The Present State of Forecasting Solar Flares

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Collaborators: G. Barnes, E. L. Wagner

Acknowledging funding from: NASA, NOAA, AFOSR, and the PSTEP program.

Why Is Forecasting Solar Flares Important?

- **Time-of-flight for impact = *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 (forecasting = best test of understanding)
  - Statistical methods of forecasting rare events

Q: What is a “solar flare”?

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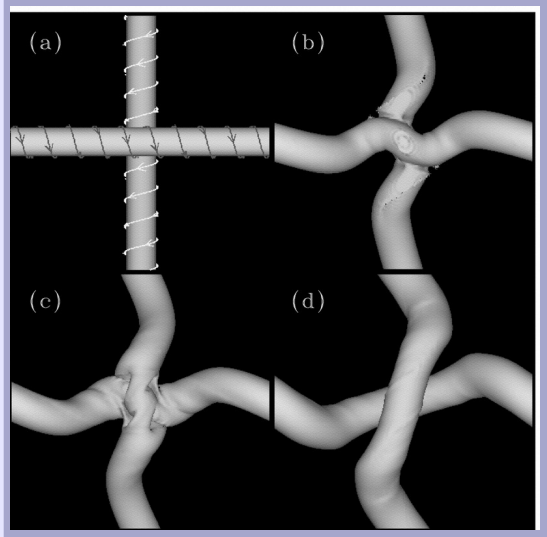
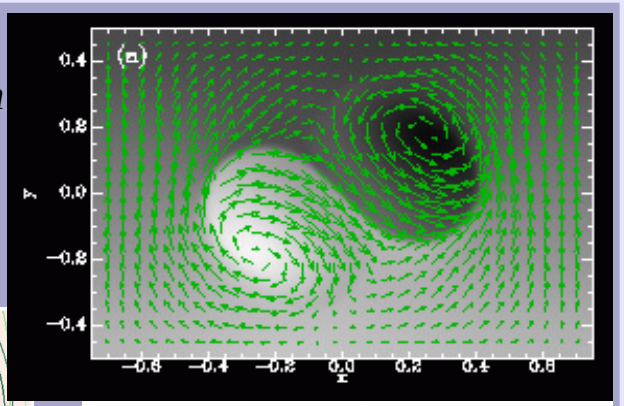
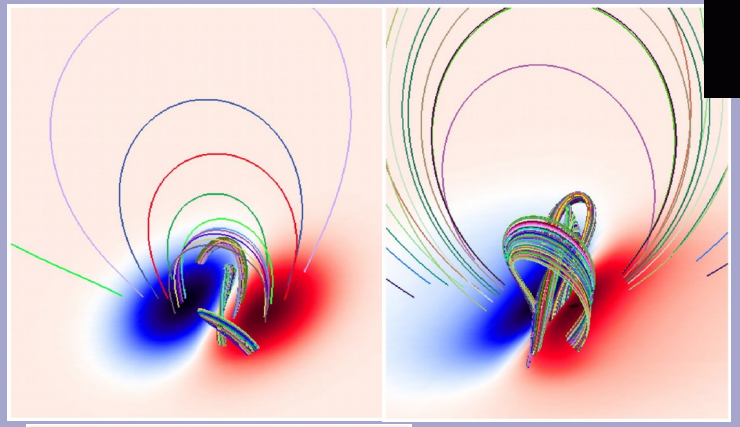
Modeler's view:

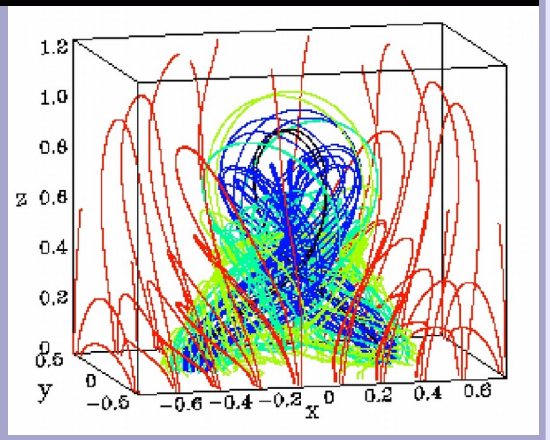


Linton & Antiochos 2002

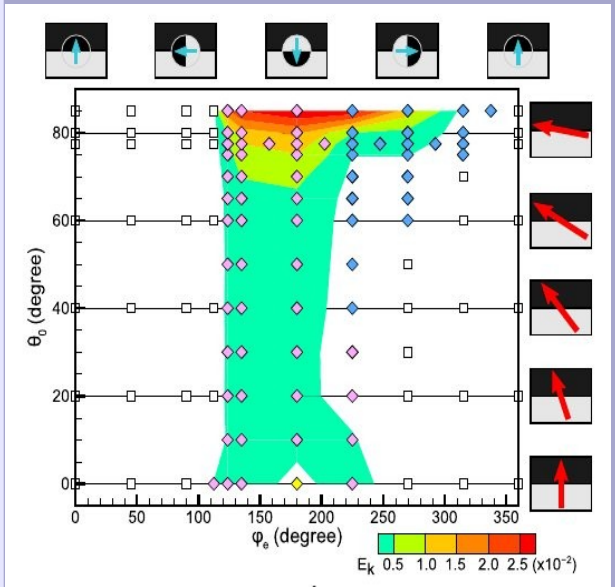
Fan & Gibson 2003, 2004

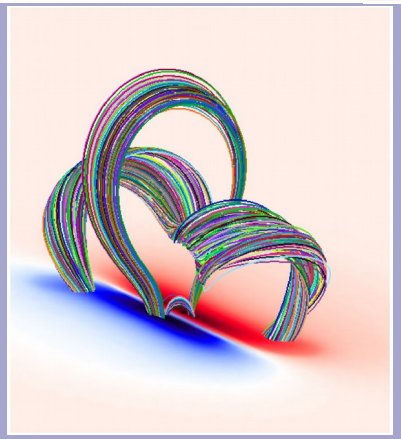




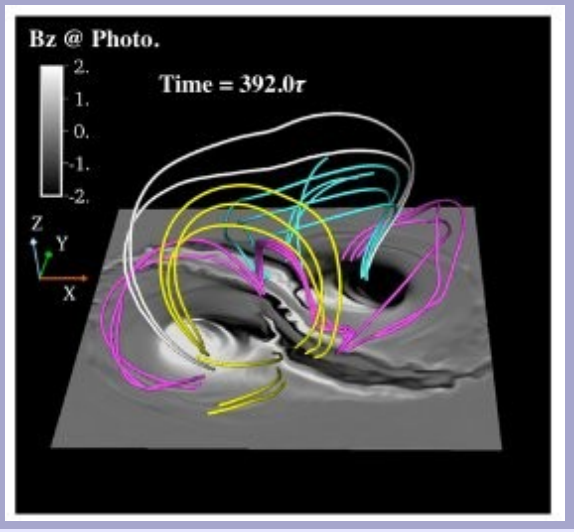


Kusano et al 2012





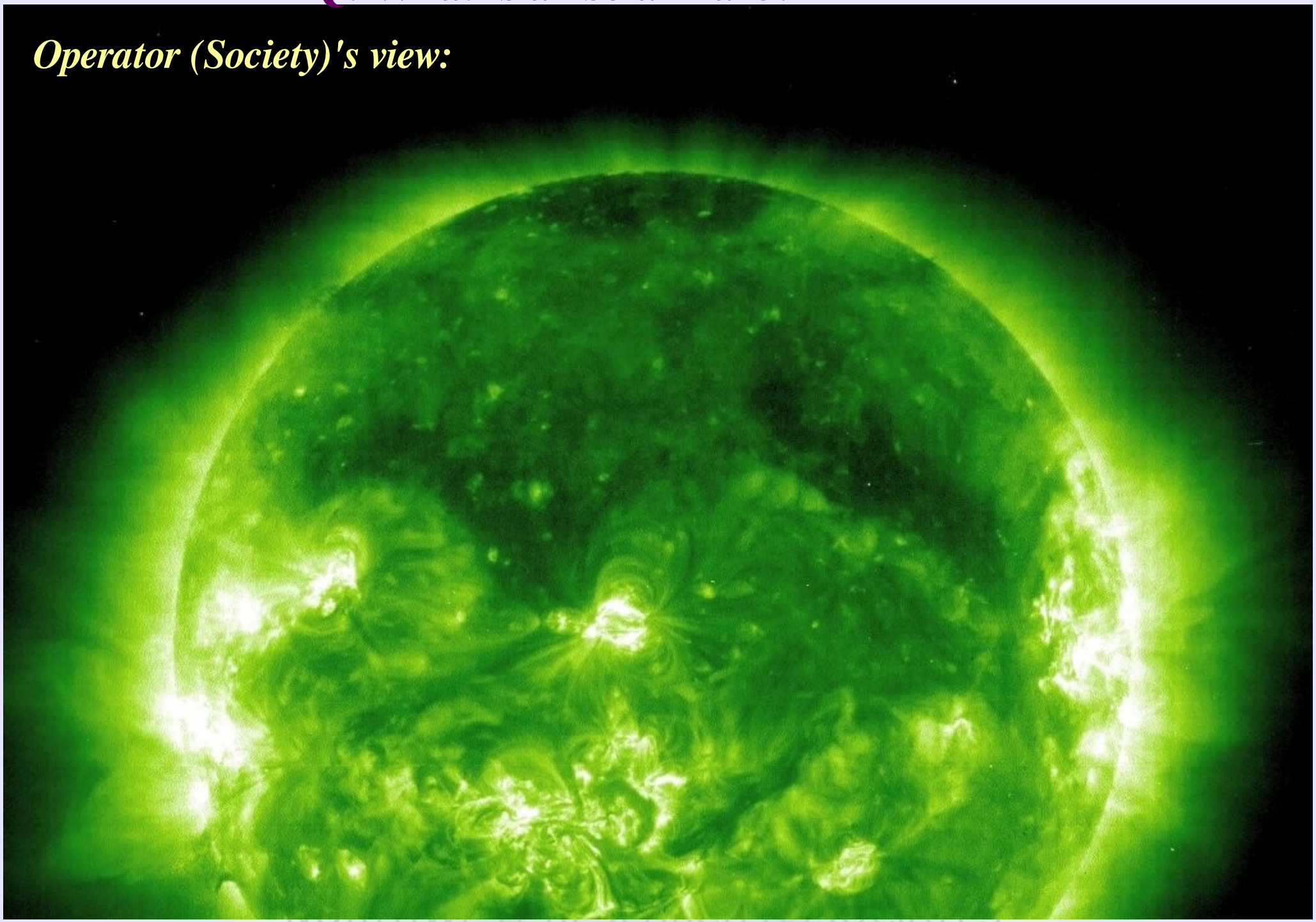
Amari, Luciani, Aly, Mikic & Linker 2003



Takasao et al 2015

Q: What is a “solar flare?”

Operator (Society)'s view:



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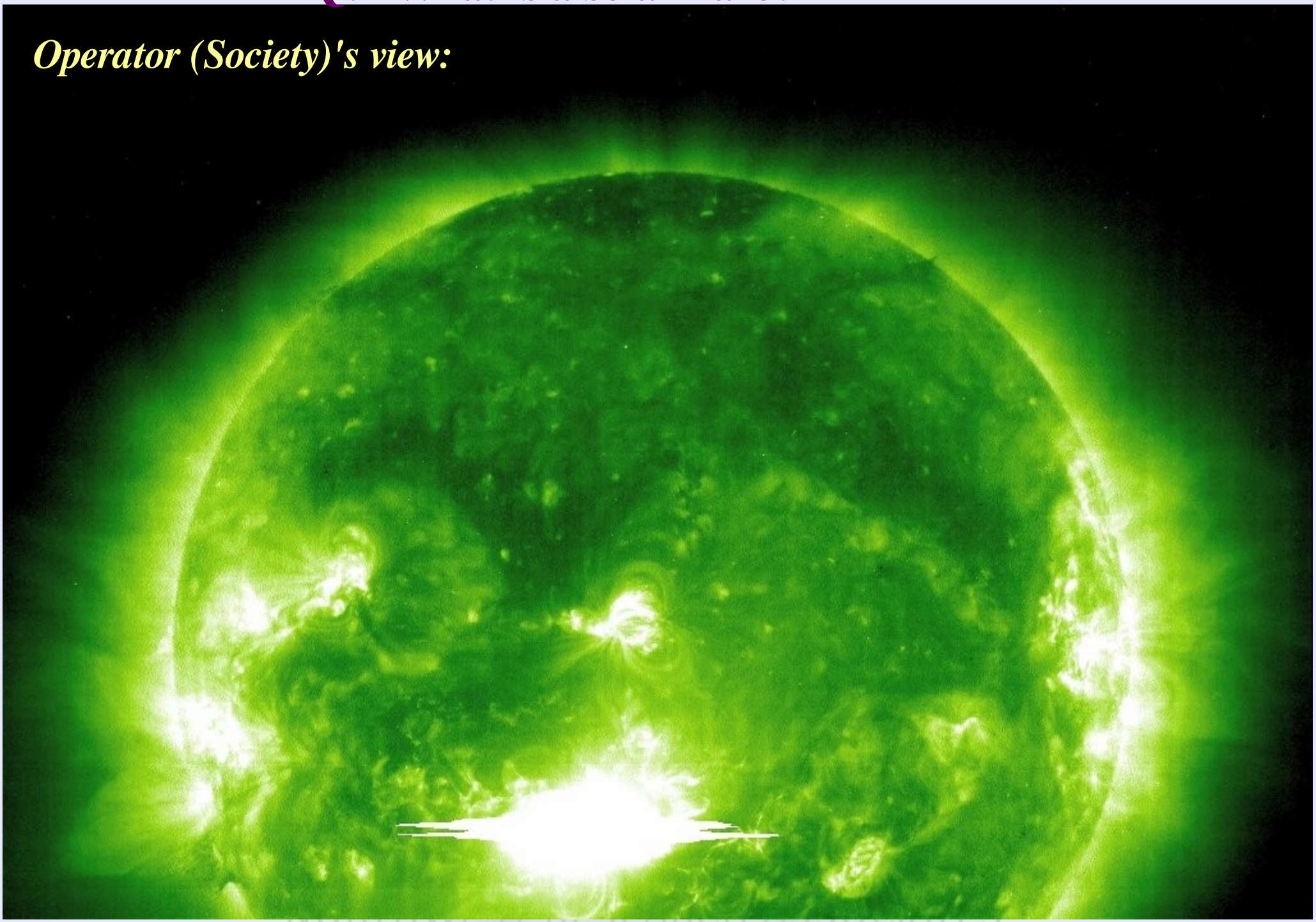

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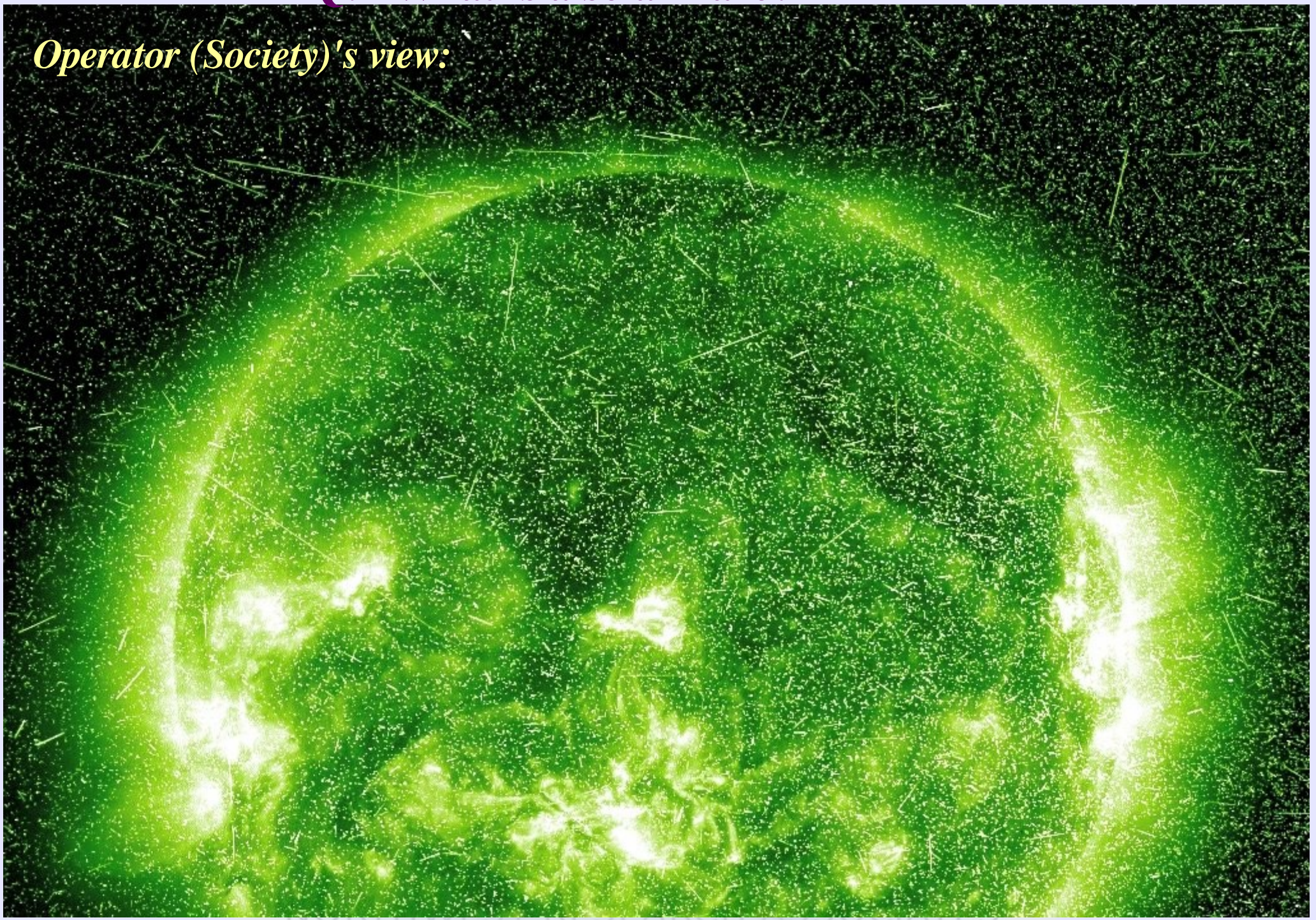


from Mitchell & Schrijver, 2013 Space Weather Week.

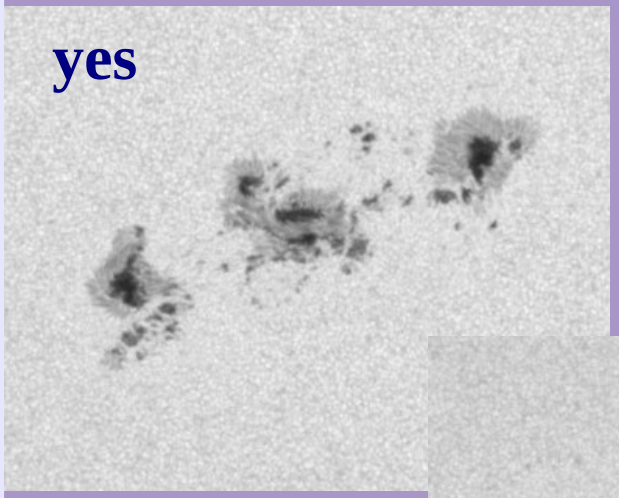
Substantial even short of extreme

- We conducted a study using public information that reveals a general correlation between large but not extreme solar flares and disturbances in the U.S. electric grid; these disturbances have an impact of $5-8 billion a year on the GDP

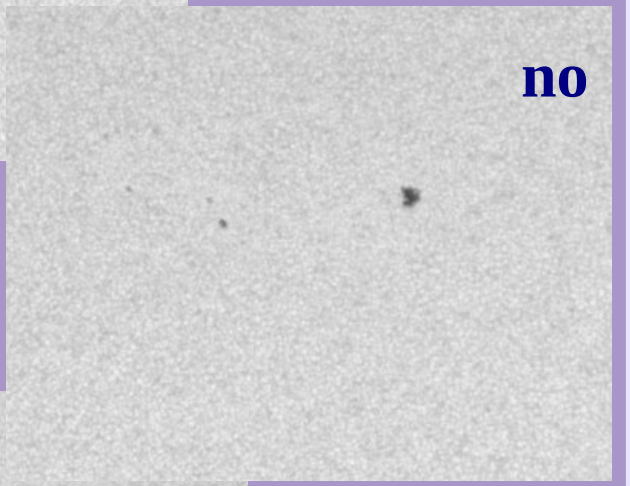
Q: What is a “solar flare?”

Forecaster's view:

yes



no



maybe...

Q: What is a “solar flare”?

- A sudden, intense, release of magnetic energy from the Sun.
- An impulse of Ultraviolet, X-ray, and high-energy particles and radiation.
- A reason to thank the Earth's magnetic field and atmosphere.
- A reason to think about our technology infrastructure and dependence.
- ***All of the above.***

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- ***All of the above.***

Q: What is a “solar flare” to a “forecast researcher”?

- A fairly rare event.
- With time-of-flight for impact = *c*.

How to Build a Solar Flare Forecast

Four Basic Pieces:

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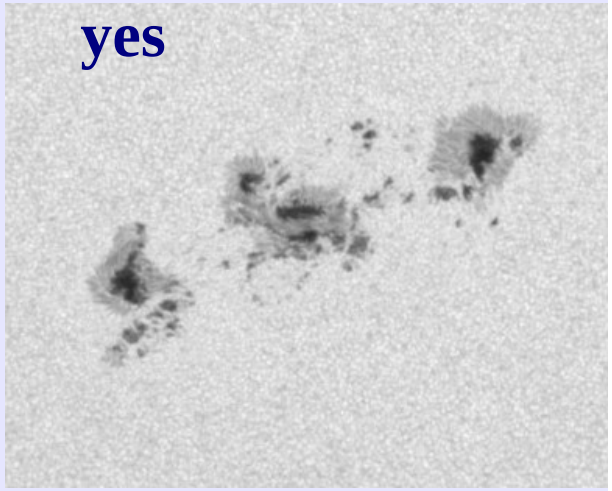
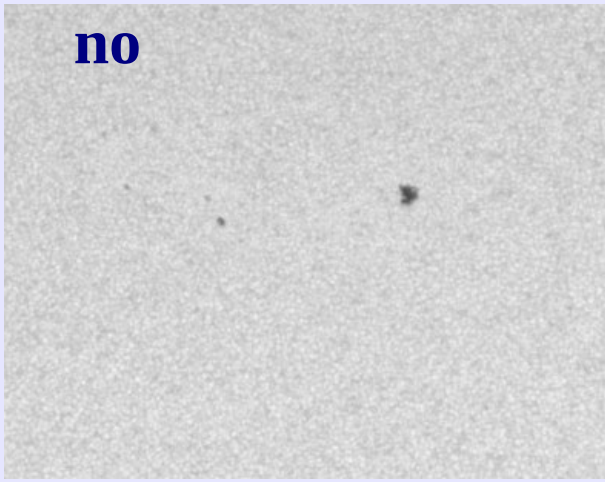
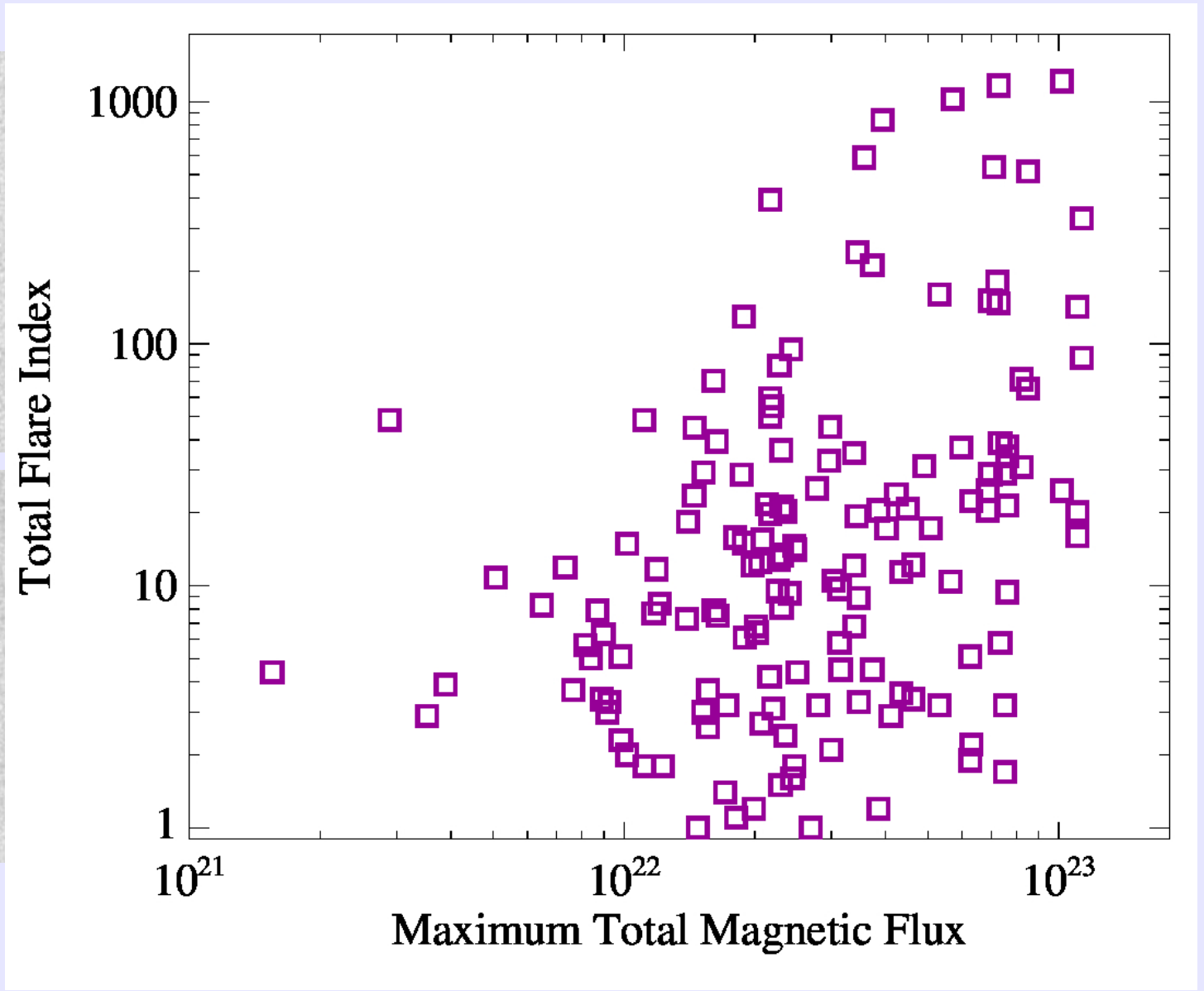
(4) An evaluation of how well you did.

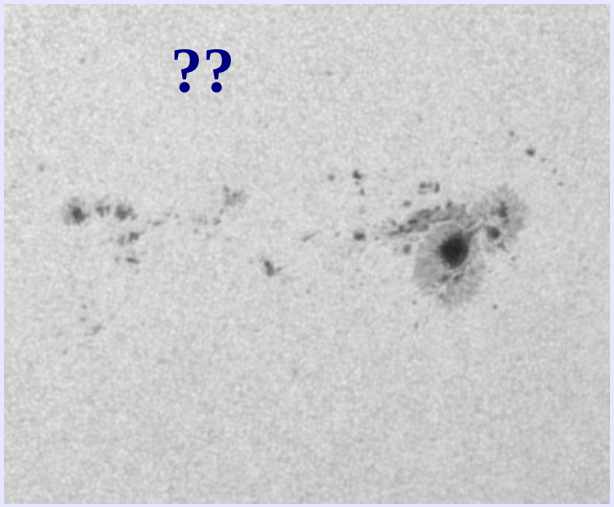
(1) Lots of historical examples of the Sun.

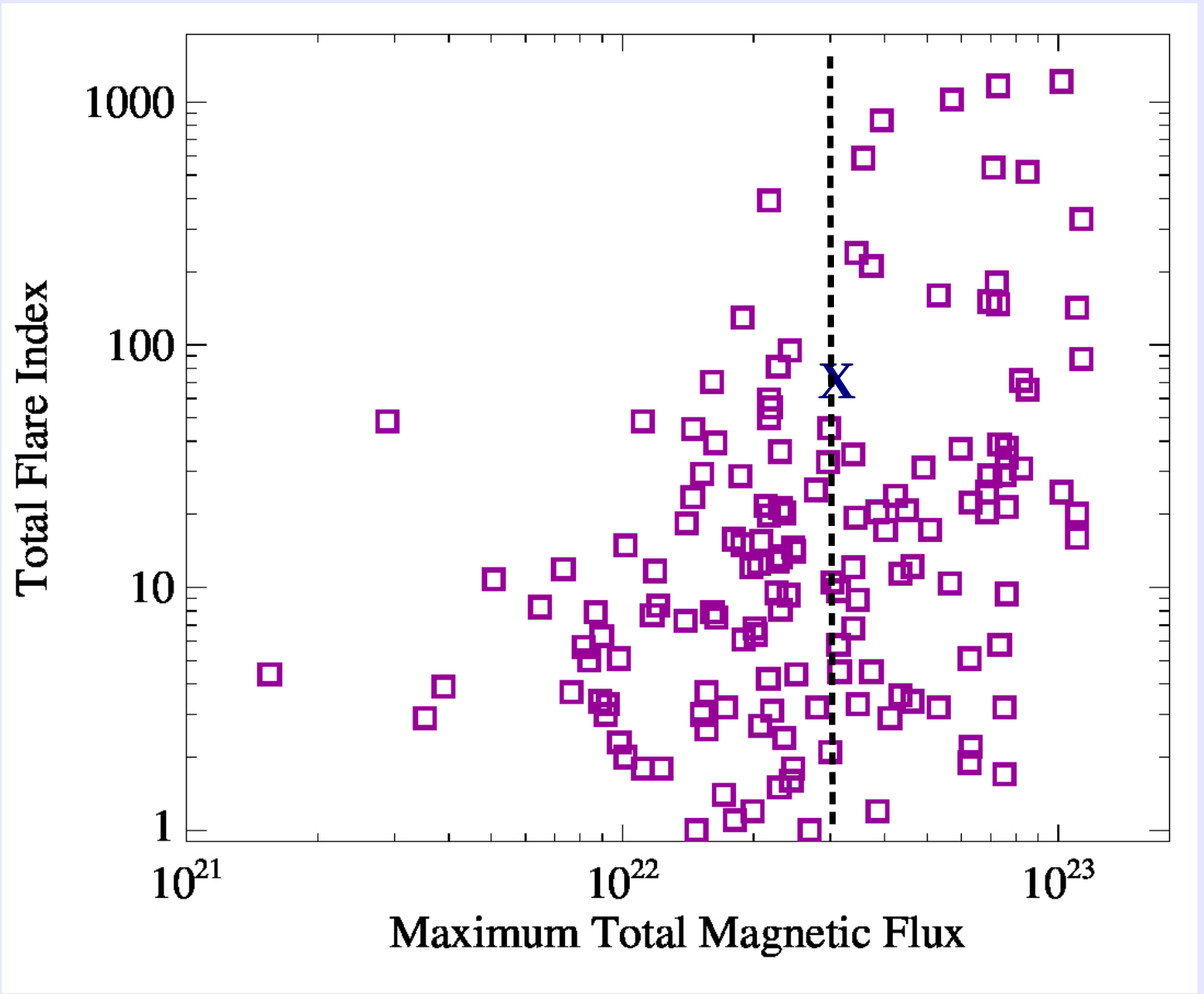




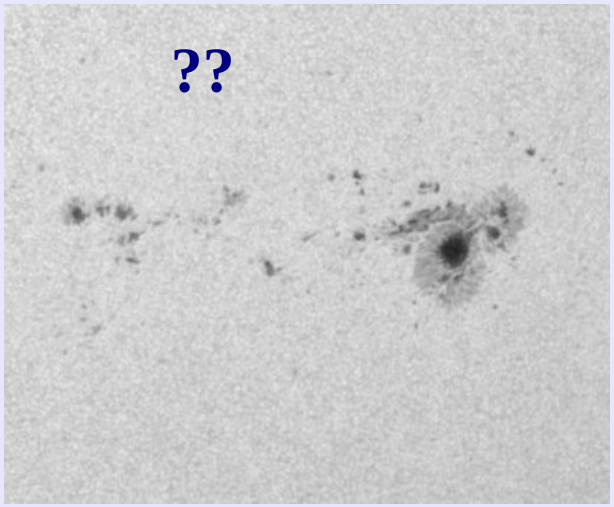


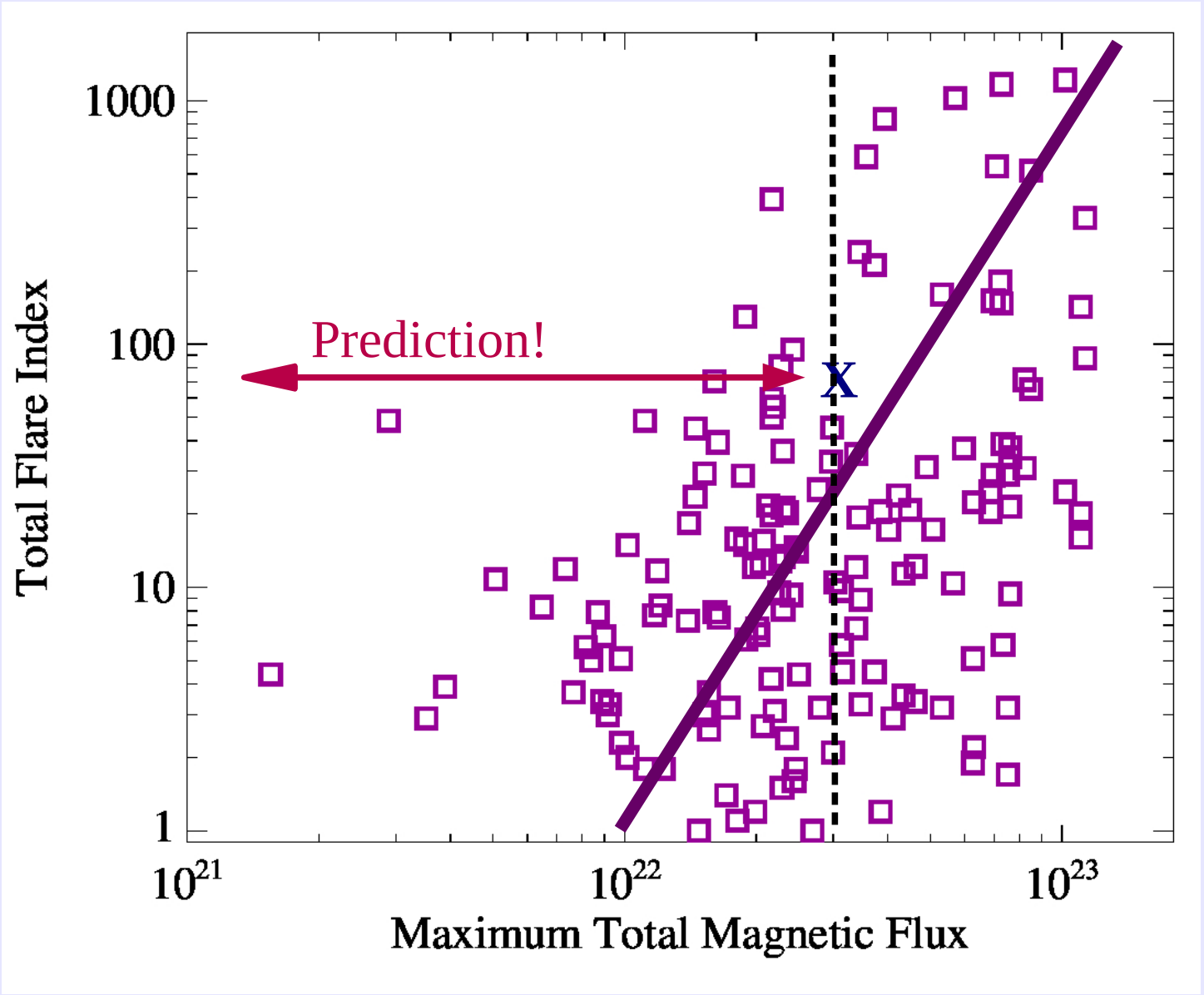
(2) New data to compare to the historical data.....





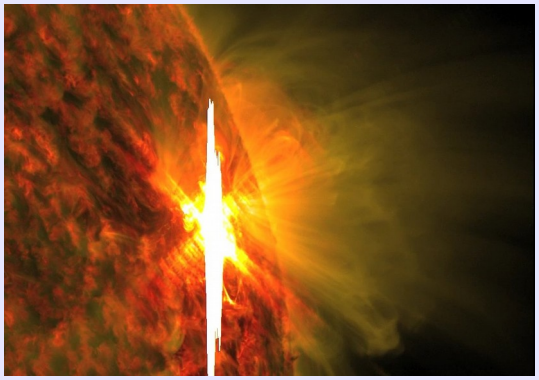
Using....(3) A statistical method to evaluate the New Data as compared to the historical data.

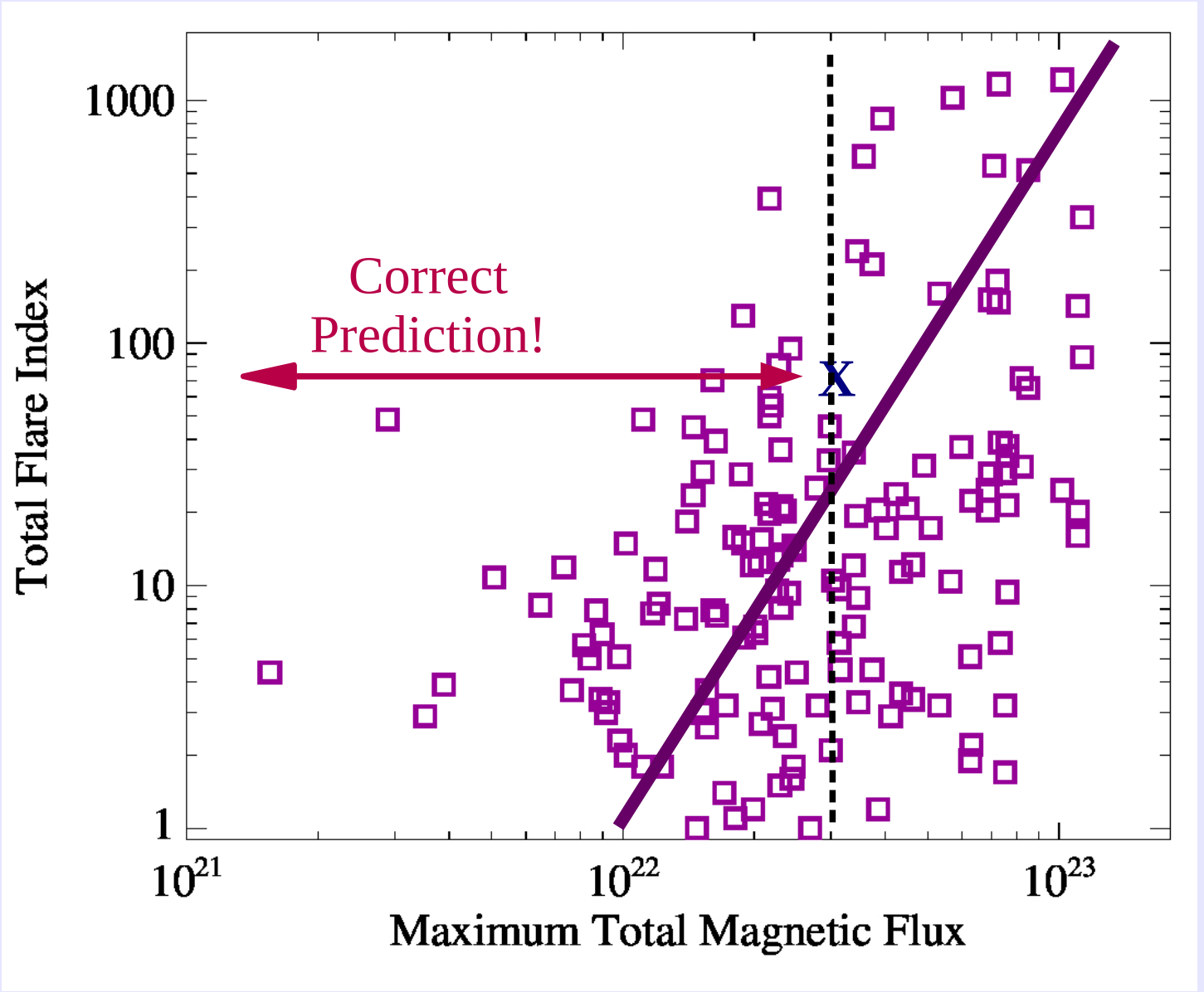




(4) An evaluation of how well you did.

Flare!





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- Correlations, Machine Learning, Neural Networks, [Non]-Parametric analysis.
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- Metrics & Skill Scores: Accuracy, POD, FAR, Hanssen & Kuiper ("True") Skill Statistic, Appleman Skill Score, Heidke Skill Score, Brier Skill Score, MSE, ROC plots, Reliability plots, *etc*.

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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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)
```

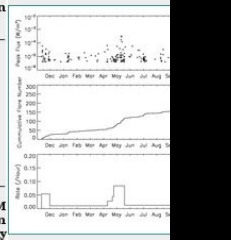
IDL code and scripts are run daily on the RHEA server at 6 AM CET, using the latest GOES 1-8 Å solar flare data obtained from NOAA. Each prediction is made for the duration of one day starting at 0000 UT of the day of the prediction, and using GOES data from the previous year (365.25 days). The text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

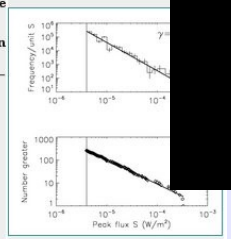
Please read the disclaimer before making use of any information provided by this service.

Latest Available GOES Data:

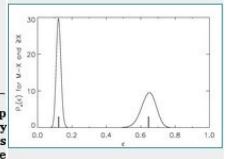
Date	Time (UT) Start	Max	End	Peak Flux (W/m2)	Class	Active Region
13/11/09	15:27	15:33	15:41	1.6e-06	(C1.6)	11892
13/11/09	15:44	15:52	15:58	1.4e-06	(C1.4)	11892
13/11/09	16:14	16:27	16:48	1.6e-06	(C1.6)	11894
13/11/09	17:00	17:07	17:20	1.7e-06	(C1.7)	11887
13/11/09	17:28	17:34	17:40	1.8e-06	(C1.8)	11895
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 Distribution



X-Ray Flare Prediction

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

ASAP Solar Flare Predicti

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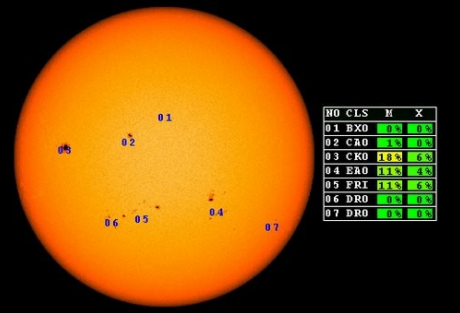
Flare Monitor (BETA)

SOLAR FLARE PROBABILITY = 20%



NO	CLS	M	X
01	BXO	0%	0%
02	CAO	0%	0%
03	CKO	18%	6%
04	EAO	18%	6%
05	FRI	18%	6%
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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http://swrl.njit.edu/

swrl.njit.edu

ASAP Solar Flare Pr

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- Data Archive
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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

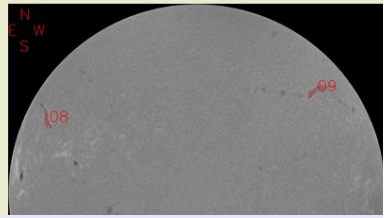
Daily Solar Flares Forecasting

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



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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

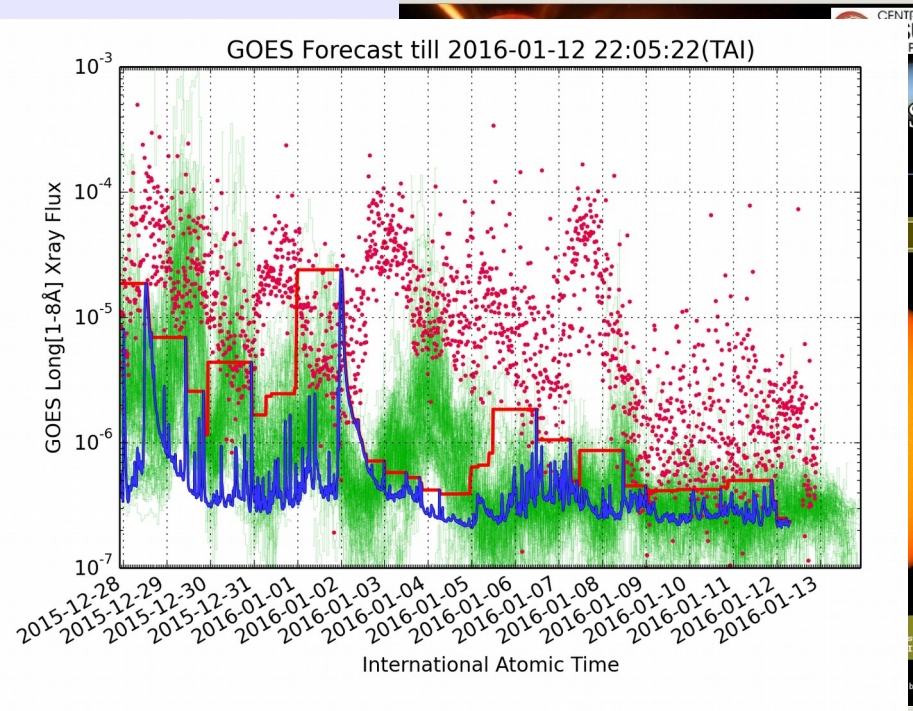
Iv. Penticton 10.7 cm Flux
Observed 14 Nov 176
Predicted 15 Nov-17 Nov 175/175/175
90 Day Mean 14 Nov 124

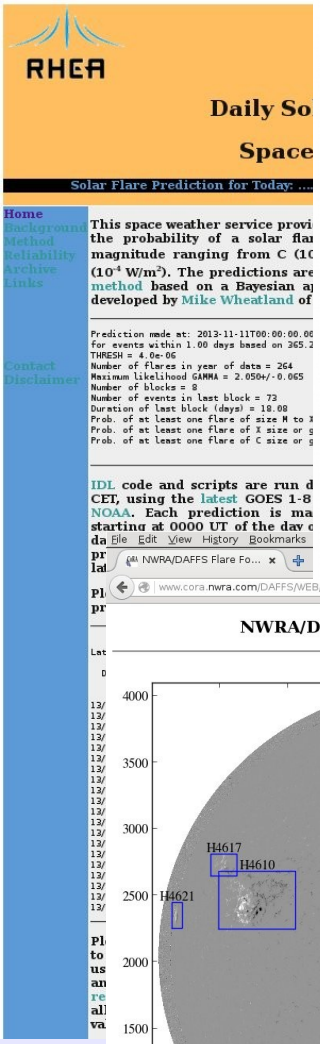
v. Geomagnetic A Indices
Observed Afr/Ap 13 Nov 002/004
Estimated Afr/Ap 14 Nov 003/003
Predicted Afr/Ap 15 Nov-17 Nov 005/005-007/008-011/012

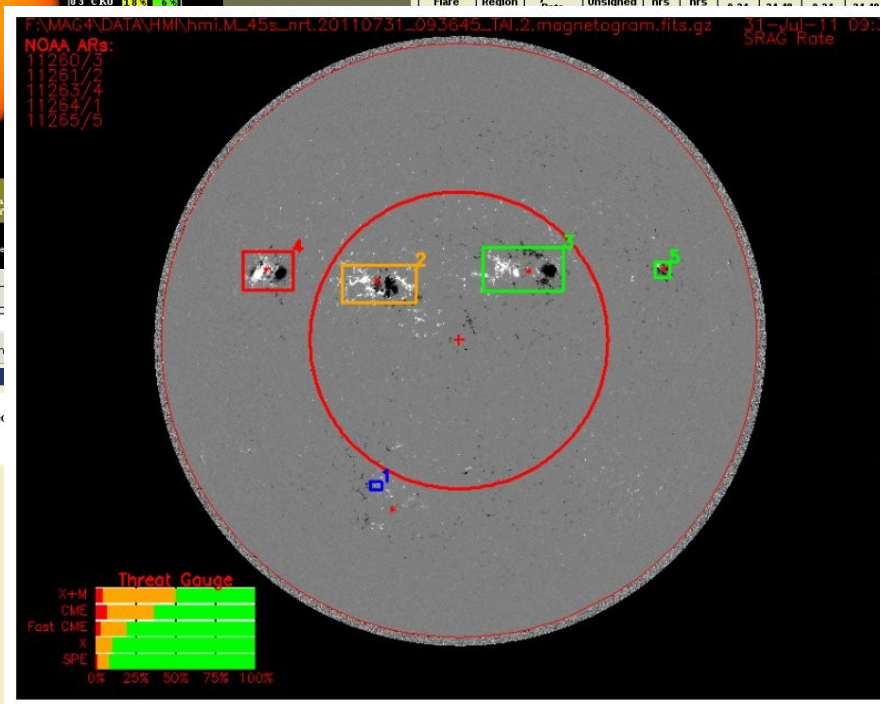
vI. Geomagnetic Activity Probabilities 15 Nov-17 Nov
A. Middle Latitudes
Active 10/20/35

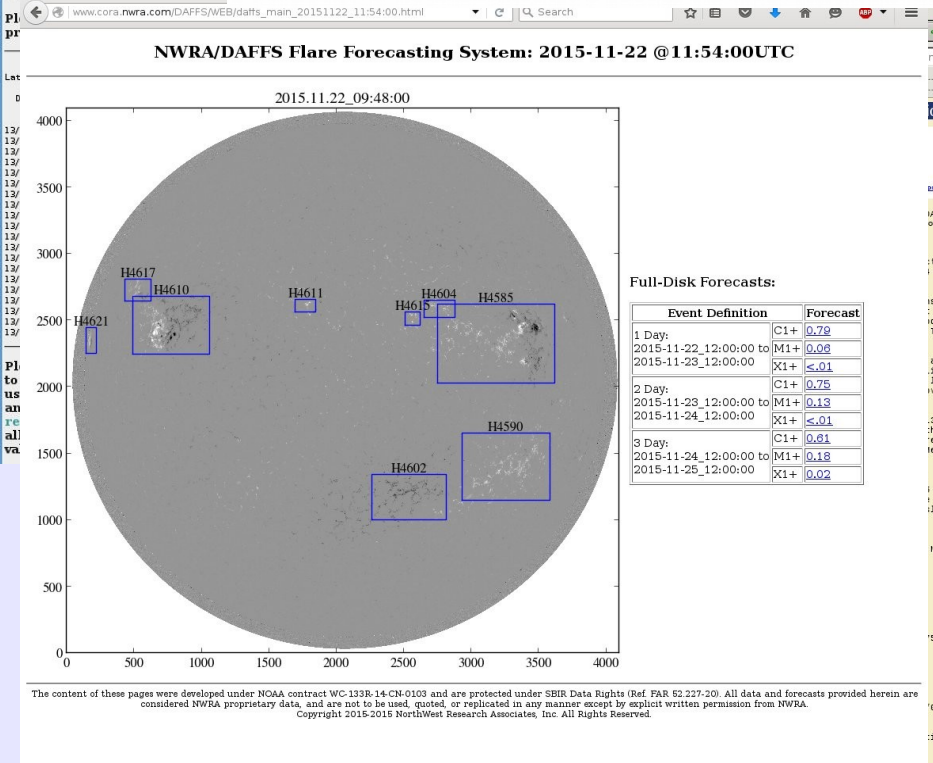
NORTHWE S

Present Status:







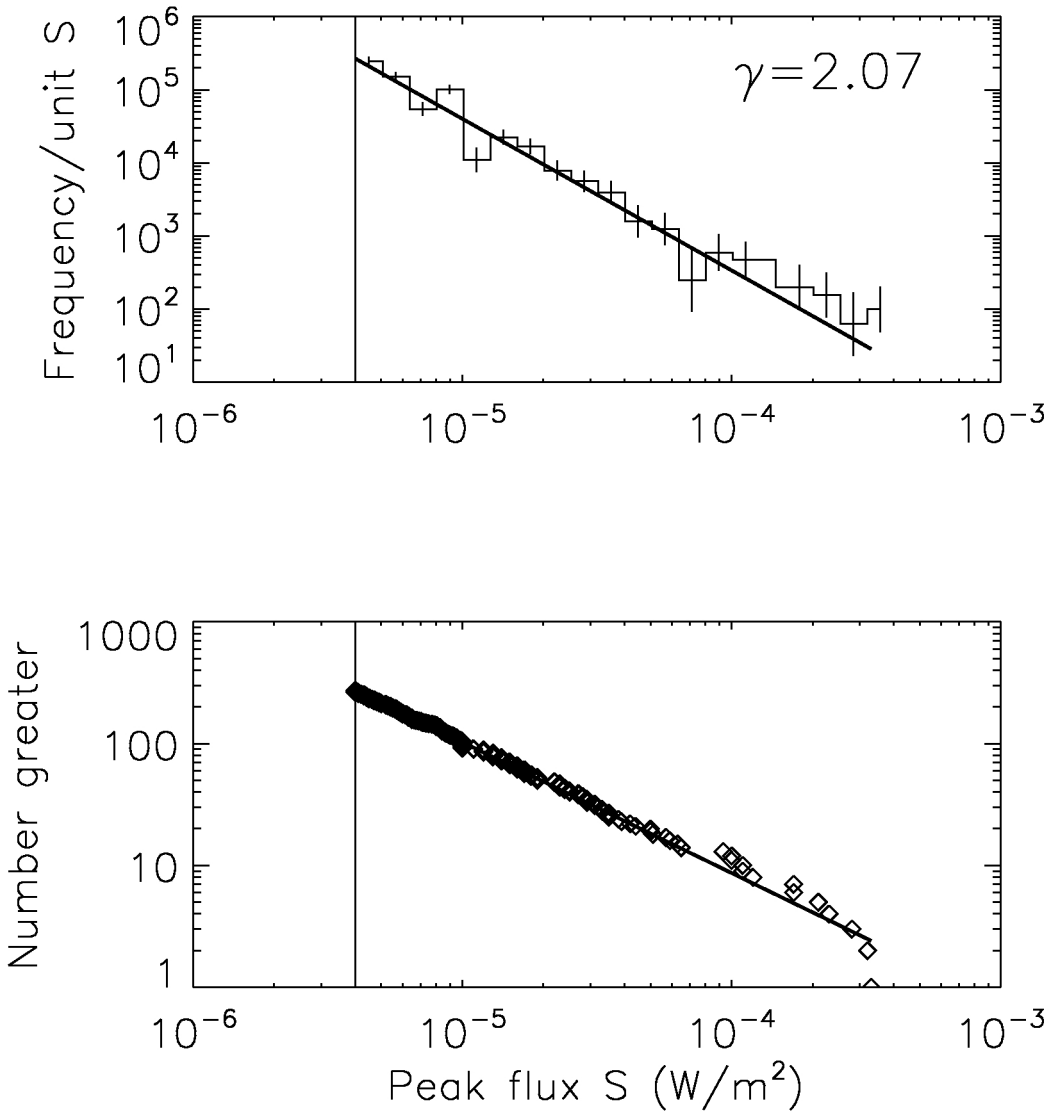


Present Status: Two basic approaches.

1) Pure Event Statistics.

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

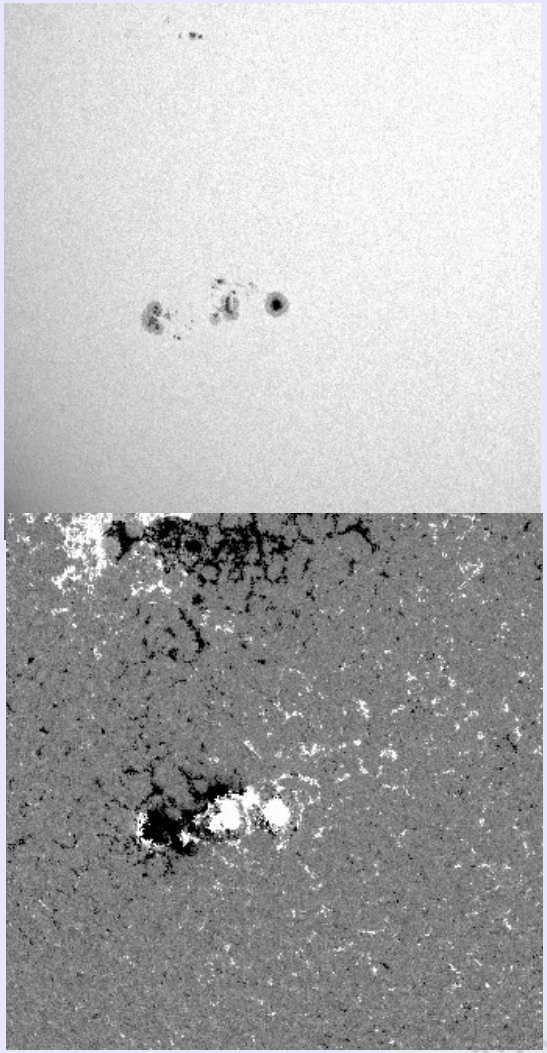
➔ **Use observed flare history to predict probable future flaring.**

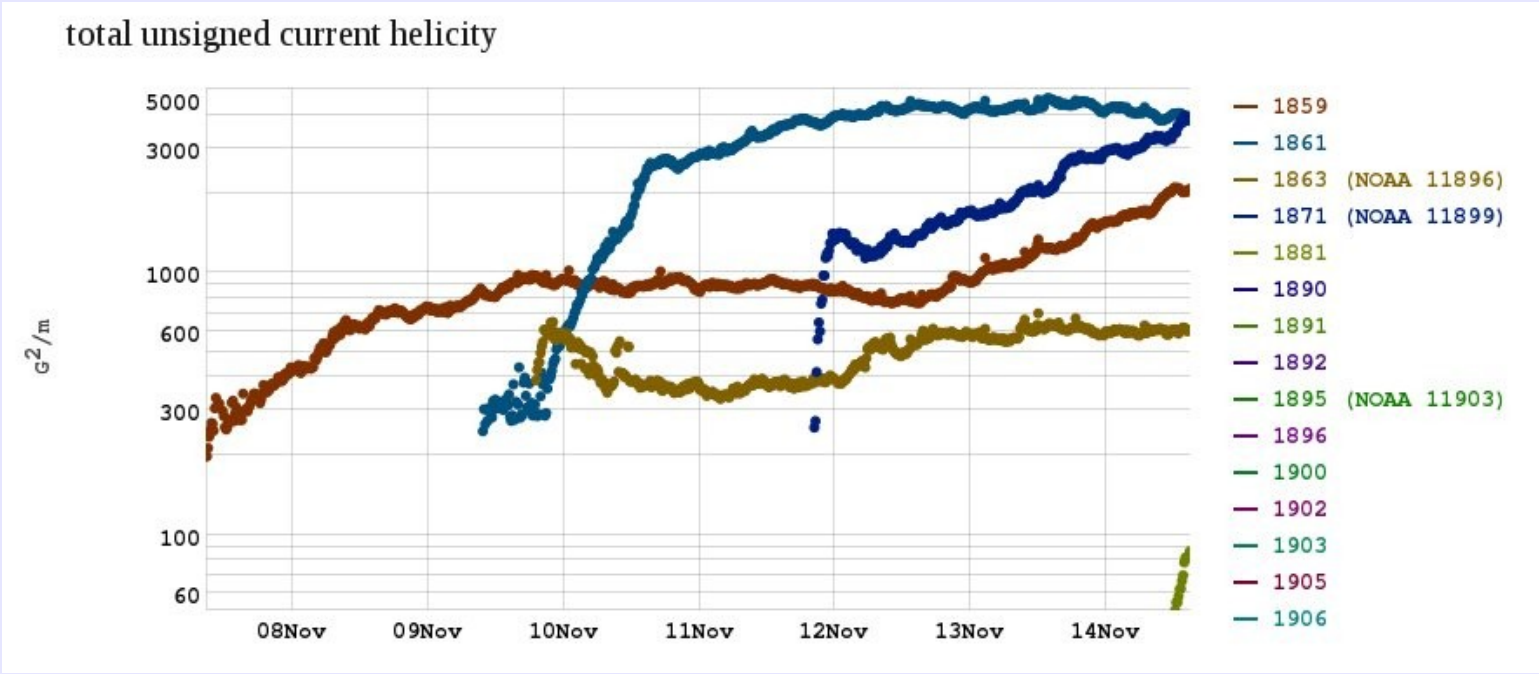


Present Status: Two basic approaches.

2) Characterize the Sun and possible flare "source regions"

➔ **Generally use solar photosphere images to parametrize characteristics.**





Present Status: How Well do Flare Forecasts work?
Answer #1: How do we measure success?

Common metrics answer different questions.

- *Skill Scores* measure how well forecasts performed *vs* a reference forecast.
    - Normalized: 1 is best, 0 is "no skill against reference"

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  - Bias
  - Accuracy
  - Reliability
  - Sharpness
  - Resolution
  - Uncertainty

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  - Bias
  - Accuracy
  - Reliability
  - Sharpness
  - Resolution
  - Uncertainty
- Different metrics are more/less sensitive to sample sizes, prior population ratios, event rates, *etc*.
- All are useful, and all must be interpreted carefully.

Present Status: How Well do Flare Forecasts work?
Answer #1: How do we measure success?

Common metrics answer different questions.

- *Example*: "Method X" predicts for the X flares.
  - Method X gets a forecast correct 98% of the time.

Present Status: How Well do Flare Forecasts work?
Answer #1: How do we measure success?

Common metrics answer different questions.

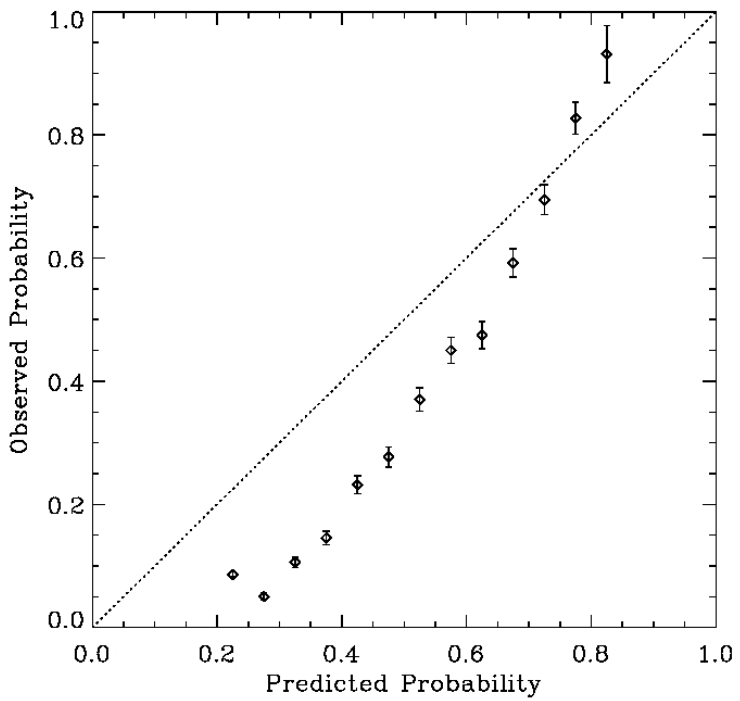
- *Example*: "Method X" predicts for the X flares.
  - Method X gets a forecast correct 98% of the time.
  - Unfortunately, these are very rare events: only occur in 1% of the data.
  - Forecast actually performs worse than simply forecasting that no events ever occur (Appleman Skill Score ≤ 0).
    - So, "98% correct" is actually *not* a very good result.

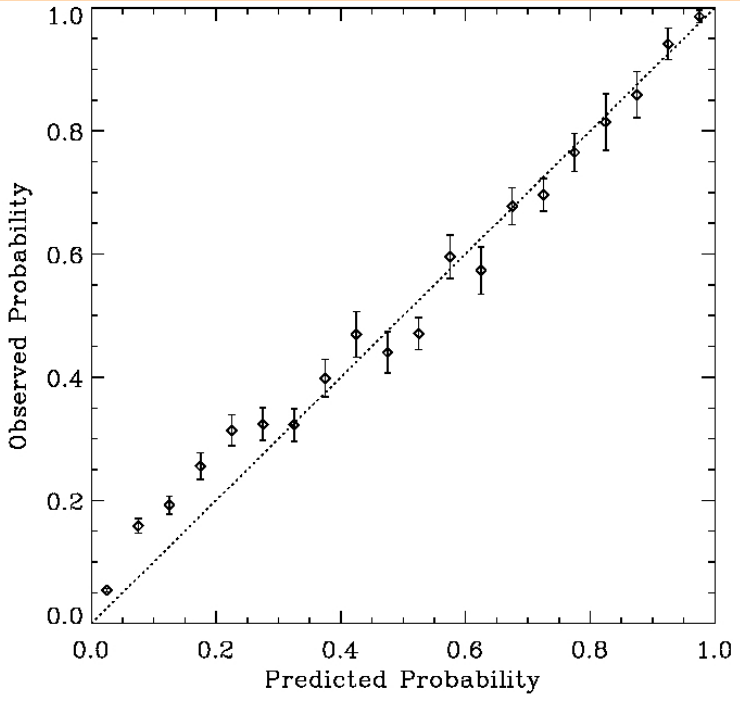
Answer #2: Who is asking, and for what purpose?

- Best for science ⇐ ?? ⇒ Best for operations.
- Example:
  - **True/Hanssen & Kuiper/Pierce metric:** measures the discrimination between probability of detection and false alarm rate (*science*).
  - **Brier/Mean Square Error Skill Score:** measures the difference between forecast probability and event fequency (*operations*).

	Method 1	Method 2	
True/H&K/Pierce metric:	0.43	0.42	← **similar**
Brier/MSE SS:	0.04	0.31	← **different**

Difference in Brier SS is reflected in ***reliability plots.***





Answer #3: There is considerable room for improvement.

- Reported scores can be high.
  - Many machine-learning methods optimize on TSS. Reported TSS scores can be high ($\geqslant 0.5$).
  - But TSS does not take prior probabilities into account, which can be significantly unequal for rare events.
  - High TSS does not necessarily mean a good operational method.

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Forecast				Reference
Flare Level	Interval (hr)	TSS	ACC	
C-class...	24	...	0.811	Colak & Qahwaji (2009)
.....	24	0.650	0.818	Song et al. (2009)[a]
.....	24	0.090	0.722	Yuan et al. (2010)
.....	24	0.443	0.711	This work: optimum TSS
.....	24	0.399	0.824	This work: optimum HSS
M-class...	24	...	0.944	Colak & Qahwaji (2009)
.....	24	0.621	0.873	Song et al. (2009)[a]
.....	24	0.054	0.652	Yuan et al. (2010)
.....	24	0.526	0.829	This work: optimum TSS
.....	24	0.272	0.949	This work: optimum HSS
X-class...	24	...	0.981	Colak & Qahwaji (2009)
.....	24	0.693	0.945	Song et al. (2009)[a]
.....	24	0.160	0.843	Yuan et al. (2010)
.....	6	0.312	0.694	Mason & Hoeksema (2010)[b]
.....	24	0.740	0.881	This work: optimum TSS
.....	24	0.241	0.988	This work: optimum HSS

Answer #3: There is considerable room for improvement.

- Reported scores can be high.
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  - But TSS does not take prior probabilities into account, which can be significantly unequal for rare events.
  - High TSS does not necessarily mean a good operational method.

- Reported Brier scores generally lower.
  - *Generally* $\leqslant 0.5$, sometimes $\leqslant 0.1$ for large flares (rare events).
  - Brier scores more applicable to operations (probabalistic forecasts).

Table 16. Optimal Performance Results: SMART2 with Cascade Correlation Neural Networks

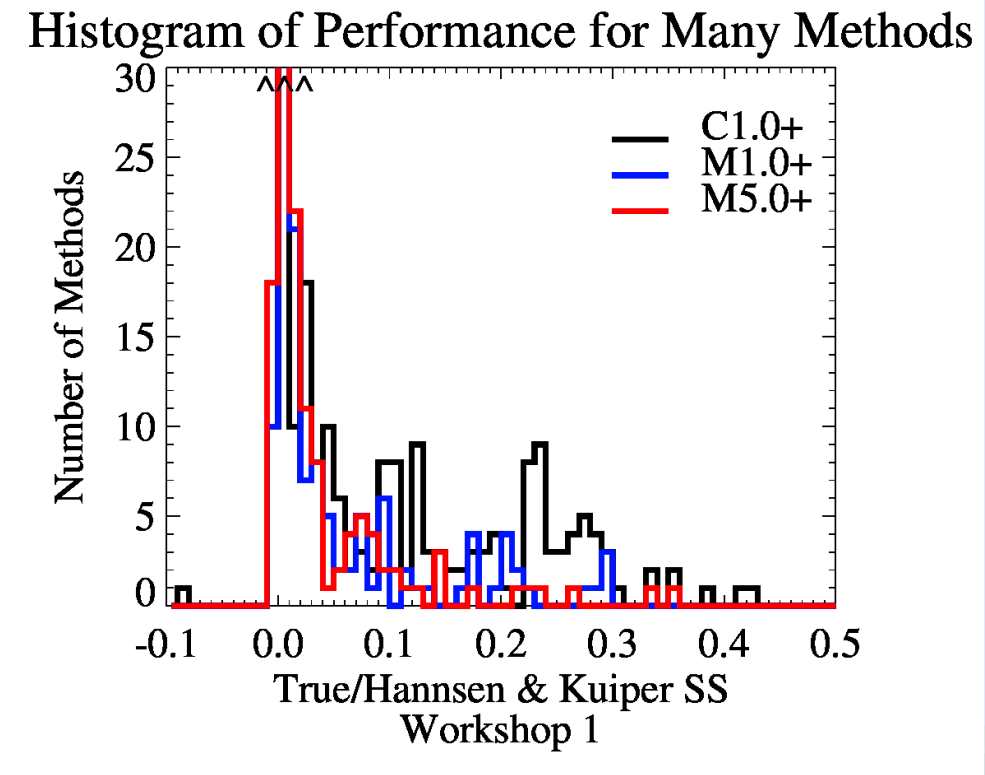
Event Definition	Sample Size	Event Rate	Rate Correct	Heidke SS	Appleman SS	Hanssen & Kuipers' SS	Brier SS
C1.0+, 24 hr	11536	0.21	0.81	0.49	0.13	0.52	-0.13
M1.0+, 12 hr	"	0.032	0.92	0.29	-1.36	0.50	-4.62
M5.0+, 12 hr	"	0.007	0.98	0.22	-2.35	0.48	-12.1

(not yet final/published)

Answer #3: There is considerable room for improvement.

- **Comparing methods is very difficult.**
  - Questions need to be posed very carefully.
  - Evaluations need be calculated very carefully.
  - Operations or Science?

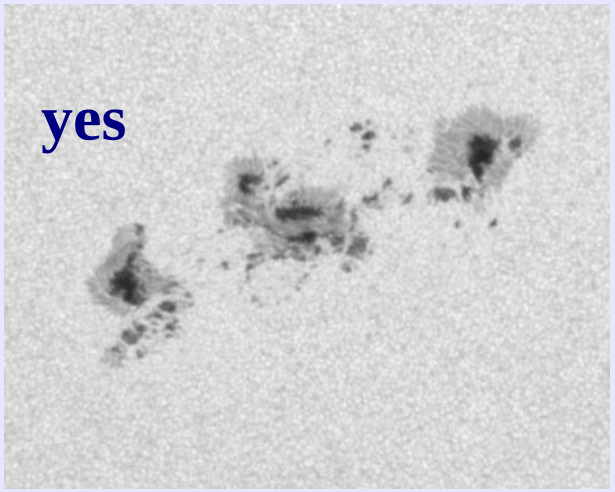
- **Some methods are better than others.**
  - Most are not significantly better than climatology.
  - None should (yet) be called “great”.

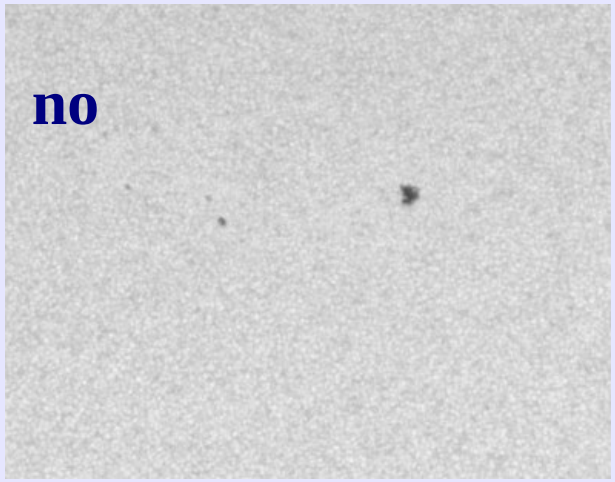


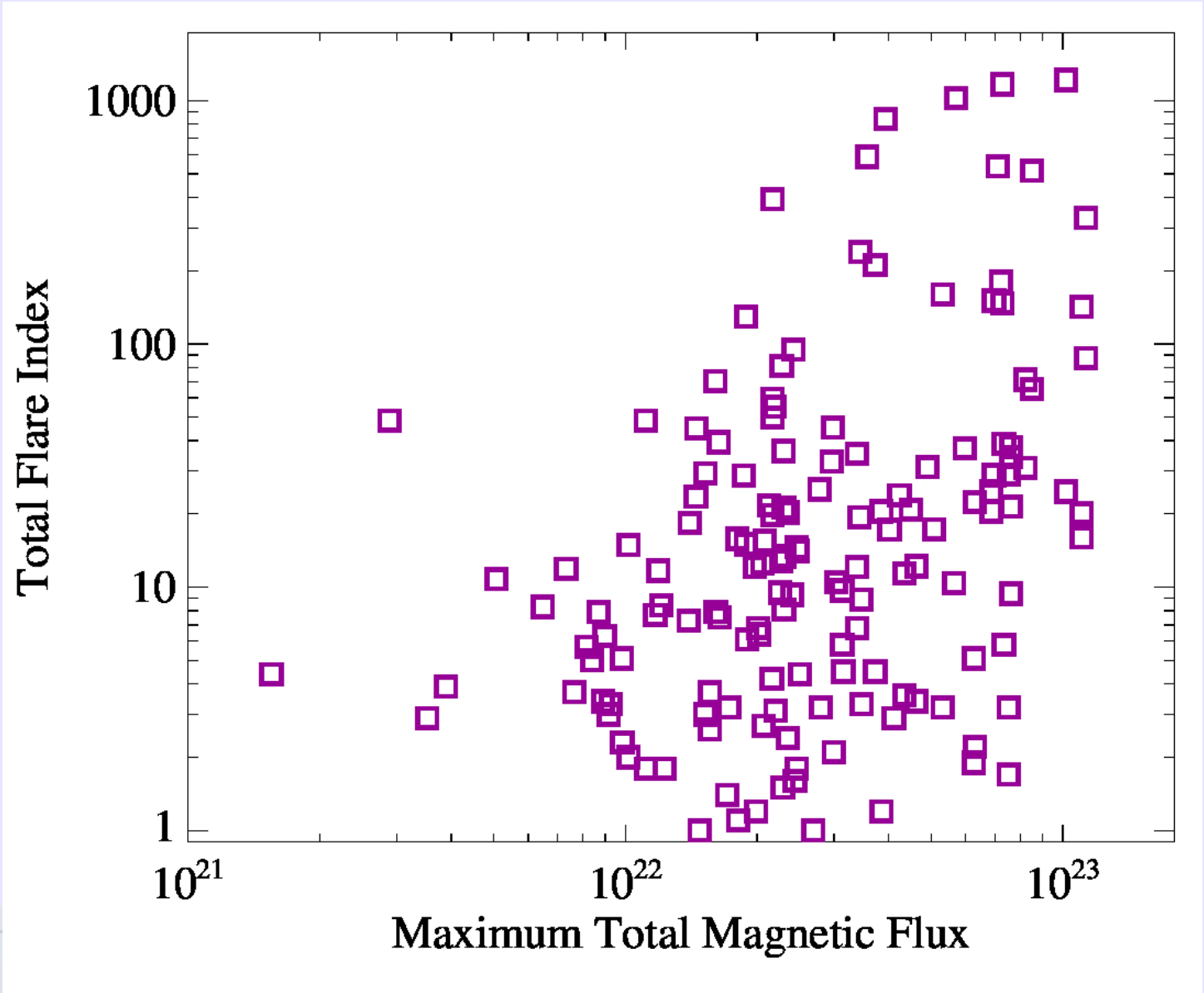
Why this is hard, I: *we do not understand the physics.*

We know "Causes of Flares":

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







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

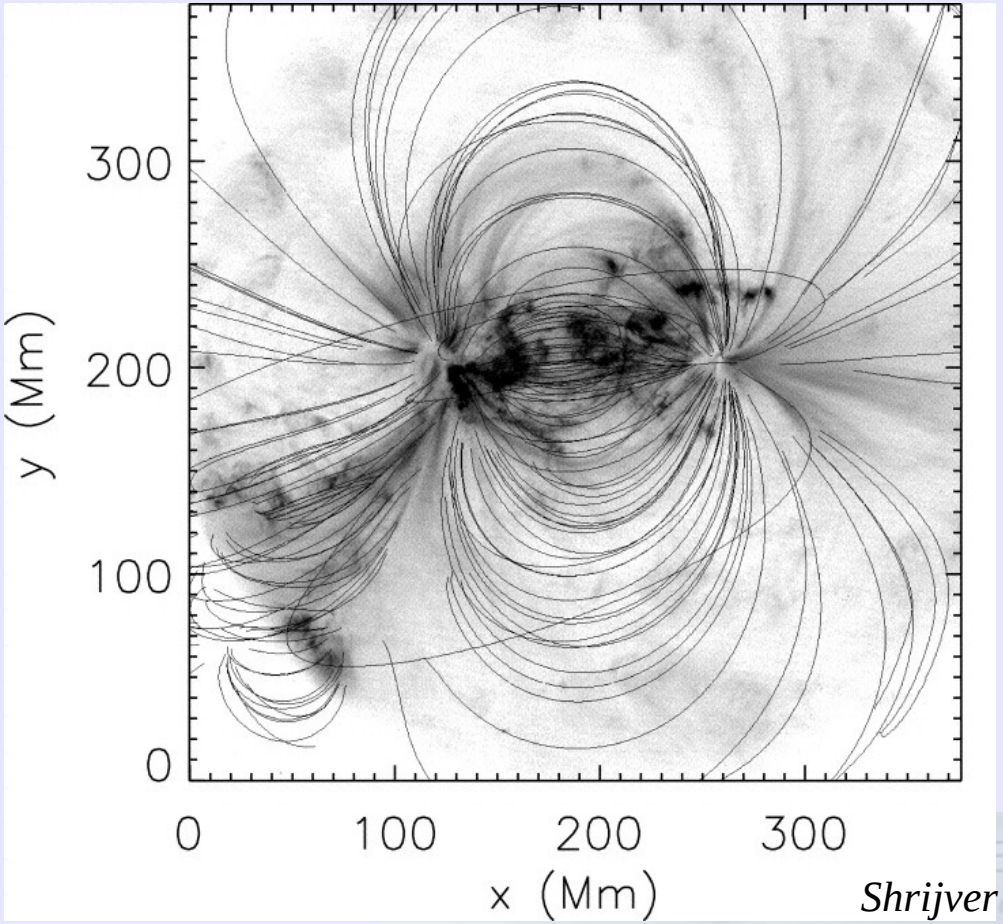
We know "Causes of Flares":

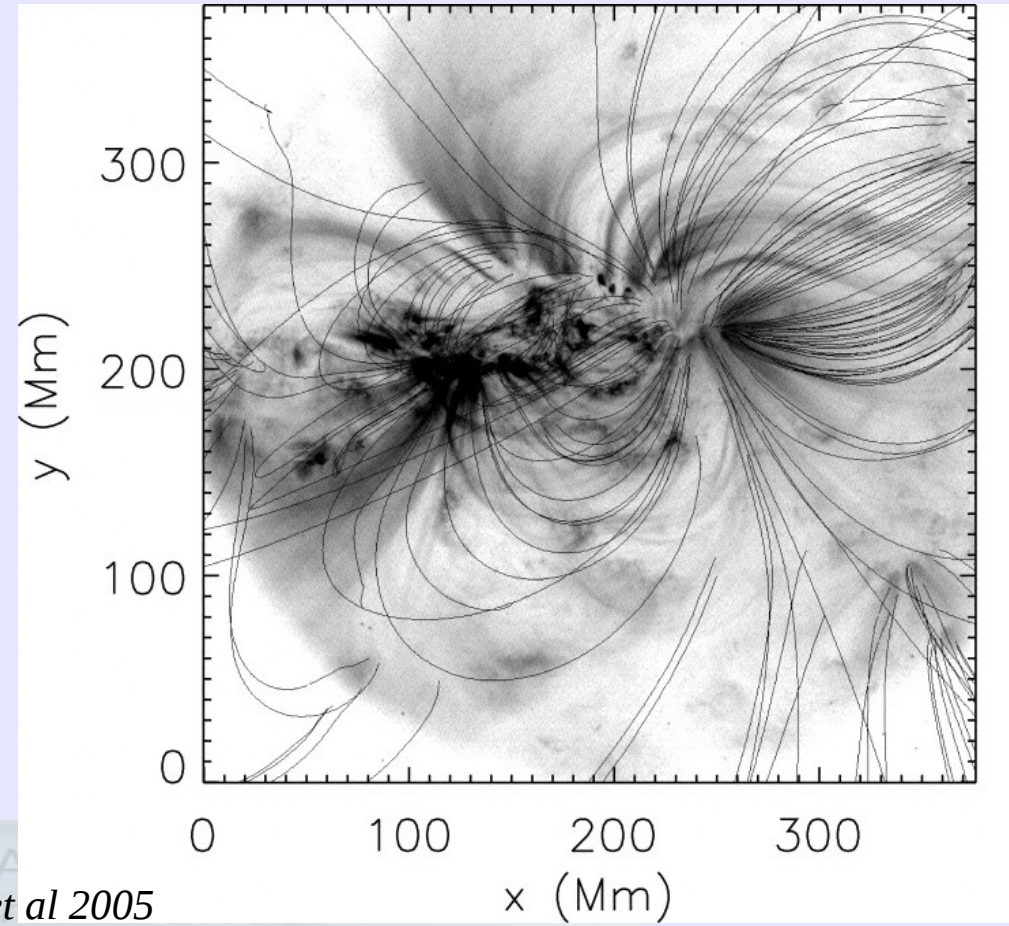
- Non-potential, complex, active-region magnetic fields.
- Indicates significant "free magnetic energy" is available.

Coronal Loops vs. Potential Extrapolations:

potential/simple

non-potential/sheared/complex



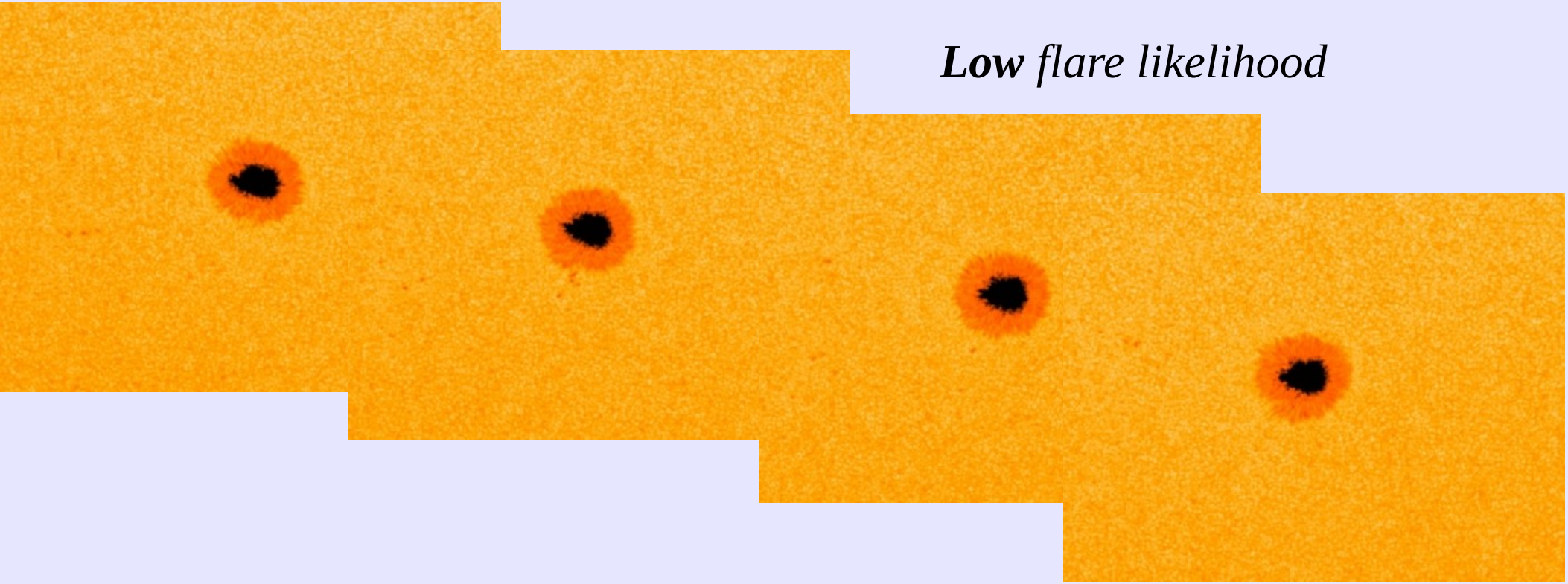


Shrijver et al 2005

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

We know "Causes of Flares":

- Rapidly evolving.



***Low** flare likelihood*

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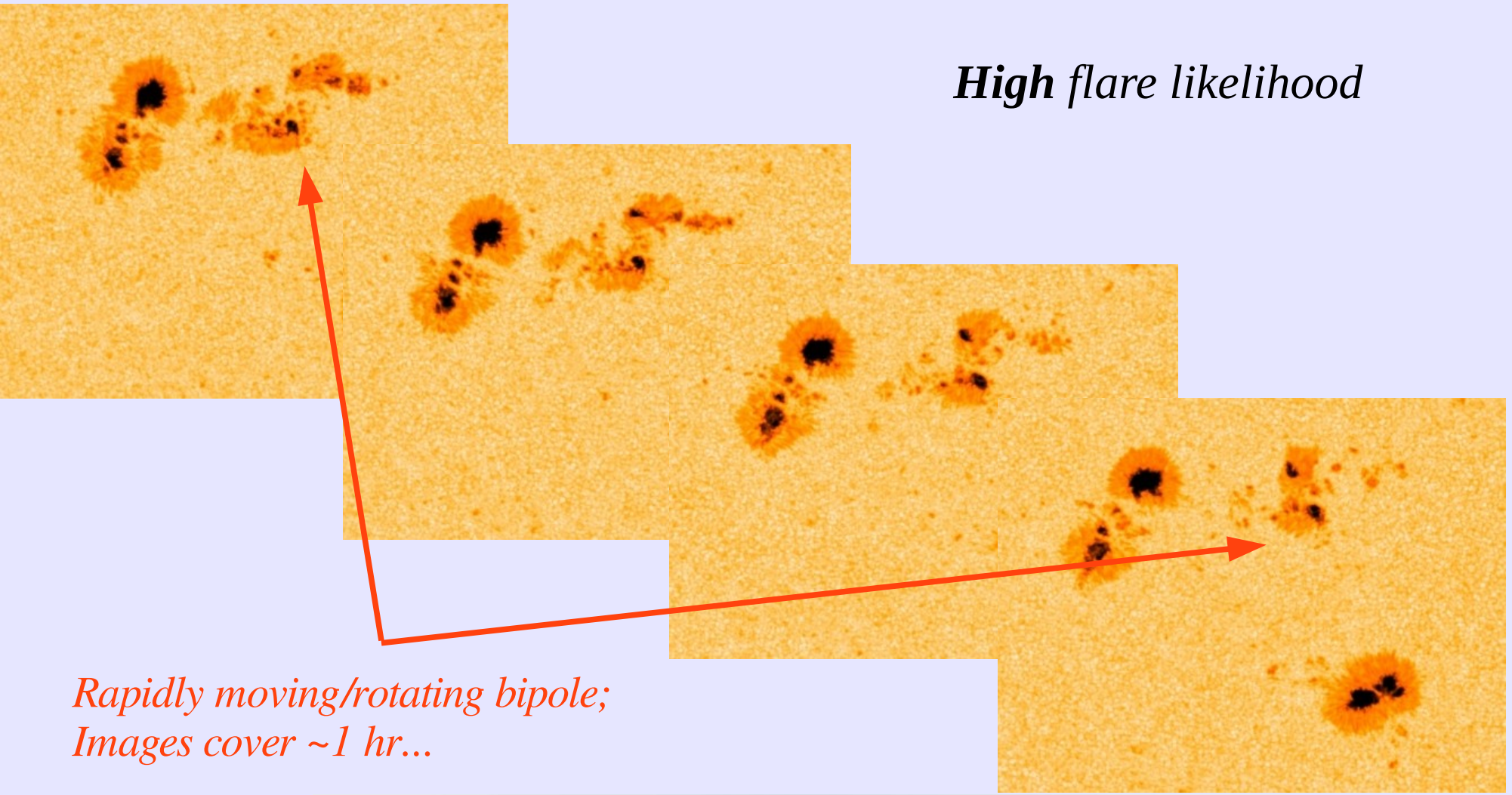

***High** flare likelihood*

Rapidly moving/rotating bipole;
Images cover ~1 hr...

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

To flare, an active region likely to be large, complex, and quickly evolving.

..... But what is the trigger?

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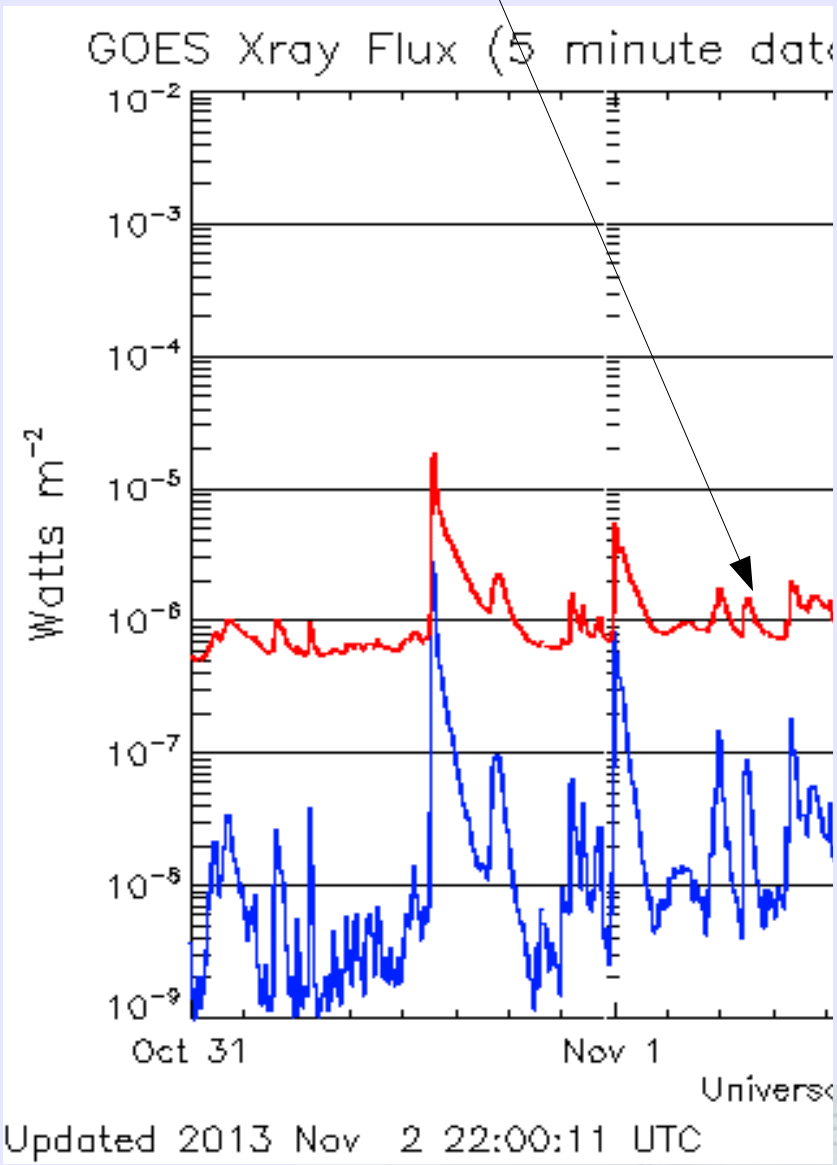
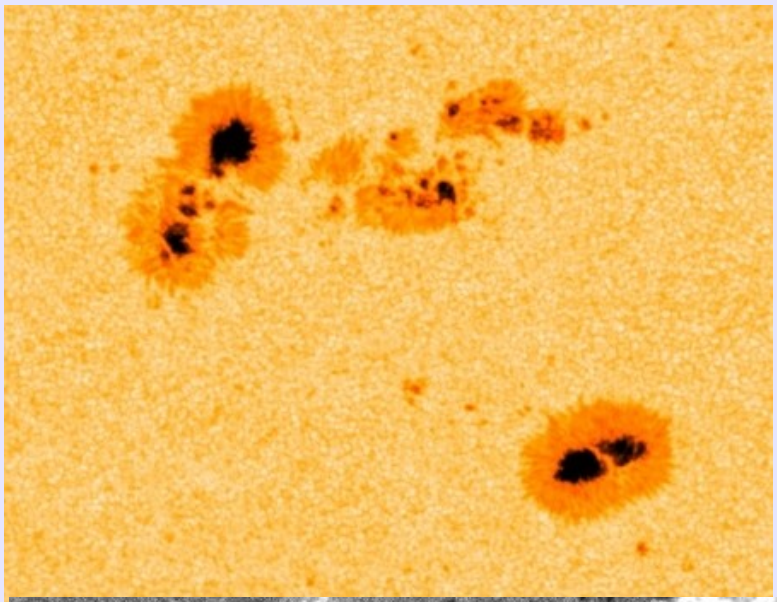
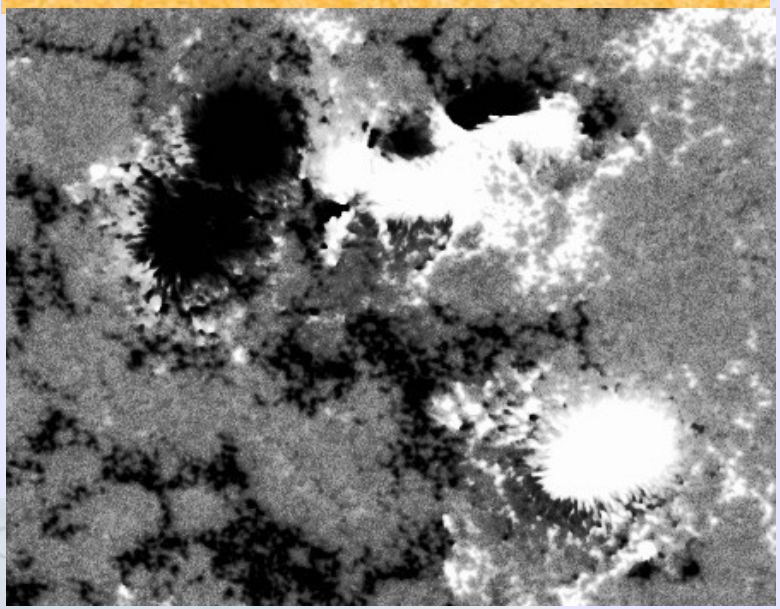
..... But what is the trigger?

Why *not* now?







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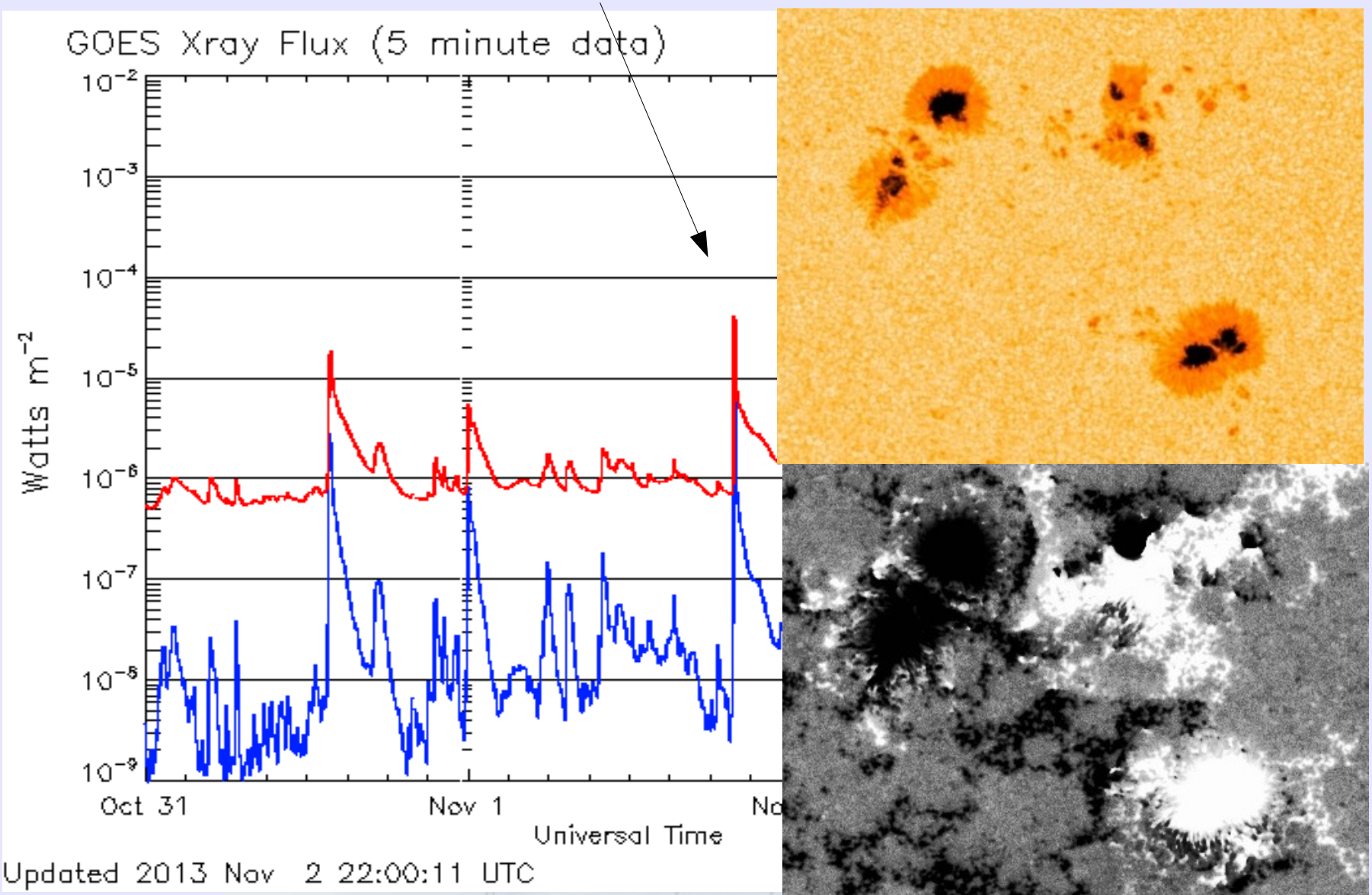
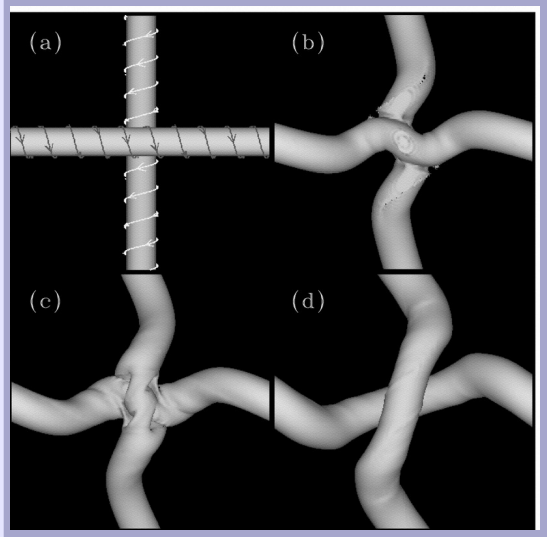
..... But what is the trigger?

But *now*?



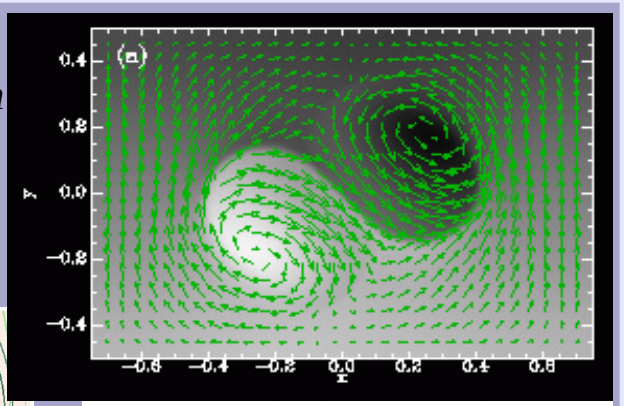
Q: What is a “solar flare”?

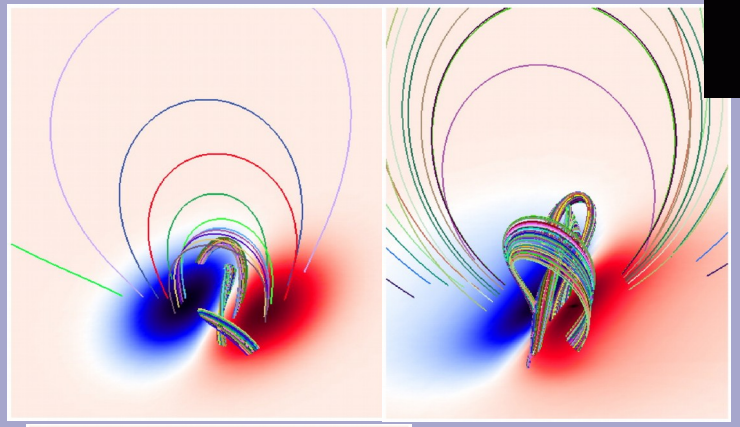
Modeler's view:

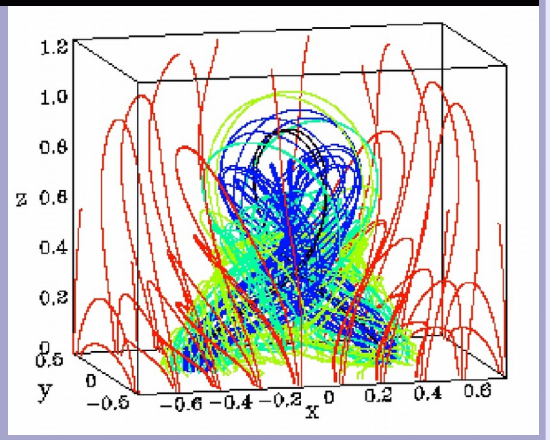


Linton & Antiochos 2002

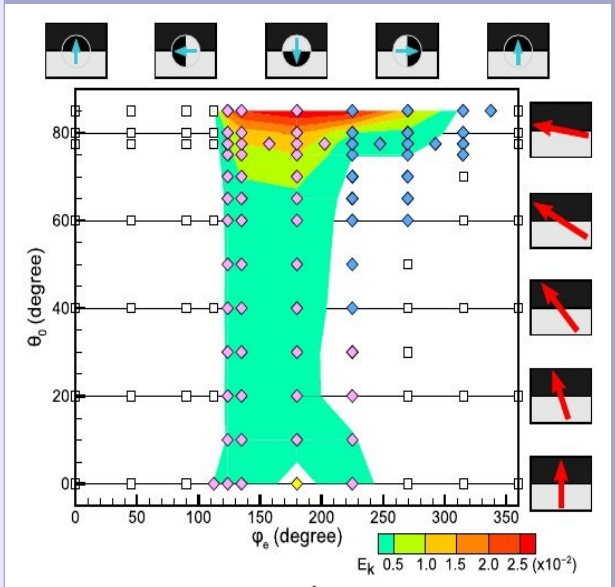
Fan & Gibson 2003, 2004

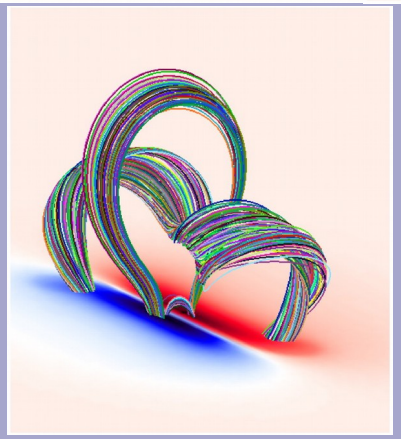




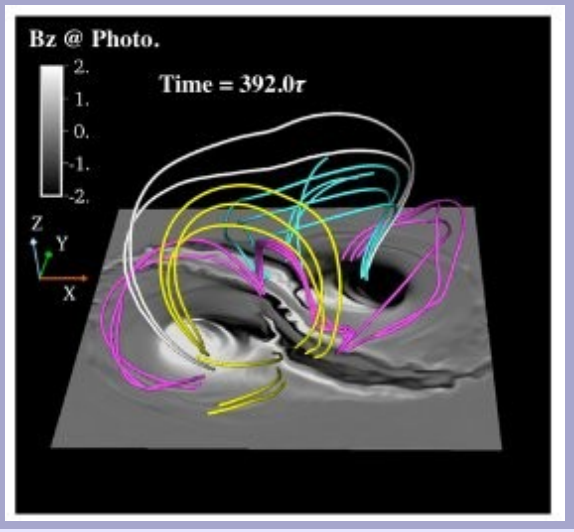


Kusano et al 2012





Amari, Luciani, Aly, Mikic & Linker 2003



Takasao et al 2015

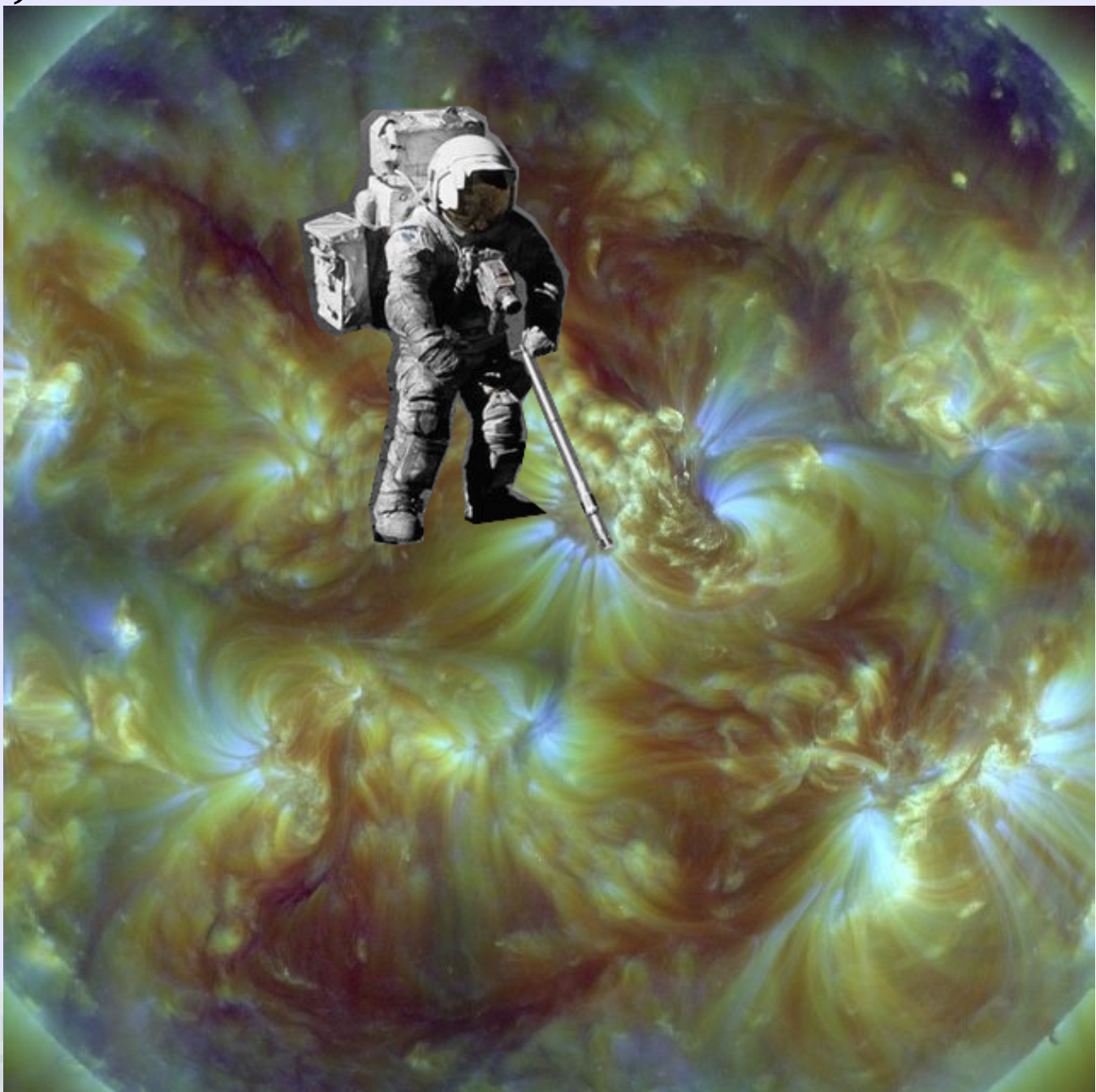
Why this is hard, II: *remote sensing*.

Unlike Terrestrial Weather,

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

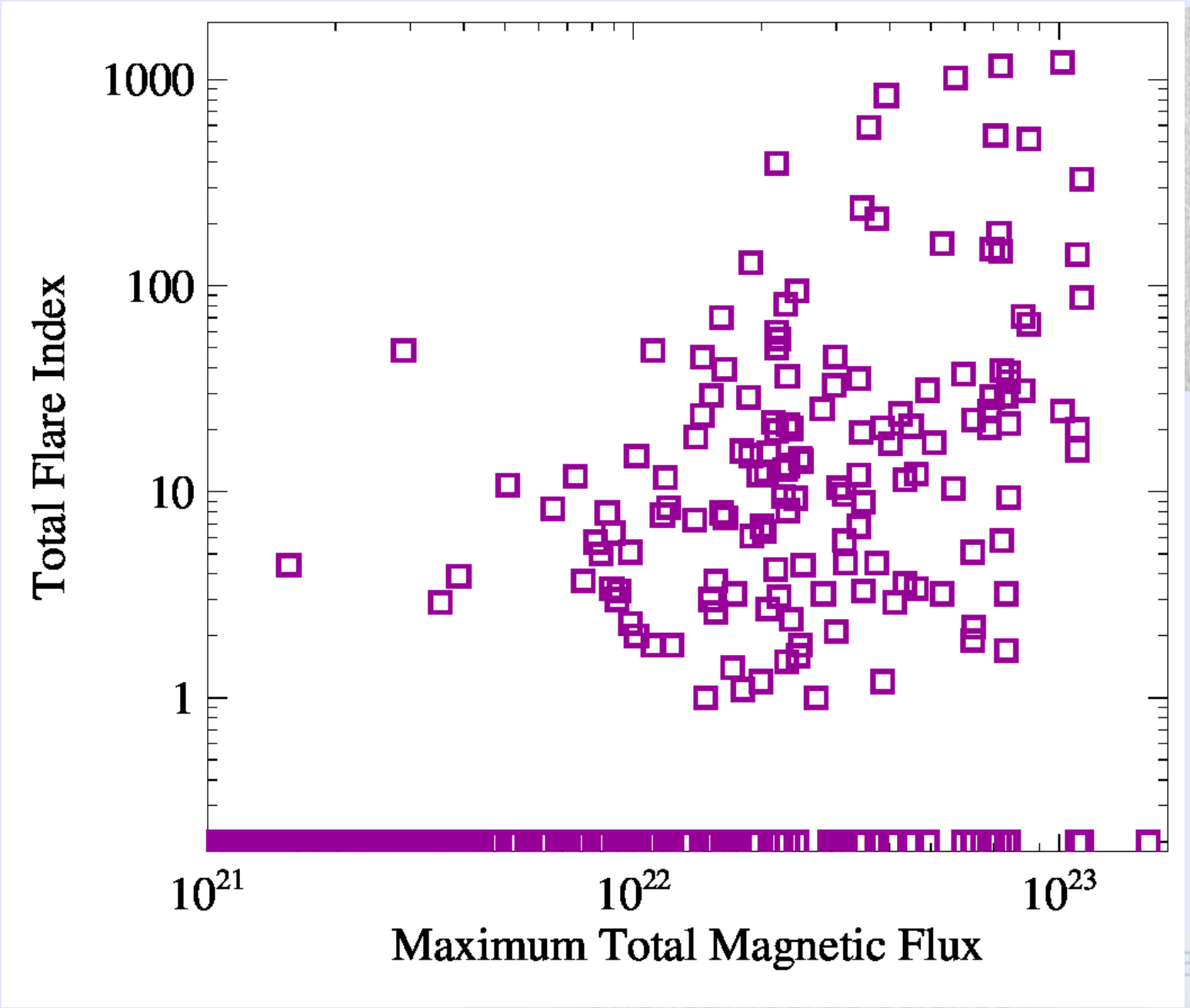
Unlike Terrestrial Weather, we will never* get *regular* in-situ measurements from the Sun.

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

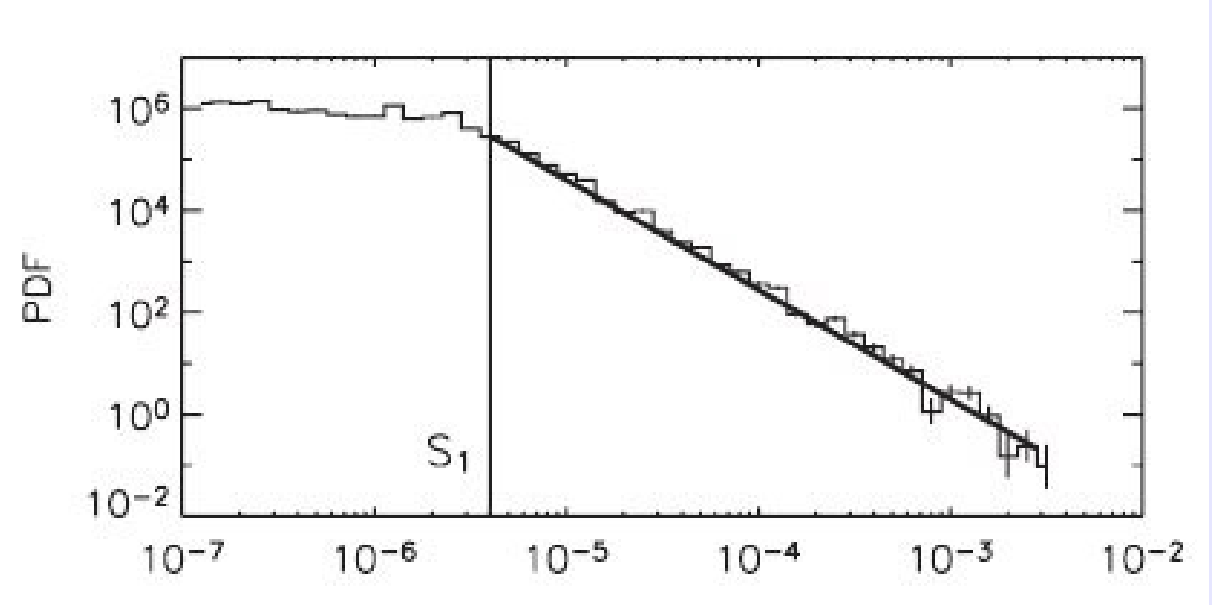


**I think I'm fairly safe saying "never" here.*

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



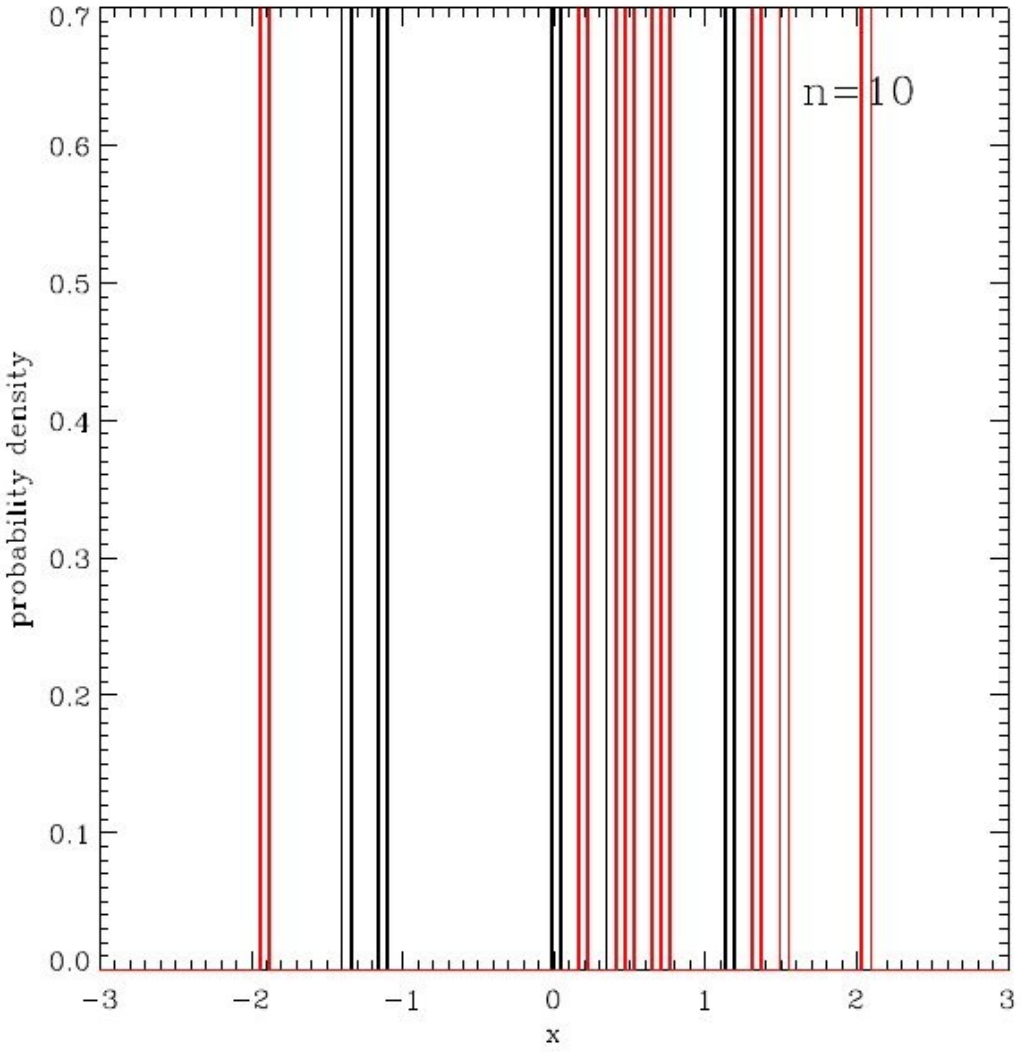
Why this is hard, IV: *Yet these are rare events.*

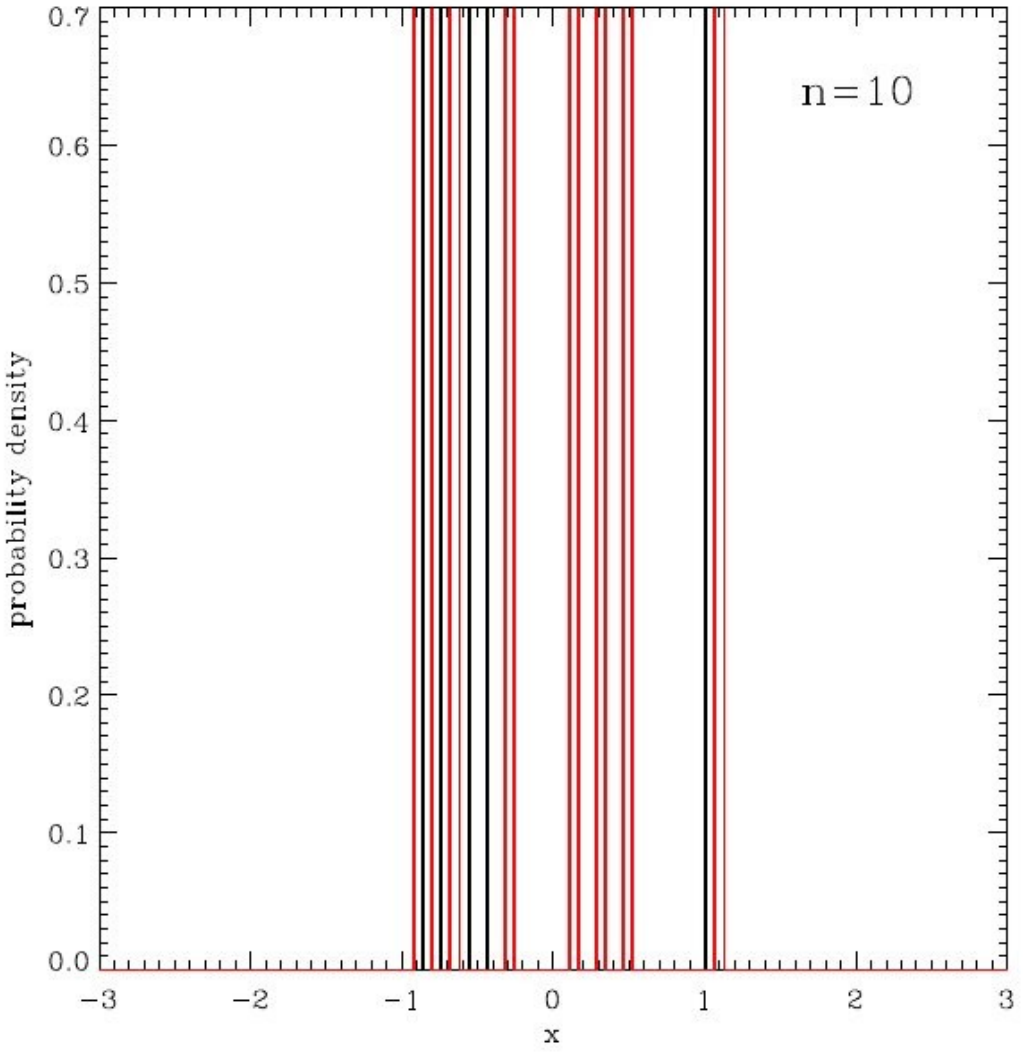


Probability Density Function of peak flare magnitude (1-8 Å, W m^{-2}), showing relative frequencies of small *vs*. large flares. From Wheatland 2005.

Small-number statistics

Are the samples in each plot drawn from different populations?

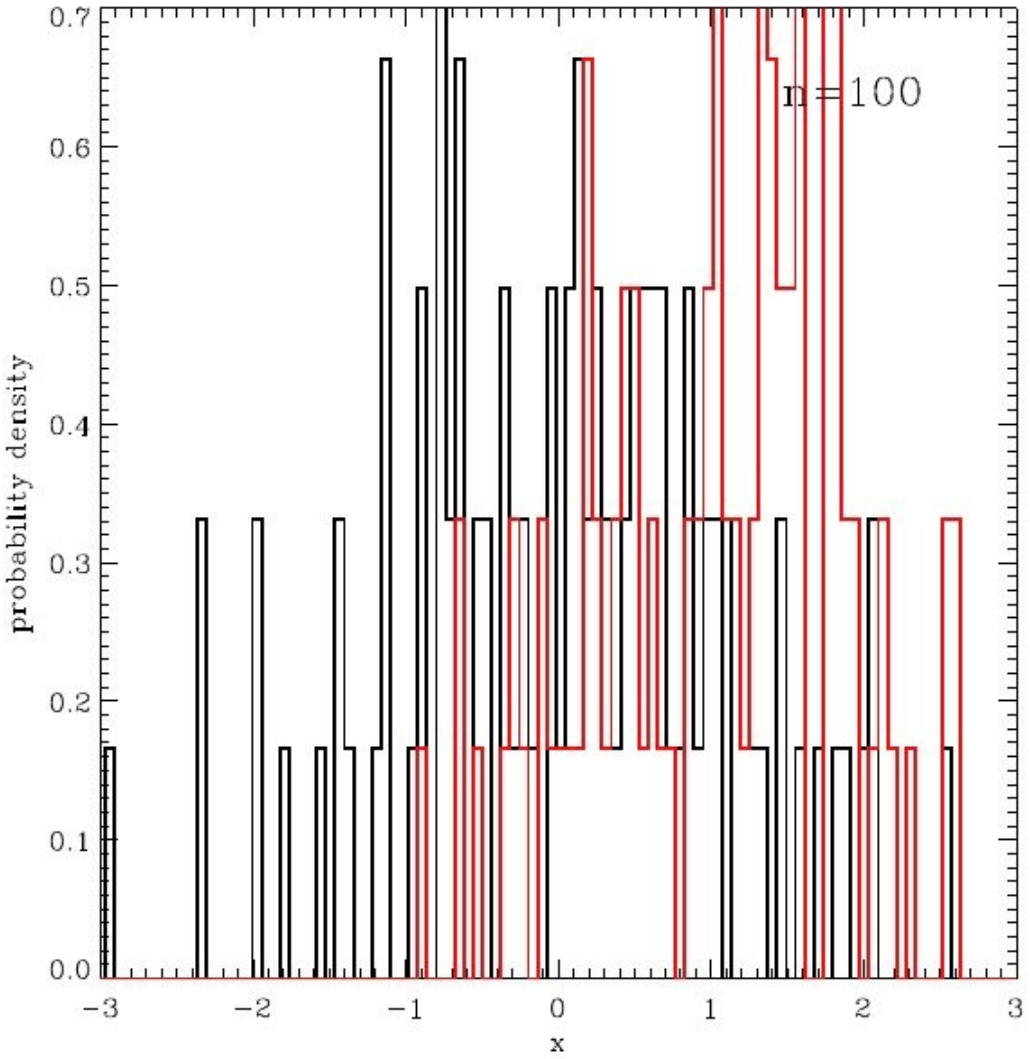


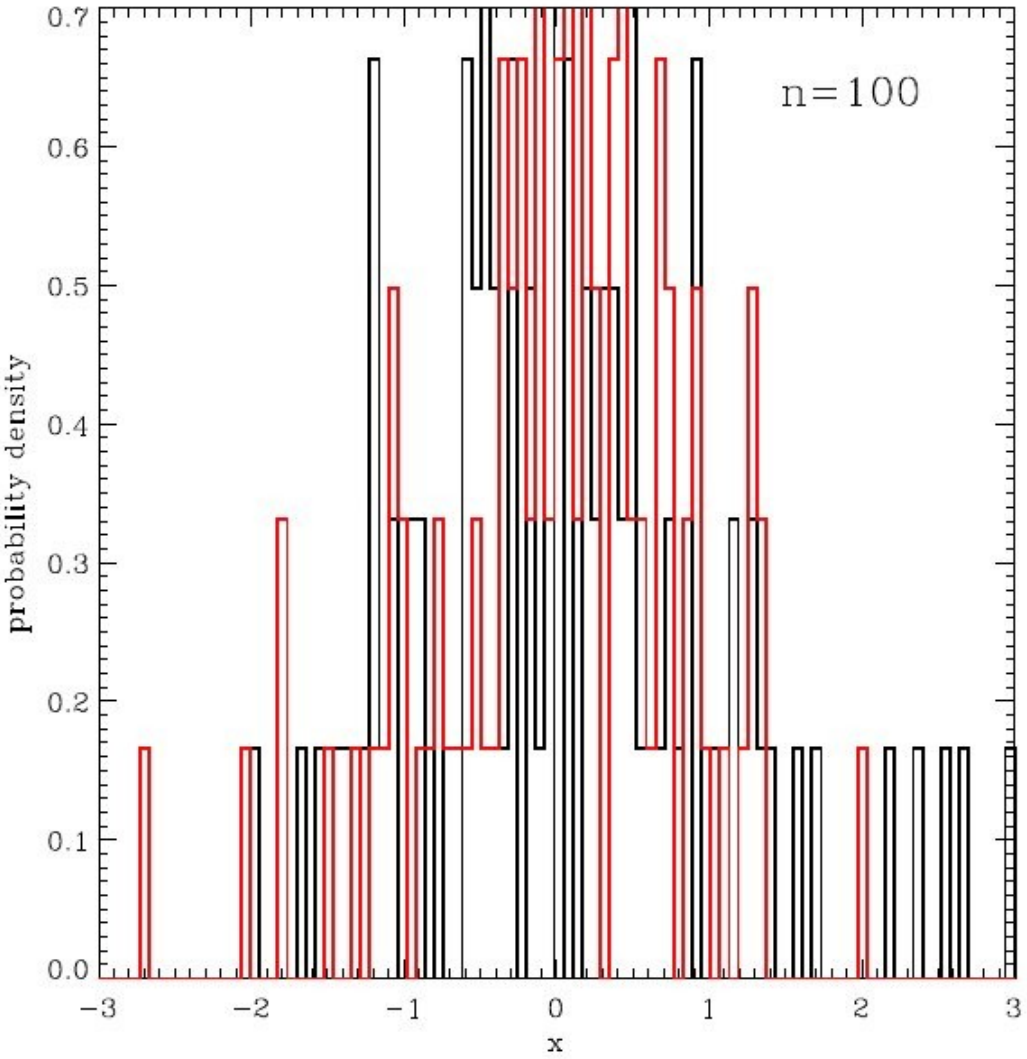


No obvious difference at this sample size.

Small-number statistics

Are the samples in each plot drawn from different populations?

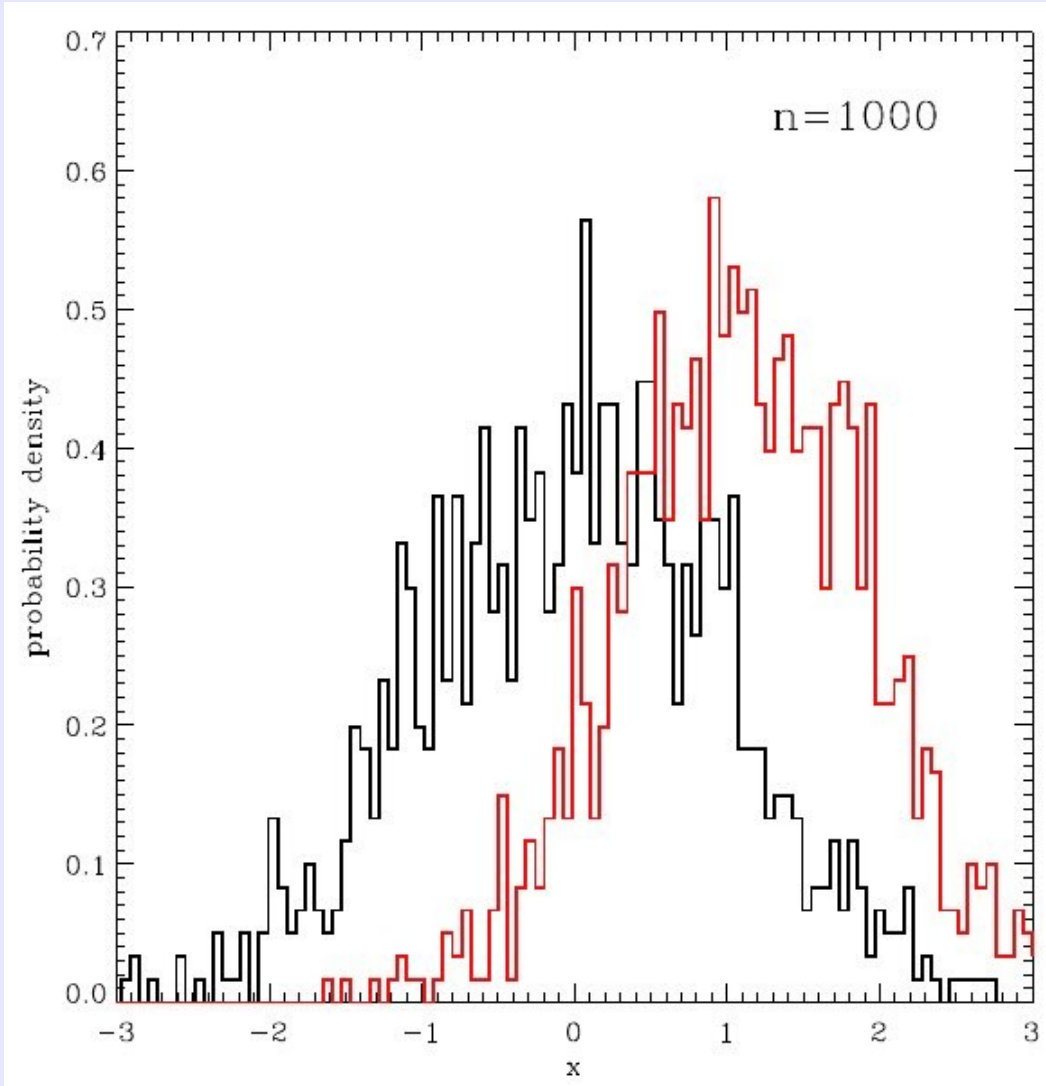


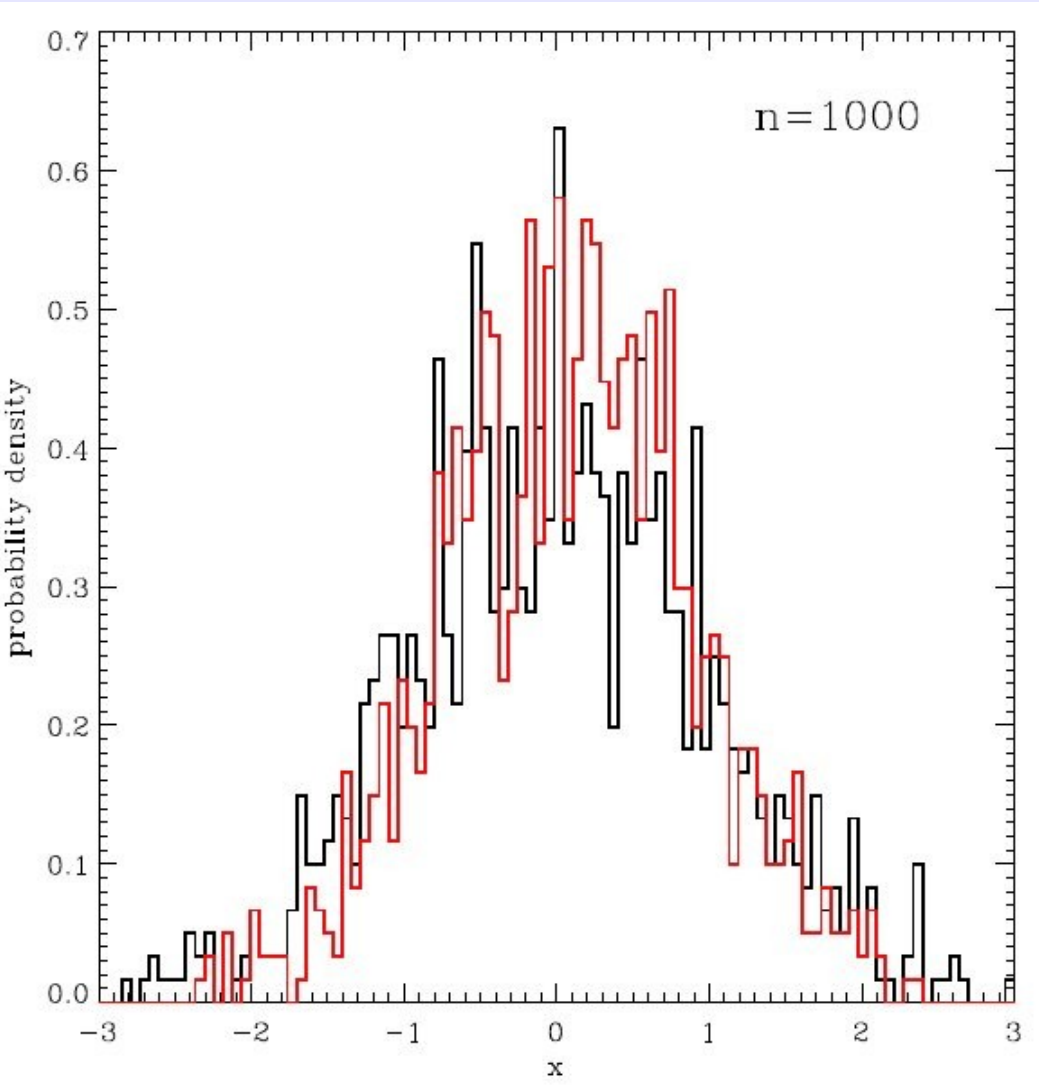


Possibly the left pair are different.

Small-number statistics

Are the samples in each plot drawn from different populations?

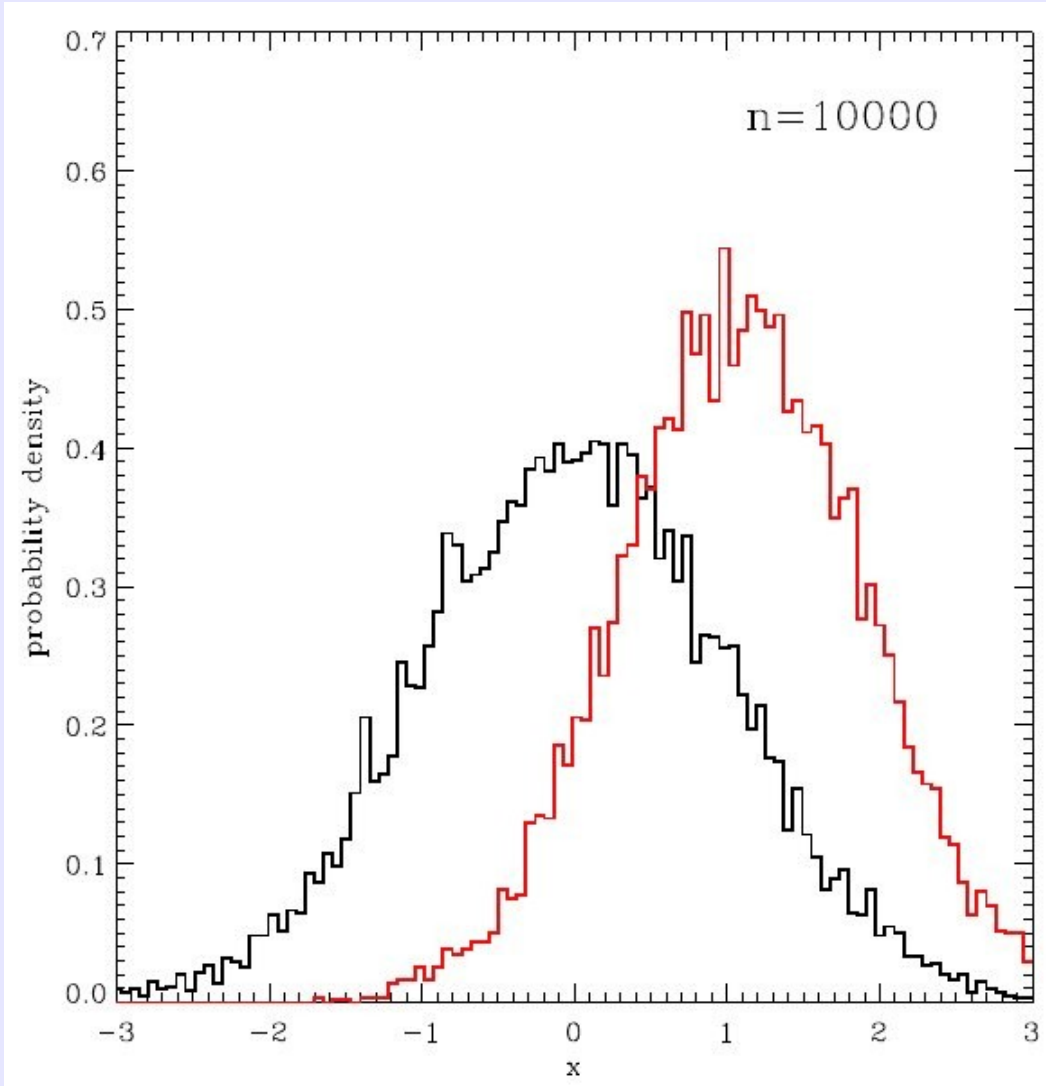


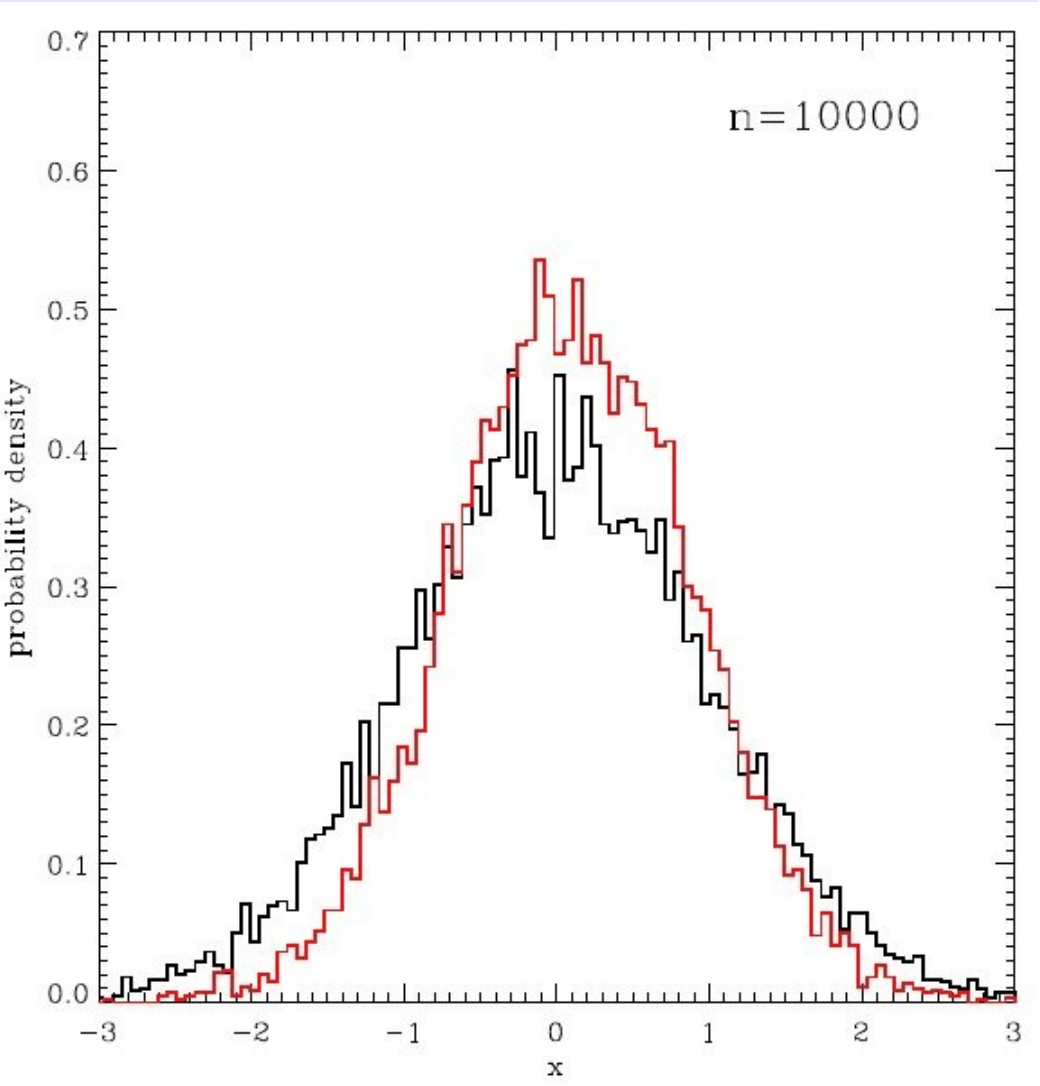


The left pair are definitely different.

Small-number statistics

Are the samples in each plot drawn from different populations?





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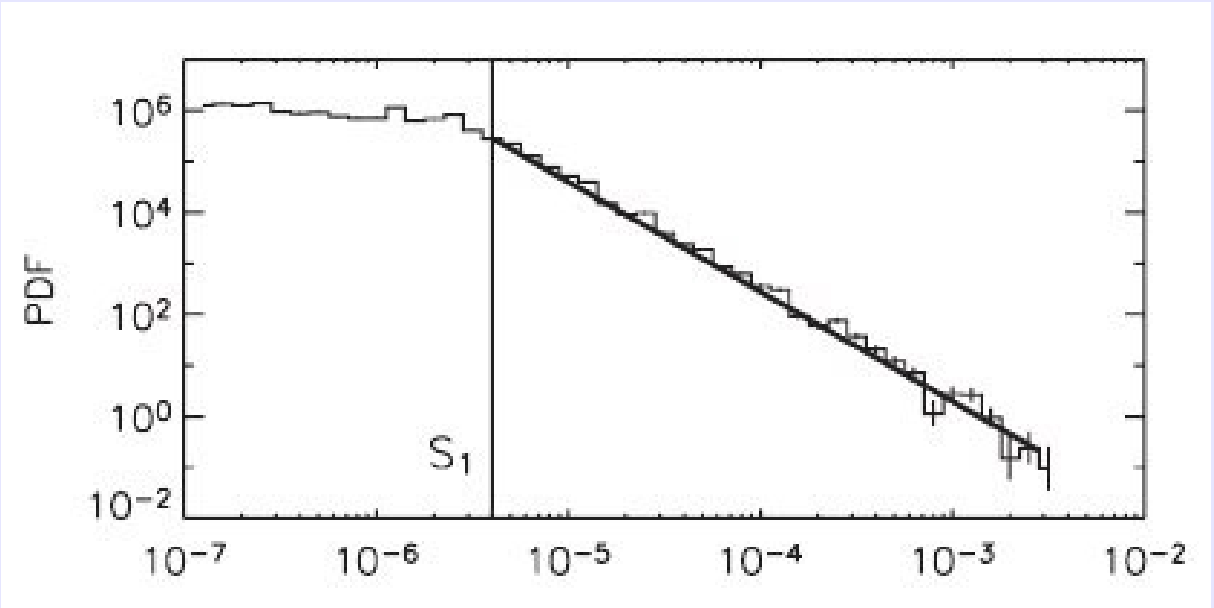
Why this is hard, IV: *Yet these are rare events.*



Probability Density Function of peak flare magnitude (1-8 Å, W m^{-2}), showing relative frequencies of small *vs*. large flares. From Wheatland 2005.

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.

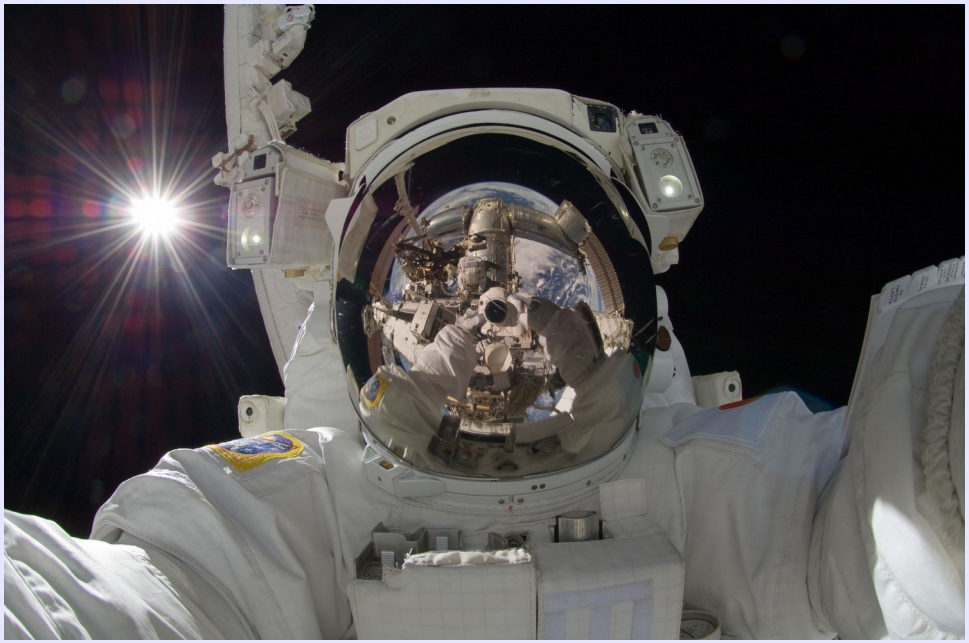
Why this is hard, V: *Different customer needs.*

Customer #1 wants:

- Basic situational awareness for 1—2 days out.
- Is very sensitive to *any* GPS disturbances.
- Simply implements "heightened awareness": false alarms are not a problem, but missed events are a big problem.

Customer #2 wants:

- "All-Clear" forecast for 12hr, starting in 6hr from forecast issuance for particular periods.
- Only large/powerful events are critical.
- False alarms are expensive, but missed events are catastrophic.



Solar Flare Forecasting: What is needed?

- **Identifying trigger(s).**
  - Can we actually observe the triggers?
  - Can we identify the parameter-space in which they are most likely to occur?
- **New data/analysis approaches.**
  - especially if unique triggers are found, how do we identify them statistically?
  - Thinking beyond surface magnetic field analysis.
  - Thus far, no statistical approach is proving revolutionary.

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, simulations.
  - New data analysis techniques.

Establishing infrastructure for systematic evaluation & method comparisons is:

- Crucial
- In progress*

* *(if interested, please see me).*