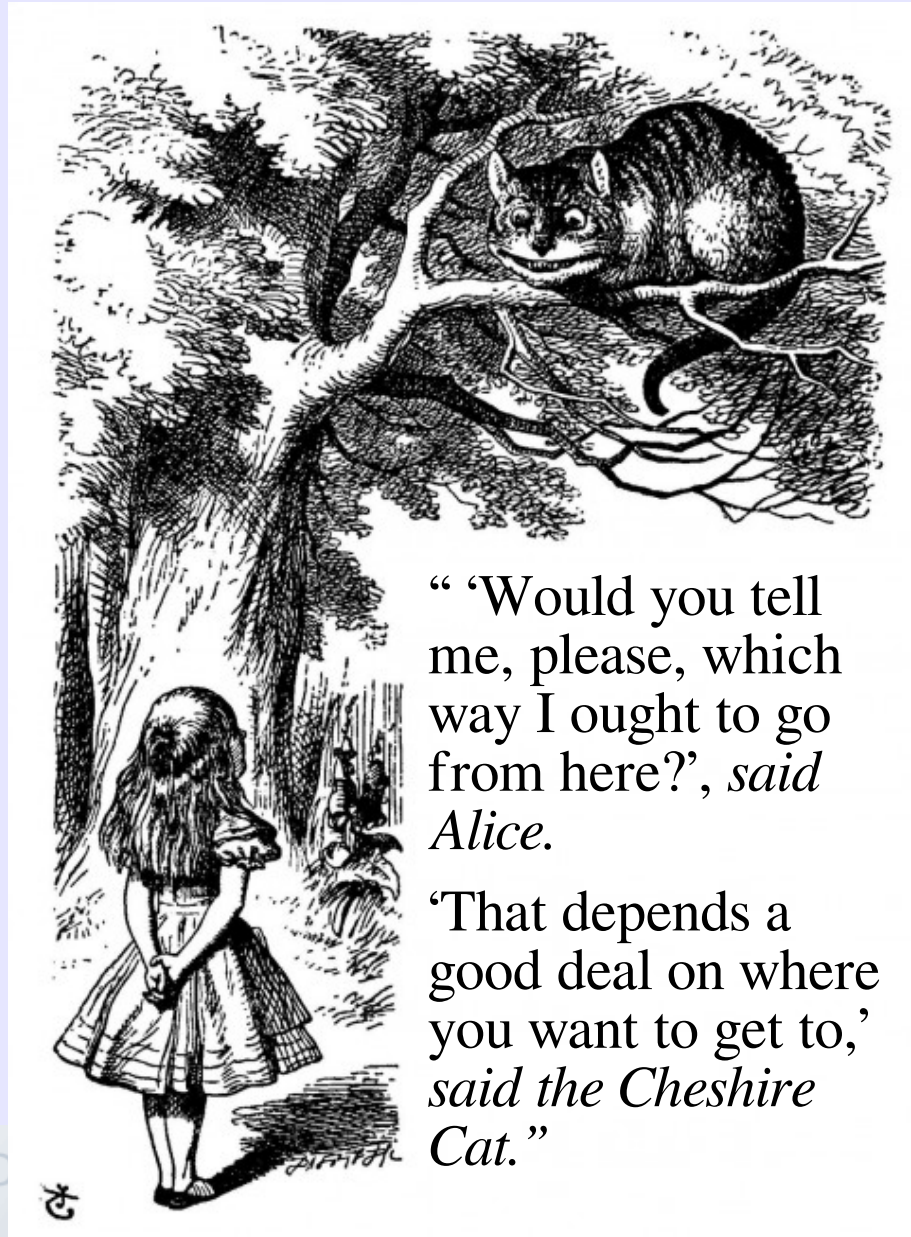


Understanding and Forecasting The Solar Origins of Space Weather

KD Leka

NorthWest Research Associates (NWRA)
“excellence in basic and applied research”

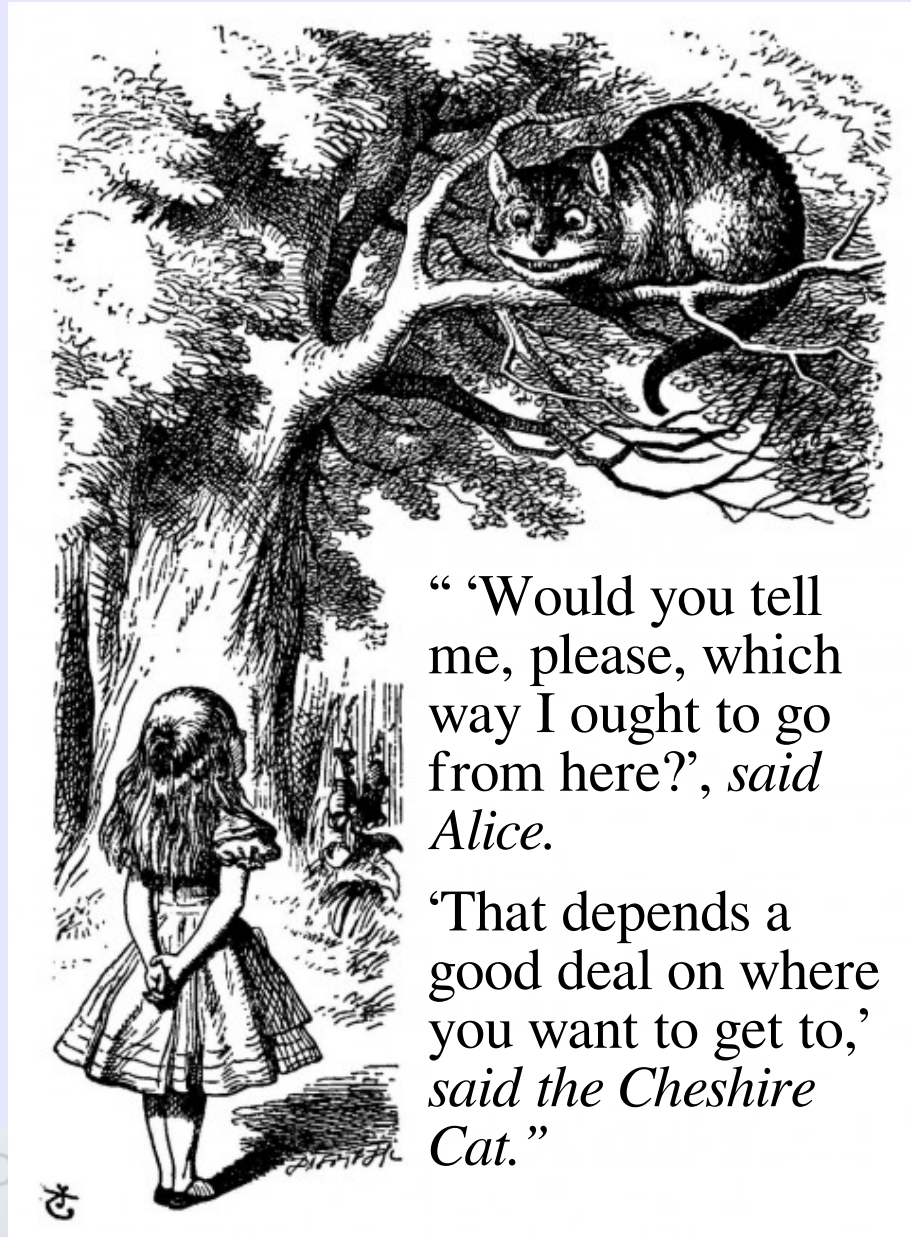
Understanding and Forecasting The Solar Origins of Space Weather



“ ‘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.*”

Understanding and Forecasting The Solar Origins of Space Weather



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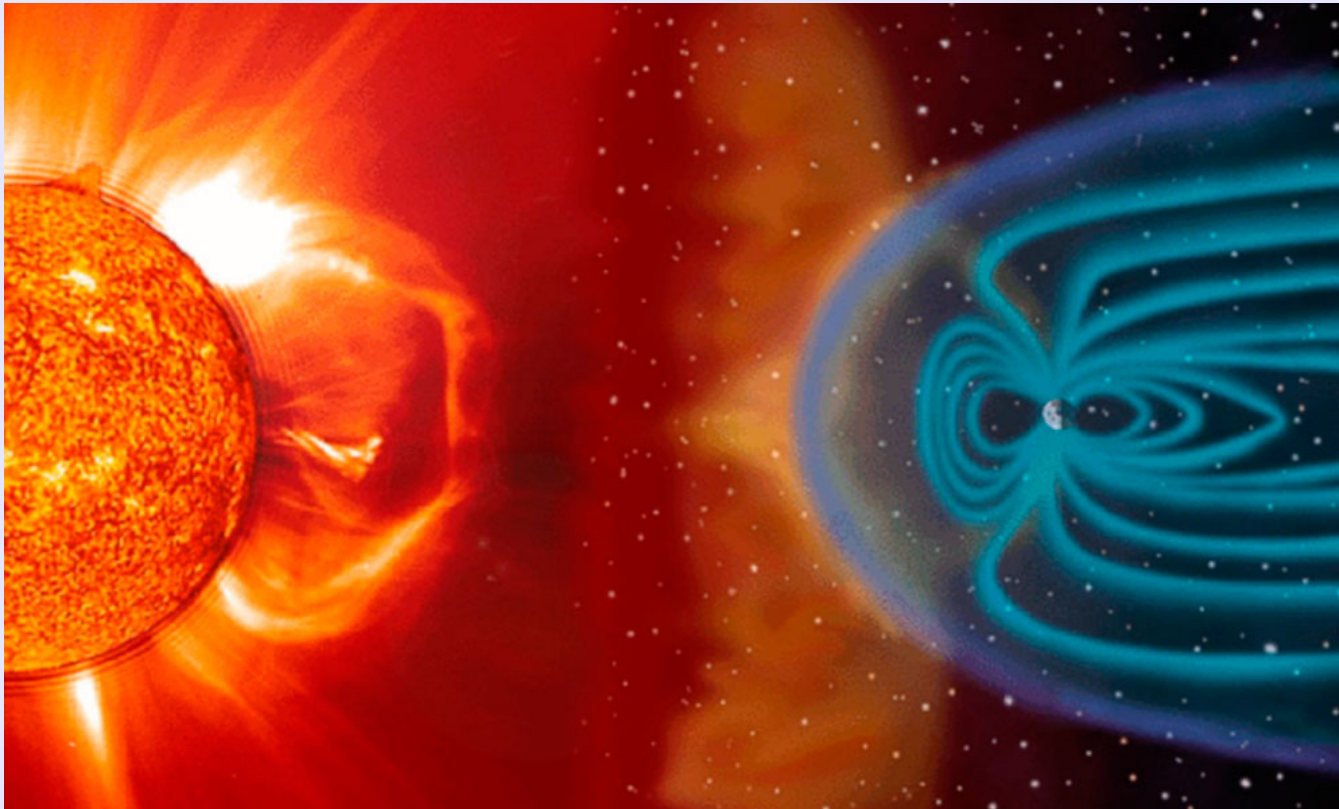
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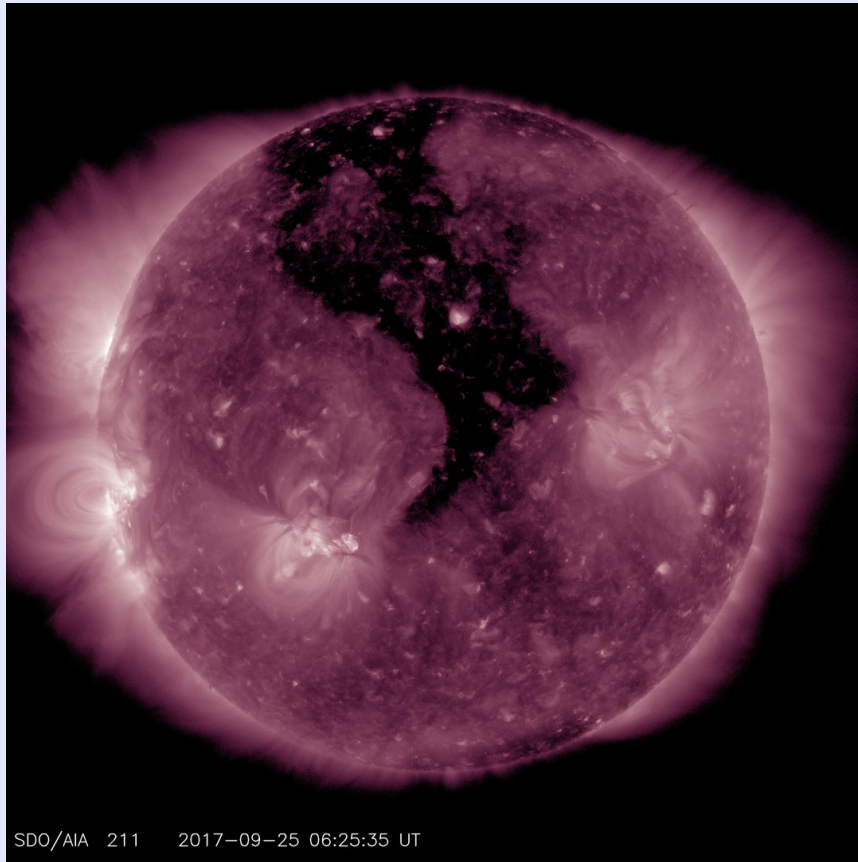
“Space Weather” is a term that covers *many* phenomena.

Focus on two:

- Origins of fast solar wind streams,
- Causes of solar energetic eruptions.
 - What is our basic understanding?
 - 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?



The Solar origins of space weather I: Hypothesis: "The high-speed solar wind streams that cause geomagnetic activity originate in solar coronal holes"



??
→



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 along general Parker spiral between coronal hole boundaries, through the heliosphere, to the timing of observed geomagnetic storms.

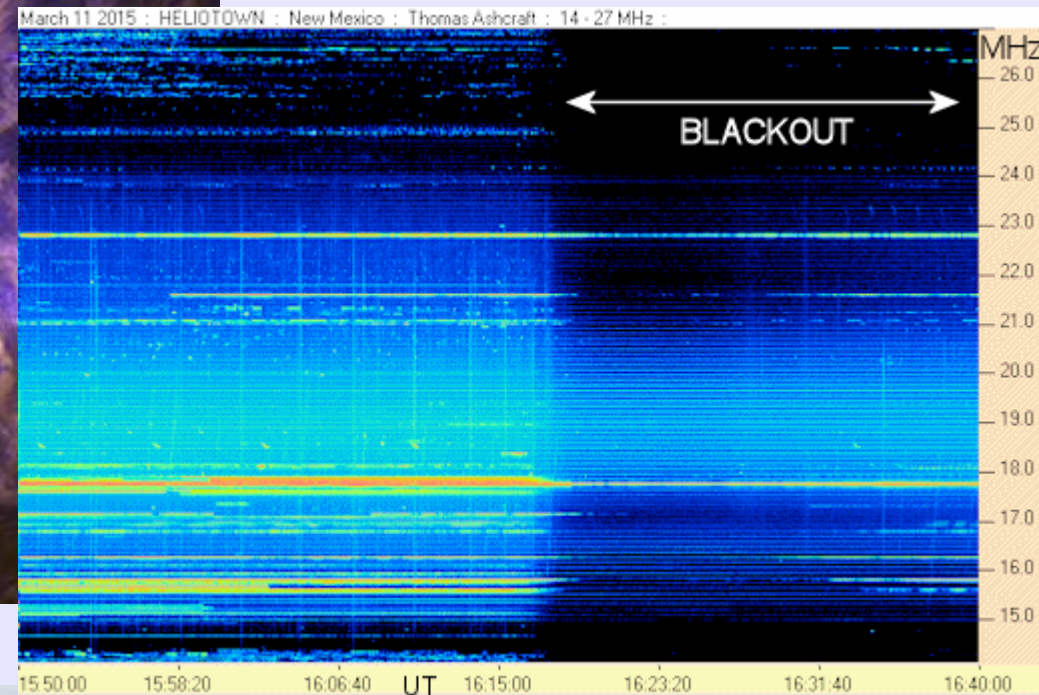
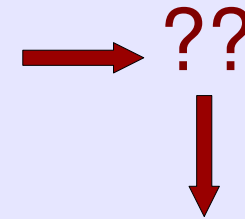
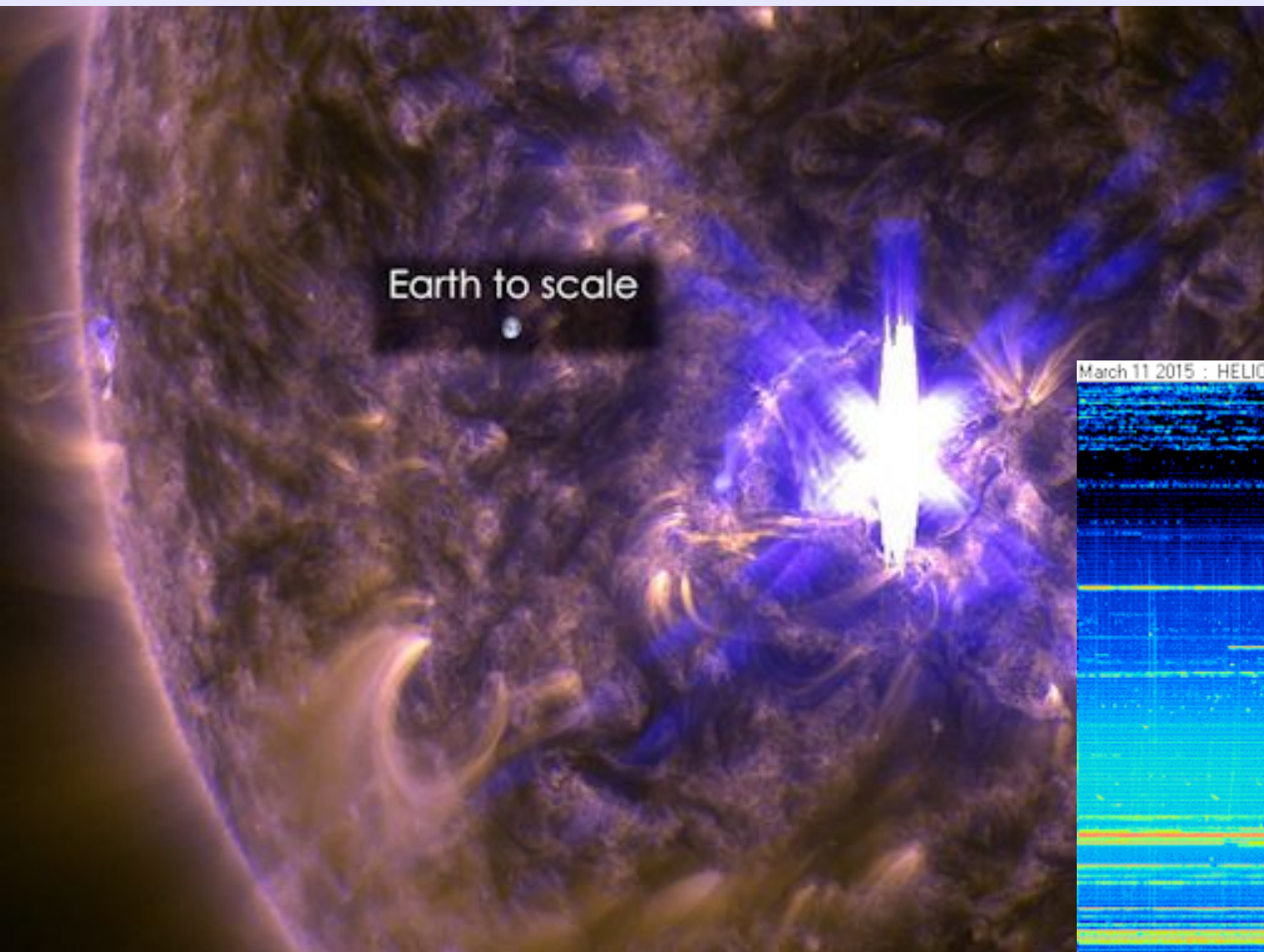
Model input: magnetic field is predominantly *open* in coronal holes, and solar wind speed inversely correlates with magnetic expansion factors.

Observations of dominant Doppler blue-shifts and broader line widths in coronal holes, through the lower corona – coupled with observed lower densities, allows for various acceleration options.

Answer: Solar origins of geo-effective high-speed streams are consistent with 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 energy stored in the solar corona."



The Solar origins of space weather II:

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

Correlation between occurrence of large flares and Earthly communications problems.

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

Model Input: Sudden influx of soft X-rays causes ionospheric scintillation; geomagnetic response to influx of charged plasma especially severe with southward-facing B_z and shock impacts.

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 energy stored in the solar corona.”

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

Observations of:

- H α “whirls” in chromospheres of flare-active sunspots
- Zeeman effect \rightarrow sunspots have strong magnetic fields
- Magnetic fields are “sheared” and “twisted” in flare-active sunspot groups
- Flares observed predominantly as chromospheric and coronal phenomena: H α brightenings, radio bursts, X-ray emission; coronal mass ejections tied to chromospheric and coronal ejecta.

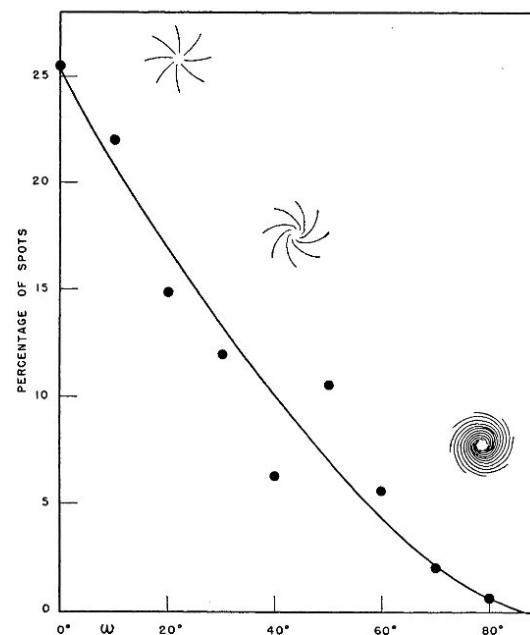
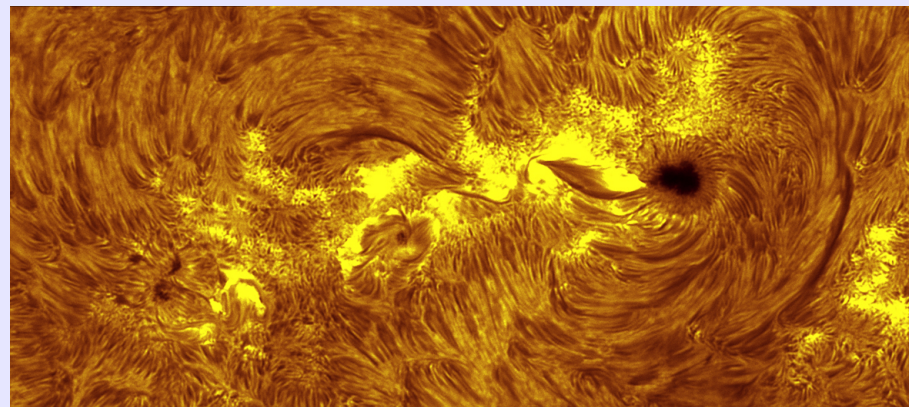


FIG. 1.—Frequency of various degrees of curvature in the hydrogen whirls surrounding 141 selected spots

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 energy stored in the solar corona.”

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

Estimates of:

- Energy needed for radiative, thermal, kinetic budgets for flares and associated CMEs, energetic particle acceleration
 - Energy sources available, timing possible to tap resources.
-
- ANSWER: Solar magnetic fields are only viable reservoir, magnetic reconnection in the chromosphere and/or corona is the only viable energy transfer mechanism.

How do we know what we know?

- Temperature / Density of solar plasma
 - Ratios of intensity from different spectral regions
 - Impacts on photons from non-solar sources
- Velocity of solar plasma
 - Doppler shifts of spectral lines (or parts of them)
 - Structure, rotation of the *inside* of the Sun too!
- 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.



How do we know what we know?

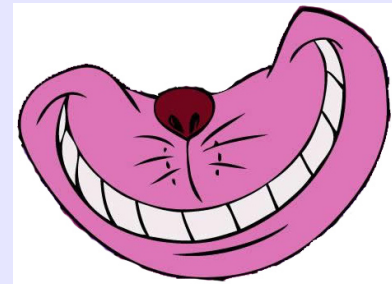
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All we have are photons...

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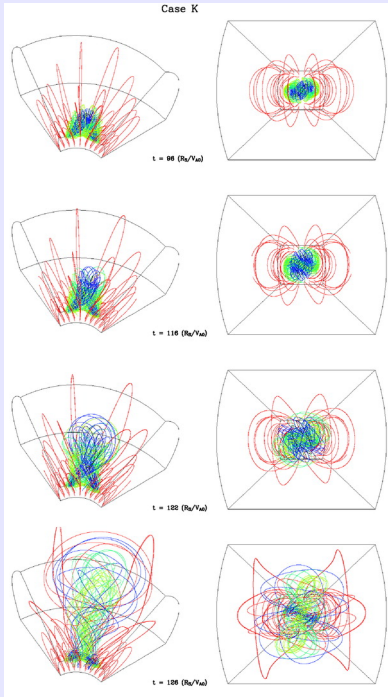
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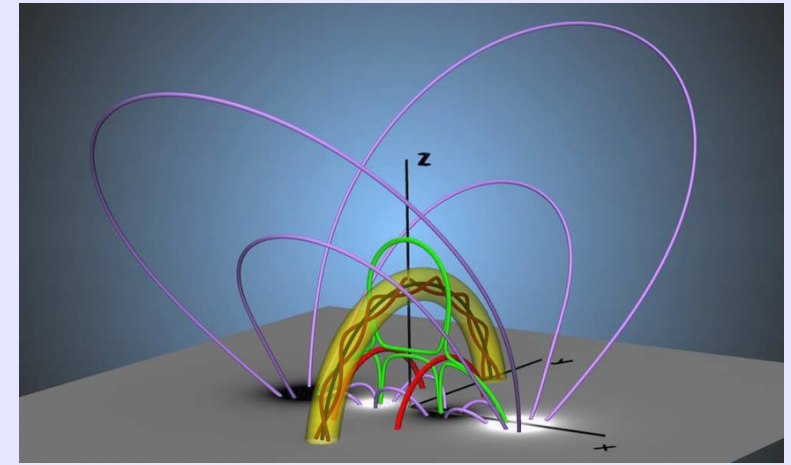
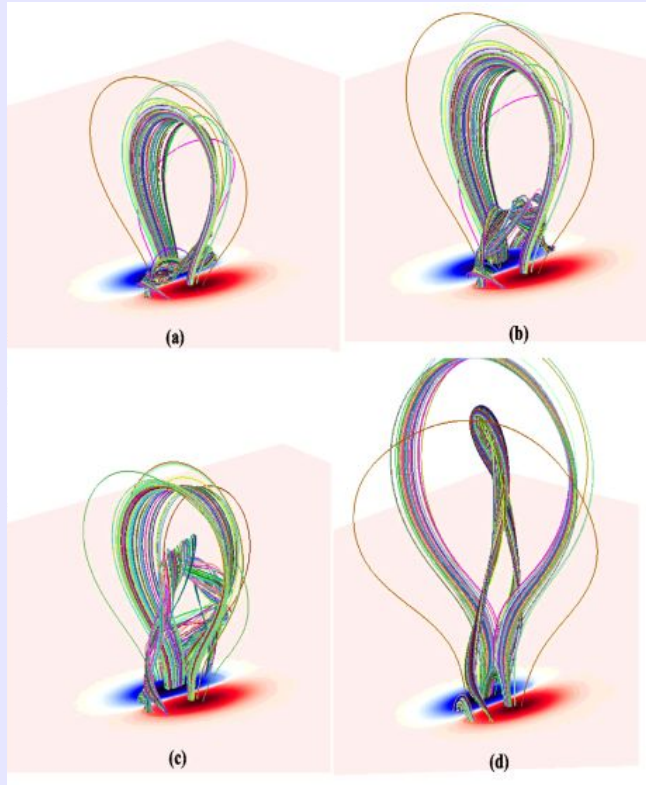


Complemented by models. Two broad categories:

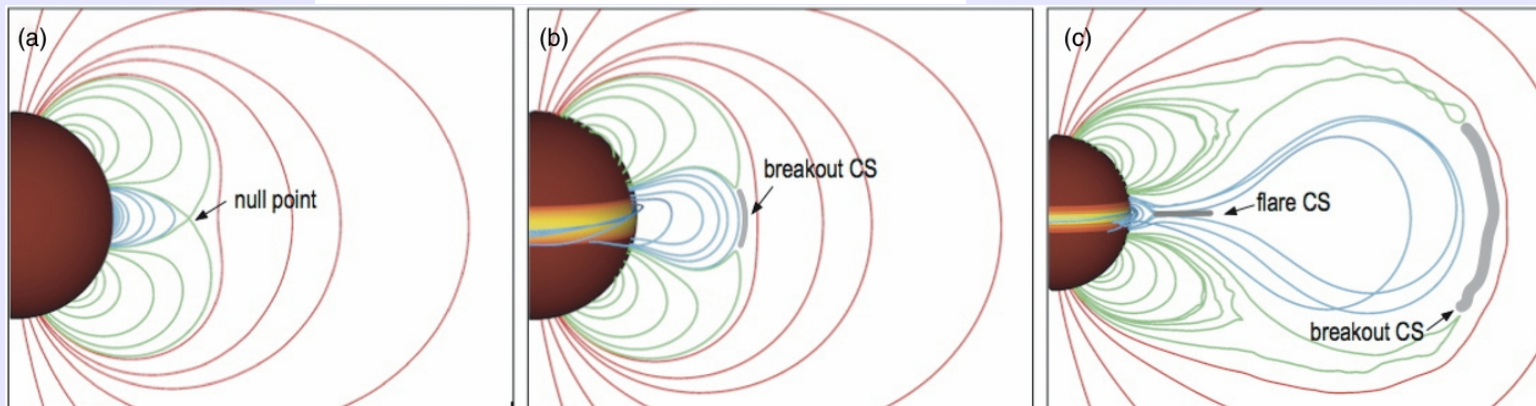
- I: Designed to explore and test proposed physical mechanisms.
 - May or may not incorporate observational data.



Fan & Gibson 2007



Demoulin & Aulanier 2014

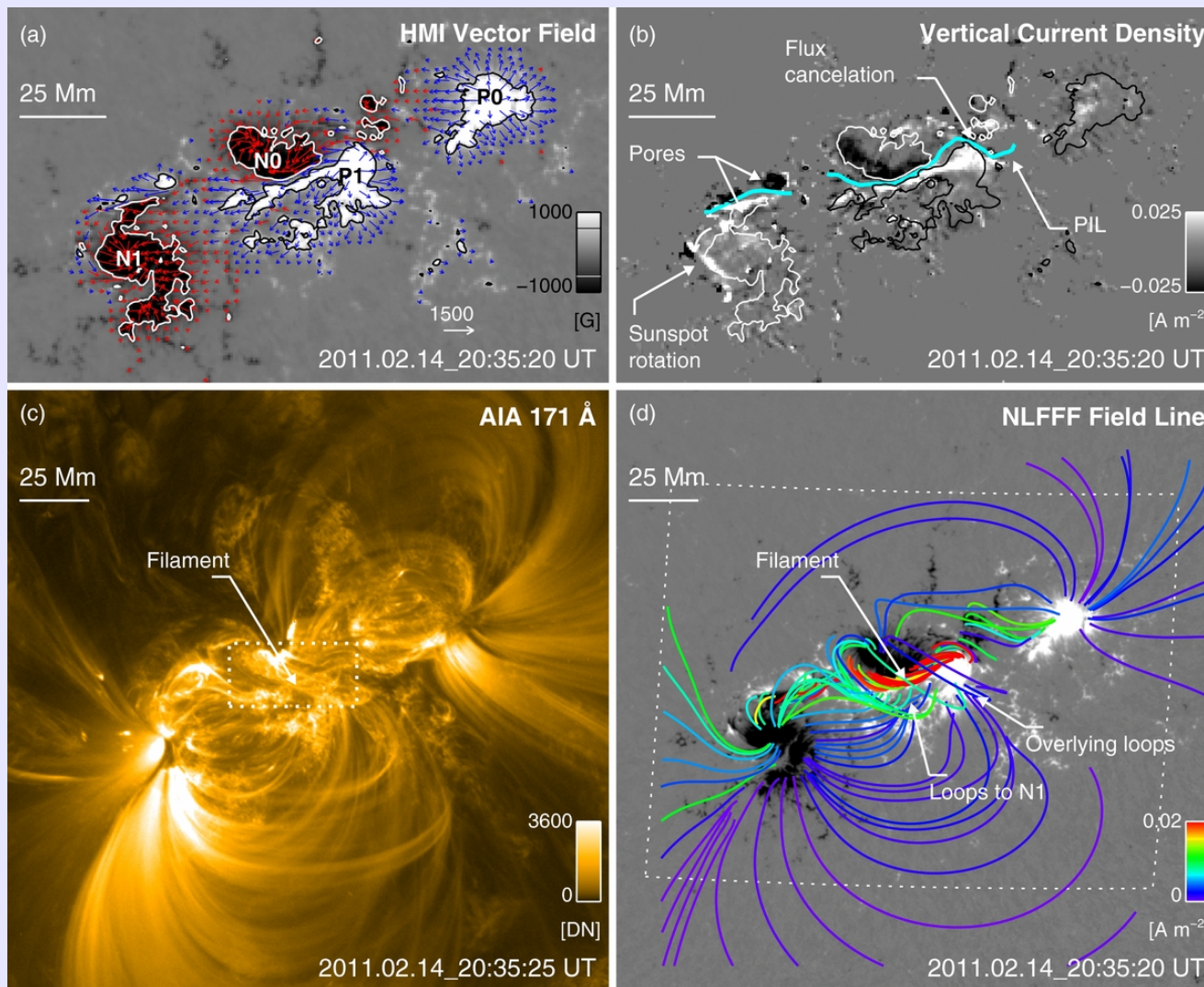


Karpen+2012

Complemented by models. Two broad categories:

- II: Designed to provide information on the unobservable.
 - Observational data plays a key role

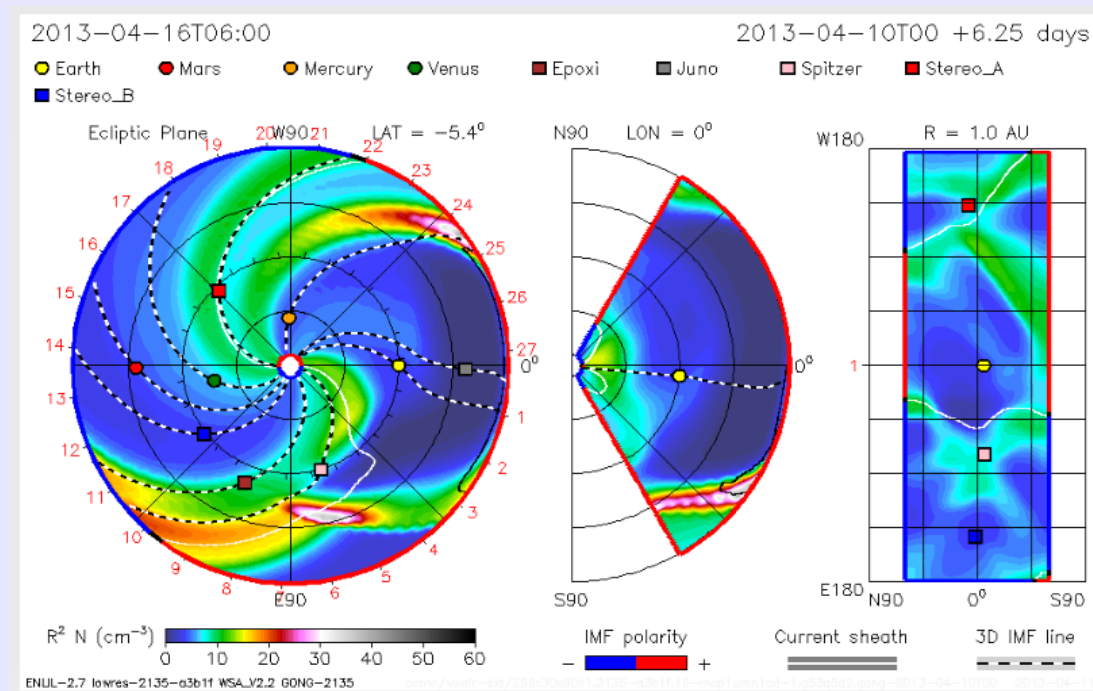
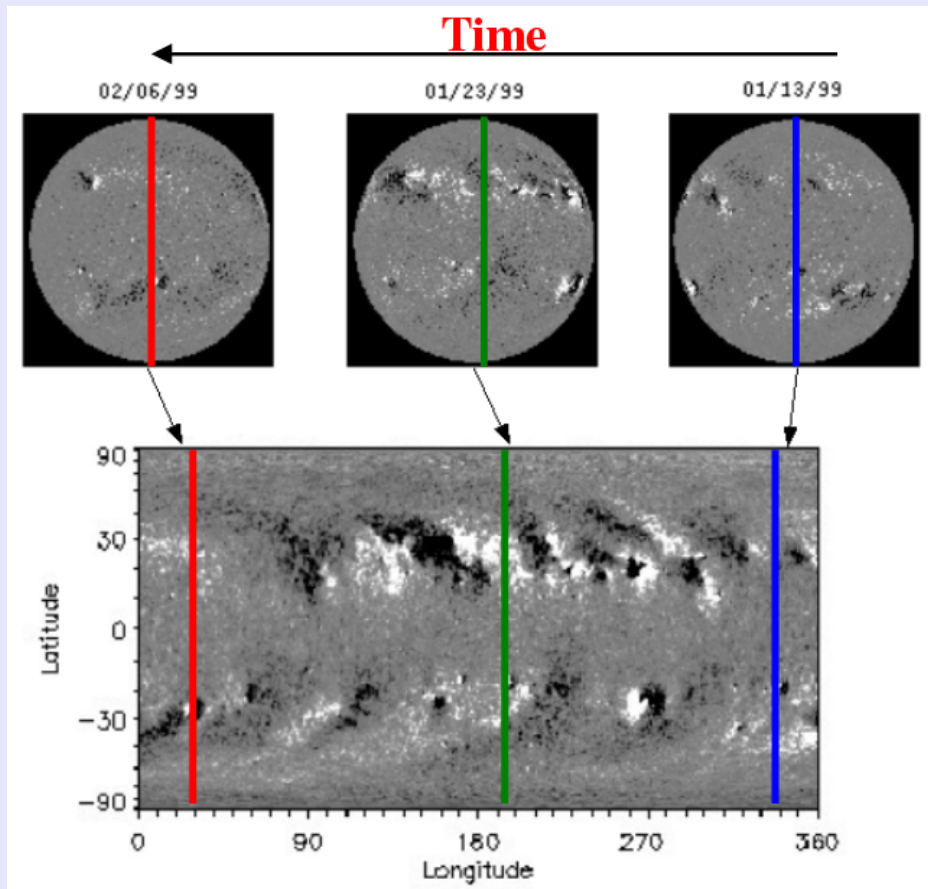
Non-Linear Force-Free Magnetic Field extrapolations use observed boundary vector field data (and sometimes coronal imaging data) to model the coronal magnetic field.



Complemented by models. Two broad categories:

- II: Designed to provide information on the unobservable.
 - Observational data plays a key role

Heliospheric models: use observed data as boundary to drive simulations of solar wind and CME propagation

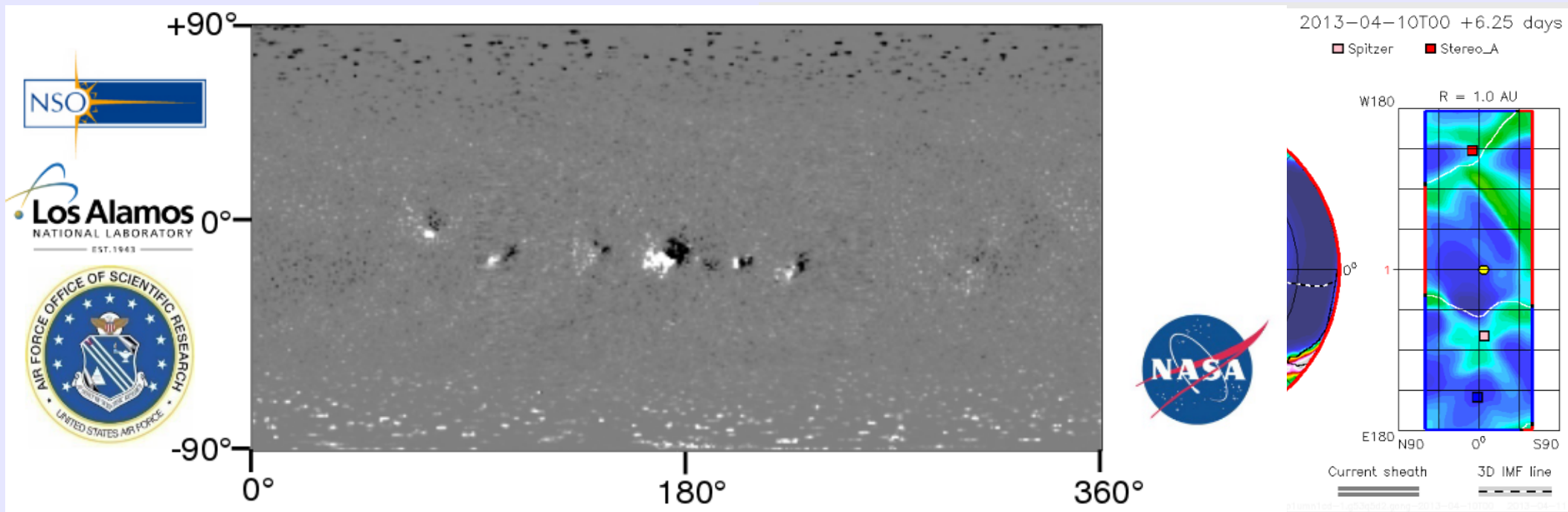


Shamelessly lifted from a talk by Nick Arge.

Complemented by models. Two broad categories:

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Heliospheric models: use observed data as boundary to drive simulations of solar wind and CME propagation



ADAPT data-assimilation and advection-based input map

So...

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

Forecasting the geomagnetic effects of solar phenomena is a piece of cake!.....right?

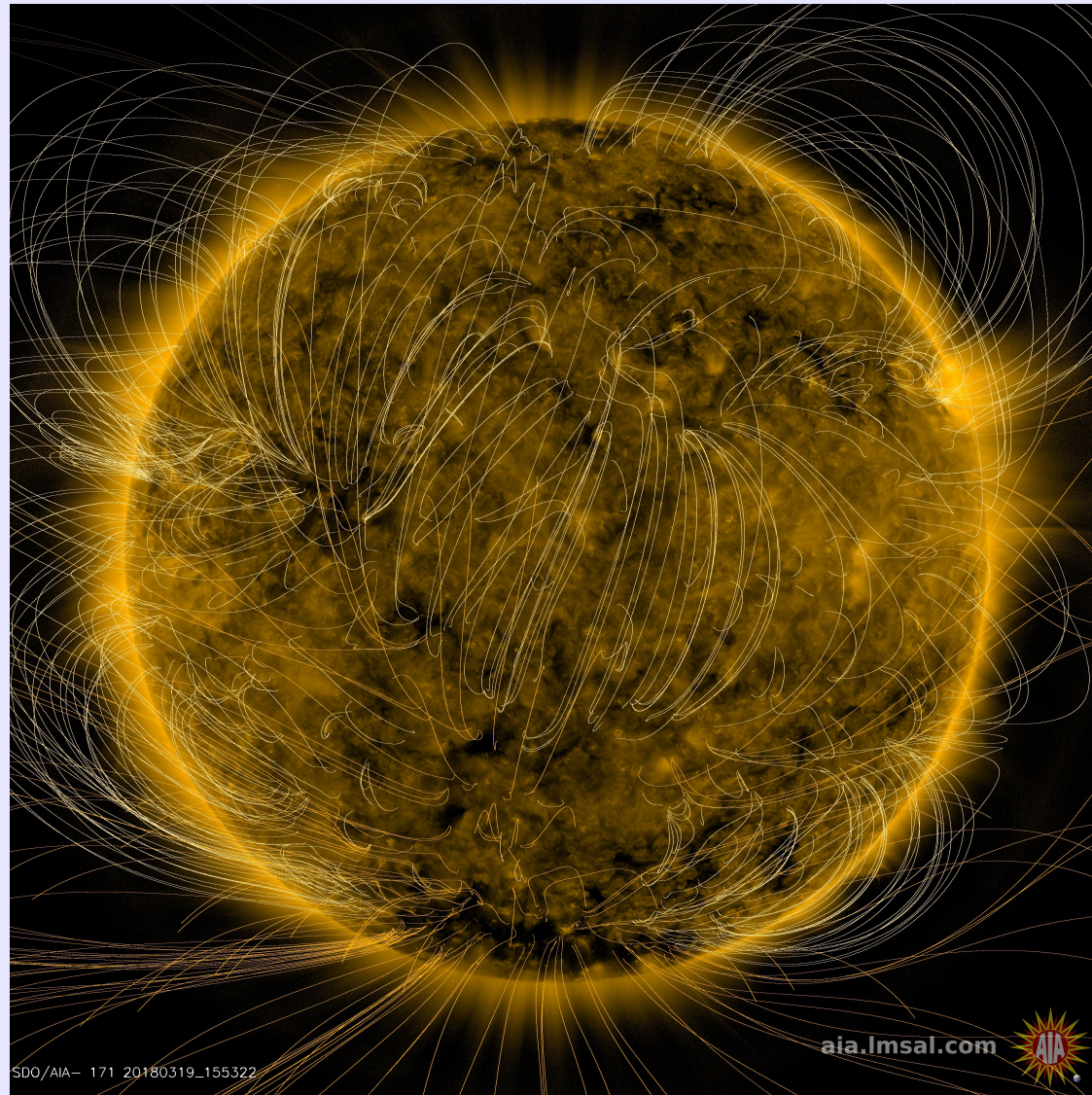
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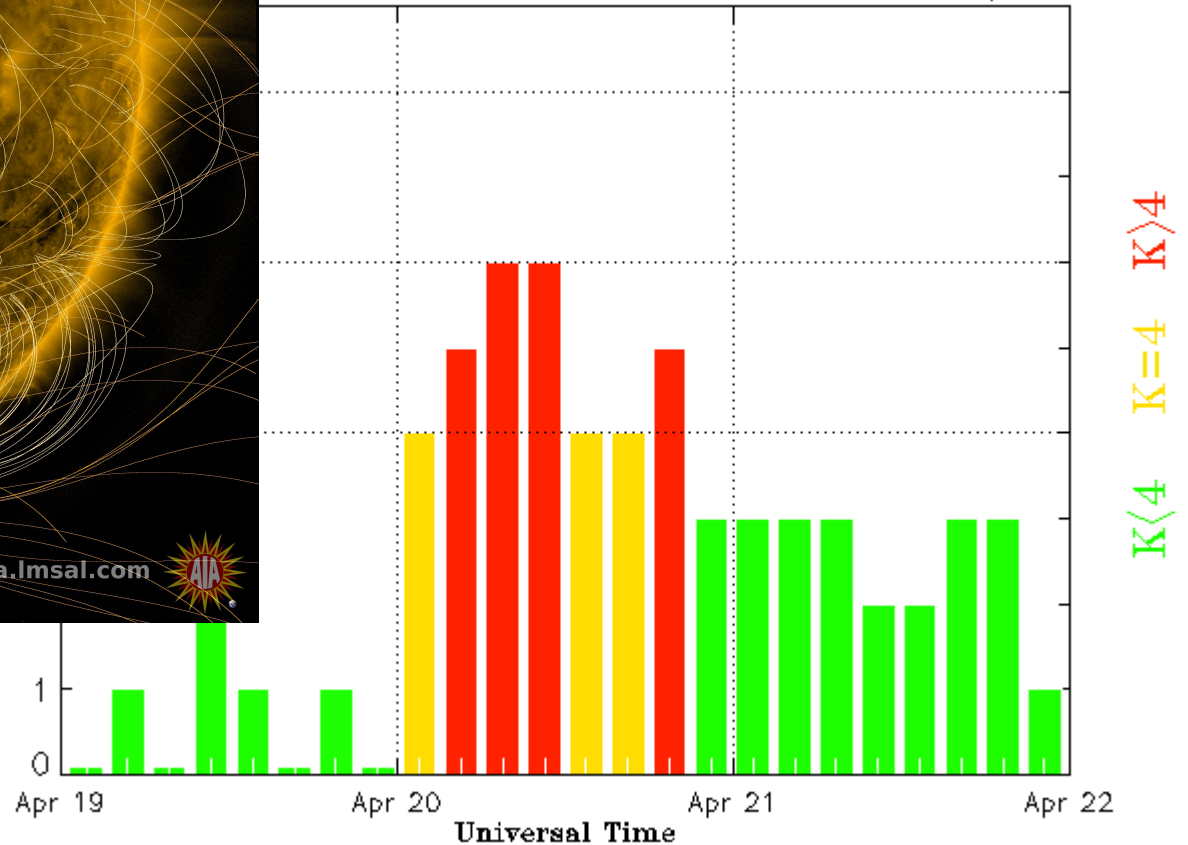
Forecasting the geomagnetic effects of solar phenomena is a piece of cake!.....right?



Yet....
 High-Speed Solar Wind streams
 can still come “out of nowhere”.



Stary K index (3 hour data) Begin: 2018 Apr 19 0000 UTC



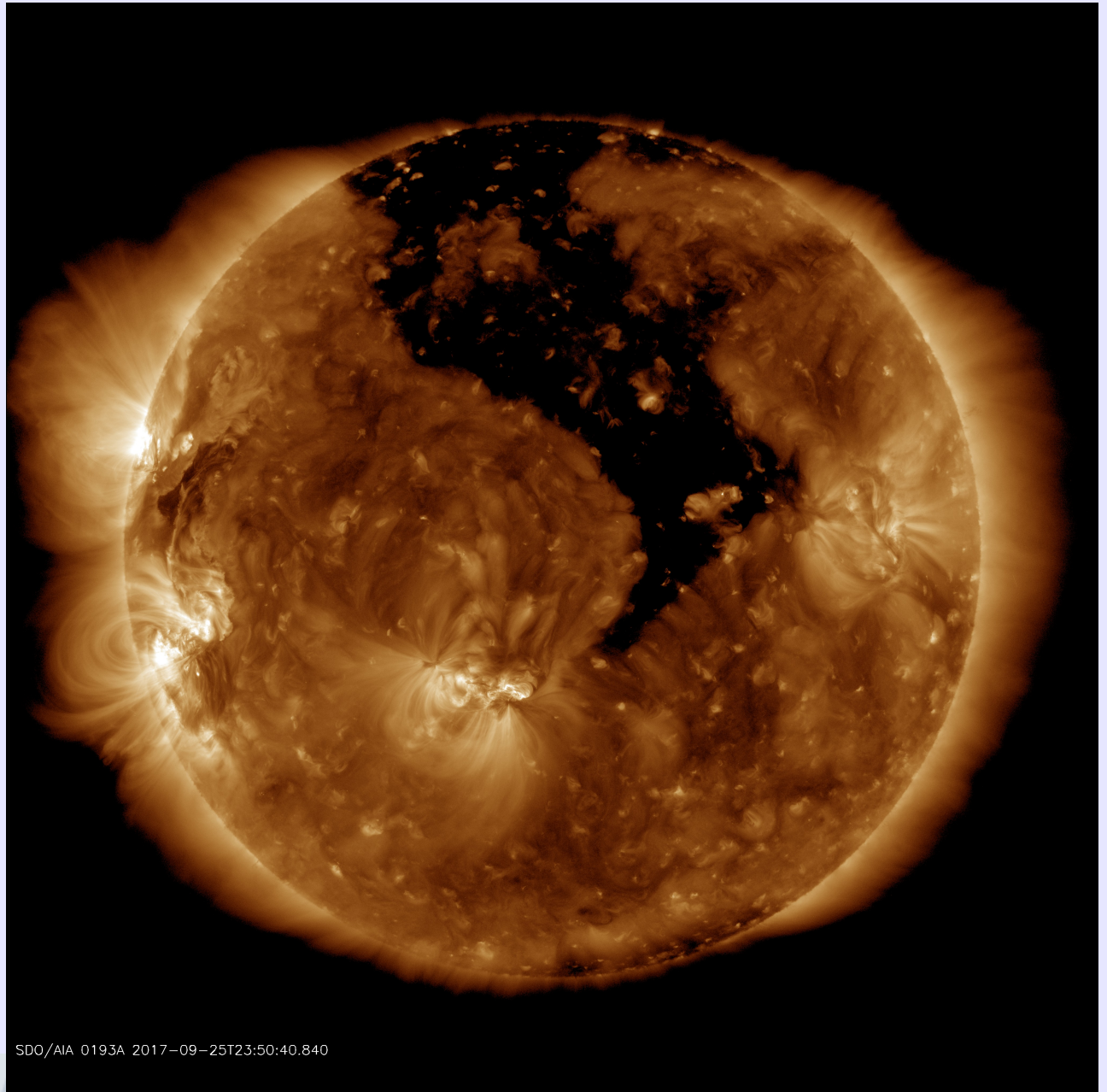
19-20 April 2018:
 No energetic events, no obvious
 coronal holes, no obvious anything,
except a G2-level storm.

Updated 2018 Apr 22 00:30:02 UTC

NOAA/SWPC Boulder, CO USA

Forecasting High-Speed Solar Wind Streams: some Challenges:

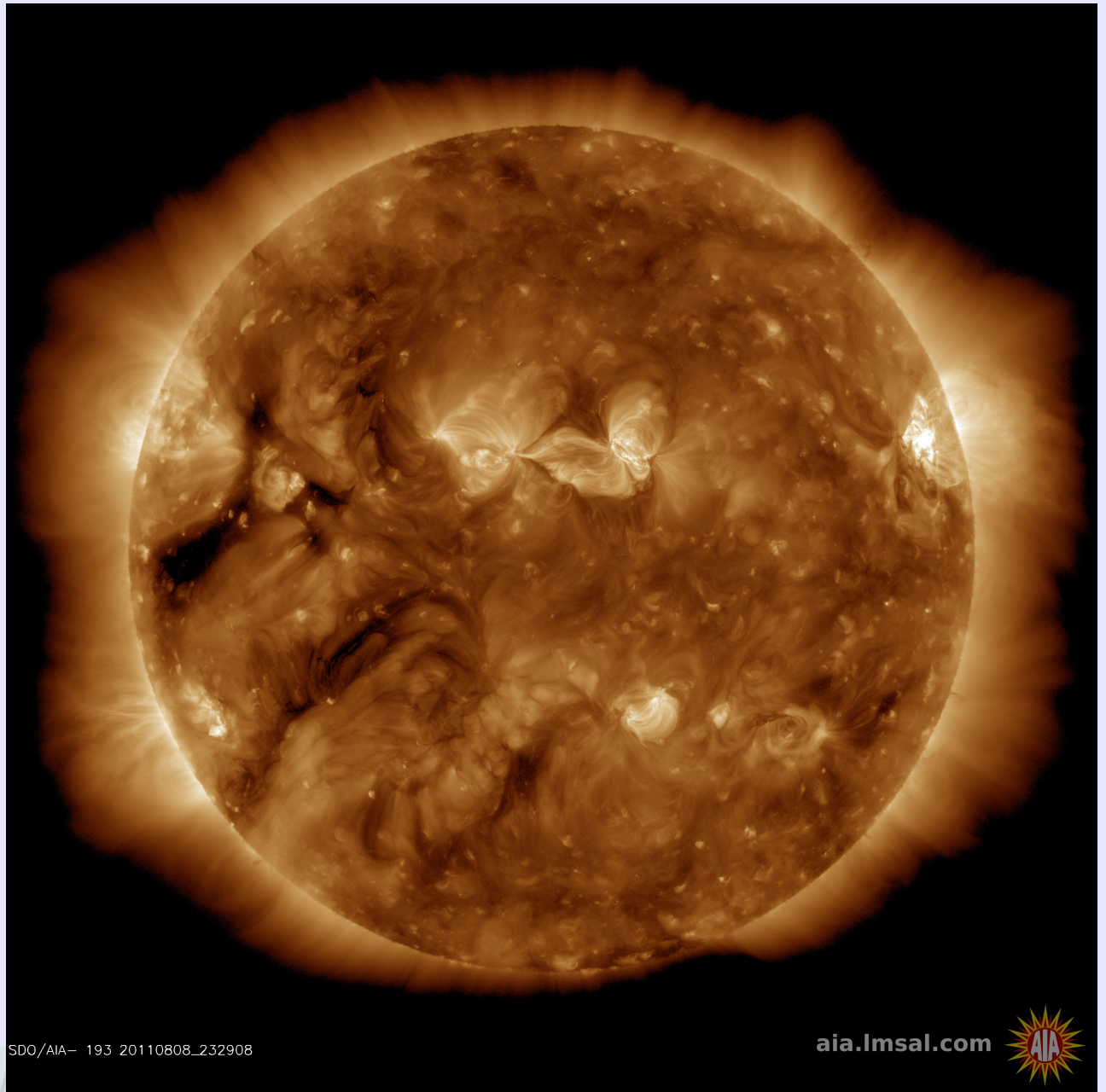
- Determining Coronal Hole boundaries
 - Sometimes the boundaries look clear.



SDO/AIA 0193A 2017-09-25T23:50:40.840

Forecasting High-Speed Solar Wind Streams: some Challenges:

- Determining Coronal Hole boundaries
 - Sometimes the boundaries look clear.
 - Sometimes less so.



SDO/AIA- 193 20110808_232908

aia.lmsal.com

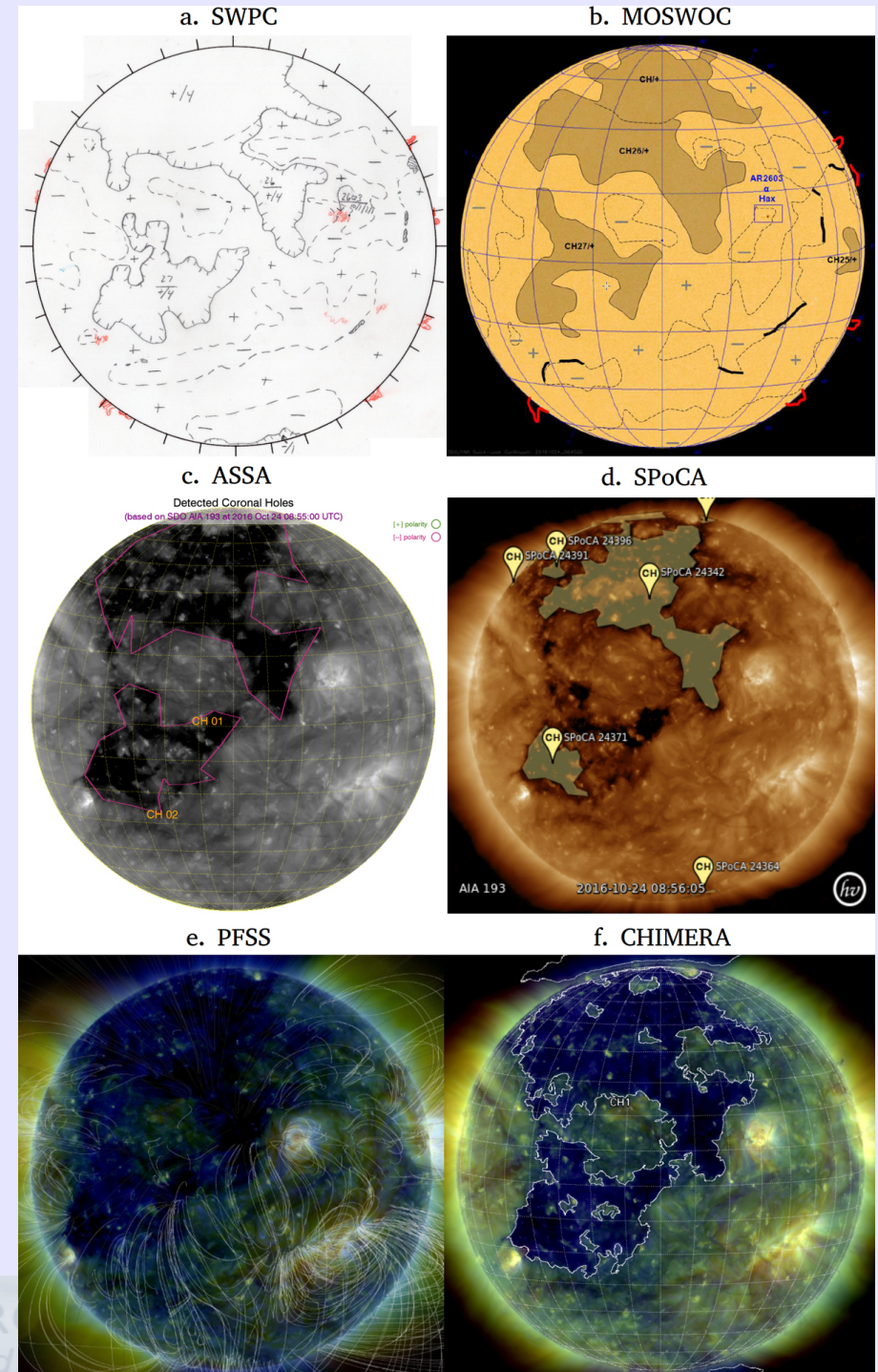


NORTHW

"unencumbered science"

Forecasting High-Speed Solar Wind Streams: some Challenges:

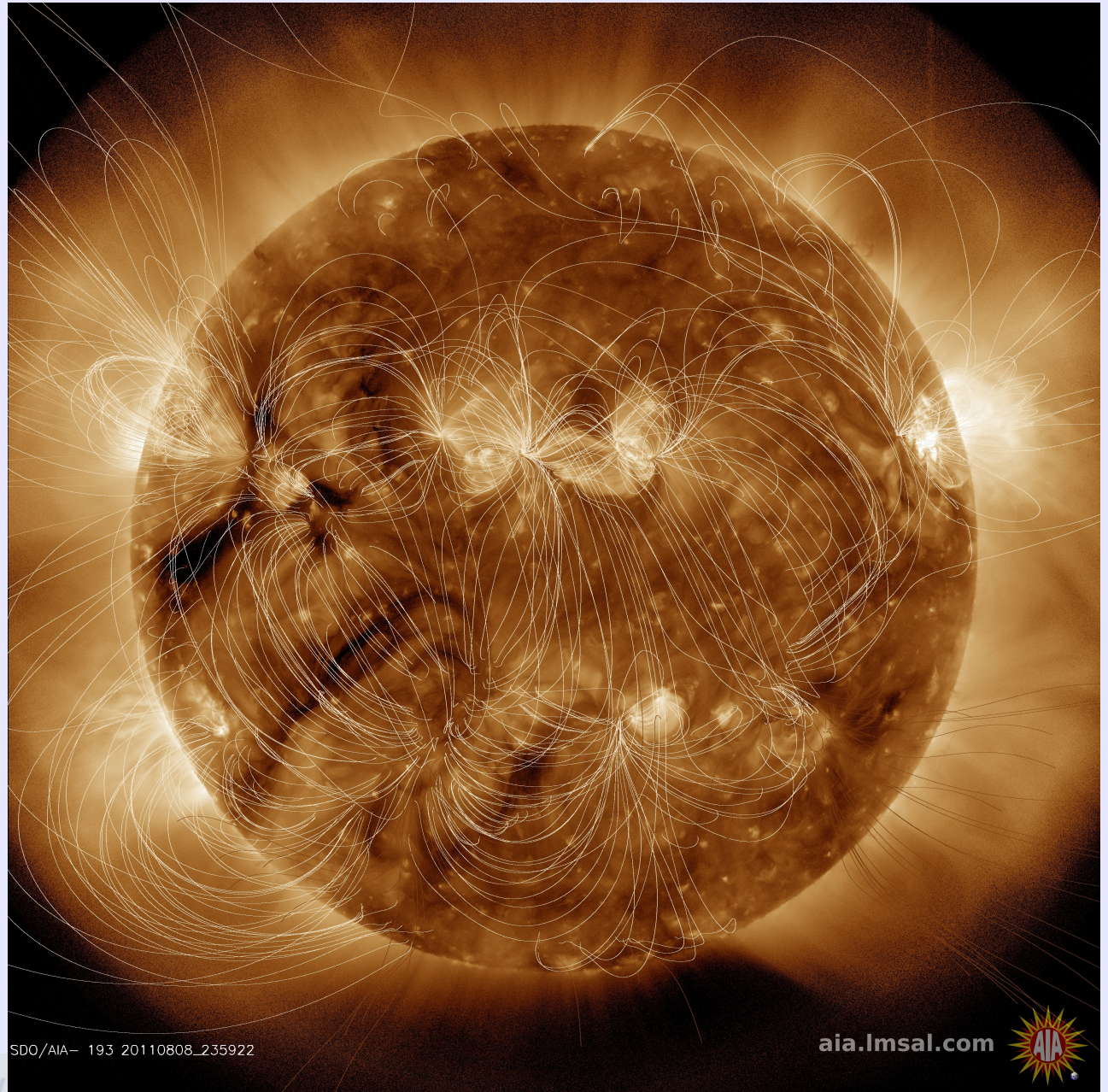
- Determining Coronal Hole boundaries
 - Sometimes the boundaries look clear.
 - Sometimes less so.
- Models and algorithms for automatic detection
 - How validate?



Forecasting High-Speed Solar Wind Streams: some Challenges:

- Determining Coronal Hole boundaries

- Sometimes the boundaries look clear.
- Sometimes less so.
- Models and algorithms for automatic detection
 - How validate?
- Where will plasma go?
 - Open field needed to enter the Heliosphere.
 - Cannot measure coronal magnetic field routinely, rely upon models.



SDO/AIA- 193 20110808_235922

Forecasting High-Speed Solar Wind Streams: some Challenges:

- Determining Coronal Hole boundaries

- Sometimes the boundaries look clear.
- Sometimes less so.

- Models and algorithms for automatic detection

- How validate?

- Where will plasma go?

- Open field needed to enter the Heliosphere.
- Cannot measure coronal magnetic field routinely, rely upon models.
- Even simplest models can imply very complex topologies, possibly impacting where/when the plasma can emerge.

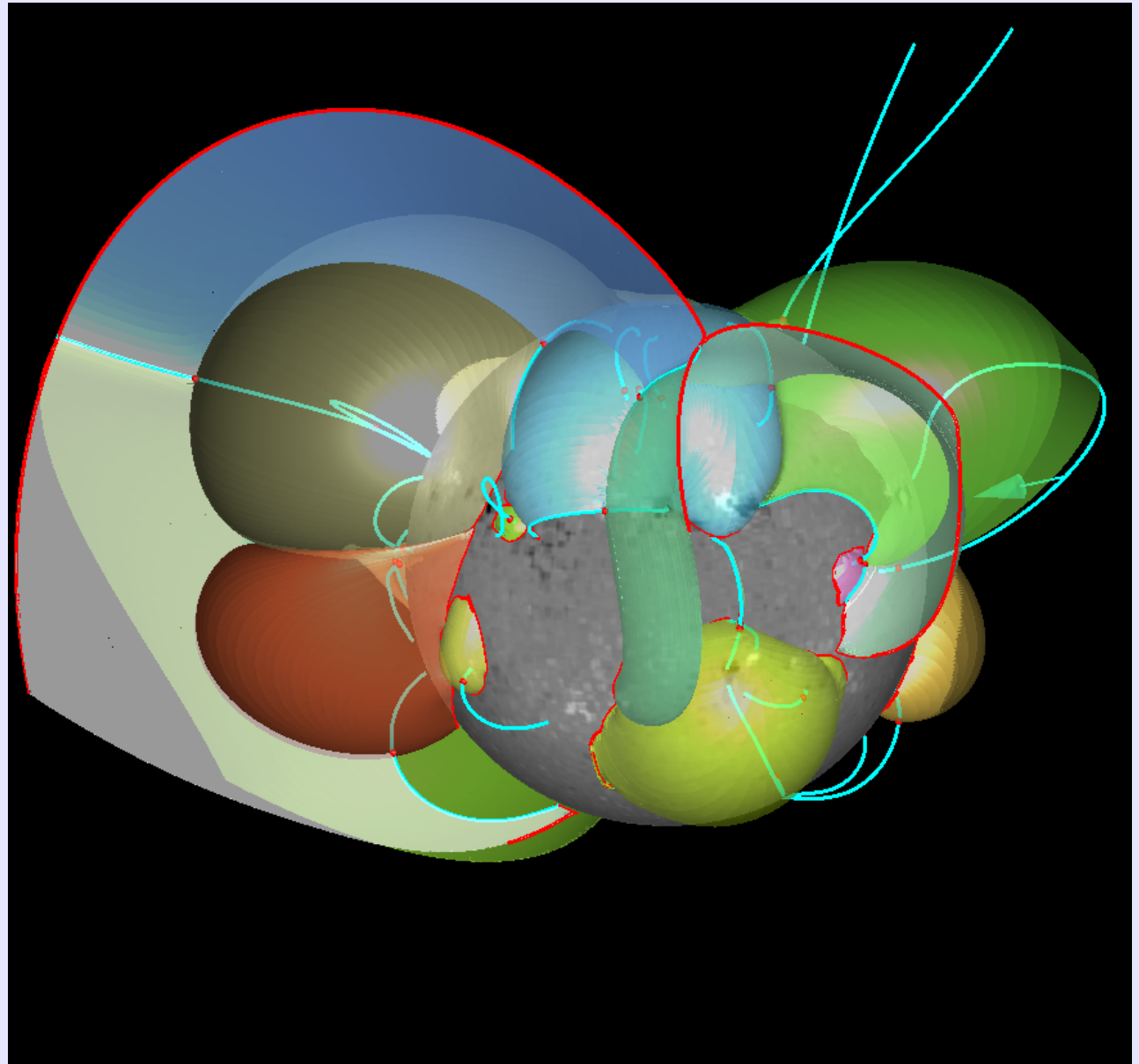
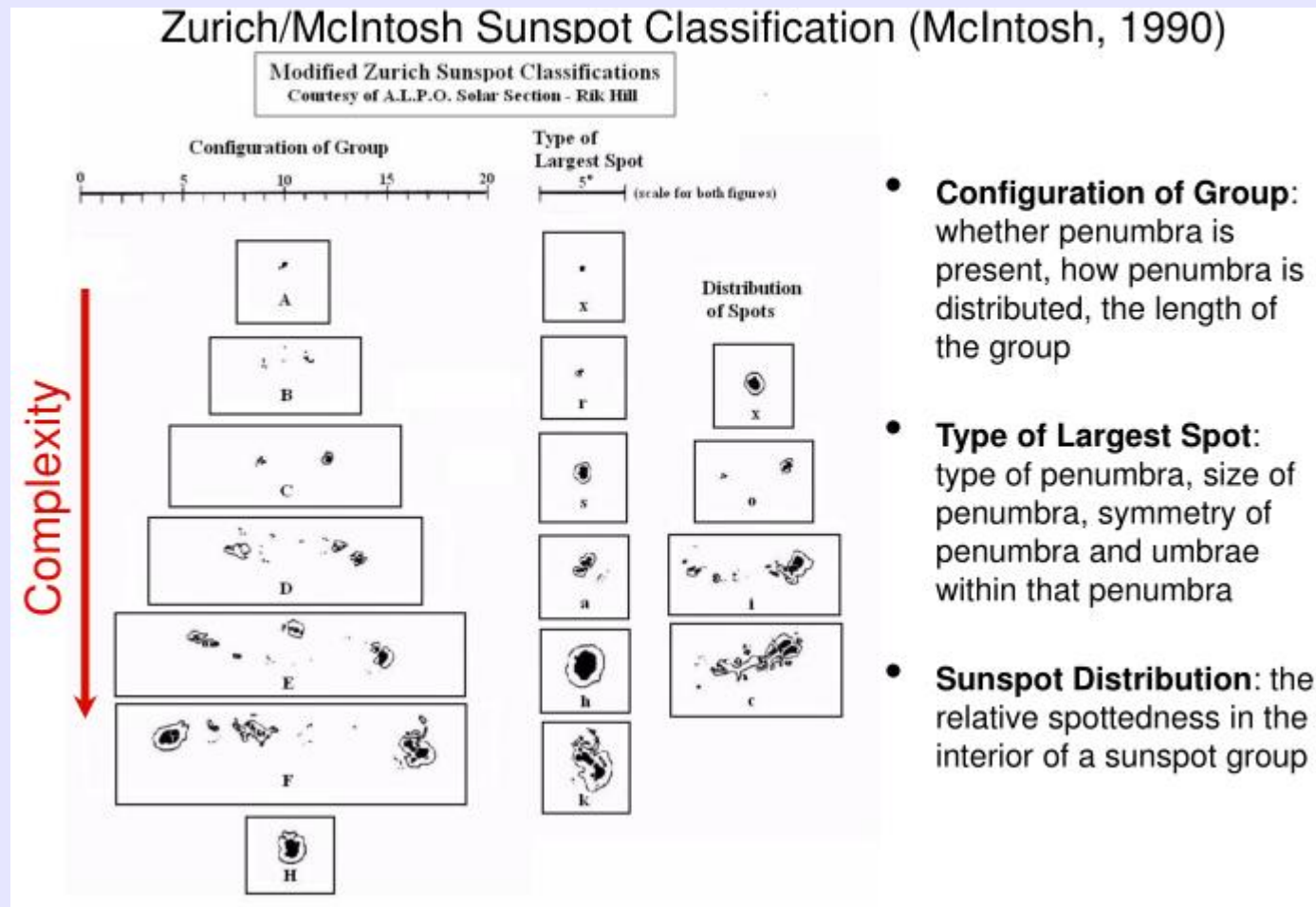


Image courtesy DeRosa & Barnes 2018

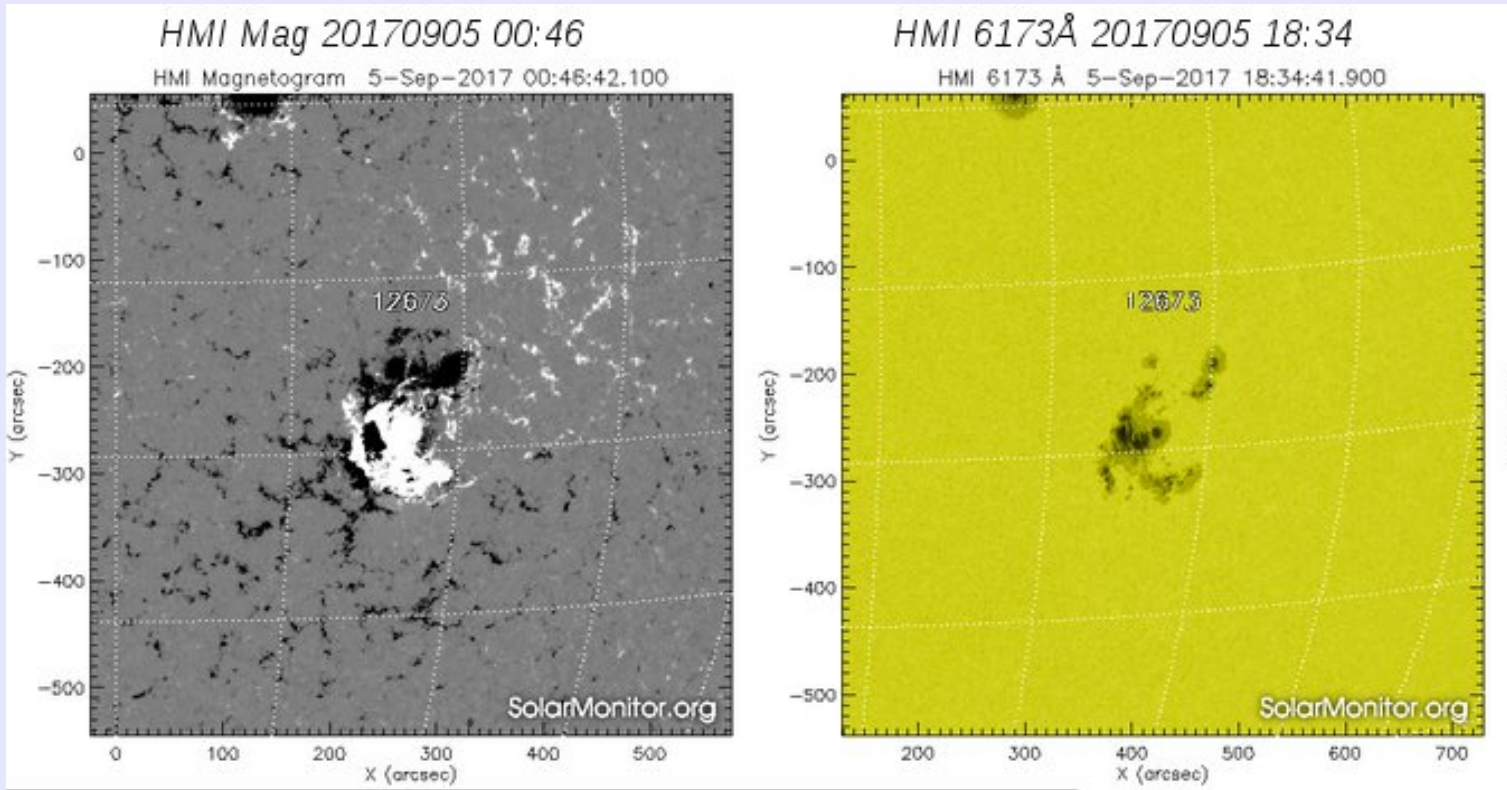
- Present basic Flare / CME paradigm:
 - Flares occur in active regions (sunspot groups) whose spots are complex and whose magnetic fields are twisted or show azimuthal “shear” along strong “Polarity Inversion Lines”.
 - Coronal Mass Ejections and particle acceleration events occur with large solar flares.



- **Configuration of Group:** whether penumbra is present, how penumbra is distributed, the length of the group
- **Type of Largest Spot:** type of penumbra, size of penumbra, symmetry of penumbra and umbrae within that penumbra
- **Sunspot Distribution:** the relative spottedness in the interior of a sunspot group

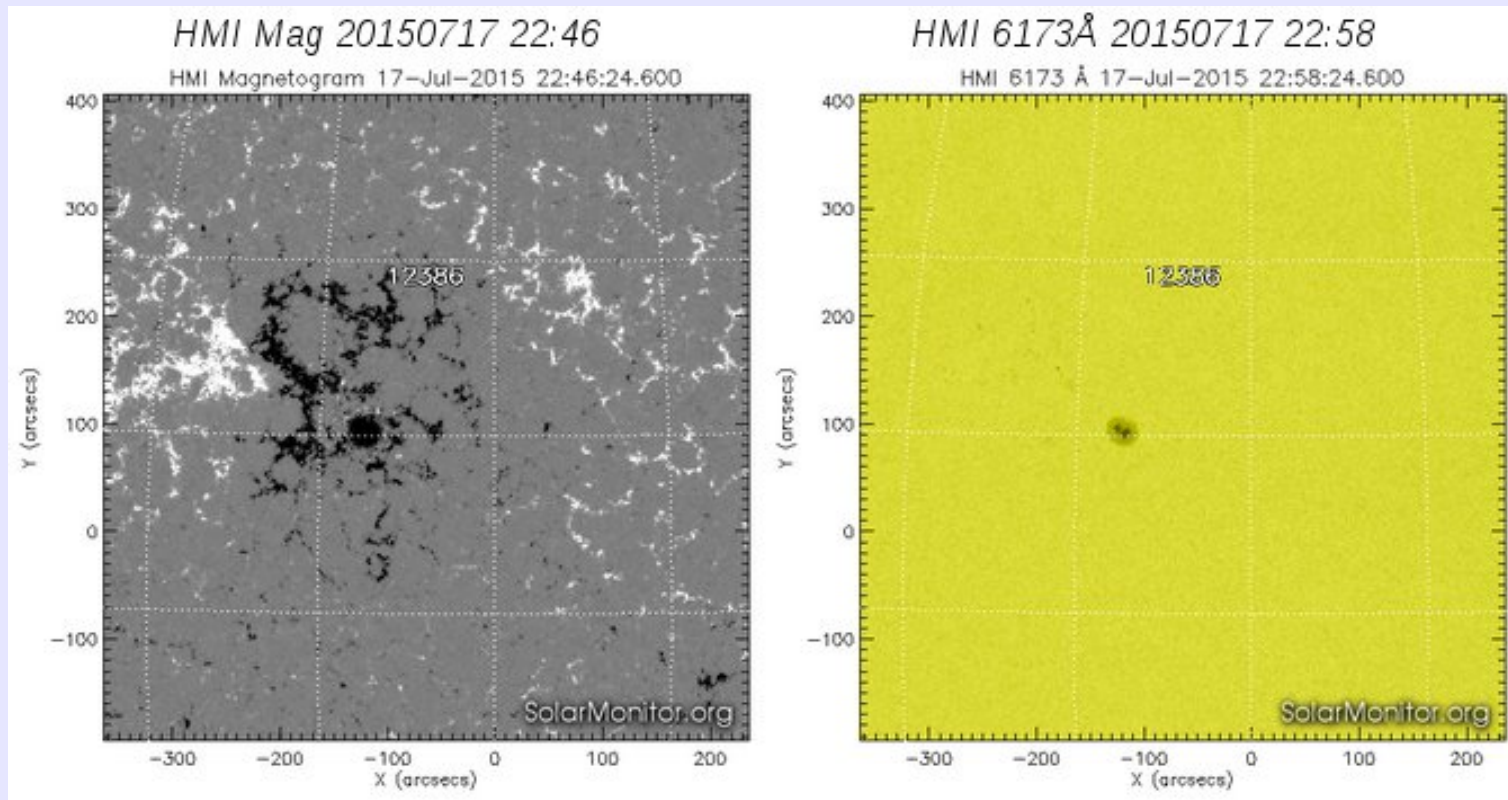
Forecasting solar flares and Coronal Mass Ejections: Some Challenges:

- The extremes are “almost” easy:



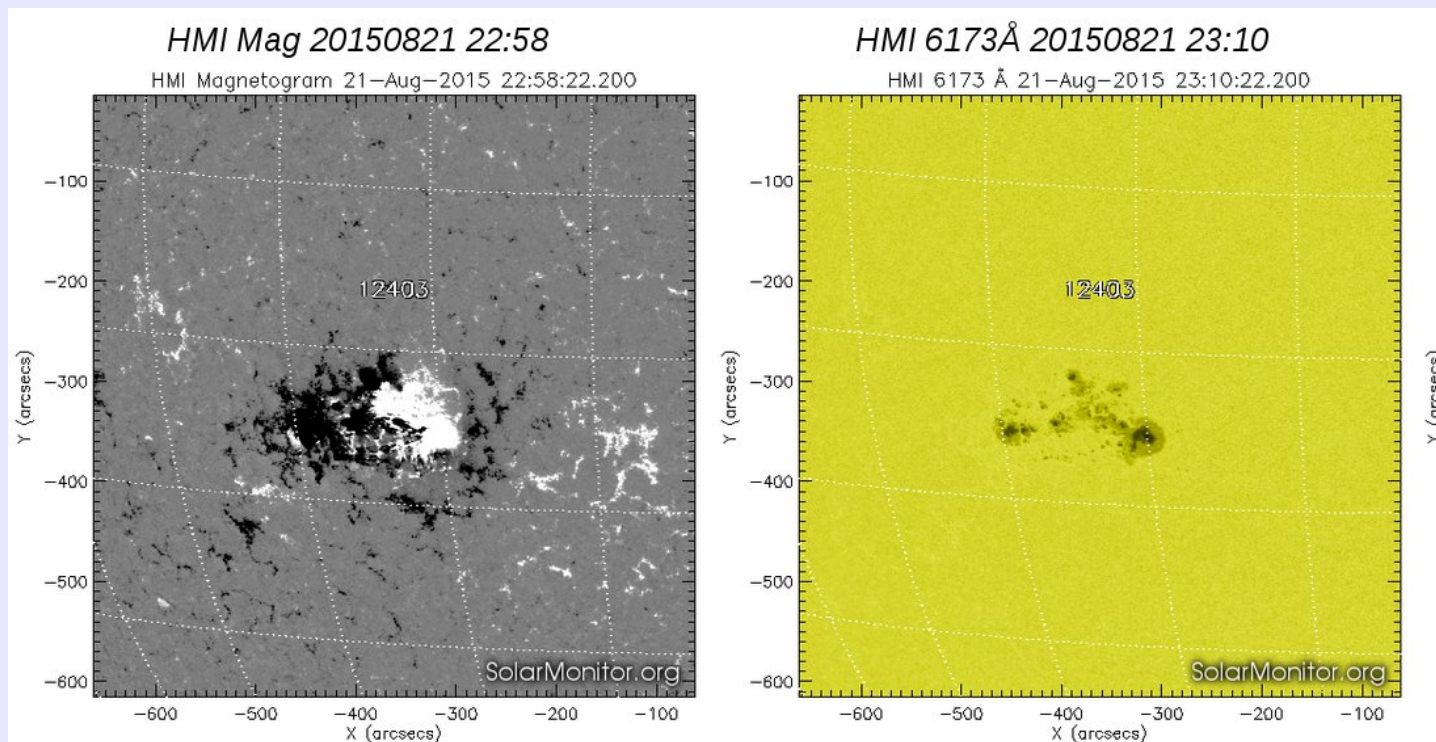
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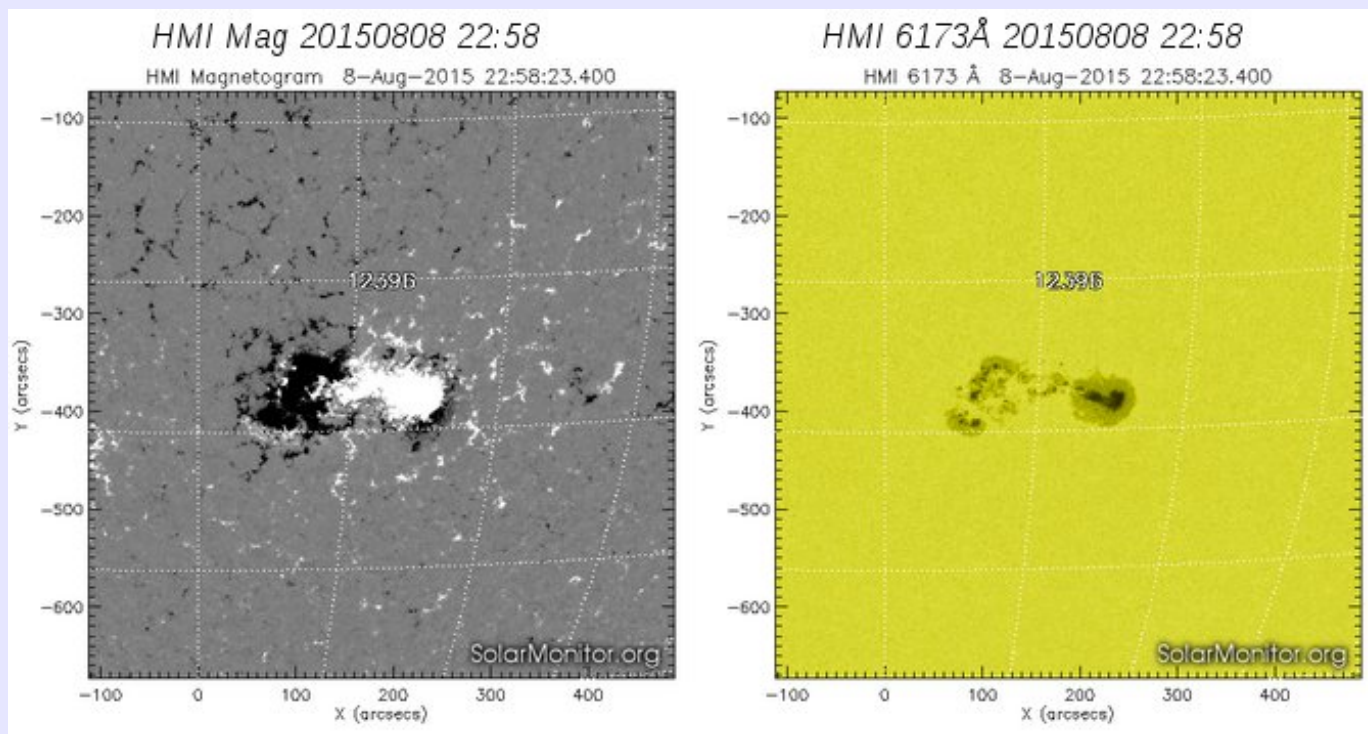
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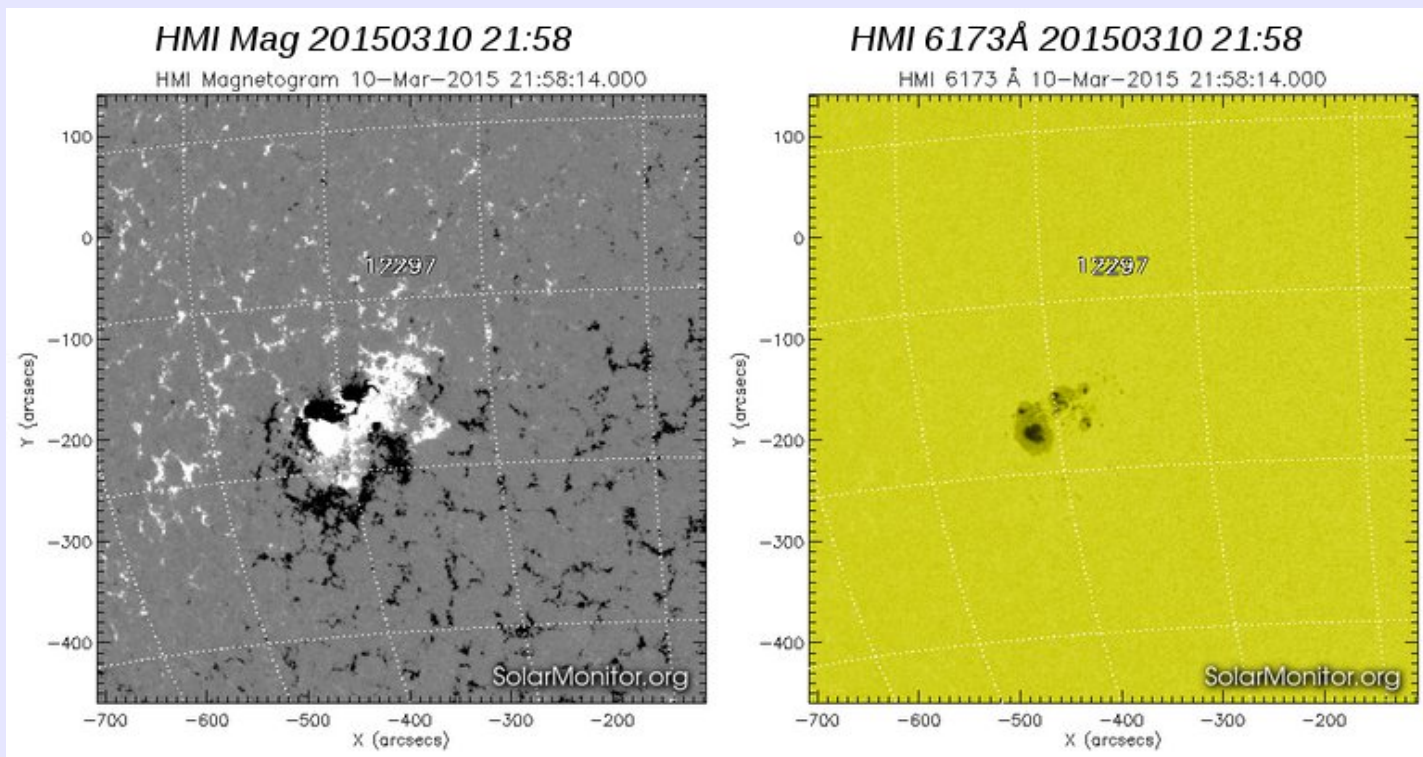
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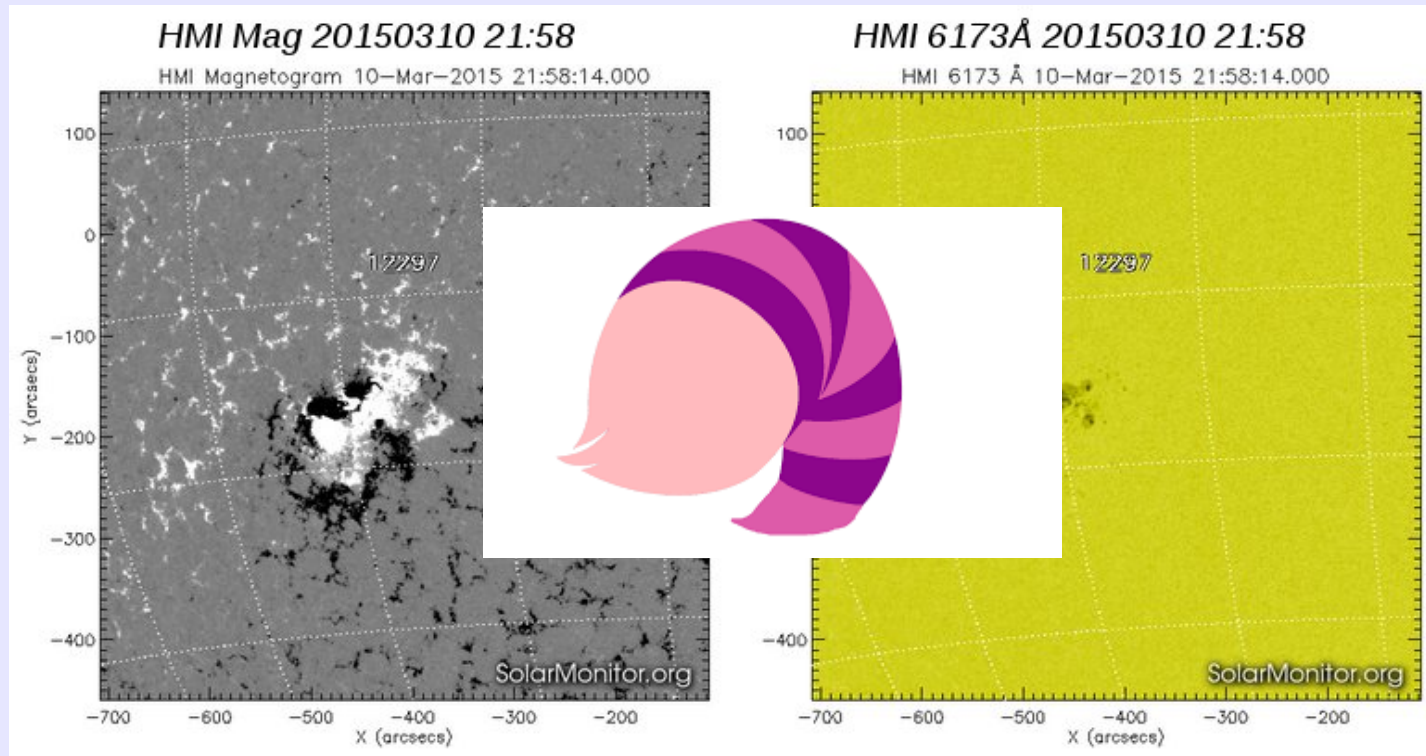
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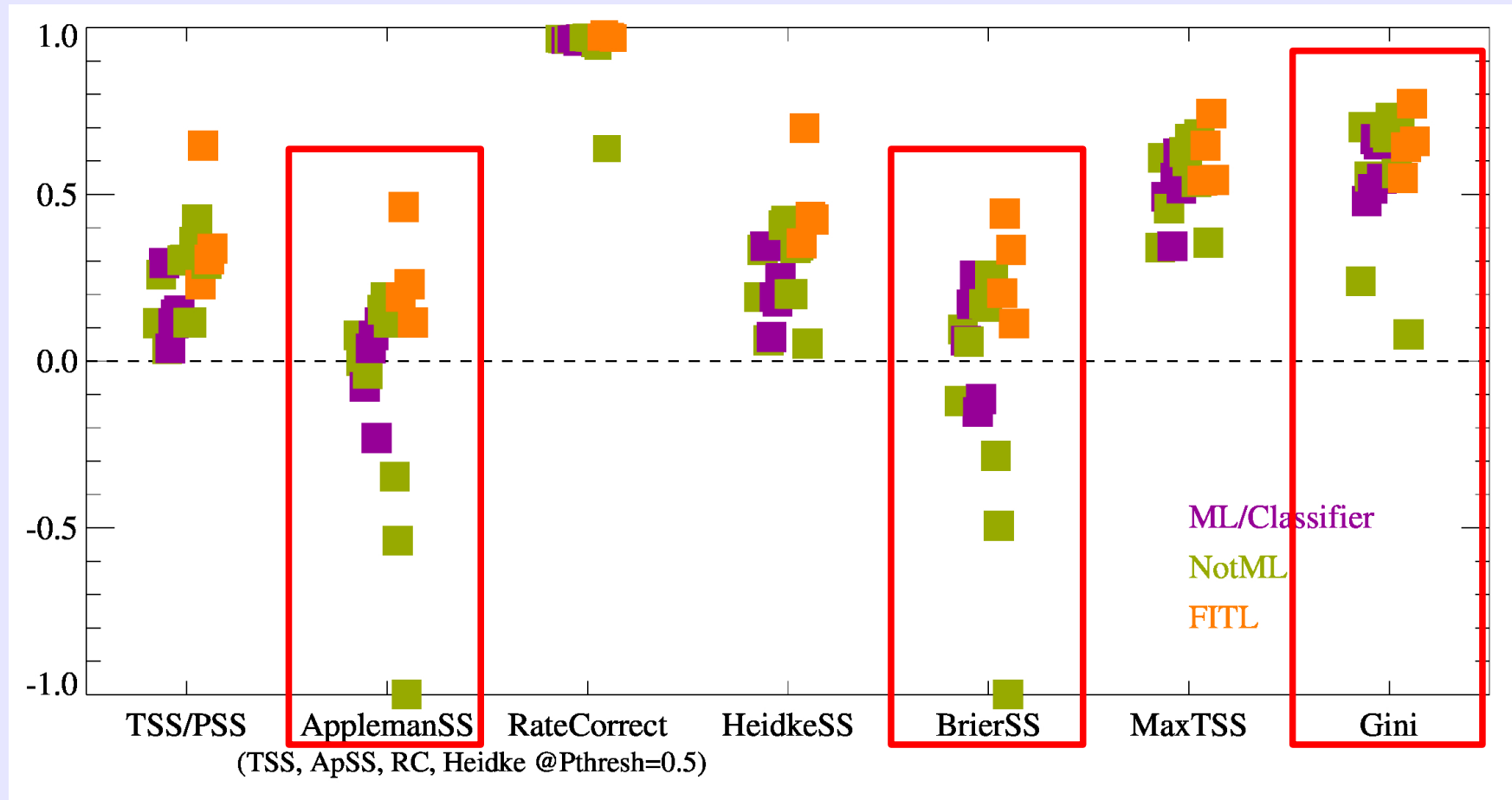


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 - Flares occur in active regions (sunspot groups) whose spots are complex and whose magnetic fields are twisted or show azimuthal “shear” along strong “Polarity Inversion Lines”.
 - Coronal Mass Ejections and particle acceleration events occur with large solar flares.
- However:
 - ➔ There are flares without CMEs
 - ➔ There are eruptions before flares
 - ➔ There are flares before eruptions
 - ➔ There are CMEs from very small flares
 - ➔ There are CMEs without sunspots
 - ➔ There are particle events from small 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 algorithms, color coded according to classification approach (Machine Learning, Not ML, and Forecaster In The Loop. Best=1.0, “No information”=0.0.



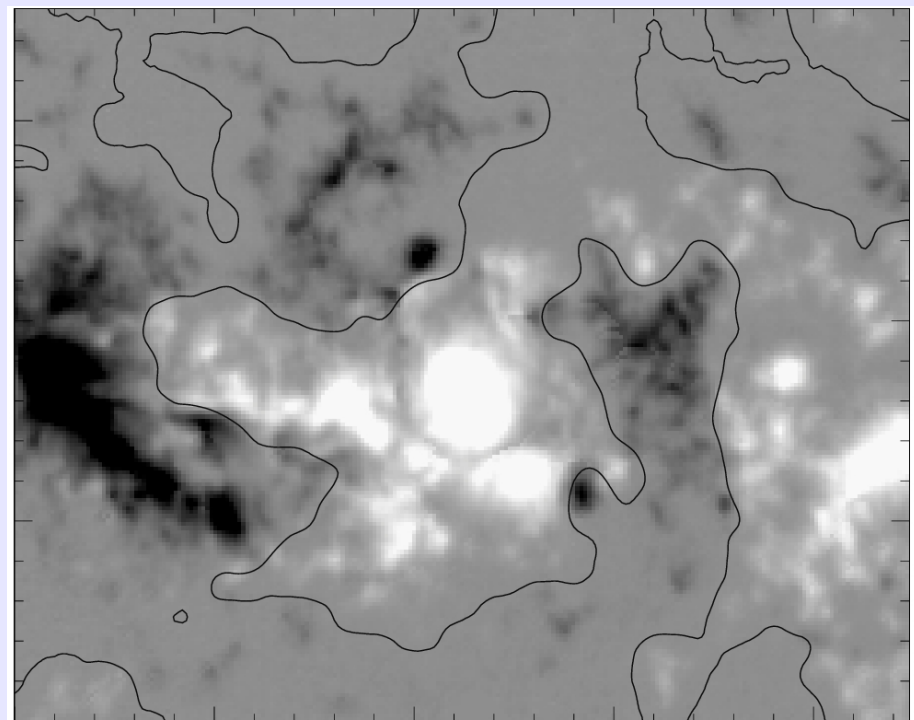
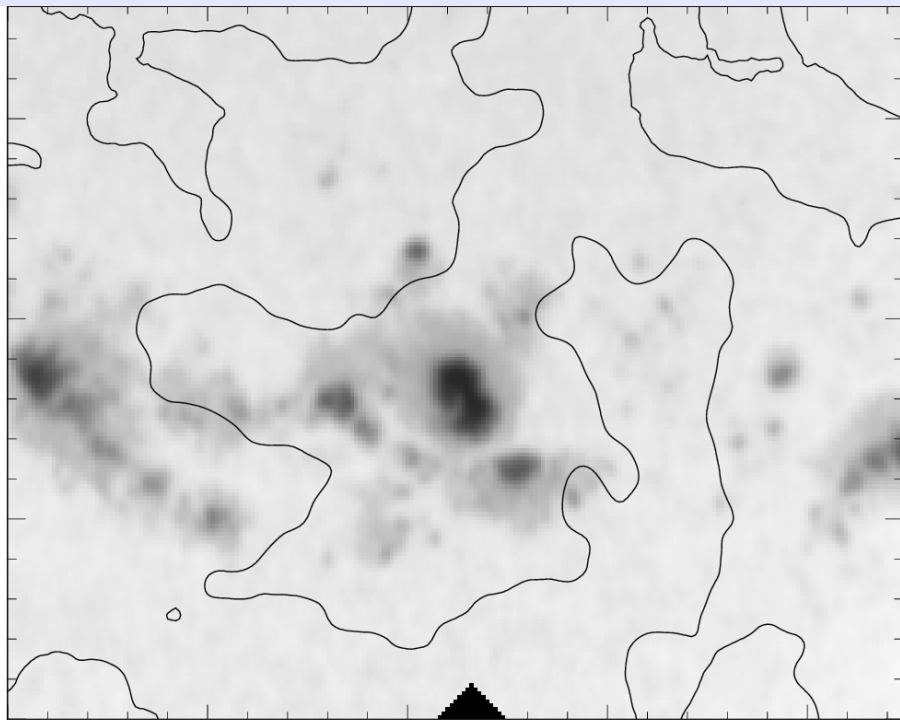
*Forecasts: event definitions are all about humans, not about the physics of the solar plasma. Are we evaluating in a helpful way?

From Leka+ 2018 *in prep.*

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

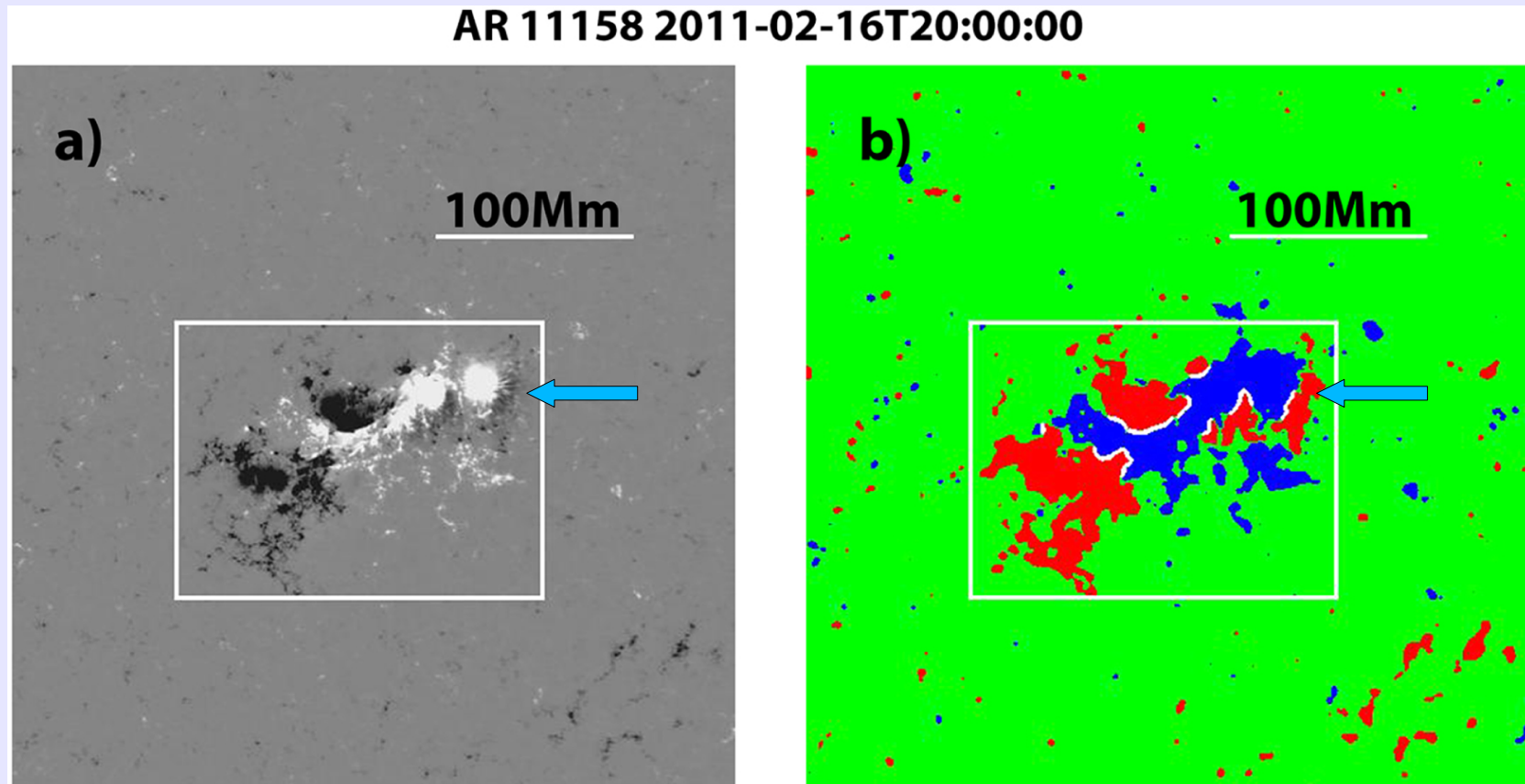
Bz + NL, IVM



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

Challenges for Observations: get the whole story.

It is *critical* to know what information the data are (*and are not*) providing.



Author 1+Author 2, 2017

The line-of-sight component of magnetic field data provides false (wrong, dislocated, erroneous, unphysical, misleading) locations of polarity inversion lines. DO NOT USE as a physical quantity without thinking this through!

See Leka+ 2017

Challenges for Observations: *get the whole story.*

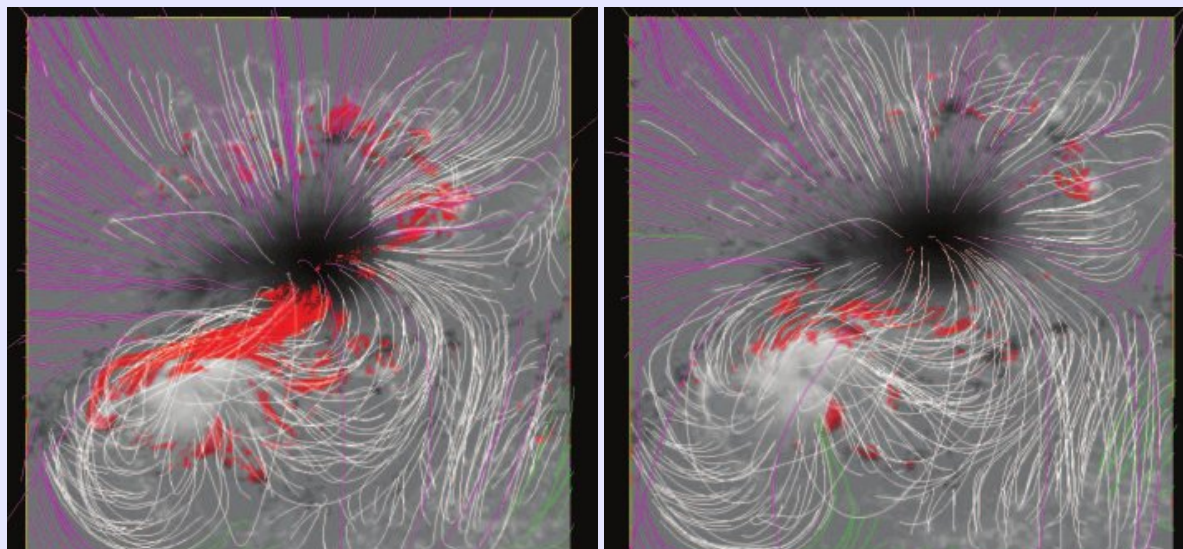
- ▶ Use as much information from each photon as possible:
 - Spectroscopy
 - Polarimetry
- ▶ Embrace under-utilized wavelength regions
 - Radio
 - Infra-red

Example:

- ▶ Images in H α line-center (± 0.5 , or $\pm 1.0\text{\AA}$) indicate:
 - Locations of thermal heating in the chromosphere
 - Locations, direction, plane-of-sky speed of cool plasma ejecta
- ▶ H α full-line imaging spectroscopy gives you: *physics.*
 - Doppler velocity and acceleration estimates.
 - Turbulence diagnostics
 - Non-thermal emission signatures (e.g., Stark broadening)
 - Temperature and velocity gradients from chromosphere to photosphere



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

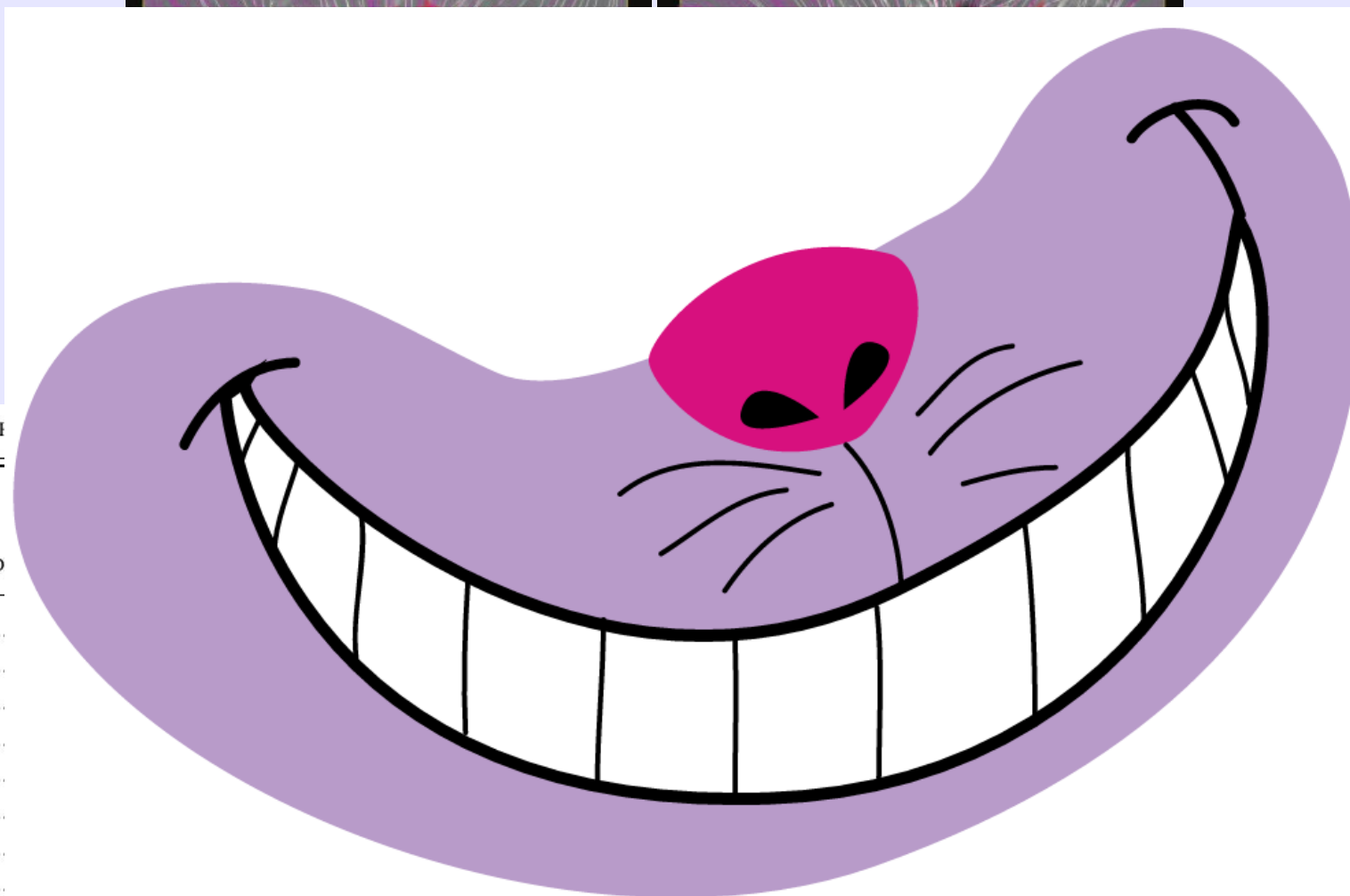
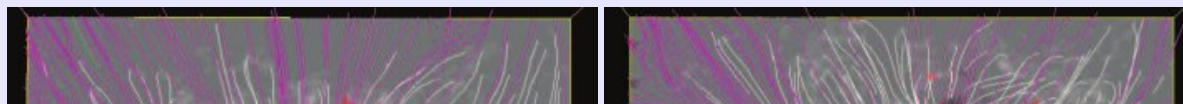


From Schrijver+ 2008

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

MODEL ¹	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 _{pp} ⁺	5	1.32	0.24	3.6	1.19	0.18	2.0
Wh _{np} ⁺	3	1.10	0.27	3.9	1.23	0.27	4.6
Wie _{wp}	3	1.09	0.35	19	1.18	0.32	13
Val _{pp}	3	1.10	0.28	230	1.27	0.31	190
Wh _{pp} ⁰	2	1.04	0.28	3.0	1.53	0.27	3.7
Wie _{ns}	2	1.04	0.43	22	1.13	0.39	30
Val _{np}	2	0.88	0.29	220	0.99	0.34	210
Wie _{np}	1	0.95	0.43	24	1.04	0.39	27
Wie _{pp}	0	1.05	0.44	18	1.15	0.39	21
McT _{pp}	0	1.01	0.61	29	1.07	0.59	25
Wh _{np} ⁰	-1	1.03	0.27	2.5	1.12	0.23	2.6
Wh _{np} ⁻	-1	1.04	0.25	2.9	1.11	0.24	2.9
Wh _{pp} ⁻	-1	1.05	0.27	3.2	1.16	0.19	2.2
McT _{np}	-2	0.95	0.64	26	1.00	0.61	24
Potential	-3	1	...	0.8	1.04	...	0.8

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



Johnson et al. 2008

METRICS FOR THE

RARE IMAGE

MOD

								$\langle f_i \rangle \times 10^8$
Wh _{pp} ⁺								2.0
Wh _{np} ⁺								4.6
Wie _{wp}								13
Val _{pp}								190
Wh _{pp} ⁰								3.7
Wie _{ns}								30
Val _{np}								210
Wie _{np}								27
Wie _{pp}	0	1.03	0.44	18	1.13	0.59		21
McT _{pp}	0	1.01	0.61	29	1.07	0.59		25
Wh _{np} ⁰	-1	1.03	0.27	2.5	1.12	0.23		2.6
Wh _{np} ⁻	-1	1.04	0.25	2.9	1.11	0.24		2.9
Wh _{pp} ⁻	-1	1.05	0.27	3.2	1.16	0.19		2.2
McT _{np}	-2	0.95	0.64	26	1.00	0.61		24
Potential	-3	1	...	0.8	1.04	...		0.8

Challenges for models:

- ▶ 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?

How do we progress? (“Which way ought we go?”)

Depends on where you want to get to:

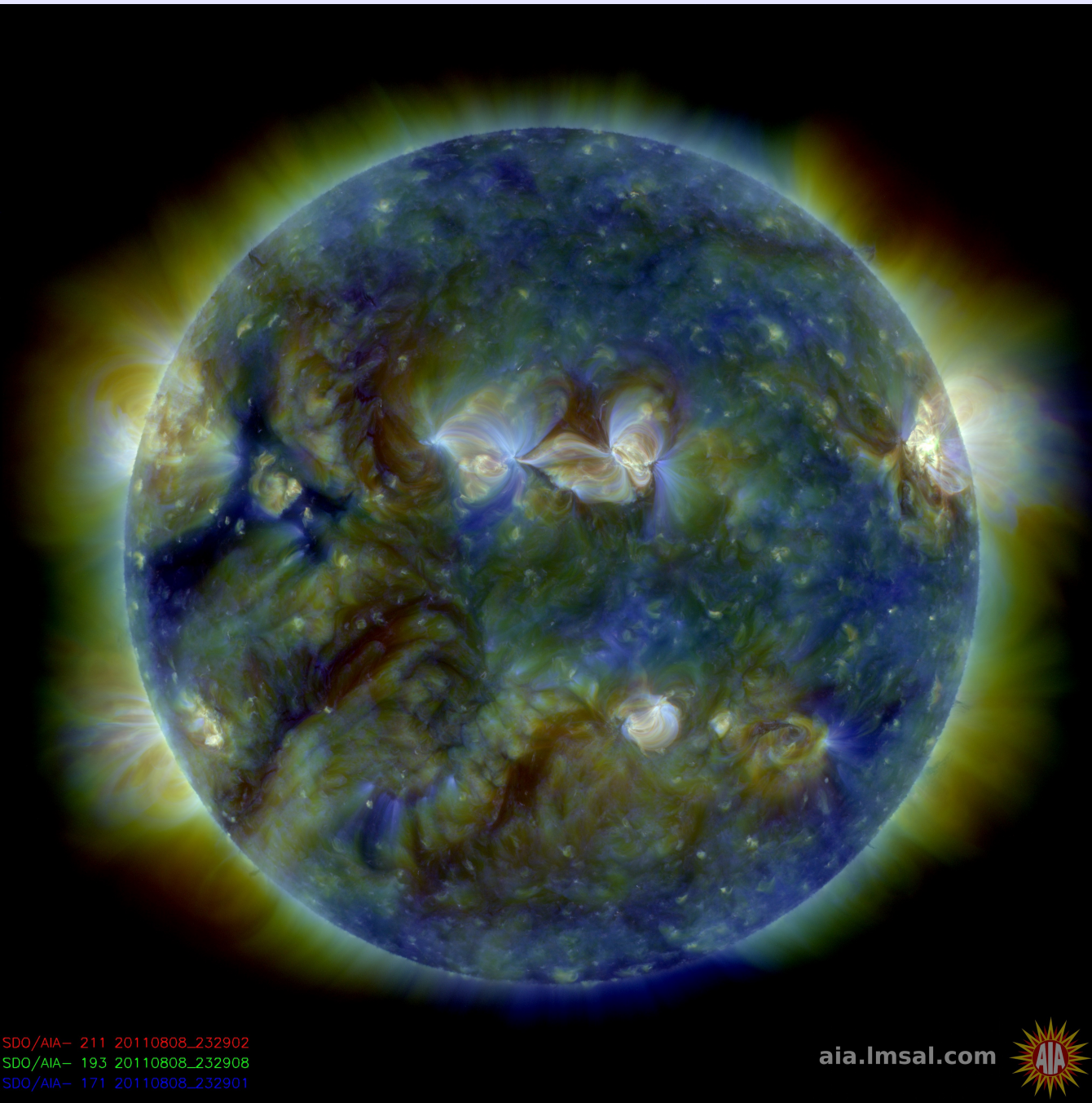
- Truly successful forecasting probably shows we understand the physics.
- Focusing on detailed physics vs observational constraints or empirical forecasting: not necessarily an ‘exclusive or’
 - ▶ Approach needs to be more like an iterative convergence.
 - ▶ When and how forecasting efforts fail should guide the way.



- If we believe we understand the physics, employ a “forecasting paradigm”
 - ▶ Challenge the hypothesis on large samples
 - ▶ Consider uniqueness and counter examples

A few things to consider:

- The solar origins of space weather is a remote-sensing science. All we have are photons.
- Progress requires synergy between:
 - modeling and observational investigations
 - Physics-based investigations and empirically-based constraints



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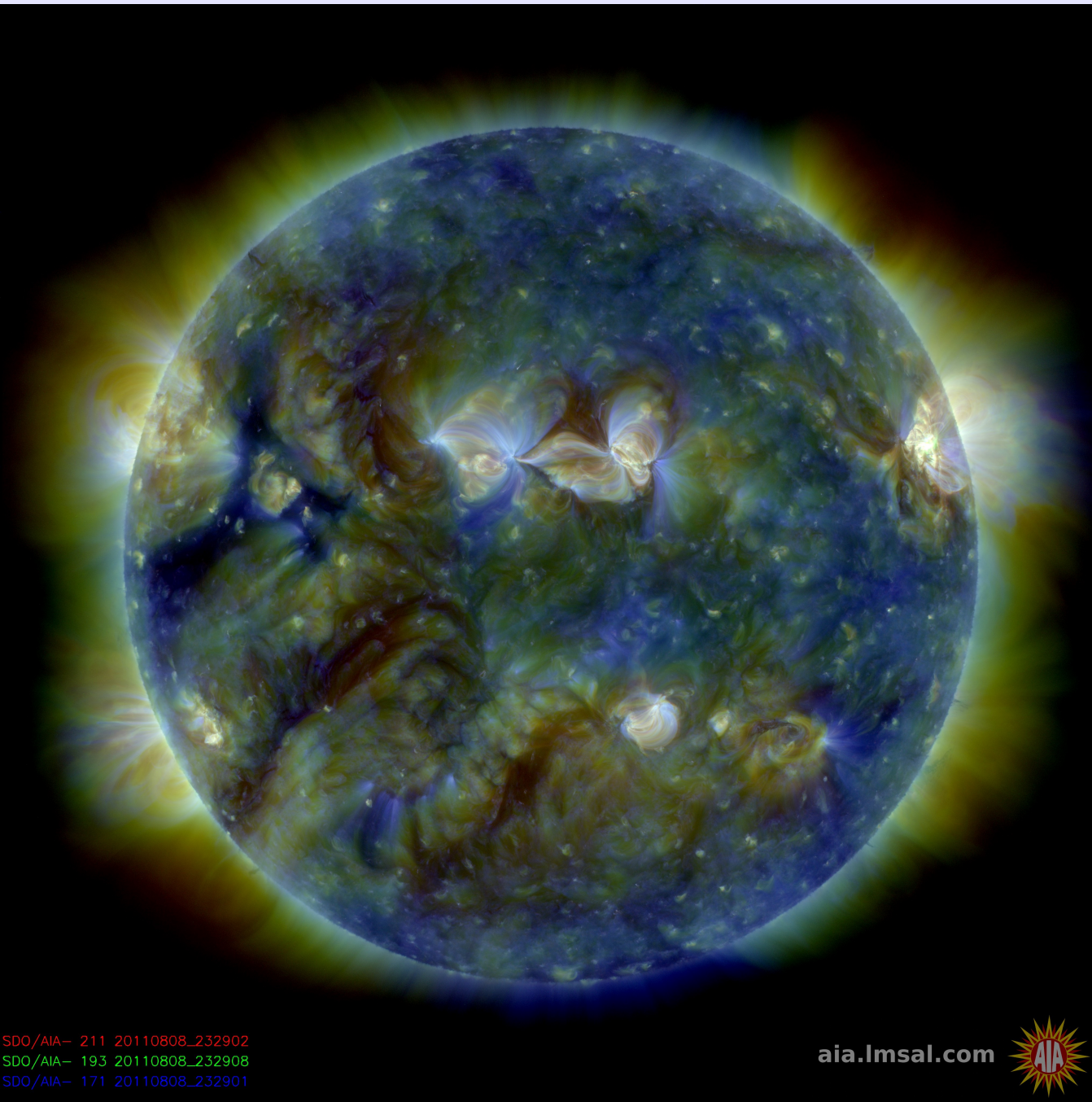
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"unencumbered science"



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