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Relative magnetic helicity as a diagnostic of solar eruptivity

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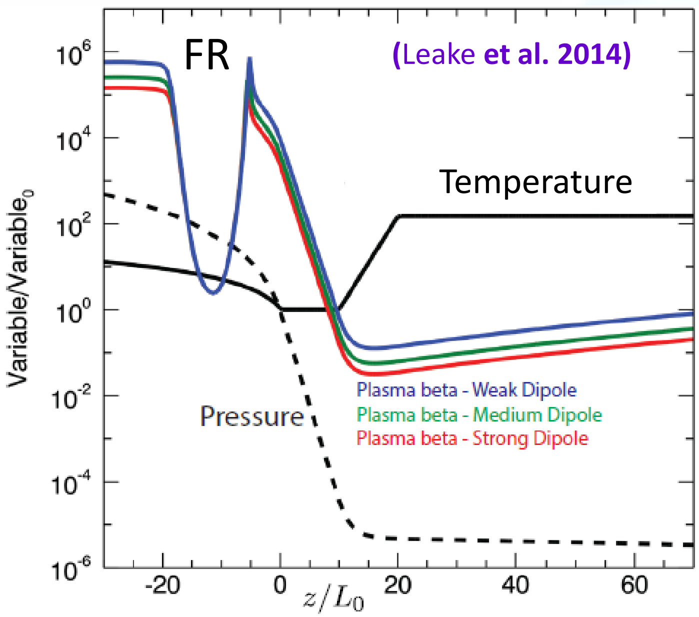
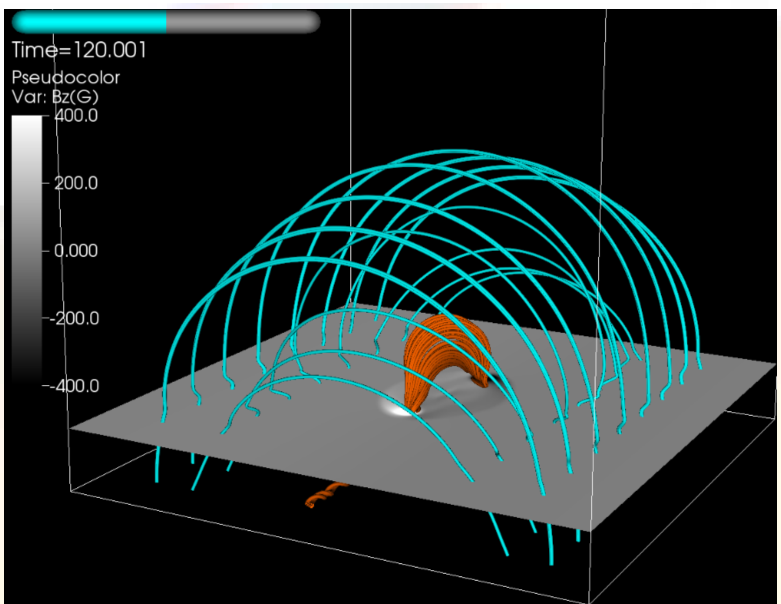
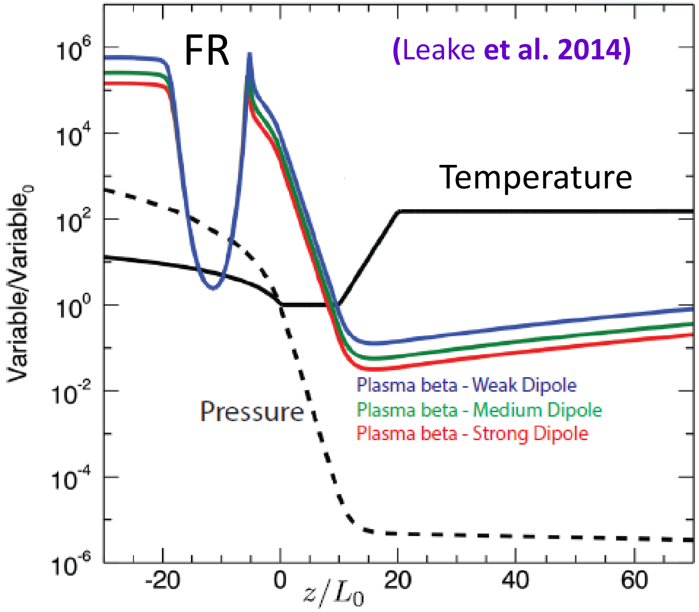
James Leake simulations





- Twisted FR emerge in coronal arcade field
- **Emerging twisted flux rope: identical in all cases**
- **Overlying arcade field: 1 param. ➔ 7 cases**
  - Signed strength, Bd, of the surrounding arcade magnetic field

James Leake simulations



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  - Bd=0: no surrounding field
    - → stable flux rope in the corona
    - No eruption
  - Bd>0: same orientation of arcade field and azimuthal part of emerging field: interaction of // fields
    - → formation of stable flux rope
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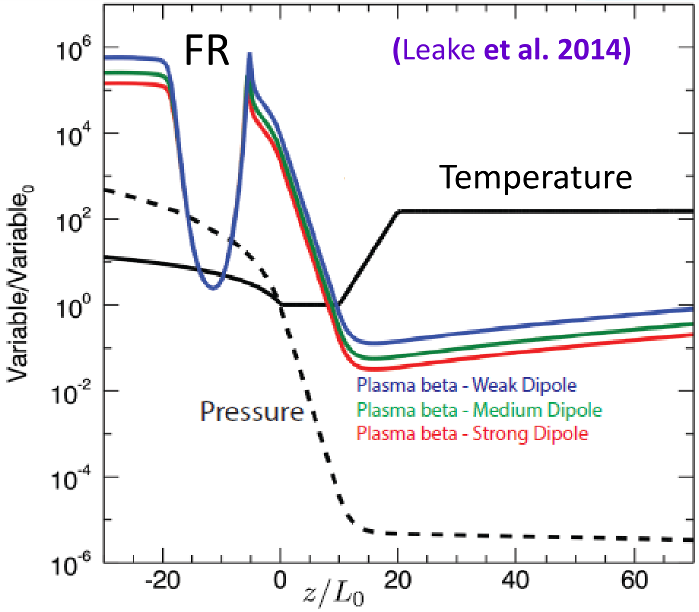
James Leake simulations



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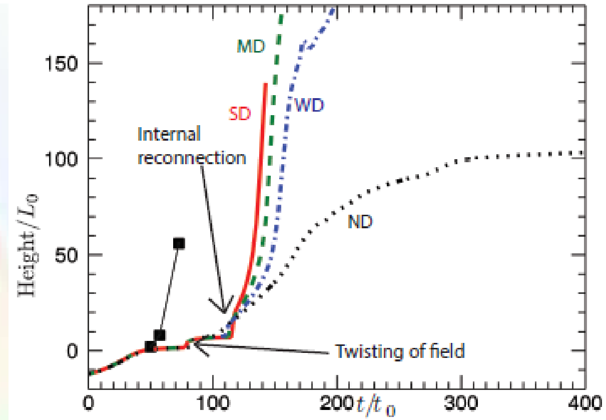
  - Bd>0: same orientation of arcade field and azimuthal part of emerging field: interaction of // fields
    - → formation of stable flux rope
    - No eruption
  - Bd<0: opposite orientation of arcade field and azimuthal part of emerging field: interaction of anti-// fields
    - → reconnection and formation of unstable flux rope
    - Eruptive behavior

Search for eruptivity criterion

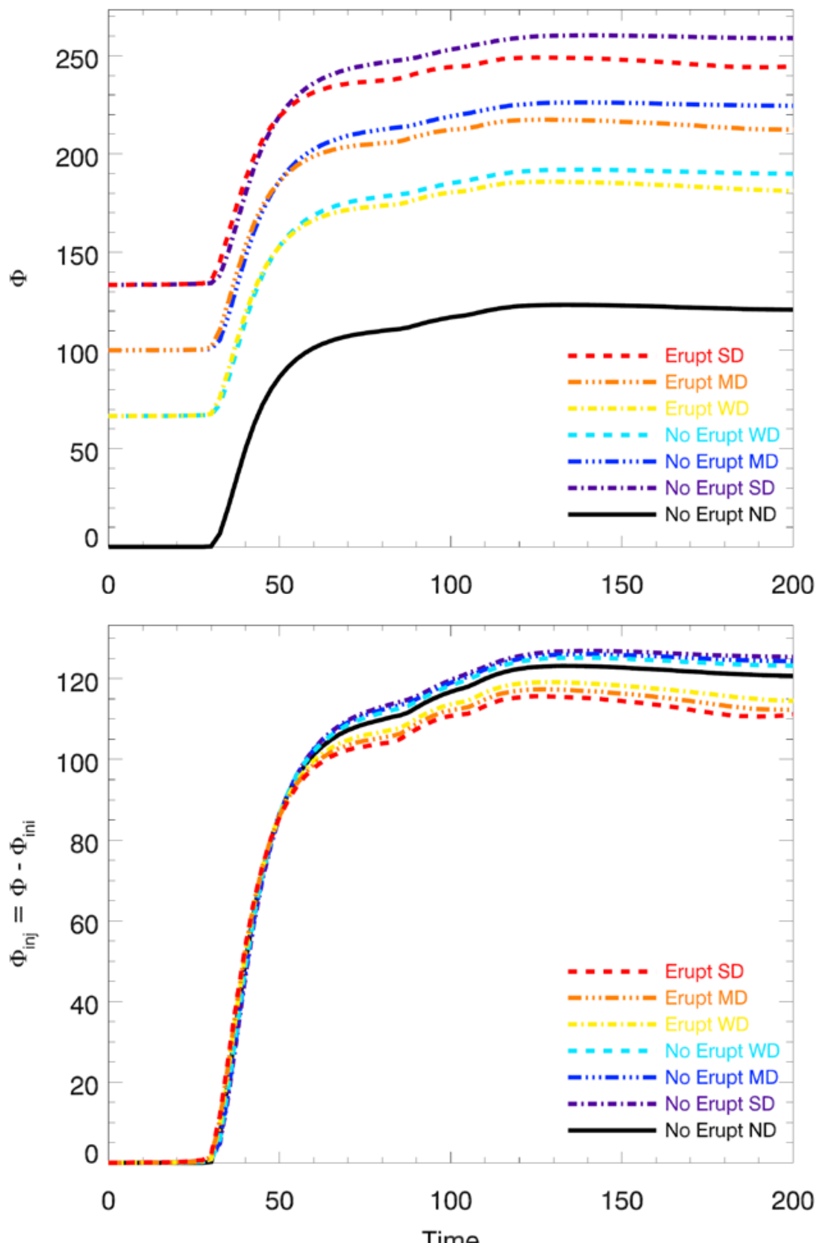
- Twisted FR emerge in coronal arcade field
- **Emerging twisted flux rope: identical in all cases**
- **Overlying arcade field: 1 param. ➔ 7 cases**

Label	No Erupt SD	No Erupt MD	No Erupt WD	No Erupt ND	Erupt WD	Erupt MD	Erupt SD
B_d	10	7.5	5	0	−5	−7.5	−10
Dipole Strength	Strong	Medium	Weak	Null	Weak	Medium	Strong
Eruption	No	No	No	No	Yes	Yes	Yes

- Eruption around t ~ 120 t0
- **Goal: determine if a scalar quantity can describe the eruptivity state of the parametric simulations**
- Good eruptivity criterion should:
  - Show similar trend between eruptive and non-eruptive simulations in post-eruptive phase
  - Discriminate eruptive and non-eruptive simulations in pre-eruptive phase
  - Higher value for eruptive simulation vs non-eruptive
  - Highest value for eruptive simulation during the pre-eruptive phase

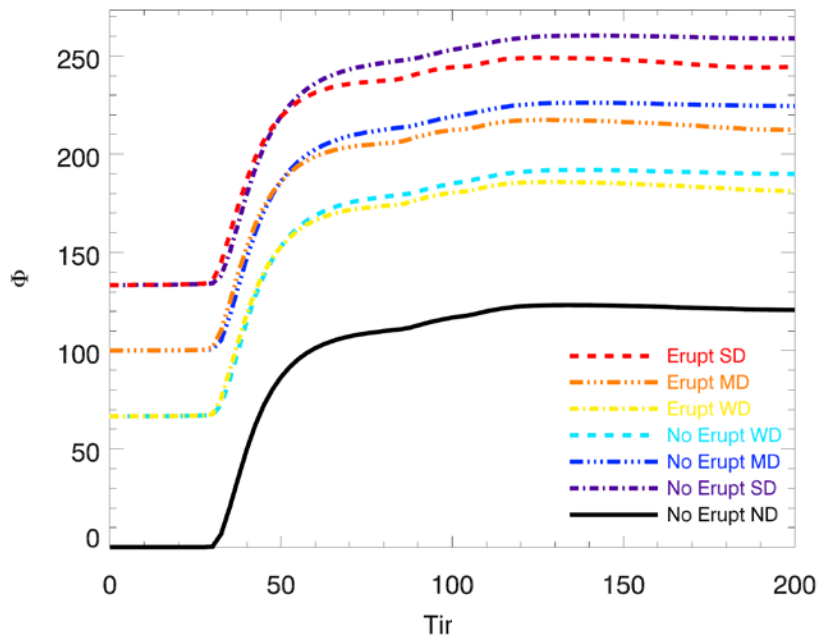


Magnetic fluxes



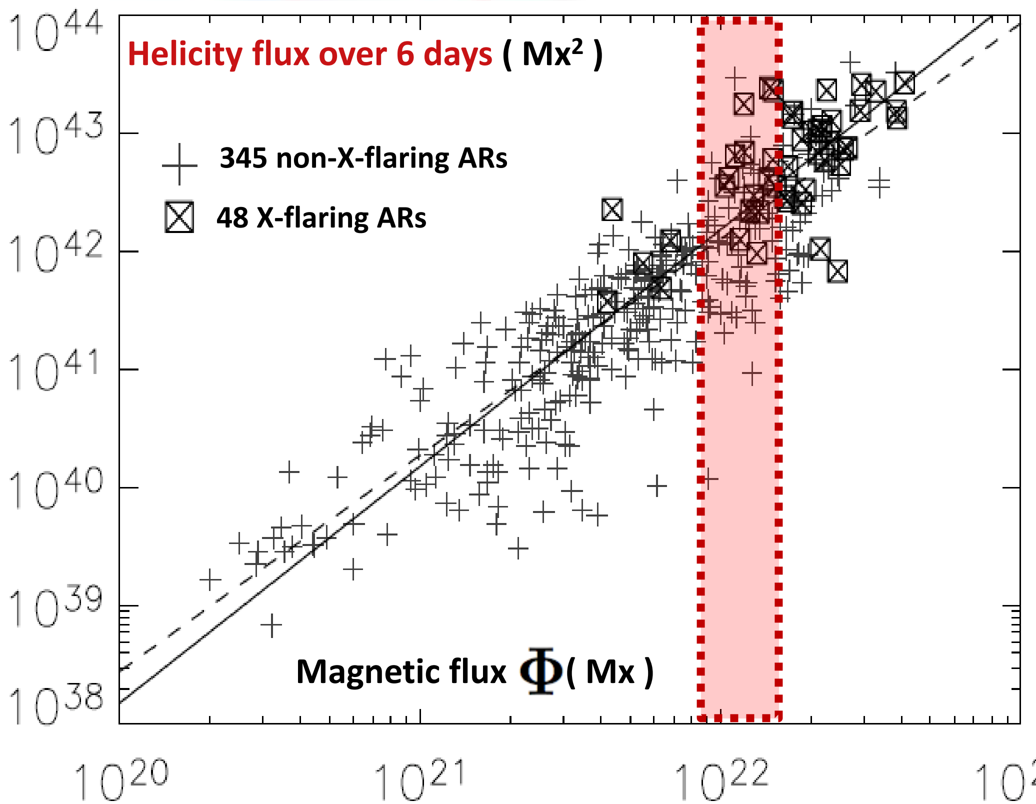
- Reference magnetic flux depends on the arcade field strength
- Injected flux by emerging flux rope is roughly identical for all 6 models

Magnetic fluxes

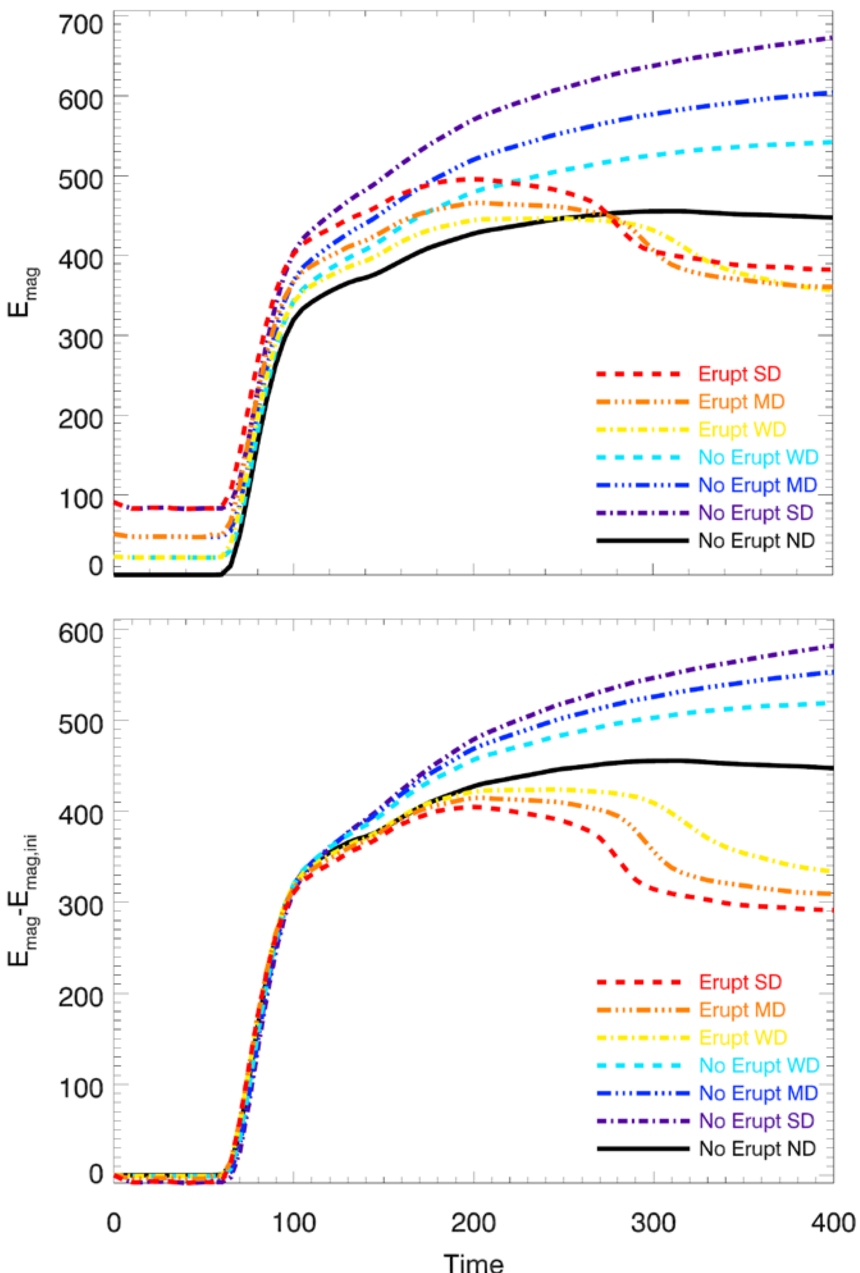


- Reference magnetic flux depends on the arcade field strength
- Injected flux by emerging flux rope is roughly identical for all 6 models

- Model limits:
- Track eruptivity criterion given a roughly constant injected magnetic flux.
  - ➔ Understand why some AR of a given magnetic flux erupt or not.
- Relatively strong background magnetic field.



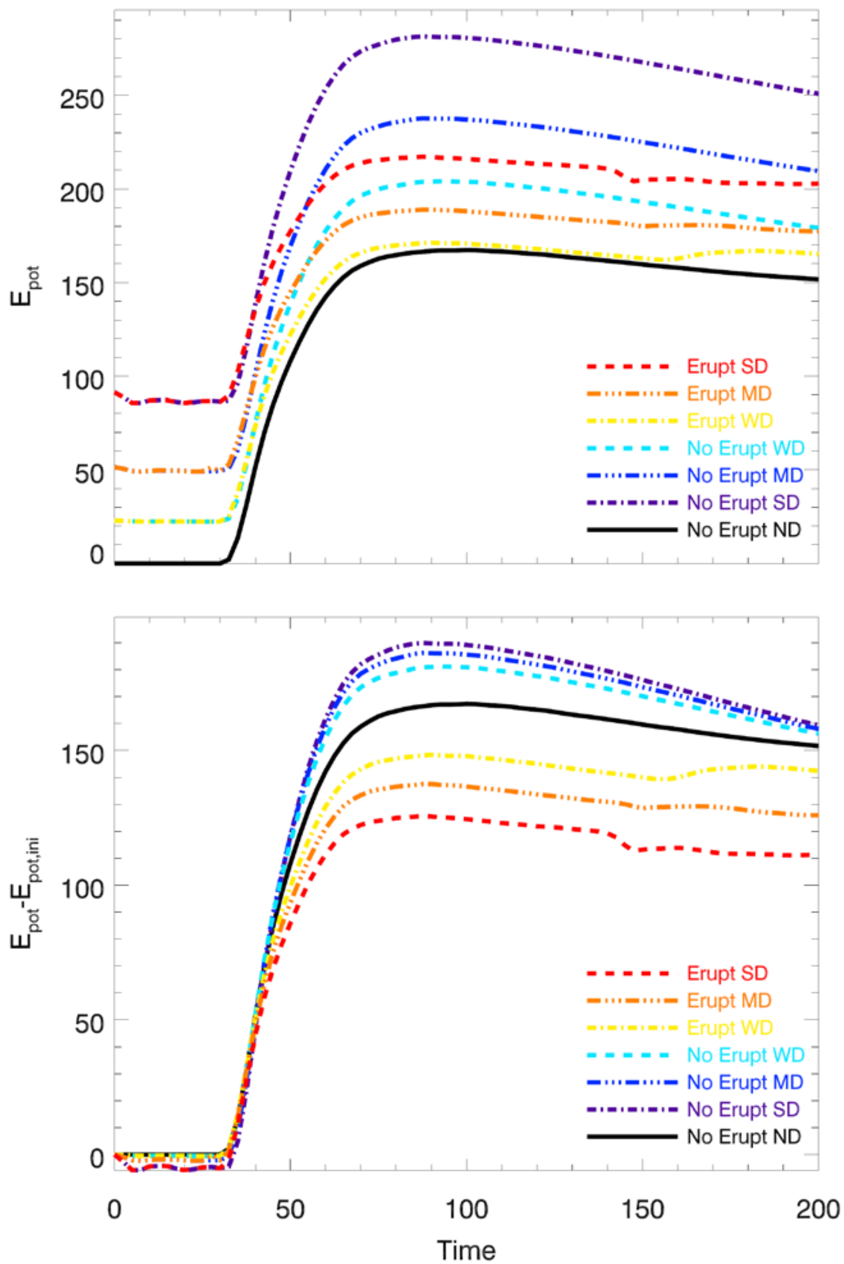
Total and potential magnetic energy



$$E_{mag} = E_{pot} + E_{free} + E_{ns}\ ,$$

- Significant injection of total magnetic energy vs initial energy of arcade dipole.
- Eruptive simulation have a lower injection of total magnetic energy
- **Total magnetic energy not a good discriminative factor on the eruptivity of the system**

Total and potential magnetic energy



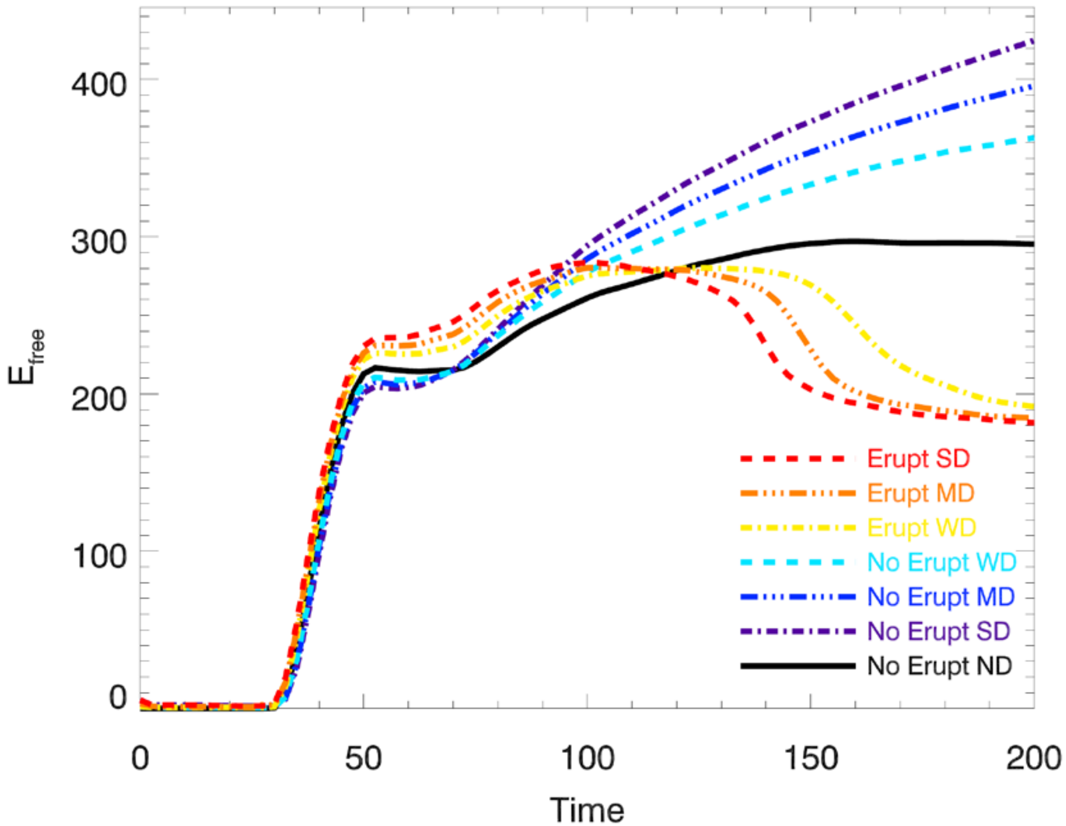
$$E_{mag} = E_{pot} + E_{free} + E_{ns}$$

- Significant injection of total magnetic energy vs initial energy of arcade dipole.
- Eruptive simulation have a lower injection of total magnetic energy
- **Total magnetic energy not a good discriminative factor of the eruptivity of the system**

- Eruptive simulation have a lower injection of potential magnetic energy (which explains the lower total magnetic energy)
- **Potential magnetic energy not a good discriminative factor on the eruptivity of the system**

Free magnetic energy

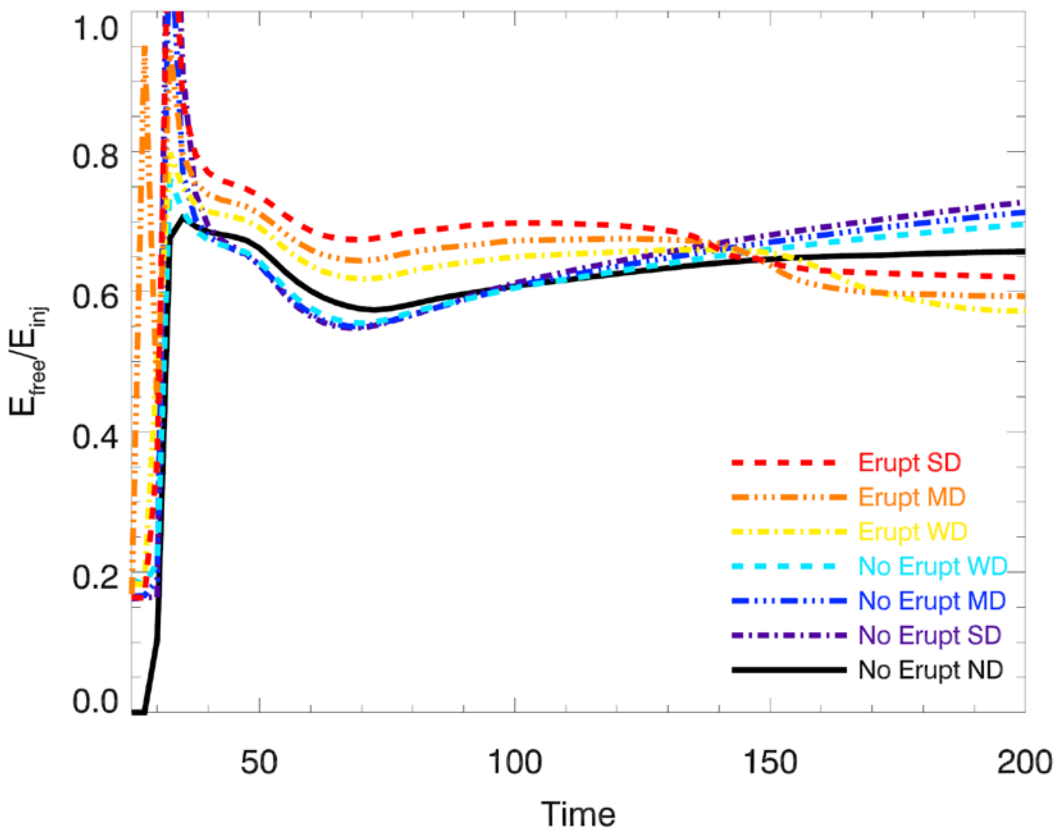
$$E_{mag} = E_{pot} + E_{free} + E_{ns}$$



- Both eruptive and non-eruptive simulation have important injection of Efree
- Free energy is slightly higher for eruptive simulation in the pre-eruption phase.
- However highest value of E free are reached by non eruptive simulations.
- **Free magnetic energy not a good discriminative factor of the eruptivity of the system**

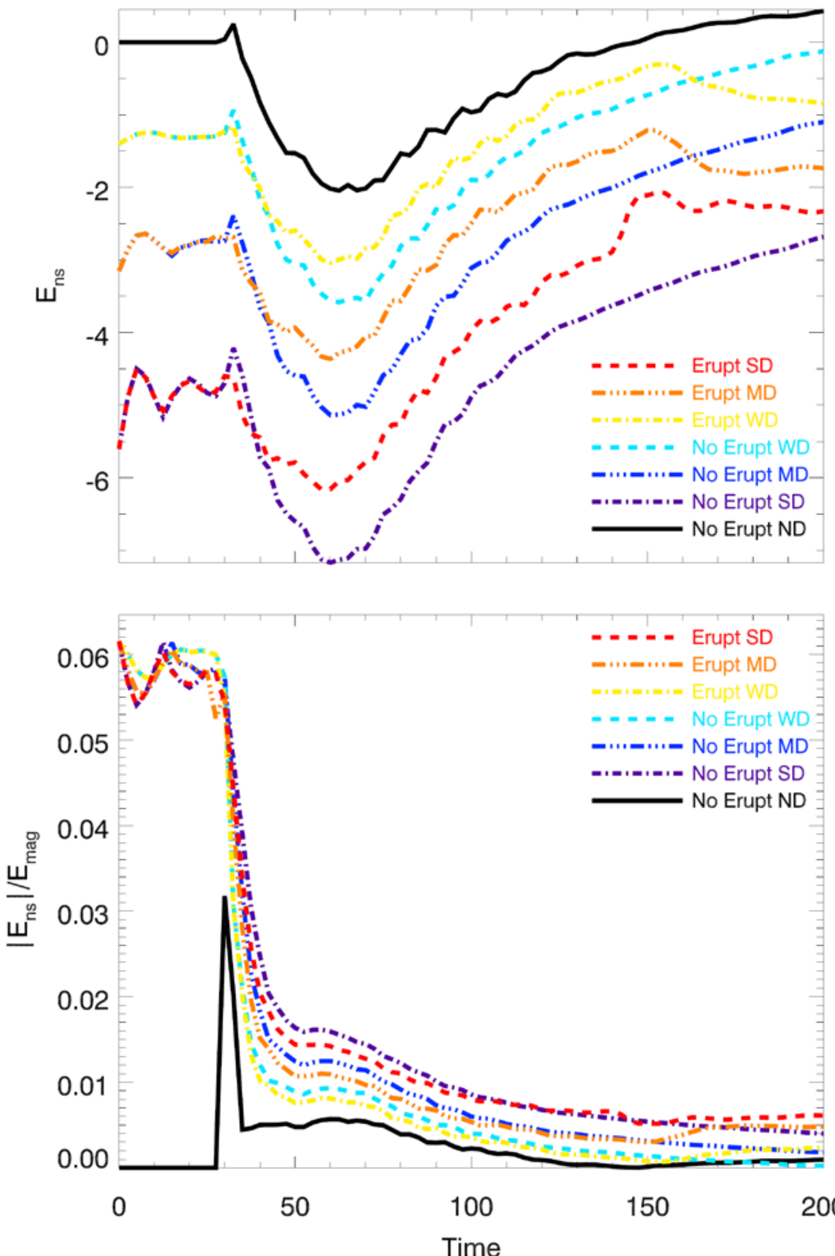
Free magnetic energy ratio

$$E_{mag} = E_{pot} + E_{free} + E_{ns}$$



- Efree/Einj is higher for eruptive simulation vs. non eruptive in the pre-eruption phase with marginally the highest values
- **Ratio of free magnetic energy to injected energy may be a proxy of eruptivity of the system, however very subtle.**

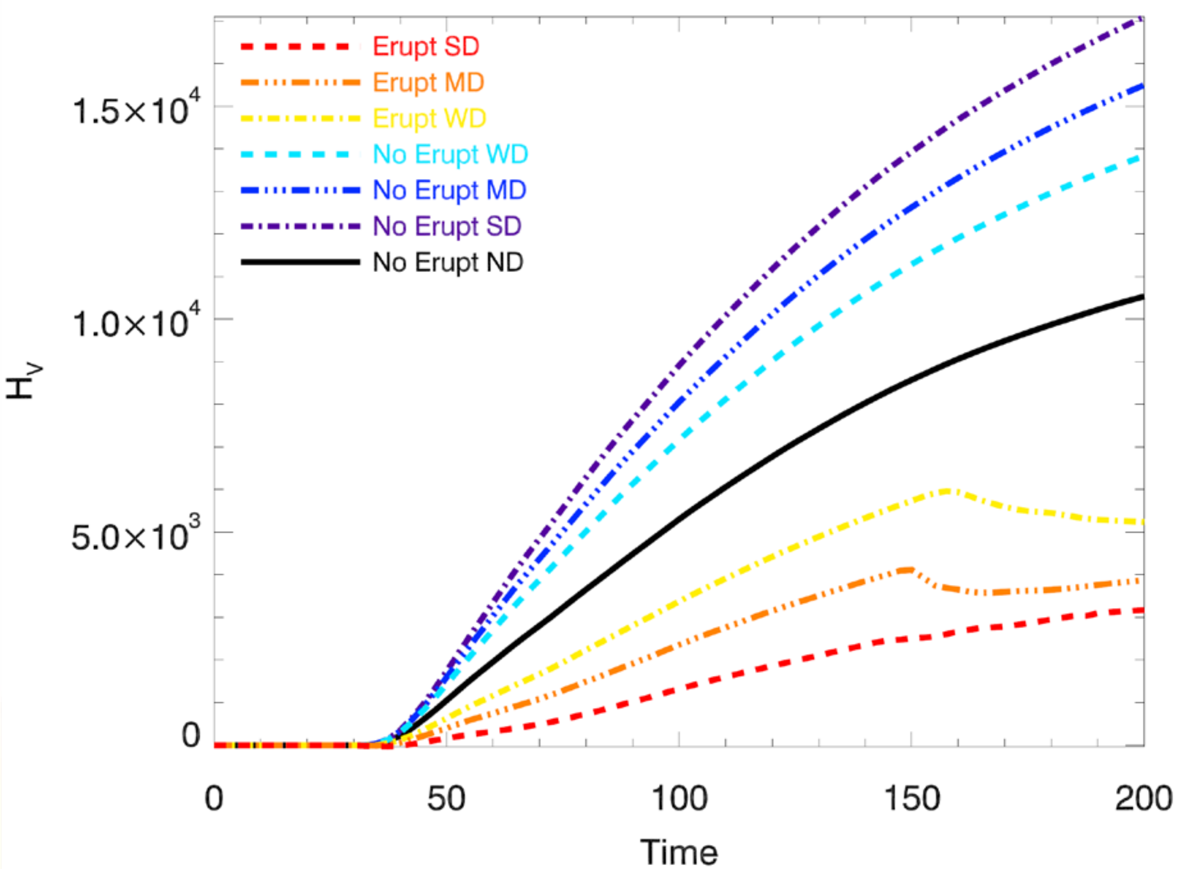
Non solenoidal magnetic energy



$$E_{mag} = E_{pot} + E_{free} + E_{ns}$$

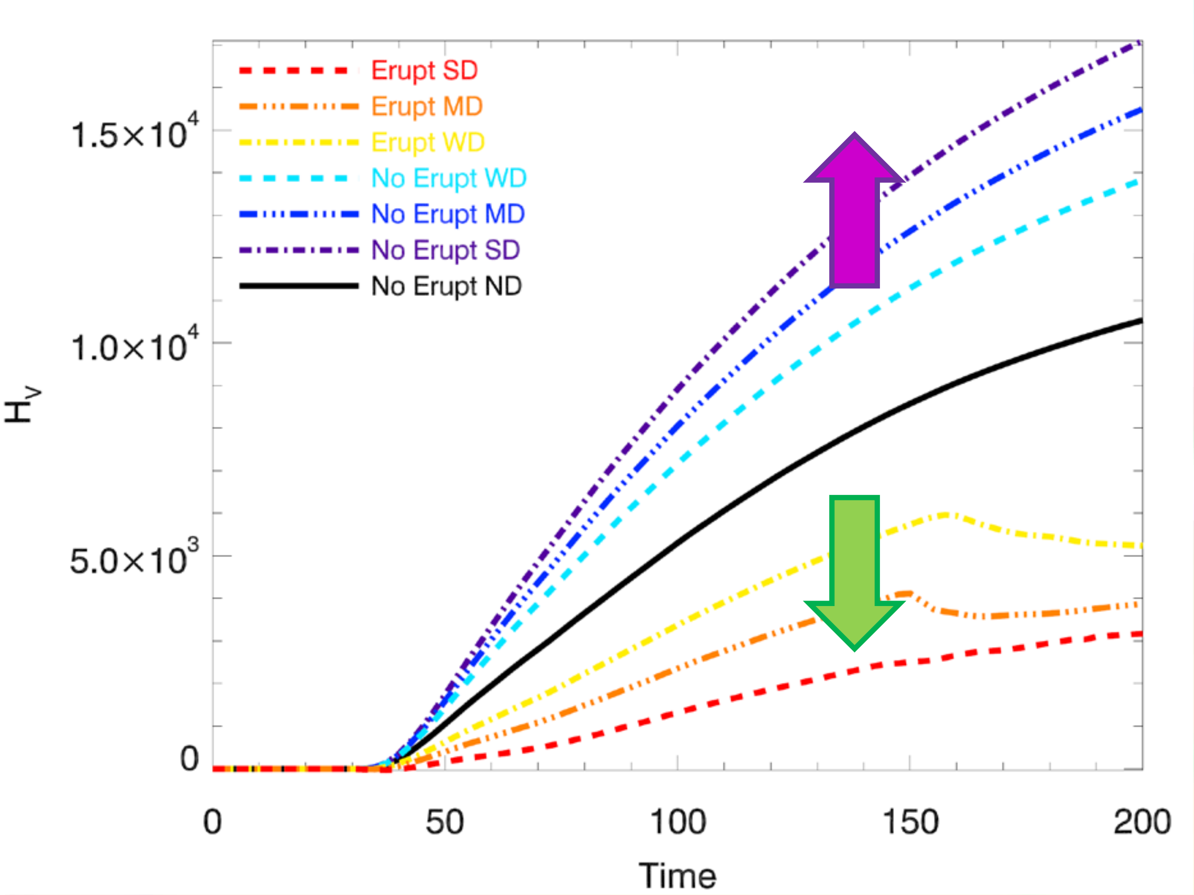
- Solenoidal effects remains limited.with |Ens/Emag|<2% for most of the simulation.
- **Good degree of confidence of the magnetic helicity estimations.**

Relative magnetic helicity evolution



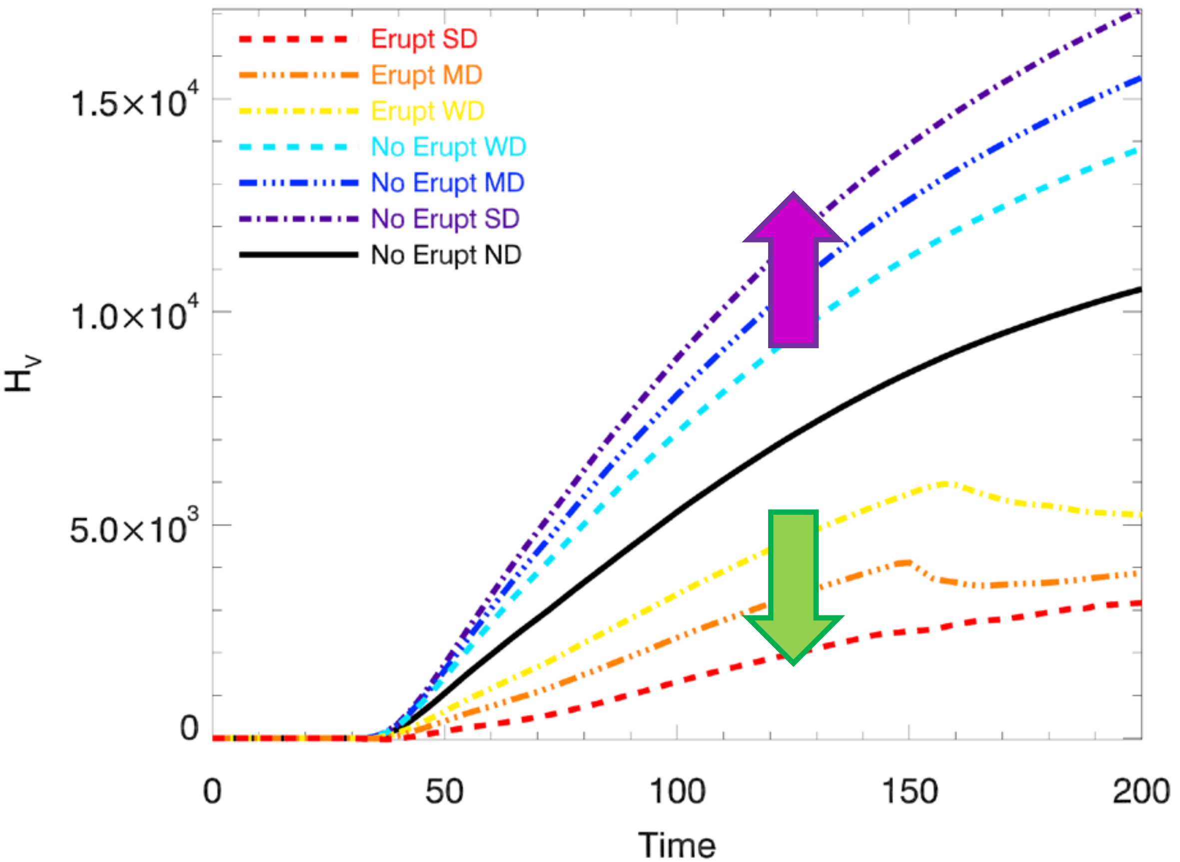
- **Unlike with magnetic flux & free energy, helicity discriminates strongly the cases**
  - Total helicity depends
    - on dipole strength
    - on dipole orientation
- The surrounding (potential) field influences the helicity content!
- **Magnetic helicity is a non-local quantity!**

Relative magnetic helicity evolution



- Helicity of the stable cases is larger than the eruptive cases !
- Helicity **increases with arcade strength for non-eruptive cases**
- Helicity **decreases with arcade strength for eruptive cases**

Self and Mutual helicity



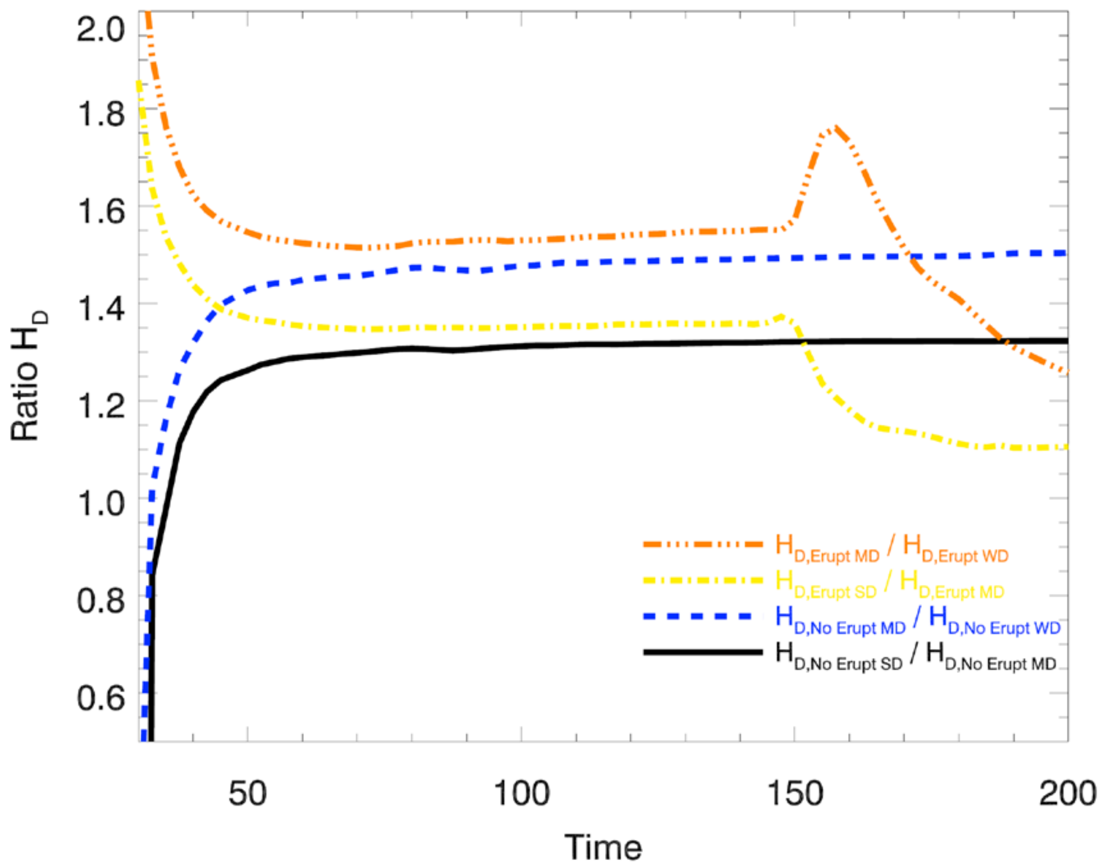
- Helicity decomposition in **self** and **mutual** helicity of flux rope and arcade

  H=$H_{self,fr}$ + H_{mutual} + $H_{self,arc}$

- $H_{self,fr}$ = H(No Erupt ND) $\alpha\ \Phi_{fr}^2$
- $H_{self,arc}$ = 0
- H_{mutual} $\alpha\ \Phi_{fr}\ \Phi_{arc}$;
  - sign depends on relative orientation

- Non-eruptive cases: FR & arcade have same orientation : **H=$H_{self,fr}$ + $|H_{mutual}|$**
- Eruptive cases: FR & arcade have opposite orientation: **H=$H_{self,fr}$ - $|H_{mutual}|$**
- With increasing dipole strength $|H_{mutual}|$ increases
  - Qualitatively & quantitative match
    - H **increases for stable cases**
    - H **decreases for unstable**

Self and Mutual helicity



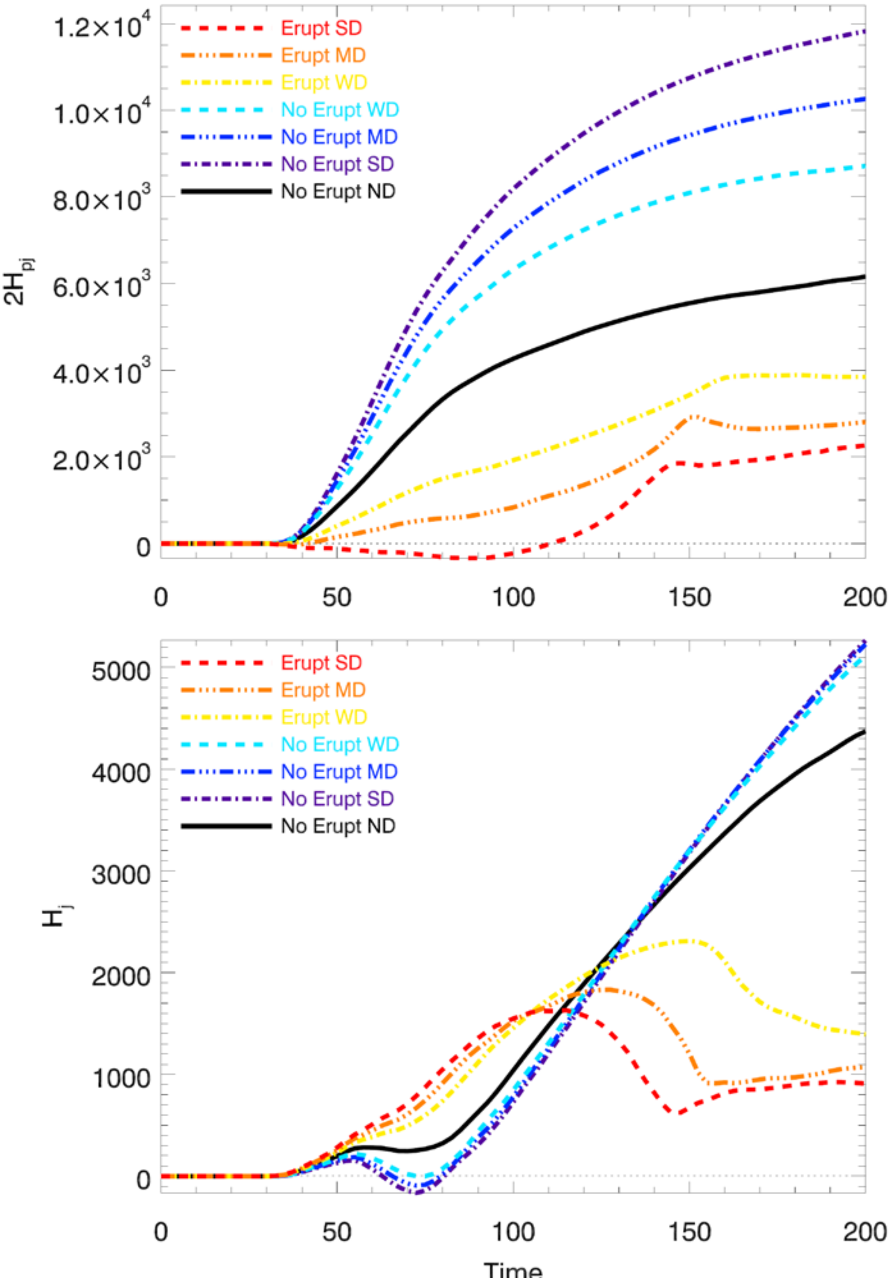
- Helicity decomposition in **self** and **mutual** helicity of flux rope and arcade

  $H = H_{self,fr} + H_{mutual} + H_{self,arc}$

- **$H_{self,fr}$** = H(No Erupt ND) $\alpha\ \Phi_{fr}^2$
- **$H_{self,arc}$** = 0
- **H_{mutual}** $\alpha\ \Phi_{fr}\ \Phi_{arc}$;
  - sign depends on relative orientation

- Very good quantitative match of this toy model
- Computation of HD: $H_D = H_V - H_{V,\,\text{No Erupt ND}} \sim \pm L\Phi_{Arc}$
- Toy model predict that ratio of HD shall be equal to magnetic flux ratios
- Good fit with expected values: $\Phi_{ini,\,MD} / \Phi_{ini,WD} = 1.5$ & $\Phi_{arcini,\,SD} / \Phi_{ini,MD} = 1.33$
- Problem: here self and mutual helicity can only be roughly estimated because we have a parametric dataset. Not the case with real data.

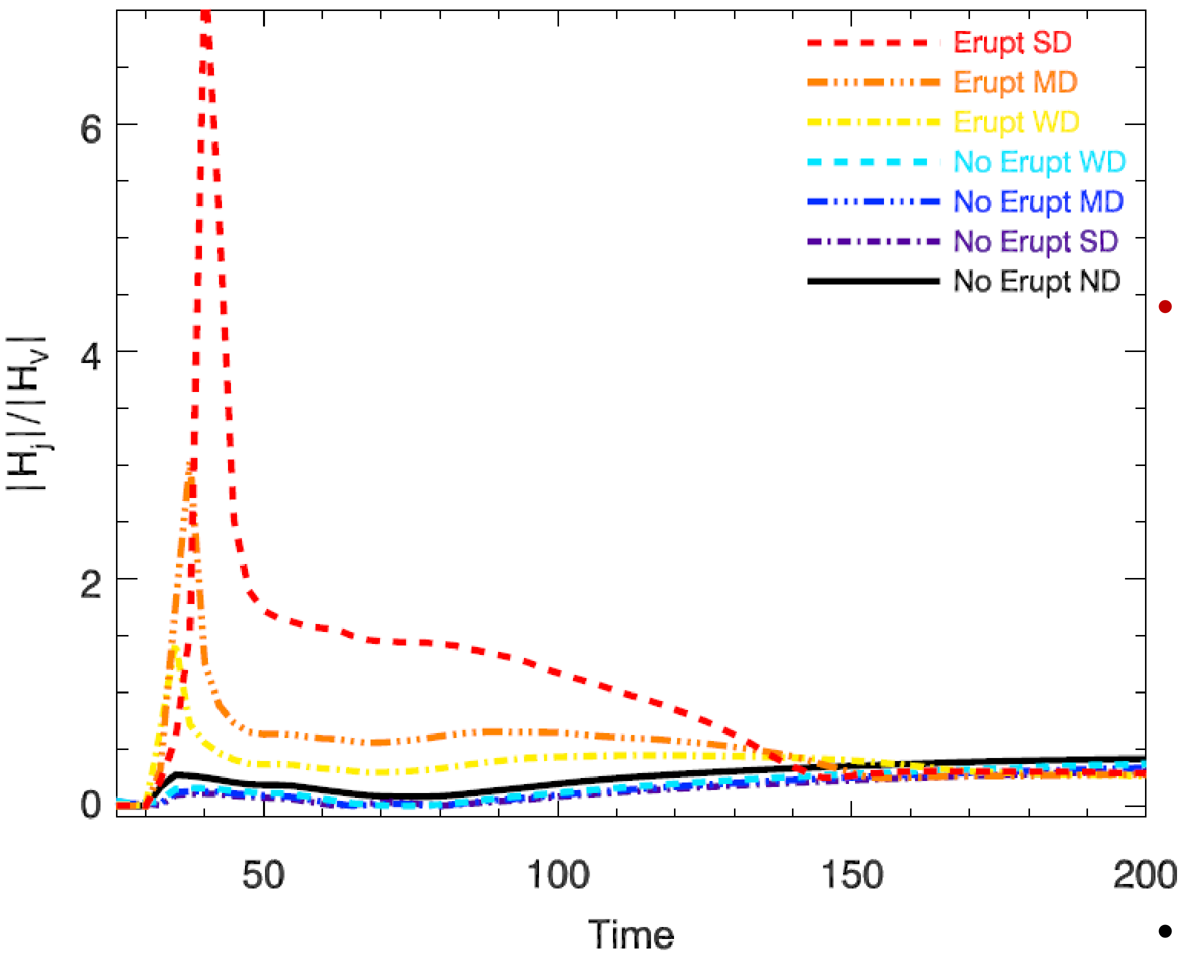
Helicity decomposition



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

- H_j = magnetic helicity of the current carrying field B_j
- Total helicity is overall dominated by $2H_{pj}$
- $2H_{pj}$ has same properties than total helicity ➔ not a good eruptivity proxy
- H_j is not very sensitive to dipole strength but strongly depends on the orientation.
- **H_j behaves similarly to Efree**
  - **higher for the eruptive simulations in the pre-eruptive phase**
  - **however higest values reached by non-eruptive simulations**
- **Hj is not a good eruptivity proxy.**

|Hj|/|H|



$$
\begin{aligned}
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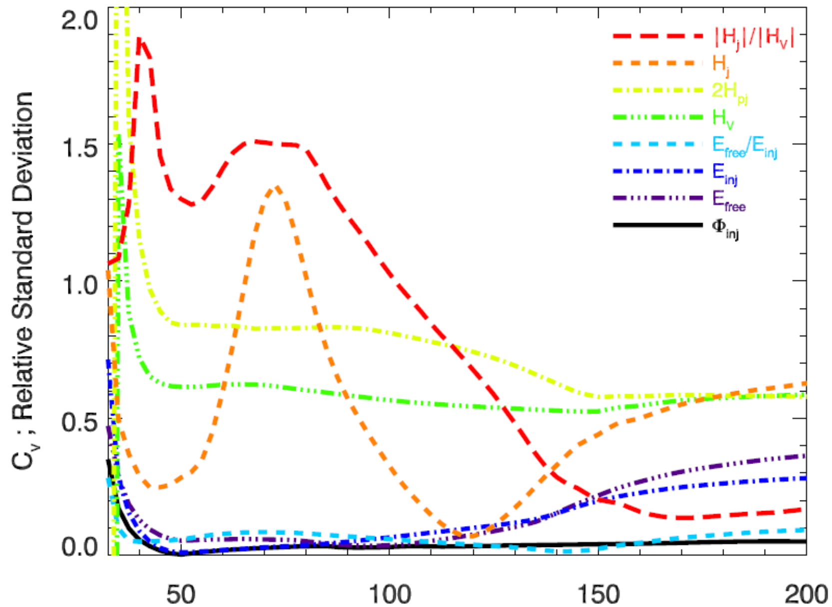
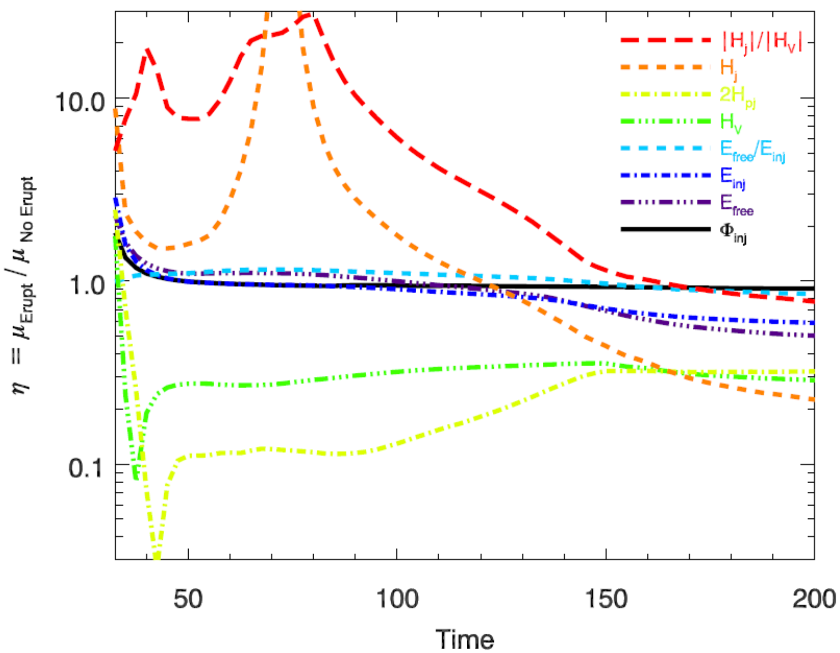
\end{aligned}
$$

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

Comparison of eruptivity proxies





- At each time estimation of the:
  - Relative standard deviation, Cv, between the different simulations
  - Ratio of the mean values of the eruptive to the non-eruptive simu.

$$\eta = \mu_{\text{Erupt}}/\mu_{\text{No Erupt}}$$

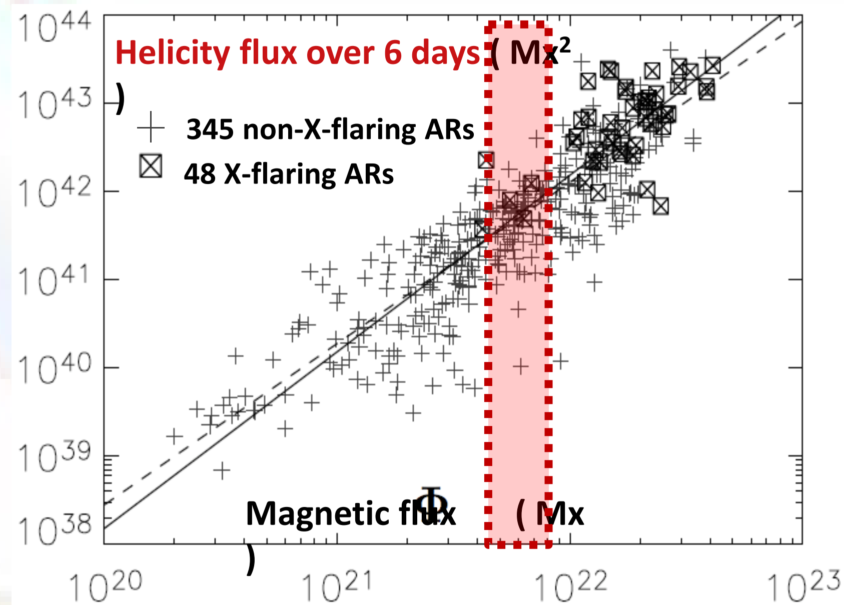
- All helicity quantities have high Cv: discriminate the different simulation

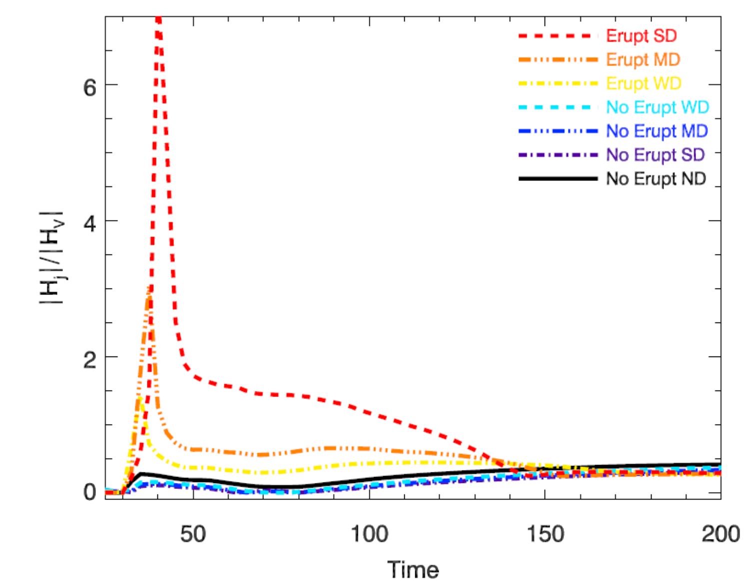
- Efree/Einj & |Hj|/|Hv| have
  - $\eta > 1$ during pre-eruptive phase
  - η ~1 during post-eruptive phase

- |Hj|/|Hv| has high value of η during pré-eruptive flare:
  - ➔ excellent proxy of the eruptivity state of these simulations

Conclusions

- Rare attempts to use parametric numerical simulation to study eruptivity proxy of solar active events.
- Magnetic helicity allows to discriminate between the geometric properties of the parametric simulations
- Magnetic helicity highly non local: potential surrounding field highly influence the helicity content of domain
- |Hj|/|Hv| excellent proxy of the eruptivity state of these simulations
- Need further study to understand this proxy and its application to observed solar events.





Thanks for your attention