SOLAR AND HELIOSPHERIC PRERESEQUITIES FOR OCCURRENCE OF EXTREME STORMS

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KEY SOLAR WIND PARAMETERS

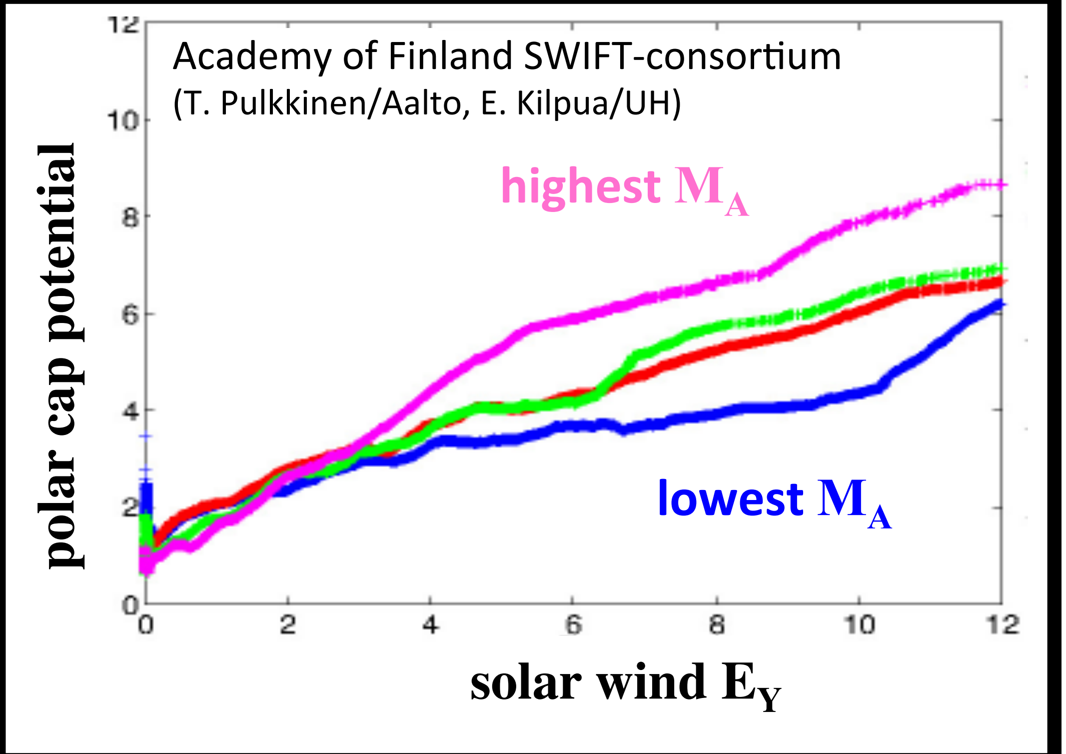
- direction & magnitude of southward IMF
- speed
- density
- Alfvén Mach number
- turbulence

speed, density } dynamic pressure

direction & magnitude of southward IMF, speed } dawn-dusk electric field

speed important (e.g., *Ballatore et al.*, 2002; *Pulkkinen et al.*, 2015)

high latitude storms
ring current build-up
radiation belts
Solar Energetic Particles

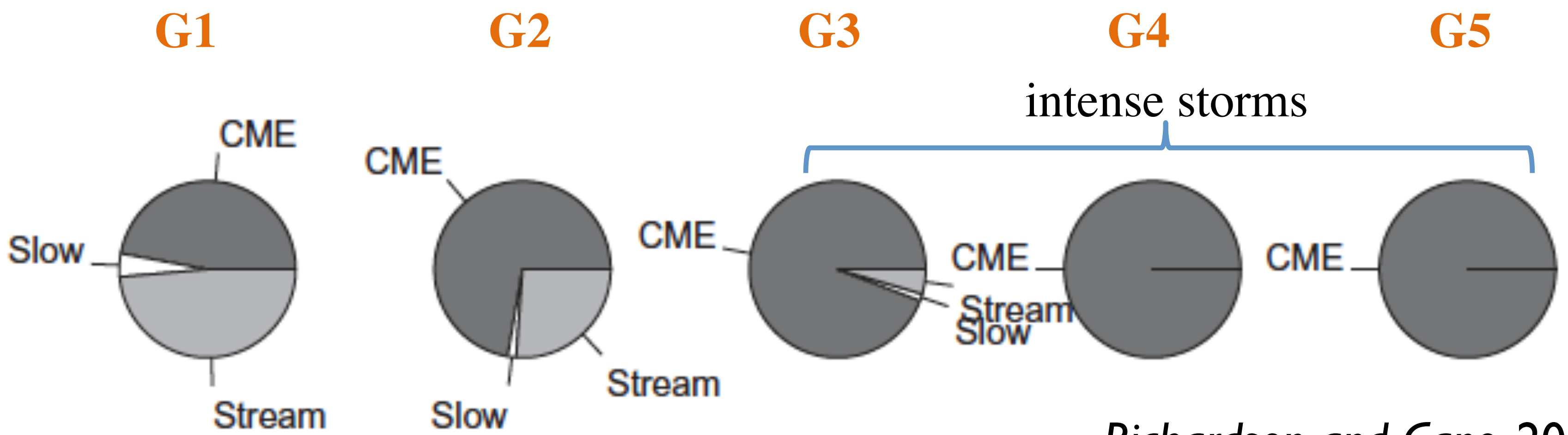


Myllys et al., in revision JGR

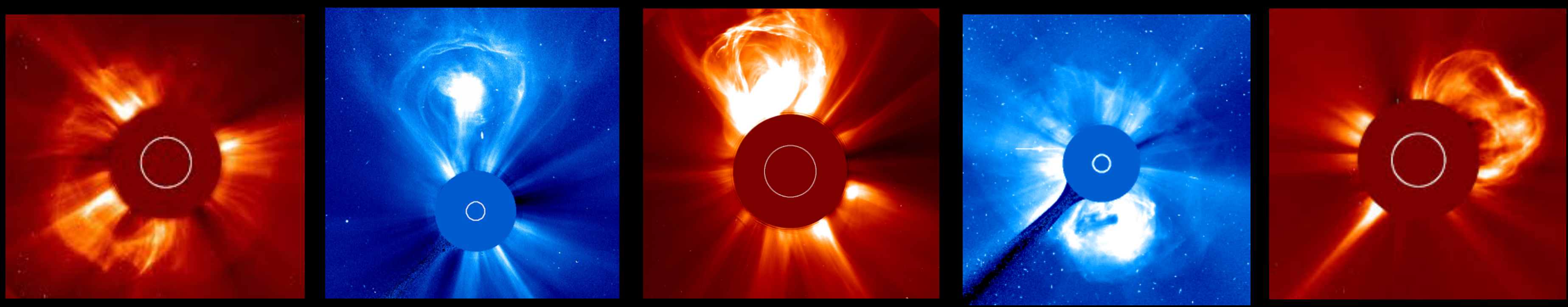
CORONAL MASS EJECTIONS DRIVE NEARLY ALL INTENSE MAGNETIG STORMS

Small to Intense storms during four solar cycles (1963 -2011)

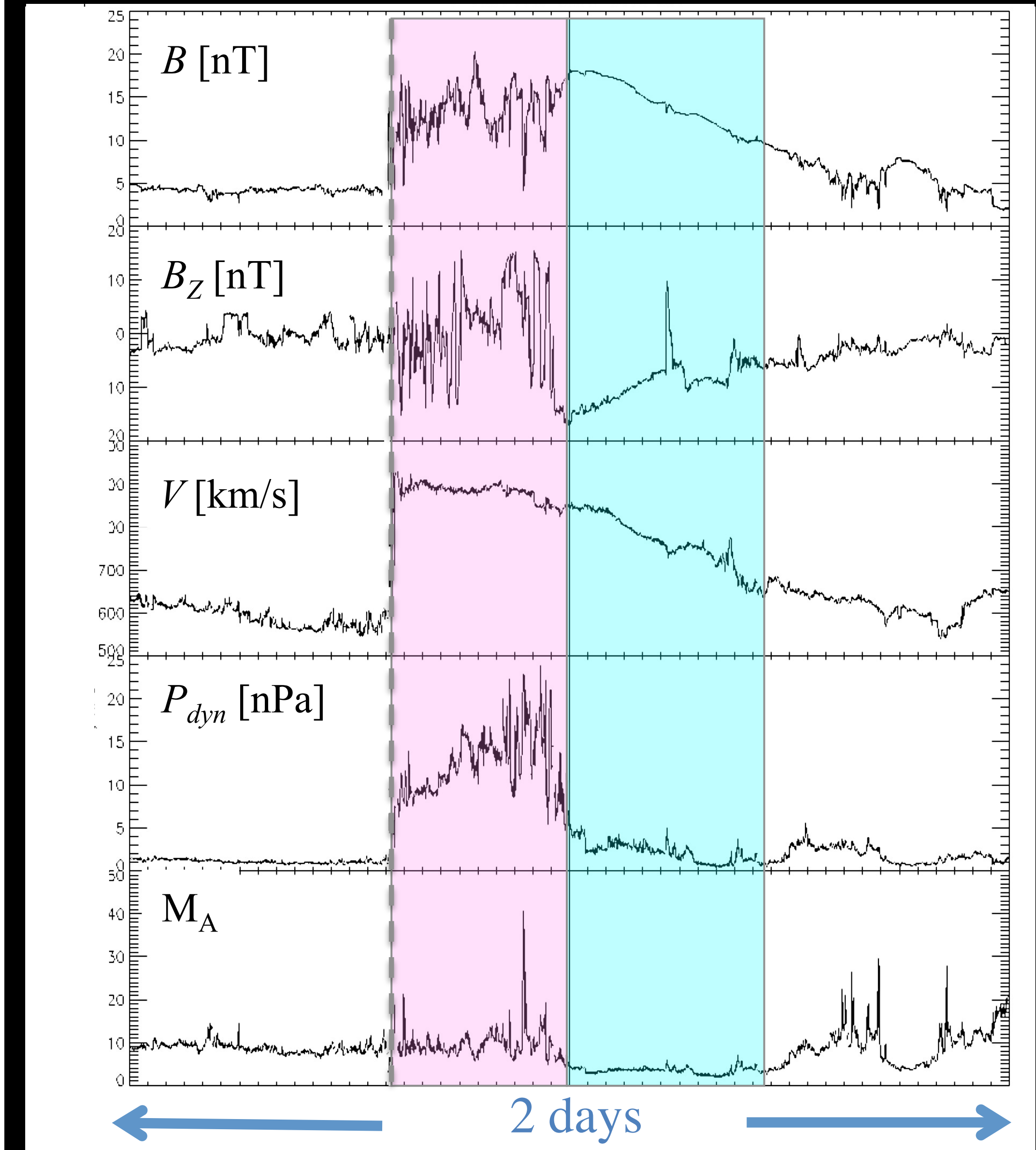
Storm intensity: Kp (NOAA scales)



Richardson and Cane, 2012



TWO MAIN CME PARTS DISTINCT CONDITIONS AND GEOSPACE RESPONSE



Shock

Sheath
- **turbulent** and compressed
- high dynamic pressure
- high Alfvén Mach numbers (M_A)
- large variation in key parameters

Flux rope (FR)
- **smooth** rotation of **B**
- lower dynamic pressure
- lower M_A
- lower variability

(e.g., *Huttunen et al.* JGR, 2002; *Yermoleav et al.*, 2012; *Kilpua et al.*, GRL, 2015)

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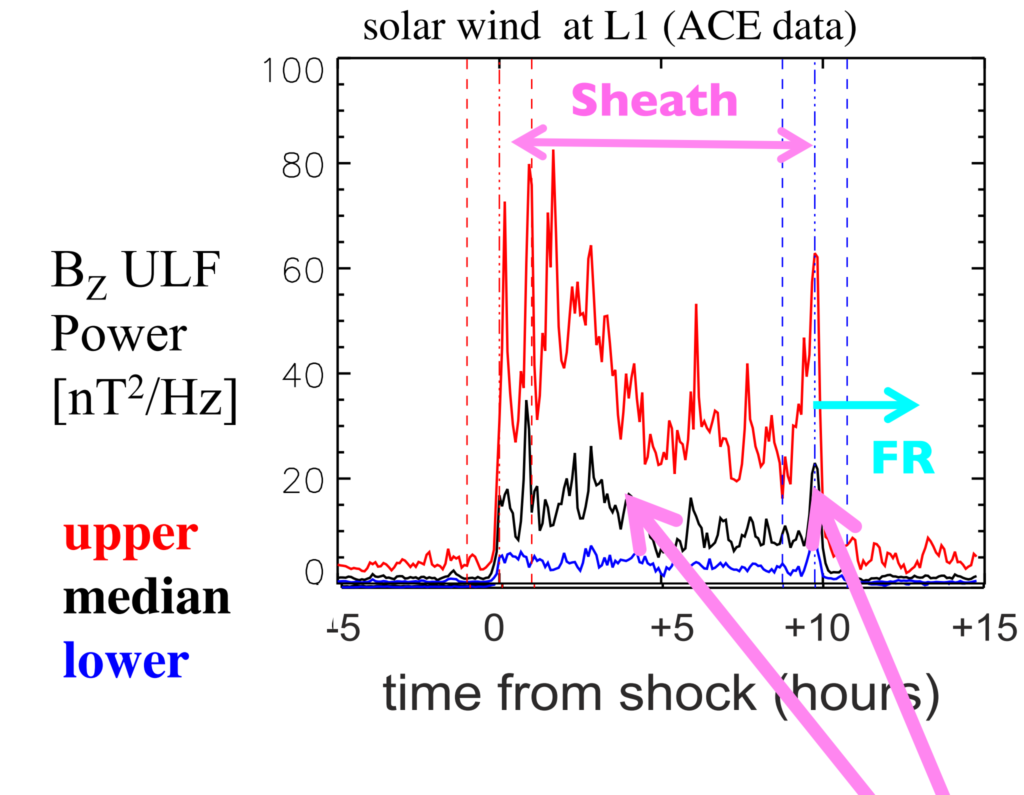

Superposed epoch analysis of 38 CMEs

Kilpua et al., 2012
http://adsabs.harvard.edu/abs/2013AnGeo..31.1559K

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largest GICs (Huttunen et al., Space Weather 2008)

INTRINSIC CME PROPERTIES, INTERACTIONS DURING THE JOURNEY FROM SUN TO EARTH & PRECONDITINING OF THE HELIOSPHERE

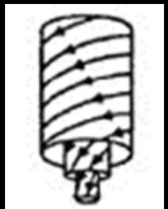
“PERFECT STORM SCENARIO”

[*Liu et al.*, 2014; 2015]

FLUX ROPE (FR) MAGNETIC TOPOLOGY

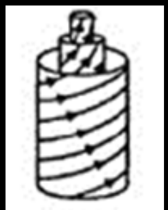
- axial field direction + orientation, helicity → four B_Z profiles
  (e.g., *Bothmer & Schwenn*, 1998; *Mulligan et al.*, 1998)
- affects strongly the geospace response and interactions
  (e.g., *Huttunen et al.*, 2005 http://adsabs.harvard.edu/abs/2005AnGeo..23..625H
  Kilpua et al., 2012 http://adsabs.harvard.edu/abs/2012AnGeo..30.1037K)

HIGH INCLINATION



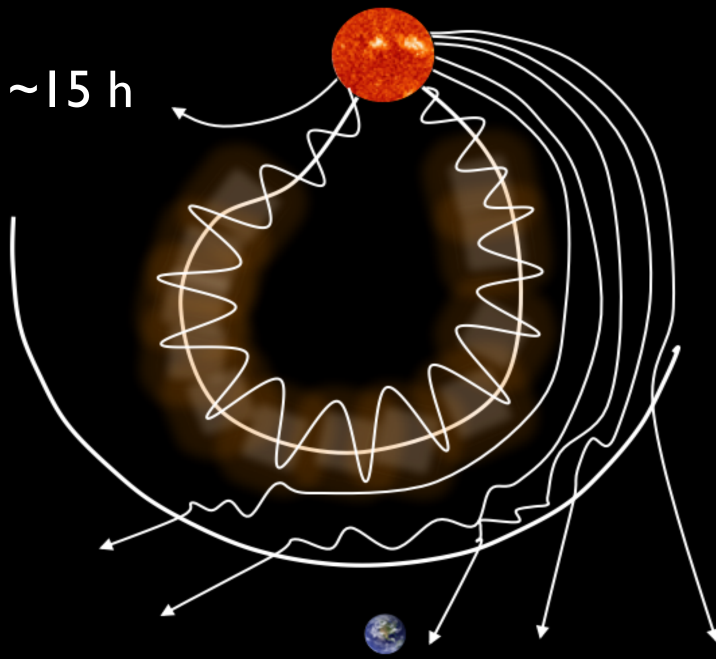
South (S)

e.g., Nov 20-21, 2003 storm, Dst= - 422 nT (Kp=9-)
(isolated S-type FR)

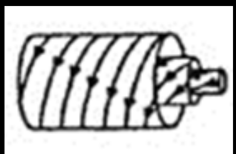


North (N)

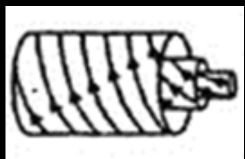
Aug 1972 Event? Transit time ~15 h
+ extreme flare. No storm
(e.g., *Tsurutani et al.*, 1992)



LOW INCLINATION

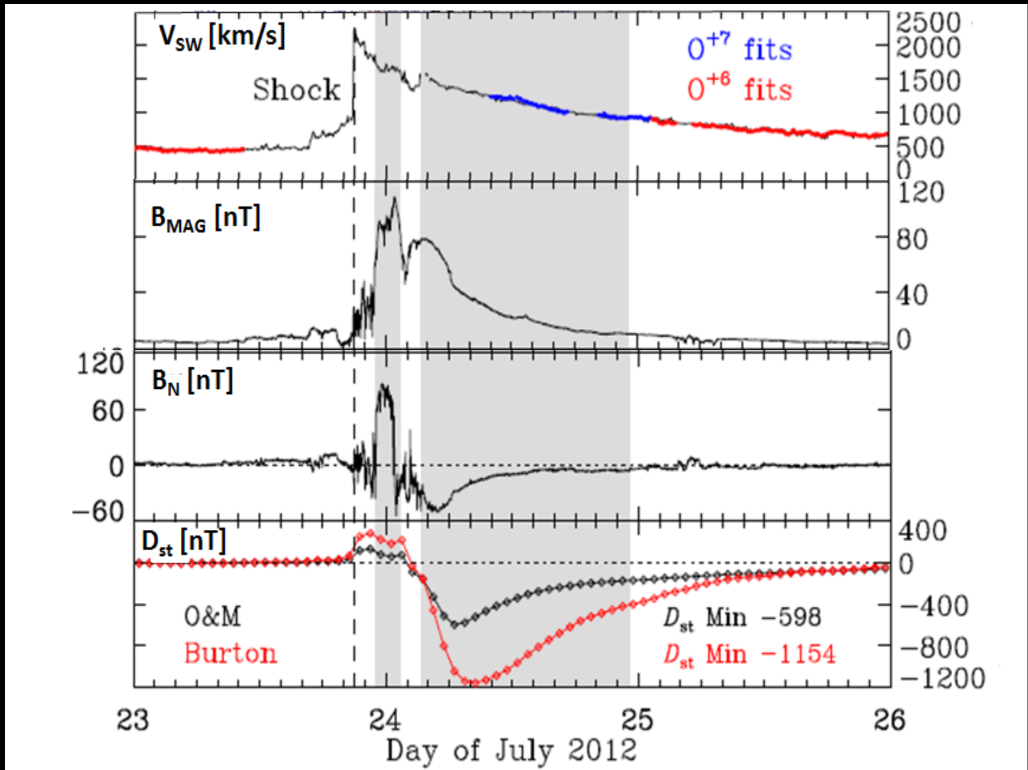


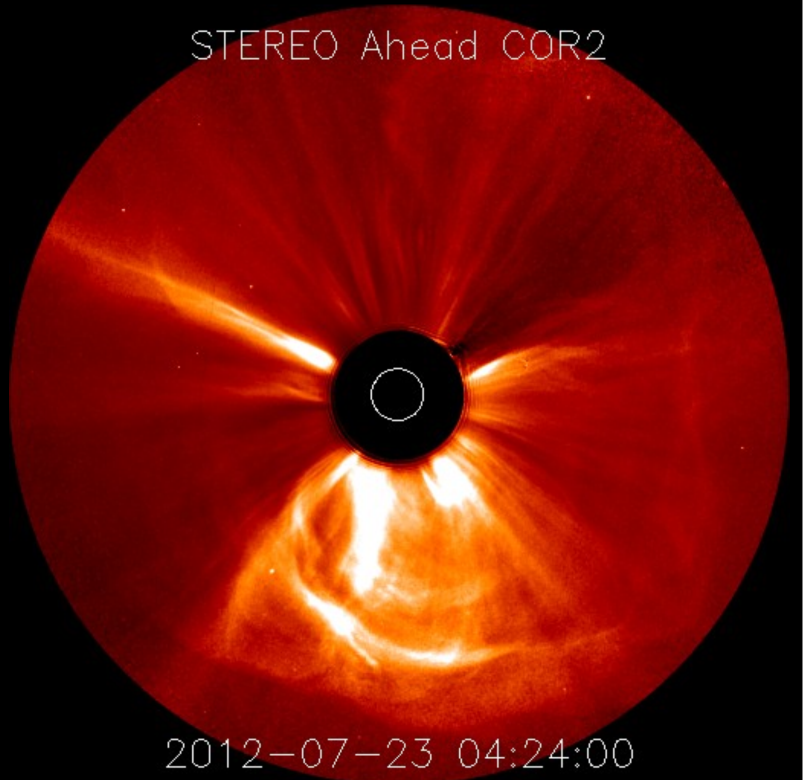
South → North (SN)



North → South (NS)

CME-CME INTRACTIONS



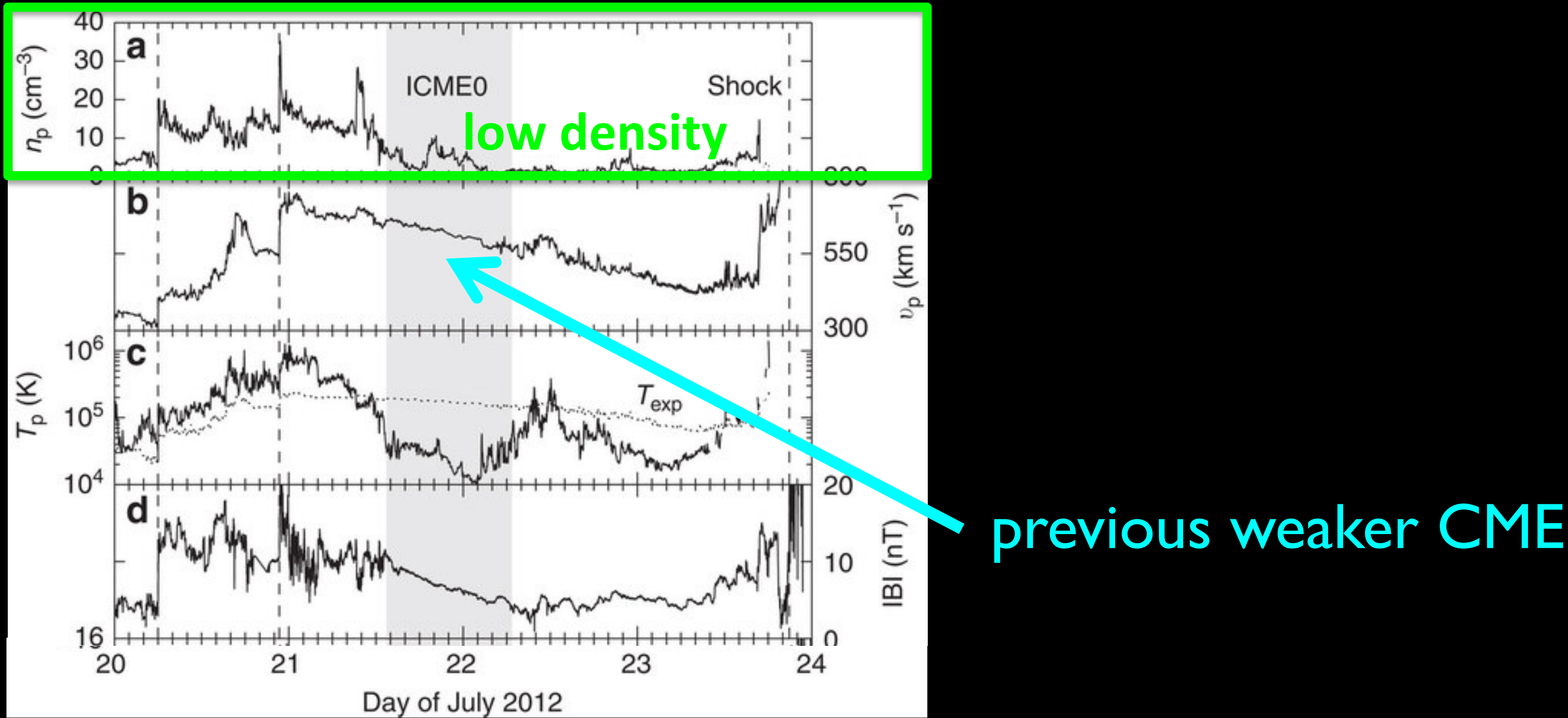


Liu et al., Nat Comm., 2014

- prevent FR expansion
- turbulent regions with high densities and fields
- "CME cannibalisms" (*Gopalswamy et al.*, 2001)
- Shock merging & compression (e.g., *Lugaz et al.*, 2015)

FR types, relative orientations & speeds, sheath fields

PRECONDITIONING OF THE HELIOSPHERE

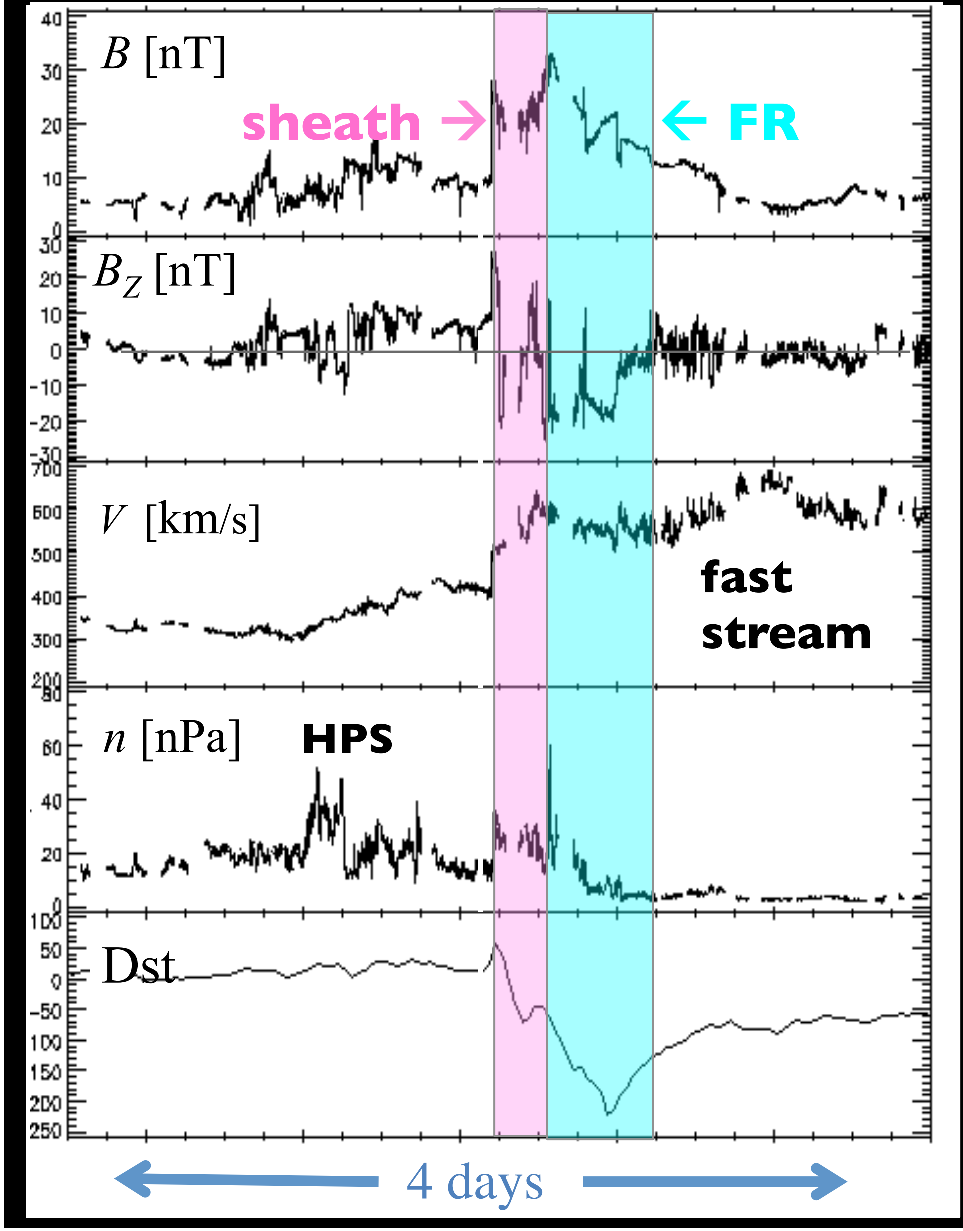


Liu et al., 2014

low density → minimal drag force → fast Sun-to-Earth transit

+ CME maintains high speeds → large E_y, larger draping in sheath, stronger interactions, ... → stronger storm

INTERACTIONS WITH OTHER SOLAR WIND STRUCTURES (HPS, SIR, FAST STREAMS)



"CME Sandwich" (March 17, 2015)

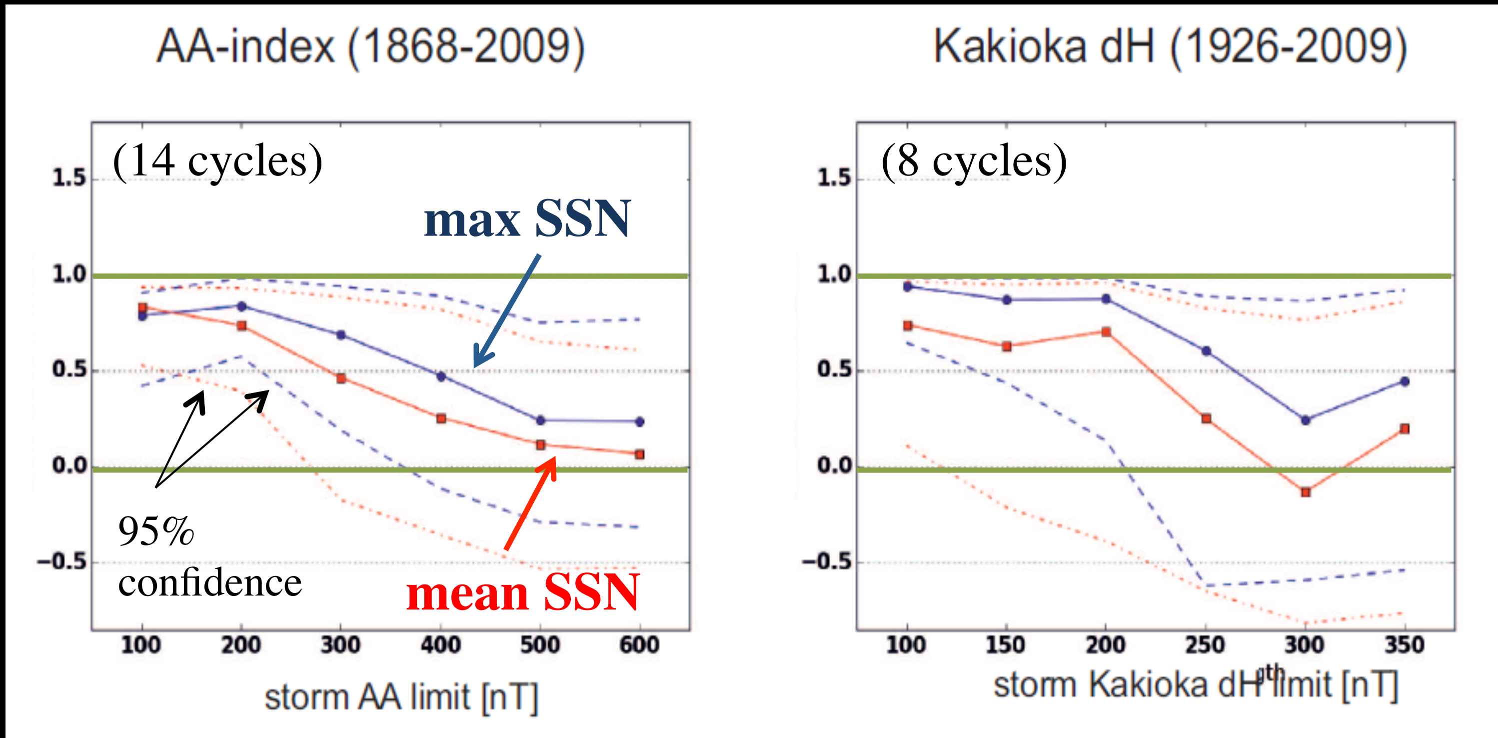
→ compresses sheath and FR
→ stronger storm than expected

Kataoka et al., GRL, 2015

Fast stream compression enhances geoeffectivity of NS-type FRs

(see e.g., *Kilpua et al.*, 2012
http://adsabs.harvard.edu/abs/2012AnGeo..30.1037K
and *Fenrich & Luhmann*, GRL, 1998)

CORRELATION BETWEEN SOLAR CYCLE SIZE AND STORM OCCURENCE

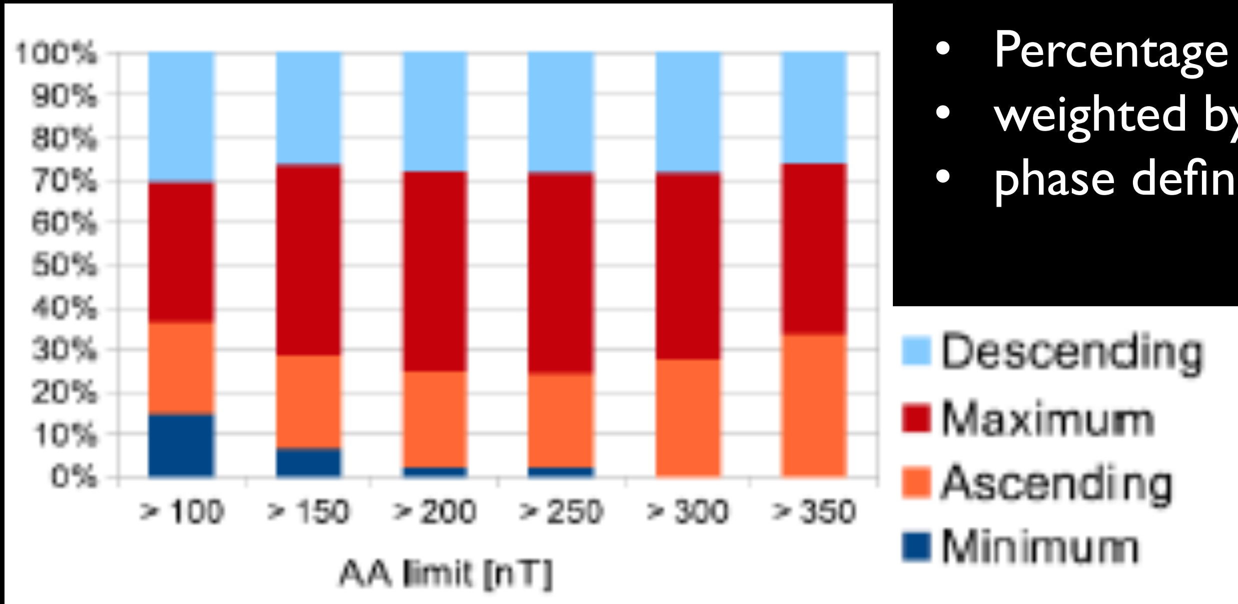


Pearson correlation coefficients

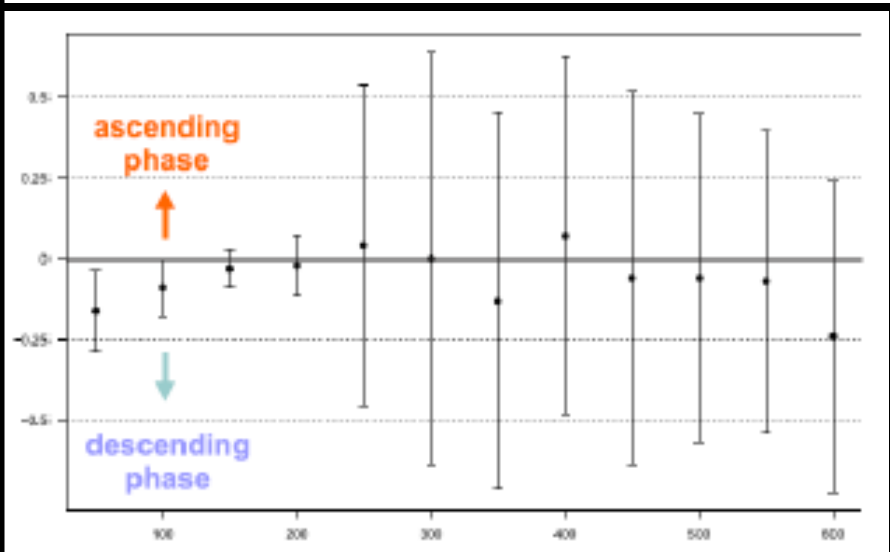
confidence intervals calculated with the bootstrap method

Kilpua et al., 2015: http://adsabs.harvard.edu/abs/2015ApJ...806..272K

SOLAR CYCLE PHASES AND STORMS



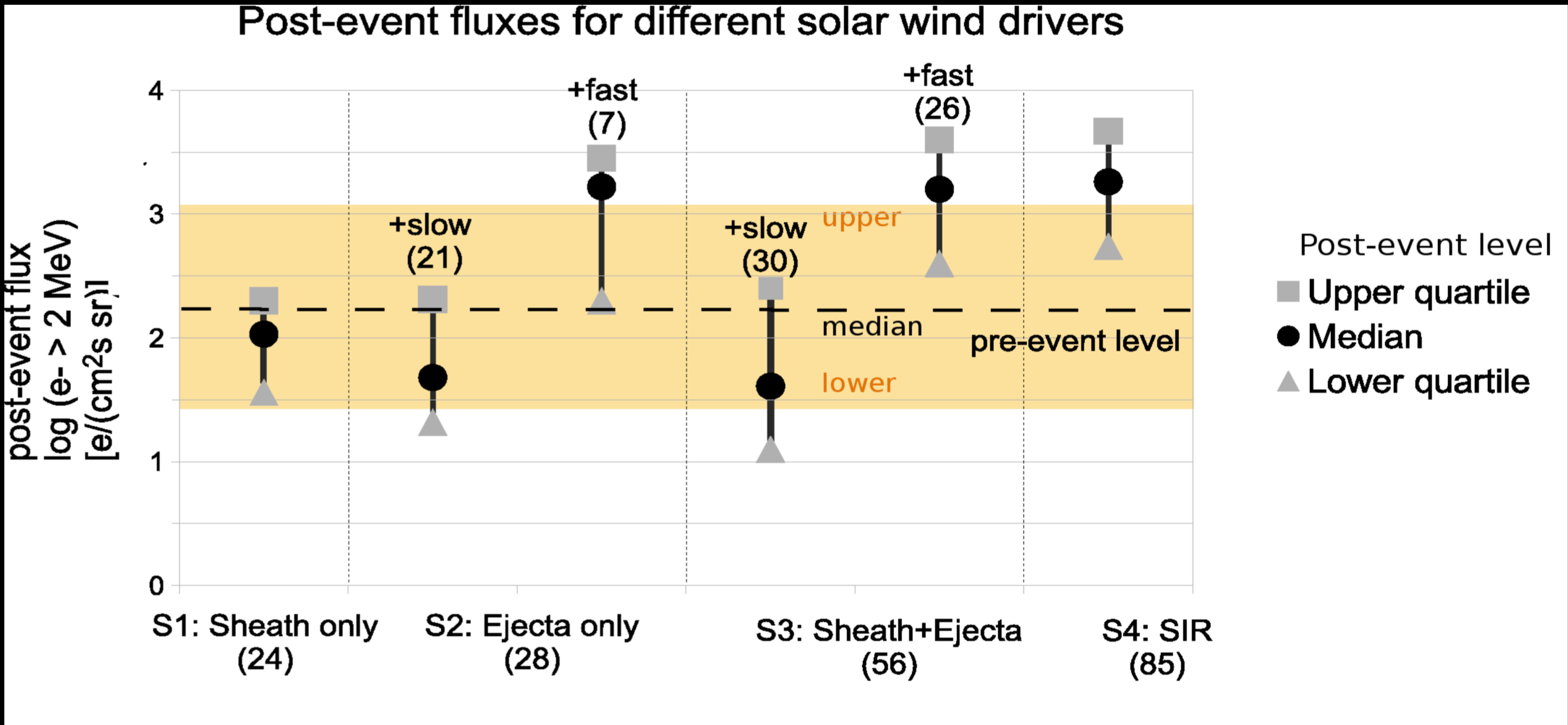
- Percentage of storms in each phase
- weighted by the duration of the phase
- phase definition by Hynönen, 2013



- phase shift between the storm and SSN distributions
- weaker storms shift towards declining phase
- stronger storms tend to occur at solar maximum

Kilpua et al., 2015: http://adsabs.harvard.edu/abs/2015ApJ...806..272K

STRONG VAN ALLEN BELT ENHANCEMENTS FAST STREAMS IMPORTANT



Kilpua et al., GRL, http://adsabs.harvard.edu/abs/2015GeoRL..42.3076K, 2015)

CONCLUSIONS

- Several solar wind parameters affect geoeffectivity
- Two main structures in a CME: sheath and the flux rope
- Intrinsic + interactions + preconditioning = "perfect storm"
- Also calmer Sun can launch super storms (+ Carrington storm and July 2012 events)
- → Occurrence of the most extreme storms does not correlate well with large-scale solar dynamo fields, source in turbulent small scale field?
- Weaker storms follow coronal poloidal field (e.g. coronal holes), strongest storms toroidal field (active regions, CMEs)