Forecasting Solar Flares:
Present Capabilities, Recent Advances, and "Mind the Gaps!"

KD Leka

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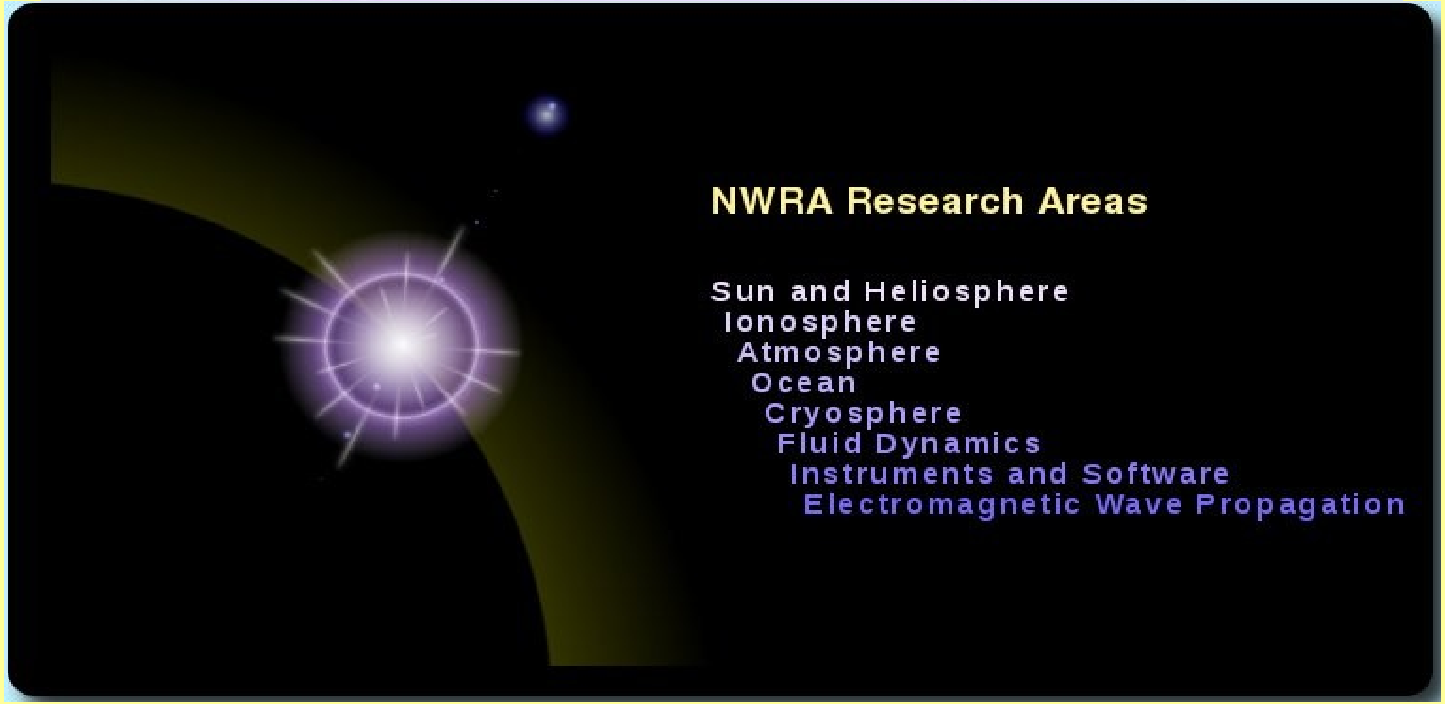
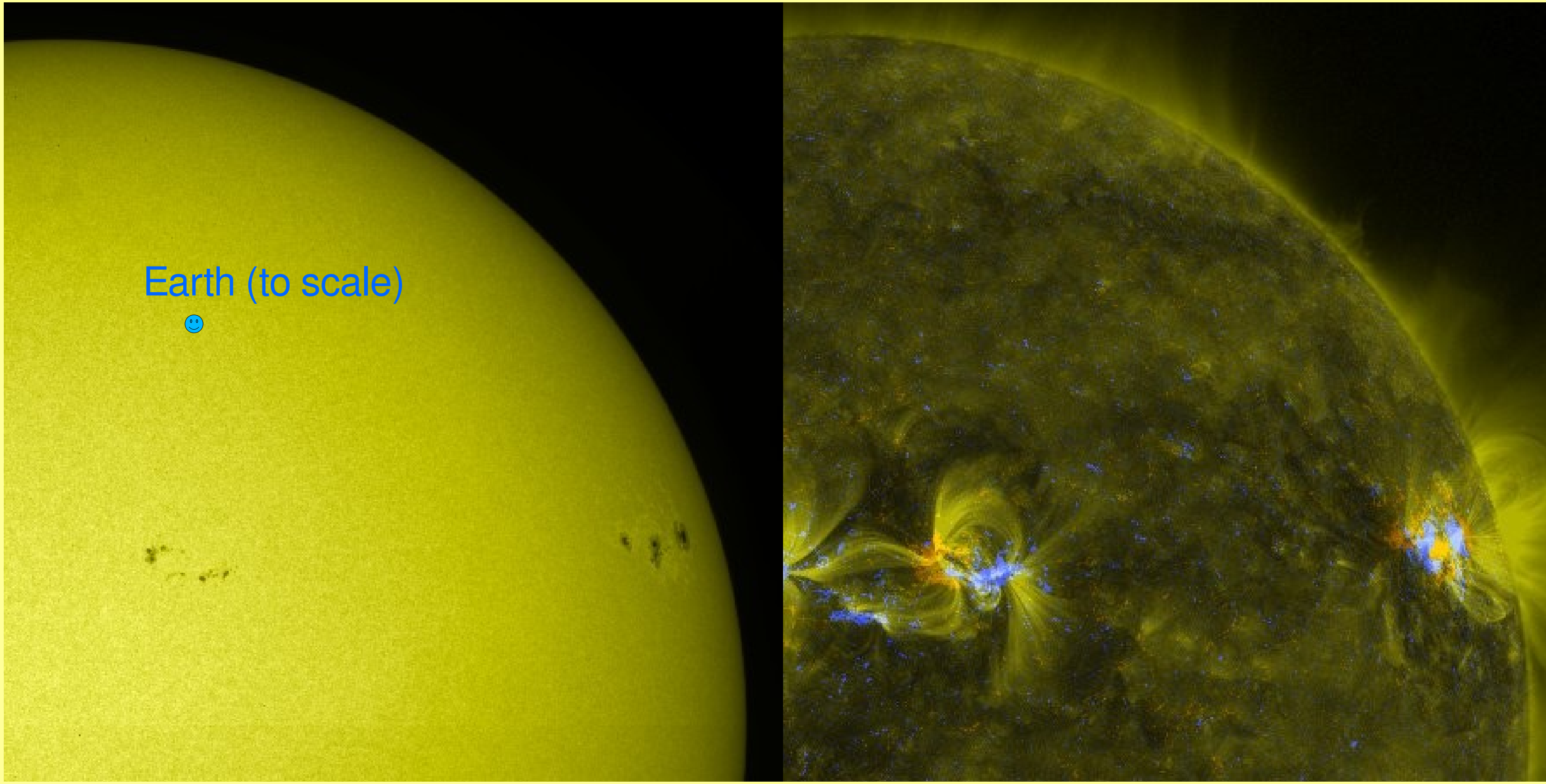
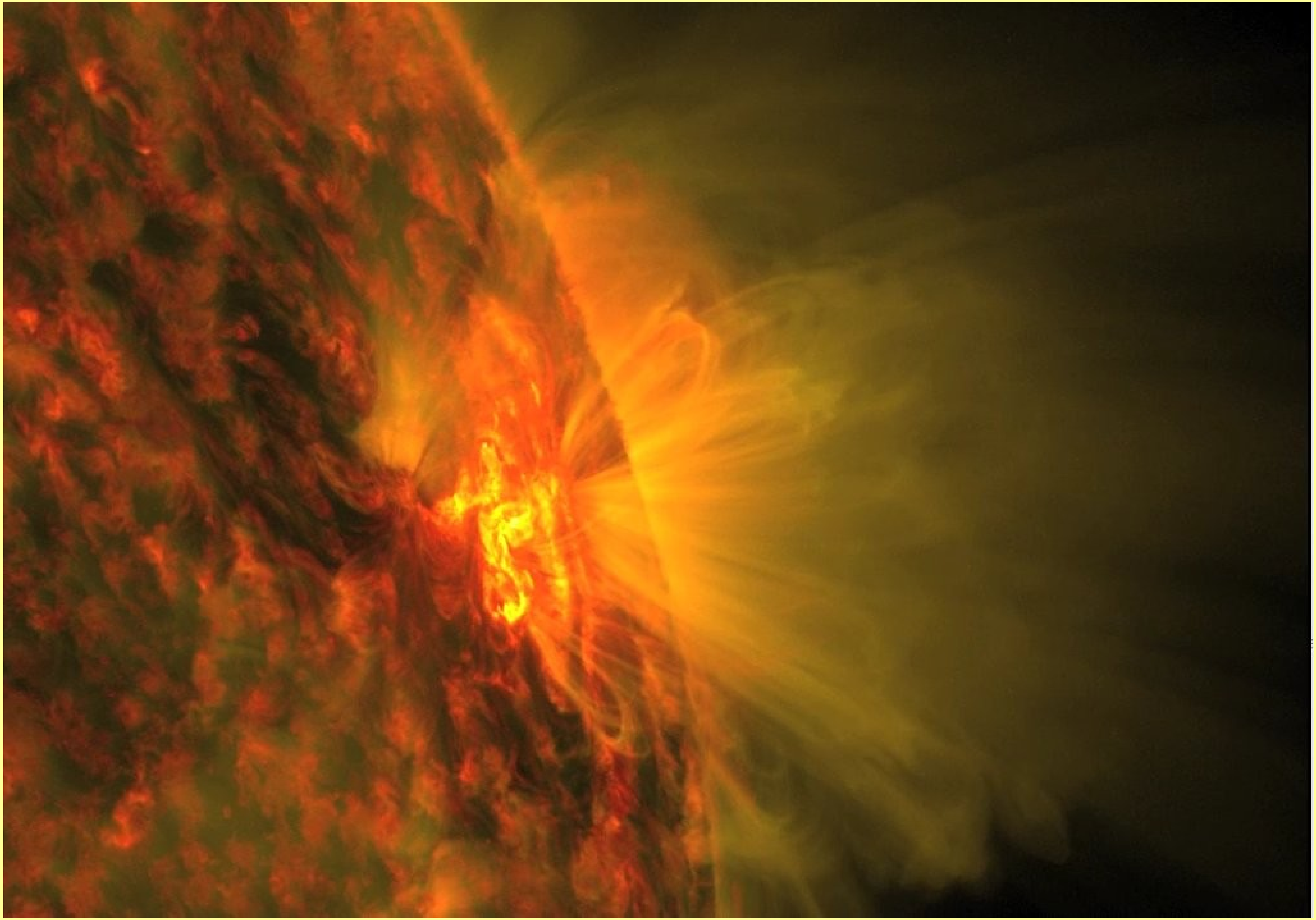


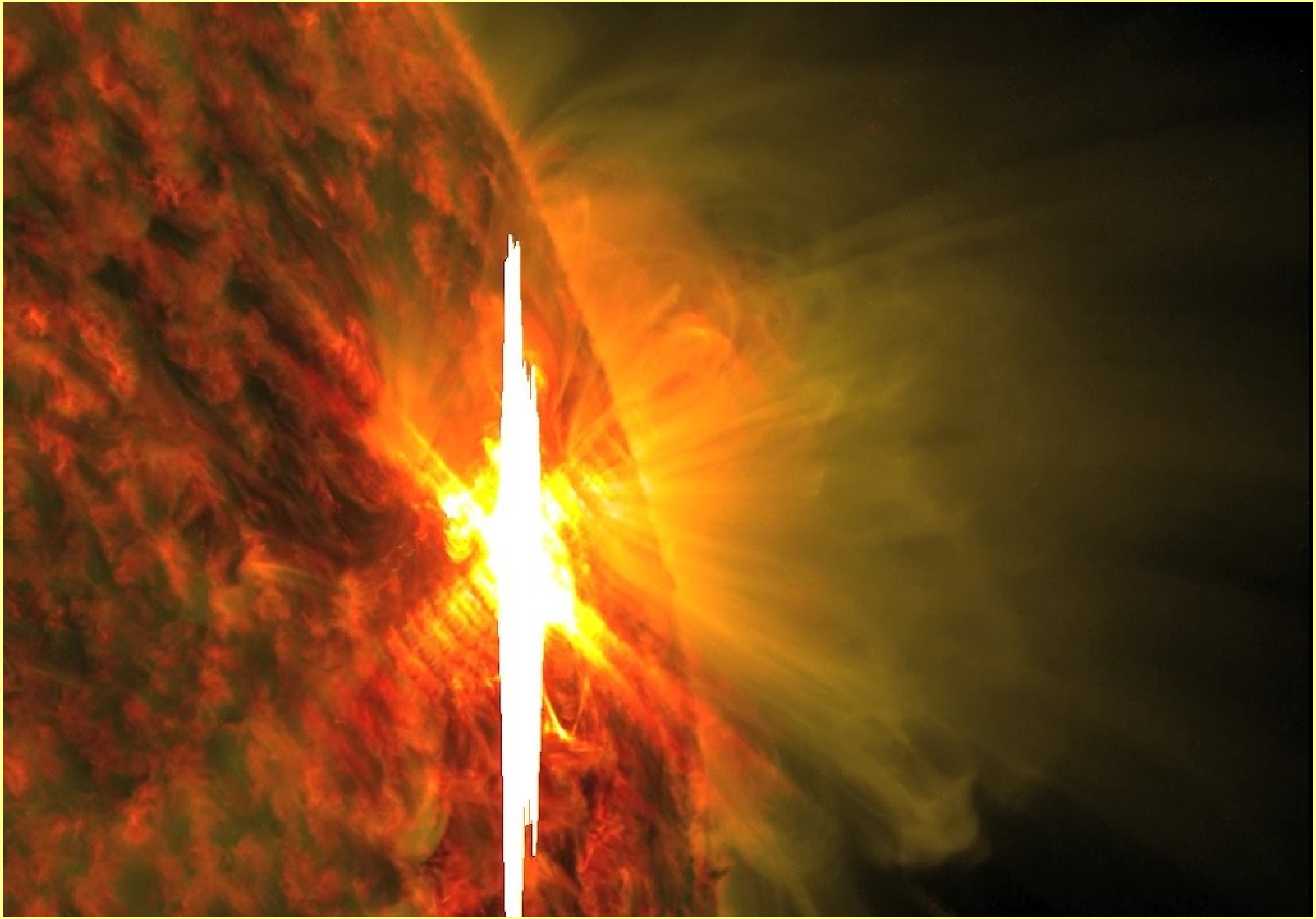
- NWRA is a scientific research group, owned and managed by its Principal Investigators (the scientists), performing pure and applied research in the space, geophysical, and related sciences.

What is a solar flare?

A sudden, intense, release of magnetic energy from the Sun.







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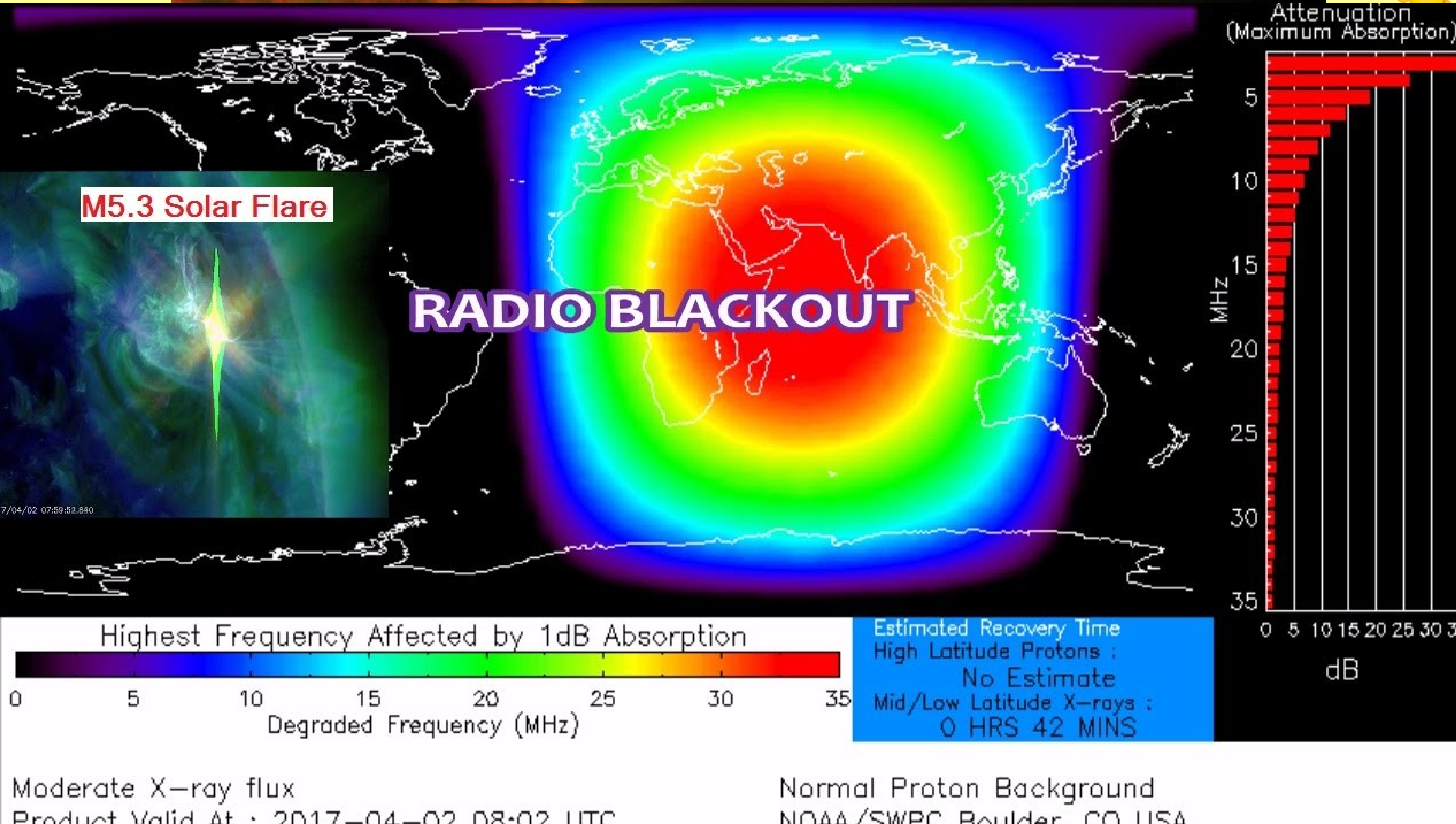
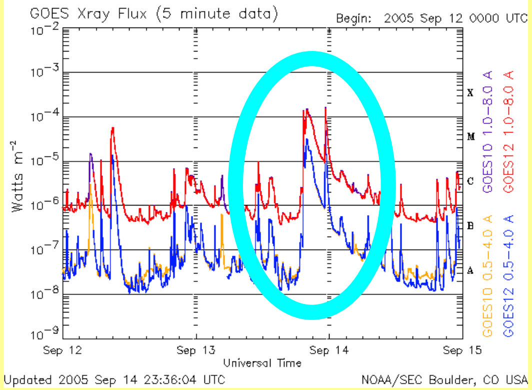

M5.3 Solar Flare
7/04/02 07:59:52.840
RADIO BLACKOUT
Attenuation
(Maximum Absorption)
MHz
5 10 15 20 25 30 35
0 5 10 15 20 25 30 35
dB
Highest Frequency Affected by 1dB Absorption
0 5 10 15 20 25 30 35
Degraded Frequency (MHz)
Estimated Recovery Time
High Latitude Protons :
No Estimate
Mid/Low Latitude X-rays :
0 HRS 42 MINS
Moderate X-ray flux
Product Valid At : 2017-04-02 08:02 UTC
Normal Proton Background
NOAA/SWPC Boulder, CO USA

What is a solar flare?



Answer:

- An abrupt increase in radiative output at all wavelengths 10^{28}—10^{32} erg over 10—1000 minutes.

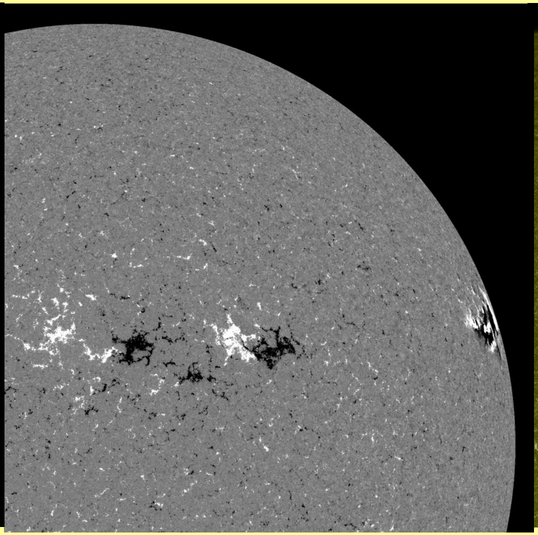
- Powered by magnetic energy stored in the solar chromosphere and corona.
  - Energies released are *consistent* with magnetic energy in active regions, *inconsistent* with other possible energy reserveds.
  - NOTE: we only *routinely* measure the magnetic field in the *photosphere* (the "surface")

Photosphere ("white-light")

"Surface" of the Sun; dark "sunspots" comprise "active regions" of strong magnetic field.

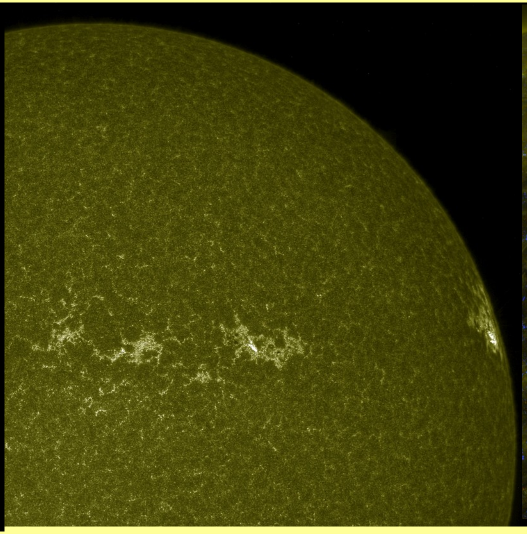
Images courtesy NASA/SDO

Photosphere (magnetic field)



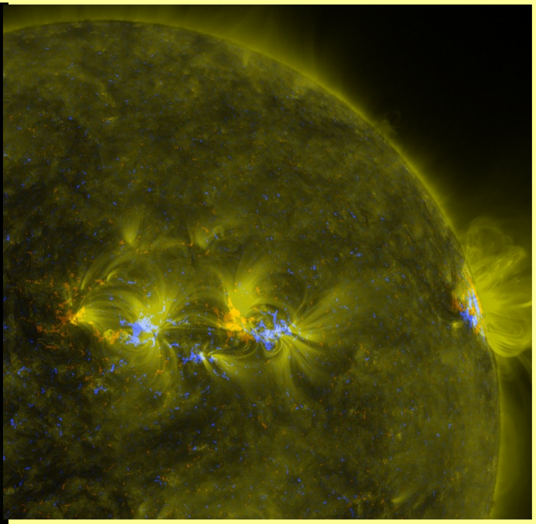
White/Black indicate opposite polarities in ares of strong magnetic field, as measured in the photosphere.

Chromosphere (UV)



The chromosphere sits ~1Mm above the photosphere; areas of strong field are bright in the UV continuum.

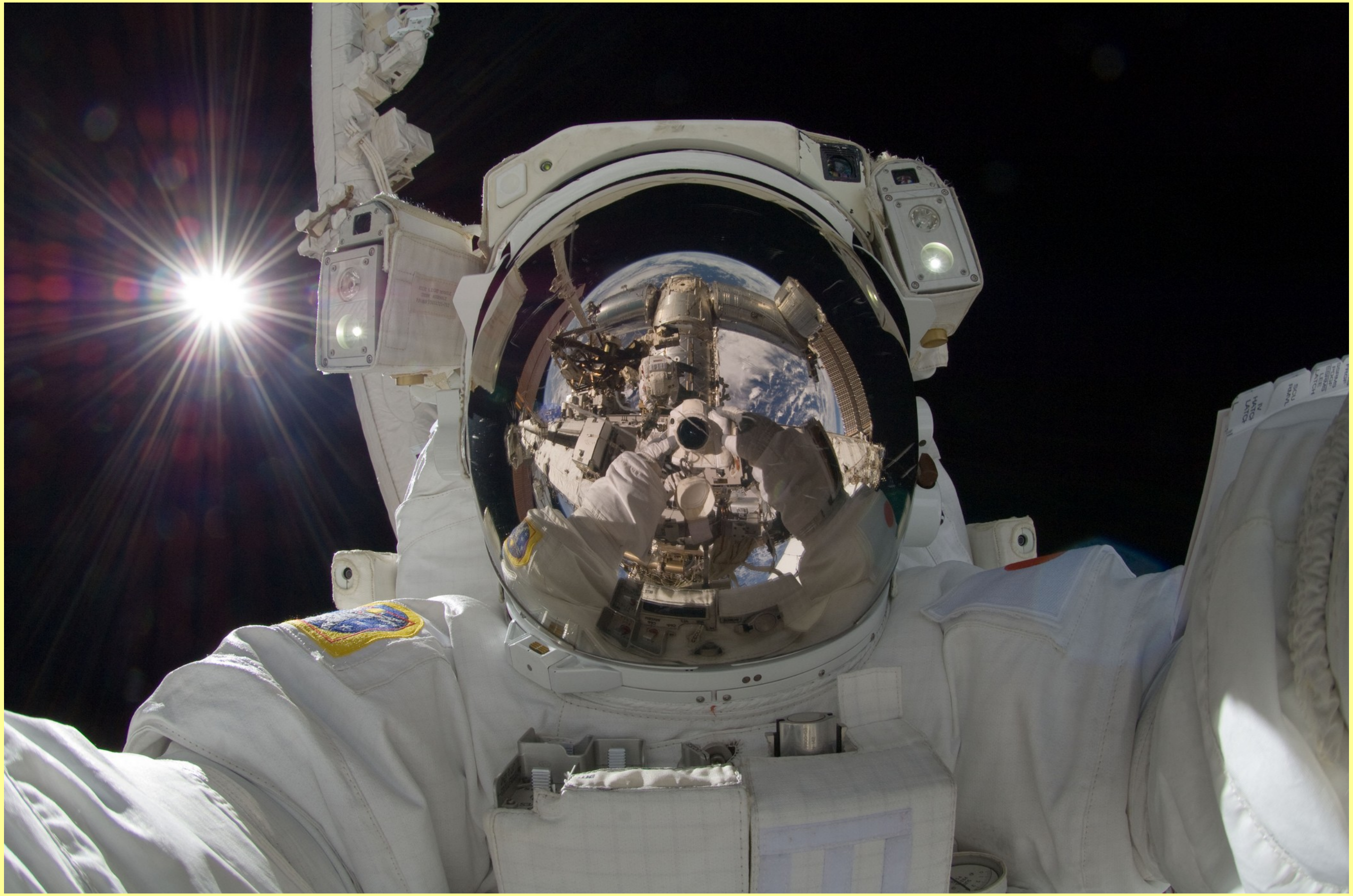
Corona & magnetic field



Coronal loops connect opposite magnetic polarity field, generally plasma-filled and bright; reconnection releases magnetic energy during a flare.

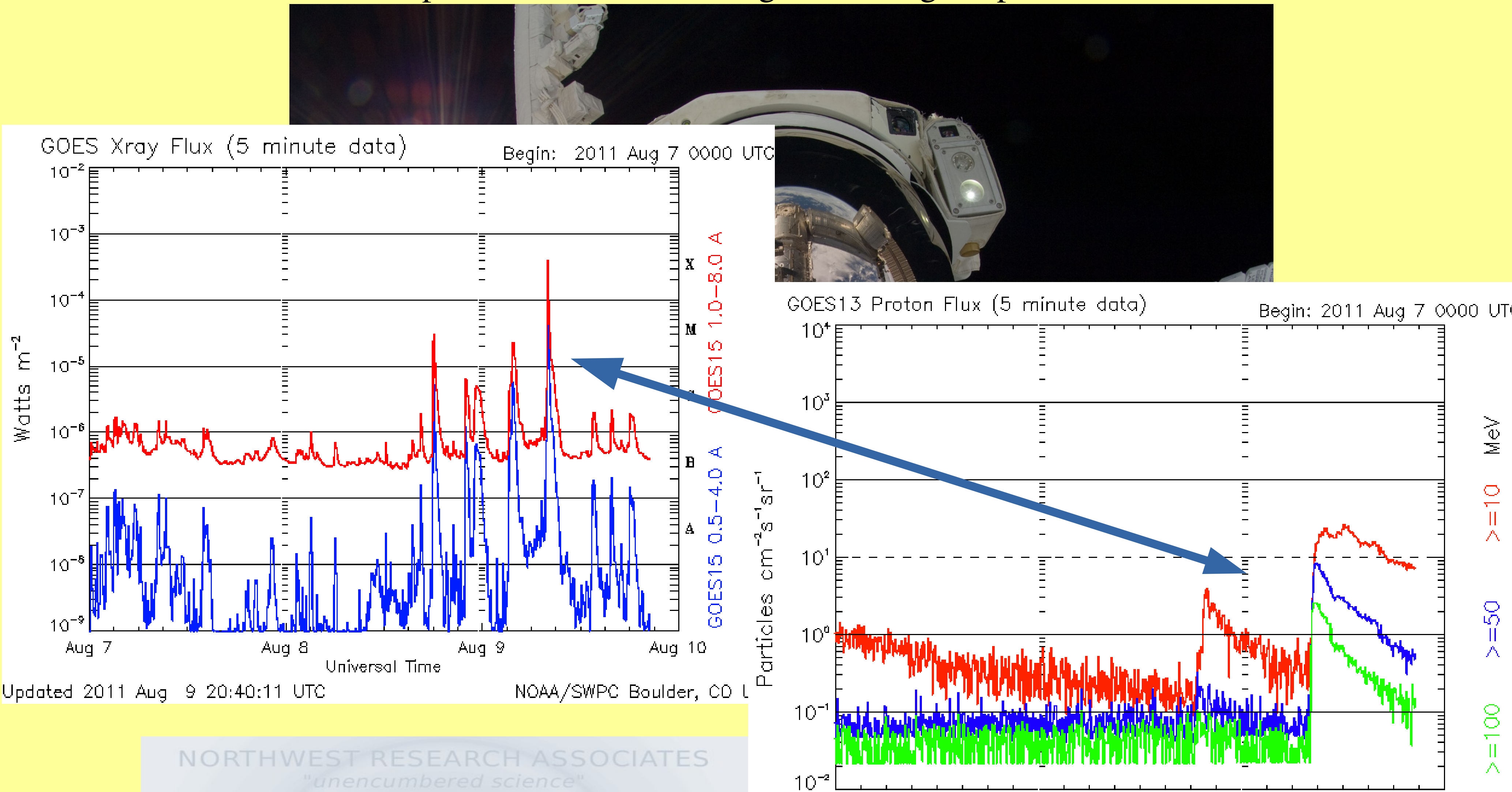
Why Forecast Solar Flares?

- Time of flight for flare-related ElectroMagnetic radiation = *speed of light*.
  (By the time you see it, you're cooked.)



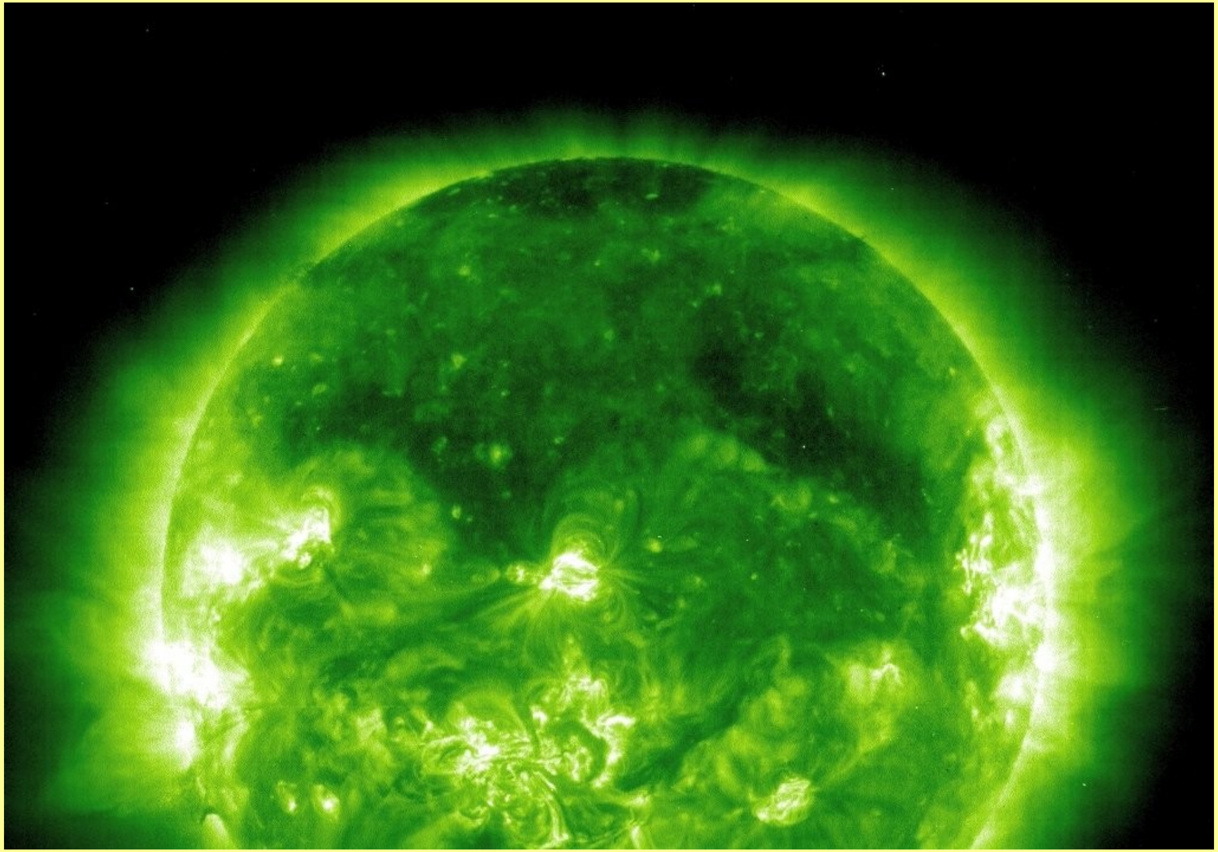
Why Forecast Solar Flares?

- Time of flight for flare-related ElectroMagnetic radiation = *speed of light*.
  (By the time you see it, you're cooked.)
- Source of other phenomena, such as dangerous energetic particle storms.



Why Forecast Solar Flares?

- Flares are correlated with, physically related to other phenomena delivering different impacts.
  - Those often have longer latencies before impact, but forecasting flares can help lead-time for preparing for other possible impacts.
  - “situational awareness”



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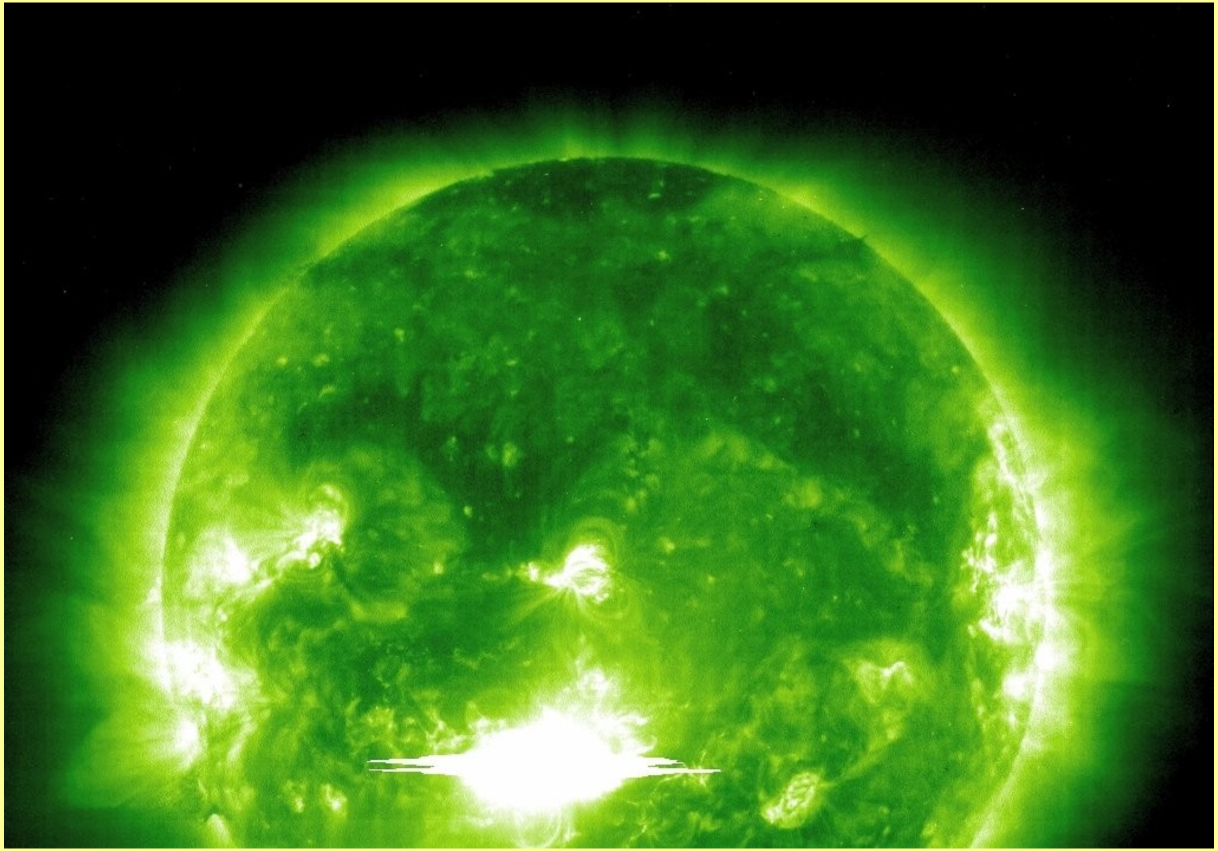

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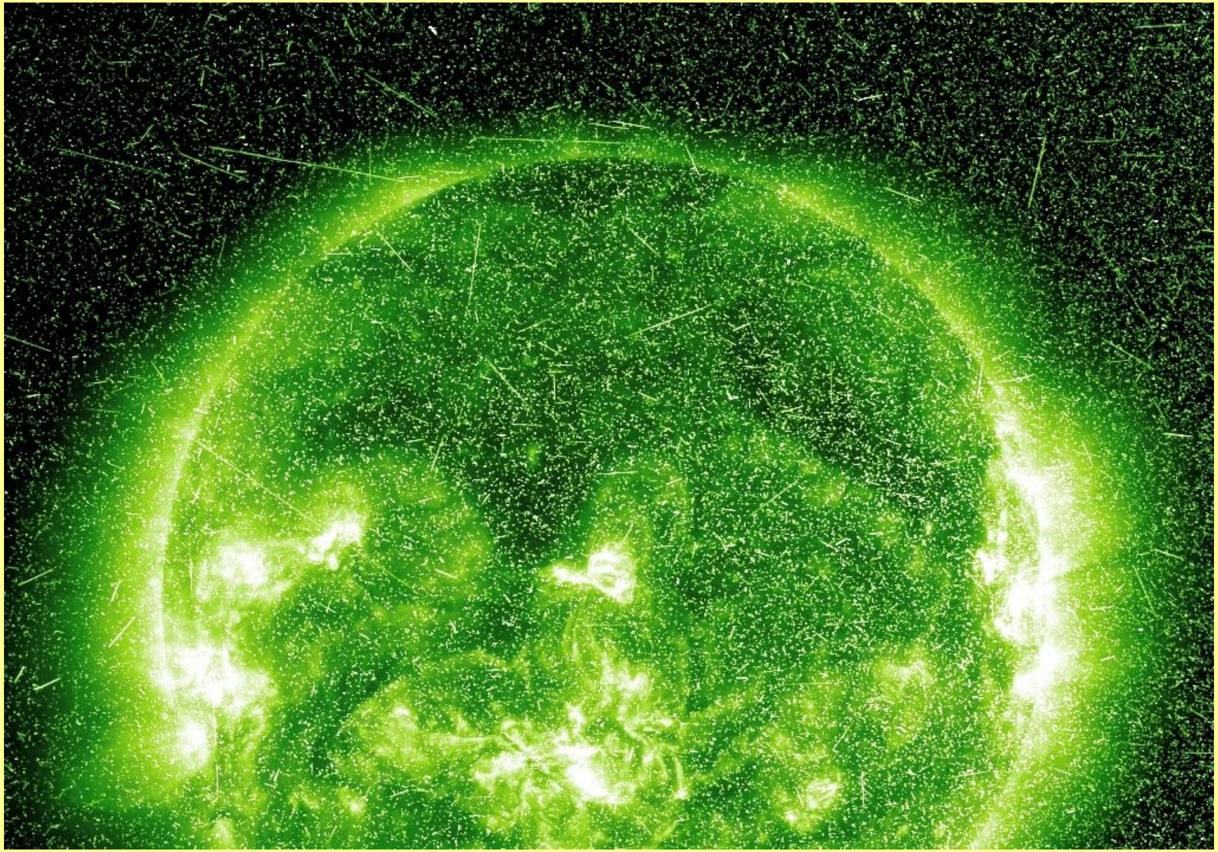

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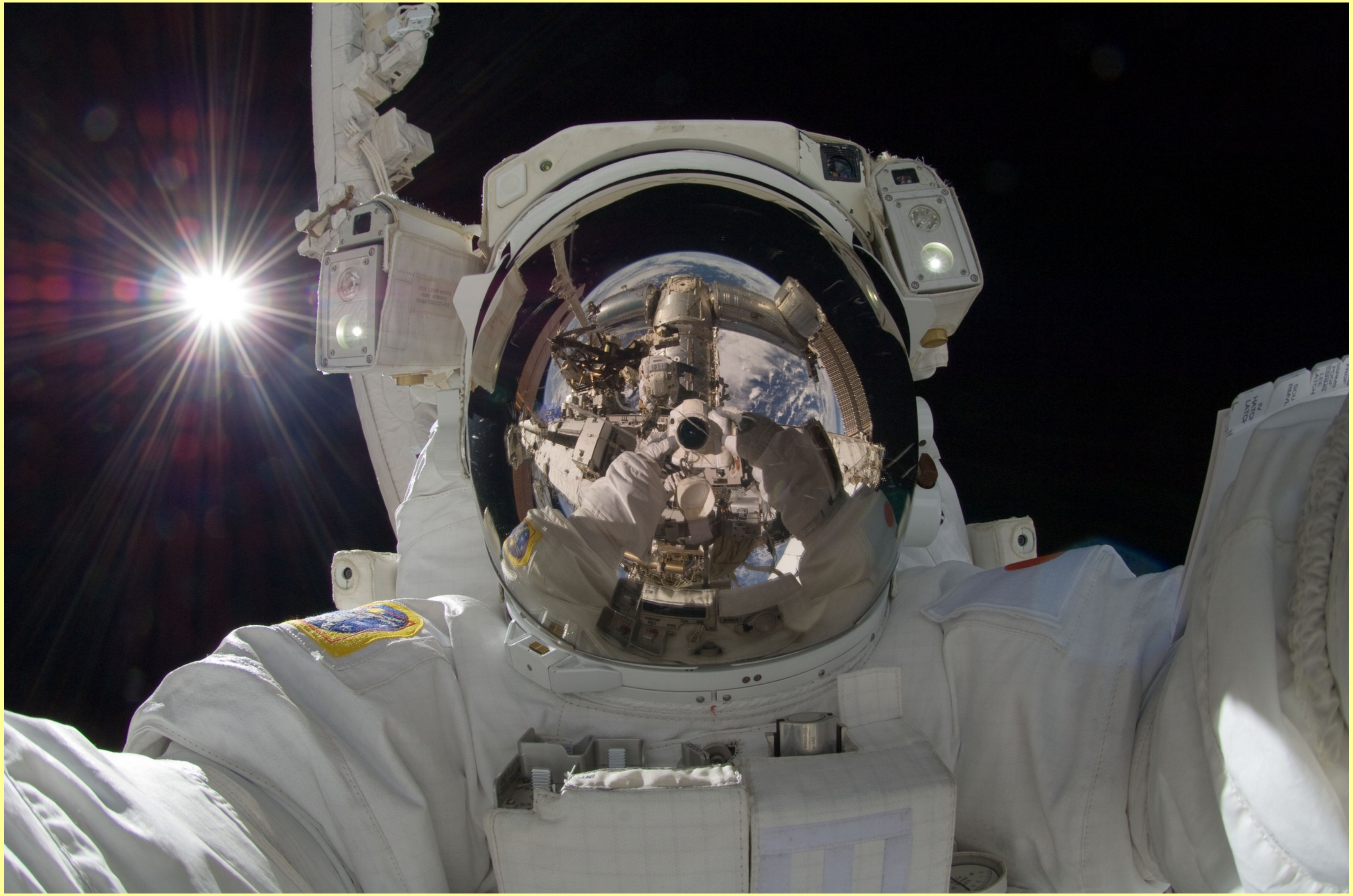
Substantial even short of extreme:

"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"

Mitchell & Schrijver, 2013 Space Weather Week.

Why Forecast Solar Flares?

- Forecasting the "All Clear" is crucial for (*e.g.*) spaceflight, launches, crucial communications.



Why Forecast Solar Flares?

- ***Unique role in solar physics research***
  - "The Sun would be a boring star if it had no magnetic field"
    - Solar Flares: dramatic examples of the magnetic field's influence.
  - **Challenge**: understand dramatic energy conversion processes – with limited remote-sensing data.
  - **Challenge**: understand physical processes in regimes almost irreproducible on Earth (magnetic reconnection, MHD instabilities)
    - Modeling these processes challenges computational limits.
  - **Challenge**: Statistics of rare events.

- ***Unique role in "Space Weather"***
  - Ionizing radiation can disrupt communications and pose radiation hazards
    - Time-of-flight governed by c
  - Initiation of other geo-effective phenomena
  - True *forecasting* capabilities are required.

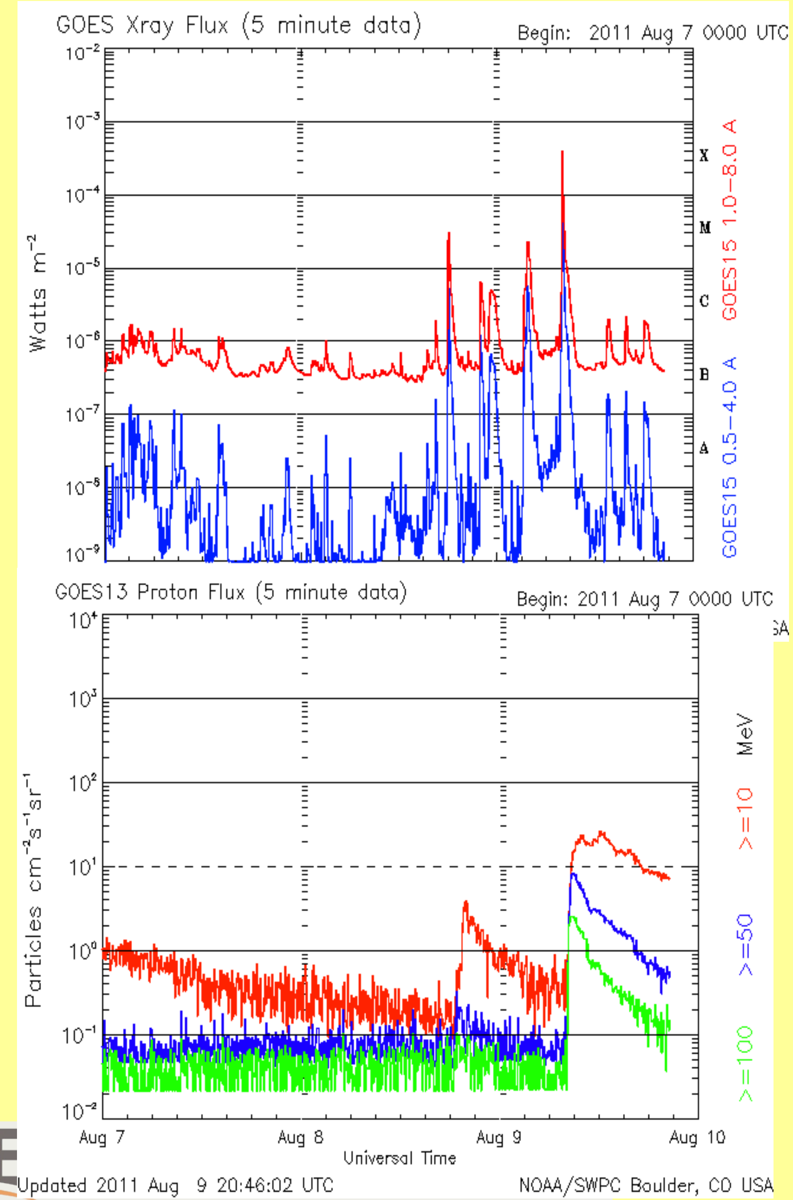
Why *and* Who Cares?

- Space Weather forecasting
  - Provides stringent tests of physical understanding
  - Pushes analysis and statistical techniques and capabilities
  - Pushes observational and numerical modeling forefronts

- Quantitative evaluation using a forecasting framework
  - Keeps you honest!
    - Keeps us all humble….
  - Clearly outlines modes of failure as well as success

Why *and* Who Cares?

- *Solar Flare Forecasting specifically:*
  - Important for Ionospheric impacts
  - Flares are the initiation event (or clearly associated) with other Space Weather drivers and phenomena
    - Coronal Mass Ejections (CMEs),
    - Solar Particle Events (SPEs)
  - Easily defined dichotomous (yes/no) events
  - Readily-available catalogs and databases



How to make a statistical forecast 101:

1) Gather historical data (your choice) and outcomes (flare / no flare)
2) Do this for a wide variety of samples.
3) Apply a statistical method of choice to historical data
    (correlation, classifier, neural network, look-up tables)
4) New data + statistical outcome → prediction.

A look back:

We find the following conditions for the occurrence of large flares:

- δ configurations of the first two kinds.
- Large spots.
- Many previous flares.
- Magnetic shear.
- Steep magnetic gradients.
- Inverse polarity.
- Spots obscured in Hα.
- Bright Hα emission.

Zirin & Liggett 1987
c.f. criteria for BearAlerts, Zirin & Marquette 1991

TABLE IV

Most flare-productive sunspot types 1969–1976 (from Kildahl, 1980)

McIntosh type	Number of occurrences	Number of class M flares	Number of class X flares	Flares/occurrence per 24 hours	
				M	X
H*sx*	1963	99	6	0.05	0.003
D*so*	553	51	6	0.09	0.01
D*ai*	324	58	7	0.18	0.02
D*kc*	100	72	10	0.72	0.10
E*ki*	81	103	11	1.27	0.14
E*kc*	63	149	21	2.36	0.33
F*ki*	47	106	17	2.26	0.36
F*kc*	27	39	13	1.44	0.48

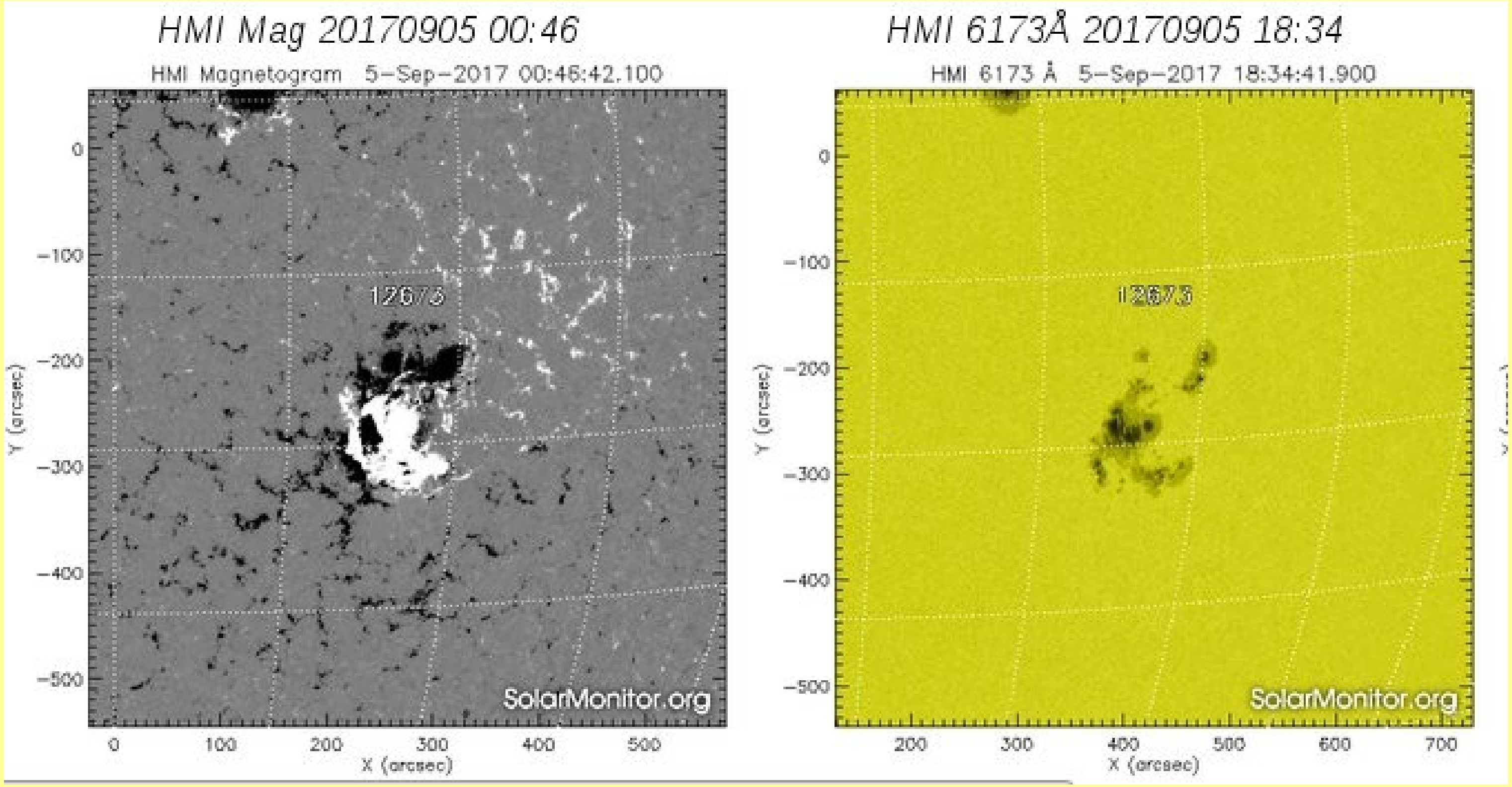
THE FLARES OF

State of the art *circa* 1970's: Hα line-center images, continuum images, line-of-sight magnetic field (BBSO images from Zirin & Tanaka 1973)

Iconic table of sunspot classification and associated flaring rates.
McIntosh 1990

Forecasting solar flares:

- The extremes are “almost” easy:



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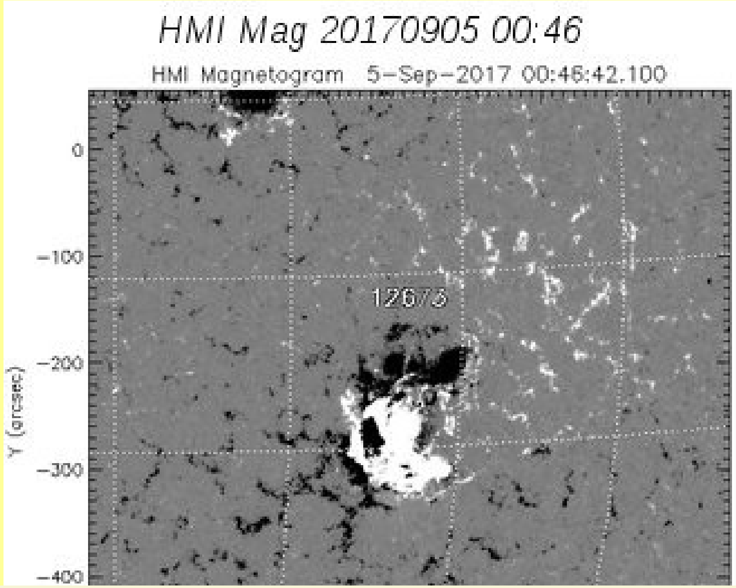
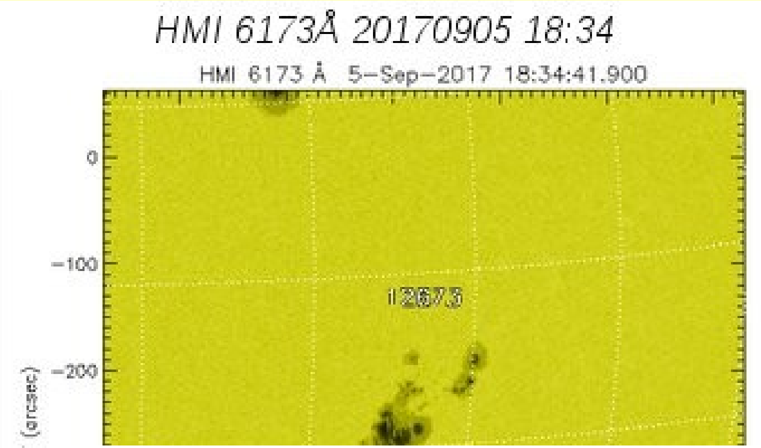
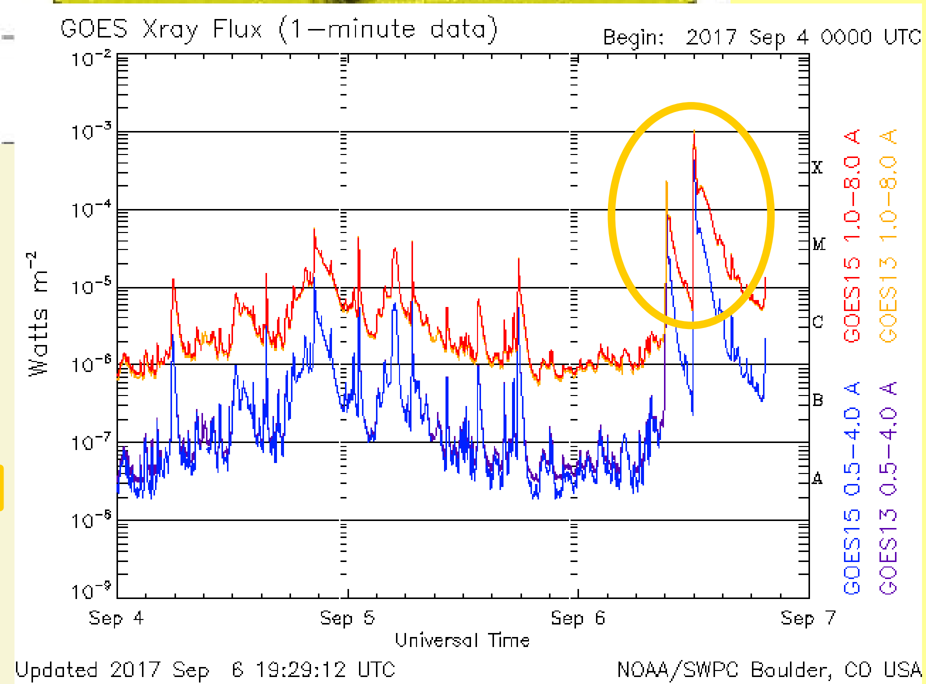





```
#
:Whole_Disk_Flare_Prob:
Class_M                 75            75            75
Class_X                 25            25            25
Proton                  99            70            15
#
# Region Flare Probabilities for 2017 Sep 06
# Region     Class C     M             X             P
:Reg Prob: 2017 Sep 05
  2673          95      55            25            95
  2674          75      20             1             1
  2675           5       1             1             1
  2676           5       1             1             1
  2677           5       1             1             1
  2678           5       1             1             1
```



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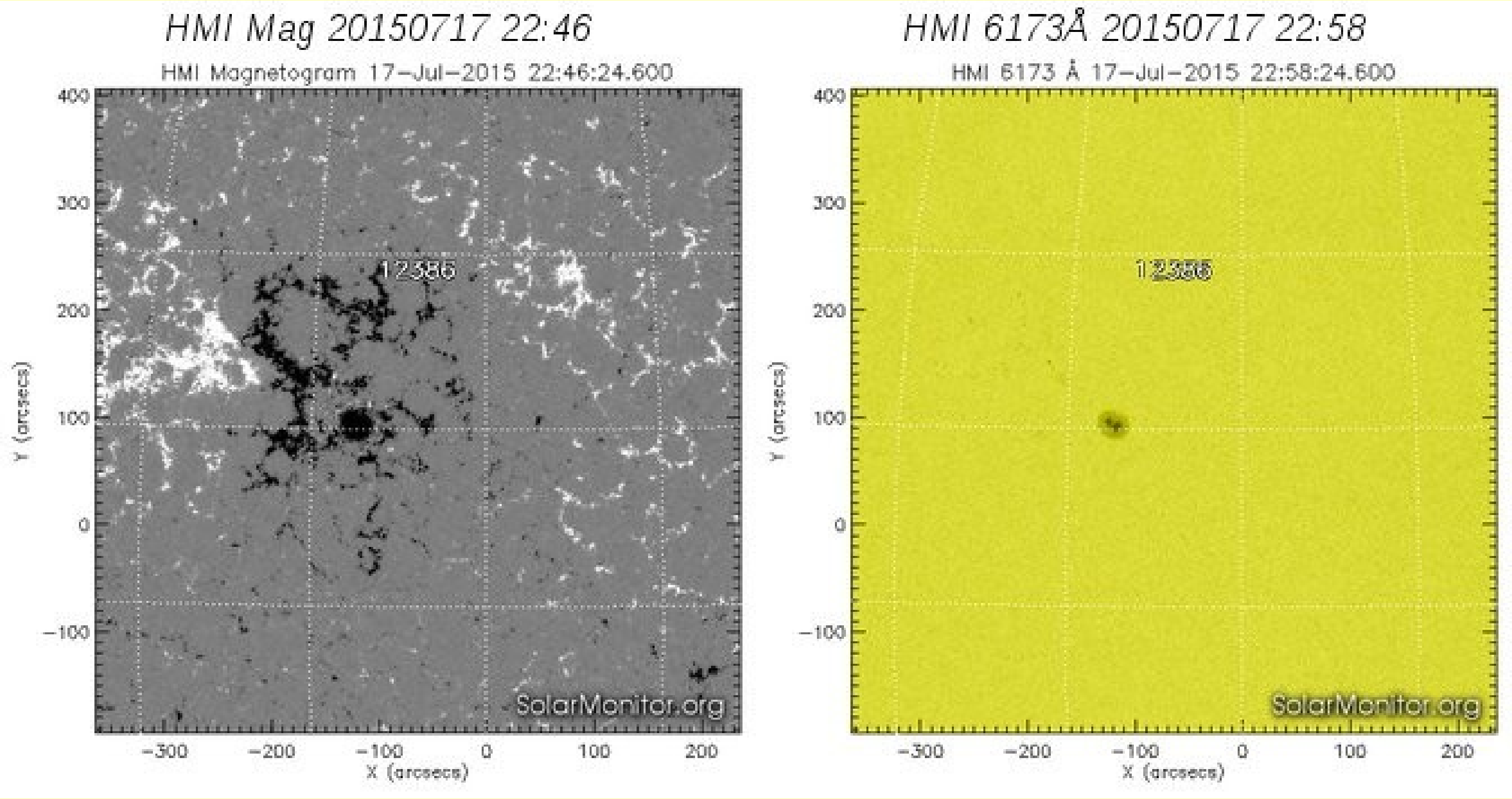

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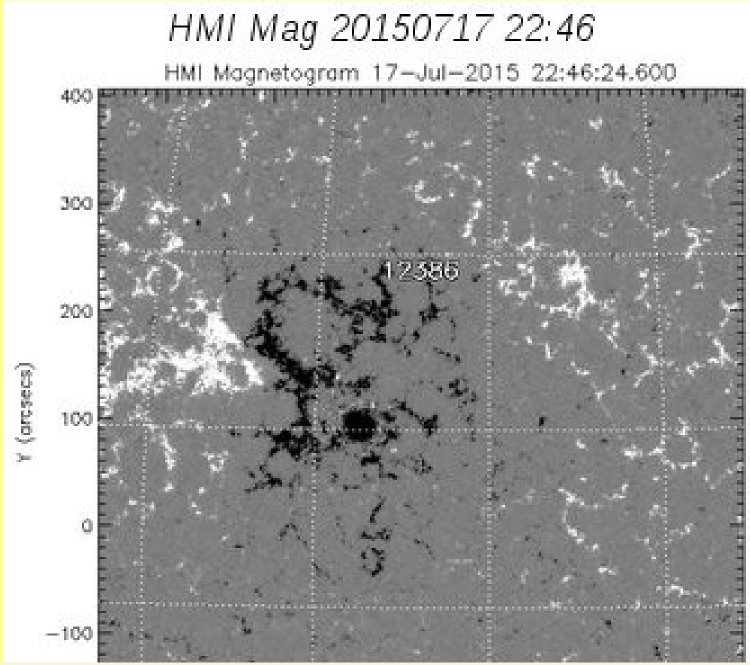
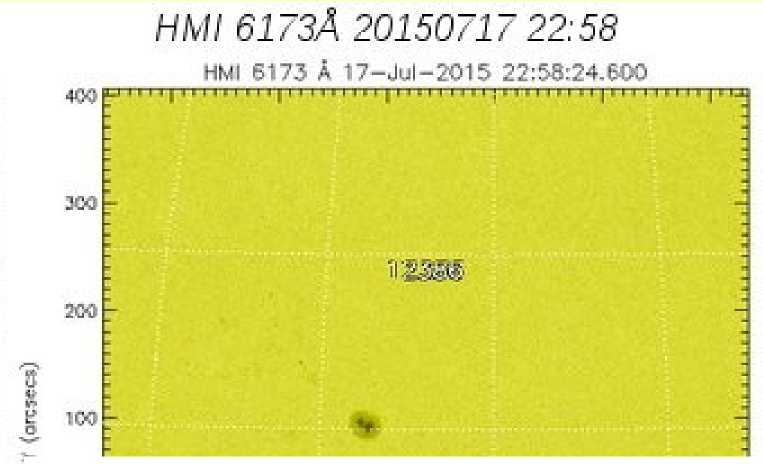
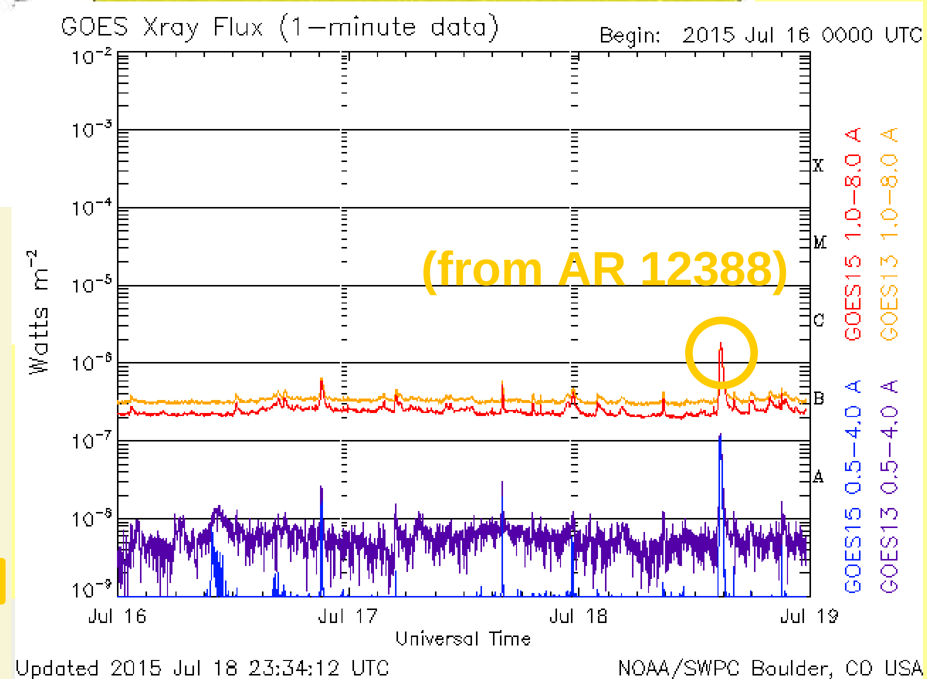


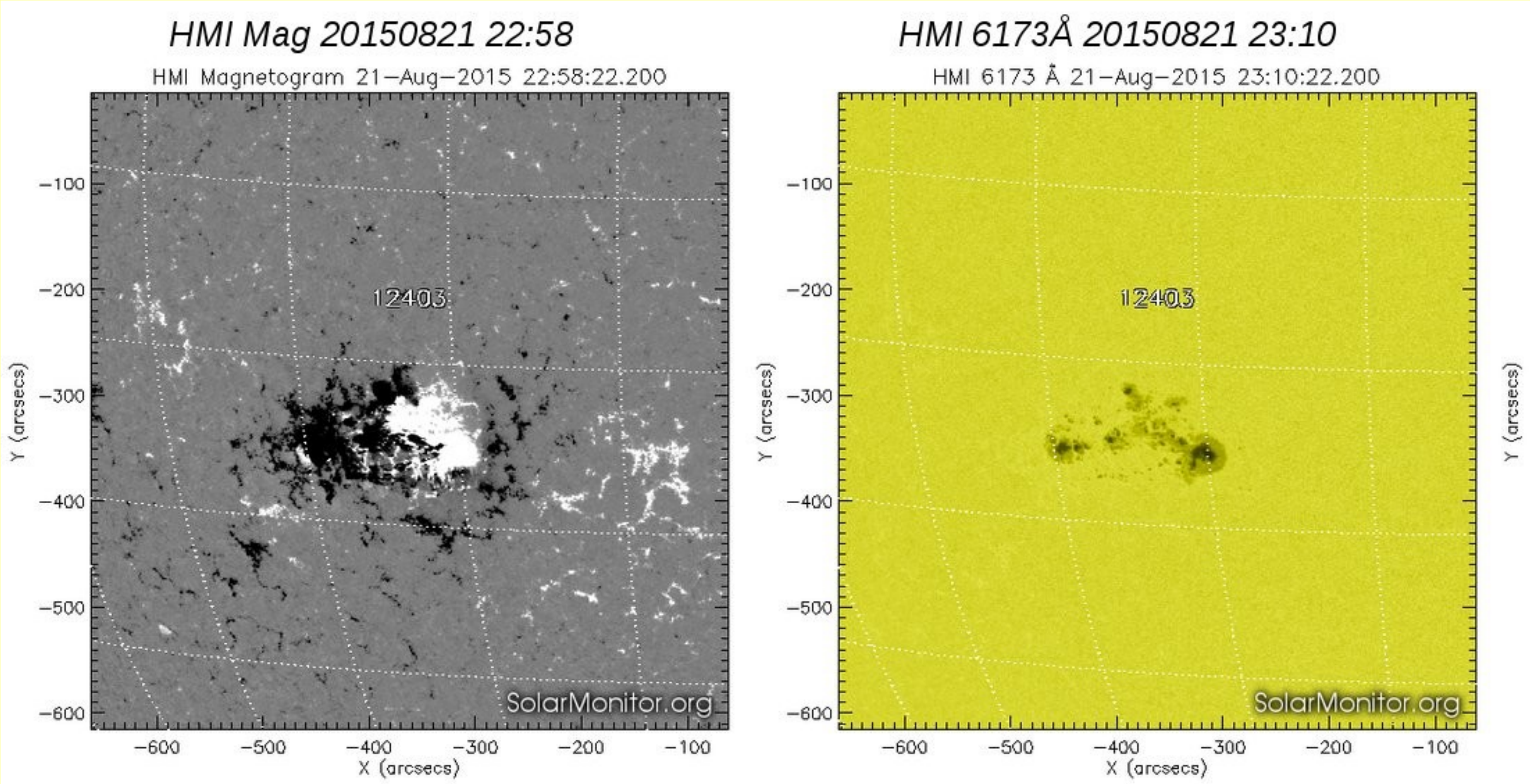



```
#
:Whole_Disk_Flare_Prob:
Class_M                    10            10            10
Class_X                     1             1             1
Proton                      1             1             1
#
# Region Flare Probabilities for 2015 Jul 18
# Region     Class C        M             X             P
:Reg_Prob: 2015 Jul 17
  2384          10          1             1             1
  2386           5          1             1             1
  2387          40         10             1             1
  2388           5          1             1             1
```



Forecasting solar flares:

- The less extremes: more difficult



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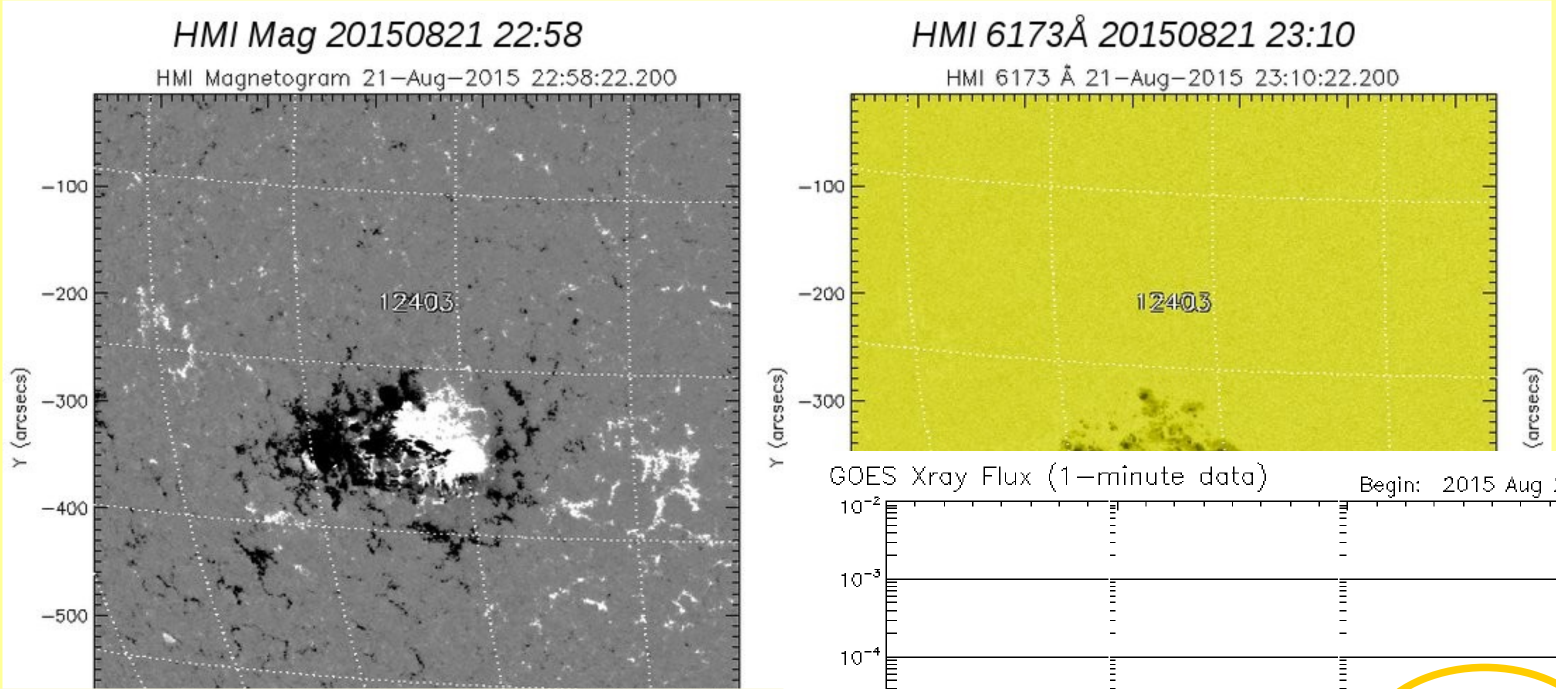

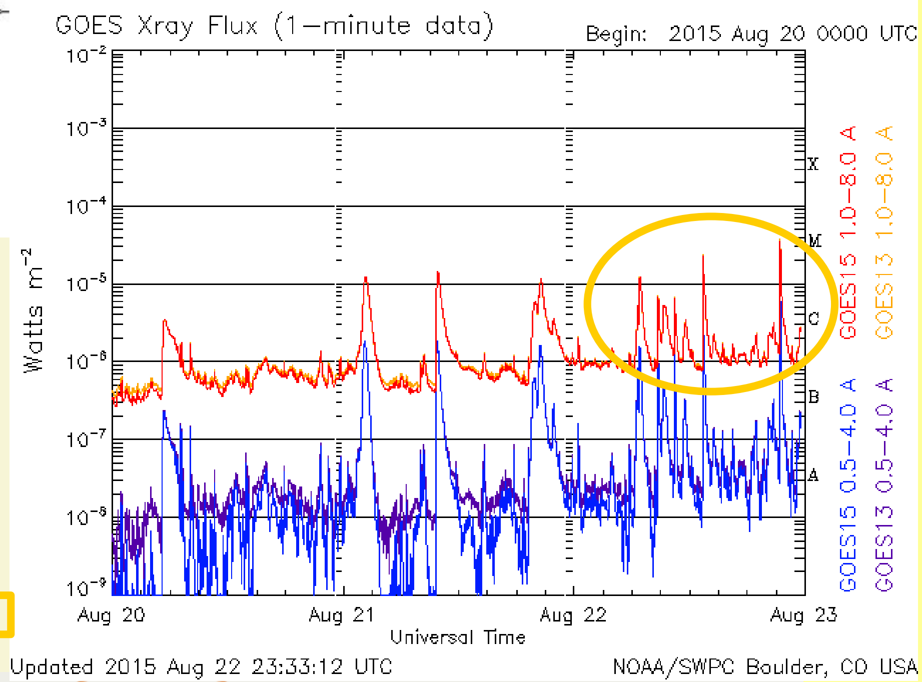


```
#
:Whole_Disk_Flare_Prob:
Class_M                   35              35              35
Class_X                   10              10              10
Proton                     1               1               1
#
# Region Flare Probabilities for 2015 Aug 22
# Region     Class C       M               X               P
:Reg_Prob: 2015 Aug 21
  2401         5           1               1               1
  2403        85          35              10               1
  2404        10           1               1               1
```

Forecasting solar flares:

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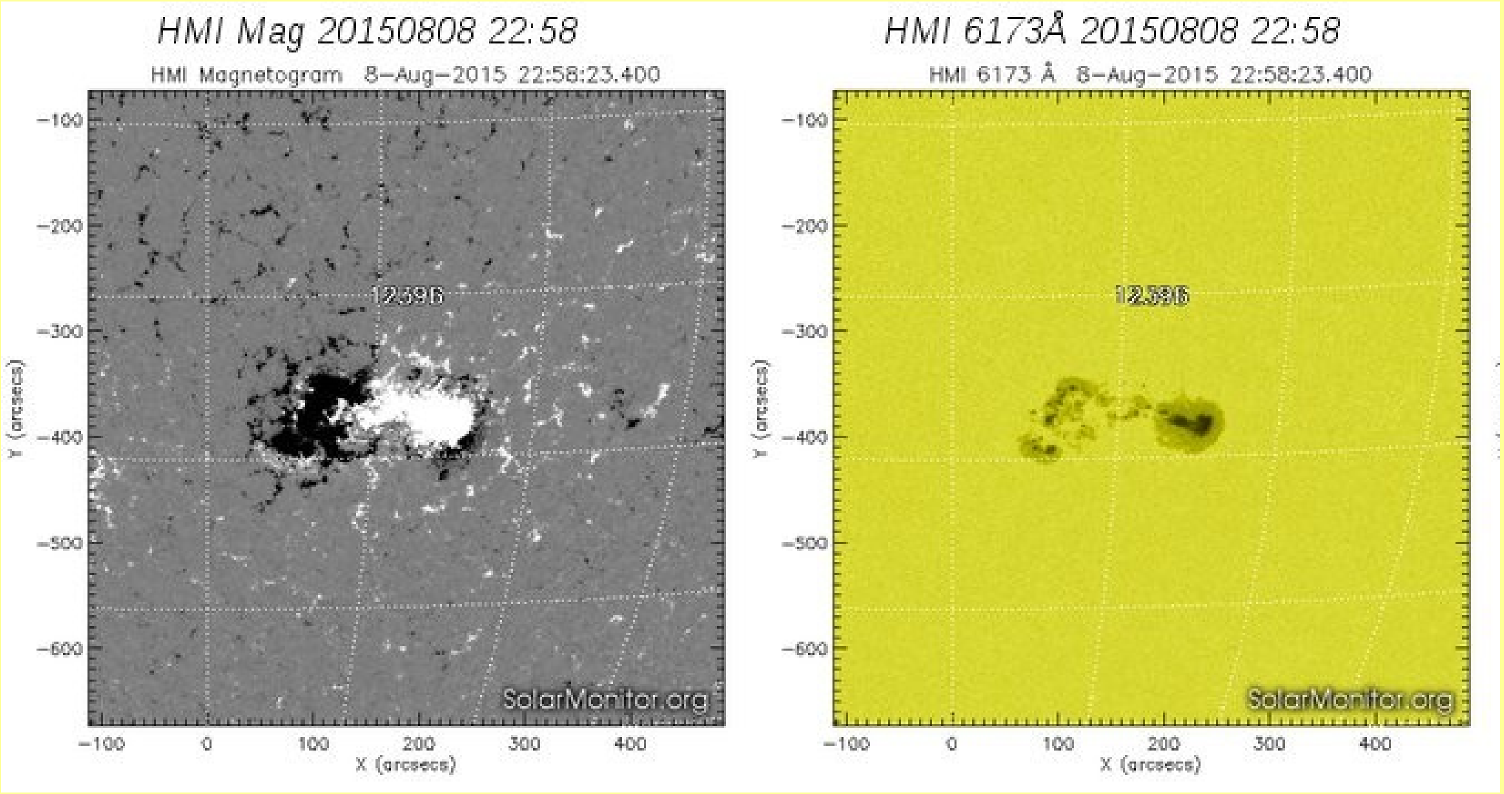

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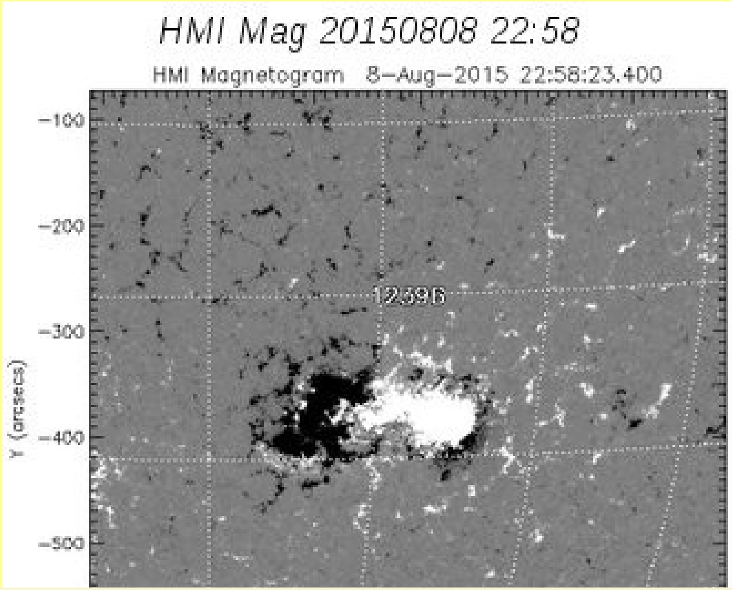
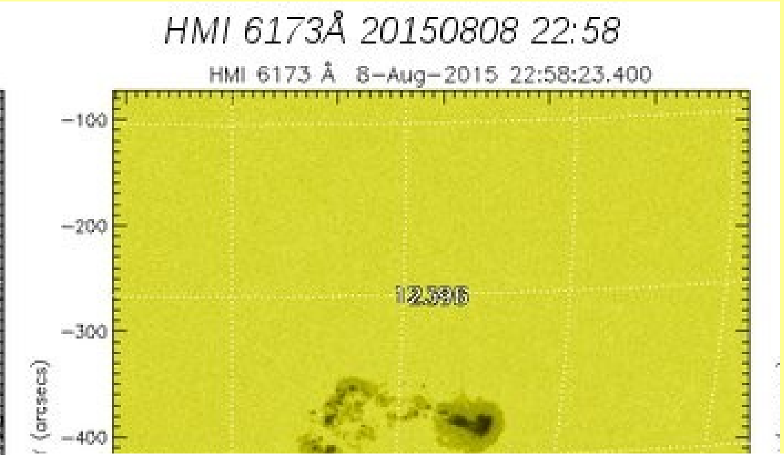
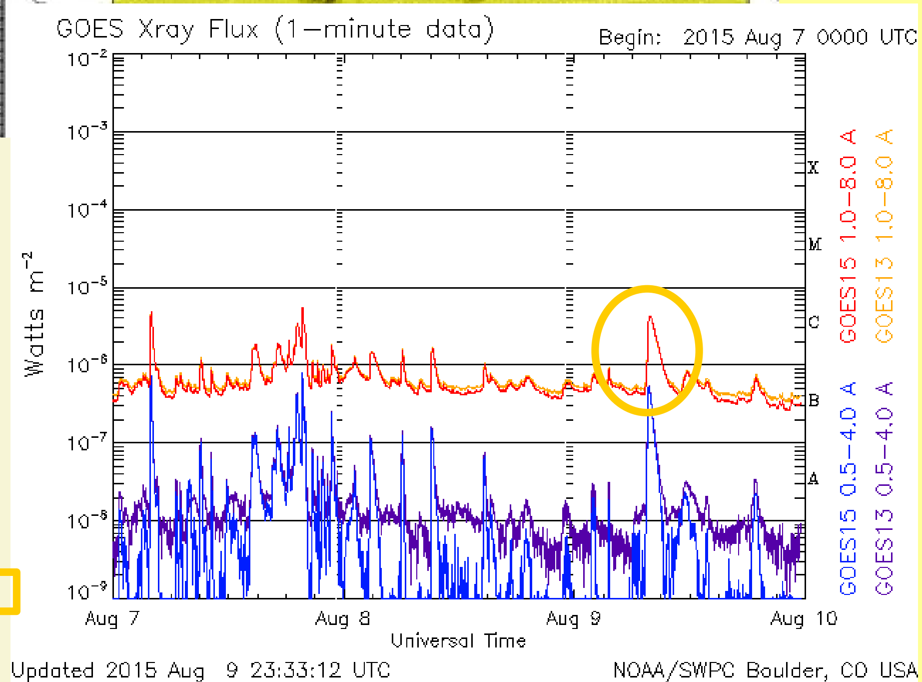





```
#
:Whole_Disk_Flare_Prob:
Class_M                     35            35            35
Class_X                      5             5             5
Proton                       1             5             5
#
# Region Flare Probabilities for 2015 Aug 09
# Region      Class C       M             X             P
:Reg_Prob: 2015 Aug 08
  2393           5          1             1             1
  2394          30          1             1             1
  2395           5          1             1             1
  2396          85         35             5             1
  2397           5          1             1             1
  2398          10          1             1             1
```



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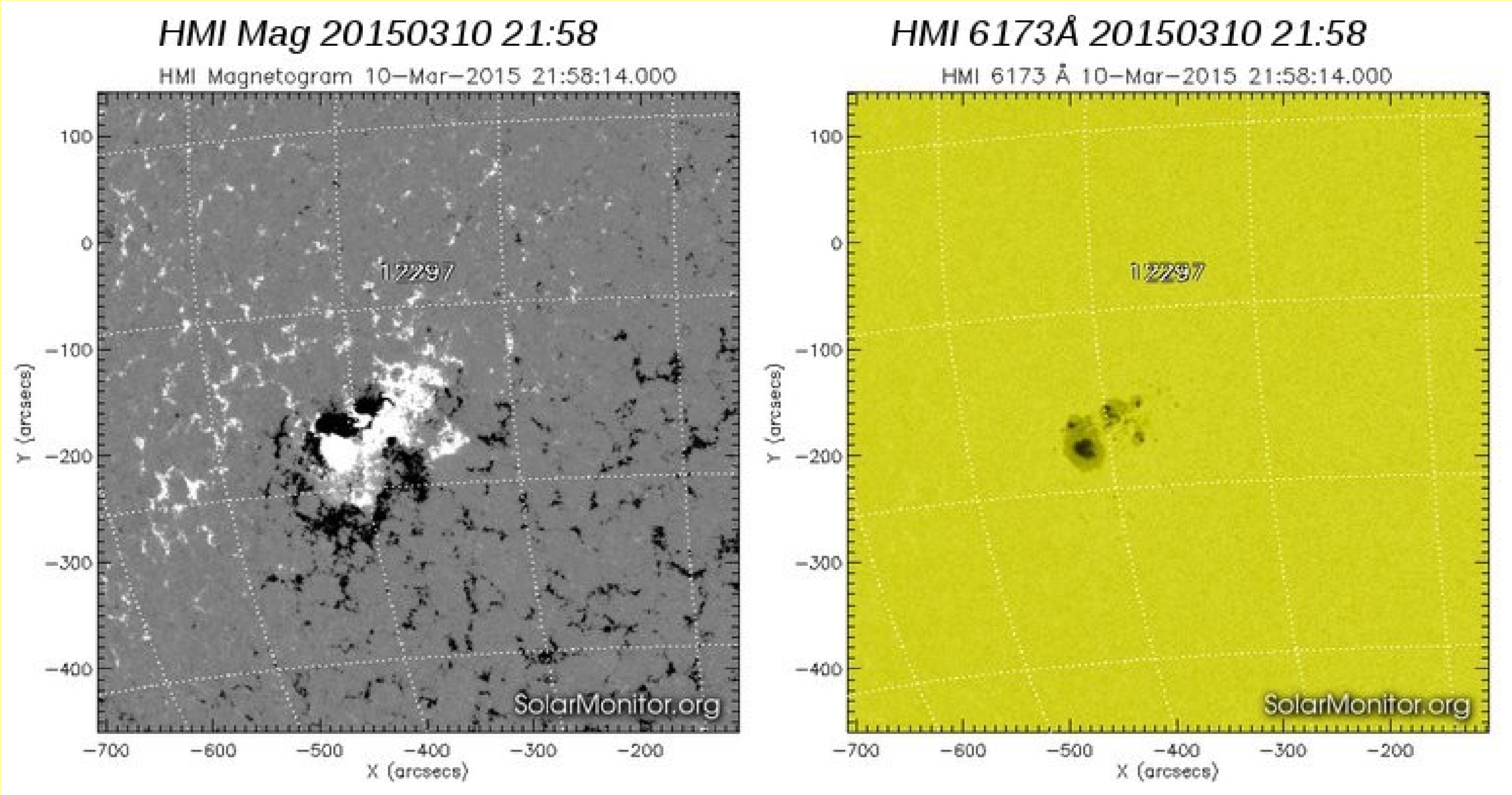

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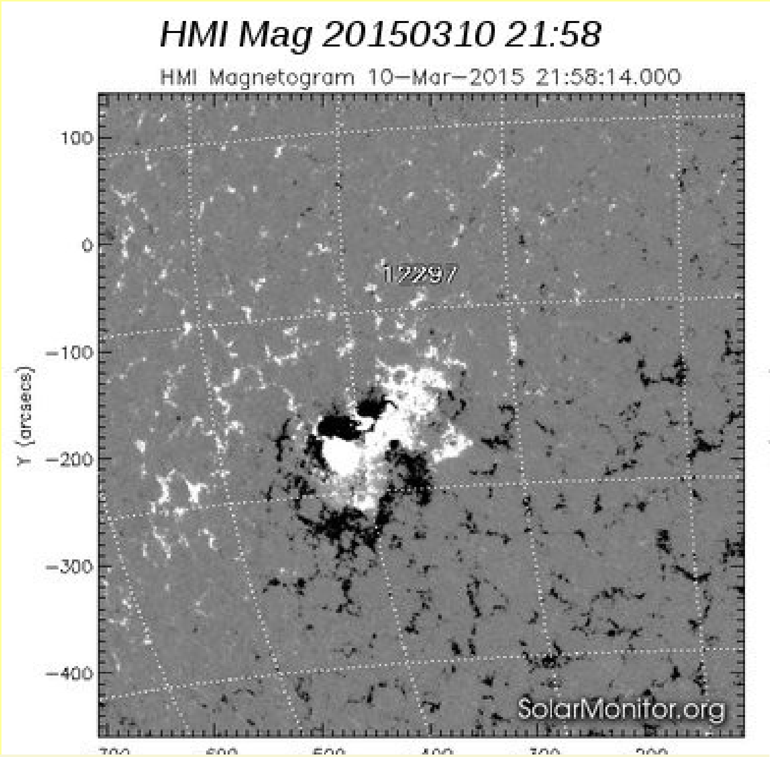
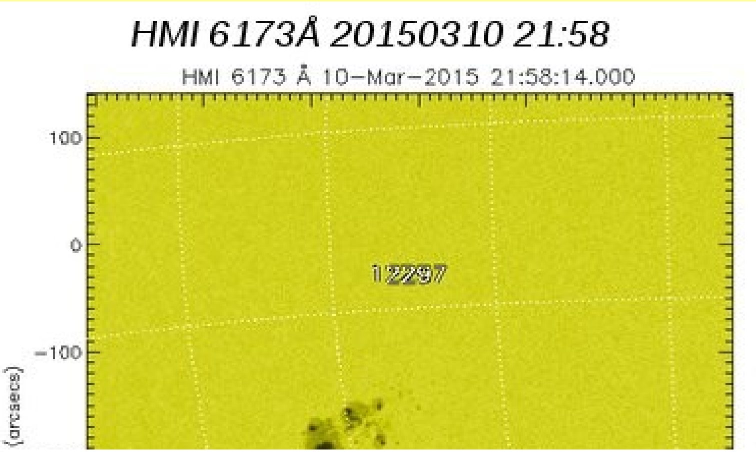
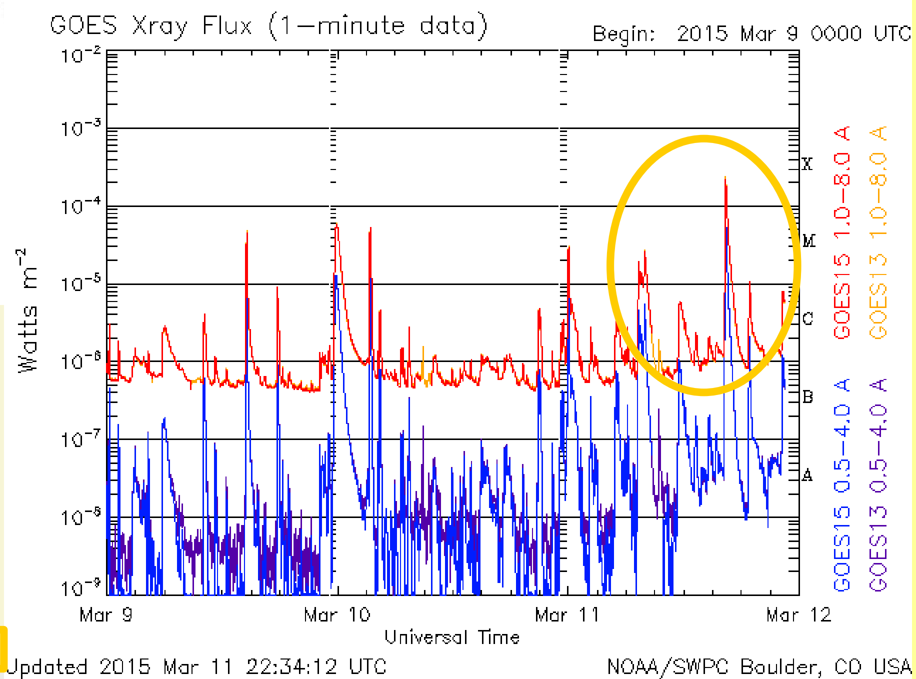





```
#
:Whole_Disk_Flare_Prob:
Class_M                   60            60            60
Class_X                   10            10            10
Proton                    10            10            10
#
# Region Flare Probabilities for 2015 Mar 11
# Region     Class C      M             X             P
:Reg_Prob: 2015 Mar 10
  2297          90        60            10            10
```



Operational Flare Forecasting

- Numerous governments established space-weather forecast centers.
  - Flare forecasting usually included.
  - Varying levels of independence from US NOAA/Space Weather Prediction center.
  - Generally based on historical paradigms

- Additional operationally-running forecast facilities
  - Some: research-based
  - Some: testbeds for new capabilities

- Research *vs*. Operational Paradigms:
  - Physics-based *vs*. not Physics-based
  - Easy requirements on data availability *vs*. Strict data requirements
  - No forecast is "OK" *vs*. Forecasts always required.

Reality Checks: Present Capabilities

Operational flare forecasting: a direct comparison

Leka+ 2019 a,b
Park+ 2020

- 2018 Workshop sponsored by: Center for International Collaborative Research, Institute for Space-Earth Environmental Research, Nagoya University — NAGOYA UNIVERSITY
- 19 operational methods:
  - Established government forecasts
  - Operationally-running research systems

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→ Coordinated testing intervals, event definitions, forecasting scope

→ Multiple quantitative metrics to evaluate performance.

→ Examine methodologies: the "*why*" for performance differences.

Reality Checks: Present Capabilities

Reality Checks 1/3

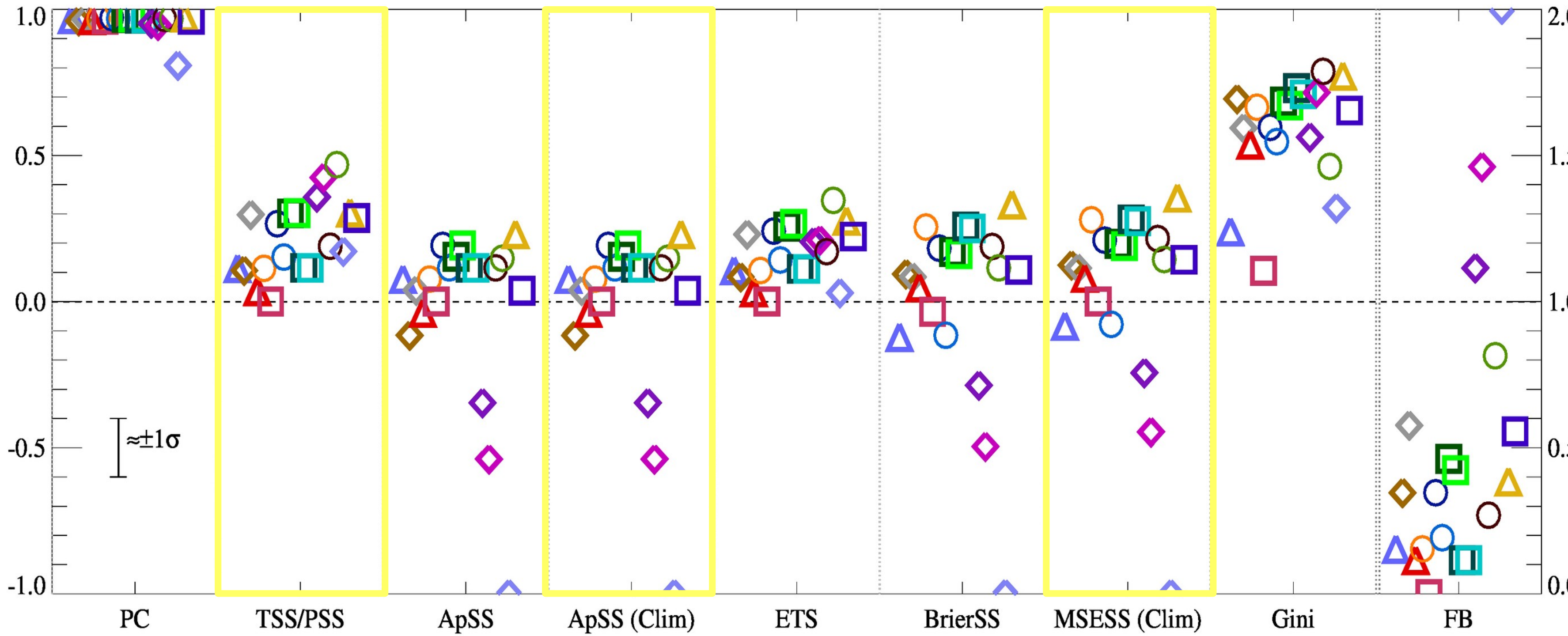
	Method	Agency / Institution	Input Parameter	Prediction Method	Training Interval	Forecast Zone on the Sun	Prior Flaring History	Region Evolution
Agency-authorized forecasts	ASSA	Korean Space Weather Center	Simple*	Not ML$	Hybrid	Limited FOV	None	None
	BOM	Australia Bureau of Meteorology	Magnetic	Not ML	Short	Limited FOV	Auto	None
	MAG4W	NASA / MSFC	Magnetic	Not ML	Hybrid	Limited FOV	None	None
	MAG4VW	NASA / MSFC	Magnetic	Not ML	Hybrid	Limited FOV	None	None
	MAG4WF	NASA / MSFC	Magnetic	Not ML	Hybrid	Limited FOV	Auto	None
	MAG4VWF	NASA / MSFC	Magnetic	Not ML	Hybrid	Limited FOV	Auto	None
	MOSWOC	UK MetOffice	Simple	Simple + Human	Long	Earth-impacting+	Other	Qualitative
	NICT	National Inst. of Info. & Comm. Tech	Simple	Simple + Human	Long	Earth-impacting	Other	Qualitative
	NOAA	NOAA / SWPC	Simple	Simple + Human	Long	Earth-impacting	Other	Qualitative
	SIDC	Royal Observatory of Belgium	Simple	Simple + Human	Long	Earth-impacting	Other	Qualitative
Forecasts from research-institution -based models	AMOS	Kyung Hee University	Simple	Not ML	Long	Full-disk	None	Quantitative
	A-EFFORT	Academy of Athens	Magnetic	Not ML	Hybrid	Limited FOV	None	None
	ASAP	University of Bradford	Simple	Advanced#	Hybrid	Limited FOV	None	None
	DAFFS	NorthWest Research Associates	Magnetic	Advanced	Short	Full-disk	Auto	None
	DAFFS-G	NorthWest Research Associates	Magnetic	Advanced	Long	Full-disk	None	None
	MCSTAT	Trinity College Dublin	Simple	Not ML	Long	Full-disk	None	None
	MCEVOL	Trinity College Dublin	Simple	Not ML	Long	Full-disk	None	Quantitative
	NJIT	New Jersey Institute of Technology	Magnetic	Not ML	Hybrid	Limited FOV	None	None

Simple*: Sunspot morphological property / **Not ML$**: Poisson statistics or Bayesian inference / **Advanced#**: Discriminant analysis or machine learning techniques / **Earth-impacting+**: Active regions behind the solar limb

Reality Checks: Present Capabilities

Operational flare forecasting: recent direct comparison

Numerous quantitative performance metrics for the same; imposed Probability Threshold Pth=0.5 for probabilistic → dichotomous assignments. Note differing performance across metrics. From Leka+ 2019.



(PC, TSS, ApSS (both), ETS, FB @Pth=0.5)

No method is consistently @top
Different Metrics = Different Information
TSS / ApSS / MSESS : no method scores > 0.5

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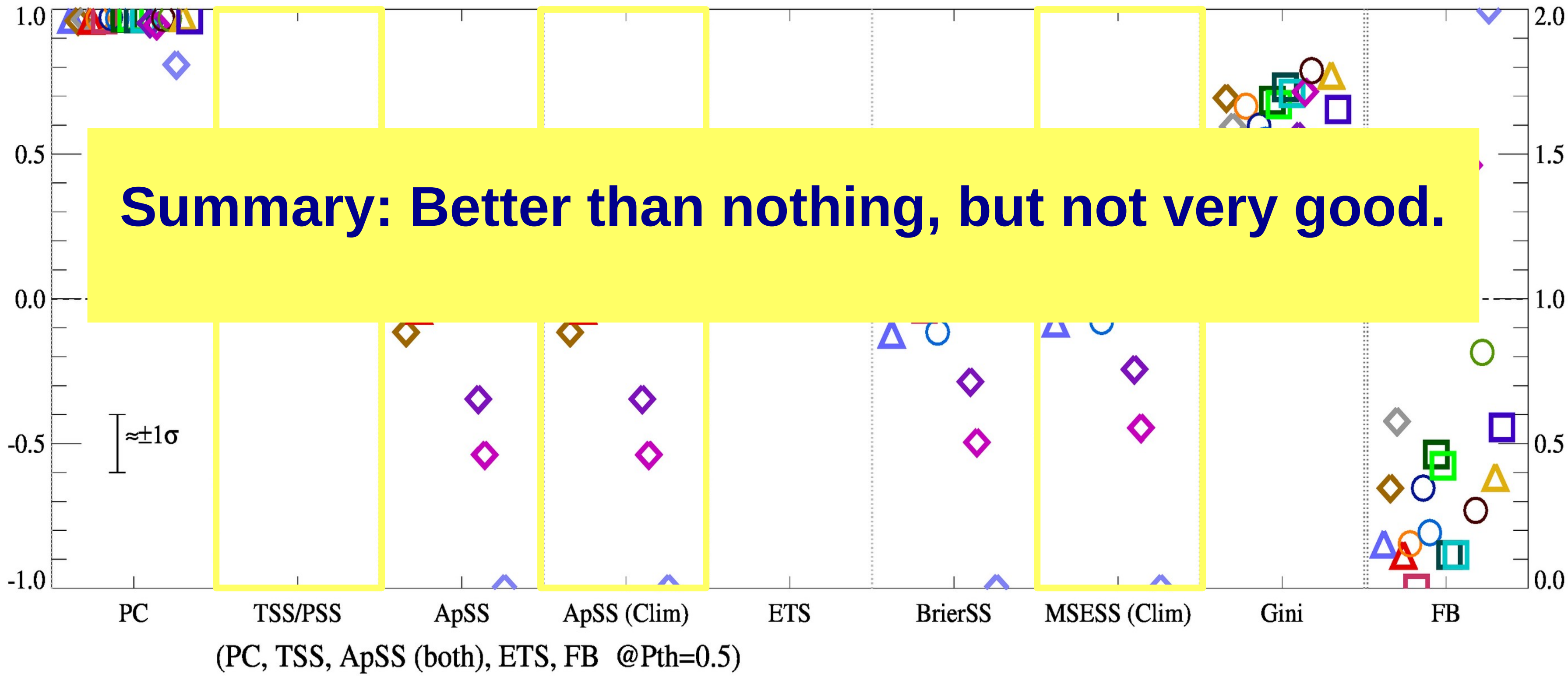


Summary: Better than nothing, but not very good.

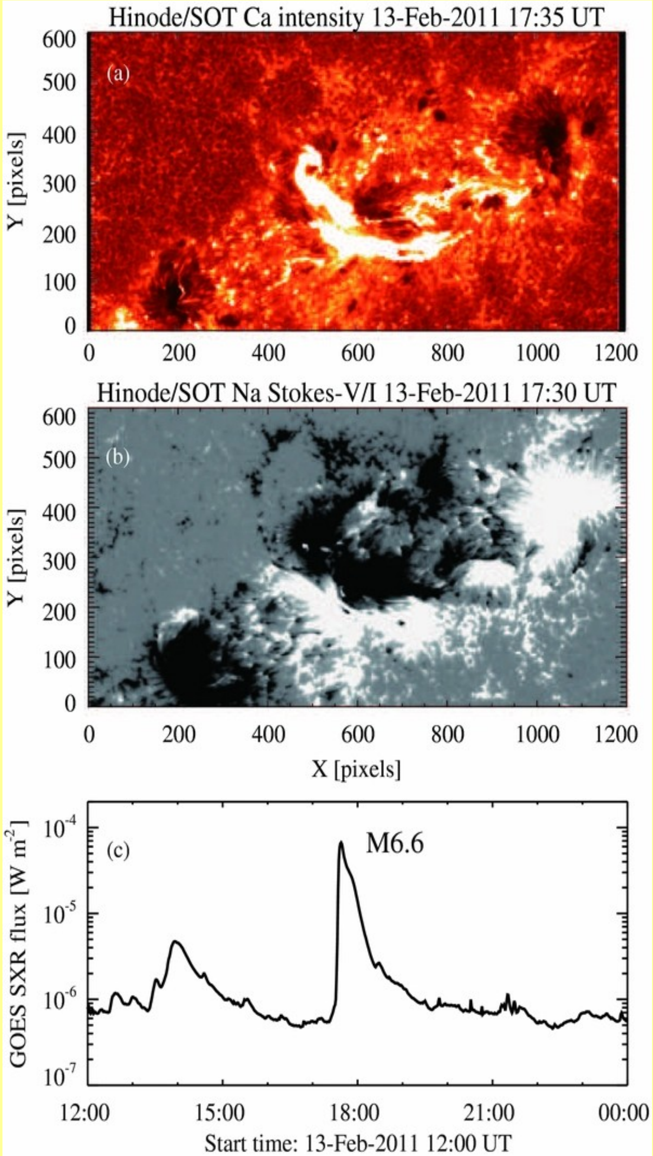
No method is consistently @top
Different Metrics = Different Information
TSS / ApSS / MSESS : no method scores > 0.5

Reality Check

What do we (think we) know?

- Observer's wisdom has been confirmed with modern data and analysis. Flaring regions:
  - are magnetically complex,
  - evolve quickly,
  - store free magnetic energy in the corona

"Solar Flares are related to electrical currents in the solar chromosphere" (Alfven & Carlqvist, 1967)

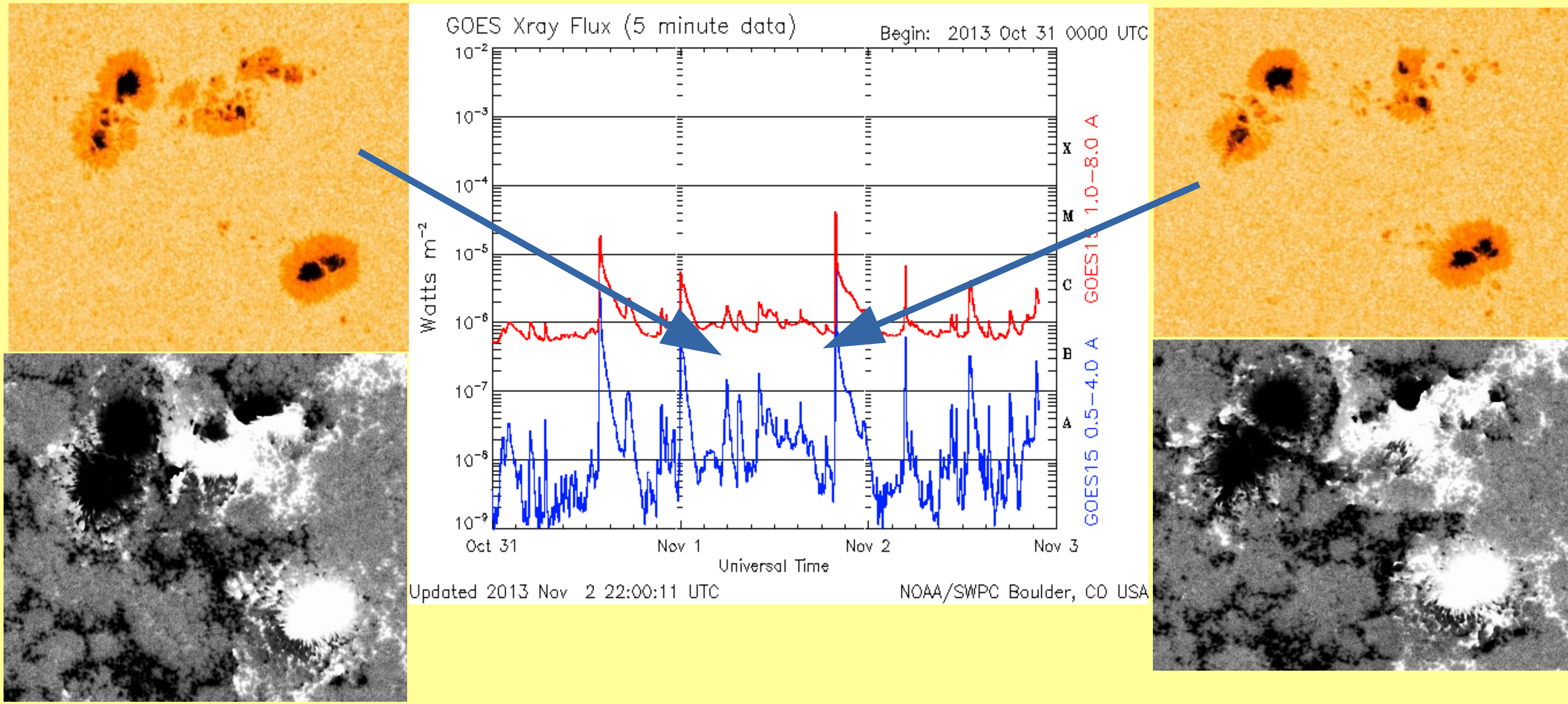


Flare-Productive NOAA AR 11158, images of the chromosphere (top), photospheric magnetic field (middle), and the GOES Soft X-Ray trace of one of its flares.
From Toriumi+ 2013

Reality Check

What do we <u>not</u> know? Triggering mechanism(s)

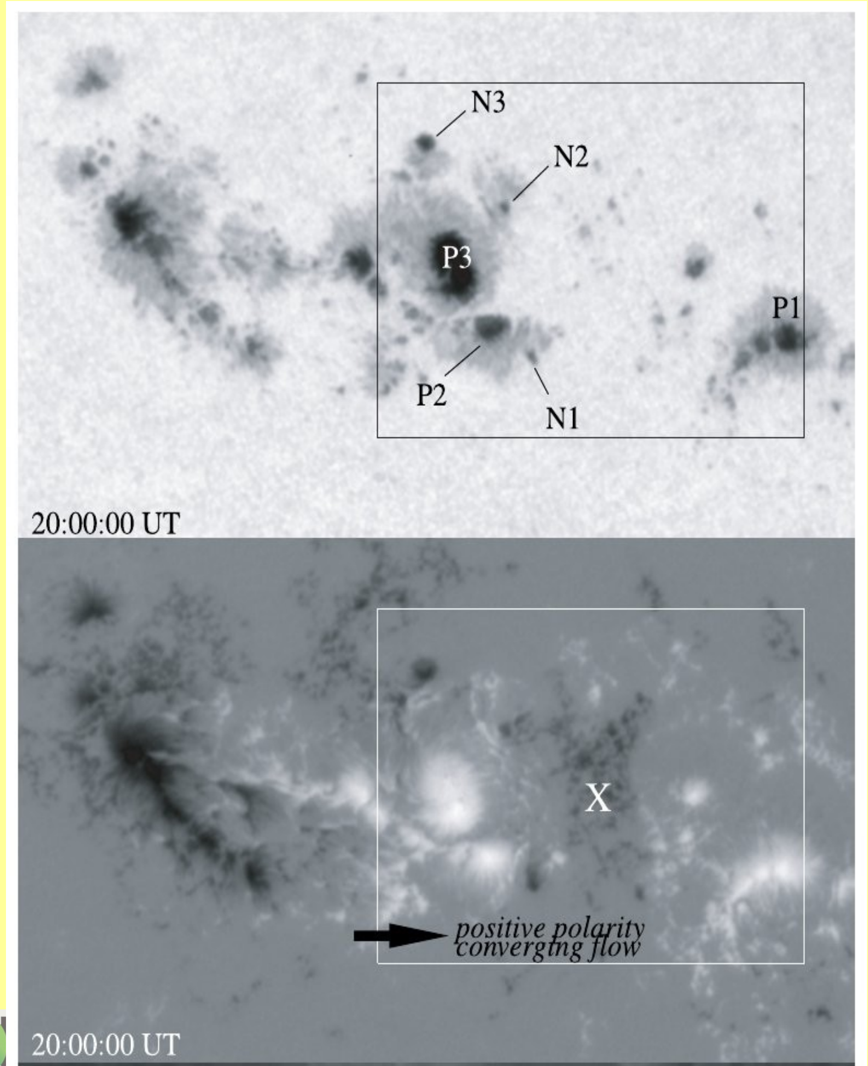
- Challenge: why not *now*….but *<u>now</u>*?



Reality Check

What do we "know"…that ain't so?

- "Large Flares *only* happen along strong-gradient magnetic polarity inversion lines."
  - *Not true.*
    - 2002 Jul 15 AR 10030 X3.0 *(Li+ 2005)*
    - 2015 Nov 04 AR 12443 M3.7 *(Wang+ 2018)*
- "Geo-impactful flares/ coronal mass ejections *require* a large sunspot region"
  - *Not true.*
    - Hyderflares (large filament eruptions, often in old "remnant" field) and C-class (smaller) flares have been frequently associated with CMEs and SPEs.

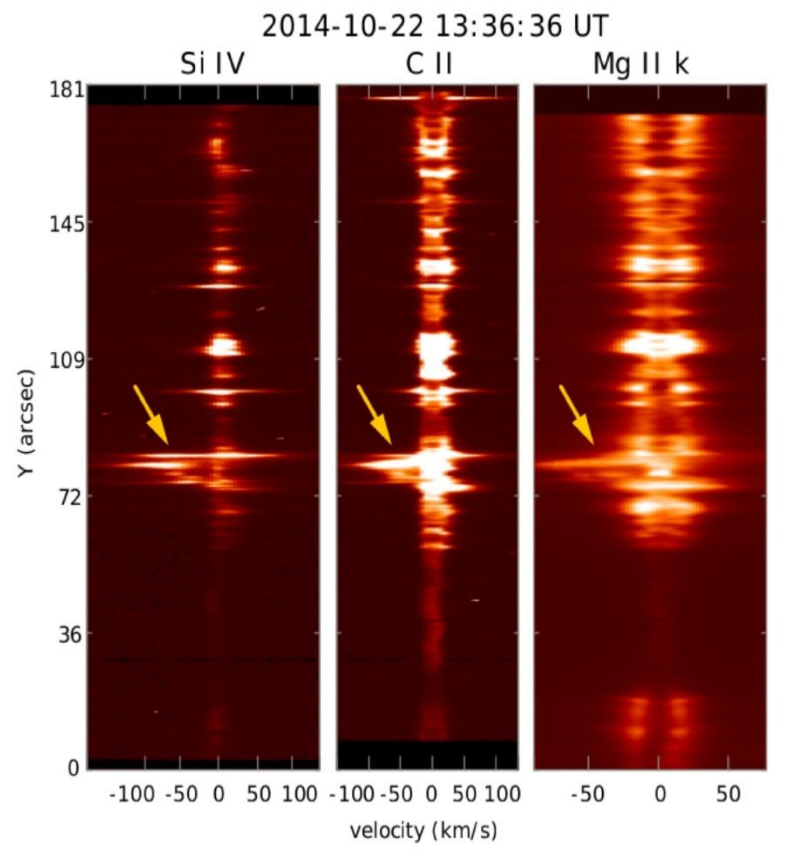


Progress Path #1: Detailed Physics

Progress Path #1: Detailed Physics

Small-sample observational studies with unique datasets

- Detailed observational analysis of flare pre-cursors.
- Higher resolution, cadence, wavelength coverage than previously available.
  - Space-based archives allow more consistent data
  - Combining with specialized ground-based data

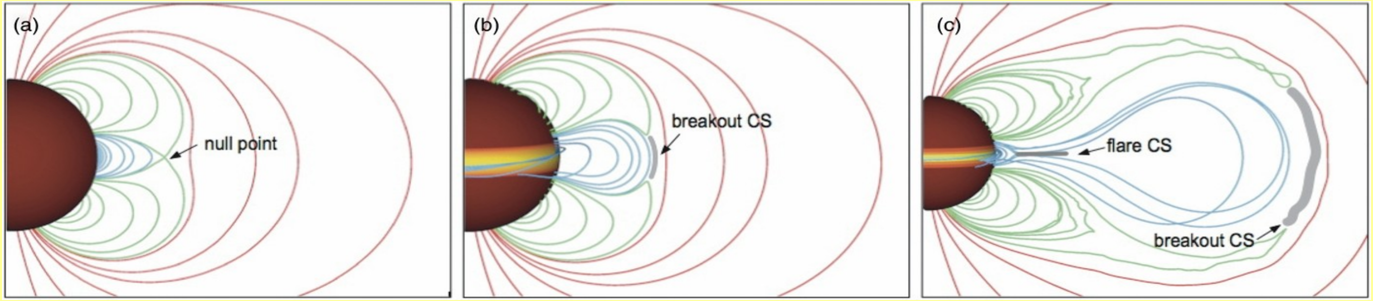


Pre-Flare brightenings along a sheared PIL observed with IRIS chromospheric spectroscopy. *Bamba+ 2017.*

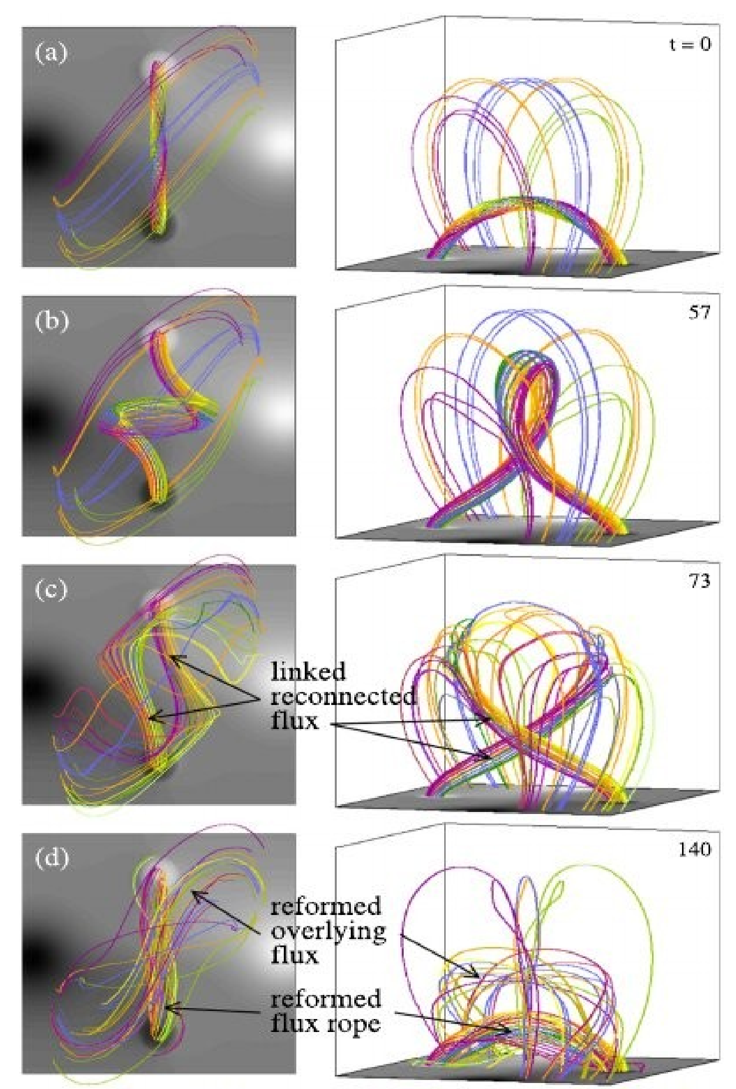
Progress Path #1: Detailed Physics

Triggering mechanism(s):

- Small scale dynamics? Or large-scale instabilities?
- Emerging flux?
- Magnetic (MHD) instability? (Which one?)
- Trigger reconnection to open the field? Or open the field to trigger reconnection?



Karpen+2012



Hassanin & Kliem 2016

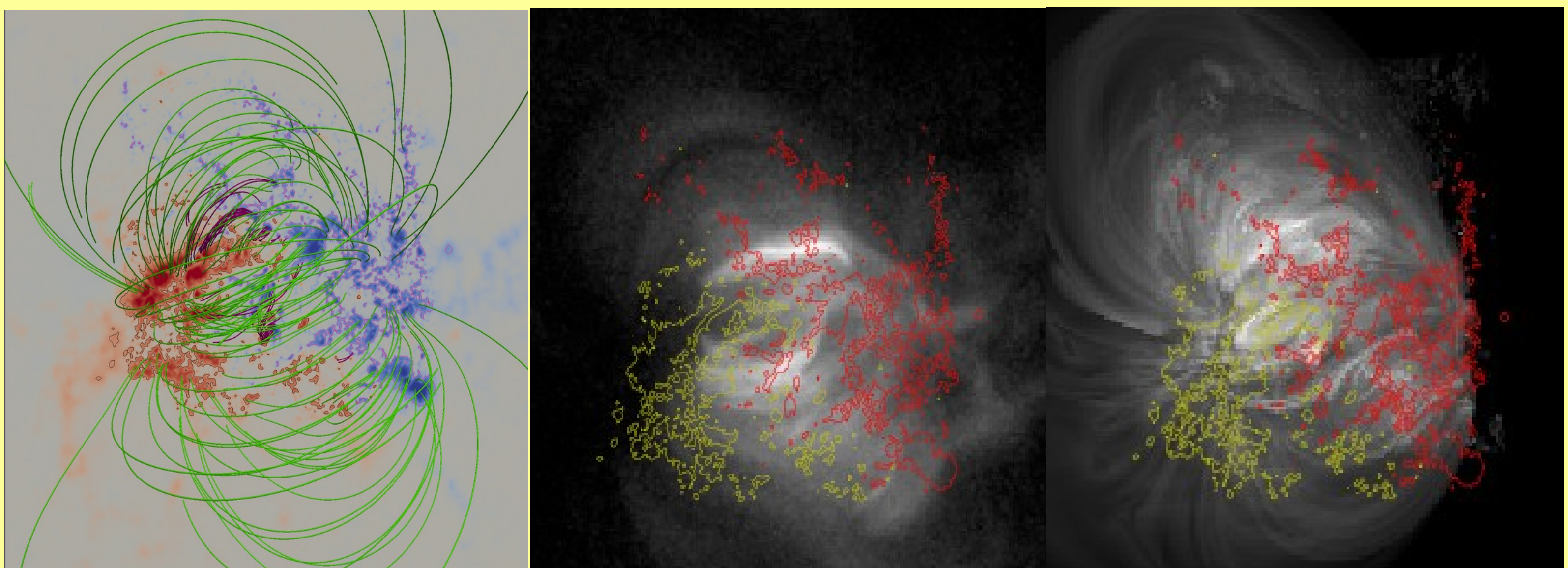
Progress Path #1: Detailed Physics

Modern / New Modeling Capabilities

- We cannot routinely directly measure coronal ***B*****,**
  - *But the corona is where the energy is stored.*

→ Model the (static) coronal magnetic field to evaluate the energy

- Non-linear force-free field models
- Allowing magnetic forces with magnetostatic and MHD approaches



Left-Right: NLFFF extrapolation of AR10978, Hinode/SP +MDI boundary, to evaluate coronal energy systems; line-of-sight integrated current density; Hinode/XRT image.
Courtesy: S. Gilchrist
(Barnes, Gilchrist & Leka, in prep)

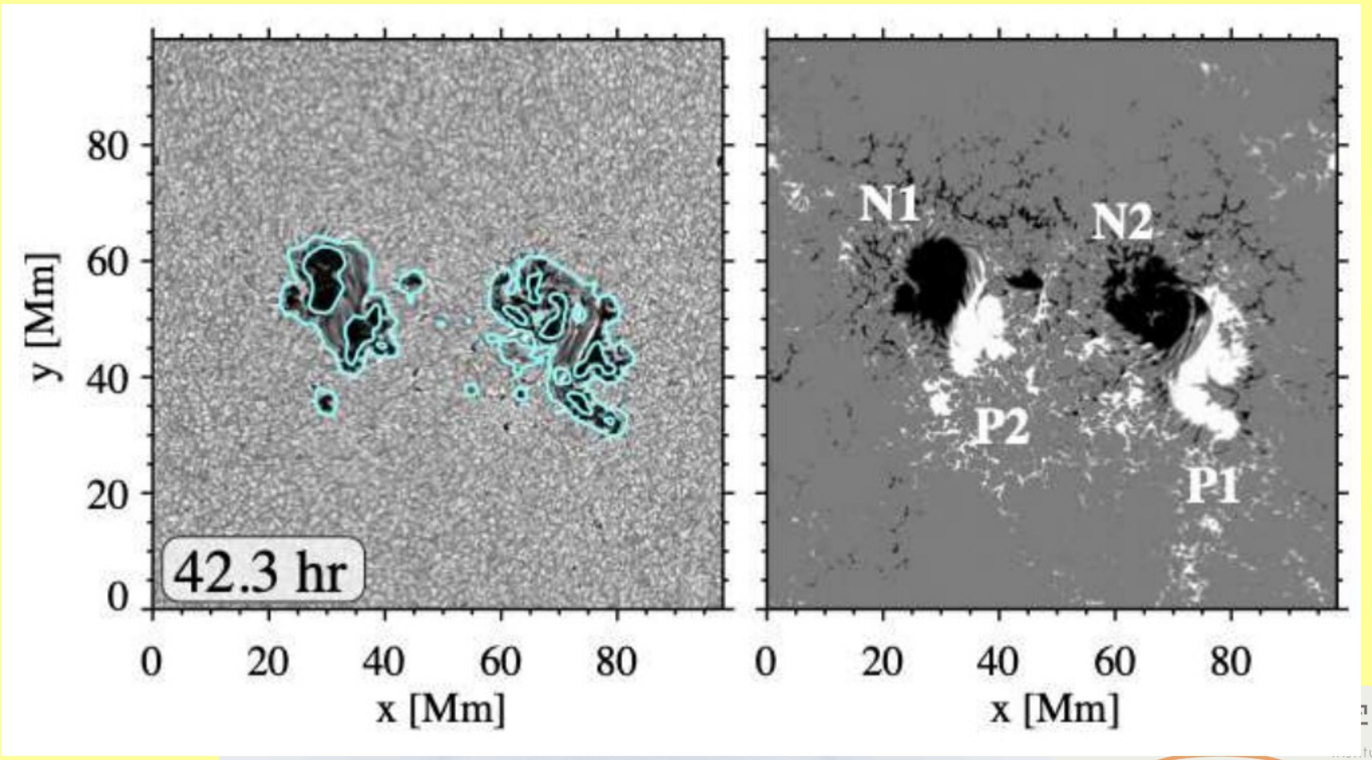
Progress Path #1: Detailed Physics

Modern / New modeling capabilities

- Better compute technology + improved mathematical algorithms → physics-based modeling

➔ Data-driven simulations, Model-inspired data analysis, Data assimilation

__Left__: Interacting emerging bipoles showing complex white-light and magnetic structure. The R2D2 calculations include full convection. ***Right****: the magnetic flux rope that forms from reconnection due to the collisions. From Toriumi & Hotta 2019;*

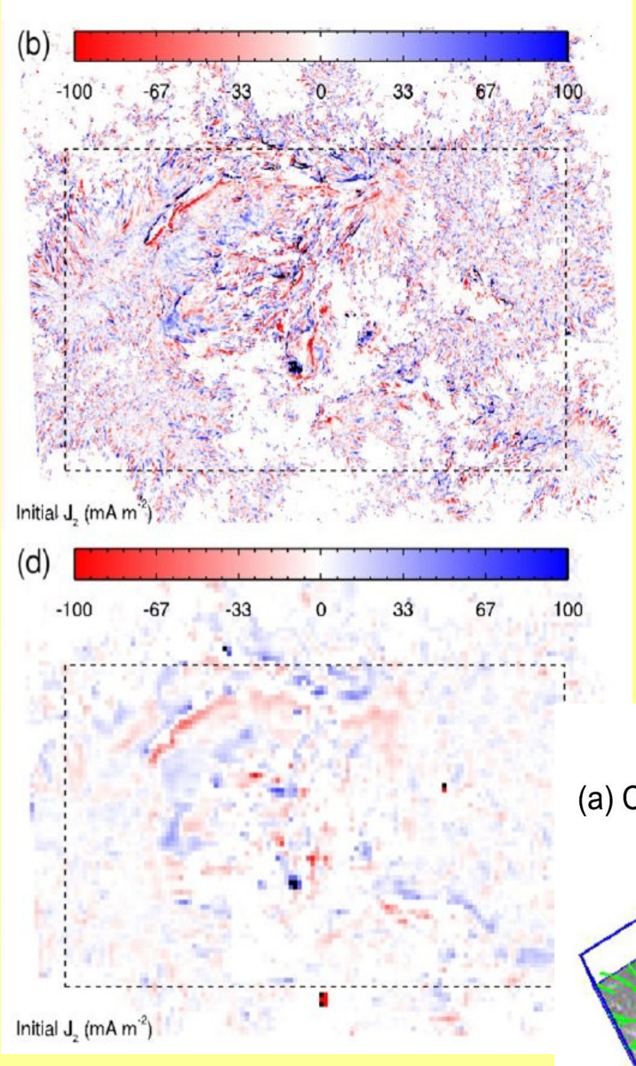


Progress Path #1: Detailed Physics

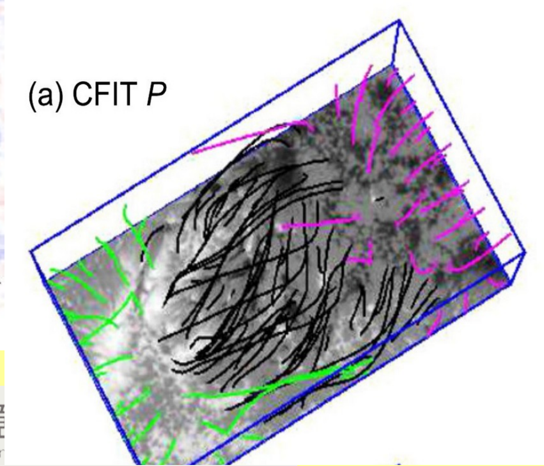
Challenge:
The Sun's complexity
vs.
model capability

- Highest-performing models still rebin, restrict, approximate
  - May "loose" important physics

- Observational evidence supports many mechanisms may possibly be at work.
  - Models *tend* to focus on one mechanism at a time



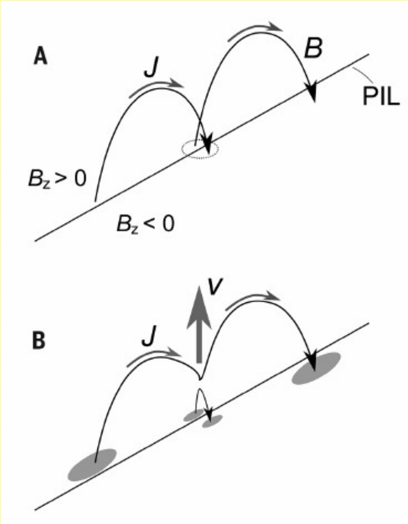
Top: Native high-resolution map of Jz (3σ only – fine structure is not noise!) from Hinode/SP. **Bottom**: same, binned by 8x for input to NLFFF extrapolations (**below**). *(DeRosa+ 2015)*



Progress Path #1: Detailed Physics

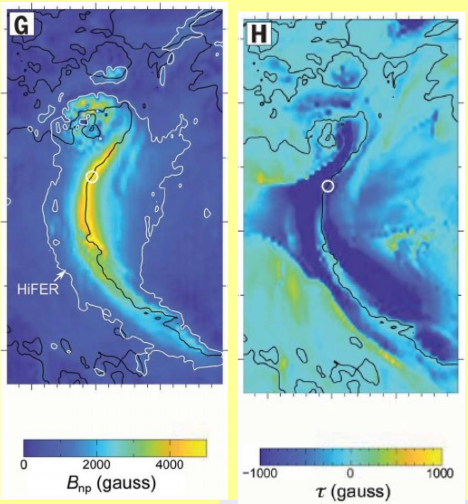
A trigger mechanism investigated on many events.

Kusano+2020

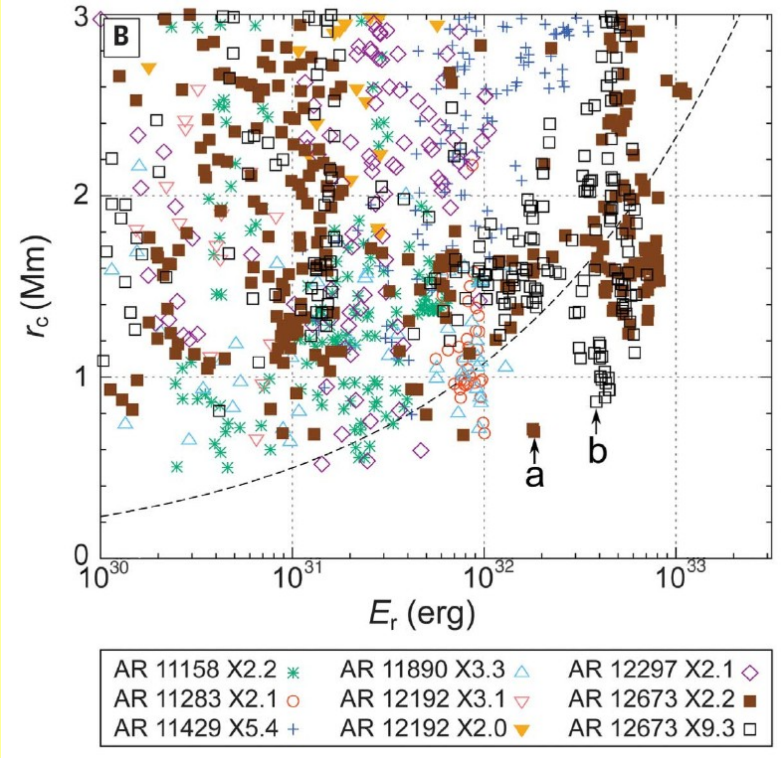


Double Arc Instability (MHD instability) and the “κ*” scheme:

- Amount of available energy estimated by free energy in the coronal field associated with “high-twist” areas
- Likelihood to flare estimated by r_{crit} vs. S_{crit} , a critical radius governing the instability of the twisted vs. overlying magnetic field lines.



Top/left: schematic of reconnection process; the small circle is the susceptible S_{crit}.
Left: Non-potential component of the field (G) and the total field-weighted twist. The small circle indicates the location of the smallest r_{crit} for this AR.
Right: the available energy (Er) if a flare started at that point (and its r_{crit}). Dashed line is a self-similarity stability threshold.



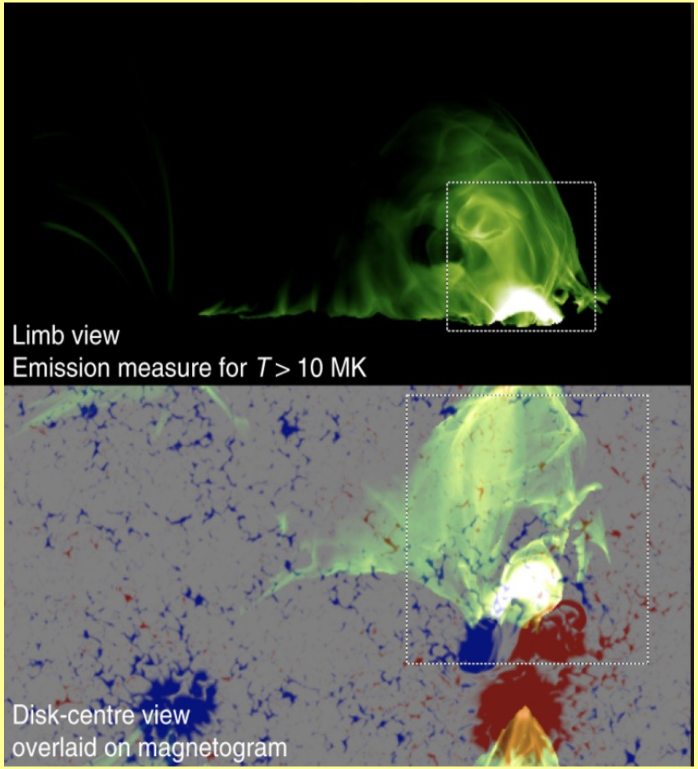
Challenge: works best for largest flares.

Progress Path #1: Detailed Physics

Challenge: Case studies vs. the Sun:

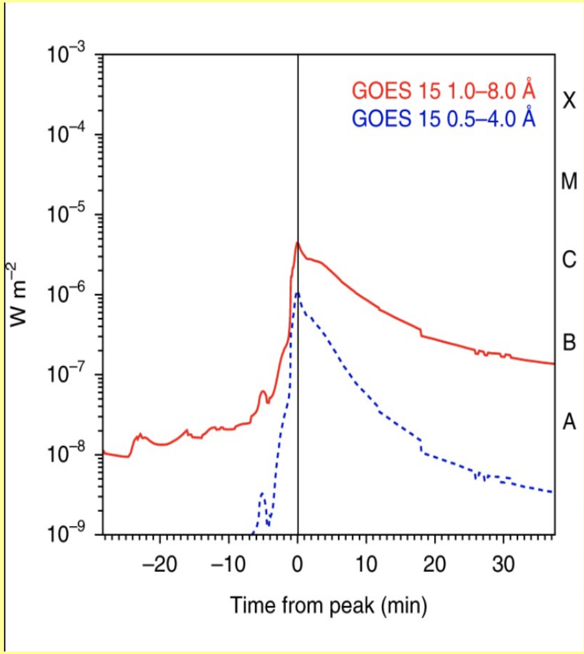
“Whatever rule you determine, the Sun will break it”

Case-studies often focus on the largest, most complex targets.



Left: data-driven model of an active region and resulting flare (*Cheung+2018)*.

Right: resulting synthetic GOES lightcurves.

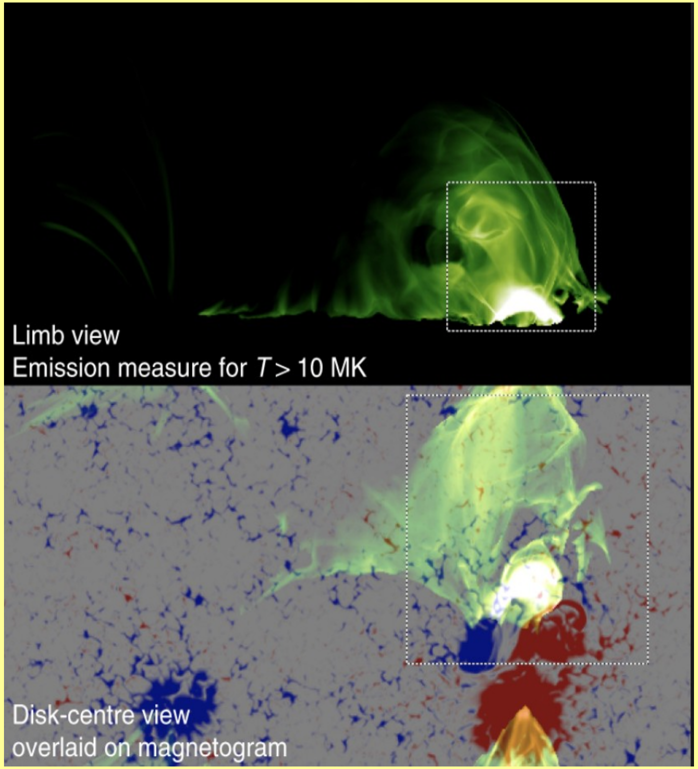


Progress Path #1: Detailed Physics

Challenge: Case studies vs. the Sun:

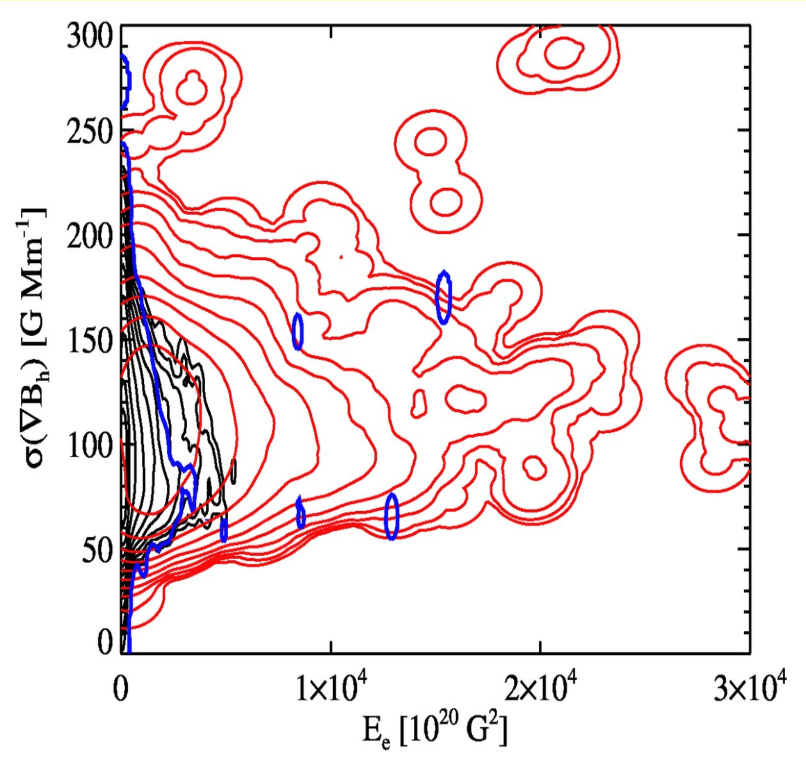
"Whatever rule you determine, the Sun will break it"

Case-studies often focus on the largest, most complex targets.
Flares and energetic events can occur over a large parameter space.



Left: data-driven model of an active region and resulting flare (*Cheung+2018*).

Right:Probability Density Functions of 32,000 daily-sampled *flare-productive* and *flare-quiet* HMI patches, with 50% probability contour for reference, in parameter-space of the standard deviation of horiztonal gradients, and a free-energy proxy (*Leka+2018*).



Progress Path #2: Large sample analysis

Enabled by ***long-running*** “missions”

- Ground-based and space-based
- International
- Multiple types of data, wavelengths
  - Magnetograms
  - Continuum images
  - UV/EUV images

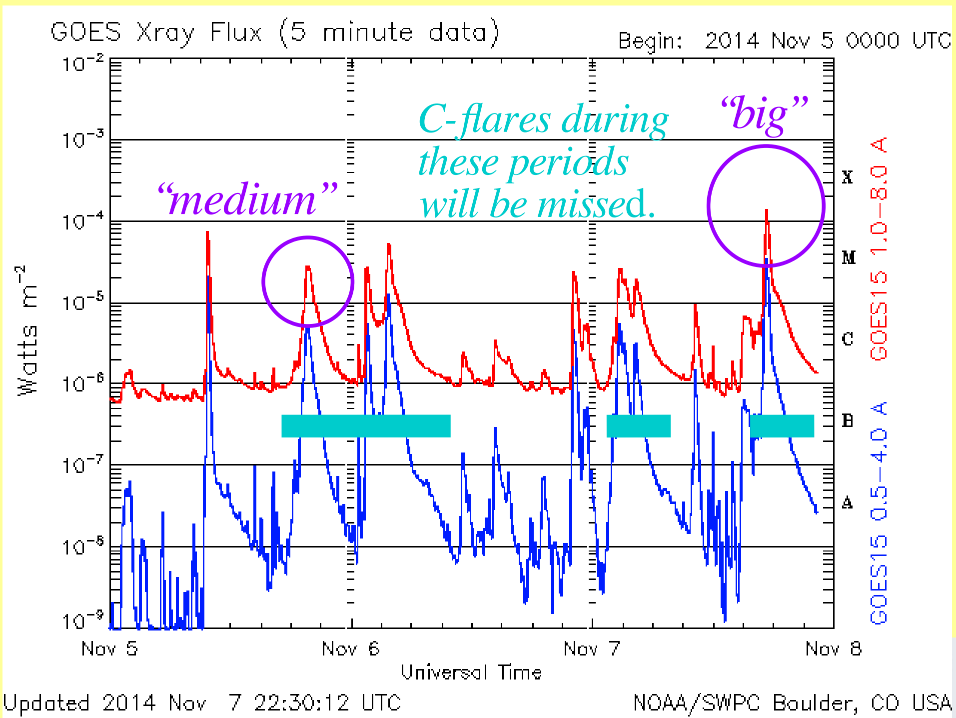
Efforts to merge datasets over multiple solar cycles

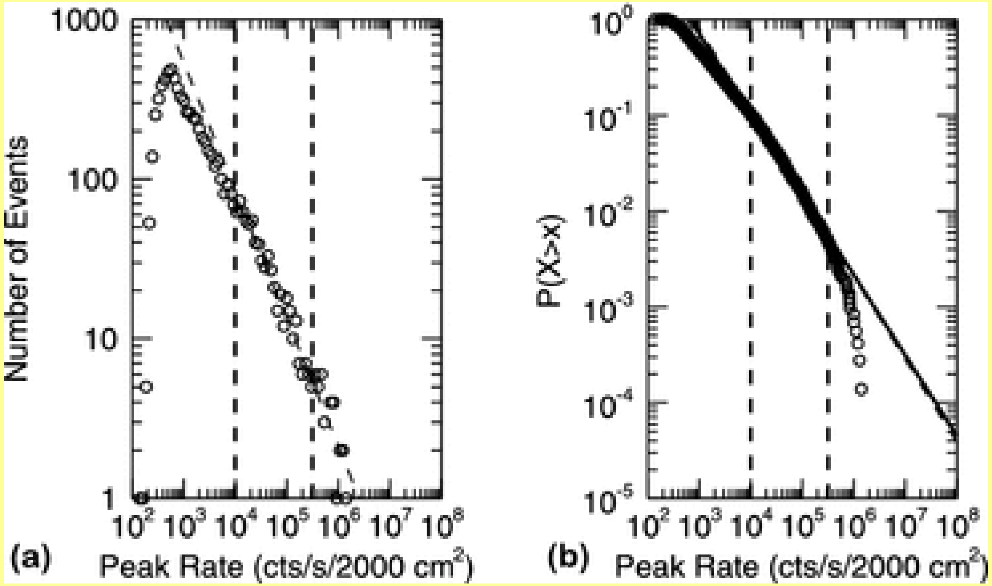
- Cycle 24: small #events
- Final dataset often the “lowest common denominator” (for resolution, sampling, information content, etc.)
- Large events are still statistically very rare.

Progress Path #2: Large sample analysis

What do we (think we) know?

- Solar Flares generally follow power-law distributions in size & frequency.
- However:
  - Smaller flares can be hidden in sun-as-star emission statistics
  - Not always the case in any given active region





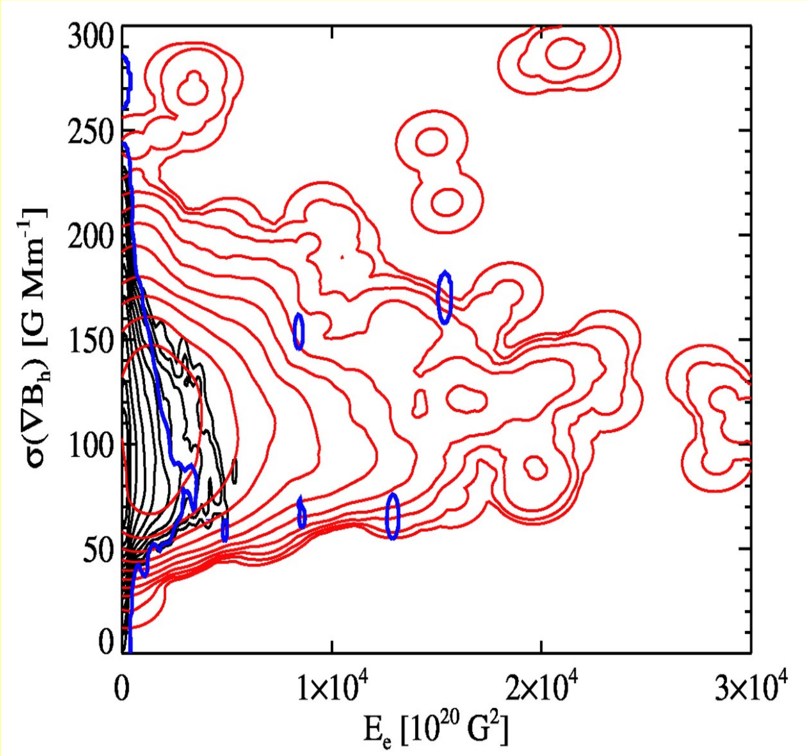
(a) Histogram of number of hard X-ray solar flares as a function of peak size, as measured by the BATSE instrument on board Compton Gamma Ray Observatory

(b) Complementary cumulative distribution function (CCDF) for the same events.

From Riley 2012

Progress Path #2: Large sample analysis

Right:Probability Density Functions of 65,000 daily-sampled *flare-productive* and *flare-quiet* HMI patches, with 50% probability contour for reference, in parameter-space of the standard deviation of horiztonal gradients, and a free-energy proxy (*Leka+2018*).



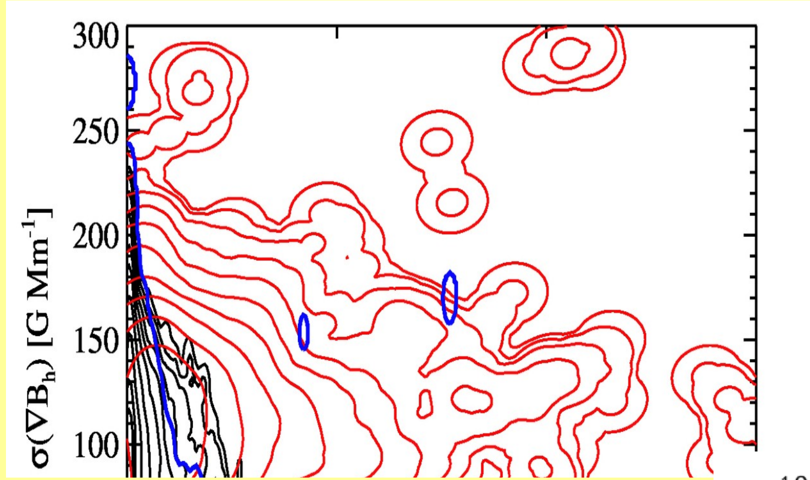
We can map out parameter space for active regions using many different measures.

Take away: flare-active regions can show a broad distribution of behaviors.

Challenge: correlated information

Progress Path #2: Large sample analysis

Right:Probability Density Functions of 65,000 daily-sampled *flare-productive* and *flare-quiet* HMI patches, with 50% probability contour for reference, in parameter-space of the standard deviation of horiztonal gradients, and a free-energy proxy (*Leka+2018*).

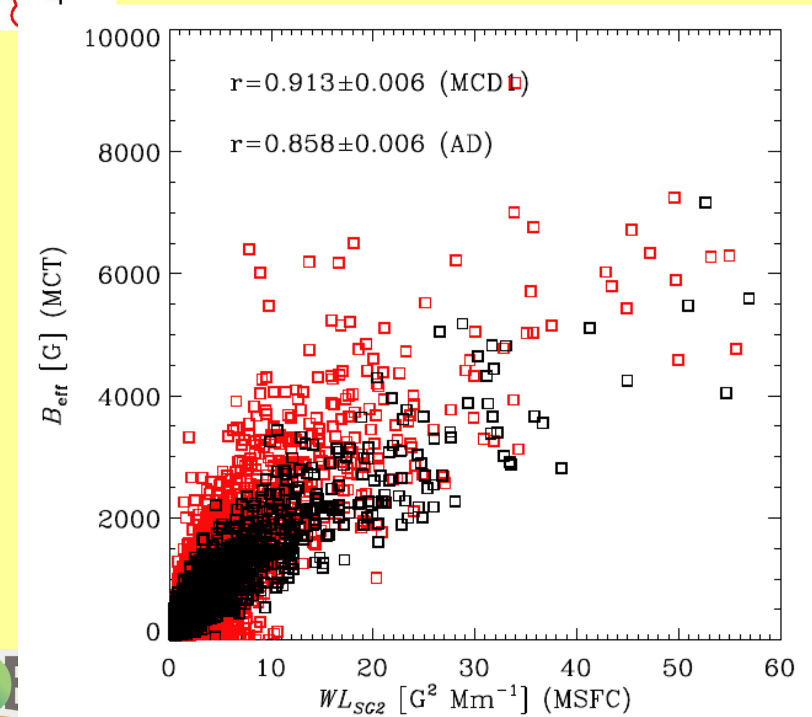


We can map out parameter space for active regions using many different measures.

Take away: flare-active regions can show a broad

Challenge: correlated information

Right: high correlation between two AR descriptors, one based on the magnetic polarity inversion line, the other on a model of the coronal energy.

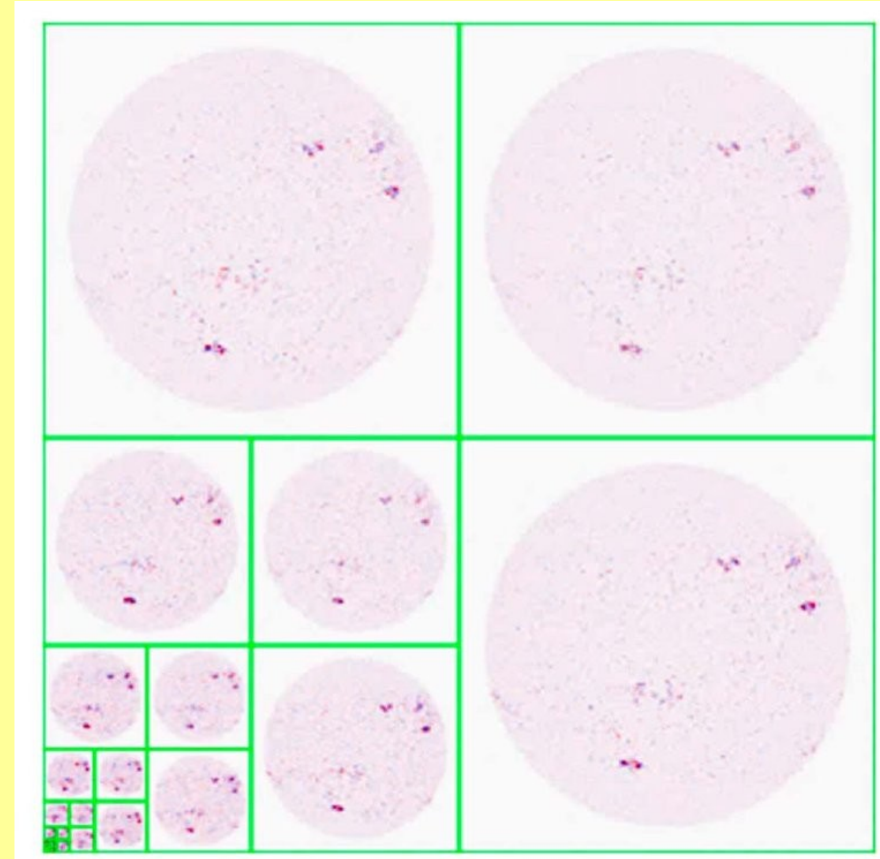


Progress Path #2: Large sample analysis

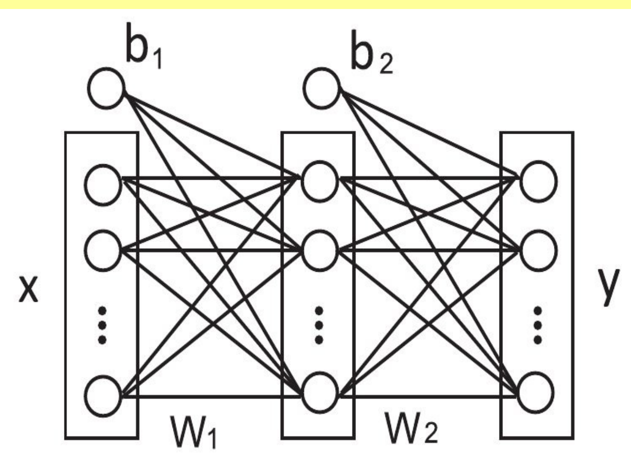
Machine Learning

- Powerful tools, readily available for user application
  - Terabytes of data now available.
  - Multiple applications using pre-selected flare-relevant “SHARP parameters” from SDO

- Can avoid human descriptions, and “let the machine figure out what is important”
  - (philosophy for “raw-image” input)



Non-standard Haar transforms applied to HMI data for input to optimized regression predictor for solar flares. *Muranushi+ 2015.*



Weights, layers, nodes, input & output for a Deep Neural Network. *From Nishizuka+ 2018.*

Progress Path #2: Large sample analysis

Machine Learning

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  - Multiple applications using pre-selected flare-relevant “SHARP parameters” from SDO

- Can avoid human descriptions, and “let the machine figure out what is important”
  - (philosophy for “raw-image” input)

➔ No breakthroughs.

- ➔ ...not terabytes of *independent* data.
- ➔ Using SHARP parameters brings nothing new to previous work. (Pre-determined “flare-relevant” descriptors).
- ➔ Class imbalance “issue”: flares are rare. This challenges ML methods. Re-sampling, etc. can improve ML performance, but *variable class imbalance **is** the Sun*.
- ➔ But….no standard evaluation methods, no standard benchmarks.

- Classifier method makes little difference. Barnes+2017,
- Most image-input ML flare forecasting *downsample the data significantly*.

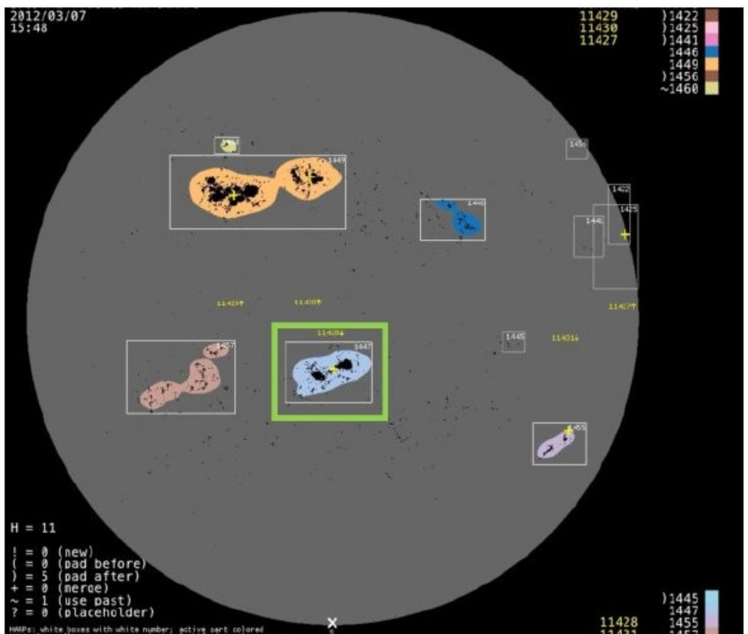
Progress Path #2: Large sample analysis

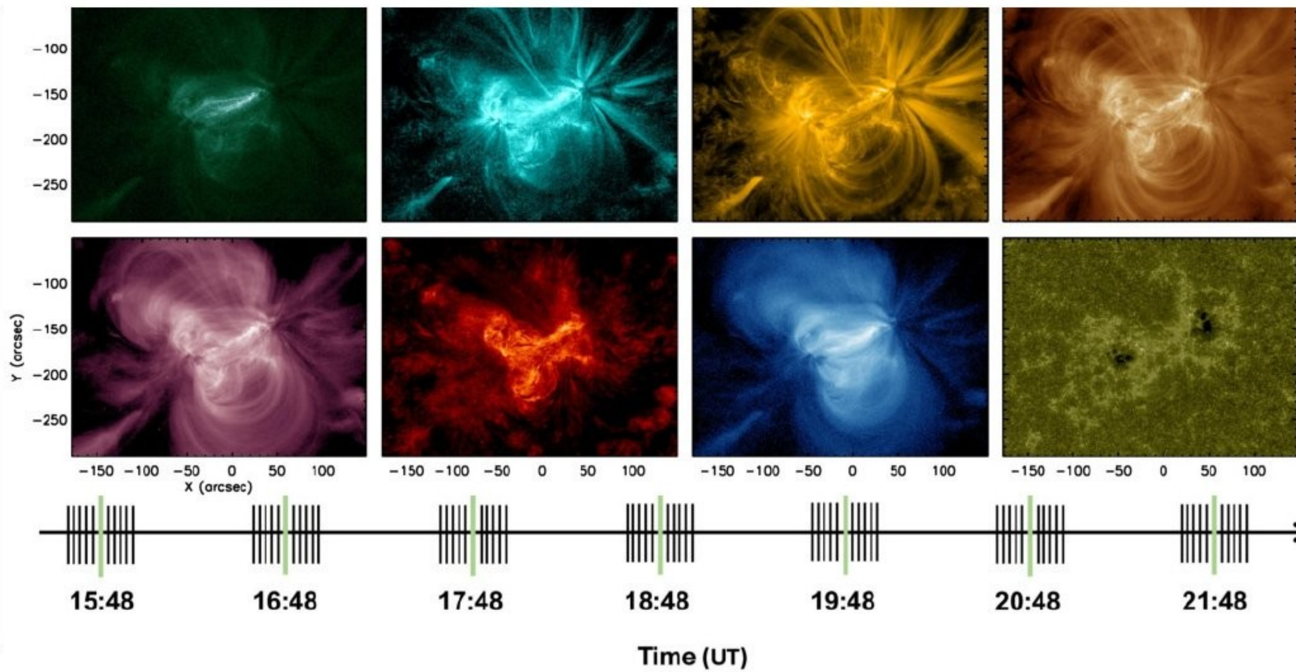
Dissauer+ 2023
Leka+2023

Identifying flare-imminent Active Regions from the chromosphere, transition region and corona

- AIA Active Region Patches (AARPs): 2010--2018

Date Range	HARP Range	NOAA AR Range	# Samples	# AARP days	Archive
06/2010 – 12/2018	36 – 7331	11073 – 12731	256,976	32,067	≈ 9.5 TB





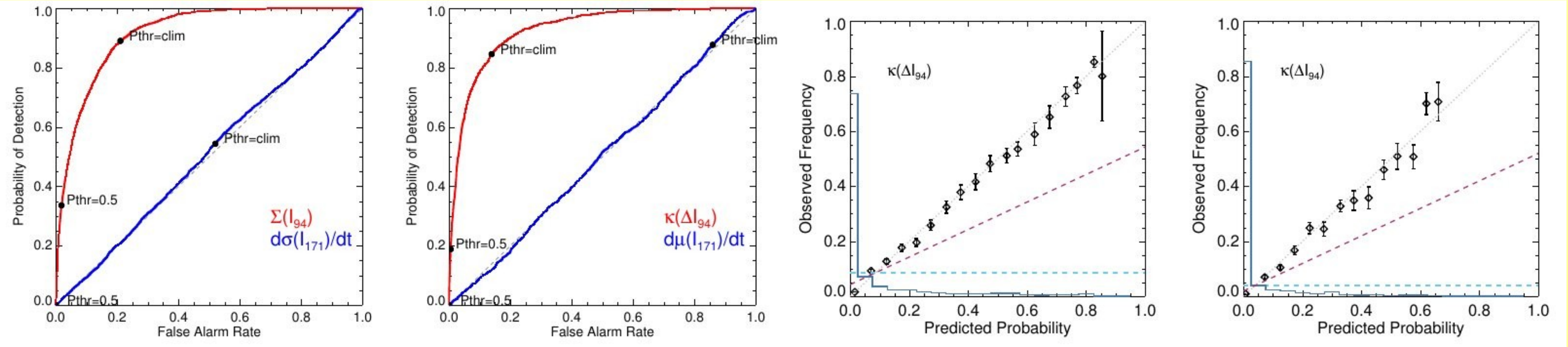
NORTHWEST RESEARCH ASSOCIATES
"unencumbered science"
ISEE 宇宙地球環境研究所
Institute for Space-Earth Environmental Research

Progress Path #2: Large sample analysis

Dissauer+ 2023
Leka+2023

Identifying flare-imminent Active Regions from the chromosphere, transition region and corona

- Discriminant analysis on derived parameters
- C+ and M+, 6-hr and 24-hr event definitions



ROC plots (left) and Reliability plots (right) for C+/24hr (left of pair) and C+/6hr (right of pair)

Results:

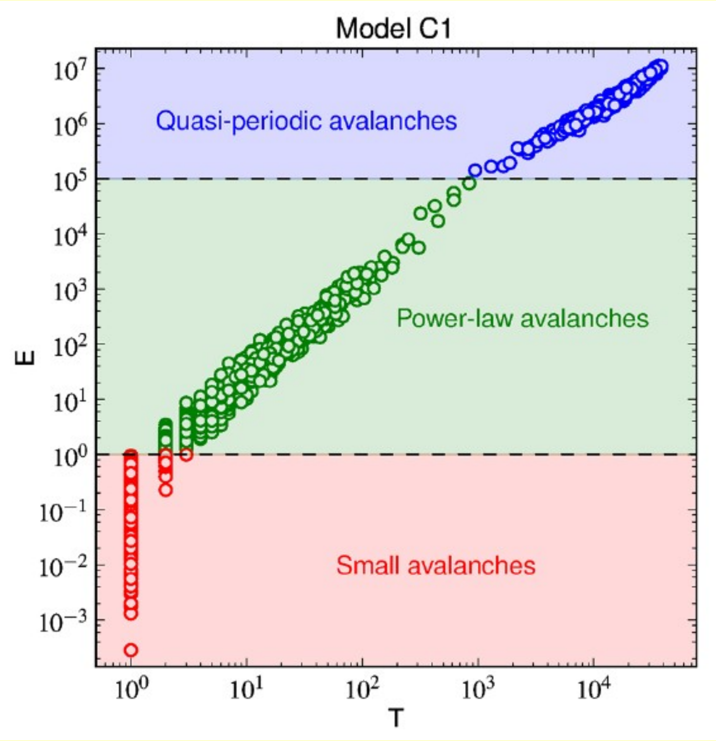
- Statistical evidence for small-scale short-lived dynamics in flare-imminent regions.
- Best-performing filter overall: 94Å (samples multiple temperature regimes)
- Skill scores / etc. are as good as magnetic field parameters (and independent of them)

Progress Path #3?? Something Completely Different

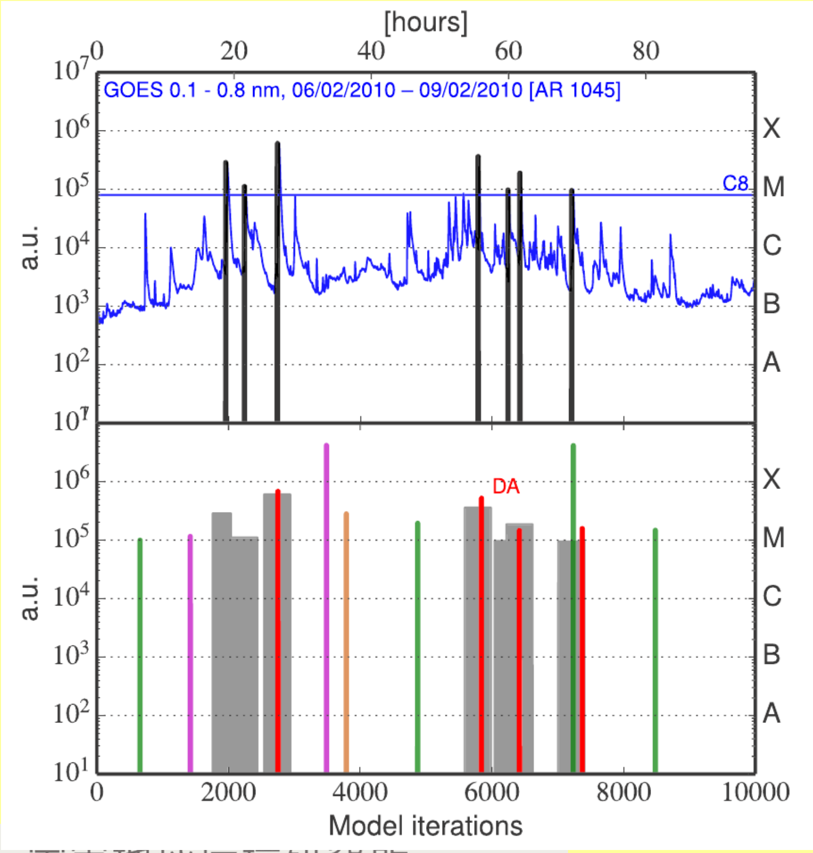
Self-organized Criticality, "Avalanche Models"

Lu & Hamilton 1991
Wheatland 2005 (Baysian)
Strugarek+2014a,b
Thibeault+2022

- Model flares statistically as energy build-up, redistribution, and release at nodes on connected lattices.
- Predictions for: waiting times, expected energy release
- Data assimilation is key for applicability; relies on prior flaring



Left: Avalanche model statistical predictions for 200 runs, showing predicted energy output of a release vs. waiting time (Strugarek+2014). **Right**: Assimilating GOES data into an avalanche model provides event-specific predictions (red-line models) once a few events have occurred, vs random model runs (other colors; Thibeault+2022)



Mind the Gaps!
(What are they?)

Capabilities:

First/Last
4π ("full-Sun") prediction capability
Shorter-latency (event-targeted) predictions
CME vs. not; (SEP vs. not)

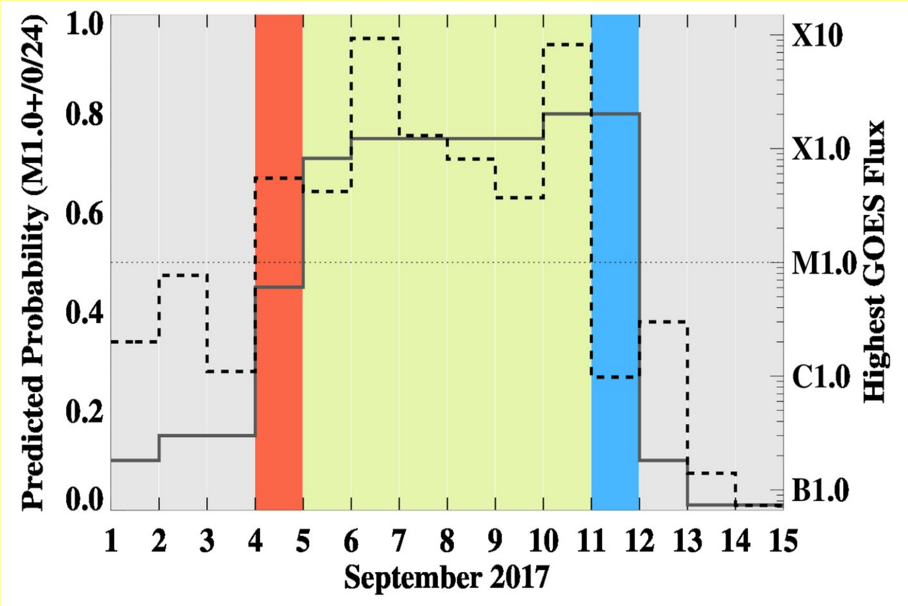
Tools:
Community Validation tools
Standardized Event lists
4π Event List Infrastructure

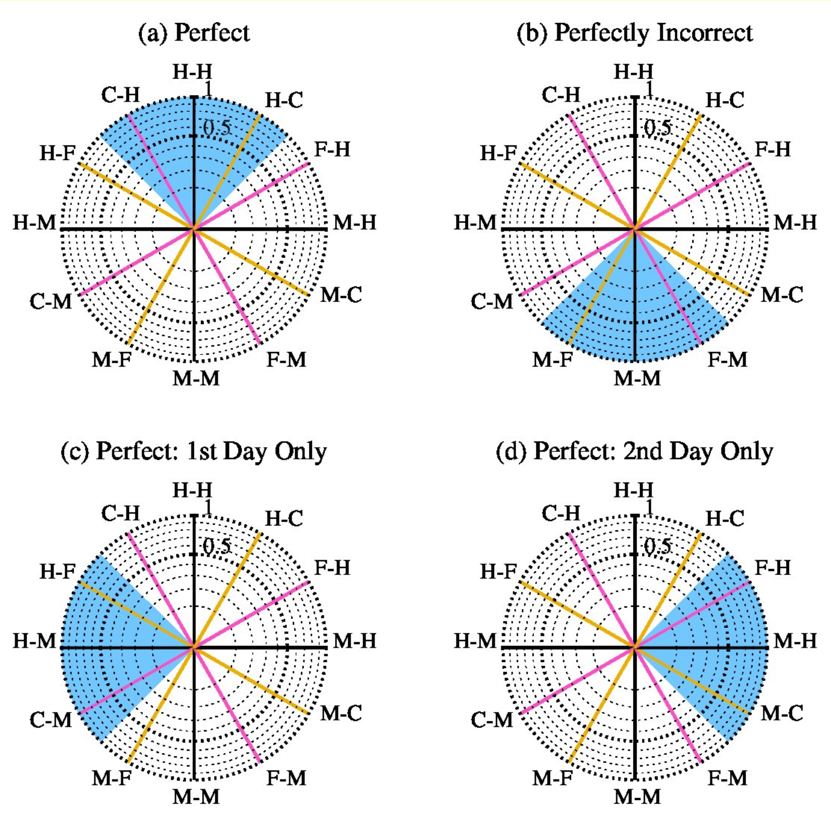
Mind the Gaps!

"First flare / last flare"

• Active regions evolve from a quiet state to flaring, and back, as they emerge, evolve, and decay. Sometimes there are periods of quiet during main development, sometimes not.

• "Persistance" (what happened today will happen tomorrow) is generally a fair predictor. But in this case, it is dangerous.





Above: varying GOES output, and predicted probabilities for 1–15 Sept 2017. For Pth=0.5 these resulted in a miss, a series of hits, and then a false alarm. **Right**: new "radar" plot evaluation tool to quantify forecast performance under varying conditions. From Park+ 2020.

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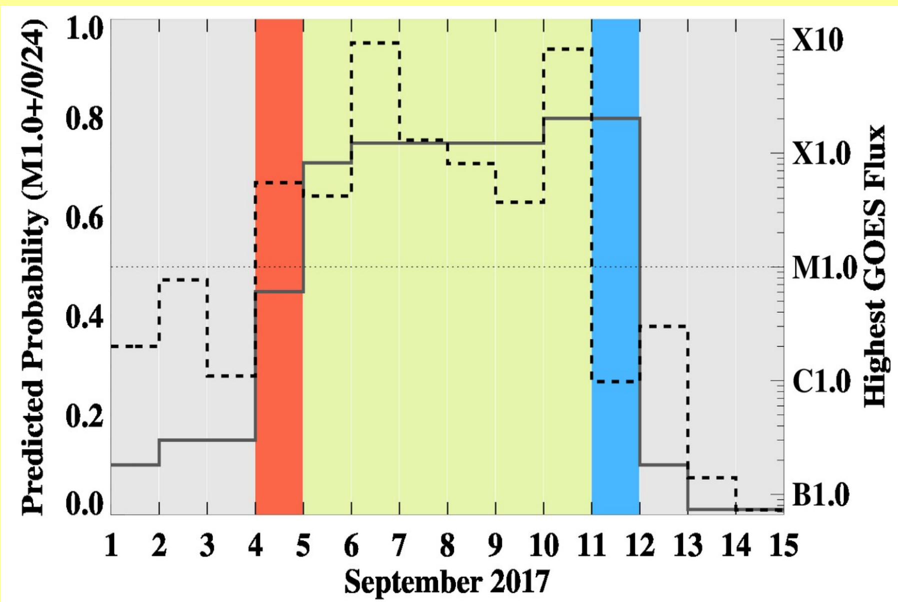

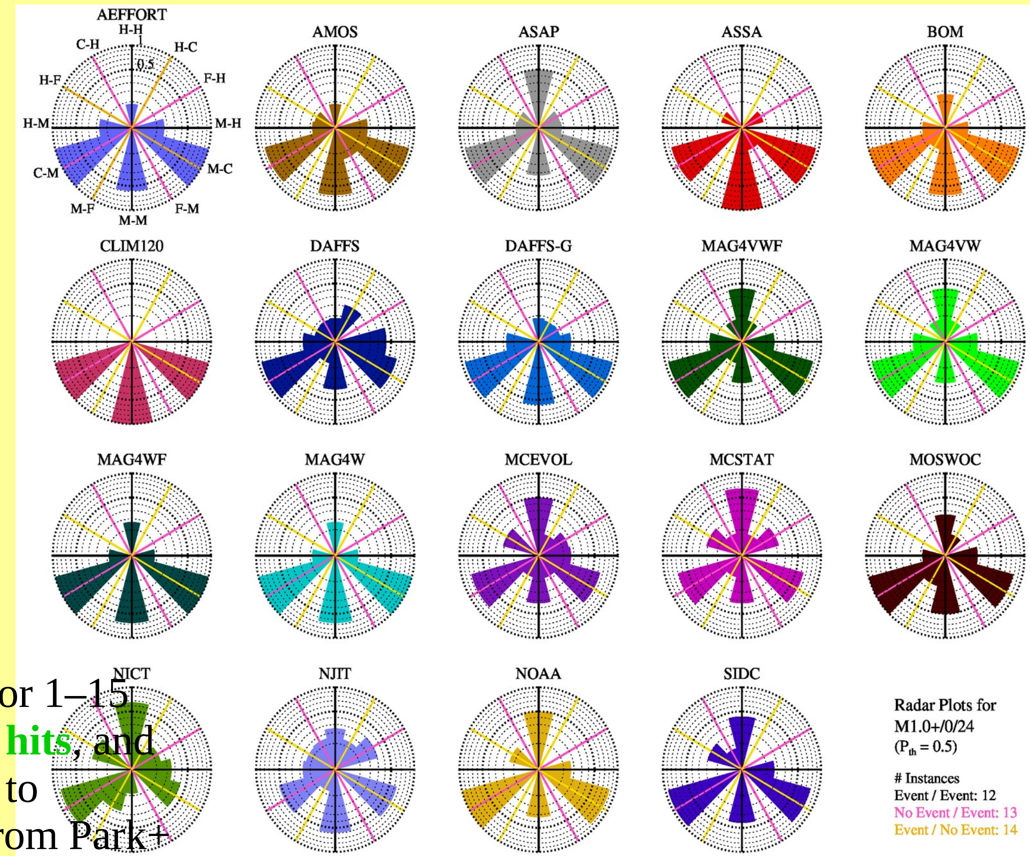

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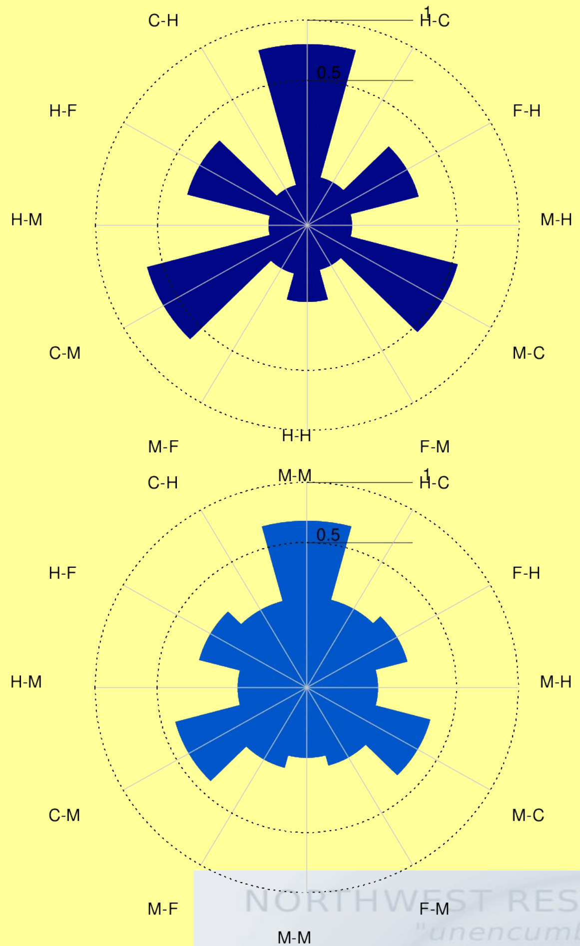
Mind the Gaps!

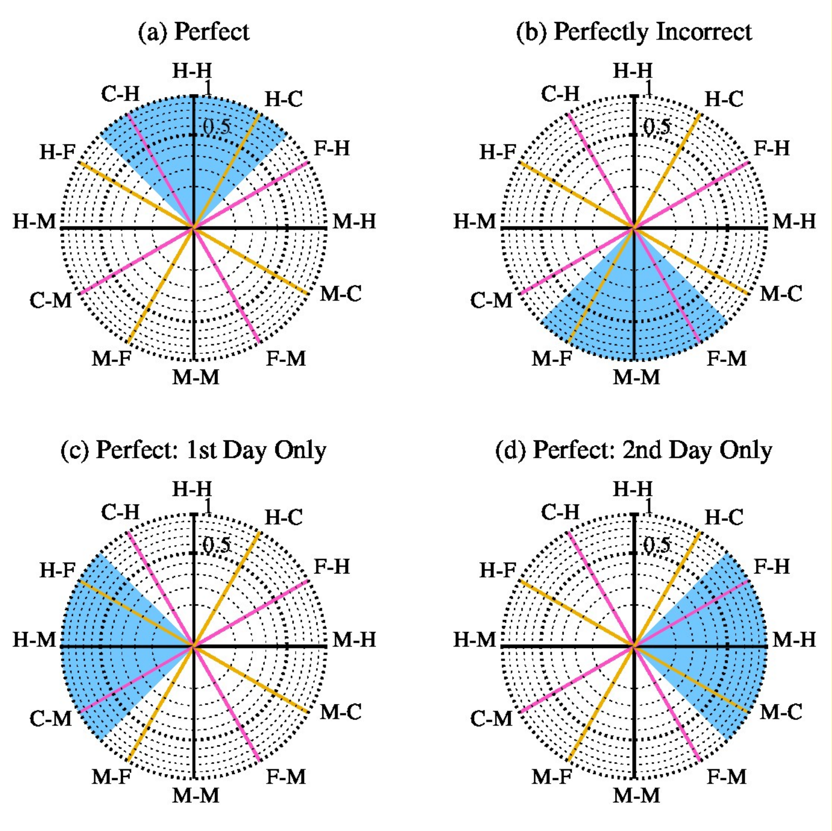
"First flare / last flare"

- NWRA: NASA-funded project to specifically address this:
  - Explicitly include *evolution-based* parameters.
  - Explicitly use new metrics for evaluation.
  - *<u>Very preliminary results</u>:* evolution-based parameters can help improve.



Left: preliminary results of forecasting (C+/24hr) evaluated for variable flare productivity. **Top**: a static "total flux" variable, **Bottom**: "Flux growth / decay rate" variable.

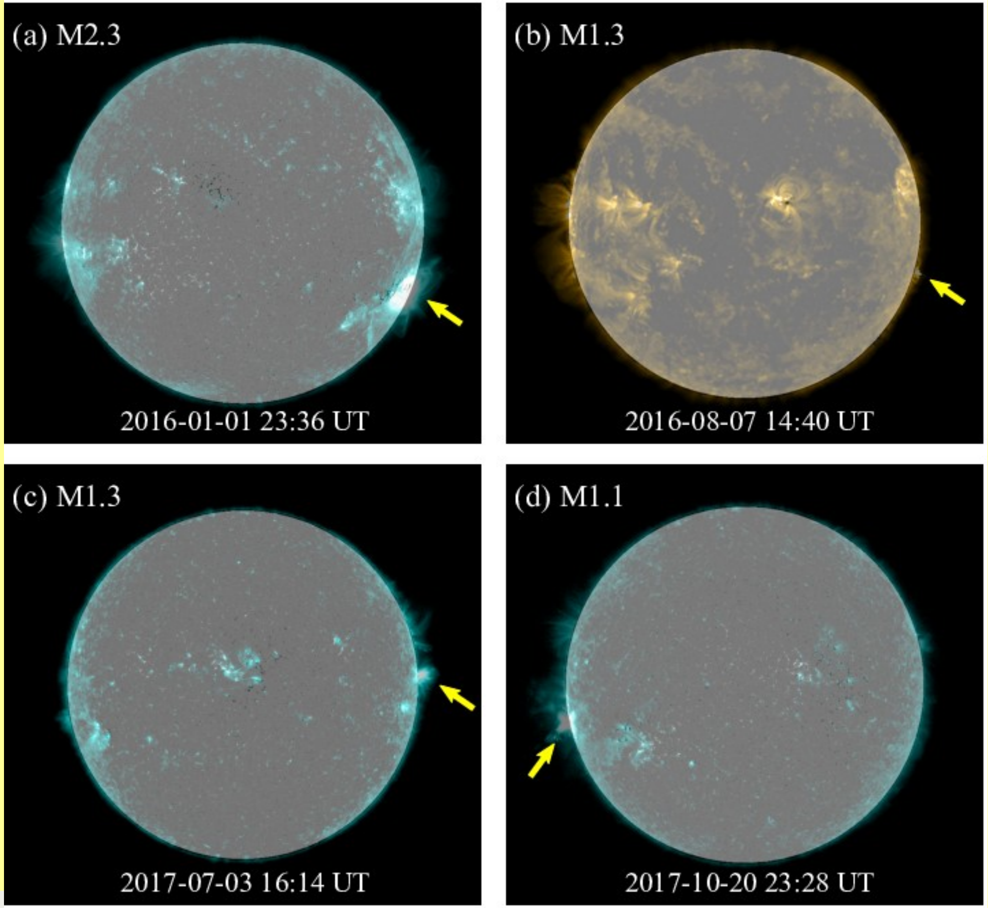
Note increase in 11, 1 o'clock (as desired), decrease 8, 4 o'clock (as desired), but slight decrease in 12o'clock (not desired).



Mind the Gaps!

Limb Flares → 4π Forecasting for Energetic Events

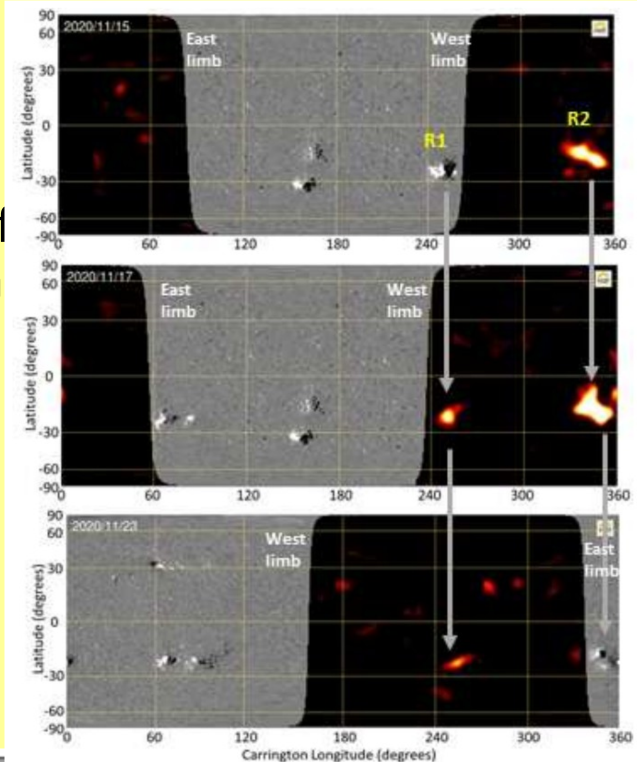
- Limb flares can be geo-impactful.
  - Ionospheric / Radio burst effects.
  - West-limb and beyond: likely magnetic connection to Earth for SEP events.
  - In 2-year testing interval **15% of large flares** occurred beyond the "observable" solar disk *(Park+ 2020)*.
- *Eventually, we need energetic-event forecasts for the solar system (M2M and beyond).*

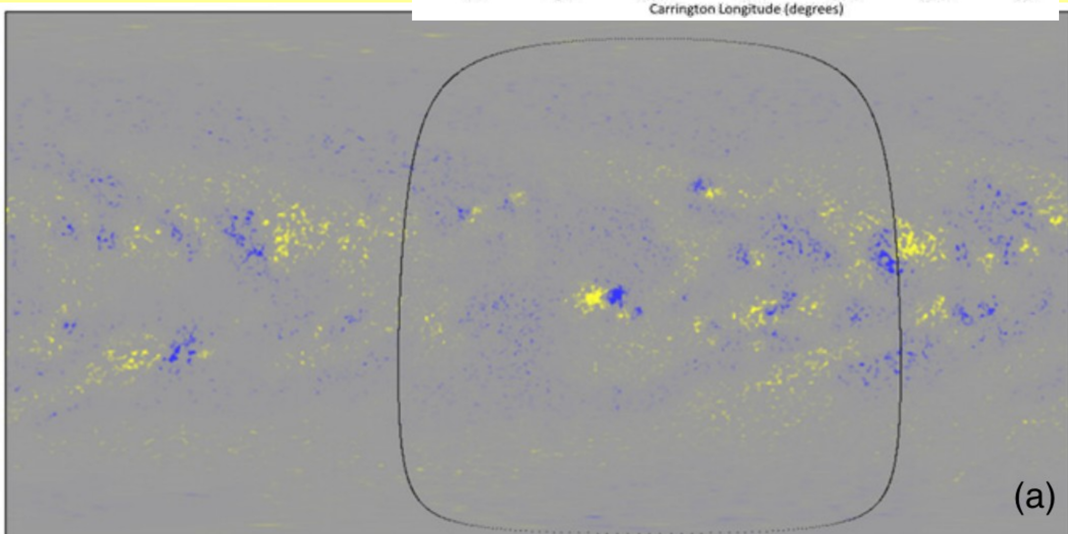


Mind the Gaps!

Limb Flares → 4π Forecasting for Energetic Events

- Limb flares can be geo-impactful.
  - Ionospheric / Radio burst effects.
  - West-limb and beyond: likely magnetic connection to Earth f
  - In 2-year testing interval **15% of large flares** occurred beyon solar disk *(Park+ 2020)*.
- *Eventually, we need energetic-event forecasts for the solar system (M2M and beyond).*
- NWRA project: incorporate far-side helioseismology (detection of new ARs) into models of far-side AR development ("flux transport models")
- Provide predictions for potentially geo-effective limb flares;
- start infrastructure for **4π Forecasting**
- ***Challenge***: Validation.





Top: Earth-facing (black/white) magnetic field, and far-side acoustic signatures of large active regions (courtesy R. Jain/ NSO).
Bottom: Earth-facing (in curve) magnetic field, and full-disk model of magnetic flux transport and evolution (from Upton & Hathaway 2014)

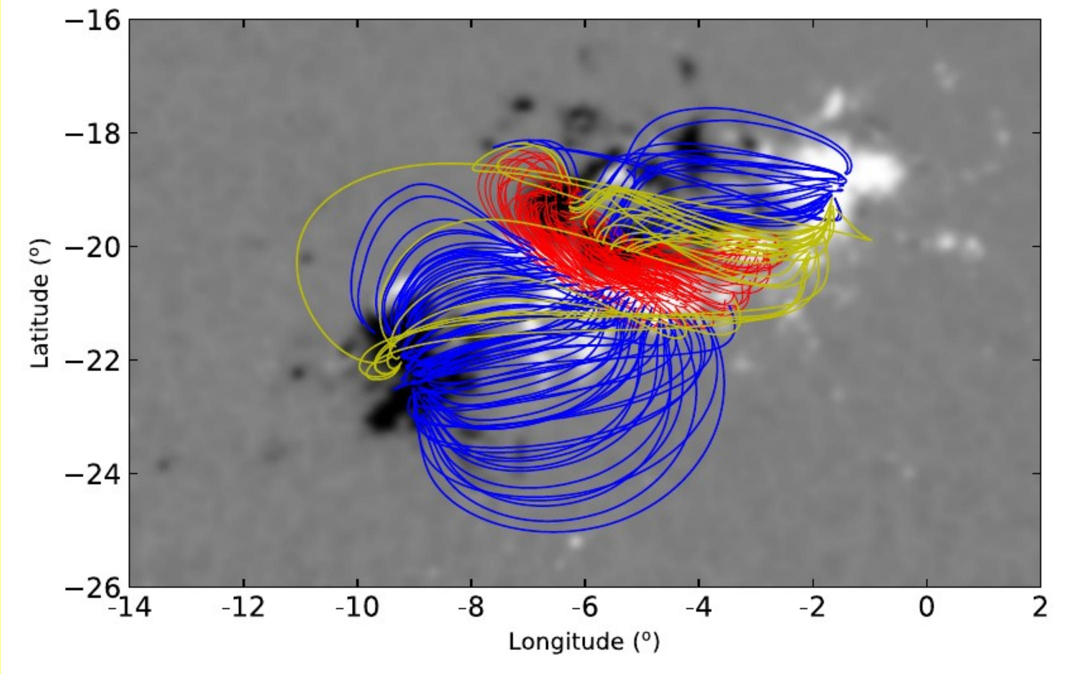
Mind the Gaps!

Eruptive vs. Confined Flares
(or)
"To CME or not to CME? That is the question…."

DeRosa & Barnes 2018.
Temmer 2021 (review)
Lin+2021 and citations therein.

Present Lines of study:

- Strength, direction, location, twist, topology of AR-specific magnetic field.
  - Overlying vs. reconnecting
  - Decay index
- Access to open flux
  - Ability for accelerated material to continue outward "unimpeded"
- Prior event history
  - Magnetic restructuring
  - "Clearing the way"



Above: from Lin+2021, characterizing the fieldlines of an extrapolation model according to their hypothesized role in the subsequent event: reconnection-initiating, "wall" field that confines expansion, overlying that will inhibit CME.

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Shorter-latency (event-targeted) predictions
CME vs. not; (SEP vs. not)

Tools:
Community Validation tools
Standardized Event lists
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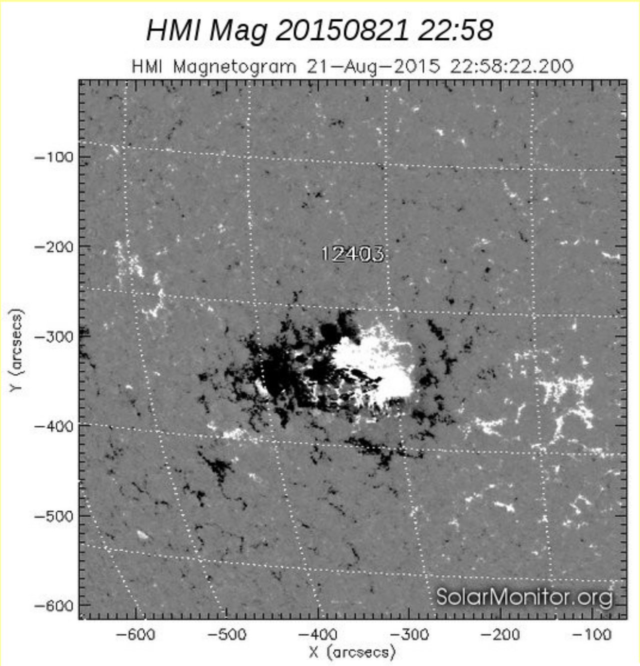
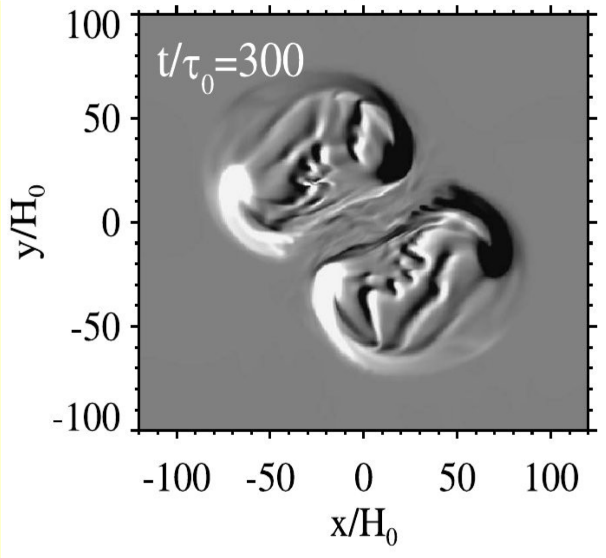
(Suggested) directions for model efforts:

- Investigative models: *Strive for "data inspired"*
  - Boundaries: move away from simple.
  - Target the tough cases, the medium-sized regions, the non-events, the counter-examples.
  - Produce observational testables.
    - This may include distributions, timing indicators, identifiable and *unique* signatures of the mechanism.

- Model the observables: *quantitative validation*
  - How sensitive is the model
    - to observational reality (noise, resolution)?
    - to fine-tuned modifications?
  - Does the model produce physical answers?
  - Can the model produce events *and nonevents* (quiet times) matching observed output and distributions?

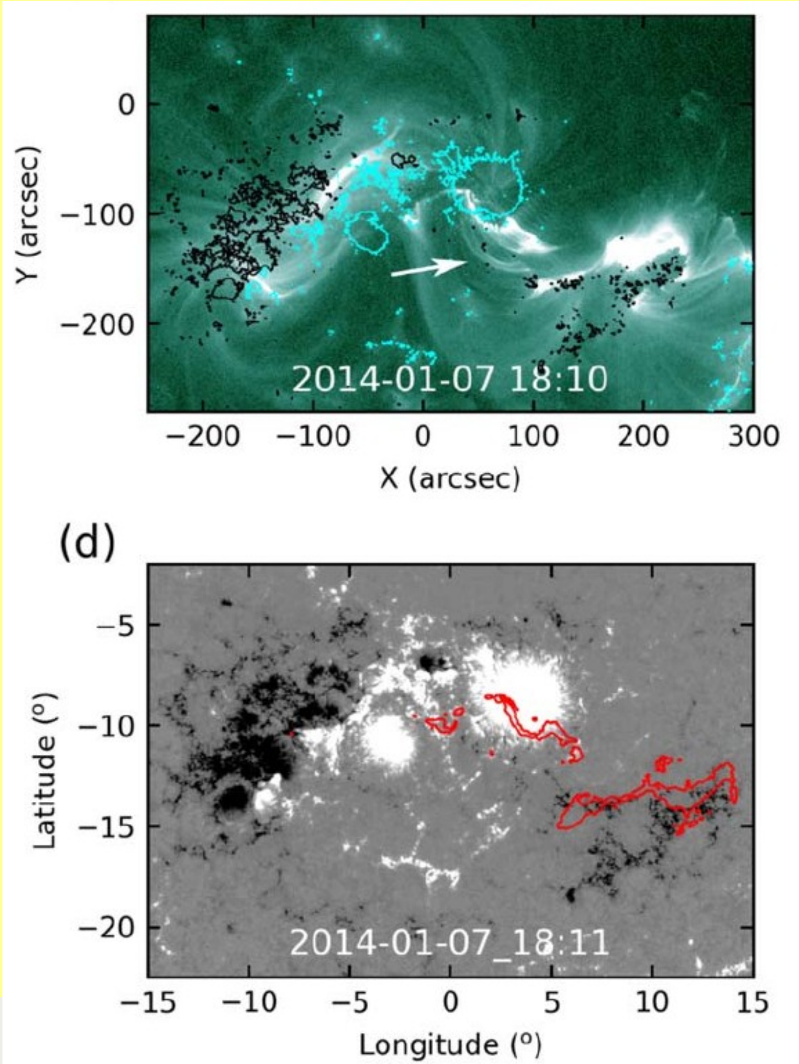




From Toriumi & Takasao 2017

(Suggested) directions for observing efforts:

- High-resolution observations: Relate to the “big picture”
  - How does the small-scale physics relate to macroscopic contexts?
- Case studies
  - Where do they fit in the known distributions
- “Big Data”
  - Expand “big” into the *information* domain.



Expected eruption site: near strong magnetic complexity (left-hand part).
Actual eruption site: between a stable sunspot and a nearby old remnant field.
Why???
(From Lin+2020)

(Suggested) directions for community efforts:

- Encourage cross-disciplinary collaborations.
  - ML experts need flare-prediction experts.
  - Data analysis efforts need experts on the data being used.
  - Everyone doing this research should read historical literature, not just last 5 years.
    - Confirming prior work is great! *Once. Maybe twice.* *Repeatedly* re-inventing the wheel is a waste of time.

- Establish accessible, citable, community-curated tools
  - enable progress and limit duplication of efforts
  - Event lists, including far-side events.
    - Numbering? Referring? Merging? Validating?
    - Who / where to host this? How to fund?

  - “Plug & Play” validation tools for easy self-evaluation
    - Who hosts this? How to fund?

Questions / Discussion