Prediction of Solar Energetic Particle Events

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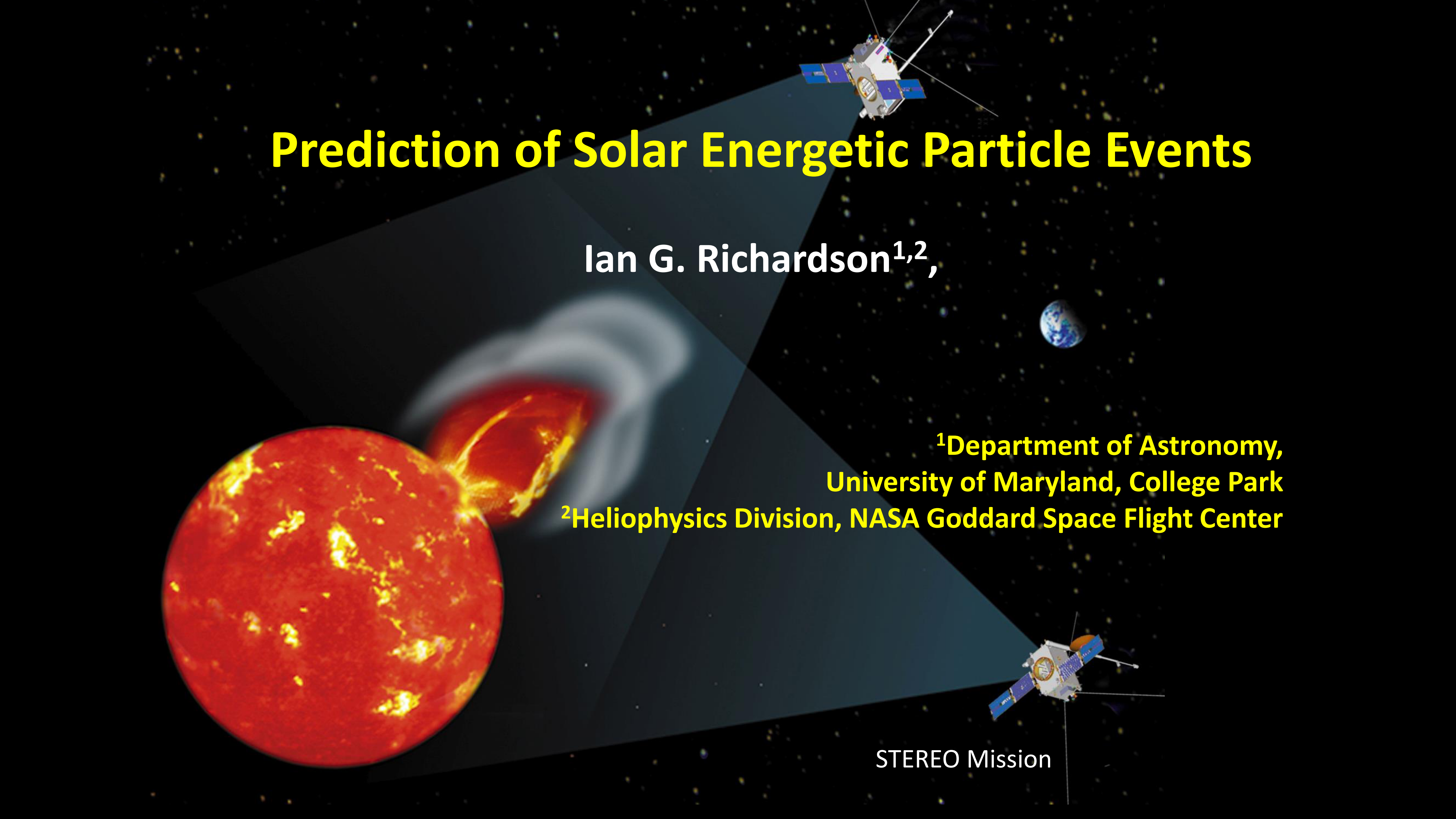
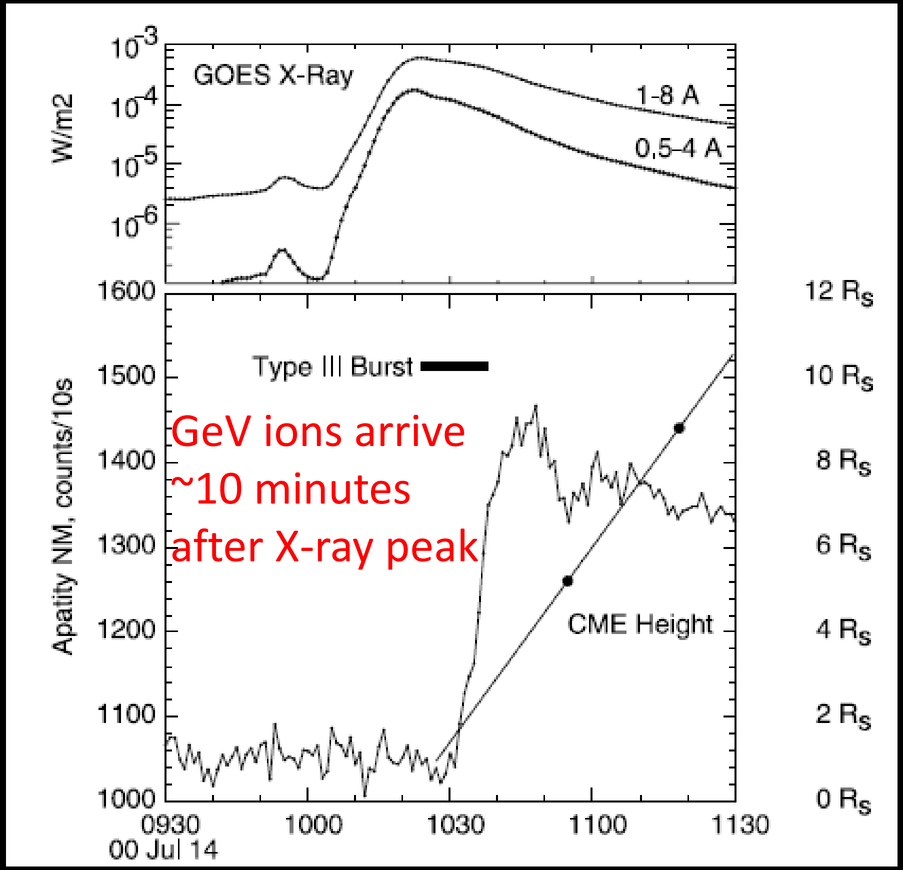


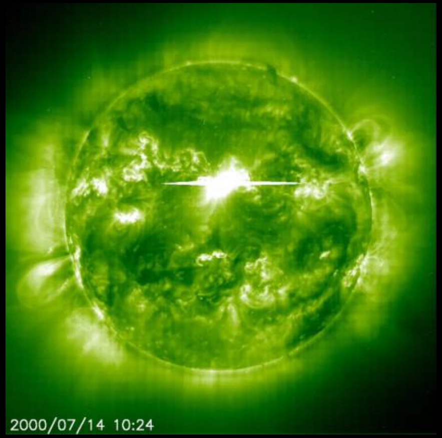
STEREO Mission

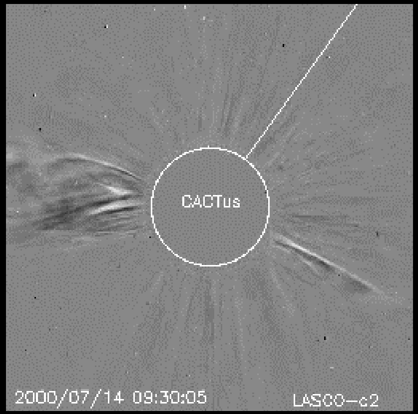
Solar energetic particle (SEP) events are accelerated by solar flares and shocks driven by coronal mass ejections (CMEs):

- Range in energy from ~10s of keVs to GeVs;
- Occur ~randomly and with little warning – the fastest particles can arrive at Earth's orbit within minutes of the solar event;
- A significant hazard to space-based assets, in particular outside the shield of Earth's magnetosphere.



Richardson et al., 2003





Discovery of Solar Energetic Particle (SEP) Events (*Forbush*, 1946)

Scott E. Forbush
1904-1984

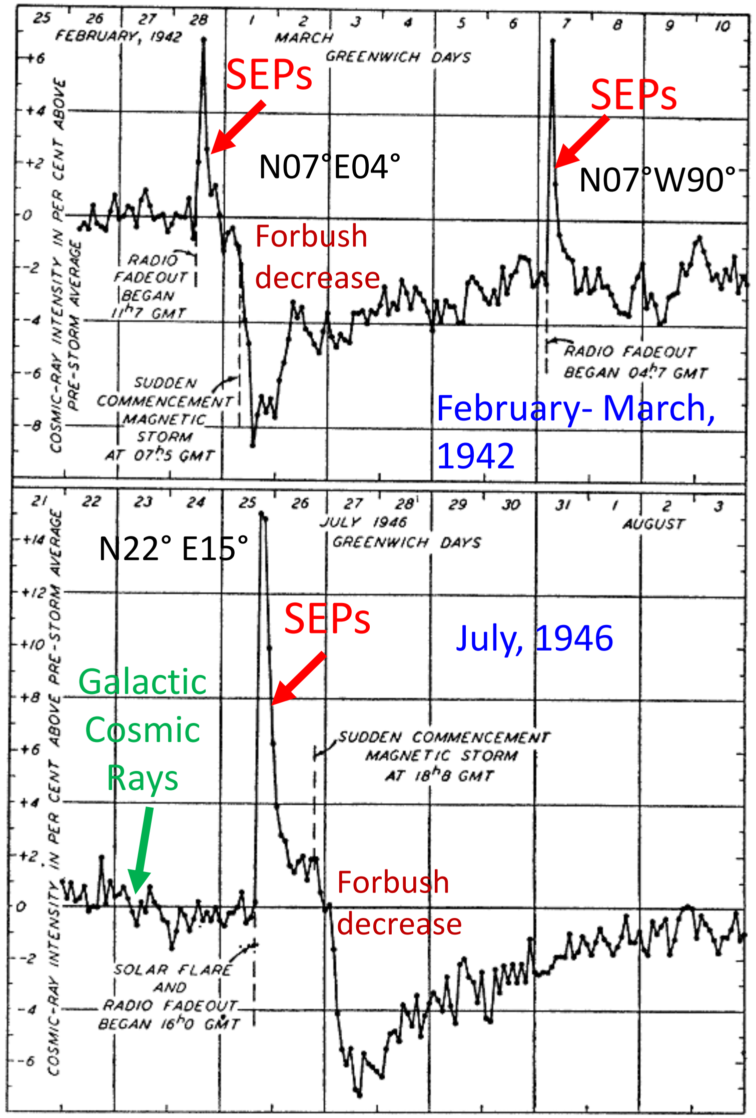


FIG. 1. Three unusual increases in cosmic-ray intensity at Cheltenham, Maryland, during solar flares and radio fadeouts.

Three Unusual Cosmic-Ray Increases Possibly Due to Charged Particles from the Sun

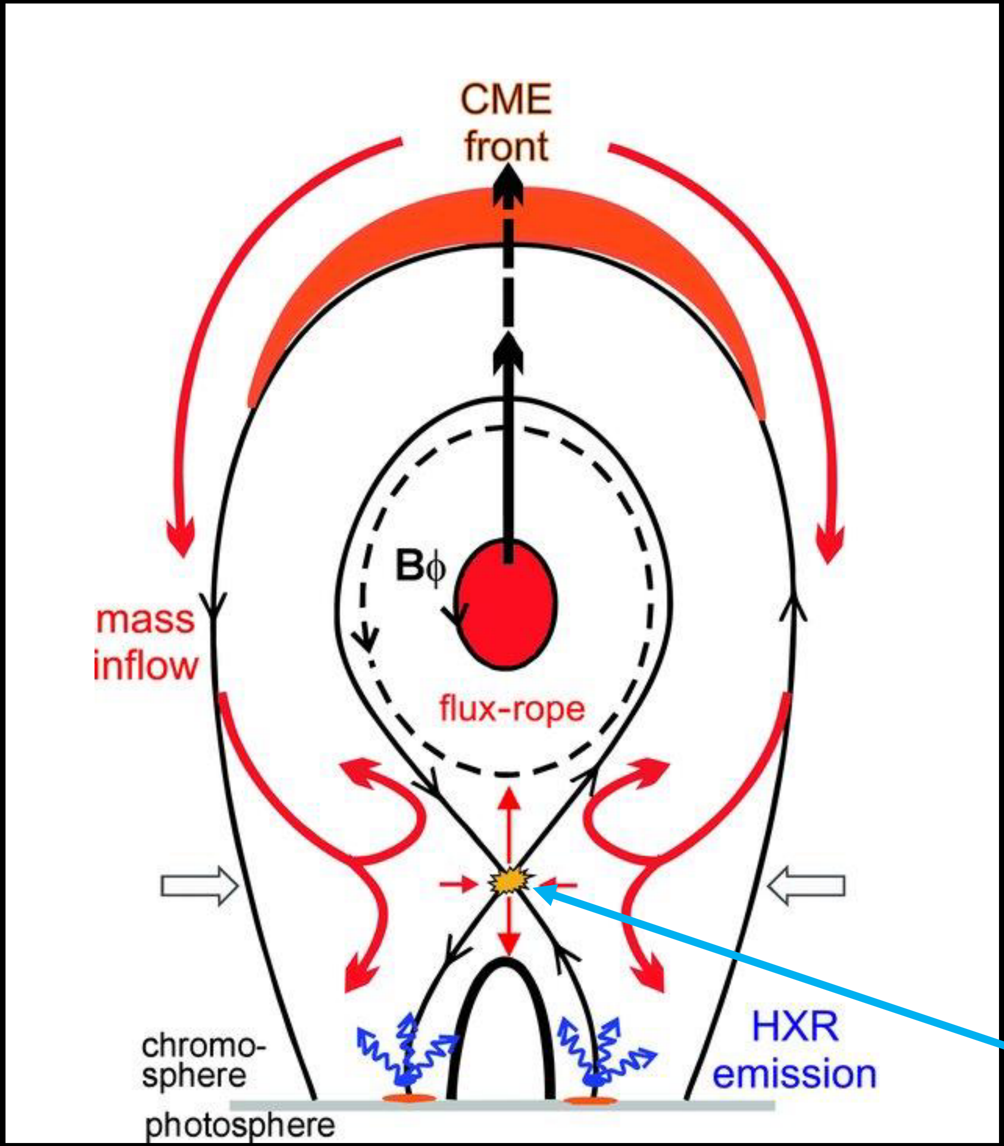
SCOTT E. FORBUSH
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.
October 10, 1946

Began ~simultaneously with (< 1 hour after) a solar flare or radio fade out indicating a flare.

These considerations suggest the rather striking possibility that the three unusual increases in cosmic-ray intensity may have been caused by charged particles actually being emitted by the Sun with sufficient energy to reach the Earth at geomagnetic latitude 48° but not at the equator. It is recognized that particles of this energy should not escape from low latitudes on the Sun except in the absence of the much-disputed permanent solar magnetic field.

But interpreted as evidence of the absence of a permanent solar magnetic field!

(Flare locations from *Shea and Smart*, 1991)



Adapted from Temmer et al., 2010

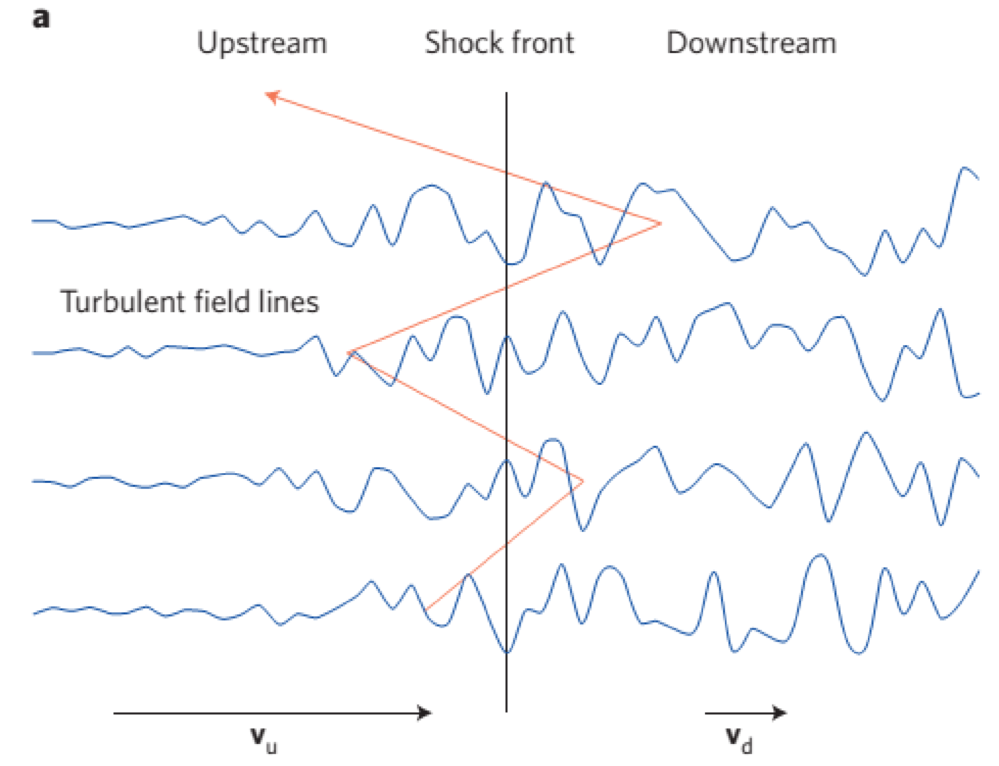
The major locations for the acceleration of SEPs appear to be:

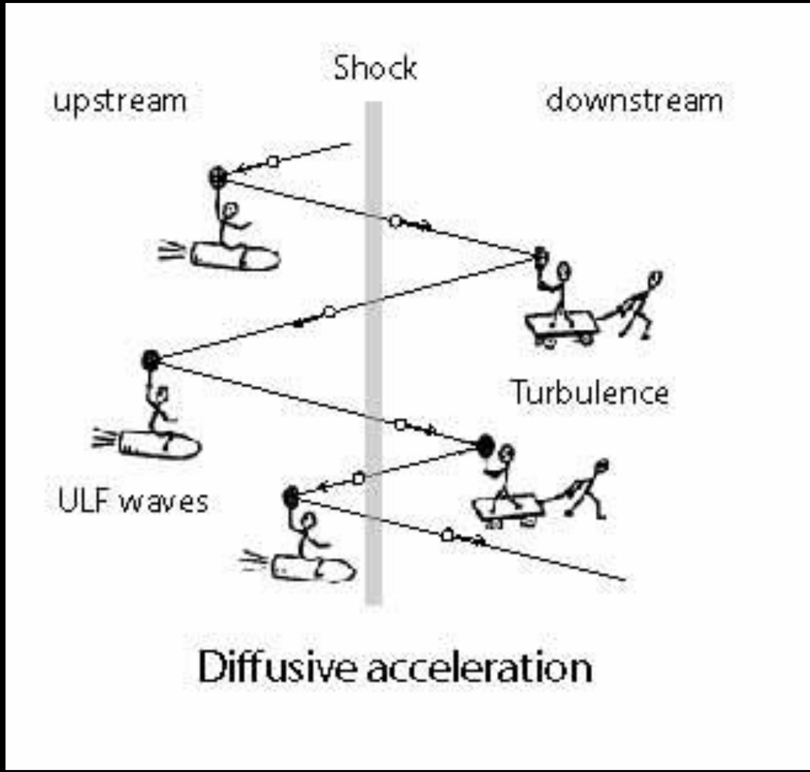
- Solar Flares (e.g., reconnection; wave-particle interactions)
- CME-driven shocks.

There is much discussion of how much these processes contribute to SEP events, or whether a combination of processes is involved e.g., initial flare acceleration followed by shock acceleration?

Particle acceleration by reconnection at neutral line below CME

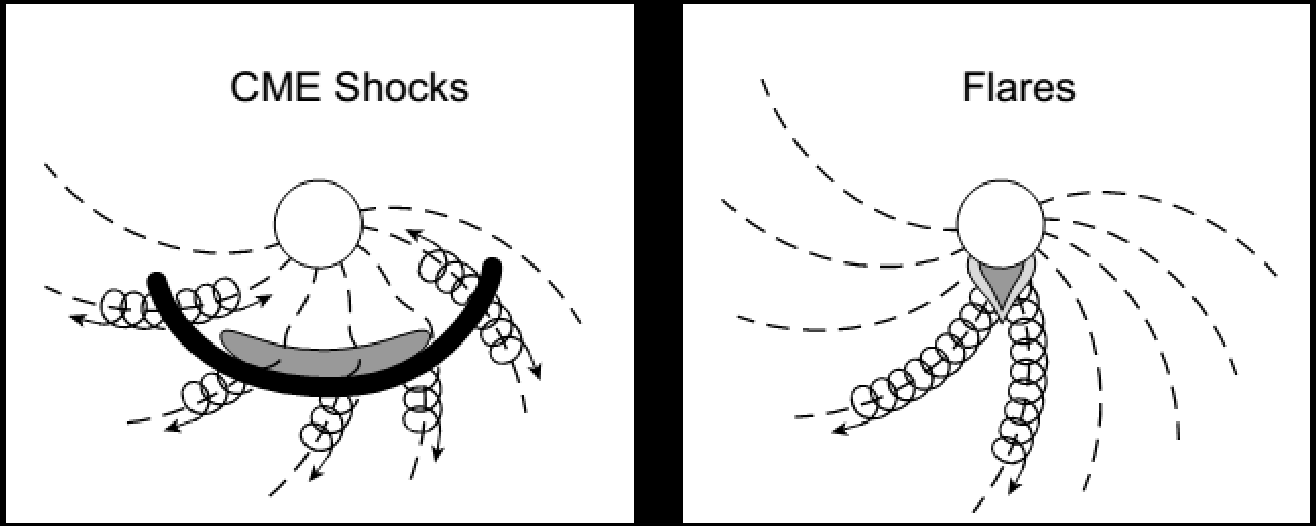
Particle Acceleration by Bouncing Between Converging Scattering Centers Upstream and Downstream of a Quasi-Parallel Shock (Diffusive Shock Acceleration)

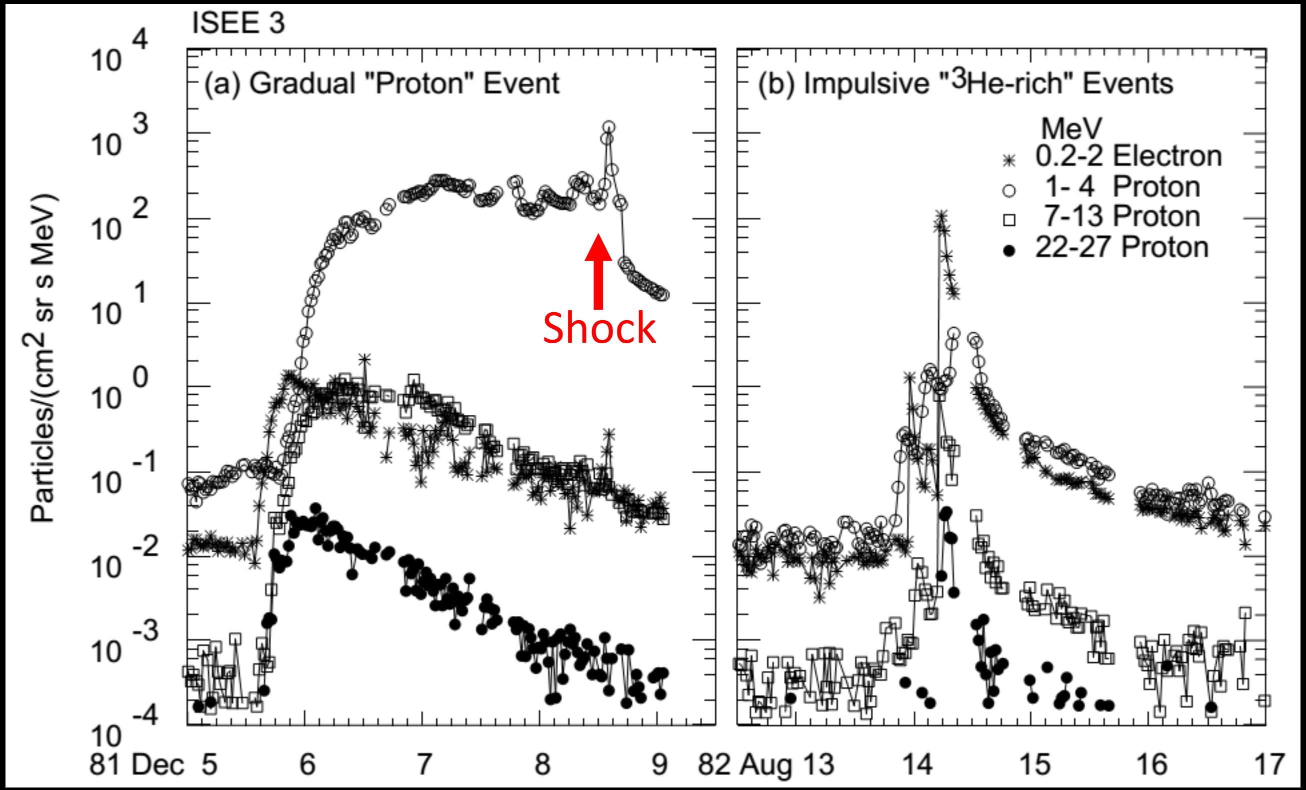




M. Scholer

Quasi parallel shock = Upstream magnetic field ~parallel to shock normal.





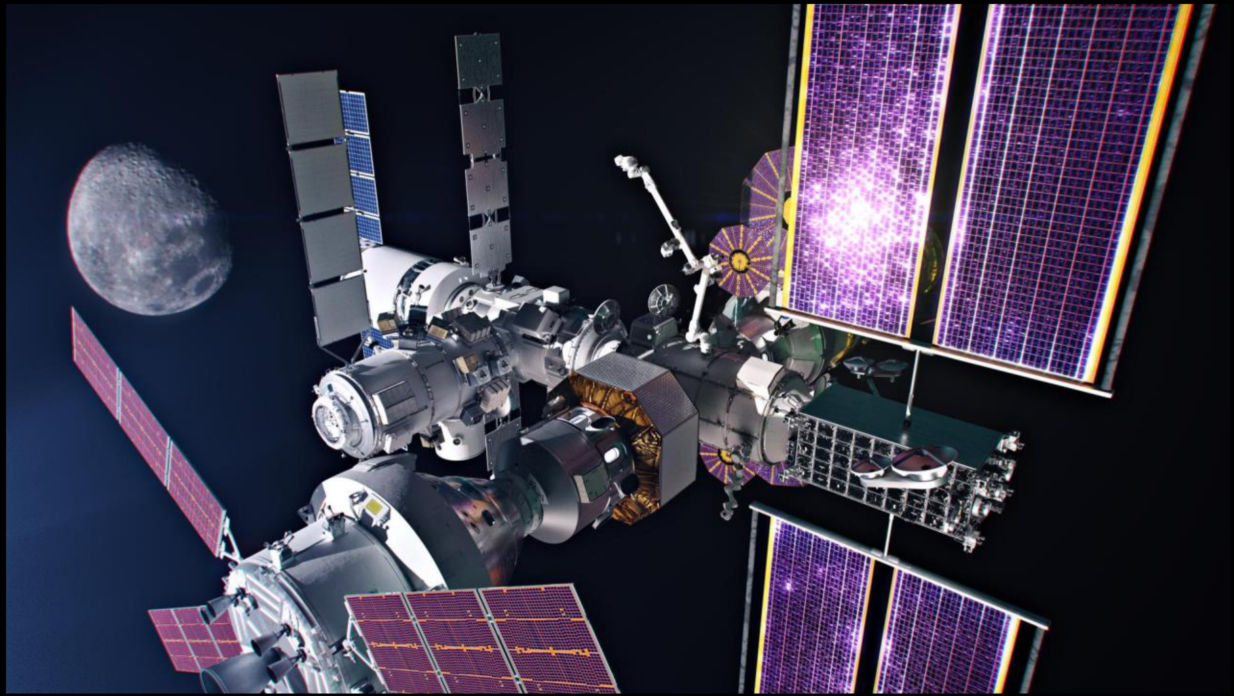
Particle acceleration in solar flares and at CME-driven shocks (*Reames* 1995, 1999)

Note the local intensity peak at shock passage.

Particle transport from the accelerator is also important, but not fully understood.

Particles tend to follow the spiral interplanetary field lines, but observations also suggest that they may be scattered by field irregularities.

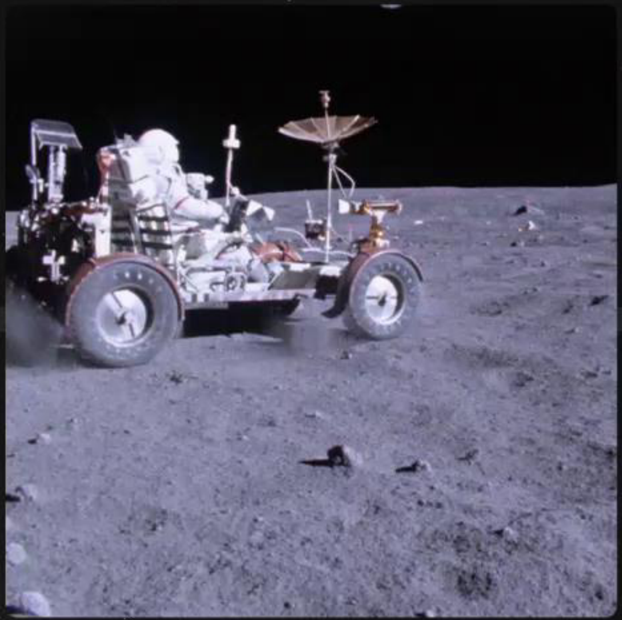
SEP Prediction for Artemis – Gateway and Lunar Exploration; Missions to Mars



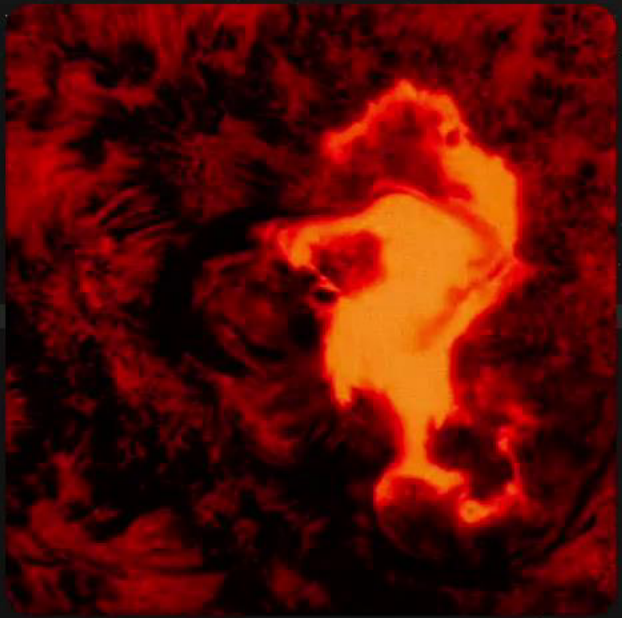
- Less shielding from vehicle and geomagnetic cut off compared to the ISS and Shuttle
- Greatest radiation hazard is from Galactic Cosmic Rays, but flux is relatively constant - monitor astronaut dosage to keep within lifetime limits.
- Intense SEP events are a rare but potentially severe radiation threat
- Need to provide forecasts of the likelihood of an SEP event occurring (e.g., in the next 24 hours) or nowcasts ("an SEP event is underway, take shelter!"), and estimates of the potential radiation hazard.

Probably the Largest SEP Event Recorded in the Space Era Occurred Between the Apollo 16 and 17 Missions

Apollo 16



APR. 1972

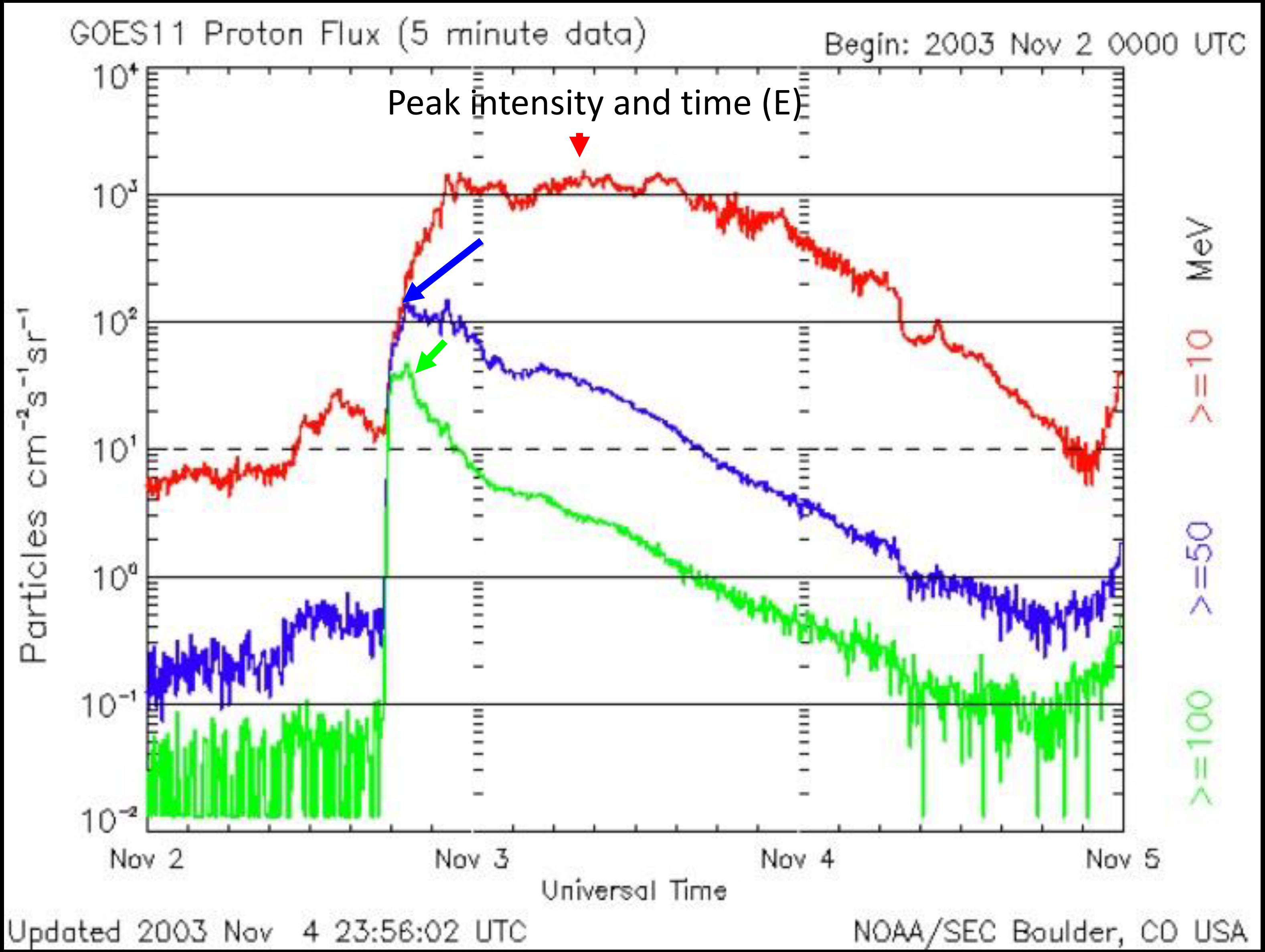


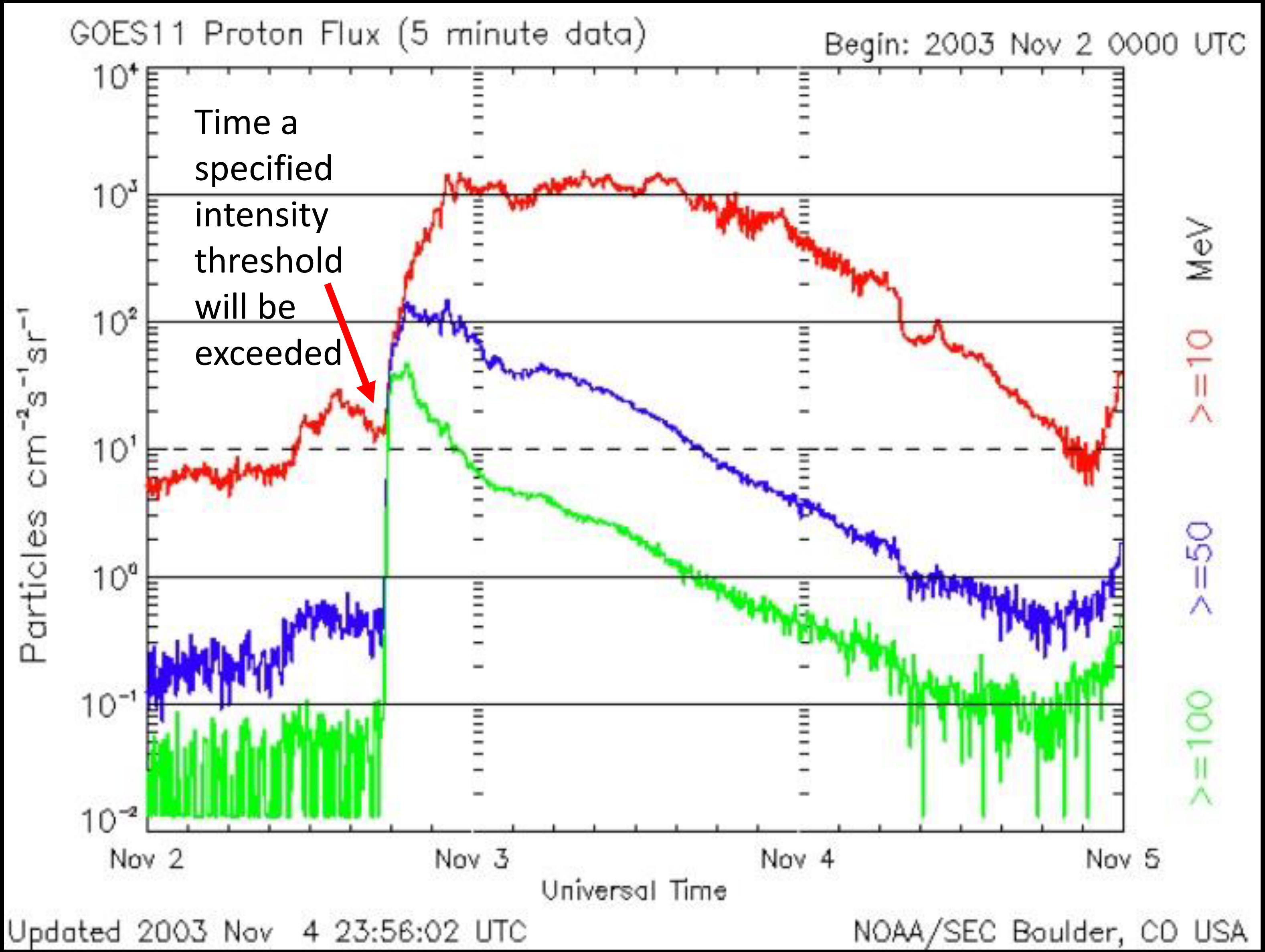
AUG. 1972

Apollo 17

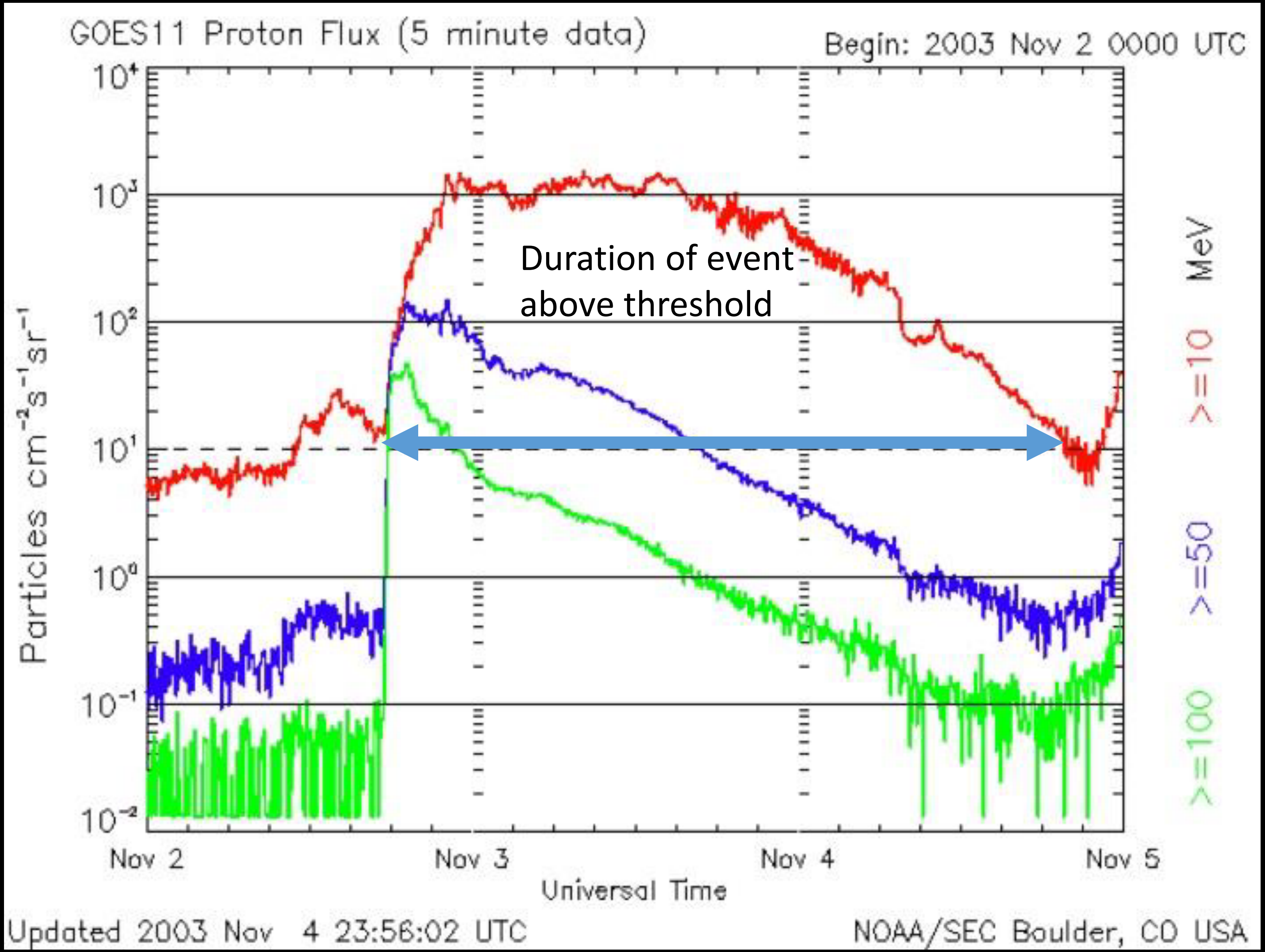
DEC. 1972

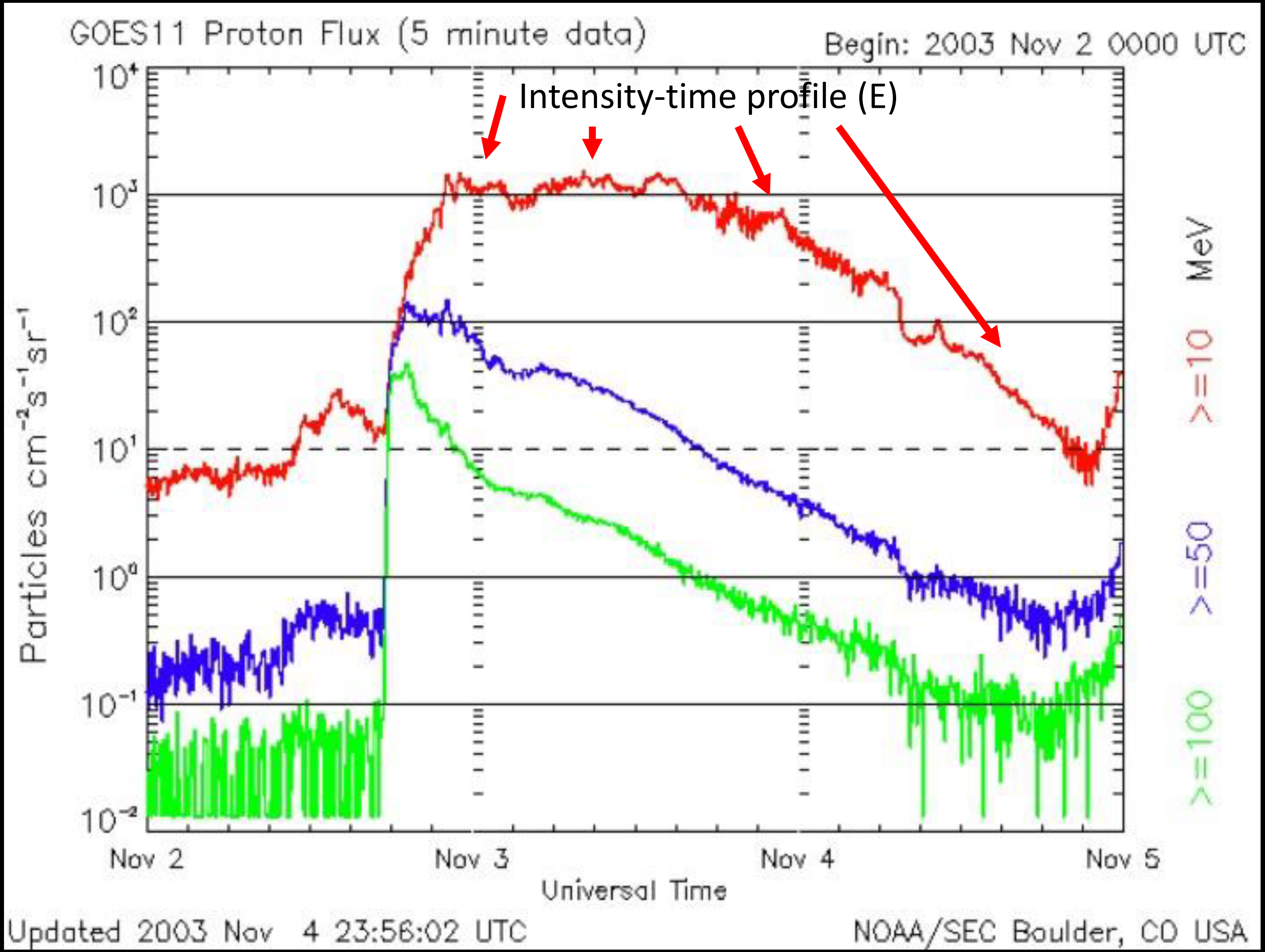
What SEP Parameters Might be Predicted?

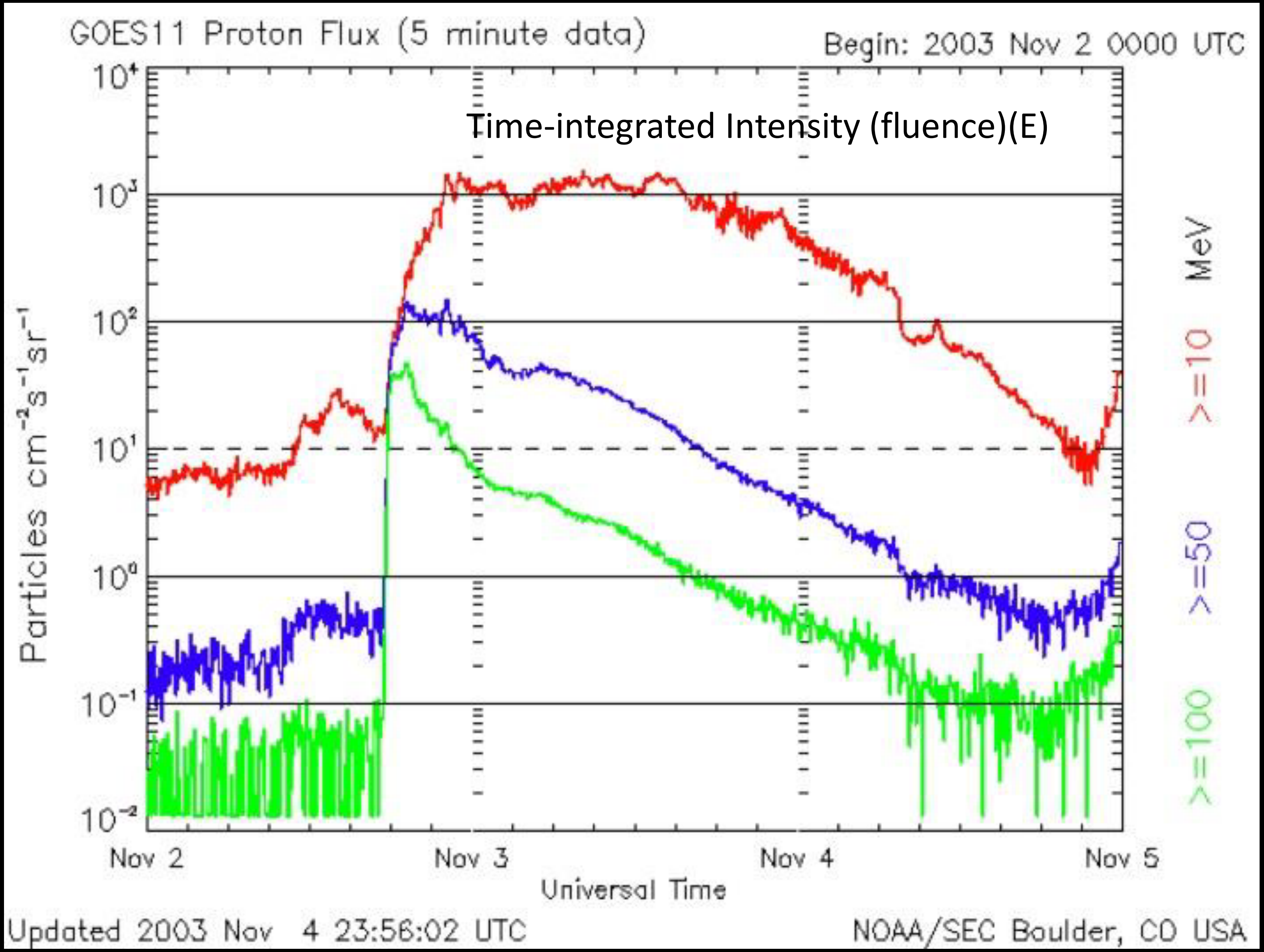




GOES11 Proton Flux (5 minute data)
Begin: 2003 Nov 2 0000 UTC
Time a specified intensity threshold will be exceeded
Particles cm^{-2}s^{-1}sr^{-1}
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Nov 2
Nov 3
Nov 4
Nov 5
Universal Time
MeV
>=10
>=50
>=100
Updated 2003 Nov 4 23:56:02 UTC
NOAA/SEC Boulder, CO USA

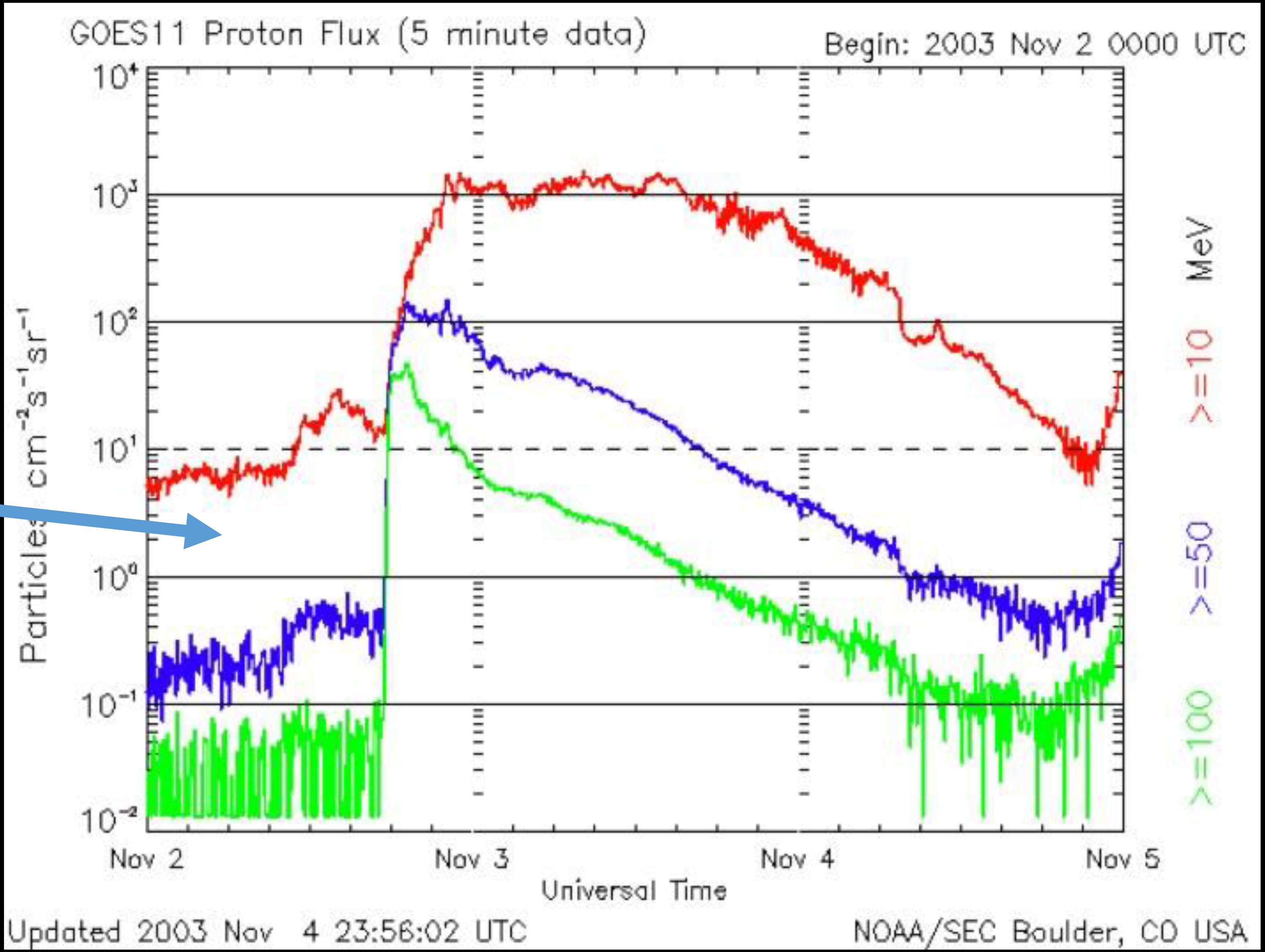

GOES11 Proton Flux (5 minute data)
Begin: 2003 Nov 2 0000 UTC
Duration of event above threshold
Particles cm⁻²s⁻¹sr⁻¹
MeV
>=10
>=50
>=100
Nov 2
Nov 3
Nov 4
Nov 5
Universal Time
Updated 2003 Nov 4 23:56:02 UTC
NOAA/SEC Boulder, CO USA

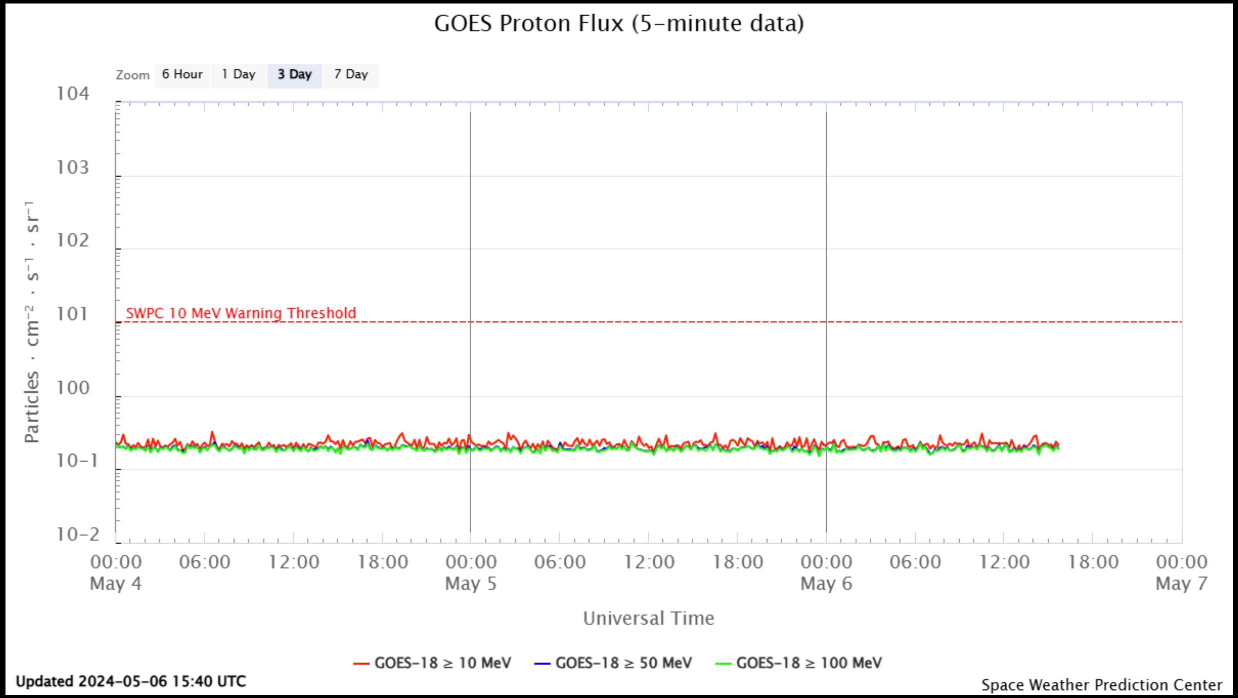

GOES11 Proton Flux (5 minute data)
Begin: 2003 Nov 2 0000 UTC
Intensity-time profile (E)
Particles cm⁻²s⁻¹sr⁻¹
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
Nov 2
Nov 3
Nov 4
Nov 5
Universal Time
MeV
>=10
>=50
>=100
Updated 2003 Nov 4 23:56:02 UTC
NOAA/SEC Boulder, CO USA

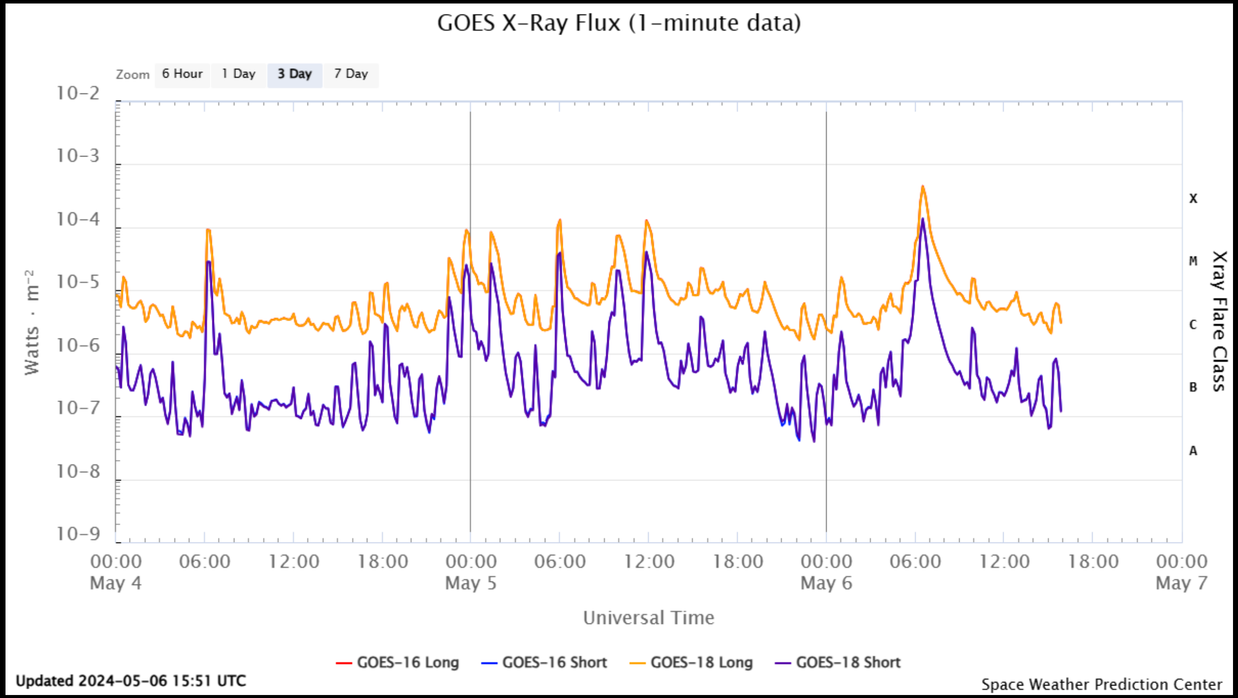


GOES11 Proton Flux (5 minute data)
Begin: 2003 Nov 2 0000 UTC
Time-integrated Intensity (fluence)(E)
Particles cm⁻²s⁻¹sr⁻¹
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
Nov 2
Nov 3
Nov 4
Nov 5
Universal Time
>=10 MeV
>=50
>=100
Updated 2003 Nov 4 23:56:02 UTC
NOAA/SEC Boulder, CO USA

The probability (%) of an SEP event occurring in the next n days (e.g., rocket launch) or hours (aviation)

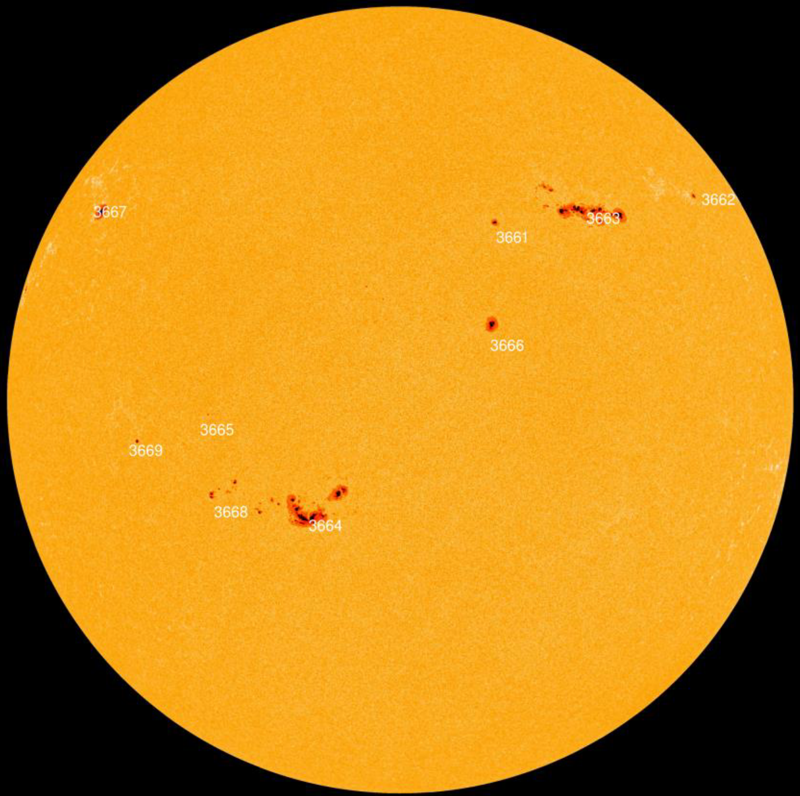






Or "All Clear" conditions – found most of the time! No interruption to operations expected.

- Easy to predict reliably when solar activity is low (e.g. no sunspots) but not when major active regions are present and large flares are occurring (May 6, 2024 shown here).
- Perhaps the evolution and magnetic "complexity" of active regions may indicate whether they will erupt and produce an SEP event?



SEP prediction is closely related to efforts to predict solar flares and coronal mass ejections since the phenomena are related. However:

Number of flares >> number of CMEs >> number of SEP events

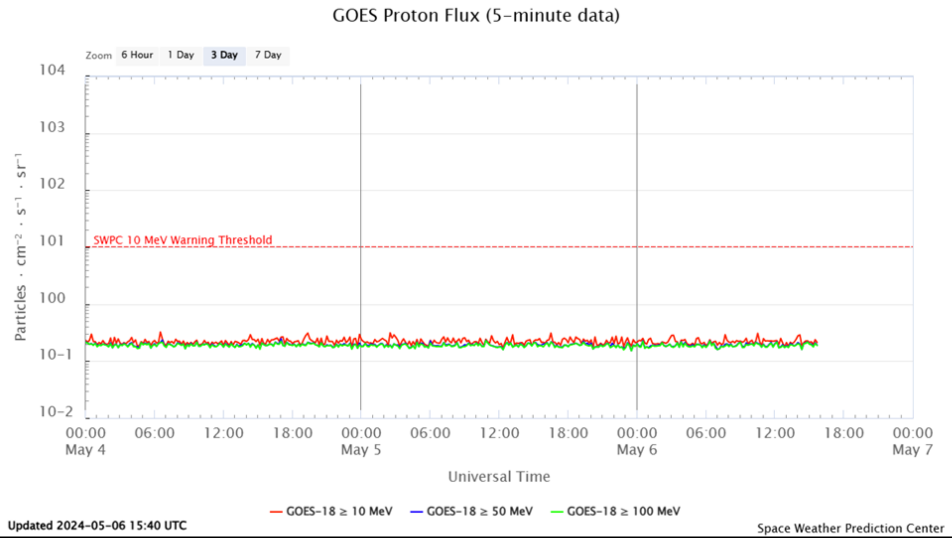
Table 1
Solar energetic particle models. For any models without an entry in the Access column, we encourage interested readers to contact the model developer. RoR stands for Runs on Request available through CCMC. *Deployment to CCMC in progress, **Will be available on SEP Scoreboard and RoR.

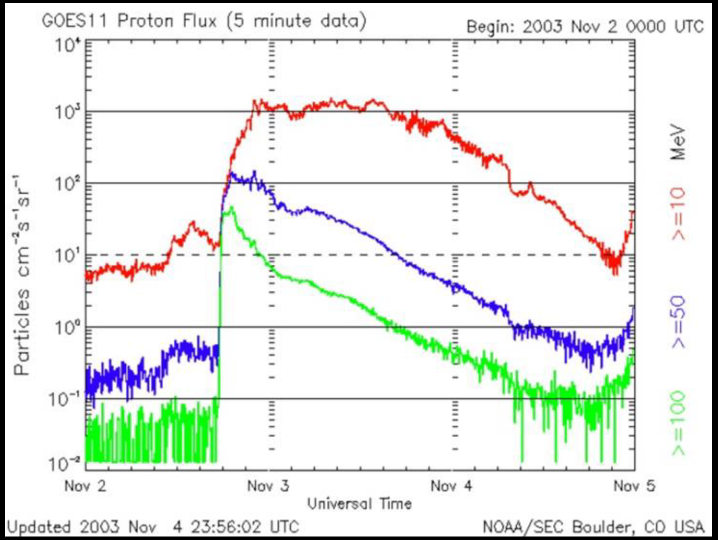
Model	Model Type	Access to Model	Reference
ADEPT	Empirical	-	Kahler and Ling (2017)
AFRL PPS	Empirical	-	Smart et al. (1979, 1989, 1992)
Aminalragia-Giamini model	ML	-	Aminalragia-Giamini et al. (2021)
AMPS	Physics-based	CCMC RoR	Tenishev et al. (2021)
Boubrahimi model	ML	-	Boubrahimi et al. (2017)
COMESEP SEPForecast	Empirical & Physics-based	Web	Dierckxsens et al. (2015), Marsh et al. (2015)
EPREM	Physics-based	-	Schwadron et al. (2010)
ESPERTA	Empirical & ML	-	Laurenza et al. (2009, 2018), Stumpo et al. (2021)
FORSPEF	Empirical	Web	Anastasiadis et al. (2017)
Georgia State University	ML	Web	Ji et al. (2020,)
iPATH	Physics-based	CCMC RoR**	Hu et al. (2017)
Lavasa Model	ML	-	Lavasa et al. (2021)
MAG4	Empirical	Web, CCMC RoR, SEP Scoreboard	Falconer et al. (2011, 2014)
MagPy	Empirical	-**	Tadesse, T., Fernandes, I., Kadadi, Y., Lee, K. T., and Falconer, D.
MEMPSEP	ML	-	Moreland et al. 2022, Chatterjee et al. 2022, Dayeh et al. 2022 (all in preparation)
M-FLAMPA	Physics-based	CCMC RoR*	Sokolov et al. (2004), Borovikov et al. (2015)
PARADISE	Physics-based	Web	Wijsen (2020, 2022)
PCA (Papaioannou) model	Empirical	-	Papaioannou et al. (2018)
PHSVM	ML	-	Pouya Hosseinzadeh, Soukaina Filali Boubrahimi
PROTONS	Empirical	-	Balch (1999, 2008)
REleASE	Empirical	Web, SEP Scoreboard	Posner, 2007; Malandraki et al., 2020
Sadykov et al. (2021) model	ML	-	Sadykov et al. (2021)
SAWS-ASPECS	Empirical	Web, SEP Scoreboard	Anastasiadis et al. (2017), Georgoulis et al. (2021), Papaioannou et al. (2022)
SEPCaster	Physics-based	-*	Li et al. (2021)
SEPMOD	Physics-based	CCMC RoR, SEP Scoreboard	Luhmann et al. (2007)
SEPSTER	Empirical	SEP Scoreboard	Richardson et al. (2018)
SEPSTER2D	Empirical	SEP Scoreboard	Bruno and Richardson (2021)
SMARP Model	ML	-	Kasapis et al. (2022)
SOLPENCO(2)	Physics-based	-	Aran et al. (2006), Aran et al. (2011), Aran et al. (2017)
South African model	Physics-based	Web	Strauss and Fichtner (2015)
SPARX	Physics-based	Web	Marsh et al. (2015)
SPREAdFAST	Physics-based	Web	Kozarev et al. (2017), Kozarev et al. (2022)
SPRINTS	ML	SEP Scoreboard	Engell et al. (2017)
STAT	Physics-based	CCMC RoR	Linker et al. (2019)
UMASEP	Empirical & ML	Web, SEP Scoreboard	Núñez (2011, 2015), Núñez et al. (2017), Malandraki et al. (2020)
Zhang model	Physics-based	-	Zhang and Zhao (2017)

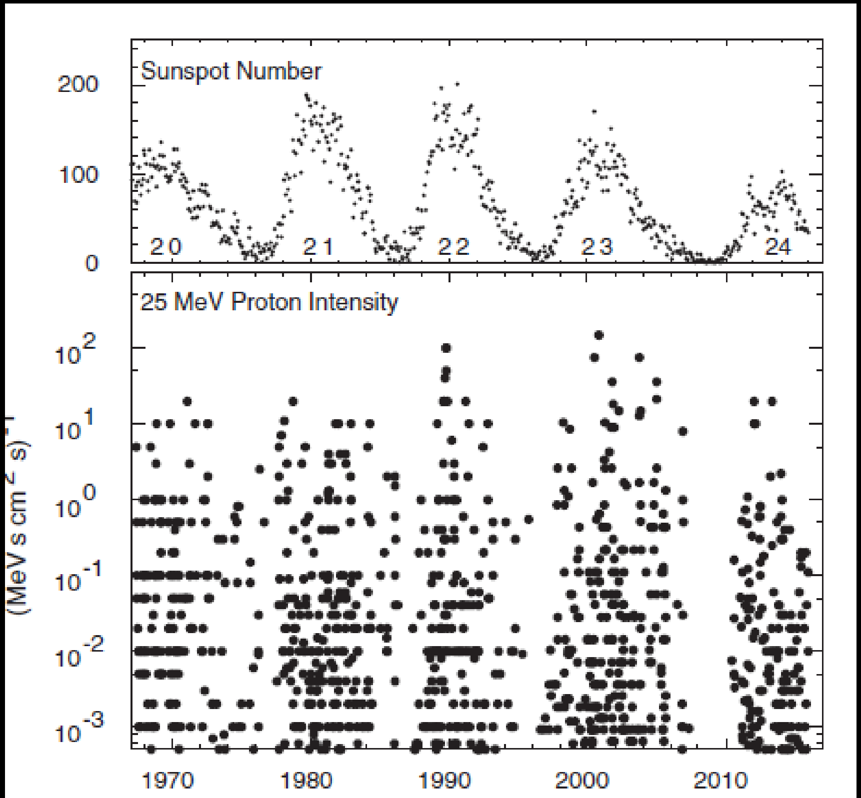
There are a plethora of SEP-prediction models – over 30 models are summarized by Whitman et al., Adv. Space Res. 72, 5161, 2023; https://doi.org/10.1016/j.asr.2022.08.006

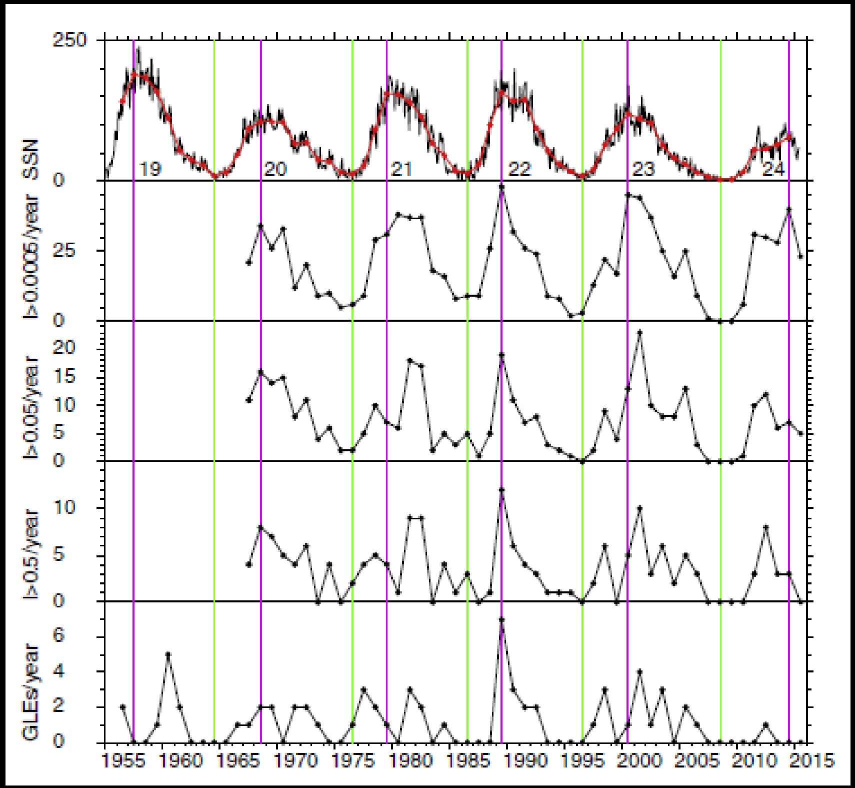
Model	Proton Energy [MeV]	Pre/Post	All Clear	Probability	Flux Point	Onset time	Peak	Peak time	End time	Fluence	Time profile	Multi loc.	3D
ADEPT	>10, >30, >50, >100	Post					x	x	x	x	x		
AFRL PPS	>5, >10, >50	Post				x	x	x	x	x	x		
Aminalragia-Giamini model	≥5	Post	x	x									
AMPS	eV to GeV	Post				x	x	x	x	x	x	x	x
Boubrahimi model	>100	Post	x										
COMESEP SEPForecast	>10, >60	Post		x		x	x	x	x				
EPREM	5 - 1000**	Post				x	x	x	x	x	x	x	x
ESPERTA	>10	Post	x										
FORSPEF	>10, >30, >60, >100	Pre/Post		x		x	x	x	x	x			
GSU	>10	Pre	x	x									
iPATH	100 keV - GeV	Post	x			x	x	x	x	x	x	x	x
Lavasa Model	>10	Pre	x										
MAG4	>10	Pre	x	x									
MagPy	>10, >100	Pre	x	x									
MEMPSEP	9-15, >5, >10, >30, >60, >100	Post		x		x	x	x	x	x			
M-FLAMPA	10 keV - 1 GeV	Post				x	x	x	x	x	x	x	x
PARADISE	keV - GeV	Post				x	x	x	x	x	x	x	x
PCA model	>10	Post		x									
PHSVM	>100	Post	x										
PROTONS	>10	Post		x			x	x					
REleASE	4-9; 9-15.8; 15.8-39.8; 28.2-50.1	Post		x	x								
Sadykov et al.	>10	Pre	x	x									
SAWS-ASPECS	>10 to >300	Pre/Post	x	x		x	x	x	x	x	x		
SEPCaster	100 keV - GeV	Post	x			x	x	x	x	x	x	x	x
SEPMOD	1 - 1000	Post					x	x	x		x	x	x
SEPSTER	14 - 24; >10, >30, >50, >100	Post					x	x				x	
SEPSTER2D	10 - 130; >130	Post					x	x	x	x		x	
SMARP Model	>10	Pre	x	x									
SOLPENCO(2)	0.125 - 64; 5 - 300	Post				x	x	x		x	x	x	
South African model	keV - GeV	Post				x	x	x	x	x	x	x	x
SPARX	>10, >60, >300	Post				x	x	x	x	x	x	x	x
SPREAdFAST	2 - 115	Post				x	x	x			x	x	x
SPRINTS	1, 5, 10, 30, 50, 100	Pre/Post	x	x									
STAT	1 - 1000	Post				x	x	x			x	x	x
UMASEP	>10, >30, >50, >100, >500	Post	x		x	x	x	x		x			
Zhang model	MeV - GeV	Post				x	x	x	x	x	x	x	x

Outputs of current SEP prediction Models (Whitman et al., 2023)









Major types of SEP predictions:

Persistence:
Assume that future conditions will be the same a current conditions (Benchmark; can we do better than this?).

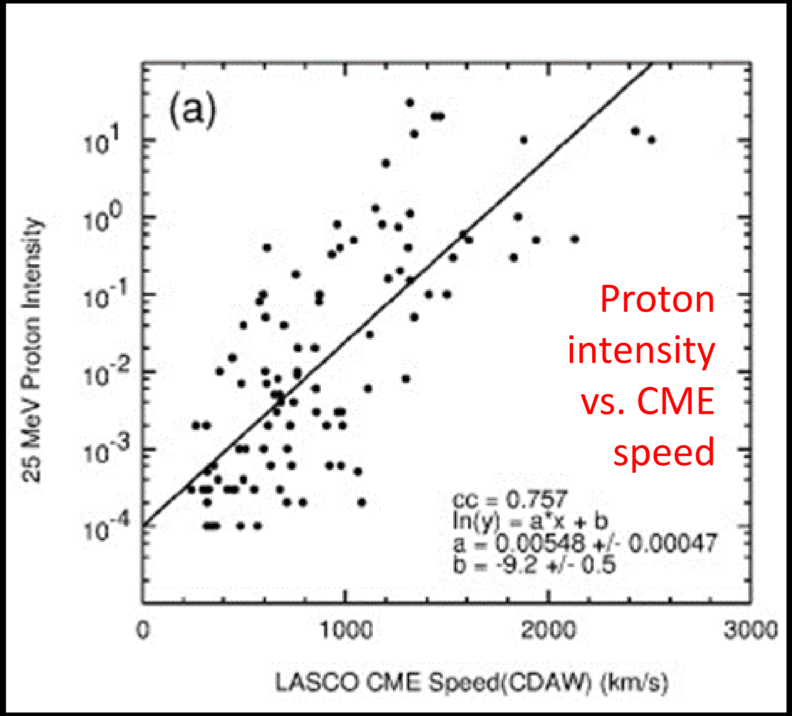
Climatological:
Use past observations of SEPs (e.g. variation in number and intensity during past solar cycles) to predict statistically the likely future exposure to solar particles (e.g., for spacecraft mission design, estimates of astronaut dose).

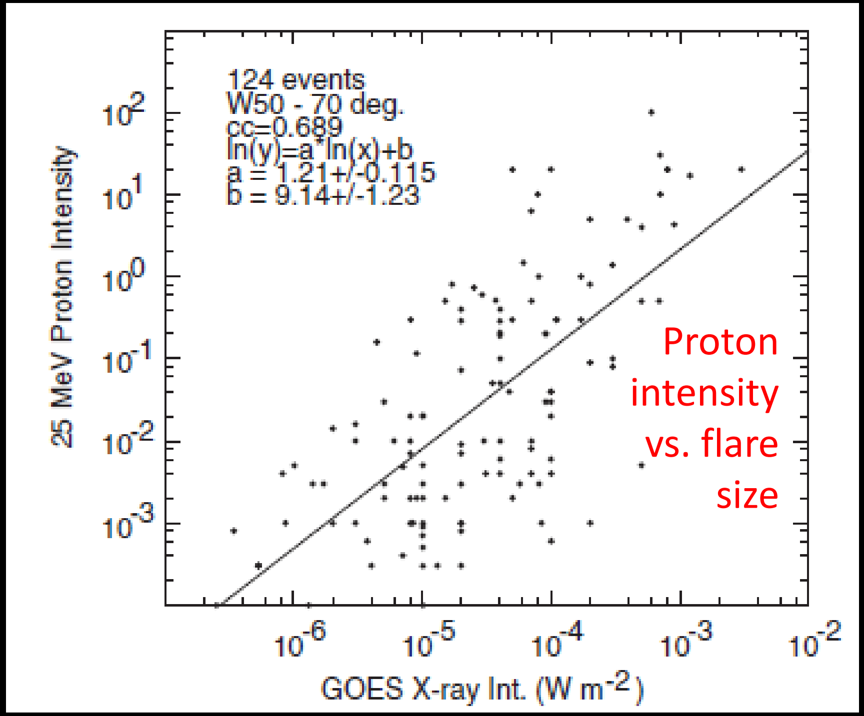
***Richardson et al*., 2017**

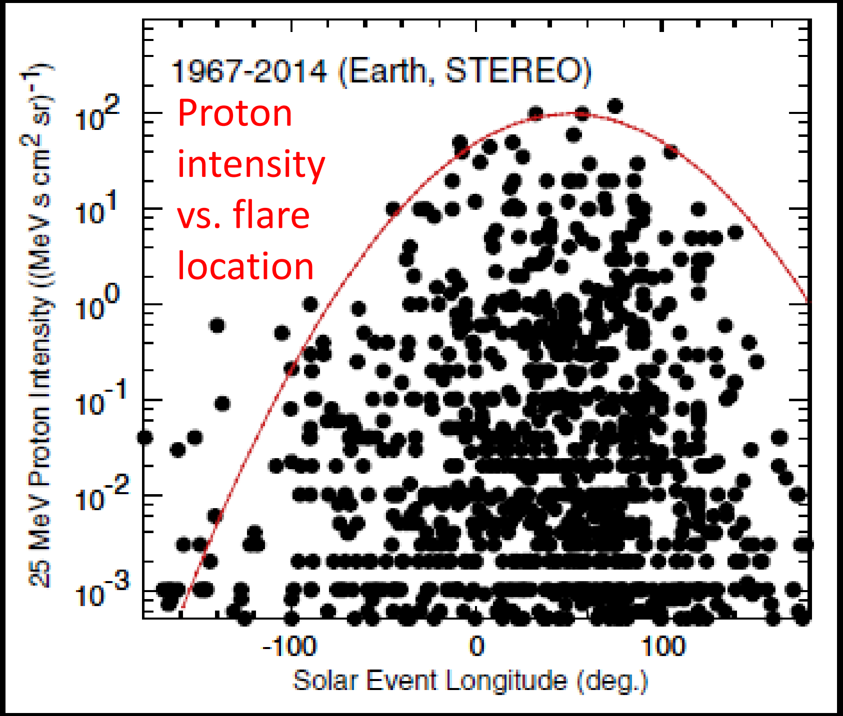
Empirical Models- use historic data to identify the conditions associated with SEP events (e.g., correlate the properties of SEP events with CME speed, X-ray flare size,magnetic connection to the observer, active region complexity).

Summarize results in an equation or other relationship between these conditions and the properties of an SEP event. Model can run rapidly with little resources.

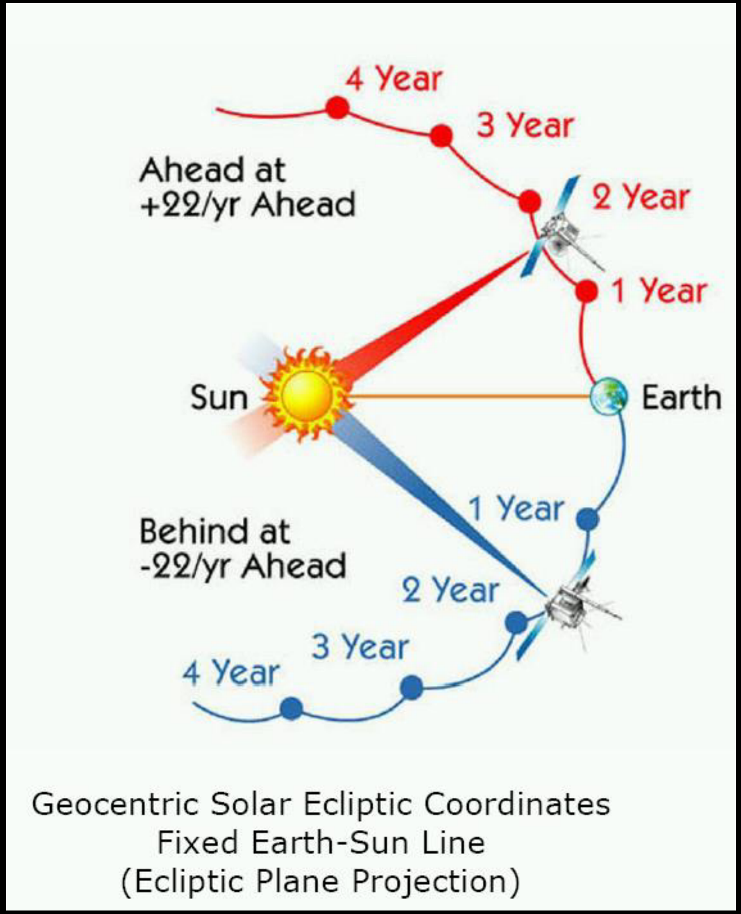
Problems: We may not understand the direct physical relationships (if any) between the input parameters and SEP events; typically difficult to predict time history of an SEP event. May give many "false predictions".







Example of an Empirical Model:
SEPSTER - SEP prediction based on STEReo Observations



STEREO – Two Spacecraft in Heliocentric Orbits at ~1 AU, Launched October, 2006

Measure SEPs using particle instruments on STEREO A and B together with similar instruments on near-Earth spacecraft (e.g., SOHO).

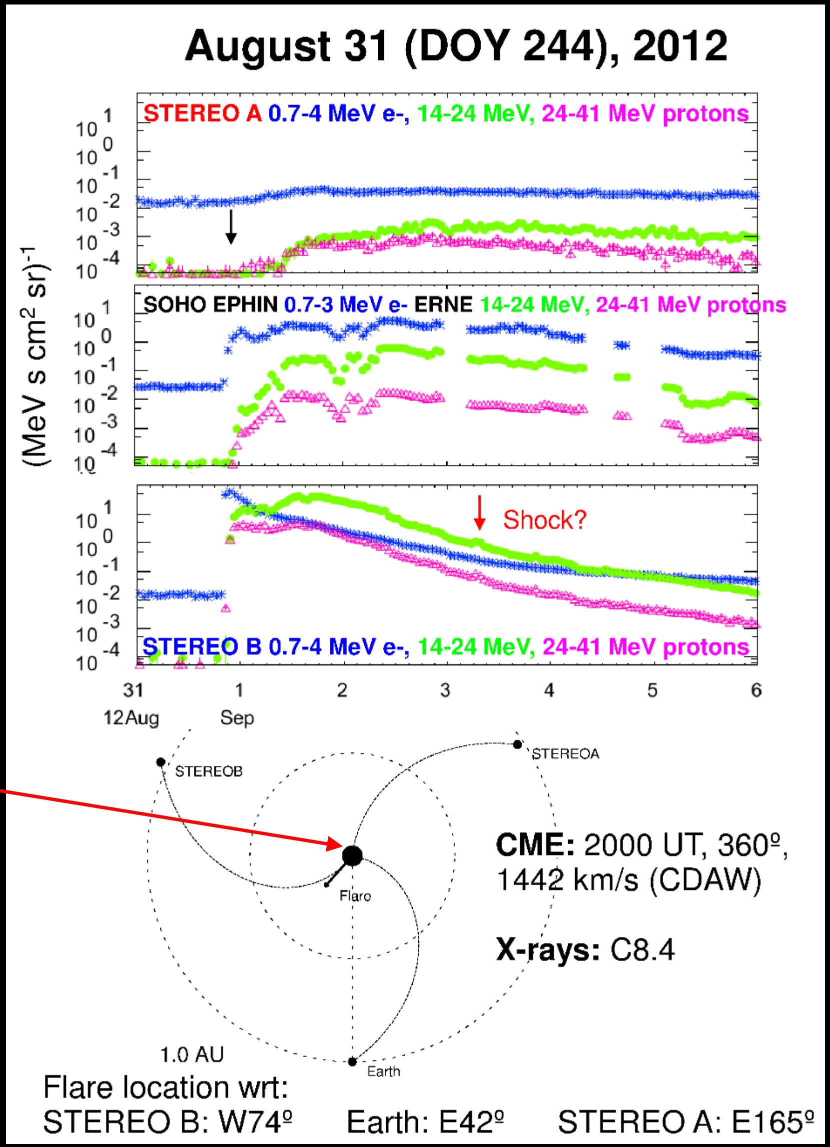
Example of a Solar Particle Event Detected at Both STEREO Spacecraft and at Earth ("3-Spacecraft Event")

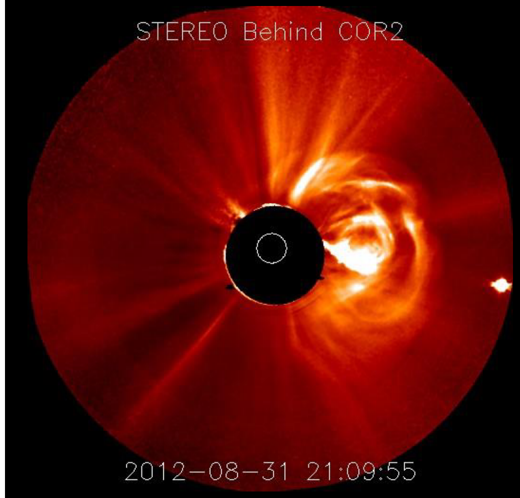
STEREO A

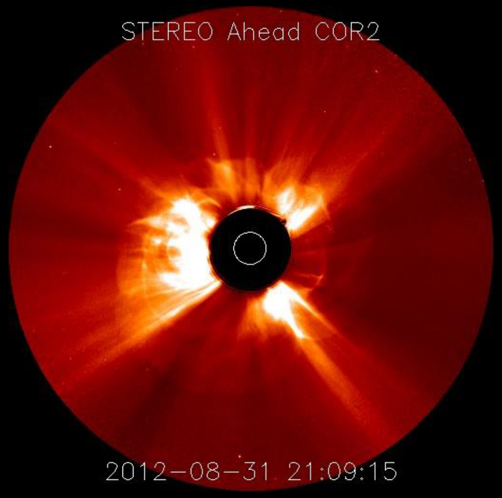
EARTH/SOHO

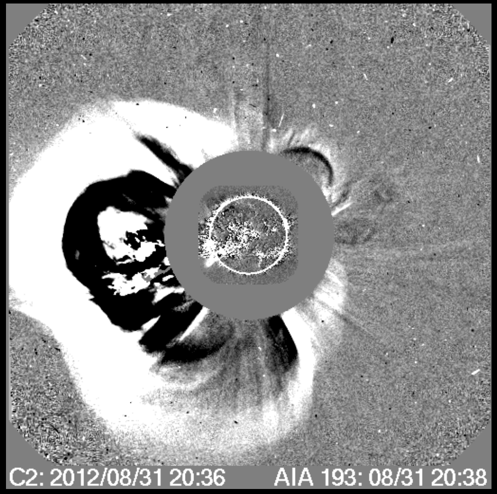
STEREO B

"Connection Angle": Angle between the spiral magnetic field footpoint at the Sun and the solar event



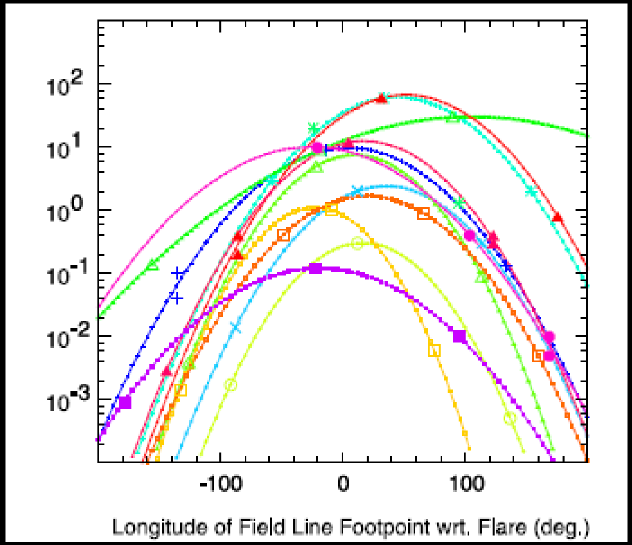






SEP Proton Intensity Formula (*Richardson et al.*, 2014)

14-24 MeV Proton Intensity Gaussian fit vs. φ for 25 3 spacecraft (STEREOs + near Earth) events



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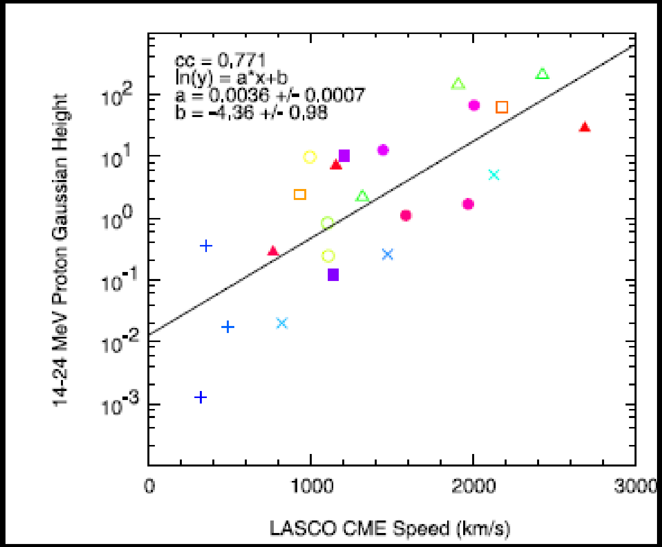
Gaussian peak intensity vs. LASCO CME speed



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I (φ) (MeV s cm² sr)⁻¹ ≈ 0.013 exp(0.0036V −φ²/2σ²)), σ = 43°, where:

$$I(\varphi)\ (\mathrm{MeV\ s\ cm^2\ sr})^{-1} \approx 0.013 \exp(0.0036V - \varphi^2/2\sigma^2)),\ \sigma = 43°$$

- *V is the CME speed (km/s),*
- *φ is the angle (degrees longitude) between the solar event and the solar footpoint of the spiral magnetic field line passing the observing spacecraft, and*
- *σ is the Gaussian width; 43° is the average value.*

SEPSTER uses this equation and observed CME speed and direction to estimate the SEP intensity I at a given location

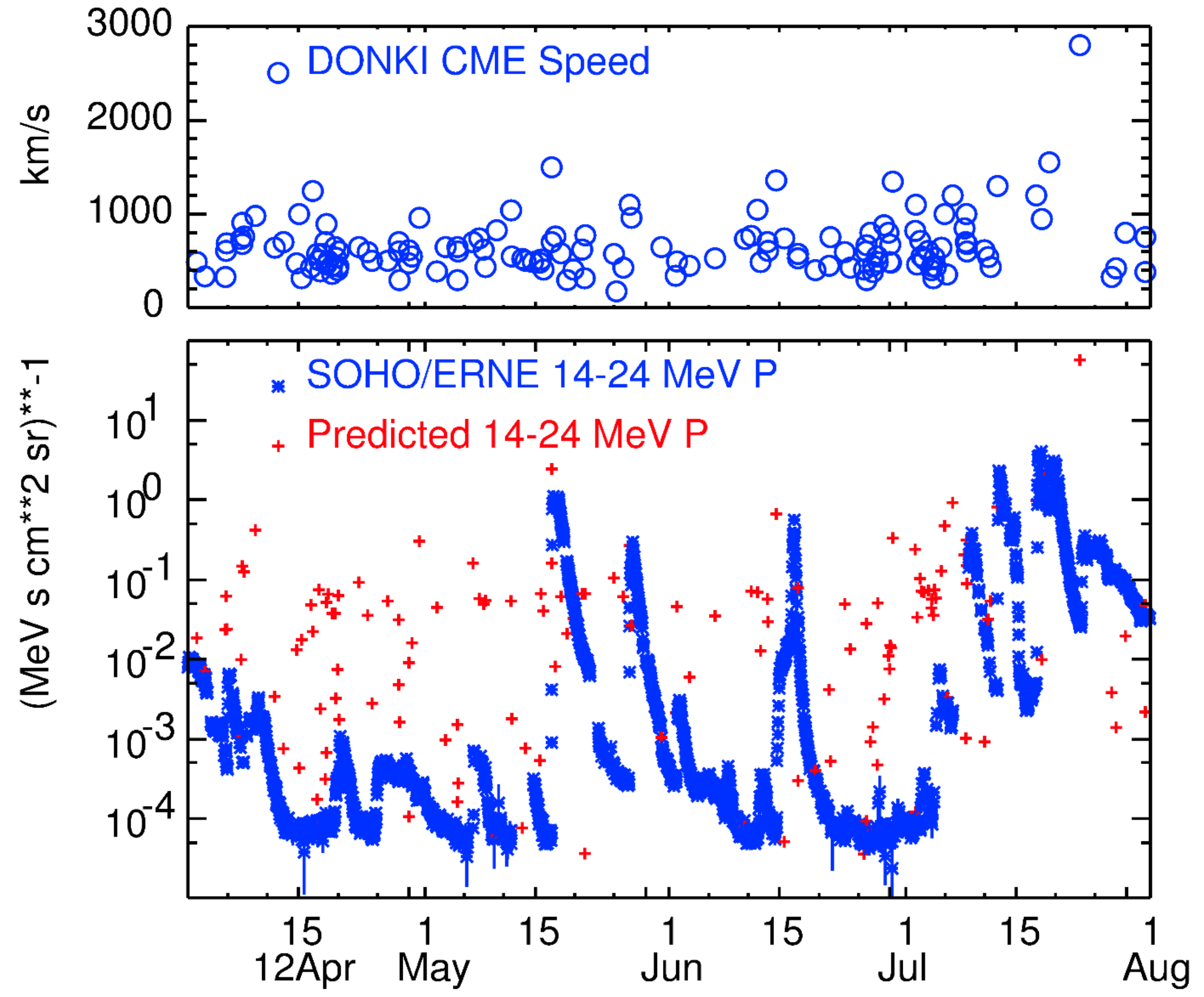
Community Coordinated Modeling Center

SEPSTER is running in near real time at the Moon to Mars Office at GSFC

Inputs:

- CME speed and direction from the CCMC “Database Of Notifications, Knowledge, Information” (DONKI) (https://kauai.ccmc.gsfc.nasa.gov/DONKI/).
- Database is checked for a new CME event every minute.
- Real-time solar wind speed from L1 spacecraft is used to calculate the spiral magnetic field line/connection to the Sun.

Observed and Predicted SEP intensities at Earth in April-July, 2012

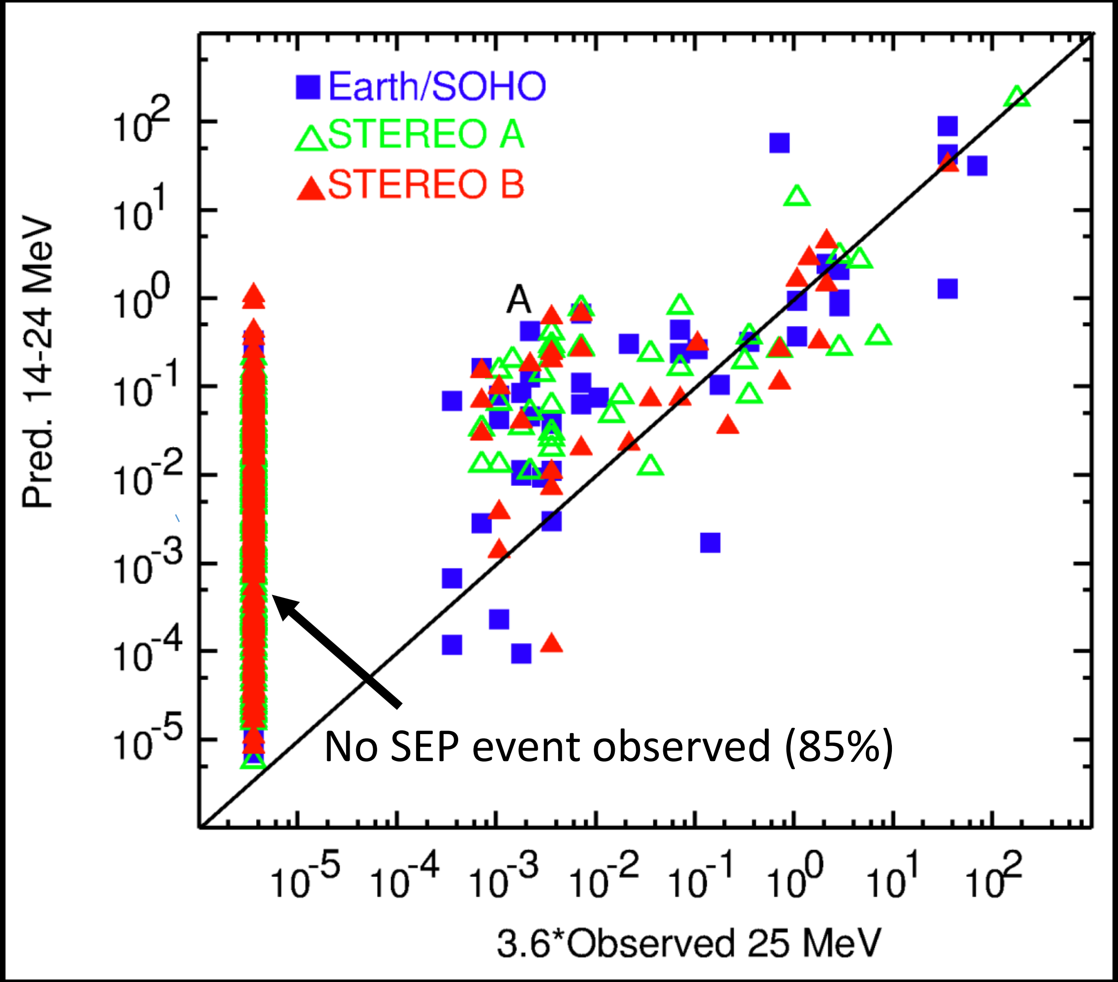


Problem: Most CMEs (~85%) are NOT accompanied by an SEP event.

Hence, there are many cases when a predicted event is not observed.

Richardson et al., 2018

SEPSTER Predicted vs. Observed SEP intensity at Earth and the STEREO Spacecraft for 334 CMEs

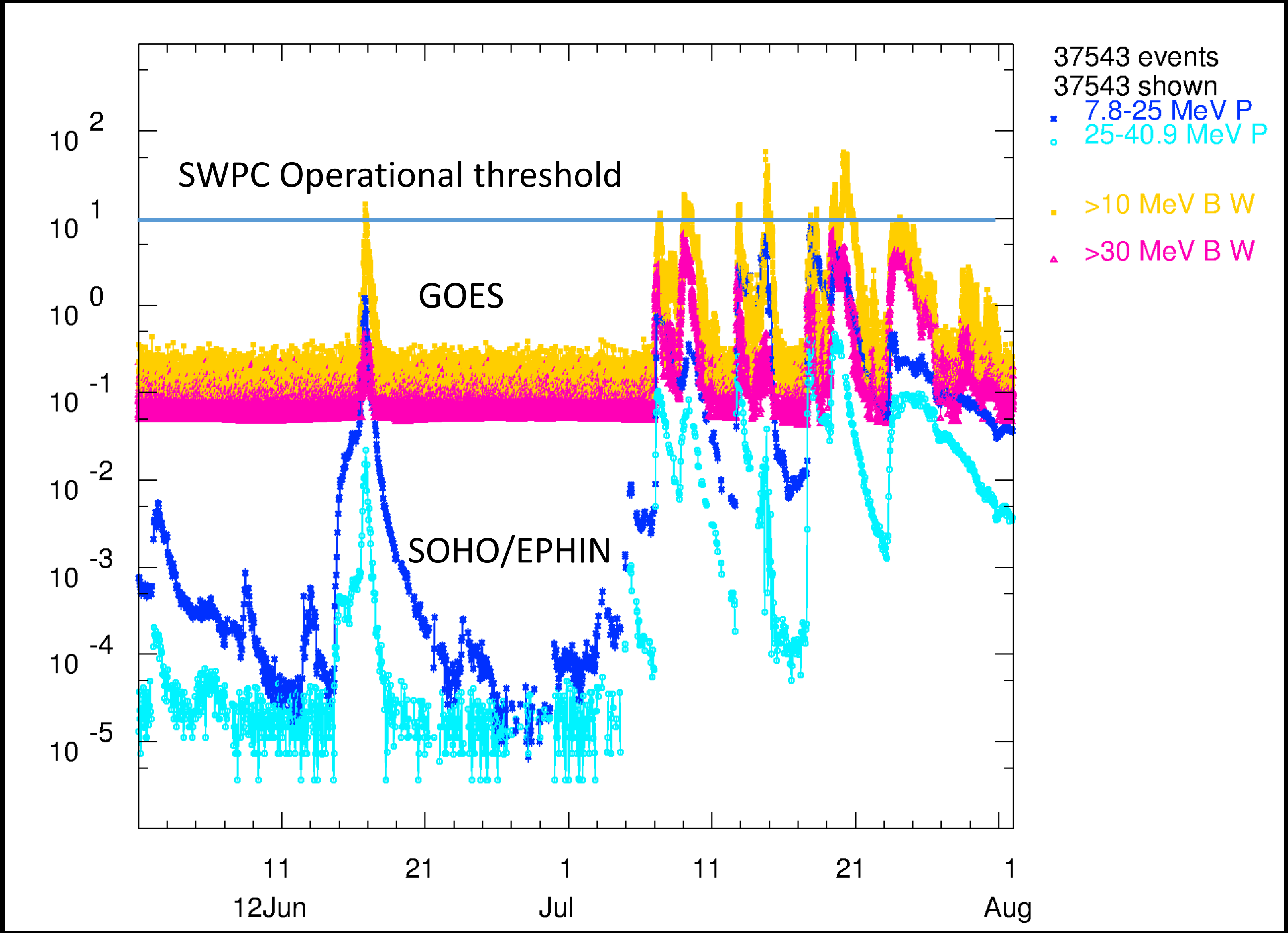


No SEP event was observed for 85% of cases; the predicted intensities are placed at an arbitrary "observed intensity" of $3.6x10^{-6}$ to include them in the figure.

Otherwise, there is a reasonable correlation between the observed and predicted SEP intensities – the diagonal line is the line of equality.

Richardson et al., 2018

N.B. GOES only sees the "tip of the SEP iceberg"!



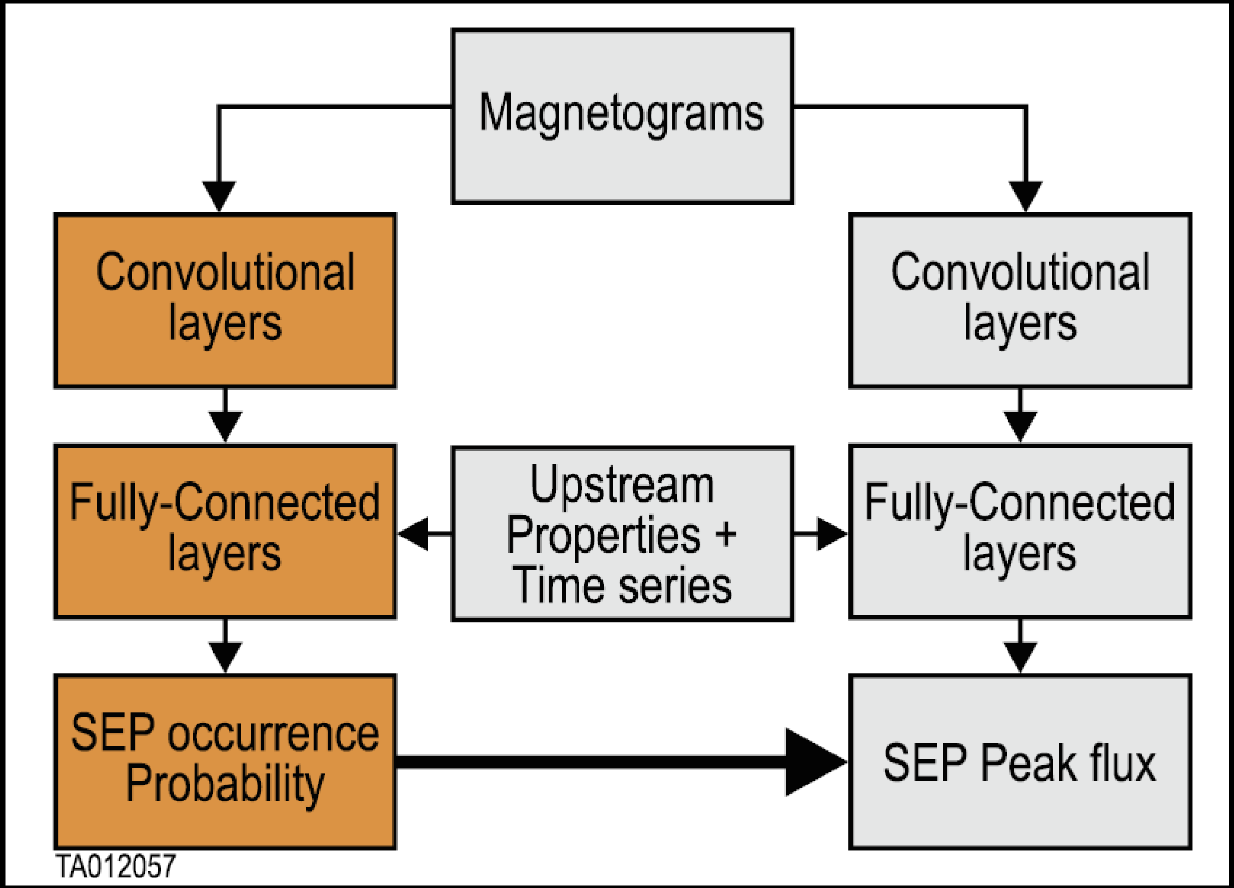
Comparison of GOES and SOHO/EPHIN shows the high background in GOES.

Many more features, including small SEP events, are visible in the EPHIN data

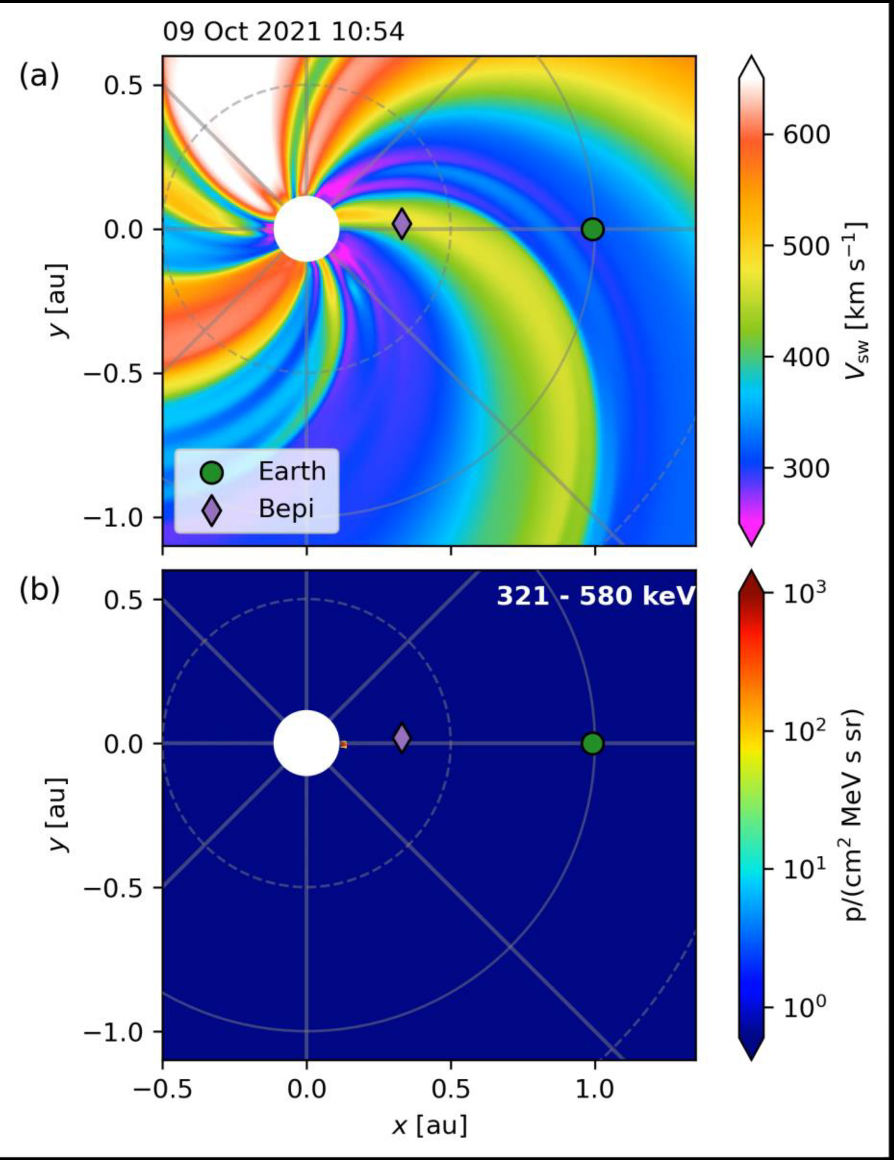
Machine Learning – typically a subset of Empirical Models, but use a large input data set to identify the relations between input parameters and SEP events through ML. May uncover relationships that have not previously been identified. No "human bias".

Problems: SEP events are rare and highly variable; inputs are highly unbalanced (most observations are "all clear" intervals).

Requires careful preparation of input data (e.g., correct association of SEP events with their solar sources) and definition of training and validation event sets.



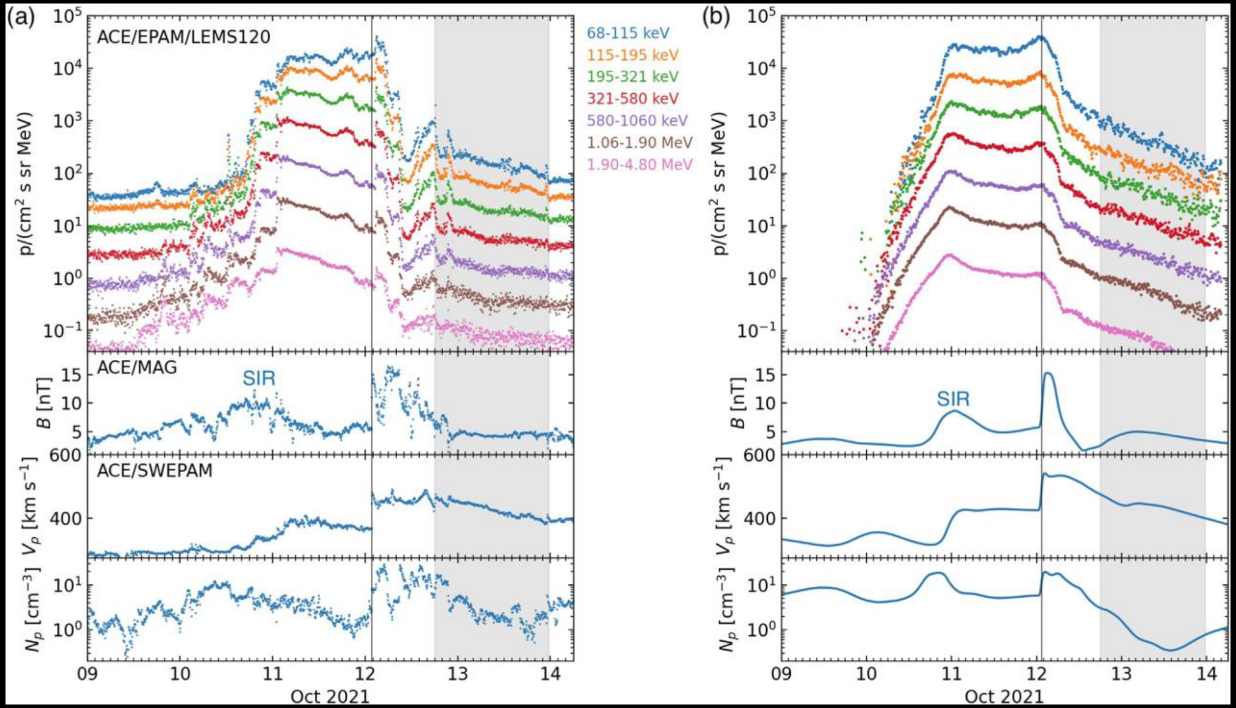
Architecture of the MEMSEP model (Dayeh et al.; Whitman et al., 2023)



Physics-based: Attempt to reproduce (some of) the physics of particle acceleration and transport.

Potentially could account for the variability of SEP events and their time history.

Problems: May be computationally intensive and expensive.
May not run fast enough for real-time predictions;
Fundamental parameters may be poorly determined (e.g., how many "seed" particles to feed into the model) or set to "default" values.
Physics may be simplified.



EUFORIA+PARADISE (Wijsen et al., 2023)

Event Triggered: A prediction is only made when something happens e.g.,

- A soft X-ray flare is observed (e.g., in GOES real-time observations)
- A CME is observed (HOWEVER, currently, CME observations from scientific spacecraft e.g., SOHO and STEREO are not transmitted to Earth in real time – latency (including data analysis) can be several hours.)
- Solar radio emission is detected (real-time from ground-based observatories but delayed from spacecraft).
- The observed SEP intensity starts to rise.

Continuous/probabilistic: Runs continuously and predicts the probability of an SEP event within a defined prediction window.

- E.g., Monitor the evolution and complexity of active regions using magnetograms or EUV imaging (training may use ML because of the large data sets involved).

Model	Type	Magnetograms	Optical Imaging	EUV Imaging	Soft X-ray Intensity	Ground-based Radio	Space-based Radio	Coronagraph	Solar Wind (n,T,p,v)	Suprathermal Particles	Energetic Protons	Energetic Electrons	Neutron Monitors
ADEPT	Empirical										x		
AFRL PPS	Empirical		x		x	x							
Aminalragia-Giamini model	ML			x	x								
AMPS	Physics-based	x		x				x					
Boubrahimi model	ML				x						x		
COMESEP SEPForecast	Emp. & Physics			x	x			x					x
EPREM	Physics-based	x		x				x		x			
ESPERTA	Emp. & ML			x	x		x				x		
FORSPEF	Empirical	x	x		x		x	x					
GSU	ML	x											
iPATH	Physics-based	x		x				x	x	x			
Lavasa Model	ML		x		x			x					
MAG4	Empirical	x	x		x								
MagPy	Empirical	x	x		x								
MEMPSEP	ML	x		x	x		x	x	x	x	x	x	
M-FLAMPA	Physics-based	x		x				x					
PARADISE	Physics-based	x		x				x					
PCA model	Empirical				x			x					
PHSVM	ML				x						x		
PROTONS	Empirical				x	x							
REleASE	Empirical											x	
Sadykov's Model	ML	x			x	x					x		
SAWS-ASPECS	Empirical	x	x		x			x			x	x	x
SEPCaster	Physics-based	x		x				x	x				
SEPMOD	Physics-based	x		x				x					
SEPSTER	Empirical			x				x	x				
SEPSTER2D	Empirical			x				x	x				
SMARP Model	ML	x											
SOLPENCO	Physics-based			x				x					
SOLPENCO(2)	Physics-based			x				x	x		x		
South African model	Physics-based			x	x			x					
SPARX	Physics-based			x	x								
SPREAdFAST	Physics-based	x		x				x		x	x		
SPRINTS	ML	x		x	x						x		
STAT	Physics-based	x		x				x		x			
UMASEP	Empirical				x	x					x		
Zhang model	Physics-based	x		x				x	x				
Total		19	6	21	19	4	3	21	7	5	11	3	2

Input observations for Current SEP Prediction Models (Whitman et al., 2023)

The most popular are:

- Coronagraph (CME) Observations (from scientific spacecraft), 21 models
- EUV imaging (from scientific and operational spacecraft), 21 models
- Magnetograms (from scientific spacecraft and ground observatories), 19 models
- GOES soft X-rays, 19 models

“Human in the Loop”

Uses predictions of (ideally) “most reliable” models, assessment of relevant data by an observer, and their own experience to produce an SEP forecast to be released to end users.

Another benchmark – Can new prediction models do better than a human in the loop? (e.g., “A Summary of National Oceanic and Atmospheric Administration Space Weather Prediction Center Proton Event Forecast Performance and Skill”, Bain et al., Space Weather, 2021, https://doi.org/10.1029/2020SW002670).

(Note – a model prediction is not a forecast!)

How to assess (validate) model performance?

Often use contingency tables and skill scores to compare predictions with observations.

Event forecast	Event observed		
	Yes	No	Marginal total
Yes	Hit	False alarm	Fc Yes
No	Miss	Correct non-event	Fc No
Marginal total	Obs Yes	Obs No	Sum total

There are many skill scores which indicate different measures of skill.

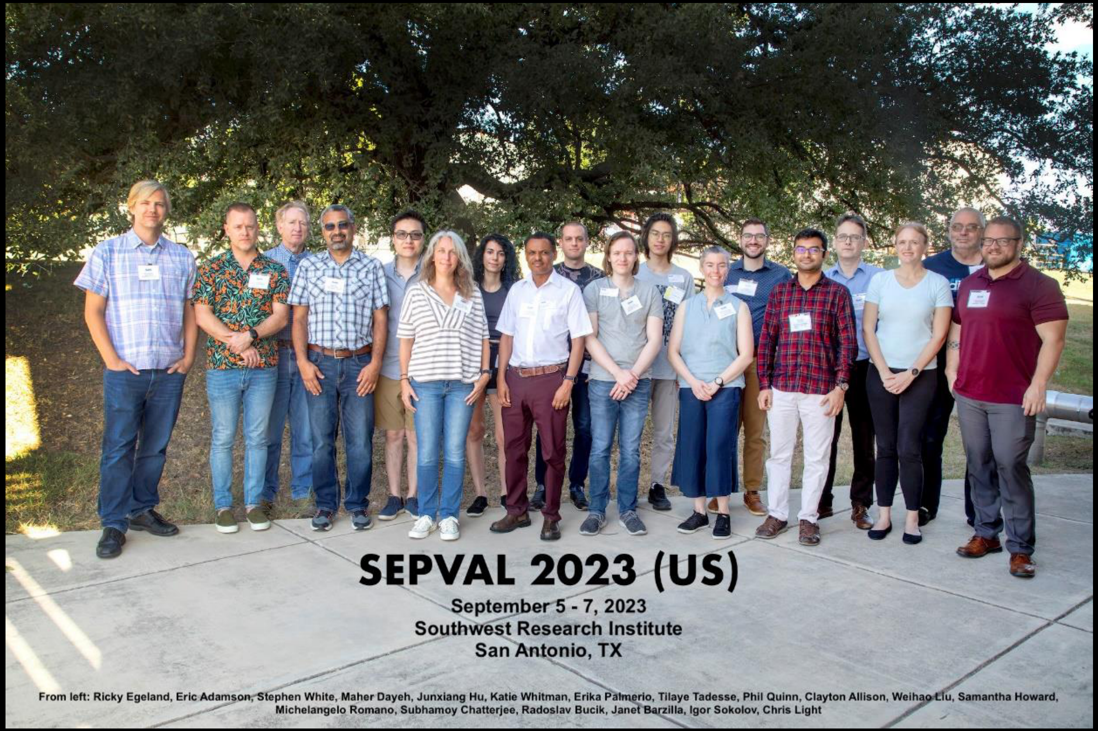
E.g., Hit rate (fraction of correct predictions) = Hits/(Hits+misses)

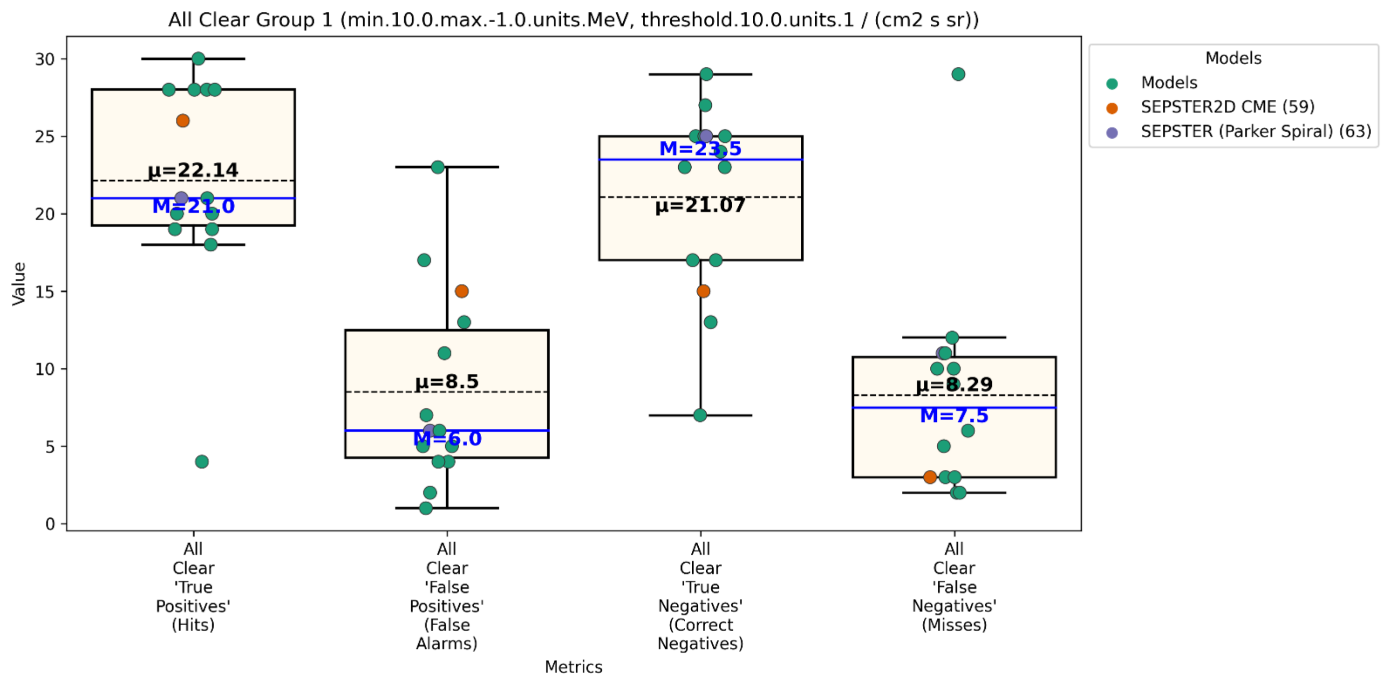
False Alarm rate = False alarms/(False alarms + Hits)

May not be applicable/meaningful for a particular model.
Model comparison using skill scores may be meaningless if different inputs are used to make predictions for different events, especially for a small sample of events.

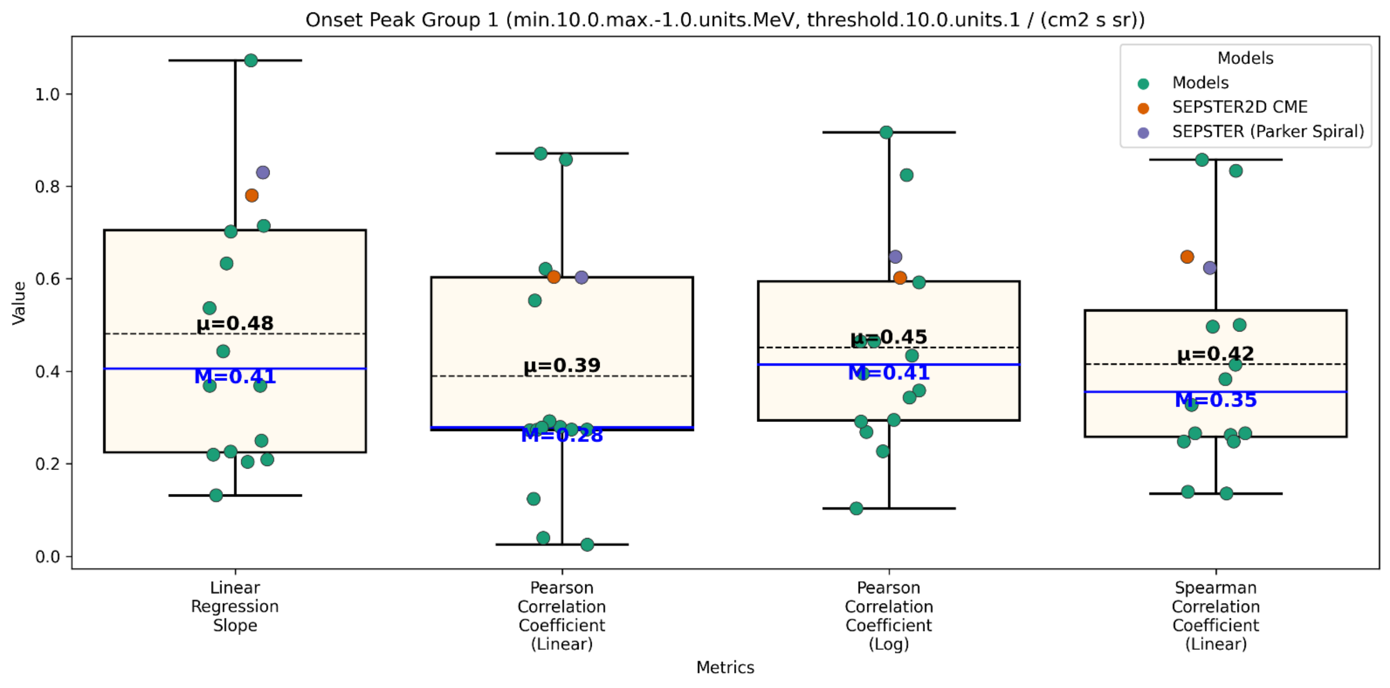
Major international initiative ("SEPVAL") to validate SEP prediction models under the COSPAR International Space Weather Action Teams (ISWAT; https://www.iswat-cospar.org/iswat-cospar)

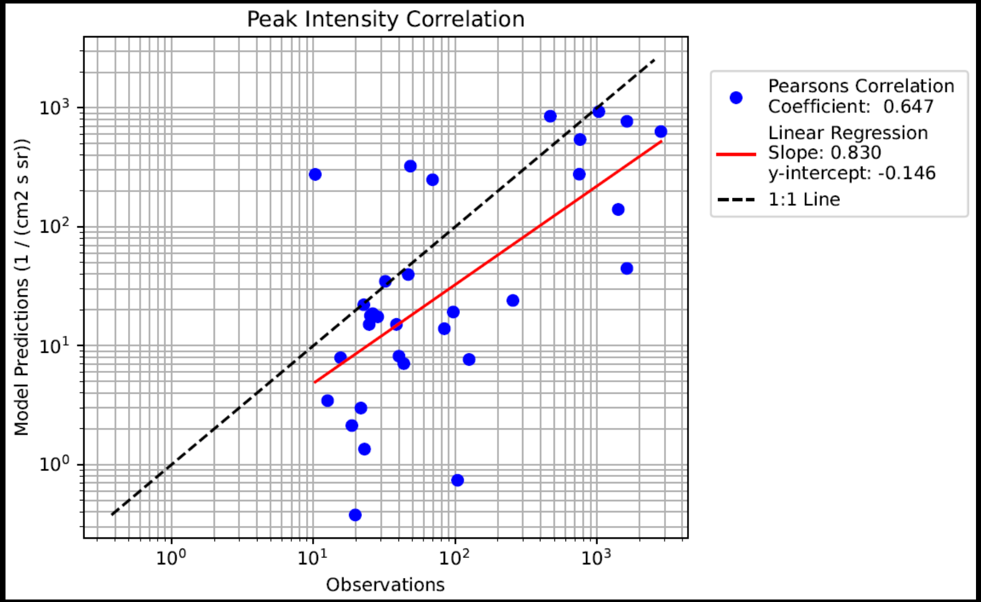
Workshops at European Space Weather Week and SHINE (USA) leading to meetings in 2023 in San Antonio (USA) and ESWW (Toulouse)





Examples of SEPSTER results from the NASA/JSC SPHINX code for the SEPVAL All clear intervals and SEP events (from Katie Whitman)





SEP Scoreboard

-1 week | -1 day | -1 hour | 2017-09-11 18:12 | +1 hour | +1 day | +1 week
Today | Refresh Plots

Proton Intensity Forecasts:

2017-09-18:12 UT

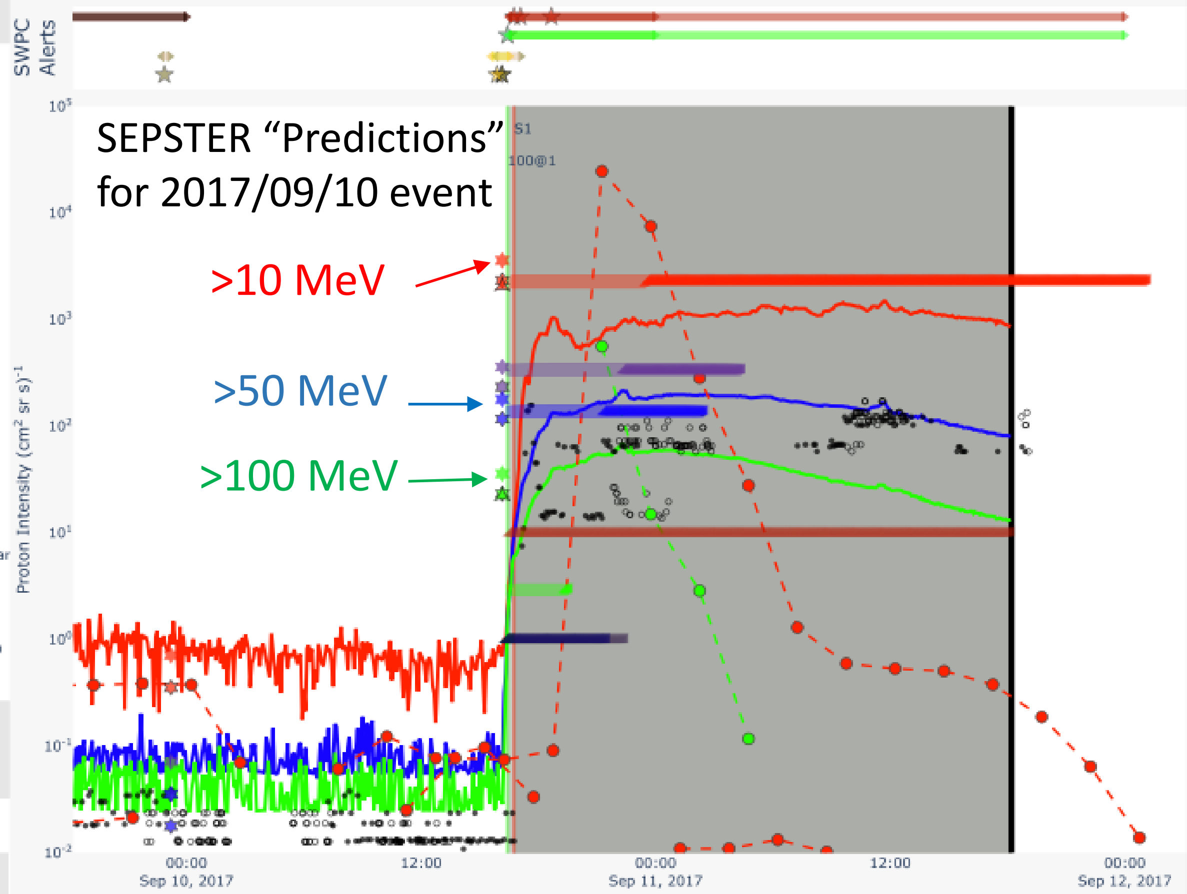
	> 10 MeV	> 100 MeV
GOES	864.0	13.2
SEPMOD	24620.0	561.0
SEPSTER	No Data	No Data
SEPSTER2D	2066.0	22.24
STAT	No Data	No Data
UMASEP	2321.1 ± 533.9	Not Clear

Proton All Clear Forecasts:

2017-09-11 18:12 UT

GOES	Not Clear	Not Clear	N/A
SEPMOD	Not Clear	Not Clear	N/A
SEPSTER	No Data	No Data	N/A

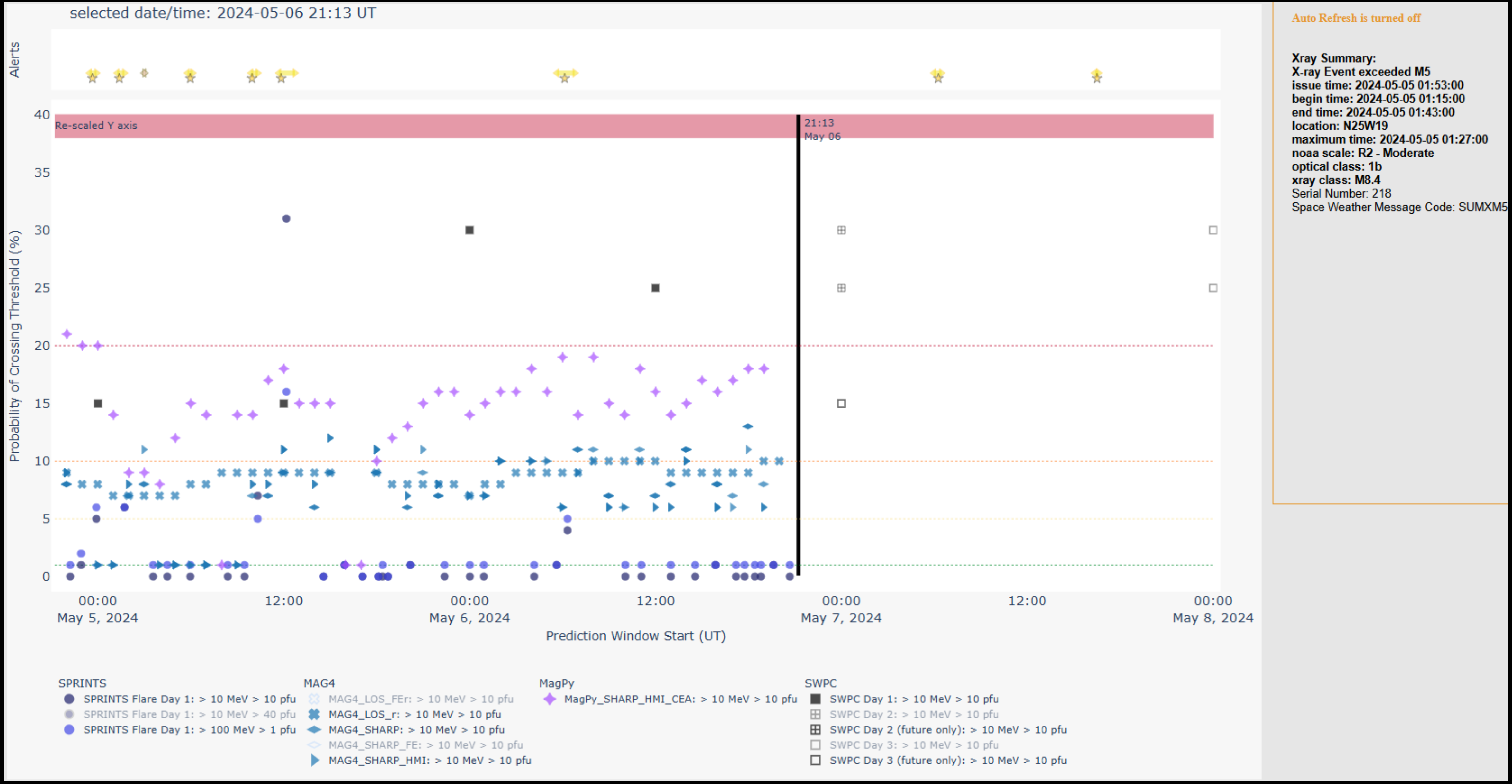
selected date/time: 2017-09-11 18:12 UT



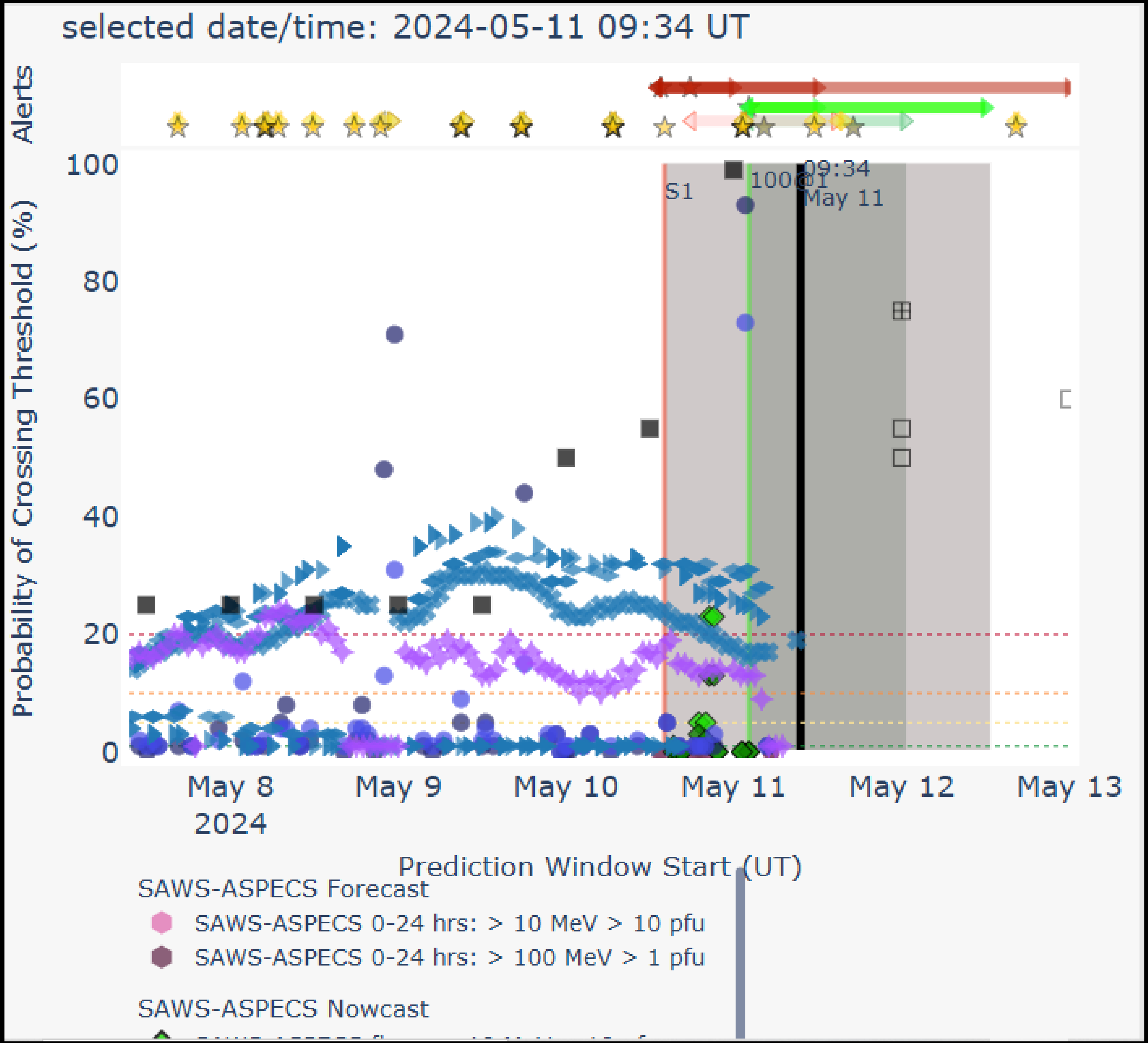
https://ccmc.gsfc.nasa.gov/scoreboards/sep/

GOES: > 10 MeV | GOES: > 30 MeV | GOES: > 50 MeV | GOES: > 100 MeV | HESPERIA REleASE ACE 60-min: 15.8 - 39.8 MeV | HESPERIA REleASE ACE 60-min: 28.2 - 50.1 MeV
HESPERIA REleASE SOHO 60-min: 28.2 - 50.1 MeV | SEPMOD-SWPC params: > 10.0 MeV | SEPMOD-SWPC params: > 100.0 MeV | SEPMOD (latest): > 10.0 MeV | SEPMOD (older): > 10.0 MeV
SEPSTER (Parker Spiral): > 10.0 MeV | SEPSTER (Parker Spiral): 14.0 - 24.0 MeV | SEPSTER (Parker Spiral): > 30.0 MeV | SEPSTER (Parker Spiral): > 50.0 MeV | SEPSTER (Parker Spira > 100.0 MeV

SEP Probability Scoreboard (on May 6, 2024)



SEP Probability Scoreboard (on May 11, 2024)



ISEP

A Joint SRAG/CCMC Collaboration to Improve Space Weather Prediction for Crew Protection during Near-Term Lunar Surface and Cis-Lunar Missions.

Summary

The reliable prediction of SEP events is vital to support exploration beyond Earth’s magnetosphere, including to the Moon and Mars.

Many SEP prediction models have been developed, but validating these models fairly requires a large community effort.

Most likely, an ensemble of these models will be used to support operations (similar to the model ensembles used to predict terrestrial weather).

The timely and continued availability of critical model inputs is a major issue – most are provided by scientific spacecraft with limited mission durations.