PROGRESS AND CHALLENGES TOWARD A FUTURE INTEGRATED SPACE WEATHER FORECASTING SYSTEM

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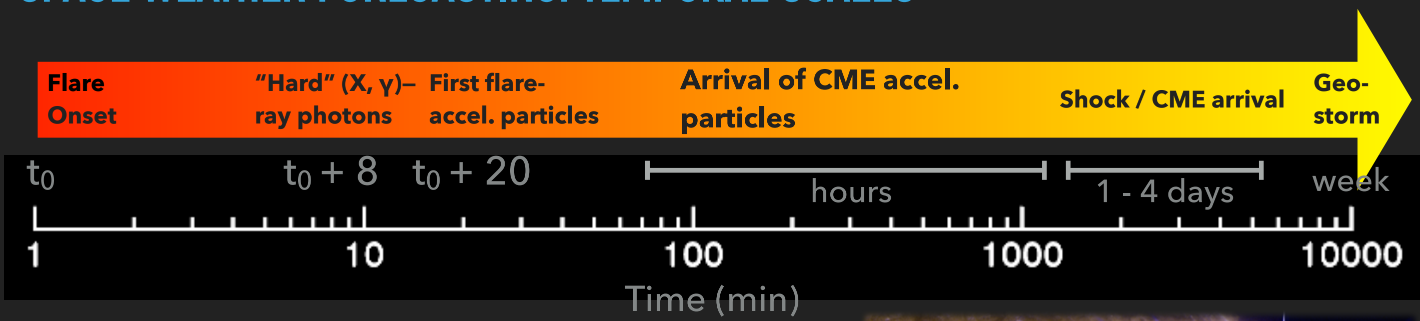
SEIBERSDORF LABORATORIES

SEPRAD Expert Workshop

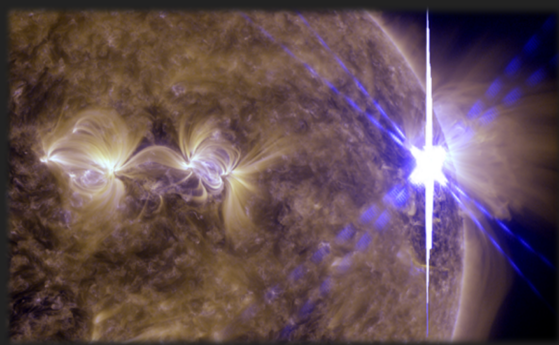
OUTLINE

- The need for an integrated SWx forecasting platform
- Fusing together solar flare, CME and SEP treatment
  - Some approaches for a combined treatment
- FLARECAST: a possible platform able to accommodate this combined treatment
  - Science extensions
  - Technical reference base
- Validation: a vital step
- Conclusions

SPACE WEATHER FORECASTING: TEMPORAL SCALES



- A total span of more than <u>4 orders of magnitude</u>



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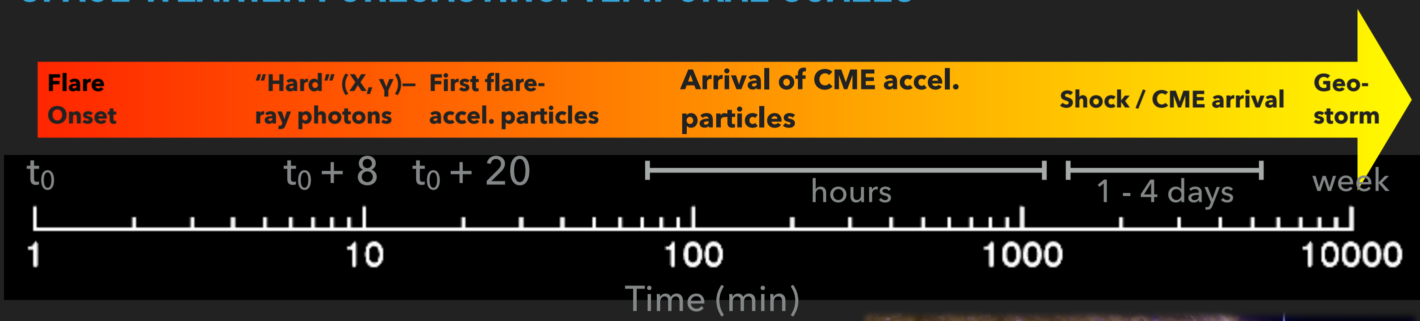

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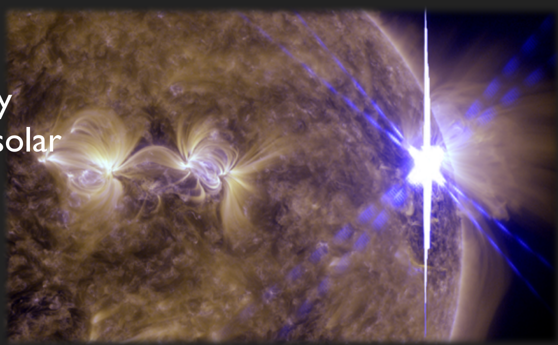
- Hard flare photons and non-thermal particulate (mostly protons >10 MeV) affect humans beyond LEO and on solar system bodies lacking an atmosphere. Detrimental for space-based electronics, radio blackouts, aviation, etc.



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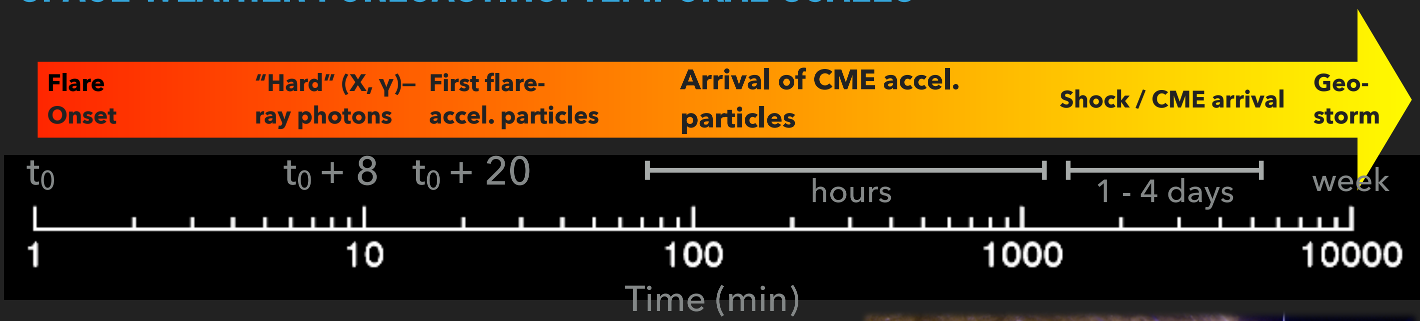

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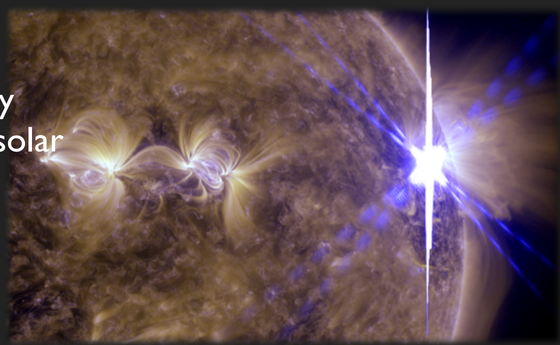
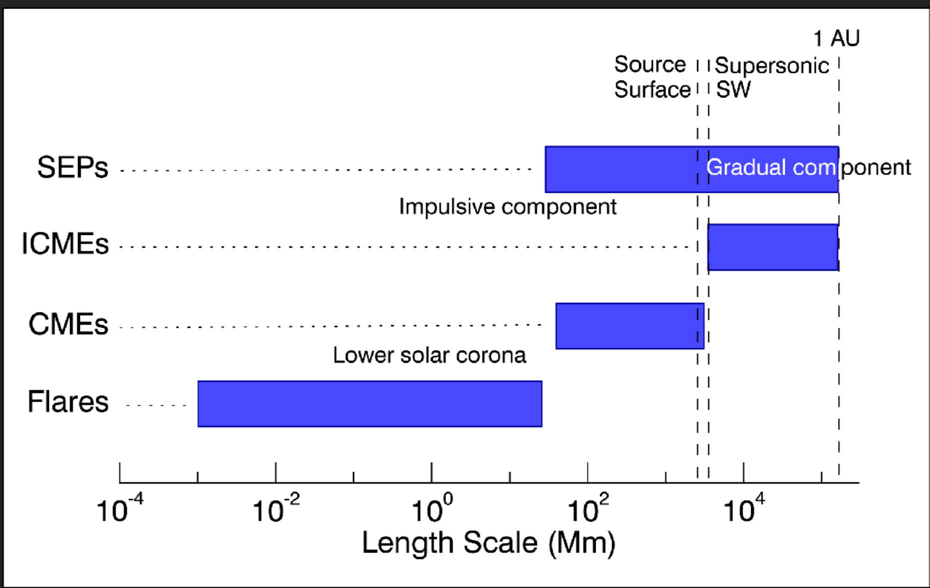
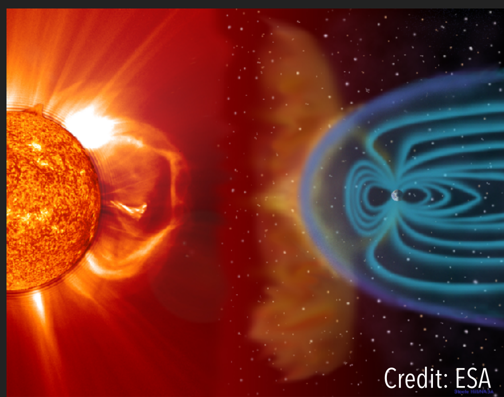
No early warning time for flare photons - slim window for particulate in worst case!



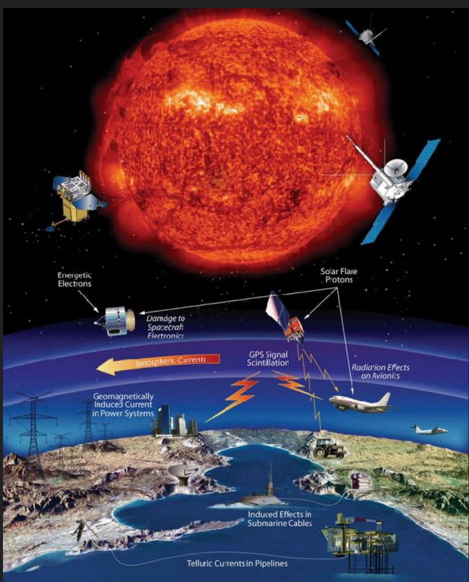
SPACE WEATHER FORECASTING: SPATIAL SCALES



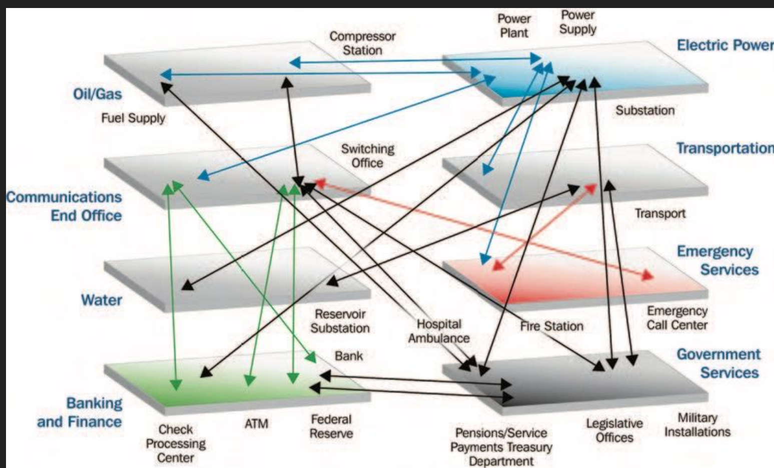
More than 8 orders of magnitude, from the flares' onset region (~ 1 km) to the CME / SEP products at 1 AU (~1.5 x 10^8 km)



AN INTERCONNECTED SOCIETAL FABRIC AROUND GEOSPACE RESPONSE TO SWX



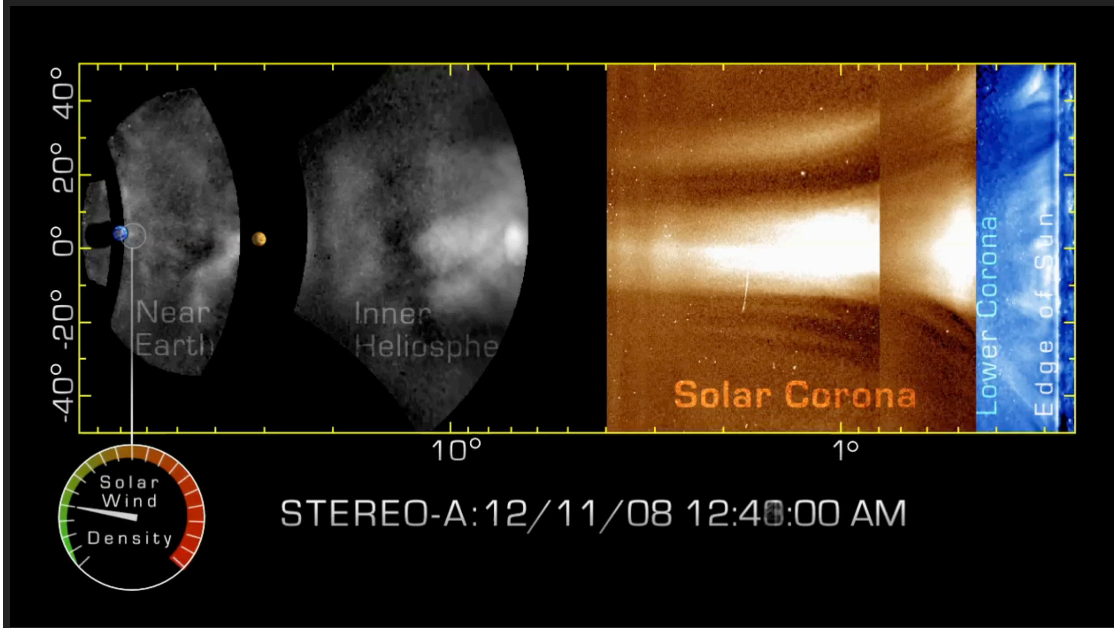
Credit: NASA

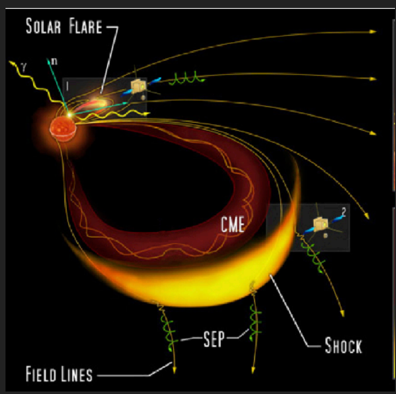


Source: Severe Space Weather Events: Understanding Societal and Economic Impact, US Space Study Board (2008) –
also, Oughton et al. (2016) for economic losses (BEUR per day)

If one sector goes down, impact is amplified due to interconnections

PHYSICALLY INTERCONNECTED SWX MANIFESTATIONS VS. A TECHNICALLY INTERCONNECTED INFRASTRUCTURE





Source: NASA / Solar Sentinels STDT Report

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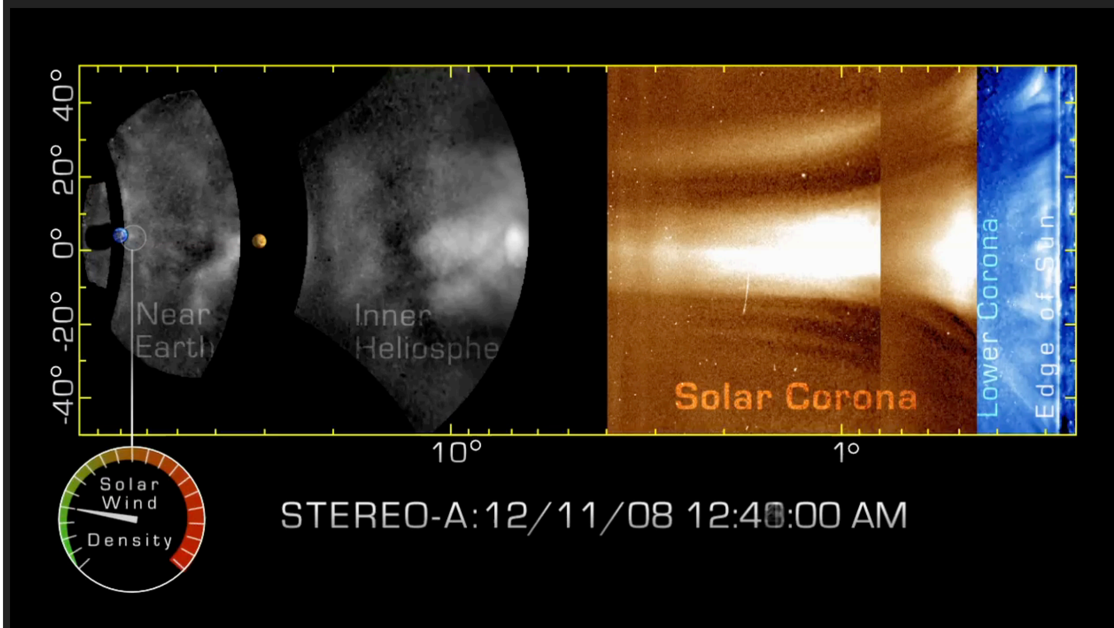

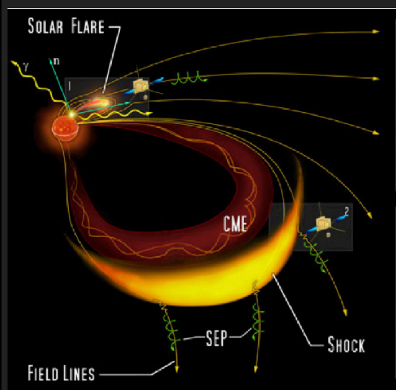

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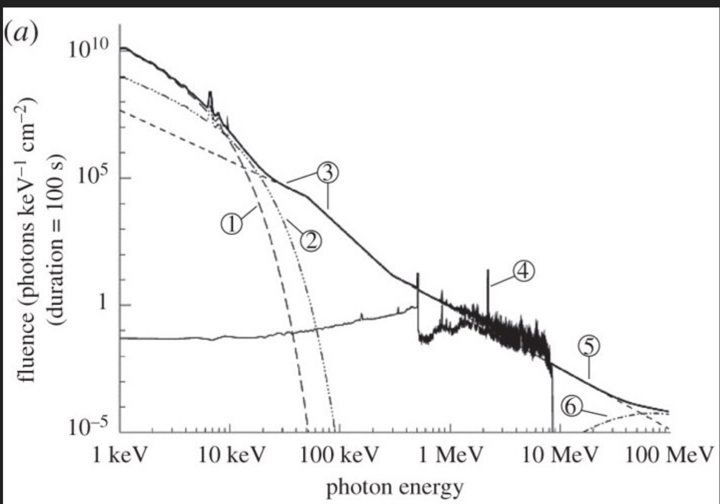
FLARE PHOTON RADIATION & SOME IMPACTS



Composite X-ray/γ-ray spectrum from 1 keV to 100 MeV for a large flare (Lin et al., 2007 – see also Vilmer 2012 for details)

Issues with X- and γ-rays (> 100 keV; ~10^{19} Hz):

Biological: cell and DNA impact or even destruction (astronauts in EVA)

Technological: saturation issues in Sun-observing telescopes (attenuators must be deployed) and, possibly, sensitive electronics

Focus on solar flare prediction

RADIO BLACKOUTS

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2 x 10-3)	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10-3)	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10-4)	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5 x 10-5)	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10-5)	2000 per cycle (950 days per cycle)

Credit: NOAA SWPC (R-scale)

- At least a few (< 10) severe (R4+) radio bursts are expected during a typical solar cycle.
- At least one extreme (R5) burst is expected in two consecutive cycles

Focus on solar flare prediction

COMBINED FLARE – CME IMPACT: GEOMAGNETIC STORMS*

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Credit: NOAA SWPC (G-scale)

* Estimated based on frequency of occurrence and assuming flare association of these CMEs

Flares > X10+

Flares ~ (M7 - X1)

Flares ~ M4

Flares ~ M2

Flares ~C5

Focus on CME prediction

COMPARED FLARE-CME IMPACT: (PARTICLE) RADIATION STORMS*

* Estimated based on frequency of occurrence and assuming flare association of these CME and SEP events

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

Flares > X10+

Flares ~ X10

Flares ~ X4

Flares ~ X3

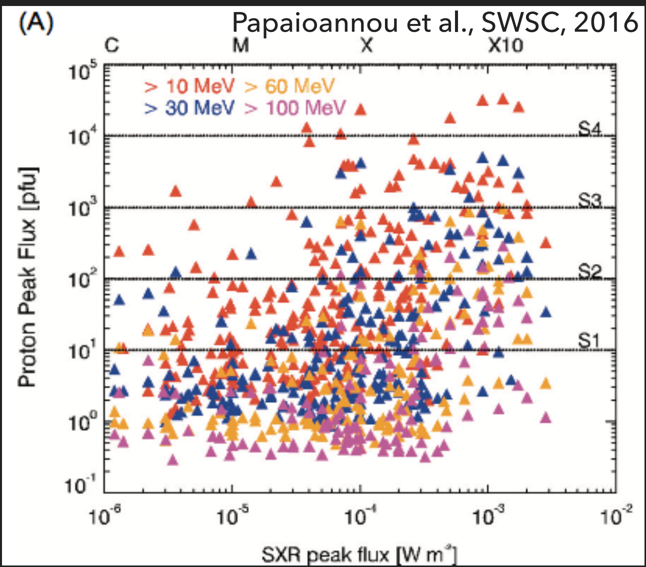
Flares ~ X2

Credit: NOAA SWPC (S-scale)

Focus on SEP prediction

A QUESTION OF WHEN, NOT WHETHER, BUT HIGHLY NONLINEAR OVERALL

Papaioannou et al., SWSC, 2016



1984 – 2013: tens of extreme flares (X10+); at least 8 severe radiation storms (S4)

Probability for a Carrington-type flare (estimated at ≳ X45 by Cliver [2013]):

- 10.3% over the next 10 yrs (>95% CI) – Riley & Love (2017)
- 4 – 6 % over the next 10 yrs – Kataoka (2013)
- 1 event very 500 yrs – Yermolaev et al. (2013)
- STEREO-B claimed an allegedly Carrington-type event detection in July 2012 (reached S/C in 19 hours only!)

Governmental actions:

Jul 2015: Space Weather Preparedness Strategy, Cabinet Office, Dept. of Business Innovation & Skills, UK Government

Oct 2015: National Space Weather Action Plan, National Science and Technology Council, US Government

Governments of China, Japan, Australia, South Korea, South Africa and India are possibly moving toward this direction

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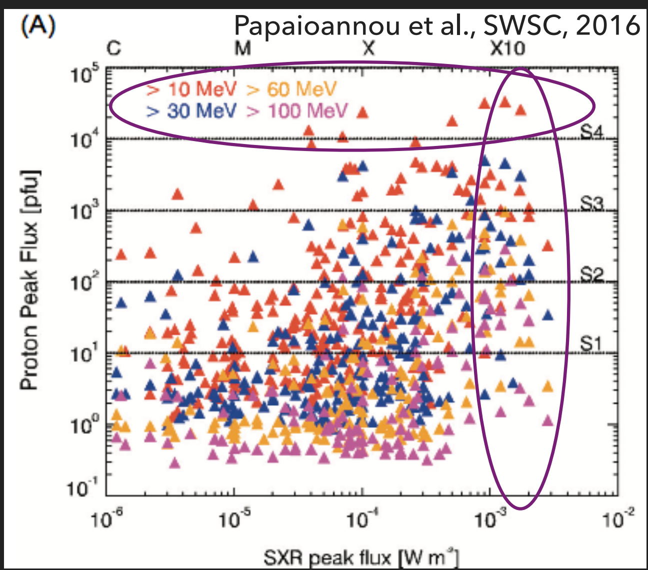

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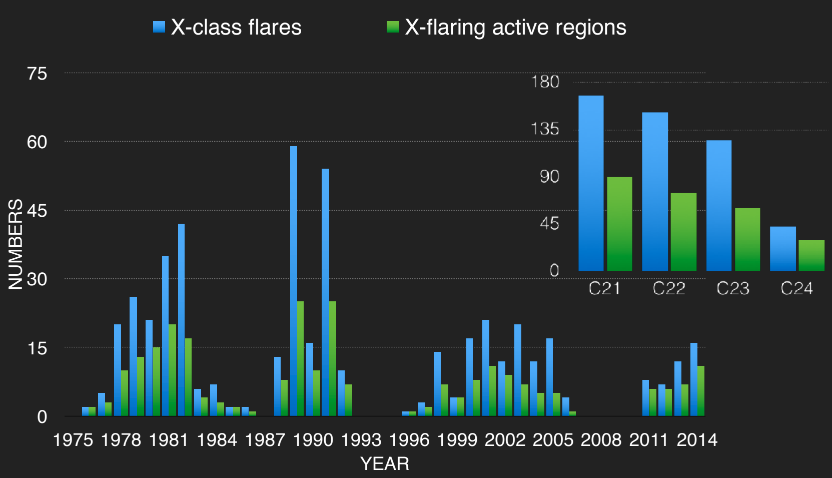
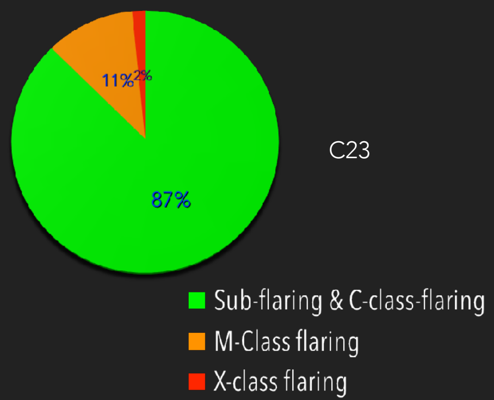
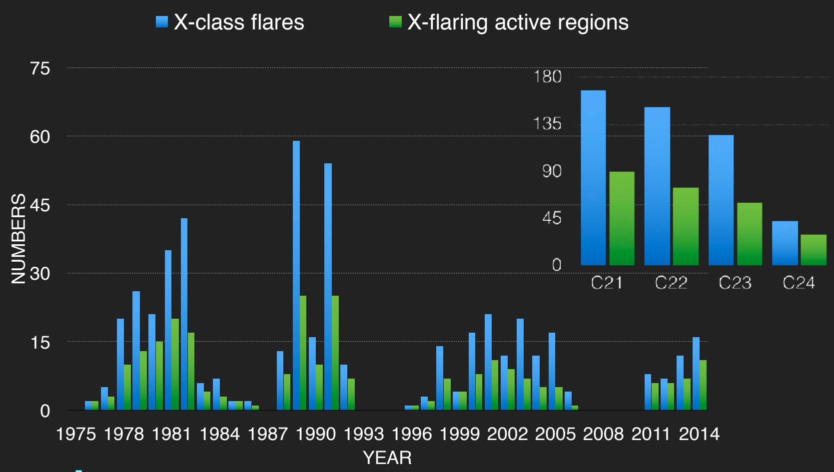
ELEMENTS OF SOLAR FLARE FORECASTING

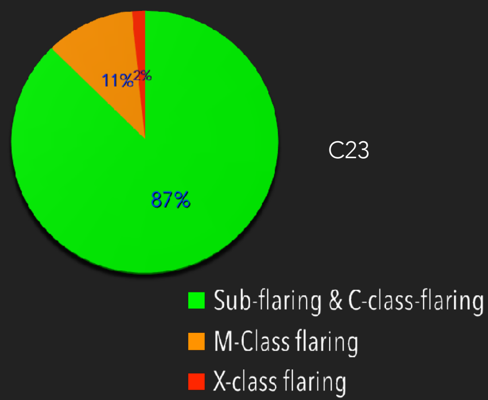




Only ~2% of active regions gave at least one X-class flare in solar cycle 23

ELEMENTS OF SOLAR FLARE FORECASTING





Only ~2% of active regions gave at least one X-class flare in solar cycle 23

Needs:

- Identification of potentially flaring regions
- Determination of "all clear"
- Determination of "when" and "how strong"

Challenges:

- Flares are a trait of a few, "privileged" regions
- Stochasticity in major flare production

ELEMENTS OF CME FORECASTING

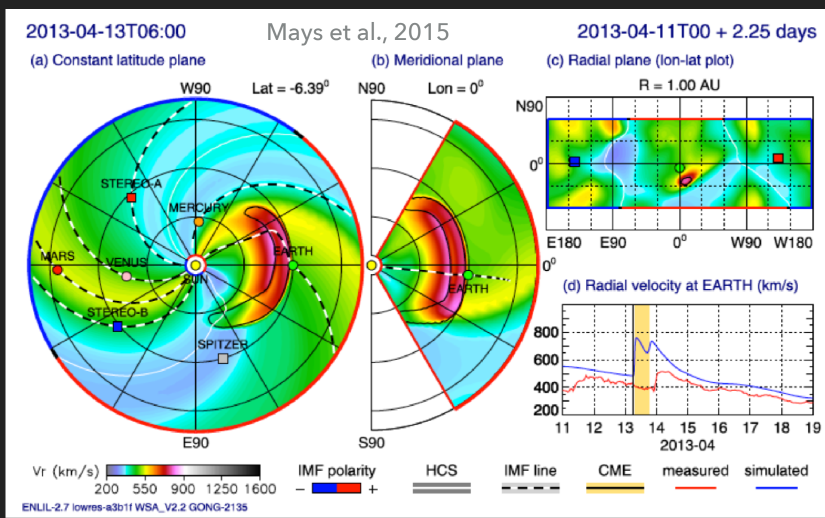
Needs:

- Identification of potentially eruptive regions
- Determination of CME directionality and speed
- Identification of CME magnetic structure and its variations during IP transit

Challenges:

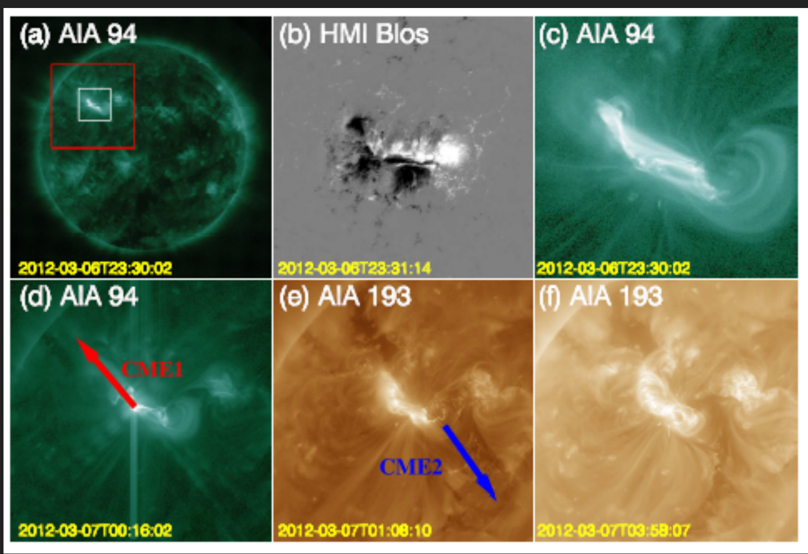
- Prediction of arrival time
- Prediction of ICME Bz and geoeffectiveness

Arrival time: YES(?)
Geoeffectiveness: NO



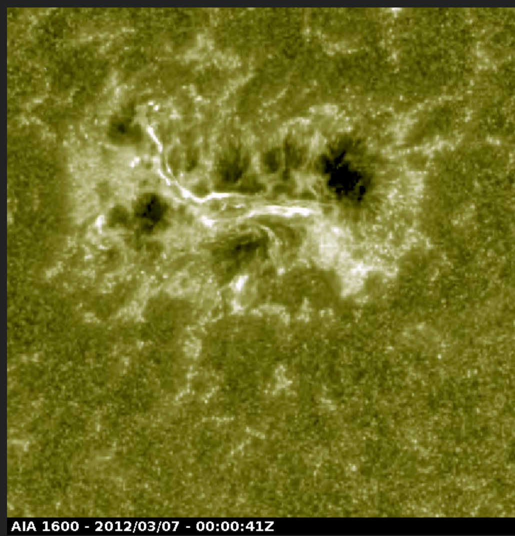
WSA - ENLIL + cone (but notice EUHFORIA results, as well

CME PREDICTION CHALLENGES: DIRECTIONALITY



Patsourakos et al., 2016

Two CMEs within ~ 1 hour; same active region

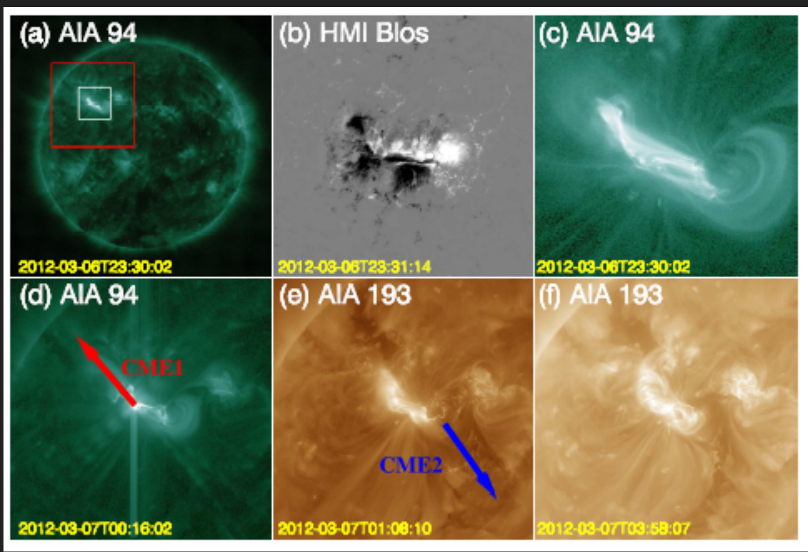


NOAA AR 11429, 6 - 7 Mar, 2012

CME 1: missed Earth

CME 2: Earth-directed

CME PREDICTION CHALLENGES: DIRECTIONALITY



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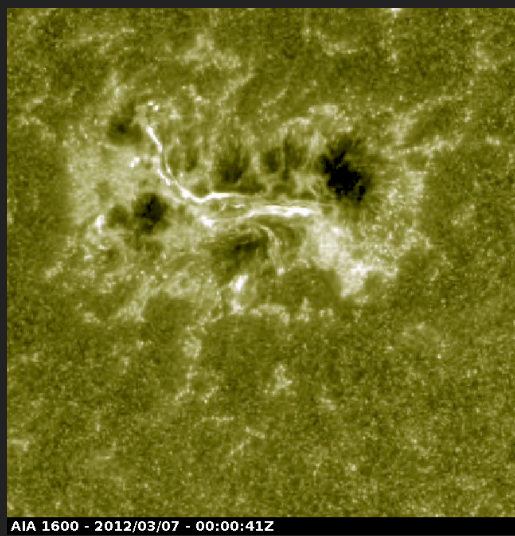

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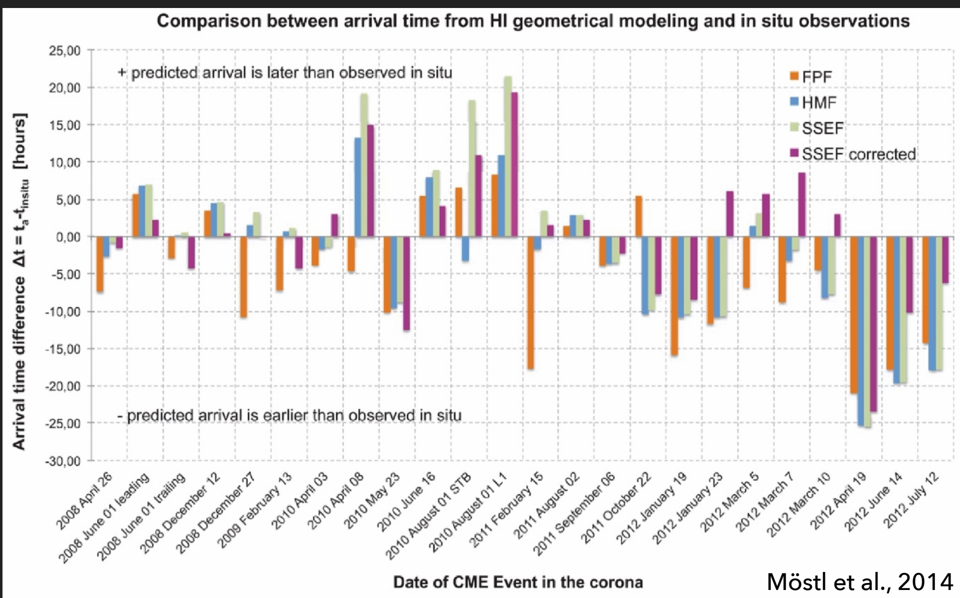
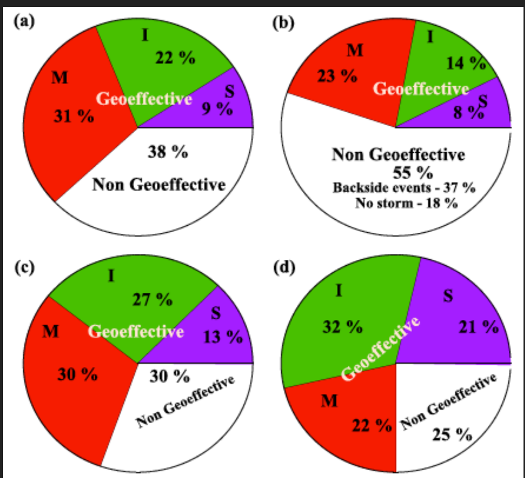
CME PREDICTION CHALLENGES: ARRIVAL TIME



22 ICMEs

- Randomness in type and amplitude of discrepancy: overestimation and underestimation of arrival times appearing from event to event
- If anything, different methods for a given event seem to agree on overestimation or underestimation (at various amplitudes, however)
- Average of arrival time difference with observations nearly zero (communication with author)

CME PREDICTION CHALLENGES: GEOEFFECTIVENESS



Vasanth et al. (2015)

Correlating different near-Sun CME characteristics (source location, speed, angular width, Type II association) to geoeffectiveness

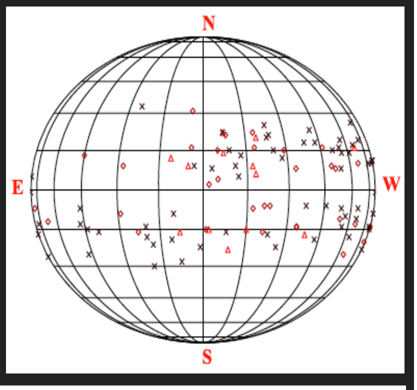
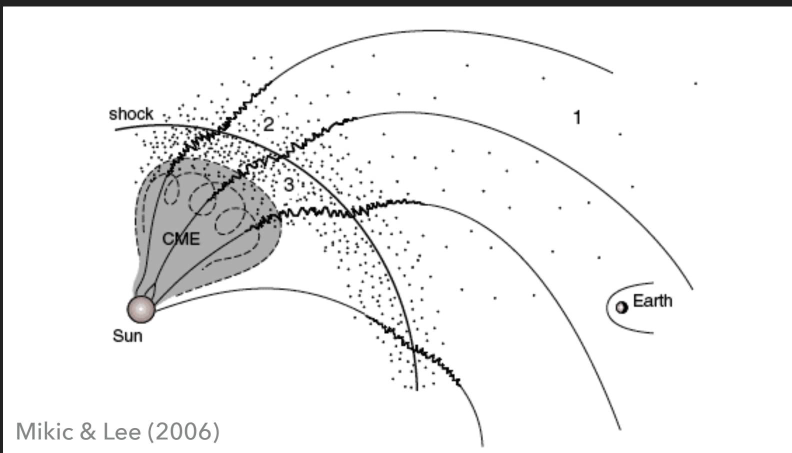


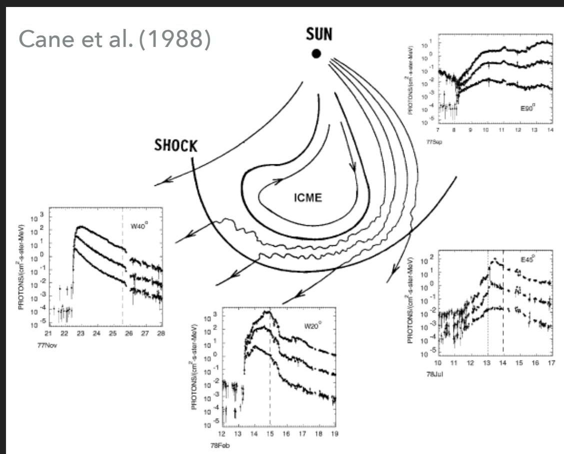
Table 2 Statistical properties of the 109 IP type II bursts associated CME events in SC 23. See text for details.

Properties	Moderate storms	Intense storms	Severe storms
CME speed ($\mathrm{km\,s^{-1}}$)	$1\,271 \pm 71$	$1\,376 \pm 134$	$1\,589 \pm 141$
HCMEs	63 % (40/64)	88 % (28/32)	92 % (12/13)
Source location [$\pm 30°$]	38 % [24/64]	53 % [17/32]	85 % [11/13]
Source location [$\pm 45°$]	47 % [30/64]	66 % [21/32]	92 % [12/13]
Source location [western events]	67 % [(43/64)	75 % (25/32)	77 % (10/13)
Dst min (nT)	-71 ± 2	-141 ± 5	-283 ± 17
End frequency (MHz)	2.07 ± 0.34	1.52 ± 0.43	1.08 ± 0.70

ELEMENTS OF SEP PREDICTION



Mikic & Lee (2006)



Cane et al. (1988)

Needs:

- Knowledge of connectivity between injection location and geospace
- Knowledge of upstream connectivity ahead of a CME shock with geospace
- Knowledge of injection location

Challenges:

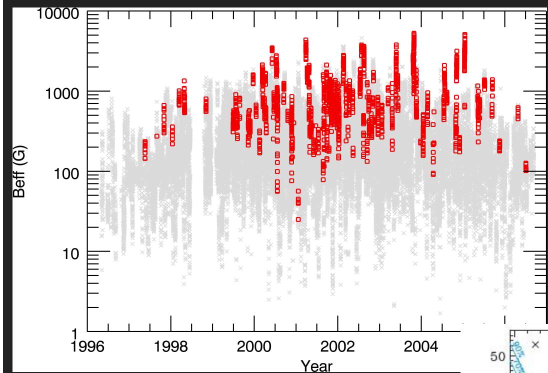
- Temporal profile <u>and peak</u>, as a function of particle energy
- Arrival time at 1 AU

SUMMING EVERYTHING UP

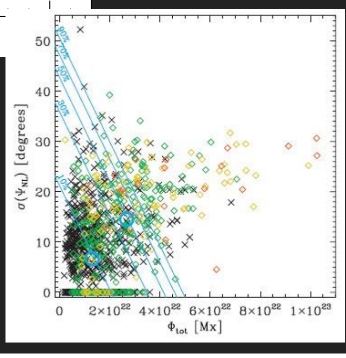
	Input	Heliographic location	Orientation	Outcome	SWx forecasting value
Flares	Solar data	YES, for SEPs (impulsive component)	–	Flare - SEP probabilities	Radio blackouts; S-storms (?); G-storms(?)
CMEs	Coronagrams; flares; solar data	YES, for SEPs (gradual component)	YES, for propagation	Arrival time; ICME Bz	S-storms; G-storms
SEPs	Flares; CMEs; shocks	YES	YES, of CMEs	Arrival time; amplitude; temporal profile	S-storms

To satisfy every forecast need, one should tackle all three problems self-consistently and combine all available information

STARTING FROM SOLAR FLARE PREDICTION



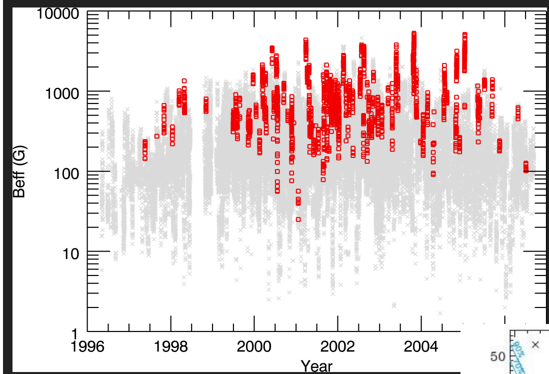
Single predictor - Bayesian inference



Multiple predictors - (linear) discriminant analysis

SEIBERSDORF LABORATORIES SEPRAD EXPERT WORKSHOP M, K. GEORGOULIS Seibersdorf, 19 Sep 2017

STARTING FROM SOLAR FLARE PREDICTION



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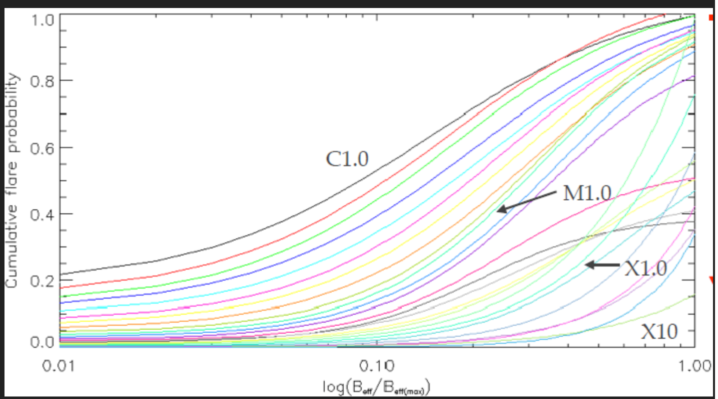
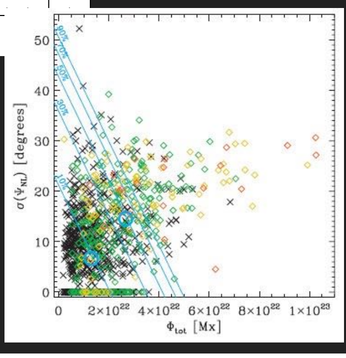


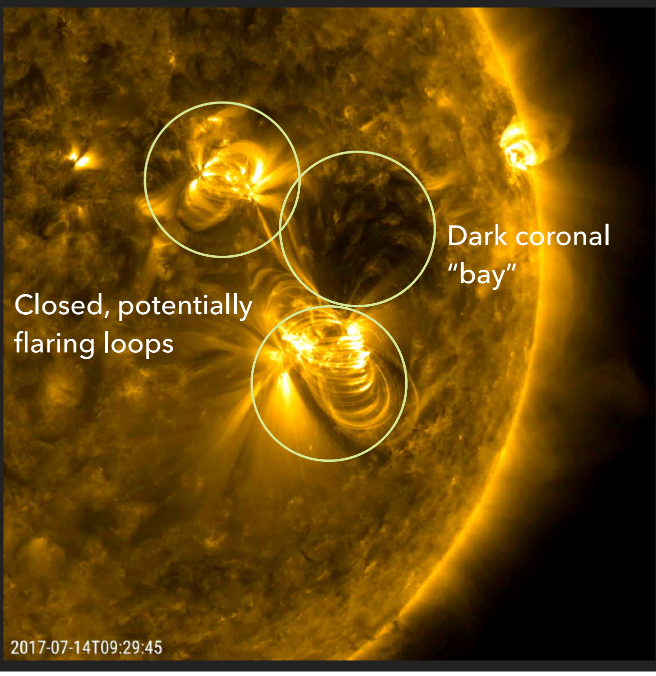
Example of single-predictor flare probability for 29 flare classes as a function of the parameter value



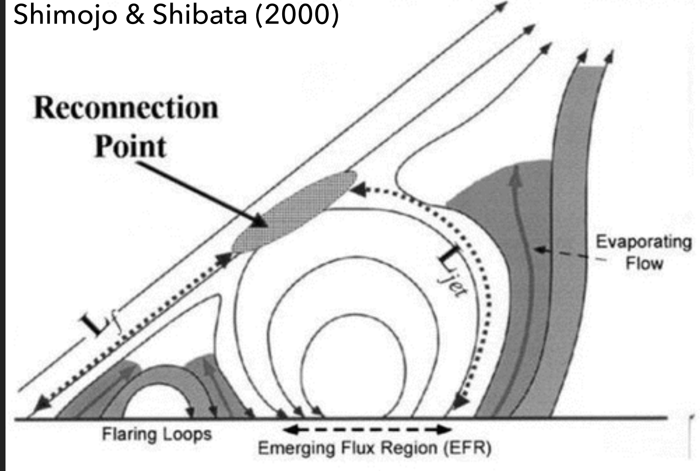
Multiple predictors - (linear) discriminant analysis

Yesterday's lecture by A. Papaioannou

EXAMPLE 1: FLARE – IMPULSIVE SEP ; IGNORING CMES

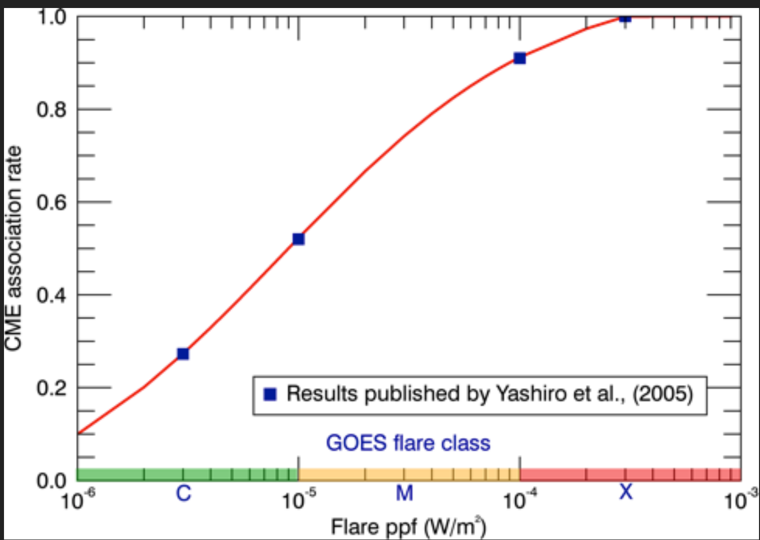


Shimojo & Shibata (2000)



Proximity of flaring loops to topologically "open" field lines may mean impulsive SEPs within minutes, even with small flares (Rust et al., 2008)

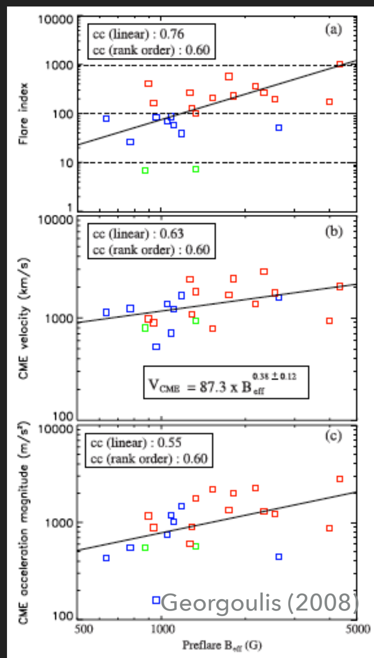
EXAMPLE 2: FROM A FLARE PREDICTION TO AN 'ERUPTIVE' FLARE PREDICTION…



The flare - CME probabilistic connection: flares ≈ X3 show a one-to-one CME association

- **and / or -**

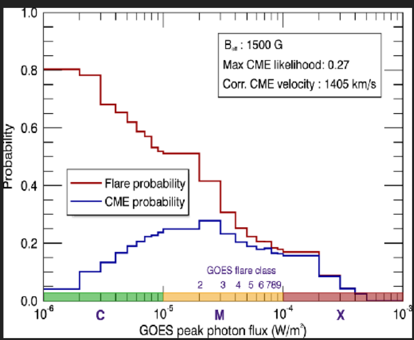
direct correlation between flare-prediction metrics and CME characteristics (work by FLARECAST team in exploratory WP)



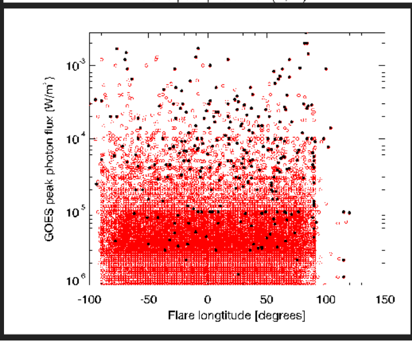
Georgoulis (2008)

... AND THEN TO A SEP PREDICTION

Papaioannou et al. (2015);
Anastasiadis et al. (2017)

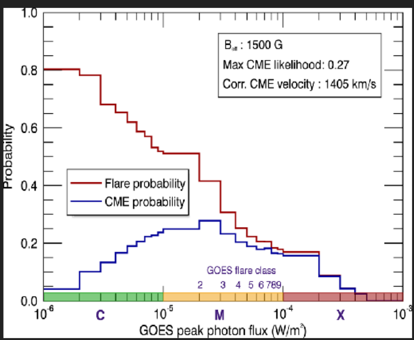


Likelihood of an eruptive flare for a given predictor value



Association of flare location with SEPs

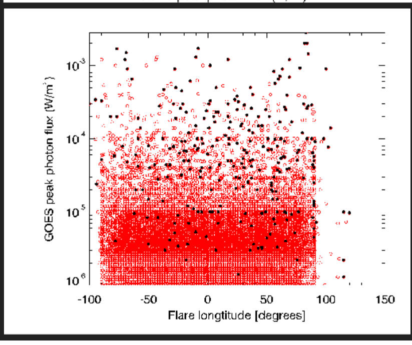
… AND THEN TO A SEP PREDICTION



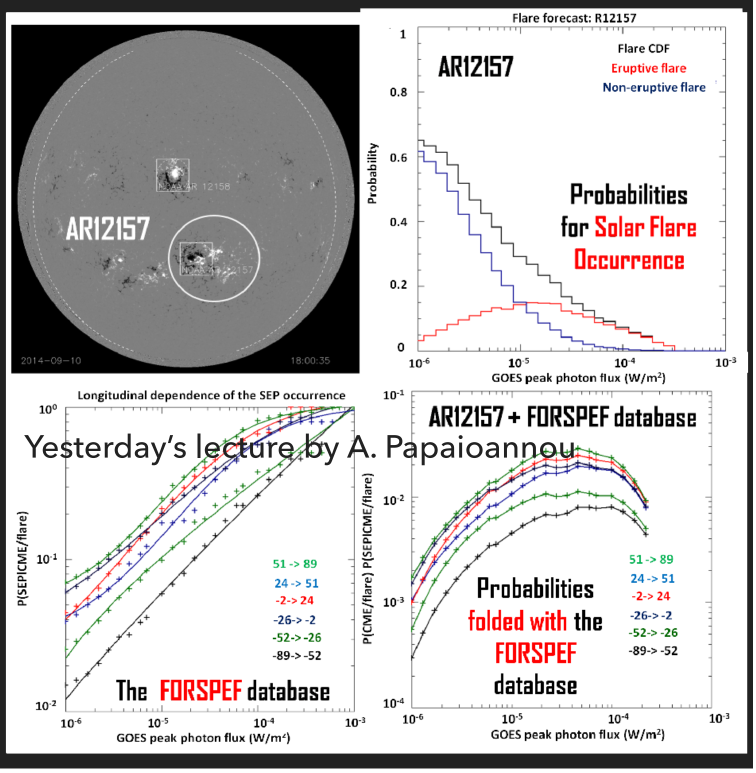
Papaioannou et al. (2015); Anastasiadis et al. (2017)

Likelihood of an eruptive flare for a given predictor value

… leading to a "folded" SEP probability from historical data

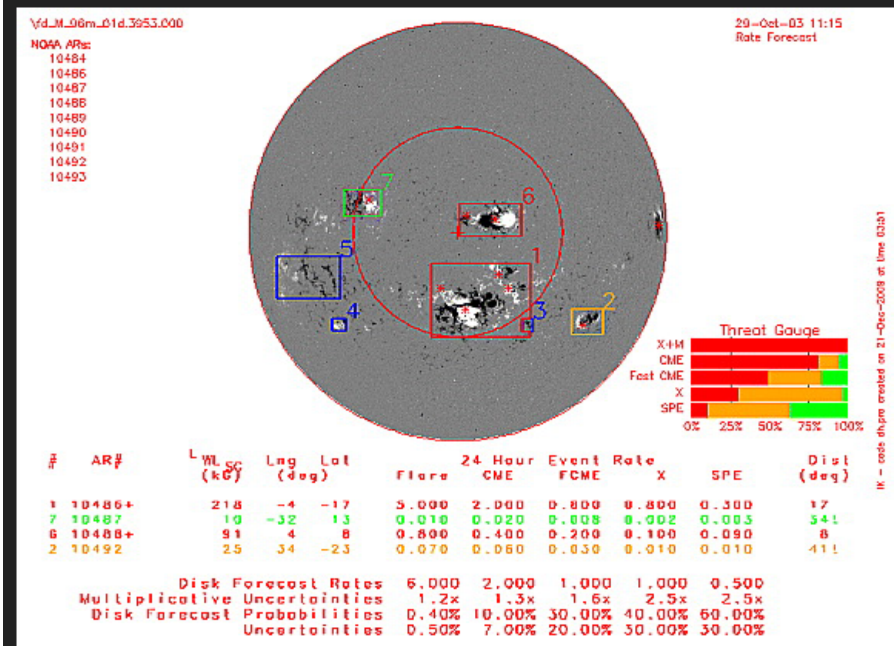


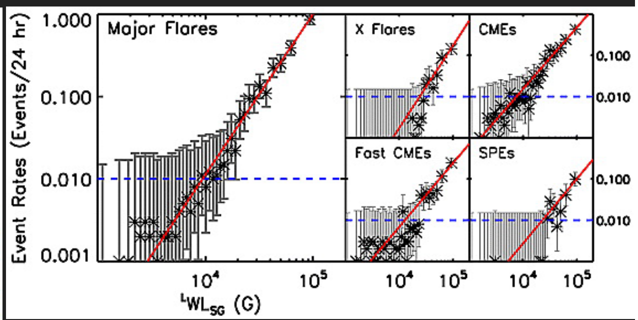
Association of flare location with SEPs



Yesterday's lecture by A. Papaioannou

EXAMPLE 3: FLARE / CME / SEP PREDICTION USING ONLY SOLAR DATA





Falconer et al., (2011)

Dealing with active-region properties only and producing forecasts for all three manifestations (see also MAG4: Falconer et al., 2014 – SPRINTS: Engell et al., 2017)

EXAMPLE 4: ACCOMMODATE AS MUCH OF THE COMPREHENSIVE APPROACH AS NECESSARY

CME shock arrival forecast:

- Anemomilos (Tobiska, 2013)
- EAM (*Effective Acceleration Model*) (Paouris *et al.*, 2017)
- ElEvo (*Ellipse Evolution*) Model (Möstl *et al.*, 2015)
- ESA (*Empirical Shock Arrival*) Model (Gopalswamy *et al.*, 2001, 2005)
- H3DMHD (HAFv.3 +3DMHD) Model (Wu *et al.*, 2011)
- HAFv.3 (Fry *et al.*, 2001, 2003, Smith *et al.*, 2009, McKenna-Lawlor *et al.*, 2006)
- SAP (Sheath-accumulating Propagation) (Takahashi and Shibata, 2017)
- SARM (*Shock ARrival Model*) (Núñez *et al.*, in preparation)
- SPM (Feng and Zhao, 2006) and SPM2 (Zhao and Feng, 2014)
- STOA (*Shock Time of Arrival*) (Dryer *et al.*, 1984, 2004, Fry *et al.*, 2001, McKenna-Lawlor *et al.*, 2006)
- WSA-ENLIL + Cone Model (Odstrcil *et al.*, 2004)
- *Ballistic projection*

CME arrival forecast:

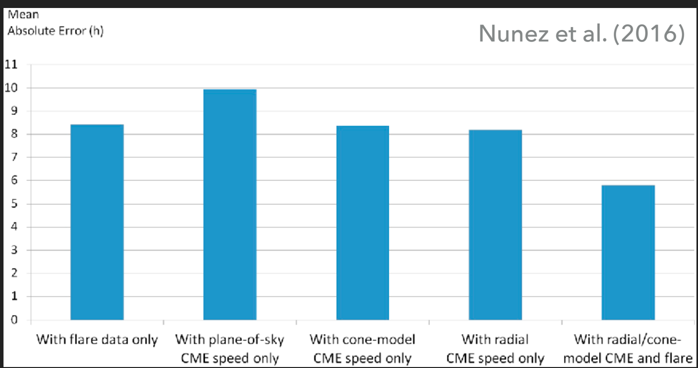
- BHV (*Bothmer Heseman Venzmer*) Model (Bothmer and Schwenn, 1998)
- DBM (*Drag Based Model*) (Vršnak *et al.*, 2013)
- DBM + ESWF (*Drag Based Model + Empirical Solar wind Forecast*) (Vršnak, Temmer, Veronig, 2007; Rotter *et al.*, 2015)
- COMESEP automated system (CGFT, Geomag24) (Crosby *et al.*, 2012)
- ECA (*Empirical CME Arrival*) Model (Gopalswamy *et al.*, 2000, 2001)
- Expansion Speed Prediction Model (Schwenn, 2005)
- WSA-ENLIL + Cone Model (Odstrcil *et al.*, 2004)
- HelTomo (Jackson *et al.*, 2010, 2011)
- HI J-map technique (Sheeley, 2008; Rouillard *et al.*, 2008; Davis *et al.*, 2009, 2011)
- TH (*Tappin-Howard*) Model (Tappin and Howard, 2009, Howard and Tappin, 2010)
- *Ballistic projection*

CME ScoreBoard

Source: NASA / CCMC

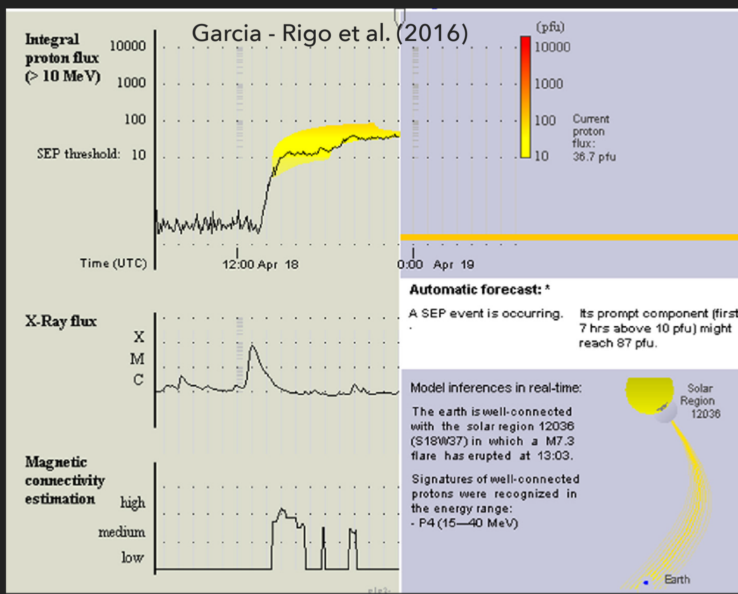
Numerous methods, with varying sophistication, at the benefit of achieving a near-realtime shock and CME arrival time – some with SEP information

EXAMPLE 5: SEP FORECASTING ONLY



Prediction of shock and SEP arrival time using various levels of information

Previous lecture by M. Núñez



SEP forecasting from solar-source information

AN INDICATIVE LIST OF FORECAST MODELS : OBVIOUSLY A THRIVING TOPIC!

Services / Projects	Flares	C M Es	S E Ps	Who
A-EFFORT	X			ESA / Acad. Athens (GR)
ASAP	X			U. Bradford (UK)
ASSA	X			Korean Space Agency (KR)
COMESEP			X	European Commission (EU)
FLARECAST	X			European Commission (EU)
FORSPEF	X	X	X	ESA / Nat. Obs. Athens (GR)
HESPERIA			X	European Commission (EU)
MAG4 / SPRINTS	X	X	X	U. Alabama-Huntsville (USA)
RELEASE			X	NASA / CCMC (USA)
SOLAR MONITOR	X			Max Millennium (USA, IE)
SOLPENCO			X	ESA / U. Barcelona (SP)
SWPC	X			NOAA (USA)
UMASEP			X	ESA / U. Malaga (SP)

More underway (EUHFORIA, PROGRESS, DAFFS, PSTEP, etc.) and many more providing input to CCMC flare and CME scoreboards

A TOP-LEVEL ASSESSMENT OF THE MULTITUDE OF MODELS

The challenge is to streamline the prediction strategy <u>in an automated way</u>

Solar Flares

* Producing a forecast probability
* Dealing with stochasticity

Coronal mass ejections

* Producing a forecast probability
* Near-Sun speed and directionality
* Axis orientation
* Arrival time at 1 AU
* Magnetospheric response at 1 AU

Solar particle events

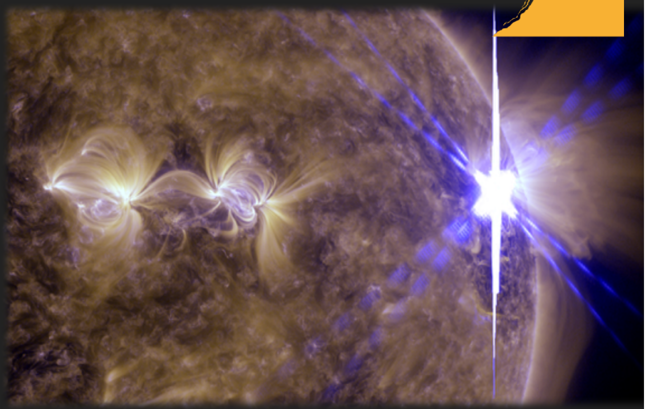
* Producing a forecast probability
  - From flares
  - From CMEs
* Profile prediction
  - From flares
  - From CMEs
* Peak vs. energy channels

Apparently, the automated prediction of CMEs and SEPs is more demanding than that of flares

A POTENTIAL AVENUE TO STREAMLINING: FLARECAST

FLARECAST

FLARECAST is an EC H2020 project aiming to develop an advanced solar flare prediction system based on automatically extracted physical properties of solar active regions, coupled with state-of-the-art solar flare prediction methods and validated using the most appropriate forecast verification measures.



Source: NASA SDO

FLARECAST top-level objectives:

- To understand the drivers of solar flare activity and improve flare prediction
- To provide a globally accessible flare prediction service that facilitates expansion
- To engage with space weather end users and inform policy makers and the public

FLARECAST DATA TYPES

Overarching science question: how far can we go in predicting solar flares?

External data:

- SDO / HMI NRT SHARPs
- NOAA / SWPC SRS data
  - Active region numbers
  - AR locations
  - Flare occurrences

Science data:

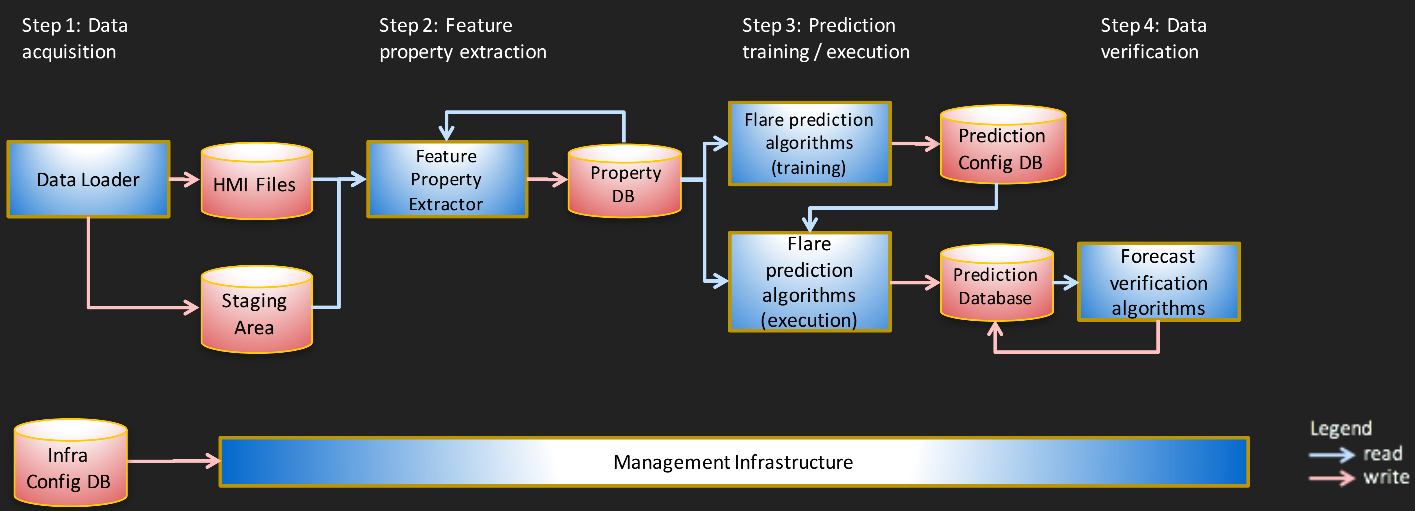
- Extracted properties
- Prediction algorithm config.
- Predictions
- Validation

Infrastructure data:

- Algorithm management
- Workflow management

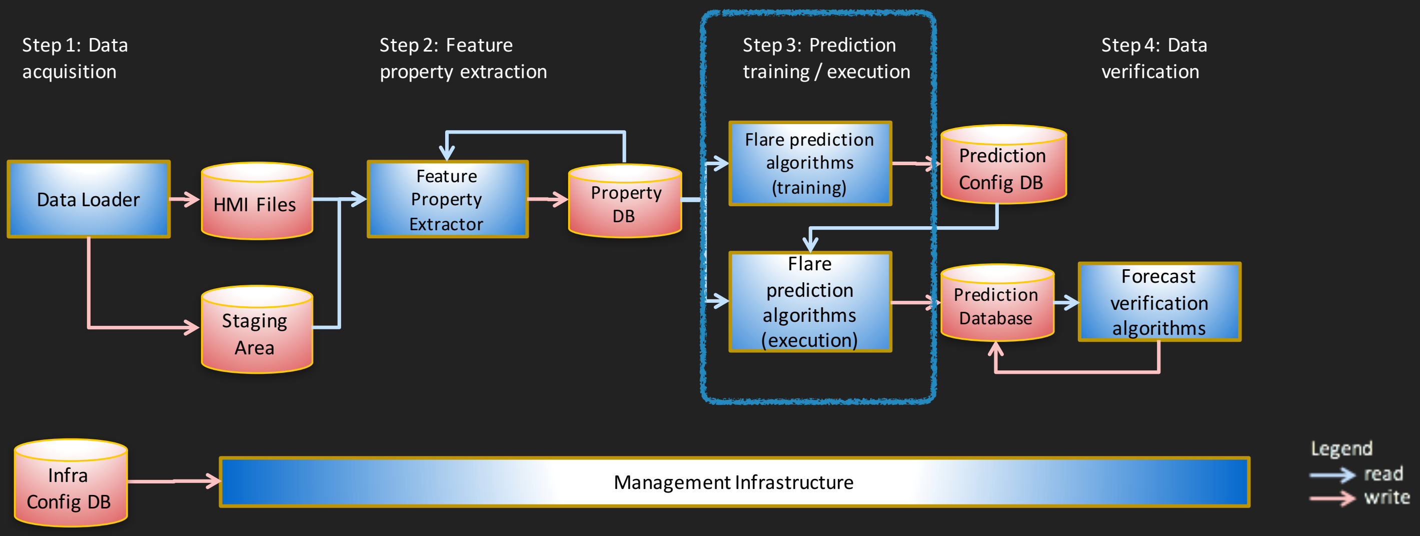
http://flarecast.eu

WHAT CAN FLARECAST DO TO HELP?



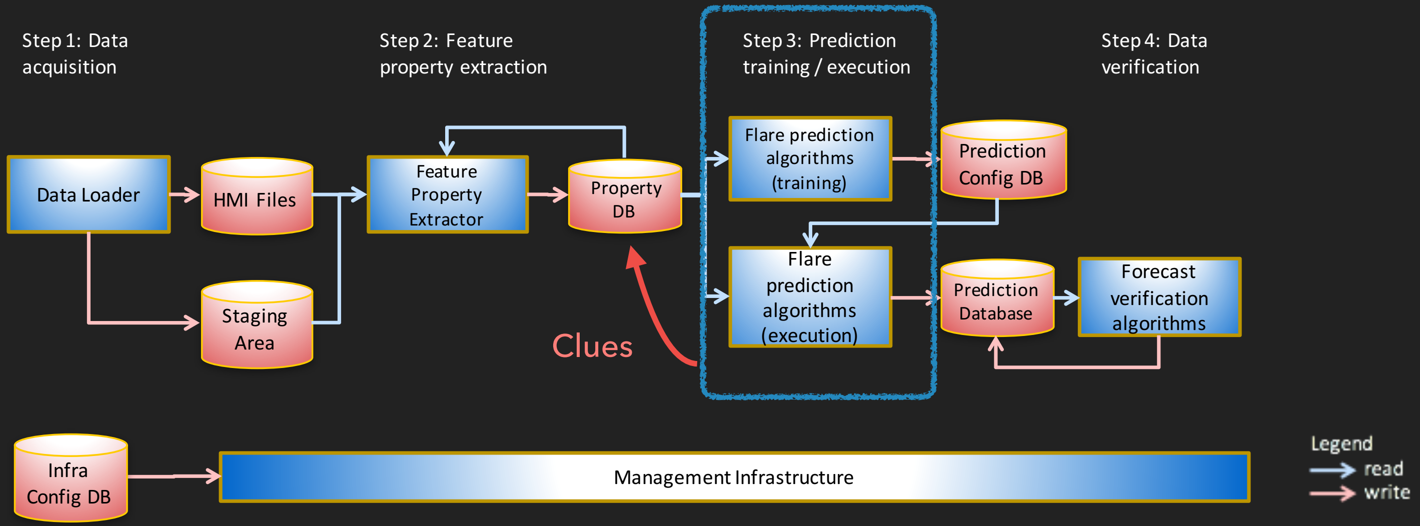
WHAT CAN FLARECAST DO TO HELP?

Potential eruption / SEP prediction



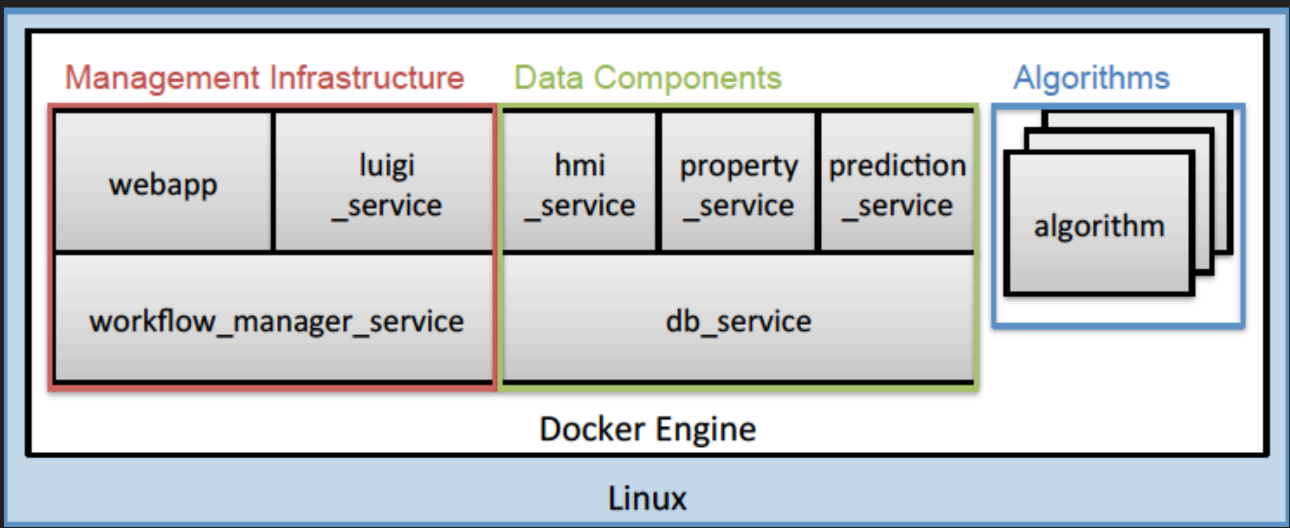
WHAT CAN FLARECAST DO TO HELP?

Potential eruption / SEP prediction



- Modify the prediction step, to include clues toward understanding / predicting CMEs and SEPs
- Complement the prediction step with prediction of CMEs and SEPs

FLARECAST INFRASTRUCTURE: PORTABLE, MODULAR, EXPANDABLE



An open-source, agile infrastructure that can add or remove components in an Docker-engine architecture

HOW CAN PROGRESS BE JUDGED? VALIDATION

Binary validation: Flare (YES) or No Flare (NO)

Tailoring according to different end user needs

	Forecast Flare	Forecast No-flare
Observed Flare	TP	FN
Observed No-flare	FP	TN

Table courtesy: Shaun Bloomfield

2 x 2 contingency table

- TP : true positives
- FN : false negatives
- FP : false positives
- TN : true negatives

- Generalized skill score:

$$SS = \frac{score - score_{reference}}{score_{perfect} - score_{reference}}$$

HOW CAN PROGRESS BE JUDGED? VALIDATION

Binary validation: Flare (YES) or No Flare (NO)

	Forecast Flare	Forecast No-flare
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Tailoring according to different end user needs

- Heidke skill score (ref: random prediction):

$$HSS = \frac{2(TP + TN) - N}{N}$$

- Appleman skill score (ref: climatology [v]):

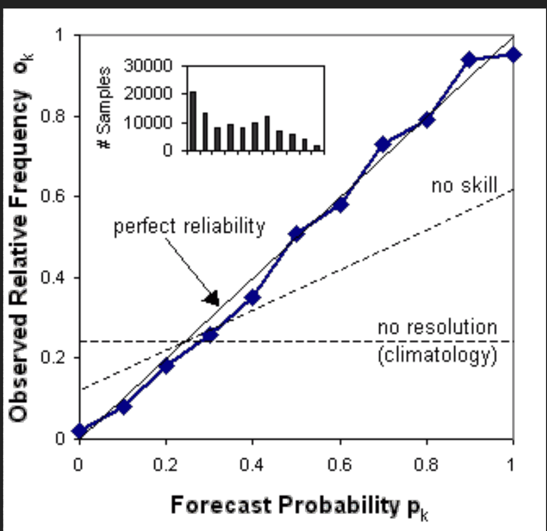
$$ApSS = \frac{TP - FP}{N}$$

- True skill statistic (ref: weighting POD w. POFD):

$$TSS = POD - POFD$$

HOW CAN PROGRESS BE JUDGED? VALIDATION

Accept that a probability 0 < p < 1 is assigned to each prediction

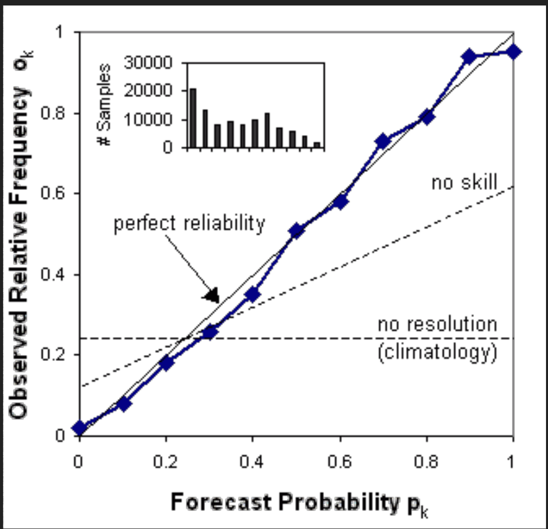


Reliabillity diagram

$$SS = 1 - \frac{MSE_{forecast}}{MSE_{reference}}$$

HOW CAN PROGRESS BE JUDGED? VALIDATION

Accept that a probability 0 < p < 1 is assigned to each prediction



Reliabillity diagram

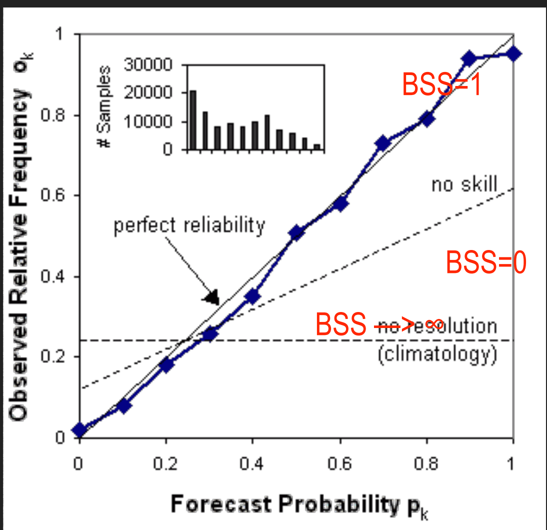
- Correlate forecast probability with observed frequency
- Compare your skill against climatology (mean flaring rate within forecast window)
- Generalized skill score:

$$SS = 1 - \frac{MSE_{forecast}}{MSE_{reference}}$$

$$MSE = \ < (o - p)^2 >$$

HOW CAN PROGRESS BE JUDGED? VALIDATION

Accept that a probability 0 < p < 1 is assigned to each prediction



Reliabillity diagram

- Correlate forecast probability with observed frequency
- Compare your skill against climatology (mean flaring rate within forecast window)
- Generalized skill score:

$$SS = 1 - \frac{MSE_{forecast}}{MSE_{reference}}$$

$$MSE = \langle (o-p)^2 \rangle$$

- Brier skill score (reference: climatology):

$$BSS = 1 - \frac{\left\langle (\tilde{o}-p)^2 \right\rangle}{\left\langle (o-\bar{o})^2 \right\rangle}$$

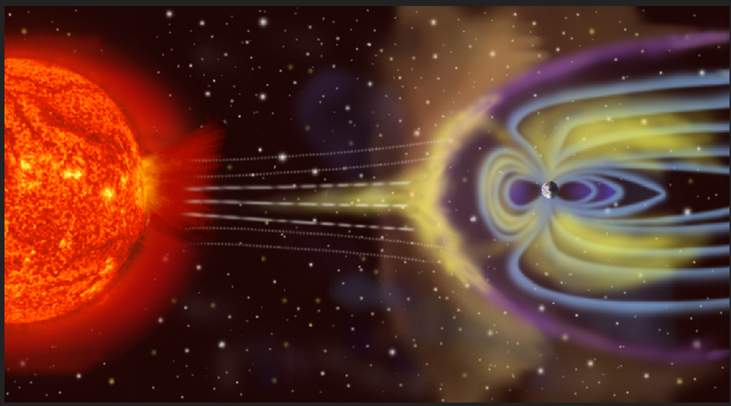
$$\tilde{o} \equiv \{0,1\}$$

$$BSS \in (-\infty, 1)$$

ONE FURTHER POINT: MORE METHODS / APPROACHES THAN NECESSARY?

- Fusion between flare and CME / SEP forecasting
- CME arrival-time prediction via drag-based models and / or HD or MHD models
- CME projected characteristics offered by more than one source (solar-source information, near-Sun observations, theoretical and numerical modeling)
- Multiple (& different) methods for SEP forecasting, from solar-only to heliospheric-only data

Credit: ESA



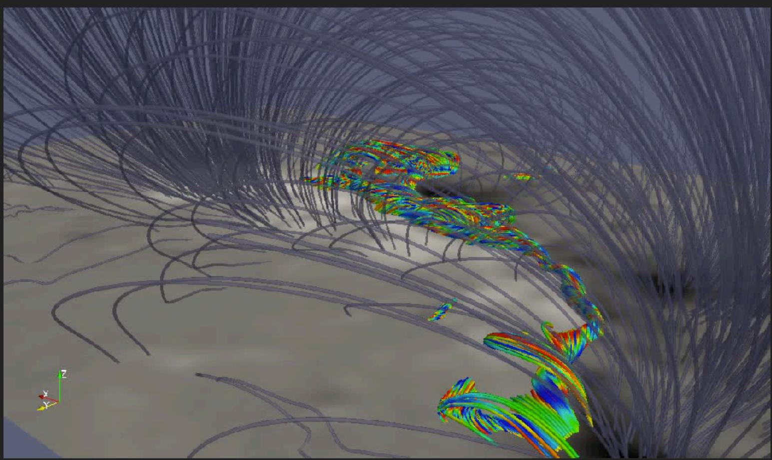
- We are over-determining the Sun-Earth line!
- Sometimes it might be good to even average (e.g., CME arrival times)
- But a consolidation exercise should identify and remove truly redundant approaches

CONCLUSIONS

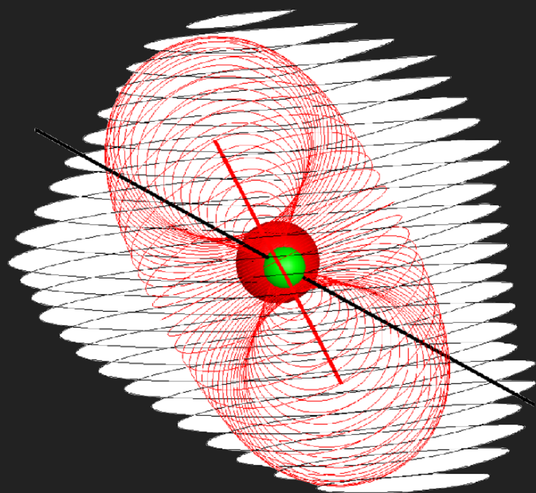
- An integrated space weather forecasting capability appears a necessity
- This said, solar flare, CME, and SEP forecasts have to be treated self-consistently, besides jointly
- This has yet to be achieved
- **Proposed course of action [1]**: use fully validated "redundant" models in conjunction; aim to constrain solutions and validate the ensemble further to see what, if anything, is gained
- **Proposed course of action [2]**: Use the expertise / infrastructure that is already available (e.g., FLARECAST) and build upon it; EU projects are fully open-source
- Task not within the realm of a single person or even group - global collaboration is necessary

BACKUP SLIDES

WHAT WE ARE UP AGAINST: SOLAR SOURCES



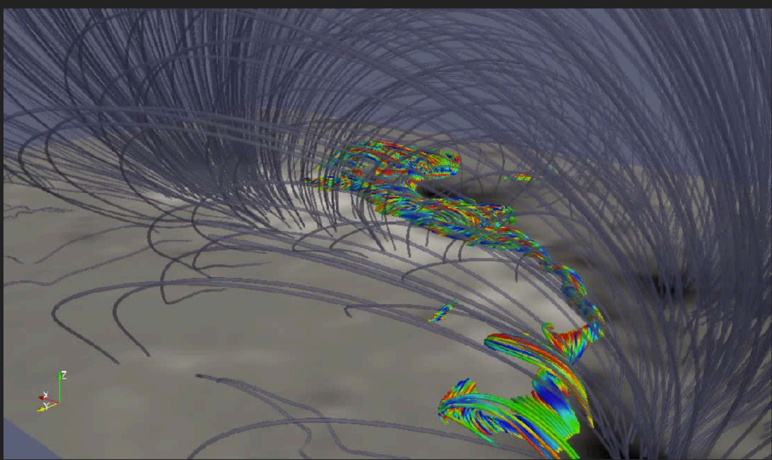
Credit: G. Chintzoglou - see also Chintzoglou et al., ApJ, 2015



Thernisien et al. (2009); Feng et al. (2012)

- Stochasticity in solar flare triggering
- The (unknown) flare - CME connection
- CME directionality
- CME axial magnetic field and axis orientation

WHAT WE ARE UP AGAINST: SOLAR SOURCES



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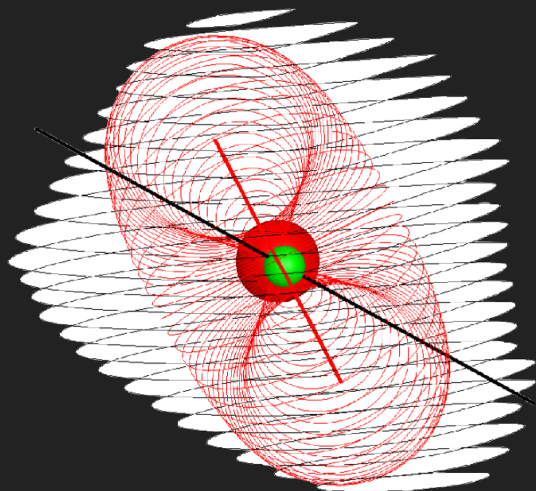
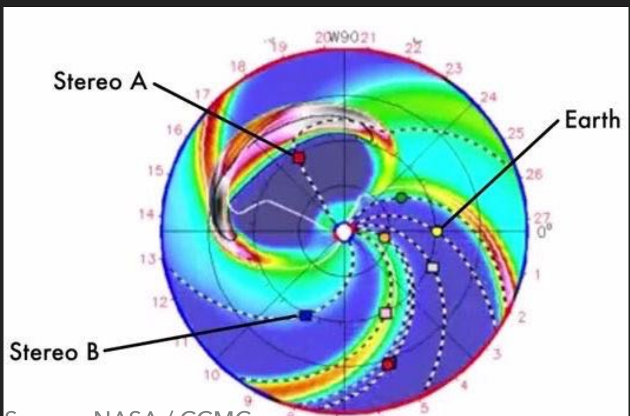


Thernisien et al. (2009); Feng et al. (2012)

- Stochasticity in solar flare triggering
- The (unknown) flare - CME connection
- CME directionality
- CME axial magnetic field and axis orientation

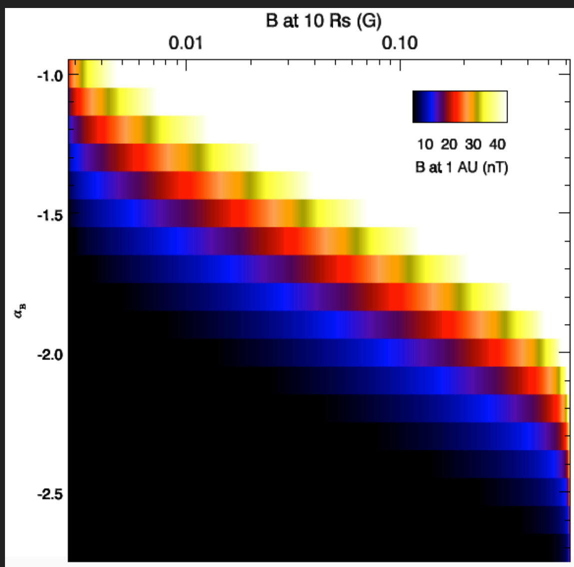
WHAT ARE WE UP AGAINST: CME IP TRANSIT & IMF BZ



Source: NASA / CCMC

- Situation of pre-existing solar wind (quiescent; perturbed; CIR)
- Inflation / erosion
- Axis rotation
- (+ heliographic location, for SPEs)

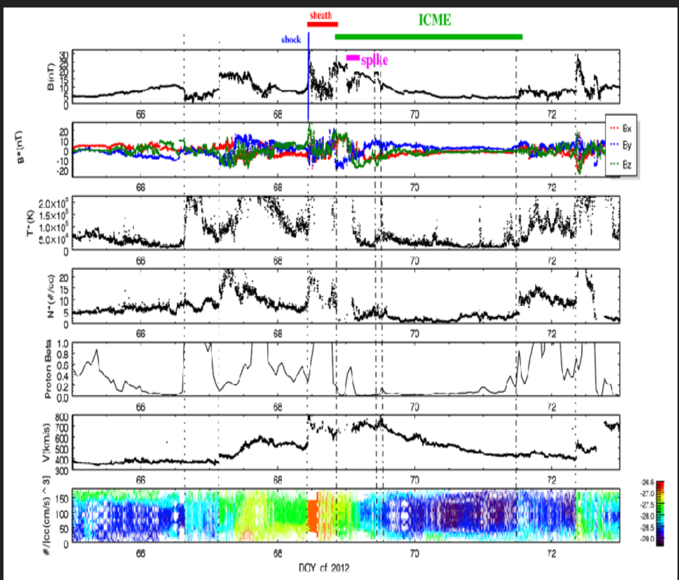
B_{ICME} @ 1 AU vs. near-Sun B_{CME}



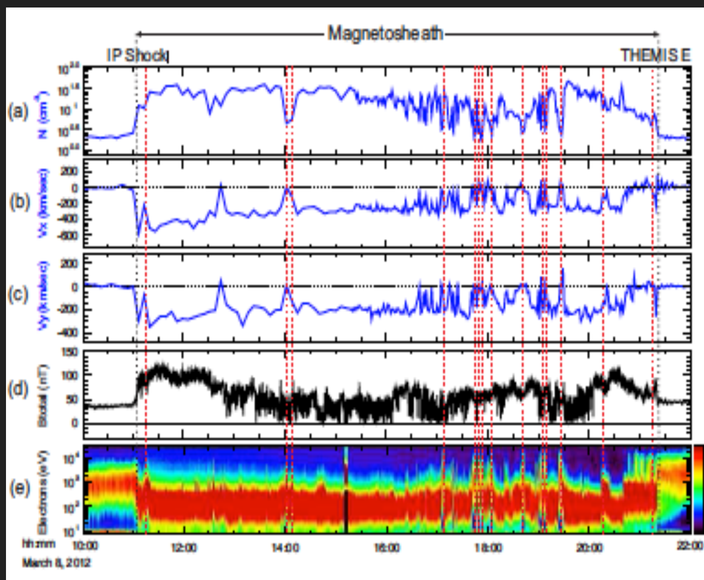
Patsourakos & Georgoulis (2016, 2017)

WHAT WE ARE UP AGAINST: COMPLEX GEOSPACE RESPONSE

Patsourakos et al. (2016)



L1 (WIND)



Magnetosphere (THEMIS)