Transport and acceleration of >300 MeV solar protons

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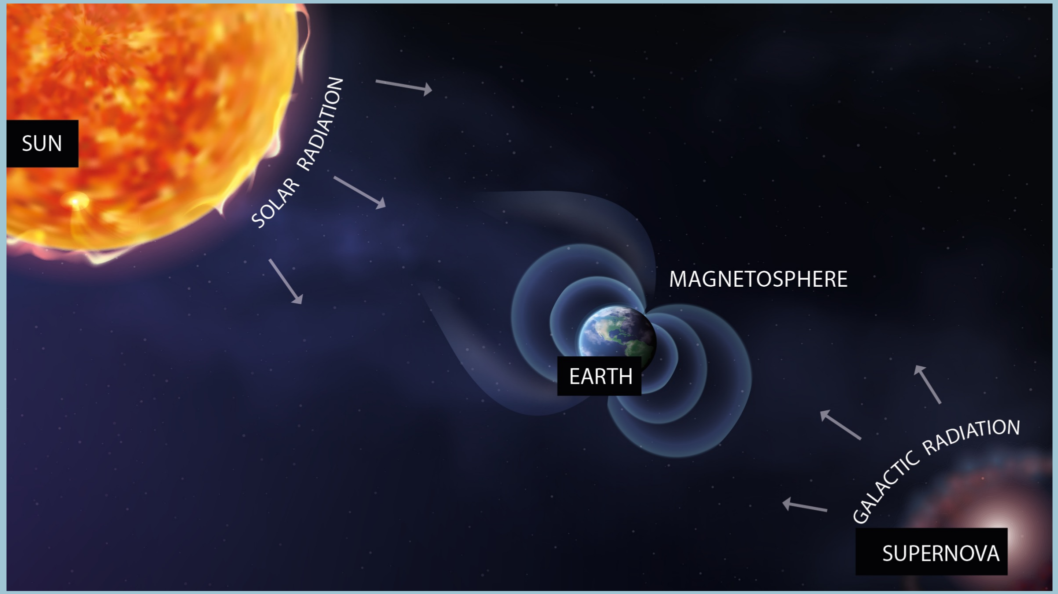
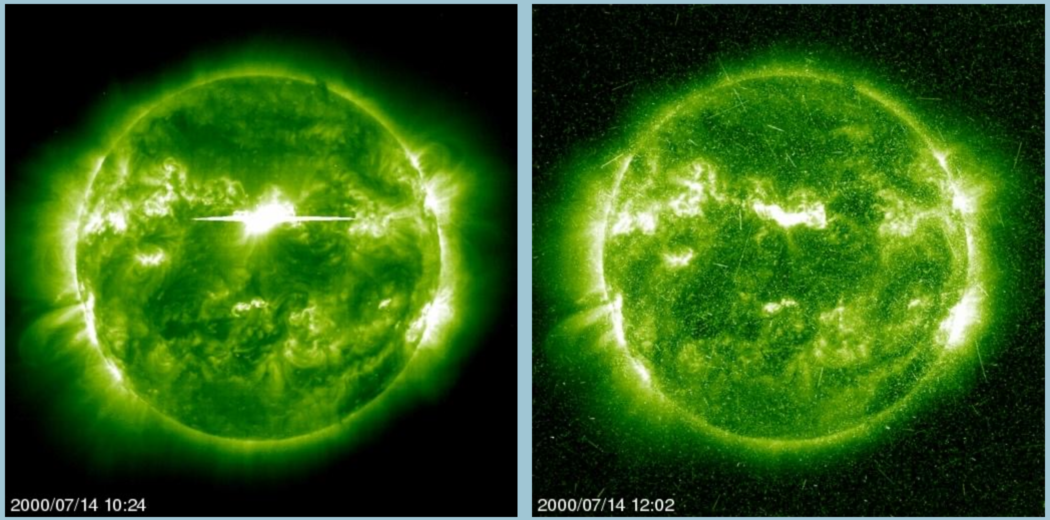
Outline

1. An introduction to solar energetic protons (SEPs)
2. Observations of SEP events
3. Modelling of SEP events
4. Conclusions

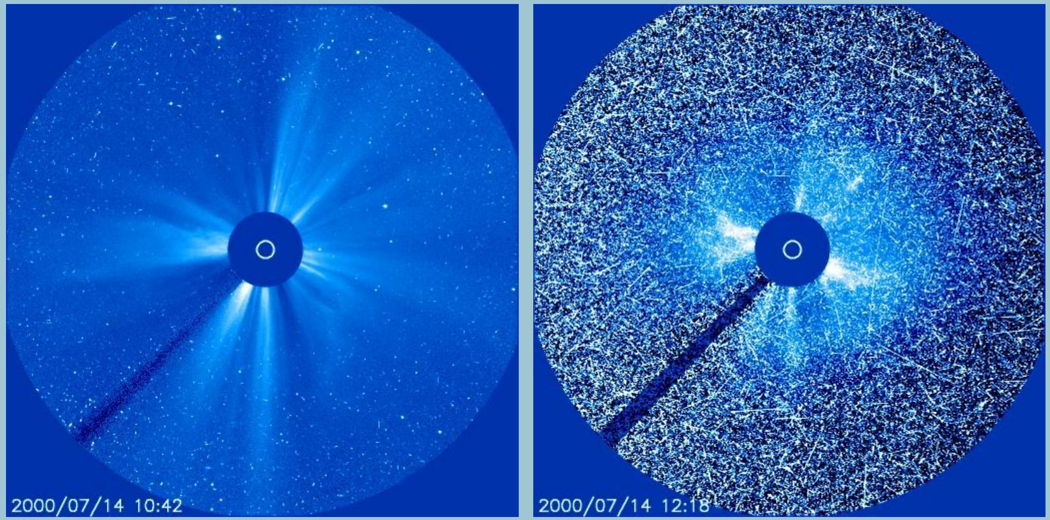


1. Introduction to solar energetic particles

- Solar energetic particles (SEPs): high energy ions and electrons originating from the Sun
- SEP events are associated with large solar flares and coronal mass ejections
- Arrive at Earth typically within 10-90 minutes



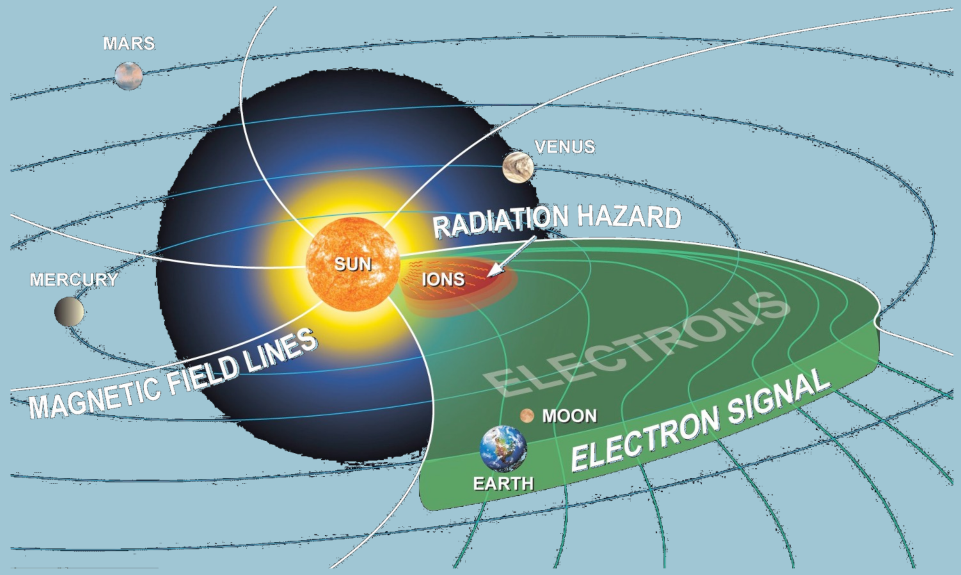
During and after solar flare
Noise in 2nd image from SEPs
Images from SDO



Pre and during coronal mass ejection
Noise in 2nd image from SEPs
Images from SOHO

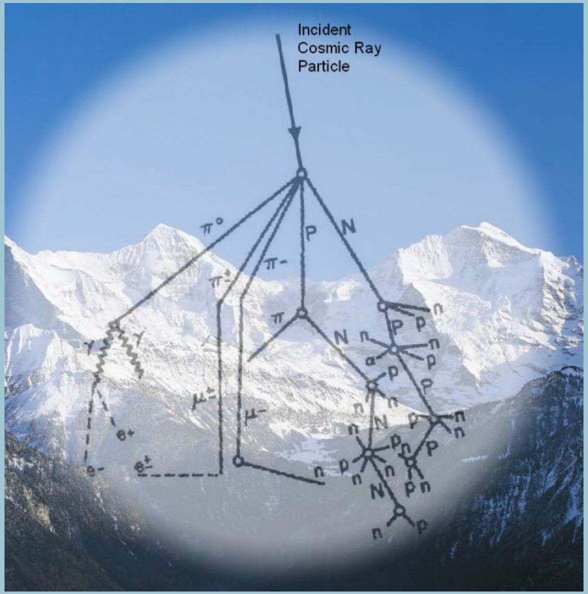
Solar energetic particles

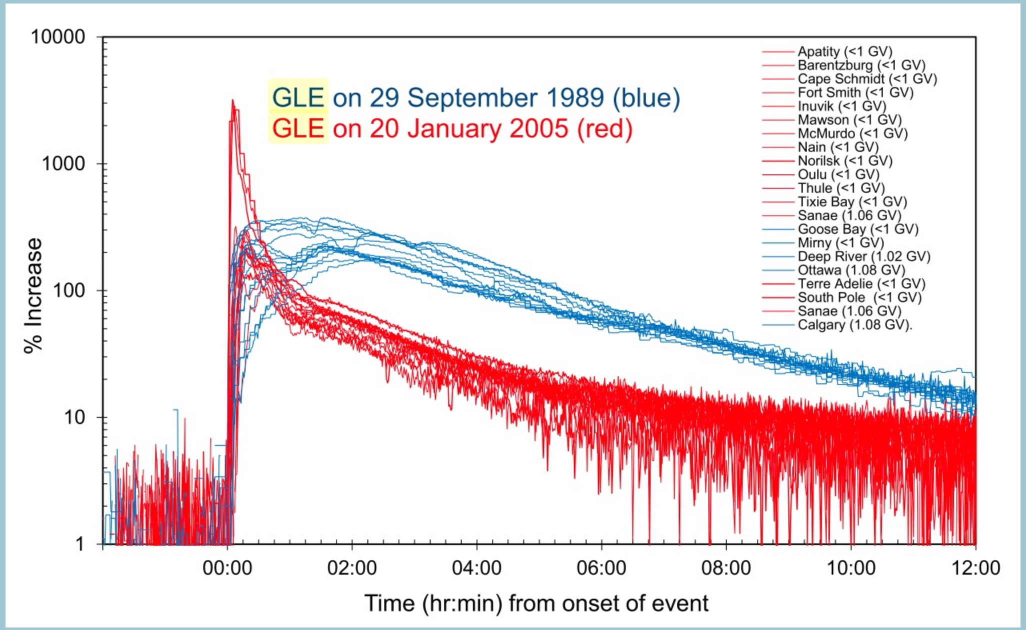
- SEPs can be accelerated to relativistic energies, up to GeV (high for solar protons!)
- Why do we care about them?
  - Increased radiation doses to astronauts
  - Damage to spacecraft electronics
  - Induce radiation storms, measured on scale: S1 (minor) to S5 (extreme)



Ground level enhancements

- Some SEPs (>500 MeV) can reach Earth and cause ground level enhancement (GLE) events
- Detected by network of neutron monitors
- Only 72 recorded since 1940s



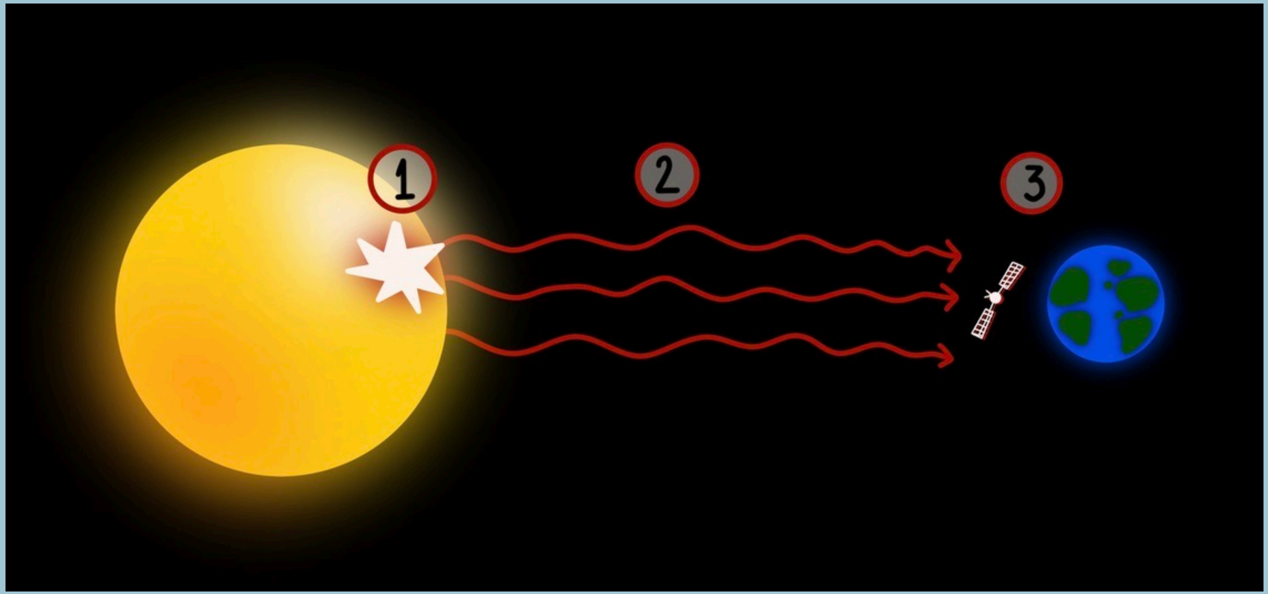


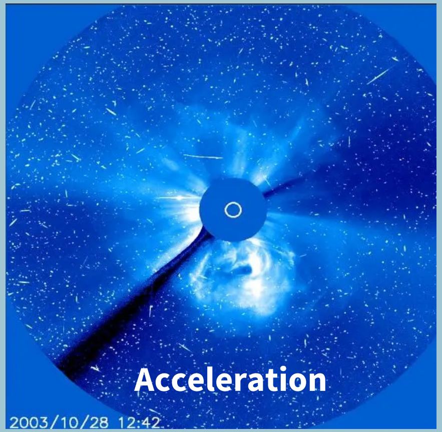
Moraal et al. 2014

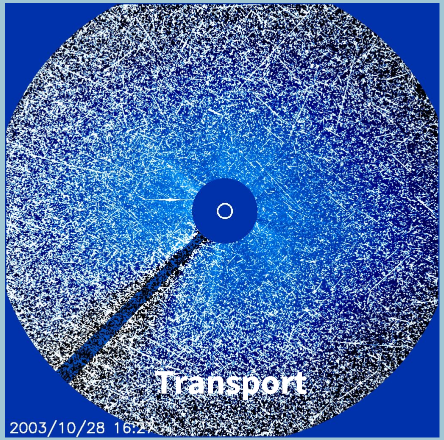
Solar energetic particles

Key questions:

- i. How are the particles accelerated?
- ii. How are they transported through space?
- iii. What determines if SEPs are detected at Earth?





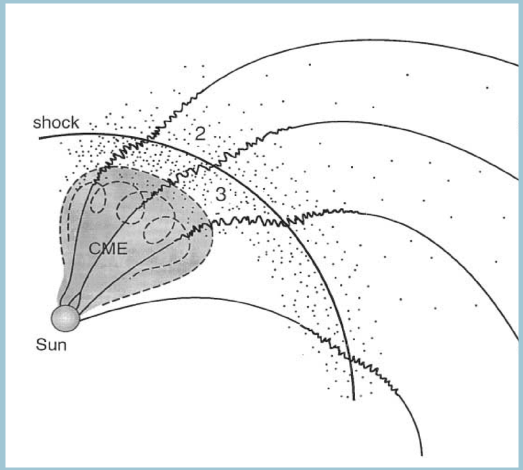


i. How are the particles accelerated?

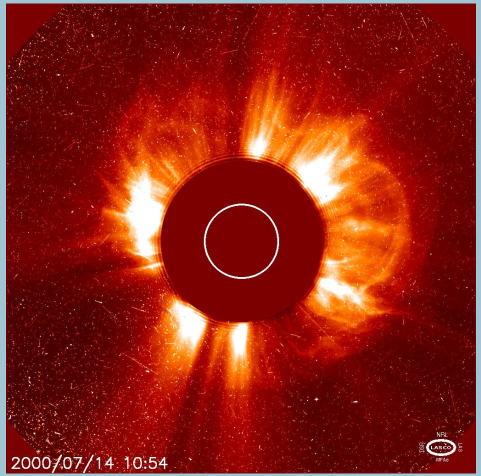
Coronal mass ejections, e.g. shocks

SEPs associated with fast (up to ~3000 km/s)

and wide (360 degree) CMEs



Lee 2005

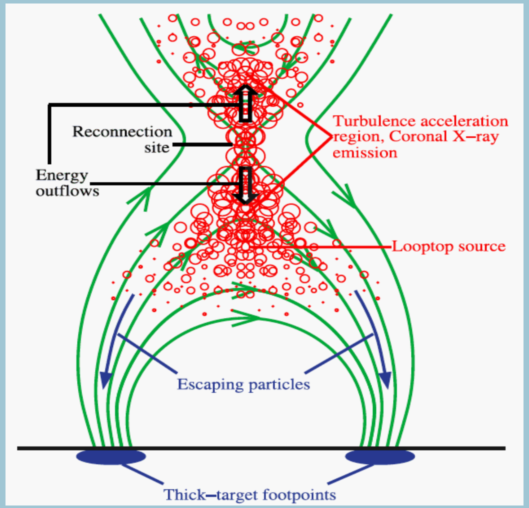


CME with 360º width

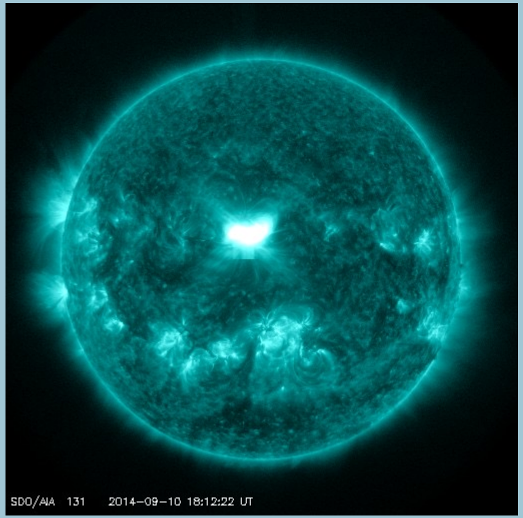
Solar flares, e.g. magnetic reconnection

SEPs are associated with large (M or X class) flares

Flares classed by SXR peak: A, B, C, M, X



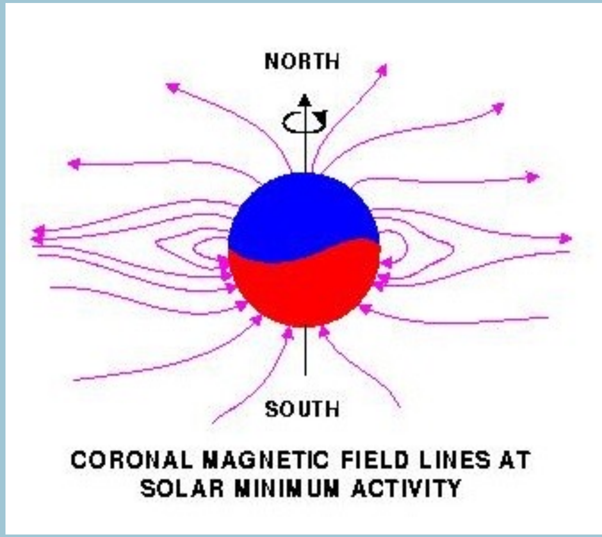
Liu, 2008

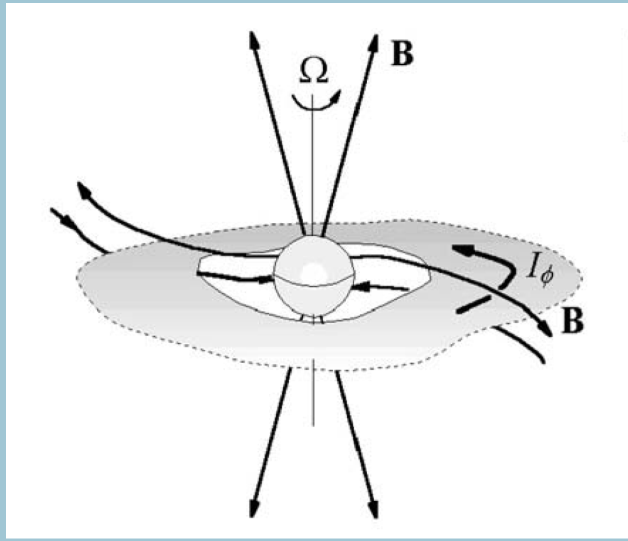


X class solar flare

ii. How are they transported through space?

- SEPs are guided through heliosphere by IMF – Parker spiral
- Propagation subject to interplanetary features, e.g. :
  - Shocks
  - Turbulence
  - Heliospheric current sheet (HCS)





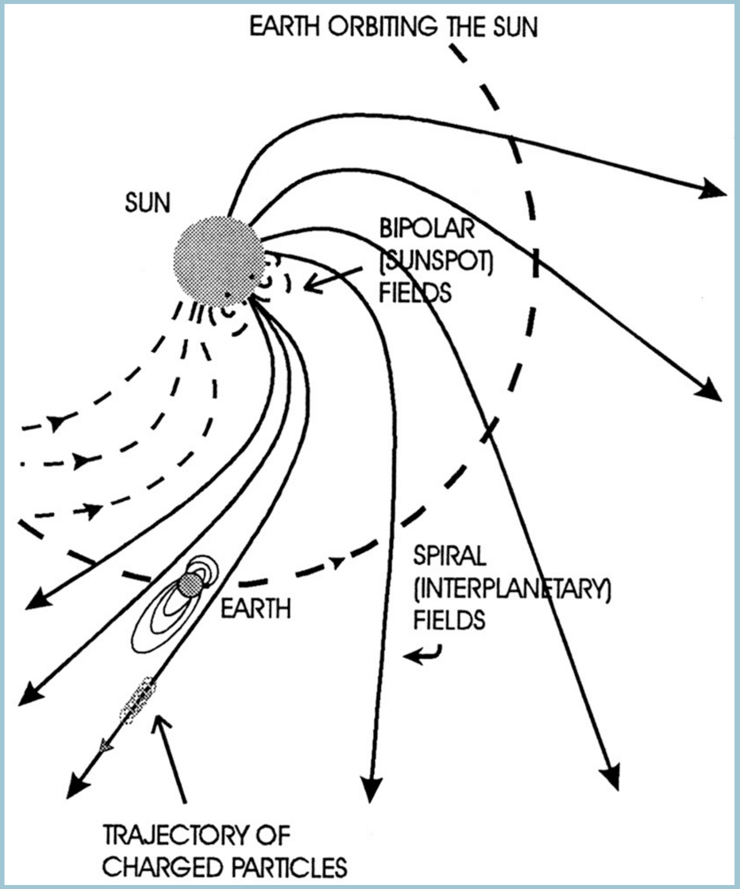
Meyer-Vernet 2007

The HCS separates regions of inward/outward pointing solar magnetic field

Around solar maximum the HCS can have a very wavy shape

iii. What determines if SEPs are detected at Earth?

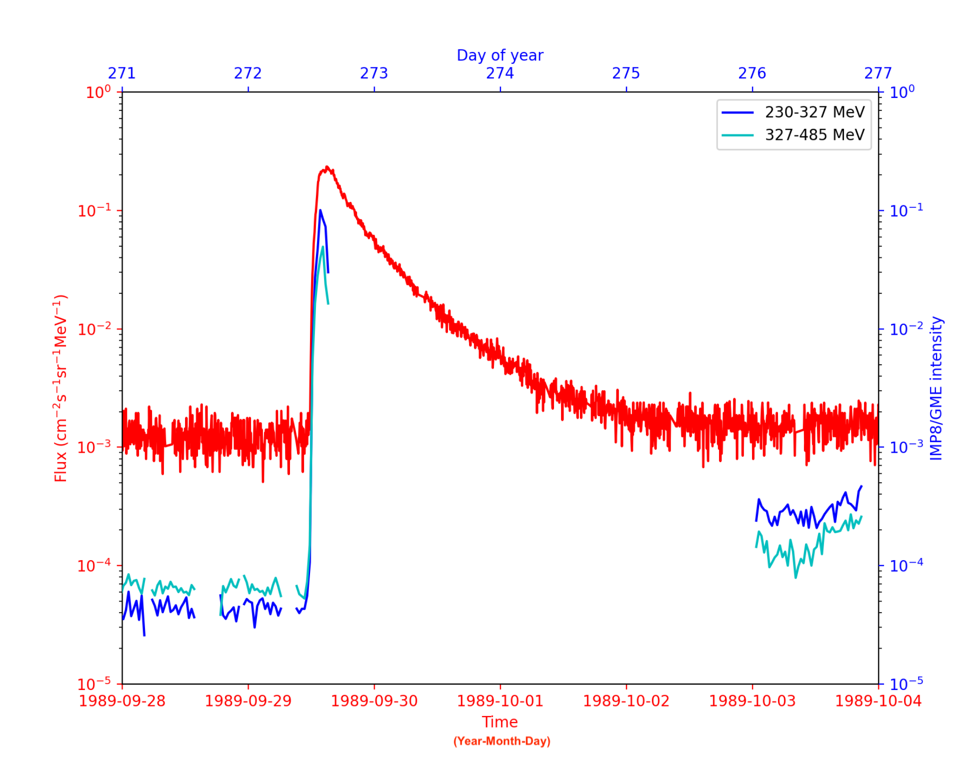
- Not all large eruptive events lead to SEP events on Earth
- Events originating in solar western hemisphere have good magnetic connection with Earth
- Important to understand more about SEP events to mitigate associated risks



Solar magnetic field forms Parker spiral: Earth-Sun best connection around W60

2. Observations of SEP events

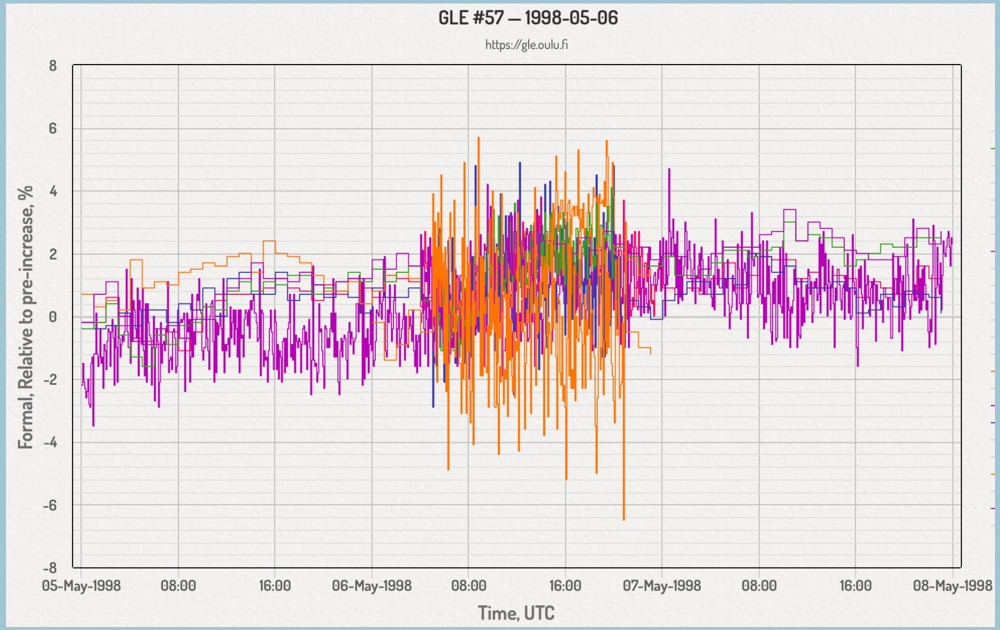
- Lack of high energy datasets to use that cover large time period
- GOES-HEPAD dataset is most comprehensive with fewest data gaps, extends to 700 MeV
- Analysed 30 SEP events (26 GLE, 4 non-GLE) within this dataset between 1989-2017
- Compared SEP event data (e.g. peak flux) with properties of the associated:
  i. GLE
  ii. Coronal mass ejection
  iii. Solar flare

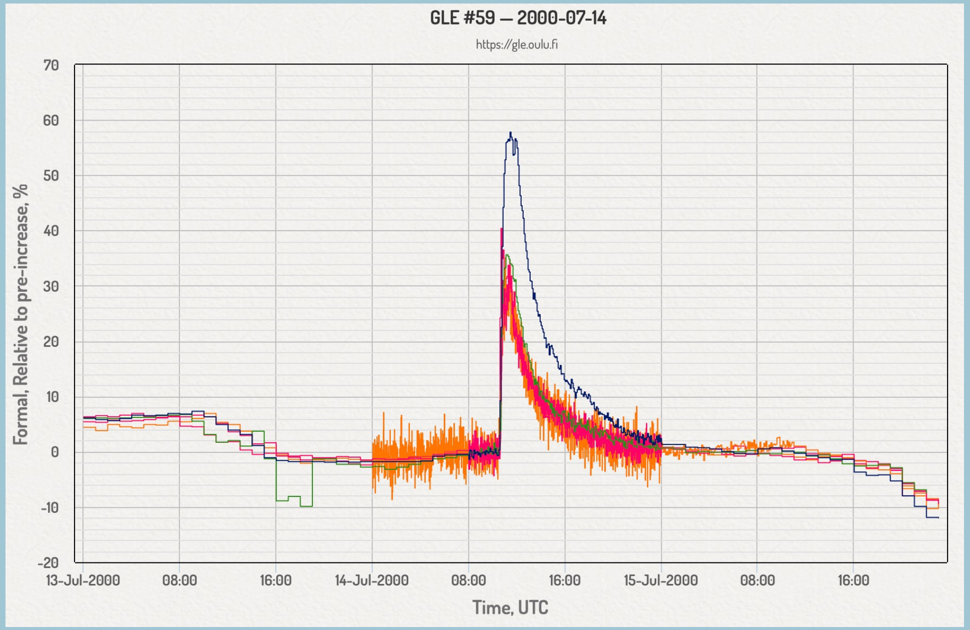


GOES-HEPAD flux profiles in red (350-420 MeV) and IMP8-GME data in blue for the GLE of September 1989

i. Comparison of SEP and GLE properties

- Properties of GLE (peak flux, fluence) taken from neutron monitor with largest increase for each GLE
- Properties only taken from events with well defined profile

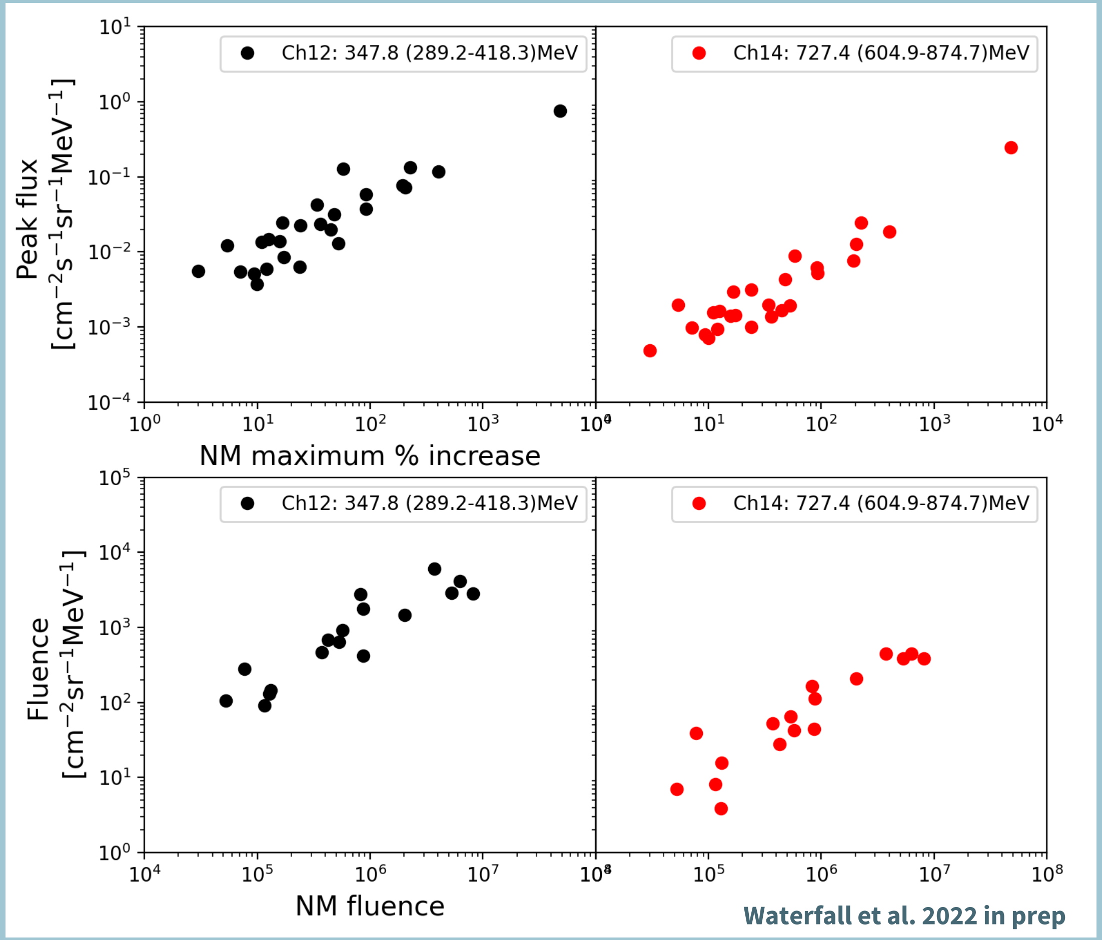




GLE database: https://gle.oulu.fi

i. Comparison of SEP and GLE properties

- Very strong correlations between peak fluxes and maximum increases (0.981 and 0.998 for Ch12 and Ch14 respectively)
- Also strong for event fluence relationships: 0.72 and 0.90 for Ch 12 and 14

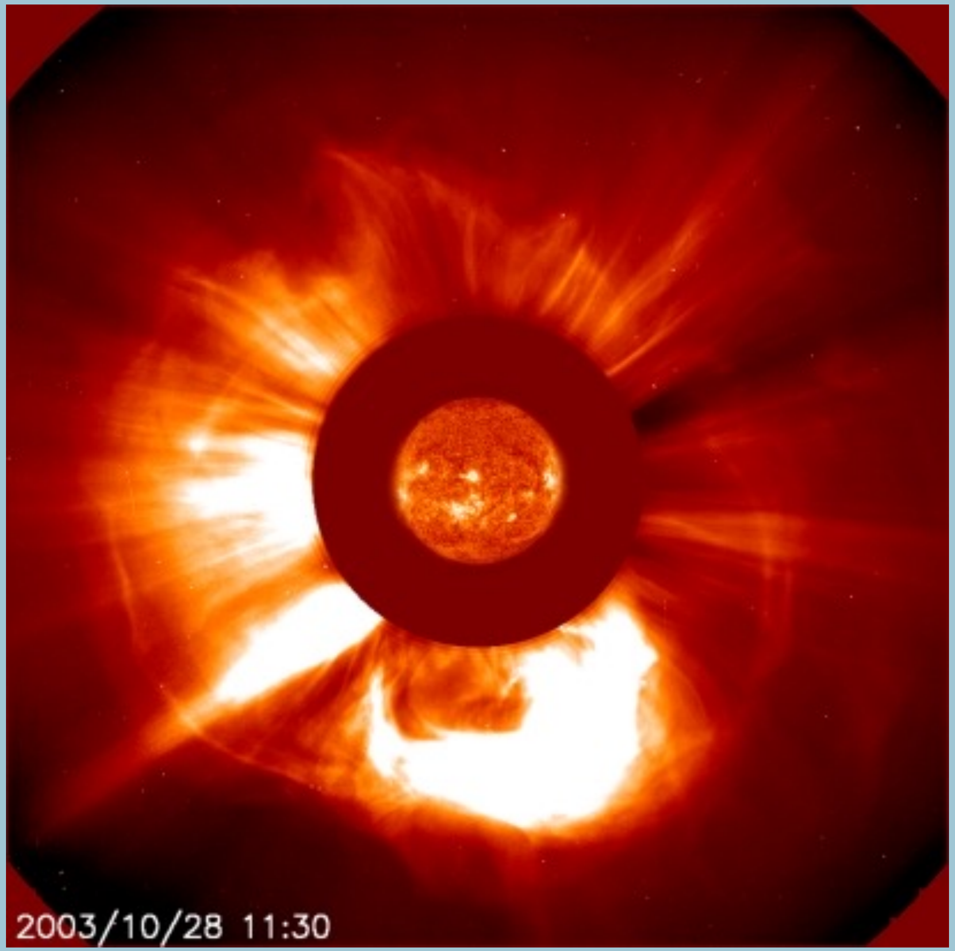


Top: NM maximum % increase for GLEs in our sample compared with Ch 12 (black) and Ch 14 (red) peak fluxes

Bottom: NM fluence vs. Ch 12 and Ch 14 fluence

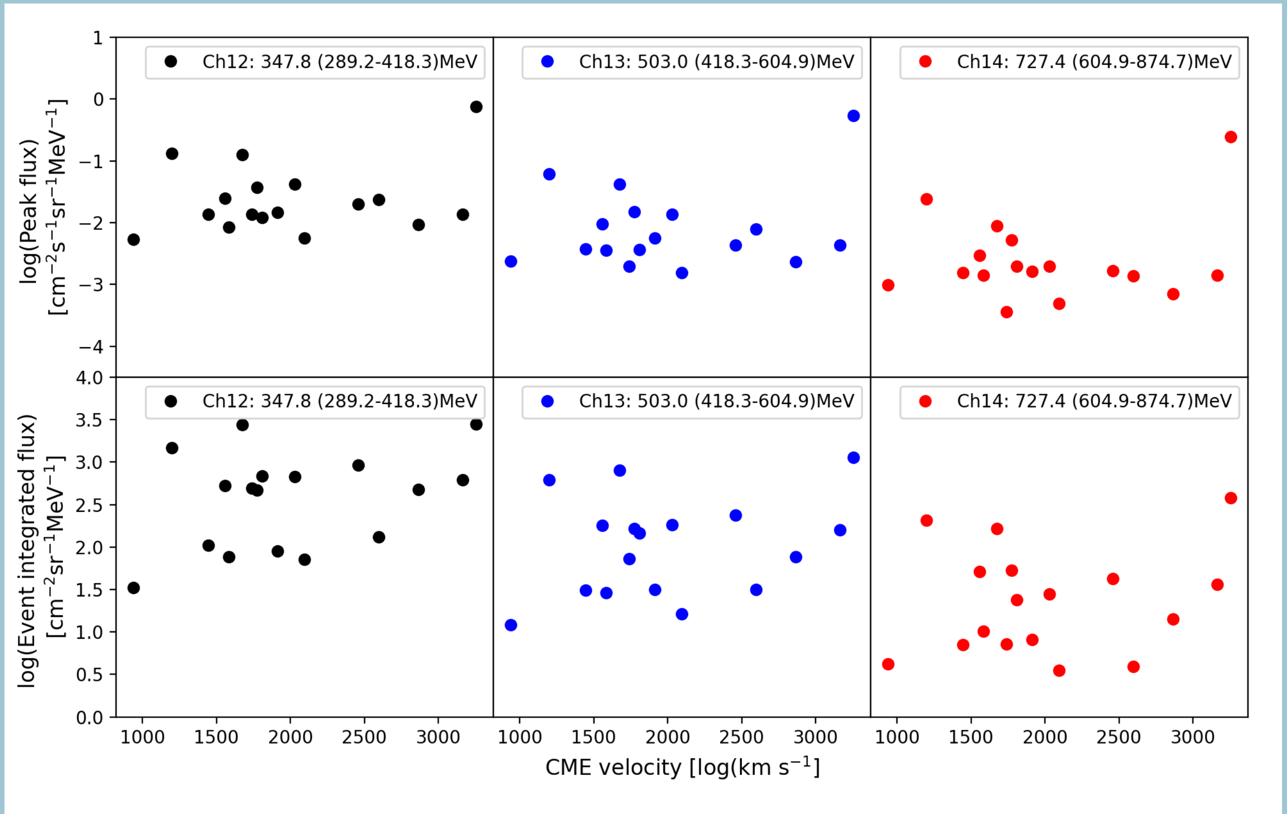
ii. Comparison of SEP and CME properties

- Different CME properties to consider: velocity, width
- 27/30 are halo CMEs
- CME data from SOHO/LASCO
- Lack of data in 1980/90s



Halo CME from Halloween storms of October 2003

ii. Comparison of SEP and CME properties



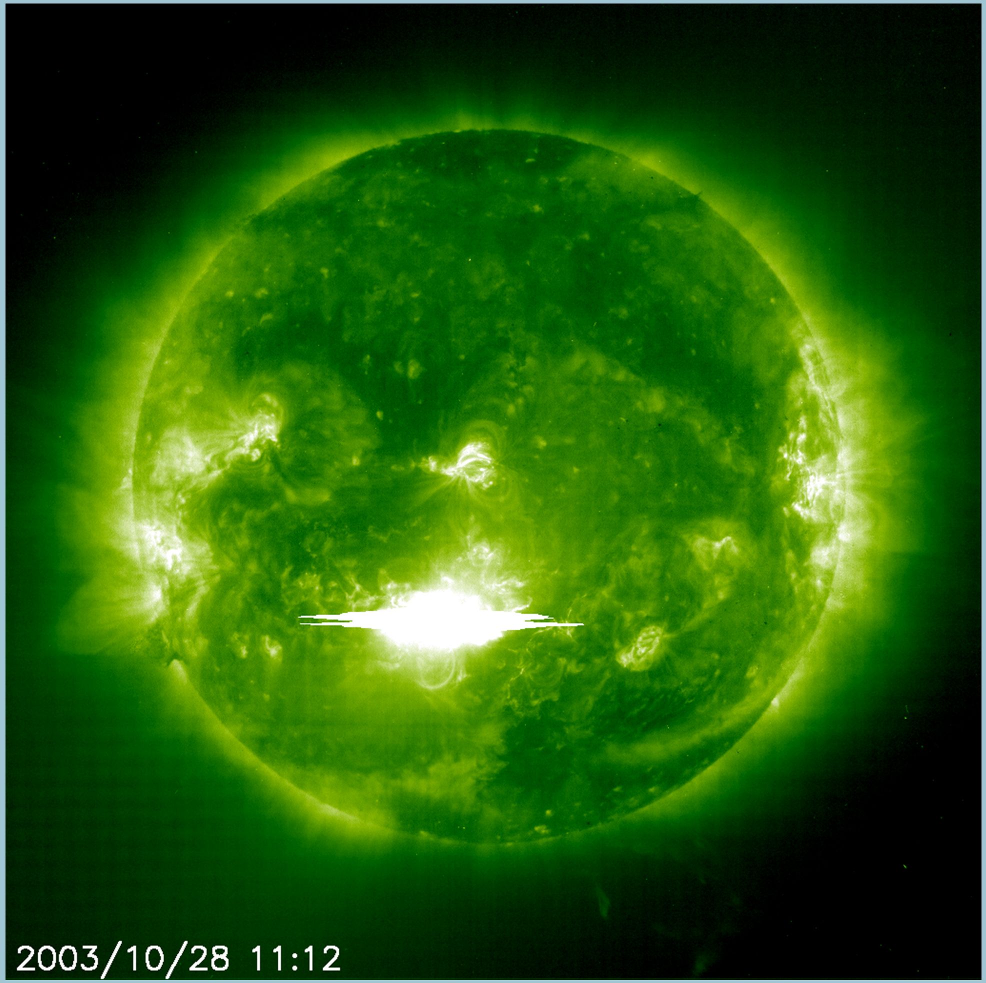
CME velocity compared with the SEP event fluence (bottom row) and peak flux (top row) in each of the three high energy channels

Waterfall et al. 2022 in prep

- Correlation coefficient between CME velocity and peak flux in Ch 12, 13 and 14 is 0.24, 0.21, 0.18
- In low energy studies (>10, >60 MeV) correlation coefficients are between 0.57-0.40
- Correlation between CME velocity and event fluence in Ch 12, 13 and 14 is 0.35, 0.28, 0.19
- In low energy studies (>10, >60 MeV) coefficients are between 0.60-0.45

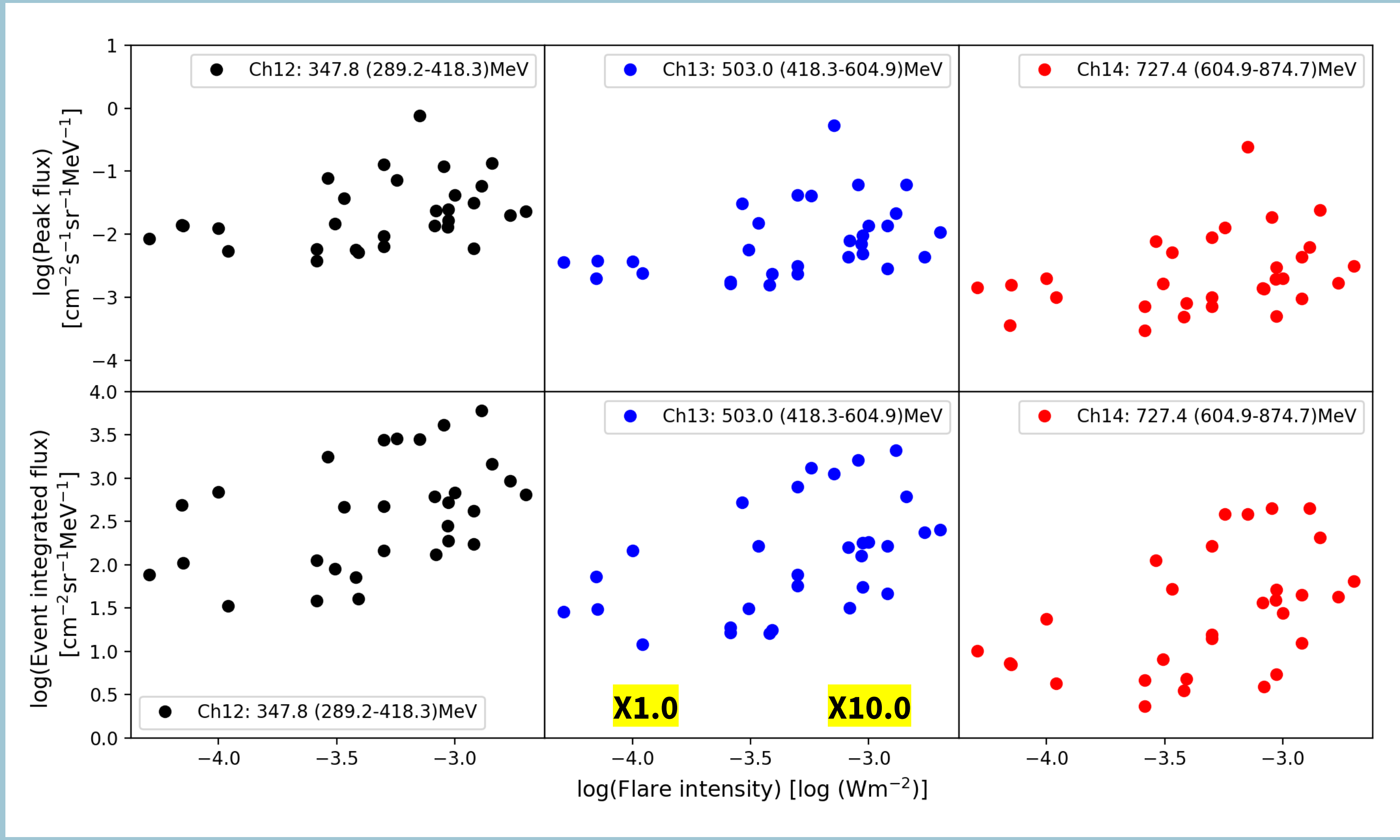
iii. Comparison of SEP and flare properties

- Flare info from GOES SXR data
- Looked at peak, duration, location, proximity to HCS etc



X class flare from Halloween storms of October 2003

iii. Comparison of SEP and flare properties

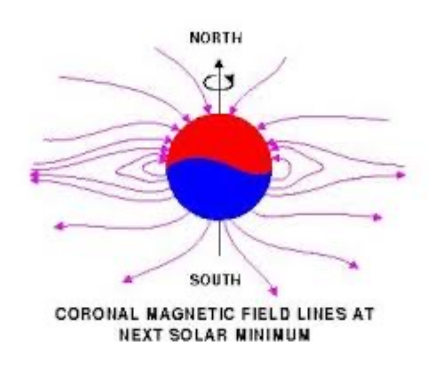


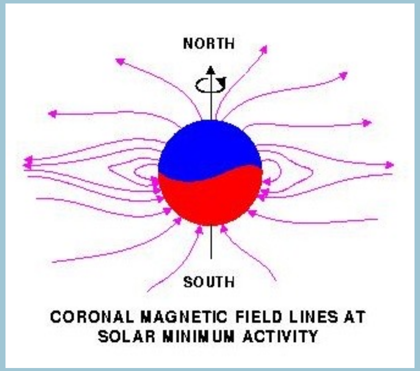
Peak flare intensity compared with the SEP event fluence (bottom row) and peak flux (top row) in each of the three high energy channels

Waterfall et al. 2022 in prep

- Correlation coefficient between peak flare intensity and peak flux in Ch 12, 13 and 14 is 0.37, 0.41 and 0.33
- In low energy studies (>10, >60 MeV) coefficients are between 0.55-0.63
- Correlation between peak flare intensity and event fluence in Ch 12, 13 and 14 is 0.44, 0.49, 0.47
- In low energy studies (>10, >60 MeV) coefficients are between 0.48-0.41

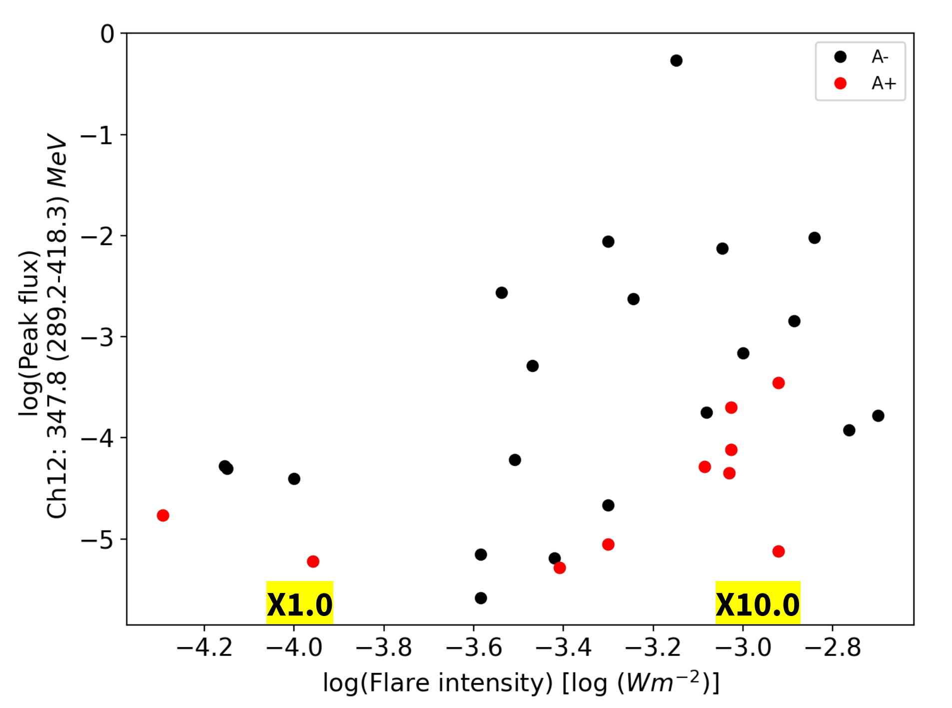
IMF polarity





- A+ polarity describes an IMF where the B field points outwards in the northern hemisphere, inwards in the southern, separated by the heliospheric current sheet

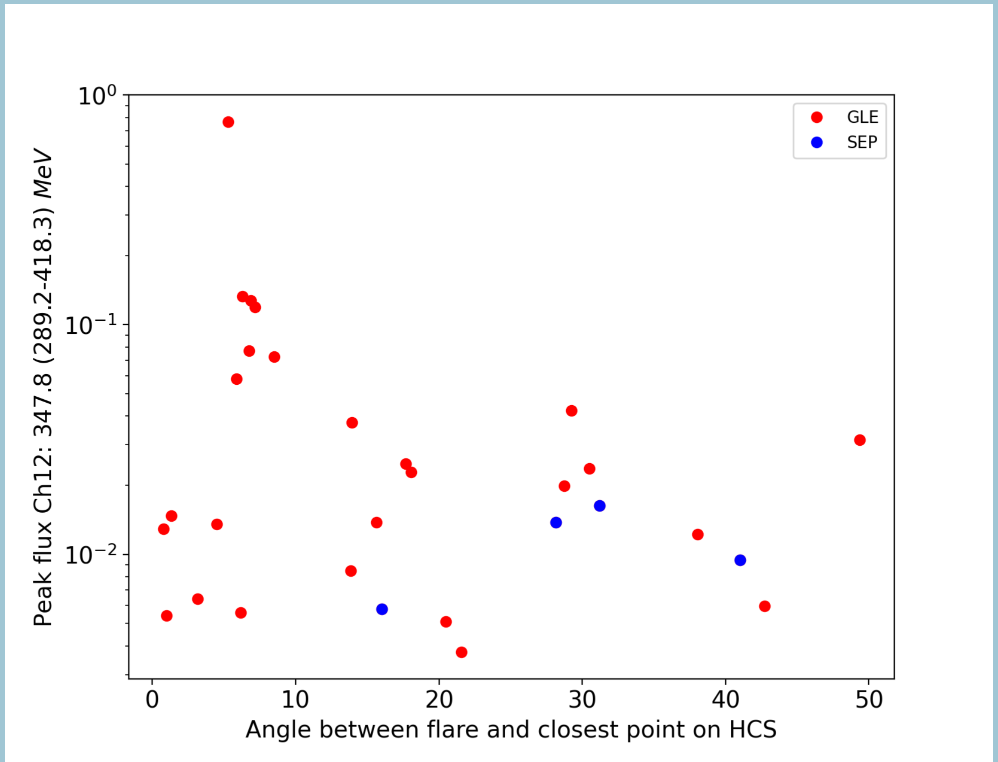
- Events that occur during A+ polarities tend to have lower peak fluxes for a given flare magnitude



Peak intensity v. Peak flux plot (from before) with events occurring during A+ (red) or A- (black) polarity highlighted

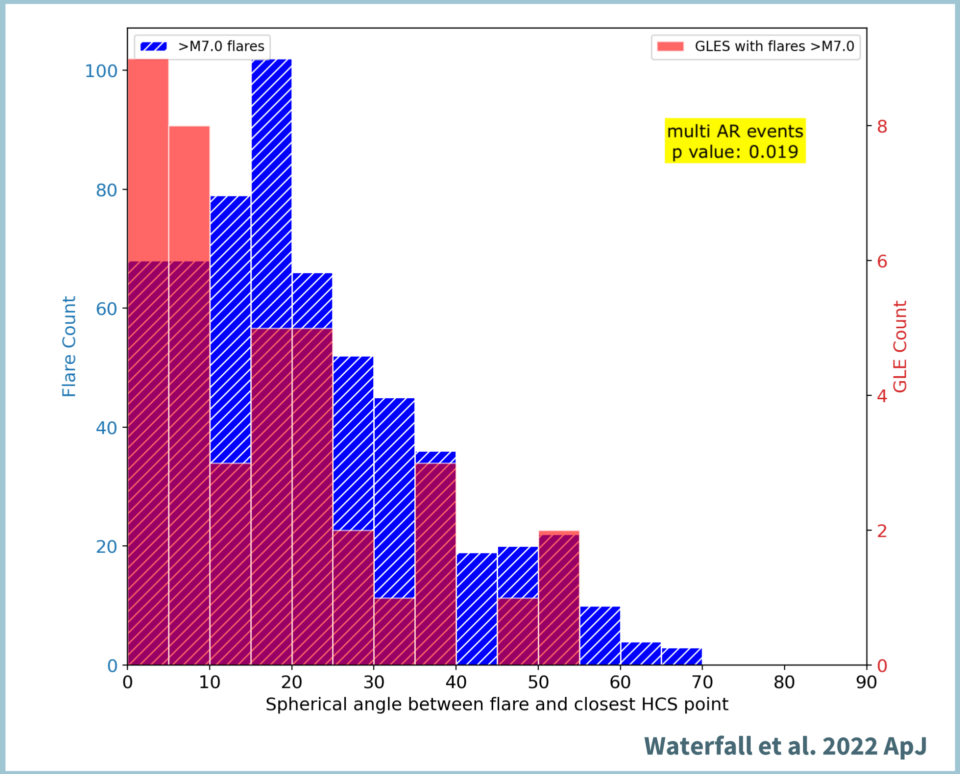
Waterfall et al. 2022 in prep

Heliospheric current sheet



Waterfall et al. 2022 in prep

Peak flux in Ch12 as a function of the spherical angle between flare and closest point on HCS



Histogram of >M7.0 flares associated with GLEs (red) and non-SEP events (blue) between 1976 and 2020

- 50% of GLEs occur at less than 10º from HCS
- HCS drifts explored in Waterfall et. al. 2022

- GLE associated flares peak closer to the HCS
- 2 sample Kolmogorov-Smirnov test suggests two samples drawn from different distributions

Conclusions from high energy observations

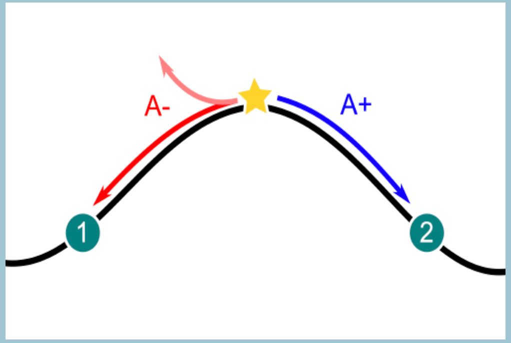
- >300 MeV SEP events show weaker correlations with flare and CME parameters than are seen at energies <100 MeV
- Correlations between SEP and neutron monitor data are strong
- Most (26/30) of our >300 MeV SEP events are associated with GLEs
- More high energy data is needed to further constrain relationships

3. Modelling of SEPs

- 3D test particle model used (Dalla & Browning 2005, Battarbee et al. 2018) which includes: drifts due to curvature and gradient of the Parker spiral and HCS drift
  - No perpendicular transport associated with turbulence is included
  - Events are modelled both with and without a HCS
- This polarity of the field relative to the current sheet has been seen to affect the direction of particle drift in previous simulations, e.g. Battarbee et al. 2018

Event (GLE #) (1)	Flare location (2)	Polarity (3)	Vsw / $km\,s^{-1}$ (4)	Δf ° (5)	ΔE ° (6)	ψ ° (7)	Counts at Earth with no HCS? (8)
1984 Feb 02 (39)	S16W94	–	500*	8.9	15.7	26.4	None
1989 Aug 16 (41)	S18W85	–	500*	18.0	6.8	31.3	None
1989 Sep 29 (42)	S36W90	–	500*	7.2	5.1	35.6	Yes[b]
1989 Oct 19 (43)	S27E10	–	500*	5.9	5.6	71.2	None
1989 Oct 22 (44)	S27W31	–	500*	6.7	6.9	41.8	None
1989 Oct 24 (45)	S30W57	–	500*	8.5	14.6	35.1	None
1991 Jun 15 (52)	N33W70	+	500*	49.3	32.8	34.9	Yes[a]
1997 Nov 06 (55)	S18W63	+	350	17.7	0.7	24.9	Yes[b]
2001 Apr 15 (60)	S20W85	–	480	6.3	11.8	31.4	Yes[b]
2001 Apr 18 (61)	S20W117	–	500	5.6	10.8	52.6	None
2003 Oct 28 (65)	S16E08	–	730	28.8	42.7	52.3	Yes[a]
2003 Oct 29 (66)	S15W09	–	1000	29.2	48.3	38.5	Yes[a]
2003 Nov 02 (67)	S14W59	–	510	30.5	48.9	18.4	Yes[a]
2005 Jan 20 (69)	N14W63	–	820	5.3	0.6	29.8	None
2006 Dec 13 (70)	S06W24	–	650	13.9	25.0	14.5	Yes[a]
2012 May 17 (71)	S11W76	–	350	13.9	14.8	14.7	None
2017 Sep 10 (72)	S08W88	+	510	15.6	8.3	41.7	None

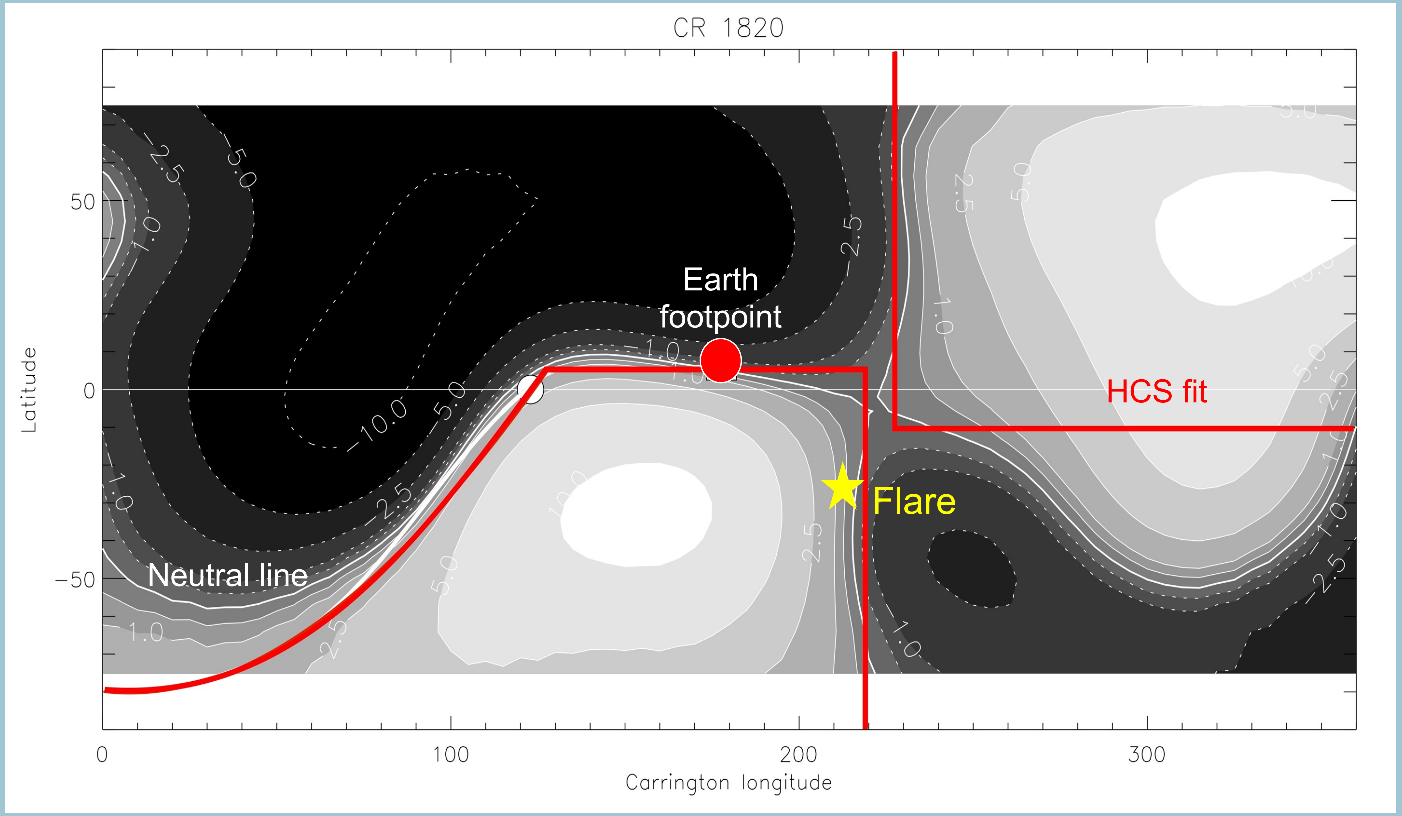
Waterfall et al. 2022 ApJ



Directional drift along the HCS during A+/A- IMF polarities

Example event with flare close to HCS: GLE 42

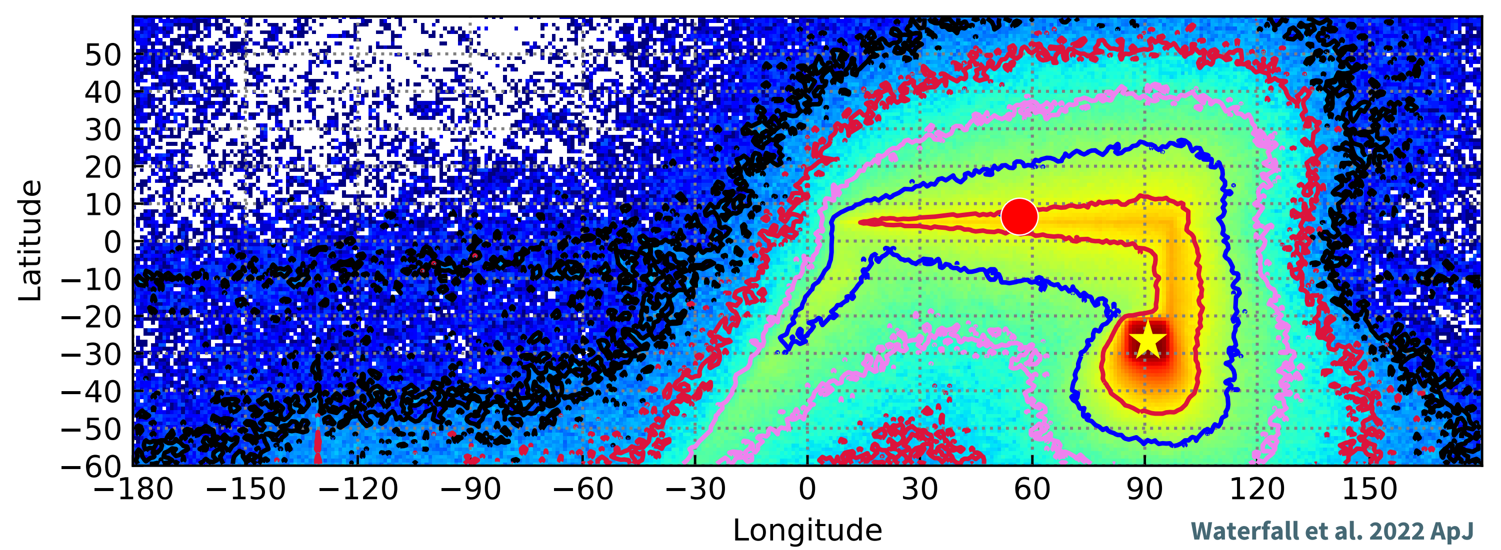
- Source surface map for GLE 42 (29 September 1989)
    - Model HCS (red line) is fit to neutral line (white line)
    - **Flare and Earth are both located on/near the HCS**
- Polarity taken as A-



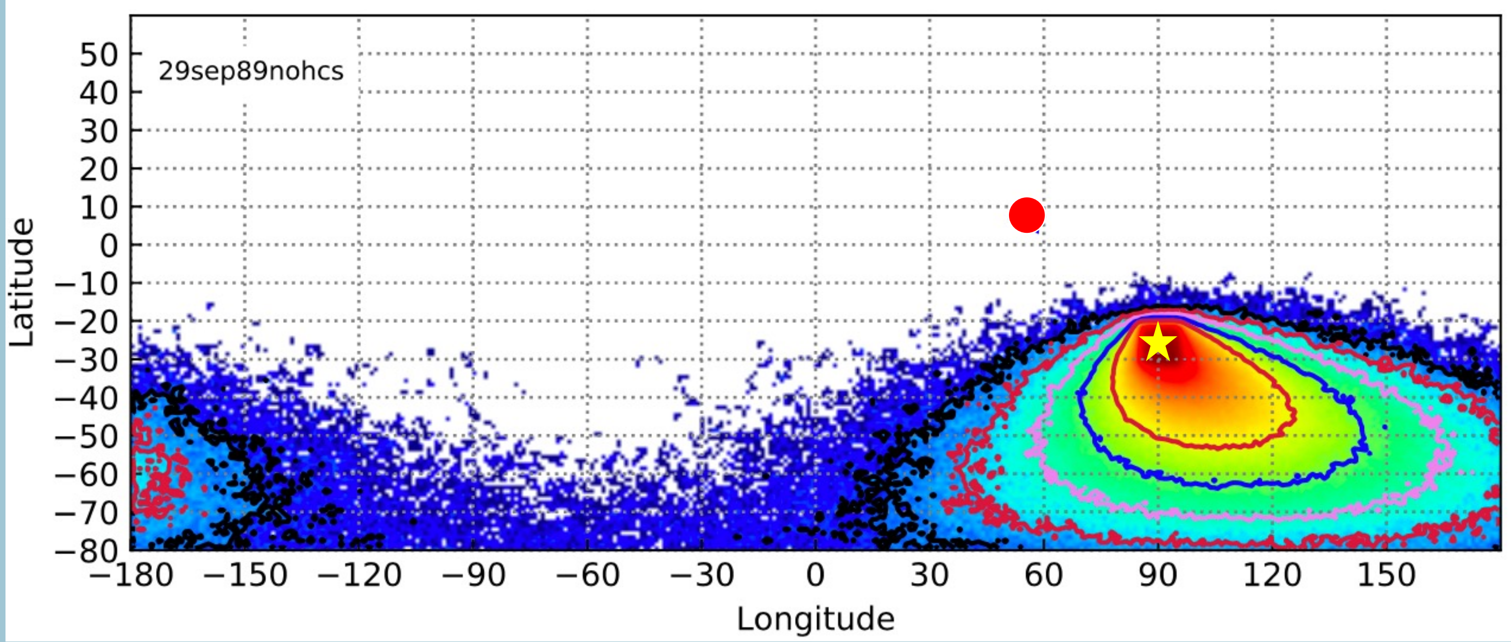
Source surface map for CR 1820

Example event with flare close to HCS: GLE 42

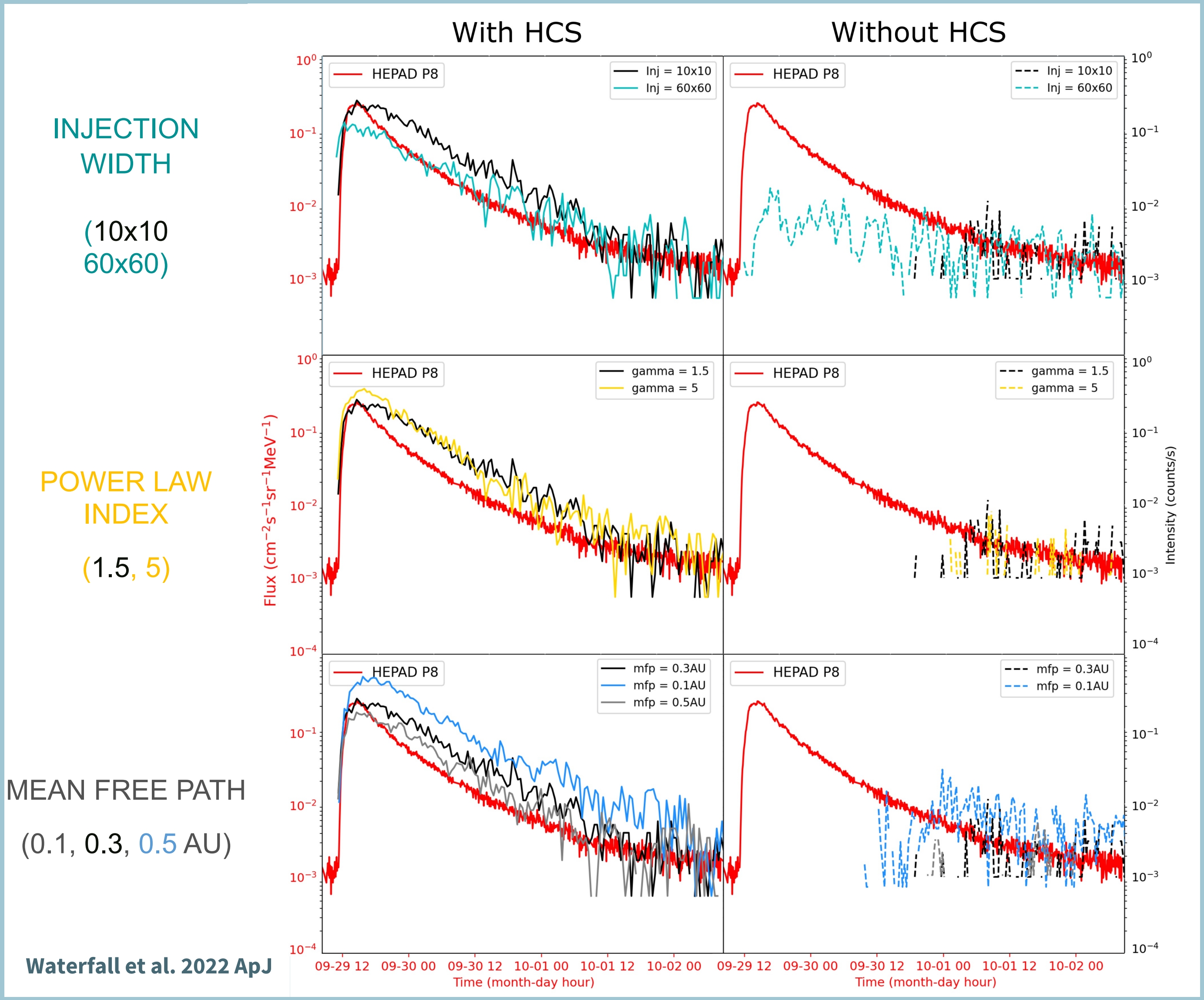
- Plots show cumulative **proton** crossings at 1AU for 72 hrs with HCS (top) and without (bottom)
- A- polarity causes drift of protons East towards the Earth with HCS
- Particles efficiently transported by HCS in heliosphere
- Parameters are varied and profiles at Earth plotted



Waterfall et al. 2022 ApJ



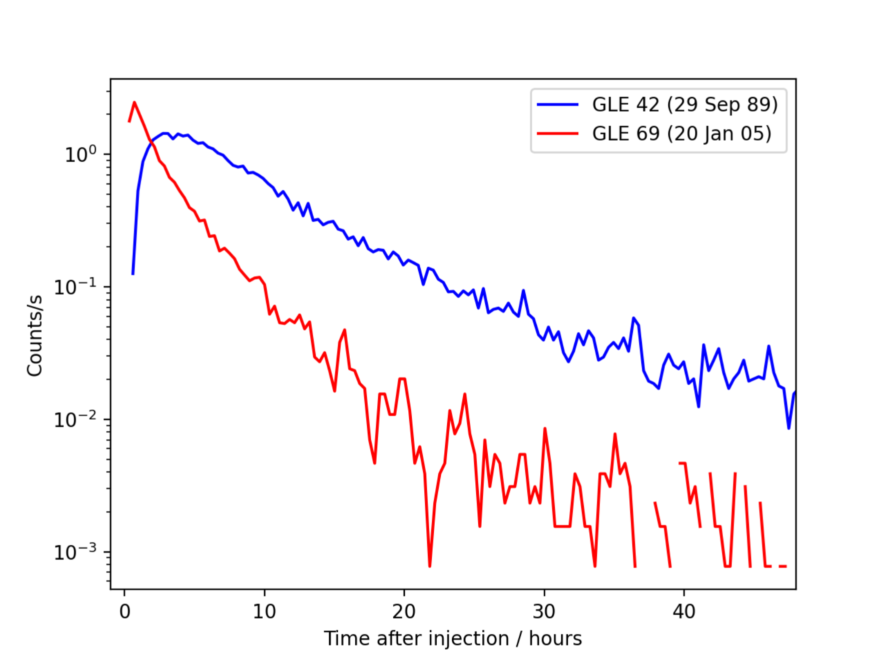
Varying model parameters: GLE 42



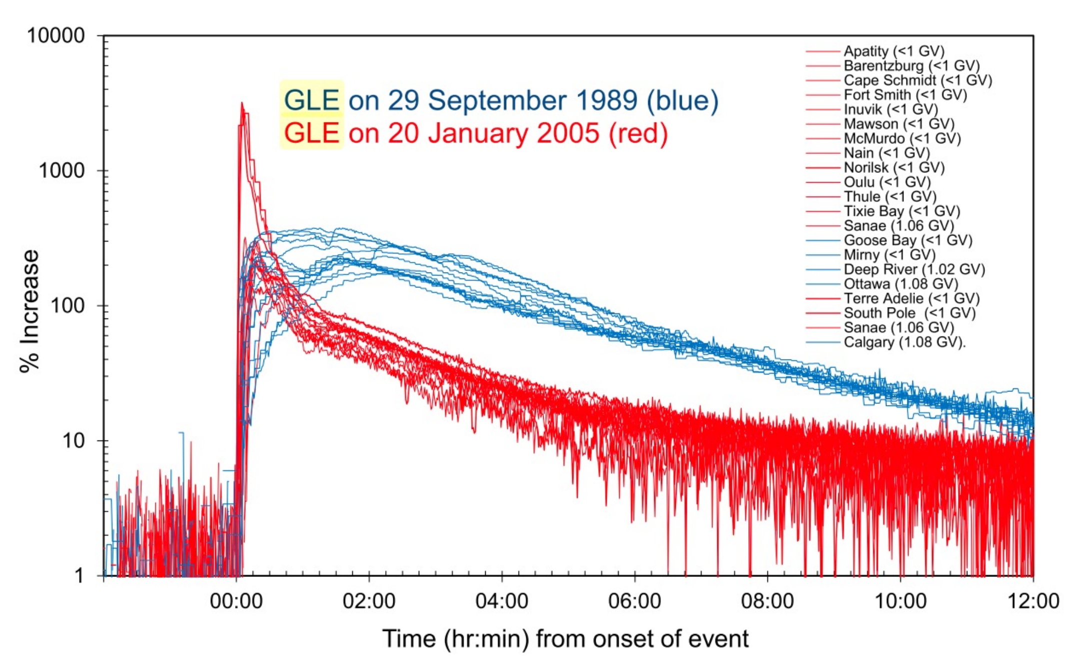
- Without the HCS, no comparable profile at Earth can be obtained
- The HCS is the dominant mechanism affecting particle transport in this simulation
- A flare closer to the HCS leads to more HCS transport
- Red profile: observed P8 profile from GOES HEPAD

Comparison of model and neutron monitor profiles

- Model fits observations well for events with source locations close to the HCS
- For example GLE 42 and 69



Simulation results for GLE 42 and 69



Moraal et al. 2014

Summary and conclusions

Modelling:

- The HCS plays a significant role in distributing energetic particles throughout the heliosphere and is necessary in >70% of our modelled events
- Particle transport along the HCS is most efficient when the flare is within 10 degrees of the HCS
- 44% of GLEs between 1976-2017 were within 10 degrees of the HCS

<u>General summary:</u>

- >300 MeV events pose the most risk to manned spaceflight and technology
- Understanding more about the nature of SEP acceleration and transport through further observations and modelling will aid in our ability to forecast these events
- >300 MeV events are rare – hopefully (!) see more of them as we approach solar maximum