SEPSTER-2D

Empirical Model of 10 – 130 MeV Solar Energetic Particle Spectra at 1 AU Based on Coronal Mass Ejection Speed and Direction

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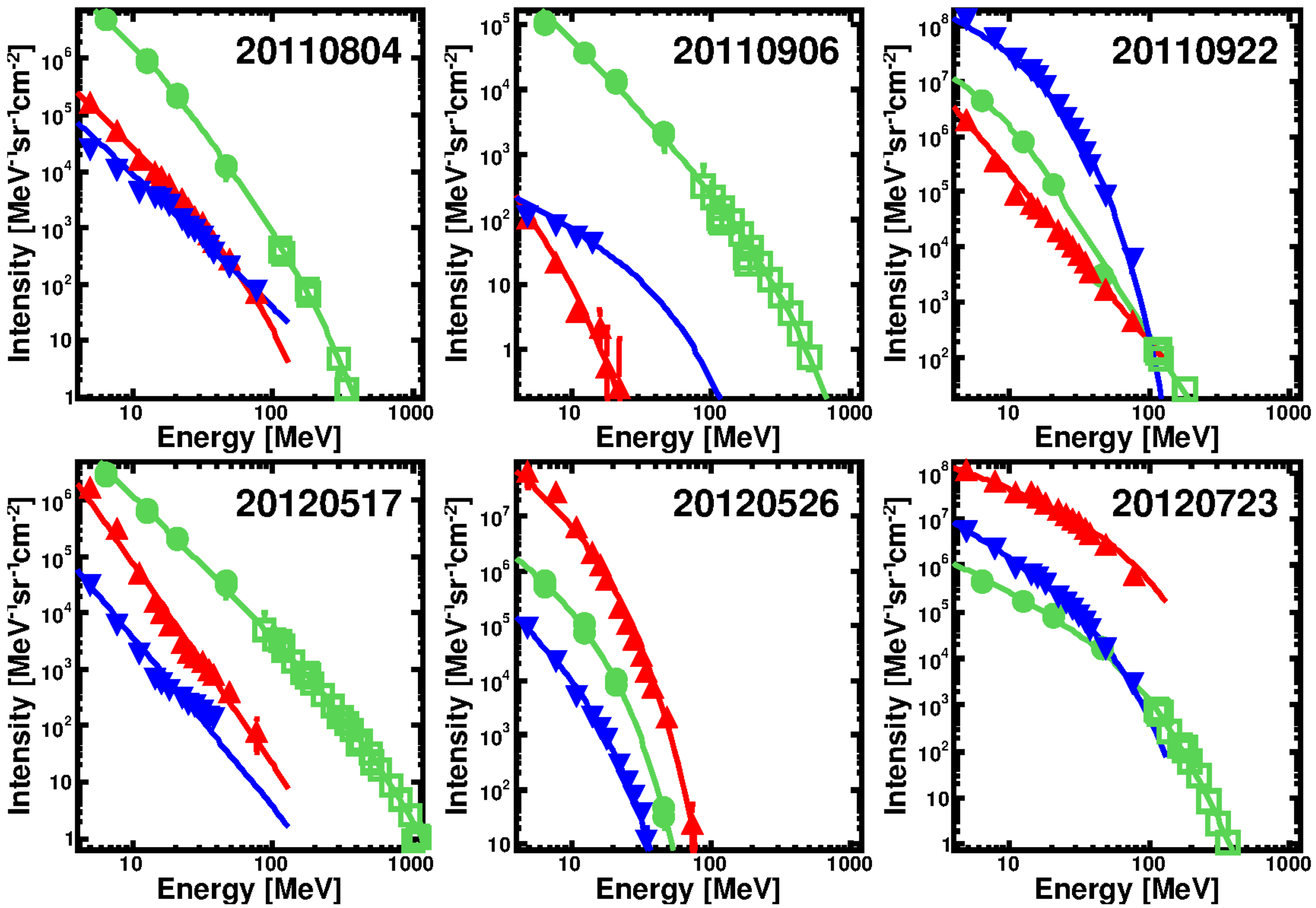
CCMC Workshop, 7 June 2022

Introduction: empirical modeling

- The SEP acceleration efficiency is predicted to depend on several concomitant factors difficult to evaluate or not currently measurable directly
  - e.g., shock speed, geometry, and age, the coronal magnetic-field strength and configuration, the presence of seed particles, and pre-existing turbulence

- Similar to SEPSTER, the **SEPSTER2D** model (*Bruno & Richardson, 2021*) is based on the experimental evidence that SEP intensities are
  - ✓ Correlated with the parent CME speed
    - indication that SEPs are accelerated by CME-driven shocks
    - proxy for the shock-acceleration efficiency
  - ✓ Anti-correlated with the connection angle
    - affecting the longitudinal distribution of SEPs and its energy dependence
    - influencing GLE occurrence

Model development

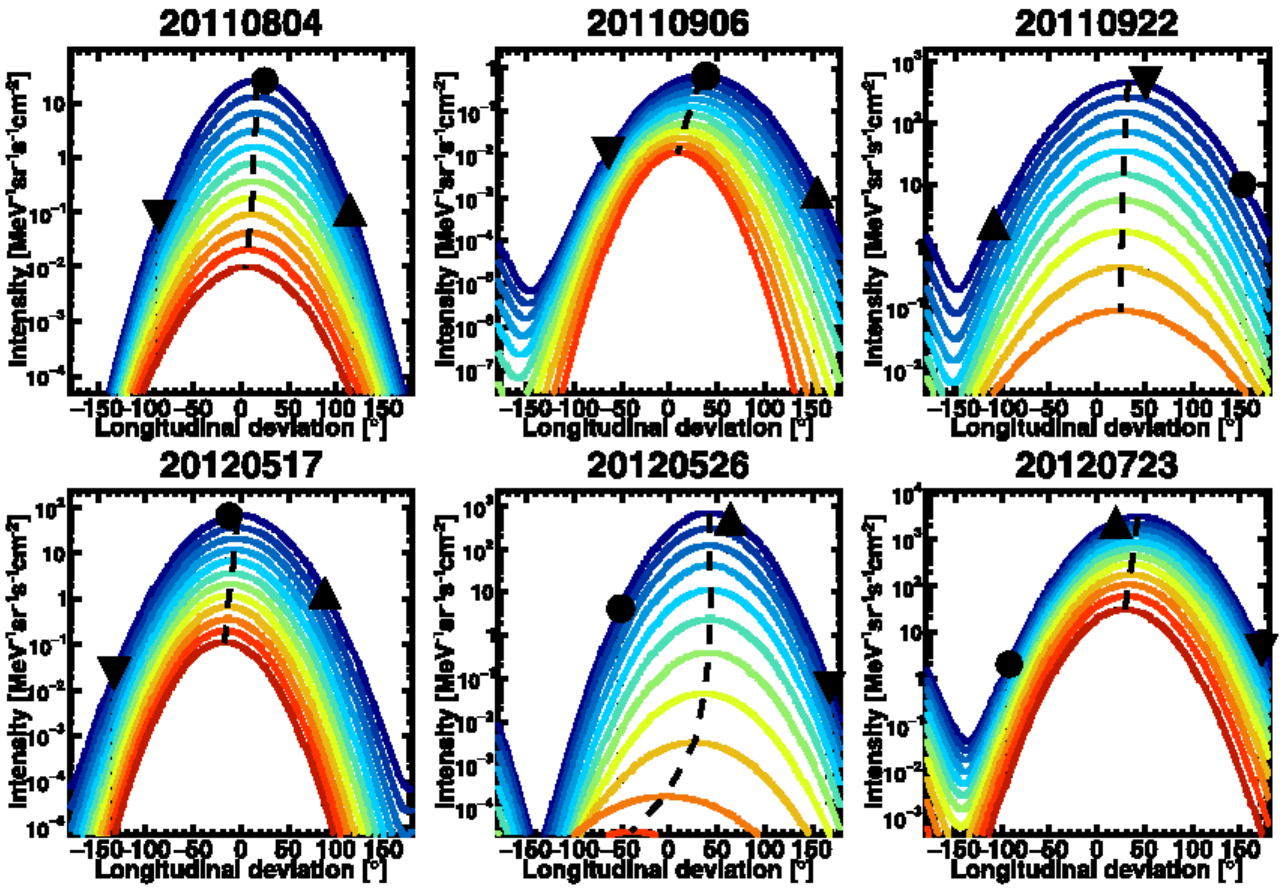


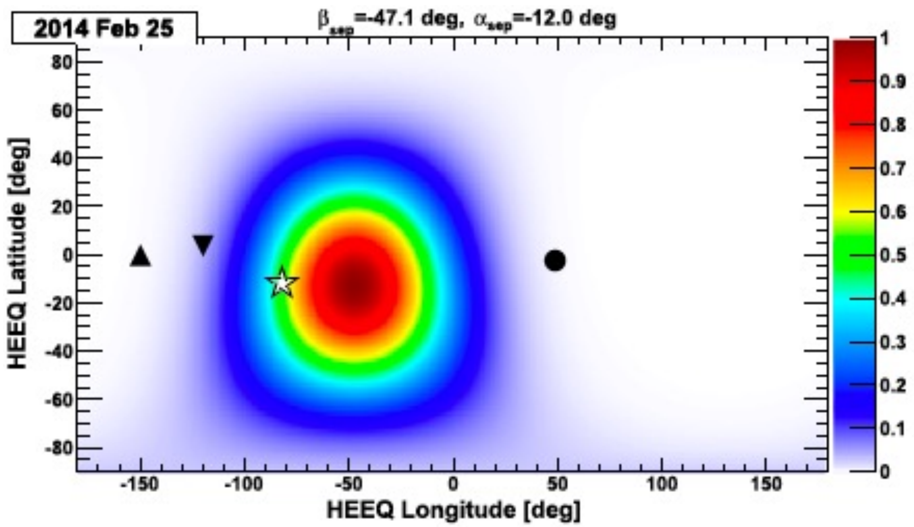
STEREO A STEREO B Earth (GOES-13/15, PAMELA)

- ○ SEPSTER2D predicts SEP event-integrated and peak intensity spectra between 10 and 130 MeV

- ✓ Based on a sample of 32 SEP events occurring between 2010 and 2014, with a statistically significant proton signal at energies in excess of a few tens of MeV, unambiguously recorded at three spacecraft locations.

Model development



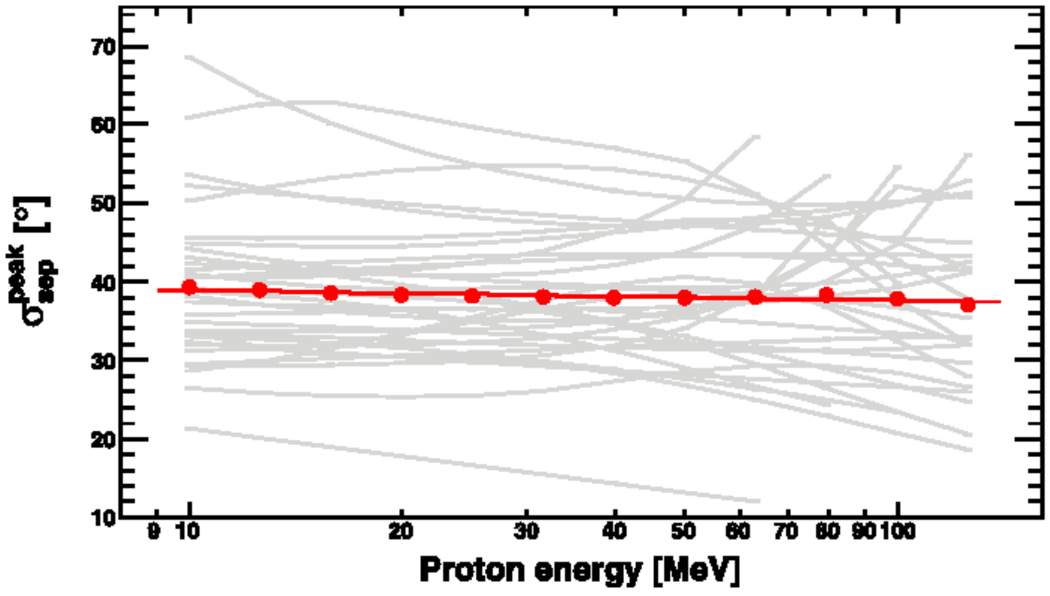


Connection angle (spherical distance between CME direction and spacecraft footpoint location) estimated with a simple Parker spiral model at 2.5 Rs

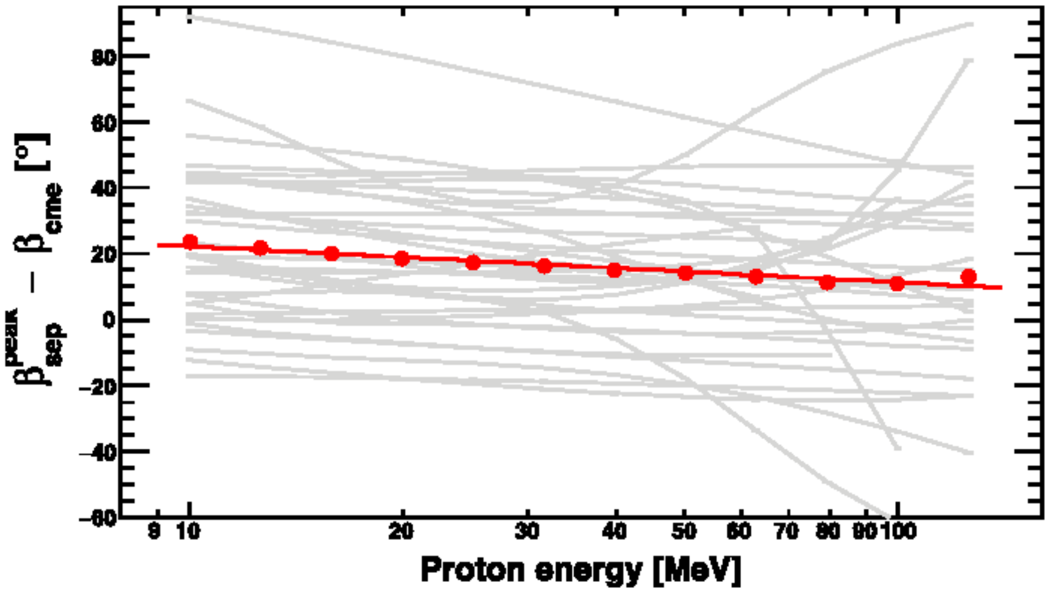
- Accounts for both longitudinal and latitudinal magnetic connectivity
  - ✓ By assuming an **energy-dependent 2D Gaussian functional form** ($\sigma_{lat} = \sigma_{lon}$)
  - ✓ The Gaussian peak is proportional to the CME speed

SEP spatial distribution

Variation of the Gaussian sigma (sigma) with SEP Energy



Variation of the angle between the Gaussian peak and CME direction with SEP Energy



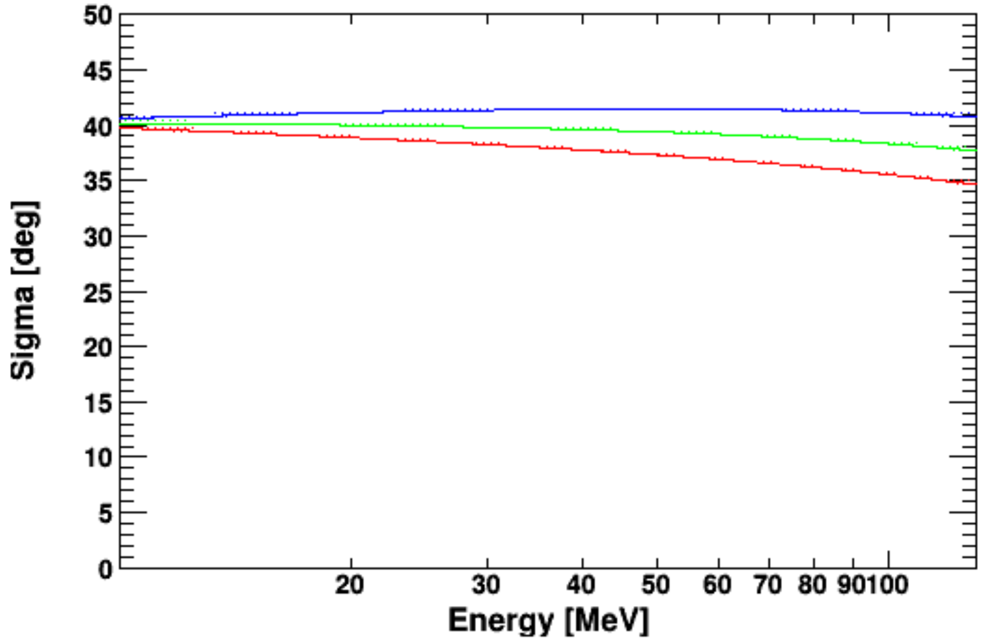
Average sigma is ~40 deg, with only a small decrease with SEP energy

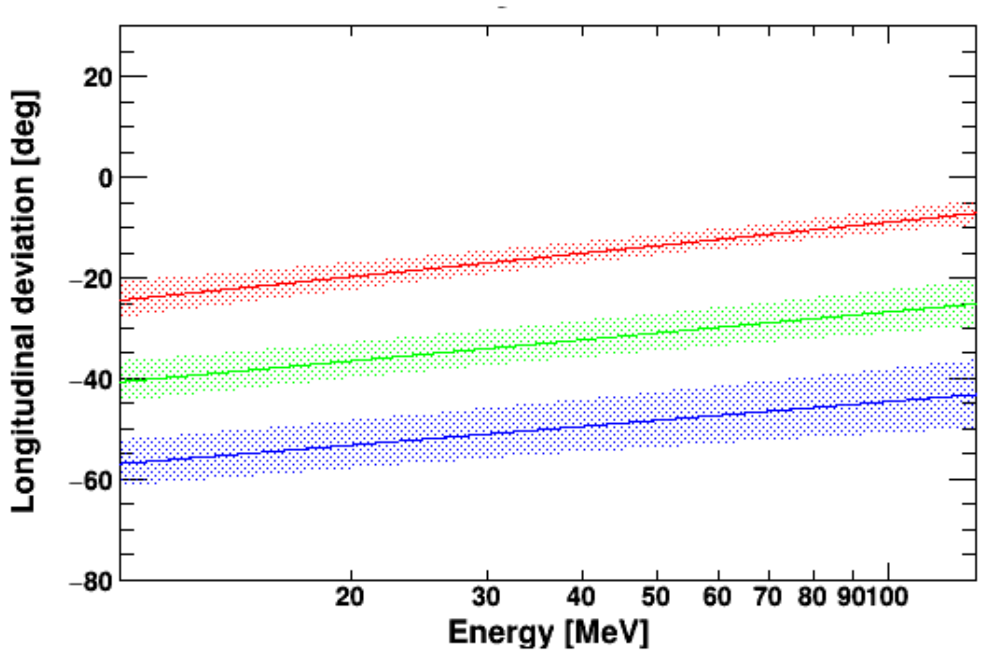
Offset is ~20 deg (West of the solar source) at 10 MeV, declining slightly with increasing energy.

SEP spatial distribution

Variations with the CME speed

preliminary

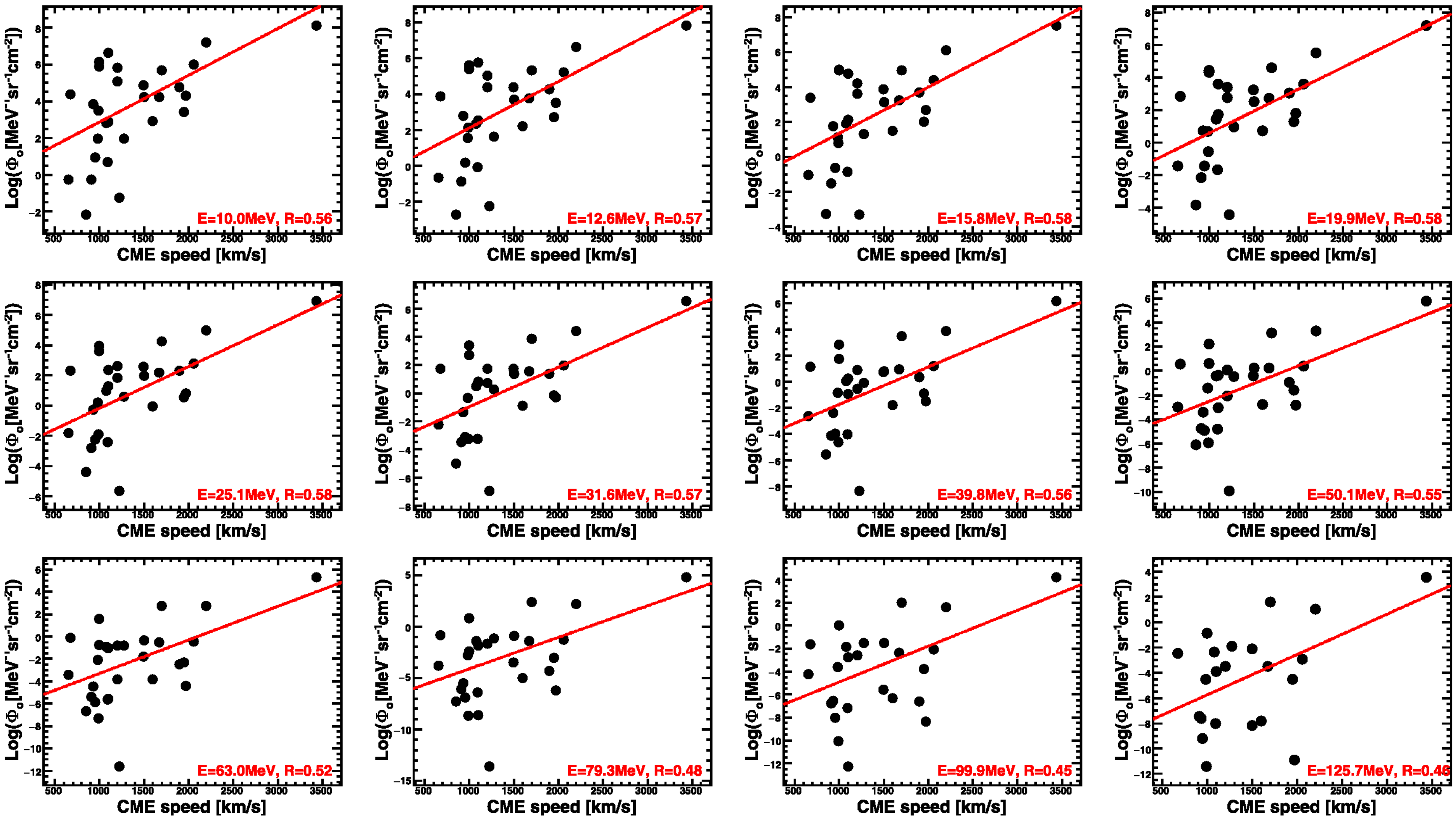




V_{cme} 1000 km/s 2000 km/s 3000 km/s

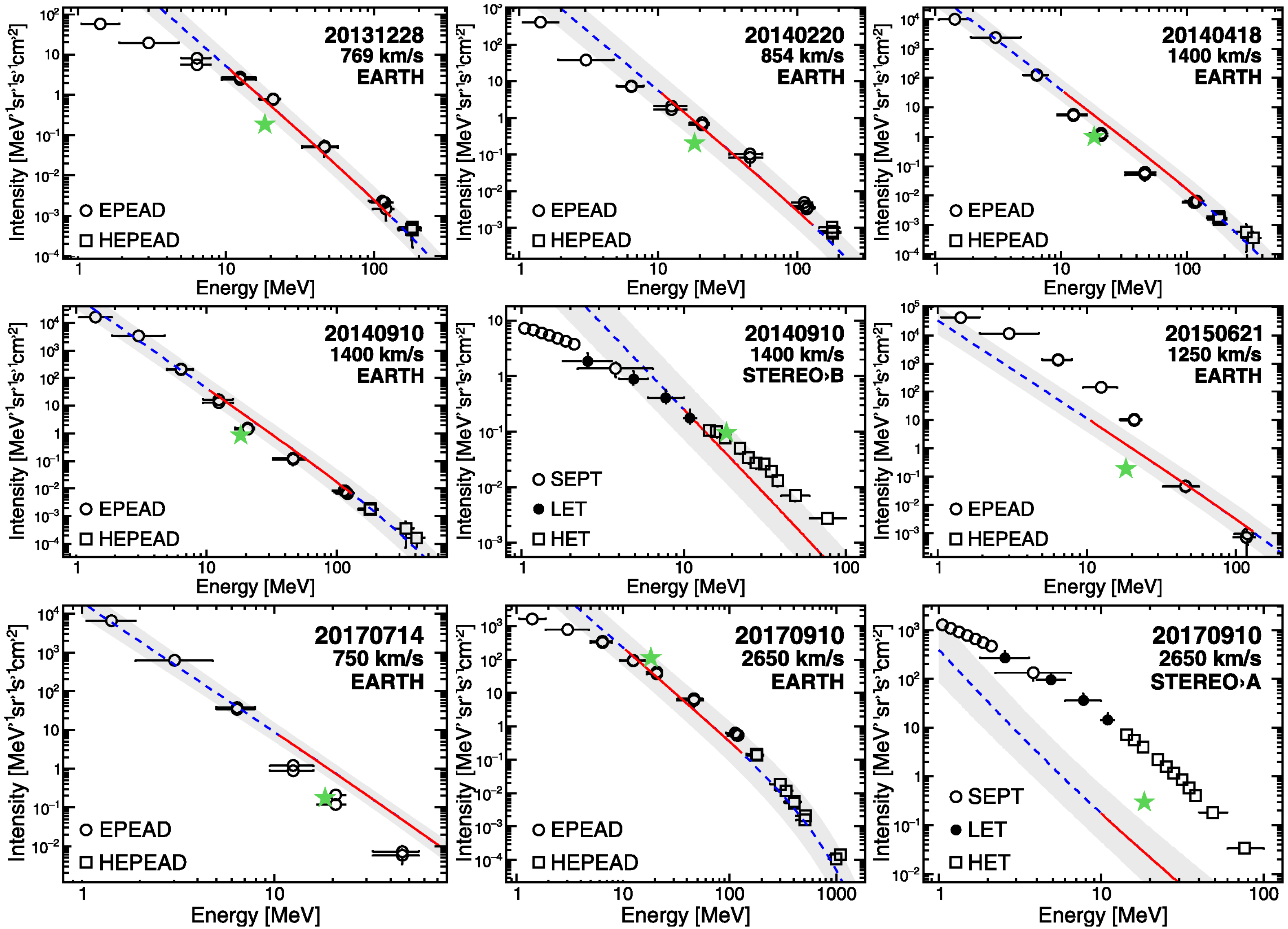
For slower CMEs the shock is weaker and the effective acceleration region is narrower, resulting in a smaller particle spatial spreading; in addition, SEPs are efficiently accelerated mostly close to the sun

Correlation with CME speed



SEP intensity at Gaussian center vs CME speed for 12 pseudo energy channels (10-130 MeV)

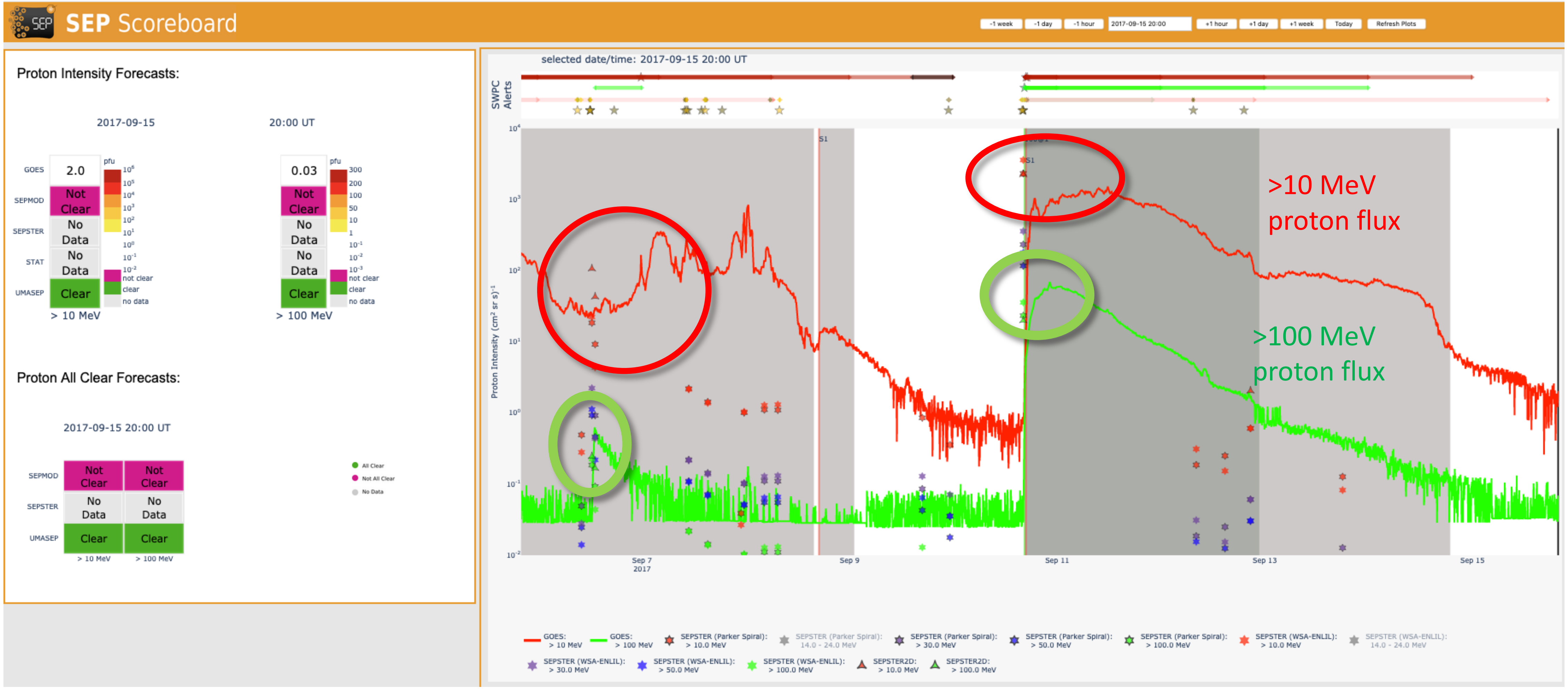
Model validation



Red=model predictions **grey**=uncertainty bands **blue dashed**=extrapolations below 10 MeV/above 130 MeV

- ○ **Tested using 20 different SEP events at STEREO and Earth in 2011-2017**
- ✓ Generally, there is remarkable agreement between the observed and predicted spectra!
- ✓ Also consistent with the SEPSTER predictions at 14-24 MeV (green)
- ❖ However, a few events show clear differences such as September 10, 2017 at STEREO-A (exceptional conditions, SW structure influences, etc.)
- ❖ Also, there may be deviations at low energies because the assumed spectral form does not include the spectral breaks at a few MeV.

SEPSTER2D predictions at CCMC SEP scoreboard

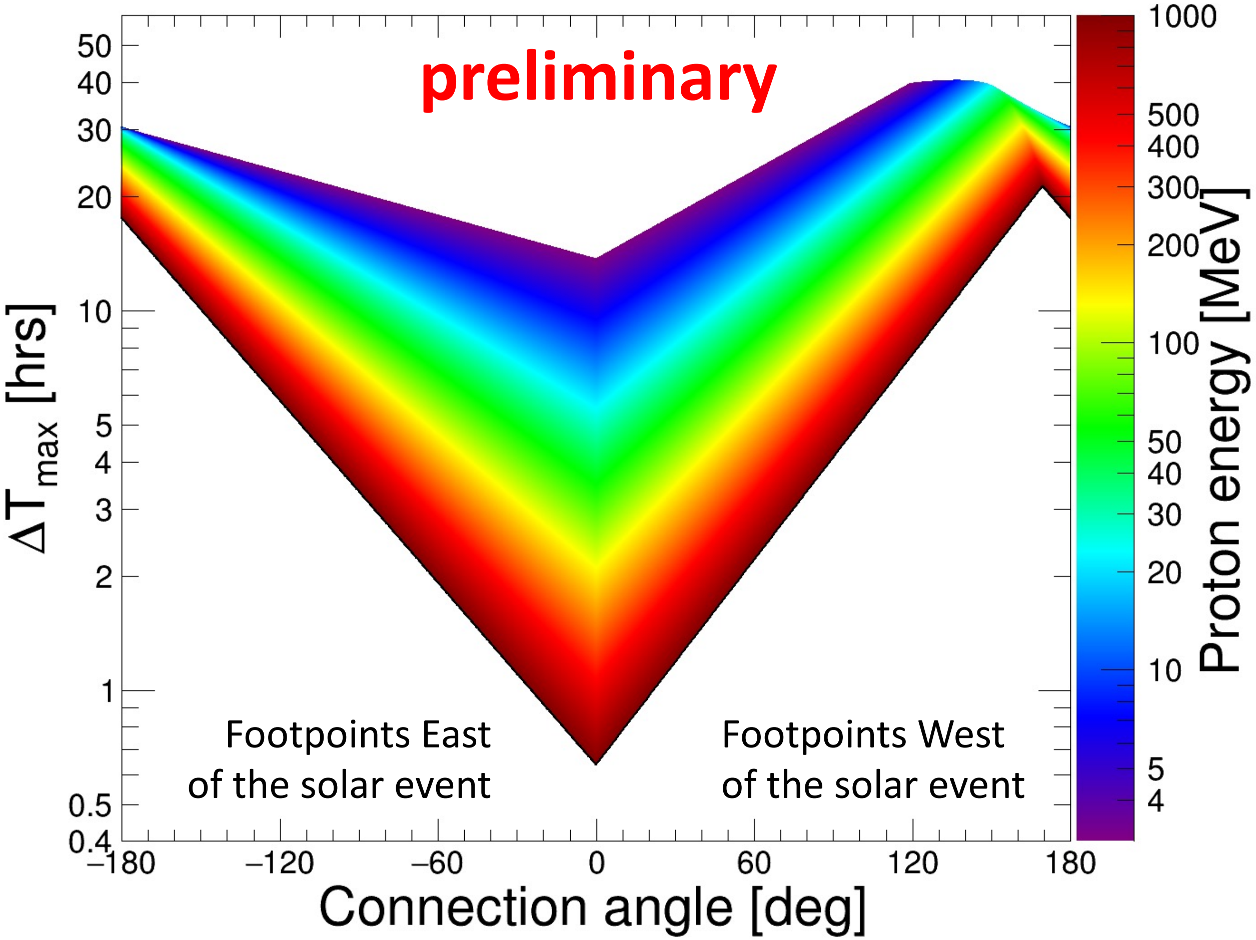


✓ The model runs in “real time” at CCMC, checking the DONKI CME catalog every minute

✓ Available SW data are used to estimate the connection angle at specific spacecraft

❖ The use of *uncalibrated* GOES intensities (especially GOES-16) affects the comparison

SEP peak-intensity times vs energy and connection angle



Estimated wrt the CME first appearance time, based on a **2D fit of experimental distributions**:

$$\Delta T_{max}(E,\phi) = \begin{cases} A(E) + B_{-}(E)|\phi| & [\phi < 0] \\ A(E) + B_{+}(E)|\phi| & [0 < \phi < \varphi_{inv}] \\ A(E) + B_{-}(E)|360^\circ - \phi| & [\phi > \varphi_{inv}] \end{cases}$$

inversion connection angle: $\delta_{inv} = 360^\circ \frac{B_{-}(E)}{B_{-}(E)+B_{+}(E)}$

Asymmetry between negative and positive connection angles

- Favored connection to western hemisphere by the spiral
- difference between SEP production at parallel/ perpendicular shocks on the eastern/western flanks
- cross-field diffusion / co-rotation
- ....

✓ The implementation of a similar calculation for SEP-event end times is in progress

Caveats

Model parameters based on widespread (3 s/c) events associated with fast (≳900 km/s) CMEs

- ❖ SEP intensity predictions overestimate observations for narrow events/slower CMEs

The model relies on the CME speed/direction measurements (DONKI catalog)

- ❖ which can be characterize by significant uncertainties depending on e.g., analysis method and number of spacecraft viewpoints available and their locations.

In addition, it requires CME observations to be available for analysis in near real time.

- ❖ At present, there may be a many hours or even days delay in obtaining CME measurements
- ❖ Need real-time CME observations (e.g., from NOAA's DSCOVER follow on (2024)), and automated CME detection/analysis to derive CME parameters rapidly.

- ✓ While SEPs may arrive even before a near-real time prediction can be made, **the peak intensity may only be reached several hours later**, so the prediction may still be useful.
- ✓ **Event-integrated spectra provided are less affected** by delays in making the prediction.
- ✓ "All clear" predictions are also of value.
- ✓ An implementation of a new, faster prediction scheme based on the **proportionality between SEP intensity and flare soft X-ray peak intensity** is in progress

Summary

- **SEPSTER-2D is an empirical model for predicting SEP event-integrated and peak intensities between 10-130 MeV, based on multi-point spacecraft observations**

  - The spatial distributions of SEP intensities are reconstructed by assuming an **energy-dependent 2D Gaussian functional form**, and accounting for the correlation between the particle intensity and the speed of the parent CME, and the magnetic-field-line connection angle.

✓ Despite the simplicity of the model, the observed and predicted intensity spectra at Earth and at the STEREO spacecraft show remarkable agreement, both in the spectral shapes and their absolute values

❖ More details can be found in Bruno and Richardson, Solar Phys (2021) 296:36, https://doi.org/10.1007/s11207-021-01779-4