Helicity 2020 : online advanced study program on helicities in astrophysics and beyond

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Magnetic helicity as a marker of solar eruptivity: the helicity-based eruptivity index

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Outline

- **Context: eruption prediction of solar eruptions/flares**

- Magnetic helicity and its estimation
  - Relative magnetic helicity and its properties
  - Helicity-based eruptivity index: definition
  - Measuring Helicity

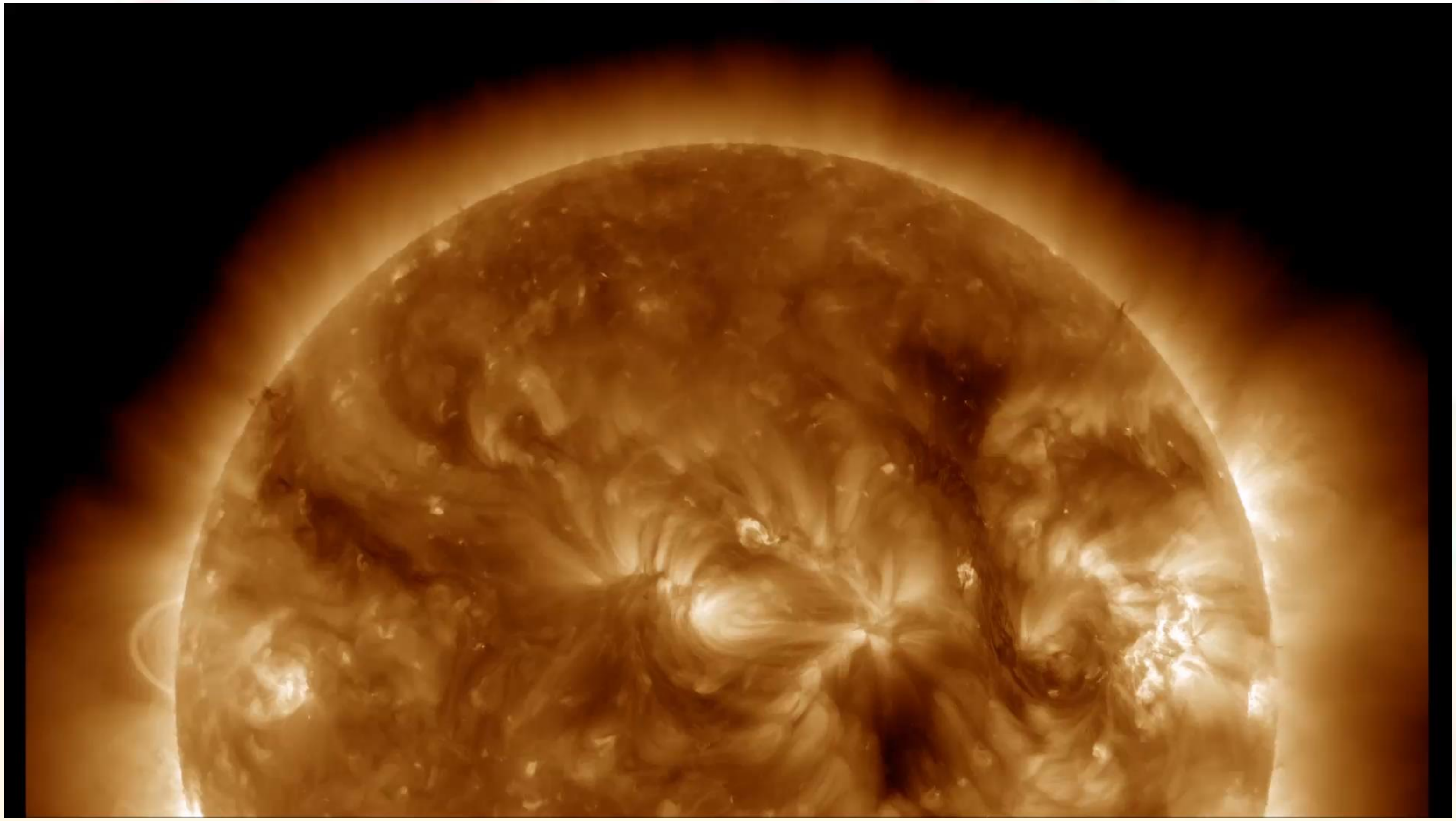
- Helicity-based eruptivity index in numerical experiments
  - Line-tied eruptive simulations
  - Flux emergence simulations

- Helicity-based eruptivity index in observations
  - Helicity measurements from observations
  - Preliminary results

- Conclusions

Solar eruptions

- Advanced forecast of onset or solar flares/eruptions 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

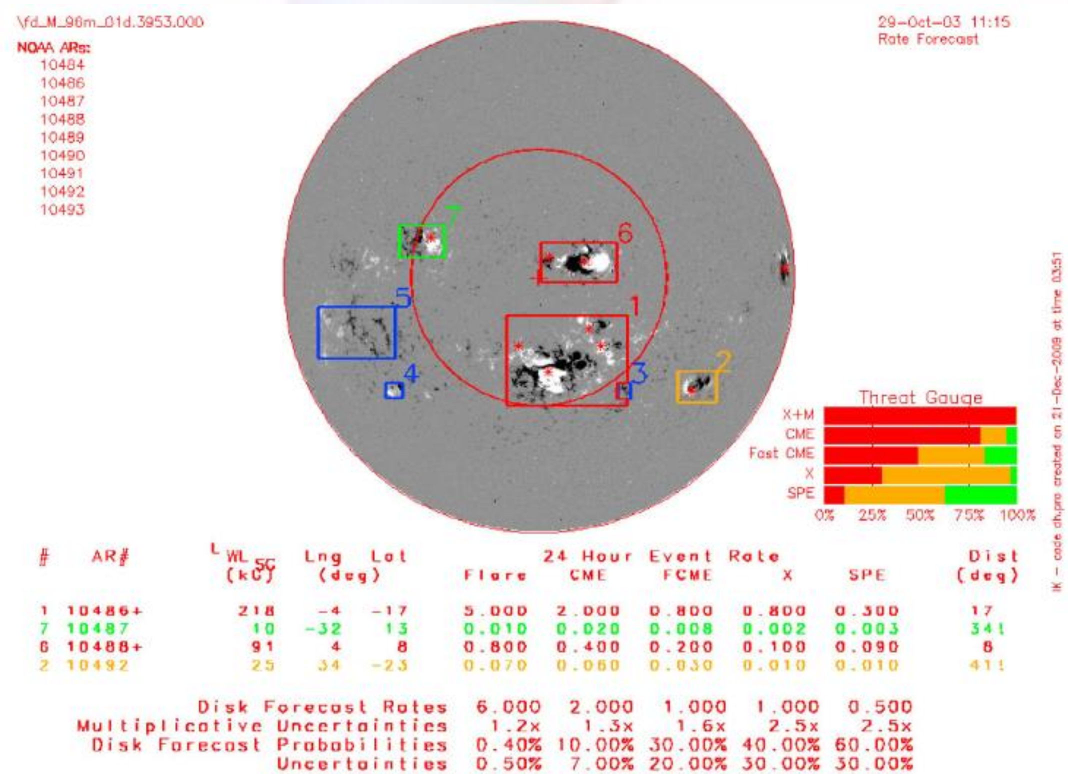
Table 4. Performance on All Data with Reference Forecast

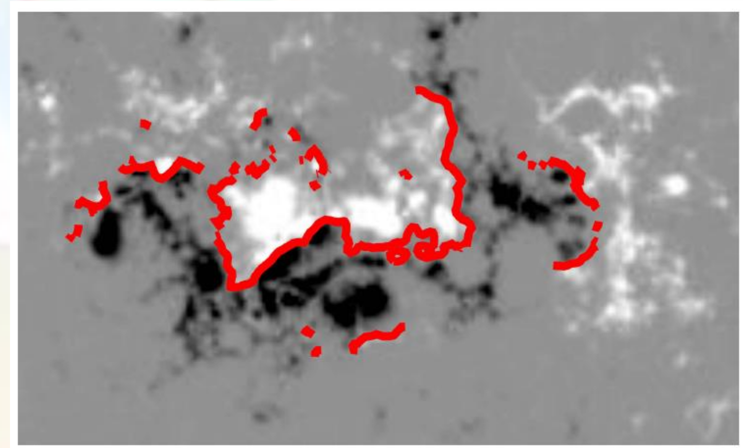
Parameter/ Method	Statistical Method	C1.0+, 24 hr ApSS	C1.0+, 24 hr BSS	M1.0+, 12 hr ApSS	M1.0+, 12 hr BSS	M5.0+, 12 hr ApSS	M5.0+, 12 hr BSS
B_{eff}	Bayesian	0.12	0.06	0.00	0.03	0.00	0.02
ASAP	Machine	0.25	0.30	0.01	-0.01	0.00	-0.84
BBSO	Machine	0.08	0.10	0.03	0.06	0.00	-0.01
WL_{SG2}	Curve fitting	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

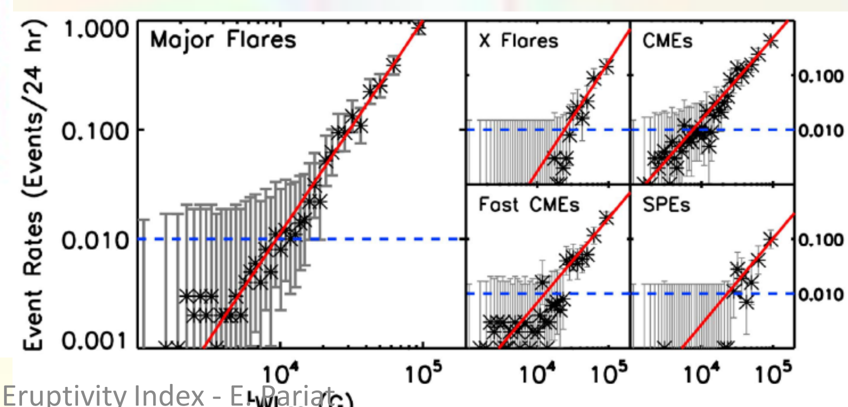
(Barnes et al 16)

Flares & eruptions forecasting approach

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





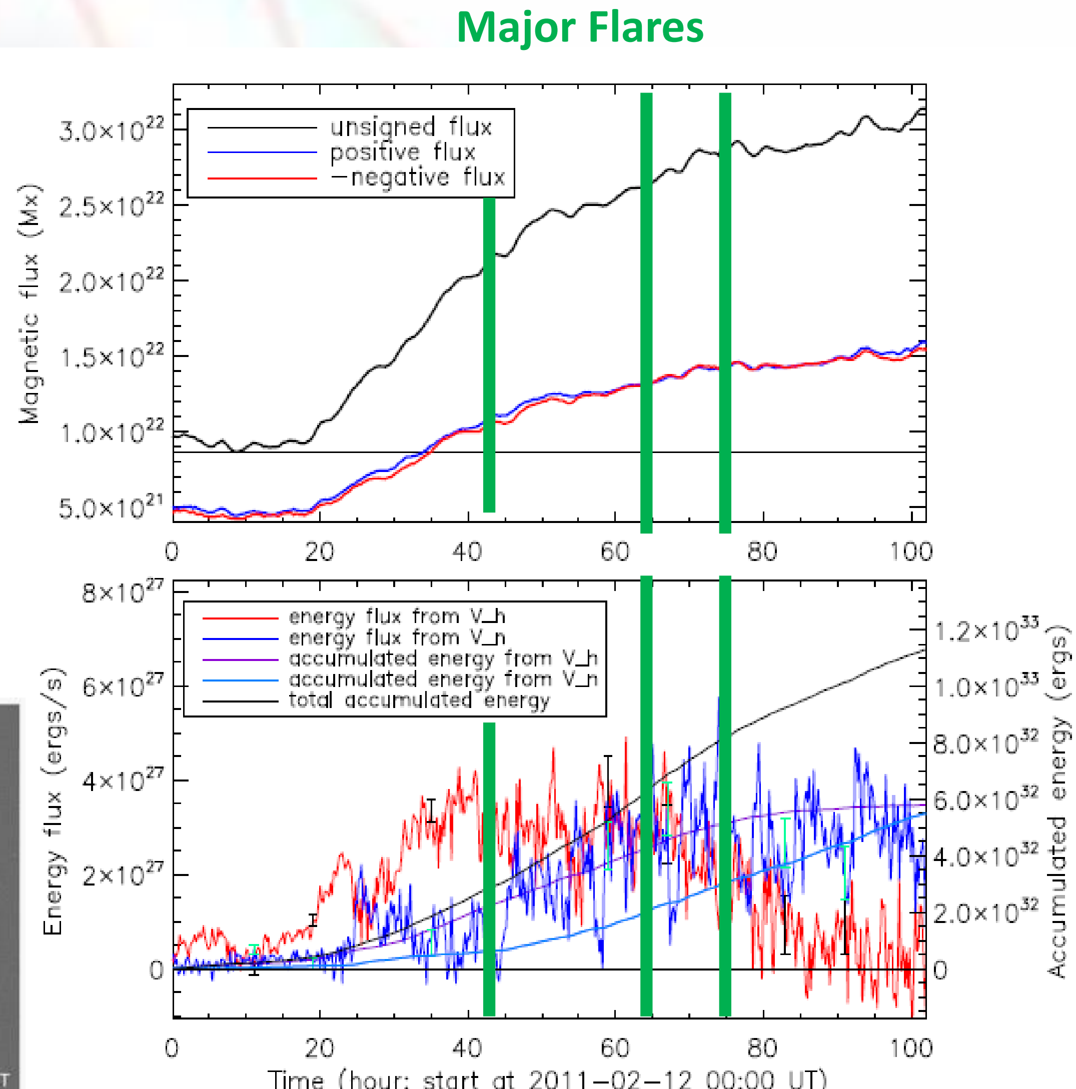


(Falconer et al. 11)

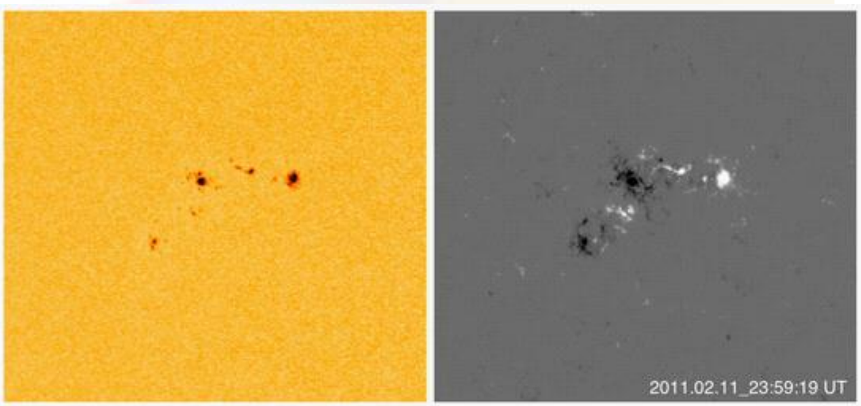
Energy build-up in an active region

- Prior and during a major active events flare: smooth evolution observed at the photosphere.
  - Magnetic flux
  - Photospheric velocities
  - Magnetic energy

- **➔ Energy release trigger is not primarily correlated with the driving mechanism of the energy injection.**



(Liu & Schuk 12)



White light (SDO/HMI) B_{los} magnetogram

Flare Predictions

- Single criteria alone gives very poor prediction
  - Combination of several criterion improves prediction.
- ➔ **Predictions are only based on necessary conditions**
  - Based on the energy build-up of active region
- **No clear physical criterion of sufficient conditions for eruption trigger**
- ➔ **Need to explore 3D structure of active regions**

TABLE 1
PARAMETERS USED IN THE DISCRIMINANT ANALYSIS

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

(Leka & Barnes 07)

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Gauge invariance of magnetic helicity

- Gauge transformation of magnetic helicity:

$$H = \int_{\mathcal{V}} \vec{A} \cdot \vec{B} \, \mathrm{d}V$$

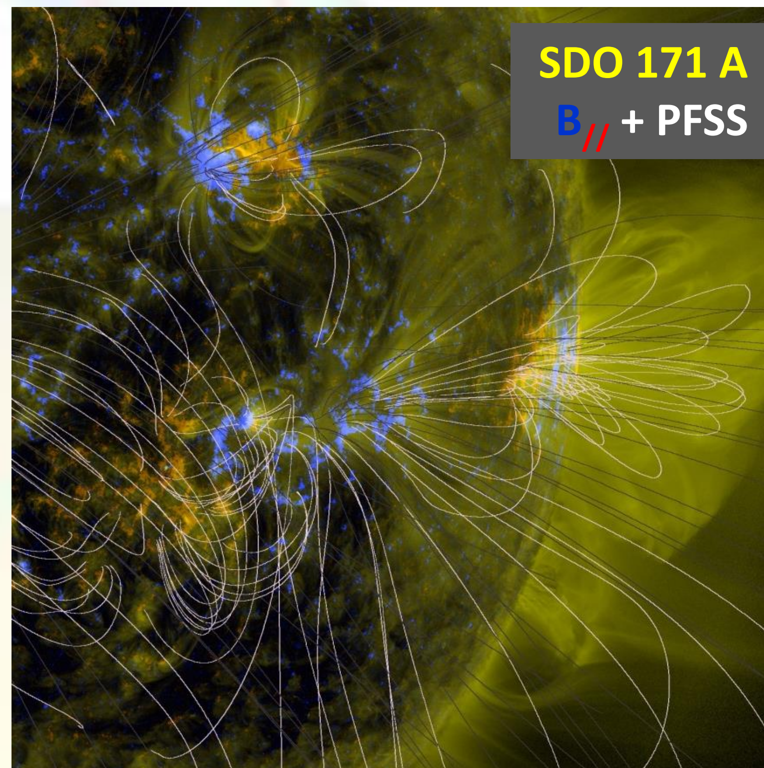
$$\mathbf{A}' \longrightarrow \mathbf{A} + \nabla\phi,$$

$$H'_m = \int_V \mathbf{A} \cdot \mathbf{B} \, \mathrm{d}V + \int_V \nabla\phi \cdot \mathbf{B} \, \mathrm{d}V = H_m + \int_S \phi \mathbf{B} \cdot \mathrm{d}S$$

- Magnetic helicity is gauge invariant only for magnetically bounded systems:

$$\mathbf{B \cdot dS}\big|_S = 0$$

- **Strict definition of magnetic helicity useless for a large number of applications:**
  - **e.g. natural plasmas, like the solar corona have boundaries threaded by magnetic fields**



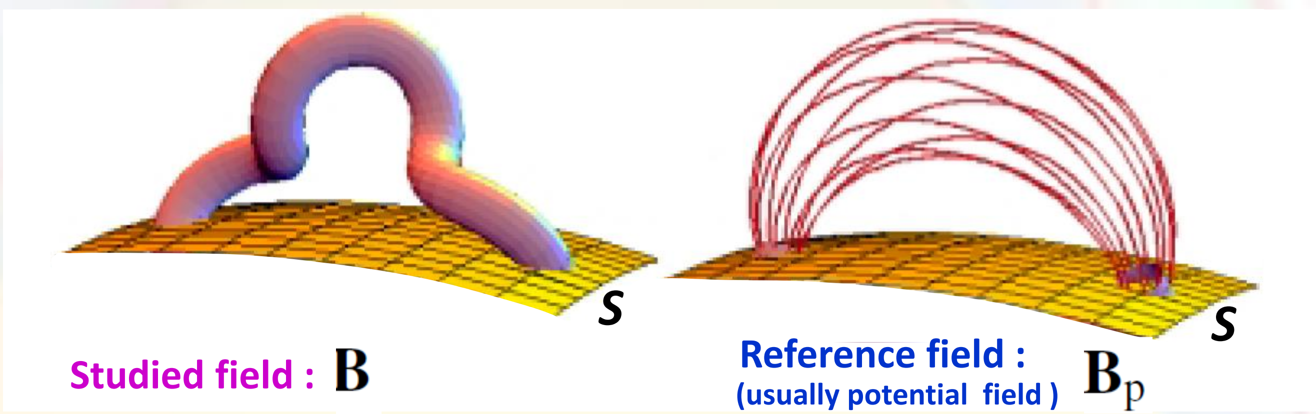
Relative Magnetic Helicity

➔ 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 : $(\mathbf{B}_{\mathrm{p}} \cdot \mathrm{d}\mathbf{S})|_{\partial\mathcal{V}} = (\mathbf{B} \cdot \mathrm{d}\mathbf{S})|_{\partial\mathcal{V}}$ $\quad \nabla \times \mathbf{A} = \mathbf{B}$

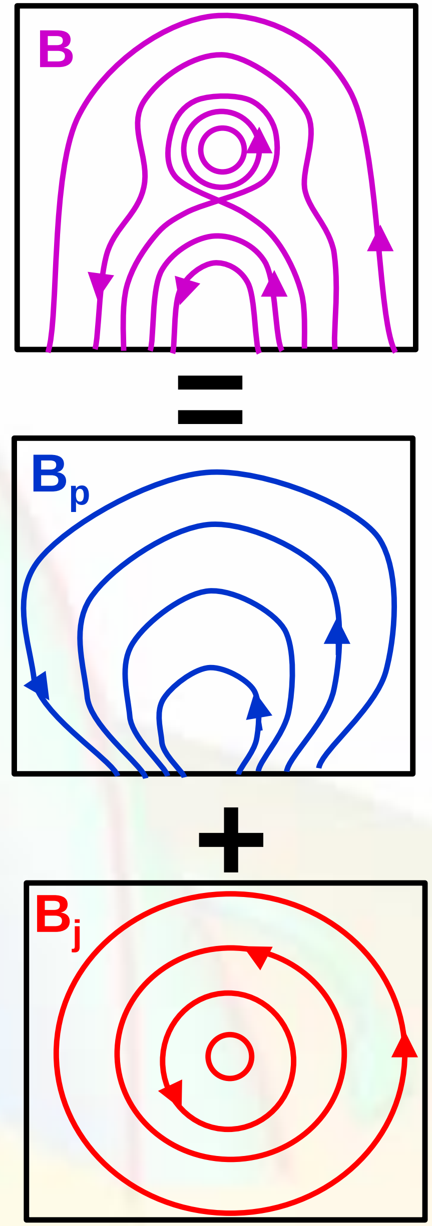
- Gauge invariant provided that studied and reference fields share the same magnetic-flux distribution on the whole boundary.
- ➔ **Smart choice of reference field depends on studied problem** **(e.g. Longcope & Malanushenko 08, Prior & Yeates 14)**



Potential & Non Potential

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

- **Potential field:** $\boldsymbol{B}_{\mathrm{p}} = \boldsymbol{\nabla}\phi,$ with $\hat{\boldsymbol{n}} \cdot (\boldsymbol{B} - \boldsymbol{B}_{\mathrm{p}})|_{\partial\mathcal{V}} = 0,$
  - the potential field has the same normal distribution than the studied field <u>on the whole boundary</u>
- **Non-potential field:**
  - The non potential field “carry” all the electric currents of the studied field. $\nabla \times \boldsymbol{B}_j = \nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j}$,
- Thomson theorem: $E_{mag} = E_{pot} + E_{free}$
  - Total magnetic energy is the sum of the mag. energy of the potential field and the “free” magnetic energy (mag. energy of the non-potential field)
- Observationally based assumption: during an eruption, **B** distribution does not change ➔ Bp and Epot do not change
  ➔ the energy source of an eruption is the free magnetic energy



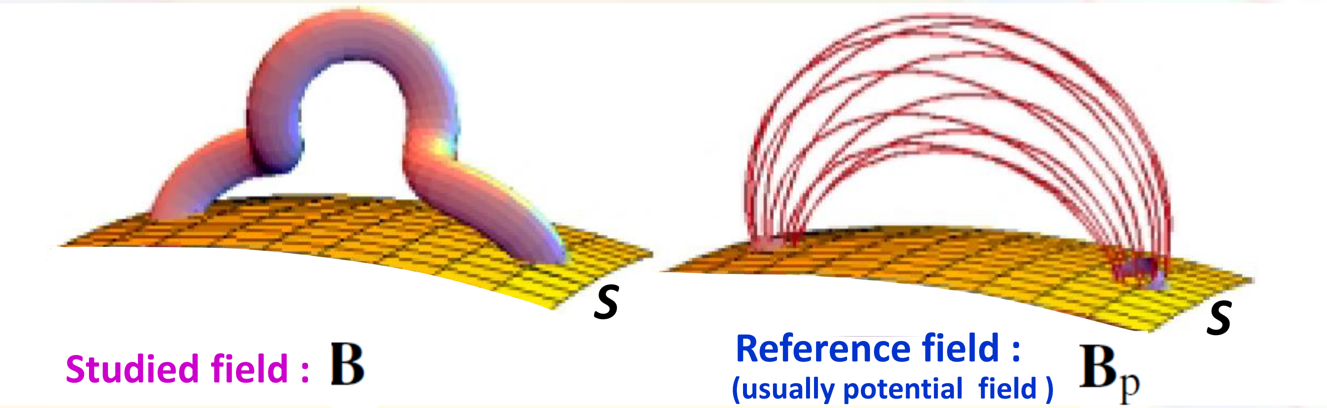
Relative Magnetic Helicity

➔ Useful quantity: **Relative Magnetic Helicity:** helicity of a studied field 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 : $(\mathbf{B}_{\mathrm{p}} \cdot \mathrm{d}\mathbf{S})|_{\partial\mathcal{V}} = (\mathbf{B} \cdot \mathrm{d}\mathbf{S})|_{\partial\mathcal{V}}$ $\nabla \times \mathbf{A} = \mathbf{B}$

- **Gauge invariant provided that studied and reference fields share the same magnetic-flux distribution <u>on the whole boundary</u>.**
- **The potential field is frequently used as standard reference field thanks to of its meaningfulness!**



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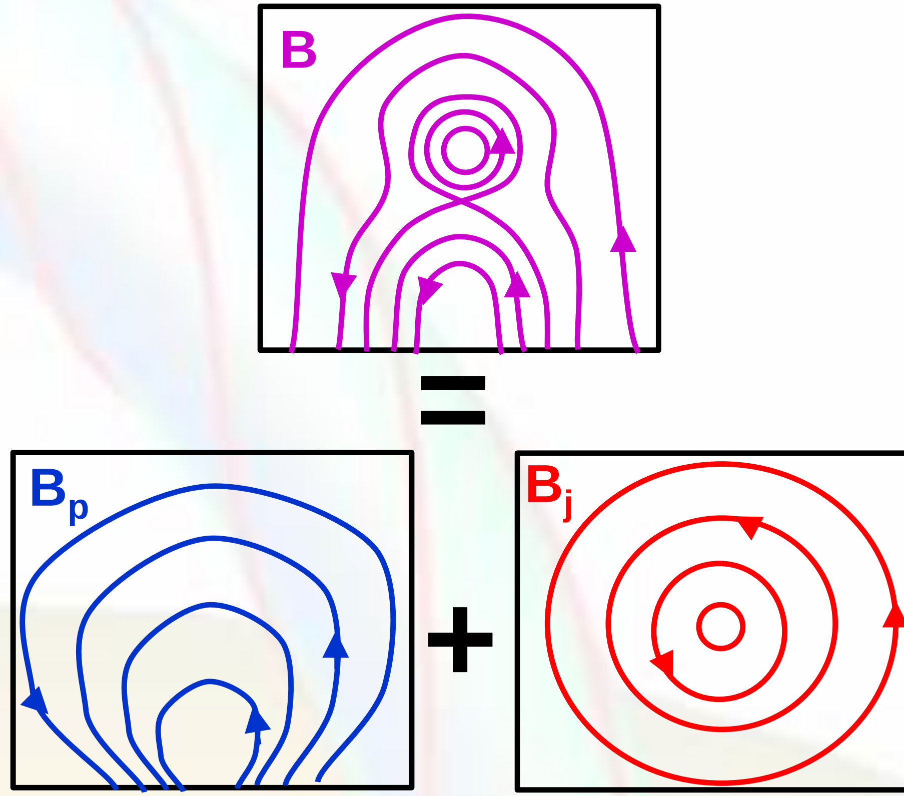
Relative magnetic helicity decomposition

- Based on the decomposition of a **magnetic field** into **potential** and **non-potential** fields….

- **Berger et al. 2003 : Relative magnetic helicity can be decomposed in 2 gauge-invariants quantities :**
  - H_j = magnetic helicity of the current-carrying field B_j (non-potential field)
  - H_{pj} = volume-threading helicity, between potential and current-carrying fields



$$
\begin{aligned}
H_V &= H_\mathrm{j} + 2H_\mathrm{pj} \quad \text{with} \\
H_\mathrm{j} &= \int_\mathcal{V} (\mathbf{A} - \mathbf{A}_\mathrm{p}) \cdot (\mathbf{B} - \mathbf{B}_\mathrm{p})\, \mathrm{d}\mathcal{V} \\
H_\mathrm{pj} &= \int_\mathcal{V} \mathbf{A}_\mathrm{p} \cdot (\mathbf{B} - \mathbf{B}_\mathrm{p})\, \mathrm{d}\mathcal{V}
\end{aligned}
$$

Helicity-based eruptivity index

- Based on the decomposition of a **magnetic field** into **potential** and **non-potential** fields….

- **Relative magnetic helicity can be decomposed in 2 gauge-invariants quantities (Berger et al. 2003) :**
  - H_j = magnetic helicity of the current-carrying field B_j (non-potential field)
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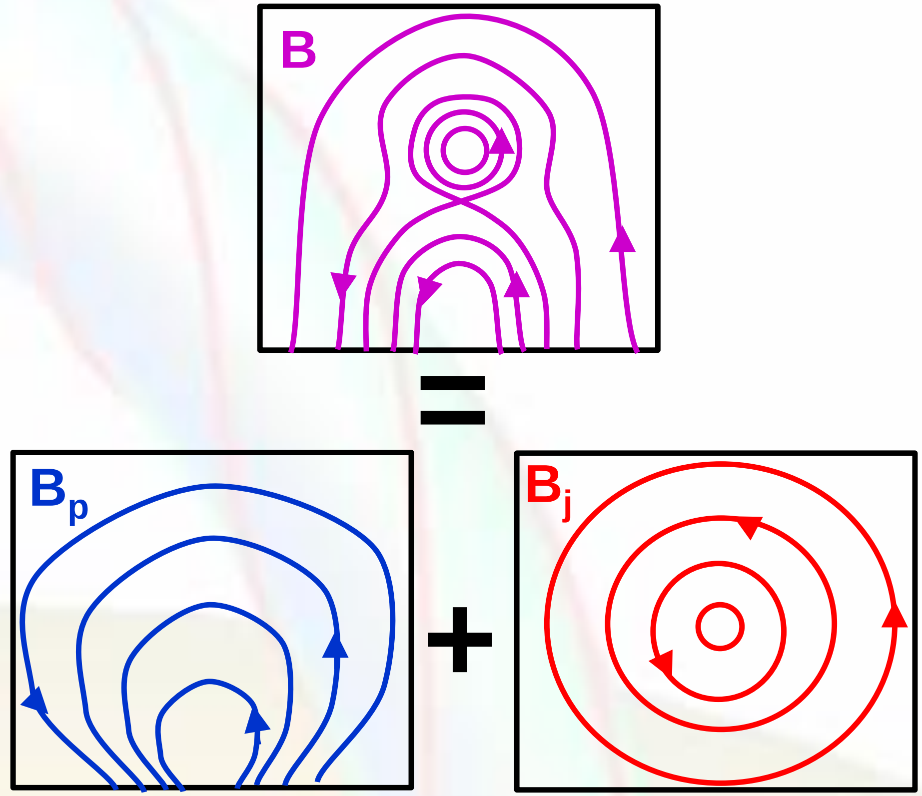

Helicity-based eruptivity index:

$$H_j/H_V$$

$$
\begin{aligned}
H_\mathcal{V} &= H_\mathrm{j} + 2H_\mathrm{pj} \quad \text{with} \\
H_\mathrm{j} &= \int_\mathcal{V} (\mathbf{A} - \mathbf{A}_\mathrm{p}) \cdot (\mathbf{B} - \mathbf{B}_\mathrm{p})\, \mathrm{d}\mathcal{V} \\
H_\mathrm{pj} &= \int_\mathcal{V} \mathbf{A}_\mathrm{p} \cdot (\mathbf{B} - \mathbf{B}_\mathrm{p})\, \mathrm{d}\mathcal{V}
\end{aligned}
$$

Underrated magnetic helicity!

- Magnetic helicity has not been extensively and thoroughly studied in eruption prediction studies…
- … despites **its fundamental and unique properties in MHD**, …
- …, mainly because of the inherent difficulty of estimation of this atypically non-local quantity!
  - Inherently 3D quantity vs. mainly 2D data available
- **Magnetic helicity estimation have been and are still largely:**
  - **difficult to perform.**
  - **imprecise when not simply incorrect**
- Hopefully, helicity measurement is becoming mature enough!

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How to measure helicity in the solar corona

Finite volume (FV)	*Helicity-flux integration (FI)*
$\mathcal{H}_\mathcal{V} = \int_\mathcal{V} (\mathbf{A} + \mathbf{A}_\mathrm{p}) \cdot (\mathbf{B} - \mathbf{B}_\mathrm{p})\, \mathrm{d}\mathcal{V}$ see Eq. (3) – Requires $\mathbf{B}$ in $\mathcal{V}$ *e.g.*, from MHD simulations or NLFFF – Compute $\mathcal{H}_\mathcal{V}$ at one time – May employ different gauges (see Table 2)	$\frac{\mathrm{d}\mathcal{H}_\mathcal{V}}{\mathrm{d}t} = 2 \int_{\partial\mathcal{V}} [(\mathbf{A}_\mathrm{p} \cdot \mathbf{B}) v_n - (\mathbf{A}_\mathrm{p} \cdot \mathbf{v}_\mathrm{t}) B_n]\, \mathrm{d}S$ – Requires time evolution of vector field on $\partial\mathcal{V}$ – Requires knowledge or model of flows on $\partial\mathcal{V}$ – Valid for a specific set of gauge and assumptions, see Pariat et al. (2017)

Discrete flux-tubes (DT)

$$\mathcal{H} \simeq \sum_{i=1}^{M} \mathcal{T}_i \Phi_i^2 + \sum_{i=1}^{M} \sum_{j=1, j\neq i}^{M} \mathcal{L}_{i,j} \Phi_i \Phi_j ,$$

see Eq. (31)

Twist-number (TN)	*Connectivity-based (CB)*
$\mathcal{H} \simeq \mathcal{T} \Phi^2$ see Eq. (32) – Estimation of the twist contribution to $\mathcal{H}$ – Requires $\mathbf{B}$ in $\mathcal{V}$ – Requires a flux-rope-like structure for computing the twist $\mathcal{T}$	$\mathcal{H} = A \sum_{i=1}^{M} \alpha_i \Phi_i^{2\delta} + \sum_{l,m=1}^{M} \mathcal{L}_{lm} \Phi_l \Phi_m$ see Eq. (35) – Requires the vector field on photosphere at one time – Models the corona connectivity as a collection of M force-free flux tubes – Minimal connection length principle

(Valori et al. 16)

Relative magnetic helicity estimations

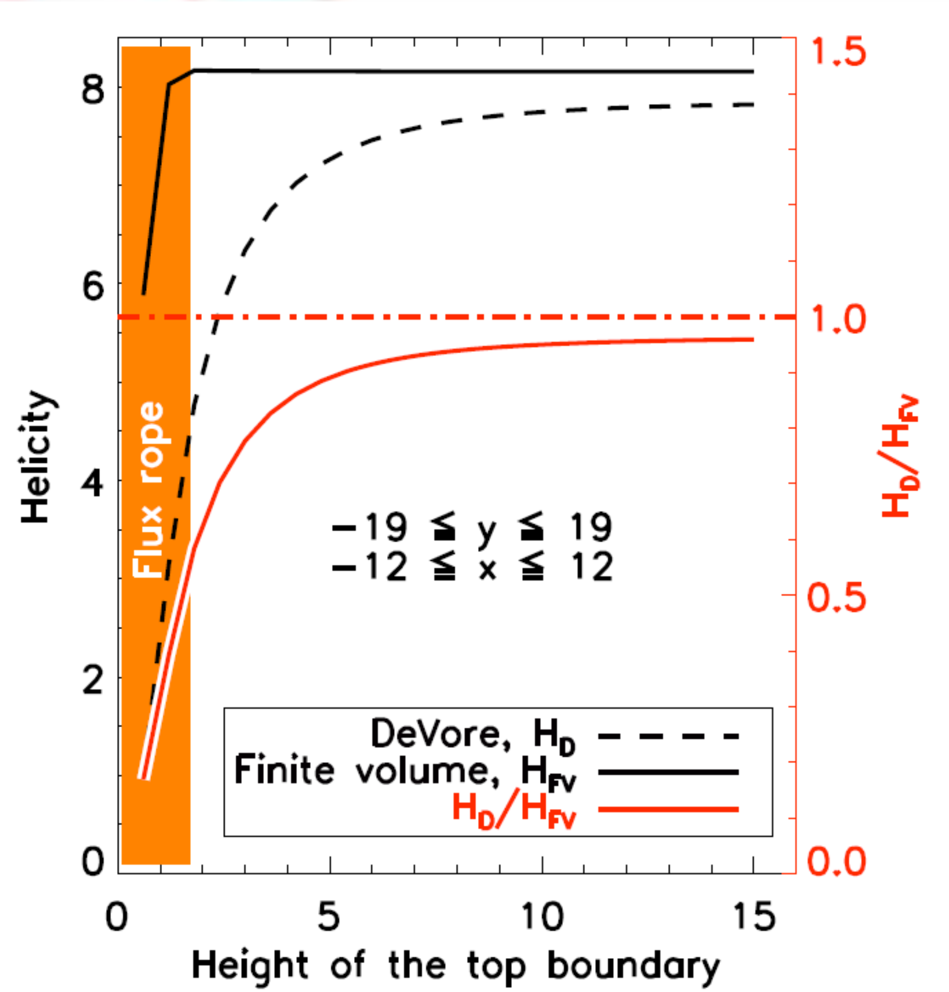
Finite volume (FV)

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

see Eq. (3)

- Requires $\mathbf{B}$ in $\mathcal{V}$ *e.g.*, from MHD simulations or NLFFF
- Compute $\mathscr{H}_\mathcal{V}$ at one time
- May employ different gauges (see Table 2)

(Valori et al. 12)



- Computation of relative helicity is not straightforward:
  - **Computation of reference field must be done imposing boundary conditions on the <u>whole domain boundary.</u>**
- Many previous methods assumed semi-infinite volumes while all existing datasets are bounded volumes ➔ can lead to incorrect results
  - error in intensity **(Valori et al. 2012, Moraitis et al. 18)**
  - **<u>even incorrect sign!</u>** **(Valori et al. 11)**

Relative magnetic helicity estimations

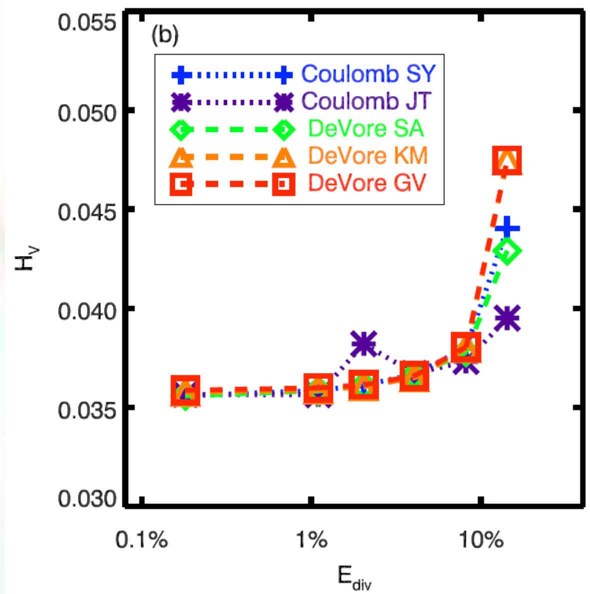
- **Several methods recently developed on 3D cuboid system** **(Valori et al. 2016)**
  - Using Coulomb gauge: $\nabla \cdot \mathbf{A} = 0$

    Thalmann et al. 2011, **Rudenko & Myshyakov 2011, Yang et al. 2013**
    - Simpler theoretical formulation
    - Harder to implement numerically
  - Using DeVore gauge **(DeVore et al. 2000)** : $A_z = 0$

    Valori et al. 2012, Moraitis et al. 2014
    - More complex theoretical formulation
    - Simpler to implement numerically: more precise
- **Method to compute relative magnetic helicity in spherical wedge domains**
  - **Moraitis et al. 2018**
- Note: available methods still requires regularly spaced grids

Relative magnetic helicity estimations

- **Benchmarking of these methods performed by ISSI team on "Helicity estimations in models and observations" (Valori et al. 2016)** :
- Numerous tests: sensibility to resolution, twist, solenoidality using various types of data.
  - Force free fields **(Low & Lou 1990)**
  - Stable flux rope (**Titov & Démoulin 1999**, data fromT. Török)
  - Flux emergence simulations **(Leake et al. 2013, 2014)**
- **Methods perform very consistently when B sufficiently solenoidal**



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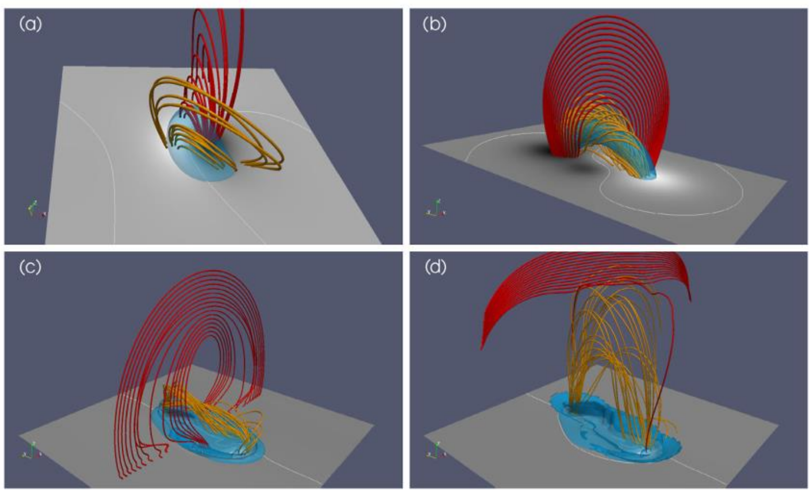

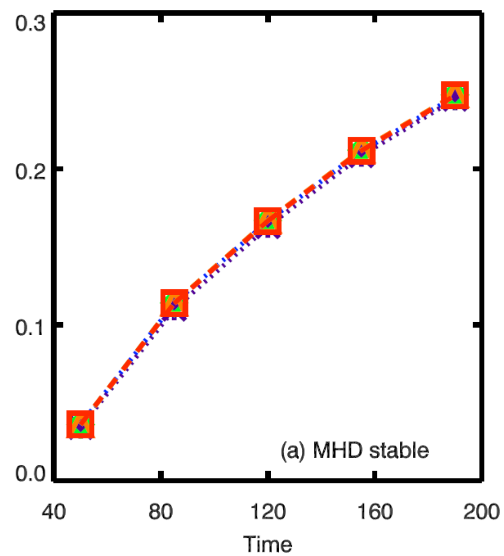

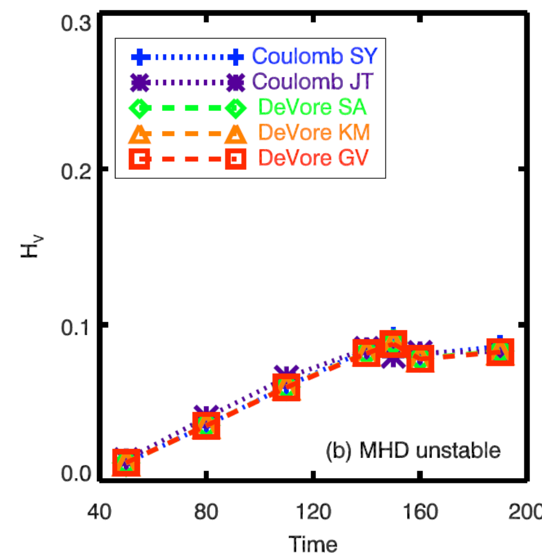

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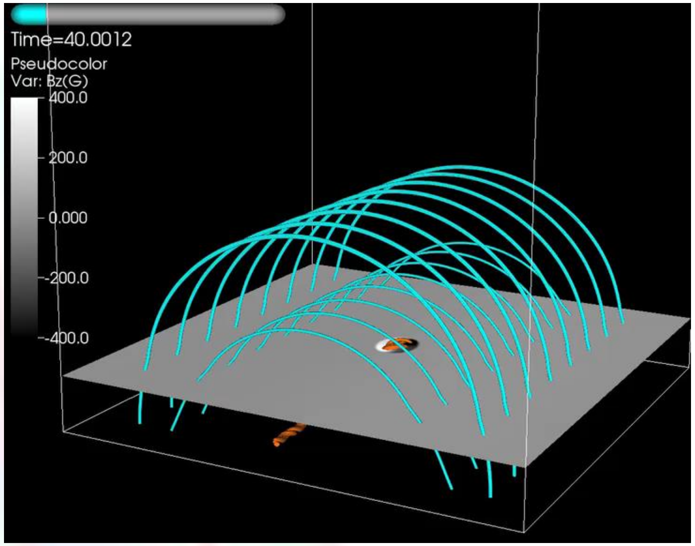
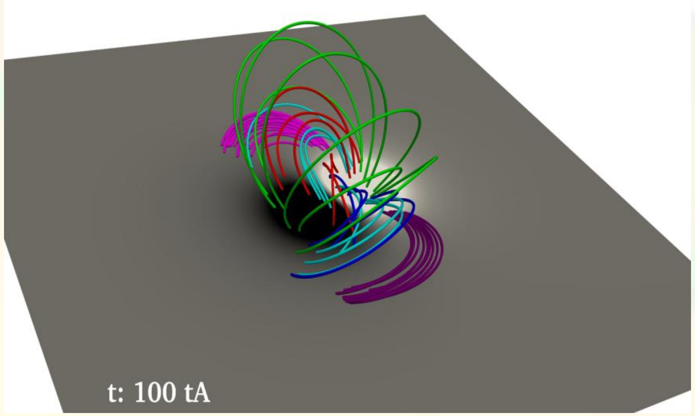
Motivations & Methodology

- **Goal: use parametric MHD simulations to search efficient eruptivity criterion**
  - **lead to eruptive and non-eruptive cases**
  - **varying few initial/boundary parameter**

- Methodology:
  - extract part of the magnetic field,
  - compute different physical quantities,
  - search for the ones that discriminates between the eruptive and non-eruptive case



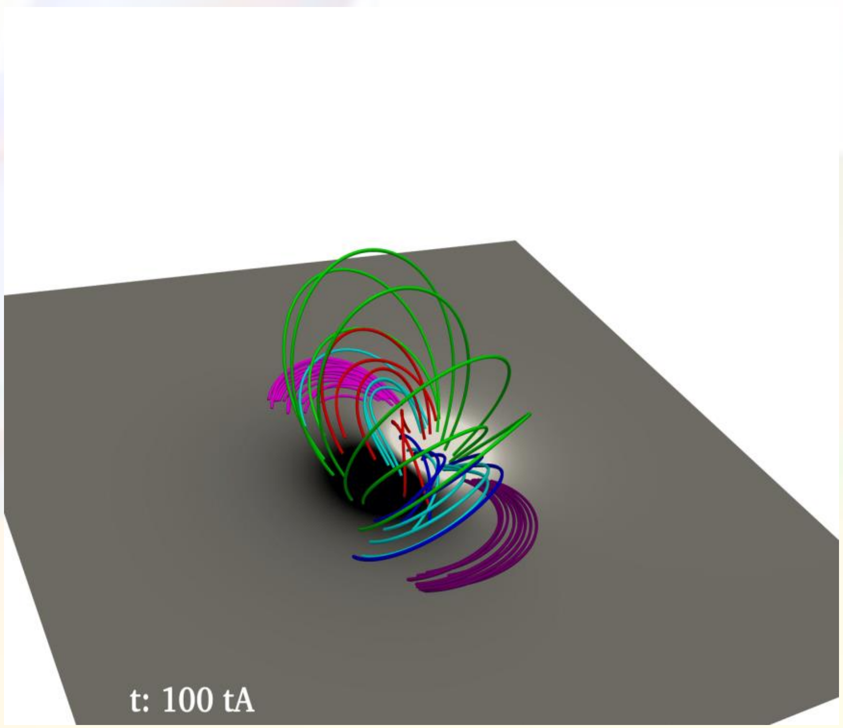
(Leake et al. 14)

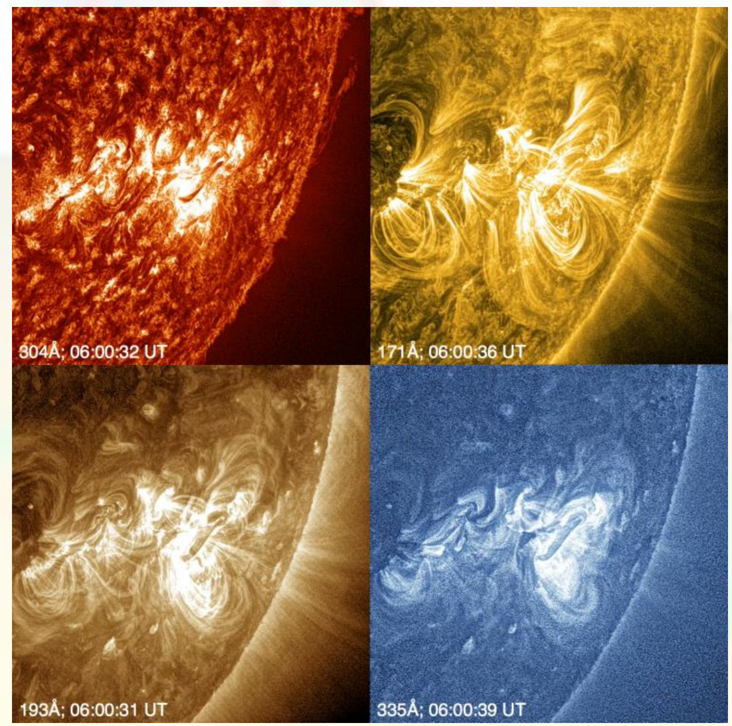


(Zuccarello et al. 15)

Line-tied eruptive simulations

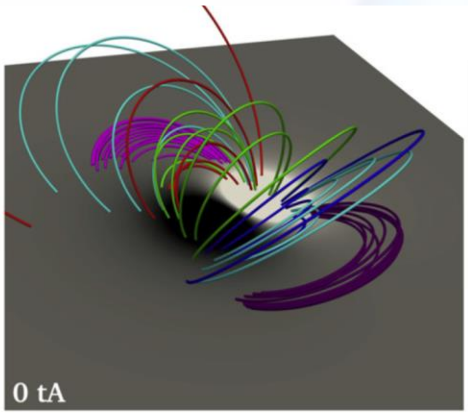
- **Line-tied boundary driven simulations of solar eruptions** **(Zuccarello et al. 15)**:
  - 3D visco-resitive MHD simulations; Ohm-MPI code **(Aulanier et al. 10, Zuccarello et al. 16)**
  - Initially potential/stable configuration ; quasi-steadly injection of energy/helicity
  - ➔ eventual trigger of solar-like eruption

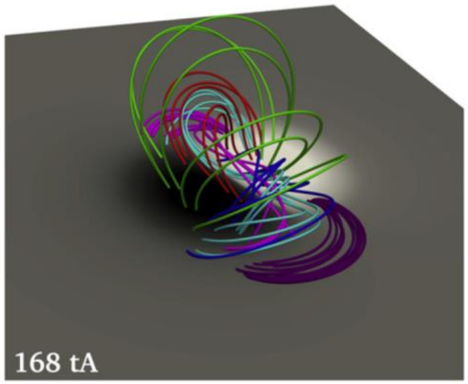




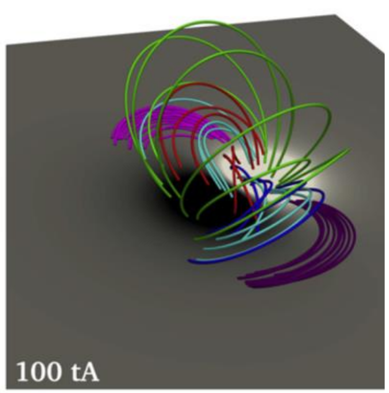
Eruption trigger time determination

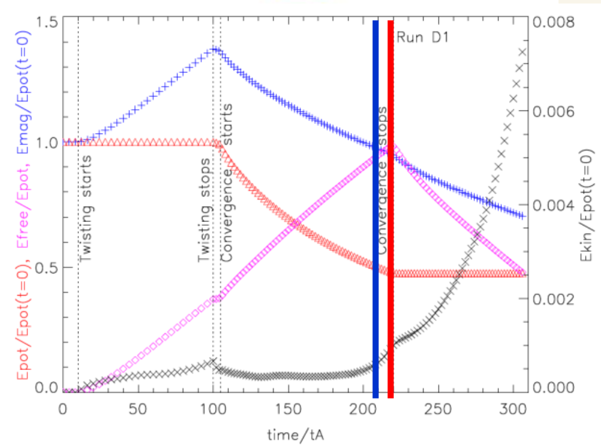
- **For each simulation, precise determination of the onset time, t_{erupt}, thanks to numerous relaxation runs initiated at regular instants.**



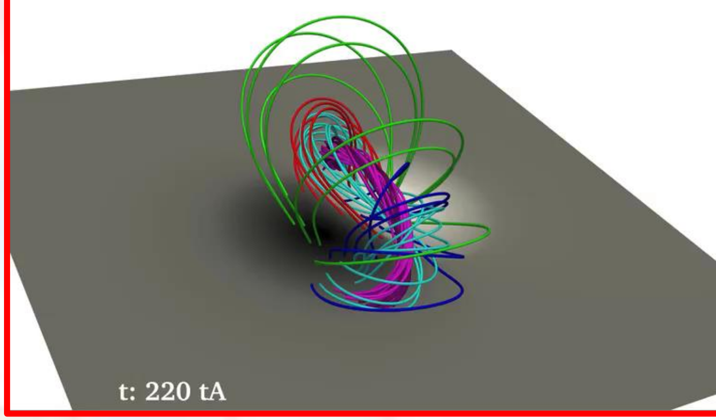


(Aulanier et al. 10, Zuccarello et al. 16)

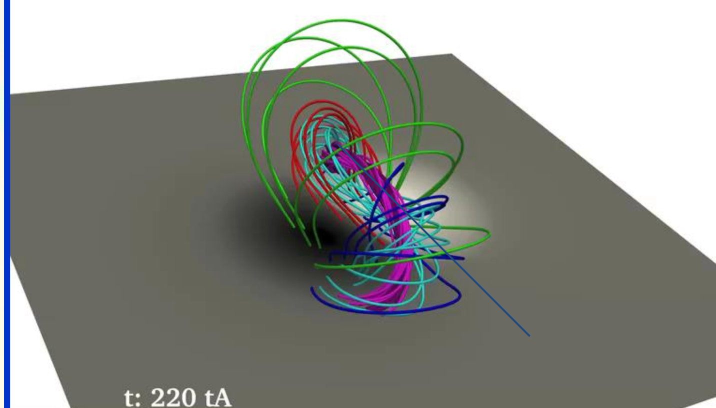




Relaxation run at t_{erupt}

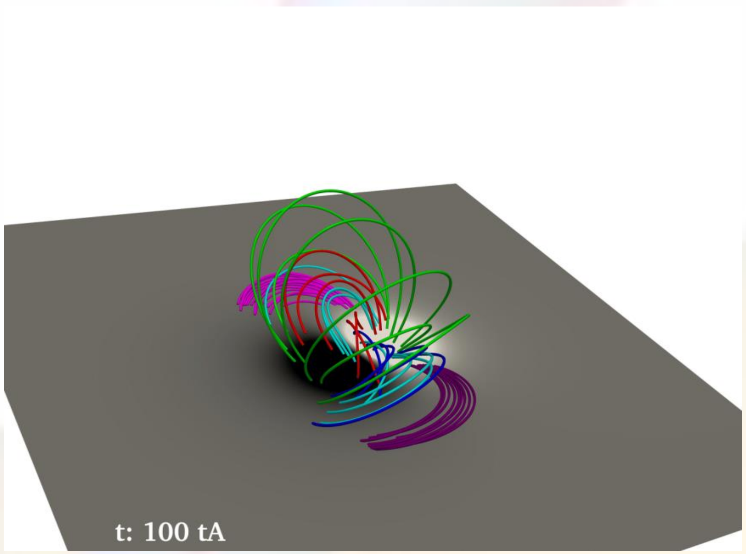


Relaxation run at $t_{erupt} - 4t_A$

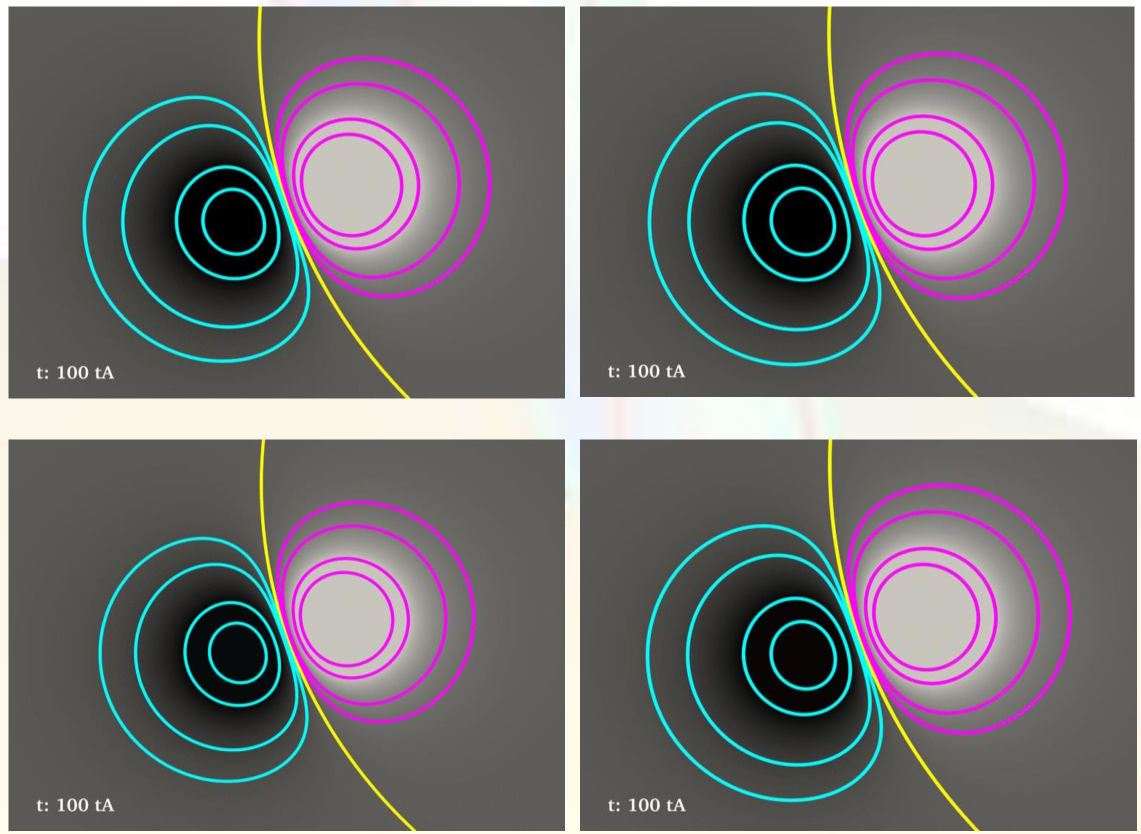


Line-tied parametric simulations

- **Zuccarello et al. 2015**: parametric eruptive simulations
- **4 different line-tied boundary driving patterns** with different: shear around the PIL magnetic flux dispersion + 1 non-eruptive control case (diffusion)

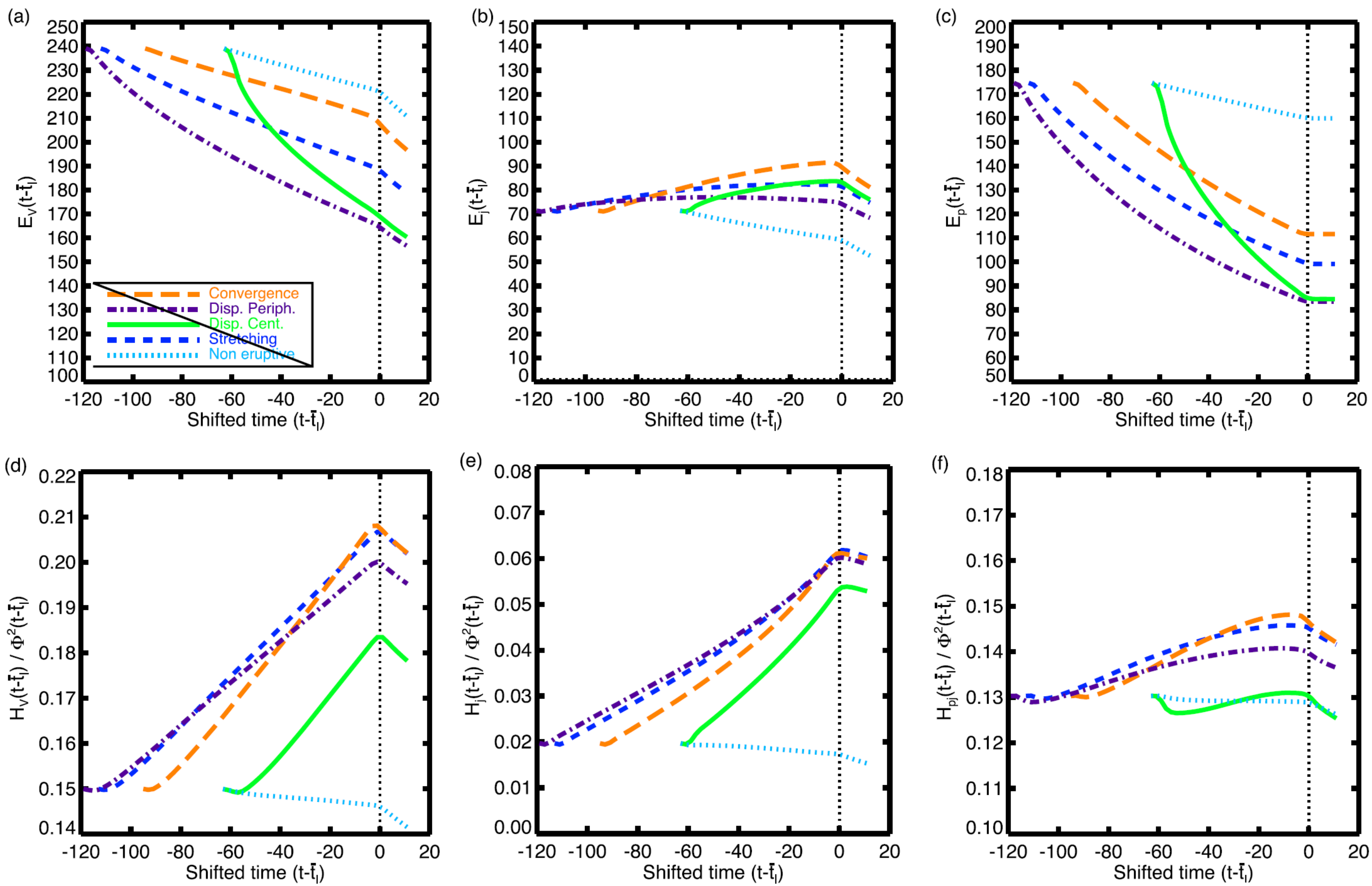


(Aulanier et al. 10, Zuccarello et al. 15)



Eruptivity criterion analysis

- Computation of several quantities relatively to their respective t_{erupt}

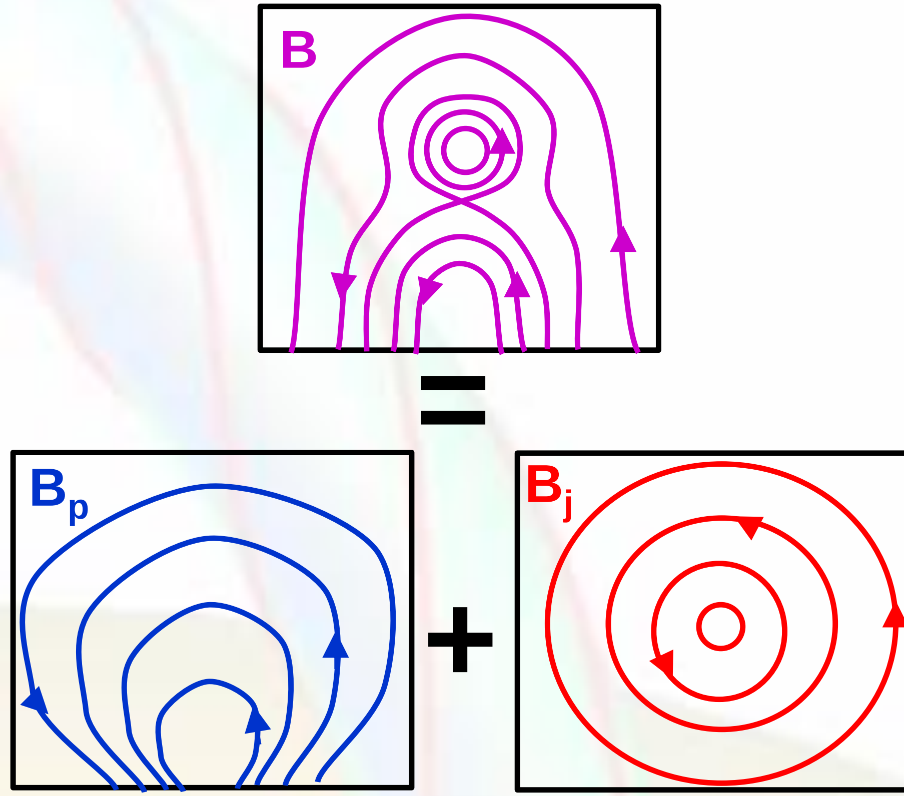


(Zuccarello et al. 18)

Helicity-based eruptivity index

- Based on the decomposition of a **magnetic field** into **potential** and **non-potential** fields….

- **Relative magnetic helicity can be decomposed in 2 gauge-invariants quantities (Berger et al. 2003) :**
  - H_j = magnetic helicity of the current-carrying field B_j (non-potential field)
  - H_{pj} = volume-threading helicity, between potential and current-carrying fields



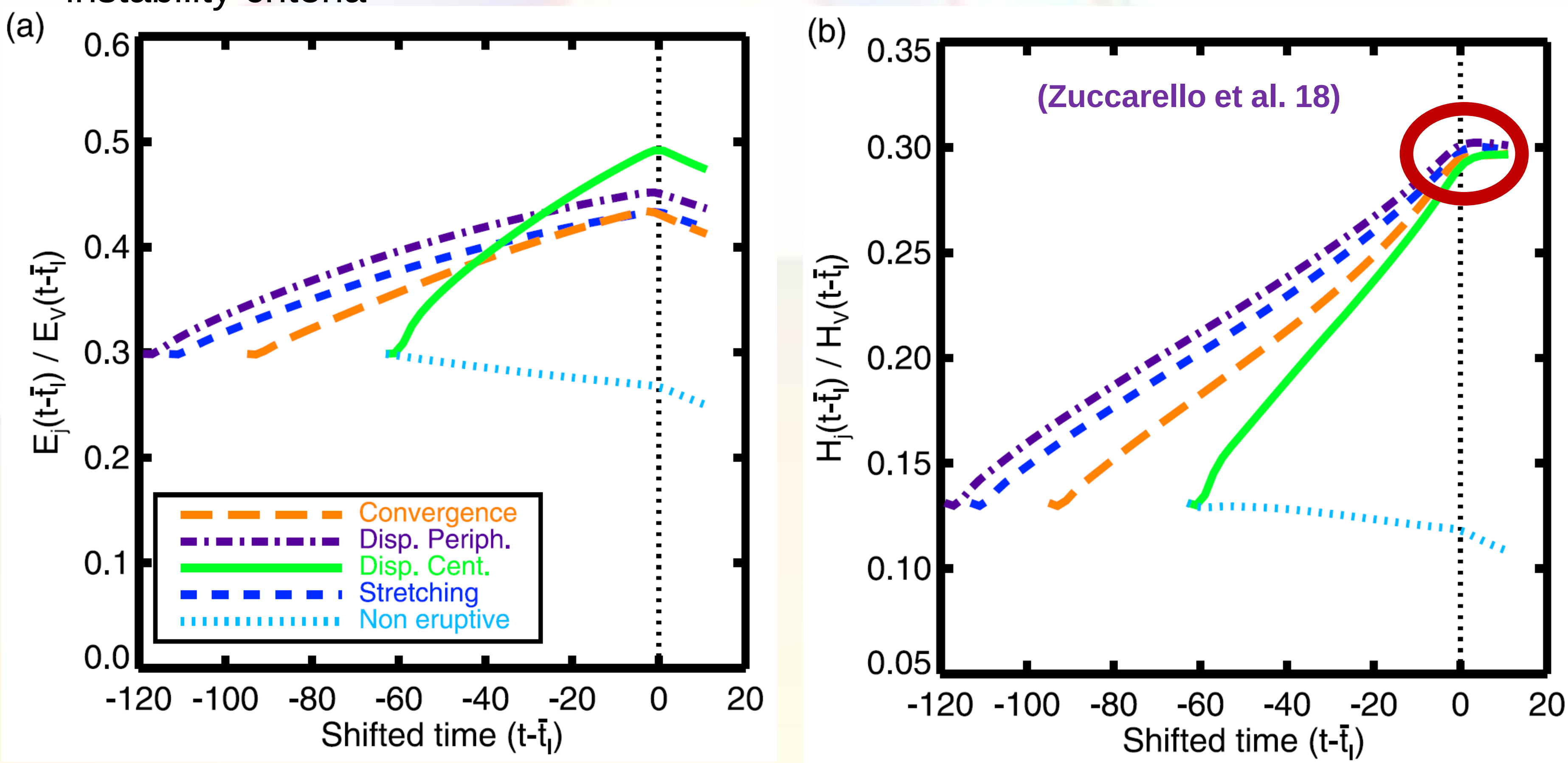
Helicity-based Eruptivity Index:

H_j/H_V

$$
\begin{aligned}
H_V &= H_{\rm j} + 2H_{\rm pj} \quad \text{with} \\
H_{\rm j} &= \int_{\mathcal{V}} (\mathbf{A} - \mathbf{A}_{\rm p}) \cdot (\mathbf{B} - \mathbf{B}_{\rm p})\, {\rm d}\mathcal{V} \\
H_{\rm pj} &= \int_{\mathcal{V}} \mathbf{A}_{\rm p} \cdot (\mathbf{B} - \mathbf{B}_{\rm p})\, {\rm d}\mathcal{V}
\end{aligned}
$$

Helicity-based Eruptivity Index

- **Despites different boundary drivers and t_{erupt}, eruptions are triggered when $|H_j|/|H_V|$ reaches the same value:**
  - <4% dispersion (within measurement precision of helicity)
- All other quantities have dispersions of values above 8 % at t_{erupt} , including torus instability criteria



Outline

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  - Measuring Helicity
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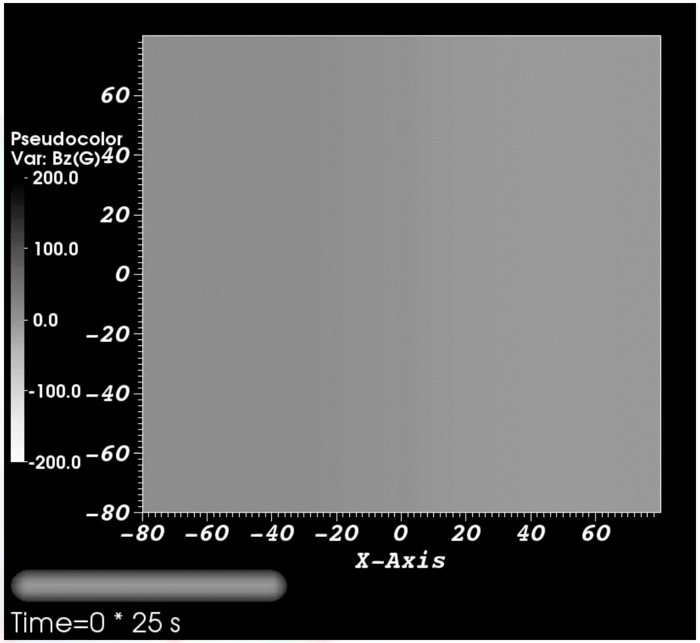
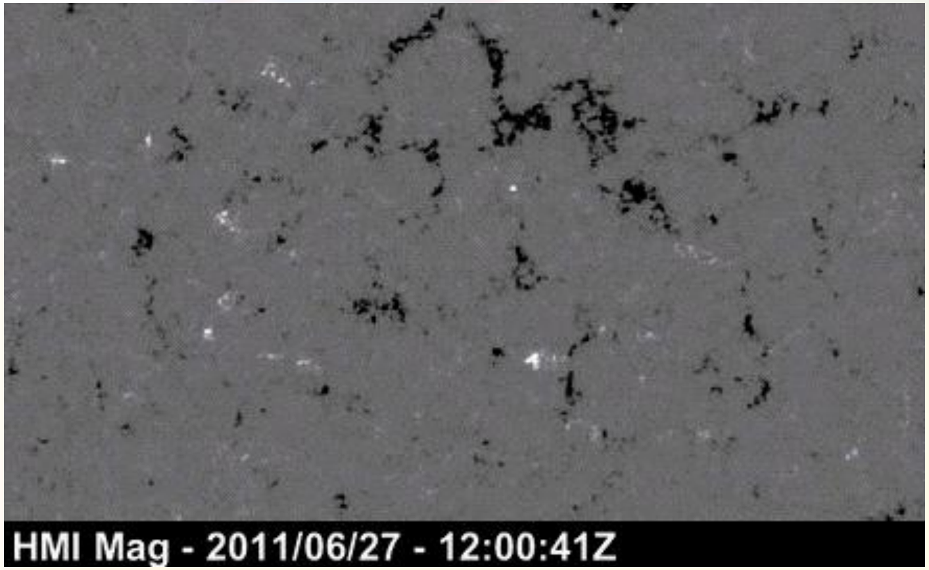
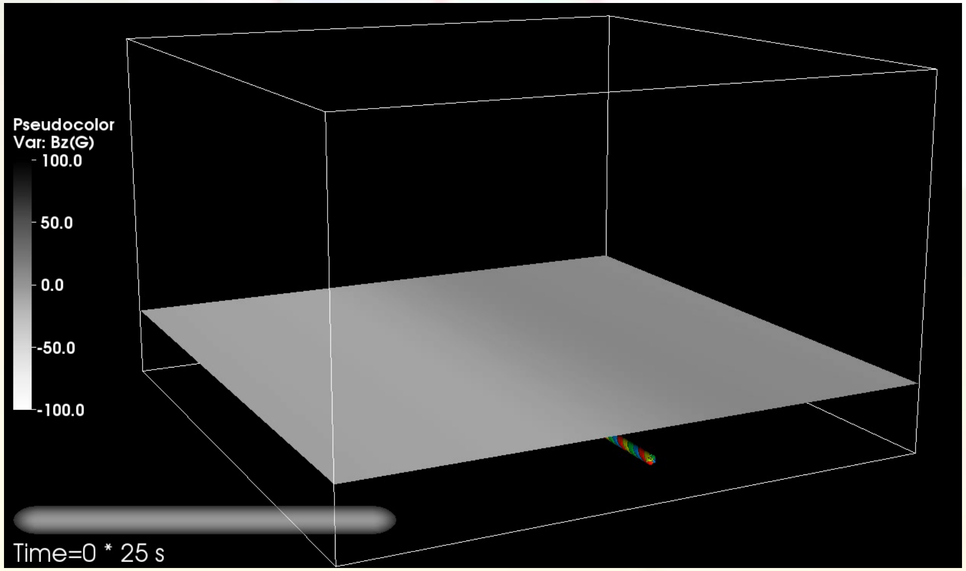
Flux emergence simulations

- **Simulate the formation of solar active regions**
  - 3D visco-resistive MHD eq. solved with Lagrangian-remap code **(Arber et al. 2001)**
  - **Evolution of a buoyant twisted magnetic flux rope from the upper layer of the solar convection zone into the solar atmosphere.**

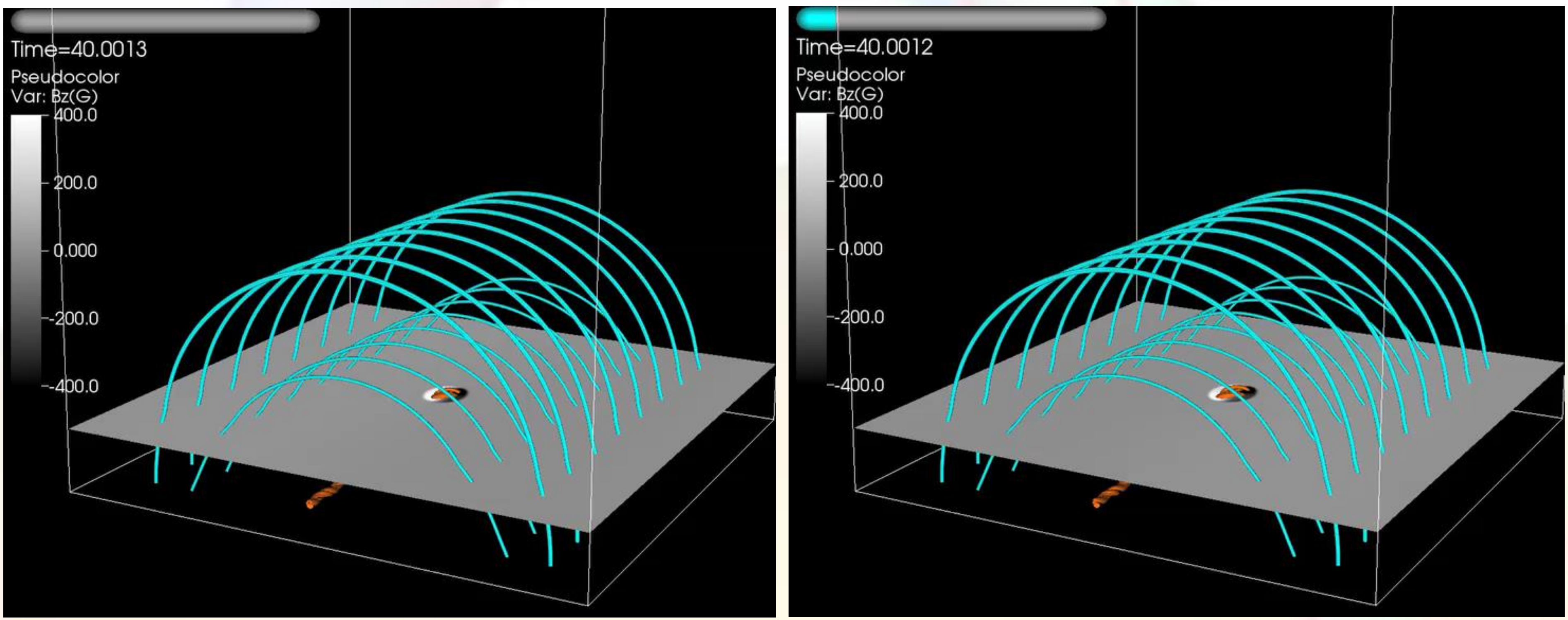






Parametric flux emergence simulations

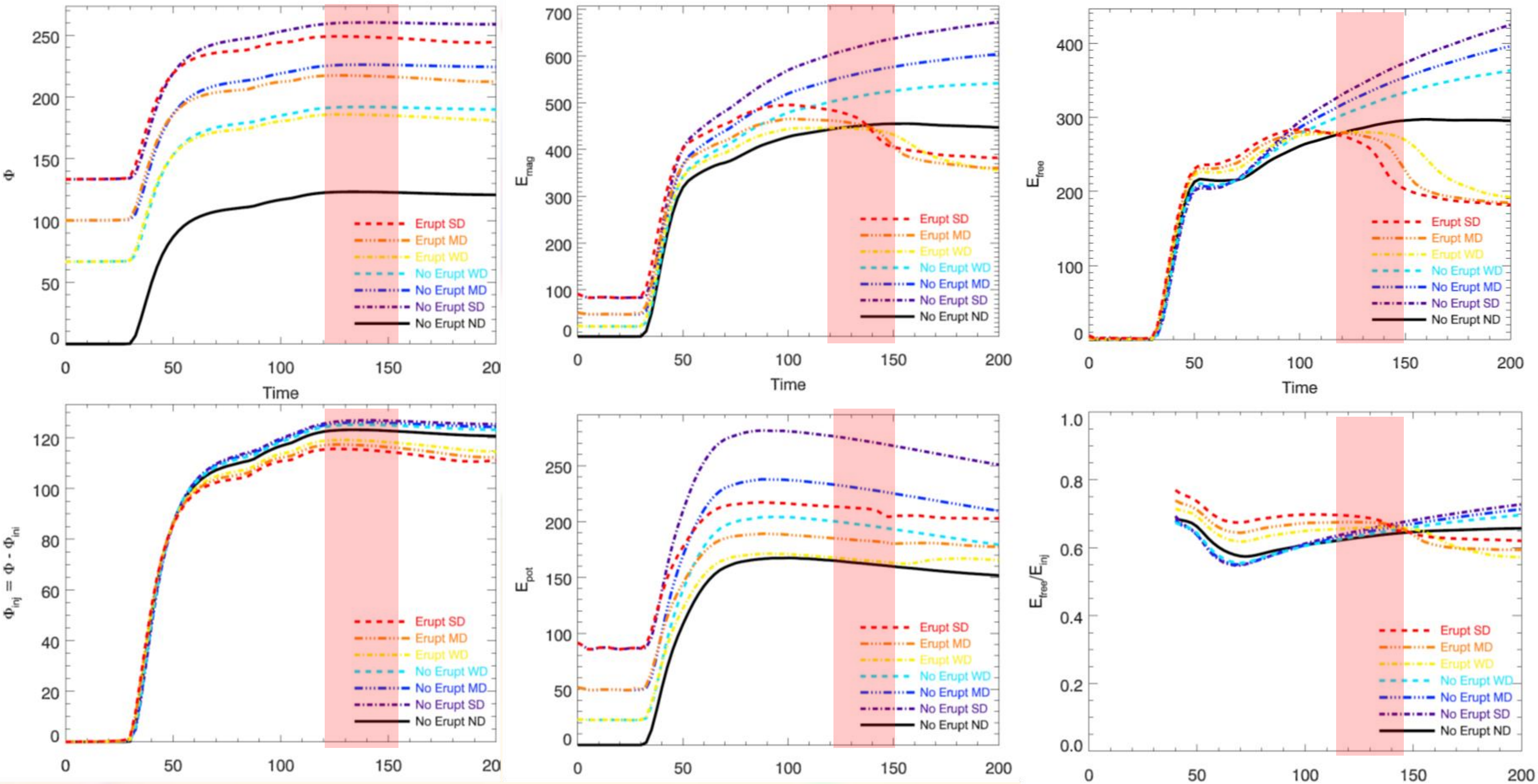
- **7 flux emergence simulations leading either to eruptive or non-eruptive dynamics** **(Leake et al. 2013, 2014)**
- Deterministically stable/instable.
  - Stability of system given by initial conditions
  - **No helicity instability threshold is expected**
  - **Is there an advance signature of eruptivity?**



(Leake et al. 13, 14)

Magnetic fluxes and energies

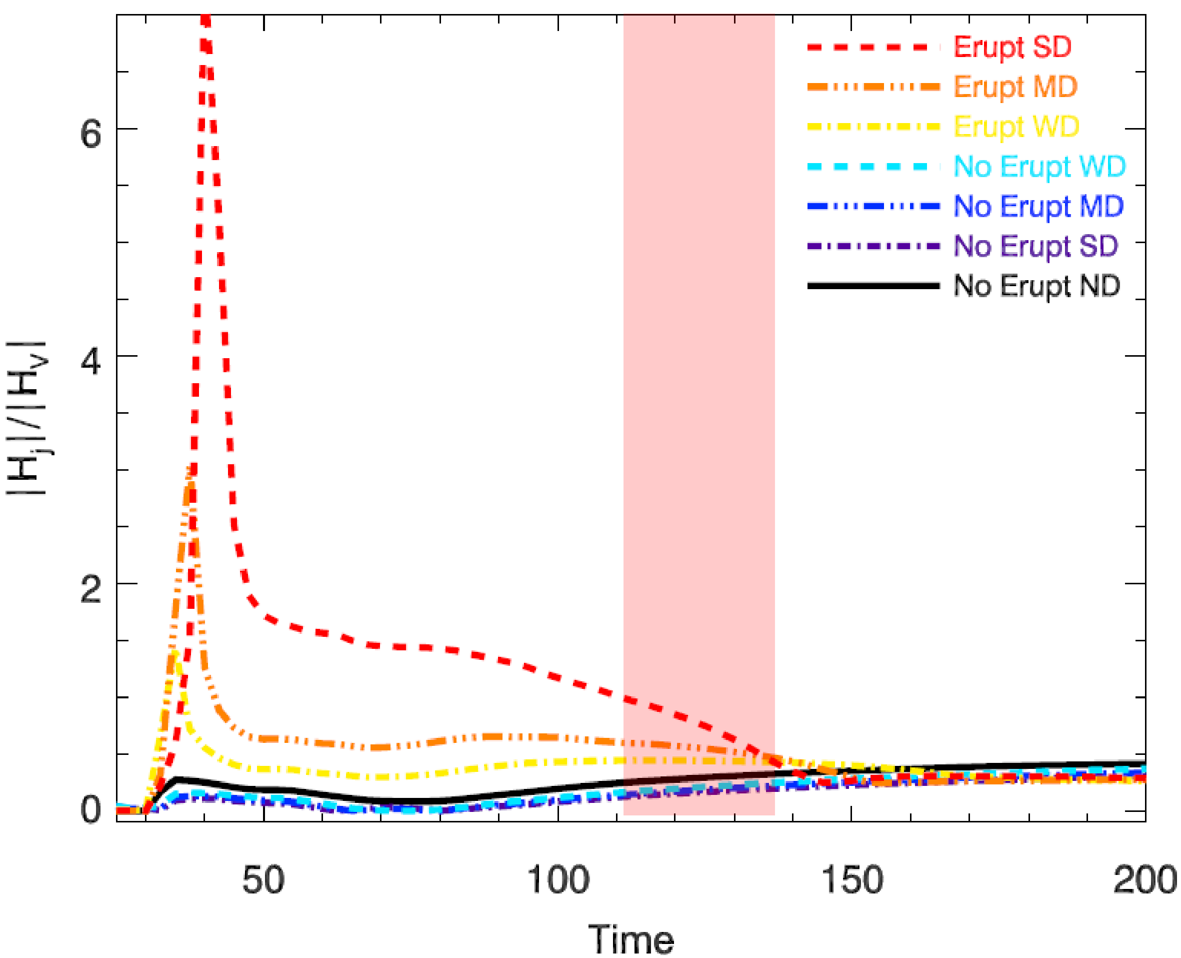
(Pariat et al. 17)



- **Neither injected magnetic flux nor magnetic energies are properly discriminating between the different simulations and do not provide reliable eruptivity diagnostics**

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

(Pariat et al. 17)

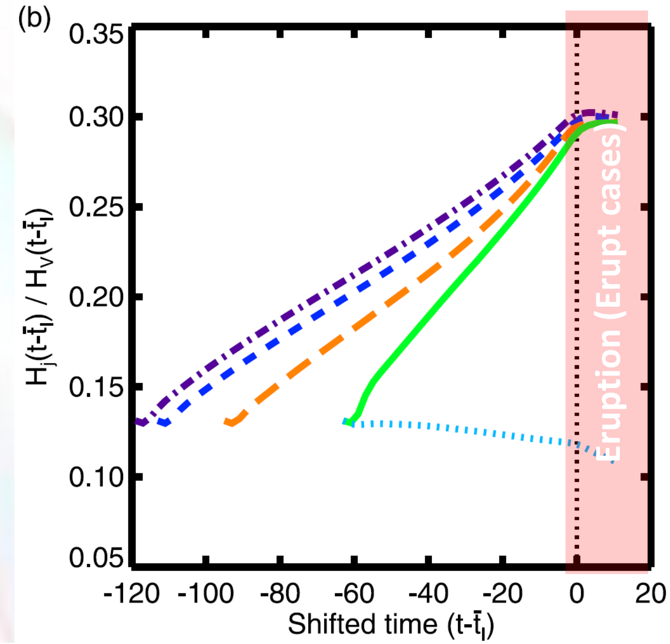


$$
\begin{aligned}
H_V &= H_\mathrm{j} + 2H_\mathrm{pj} \quad \text{with} \\
H_\mathrm{j} &= \int_{\mathcal{V}} (\mathbf{A} - \mathbf{A}_\mathrm{p}) \cdot (\mathbf{B} - \mathbf{B}_\mathrm{p}) \, \mathrm{d}\mathcal{V} \\
H_\mathrm{pj} &= \int_{\mathcal{V}} \mathbf{A}_\mathrm{p} \cdot (\mathbf{B} - \mathbf{B}_\mathrm{p}) \, \mathrm{d}\mathcal{V}
\end{aligned}
$$

- **$|H_j|/|H_V|$ appears as an excellent eruptivity predictor of these sims.**
  - **Highest value for the eruptive simulations in the pre-eruptive phase**
  - **Eruptive and non-eruptive simulations have similar values in post-eruption phase**
- $|H_j|/|H_V|$ is also sensitive to dipole strength which fits with promptness to erupt

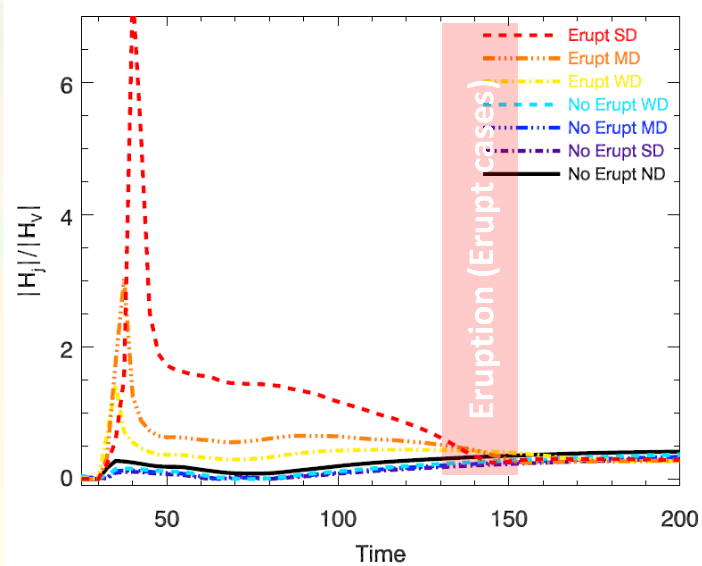
Partial conclusion

(Zuccarello et al. 18)



- Helicity eruptivity index was also found to be work in other numerical models
  - Flux emergence simulations **(Moraitis et al. 14)**
  - Coronal jets **(Linan et al. 18)**

- **The ratio |Hj|/|Hv| is an excellent indicator of the eruptive state in several numerical models**
  - 15 different numerical simulations
  - inducing 11 eruptions & 6 stable systems
  - in 4 very different magnetic configuration
  - performed by 3 different MHD numerical codes



(Pariat et al. 17)

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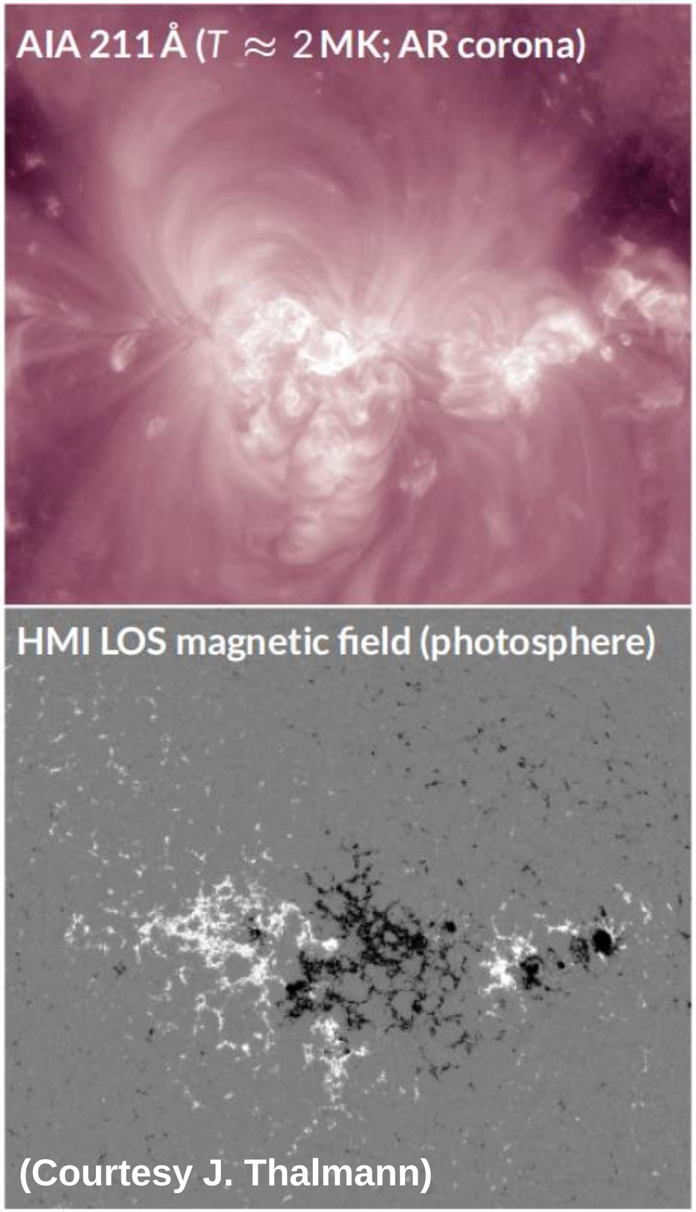
Measuring magnetic helicity in observations - 1

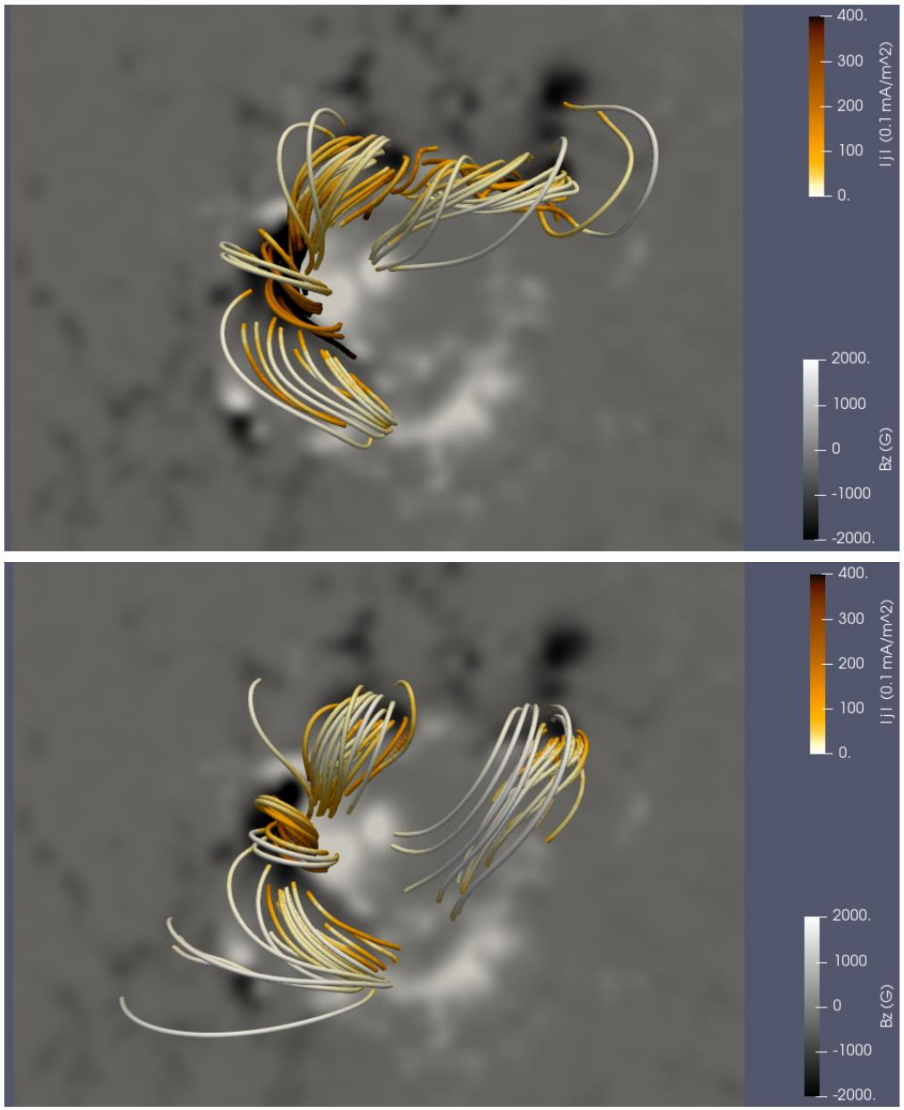


Credit: NASA/ESA/JAXA

$$
\begin{aligned}
H_V &= H_{\mathrm{j}} + 2H_{\mathrm{pj}} \quad \text{with} \\
H_{\mathrm{j}} &= \int_{\mathcal{V}} (\mathbf{A} - \mathbf{A}_{\mathrm{p}}) \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}})\, \mathrm{d}\mathcal{V} \\
H_{\mathrm{pj}} &= \int_{\mathcal{V}} \mathbf{A}_{\mathrm{p}} \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}})\, \mathrm{d}\mathcal{V}
\end{aligned}
$$

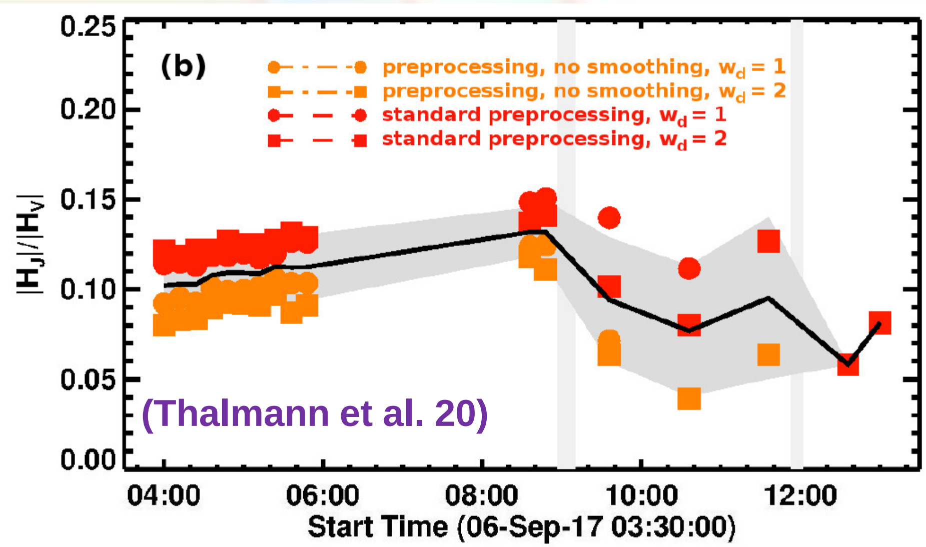
- Helicity eruptivity index requires the knowledge of the distribution of B in the 3D coronal domain
- **However 3D magnetic field vector is NOT routinely measured in the corona**
- Lack of measurements may be compensated :
  - photospheric B field vector routinely measured
  - **+ "EXTRAPOLATION" of the surface field into the corona: model-dependant reconstruction of the 3D magnetic field**

Measuring magnetic helicity in observations - 2



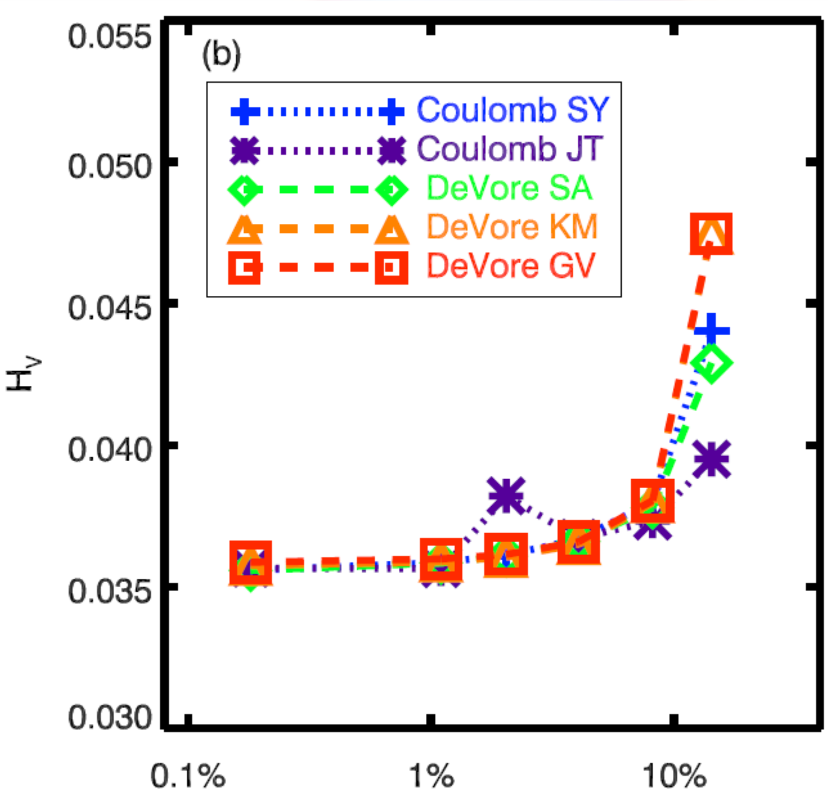
(Moraitis et al. 19)

- **3D coronal magnetic field reconstruction is an art !**
  - numerous assumption, model-dependent, solve ill-posed mathematical problems.
- ➔ No unique solutions
  - Different parameters → different B
  - No ground truth of coronal B
- **➔ No absolute determination of the helicity content!**

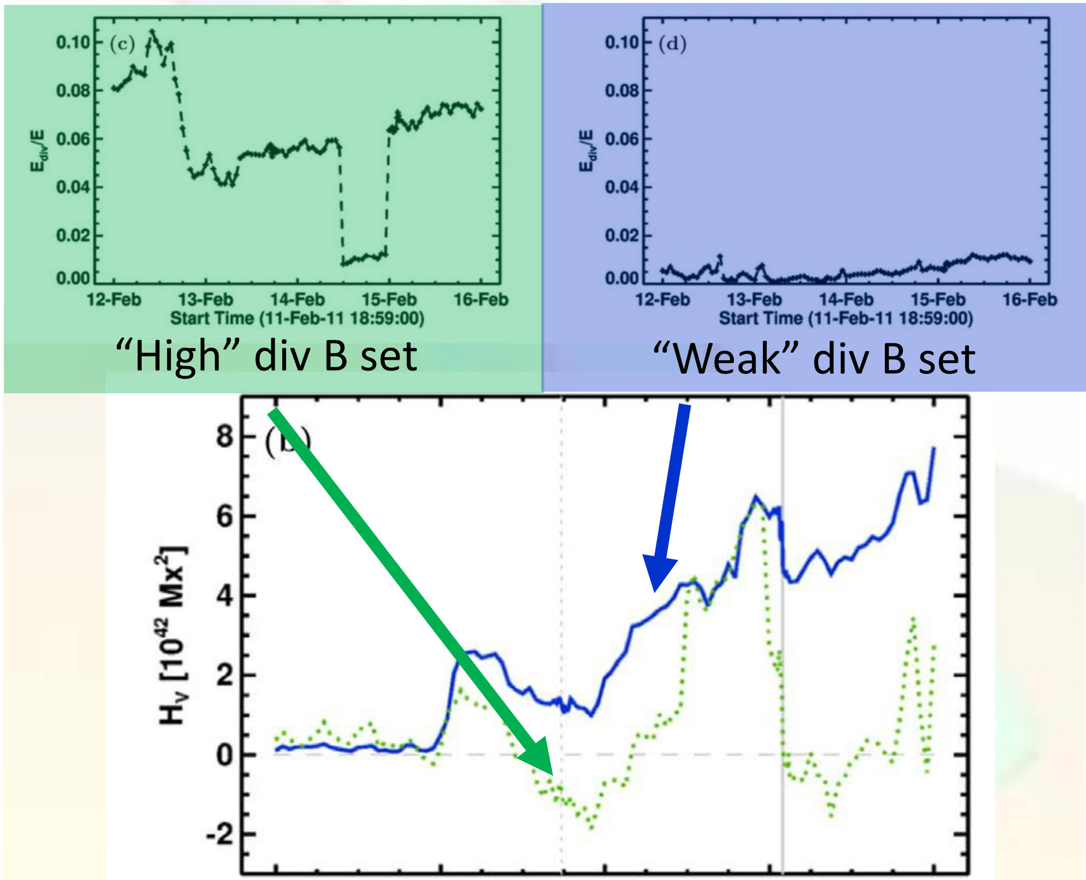


Measuring magnetic helicity in observations - 3

- Many extrapolation methods (the most popular ones) do not produce pure solenoidal magnetic field (with strict Div B=0)
- Magnetic Helicity is not strictly defined when the field has a finite div B
- ➔ Important source of error on the computation of relative helicity



(Valori et al. 16)



(Thalmann et al. 19a)

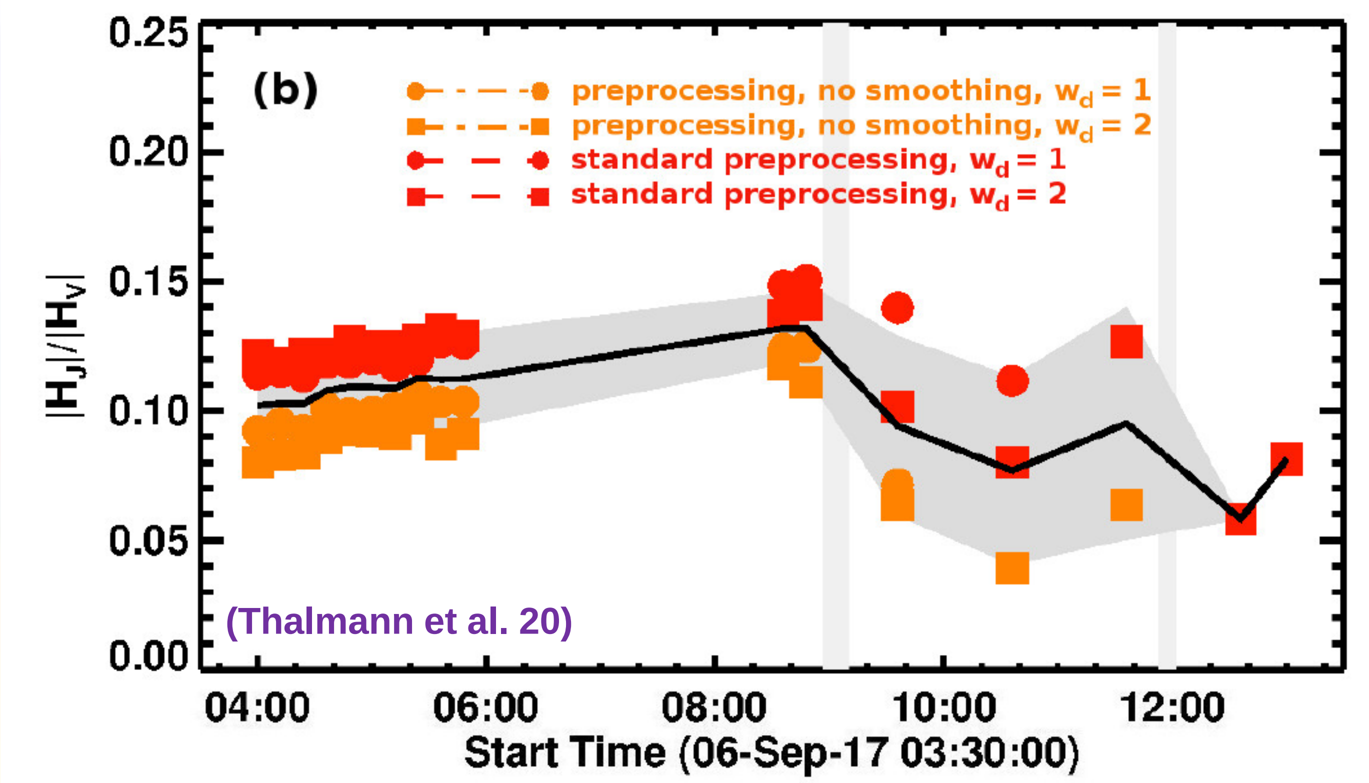
Measuring magnetic helicity in observations - 3

Words of advice:

- **While magnetic helicity can be evaluated from observational data …**
- **These estimations shall be evaluated with a critical eye !**

  (Thalmann et al. 19, 20 + Talk of J. Thalmann in Helicity 2020 online seminars)

  – Hopefully precision will improve in the future



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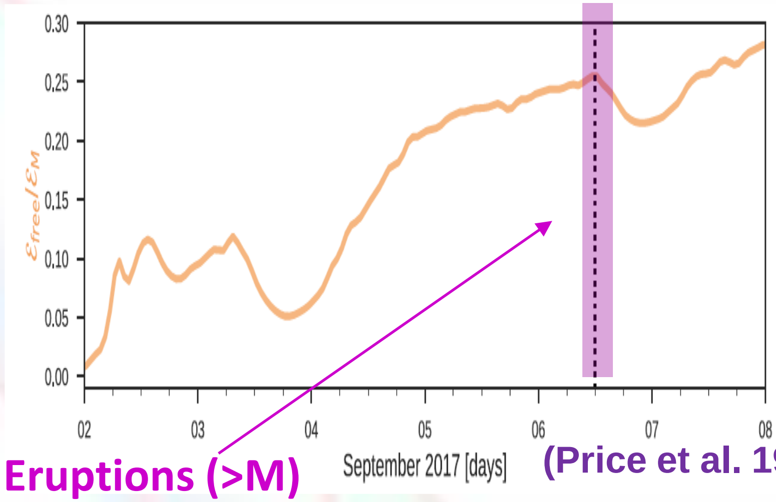
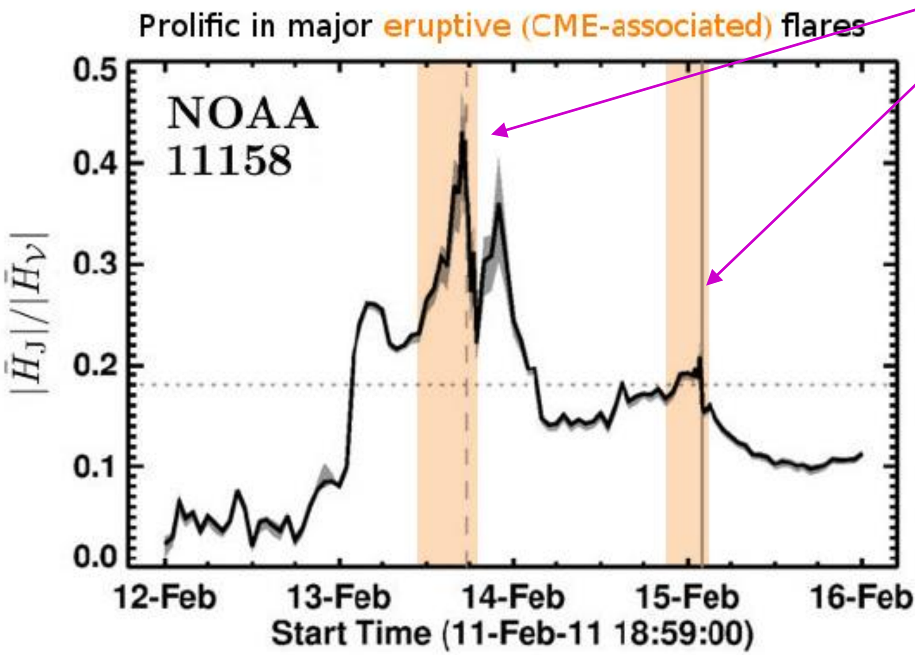
Helicity and eruptive flares

- **Helicity eruptivity index tends to show pronounced flare-related responses**
  (Moraitis et al. 19, Thalmann et al. 19b, Price et al. 19)
- But also
  - Peaks of Hj/Hv without flare
  - Some CME-less flares with no peak of helicity eruptivity index

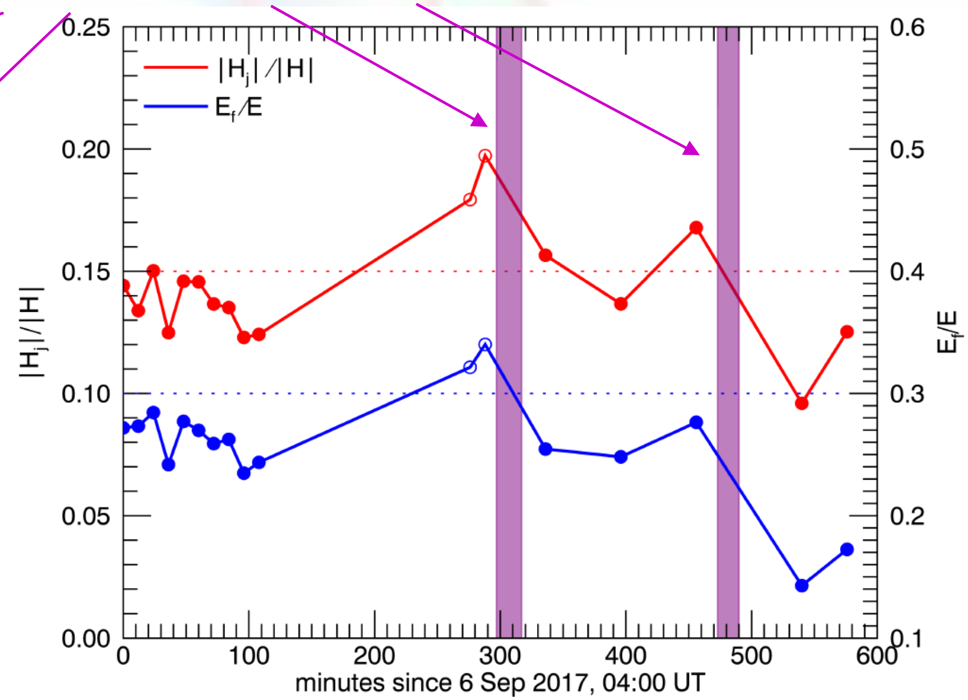


(Price et al. 19)

Major Eruptions (>M)



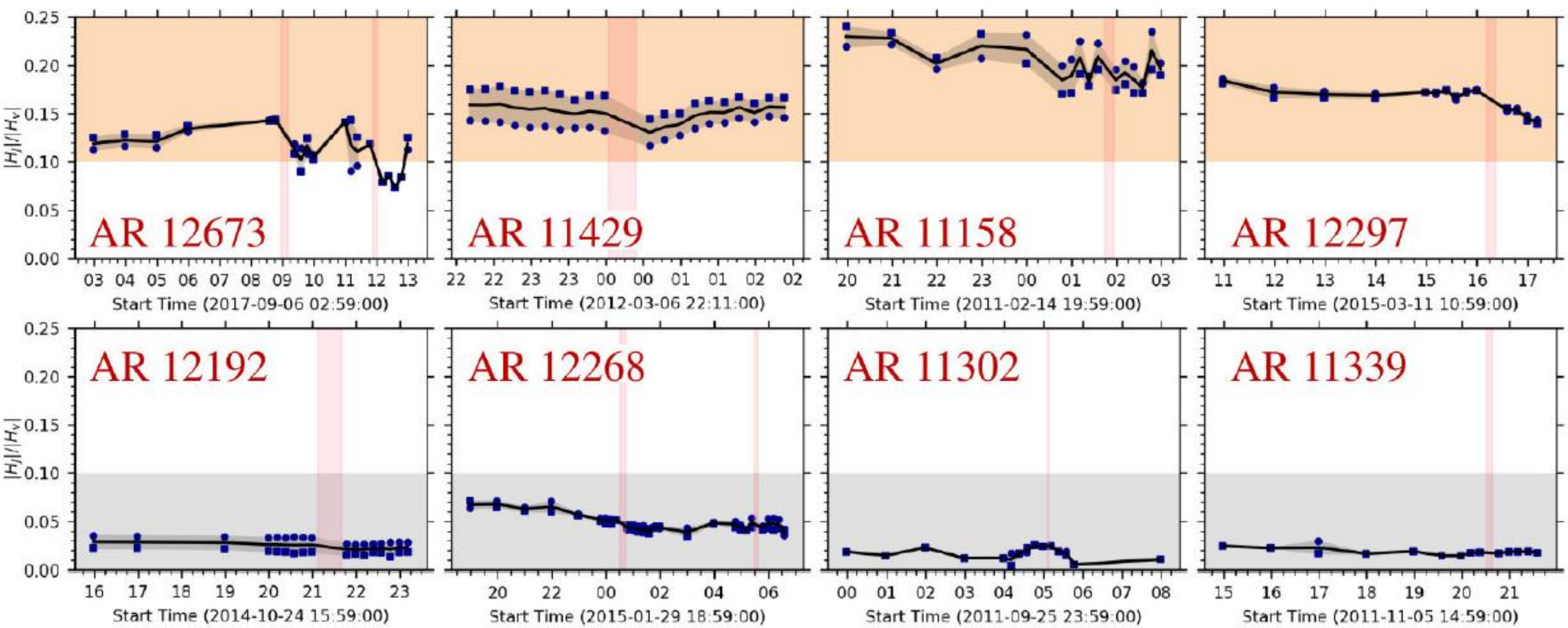
(Thalmann et al. 19b)



(Moraitis et al. 19)

Helicity eruptivity index and CME productive ARs

- Study of 12 solar ARs seems to show a link between high helicity eruptivity index and CME-productive active regions **(Gupta et al., in prep)**.
  - higher characteristic values in CME-productive ARs (Hj/Hv > 0.1)
  - lower characteristic values in CME-less ARs (Hj/Hv < 0.1)



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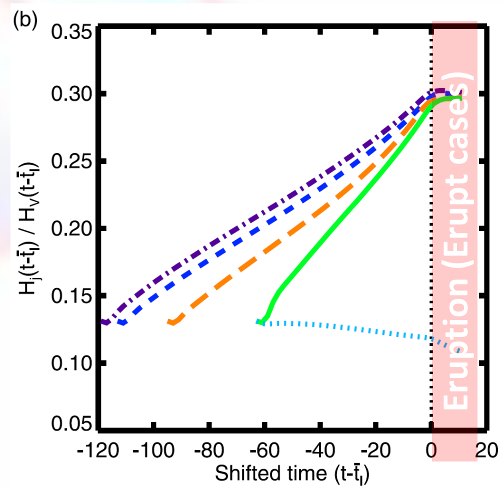
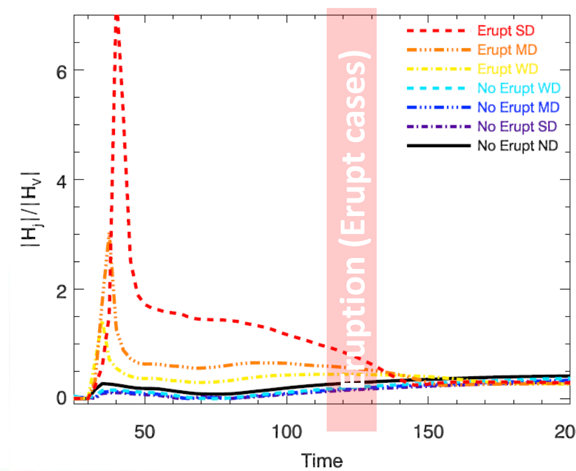
Conclusions

- **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

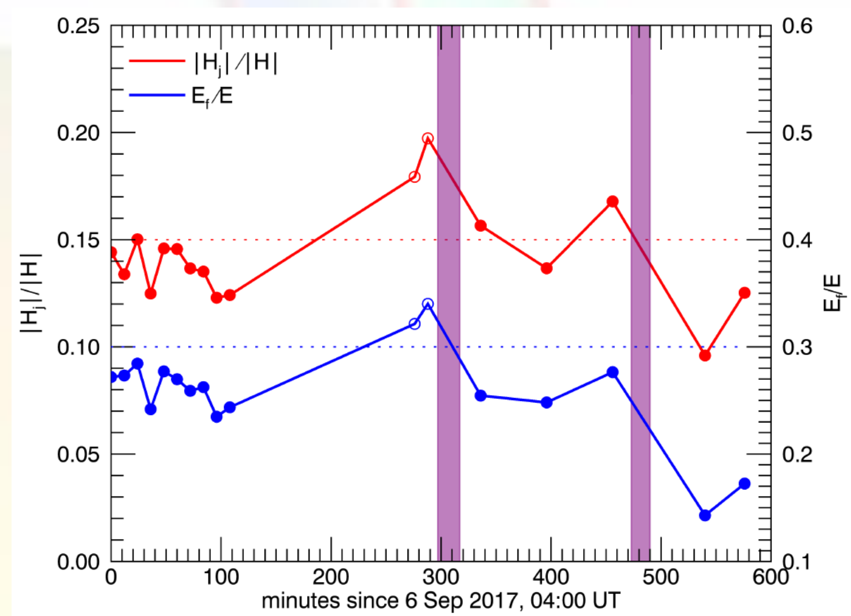
- **➔ needs to be fully validated against observational results:**
  - **statically significant**
  - **of a sufficiently good quality!**
- …. hard to do simultaneously!



(Zuccarello et al. 18)



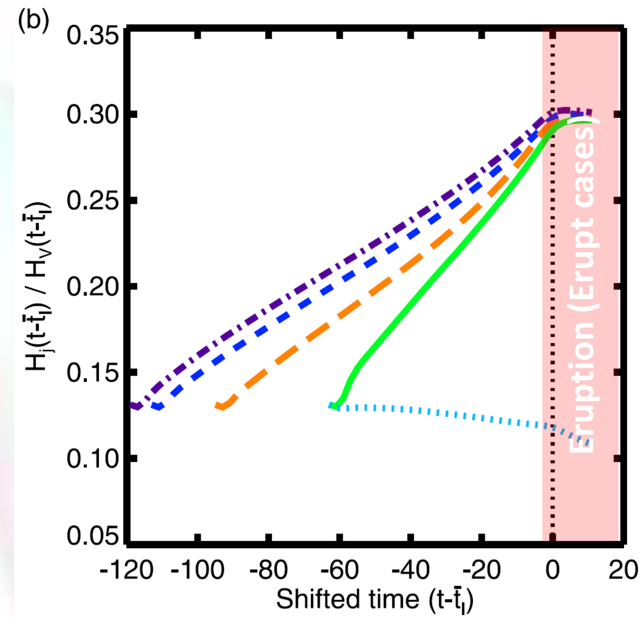
(Pariat et al. 17)



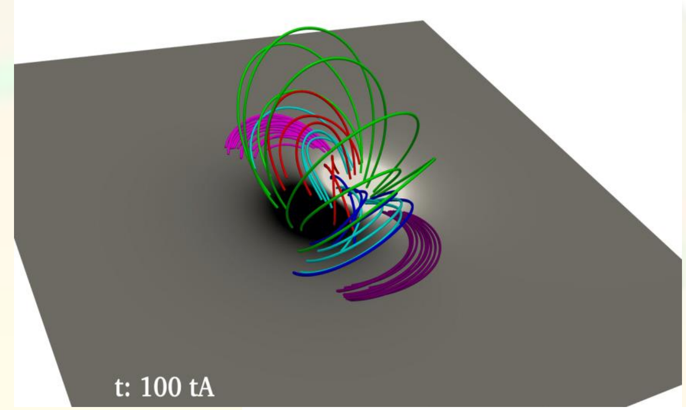
(Moraitis et al. 19)

Open questions

- **The helicity-based eruptivity index is likely perfectible**
  - Issue of non simple-additivity of relative magnetic helicity: **cf. Valori et al. 2020**
  - Choice of pertinent volume of interest
    - Index can be computed on whole Sun but likely not meaningful.
  - Other possible pertinent indices?
    - e.g. **Yang, Kai E et al. 2020**



- **If the helicity-based eruptivity index is indeed a strict marker of eruptivity, what does it implies on the eruptions trigger mechanism?**
  - → Torus instability?



(Zuccarello et al. 18)