Forecasting Solar Flare Events: A Critical Review

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Acknowledging funding from AFOSR, NASA, and NOAA.

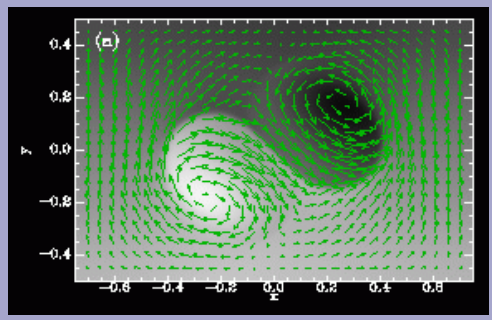
Why Important?

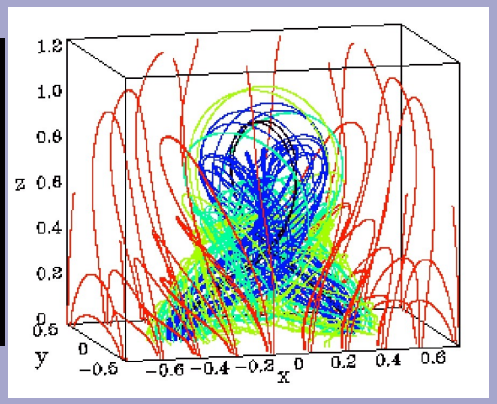
- **Time-of-flight = c**
  - **Space Assets (including humans)**
  - **High-Altitude radiation exposure**
- **Ionospheric/Stratospheric effects: few minutes.**
  - **Communications/Time/Location**
- **Geomagnetic impacts**
  - **Association with CMEs/SEPs**
- **Science/Physics/Mathematics/Computer Science**
  - **Basic physics (best test of understanding)**
  - **Statistical methods of forecasting rare events.**

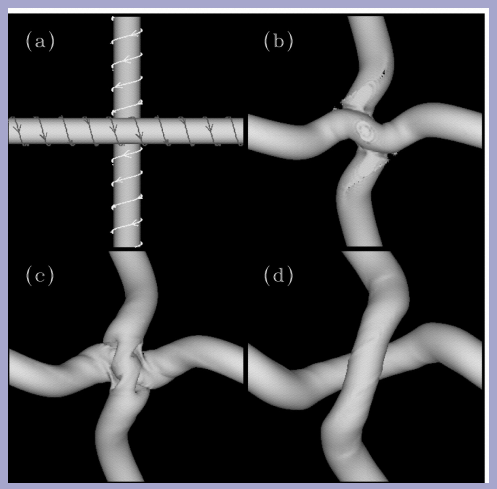
“So a numerical modeler and a flare forecaster walk into a bar and ask...how do I get to a solar flare?”

Modeler's view:

Fan & Gibson 2003, 2004

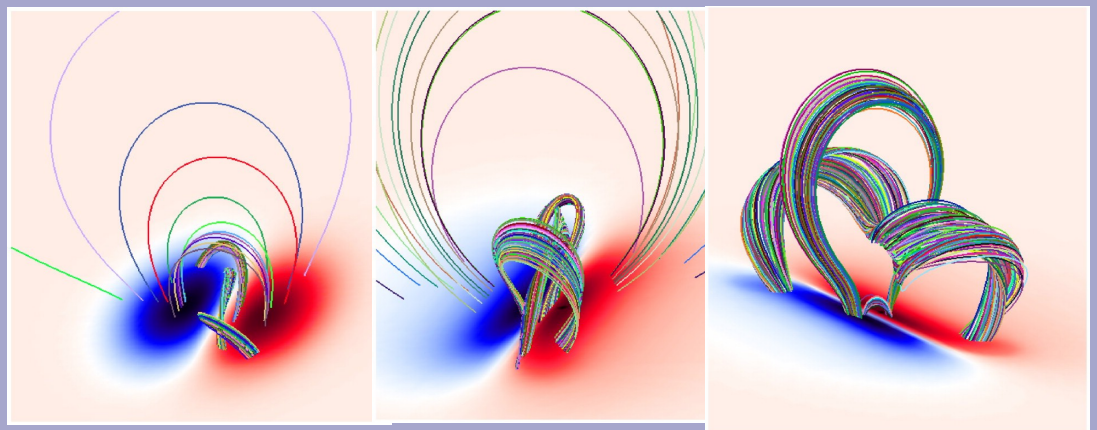




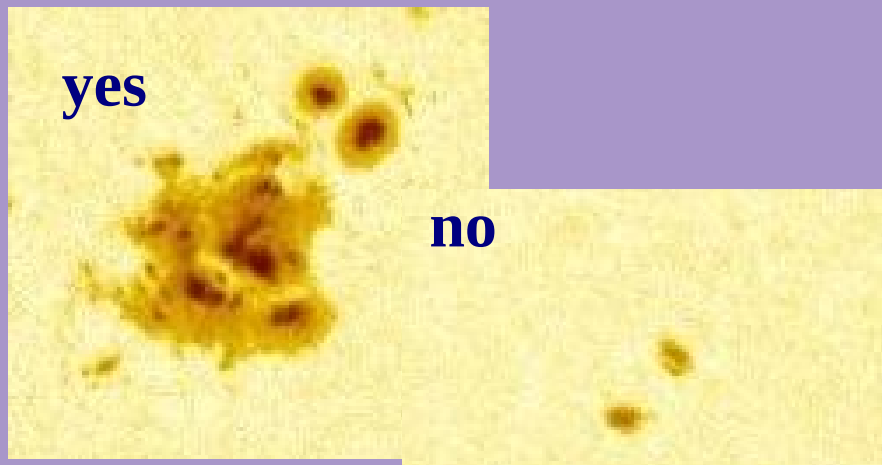


Linton & Antiochos 2002

Amari, Luciani, Aly, Mikic & Linker 2003



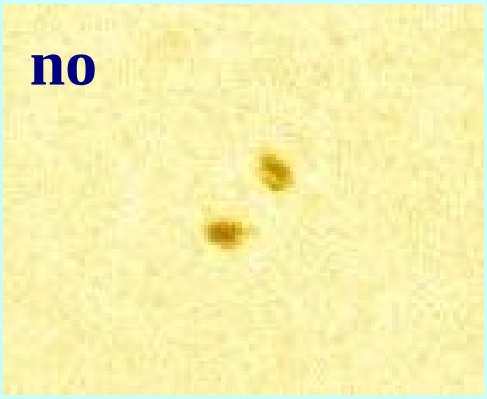
Forecaster's view:

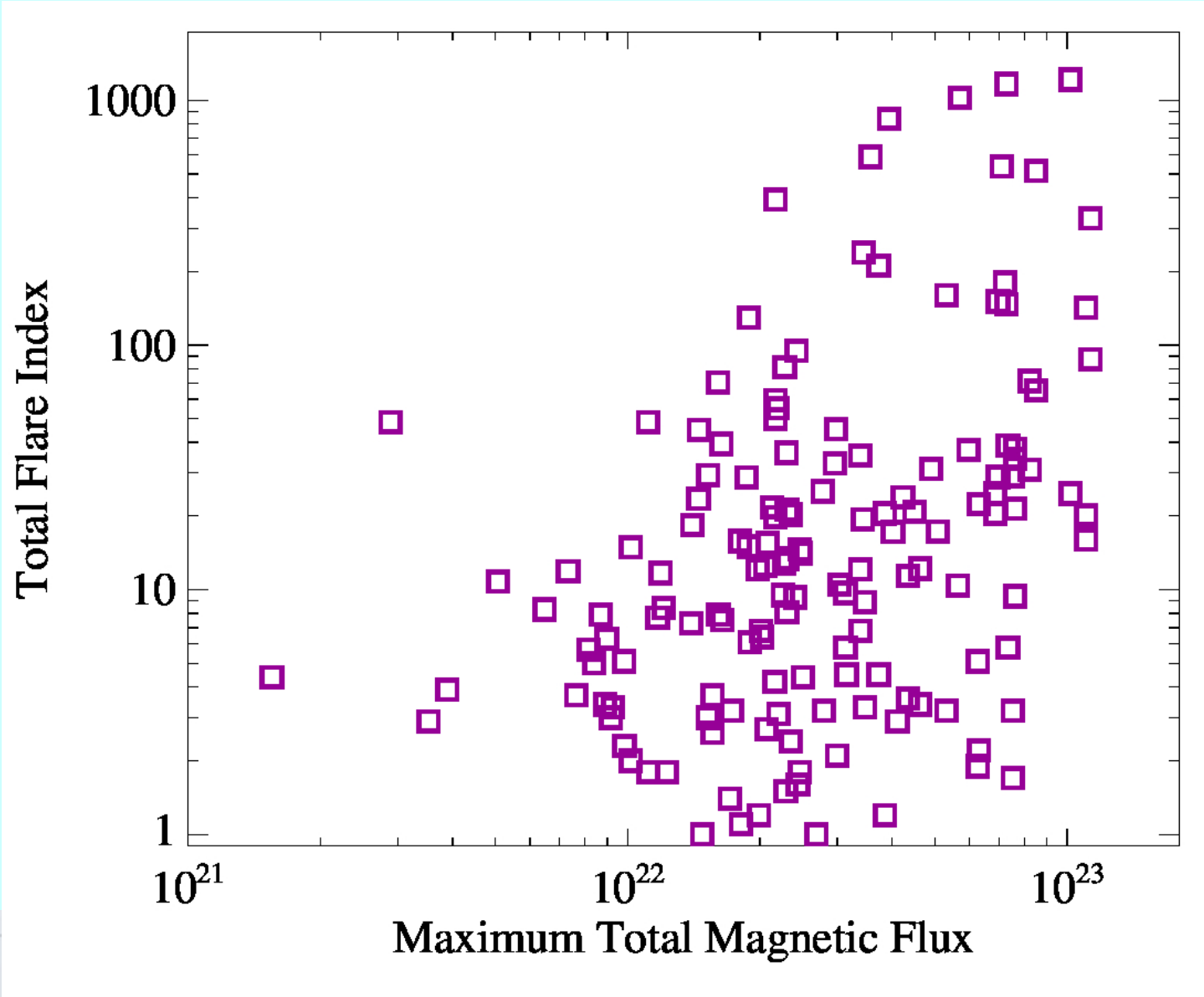


Why this is hard, I: *we do not understand the physics.*

"Causes of Flares":

- Larg(er) active regions are more flare productive.
- More magnetic energy $B^2/8\pi$





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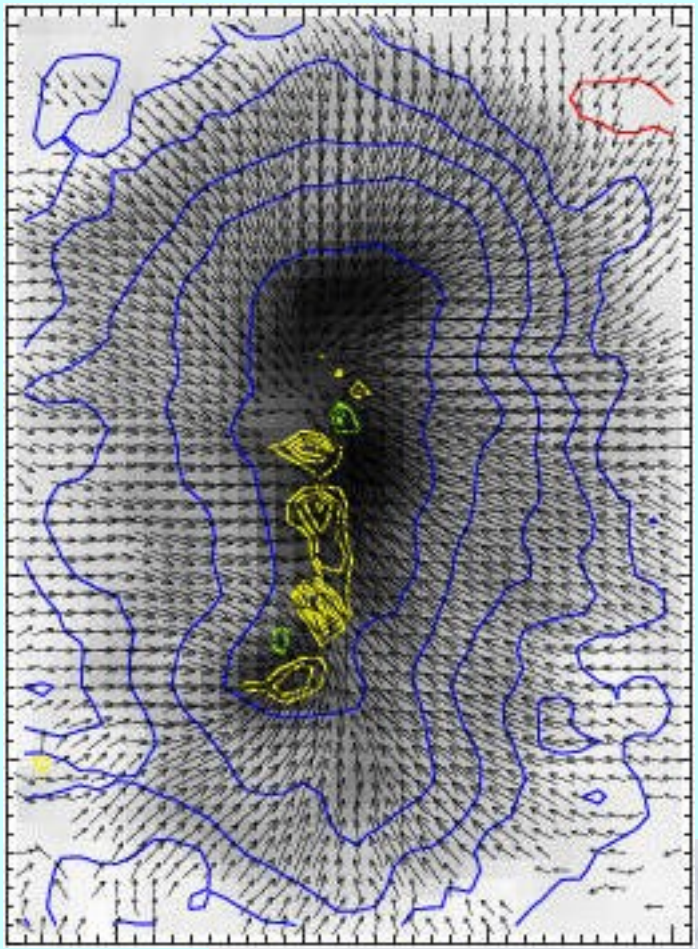
“Causes of Flares”:

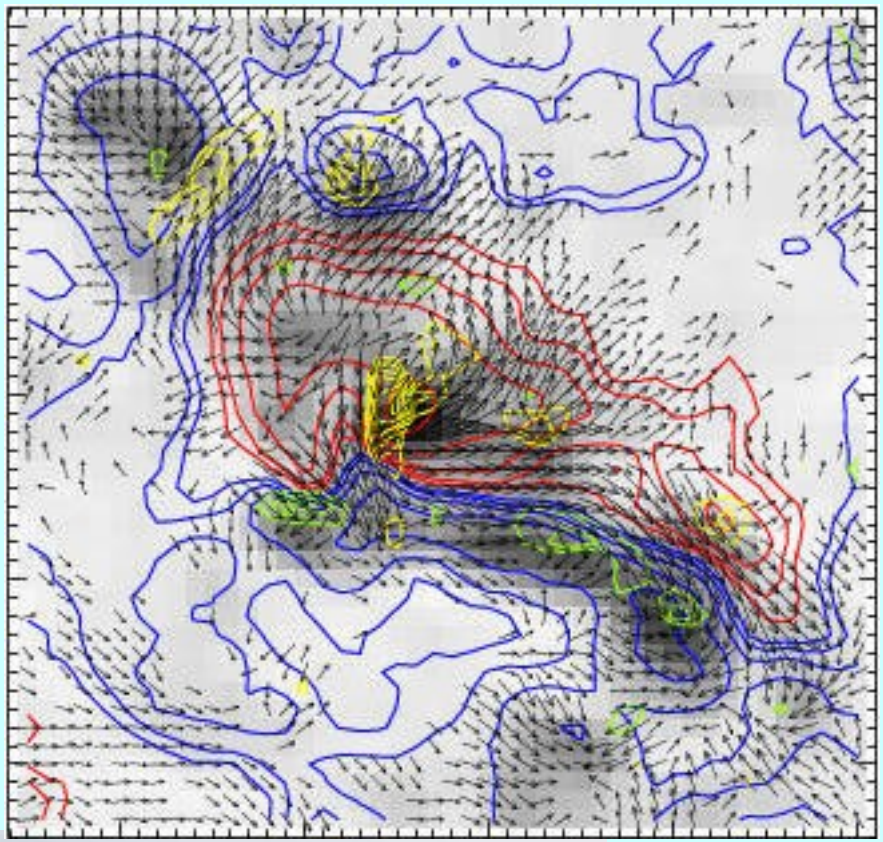
- Non-potential, complex, active-region magnetic fields.
- Indicates significant “free magnetic energy” is available.

Photospheric Magnetic Field examples:

potential/simple



non-potential/sheared/complex



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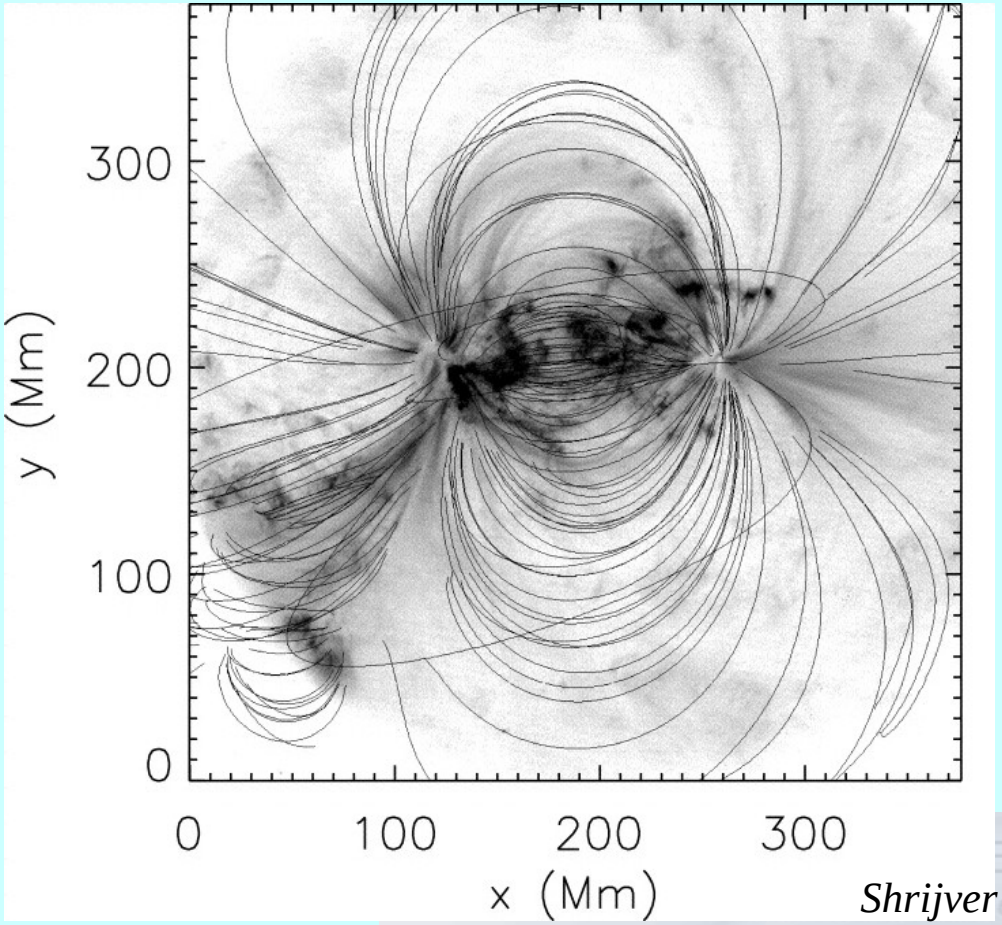
“Causes of Flares”:

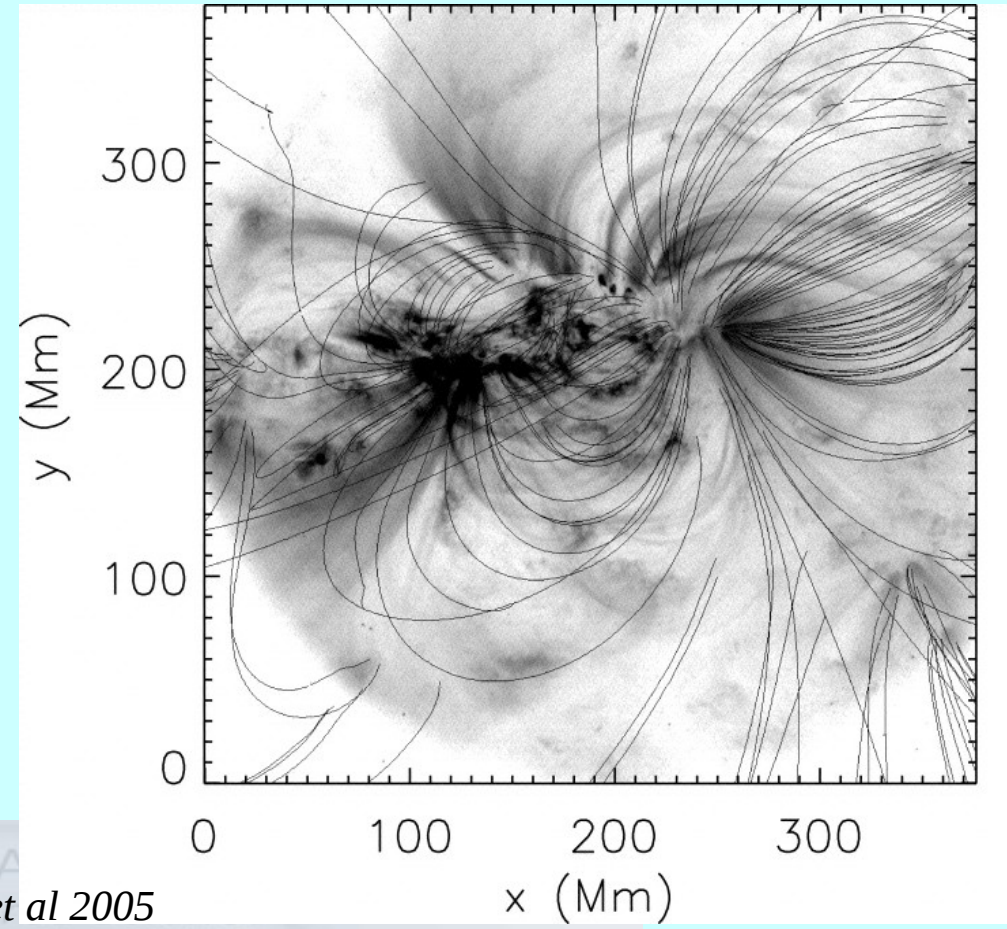
- **Non-potential, complex, active-region magnetic fields.**
- **Indicates significant “free magnetic energy” is available.**

Coronal Loops vs. Potential Extrapolations:

potential/simple

non-potential/sheared/complex





Shrijver et al 2005

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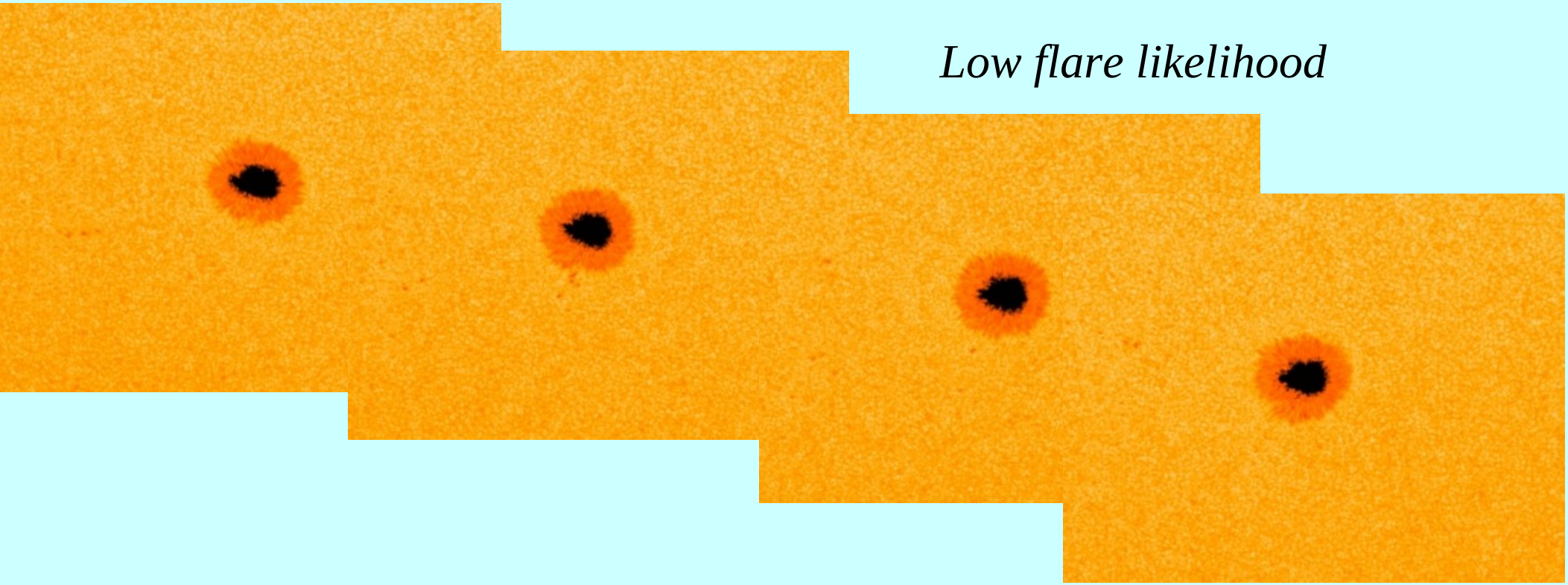
"Causes of Flares":
• Rapidly evolving.



Low flare likelihood

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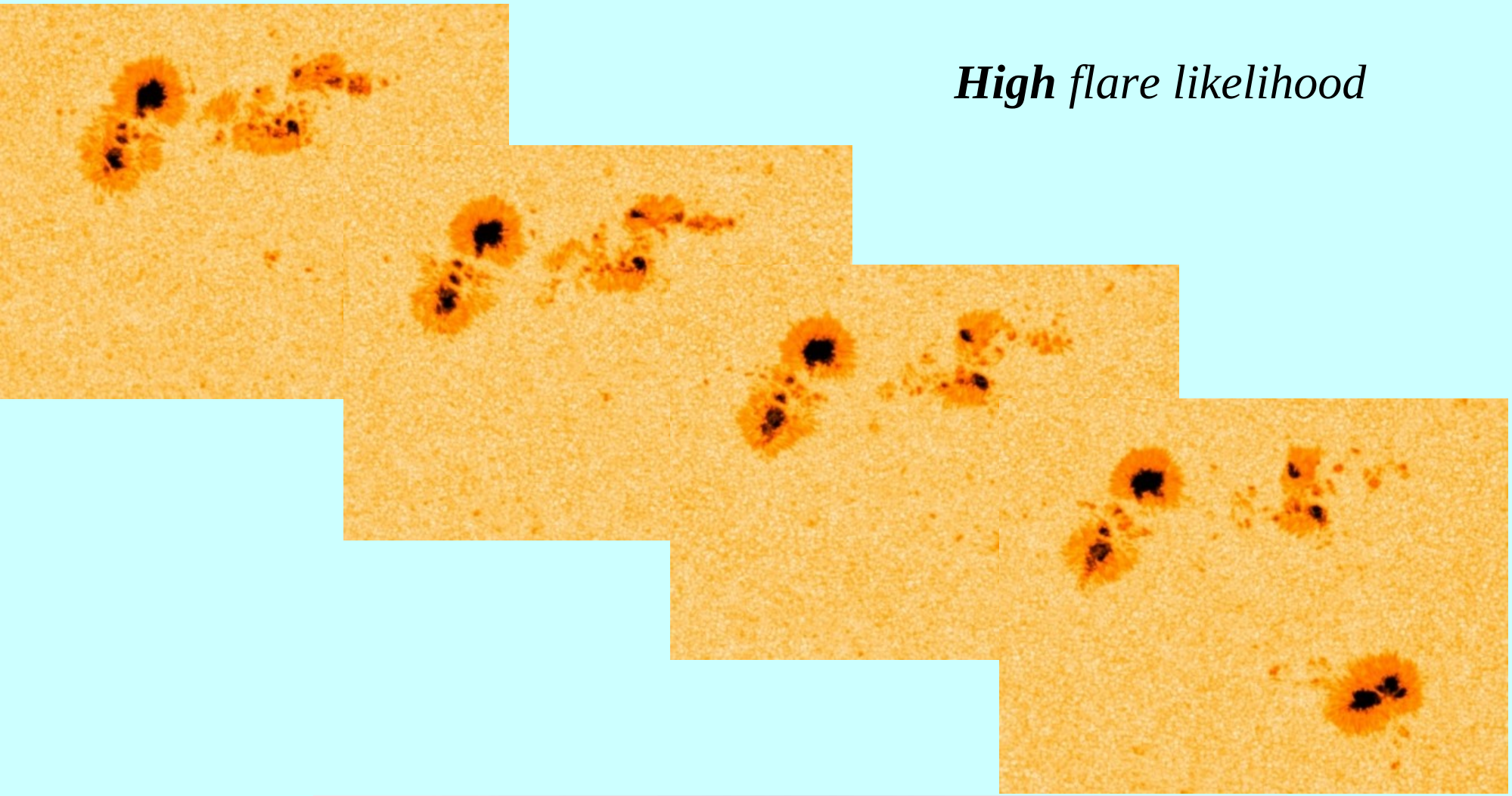

***High** flare likelihood*

Why this is hard, I: *we do not understand the physics.*

To flare, an active region must be “Big, Bad, and Angry”

..... But what is the trigger?

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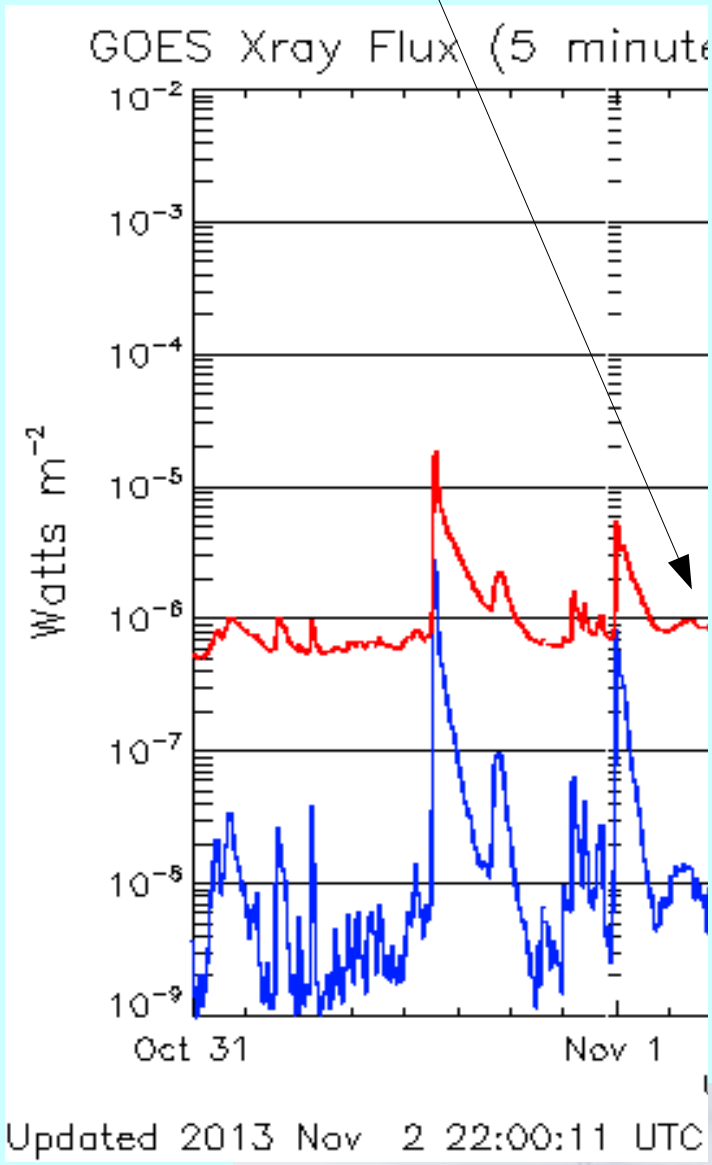
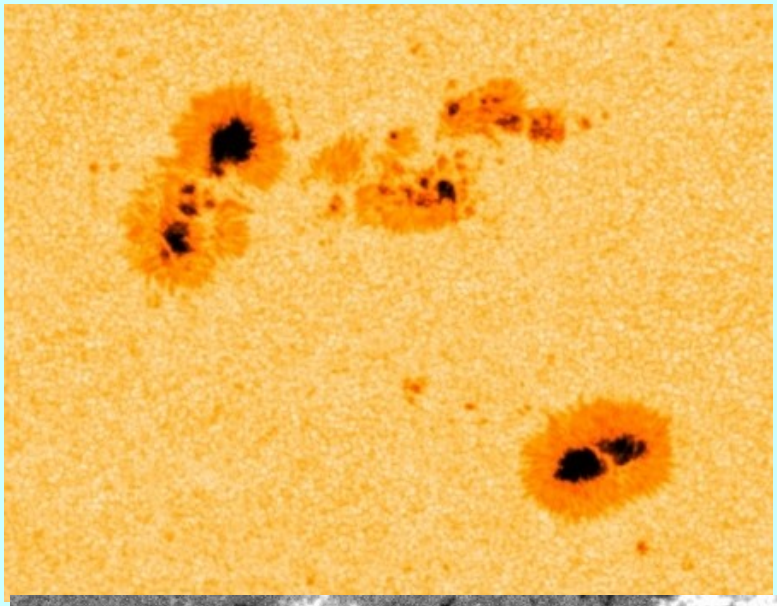
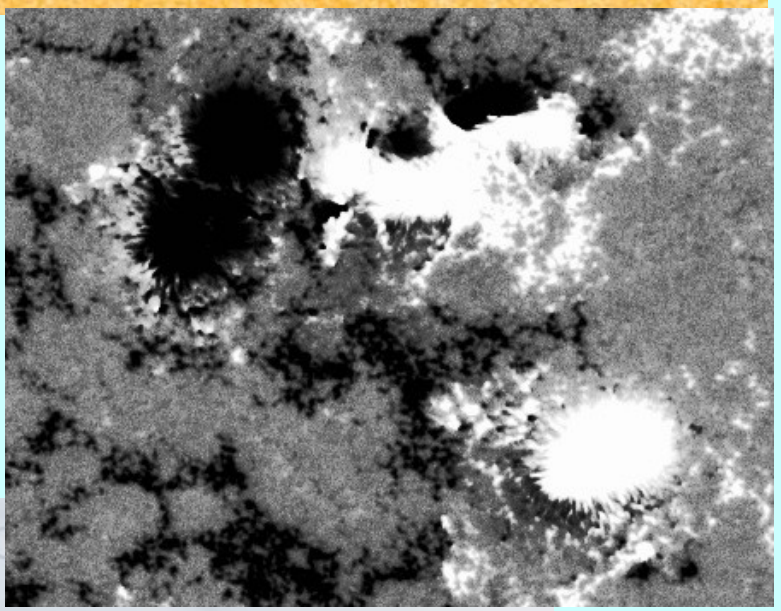
Why *not* now ....







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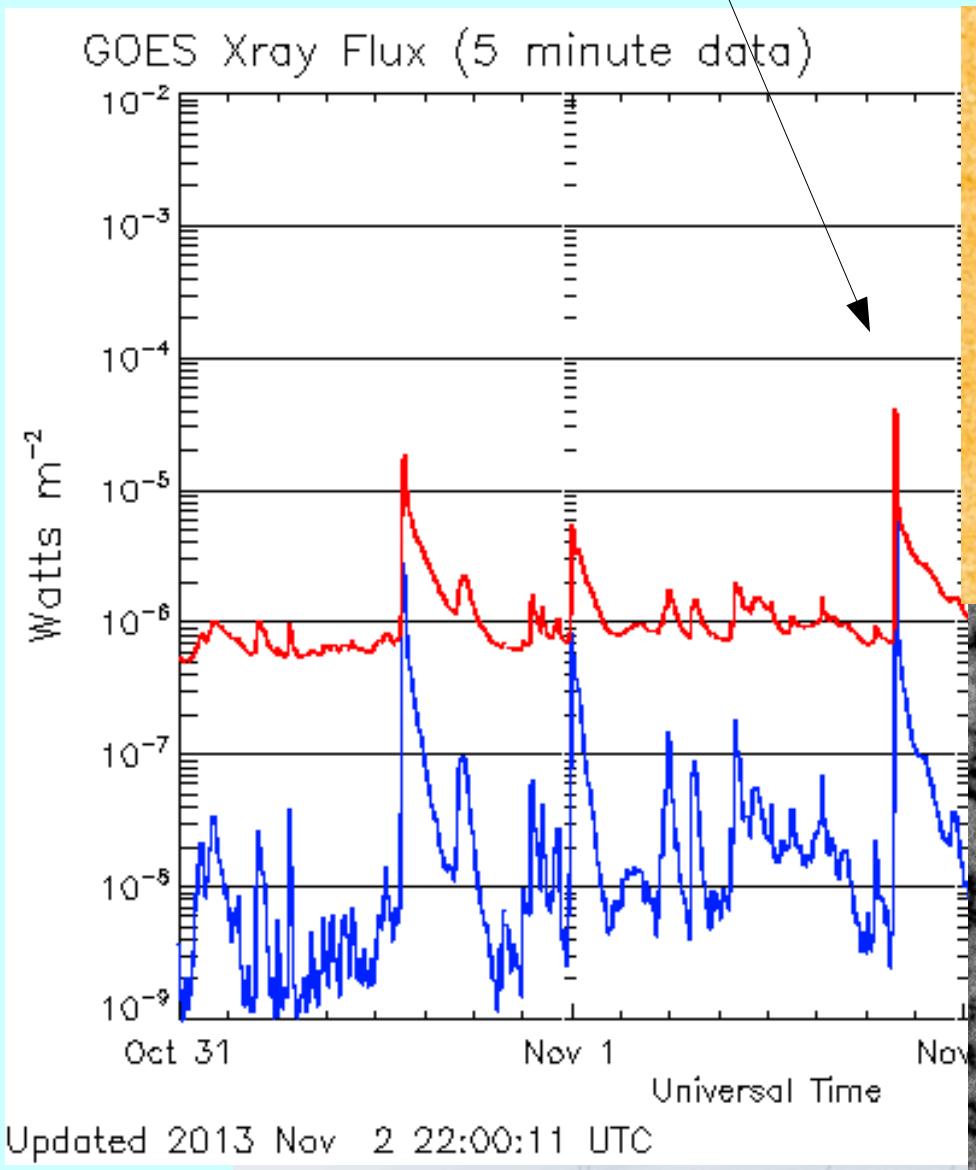
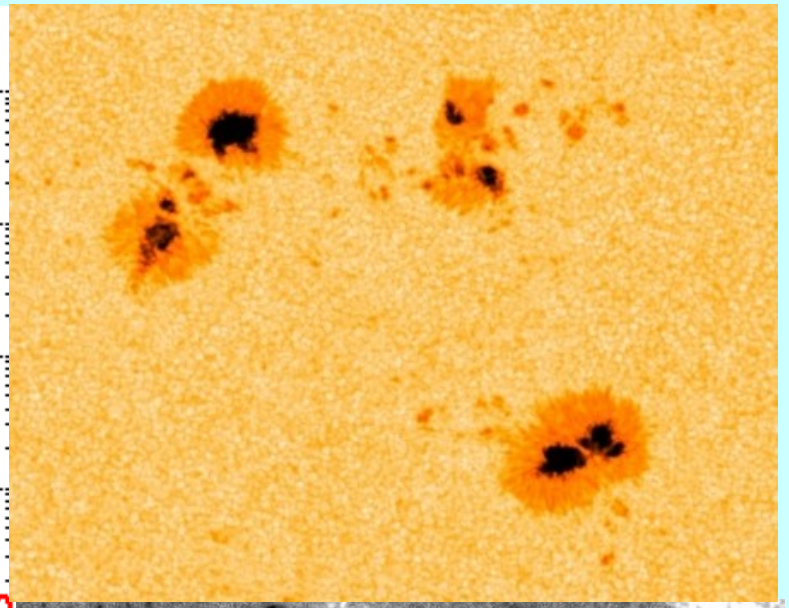
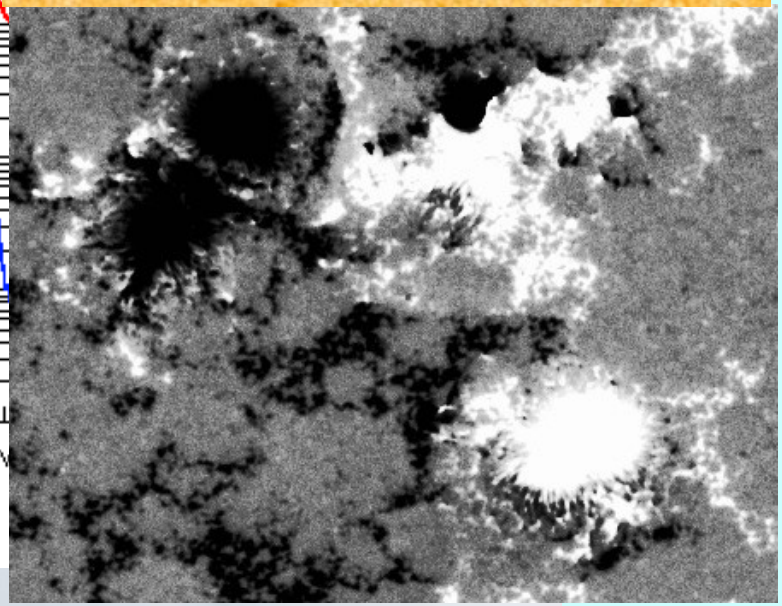
Why *not* now .....but now??







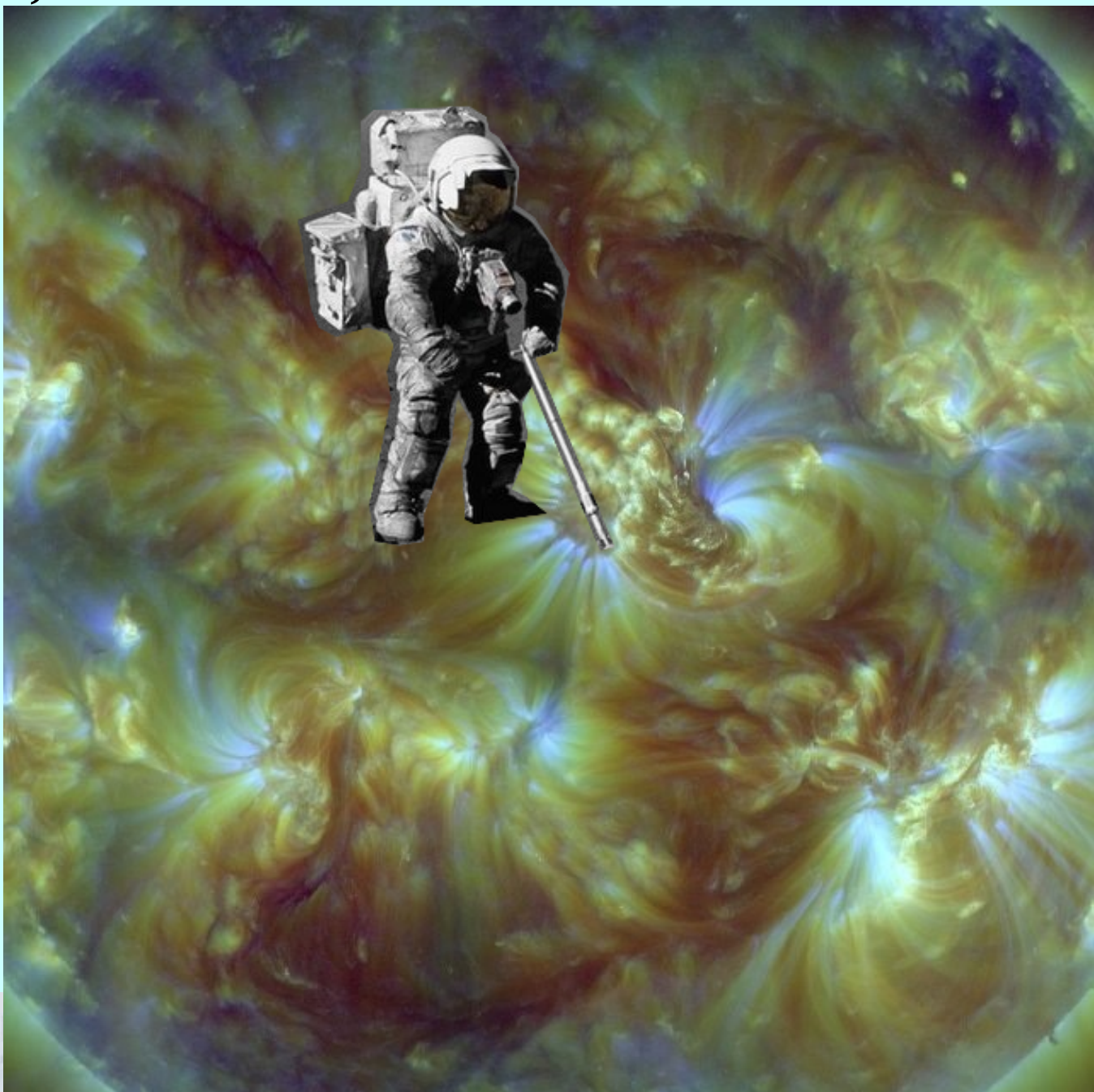
Why this is hard, II: *remote sensing*.

Unlike Terrestrial Weather,

Why this is hard, II: *remote sensing*.

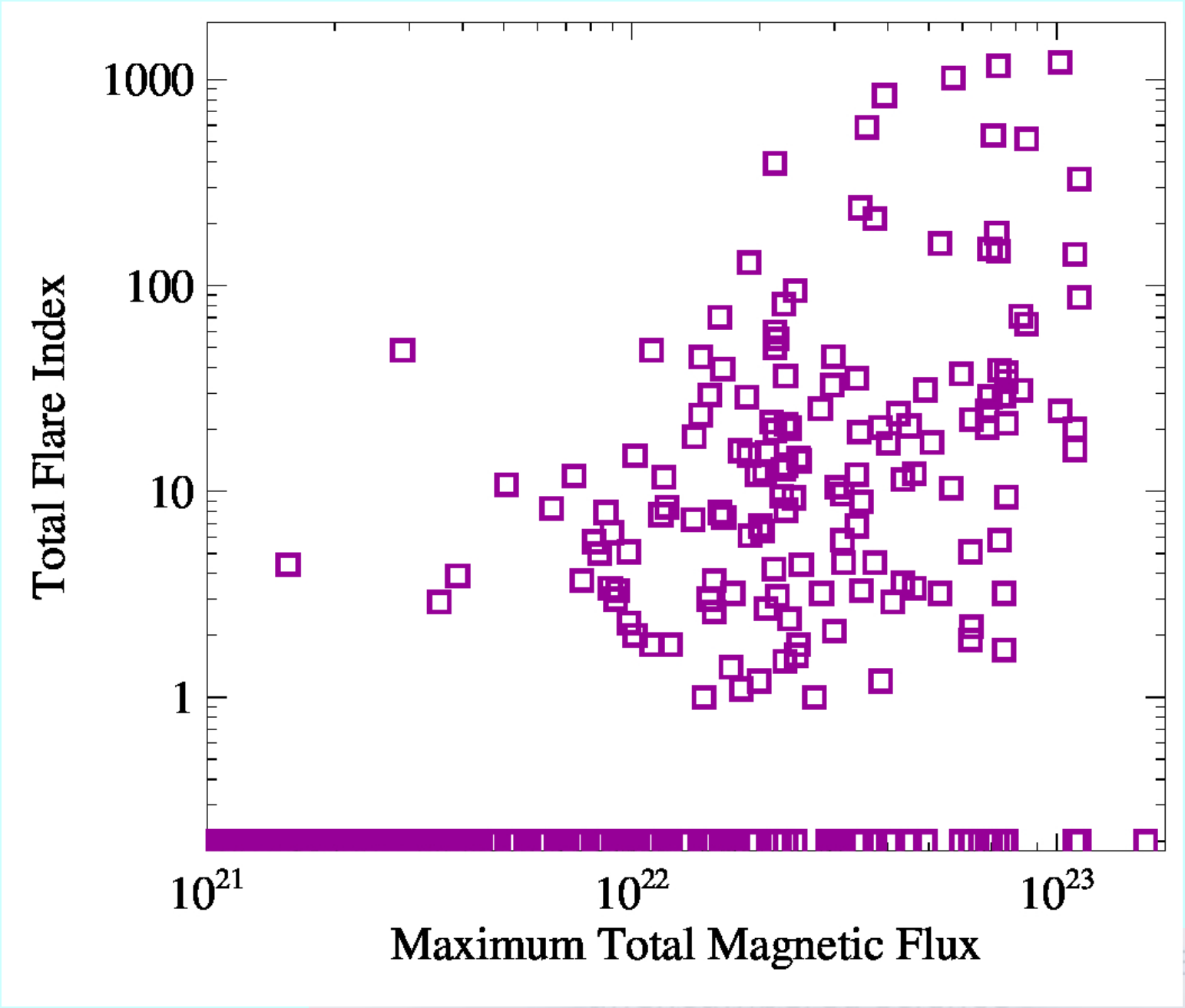
Unlike Terrestrial Weather, we will never* get *regular* in-situ measurements from the Sun.

This means *all* of our measurements (of field, temperature, density, velocities) are *indirect*.



**I think I'm fairly safe saying "never" here.*

Why this is hard, III: *Flaring and Flare-Quiet regions can be very similar, at any given moment.*



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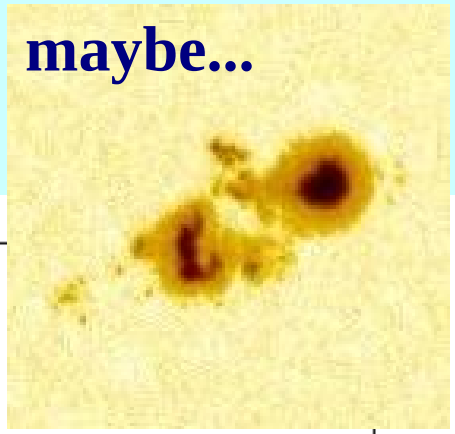
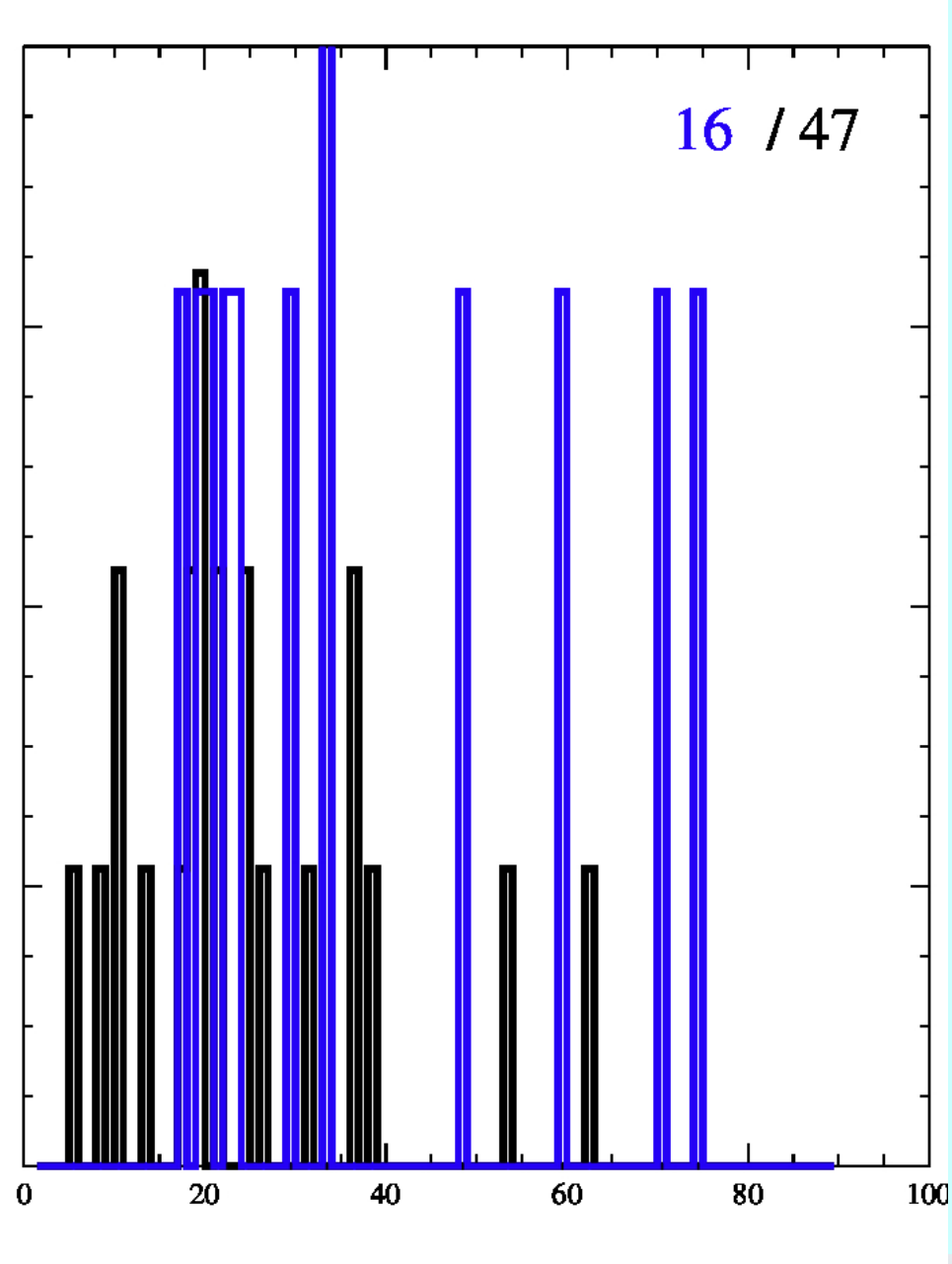


Why this is hard, IV: *Yet these are rare events.*



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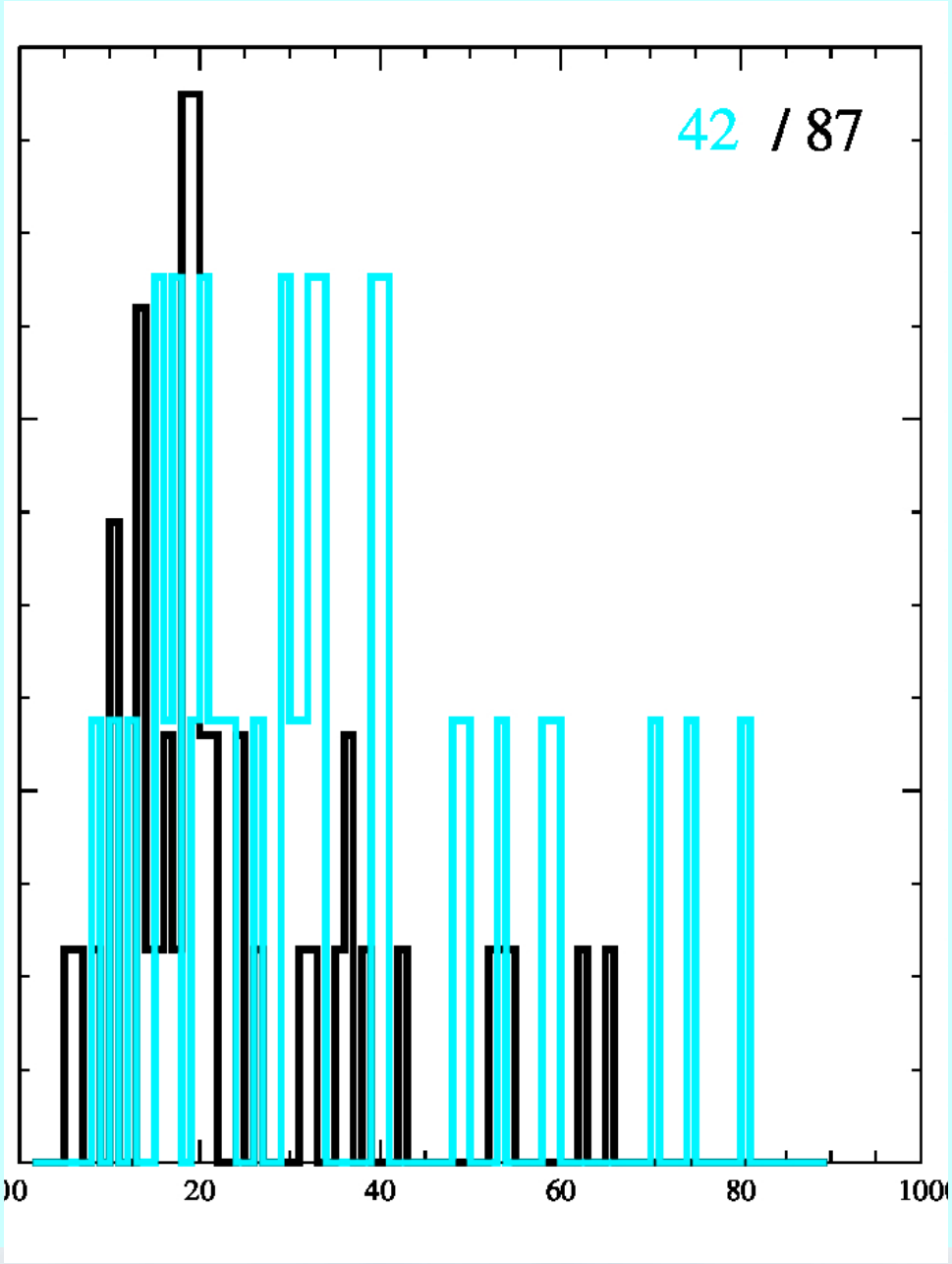

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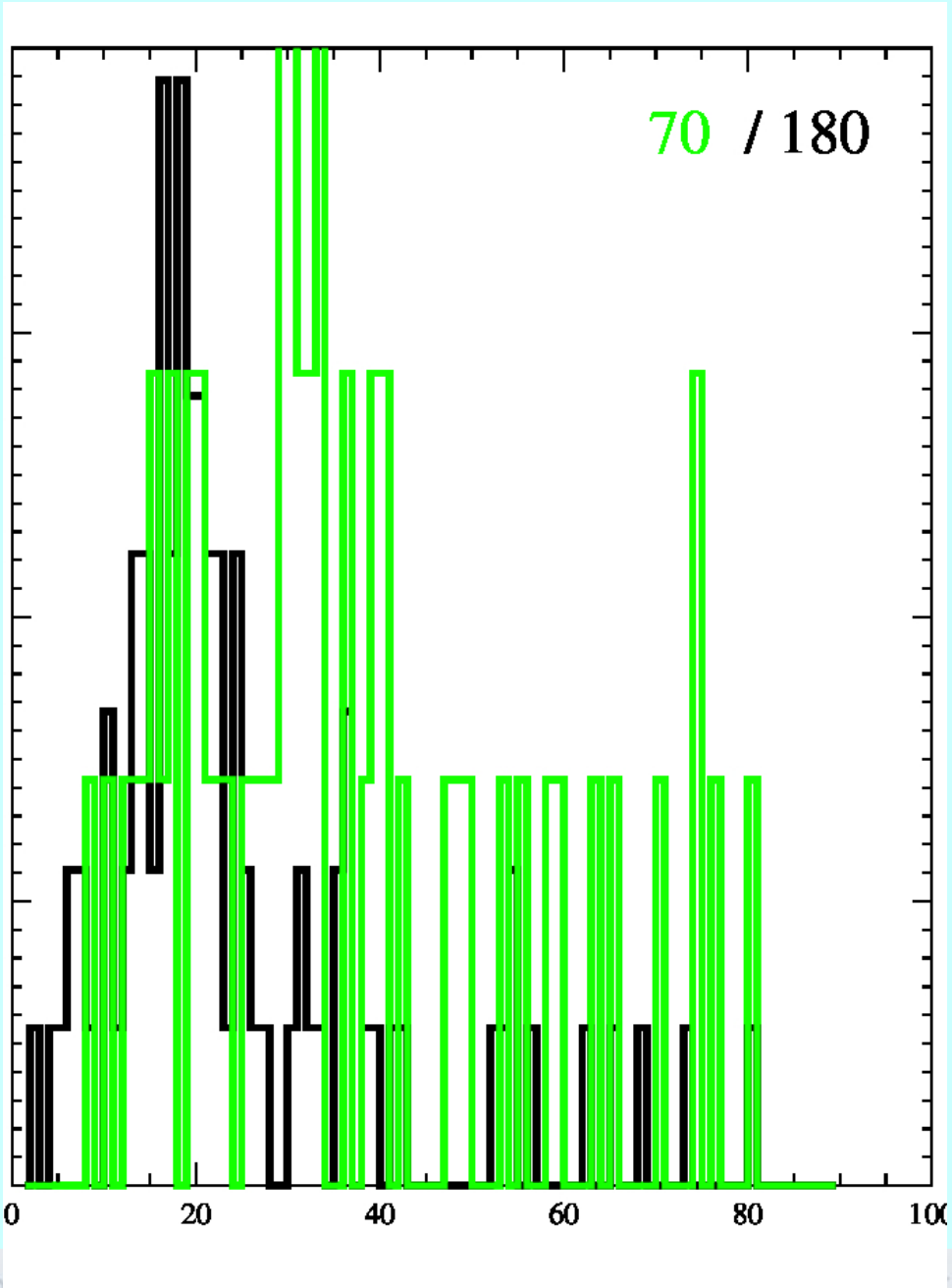

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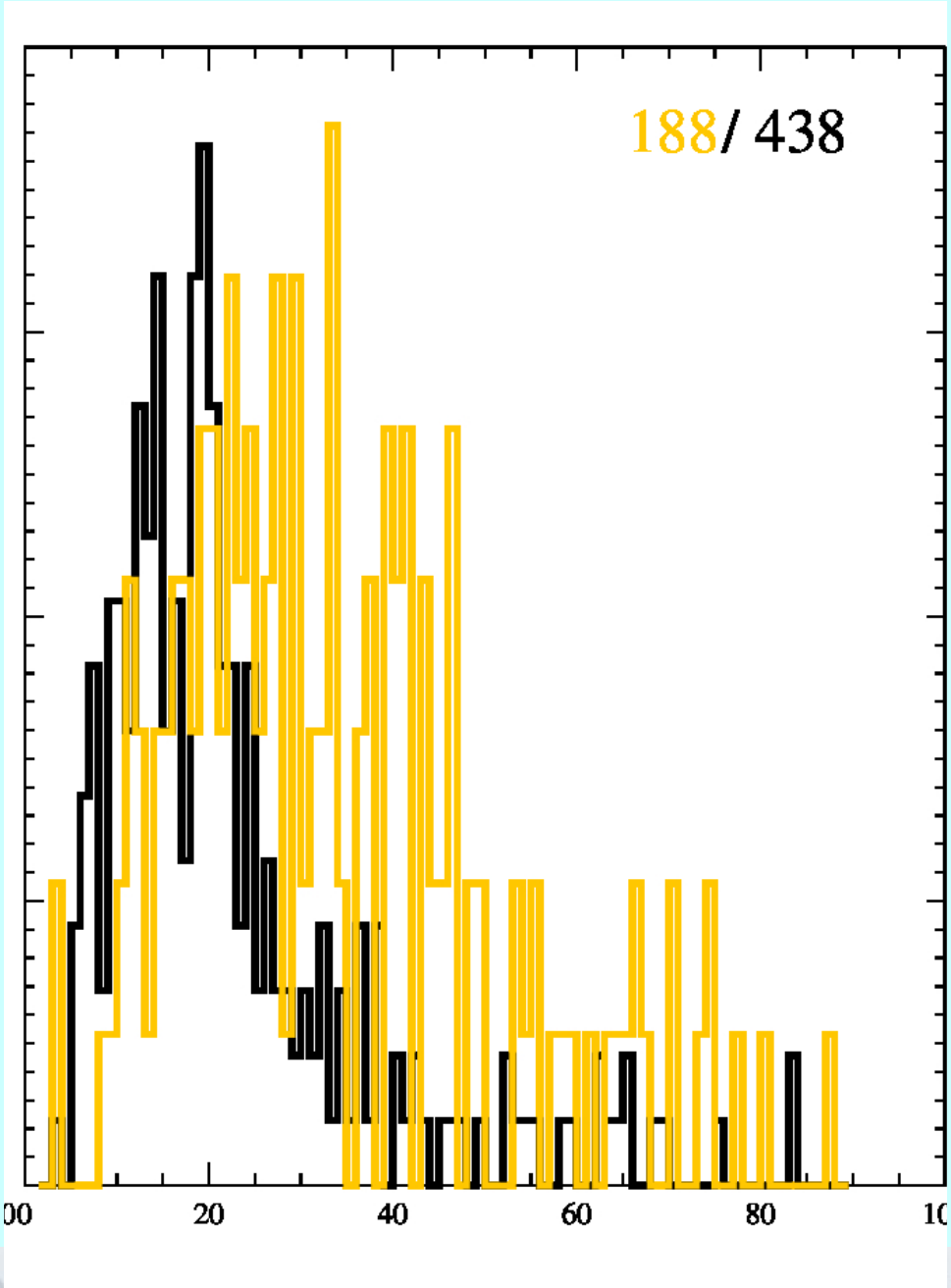

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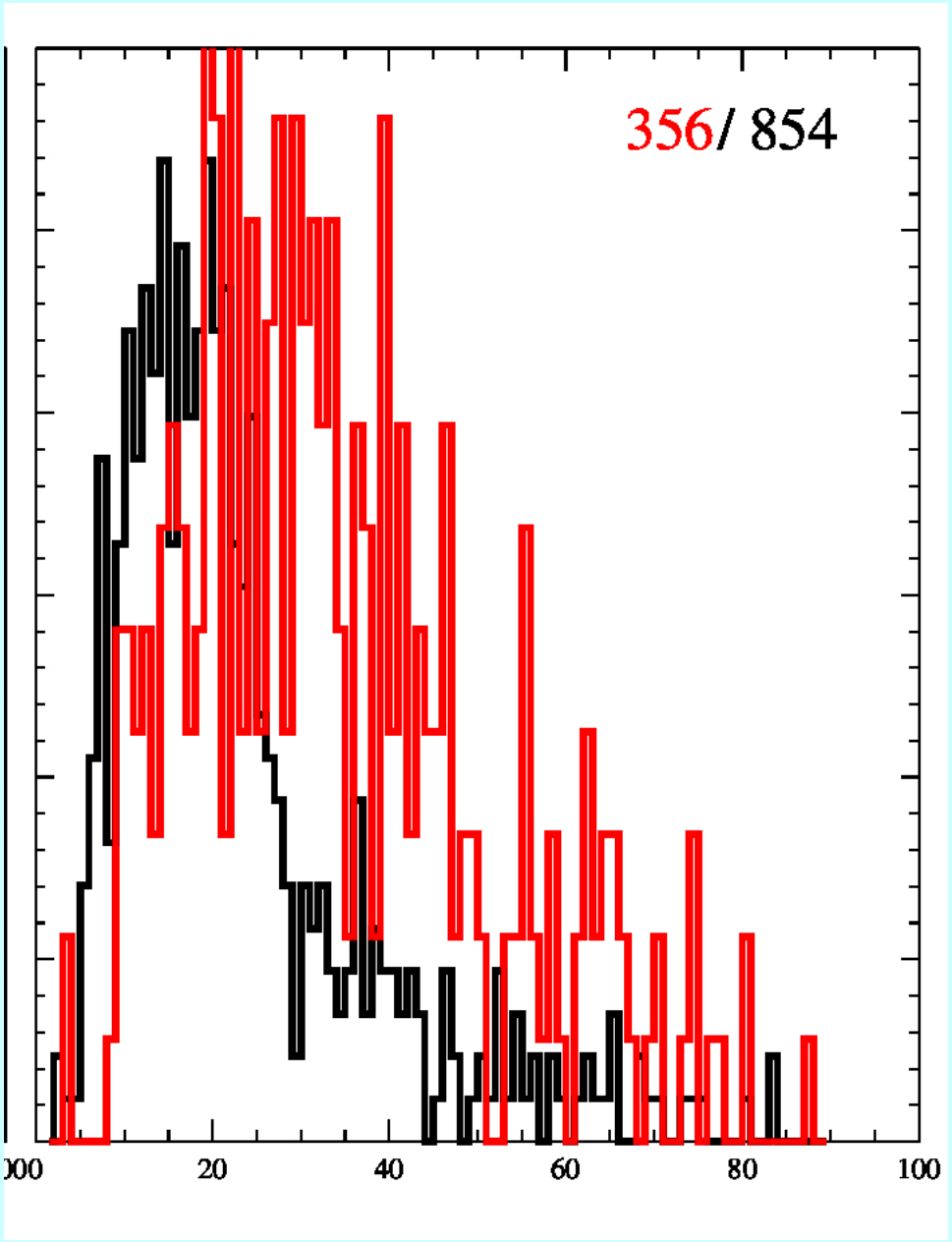

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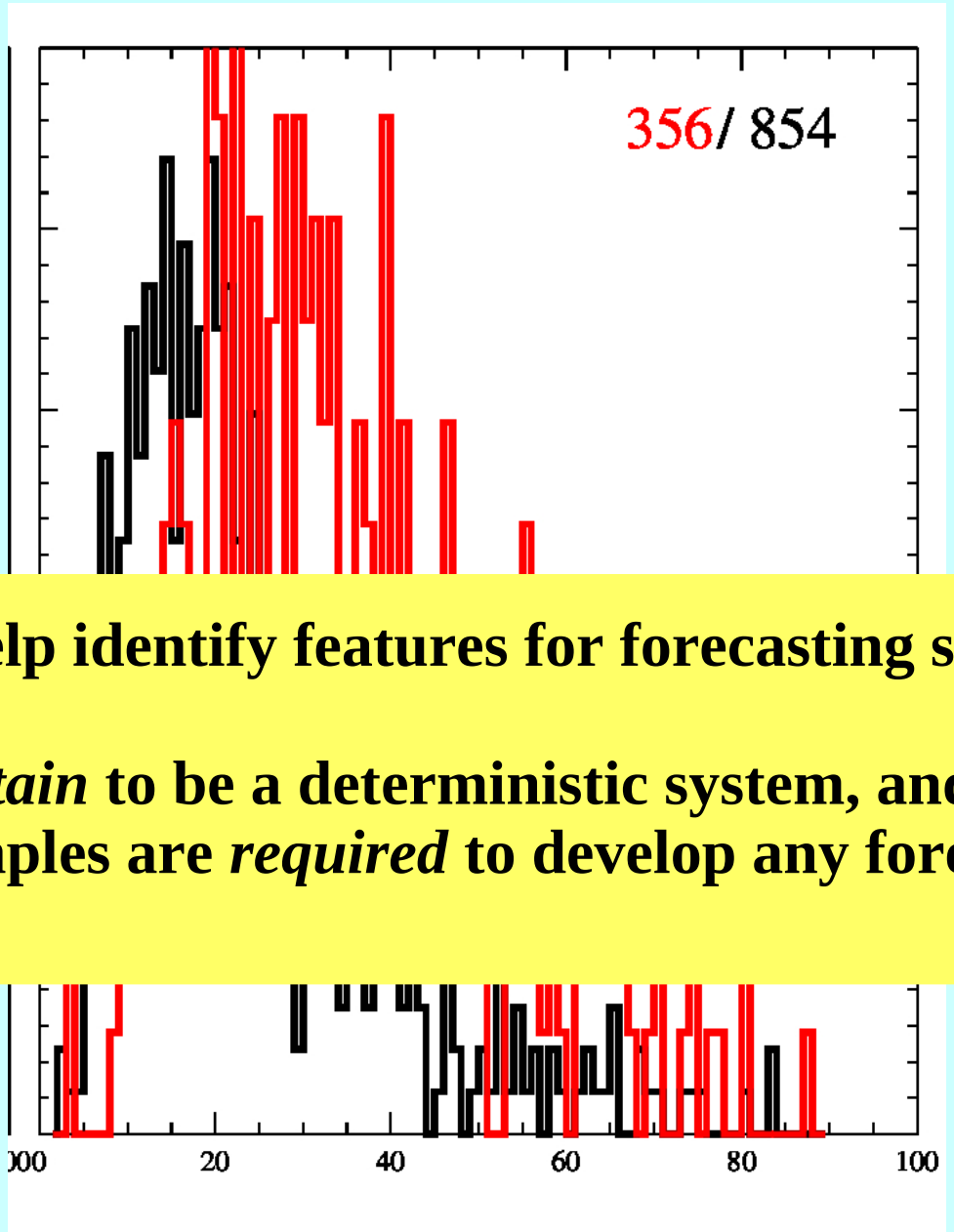


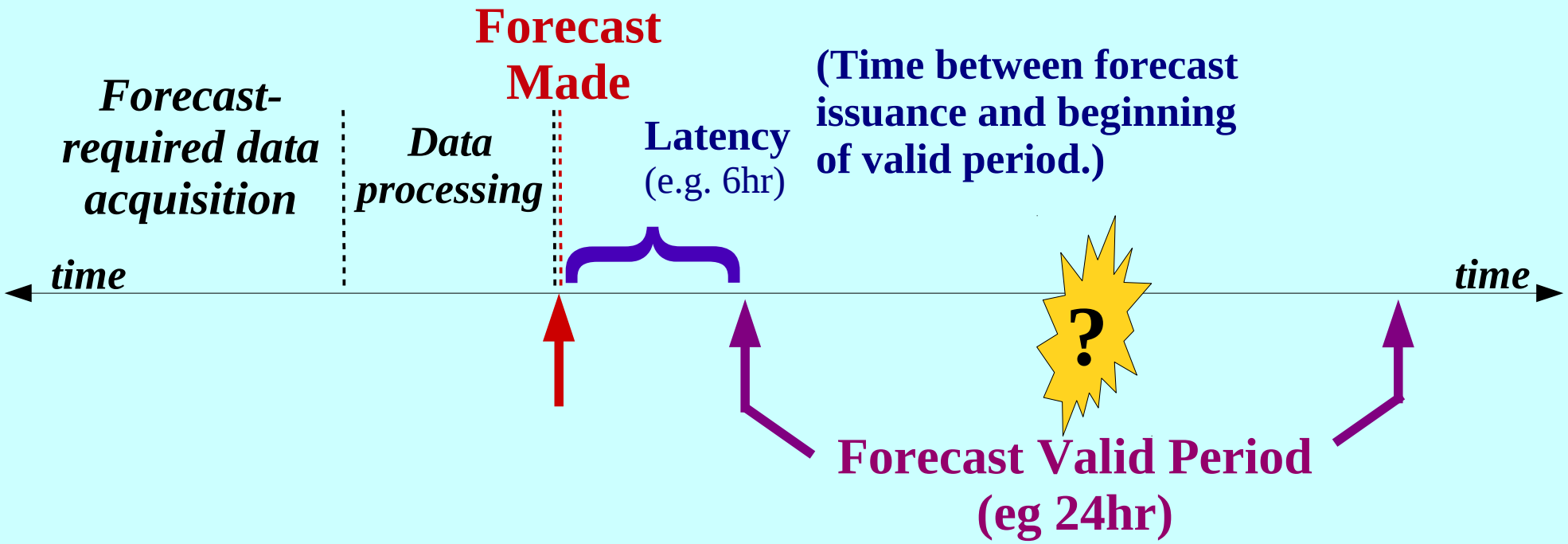
Modeling may help identify features for forecasting science to look for.

But until it is *certain* to be a deterministic system, and a unique trigger is *known*, large samples are *required* to develop any forecasting system.

Why this is hard, V: *Different customer needs.*

- Requirements for Events
  (only large flares, only Geo-Effective SEPs, etc.)

- Required/Acceptable Forecast Windows, Latencies



Why this is hard, V: *Different customer needs.*

- Required/Acceptable Accuracy, False-Alarm, Missed-Event Rates

	Predicted	
Observed	*Event*	*No Event*
Event	True Positive (TN "hit)	False Negative (FN, "miss")
No Event	False Positive (FP, "false alarm")	True Negative (TN, "correct negative")

Goal:

Observed \ *Predicted*	flare	quiet
flare	**all**	**0**
quiet	**0**	**all**

Reality:

Observed \ *Predicted*	flare	quiet
flare	**some**	**>0**
quiet	**>0**	**some**

What is acceptable?

Present Status:

THE UNIVERSITY OF

RHEA

Daily Solar Flare Prediction

Space Weather Service

Solar Flare Prediction for Today: ..... ≥ X Class 12 % ..... M-X Class 65 % ..... ≥ C Class 100 %

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Disclaimer

This space weather service provides automated daily predictions of the probability of a solar flare event occurring with a peak magnitude ranging from C (10^{-6} W/m^2) to greater than X class (10^{-4} W/m^2). The predictions are made using a statistical forecast method based on a Bayesian approach to solar flare prediction developed by Mike Wheatland of the University of Sydney.

```
Prediction made at: 2013-11-11T00:00:00.000Z
for events within 1.00 days based on 365.25 days of data
THRESH = 4.0e-06
Number of flares in year of data = 264
Maximum likelihood GAMMA = 2.050+/-0.065
Number of blocks = 8
Number of events in last block = 73
Duration of last block (days) = 10.08
Prob. of at least one flare of size M to X = 0.645+/-0.042      (1)
Prob. of at least one flare of X size or greater = 0.123+/-0.013 (1)
Prob. of at least one flare of C size or greater = 0.998+/-0.000 (1)
```

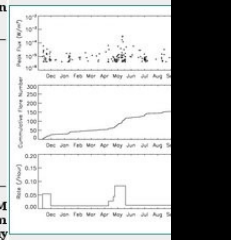
IDL code and scripts are run daily on the RHEA server at 6 AM CET, using the latest GOES 1-8 Å solar flare data obtained from NOAA. Each prediction is made for the duration of one day starting at 0000 UT of the day of the prediction, and using GOES data from the previous year (365.25 days). The text output produced by the prediction code is duplicated above, and the latest available GOES data are listed below.

Please read the disclaimer before making use of any information provided by this service.

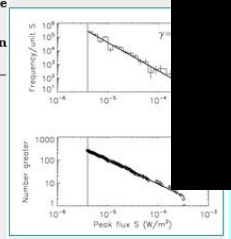
Latest Available GOES Data:

Date	Time (UT) Start	Max	End	Peak Flux (W/m2)	Class	Active Region
13/11/09	15:27	15:33	15:41	1.6e-06	(C1.6)	11893
13/11/09	15:44	15:52	15:58	1.4e-06	(C1.4)	11892
13/11/09	16:14	16:27	16:48	1.6e-06	(C1.6)	11894
13/11/09	17:00	17:07	17:20	1.7e-06	(C1.7)	11887
13/11/09	17:28	17:34	17:40	1.8e-06	(C1.8)	11895
13/11/09	18:01	18:04	18:09	1.3e-06	(C1.3)	11895
13/11/09	19:28	19:46	19:50	1.0e-06	(C1.0)	11895
13/11/09	20:39	20:43	20:46	1.4e-06	(C1.4)	11895
13/11/09	22:54	23:00	23:07	2.2e-06	(C2.2)	11895
13/11/10	01:47	01:52	02:00	1.5e-06	(C1.5)	11895
13/11/10	03:20	03:40	03:45	3.0e-06	(C3.0)	11895
13/11/10	05:08	05:14	05:18	1.1e-04	(X1.1)	11890
13/11/10	09:18	09:27	09:48	3.2e-06	(C3.2)	11890
13/11/10	12:47	12:52	12:58	3.1e-06	(C3.1)	11890
13/11/10	15:12	15:47	16:12	1.9e-06	(C1.9)	11895
13/11/10	17:08	17:25	17:33	1.3e-06	(C1.3)	11890
13/11/10	17:41	17:45	17:48	1.4e-06	(C1.4)	11887
13/11/10	18:48	18:55	18:58	1.3e-06	(C1.3)	11895
13/11/11	00:26	00:32	00:39	6.4e-06	(C6.4)	11890
13/11/11	00:43	00:48	00:51	7.8e-06	(C7.8)	11890

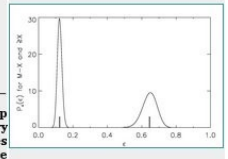
Plots generated by the code are displayed on the right. From top to bottom, the plots represent the GOES solar flare event history used to make the prediction, the size distribution of the flares and the probability function of the prediction. In addition, the reliability of the prediction method is quantified and plotted to allow a running comparison between predicted and observed values.



GOES X-Ray Flare Event Hist



GOES X-Ray Flare Event Distribution



X-Ray Flare Prediction

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spaceweather.inf.brad.ac.uk/fm/

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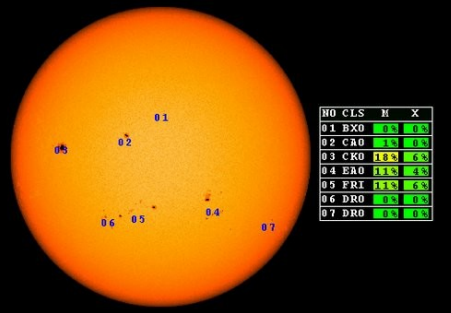
Flare Monitor (BETA)

SOLAR FLARE PROBABILITY = 20 %



NO	CLS	M	X
01	BXO	0%	0%
02	CAO	0%	0%
03	CKO	10%	0%
04	EAO	10%	0%
05	FRI	10%	0%
06	DRO	0%	0%
07	DRO	0%	0%

SOLAR FLARE MONITOR
Generated by ASAP 15/11/2013 15:00 UTC
http://spaceweather.inf.brad.ac.uk/ UNIVERSITY OF BRADFORD

How does flare monitor work?

Our agent program "SPIDER" connects to the SDO website every two minutes to search for the new HMI images and download them to our server.

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Latest SWPC 3-day Space Weat...

www.swpc.noaa.gov/forecast.html

Solar Flare Forecasts

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NOAA / Space Weather Prediction Center

3-day Report of Solar and Geophysical Activity

Last 75 Reports | Today's Space Weather | Space Weather Now

Prepared jointly by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center and the U.S. Air Force.
Updated 2013 Nov 14 2200 UTC

Joint USAF/NOAA Solar Geophysical Activity Report and Forecast
SDF Number 318 Issued at 2200Z on 14 Nov 2013

IA. Analysis of Solar Active Regions and Activity from 13/2100Z to 14/2100Z: Solar activity has been at low levels for the past 24 hours. The largest solar event of the period was a C4 event observed at 14/0800Z from Region 1897 (S21E26). There are currently 8 numbered sunspot regions on the disk.

IB. Solar Activity Forecast: Solar activity is expected to be low with a chance for M-class flares and a slight chance for an X-class flare on day one (15 Nov) and expected to be low with a chance for M-class flares on days two and three (16 Nov, 17 Nov).

IIA. Geophysical Activity Summary 13/2100Z to 14/2100Z: The geomagnetic field has been at quiet levels for the past 24 hours. Solar wind speed, as measured by the ACE spacecraft, reached a peak speed of 405 km/s at 14/1512Z. Electrons greater than 2 Mev at geosynchronous orbit reached a peak level of 475 pfu.

IIB. Geophysical Activity Forecast: The geomagnetic field is expected to be at quiet levels on day one (15 Nov), quiet to unsettled levels on day two (16 Nov) and quiet to active levels on day three (17 Nov). Protons greater than 10 Mev have a slight chance of crossing threshold on day one (15 Nov).

III. Event probabilities 15 Nov-17 Nov

Class M	50/40/40
Class X	15/05/05
Proton	20/05/05
PCAF	green

Iv. Penticton 10.7 cm Flux

Observed	14 Nov 176
Predicted	15 Nov-17 Nov 175/175/175
90 Day Mean	14 Nov 124

v. Geomagnetic A Indices

Observed Afr/Ap 13 Nov	002/004
Estimated Afr/Ap 14 Nov	003/003
Predicted Afr/Ap 15 Nov-17 Nov	005/005-007/008-011/012

VI. Geomagnetic Activity Probabilities 15 Nov-17 Nov

A. Middle Latitudes	
Active	10/20/35

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ASAP Solar Flare Pr

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SWRL is currently providing daily Solar Flares Forecasting and Solar Filaments Detection, upon work supported by NSF under Grant ATM 07-16950 and AGS-1250374, and NASA under NNX11AQ55G. Any opinions, findings, and conclusions or recommendations expressed in those of the author[s] and do not necessarily reflect the views of the National Science Fou

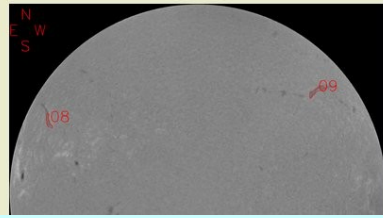
Daily Solar Flares Forecasting

Flare Event Date	Region Number	Helicity Injection Rate (10^40 Mx^2/hr)	Total Unsigned Flux (10^20 Mx)	0-24 hrs flare index	24-48 hrs flare index	C-flare 0-24 hrs	C-flare 24-48 hrs	M-flare 0-24 hrs	M-flare 24-48 hrs
2013-11-14	11898	0.04	33	0.5	0.9	13%	13%	3%	3%
2013-11-14	11897	1.4	160	2.5	3.6	24%	24%	6%	6%
2013-11-14	11896	0.52	66	1.6	2.4	20%	20%	5%	5%
2013-11-14	11895	0.13	67	0.8	1.4	20%	19%	5%	5%
2013-11-14	11893	0.6	106	1.7	2.5	22%	21%	6%	5%
2013-11-13	11898	0	26	0.2	0.3	10%	10%	3%	2%
2013-11-13	11897	2.14	196	3.1	4.2	25%	25%	7%	7%
2013-11-13	11896	0.2	65	1	1.6	20%	20%	5%	5%
2013-11-13	11895	0.61	68	1.7	2.5	20%	21%	5%	5%
2013-11-13	11893	0.22	96	1.1	1.7	21%	21%	5%	6%
2013-11-13	11890	0.54	148	1.6	2.4	23%	23%	6%	6%

For historical forecasting results, click here.
For information on the Helicity based forecasting, click here.
For information on the Flare List, click here.
For information on the Logistic Regression based forecasting, click here.

Daily Solar Filaments Detection

ID	Area(Square Megametres)	Longitude(degrees)	Latitude(degrees)
1	243.0	-18.9	-45.7
2	1141.8	12.3	-37.6
3	438.3	15.3	-31.3
4	806.0	39.5	-28.7
5	6939.6	56.6	-19.3
6	435.1	25.9	-16.7
7	423.4	35.5	-10.6
8	555.5	-58.6	22.0
9	901.5	48.4	32.6



NORTHWE S

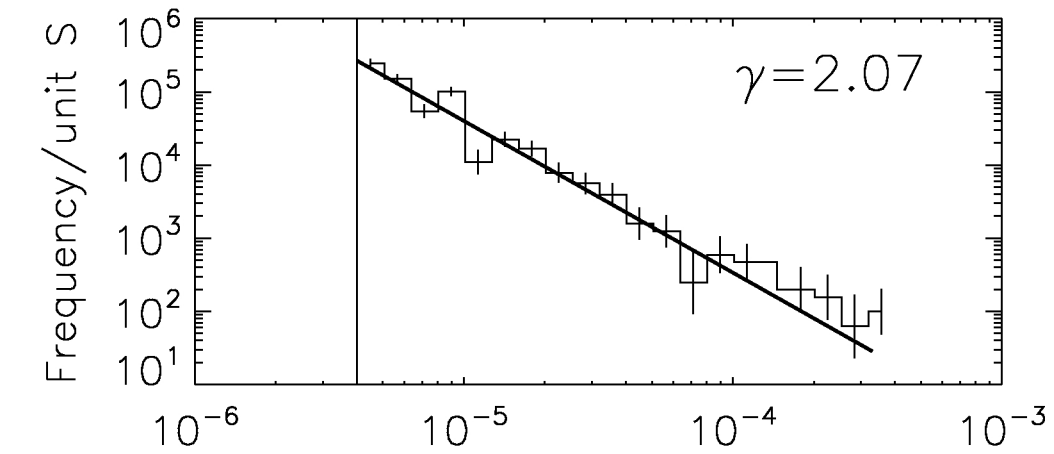
Present Status: Two basic approaches.

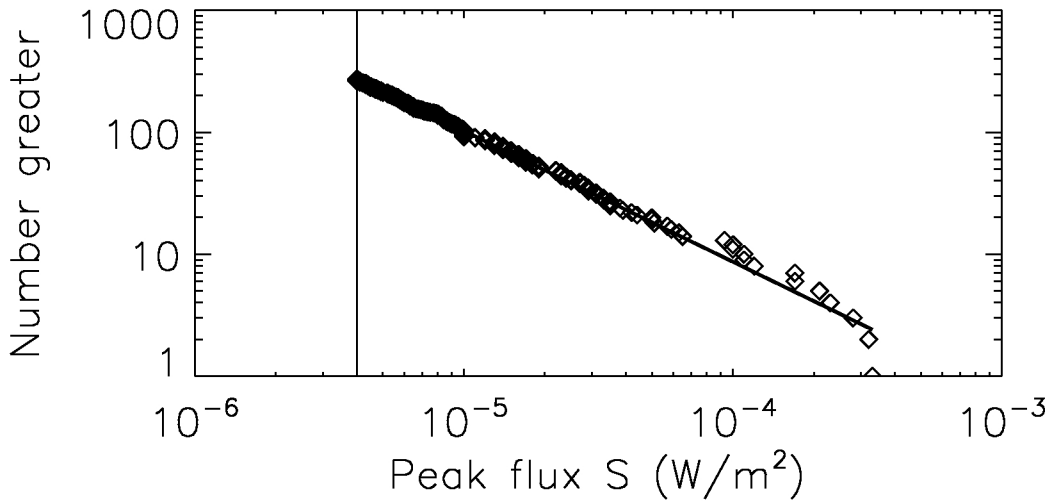
1) Event Statistics.

➔ Model flaring rate behavior (e.g., power law)

➔ Use observed flare history to predict probable future flaring.

➔ *See Mike Wheatland's talk.*

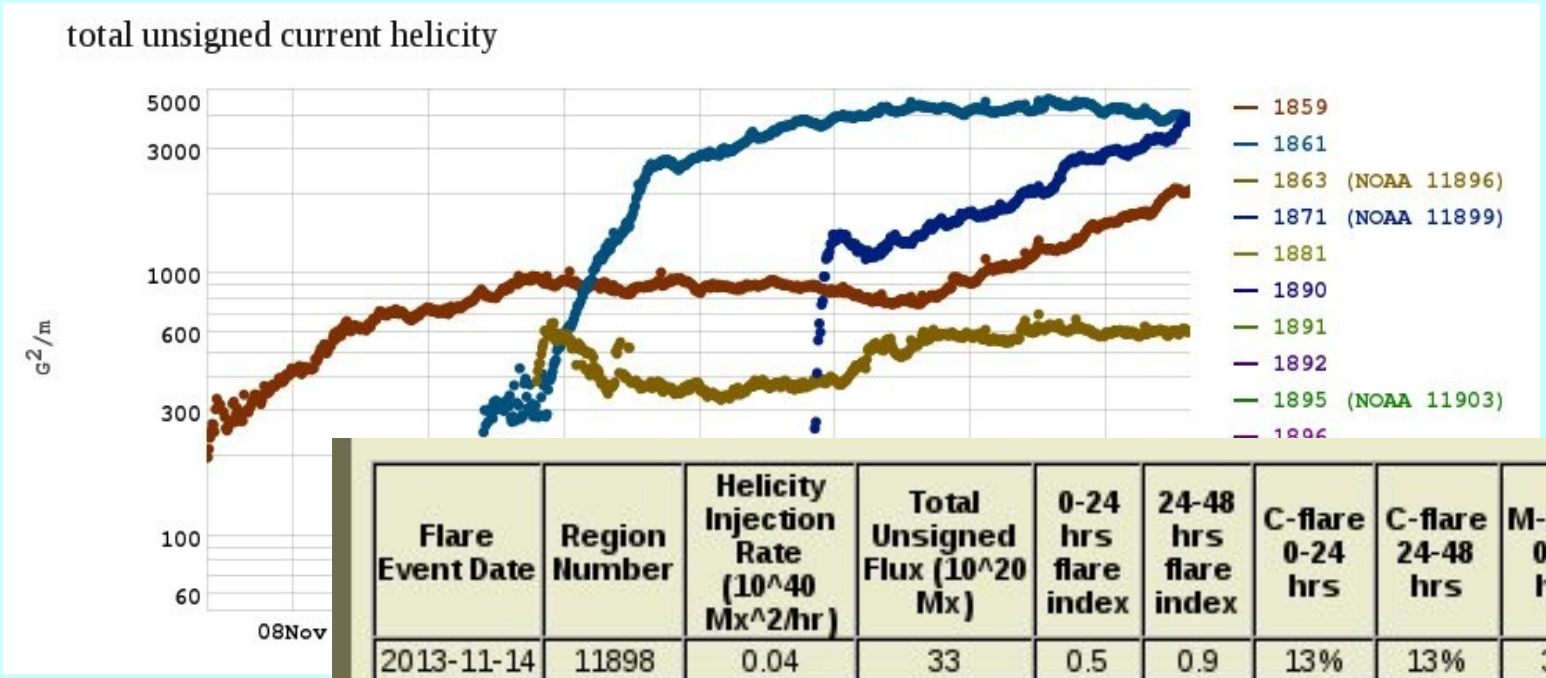




Present Status: Two basic approaches.

2) Characterize the Sun, give results to statistical analysis.

- **Generally use solar photosphere images to calculate parameters.**
- **Forecast based on training set.**
- **Statistical analysis: varies, from simple to very complex.**
- **Present-state forecasts available.**



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2013-11-14	11898	0.04	33	0.5	0.9	13%	13%	3%	3%	1%	1%
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2013-11-13	11897	2.14	196	3.1	4.2	25%	25%	7%	7%	4%	3%

Critical Review: Limitations

1) Event Statistics:

- **Most applicable to larger flares.**
- **Requires prior flares to predict future (no information on start of flaring activity).**

2) Data Parametrization + statistical analysis

- **Perform best when training sets are**
  - **Very large**
  - **Absolutely consistent with forecasts.**
- **Analysis methods as important as input data (and its handling).**

- **Present NOAA/SWPC flare forecasts essentially use a little of both.**
  - **All current//in-development methods are essentially just refinements.**
    - **But *important* refinements.**

Critical Review: Evaluation.

(This is hard.)

- Rare Events: High accuracy rates are *easy*!
  - Accuracy = (TP+TN)/N
  - Example: if X-flares only happen "climatologically" during 3% of observations, 97% "accuracy rate" means.....*no forecast value*.

- Only true way to evaluate performance is with
  - Standardized Input Data
  - Standardized Event Lists
  - Standardized Forecasting Evaluation Intervals
  - Multiple Skill Scores

NWRA Flare Forecasting Comparison Workshops

- Two workshops so far (2009, 2013).
- Different, but standardized datasets distributed
- Different, but standardized event lists generated.
- Participants open about their methods, sharing information, participating, and allowing their methods to be subjected to evaluation.
  - 2009 results are being compiled now,
  - 2013 data are not complete, will come soon.

See poster 10.07, "The NWRA Flare-Forecast Comparison Workshops" (it's the tall poster)

- Some interesting initial points thus found:

1) Different Skill Scores *(there are many...)* evaluate different things.

Observed		***Predicted***	
		flare	quiet
	flare	**TP**	**FN**
	quiet	**FP**	**TN**

- SSs are *crucial* to objectively evaluate performance.
- Many based on ratios of entries in contingency table:
- Some are more/less sensitive to differences in event ratios, sample sizes, and reference forecasts.

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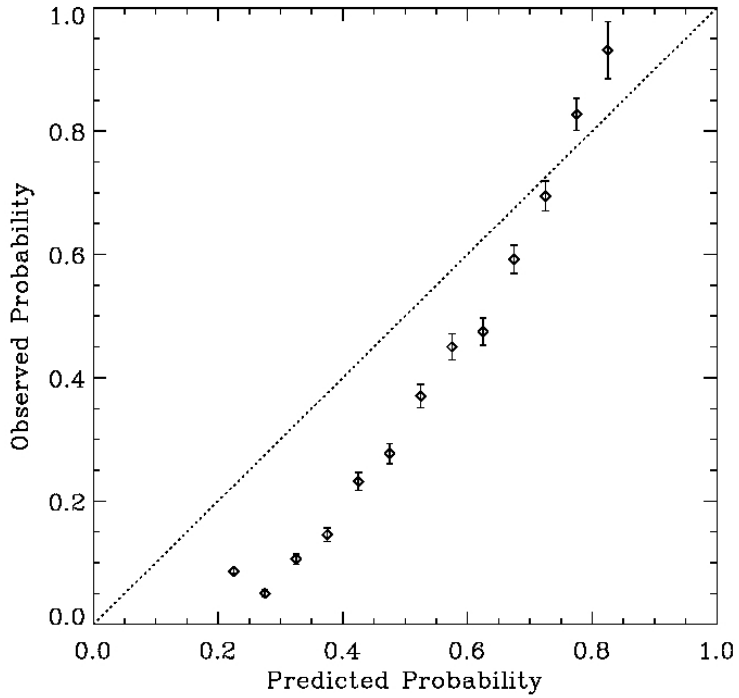
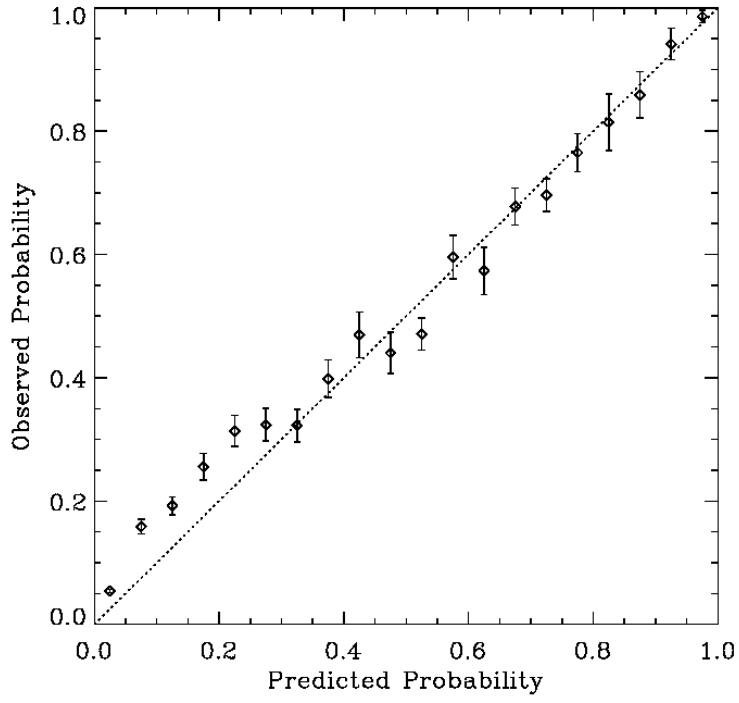
- Some are more/less sensitive to differences in event ratios, sample sizes, and reference forecasts.

	Method 1	Method 2	
True/HanssenKuiper/Pierce SS:	0.43	0.42	← **similar**
Brier/MSE SS:	0.04	0.31	← **different**

Difference in Brier SS is reflected in reliability plots.





2) Standardized Data Sets:

- Removes bias if method performance is only reported for select data.
- If a method works well *only* on select, restricted data, *operational use will be limited.*

  - Example: a method requires data from single ground-based observatory, available 06:00 – 12:00 UT, when sunny, except Sundays.
    - Method reports high Skill Score for those special periods data.
    - What happens Sunday night?

2) Standardized Data Sets:

- Removes bias if method performance is only reported for select data.
- If a method works well *only* on select, restricted data, *operational use will be limited.*

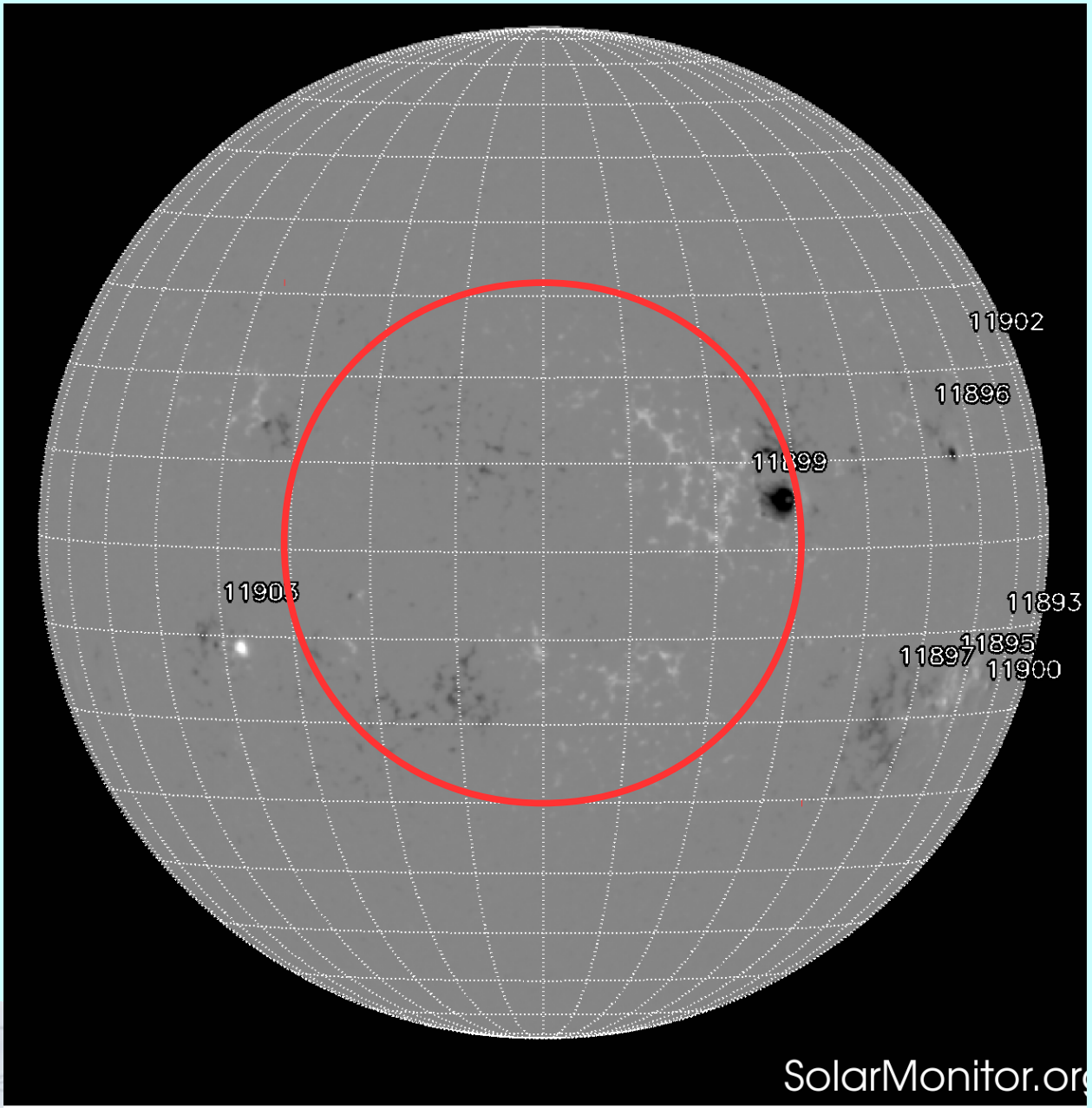
Example:
Method 3 only produces a forecast within 30° of solar disk center, and only for certain kinds of regions, and only for strong (M1.0+) flares.

For that subset of data:

HK/P/T SS:	0.21
Brier SS:	0.19

When "reference forecast" used to include all data in standard set:

HK/P/T SS:	0.07
Brier SS:	0.06



3) How the Sun is characterized matters:

Example: Two parameters, Same Statistical Analysis.

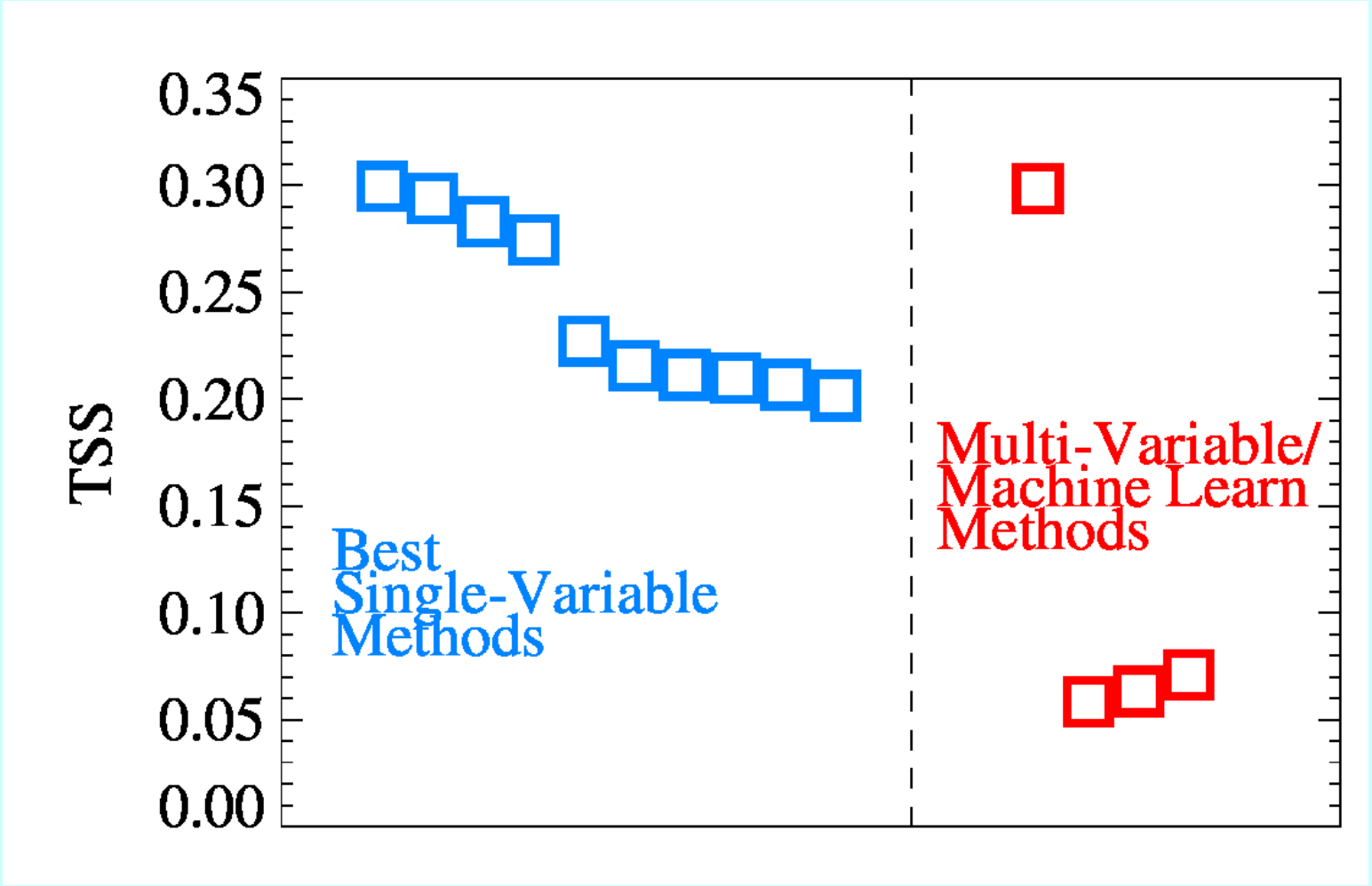
	Parameter #1	Parameter #2
HK/P/T SS:	0.41	0.00
Brier SS:	0.31	0.05

4) The Statistical Method matters:

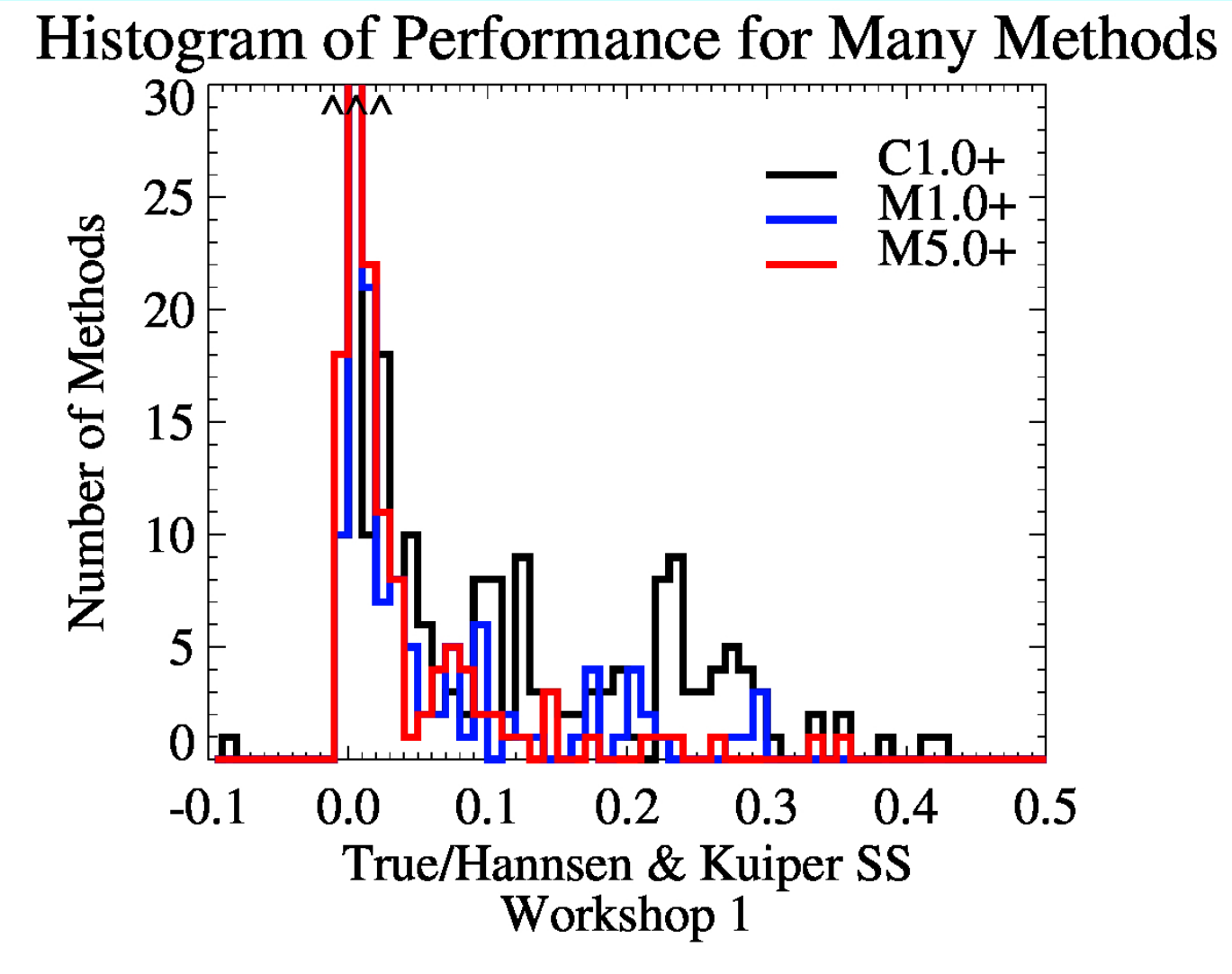
Example: Same parameters, Different Statistical Analysis.

	Analysis #1	Analysis #2
HK/P/T SS:	0.27	0.43
Brier SS:	0.22	0.04

5) Surprisingly, multiple parameters + sophisticated computer-learning algorithms do *not* necessarily perform better than single variables and simpler statistical-methods.



6) Many methods perform fairly similarly, scoring 0.2—0.4 on a variety of skill-score tests, even for M5.0+ flare events.



7) Somewhat higher Skill Scores (0.1 - 0.2dex) initially coming from 2nd workshop data and methods.

- *Why?*
  - Data?
  - Algorithm improvement?
- *(Find out next year....when we've analyzed it.)*

8) Did you notice that none of these skill scores have error bars?

- That's hard, too.
- Smaller sample sizes lead to (understandably) huge error bars.
- But it's do-able by various methods. *See talks on Friday.*

Summary

Forecasting solar flares is:

- Difficult
- Important

Knowing whether a forecast *is even any good* is:

- Difficult
- Important

The state of forecasting solar flares is:

- Not perfect.
  - *Maybe not even very good.*
- Getting better.
- Could improve greatly by direction from:
  - Modelers.
  - Coronal imaging.
  - Helioseismology.

Establishing infrastructure for systematic evaluation is:

- Crucial
- Available and open for others to join.