Forecasting Space Weather from Magnetograms

David A. Falconer (UAHuntsville/MSFC), Ronald L. Moore(MSFC), Abdulnasser F. Barghouty(MSFC), and Igor Khazanov(UAHutsville)

Large flares and fast CMEs are the drivers of the most severe space weather including Solar Energetic Particle Events (SEP Events). Large flares and their co-produced CMEs are powered by the explosive release of free magnetic energy stored in non-potential magnetic fields of sunspot active regions. The free energy is stored in and released from the low-beta regime of the active region's magnetic field above the photosphere, in the chromosphere and low corona. From our work over the past decade and from similar work of several other groups, it is now well established that (1) a proxy of the free magnetic energy stored above the photosphere can be measured from photospheric magnetograms, maps of the measured field in the photosphere, and (2) an active region's rate of production of major CME/flare eruptions in the coming day or so is strongly correlated with its present measured value of the free-energy proxy. These results have led us to use the large database of SOHO/MDI full-disk magnetograms spanning Solar Cycle 23 to obtain empirical forecasting curves that from an active region's present measured value of the free-energy proxy give the active region's expected rates of production of major flares, CMEs, fast CMEs, and SEP Events in the coming day or so (Falconer et al 2011, Space Weather, 9, S04003). For each type of event, the expected rate is readily converted to the chance that the active region will produce such an event in any given forward time window of a day or so. If the chance is small enough (e.g. <5%), the forecast is All Clear for that type of event. We will present these forecasting curves and demonstrate the accuracy of their forecasts. In addition, we will show that the forecasts for major flares and fast CMEs can be made significantly more accurate by taking into account not only the value of the free energy proxy but also the active region's recent productivity of major flares; specifically, whether the active region has produced a major flare (GOES class M or X) during the past 24 hours before the time of the measured magnetogram.

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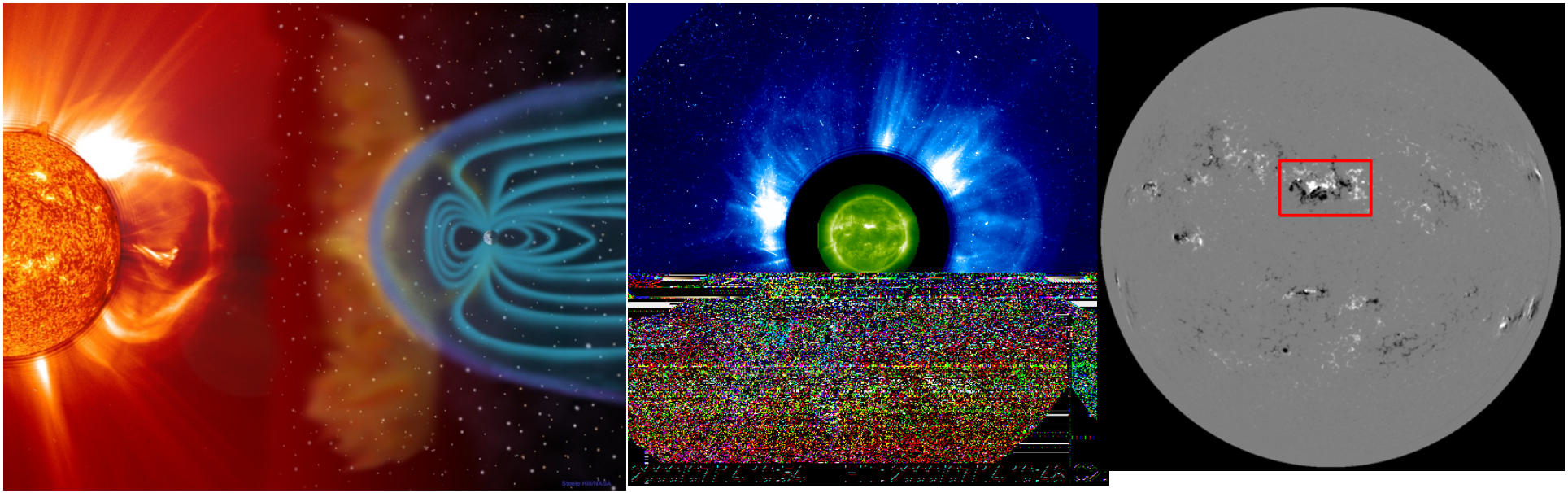


Forecasting X-class, M-class, CMEs, and SPEs from active region magnetograms.

Overview

•In 2010, we delivered to NASA/SRAG a solar major-event forecasting tool based on a free-energy proxy that can be measured from a SOHO/MDI magnetogram (Falconer et al, SPACE WEATHER, VOL. 9, S04003). **Slides 3-8**

•We have looked for secondary measures that can be used to improve forecasts

•Previous Flare Activity **Slide 9**	Promising
•Total Magnetic Flux **Slide 10**	Negligible at most

•Since then, the higher-resolution, higher-cadence, SDO/HMI vector magnetograph has replaced SOHO/MDI. **Slide 11**

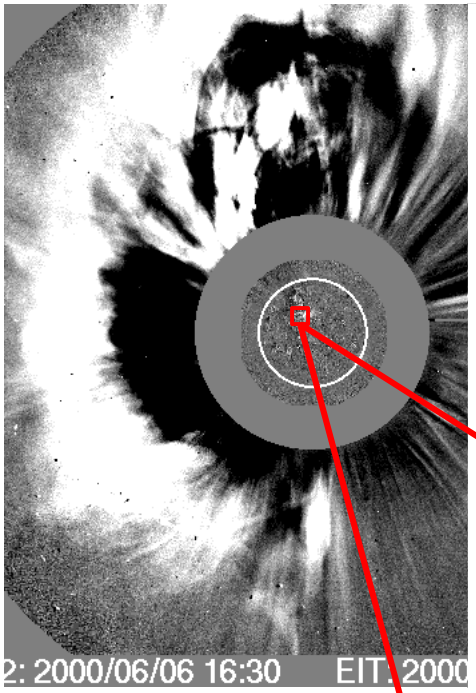
•In March 2011, we installed at SRAG a modified forecasting tool that uses SDO/HMI line-of-sight magnetograms. We have given NOAA access to forecast. **Slides 12-14**

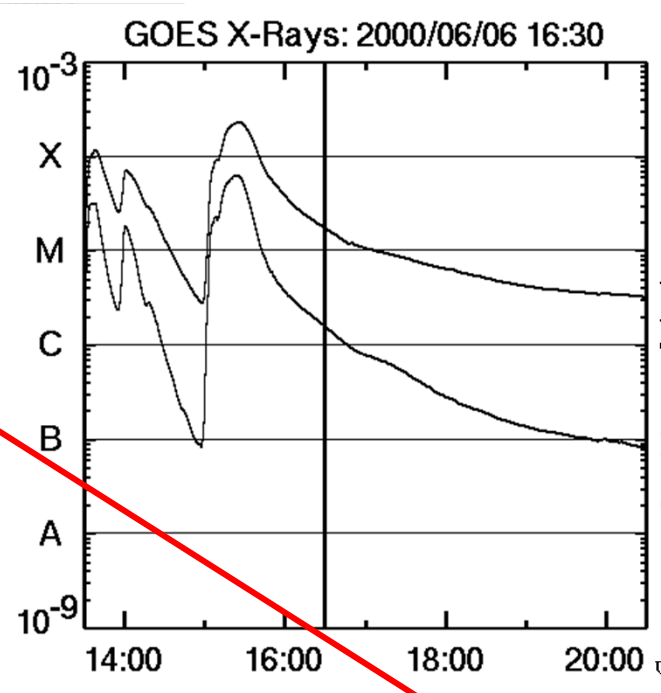
•Modified tool can use GONG as backup.

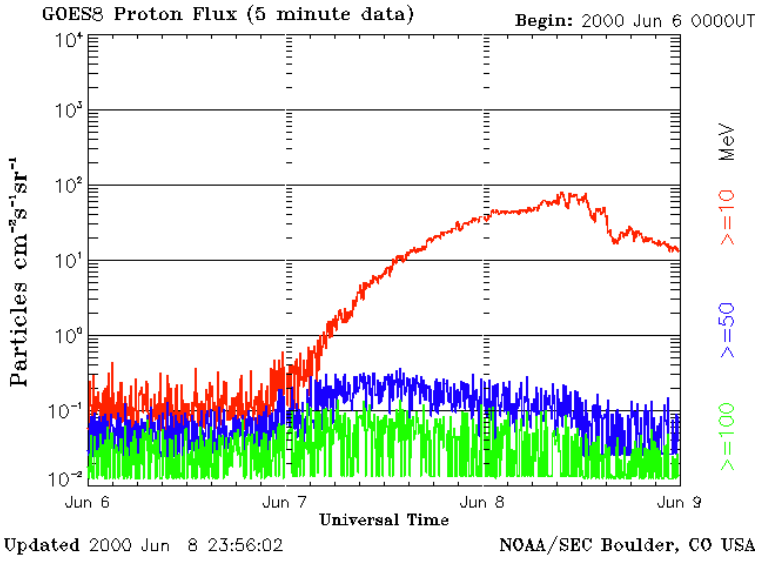
Science behind Forecast

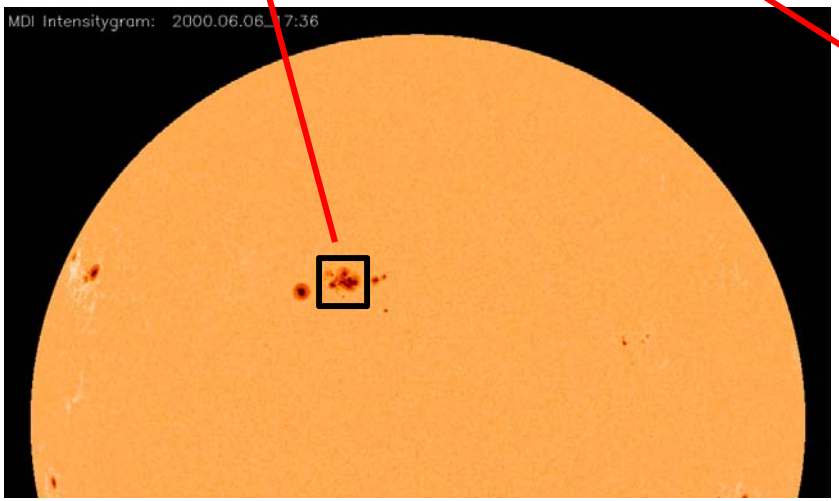
- Active regions (ARs) with large free energy are more able and more likely to produce large flares and CMEs than active regions with little free energy (See example AR in **slides 4-5**).
- It is reasonable to expect AR free energy to be strongly correlated with AR CME/flare rate.
- Present observations do not allow us to directly measure the free energy of an active region, but there are a variety of free-energy proxies that are strongly correlated with flare/CME event rates.
- These correlations can be determined empirically (**Slide 7)**.

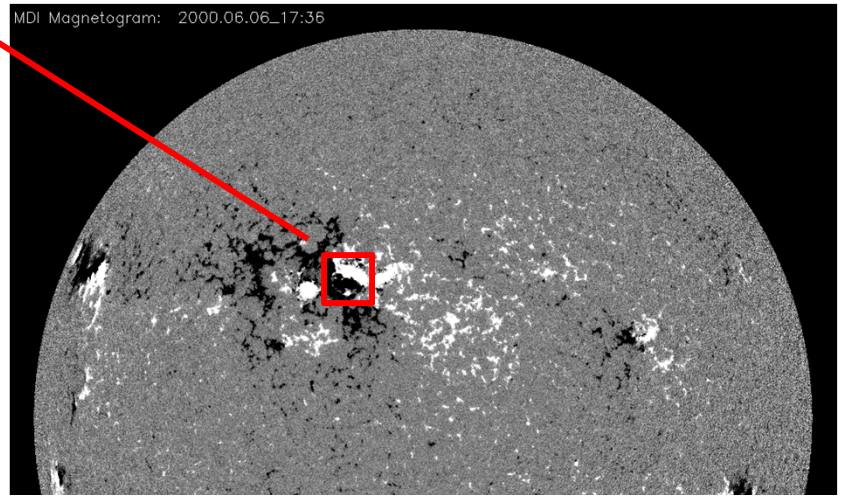
Example: Halo CME, X-Flare, SEP Event and δ-Sunspot Source Region



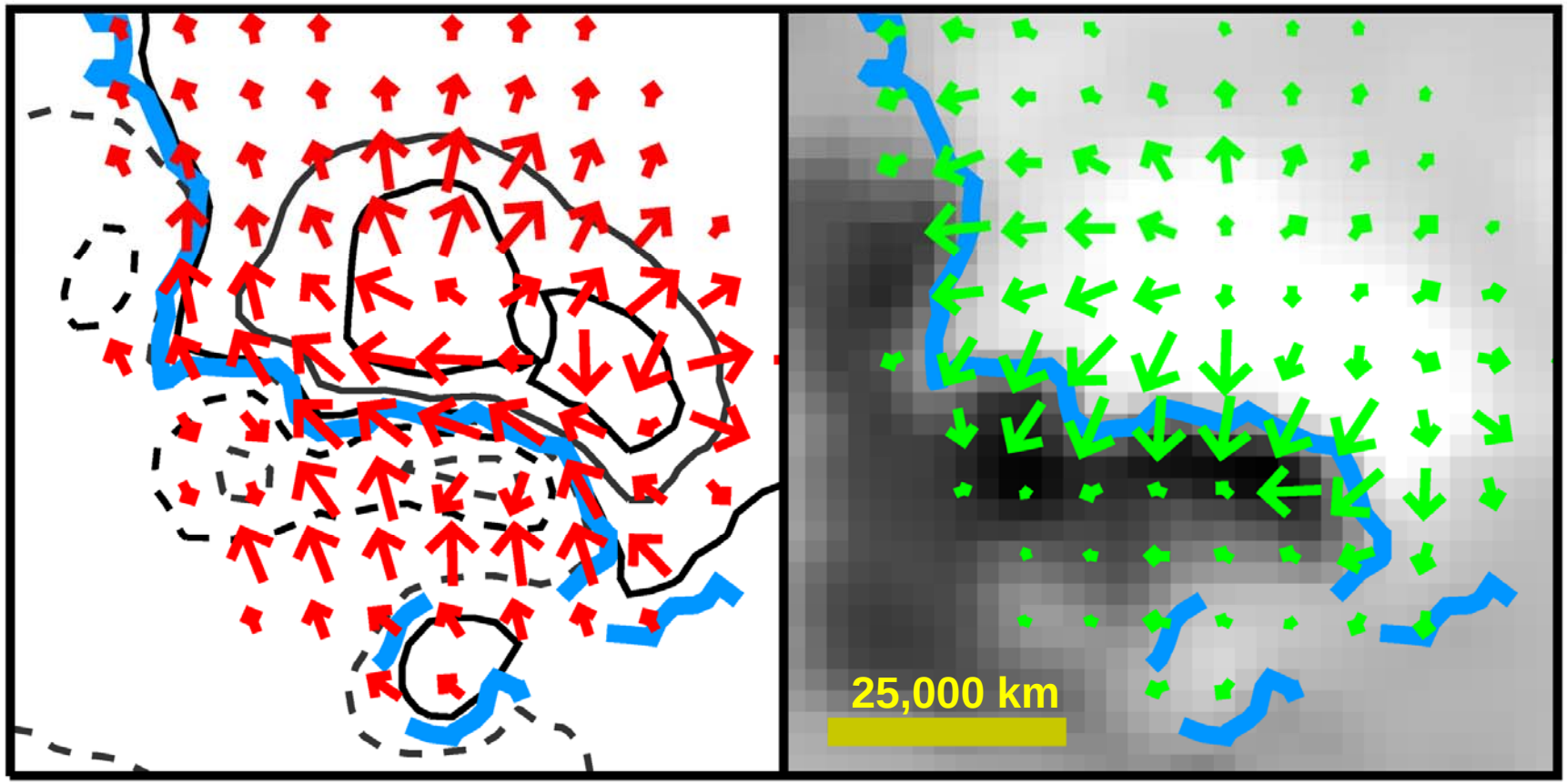








MSFC Vector Magnetogram of δ-Sunspot Source Region of Example CME/Flare Eruption



An active-region field's horizontal shear is concentrated along neutral lines where the field's horizontal component is strong and the vertical component's horizontal gradient is steep.

Observed-field upward (downward) vert. comp. is shown by solid contours or light shading (dashed contours or dark shading); red arrows show observed hor. comp. ; green arrows show hor. comp. of pot. field computed from obs. vert. comp. ; strong-observed-field (>150G) intervals of neutral lines are blue.

Free-energy proxy from vertical-field component of vector magnetogram or from line-of-sight magnetogram:

- Active regions that have large magnetic shear along neutral lines (where the observed field is nearly perpendicular to the potential field, and thus has a large free energy content) also develop large transverse gradients along the neutral line (see example AR in **slides 4-5**).

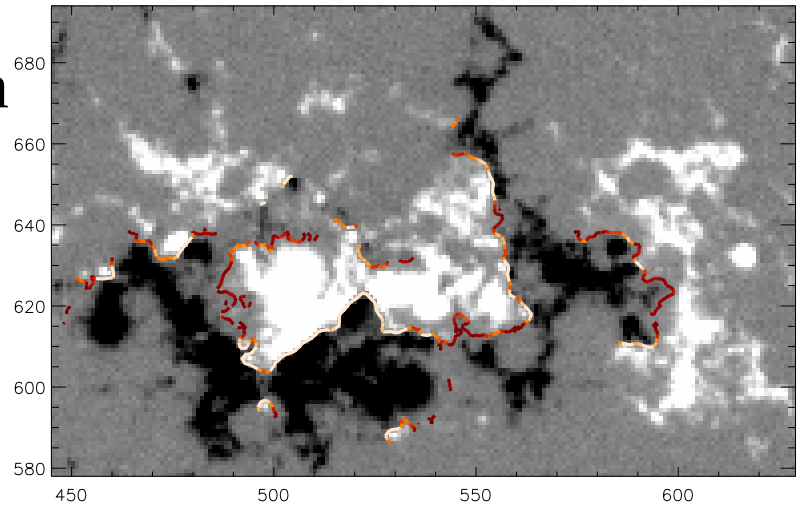
Deprojected vector magnetogram version

$$\mathbf{WL_{SG}=\int(\nabla B_Z)dl}$$

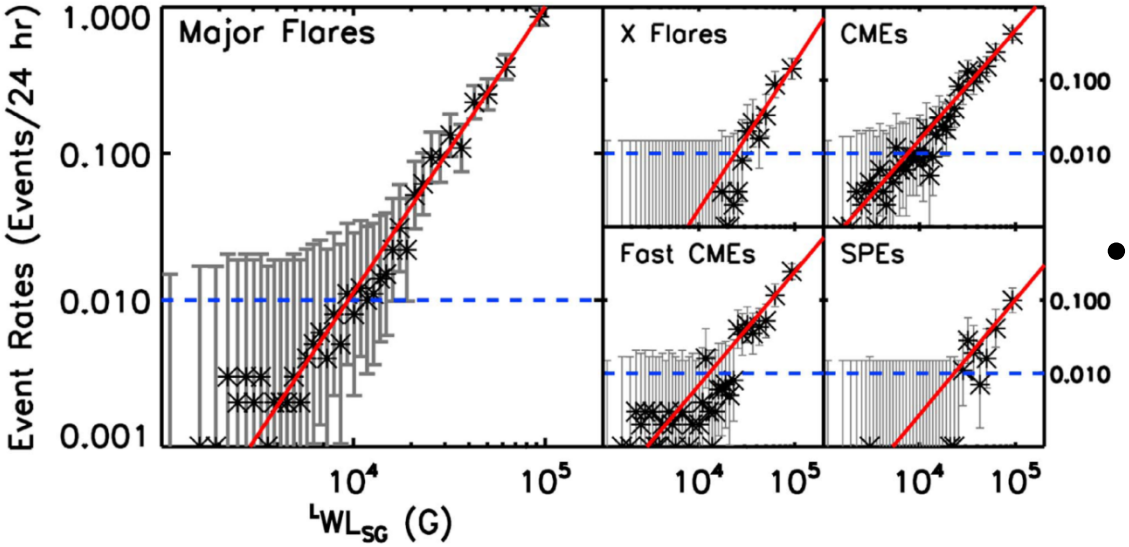
or line-of-sight approximation

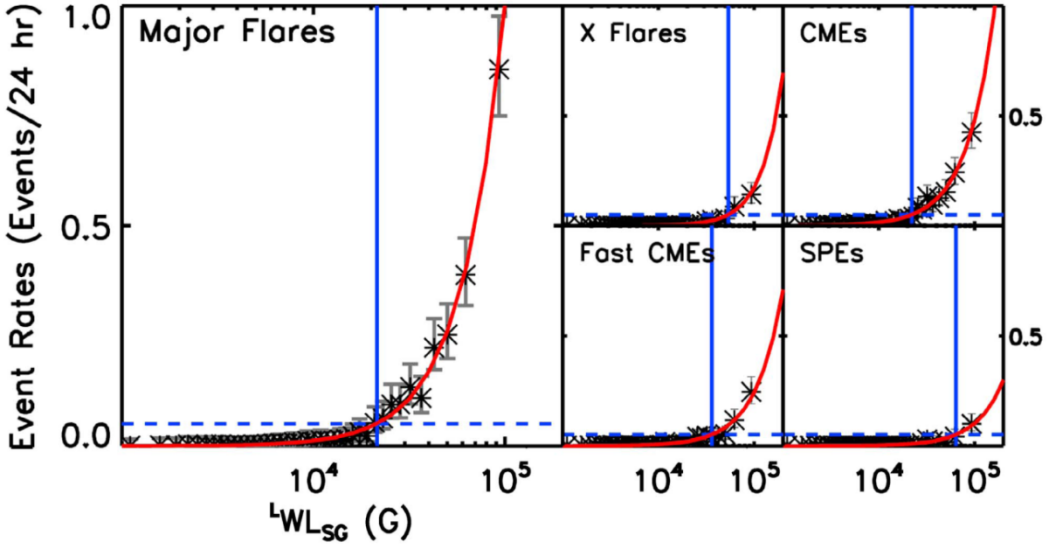
$$\mathbf{{}^{L}WL_{SG}=\int(\nabla B_{LOS})dl.}$$

Integration is along strong-field intervals of the AR neutral lines.



The Heart of the Forecasting Tool: The Forecast Curves





- Only active regions that have a large free energy are likely to produce major events in the next 24 hours.
- Most active regions have a negligible (All Clear) chance of producing an event.

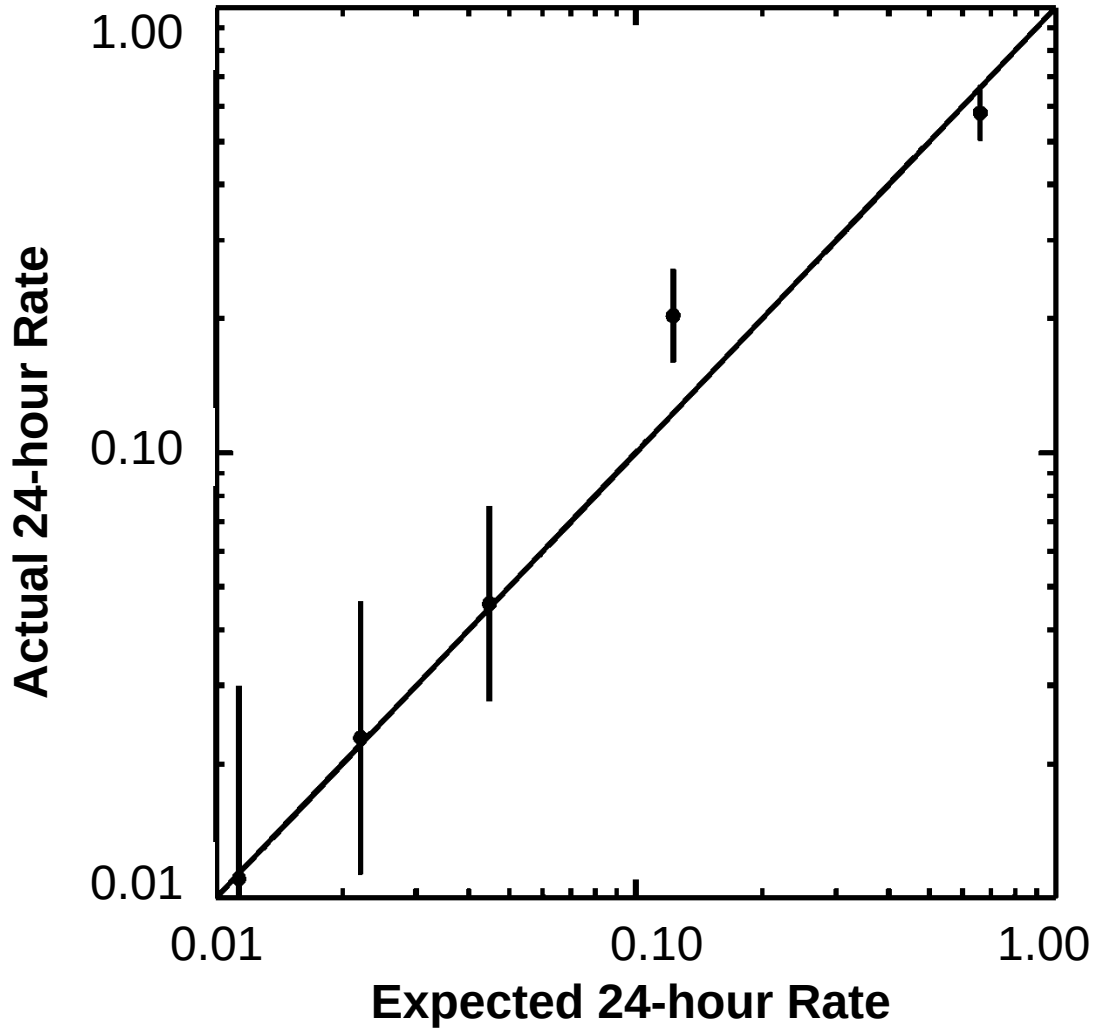
Verification of Accuracy of Forecast

Actual Performance versus Predicted Performance.

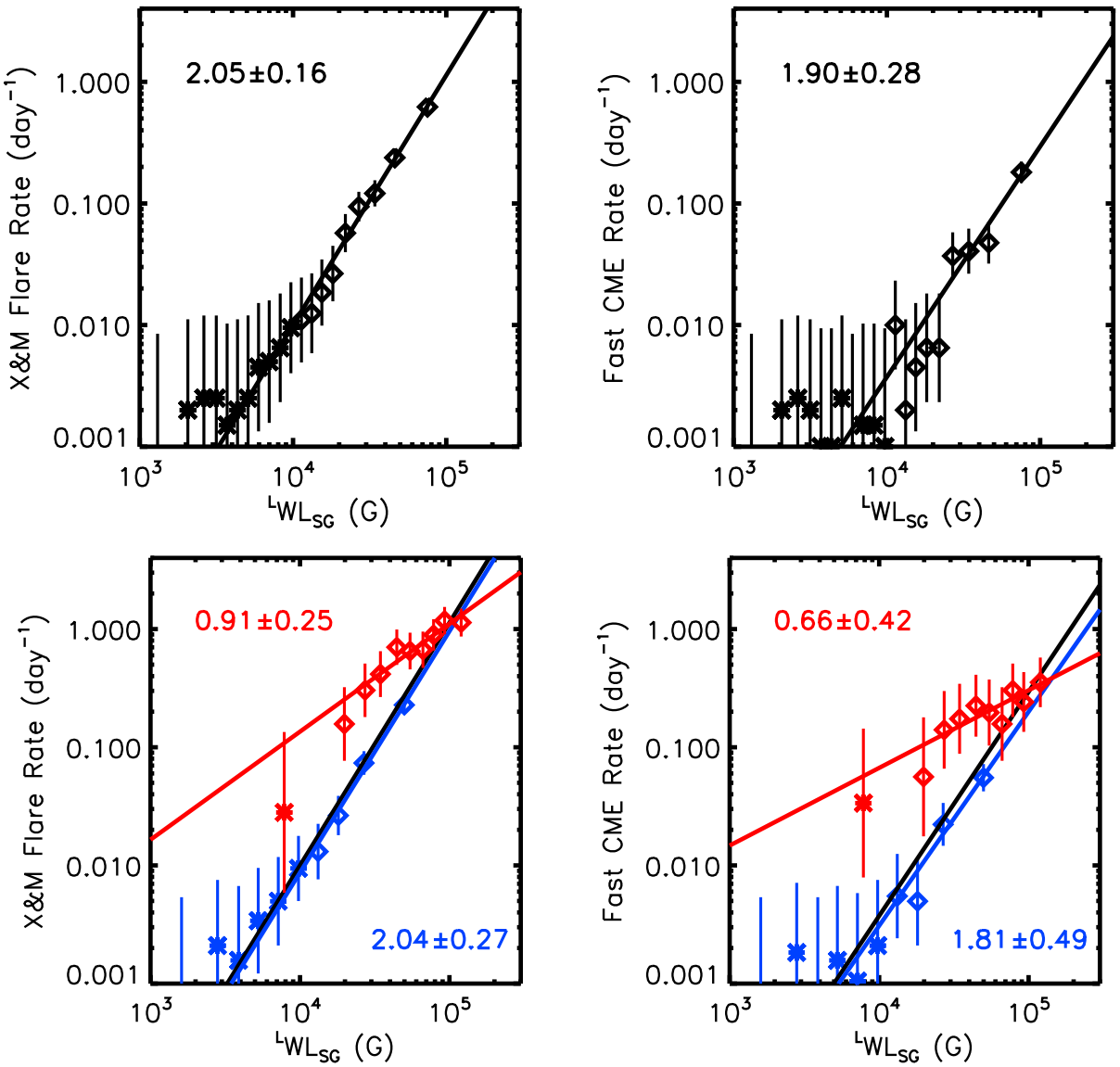
Predicted Performance from first 75% of sample.

Actual Performance of last 25% of sample.

1-sigma error bars



Incorporation of Previous Flaring Improves the Forecast



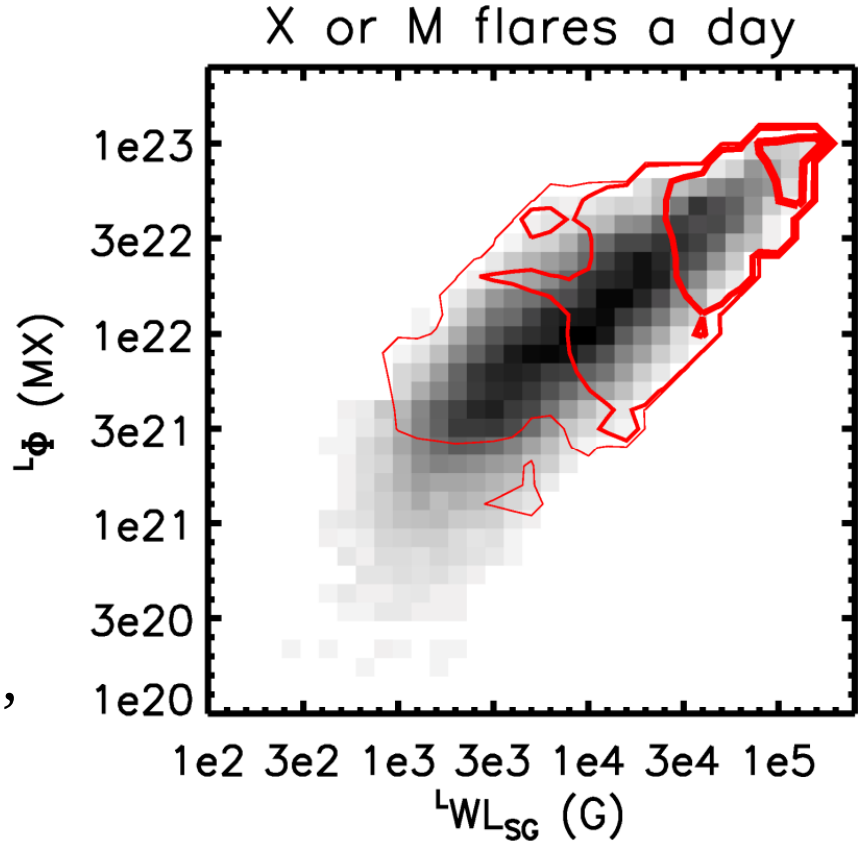
Free Energy Only

Recently Flaring

Recently Non-flaring

Flux Content is Not an Important Additional Determinant

Gray scale plot shows free energy/magnetic size distribution of 40,000 magnetograms of 1,300 active regions. Red contours are 0.001, 0.01, and 0.1, and 0.5 event/day levels.



Forecasting with HMI using MDI Forecast Curves

Comparison of HMI and MDI Magnetographs

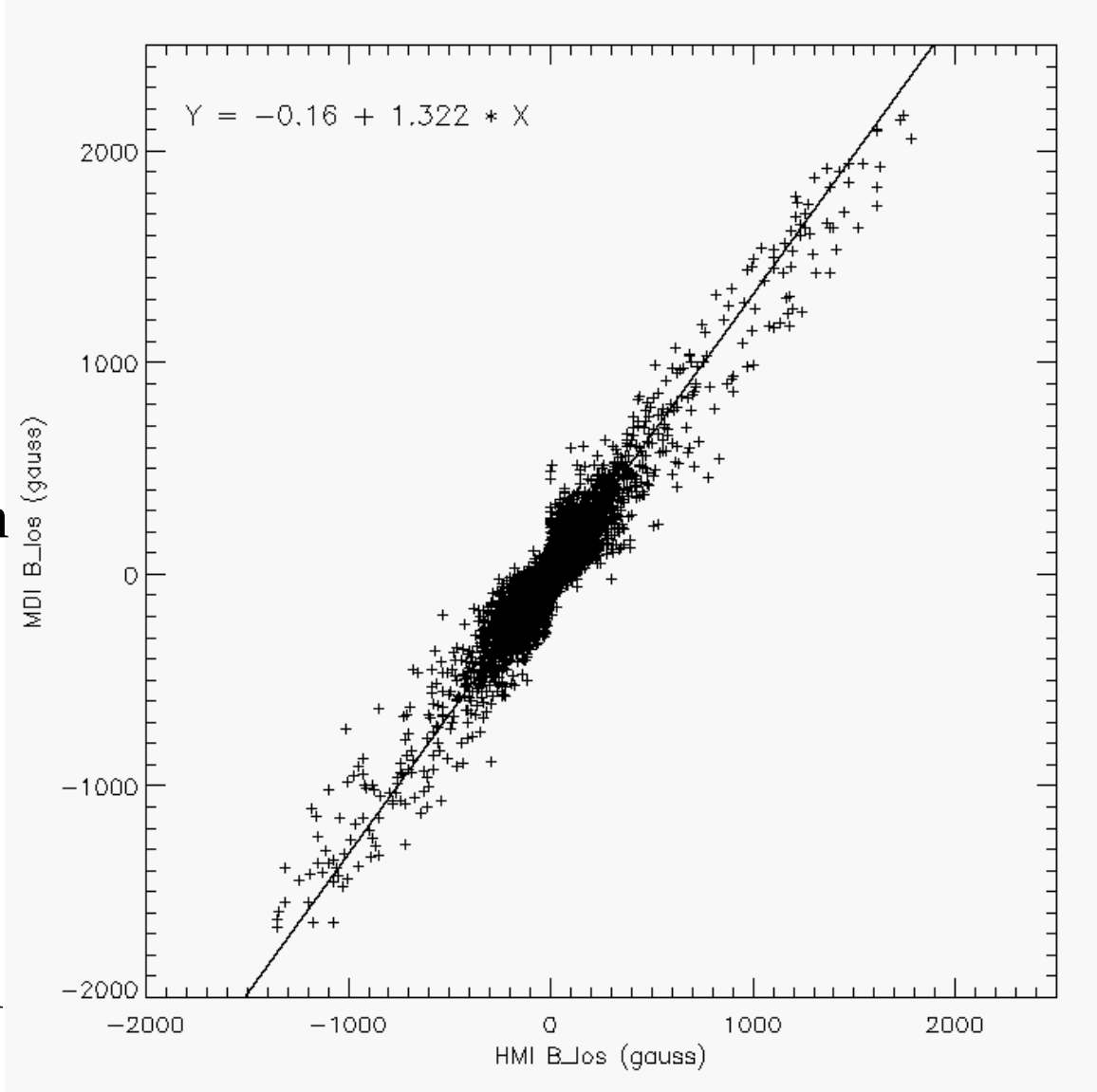
	MDI	HMI
pixels	2”	0.5”
Cadence	96 minutes	45 sec LOS, 90 sec Vector
Latency	Approximately a day	tens of minutes
Magnetograph Type	Line-of-sight	Vector
Operational	1996-Jan 2011 **Now Turned off**	May 2010 to present **Now Operating**

Calibration of HMI B_{LOS} to MDI

Empirical conversion of HMI magnetic field strength to MDI magnetic field strength

Hoeksema and the HMI team has done this work.

Early HMI Magnetic Field Observations Hoeksema et al



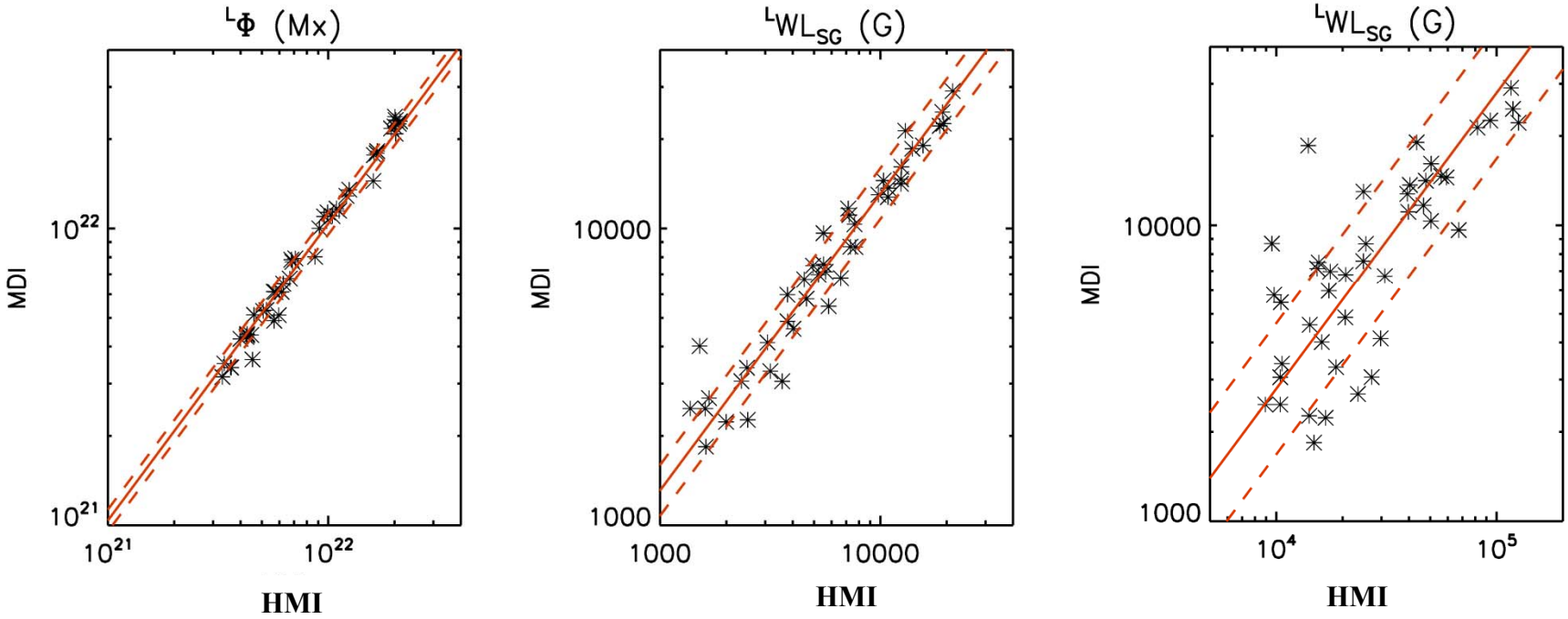
Scaling the HMI Value of $^{L}WL_{SG}$ to MDI

For MDI resolution

- $^{L}WL_{SG}(MDI)=1.31*{}^{L}WL_{SG}(HMI)$
- Multiplicative uncertainty is 1.22

1σ Multiplicative uncertainty in forecast event rate due to for different instruments and spatial resolutions			
Event Type	MDI	**HMI-MDI-res**	HMI-full res
X and M Flares	1.07	**1.48**	2.71
X Flares	1.29	**1.60**	2.86
CMEs	1.10	**1.36**	2.16
Fast CMEs	1.17	**1.41**	2.24
SPEs	1.32	**1.51**	2.33

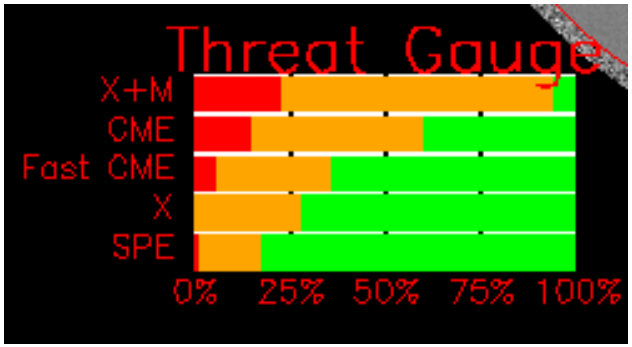
HMI Smoothed to MDI Resolution Unsmoothed

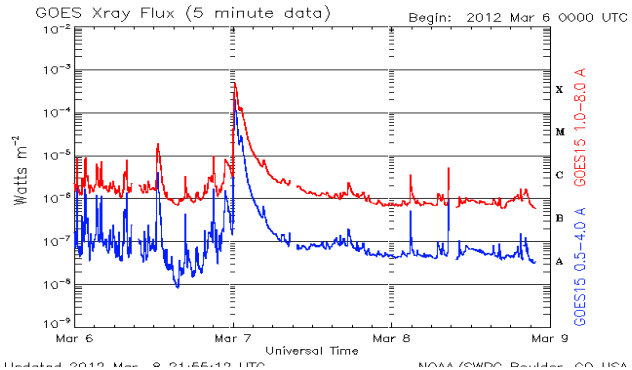


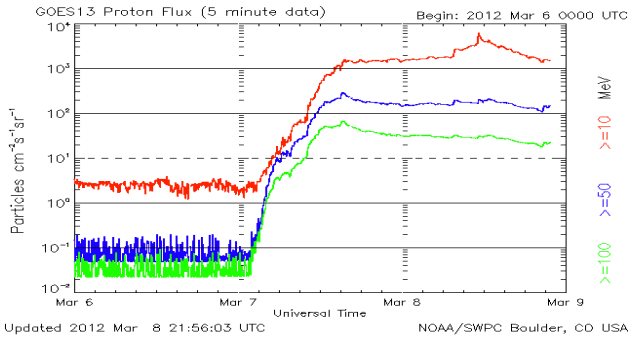
SRAG MAG4 Forecast Tool

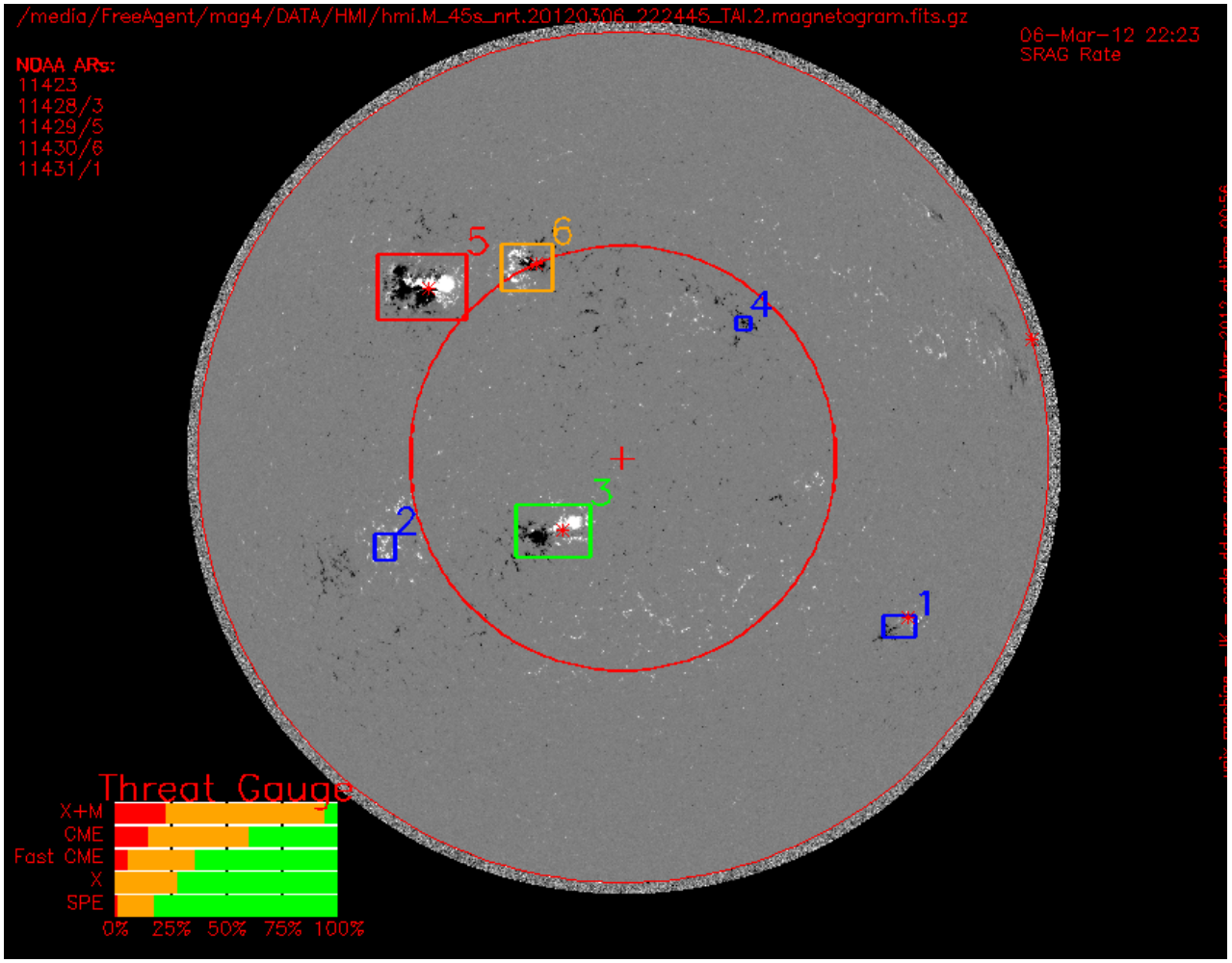
Example Display (March 6, 2012)

- Active region in upper-left corner that produce the March 7 Solar Energetic particle event and geo-effective CME









Future Work:
Tool upgrades to be done using HMI

- **Use deprojected vector magnetograms to measure WL_{SG}**
  - Waiting for automated ambiguity resolution
  - Will incorporate de-projecting of ambiguity-resolved active-region magnetograms
- **Determine whether any vector free-energy proxies are more strongly correlated with AR production of major events than WL_{SG}**

- **Does HMI's higher resolution give WL_{SG} values that are more strongly correlated with AR major-event production than does the lower resolution of MDI?**

Last two need a large HMI database to determine. Between May 2010 (HMI first-light) and March 16, 2011 there have been 40 M and 2 X-class flares; most of these (30 M and 2 X) occurred in 2011. This means that preliminary results are likely possible by year end.