SOLAR ERUPTIONS:

FROM UNDERSTANDING TO FORECASTING

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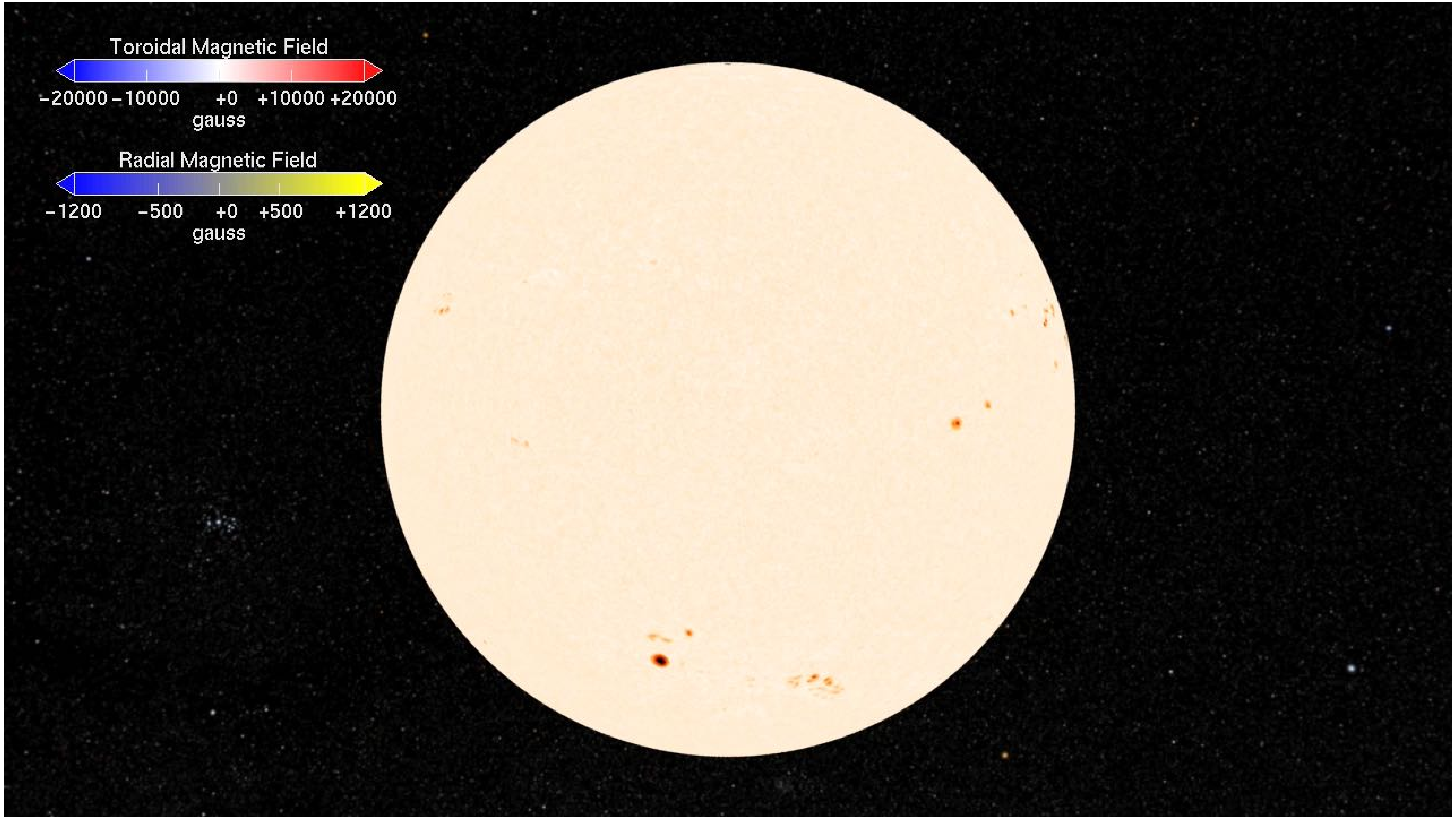
ΠΡΟΧΩΡΗΜΕΝΕΣ ΣΠΟΥΔΕΣ ΣΤΗ ΦΥΣΙΚΗ

Πανεπιστήμιο Πατρών, 13 Δεκεμβρίου, 2021

OUTLINE

- Solar magnetism: the physics under the hood
- Active regions: solar magnetic ‘hotspots’
- Instabilties in active regions
- The solar end of Space Weather
- Forecasting solar weather: research-to-operations (R2O) & research-to-operations-to-research (R2O2R)
- Current status of SWx forecast efforts
- Conclusions

SOLAR MAGNETISM: ORIGIN



Source: NASA Scientific Visualization Studio

- Cyclic generation of toroidal magnetic field by buoyant instabilities of poloidal fields in the solar interior
- Emerging fields penetrating the Sun’s visible surface, the photosphere

MAGNETIC FIELDS: SOLAR ATMOSPHERE

Credit: Holly Gilbert (NASA/GSFC)

- The Sun is a magnetically active star

$$\boxed{\beta = \frac{nkT}{B^2/8\pi}}$$

  - Photosphere: $\beta \gtrsim 1$
  - Chromosphere: $\beta < 1$
  - Corona: $\beta << 1$

- However, its magnetic fields are only measured on its visible surface, the photosphere. Higher in the corona, they can only be guessed, calculated or extrapolated

(magnetohydrostatic [MHS])

$$0 = -\nabla P + [c/(4\pi)](\nabla \times \mathbf{B}) \times \mathbf{B} \quad [+\rho \mathbf{g}]$$

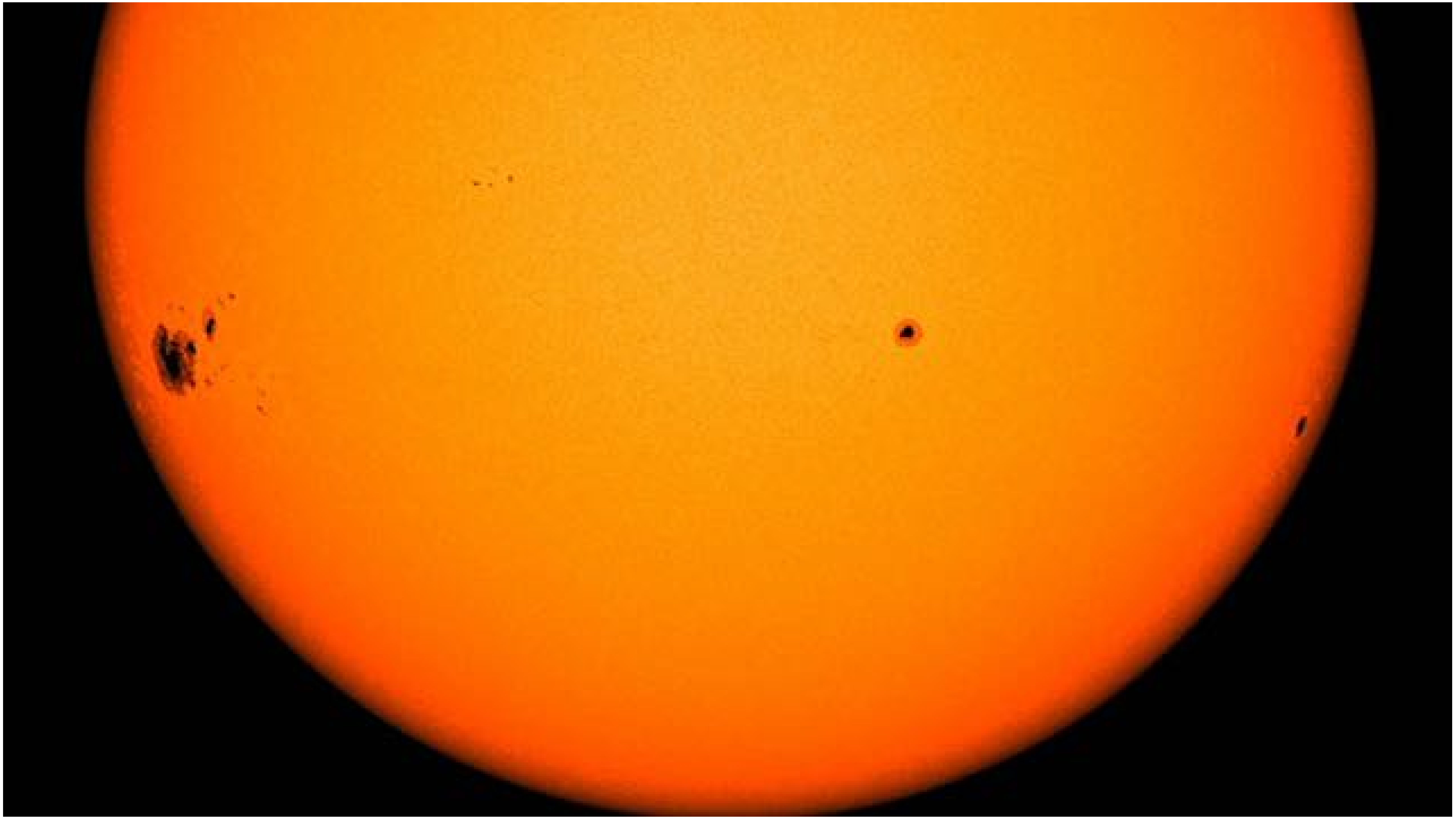
(magnetohydrodynamic [MHD])

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla P + [c/(4\pi)](\nabla \times \mathbf{B}) \times \mathbf{B} + \rho \mathbf{g}$$

$$\nabla \cdot \mathbf{B} = 0 \; ; \quad \nabla \times \mathbf{B} = 0 \quad \text{(vacuum)}$$

$$\nabla \cdot \mathbf{B} = 0 \; ; \quad \nabla \times \mathbf{B} = \alpha(r)\mathbf{B} \quad \text{(force-free)}$$

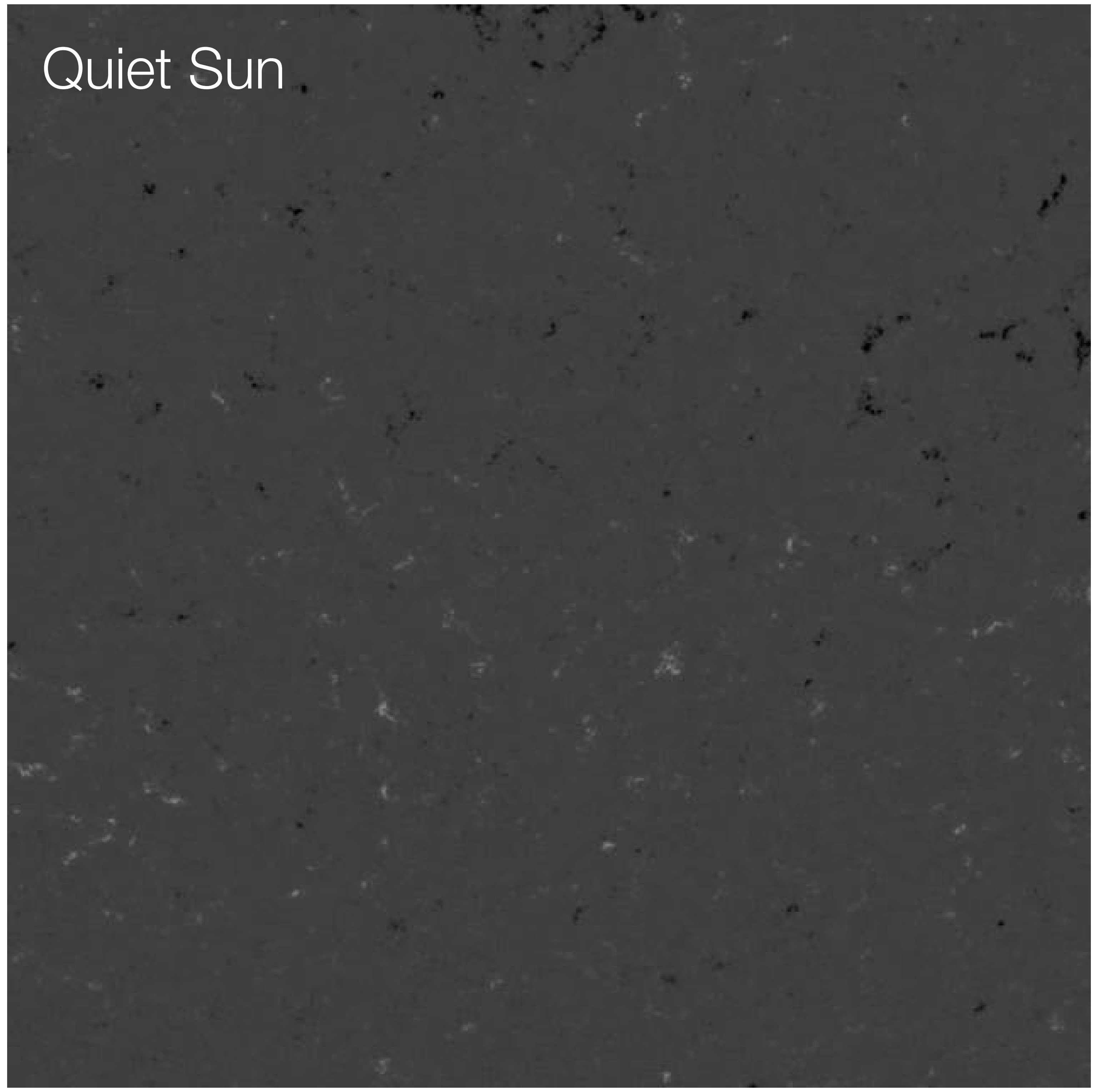
ACTIVE REGIONS: MAGNETIC ENERGY HOTSPOTS

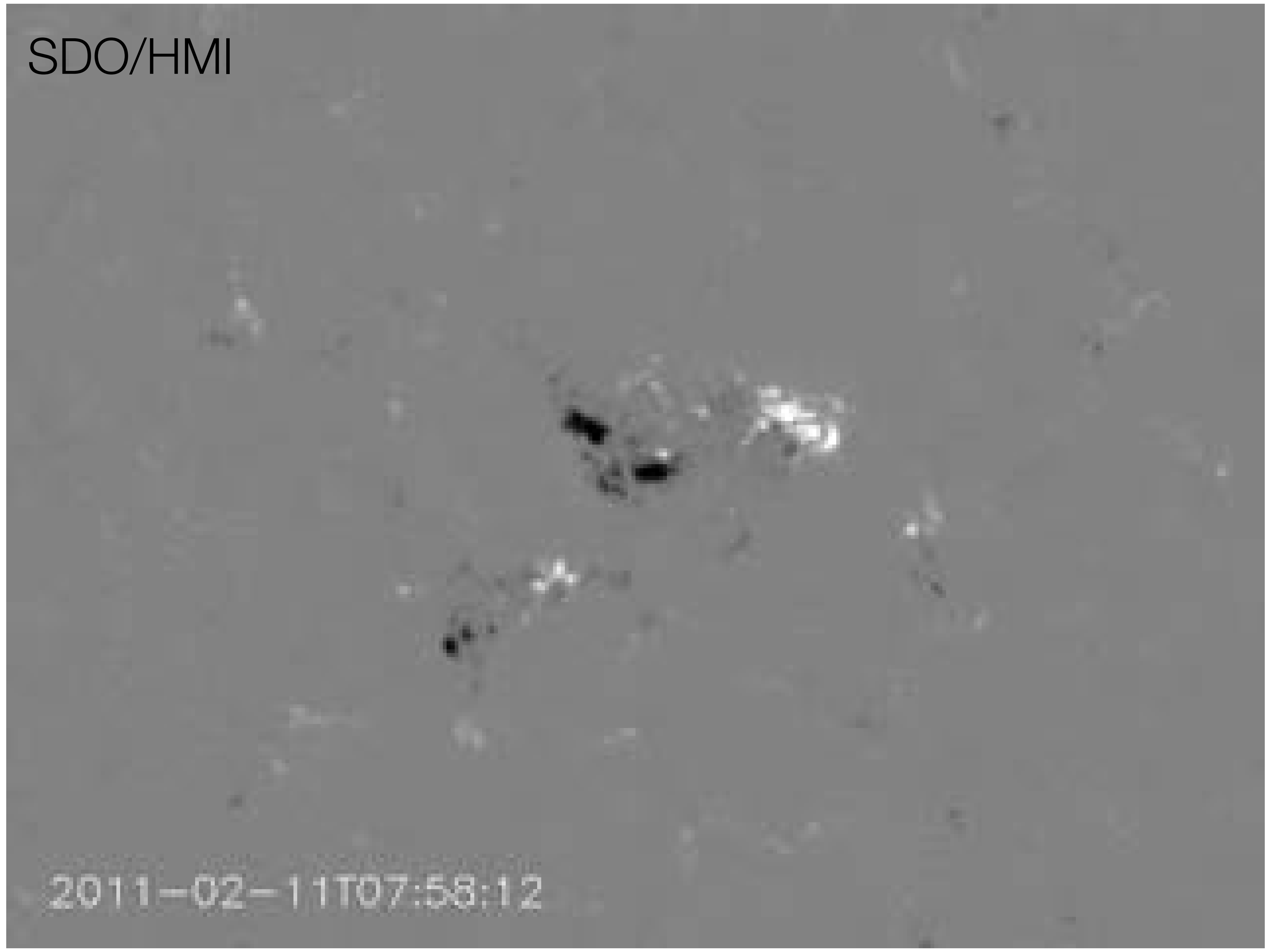


Source: NASA Scientific Visualization Studio

- Referring to active regions is practically equivalent to referring to sunspot complexes
- Active regions are prevalent features in the solar atmosphere, from the photosphere to 100s of Mm high in the corona

STUDYING SOLAR ACTIVE REGIONS





Active regions (and the solar corona, in general) are <u>magnetohydrodynamic</u> environments with a key characteristic:

$$R_m = \frac{uL}{\eta} \gg 1$$

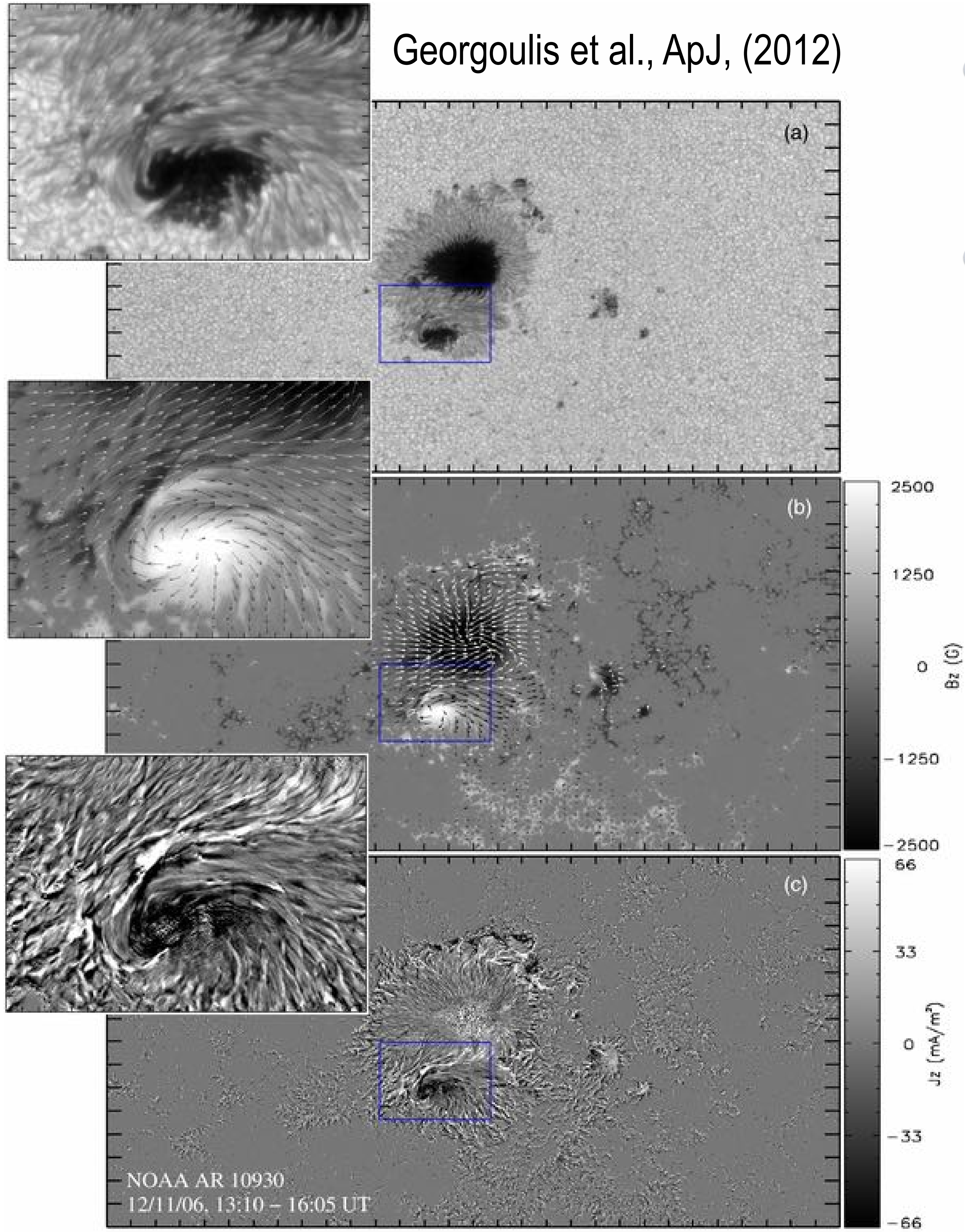
They have a huge magnetic Reynolds number (~ 10^7 - 10^{12}) meaning that they are an almost perfectly conducting plasma (η ~ 0) at relevant macroscopic spatial scales *L*.

MHD requires magnetic fields **B** and velocity fields **u** to study:

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla P + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} + \rho \mathbf{g} + \rho \nu \nabla^2 \mathbf{u} \;\; ; \text{ where } \;\; \frac{D}{Dt} = \frac{\partial}{\partial t} + (\mathbf{u} \cdot \nabla)$$

The main terms in the rhs are the gradients of pressure and the magnetic forces (the 'fight' of plasma vs. field)

KEY PROPERTIES OF ACTIVE REGIONS: MAGNETIC ENERGY



Georgoulis et al., ApJ, (2012)

- To work with active-region magnetic fields, one first needs to deal with the intrinsic 180° ambiguity in the orientation of the transverse field
- Assuming (a big discussion) that disambiguation has been achieved, one may calculate the electric current density in active regions

$$\mathbf{J} = \frac{c}{4\pi}\nabla \times \mathbf{B} \quad \text{or} \quad J_z = \frac{c}{4\pi}\left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right) \quad \text{in the photosphere}$$

- Electric currents give us an idea about magnetic complexity. They are also needed to calculate the excess magnetic energy of an active region

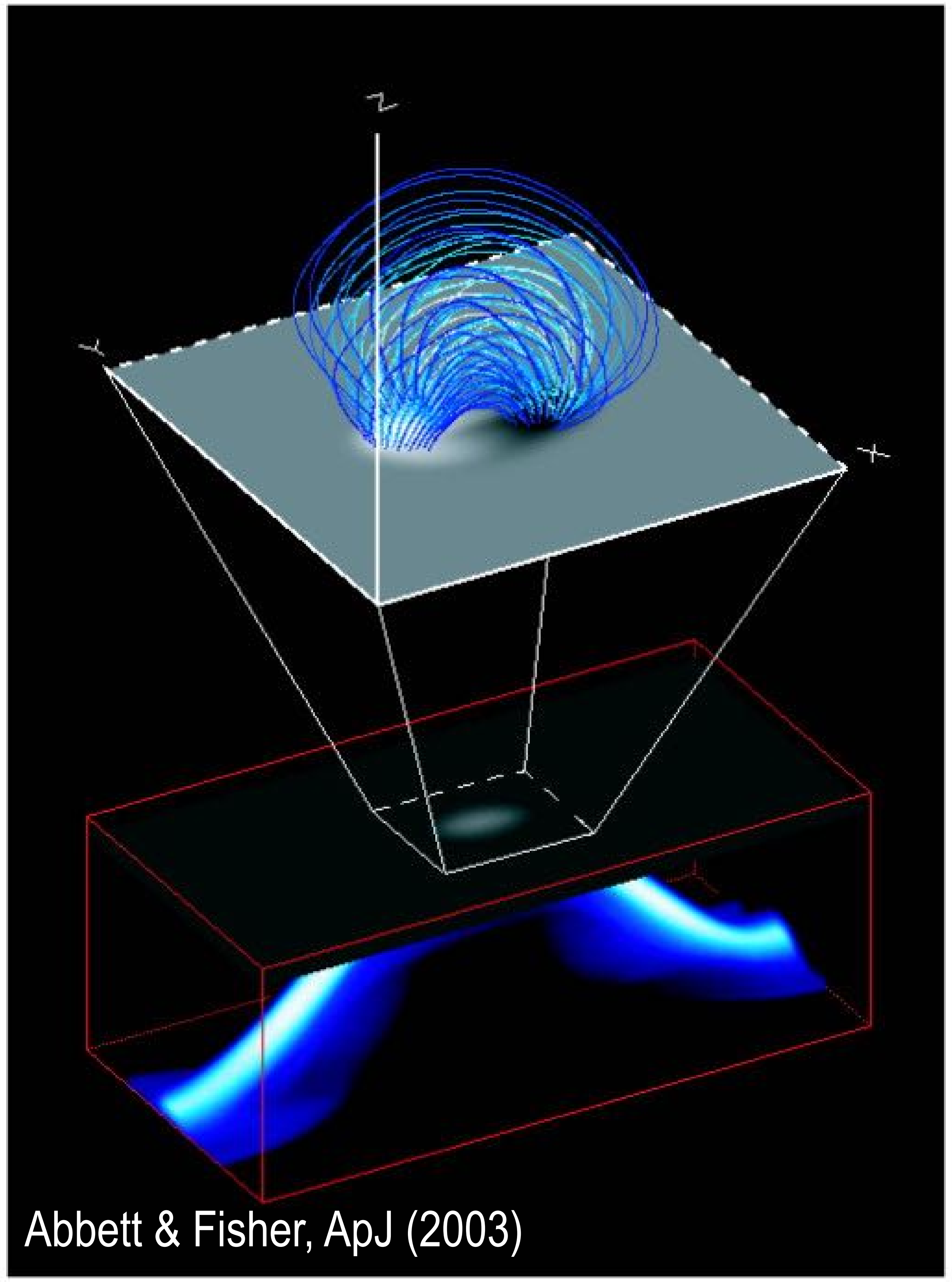
$$E_m = \frac{1}{8\pi}\int_V B_{ref}^2 dV + \frac{1}{2c}\int_V \mathbf{A}\cdot\mathbf{J}dV$$

where $\nabla \times \mathbf{B_{ref}} = 0$; $\nabla \times \mathbf{B} \sim \mathbf{J}$; $\nabla \times \mathbf{A} = \mathbf{B}$

- The energy integral including **A** and **J** provides the energy available in the active region to power instabilities and eruptions

KEY PROPERTIES OF ACTIVE REGIONS: MAGNETIC HELICITY

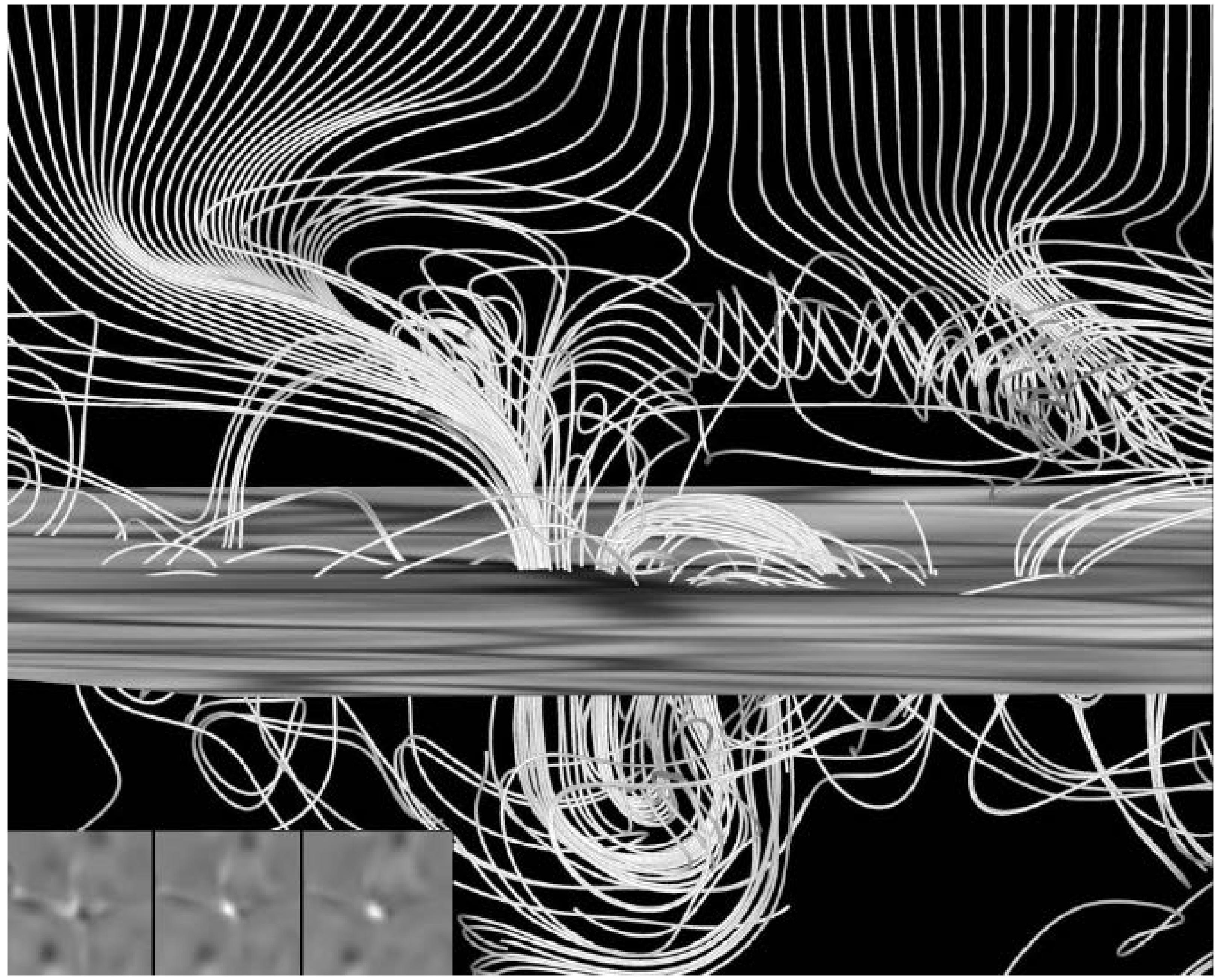
We have come a long way in our perception of solar magnetic fields; from this beauty …



Abbett & Fisher, ApJ (2003)

… to this mess

Abbett, ApJ (2007)



This is a manifestation of magnetic helicity, namely, twist, writhe and linkage

$$H_m = \int_V (\mathbf{A} + \mathbf{A_{ref}}) \cdot (\mathbf{B} - \mathbf{B_{ref}}) dV$$

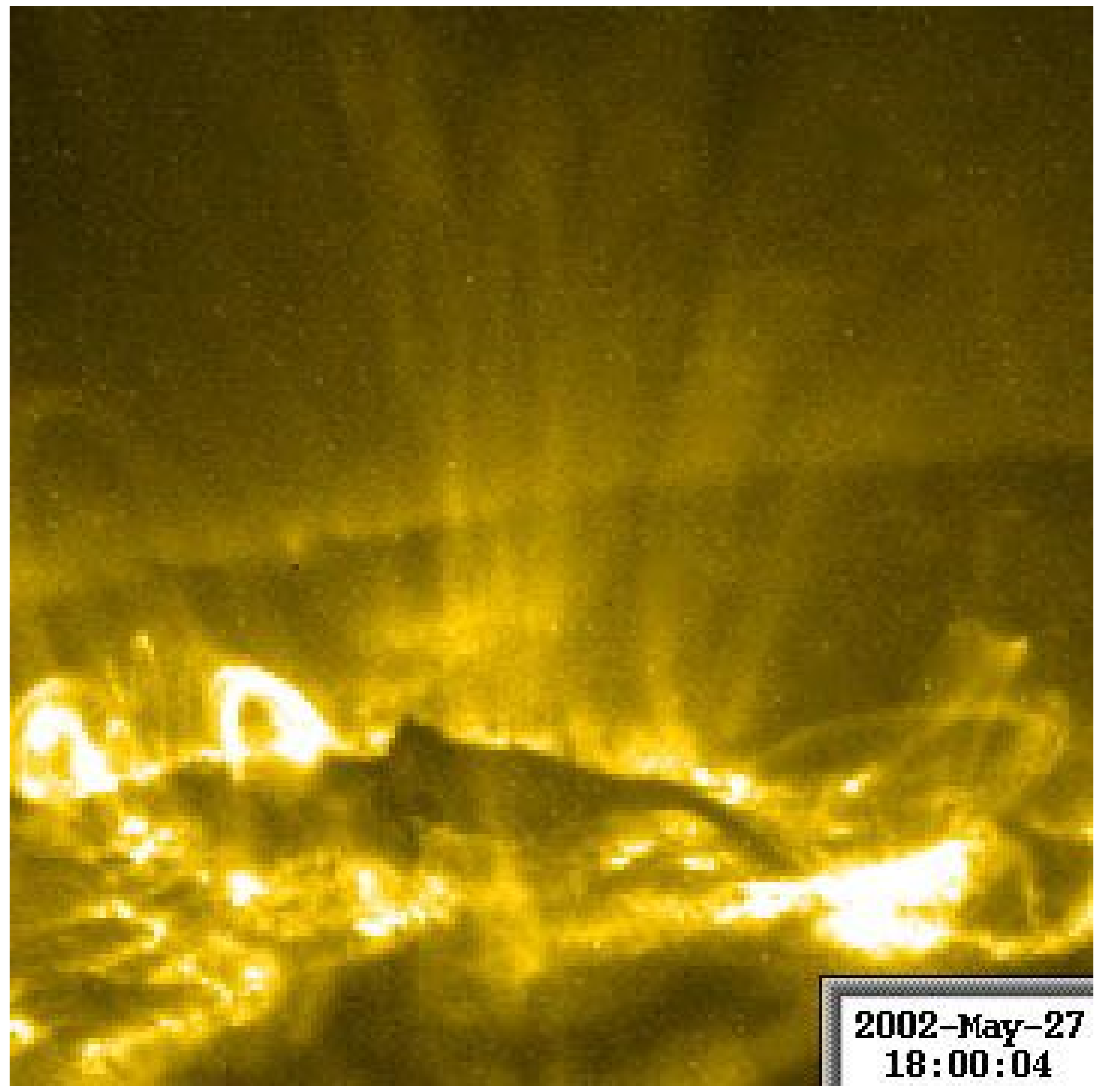
Magnetic helicity requires electric currents

- A fundamental property of magnetic helicity is that is dissipation rate is nearly 0 in the solar corona:

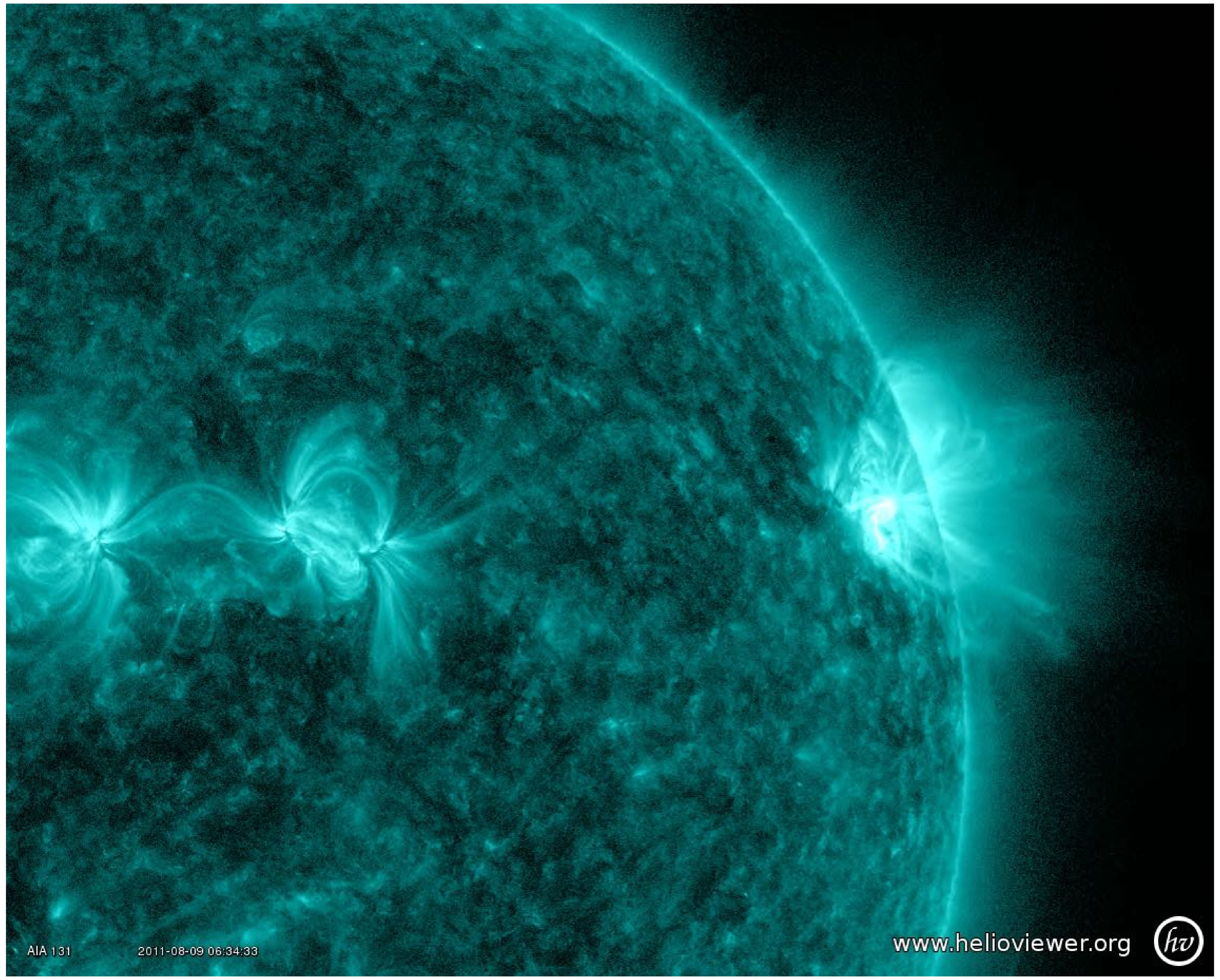
$$\frac{\Delta H_m}{\Delta t} \sim \frac{1}{\sqrt{R_m}}$$

- This intimately connects electric currents, magnetic energy and magnetic helicity in the evolution of solar active regions

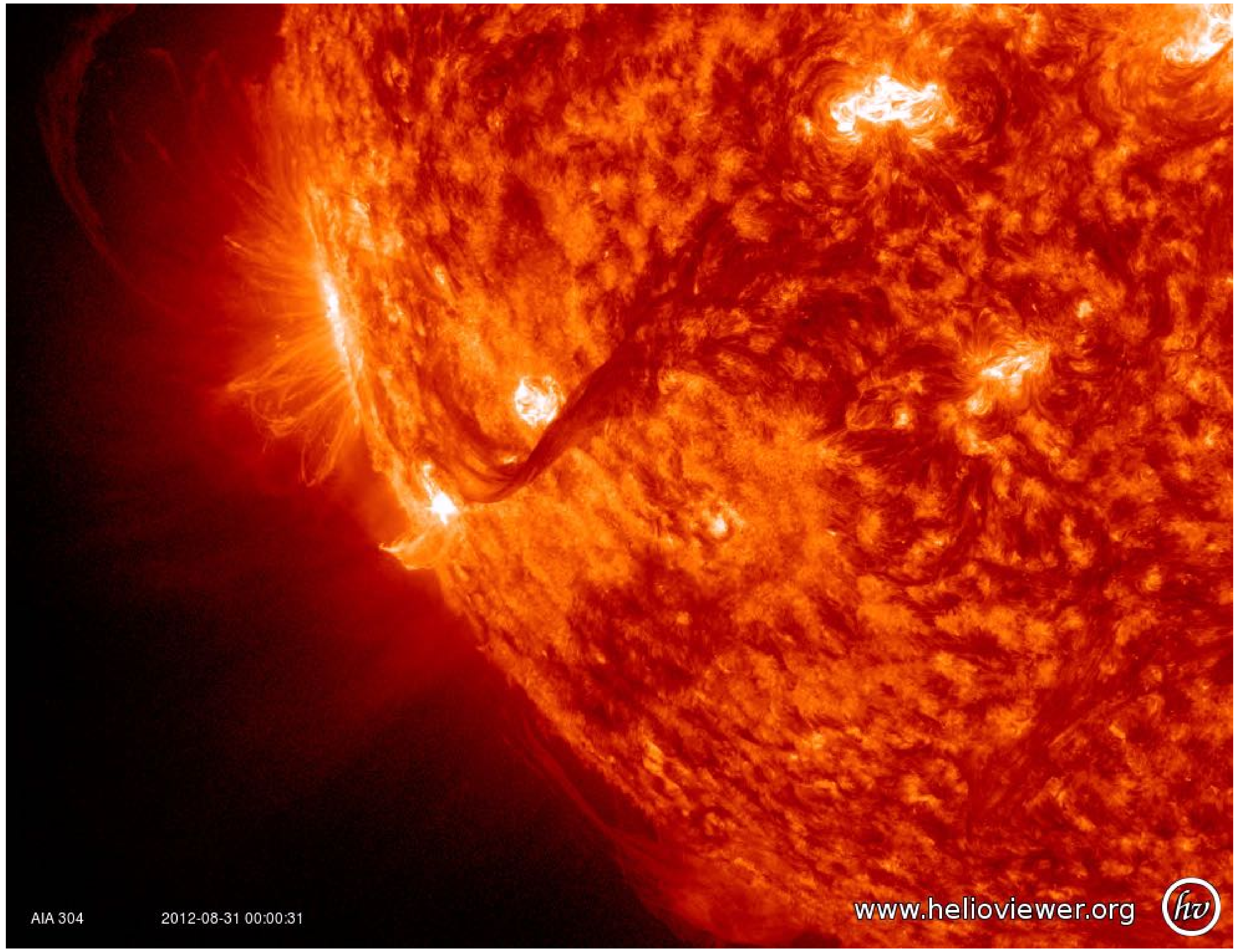
Source: TRACE



ERUPTIVE INSTABILITIES: FLARES & CORONAL MASS EJECTIONS



Earth in relative scale

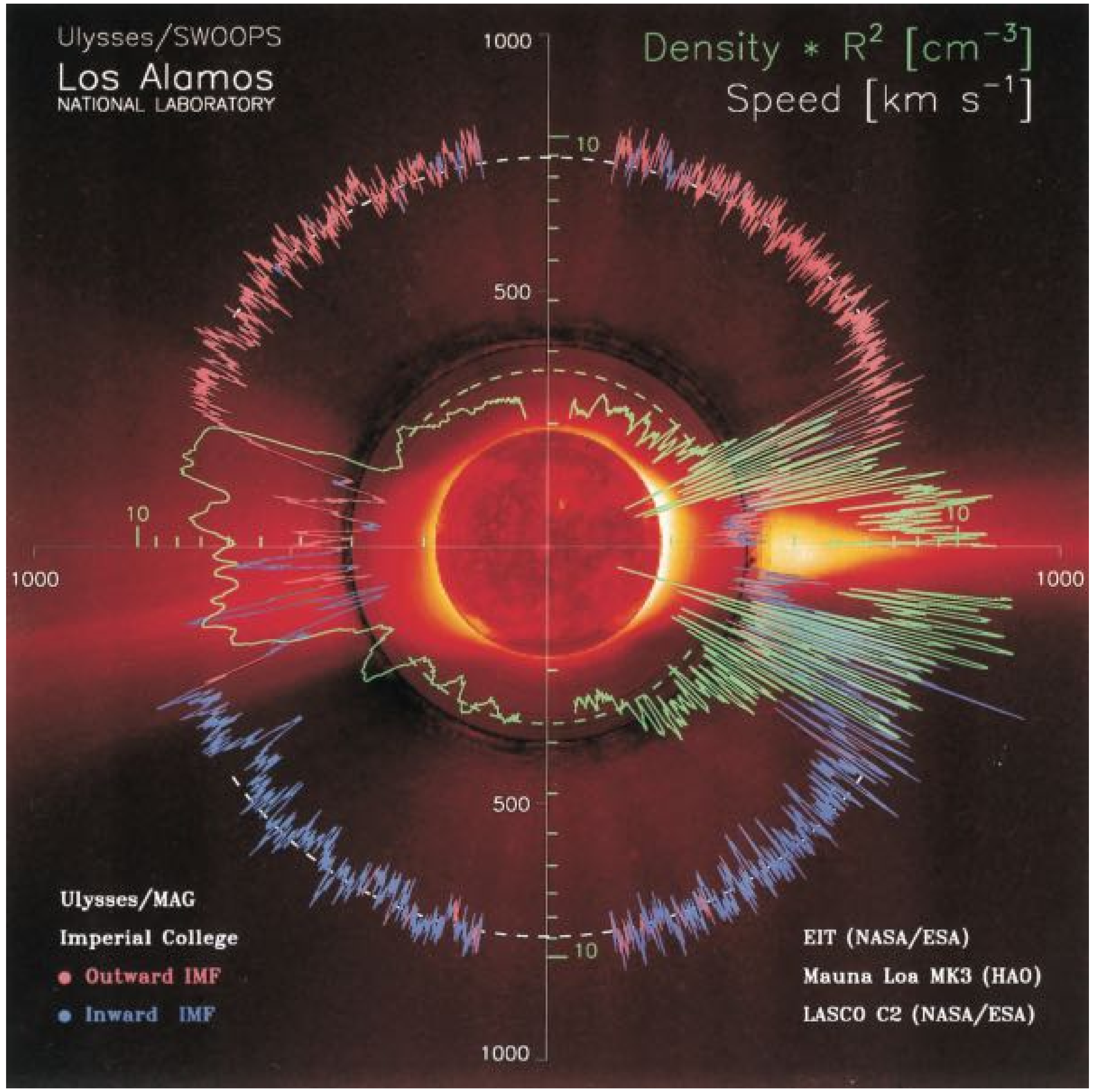


Solar Flare: “A sudden eruption of magnetic energy released on or near the surface of the sun, usually associated with sunspots and accompanied by bursts of electromagnetic radiation and particles.”, *American Heritage Dictionary*

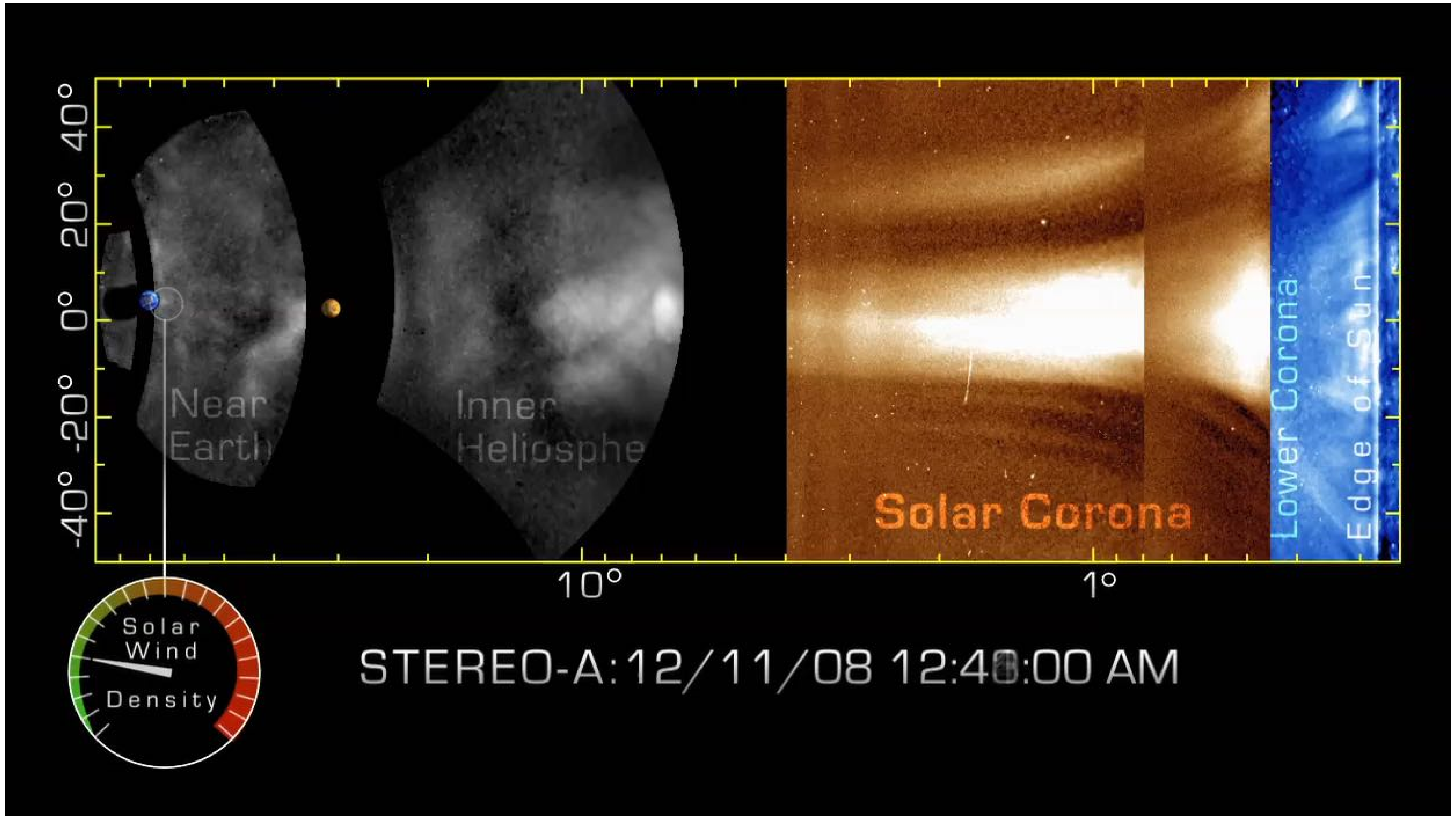
Coronal Mass Ejection (CME): “A massive, bubble-shaped burst of plasma expanding outward from the Sun's corona, in which large amounts of superheated particles are emitted at nearly the speed of light.”, *American Heritage Dictionary*

SOLAR WIND

McComas et al., JGR, 2000



Source: NASA/STEREO



Continuous expulsion of plasma at speeds of the order 400 - 800 km/s

$$B_r(r,\theta,\phi) = B(\theta,\phi_0)(b/r)^2$$
$$B_\theta(r,\theta,\phi) = 0$$
$$B_\phi(r,\theta,\phi) = B(\theta,\phi_0)(\omega/v_m)(r-b)(b/r)^2 sin\theta$$

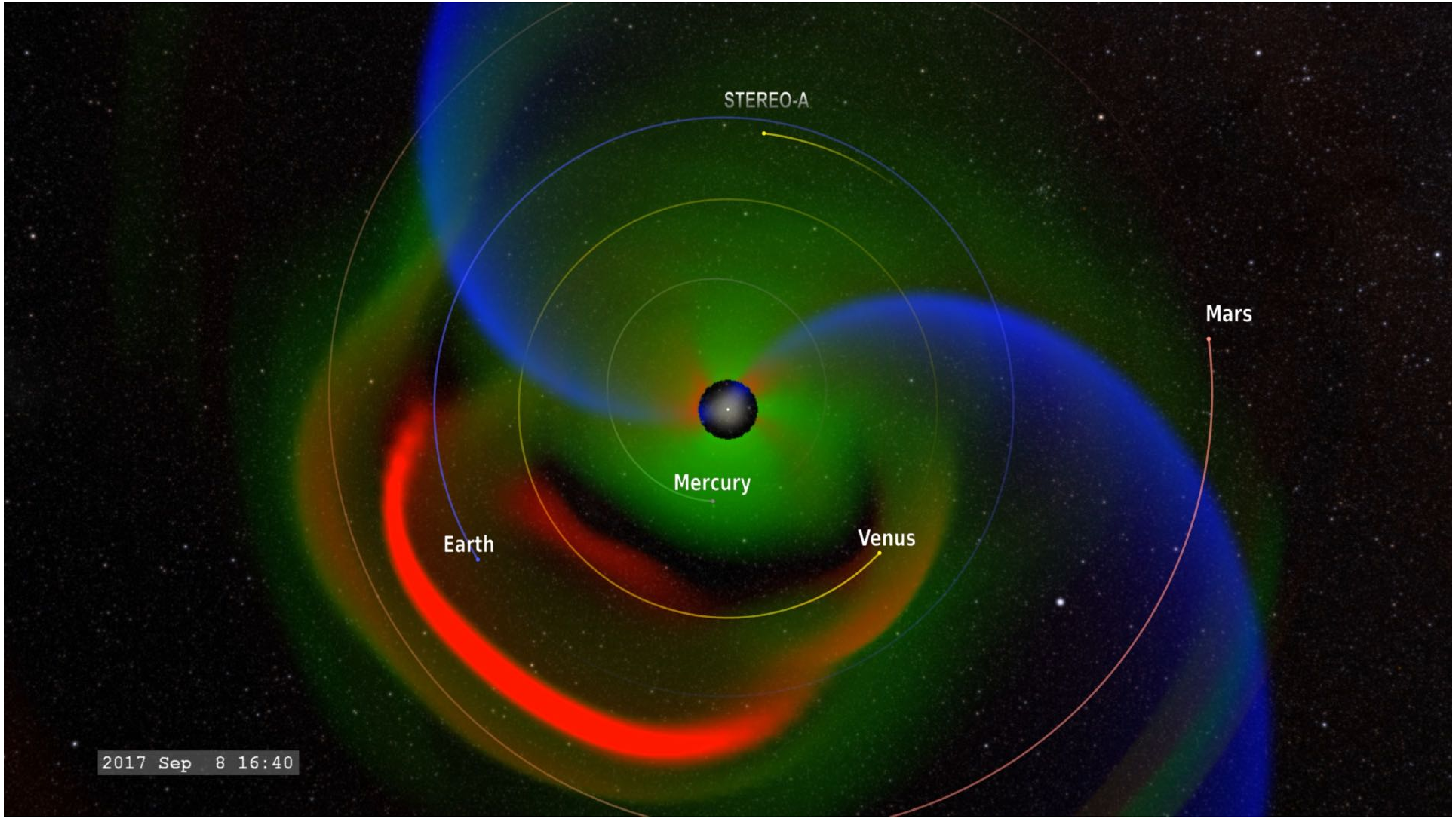
$$v_r = v_m$$
$$v_\theta = 0$$
$$v_\phi = \omega(r-b)sin\theta$$

Streamline (Archimedean spiral):

$$\frac{r}{b} - 1 - \ln(\frac{r}{b}) = \frac{v_m}{b\omega}(\phi - \phi_0)$$

Parker, ApJ, 1958

PUTTING IT TOGETHER



Source: NASA Scientific Visualization Studio

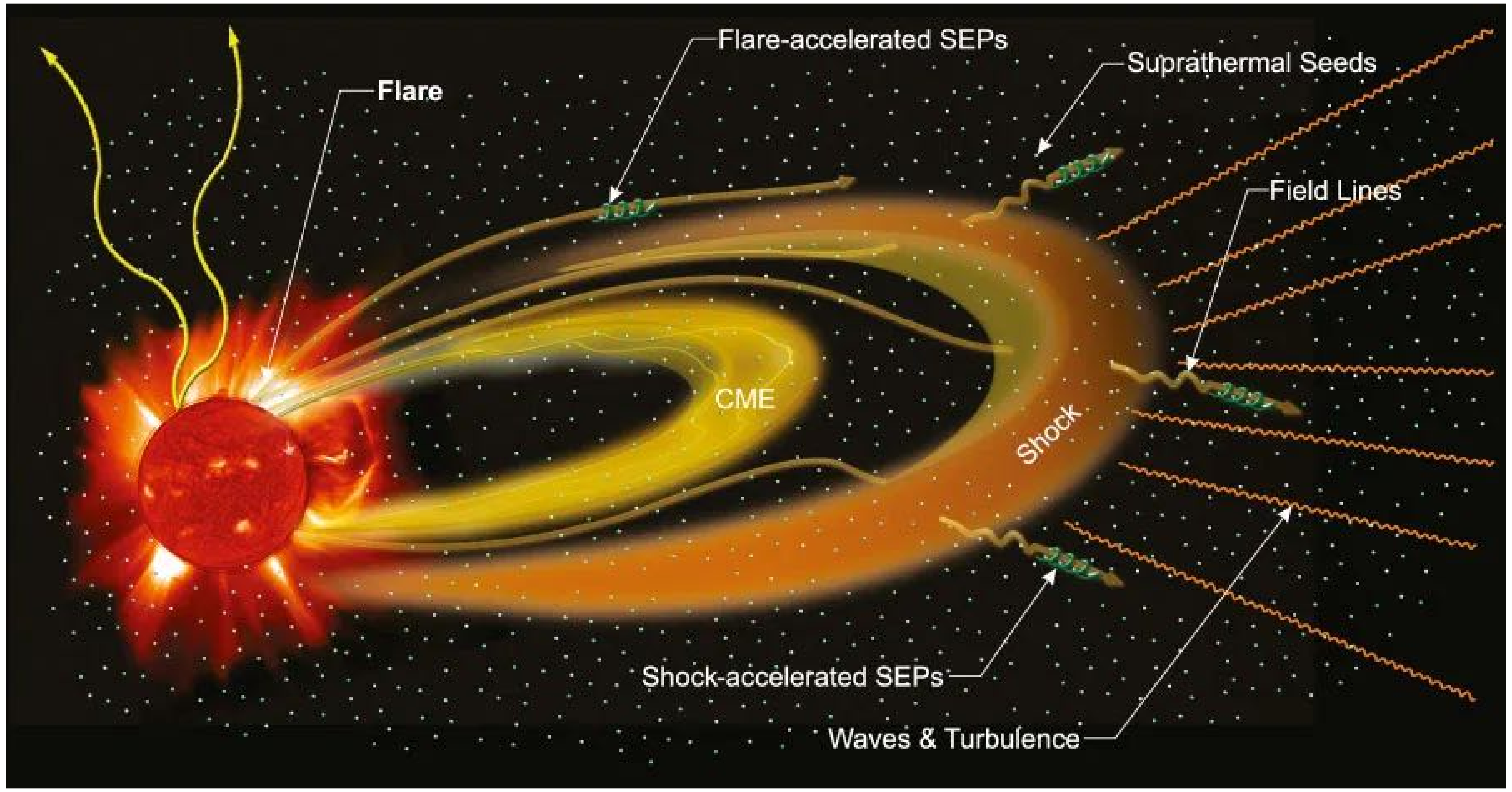
The synthesis of solar magnetic activity comprises photons, magnetic fields, sub-relativistic plasma (collisionless gas) and energetic (relativistic particles)

- Solar flare photons propagate radially with no preference in directionality (intensity ∝ $1/r^2$)
- CME ejecta propagate with a directionality in place (intensity ∝ $1/r^\alpha$; $\alpha \neq 2$)
- CME shocks, when formed, also accelerate particles at relativistic speeds

PUTTING IT TOGETHER IN ACTUAL OBSERVATIONS

Source: NASA Scientific Visualization Studio

THE SOLAR END OF SPACE WEATHER AND PLANETARY FORCING



Desai & Burgess, JGR, 2008

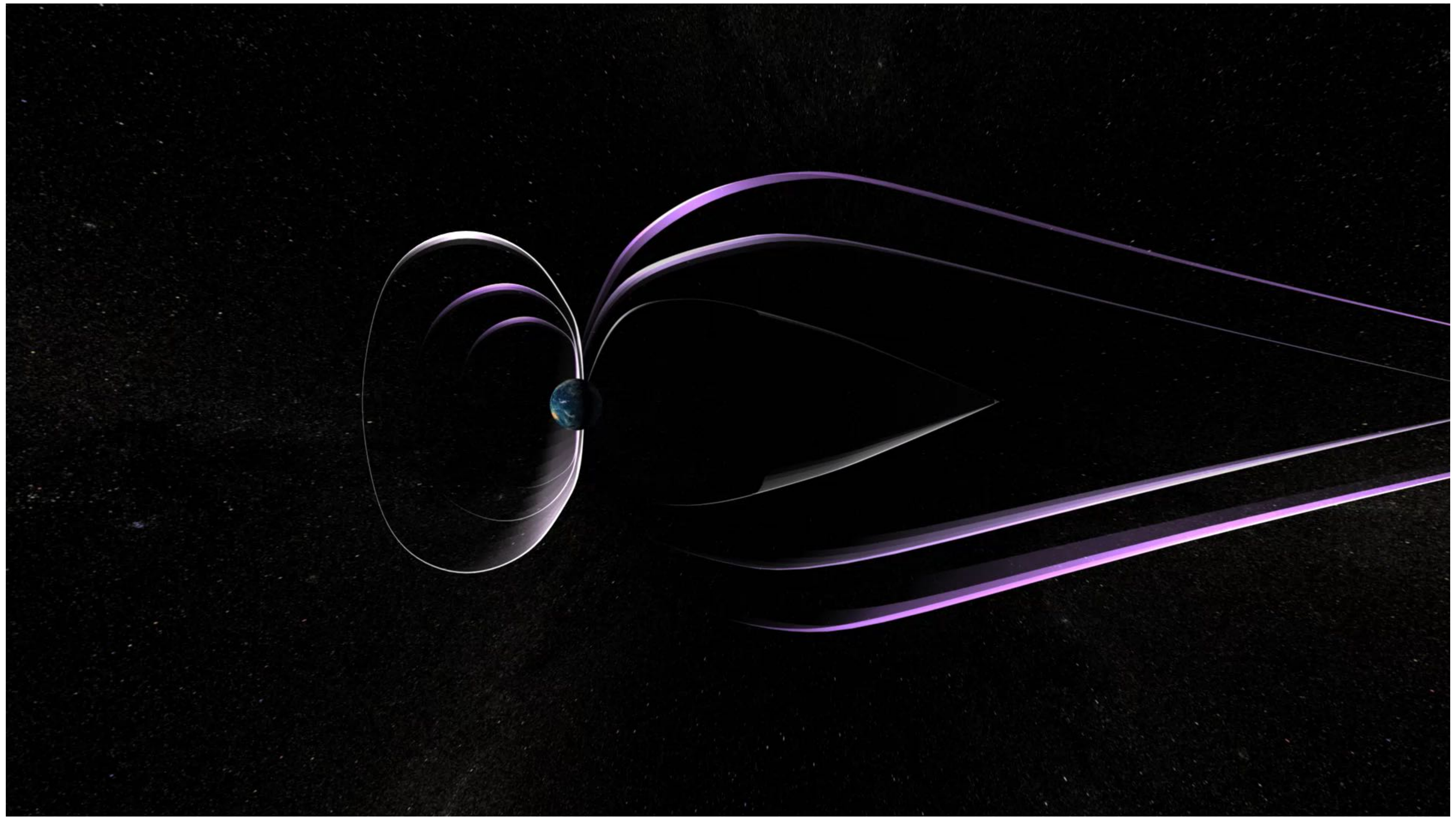
Major solar eruptions and products (flares, CMEs, SEP events) are the strongest eruptions in the solar system

- Solar flare energy: up to 10^{33} erg
- Typical CME mass: 10^{16} g ; speed: (300 - >3000) km/s
- SEP (proton) energies: from 10 MeV up to >500 MeV

Every solar system body 'feels' interplanetary CMEs differently. For bodies with a magnetosphere

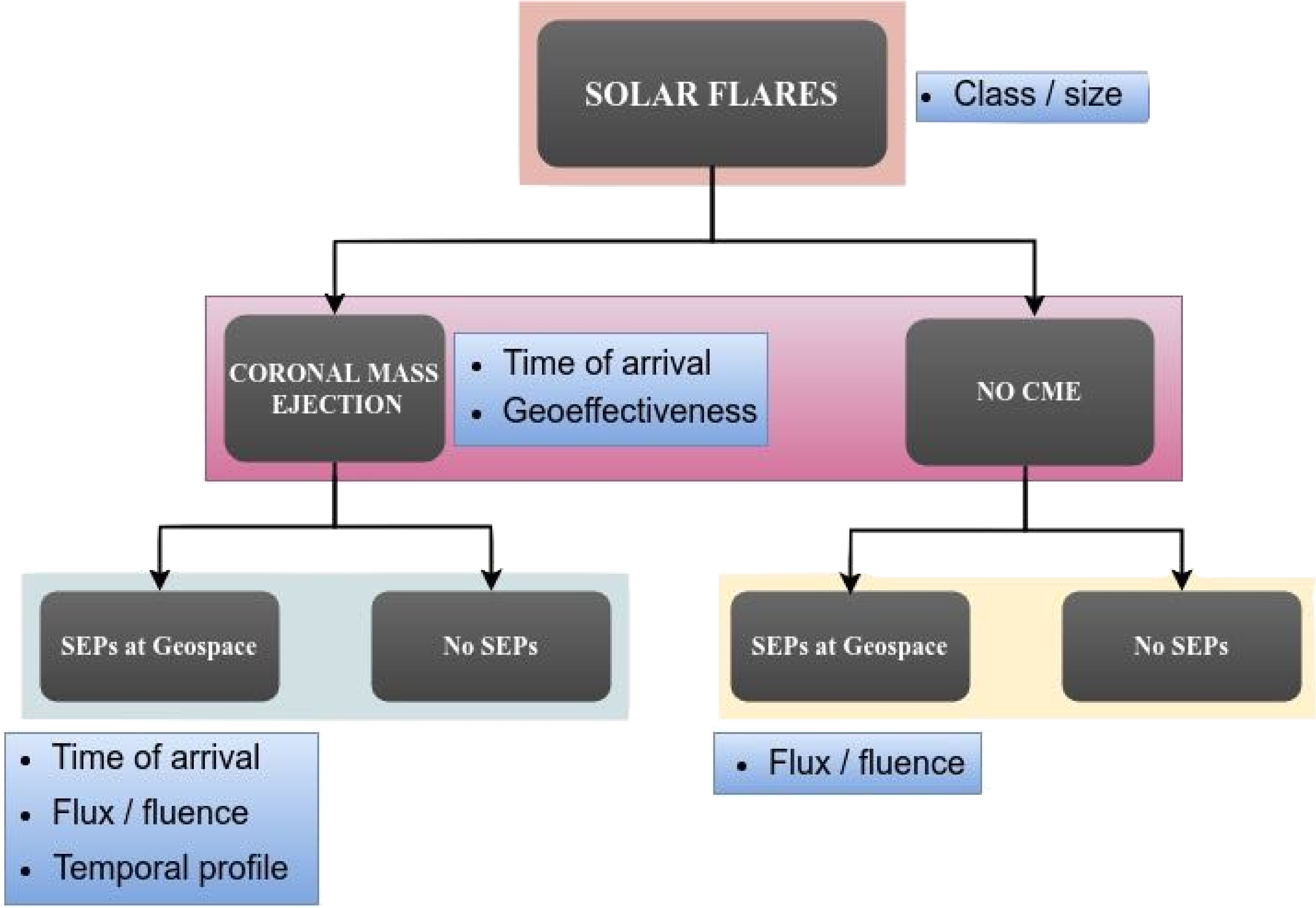
$$\boxed{\rho v^2 + nkT + \frac{B^2}{8\pi}} \longleftrightarrow \boxed{\frac{B^2}{8\pi} + nkT}$$

ICME Magnetosphere



Source: NASA Scientific Visualization Studio

SOLAR WEATHER MANIFESTATIONS AND PREDICTION OBJECTIVES



SOLAR FLARES

- Class / size

CORONAL MASS EJECTION

- Time of arrival
- Geoeffectiveness

NO CME

SEPs at Geospace

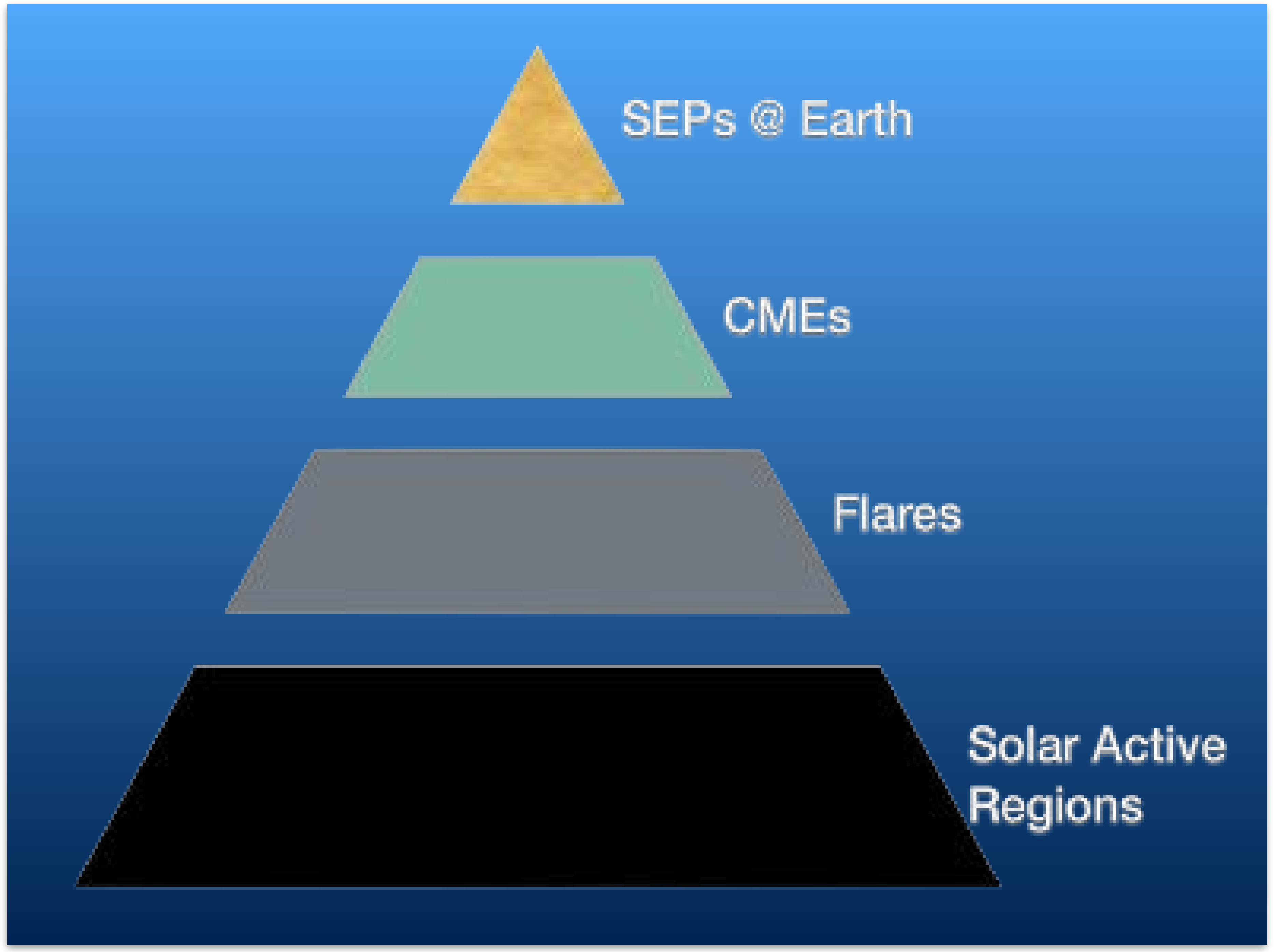
No SEPs

SEPs at Geospace

No SEPs

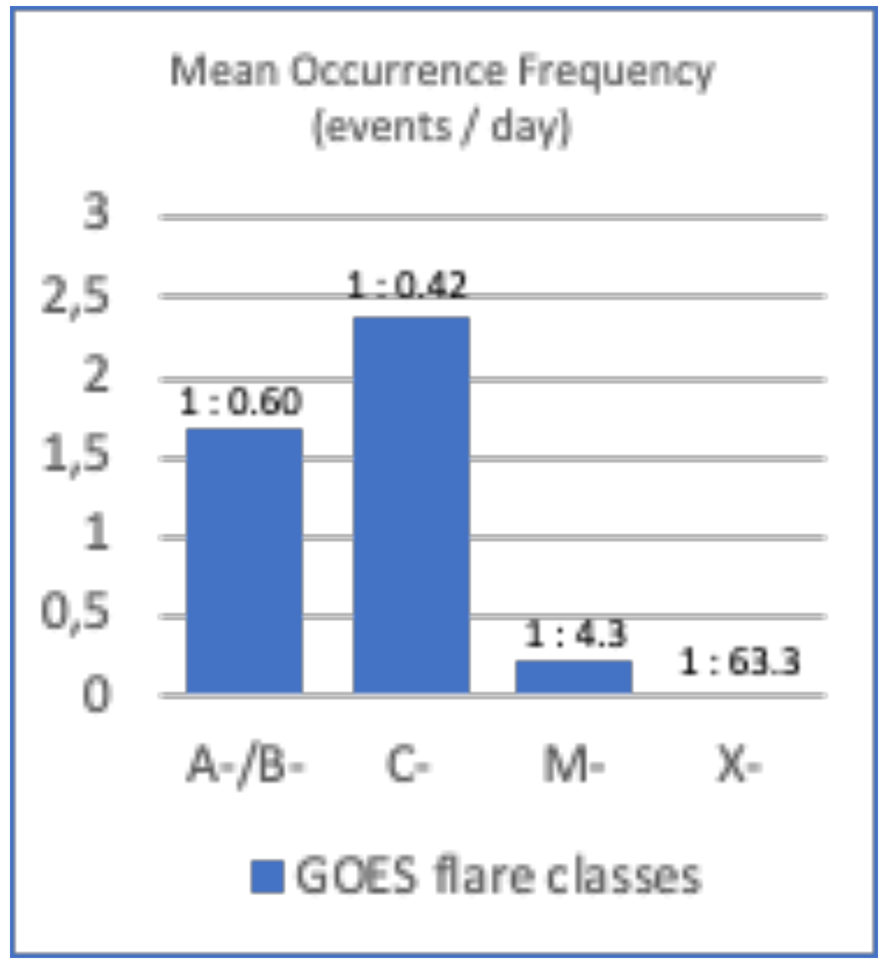
- Time of arrival
- Flux / fluence
- Temporal profile

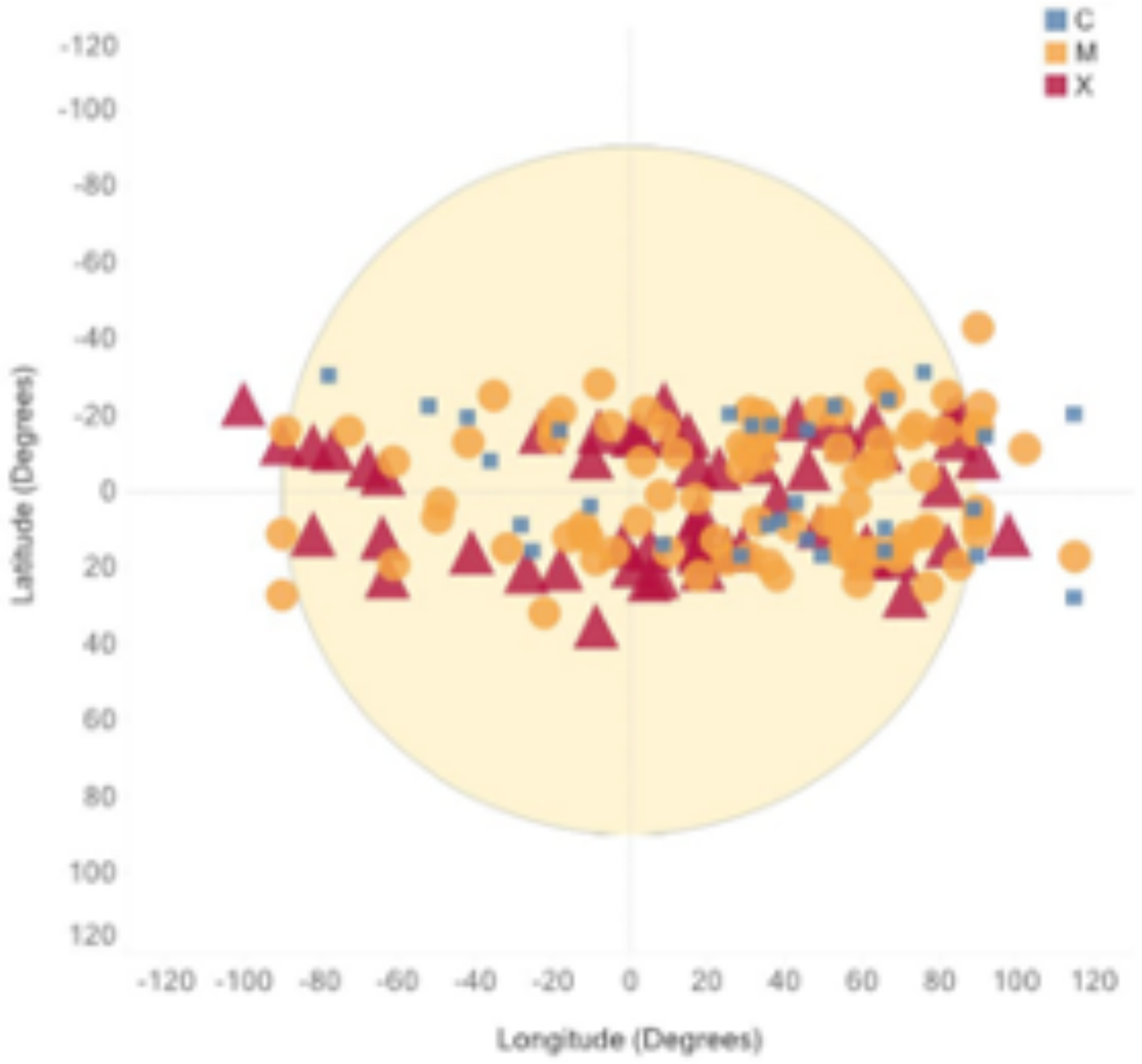
- Flux / fluence



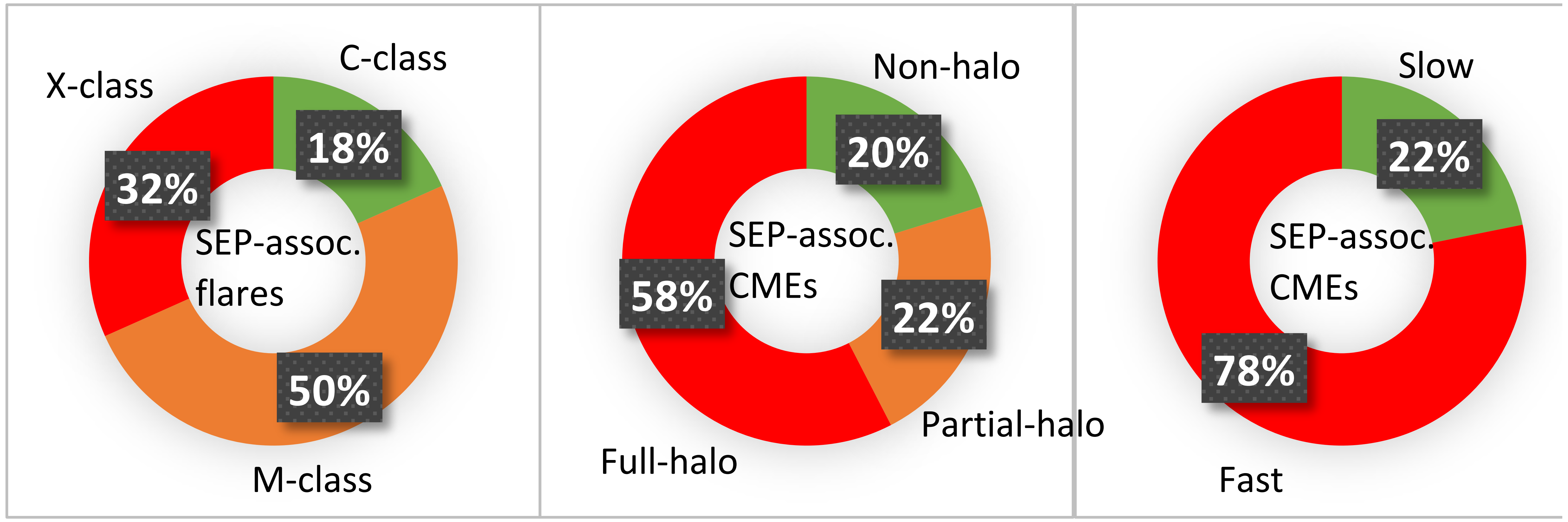
Events become increasingly rare as we go toward SEPs: in any given solar cycle, there are 1000s modest flares but only few great ones; tens of thousands modest CMEs but only few very fast and fully oriented toward Earth; and there are very few (10s) SEP events at Earth

SOLAR WEATHER IN HARD, COLD NUMBERS: APRIL 1997 - NOVEMBER 2017





- Over period of interest: 23,129 flares; 29,390 CMEs; **206 SEPs**



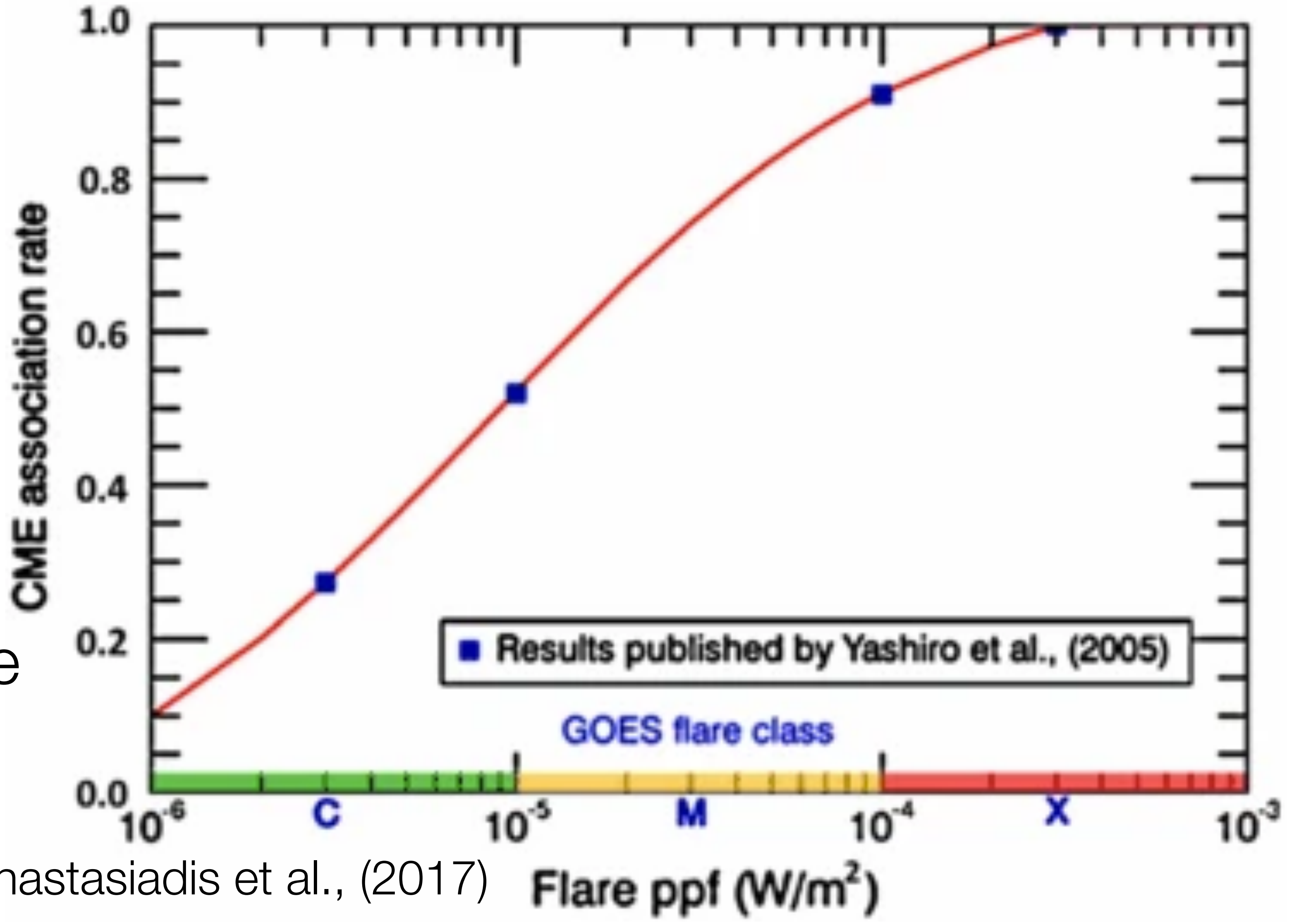
Overall flare and SEP association regardless of heliographic location:

- ☐ C-class flares: **1 : 634**
- ☐ M-class flares: **1 : 24**
- ☐ X-class flares: **1 : 3**

Overall CME and SEP association regardless of heliographic location:

- ☐ Non-halo CMEs: **1 : 630**
- ☐ Fast CMEs (>750 km/s): **1 : 12**
- ☐ Halo CMEs: **1 : 6**
- ☐ Fast & halo CMEs: **1 : 1.8**

- Larger flares are increasingly rare
- Larger flares are increasingly associated with CMEs
- CMEs associated with major flares are statistically faster



Anastasiadis et al., (2017)

Predicting major flares and fast, shock-fronted, Earth-oriented CMEs presents the central objective of solar weather forecasting

WHY CARE? AVIATION, BUT MOSTLY SPACE EXPLORATION

HIGH RISK

MEDIUM RISK


Credit: NASA

ISS extravehicular activities (present)

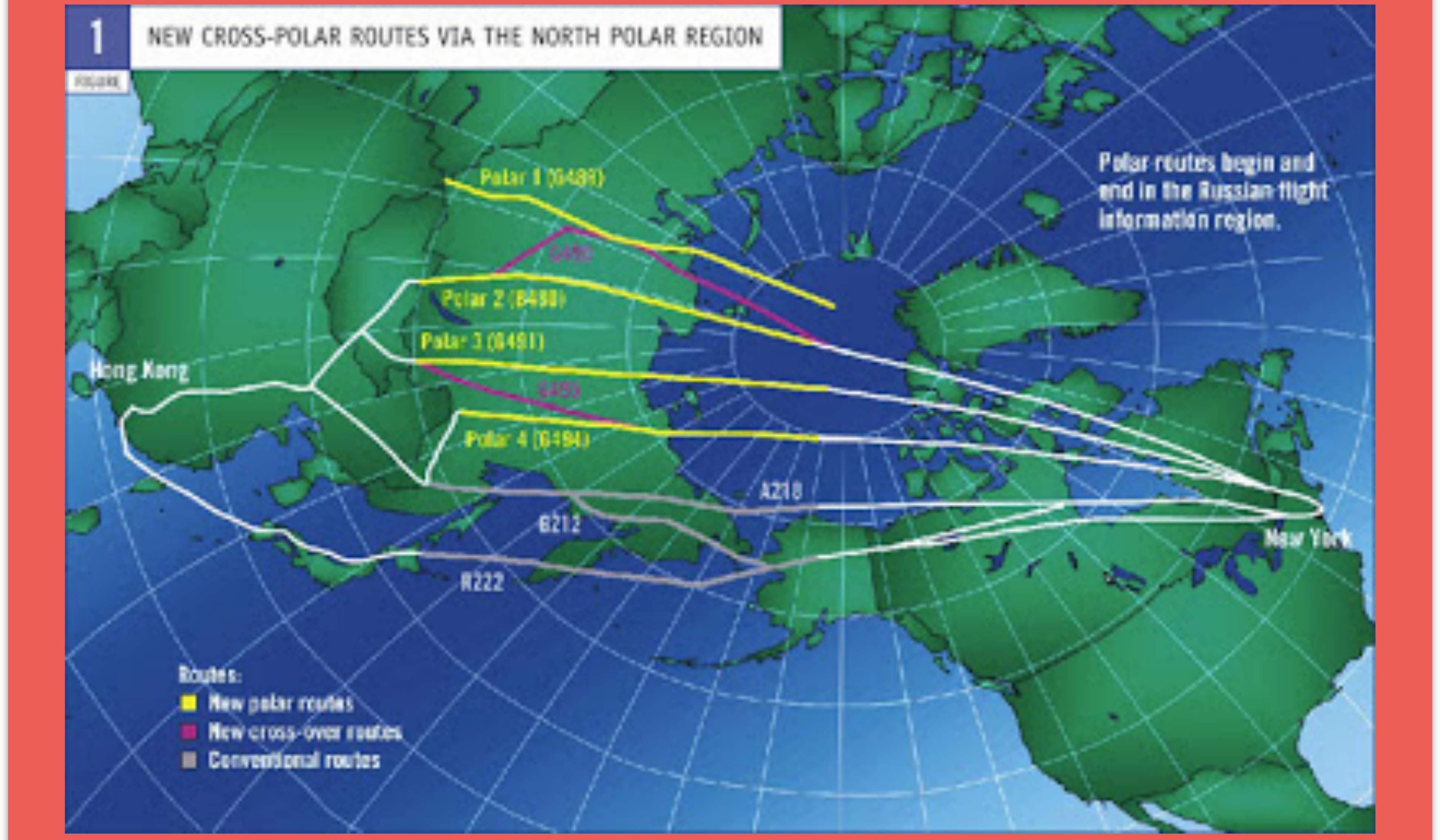

Credit: ESA

Lunar outposts / Moonvilage (near future)

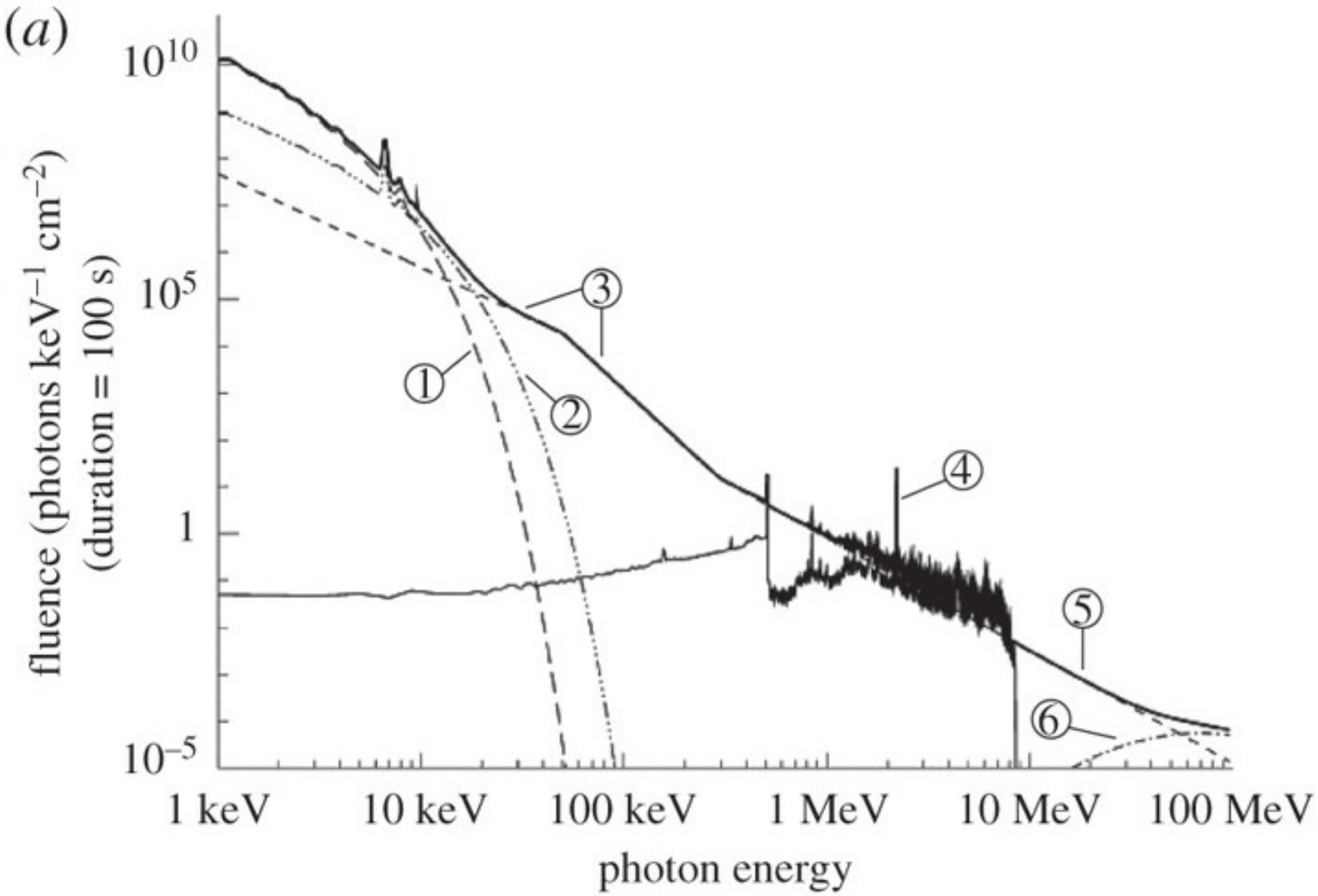

Space travel (future)


Martian outposts (future)


Transpolar flights (present)



BIOLOGICAL IMPACT: ELECTROMAGNETIC FLARE EMISSION



Composite X- / γ -ray EM spectrum of a large flare (Lin et al., 2003; Vilmer 2012)

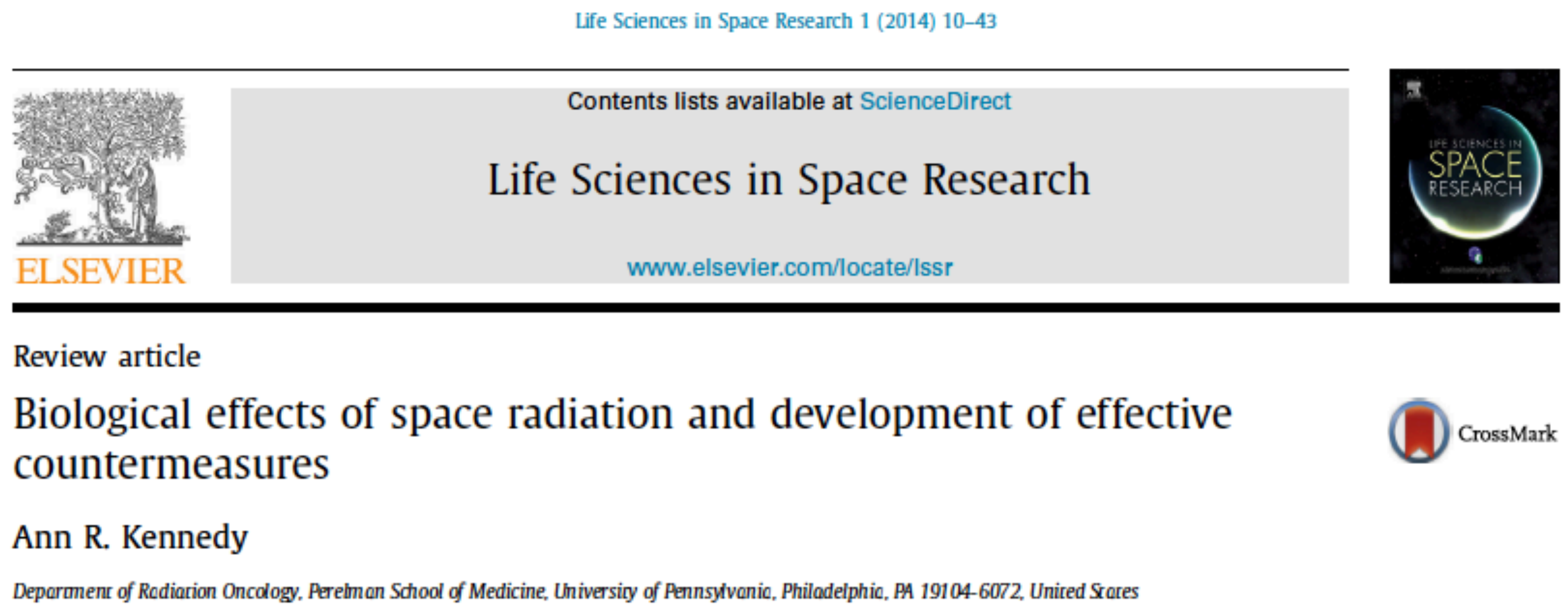
- Any photons above 10 keV: X-rays
- Anything above 100 keV: hard X-rays
- Anything above 500 keV: γ-rays
- Take a 100 keV hard X-ray photon:

— frequency: ~ 10^{19} Hz

— wavelength: ~ 0.012 nm (1.2 x 10^{-5} microns)

Can wreak havoc in cells, DNA sequences, etc.

Kennedy (2014)



Life Sciences in Space Research 1 (2014) 10–43

Contents lists available at ScienceDirect

Life Sciences in Space Research

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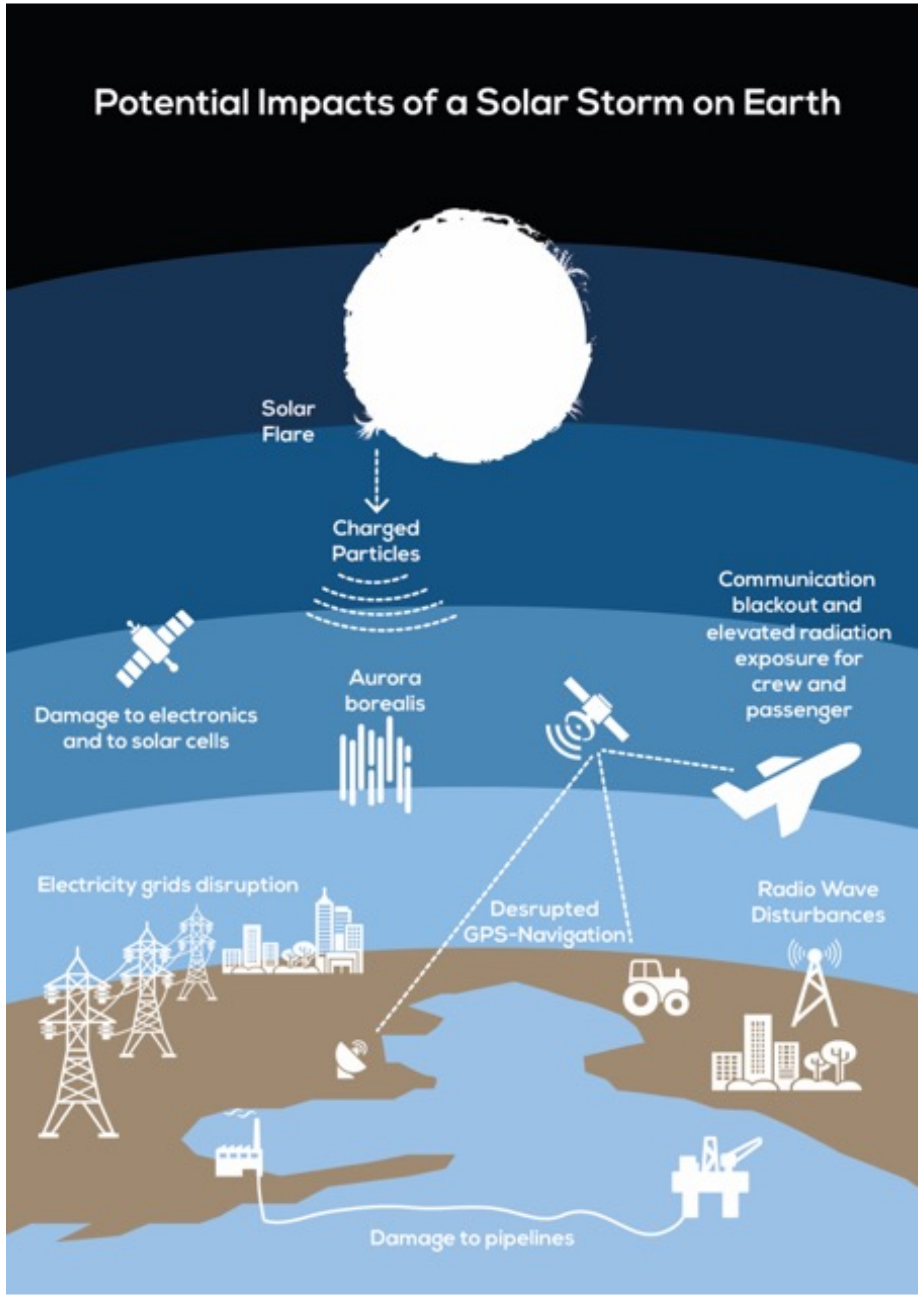
Review article

Biological effects of space radiation and development of effective countermeasures

Ann R. Kennedy

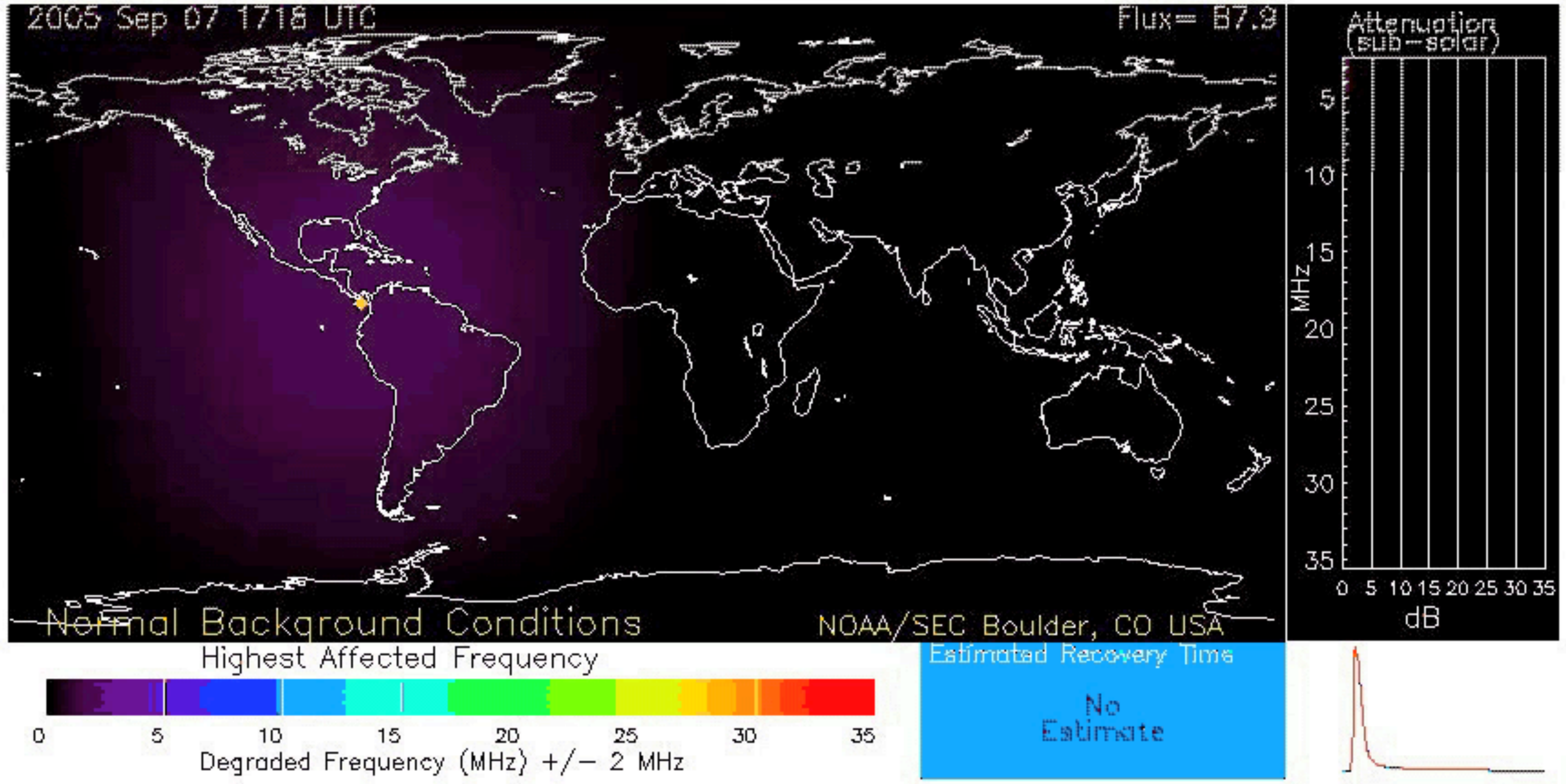
Department of Radiation Oncology, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA 19104-6072, United States

TECHNOLOGICAL IMPACT



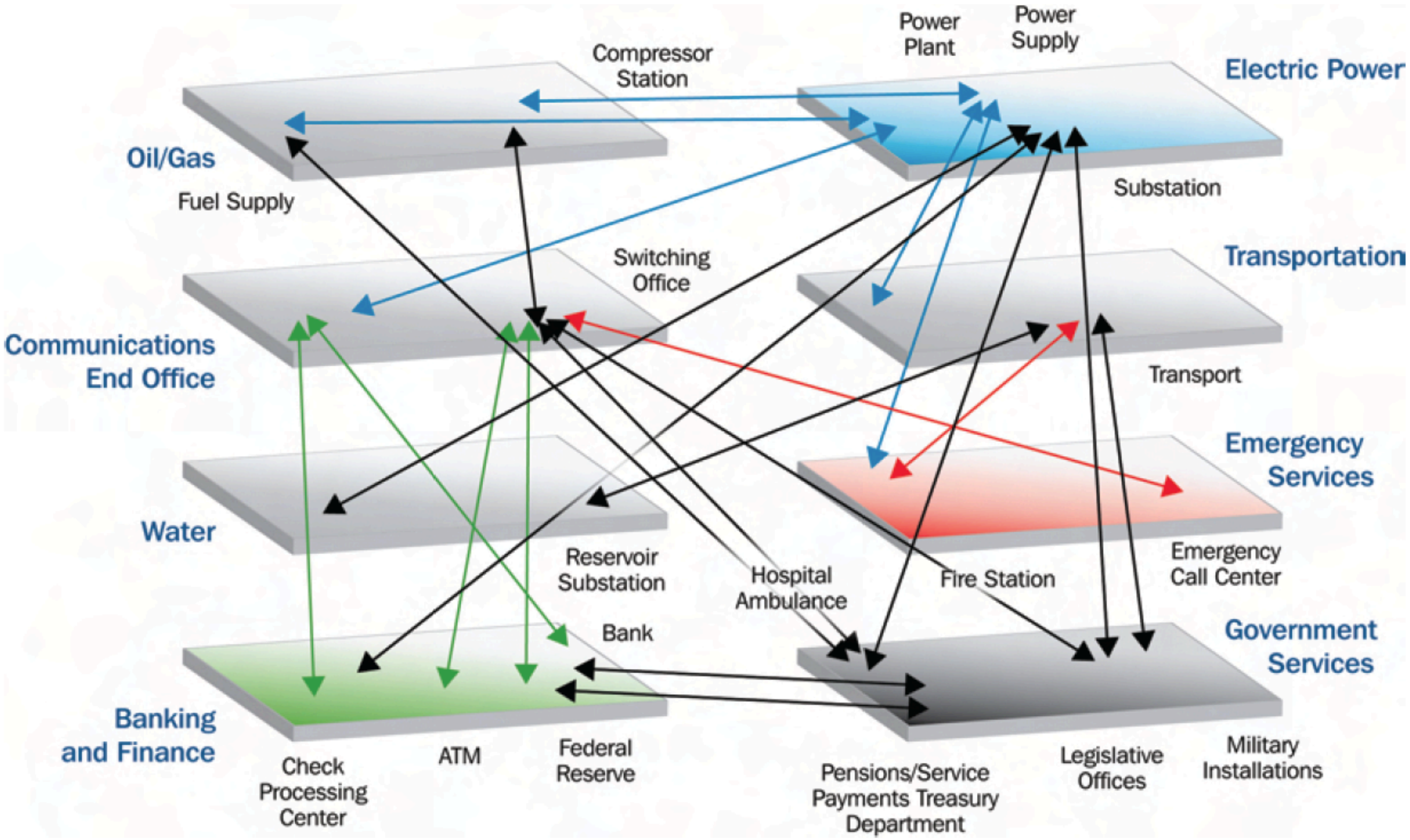
Source: Facchochschule Nordwestschweiz

Radars, telecommunications, satellite operations, GPS, long-range high-voltage electricity networks, activities on the ground



Global ionospheric disturbances virtually immediately after major flares

(TECH) IMPACT OF SOLAR ERUPTIONS: THE BIG PICTURE



Source: Severe Space Weather Events: Understanding Societal and Economic Impacts, NAS Press (2008)

Nonlinearly interconnected societal infrastructures, meaning that an if an infrastructure goes down, others will be affected virtually instantly in a hardly predictable manner.

For example, notice that a significant GPS disruption may not allow you to withdraw cash from an ATM because the ATM itself will not be able to verify its position, hence will not 'know' whether it is where it should be

SOLAR WEATHER PROBLEMS AT A GLANCE

solar flare

arrival of "hard" (X-, γ)-ray photons

arrival of first flare-accelerated SEPs

More SEPs

arrival of CME

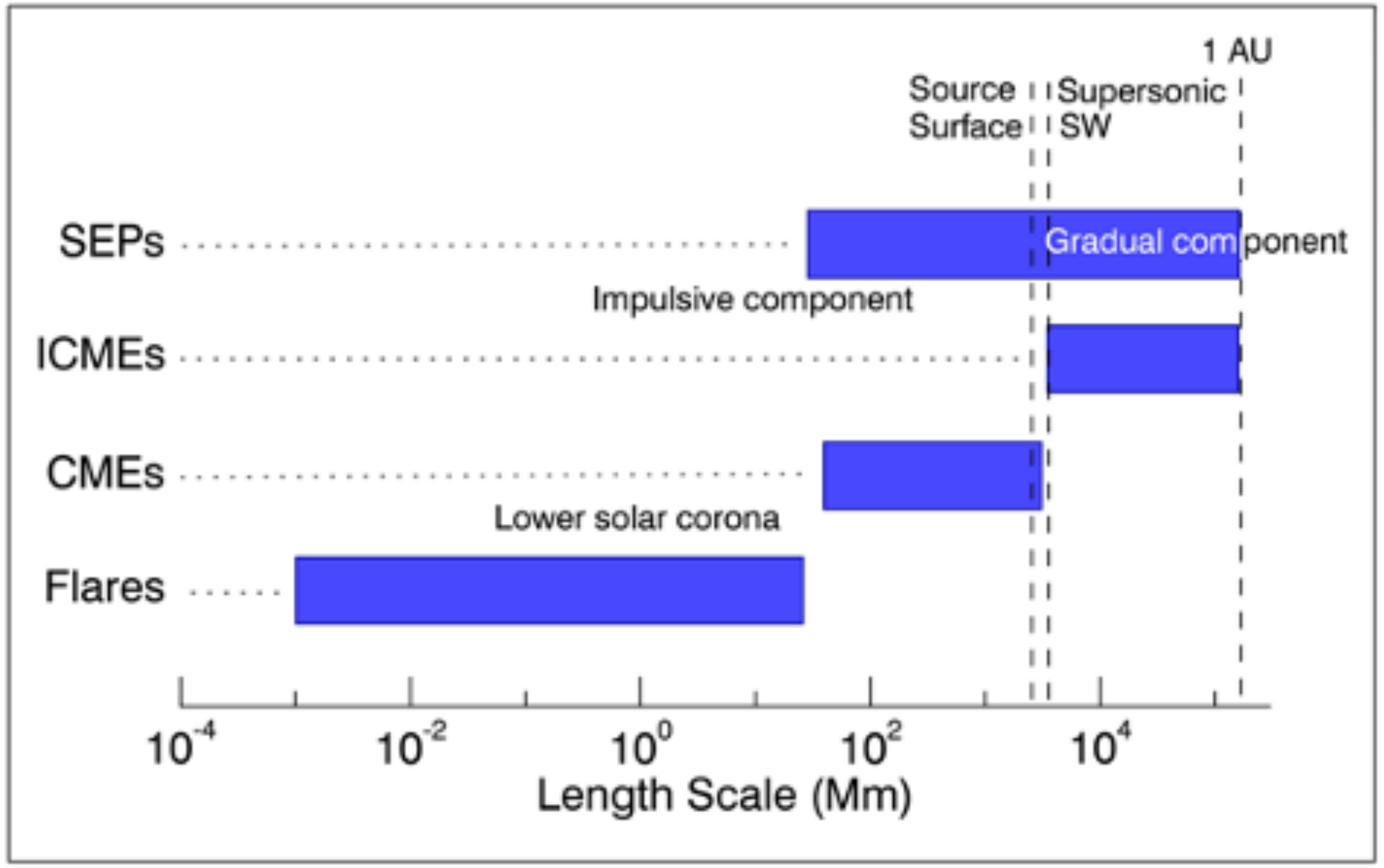
arrival of CME-shock-accelerated particles

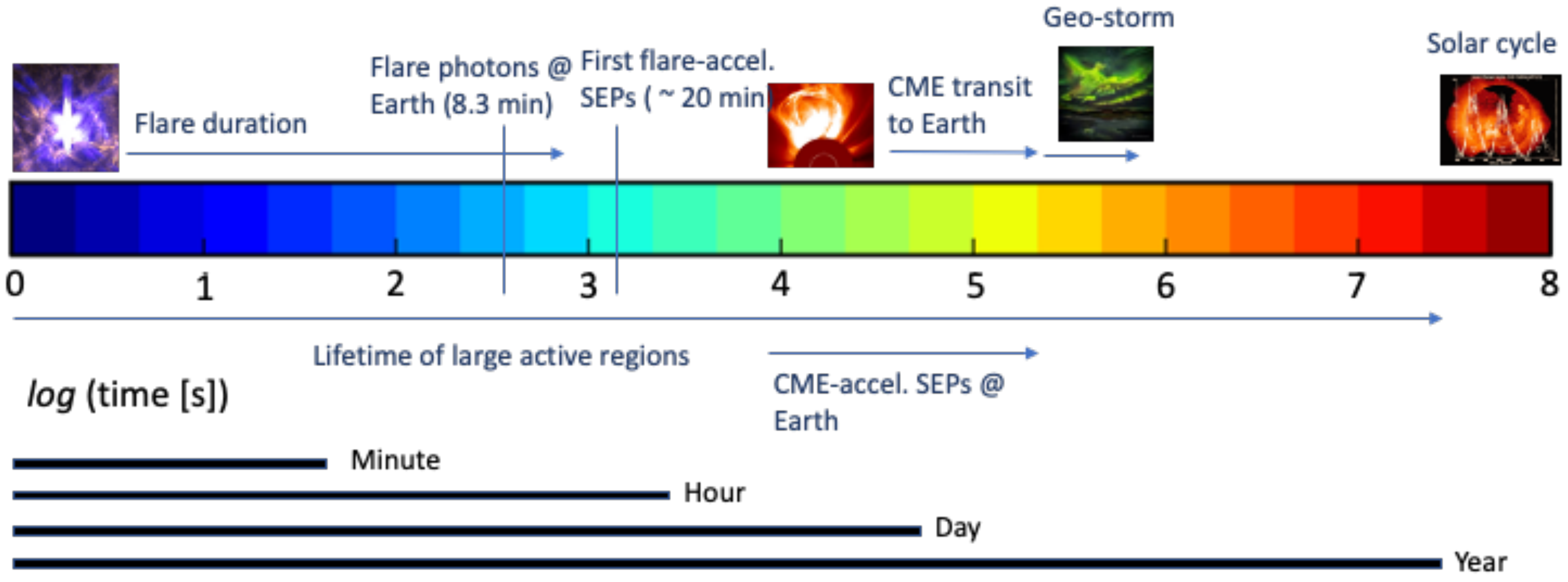
t_0

t_0+ 8 min

~ t_0+ 20 min

t_0+ 2-4 days





If we wanted to predict the entire solar weather (wishful thinking) then we would need to account for 8 orders of magnitude of variation in space and 8 orders or magnitude of variation in time!

SPACE WEATHER FORECASTING: WHAT IS IT?

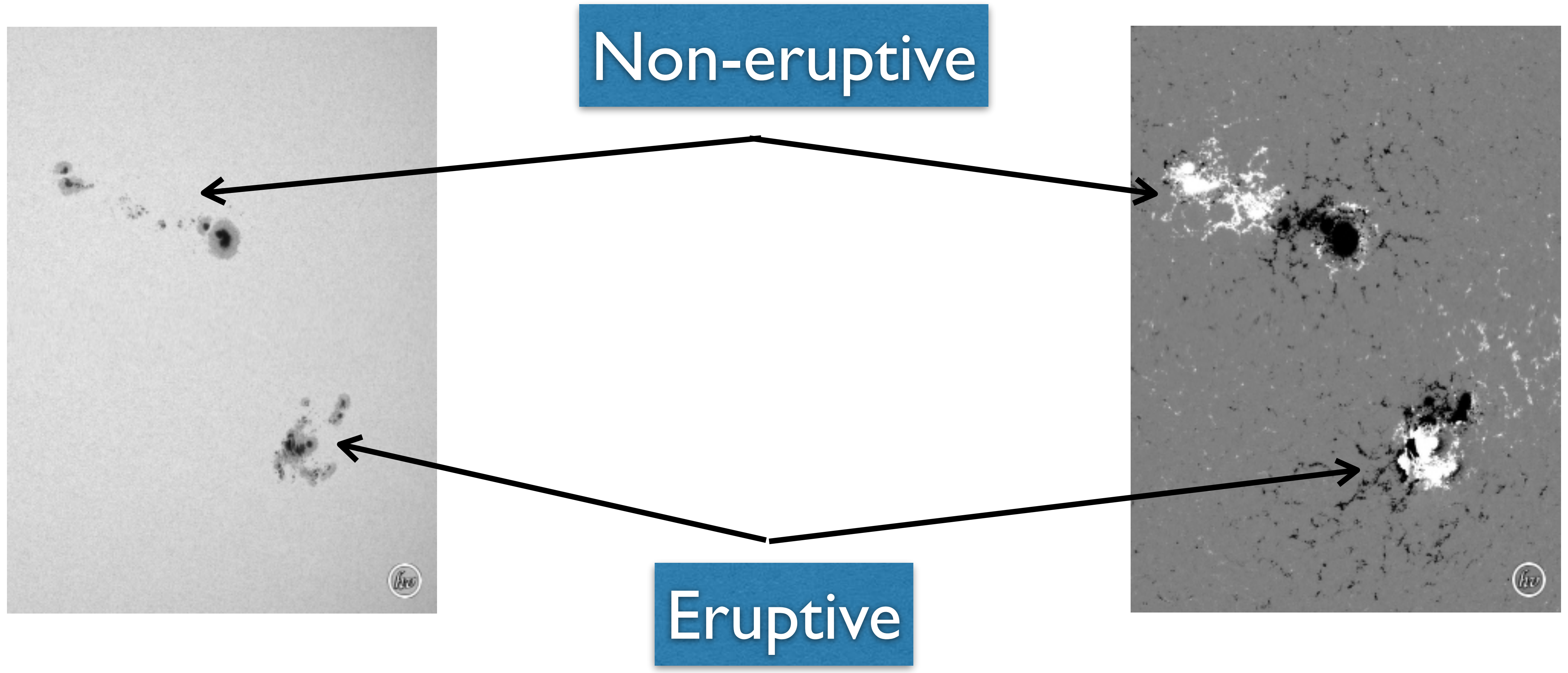
In simple terms, let us call it the passage from research to operations (R2O)

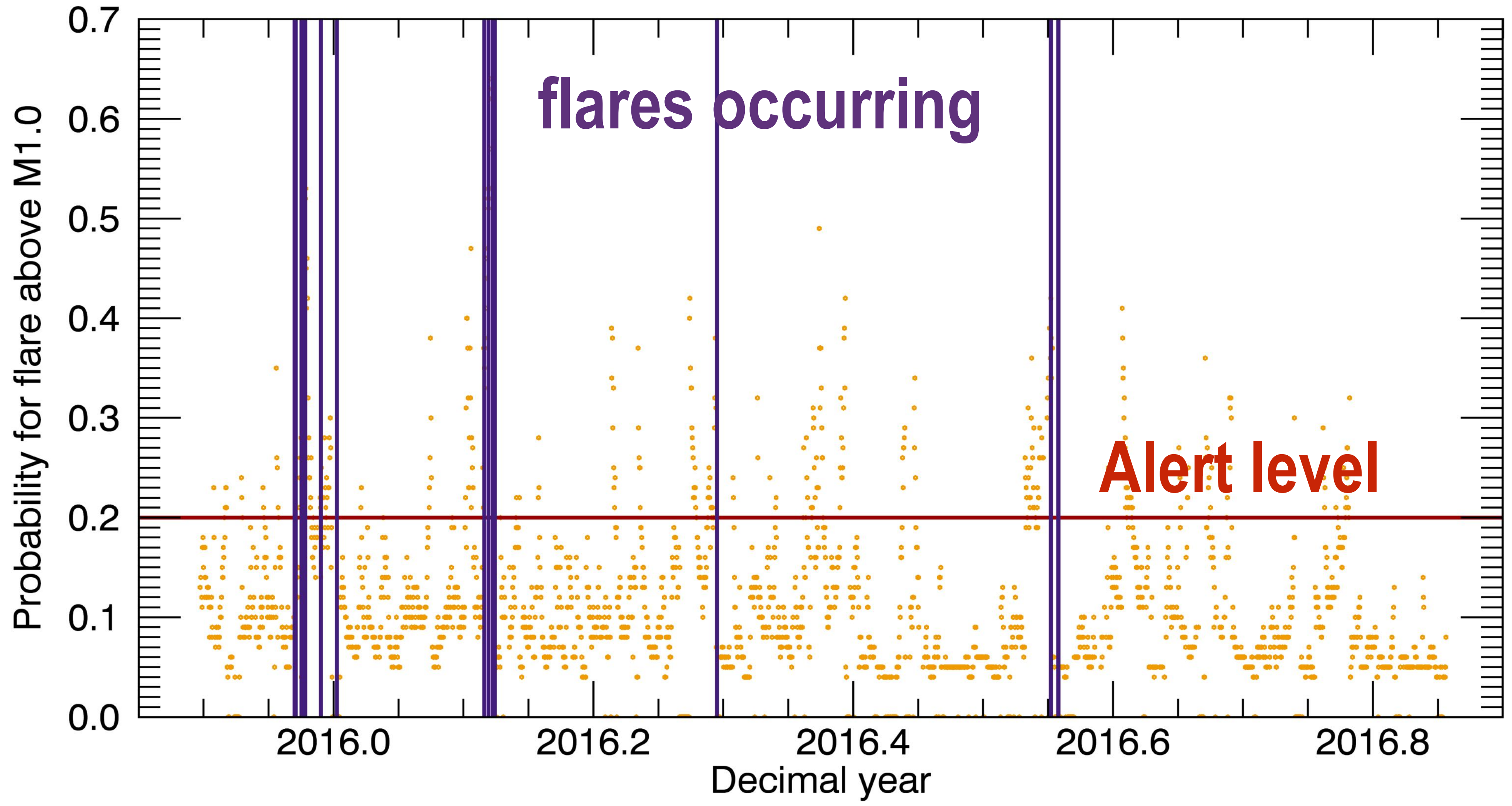
Research

To be able to physically understand and distinguish between eruptive and non-eruptive situations, active regions, etc.

Operations

To be able to say when an event of foreseen properties will be happening within a well-defined time interval



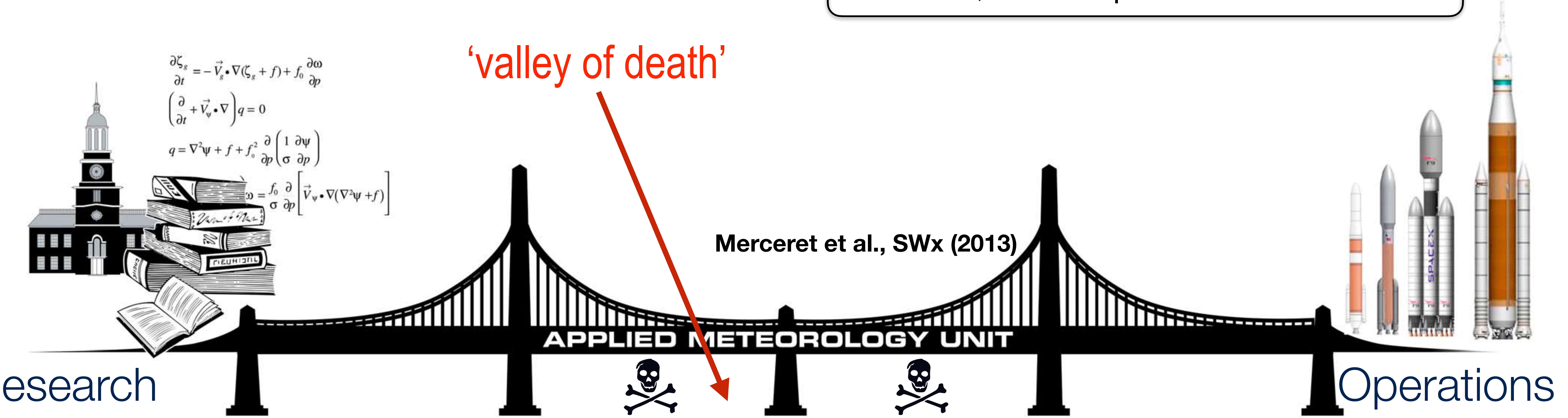


SPACE WEATHER FORECASTING: HOW TO?

- A complex, multi-level research to operations (R2O), real-world problem
- Use basic, interdisciplinary research to reach results with a (hopefully) operational benefit

Task: how to transform the ‘valley of death’ into a valley of opportunity

- One or more forecast models
- Data to train and test on
- Data, model & performance verification



‘valley of death’

Merceret et al., SWx (2013)

Research

Operations

SOLAR FLARE PREDICTION

- **What we know:**

— flares are a stochastic phenomenon, statistically occurring in a self-similar fashion

— only a slim minority of active regions (< 2%) will ever give one or more major flares of NOAA GOES X-class (X-ray flux > 10^{-4} W / m^2)

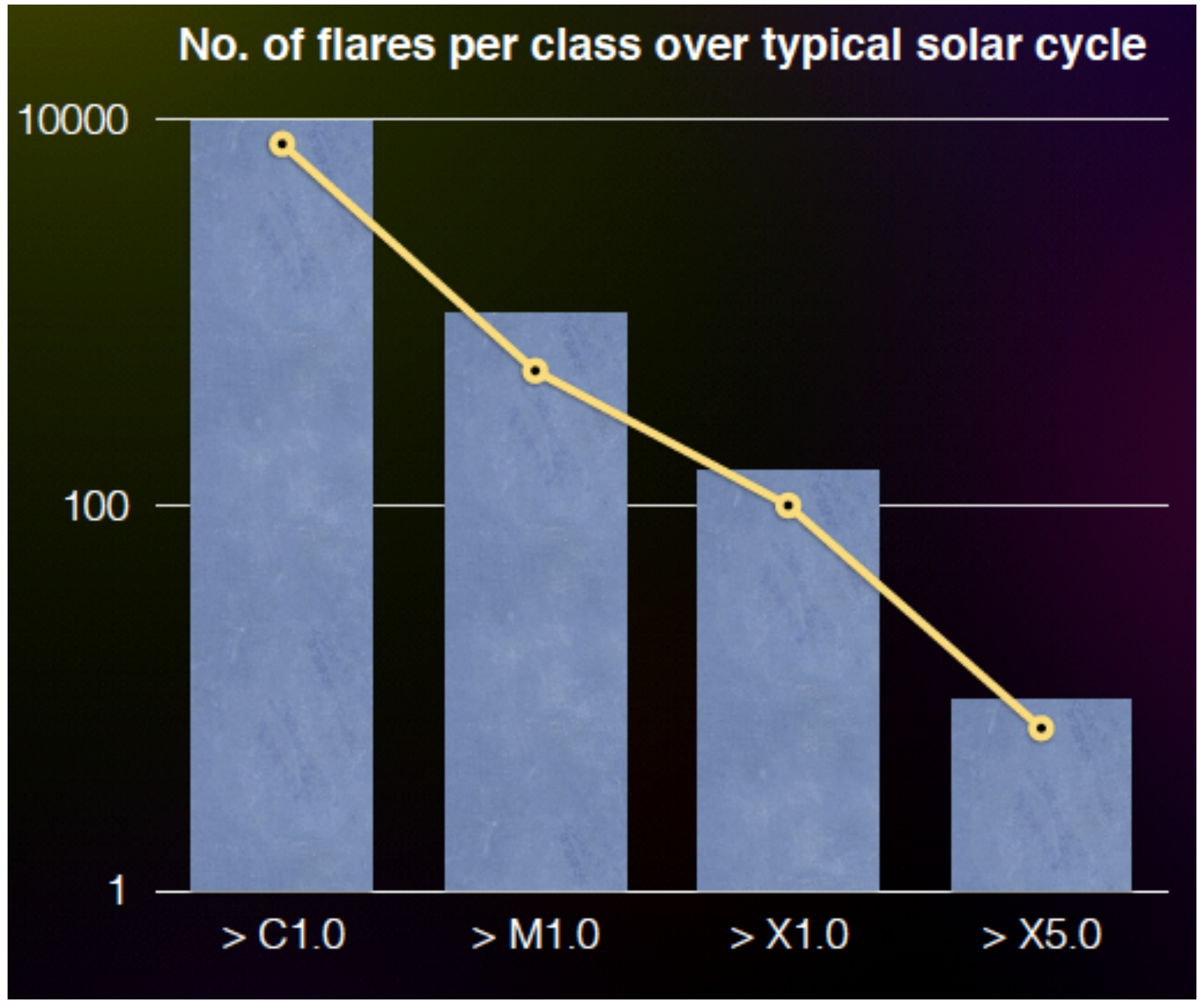
— statistically, severely class-imbalanced events

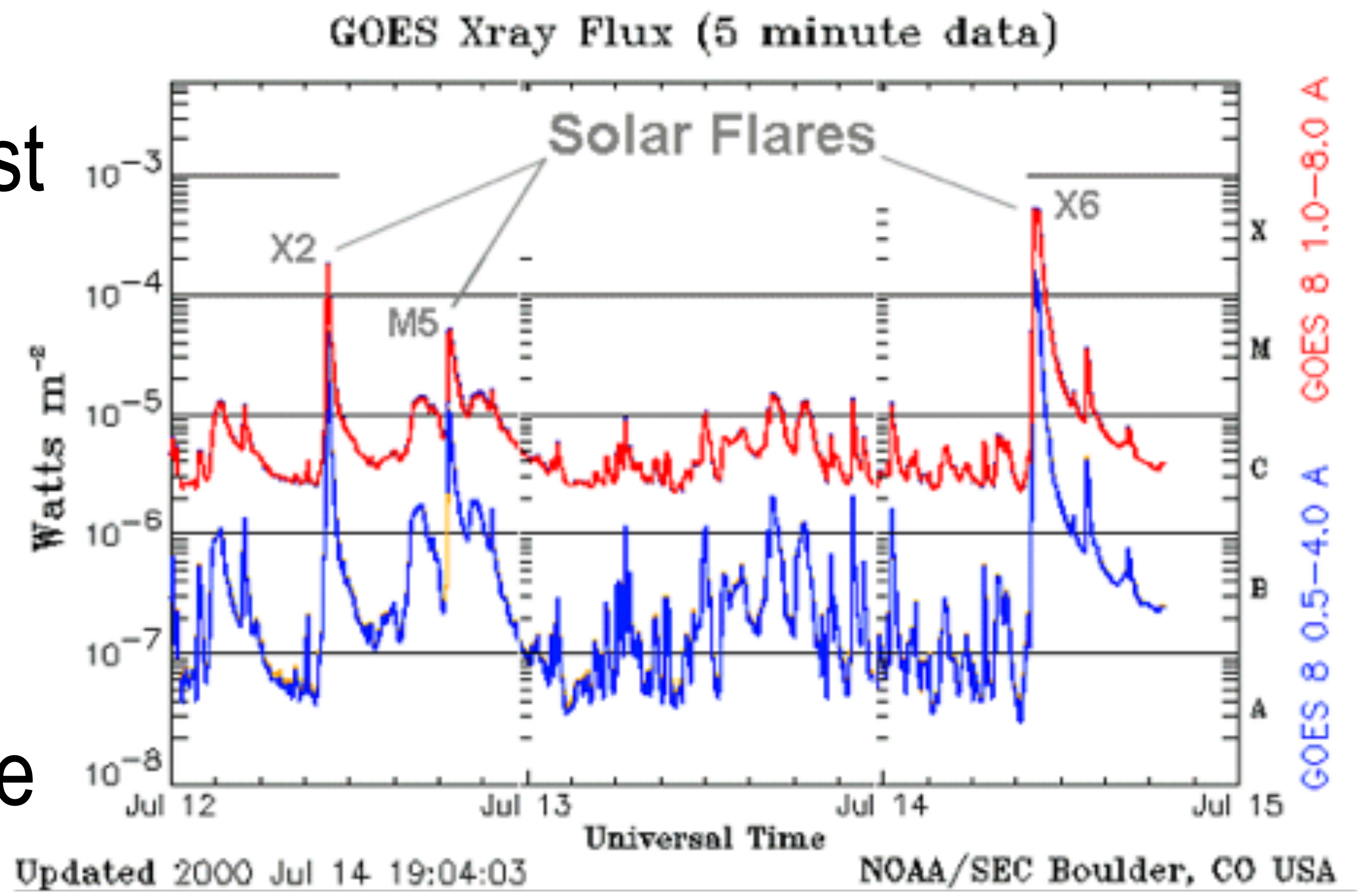
— essentially restricted in photosphere, where **B**-field measurements exist

— due to stochasticity, the classical magnetic energy and helicity parameters are not appropriate for forecasting

- **What we aim for:**

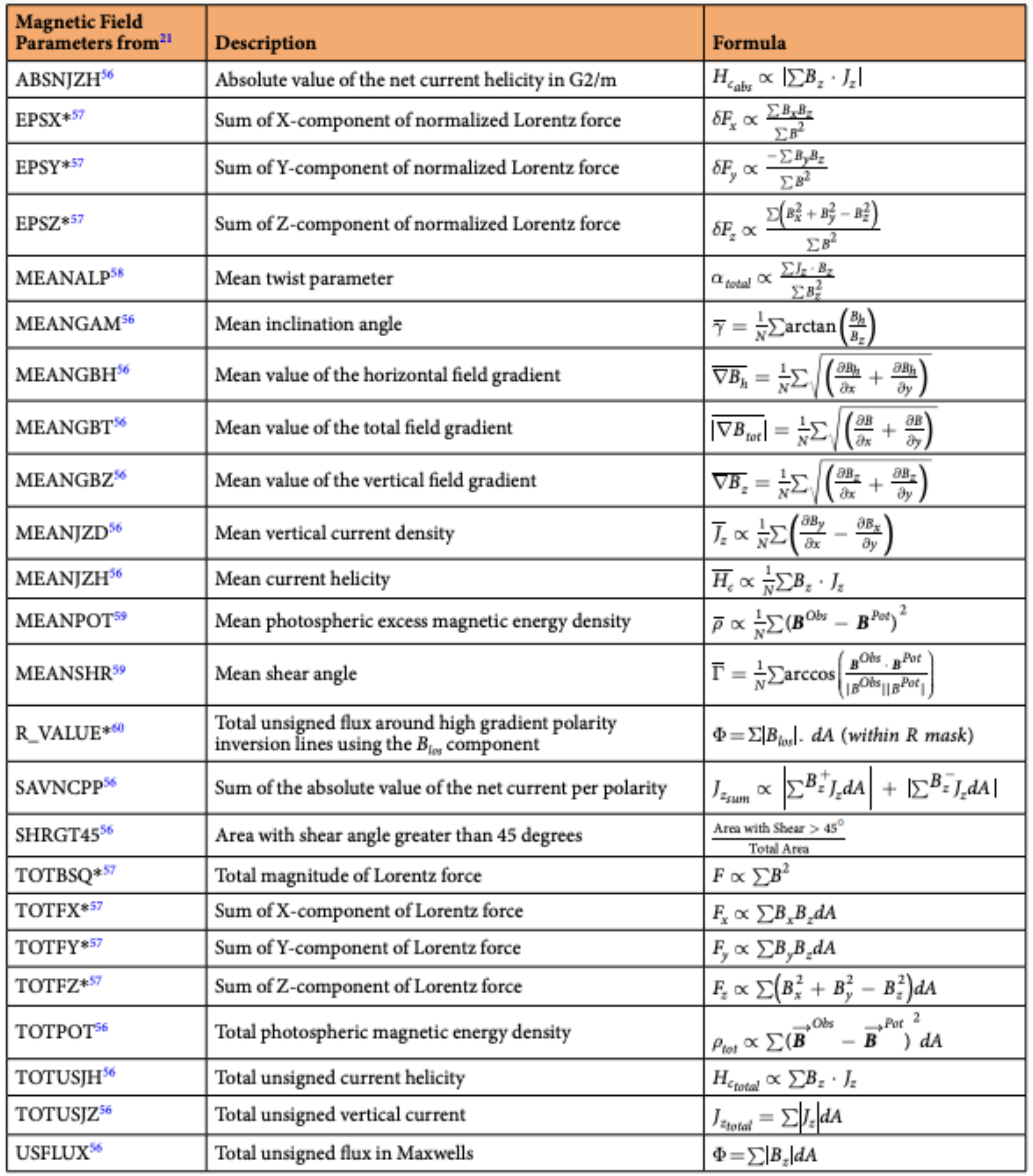
— reliable (i.e., verified) flare forecast 6 - 24 hours <u>before</u> flare occurrence in the Sun (since there is no early-warning window for flare photons)





"Active" solar conditions

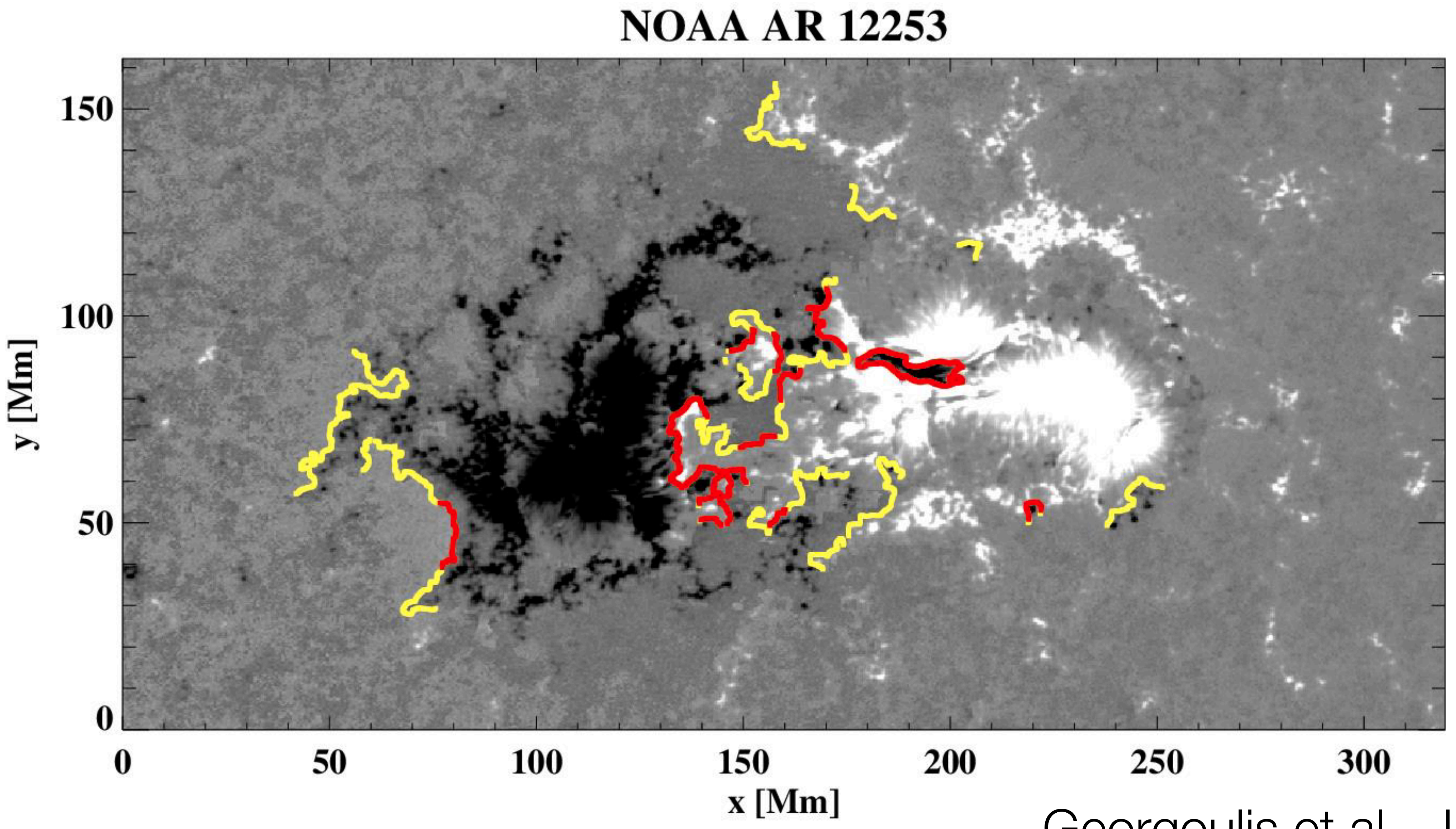
SOLAR FLARE PREDICTION: HOW TO



Magnetic Field Parameters from[21]	Description	Formula
ABSNJZH[56]	Absolute value of the net current helicity in G2/m	$H_{c_{abs}} \propto \lvert \sum B_z \cdot J_z \rvert$
EPSX*[57]	Sum of X-component of normalized Lorentz force	$\delta F_x \propto \frac{\sum B_x B_z}{\sum B^2}$
EPSY*[57]	Sum of Y-component of normalized Lorentz force	$\delta F_y \propto \frac{-\sum B_y B_z}{\sum B^2}$
EPSZ*[57]	Sum of Z-component of normalized Lorentz force	$\delta F_z \propto \frac{\sum\left(B_x^2 + B_y^2 - B_z^2\right)}{\sum B^2}$
MEANALP[58]	Mean twist parameter	$\alpha_{total} \propto \frac{\sum J_z \cdot B_z}{\sum B_z^2}$
MEANGAM[56]	Mean inclination angle	$\overline{\gamma} = \frac{1}{N}\sum \arctan\left(\frac{B_h}{B_z}\right)$
MEANGBH[56]	Mean value of the horizontal field gradient	$\overline{\nabla B_h} = \frac{1}{N}\sum\sqrt{\left(\frac{\partial B_h}{\partial x} + \frac{\partial B_h}{\partial y}\right)}$
MEANGBT[56]	Mean value of the total field gradient	$\overline{\lvert\nabla B_{tot}\rvert} = \frac{1}{N}\sum\sqrt{\left(\frac{\partial B}{\partial x} + \frac{\partial B}{\partial y}\right)}$
MEANGBZ[56]	Mean value of the vertical field gradient	$\overline{\nabla B_z} = \frac{1}{N}\sum\sqrt{\left(\frac{\partial B_z}{\partial x} + \frac{\partial B_z}{\partial y}\right)}$
MEANJZD[56]	Mean vertical current density	$\overline{J_z} \propto \frac{1}{N}\sum\left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right)$
MEANJZH[56]	Mean current helicity	$\overline{H_c} \propto \frac{1}{N}\sum B_z \cdot J_z$
MEANPOT[59]	Mean photospheric excess magnetic energy density	$\overline{\rho} \propto \frac{1}{N}\sum\left(\boldsymbol{B}^{Obs} - \boldsymbol{B}^{Pot}\right)^2$
MEANSHR[59]	Mean shear angle	$\overline{\Gamma} = \frac{1}{N}\sum\arccos\left(\frac{\boldsymbol{B}^{Obs} \cdot \boldsymbol{B}^{Pot}}{\lvert B^{Obs}\rvert\lvert B^{Pot}\rvert}\right)$
R_VALUE*[60]	Total unsigned flux around high gradient polarity inversion lines using the B_{los} component	$\Phi = \sum\lvert B_{los}\rvert .\ dA\ (within\ R\ mask)$
SAVNCPP[56]	Sum of the absolute value of the net current per polarity	$J_{z_{sum}} \propto \left\lvert\sum^{B_z^+} J_z dA\right\rvert + \lvert\sum^{B_z^-} J_z dA\rvert$
SHRGT45[56]	Area with shear angle greater than 45 degrees	$\frac{\text{Area with Shear} > 45^{0}}{\text{Total Area}}$
TOTBSQ*[57]	Total magnitude of Lorentz force	$F \propto \sum B^2$
TOTFX*[57]	Sum of X-component of Lorentz force	$F_x \propto \sum B_x B_z dA$
TOTFY*[57]	Sum of Y-component of Lorentz force	$F_y \propto \sum B_y B_z dA$
TOTFZ*[57]	Sum of Z-component of Lorentz force	$F_z \propto \sum\left(B_x^2 + B_y^2 - B_z^2\right)dA$
TOTPOT[56]	Total photospheric magnetic energy density	$\rho_{tot} \propto \sum\left(\overrightarrow{\boldsymbol{B}}^{Obs} - \overrightarrow{\boldsymbol{B}}^{Pot}\right)^2 dA$
TOTUSJH[56]	Total unsigned current helicity	$H_{c_{total}} \propto \sum B_z \cdot J_z$
TOTUSJZ[56]	Total unsigned vertical current	$J_{z_{total}} = \sum\lvert J_z\rvert dA$
USFLUX[56]	Total unsigned flux in Maxwells	$\Phi = \sum\lvert B_z\rvert dA$

Bobra et al., SoPh (2014, 2015) bur also Angryk et al., Nat.Sci.Data, 2020, Georgoulis et al., JSWSC, 2021

- Using photospheric (line-of-sight or vector) magnetic field measurements to extract a set of properties, to be also treated as predictors



Georgoulis et al., JSWSC 2021

- Train and test on these parameters, by means of statistical and / or artificial intelligence (machine / deep learning) methods
- Validate data, methods and results

CORONAL MASS EJECTIONS

- **What we know:**

— flares are not one-to-one associated with CMEs, but large flares tend to be

— faster CMEs tend to be more geoeffective

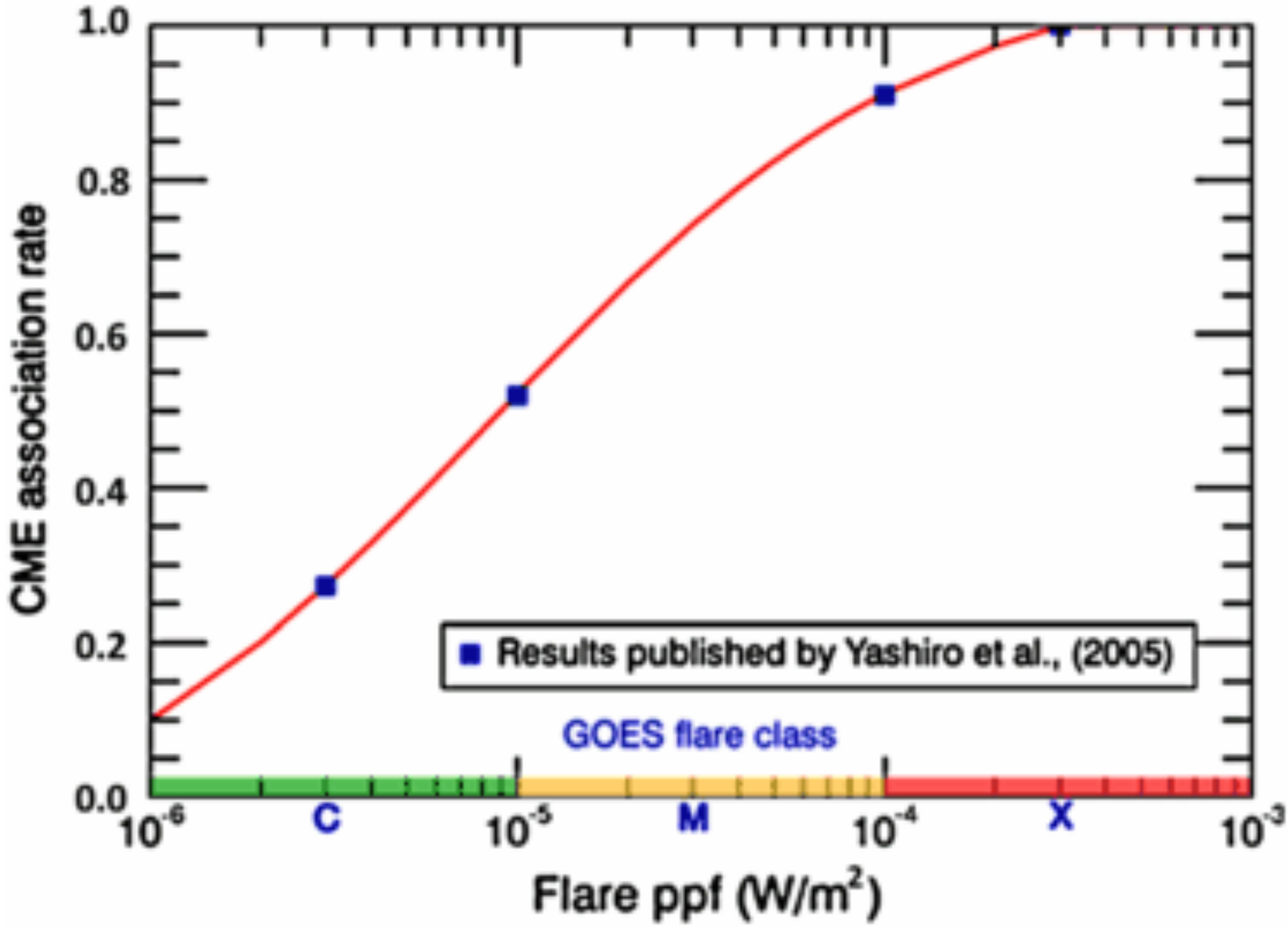
— CMEs originating from the western solar hemisphere tend to be more geoeffective

- **What we aim for:**

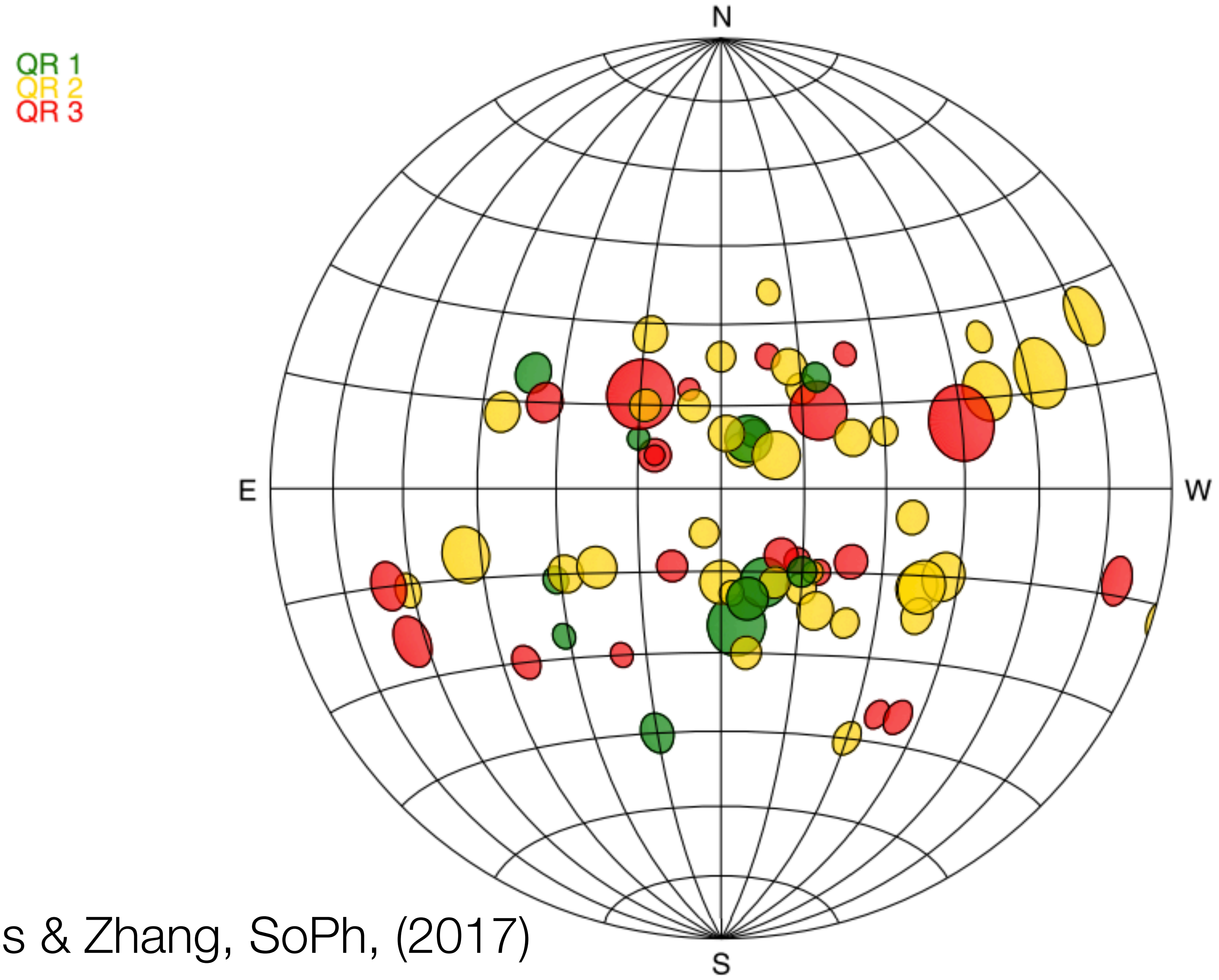
— reliable (i.e., verified) flare forecast 6 - 24 hours before CME occurrence, complete with projected CME characteristics

— CME arrival time at geospace

— CME geoeffectiveness, that is, the amplitude of its G-storm, if any



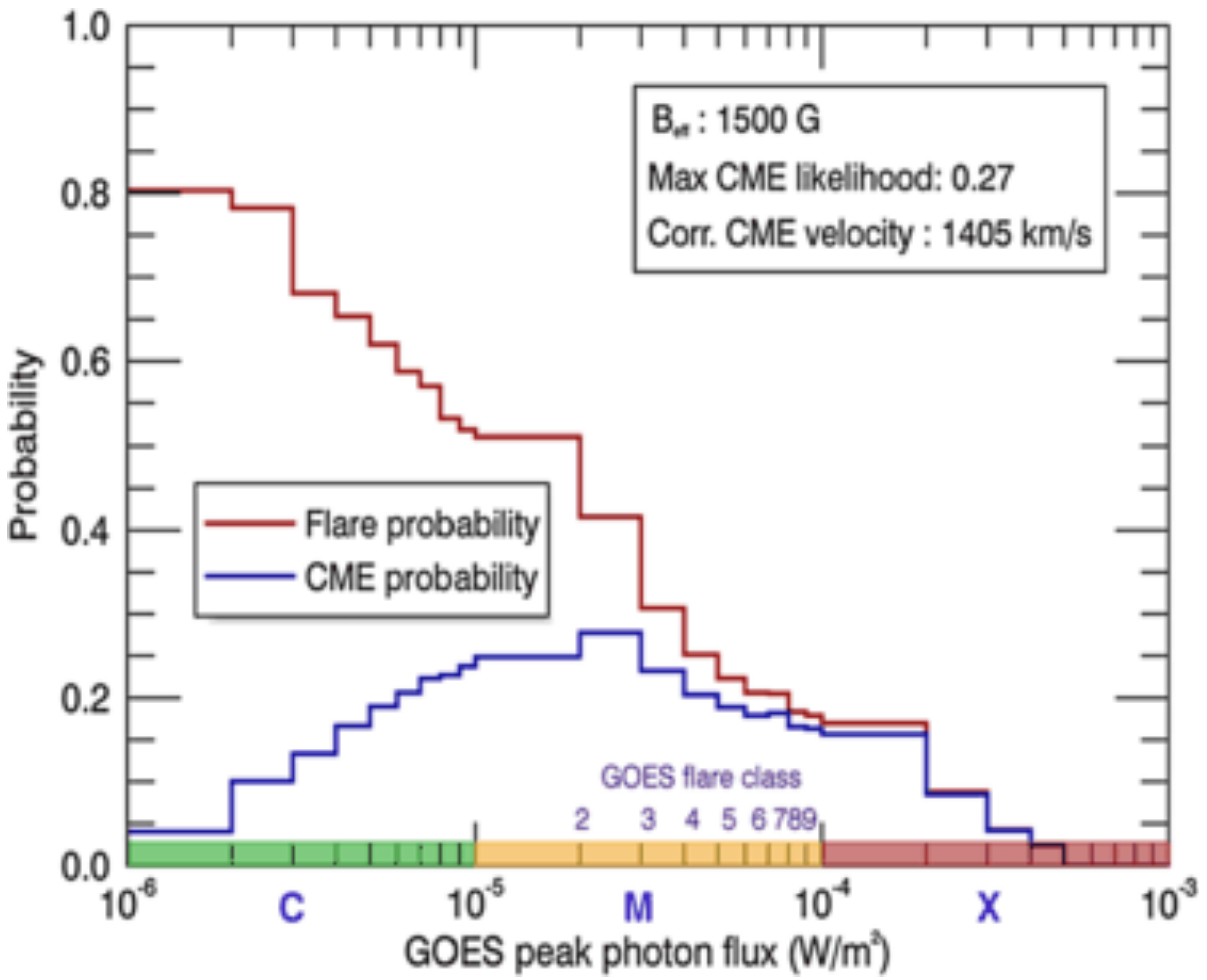
Anastasiadis et al., SoPh, (2017)



Hess & Zhang, SoPh, (2017)

CME PREDICTION: HOW TO

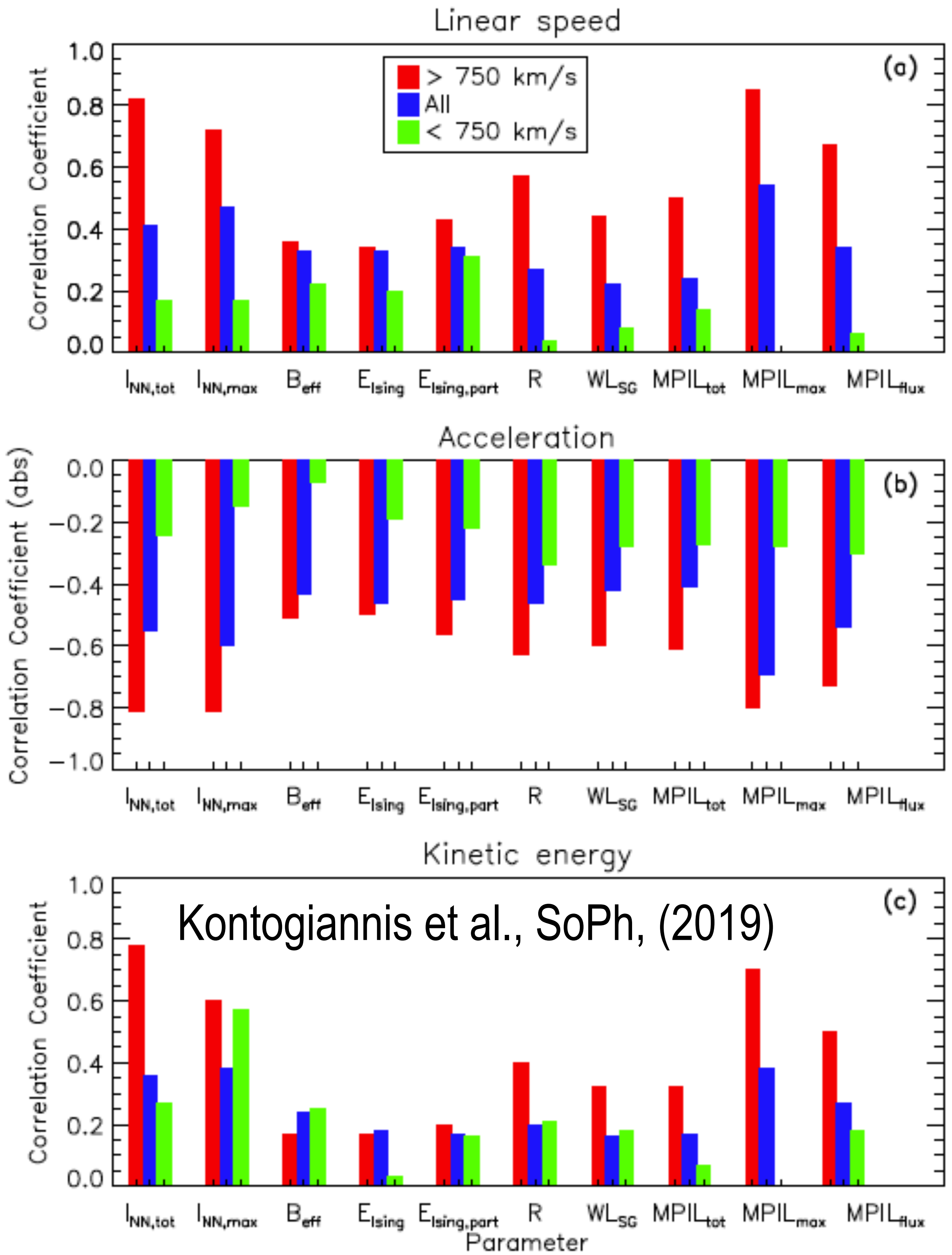
- Occurrence forecasting:



Anastasiadis et al., SoPh, (2017)

Combining flare probabilities with statistical CME associations to find a maximum CME likelihood for each solar flare prediction

- Kinematic characteristics of CMEs



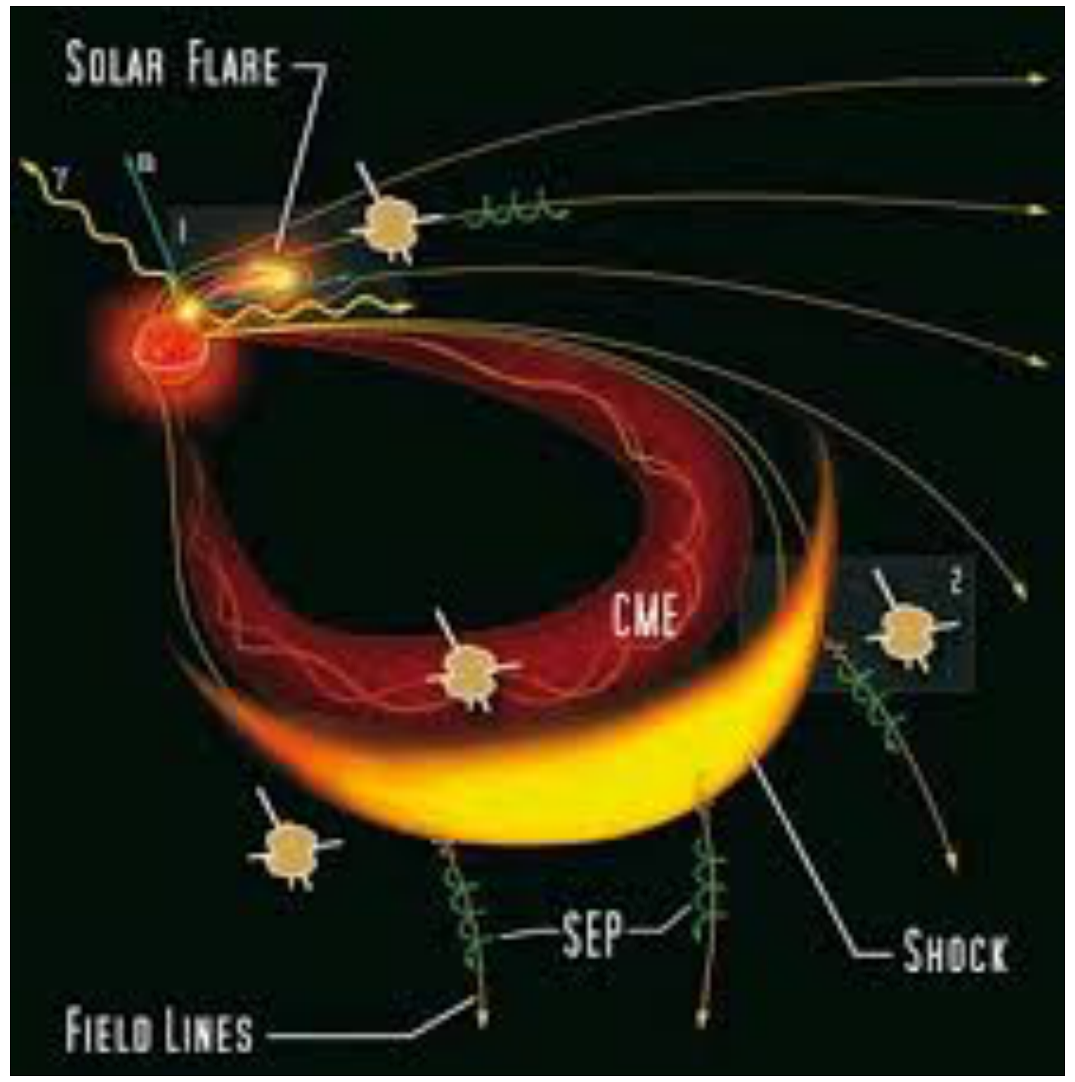
Kontogiannis et al., SoPh, (2019)

Correlate CME near-Sun linear speed, acceleration and kinetic energy with the most promising photospheric characteristics of active regions, to project crucial CME properties for each flare / CME prediction

A particular methodological advantage exists when training from flare to eruptive(i.e., CME-associated) flare prediction

SOLAR ENERGETIC PARTICLE EVENTS

Solar Sentinels STDT Report (2006)



- **What we know:**

— their temporal profiles are sensitive to the source’s location in the solar disk

— typically CME-shock associated, meaning that the source CME should have a shock

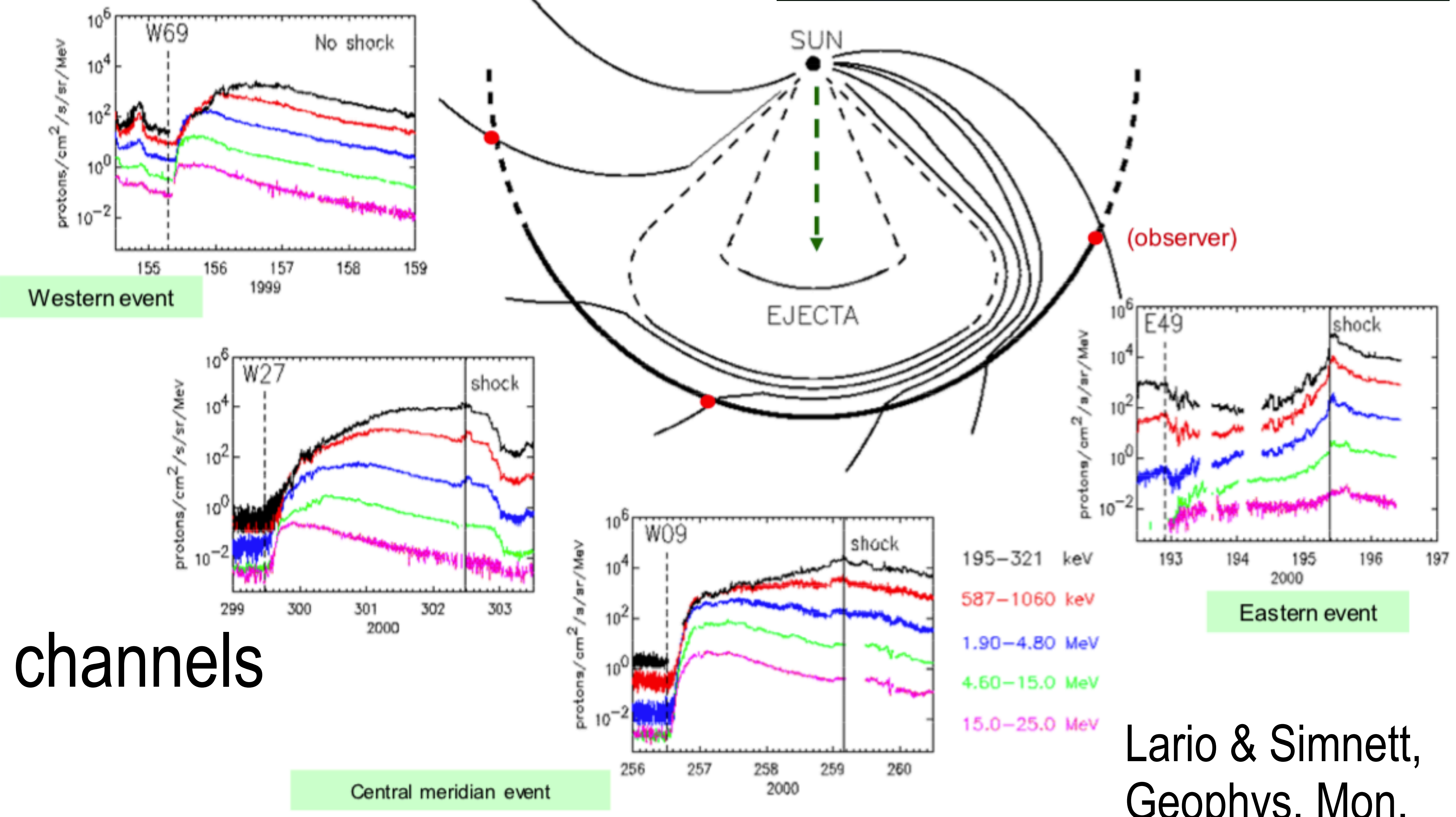
— events originating from the western solar hemisphere are much more likely to be acutely felt at Earth

— major events much more rare than major flares and CME

- **What we aim for:**

— reliable (i.e., verified) forecast 6 - 24 hours prior to the occurrence of event at Earth, regarding

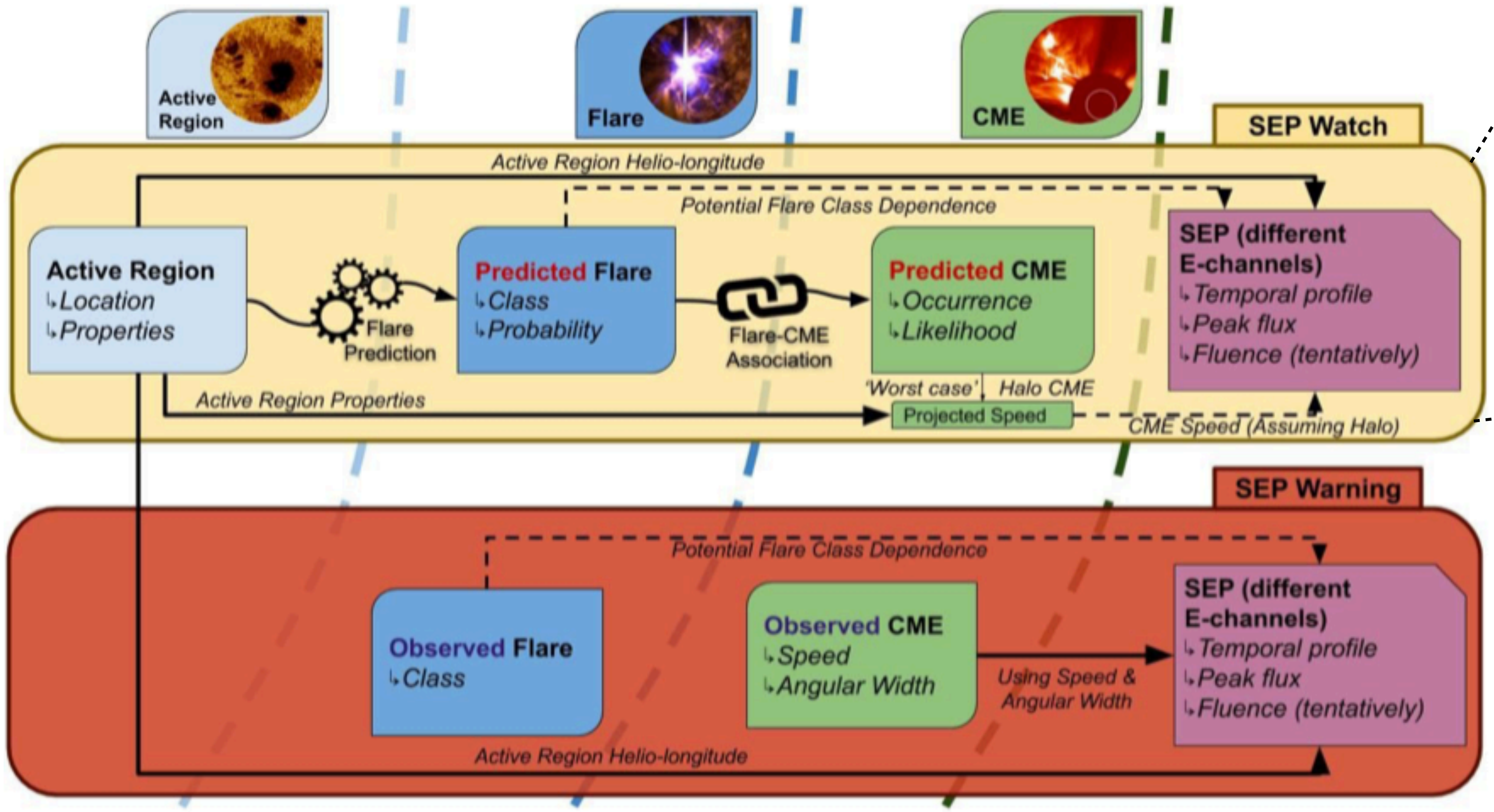
  - event arrival time
  - event peak (proton flux / fluence) for different energy channels
  - event temporal profile

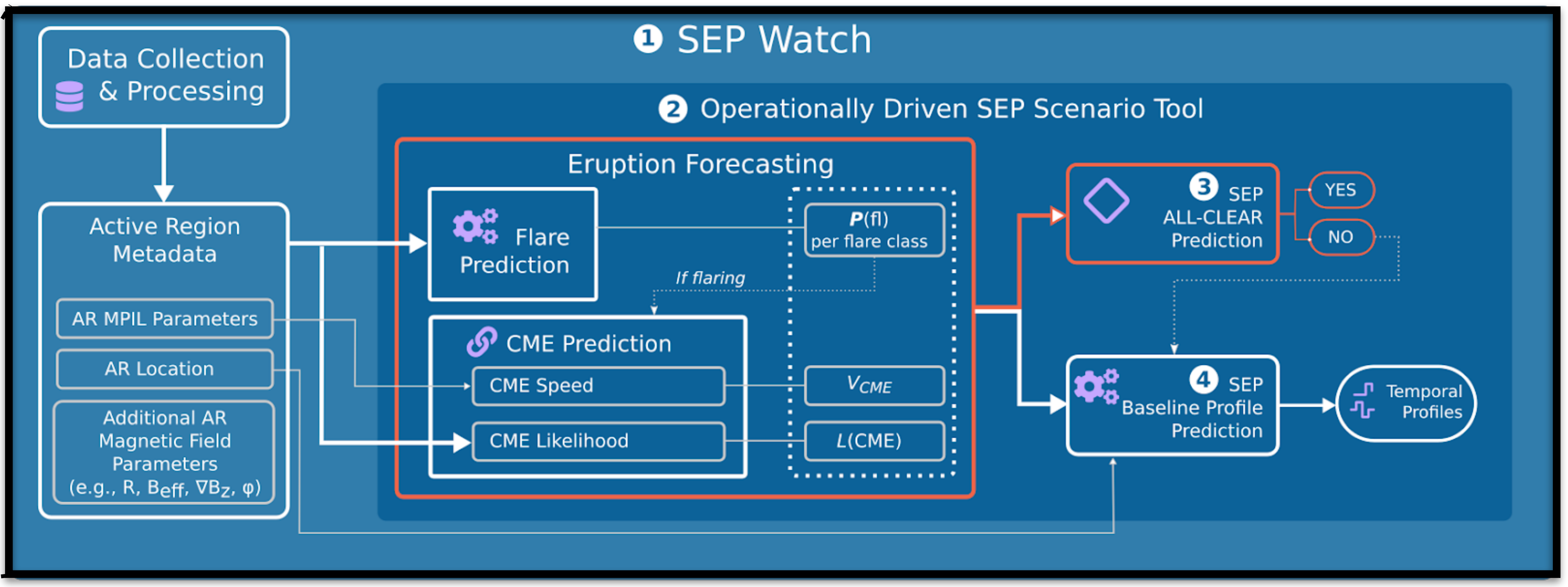


Lario & Simnett, Geophys. Mon. Series, (2004)

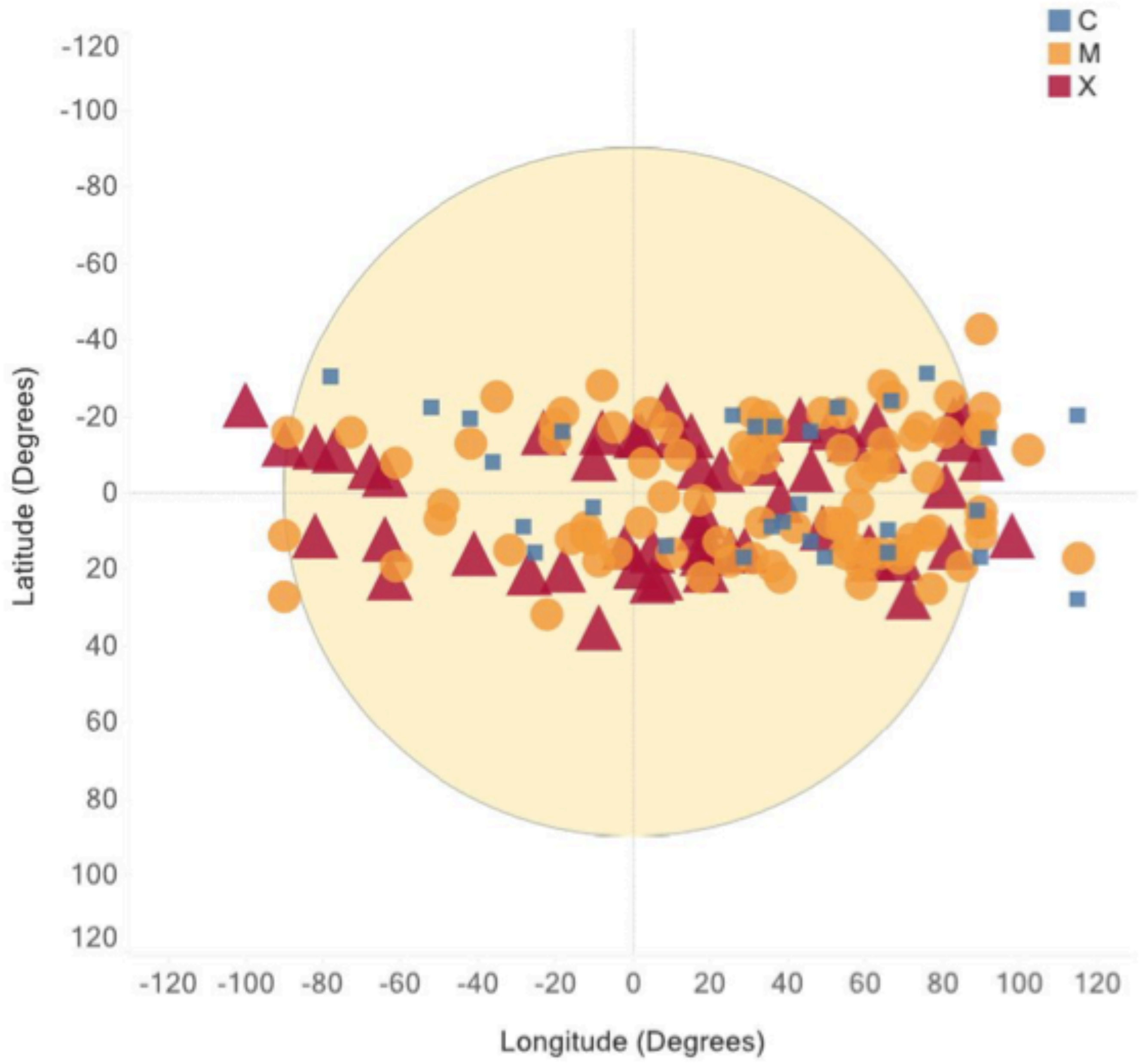
SOLAR ENERGETIC PARTICLE EVENTS FORECASTING: HOW TO

From flares → to eruptive flares → to SEP-assoc. shocks





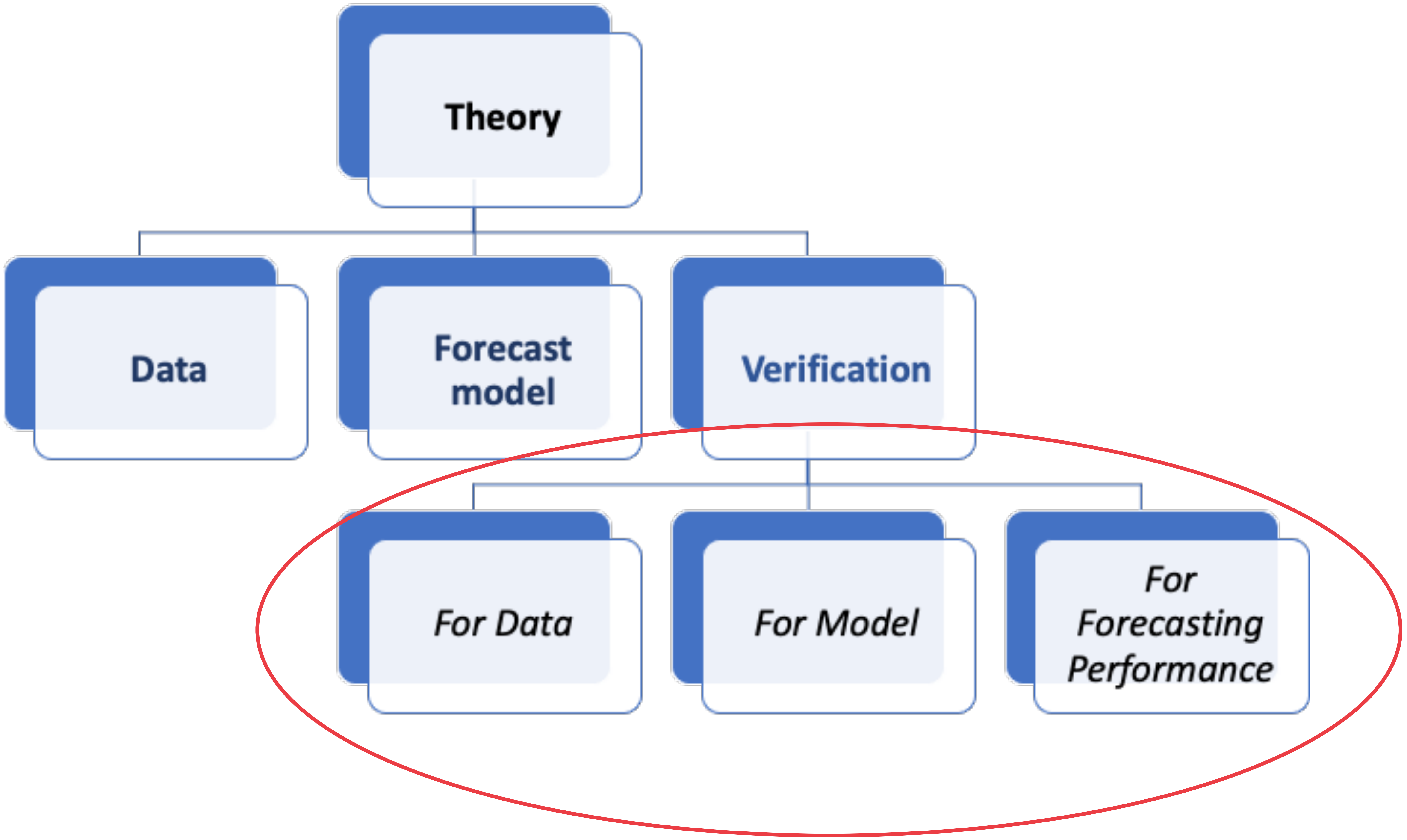
Two-tier forecasting of SEP events all the way from Sun to Earth, in terms of 'SEP Watch' and 'SEP Warning' phases, succeeding an 'All Clear' phase when applicable



Source locations of 174 SEP events in the Sun, categorized as per flare class from 1997 - 2017

A SUGGESTED R2O COURSE OF ACTION

A theory analog:



Does it work?

- To test the theory (the hypothesis-based idea), one needs:

  * Data to train on, statistically or using AI methods

  * The (AI or statistical) model to feed the data

  * Verification at three different levels:

    o Data verification

    o Model verification

    o Performance verification (validation)

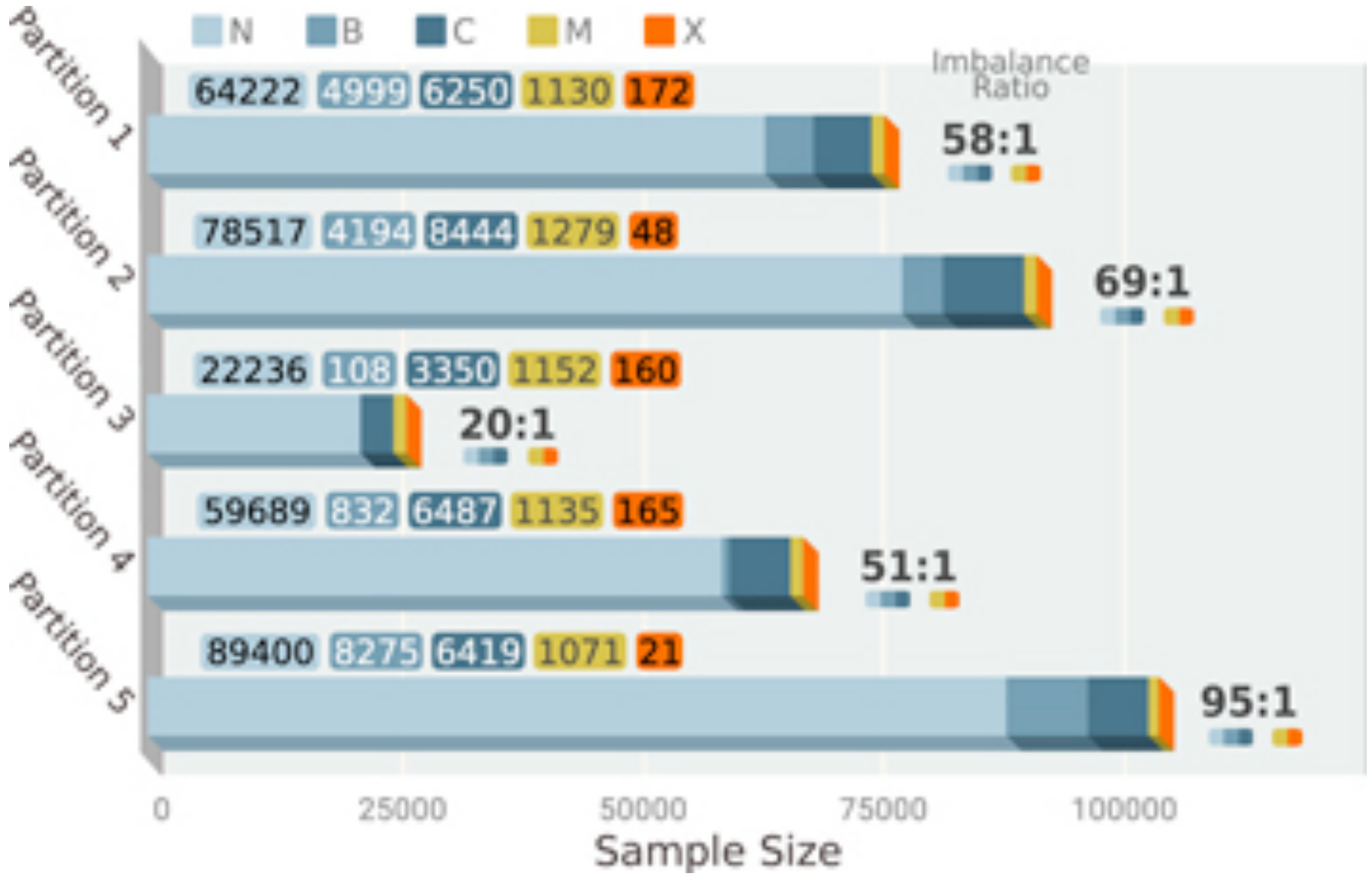
- Interpretation of the performance, via parameter (i.e. predictor) ranking

Why does it work?

BENCHMARK DATASETS: SOLAR FLARES

- Space Weather Analytics for Solar Flares (SWAN-SF)
(definitive SDO / HMI SHARPs)

Ahmadzadeh et al., IEEE, (2020)



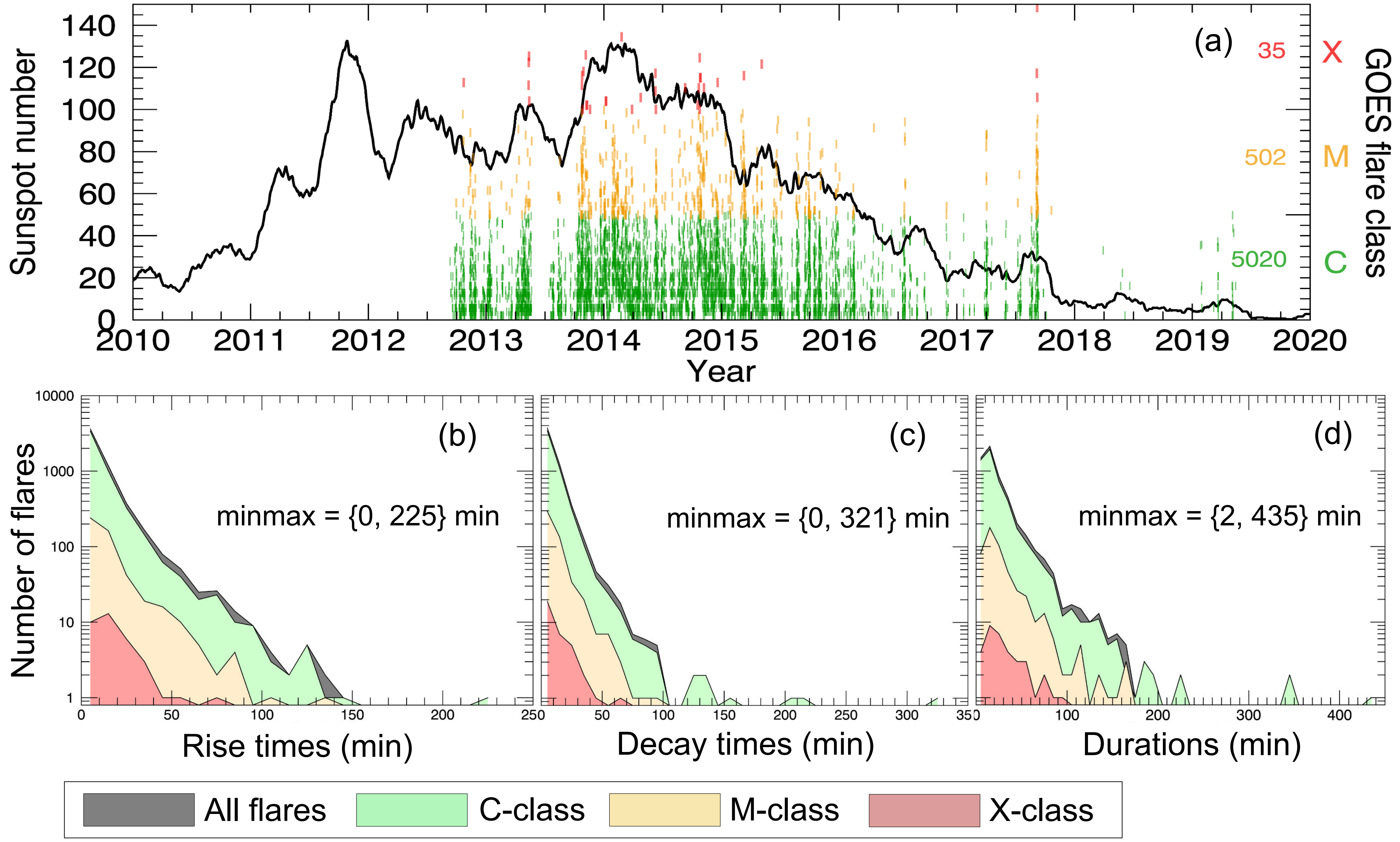
Angryk et al., NatSciData, 2020

Numbers of verified GOES flares:

- ✳ A-/B-class: 5305
- ✳ C-class: 7556
- ✳ M-class: 730
- ✳ X-class: 50

Accessible at Harvard Dataverse: https://bit.ly/3wjHBIi

- FLARECAST Predictor Database
(near-realtime SDO / HMI SHARPs)



Georgoulis et al., JSWSC, 2021

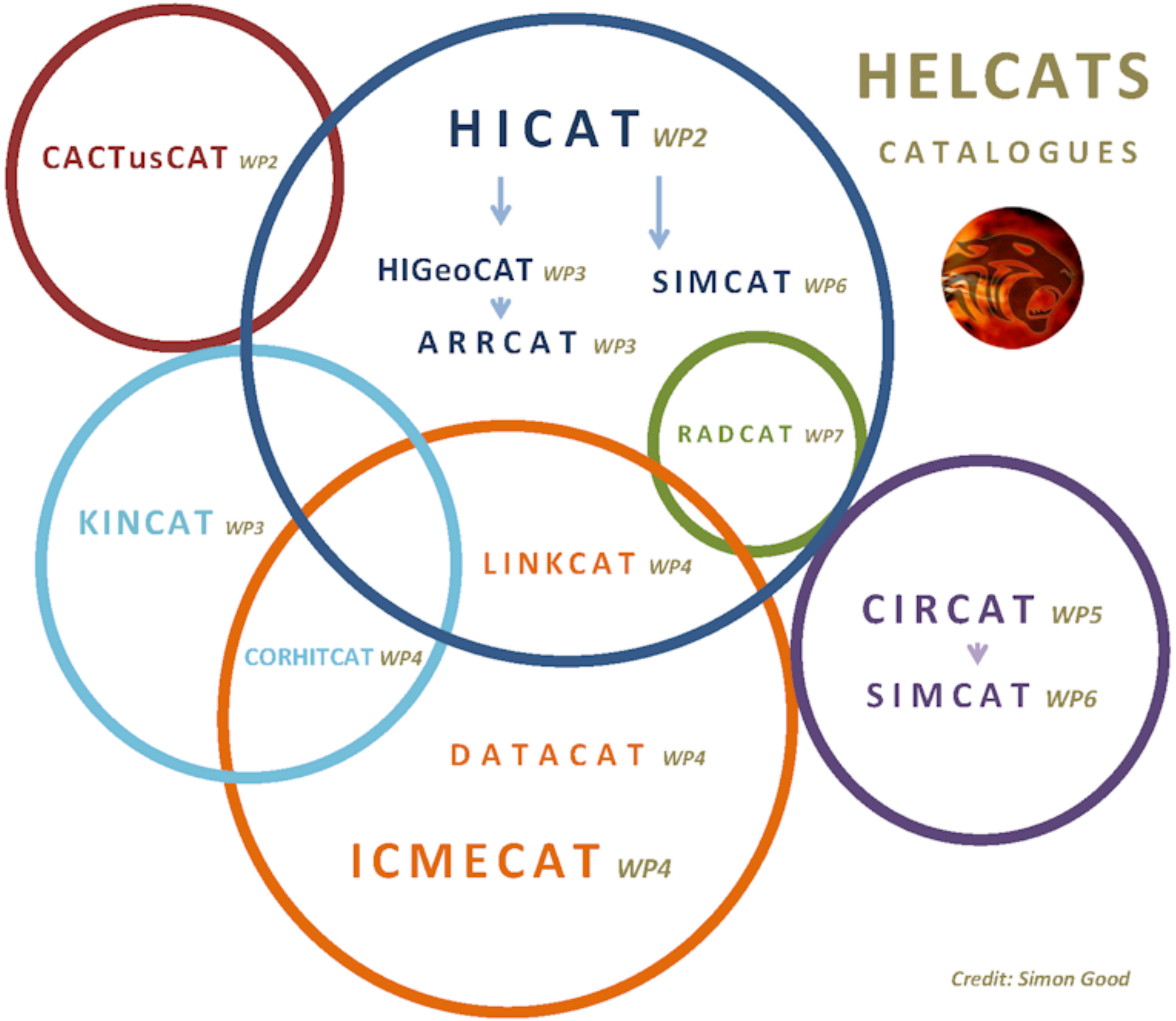
Numbers of verified GOES flares:

- ✳ C-class: 5020
- ✳ M-class: 502
- ✳ X-class: 35

Accessible at FLARECAST property database: https://api.flarecast.eu/property/ui

DATA VERIFICATION

BENCHMARK DATASETS: CMEs & SEP EVENTS



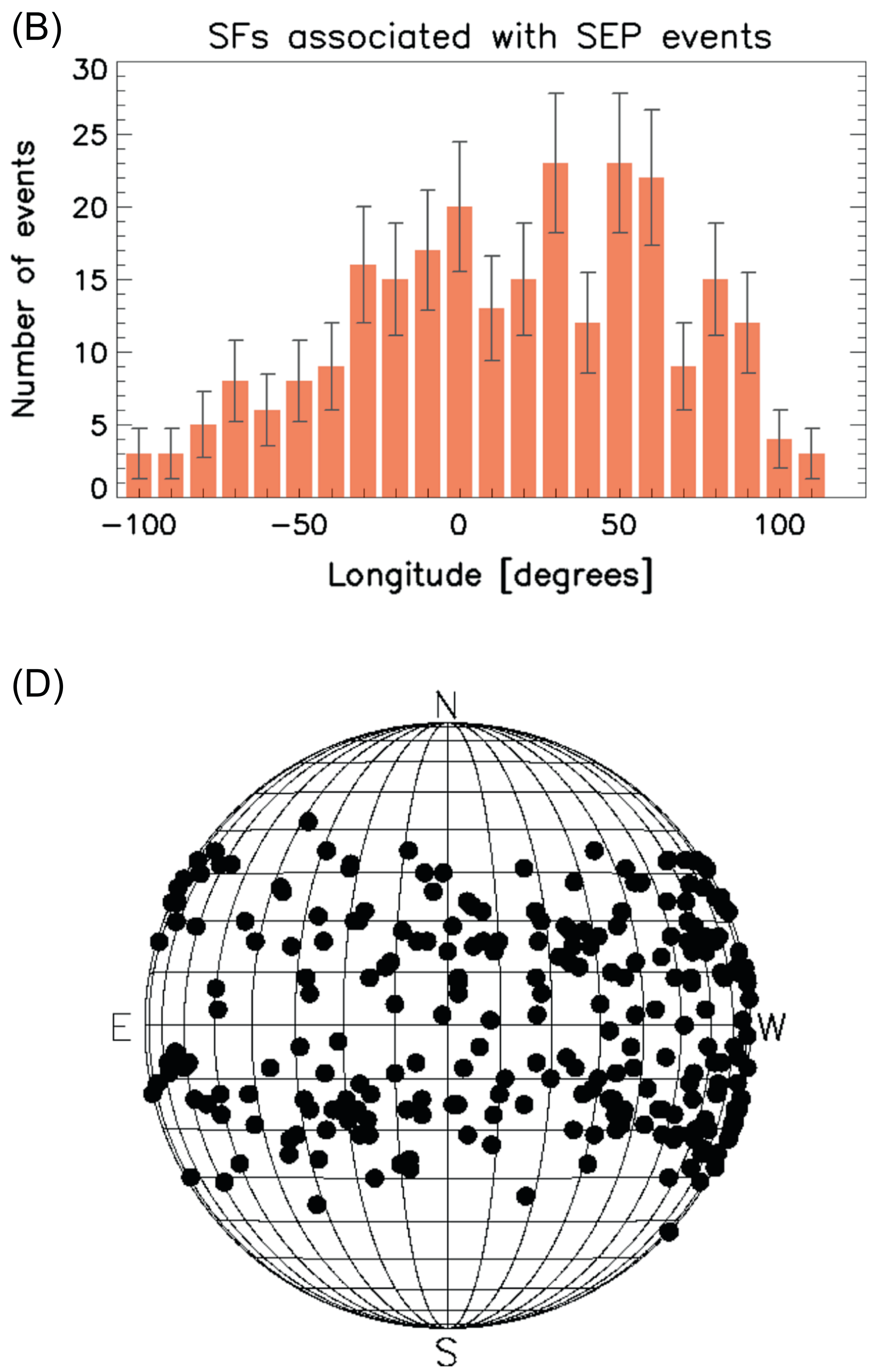
Credit: Simon Good

https://www.helcats-fp7.eu/

Community Coordinated Modeling Center

Space Weather Database Of Notifications, Knowledge, Information (DONKI)

https://kauai.ccmc.gsfc.nasa.gov/DONKI/

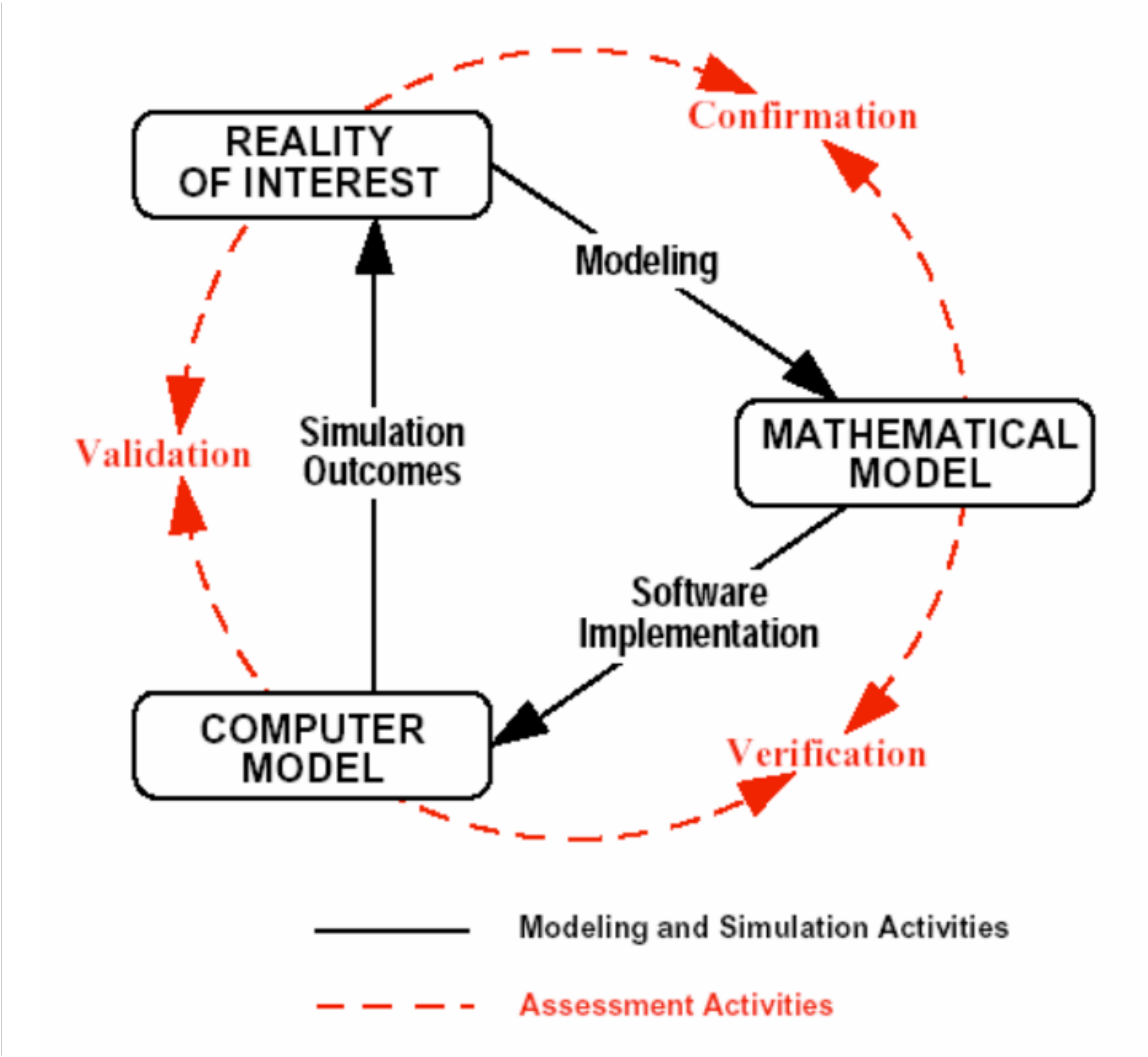


Papaioannou et al., JSWSC, 2016

SEP Event Databases:

- FORSPEF / ASPECS
- SEPEM
- HESPERIA
- SEPServer
- GSU / DMLab
- NASA / SRAG
- NOAA / SWPC
- …

MAKING SURE A MODEL PERFORMS AS EXPECTED



Thacker et al., IAEA / INIS Repository, RN:36030870, 2004

Essentially, making sure that a model is performing as expected from its conception and implementation

Conceptual, simplified diagram of model verification:

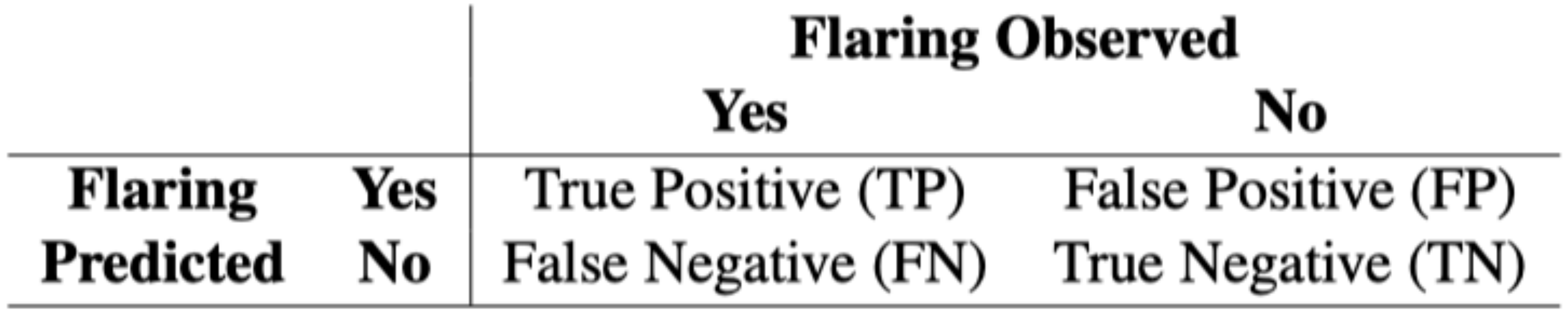
- Three verification levels (mathematical model, algorithmic model, reality of interest)
- Dependencies, in terms of software implementation, simulation outcomes, and modeling
- Three verification actions, in terms of narrow model verification (i.e., debugging), model / reality validation, and reality / mathematics confirmation

DOES THE WHOLE THING WORK?

Simplest possible prediction case: a YES or a NO for an event (say, a solar flare)

- Forecasting **YES**: did it actually happen?
  - YES —> a hit, or true positive
  - NO —> a false alarm, or false positive
- Forecasting **NO**: did it actually happen?
  - YES —> a miss, or false negative
  - NO —> a true negative

- 2 x 2 contingency table (confusion matrix):



		Flaring Observed	
		Yes	**No**
Flaring Predicted	**Yes**	True Positive (TP)	False Positive (FP)
	No	False Negative (FN)	True Negative (TN)

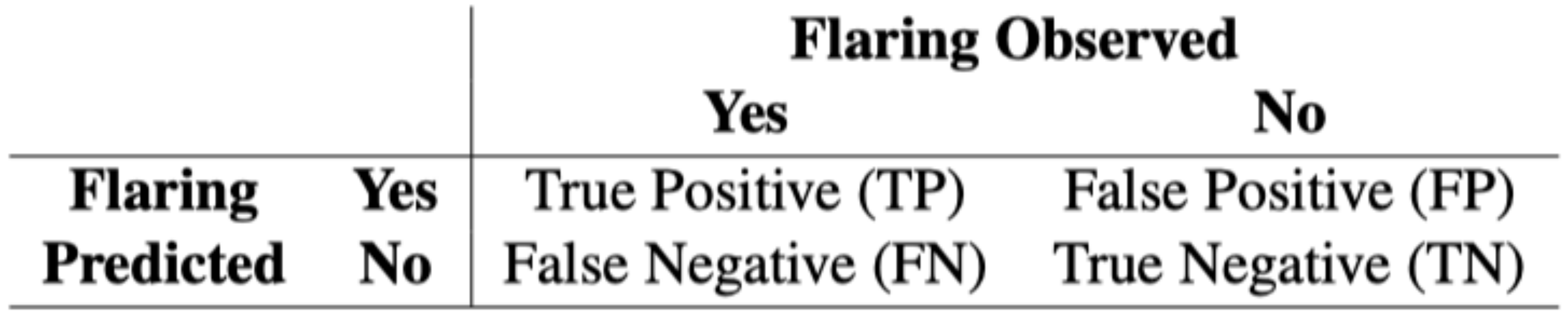
- A generic skill score definition:

$$\boxed{SS = \frac{S - S_{ref}}{S_{perfect} - S_{ref}}}$$

- S: a given comparison metric
- S_{ref} : a reference value of the metric
- $S_{perfect}$: a perfect-performance metric value

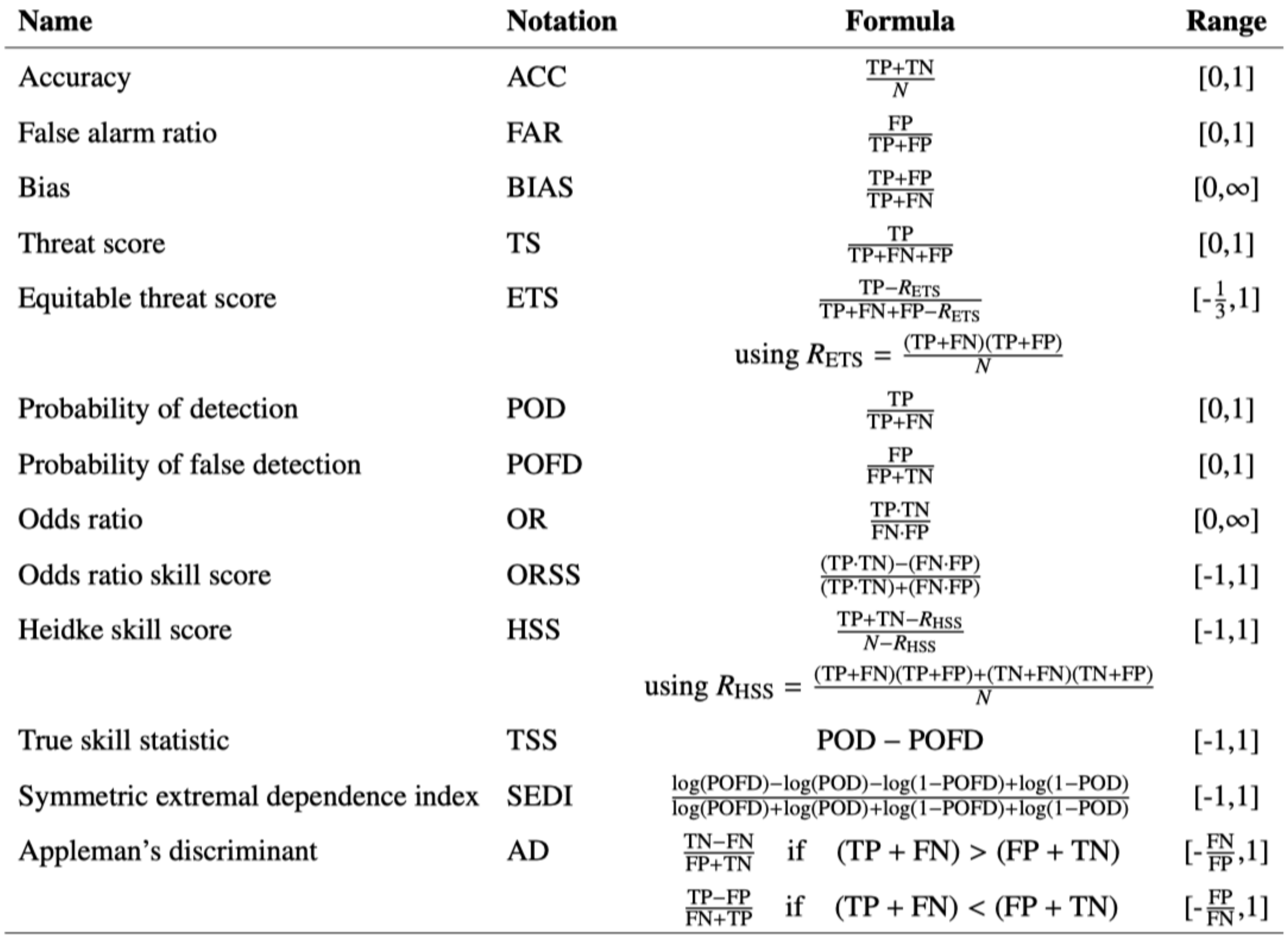
Iff SS > 0 (SS <0) the method works better (worse) than the reference method

A WHOLE LOT FROM A SIMPLE 2 x 2 MATRIX



		Flaring Observed	
		Yes	**No**
Flaring Predicted	**Yes**	True Positive (TP)	False Positive (FP)
	No	False Negative (FN)	True Negative (TN)

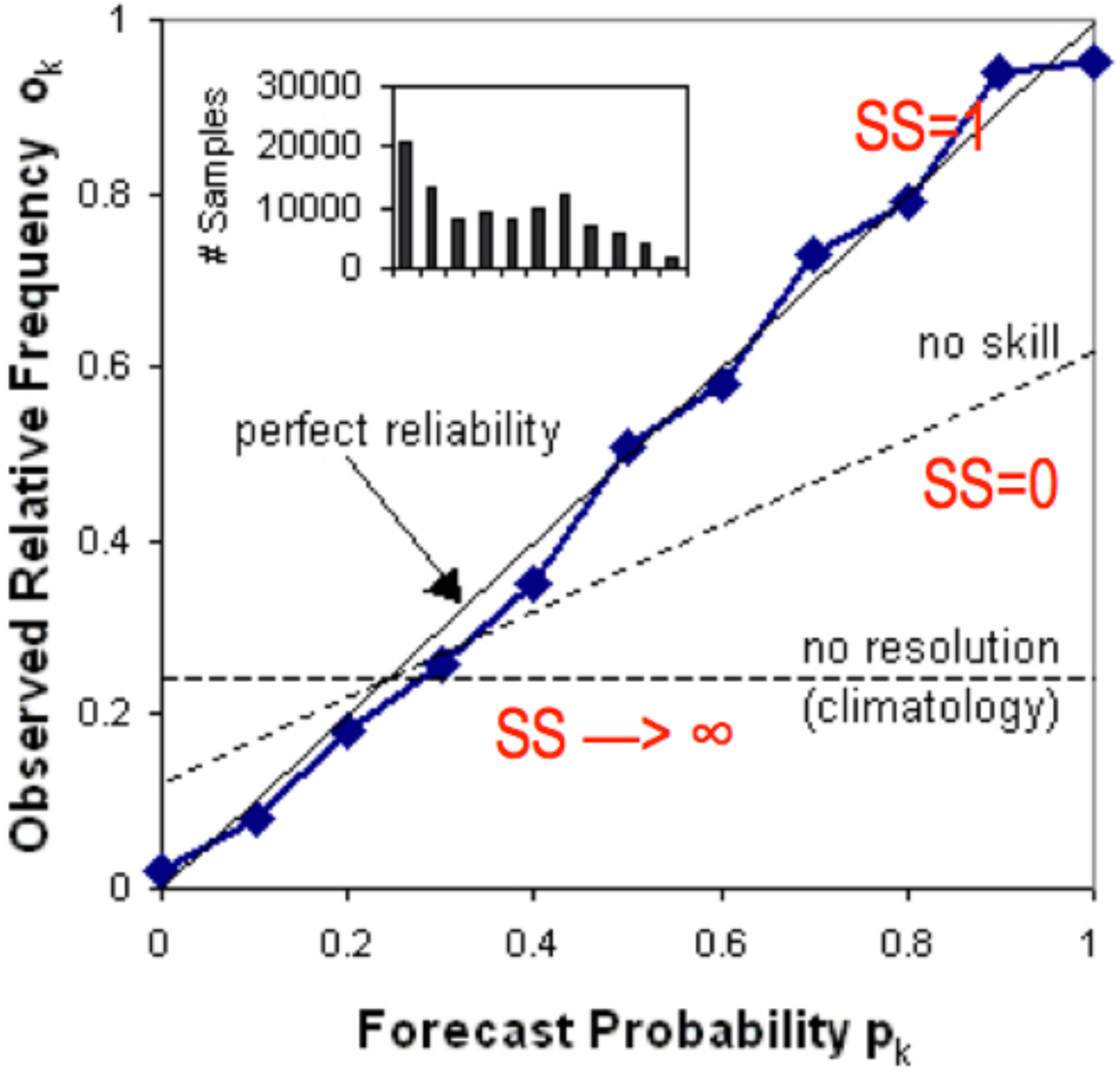
- A bunch of skill scores, most of them invented by the meteorology community, with each having each own reasoning
- One needs to choose from this ‘basket’ the metrics that better fit and are meaningful to their problem
- For a valuable introduction, see https://www.cawcr.gov.au/projects/verification/verif_web_page.html



Name	**Notation**	**Formula**	**Range**
Accuracy	ACC	$\frac{\mathrm{TP+TN}}{N}$	[0,1]
False alarm ratio	FAR	$\frac{\mathrm{FP}}{\mathrm{TP+FP}}$	[0,1]
Bias	BIAS	$\frac{\mathrm{TP+FP}}{\mathrm{TP+FN}}$	$[0,\infty]$
Threat score	TS	$\frac{\mathrm{TP}}{\mathrm{TP+FN+FP}}$	[0,1]
Equitable threat score	ETS	$\frac{\mathrm{TP}-R_{\mathrm{ETS}}}{\mathrm{TP+FN+FP}-R_{\mathrm{ETS}}}$	$[-\frac{1}{3},1]$
		using $R_{\mathrm{ETS}} = \frac{\mathrm{(TP+FN)(TP+FP)}}{N}$	
Probability of detection	POD	$\frac{\mathrm{TP}}{\mathrm{TP+FN}}$	[0,1]
Probability of false detection	POFD	$\frac{\mathrm{FP}}{\mathrm{FP+TN}}$	[0,1]
Odds ratio	OR	$\frac{\mathrm{TP\cdot TN}}{\mathrm{FN\cdot FP}}$	$[0,\infty]$
Odds ratio skill score	ORSS	$\frac{\mathrm{(TP\cdot TN)-(FN\cdot FP)}}{\mathrm{(TP\cdot TN)+(FN\cdot FP)}}$	[-1,1]
Heidke skill score	HSS	$\frac{\mathrm{TP+TN}-R_{\mathrm{HSS}}}{N-R_{\mathrm{HSS}}}$	[-1,1]
		using $R_{\mathrm{HSS}} = \frac{\mathrm{(TP+FN)(TP+FP)+(TN+FN)(TN+FP)}}{N}$	
True skill statistic	TSS	POD − POFD	[-1,1]
Symmetric extremal dependence index	SEDI	$\frac{\log(\mathrm{POFD})-\log(\mathrm{POD})-\log(1-\mathrm{POFD})+\log(1-\mathrm{POD})}{\log(\mathrm{POFD})+\log(\mathrm{POD})+\log(1-\mathrm{POFD})+\log(1-\mathrm{POD})}$	[-1,1]
Appleman’s discriminant	AD	$\frac{\mathrm{TN-FN}}{\mathrm{FP+TN}}$ if $\mathrm{(TP+FN)>(FP+TN)}$	$[-\frac{\mathrm{FN}}{\mathrm{FP}},1]$
		$\frac{\mathrm{TP-FP}}{\mathrm{FN+TP}}$ if $\mathrm{(TP+FN)<(FP+TN)}$	$[-\frac{\mathrm{FP}}{\mathrm{FN}},1]$

Georgoulis et al., JSWSC, 2021

PROBABILISTIC VALIDATION



Reliability diagram: correlating forecast probability with observed relative frequency

Example: if for 100 times I predict a 30% probability of events happening and I have 30 events actually occurring in those 100 times, then I am on the desired 'perfect reliability' diagonal of the reliability diagram. If >30 events happen, then I am under-predicting (above diagonal). If <30 events happen, then I am over-predicting (below diagonal).

Brier Skill Score (BSS): a very commonly used metric, showing how close my probabilistic (0 < P < 1) forecast to a binary (YES [P=1] / NO [P=0]) forecast

- To get there, one calculates:
  - (a) the tested Brier score BS_{test} with respect to a binary occurrence, most commonly as a mean squared error

$$BS_{test} = \frac{1}{N}\sum_{i=1}^{N}(\bar{o}_i - p_i)^2 \quad \text{for N forecasts and} \quad \bar{o} \equiv \{0,1\}$$

  - (b) the reference Brier score BS_{ref}, with respect to climatology, i.e., mean occurrence frequency:

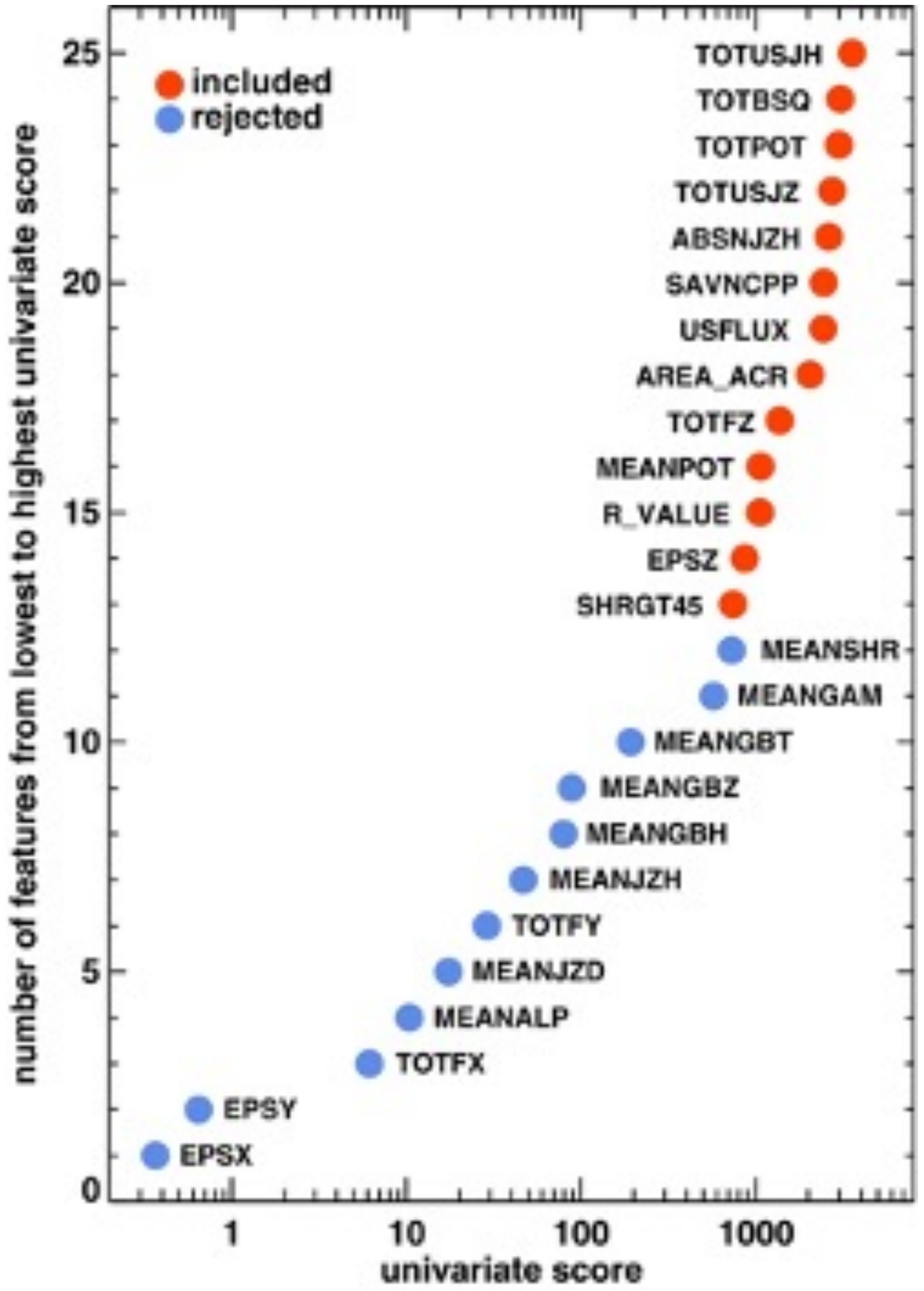
$$BS_{ref} = \frac{1}{N}\sum_{i=1}^{N}(\tilde{o} - p_i)^2 \quad \text{for N forecasts and} \quad \tilde{o} = \frac{1}{N}\sum_{i=1}^{N} o_i$$

Then, using the generic skill score formula

$$\boxed{BSS = 1 - \frac{BS_{test}}{BS_{ref}}}$$

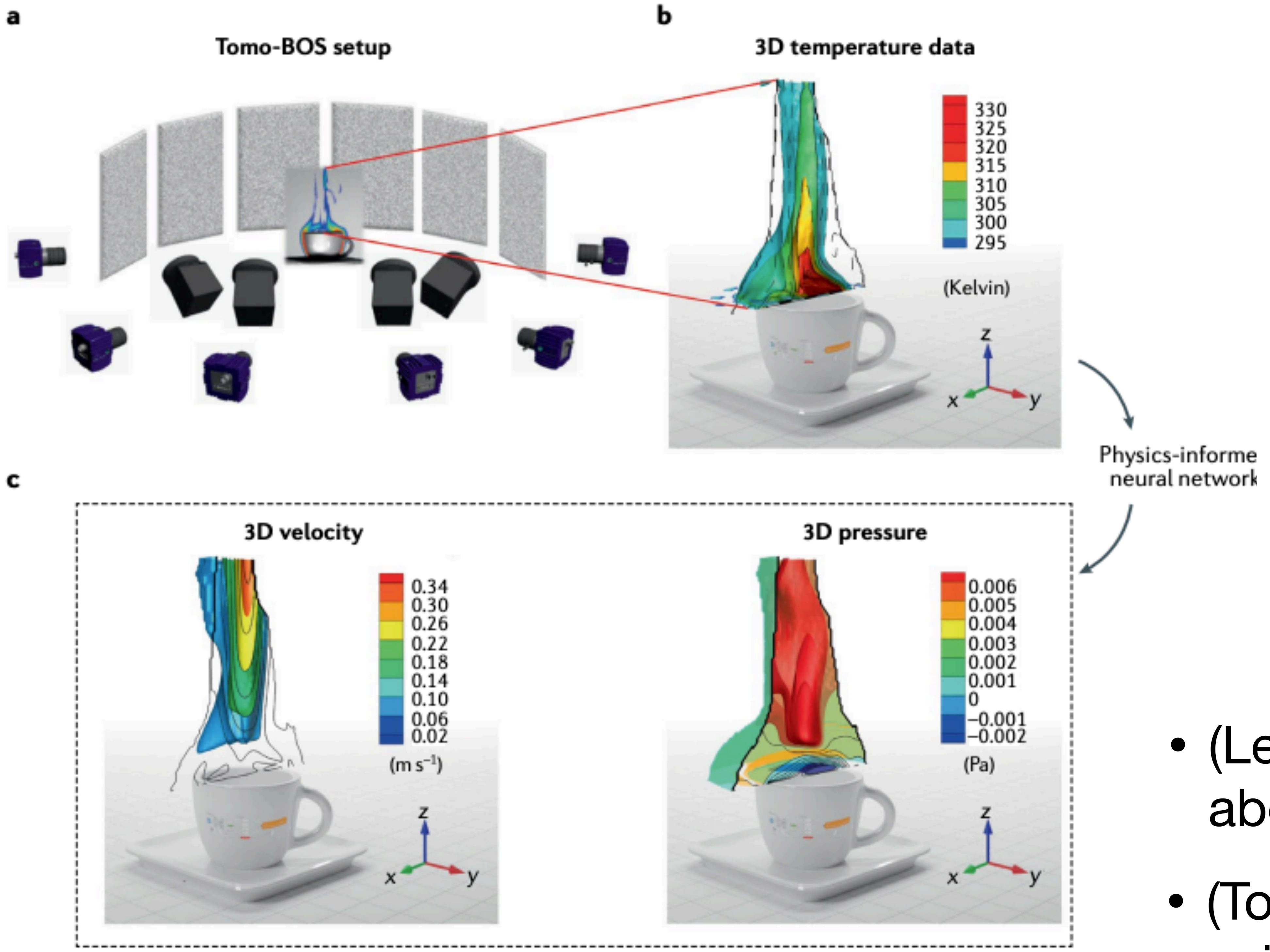
RESEARCH-TO-OPERATIONS-TO-RESEARCH (R2O2R)

- Interpretable artificial intelligence (machine & deep learning)



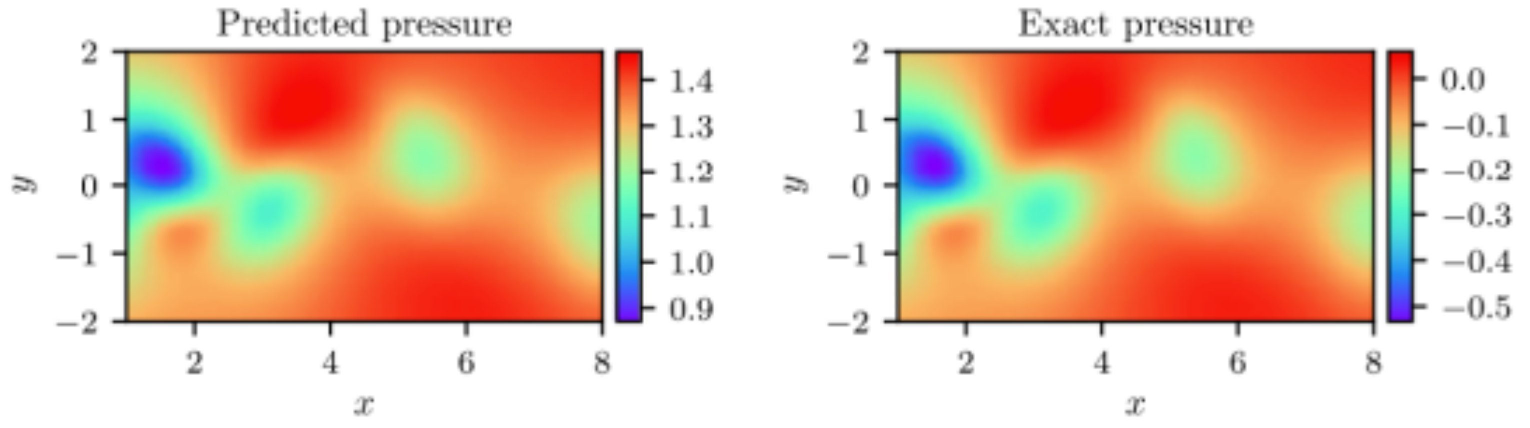
Bobra & Couvidat, ApJ, 2015

Find out which parameters work better in forecasting - **then investigate why**



Karniadakis et al., Nature Rev. / Phys., 2021

Physics-informed neural networks, for problems with partial differential equations



Correct PDE	$u_t + (uu_x + vu_y) = -p_x + 0.01(u_{xx} + u_{yy})$ $v_t + (uv_x + vv_y) = -p_y + 0.01(v_{xx} + v_{yy})$
Identified PDE (clean data)	$u_t + 0.999(uu_x + vu_y) = -p_x + 0.01047(u_{xx} + u_{yy})$ $v_t + 0.999(uv_x + vv_y) = -p_y + 0.01047(v_{xx} + v_{yy})$
Identified PDE (1% noise)	$u_t + 0.998(uu_x + vu_y) = -p_x + 0.01057(u_{xx} + u_{yy})$ $v_t + 0.998(uv_x + vv_y) = -p_y + 0.01057(v_{xx} + v_{yy})$

Raissi et al., J. Comp. Phys., 2019

- (Left) recovering the 3D velocity and pressure above an espresso cup using PINNs
- (Top) solving the Navier-Stokes equation using PINNs. Solution recovered up to a certain constant by definition

The groundwork to apply to SWx problems is still to be done

WHERE DO WE STAND? — FLARE PREDICTION

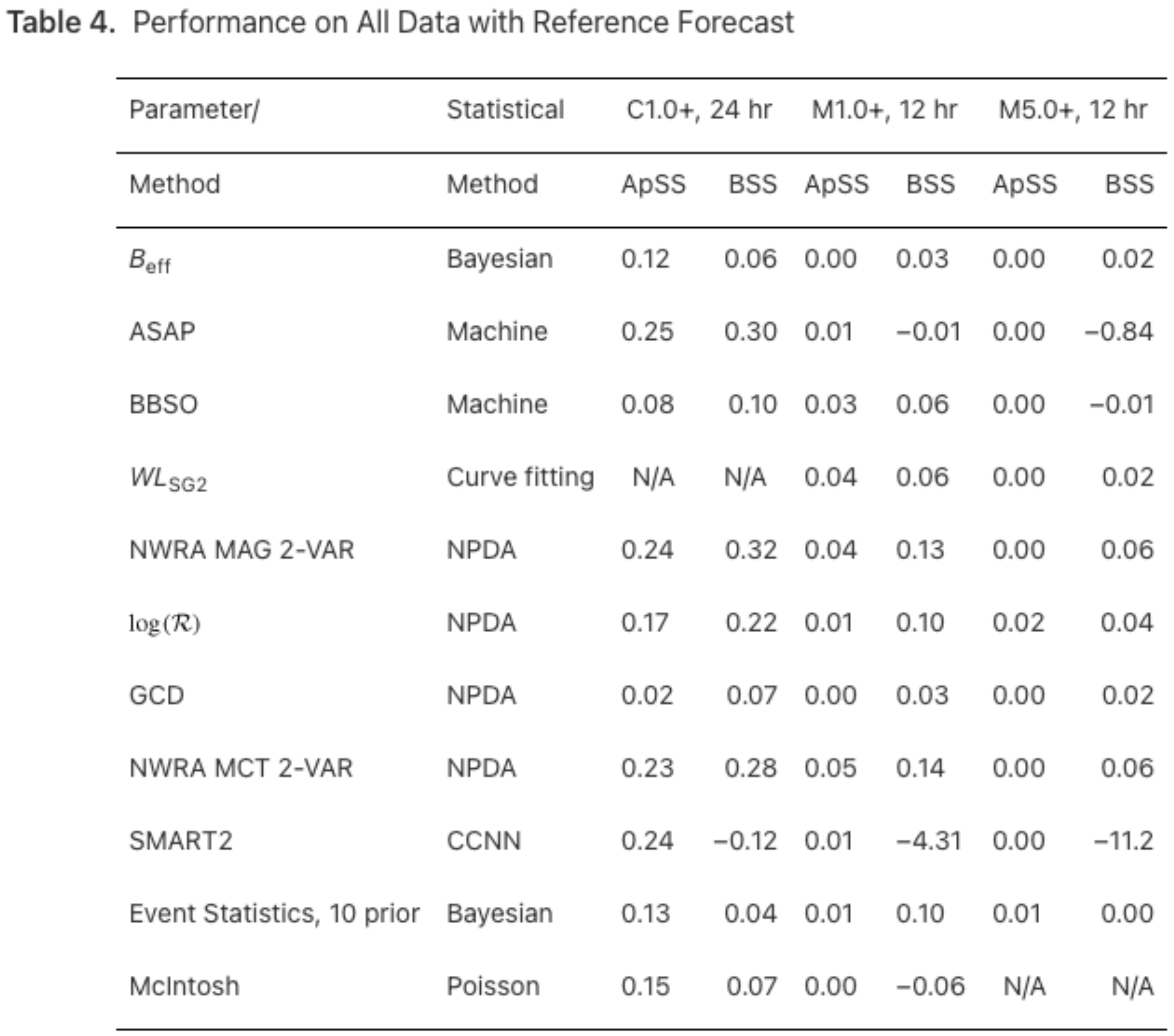
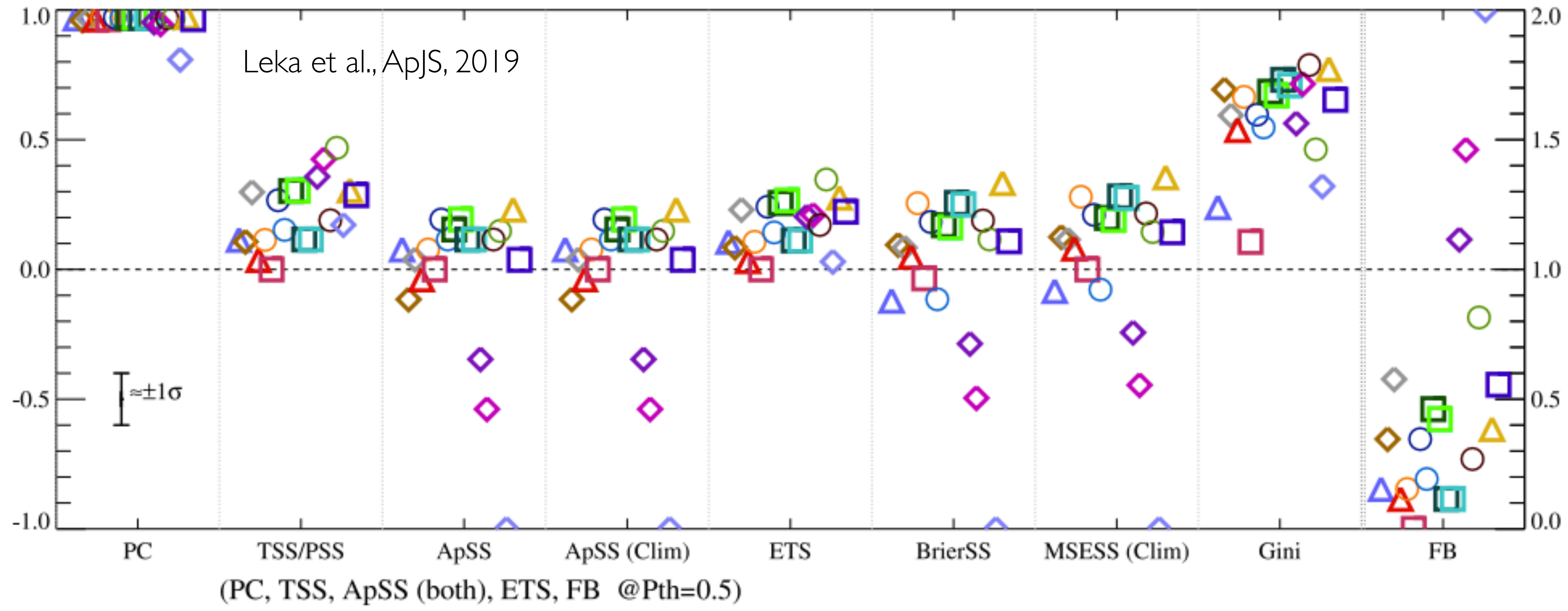
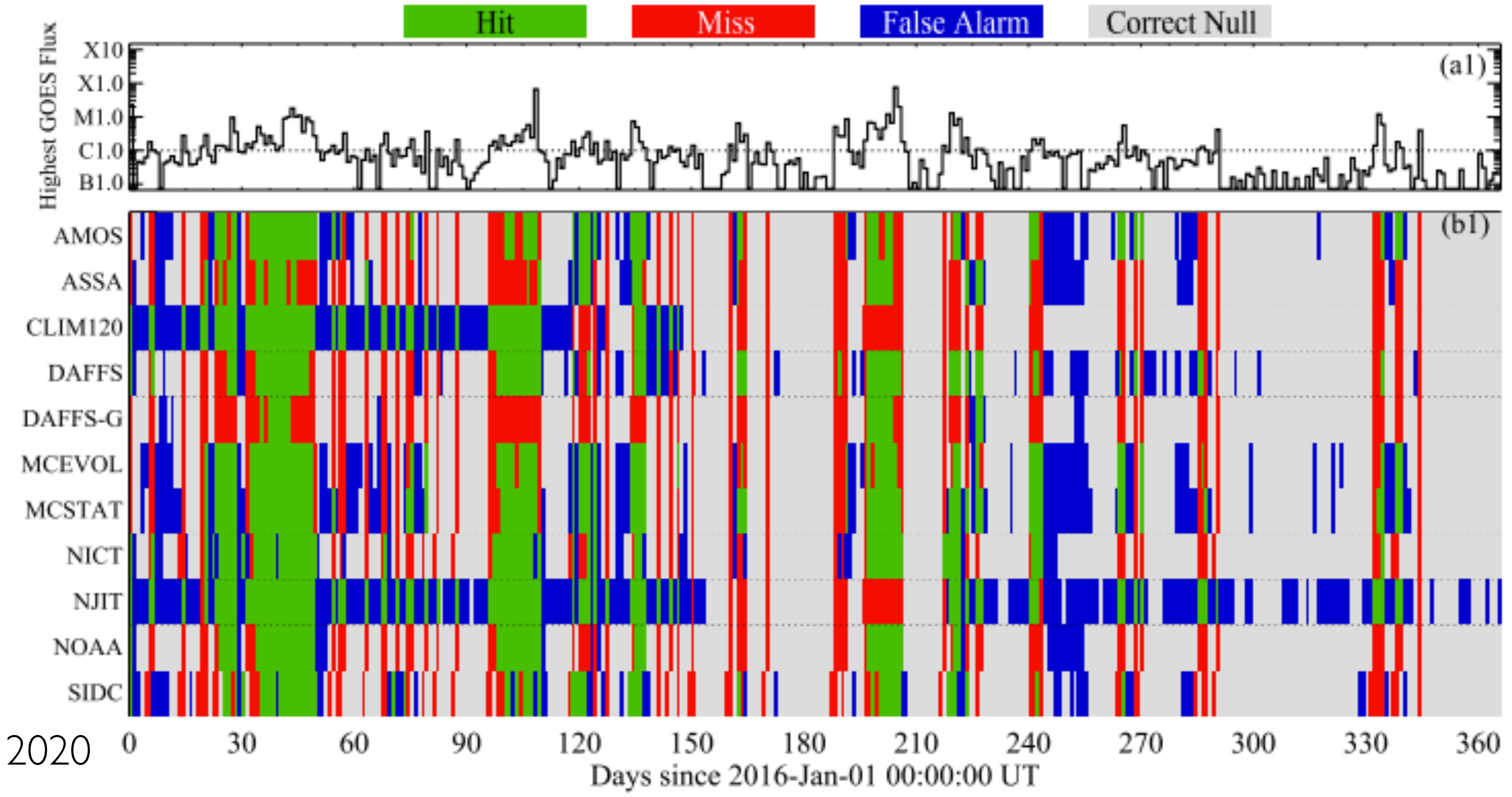


Table 4. Performance on All Data with Reference Forecast

Parameter/	Statistical	C1.0+, 24 hr		M1.0+, 12 hr		M5.0+, 12 hr	
Method	Method	ApSS	BSS	ApSS	BSS	ApSS	BSS
$B_{\rm eff}$	Bayesian	0.12	0.06	0.00	0.03	0.00	0.02
ASAP	Machine	0.25	0.30	0.01	−0.01	0.00	−0.84
BBSO	Machine	0.08	0.10	0.03	0.06	0.00	−0.01
$WL_{\rm SG2}$	Curve fitting	N/A	N/A	0.04	0.06	0.00	0.02
NWRA MAG 2-VAR	NPDA	0.24	0.32	0.04	0.13	0.00	0.06
$\log(\mathcal{R})$	NPDA	0.17	0.22	0.01	0.10	0.02	0.04
GCD	NPDA	0.02	0.07	0.00	0.03	0.00	0.02
NWRA MCT 2-VAR	NPDA	0.23	0.28	0.05	0.14	0.00	0.06
SMART2	CCNN	0.24	−0.12	0.01	−4.31	0.00	−11.2
Event Statistics, 10 prior	Bayesian	0.13	0.04	0.01	0.10	0.01	0.00
McIntosh	Poisson	0.15	0.07	0.00	−0.06	N/A	N/A

Barnes et al., ApJ, 2016


Leka et al., ApJS, 2019



Park et al., ApJ, 2020

— Predictions far from perfect

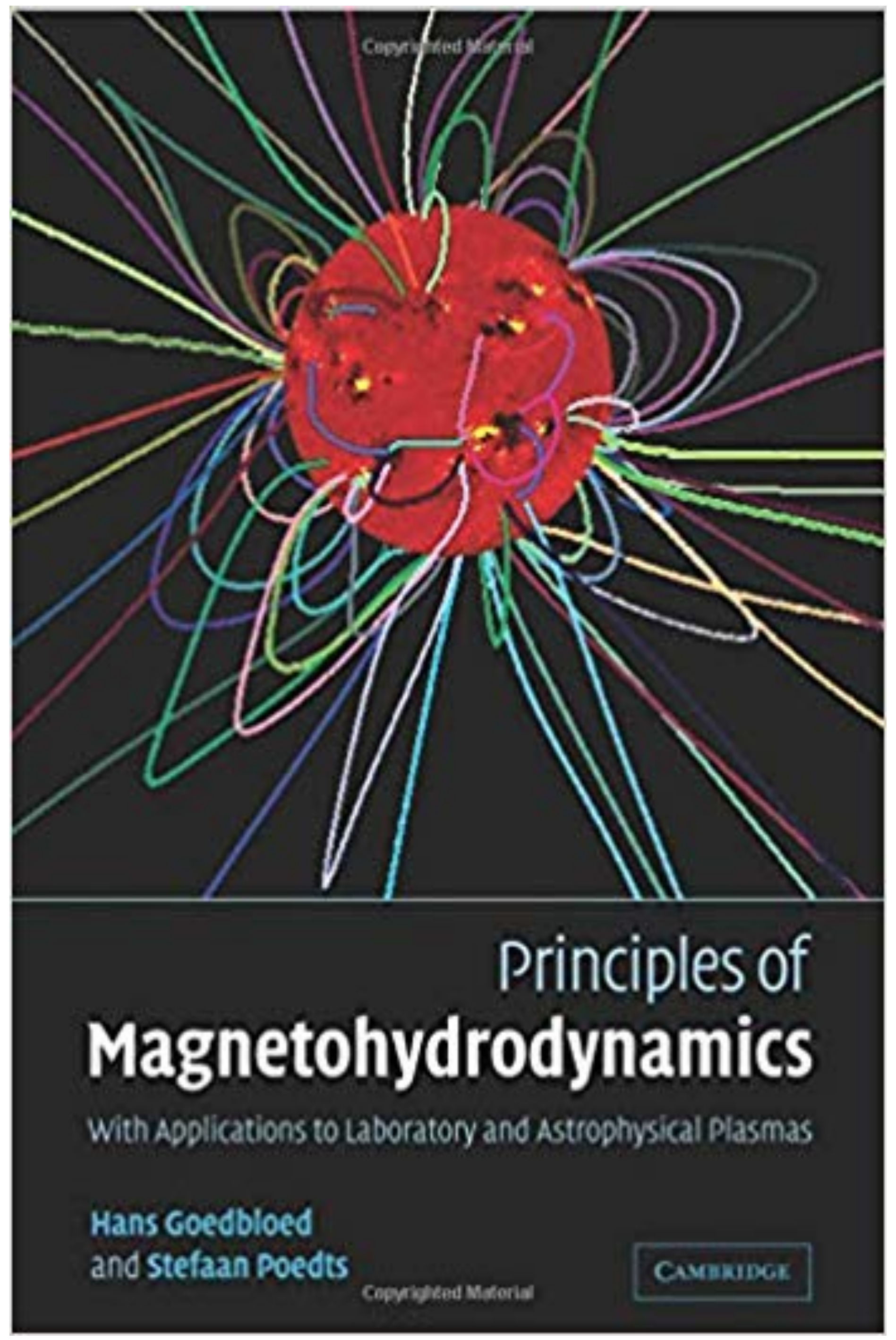
— Many, very different methods clump around each other, in terms of performance

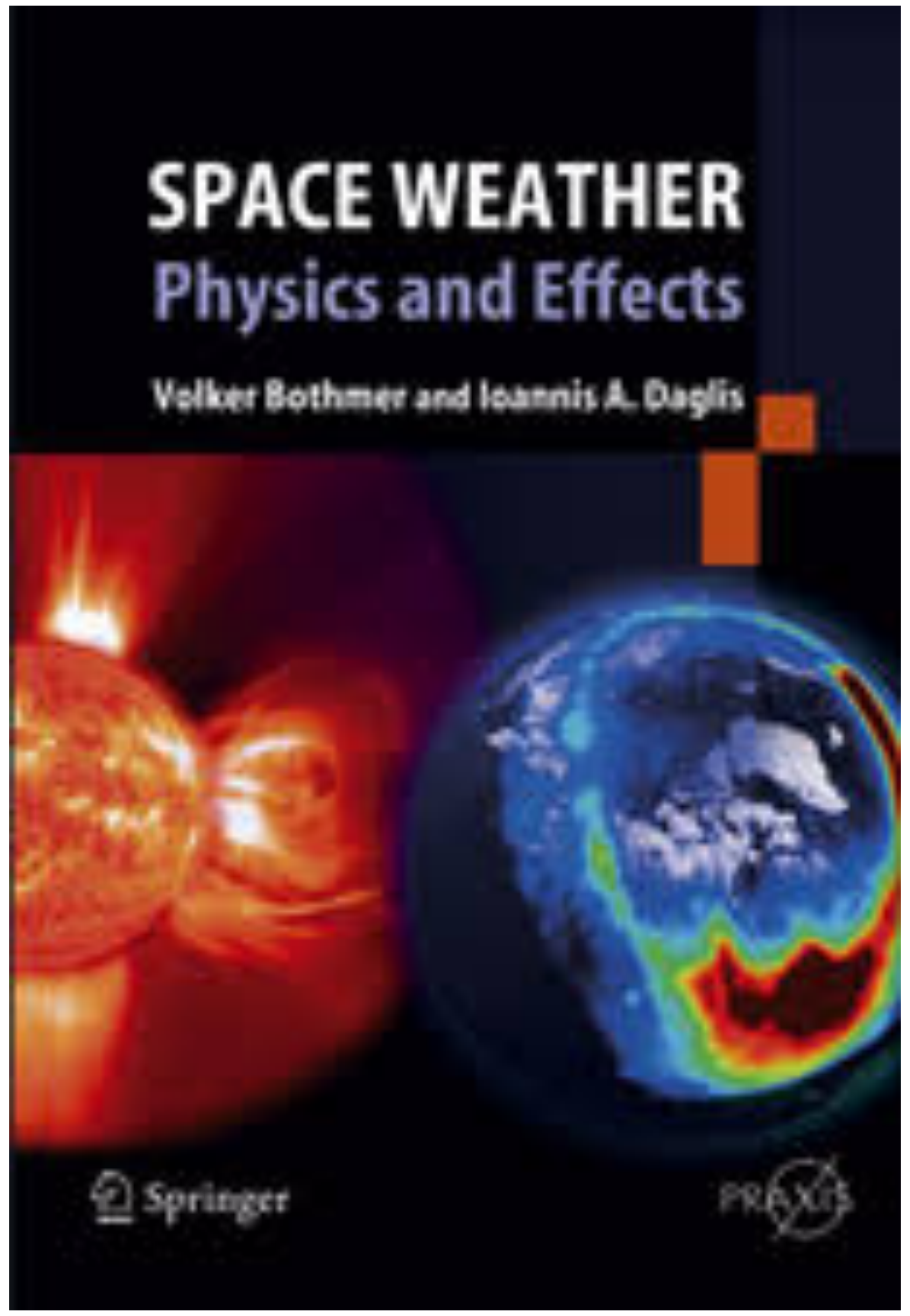
— Many riddles lurking out there to decipher

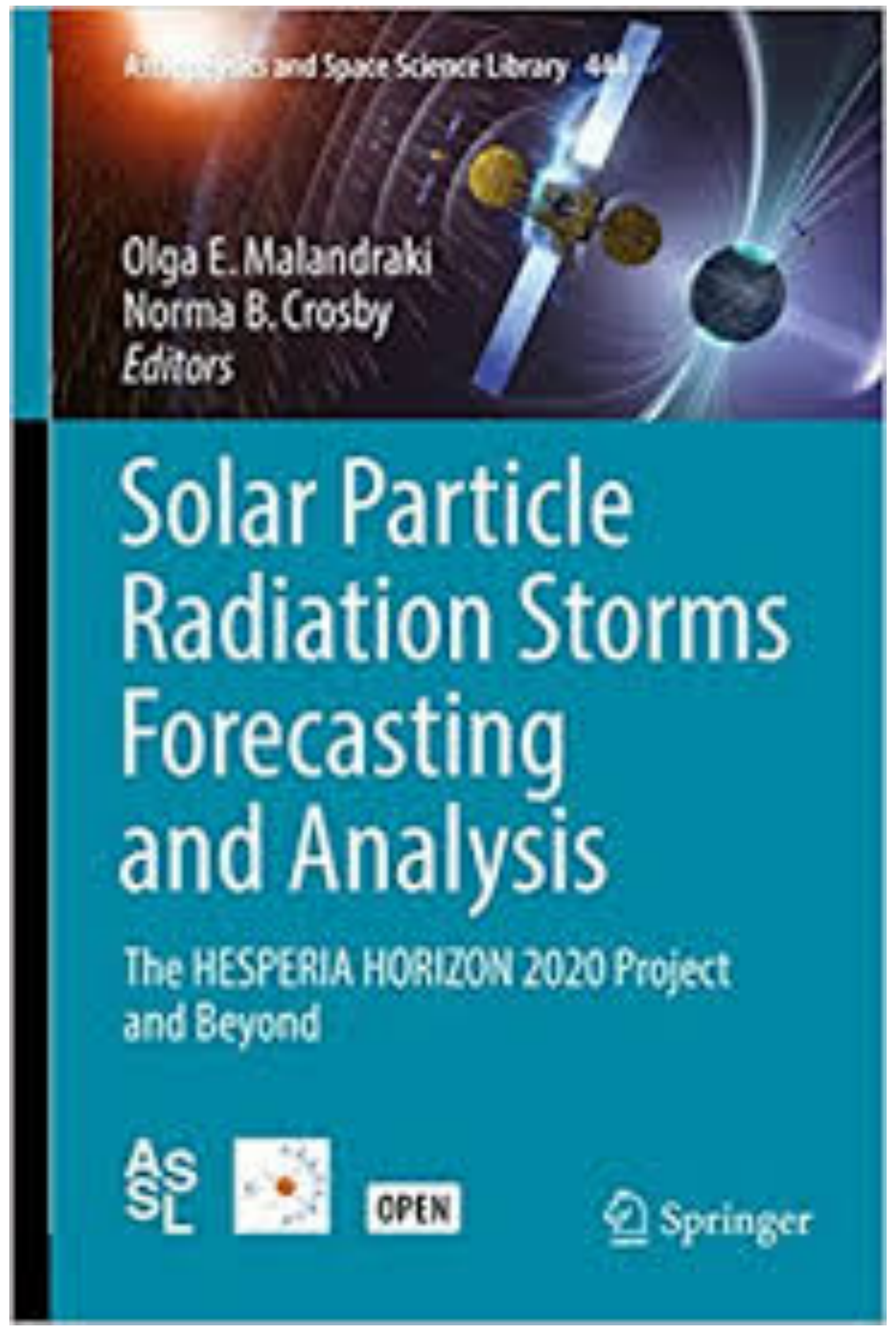
CONCLUSIONS

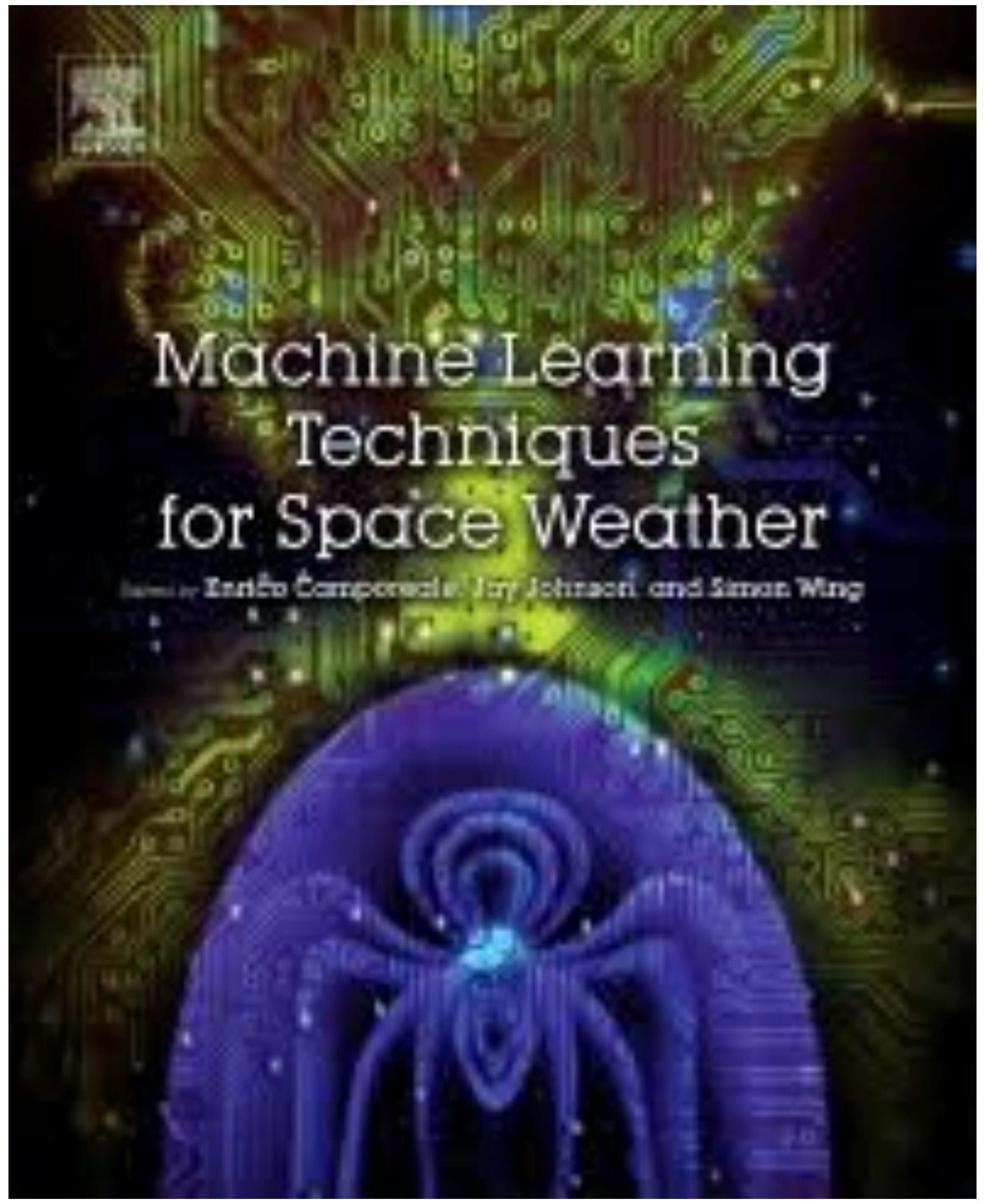
- Space weather is a forefront physics problem, at the junction of astrophysics and space physics, with ramifications all the way to everyday life (a ‘real-world’ problem)
- Forecasting Space Weather exceeds the realms of physics, extending well into inter-disciplinarity (Big Data - data and computer science, statistics, artificial intelligence [to handle Big Data])
- A viable path — R2O: from solar and space physics (research) to routine forecasting (operations)
- R2O gets you up to a certain point: one needs to learn from the results toward more educated research and improved forecasts — R2O2R
- R2O2R is a self-feeding loop, but an optimal path to achieve is yet to be determined
- R2O2R is a necessity, however, because current Space Weather forecasts leave a lot to de desired: problems with class imbalance, varying occurrence frequency, robustness, accuracy, …

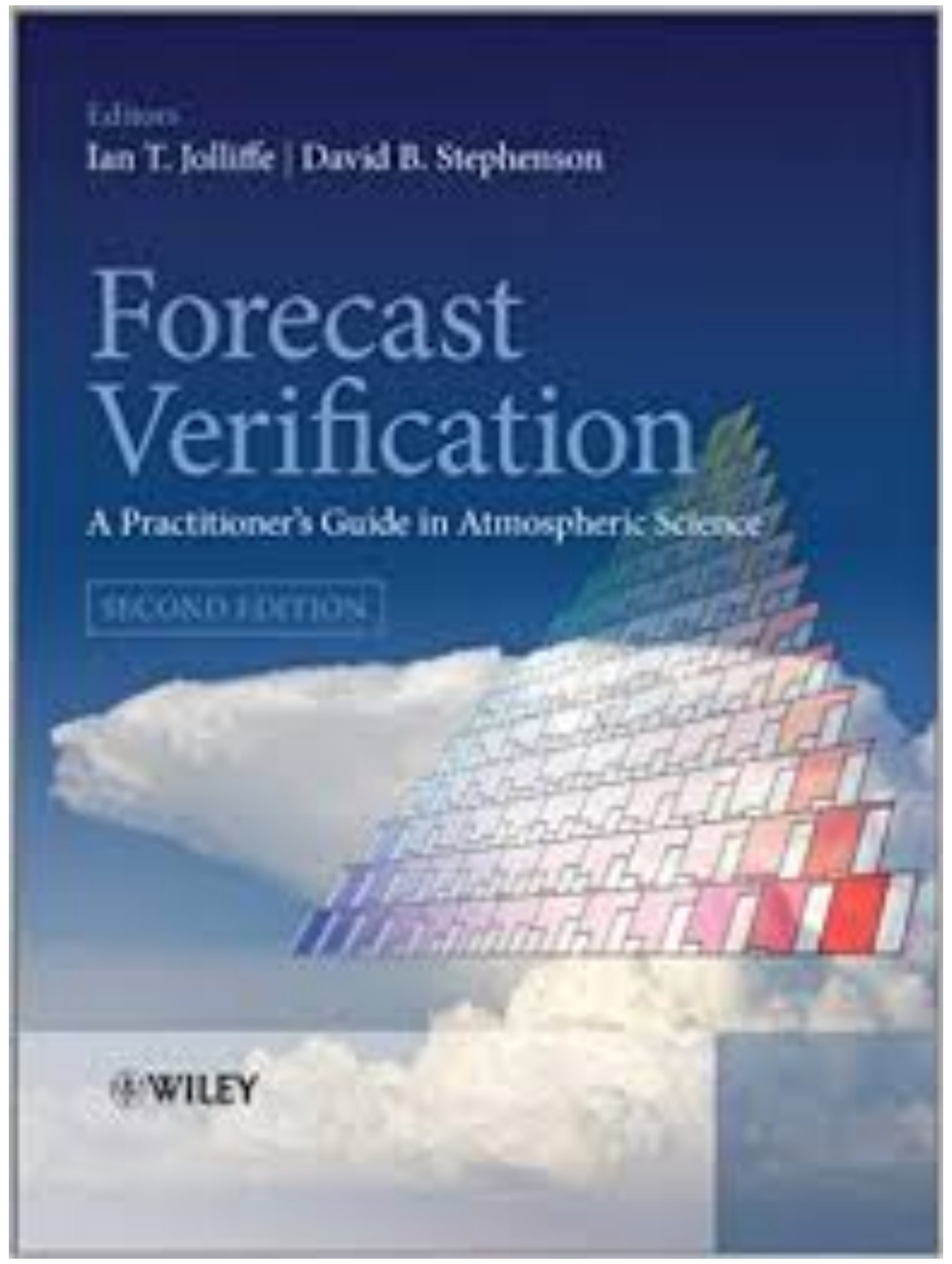
SUGGESTED READING (BOOKS)











1. Principles of Magnetohydrodynamics: With Applications to Laboratory and Astrophysical Plasmas, J. P. Goedbloed & S. Poedts, Cambridge Univ. Press, ISBN: 978-0521626071
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3. Solar Particle Radiation Storms Forecasting and Analysis: The Hesperia Horizon 2020 Project and Beyond (O. E. Malandraki & N. B. Crosby, Editors), Springer, 2018, ISBN: 978-3-319-60051-2 **(Open Access)**
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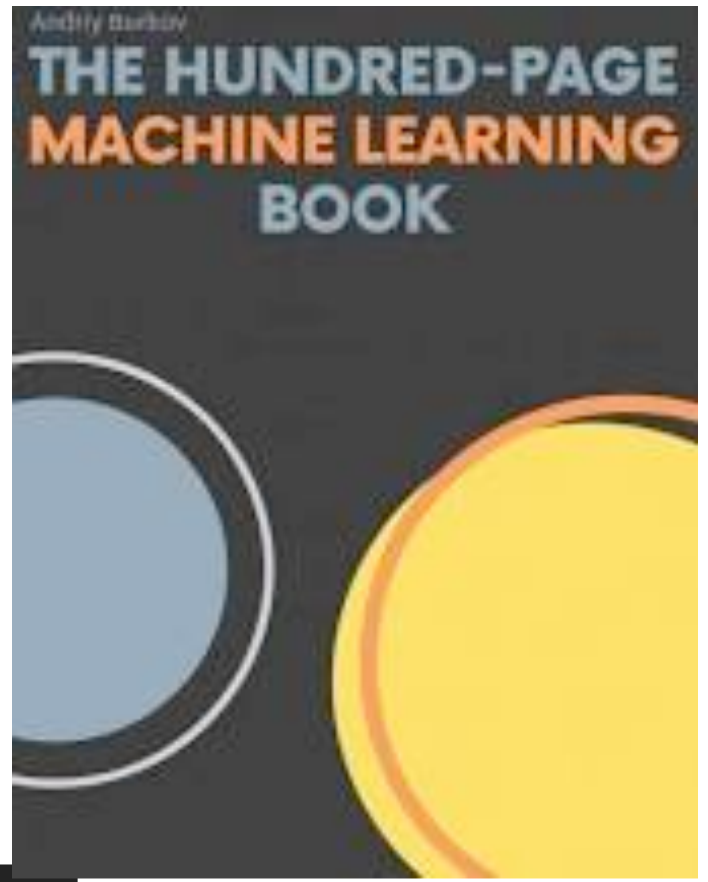

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