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Magnetic helicity and its conservation: a future proxy for solar eruptions?

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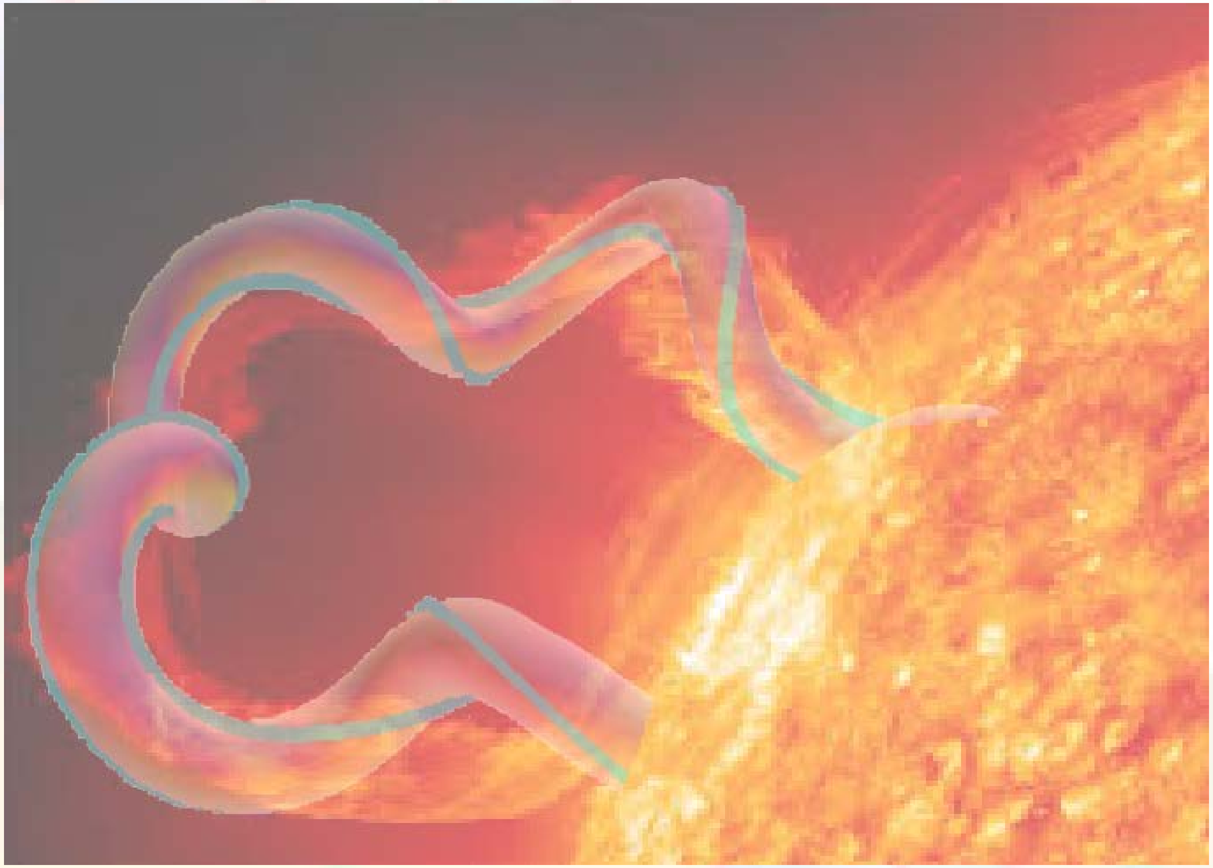
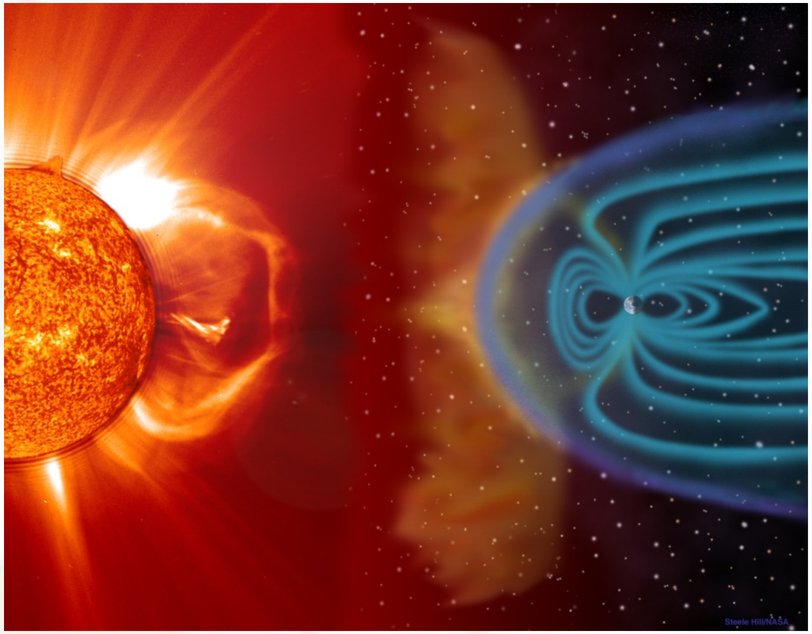
Outline

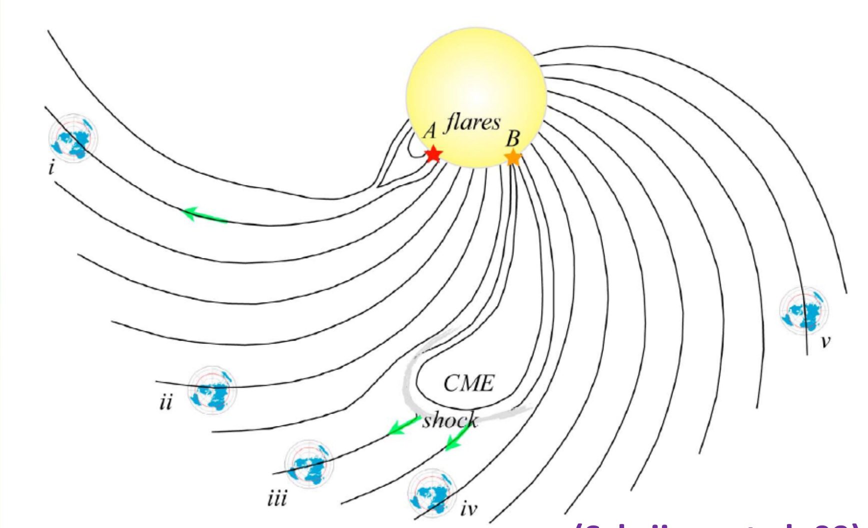
- Introduction: solar flare predictions
- Magnetic helicity: definition & properties
- Magnetic Helicity conservation in solar physics
- Measuring magnetic helicity and its conservation
- New tests on helicity conservation: solar active-like event
- Conclusion: the way forward



Space Weather Prediction

- Need to quantify and predict the **specific and cumulative impact** of solar activity on Earth.
- Necessary to understand the underlying physics of Sun-Earth relationships
- Key Questions:
  - Heliophysics problematic: if an eruption occurred:
    - Will it impact the Earth?
    - Will it create damages?
  - **Solar physics problematic: will an eruption occur?**
    - When will it occur?
    - Where does it occurs?
    - What are its properties?



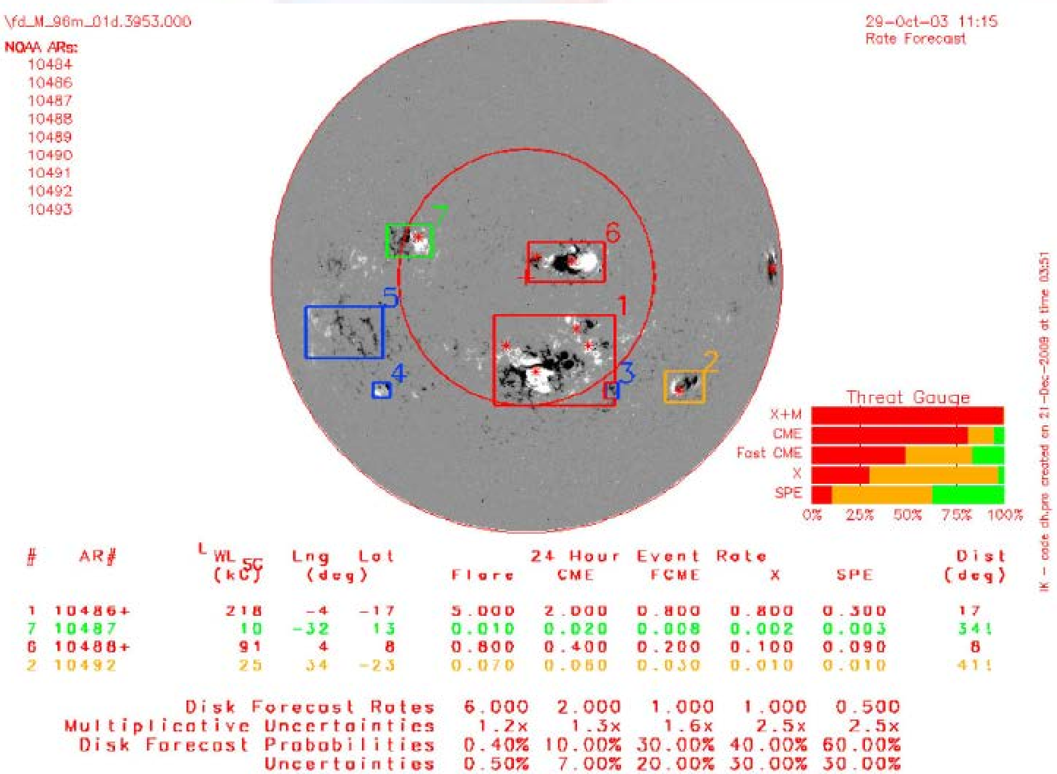


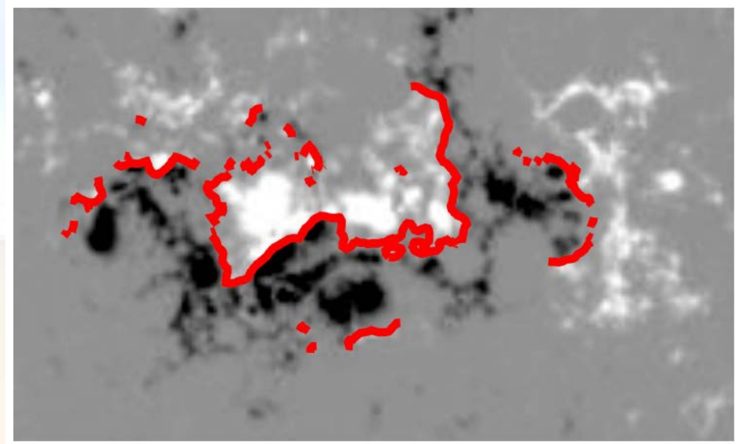
(Schrijver et al. 09)

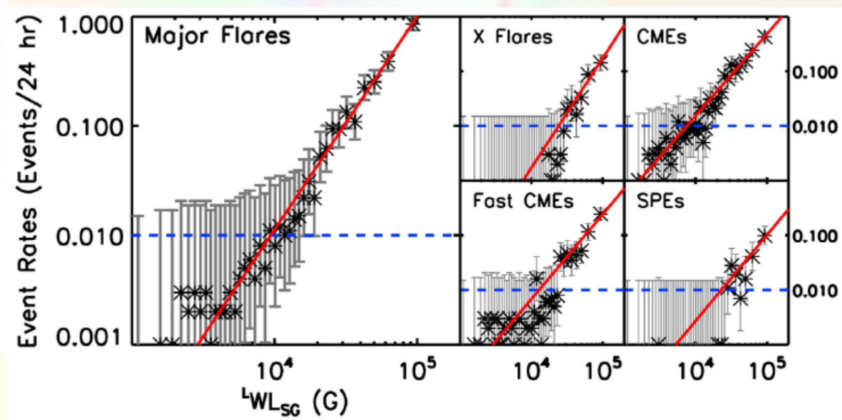
Flare Predictions

- **Empirical models** used to predict flares: correlation between:
  - **Characteristics of an AR** (McIntosh class, Mt Wilson magnetic class, PIL length, …)
  - **Observed probability** for a region with a given characteristic to flare

➔ **Not a deterministic approach!**







(Falconer et al. 11)

Flare Predictions

- Daily forecasts: SWPC, SIDC, …
  - Works with a relatively large time window for prediction (> 24hrs)
  - Subjectivity improves forecast
  - Prediction for large flare (X-class): 40-50%
    - Using “best” time window for prediction

(Crown 12)

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

Flare Predictions

- No eruption precursor has yet been discovered by coronal observations:
  - **➔ eruptive events: long energy accumulation and catastrophic energy release**
- Multiples criterion of photospheric dynamics have been used.
- Single criterion alone gives very poor prediction
  - Combination of several criteria improves prediction.

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	$\Phi_{\mathrm{tot}} = \sum \lvert B_z \rvert\, dA$	Φ_{tot}
Absolute value of the net flux	$\lvert \Phi_{\mathrm{net}} \rvert = \lvert \sum B_z\, dA \rvert$	$\lvert \Phi_{\mathrm{net}} \rvert$
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	$\lvert \nabla_h B_z \rvert = \left[(\partial B_z/\partial x)^2 + (\partial B_z/\partial y)^2\right]^{1/2}$	$\mathcal{M}(\lvert \nabla_h B_z \rvert)$
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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	$I_{\mathrm{tot}} = \sum \lvert J_z \rvert\, dA$	I_{tot}
Absolute value of the net vertical current	$\lvert I_{\mathrm{net}} \rvert = \lvert \sum J_z\, dA \rvert$	$\lvert I_{\mathrm{net}} \rvert$
Sum of absolute value of net currents in each polarity	$\lvert I_{\mathrm{net}}^B \rvert = \lvert \sum J_z(B_z > 0)\, dA \rvert + \lvert \sum J_z(B_z < 0)\, dA \rvert$	$\lvert I_{\mathrm{net}}^B \rvert$
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	$I_{\mathrm{tot}}^h = \sum \lvert J_z^h \rvert\, dA$	I_{tot}^h
Absolute value of net vertical heterogeneity current	$\lvert I_{\mathrm{net}}^h \rvert = \lvert \sum J_z^h\, dA \rvert$	$\lvert I_{\mathrm{net}}^h \rvert$
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]	$\boldsymbol{B} = \alpha_{\mathrm{ff}} \nabla \times \boldsymbol{B}$	$\lvert \alpha_{\mathrm{ff}} \rvert$
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	$H_c^{\mathrm{tot}} = \sum \lvert h_c \rvert\, dA$	H_c^{tot}
Absolute value of net current helicity	$\lvert H_c^{\mathrm{net}} \rvert = \lvert \sum h_c\, dA \rvert$	$\lvert H_c^{\mathrm{net}} \rvert$
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	$\Psi_{\mathrm{NL}} = \cos^{-1}(\boldsymbol{B}_{\mathrm{NL}}^p \cdot \boldsymbol{B}_{\mathrm{NL}}^o / B_{\mathrm{NL}}^p B_{\mathrm{NL}}^o)$	$\mathcal{M}(\Psi_{\mathrm{NL}})$
Length of neutral line with shear $>\Psi_0$	$L(\Psi_{\mathrm{NL}} > \Psi_0) = \sum_{\Psi_{\mathrm{NL}} > \Psi_0} dL$	$L(\Psi_{\mathrm{NL}} > 45°)$, $L(\Psi_{\mathrm{NL}} > 80°)$
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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

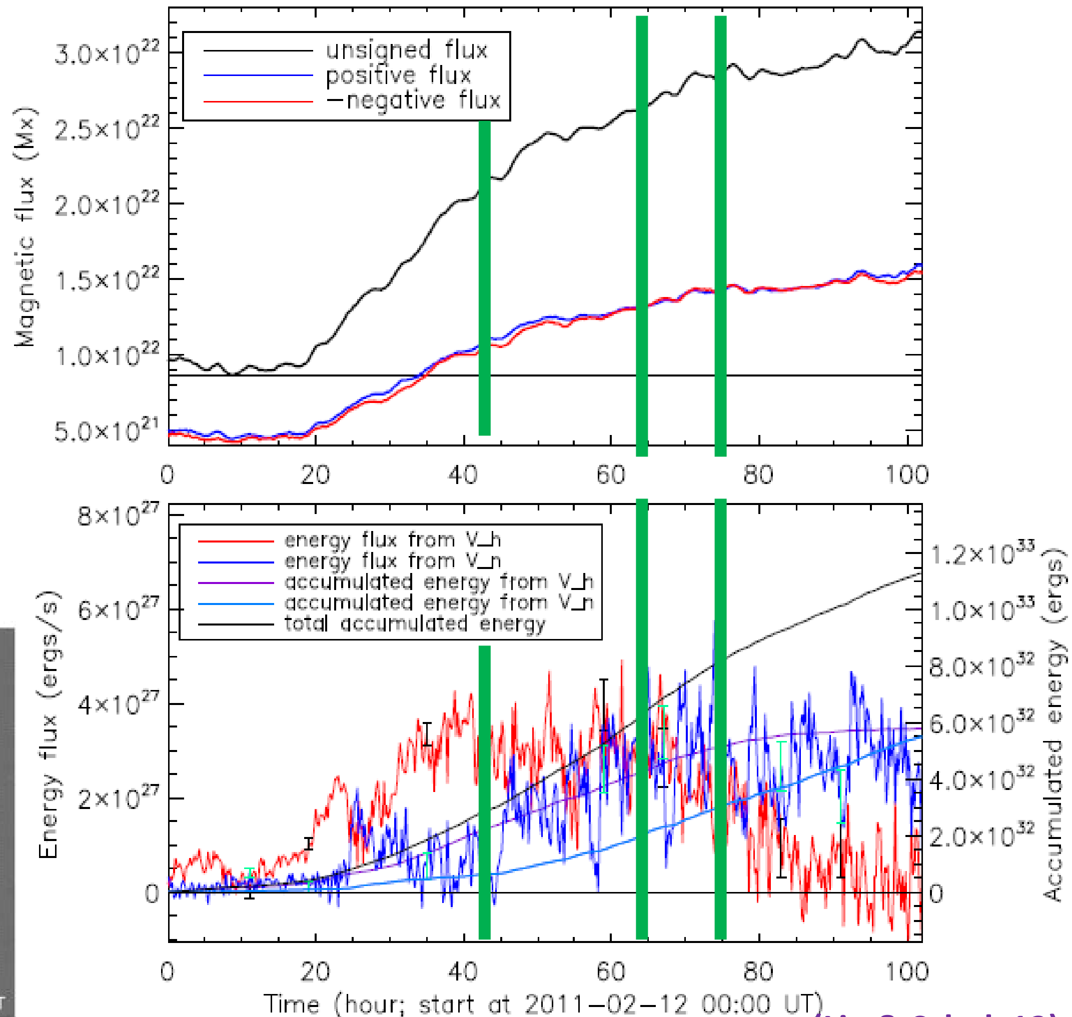
(Leka & Barnes 07)

Energy build-up in an active region

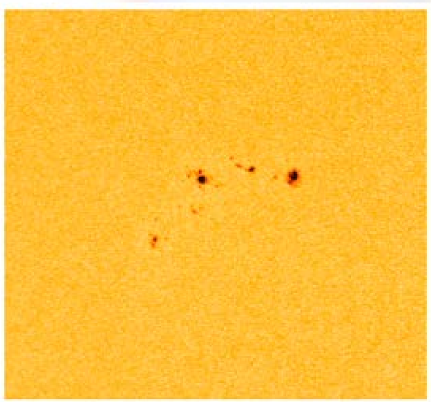
- Prior and during a major active events flare: smooth evolution observed at the photosphere.
  - Magnetic flux
  - Photospheric velocities
  - Magnetic energy

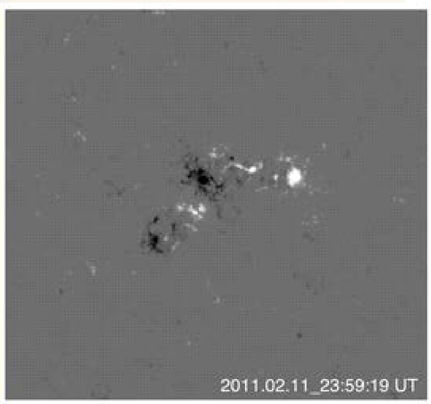
- **➔ Energy release trigger is not primarily correlated with the driving mechanism of the energy injection.**

Major Flares



(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**

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(Leka & Barnes 07)

« Best » criterions

- Recent study of the best photospheric proxies using **vector magnetograms**
- Improves existing prediction skill scores
- Four best criterions gives as good results as all accumulated

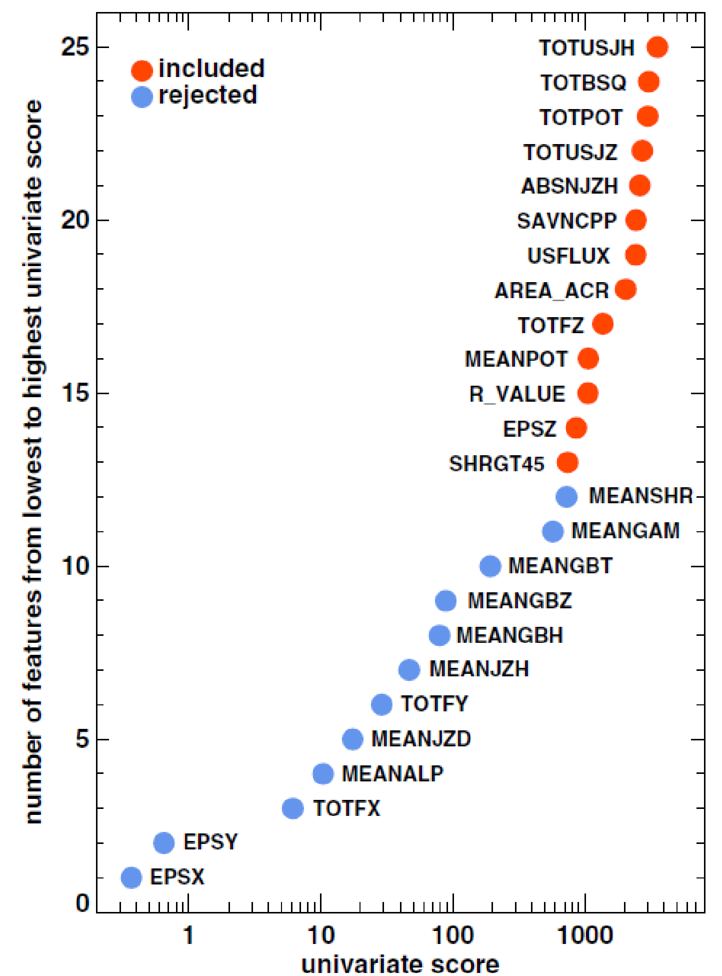


Table 1
SHARP Active Region Parameter Formulae

Keyword	Description	Formula	F-Score	Selection
TOTUSJH	Total unsigned current helicity	$H_{c_{\text{total}}} \propto \sum \lvert B_z \cdot J_z \rvert$	3560	Included
TOTBSQ	Total magnitude of Lorentz force	$F \propto \sum B^2$	3051	Included
TOTPOT	Total photospheric magnetic free energy density	$\rho_{\text{tot}} \propto \sum \left(\boldsymbol{B}^{\text{Obs}} - \boldsymbol{B}^{\text{Pot}}\right)^2 dA$	2996	Included
TOTUSJZ	Total unsigned vertical current	$J_{z_{\text{total}}} = \sum \lvert J_z \rvert dA$	2733	Included
ABSNJZH	Absolute value of the net current helicity	$H_{c_{\text{abs}}} \propto \left\lvert \sum B_z \cdot J_z \right\rvert$	2618	Included
SAVNCPP	Sum of the modulus of the net current per polarity	$J_{z_{\text{sum}}} \propto \left\lvert \sum^{B_z^+} J_z dA \right\rvert + \left\lvert \sum^{B_z^-} J_z dA \right\rvert$	2448	Included
USFLUX	Total unsigned flux	$\Phi = \sum \lvert B_z \rvert dA$	2437	Included
AREA_ACR	Area of strong field pixels in the active region	$\text{Area} = \sum \text{Pixels}$	2047	Included
TOTFZ	Sum of z-component of Lorentz force	$F_z \propto \sum (B_x^2 + B_y^2 - B_z^2) dA$	1371	Included
MEANPOT	Mean photospheric magnetic free energy	$\overline{\rho} \propto \frac{1}{N} \sum \left(\boldsymbol{B}^{\text{Obs}} - \boldsymbol{B}^{\text{Pot}}\right)^2$	1064	Included
R_VALUE	Sum of flux near polarity inversion line	$\Phi = \sum \lvert B_{LoS} \rvert dA$ within R mask	1057	Included
EPSZ	Sum of z-component of normalized Lorentz force	$\delta F_z \propto \frac{\sum (B_x^2 + B_y^2 - B_z^2)}{\sum B^2}$	864.1	Included
SHRGT45	Fraction of Area with shear $> 45°$	Area with shear $> 45°$ / total area	740.8	Included
MEANSHR	Mean shear angle	$\overline{\Gamma} = \frac{1}{N} \sum \arccos\left(\frac{\boldsymbol{B}^{\text{Obs}} \cdot \boldsymbol{B}^{\text{Pot}}}{\lvert \boldsymbol{B}^{\text{Obs}} \rvert \lvert \boldsymbol{B}^{\text{Pot}} \rvert}\right)$	727.9	Discarded
MEANGAM	Mean angle of field from radial	$\overline{\gamma} = \frac{1}{N} \sum \arctan\left(\frac{B_h}{B_z}\right)$	573.3	Discarded
MEANGBT	Mean gradient of total field	$\overline{\lvert \nabla B_{\text{tot}} \rvert} = \frac{1}{N} \sum \sqrt{\left(\frac{\partial B}{\partial x}\right)^2 + \left(\frac{\partial B}{\partial y}\right)^2}$	192.3	Discarded
MEANGBZ	Mean gradient of vertical field	$\overline{\lvert \nabla B_z \rvert} = \frac{1}{N} \sum \sqrt{\left(\frac{\partial B_z}{\partial x}\right)^2 + \left(\frac{\partial B_z}{\partial y}\right)^2}$	88.40	Discarded
MEANGBH	Mean gradient of horizontal field	$\overline{\lvert \nabla B_h \rvert} = \frac{1}{N} \sum \sqrt{\left(\frac{\partial B_h}{\partial x}\right)^2 + \left(\frac{\partial B_h}{\partial y}\right)^2}$	79.40	Discarded
MEANJZH	Mean current helicity (B_z contribution)	$\overline{H_c} \propto \frac{1}{N} \sum B_z \cdot J_z$	46.73	Discarded
TOTFY	Sum of y-component of Lorentz force	$F_y \propto \sum B_y B_z dA$	28.92	Discarded
MEANJZD	Mean vertical current density	$\overline{J_z} \propto \frac{1}{N} \sum \left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right)$	17.44	Discarded
MEANALP	Mean characteristic twist parameter, α	$\alpha_{\text{total}} \propto \frac{\sum J_z \cdot B_z}{\sum B_z^2}$	10.41	Discarded
TOTFX	Sum of x-component of Lorentz force	$F_x \propto -\sum B_x B_z dA$	6.147	Discarded
EPSY	Sum of y-component of normalized Lorentz force	$\delta F_y \propto \frac{-\sum B_y B_z}{\sum B^2}$	0.647	Discarded
EPSX	Sum of x-component of normalized Lorentz force	$\delta F_x \propto \frac{\sum B_x B_z}{\sum B^2}$	0.366	Discarded

(Bobra & Couvidat 15)

« Best » criterions

- Four best criterions gives as good results as all accumulated

Description	Formula
Total unsigned current helicity	$H_{c_{\text{total}}} \propto \sum \lvert B_z \cdot J_z \rvert$
Total magnitude of Lorentz force	$F \propto \sum B^2$
Total photospheric magnetic free energy density	$\rho_{\text{tot}} \propto \sum \left(\boldsymbol{B}^{\text{Obs}} - \boldsymbol{B}^{\text{Pot}}\right)^2 dA$
Total unsigned vertical current	$J_{z_{\text{total}}} = \sum \lvert J_z \rvert dA$

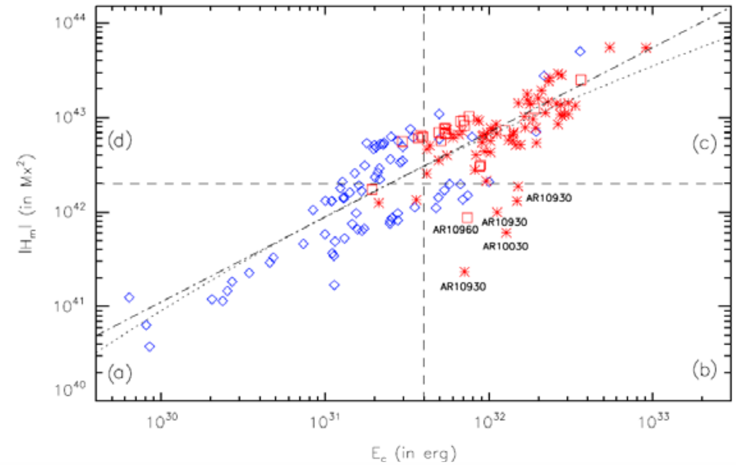
(Bobra & Couvidat 15)

Criterions based on current helicity, currents (Jz), and non-potential magnetic energy

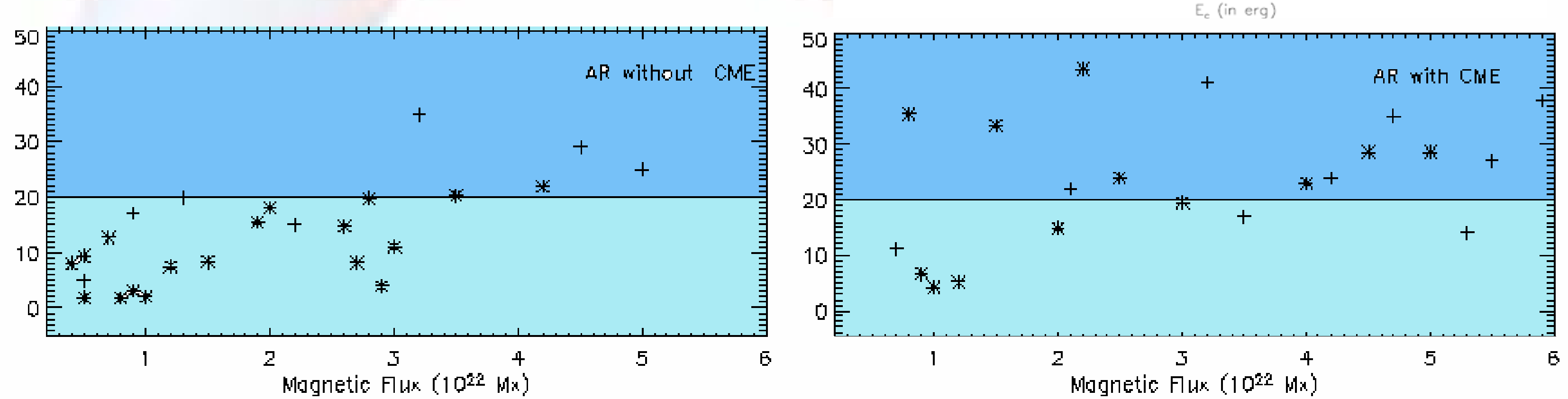
➔ While not directly tested all are related to magnetic helicity!

Is there an helicity threshold to trigger eruptions event?

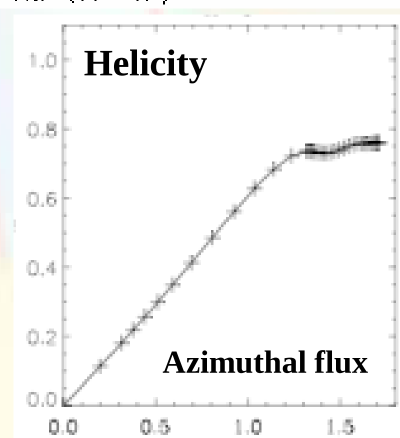
- Observations :
  - Minimum helicity & free energy threshold to trigger >M class flares?: **Yes**: 2×10^{42} Mx^2 **(Tziotziou et al. 12)**
  - **Magnetic helicity of CME productive ARs is higher than other ARs (Nindos 05)**



Total Coronal Helicity (10^{42} Mx^2)



- Numerical simulations : controversial debates
  - Magnetic helicity poorly studied (freq. & quality).
- Theory : Helicity is one of the few invariant of MHD!
  - Upper bound of magnetic helicity that force free fields can contains **(Zhang & Low 06)**



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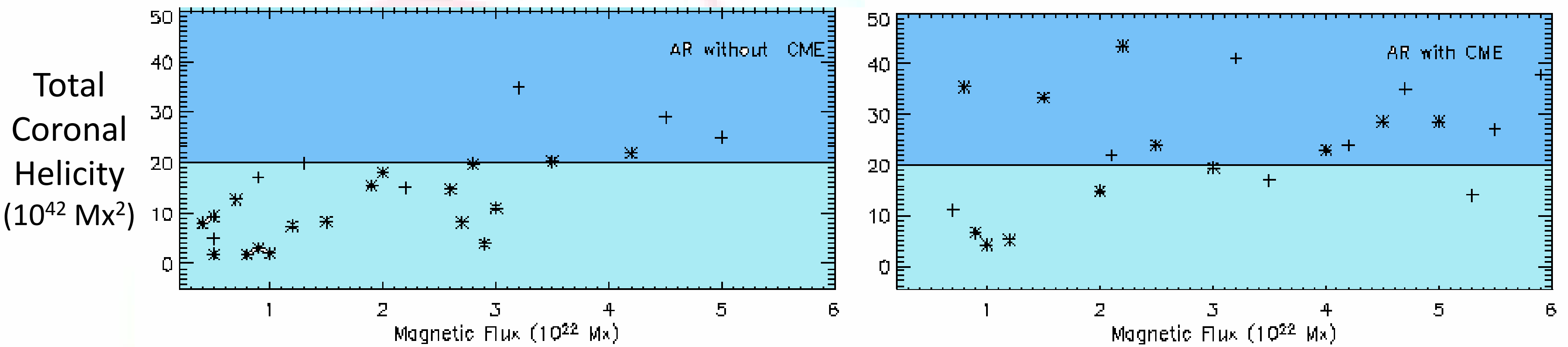
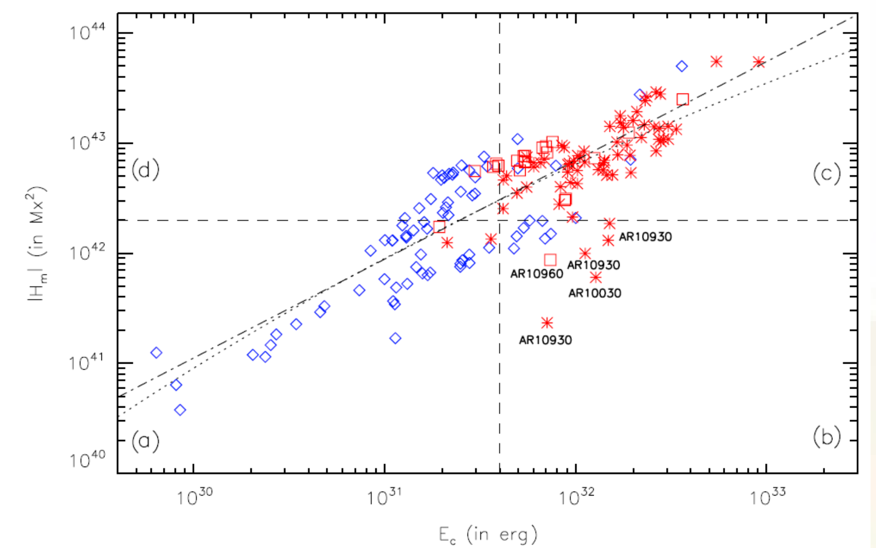


➔ **Hints that magnetic helicity is worth being further tested as an eruptive/flaring proxy !**



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- Introduction: solar flare predictions
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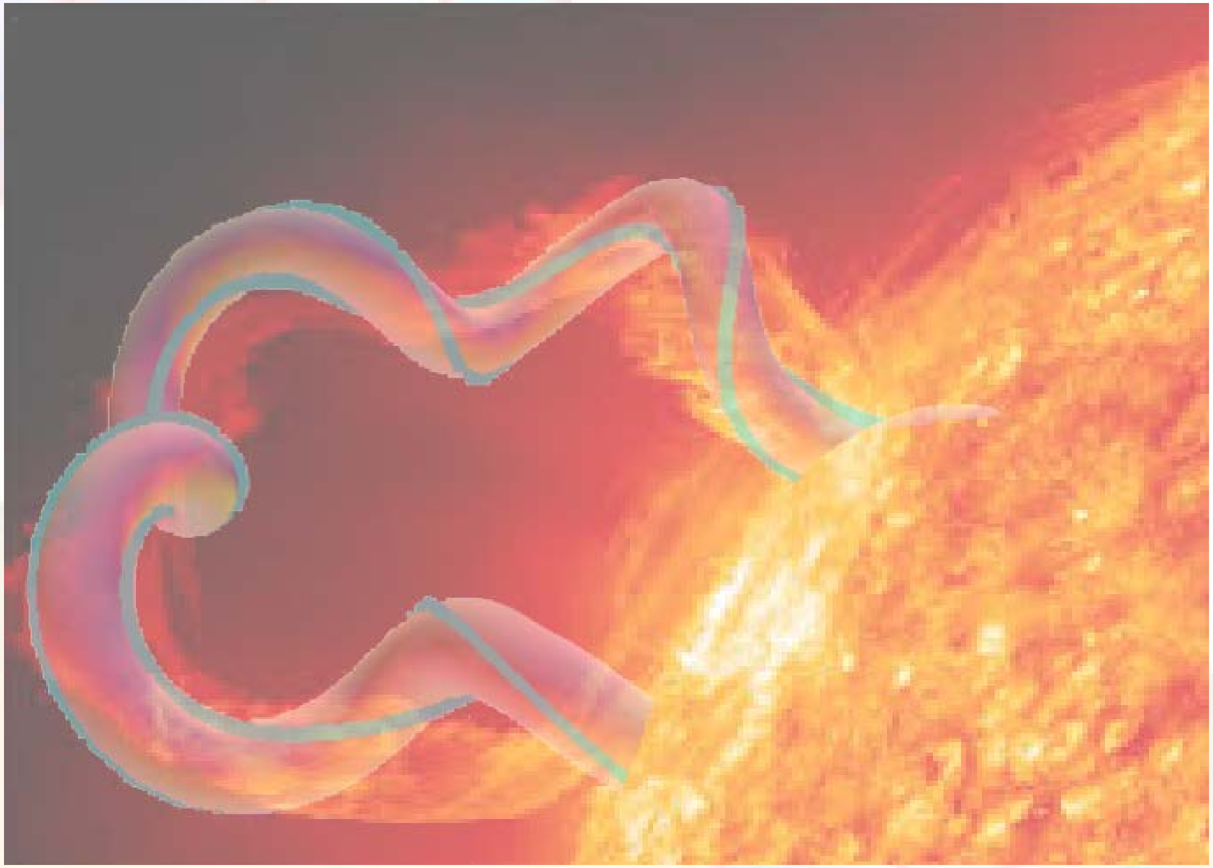
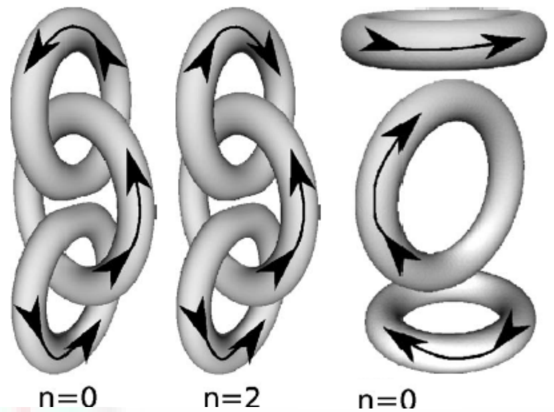


Definition of Magnetic Helicity

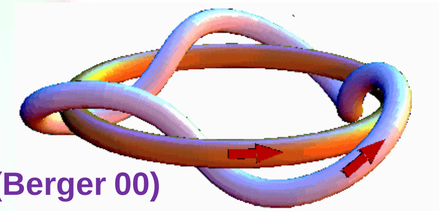
$$H = \int_{\mathcal{V}} \vec{A} \cdot \vec{B}\, \mathrm{d}V \quad , \quad \vec{B} = \vec{\nabla} \times \vec{A} \leftarrow$$

Magnetic vector potential



(Del Soro 10)

- **Helicity of the magnetic field in MHD plasmas** (Elsasser 56)
  - Current helicity: $\int_V \mathbf{B} \cdot \nabla \times \mathbf{B} d^3x,$
  - Kinetic helicity: $\int_V \mathbf{u} \cdot \nabla \times \mathbf{u} d^3x,$



(Berger 00)

- **Magnetic helicity: signed level of knotedness and twist of magnetic field lines**
  - Magnetic flux weighted **Gauss Linking Number** of pairs of magnetic field lines (Moffatt 1968)

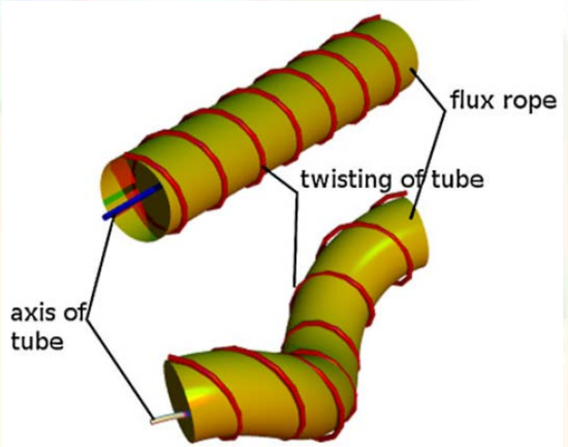
$$L_{12} = -\frac{1}{4\pi} \oint_1 \oint_2 \frac{d\mathbf{x}}{d\sigma} \cdot \frac{\mathbf{r}}{r^3} \times \frac{d\mathbf{y}}{d\tau}\, d\tau\, d\sigma$$

$$H = -\frac{1}{4\pi} \int \int \mathbf{B}(\mathbf{x}) \cdot \frac{\mathbf{r}}{r^3} \times \mathbf{B}(\mathbf{x}')\, d^3x\, d^3x'$$

  - Magnetic twist and writhe

$$H = N\, \Phi_{ax}^2$$

N:nbr of turns, Φ_{ax}: axial flux



(Prior & Berger 12)

Magnetic helicity properties

- **Magnetic helicity is an <u>ideal MHD</u> invariant. For E⊥B: no dissipation ➔ magnetic helicity is conserved** (Woltjer 58).

Time variations — **Surface Flux** — **Dissipation**

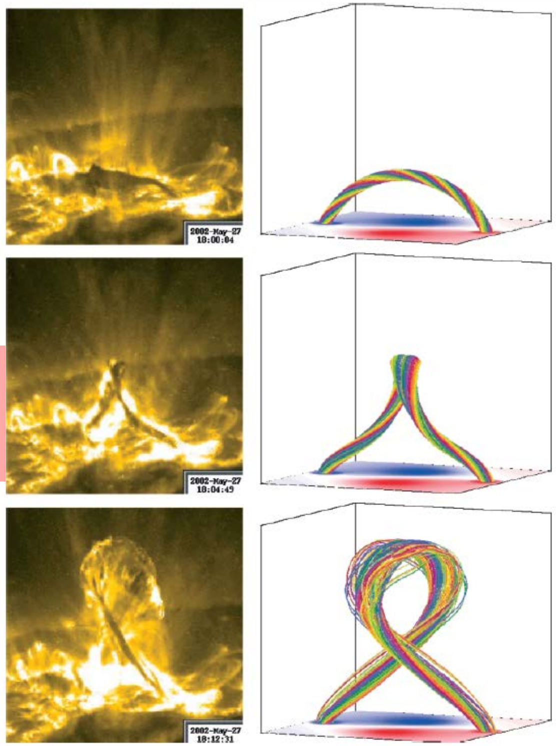
$$\frac{dH_m}{dt} = \int_{\partial\mathcal{V}} \left(\mathbf{A} \times \frac{\partial \mathbf{A}}{\partial t}\right) \cdot \mathrm{d}\mathbf{S} - 2\int_{\partial\mathcal{V}} (\mathbf{E} \times \mathbf{A}) \cdot \mathrm{d}\mathbf{S} - 2\int_{\mathcal{V}} \mathbf{E} \cdot \mathbf{B} \;\mathrm{d}\mathcal{V}$$

- Magnetic helicity bounds the energy distribution in the system: $\mu_0 \hat{E}(k) > k\hat{H}(k)$ (Frisch et al. 75)

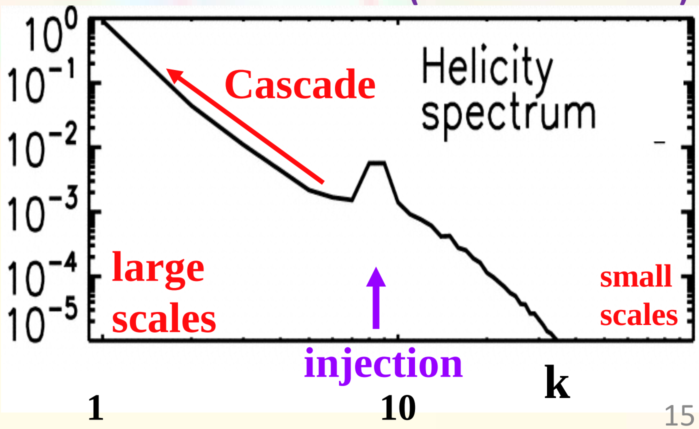
- Minimum energy solution of an isolated magnetic system for a given magnetic helicity: Linear Force Free (LFF) magnetic fields (**j**=α **B**)

- **Inverse helicity cascade:** Helicity goes from small to large spatial scales. (Frisch et al. 75, Alexakis et al. 06)

(Török et al. 05)



(Alexakis et al. 06)

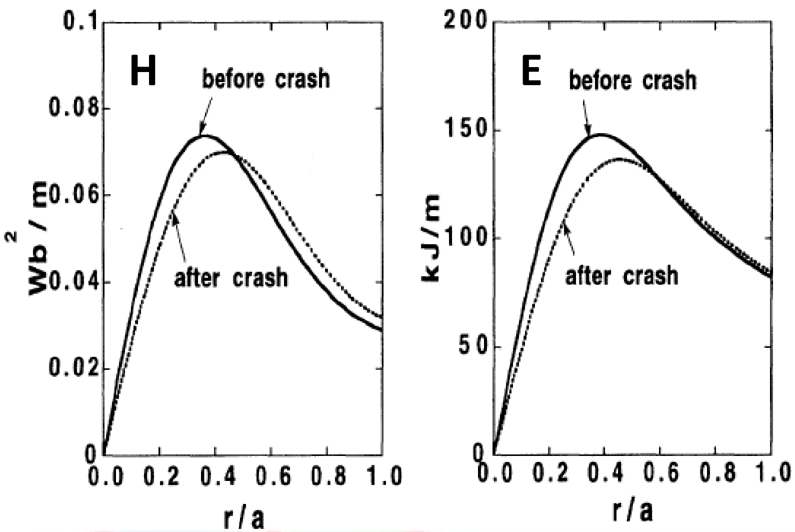


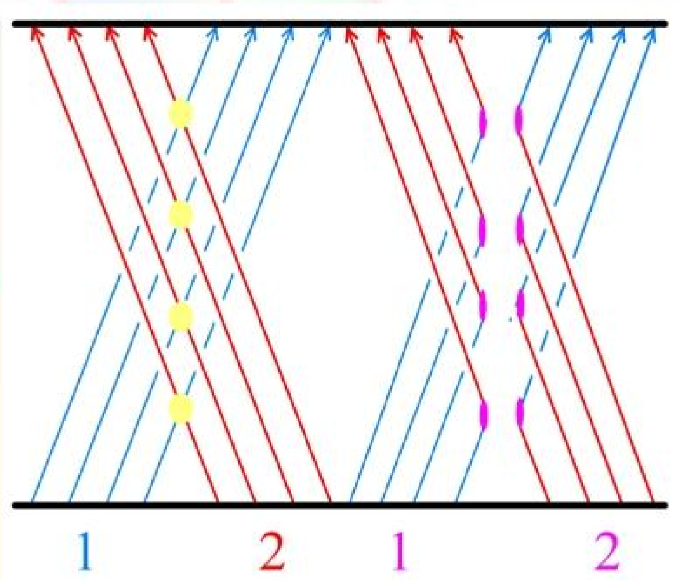
Taylor conjecture

- **Taylor relaxation conjecture: even in <u>non-Ideal MHD</u> magnetic helicity should be well conserved (Taylor 74)**
- Magnetic energy cascades to small scales where it is dissipated while helicity cascades to large scales **(Ji et al. 95, Heidbrink & Dang 00)**.
- Volume over which reconnection develop is small: large scale twist/helicity is not affected **(Berger 03)**.
- In resistive MHD, helicity dissipation is bounded and slow compared to energy dissipation **(Berger 84, Berger 99)**
  - Dissipation time of helicity in typical active region:~ several 100 year

$$\left|\frac{\mathrm{d}H}{\mathrm{d}t}\right|_{\mathrm{dis.}} \leq \sqrt{\frac{8\mu_0}{\sigma}W\left|\frac{\mathrm{d}W}{\mathrm{d}t}\right|}$$

(Ji et al. 95)



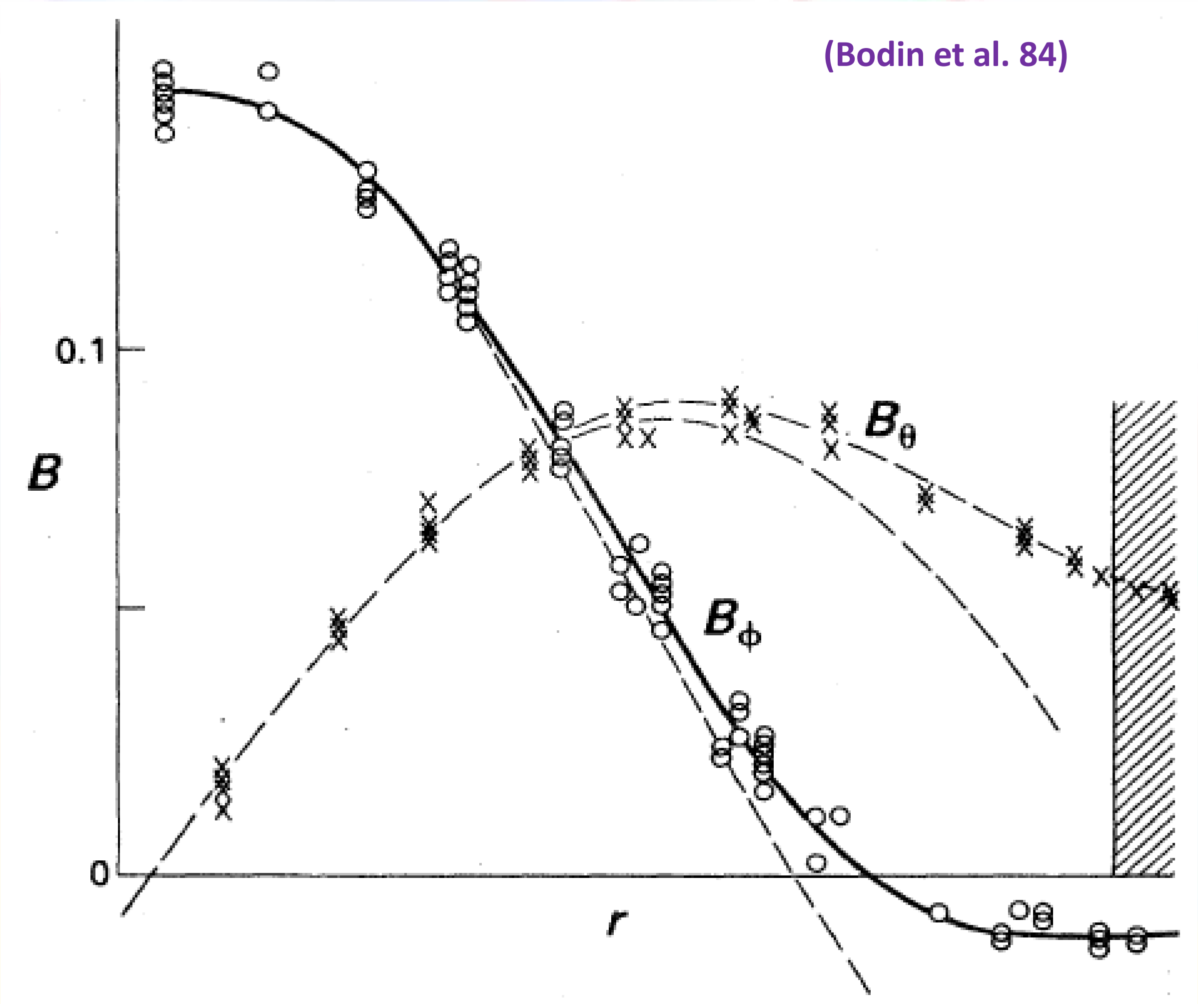


(Berger 03)

Magnetic Helicity in Tokamak

- Relaxation in lab. experiments: plasma relax to minimum energy state, i.e. linear force free field (LFFF) **e.g. Bodin et al. 84, Taylor et al. 86, Yamada et al. 99**

(Bodin et al. 84)



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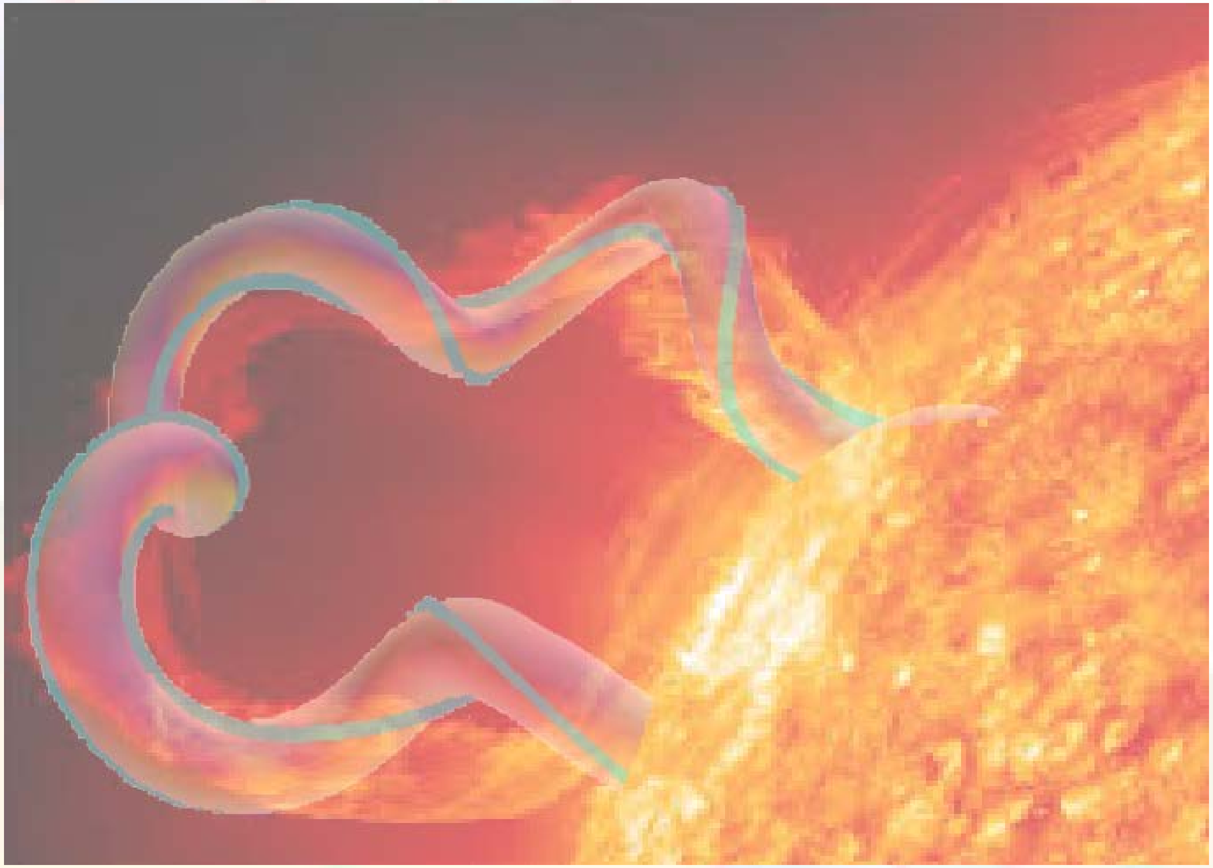
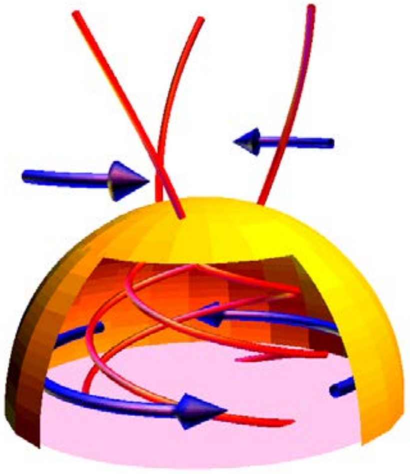


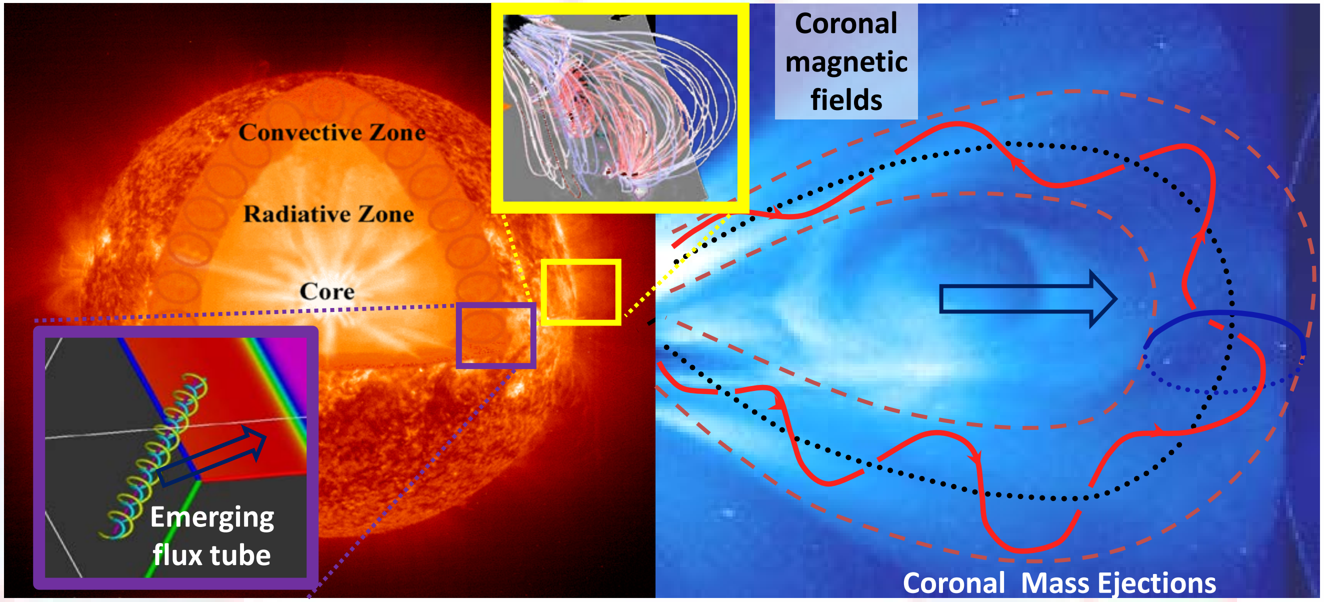
Why is helicity important ?



- ➔ **If effectively conserved, links the physics of:**
  - the convective zone (dynamo)
  - the corona (sigmoids, CMEs)
  - the interplanetary space (magnetic clouds, ICMEs)

- **Main questions related to magnetic Helicity:**
  - **Solar Dynamo:**
    - Is magnetic helicity responsible of the dynamo saturation ?
    - How is non-null helicity generated ? At which scale ?
  - **Active regions:**
    - What are the properties of magnetic helicity in ARs?
  - **Solar Flares :**
    - How helicity influences magnetic reconnection
    - Does helicity annihilation allow to trigger more intense flares ?
  - **Coronal Mass Ejections :**
    - Are they the consequence of the global helicity conservation?
    - Is there a threshold in helicity ?
  - **Coronal heating:**
    - Does helicity conservation constraint the DC heating mechanism?

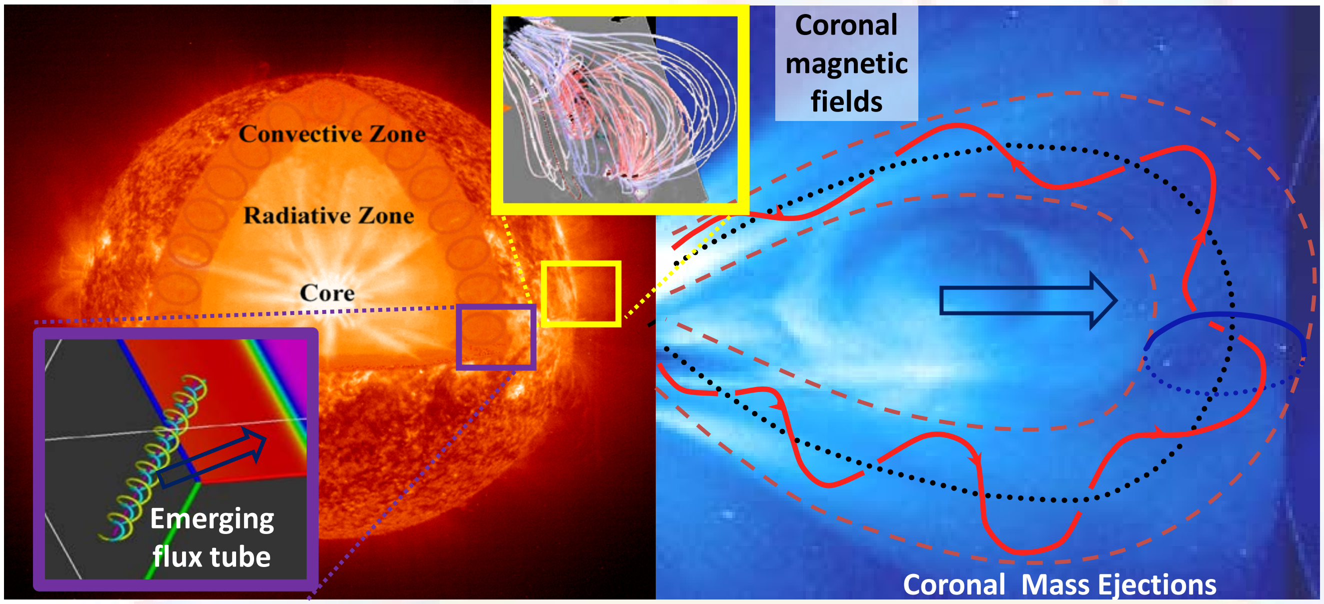
Conservation principle

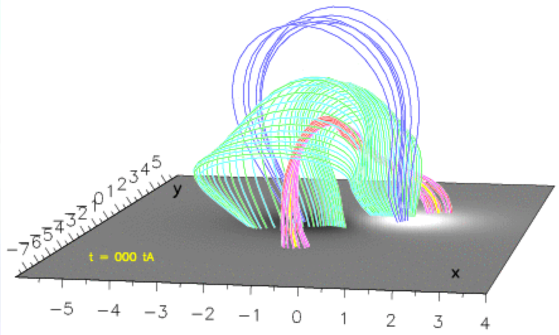


Magnetic helicity conservation is the “raison d’être” of CMEs:

- **No helicity dissipation in the corona.** The variation of helicity is only due to terms of flux **(Berger and Field, 84)** :
- **No helicity creation either:** no efficient dynamo
- **Some helicity is constantly injected through the photosphere:**
- Hypothesis: **magnetic helicity cannot be infinitely stored in the corona**
- **➔ Coronal Mass ejections (CMEs) appear as a natural way to eject magnetic helicity (Rust 94, Low 96).**

Magnetic Helicity in Solar Physics





(Aulanier et al. 10, Janvier et al 13)

Is magnetic helicity effectively conserved during eruptive events?

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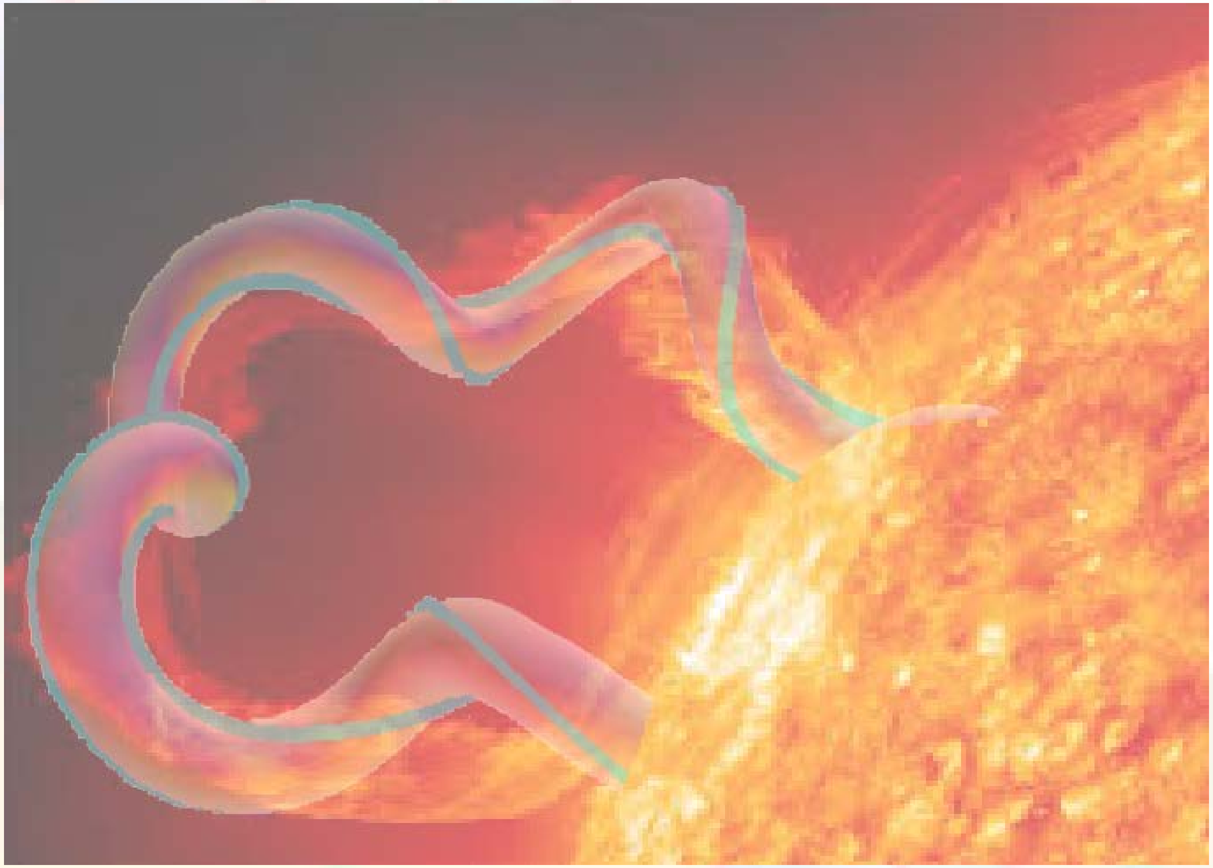
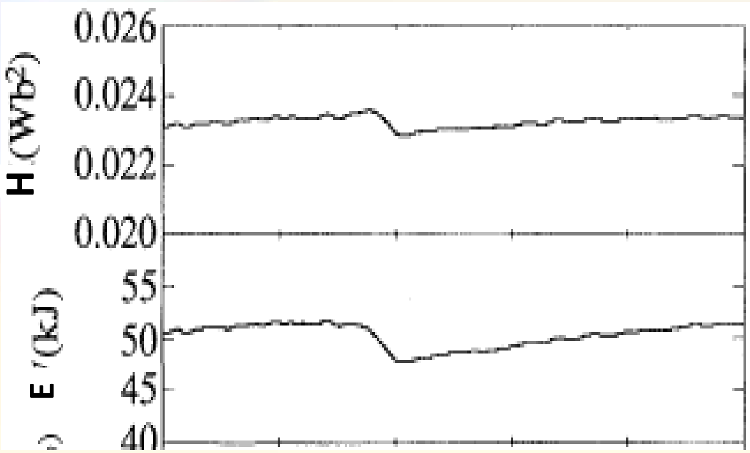


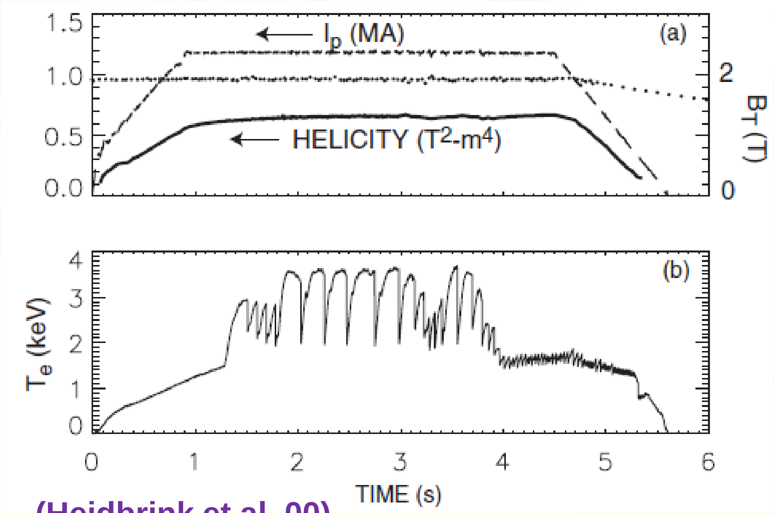
Tests on Magnetic Helicity Conservation

- **Despites its potential importance, tests on Taylor's conjecture have been very limited!**
  - Test on "relaxation" toward minimum energy state (LFFF): mixed results
    ➔ not direct test of magnetic helicity conservation, but of relaxation dynamics
- Laboratory experiments: difficult sampling of the full 3D magnetic field ; axisymmetric assumption **(Ji et al. 95, Barnes et al. 86, Heidbrink et al. 00, Gray et al. 10)**
  - Sawtooth relaxation: $\Delta H/H$=1-5% ; $\Delta E/E$=5-10%
  - Sawtooth crash: $\Delta H/H$=1%

- **Numerical simulation: no test in general conditions**, i.e. in 3D, active-like conditions, no periodicity …



(Ji et al. 95)



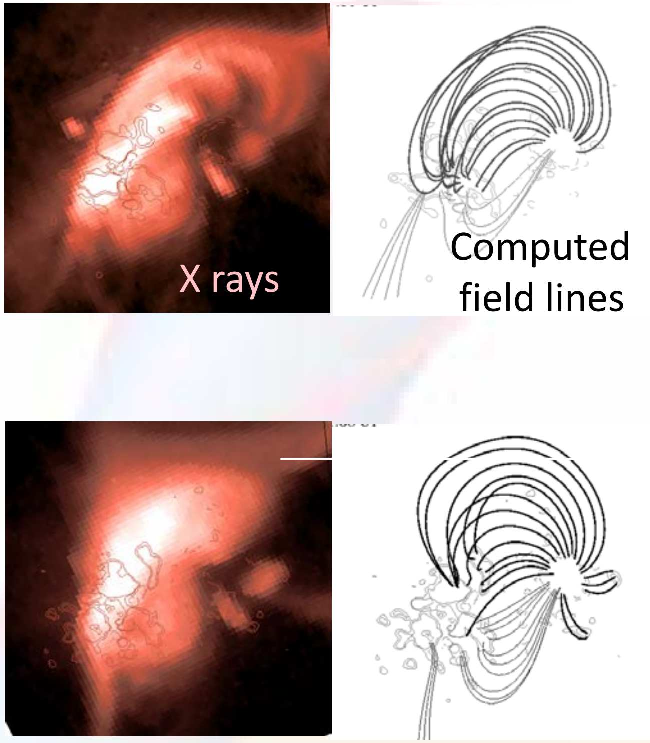
(Heidbrink et al. 00)

Linking coronal & interplanetary physics

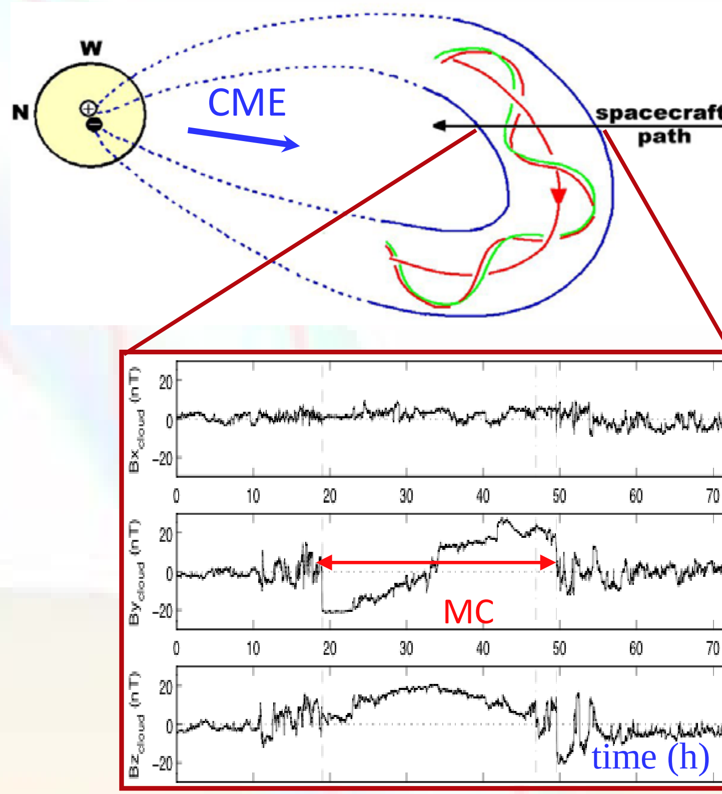
AR 7912, 14 Oct. 1995

before CME

after CME



4 days later



Data : Remote sensing but global

Magnetograms + coronal loops
+ extrapolation

-> ΔH_{corona}

In situ but local

Green et al. 07

Measurements of the 3 components of B
+ flux rope model

-> $H_{Magnetic\ Cloud}$

H conservation : $\Delta H_{corona} \sim H_{Magnetic\ Cloud}$?

- **Clear qualitative link**: same chirality / sign of helicity
- **Rough quantitative agreement** between AR & MC helicity
  - within large measurement imprecision

ICME	Solar source AR		Total
	Positive	Negative	
Positive	10	3	13
Negative	1	20	21
Total	11	23	34

(Mandrini et al. 2005, Luoni et al. 2005,Dasso et al. 2006, Nakwacki et al. 11, Cho et al. 13)

tiny event

11 May 1998

$L_{cloud} = 0.5$ AU

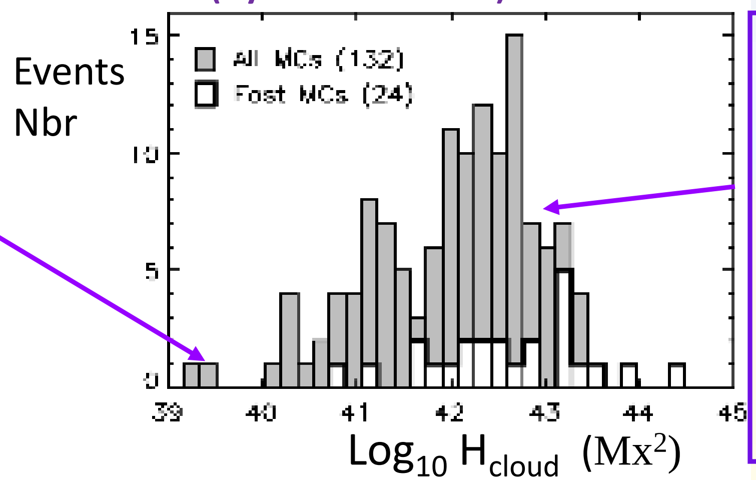
$2.3 \le |\Delta H_{corona}| \le 3.1$

$1.5 \le |H_{cloud}| \le 3.0$

~

Units : 10^{39} Mx^2

(Lynch et al. 2005)



large event

14 Oct. 1995

$L_{cloud} = 2$ AU

$3 \le \Delta H_{corona} \le 6$

$7 \le H_{cloud} \le 12$

factor ~ 2

Units : 10^{42} Mx^2

Gauge invariance of magnetic helicity

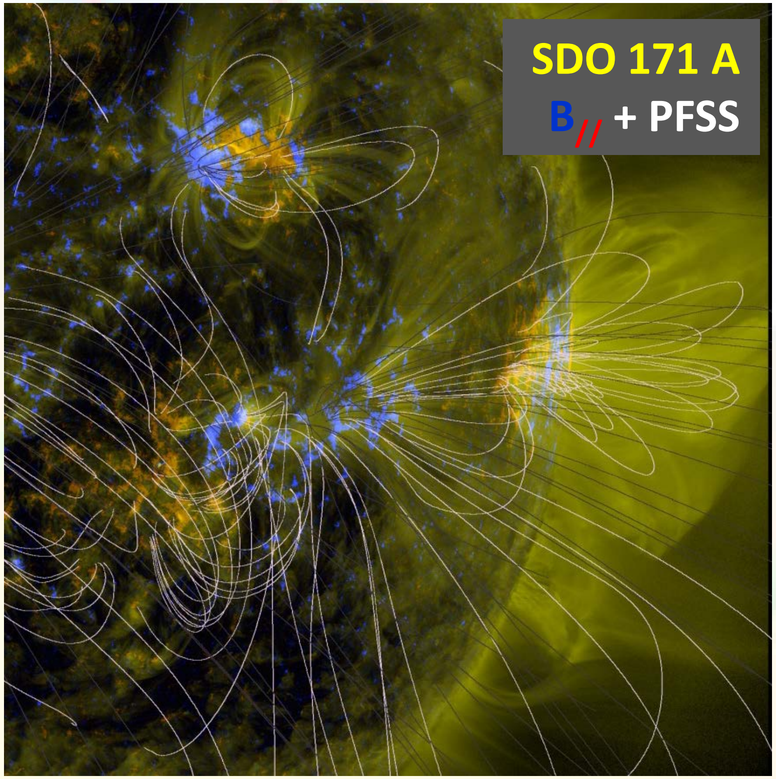
- Gauge transformation of magnetic helicity: $H = \int_{\mathcal{V}} \vec{A} \cdot \vec{B} \, \mathrm{d}V$

$$\vec{A}' \mapsto \vec{A} + \vec{\nabla}\varphi \qquad H_{A'} = H_A + \oint_S \varphi \, \vec{B} \cdot \overrightarrow{\mathrm{dS}}$$

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

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

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



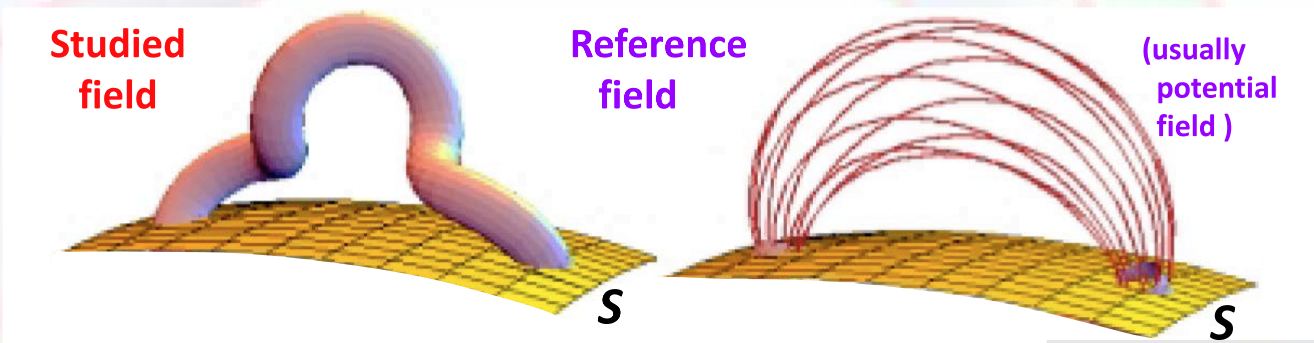
Relative Magnetic Helicity

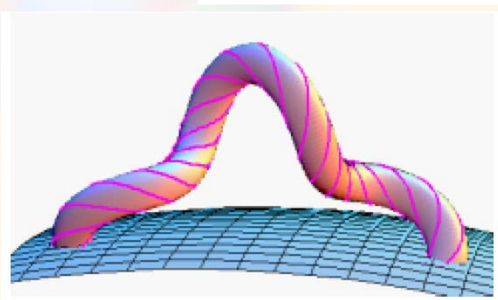
➔ Useful quantity: **Relative Magnetic Helicity:** helicity of a studied field relative to a reference field **(Berger 84)**.

$$H_{\mathcal{V}} = \int_{\mathcal{V}} (\mathbf{A} + \mathbf{A}_{\mathrm{p}}) \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) \ \mathrm{d}\mathcal{V}$$ **(Finn & Antonsen 85)**

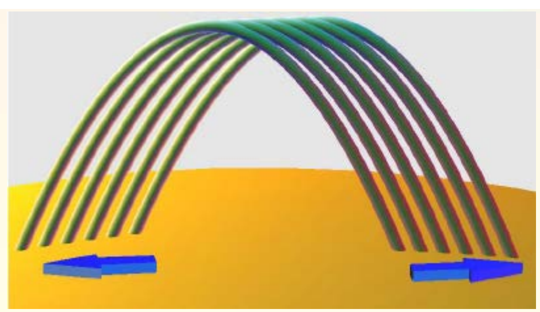
with boundary condition : $(\mathbf{B}_{\mathrm{p}} \cdot \mathrm{d}\mathbf{S})\,|_{\partial\mathcal{V}} = (\mathbf{B} \cdot \mathrm{d}\mathbf{S})\,|_{\partial\mathcal{V}}$ $\quad \nabla \times \mathbf{A} = \mathbf{B}$

- **Gauge invariant provided that studied and reference fields share the same magnetic-flux distribution on the boundary.**

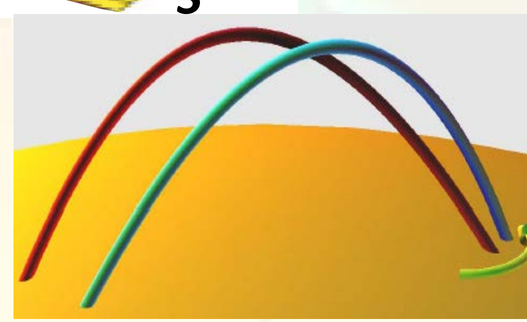




Twisted and writhed flux tube



Sheared arcade



Braided flux tubes

Relative Magnetic Helicity Estimations

- The computation of relative magnetic helicity on a 3D cuboid system has not been straightforward
  - Volume computation of consistent gauges for the studied and reference fields
  - Impose boundary conditions simultaneously on all 6 faces

- Methods recently developed:
  - Using Coulomb gauge: $\nabla \cdot \mathbf{A} = 0$

    Thalmann et al. 11, **Rudenko & Myshyakov 11, Yang et al. 13**
    - Simpler theoretical formulation
    - Harder to implement numerically
  - Using DeVore gauge: $A_z = 0$

    Valori, Démoulin & Pariat 12
    - More complex theoretical formulation
    - Simpler to implement numerically: more precise

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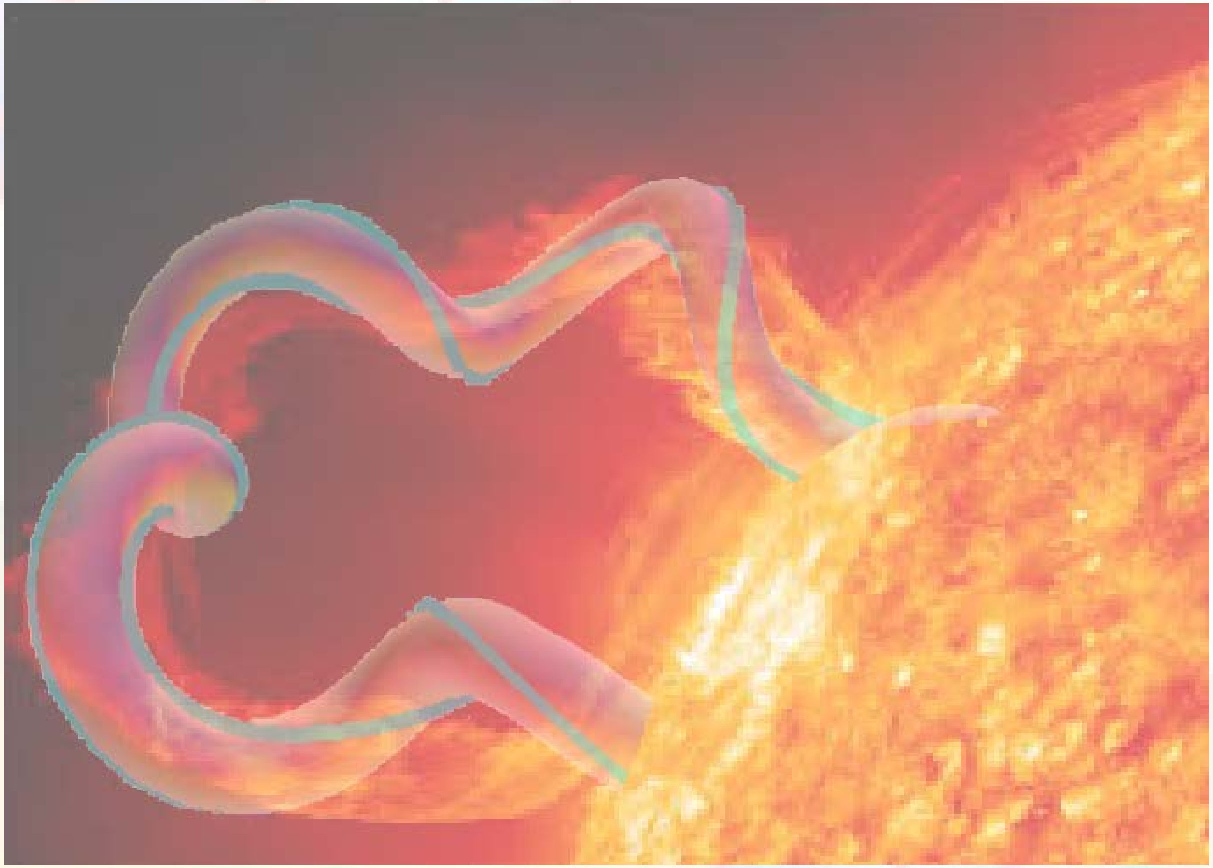


Magnetic helicity dissipation estimation

- General formulation of the time variation of the relative magnetic helicity:

Magnetic helicity dissipation

Time variation of relative magnetic helicity

$$\frac{dH}{dt} = -2\int_{\mathcal{V}} \mathbf{B}\cdot\mathbf{E}\ d\mathcal{V} + 2\int_{\mathcal{V}} \frac{\partial\phi}{\partial t}\nabla\cdot\mathbf{A}_{\mathrm{p}}\, d\mathcal{V}$$
$$+ \int_{\partial\mathcal{V}} \left((\mathbf{A}-\mathbf{A}_{\mathrm{p}})\times\frac{\partial(\mathbf{A}+\mathbf{A}_{\mathrm{p}})}{\partial t}\right)\cdot d\mathbf{S} - 2\int_{\partial\mathcal{V}} \frac{\partial\phi}{\partial t}\mathbf{A}_{\mathrm{p}}\cdot d\mathbf{S}$$
$$+ 2\int_{\partial\mathcal{V}} (\mathbf{B}\cdot\mathbf{A}_{\mathrm{p}})\mathbf{v}\cdot d\mathbf{S} - 2\int_{\partial\mathcal{V}} (\mathbf{v}\cdot\mathbf{A}_{\mathrm{p}})\mathbf{B}\cdot d\mathbf{S}$$

Helicity variation and flux of the reference field

(Pariat et al. 15)

Flux of helicity of the studied field

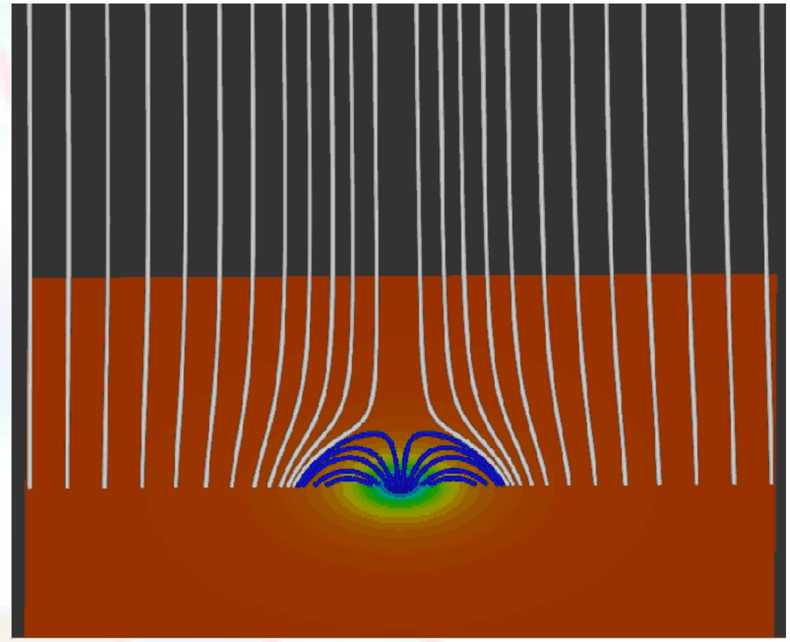
- **Helicity-conservation estimation:** measure the difference between
  - **helicity variations in $\mathcal{V}$**
  - **helicity flux through the boundary sides $\mathcal{S}$.**
  - Method independent of the non-ideal processes, i.e. reconnection-model

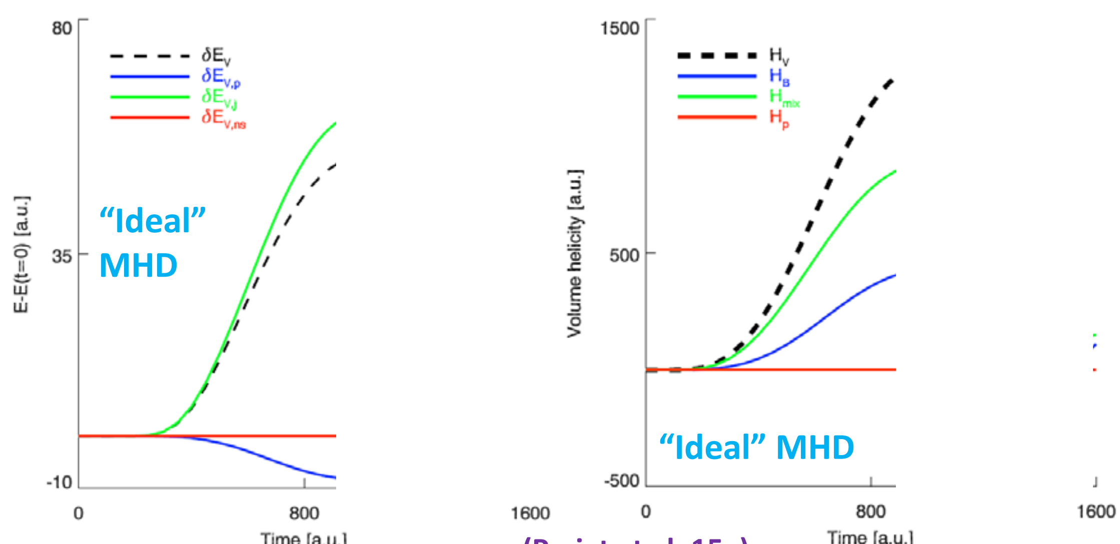
$$C_m = -2\int_{\mathcal{V}} \mathbf{E}\cdot\mathbf{B}\ d\mathcal{V} = \frac{dH}{dt} - F_{tot}$$

Test Case

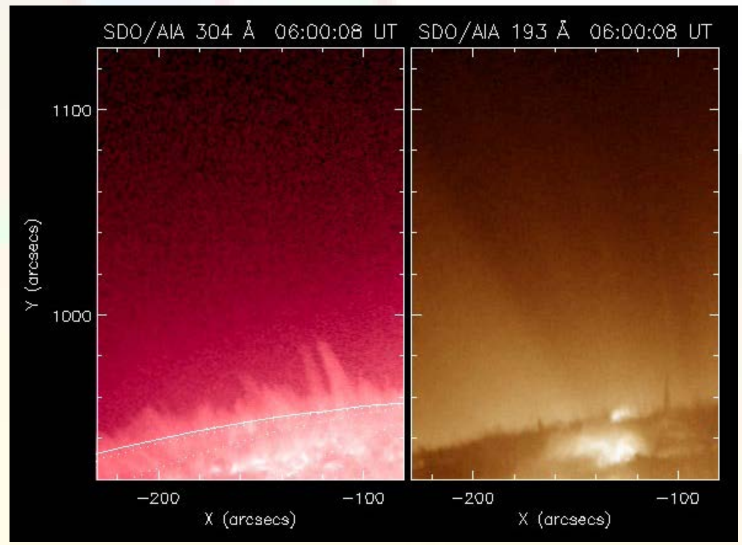
(Pariat et al. 10)

- **3D MHD simulation of a solar coronal jet:**
  Pariat et al. 09,10,15b ; Dalmasse et al. 12
  - Magnetic helicity/energy injected by bottom boundary motions
- **First phase: helicity/energy storage.**
  - Quasi-ideal MHD: reconnection inhibited.
- **Second phase: Jet generation**
  - Very impulsive energy release by recon.
  - Ejection of helicity.





(Pariat et al. 15a)



(Shen et al. 11)

Helicity conservation - 1

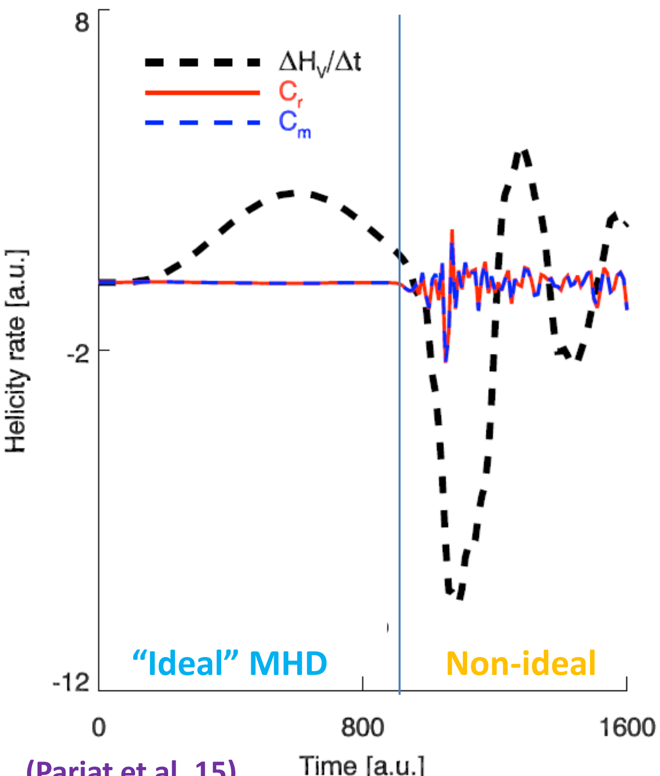
- Helicity and its flux are estimated independently
  - Direct volume helicity computation (Valori et al. 12) : **B** in $\mathcal{V}$
  - Helicity flux computation: **B**, **v** on $\mathcal{S}$

- ➔ **Magnetic helicity is very well conserved both during the quasi-ideal MHD and non-ideal phases.**

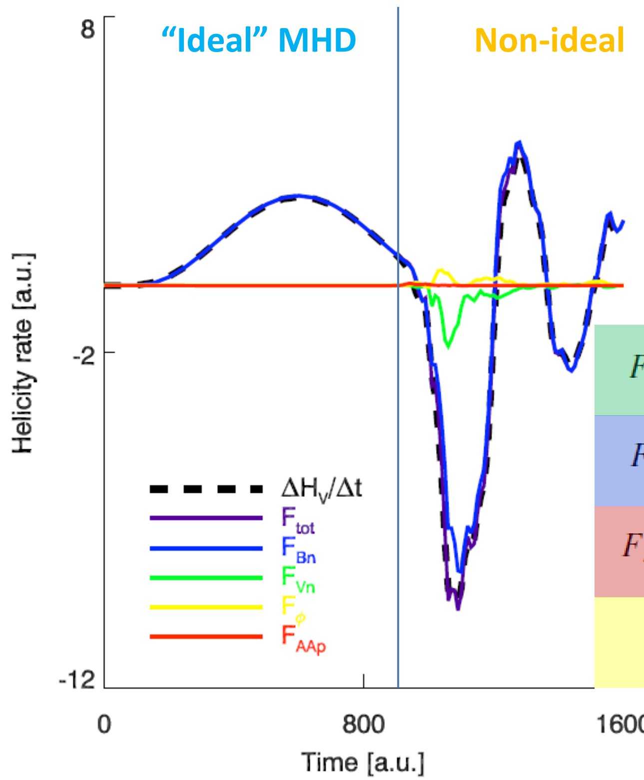
$$H_{\mathcal{V}} = \int_{\mathcal{V}} (\mathbf{A} + \mathbf{A}_{\mathrm{p}}) \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) \, \mathrm{d}\mathcal{V}$$

$$F_{tot} = F_{Vn} + F_{Bn} + F_{mix} + F_{\phi}$$

$$C_m = \frac{dH}{dt} - F_{tot}$$



(Pariat et al. 15)



$$F_{Vn} = 2 \int_{\partial\mathcal{V}} (\mathbf{B} \cdot \mathbf{A}) \mathbf{v} \cdot \mathrm{d}\mathbf{S}$$

$$F_{Bn} = -2 \int_{\partial\mathcal{V}} (\mathbf{v} \cdot \mathbf{A}) \mathbf{B} \cdot \mathrm{d}\mathbf{S}$$

$$F_{mix} = \int_{\partial\mathcal{V}} \left((\mathbf{A} - \mathbf{A}_{\mathrm{p}}) \times \frac{\partial(\mathbf{A} + \mathbf{A}_{\mathrm{p}})}{\partial t} \right) \cdot \mathrm{d}\mathbf{S}$$

$$F_{\phi} = -2 \int_{\partial\mathcal{V}} \frac{\partial\phi}{\partial t} \mathbf{A}_{\mathrm{p}} \cdot \mathrm{d}\mathbf{S}$$

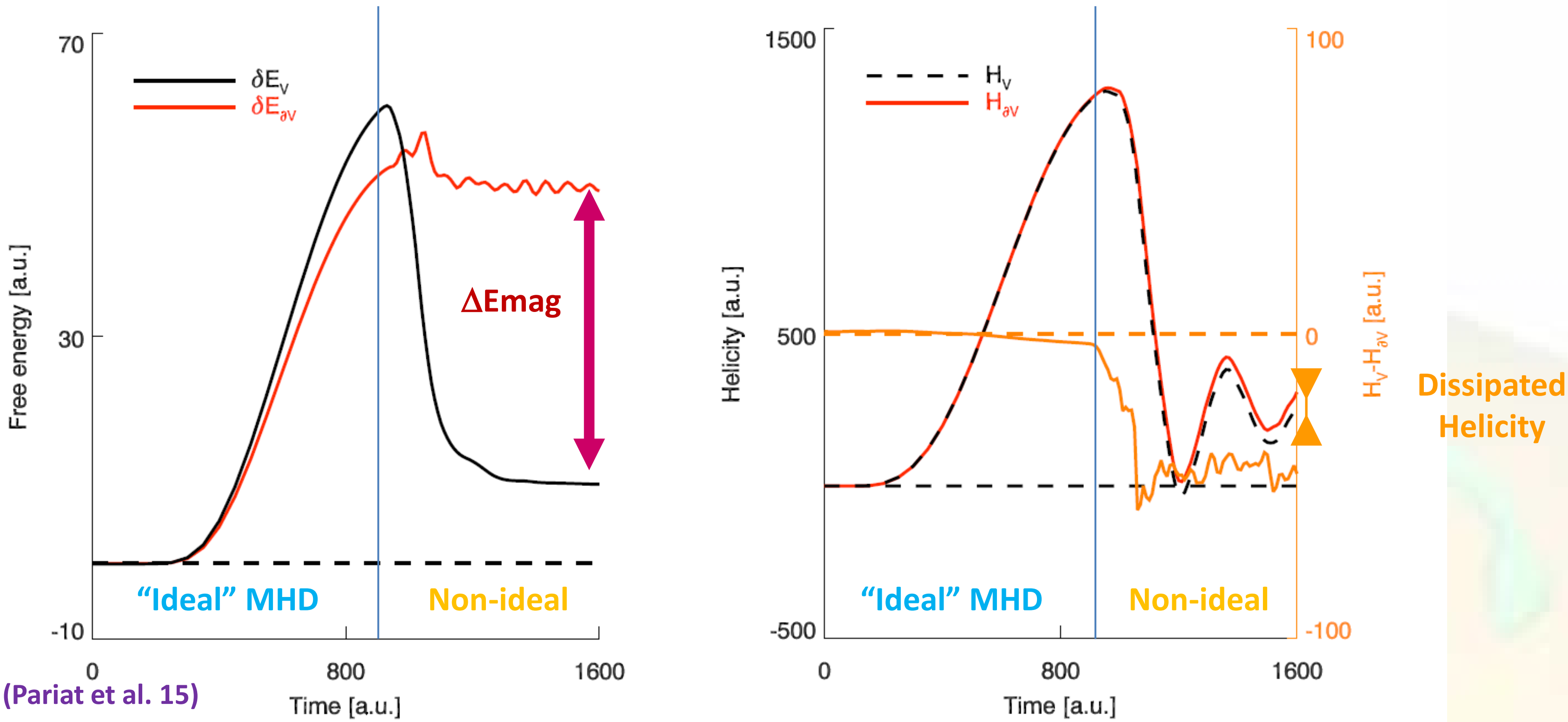
Helicity conservation - 2

- **Magnetic helicity is very well conserved.**
  - Dissipated helicity is very small compared to the helicity injected in the system.
  - The dissipated helicity is very small compared to the amount of magnetic energy dissipated.

$$\frac{\Delta H_{\mathrm{diss,Ideal}}}{\Delta H_{\mathrm{inj}}} < 3 \times 10^{-3}$$

$$\frac{\Delta H_{\mathrm{diss,\ Non\text{-}ideal}}}{\Delta H_{\mathrm{ini}}} < 0.04$$

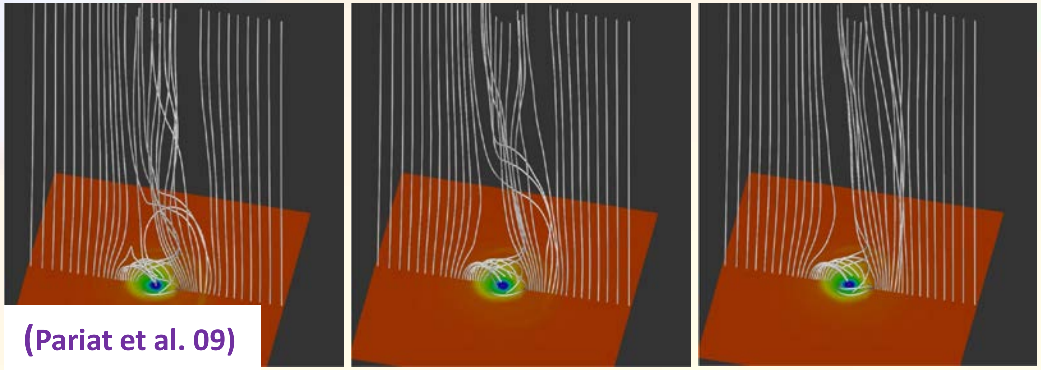
$$\frac{\Delta E_{\mathrm{diss,\ Non\text{-}ideal}}}{\Delta E_{\mathrm{inj}}} < 0.5$$



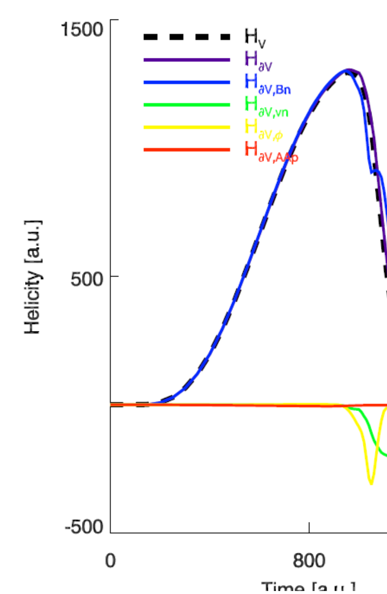
(Pariat et al. 15)

Helicity conservation tests

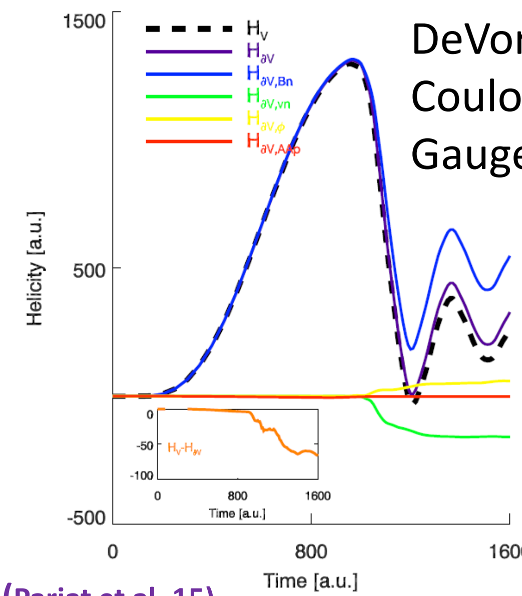
- **Forty years after, the Taylor conjecture can now be numerically tested in general configurations, using typical numerical data sets**.
- Estimations of the helicity conservation on an impulsive solar active like events (coronal jet).
  - Independent of reconnection models
  - Using several general gauges.
- **As conjectured, magnetic helicity is very well conserved in this application**
  ➔ H is not dissipated but ejected by the helical jet



(Pariat et al. 09)



DeVore Gauge



DeVore-Coulomb Gauge

(Pariat et al. 15)

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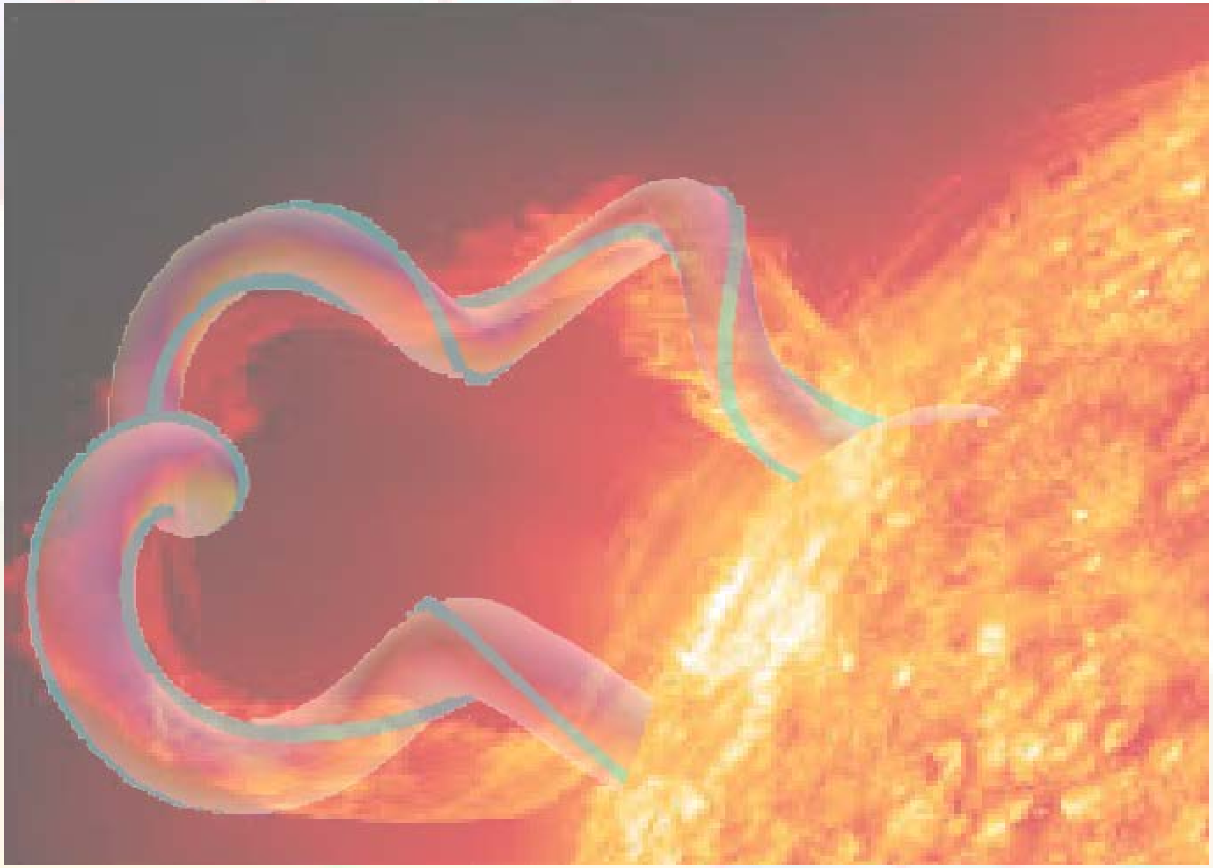
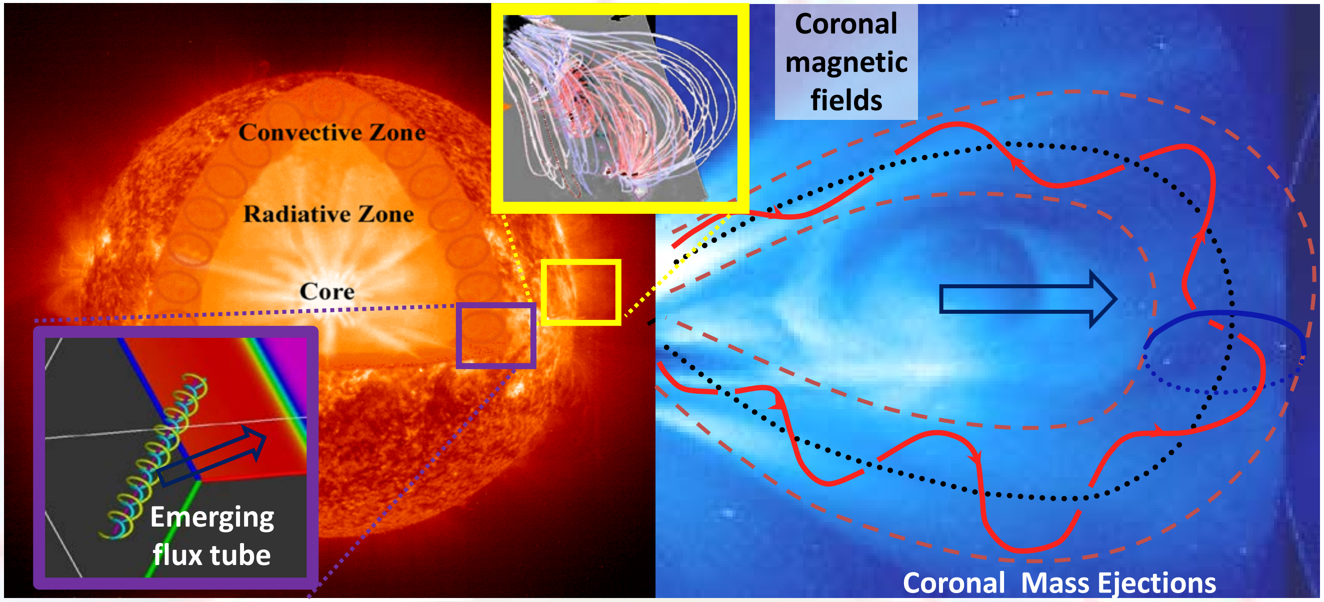


Magnetic Helicity in Space Weather

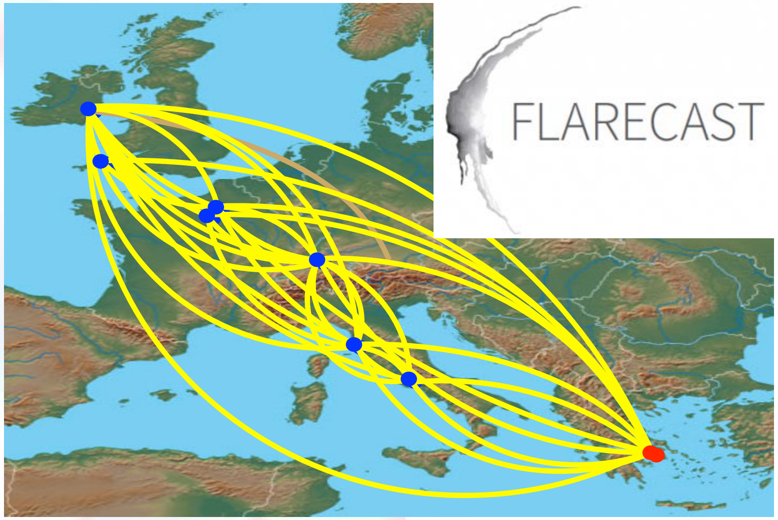


- Physics is based on conservation principles
- Most of the evolution of eruptions/CME is properly described within MHD
- Magnetic helicity is one of the few quantity conserved in MHD

- **New methods to estimate magnetic helicity in observations and simulations**
- New ways to test whether magnetic helicity conservation is the “raison d’être” of CMEs.
- **Possibly strong deterministic proxy of solar eruption**

Magnetic Helicity in Space Weather

- Implementation in next generation of prediction methods: European commission H2020: **FLARECAST network**
  - **Magnetic helicity used as criteria**, along with other proxy, in classical empirical prediction method
  - Use of data mining and machine learning methods
  - **Fundamental research on magnetic helicity**



FLARECAST

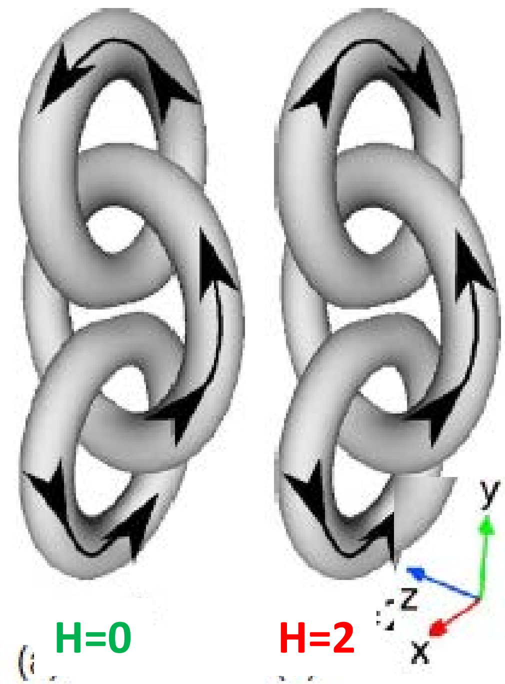
http://flarecast.eu

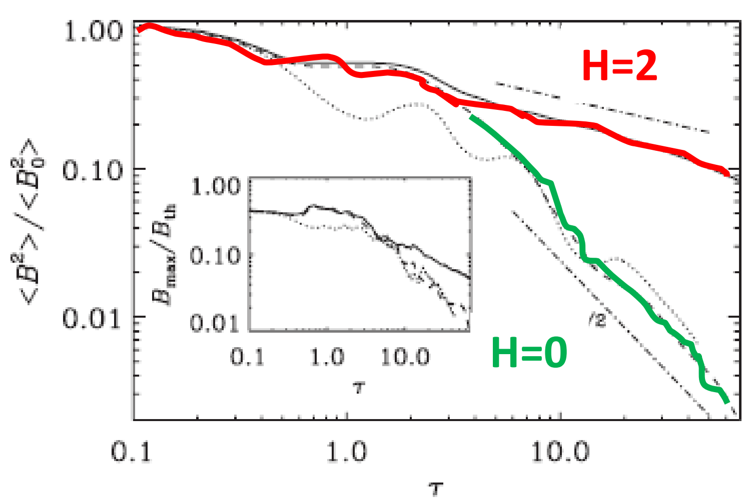
- ISSI team on "**Magnetic Helicity estimations in models and observations of the solar magnetic field**" led by G. Valori and myself
  - Benchmark almost all magnetic helicity estimation methods on analytical, numerical and observational data sets.
  - Provide state of the art uncertainty level on helicity measurements
- ANR "jeune chercheur" proposal on the study of magnetic helicity

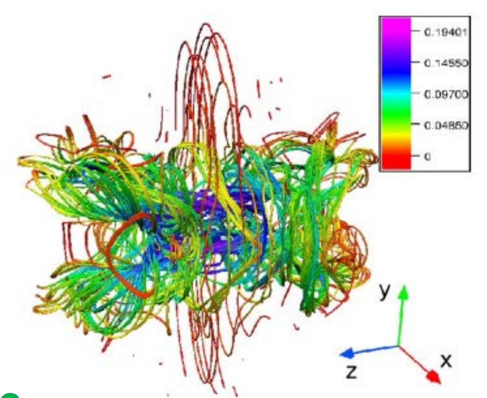
Helicity and reconnection

(Del Sordo et al. 10)

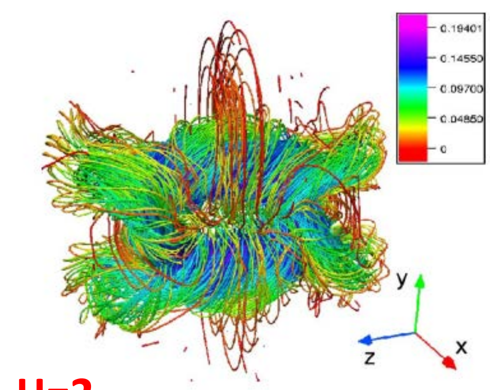
- **Helicity modifies the properties & dynamics of reconnection / energy dissipation.**
- **How does Helicity evolves during reconnection events?**
- **How is helicity transferred from one connectivity domains to the other?**







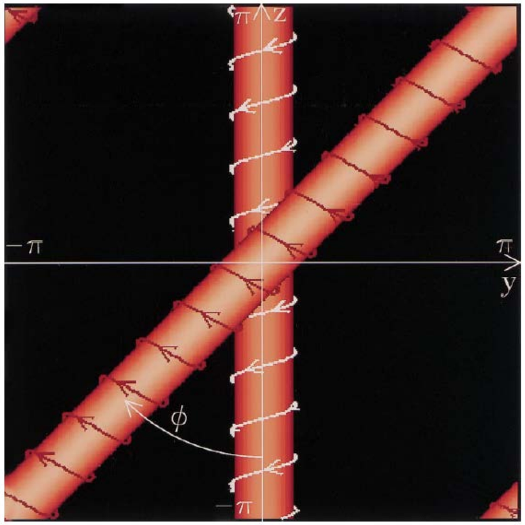
H=0



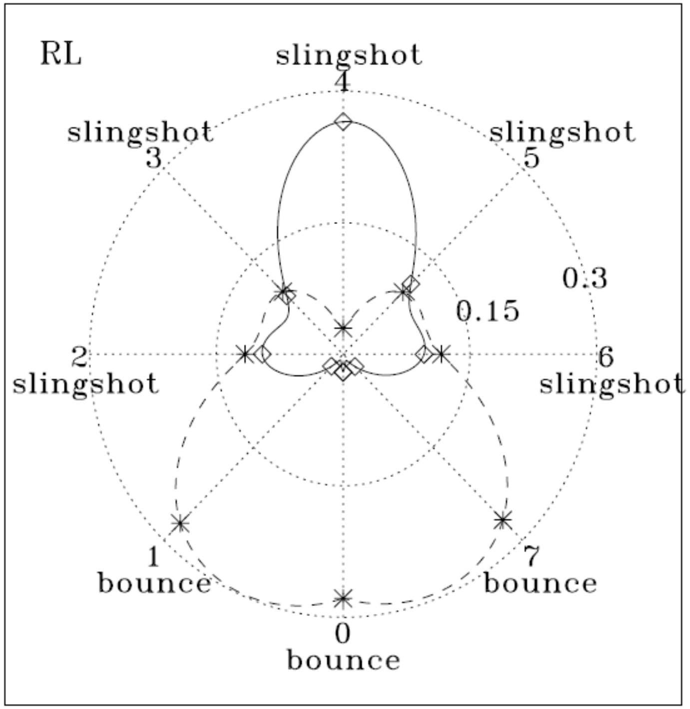
H=2

Helicity and reconnection

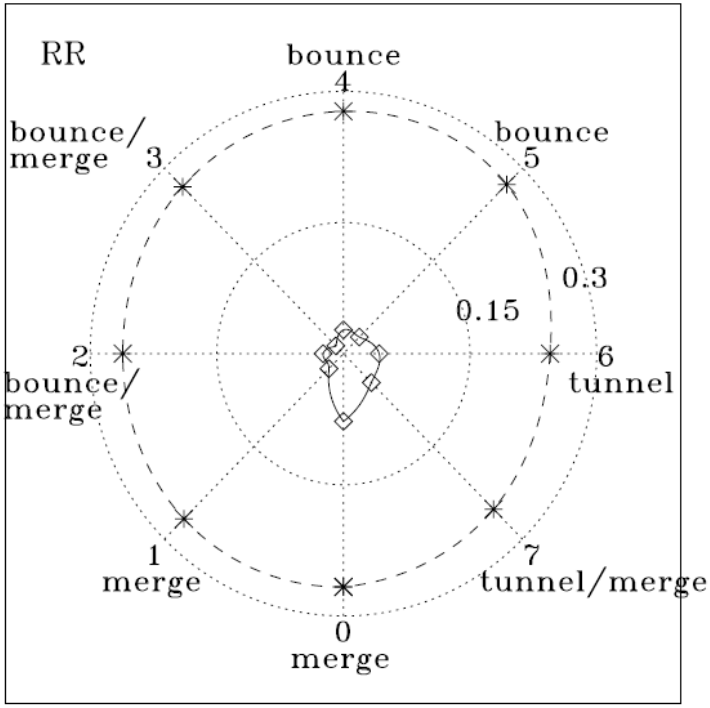
- **Woltjer-Taylor theorem:**
  - For a given H, minimum energy is the linear force free **B**
  - Minimum energy limited by the amount of H.
- **Helicity annihilation should allows more free energy to be released: access to lower energy level**
  (Linton et al. 01, 02)



Opposite helicity



Same helicity



——— $E_{kin}(t_{middle})$

- - - - - - $E_{mag}(t_{final})$

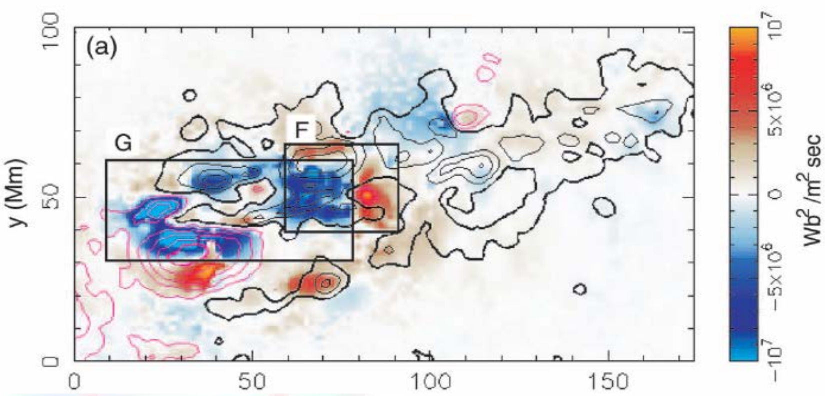
(Linton et al. 01)

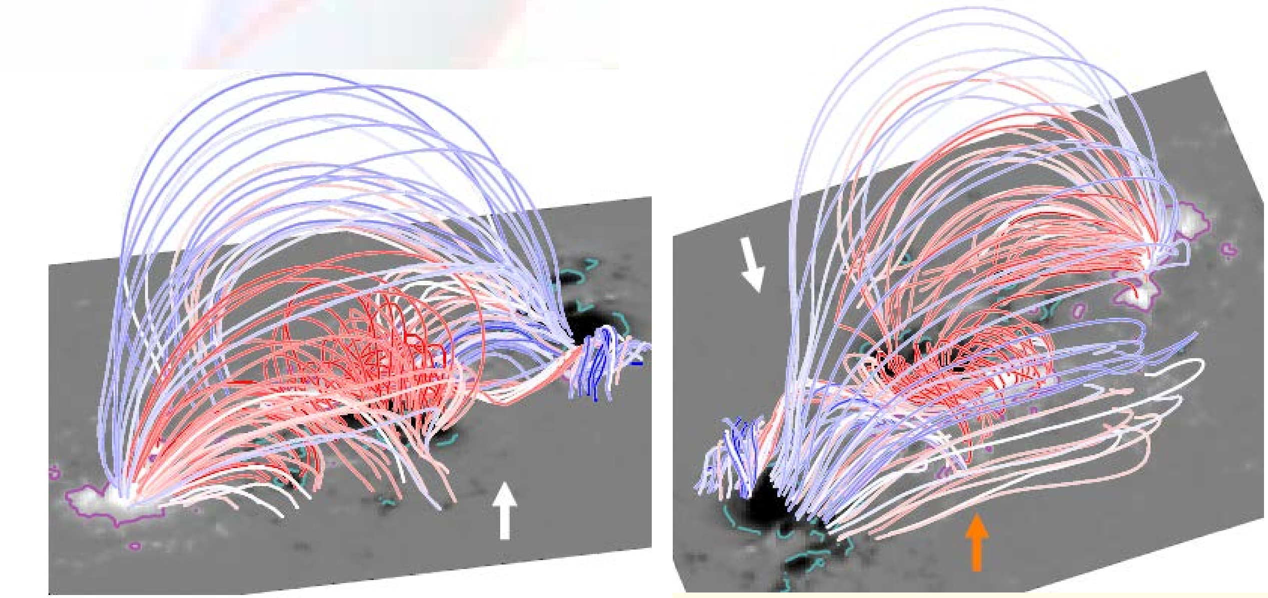
Helicity and flare energy

- **ARs presenting helicity of both signs**
  ➔ more energetic flares?
  - Model based simultaneous injection of both signs of H. **(Kusano et al. 02)**
  - Observations: **Park et al. 10, Romano et al. 2011; Jing et al. 2012; Vemareddy et al. 2012, Dalmasse et al. 14**
- **Need of properly determining the helicity distribution/injection in ARs**

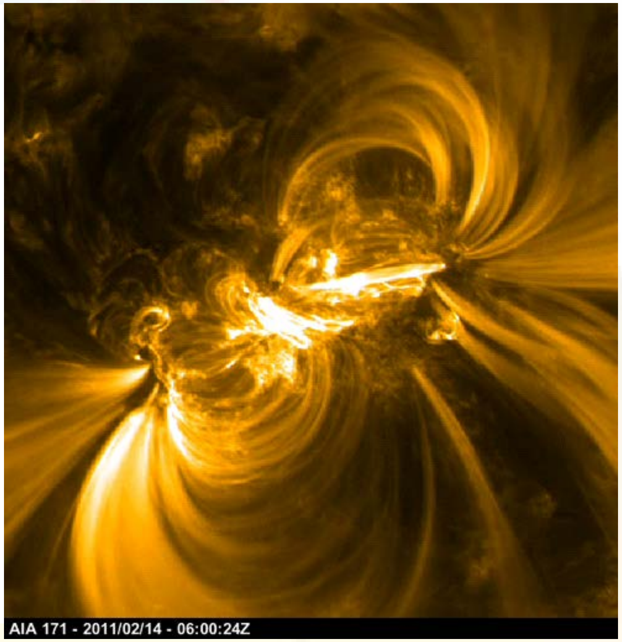
➔ New methods developed: Dalmasse et al. 13, Dalmasse et al. 14

Helicity flux density (Kusano et al. 02)





(Dalmasse et al. 14)



Thanks for your attention