Supporting Evidence for the Action of Self-Organized Criticality in Turbulent, Multiscale Solar Active Regions

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OUTLINE

Evidence of SOC in solar active-region magnetic fields?

A. Evolution of (most) eruptive ARs:

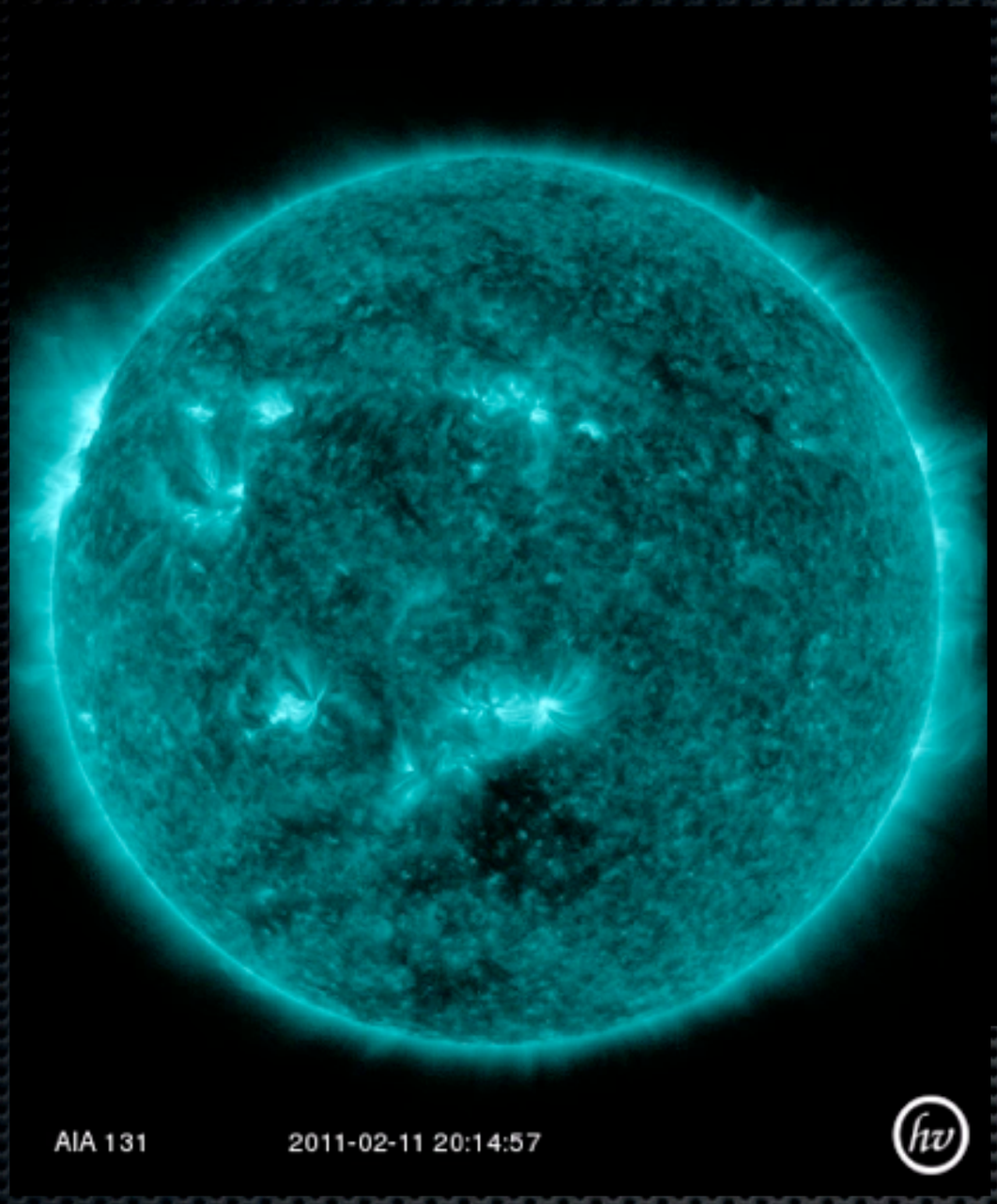
- Metastability through irreversibility
  * The “point of no return” - physical mechanism
- Marginal stability
  * A possible nature of the critical threshold involved
  * How do we get there?
- A numerical test and implications

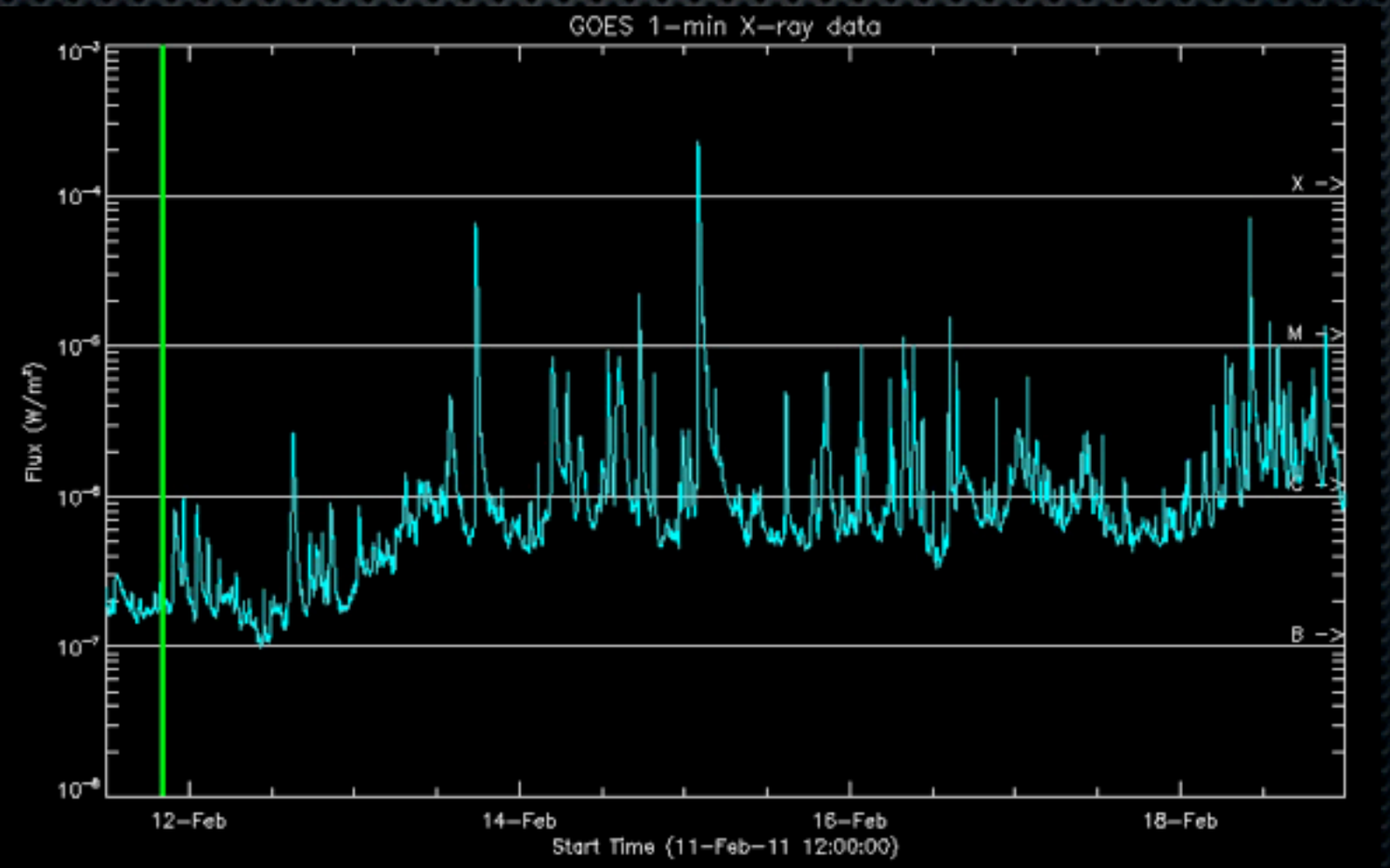
Extrapolated force-free field → SOC-state 3D field ≠ initial → Initial field, but in SOC state

B. Open questions:

C. Conclusions

THE CASE OF NOAA AR 11158



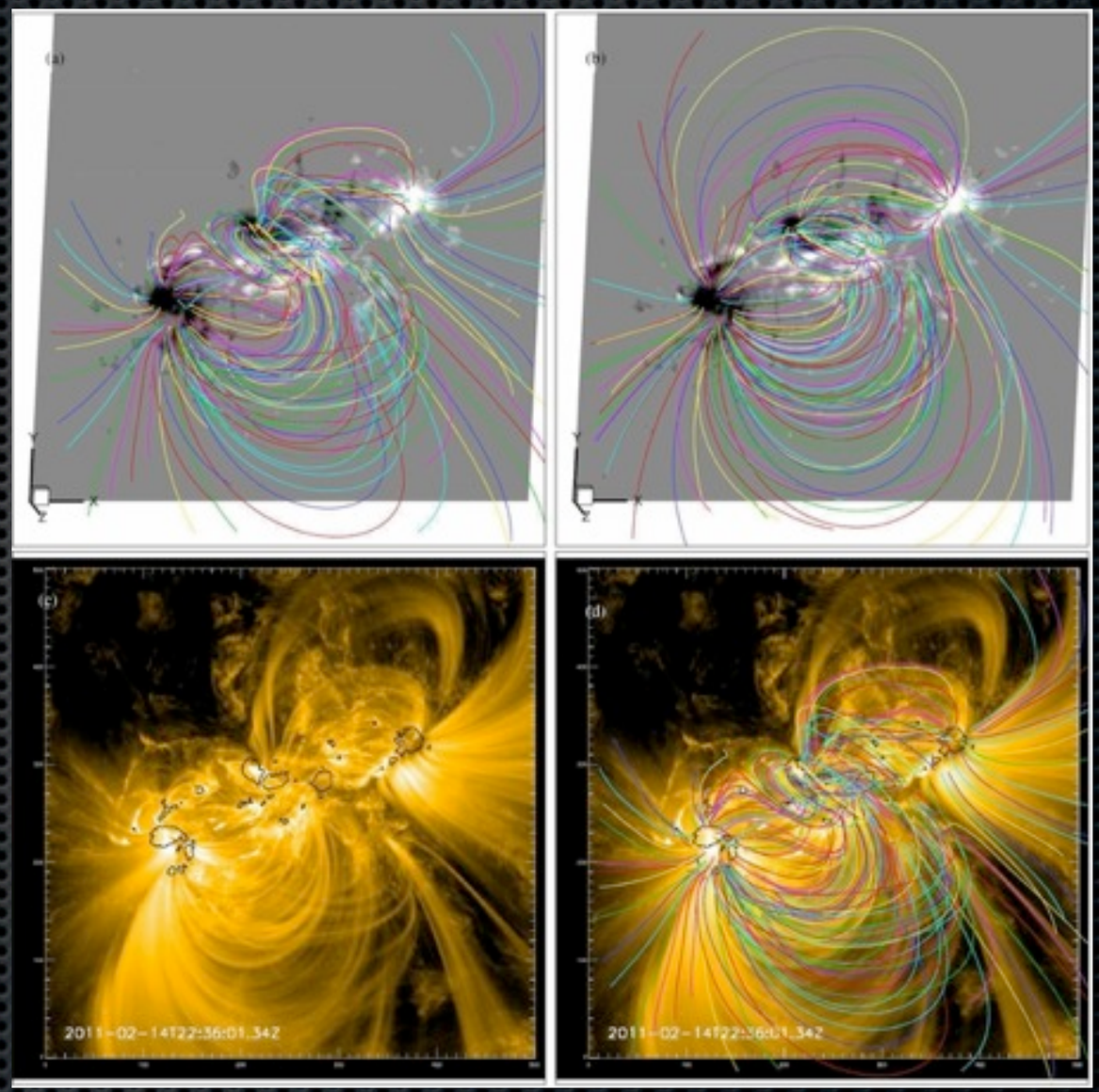


A super-eruptive AR with 1 X- and 3 M-class eruptive flares, including > 30 C-class flares, many of which eruptive, over a 5-day period

MAGNETIC-FIELD EVOLUTION IN THE AR

SDO / HMI

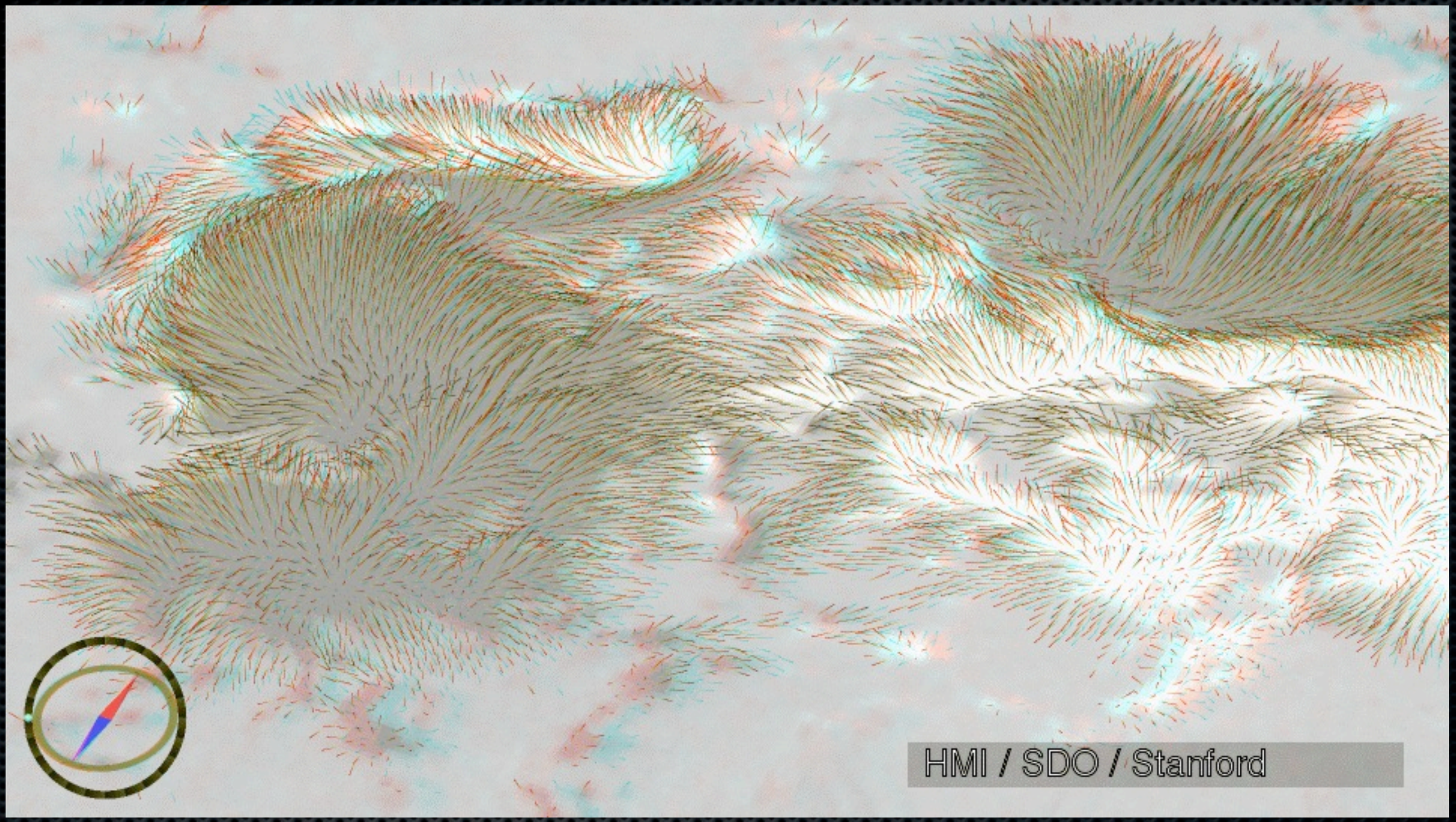
Jiang & Feng (2013)



A very complex observed photospheric magnetic field...

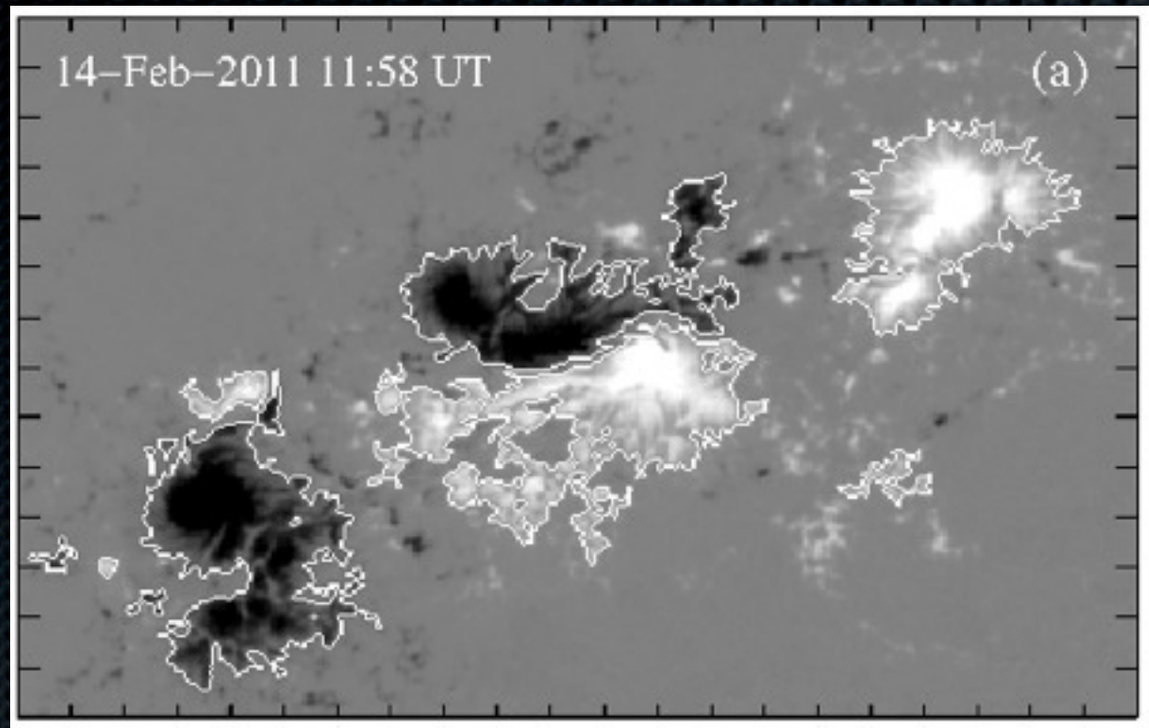
... and an equally complex extrapolated field in the AR's corona

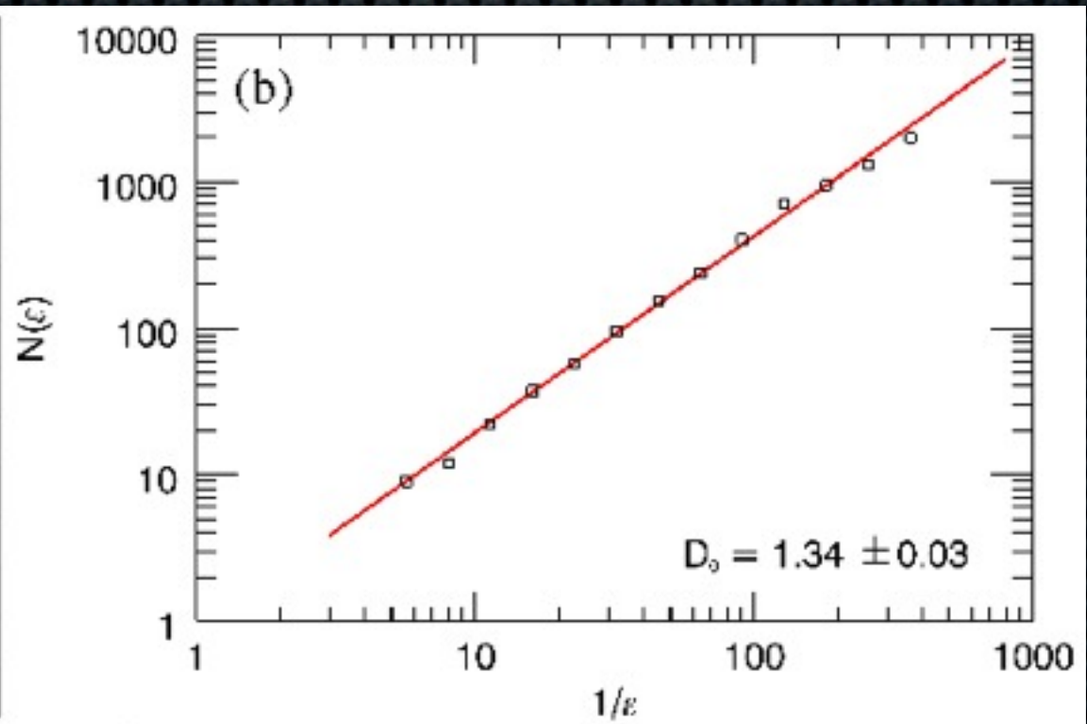
STRONGLY SHEARED PHOTOSPHERIC FIELDS

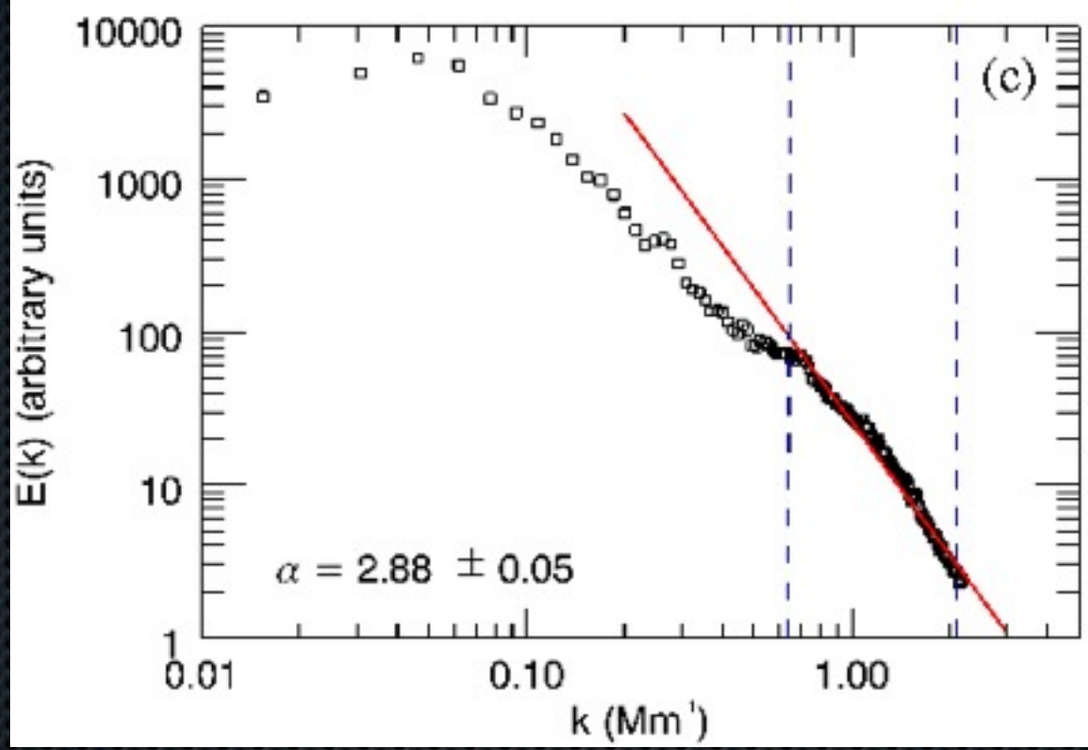


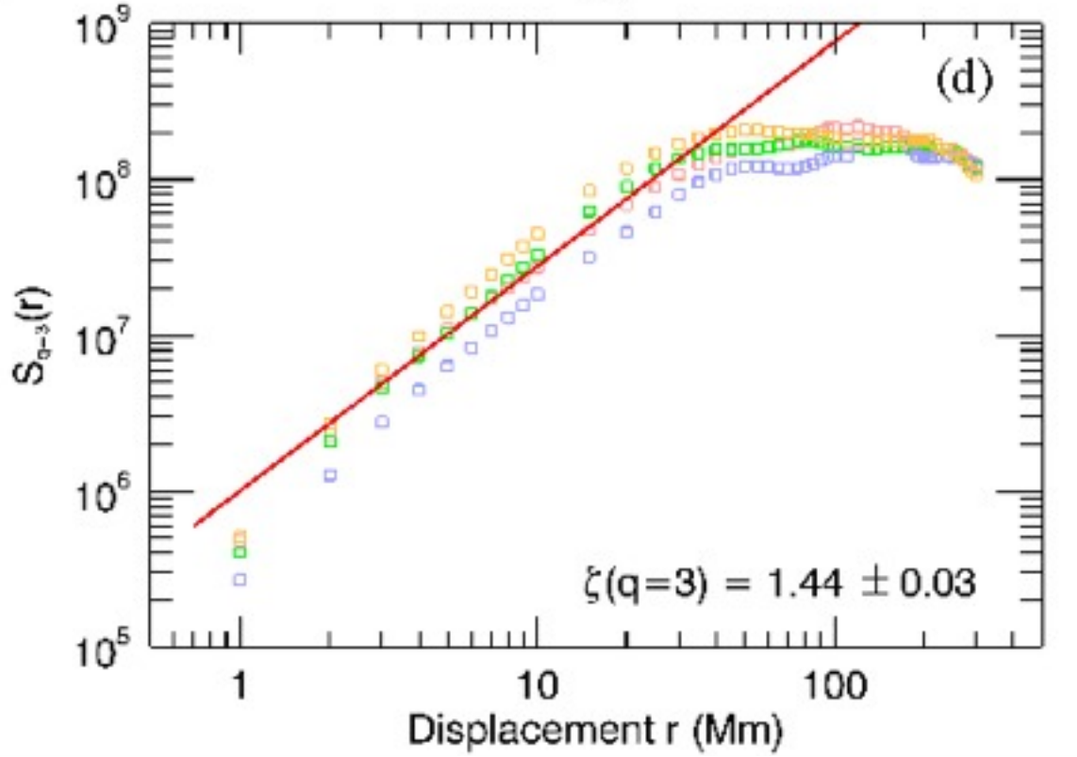
Source: Keiji Hayashi - Stanford U.

AND A WELL-MANIFESTED MULTISCALE BEHAVIOR





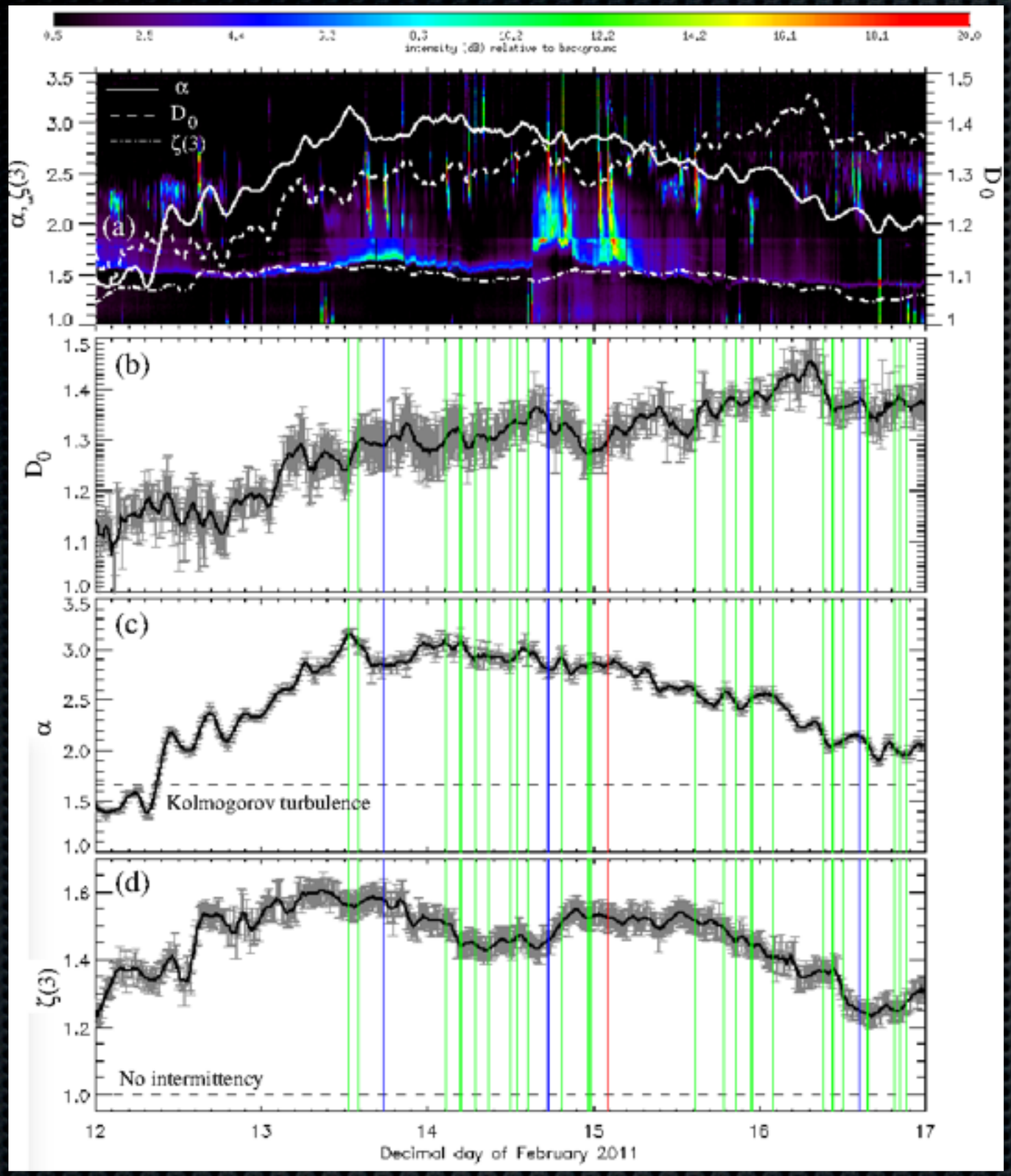




Georgoulis (2013), submitted

$$S_q(r) = \left\langle \left| B_z(\bar{x}+\bar{r}) - B_z(\bar{x}) \right|^q \right\rangle \sim r^{\varsigma(q)}$$

FOR THE ENTIRE SDO/HMI OBSERVING INTERVAL



background: WIND/WAVES frequency-time radio spectra

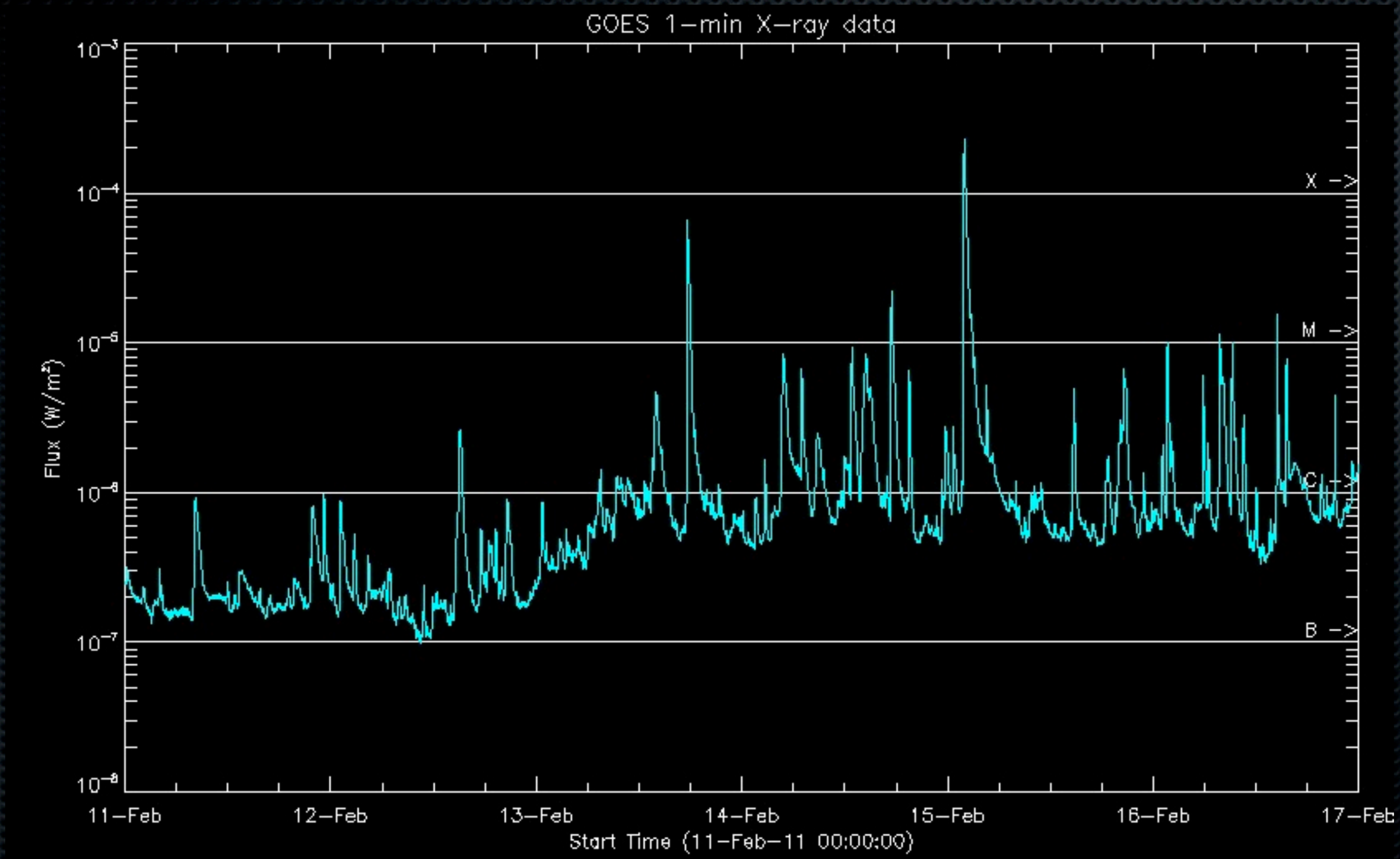
fractal dimension

power-law index of turbulent power spectrum

intermittency scaling index

Georgoulis (2013), submitted

FREQUENCY DISTRIBUTION OF GOES X-RAY FLUX



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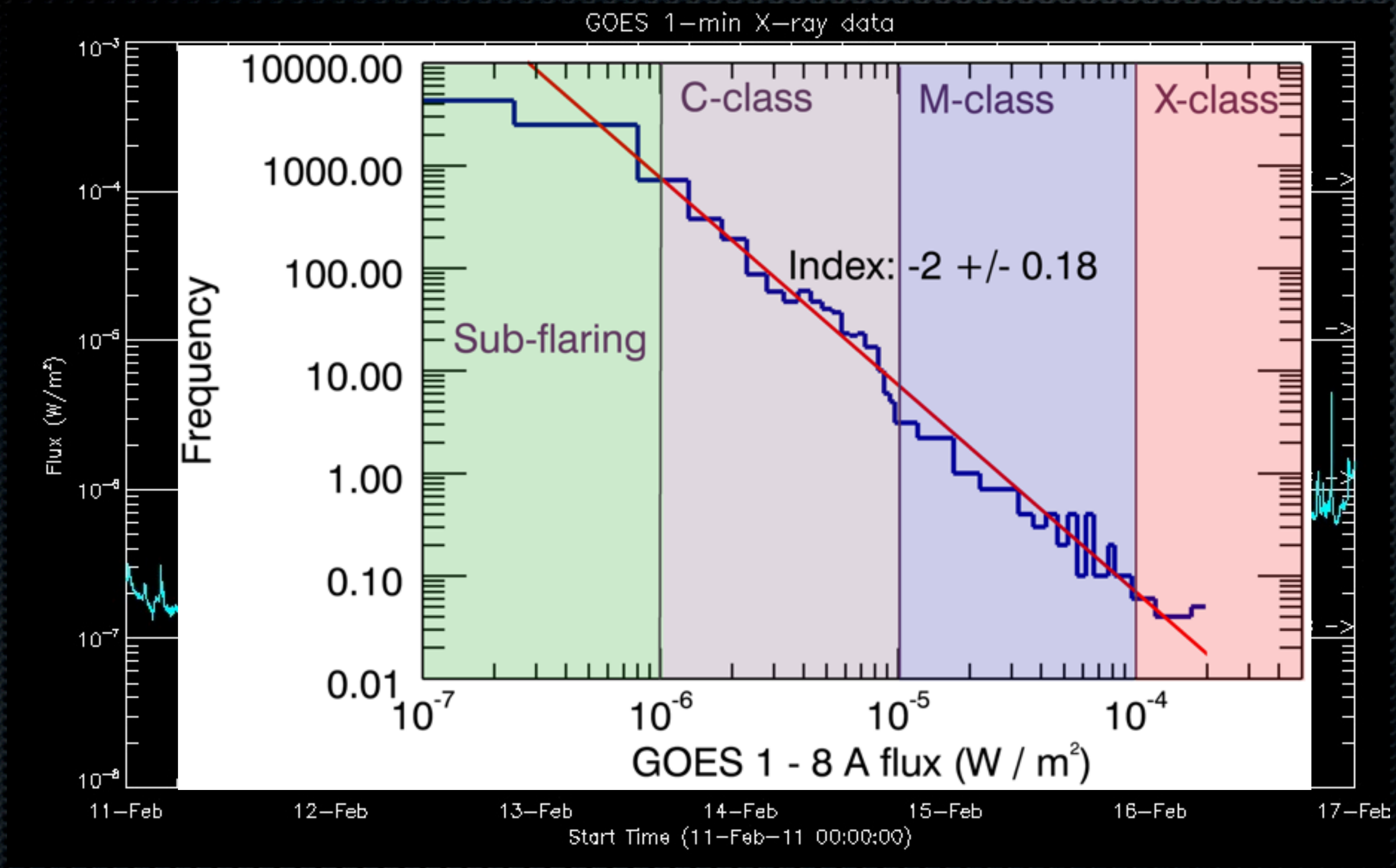

A well-defined power law!

Q: Could this (and similar) active regions be in a SOC state?

A PROPOSITION

Active regions with a strong photospheric magnetic polarity-inversion line do not die out without at least one major eruption (flare + CME)

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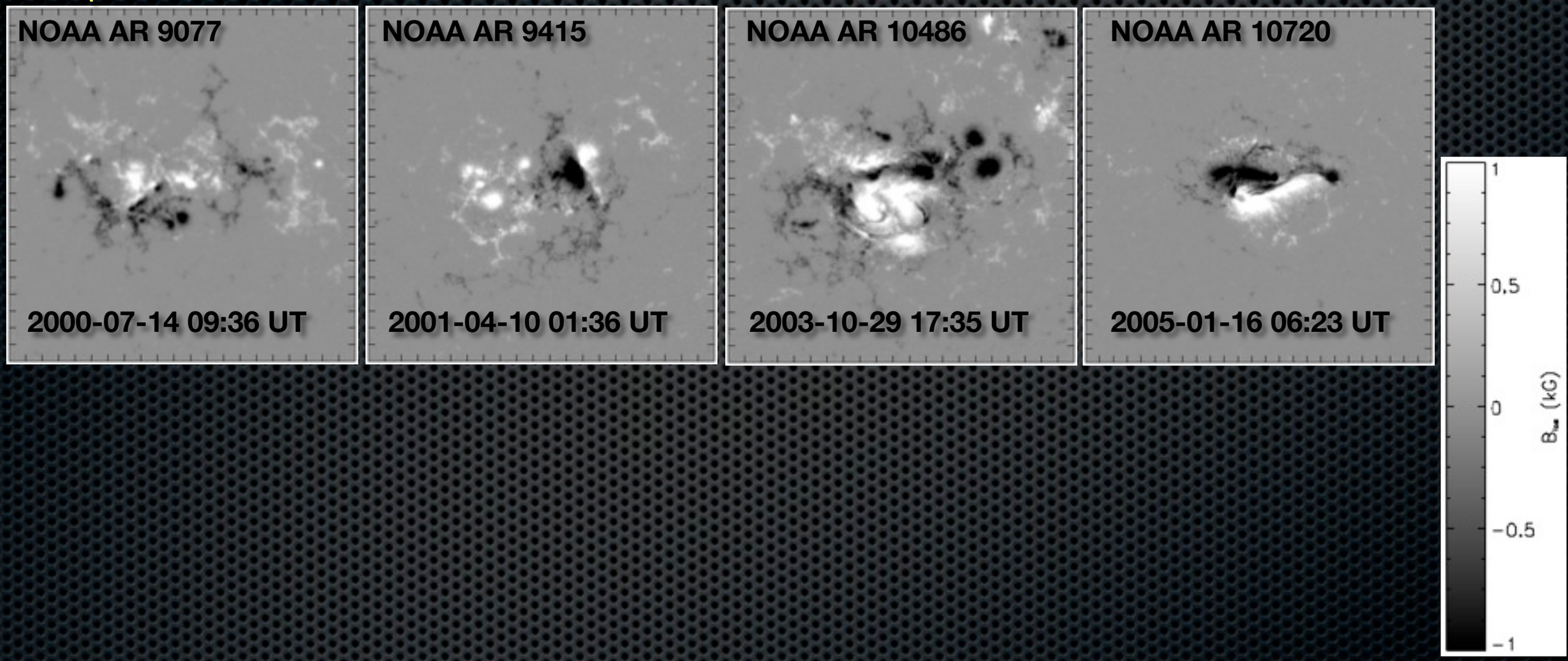

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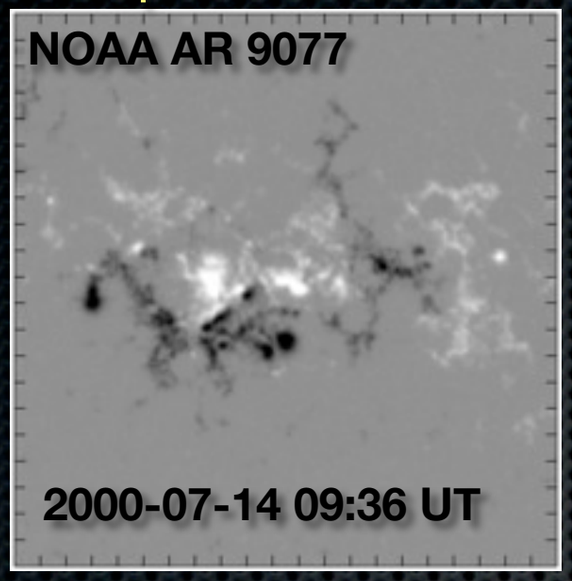
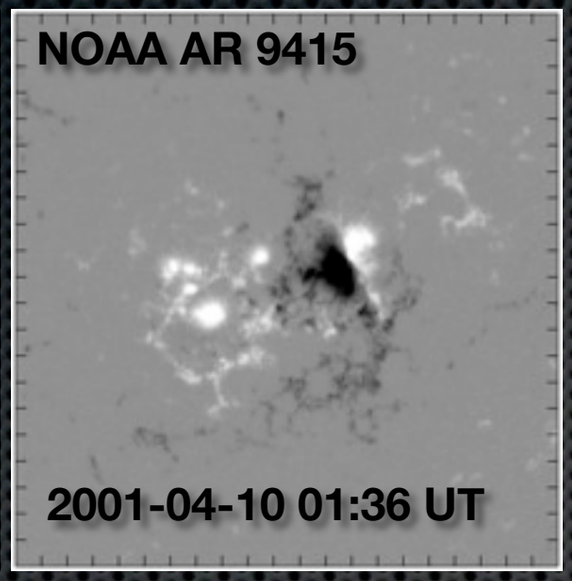
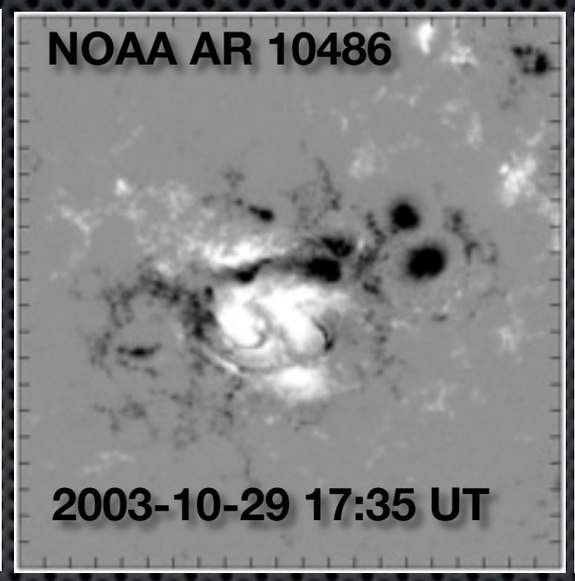
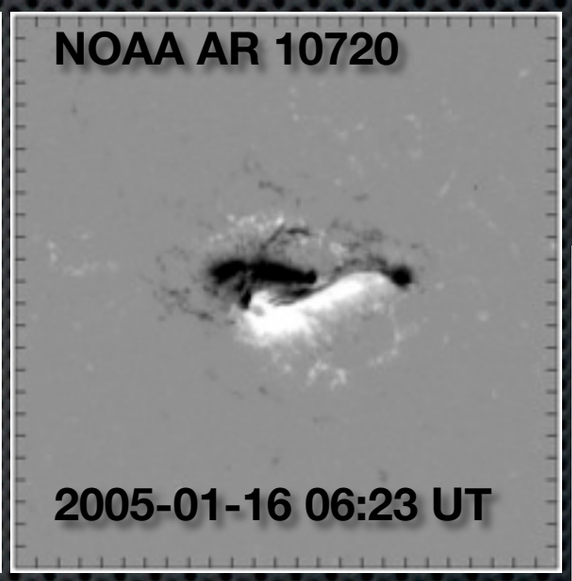
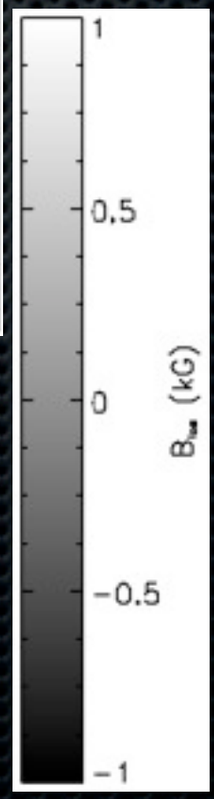


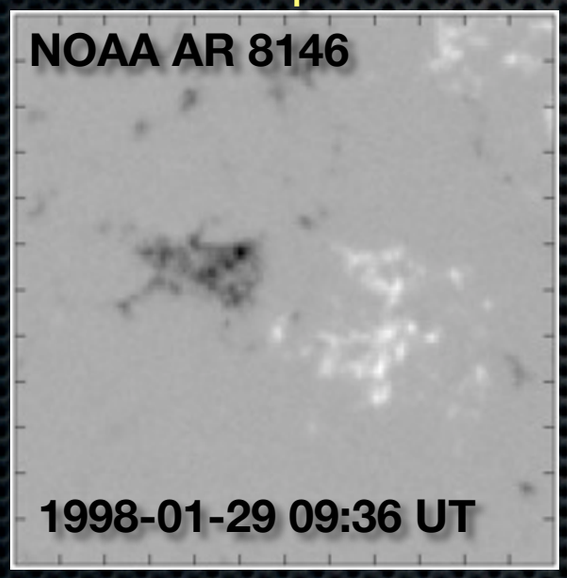


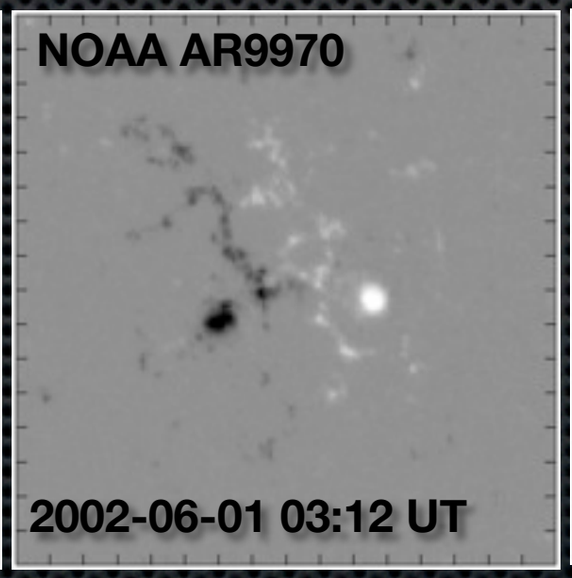


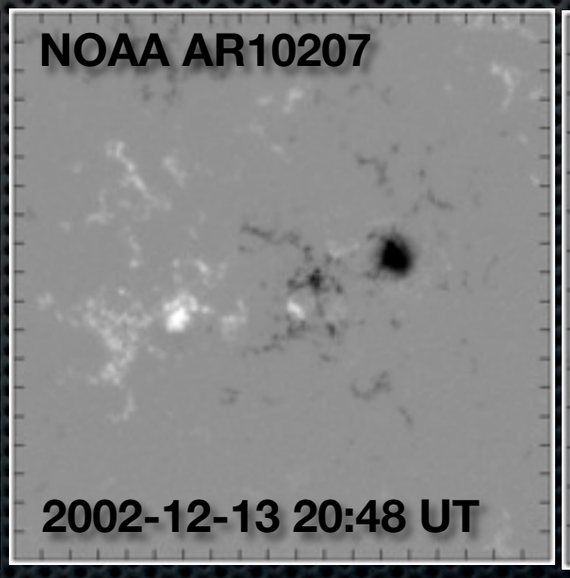


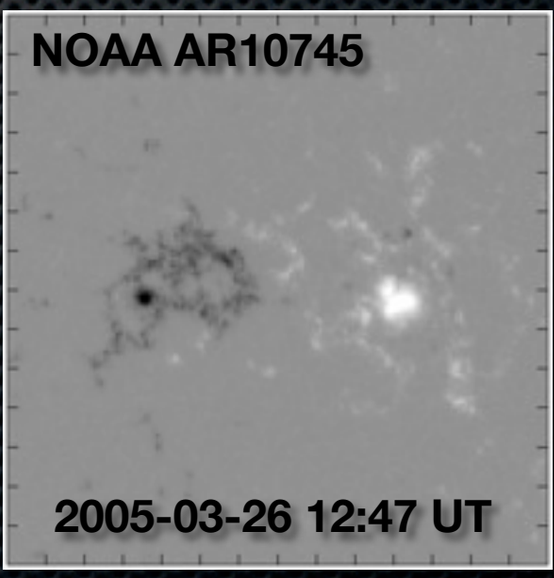


Non-eruptive ARs:









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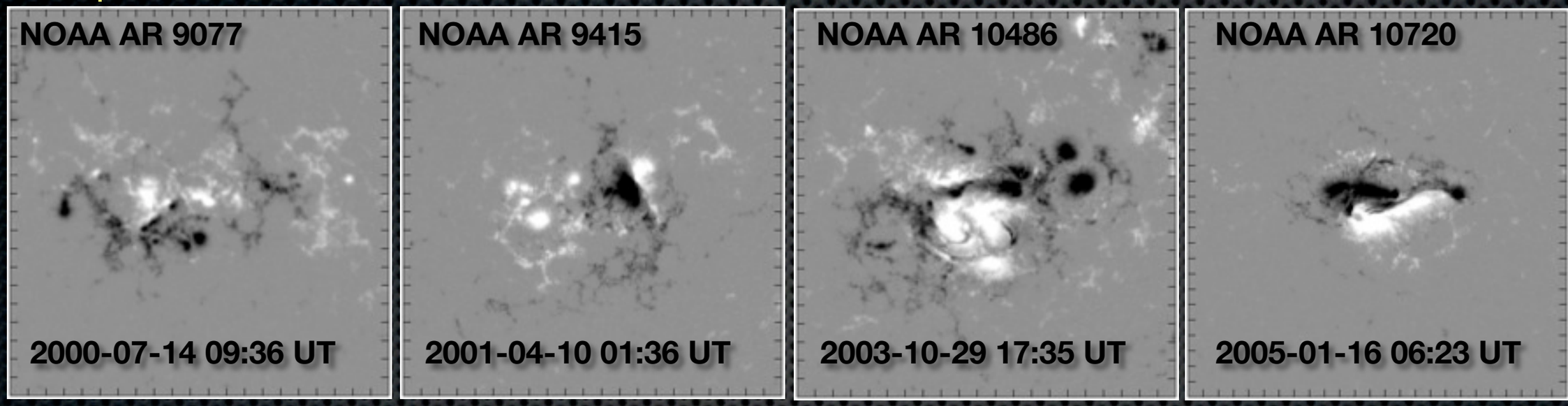

After a certain "point of no return" (strong-PIL formation), irreversibility sets in!

A SEEMINGLY “IRRELEVANT” STUDY

Are electric currents injected in the solar atmosphere via magnetic flux emergence neutralized?

Parker (1996)

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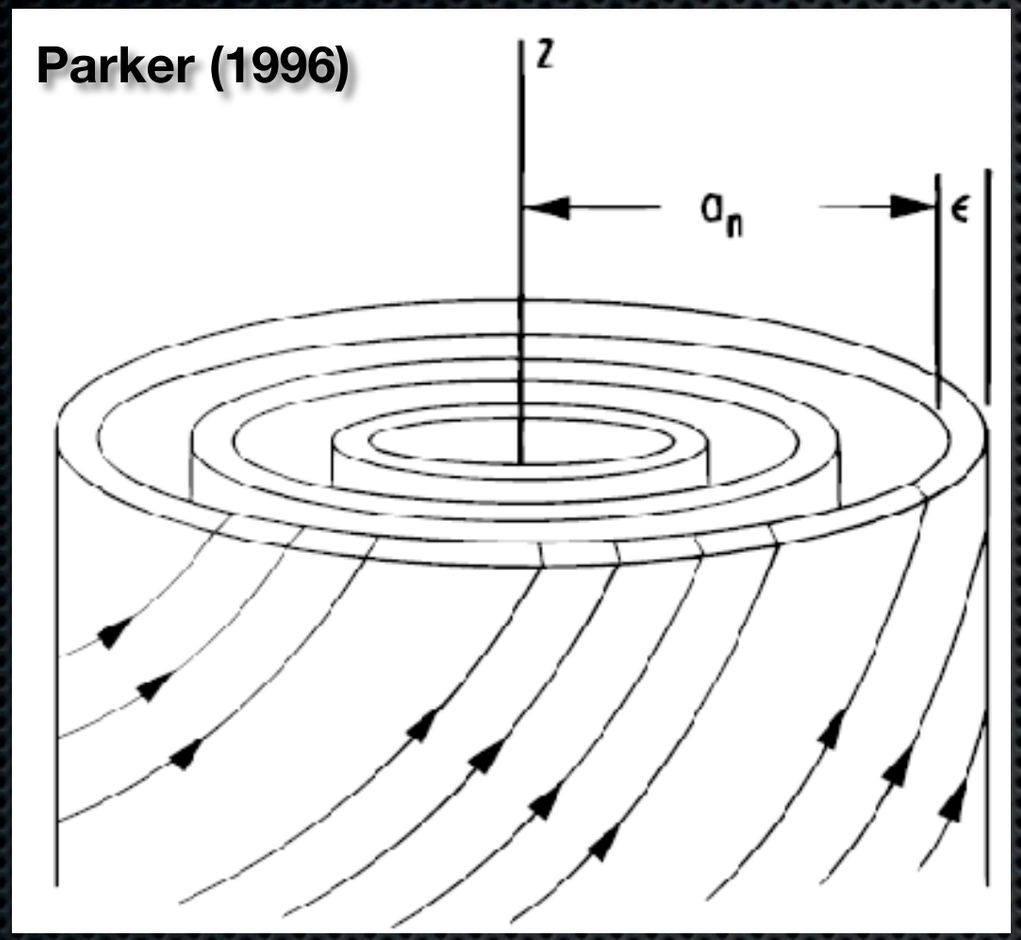

$$\nabla \times \bar{B} = \frac{4\pi}{c} \bar{J}$$

Observationally inferred photospheric density:

$$J_z = \frac{c}{4\pi}\left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right)$$

"... the curl of the transverse magnetogram of magnetic fields composed of unresolved separate fibrils bears no direct relation to the mean longitudinal electric current density. The mean current density is essentially zero." (Parker, 1996)

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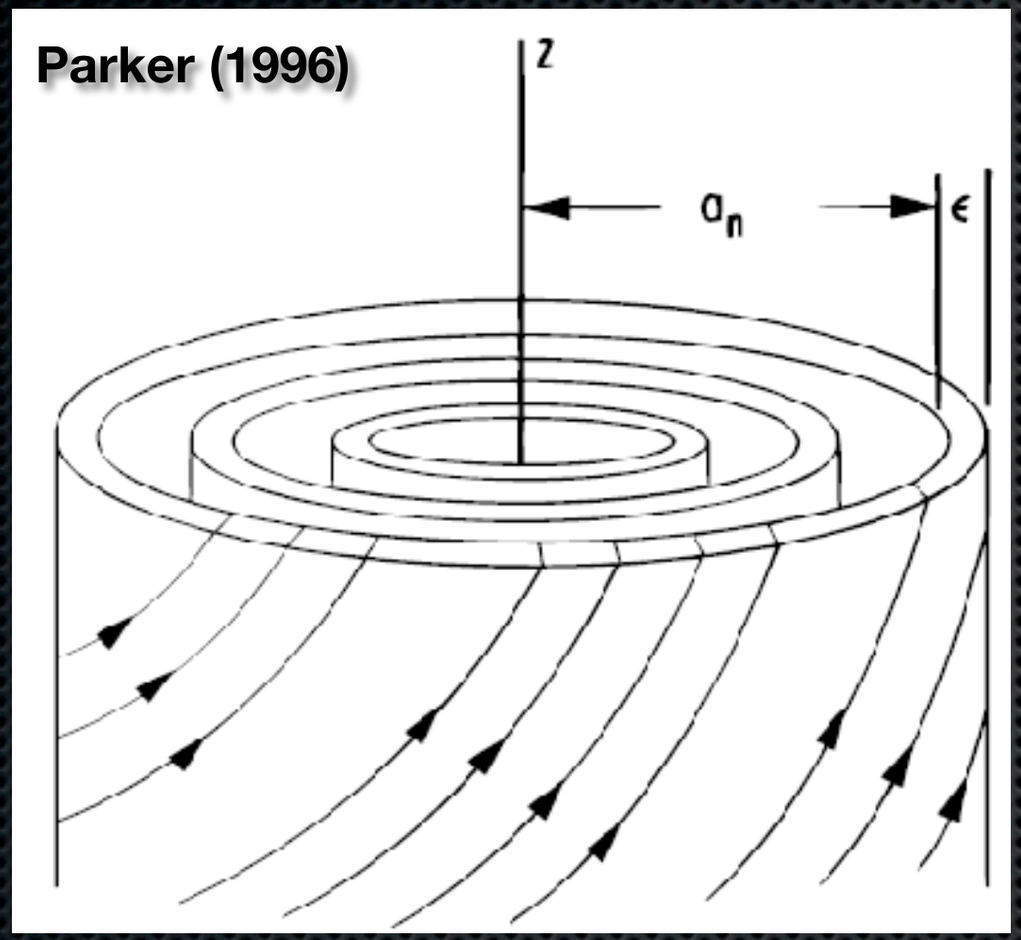

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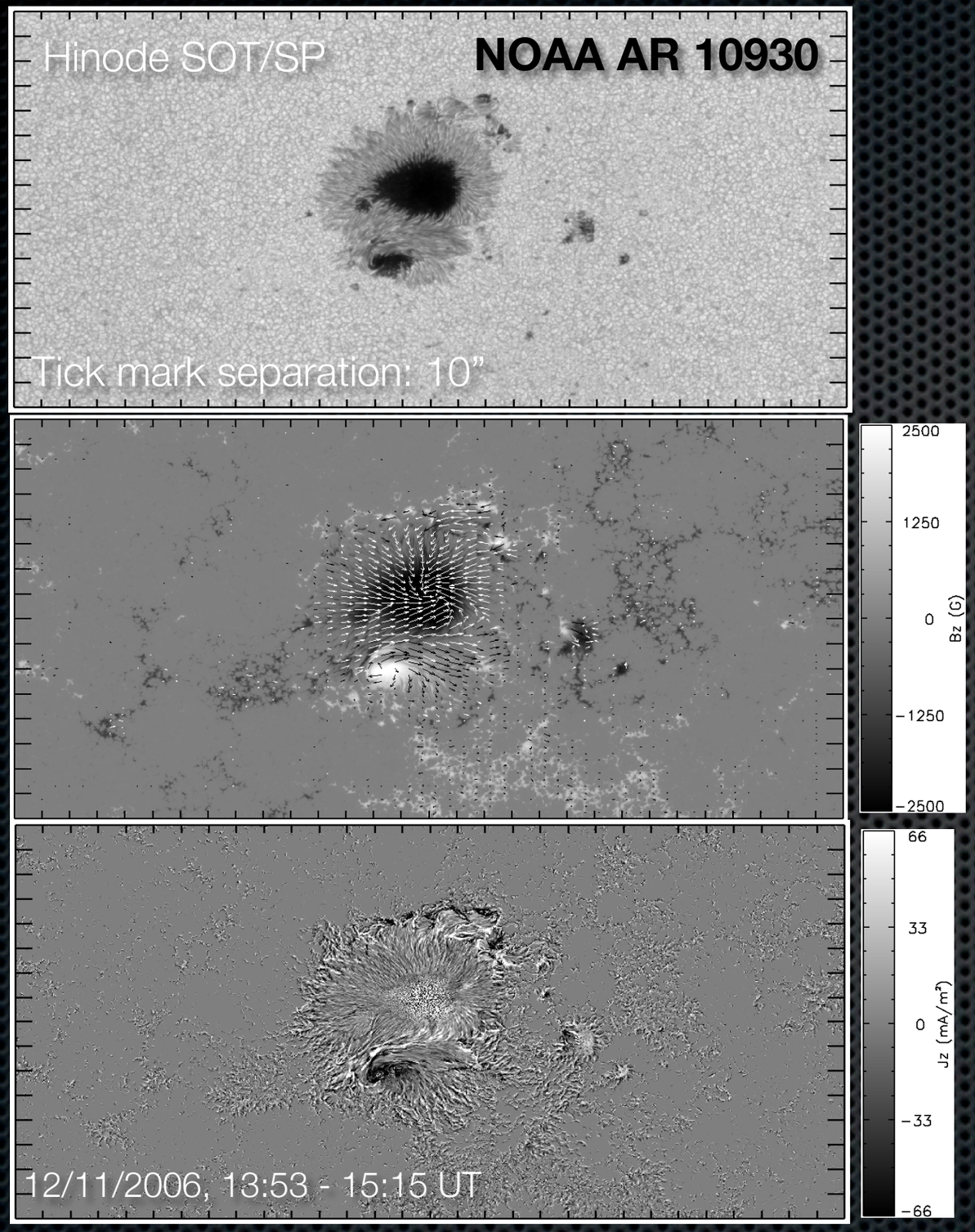
Notice, however, that Parker refers to isolated magnetic flux tubes

THE SITUATION ALONG PILs: ERUPTIVE AR

Georgoulis, et al. (2012a)



Continuum Intensity

Vector magnetogram

Vertical electric current density

Pixel size: 0.1585”
Sigma (LOS): 2.4 Mx cm^{-2}
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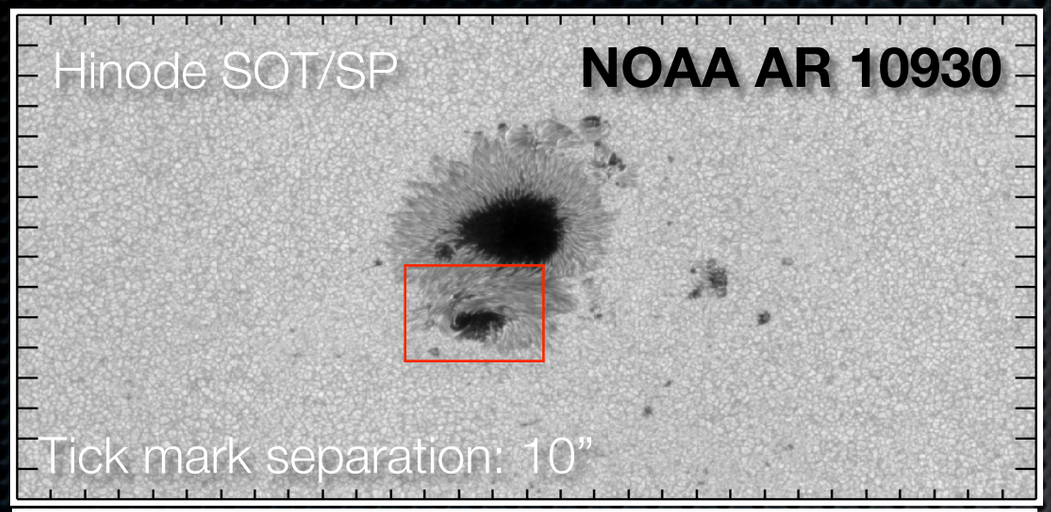

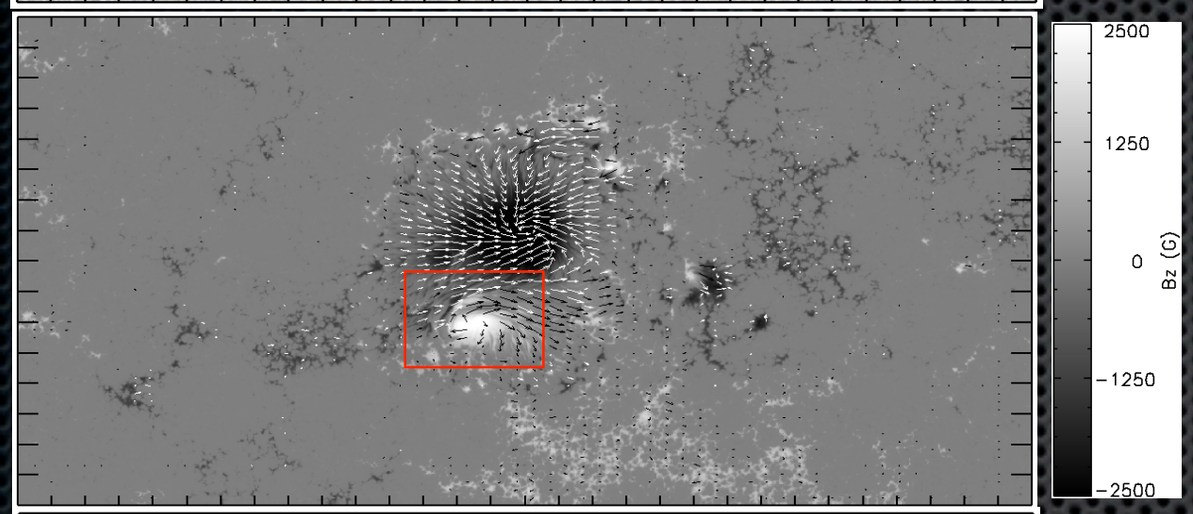

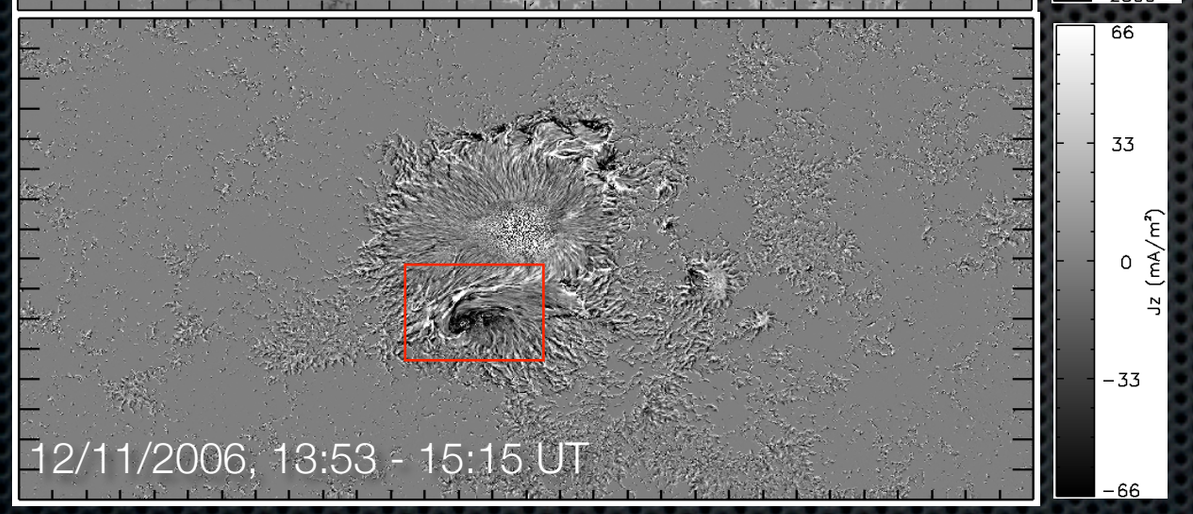

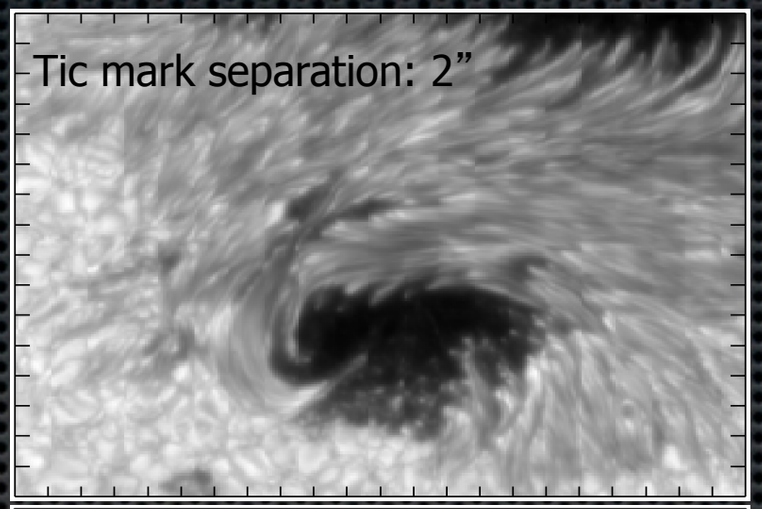

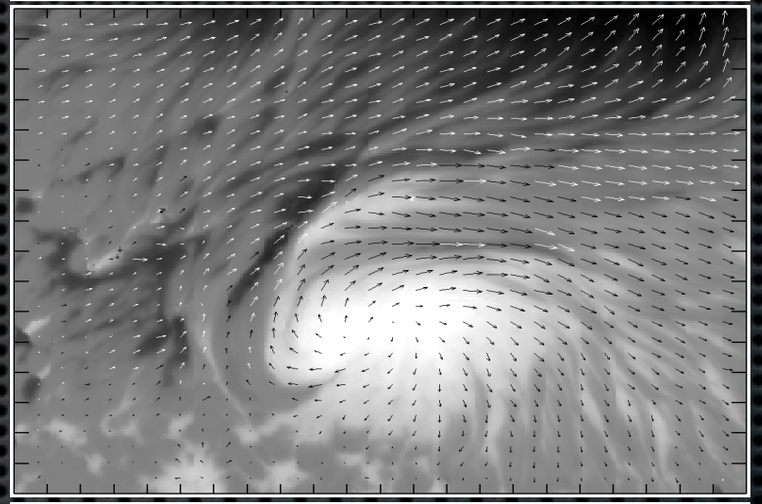

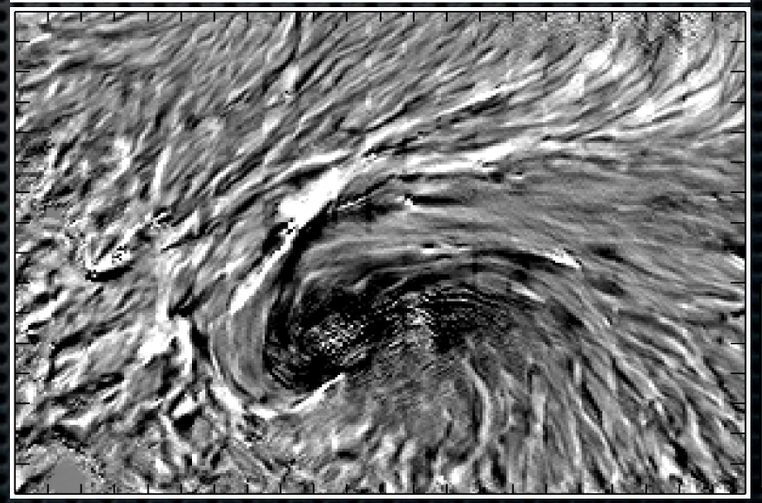

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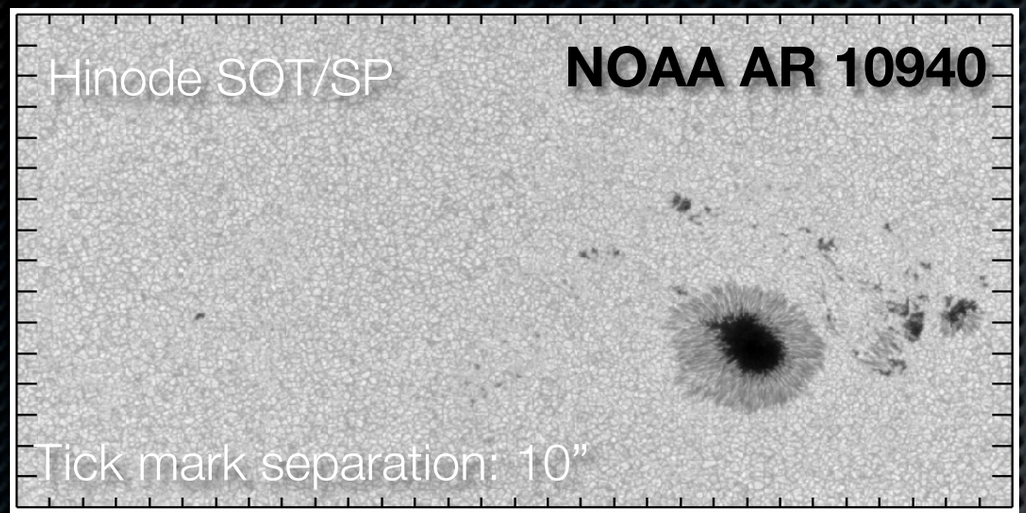

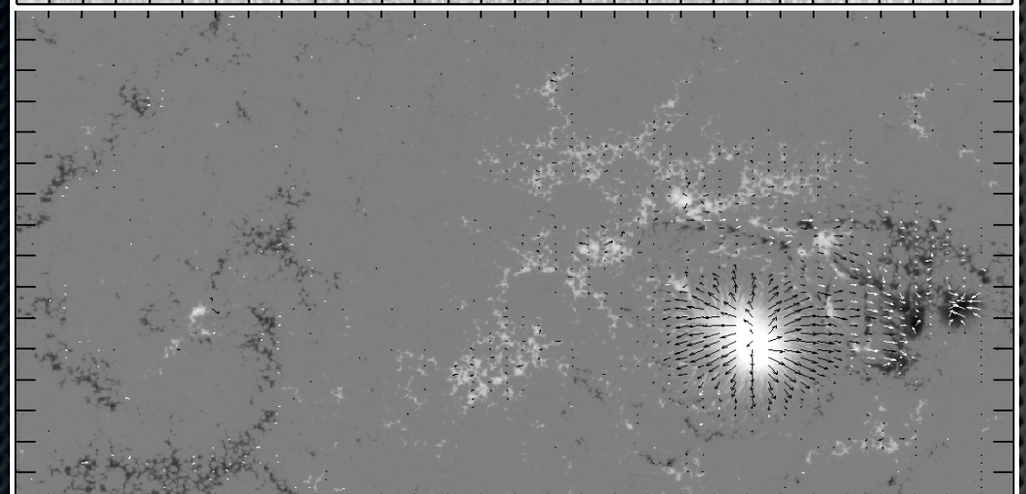

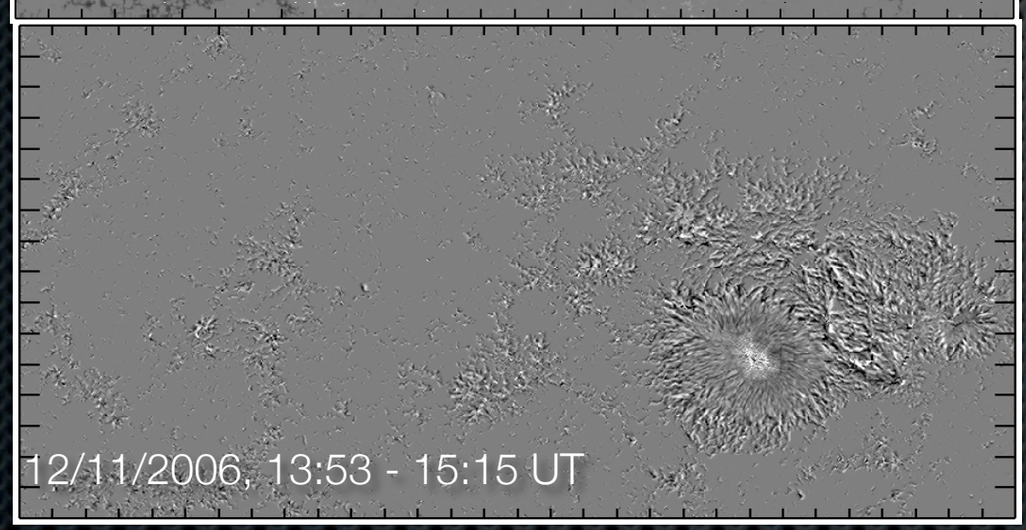

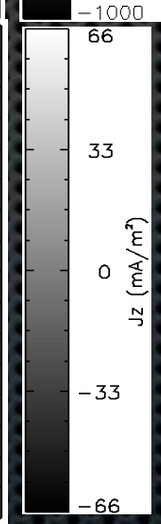

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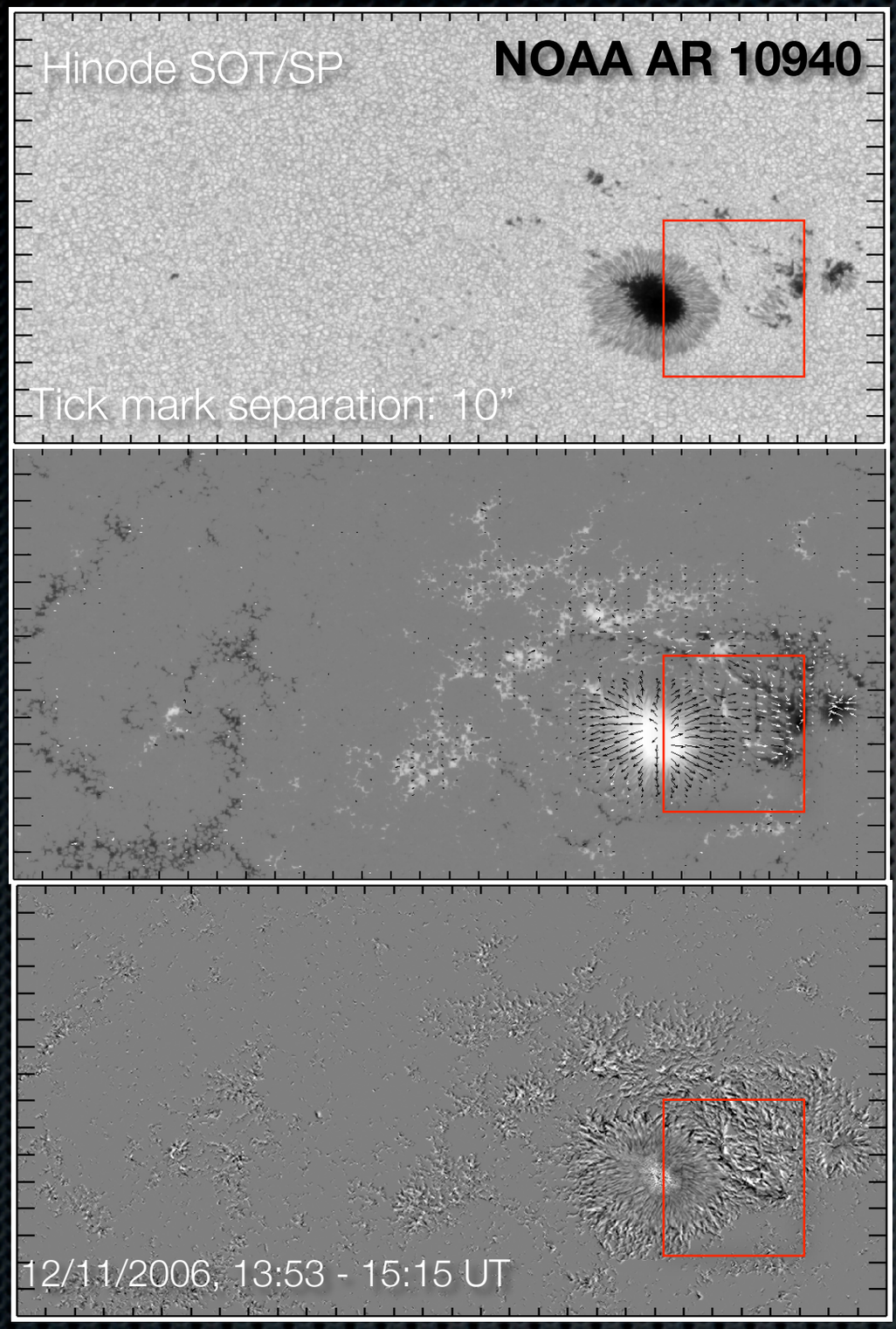

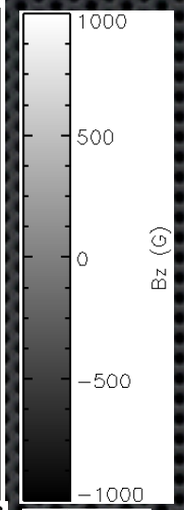

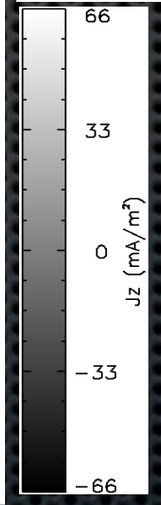

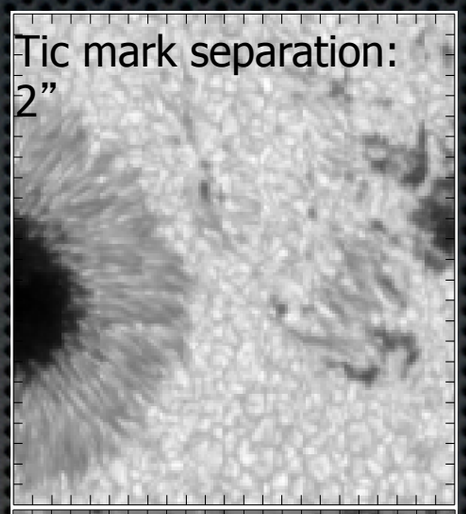

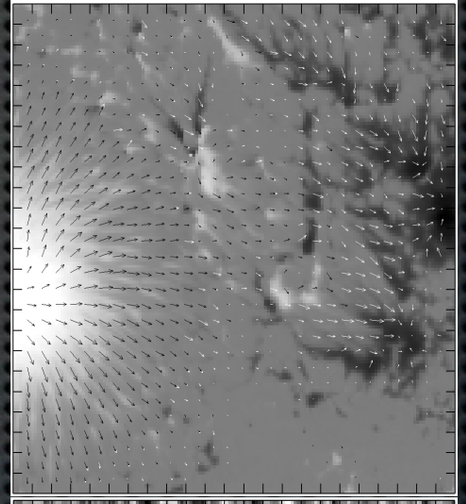

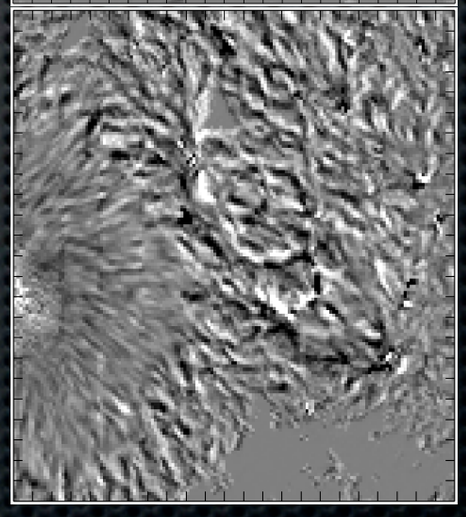

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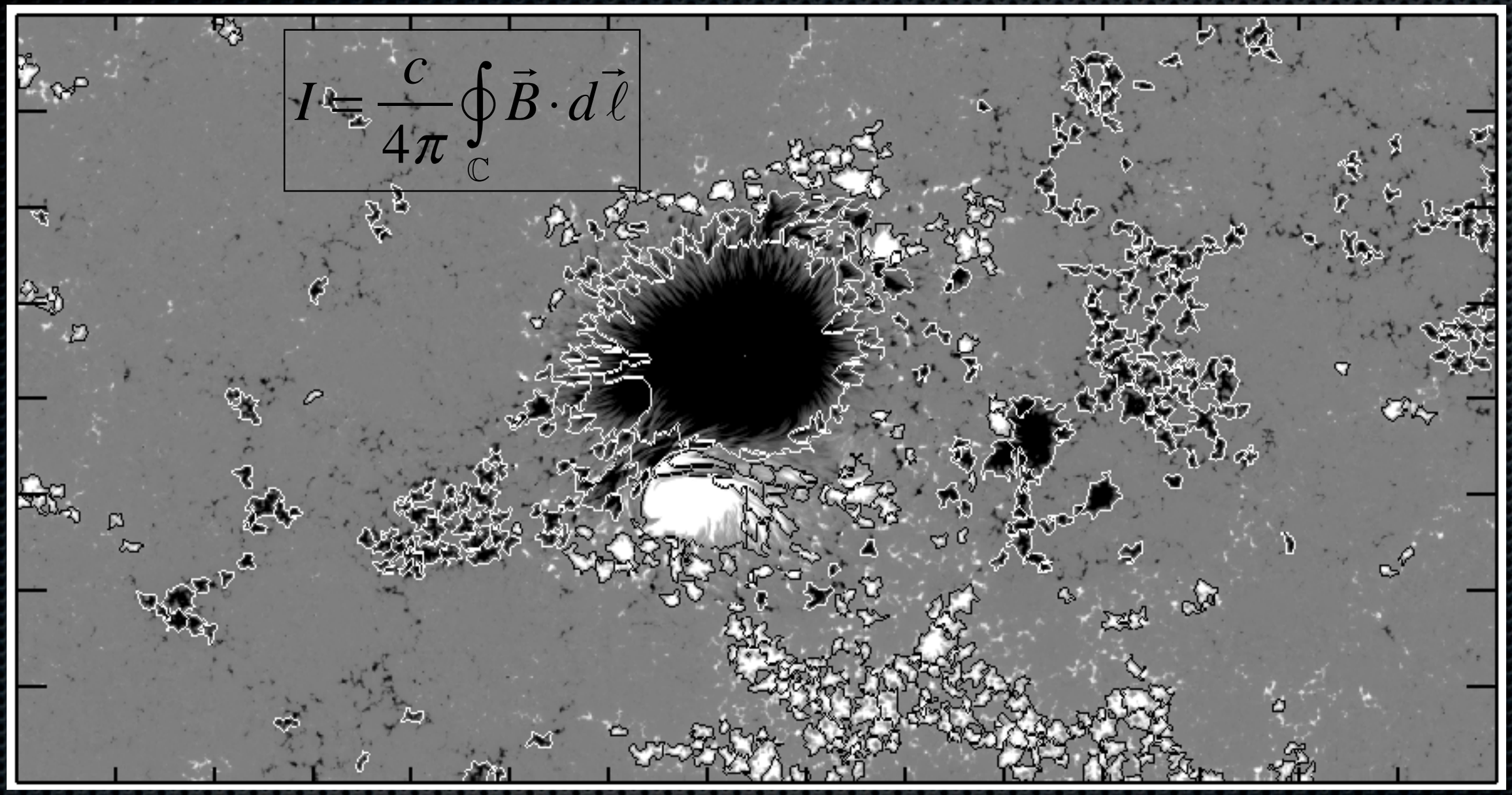
NON-NEUTRALIZED CURRENTS ALONG STRONG PILs

$$I = \frac{c}{4\pi} \oint_{\mathbb{C}} \vec{B} \cdot d\vec{\ell}$$



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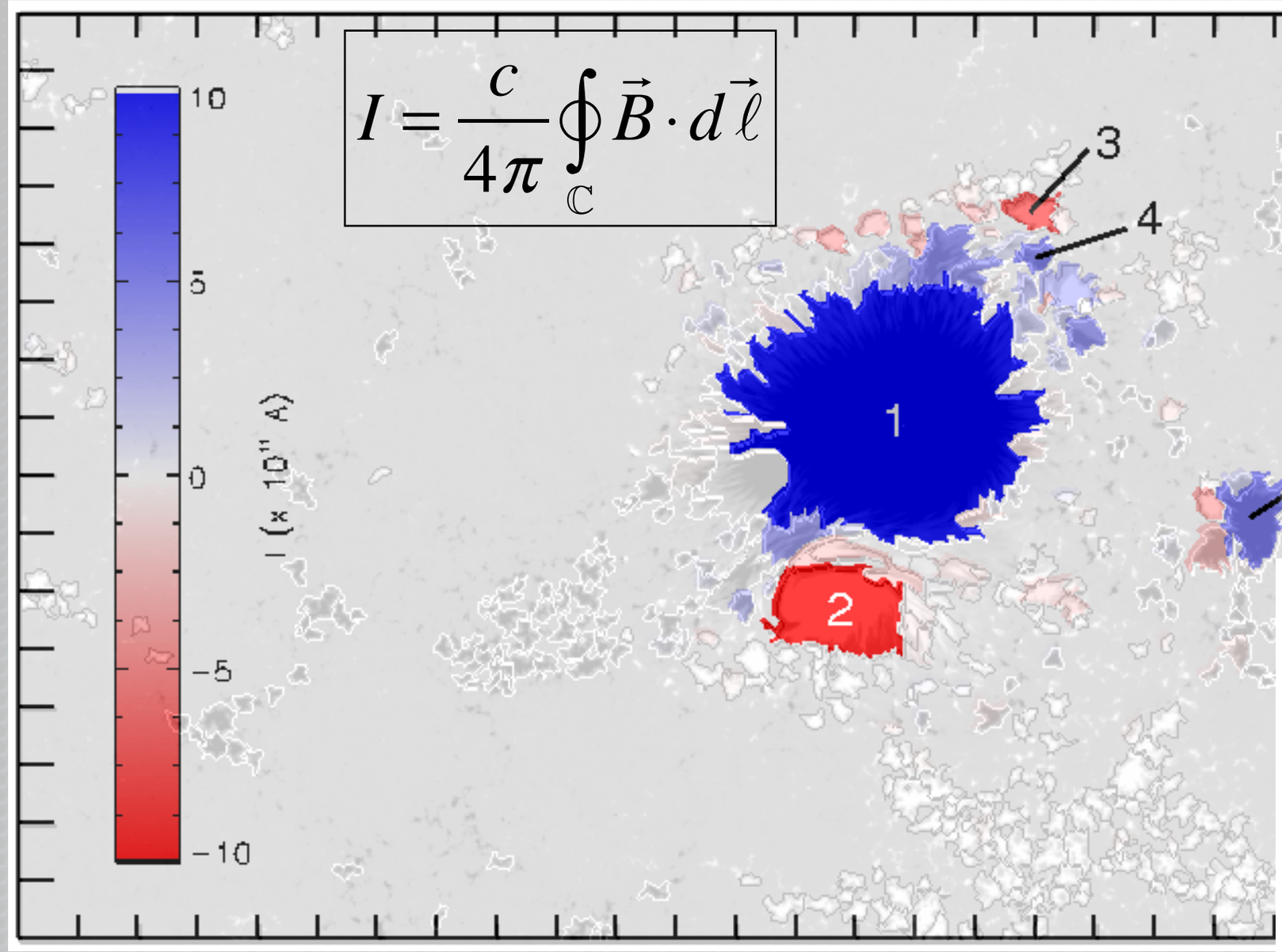
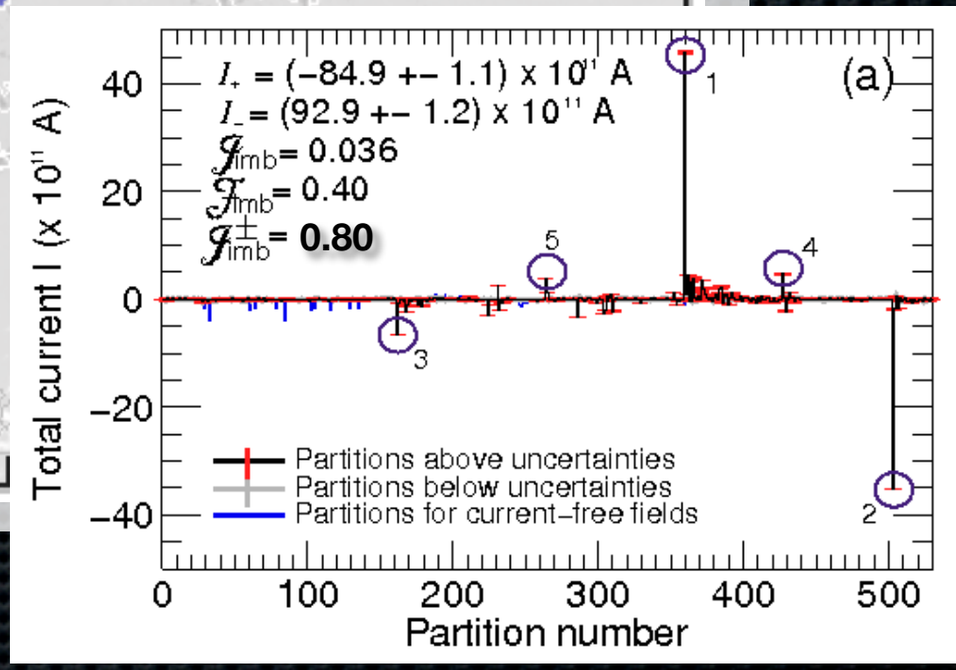
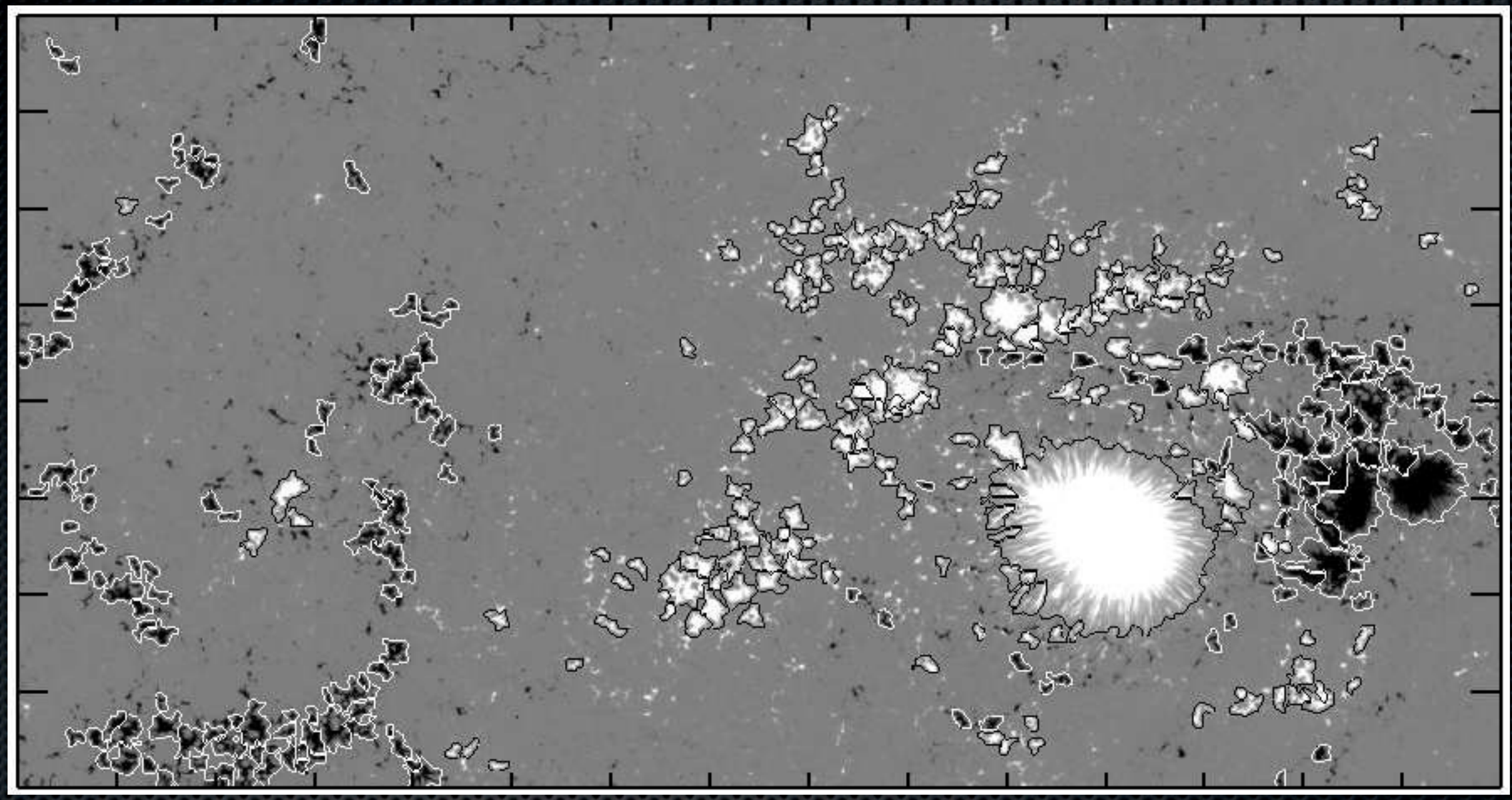




- Significant net currents <u>exclusively</u> along PILs
- Overall, AR current neutralized (~3.6%)
- Large consistency of sense of currents per polarity (~80%)

WEAK NON-NEUTRALIZED CURRENTS, IF ANY, IN WEAK PILs



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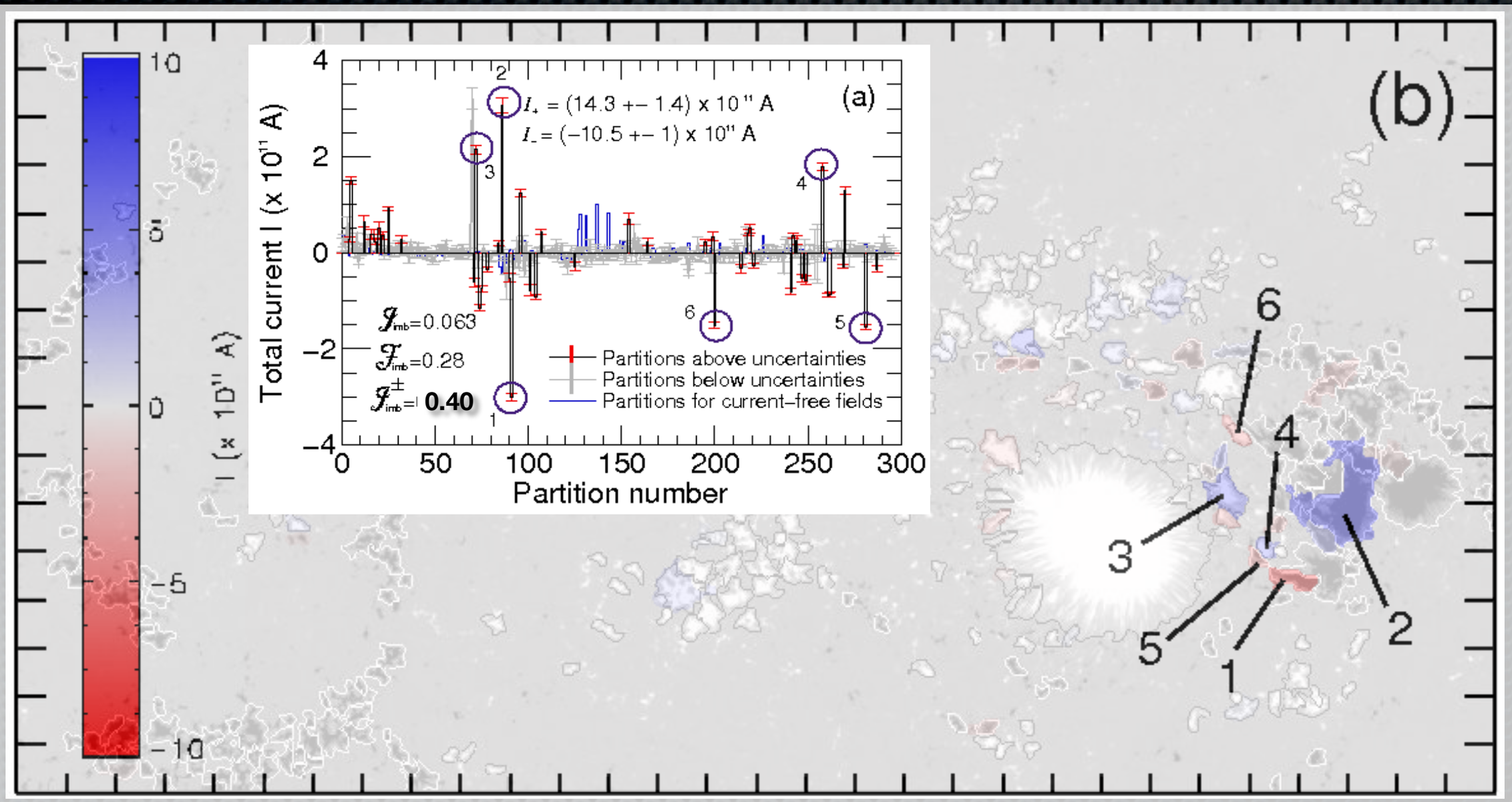
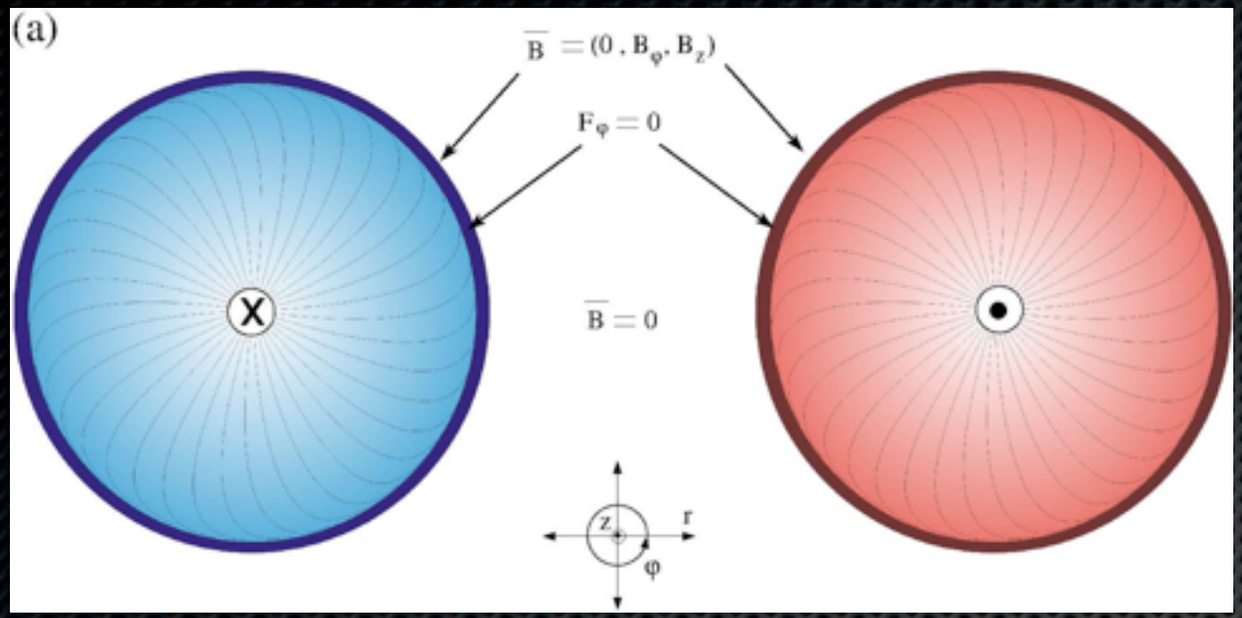


- Much smaller net currents, also <u>exclusively</u> along PILs
- Overall, AR current neutralized (~6.3%)
- Much more inconsistent sense of currents per polarity (~40%)

INTERPRETATION: LORENTZ FORCE ALONG PILs



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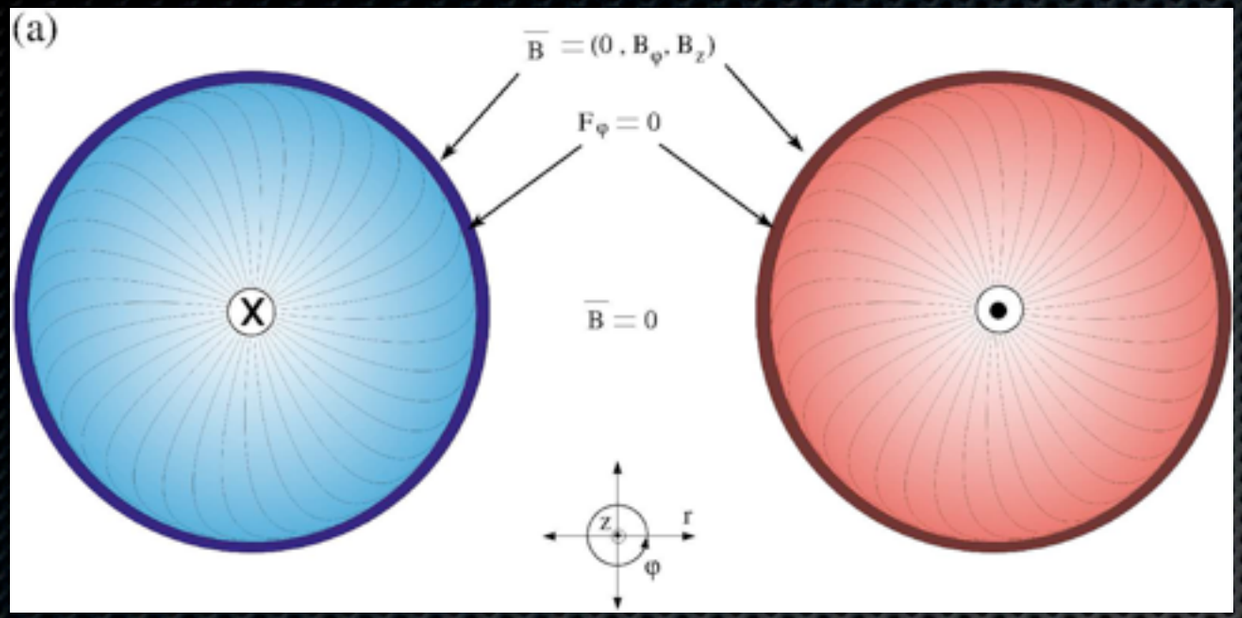
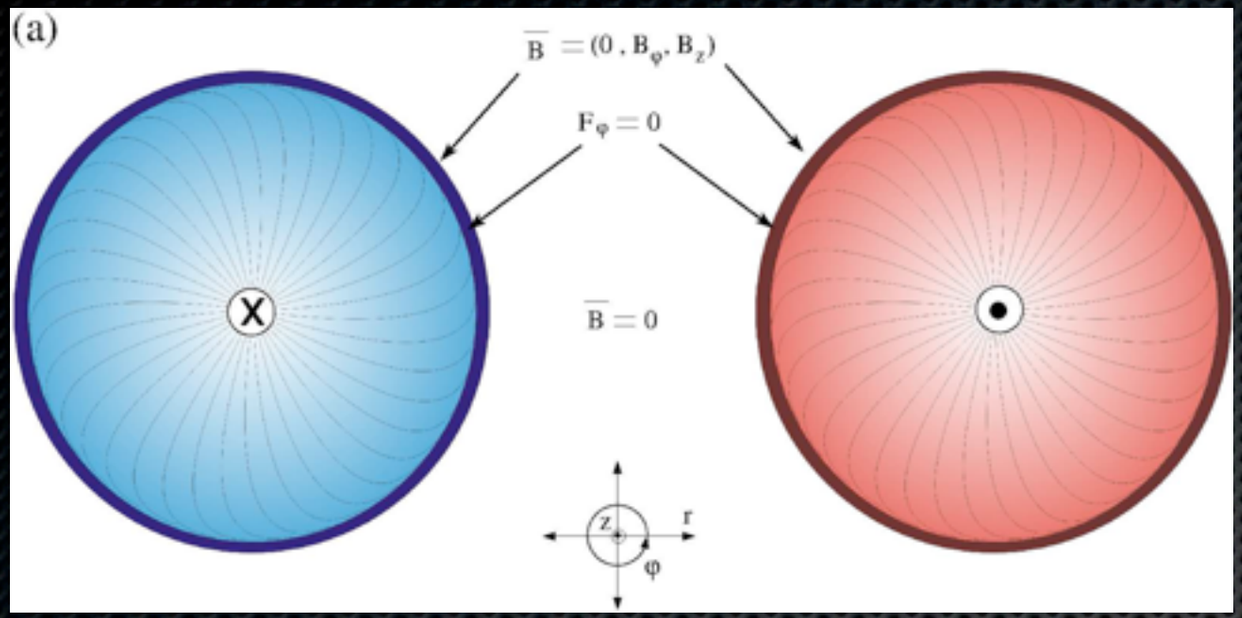


- Azimuthal Lorentz force on edges of flux tube footprints embedded in field-free space:

$$F_\varphi \approx \frac{B_n}{4\pi}\left(-\frac{1}{r}\frac{\partial B_n}{\partial \varphi} + \frac{\partial B_\varphi}{\partial n}\right)$$

(tension component)

INTERPRETATION: LORENTZ FORCE ALONG PILs



- Azimuthal Lorentz force on edges of flux tube footprints embedded in field-free space:

$$F_\varphi \approx \frac{B_n}{4\pi}\left(-\frac{1}{r}\frac{\partial B_n}{\partial \varphi}+\frac{\partial B_\varphi}{\partial n}\right)$$

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- In case of non-interacting, distant footprints:

$$|B_n| \to 0;\ \partial/\partial\varphi \to 0 \Rightarrow F_\varphi \approx 0$$

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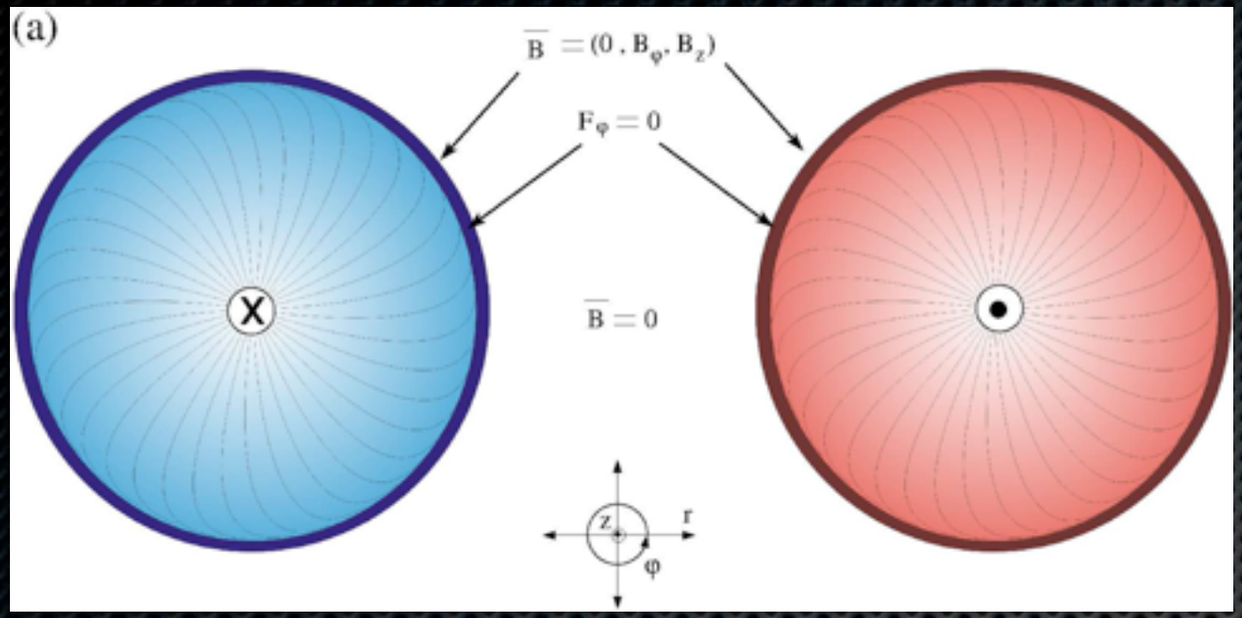

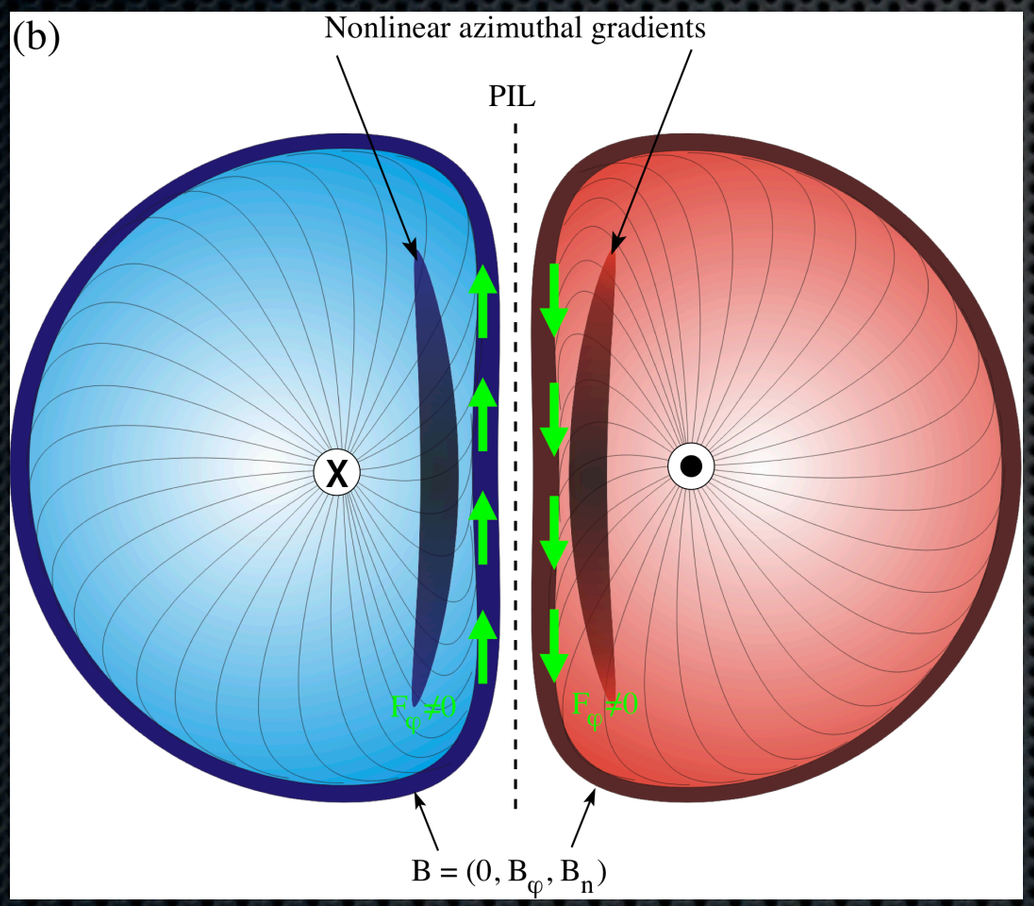

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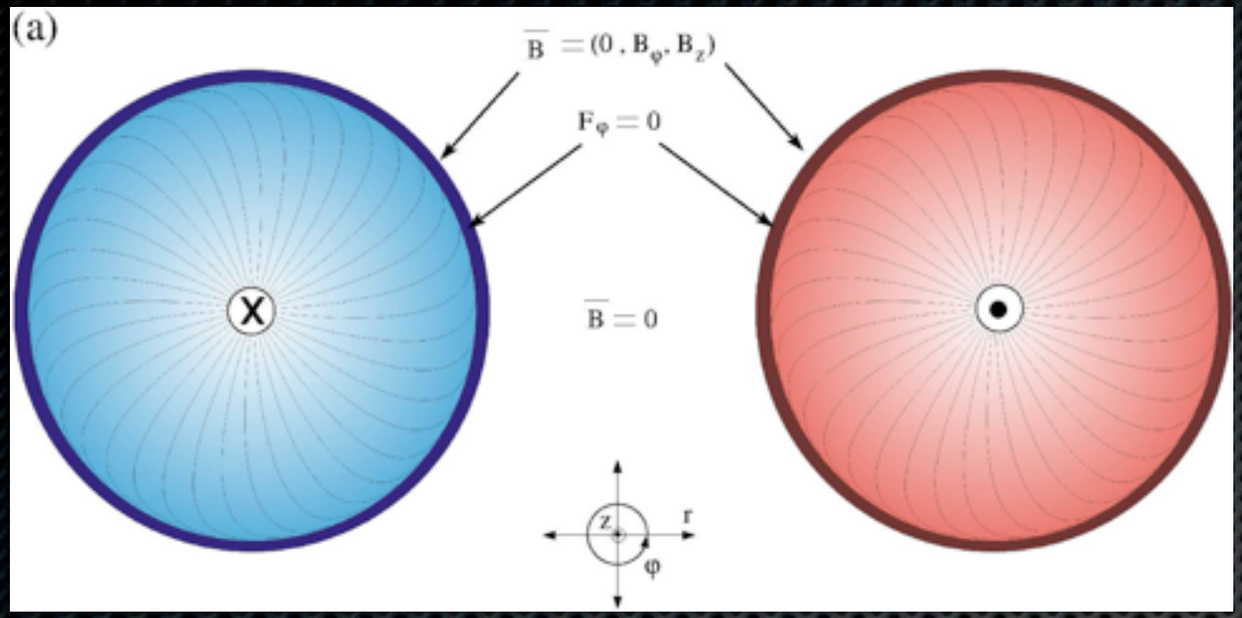

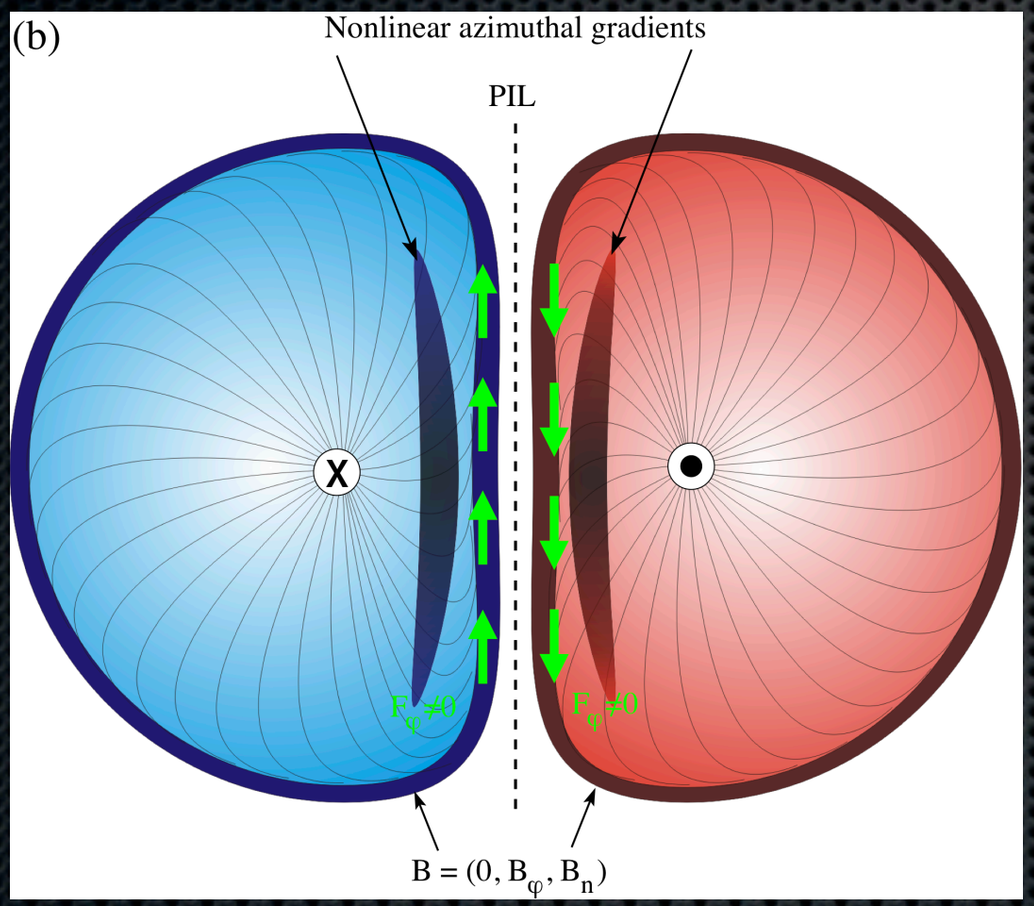

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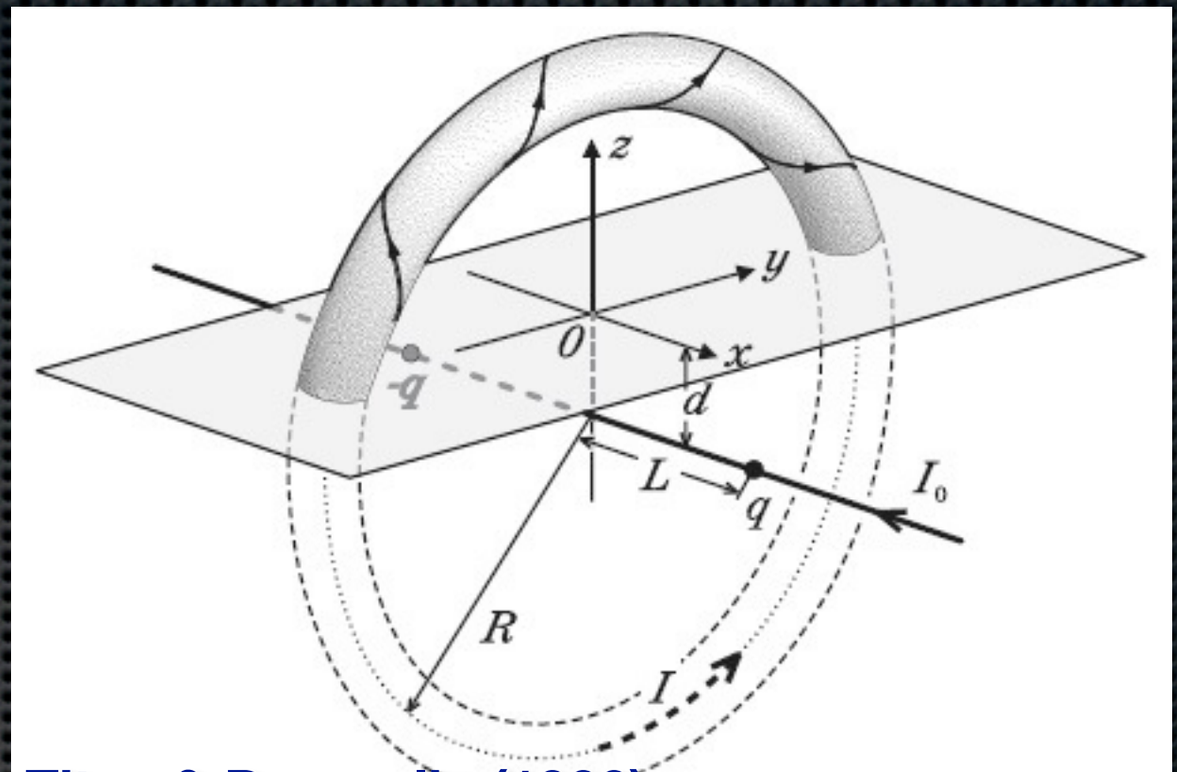
Lorentz force appears along strong PILs when the interacting magnetic polarities deform as a result of this interaction. Apparently it causes consistent shearing

IS LORENTZ FORCE CAPABLE OF MOVING THE PLASMA?

--> Magnetic field lines are thought to be anchored deep in the dense, fluid-dominated photosphere



Titov & Demoulin (1999)

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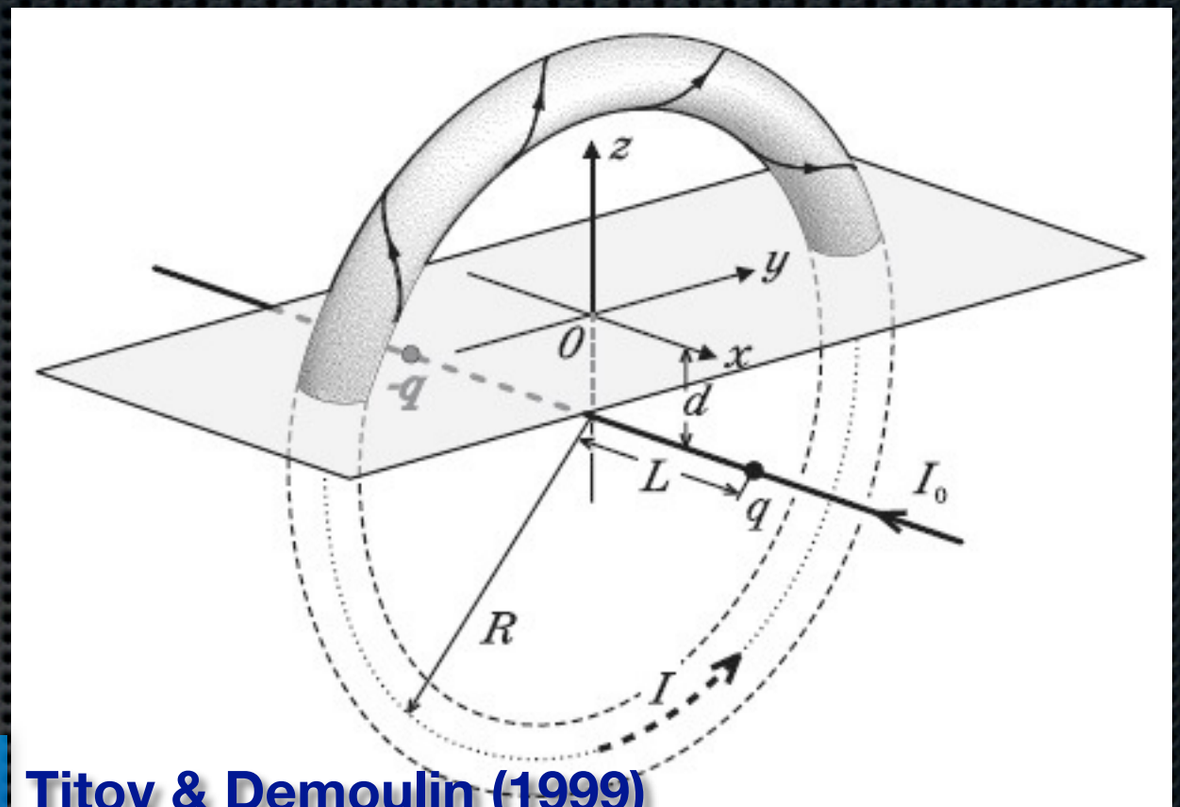

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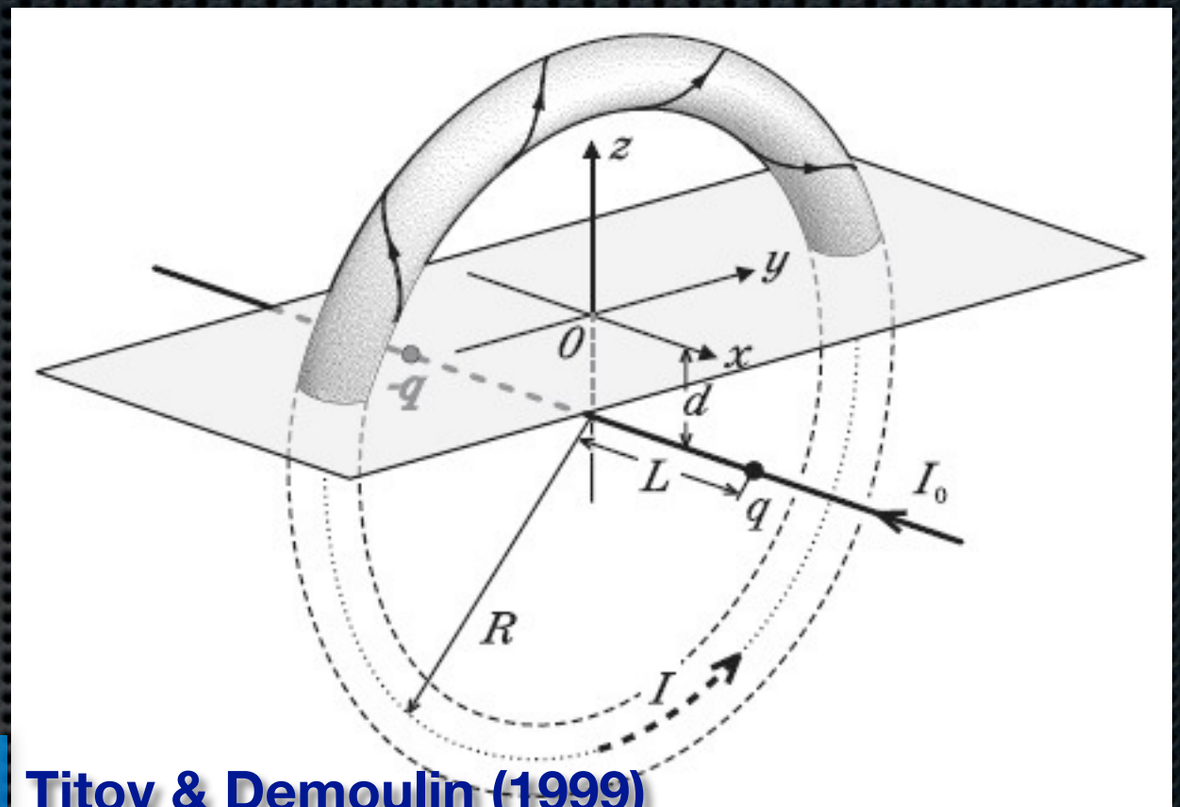

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--> Magnetic-field equipartition value:

$$\frac{B_{eq}^2}{8\pi} = \frac{1}{2}\rho u^2 \Rightarrow B_{eq} \simeq 200\ G \quad \text{(kinetic)}$$

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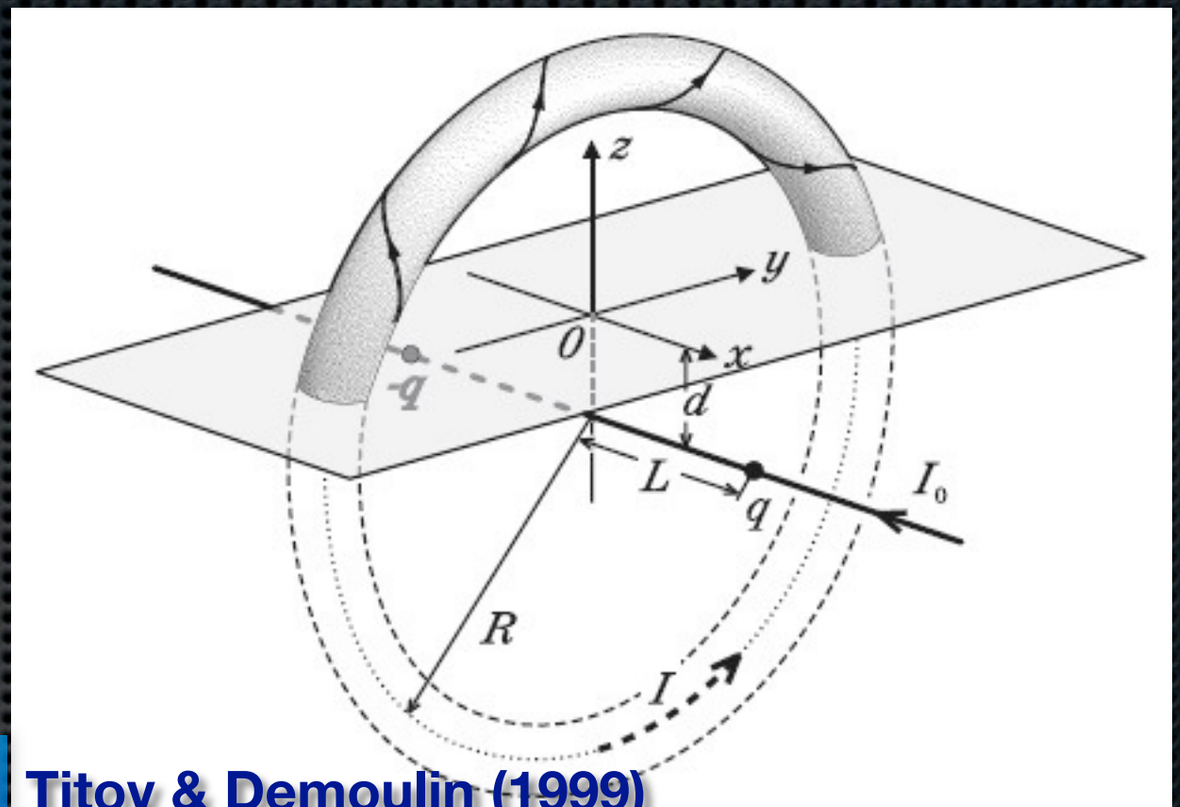

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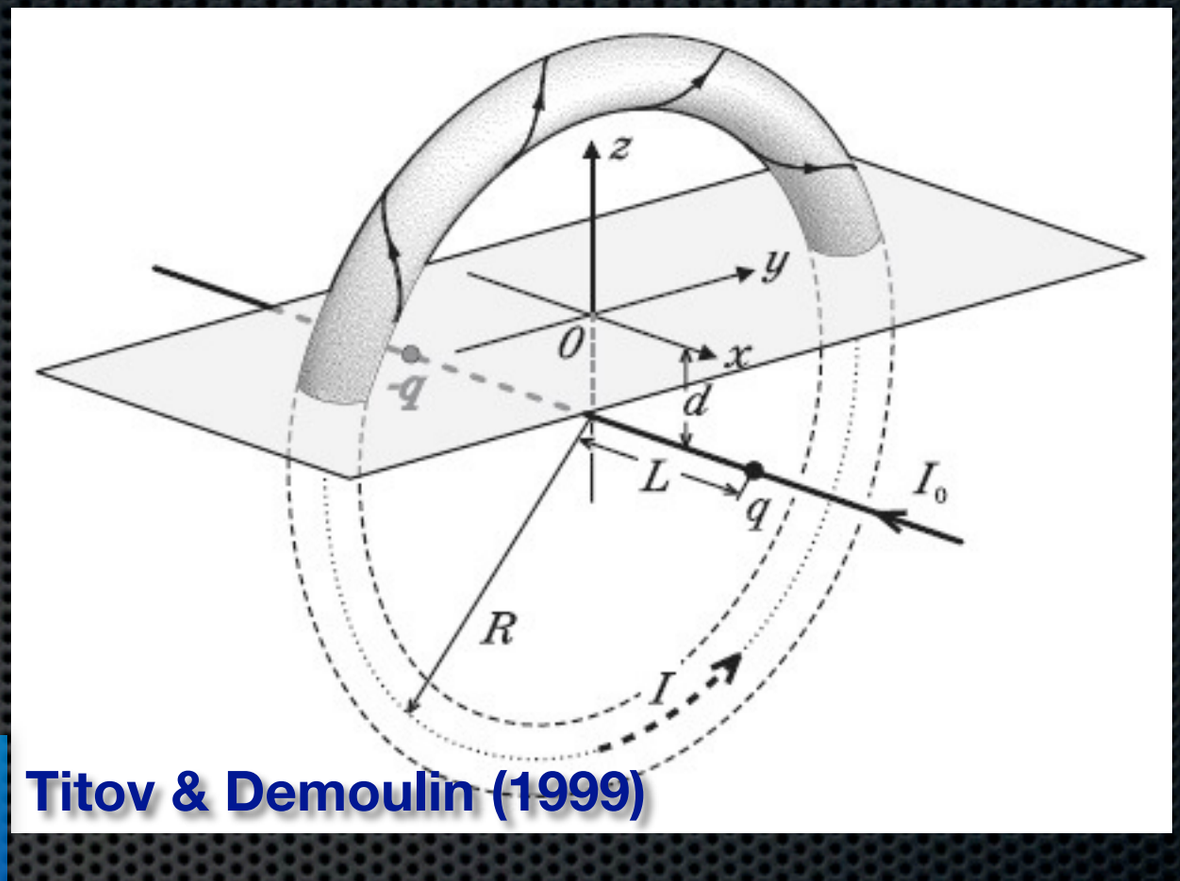

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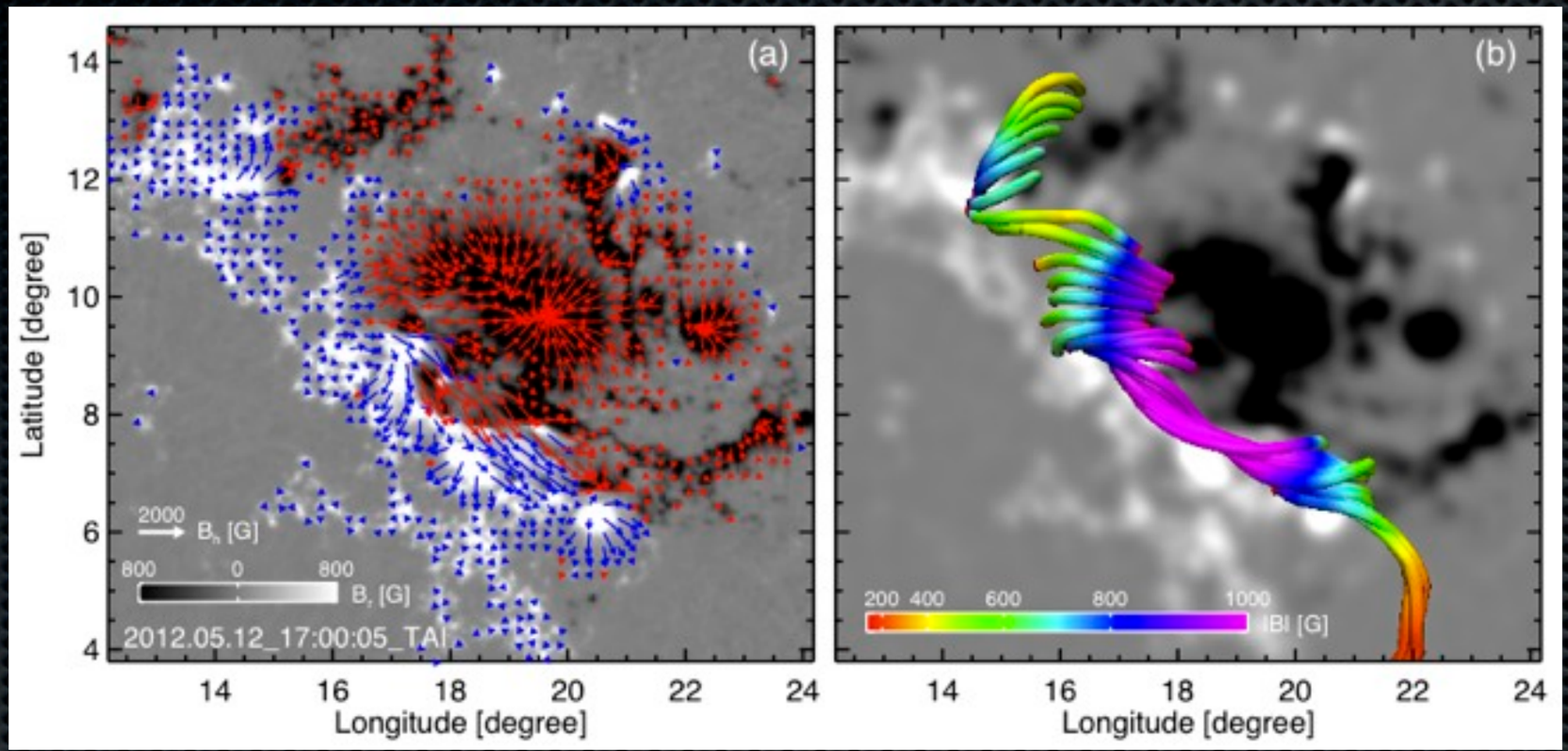
- In eruptive NOAA AR 10930 (strong shear flows), $B_{PIL} > 1500$ G in all cases.
- In non-eruptive NOAA AR 10940 (very weak shear flows, if any), B_{PIL} ranges from few hundred to < 1500 G

INTERPETATION OF IRREVERSIBILITY IN STRONG PILs

Courtesy: X. Sun



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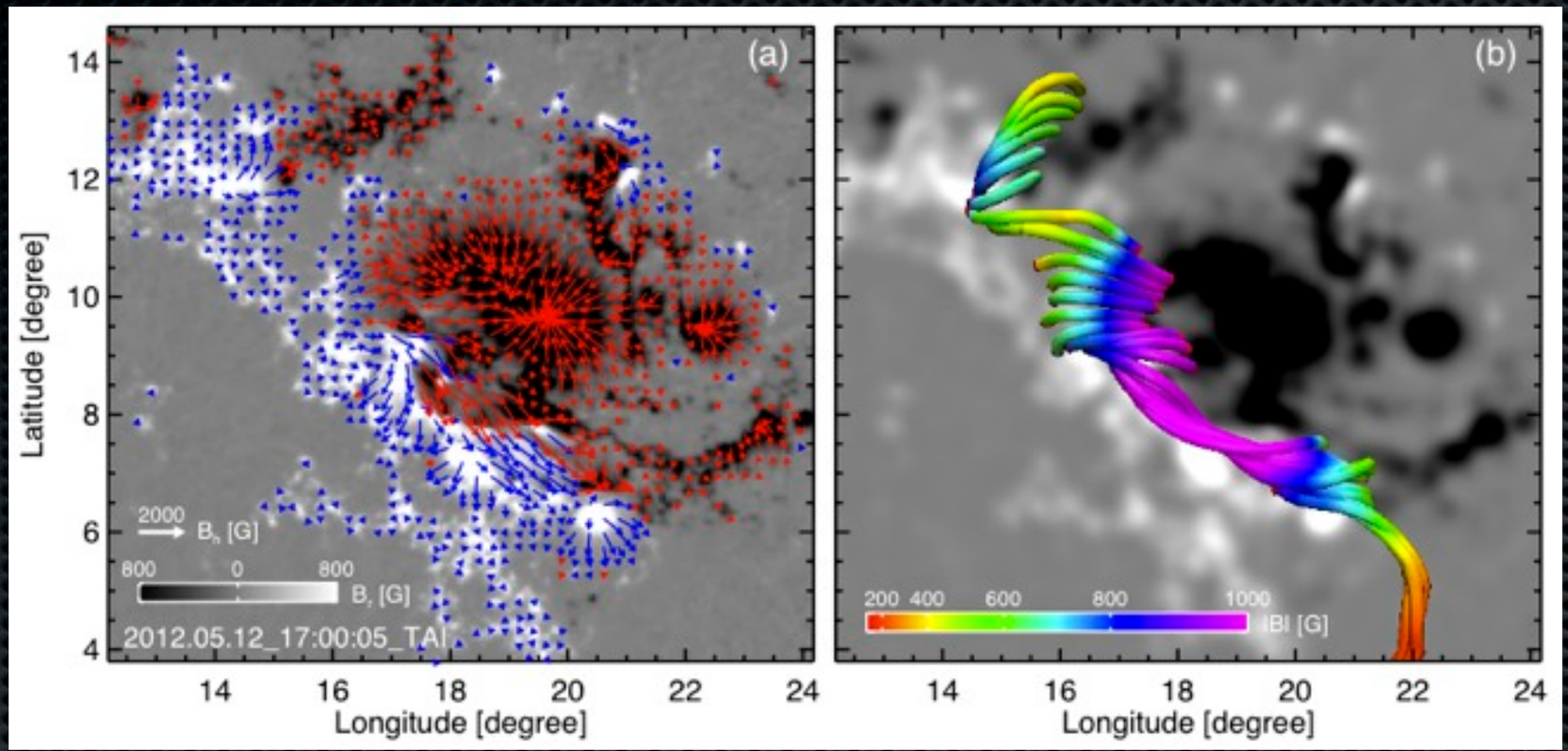

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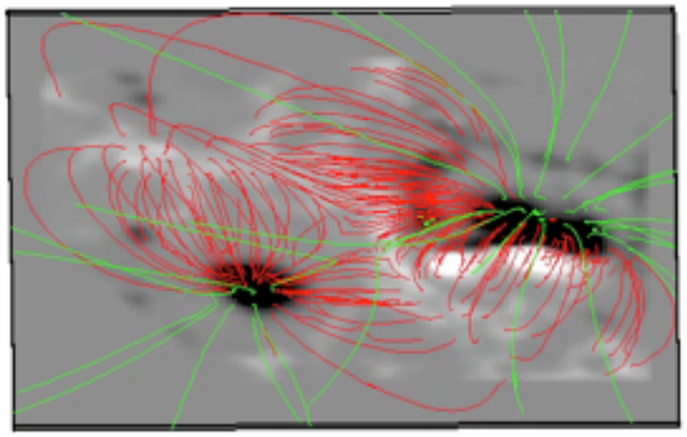
- For a consistent sense of twist in the structure (strong coherence), the action of shear is additive and will continue to stress the system for as long as the sunspots interact

INCREASING FREE MAGNETIC ENERGY



- Photospheric field of ARs is known - coronal field above is unknown and is estimated by MS magnetic field extrapolation (∂/∂t ~0) or MHD modeling
- In the simplest case (extrapolation) we assume that the plasma-β parameter is zero:

$$\beta \equiv \frac{nkT}{B^2/(8\pi)} \rightarrow 0$$

- Then the predominant energy budget is the magnetic-energy budget:

$$\frac{1}{8\pi}\int_V B^2 dV = \frac{1}{8\pi}\int_V B_p^2 dV + \frac{1}{8\pi}\int_V B_c^2 dV$$

Total **Current-free** **Free (available for release)**

-- **B** --> overall magnetic field
-- $\mathbf{B_p}$ --> current-free (potential) field
-- $\mathbf{B_c}$ --> current-carrying field

- The Sun needs to dissipate "free" magnetic energy accumulated due to electric currents:

$$E_c = \frac{1}{8\pi}\int_V B_c^2 dV = \frac{1}{8\pi}\int_V \bar{A}_c \cdot \bar{J}\ dV$$

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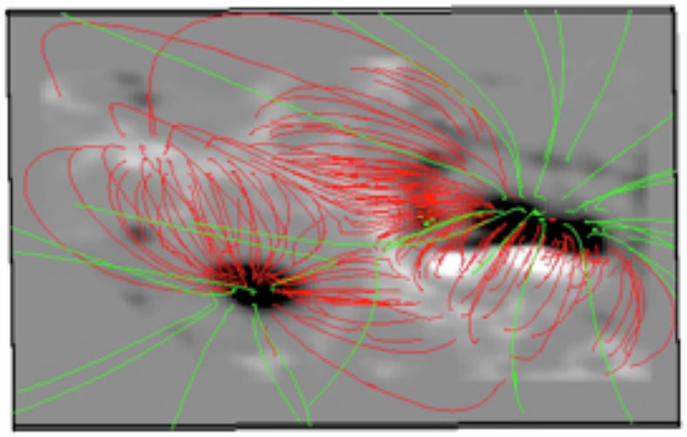

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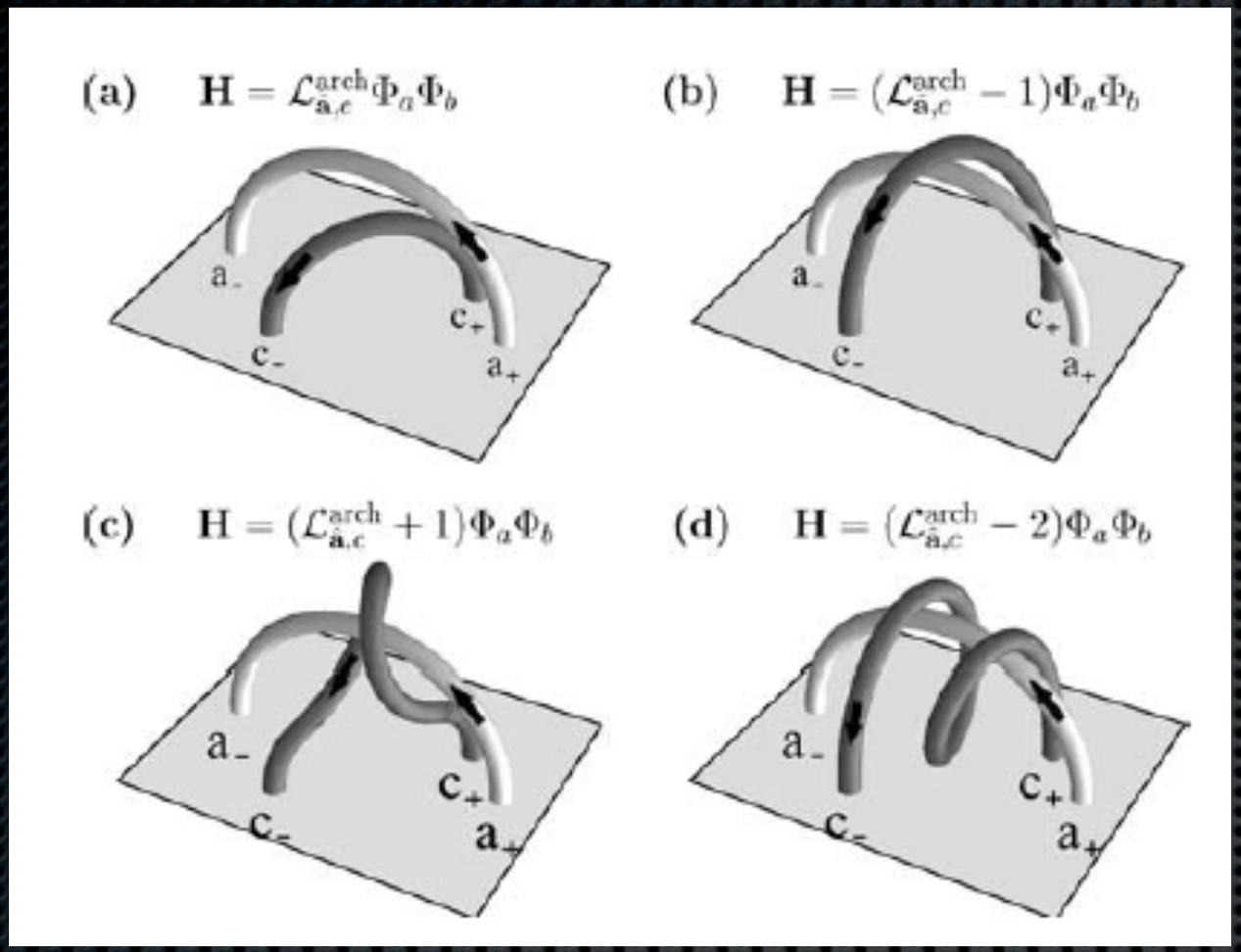
Free magnetic energy increases, but continuously dissipates via magnetic reconnection

MAGNETIC HELICITY ALSO ACCUMULATES

Magnetic helicity: a measure of the twist, shear, and linkage in a magnetic configuration



Demoulin et al. (2006)

- Relative magnetic helicity in a volume V above the lower-boundary plane

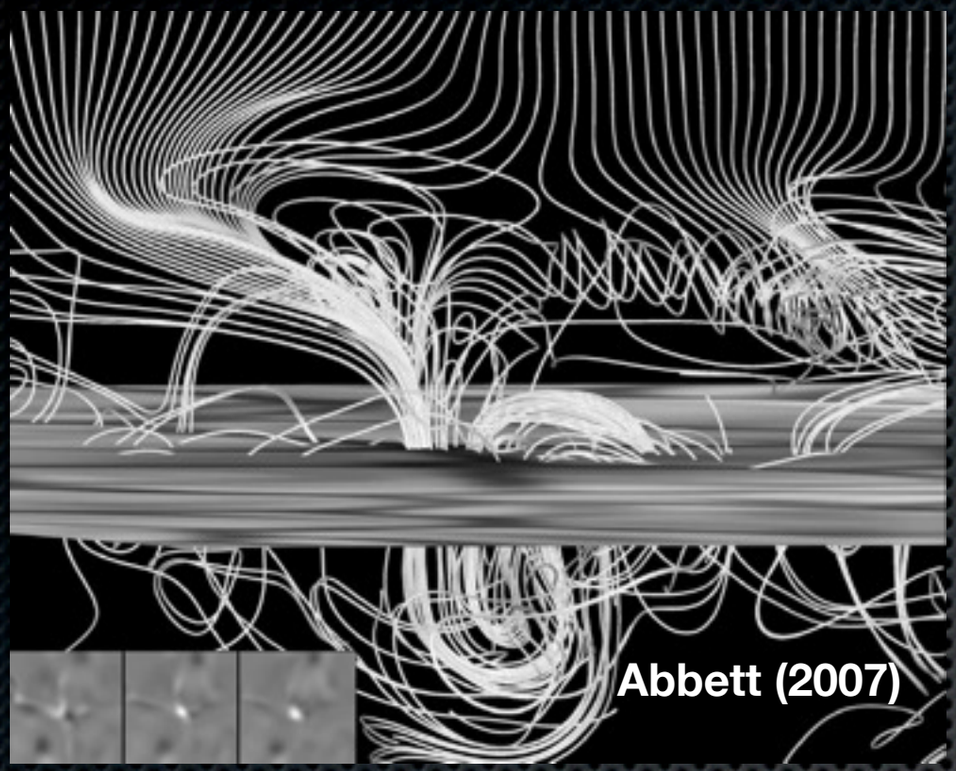
$$H_m = \int_V \left(\overline{A} + \overline{A}_p\right) \cdot \left(\overline{B} - \overline{B}_p\right)\, dV$$

- Per the used gauges

$$H_m = \int_V \overline{A} \cdot \overline{B}\, dV$$

Helicity is a signed quantity; left or right-handed. For a consistent shear resulting from a consistent twist, however, helicity accumulation is also a generally additive effect

WE'VE COME A LONG WAY TO APPRECIATE HELICITY



TRACE 195 Å

$$H_m = \begin{bmatrix} H_{11} & H_{12} & \dots & \dots & \dots & H_{1j} & \dots & H_{1N} \\ H_{21} & H_{22} & \dots & \dots & \dots & H_{2j} & \dots & H_{2N} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ H_{i1} & H_{i2} & \dots & H_{ii} & \dots & H_{ij} & \dots & H_{iN} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & H_{jj} & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ H_{N1} & H_{N2} & \dots & \dots & \dots & H_{Nj} & \dots & H_{NN} \end{bmatrix}$$

Magnetic helicity can be thought of as a matrix, with diagonal (self) terms and non-diagonal (mutual) terms

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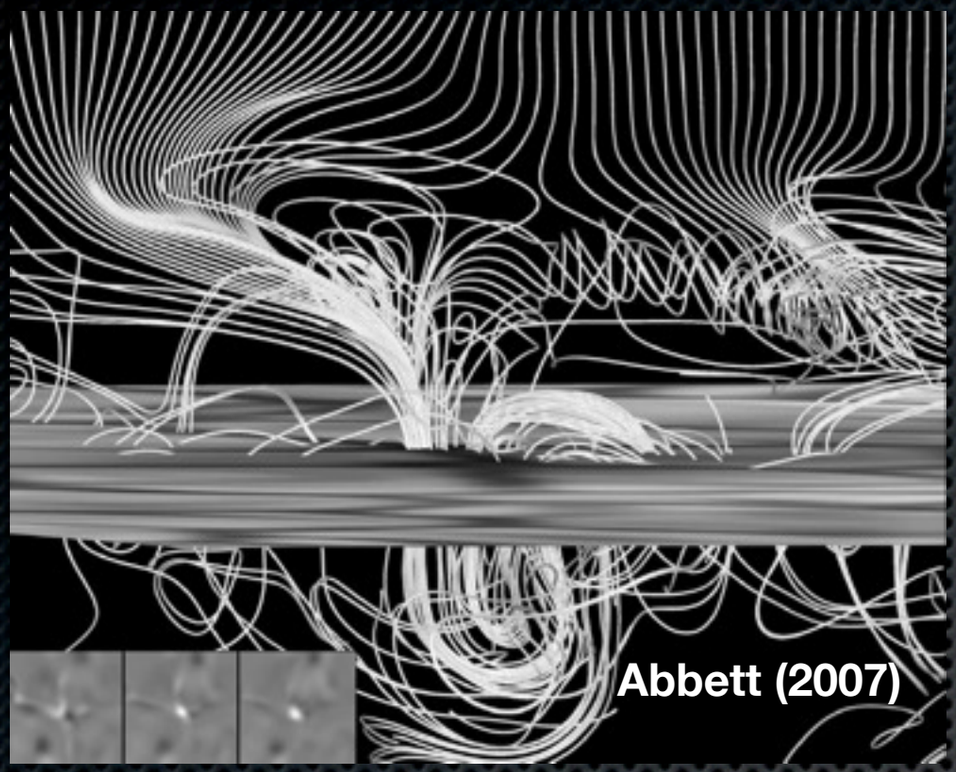

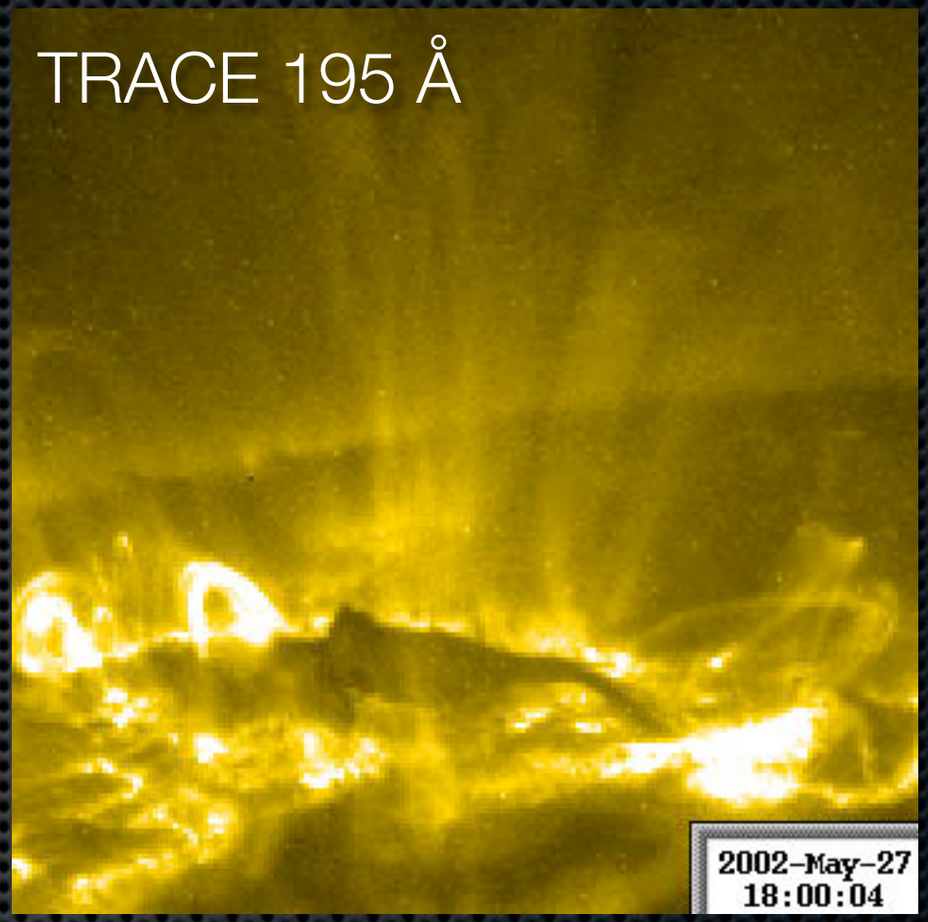

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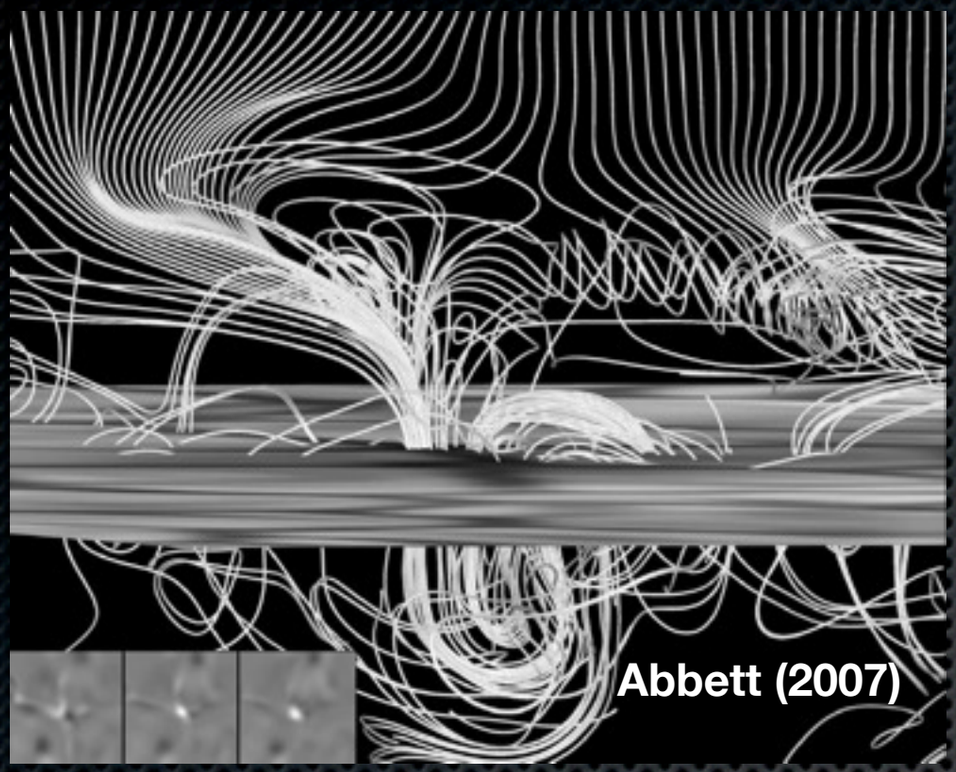

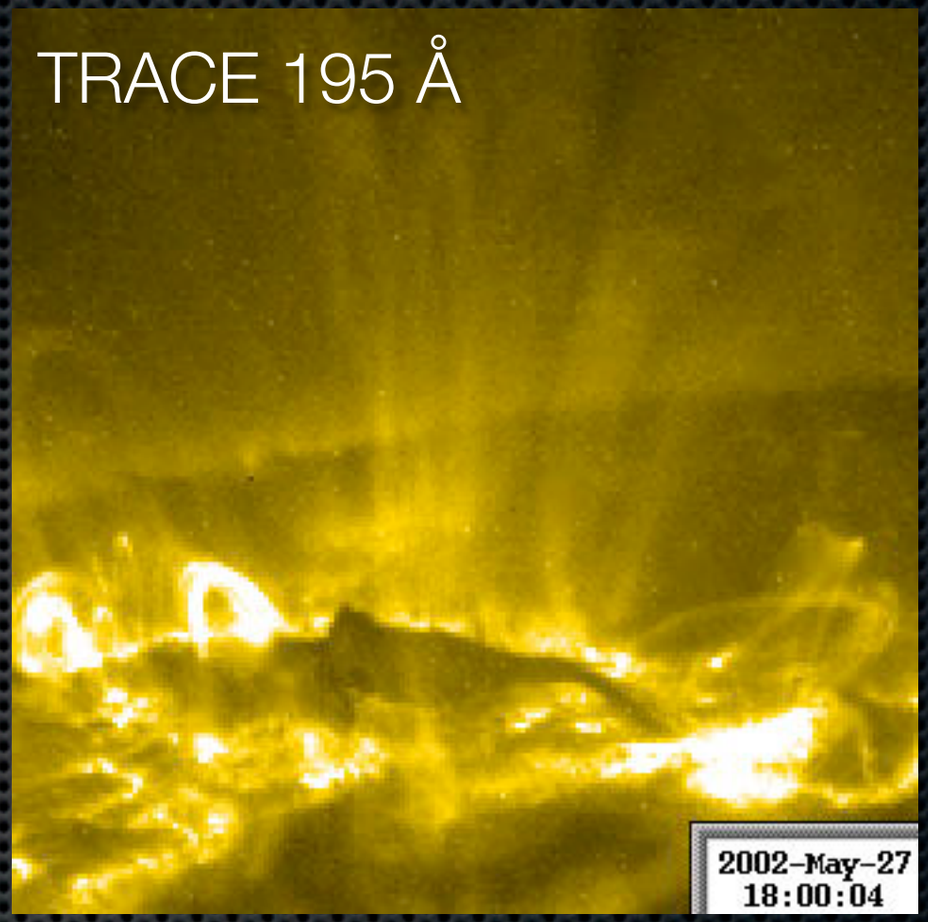

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Mutual terms

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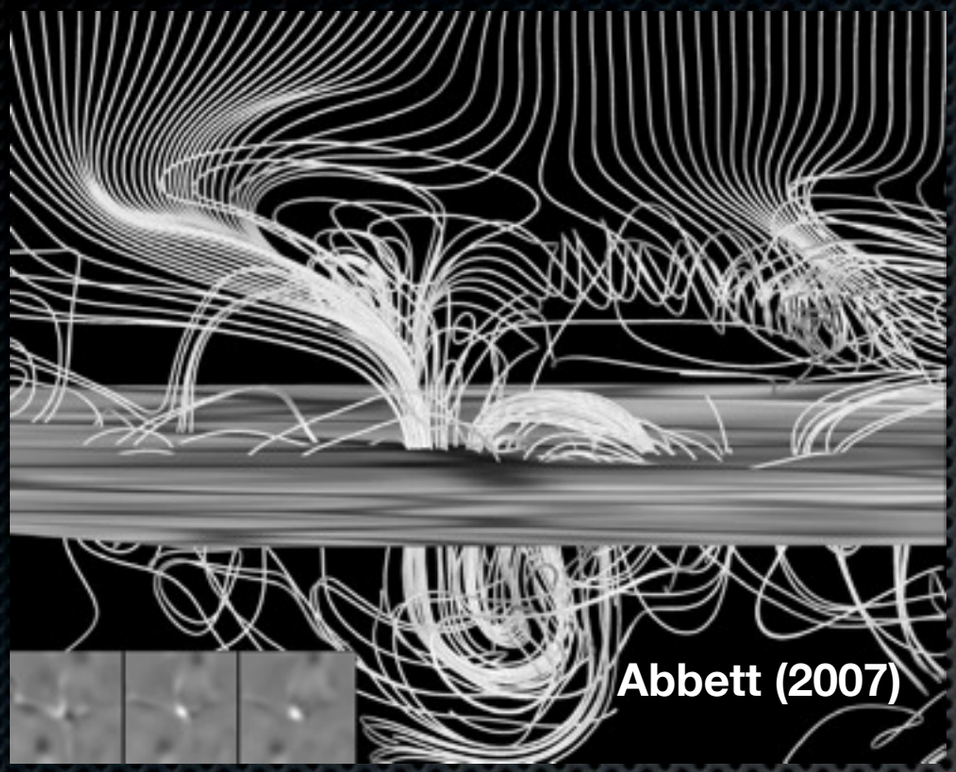

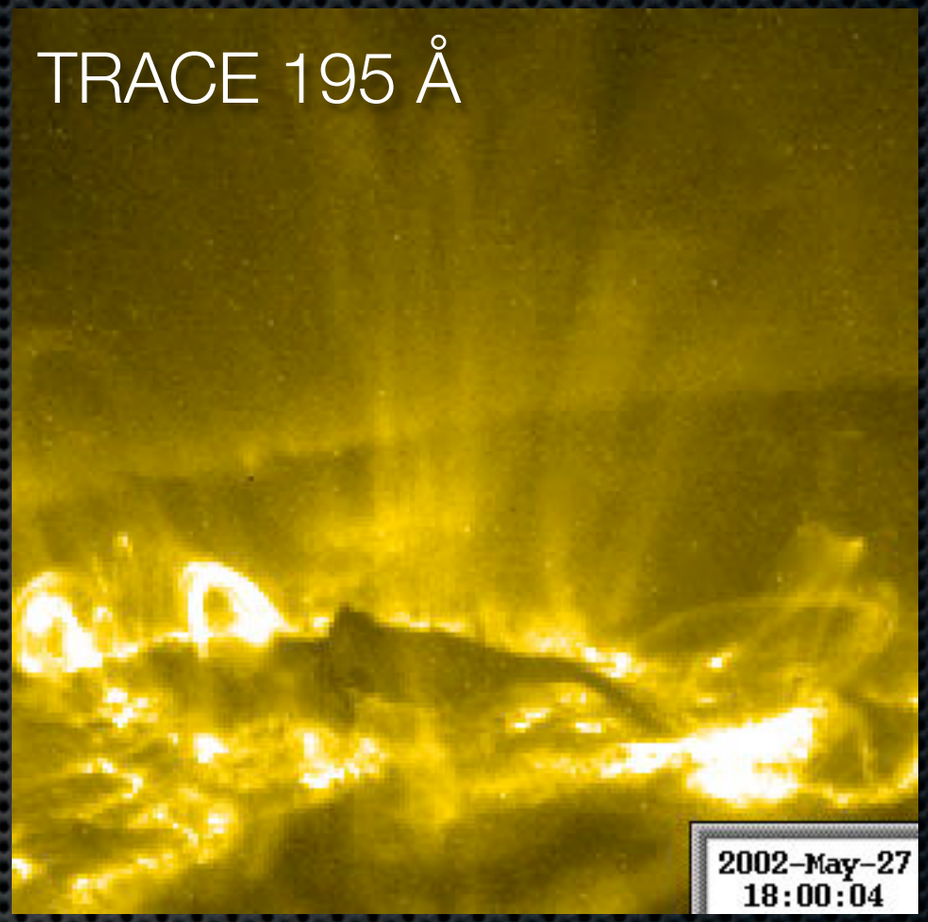

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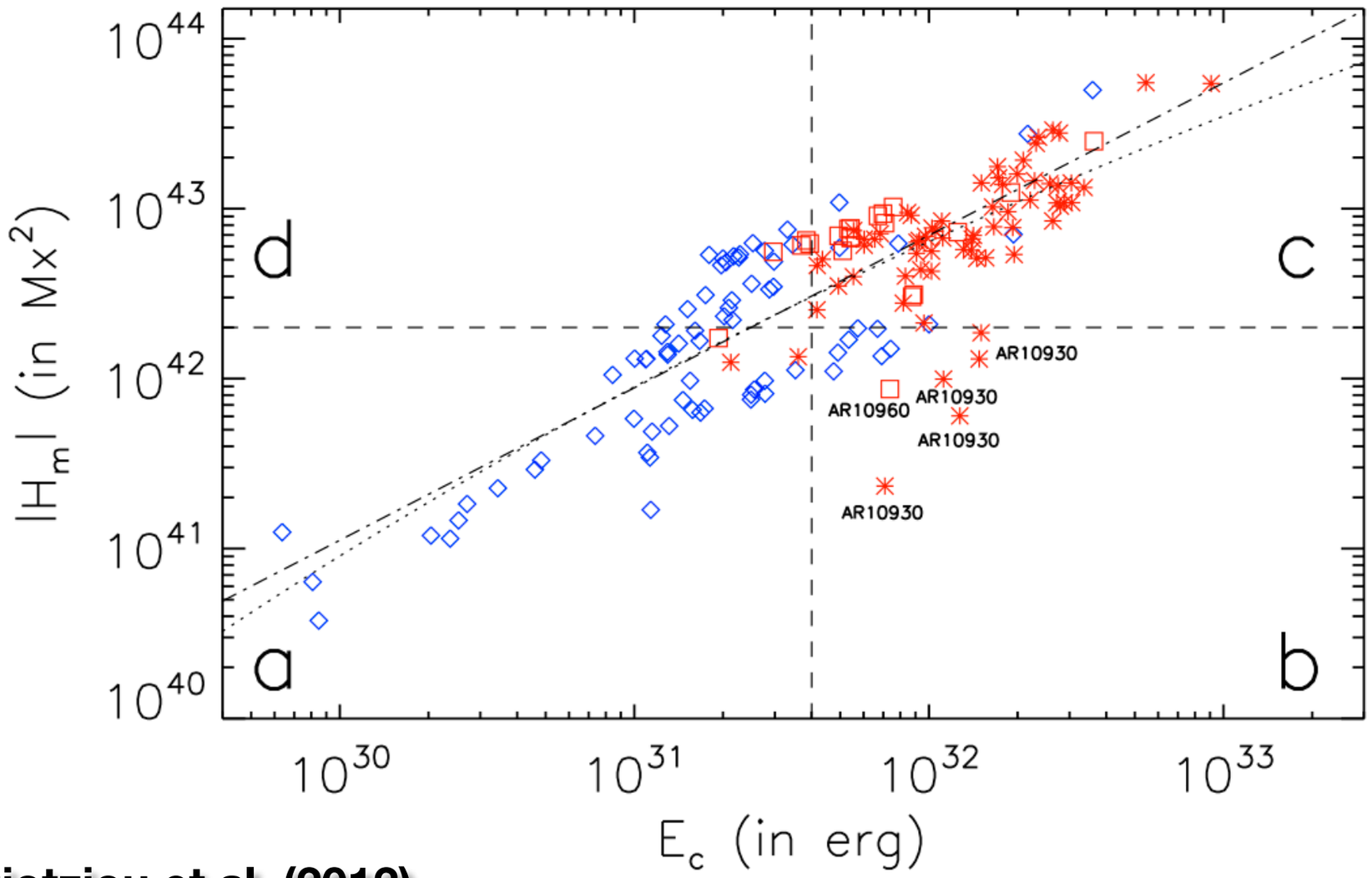
Basic property of magnetic helicity: Conservation even in the course of magnetic reconnection for high Reynolds-number plasmas

THE ENERGY-HELICITY DIAGRAM OF SOLAR ARs

162 magnetograms; 42 different ARs



Tziotziou et al. (2012)

1) Free magnetic energy and relative magnetic helicity in ARs are related
2) ARs that manage to accumulate more that 4×10^{31} erg of free energy and 2×10^{42} Mx^2 of relative helicity are almost exclusively eruptive

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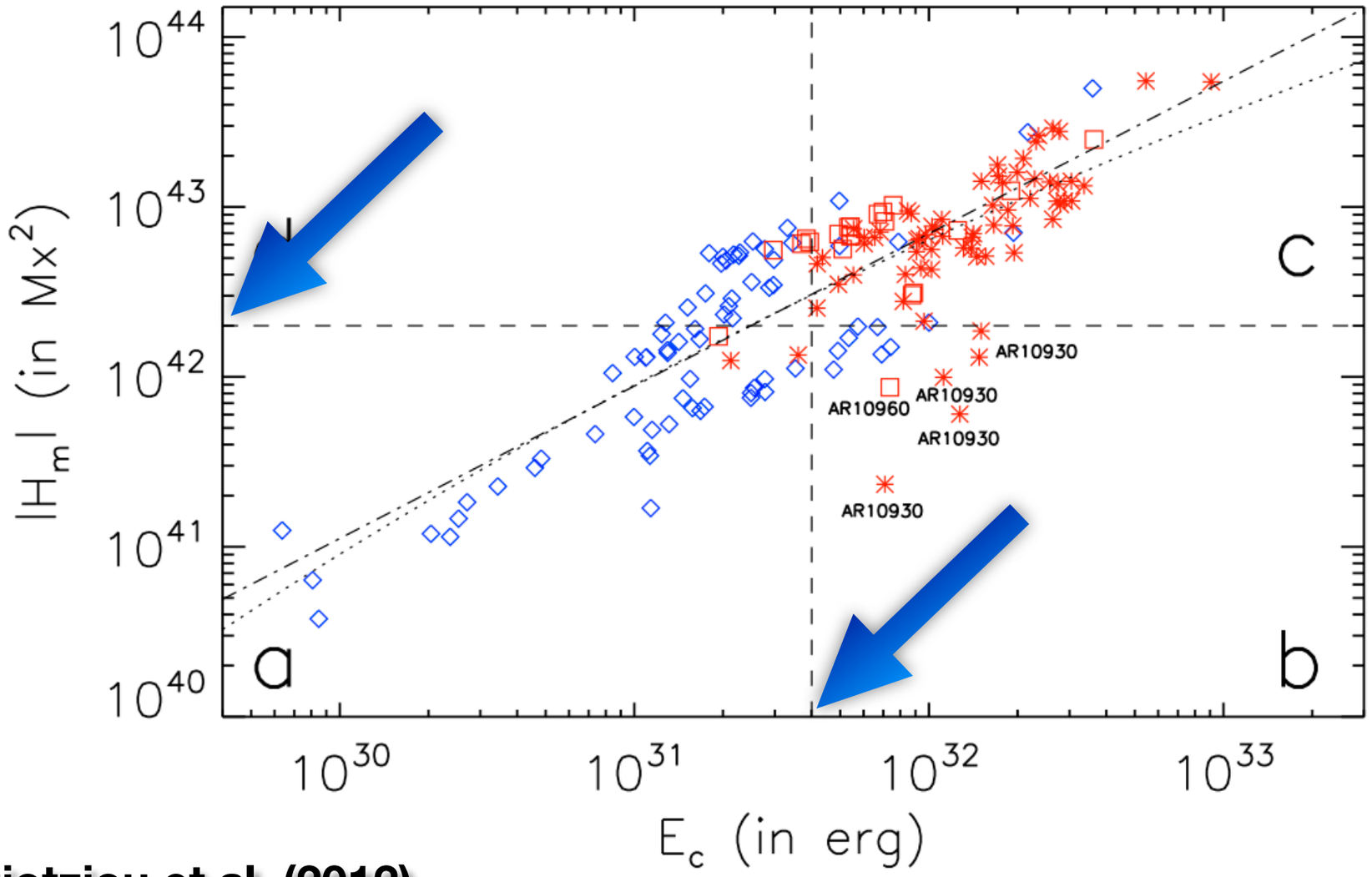

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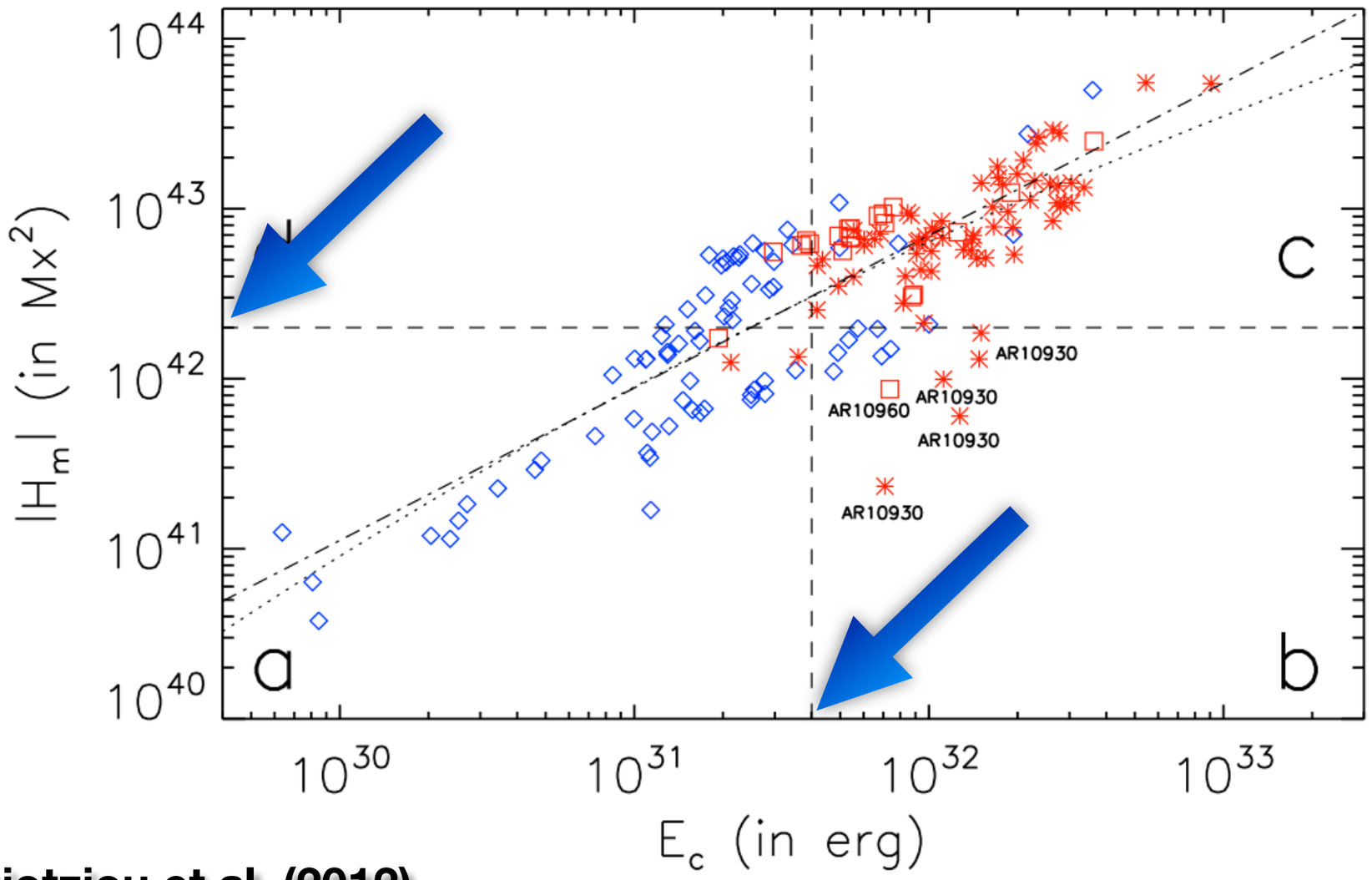

Tziotziou et al. (2012)

Energy / helicity thresholds: point of no return quantified(?)

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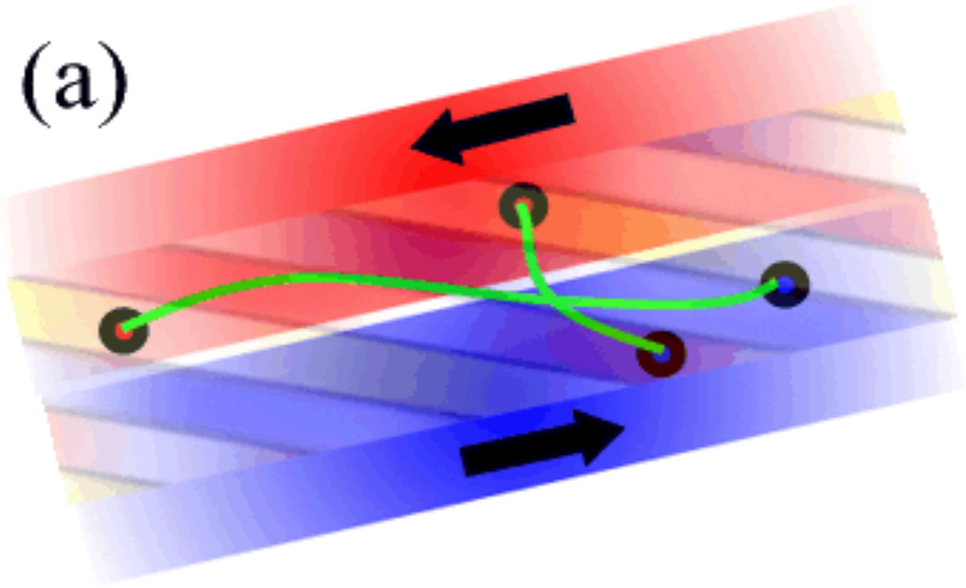
HELICITY ACCUMULATION VIA SHEAR/HELICITY INTERLAY

- As PIL evolves, interaction occurs between pre-existing, strongly sheared, and newly emerged, weakly sheared, field lines approaching the PIL

- Although the self-helicities of the two field lines may not be large, their mutual helicity is large



$$H_m^{(a)} = H_{1\,(self)}^{(a)} + H_{2\,(self)}^{(a)} + H_{(mutual)}$$

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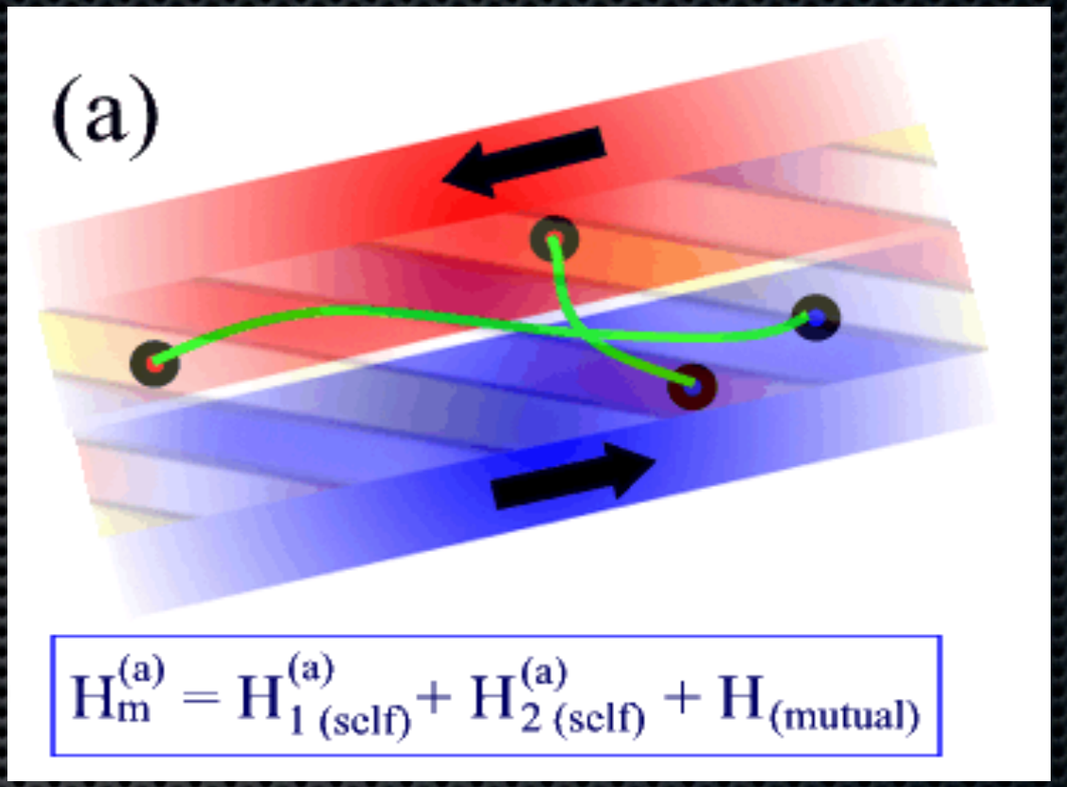

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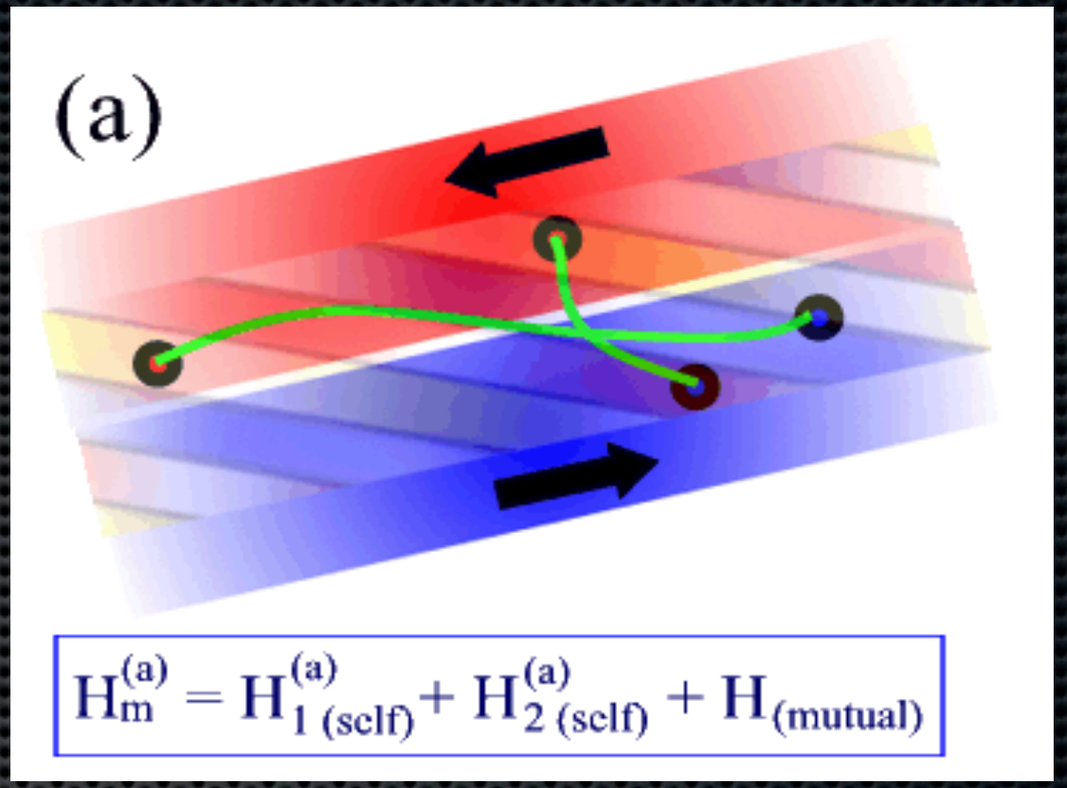
- ... that may rise and reconnect with the overlaying magnetic structure, supplying it with self helicity



HELICITY ACCUMULATION VIA SHEAR/HELICITY INTERLAY

- As PIL evolves, interaction occurs between pre-existing, strongly sheared, and newly emerged, weakly sheared, field lines approaching the PIL

- Although the self-helicities of the two field lines may not be large, their mutual helicity is large

- Magnetic reconnection between the two field lines (1) relaxes some of the shear, (2) minimizes mutual helicity, (3) due to helicity conservation, enhances self-helicity forming a strongly twisted, potentially kink-unstable field line...

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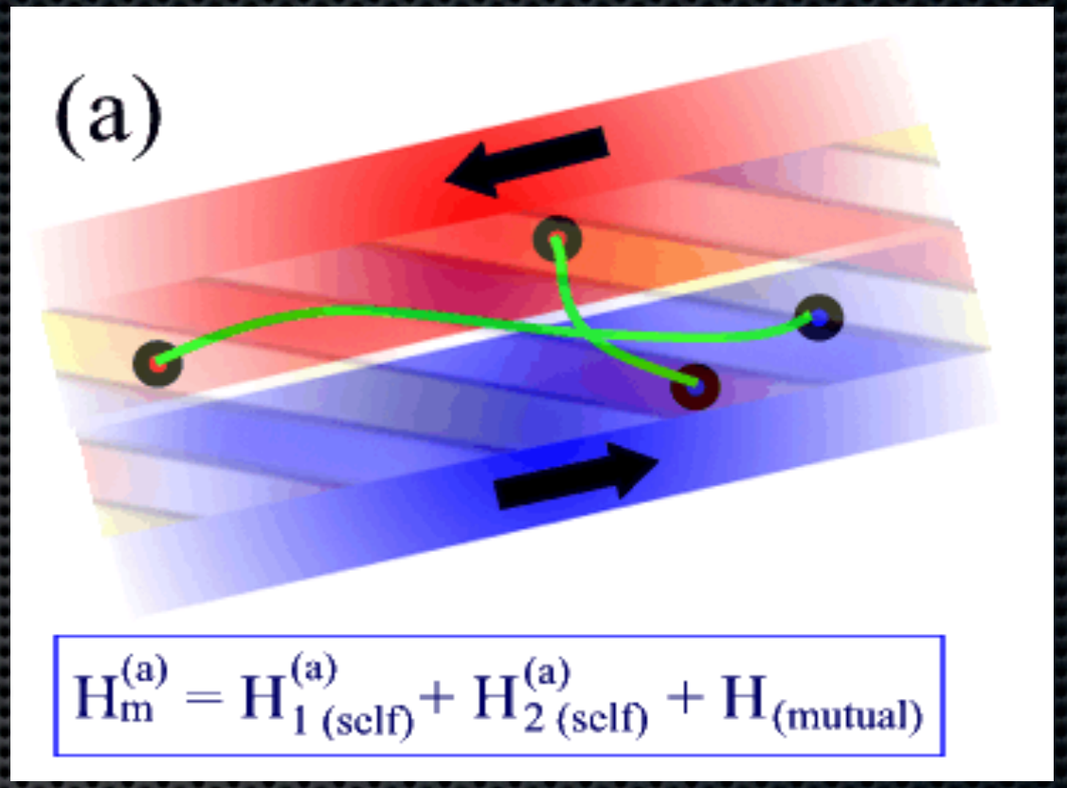
A continuous action of this mechanism may result in a strongly helical magnetic structure along the PIL, prone to one or more major eruptions



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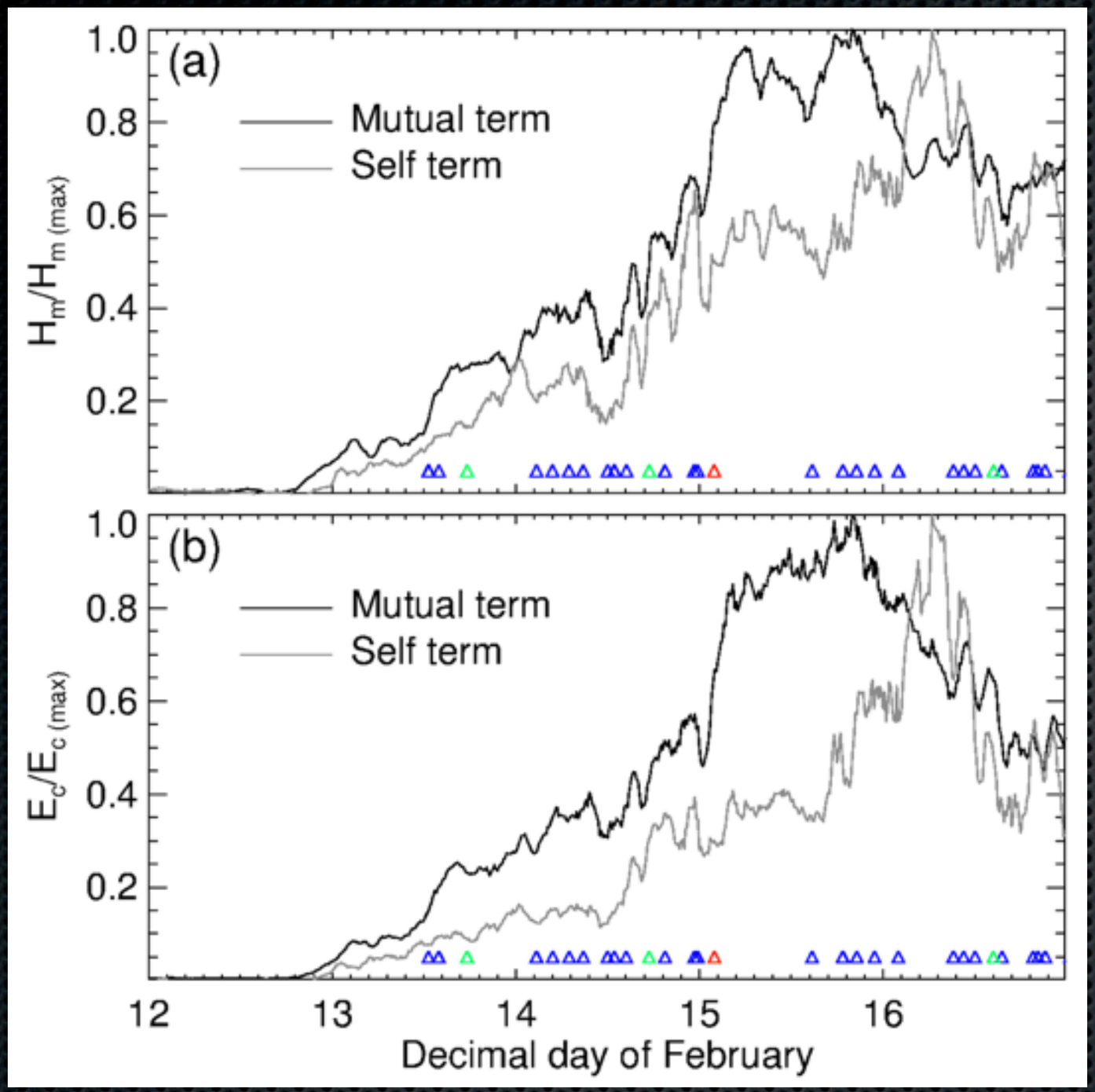

NOAA AR 11158: strongly sheared PIL area (strong mutual helicity) works to transferring mutual helicity into self helicity (twist & writhe). Increasingly helical magnetic structures obtained in the AR.

Tziotziou et al. (2013)

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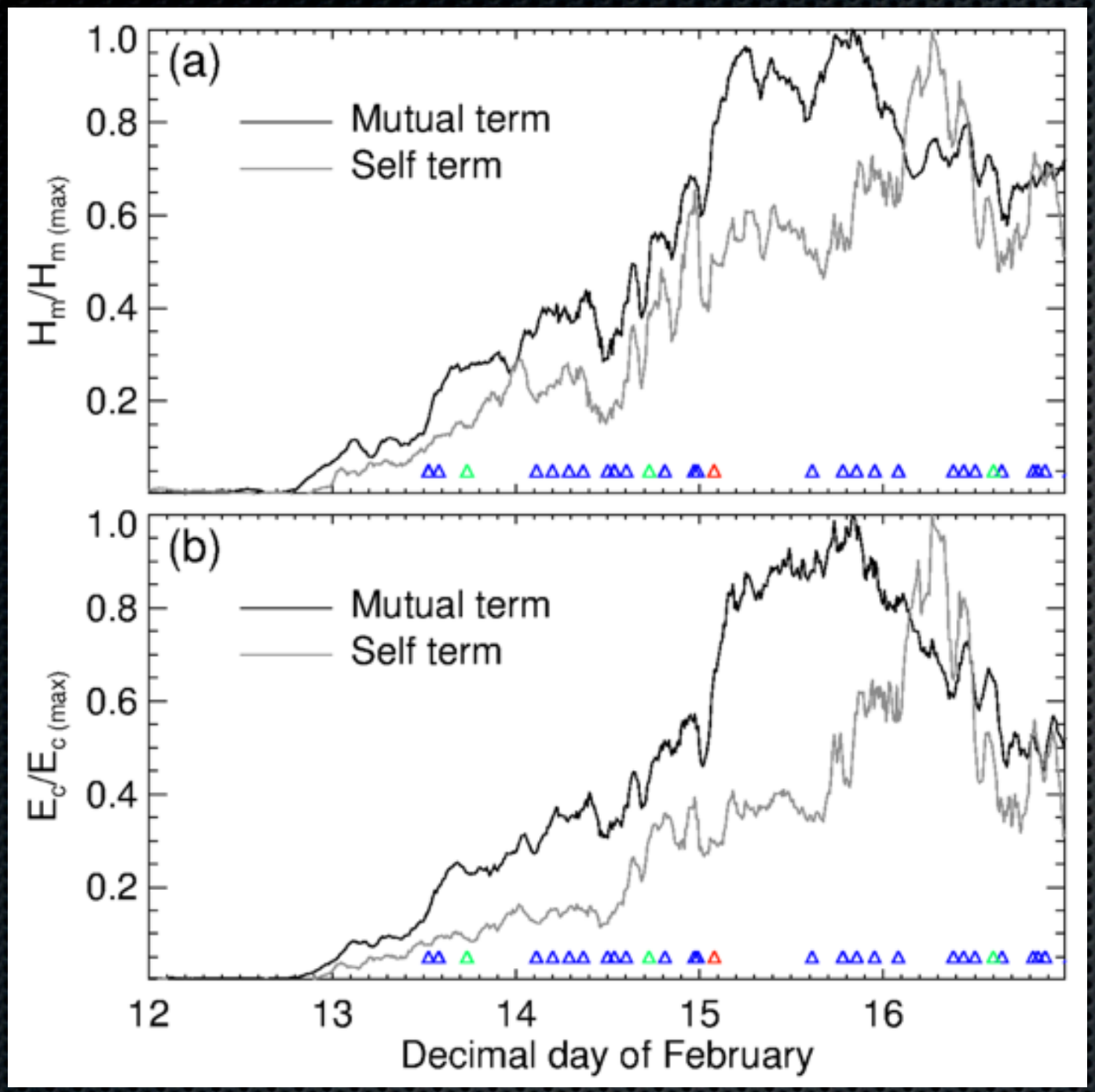

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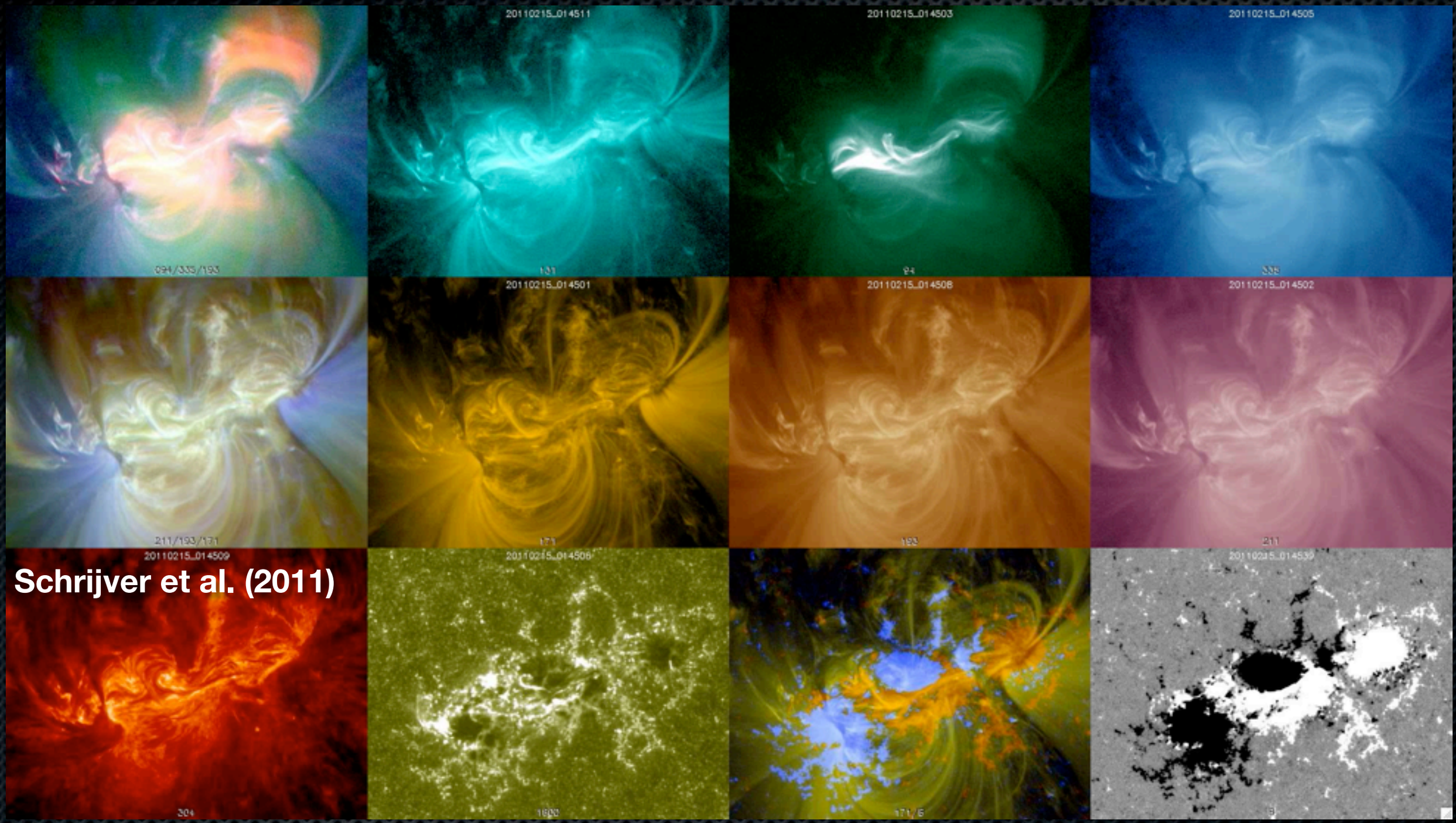
NOAA AR 11158: strongly sheared PIL area (strong mutual helicity) works to transferring mutual helicity into self helicity (twist & writhe). Increasingly helical magnetic structures obtained in the AR.

How much helicity can the AR accumulate?

ERUPTIVE X-CLASS FLARE IN MULTIPLE WAVELENGTHS



Schrijver et al. (2011)

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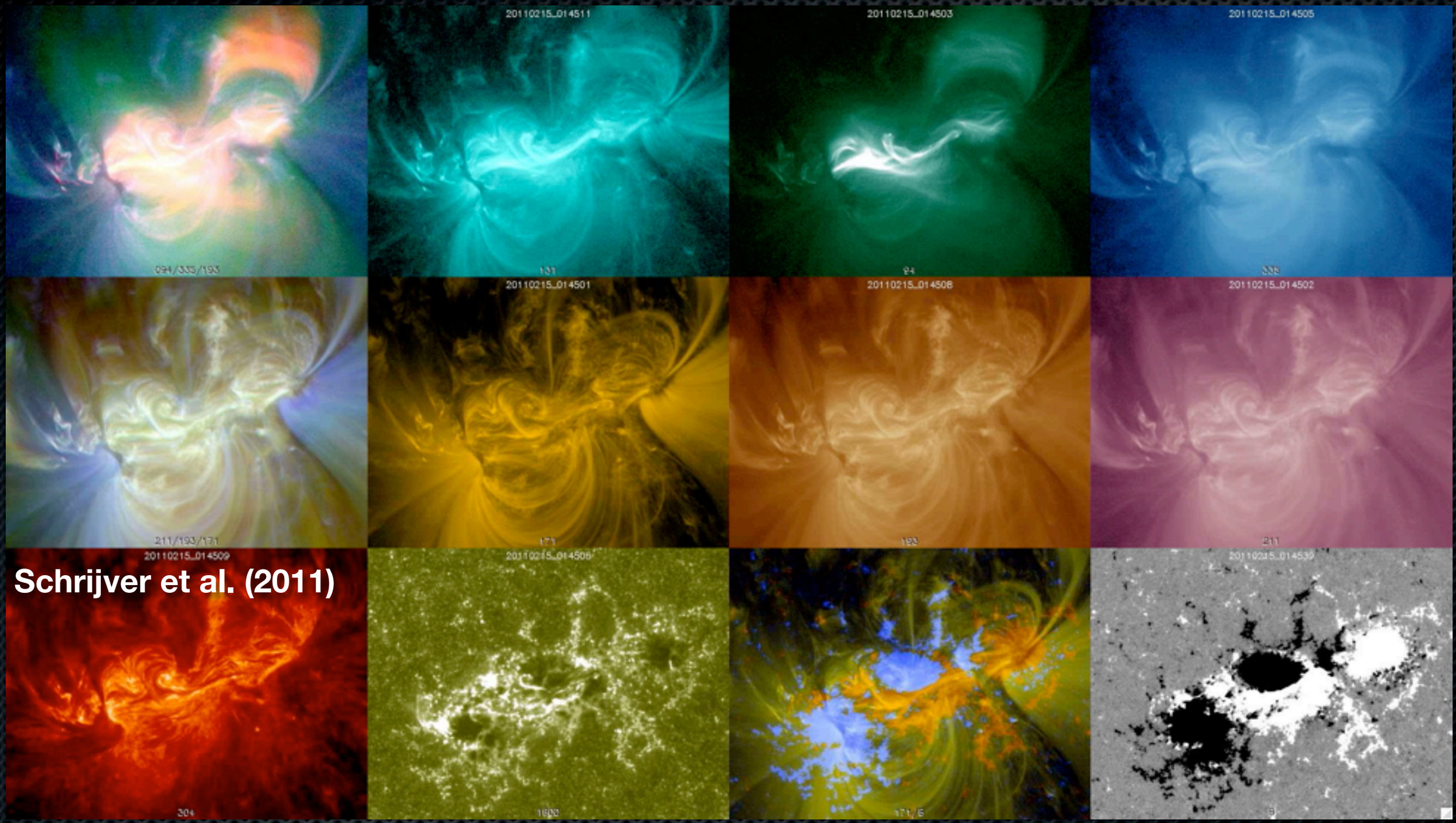
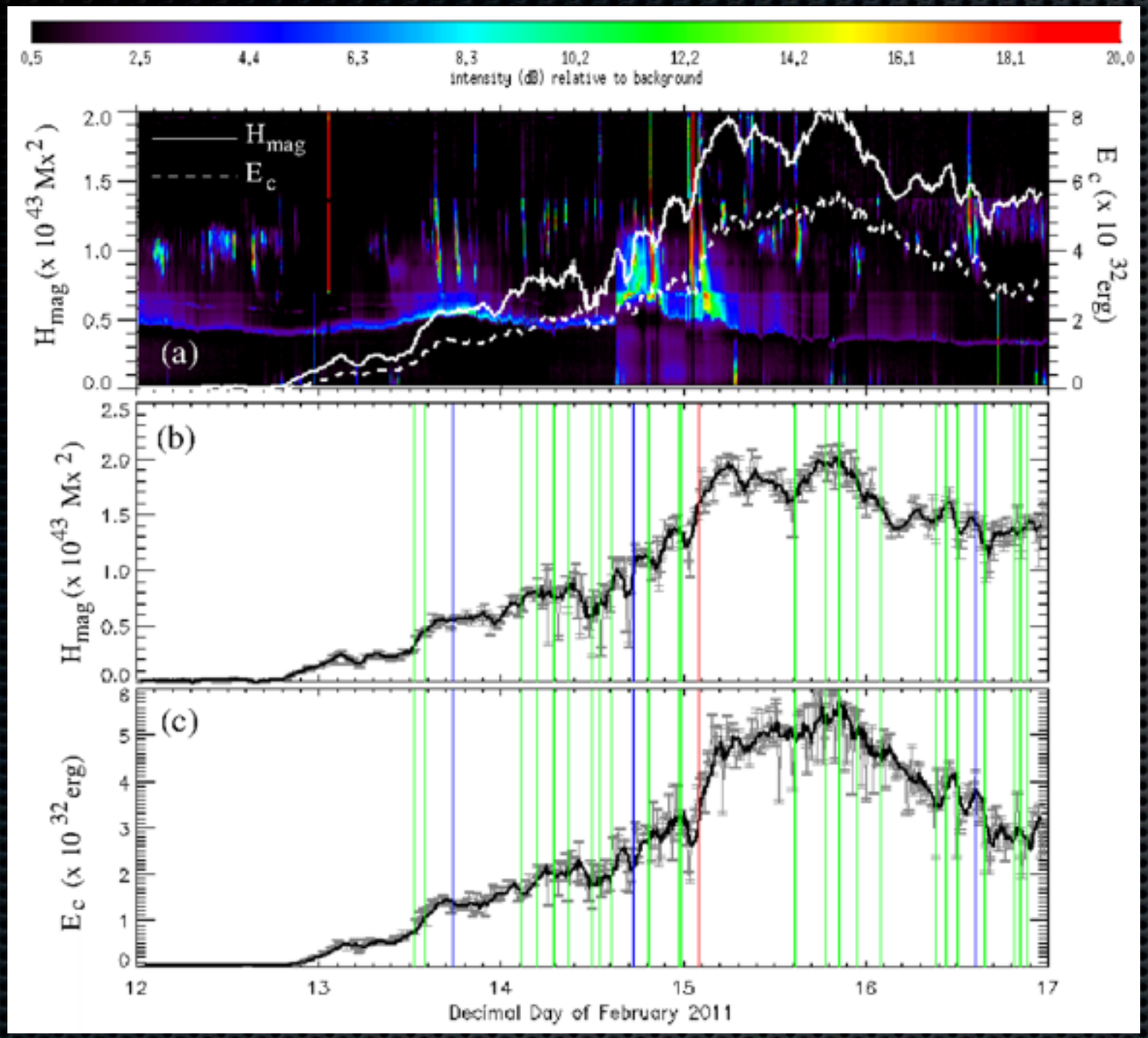


Schrijver et al. (2011)

Does eruption occur within a marginally stable configuration?

MARGINAL STABILITY IN TERMS OF HELICITY?



Georgoulis (2013), submitted; Tziotziou et al. (2013)

Free magnetic energy and relative magnetic helicity climax and then start decreasing while the AR is still growing in terms of magnetic flux.

Results in agreement with theoretical analysis of an upper helicity bound in force-free (axisymmetric) confirurations (Zhang & Flyer 2008)

$$H_{m_{(\max)}}(t) \sim T_{\max}\ \Phi^2(t)$$

SMALL-SCALE HELICAL KINK INSTABILITY

- A conceptual mechanism to assess the accumulation of helicity along sheared PILs
- Single force-free flux tube with (self) relative helicity (Georgoulis & LaBonte 2007):

$$H_m = 8\pi \; d^2 \alpha A \Phi^{2\delta}$$

- Classical definition of magnetic helicity for a single flux tube (e.g., Moffatt & Ricca 1992):

$$H_m \sim (T+W)\Phi^2 \Rightarrow H_m = c_h (T+W)\Phi^2$$

- Substitute and solve for the ratio of writhe W vs. twist T:

$$K = \lambda^2 \frac{W}{T} = \frac{2\,d^2}{L\,c_h} A\Phi^{2(\delta-1)} - \lambda^2$$

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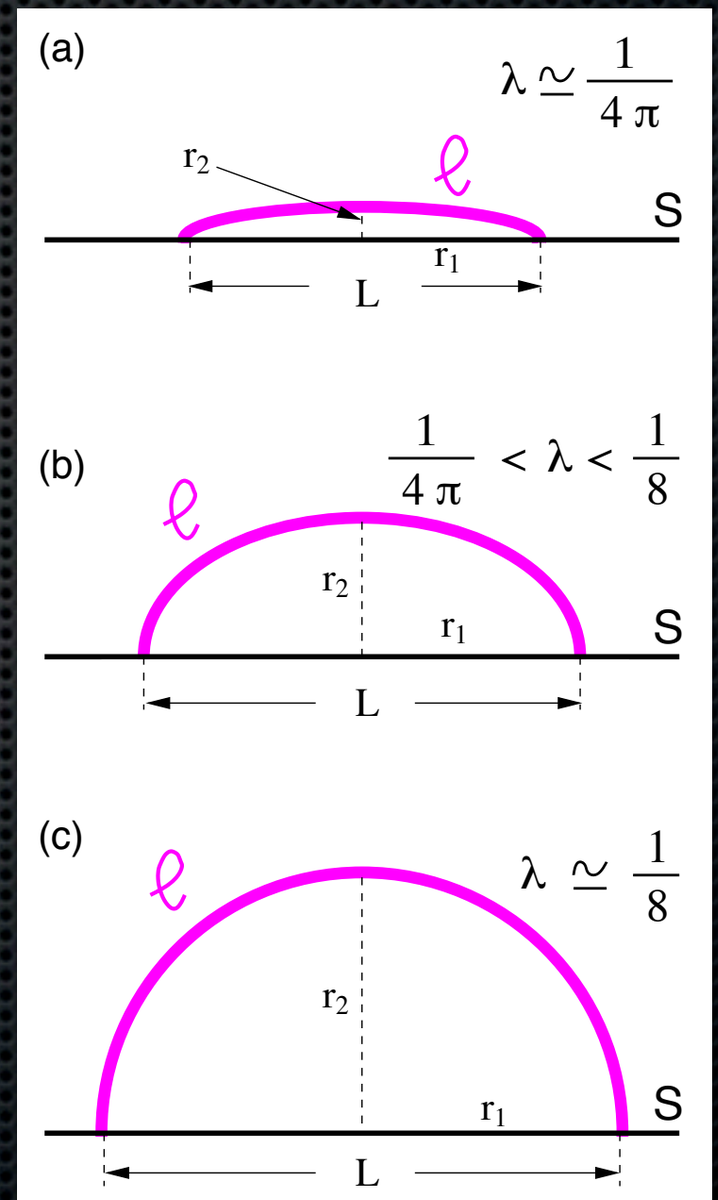

$$T = \lambda(\alpha\ \ell);\ \ell = 4\pi\ \mathrm{L}\ \lambda$$

(slender flux tube)

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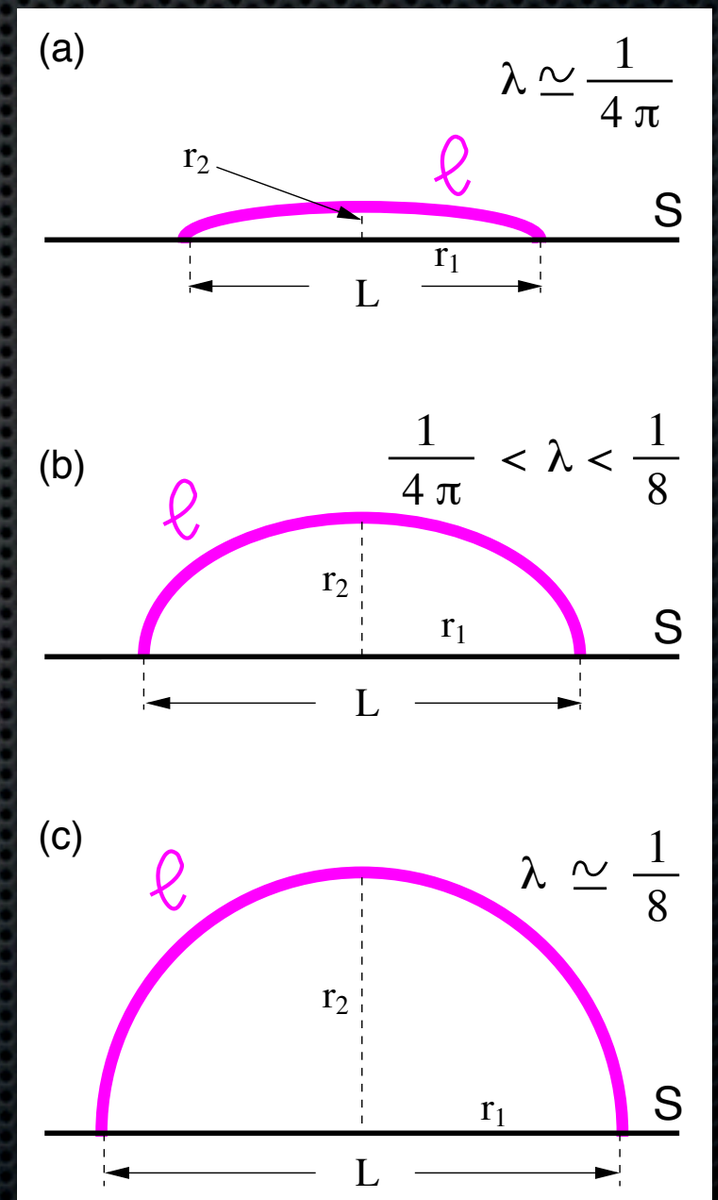

$T_w = \lambda(\alpha\ \ell);\ \ell = 4\pi\ \mathrm{L}\ \lambda$

(slender flux tube)

Kink instability ensues when W/T > 0, or K > 0

REQUIREMENTS FOR SMALL-SKALE HKI

- A minimum magnetic flux is required for K>0

$$\Phi_{\min} = \left(\frac{\lambda^2 \, \mathrm{L} \, c_h}{2 \, d^2 A} \right)^{\frac{1}{2(\delta-1)}}$$

- Leading to a minimum vertical field strength per area element d^2:

$$B_{z_{\min}} = \Phi_{\min} / d^2$$

- For shear to act along a PIL, B_z must exceed ~800 G (Georgoulis et al 2012). This constrains the unknown constant c_h, that obtains a minimum value:

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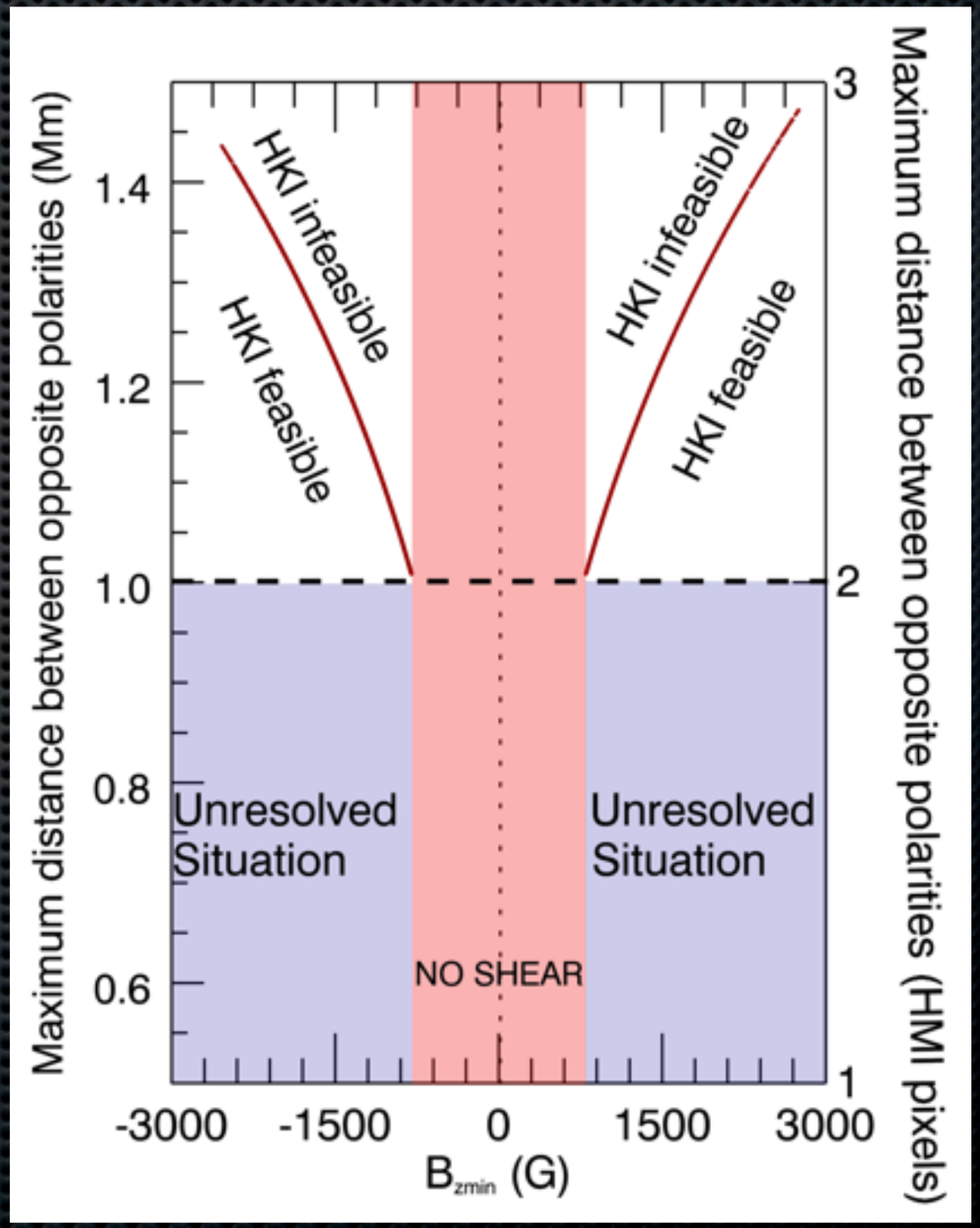
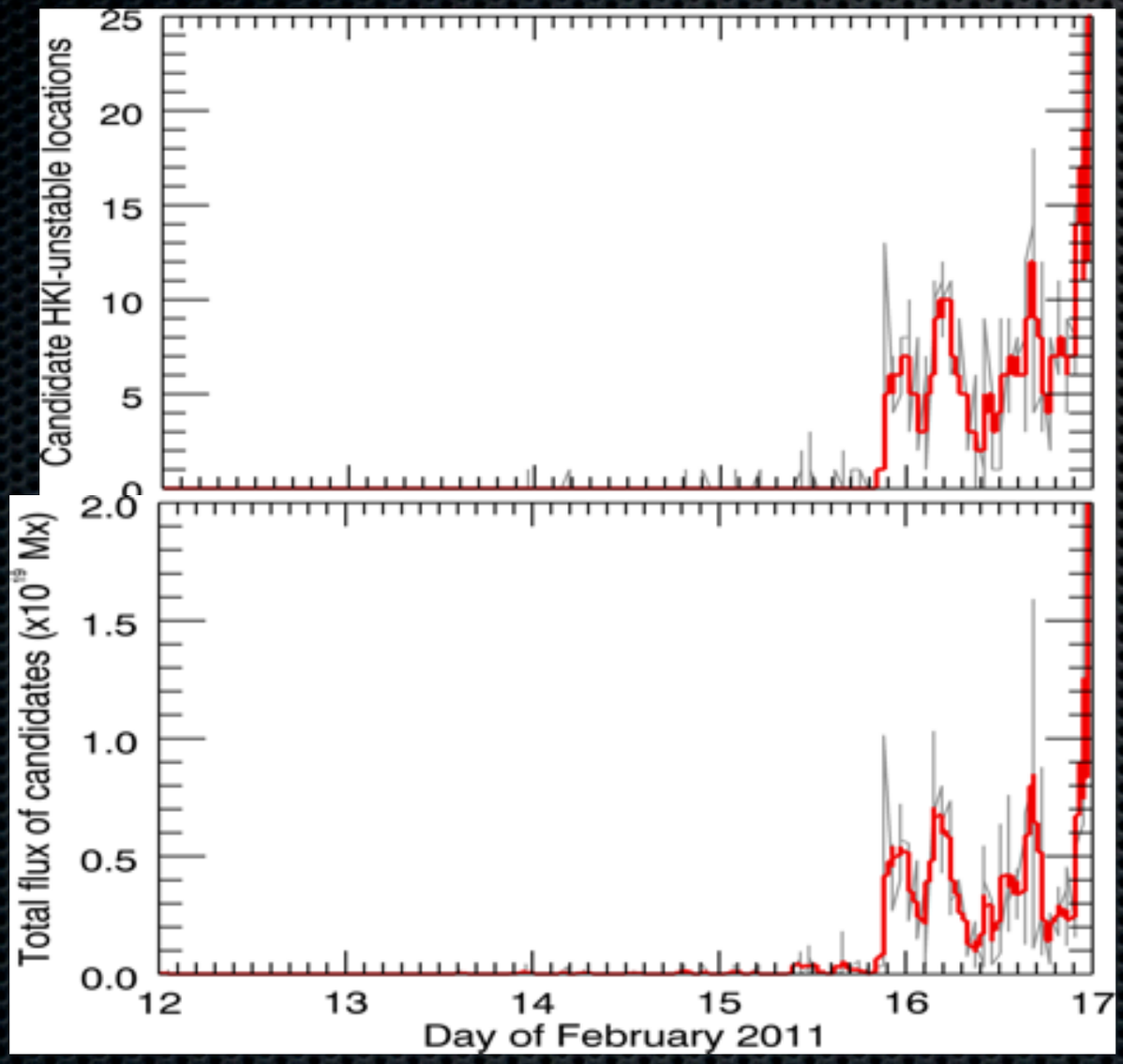
HKI condition a very stringent one - it can occur only along PILs



GENERALIZATION & APPLICATION TO NOAA AR 11158

In this view of marginal stability scenario, the critical threshold becomes the threshold number of turns for the helical kink instability

- Candidate small-scale HKI locations and their total flux for NOAA AR 11158



Spatial distribution of candidate locations

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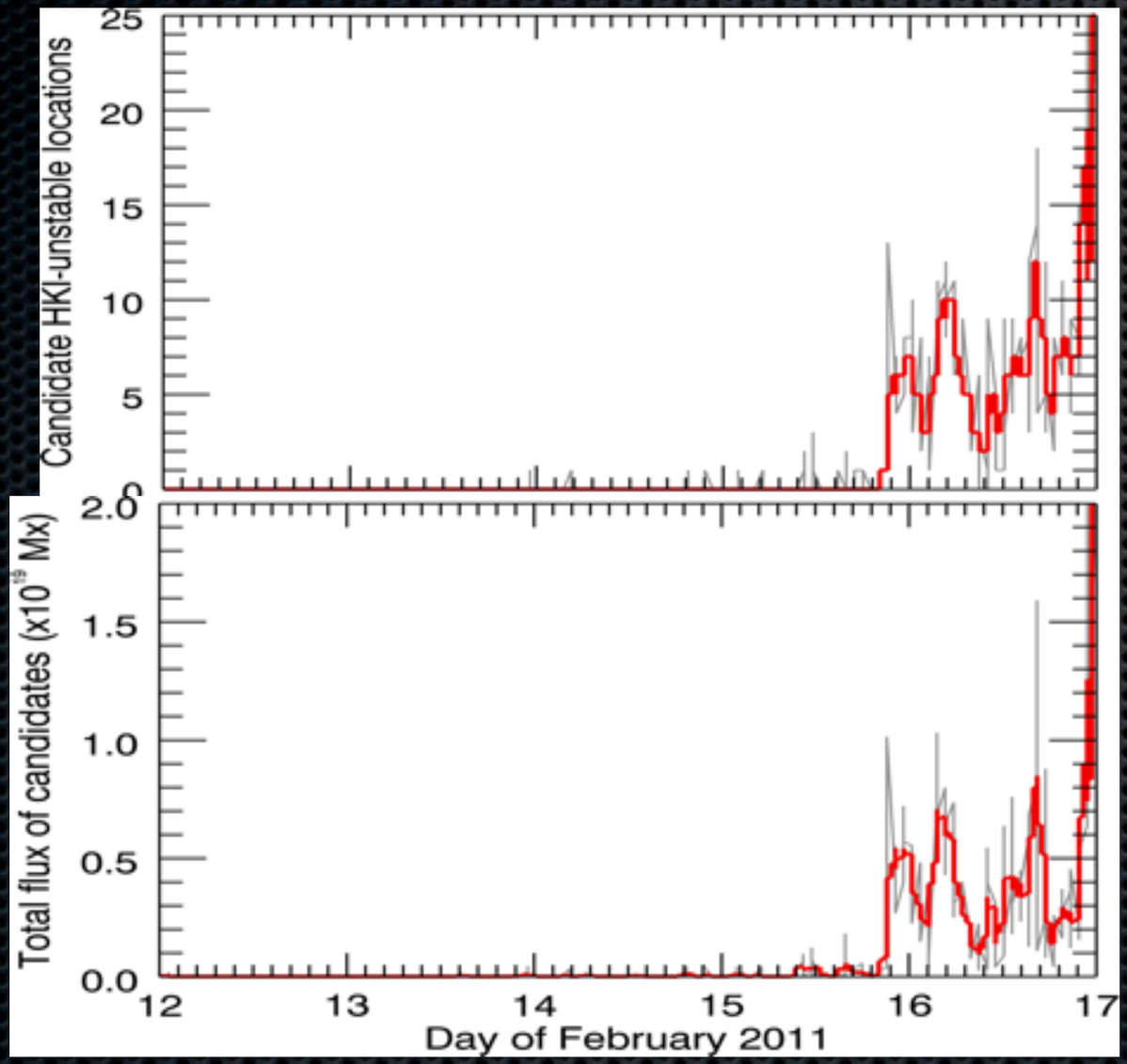
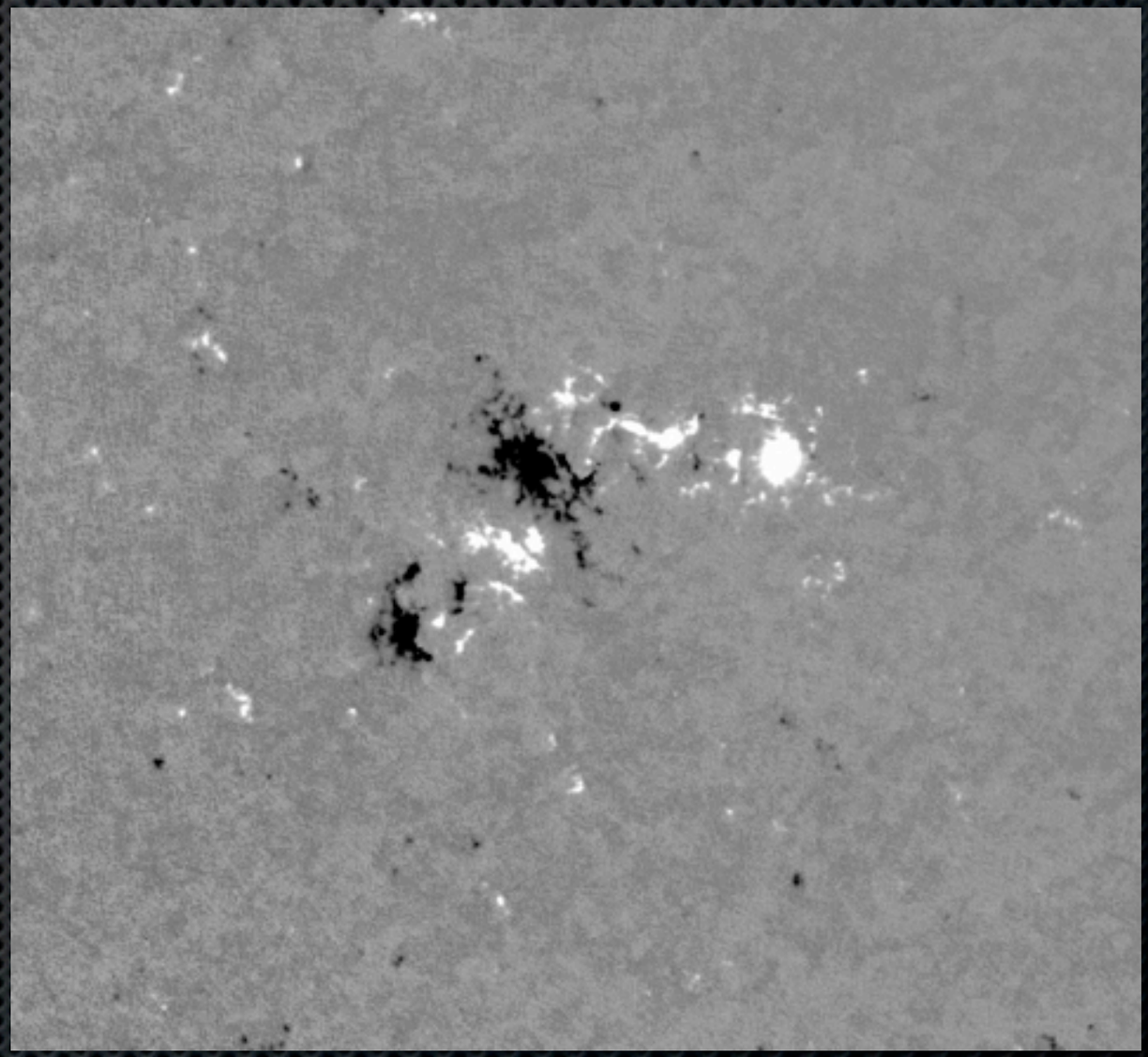
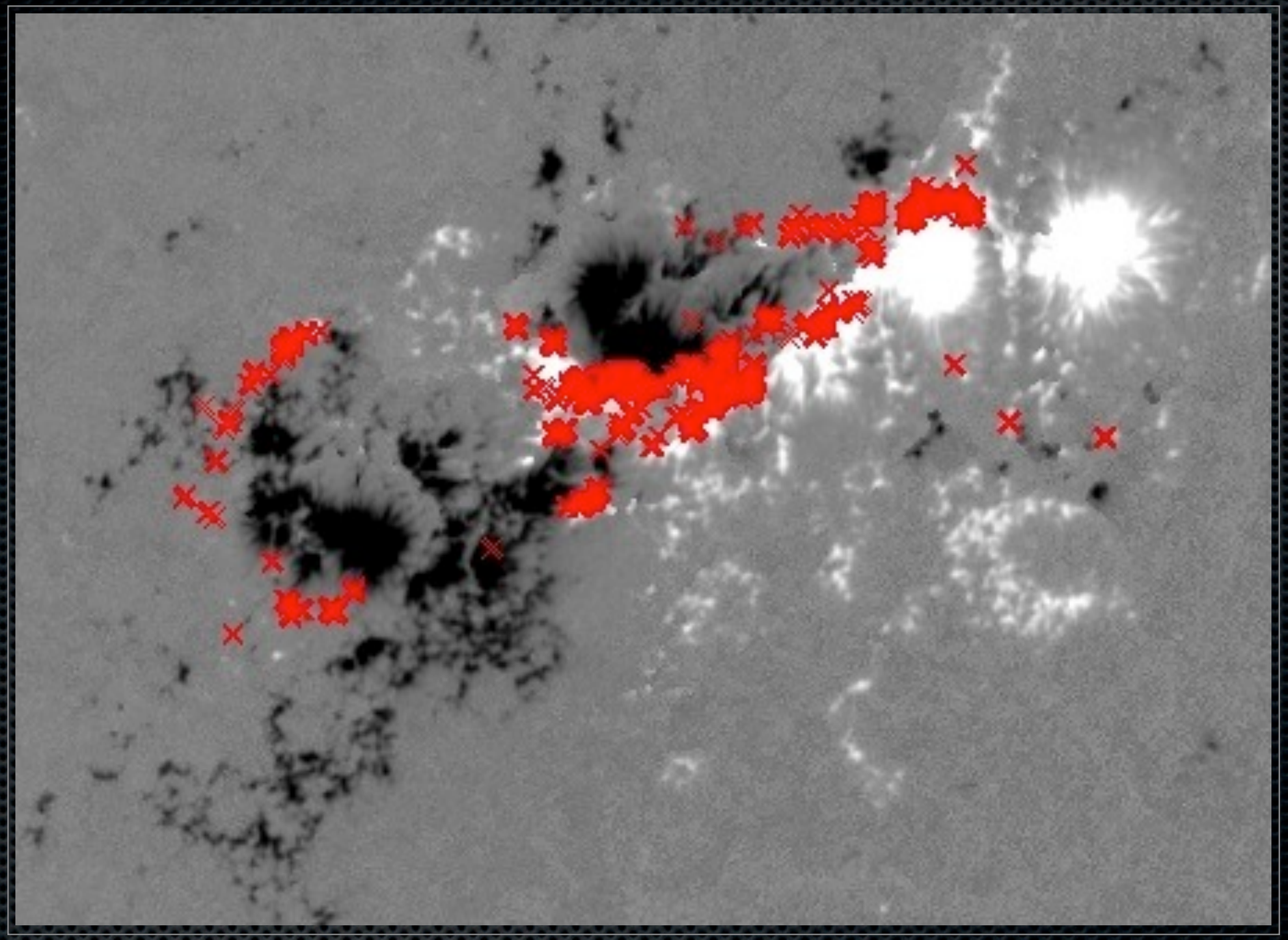




Spatial distribution of candidate locations

OVERVIEW OF LIKELY HKI LOCATIONS IN AR 11158



PIL(s) and “parasitic-polarity” areas included

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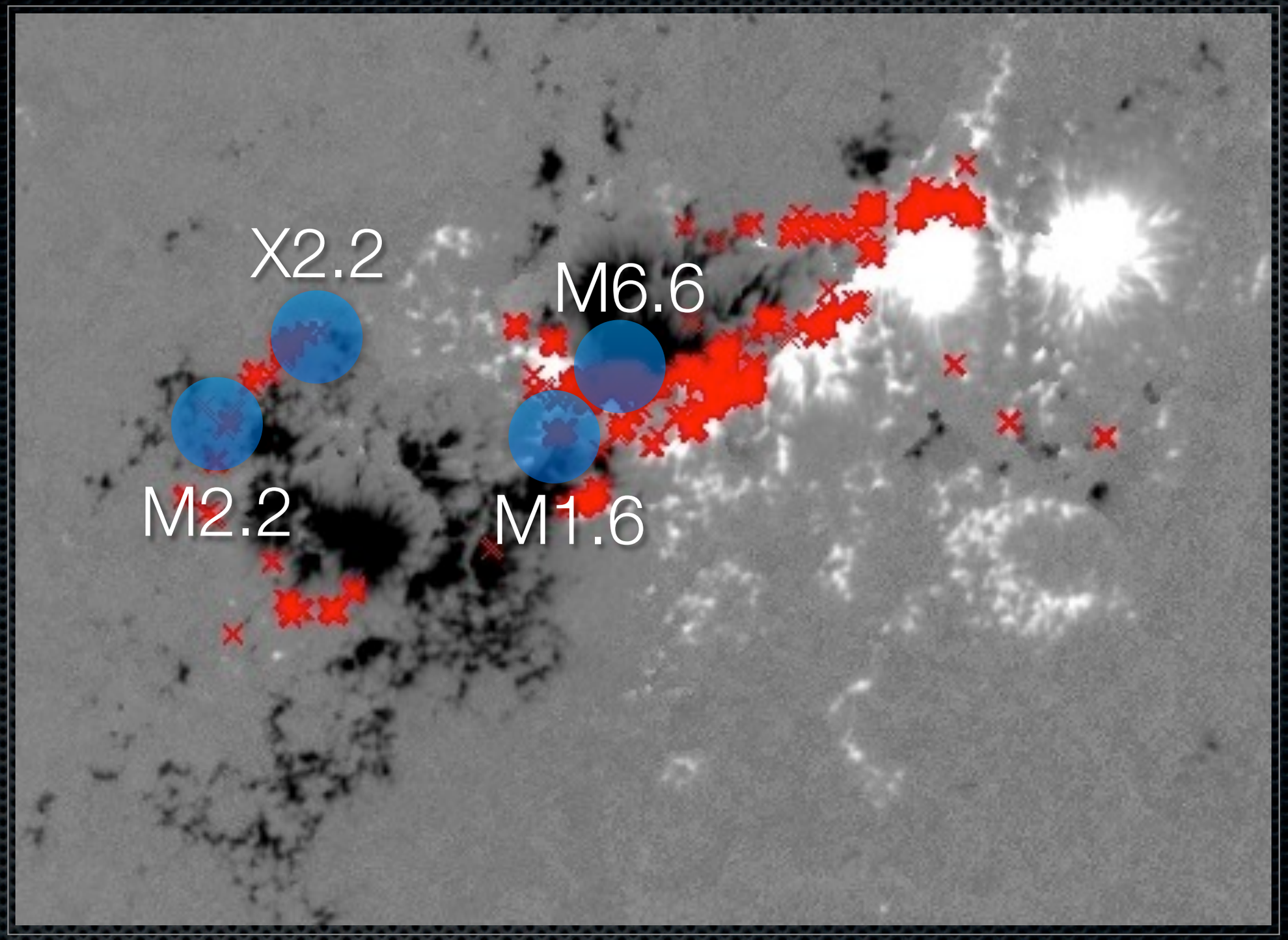

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TEST AIMING TO BUILD AN ARGUMENT

Key Q: are magnetic fields of eruptive ARs in a SOC state?

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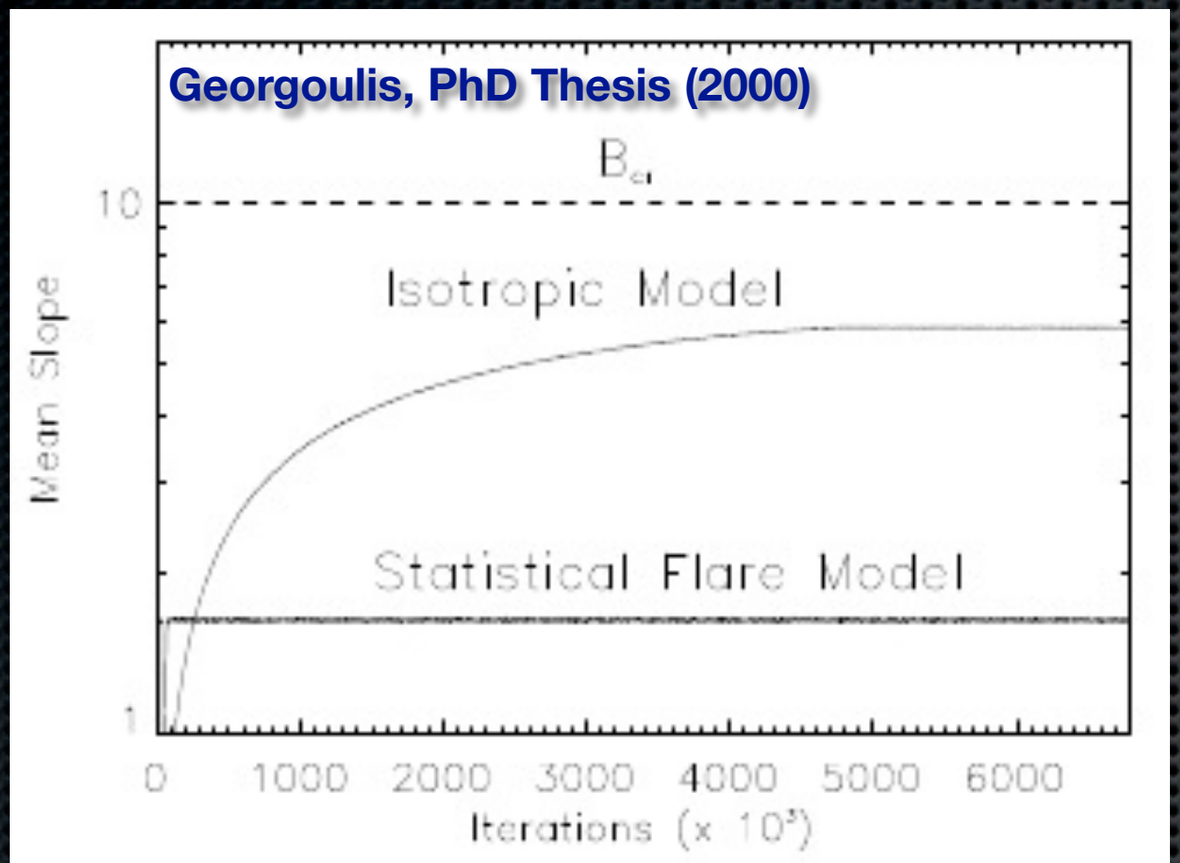

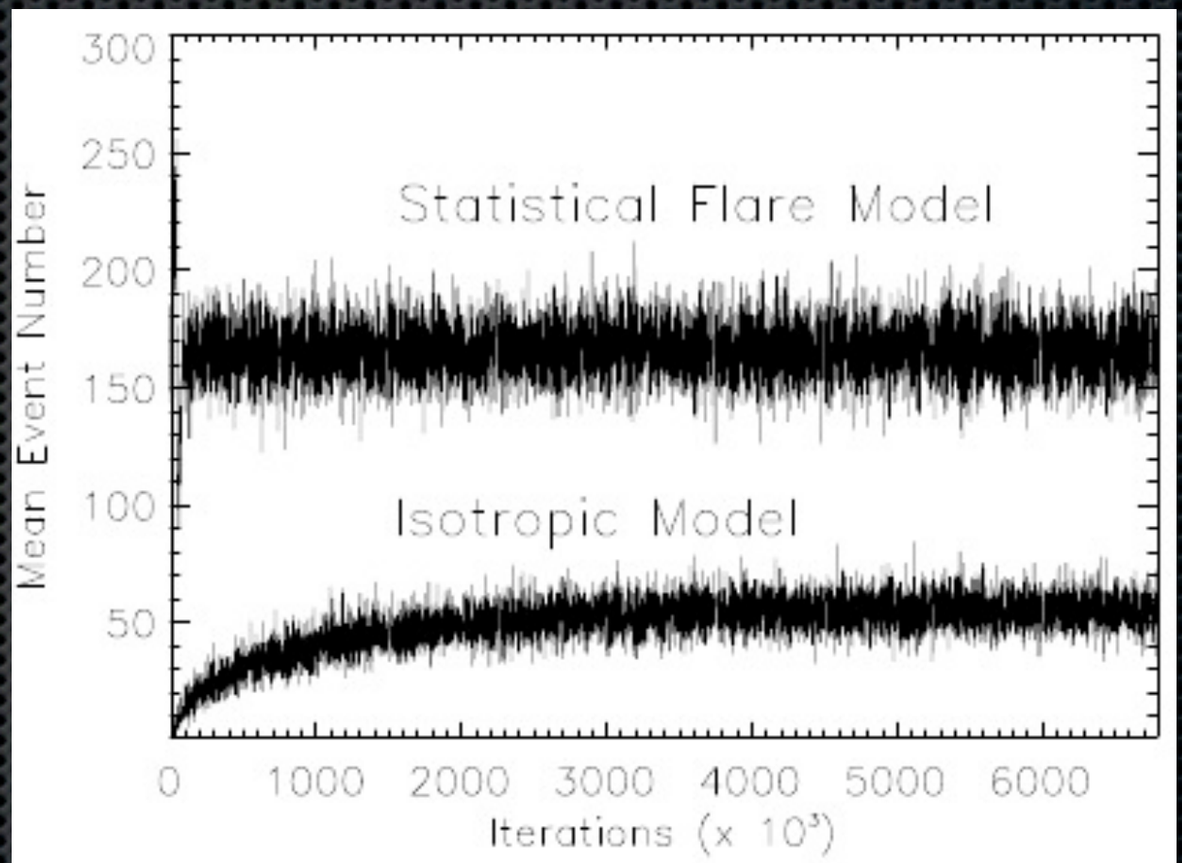

To conclude on SOC existence,
one must have a time sequence available

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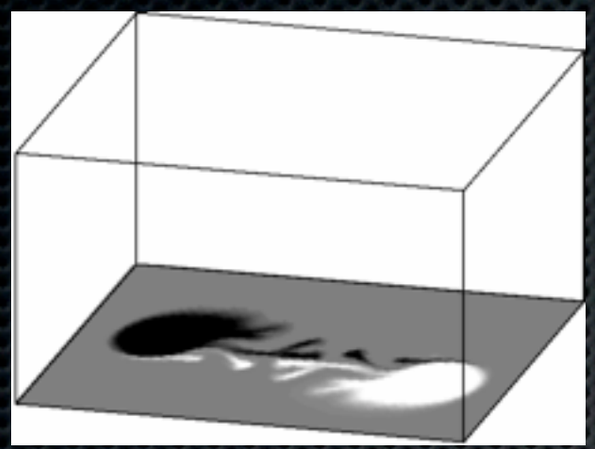
See M. Dimitropoulou's talk

Observed magnetogram



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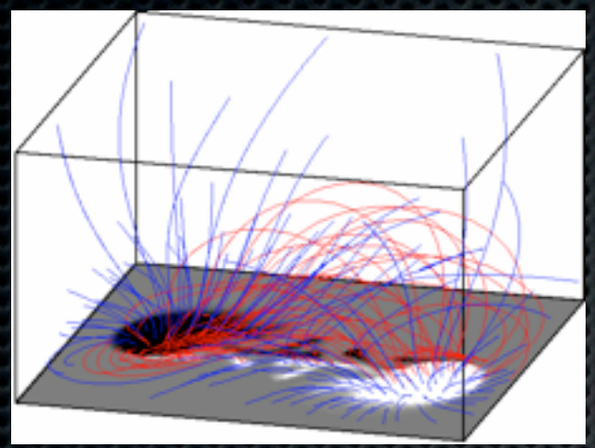

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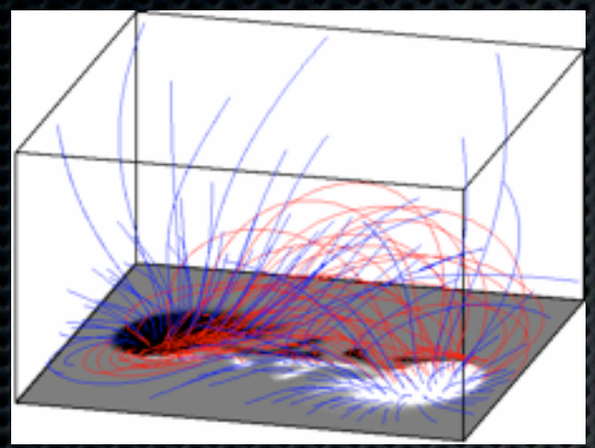

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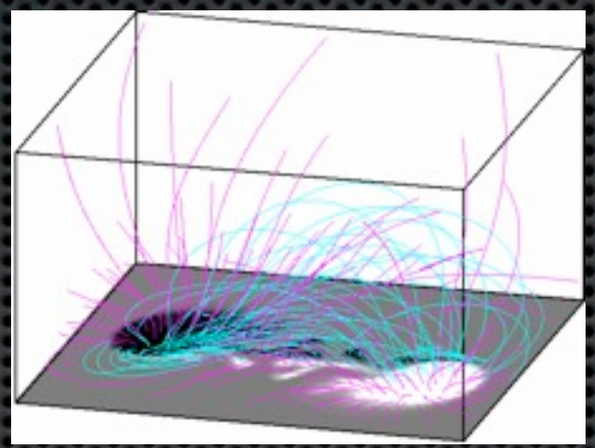
Bring to SOC state

S-IFM



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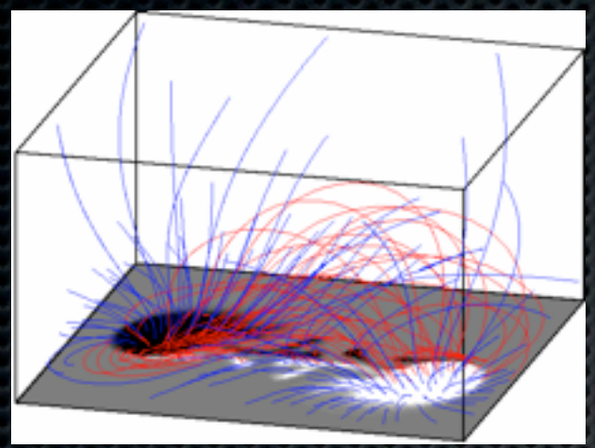

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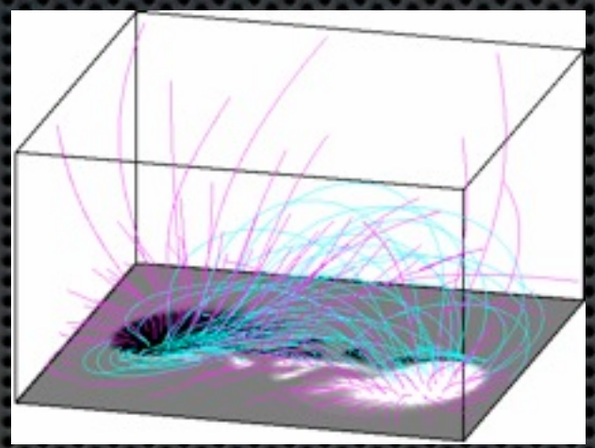
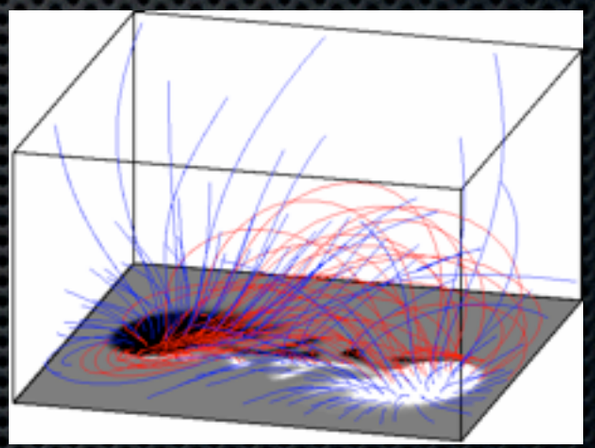


SOC state (monitored)

Return to initial state

D-IFM



Initial extrapolated state

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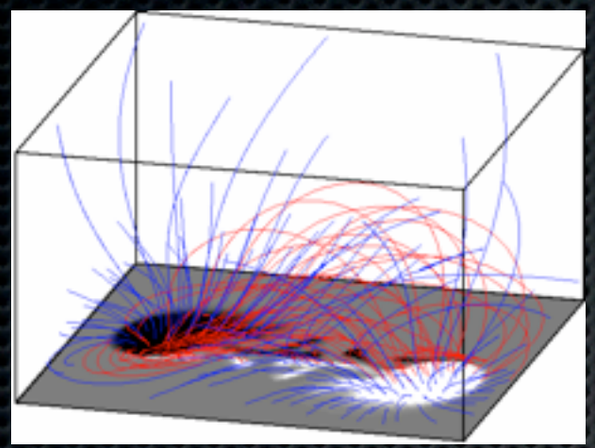

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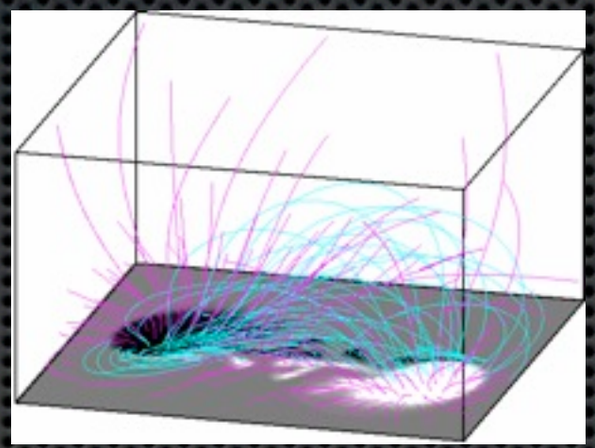

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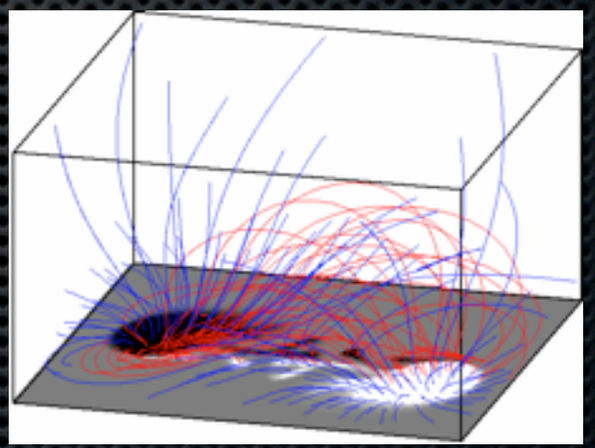


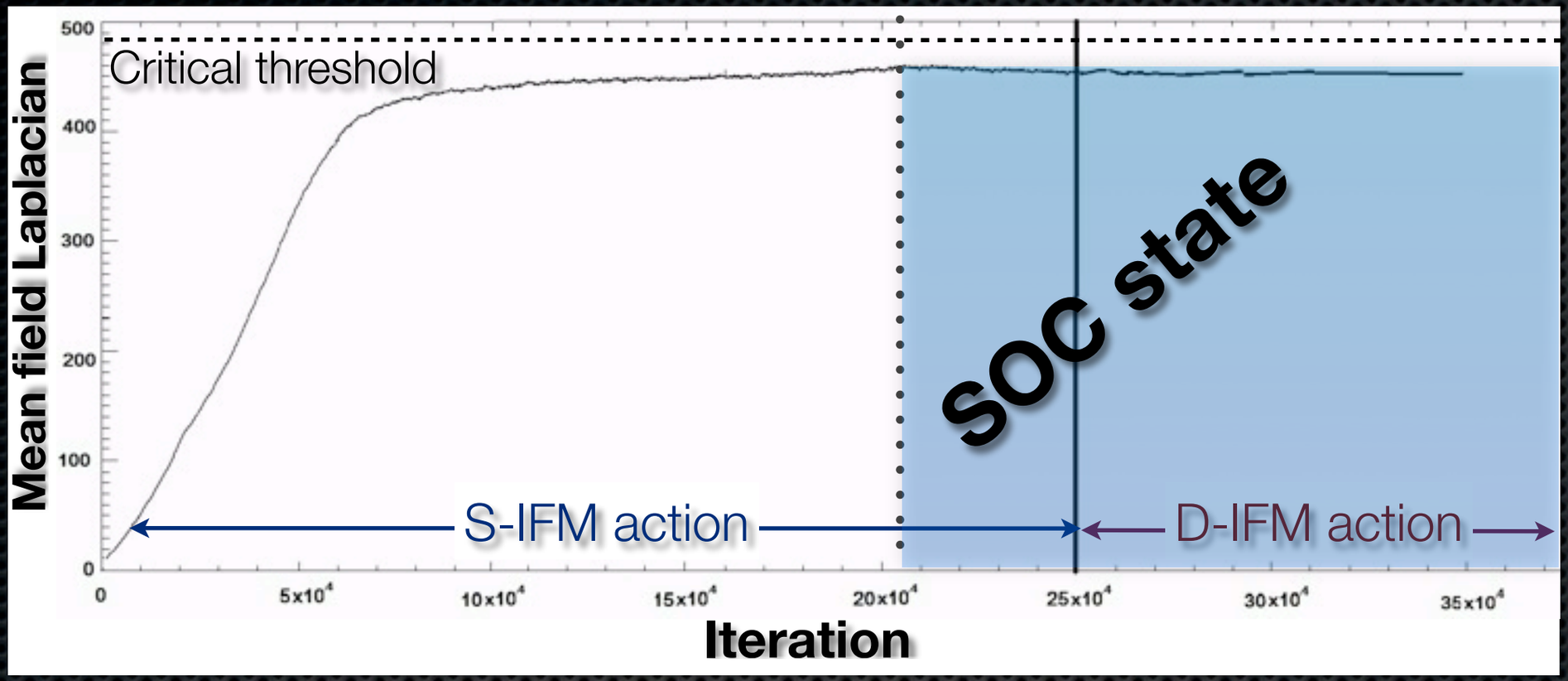
Initial extrapolated state

* SOC will continue to be monitored in the course of the D-IFM interpolation

Will SOC be destroyed when trying to reach the initial 3D magnetic-field state?

TEST RESULTS ON NOAA AR 11158

The mean Laplacian of the magnetic field is stabilized



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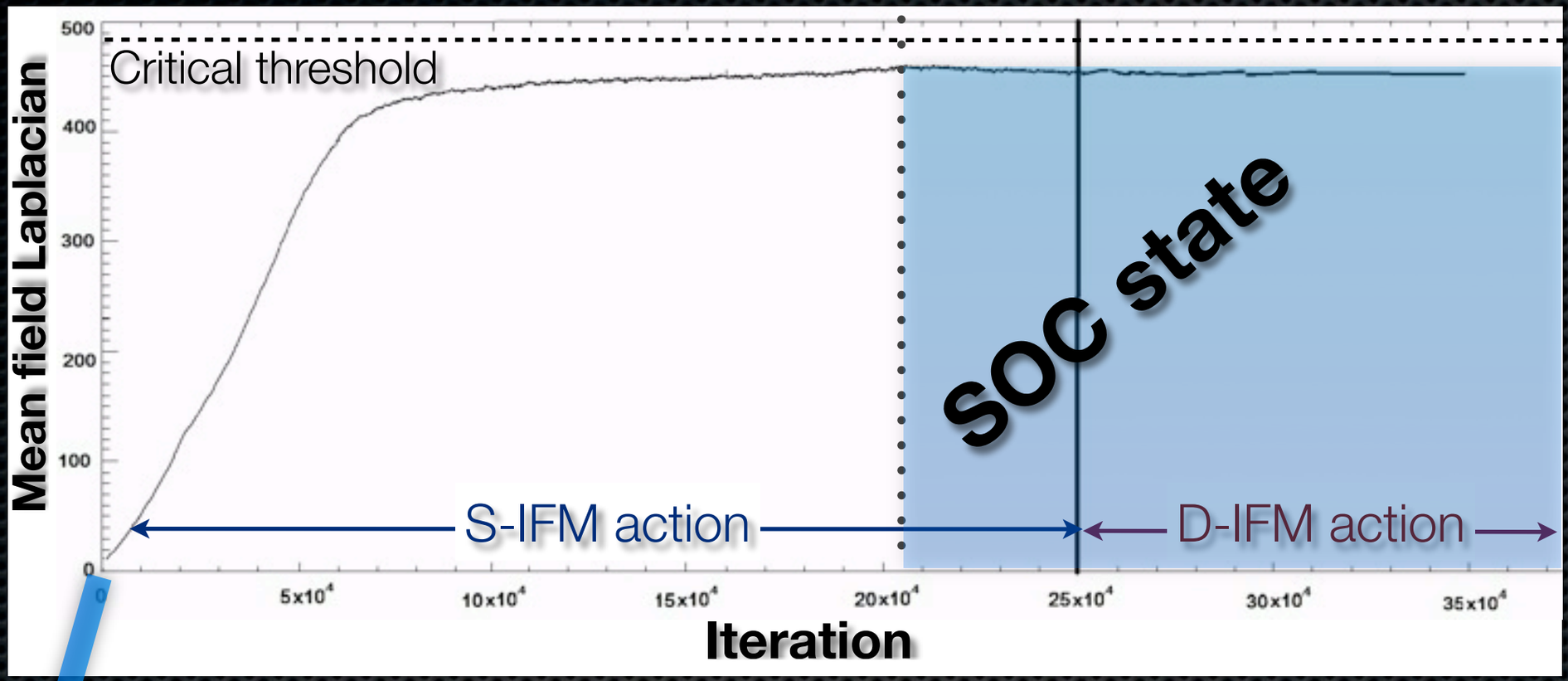

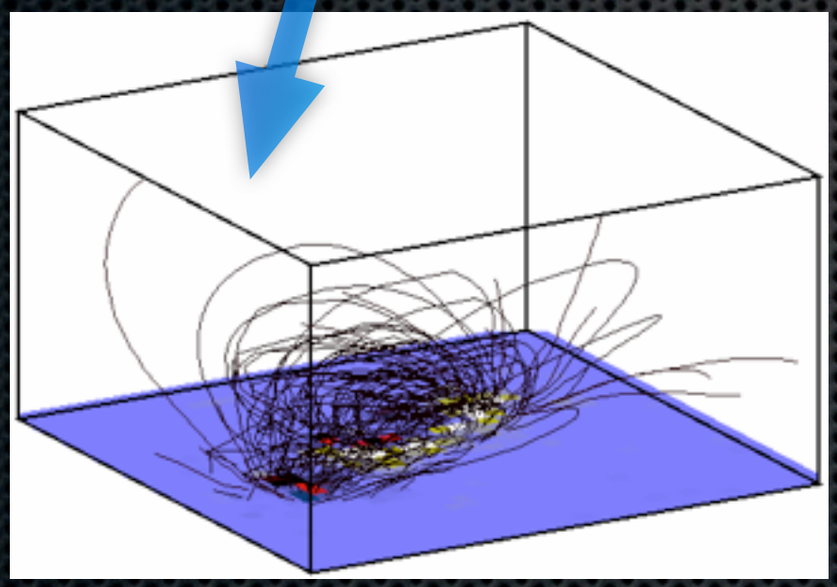

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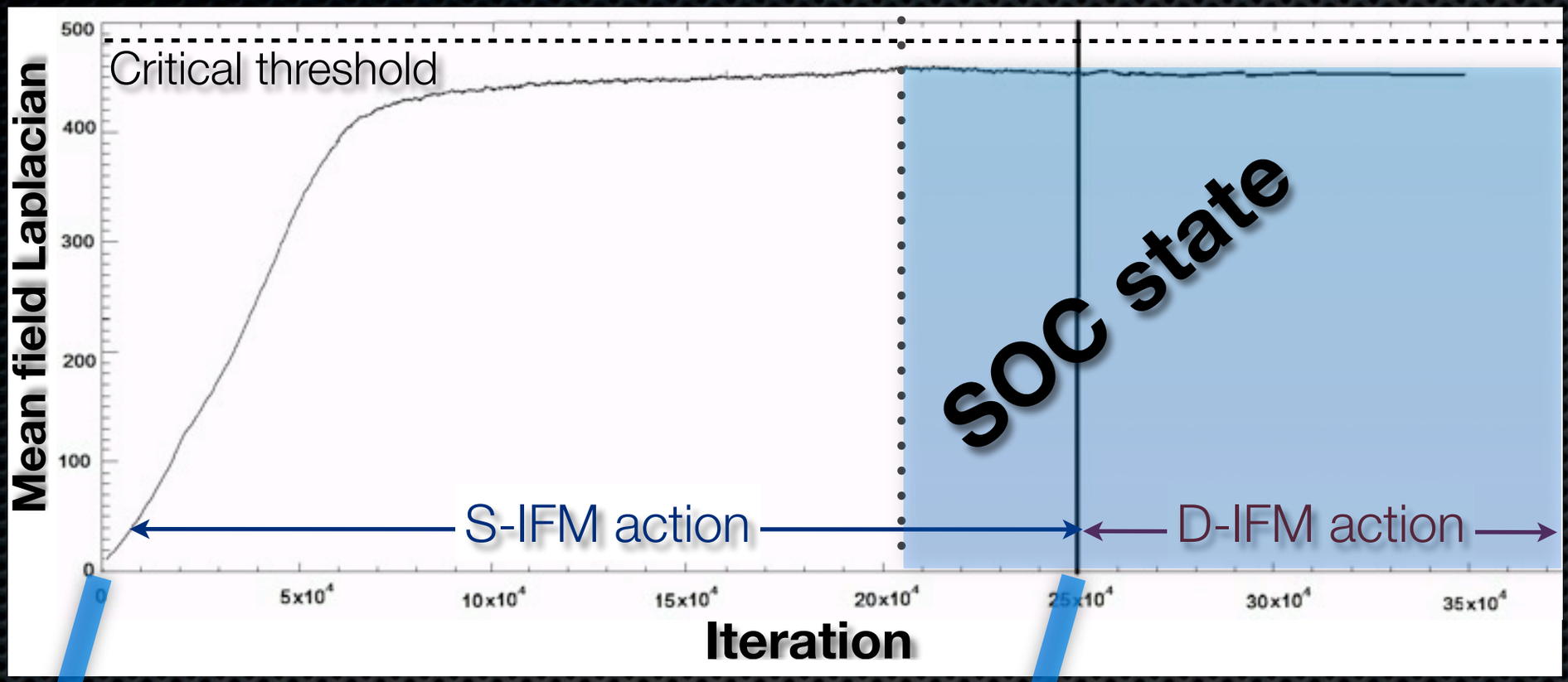

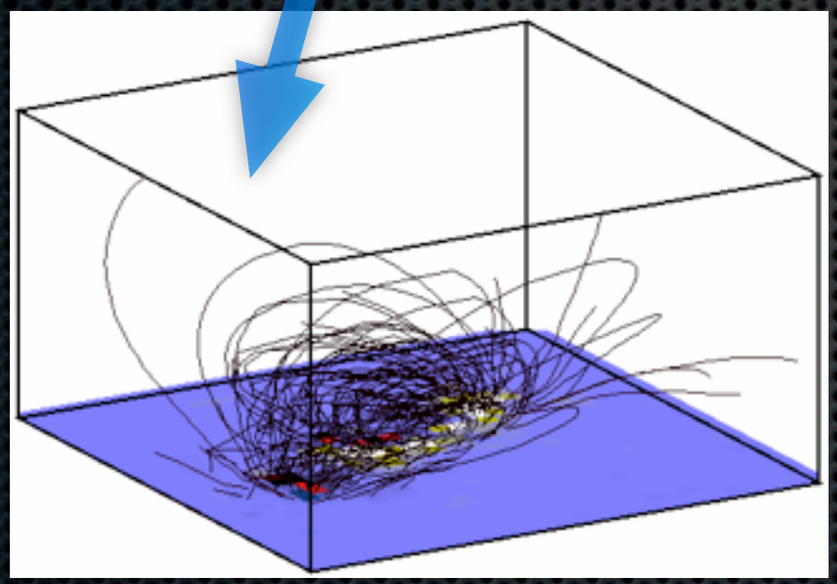

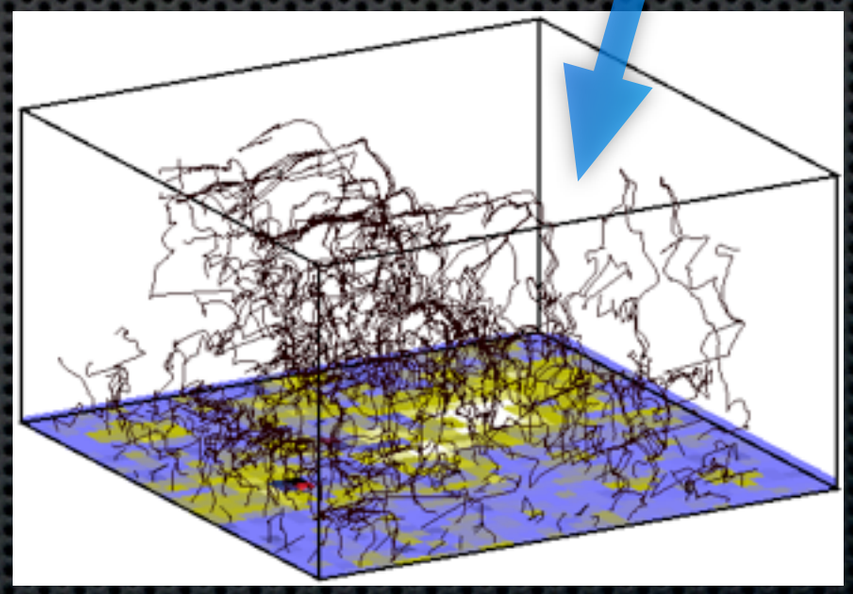

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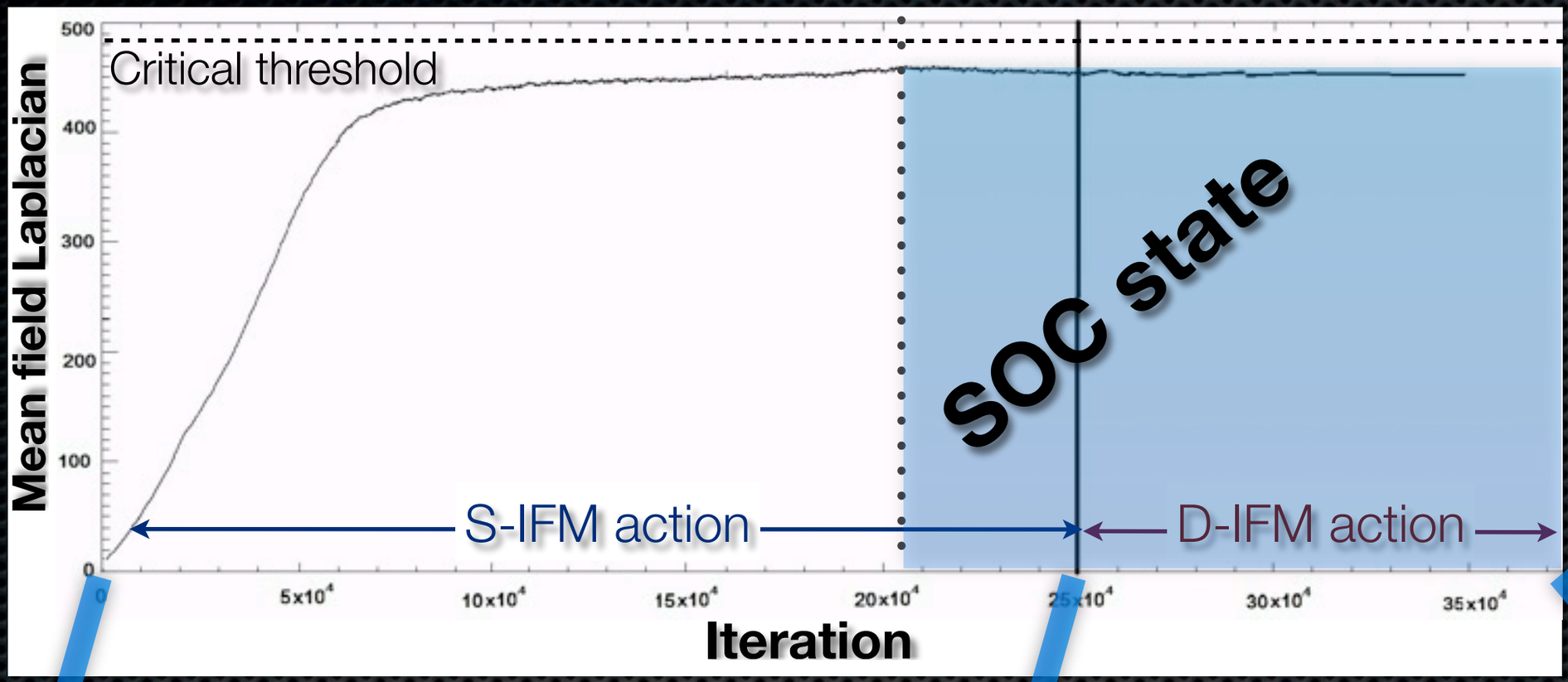

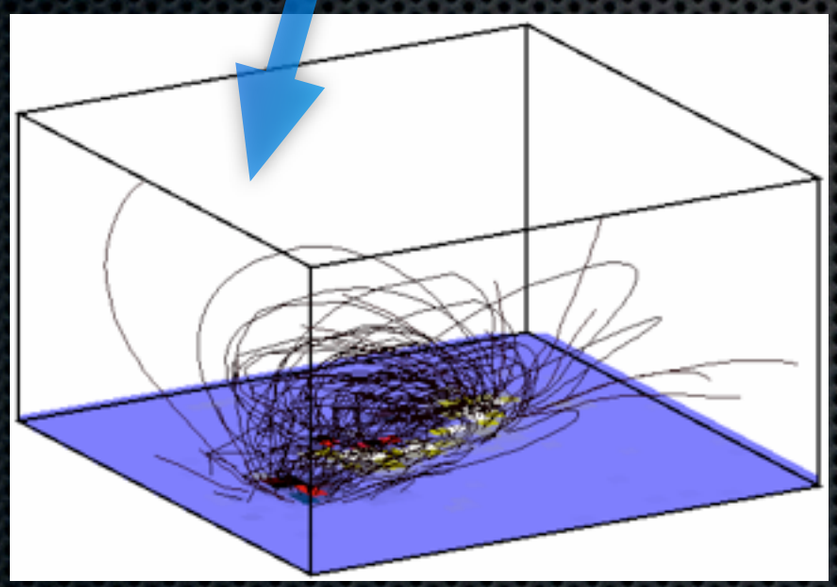

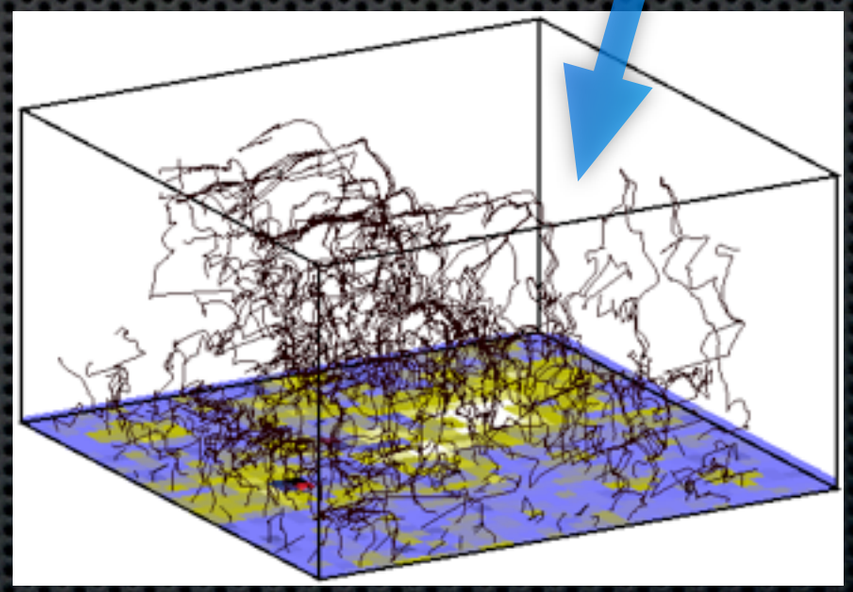

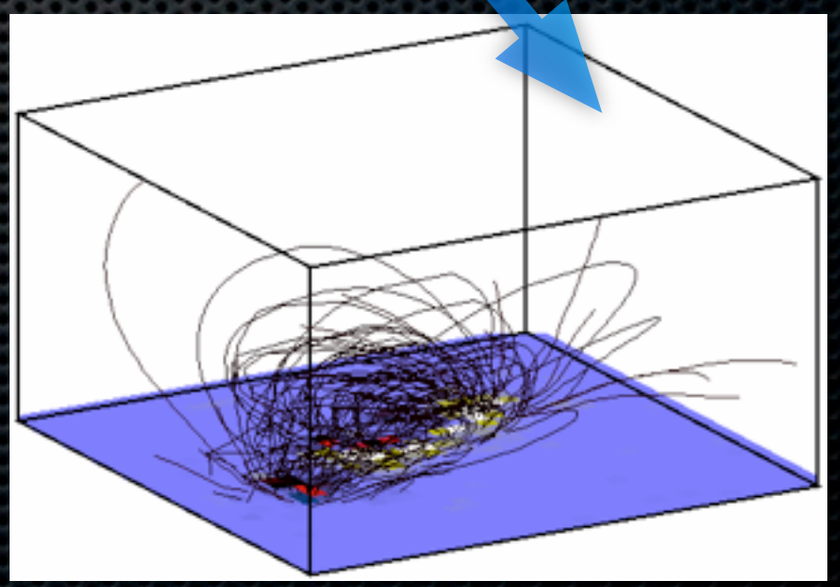

Test seems successful!

OPEN QUESTIONS

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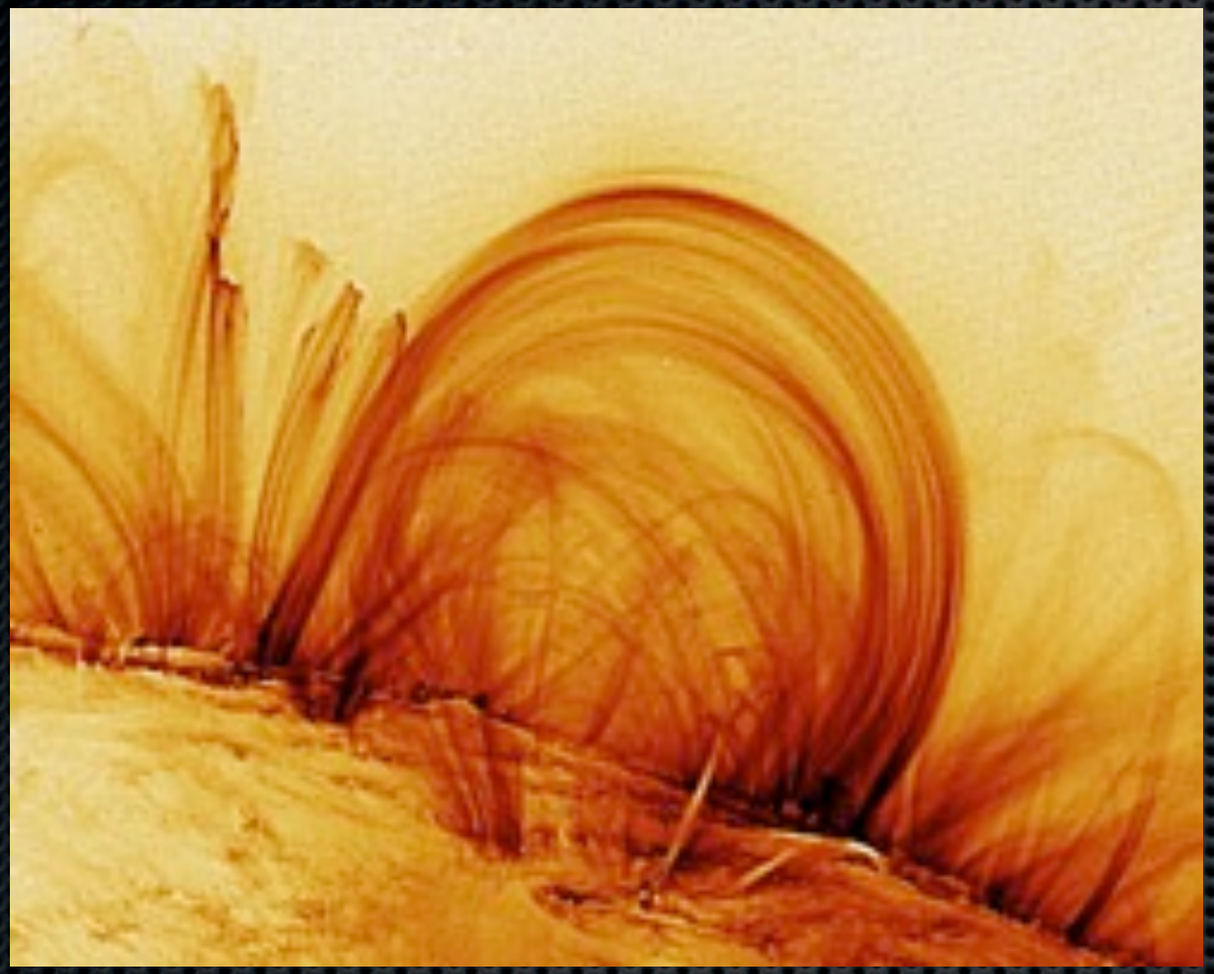
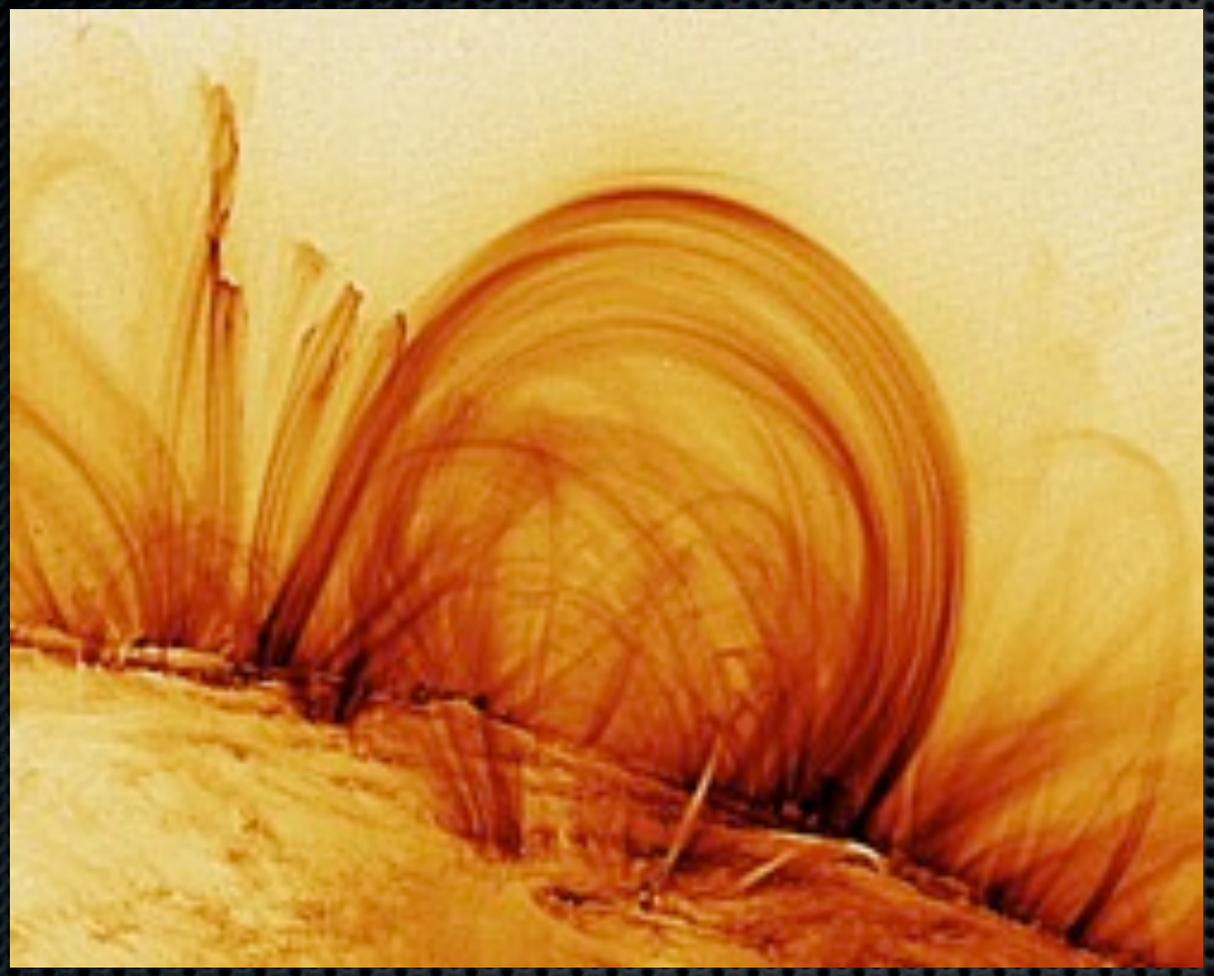


Courtesy: TRACE

OPEN QUESTIONS

- Magnetic fields of eruptive ARs may be on a SOC state
- But what is the case for non-eruptive ARs?
- Or the quiet Sun?



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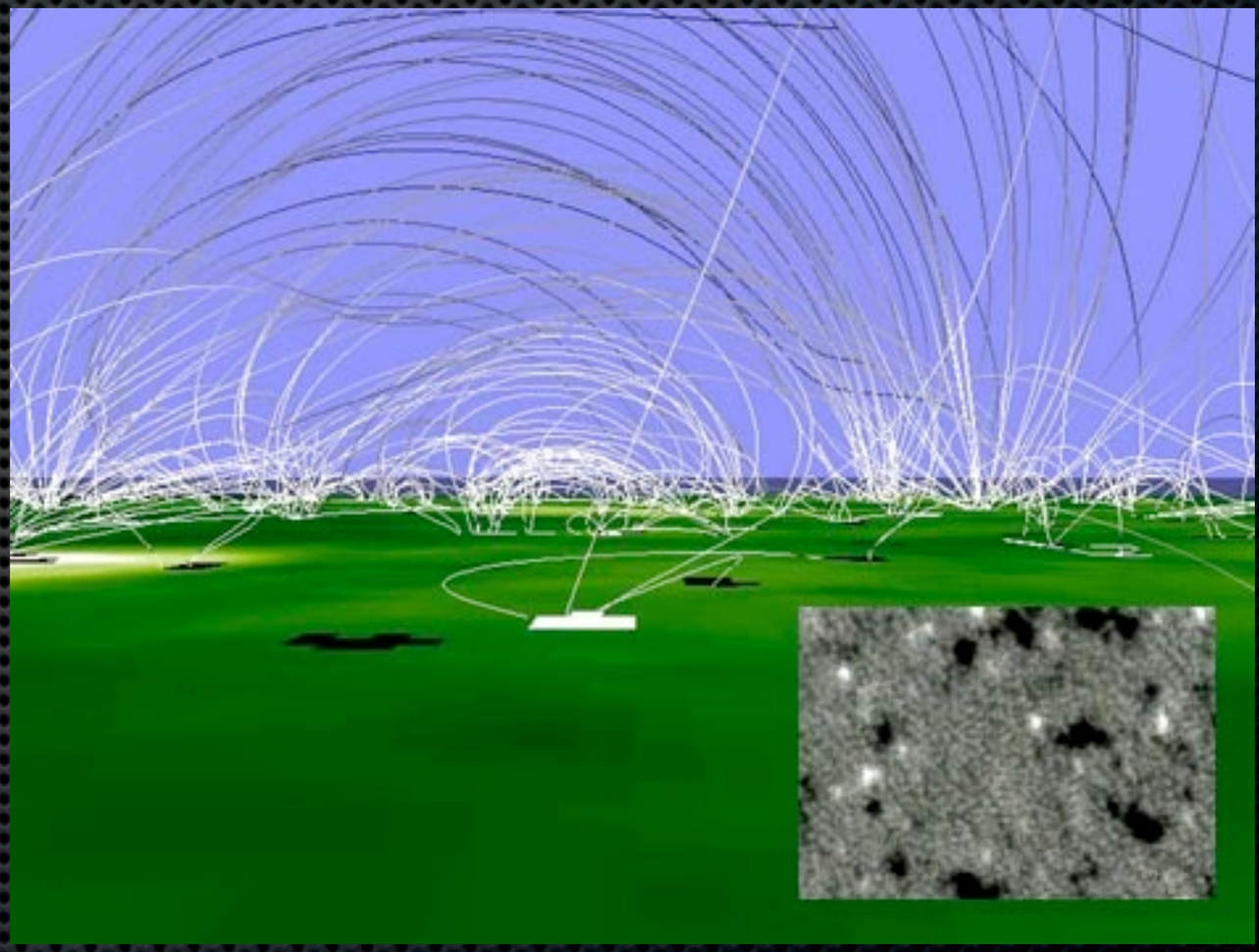

Courtesy: SOHO

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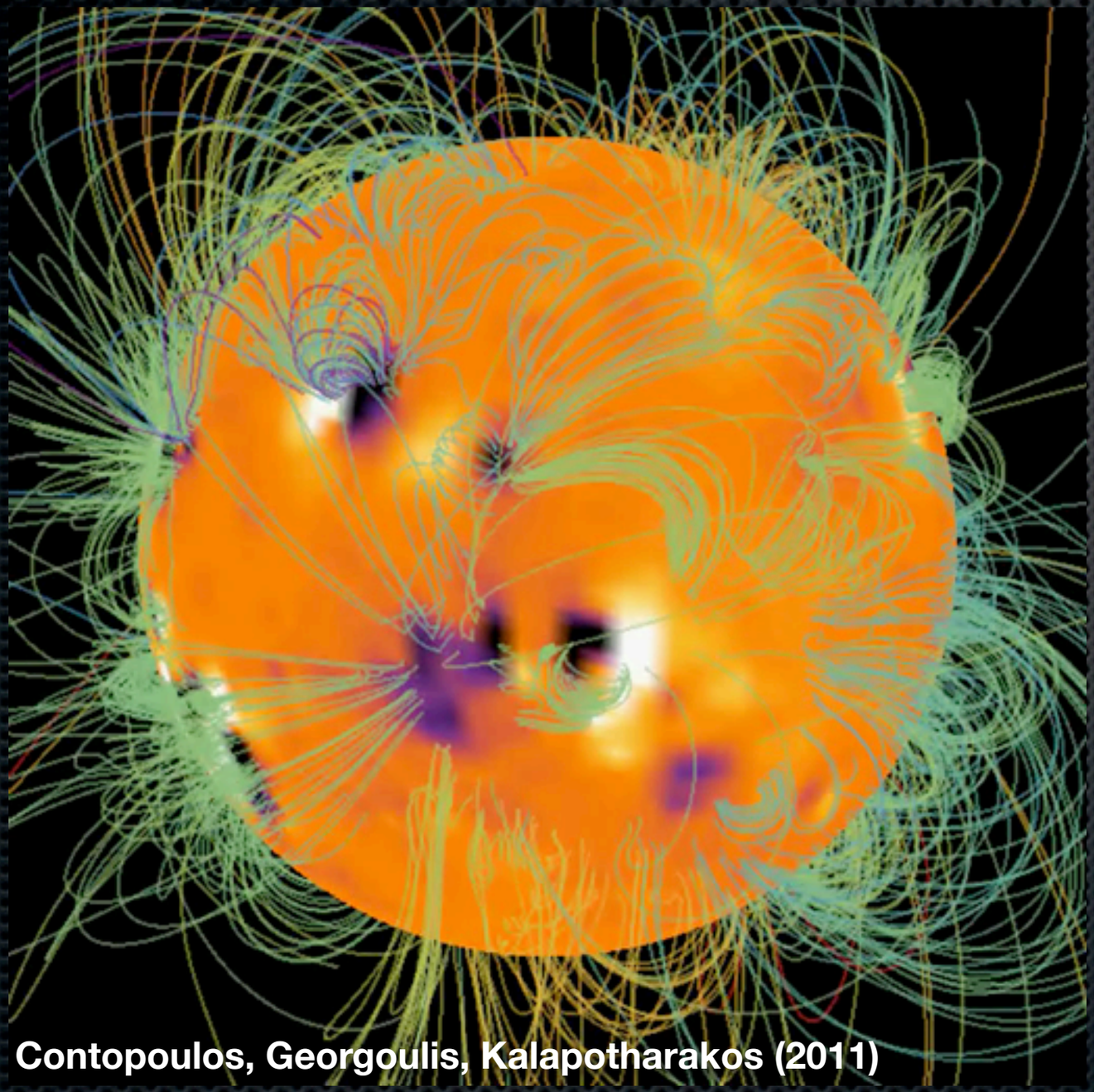

Contopoulos, Georgoulis, Kalapotharakos (2011)

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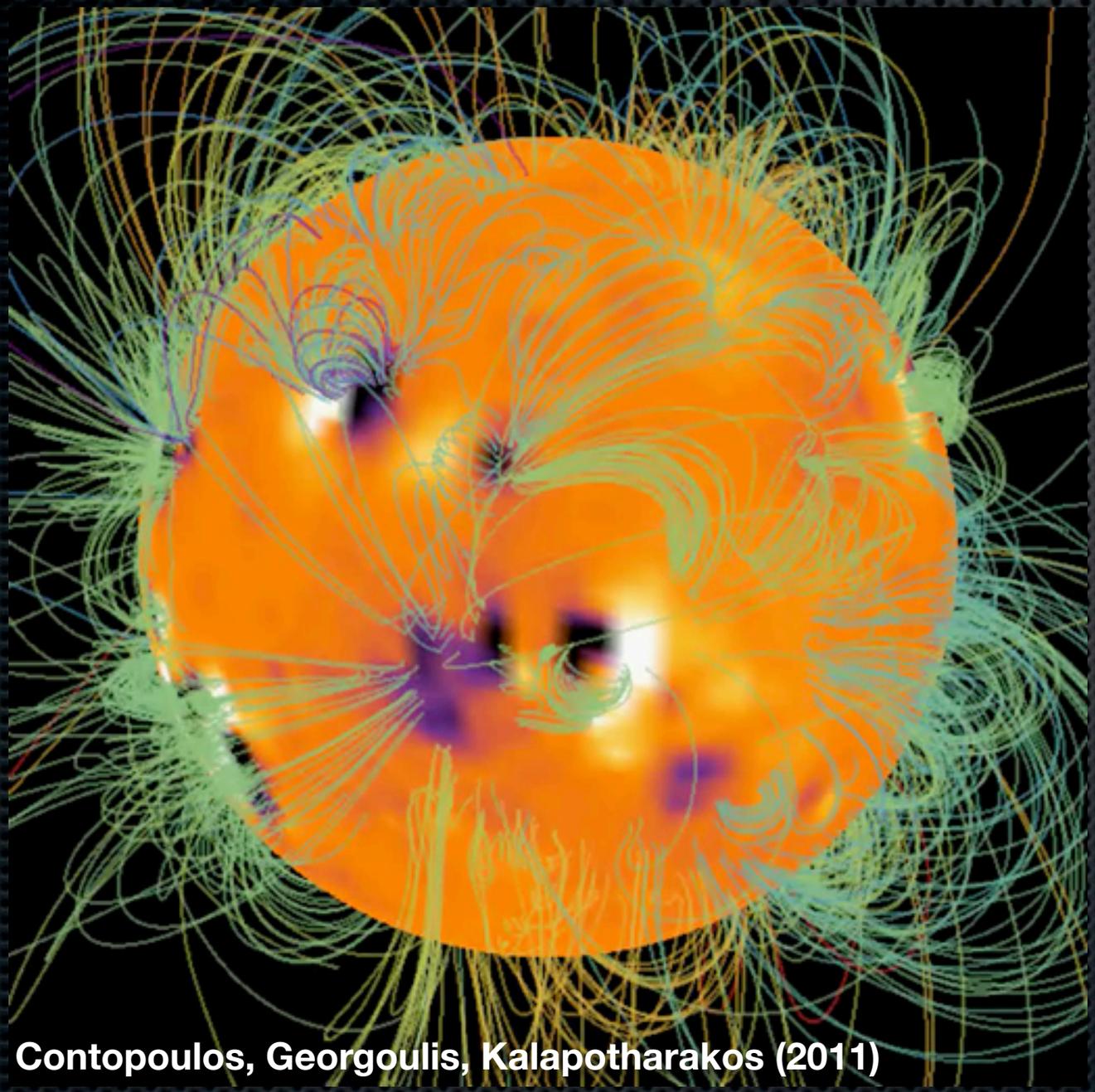

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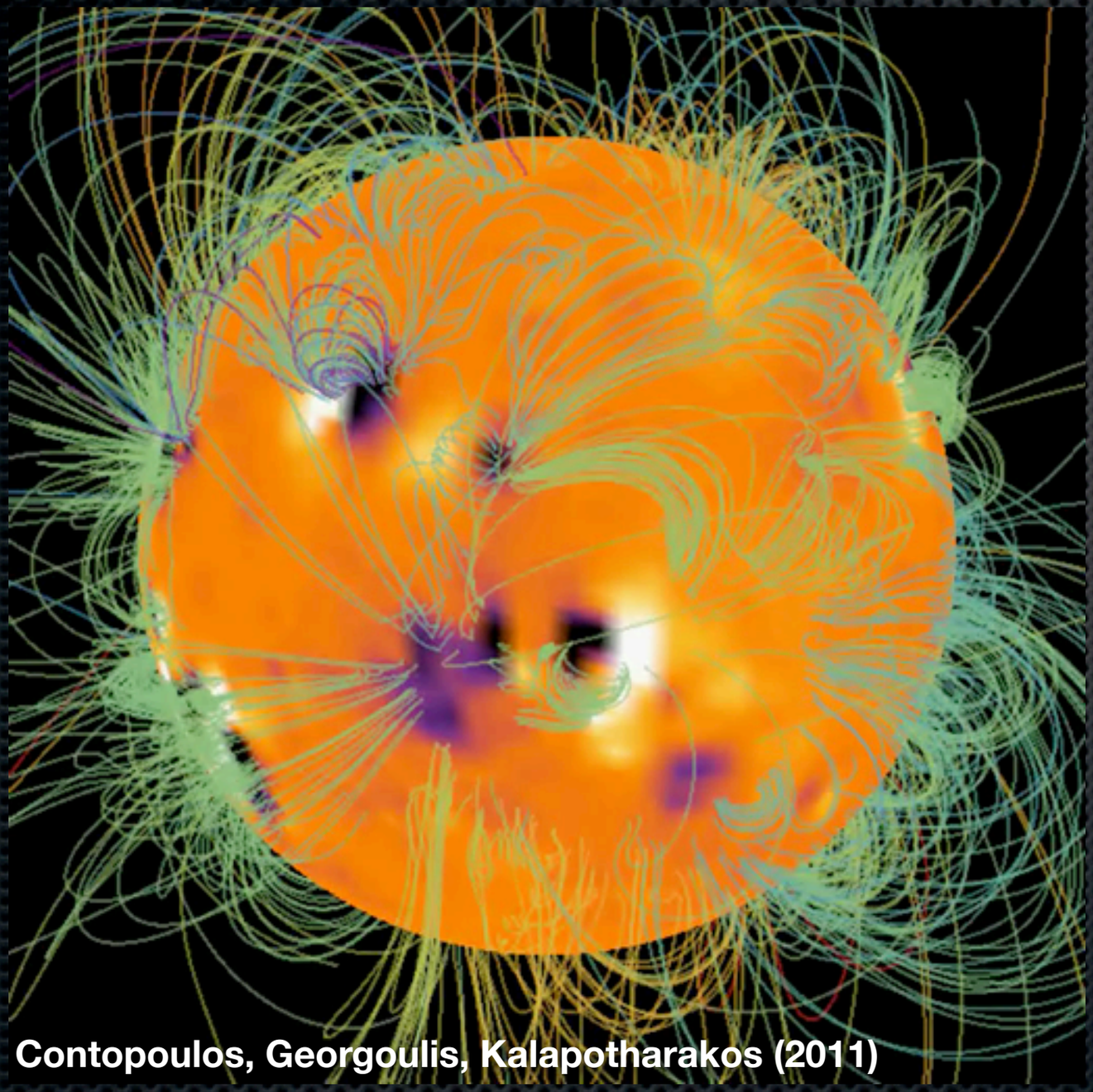

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Yet unclear how far could such an interpretation reach, if successful

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- Open questions remain for non-eruptive ARs, quiet-Sun magnetic fields, and the Sun as a whole - more effort is necessary