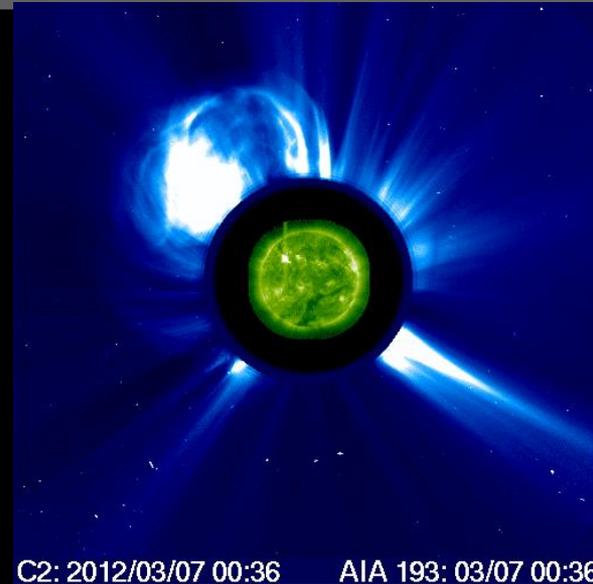
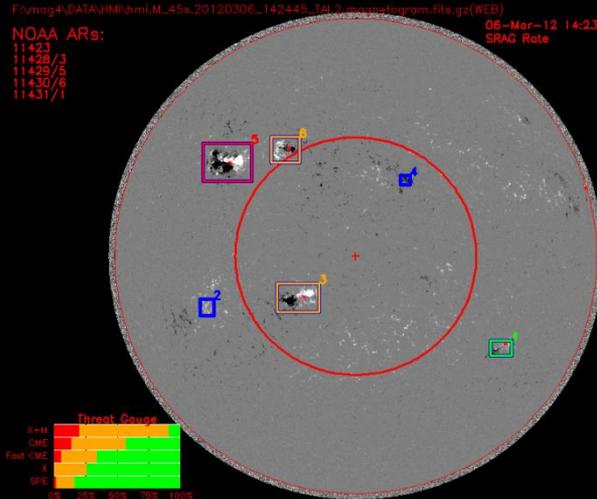




## SCIENCE & TECHNOLOGY OFFICE



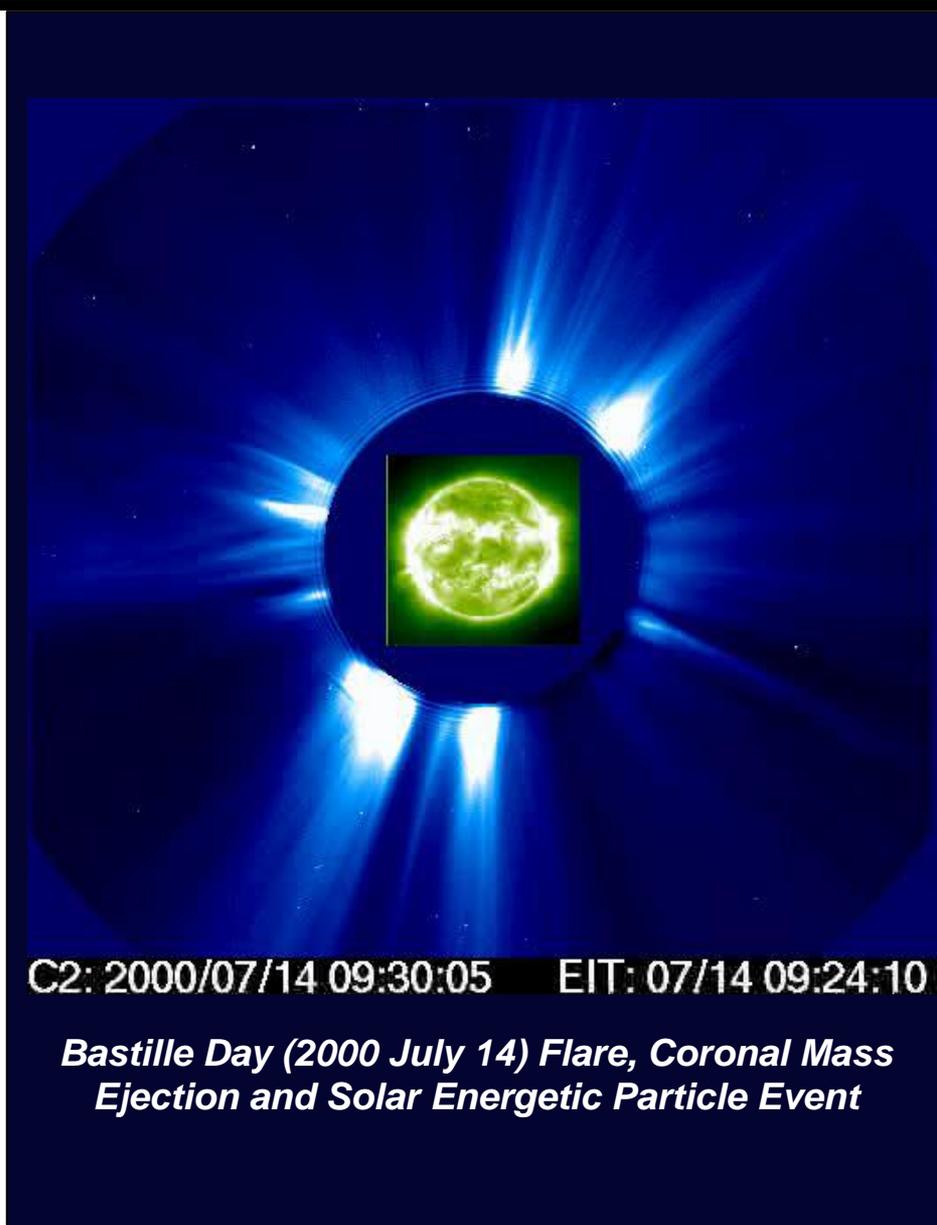
# An All-Clear Space Weather Forecasting System Based on Magnetogram in Near Real Time

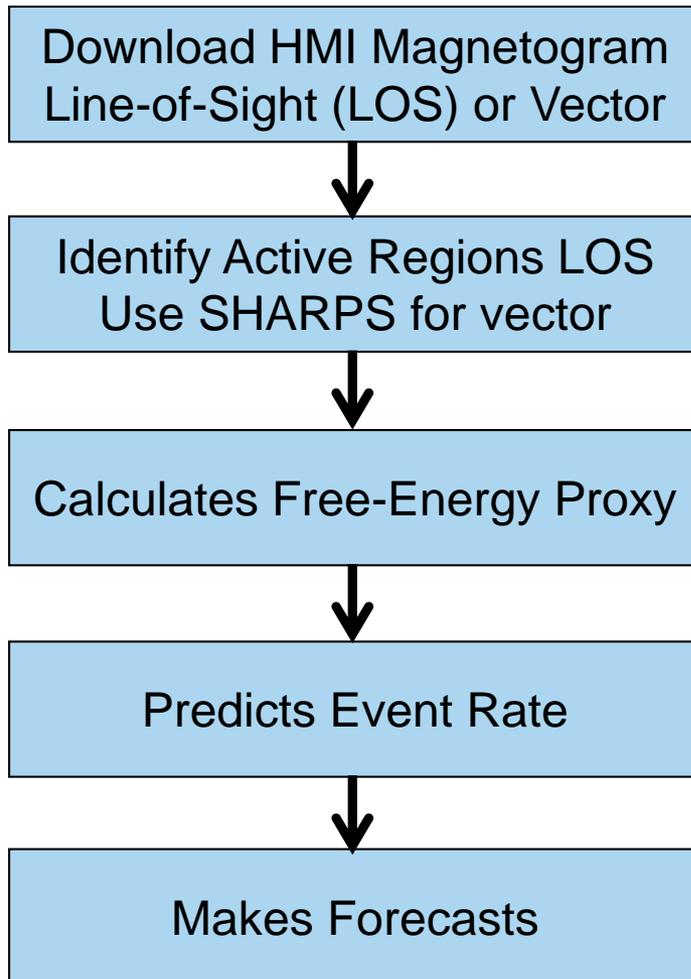
David Falconer, Nasser Barghouty, Igor Khazanov, and Ron Moore

**Jan 11, 2016**

<http://www.uah.edu/cspar/research/mag4-page>

1. MAG4 background
2. Measurement
3. Effectiveness
4. Transitioning to Vector
5. Future improvements





MAG4 is completely automated, from downloading magnetograms to outputting and storing forecast products.

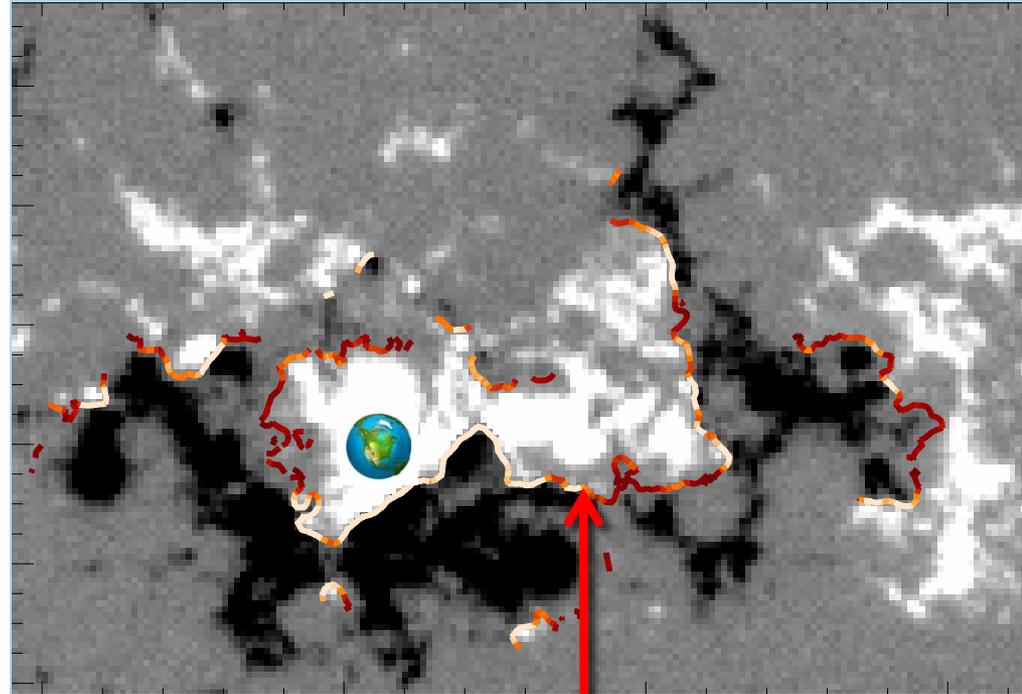
- Flares and CMEs are known to be drivers of the most severe space weather
- Flares and CMEs typically originate in active regions (aka sunspots)
- Flares and CMEs are examples of exceptionally large explosive releases of magnetic energy stored in the corona
- While the amount of free energy cannot be measured directly, **free-energy proxies** can be measured
- Event rates have been shown to be correlated with the magnitude of the free-energy proxies

- MAG4 (Magnetogram Forecast), developed originally for NASA/SRAG (Space Radiation Analysis Group), is an automated program that analyzes magnetograms from the HMI (Helioseismic and Magnetic Imager) instrument on NASA SDO (Solar Dynamics Observatory), and automatically predicts the event rate (or probability) of major flares (M- and X-class), Coronal Mass Ejections (CMEs), and Solar Energetic Particle Events
- MAG4 does not forecast that a flare will occur at a particular time in the next 24 or 48 hours; rather the **probability of one occurring!**
- GONG ([Global Oscillations Network Group](#)) magnetograms, can be used instead as a **backup** but at a lower forecast accuracy
- Present cadence of new forecasts: **96 minutes** (60 minutes for CCMC)  
Vector magnetogram actual cadence: **12 minutes**

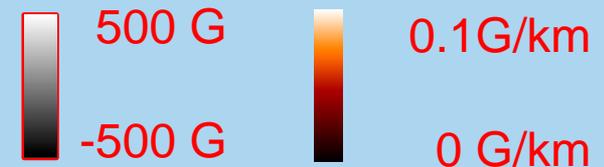
- **1973** The MSFC (Marshall Space Flight Center) vector magnetograph was built to support Skylab
- **2000-present** MSFC used vector magnetograms to study CME correlation with free-energy proxy
- **2007-12** A DOD/Multidisciplinary University Research Initiative/Neutral Atmosphere Density Interdisciplinary Research helped support funding of the basic research
- **2008** Partnered with JSC/SRAG (Space Radiation Analysis Group) and won an R20 NASA/Technical Excellence Initiative grant: Began building a database that grew to ~40,000 magnetograms of ~1,300 active region, covering years 1996-2004 with event catalog from SOHO/MDI (Solar and Heliospheric Observatory/Michelson Doppler Imager) observations
- **2010-present** NASA's HEOMD (Human Exploration and Operations Mission Directorate) support
- **2010** SDO is launched began transitioning from MDI to HMI line-of-sight magnetograms.
- **2011** **MAG4 installed at SRAG a NRT (Near-Real-Time) forecasting tool, and SRAG began pre-operations testing**
- **2012** Provided NOAA web access to MAG4 NRT forecasts
- **2013** Improve MAG4 so that it can use a combination of **free-energy proxy** and previous **flare activity**
- **2015** Transition to HMI line-of-sight to vector magnetograms

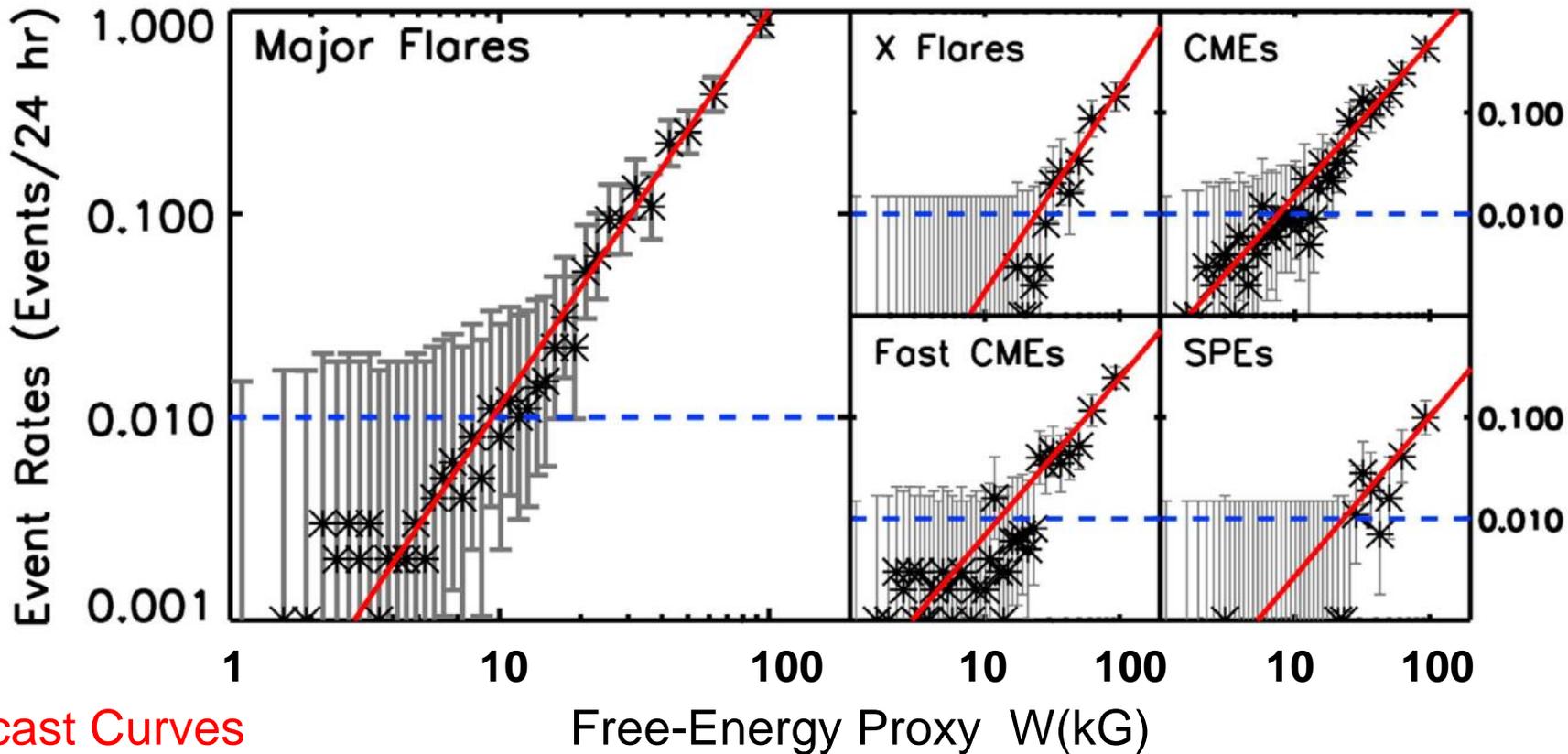
- When the transverse gradient of the vertical (or line-of-sight) magnetic field is large, there is more free-energy stored in the magnetic field
- For **each Active Region**:  
The integral of the gradient along the neutral line is the free-energy proxy

## A magnetogram of an active region



Neutral Line, color coded for gradient





## Forecast Curves

These empirical forecast curves are used to convert our free-energy proxy into predicted event rates. Curves are derived from a sample of 40,000 magnetograms, from 1300 active regions observed between 1996-2004.

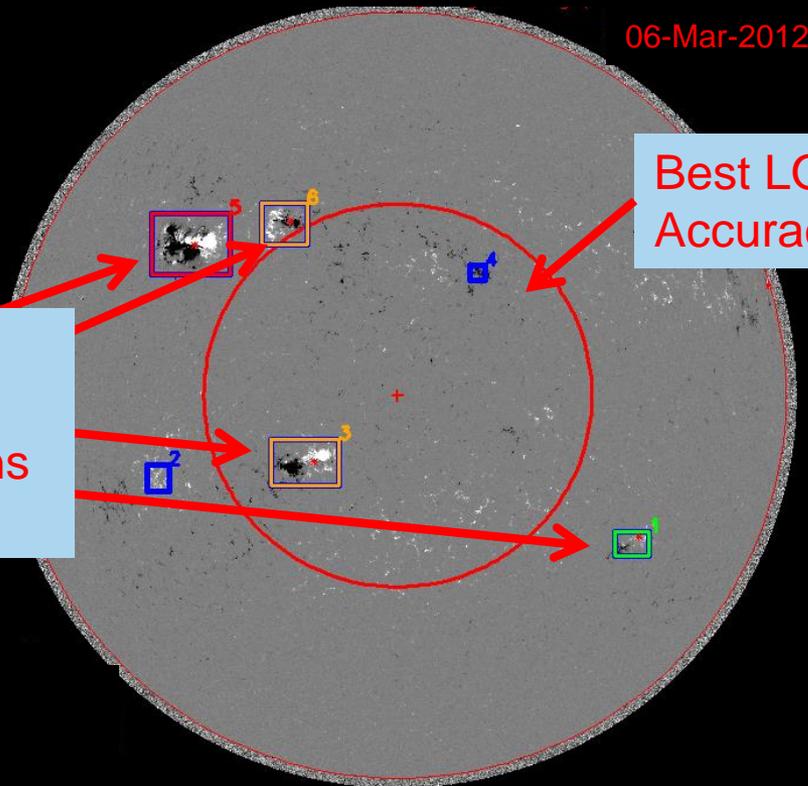
- Magnetograms are spatial maps of the magnetic field strengths
- They come in two basic types
  - line-of-sight (right)
  - vector magnetograms
- Free-energy proxies can be measured for Active Regions (areas with sunspots) from either type of magnetogram
- Line-of-sight magnetograms suffer reduced accuracy further from disk center

NOAA ARs  
11423  
11426/3  
11429/5  
11430/6  
11431/1

06-Mar-2012 14:23

NOAA Active Regions (ARs)

Best LOS Accuracy



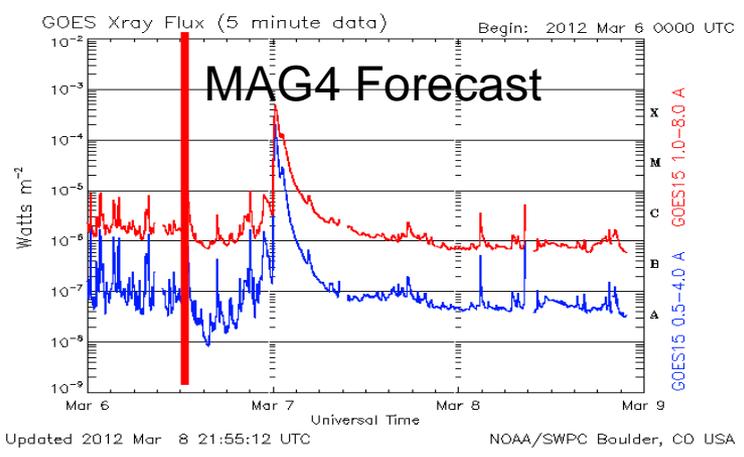
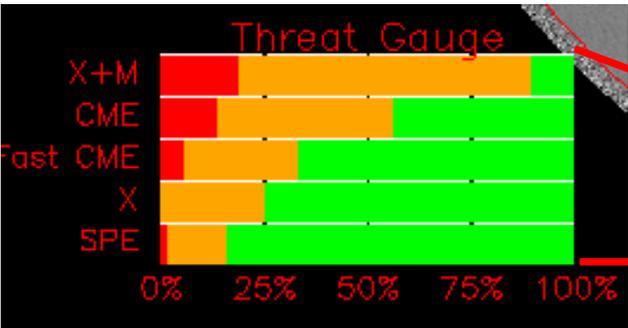
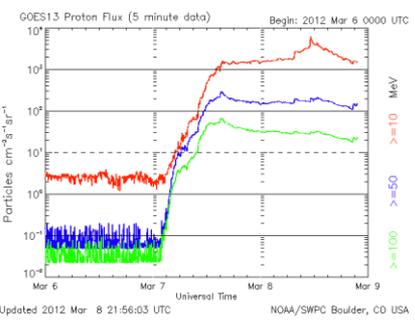
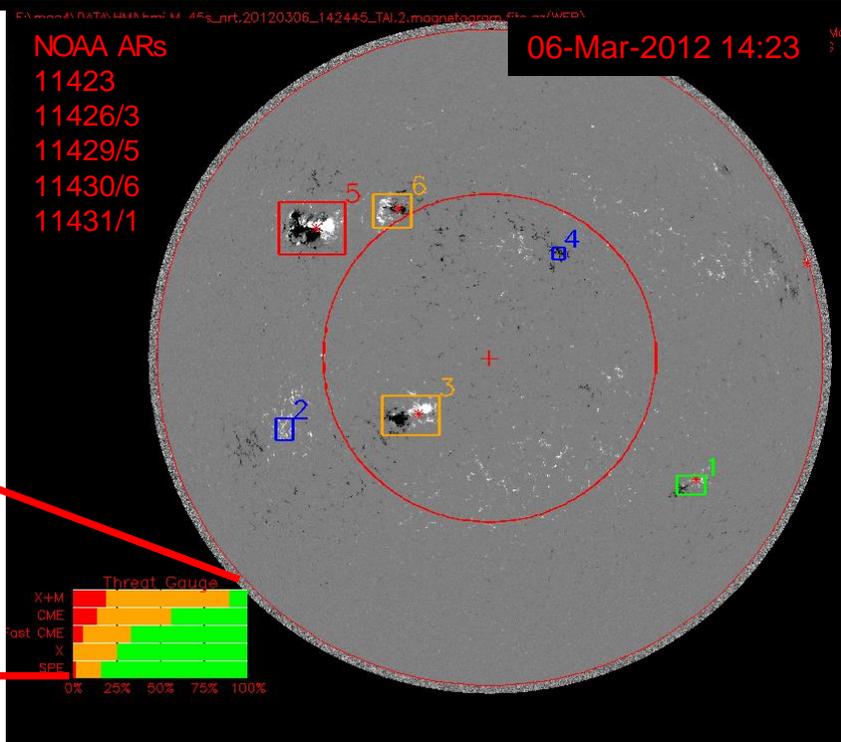
*A full-disk line-of-sight magnetogram of the Sun, from SDO/HMI.*

Magnetograms & identify ARs

## Multiplicative uncertainty example

Rate	1 sigma	Probability
Events/day	66% Confidence	
0.02	0.01-0.05	0.7-5%
0.7	0.3-1.9	20-80%

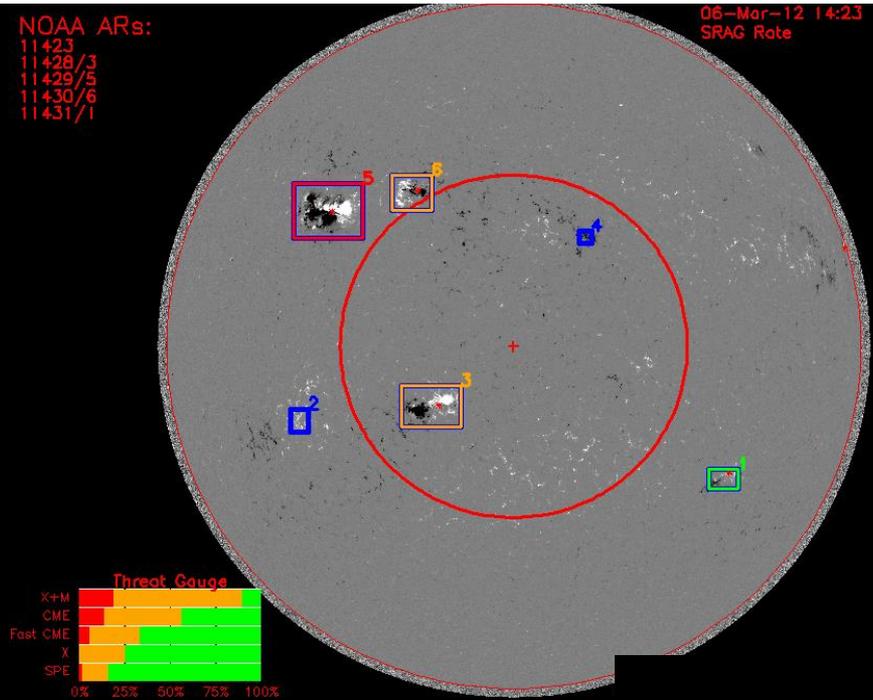
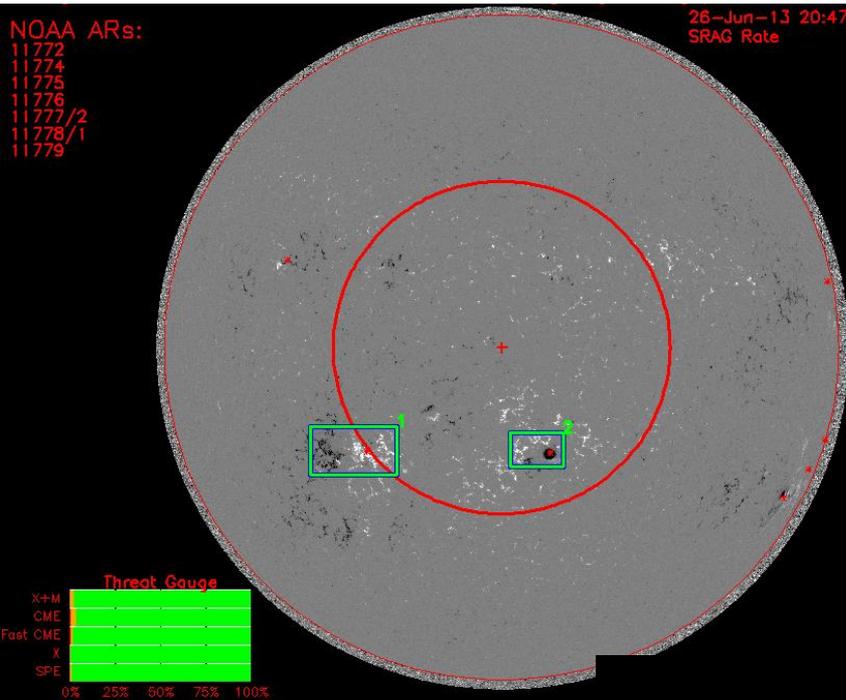
For a Multiplicative Uncertainty of 2.7x



2012/03/06 14:23		Lng Lat		24 Hour Event Rate					Dist
#	AR#	WL <sub>SG</sub> (kG)	(deg)	M&X	CME	FCME	X	SPE	(deg)
3	11428	9	-21 -17	0.020	0.020	0.009	0.002	0.003	27
5	11429	65	-41 17	0.700	0.400	0.200	0.100	0.080	44!
6	11430	11	-25 20	0.020	0.030	0.010	0.004	0.005	32!
1	11431	1	36 -27	0.000	0.001	0.001	0.000	0.000	45!
Disk Forecast Rates				0.800	0.400	0.200	0.100	0.090	
Multiplicative Uncertainties				2.7x	2.1x	2.2x	3.0x	2.4x	
Disk All-Clear Forecast Probabilities				50.00%	70.00%	80.00%	90.00%	92.00%	
Uncertainties				40.00%	20.00%	10.00%	10.00%	7.00%	

June 26, 2013  
C1, C1.5 flares

March 7, 2012  
X5.4, X1.3, C1.6  
CME 2684, 1825 km/sec,  
Solar Energetic Proton Event reaches  
6530 particle flux unit >10MeV



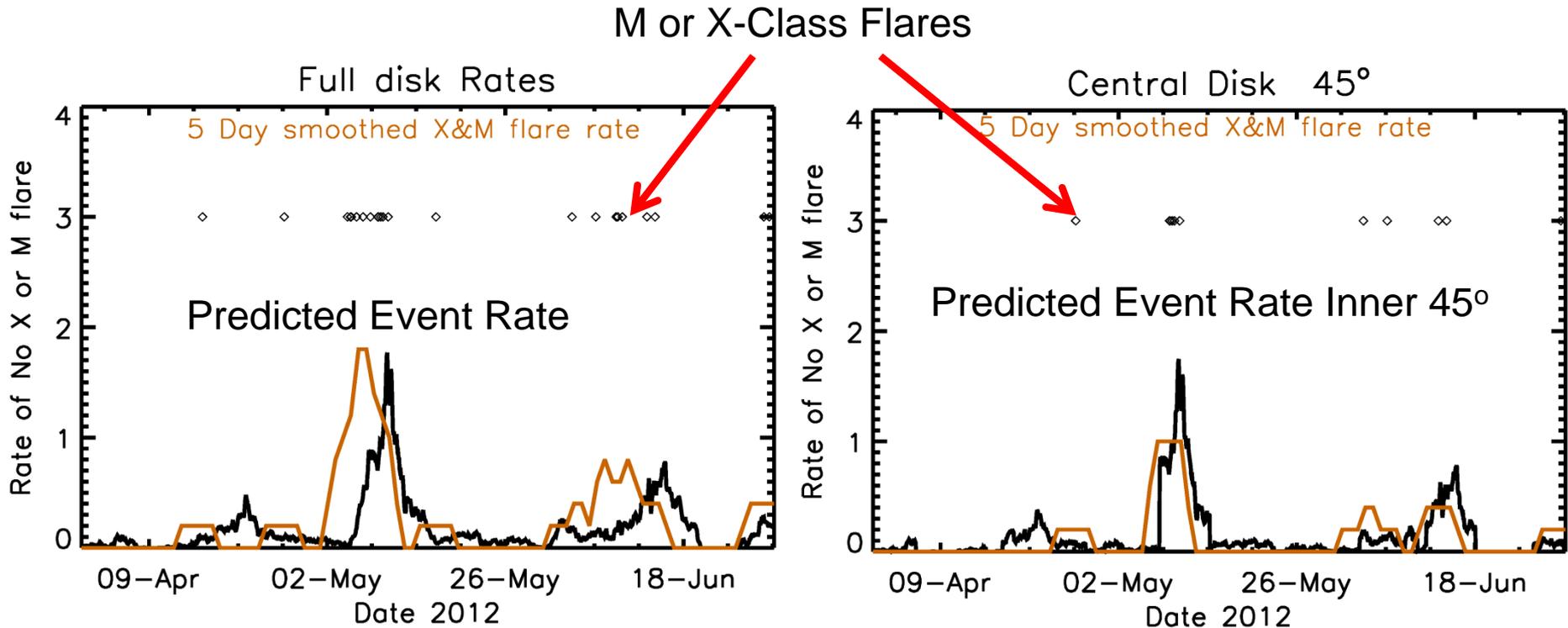
## 2. Skill Metrics Significance of Upgrade

Forecast Method	YY	YN	NY	NN	PC(%)	POD	FAR	HSS	TSS
McIntosh/NOAA	259	638	631	18476	93.7	0.29	0.71	0.26	0.26
Free-Energy Proxy <b>Present MAG4</b>	273	284	618	18830	95.5	0.31	0.50	0.35	0.47
Free-energy proxy and previous flare activity <b>Upgraded MAG4</b>	340	317	551	18797	<b>95.7</b>	<b>0.38</b>	<b>0.48</b>	<b>0.42</b>	<b>0.49</b>
Best	890	0	0	19114	100	1	0	1	1

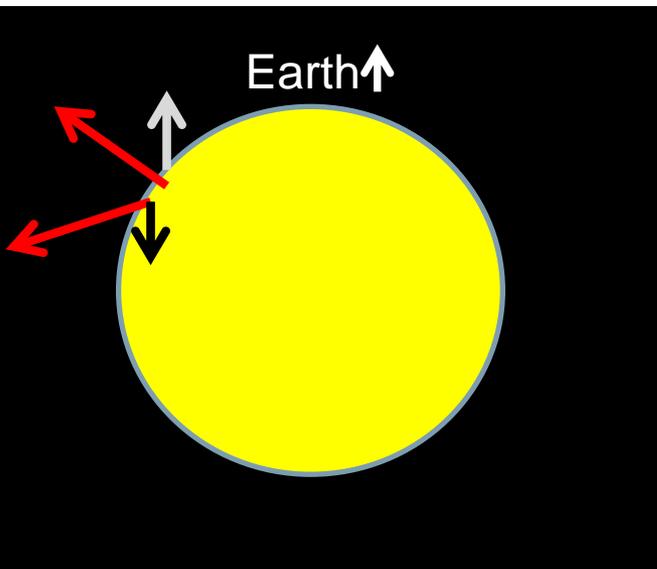
Improvement in Metric	PC(%)	POD	FAR	HSS	TSS
McIntosh/NOAA <b>Present MAG4</b>	1.8±0.5 <b>(4σ)</b>	0.03±0.05 <b>(0.3σ)</b>	0.21±0.07 <b>(3σ)</b>	0.10±0.04 <b>(2σ)</b>	0.21±0.07 <b>(3σ)</b>
<b>Present MAG4</b> <b>Upgraded MAG4</b>	0.2±0.2 <b>(0.7σ)</b>	0.08±0.03 <b>(2σ)</b>	0.02±0.05 <b>(0.5σ)</b>	0.06±0.03 <b>(2σ)</b>	0.03±0.05 <b>(0.5σ)</b>

## 1. Situational Awareness

- During periods when flare-productive active regions cross the disk, the predicted rate and actual rate both increase, providing situational awareness
- The results are best when flares and predicted rates are limited to inner 45 degree circle (Right)



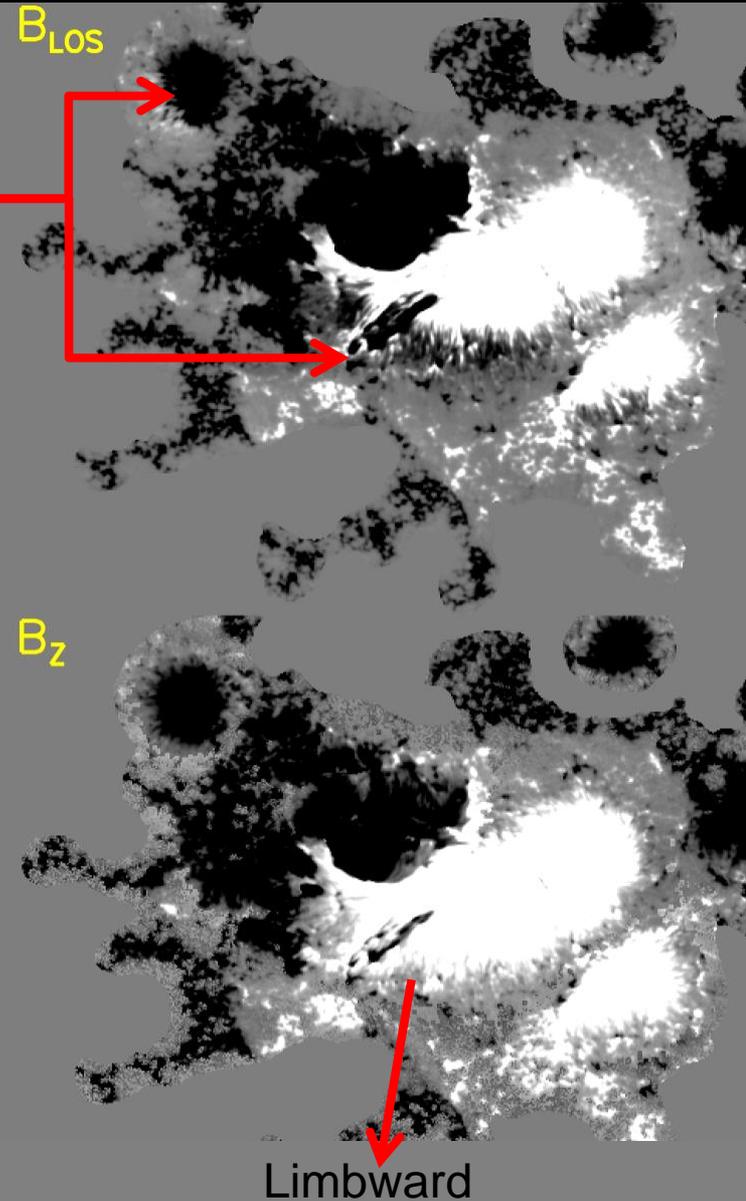
- Both vectors shown in red have positive  $B_z$  (magnetic field out of the sun), but have opposite sign  $B_{LOS}$  and thus a false (unphysical) neutral line in the line-of-sight (LOS) field.



Actual Examples

False Neutral Lines occur on limbward sides of sunspots.

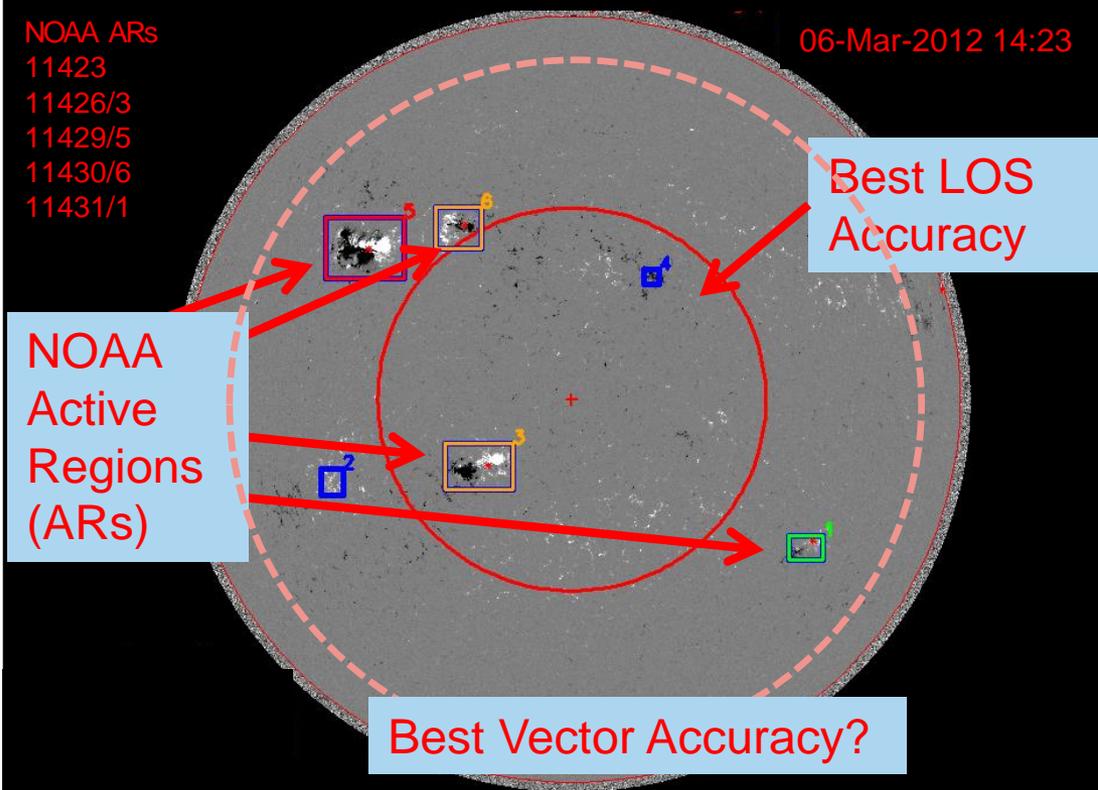
Problem fixed by converting from  $B_{LOS}$  and  $B_{Transverse}$  to  $B_z$  and  $B_{Horizontal}$



- For LOS most accurate to 30 heliocentric degrees. (RED)
- For Vector similar accuracies should exist to 60 heliocentric degrees.

NOAA ARs  
11423  
11426/3  
11429/5  
11430/6  
11431/1

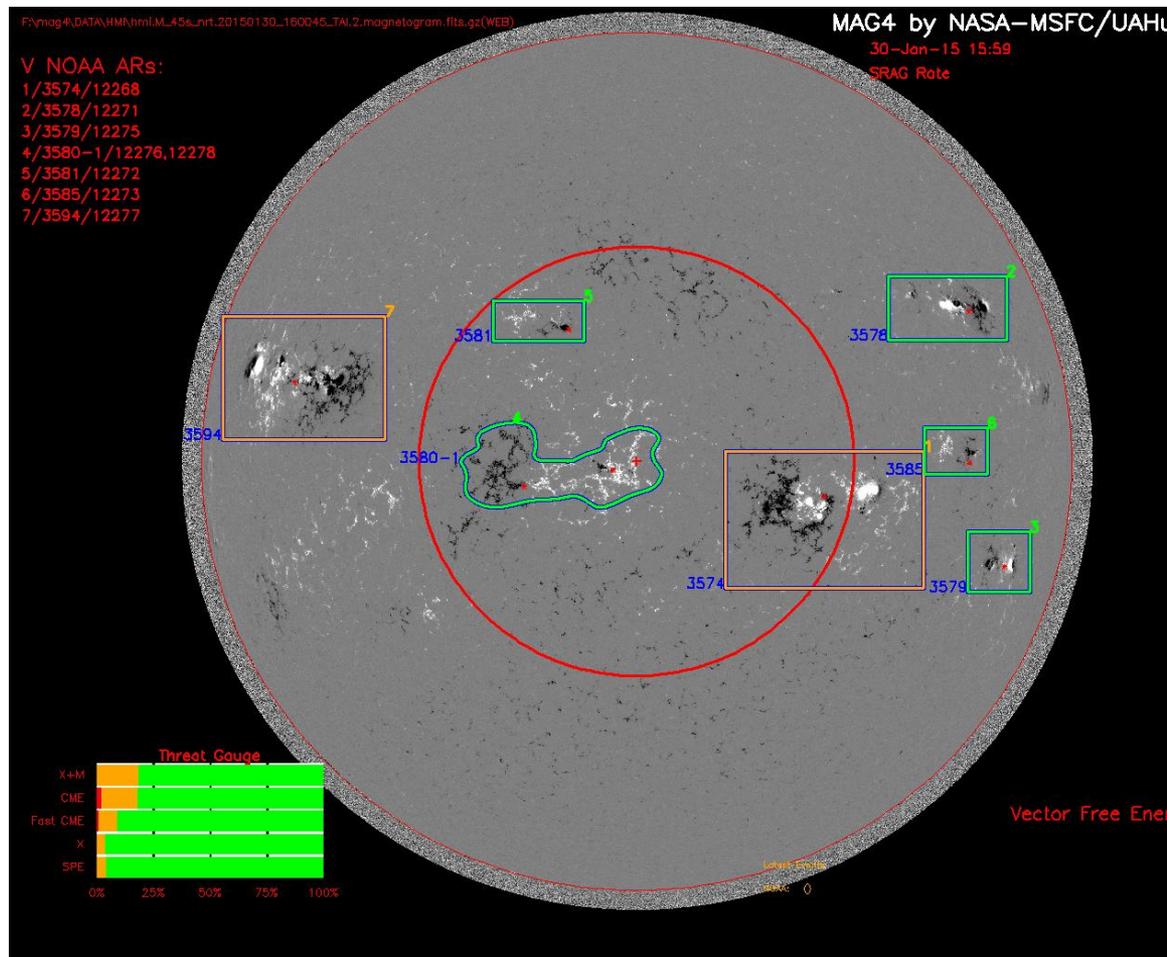
06-Mar-2012 14:23



*A full-disk line-of-sight magnetogram of the Sun, from SDO/HMI.*

Magnetograms & identify ARs

- MAG4 presently
  - Predicts what MDI will measure if AR was at disk center.
  - Then uses the forecast curves from MDI to forecast events.
- MAG4 needs to upgrade to take full advantage of vector magnetograms.
- <http://www.uah.edu/csp/ar/research/mag4-page>





## 2. Skill Metrics Equations

	Actual Yes	Actual No
Predict Yes	YY	YN
Predict No	NY	NN

### Metric Equations

Percent Correct	$PC = (YY + NN) / (YY + YN + NY + NN)$
Probability of Detection	$POD = YY / (YY + NY)$
False Alarm Rate	$FAR = YN / (YY + YN)$
Heidke Skill Score	$HSS = 2 * (YY * NN - YN * NY) / [(YY + NY) * (NY + NN) + (YY + YN) * (YN + NN)]$
True Skill Score	$TSS = (YY * NN - NY * YN) / ((YY + NY) * (YN + NN))$

## 2. Skill Metrics

Truth Table	Actual Yes	Actual No
Predict Yes	YY	YN
Predict No	NY	NN

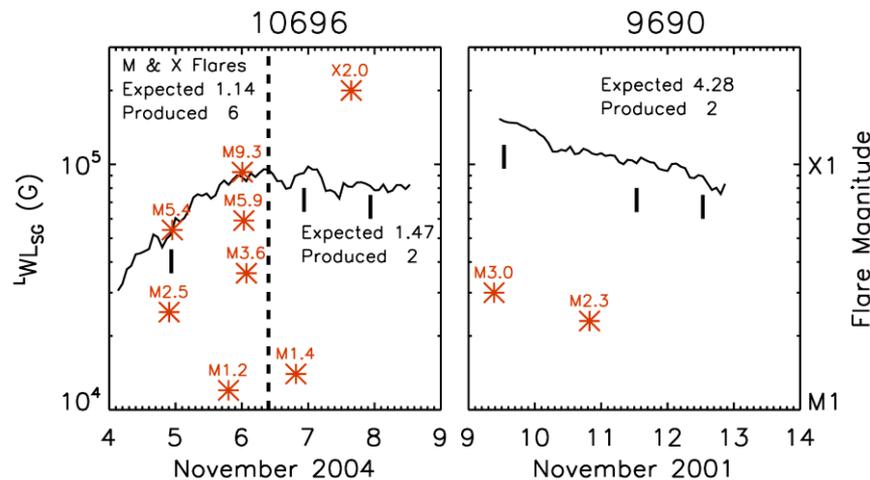
PC Percent Correct (0 to 100%)  
 POD Probability of Detection (0 to 1)  
 FAR False Alarm Rate (1 to 0)  
 HSS Heidke Skill Score (-1 to 1)  
 TSS True Skill Score (-1 to 1)

Forecast Method	YY	YN	NY	NN	PC (%)	POD	FAR	HSS	TSS
McIntosh/NOAA	259	638	631	18476	93.7	0.29	0.71	0.26	0.26
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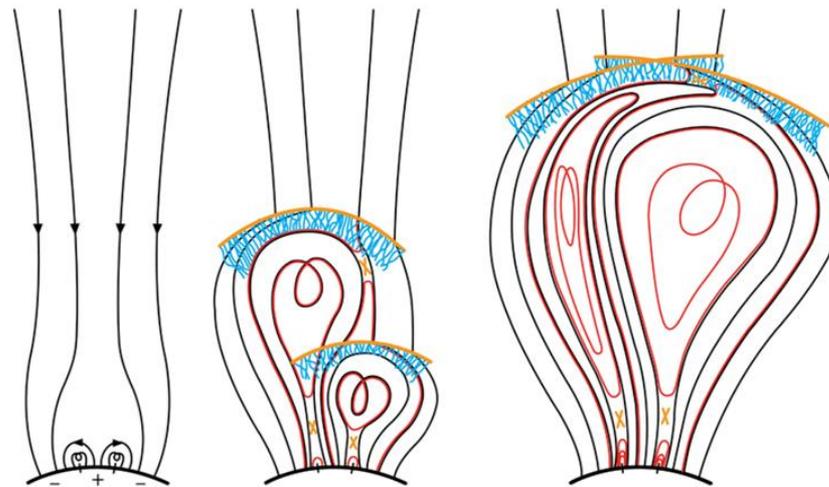
## Improvements with Vector MAG4

- Correct for systemic errors in measurements due to radial dependence of transverse field noise and foreshortening.
- Access skill scores relative to present LOS
- Investigate if a vector measure is better than LOS measure
- Investigate if change of measure is important
- Investigate if combination produces better measure
- Correct SPE forecasts based on Longitude of source region
- Partner with heliosphere modeling to better forecast where the particles would go.
- Twin CME`

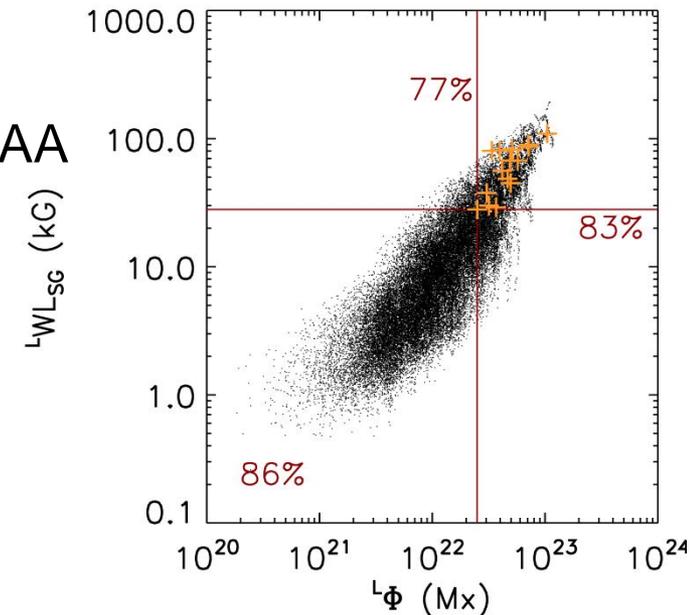
- Determine if growth/decay phase of an active region has additional prediction ability



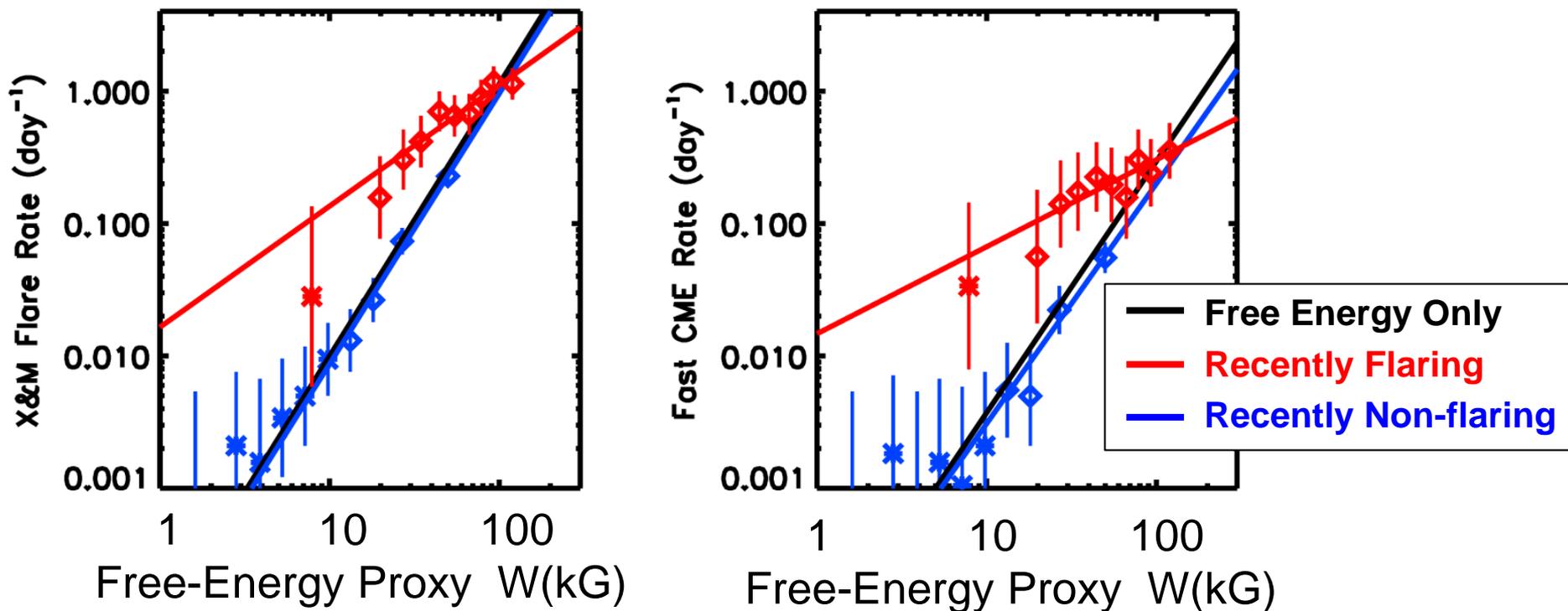
- Determine if looking at twin-CME or single-CME can produce improved SEP forecasts



- Continue to supply support, and upgrades to NASA/SRAG
- Finish and evaluate using vector magnetograms
- Fully implement in consultation with SRAG using combined free-energy proxy and previous flare activity
- Improve All Clear Forecast for SEP
- Partner with Air Force, and through them NOAA



## 1. Recent Flare History

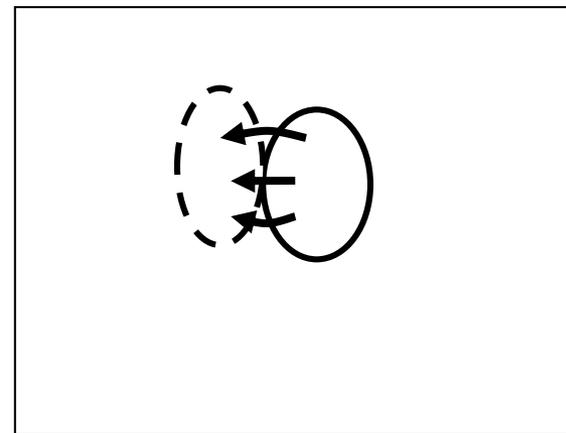
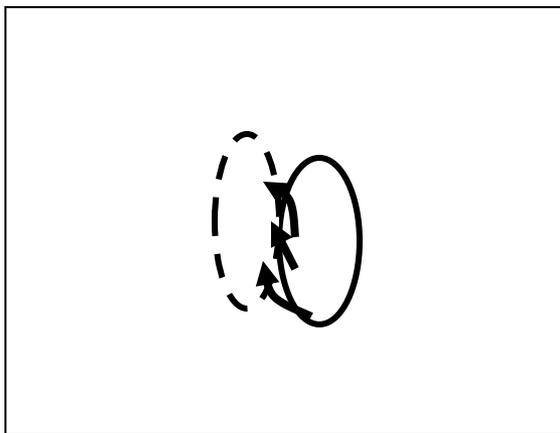
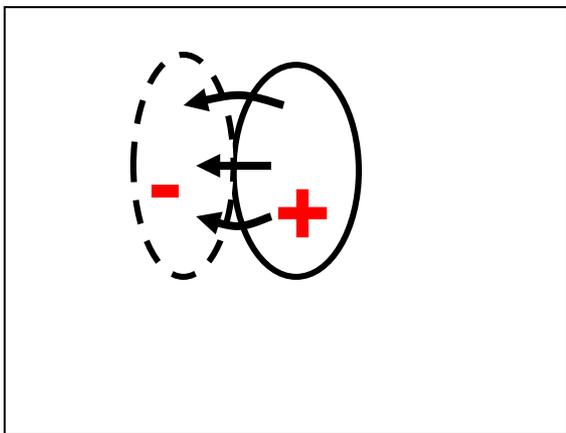


Active regions that have recently produced an X- or M-Class flare are more likely to produce flares in the near future

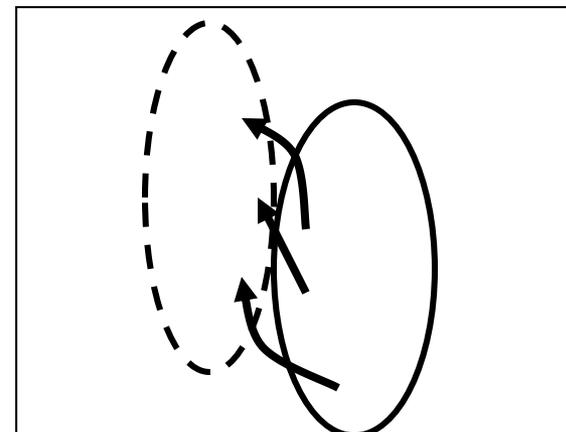
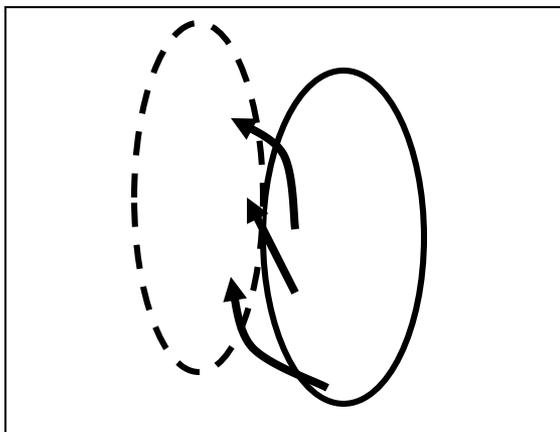
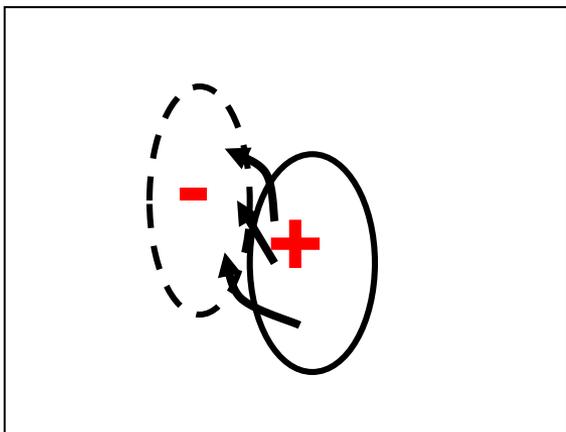
Contours Vertical Magnetic Field  
 Arrows Transverse Magnetic Field

Currents  $\sim 10^{12}$  Amps

Less



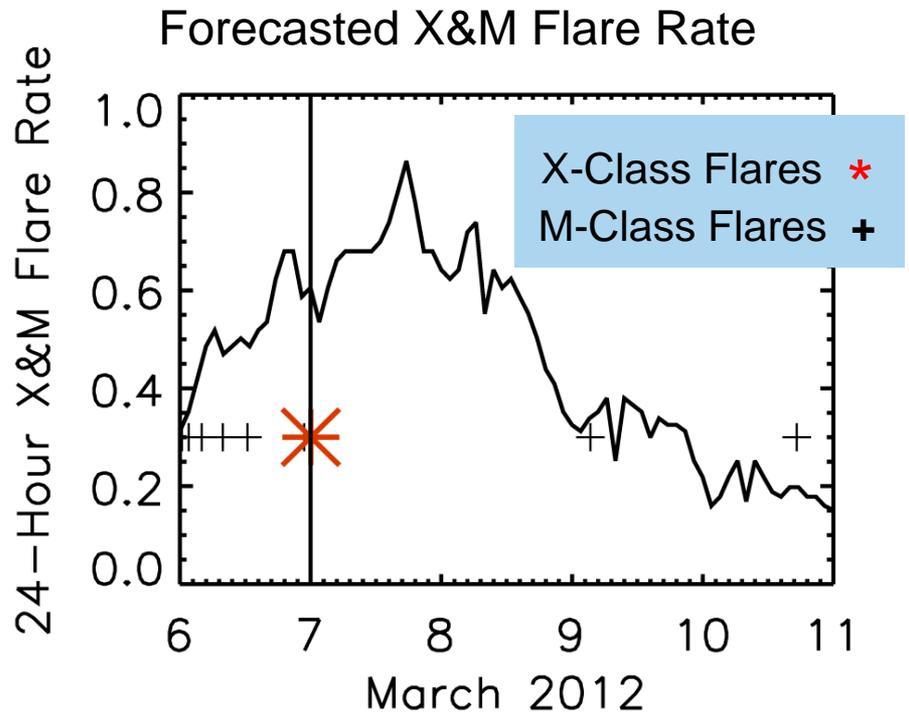
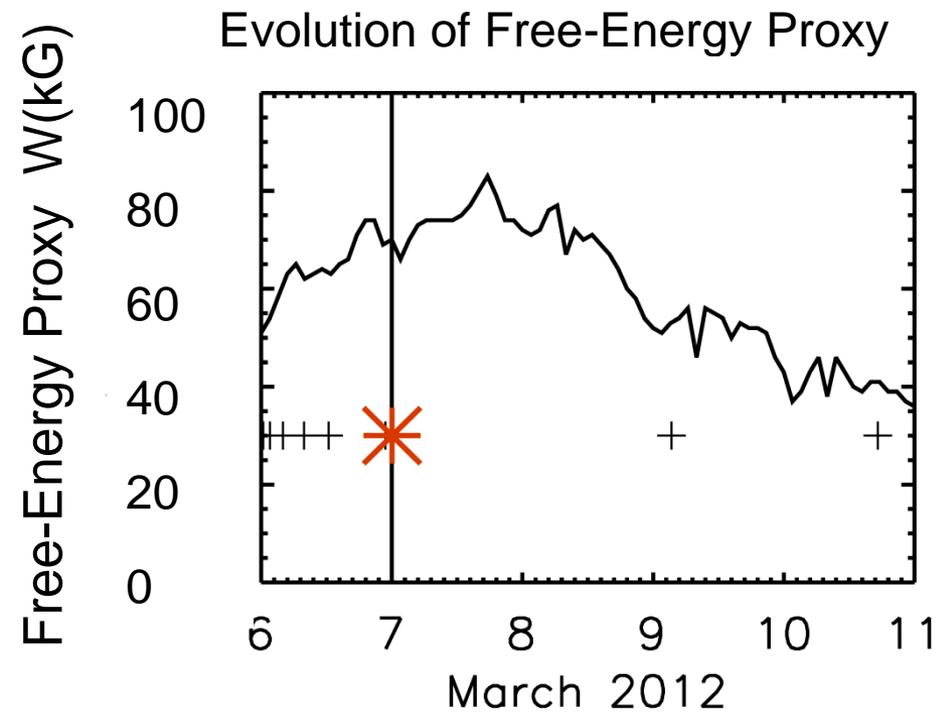
More



Twist

Size

**Free Magnetic Energy  
 Or Nonpotentiality**



The free-energy proxy evolves on time periods of days => the forecast is on those time scales

Flares occur when high free-energy proxy active regions crossing disk.

## All Clear Probability

