A Mechanism Driving Recurrent Eruptive Activity on the Sun

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Abstract

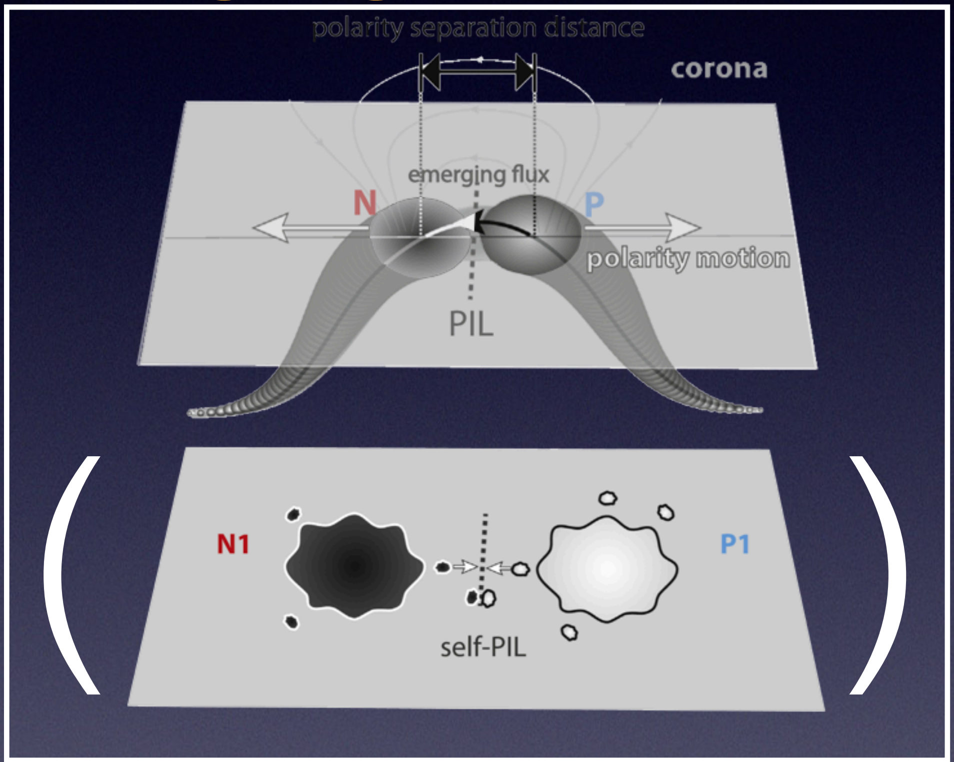
Active Regions (ARs) in their emergence phase are known to be more flare productive and eruptive than ARs in their decay phase. In this work, we focus on complex emerging ARs composed of multiple bipoles. Due to the compact clustering of the different emerging bipoles within such complex multipolar ARs, collision and shearing between opposite non-conjugated polarities produce “collisional polarity inversion lines” (cPILs) and drive rapid photospheric cancellation of magnetic flux. The strength and the duration of the collision, shearing, and cancellation are defined by the natural separation of the conjugated polarities during the emergence phase of each bipole in the AR. This mechanism is called “collisional shearing”. In Chintzoglou et al (2019), collisional shearing was demonstrated using two emerging flare- and CME-productive ARs (NOAA AR11158 and AR12017) by measuring significant amounts of magnetic flux canceling at the cPIL. This finding supported the formation and energization of magnetic flux ropes before their eruption as CMEs and the associated flare activity.

Here, we provide results from data-driven 3D modeling of the coronal magnetic field, capturing the recurrent formation and eruption of energized structures in support of the collisional shearing process. We discuss our results in relation to flare and eruptive activity.

Observational facts

- The Sun's disk, when featureless, is referred to as the "*Quiet Sun*".
- When sunspots appear on the disk, they indicate areas called "**Active Regions**" (**ARs**).

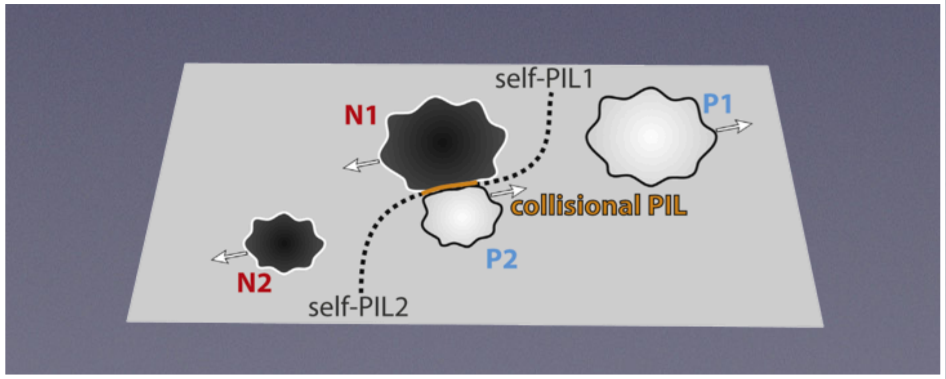
Emerging Bipolar ARs



During emergence of simple bipolar ARs: **low potential for flares & CMEs** (e.g., Sammis et al 2000)

(NOTE: **decay phase**: **cancellation may produce eruptions** (Ballegooijen & Martens 1989; Mackay 2009; Green et al 2011; Yardley et al 2018; Chintzoglou et al 2019; Dhakal et al 2020))

Emerging Complex ARs



During emergence of complex ARs: **high potential for flares & CMEs** (Zirin & Liggett 1987; Sammis et al 2000; Schrijver 2007; Toriumi & Takasao 2017; Chintzoglou et al 2019)

But why some ARs are more flare productive and eruptive than other ARs?

Challenge: Many potent ARs rotate into Earth view already developed and thus witnessing how they evolve in becoming flare active and eruptive is as of now not possible.

It appears that **emerging ARs** are more flare- (and CME-) productive than decaying ARs (e.g. Schrijver 2009). Same goes with **increasing complexity** of the magnetic configuration (β, βγ, βγδ, etc; e.g., Hale & Nicholson 1938; Sammis et al 2000).

"δ"-spot ARs the most flare productive (Künzel 1960; Zirin & Liggett 1987; Schrijver 2007) – "statistical" inferences: large spread in activity.

Why some ARs are more flare productive and eruptive than other ARs?

Understanding of Major Activity at present is not clear. Many theories proposed:

- Sunspot Rotation (e.g., Aulanier et al 2010)?
- MHD instabilities (e.g., Torok & Kliem 2005; Kliem & Torok 2006; Amari et al 2018; Kusano et al. 2020)
- *Shearing (e.g., Breakout: Antiochos et al 1999, DeVore & Antiochos 2008)?*
- *Tether-cutting (e.g., Moore et al 2003, Syntelis et al 2017)?*
- *Cancellation (e.g., Ballegooijen & Martens 1989, Amari et al 2011)*?
- Emergence (e.g., Manchester et al 2004, Archontis & Torok 2008)?
- "bodily emergence" (of a pre-eruptive structure — the magnetic flux rope) (e.g., Okamoto et al 2008)?

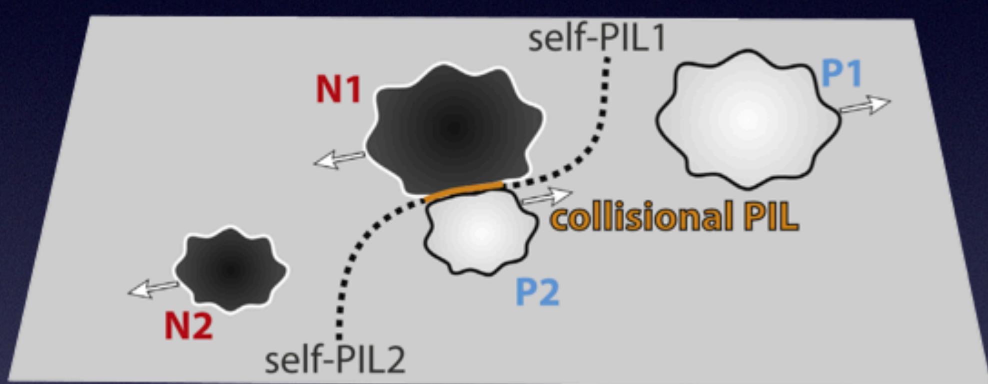
Inconclusive evidence (limb or disk obs).

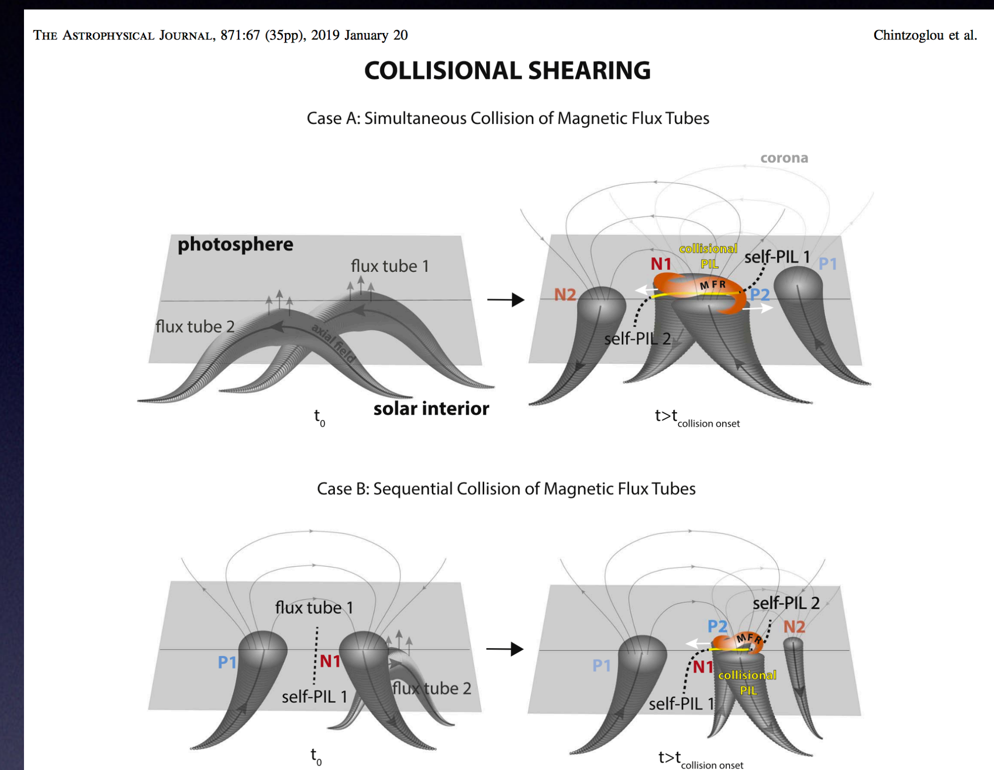
Best "single quantity" predictor for activity in ARs is total flux: Φtot (e.g., Leka & Barnes 2008).

Welsch et al (2009) found that emergence is more correlated with activity than flux cancellation.

However, with a few exceptions, models are bipolar. Also, none of the works or theories mentioned above consider the effect of **cancellation during the emergence phase of complex ARs** (likely because the effect is not visible in "traditional" Φtot measurements; see discussion in Chintzoglou et al 2019).

Collisional Shearing





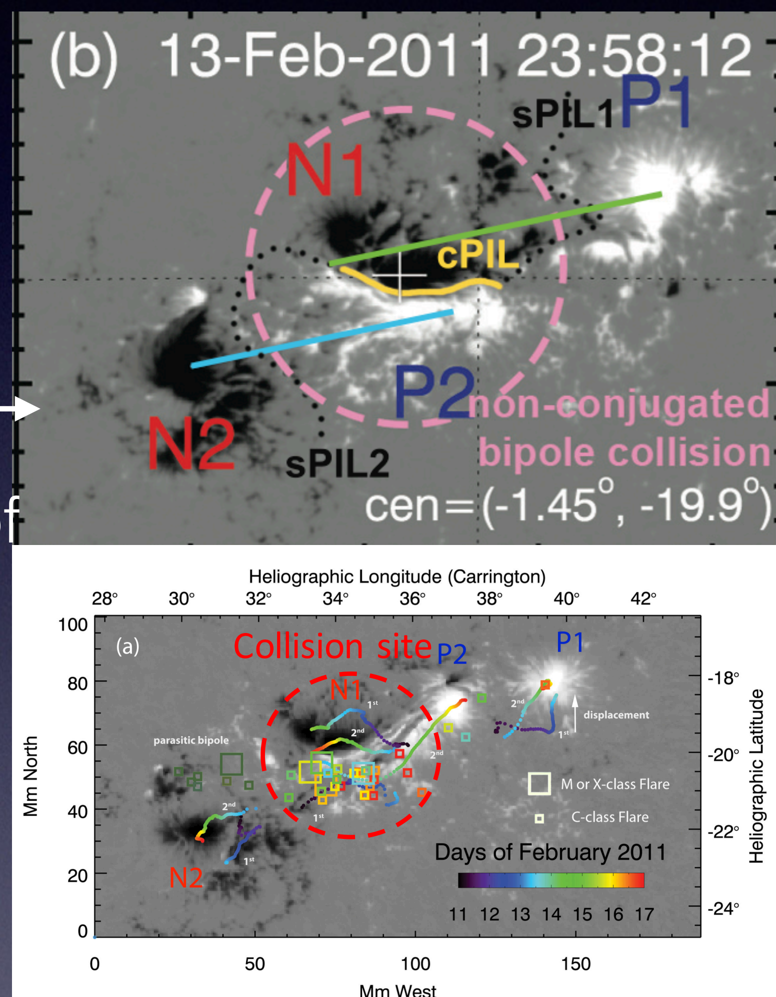
Chintzoglou et al 2019

- Collision -> collisional Polarity Inversion Lines (cPILs) -> conditions for shearing + cancellation are driven by the emergence and evolution of individual bipoles within the same AR.
- We call this process **collisional shearing** (*different* from cancellation within a conjugate bipole; van Ballegooijen & Martens 1989)
- Also, (super)granular diffusion and differential rotation in van Ballegooijen & Martens 1989; an effect << collisional shearing during emergence.
- Formation of cPILs suggests conversion of sheared arcade to an MFR-> explosive activity?

Collisional Shearing & Recurrent (Homologous) Explosive Activity

Total Flare Index (TFI) to express all flare activity as multiples of C1.0 flares

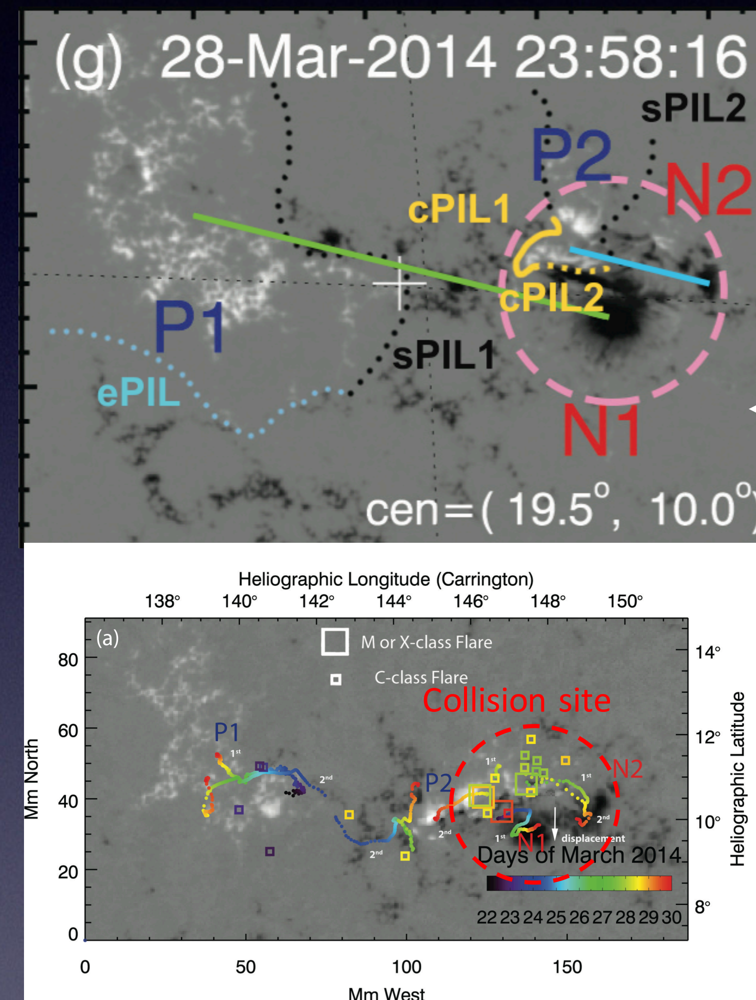
AR11158



(**T.F.I. 591**)

i.e., an equivalent of 591 C1.0 flares over a period of 8 days!!!

AR12017



(**T.F.I. 202**)

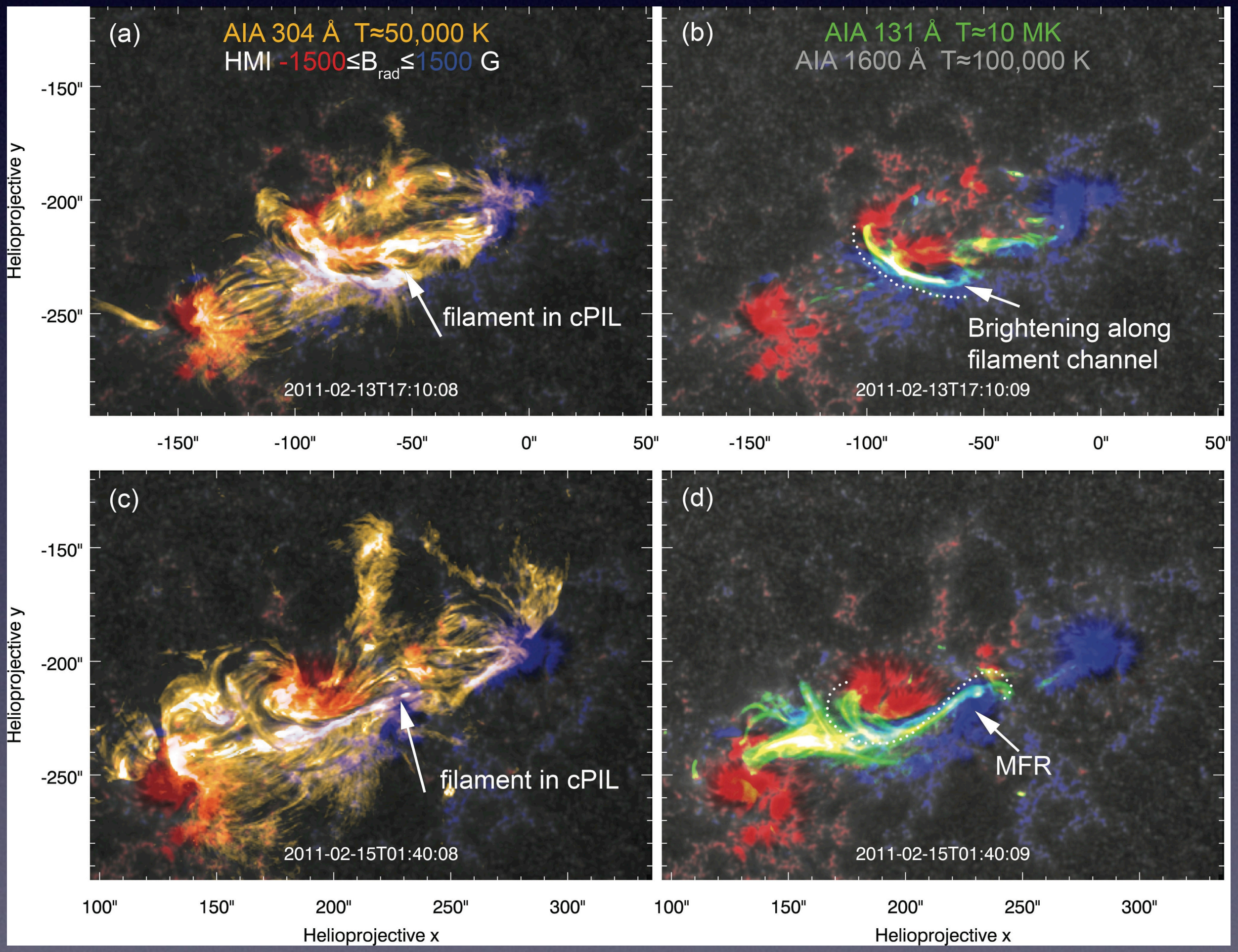
also over a period of 8 days!!!

Chintzoglou et al 2019

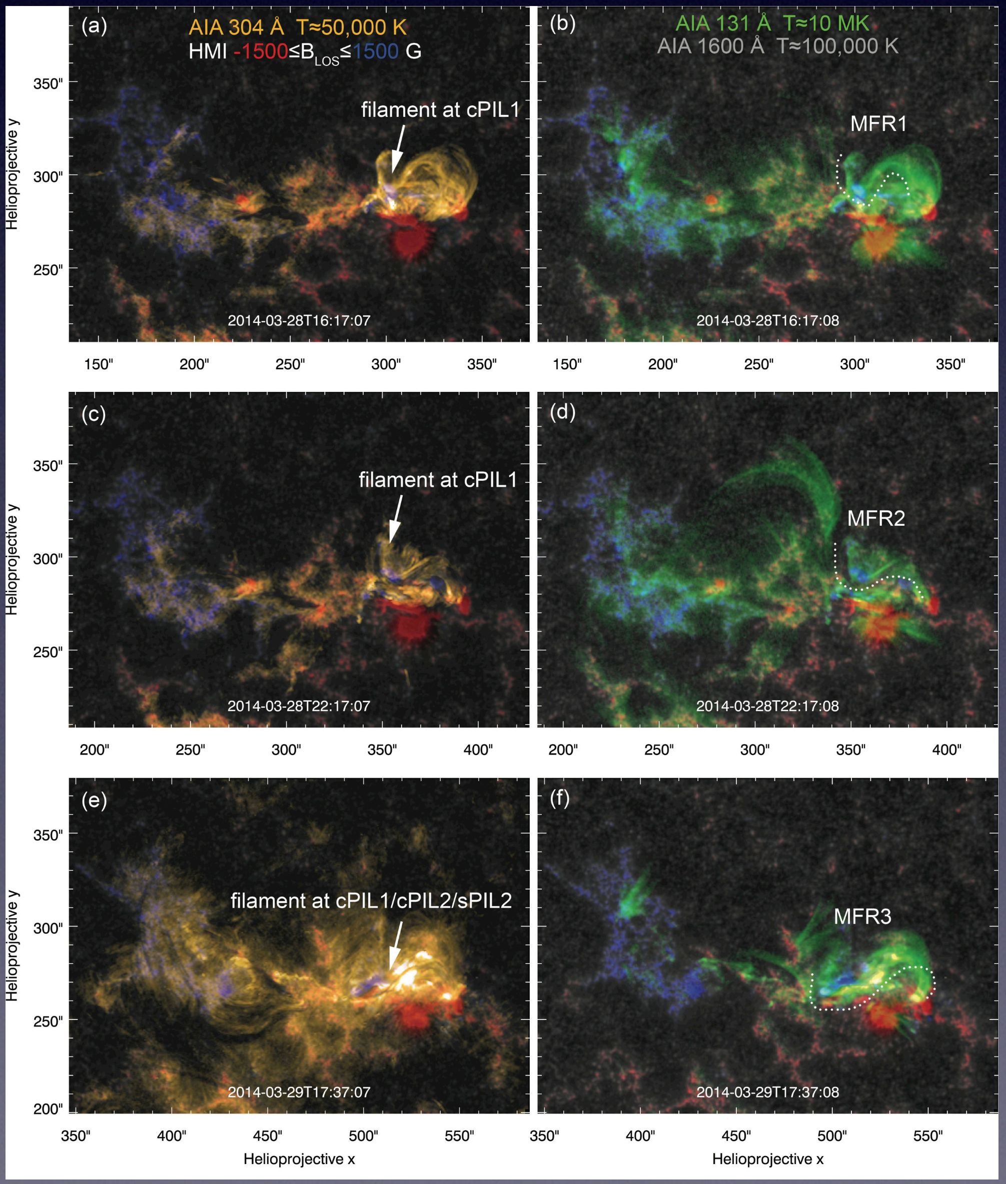
- Flux cancellation during emergence of ~1–2 x 10^{21} Mx (quantified using the *flux deficit method*; Chintzoglou et al 2019).
- cancellation @ cPIL -> consistent with formation of MFRs @ cPIL.
- Question: **Amount of canceled flux => poloidal flux in corona (MFRs)?**

SDO/AIA: Collisional Shearing Forming Filament Channels above cPILs

Simultaneous Emergence/Collision
AR11158 (**T.F.I.** **591**)



Sequential Emergence/Collision
AR12017 (**T.F.I.** **202**)



Chintzoglou et al 2019

Collisional Shearing found in all ARs which emerged in the East Hemisphere

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The Source Locations of Major Flares and CMEs in Emerging Active Regions

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Abstract

Major flares and coronal mass ejections (CMEs) tend to originate from compact polarity inversion lines (PILs) in solar active regions (ARs). Recently, a scenario named "collisional shearing" was proposed by Chintzoglou et al. to explain the phenomenon, which suggests that the collision between different emerging bipoles is able to form a compact PIL, driving the shearing and flux cancellation that are responsible for the subsequent large activities. In this work, by tracking the evolution of 19 emerging ARs from their birth until they produce the first major flares or CMEs, we investigated the source PILs of the activities, i.e., the active PILs, to explore the generality of "collisional shearing." We find that none of the active PILs is the self PIL (sPIL) of a single bipole. We further find that 11 eruptions originate from the collisional PILs (cPILs) formed due to the collision between different bipoles, six from the conjoined systems of sPIL and cPIL, and two from the conjoined systems of sPIL and ePIL (external PIL between the AR and the nearby pre-existing polarities). Collision accompanied by shearing and flux cancellation is found to develop at all PILs prior to the eruptions, with 84% (16/19) cases having collisional length longer than 18 Mm. Moreover, we find that the magnitude of the flares is positively correlated with the collisional length of the active PILs, indicating that the more intense activities tend to originate from PILs with more severe collisions. The results suggest that "collisional shearing," i.e., bipole–bipole interaction during the flux emergence, is a common process in driving the major activities in emerging ARs.

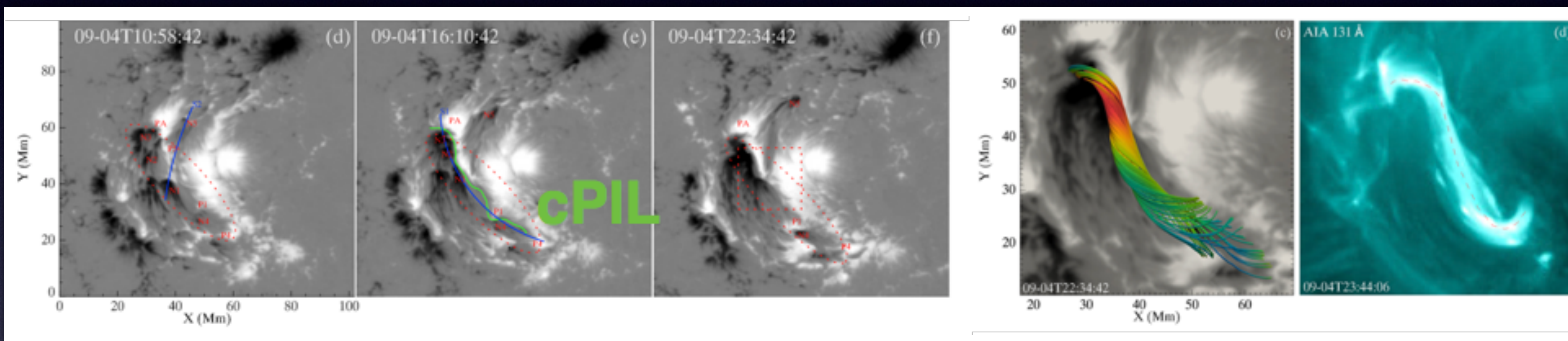
Unified Astronomy Thesaurus concepts: Solar active regions (1974); Solar active region magnetic fields (1975); Solar activity (1475); Solar flares (1496); Solar coronal mass ejections (310)

Supporting material: animations

Liu et al 2021, ApJ

Collisional Shearing in AR12673 (highest T.F.I. AR of Solar Cycle 24)

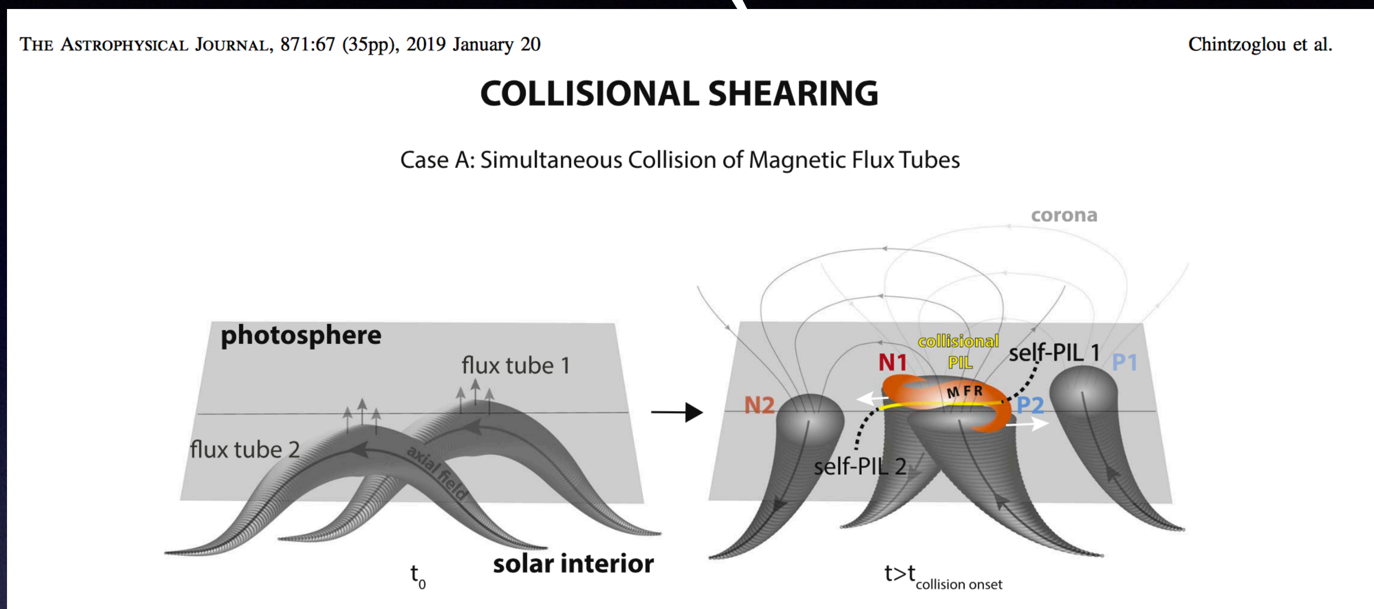
T.F.I. 2977 (=5x T.F.I. of AR11158)



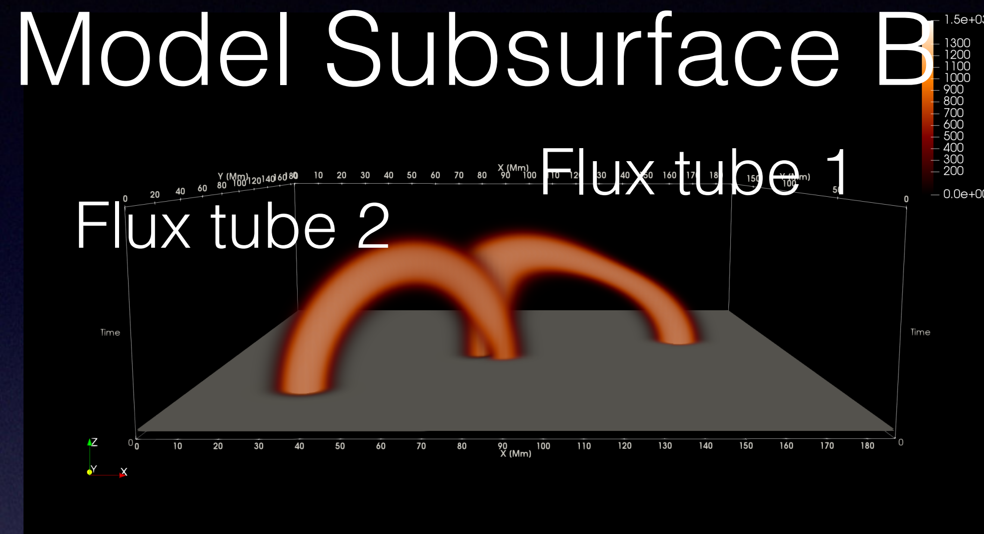
Liu et al 2019

Collisional Shearing was found behind the rapid formation of the eruptive flux rope in “super AR” AR12673 (Sep 04 2017, first X-flare/CME)

Putting the Cartoon to the (Numerical) Test

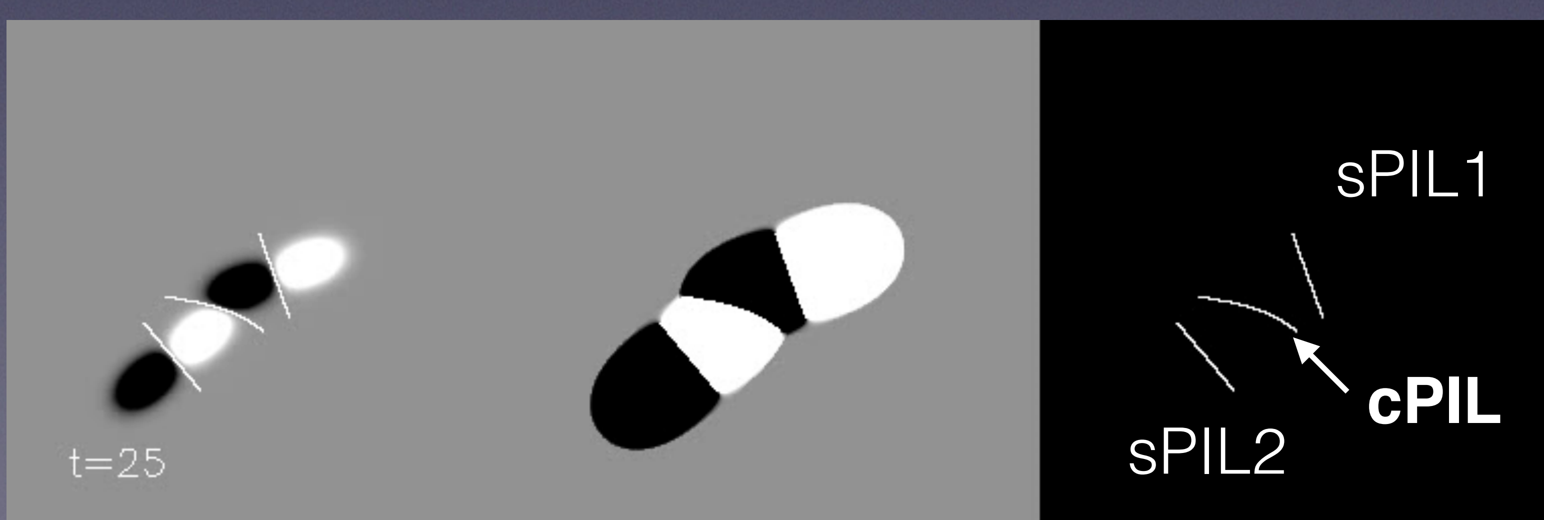


Model Subsurface B



Using an evolutionary data-driven magnetofrictional model (Cheung & DeRosa 2012) to investigate the collisional shearing process.

Time-evolving photospheric boundary condition (B.C.):



E-field at photosphere

$$\boxed{\mathbf{E}|_{z=0} = -\frac{1}{c}\boldsymbol{v}\times\mathbf{B}(x,y,z=0;t)}$$

Numerical method

The magnetofrictional (MF) code solves for the magnetic vector potential, **A**, and utilizes **E**-fields to drive the evolution of **B** in the volume.

$$\boxed{\frac{\partial \mathbf{A}}{\partial t} = \mathbf{v} \times \mathbf{B}}$$ Induction Equation

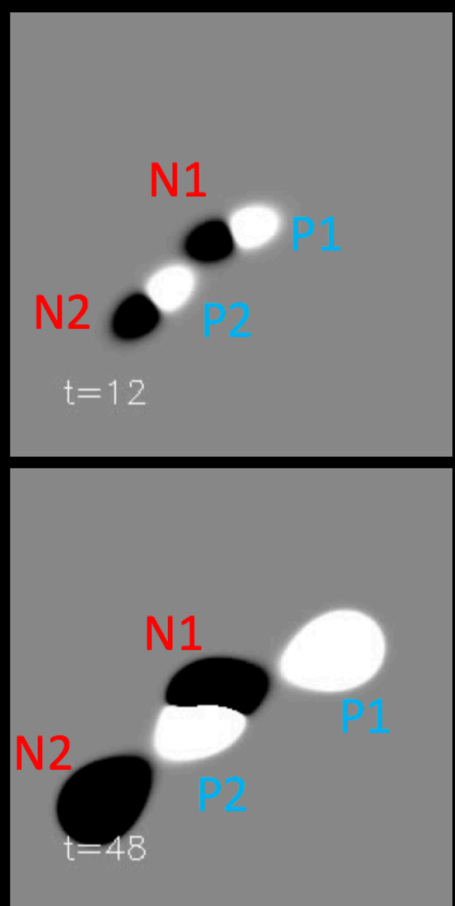
$\mathbf{B} = \nabla \times \mathbf{A}$ $\mathbf{J} = \nabla \times \mathbf{B}$ $\mathbf{v} = \frac{1}{\nu} \mathbf{J} \times \mathbf{B}$ $\nu = \nu_0 B^2 (1 - e^{-\frac{z}{L}})$

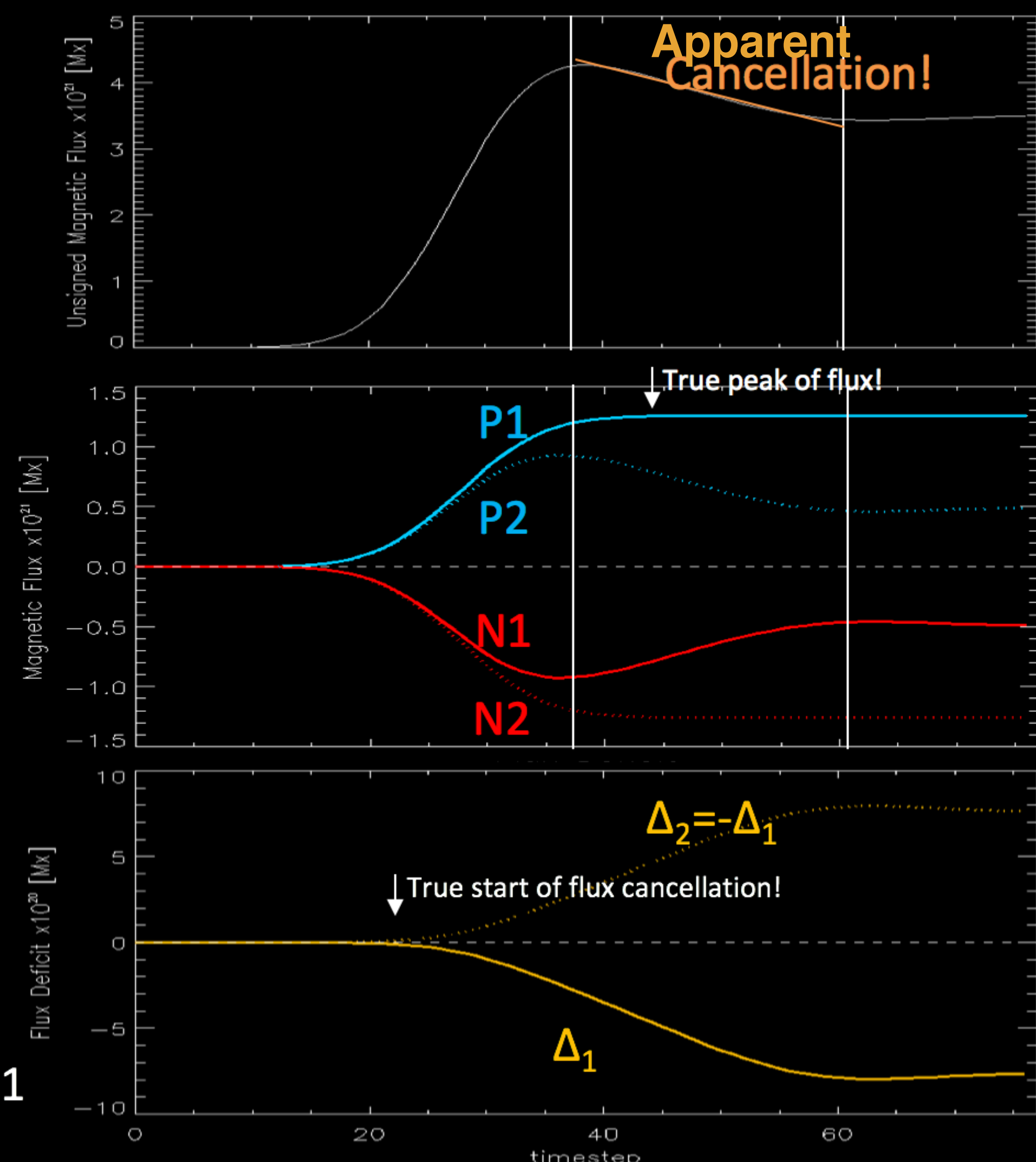
Our numerical scheme is a modification of Cheung & DeRosa (2012) and uses:
(1) a staggered grid (Yee mesh) and
(2) a *van Leer* (1977) slope limiter to interpolate **v** onto cell edges when computing **E**=-**v**x**B**

This scheme is more stable and less diffusive than explicitly imposing an anomalous resistivity (Cheung et al 2015).

Computational volume : 256x256x128 pixels^3
spatial scale dx=500 km; **Box size: 129 Mm**
Δt=720 sec
Duration in **"solar time" ≈ 0.5 day**

Prescribed evolution for the magnetic flux in the B.C.





$\Phi tot=4.3x10^{21}$ **Mx**

True cancellation

$\Delta=0.8x10^{21}$ Mx

- **Define Flux Deficit:**

e.g. for conjugated bipole 1

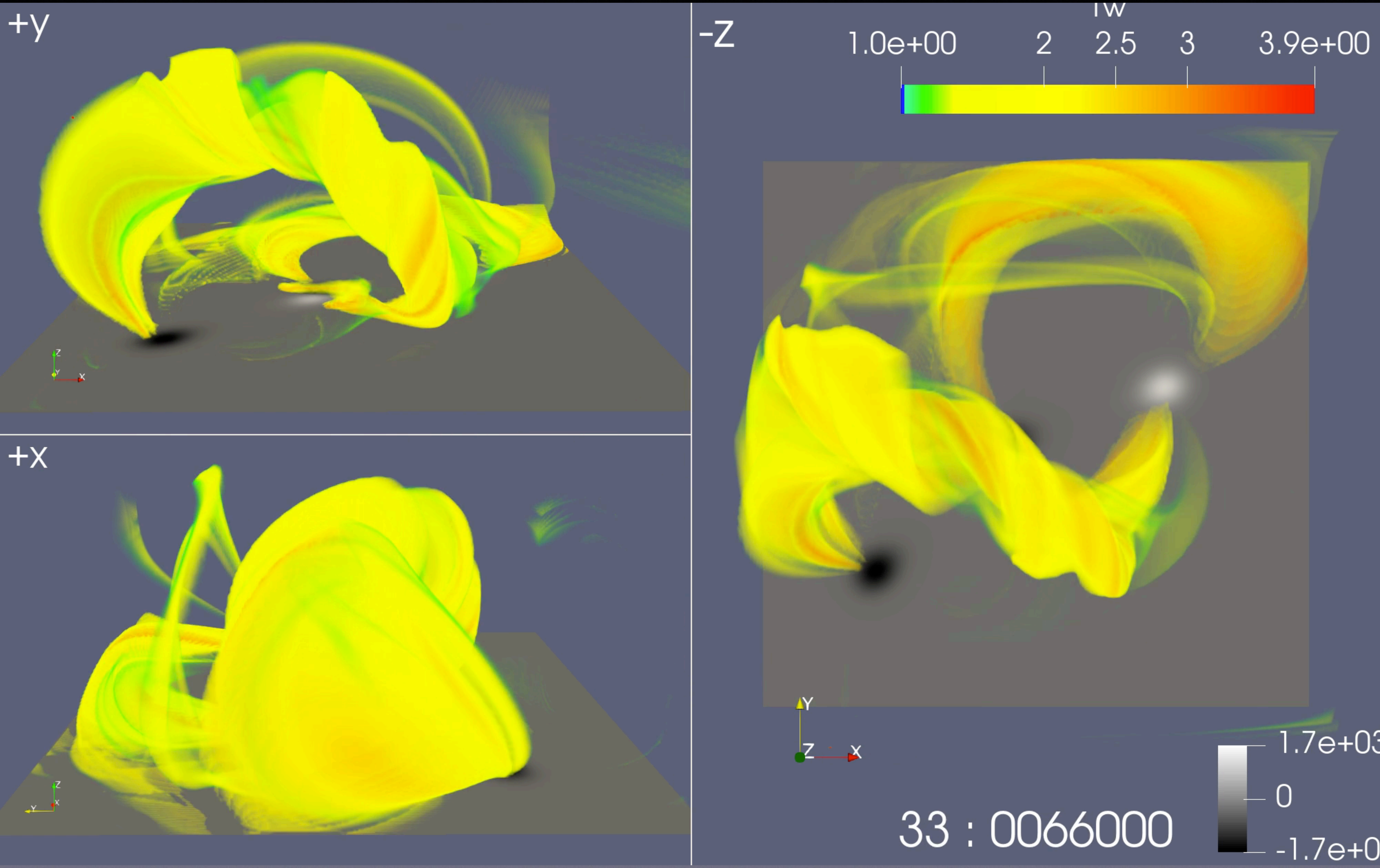
$\Delta_1=|\Phi_{N1}|-\Phi_{P1}$

(see more in Chintzoglou et al 2019)

Chintzoglou et al 2019 measured in emerging ARs $\Delta = 1 - 2 \times 10^{21}$ Mx

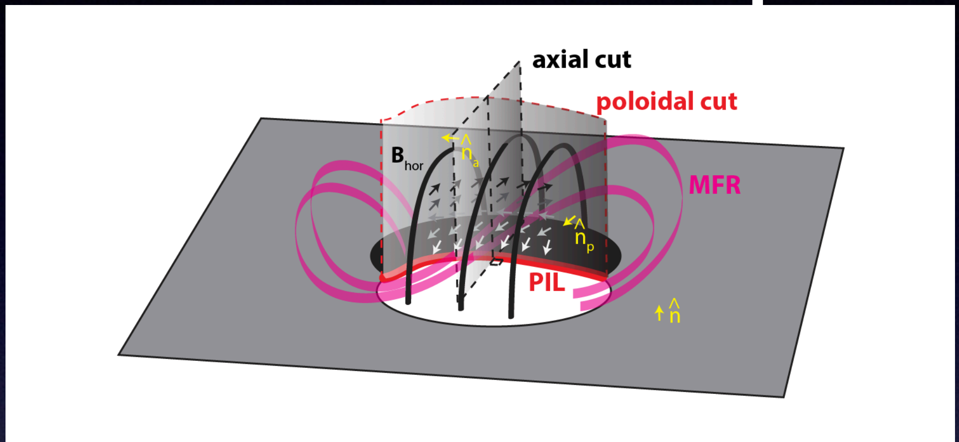
The deficit Δ equals to the total amount of flux cancelled

Q: Is deficit Δ the poloidal flux in the corona before a CME?



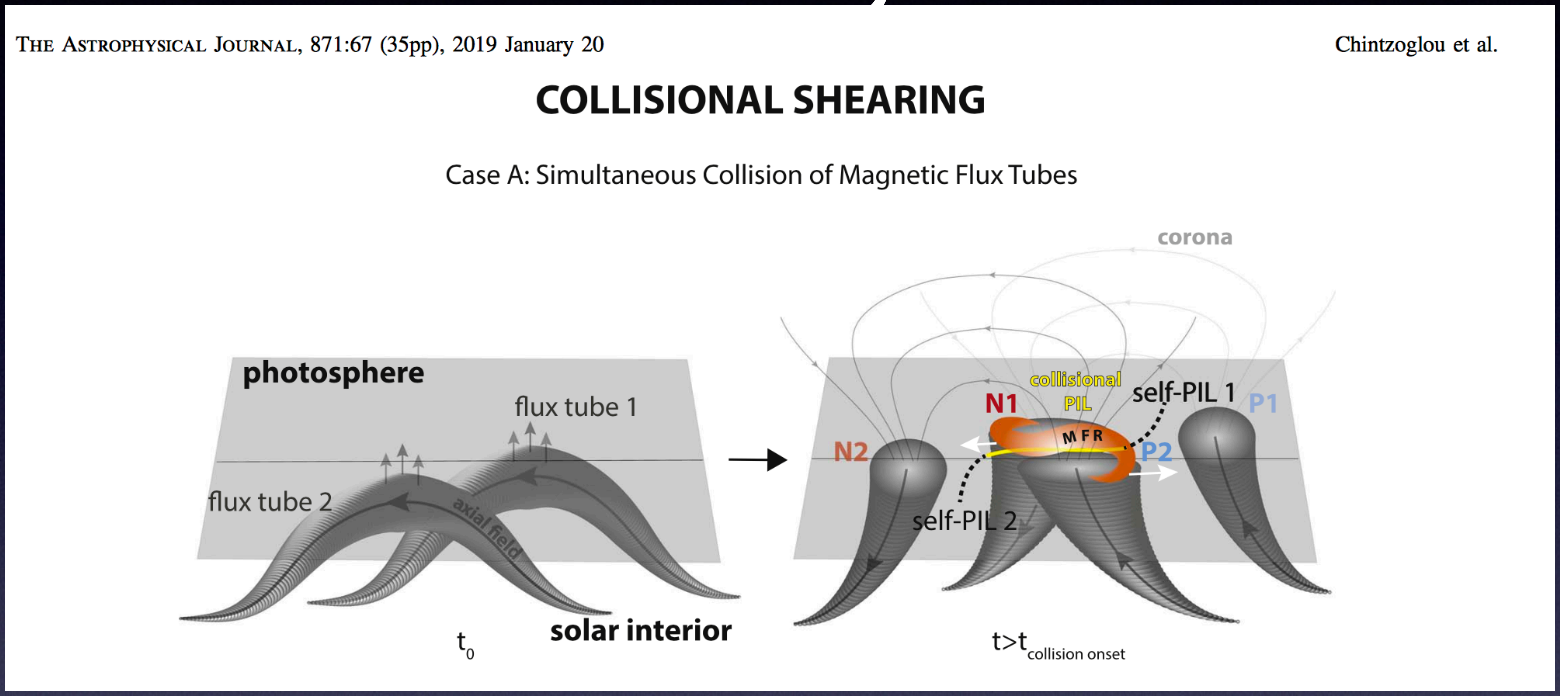
Chintzoglou & Cheung 2021 (in preparation)

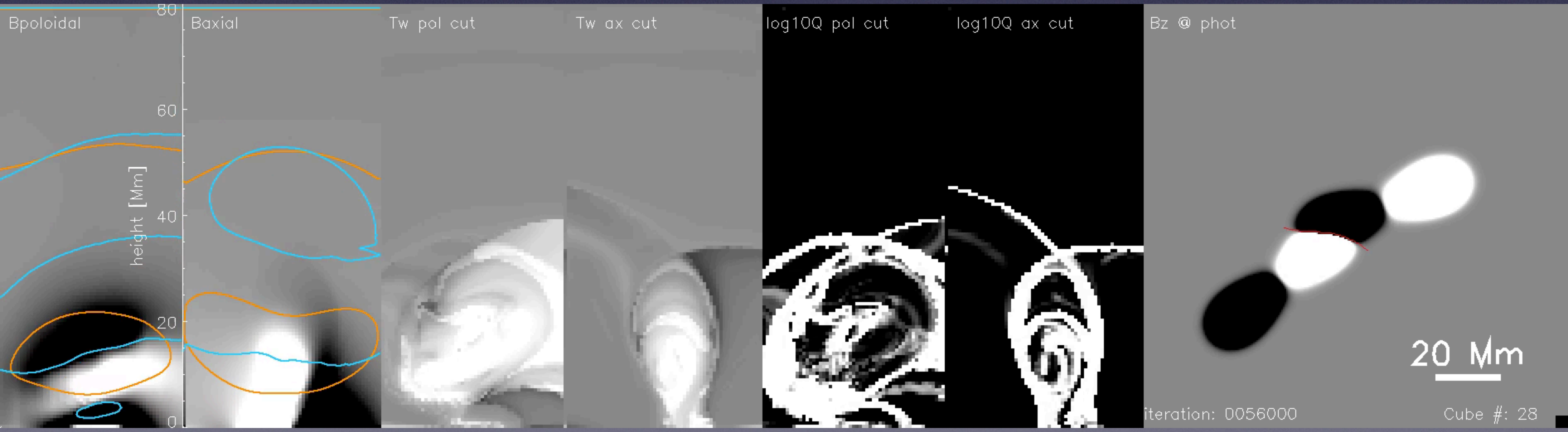
Major result: Recurrent Explosive Activity!



$$\Phi_{phot} = \int \mathbf{B} \cdot \hat{\mathbf{n}}\, da$$

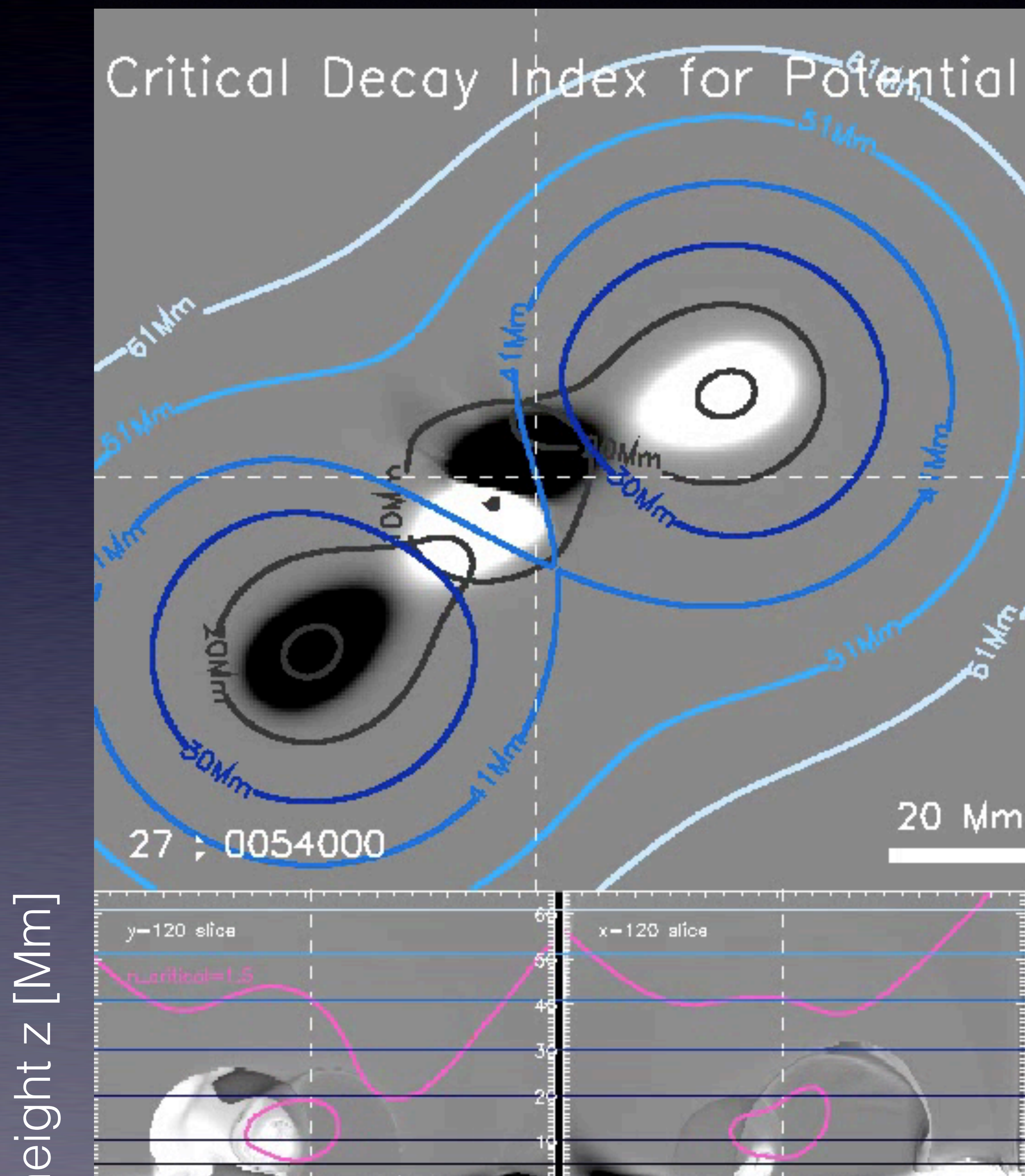
$$\Phi_{poloidal} = \int \mathbf{B}_{hor} \cdot \hat{\mathbf{n}}_p\, da \qquad \Phi_{axial} = \int \mathbf{B}_{hor} \cdot \hat{\mathbf{n}}_a\, da$$





Chintzoglou & Cheung 2021 (in preparation)

Critical height (surface) evolves with time during emergence!



Decay index n:

quantifies **the decay rate** at which the overlying horizontal magnetic field (which straps the MFR down) **weakens with increasing height from the photosphere**.

$$n = \frac{-d\log B_{horizontal}}{d\log z}$$

Useful assumption:

"critical decay index"

$\mathbf{n_{crit}=3/2}$ (Kliem & Torok 2006)

↓

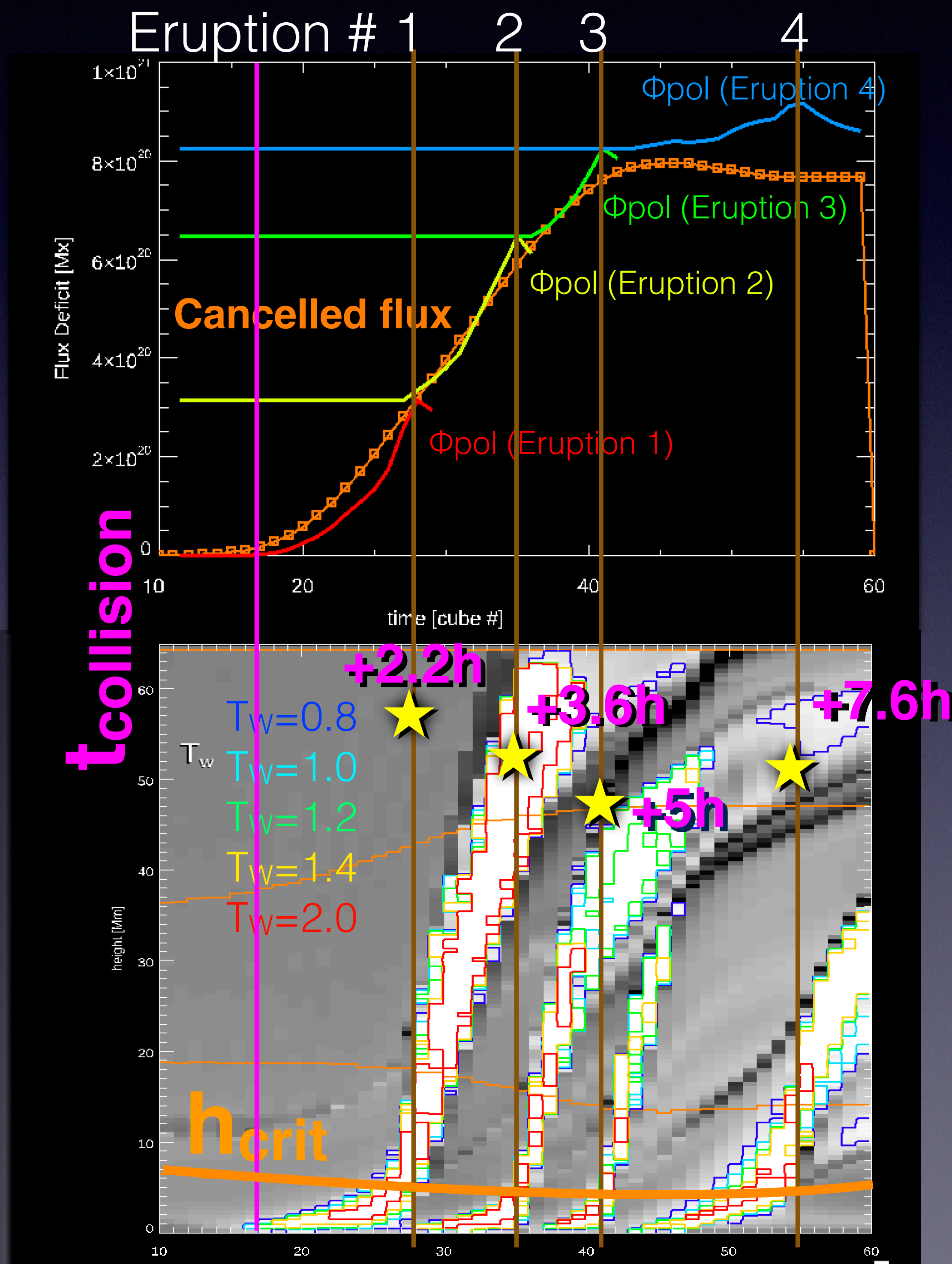
critical height

$\mathbf{h_{crit}=z(n=n_{crit})}$

←

Chintzoglou & Cheung 2021 (in preparation)

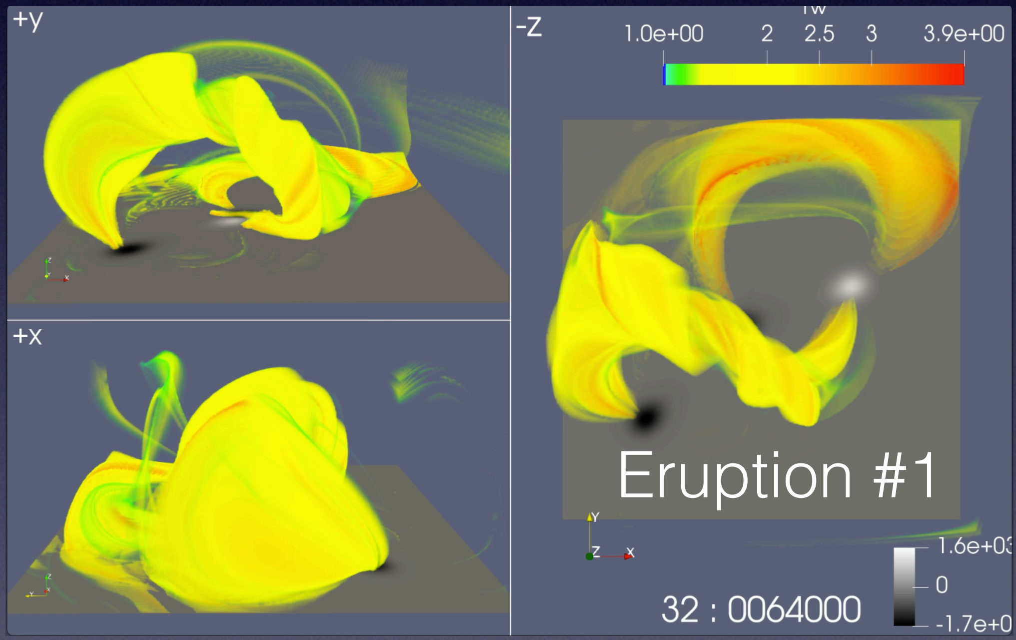
Collisional Shearing Drives Homologous Explosive Activity



Chintzoglou & Cheung 2021 (in preparation)

We find, for the duration of the collision:

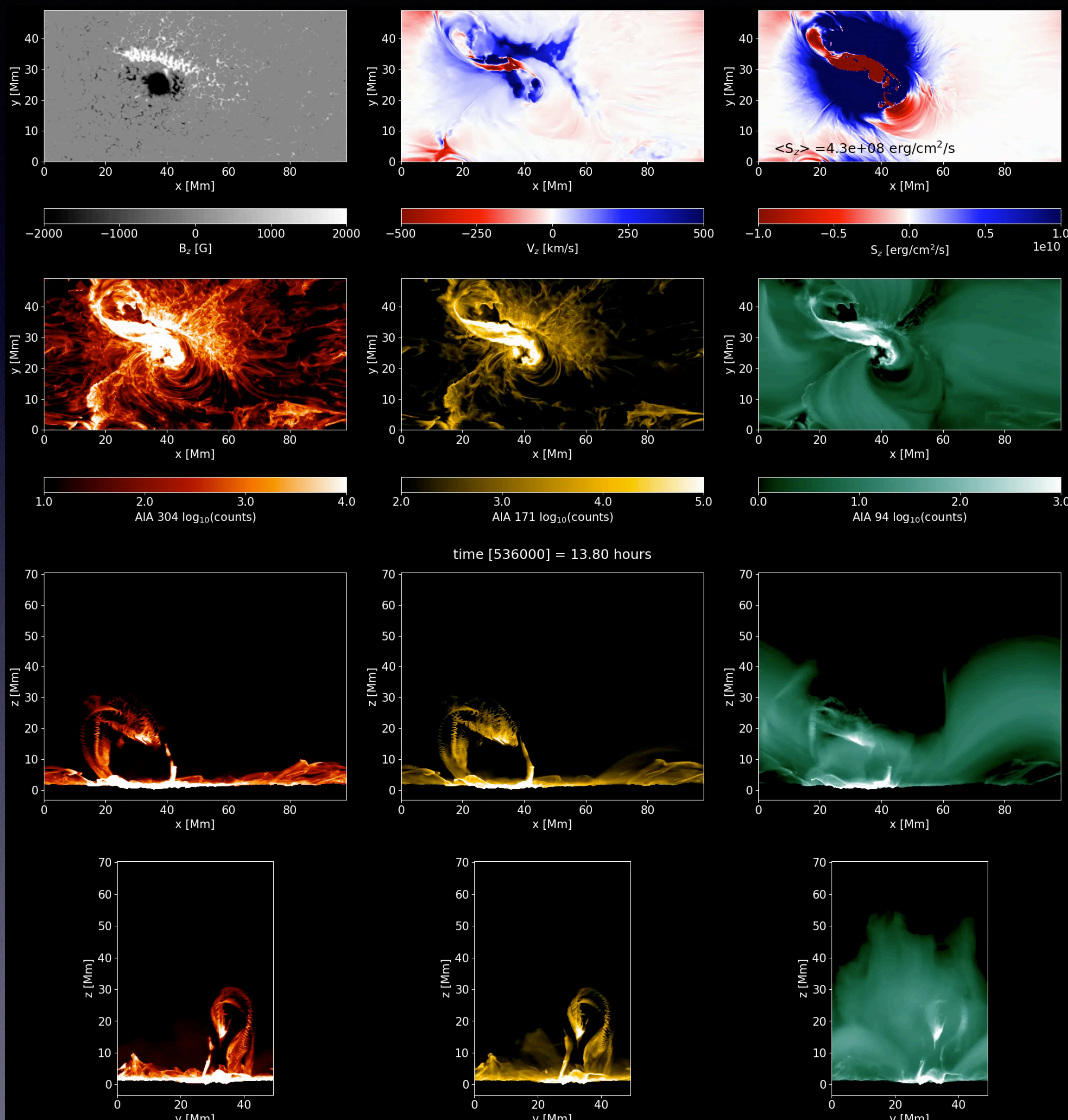
a. **Cancelled flux amounts to the poloidal flux, Φ_{pol}.** Cancelled flux is stored as MFRs above the photosphere.



b. When the MFR's top reaches the critical height, h_{crit}, eruption begins (consistent with MHD models!). **This also limits the amount of poloidal flux in the flux rope.**

c. The **evolution** of the colliding configuration governs both the recurrent MFR formation and their eruption. **Collisional shearing is driving homologous explosive activity.**

Future Outlook



Collisional Shearing with 3D radiative MHD simulations in different realistic emerging and colliding configurations

Identify the Physics of Eruption onsets and compare with observations

Preliminary results with the MURaM 3D MHD code with simulated Corona
Rempel, Chintzoglou & Cheung 2021 (in preparation)

Summary & Conclusions

Part (1) What makes some ARs more eruptive than others? Introducing the Collisional Shearing Process:

Our proposed mechanism (Chintzoglou et al 2019) considers the effect of magnetic cancellation during emergence in complex multipolar ARs.

We name this process “**collisional shearing**” to emphasize that it is different from the cancellation scenario of Ballegooijen & Martens (1989) who considered cancellation in the internal PIL of a singular bipole during it’s decay phase.

We **demonstrate that cancellation occurs during emergence in significant amounts** (1—2x10^{21} Mx or more), i.e., comparable to the total flux of the AR, **which has been neglected in the past solar eruptive models** (Chintzoglou et al 2019).

Our proposed mechanism **supports the formation and energization of magnetic flux ropes before their eruption** as CMEs and the associated flare activity.

Part (2) An evolutionary data-driven numerical model for Collisional Shearing

Model captures in 3D the gradual formation and evolution of the energized MFR structures during the Collisional Shearing process, producing recurrent homologous activity in a multipolar AR.

The cancelled flux amounts to the poloidal flux in the coronal volume. Therefore, the Flux Deficit Method (Chintzoglou et al 2019) provides a reasonable estimate of the poloidal flux accumulated in the magnetic flux rope as it forms in a complex emerging AR.

Eruption begins once the MFR’s top reaches the critical height (similar to MHD models).

Since the critical height changes with time (due to the time-evolving photospheric configuration), it also limits the amount of poloidal flux stored and the onset of eruptions over the evolution of the AR, likely controlling the fate of eruptions (either powerful or failed eruptions).