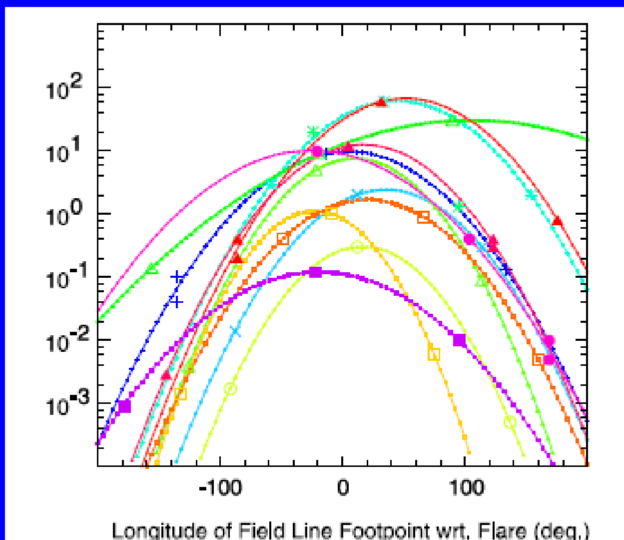
Prediction of SEP Peak Proton Intensity Based on CME Speed, Direction and Observations of Associated Solar Phenomena

I. G. Richardson[1,2], M. L. Mays[2], B. J. Thompson[2]

[1]GPHI/Department of Astronomy, University of Maryland, College Park
[2]Heliophysics Division, NASA Goddard Space Flight Center, Greenbelt, MD

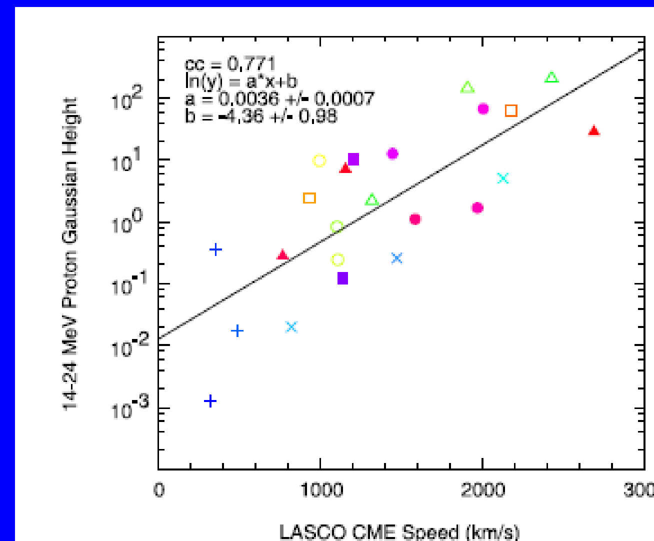
SEP Proton Intensity Prediction Formula (*Richardson et al.*, 2014)

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



=>

Gaussian peak intensity vs. CME speed (CDAW)



=>

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

φ is the connection angle (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.

To simulate how this method might work in a forecasting environment:

- Start with all 334 CMEs in the Space Weather “Database Of Notifications, Knowledge, Information” (DONKI) between October, 2011 and July 2012 (https://kauai.ccmc.gsfc.nasa.gov/DONKI/).

- DONKI includes reports of observations of space weather phenomena since April 2010, and their interpretation, forecasts, models and notifications provided by Coordinated Community Modeling Center CCMC Space Weather Research Center staff.

- For CMEs, DONKI reports their speed, direction (both required for the SEP prediction formula) and width, inferred, where possible, from SOHO and STEREO coronagraph observations.

The October 2011-July 2012 period is chosen because:

- Observations are available from both STEREO spacecraft;
- Earth and the STEREOs were approximately equally spaced in longitude around the Sun, ideally positioned to obtain a global view of CMEs and SEPs.
- Solar activity is high near the maximum of solar cycle 24 so there are sufficient CMEs and SEPs for a statistical study;
- SEPs of a variety of intensities occurred, including the especially intense July 23, 2012 event, and the widespread, rapid-onset, November 3, 2011 event.

SEP Intensity Prediction:

- Use the *Richardson et al*. (2014) formula and the DONKI CME speed and direction to “predict” the peak 14-24 MeV proton intensity at Earth and the STEREOs.

- With 334 CMEs, this gives potentially 1002 predictions of the SEP intensity to test against observations.

- A Parker spiral field is assumed to estimate the field line footpoint location and hence obtain the connection angle for each observing spacecraft.

Comparison of Predicted and Observed Intensities at Earth and the STEREO Spacecraft

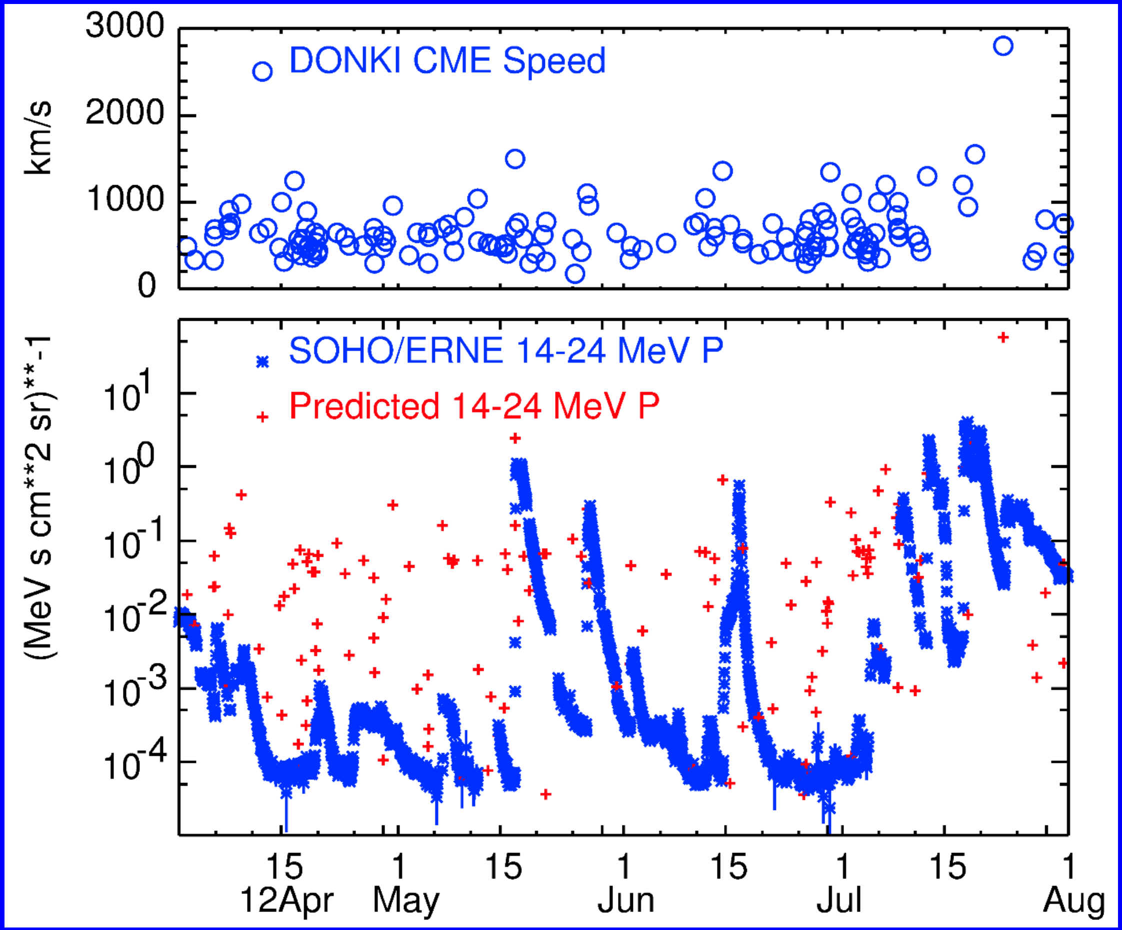
- Examined SEP observations at Earth, STEREO A or STEREO B at the time of each of the 334 DONKI CMEs in October 2011-July 2012;

- SEP events are already identified by *Richardson et al.* (2014). Their list includes all 25 MeV proton events detectable above a low instrumental threshold of ~10^{-4} (MeV s cm2 sr)$^{-1}$.

- Since the prediction formula gives the intensity at 14-24 MeV, the 25 MeV proton intensities of *Richardson et al.* (2014) were multiplied by 3.6 to compare with the predicted intensities at 14-24 MeV.

- 284 cases (out of 1002) when an enhanced particle background was present that might obscure an SEP onset were removed from further consideration in this study.

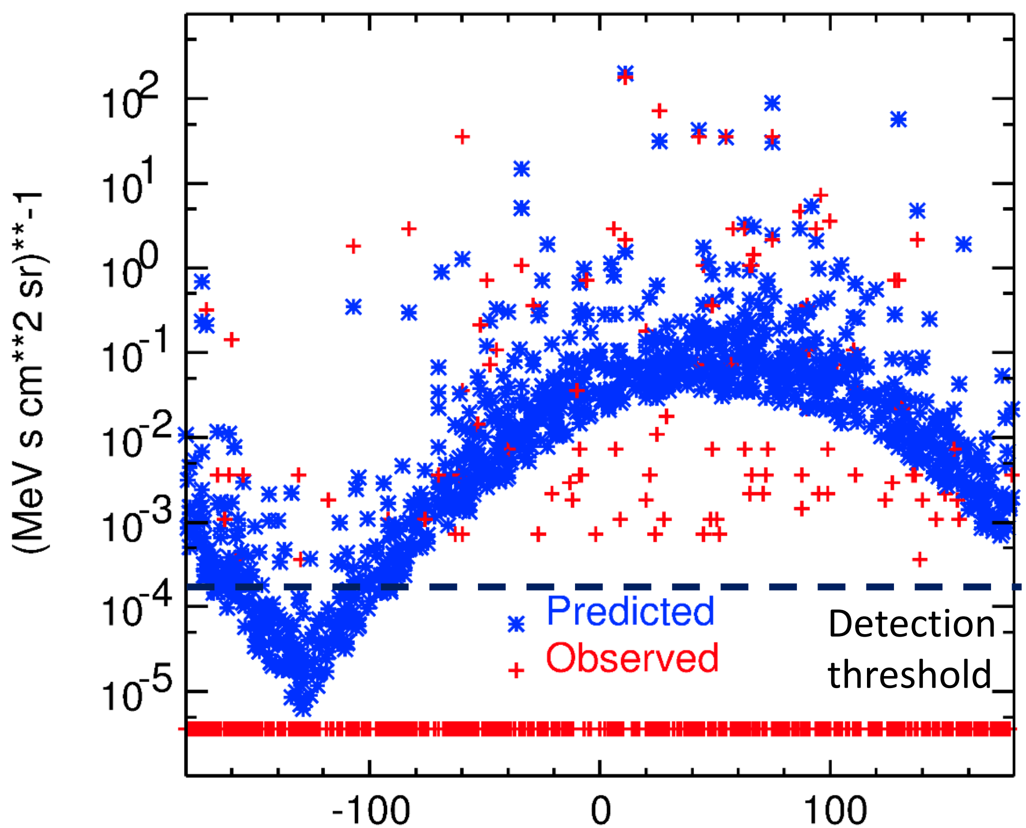
Observed and Predicted SEP intensities at Earth in April-July, 2012



Most CMEs (~85%) are not accompanied by an SEP event. There are many false alarms, when a predicted event is not observed.

Observed and Predicted Proton Intensity vs. CME Longitude wrt. Spacecraft

14-24 MeV
Proton Intensity



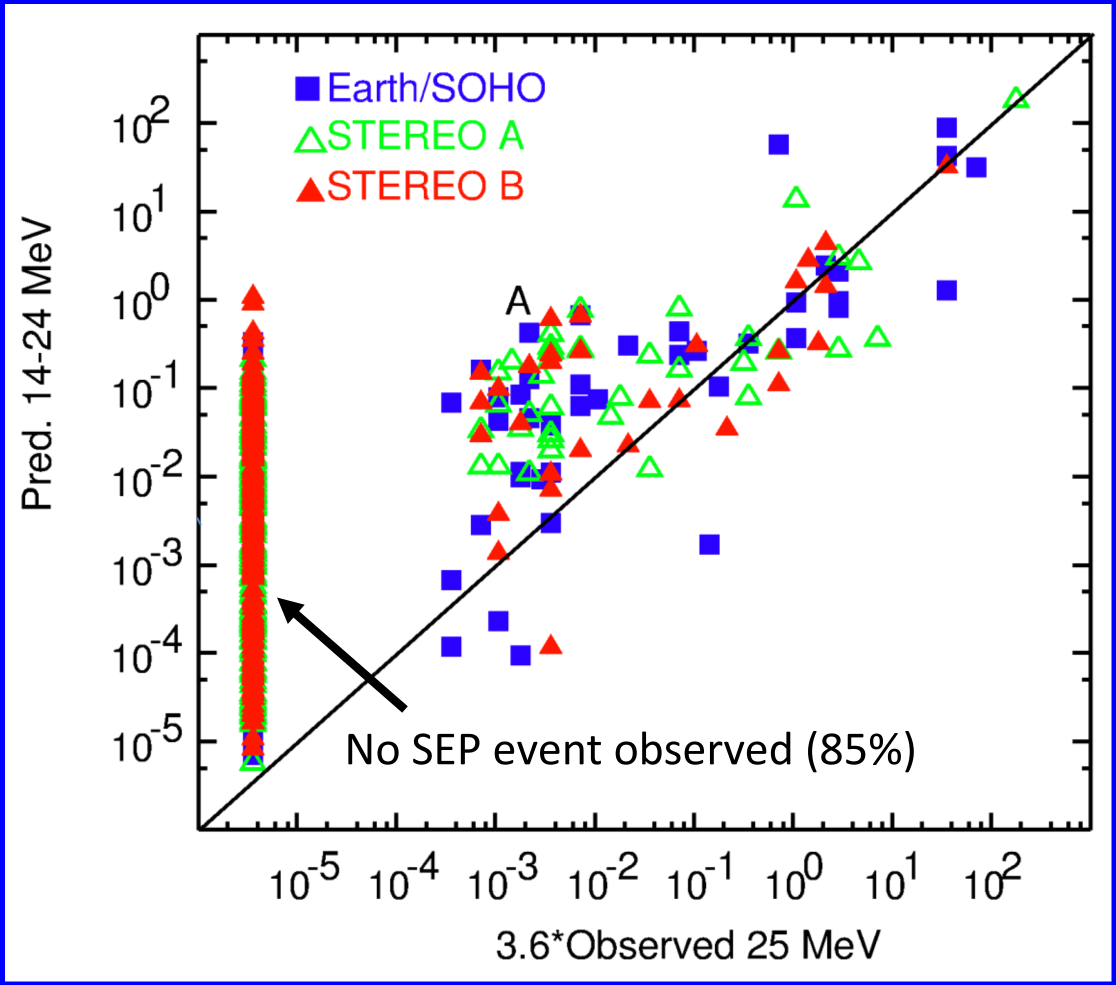
CME Direction With Respect to Observing S/C (° Longitude)

Observed (red) and predicted (blue) 14-24 MeV proton intensities vs. the CME direction (longitude) relative to the observing spacecraft (Earth and both STEREOs).

The prediction method (based on large three-spacecraft events) tends to over-predict the intensity for small well-connected events.

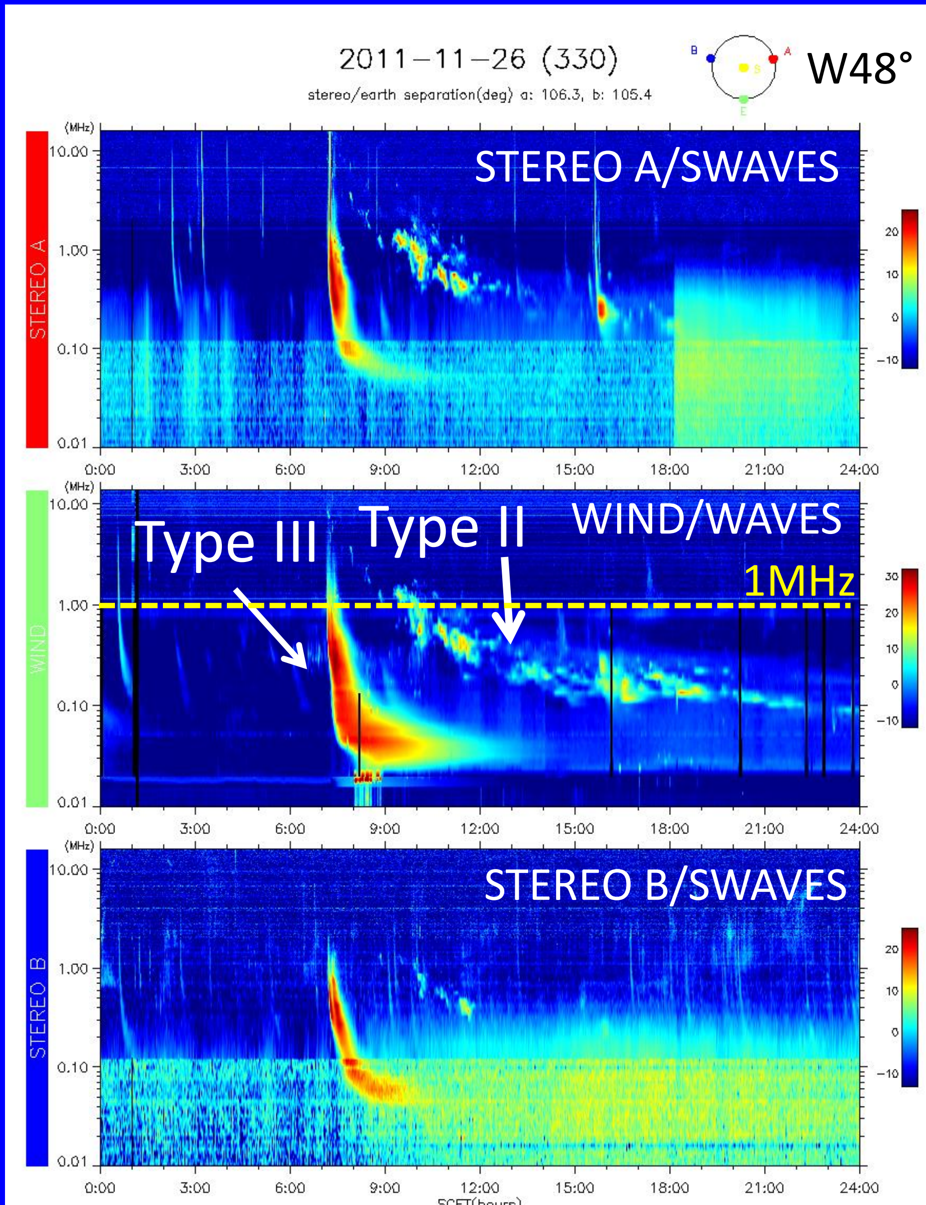
Predicted intensities far from the solar event may fall below the detection threshold ("BT").

Predicted vs. Observed SEP intensity at Earth and the STEREO Spacecraft



No SEP event was observed for 85% of 709 cases; these are placed at an arbitrary "observed intensity" of 3.6×10^{-6} to include them in the figure.

The remaining cases do however show a reasonable correlation between the observed and predicted SEP intensities – the dashed line is the line of equality.



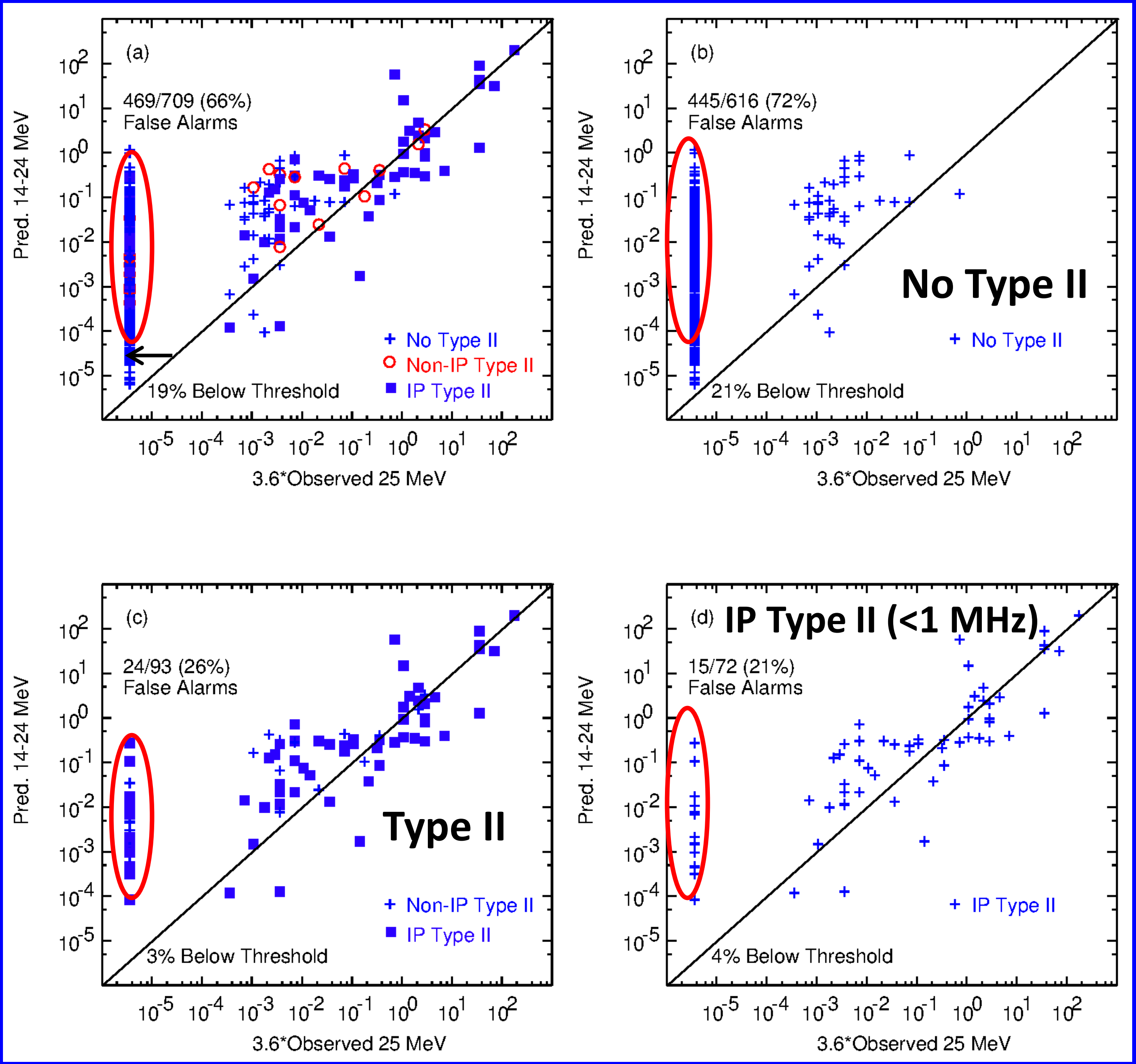
Since most DONKI CMEs are not accompanied by SEPs, how can we identify those that are likely to have SEP events?

- We first examined reports of **Type II (slow drift) radio emissions** (evidence for particle acceleration at CME-driven shocks) observed by the WIND/WAVES and STEREO SWAVES instruments (https://solar-radio.gsfc.nasa.gov/wind/).

- Emissions that extend below 1 MHz are “interplanetary (IP)” type IIs since emission continues far from the Sun.

- Global view of the radio emissions.

Predicted vs. Observed ~14-25 MeV Proton Intensity Filtered by Type II



Considering all the ~700 cases (top left):

- 19% of the predictions are below detection threshold and
- 66% are "false alarms".

With type II emissions, false alarm rate is 26%, falling to 21% if IP type II is required. However, some events are missed.

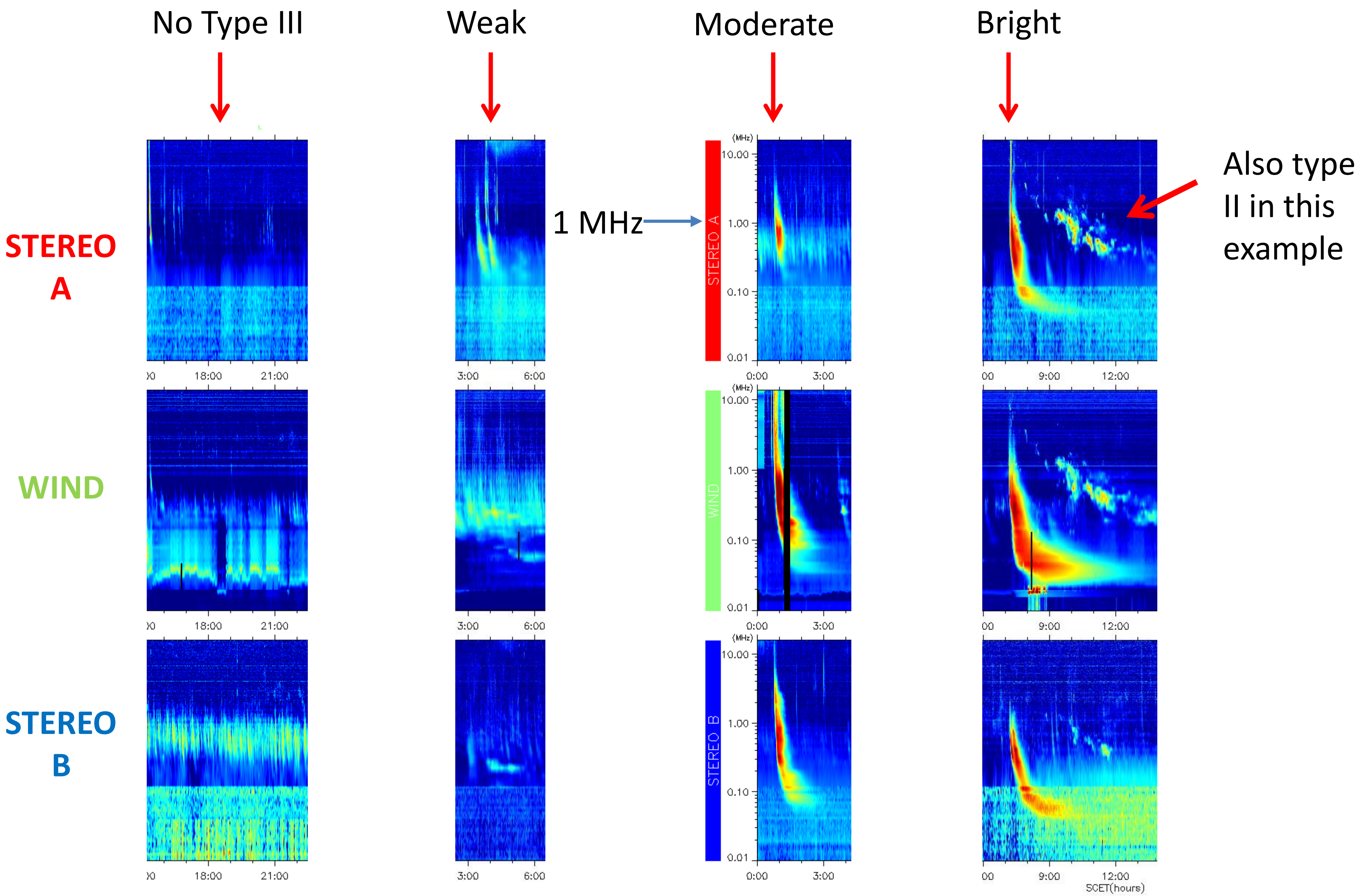
SEP events are also usually associated with type III (fast drift) radio emissions generally attributed to flare-accelerated electrons (e.g., *Cane et al.*, 2002, 2010; *MacDowall et al.*, 2003, 2009; *Laurenza et al.,* 2009; *Winter and Ledbetter*, 2015).

For this study, we characterized the type III emissions observed at WIND and the STEREOs associated with each DONKI CME in two simple ways:

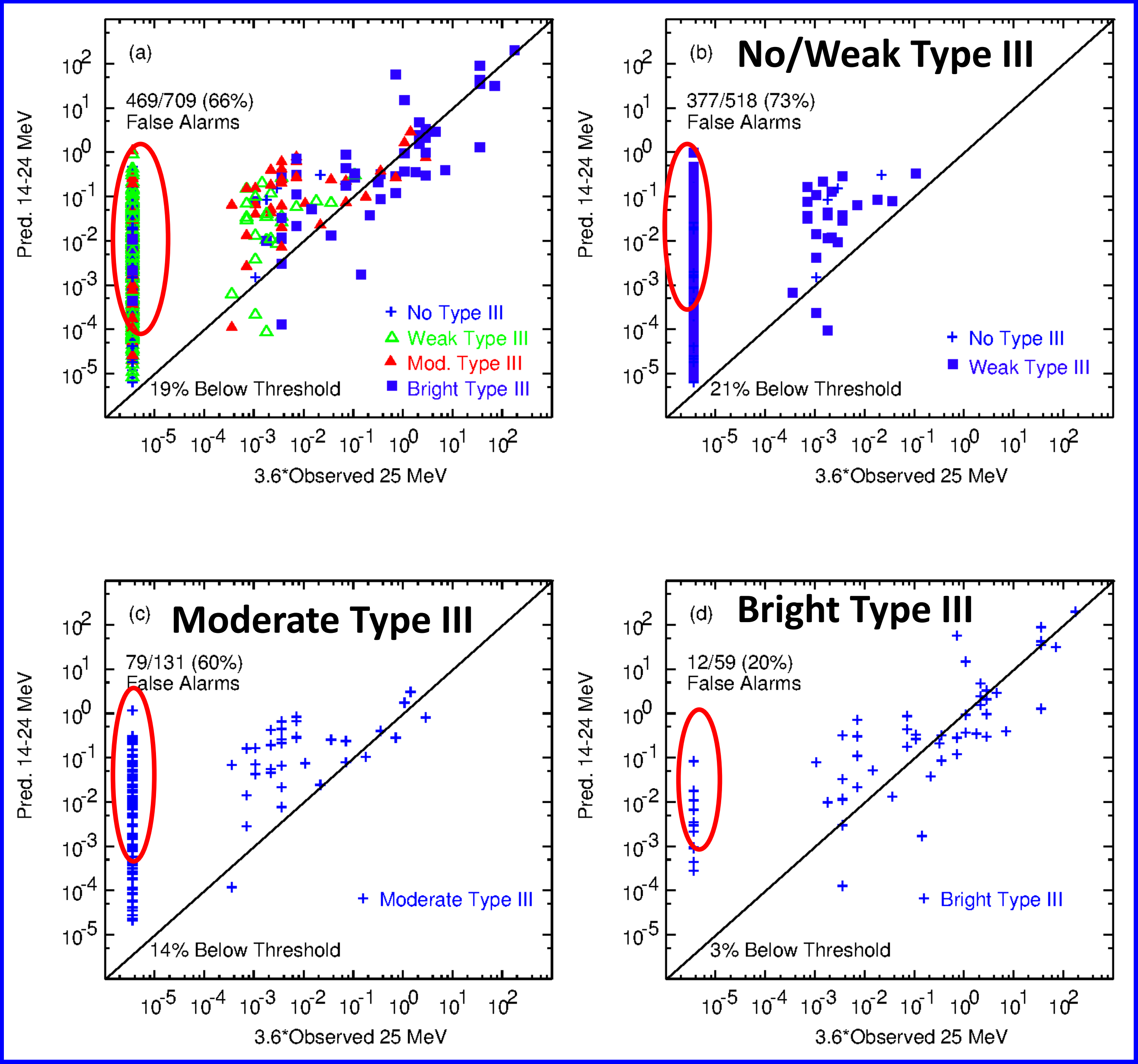
1. Based on the visual character of the type III emissions in the WIND/STEREO Daily summary plots (https://swaves.gsfc.nasa.gov/cgi-bin/wimp.py),

2. We estimated the duration of the type III intensity at 1 MHz > 6 dB (4x) the daily background (cf., *MacDowall et al.* (2003, 2009)) at each spacecraft, then chose the longest duration as representative for this event.

Examples of Type III Classes (STEREO SWAVES/WIND WAVES)



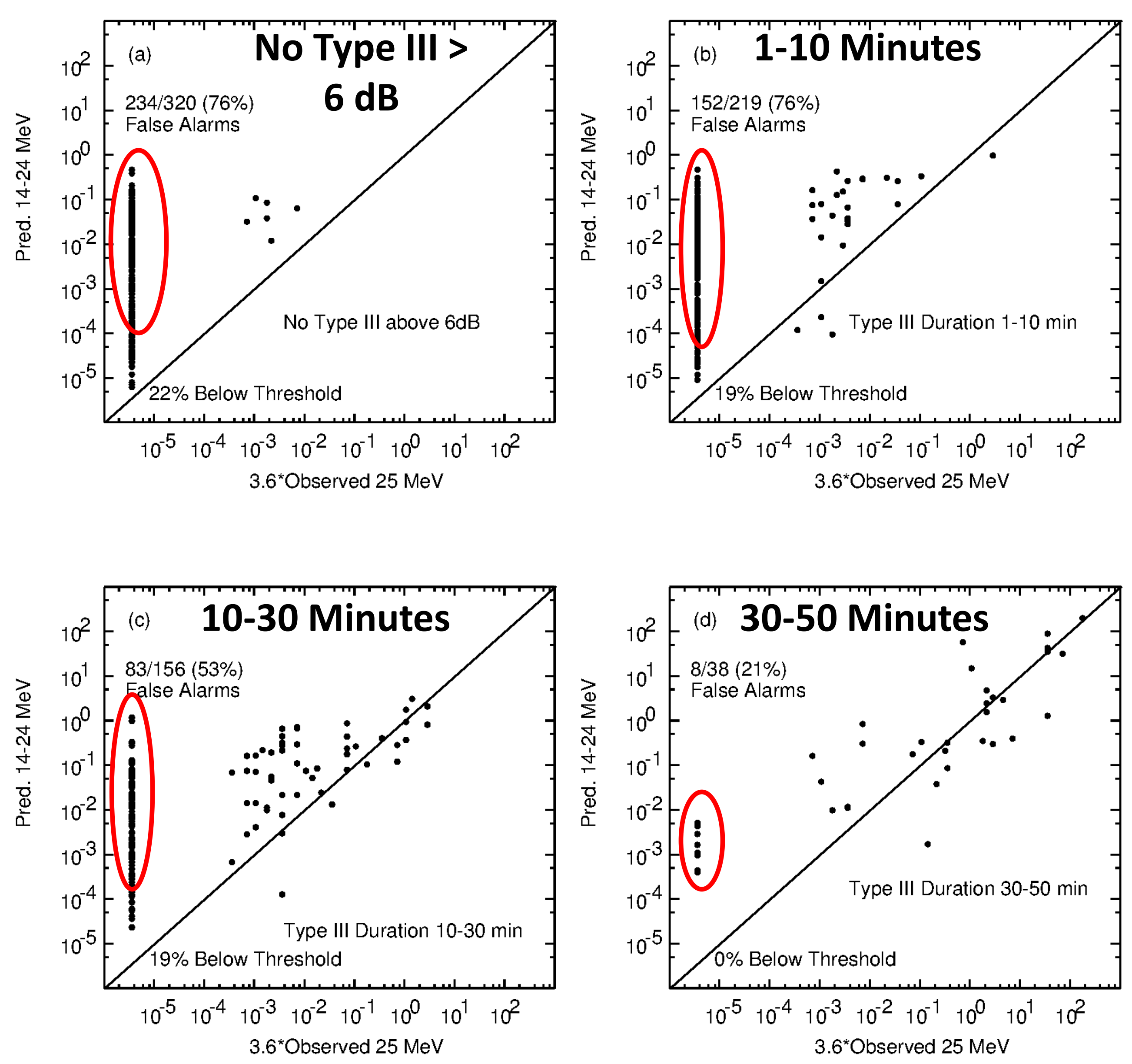
Predicted vs. Observed ~14-25 MeV Proton Intensity Filtered by Type III



If bright, extended type III emissions accompany a CME (bottom right), the false alarm rate is reduced to around one in five.

The SEP event size is also predicted fairly successfully, including the largest events which tend to be associated with bright type III emissions.

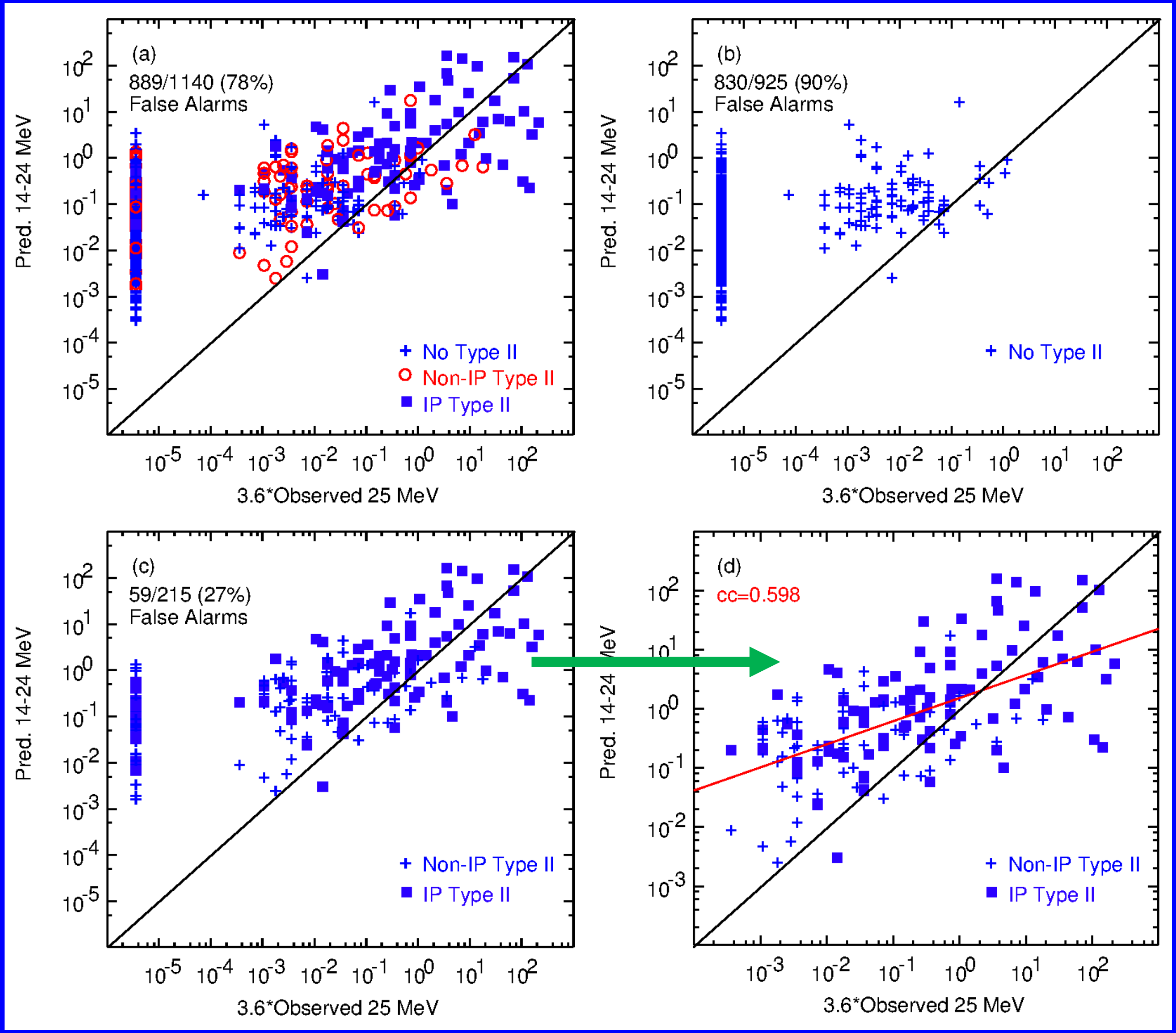
Predicted vs. Observed ~14-25 MeV Proton Intensity Filtered by Type III Maximum Duration > 6dB at 1 MHz at Any Spacecraft



The SEP false alarm rate falls from 76% if a CME is not accompanied by type III emission above 6 dB to
~ one in five if accompanied by type III emissions lasting 30-50 min at 1 MHz.

The largest SEP events are also associated with the longest duration type III emissions (cf., Macdowall et al, 2009).

Application to Solar Cycle 23:
1140 CMEs (Speed > 300 km/s, Width >50°) in 1997-2006



Use WIND/WAVES type II reports to select events here.

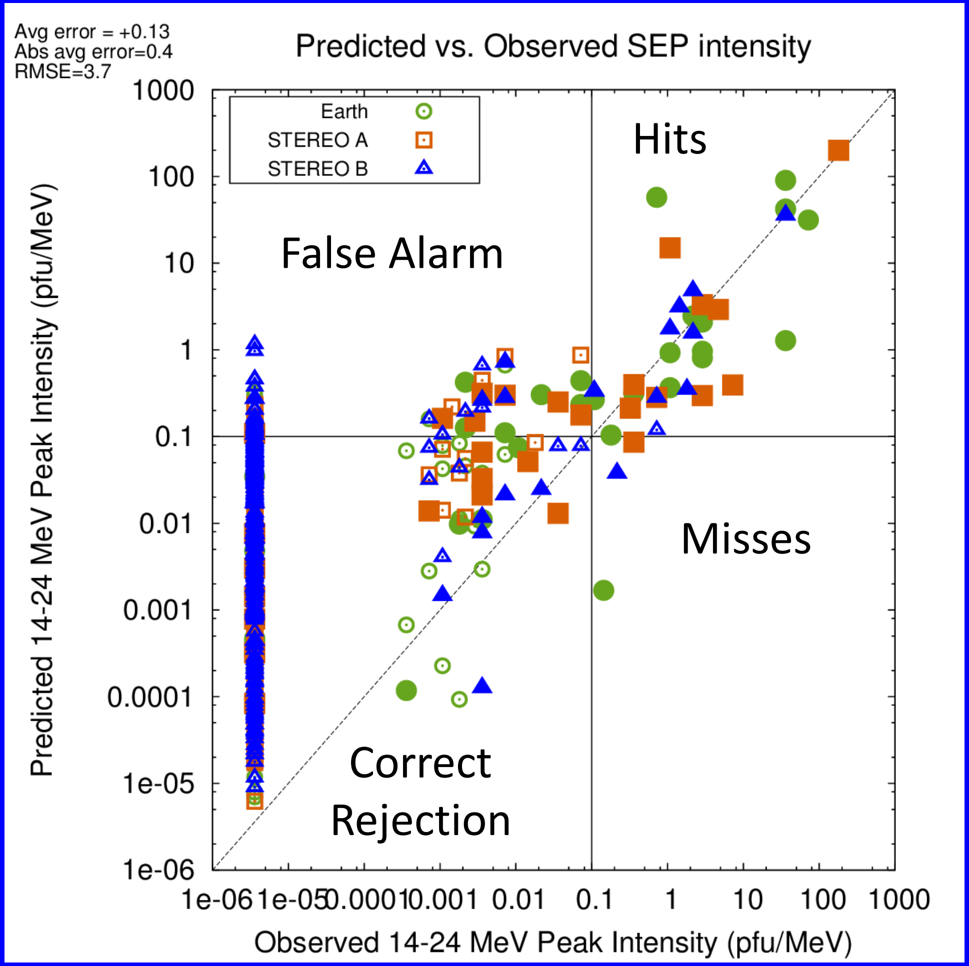
Again, considering the presence of type II emissions reduces the false alarm rate.

Note the absence of weak events in the distribution compared to the cycle 24 cases, due to the limited longitudinal ranges of the SEP sources, generally on the frontside.

=> No events from distant sources.

Skill Scores

Various methods are available to assess the “skill” of the preceding predictions, both with and without filters that require the presence of certain radio emissions.



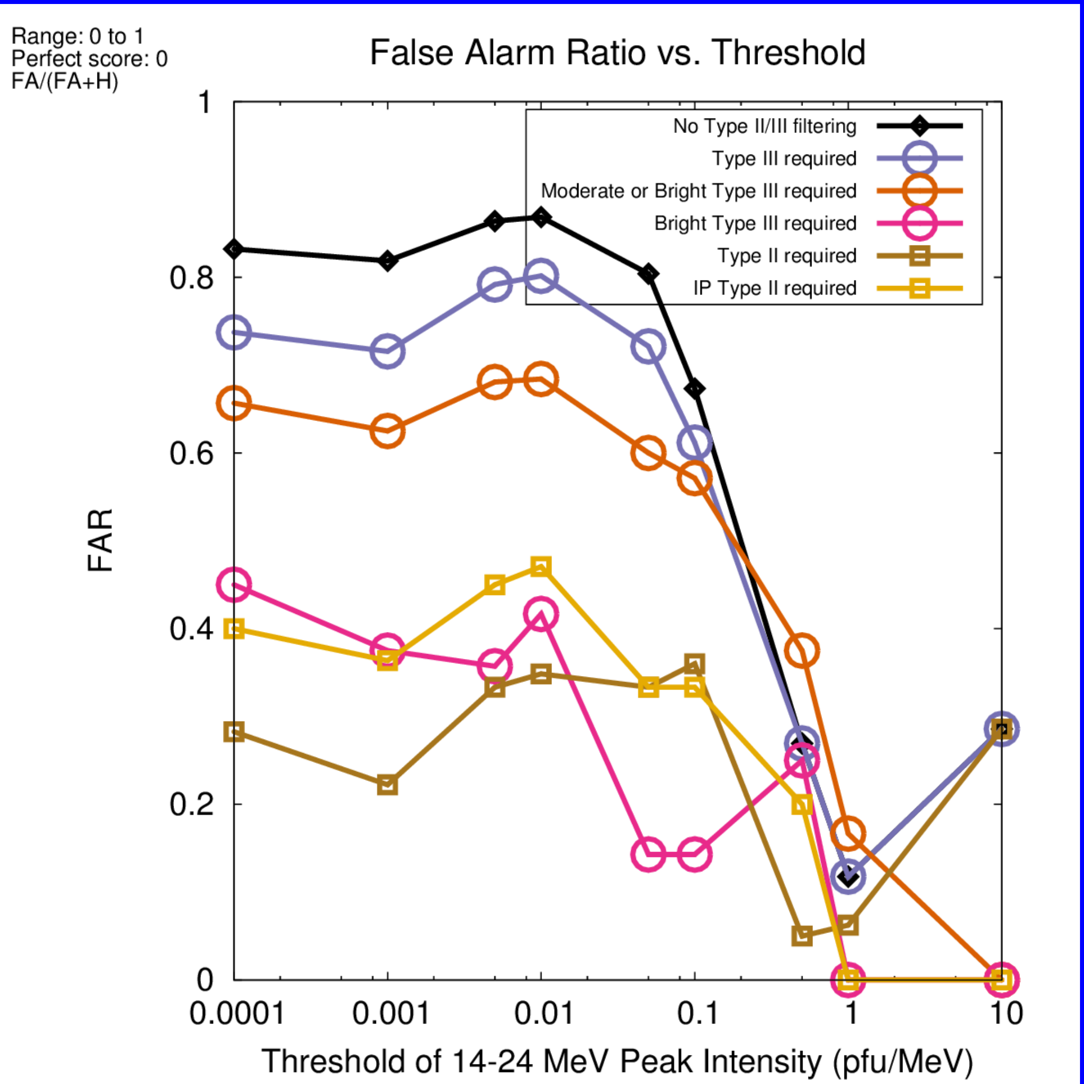
Consider how the numbers of events in the four quadrants defined by the cross hairs set at a particular SEP threshold intensity vary as the threshold intensity is changed.

Compares the observed and predicted intensities, rather than just giving a simple hit/miss assessment of whether a predicted SEP was actually observed.

Calculate skill scores in various ways as functions of threshold intensity.

Predictions below the detection threshold are not included.

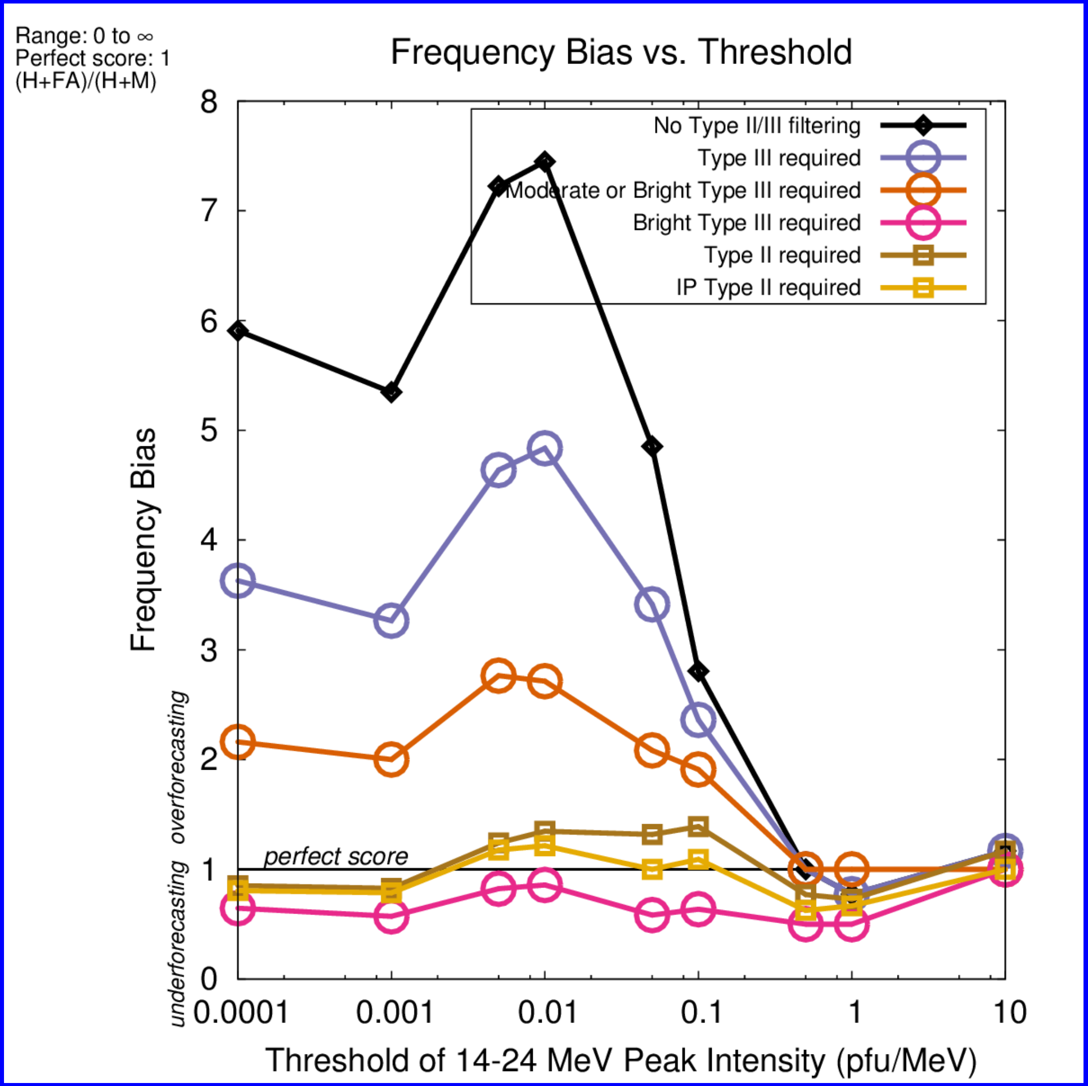
False alarm ratio FA/(FA + Hits) vs. threshold intensity



0 is a perfect score.

The lowest FA ratios are obtained when type II or bright type III emissions accompany a CME.

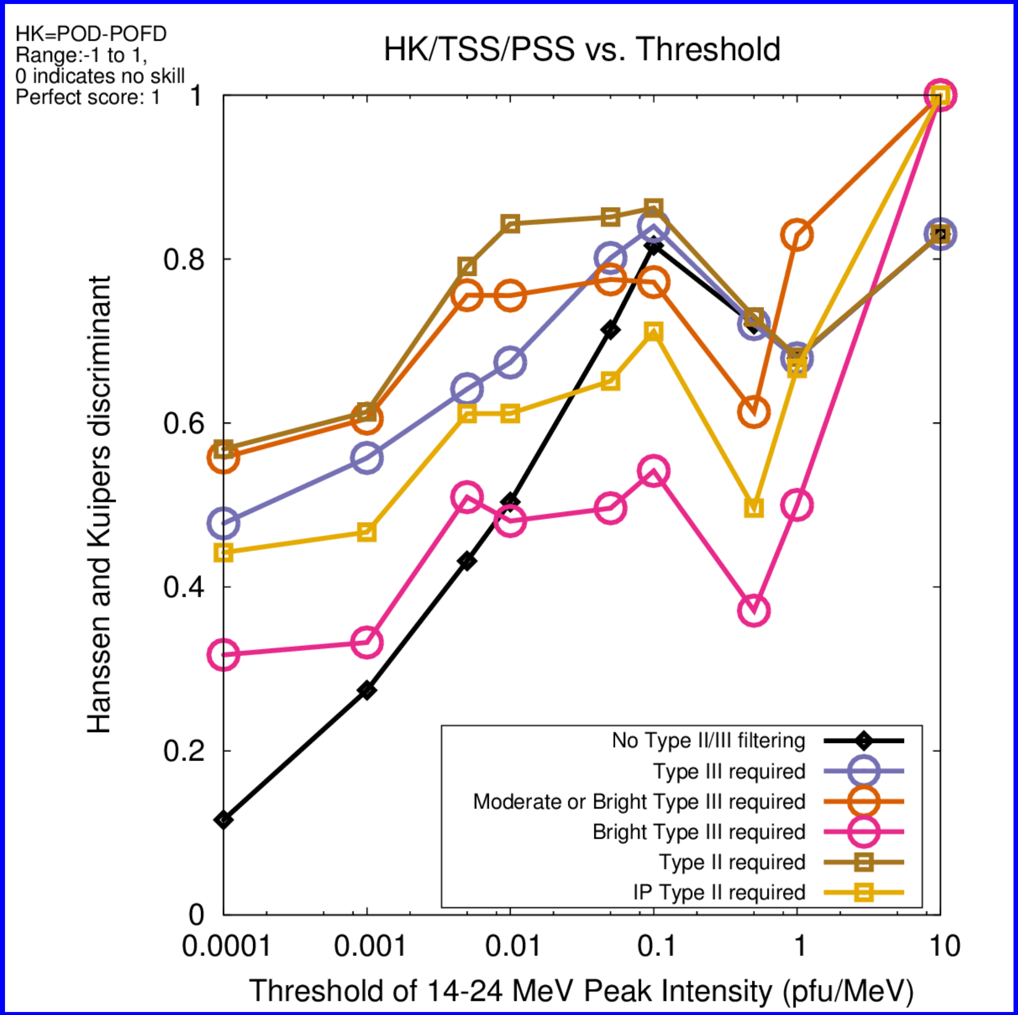
Little improvement for the largest events which are usually accompanied by type II and III radio emissions.



Frequency bias (Hits+False Alarms)/(Hits+Misses) vs. SEP intensity threshold.

The ratio of predicted SEP events to observed SEP events. Perfect score is 1 (no false alarms and no misses)

Larger or smaller values indicate a bias towards false alarms (overforecasting) or misses (underforecasting), respectively



<u>"Hanssen and Kuipers Discriminant", the Probability of detection – Probability of false detection.</u>

POD=hits/(hits+misses)
POFD=FA/(correct rejections+FA)

1 is a perfect score. Accounts for variations in the false alarms and missed events.

The highest values for the largest events where the POD is high and the POFD is low.

For smaller events, modest filtering produces the largest increase in the HK discriminant.

Conclusions

A sample of DONKI CMEs, simulating observations in an operational environment, were used to make more than 700 predictions of SEP intensity that were tested against SEP observations at three widely separated locations.

Only ~15% of these CMEs were accompanied with ~25 MeV proton events. The presence of type II or type III emissions accompanying the CME helps to identify those CMEs that are more likely to be associated with SEP events.

Predictions were also made for ~1000 CMEs in solar cycle 23.

The SEP intensity predictions look promising, but delays in obtaining spacecraft CME and radio observations in near real time pose an obstacle to using such methods for an operational prediction of SEP intensities for well connected events. However, they may be of value for less well connected observers and for issuing "all clears".