Space Weather Prediction and the role of the MHD

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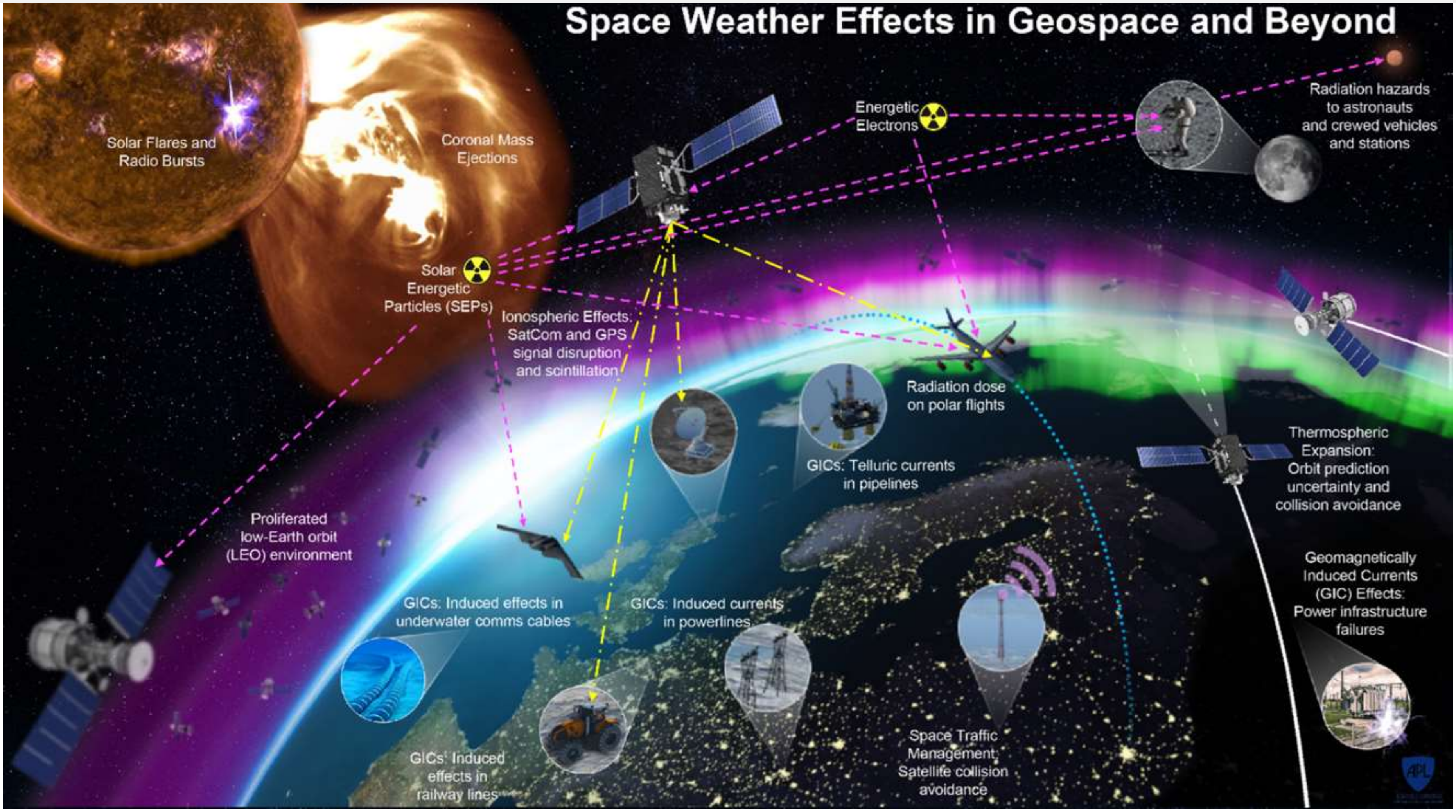
16-20 September 2024, Ioannina

Space Weather definition (by ESA)

“Space weather refers to the environmental conditions in Earth’s magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of space-borne and ground-based systems and services or endanger property or human health. Space weather deals with phenomena involving ambient plasma, magnetic fields, radiation, particle flows in space and how these phenomena may influence man made systems. In addition to the Sun, non-solar sources such as galactic cosmic rays can be considered as space weather since they alter space environment conditions near the Earth”

Space Weather Effects



https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GapAnalysisReport_full_final.pdf

Some Papers...

Living Reviews in Solar Physics (2021) 18:4
https://doi.org/10.1007/s41116-021-00030-3

REVIEW ARTICLE

Check for updates

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ished online: 29 June 2021

f energetic phenomena that structure
ospheres. The effects of Space Weather
ng importance as human spaceflight is
s review is focusing on the solar per-
omena, coronal mass ejections (CMEs)
solar wind stream interaction regions
sion (launched in 2006), literally, new
he first time to study coronal structures
three dimensions. New imaging capa-

PHILOSOPHICAL TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Review

Check for updates

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One contribution of 9 to a theme issue 'Physics of solar eruptions and their space weather impact'.

Subject Areas:
astrophysics, plasma physics, high energy physics

Keywords:
solar energetic particles, solar flares, coronal mass ejections

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Solar energetic particles in the inner heliosphere: status and open questions

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Solar energetic particle (SEP) events are related to both solar flares and coronal mass ejections (CMEs) and they present energy spectra that span from a few keV up to several GeV. A wealth of observations from widely distributed spacecraft have revealed that SEPs fill very broad regions of the heliosphere, often all around the Sun. High-energy SEPs can sometimes be energetic enough to penetrate all the way down to the surface of the Earth and thus be recorded on the ground as ground level enhancements (GLEs). The conditions of the radiation environment are currently unpredictable due to an as-yet incomplete understanding of solar eruptions and their corresponding relation to SEP events. This is because the complex nature and the interplay of the injection, acceleration and transport processes undergone by the SEPs in the solar corona and the interplanetary space prevent us from establishing an accurate understanding (based on observations and modelling). In this work, we review the current status of knowledge on SEPs, focusing on GLEs and multi-spacecraft events. We extensively discuss the forecasting and nowcasting efforts of SEPs, dividing these into three categories.

THE ROYAL SOCIETY PUBLISHING

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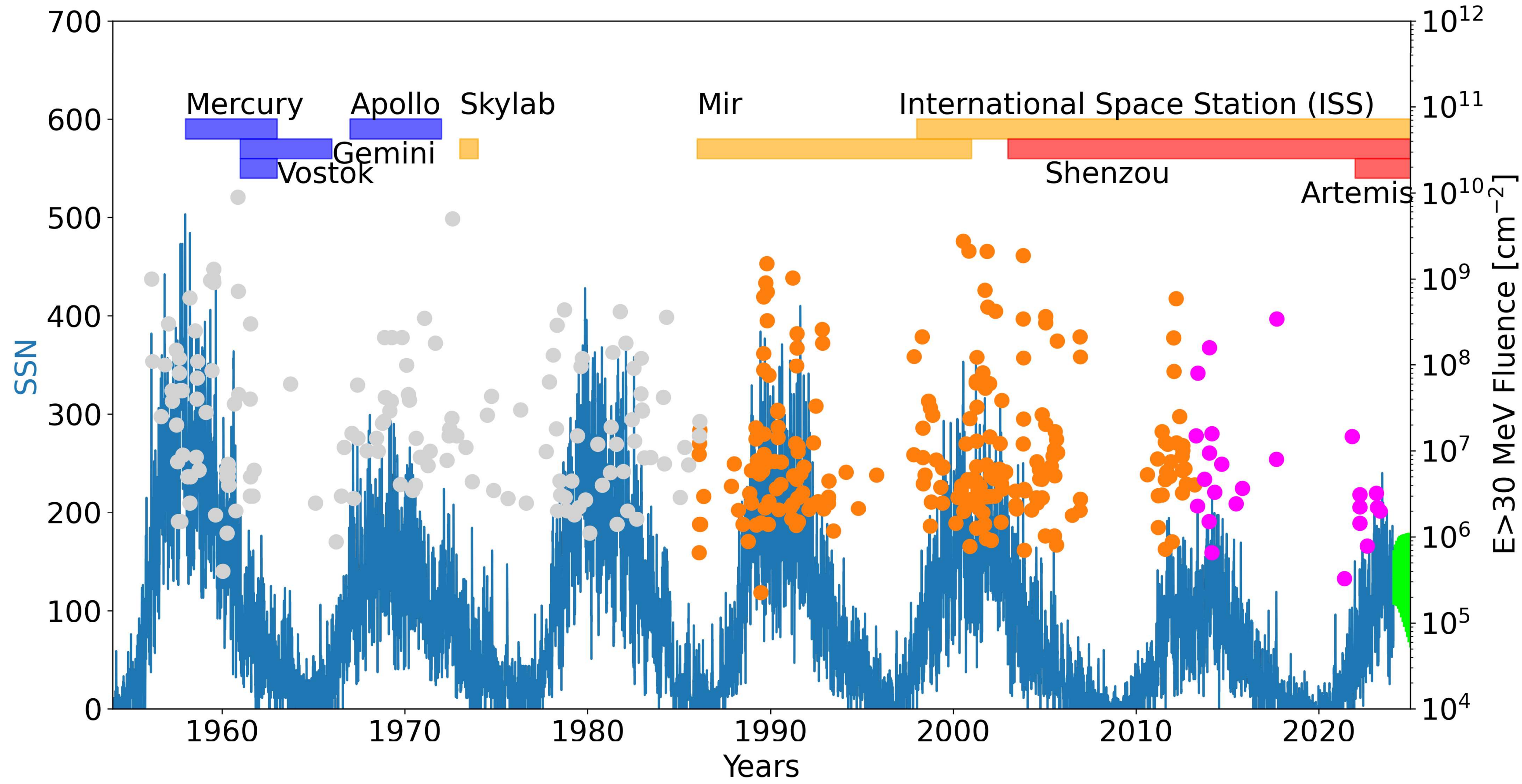
More Definitions…

- SEP event is defined as a flux enhancement of protons with energy >10MeV in excess of 10 protons cm^{-2} s^{-1} $ster^{-1}$ (pfu)
- Single event effects (SEEs) are produced during periods of intense solar activity and are caused by protons with energies higher than 50 MeV and heavier ions with energies higher 10 MeV/nucleon

Solar Circle and SEPs



Papaioannou et.al. Space Sci. Rev. submitted

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Particle Acceleration…

Consider a particle subject to external force, then the dynamics of particle is described by

$$\frac{d\vec{p}}{dt} = \vec{F}(x,t)$$

$x = \vec{X}(t)$ Is the particle's trajectory

The change in The momentum $t = 0$ $t = \Delta t$

$$\Delta p = \int_0^{\Delta t} dt' F(X(t'), t')$$

Single particle motion in EM fields…

The Lorenz Force :

$$m_j \frac{d\vec{v}_j}{dt} = q_j [\vec{E}(\vec{r},t) + \frac{\vec{v}_j \times \vec{B}(\vec{r},t)}{c}]$$

$$\nabla \vec{E}(\vec{r},t) = 4\pi\rho(\vec{r},t)$$

$$\nabla \vec{B}(\vec{r},t) = 0$$

$$\nabla \times \vec{E}(\vec{r},t) = -\frac{1}{c}\frac{\partial \vec{B}(\vec{r},t)}{\partial t}$$

$$\nabla \times \vec{B}(\vec{r},t) = \frac{4\pi}{c}\vec{J}(\vec{r},t) + \frac{1}{c}\frac{\partial \vec{E}(\vec{r},t)}{\partial t}$$

$$\vec{J}(\vec{r},t) = \frac{1}{V}\sum_{j=1}^{N} \vec{v}_j q_j$$

$$\rho(\vec{r},t) = \frac{1}{V}\sum_{j=1}^{N} q_j$$

Particle Distribution in EM fields…

$$\frac{\partial f_j}{\partial t} + \vec{v}\nabla_r f_j + \frac{q_j}{m_j}\left[\vec{E} + \frac{\vec{v}\times\vec{B}}{c}\right]\nabla_v f_j = 0$$

$$\nabla\vec{E}(\vec{r},t) = 4\pi\rho(\vec{r},t)$$

$$\nabla\vec{B}(\vec{r},t) = 0$$

$$\nabla\times\vec{E}(\vec{r},t) = -\frac{1}{c}\frac{\partial\vec{B}(\vec{r},t)}{\partial t}$$

$$\nabla\times\vec{B}(\vec{r},t) = \frac{4\pi}{c}\vec{J}(\vec{r},t) + \frac{1}{c}\frac{\partial\vec{E}(\vec{r},t)}{\partial t}$$

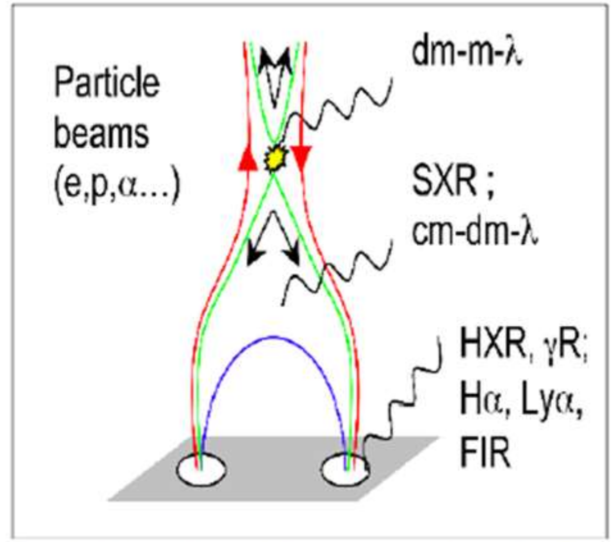
$$\vec{J}(\vec{r},t) = \sum_{j=e,i} q_j \int \vec{v} f_j(\vec{r},\vec{v},t)d\vec{v}$$

$$\rho(\vec{r},t) = \sum_{j=e,i} q_j \int f_j(\vec{r},\vec{v},t)d\vec{v}$$

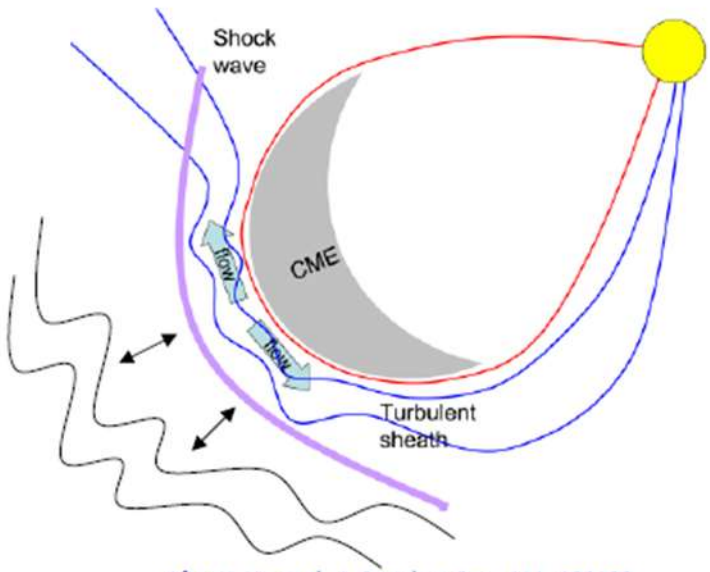
Origin of SEPs (acceleration)

[1] Flare acceleration:

- reconnecting current sheet, induced E, waves, possibly reconnection shock
- active region, mainly low corona
- particles reveal by radiative signatures (gamma, HXR, radio), evidence for e (>10 MeV), p (>300 MeV)



After K.-L. Klein., *Solar Orbiter* Workshop, Athens, ESA-SP



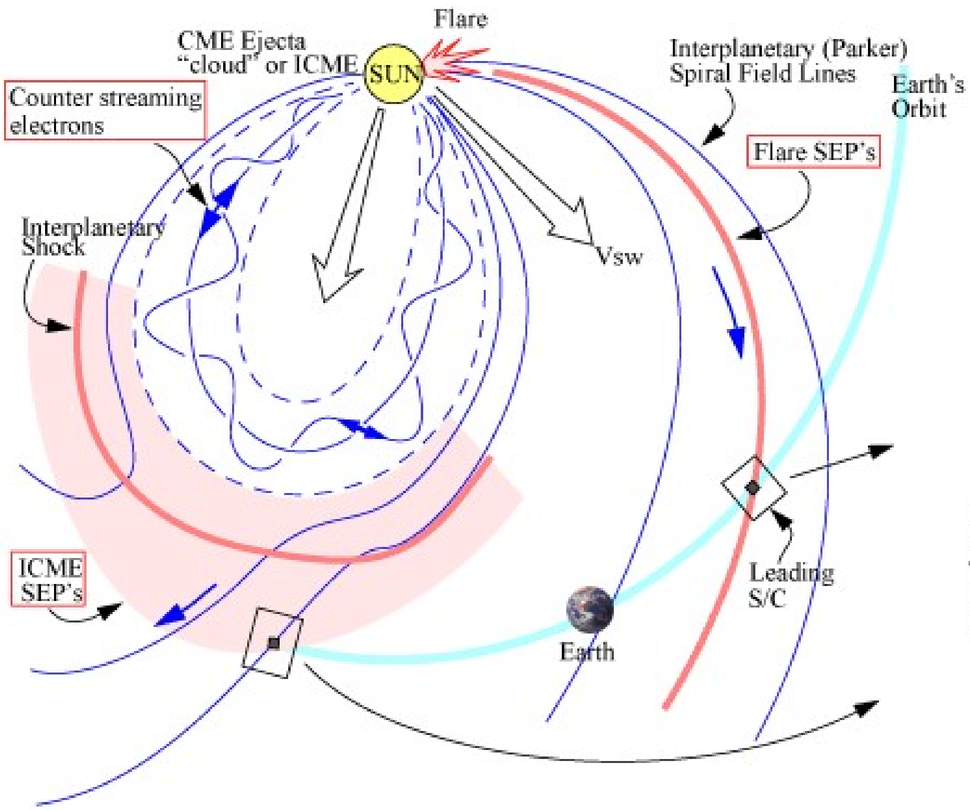
After Y. Liu et al., J. Geophys. Res., 111, A09108

[2] CME acceleration:

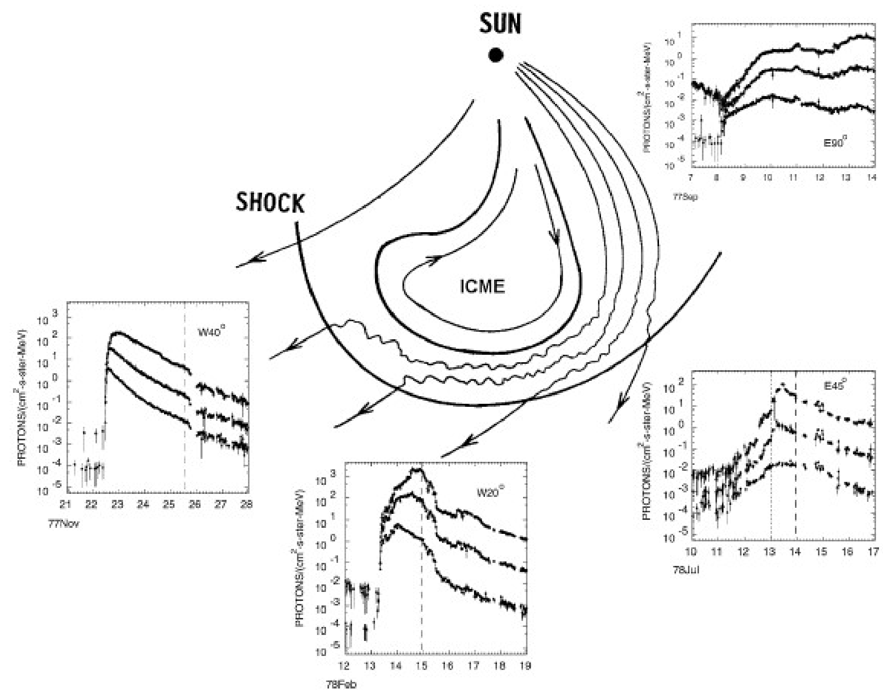
- fast CME drives shock wave
- particles scatter between shock and the upstream turbulence (***diffusive shock acceleration***) or drift along shock front (***shock drift acceleration***)
- evidence in situ (IP space, planetary bow shocks; up to which energy ?

The Origin of SEP events

Luhman et al, Space Sci. Rev, 2008

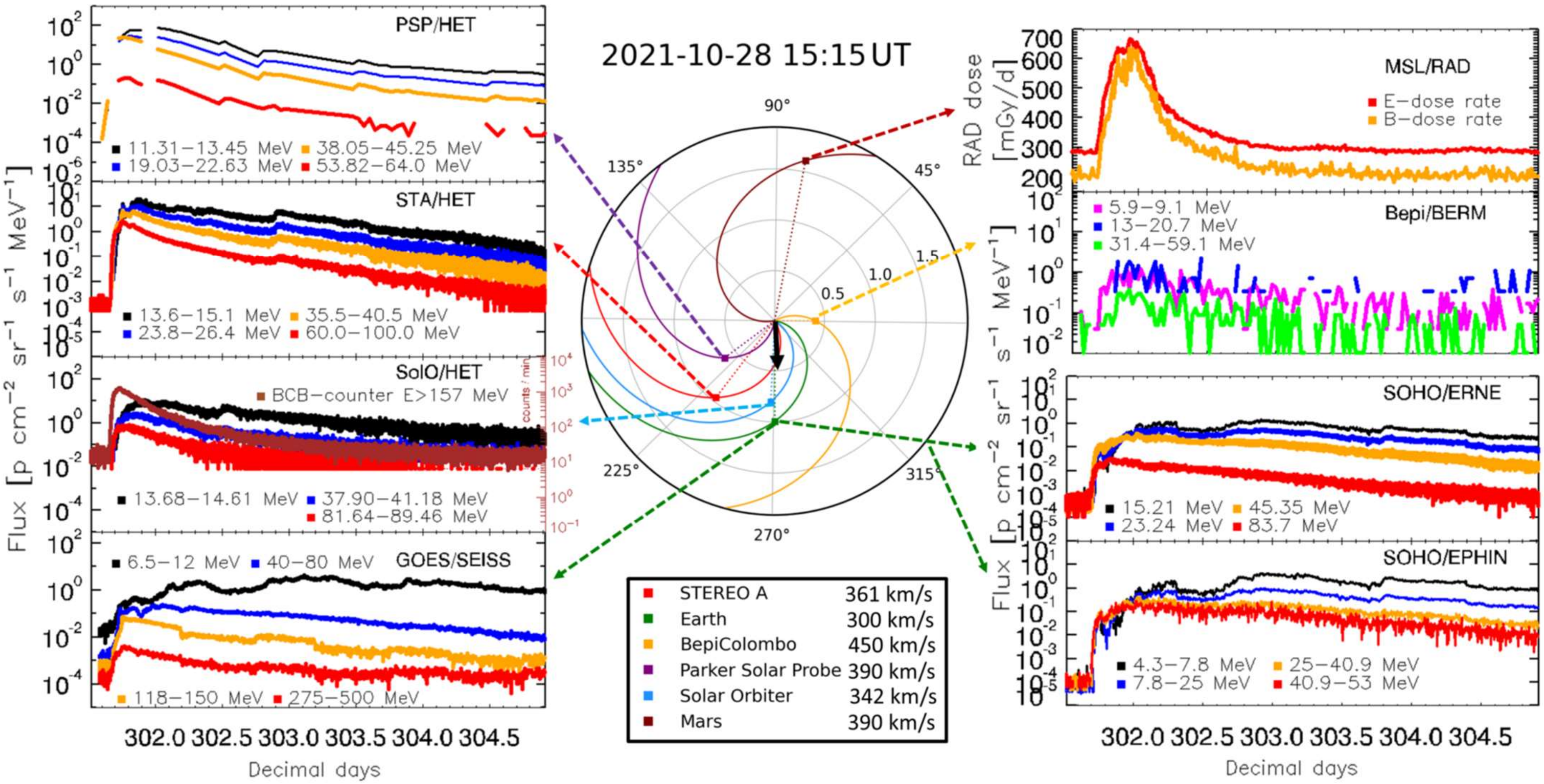


Cane and Lario, Space Sci. Rev, 2006



An important parameter: No matter the causative, particles should be rooted to the s/c to be recorded in-situ -> ***magnetic connection to the observer holds a significant role***

SEP Event (multi s/c observations)



Kouloumvakos et.al. ApJ, 2024

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Classes of SEP events… (?)

Since the 90s:

• distinction of 2 classes of events:

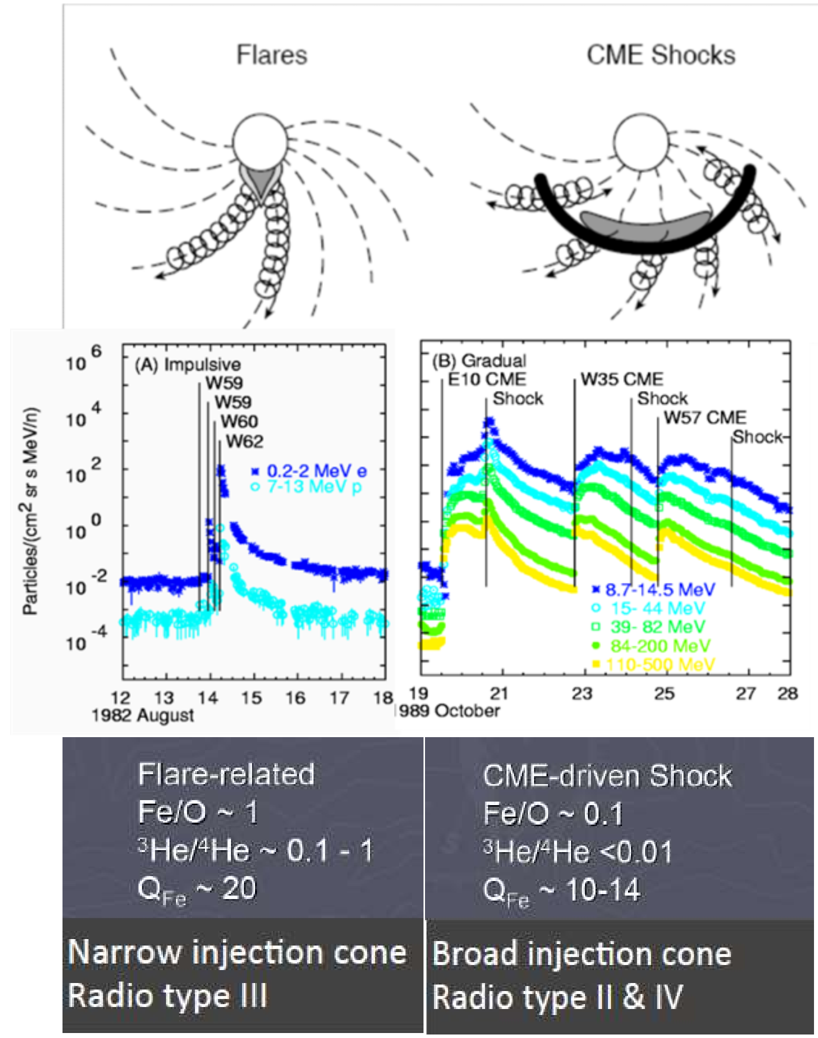
-**Impulsive** (small, frequent, presumably flare related)

- **Gradual** (large, rare, presumably fast CME related)

Current view:

• observational evidence point to the existence of **mixed** or **hybrid** events, i.e., both flares and CMEs are the drivers of SEP events

Reames, Space Scie. Rev., 2013



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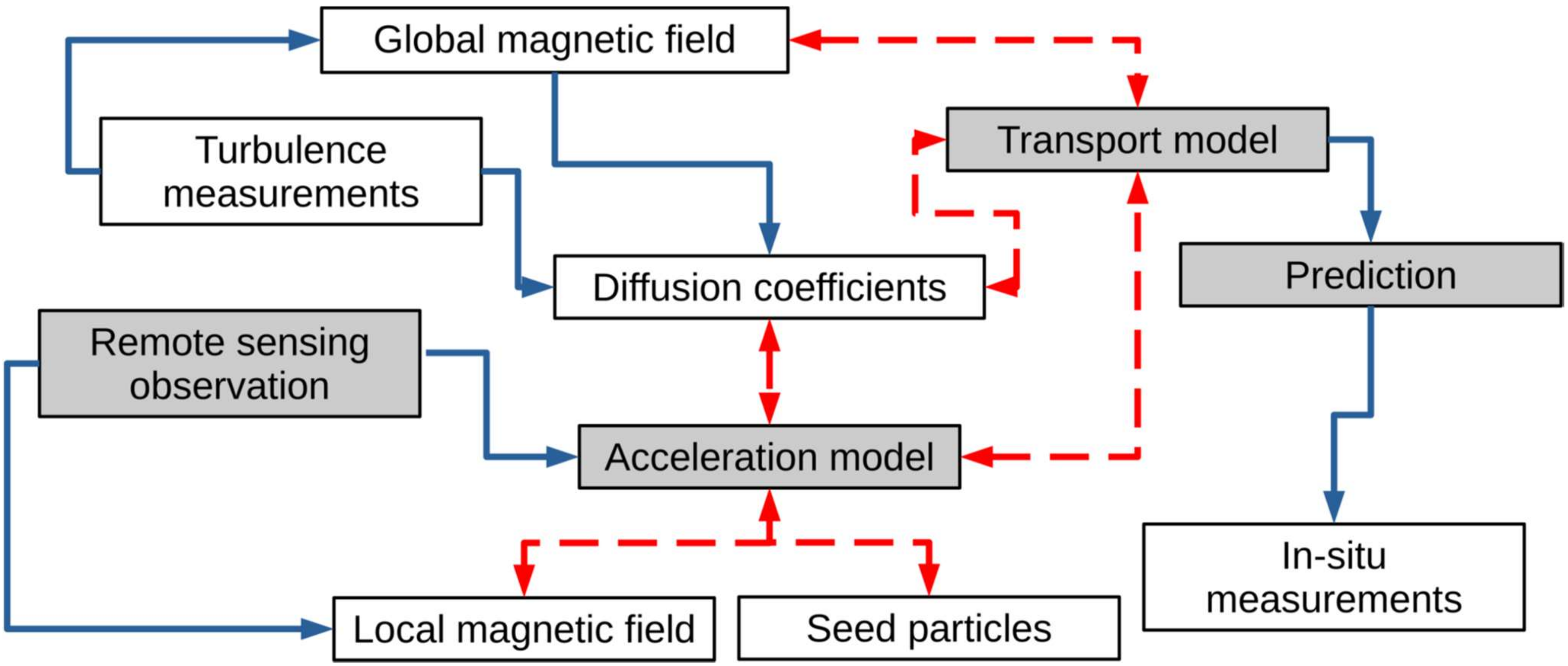
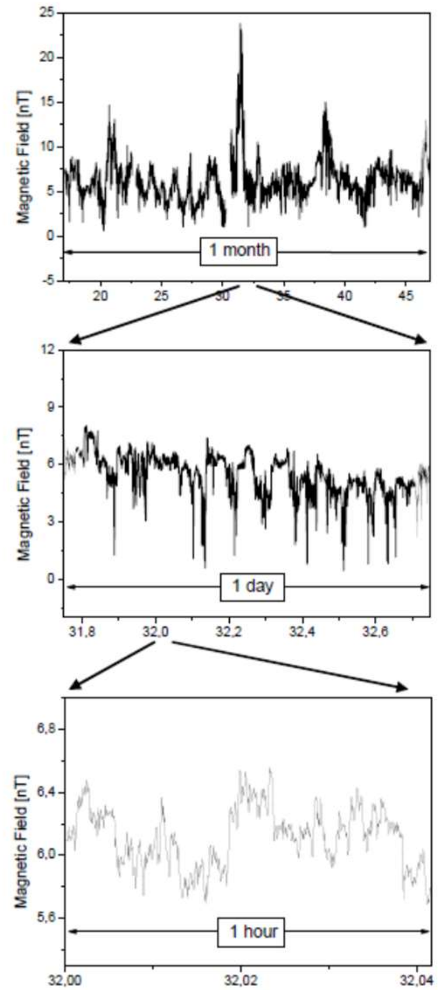
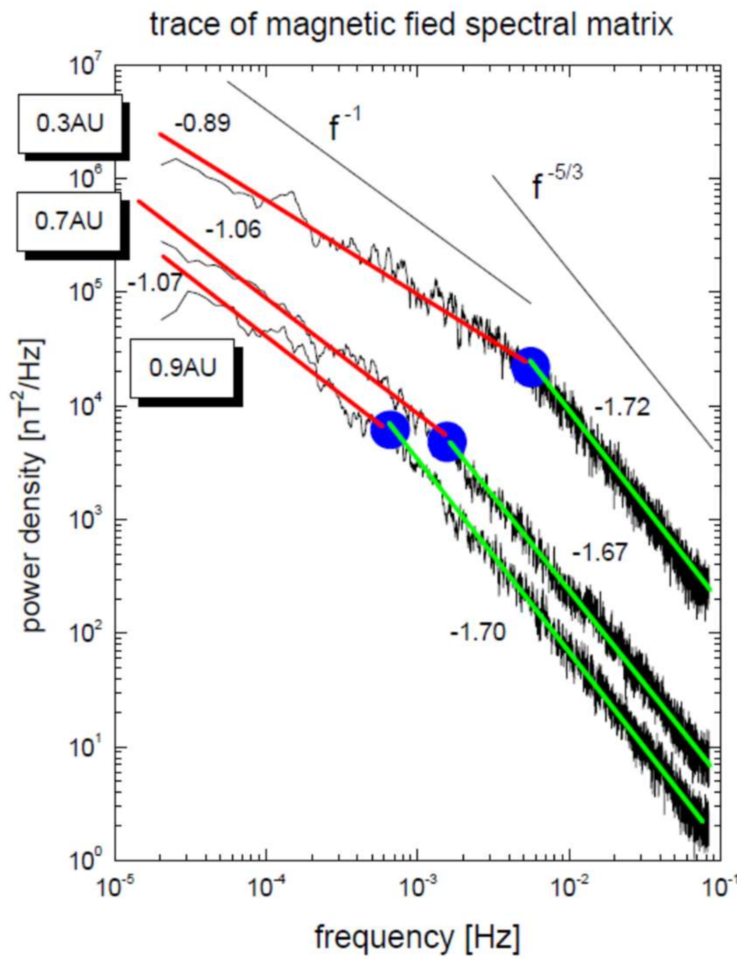
Acceleration, Transport, Prediction



Papaioannou et.al. Space Sci. Rev. submitted

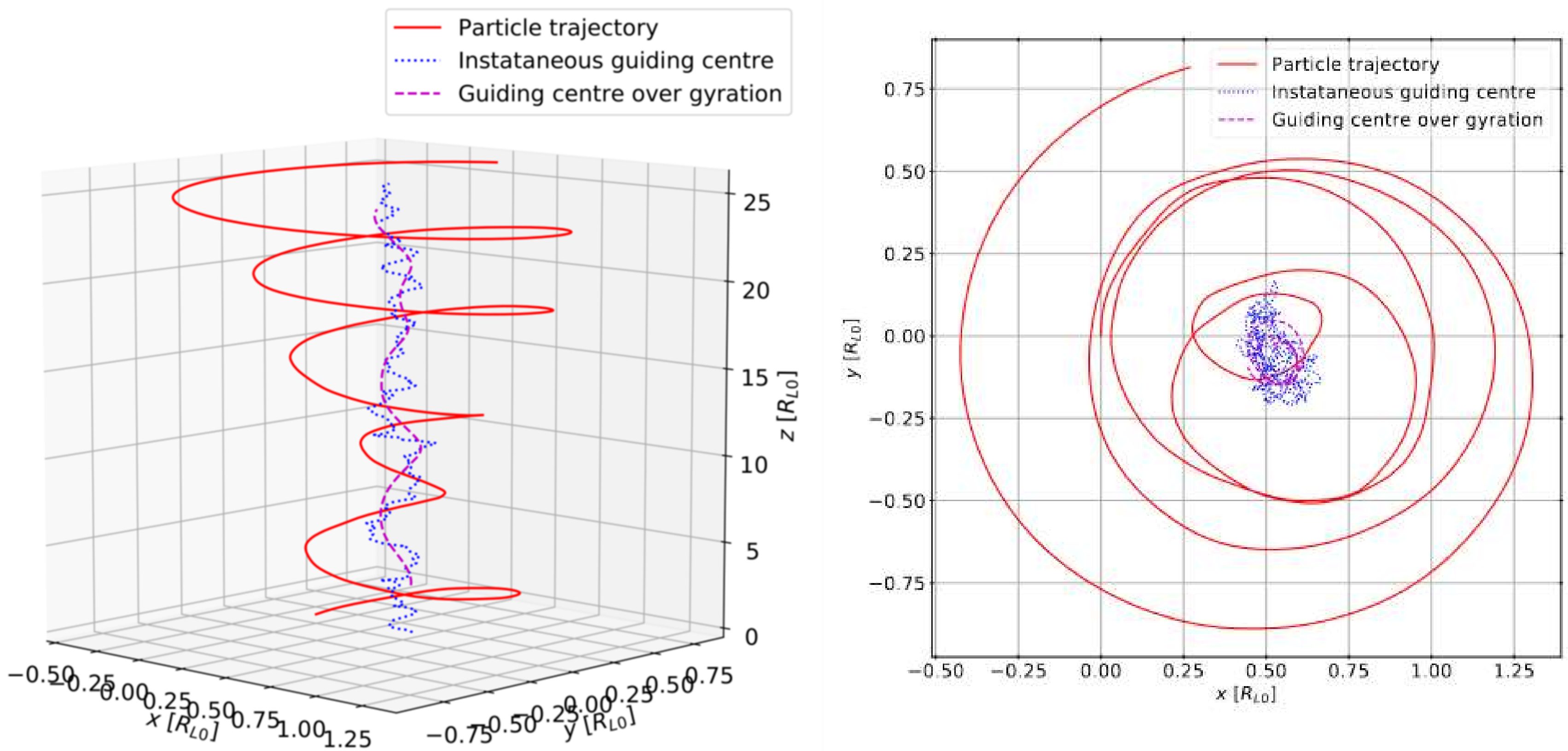
Heliospheric Magnetic Field





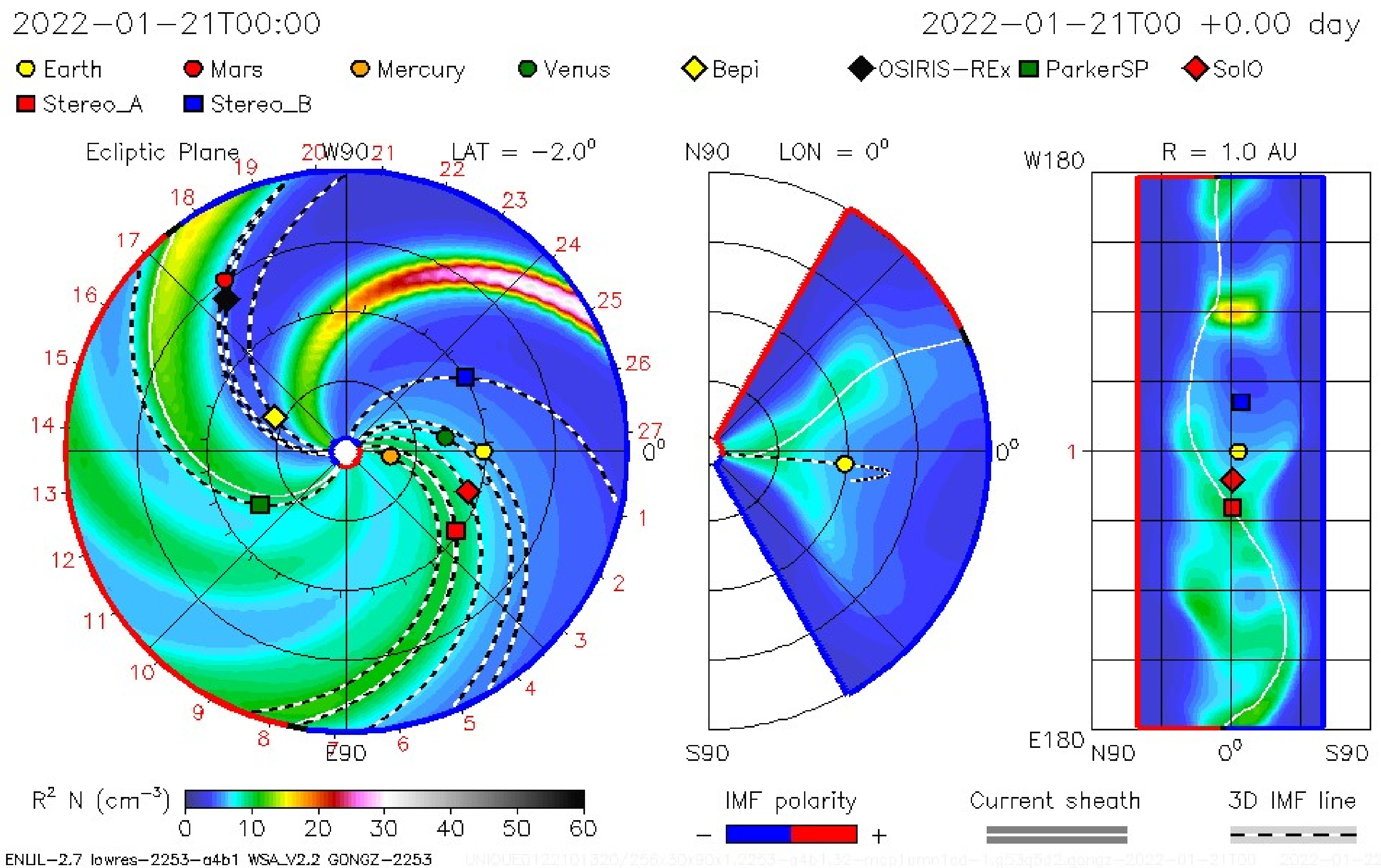
Bruno & Carbone (2005)

Single Particle Trajectory

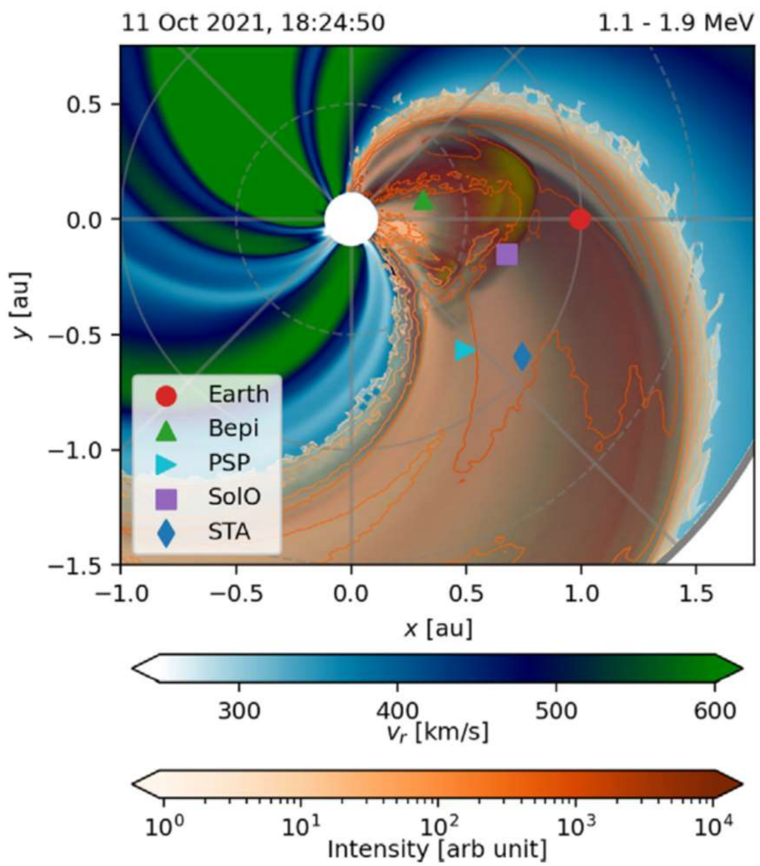


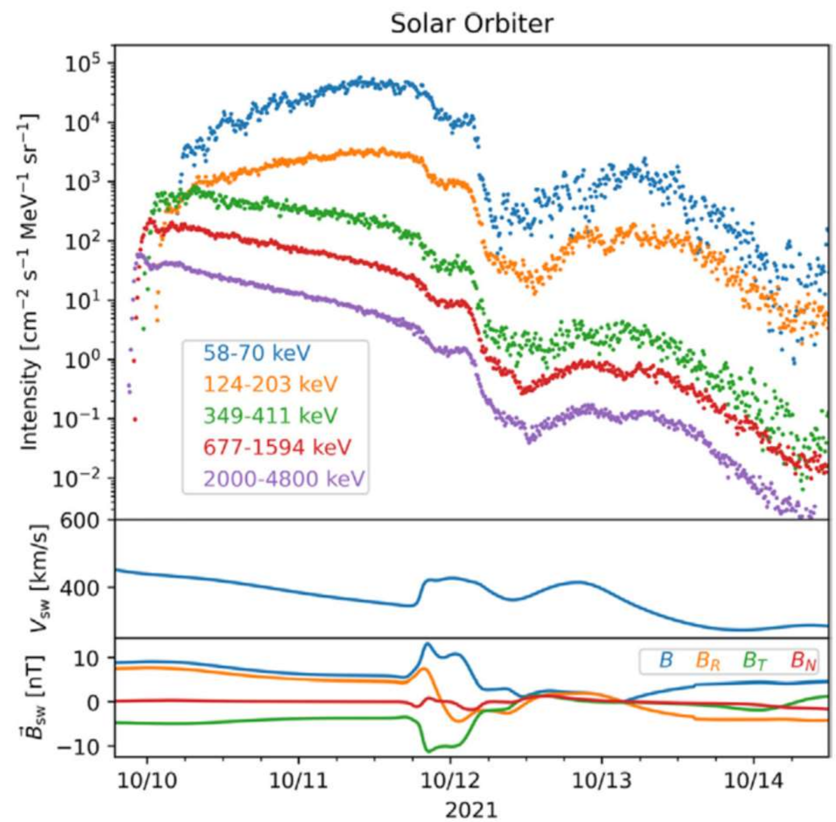
van den Berg et al. (2020)

Heliosphere (numerical simulation)



PARADISE…

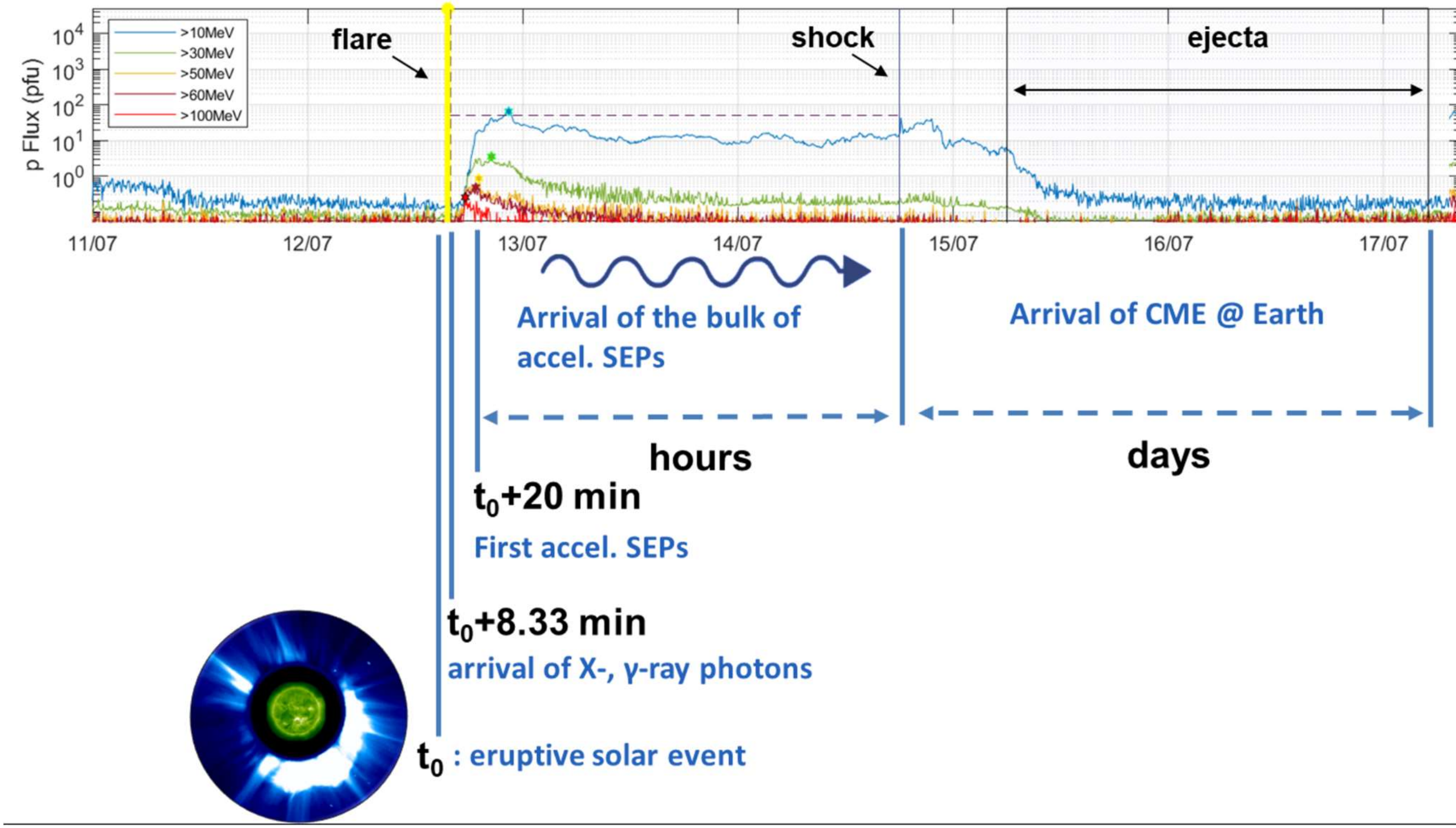




The PARADISE model is probably the best example of the state-of-the-art when it comes to particle transport; Whitman et al. (2023)

However, this is far from the complete picture: Coefficients and seed-particles are ad-hoc, SEP source probably not resolved... Predictive simulations not yet possible

SEP Event (12 July 2012)



Papaioannou et.al. Space Sci. Rev. submitted

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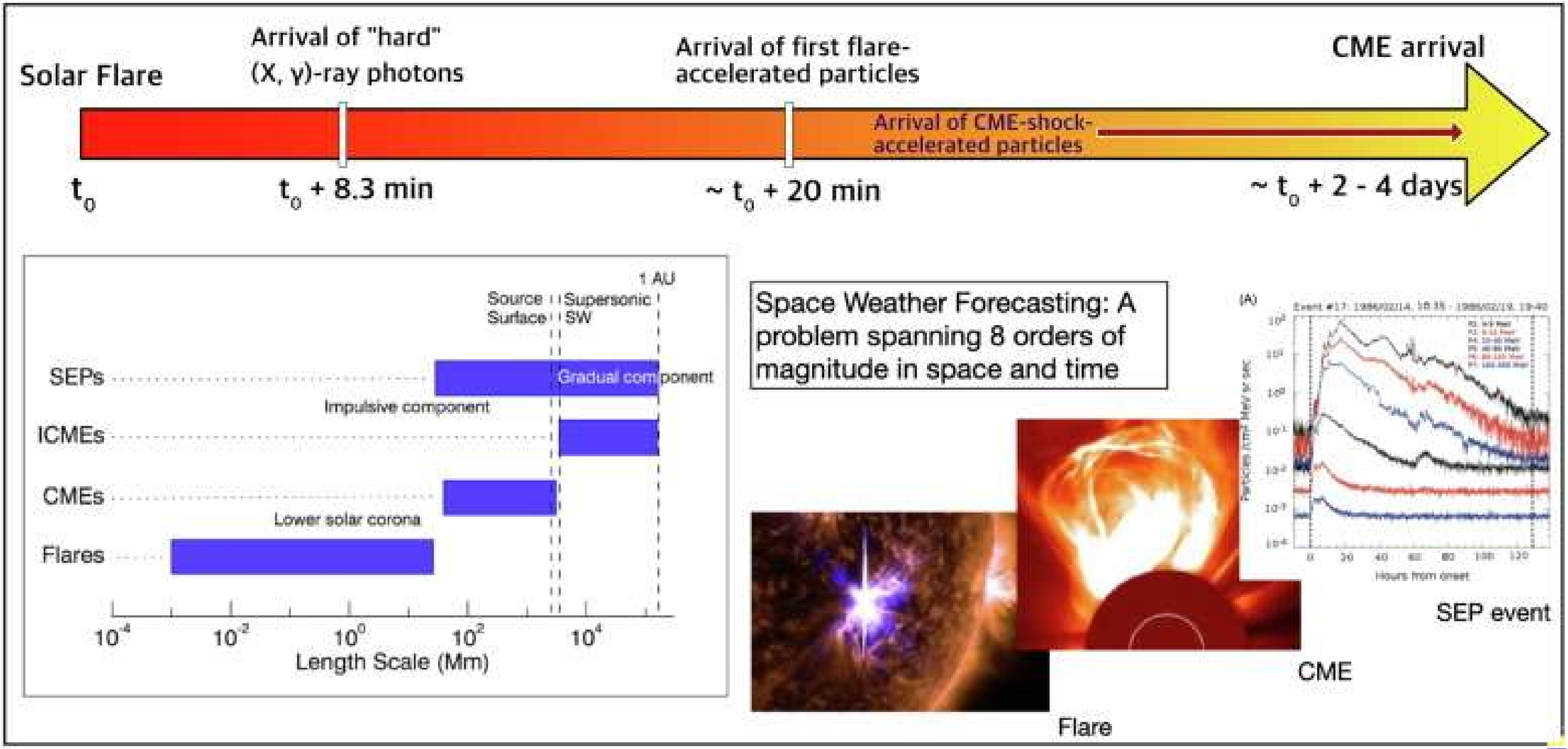
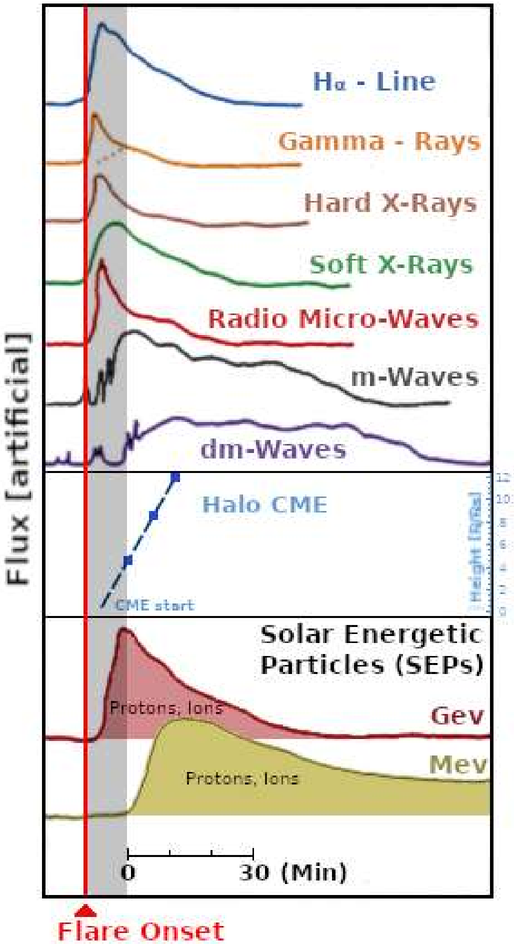
Scales…

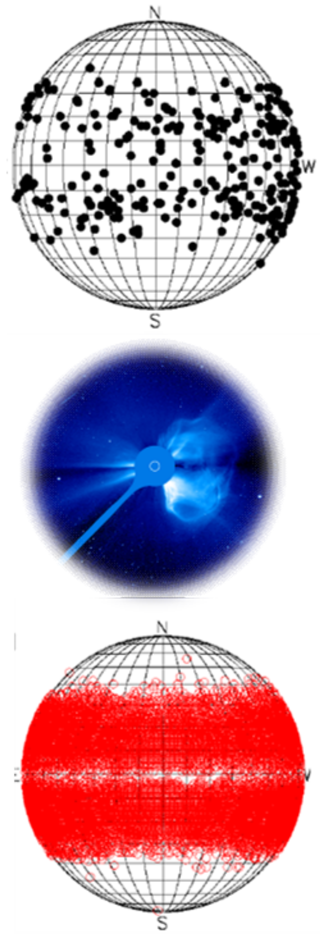


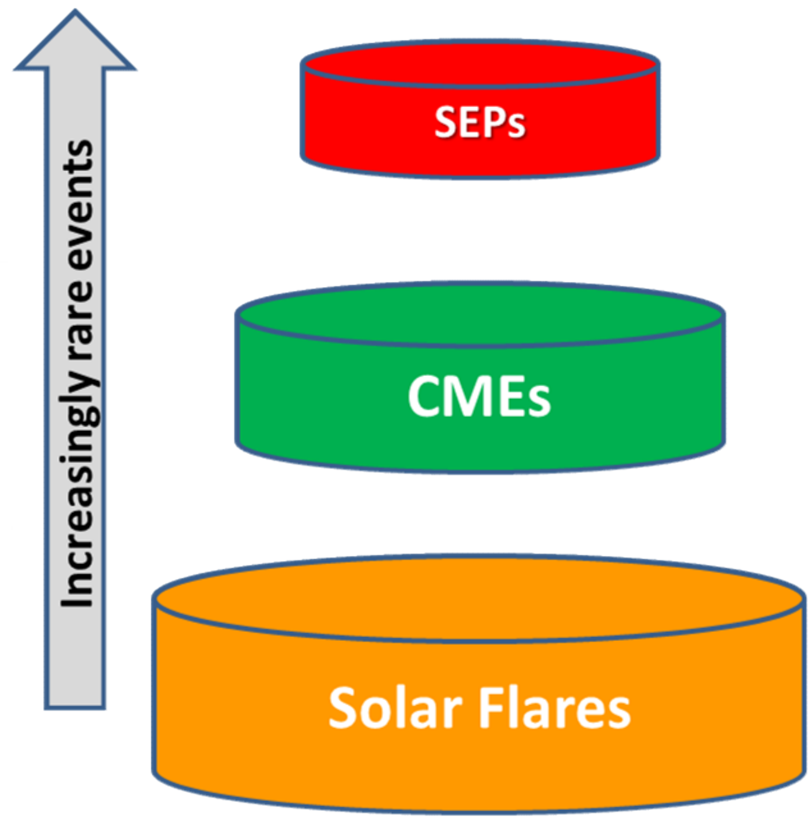
Georgoulis et.al. Adv. Space Res.., 2024

Observations...

Anastasiadis et al., *RSTA*, (2019)



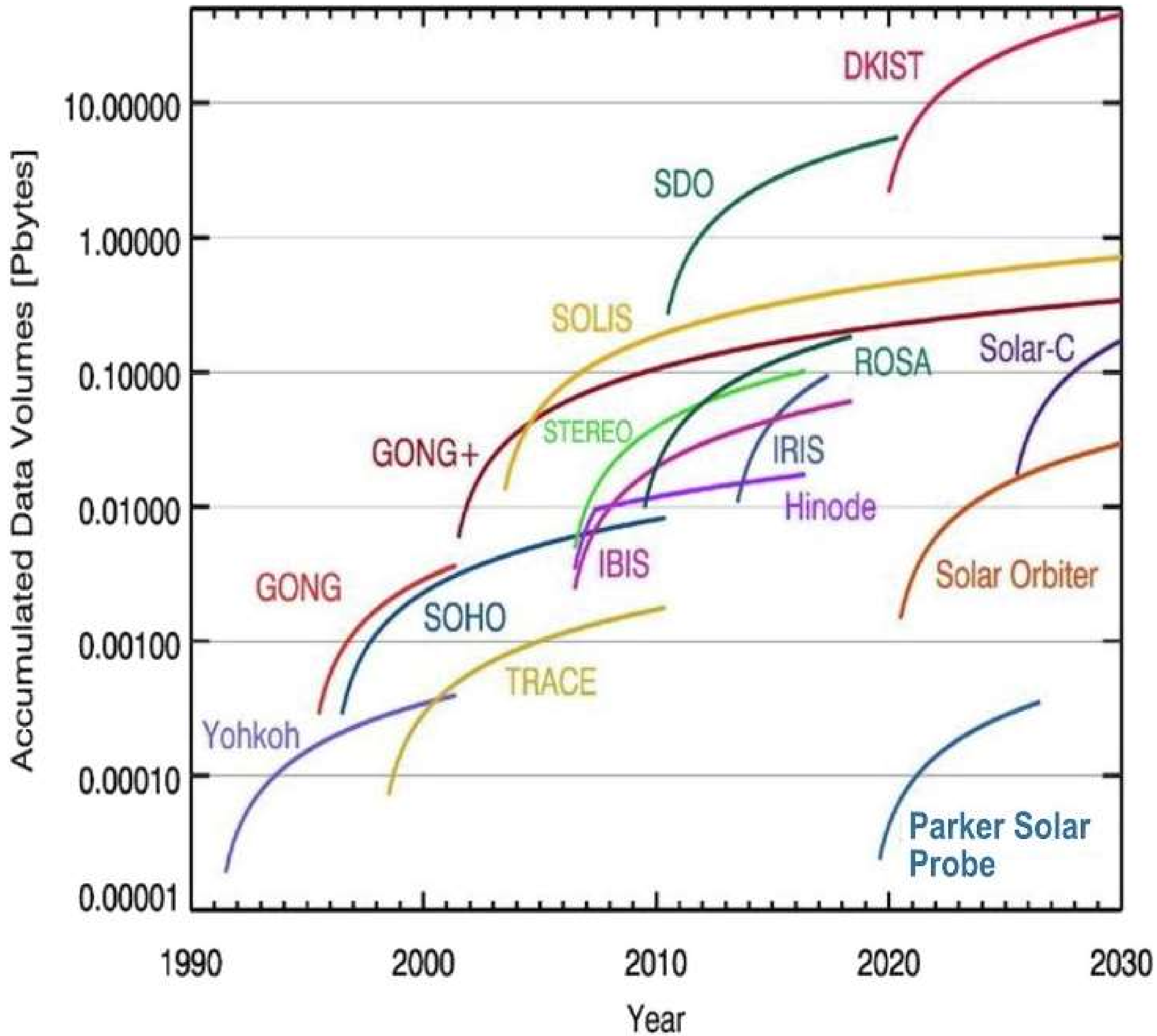




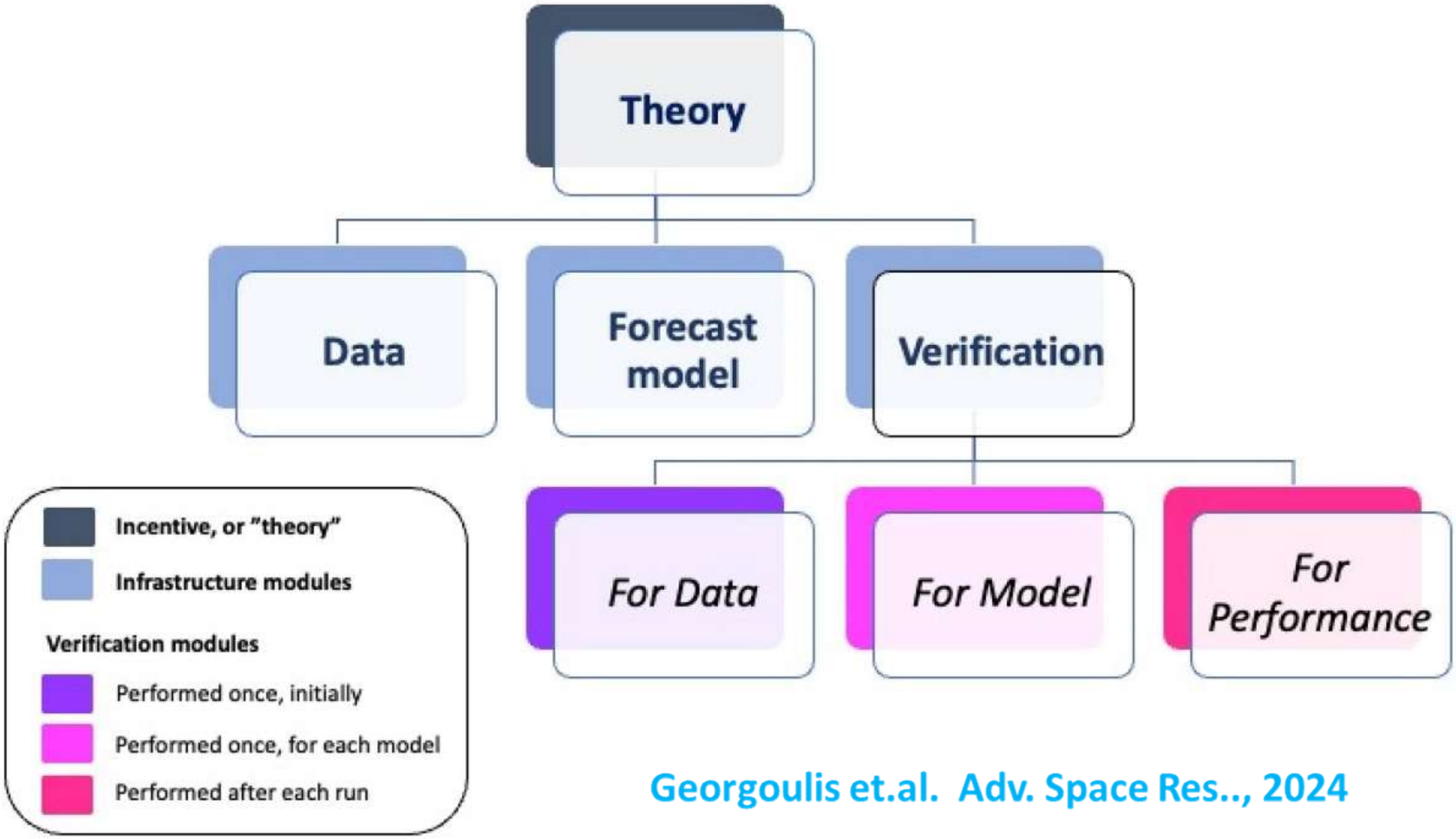
Papaioannou et al., *JSWSC*, (2016)

Observations…

Georgoulis et.al. Adv. Space Res.., 2024



General Concept for SW forecasting



Georgoulis et.al. Adv. Space Res.., 2024

SEP Forecasting Models…

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Review

Review of solar energetic particle models

Kathryn Whitman [a,b,*], Ricky Egeland [c], Ian G. Richardson [d,e], Clayton Allison [f], Philip Quinn [f], Janet Barzilla [f], Irina Kitiashvili [g], Viacheslav Sadykov [h], Hazel M. Bain [i,j], Mark Dierckxsens [k], M. Leila Mays [d], Tilaye Tadesse [f], Kerry T. Lee [c], Edward Semones [c], Janet G. Luhmann [l], Marlon Núñez [m], Stephen M. White [n], Stephen W. Kahler [n], Alan G. Ling [o], Don F. Smart [p], Margaret A. Shea [p], Valeriy Tenishev [l], Soukaina F. Boubrahimi [r], Berkay Aydin [h], Petrus Martens [h], Rafal Angryk [h], Michael S. Marsh [s], Silvia Dalla [t], Norma Crosby [k], Nathan A. Schwadron [u], Kamen Kozarev [v], Matthew Gorby [w], Matthew A. Young [u], Monica Laurenza [x], Edward W. Cliver [y], Tommaso Alberti [x], Mirko Stumpo [z,x], Simone Benella [x], Athanasios Papaioannou [aa], Anastasios Anastasiadis [aa], Ingmar Sandberg [ab], Manolis K. Georgoulis [ac], Anli Ji [h], Dustin Kempton [h], Chetraj Pandey [h], Gang Li [ad], Junxiang Hu [ad], Gary P. Zank [ad], Eleni Lavasa [ae,aa], Giorgos Giannopoulos [af], David Falconer [ad,ag], Yash Kadadi [ah], Ian Fernandes [ai], Maher A. Dayeh [aj,al], Andrés Muñoz-Jaramillo [ak], Subhamoy Chatterjee [ak], Kimberly D. Moreland [al,aj], Igor V. Sokolov [q], Ilia I. Roussev [l], Aleksandre Taktakishvili [am], Frederic Effenberger [an], Tamas Gombosi [q], Zhenguang Huang [q], Lulu Zhao [q], Nicolas Wijsen [ao], Angels Aran [ap], Stefaan Poedts [ao,aq], Athanasios Kouloumvakos [ar], Miikka Paassilta [as], Rami Vainio [as], Anatoly Belov [at], Eugenia A. Eroshenko [at,1], Maria A. Abunina [at], Artem A. Abunin [at], Christopher C. Balch [j], Olga Malandraki [aa], Michalis Karavolos [aa], Bernd Heber [au], Johannes Labrenz [au], Patrick Kühl [au], Alexander G. Kosovichev [av,g], Vincent Oria [av], Gelu M. Nita [av], Egor Illarionov [aw,ax], Patrick M. O'Keefe [av], Yucheng Jiang [av], Sheldon H. Fereira [av], Aatiya Ali [h], Evangelos Paouris [ay,az], Sigiava Aminalragia-Giamini [ab,ac], Piers Jiggens [ba], Meng Jin [bb], Christina O. Lee [l], Erika Palmerio [bc], Alessandro Bruno [d,am], Spiridon Kasapis [q], Xiantong Wang [q], Yang Chen [q], Blai Sanahuja [ap], David Lario [d], Carla Jacobs [bd], Du Toit Strauss [be], Ruhann Steyn [be], Jabus van den Berg [be,bf], Bill Swalwell [t], Charlotte Waterfall [t], Mohamed Nedal [v], Rositsa Miteva [v], Momchil Dechev [v], Pietro Zucca [bg], Alec Engell [bh], Brianna Maze [bh], Harold Farmer [bh], Thuha Kerber [bh], Ben Barnett [bh], Jeremy Loomis [bh], Nathan Grey [bh], Barbara J. Thompson [d], Jon A. Linker [bc], Ronald M. Caplan [bc], Cooper Downs [bc], Tibor Török [bc], Roberto Lionello [bc], Viacheslav Titov [bc], Ming Zhang [bi], Pouya Hosseinzadeh [r]

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[1] Deceased.

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Summarize 35 SEP models in the community with over 100 coauthors

Inputs/Outputs
Caveats
Validation

Critical observations to run and validate SEP models

Understand forecasting coverage and identify gaps

https://doi.org/10.1016/j.asr.2022.08.006

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SEP Forecasting Models…

Table 1

Solar energetic particle models. For any models without an entry in the Access column, we encourage interested readers to contact the model developer. RoR stands for Runs on Request available through CCMC. *Deployment to CCMC in progress, **Will be available on SEP Scoreboard and RoR.

Model	Model Type	Access to Model	Reference
ADEPT	Empirical	-	Kahler and Ling (2017)
AFRL PPS	Empirical	-	Smart et al. (1979, 1989, 1992)
Aminalragia-Giamini model	ML	-	Aminalragia-Giamini et al. (2021)
AMPS	Physics-based	CCMC RoR	Tenishev et al. (2021)
Boubrahimi model	ML	-	Boubrahimi et al. (2017)
COMESEP SEPForecast	Empirical & Physics-based	Web	Dierckxsens et al. (2015), Marsh et al. (2015)
EPREM	Physics-based	-	Schwadron et al. (2010)
ESPERTA	Empirical & ML	-	Laurenza et al. (2009, 2018), Stumpo et al. (2021)
FORSPEF	Empirical	Web	Anastasiadis et al. (2017)
Georgia State University	ML	Web	Ji et al. (2020,)
iPATH	Physics-based	CCMC RoR**	Hu et al. (2017)
Lavasa Model	ML	-	Lavasa et al. (2021)
MAG4	Empirical	Web, CCMC RoR, SEP Scoreboard	Falconer et al. (2011, 2014)
MagPy	Empirical	-**	Tadesse, T., Fernandes, I., Kadadi, Y., Lee, K. T., and Falconer, D.
MEMPSEP	ML	-	Moreland et al. 2022, Chatterjee et al. 2022, Dayeh et al. 2022 (all in preparation)
M-FLAMPA	Physics-based	CCMC RoR*	Sokolov et al. (2004), Borovikov et al. (2015)
PARADISE	Physics-based	Web	Wijsen (2020, 2022)
PCA (Papaioannou) model	Empirical	-	Papaioannou et al. (2018)
PHSVM	ML	-	Pouya Hosseinzadeh, Soukaina Filali Boubrahimi
PROTONS	Empirical	-	Balch (1999, 2008)
RElEASE	Empirical	Web, SEP Scoreboard	Posner, 2007; Malandraki et al., 2020
Sadykov et al. (2021) model	ML	-	Sadykov et al. (2021)
SAWS-ASPECS	Empirical	Web, SEP Scoreboard	Anastasiadis et al. (2017), Georgoulis et al. (2021), Papaioannou et al. (2022)
SEPCaster	Physics-based	-*	Li et al. (2021)
SEPMOD	Physics-based	CCMC RoR, SEP Scoreboard	Luhmann et al. (2007)
SEPSTER	Empirical	SEP Scoreboard	Richardson et al. (2018)
SEPSTER2D	Empirical	SEP Scoreboard	Bruno and Richardson (2021)
SMARP Model	ML	-	Kasapis et al. (2022)
SOLPENCO(2)	Physics-based	-	Aran et al. (2006), Aran et al. (2011), Aran et al. (2017)
South African model	Physics-based	Web	Strauss and Fichtner (2015)
SPARX	Physics-based	Web	Marsh et al. (2015)
SPREAdFAST	Physics-based	Web	Kozarev et al. (2017), Kozarev et al. (2022)
SPRINTS	ML	SEP Scoreboard	Engell et al. (2017)
STAT	Physics-based	CCMC RoR	Linker et al. (2019)
UMASEP	Empirical & ML	Web, SEP Scoreboard	Núñez (2011, 2015), Núñez et al. (2017), Malandraki et al. (2020)
Zhang model	Physics-based	-	Zhang and Zhao (2017)

35 models of many different approaches:

- Statistical and empirical relationships (11)
- Machine Learning approaches (8)
- Physics-based models (13)
- Combination approaches (3)
- Networks of linked forecast modules (4) (COMESEP, FORSPEF, GSU, SAWS-ASPECS)
- Categories somewhat arbitrary – all models are capturing key physics

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SEP Forecasting Models…

Forecasted Quantities: Pre/Post Eruption

Model	Proton Energy [MeV]	Pre/Post	All Clear	Probability	Flux Point	Onset time	Peak	Peak time	End time	Fluence	Time profile	Multi loc.	3D
ADEPT	>10, >30, >50, >100	Post					x	x	x	x	x		
AFRL PPS	>5, >10, >50	Post				x	x	x	x	x	x		
Aminalragia-Giamini model	≥5	Post	x	x									
AMPS	eV to GeV	Post				x	x	x	x	x	x	x	x
Boubrahimi model	>100	Post	x										
COMESEP SEPForecast	>10, >60	Post		x		x	x	x	x				
EPREM	5 - 1000**	Post				x	x	x	x	x	x	x	x
ESPERTA	>10	Post	x										
FORSPEF	>10, >30, >60, >100	Pre/Post		x		x	x	x	x	x			
GSU	>10	Pre	x	x									
iPATH	100 keV - GeV	Post				x	x	x	x	x	x	x	x
Lavasa Model	>10	Pre	x										
MAG4	>10	Pre	x	x									
MagPy	>10	Pre	x	x									
MEMPSEP	9-15, >5, >10, >30, >60, >100	Post		x		x	x	x	x	x			
M-FLAMPA	10 keV - 1 GeV	Post				x	x	x	x	x	x	x	x
PARADISE	keV - GeV	Post				x	x	x	x	x	x	x	x
PCA model	> 10	Post		x									
PROTONS	>10	Post		x			x	x					
REleASE	4-9; 9-15.8; 15.8-39.8; 28.2-50.1	Post		x	x								
Sadykov et al.	>10	Pre	x	x									
SAWS-ASPECS	>10 to >300	Pre/Post	x	x		x	x	x	x	x	x		
SEPCaster	100 keV - GeV	Post	x			x	x	x	x	x	x	x	x
SEPMOD	1 - 1000	Post					x	x	x		x	x	x
SEPSTER	14 - 24; >10, >30, >50, >100	Post					x	x				x	
SEPSTER2D	10 - 130; >130	Post					x	x	x	x		x	
SMARP Model	>10	Pre	x	x									
SOLPENCO(2)	0.125 - 64; 5 - 300	Post				x	x	x		x	x	x	
South African model	keV - GeV	Post				x	x	x	x	x	x	x	x
SPARX	>10, >60, >300	Post				x	x	x	x	x	x	x	x
SPREAdFAST	2 - 115	Post				x	x	x			x	x	x
SPRINTS	1, 5, 10, 30, 50, 100	Pre/Post	x	x									
STAT	1 - 1000	Post				x	x	x			x	x	x
UMASEP	>10, >30, >50, >100, >500	Post	x		x	x	x	x		x			
Zhang model	MeV - GeV	Post				x	x	x	x	x	x	x	x

- 9/35 models make pre-eruption forecasts (highlighted)
- Nearly every pre-eruption model applies machine learning
- Most pre-eruption forecasts are for >10 MeV (6/9 models);
    - *Forecasting Gap: >100 MeV is also important for human space exploration*
- Most models (26/35) make post-eruption forecasts

SEP Forecasting Models…

Table 10: Observational measurements used as inputs into SEP models.

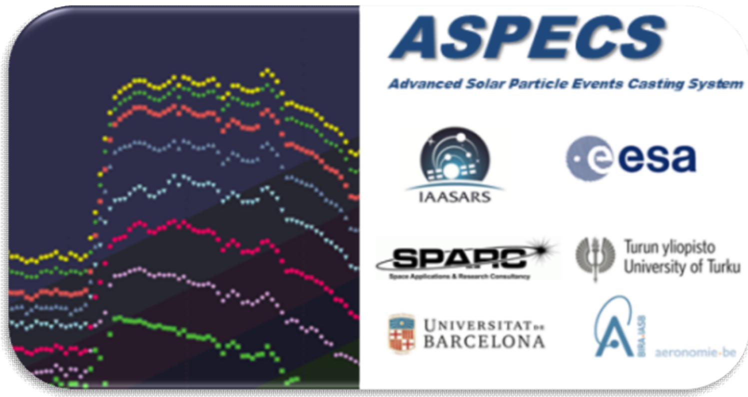
Model	Type	Magnetograms	Optical Imaging	EUV Imaging	Soft X-ray Intensity	Ground-based Radio	Space-based Radio	Coronagraph	Solar Wind (n,T,p,v)	Suprathermal Particles	Energetic Protons	Energetic Electrons	Neutron Monitors
ADEPT	Empirical										x		
AFRL PPS	Empirical		x		x	x							
Aminalragia-Giamini model	ML			x	x								
AMPS	Physics-based	x		x				x					
Boubrahimi model	ML				x						x		
COMESEP SEPForecast	Emp. & Physics			x	x			x					x
EPREM	Physics-based	x		x				x		x			
ESPERTA	Emp. & ML			x	x		x				x		
FORSPEF	Empirical	x	x		x		x	x					
GSU	ML	x											
iPATH	Physics-based	x		x				x	x	x			
Lavasa Model	ML		x		x			x					
MAG4	Empirical	x	x		x								
MagPy	Empirical	x	x		x								
MEMPSEP	ML	x		x	x		x	x	x	x	x	x	
M-FLAMPA	Physics-based	x		x				x					
PARADISE	Physics-based	x		x				x					
PCA model	Empirical				x			x					
PROTONS	Empirical				x	x							
REleASE	Empirical											x	
Sadykov's Model	ML	x			x	x					x		
SAWS-ASPECS	Empirical	x	x		x			x			x	x	x
SEPCaster	Physics-based	x		x				x	x				
SEPMOD	Physics-based	x		x				x					
SEPSTER	Empirical			x				x	x				
SEPSTER2D	Empirical			x				x	x				
SMARP Model	ML	x											
SOLPENCO	Physics-based			x				x					
SOLPENCO(2)	Physics-based			x				x	x		x		
South African model	Physics-based			x	x			x					
SPARX	Physics-based			x	x								
SPREAdFAST	Physics-based	x		x				x		x	x		
SPRINTS	ML	x		x	x						x		
STAT	Physics-based	x		x				x		x			
UMASEP	Empirical				x	x					x		
Zhang model	Physics-based	x		x				x	x				
Total		19	6	21	18	4	3	21	7	5	10	3	2

Model	Proton Energy [MeV]	Pre/Post	All Clear	Probability	Flux Point	Onset time	Peak	Peak time	End time	Fluence	Time profile	Multi loc.	3D
ADEPT	>10, >30, >50, >100	Post					x	x	x	x	x		
AFRL PPS	>5, >10, >50	Post				x	x	x	x	x	x		
Aminalragia-Giamini model	≥5	Post	x	x									
AMPS	eV to GeV	Post				x	x	x	x	x	x	x	x
Boubrahimi model	>100	Post	x										
COMESEP SEPForecast	>10, >60	Post		x		x	x	x	x				
EPREM	5 - 1000**	Post				x	x	x	x	x	x	x	x
ESPERTA	>10	Post	x										
FORSPEF	>10, >30, >60, >100	Pre/Post		x		x	x	x	x	x			
GSU	>10	Pre	x	x									
iPATH	100 keV - GeV	Post				x	x	x	x	x	x	x	x
Lavasa Model	>10	Pre	x										
MAG4	>10	Pre	x	x									
MagPy	>10	Pre	x	x									
MEMPSEP	9-15, >5, >10, >30, >60, >100	Post		x		x	x	x	x	x			
M-FLAMPA	10 keV - 1 GeV	Post				x	x	x	x	x	x	x	x
PARADISE	keV - GeV	Post				x	x	x	x	x	x	x	x
PCA model	> 10	Post		x									
PROTONS	>10	Post		x			x	x					
REleASE	4-9; 9-15.8; 15.8-39.8; 28.2-50.1	Post		x	x								
Sadykov et al.	>10	Pre	x	x									
SAWS-ASPECS	>10 to >300	Pre/Post	x	x		x	x	x	x	x	x		
SEPCaster	100 keV - GeV	Post	x			x	x	x	x	x	x	x	x
SEPMOD	1 - 1000	Post					x	x	x		x	x	x
SEPSTER	14 - 24; >10, >30, >50, >100	Post					x	x				x	
SEPSTER2D	10 - 130; >130	Post					x	x	x	x		x	
SMARP Model	>10	Pre	x	x									
SOLPENCO(2)	0.125 - 64; 5 - 300	Post				x	x	x		x	x	x	
South African model	keV - GeV	Post				x	x	x	x	x	x	x	x
SPARX	>10, >60, >300	Post				x	x	x	x	x	x	x	x
SPREAdFAST	2 - 115	Post				x	x	x			x	x	x
SPRINTS	1, 5, 10, 30, 50, 100	Pre/Post	x	x									
STAT	1 - 1000	Post				x	x	x			x	x	x
UMASEP	>10, >30, >50, >100, >500	Post	x		x	x	x	x		x			
Zhang model	MeV - GeV	Post				x	x	x	x	x	x	x	x

SEP Forecasting Models - Summary

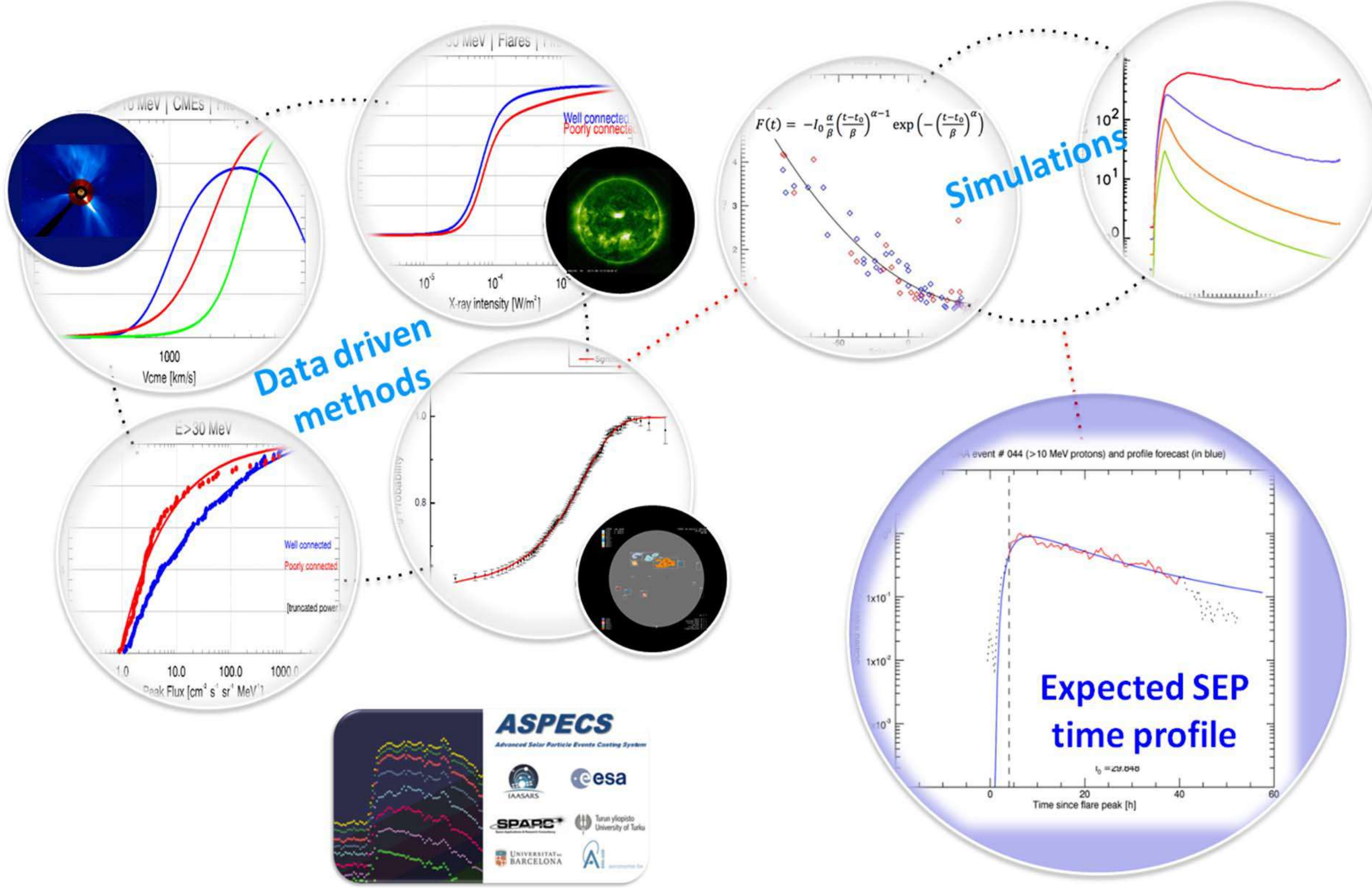
- 35 models in different stages of development using many approaches and a wide variety of observational inputs
  - **1/3 models are currently running in a real time environment (11/35)**
  - **1/3 models are primarily research-focused (12/35)**
  - **1/3 models have been recently developed (13/35)**
  - **1/2 models can make forecasts with near real time data sources (17/35)**
  - **2/3 models require data sources that have low cadence, high latency, and that are not operationally supported (22/35)**
- Models that address these questions can have a role in forecasting:
  - Will an event occur? How intense will it be? How long will it last?
- The variety of models, their capabilities, and predicted quantities is of value to the forecasting community – ensemble

SAWS-ASPECS: Advanced Solar Particle Events Casting System

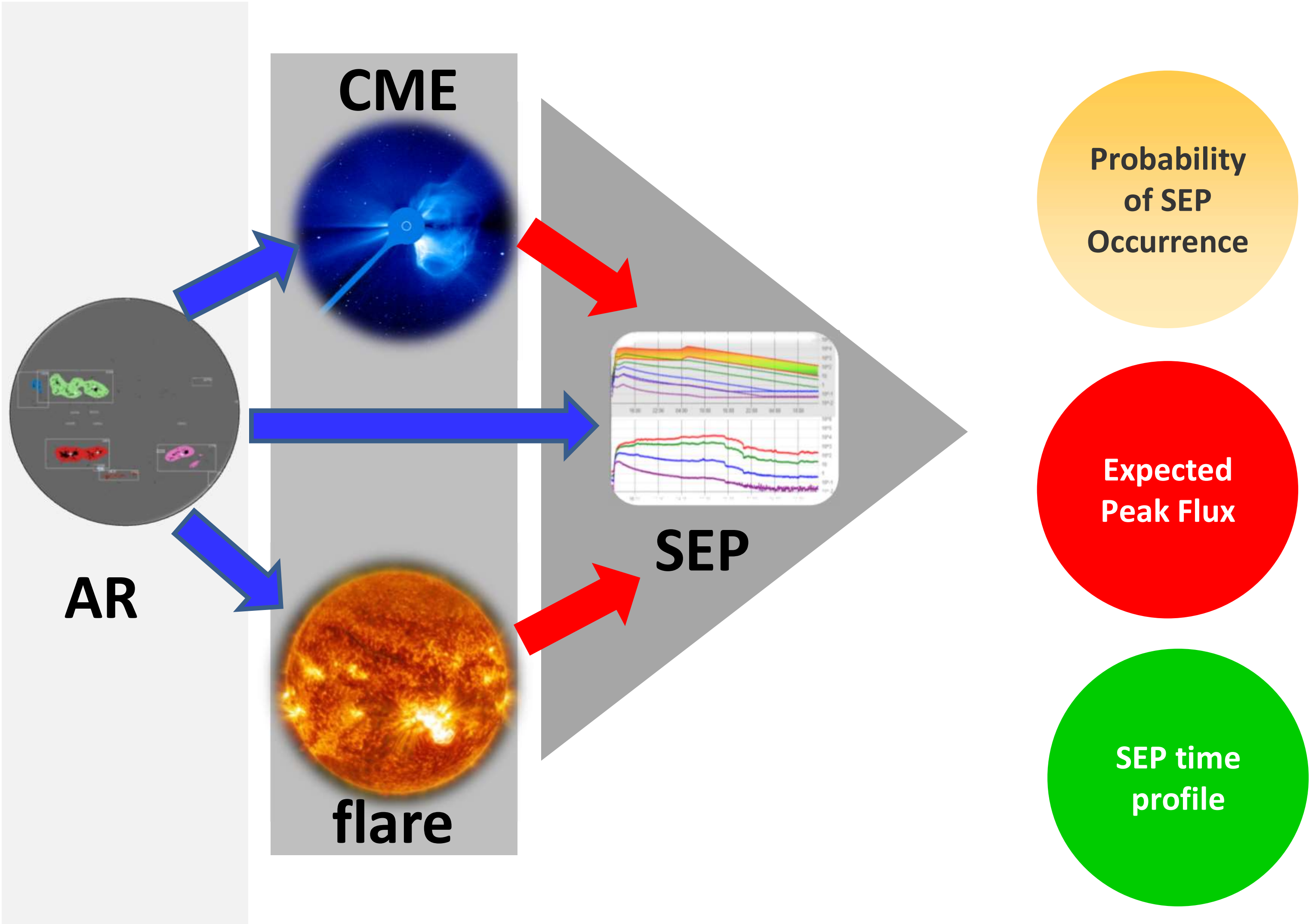


ESA Contract No. 4000120480/17/NL/LF/hh

http://tromos.space.noa.gr/aspecs



The SAWS-ASPECS system



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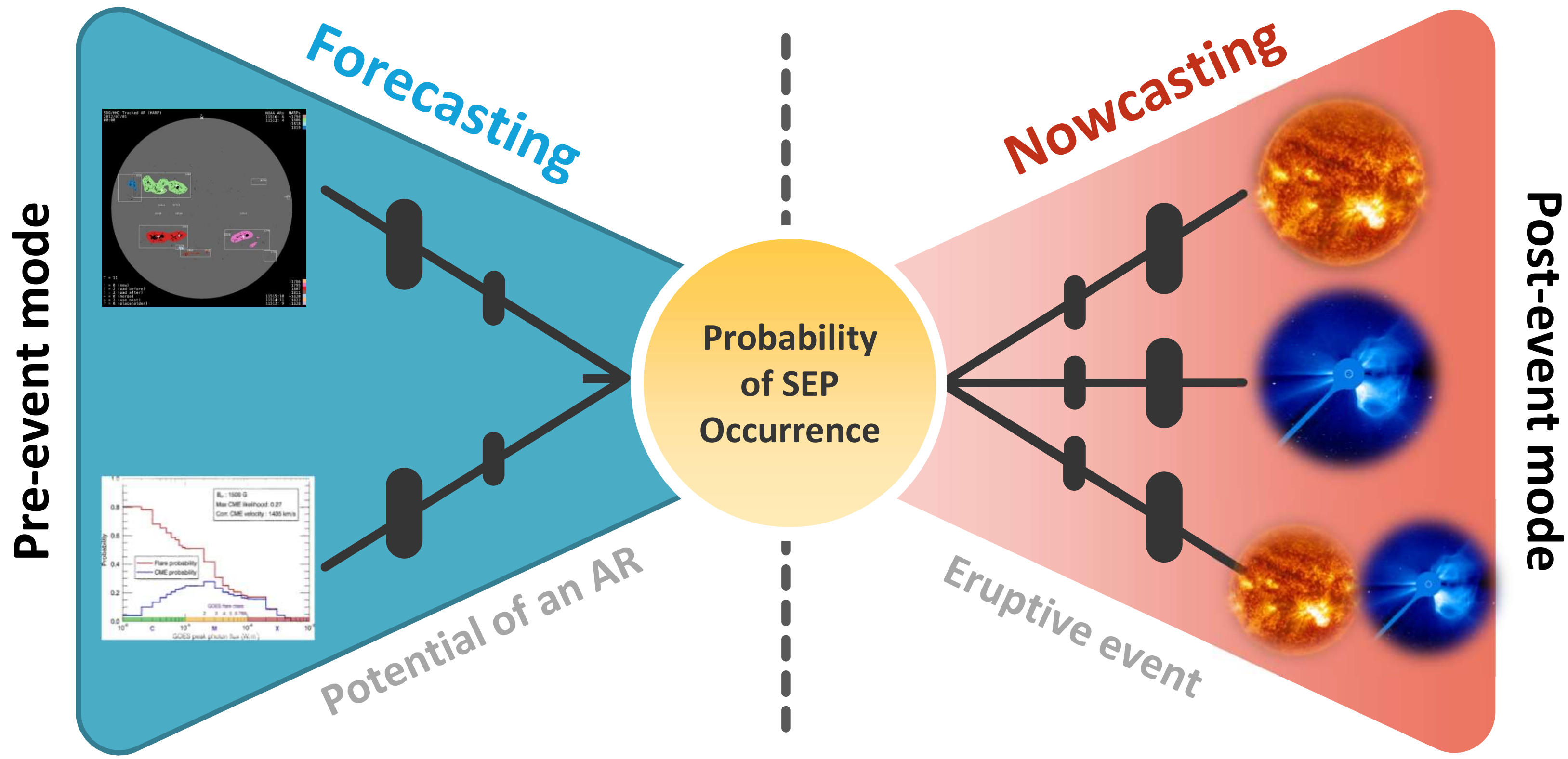
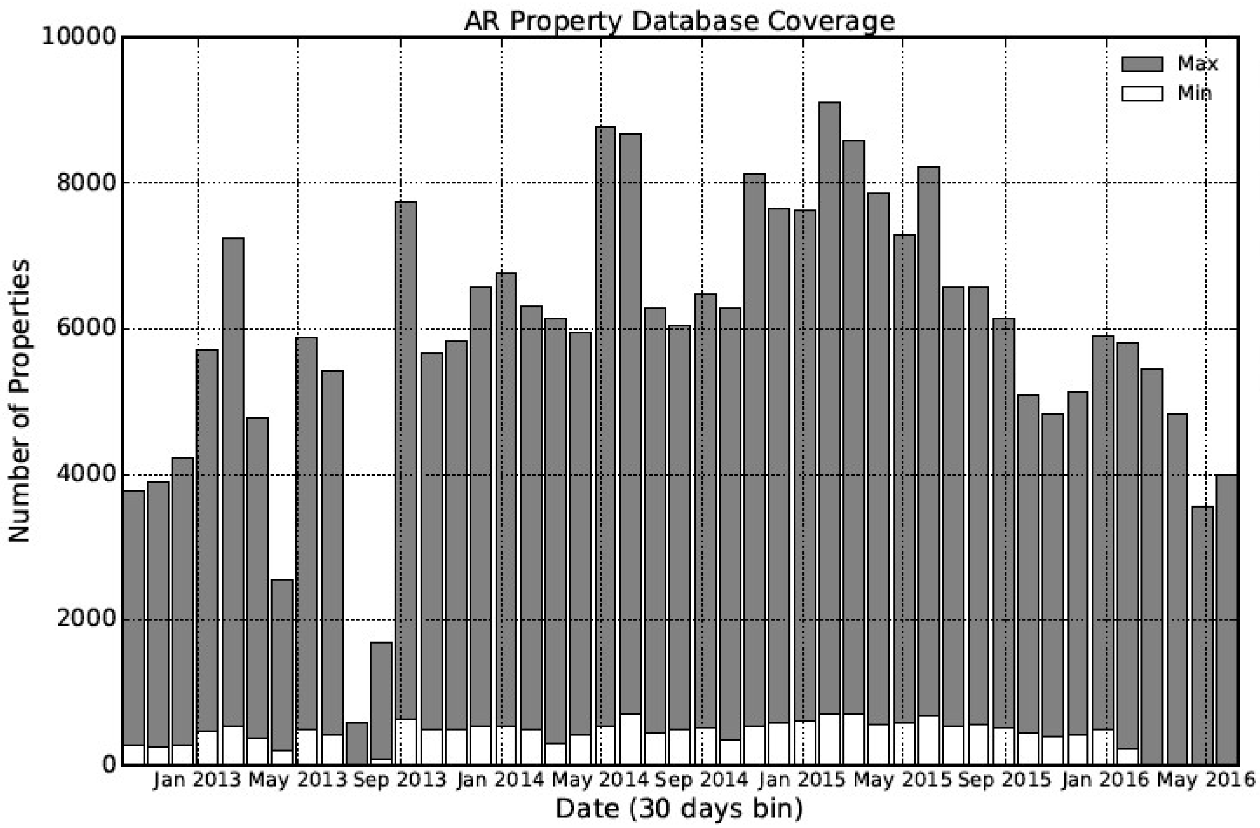

Pre-event mode
Forecasting
Nowcasting
Probability of SEP Occurrence
Potential of an AR
Eruptive event
Post-event mode

The SAWS-ASPECS database

SHARPs



Data at a glance:

- **2,313** data-filled calendar days
- **811** different **ARs**
- **~64,000** magnetograms

FLARECAST
flarecast.eu

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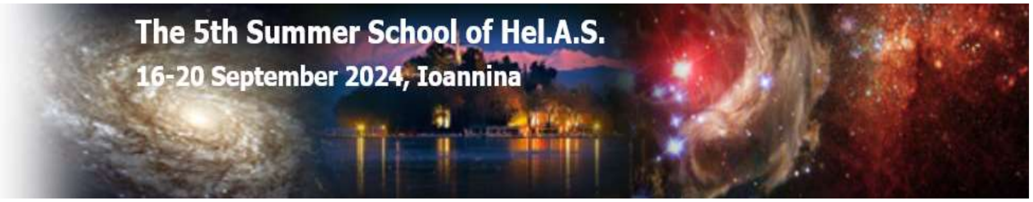
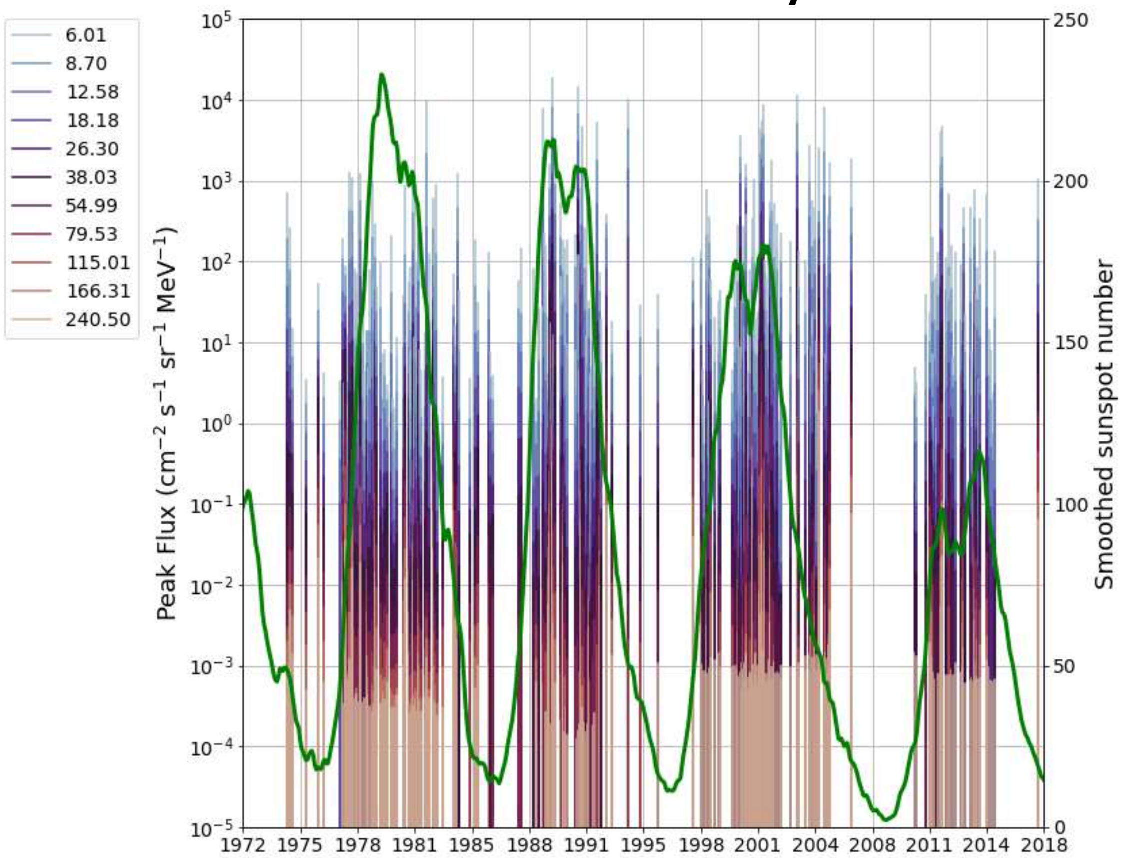


The SAWS-ASPECS database

Database of SFs, (I)CMEs, radio & SEP events

1976-2018 ~ 4 Solar Cycles



Data at a glance:

- **49,546** Soft X-ray solar flares (**≥ C1.0**)
- **23,152** Coronal Mass Ejections (**CMEs**)
- **Cleaned** GOES differential Proton Fluxes (SEPEM RDS)
- **314 SEP** events

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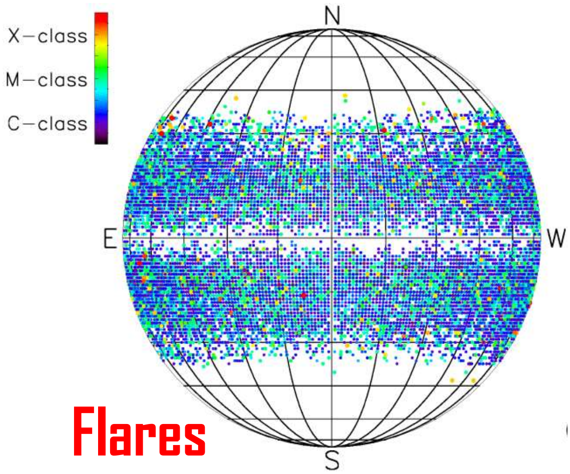
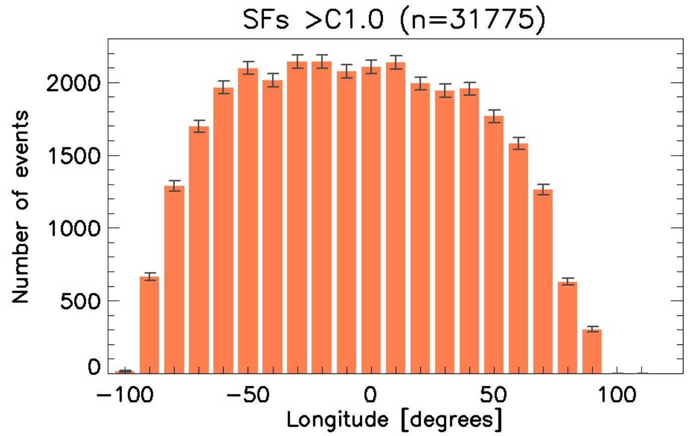
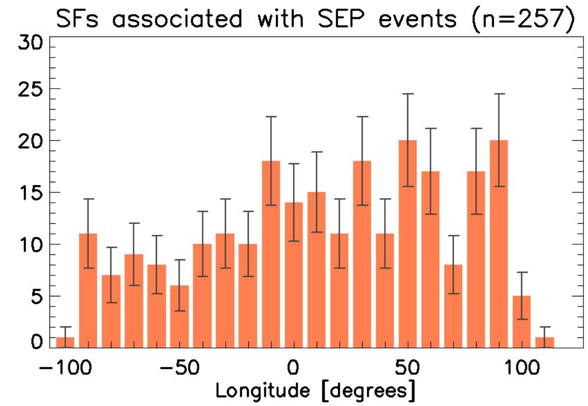
The SAWS-ASPECS database

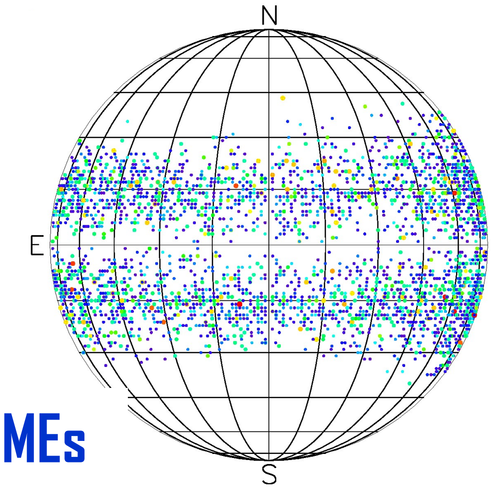
@ a glance



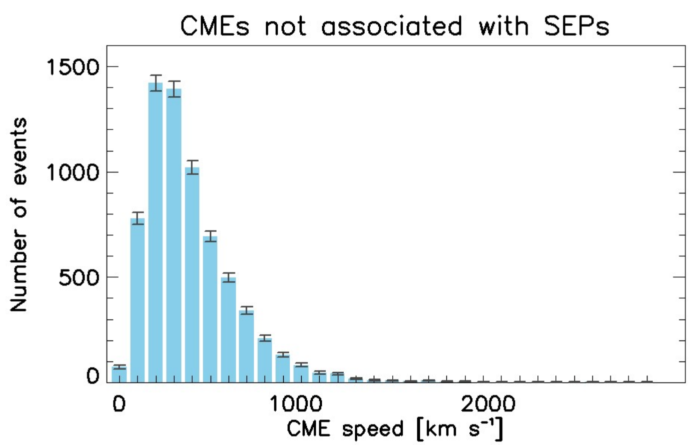
Flares

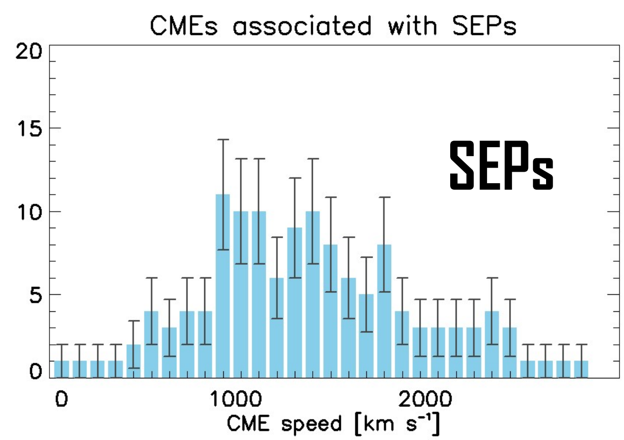






CMEs





SEPs

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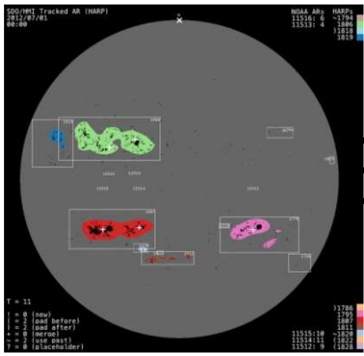
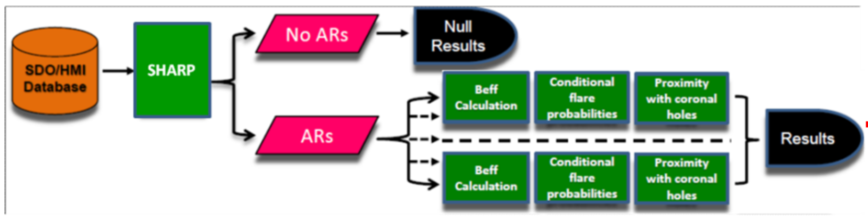
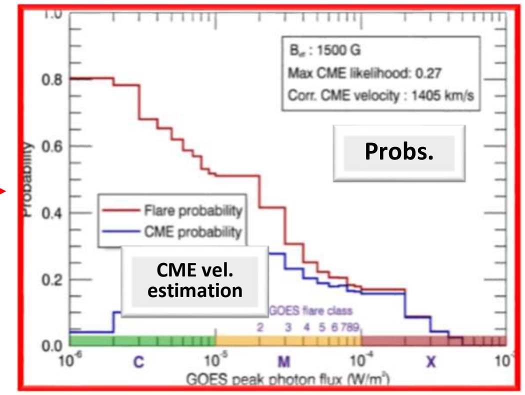
The SAWS-ASPECS system

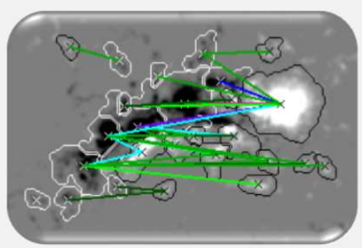
Forecasting mode | Solar Flares







Core of the Forecasting Mode (SFs)



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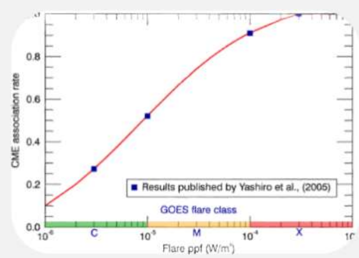
flarecast.eu



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The SAWS-ASPECS system

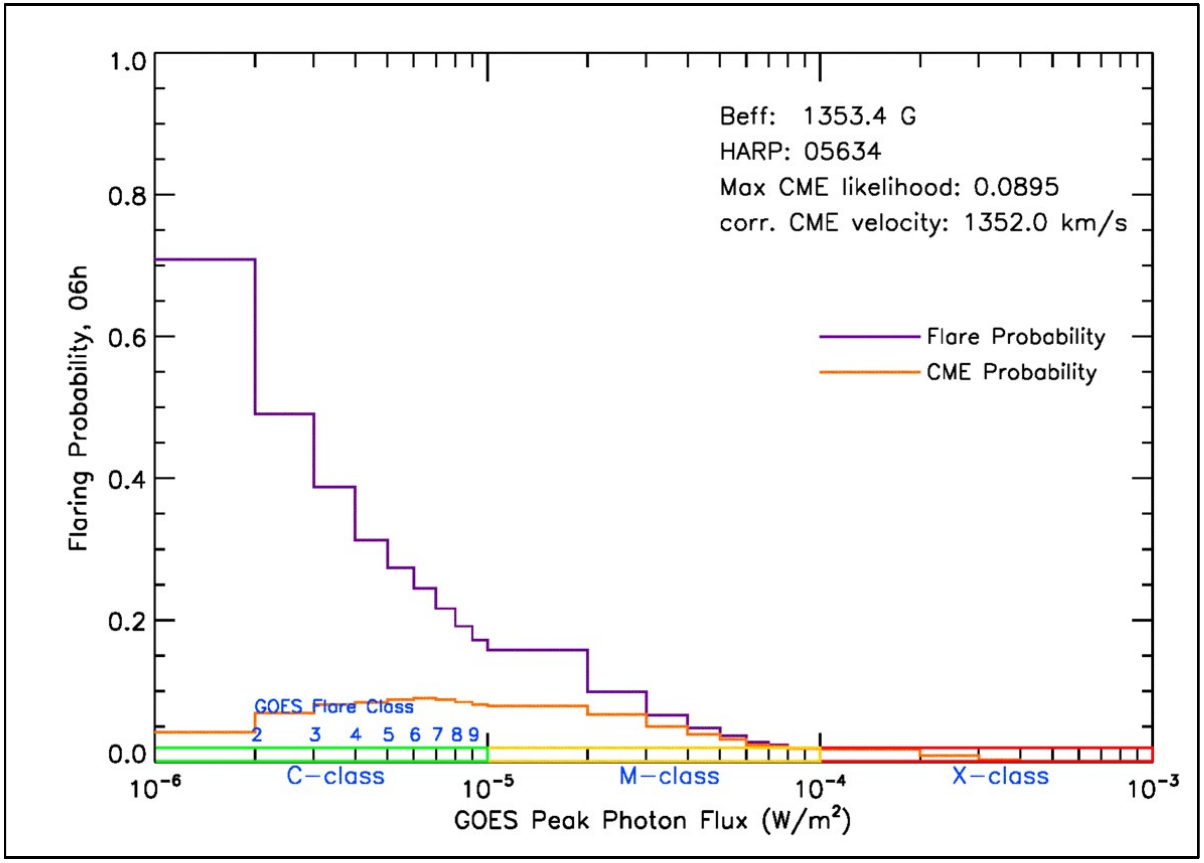
Forecasting mode | Solar Flares

> Final Output:

Flare & (Projected) CME prob.

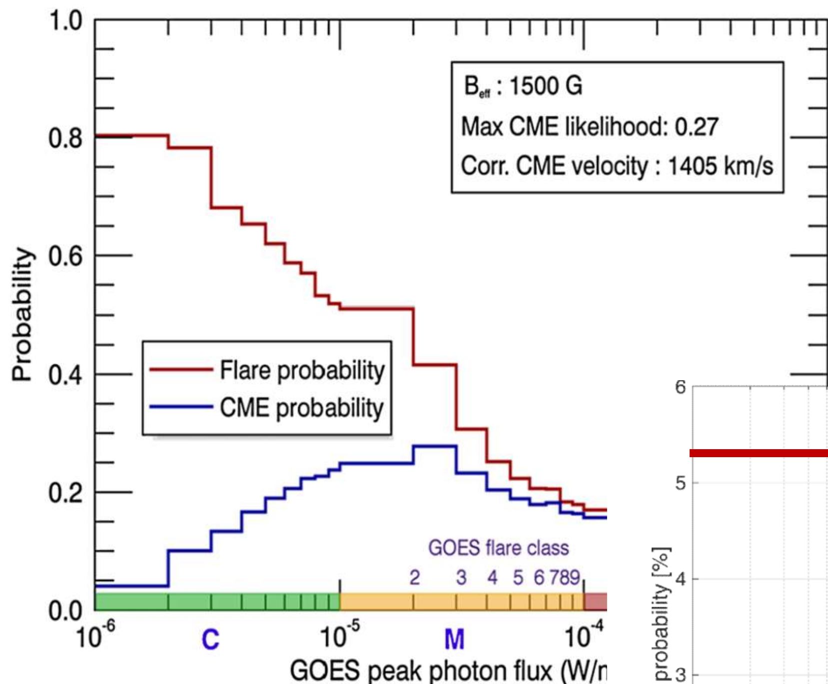
A pictorial output of the range of probabilities for different flare classes (**magenta histogram**). Also shown is the respective CME likelihood curve (**orange histogram**).

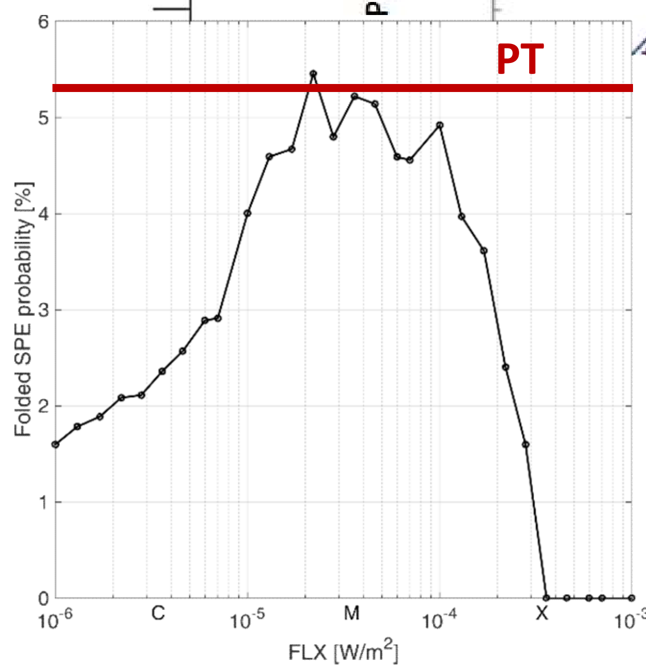
A range of time windows

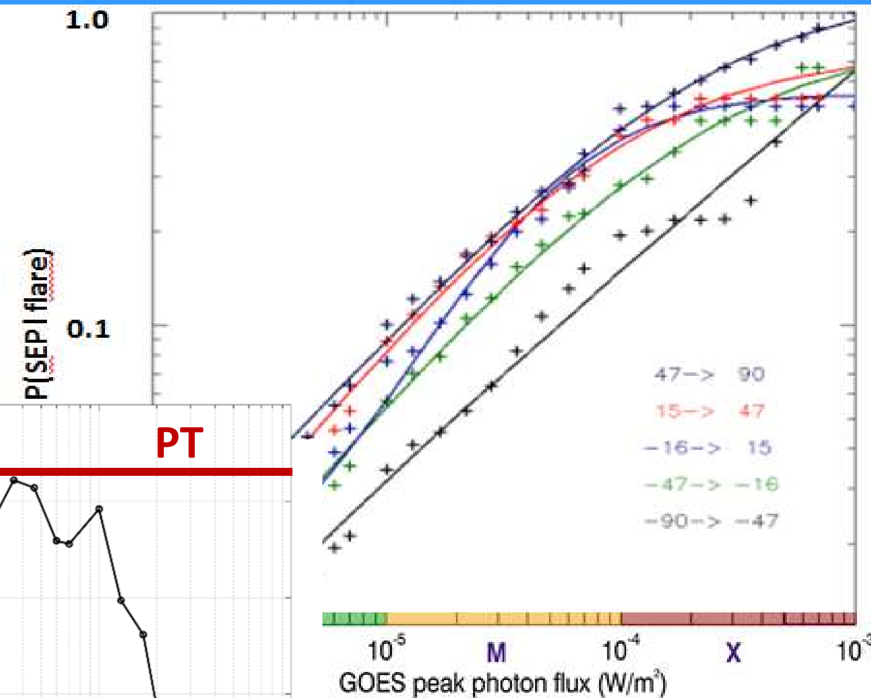


The SAWS-ASPECS system

Forecasting mode | SEP events







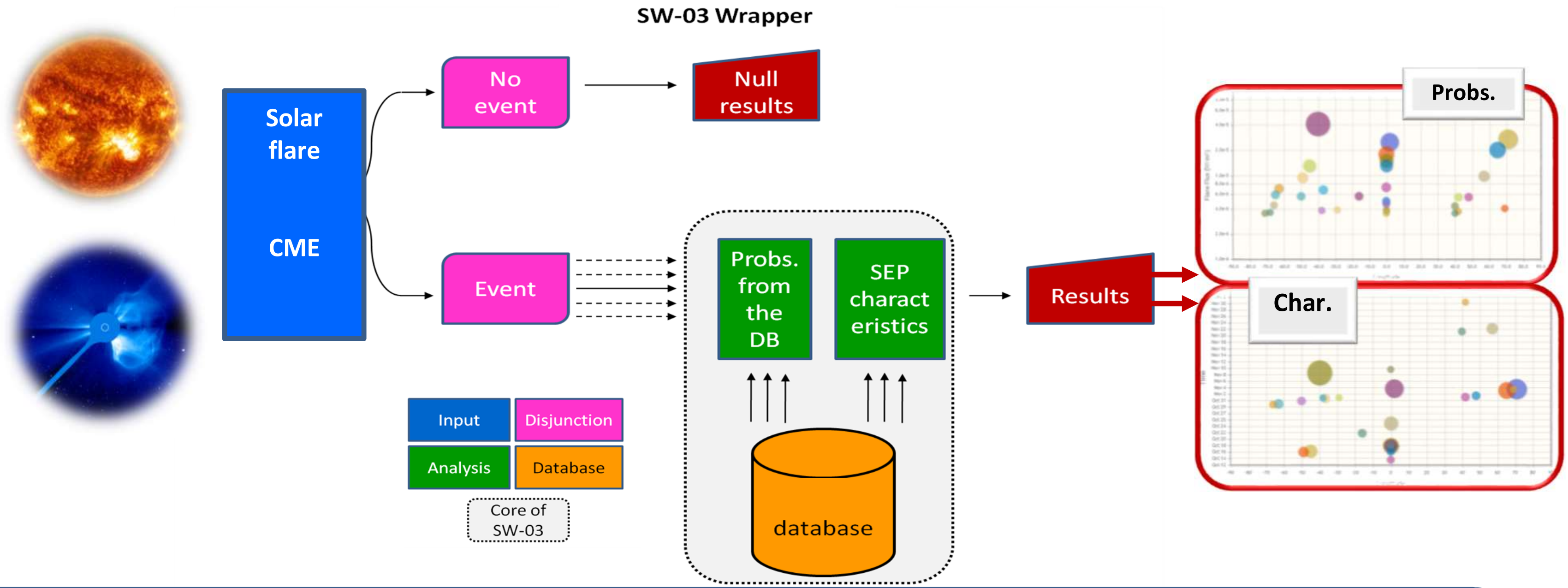
Probability of SEP Occurrence

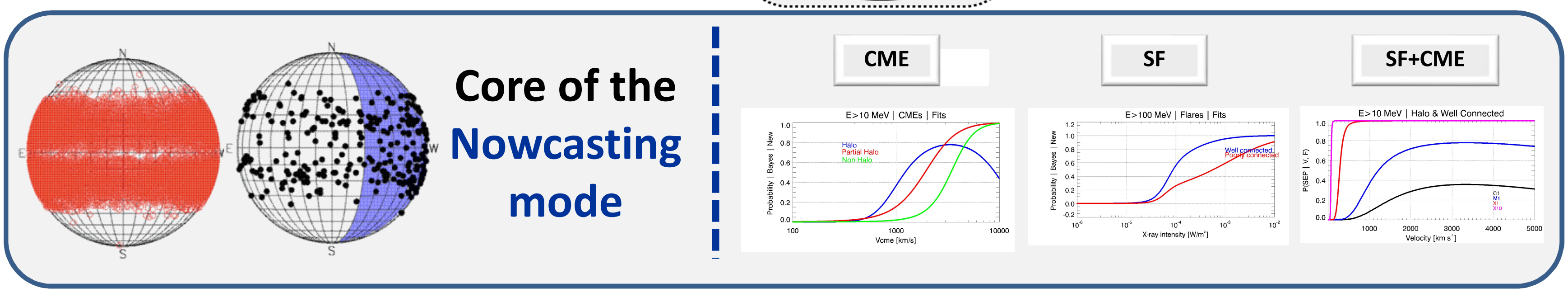
[Papaioannou et al., J. Phys.: Conf. Ser., 2015]()

[Anastasiadis et al., Sol. Phys., 2017]()

The SAWS-ASPECS system

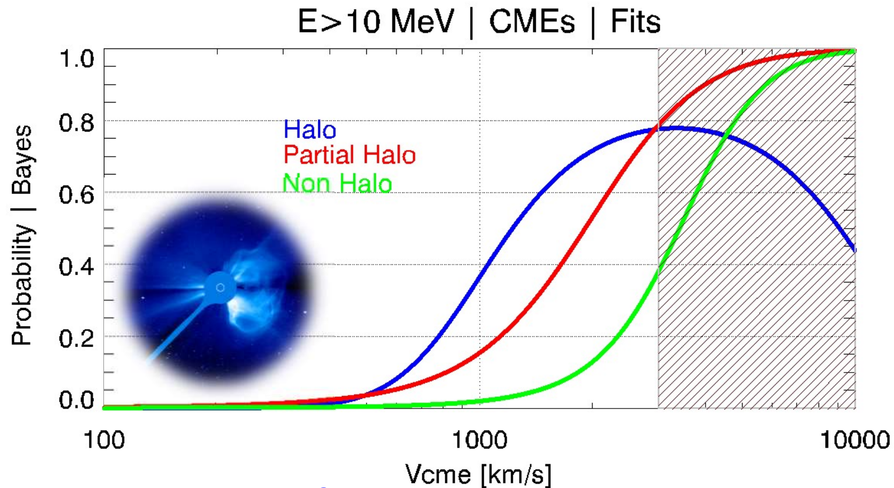
Nowcasting mode | SEP events

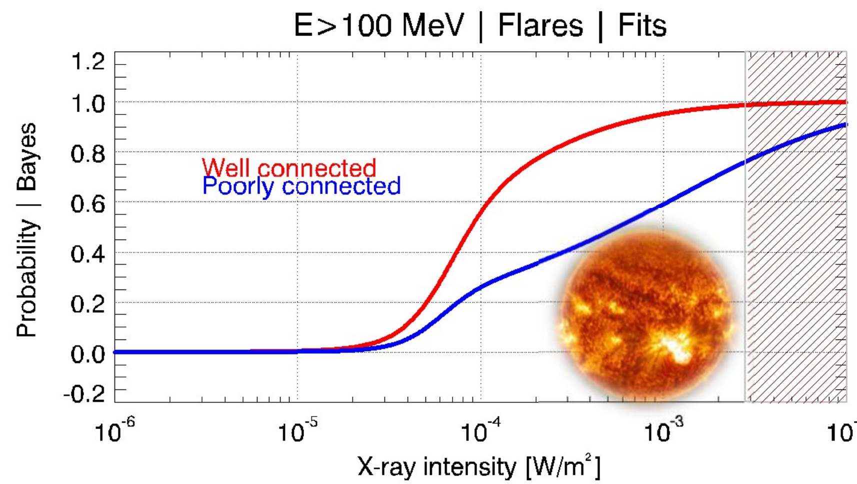




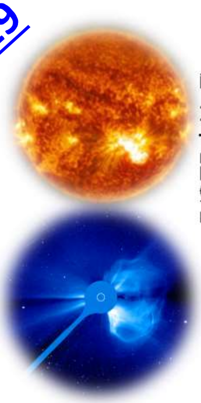
The SAWS-ASPECS system

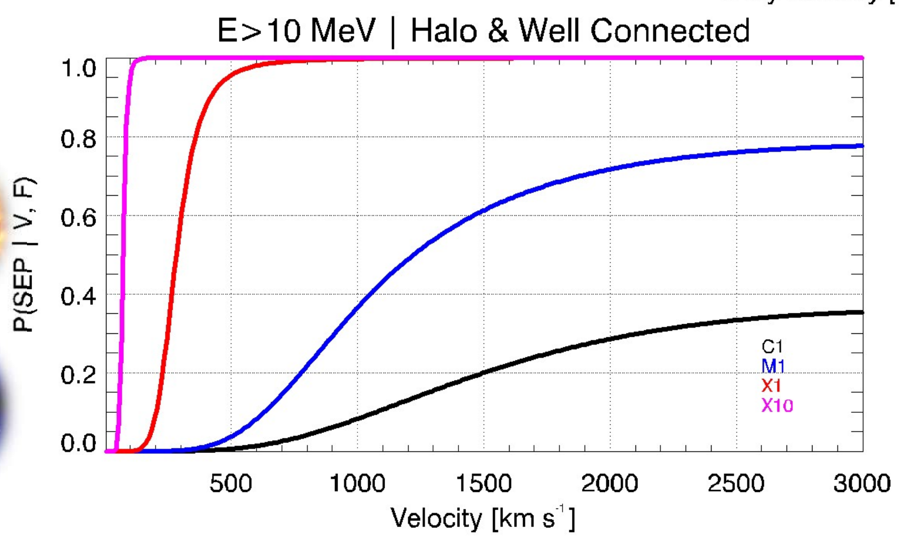
Nowcasting mode | SEP events



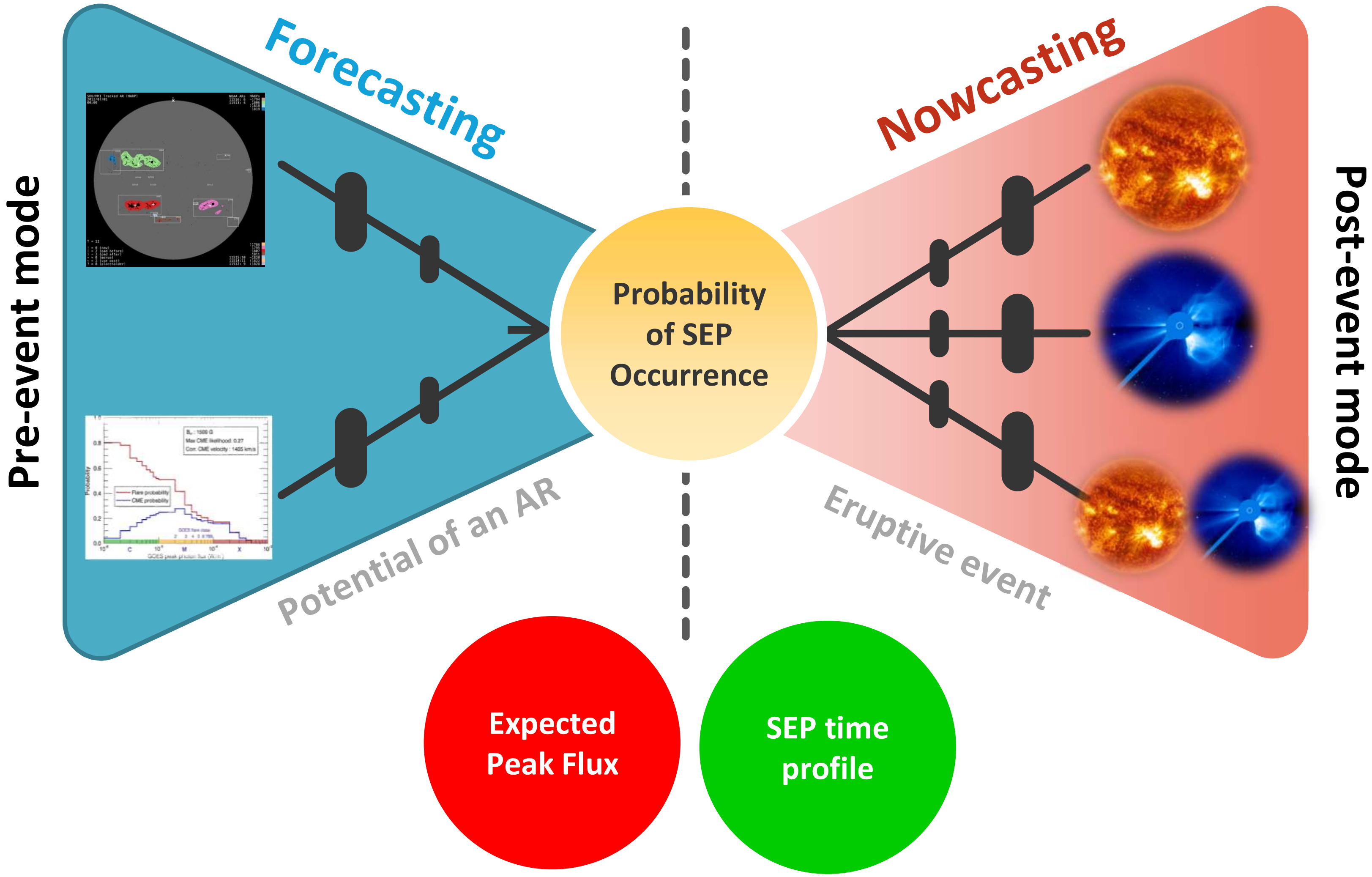


[Papaioannou et al., 2022 JSWSC, DOI: 10.1051/swsc/2022019](https://doi.org/10.1051/swsc/2022019)





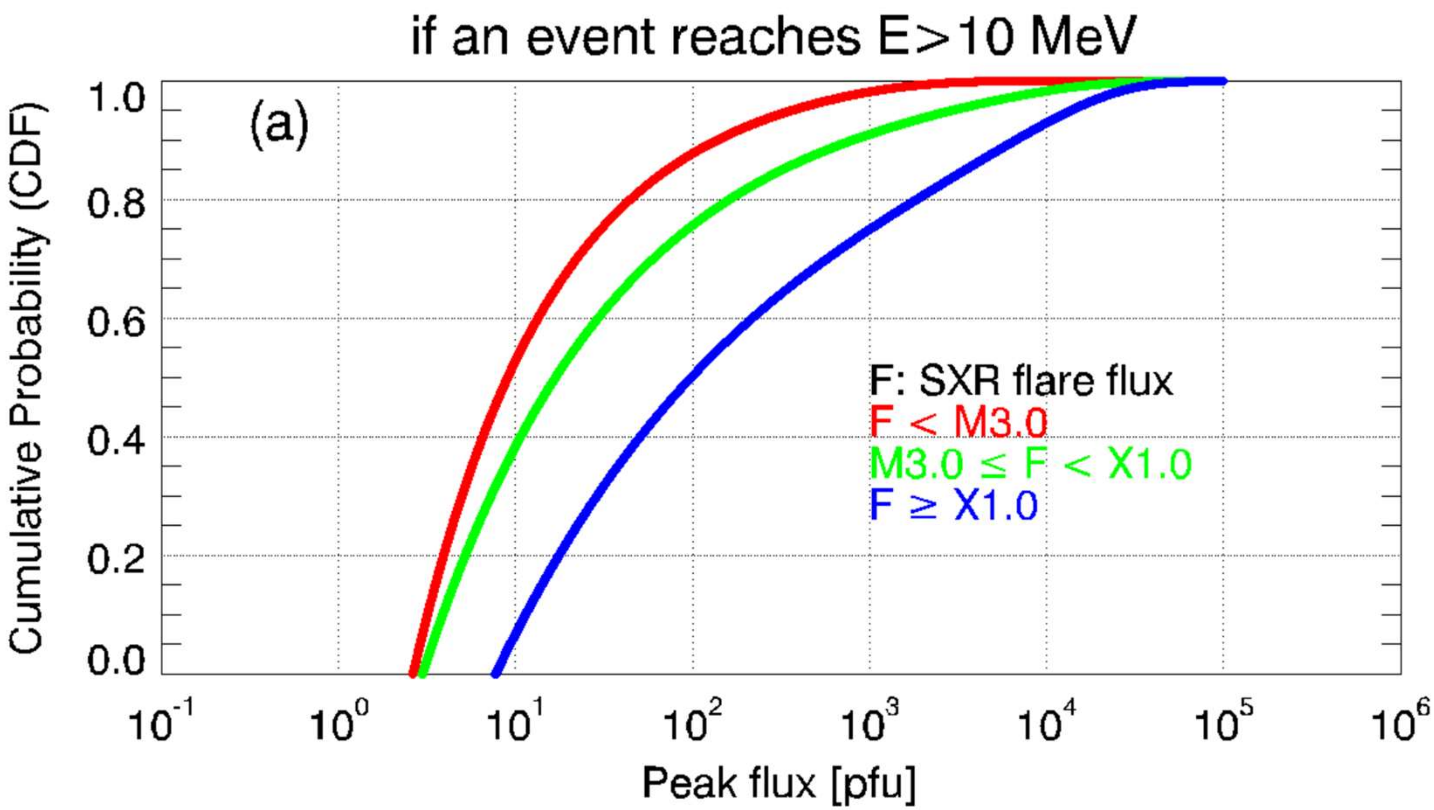
Probability of SEP Occurrence


Forecasting
Nowcasting
Pre-event mode
Post-event mode
Probability of SEP Occurrence
Potential of an AR
Eruptive event
Expected Peak Flux
SEP time profile

The SAWS-ASPECS system

SEP event time profiles

I_{peak} ***Expected Peak Flux @ Different Confidence Levels***



Expected Peak Flux

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The SAWS-ASPECS system

SEP event time profiles

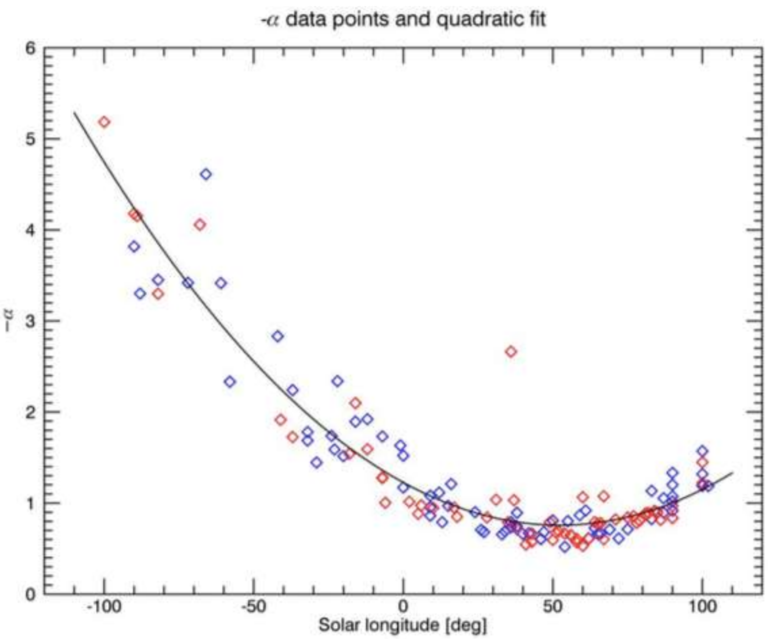
Time profile

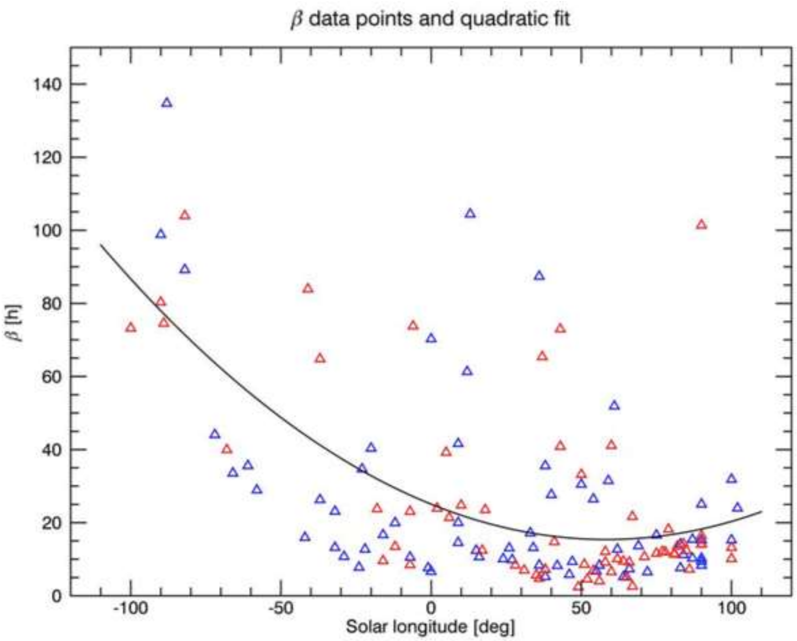
SEP time profile

Kahler & Ling, Sol. Phys. 2017

Paassilta et al., Adv. Space Res., 2023

$$F(t) = -I_0 \frac{\alpha}{\beta}\left(\frac{t-t_0}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{t-t_0}{\beta}\right)^{\alpha}\right)$$





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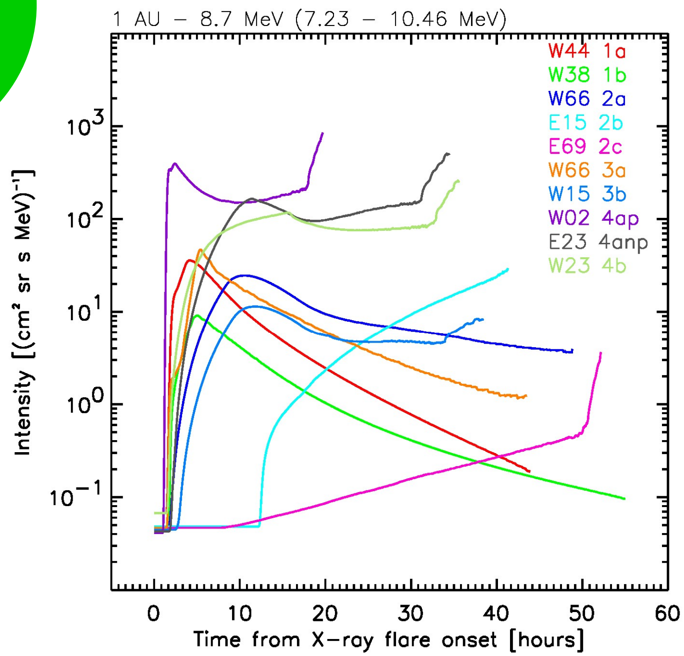
The SAWS-ASPECS system

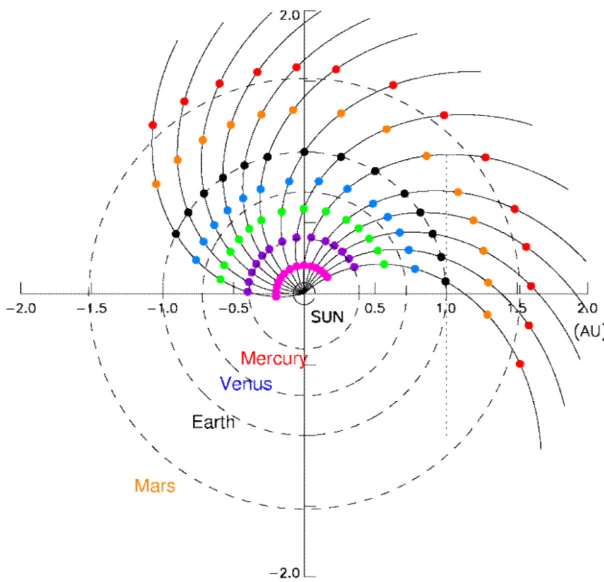
SEP event time profiles

SEP time profile

Time profile

Aran et al., SEPEM Tech. Rep., 2011





> Select ***reference cases*** considering the *heliolongitude of their solar origin* to better describe the **shape of the intensity-time profiles**.

> Generate **synthetic time profiles** for *a number of scenarios* using MHD transport codes and store them in a database.

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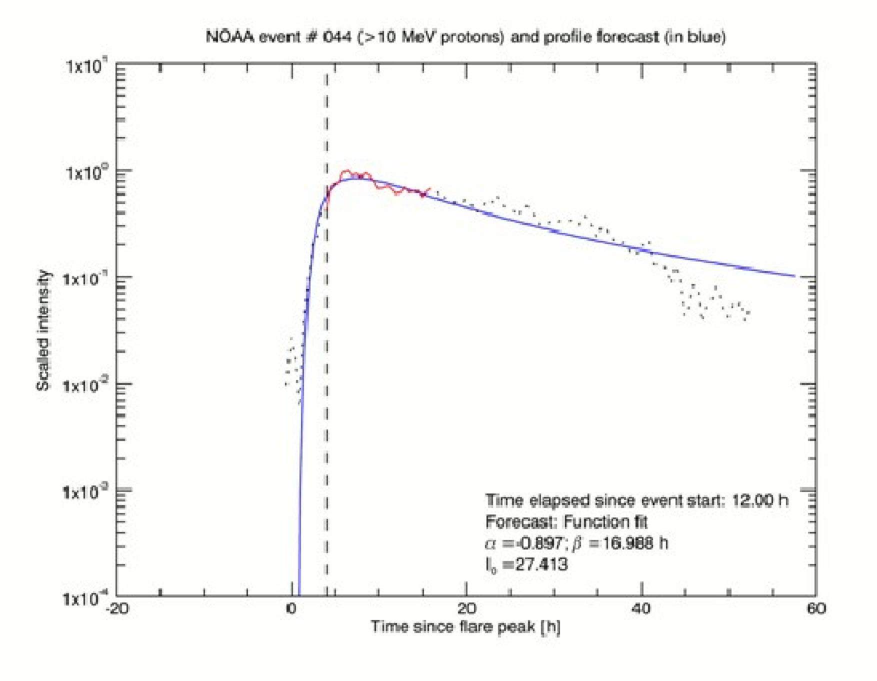
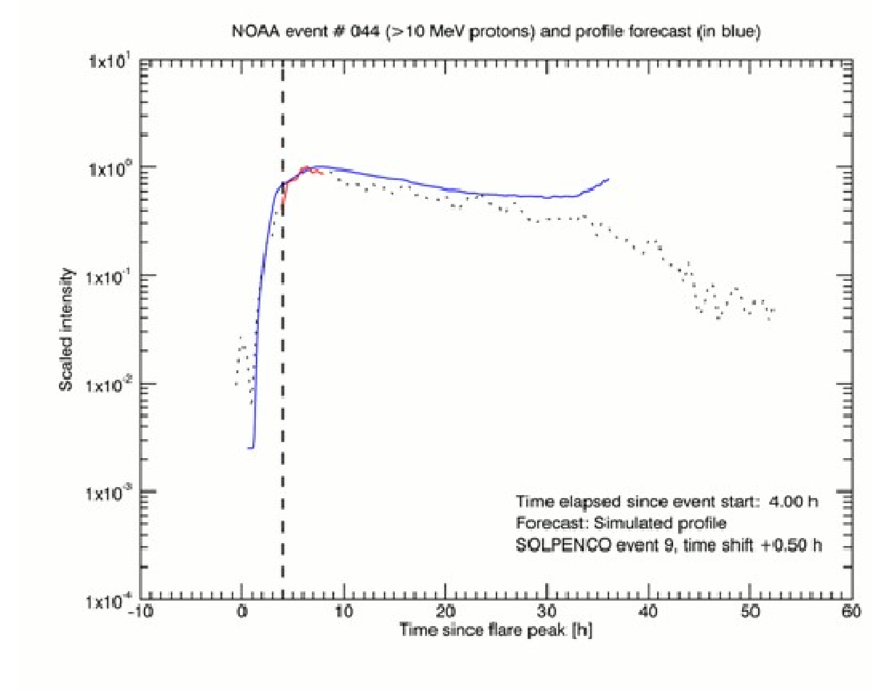
The SAWS-ASPECS system

SEP event time profiles

Mock-up based on actual data (SEP events)





> Data
> KL fit

> Data
> SOLPENCO-2

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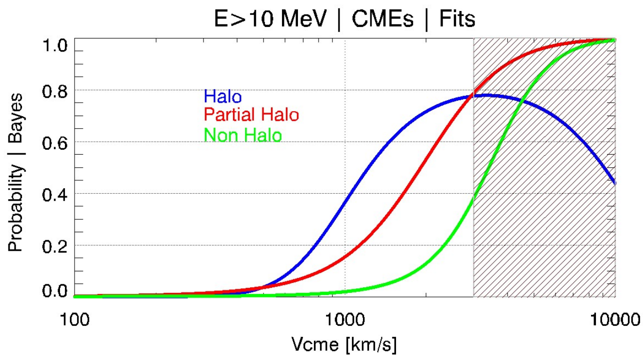
The SAWS-ASPECS system

In a nutshell



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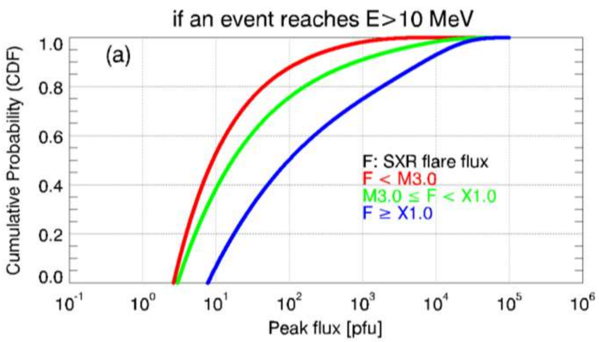

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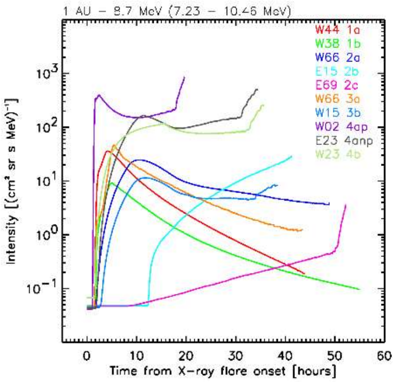


Probability of SEP Occurrence

Expected Peak Flux

SEP time profile

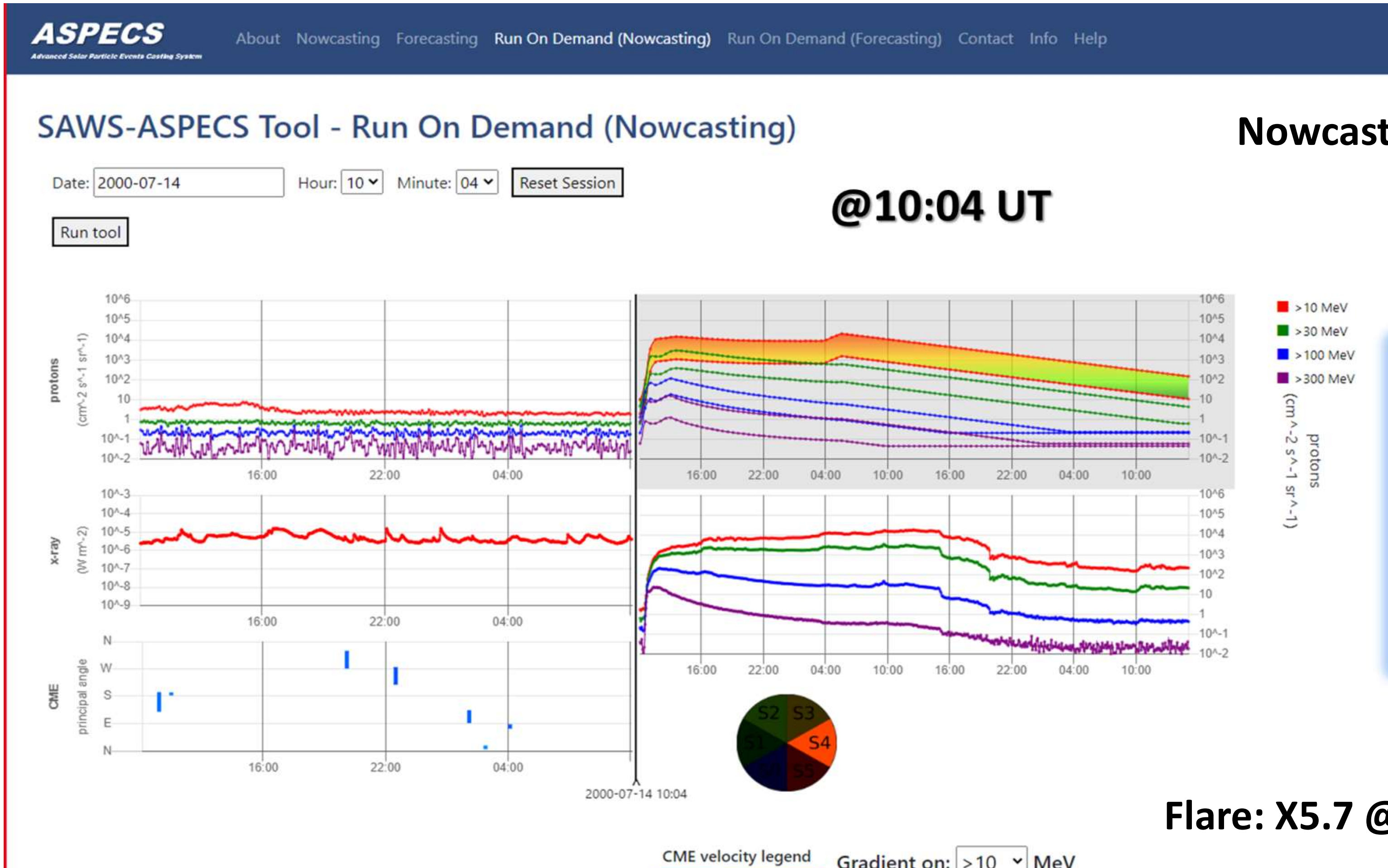
IAASARS

HELLENIC ASTRONOMICAL SOCIETY

The SAWS-ASPECS system

Outputs | SEP time profile

http://phobos-srv.space.noa.gr/



Nowcasting

@10:04 UT

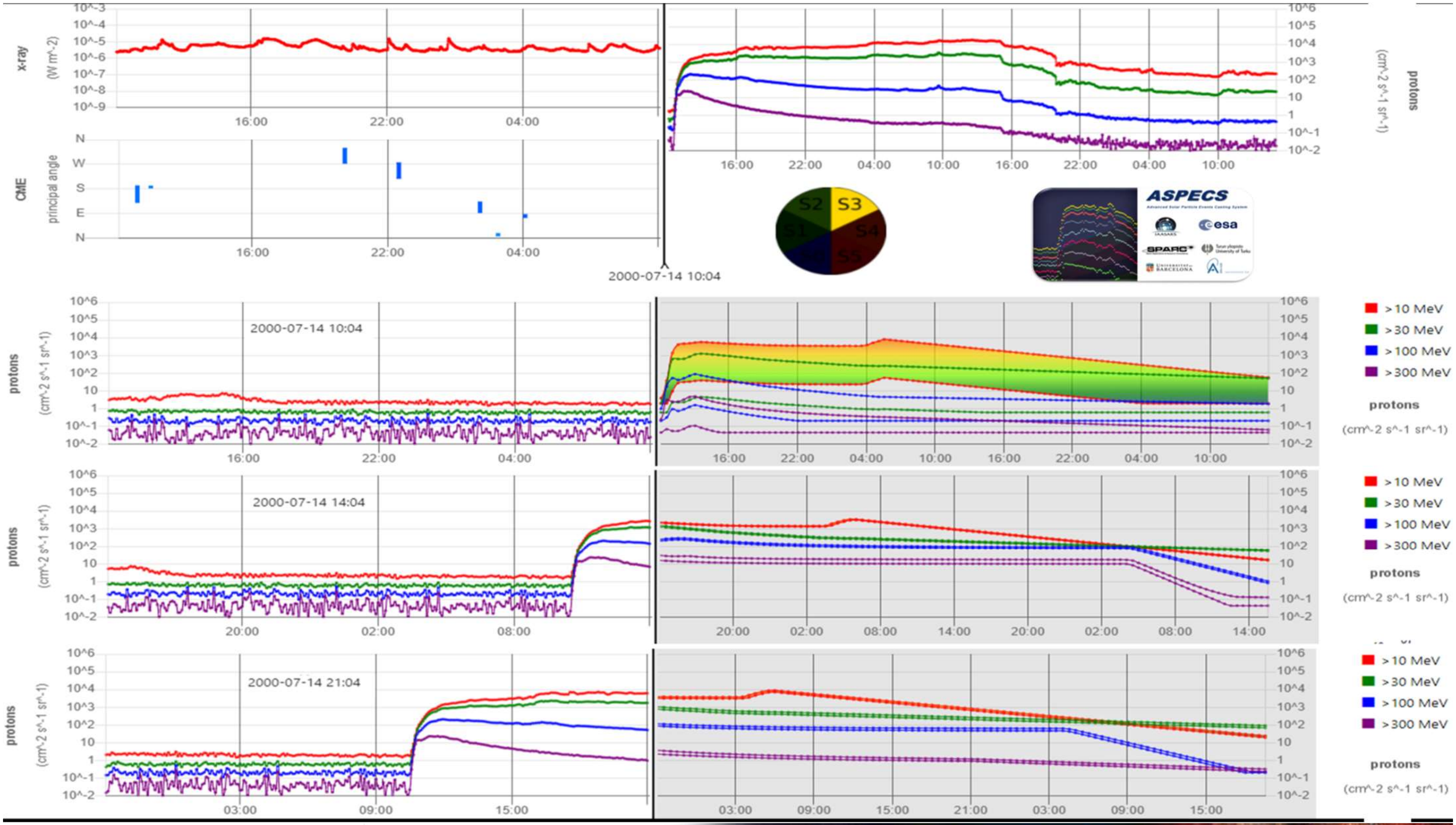
Available online

Flare: X5.7 @ N22W07

IAASARS

HELLENIC ASTRONOMICAL SOCIETY

Outputs | SEP time profile



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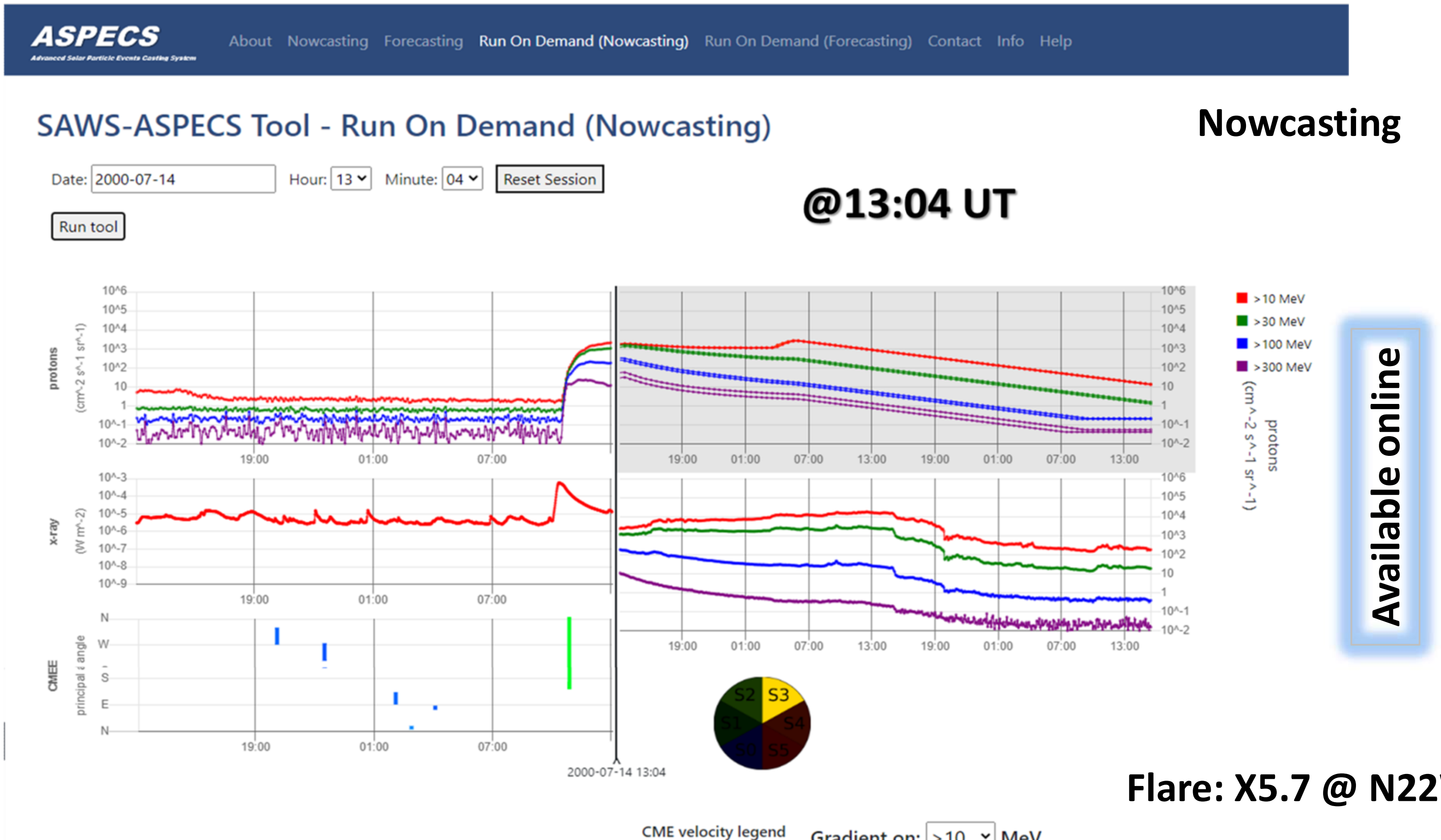
HELLENIC ASTRONOMICAL SOCIETY

The SAWS-ASPECS system

Outputs | SEP time profile

http://phobos-srv.space.noa.gr/



Nowcasting

@13:04 UT

Available online

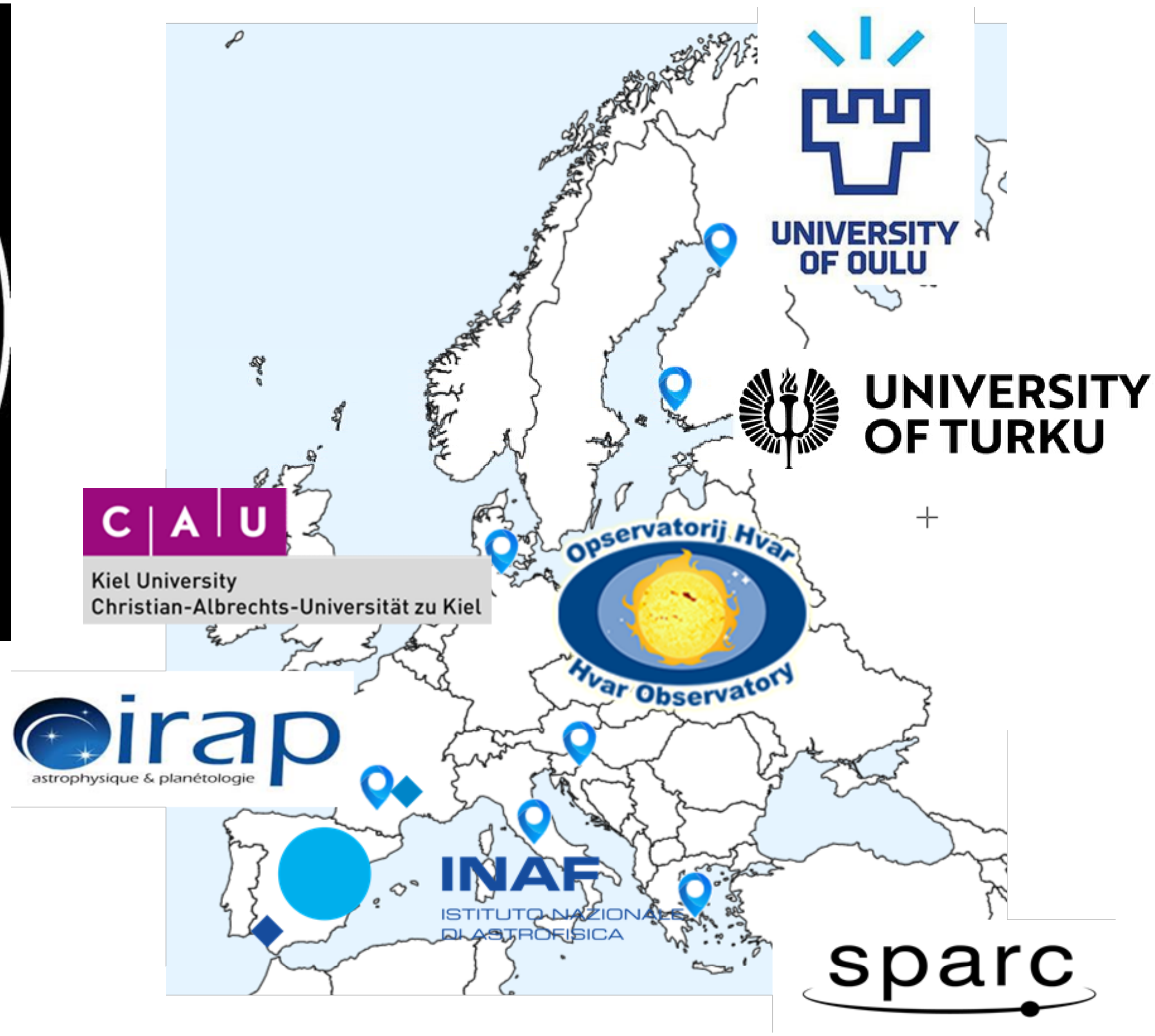
Flare: X5.7 @ N22W07

SPEARHEAD Project

SPEcification, Analysis & Re-calibration of High Energy pArticle Data

SPEARHEAD

Funded by
the European Union



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ΕΘΝΙΚΟΝ ΑΣΤΕΡΟΣΚΟΠΕΙΟΝ ΑΘΗΝΩΝ
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The 5th Summer School of Hel.A.S.
16-20 September 2024, Ioannina

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