National Aeronautics and Space Administration

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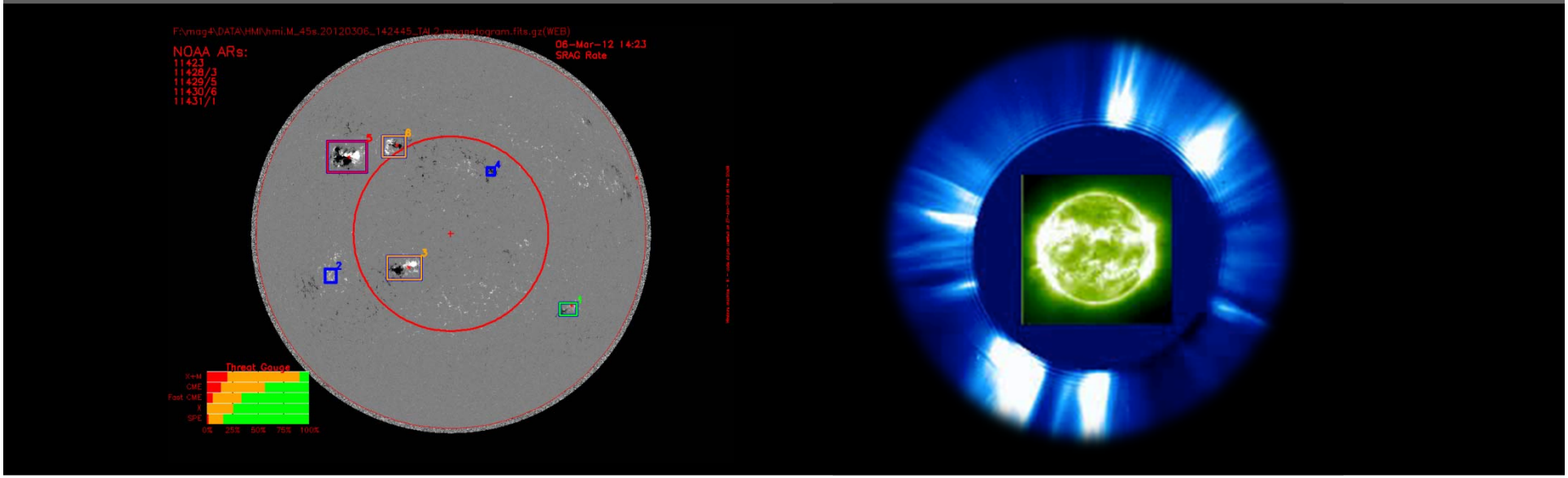

How MAG4 Improves Space Weather Forecasting

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Outline

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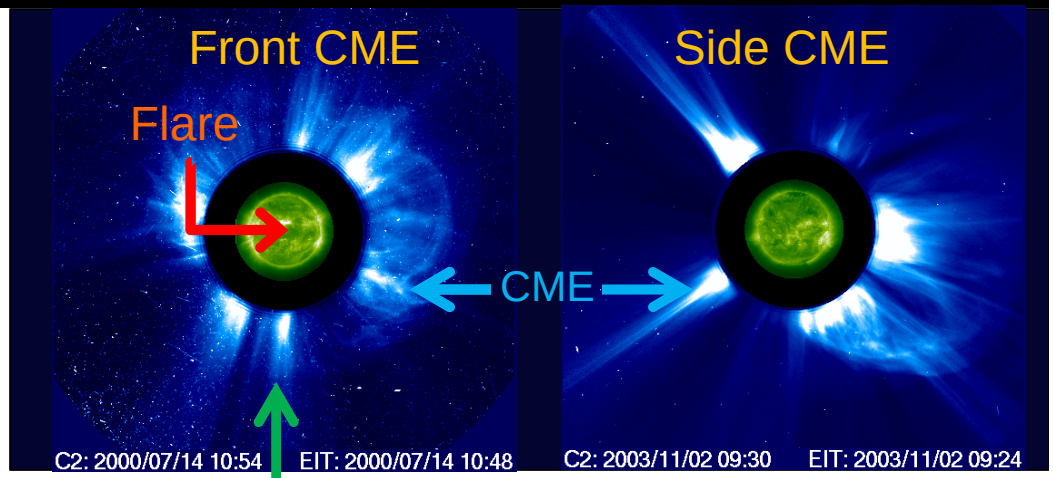
2. MAG4 (Magnetogram Forecast)
   a. What it is
   b. Brief Background
   c. History of R2O
3. MAG4 Automatic Process
4. Demo by Igor Khazanov
5. Improvements in the Pipeline
   a. Recent Flare History
   b. Vector Magnetograms
6. How Effective
   a. Situational Awareness
   b. 2x2 Contingence Table Metrics
7. Suggested Collaborations with AFWA

Bastille Day (2000 July 14) Flare, Coronal Mass Ejection and Solar Energetic Particle Event

Various Forms of Space Weather

Dangerous space weather is driven by solar flares and Coronal Mass Ejection (CMEs).

Forecasting flares and CMEs is the first step to forecasting either dangerous space weather or All Clear.



Flare

Solar Energetic Particle Event (SPE or SEP Event)

CME

ELECTROMAGNETIC RADIATION (IMMEDIATE: TIME 8 MIN)

- X-EUV
- ULTRA-VIOLET
- VISIBLE LIGHT
- RADIO WAVES

HIGH ENERGY PARTICLES (DELAYED < HOUR)

- ATOMIC NUCLEI

ENHANCED SOLAR WIND (DELAYED ~3 Days)

- IONS AND ELECTRONS

Space Weather

SIMULTANEOUS EFFECTS

- INCREASED D-LAYER IONIZATION
  - GEOMAGNETIC DISTURBANCE
  - ANOMALOUS RADIO PROPAGATION
- OUTBURST OF RADIO NOISE
  - RADIO INTERFERENCE

DELAYED EFFECTS

- ENHANCED ENERGETIC PARTICLES
  - MANNED FLIGHT RADIATION HAZARD(I)
  - SPACECRAFT RADIATION HAZARD (C^3)
- IONIZATION
  - ANOMALOUS RADIO PROPAGATION
  - RADAR CLUTTER
- GEOMAGNETIC STORM
  - IONOSPHERIC STORM AND
  - INDUCED CURRENTS
  - RADIO EFFECTS
  - SATELLITE DRAG
  - AURORA

What is MAG4?

- 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 converts the rate (or probability) of major flares (M- and X-class), Coronal Mass Ejections (CMEs), and Solar Energetic Particle Events.

- MAG4 does not forecast a flare will occur at 12:02 tomorrow, but the probability of one occurring tomorrow.

- 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**.
  Vector magnetogram actual cadence: **12 minutes**.

MAG4 Background

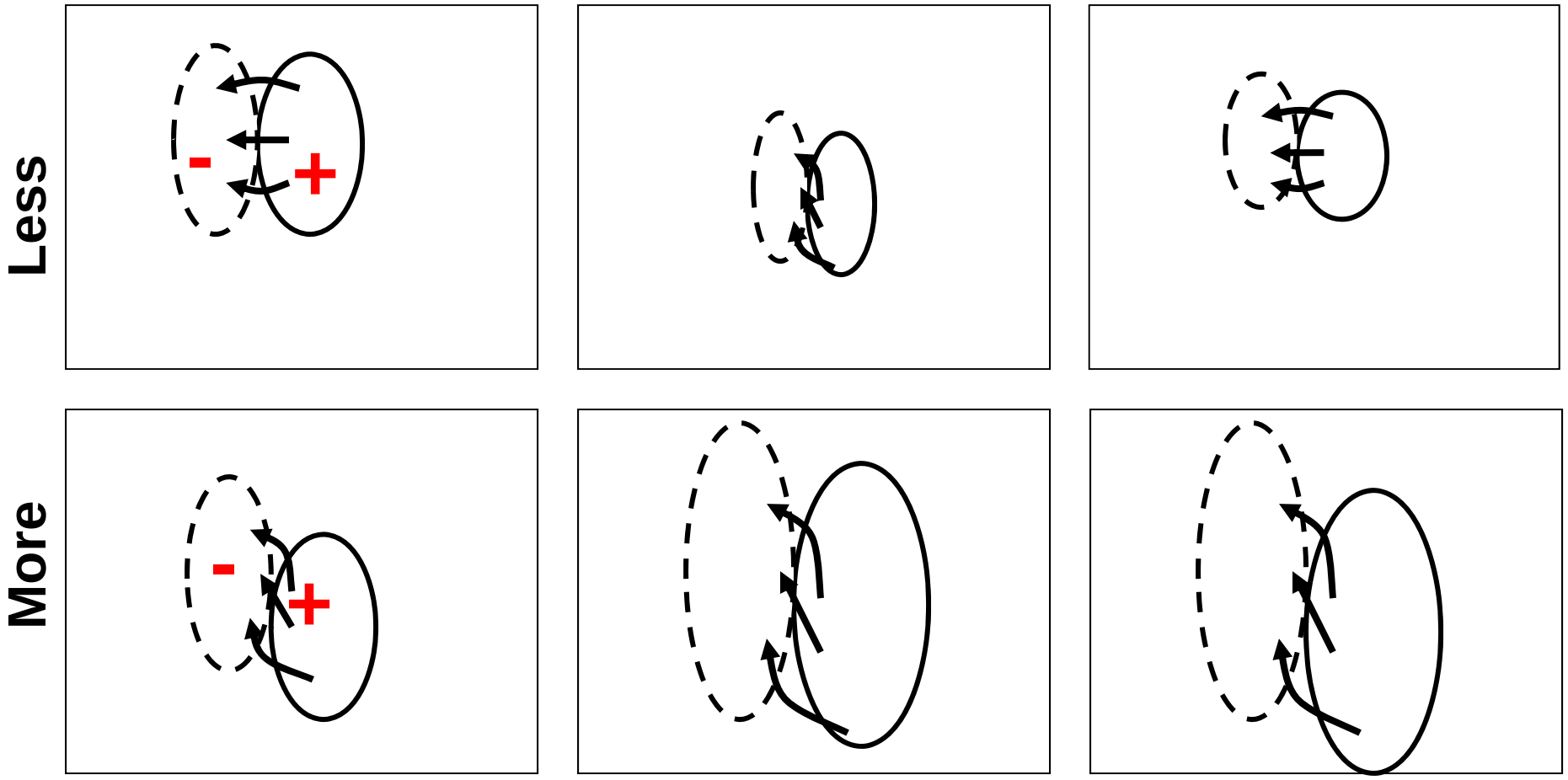
- Flares and CMEs are known to be drivers of the most severe space weather
- Flares and CMEs typically originate in active regions (aka sunspots)
- Flares and CMEs are examples of exceptionally large explosive releases of magnetic energy stored in the corona
- While the amount of free energy cannot be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

Magnetic Free Energy

Is it Magnetic Free (title) or Free Magnetic as below?

Contours Vertical Magnetic Field
Arrows Transverse Magnetic Field

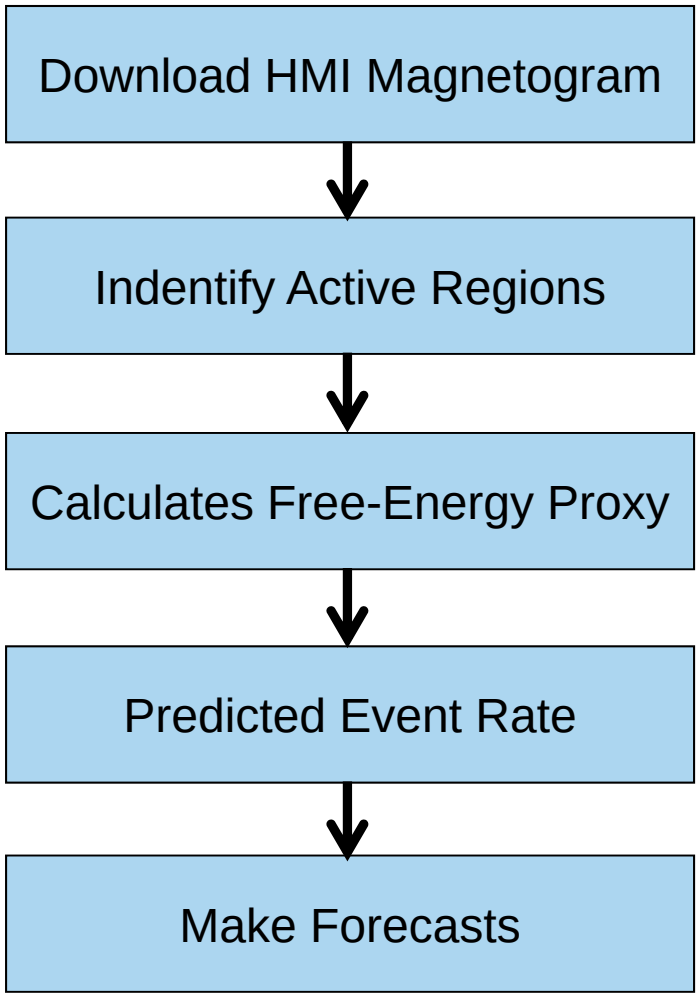
Currents ~10^{12} Amps



R2O Timeline of MAG4

- *1973* The MSFC (Marshall Space Flight Center) Vector Magnetograph was made to support Skylab.
- *2000-present* MSFC analyzed vector magnetograms to study CME correlation with free-energy proxy.
- *2007-12* Co-I in a Multidisciplinary University Research Initiative/Neutral Atmosphere Density Interdisciplinary Research
- *2008* Partnered with 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**.
- *2013* Transition to HMI line-of-sight to vector magnetograms.

Flowchart MAG4 Automated Processes

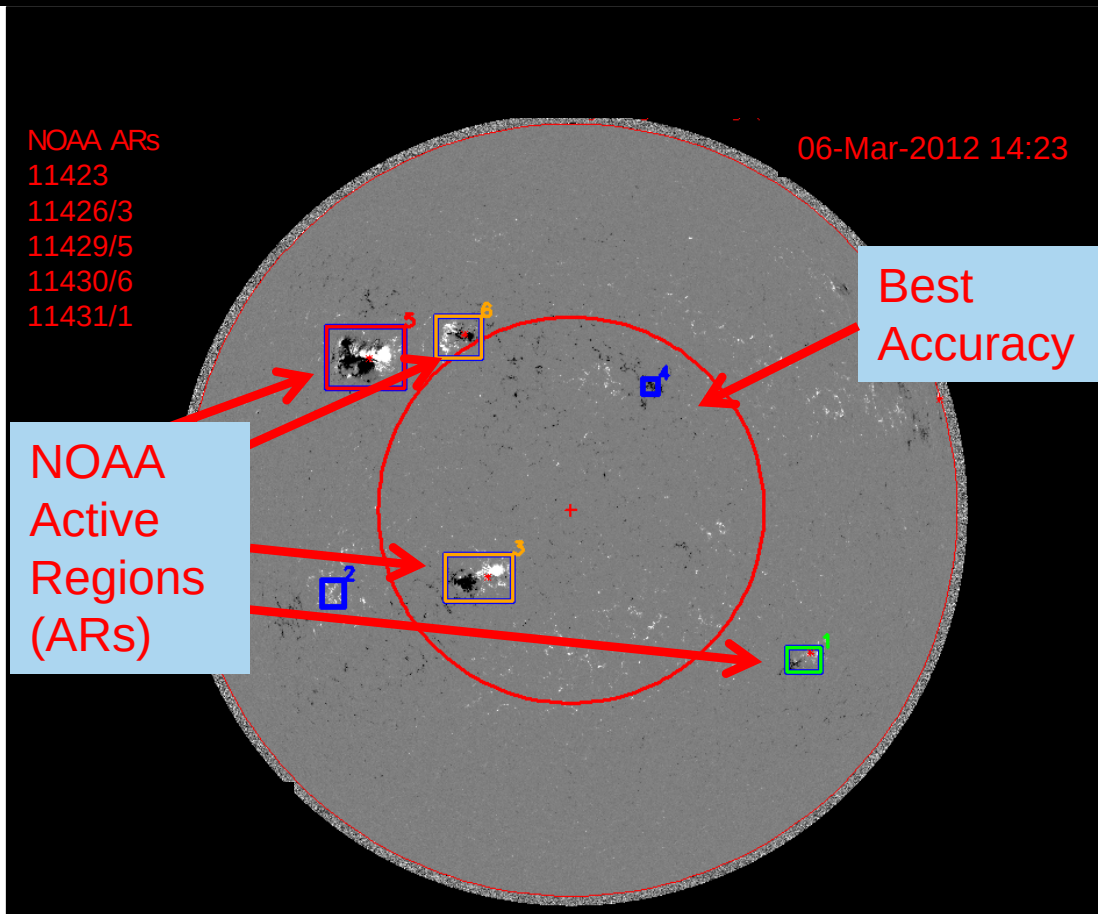


MAG4 is completely automated, from downloading magnetograms to outputting forecast products.

Process 1: Identifying Active Regions

- 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.

Introduce Magnetogram, indentify ARs.

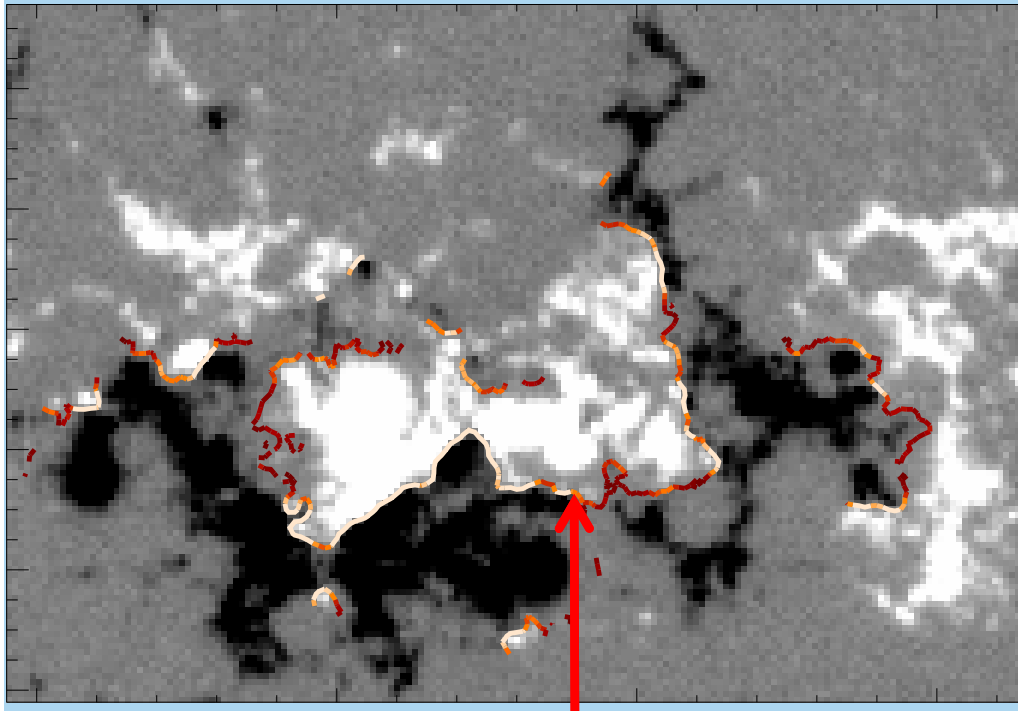


A full-disk line-of-sight magnetogram of the Sun, from SDO/HMI.

Process 2: Calculating the Free-Energy Proxy

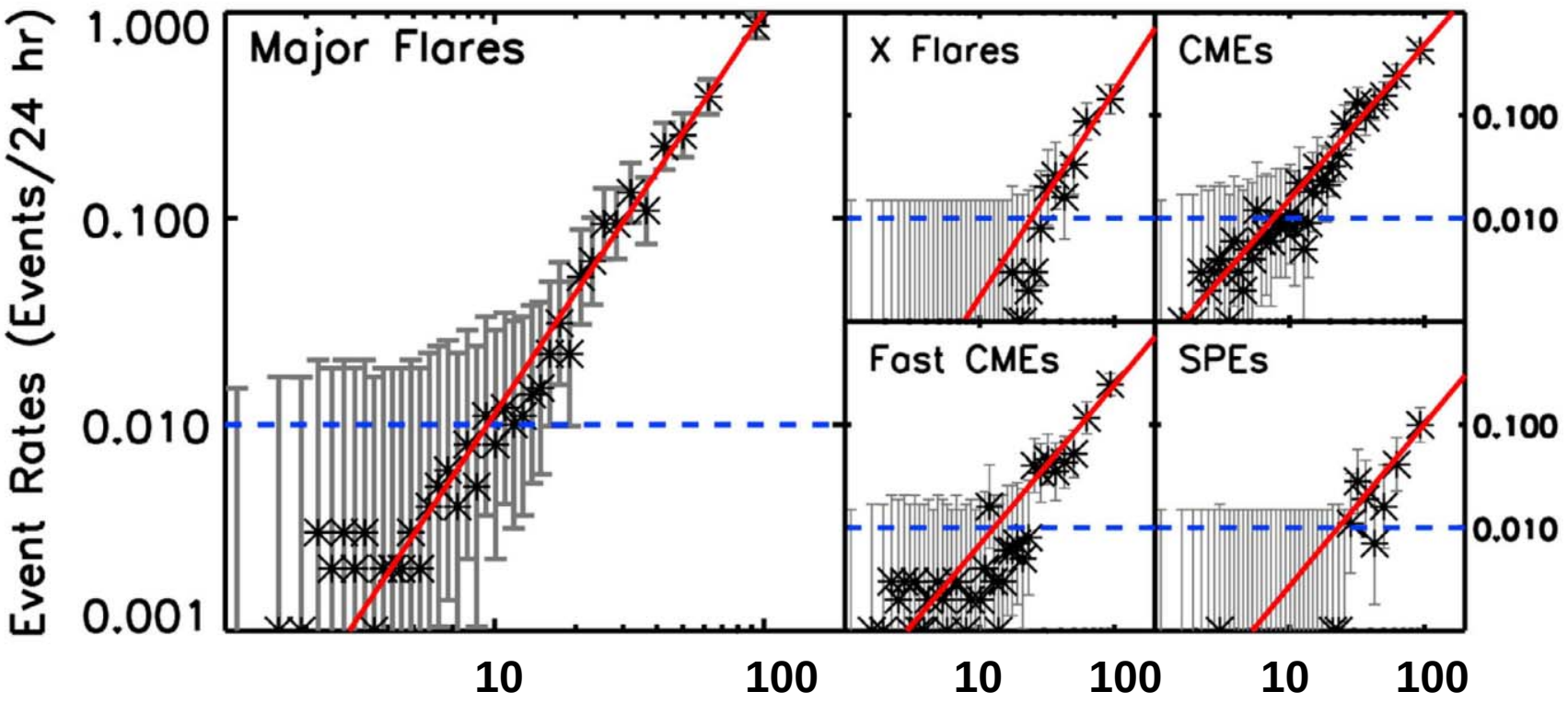
- Where the transverse gradient of the vertical (or line-of-sight) magnetic field is large, there is more free-energy stored in the magnetic field
- For **each Active Region**: The integral of the gradient along the neutral line is the free-energy proxy

A magnetogram of an active region



Neutral Line, color coded for gradient

Process 3: Converting Free-Energy Proxy to Predicted Event Rates



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.

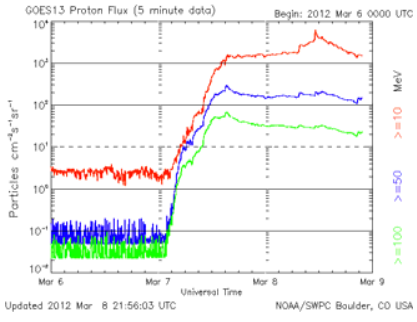
Process 4: Forecast

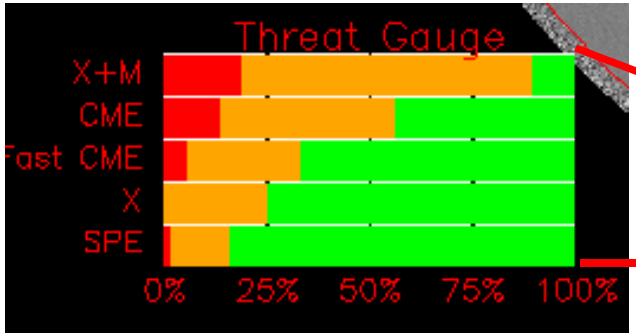
lots of layers on this page – not sure what you wanted showing

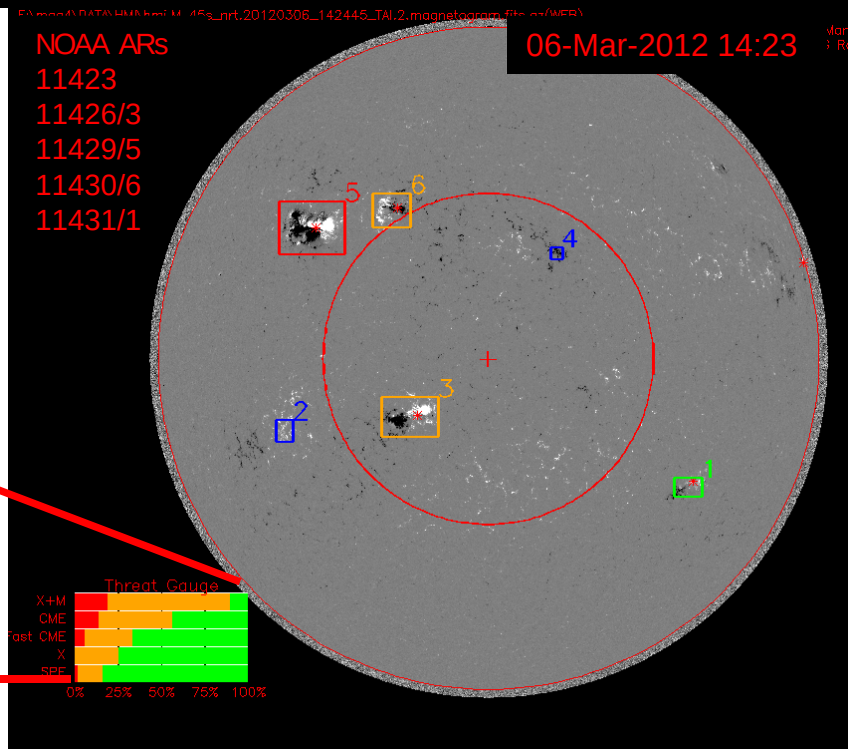
Multiplicative uncertainty example

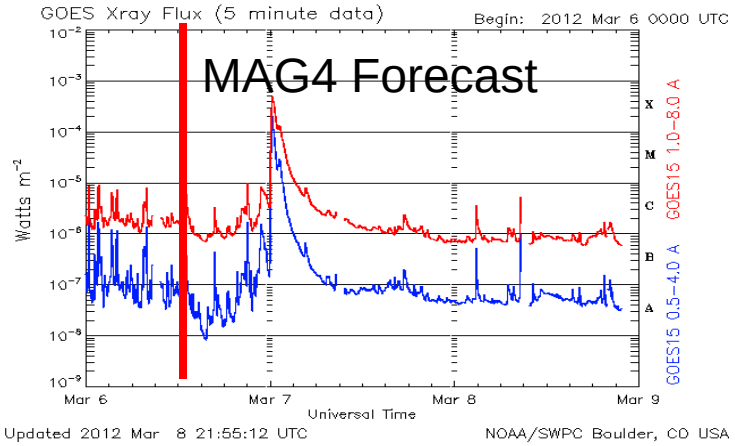
Rate	1 sigma	Probability
Events/day	66% Confidence	
0.02	0.01-0.05	0.7-5%
0.7	0.3-1.9	20-80%

For a Multiplicative Uncertainty of 2.7x









2012/03/06 14:23

#	AR#	WL!DSG!N	Lng (kG)	Lat (deg)	24 Hour Event Rate M&X	CME	FCME	X	SPE	Dist (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%	

Comparison of Safe and Not Safe Days

June 26, 2013

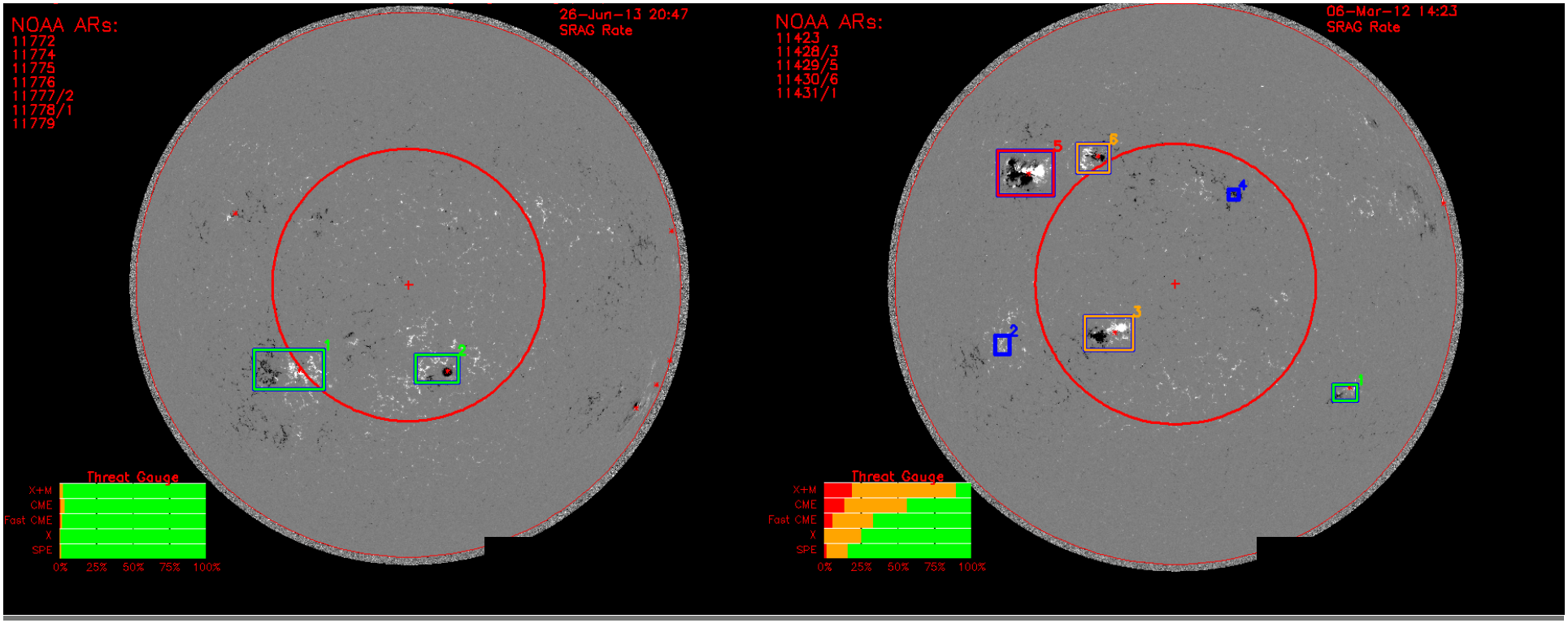
C1, C1.5 flares

March 7, 2012

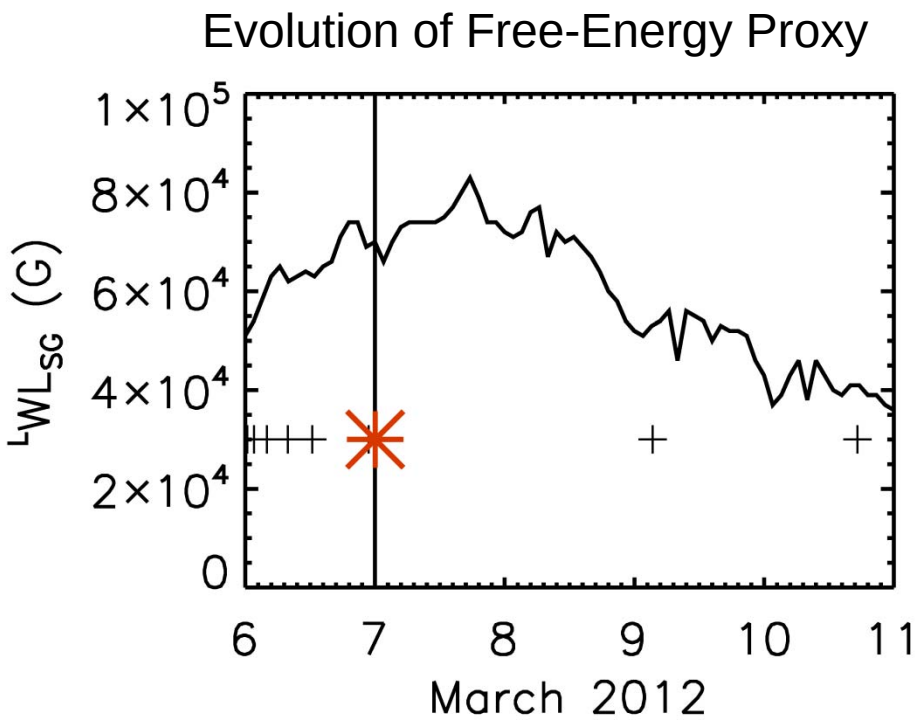
X5.4, X1.3, C1.6

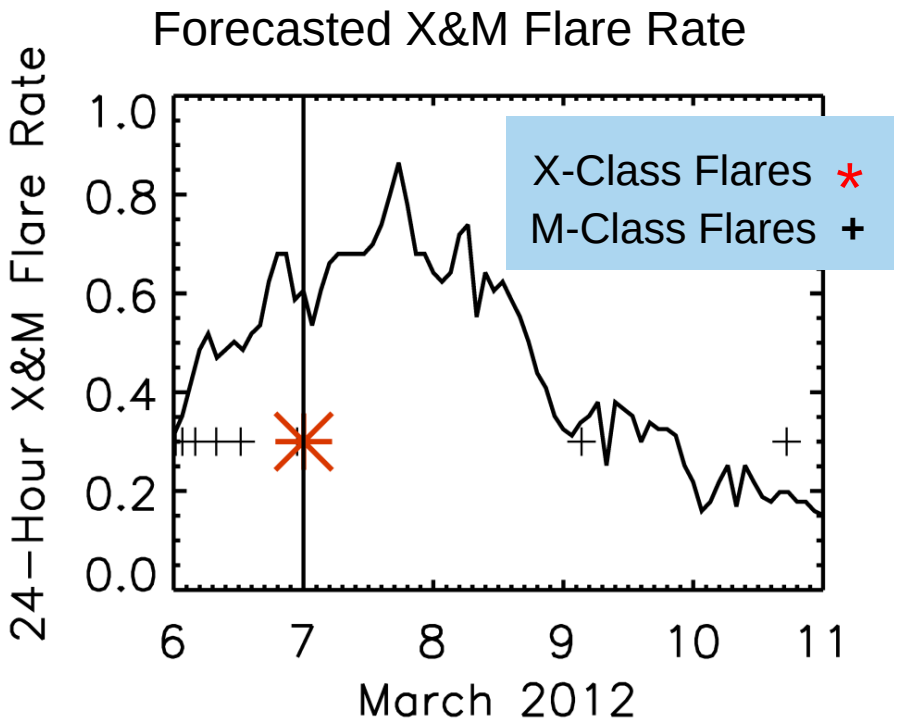
CME 2684, 1825 km/sec,

Solar Energetic Proton Event reaches 6530 particle flux unit >10MeV



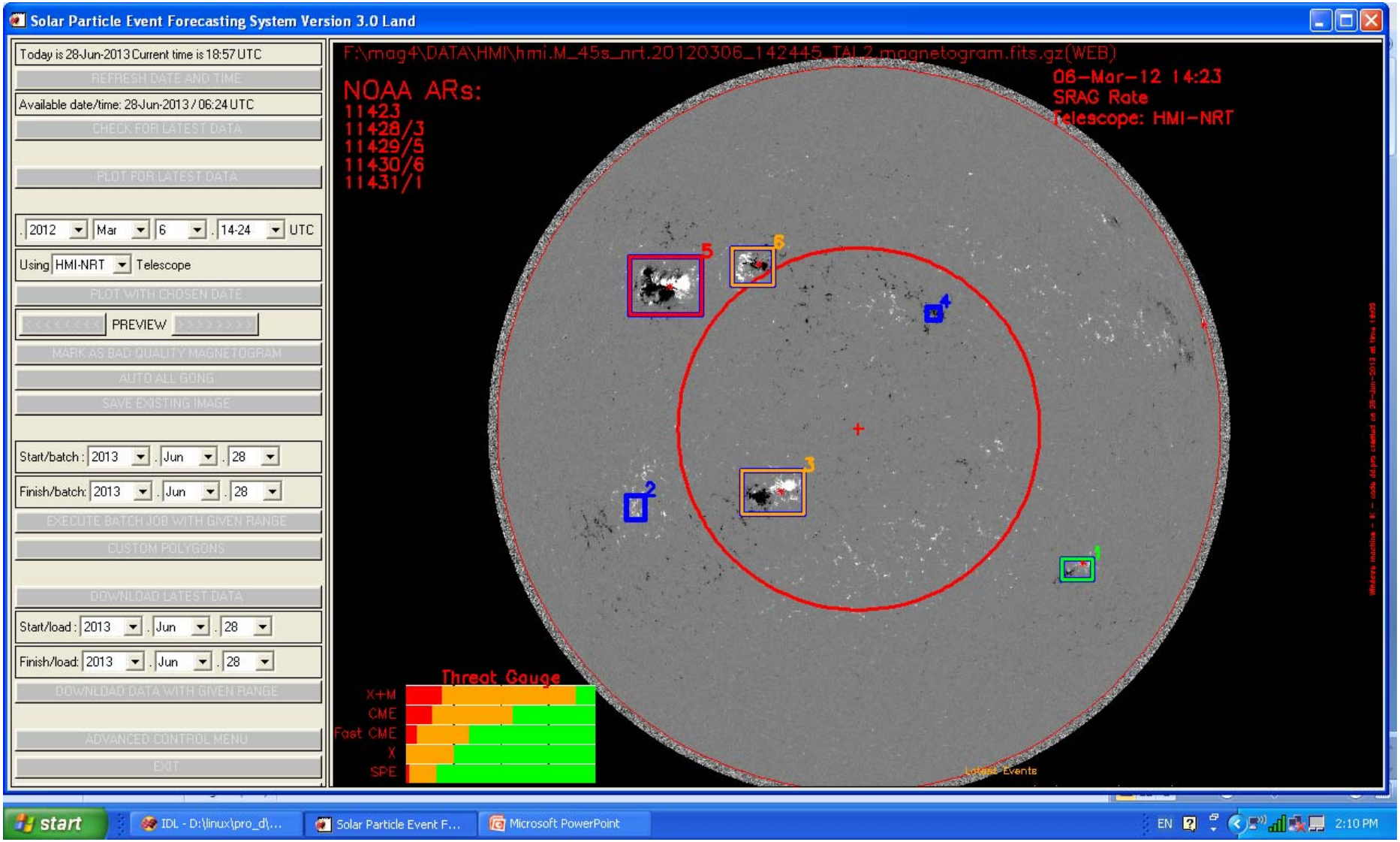
How Free Energy Proxy Evolves





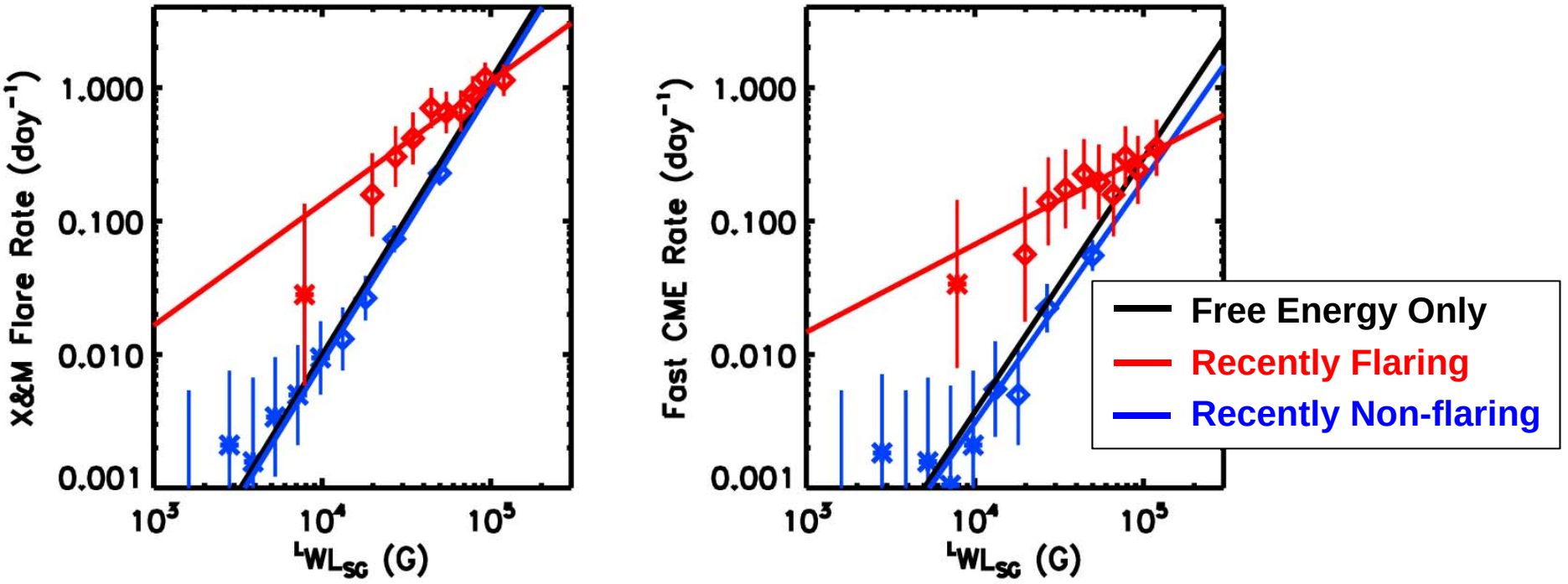
The Free-Energy Proxy evolves on time periods of days, and the forecast is on those time scales.

Operation of MAG4



Improving the Forecasts:

1. Recent Flare History (In Progress)

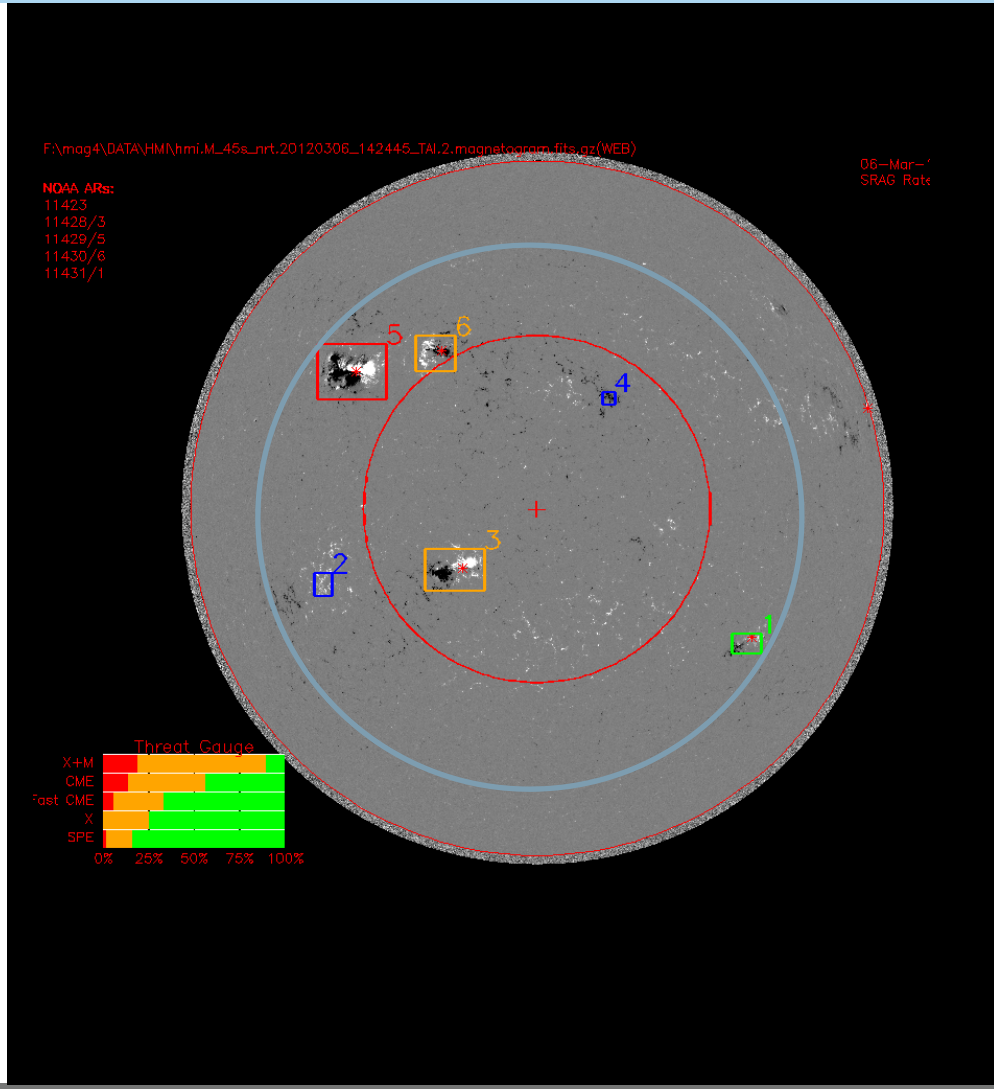


Active regions that have recently produced an X- or M-Class flare are more likely to produce flares in the near future

Improving the Forecasts:

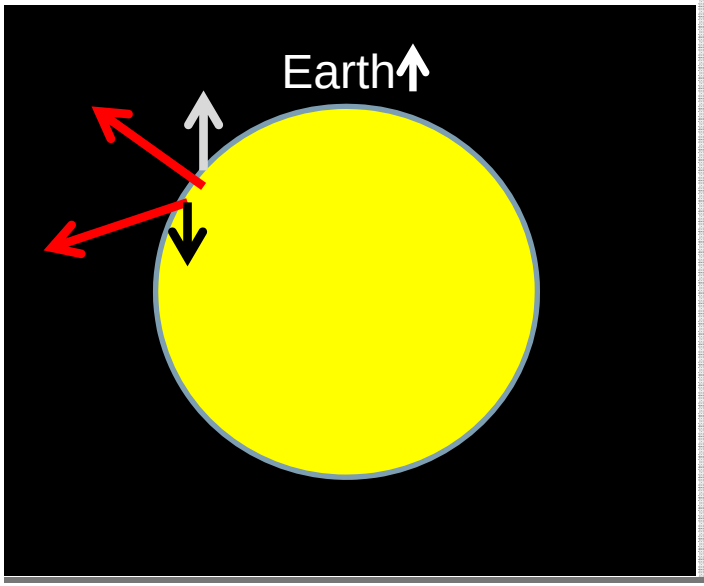
2. Vector Magnetograms (In Progress)

- MAG4 presently uses SDO/HMI line-of-sight magnetograms
- Near-real-time Ambiguity-Resolved SDO/HMI vector-magnetograms have recently become available
- We are transitioning to using these new data from SDO
- Implementation just started



MAG4 Improvements: Vector Magnetograms

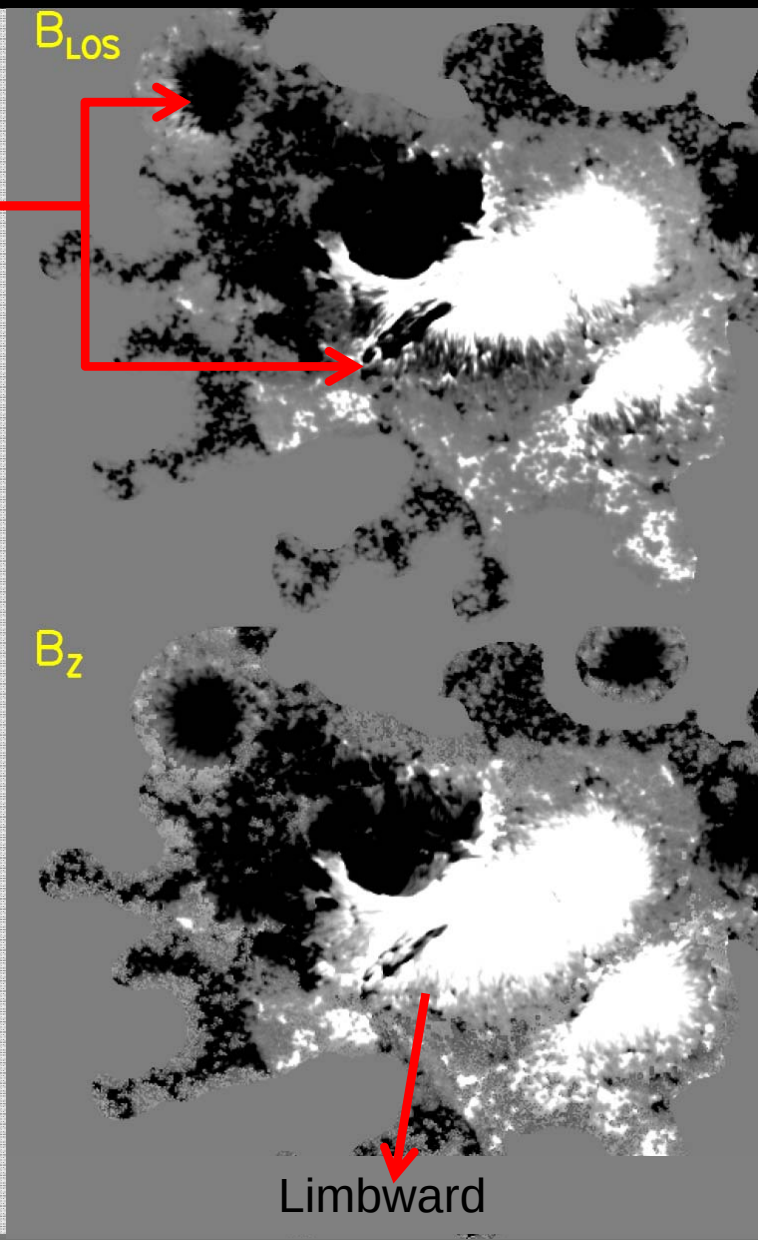
- Both vectors shown in red have positive B_z (magnetic field out of the sun), but have opposite sign B_{LOS} and thus a false (unphysical) neutral line in the line-of-sight (LOS) field.



Actual Examples

False Neutral Lines occur on limbward sides of sunspots.

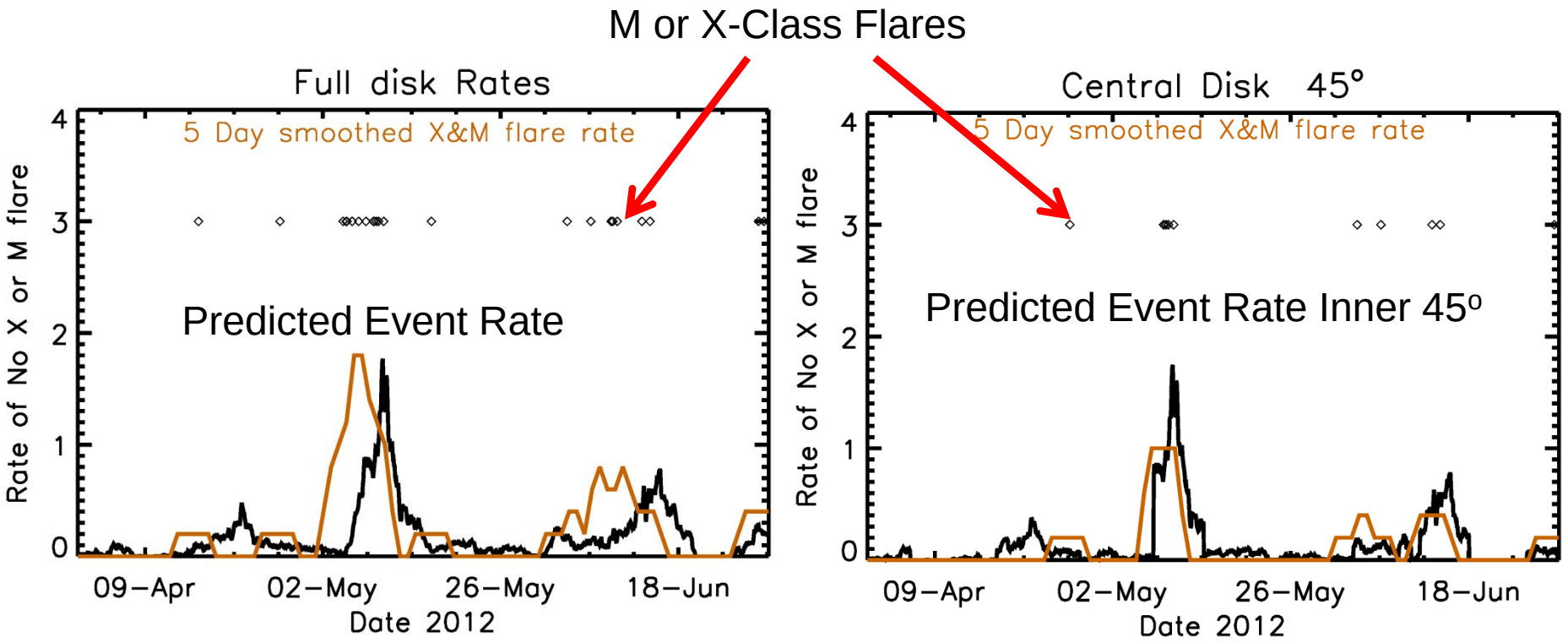
Problem fixed by converting from B_{LOS} and $B_{Transverse}$ to B_Z and $B_{Horizontal}$



How Well Does MAG4 Forecast:

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)



How Well Does MAG4 Forecast:

2. Skill Metrics

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

PC	Percent Correct
POD	Probability of Detection
FAR	False Alarm Rate
HSS	Heidke Skill Score
TSS	True Skill Score

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 **Present MAG4**	273	284	618	18830	95.5	0.31	0.50	0.35	0.47
Free-energy proxy and previous flare activity **Upgraded MAG4**	340	317	551	18797	**95.7**	**0.38**	**0.48**	**0.42**	**0.49**
Best	890	0	0	19114	100	1	0	1	1

Suggested Collaboration Tasks with AFWA

- Customizing MAG4 to AFWA needs
- Further development of MAG4
  - R2O: use time series, Heliosphere propagation of CME, Helioseimology, Improve forecasts as with flare history
  - Operational Tool: Robustness, usability, interface
- Independent Verification Tests

Backup Slides

How Well Does MAG4 Forecast:

2. Skill Metrics Equations

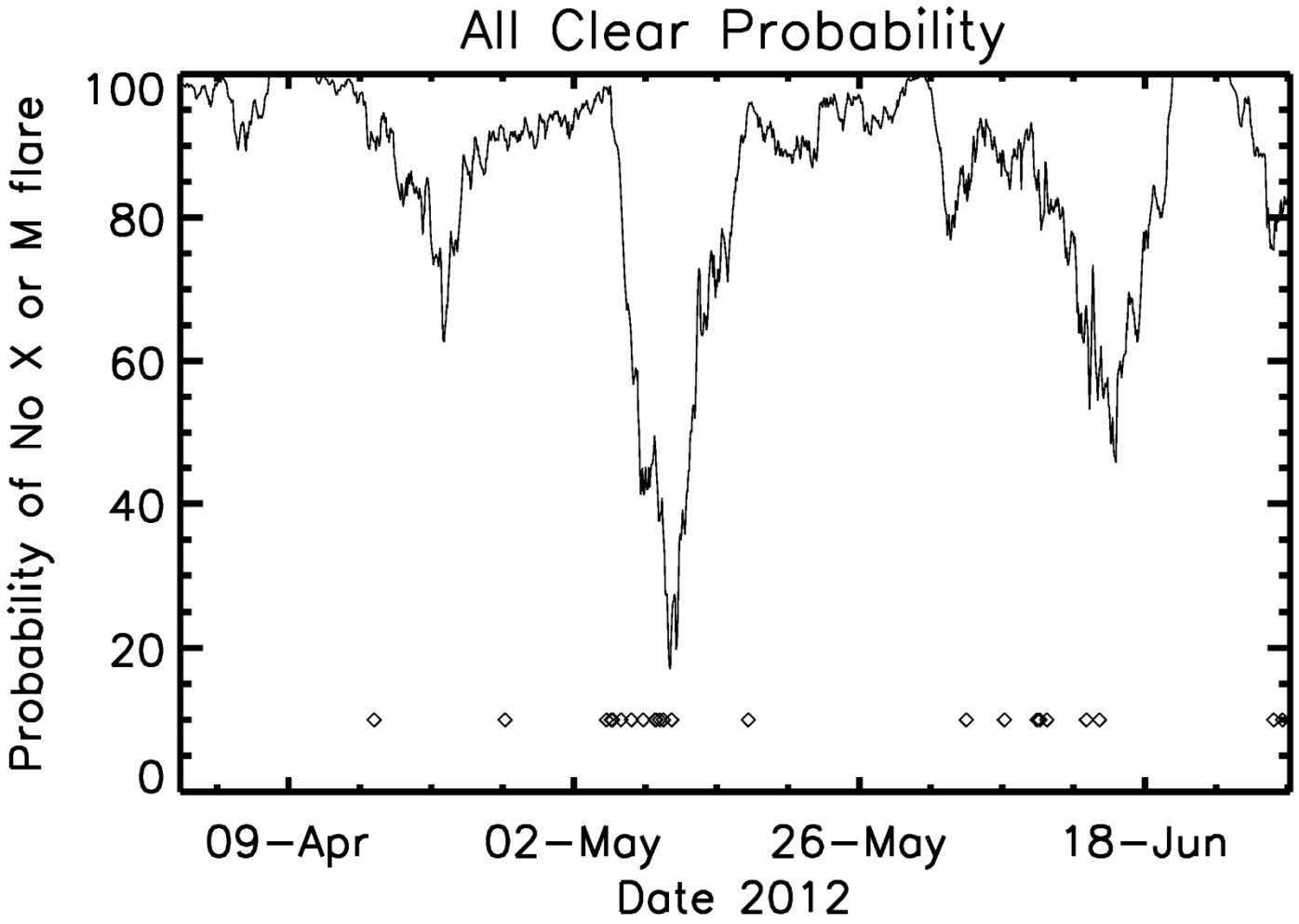
	Actual Yes	Actual No
Predict Yes	YY	YN
Predict No	NY	NN

Metric Equations

Percent Correct	PC=(YY+NN)/(YY+YN+NY+YY)
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))

How well it works (All-Clear)

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



Times of X or M Flares