Type II bursts and large solar energetic particle events

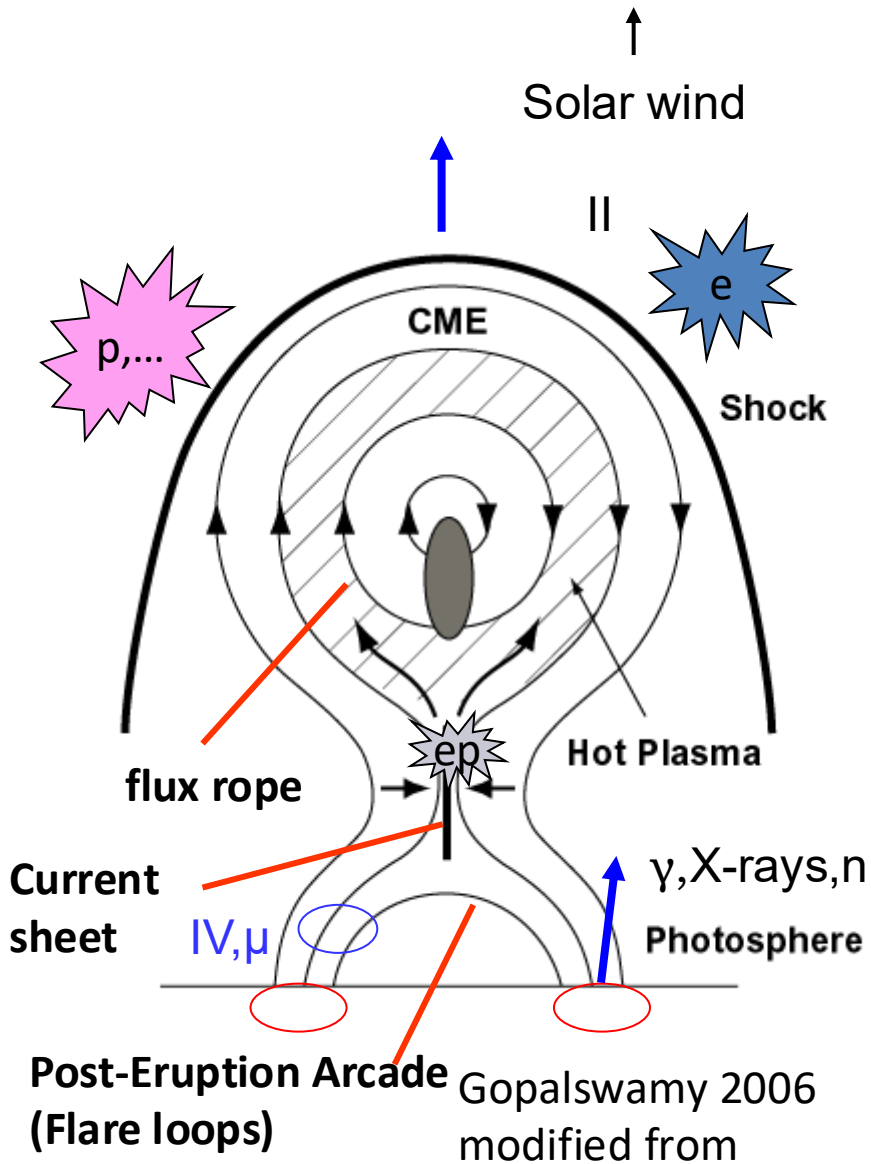
NAT GOPALSWAMY

NASA GSFC



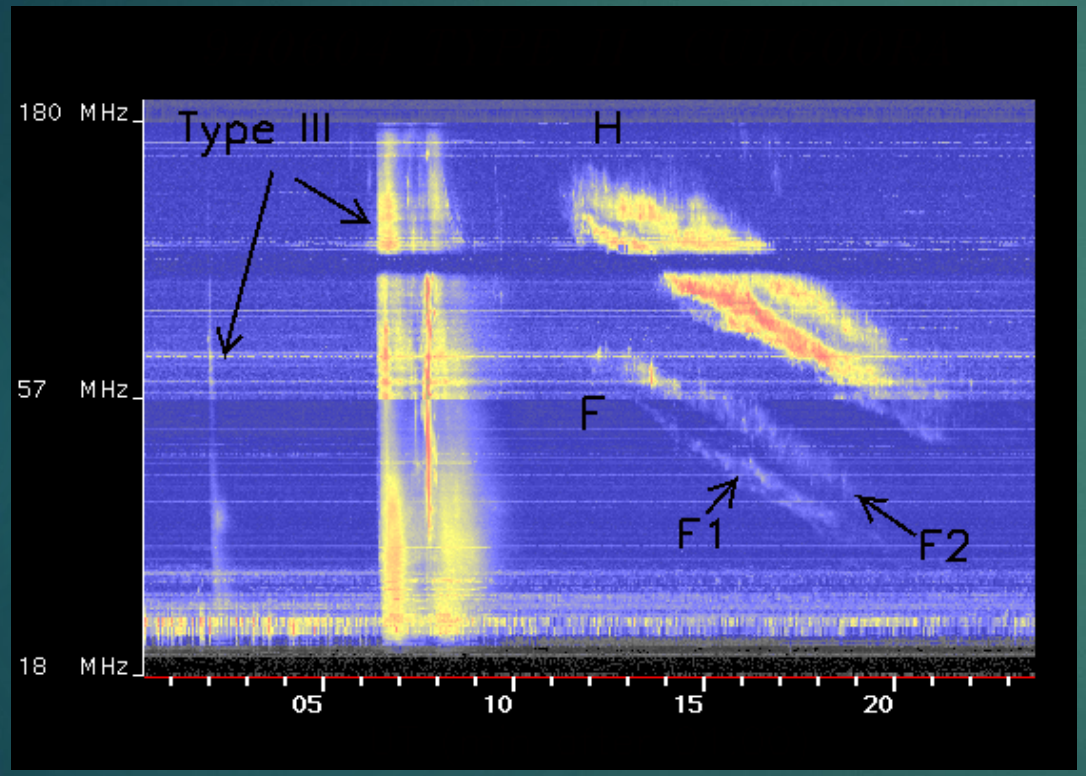
CMEs and Particle Acceleration

- Two sites of particle acceleration on the Sun
- Reconnection region above the polarity inversion line (Flare reconnection)
- CME-driven shock
- Both electrons and protons (and heavier ions)
- are accelerated
- Radio, X-ray emissions are from electrons
- Only gamma-rays are due to accelerated protons



Gopalswamy 2006 modified from Martens and Kuin 1989

Type II & Type III Radio Bursts

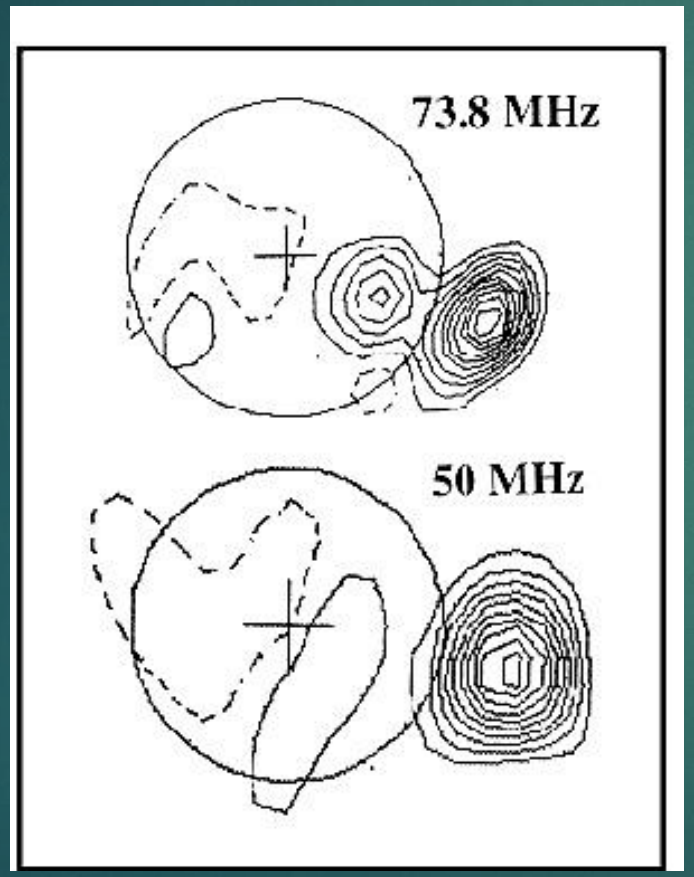


Fast CMEs drive MHD shocks
Shock accelerates electrons (~10 keV)

Nonthermal electrons generate Langmuir waves at local plasma frequency (fp)

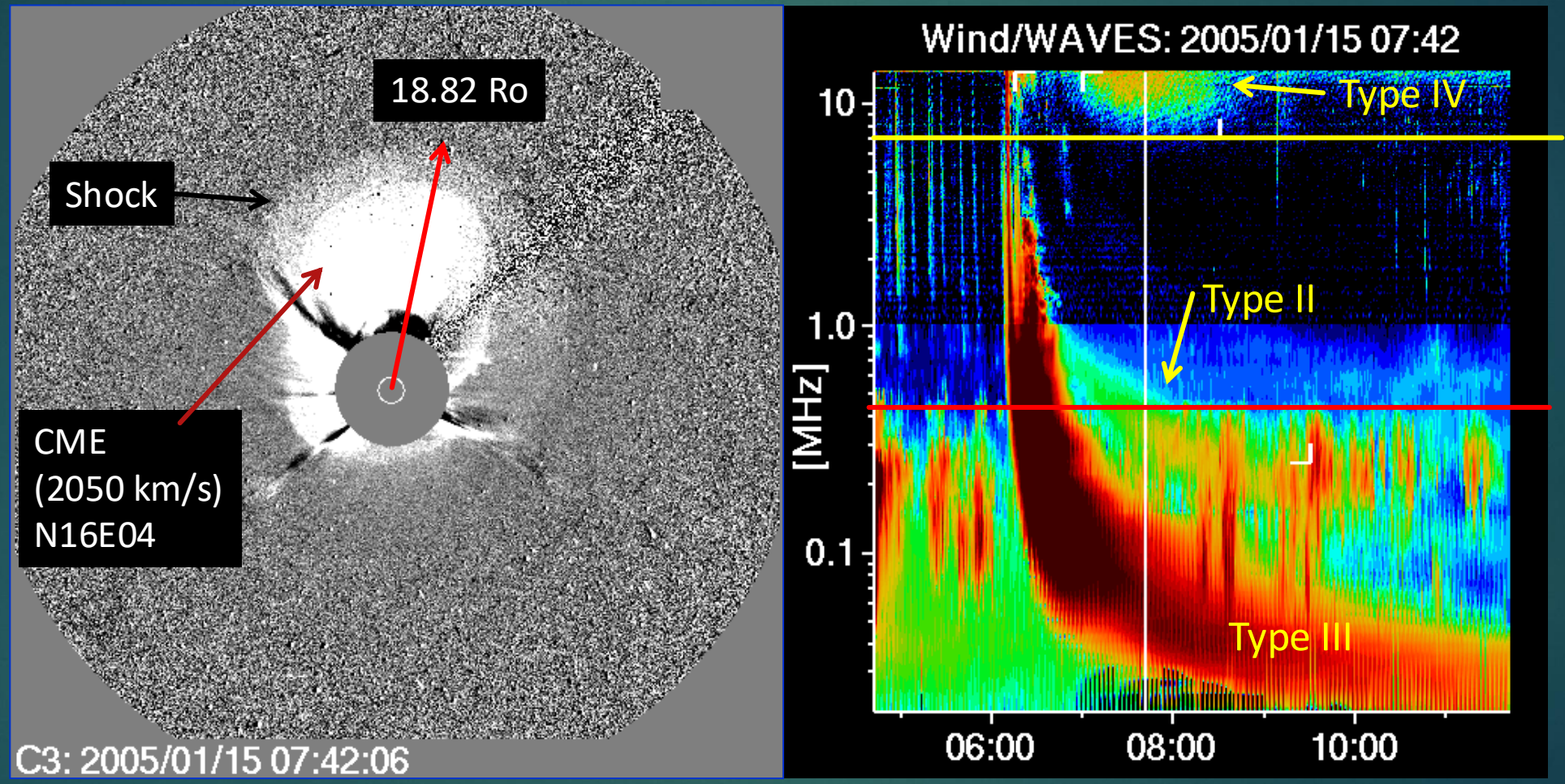
Langmuir waves scatter off of ions or combine to produce radio emission at fp (fundamental) and 2fp (harmonic)

Image of a type II Burst



- Imaged by the Clark Lake Radioheliograph in the 1980s
- We need to go to space to observe/image at lower frequencies (below 20 MHz)

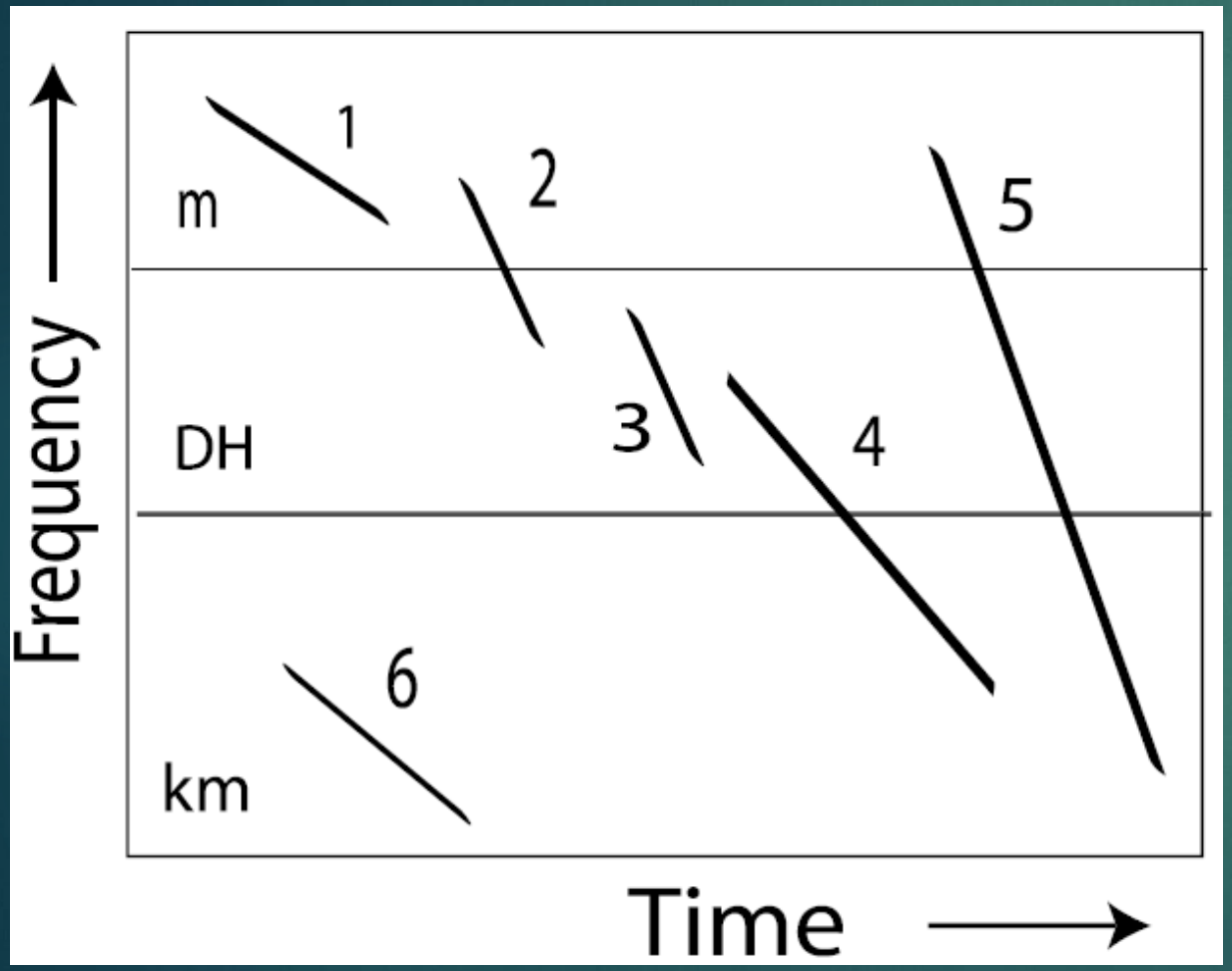
Three Types of low-frequency bursts that can be observed only from space: type III, type II, type IV

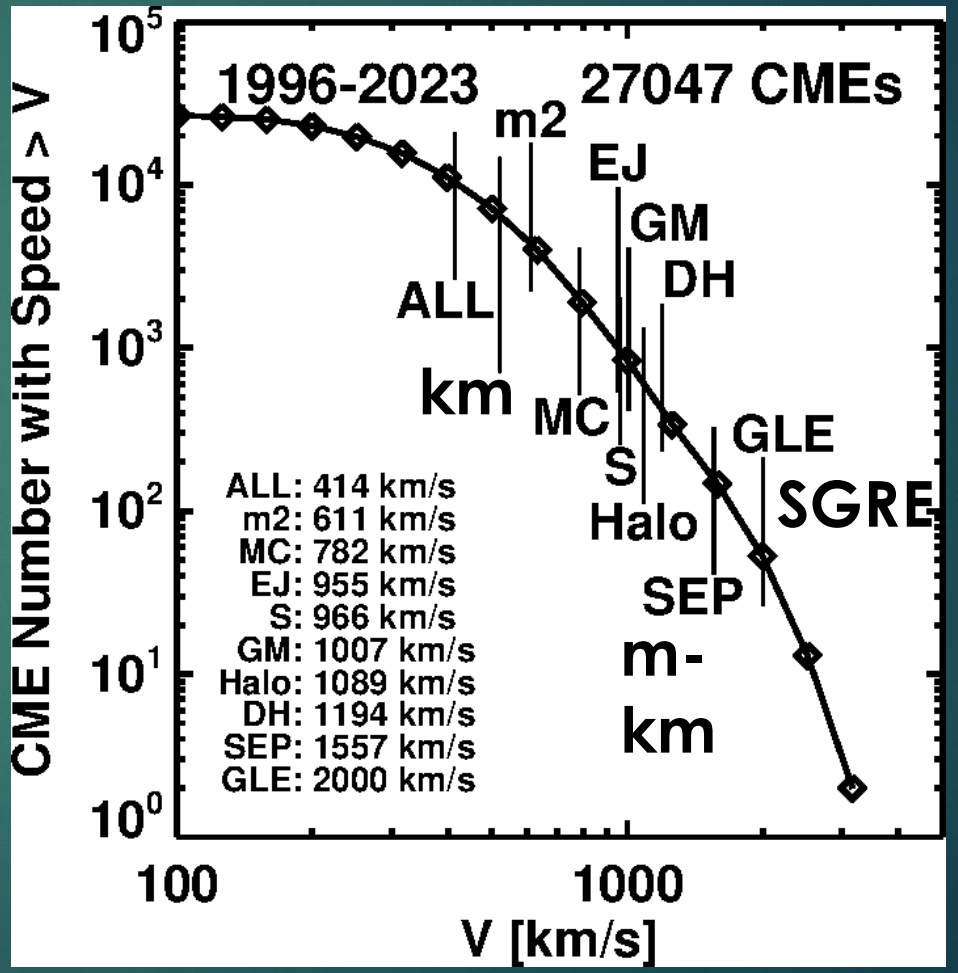


When the shock is at a distance of 18.82 Rs, the Type II burst occurs at 450 kHz as observed by the WAVES experiment on board Wind (n = 2450/cc)

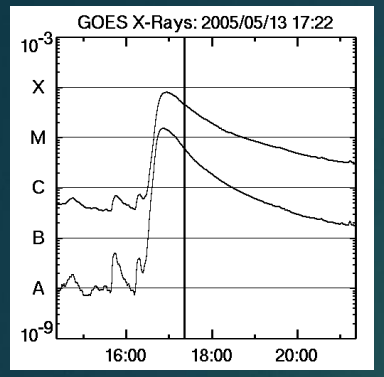
Type II Variants

Property	All	m	DH	mkm	km
Speed (km/s)	487	610	1115	1490	539
Width (deg)	45	96	139	171	80
Halos (%)	3.3	3.8	45.2	71.4	17.2
Acceleration (m/s^2)	−2	−3	−7	−11	+3

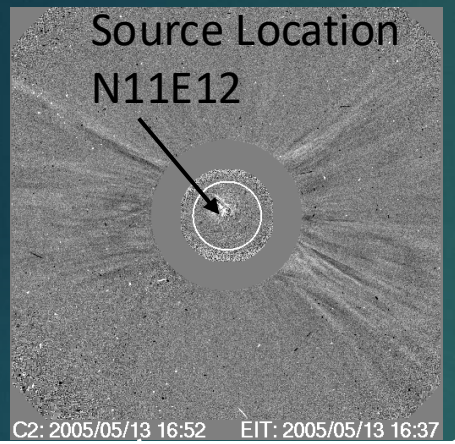


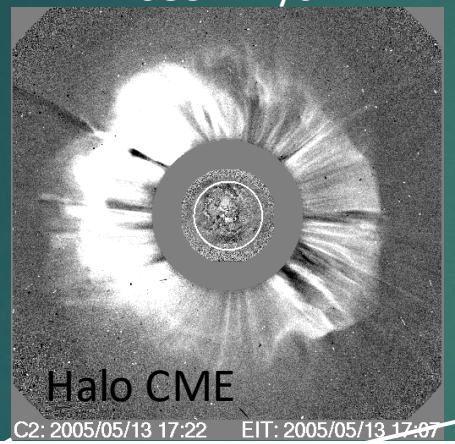


Close relation between type II & SEP

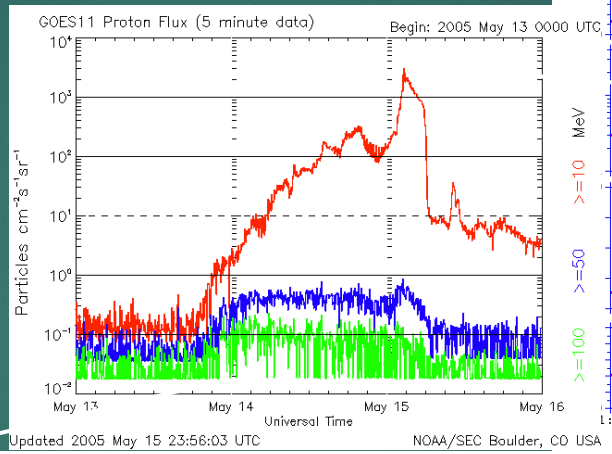


1689 km/s

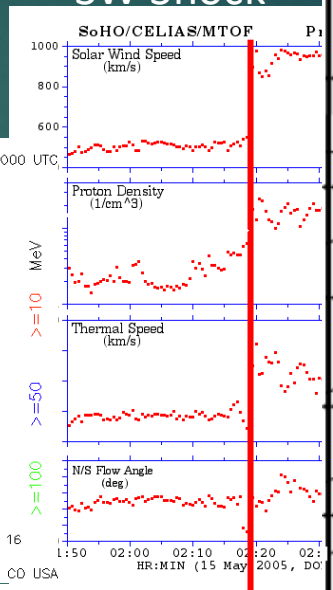


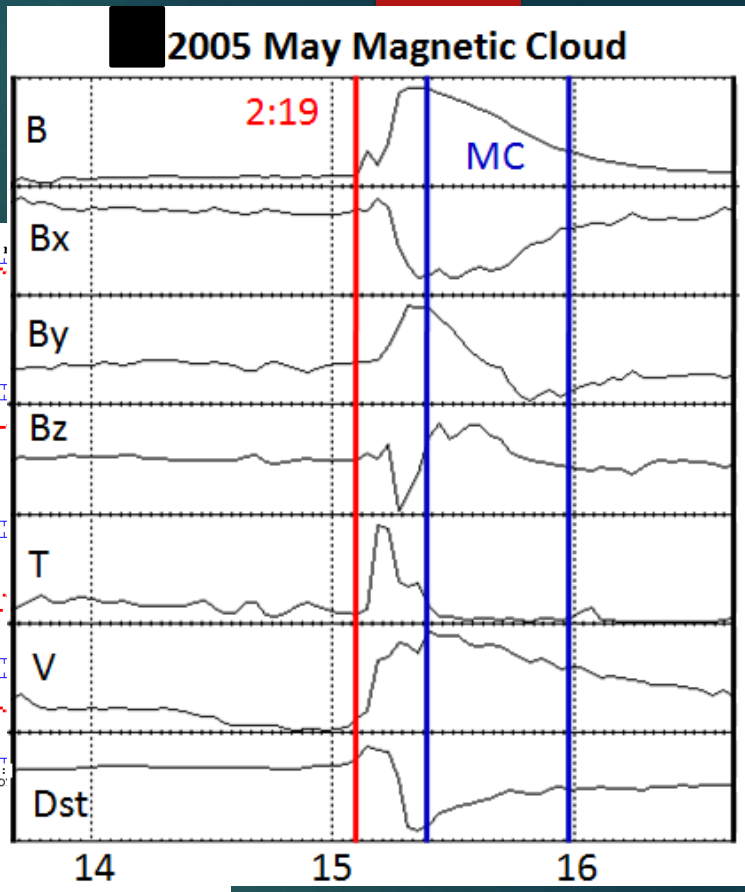


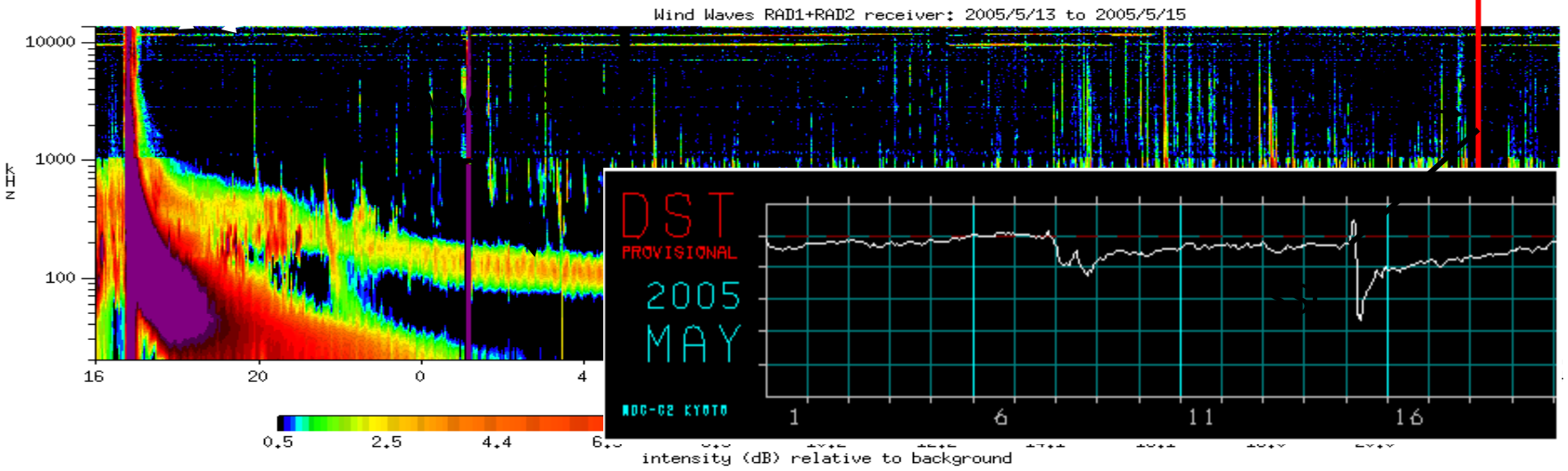
ESP 100 →3000 pfu



SW Shock

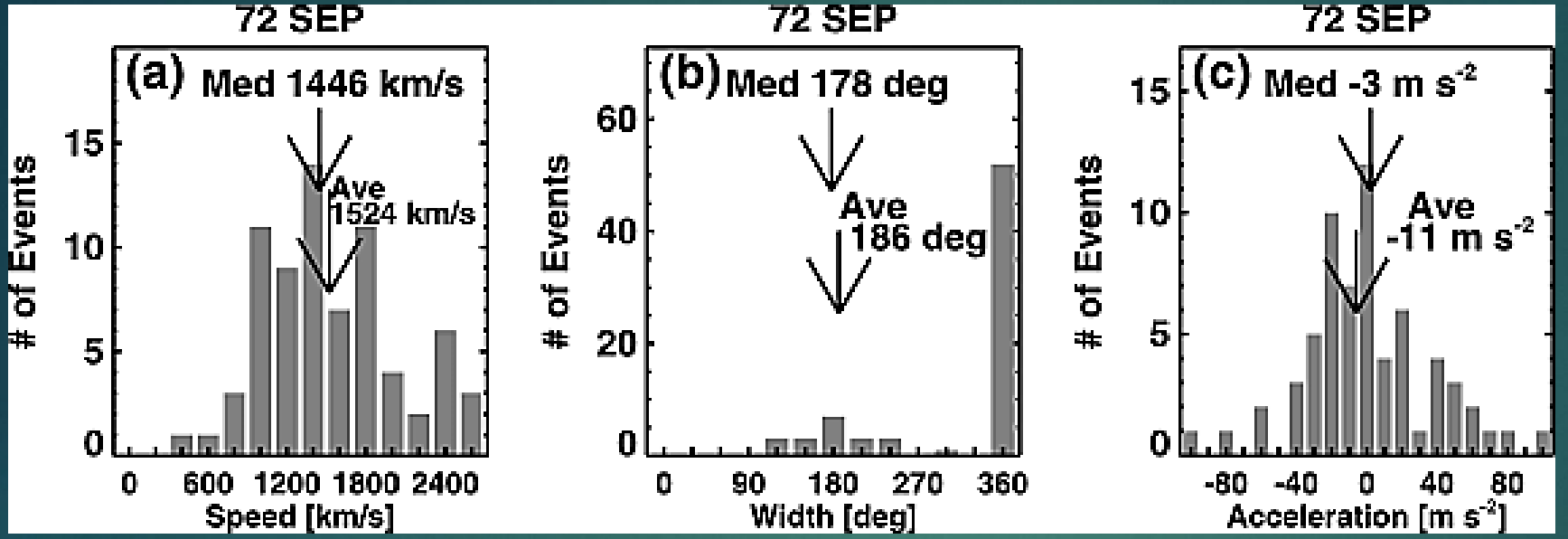


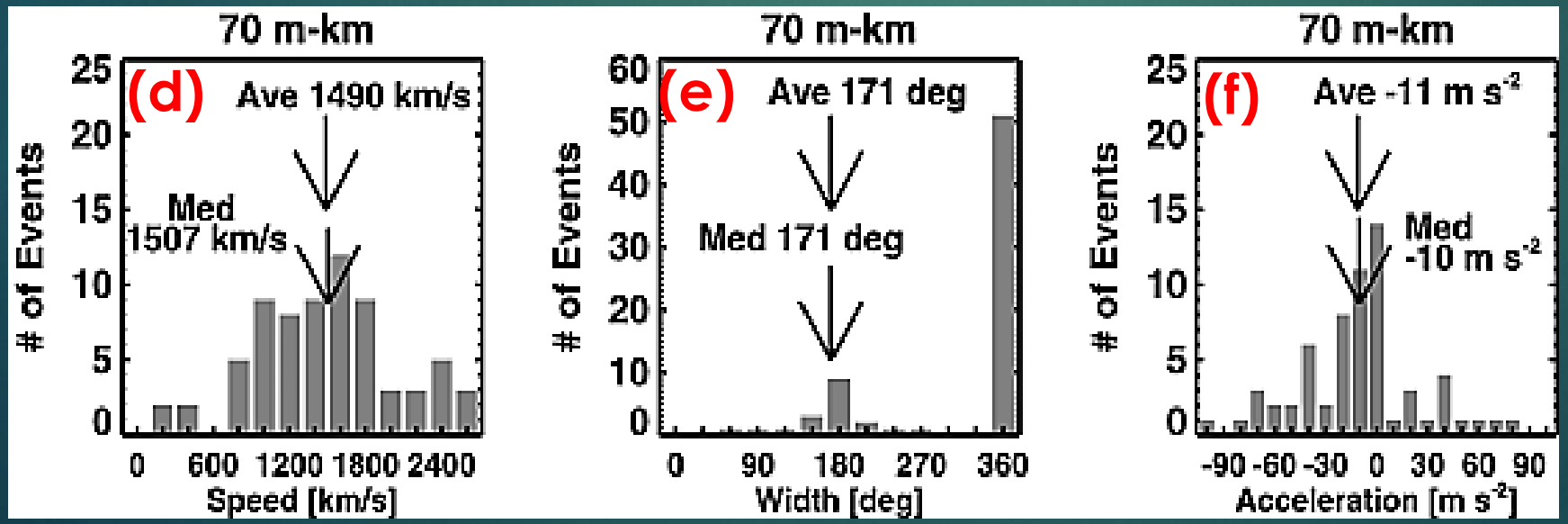




in-situ "view" of the CME

CMEs causing type II & SEP are similar





Similar speed, width, and acceleration

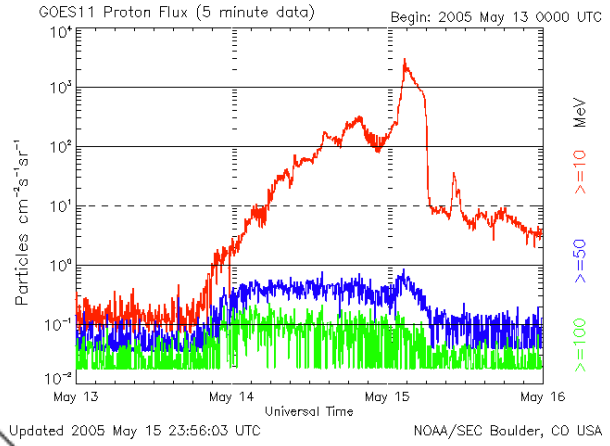
Type II Radio Burst

- Fast CMEs drive MHD shocks
- Shock accelerates electrons (~10 keV)
- Nonthermal electrons generate Langmuir waves at local plasma frequency (fp)
- Langmuir waves scatter off of ions or combine to produce radio emission at fp (fundamental) and 2fp (harmonic)

CME, Flare, Shock, Type II, SEP – All Closely Related

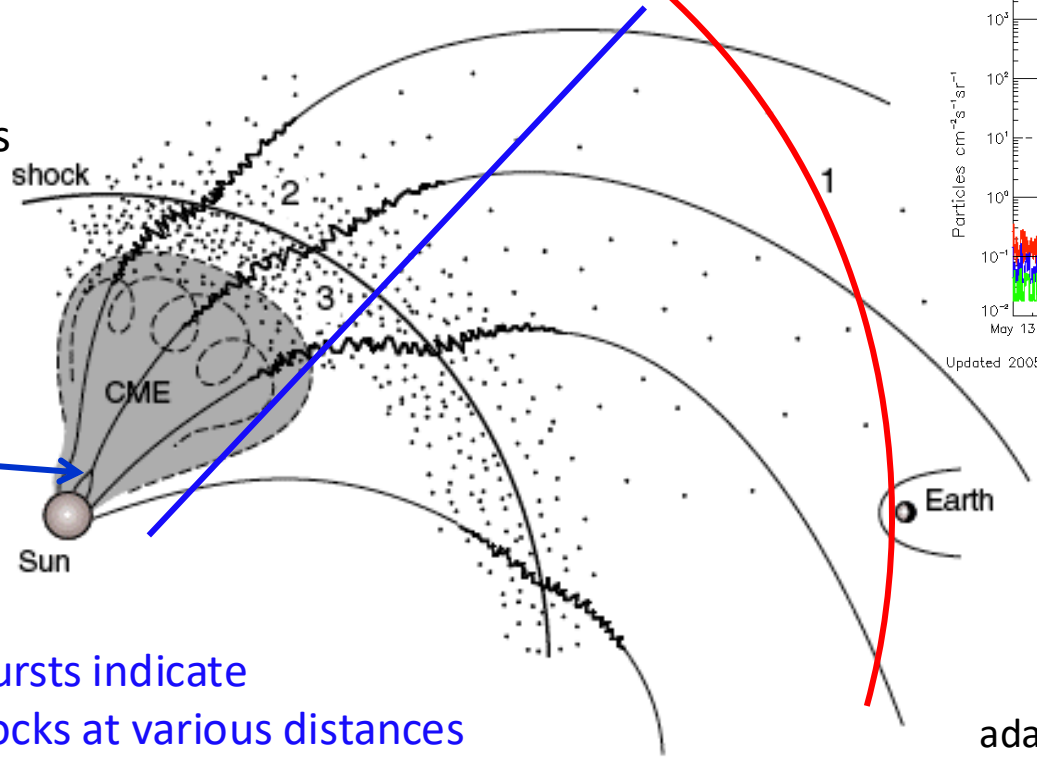
IP shocks detected in situ by Spacecraft such as Wind, ACE and SOHO (also by local type II)

shock at 1 AU



Shocks accelerate electrons and ions

Type III bursts are due to electrons from flares

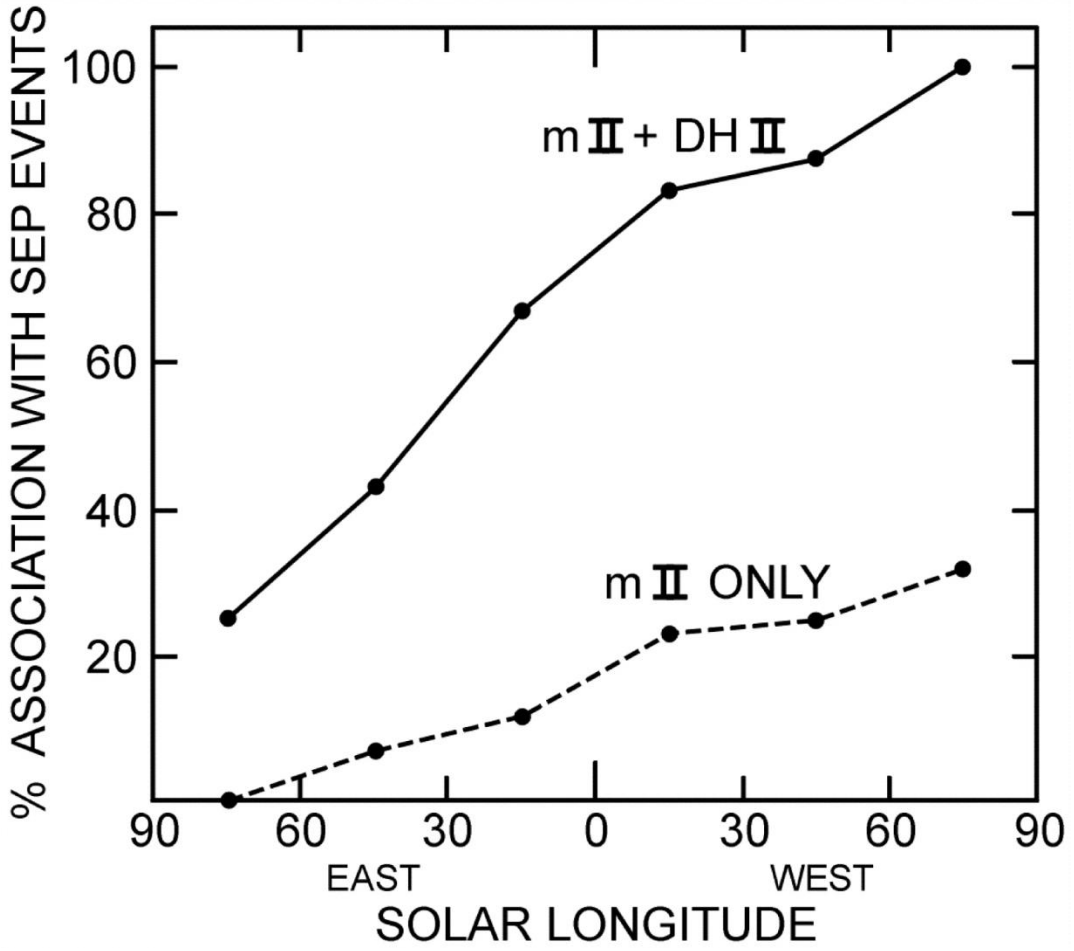


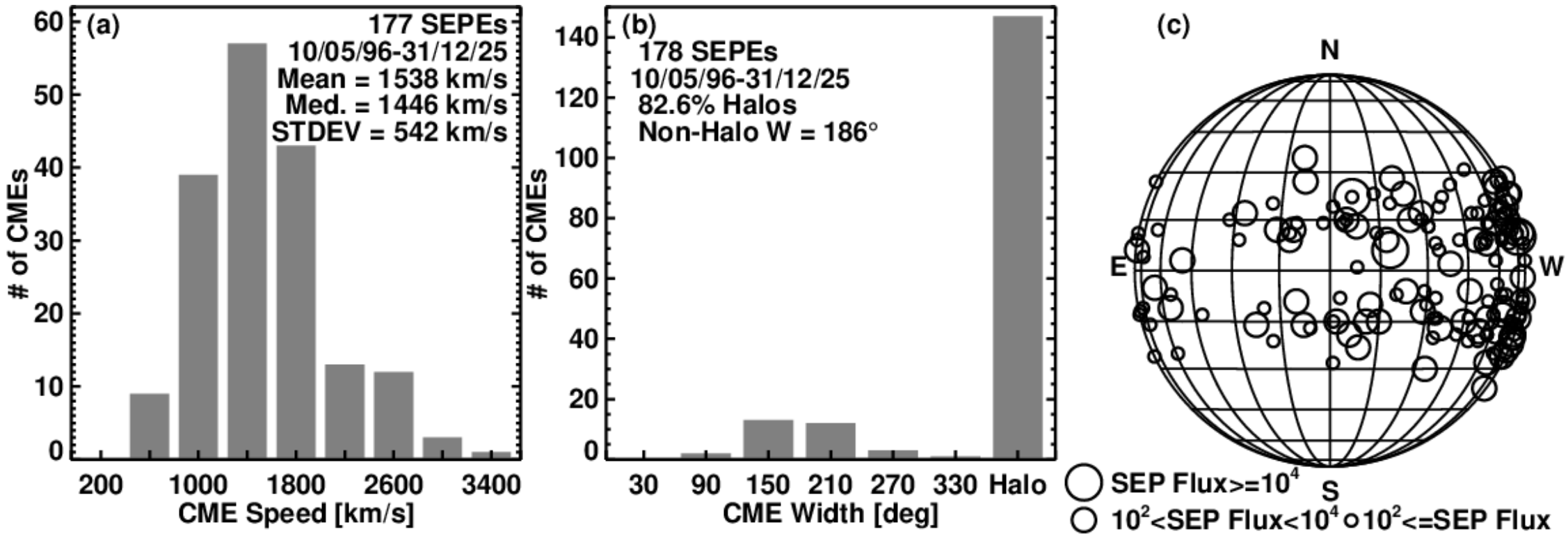
Type II Radio Bursts indicate CME-driven shocks at various distances from the Sun (emitted by accelerated electrons)

adapted from Lee 1997

Shocks studied using type II bursts, CMEs, and in-situ plasmag observations

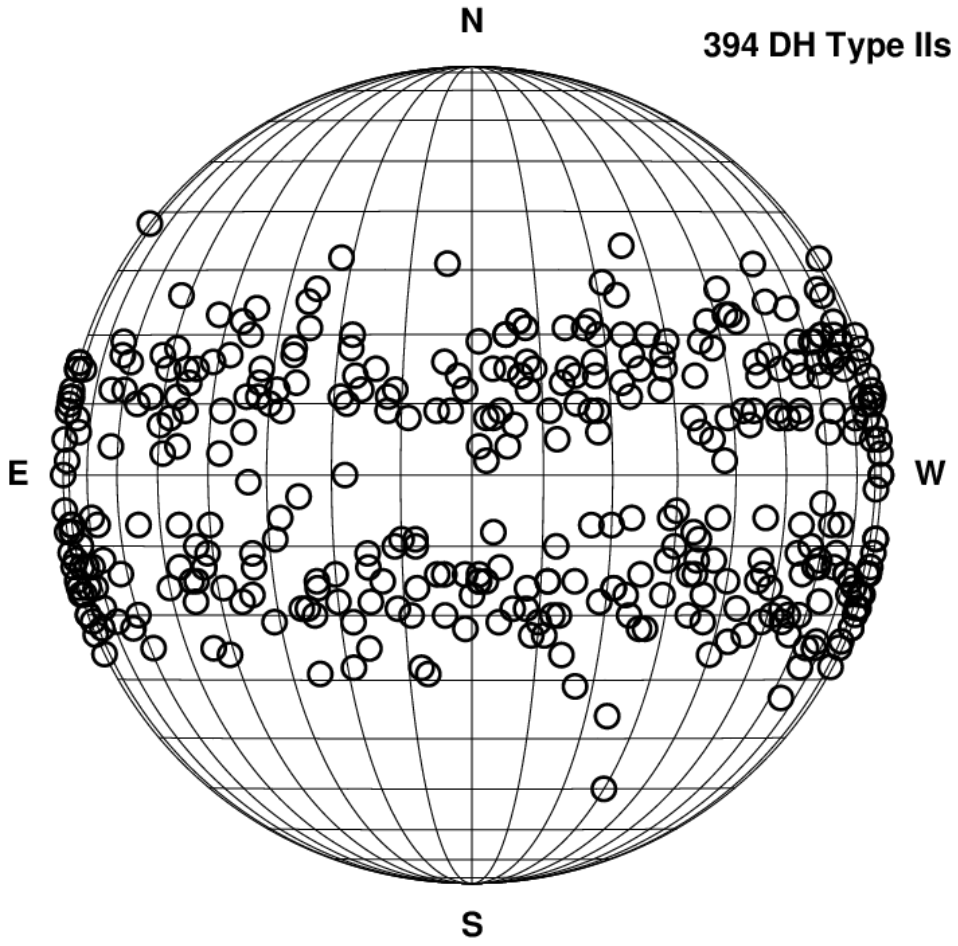
SEP association higher when type II occurs at metric and longer wavelengths




(a)
177 SEPEs
10/05/96-31/12/25
Mean = 1538 km/s
Med. = 1446 km/s
STDEV = 542 km/s
# of CMEs
CME Speed [km/s]
(b)
178 SEPEs
10/05/96-31/12/25
82.6% Halos
Non-Halo W = 186°
# of CMEs
CME Width [deg]
(c)
N
E
W
S
SEP Flux>=10^4
10^2<SEP Flux<10^4
10^2<=SEP Flux

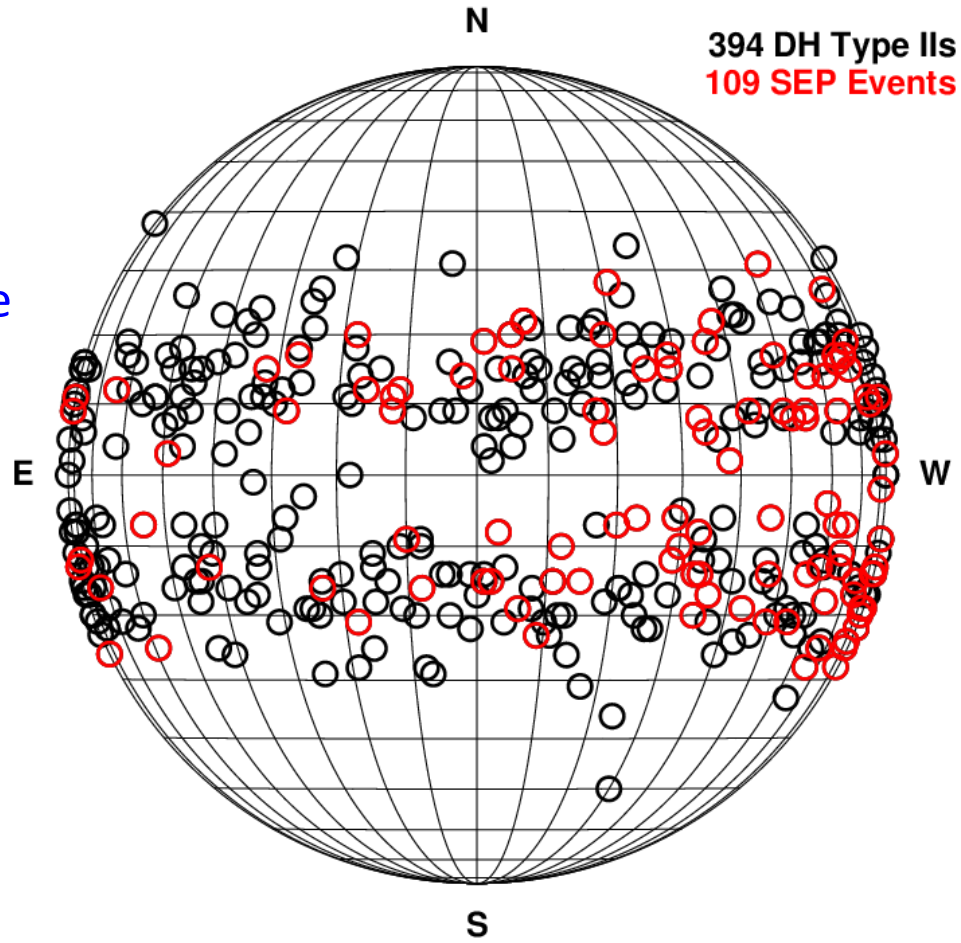
Type II Producing CME Source Locations

- 524 Type II bursts from cycles 23 and 25
- CME information is available only for 496 bursts.
- Of the 496 bursts, only 394 (or ~80%) have sources on the frontside of the Sun



Type II Bursts with Large SEP events

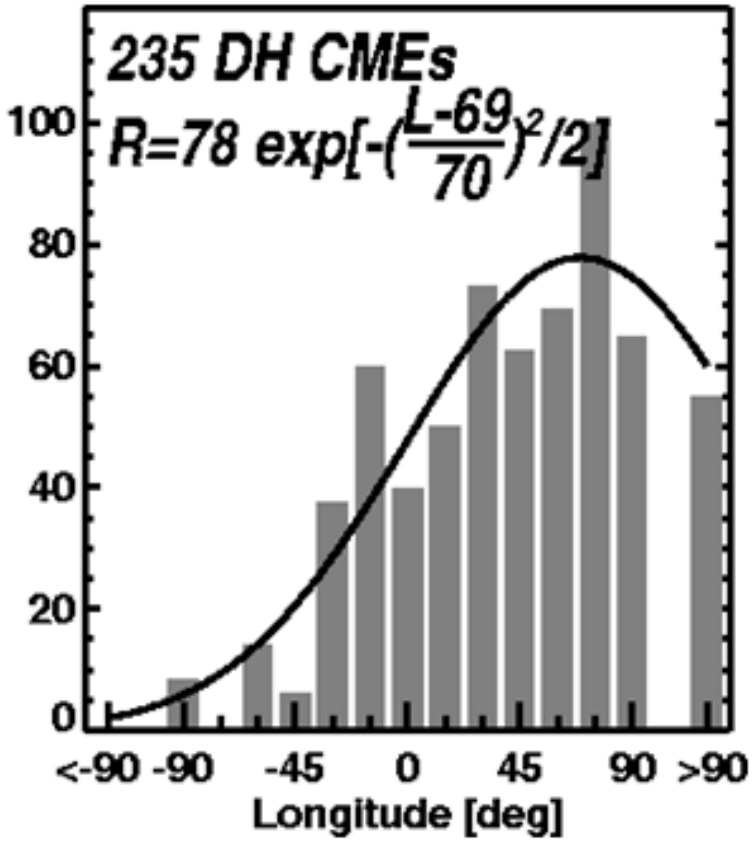
- The latitude range of SEP sources is even tighter than that of the DH type II bursts.
- In fact, none of the 11 DH type II bursts occurring at latitudes >30° are associated with SEP events.
- Most of the SEP-associated type II bursts originate from the western hemisphere.
- Only 23 of the 109 SEP events (or 21%) originate from the eastern hemisphere.



- There are 152 large SEP events → 43 large SEP events are not plotted
- Eight of the 43 SEP events occurred during LASCO data gaps
- In 19 cases, the sources were behind the limb and associated with DH type II bursts.
- In 6 cases, the SEP event is an energetic storm particle event
- Remaining 10: fuzzy type II or type II below 1 MHz

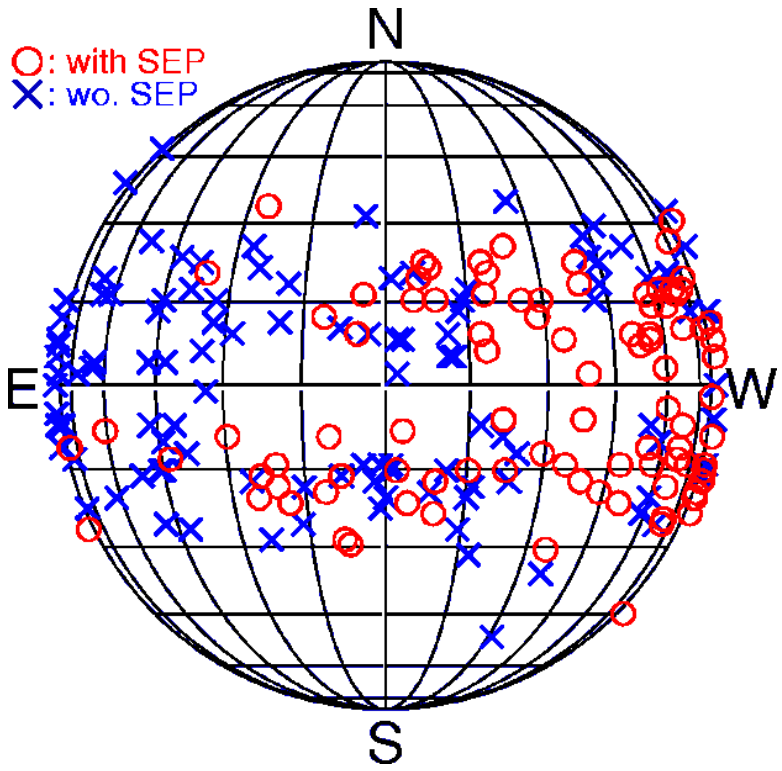
Gopalswamy+ 2019

What Fraction of Radio-loud CMEs Produce SEPs?



Gopalswamy+ 2008

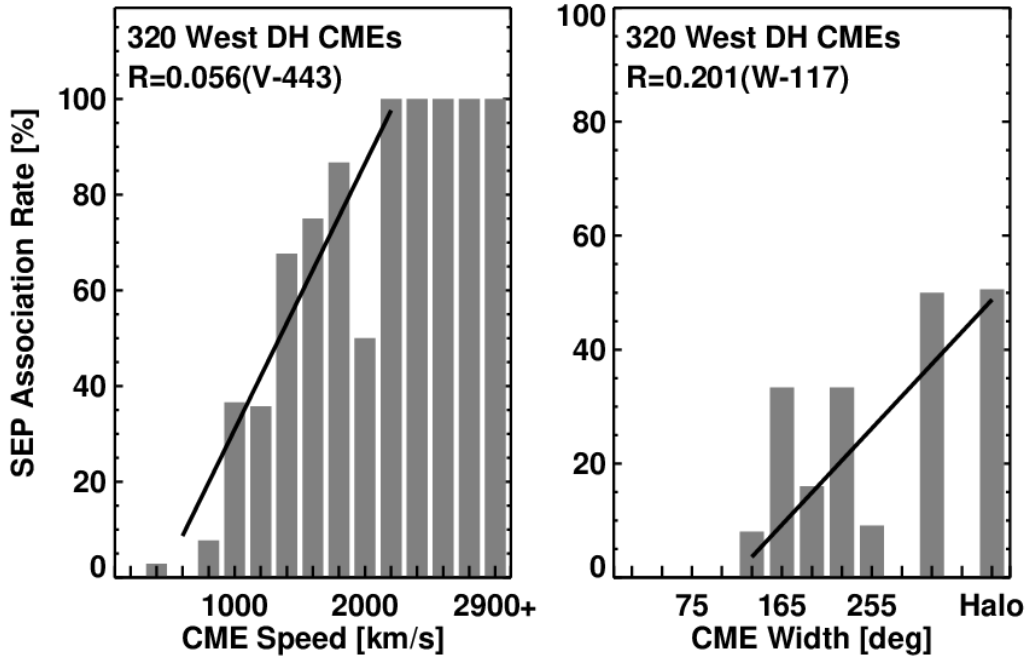
Sources of CMEs associated with DH type II bursts



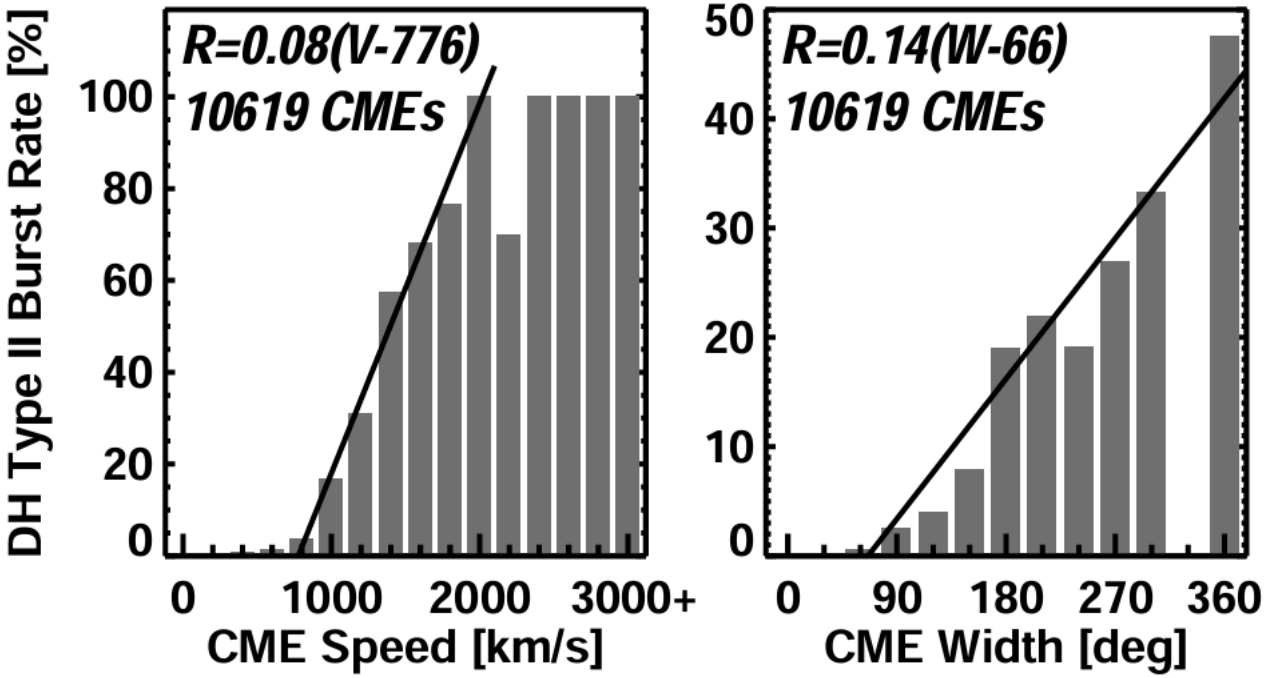
Answer: About 50% because magnetic connectivity needed for SEPs, not for EM radiation

SEP Association Rates

DH CMEs: CMEs with DH type II bursts



Similar to type II burst association rate with CMEs

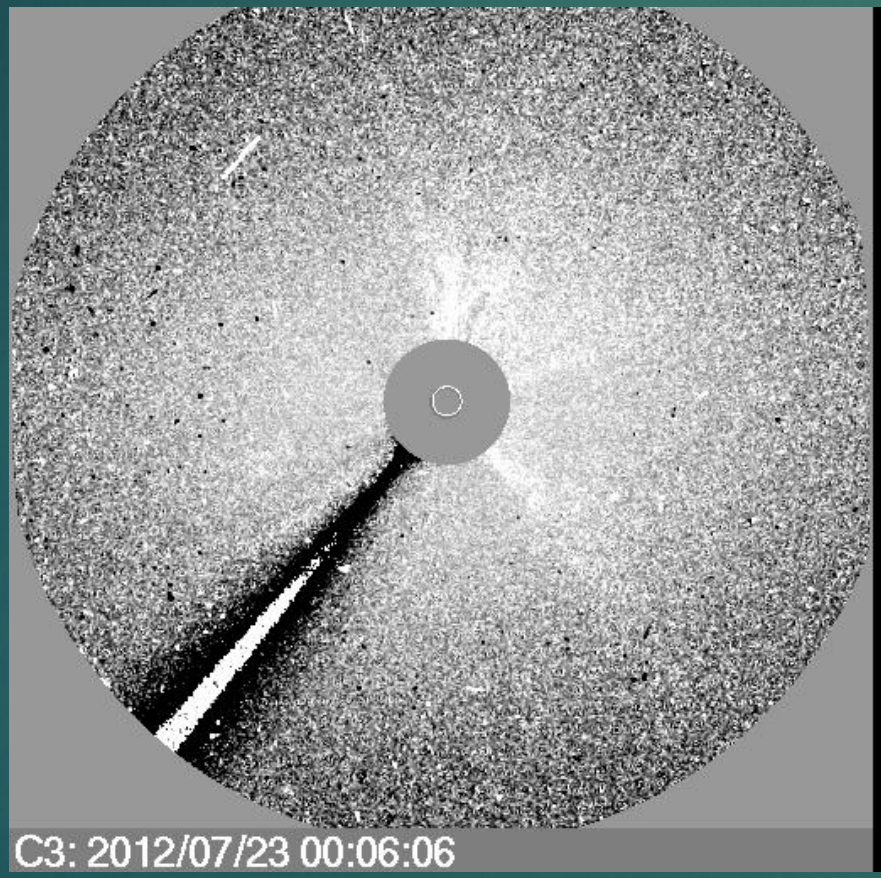


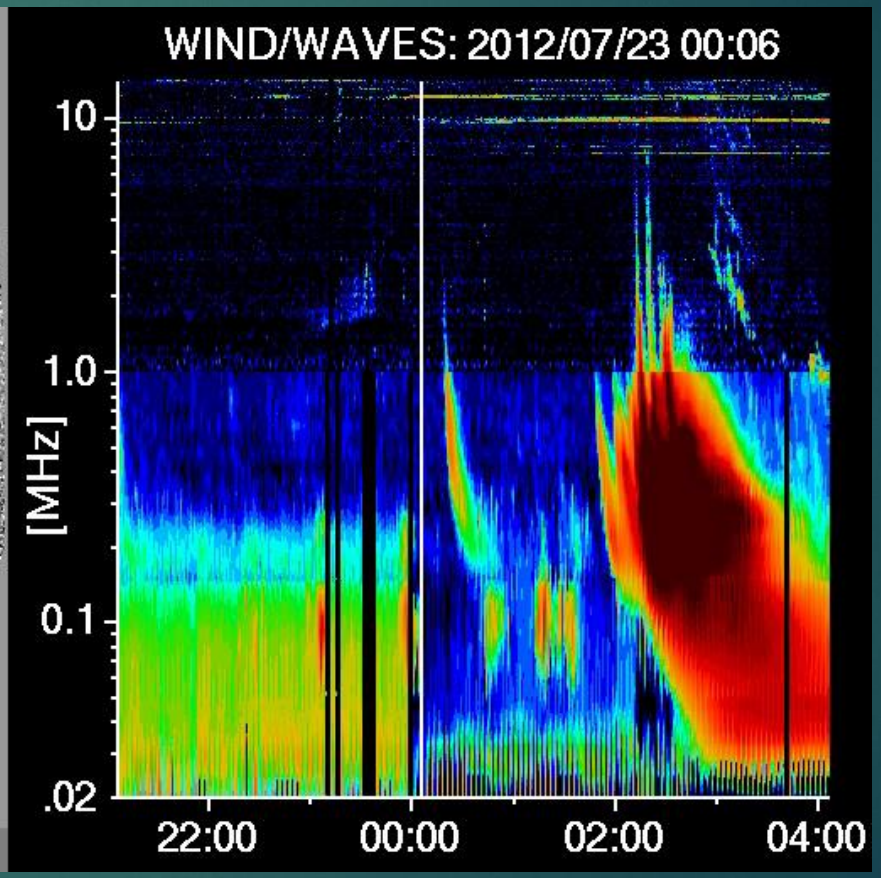
- The SEP association rate rapidly increases with speed and width
- ~40% of 1000 km/s DH CMEs have SEP association
- 100% association for speed > 2000 km/s

Gopalswamy+ 2008

SEP Association Rate of Backside Type IIs

Observations From Sun-Earth Line: A Small Type II Burst



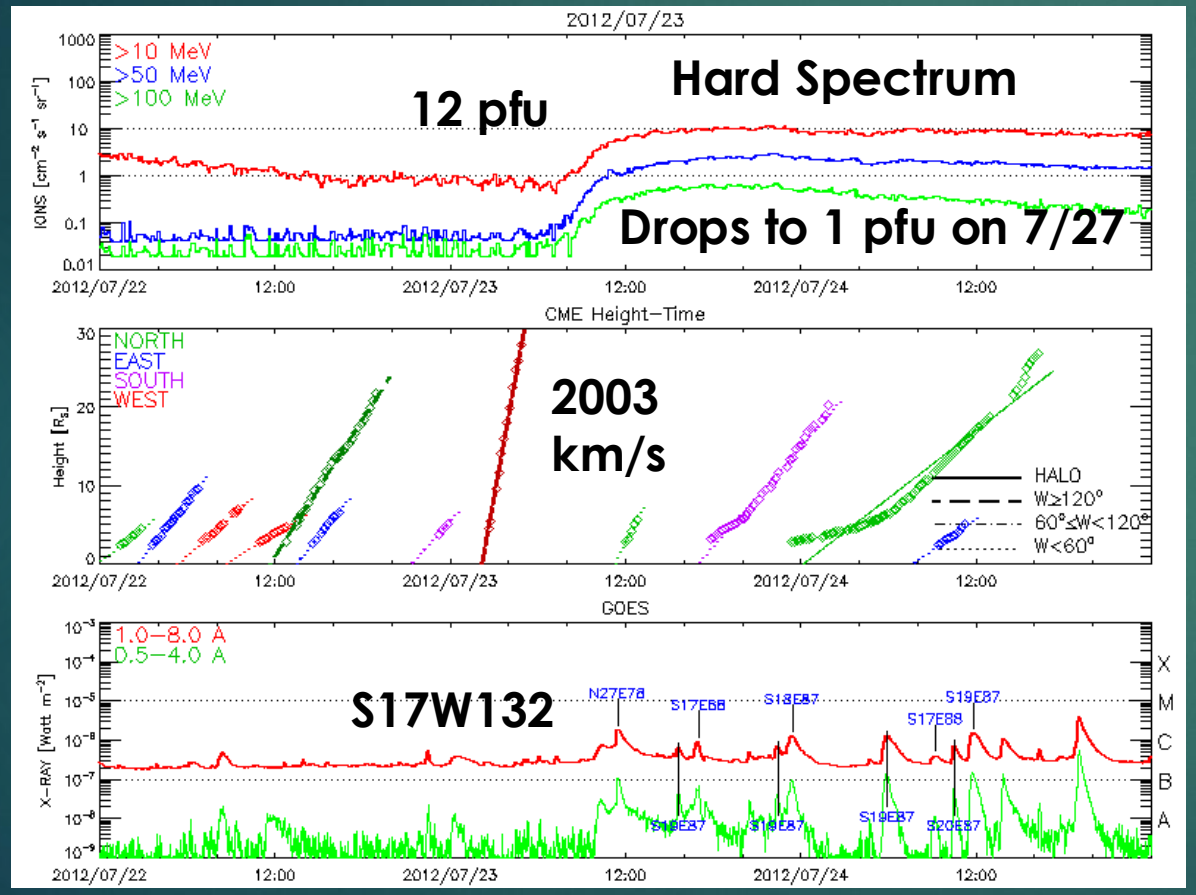


Weak type II; low starting frequency
Type III indicates occultation

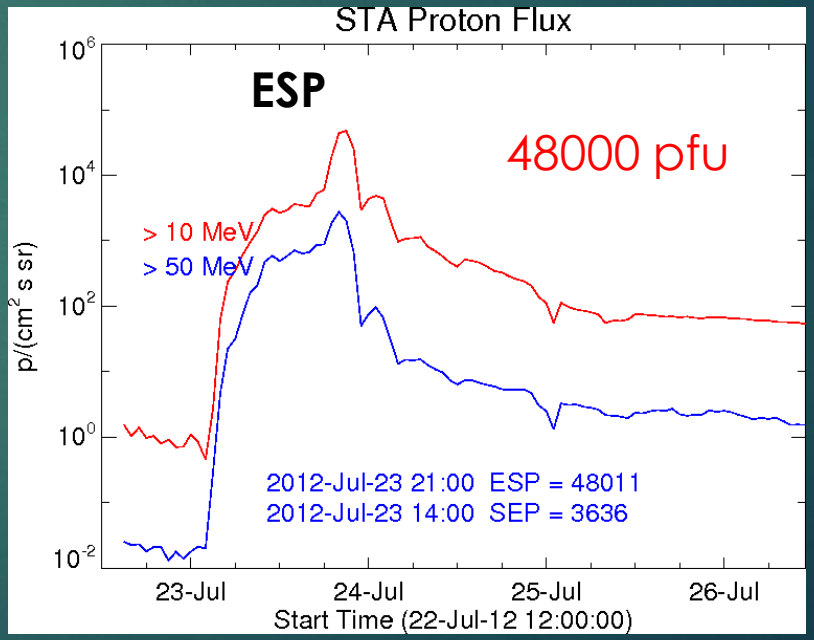
2012 July 23 SEP Event

10/19/1989 – 40,000
03/21/1991 – 43,000

1 pfu = 1 particle cm^{-2} s^{-1} Sr^{-1}

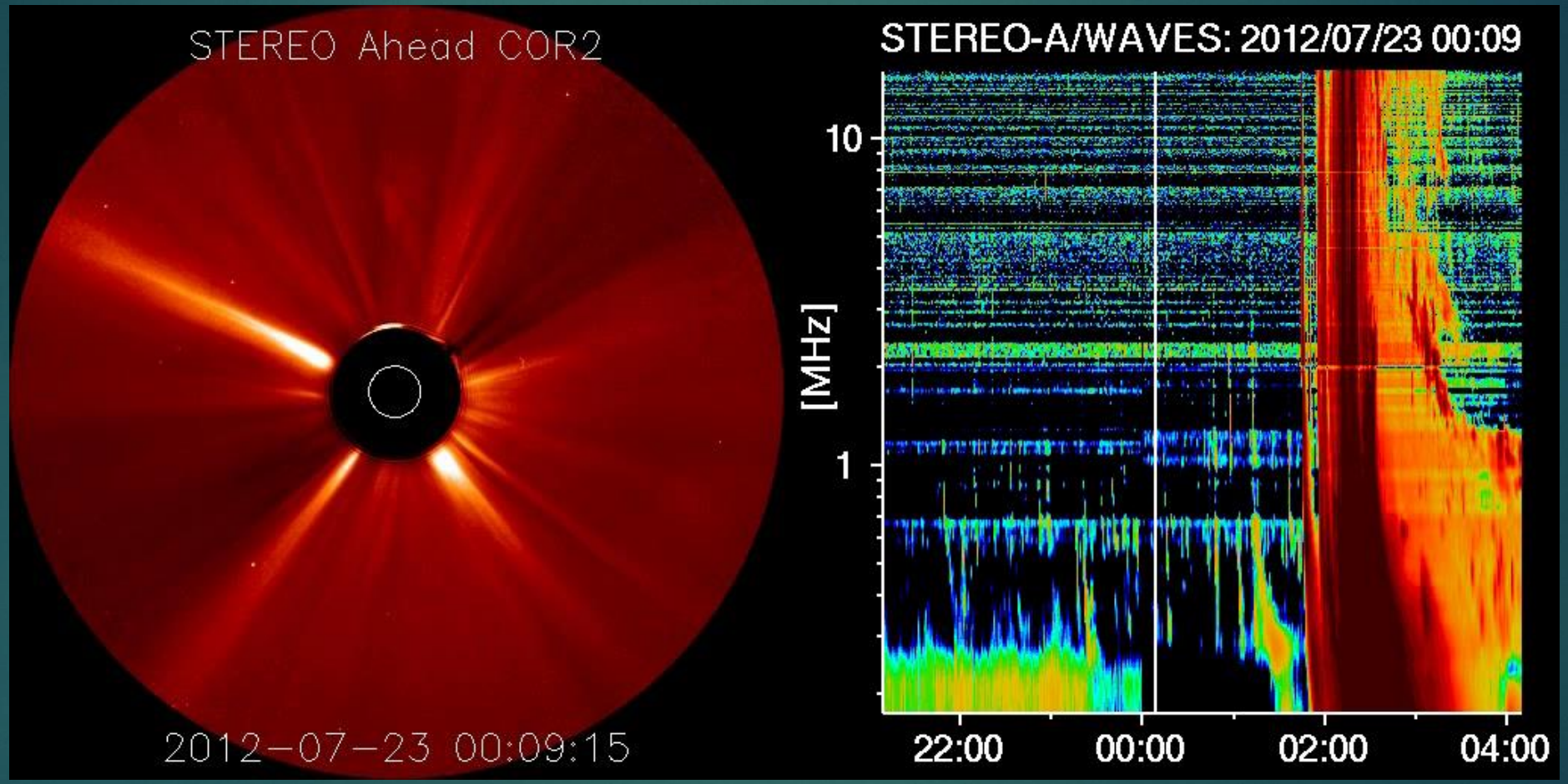


No Eruption Activity → Backsided Ultrafast CME
Small SEP Event observed by GOES
But the spectrum was hard
Lasted for 4 days at Earth

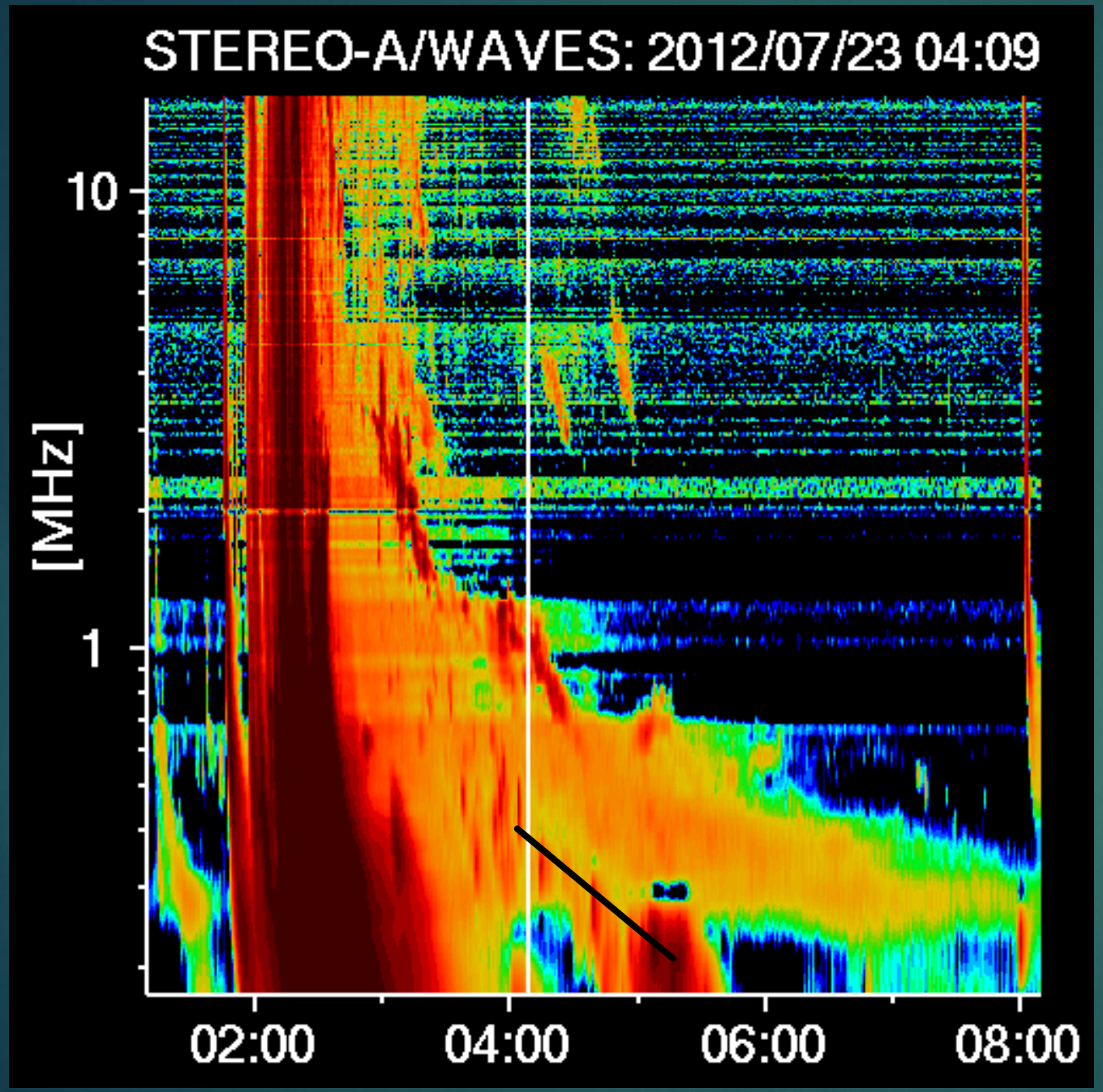


https://cdaw.gsfc.nasa.gov/CME_list/daily_plots/sephtx/2012_07/sephtx_20120723.png

STEREO-A Observed a Huge Type II



Halo CME in STA view: CME heading towards STA.
Intense and broadband type II implies a very band type shock



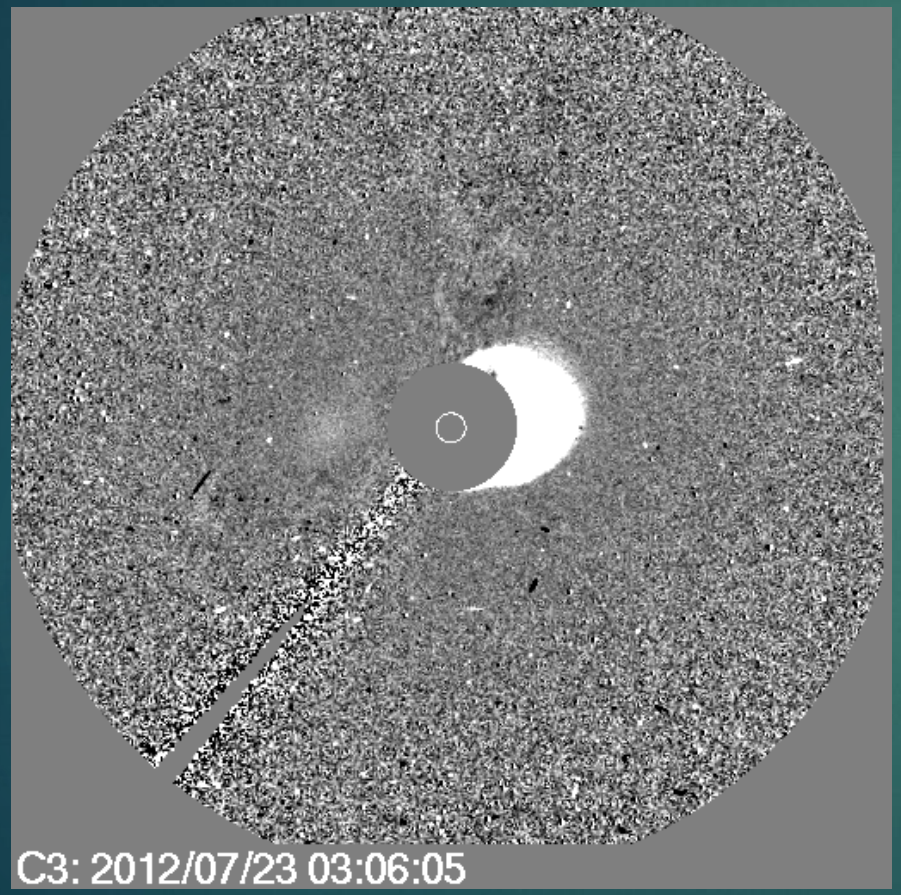
df/dt = 4.4e-5 MHz/s
1/f df/dt = 1.5e-4
(f =0.3 MHz)
V = 2L (1/f) df/dt
L = $|1/n.\ dn/dr|^{-1}$
n = no r^{-a} a ~2 → L = r/a
r = 29 Rs
V = 29Rs*1.5e-4
= 3047 km/s

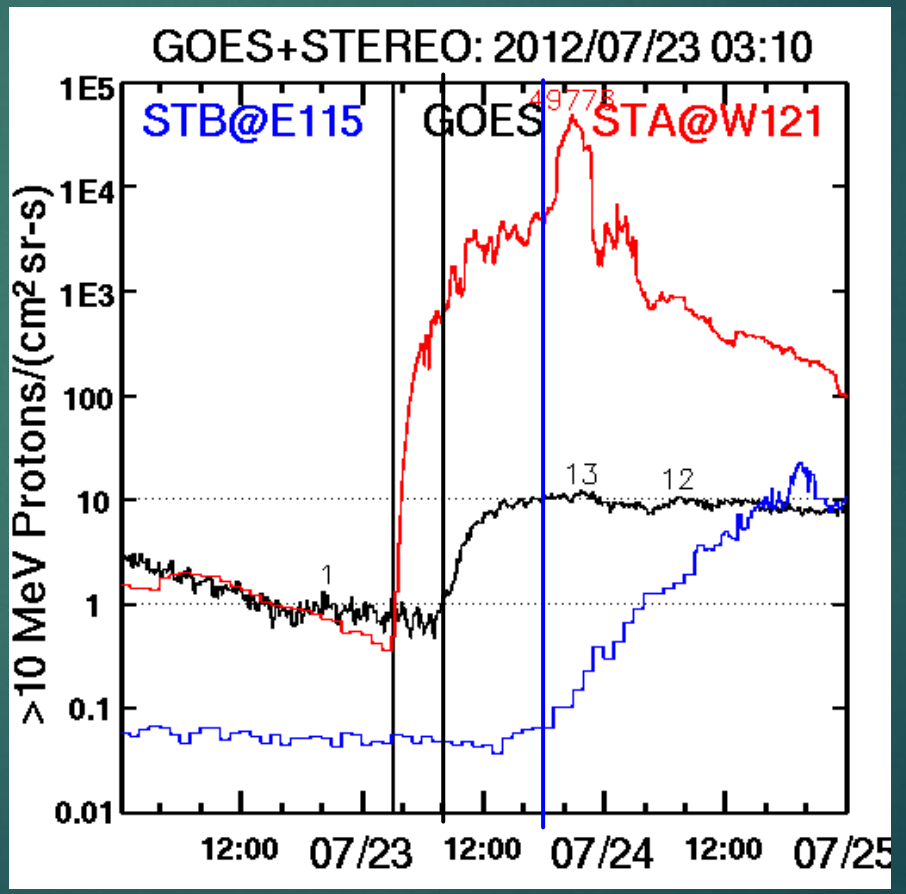
White-light observations from STEREO confirm this speed

Shock arrived at STEREO A S/C in 19h

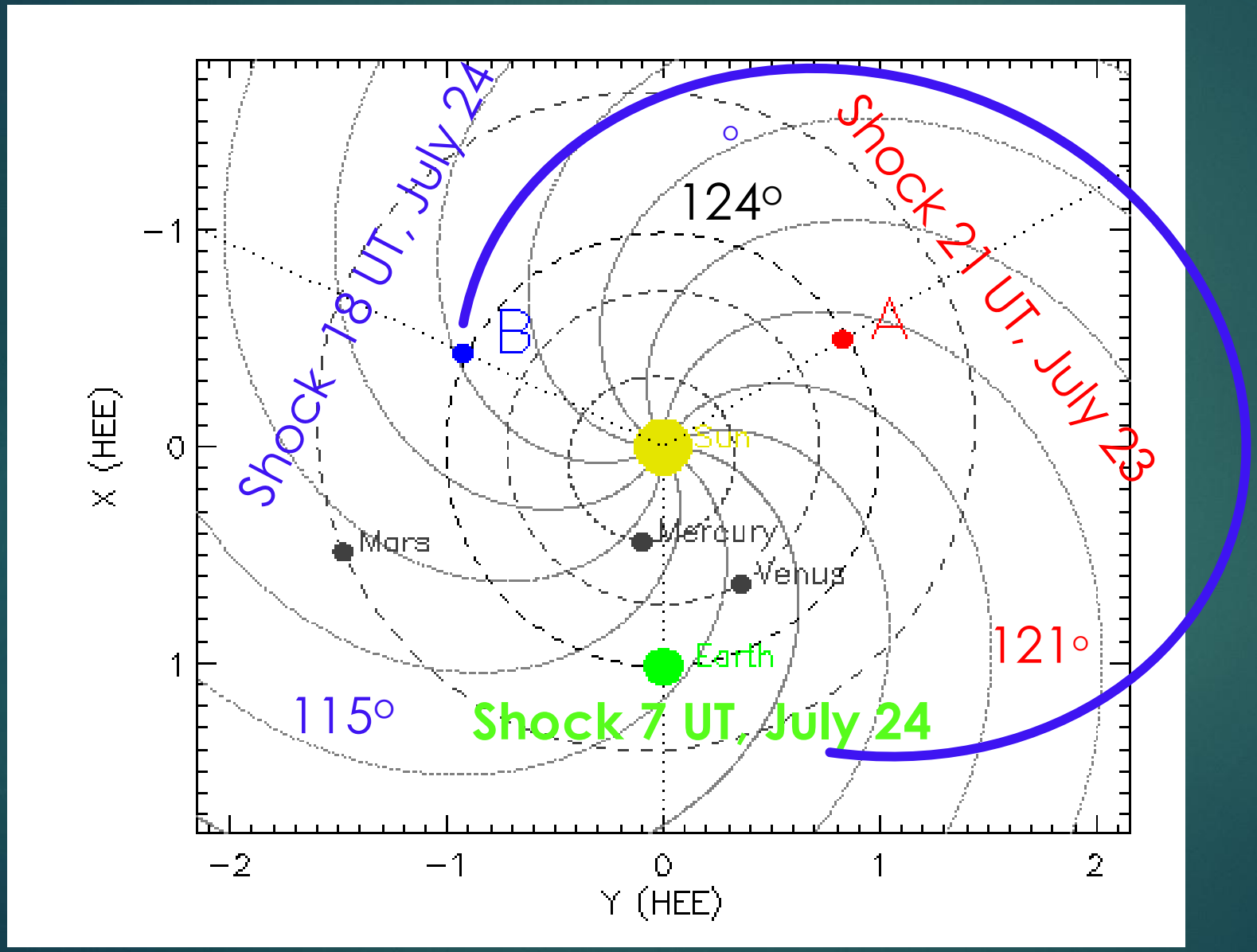
Circumsolar Event

03:06 08:00 18:00





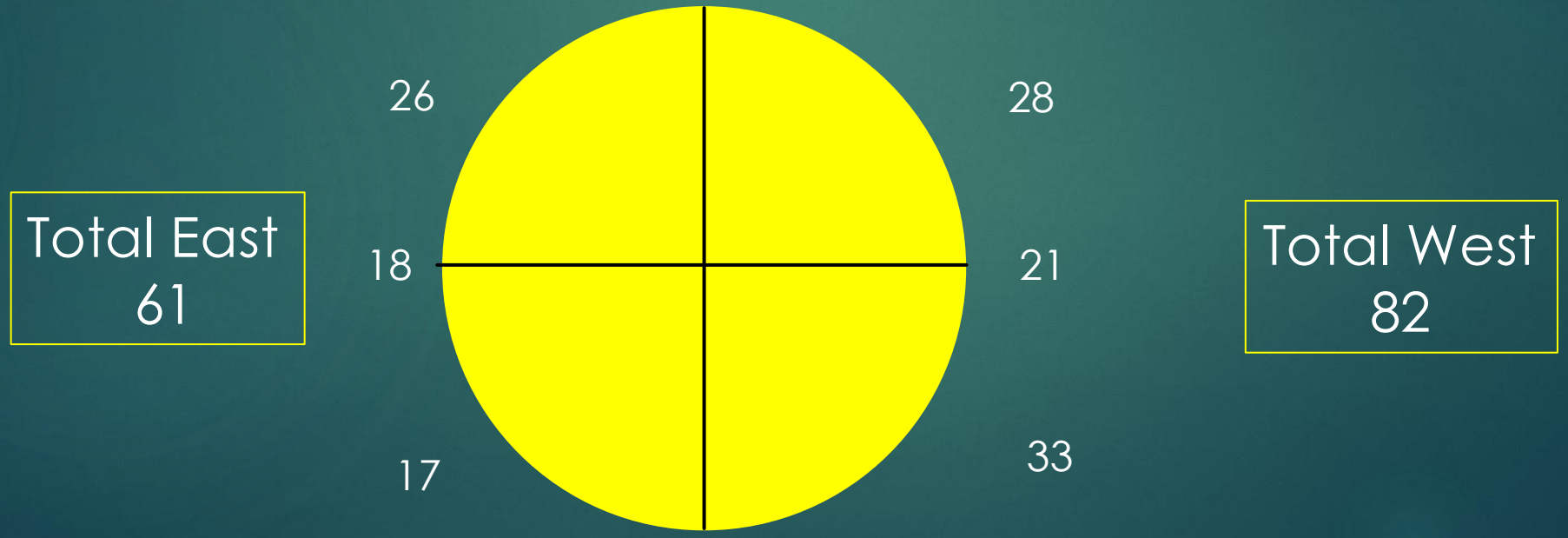
Shock Extends >240°!



SEP Events associated with backside DH Type II bursts

SEP Events & backside Type II bursts: Statistics

- Surveyed backside type II bursts in the decameter-hectometric (DH) wavelength range: https://cdaw.gsfc.nasa.gov/CME_list/radio/waves_type2.html.
- Identified 143 DH type II bursts since 1996 to the end of 2024.



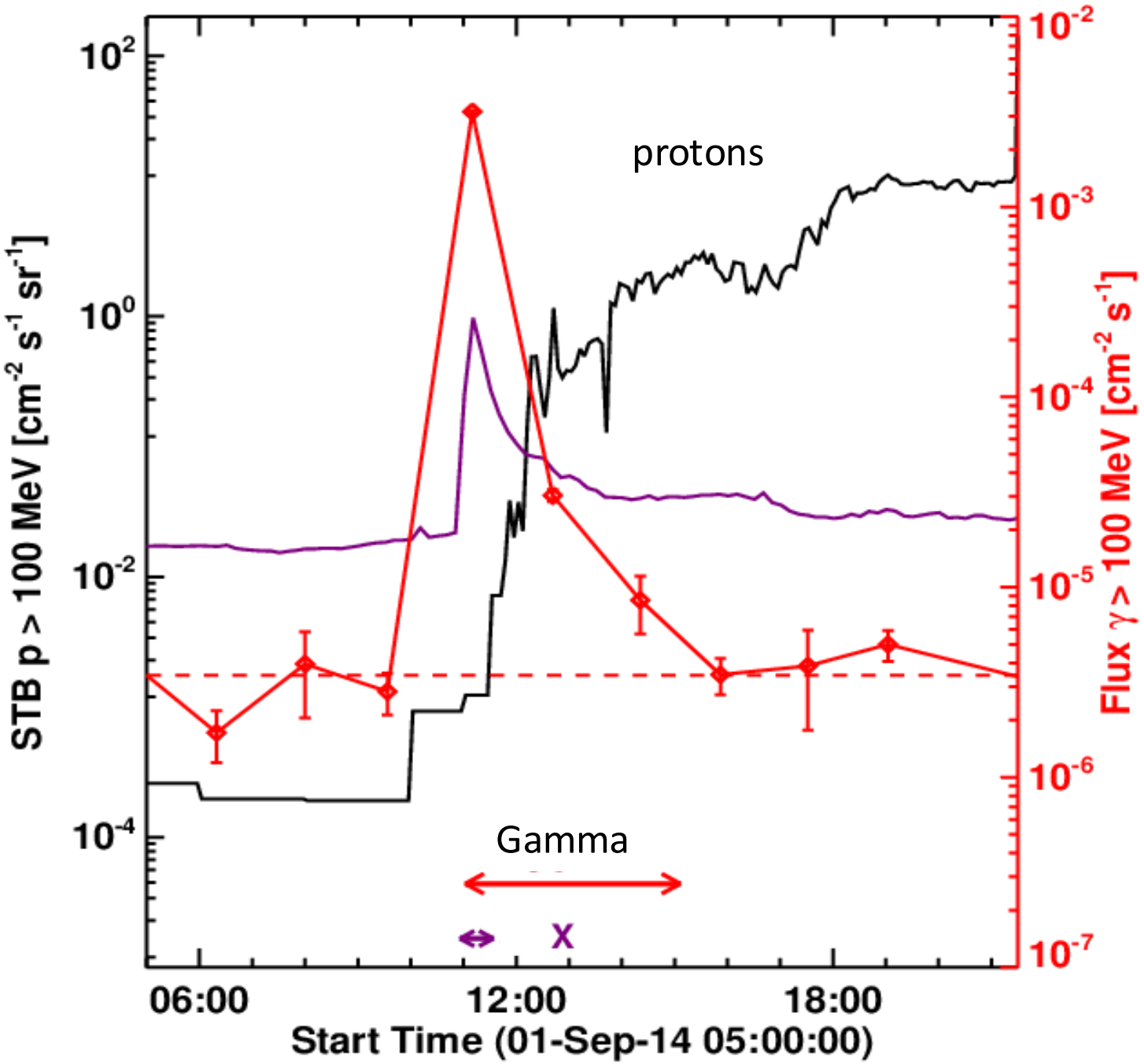
SEP Association of BTL Type II Bursts

Limb Type	No. Events	SEP association	Comments
Fully backside	8	1Y, 3m	SE, NW, SW,SW,NE, SE, SW,SE
N90b	2	None	NE, NE
E90b	18	2Y	
S90b	5	2m	SW, SW, SW,SW,SE
W90b	21	3Y, 3M, 3m	
NE	23	2Y, 2m	
SE	13	None	
NW	27	10Y, 1 M, 4m	
SW	26	11Y, 4 m	
Total West	81	25Y, 4M, 14m	30.9% (Y); 53.0 % (all)
Total East	61	4Y, 0 M, 4m	6.4% (Y); 12.9% (all)
Total	143	29Y, 4M, 18m	62E, 81W

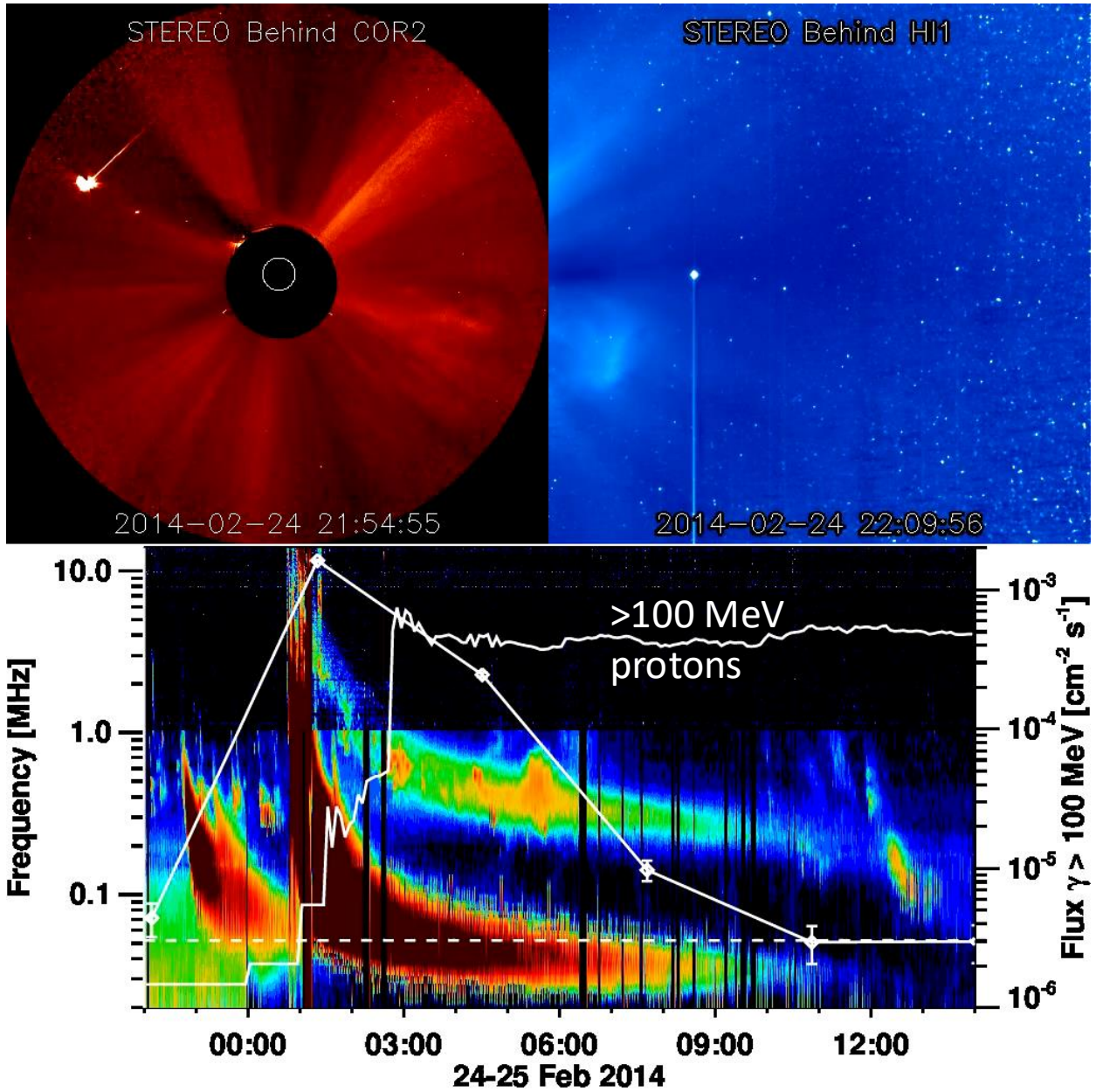
Y – yes, Large SEP (≥ 10 pfu)
M – Minor SEP (1-9 pfu)
m – tiny SEP event (<1 pfu)

Western Backside Events are also important in producing particle impact at Earth

Sustained Gamma-Ray Emission (SGRE) from the Sun & Type II

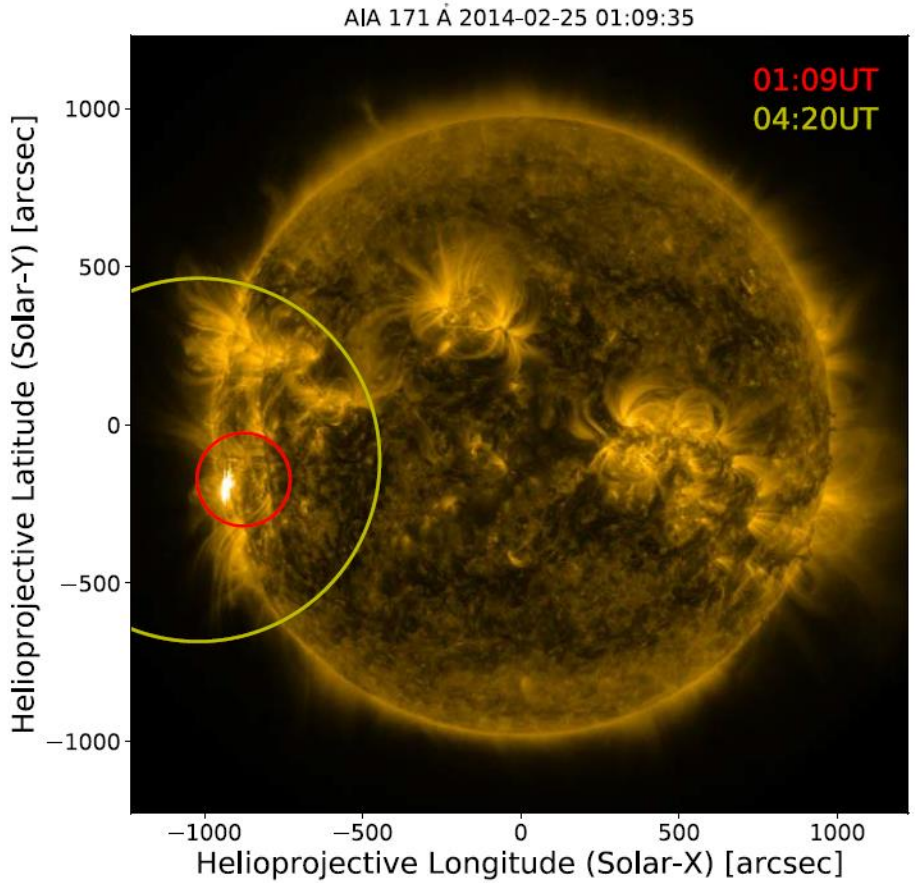


- X-ray flare lasting for about half an hour
- Gamma ray event lasting for about 4 hours
- High energy protons present throughout



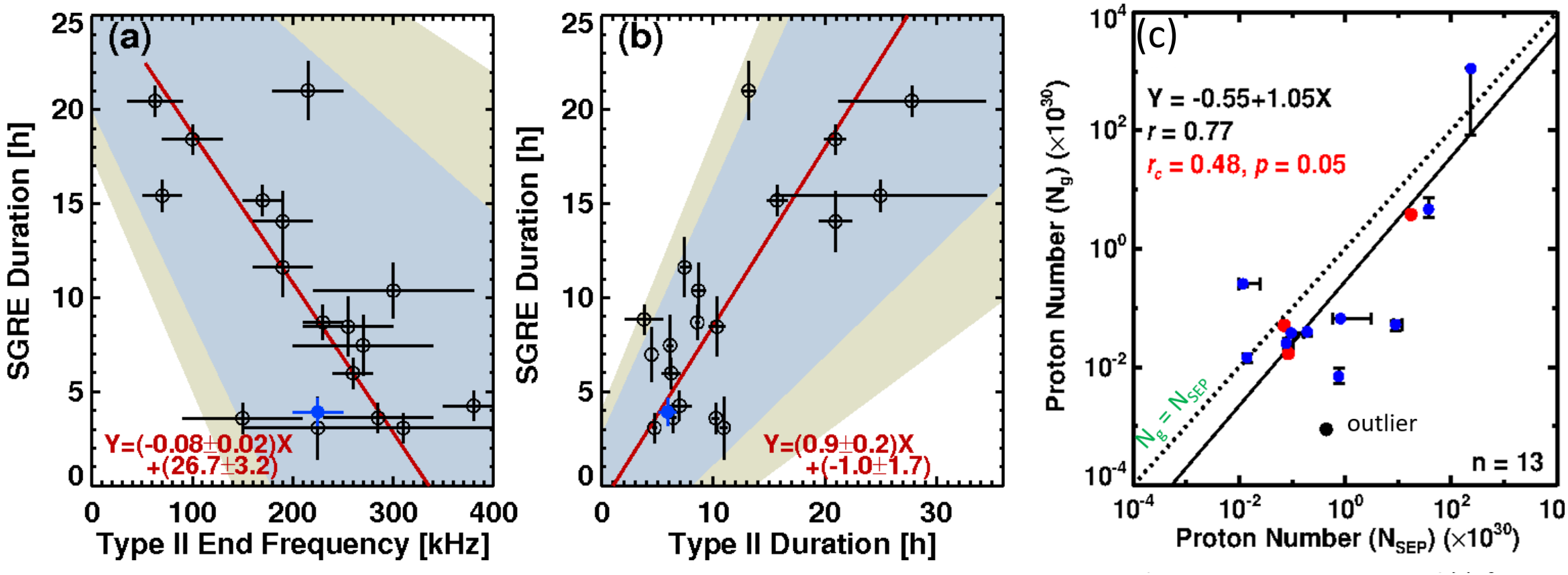
Gopalswamy+ 2018

- SGRE ends when Type II ends
- CME at ~65 Rs when type II & SGRE end
- Large distances also indicated by the ending frequency of type II (~200 kHz)
- Copious >100 MeV particles from STEREO-B



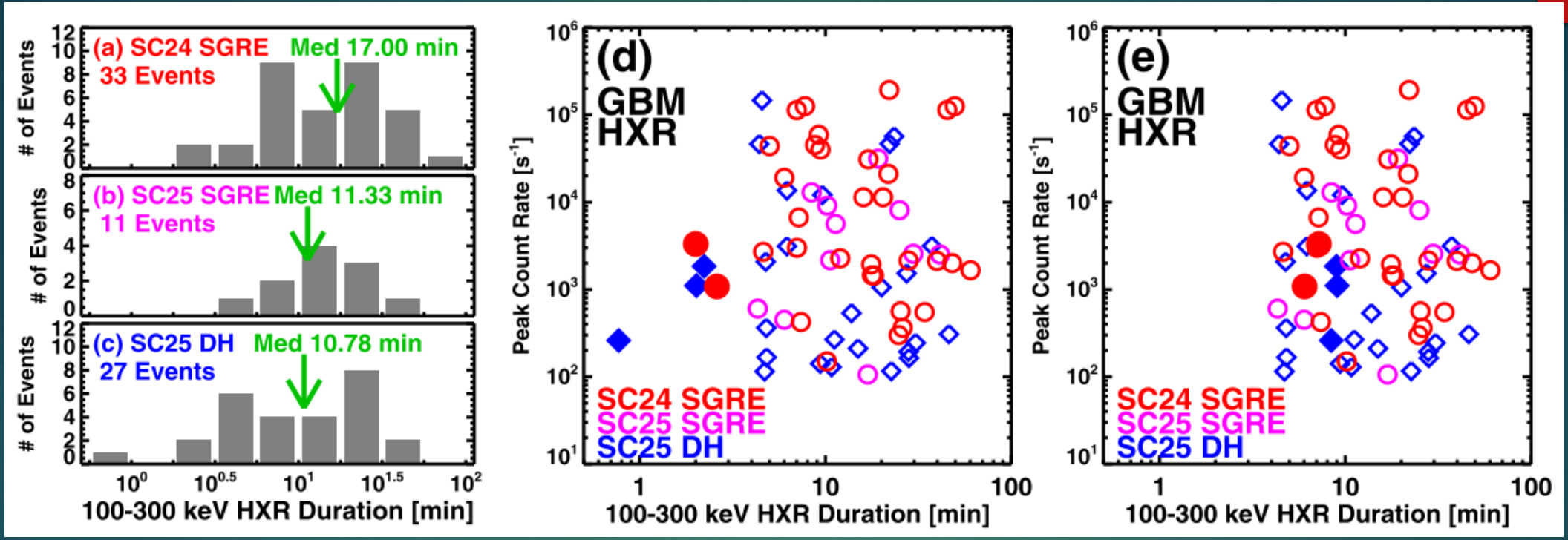
Ajello+ 2021

Type II burst, SEP Event, and SGRE Events linked by CME-driven shocks



Gopalswamy et al. 2018; 2021

Hard X-ray Duration &Energetic Events



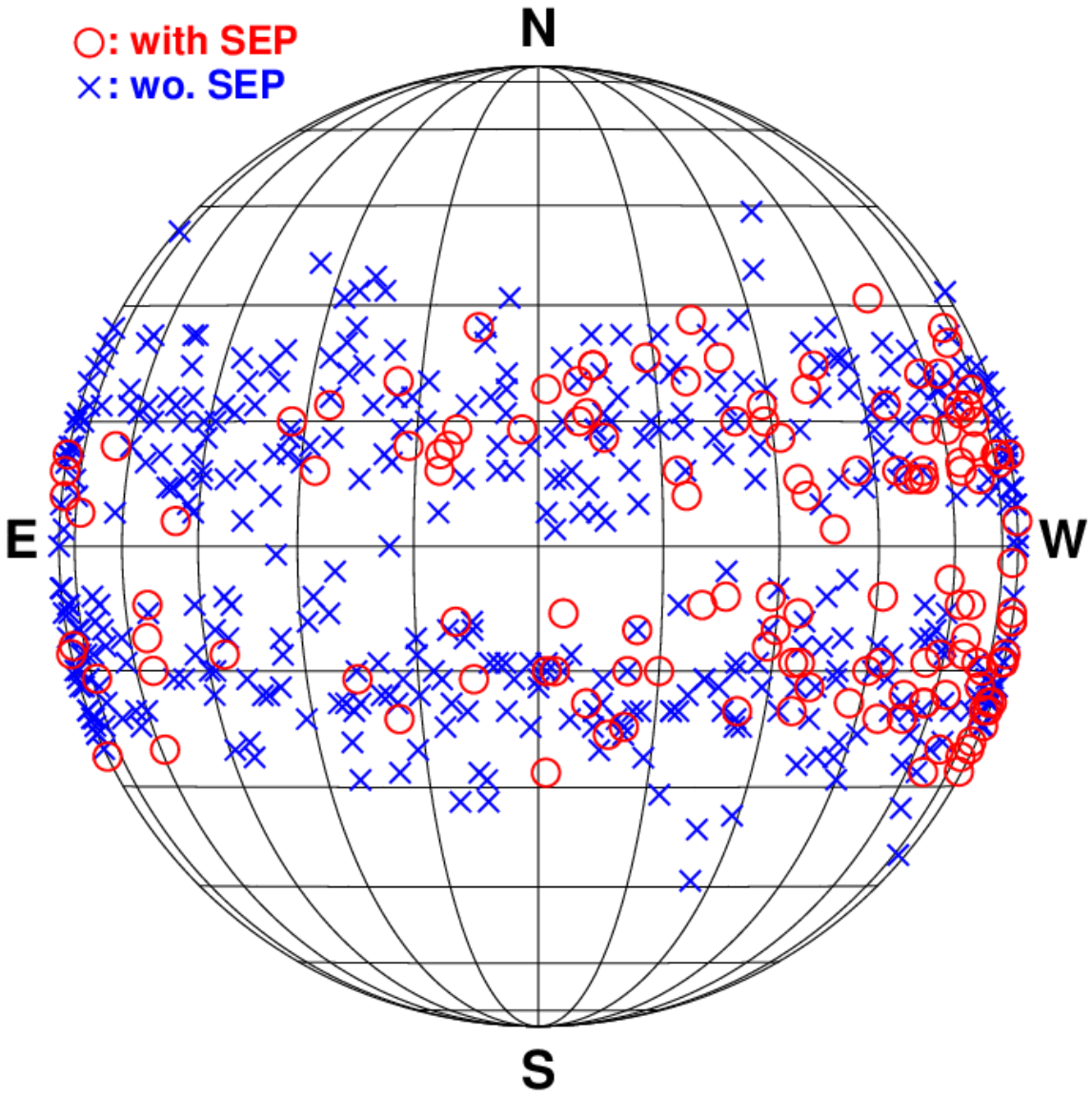
Long duration HXR bursts are known to be associated with SEP events (Kiplinger+ 1995; Garcia 1994); Fast and wide CMEs (Kahler and Ling 2020; Ling and Kahler 2020).
Natural to expect such HXR bursts to be associated with DH type II bursts and SGRE events

>100 keV Hard X-ray Bursts lasts for more than~5 min in DH type II bursts and SGRE events
Mechanism: along with electrons, sub-MeV ions are accelerated in the flare site, which are further accelerated by the associated CME shock (Share+ 2018; Gopalswamy+ 2016; 2026)

Summary

- If a CME originating from the western hemisphere is accompanied by a DH type II burst, there is a high probability that it will produce an SEP event.
- Western backside events are also important in producing particle impact at Earth (25/82 or 31% association)
- Only occasionally do Eastern backside events have SEP association at Earth (4/61 or 6.4%)
- Sustained gamma-ray emissions are indicative of >300 MeV protons accelerated by CME shocks and hence have close relation to interplanetary type II bursts

Abstract


○: with SEP
×: wo. SEP
N
E
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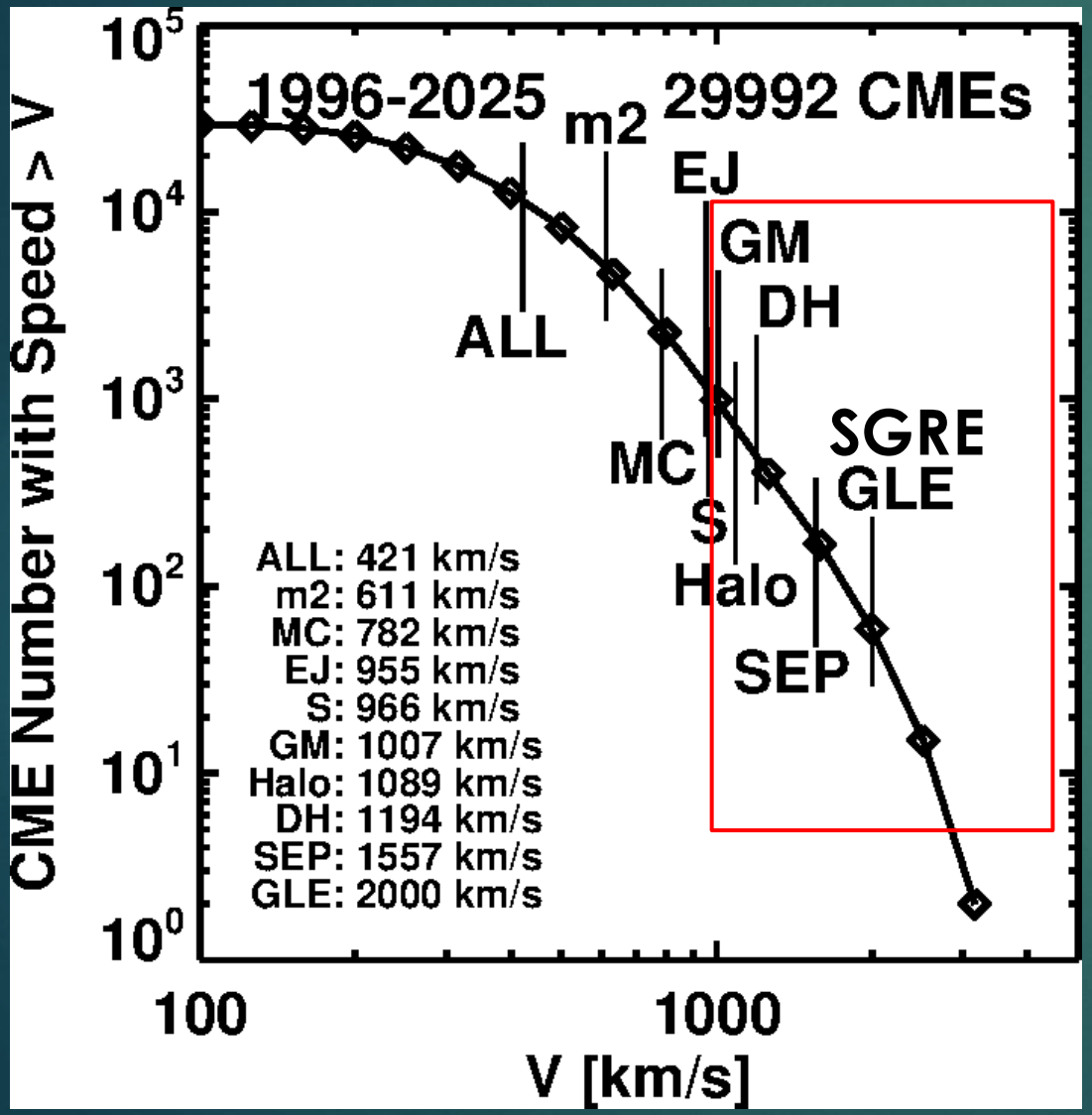
Energetic Phenomena & CME Speed



CMEs with speeds ≥800 km/s cause most energetic phenomena:

Geomagnetic storms, DH type II bursts, large SEP events, sustained gamma-ray emission (SGRE), and ground level enhancement (GLE) in SEP events.

Updated from Gopalswamy 2018