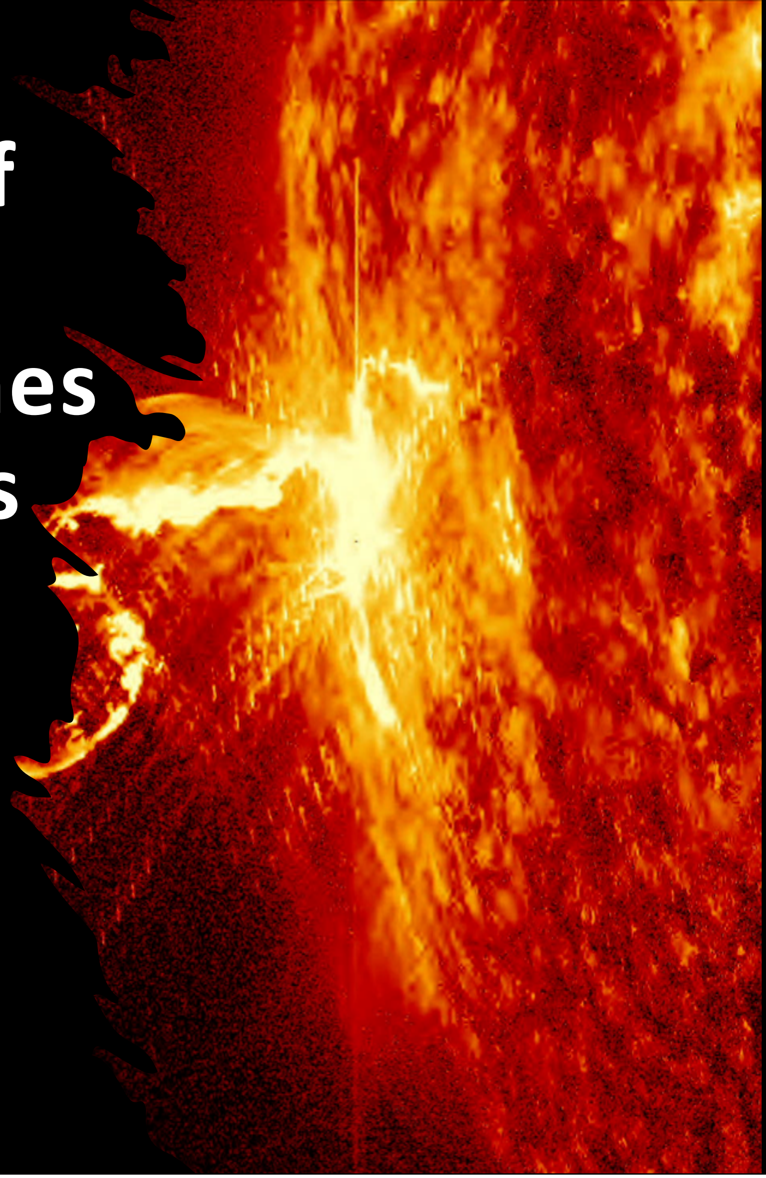
First insights into the applicability and importance of different 3D magnetic field extrapolation approaches for studying the pre-eruptive conditions



Marianna B. Korsos

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HSPF Hungarian Solar Physics Foundation

Universität Graz / University of Graz

University of Sheffield

Prifysgol Aberystwyth University

Motivations of that work
How to make a big leap in the solar eruption prediction?

Most of the pre-eruptive conditions of the source regions are identified only based on solar surface data.

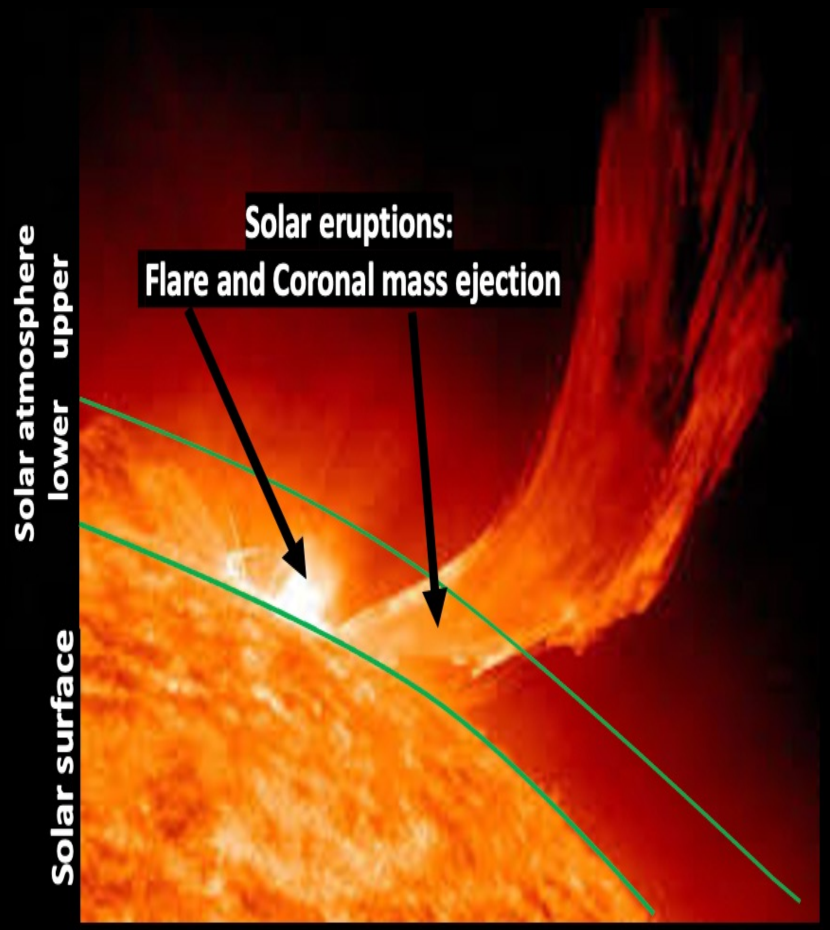
But they manifest in the lower solar atmosphere.

Pre-eruptive conditions could be determined more accurately based on lower solar atmospheric data.

(Korsos et al. ApJ 2019, 2021, 2022)

Different referee reports:

- Why do/did you use this extrapolation approach?
- Why not that one?

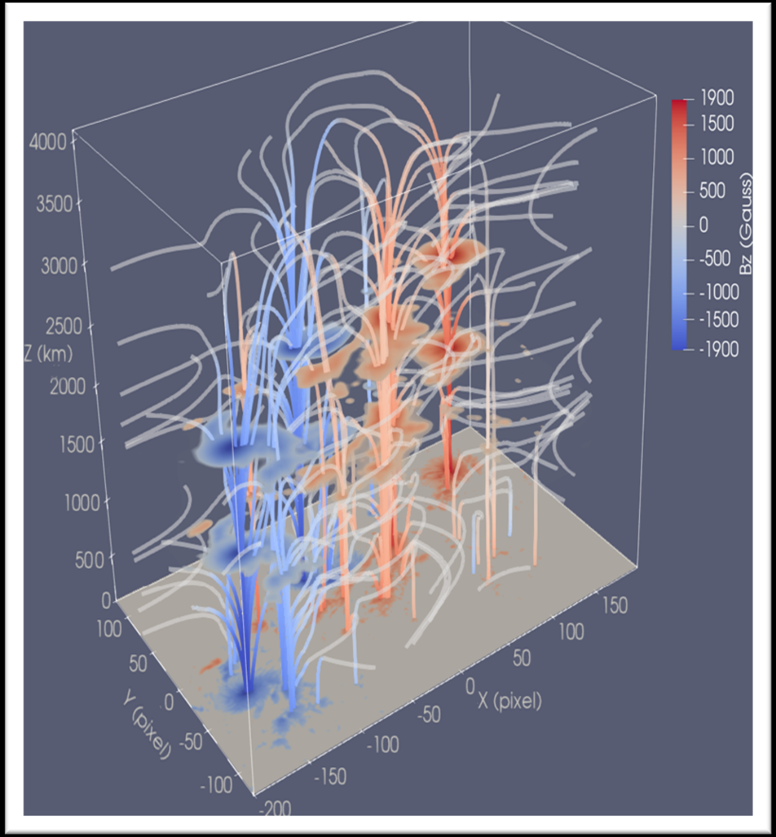


Studying the magnetic field evolution in the lower solar atmosphere

- The potential field (PF), linear force-free field (LFFF), and nonlinear force-free field (NLFFF) extrapolation models of *Wiegelmann & Sakurai (2021).*

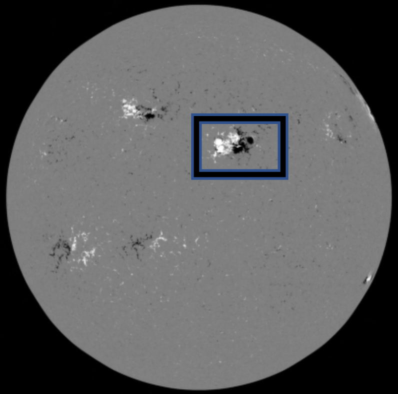
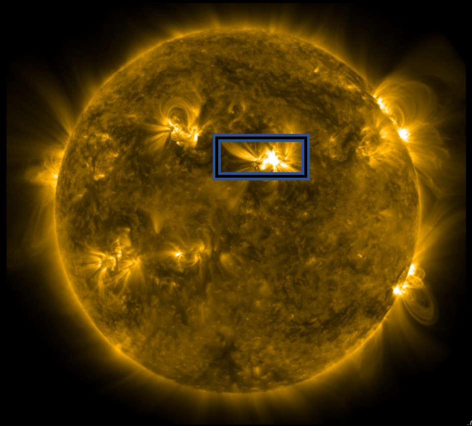
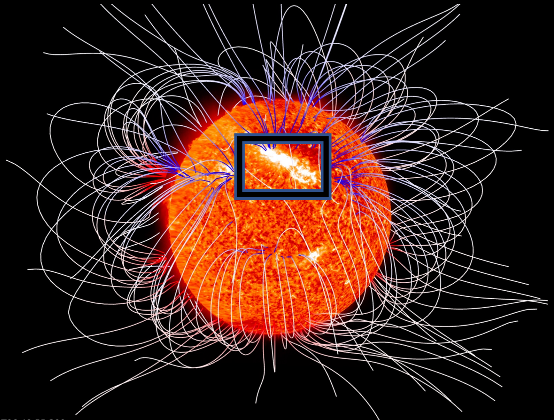
- A neural network-based method that integrates observational data and the physical NLFFF model of *Jarolim et al. Nat. Ast. (2023).*

- The photospheric Br, Bt, and Bp vector magnetic fields that are obtained from the Spaceweather Helioseismic MagneticImager Active Region Patches (SHARPs).

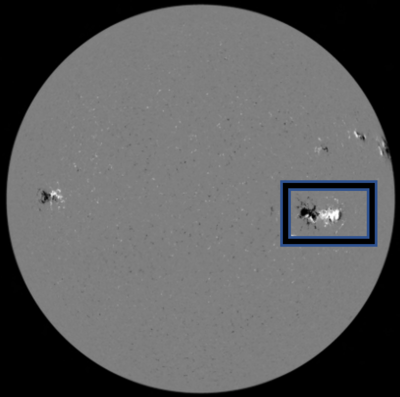
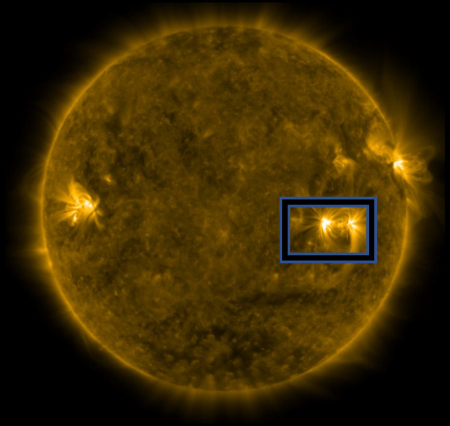
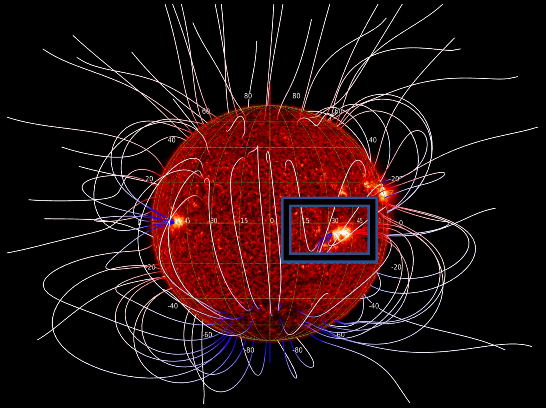


Studying the magnetic field evolution of two magnetically complex active regions in the lower solar atmosphere

AR11166
complex and ”furious”
Active Region

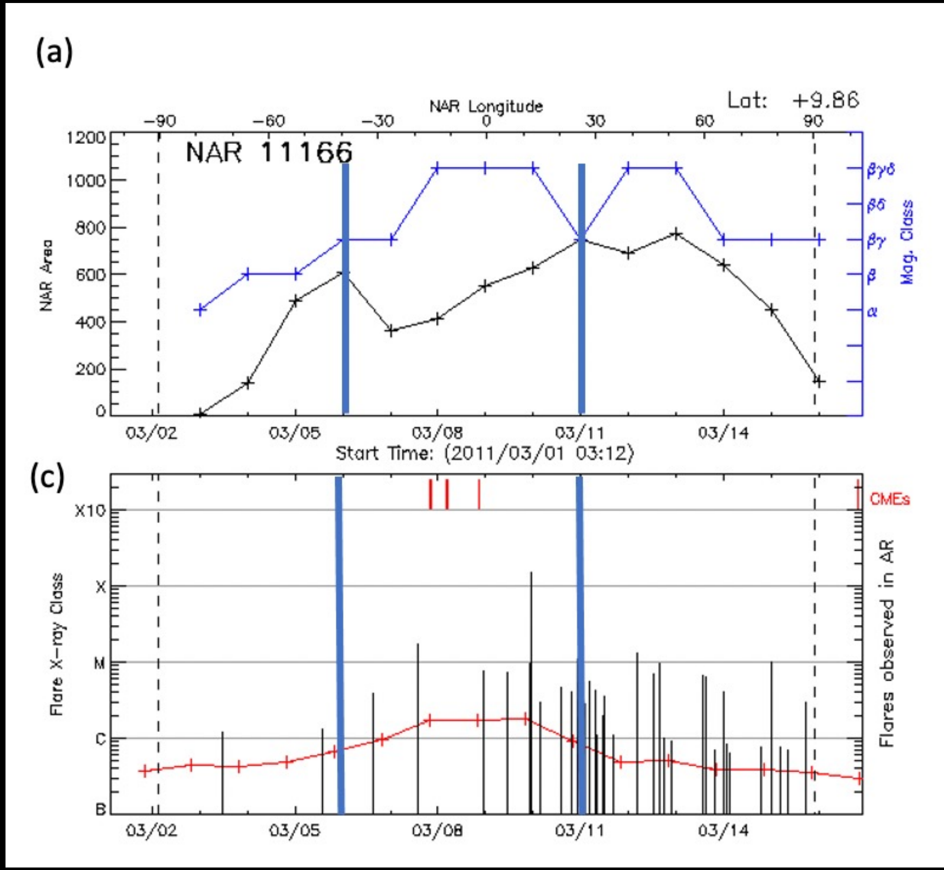
AR12645
complex but ”peaceful”
Active Region

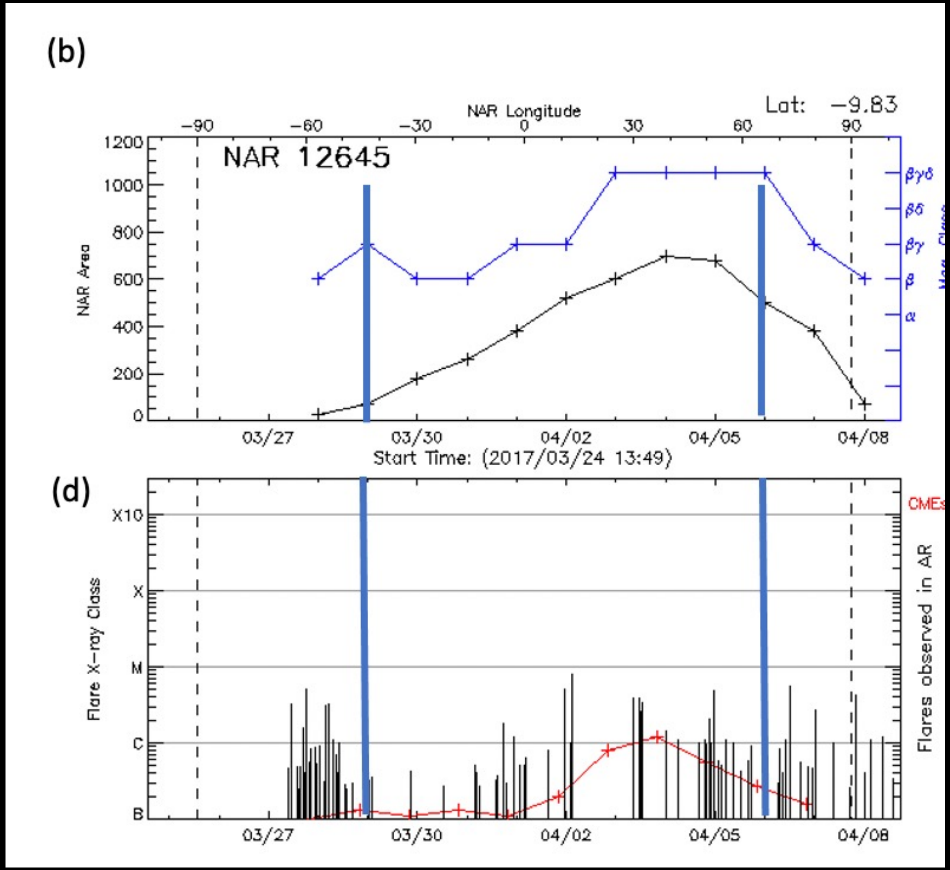
Credits: idl PFSS and https://helioviewer.org/

Evolution of the two magnetically complex active regions

”furious” Active Region



”peaceful” Active Region

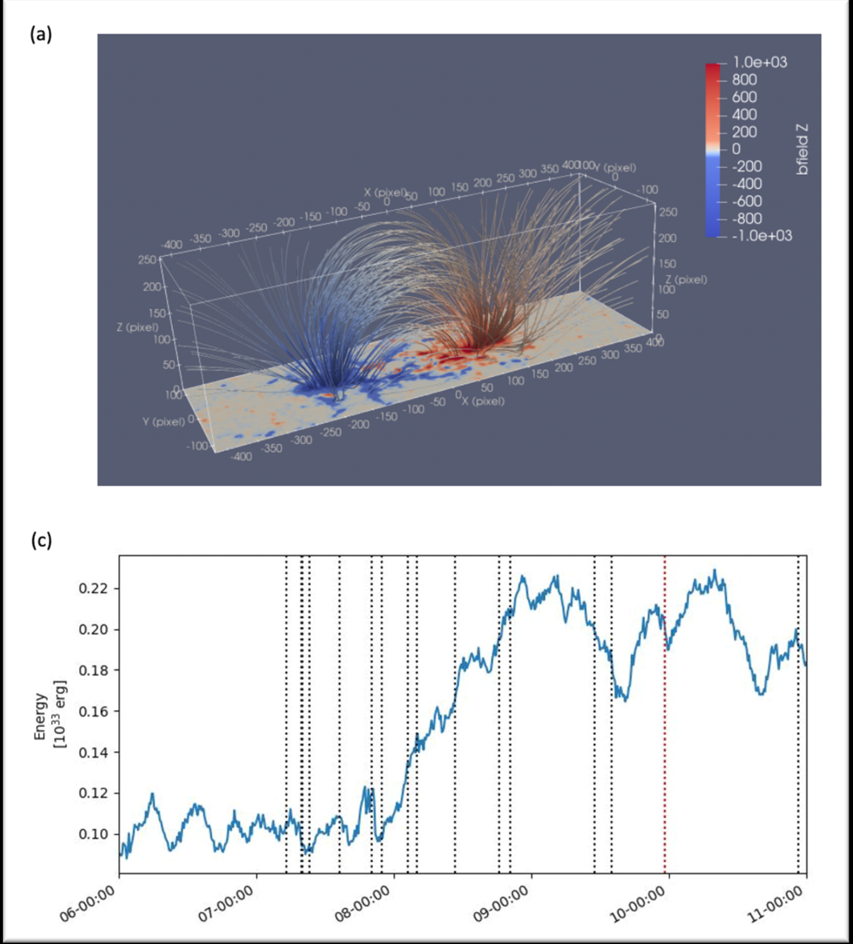


Credit: http://helio.mssl.ucl.ac.uk/

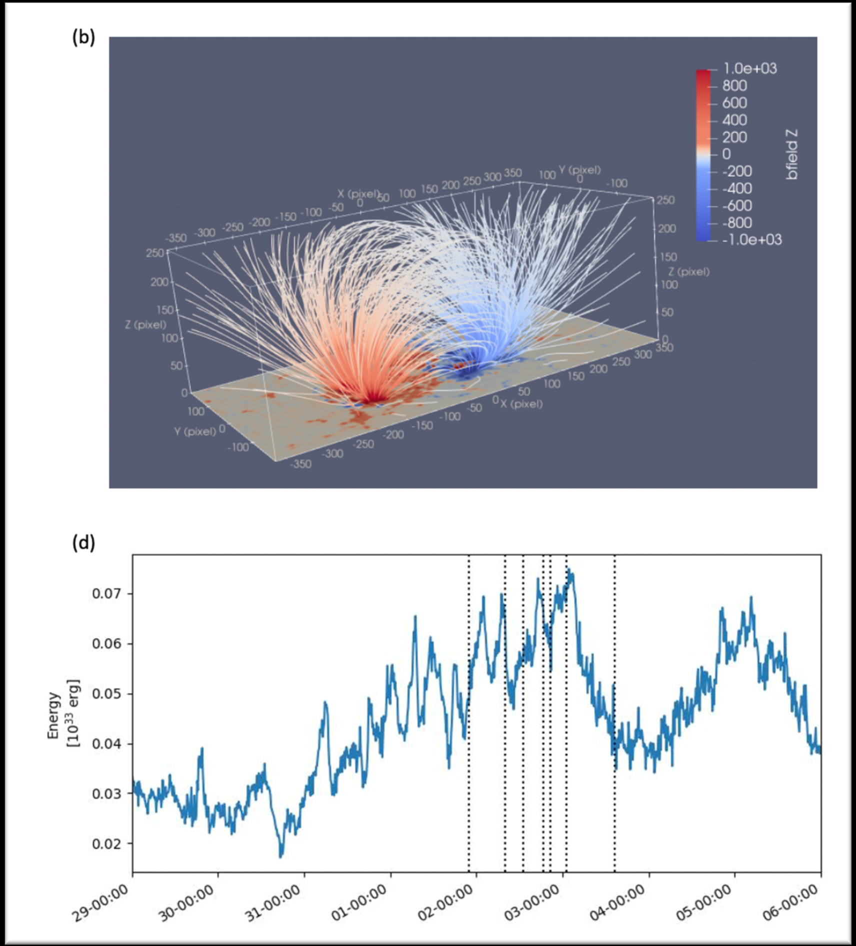
How much free magnetic energy do they have?

$E_{free} > 2*10^{32}$ [erg] *(Liokati et al. 2022)*

"furious" Active Region

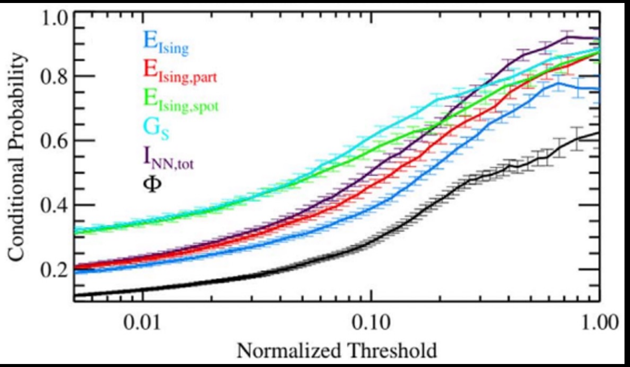


"peaceful" Active Region

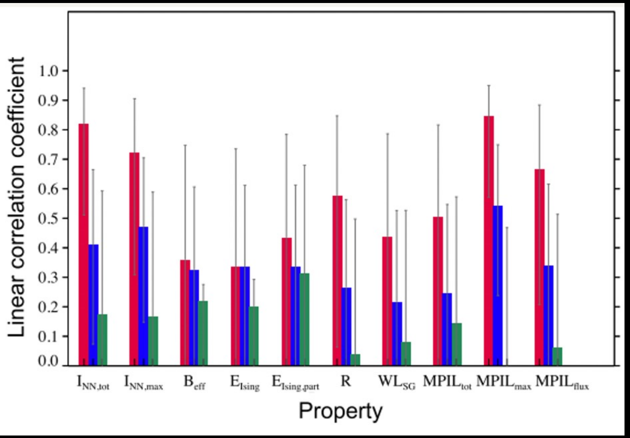


Studying the magnetic field evolution at different lower solar atmosphere heights with promising flare predictors

Proxy parameters	Treshold
Free Magnetic Energy E_{free} (Liokati et al. 2022)	2*10^32 [erg]
Main polarity inversion line MPIL (Mason & Hoeksema 2010)	62 [Mm]
Unsigned magnetic flux of the PIL $logR$ (Schrijver 2007)	5
Effective connected magnetic field B_{eff} (Georgoulis & Rust 2007)	750 [G]
Gradient-weighted length of strong-field PILs WL_{SG} (Falconer et al. 2012)	10^4 [G]
Ising Energy E_{Ising} (Ahmed et al. 2010)	10^4 [1/pixels]
Oscillatory behaviour of magnetic helicity fluxes (Korsós et al. 2022)	Common period



Credits: *Georgoulis et al (2021)*



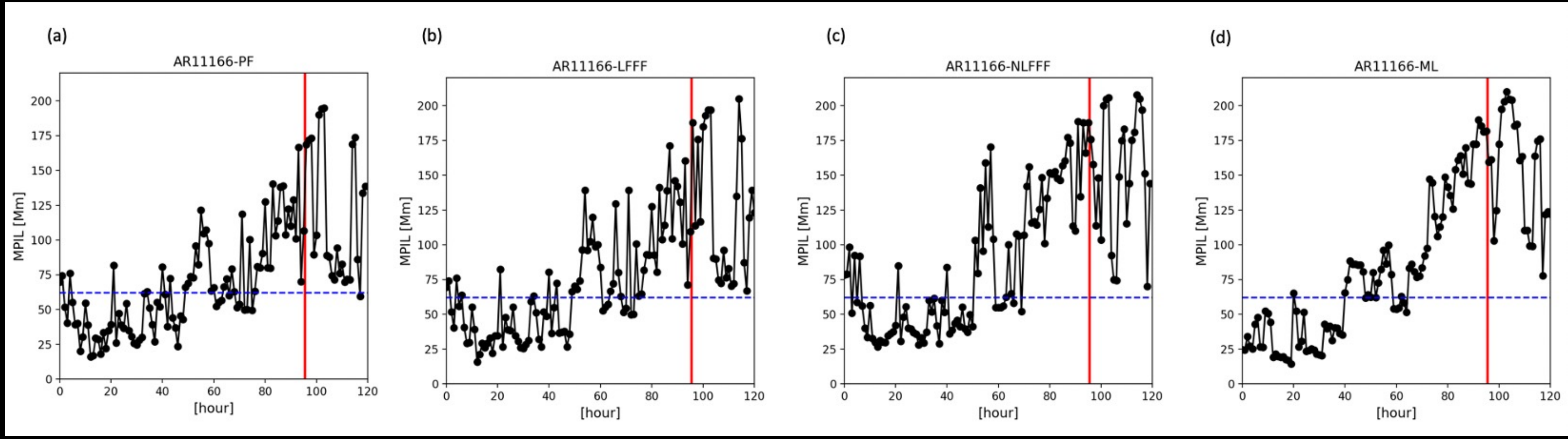
Credits: *Georgoulis et al (2021)*

Selected most promising predictor parameters based on the FLARECAST project.

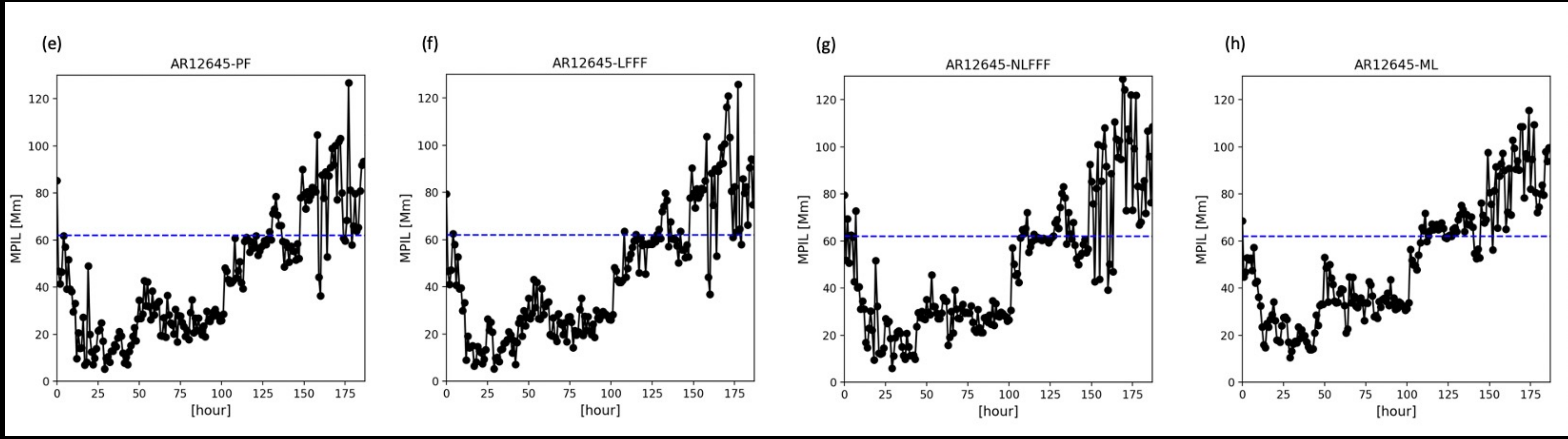
Georgoulis et al. (J. Space Weather Space Clim. Volume 11, 39,37, Agora, 2021)

Studying the magnetic field evolution at different lower solar atmosphere heights with MPIL flare predictors at 0.4 Mm

"furious" Active Region



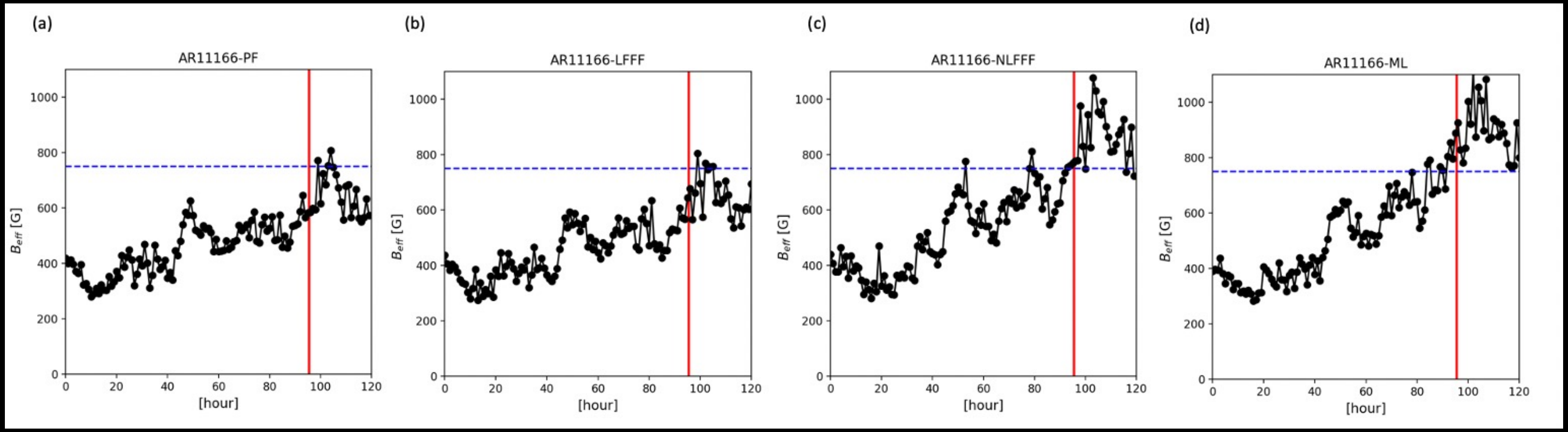
"peaceful" Active Region



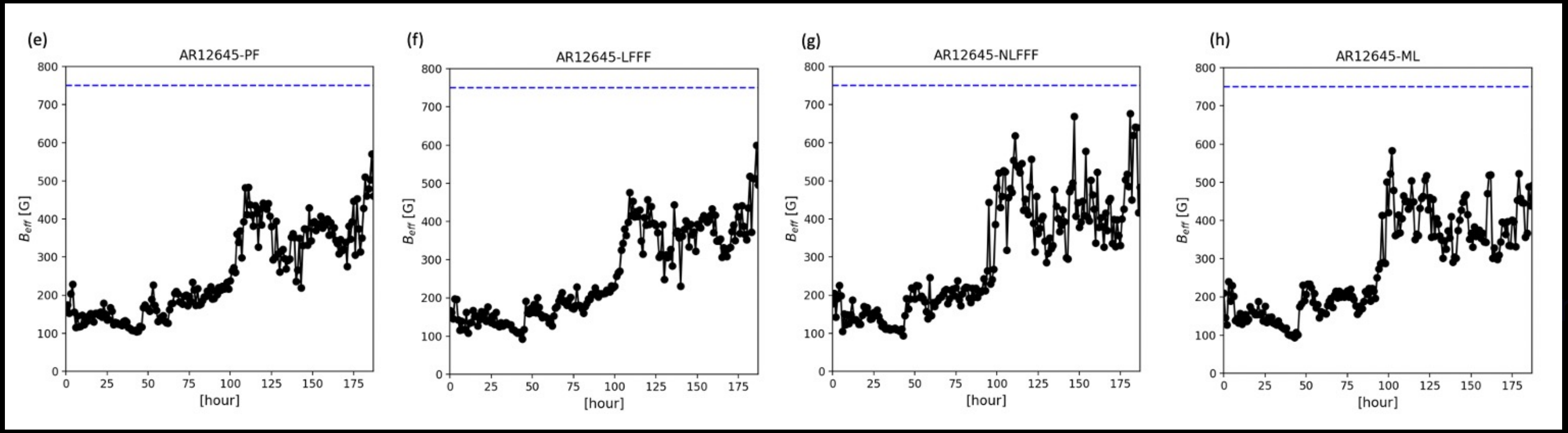
Height [Mm]	$T_{Before MPIL>62Mm}$ [hours]				$MPIL$ [Mm] at the reference time			
	PF	LFFF	NLFFF	ML	PF	LFFF	NLFFF	ML
AR11166								
0	51	50	46	54	179.9	193.3	181.6	163.2
0.36	49	49	45	56	168.6	187.6	175.9	159.3
0.72	50	51	45	45	89.7	91.5	152.7	124.1
1.08	54	53	44	45	64.0	73.4	125.3	123.1
1.44			45	33	59.4	59.4	123.7	125.8
1.8			54	33	57.6	60.2	121.7	171.9
2.16			56	34	34.3	34.2	113.6	170.2
2.52			37	35	33.2	33.2	118.5	168.5
2.88			29	34	22.8	31.7	190.3	166.1
3.24			39	34	15.2	16.7	103.8	125.1
3.6			39	34	15.3	18.4	84.4	115.7
AR12645								
0	71	71	71	75	137.2	139.6	142.4	140.3
0.36	59	59	72	74	93.4	93.5	108.5	95.5
0.72	38	38	54	51	89.0	88.9	79.1	89.0
1.08	39	35	38	40	85.9	85.6	95.7	86.9
1.44	20	35	38	37	83.5	83.1	71.5	72.5
1.8	6	6	36	37	80.8	90.3	71.2	71.9
2.16			39	10	60.0	59.5	70.9	66.8
2.52			38	7	58.0	57.7	72.3	67.2
2.88			4	3	56.2	55.9	72.6	66.8
3.24			5	2	53.2	52.4	72.8	66.4
3.6			4	2	47.0	52.3	73.5	66.2

Studying the magnetic field evolution at different lower solar atmosphere heights with B_{eff} flare predictors at 1.44 Mm

"furious" Active Region



"peaceful" Active Region



Height [Mm]	$T_{BeforeBeff>750G}$ [hours]				B_{eff} at the reference time			
	PF	LFFF	NLFFF	ML	PF	LFFF	NLFFF	ML
AR11166								
0	6	6	7	15	1211.9	1163.1	1188.1	1335.1
0.36	4	4	6	12	854.0	843.3	992.8	1405.7
0.72			6	5	735.7	732.4	895.4	1050.0
1.08			5	5	641.3	654.4	811.8	847.1
1.44			3	4	583.9	677.7	778.3	925.7
1.8				2	553.5	566.3	720.9	780.1
2.16					549.7	563.8	655.3	721.4
2.52					515.8	514.4	622.5	633.3
2.88					440.0	444.5	537.9	704.7
3.24					388.2	393.5	578.9	640.8
3.6					367.1	465.1	588.0	627.7
AR12645								
0					624.1	667.3	633.5	504.4
0.36					622.0	637.6	582.5	595.3
0.72					507.1	446.4	584.1	447.1
1.08					565.2	510.4	594.4	489.9
1.44					460.7	495.4	483.5	491.7
1.8					514.7	470.6	429.5	435.6
2.16					430.6	429.9	385.3	390.0
2.52					358.8	283.3	480.2	392.4
2.88					309.5	316.9	382.4	261.6
3.24					350.9	245.3	284.6	239.1
3.6					228.2	241.9	269.8	253.4

Studying the magnetic field evolution at different lower solar atmosphere heights with promising flare predictors

		AR 11166				AR 12645			
Proxy parameters	**Treshold**								
Free Magnetic Energy E_{free} (Liokati et al. 2022)	2*10^32 [erg]	Yes				n/a			
		Atmospheric height range [Mm]				**Atmospheric height range [Mm]**			
		PF	LFFF	NLFFF	ML	PF	LFFF	NLFFF	ML
Main polarity inversion line MPIL (Mason & Hoeksema 2010)	62 [Mm]	0-1.08	0-1.08	0-3.6	0-3.6	0-1.8	0-1.8	0-3.6	0-3.6
Unsigned magnetic flux of the PIL $logR$ (Schrijver 2007)	5	0	0	0-0.72	0-0.72	n/a	n/a	n/a	n/a
Effective connected magnetic field B_{eff} (Georgoulis & Rust 2007)	750 [G]	0-0.36	0- 0.36	0-1.44	0-1.8	n/a	n/a	n/a	n/a
Gradient-weighted length of strong-field PILs WL_{SG} (Falconer et al. 2012)	10^4 [G]	0-2.16	0-2.16	0-3.6	0-3.6	0-2.52	0-2.52	0-3.6	0-3.6
Ising Energy E_{Ising} (Ahmed et al. 2010)	10^4 [1/pixels]	0-3.6	0-3.6	0-3.6	0-3.6	0-3.6	0-3.6	0-3.6	0-3.6
Oscillatory behaviour of magnetic helicity fluxes (Korsós et al. 2022)	Common period	0-2.16	0-2.16	0-1.8	0-1.8	n/a	n/a	n/a	n/a

Summary

- Morphological/proxy parameters were similarly developed based on the PF, LFFF, NLFFF and ML extrapolation data.

- The PF-LFFF and NLFFF-ML pairs share the same maximum height in the lower solar atmosphere, where the proxies reach their respective threshold levels.

- For prediction purposes, that PF, LFFF, and ML methods are viable options due to their required computation times.
  i) PF is 20-50 mins/observation,
  ii) LFFF is 40-70 mins/observation,
  iii) ML is 60-100 mins/observation,
  iv) NLFFF could be as long as from several hours up to 24 hour,
  depending on the size of the active region.

- However, if one would like to use a more accurate assumption based on non-linear force-free fields then the new neural network-based extrapolation method *Jarolim et al (2023)* is the most recommended one.

- There is merit in broadening the utilization of a combination of distinct prediction parameters in the lower solar atmosphere.