MAGNETIC HELICITY
Marker of solar eruptivity

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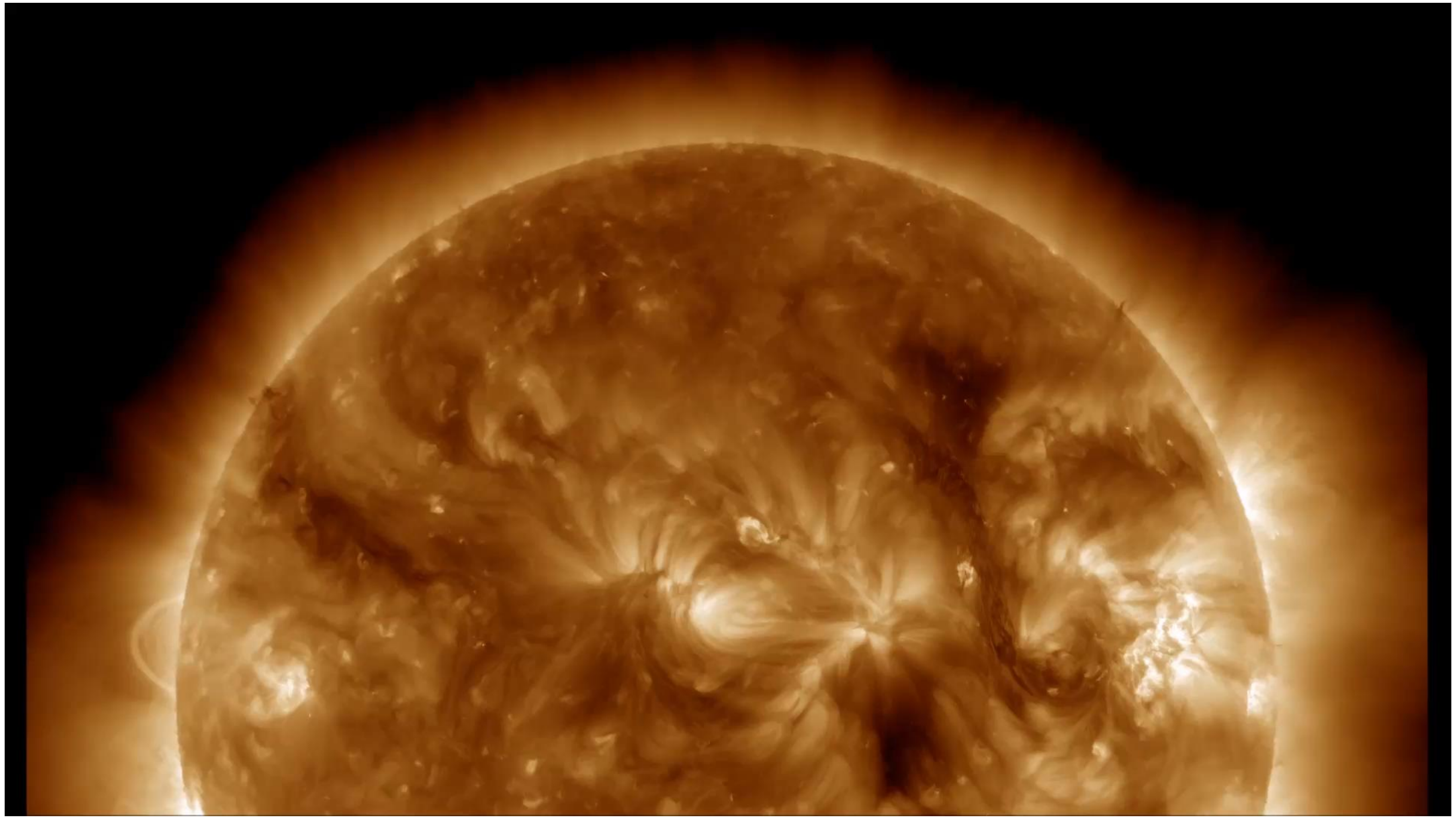
Outline

- Context : prediction of solar flare/eruption
- Magnetic heliciti**es**
- Helicity eruptivity index : results from numerical simulations
- Helicity eruptivity index : results from observations
- Conclusion

Solar eruptions

- Advanced forecast of solar eruption onset is one of the key need in space weather.
  - Surveillance allows very limited anticipation window against impact of electromagnetic emissions and energetic particles

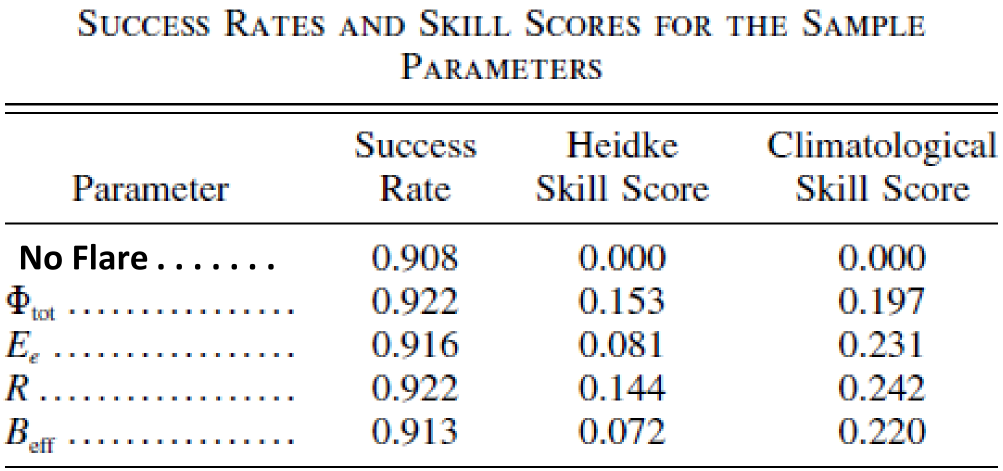


Credit: NASA/SDO

Efficiency of flares & eruptions forecasting

(Crown et al. 12)

- Efforts toward predictions of flares and eruptions in advance has grown in the last decade.
- Multiplication of daily forecasts centers and methods: MET Office, SWPC, SIDC, …
- **Barnes et al. 2016**: comparison of a large number of forecasting methods with a common dataset:
  - **"[…], none of the methods achieves a particularly high skill score. […].Thus there is considerable room for improvement in flare forecasting."**



SUCCESS RATES AND SKILL SCORES FOR THE SAMPLE PARAMETERS

Parameter	Success Rate	Heidke Skill Score	Climatological Skill Score
No Flare	0.908	0.000	0.000
Φ_{tot}	0.922	0.153	0.197
E_e	0.916	0.081	0.231
R	0.922	0.144	0.242
B_{eff}	0.913	0.072	0.220

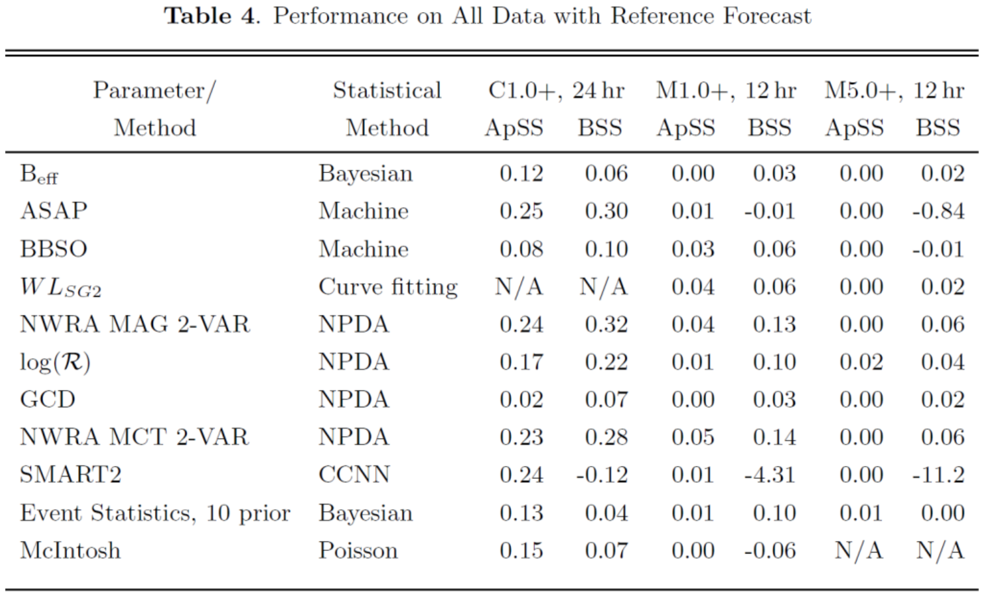


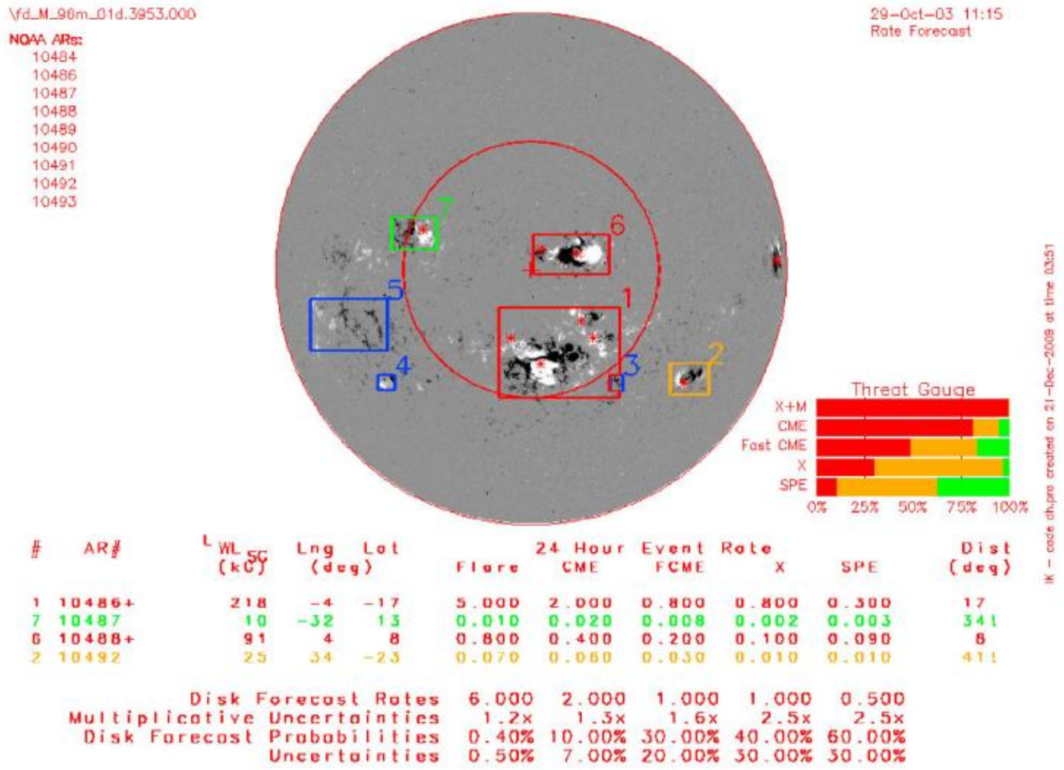
Table 4. Performance on All Data with Reference Forecast

Parameter/ Method	Statistical Method	C1.0+, 24 hr		M1.0+, 12 hr		M5.0+, 12 hr	
		ApSS	BSS	ApSS	BSS	ApSS	BSS
$\mathrm{B_{eff}}$	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_{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 16)

Flares & eruptions forecasting approach

- **Prediction are not based on determinist approach but on an empirical one**:
- Correlations between:
    - Characteristics of ARs: McIntosh class, Mt Wilson magnetic class, PIL length, magnetic properties, …
    - Observed probability for a region with a given characteristic to flare



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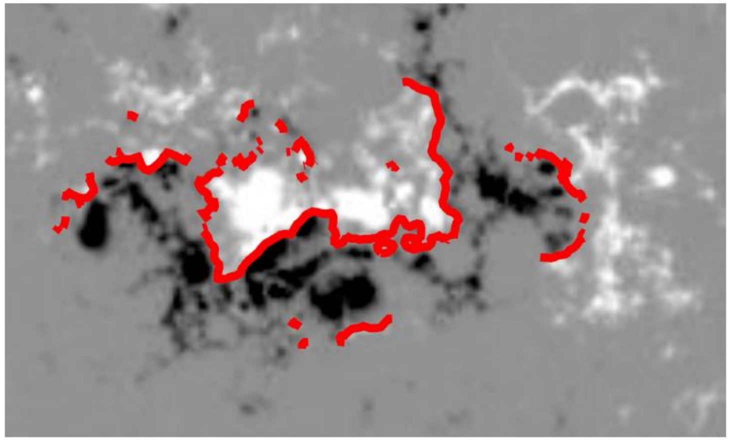
NOAA ARs:
10484
10486
10487
10488
10489
10490
10491
10492
10493

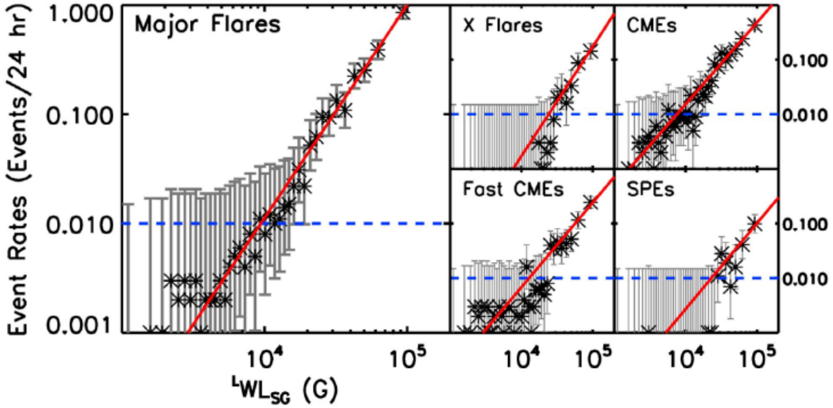
29-Oct-03 11:15
Rate Forecast

#	AR#	$^{L}WL_{SG}$ (kG)	Lng (deg)	Lat	24 Hour Event Rate Flare	CME	FCME	X	SPE	Dist (deg)
1	10486+	218	-4	-17	5.000	2.000	0.800	0.800	0.300	17
7	10487	10	-32	13	0.010	0.020	0.008	0.002	0.003	34!
6	10488+	91	4	8	0.800	0.400	0.200	0.100	0.090	8
2	10492	25	34	-23	0.070	0.060	0.030	0.010	0.010	41!

	Flare	CME	FCME	X	SPE
Disk Forecast Rates	6.000	2.000	1.000	1.000	0.500
Multiplicative Uncertainties	1.2x	1.3x	1.6x	2.5x	2.5x
Disk Forecast Probabilities	0.40%	10.00%	30.00%	40.00%	60.00%
Uncertainties	0.50%	7.00%	20.00%	30.00%	30.00%

(Falconer et al. 11)





Flare Predictions

- Extensive search for eruption proxy: e.g. Leka & Barnes 07, Sinha et al. 22, FLARECAST Project (Manolis et al. 21),
    - Single criteria alone gives very poor prediction : combination of several criterion improves prediction.
- Predictions are only based on necessary conditions
    - No clear physical criterion of sufficient conditions for eruption trigger
- Prediction are only based on 2D photospheric data
- **➔ Need to explore 3D structure of active regions:**
    - **➔ Magnetic Helicity**

(Leka & Barnes 07)

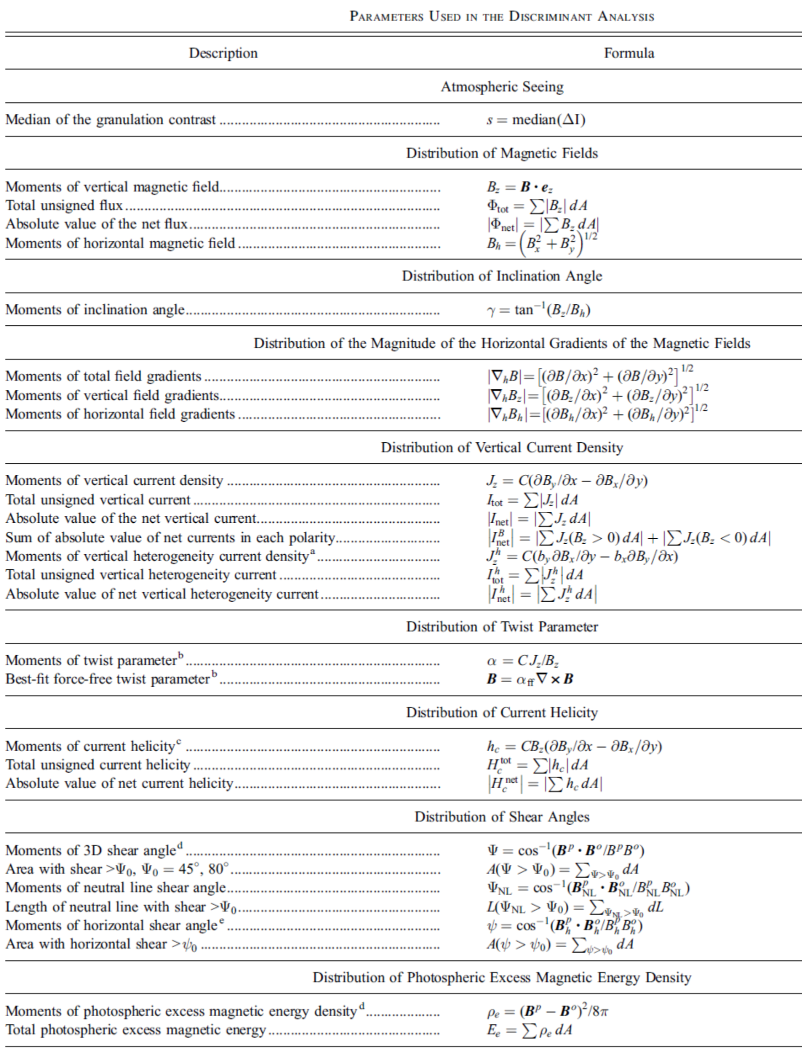
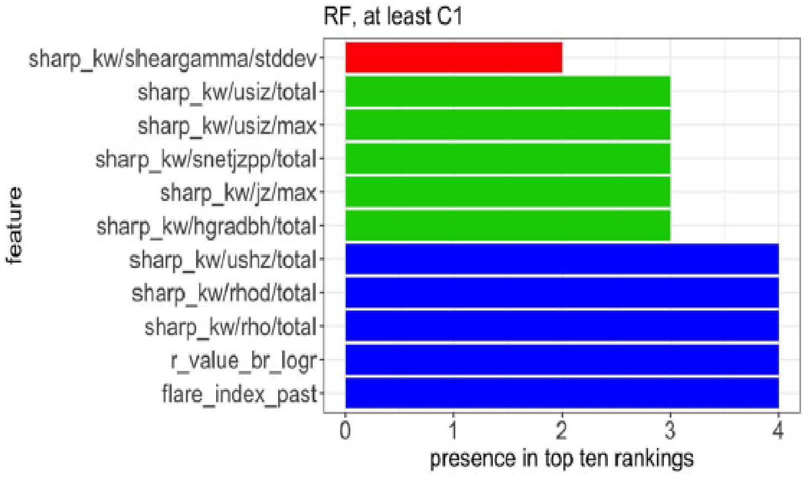


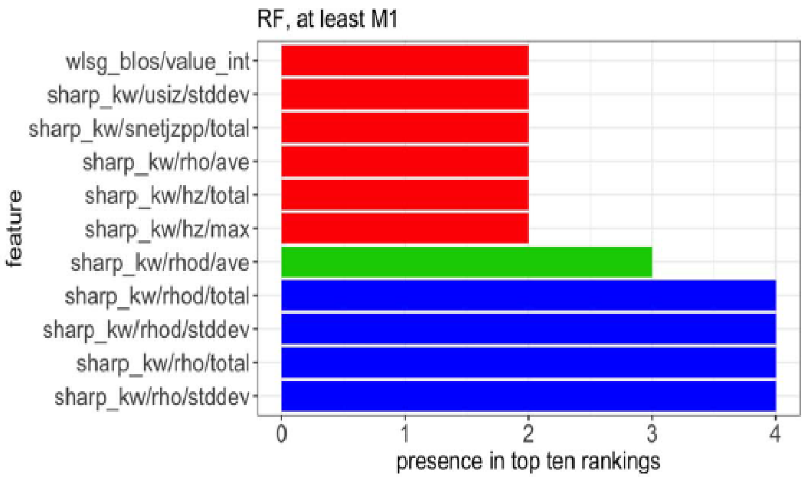
TABLE 1

PARAMETERS USED IN THE DISCRIMINANT ANALYSIS

Description	Formula
Atmospheric Seeing	
Median of the granulation contrast	$s = \mathrm{median}(\Delta I)$
Distribution of Magnetic Fields	
Moments of vertical magnetic field	$B_z = \boldsymbol{B} \cdot \boldsymbol{e}_z$
Total unsigned flux	$\Phi_{\mathrm{tot}} = \sum \lvert B_z \rvert \, dA$
Absolute value of the net flux	$\lvert \Phi_{\mathrm{net}} \rvert = \lvert \sum B_z \, dA \rvert$
Moments of horizontal magnetic field	$B_h = \left(B_x^2 + B_y^2 \right)^{1/2}$
Distribution of Inclination Angle	
Moments of inclination angle	$\gamma = \tan^{-1}(B_z / B_h)$
Distribution of the Magnitude of the Horizontal Gradients of the Magnetic Fields	
Moments of total field gradients	$\lvert \nabla_h B \rvert = \left[(\partial B / \partial x)^2 + (\partial B / \partial y)^2 \right]^{1/2}$
Moments of vertical field gradients	$\lvert \nabla_h B_z \rvert = \left[(\partial B_z / \partial x)^2 + (\partial B_z / \partial y)^2 \right]^{1/2}$
Moments of horizontal field gradients	$\lvert \nabla_h B_h \rvert = \left[(\partial B_h / \partial x)^2 + (\partial B_h / \partial y)^2 \right]^{1/2}$
Distribution of Vertical Current Density	
Moments of vertical current density	$J_z = C(\partial B_y / \partial x - \partial B_x / \partial y)$
Total unsigned vertical current	$I_{\mathrm{tot}} = \sum \lvert J_z \rvert \, dA$
Absolute value of the net vertical current	$\lvert I_{\mathrm{net}} \rvert = \lvert \sum J_z \, dA \rvert$
Sum of absolute value of net currents in each polarity	$\lvert I_{\mathrm{net}}^B \rvert = \lvert \sum J_z(B_z > 0) \, dA \rvert + \lvert \sum J_z(B_z < 0) \, dA \rvert$
Moments of vertical heterogeneity current density[a]	$J_z^h = C(b_y \partial B_x / \partial y - b_x \partial B_y / \partial x)$
Total unsigned vertical heterogeneity current	$I_{\mathrm{tot}}^h = \sum \lvert J_z^h \rvert \, dA$
Absolute value of net vertical heterogeneity current	$\lvert I_{\mathrm{net}}^h \rvert = \lvert \sum J_z^h \, dA \rvert$
Distribution of Twist Parameter	
Moments of twist parameter[b]	$\alpha = C J_z / B_z$
Best-fit force-free twist parameter[b]	$\boldsymbol{B} = \alpha_{\mathrm{ff}} \nabla \times \boldsymbol{B}$
Distribution of Current Helicity	
Moments of current helicity[c]	$h_c = C B_z (\partial B_y / \partial x - \partial B_x / \partial y)$
Total unsigned current helicity	$H_c^{\mathrm{tot}} = \sum \lvert h_c \rvert \, dA$
Absolute value of net current helicity	$\lvert H_c^{\mathrm{net}} \rvert = \lvert \sum h_c \, dA \rvert$
Distribution of Shear Angles	
Moments of 3D shear angle[d]	$\Psi = \cos^{-1}(\boldsymbol{B}^p \cdot \boldsymbol{B}^o / B^p B^o)$
Area with shear $>\Psi_0$, $\Psi_0 = 45°, 80°$	$A(\Psi > \Psi_0) = \sum_{\Psi > \Psi_0} dA$
Moments of neutral line shear angle	$\Psi_{\mathrm{NL}} = \cos^{-1}(\boldsymbol{B}_{\mathrm{NL}}^p \cdot \boldsymbol{B}_{\mathrm{NL}}^o / B_{\mathrm{NL}}^p B_{\mathrm{NL}}^o)$
Length of neutral line with shear $>\Psi_0$	$L(\Psi_{\mathrm{NL}} > \Psi_0) = \sum_{\Psi_{\mathrm{NL}} > \Psi_0} dL$
Moments of horizontal shear angle[e]	$\psi = \cos^{-1}(\boldsymbol{B}_h^p \cdot \boldsymbol{B}_h^o / B_h^p B_h^o)$
Area with horizontal shear $>\psi_0$	$A(\psi > \psi_0) = \sum_{\psi > \psi_0} dA$
Distribution of Photospheric Excess Magnetic Energy Density	
Moments of photospheric excess magnetic energy density[d]	$\rho_e = (\boldsymbol{B}^p - \boldsymbol{B}^o)^2 / 8\pi$
Total photospheric excess magnetic energy	$E_e = \sum \rho_e \, dA$

(Campi et al. 19)





Outline

- Context : prediction of solar flare/eruption
- Magnetic helicitie**S**
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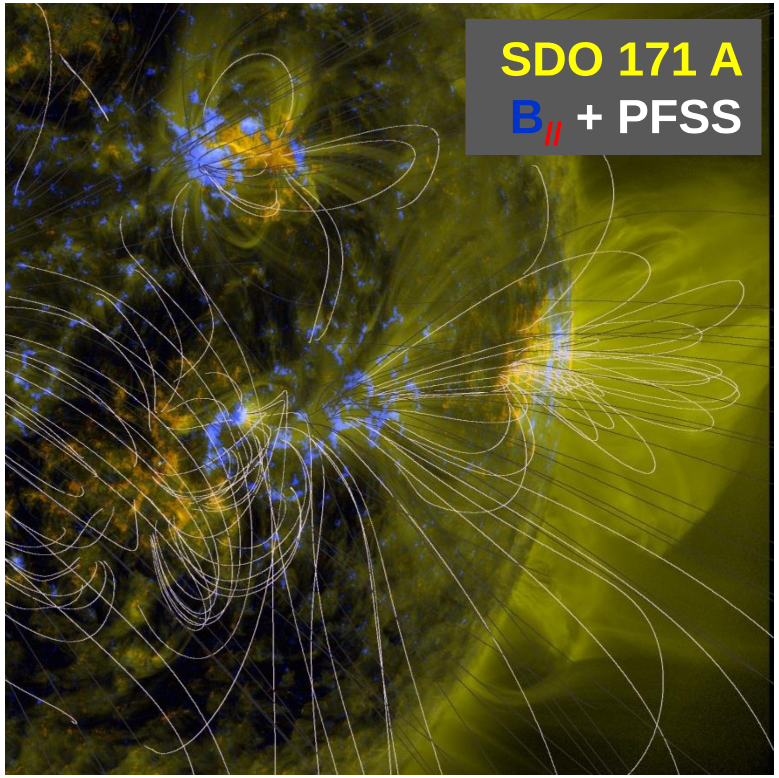
Definition of Magnetic Helicity

- Helicity of the magnetic field in MHD plasmas (**Elsasser 56**)

$$H_{\mathrm{m}} = \int_{\mathrm{V}} A \cdot B \, \mathrm{d}V, \qquad \nabla \times \mathbf{A} = \mathbf{B} \leftarrow$$

Magnetic vector potential

- **Magnetic helicity: signed level of knotedness and twist of magnetic field lines**
- Helicity gauge invariant only for magnetically bounded systems: $\mathbf{B} \cdot \mathbf{dS}\,|_{S}=0$
- Strict definition of magnetic helicity useless for large number of cases



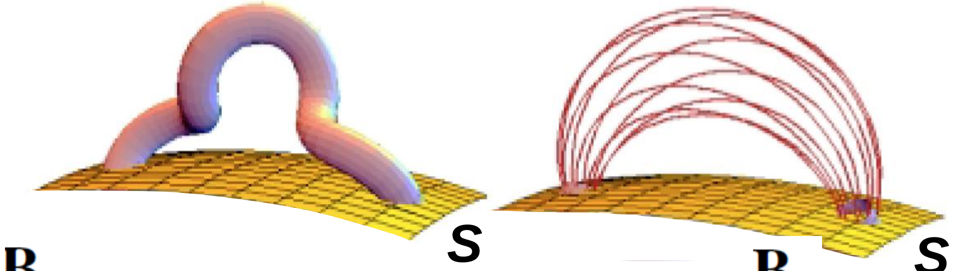
➔ Useful quantity: **Relative Magnetic Helicity:**

helicity of the studied field, **B**, relative to a reference field **(Berger 84, Finn & Antonsen 85)**.

$$H_{\mathcal{V}} = \int_{\mathcal{V}} (\mathbf{A} + \mathbf{A}_{\mathrm{p}}) \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) \; \mathrm{d}\mathcal{V}$$

(Finn & Antonsen 85)

with boundary condition : $(\mathbf{B}_{\mathrm{p}} \cdot \mathrm{d}\mathbf{S})\,|_{\partial\mathcal{V}} = (\mathbf{B} \cdot \mathrm{d}\mathbf{S})\,|_{\partial\mathcal{V}}$



$\mathbf{B}$ **Studied field :**

Reference field . $\mathbf{B}_{\mathrm{p}}$

(usually potential field)

Potential & Non Potential: Field; Energy & Helicity

- **For a given distribution of a magnetic field, B, on the boundary of a domain, there is an <u>unique</u> decomposition of the magnetic field in potential and non-potential field.**

$$B = B_p + B_j$$

- Magnetic Energy is also simply divided

$$E_{mag} = E_p + E_{free}$$

- **Relative magnetic helicity can be decomposed in 2 gauge-invariants quantities (Berger et al. 2003) :**

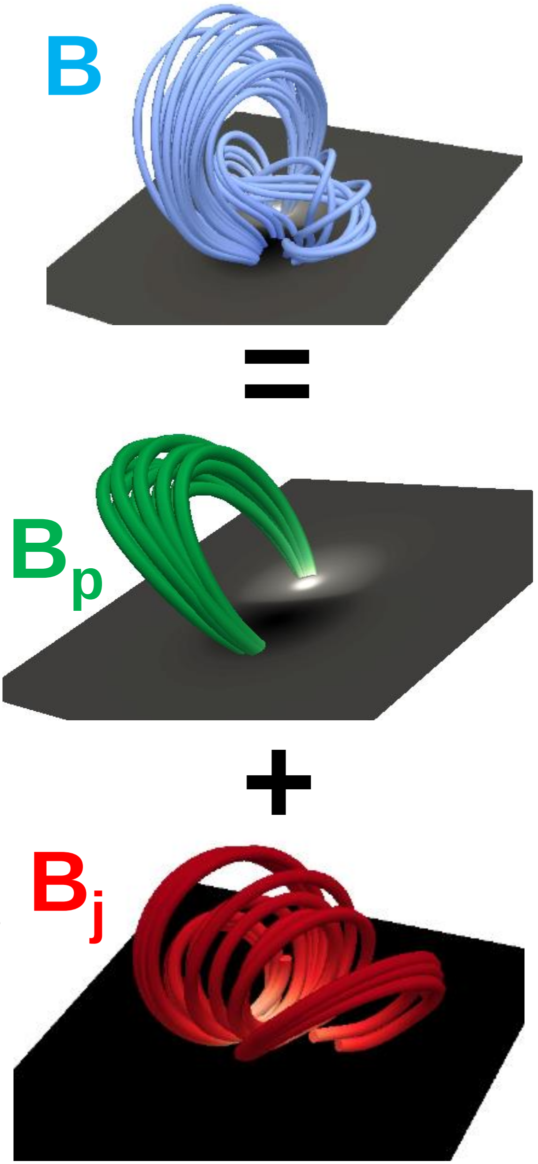
$$H_j = \int_V \boldsymbol{A}_j \cdot \boldsymbol{B}_j \, \mathrm{d}V$$

$$H_{pj} = 2 \int_V \boldsymbol{A}_p \cdot \boldsymbol{B}_j \, \mathrm{d}V,$$

$$H_v = H_{pj} + H_j$$

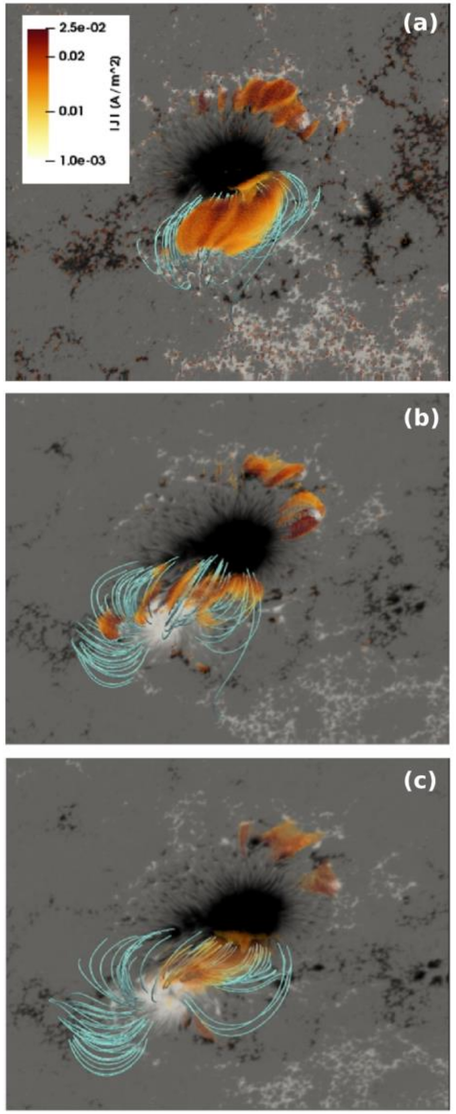
  - **H_j = magnetic helicity of the current-carrying field B_j**
  - H_{pj} = volume-threading helicity, between potential and current-carrying fields

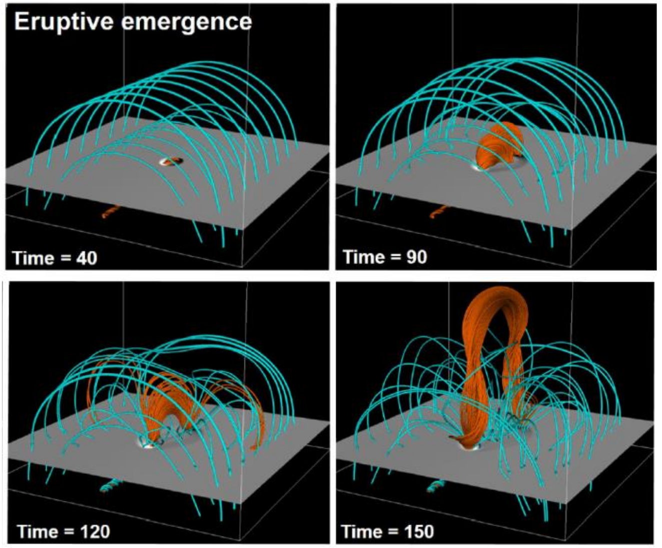
Helicity Eruptivity Index: H_j/H_V



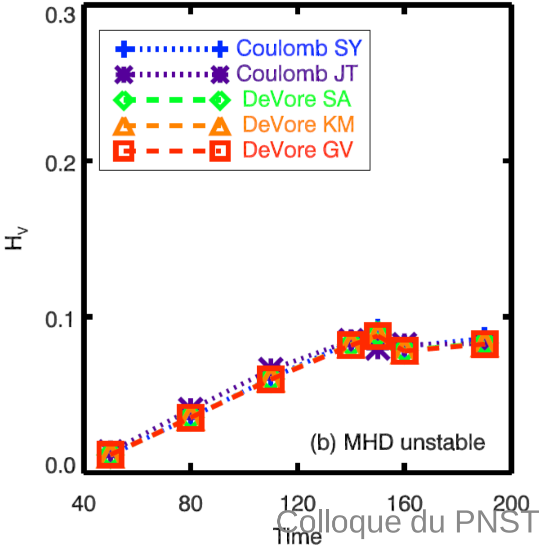
Benchmarking of relative helicity estimation methods

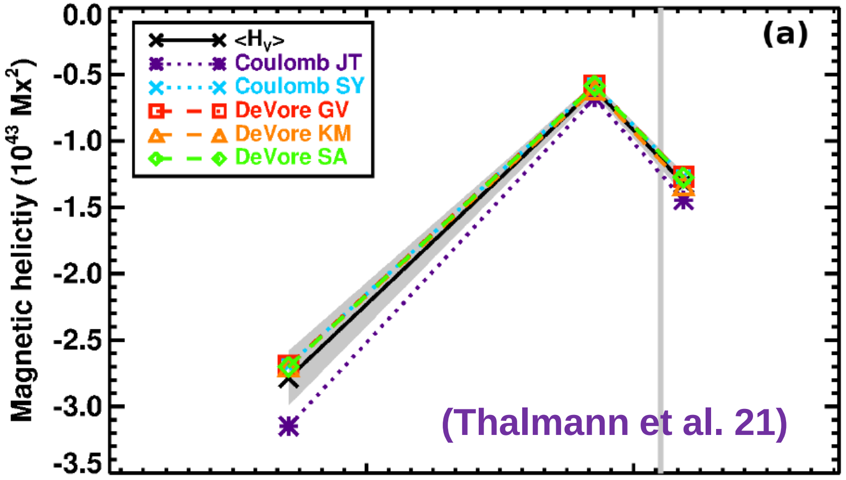
- **Benchmarking of measurment methods performed by ISSI team on "Helicity estimations in models and observations"**
  - **Valori et al. 16, Guo et al. 17, Thalman et al. 21, Pariat et al. in prep.**
- Numerous tests: sensibility to resolution, twist, solenoidality, data types (semi-analytical, numerical, observational) e.g.
  - Flux emergence simulations **(Leake et al. 13, 14)**
  - NLFFF 3D coronal reconstruction **(Schrijver et al. 08)**
- **Methods perform very consistently when B sufficiently solenoidal**





(Valori et al. 16)





(Thalmann et al. 21)

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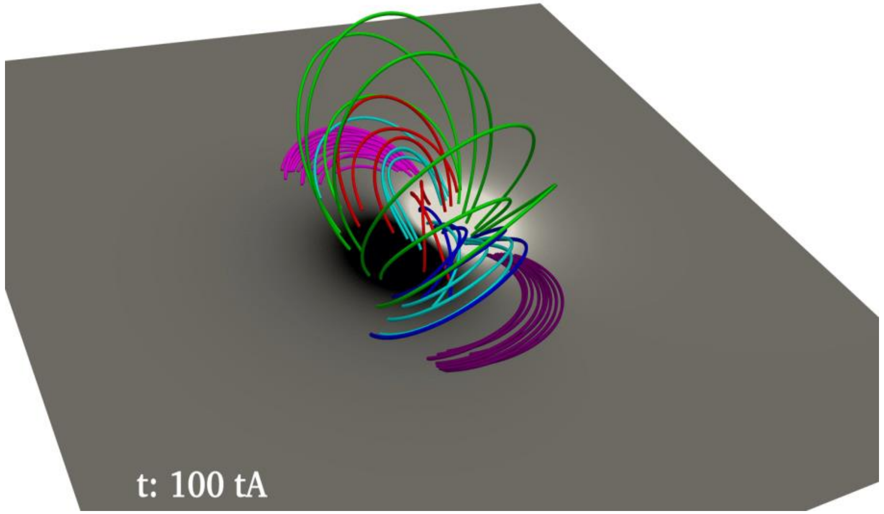
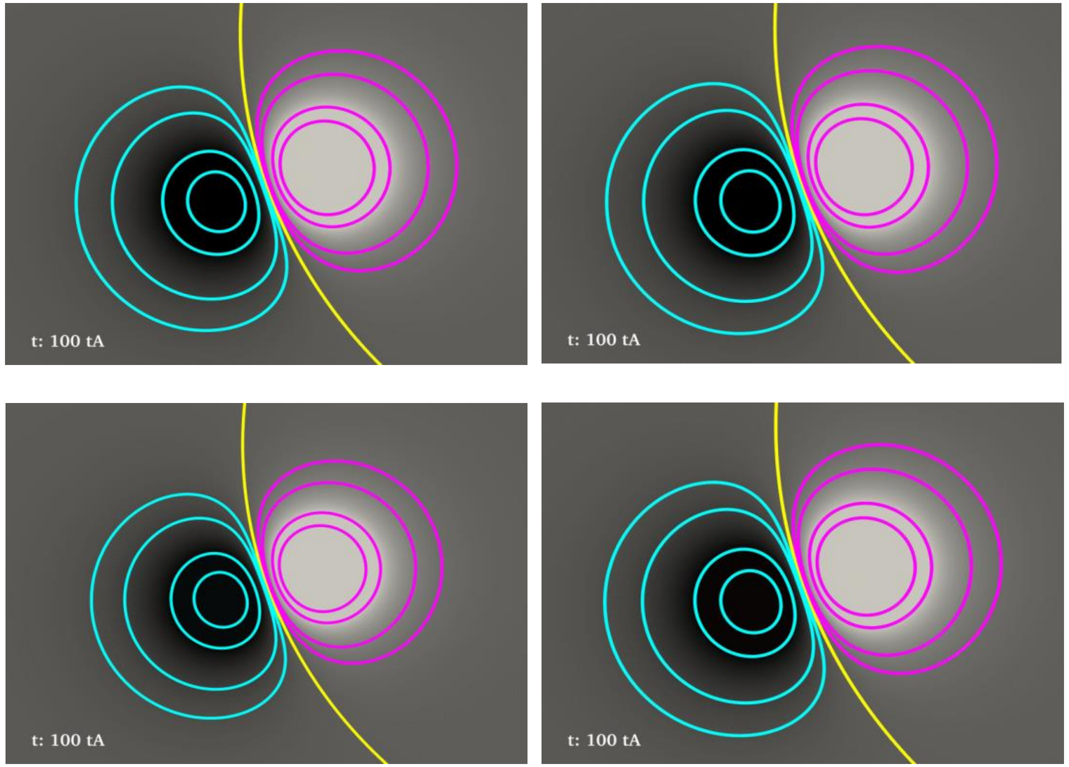
Line-tied 3D MHD parametric simulations

- **Parametric line-tied boundary driven 3D MHD simulations of solar eruptions** **(Zuccarello et al. 15)**:
  - 3D visco-resitive MHD simulations; Ohm-MPI code **(Aulanier et al. 10, Zuccarello et al. 16)**
  - Initial potential/stable config. ; quasi-steadly injection of energy/helicity ➔ eventual trigger of eruption
- **4 different line-tied boundary driving patterns** with different: shear around the PIL & magnetic flux dispersion + 1 non-eruptive control case (diffusion)

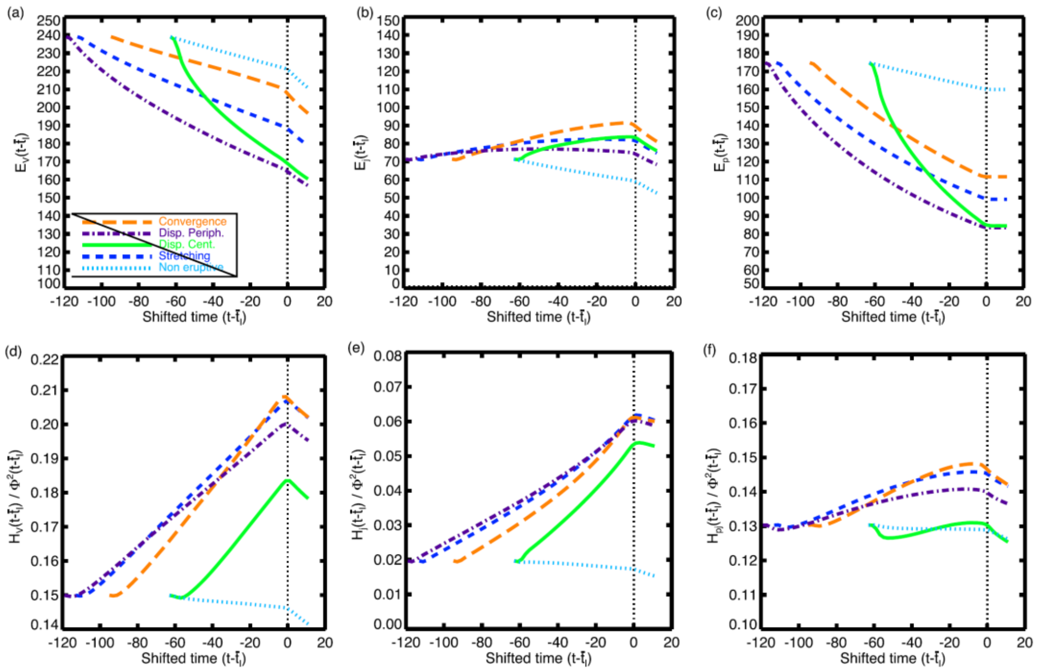
(Aulanier et al. 10, Zuccarello et al. 15)



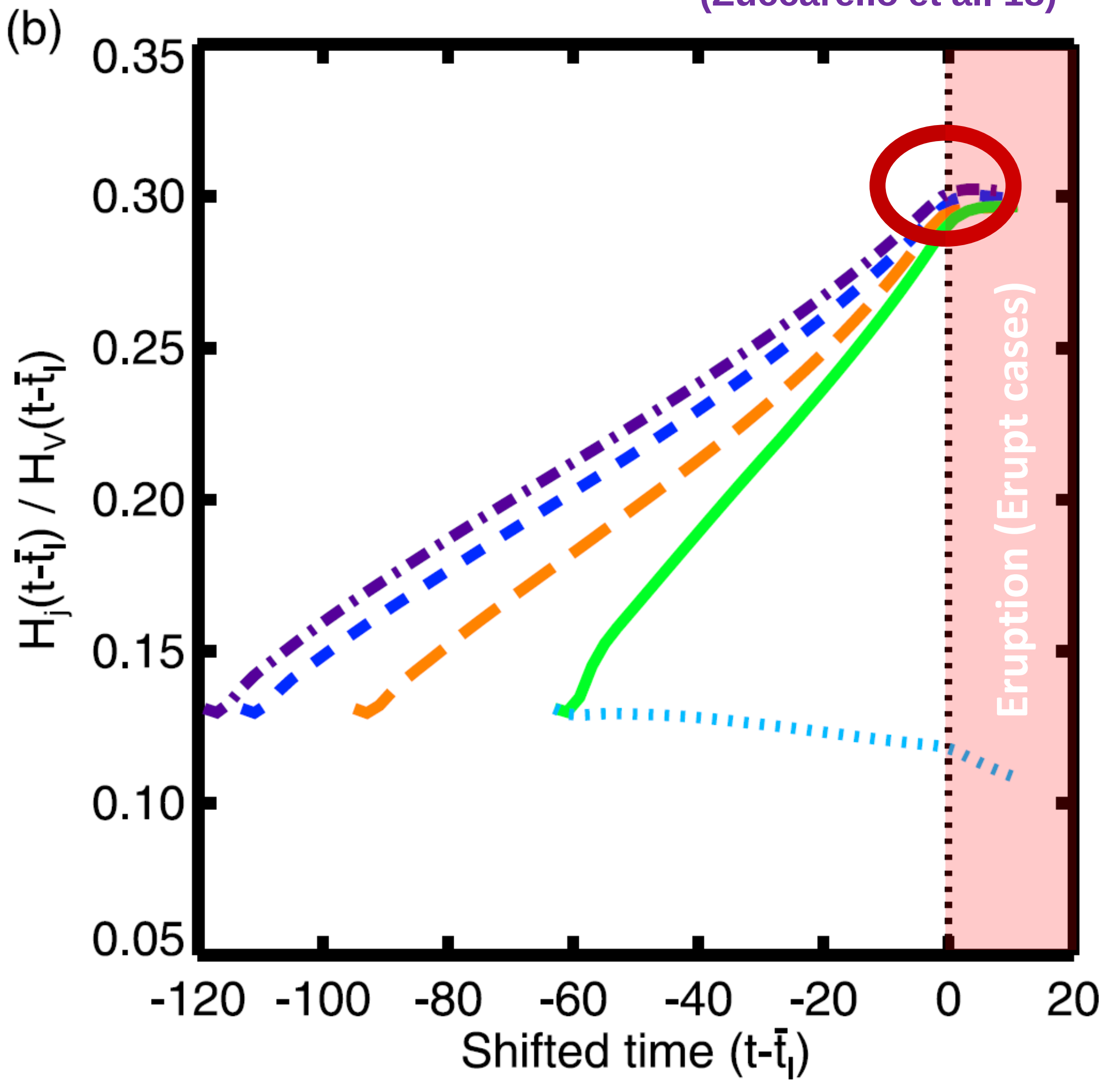


Helicity Eruptivity Index

- **Despites different boundary drivers and t_{erupt}, eruptions are triggered when an Helicity Eruptivity Index reaches a threshold:**
  - <4% dispersion (within measurement precision)
  - Unique quantity with such behavior

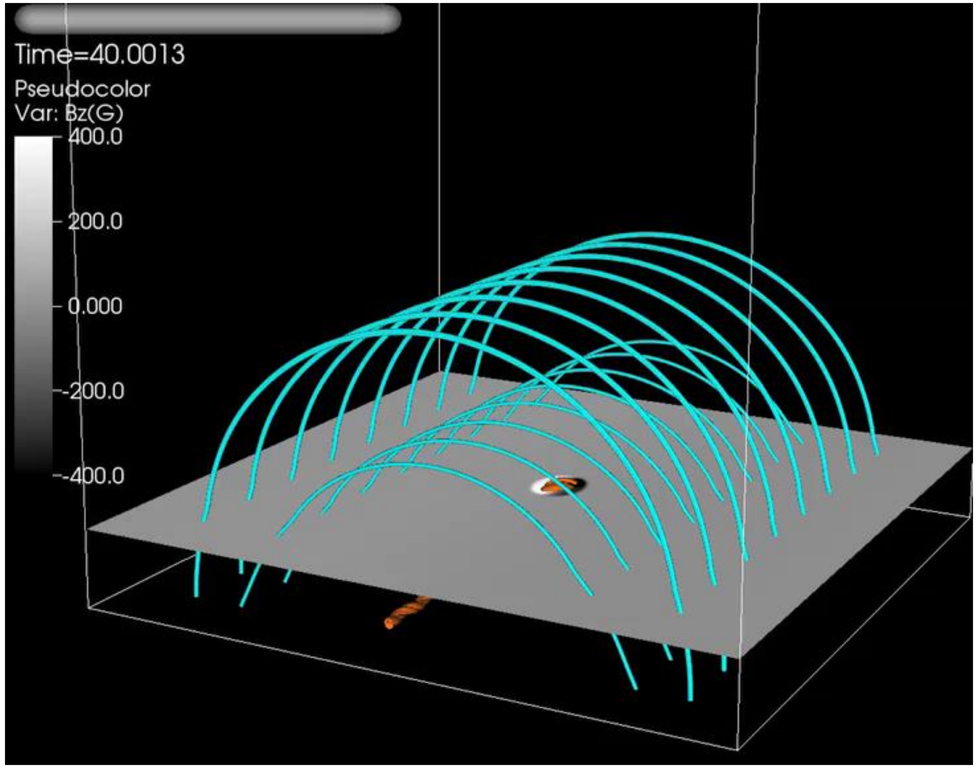


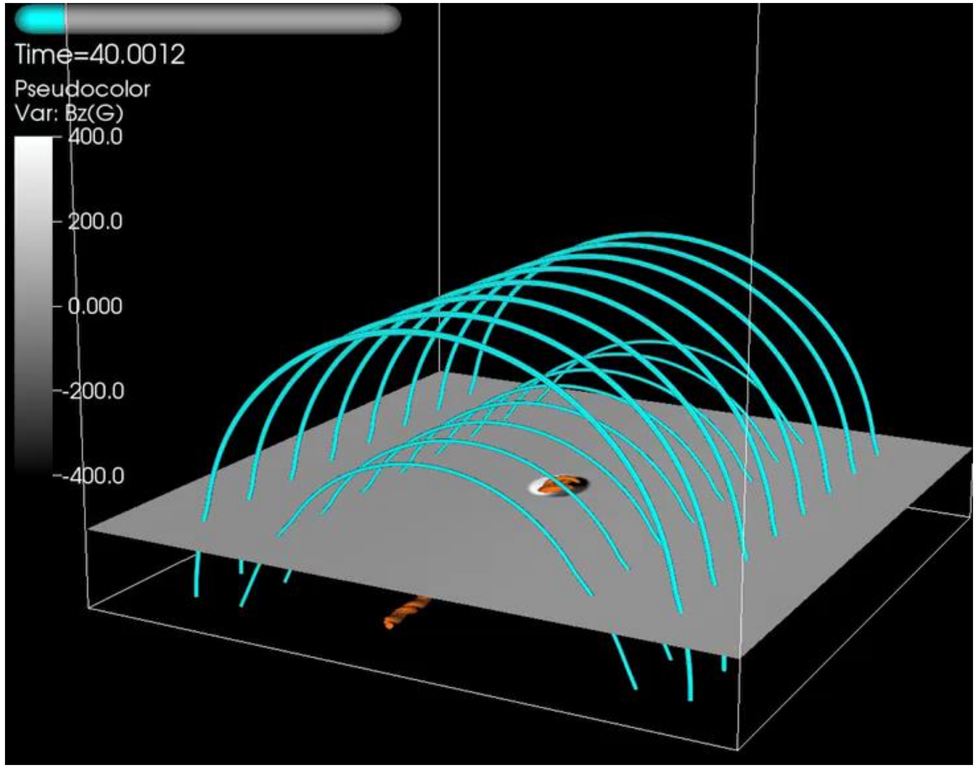
(Zuccarello et al. 18)



Parametric flux emergence simulations

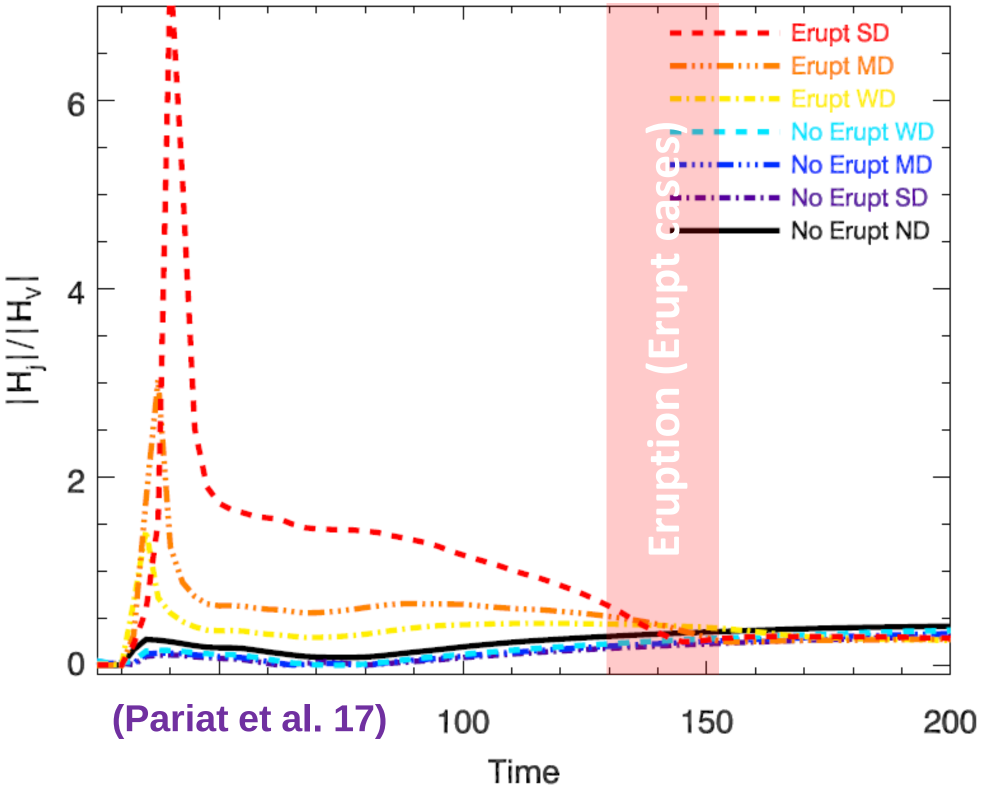
- **7 flux emergence simulations leading either to eruptive or non-eruptive dynamics (Leake et al. 2013, 2014)**
- Deterministically stable/instable: Stability of system given by initial conditions
  - **No helicity instability threshold is expected**
  - **Is there an advance signature of eruptivity?**



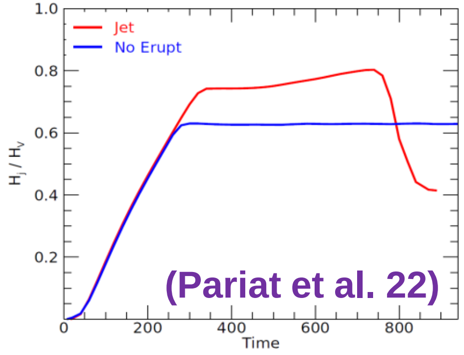


(Leake et al. 13, 14)

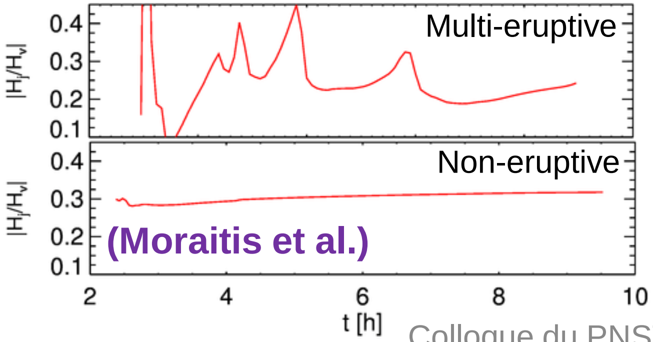
$|H_j|/|H_V|$: excellent eruptivity indicators



(Pariat et al. 17)



(Pariat et al. 22)



(Moraitis et al.)

- **$|H_j|/|H_V|$ appears as an excellent eruptivity predictor of these flux emergence simulation**
  - Highest value for the eruptive simulations in the pre-eruptive phase
  - Eruptive and non-eruptive simulations have similar values in post-eruption phase

- **Results now confirmed in several 3D MHD numerical experiments of active events**
  - Eruptions **(Zuccarello et al. 18)**
  - Flux emergence **(Pariat et al. 17, Moraitis et al. 14)**
  - Coronal jets **(Linan et al. 18, Pariat et al. 22 in prep)**
  - 17 different simulations, using 3 different 3D MHD numerical codes
  - 5 different mag. config. inducing 10 eruptive & 7 stable systems

- **What about observations?**

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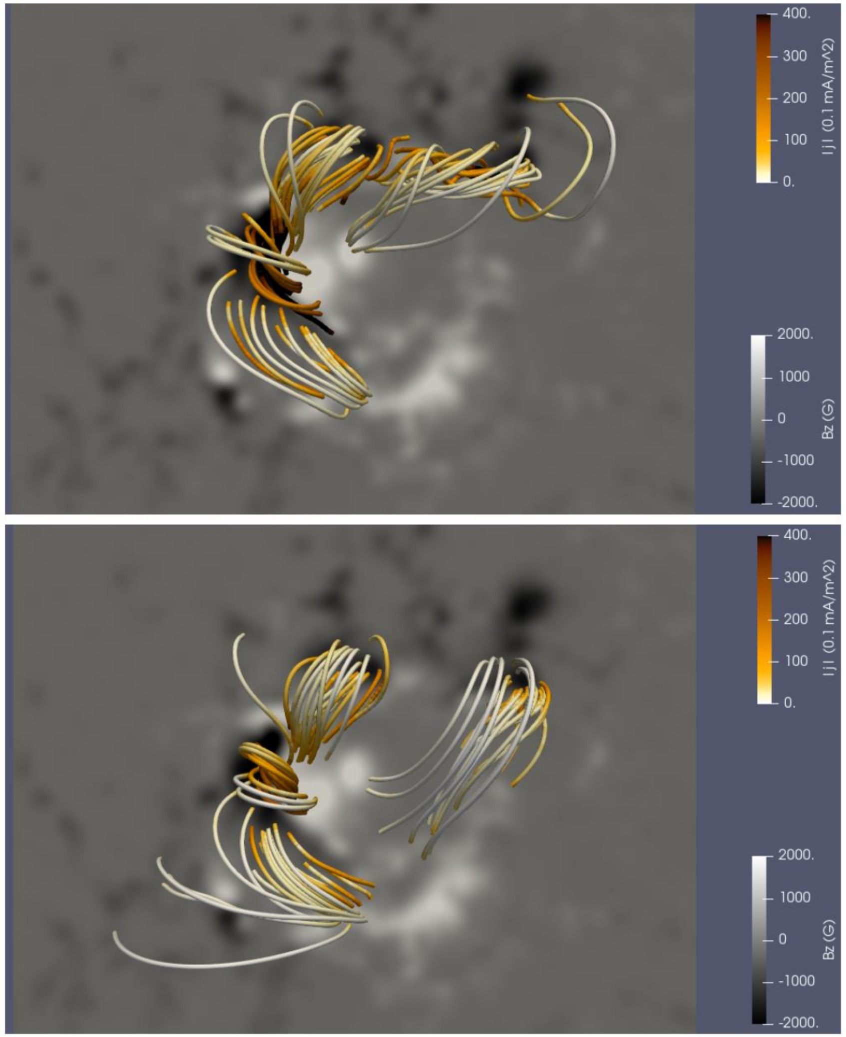
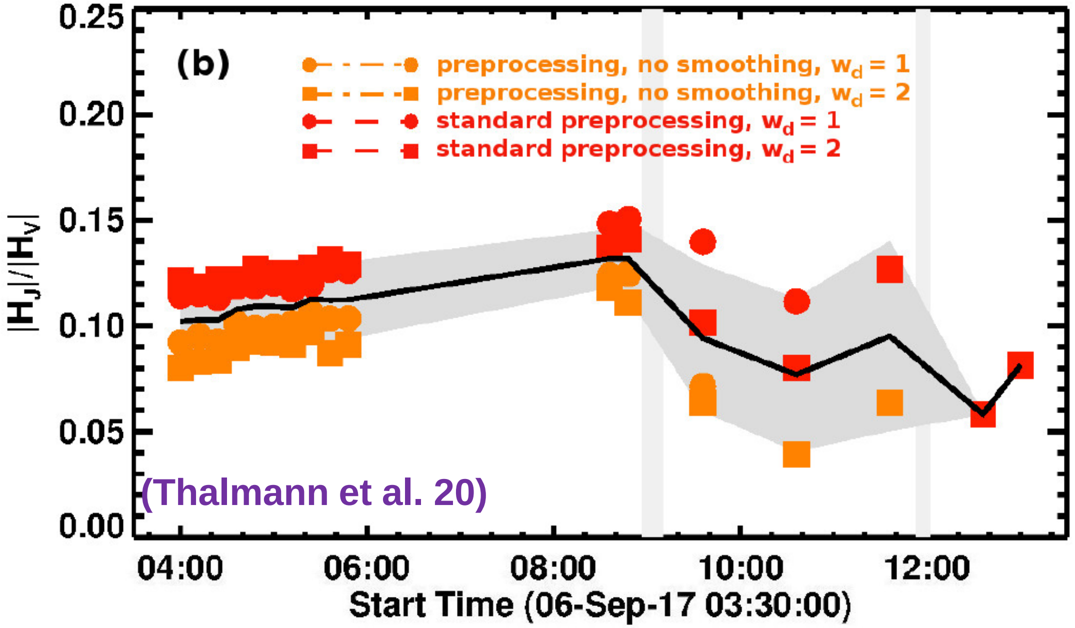
Measuring magnetic helicity in observations

- **Helicity eruptivity index estimations requires magnetic field extrapolation of the 3D coronal field.**
- 3D coronal magnetic field reconstruction are complex
  - Requires information about J_z vs 180° ambiguity in obs.
  - numerous assumptions, model-dependent,
  - ➔ No unique solutions
- **➔ No absolute determination of the helicity content!**



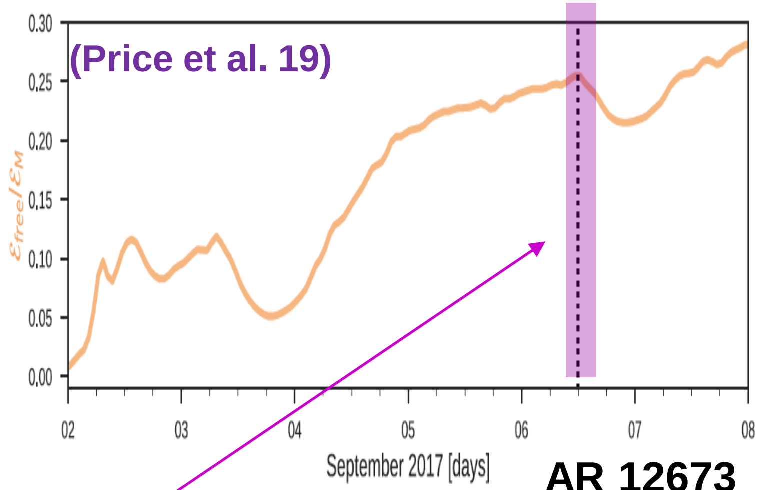
(Moraitis et al. 19)



(Thalmann et al. 20)

Helicity and eruptive flares

- **Preliminary observational studies indicates that Helicity Eruptivity Index shows pronounced eruption-related link**
  - **e.g. Moraitis et al. 19, Thalmann et al. 19b, Price et al. 19**
- However there is also: peaks of Hj/Hv without activity & some CME-less flares with no peak of the helicity index



(Price et al. 19)

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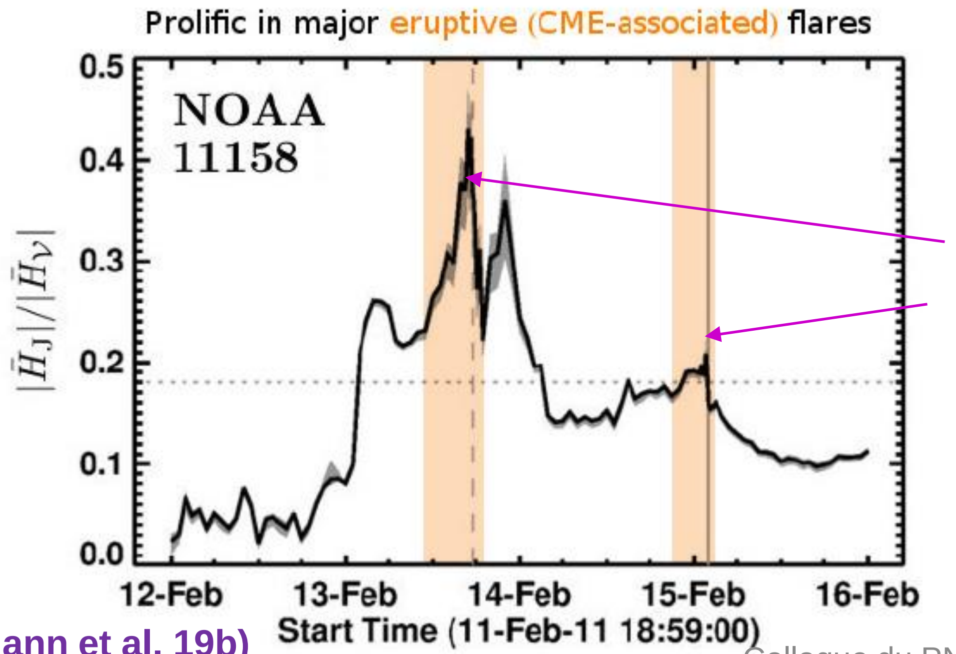
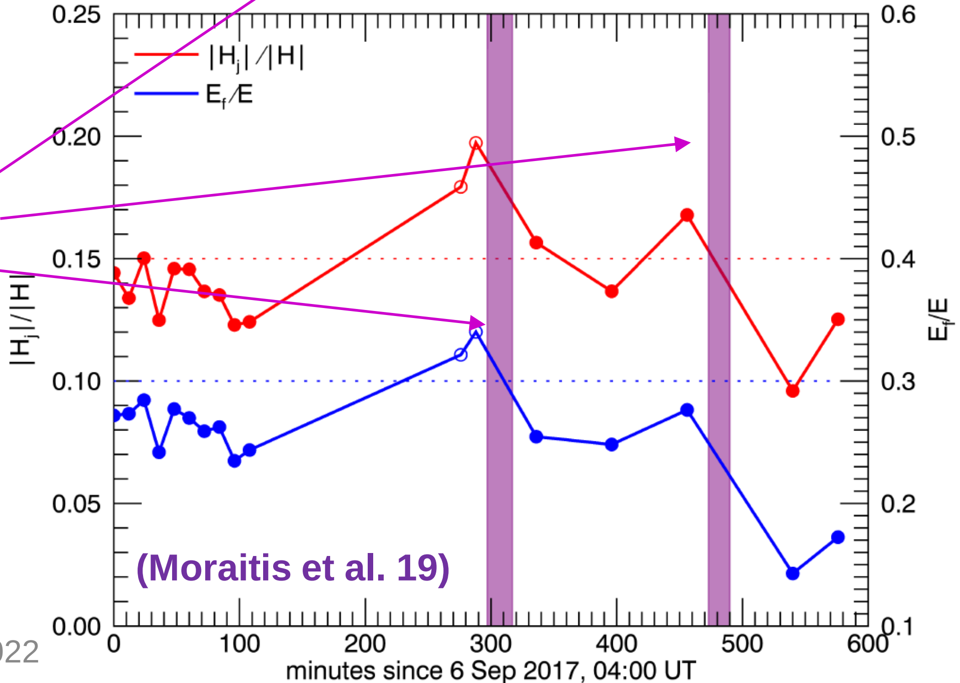


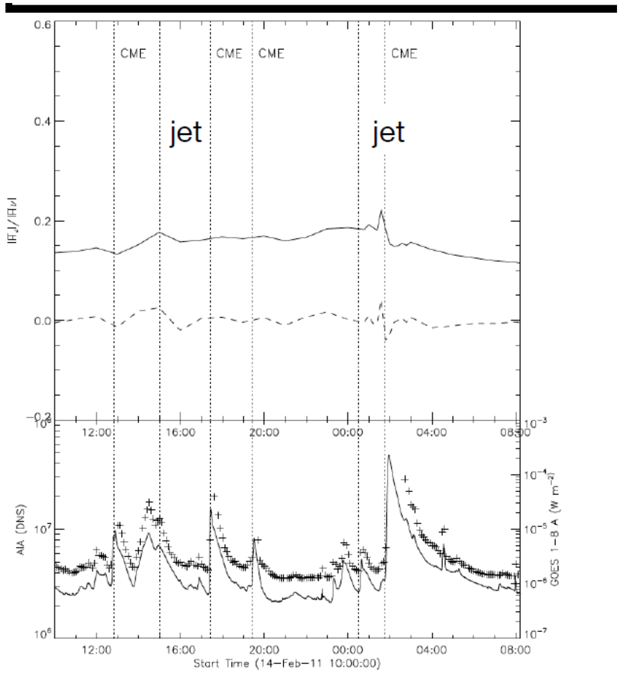
(Thalmann et al. 19b)

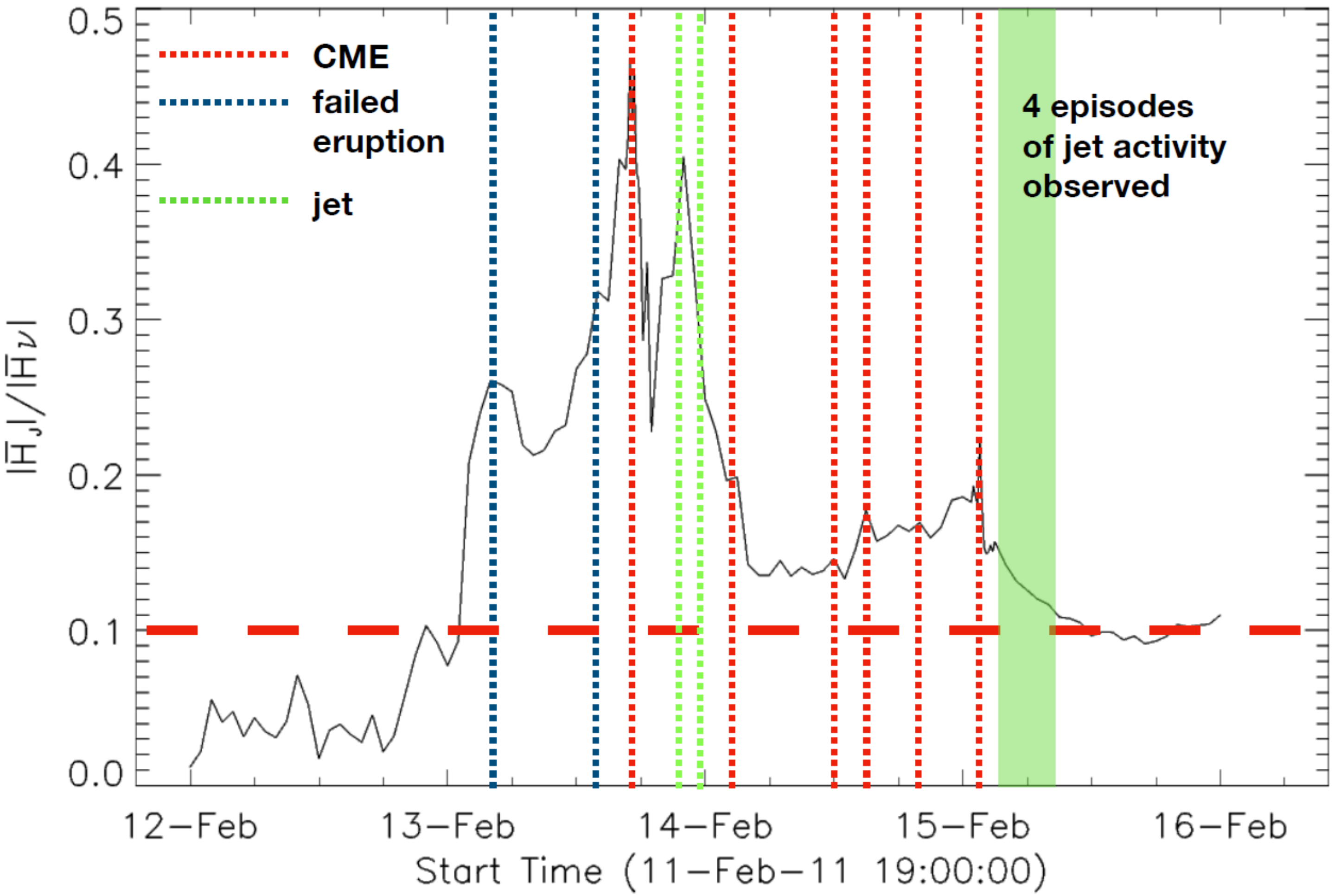
Major eruptions (>M class)



(Moraitis et al. 19)

- **Detailed observational studies confirm link between helicity eruptivity index and activity**
  Green et al. in prep.
  - Still peaks of Hj/Hv without activity & some CME-less flares with no peak of the helicity index





(Green et al. 22, in revision)

Outline

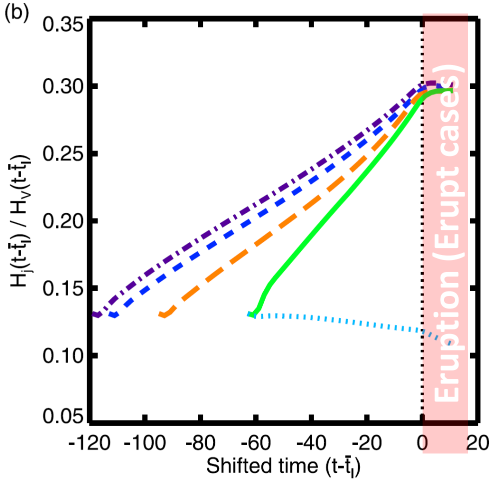
- Context : prediction of solar flare/eruption
- Magnetic helicitie**S**
- Helicity eruptivity index : results from numerical simulations
- Helicity eruptivity index : results from observations
- Conclusion

Helicity & Eruptivity: conclusions

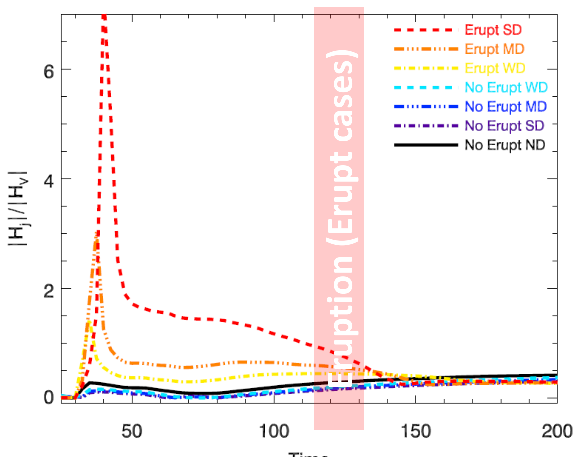
- **The helicity-based eruptivity index, i.e. the ratio |Hj|/|Hv| is a promising marker of the eruptive state of solar magnetic systems**
  - Clear discriminating role noted in numerical experiments of solar-like active
  - Preliminary observational results are compatible

- ➔ needs to be fully validated against observational results:
  - statically significant
  - <u>of a sufficiently good quality!</u>

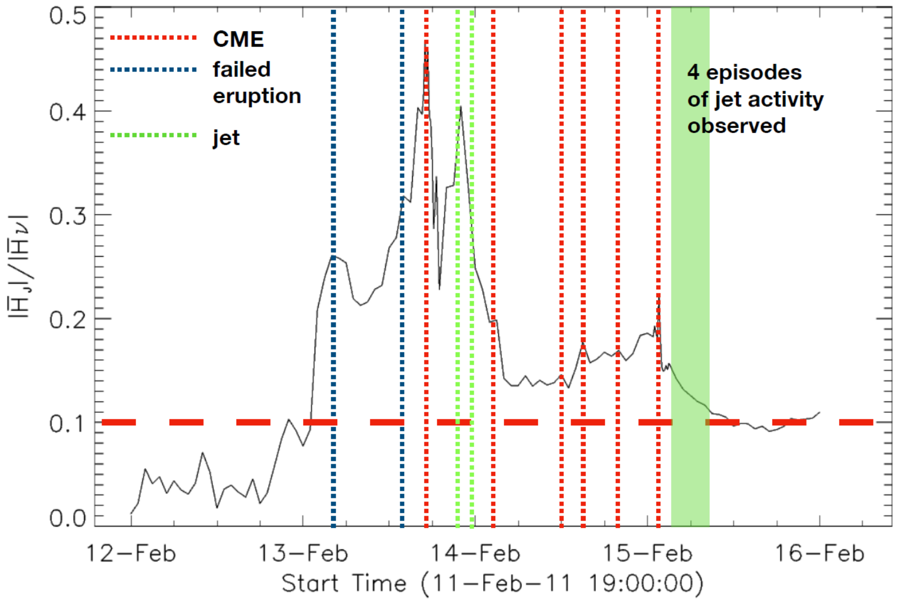
- **Solar Orbiter/PHI shall help to provide the next generation of magnetic field measurements (resolution ; stereoscopy)**



(Zuccarello et al. 18)



(Pariat et al. 17)



(Green et al. 22, in revision)