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Laboratoire de physique des plasmas

What's new about magnetic helicity?

Properties & potential impact on solar eruption prediction

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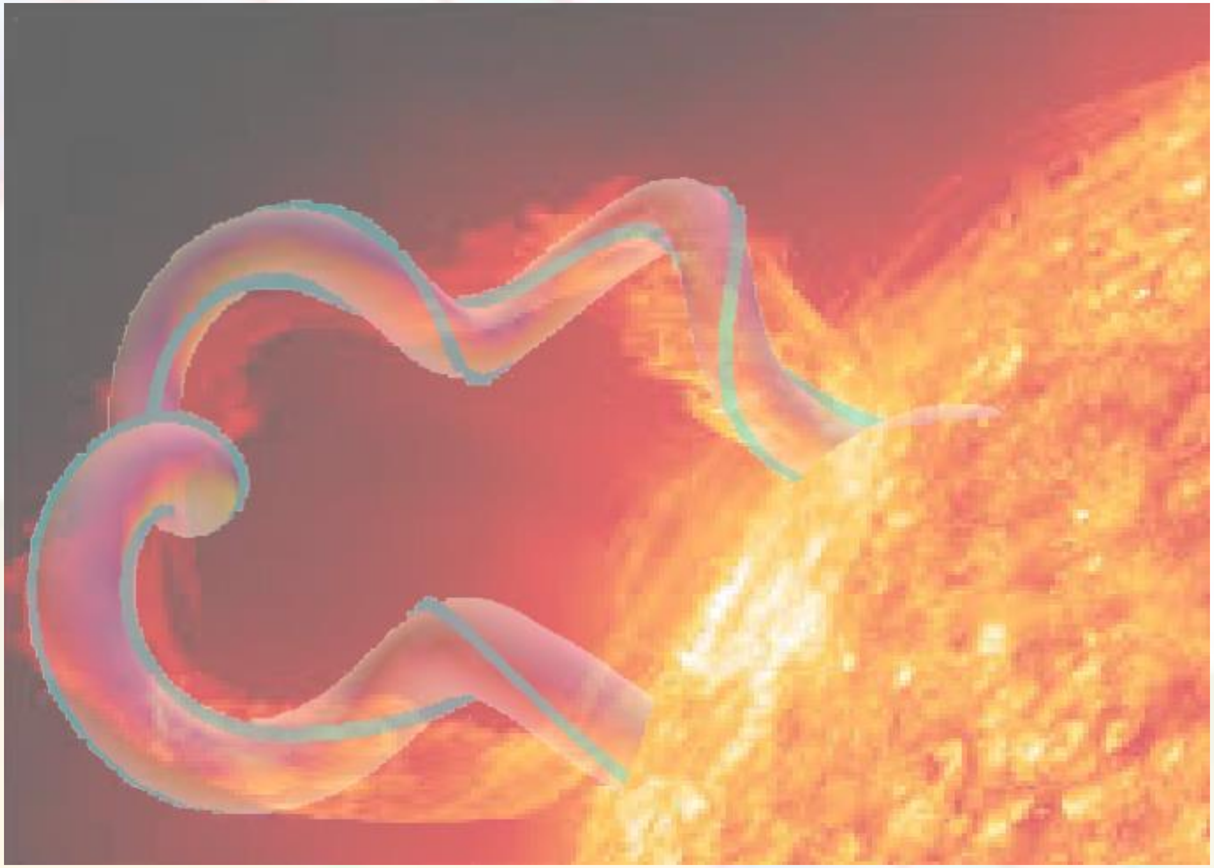
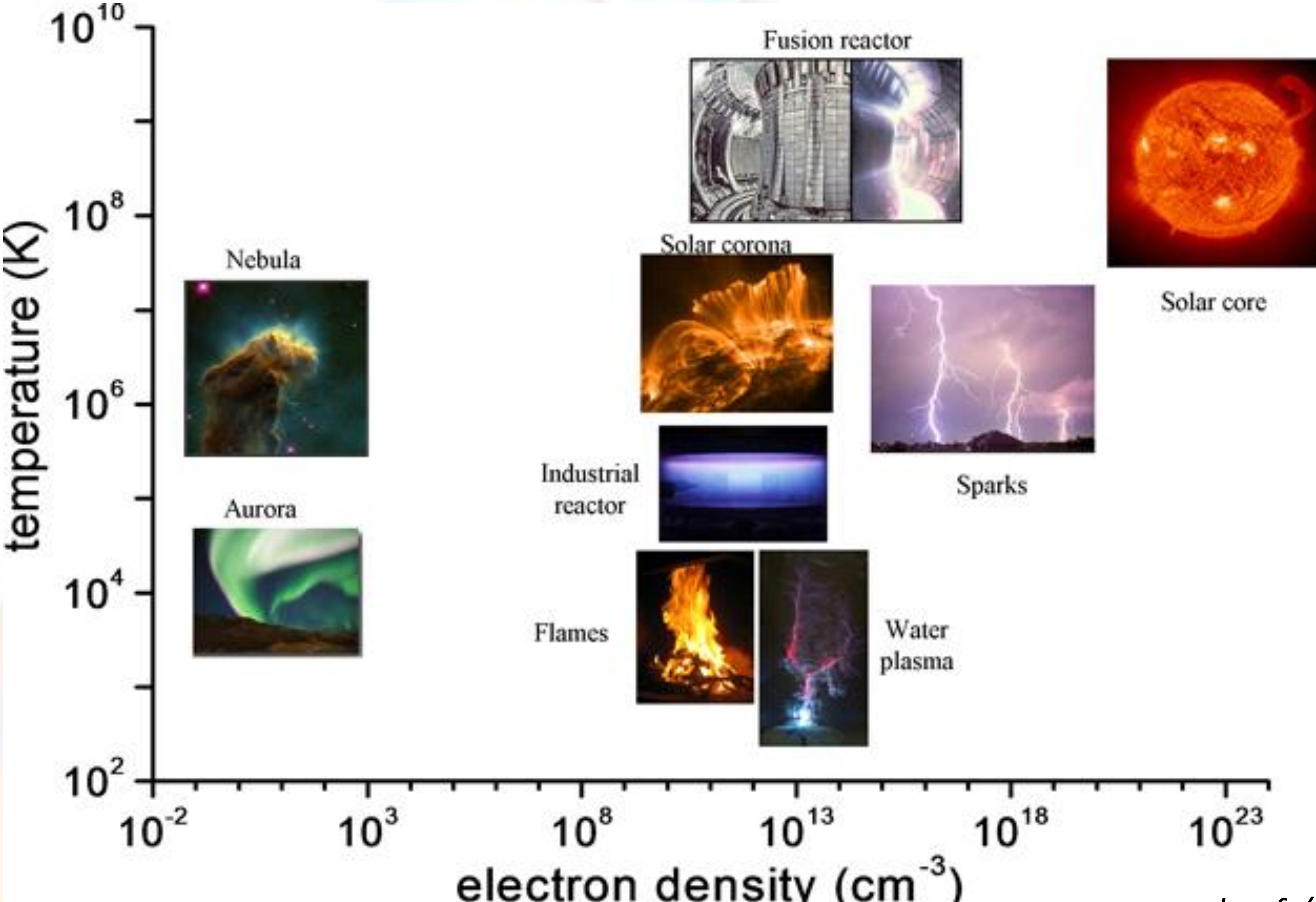
Outline

- Context
- Magnetic helicity:
  - Definition
  - Properties
  - Measurements
- Magnetic helicity conservation in non-ideal MHD
  - past experiments
  - new tests
- Magnetic helicity as an eruptivity proxy
- Conclusions



Solar coronal plasma



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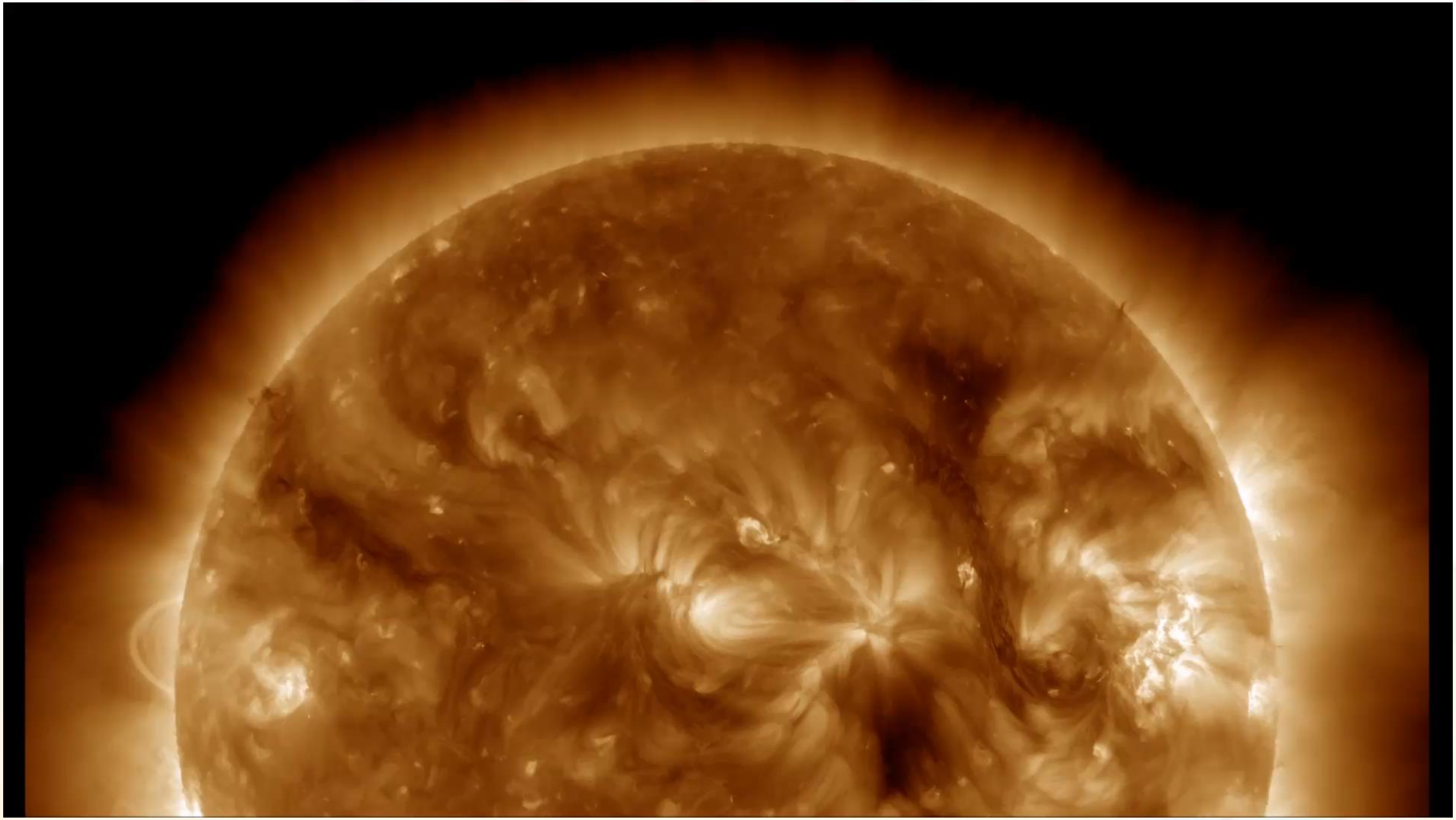
Solar Eruptions

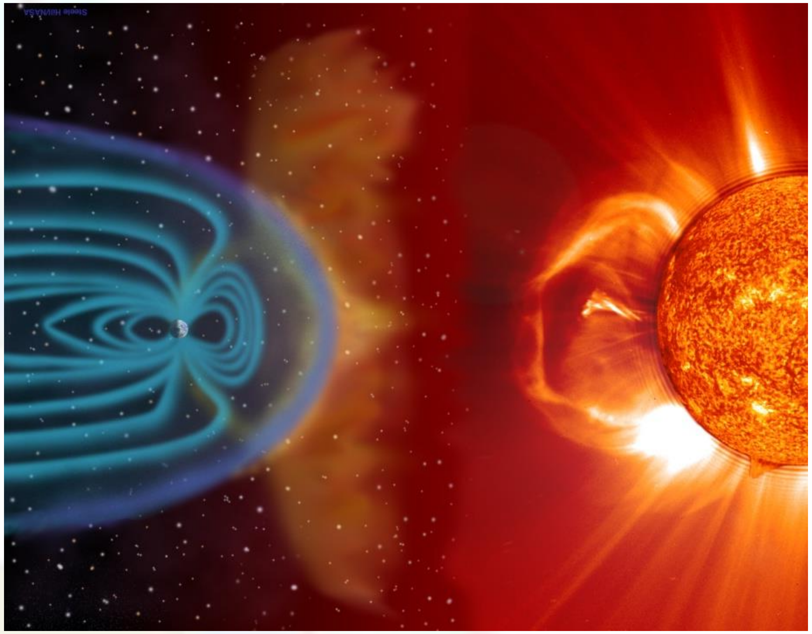


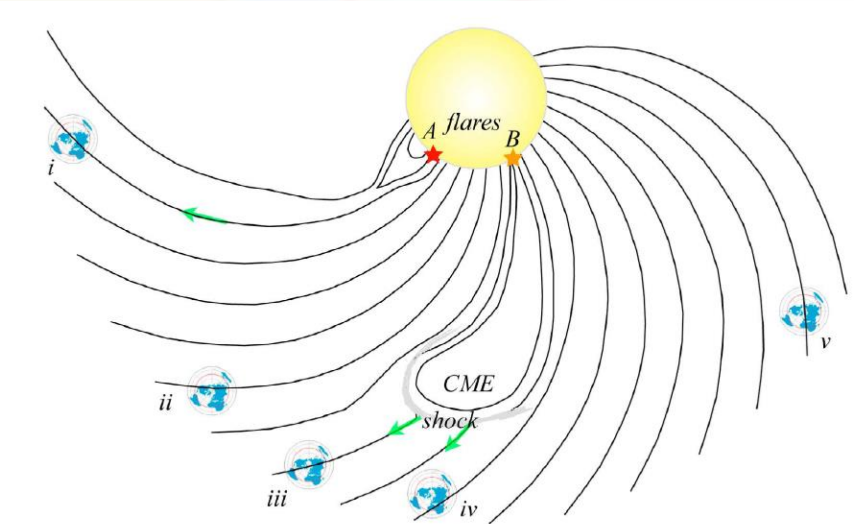
Space Weather Prediction

- 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)

Magnetohydrodynamics (MHD) paradigm

- **Fluid approximation** valid for AR dynamics but some particle dynamics at small scales
  - Mean free path: 10^3 -10^5m < length scale of active region: 10^6m - 10^8m
  - Collision time: 10^{-3} s to 1s < typical time scale of active region: 1 min – 1 day

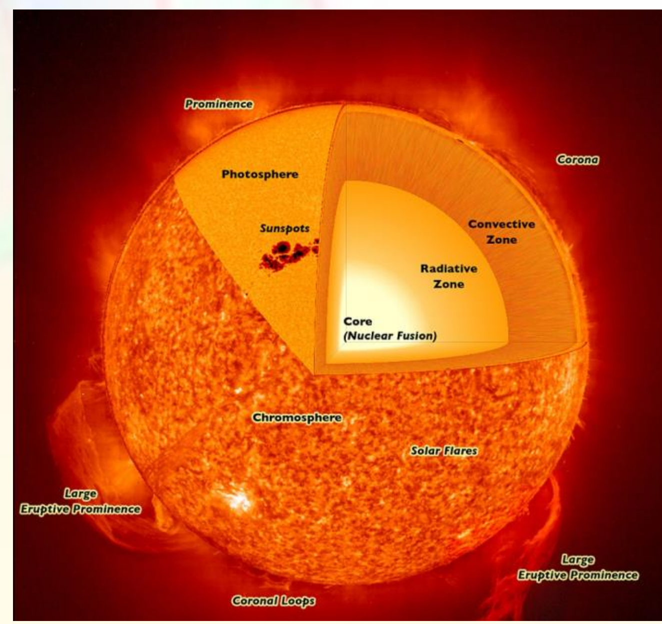
	T (K)	n (m^{-3})	P (Pa)
Intérieur ($z \approx -10$ Mm)	7×10^4	6×10^{26}	7×10^8
Photosphère ($z = 0$)	5800	9×10^{22}	7×10^3
Chromosphère ($z = 2$ Mm)	10^4	5×10^{16}	2×10^{-2}
Couronne ($z \approx 50$ Mm)	2×10^6	2×10^{14}	2×10^{-3}

- **Fully ionized** (high T, low dens) ➔ atmosphere made of plasma

- **Quasi-neutral**
  - Length scale >> Debye length, ~ 1 cm in the corona

- **Non relativistic** scales (v_0 << c)
  - Electric currents are induced by the magnetic field : Ampère Law

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}.$$



MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{u}) = 0,$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} + \frac{1}{\rho}\nabla(P + \underline{\underline{\tau}}) = \frac{\mathbf{J} \times \mathbf{B}}{\rho} + \mathbf{g},$$

$$\frac{\partial(e)}{\partial t} + \nabla \cdot (e\mathbf{u}) + P\nabla \cdot \mathbf{u} = \nabla \cdot \mathbf{F}_r + \nabla \cdot \mathbf{F}_c + Q_{\text{Joule}} + Q_{\text{visc}},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \nabla \times (\mathbf{R})$$

Lorentz force dominated medium

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\mathbf{J} \times \mathbf{B} + g\mathbf{e}_z + \frac{1}{\rho}\nabla \cdot \tau$$

- Lorentz force: 10^{-6} N.m^{-3}
    - B~0.01 T, L~10^7
  - – Plasma pressure: 10^{-9} N.m^{-3}
    - P~10^{-2} Pa, L~10^7m
  - – Viscous stress & Advection: 10^{-10}N.m^{-3}
    - V~10^5 m.s^{-1}, L~10^7m, ρ~10^{-13} kg.m^{-3}
  - Gravity: 10^{-11} N.m^{-3}
    - g~280 m.s^{-2}, ρ~10^{-13} kg.m^{-3}

Ideal & non-ideal MHD

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) - \nabla \times (\mathbf{R})$$

- For $\mathbf{R}=\eta\mathbf{j}$; Magnetic Reynolds number:
  - Rm >> 1: Ideal MHD
  - Rm << 1: Resistive MHD

$$\frac{\partial \mathrm{B}}{\partial t} - \boldsymbol{\nabla} \times (\mathbf{v} \cdot \mathrm{B}) = -\boldsymbol{\nabla} \times (\eta \boldsymbol{\nabla} \times \mathrm{B})$$

$$\mathcal{R}_m = \frac{V_0 L_0}{\eta}$$

- Solar Corona:
  - $V_0 \sim 10^5$ m s^{-1}, $\eta \sim 1$ m^2 s^{-1}, $L_0 \sim 10^7$ m
  - **Rm > 10^{12} : ideal MHD is a very good approximation of the solar corona, for large scale structure**

- **Exception to the rule: generation of solar eruption**
  - **Non-ideal effect can be LOCALLY (scale < 1^{1-3} m) important**

vs. active regions scale (> 10^7 m)

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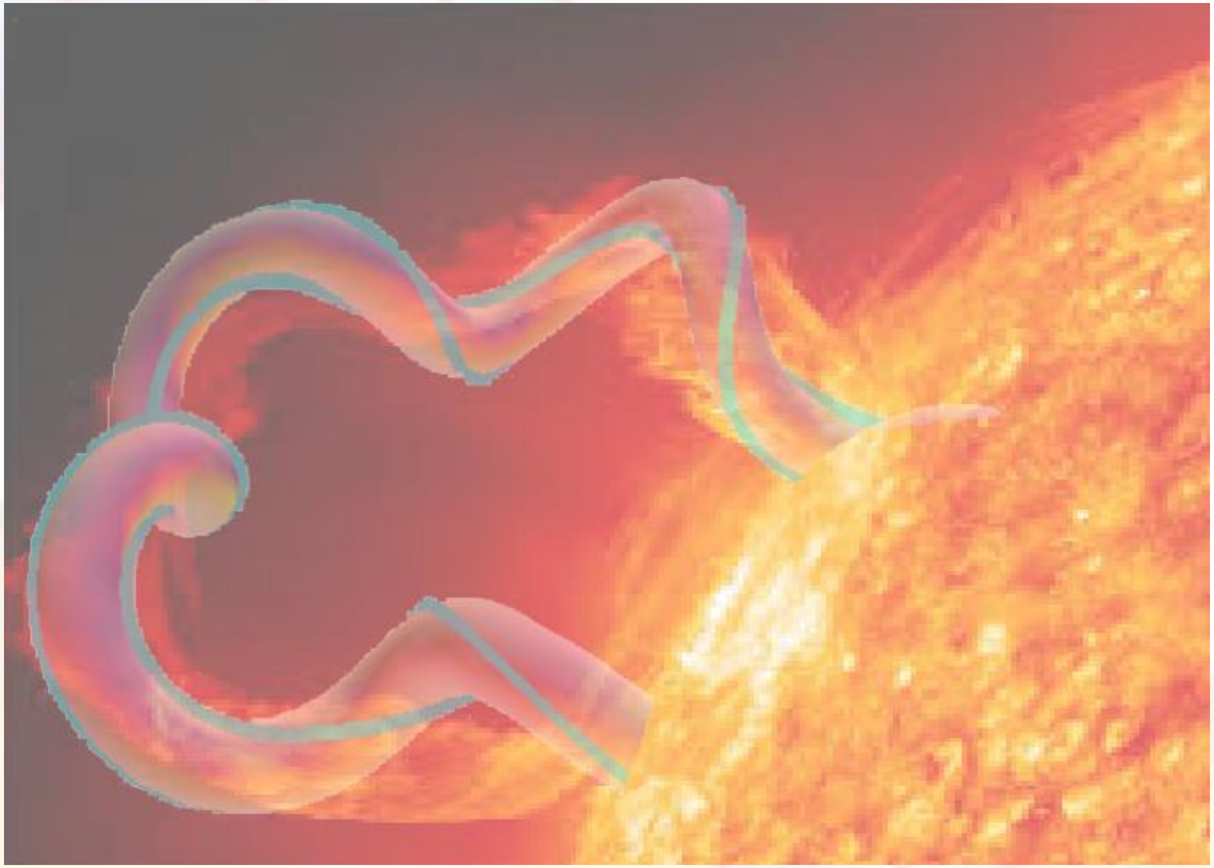
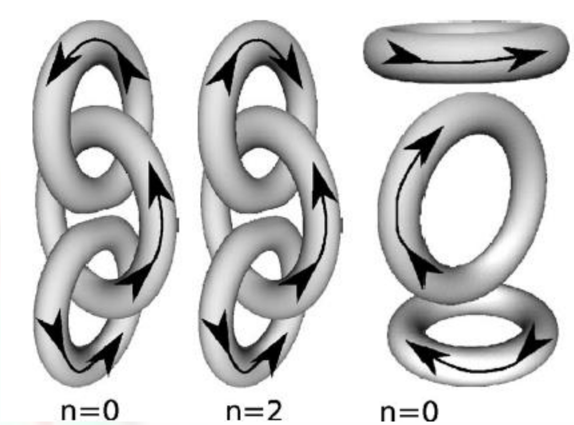


Definition of Magnetic Helicity

$$\boldsymbol{H} = \int_{\mathcal{V}} \vec{A} \cdot \vec{B} \, \mathrm{d}V \quad , \quad \vec{B} = \vec{\nabla} \times \vec{A}$$ ← **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: $\int_V \mathbf{u} \cdot \nabla \times \mathbf{u} d^3x,$

- **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)

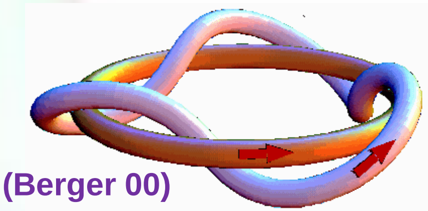
$$L_{12} = -\frac{1}{4\pi} \oint_1 \oint_2 \frac{d\mathbf{x}}{d\sigma} \cdot \frac{\mathbf{r}}{r^3} \times \frac{d\mathbf{y}}{d\tau} \, d\tau \, d\sigma$$

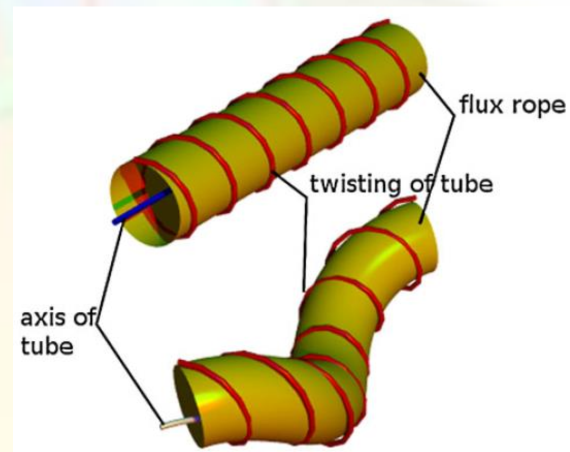
$$H = -\frac{1}{4\pi} \int \int \mathbf{B}(\mathbf{x}) \cdot \frac{\mathbf{r}}{r^3} \times \mathbf{B}(\mathbf{x}') \, d^3x \, d^3x'$$

  - Magnetic twist and writhe

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

N:nbr of turns, Φ_{ax}: axial flux


(Berger 00)



(Prior & Berger 12)

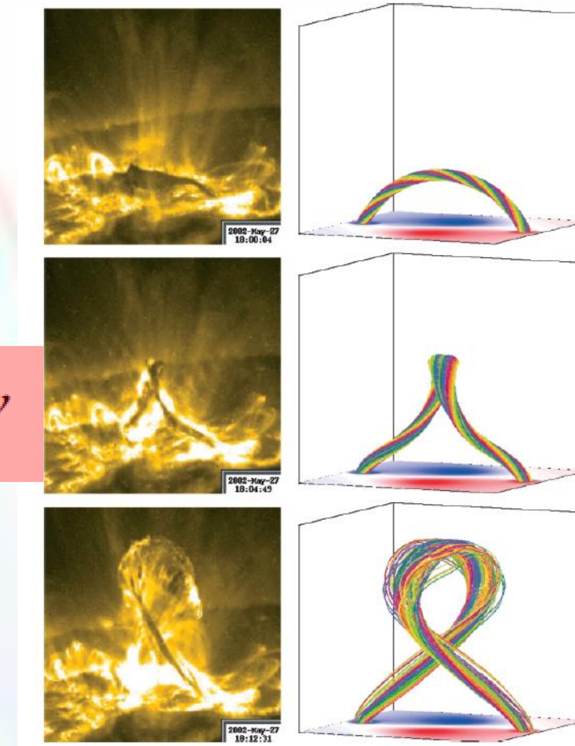
Magnetic helicity properties

- **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**

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

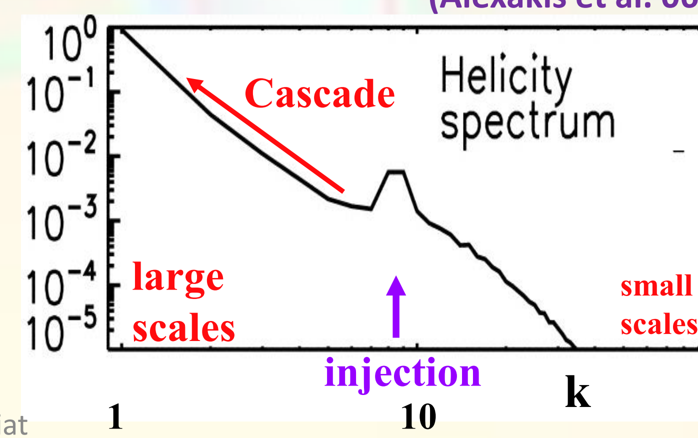
(Török et al. 05)



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

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

(Alexakis et al. 06)



Gauge invariance of magnetic helicity

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

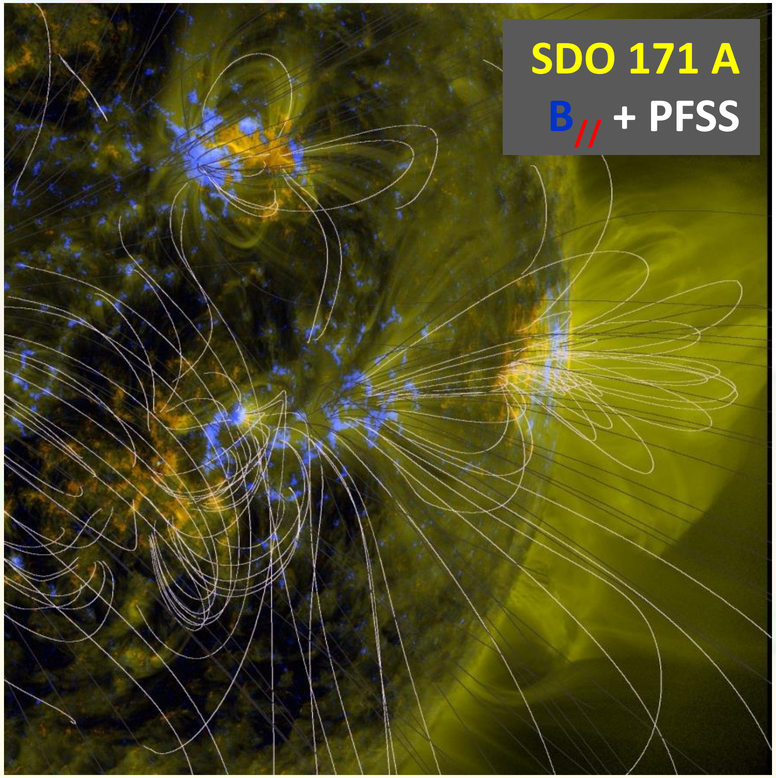
$$\mathbf{A}' \longrightarrow \mathbf{A} + \nabla\phi,$$

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

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

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

- 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



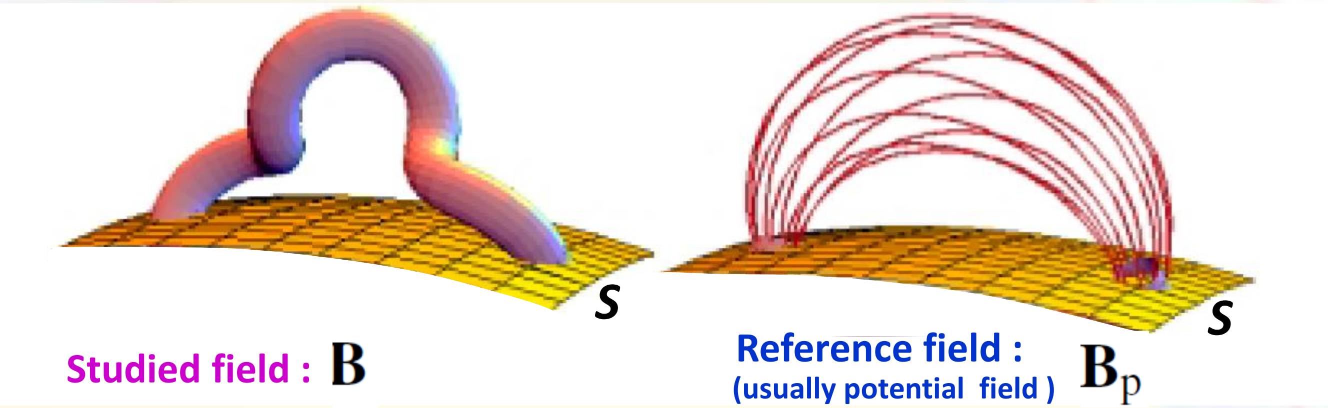
Relative Magnetic Helicity

➔ Useful quantity: **Relative Magnetic Helicity:** helicity of the studied field, **B**, relative to a reference field **(Berger 84, Finn & Antonsen 85)**.

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

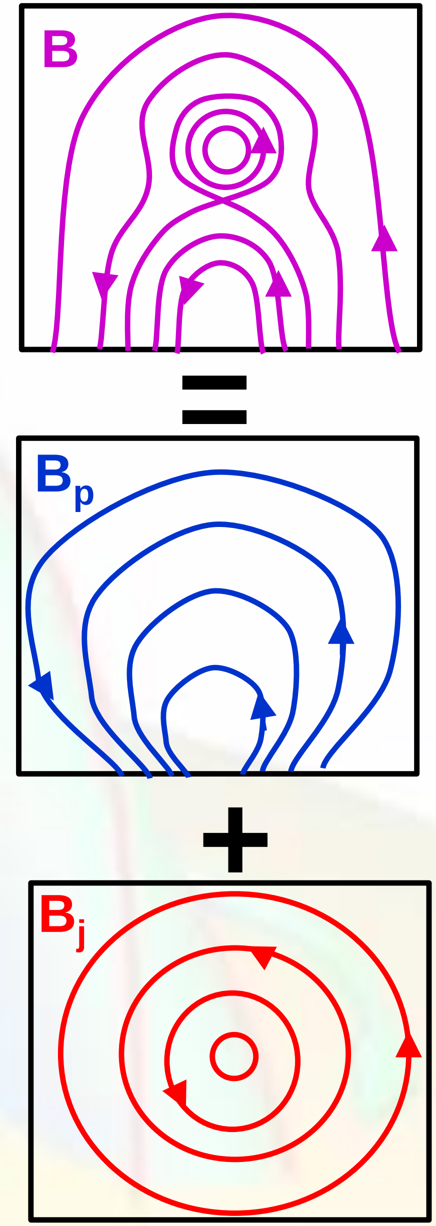
with boundary condition : $(\mathbf{B}_{\rm p} \cdot {\rm d}\mathbf{S})|_{\partial\mathcal{V}} = (\mathbf{B} \cdot {\rm d}\mathbf{S})|_{\partial\mathcal{V}}$ $\quad \nabla \times \mathbf{A} = \mathbf{B}$

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



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:** $B_p = \nabla\phi,$ with $\hat{n}\cdot(B - B_p)|_{\partial\mathcal{V}} = 0.$
  - 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. $\nabla\times B_j = \nabla\times B = \mu_0 j\,,$
- 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



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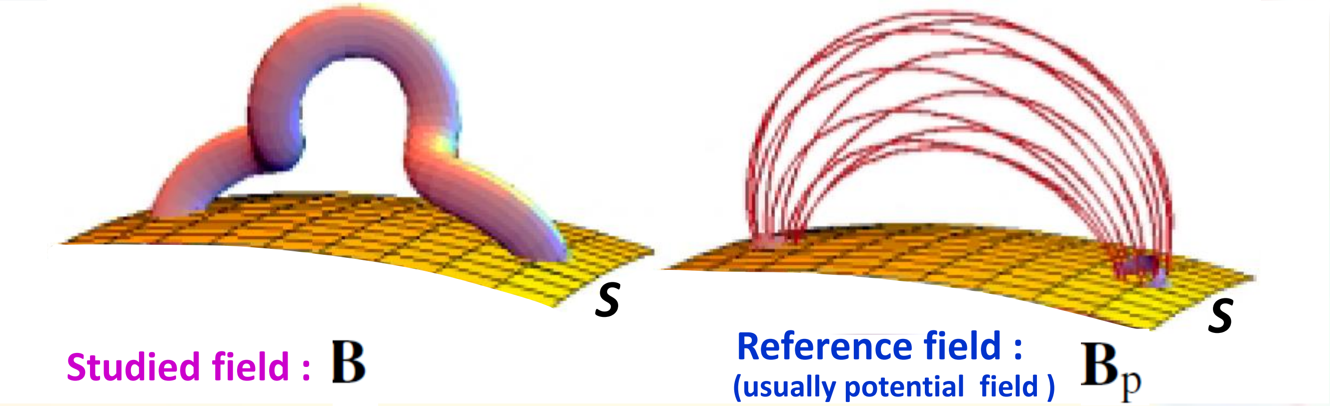
- **Gauge invariant provided that studied and reference fields share the same magnetic-flux distribution on the whole boundary.**
- **Standard reference field is the potential field!**



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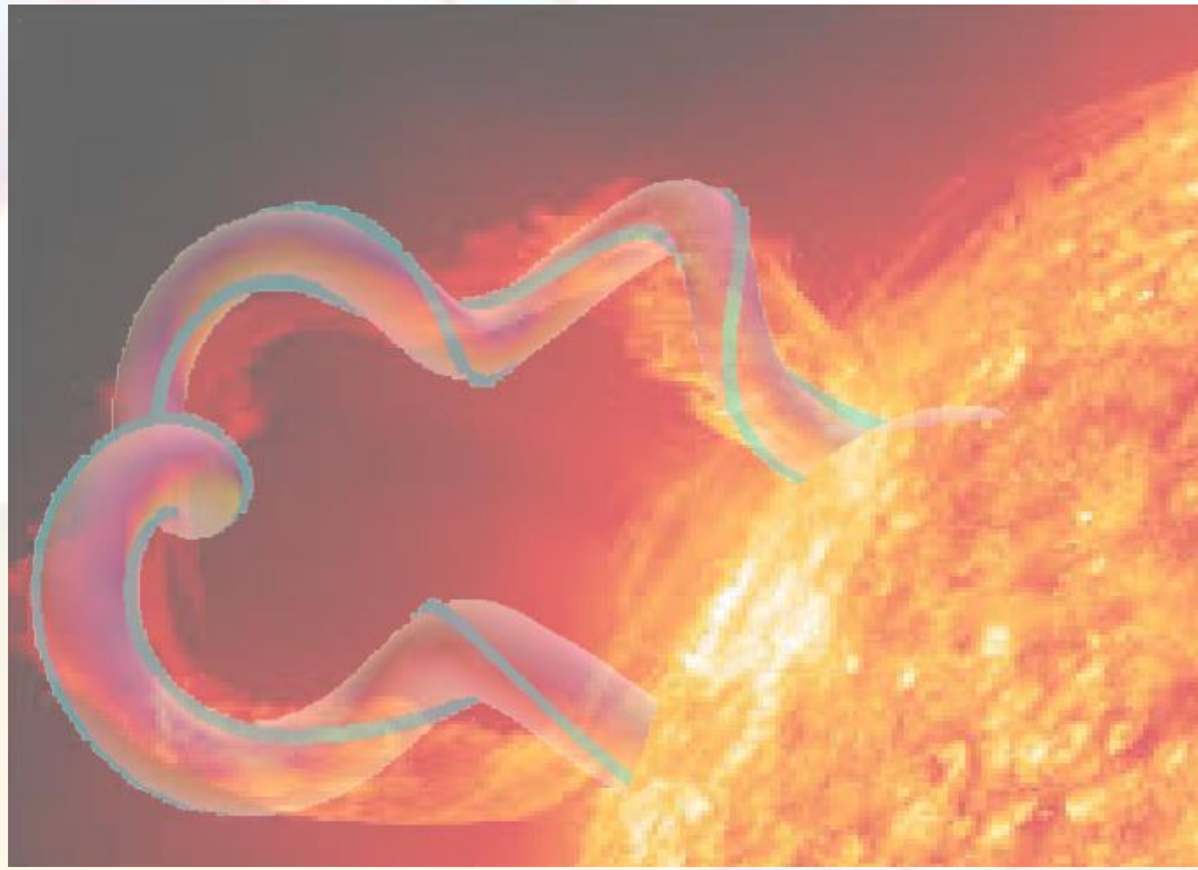


Taylor conjecture

- **Taylor relaxation conjecture: even in <u>non-Ideal MHD</u> magnetic helicity should be well conserved (Taylor 1974)**

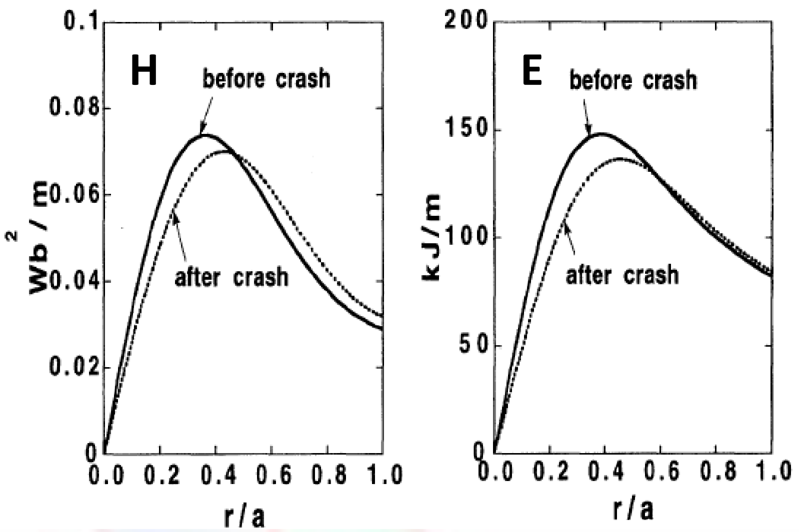
- Magnetic energy cascades to small scales where it is dissipated while helicity cascades to large scales **(Ji et al. 95, Heidbrink & Dang 00)**.

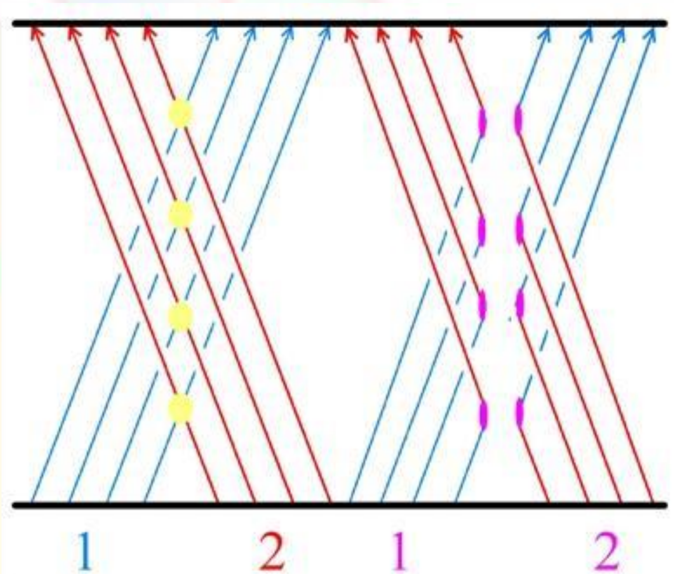
- Volume over which reconnection develops is small: large scale twist/helicity is not affected **(Berger 03)**.

- 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)

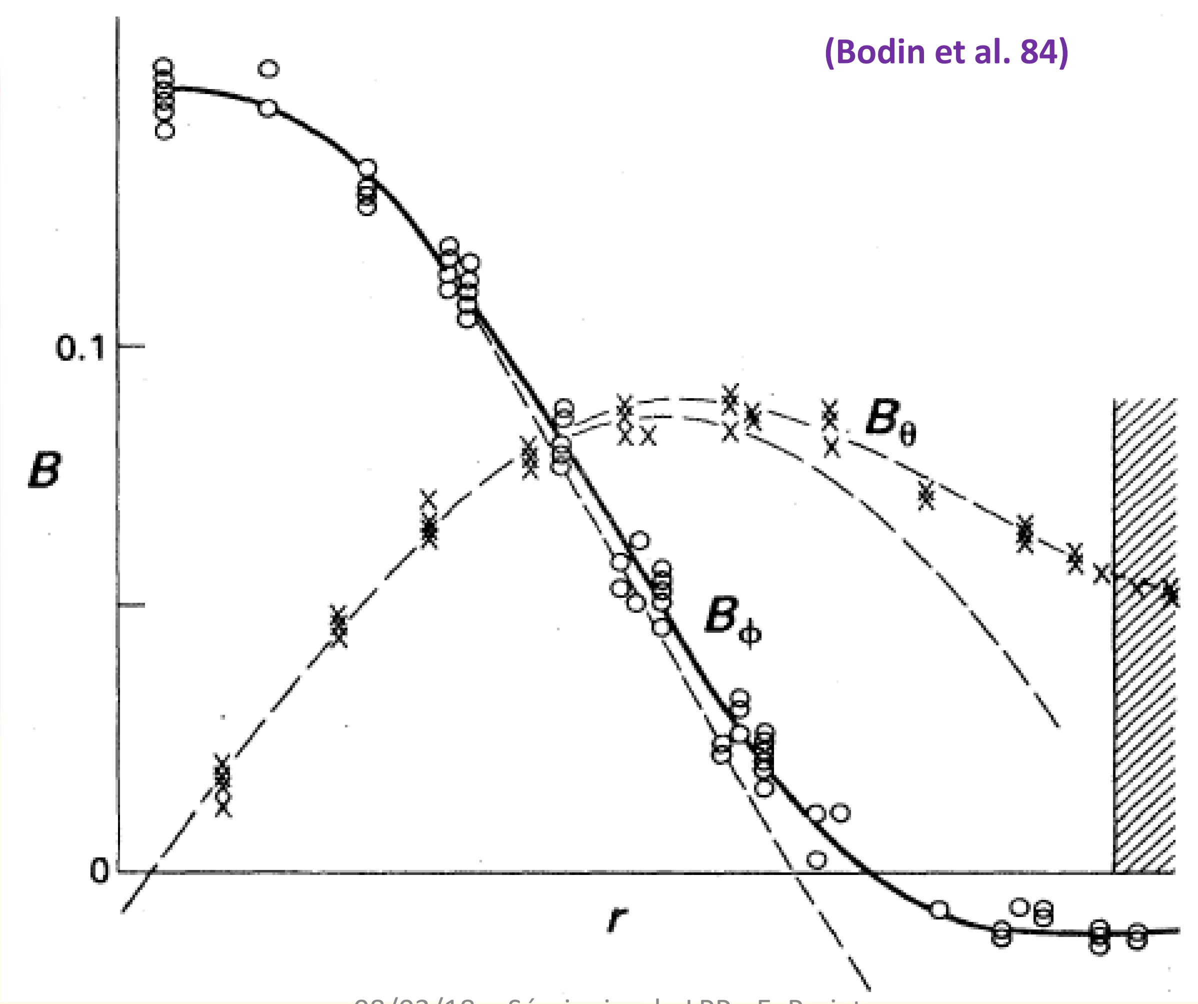




(Berger 03)

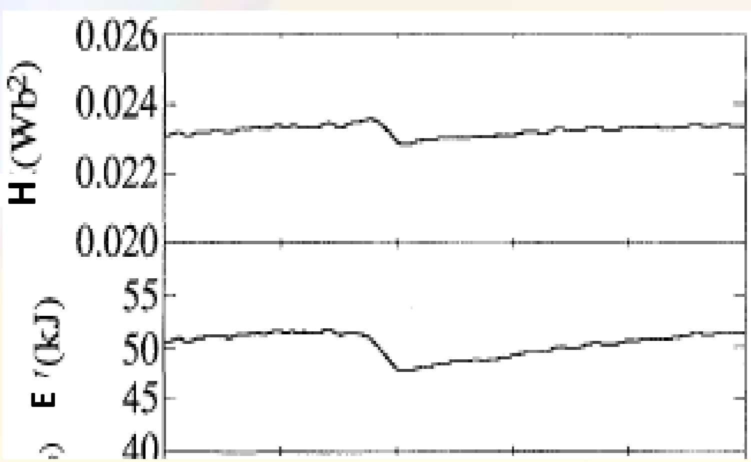
Helicity conservation consequence in Tokamaks

- Relaxation in laboratory 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**

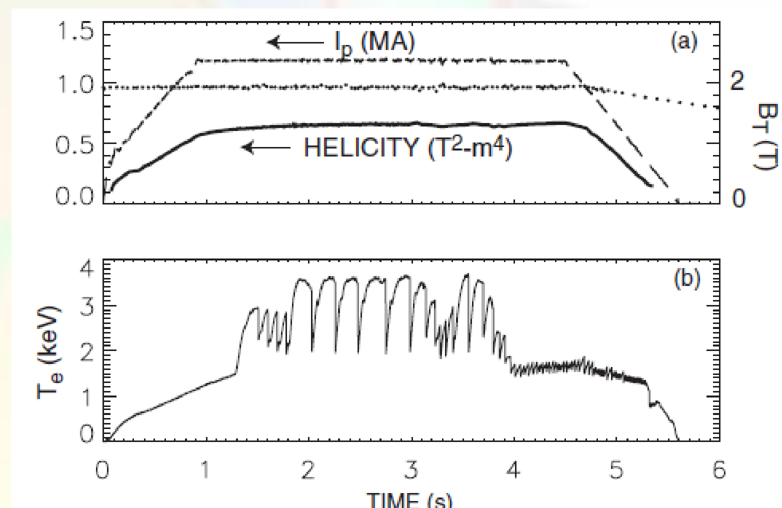


Tests on magnetic helicity Conservation

- **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 …

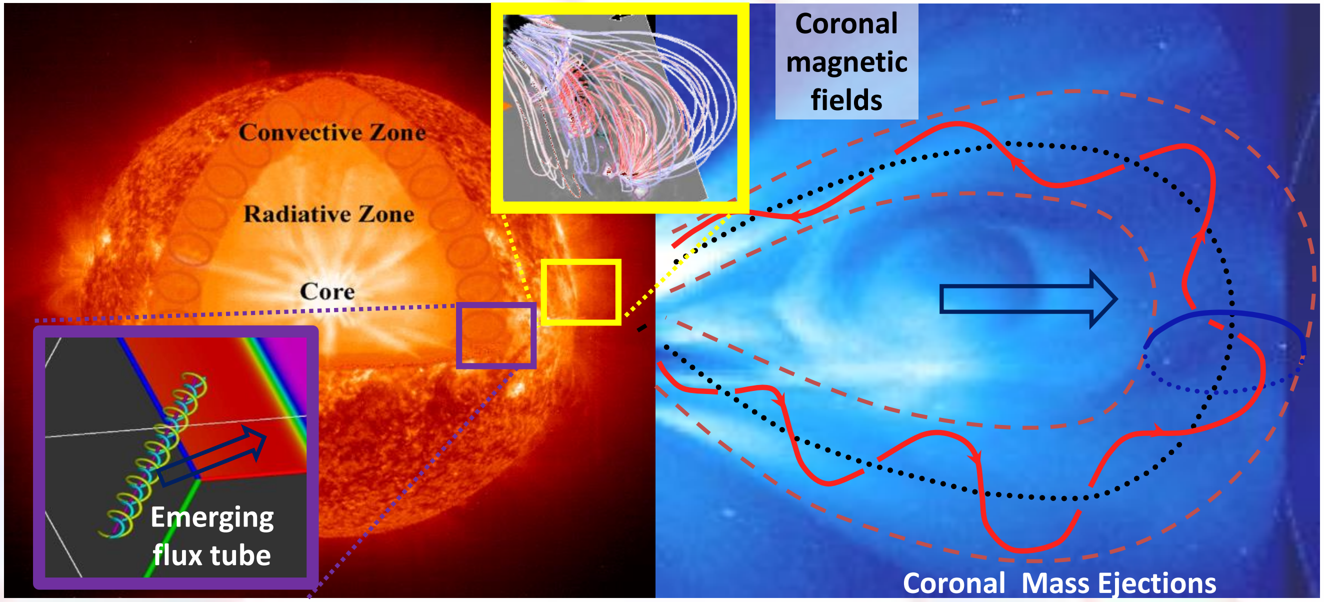


(Ji et al. 95)



(Heidbrink et al. 00)

Helicity conservation & solar eruptions: concept

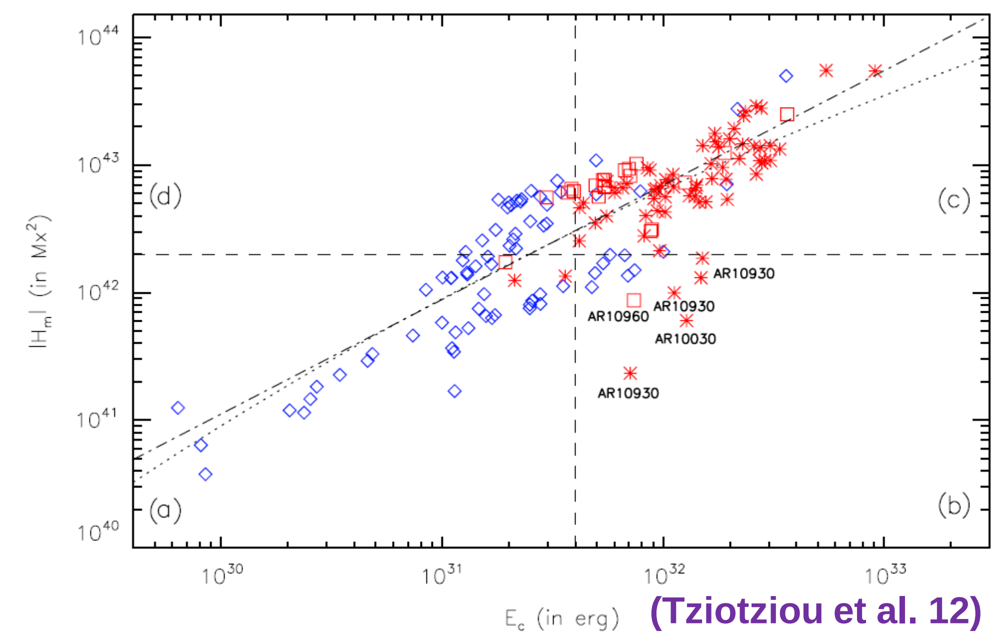


Magnetic helicity conservation is the "raison d'être" of CMEs:

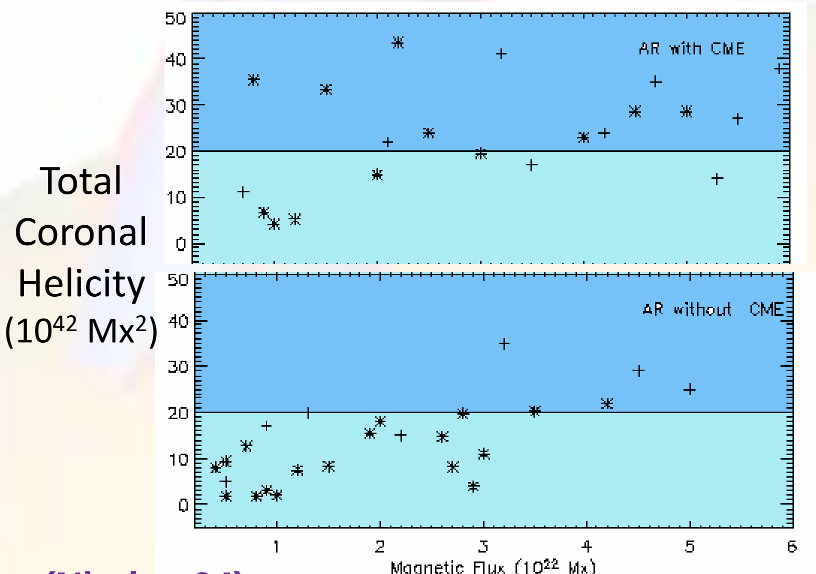
- **No helicity dissipation in the corona**. The variation of helicity is only due to terms of flux **(Berger and Field, 84)** :
- **No helicity creation either:** no efficient dynamo
- **Some helicity is constantly injected through the photosphere:**
- Hypothesis: **magnetic helicity cannot be infinitely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

Helicity & solar eruption: observations

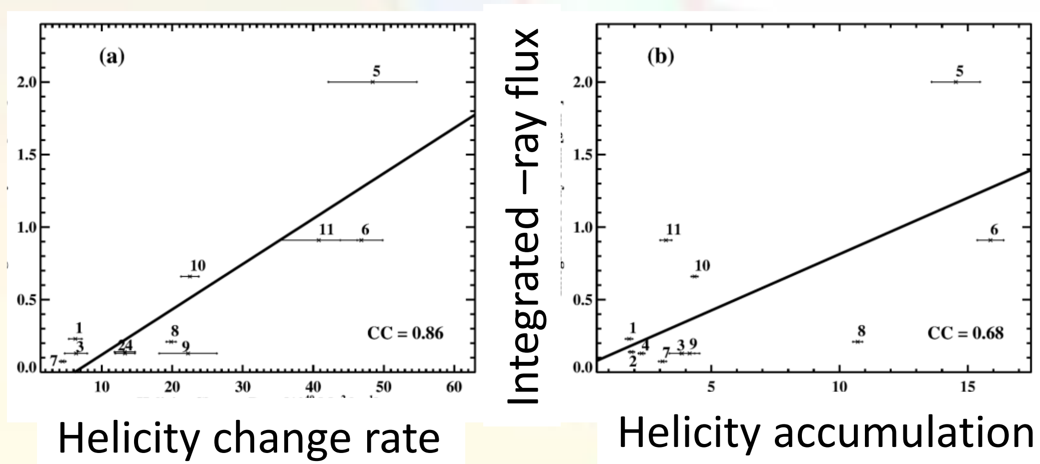
- Several observational studies have shown diverse indications that magnetic helicity can be tightly linked with enhanced eruptivity: **(Nindos et al. 04, Labonte et al. 07, Park et al. 08, 10, Tziotziou et al. 12, …)**



(Tziotziou et al. 12)



(Nindos 04)



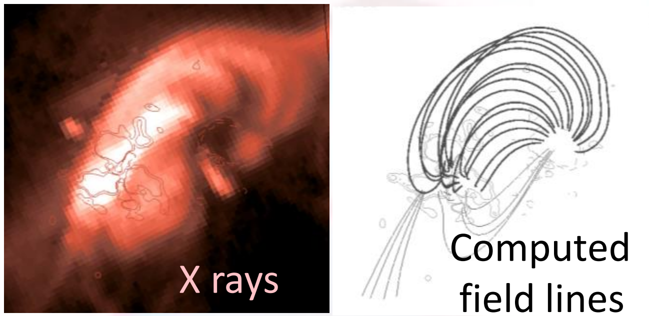
(Park et al. 08)

Linking coronal & interplanetary physics

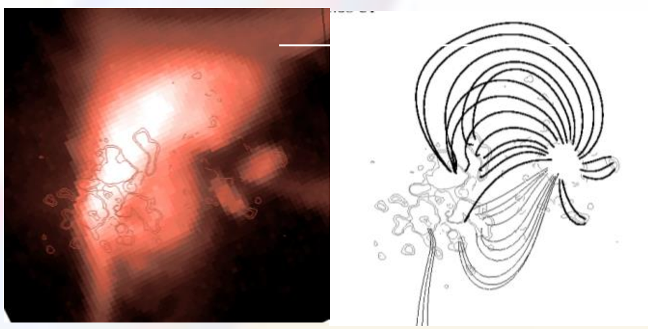
AR 7912, 14 Oct. 1995

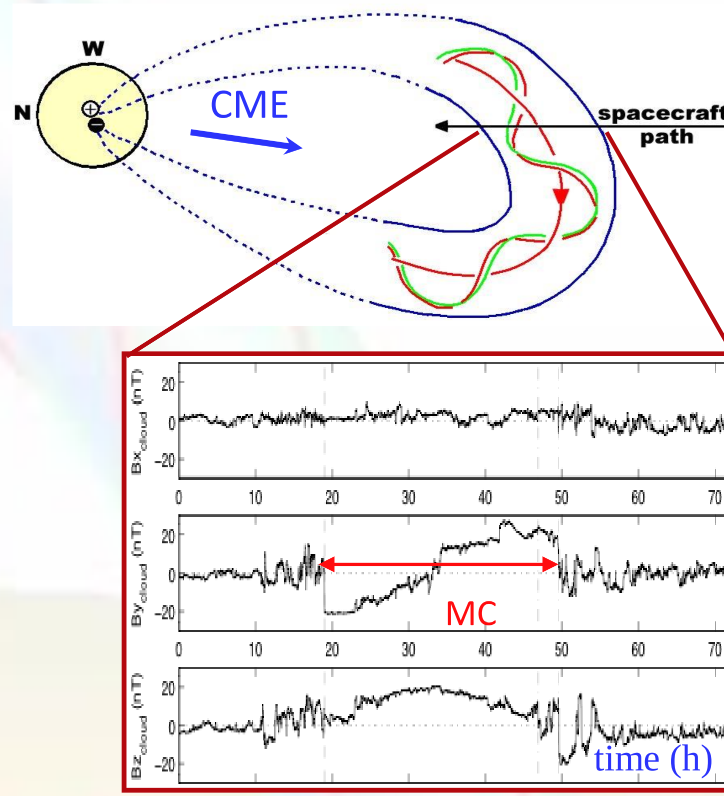
4 days later

before CME



after CME





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

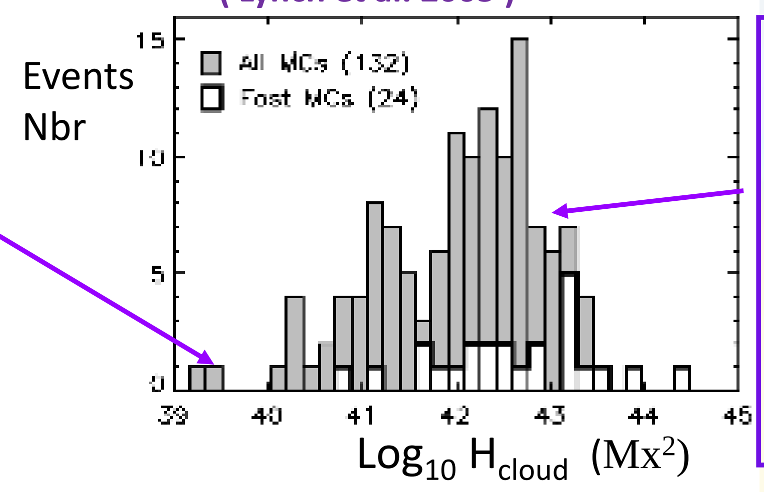
$2.3 \leq |\Delta H_{corona}| \leq 3.1$

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

~

Units : 10^{39} Mx^2

(Lynch et al. 2005)



large event

14 Oct. 1995

$L_{cloud} = 2$ AU

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

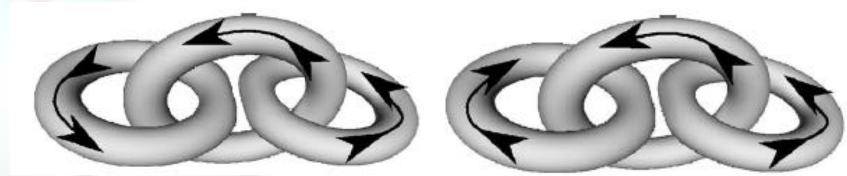
$7 \leq H_{cloud} \leq 12$

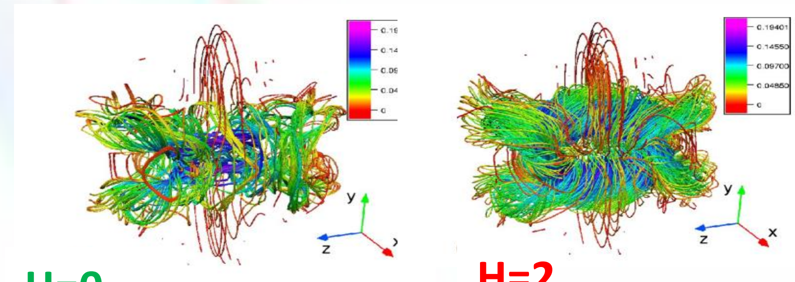
factor ~ 2

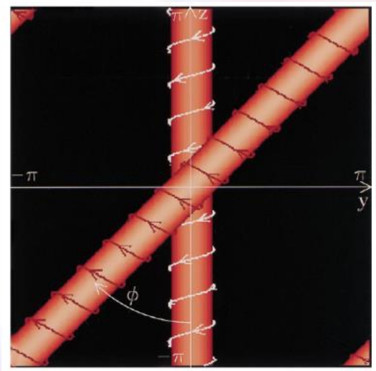
Units : 10^{42} Mx^2

Helicity and magnetic reconnection

- **Helicity modifies the properties & dynamics of reconnection / energy dissipation :** **e.g. Linton et al. 01, Del Soro et al. 10**





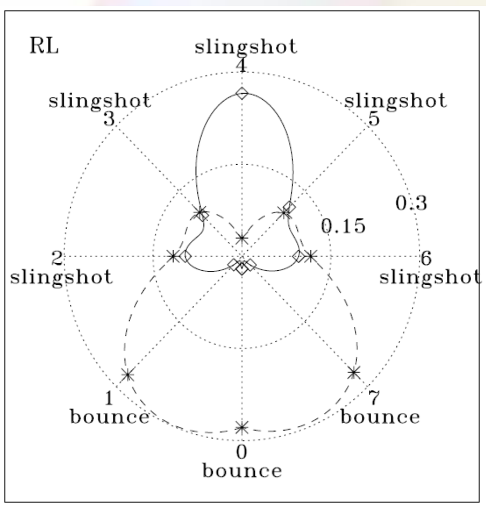


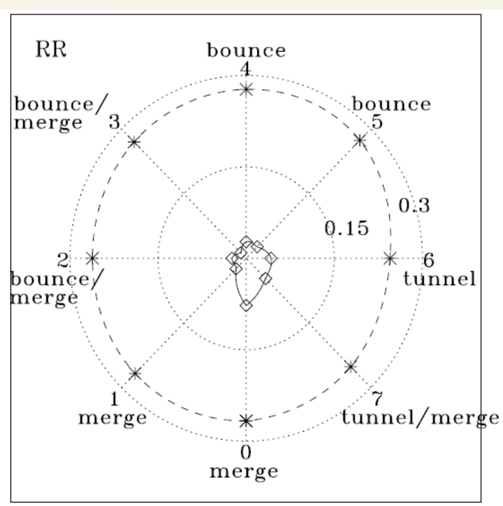
opposite helicity

same helicity

—— E_{kin}

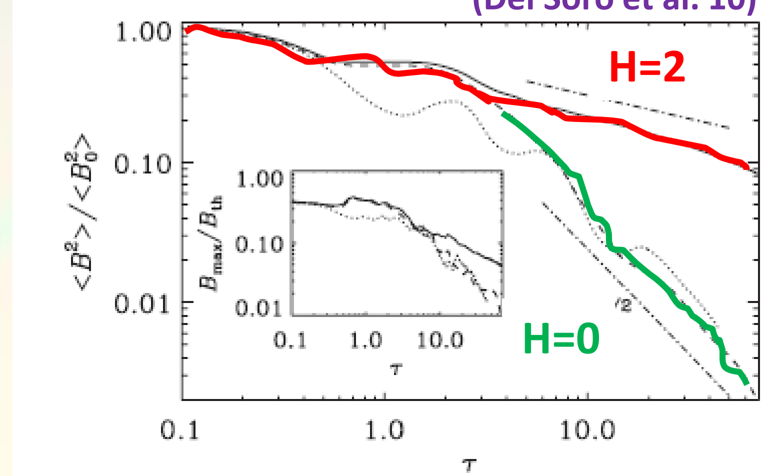
------- E_{mag}





(Linton et al. 01)

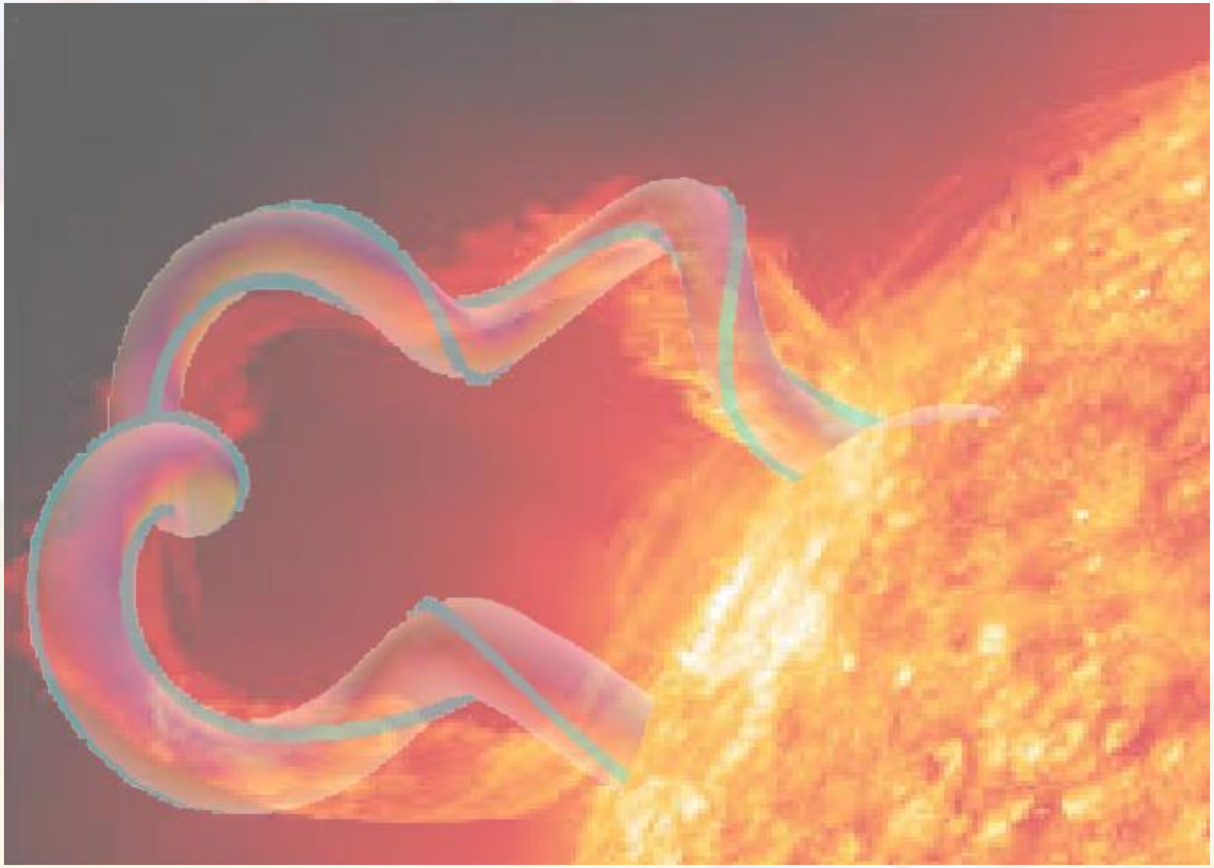
(Del Soro et al. 10)



(Del Soro et al. 10)

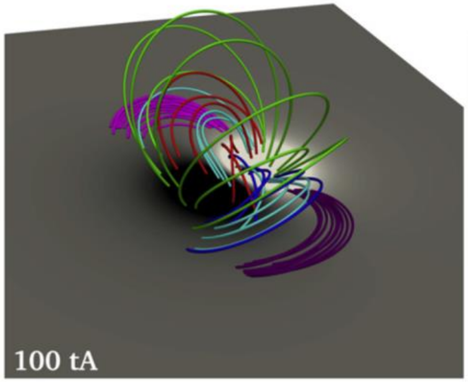
Outline

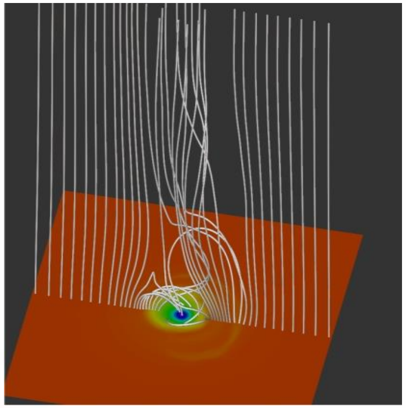
- Context
- Magnetic helicity:
  - Definition
  - Properties
  - Measurements
- Magnetic helicity conservation in non-ideal MHD
  - past experiments
  - new tests
- Magnetic helicity as an eruptivity proxy
- Conclusions



Relative magnetic helicity conservation ?

- For most configuration in natural plasma, classical definition of helicity cannot be used!
- **To study the conservation of magnetic helicity in general configurations ➔ study the conservation of relative magnetic helicity.**



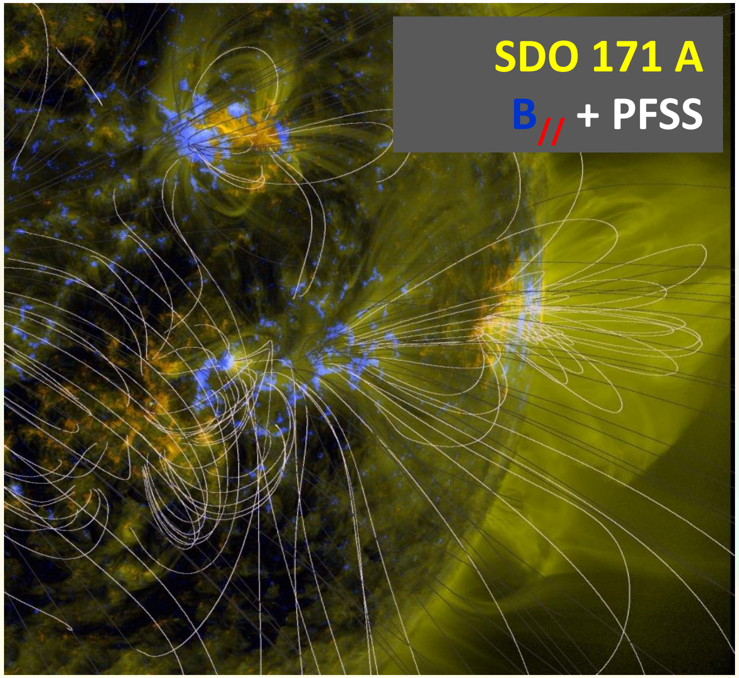


$$H_{\mathcal{V}} = \int_{\mathcal{V}} (\mathbf{A} + \mathbf{A}_{\mathrm{p}}) \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) \; \mathrm{d}\mathcal{V}$$

$$\nabla \times \mathbf{A} = \mathbf{B}$$

with boundary condition :

$$(\mathbf{B}_{\mathrm{p}} \cdot \mathrm{d}\mathbf{S})|_{\partial\mathcal{V}} = (\mathbf{B} \cdot \mathrm{d}\mathbf{S})|_{\partial\mathcal{V}}$$



Relative Magnetic Helicity: helicity of a studied field relative to a reference field **(Berger 84, Finn & Antonsen 85)**.

Relative magnetic helicity estimations

- The computation of relative magnetic helicity is not straightforward:
  - **Computation of reference field must be done imposing boundary conditions on the whole domain boundary.**
  - Many previous methods assumed semi-infinite volumes while all existing datasets are bounded volumes: could lead to incorrect results **(Valori et al. 11, 12)** error in intensity, even in sign!

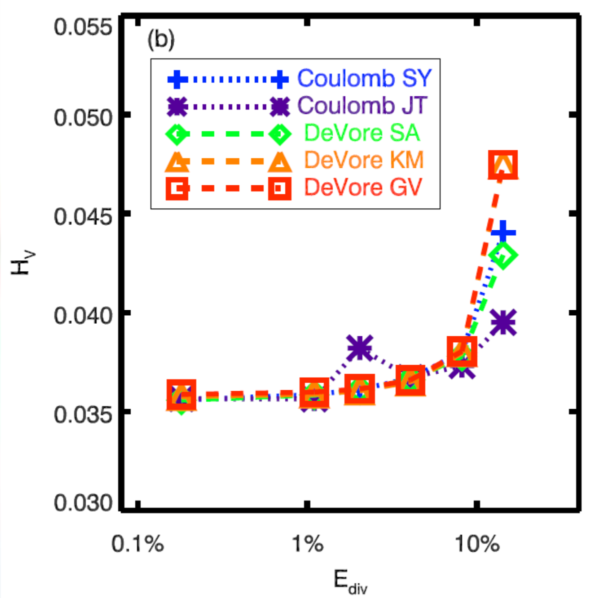
- **Several methods recently developed on 3D cuboid system** **(Valori et al. 2016)**
  - Using Coulomb gauge: $\nabla \cdot \mathbf{A} = 0$

    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)** : $A_z = 0$

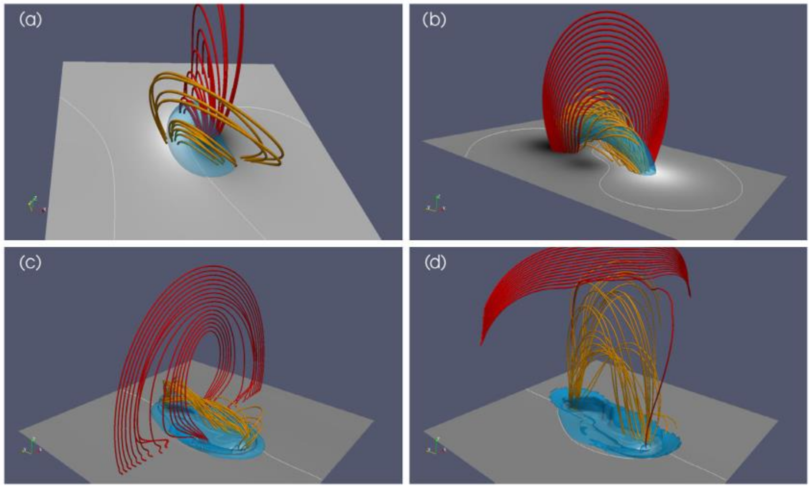
    Valori, Démoulin & Pariat 2012, Moraitis et al. 2014
    - More complex theoretical formulation
    - Simpler to implement numerically: more precise
- **New method to compute relative magnetic helicity in spherical wedge domains**. **(Moraitis et al. submitted)**

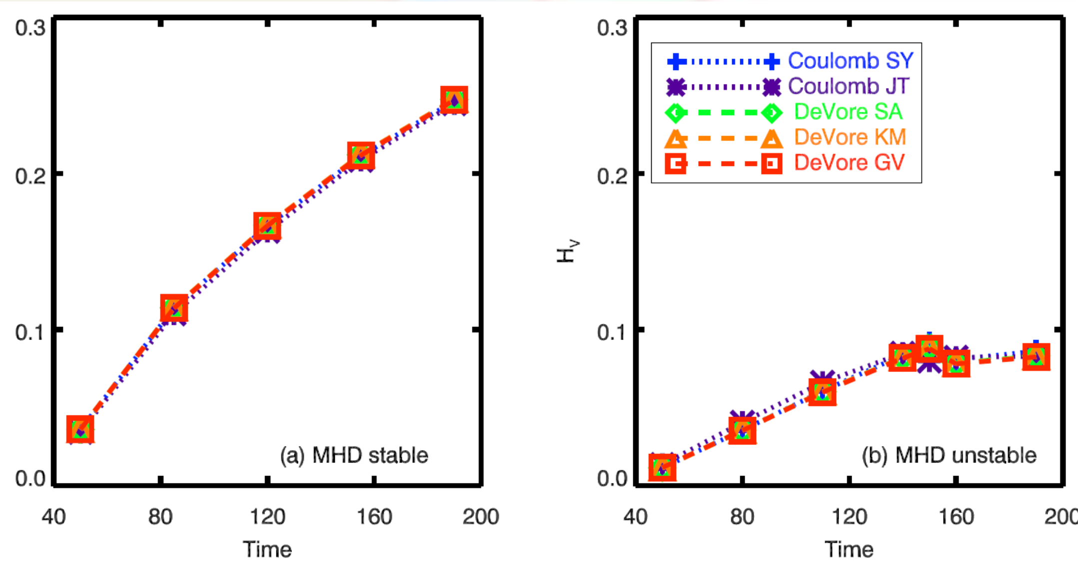
Relative magnetic helicity estimations

- **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**



(Valori et al. 16)





Magnetic helicity dissipation estimation

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

Magnetic helicity dissipation

Helicity variation and flux of the reference field

Time variation of relative magnetic helicity

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

(Pariat et al. 15)

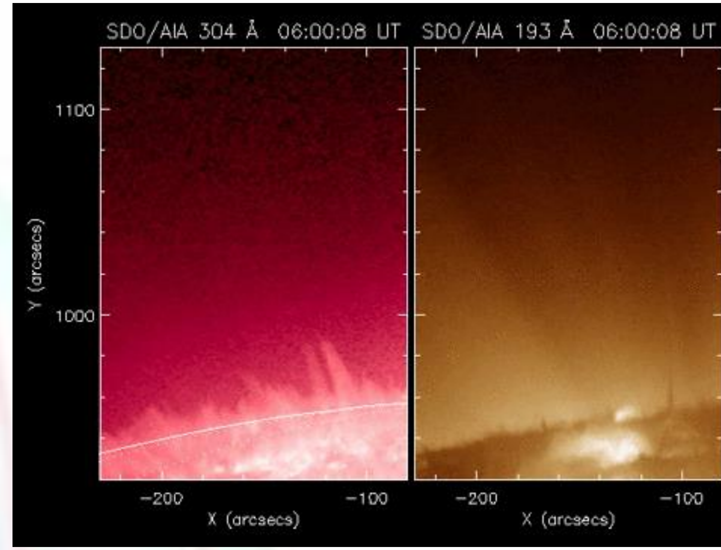
Flux of helicity of the studied field

- **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

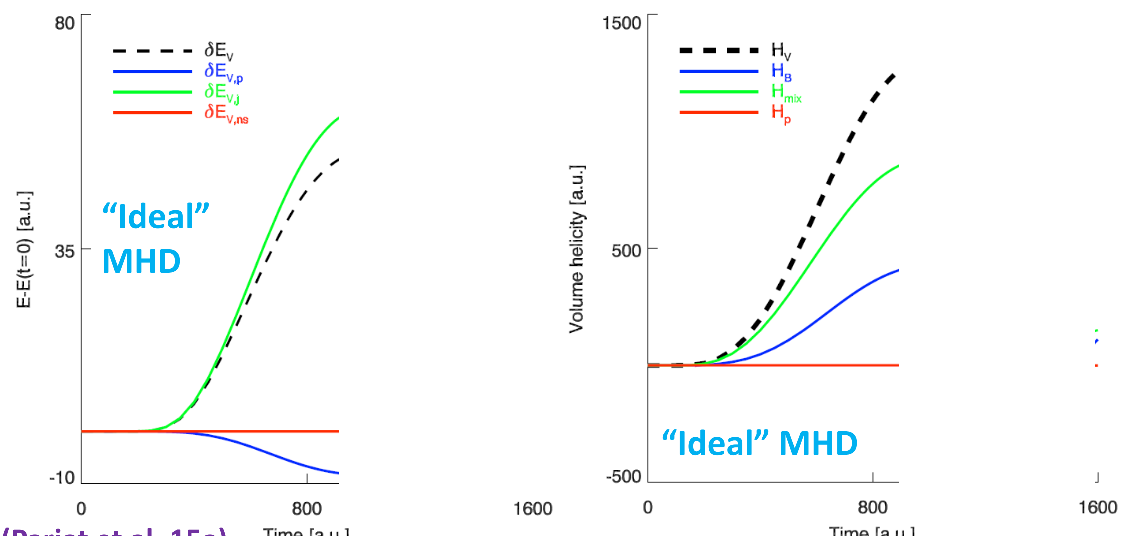
$$C_m = -2\int_{\mathcal{V}} \mathbf{E}\cdot\mathbf{B}\, d\mathcal{V} = \frac{dH}{dt} - F_{tot}$$

Test case: coronal jet simu.

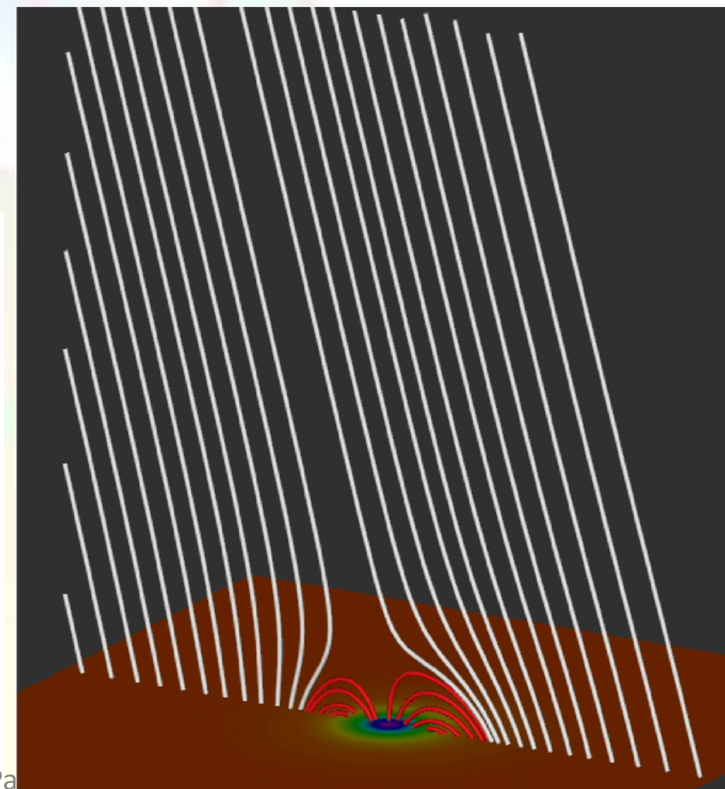
- **3D MHD simulation of a solar coronal jet:**
  Pariat et al. 09,10,15b ; Dalmasse et al. 12
  - Magnetic helicity/energy injected by bottom boundary motions
- **First phase: helicity/energy storage.**
  - Quasi-ideal MHD: reconnection inhibited.
- **Second phase: Jet generation**
  - Very impulsive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



(Shen et al. 11)



(Pariat et al. 15a)



Helicity conservation - fluxes

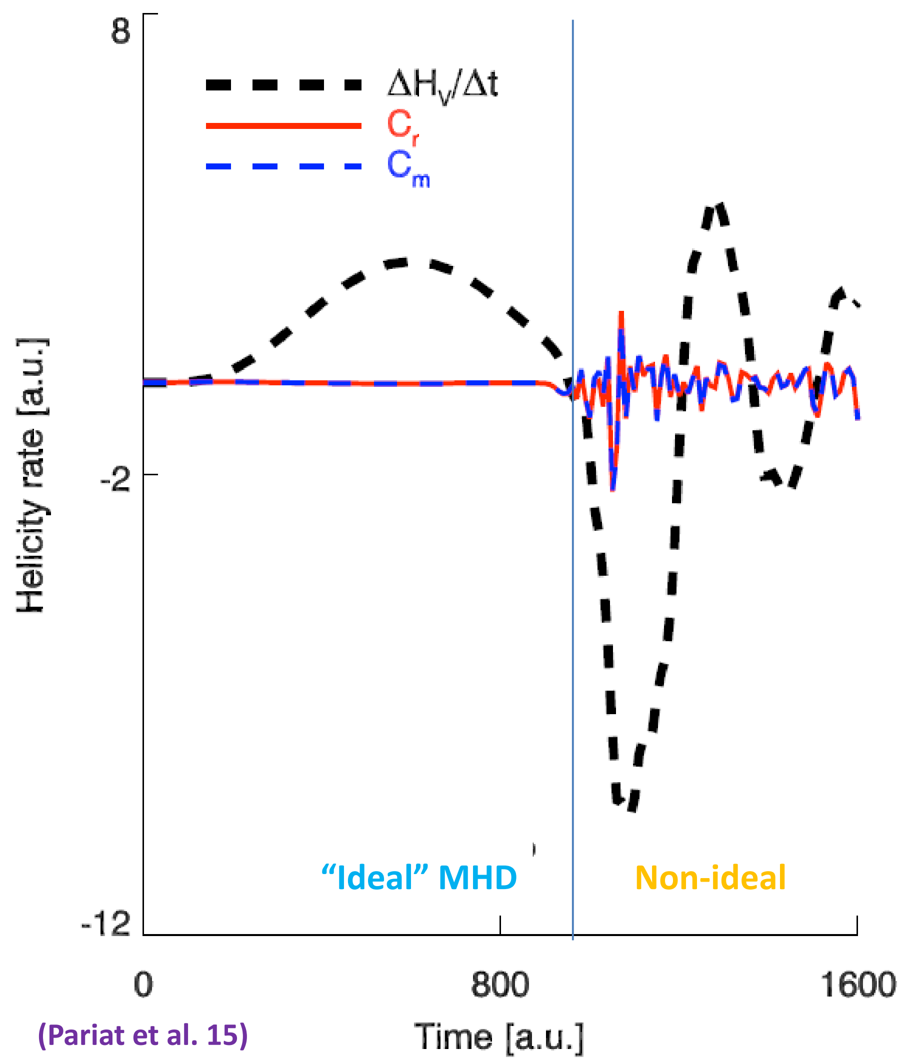
- Helicity and its flux are estimated independently
  - Direct volume helicity computation (**Valori et al. 12**) : **B** in $\mathcal{V}$
  - Helicity flux computation: **B**, **v** on $\mathcal{S}$

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

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

$$F_{tot} = F_{\mathcal{V}n} + F_{Bn} + F_{mix} + F_{\phi}$$

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



(Pariat et al. 15)

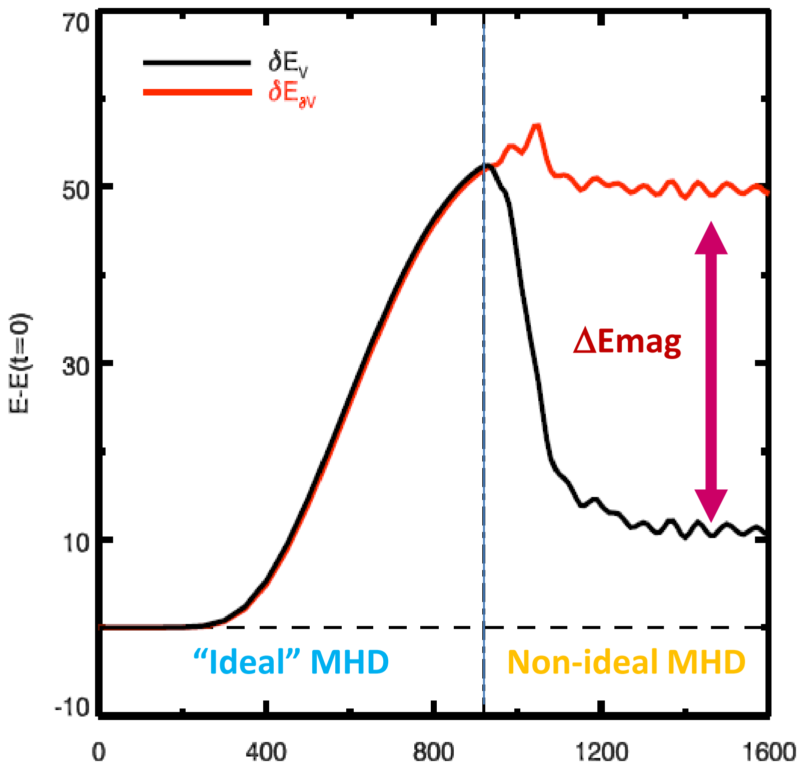
Helicity conservation vs Energy

- **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.

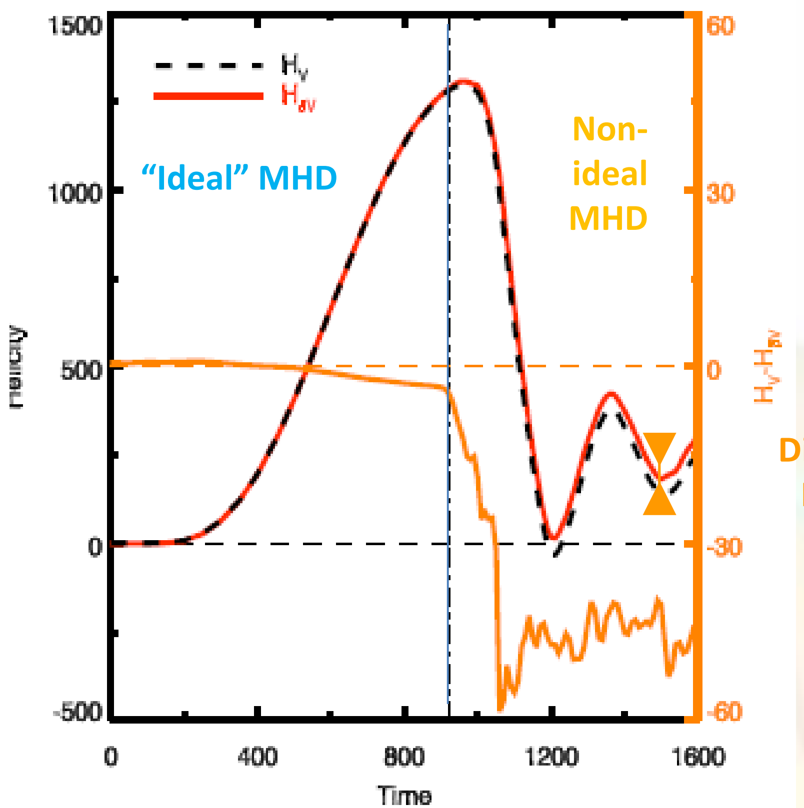
$$\frac{\Delta H_{\text{diss,Ideal}}}{\Delta H_{\text{inj}}} < 3 \times 10^{-3}$$

$$\frac{\Delta H_{\text{diss, Non-ideal}}}{\Delta H_{\text{inj}}} < 0.02$$

$$\frac{\Delta E_{\text{diss, Non-ideal}}}{\Delta E_{\text{inj}}} \sim 0.6$$



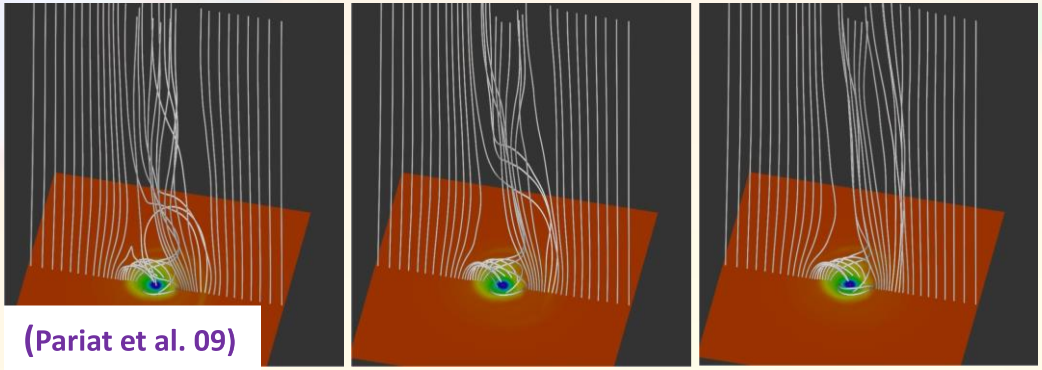
(Pariat et al. 15)



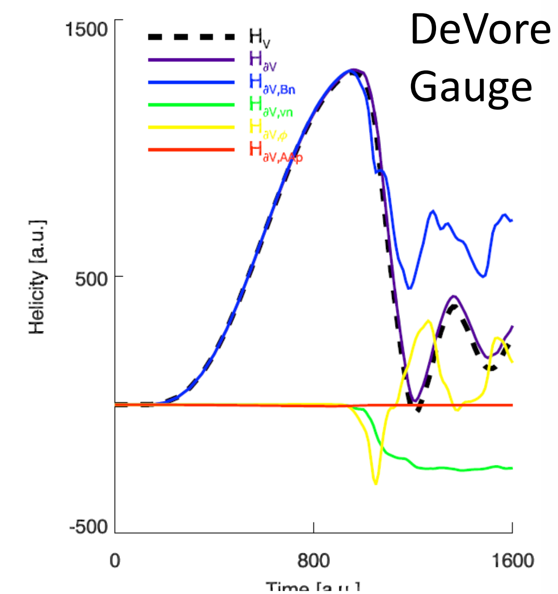
Helicity conservation tests

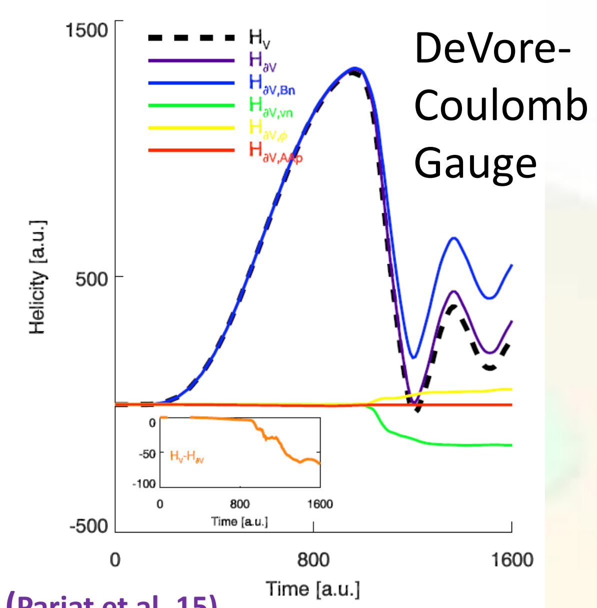
- **Forty years after, the Taylor conjecture can now be numerically tested in general configurations, using typical numerical data sets**.
- Estimations of the helicity conservation on an impulsive solar active like events (coronal jet).
  - Independent of reconnection models
  - Using several general 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)





(Pariat et al. 15)

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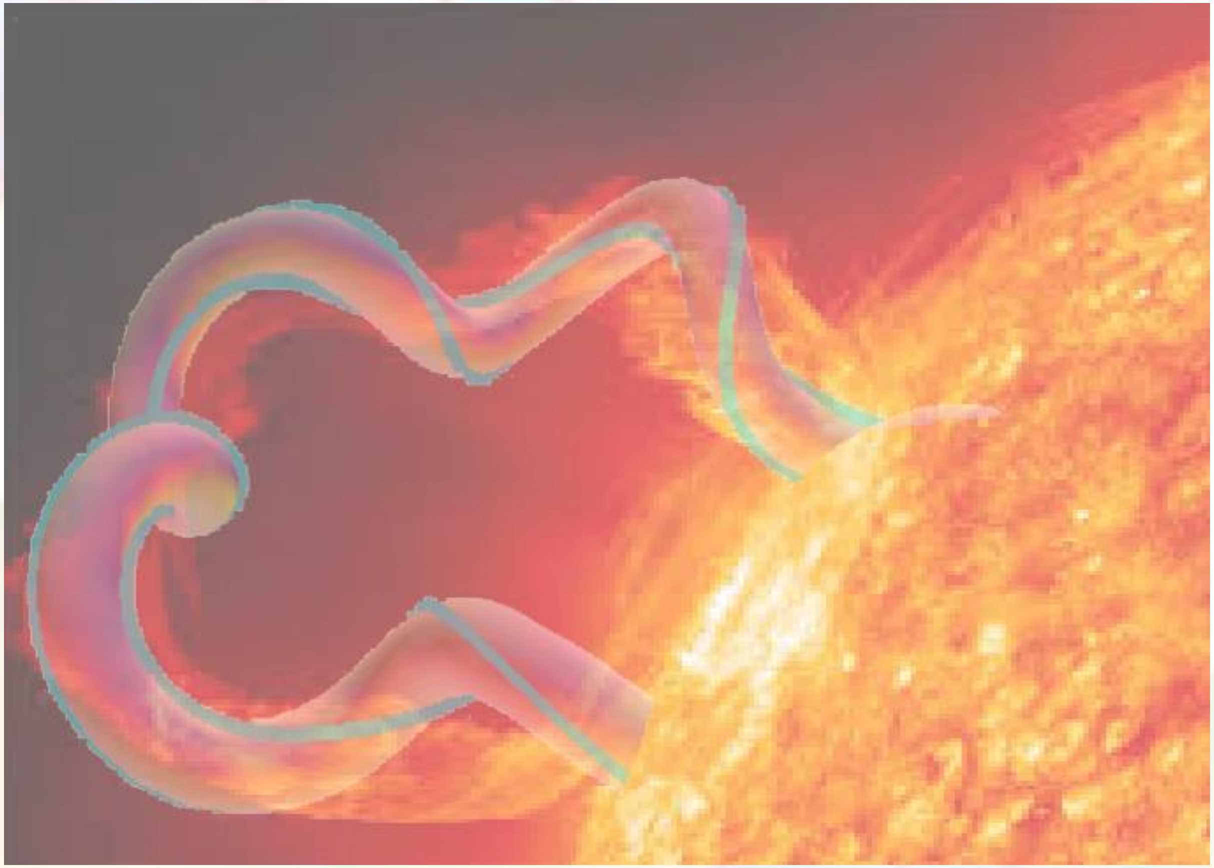
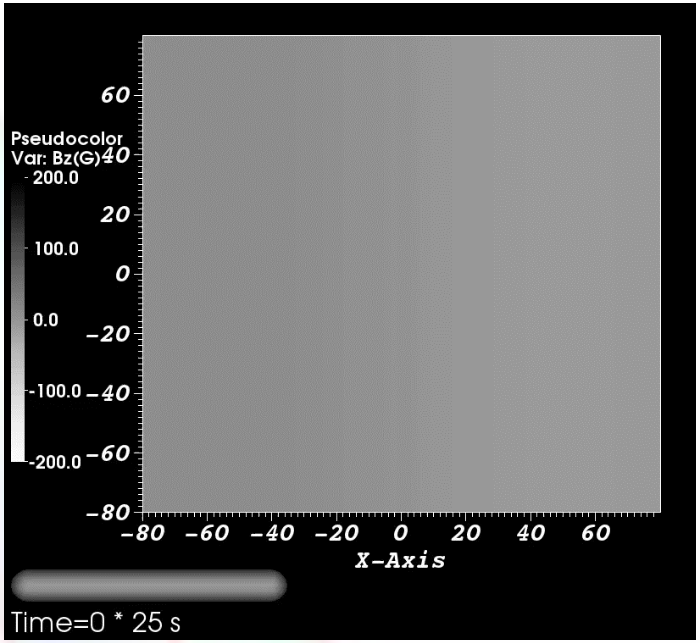
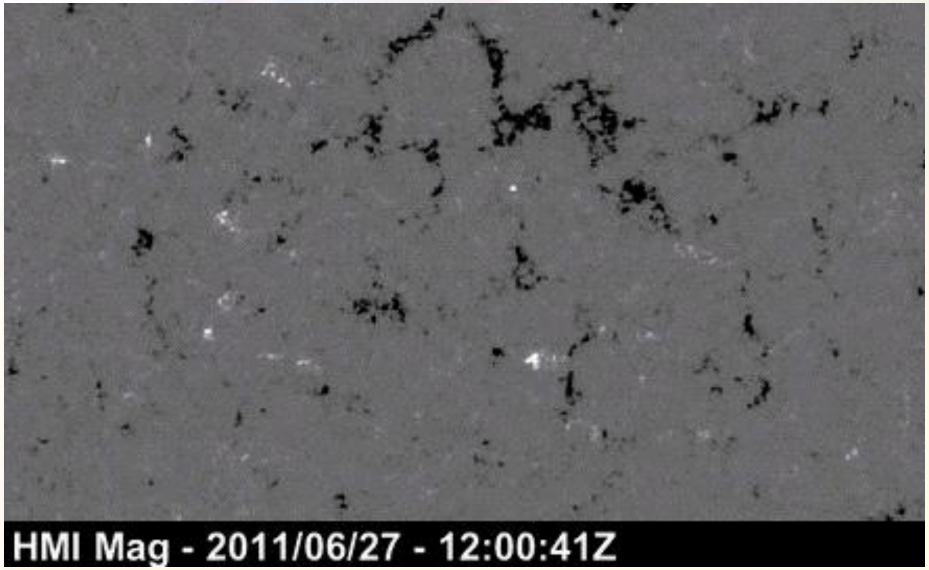
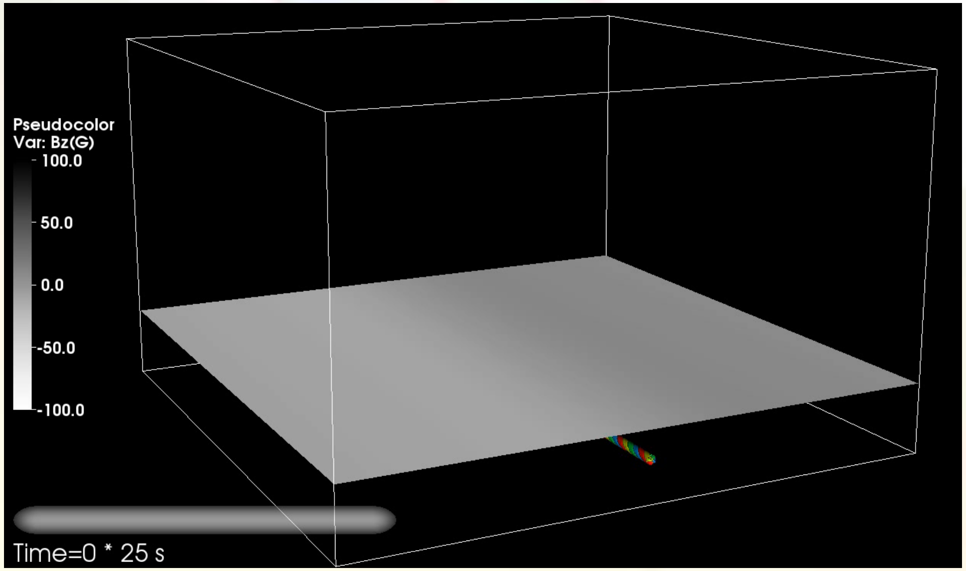


Flux emergence simulations

- **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.**

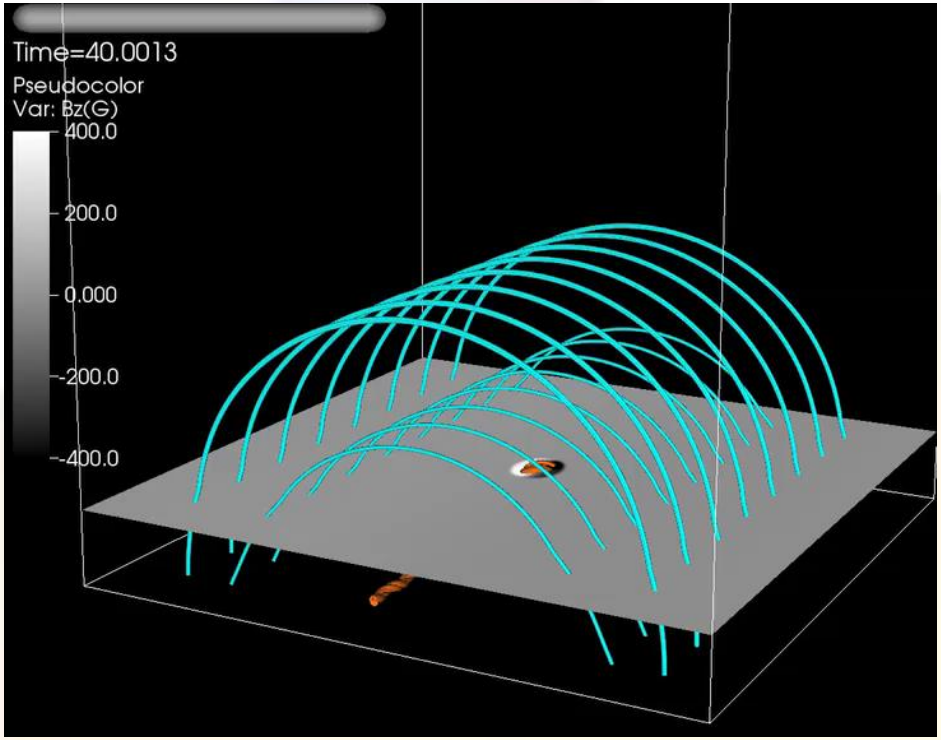


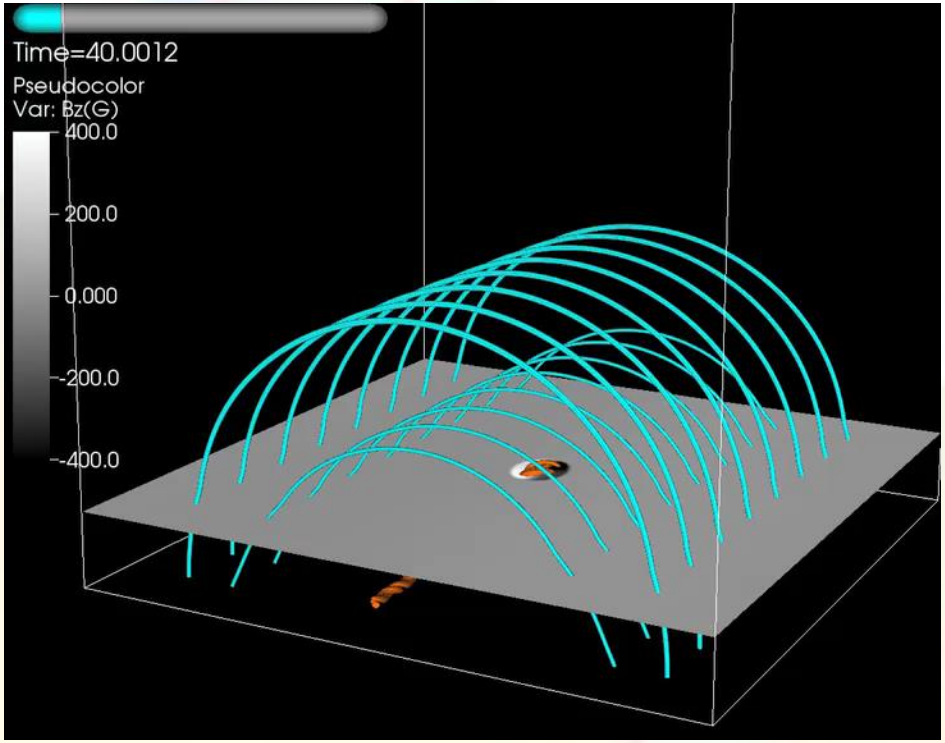




Parametric flux emergence simulations

- **7 flux emergence simulations leading either to eruptive or non-eruptive dynamics (Leake et al. 2013, 2014)**
- Determine eruptivity criteria: methodology:
  - extract part of the magnetic field,
  - compute different physical quantities,
  - search those that discriminates between the eruptive and non-eruptive cases

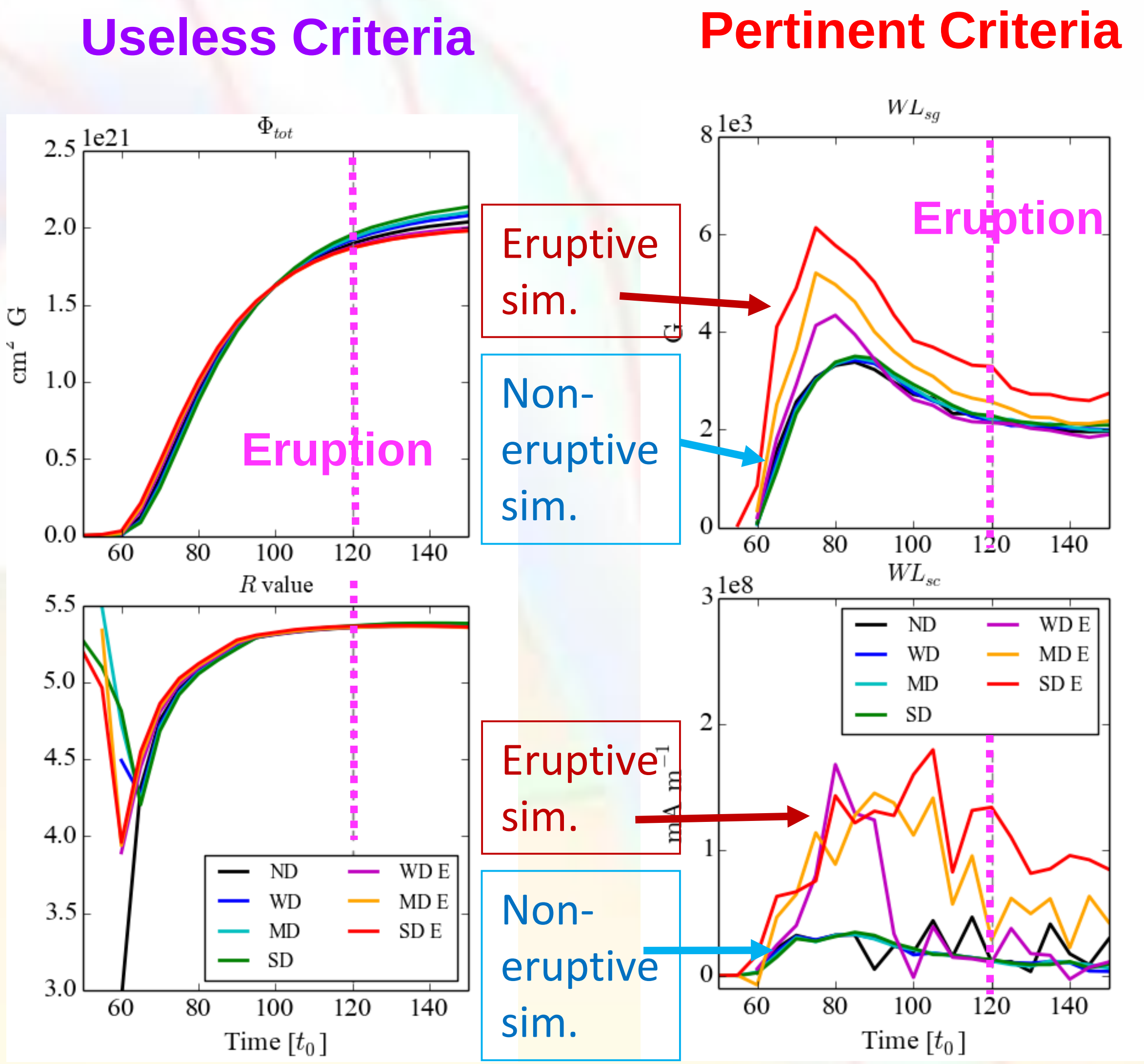




(Leake et al. 13, 14)

Search for eruptivity criterion

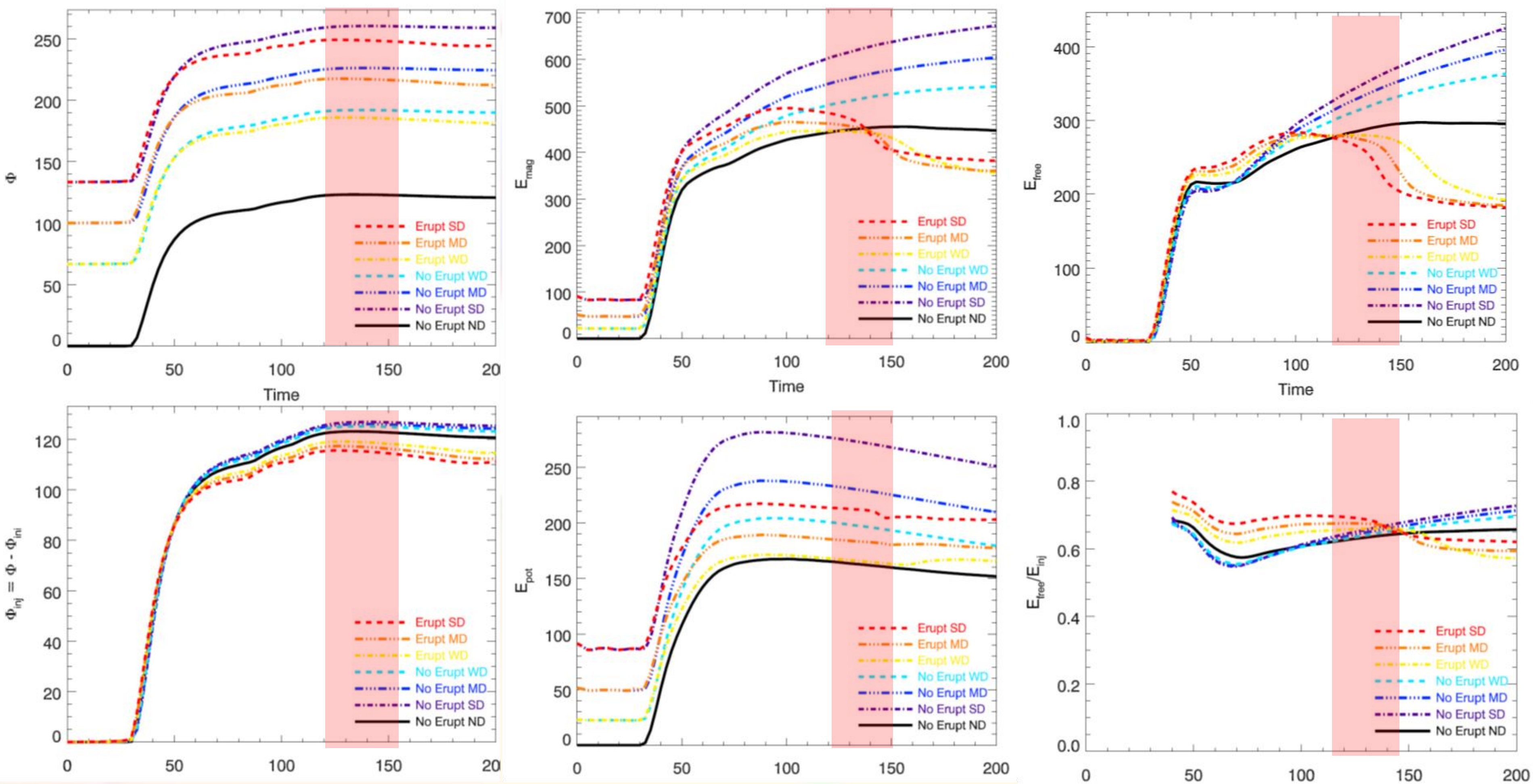
- **Goal: search for eruptivity indicators from 3D coronal magnetic datacube**
- Good eruptivity criterion should:
  - Discriminate eruptive and non-eruptive sim. during pre-eruptive phase
  - Reach its highest value
    - for eruptive simulation only,
    - during the pre-eruptive phase only.
  - Present similar trend for eruptive and non-eruptive sim. in post-eruptive phase



(Guennou et al. 17)

Magnetic fluxes and energies

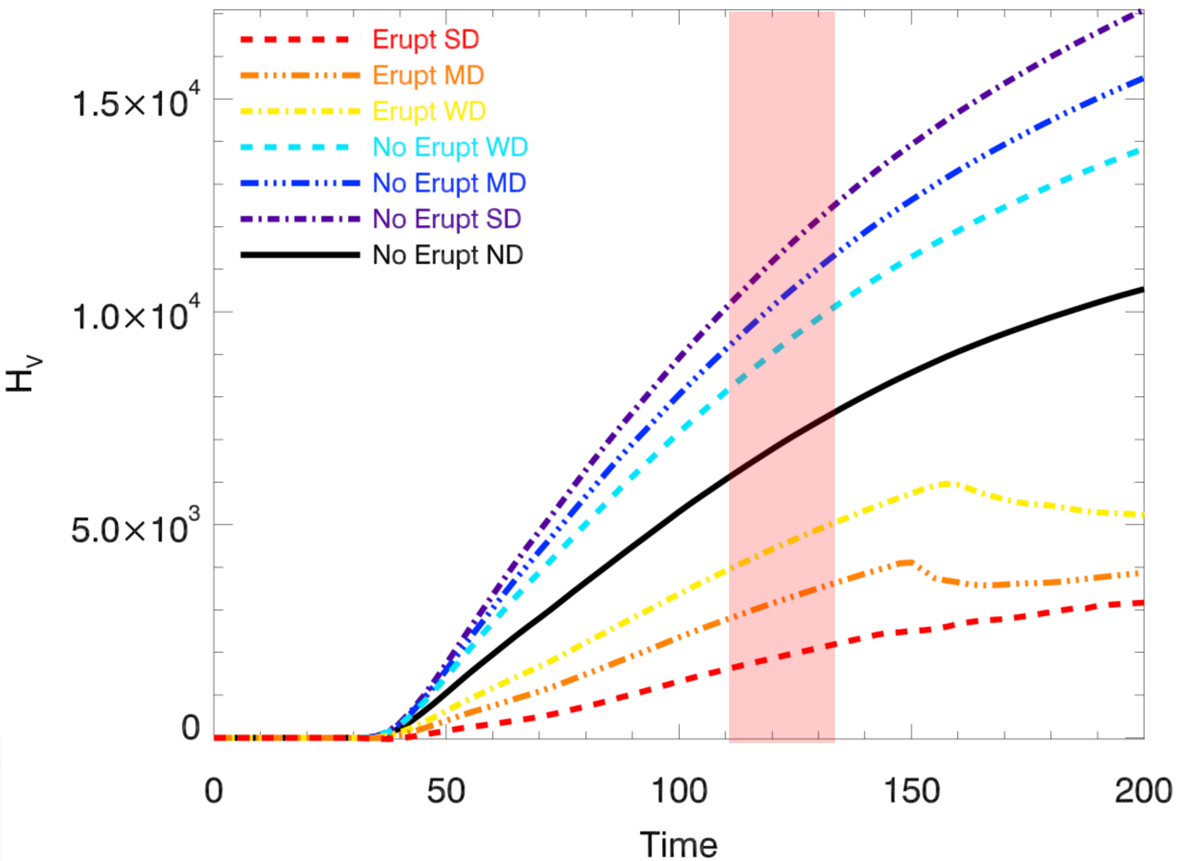
(Pariat et al. 17)



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

Relative magnetic helicity evolution

(Pariat et al. 17)



- **Unlike with magnetic flux & free energy, helicity discriminates strongly the cases**
  - Total helicity depends
    - on dipole strength
    - on dipole orientation

- The surrounding (potential) field influences the helicity content!

  ← magnetic helicity is a non-local quantity!

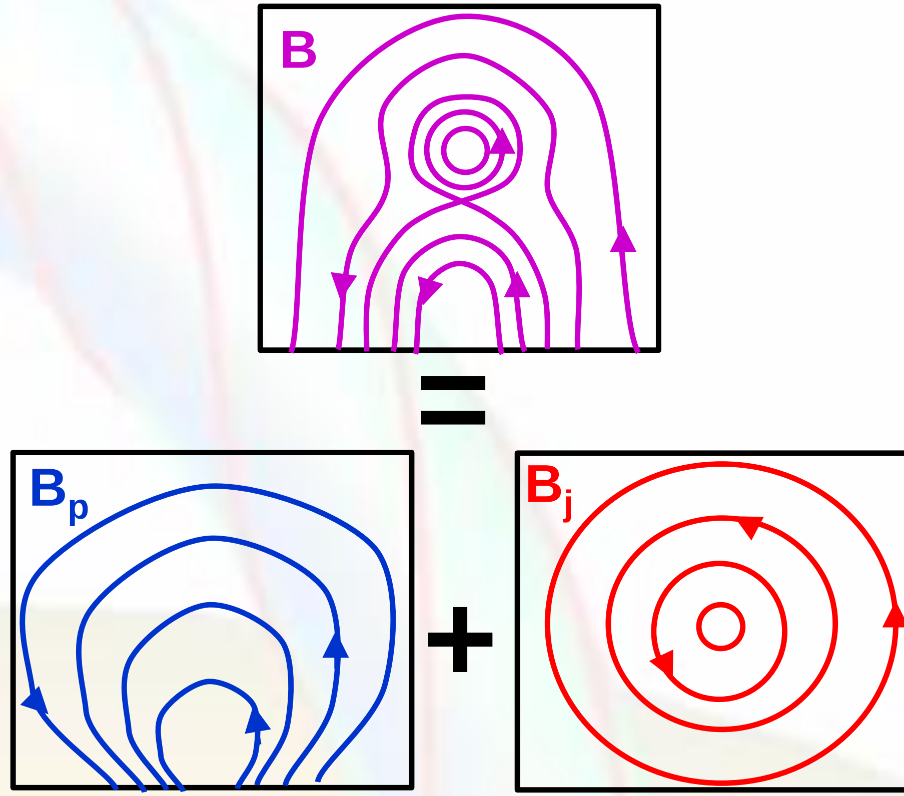
- Here, eruptive simulations have lower helicity than non-eruptive one

  ➔ unlike what is commonly believed/expected, large total helicity is not a sufficient condition of eruptivity.

Relative magnetic helicity decomposition

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

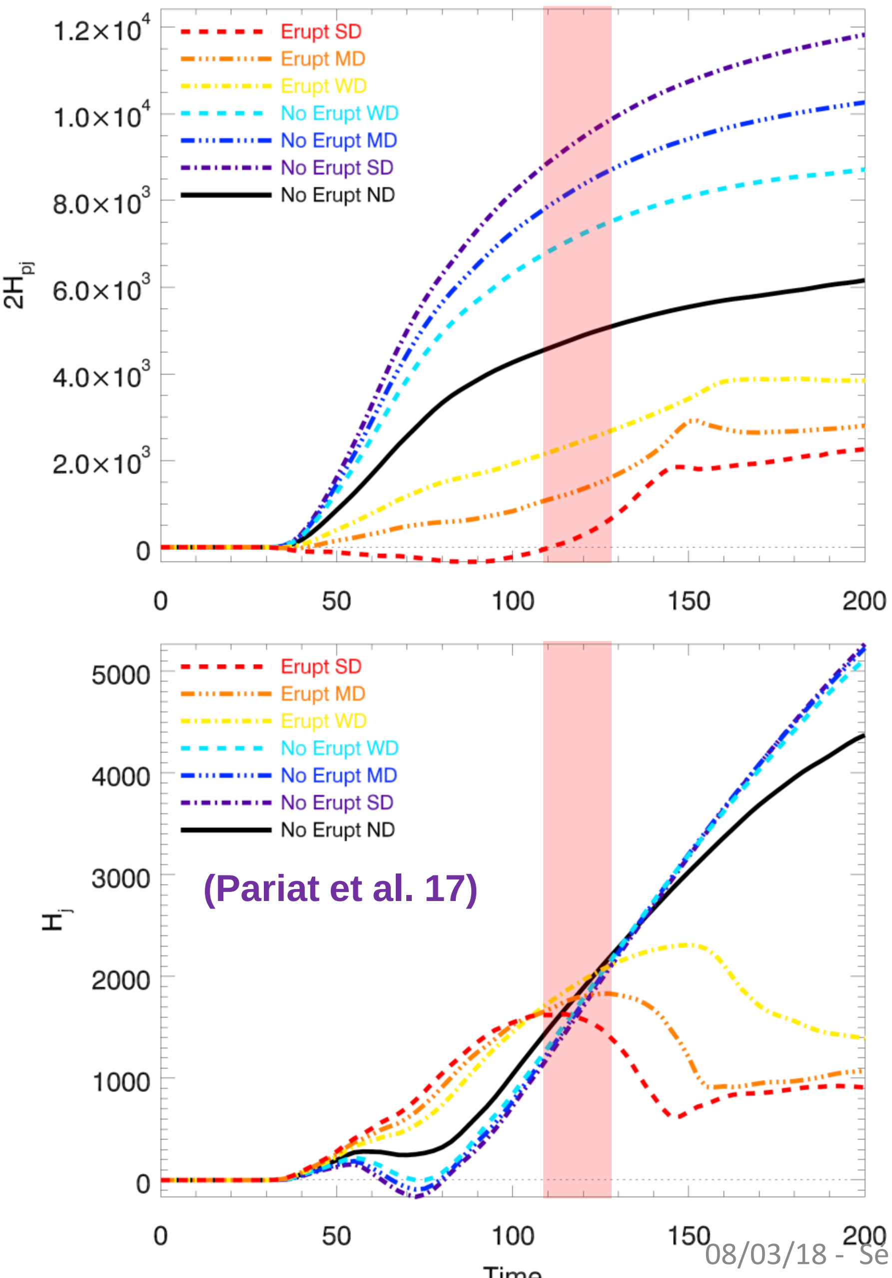
- **Relative magnetic helicity can be decomposed in 2 gauge-invariants quantities (Berger et al. 2003) :**
  - H_j = magnetic helicity of the current-carrying field B_j (non-potential field)
  - H_{pj} = volume-threading helicity, between potential and current-carrying fields



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

- Remark for the heli-aware: H_j & H_{pj} are different from the “self” and “mutual” helicities

Helicity decomposition evolution

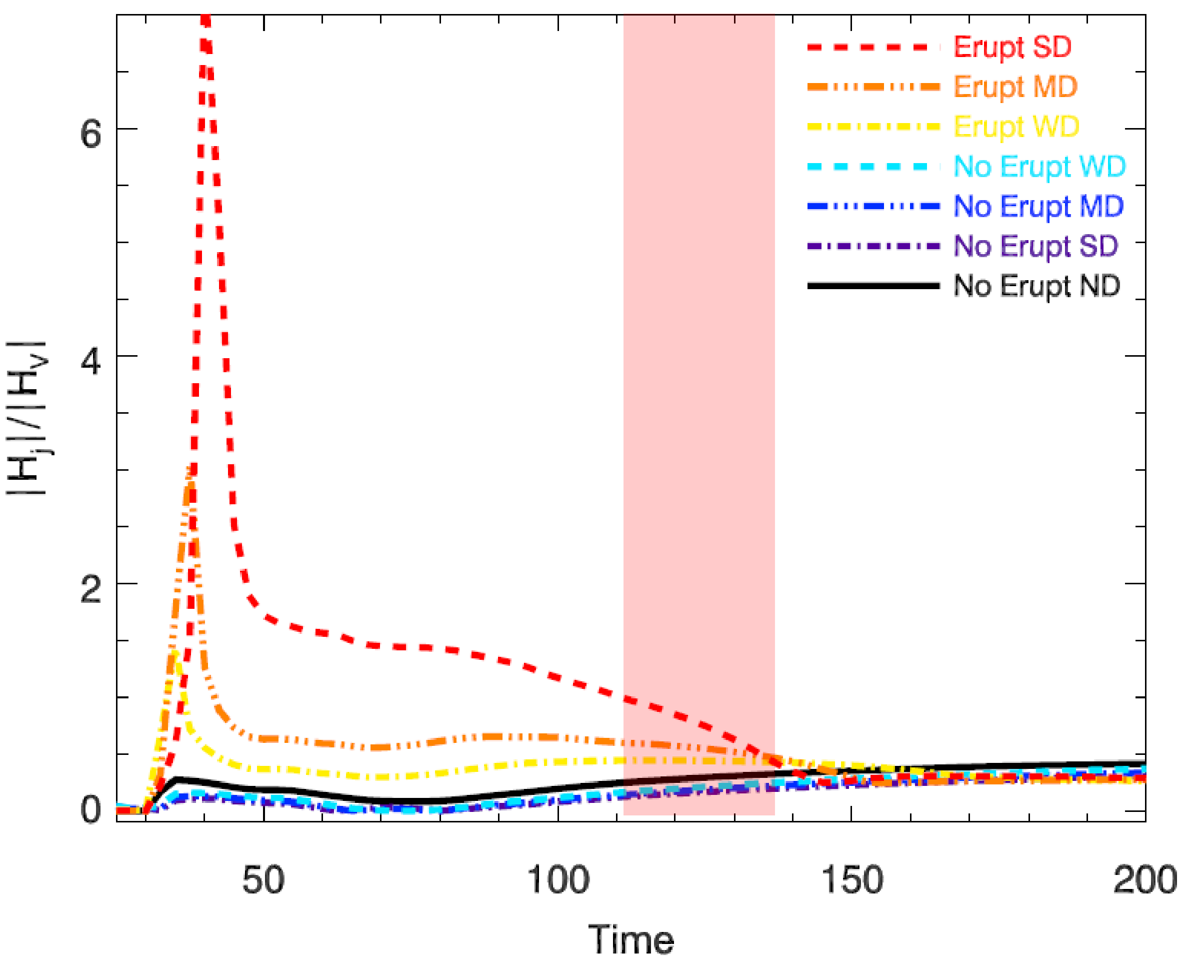


$$
\begin{aligned}
H_V &= H_j + 2H_{pj} \quad \text{with} \\
H_j &= \int_{\mathcal{V}} (\mathbf{A} - \mathbf{A}_p) \cdot (\mathbf{B} - \mathbf{B}_p)\, d\mathcal{V} \\
H_{pj} &= \int_{\mathcal{V}} \mathbf{A}_p \cdot (\mathbf{B} - \mathbf{B}_p)\, d\mathcal{V}
\end{aligned}
$$

- Total helicity is overall dominated by $2H_{pj}$
- $2H_{pj}$ has same properties than total helicity ➔ not a good eruptivity proxy
- **H_j behaves similarly to E_{free}**
  - **higher for the eruptive simulations in the pre-eruptive phase**
  - **however higest values reached by non-eruptive simulations**
- **H_j is not a good eruptivity proxy.**

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

(Pariat et al. 17)



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

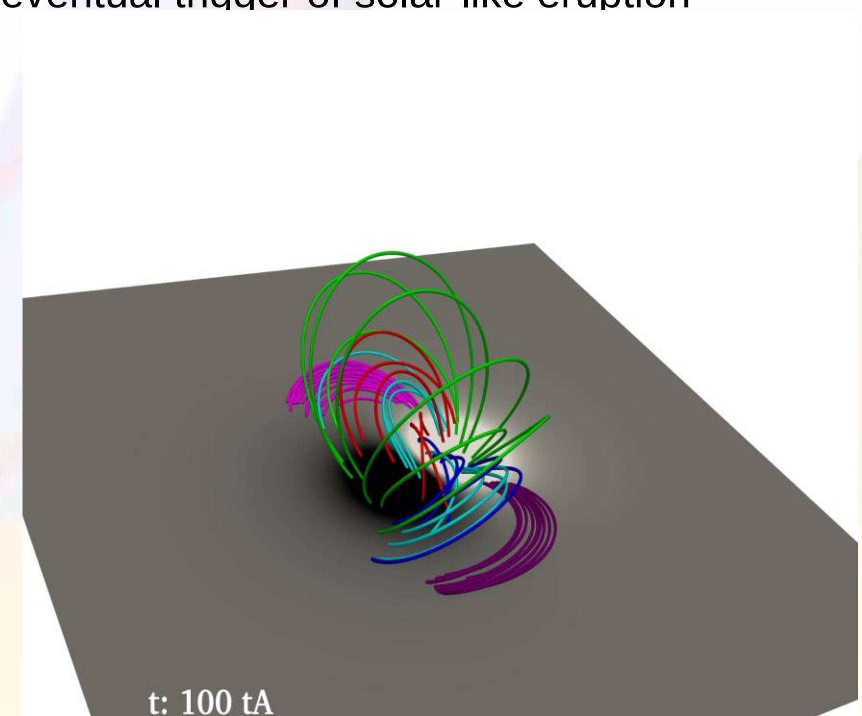
- **$|H_j|/|H_V|$ appears as an excellent eruptivity predictor of these sims.**
  - **Highest value for the eruptive simulations in the pre-eruptive phase**
  - **Eruptive and non-eruptive simulations have similar values in post-eruption phase**

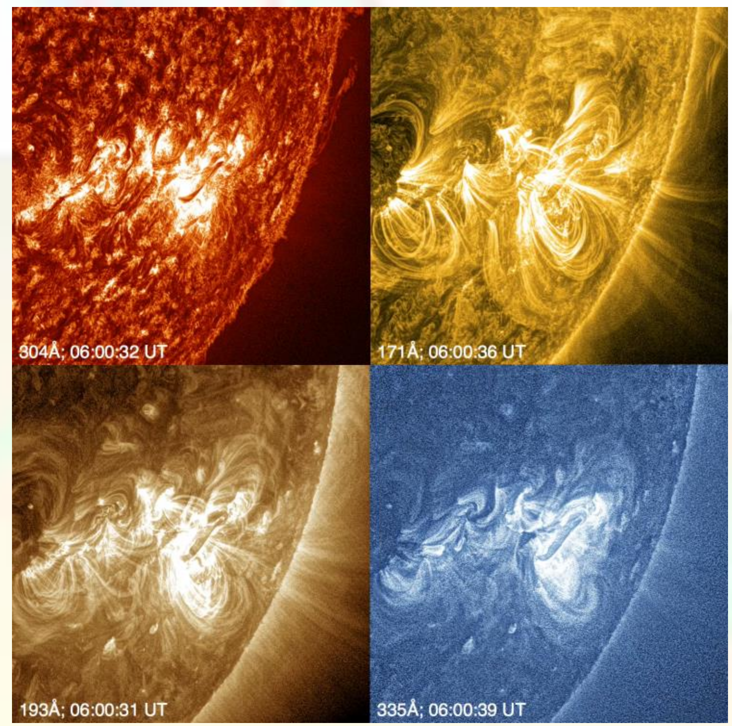
- $|H_j|/|H_V|$ is also sensitive to dipole strength which fits with promptness to erupt

Line-tied eruptive simulations

- The parametric flux simulations may be deterministically stable/instable.
  - They are not starting from a stable configuration that is brought toward instability
  - **One cannot study the existence of an helicity instability threshold**

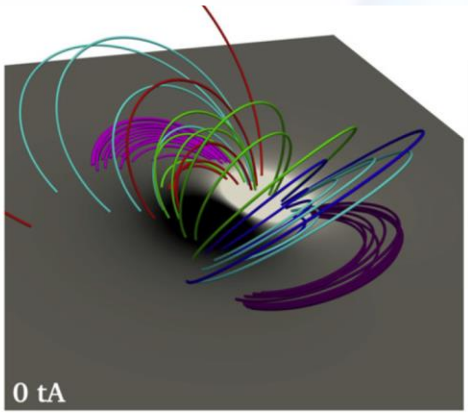
- ➔ **line-tied boundary driven simulations of solar eruptions** **(Zuccarello et al. 15)**:
  - 3D visco-resitive MHD simulations; Ohm-MPI code **(Aulanier et al. 10, Zuccarello et al. 16)**
  - Initially potential/stable configuration ; quasi-steadly injection of energy/helicity
  - ➔ eventual trigger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

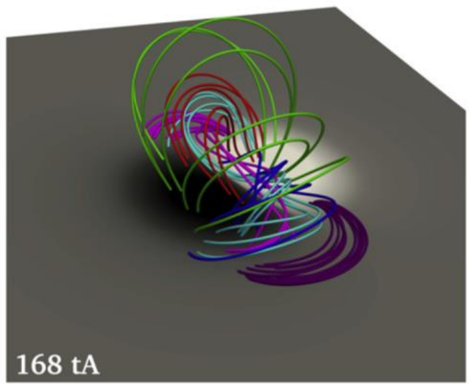




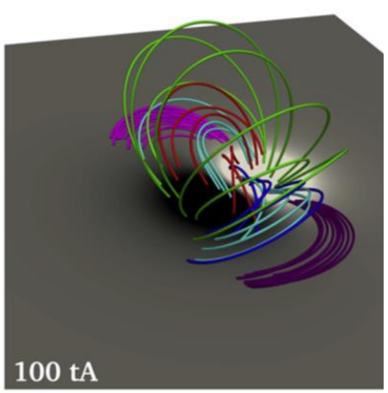
Eruption trigger time determination

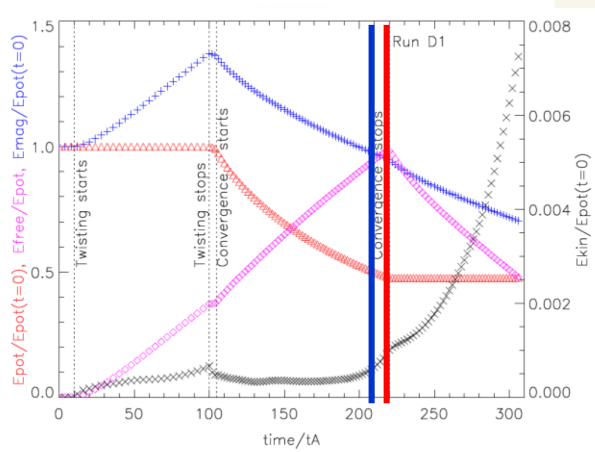
- **For each simulation, precise determination of the onset time, t_{erupt}, thanks to numerous relaxation runs initiated at regular instants.**



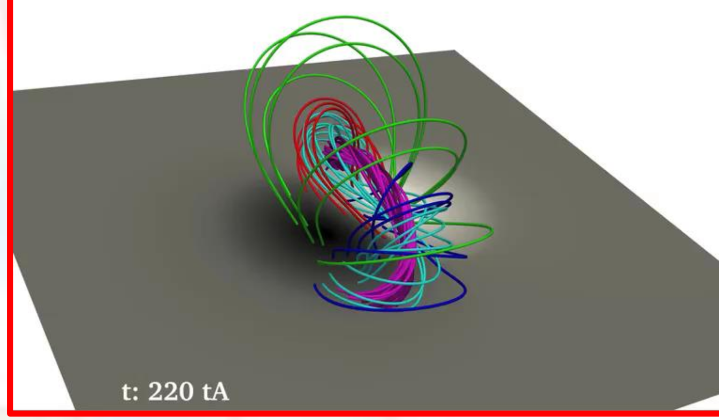


(Aulanier et al. 10, Zuccarello et al. 16)

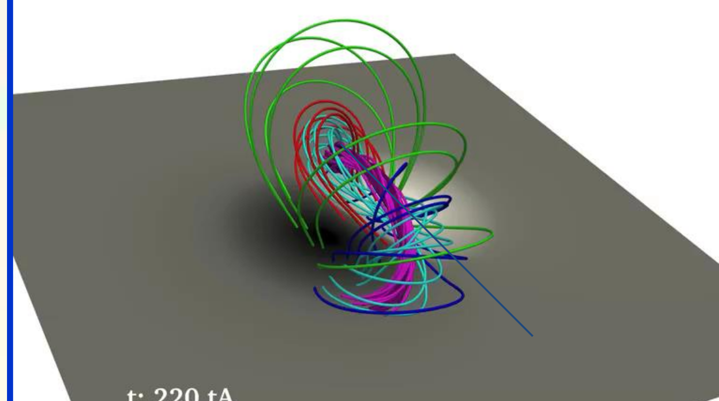




Relaxation run at t_{erupt}

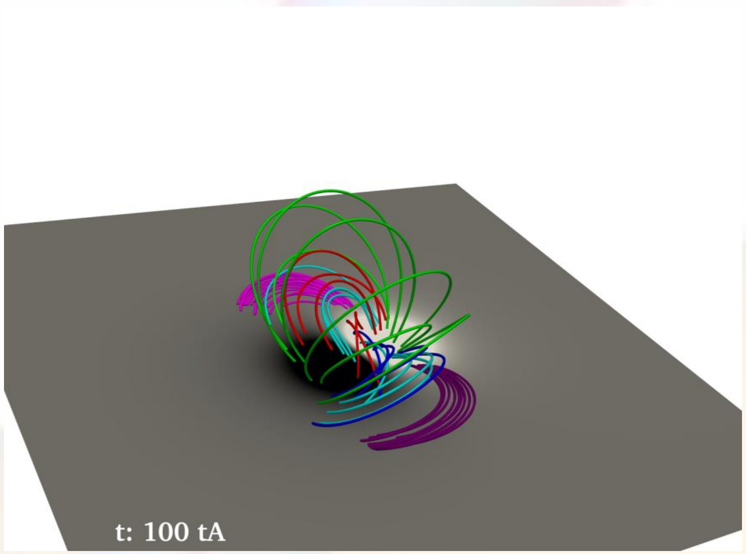


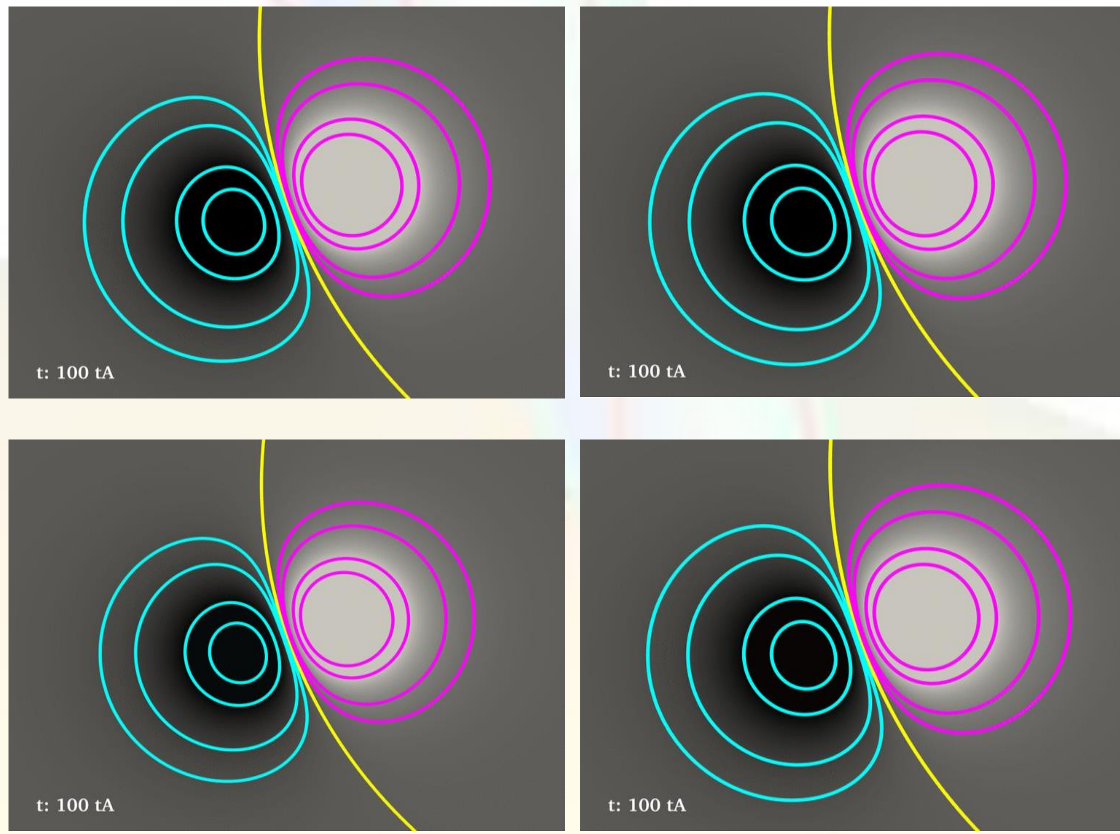
Relaxation run at $t_{erupt} - 4t_A$



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)



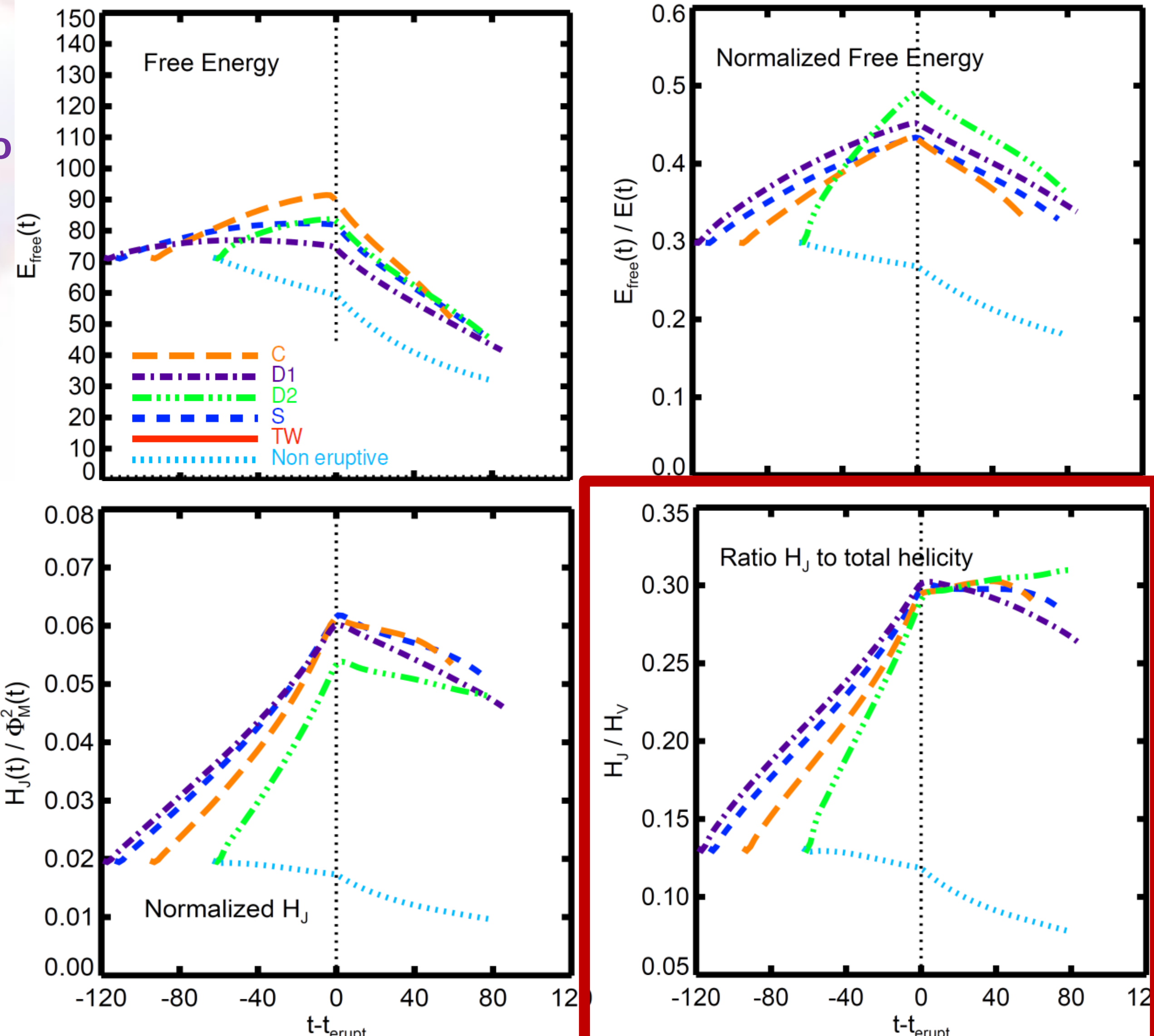


(Aulanier et al. 10, Zuccarello et al. 16)

Further evidences : line-tied eruptive simulations

(Zuccarello et al. tbs)

- Computation of several quantities at the sim. respective t_{erupt} : **Zuccarello et al. to be submitted.**
- **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



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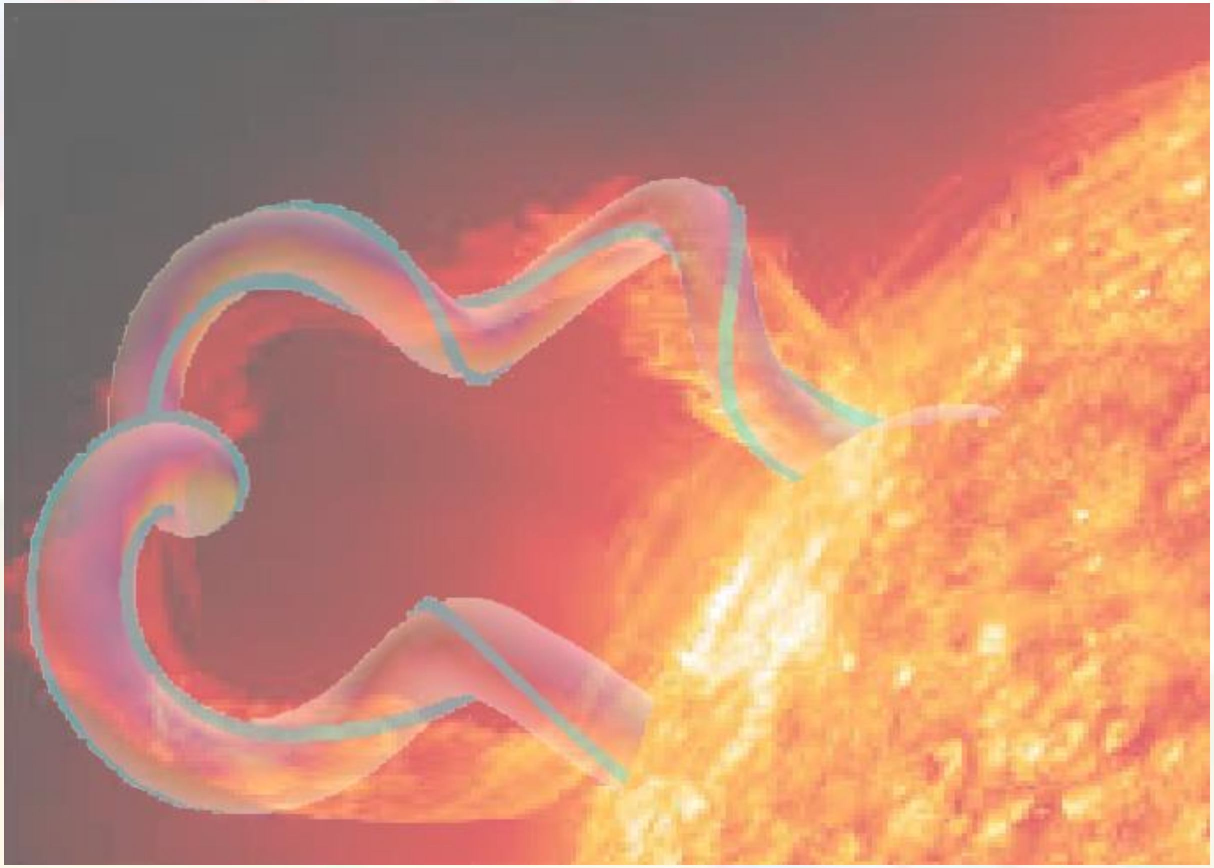
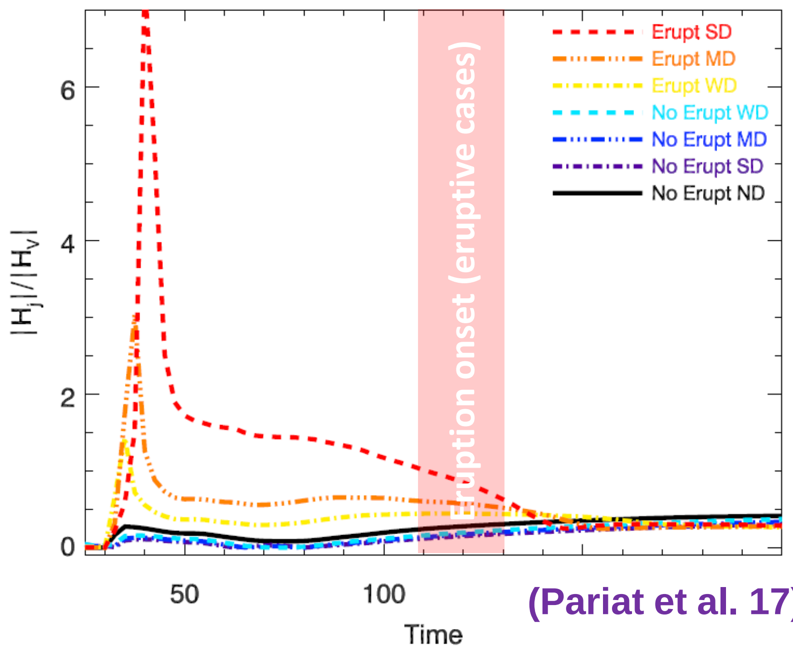
- Magnetic helicity as an eruptivity proxy
- Conclusions



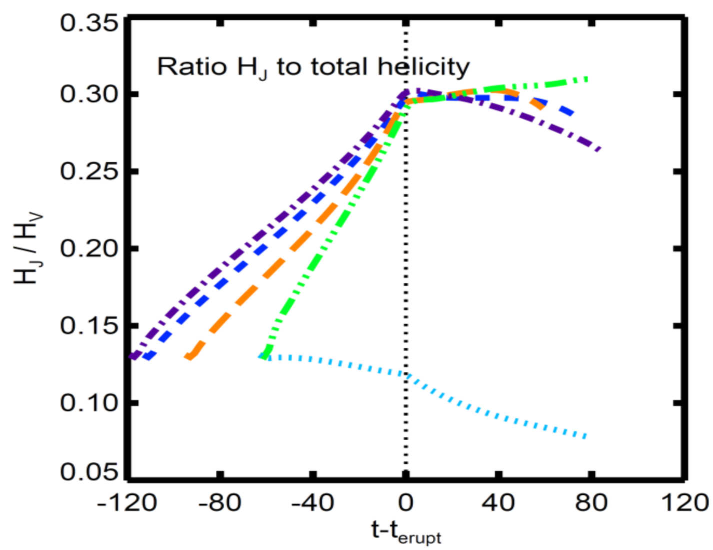
Conclusions - 1

- **The ratio |Hj|/|Hv| is an excellent indicator of the eruptivity 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)

- **➔ Now needs to be validated against <u>proper</u> observational datasets, of a sufficiently good quality!**
  - May not be that easy… !



(Zuccarello et al. tbs)

- **Possibly strong deterministic proxy of solar eruption**

Conclusions - 2

- If one can describe a phenomena within the MHD paradigm, magnetic helicity may be worth looking at!
  - Physics is based on conservation principles
  - Magnetic helicity is one of the few quantity conserved in MHD
- **New robust (benchmarked) methods to estimate magnetic helicity in observations and simulations datasets**
  - Cartesian or spherical system of coordinates
  - 3D datacubes of **B** is all what is needed!