

# Understanding and Forecasting The Solar Origins of Space Weather

**KD Leka**

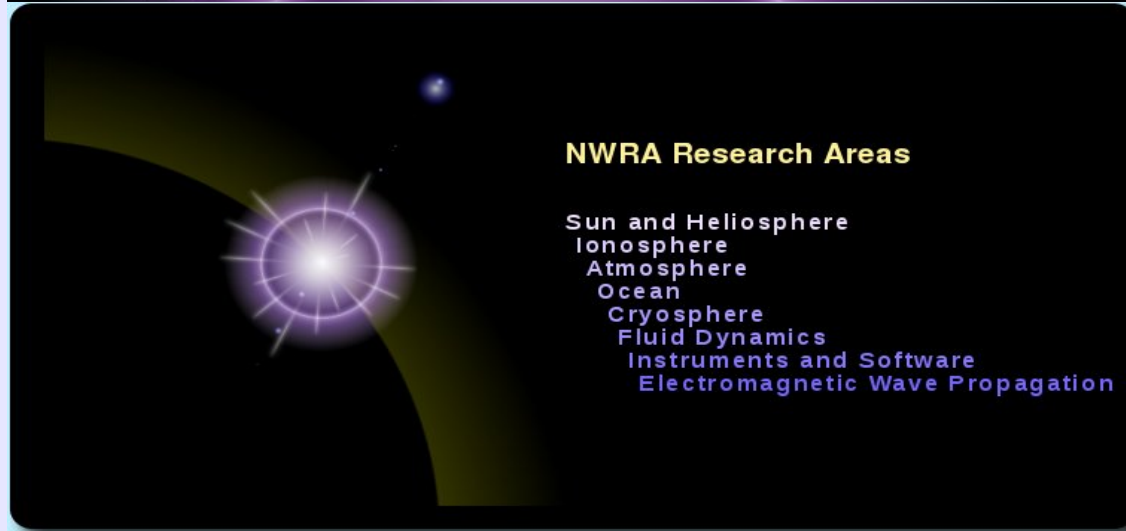
**NorthWest Research Associates (NWRA)**

*“excellence in basic and applied research”*

*and*

**Nagoya University**

**Institute for Sun-Earth Environmental Research (ISEE)**



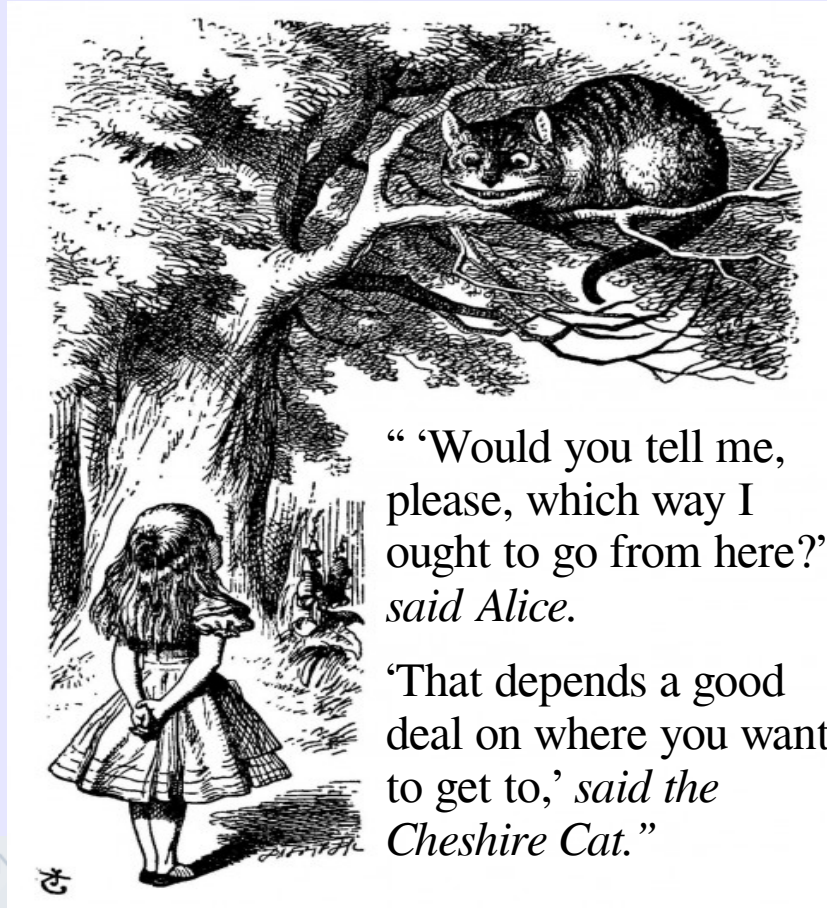
- Private Scientific Research Company
- Owned and managed by the Principal Investigators (the scientists)
- 80 Employees in the US: Washington State, Colorado, California
- Pure and applied research with broad topic range.

“Honorary” Degrees earned:

- MSc in Project Management
- MBA in Budget Management
- JD in Intellectual Property Law

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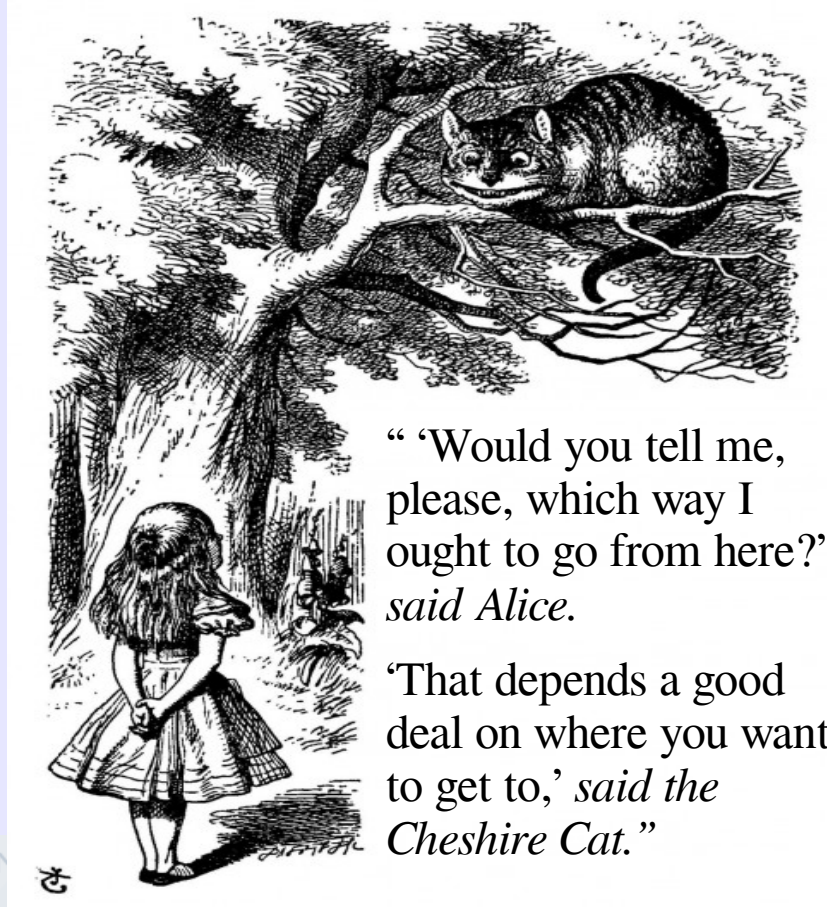


“ ‘Would you tell me, please, which way I ought to go from here?’, said Alice.

‘That depends a good deal on where you want to get to,’ said the Cheshire Cat.”

From  
*Alice's Adventures in Wonderland*  
by Lewis Carrol, illustrated by John Tennel

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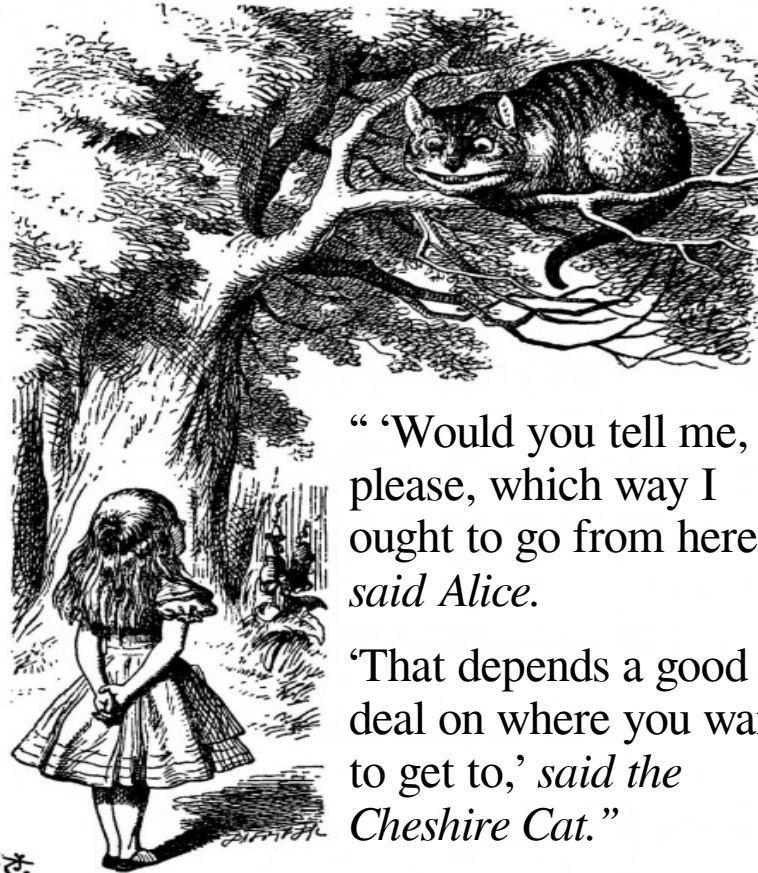
- Some background
- How do we know what we know?
- How *well* do we know what we think we know?
- Where do we want to go, and how do we get there?

“ ‘Would you tell me, please, which way I ought to go from here?’,  
*said Alice.*

‘That depends a good deal on where you want to get to,’  
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“Space Weather” is a term that covers *many* phenomena.  
From the Earth-bound point of view:

- Sky-ward events
  - aurora, radio-propagation disruptions, radio bursts



*Aurora Borealis over  
Tromsø, Norway  
courtesy SpaceWeather.com*

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*Aurora Australis over  
Melbourne, Australia  
courtesy TimeOut.com*

“Space Weather” is a term that covers *many* phenomena.  
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- Sky-ward events
  - aurora, radio-propagation disruptions, radio bursts
- Earth-ward events
  - ground currents, grid disruptions

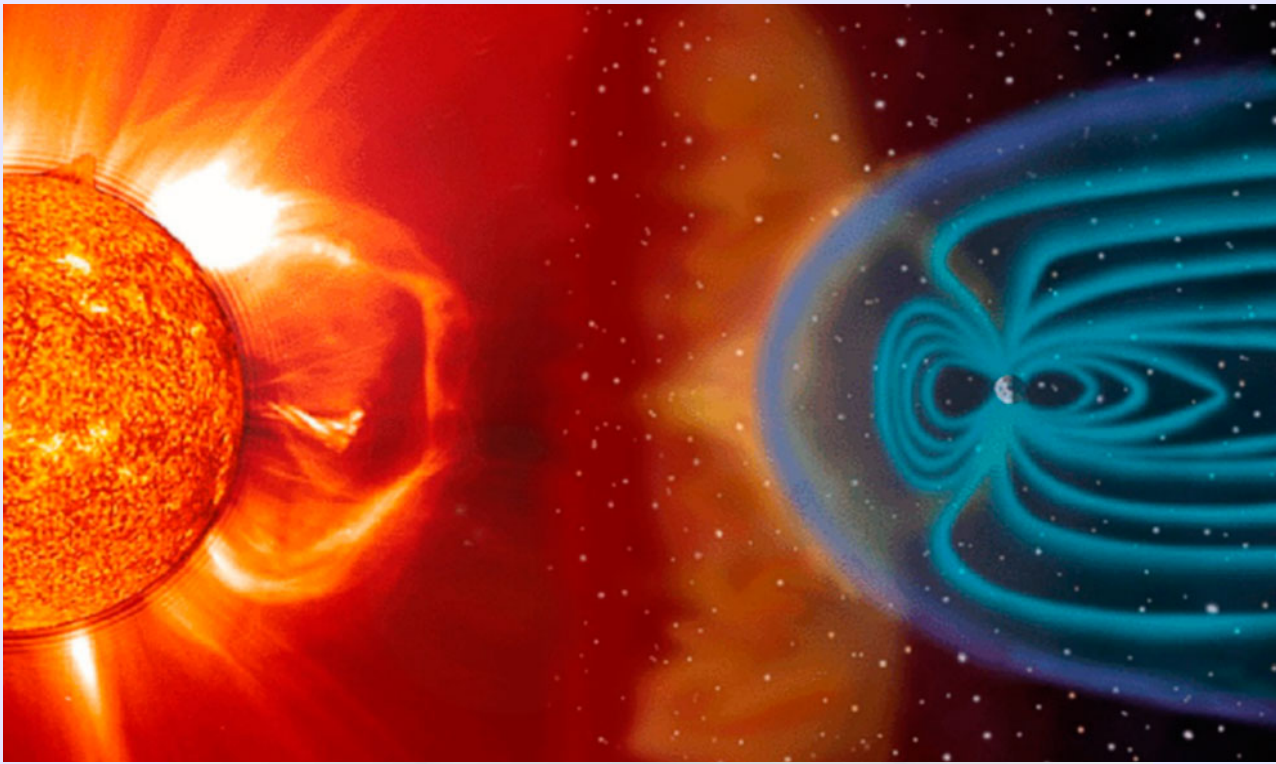
- “We conducted a study using public information that reveals a general correlation between large but not extreme solar flares and disturbances in the U.S. electric grid; these disturbances have an impact of \$5-8 billion a year on the GDP”

*from Mitchell & Schrijver, 2013 Space Weather Week.*



“Space Weather” is a term that covers *many* phenomena.  
From the Earth-bound point of view:

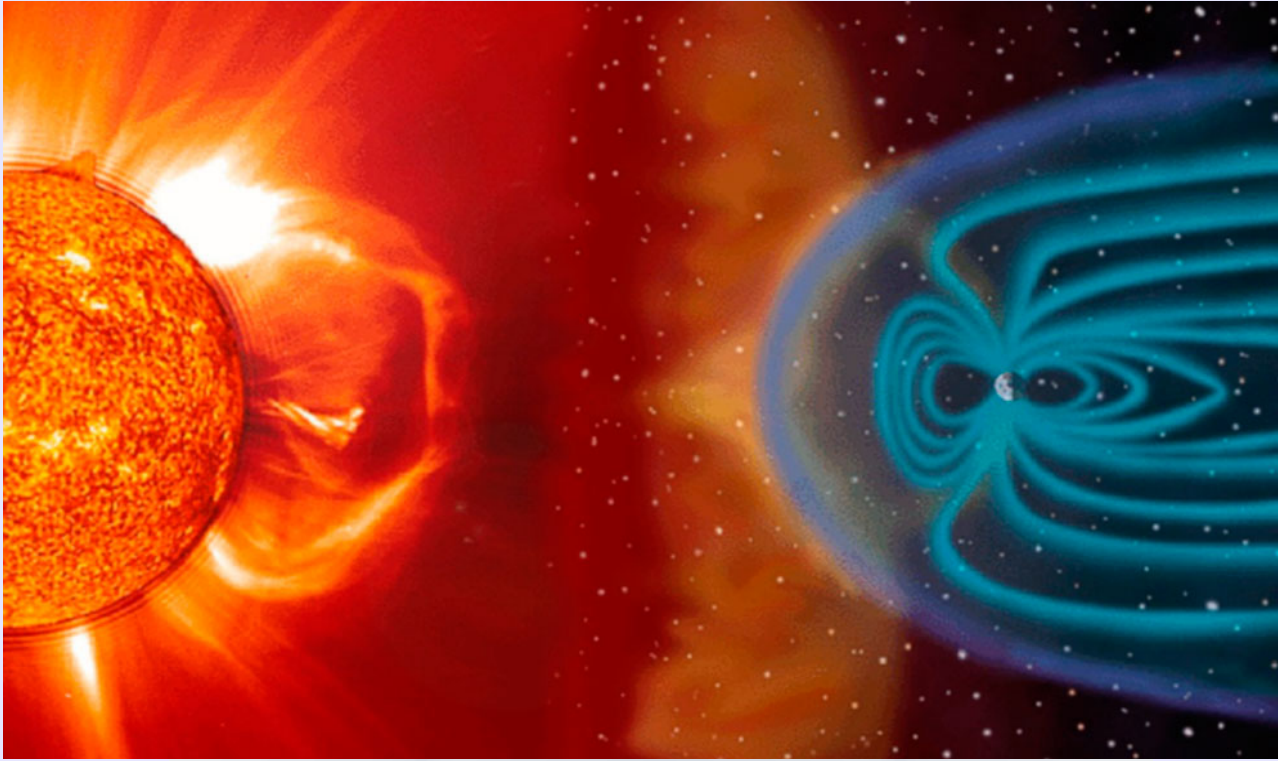
- Sky-ward events
  - aurora, radio-propagation disruptions, radio bursts
- Earth-ward events
  - ground currents



“Space Weather” is a term that covers *many* phenomena.

Focus on two different origins of Geomagnetic Storms:

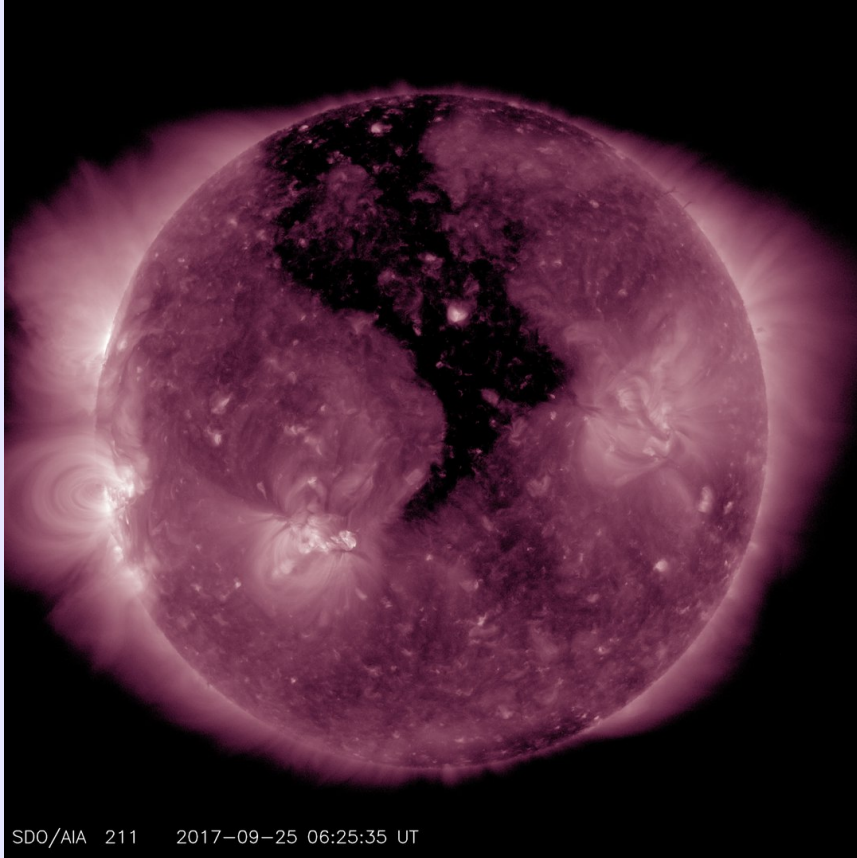
- from solar wind streams flowing from coronal holes...long-lived, benign...?
- from solar energetic eruptions...fast, powerful, news-worthy!



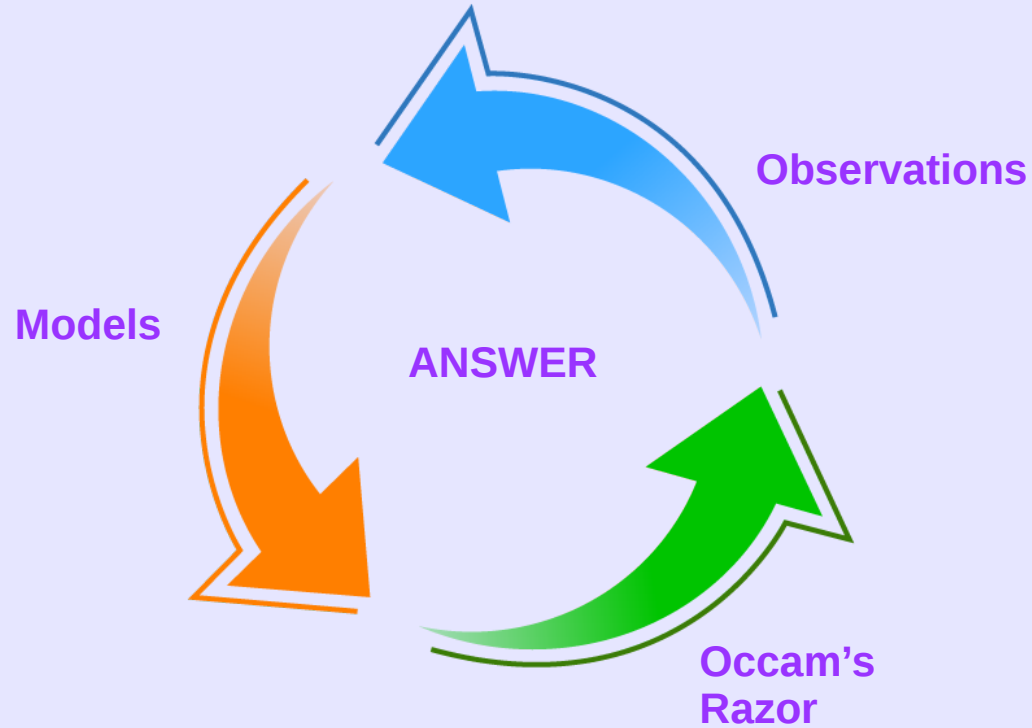
# The Solar origins of space weather I:

Hypothesis:

“The high-speed solar wind streams that cause geomagnetic activity originate in solar coronal holes”

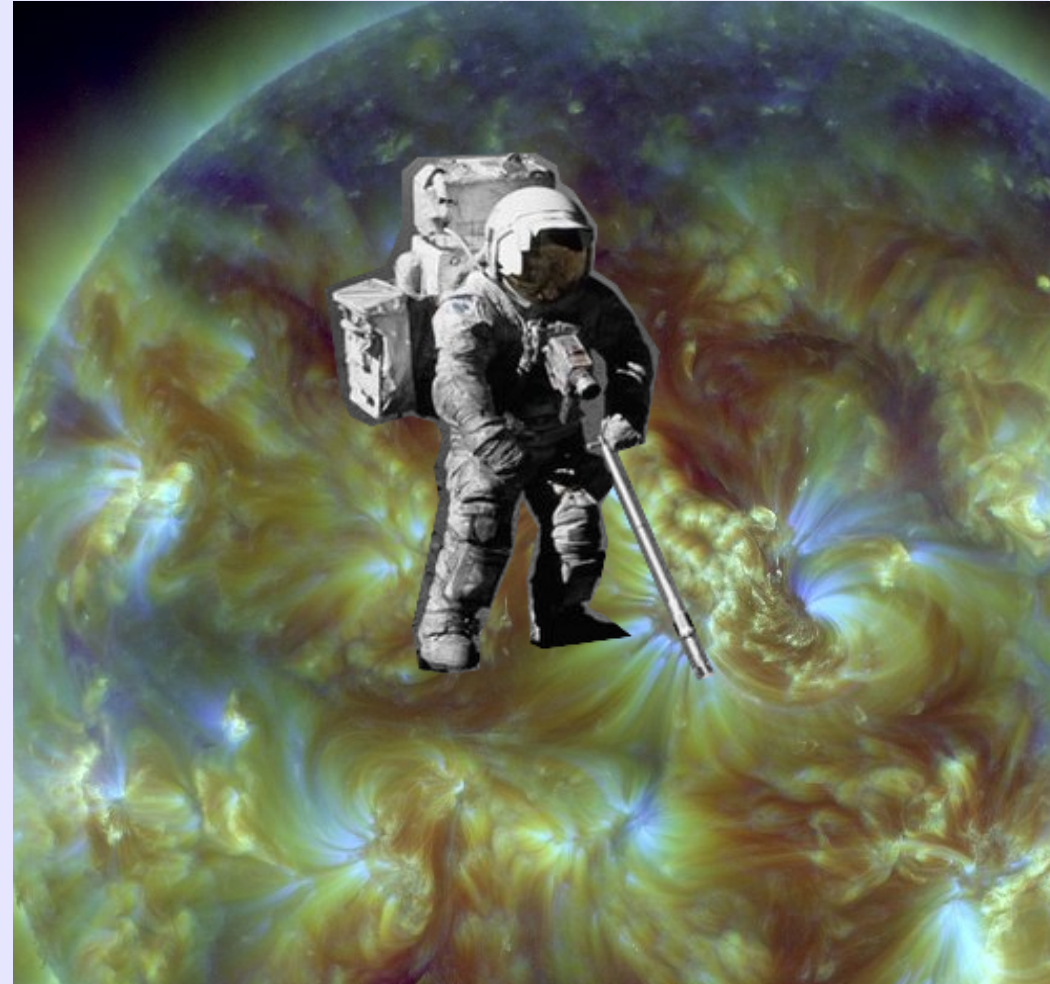


# How do we know what we know?



## Observations...

- **Temperature / Density** of solar plasma
  - Ratios of intensity from different spectral regions
  - Impacts on solar photons from non-solar sources
- **Velocity** of solar plasma
  - Doppler shifts of spectral lines (or parts of them)
- **Composition** of solar plasma
  - Spectral line properties
  - ...*more* spectral lines
- **Magnetic fields** in the solar plasma
  - Polarization and frequency splitting in certain spectral lines  
....and *not* in others.



# Observations...

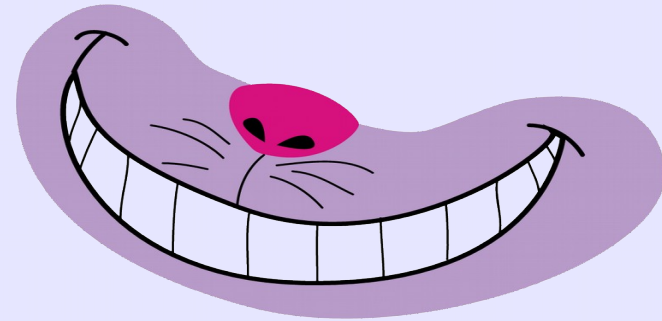
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*All we have are photons...*

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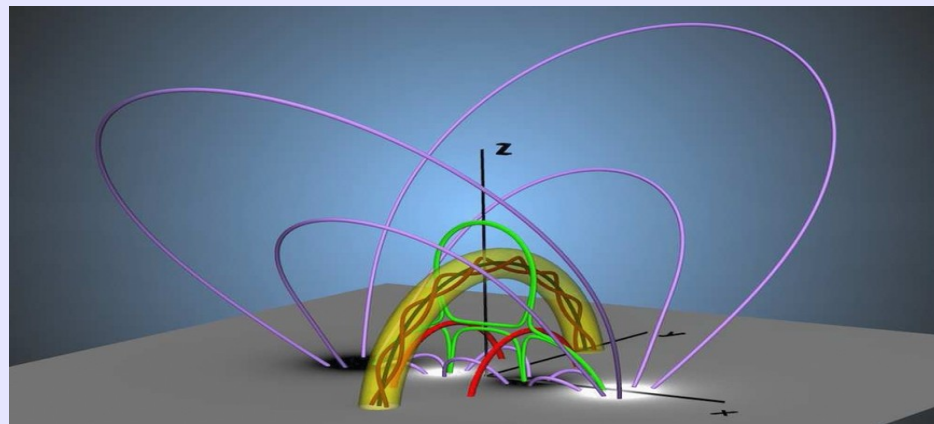
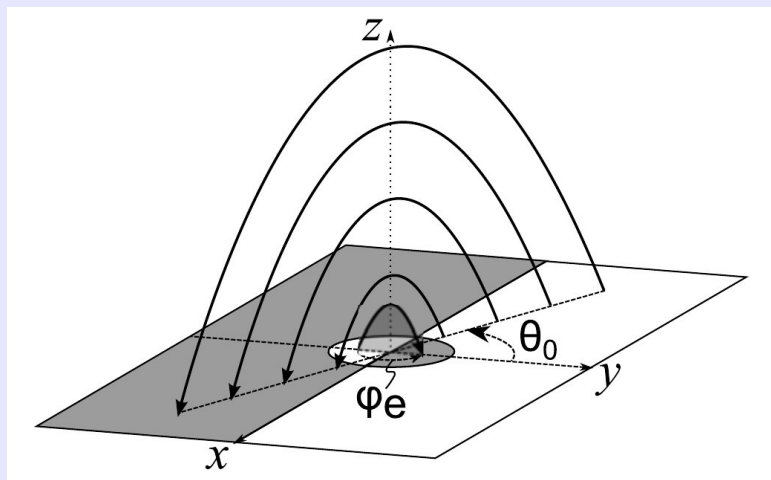
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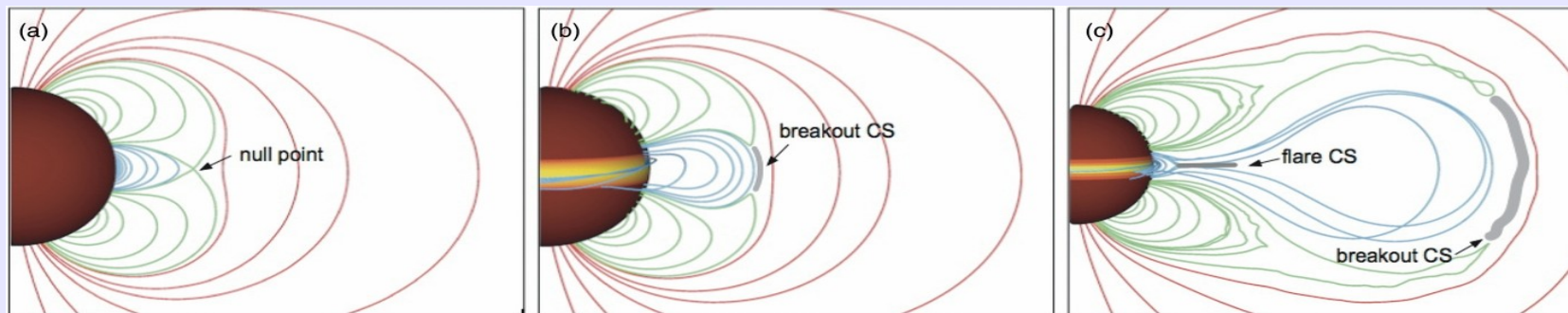


## Complemented by models. Two broad categories:

- I: Designed to explore and test proposed physical mechanisms.
  - May or may not incorporate observational data



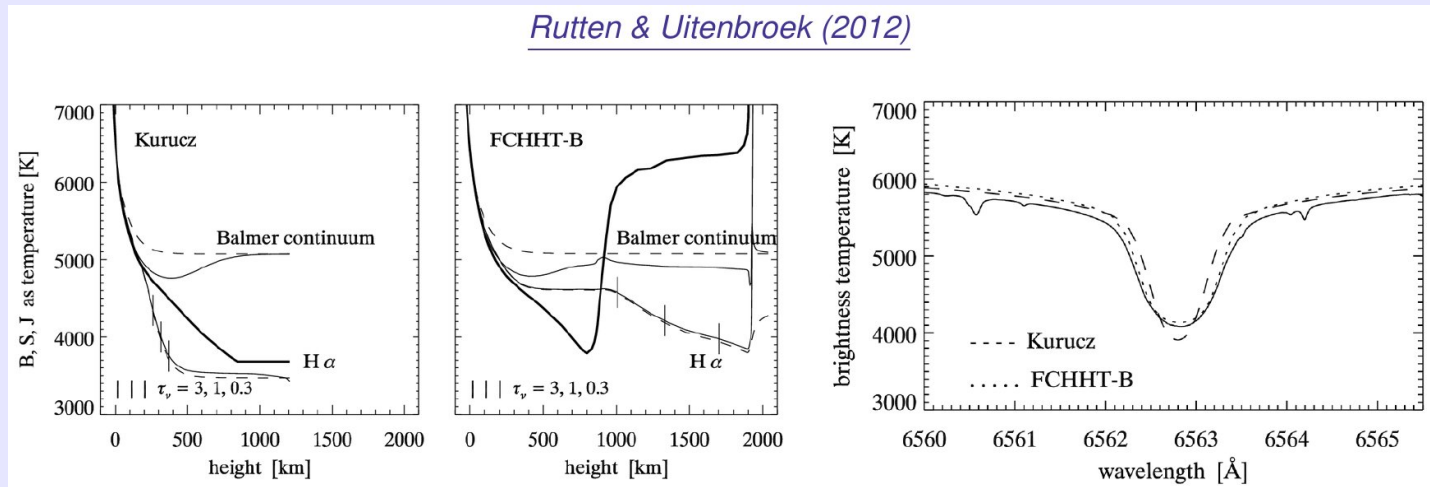
*Demoulin & Aulanier 2014*



*Karpen+2012*

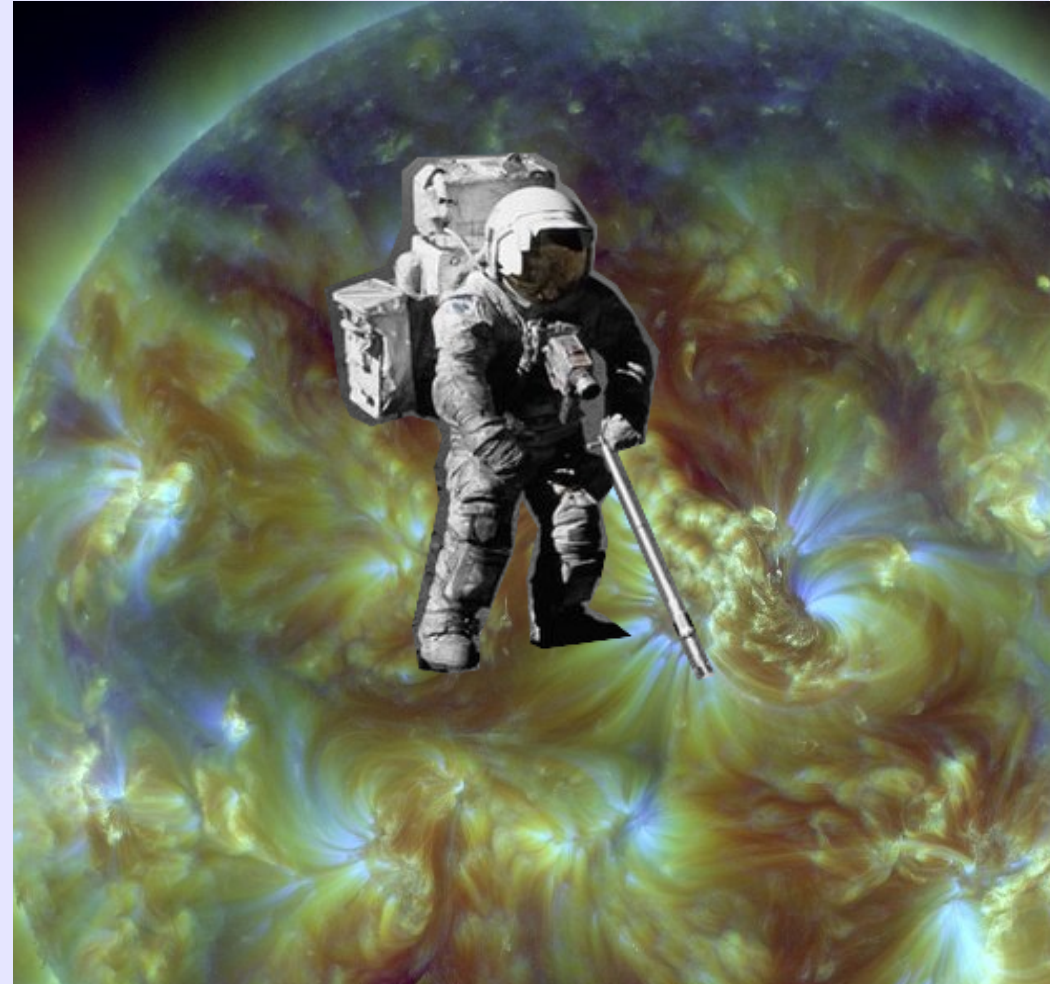
## Complemented by models. Two broad categories:

- II: Designed to provide information on the unobservable.
  - Observational data play key roles
  - Frequent purpose: extract additional information from observables



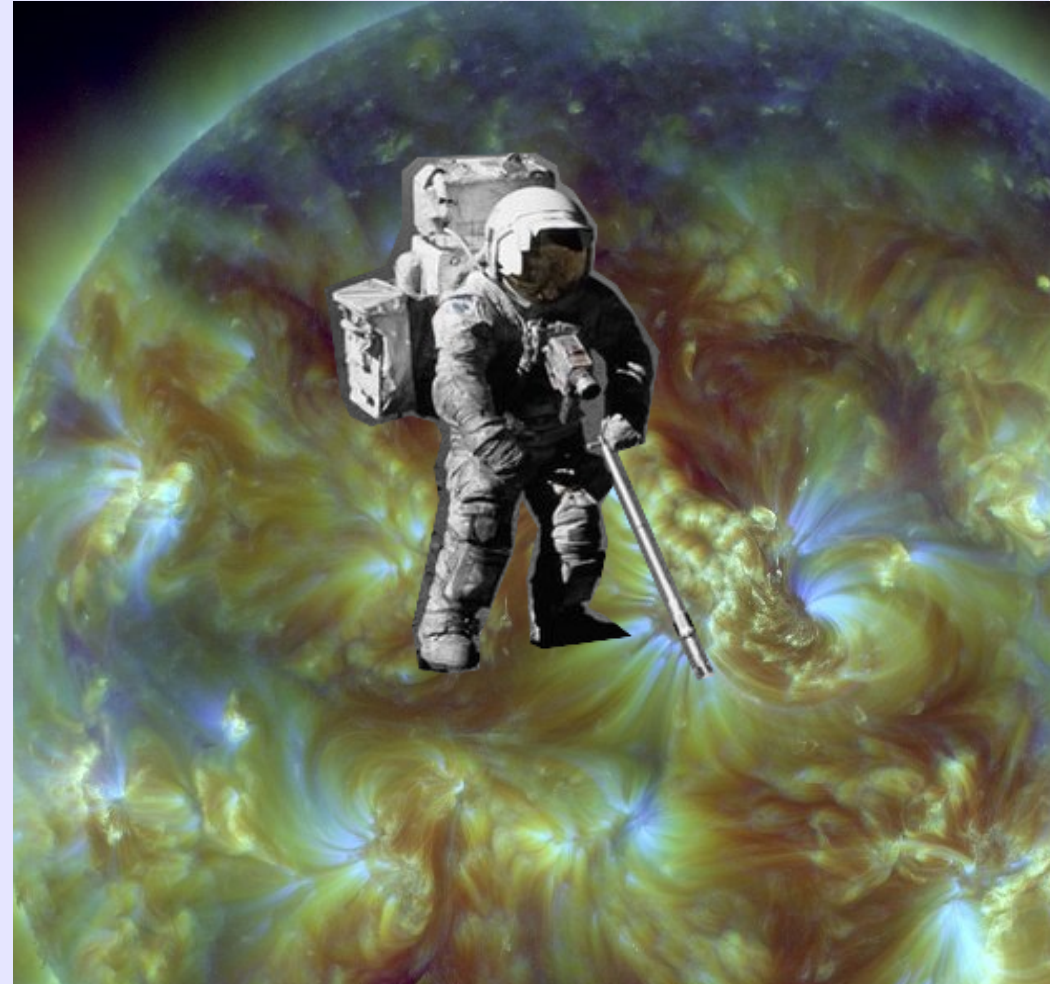
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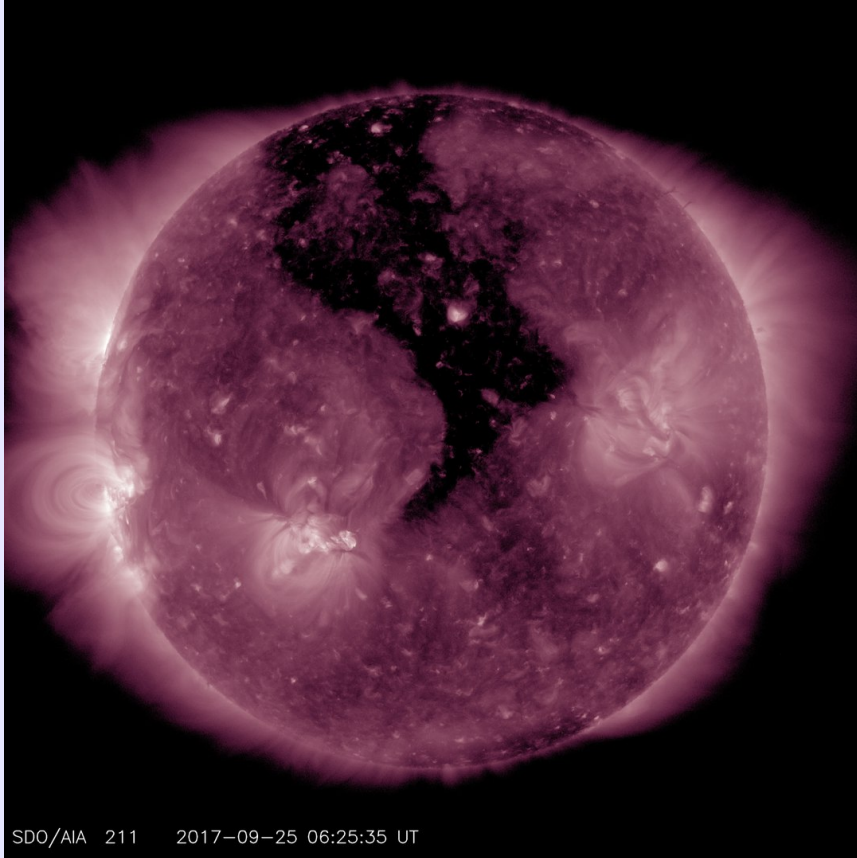
- Temperature / Density of solar plasma
  - Ratios of intensity from different spectral regions
  - Impacts on solar photons from non-solar sources
  - *Inversions in context of non-Local Thermodynamic Equilibrium model atmospheres*
- Velocity of solar plasma
  - Doppler shifts of spectral lines (or parts of them)
  - *Inversions in contexts of MHD equations, depth-sampling kernels, wave propagation theory, induction equation*
- Composition of solar plasma
  - Spectral line properties
  - ...more spectral lines
- Magnetic fields in the solar plasma *and forces, energy transfer*
  - Polarization and frequency splitting in certain spectral lines  
....and *not* in others.
  - *Inversions in context of magnetized radiative transfer theory, Maxwell's equations*
  - *Numerical extrapolations, data-driven simulations*



# The Solar origins of space weather I:

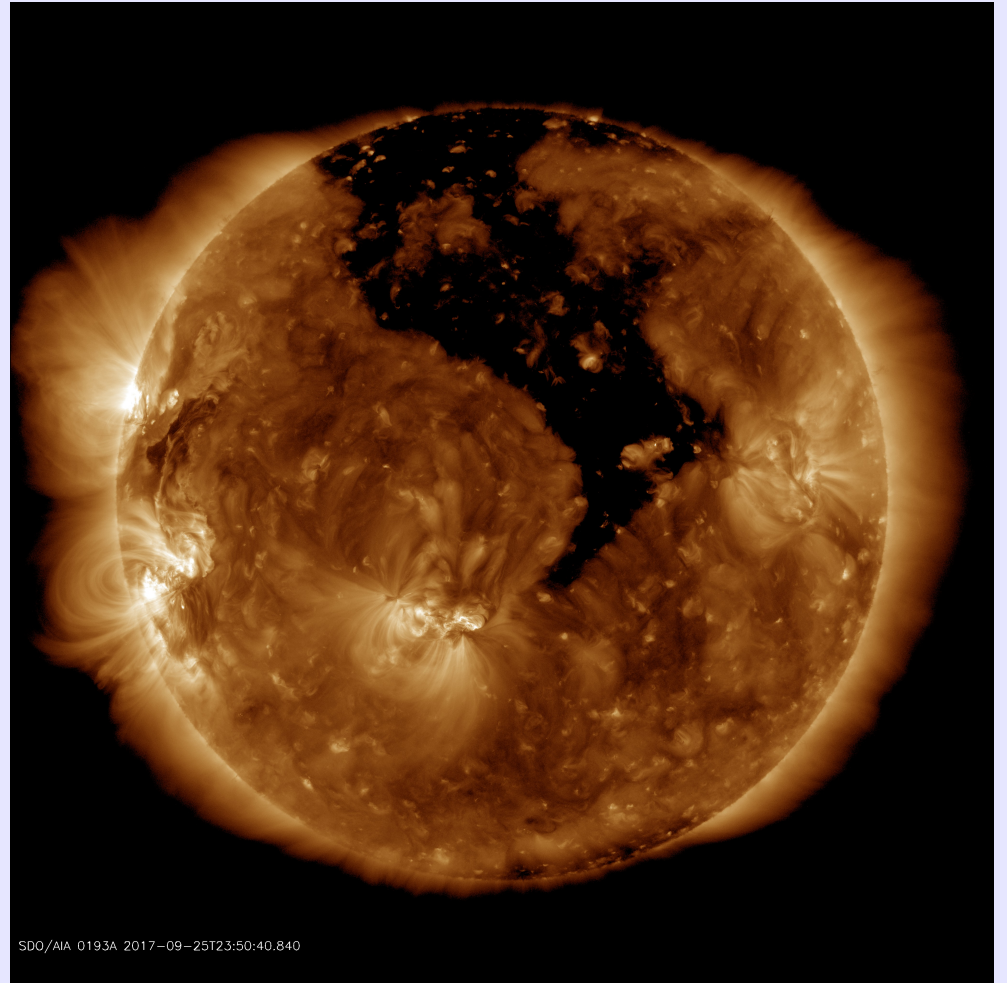
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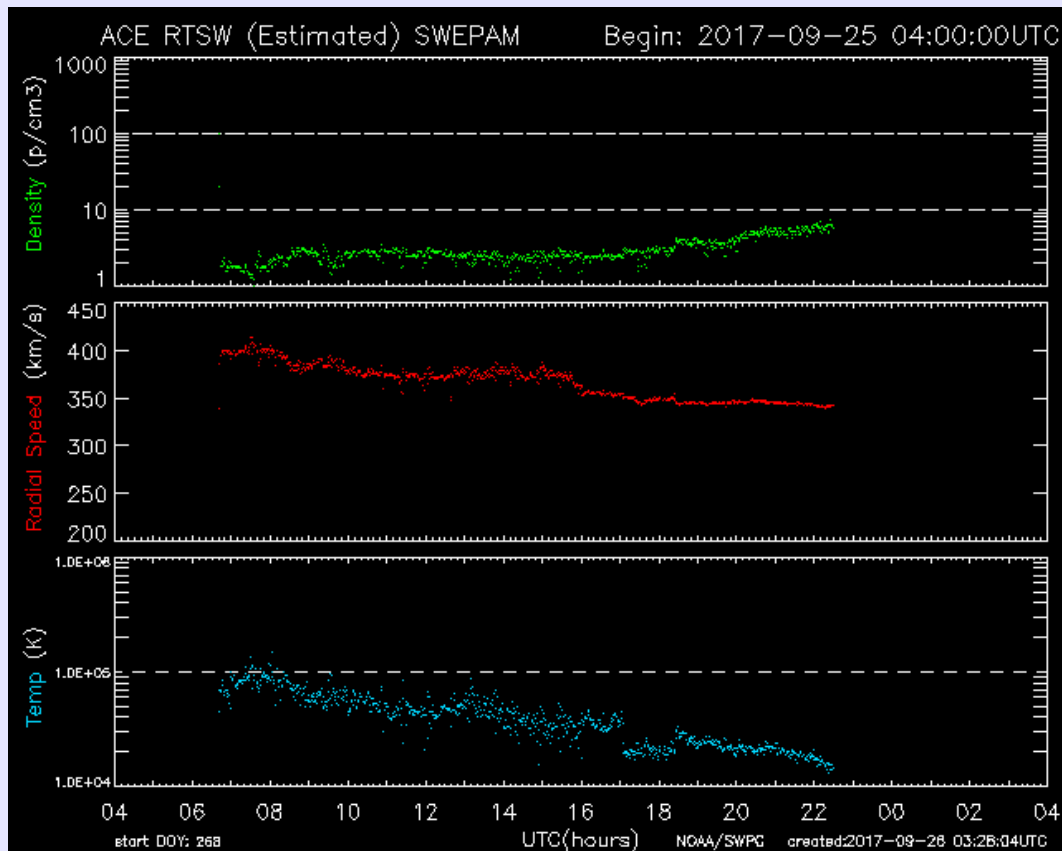
## The Solar origins of space weather I:

*Correlation* the appearance of solar coronal holes,



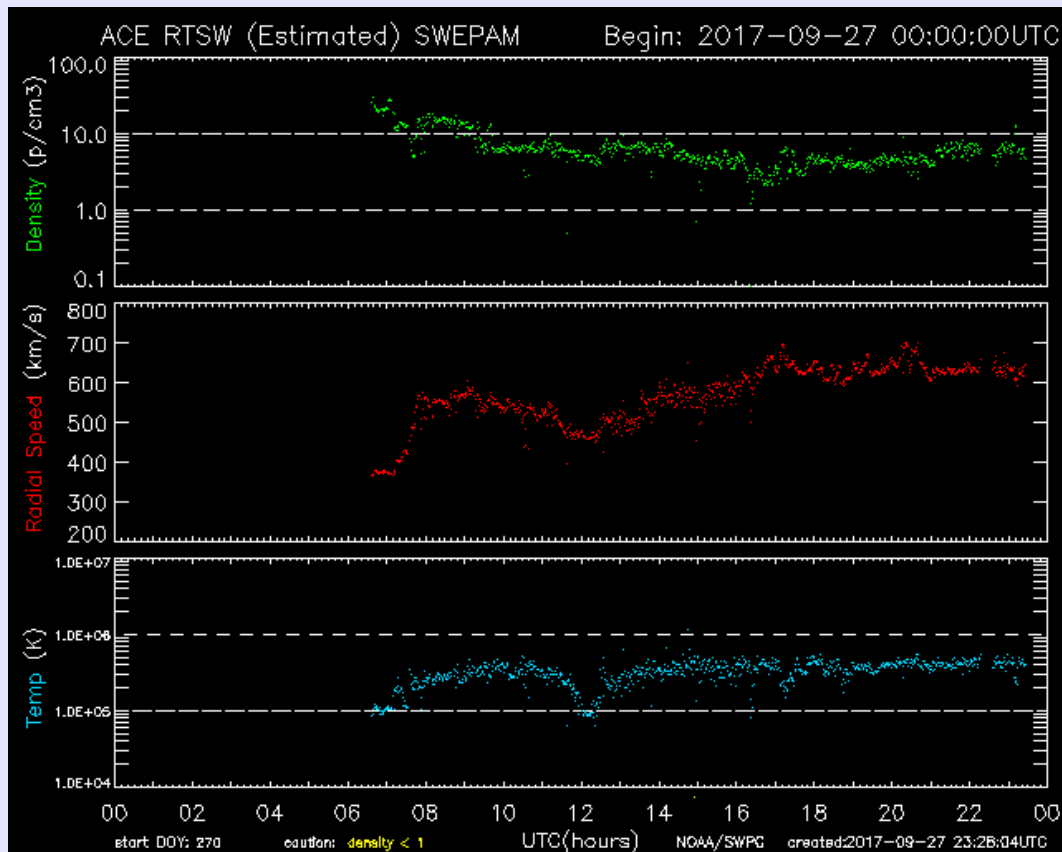
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*Correlation* the appearance of solar coronal holes, high speed solar wind a few days later,



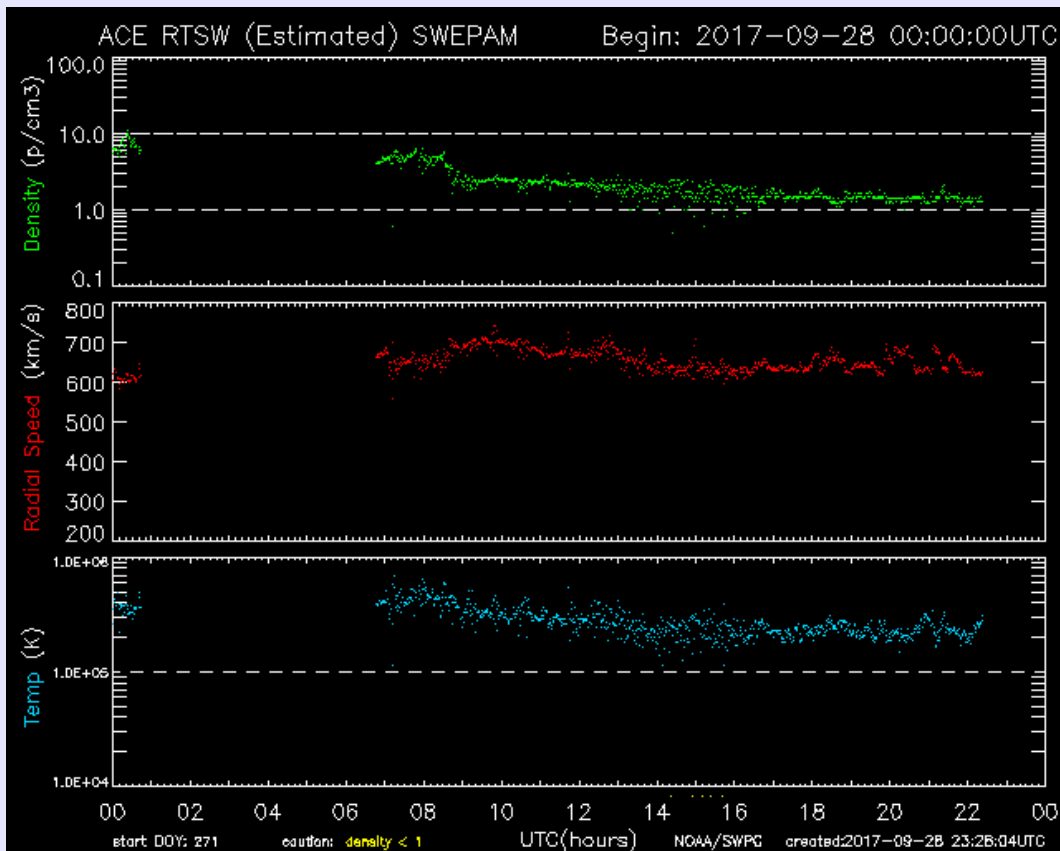
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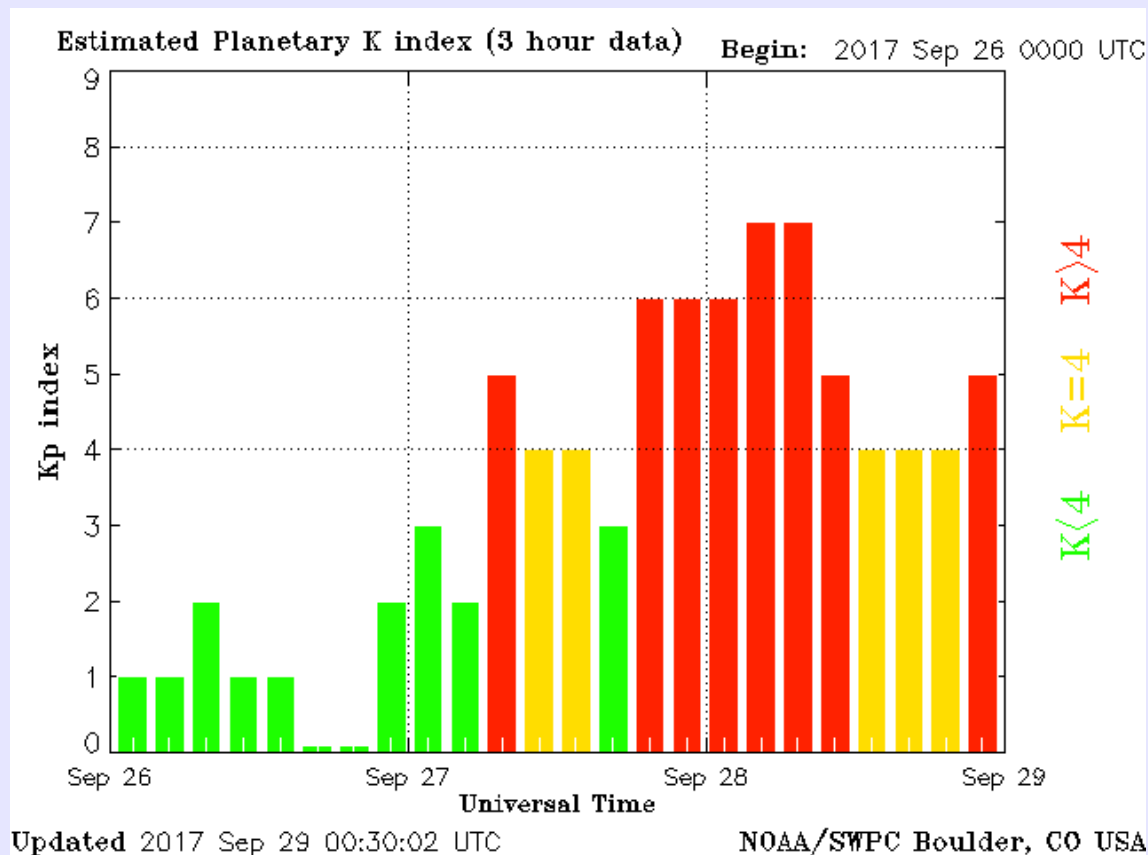
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## The Solar origins of space weather I:

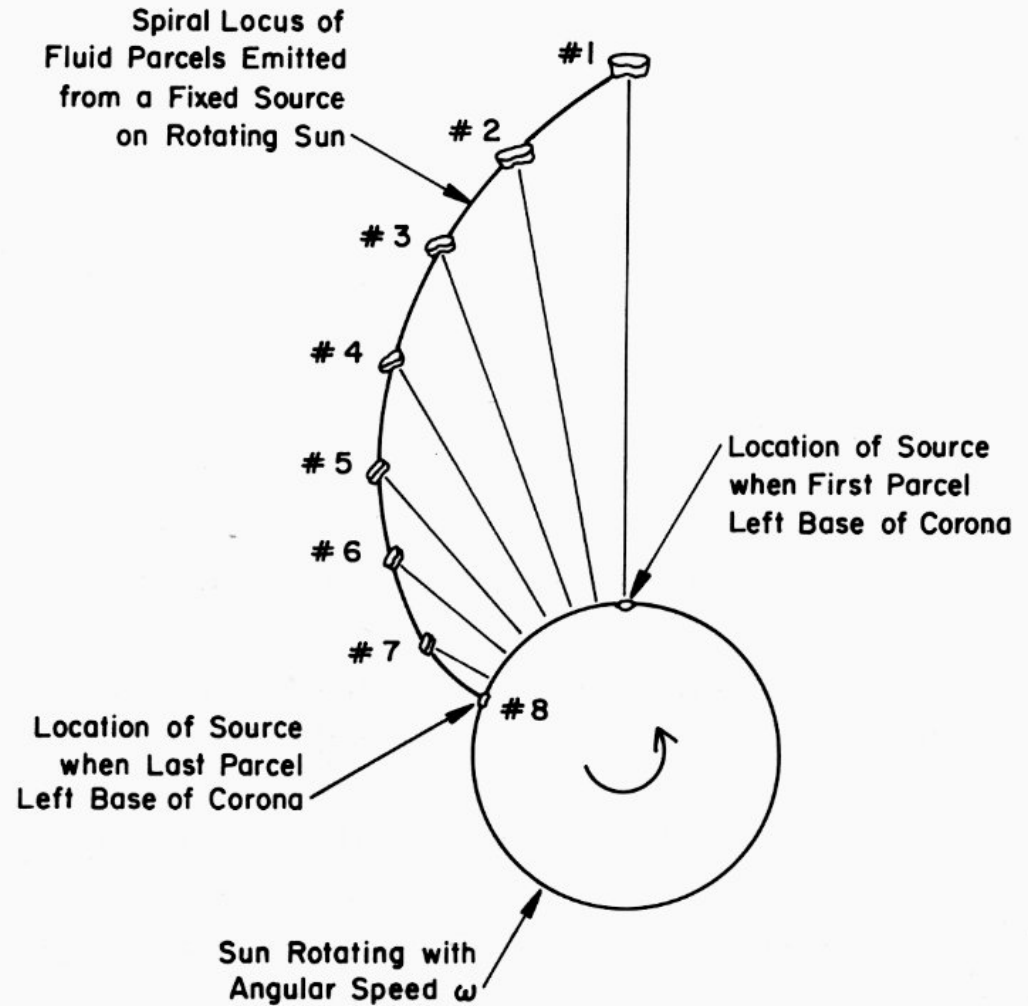
*Correlation* the appearance of solar coronal holes, high speed solar wind a few days later, and a geomagnetic storm.



## The Solar origins of space weather I:

*Model Input:* the solar wind propagation along an Archimedian “Parker spiral” through the heliosphere,

*Solar wind: plasma and its frozen-in magnetic field accelerated by gas and magnetic pressure into the heliosphere. It is “swept” into an Archimedian spiral by solar rotation, and distorted into a messy “heliospheric current sheet” by solar coronal magnetic topology.*

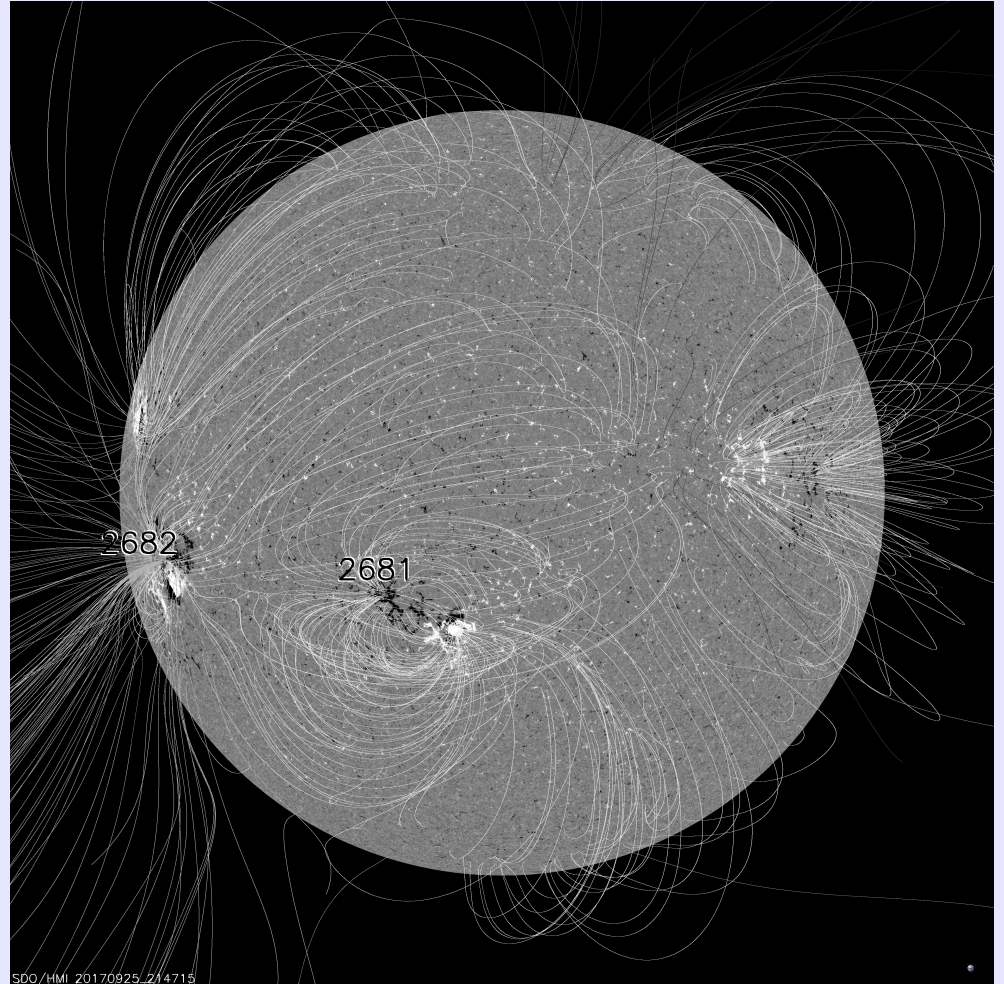


$$U_{\phi} = -\omega r$$

## The Solar origins of space weather I:

*Model Input:* the large-scale magnetic field is predominantly *open* in coronal holes, extending into the heliosphere.

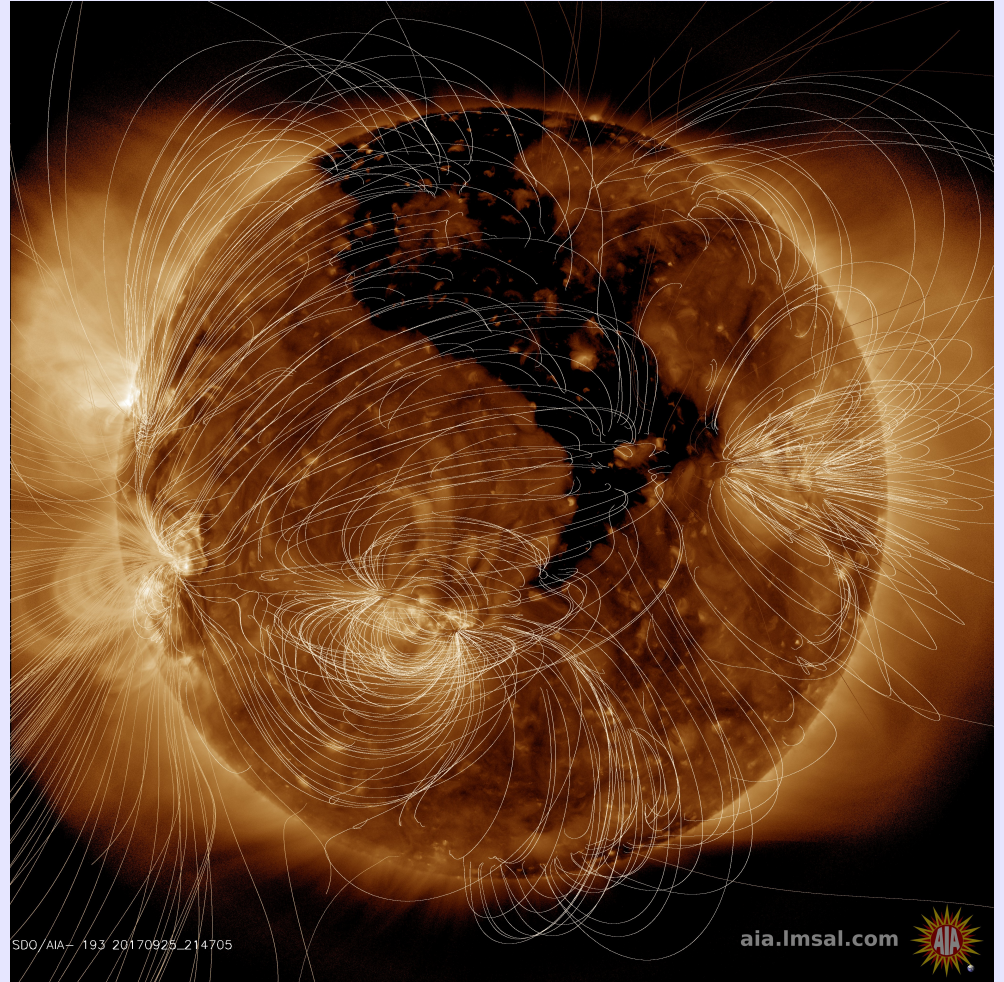
Potential-Field Source Surface model extrapolated from photospheric magnetogram, overlaid on 19.3nm coronal image.



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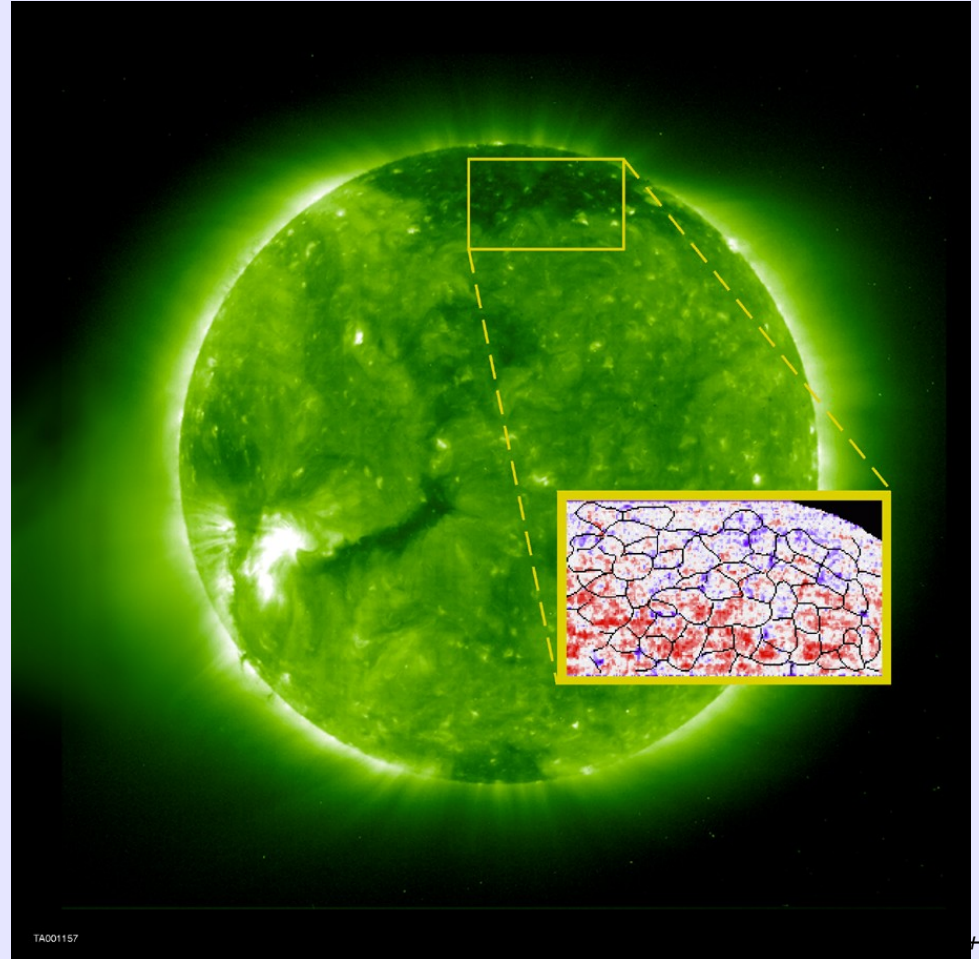
Potential-Field Source Surface model extrapolated from photospheric magnetogram, overlaid on 19.3nm coronal image.



## The Solar origins of space weather I:

*Observation:* of dominant Doppler blue-shifts and broader line widths in coronal holes, through the lower corona, lower densities.

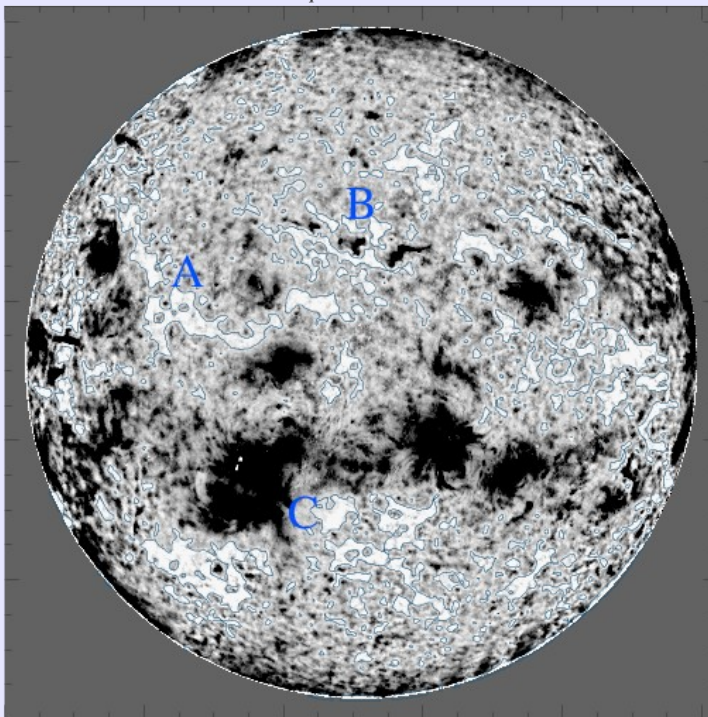
Blueshifts dominate in coronal holes.



## The Solar origins of space weather I:

**Observation:** of dominant Doppler blue-shifts and broader line widths in coronal holes, through the lower corona, lower densities.

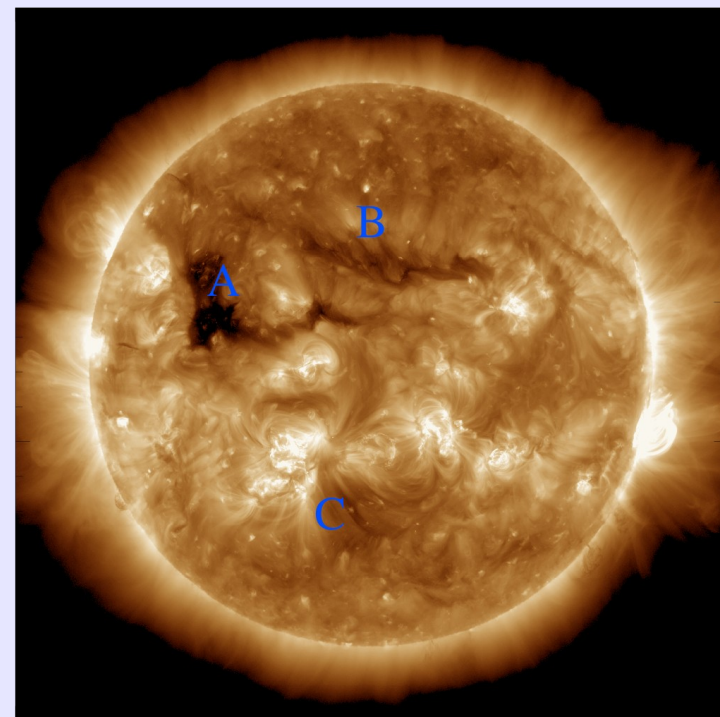
SOLIS He 10830 Equiv Width 2013.10.31 16:00UT



Greater equivalent widths (bright near A, B, C, left image) dominate in He 1083.0nm line at mid-height solar atmosphere in coronal holes (dark near A, B, C, right image).

He 1083.0 can sometimes “see through” overlying obscuration.

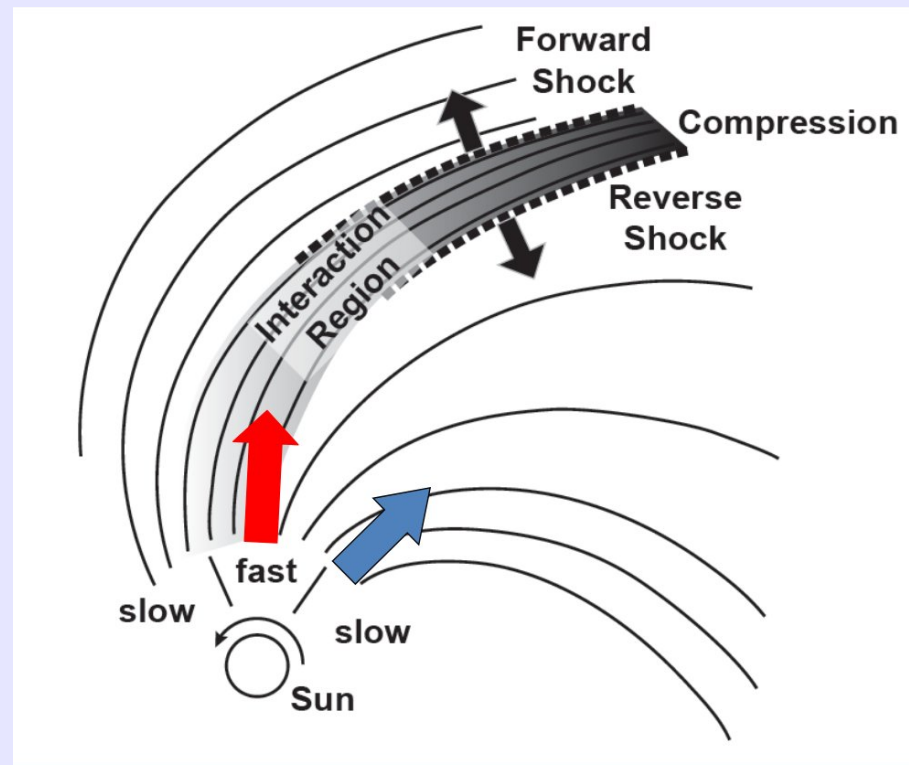
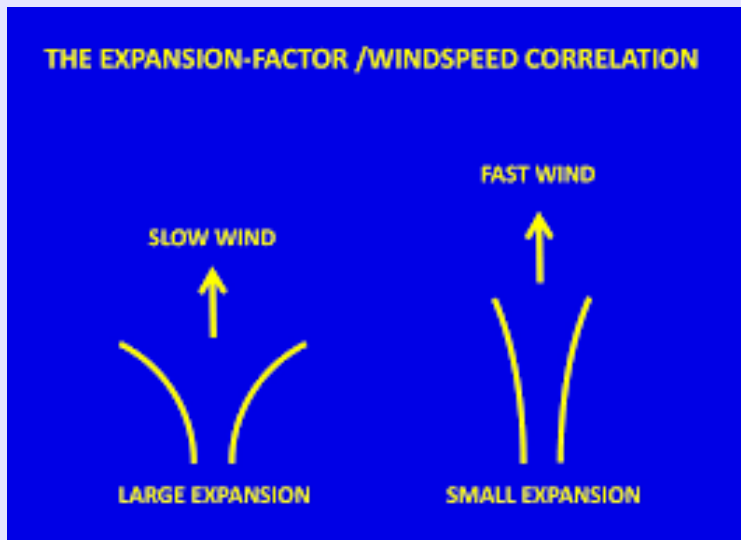
SDO/AIA 193A 2013.10.31 17:09UT



# The Solar origins of space weather I:

*Model Input:* solar wind speed is inversely proportional to the super-radial magnetic expansion factor.

Fast wind stream colliding into slow (ambient) creates shocks, material for magnetospheric trouble.



Shamelessly lifted from a talk by David Burgess 2017

The Solar origins of space weather I:

Hypothesis: “The high-speed solar wind streams that cause geomagnetic activity originate in solar coronal holes”

**Observations + Models + Observations + Occam’s Razor = answer.**

*Correlation* the solar location of coronal holes, a propagation along Archimedian “Parker spiral” through the heliosphere, to the start (and end) of observed geomagnetic storms.

*Model input:* large-scale magnetic field is predominantly *open* in coronal holes, and solar wind speed inversely correlates with magnetic super-radial expansion factors.

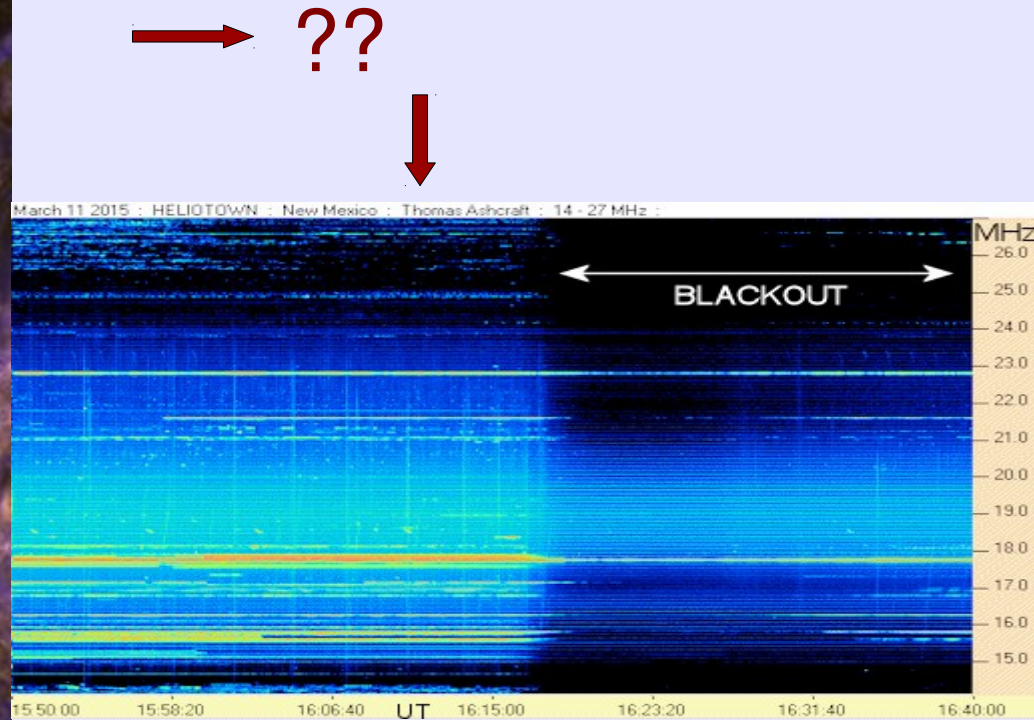
*Observations* of dominant Doppler blue-shifts and broader line widths in coronal holes, through the lower corona.

*Model input:* high-speed solar wind streams can form shocks with up-stream slower-moving plasma to drastically intensify magnetic field and density.

**Answer:** Solar origins of geo-effective high-speed streams are consistent with the appearance, location, and understood properties of coronal holes.

## The Solar origins of space weather II:

Hypothesis: "Ionospheric and magnetospheric disruptions are caused by impacts from the ionizing radiation of solar flares and plasma from associated coronal mass ejections, ultimately fueled by magnetic energy stored in the solar corona."



RCH ASSOCIATES

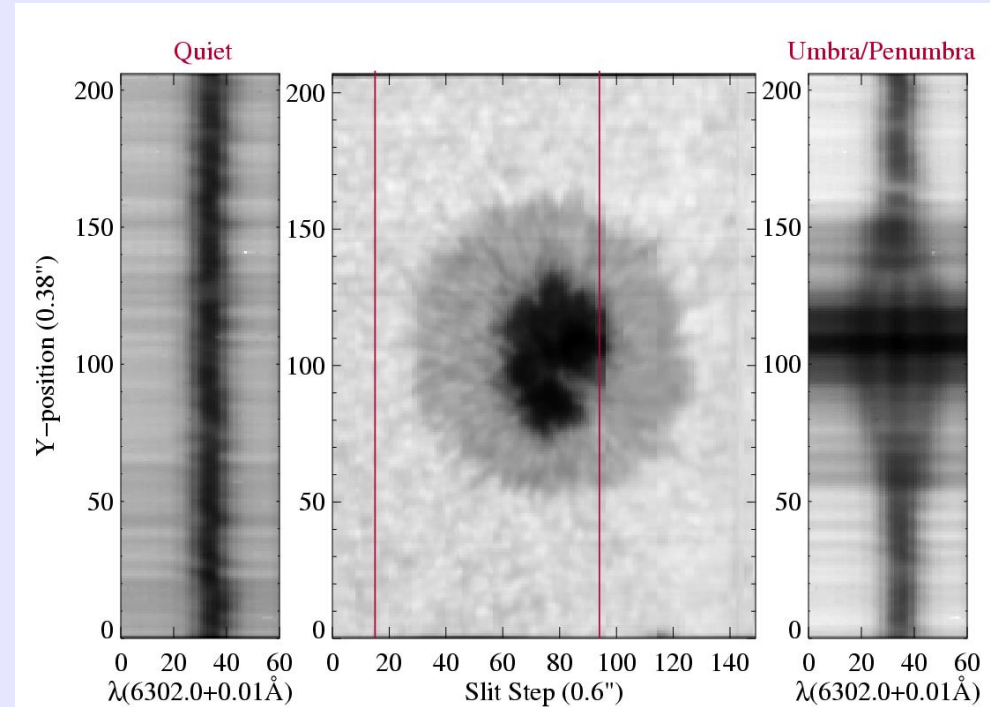
"unencumbered science"

## The Solar origins of space weather II:

Hypothesis: "Ionospheric and magnetospheric disruptions are caused by impacts from the ionizing radiation of solar flares and associated coronal mass ejections, ultimately fueled by magnetic energy stored in the solar corona."

### Observations of:

- Zeeman effect → sunspots have strong magnetic fields

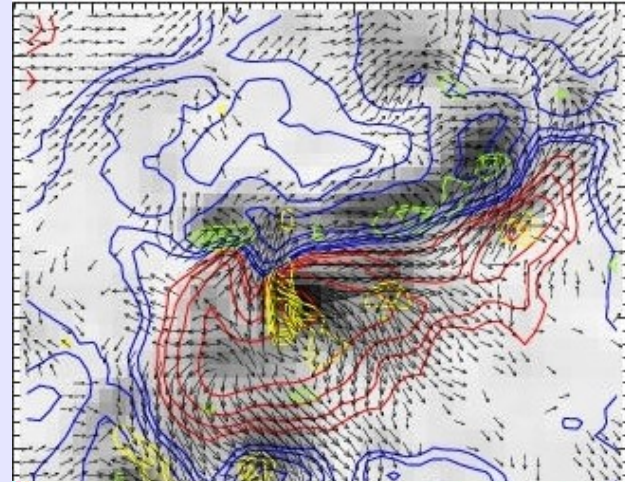


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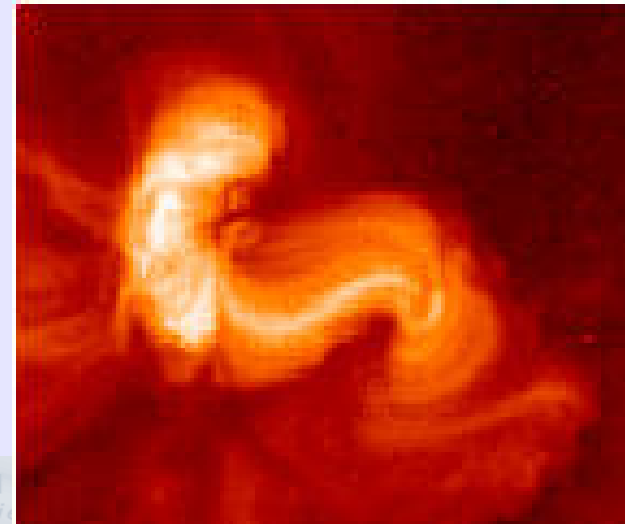
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### Observations of:

- Zeeman effect → sunspots have strong magnetic fields
- Magnetic fields and coronal loops are “complex”, “sheared” and “twisted” in flare-active sunspot groups: the magnetic field is storing energy (above the “ground state” of a potential-field configuration).



Photospheric **B**:  
Twist, current,  
strong spatial  
gradients.



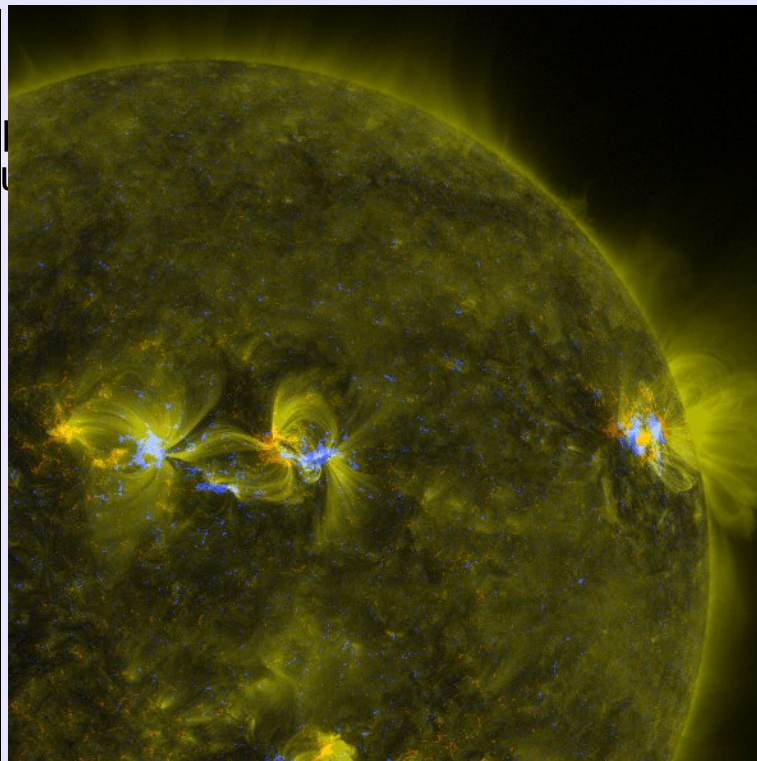
Coronal loops

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### Observations of:

- Zeeman effect → sunspots have strong magnetic fields
- Magnetic fields are "sheared" and in a "sheared state" of a

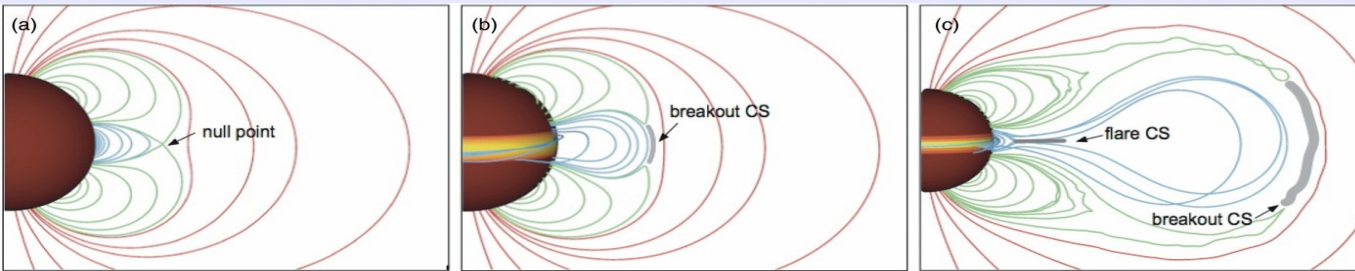


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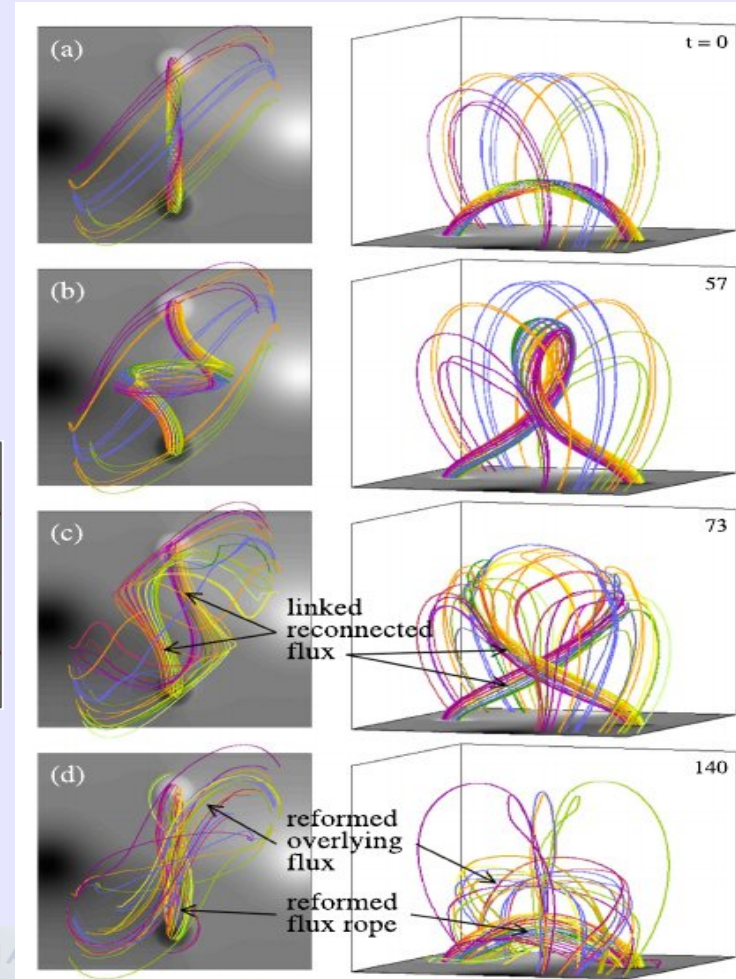
### Models:

- Magnetic twist, converging flows, emerging bipoles etc. can produce eruptions in MHD simulations.



*Karpen+2012*

*Hassanin & Kliem 2016*

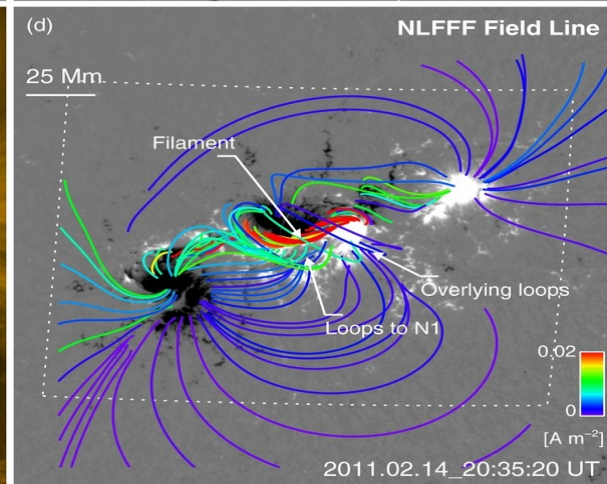
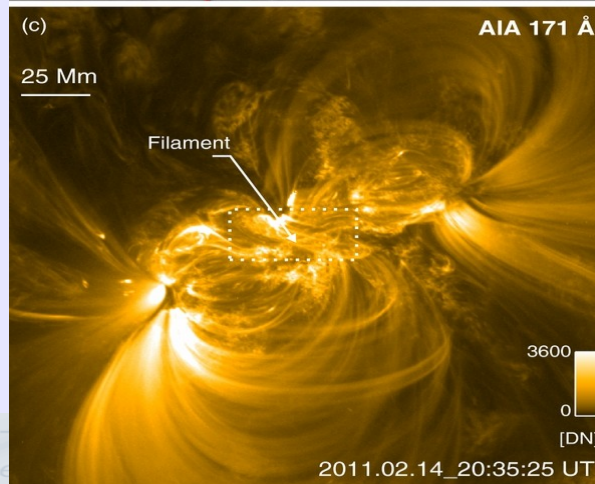
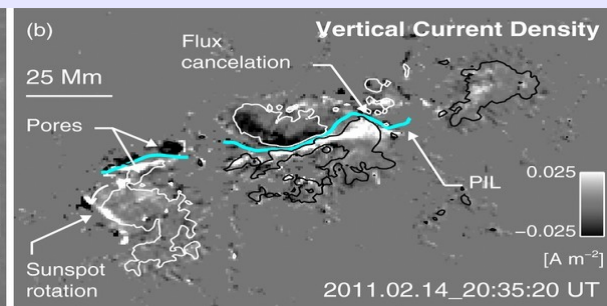
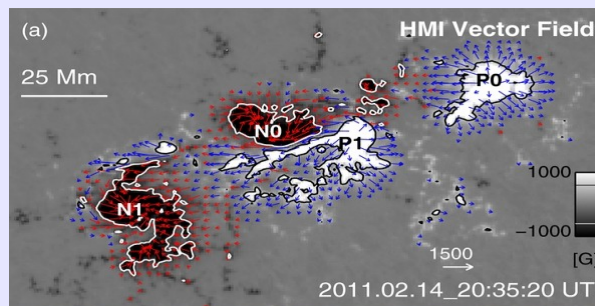


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Hypothesis: “Ionospheric and magnetospheric disruptions are caused by impacts from the ionizing radiation of solar flares and associated coronal mass ejections, ultimately fueled by magnetic energy stored in the solar corona.”

### Models:

- Non-linear force-free magnetic field extrapolations use observations for boundary data and solution constraints.



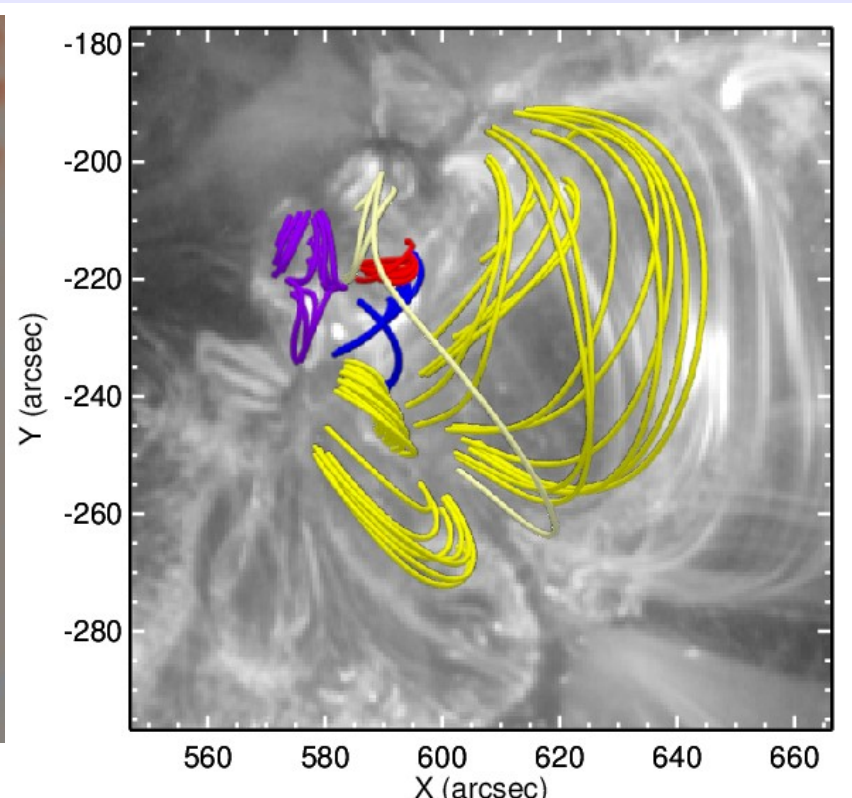
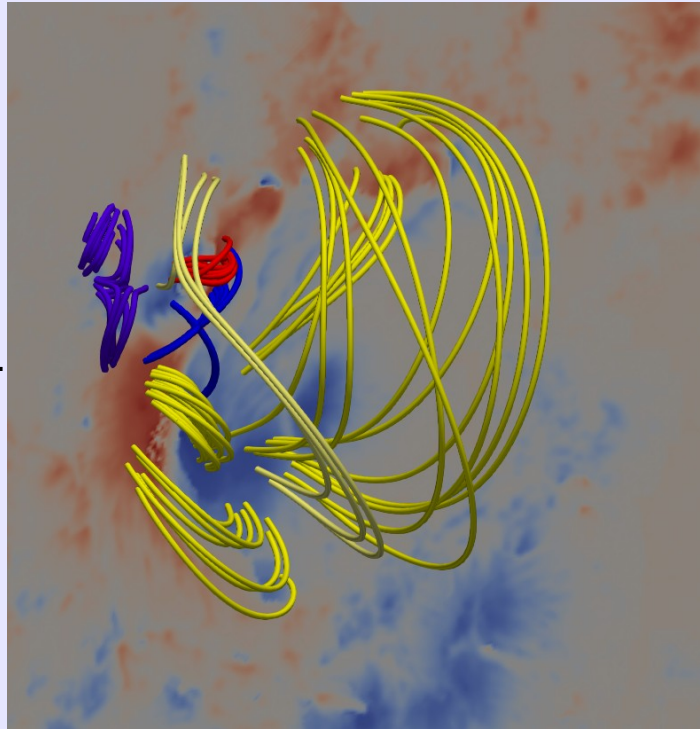
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Numerical extrapolations (Wheatland 2007) of the solar coronal magnetic field for AR 12673, 2017.09.06; comparison with coronal loop images. Courtesy Alpha Mastrano

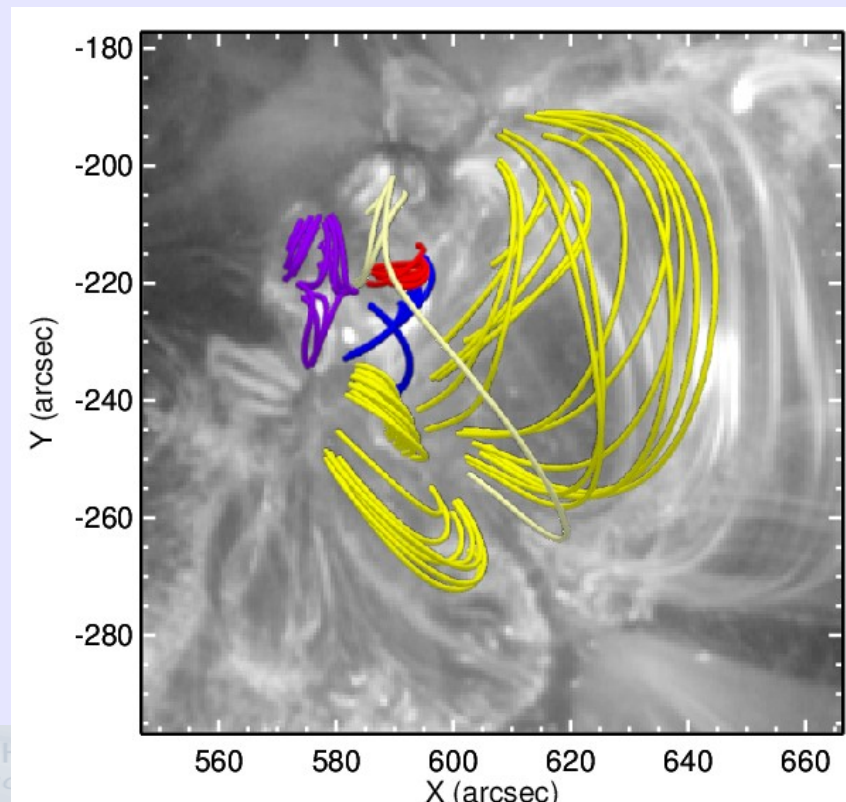


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- Data-driven simulations that include full atmospheric models are becoming more realistic.

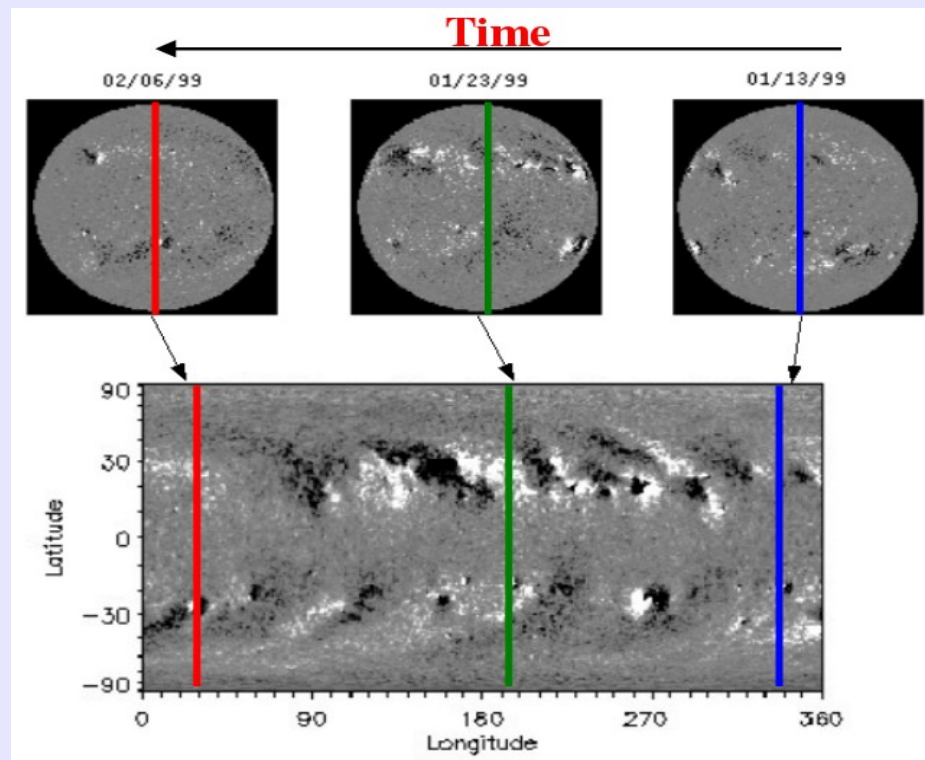
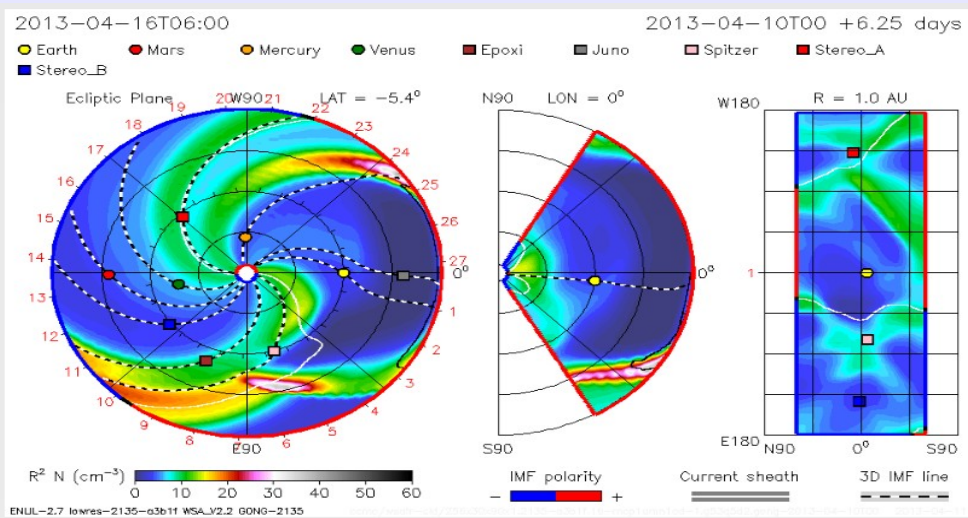


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### Models:

- Non-linear force-free magnetic field extrapolations use observations for boundary data and solution constraints.
- Data-driven simulations that include full atmospheric models are becoming more realistic.
- Heliospheric models: use observed data as boundary to drive simulations of solar wind and CME propagation

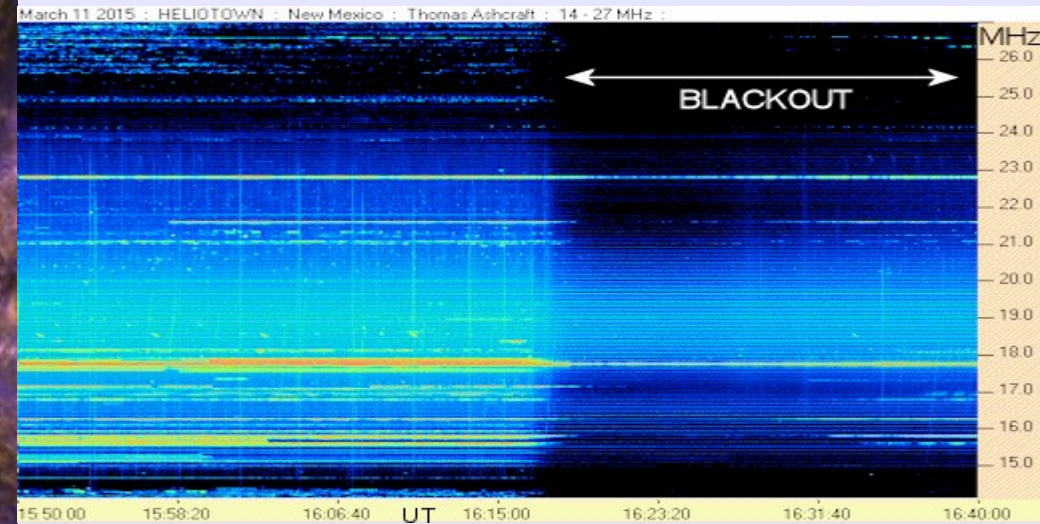


*Shamelessly lifted from a talk by Nick Arge.*

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*Correlation* between large flares and Earthly communications problems.

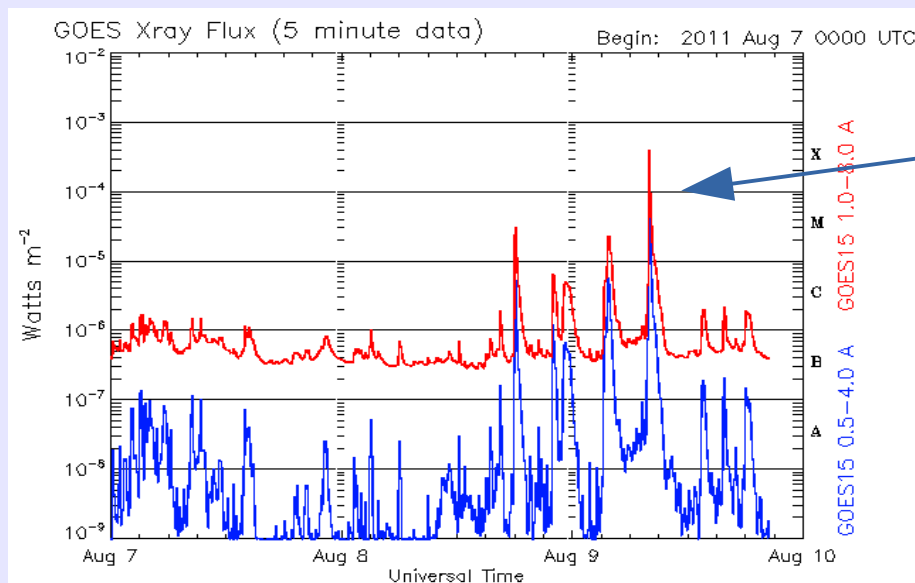


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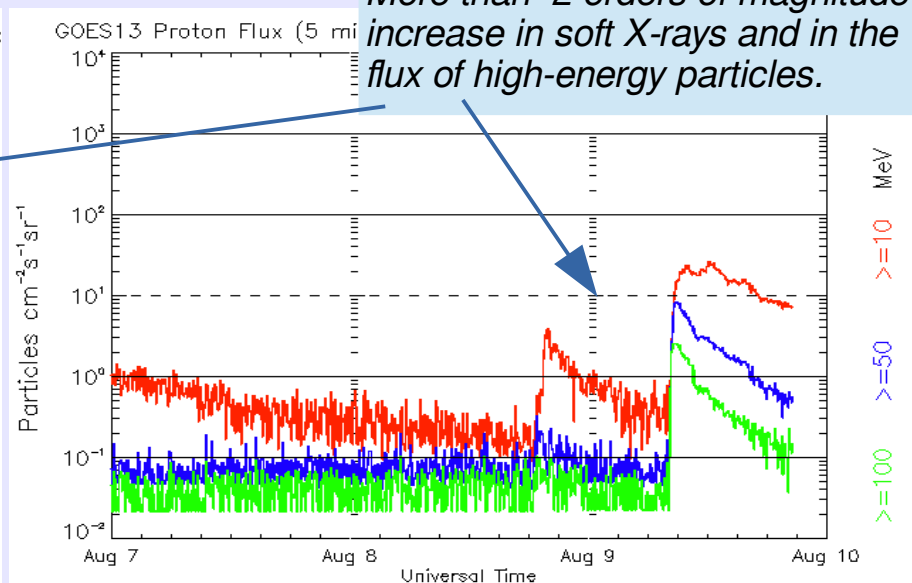
*Correlation* between large flares and Earthly communications problems.

*Correlation* between “eruptions” of mass from the solar atmosphere and strong geomagnetic activity (ground currents, aurora visible at low latitudes, energetic particles detected).



Updated 2011 Aug 9 20:40:11 UTC

NOAA/SWPC Boulder, CO USA



More than 2 orders of magnitude increase in soft X-rays and in the flux of high-energy particles.

Updated 2011 Aug 9 20:46:02 UTC

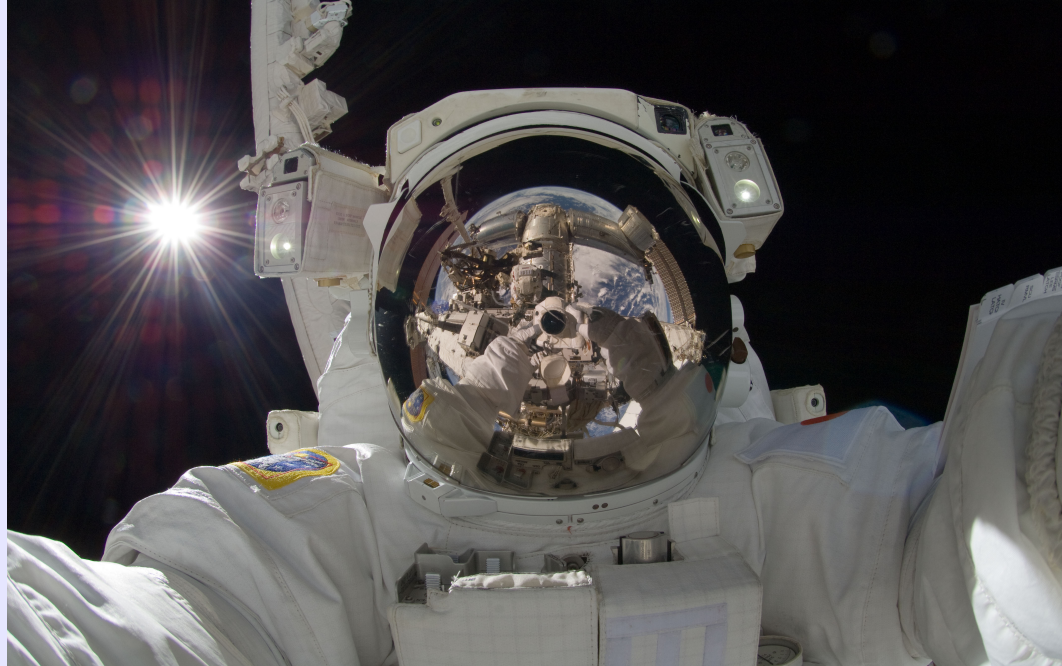
NOAA/SWPC Boulder, CO USA

## The Solar origins of space weather II:

Hypothesis: “Ionospheric and magnetospheric disruptions are caused by impacts from the ionizing radiation of solar flares and associated coronal mass ejections, ultimately fueled by magnetic energy stored in the solar corona.”

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*A reason to be thankful  
for Earth's magnetic  
field...*

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*Observations* of thousands of active regions and flares now describe underlying distributions:

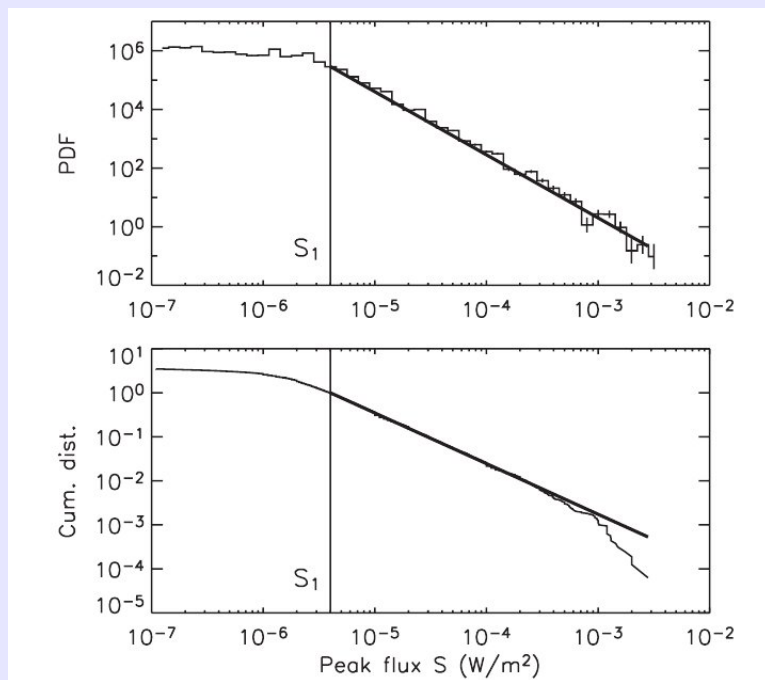
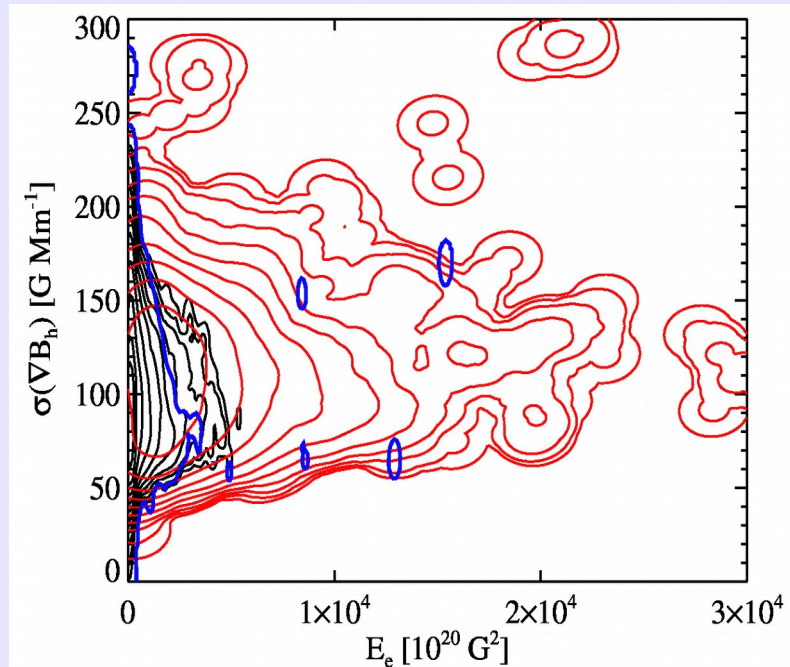


Figure 1. (top) Probability density function (PDF) for the peak flux (1–8 Å) of GOES events 1975–2003, together with the threshold  $S_1$  (vertical line) and the power law model (thick line). (bottom) Cumulative distribution.

Wheatland 2005



Non-parametric density estimates of free magnetic energy and spatial gradients of the magnetic fields for 65,000 samples; flare-producing and flare-quiet, with 50% probability threshold. Leka+ 2018.

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Hypothesis: “Ionospheric and magnetospheric disruptions are caused by impacts from the ionizing radiation of solar flares and associated coronal mass ejections, ultimately fueled by magnetic energy stored in the solar corona.”

### *Estimates of:*

- Energy reserves *needed* for radiative, thermal, kinetic energy budgets
- Energy sources *available* on timescales *required*

### *Models of:*

- Ionospheric response to sudden influx of soft X-rays: turbulence & scintillation
- Geomagnetic response to influx of charged plasma: magnetotail reconnection, substorms, especially severe with southward-facing Bz and shock impacts.

Observations + Models + Occam's Razor = ANSWER.

- **ANSWER:** Solar magnetic fields are the ultimate source of Geomagnetic activity.

So...

... we observe so much, model so well, and perfectly understand all the “Solar Origins of Space Weather” .....

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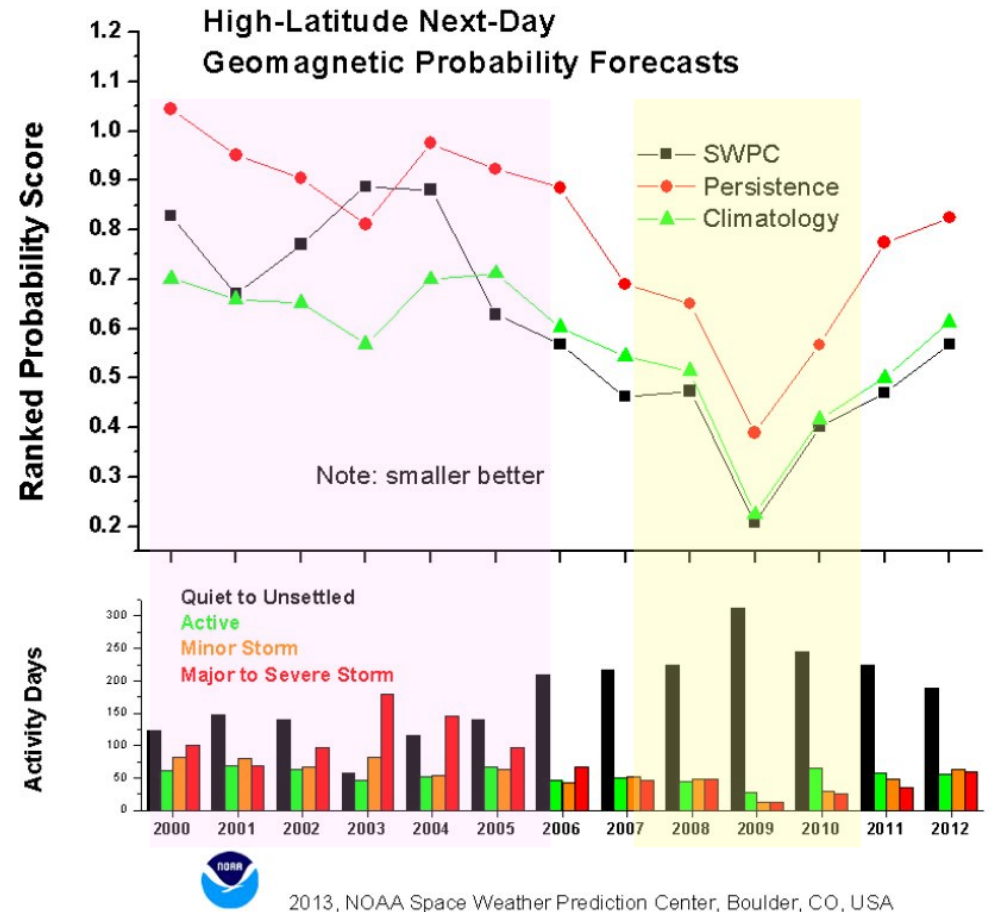
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# Forecasting Geomagnetic Storms from High-Speed Solar Wind Streams: some Success

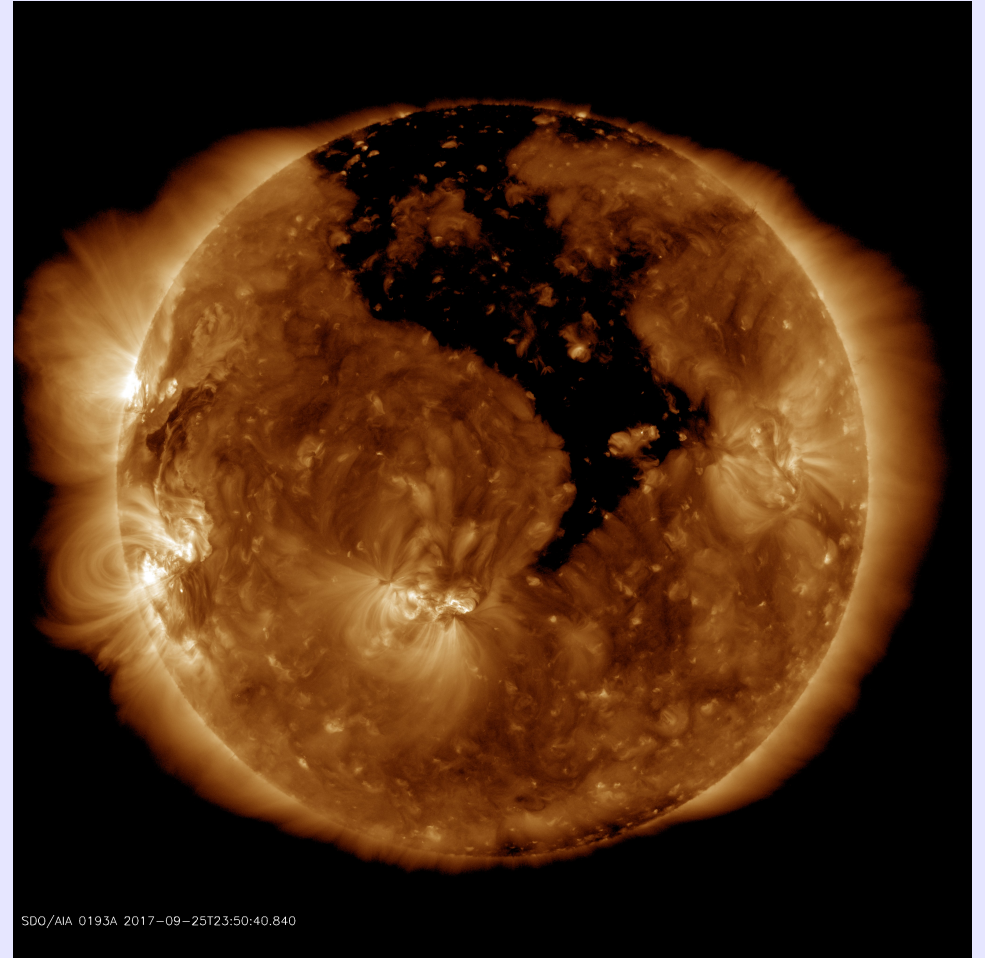
Solar minimum (**yellow**): forecasts improve (easier to uniquely detect coronal holes).

Solar maximum (**pink**): forecasts hindered by other solar activity.



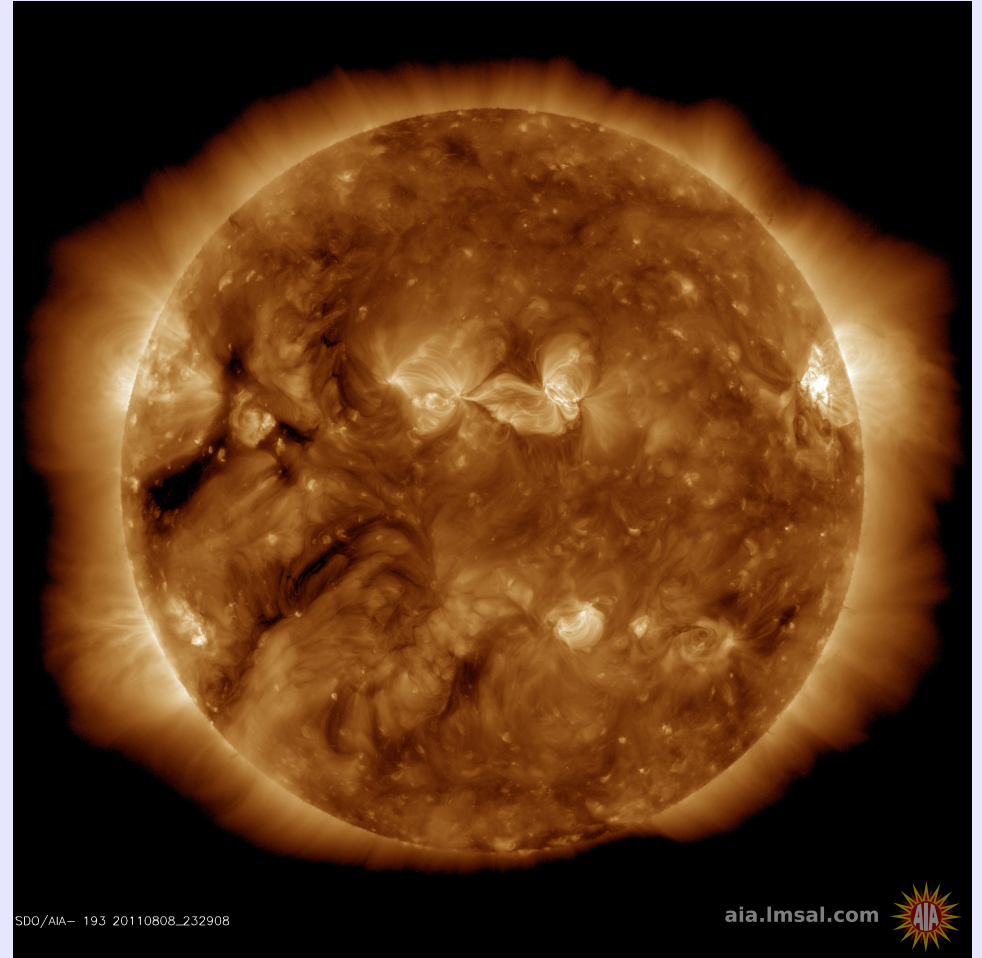
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- Detecting Coronal Holes
  - Sometimes the boundaries look clear.



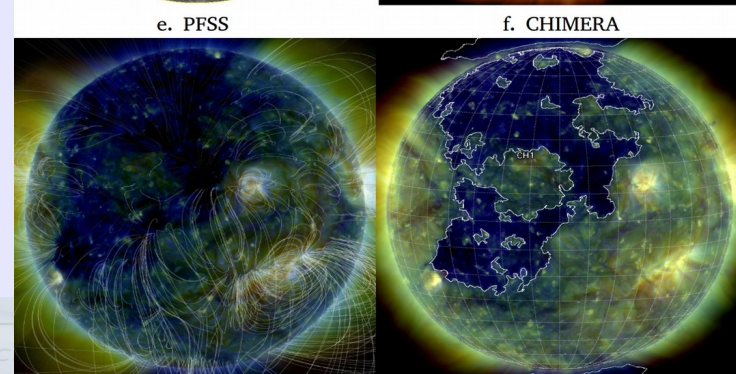
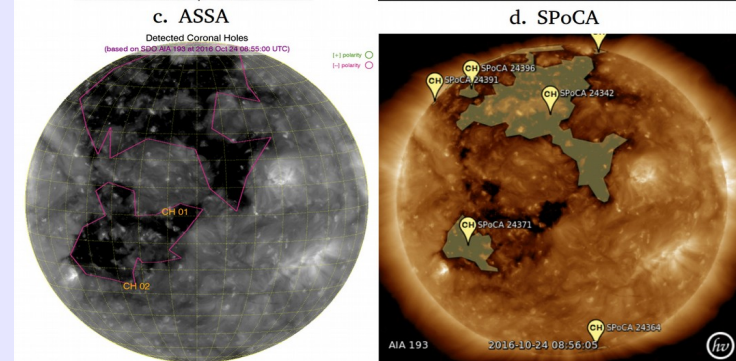
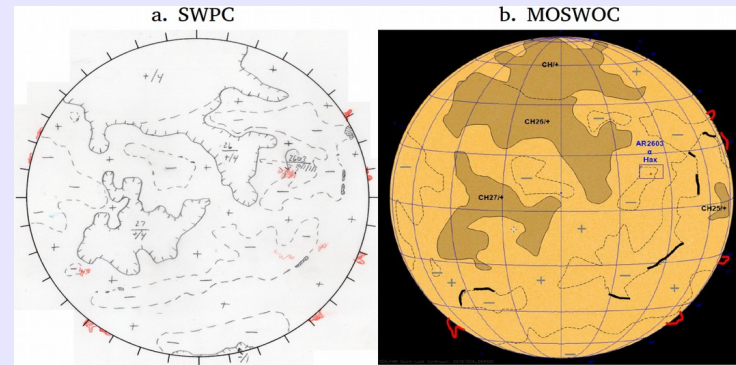
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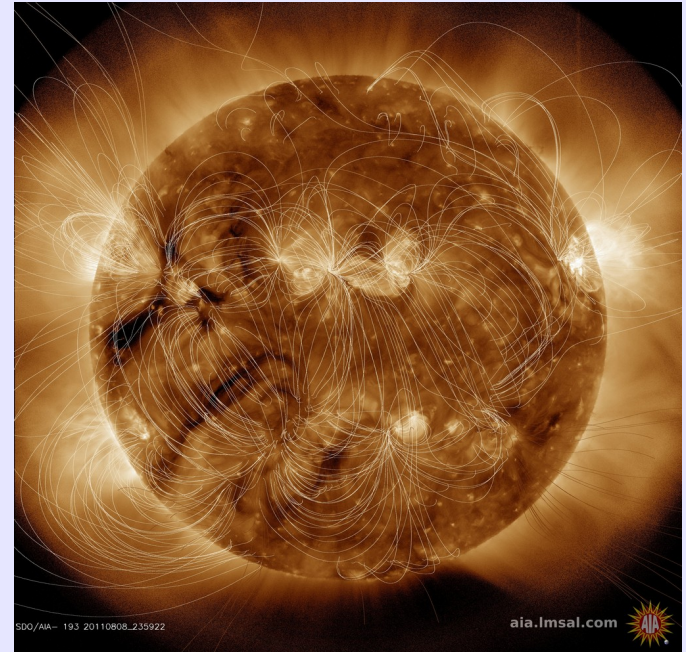
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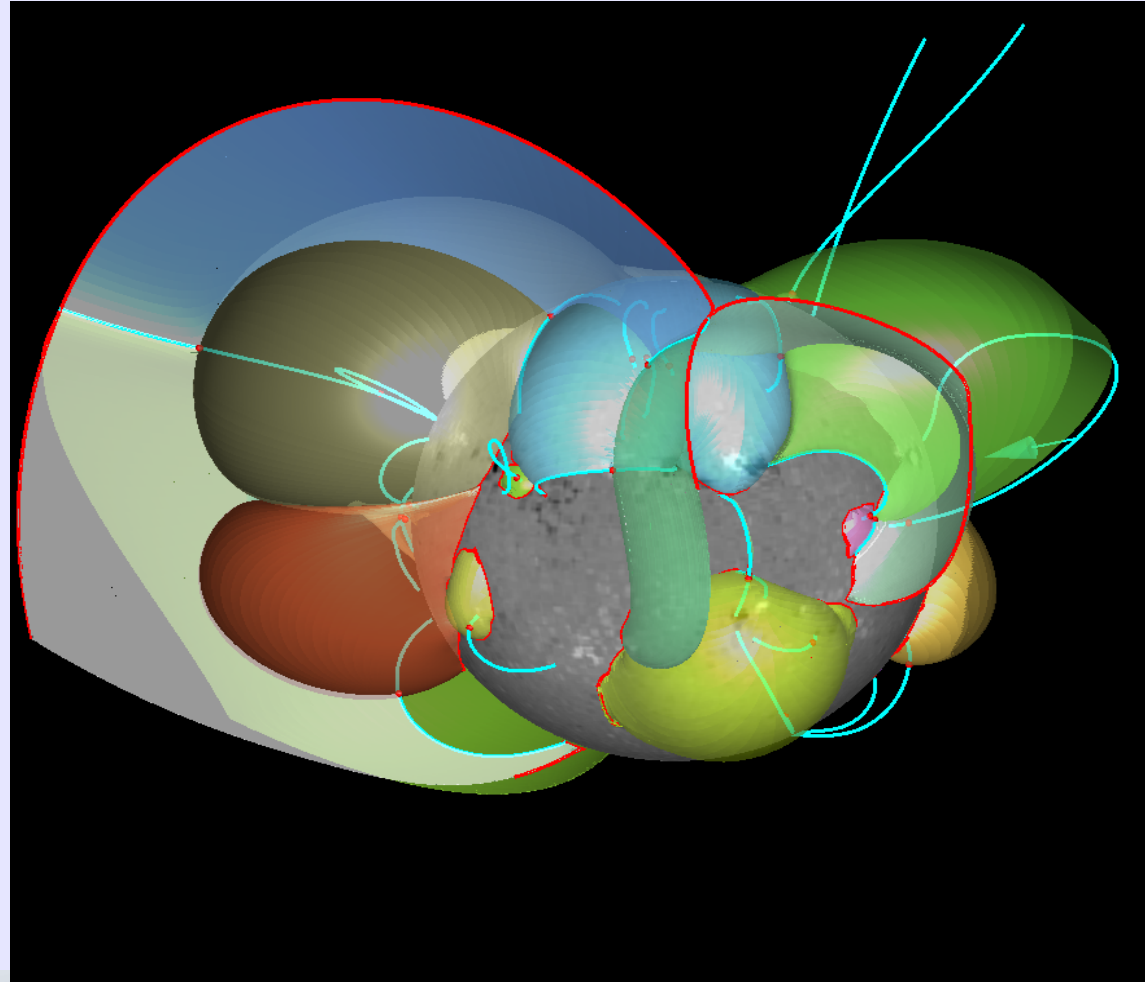
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DeRosa & Barnes 2018

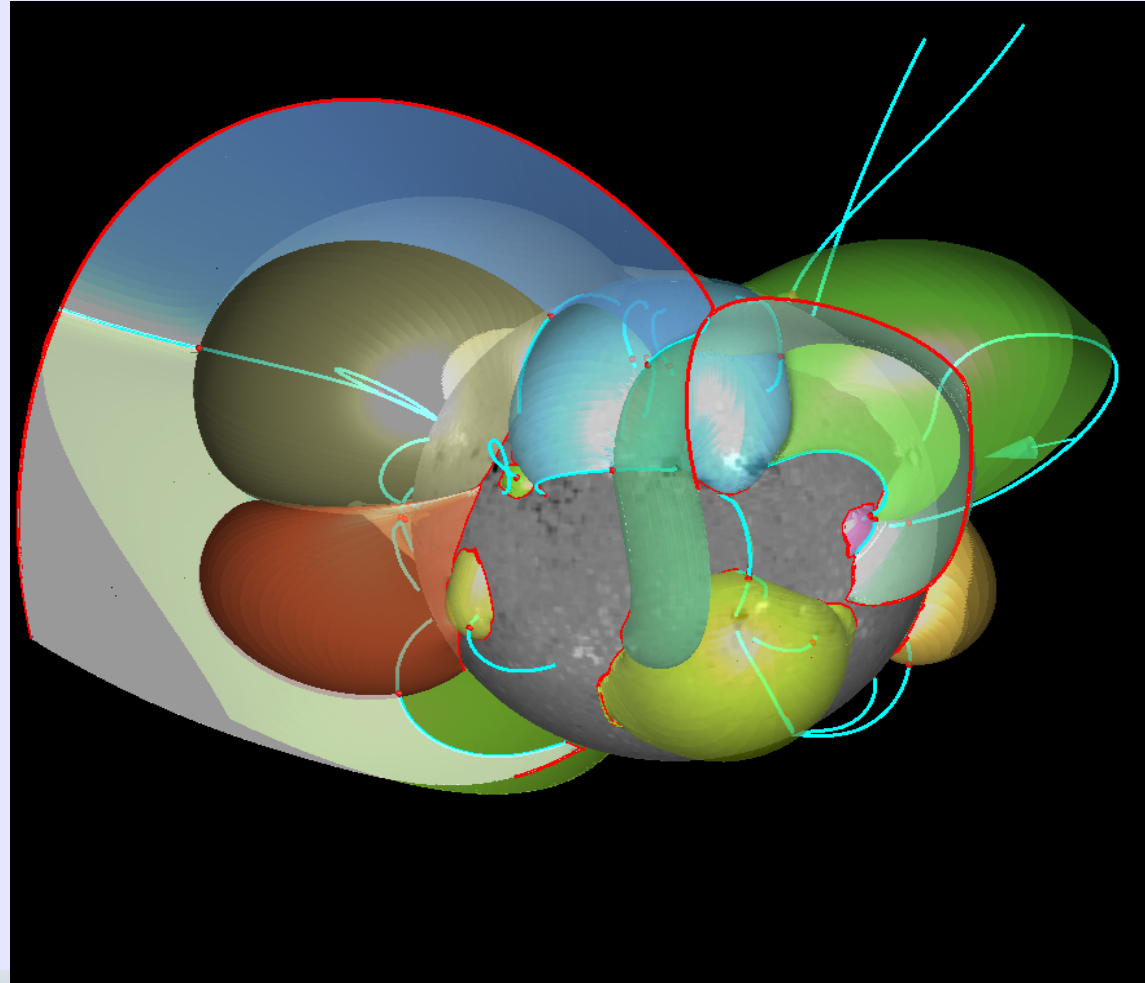
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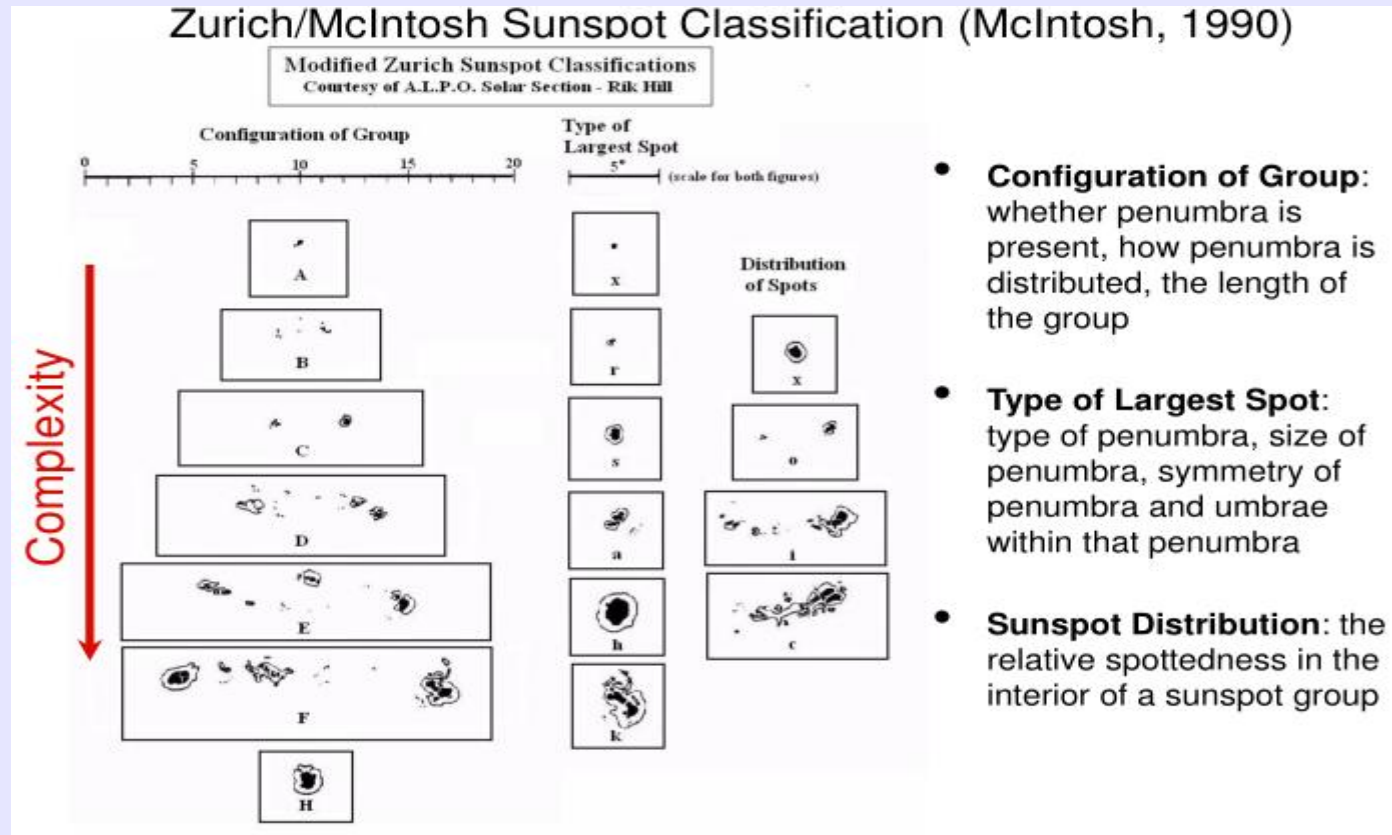


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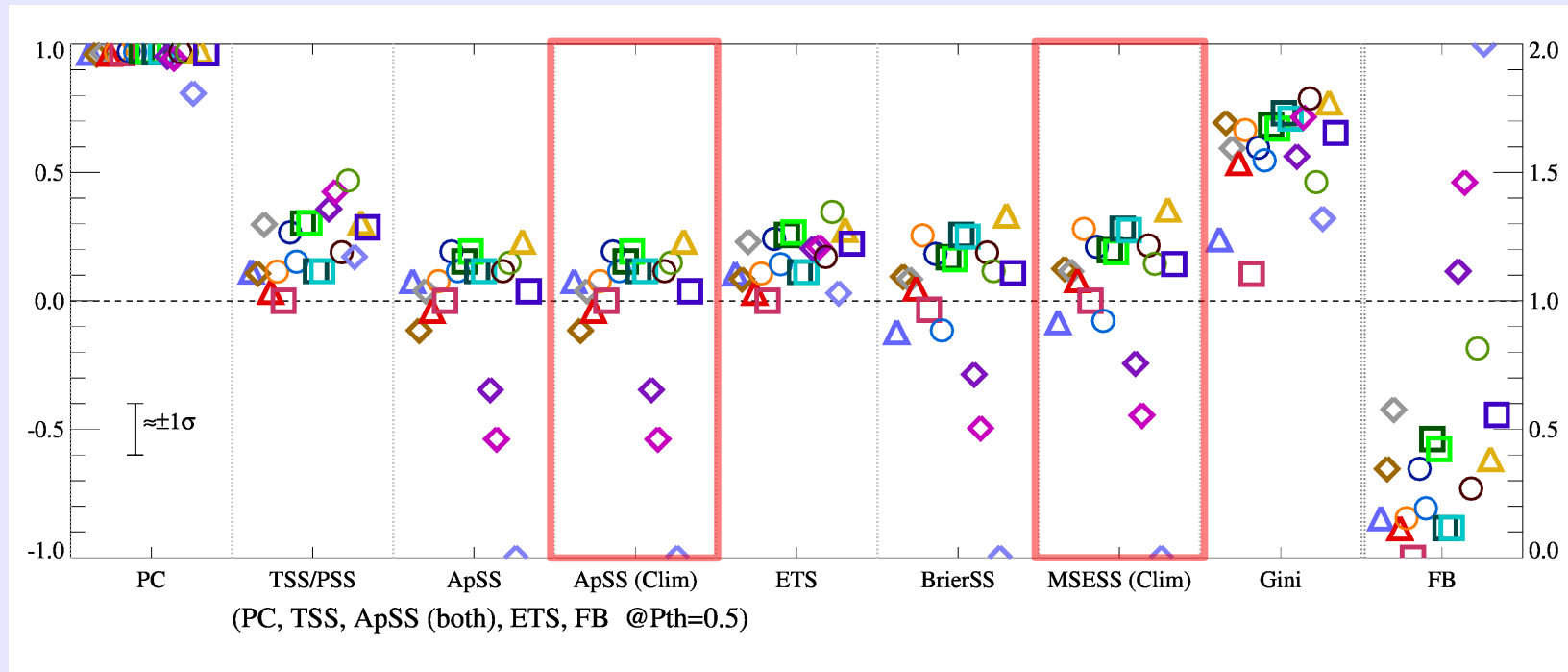


# Forecasting Solar Energetic Events: Present Forecasting Paradigm

- Flares occur in active regions (sunspot groups) whose spots are complex, rapidly evolving, and whose magnetic fields indicate stored magnetic energy especially along strong-gradient “Polarity Inversion Lines”.
- Coronal Mass Ejections and particle events occur with large solar flares.



Generally speaking, forecasting solar flares and Coronal Mass Ejections really does not do very well, *as we presently judge them*\*

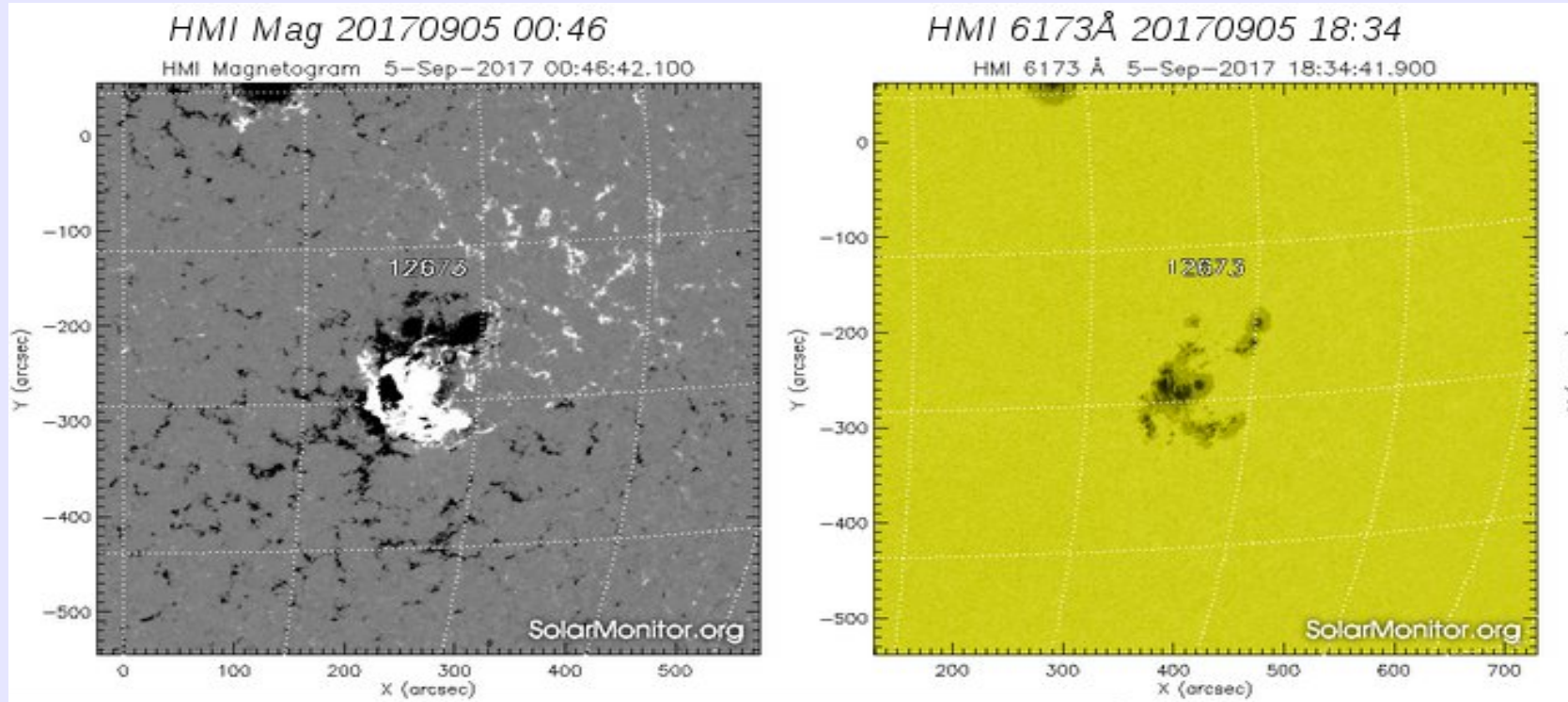


Metrics evaluating performance of operational flare forecast facilities across a standard evaluation period. Metrics shown should tend toward 1.0; scoring 0.0 indicates “no skill”. *From Leka+++ 2019.*

\* The event definitions, detectors, timing, etc. are all about humans, not about the physics of the solar plasma. Are we evaluating in a helpful way?

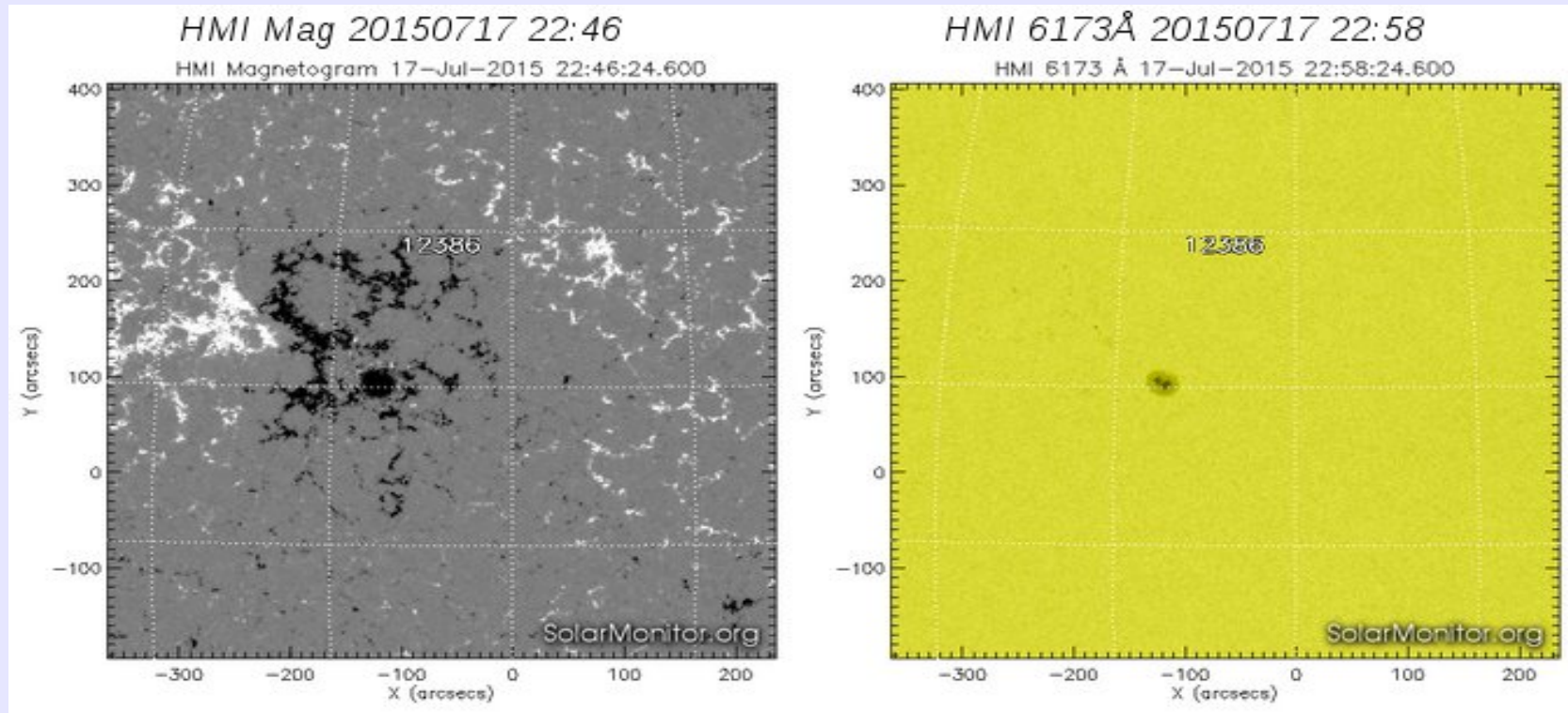
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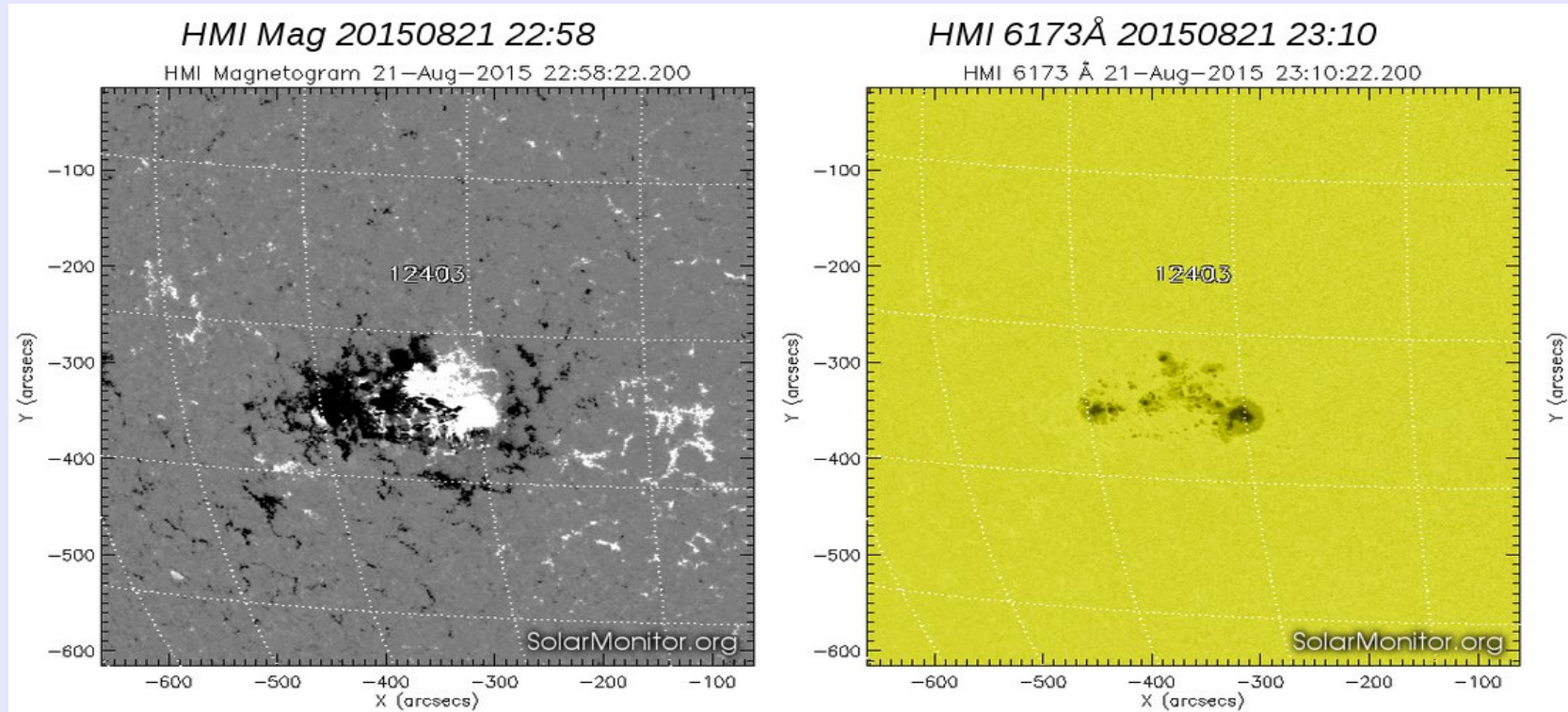
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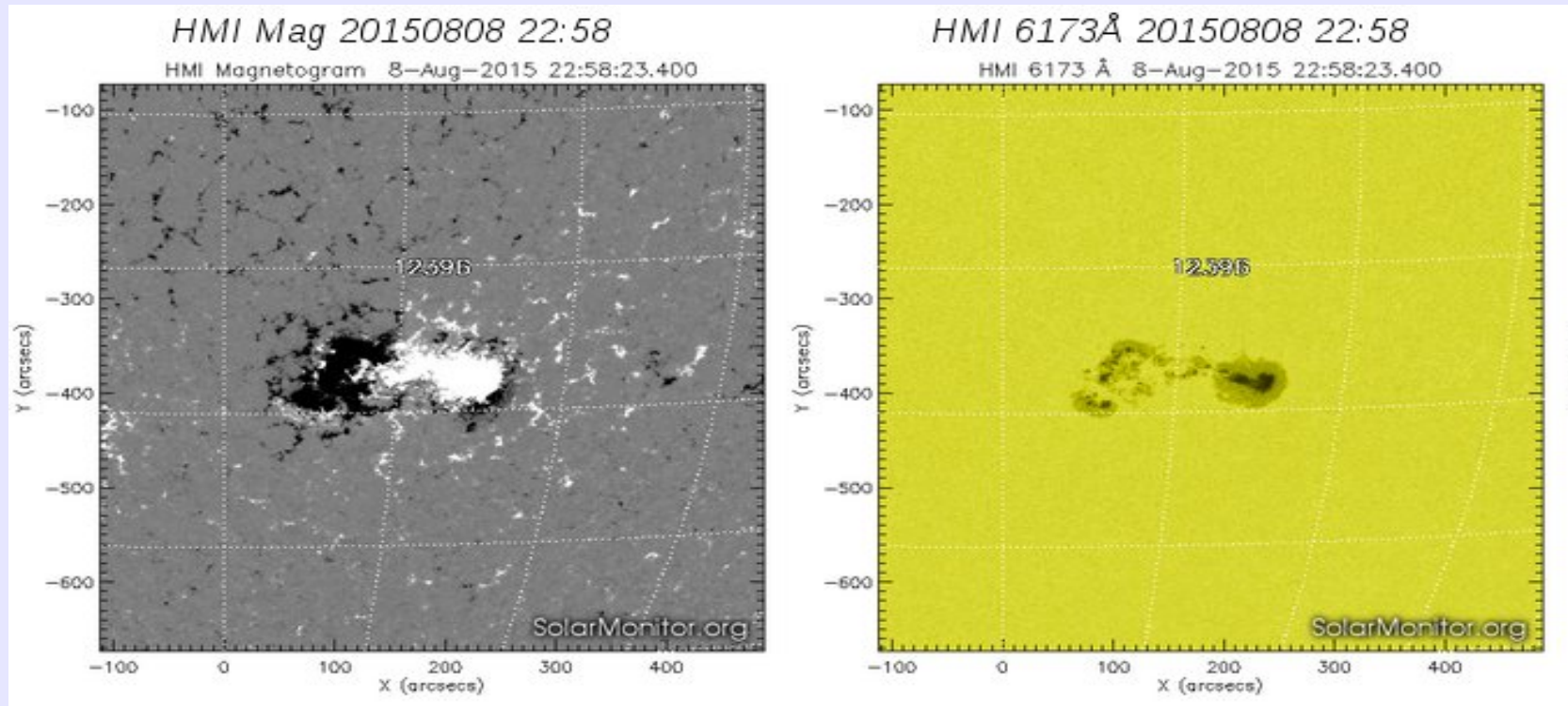
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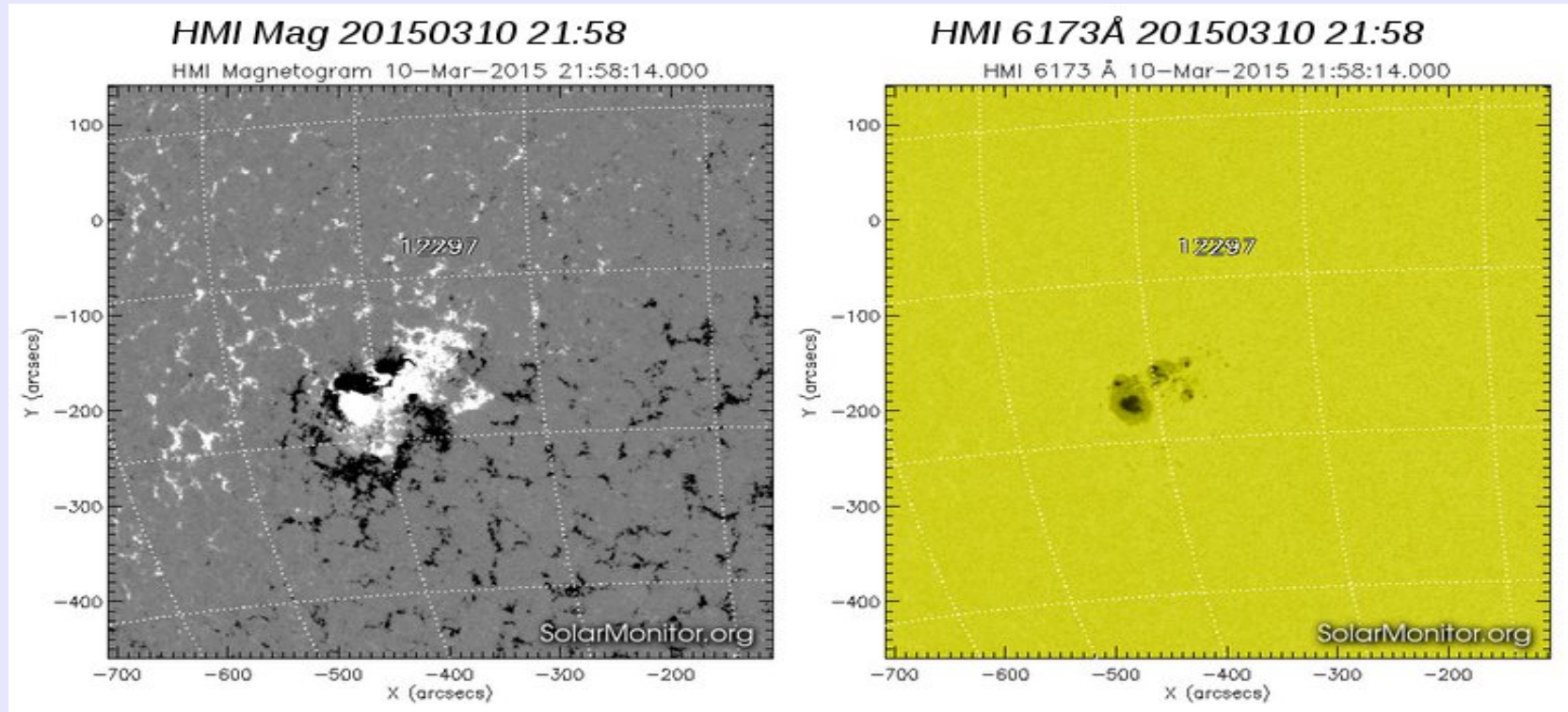
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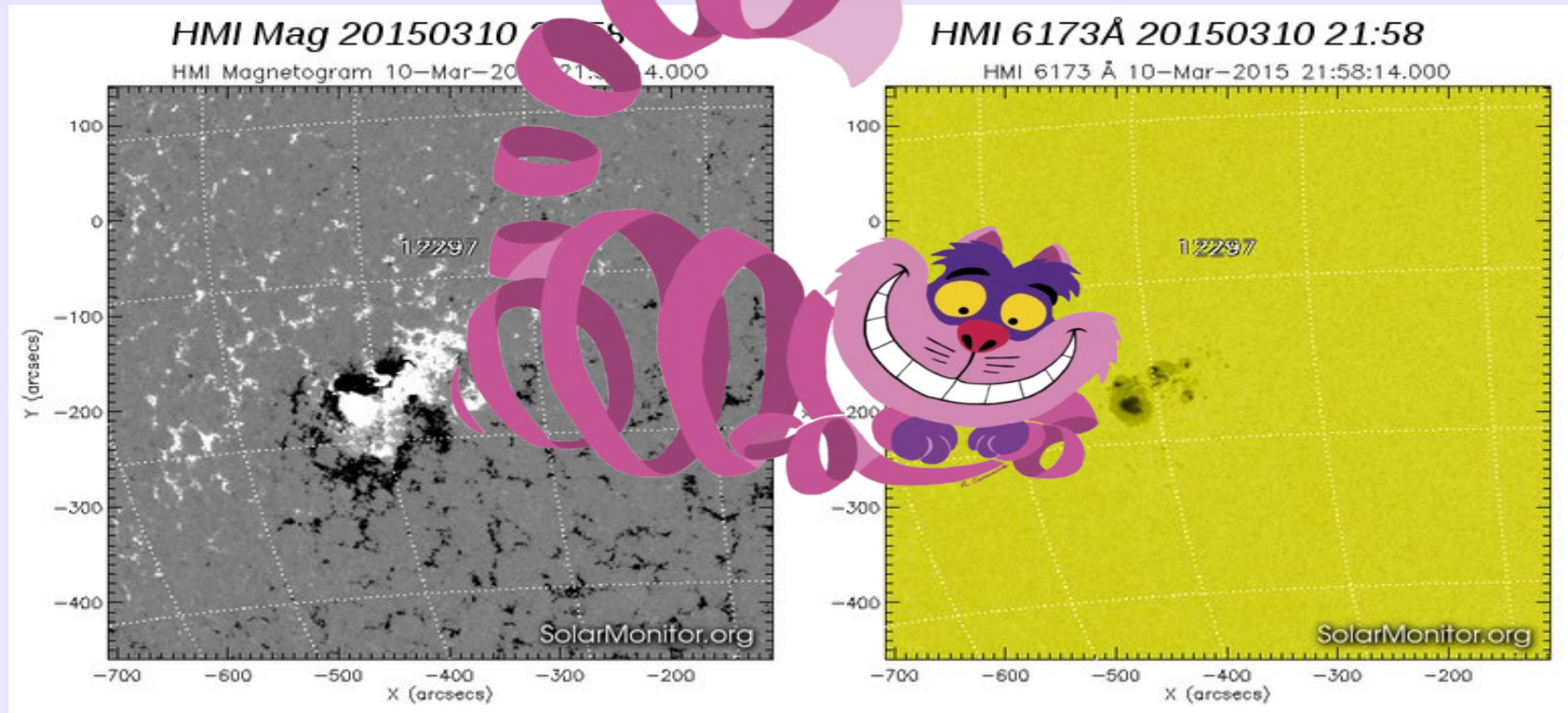
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However:

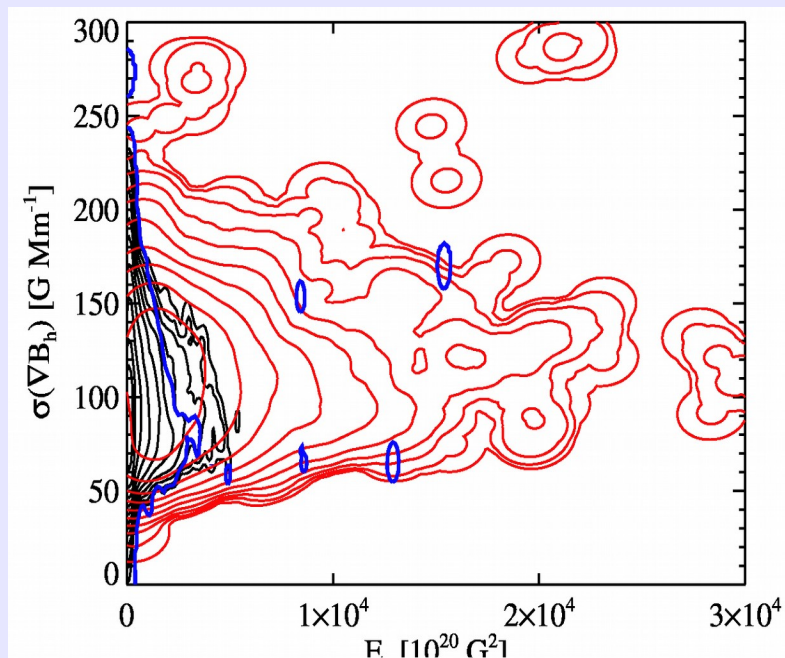
- There are flares without CMEs
- There are eruptions before flares
- There are flares before eruptions
- There are eruptions without strong-gradient PILs
- There are CMEs from very small flares
- There are CMEs without sunspots
- There are particle events from small flares

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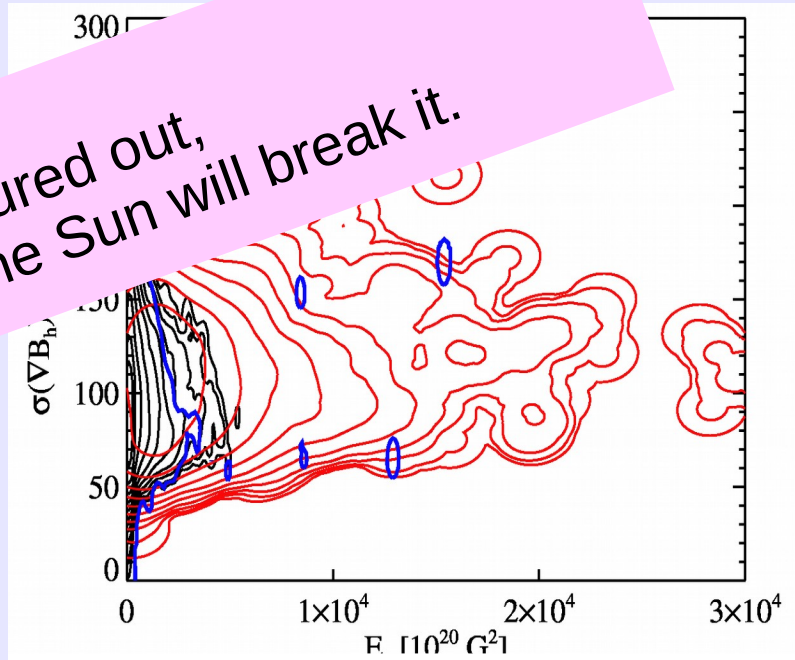
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KD's paradigm:  
whatever “rule” you think you’ve figured out,  
the Sun will break it.



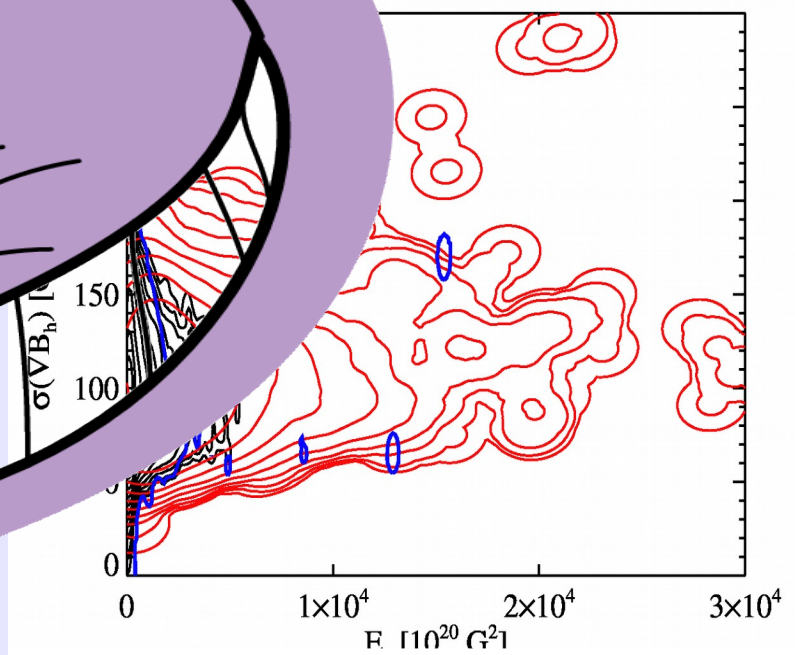
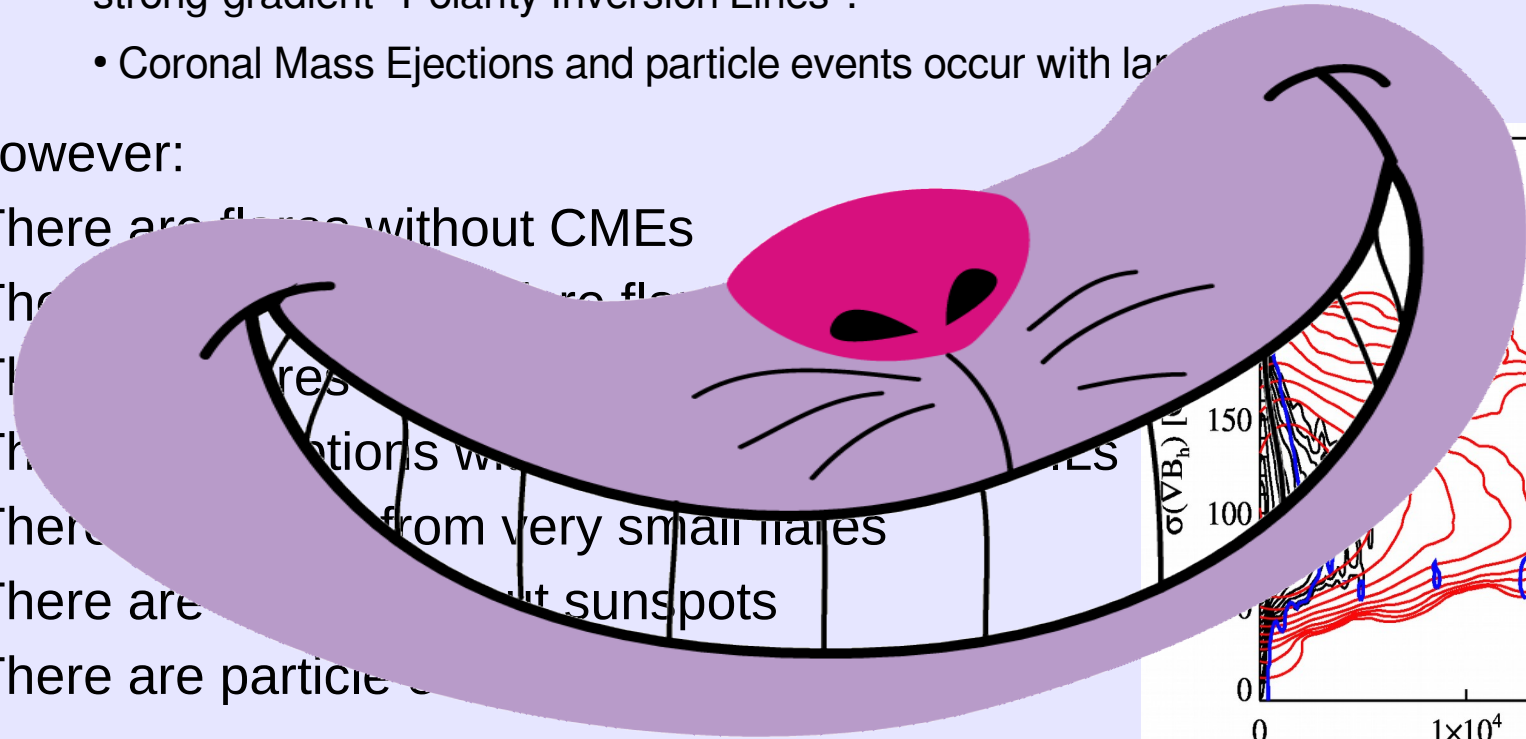
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- There are flares without sunspots
- There are sunspots without flares
- There are correlations with CMEs
- There are correlations with solar wind
- There are correlations with geomagnetic storms
- There are correlations with auroras
- There are correlations with particle events



Non-parametric density estimates of free magnetic energy and spatial gradients of the magnetic fields for 65,000 samples; flare-producing and flare-quiet, with 50% probability threshold. Leka+ 2018.

## Which way ought we go? Depends on where you want to get to:

- Focusing on detailed physics vs observational constraints or empirical forecasting:

- ▶ Not necessarily an 'exclusive or'
- ▶ Approach needs to be more like an iterative convergence.
- ▶ When and how forecasting efforts *fail* should guide the way.



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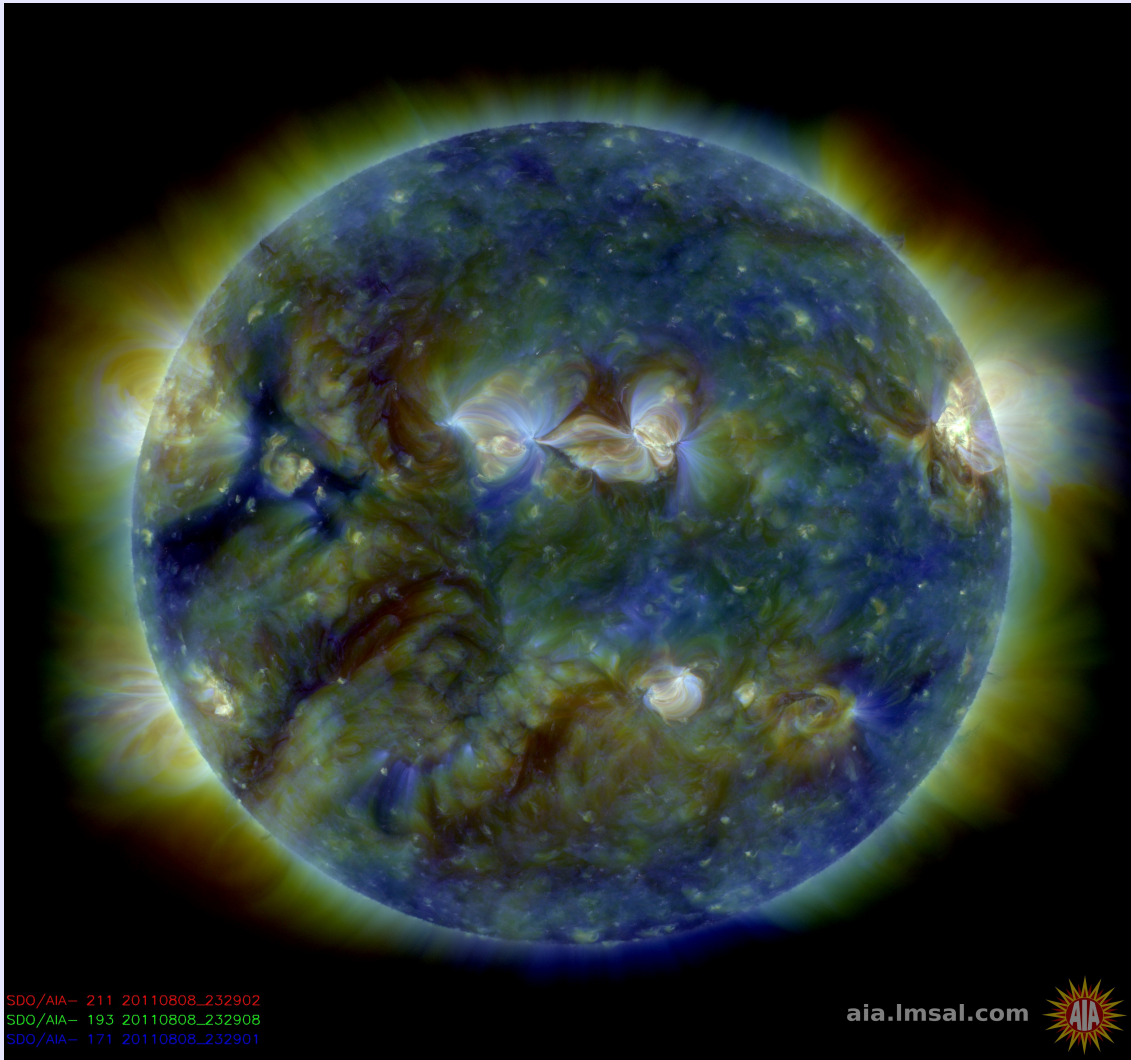
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- If we believe we understand the physics, then employ a “forecasting paradigm”

- ▶ Challenge the model, the hypothesis on large samples
- ▶ Consider uniqueness and counter examples



## A few things to consider:

- The “solar origins of space weather” is (mostly) a remote-sensing science. *All we have are photons.*
- Progress requires synergy between:
  - Modeling *and* observations..., (and Occam’s razor)
  - Investigations of detailed physics *and* empirically-based constraints
- Sometimes you just gotta go down that rabbit hole...



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## Challenges for model efforts:

- ▶ Investigative models: *Strive for “data inspired”*
  - Models for solar energetic events are still almost cartoons. Boundaries are too simplistic.
  - Model 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.
- ▶ Modeling the unobservables: *quantitative validation*
  - How sensitive is the result
    - to observational reality (noise, resolution)
    - to modifications required for the model to run
  - Does the model produce physical answers?

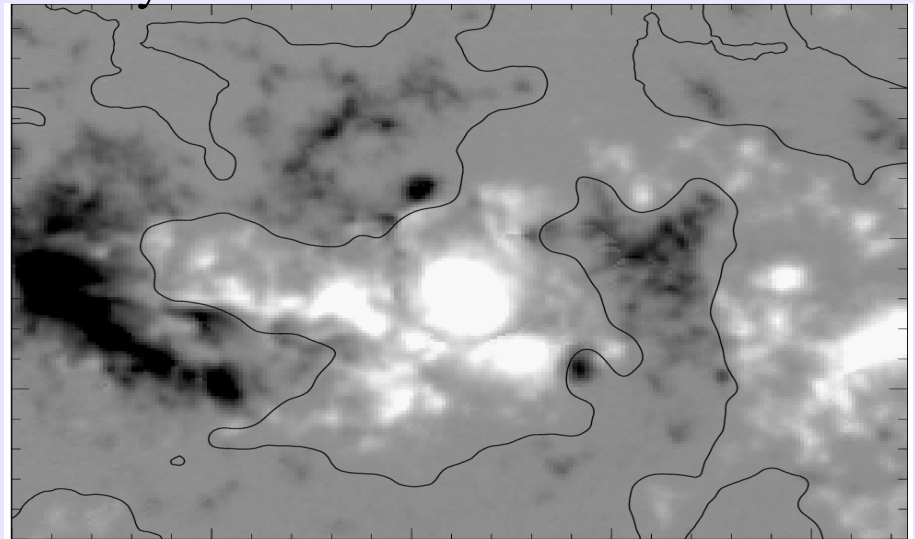
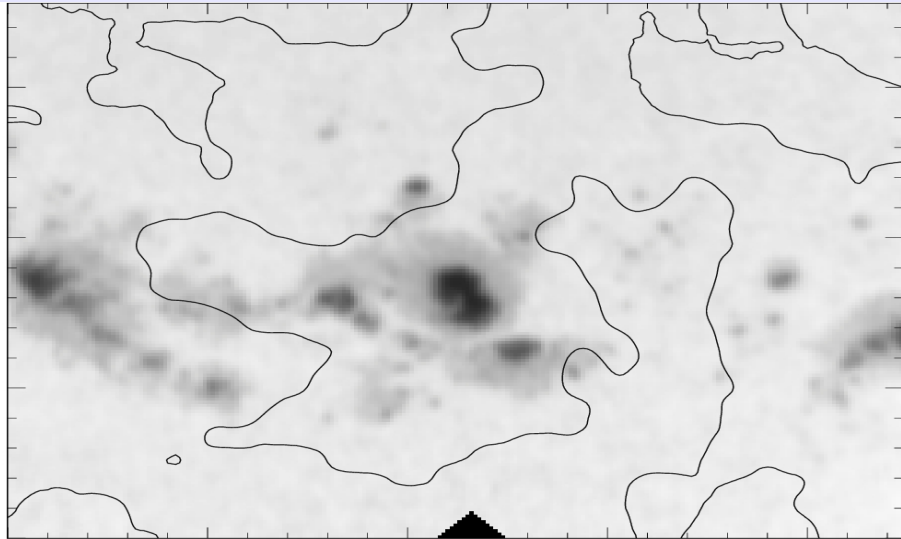
## Challenges for observing efforts:

- ▶ High-resolution observations: *Relate to “big picture”*
  - New 4m DKIST telescope data
    - Still photon-starved
    - How relate small-scale physics to macroscopic context?
- ▶ Case-study events
  - Where do they fit in known distributions?
- ▶ “Big Data”
  - Not as big as you think (for large events)
  - Time to expand “big” into the “information” domain
    - Wavelengths, regions probed, etc.

# How well do we know what we think we know?

KD's solar paradigm: whatever "rule" you think you've figured out, the Sun will break it.

NOAA AR 10030 15 July 2002



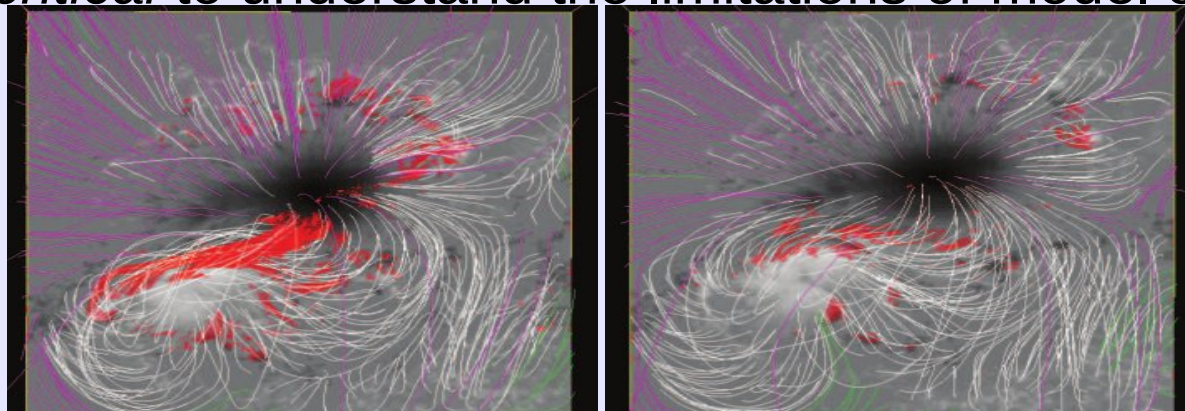
Continuum + NL, Imaging Vector Magnetograph

Bz + NL, IVM



See: Li+ 2005, Allen & Moore 2004, Harra+2005, Liu+2003, Tian+ 2007, Park+ 2008.

Challenges for Model users: get the whole story.  
It is *critical* to understand the limitations of model output.



From Schrijver+ 2008

METRICS FOR THE FIELD EXTRAPOLATIONS, IN ORDER OF QUALITY  $Q$  BASED ON THE VISUAL CORRESPONDENCE TO THE CORONAL PREFLARE IMAGE

MODEL <sup>1</sup>	$Q_m^2$	PREFLARE: 2006 DEC. 12			POSTFLARE: 2006 DEC. 13		
		$E/E_{p,pre}^3$	$CW \sin \theta^4$	$\langle  f_i  \rangle \times 10^{85}$	$E/E_{p,pre}$	$CW \sin \theta$	$\langle  f_i  \rangle \times 10^8$
Wh <sub>pp</sub> <sup>+</sup> .....	5	1.32	0.24	3.6	1.19	0.18	2.0
Wh <sub>np</sub> <sup>+</sup> .....	3	1.10	0.27	3.9	1.23	0.27	4.6
Wie <sub>wp</sub> .....	3	1.09	0.35	19	1.18	0.32	13
Val <sub>pp</sub> .....	3	1.10	0.28	230	1.27	0.31	190
Wh <sub>pp</sub> <sup>0</sup> .....	2	1.04	0.28	3.0	1.53	0.27	3.7
Wie <sub>ns</sub> .....	2	1.04	0.43	22	1.13	0.39	30
Val <sub>np</sub> .....	2	0.88	0.29	220	0.99	0.34	210
Wie <sub>np</sub> .....	1	0.95	0.43	24	1.04	0.39	27
Wie <sub>pp</sub> .....	0	1.05	0.44	18	1.15	0.39	21
McT <sub>pp</sub> .....	0	1.01	0.61	29	1.07	0.59	25
Wh <sub>np</sub> <sup>0</sup> .....	-1	1.03	0.27	2.5	1.12	0.23	2.6
Wh <sub>np</sub> .....	-1	1.04	0.25	2.9	1.11	0.24	2.9
Wh <sub>pp</sub> <sup>-</sup> .....	-1	1.05	0.27	3.2	1.16	0.19	2.2
McT <sub>np</sub> .....	-2	0.95	0.64	26	1.00	0.61	24
Potential .....	-3	1	...	0.8	1.04	...	0.8