Current Trends in the Study of Solar Energetic Particle Events

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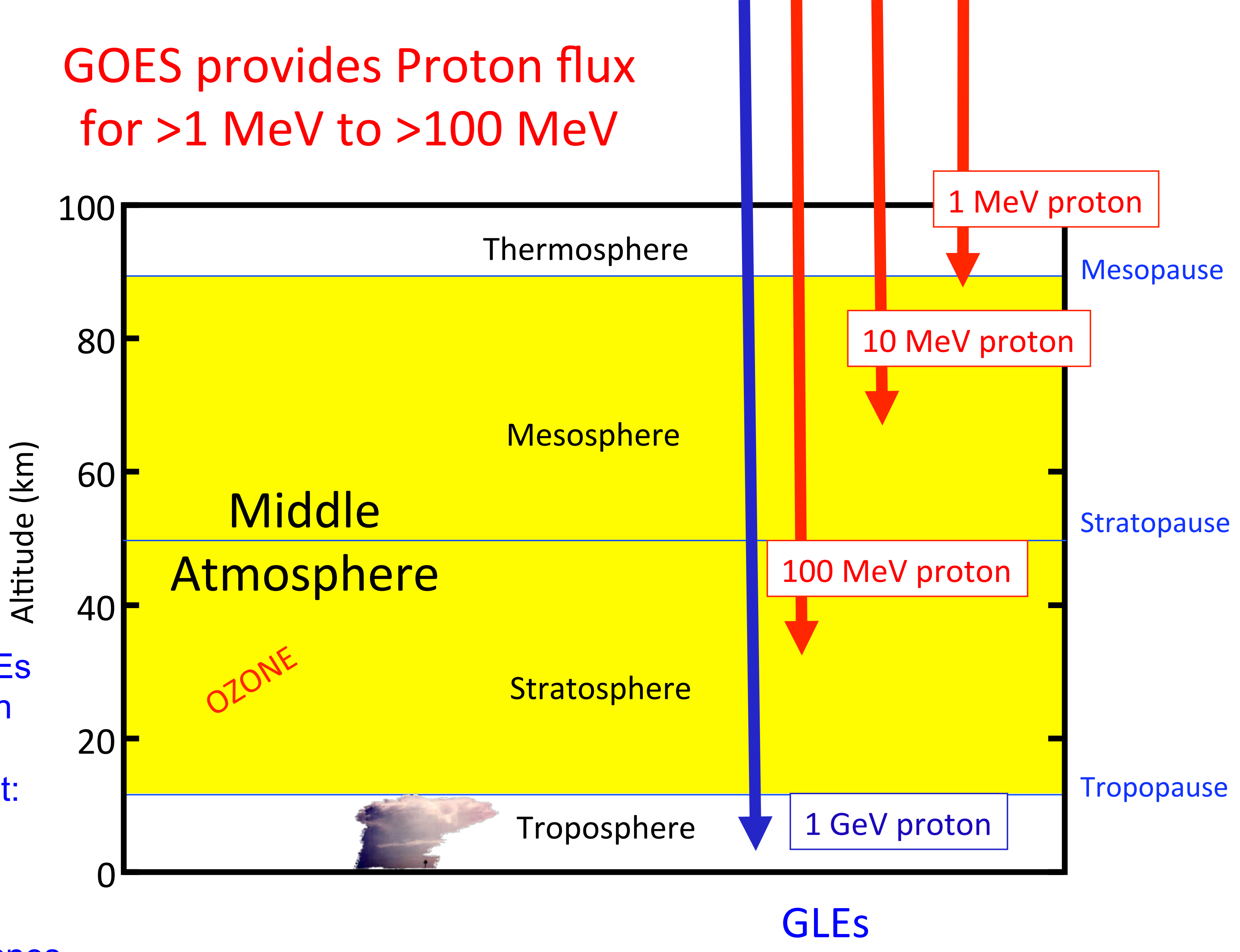
SEPs: Science &Applications

One if the important Earth-affecting Transients

- Source of SEPs: Flares & CMEs
- Physics of particle energization
- Direct impact on IP spacecraft
- SEPs trapped in Radiation Belt: Impact on satellites
- Impact on Atmosphere: Ozone depletion and Direct impact on humans in airplanes

GOES provides Proton flux for >1 MeV to >100 MeV



courtesy: C. Jackman

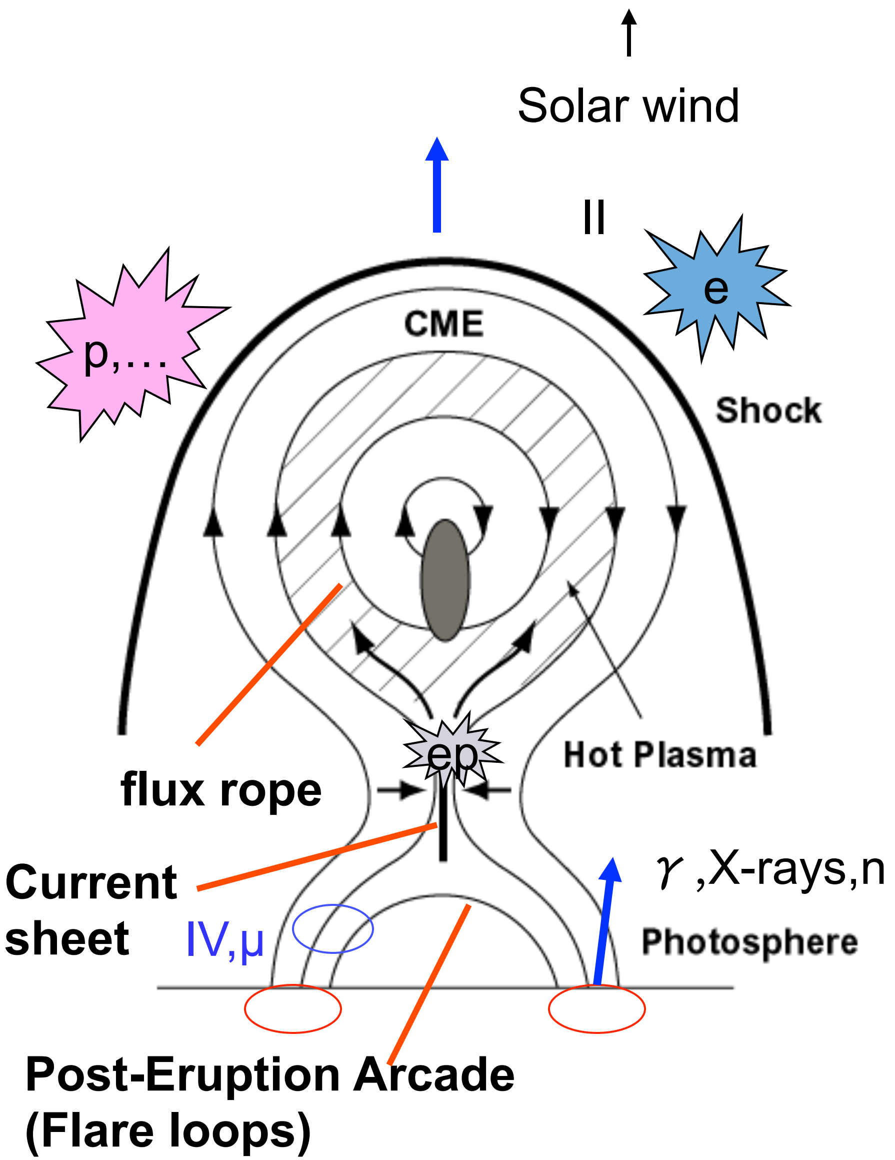
Two Processes for Particle Acceleration

Flare Reconnection
Shock

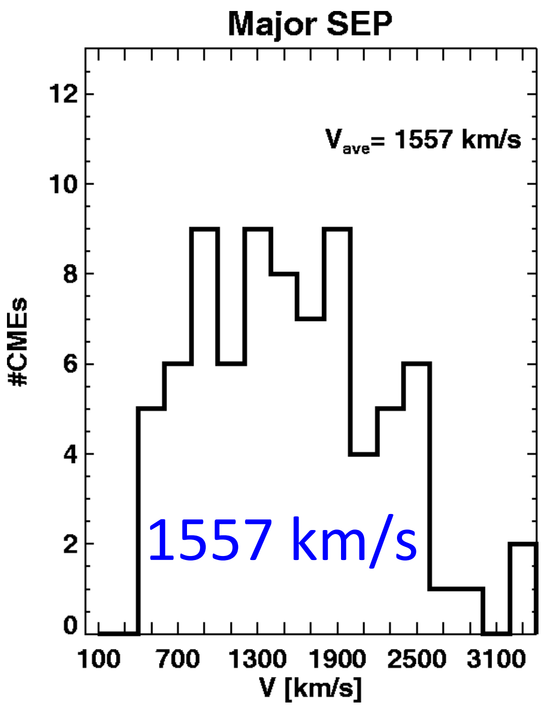
Shock: large SEP events
CME a must

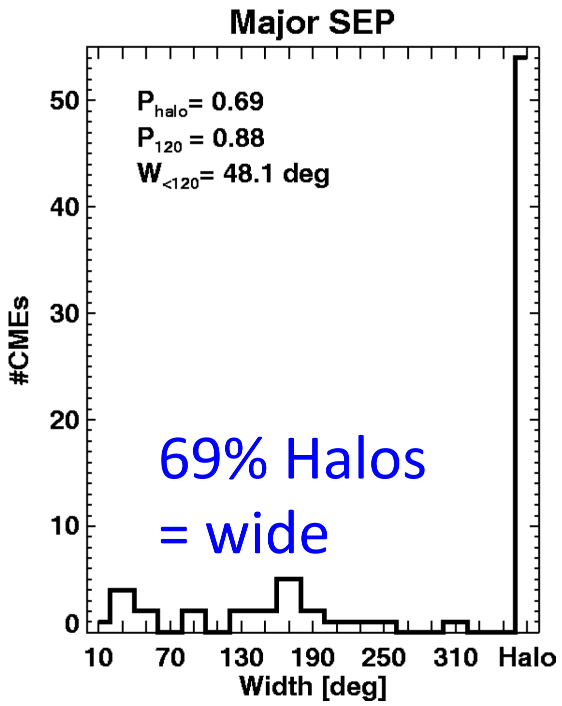
Flare: impulsive SEP events,
Much smaller, high charge states
CME may or may not accompany

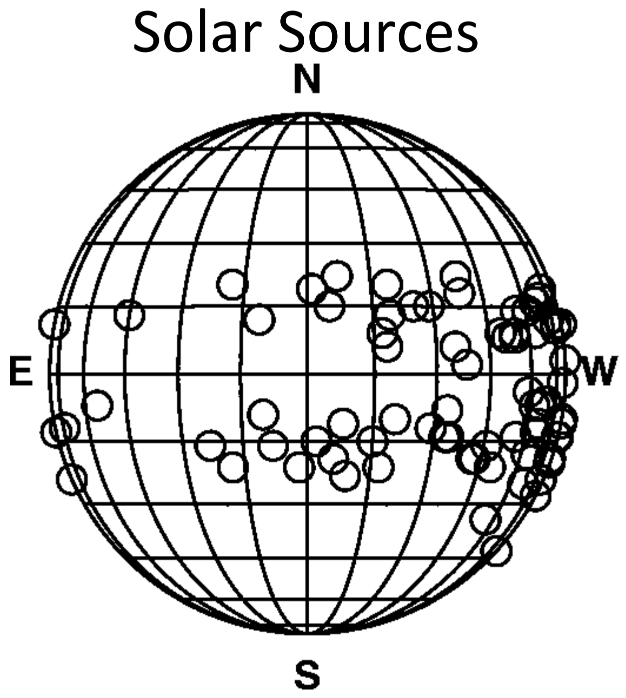
The relative contribution from
Flare & CME in a given event
under debate



Characteristics of SEP-associated CMEs







Sources need to be on the western hemisphere

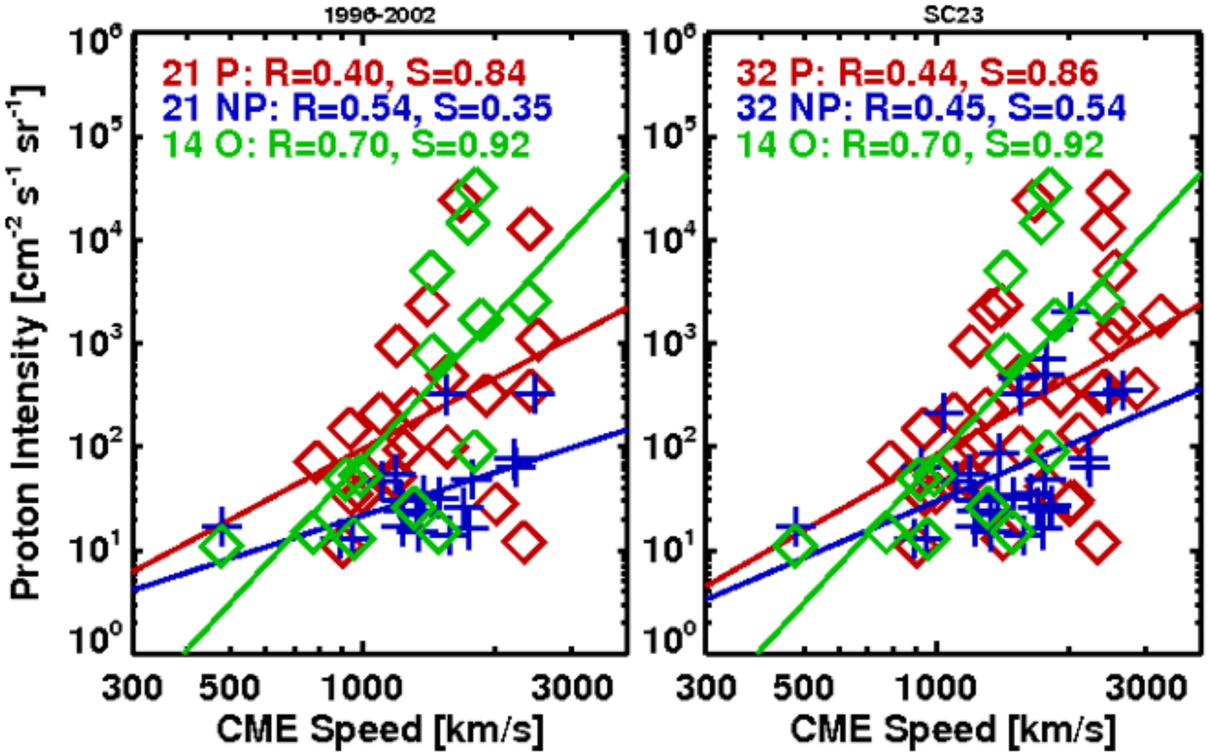
Strong shock & Good magnetic connectivity required

SEP Paradigm

CME – SEP Intensity Correlation

- Needs to be good because SEPs are caused by CME-driven shocks
- Strong shocks when the CME is fast
- For a given CME speed the SEP intensity can vary over 3 orders of magnitude → weak correlation
- But the environment (density, Alfven speed) can make a fast CME drive a weak shock and a slow CME drive a fast shock depending on the ambient Alfven speed
- Preceding CME is another environmental factor modifying the shock strength, seed particles

CME – SEP Intensity Correlation



1996-2002
Gopalswamy et al. 2004

1996-2007

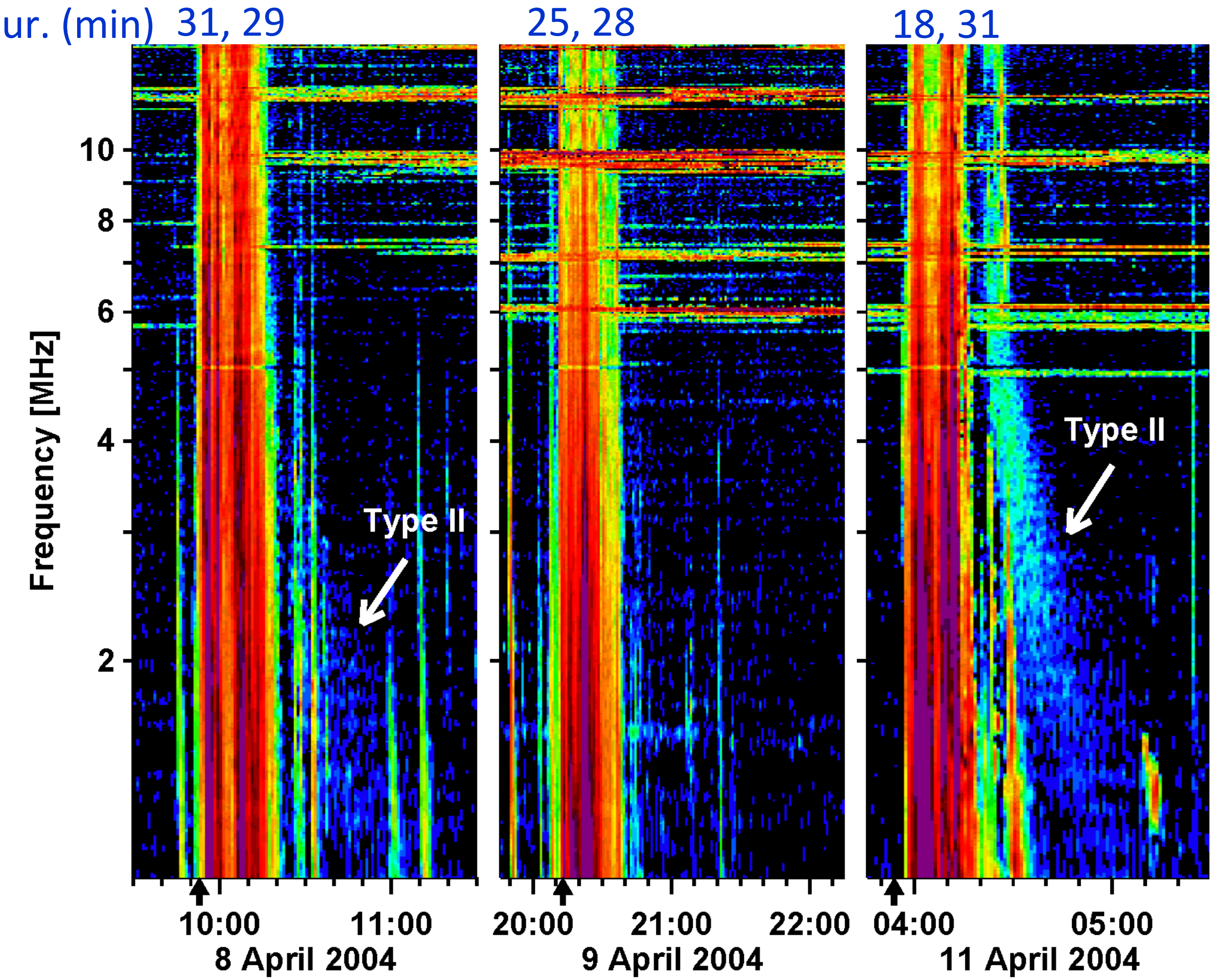
- P events: The primary CMEs are preceded by at least one wide CME (W ≥ 60^o) launched from the same source region within 24 hours ahead of the onset time of the primary CMEs.
- O events:
  - Possible CME-CME interaction within the occulting disk
  - CME-Streamer interaction
  - Halo CME-Halo CME interaction launched from the nearby (not same) source region.
- NP events: "No Preceding" CME events
- All high-intensity events in SC 24 have CME interaction

Scatter reduced when NP, P+O considered separately → preconditioning is a factor in causing the scatter

Type II / Type III Bursts and SEP Events

- Type III bursts lasting for ≥ 20 min seem to be linked to SEP events (Cane et al. 2002; MacDowall et al., 2003; 2009) : Flare origin for SEPs?

- The presence of a complex long-duration, low-frequency type III burst is not a sufficient condition for SEPs (Gopalswamy & Mäkelä, 2010, 2011)
- SEP events with only type III bursts may be impulsive events? (Miteva et al 2013; Kouloumvokos et al. 2015)



The middle one lacked type II and SEP event

Gopalswamy & Mäkelä, 2010

Solar Flares, CMEs, and SEP Events

Solar Flares, CMEs, and SEP Events

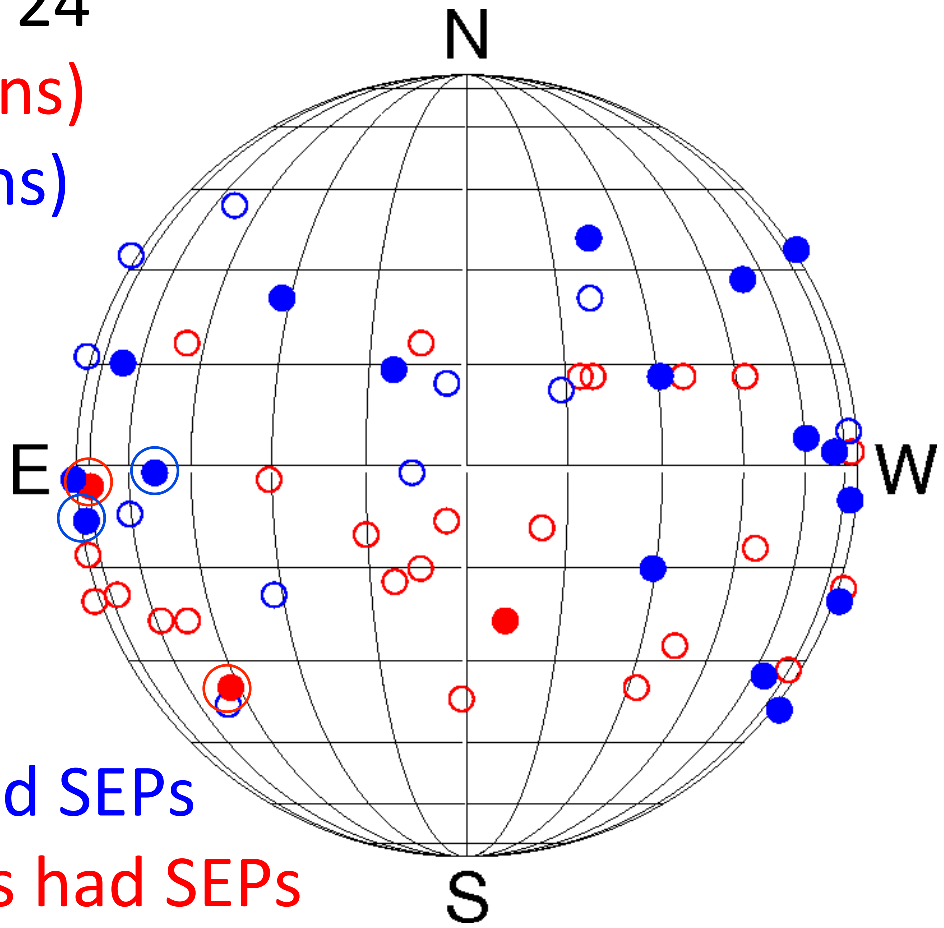
55 Eruptions (≥M5) in SC 24

<1500 km/s (27 eruptions)

≥ 1500 km/s (28 eruptions)

With large SEP Events

≥10 pfu in >10 MeV channel



Slower CMEs with SEPs
1384 km/s
837 km/s
1415 km/s

Large-SEP association

17/28 - 61% fast CMEs had SEPs

3/27 - 11% of slower ones had SEPs

4 STEREO-B SEP events included

CME speed is important for SEP association

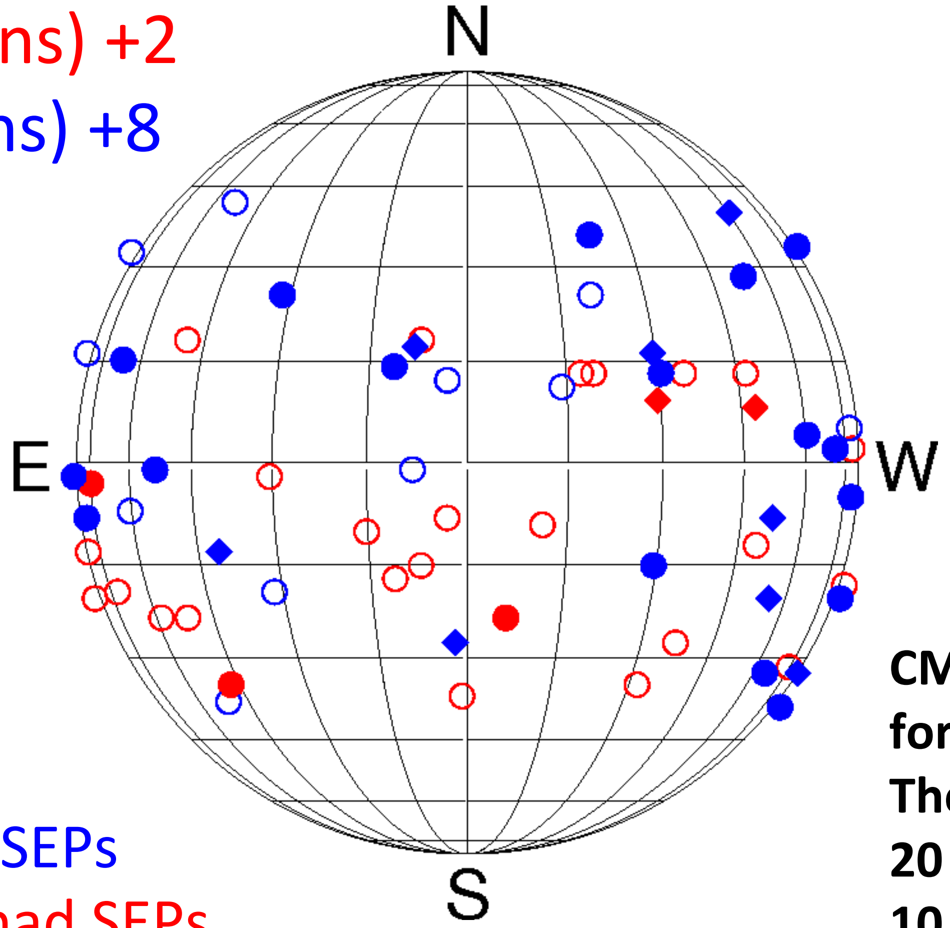
But there are SEP events from <M5.0 eruptions!

<1500 km/s (27 eruptions) +2

≥ 1500 km/s (28 eruptions) +8

CMEs with ≥M5 flares and SEP events

CMEs with <M5 flares and SEP events



Slower CMEs with SEPs
1384 km/s
837 km/s
1415 km/s
1187 km/s
1479 km/s

] <M5 flares

25/36 - 69% fast CMEs had SEPs

5/29 - 17% of slower ones had SEPs

(slowest: 837 km/s – space speeds)

CME speed is important for SEP association, but The flare size is not:

20 SEP events with ≥M5 flares

10 SEP events with <M5 flares (6 C-class flares)

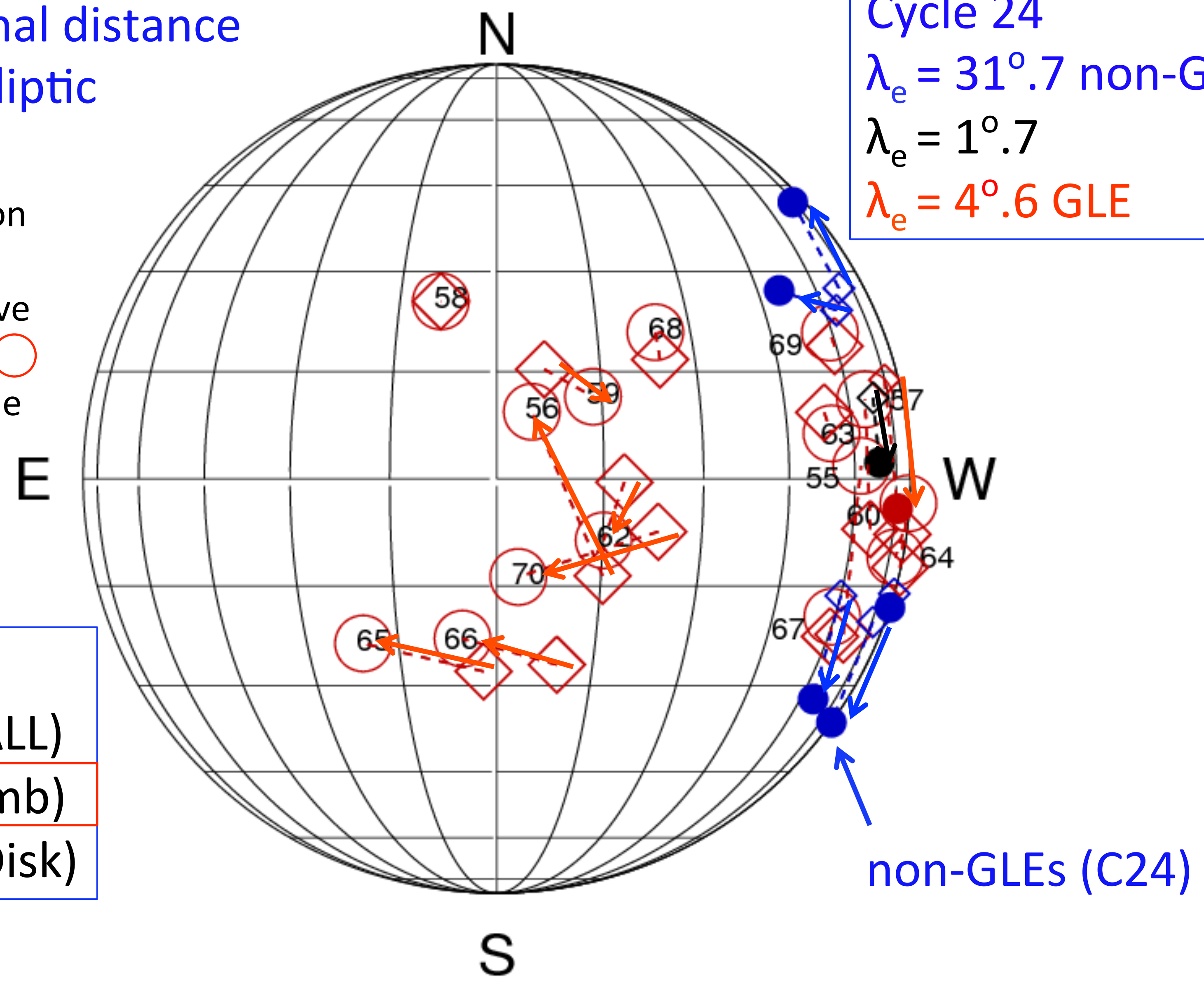
GLEs in SEPs

- Latitudinal Connectivity
- CME speed
- Ambient conditions
- Height of shock formation

GLEs and CMEs: Latitudinal Connectivity

λ_e = latitudinal distance from the ecliptic

Non-radial motion and the B0 angle make the effective source location ◯ different from the flare location ◇



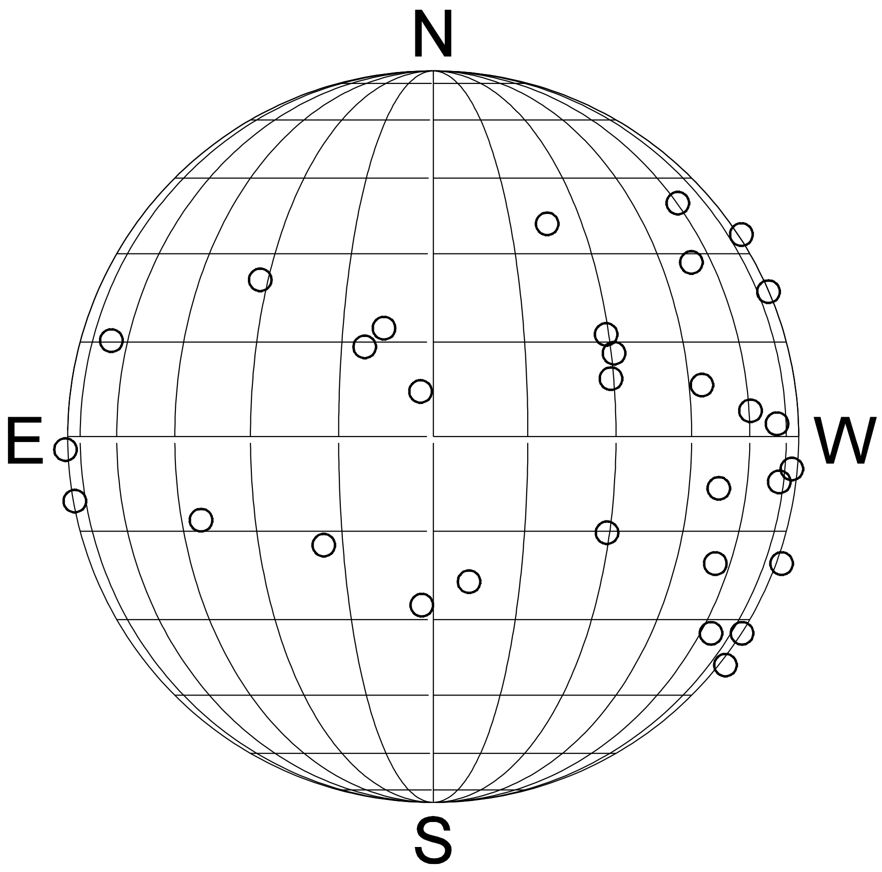
Cycle 24
$\lambda_e = 31^o.7$ non-GLE
$\lambda_e = 1^o.7$
$\lambda_e = 4^o.6$ GLE

Cycle 23
$\lambda_e = 13^o.1$ (ALL)
$\lambda_e = 9^o.3$ (Limb)
$\lambda_e = 15^o.4$ (Disk)

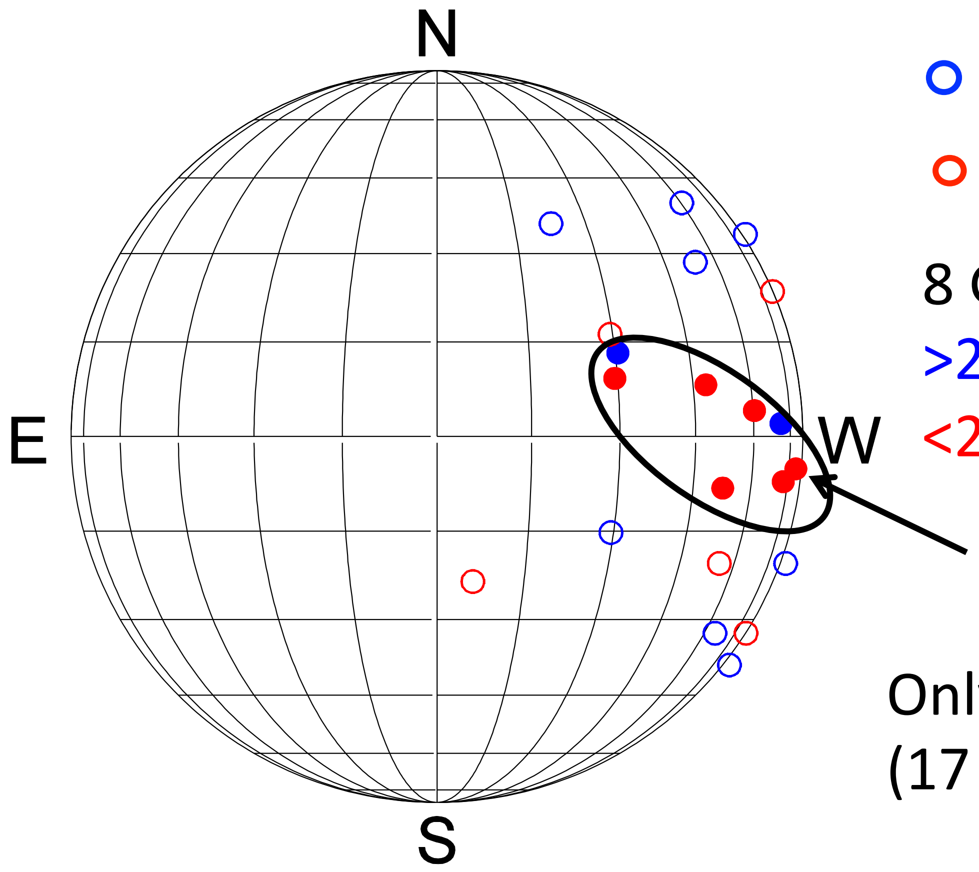
GLE Candidates

13 events had ecliptic distance >13°
8/13 or 62% had V >2000 km/s
5/13 or 38% had V <2000 km/s

Flux rope locations, corrected for B0 angle



Start with 31 Front-side SEP events in cycle 24



≥ 2000 km/s
< 2000 km/s

8 GLE Candidates
>2000 km/s: 2
<2000 km/s: 6

Only one was a GLE
(17 May 2012)

Consider 21 Western events; select events with ecliptic distance <13° as GLE candidates

Gopalswamy et al. 2015

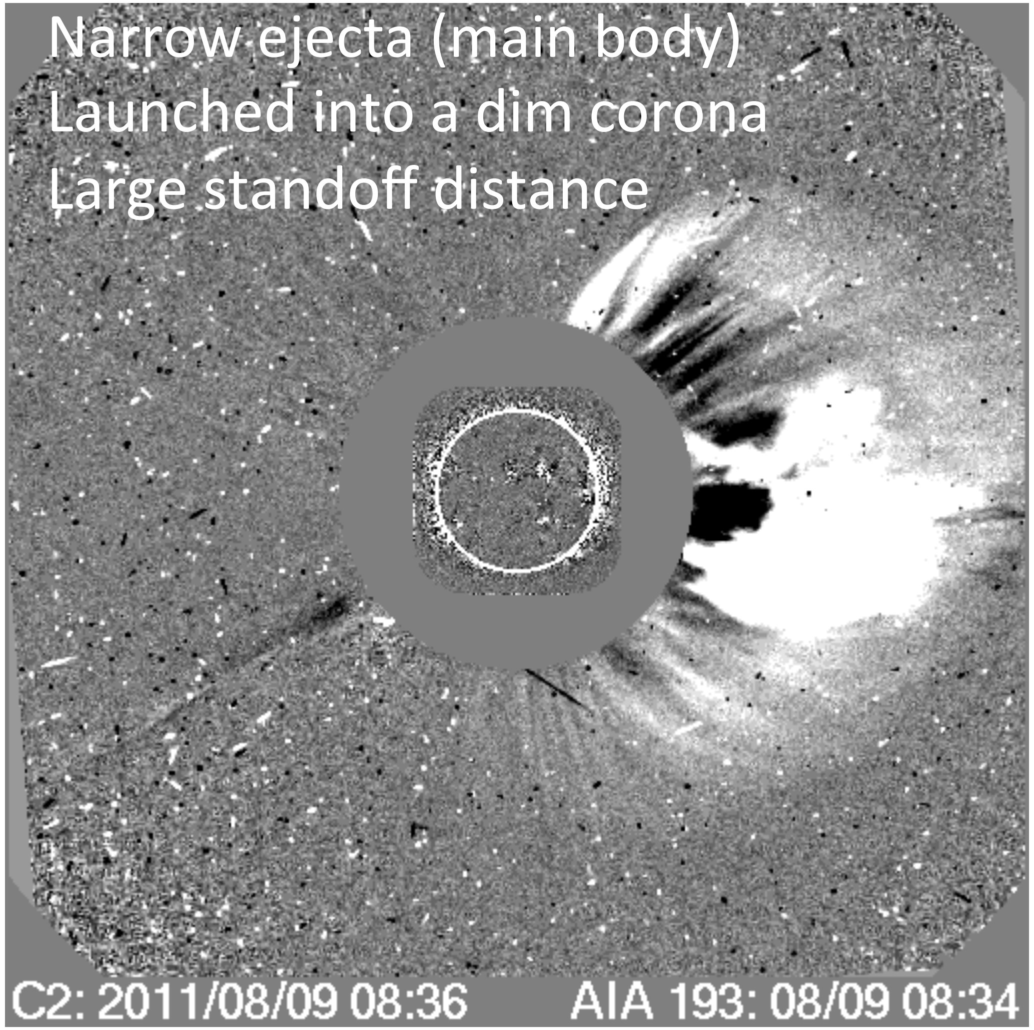
The 8 GLE Candidates: Only One GLE Event

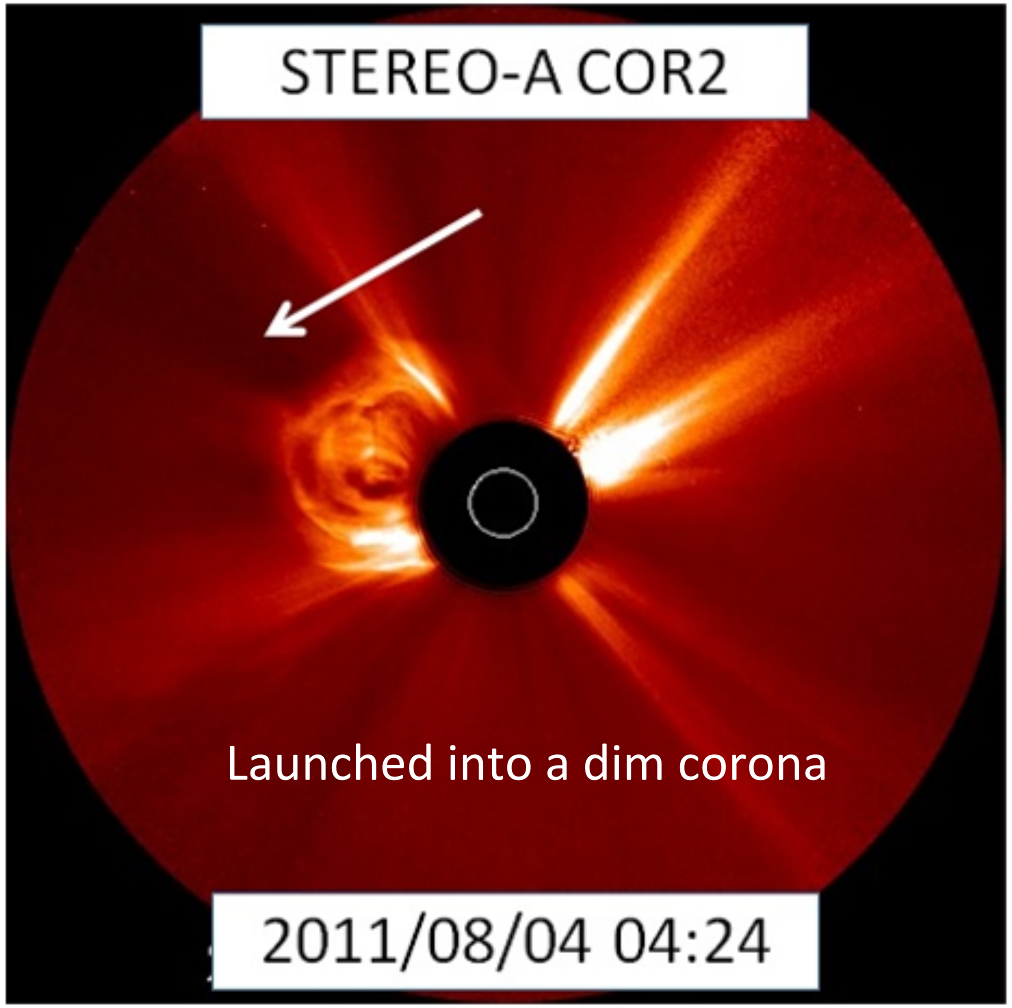
Table 2. List of candidate GLE events

#	CME Date UT	Imp.	Flr Loc.	FR Loc	B0	Final Loc	Vsp	Max E	Ip	
4	2011/06/07 06:16	M2.5	S21W54	S08W51	+0.1	S08W51	1680	330-420	72	
5	2011/08/04 03:41	M9.3	N19W36	N19W30	+6.0	N13W30	2450	165-500	96	
6	2011/08/09 07:48	X6.9	N17W69	N08W68	+6.3	N02W68	2496	330-420	26	
8	2011/11/26 06:09	C1.2	N08W49	N10W47	+1.5	N08W47	1187	40-80	80	
13	2012/05/17 01:25	M5.1	N11W76	S07W76	-2.4	S05W76	1997	>700	255	GLE
23	2012/09/27 23:24	C3.7	N06W34	N16W29	+6.9	N09W29	1479	80-165	28	
27	2013/05/22 13:08	M5.0	N15W70	N02W59	-1.8	N04W59	1881	330-420	1660	
33	2014/02/20 07:26	M3.0	S15W73	S14W70	-7.0	S07W70	1281	330-420	22	

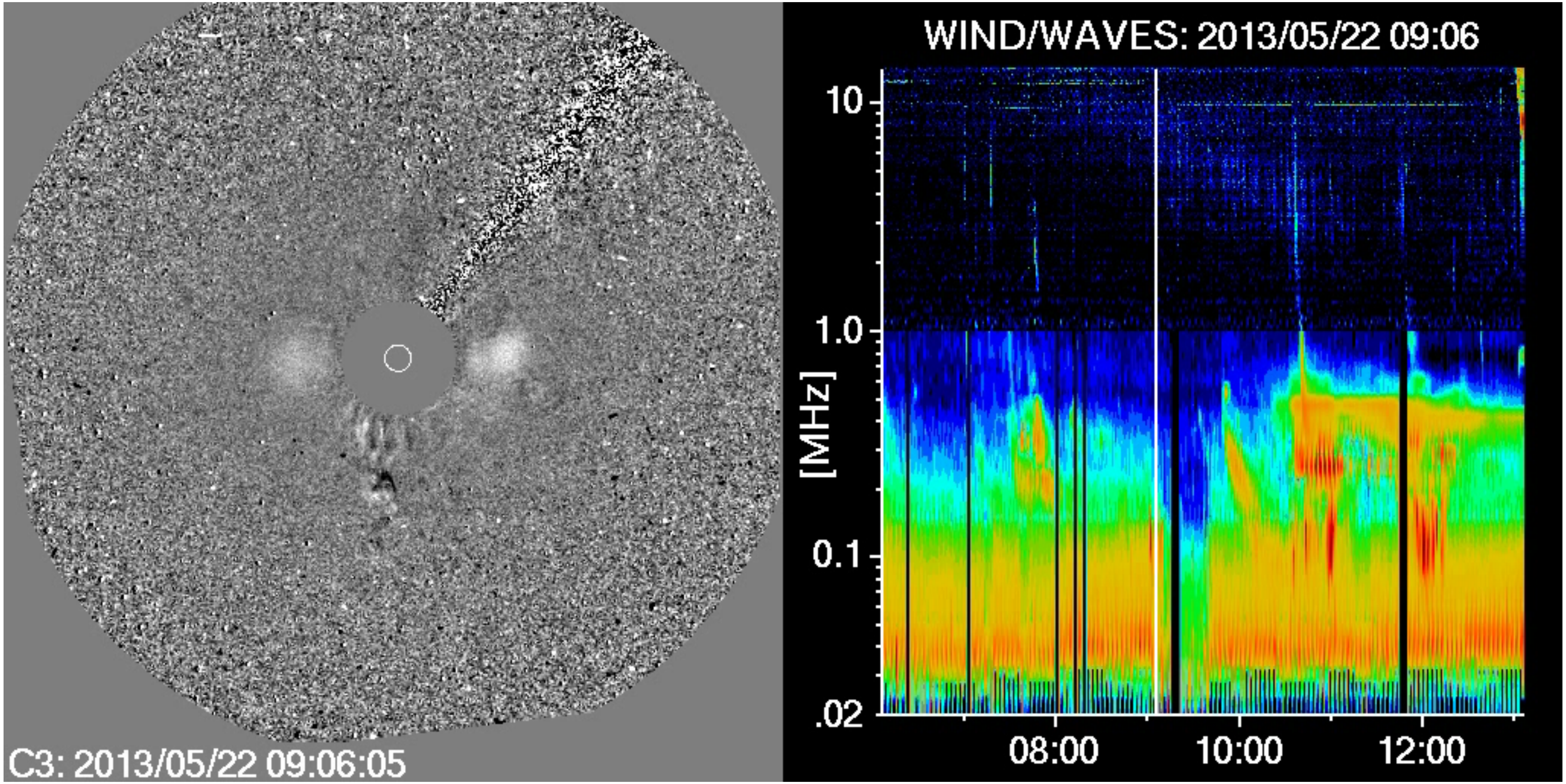
- #13 is the 2012 May 17 GLE
- ## 4, 8, 23, 33 have speeds well below typical GLE CME speeds
- #27 Cannibalism event, but the interaction is at >20 Rs; Peak speed attained at >7 Rs
- ## 5, 6 Ambient conditions not favorable

The two fastest events (~2500 km/s; no GLE)





CME Interaction beyond 20 Rs



Radio direction finding points the radio source to the interaction region

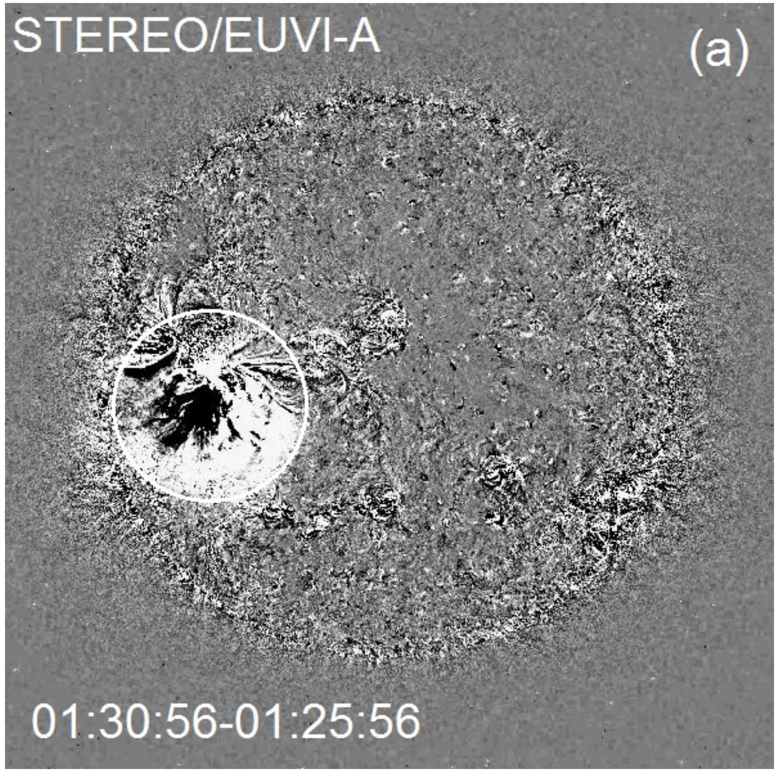
SEPs in FE CMEs

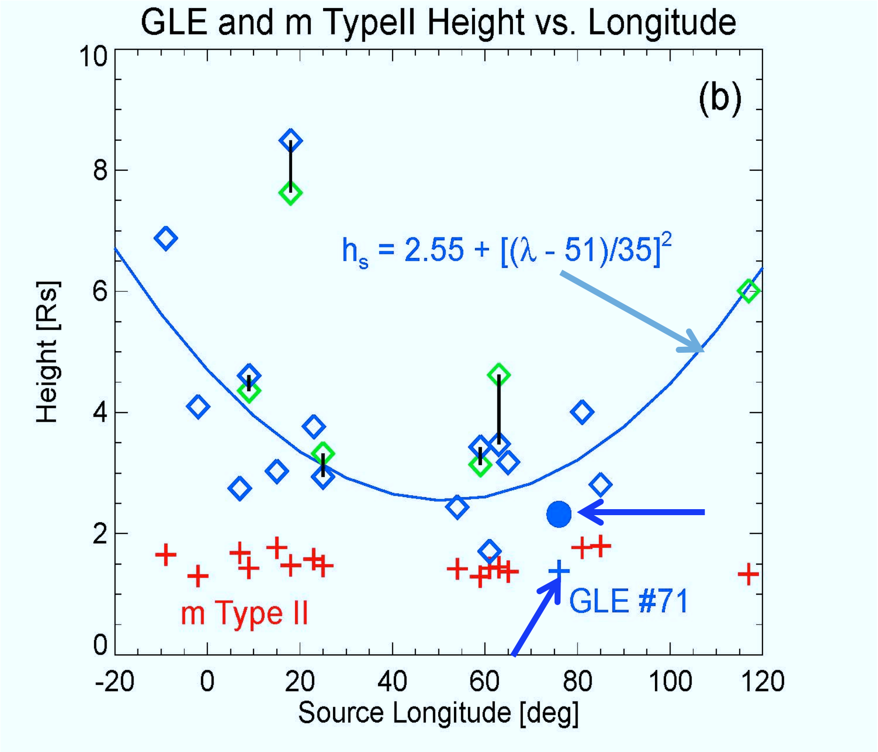
- Large shock formation heights
- Soft spectrum (10-100 MeV range)
- Examples of pure shock acceleration
- GLE and FE-SEP events are at opposite ends of acceleration and spectral index values (see FE – SEP paper in ApJ)
- Maximum energy of accelerated particles seem to be inversely proportional to the shock formation height

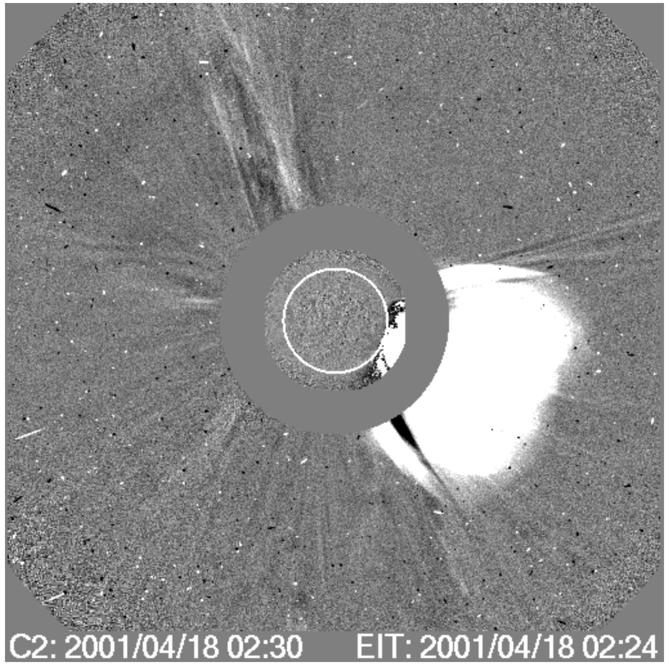
Shock & CME height at GLE Particle Release

The 2012 May 17 GLE is consistent with the particle release height as a function of longitude

◇ With minimal extrapolation





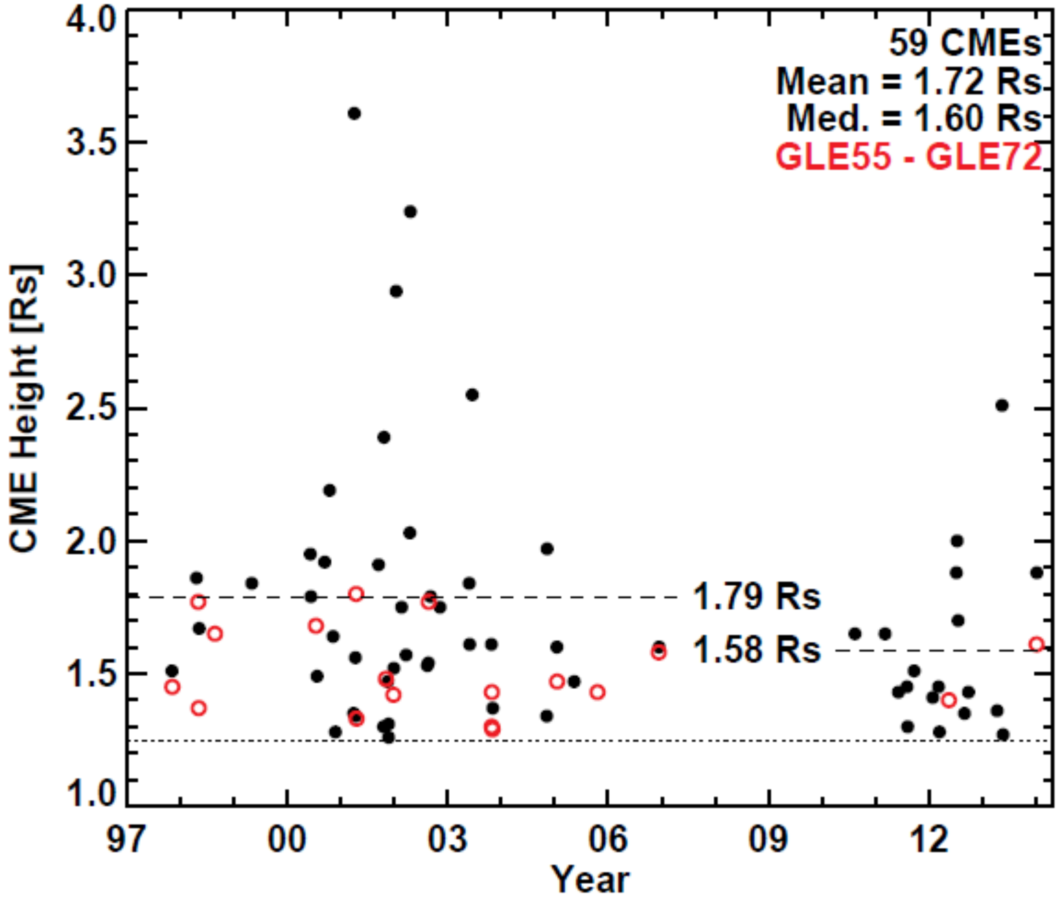


Height of shock formation from wave radius at the time of type II radio burst

Reames, 2009; Gopalswamy et al. 2012

Shock-formation Height

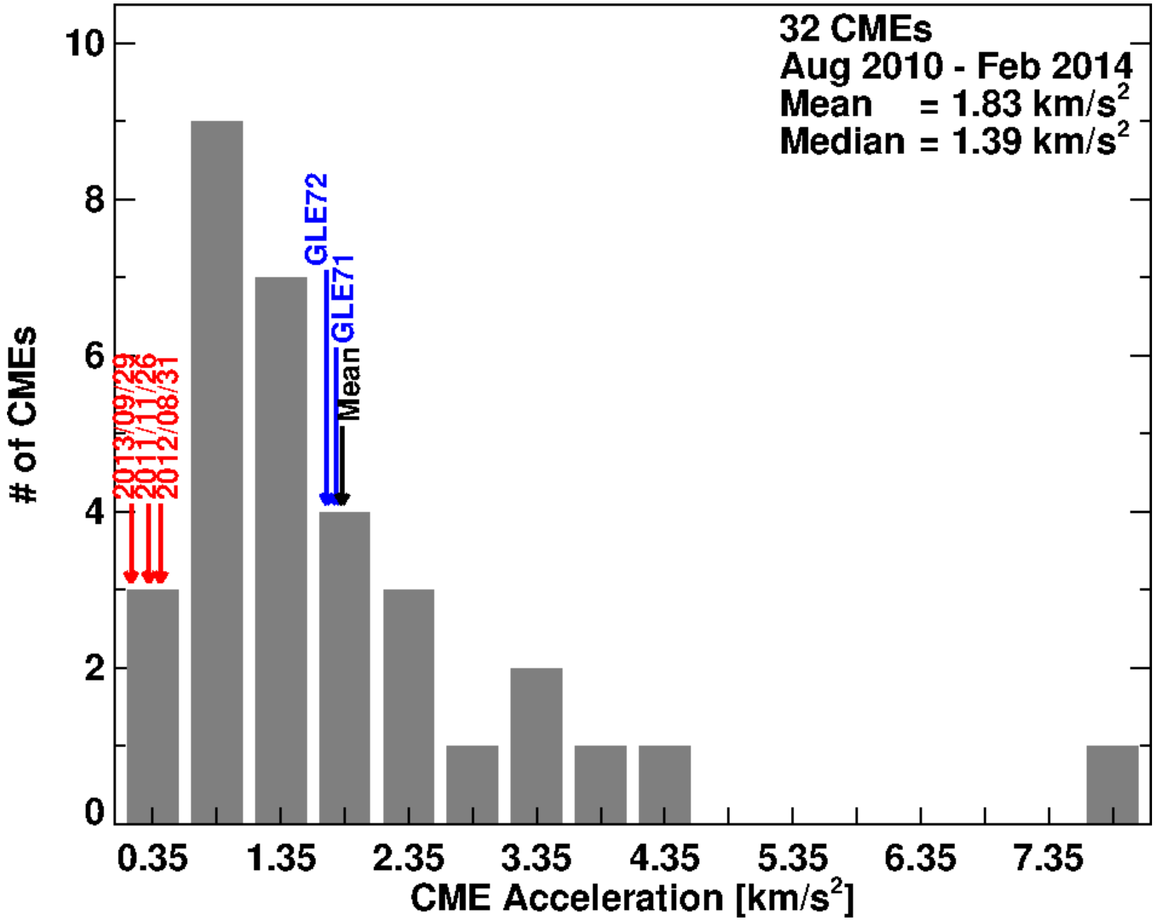
1997 Jan – 2014 Jan



- Metric type II radio bursts associated with large SEP events during solar cycles 23 and 24
- CME heights using a flare-onset method
- The mean CME height for non-GLE SEP events (1.72 *Rs*) is ~12% greater than that (1.53 *Rs*) for cycle-23 GLEs
- The mean CME height in cycle 23 non-GLE SEP events (1.79 *Rs*) is greater than that in cycle 24
- The lower shock formation height in cycle 24 indicates a change in the Alfven speed profile because of weaker magnetic fields and plasma levels are closer to the Sun

Mäkelä et al. 2015

Initial Acceleration (Shock Formation Height)



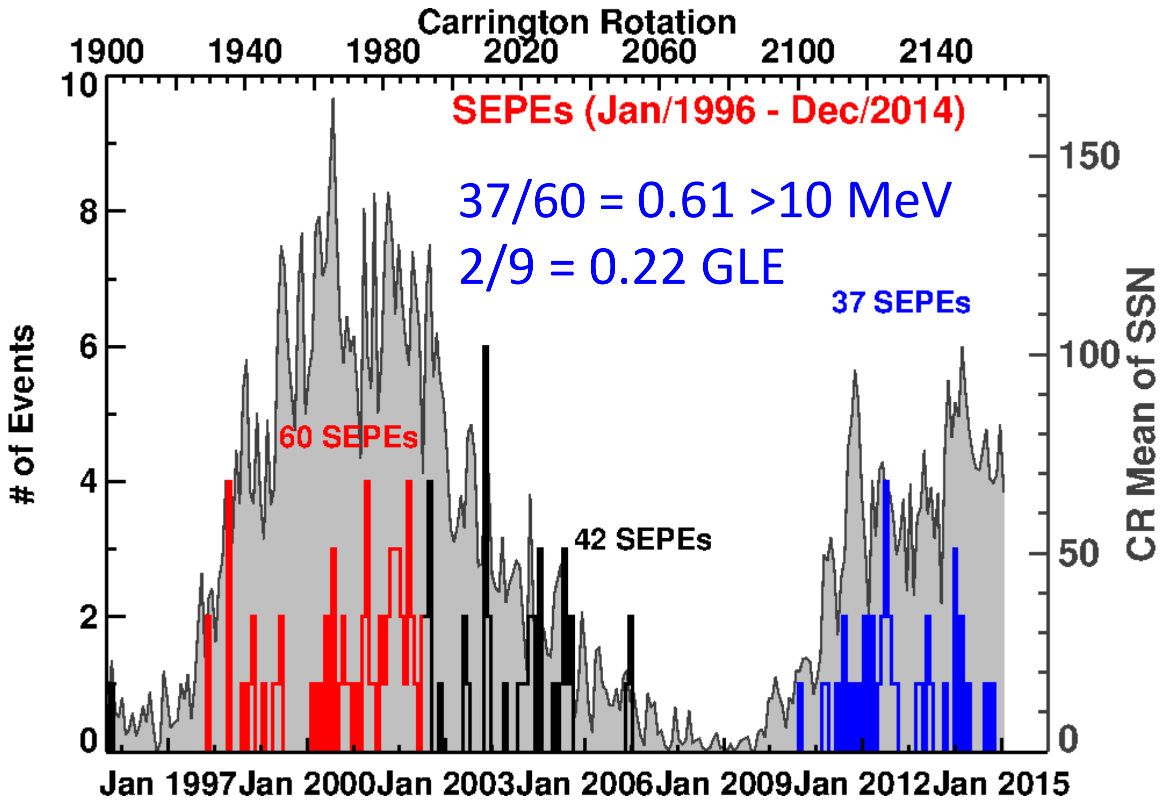
Accelerations from height-time measurements of CME Flux ropes fit to SOHO/STEREO CMEs

SEP events associated with CMEs from quiescent filament eruption accelerate slowly and form shocks at distances >2-3 Rs

GLE associated CMEs impulsively accelerate and form shocks at distances ~1.4 Rs

Solar Cycle Variation of SEPs

- First 73 months of the two cycles compared
- Average sunspot number (SSN) dropped by 40% (76 to 46)
- # Fast and wide CME rate dropped by 30% (3.74/mo to 2.62/mo)
- # of large SEP events (>10 MeV) dropped by 40% (60 to 37)
- # of GLE events (>700 MeV) dropped by 78% (9 to 2)
- Drop in # of >10 MeV events similar to SSN, but not the # of GLEs
- Drop in # FW CMEs is smaller than SSN



SSN 76
9 GLEs

SSN 46
2 GLEs

Gopalswamy et al. 2014 GRL

Paucity of GLEs, not of >10 MeV SEPs

30%

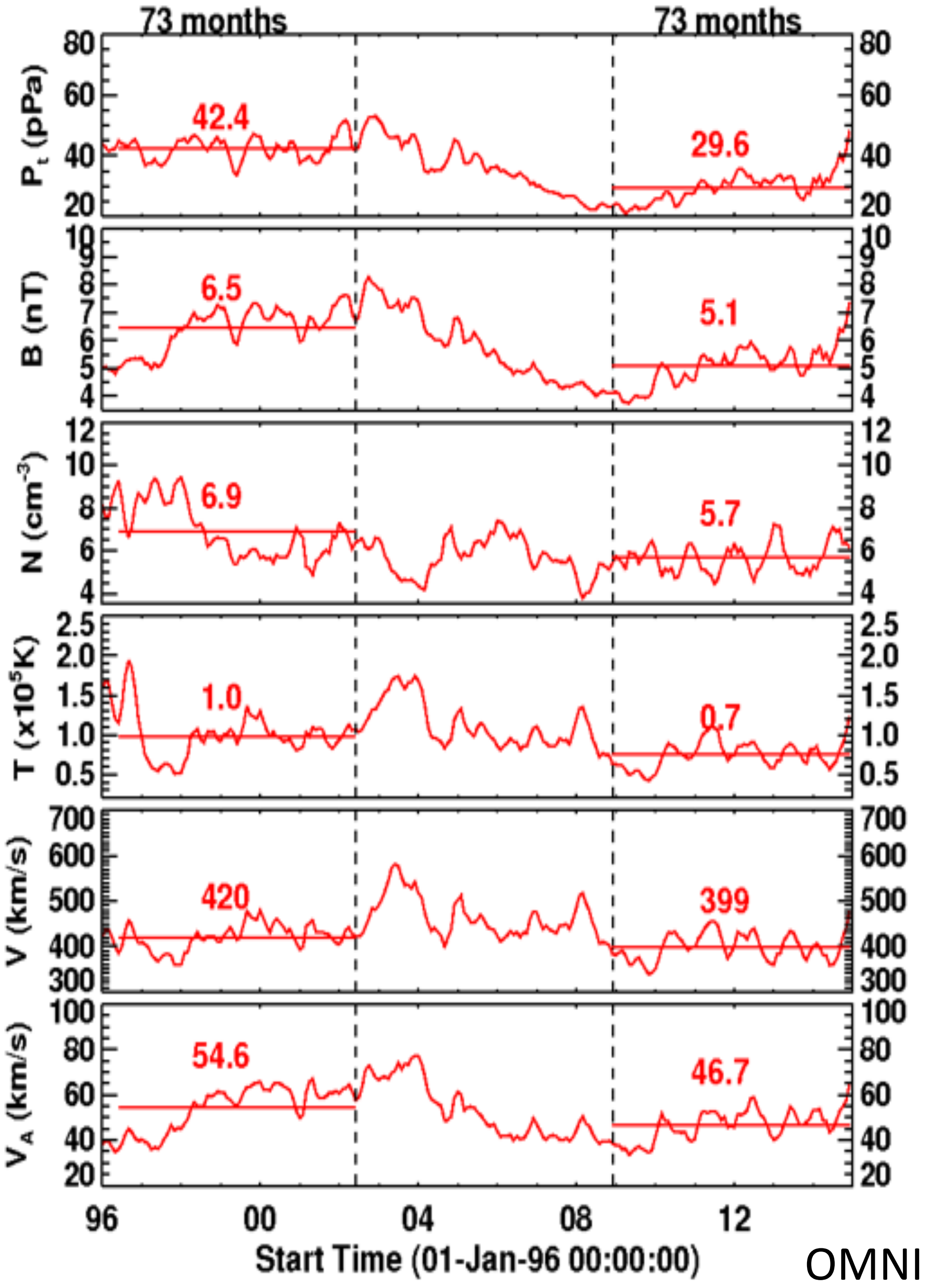
22%

18%

30%

5%

15%



Reduced B in the heliosphere

→ Reduced acceleration efficiency (Kirk, 1994)

dE/dt ∝ B (rate of energy gain)

With the available time of ~10 min, it is difficult to accelerate SEPs to GeV energies

Reduced Alfven speed near Sun

→No major reduction in the # SEP Events

Gopalswamy et al. 2014 GRL; McComas et al. 2013

Wavelength Range of Type II Bursts

λ Domain	Cycle 23	Cycle24
mD	13	5
D	4	2
Dk	5	6
mk	29	22
mk+Dk	34 (66%)	28 (80%)

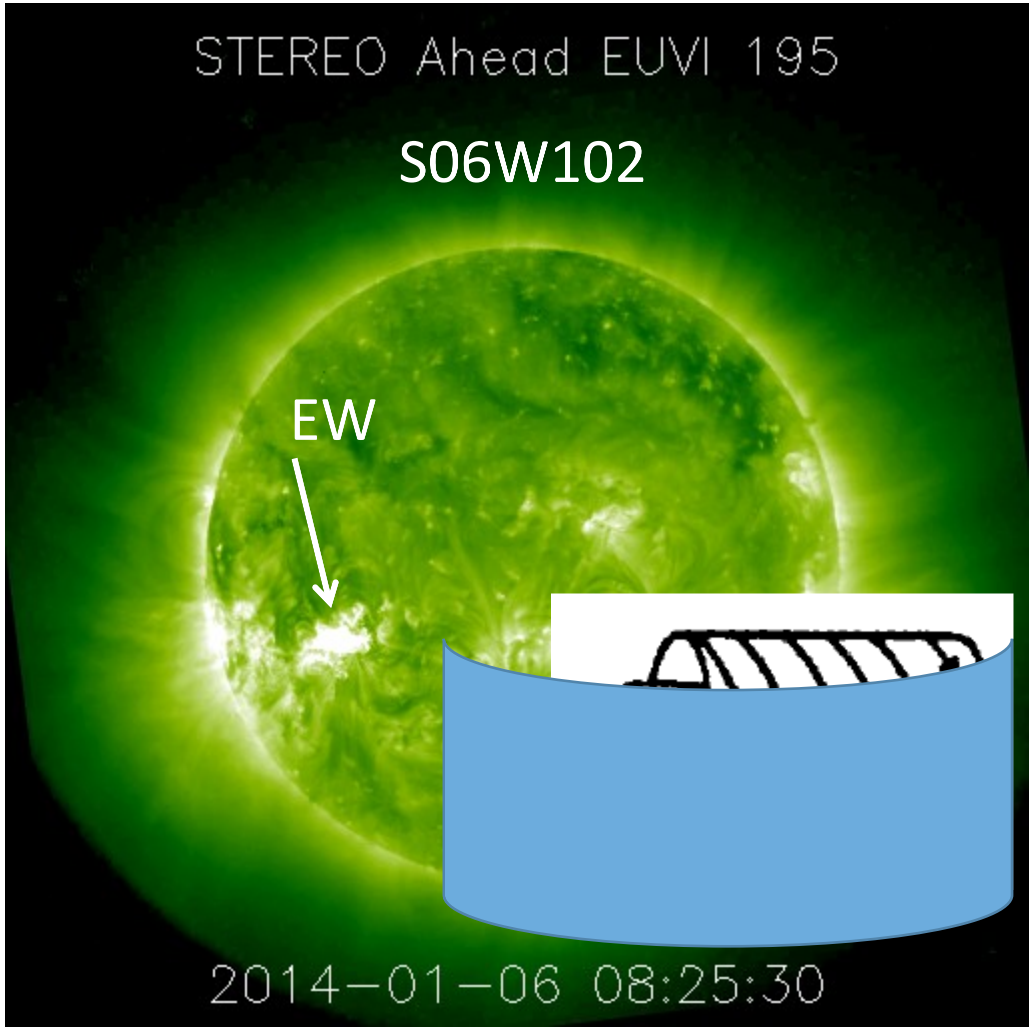
mD = meter to decameter-hectometric
D = decameter-hectometric
Dk = decameter-hectometric to kilometric
mk = meter to kilometric wavelengths

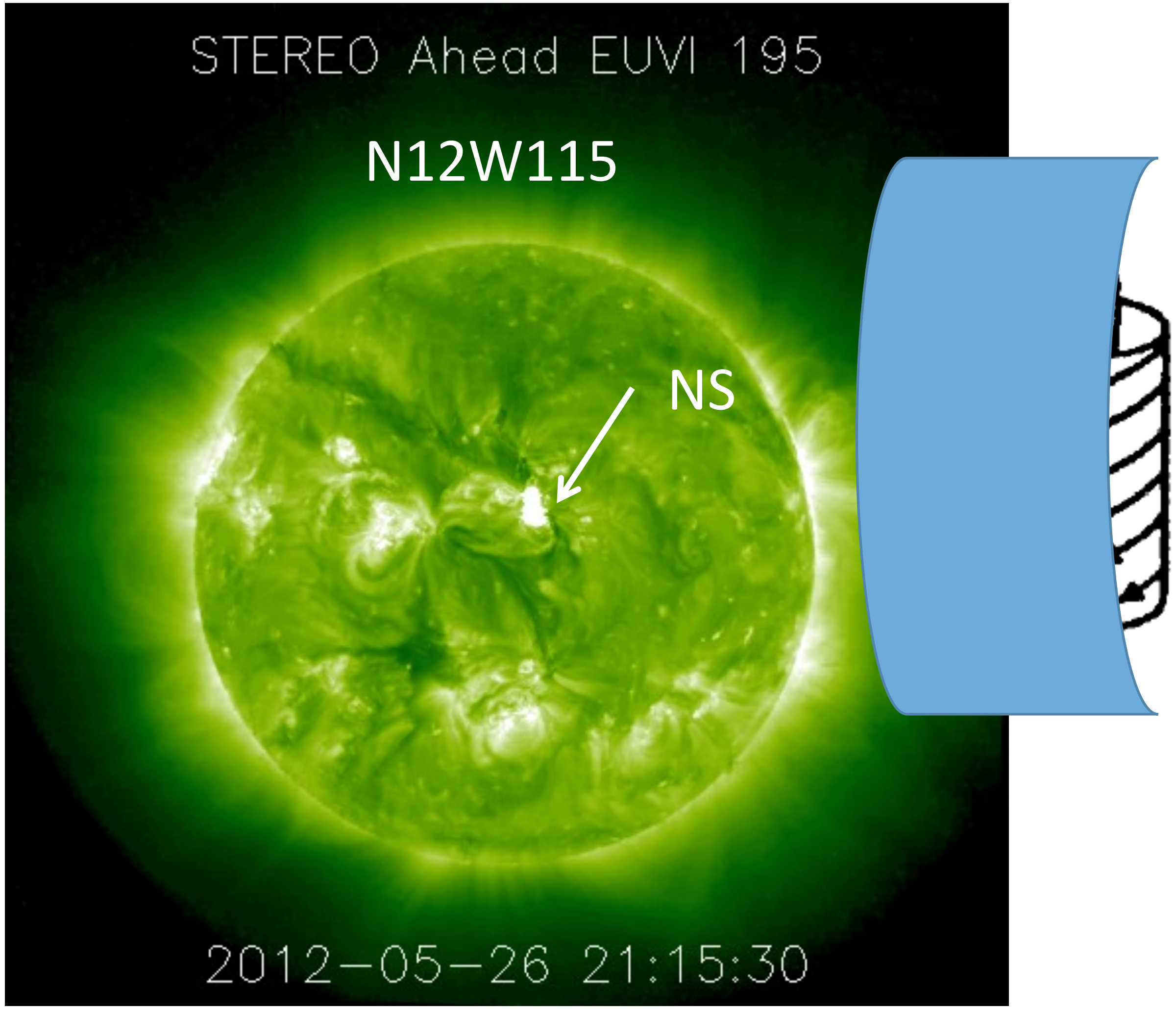
Consistent with stronger shocks in cycle 24 due to lower VA

Longitudinal Extent of SEP events

- Cycle 24 is favorable for larger longitudinal extent?
- More halos – anomalous expansion
- Wider shocks
- Flux rope orientation: high-inclination flux ropes may have smaller longitudinal extent compared to the low-inclination events

Does the Flux Rope Orientation Matter?





Summary

- CME speeds are consistently important for SEP occurrence; Flare size is not
- Complex type III bursts are not sufficient for SEP events
- Anomalous expansion of CMEs may be linked to longitudinal spread of SEPs
- Low shock formation height is important for high-energy SEP events
- # of high-energy SEP events in SC 24 is small compared to SC 23
- The reduction is far more than that in SSN and FW CMEs
- Several factors seem to be responsible
- Reduced efficiency of shock acceleration (weak heliospheric B)
- Large-ecliptic distance to solar sources (poor latitudinal connectivity)
- Variation in local ambient conditions (e.g. high Alfven speed)
- Shock formation at large heights (beyond typical GLE release heights)