Forecasting Shock-associated Energetic Particle Intensities in the Inner Heliosphere: A Proof-of-Concept Capability for the PUNCH Mission

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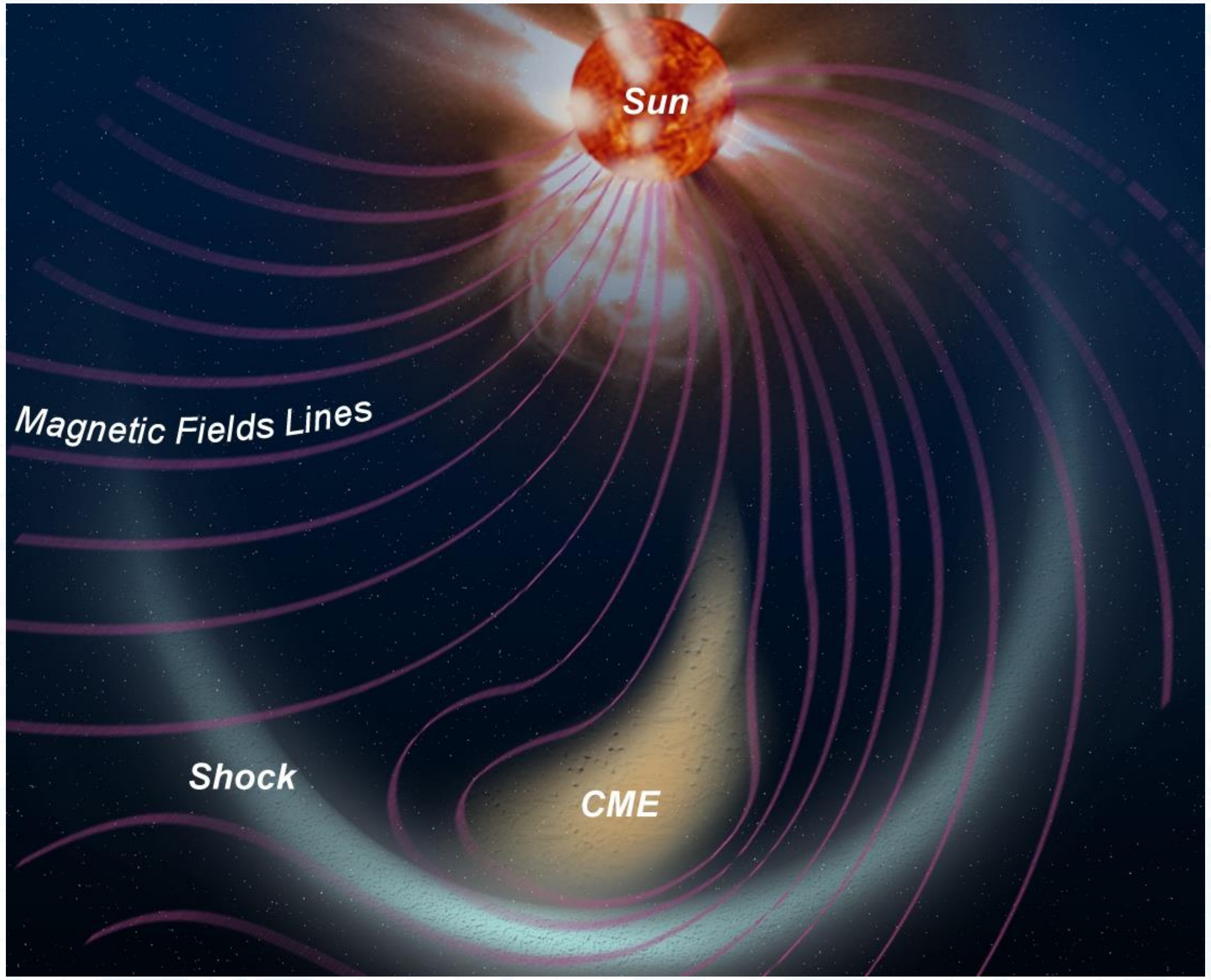
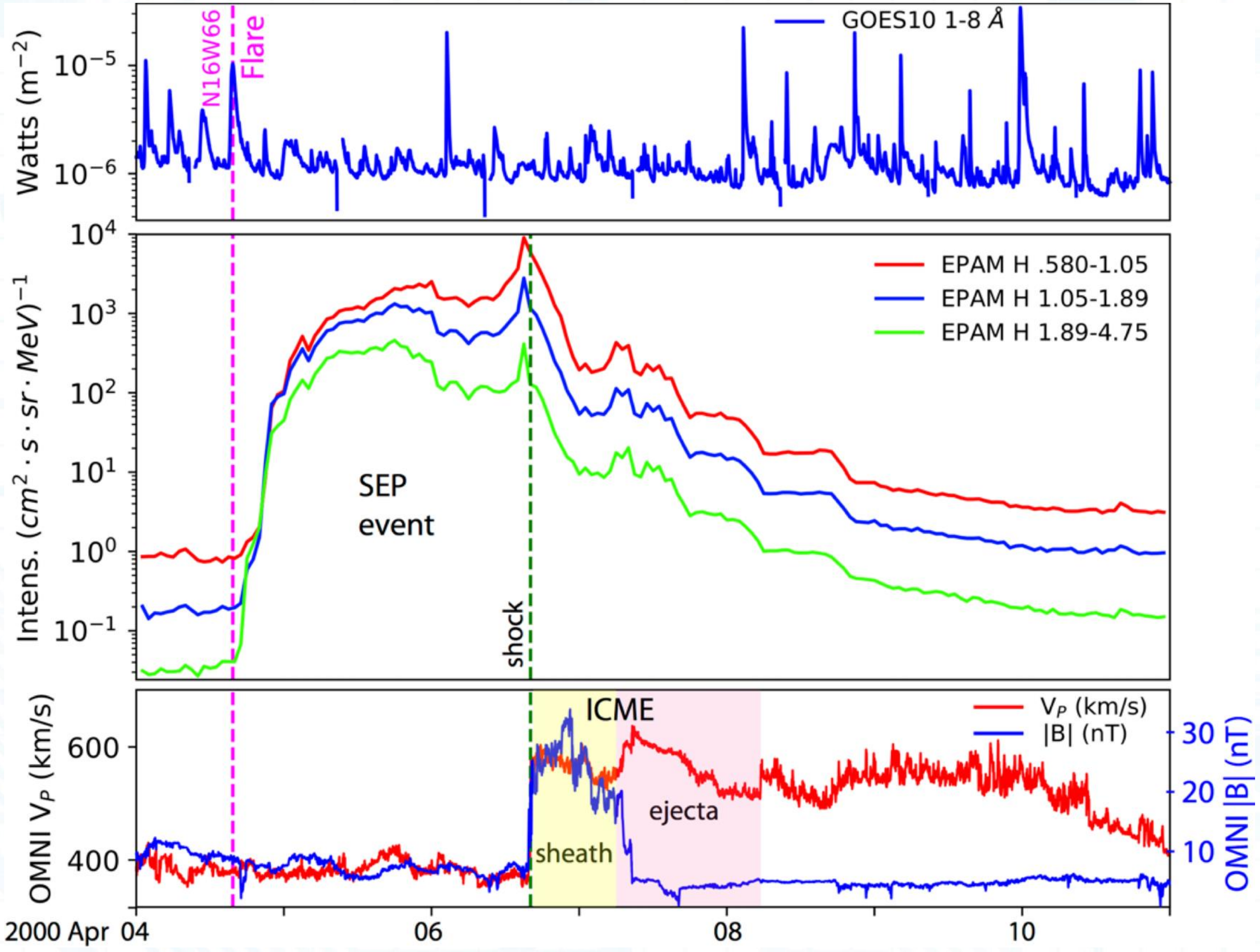
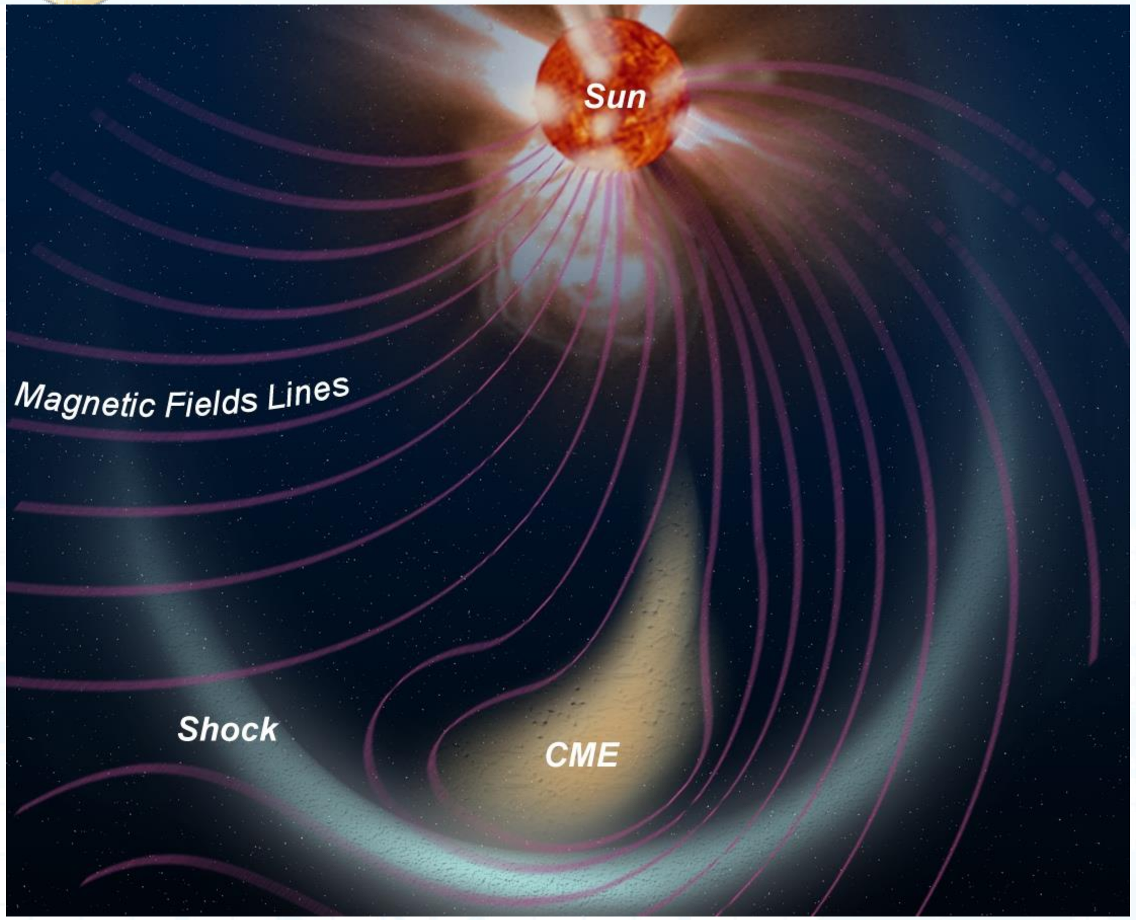
CME Shocks & Energetic Particles





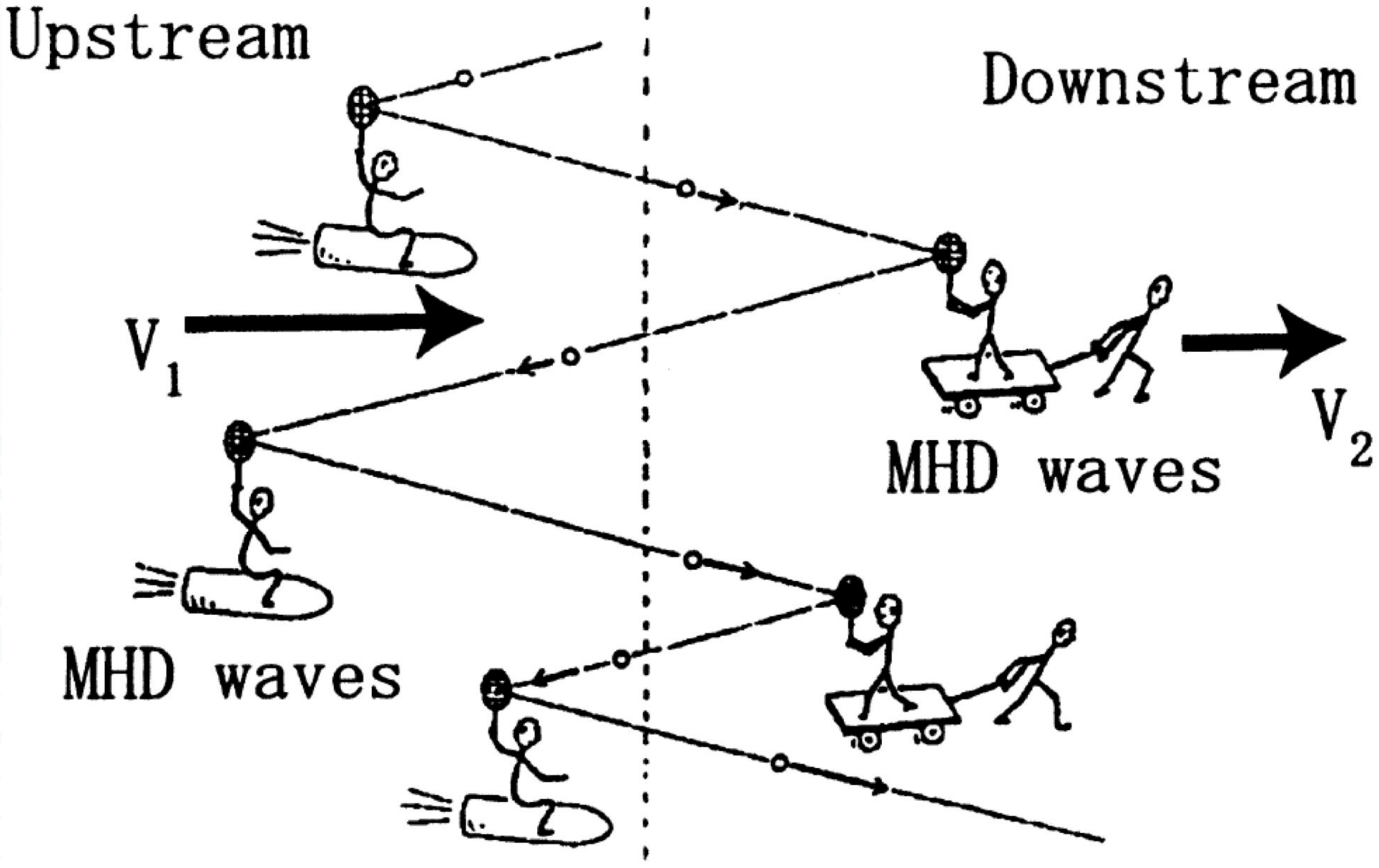
- **CMEs drive shocks in the corona and the interplanetary medium**
- **Coronal Shocks ➔ SEPs**
- **IP shocks ➔ESPs**

Shock Acceleration Mechanisms



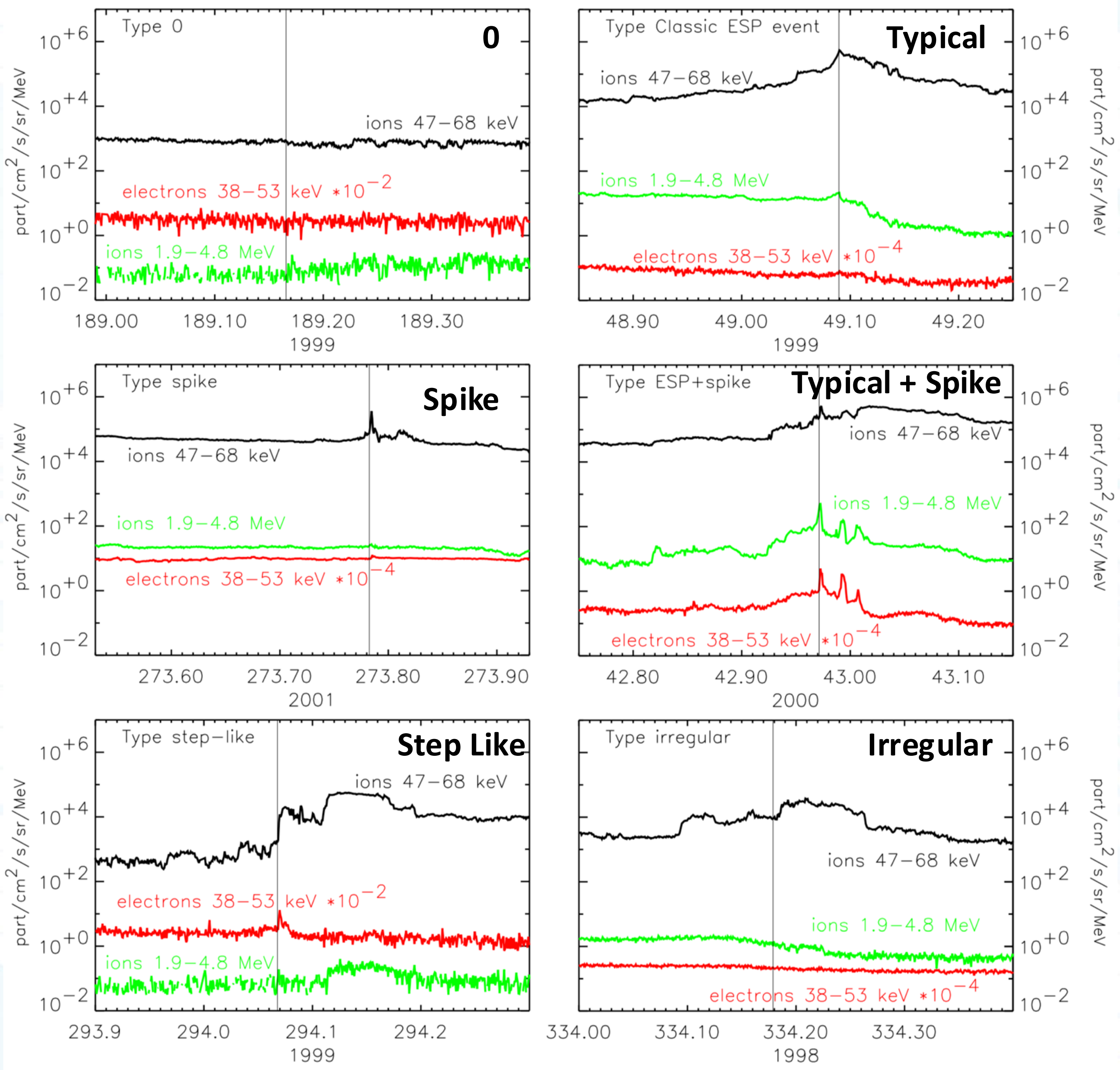
Fast CMEs drive shocks

Diffusive shock acceleration of solar wind or suprathermal ions?



(Ohira 2008)

ESP Time Profiles



Lario et al. 2003

Can be described in 6 categories:

- "0": shocks without ESP signature
- "spike": short-times enhancement
- "step-like": sudden increase downstream
- "typical": exponential rise pre-shock, and downstream decay
- "typical+spike"
- "Irregular": Complex profile

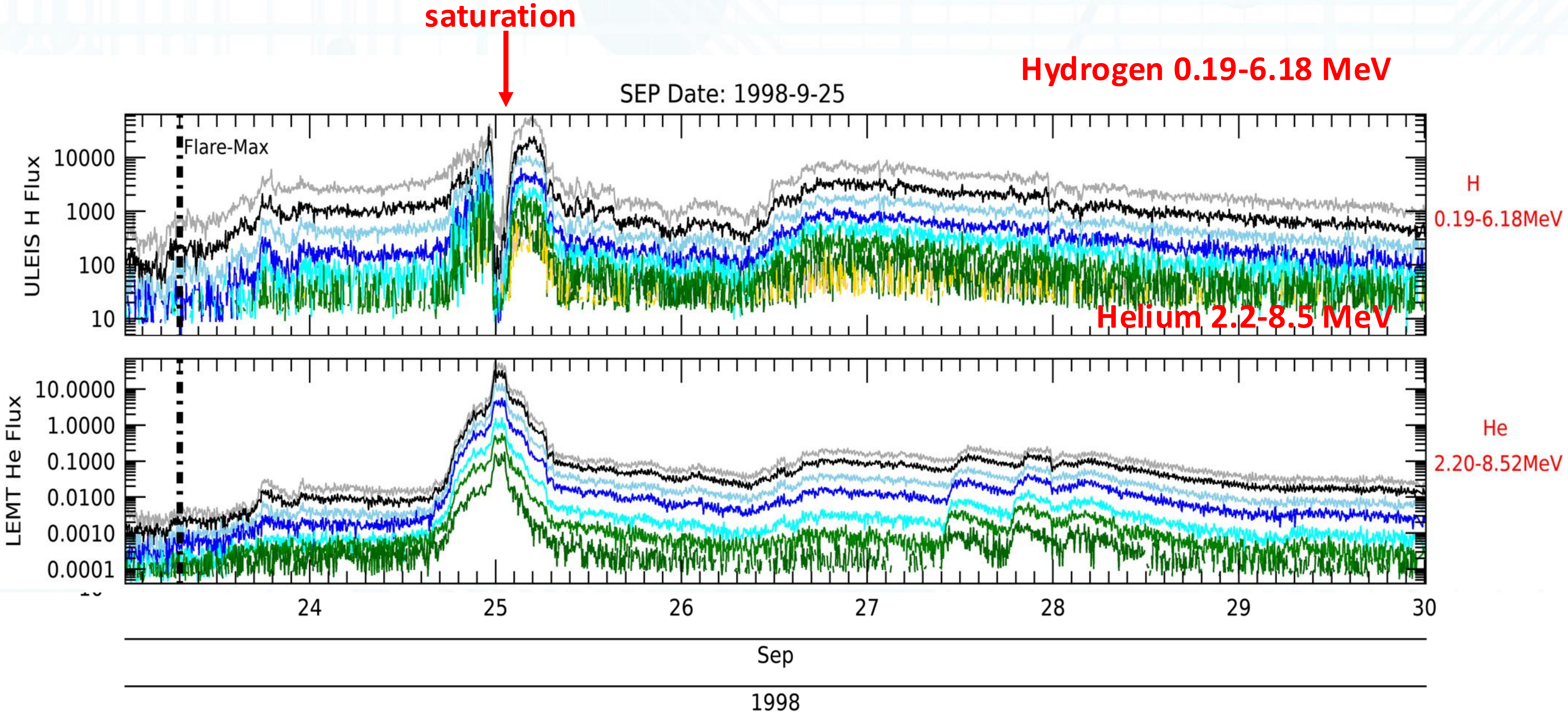
Why study ESPs?

- Yield crucial information on energetic particle acceleration in propagating shocks, magnetic connectivity, and interplanetary transport during individual SEP events.

- Understanding ESP drivers provides understanding of shock-acceleration and ultimately SEP forecasting

- Enhancements exceed several order of magnitude at time, creating saturation in particle instruments and are very geoeffective.

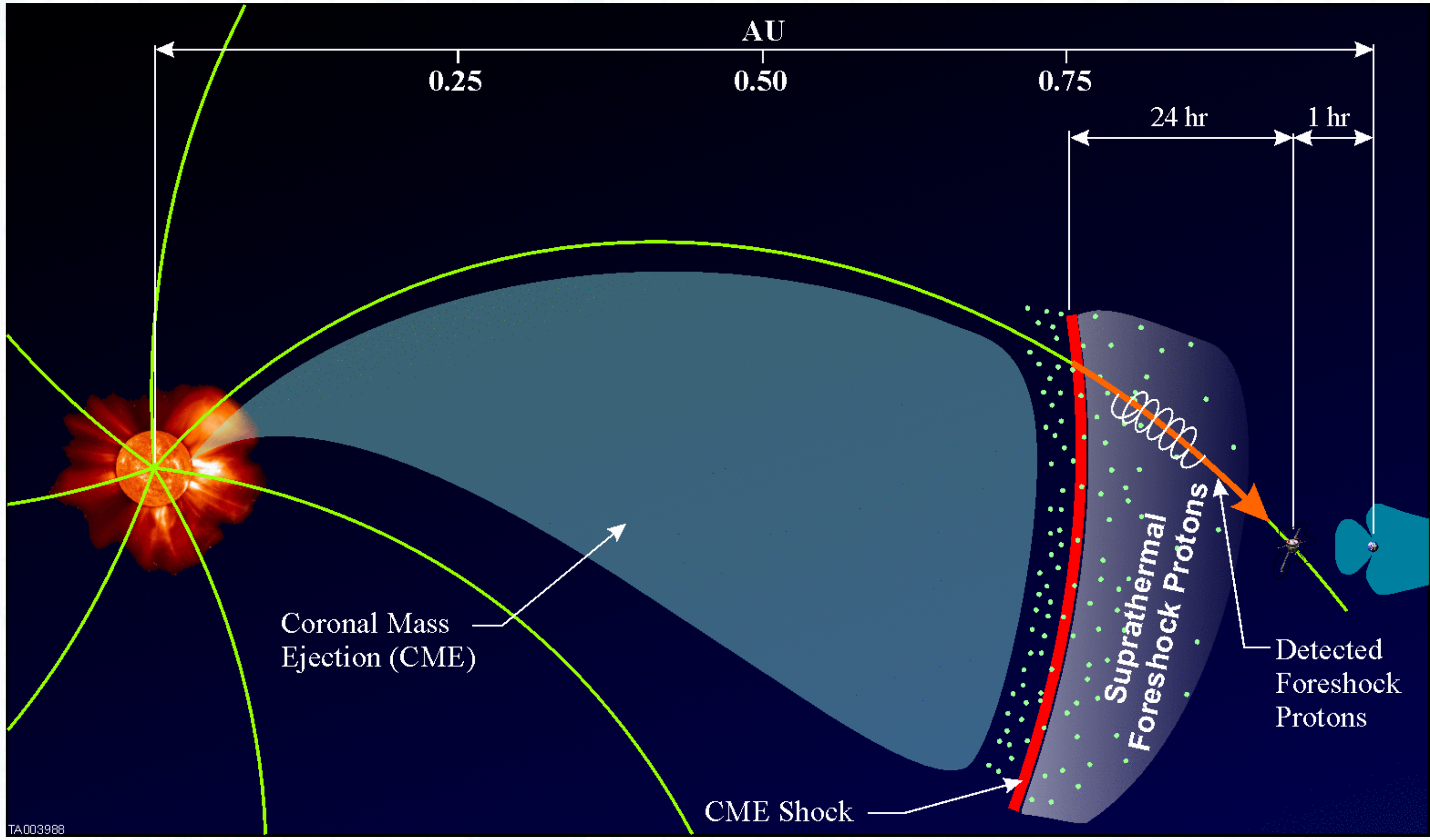
- Forecasting these events is thus critical in the big picture of SWx forecasting.



Forecasting ESPs

Hints from previous studies:

- Posner et al. 2004: Signatures in the suprathermal anisotropy and energy distribution can indicate the arrival of an IP shock up to ~24 hrs ahead of time
- Vandegriff et al. 2005: Suprathermal ions escaping from the foreshocks ahead of the IP shocks can be used to predict the arrival times of the peak intensity of ESP events
- Dayeh (2007): Trapping time of low-E particles at shocks is directly related to the peak intensities of of the ESP component.

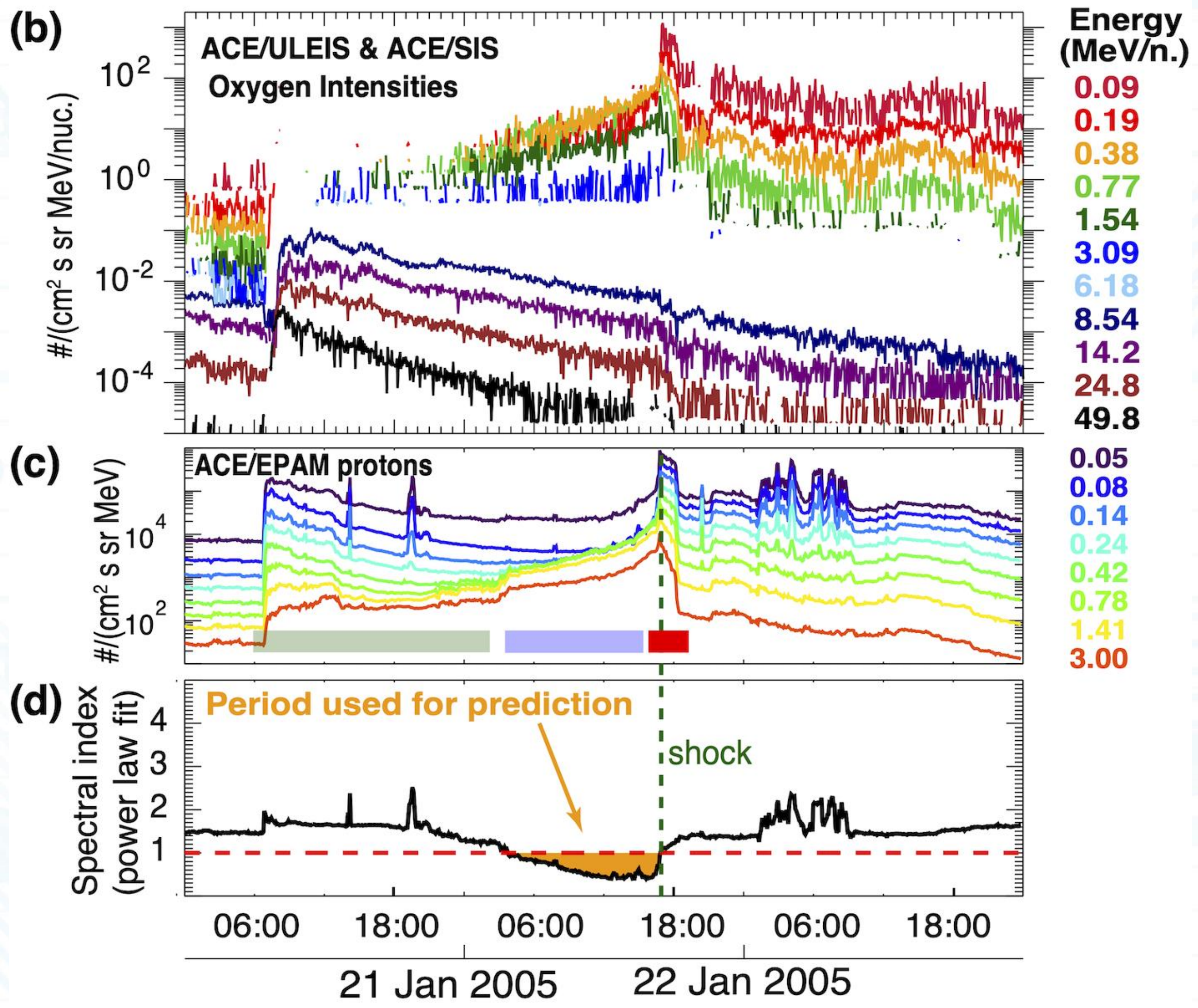


Success rate ~50-70%. No reliable method for forecasting ESP events exists, partly due to the lack of relevant observations.

Forecasting ESPs

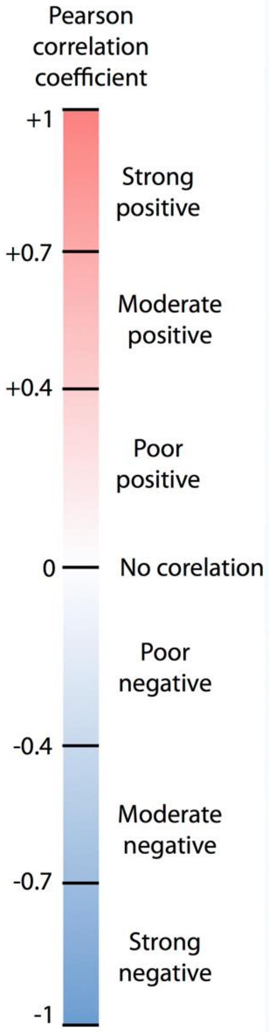
Ongoing effort:

- Exploiting the spectral evolution starting at SEP onsets to continuously forecast ESP peak fluxes.



Shock-ESP relations

		ESP								
		γ_C	E_0^C	γ_O	E_0^O	γ_{Fe}	E_0^{Fe}	J_{max}^O	$^3He/^4He$	Fe/O
ESP	γ_C	**1.00**	**-0.29**	**0.98**	**-0.34**	**0.69**	-0.06	**-0.48**	**0.39**	**0.29**
	E_0^C	**-0.29**	**1.00**	**-0.31**	**0.86**	**-0.44**	**0.55**	0.05	-0.04	**0.58**
	γ_O	**0.98**	**-0.31**	**1.00**	**-0.34**	**0.76**	-0.07	**-0.54**	**0.37**	0.23
	E_0^O	**-0.34**	**0.86**	**-0.34**	**1.00**	**-0.43**	**0.47**	-0.01	-0.11	**0.41**
	γ_{Fe}	**0.69**	**-0.44**	**0.76**	**-0.43**	**1.00**	-0.10	**-0.56**	0.07	-0.15
	E_0^{Fe}	-0.06	**0.55**	-0.07	**0.47**	-0.10	**1.00**	-0.12	-0.03	0.26
	J_{max}^O	**-0.48**	0.05	**-0.54**	-0.01	**-0.56**	-0.12	**1.00**	-0.17	-0.15
	$^3He/^4He$	**0.39**	-0.04	**0.37**	-0.11	0.07	-0.03	-0.17	**1.00**	**0.55**
	Fe/O	**0.29**	**0.58**	0.23	**0.41**	-0.15	0.26	-0.15	**0.55**	**1.00**
Upstream and downstream of the IP shock	$Fe/O\|_U$	0.03	**0.39**	0.01	0.23	-0.12	0.15	0.00	**0.42**	**0.53**
	$Fe/O\|_D$	-0.10	**0.76**	-0.11	**0.61**	-0.21	0.21	-0.09	**0.30**	**0.64**
	$B\|_U$	0.08	0.08	0.04	-0.08	-0.10	-0.10	0.20	0.03	0.21
	$B\|_D$	-0.12	**0.47**	-0.18	**0.31**	**-0.32**	0.01	**0.31**	-0.08	0.22
	$B\|_D / B\|_U$	**-0.26**	**0.60**	**-0.29**	**0.55**	**-0.29**	0.12	0.13	-0.13	0.08
	$V\|_U$	-0.18	0.27	-0.16	0.27	-0.22	**0.39**	0.10	0.16	0.15
	$V\|_D$	**-0.33**	**0.32**	**-0.35**	**0.32**	**-0.32**	**0.36**	**0.29**	-0.02	0.07
	Δ_V	**-0.33**	0.19	**-0.38**	0.20	**-0.26**	0.11	**0.37**	-0.24	-0.08
	$n\|_U$	-0.03	**0.41**	-0.02	**0.31**	-0.15	-0.12	0.06	-0.03	0.23
	$n\|_D$	0.00	**0.31**	0.00	0.18	-0.08	-0.16	-0.01	-0.09	0.07
	$n\|_D / n\|_U$	0.03	-0.12	0.02	-0.10	0.10	-0.15	-0.09	-0.17	-0.22
	$T\|_U$	-0.13	-0.01	-0.14	0.01	-0.17	-0.05	0.17	-0.06	-0.01
	$T\|_D$	**-0.31**	0.21	**-0.31**	**0.29**	-0.23	**0.29**	0.23	-0.16	-0.07
	$T\|_D / T\|_U$	-0.24	0.20	**-0.26**	0.27	-0.14	0.27	0.02	-0.13	-0.03
	θ_{B_n}	0.02	0.01	0.02	-0.11	-0.04	-0.26	-0.07	0.01	0.02
	V_{shock}	**-0.34**	**0.34**	**-0.40**	**0.28**	**-0.38**	**0.39**	**0.52**	-0.16	0.07
ICME	P_{sheath}	-0.10	0.13	-0.11	0.20	-0.12	-0.13	0.02	-0.16	0.05
	T_{sheath}	**-0.39**	**0.40**	**-0.41**	**0.40**	**-0.41**	**0.28**	**0.44**	-0.17	-0.02
	n_{sheath}	0.10	-0.09	0.11	-0.12	0.09	**-0.29**	-0.08	-0.14	-0.07



Dayeh et al. 2018

Shock vs ESP properties have been investigated thoroughly:

Some relations (statistically significant) stand out as indicative of physical processes, such as:

- Spectral roll-over energy vs. elemental abundances, indicating a clear rigidity dependence effect.
- ESP peak intensities vs. shock speed, indicating that strong shocks have a stronger ESP component.
- Sheath temperature vs. peak fluxes, this could come from several effects.

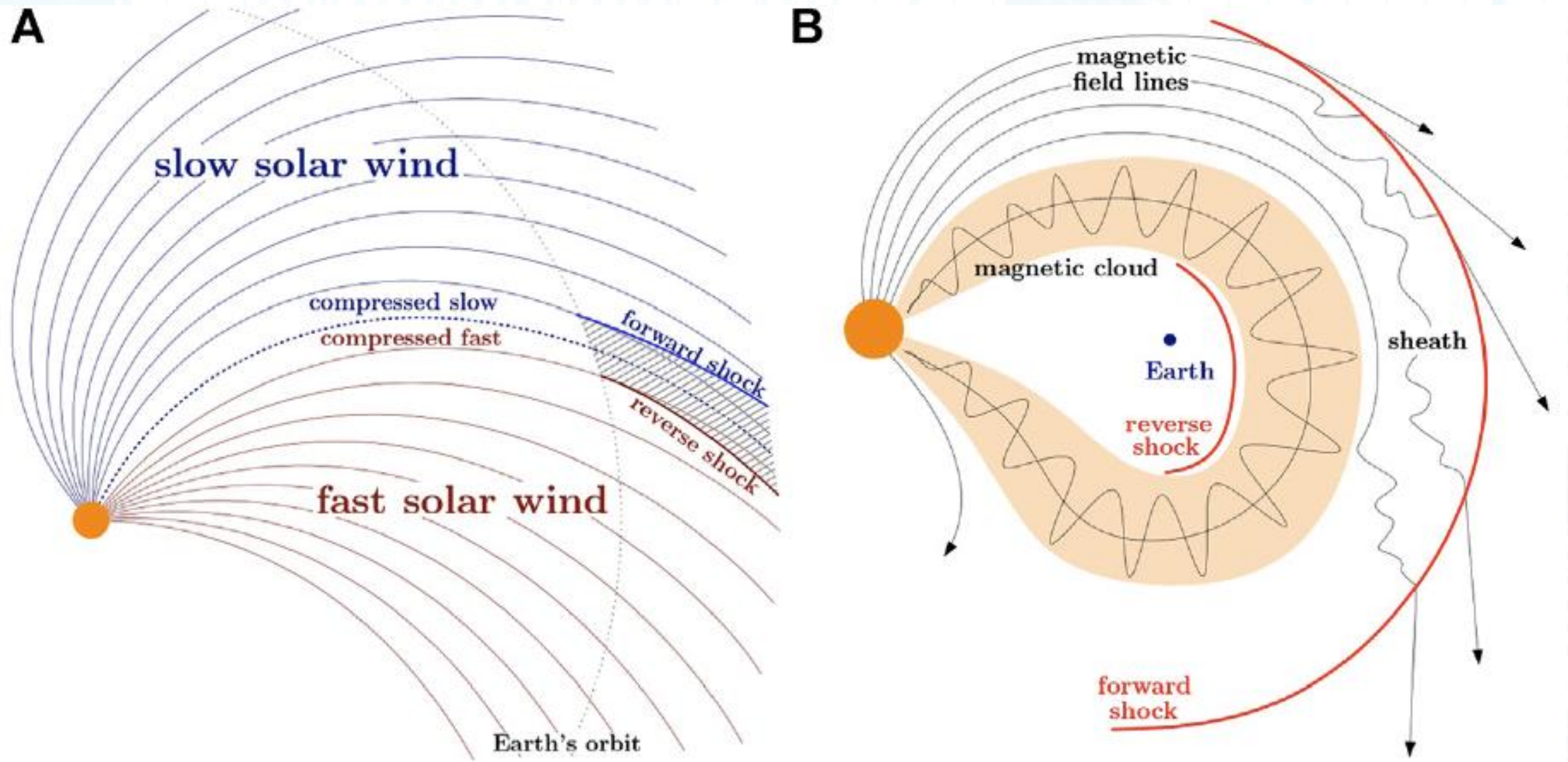
Armstrong et al, 1985, Richter et al, 1985, Scholer 1985, Kennel et al, 1986, Reames, 1999, Cohen 2006, Giacalone 2012, Lario et al, 2003, 2005, Desai et al. 2003, 2016, Dayeh et al. 2018, among others

Problem: Event selection and a broad range of correlations.

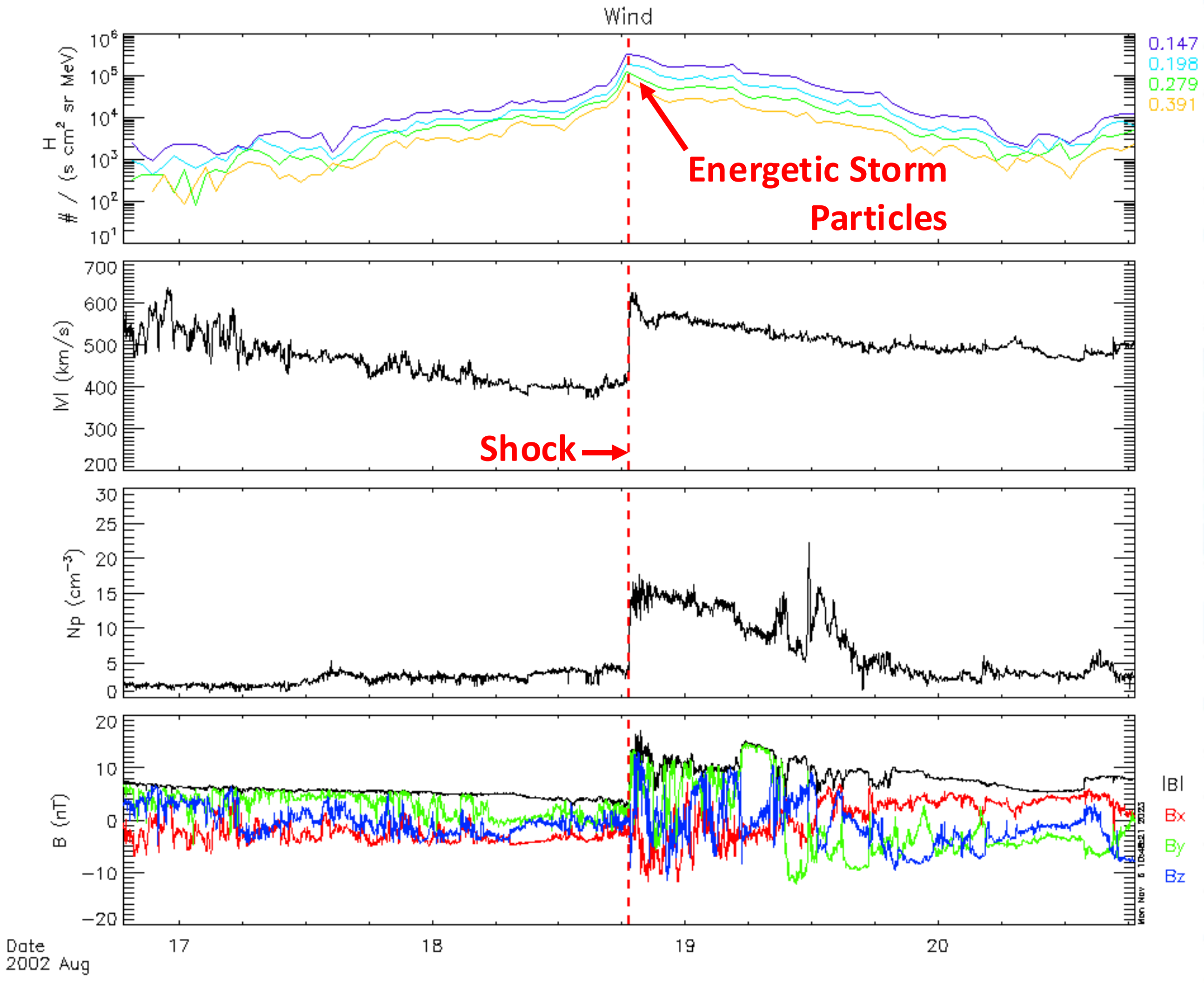
Objective

Use shock properties inferred by PUNCH (speed, number density, or speed jump) to forecast energetic particle enhancements at interplanetary shocks (CME- and CIR-driven)

CIR Shocks **Fast CME Shocks**



Fast Forward shocks from Helsinki IP database, Wind, ACE, STEREO-A/B

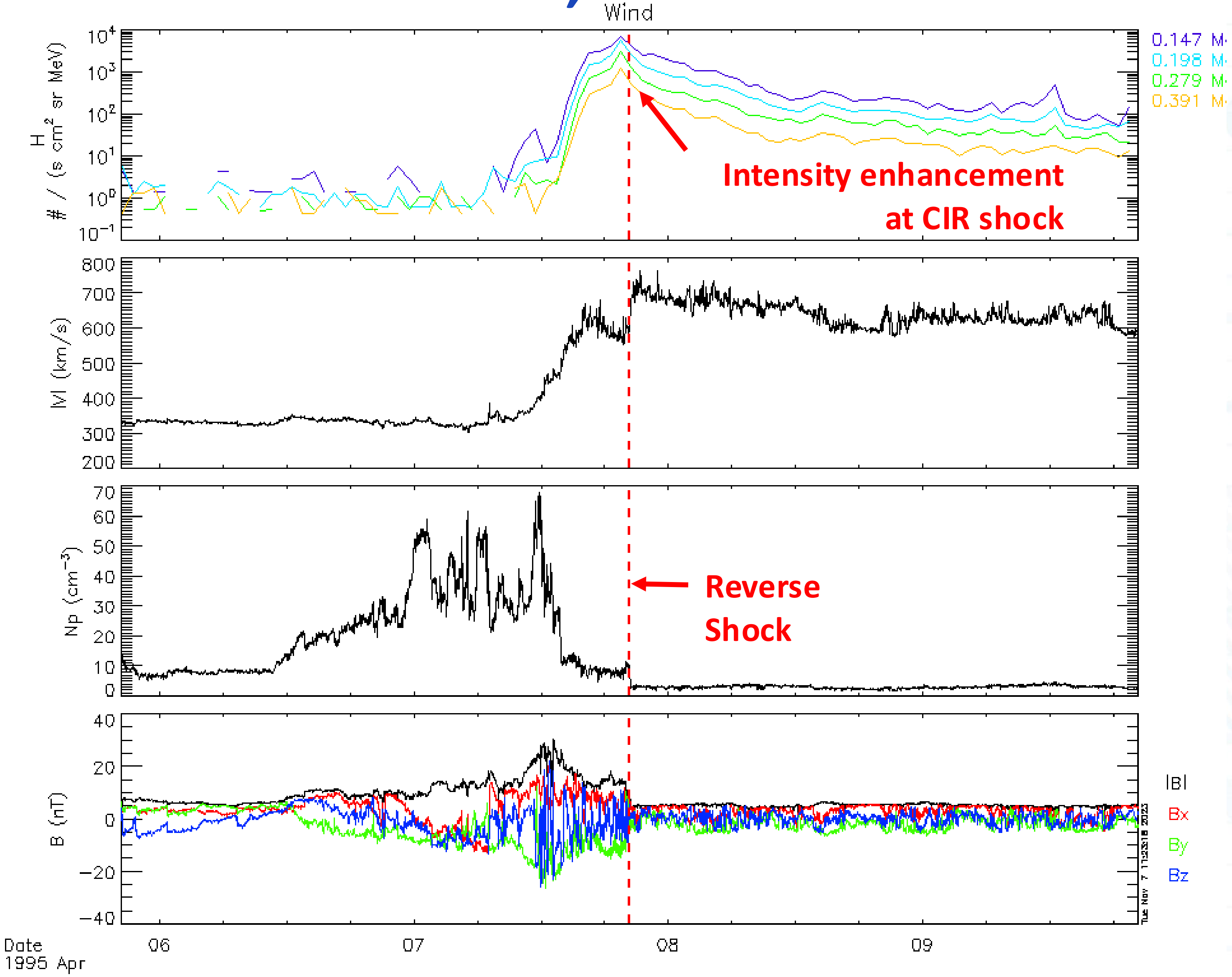


ESP peak flux determination:

1. Restrict timeseries flux to 12-hour window centered on shock time
2. Create 1D flux time series from single energy channel closest to user-defined energy (e.g., 0.2 MeV)
3. Compute maximum value of flux within time window 'ESP Time Window' centered on shock time

CIR peak flux determination

Wind CIR events, Broiles et al. 2012

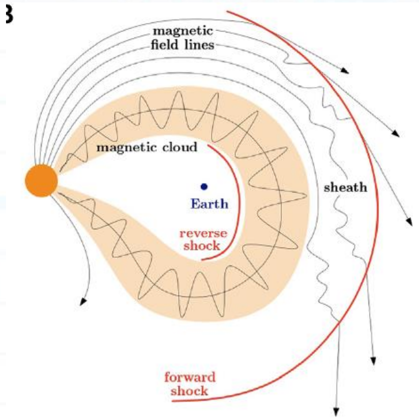


1. Restrict timeseries flux to 12-hour window centered on shock time

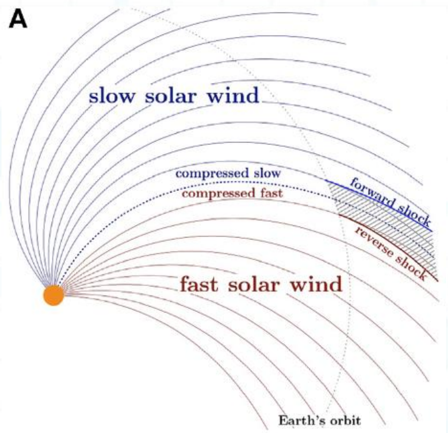
2. Integrate flux over user-defined energy range (e.g., 0.1-1.0 MeV)

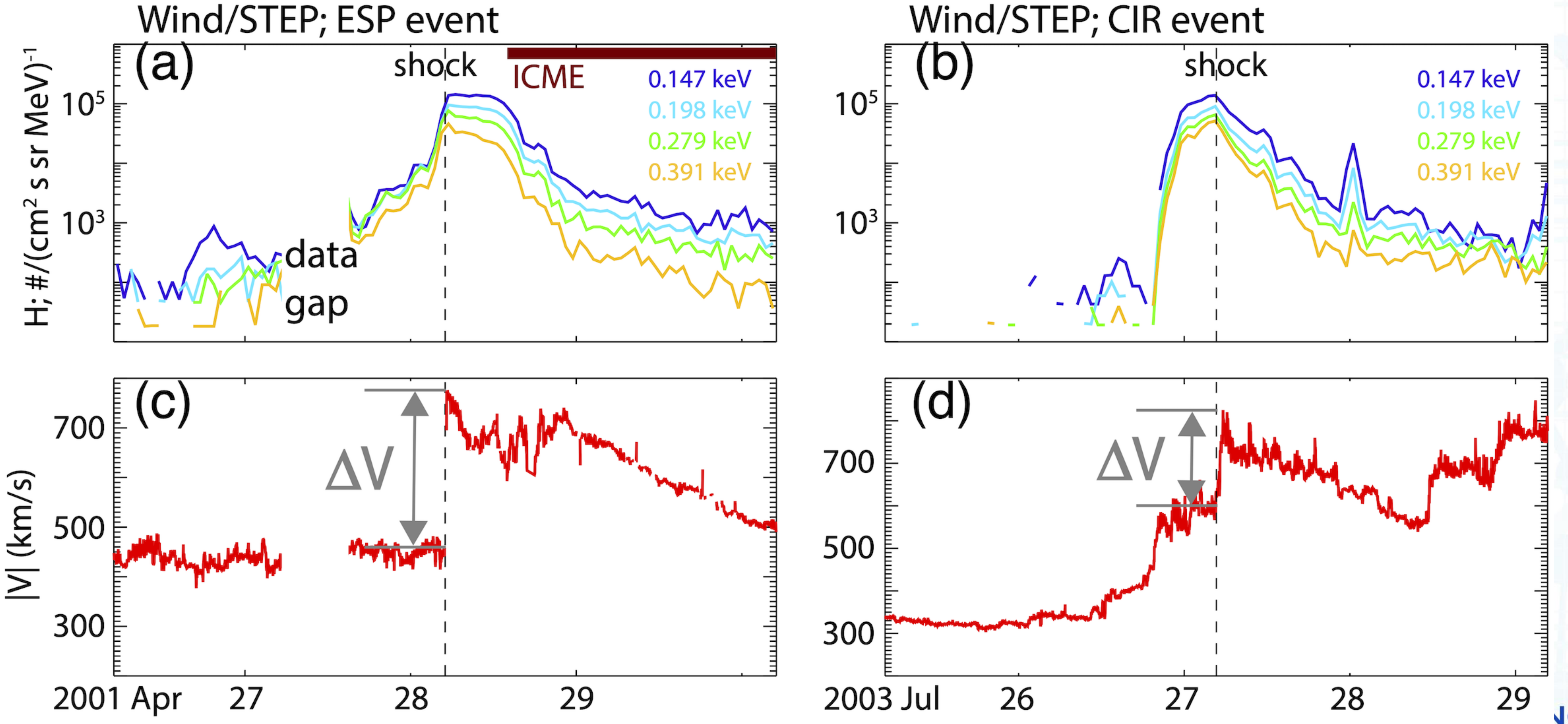
3. Compute maximum value of flux within time window 'ESP Time Window' centered on shock time

Fast CME Shocks

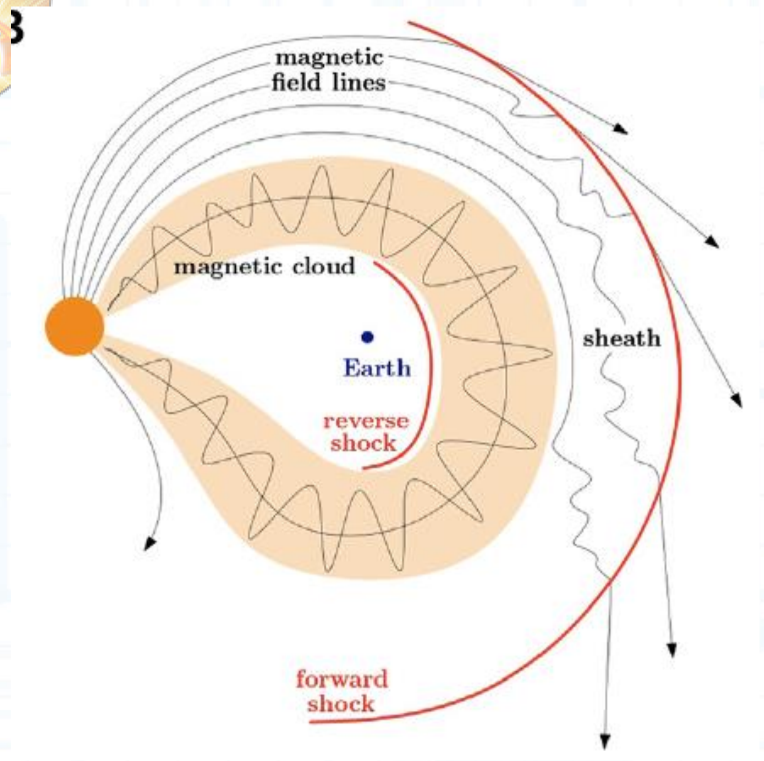


CIR Shocks

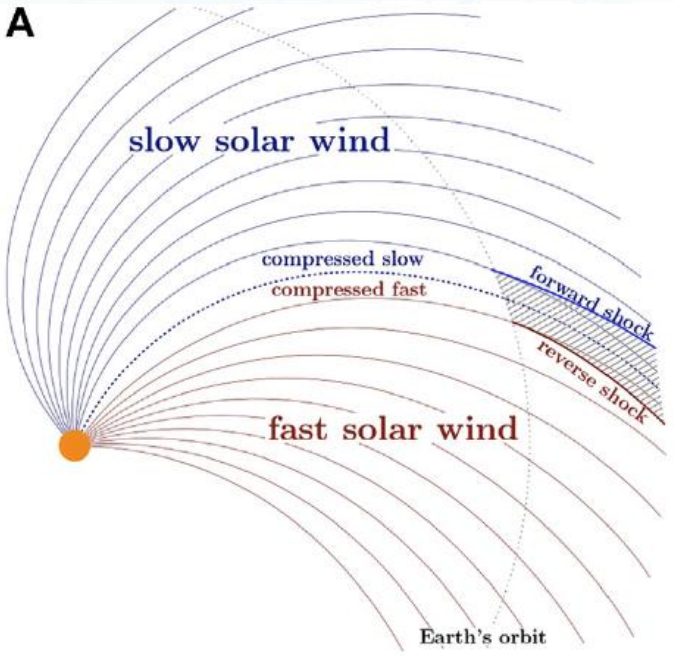


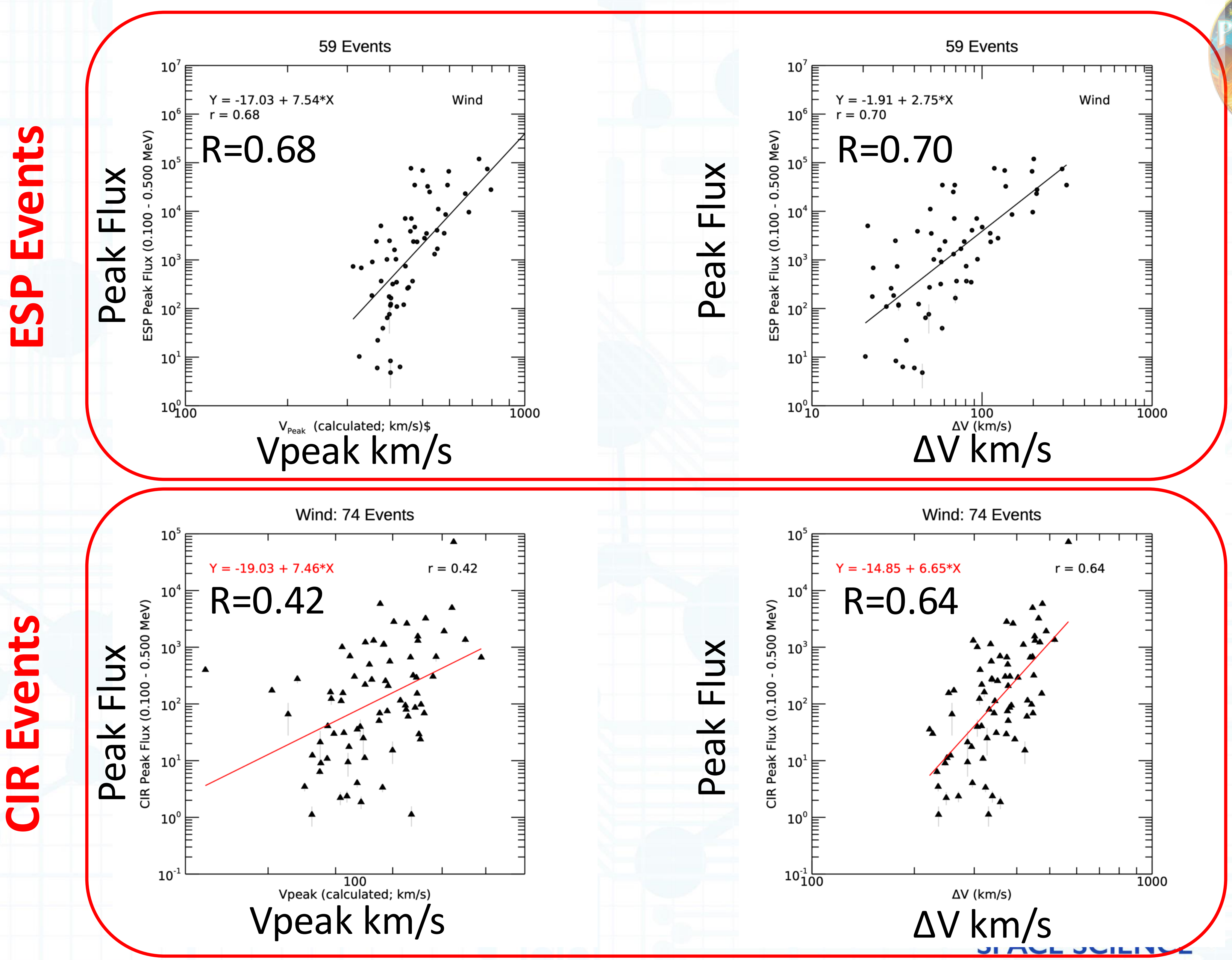


Fast CME Shocks

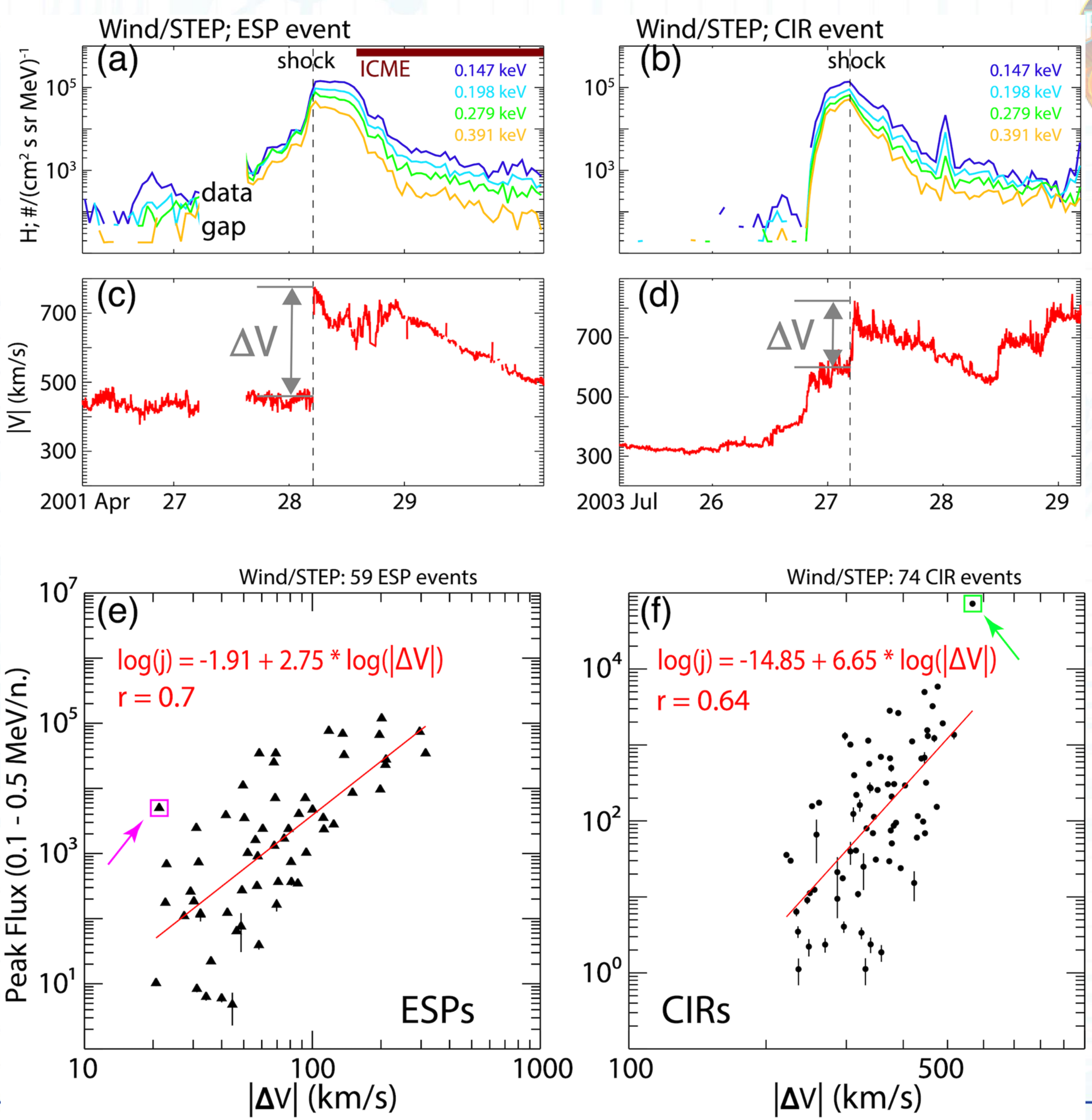


CIR Shocks

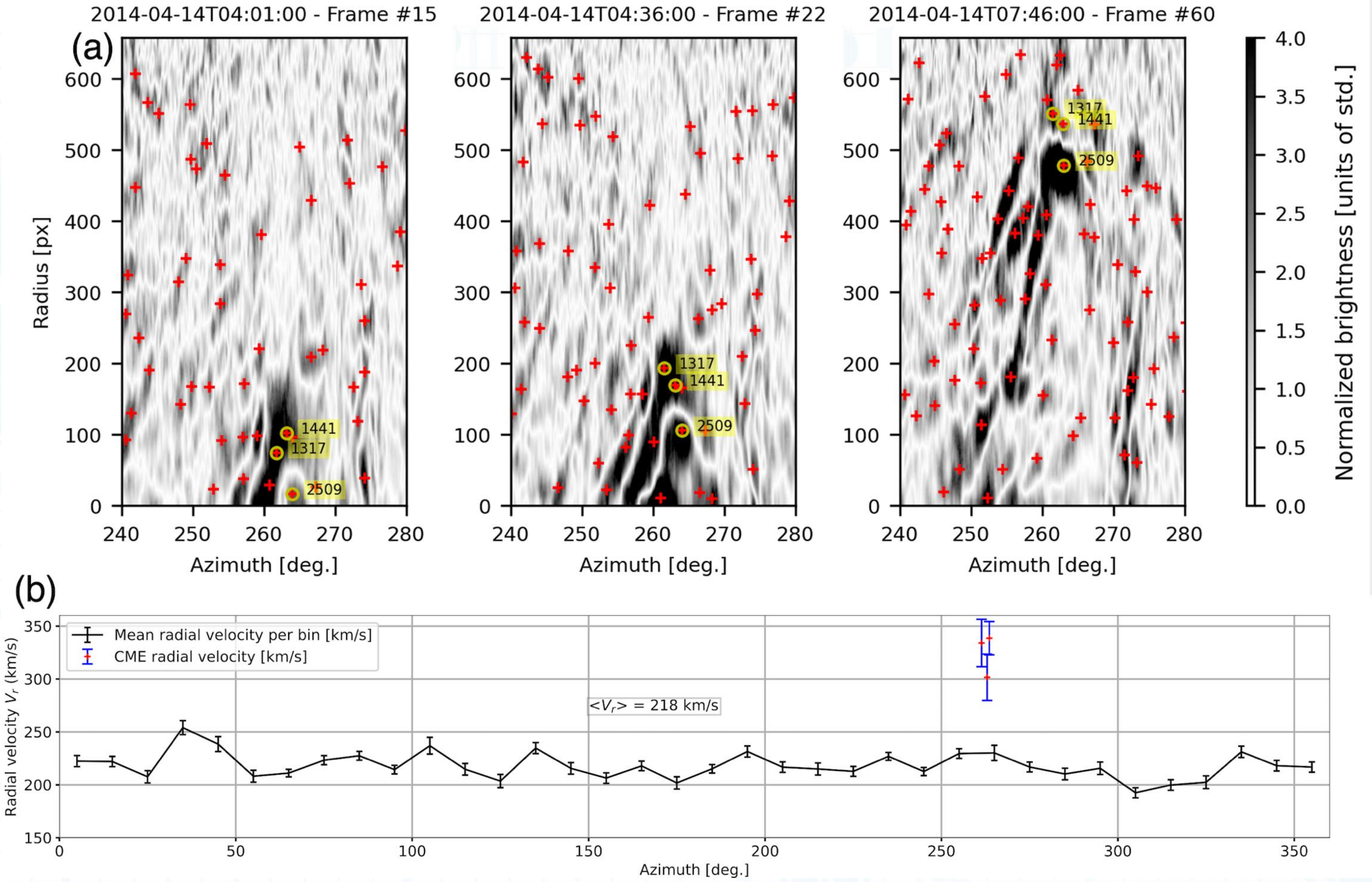




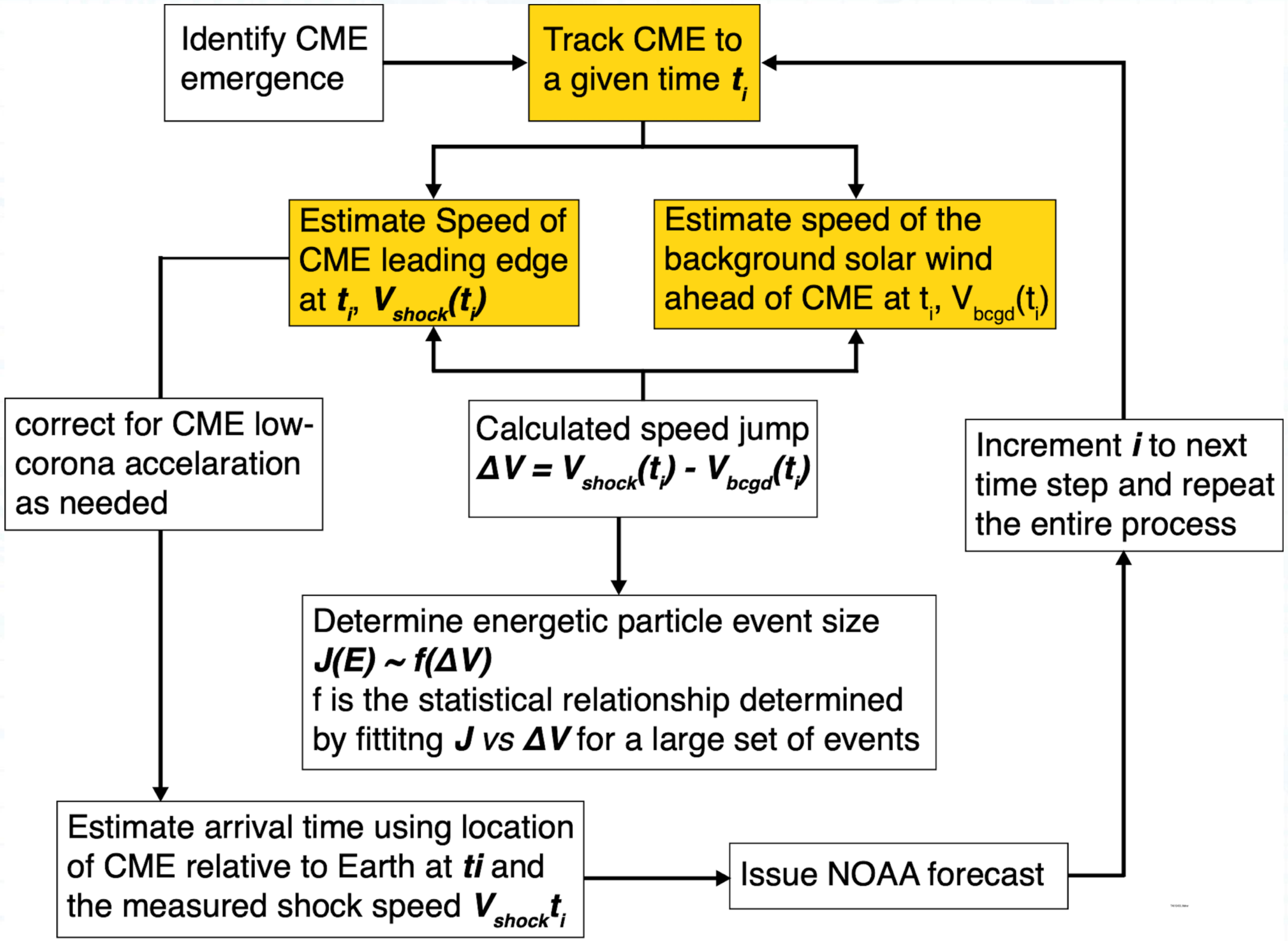
Peak Fluxes vs. *Δ*V show the strongest correlation for both CIR and ESP events



PUNCH enables estimates of shock-associated particle properties as an evolving forecast



Architecture of a Potential Forecasting Algorithm



Not for public distribution

Summary

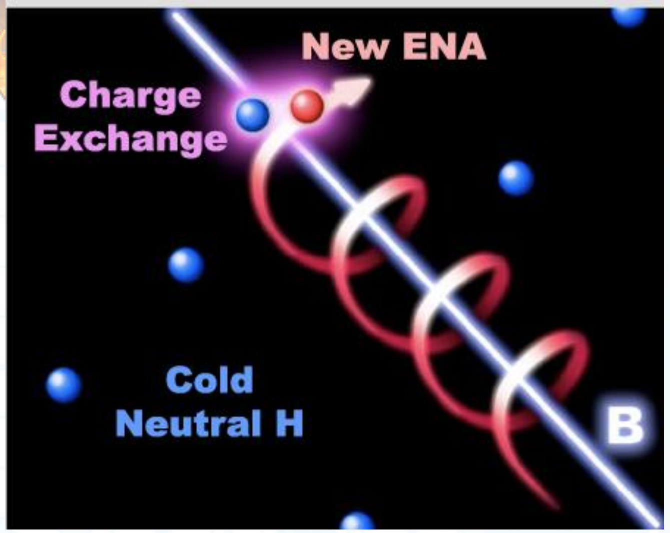
- **Problem:** Properties of energetic particles accelerated by shocks are difficult to predict and pose serious SWx risks that require mitigation.
- **Solution:** Utilize PUNCH data to estimate shock quantities near the Sun to continuously forecast ESPs in the inner heliosphere and beyond.
- **Caveat:** Small-scale shock structure and field-line connectivity likely plays an important role. Models describing shock structure, evolution, and propagation will enable more reliable and accurate forecasts.
- Paper is published in the PUNCH collection special issue:

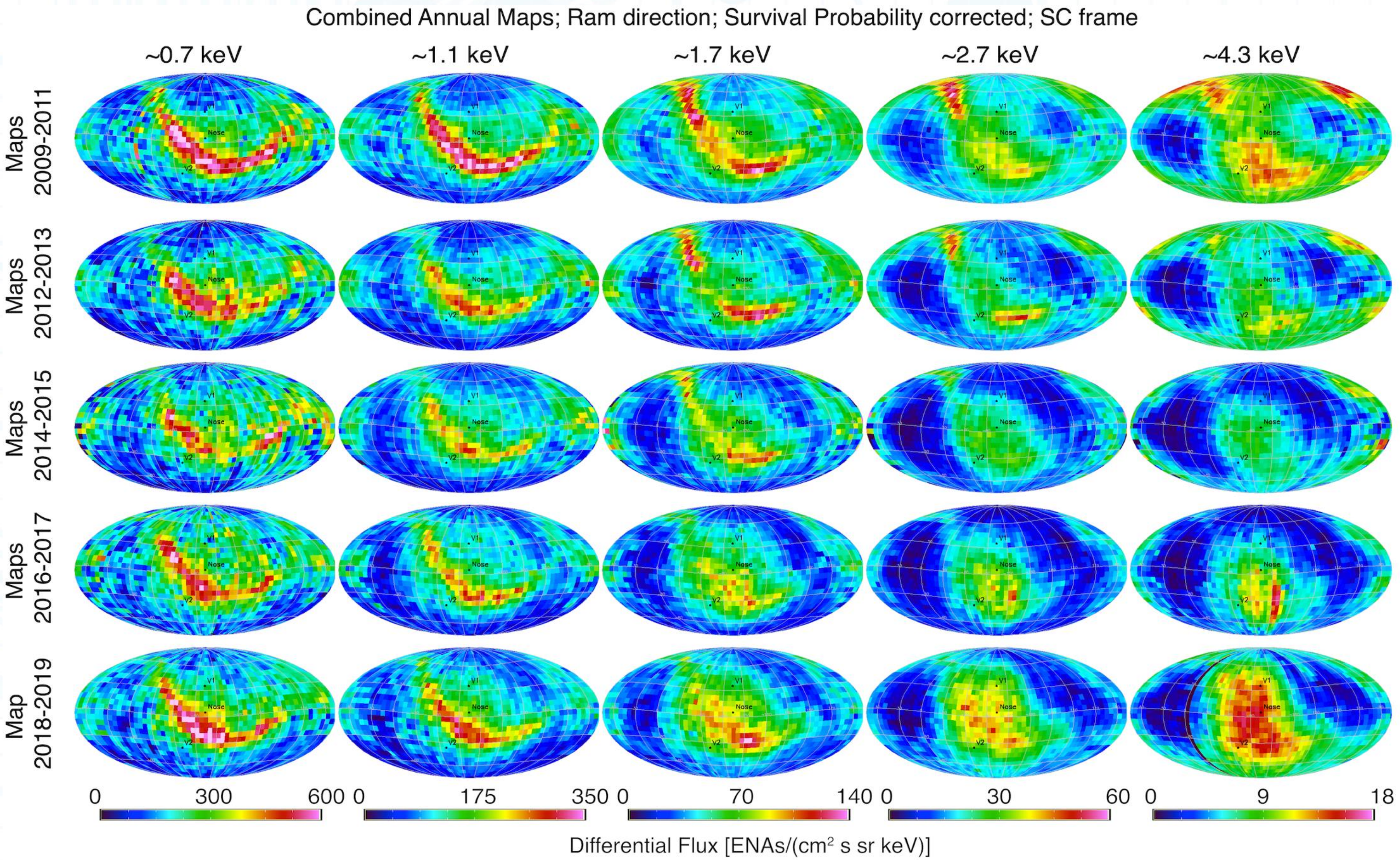
Dayeh, M.A., Starkey, M.J., Elliott, H.A. *et al.* Forecasting Shock-Associated Energetic Particle Intensities in the Inner Heliosphere: A Proof-of-Concept Capability for the PUNCH Mission. *Sol Phys* **300**, 1 (2025). https://doi.org/10.1007/s11207-024-02409-5

Thank you

Deducing short-scale temporal variations in IBEX ENA maps

(a PUNCHy thing though)



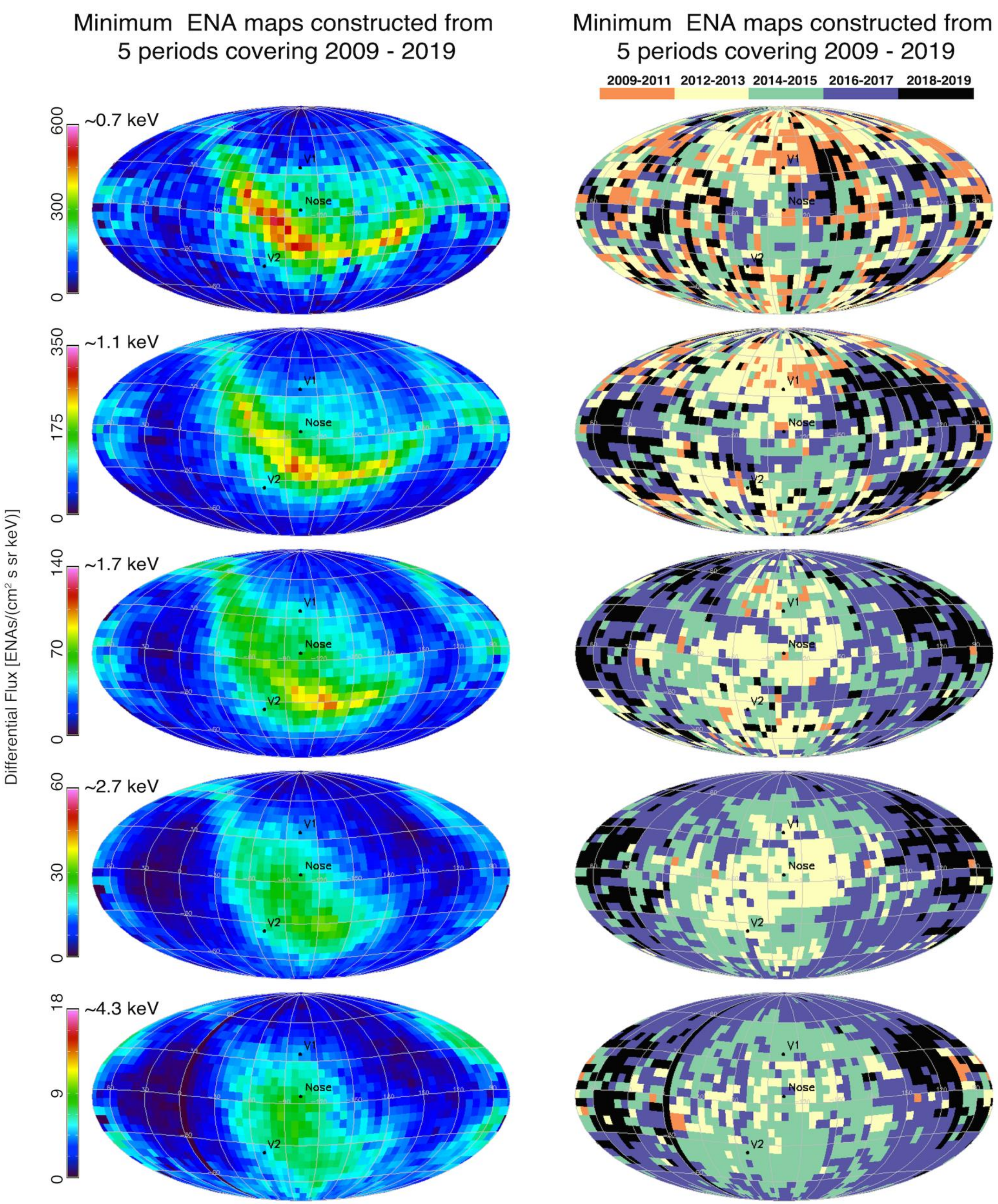


IBEX annual ENA sky maps combined over 5 time periods representing a full solar cycle

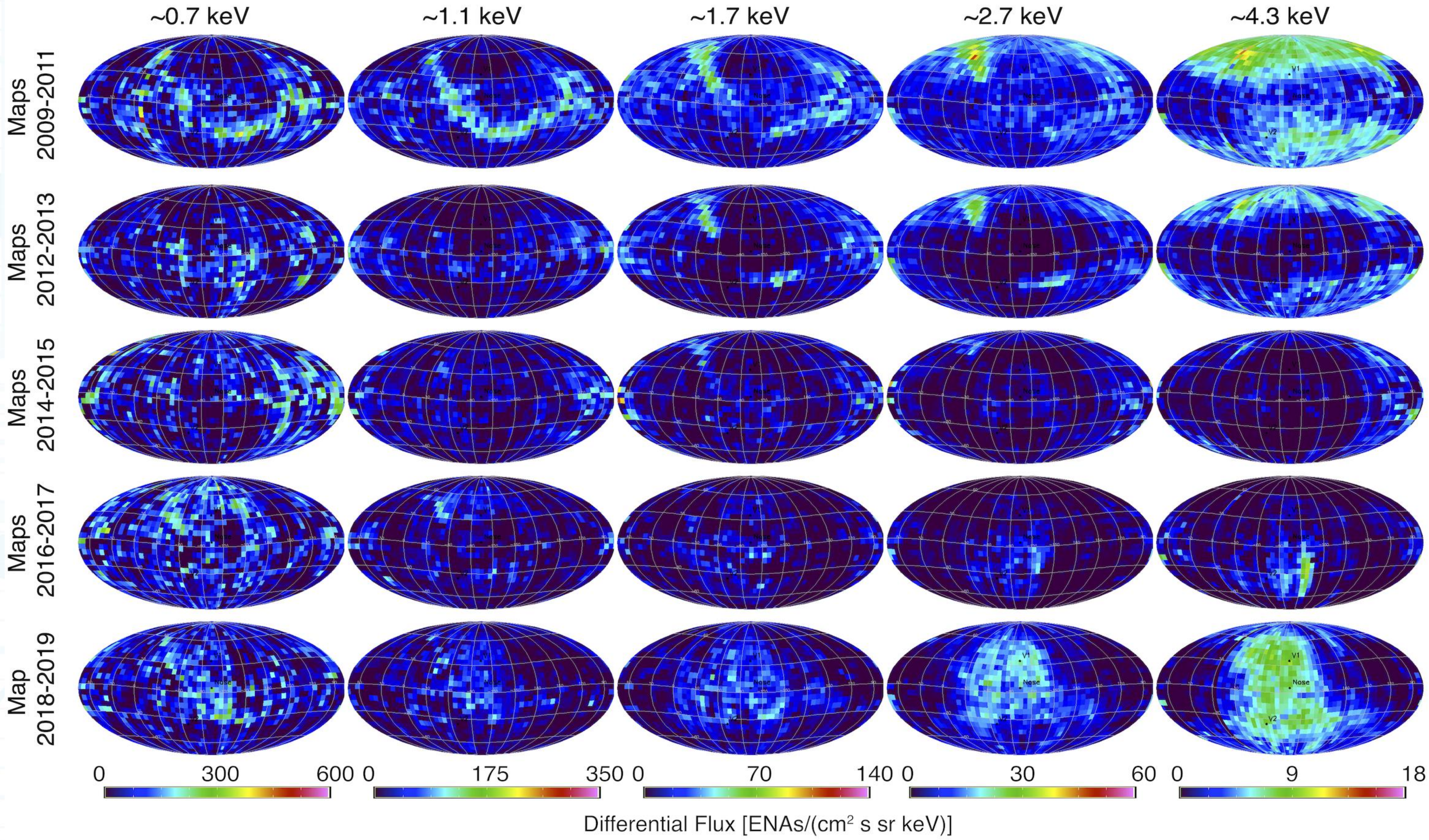
For each energy in the previous slide, we determine the minimum value in each pixel using the 5 time periods.

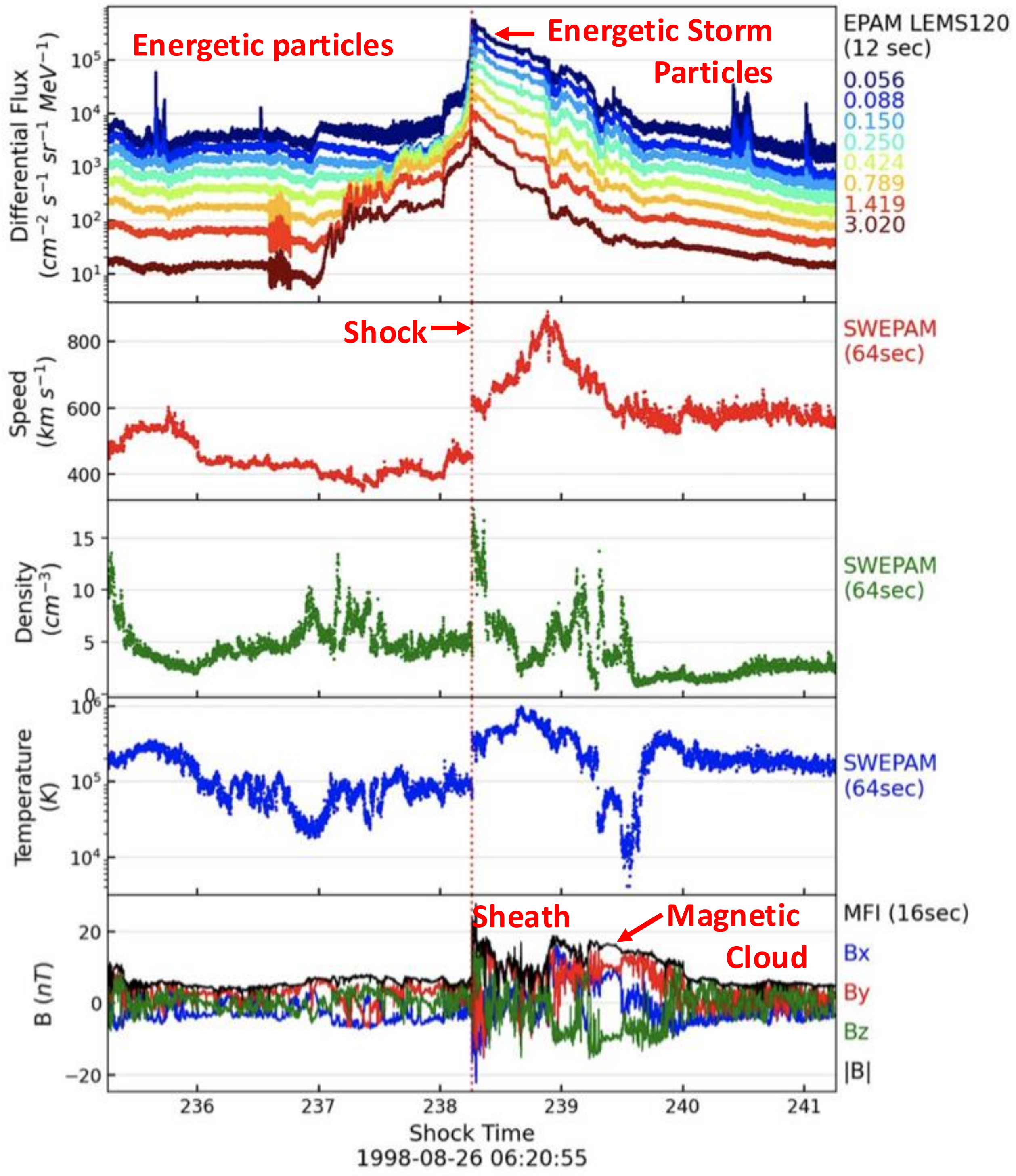
Left column shows the "minimum maps" for different energies

Right column: Index of minimum pixels, showing from which original maps the left column plots were constructed



Combined Maps minus Minimum maps; Short-scale variation in the sky are revealed.





Energetic Storm Particle (ESP) events

- Significant enhancements of > 0.05 MeV ions, > 10s keV electrons associated with the arrival of the interplanetary shock
- Enhancements could occur ahead/behind the IP shock
- Sudden multi-orders of magnitude enhancements of ions pose high space weather risk (very geoeffective).

First Observations of ESPs

- Bryant 1962, Explorer 12, Sept 30, 1961
- 9-14 MeV and > 30 MeV proton channels
- Associated with Forbush decrease and geomagnetic storm ➔ "Energetic Storm Particles"
- Softer spectra than SEP event
- Theories
  - Stored in magnetic cloud (Bryant 1961)
  - Trapping or in-situ acceleration (Rao 1967)
  - Flare material pushed by cloud (Kahler, 1969)
  - Diffusive shock Acceleration (Jokipii, 1966)
  - Shock Drift Acceleration (Hudson, 1965)