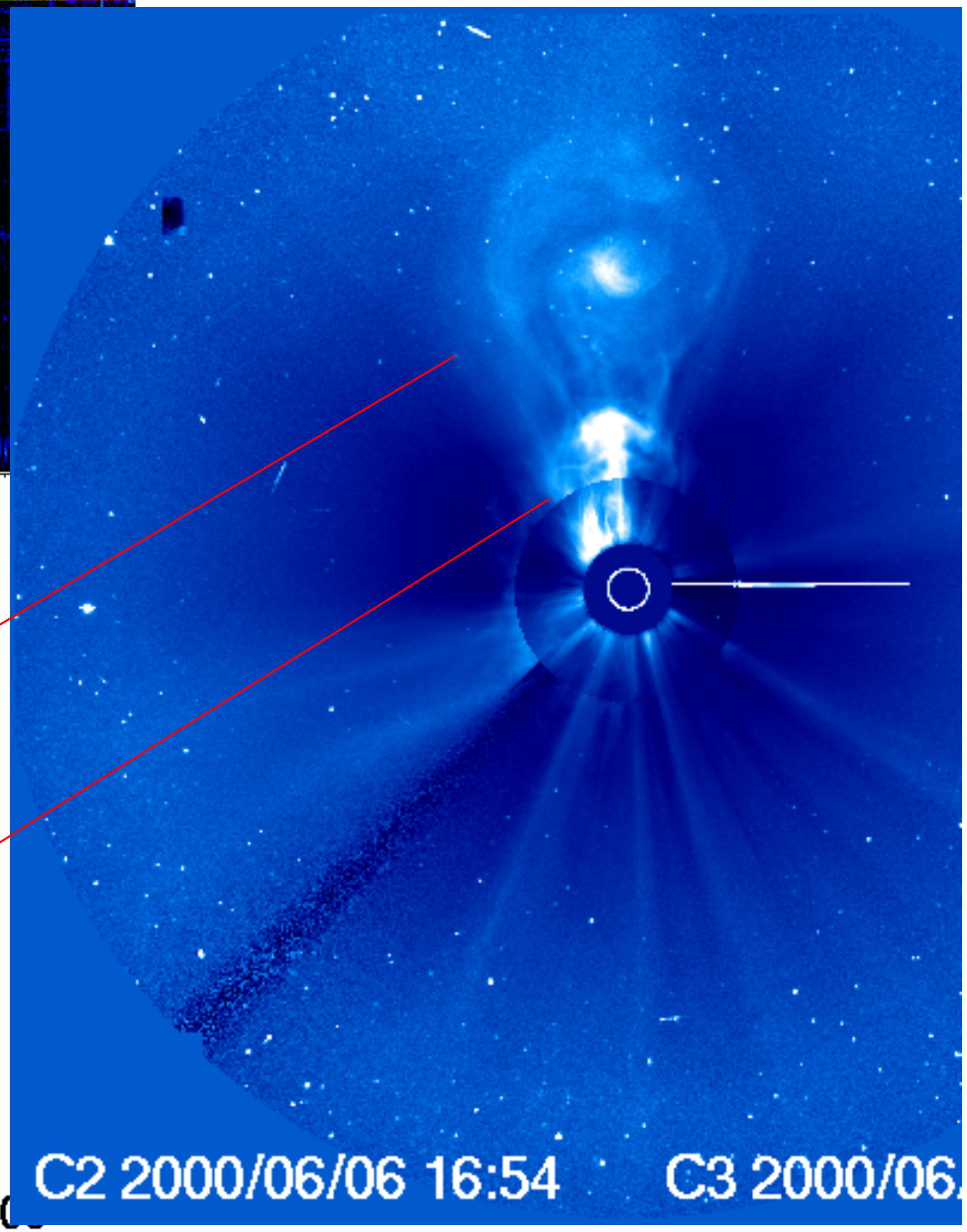
No Radio Emission
Before interaction!

Reconnection??

Slope Change 2000/06/06

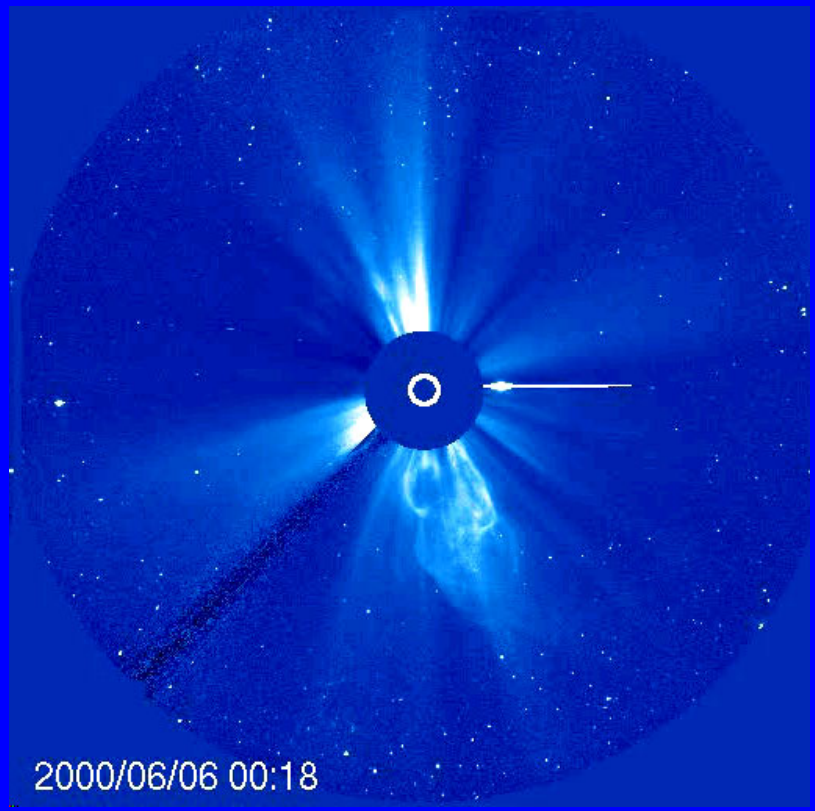






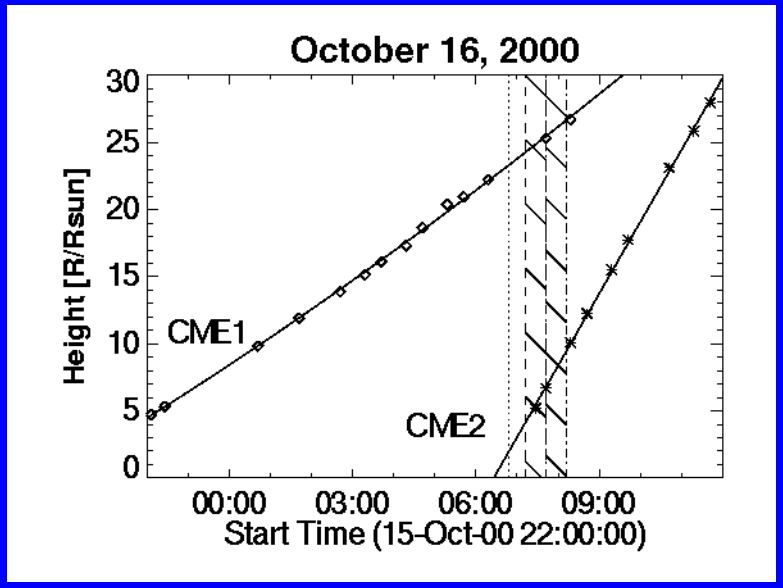
2000 06 06 CME interaction

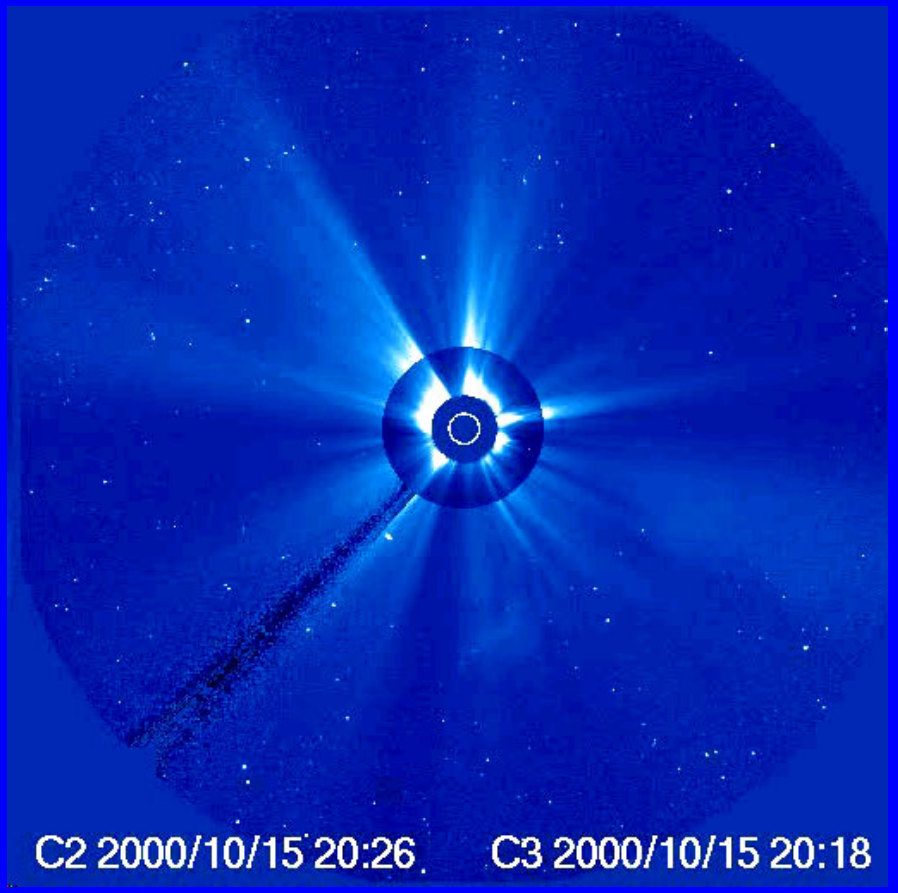
- Slow CME (337 km/s) followed by fast CME (940 km/s)
- Both eruptions from the same region on the Sun

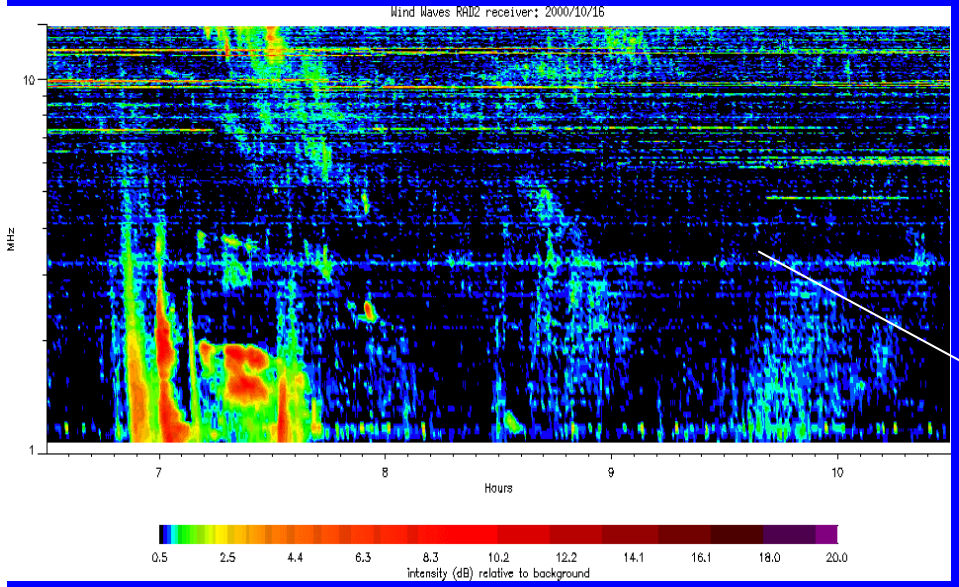


LASCO C3 Movie

Multiple Interaction?

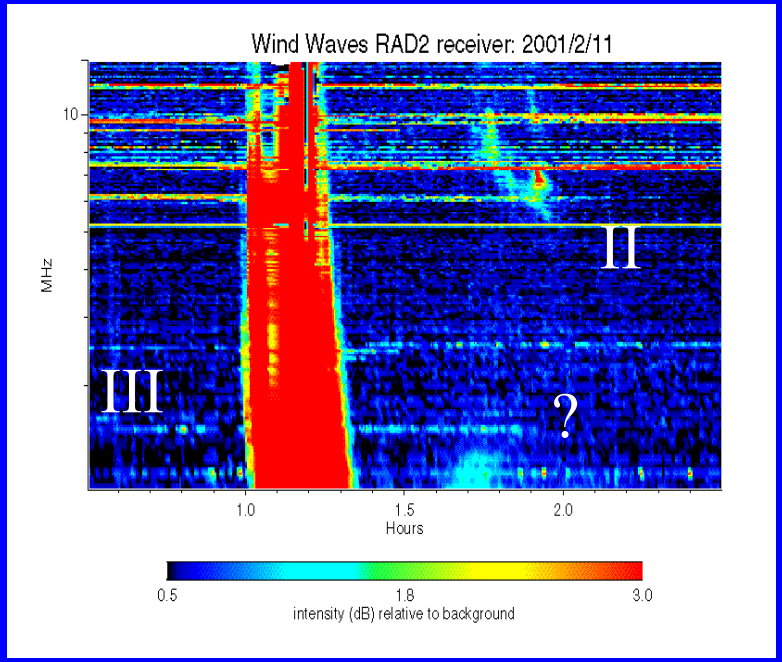


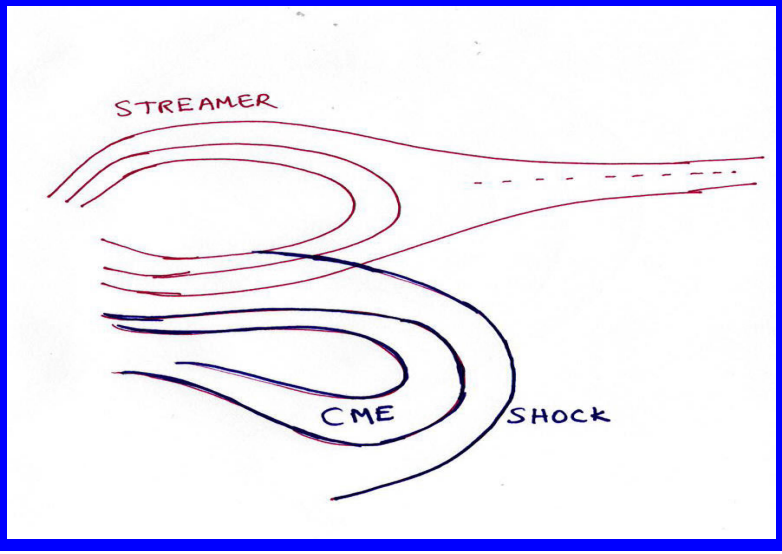




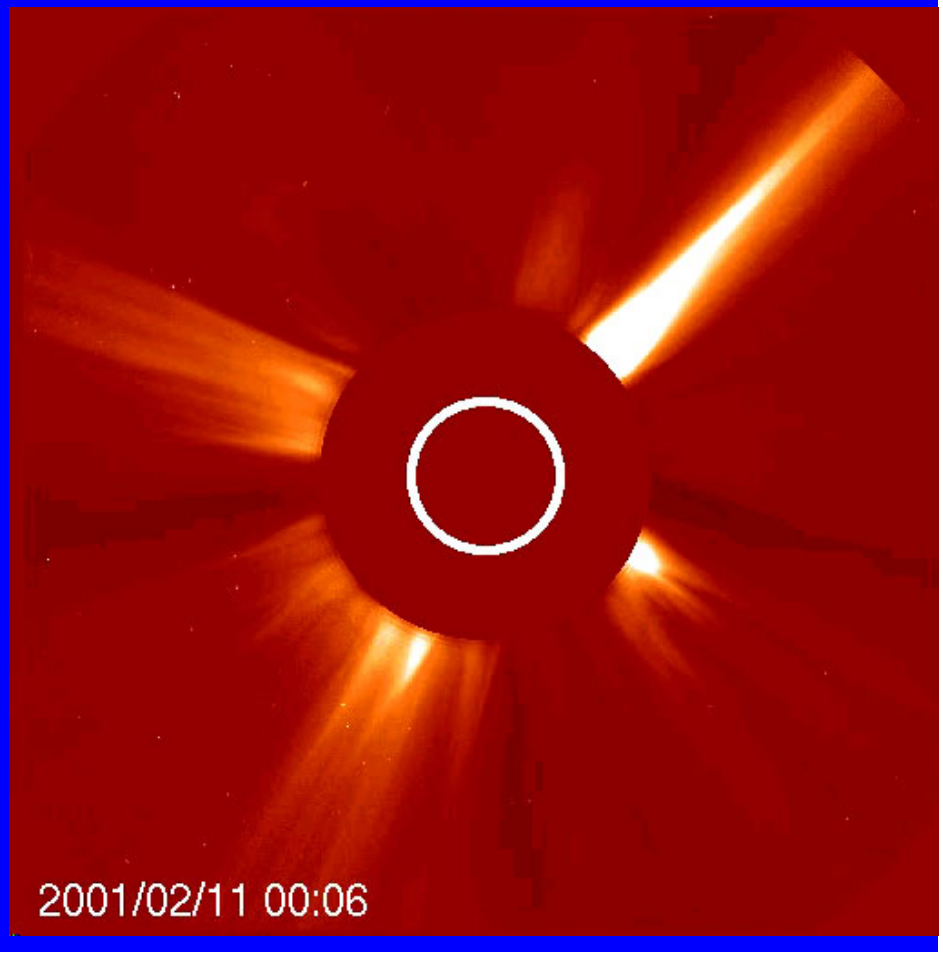
Dynamic spectrum highly complex

CME-Streamer Interaction 01/02/11



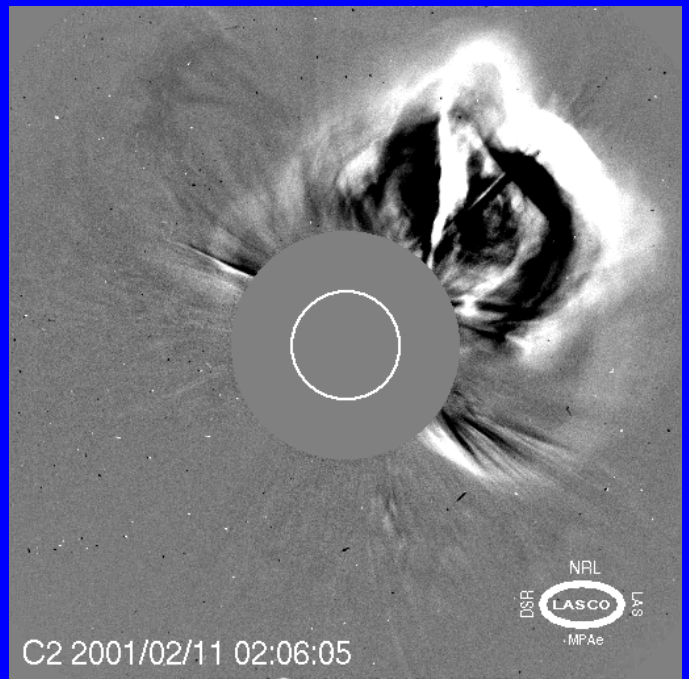


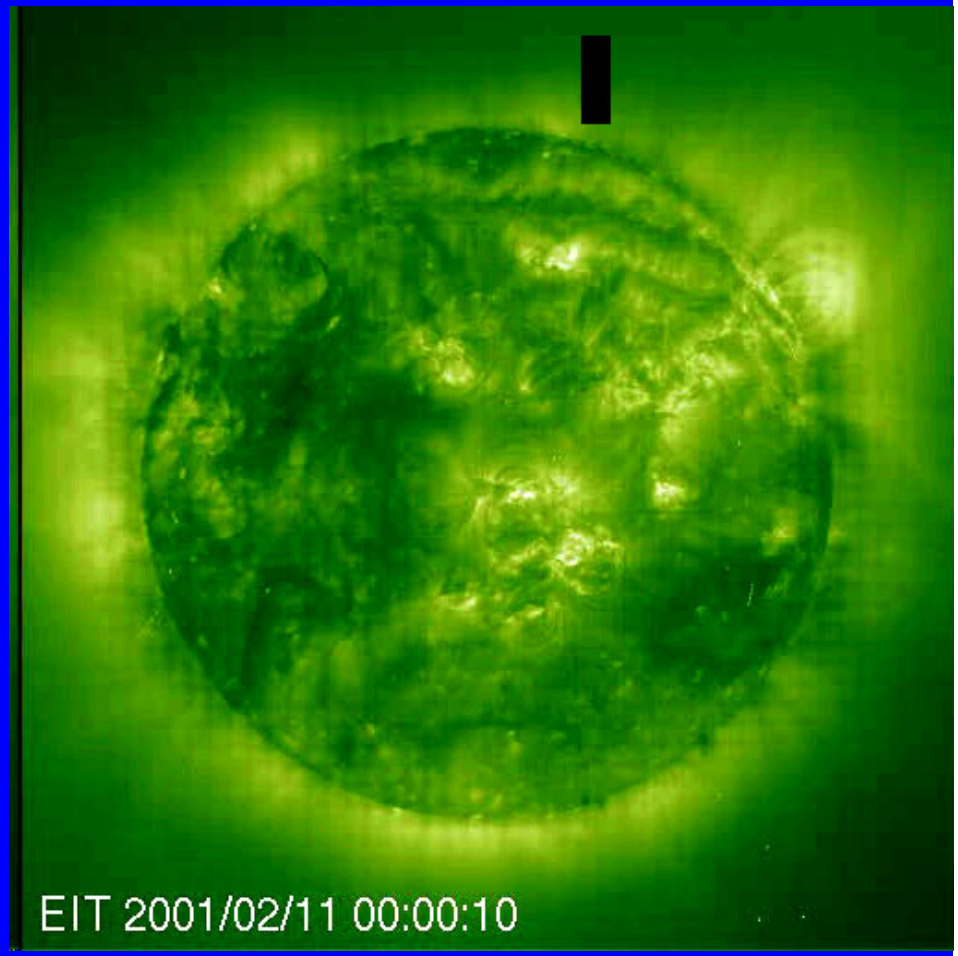
LASCO C2 Movie showing CME-Streamer interaction



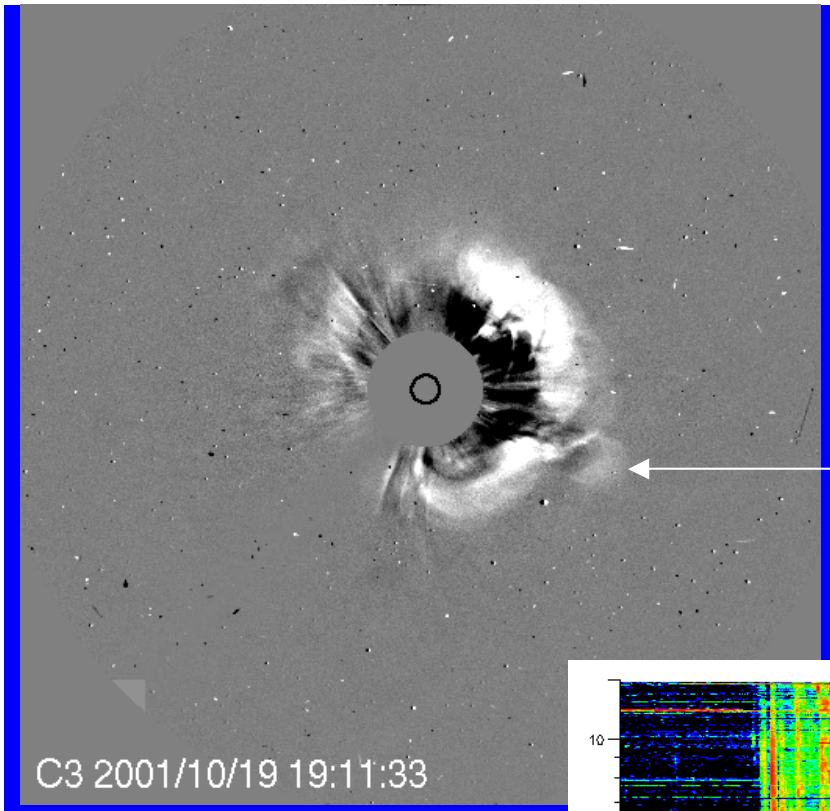
Solar Sources of CME & Streamer

- Streamer at the limb
- Filament at N24W57
- Surge (hot)
- NS ribbon/arcade

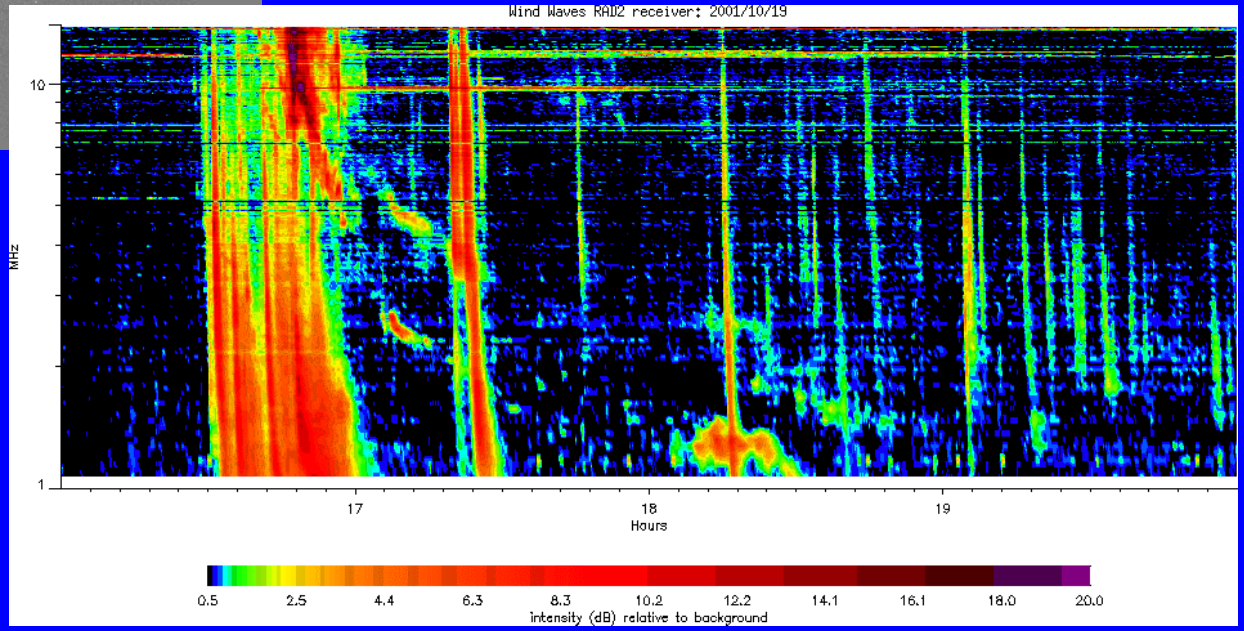




Complex Type II



Preceding CME



Summary Of Radio Signature of CME Interactions
(1-14 MHz Wind/WAVES)

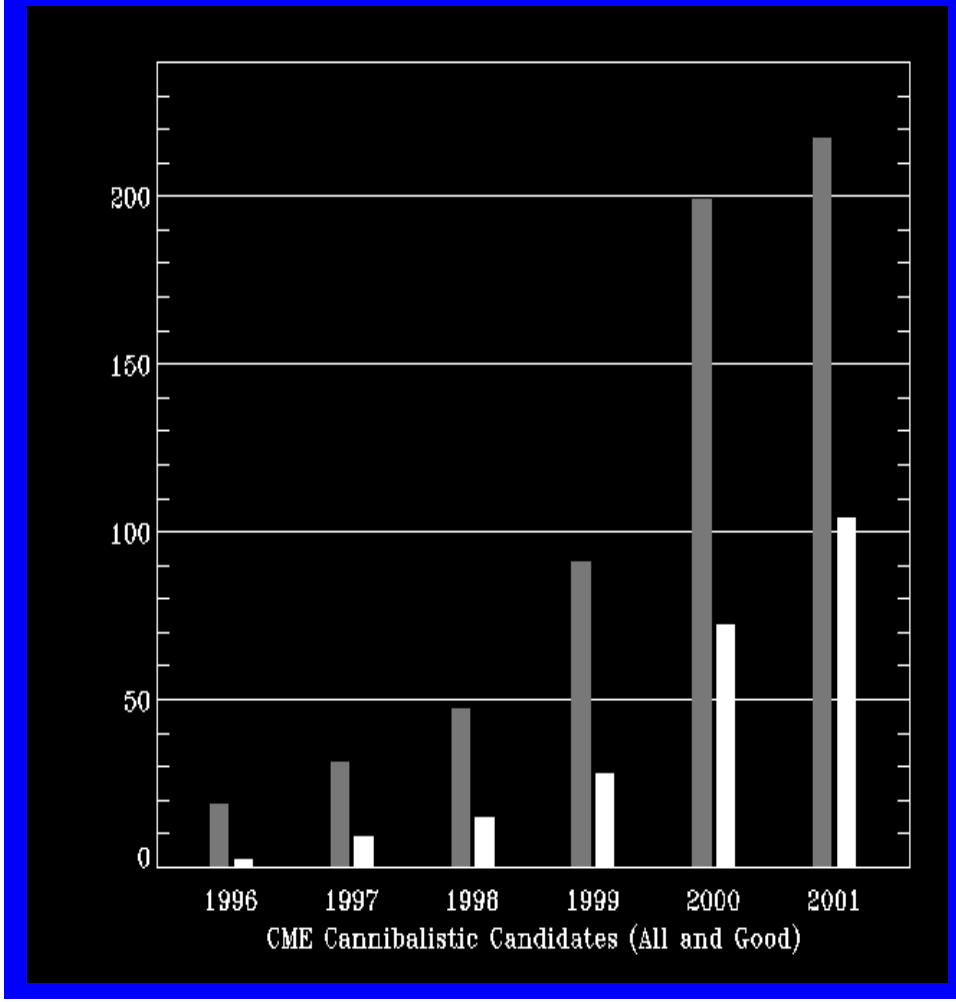
- ï Deviation from normal type II signature of narrow-band drifting feature ñ generally broadband (df/f >> 10%) and fragmented
- ï Slope changes
- ï Irregular enhancements
- ï Enhanced complexity in type III bursts

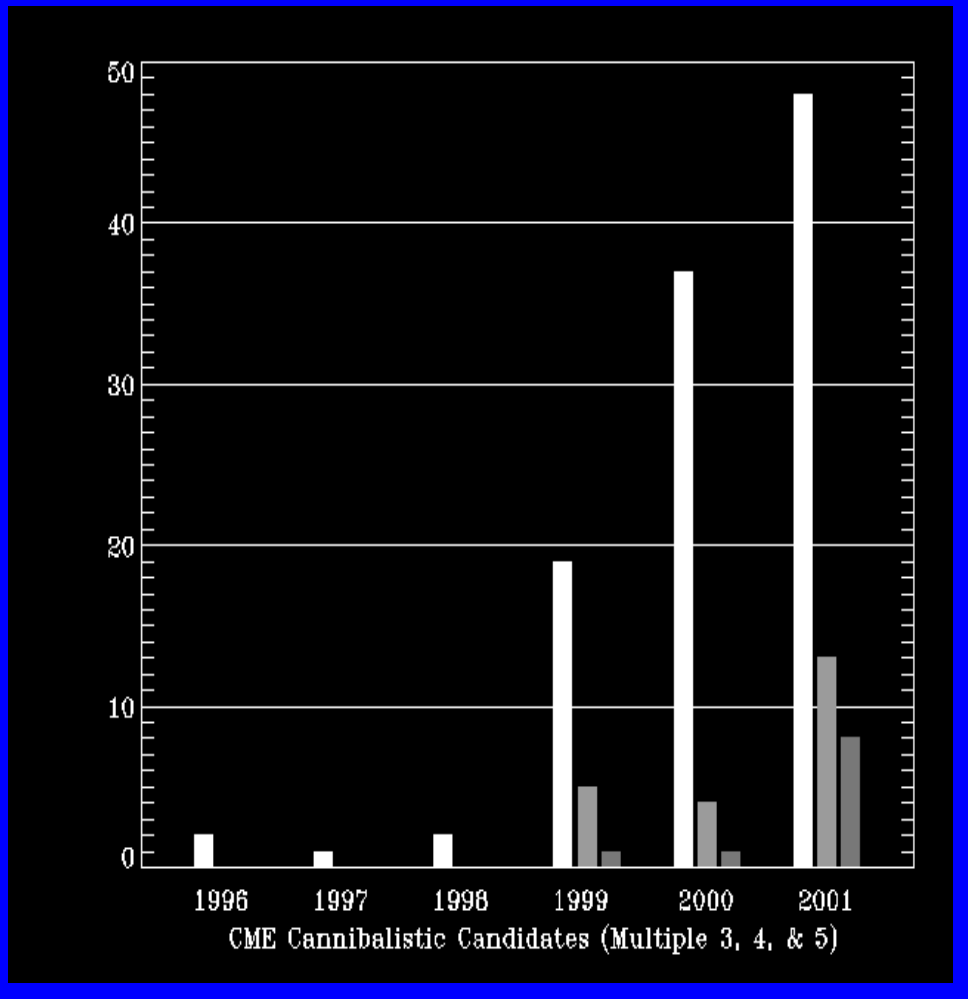
How Frequent?

~ 24 % of All CMEs seem to interact (Preliminary results)

Year (Tot. #CMEs)	# Interaction events
1996 (198)	19 (10%)
1997 (334)	31 (9%)
1998 (622)	47 (8%)
1999 (939)	91 (10%)
2000 (1533)	199 (13%)
2001 (1410)	217 (15%)
Total (5036)	604 (12%)

Colliding CMEs: Multiple Interactions



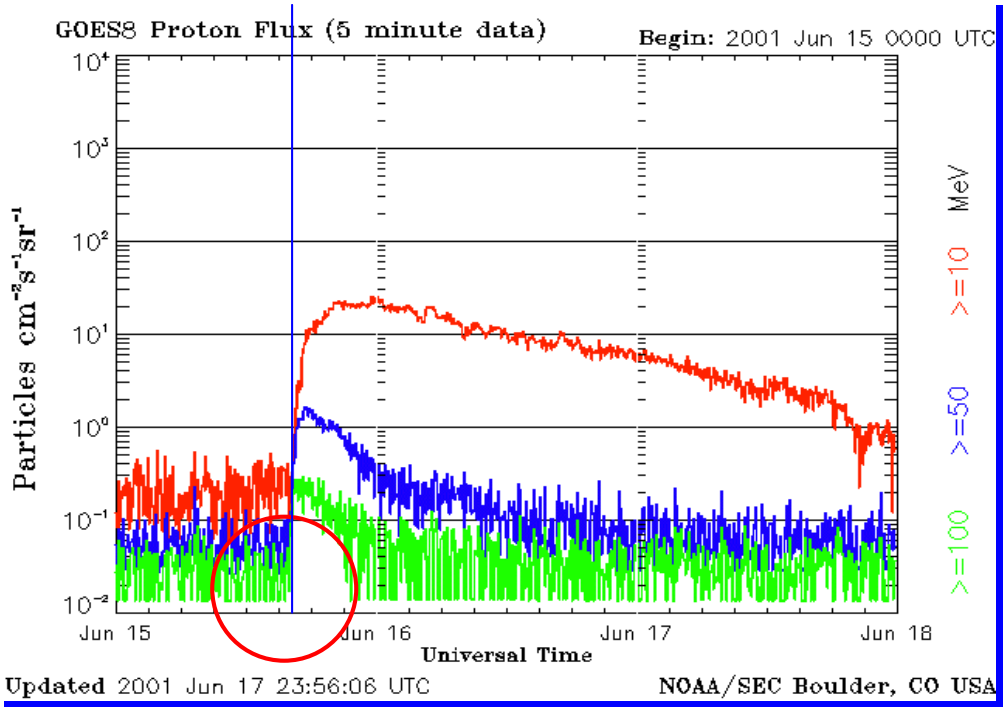


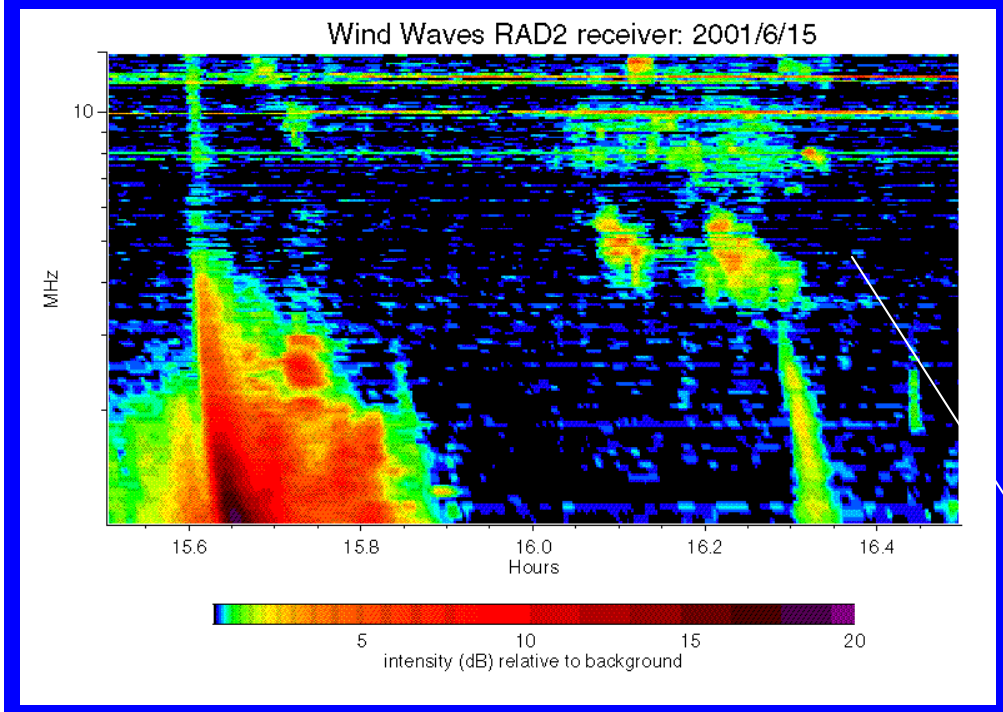
Interacting CMEs & SEPs: Statistics

→ Nonthermal radio signatures at the time of CME interactions indicate production of nonthermal electrons.

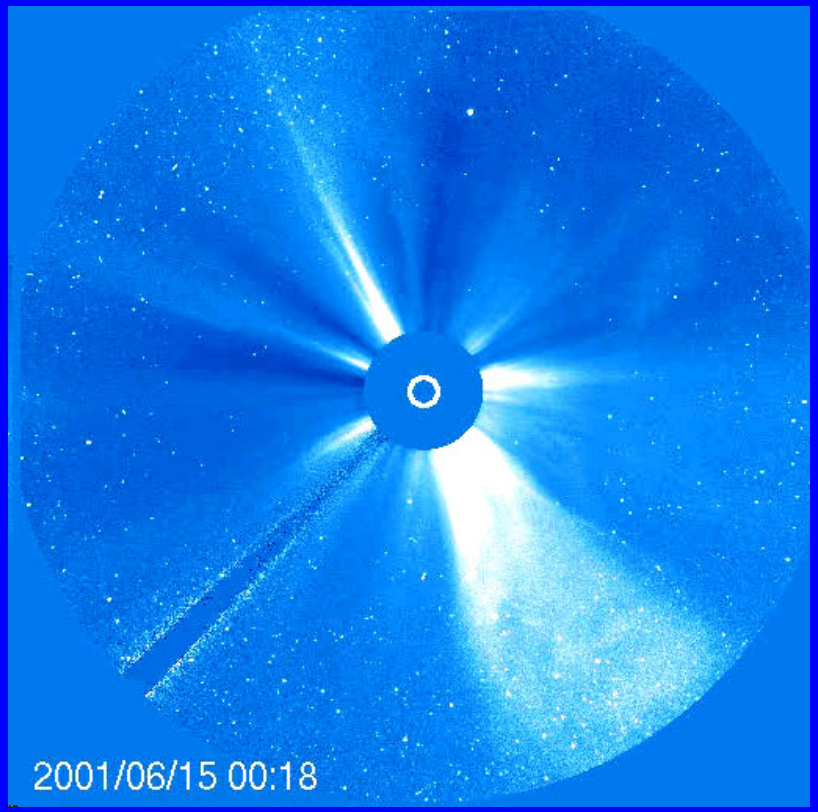
→ Can protons also be produced at the same time?

→ But the conditions for detection of electromagnetic waves (signature of nonthermal electrons) and SEPs are different: electrons need not escape; protons need to escape from the acceleration region and arrive at the spacecraft.





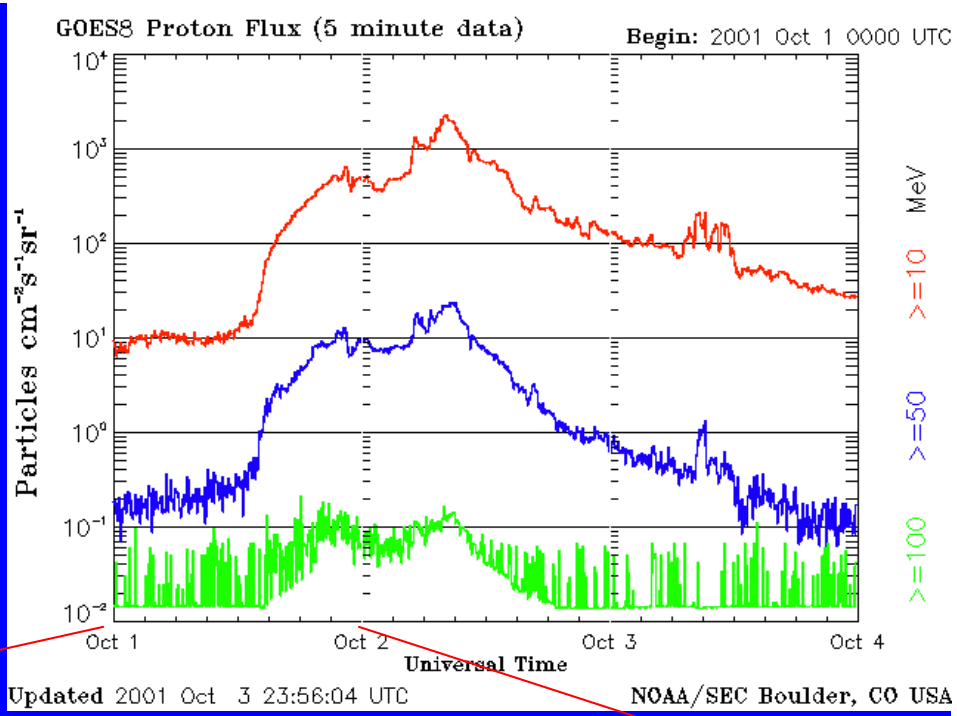
GOES SEP onset 16 UT
CME onset 15:56 UT

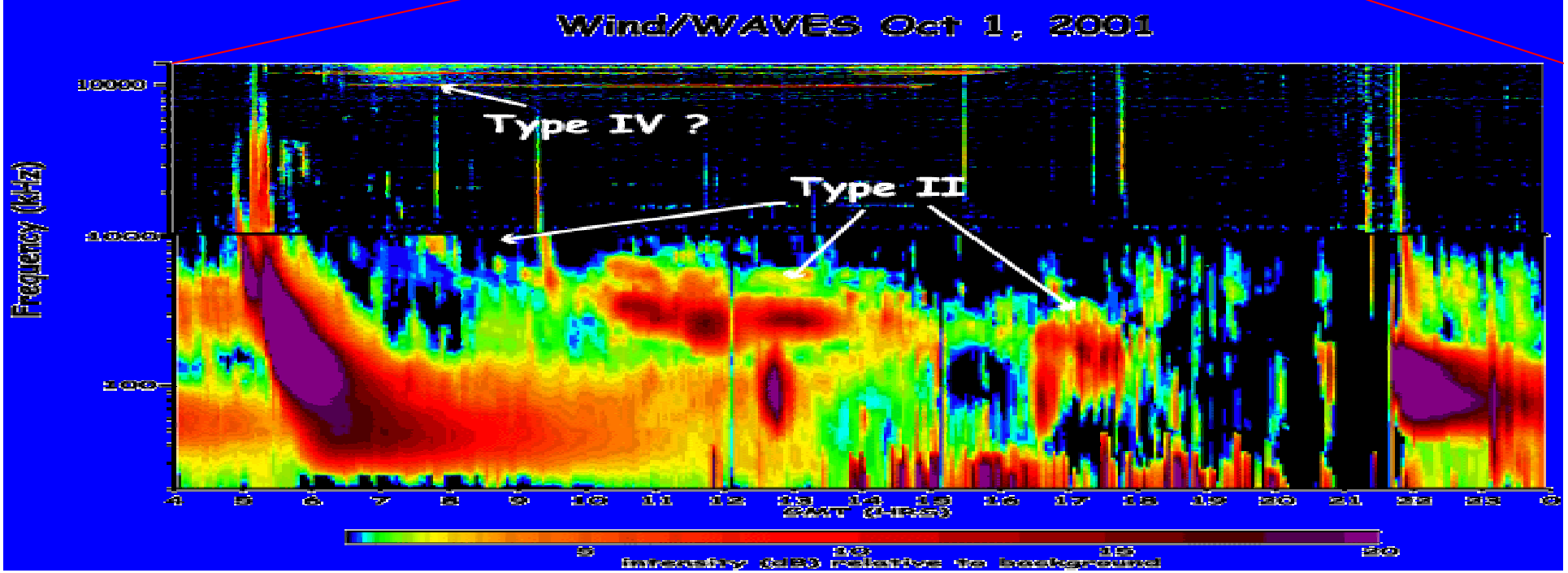


WAVES Radio enhancement

2001/10/01: Electrons & Protons

Protons and electrons were accelerated during the 2001/10/01 CME.
The type II enhancements may be due to CME interactions.



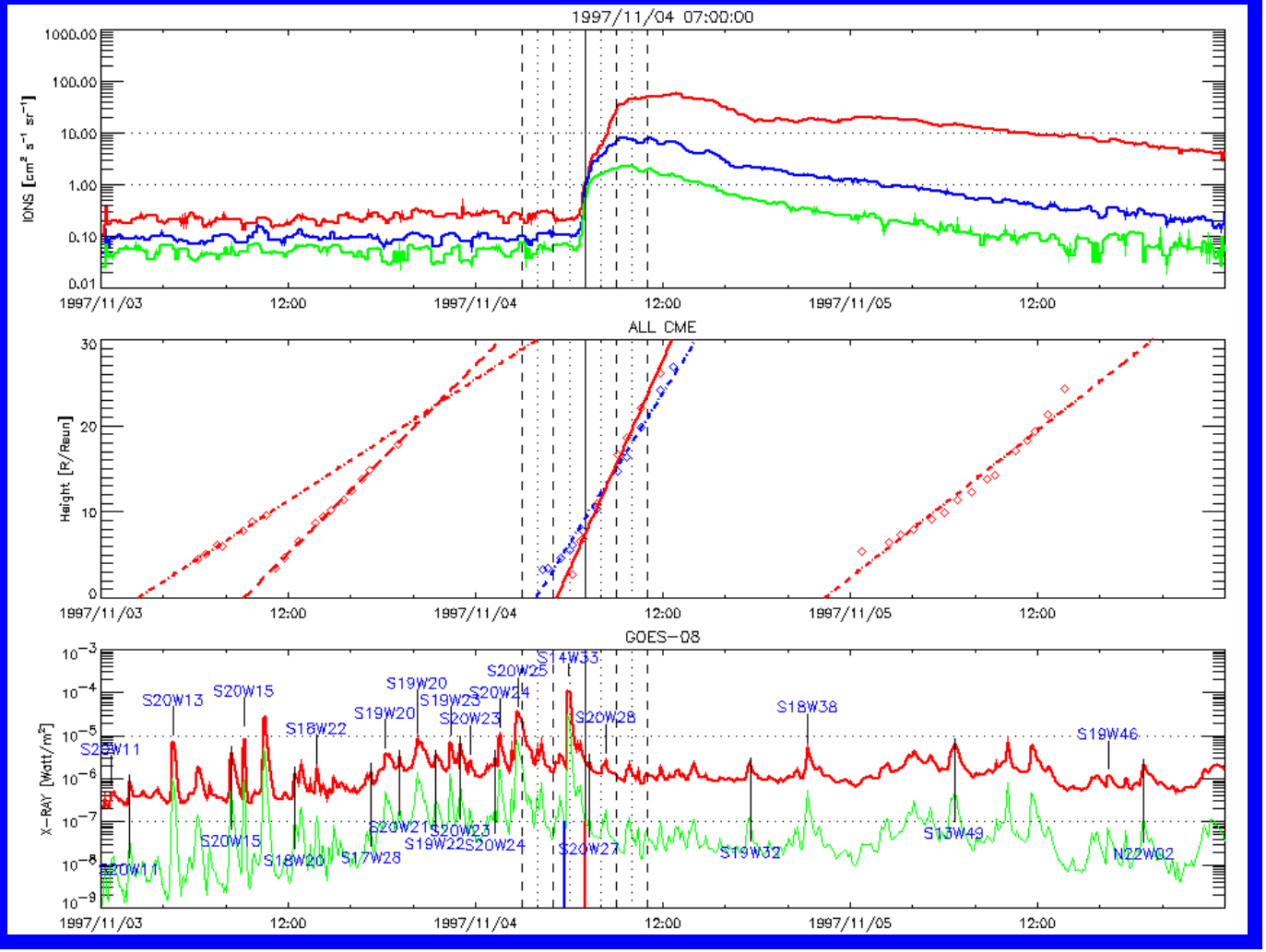


SEP ñ CME Analysis Plots: 97/11/04 Event

GOES SEPs
- ➢10 MeV (red)
- ➢50 MeV (blue)
- ➢100 MeV (green)

CME height-time plots around SEP onset:
red: west limb
Blue: east limb

GOES flare data

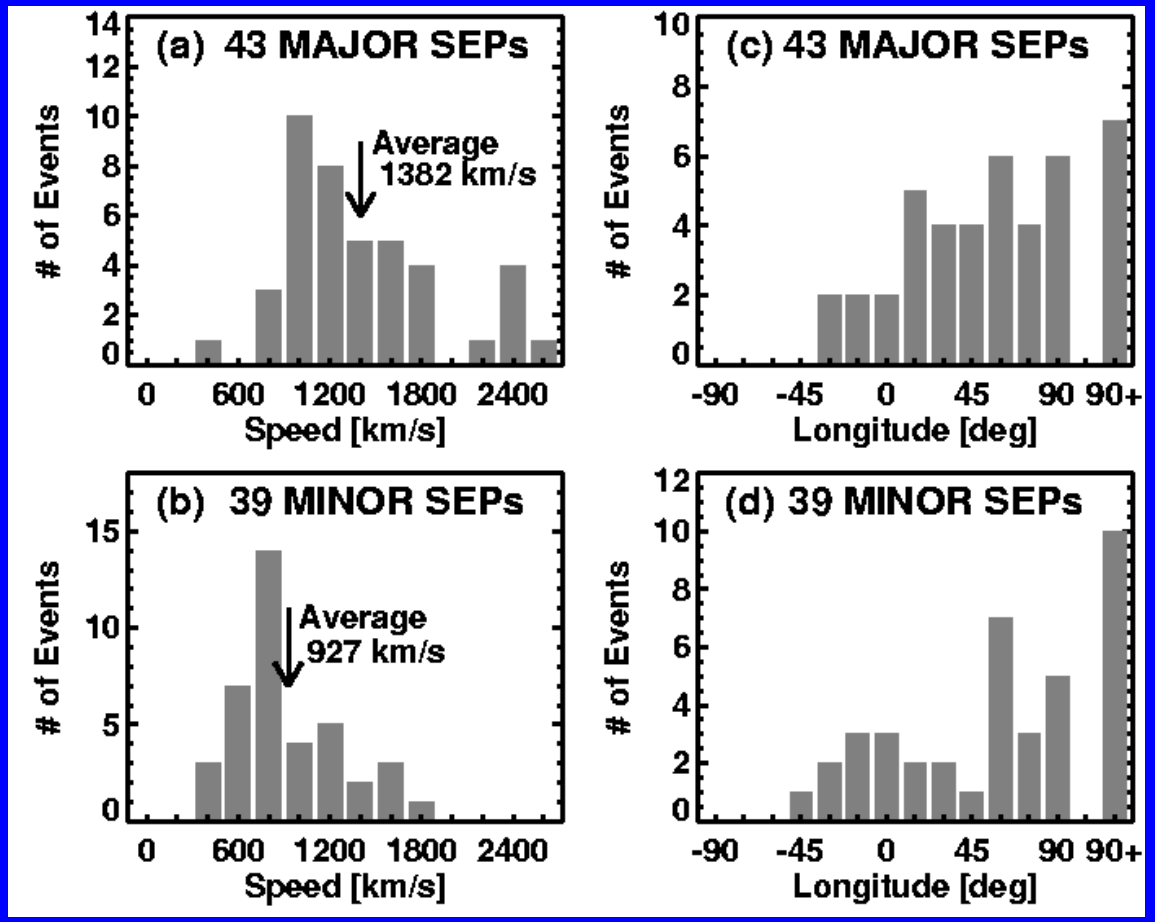


Some definitions

- Primary CME: The CME which is clearly responsible for the SEP event.
- Preceding CME: The CME that leaves the Sun before the primary, and hence is overtaken by it typically within the LASCO FOV. (In principle, there must be interactions at various distances between Sun and Earth)
- Major SEPs: proton intensity > 10 pfu
- Minor SEPs: proton intensity between 1 and 10 pfu
- The CME interaction typically starts (a few hours) before the time the height-time plots intersect.

Primary CME Speed & Source Longitude

- SEP CMEs are very fast (> 900km/s)
- They occur west of E45

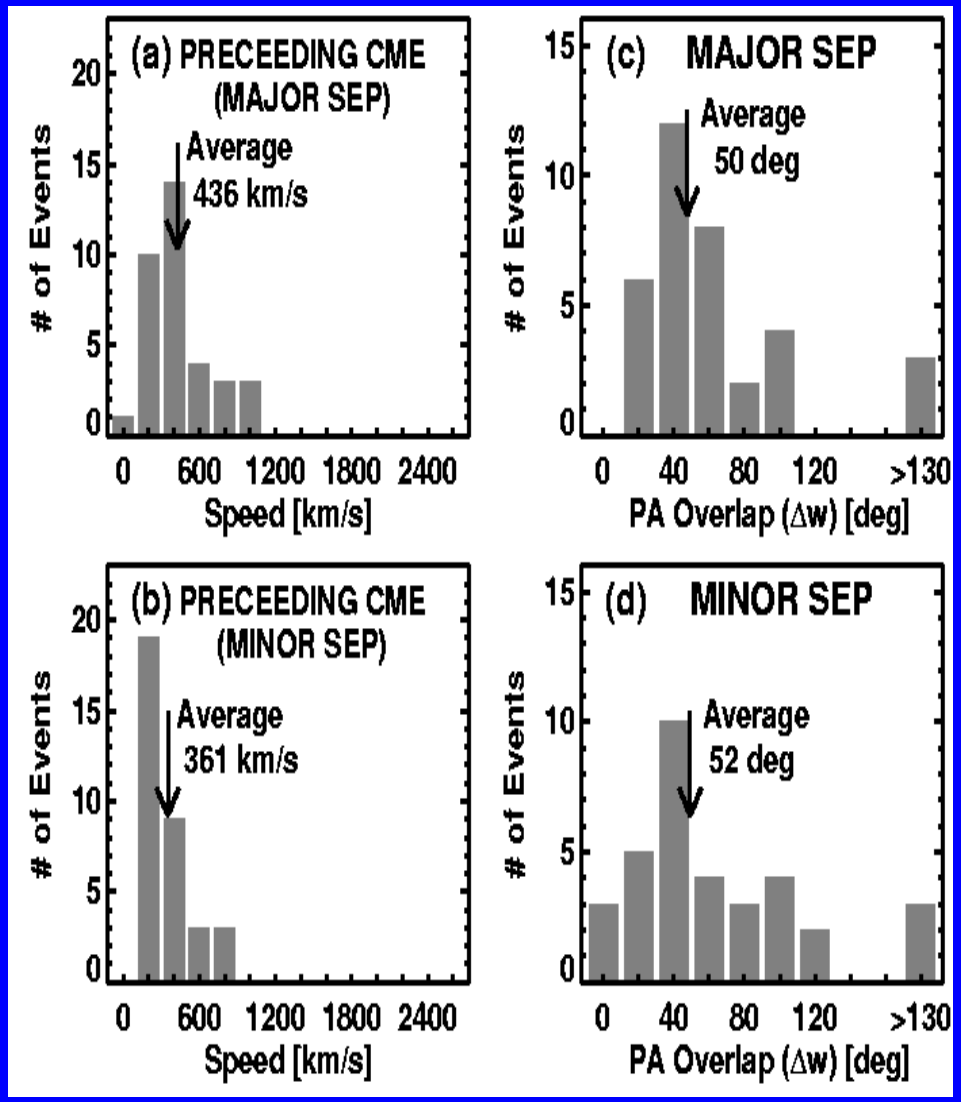


Preceding CMEs are slow

The speed of preceding CMEs is small
→ may not provide seed particles.

→ Preceding fast CME may provide seed particles for the following shock

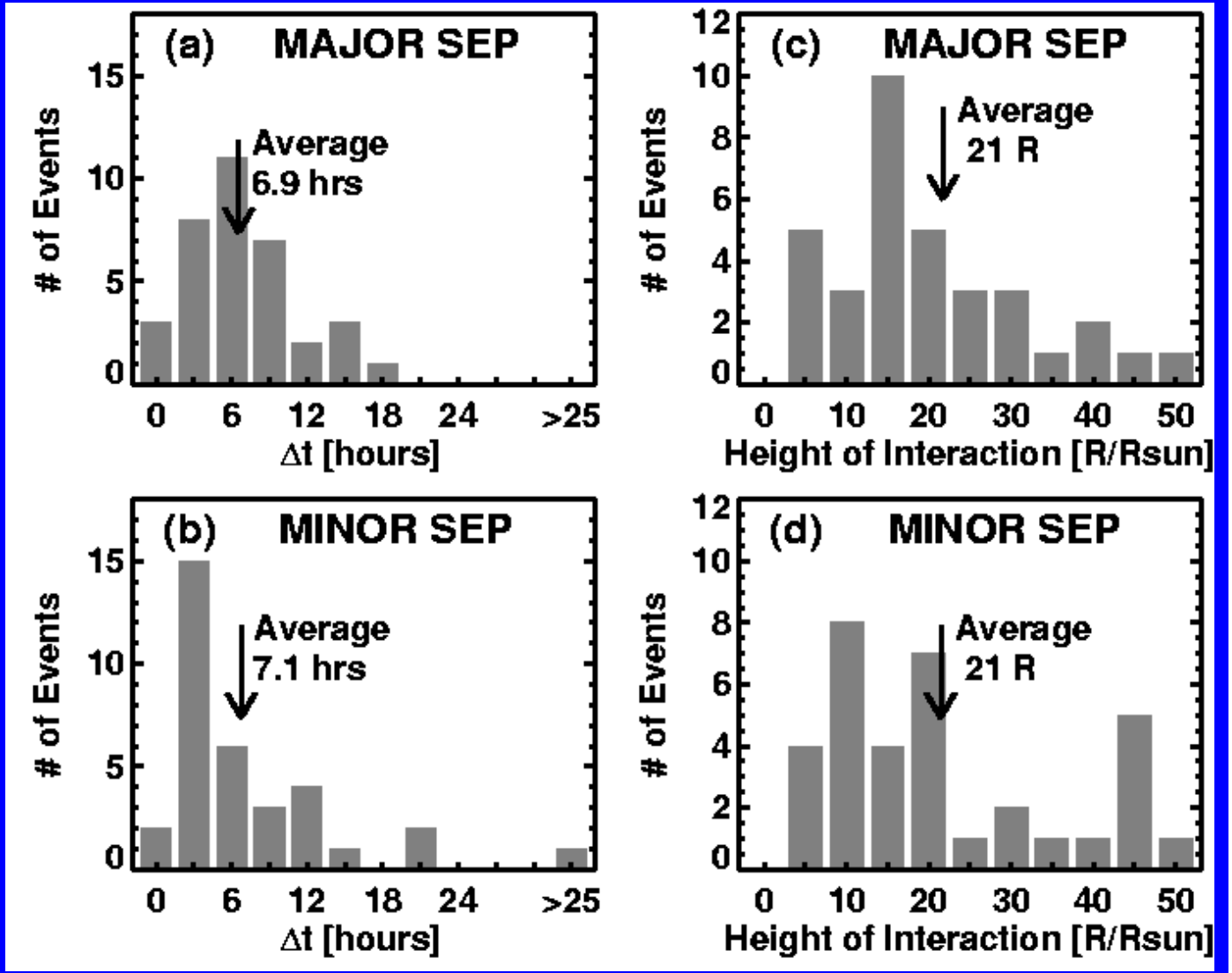
Typically there is a large Position angle overlap between primary and preceding CMEs



Onset Time Diff & Intersection of Trajectories

Preceding CMEs typically leave a few hours before the primaries

The primaries catch up with the preceding ones within the LASCO Field of View.



CME Interaction & SEPs: Statistics

Property	Major	Minor
Total #	43	39
Avg Speed km/s	1393	927
Width >100 deg	98% (41/42)	87% (34/39)
CME Interaction	83% (35/42)	87% (34/39)
All Interactions	93% (39/42)	97% (38/39)
Assoc.w/DH II	95% (40/42)	56% (22/39)
Onset time Diff	6.9 hrs	7.1 hrs
Intersec. Height	21 Ro	21 Ro
Avg PA overlap	50 deg	52 deg

Inverse Study: Fast &Wide CMEs

ï 52 fast (> 900km/s) & Wide (> 60deg) frontside, western hemispheric CMEs

	No SEP	SEP
No Interaction	4	2 (7)
Interaction	6	40 (35)

minor

Marginal

Including streamer interaction

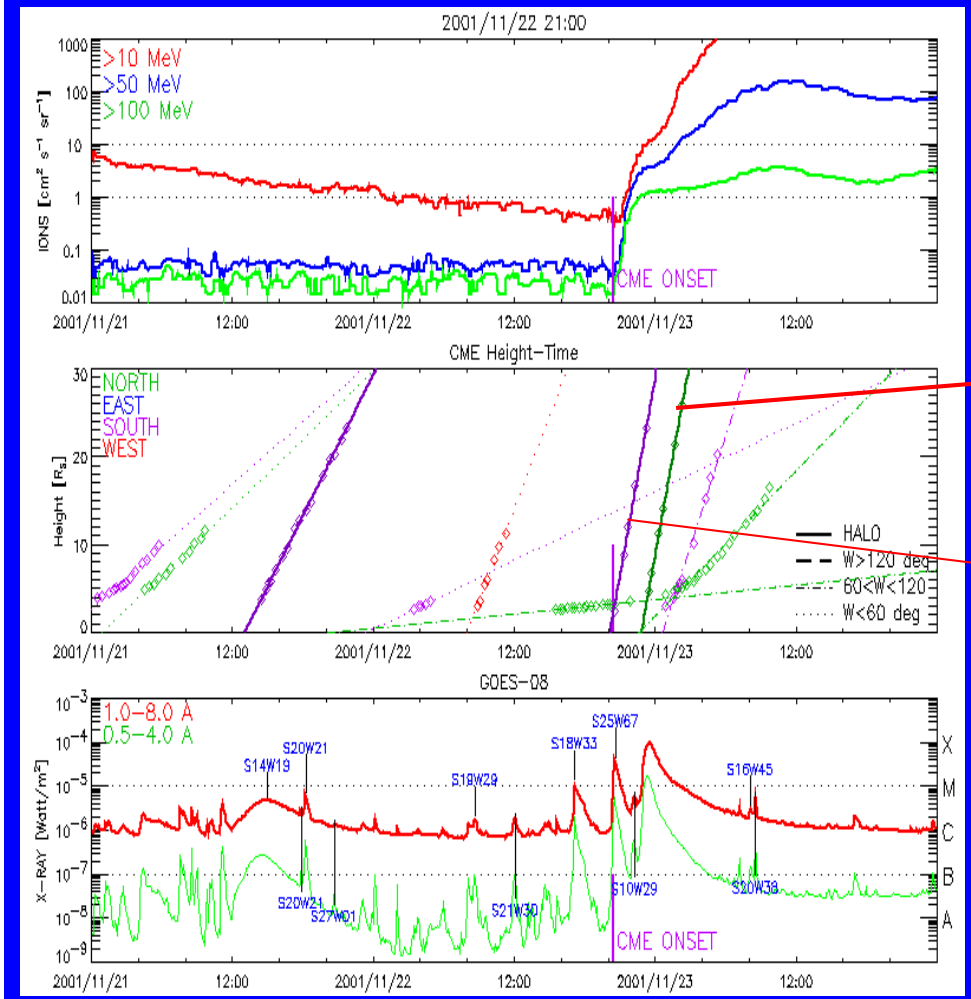
CME Interaction discriminates SEP-poor from SEP-rich

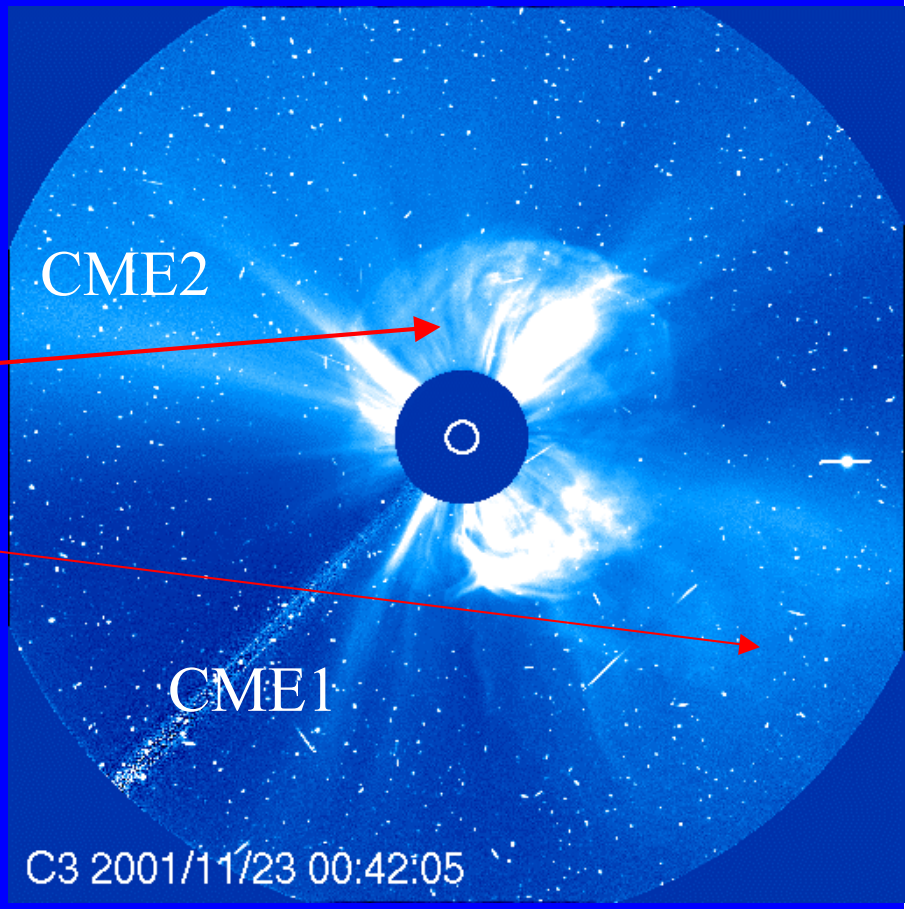
Two closely-spaced fast CMEs

CME1: 20:30 UT (S25W69 AR 9698)

CME2: 23:30 UT (S15W34 AR 9704)

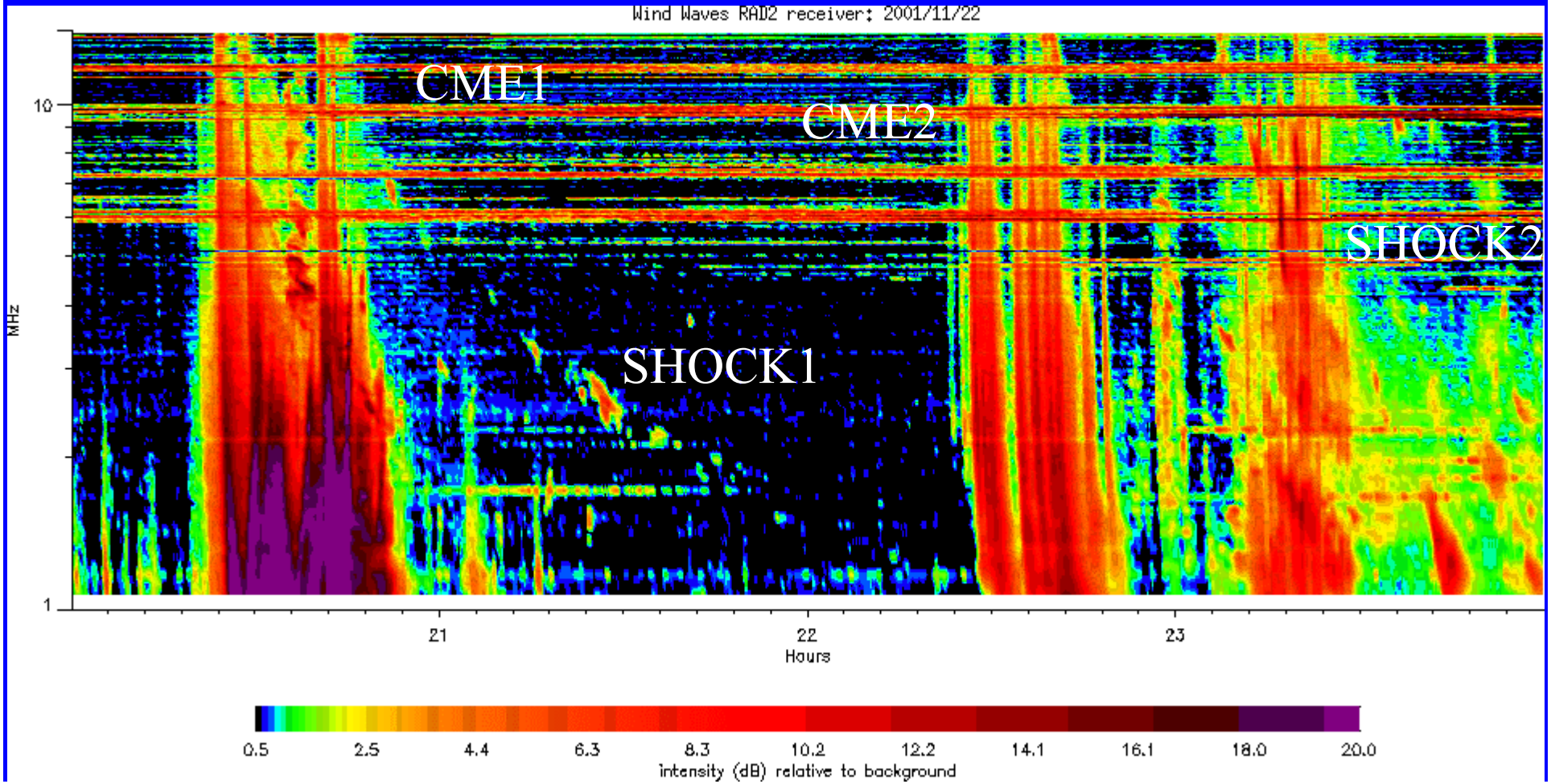
Also Resulted in spectacular radio signature (see next slide)



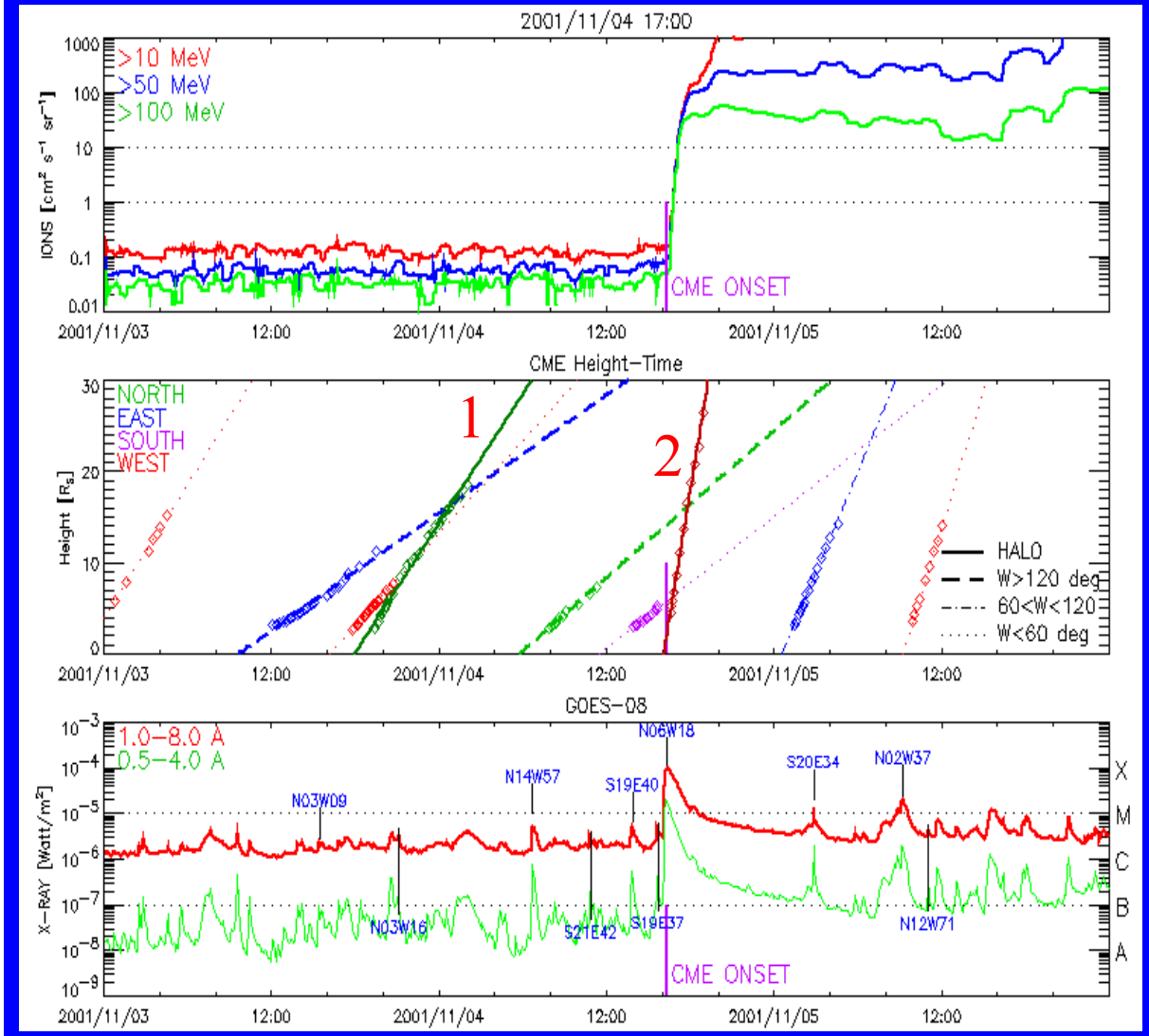


2001/11/22 Interaction:

CME1 has a narrowband type II & CME2 has an extremely broadband type II. Shock2 travels through the material of CME1, and the corona disturbed by it. Shock1 may have minor interactions.

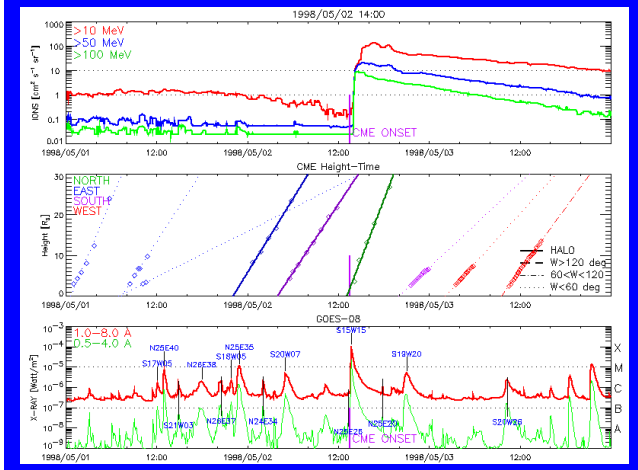


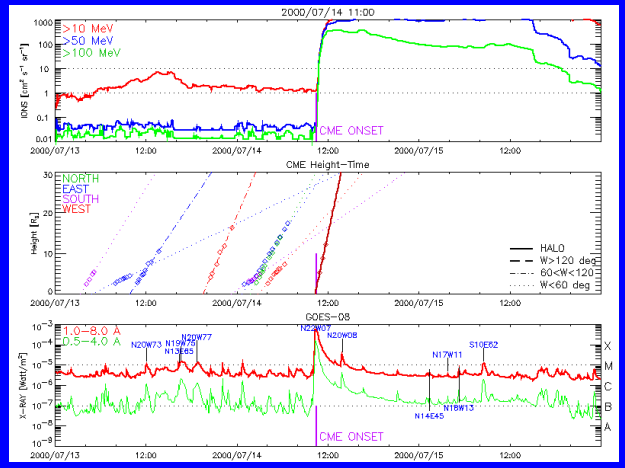
SEP-CME preceded by halo

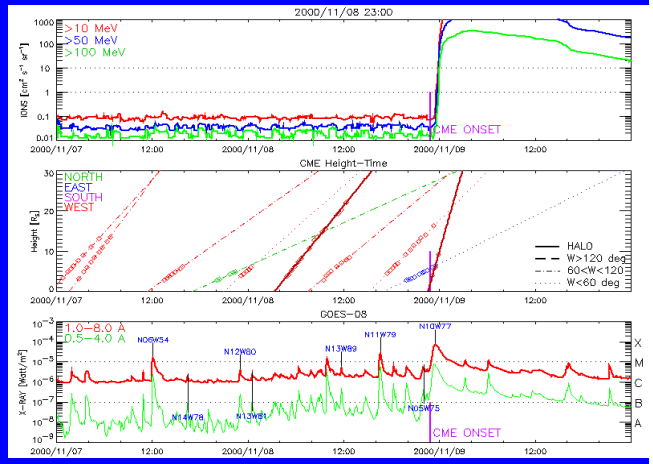


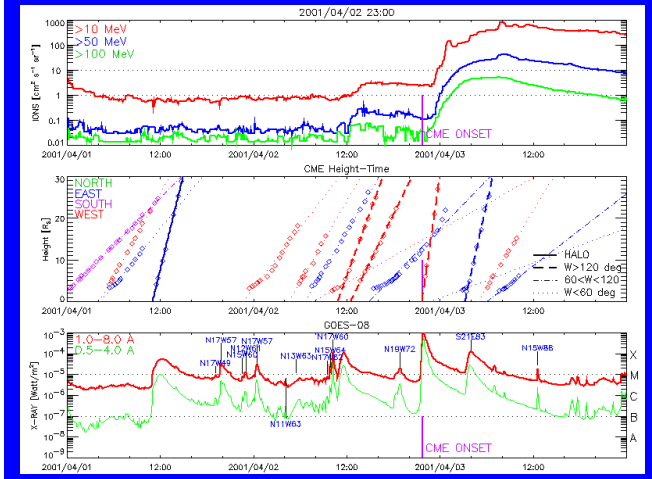
- CME1 & CME2 from same region
- CME1 precedes CME2 by 22 hrs
- The medium ahead of CME2 is modified by CME1
- 75% SEP events with > 100 pfu (E >10 MeV) had this situation
- Only 16% of < 50 pfu events had this situation

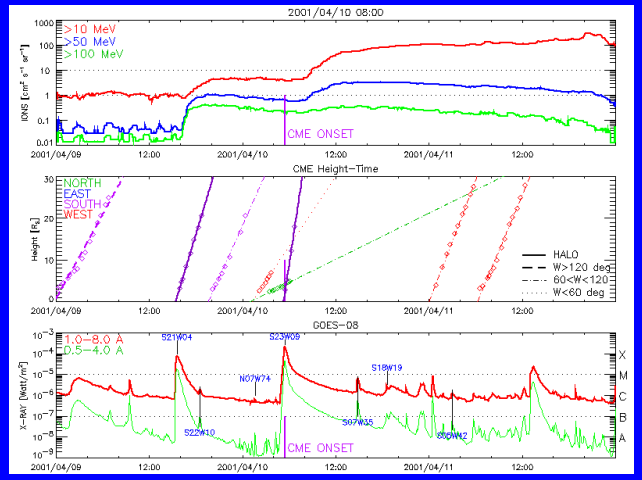
Large SEP events (>100 pfu)

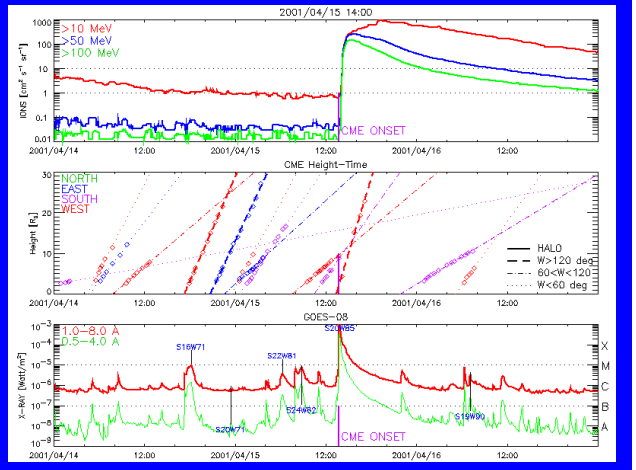




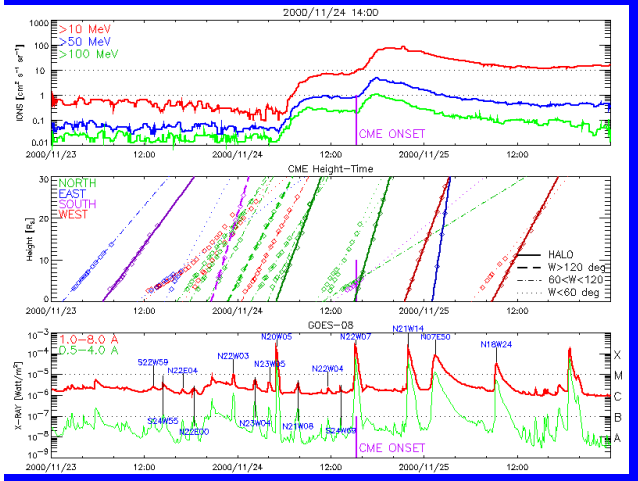


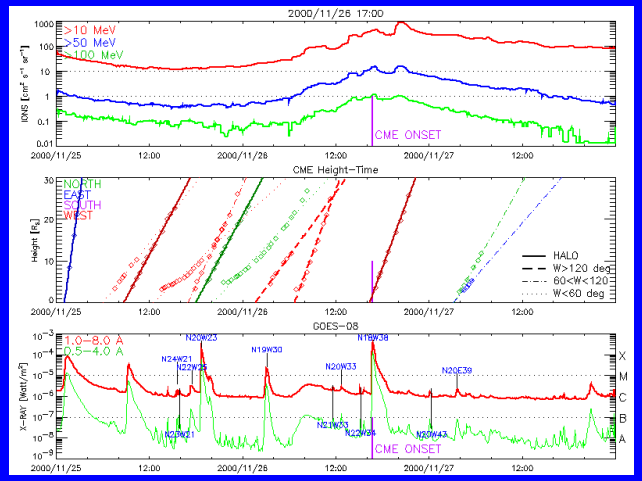


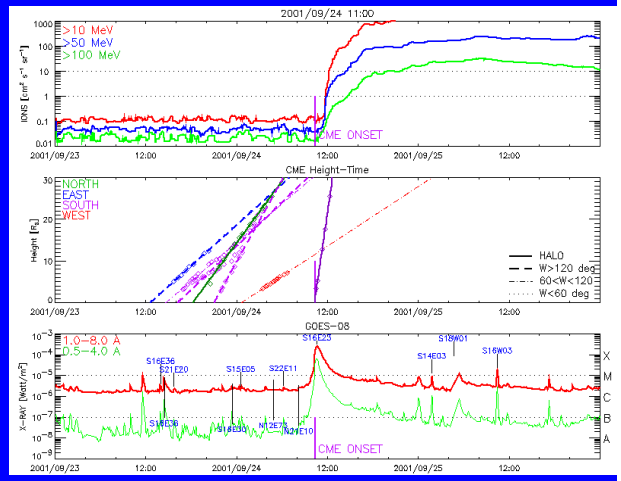


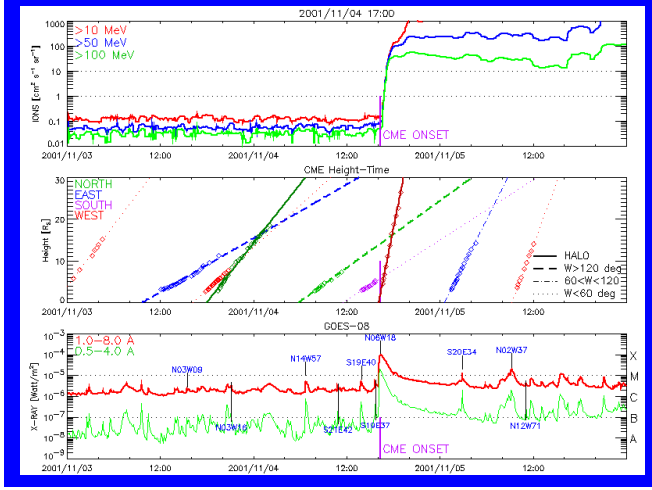


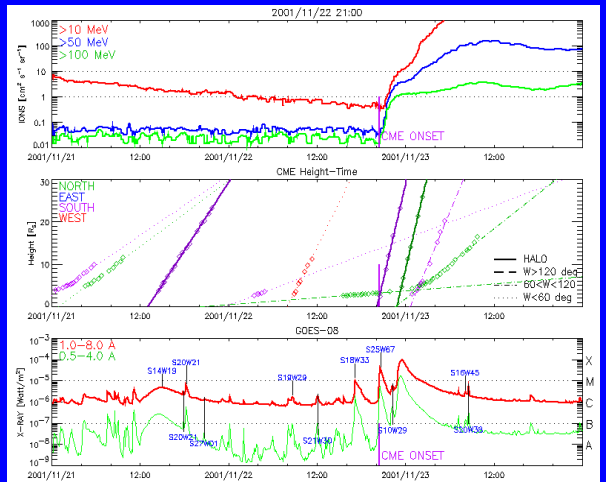
More Halo-Halo Events

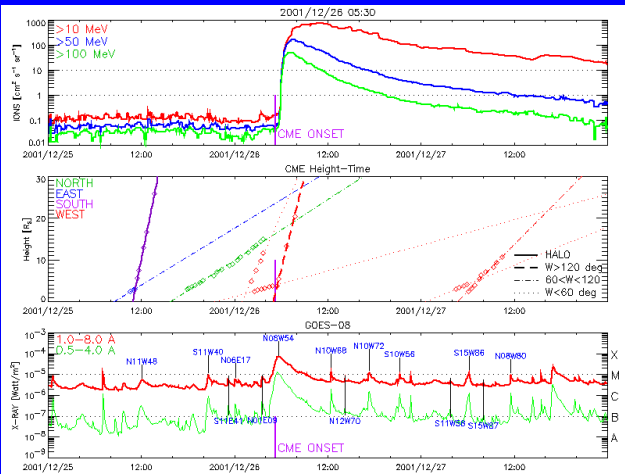












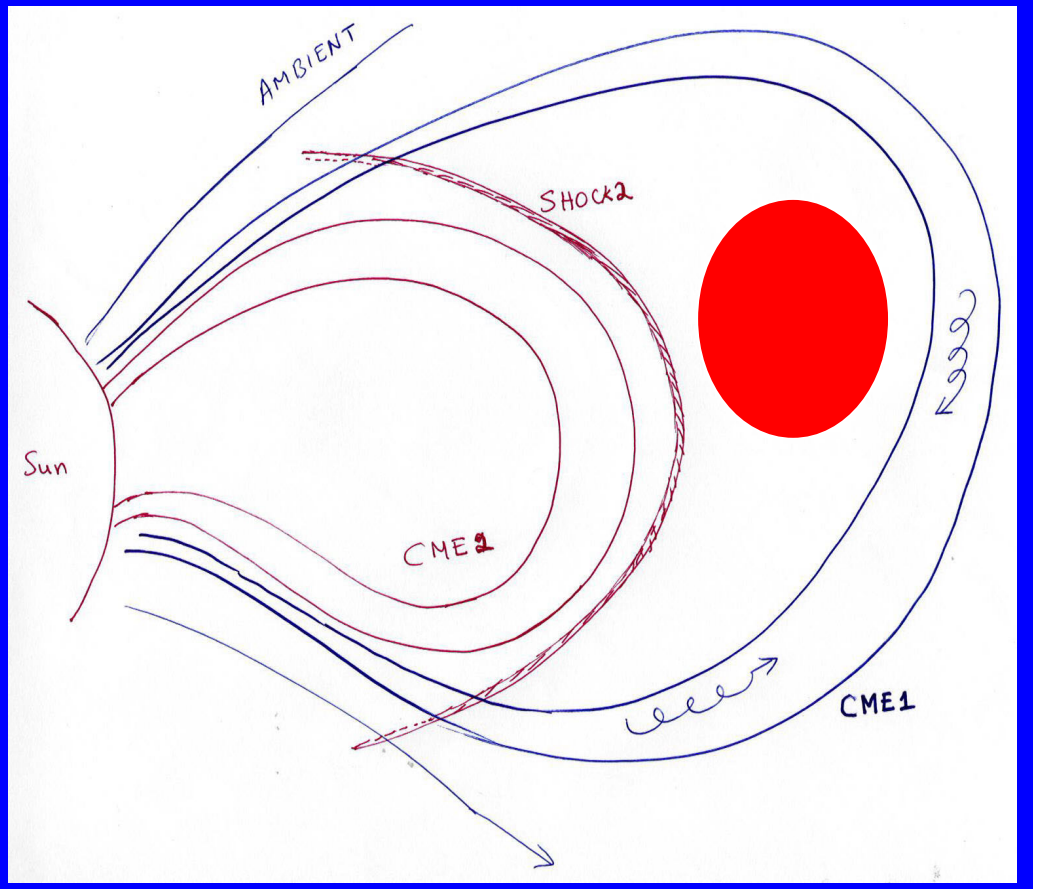
Interaction between two Fast & Wide CMEs

- If both CMEs have roughly the same speed, CME2 may or may not catch up with CME1
- But CME1 field lines connected to shock2 continue to send back particles to the shock to be reaccelerated
- If CME1 also drives a shock, then particles can bounce between shocks
- Shock2 passing thru core1 may become stronger:

  $Vs \sim B.n^{-1/2}$

- CME1, when far away, can create a ìquasi-parallelî situation for shock2

Particles can return to shock2 in sec to min depending upon separation



Implications of SEP Association with CME Interactions

- SEP-producing CMEs are almost always launched into preceding CMEs

→ SEP acceleration not from plain solar wind

→ Shock strengthening

→ particles trapped in preceding CME loops

→ Different environment for the second CME

- Interaction close to Sun

  → Time Dependence of SEP charge state composition (before and after interaction)

- Density/Temperature Effects
  - Additional stripping by dense preceding CMEs
  - Seed particles from preceding shocks
  - High temperature/density from preceding CME core

→Mixed impulsive-gradual signatures