ΑΚΑΔΗΜΙΑ ΑΘΗΝΩΝ

MAGNETIC HELICITY IN THE SOLAR ATMOSPHERE: MUCH GAINED, STILL A LOT TO LEARN

MANOLIS K. GEORGOULIS

RCAAM OF THE ACADEMY OF ATHENS

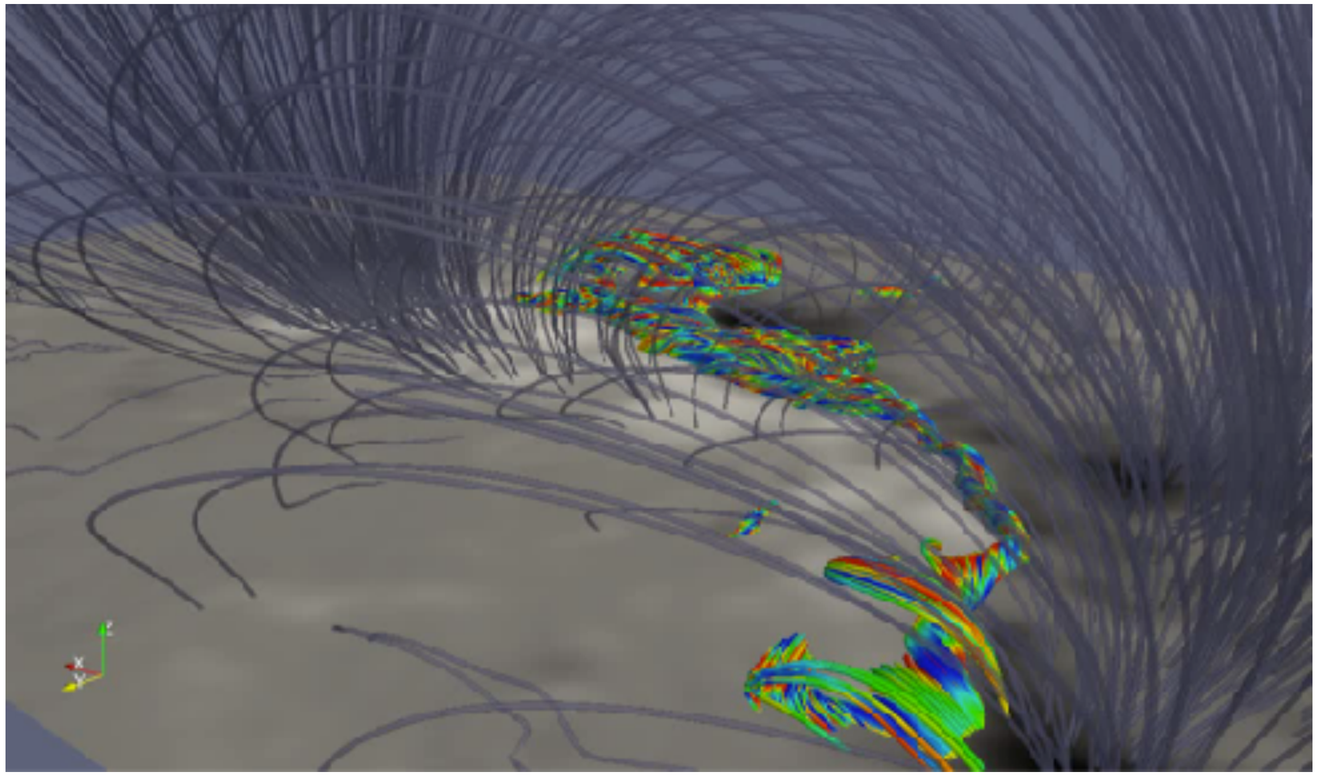
From Pioneering Thinking and Reasoning …

- Gauge-invariance theorem by Woltjer (1958) $\int_V \boldsymbol{A}\cdot \mathrm{curl}\, \boldsymbol{A} dV = \mathrm{constant},$
- Taylor's min-energy works in the seventies (1974, 1976)
- Mitch's decompositions / flux calculations in the eighties (1984)
- N. Seehafer's current helicity in1990
- Calugareanu invariant of Moffatt & Ricca (1992)
- Assertion on CMEs by B. C. Low (1994)
- Alexei's major observational finding in 1995
- D. Rust's and A. Kumar's works in 1996
- D. Canfield's and co. work on sigmoids in 1999

Many researchers in the 2000s and 2010s, aiming toward a practical calculation: H. Zhang, K. Kusano, P. Demoulin, A. Nindos, B. J. LaBonte, M. Zhang, K. Kuzanyan, E. Pariat, G. Valori, S. Regnier, J. Thalmann, A. Yeates, Y. Guo …

… to Recent Developments

- Formation of helical magnetic flux ropes <u>prior</u> to eruptions



Courtesy: George Chintzoglou (LMSAL)

Also, Chintzoglou et al., (2015);
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(see also works on helical flux ropes by S. Gibson)

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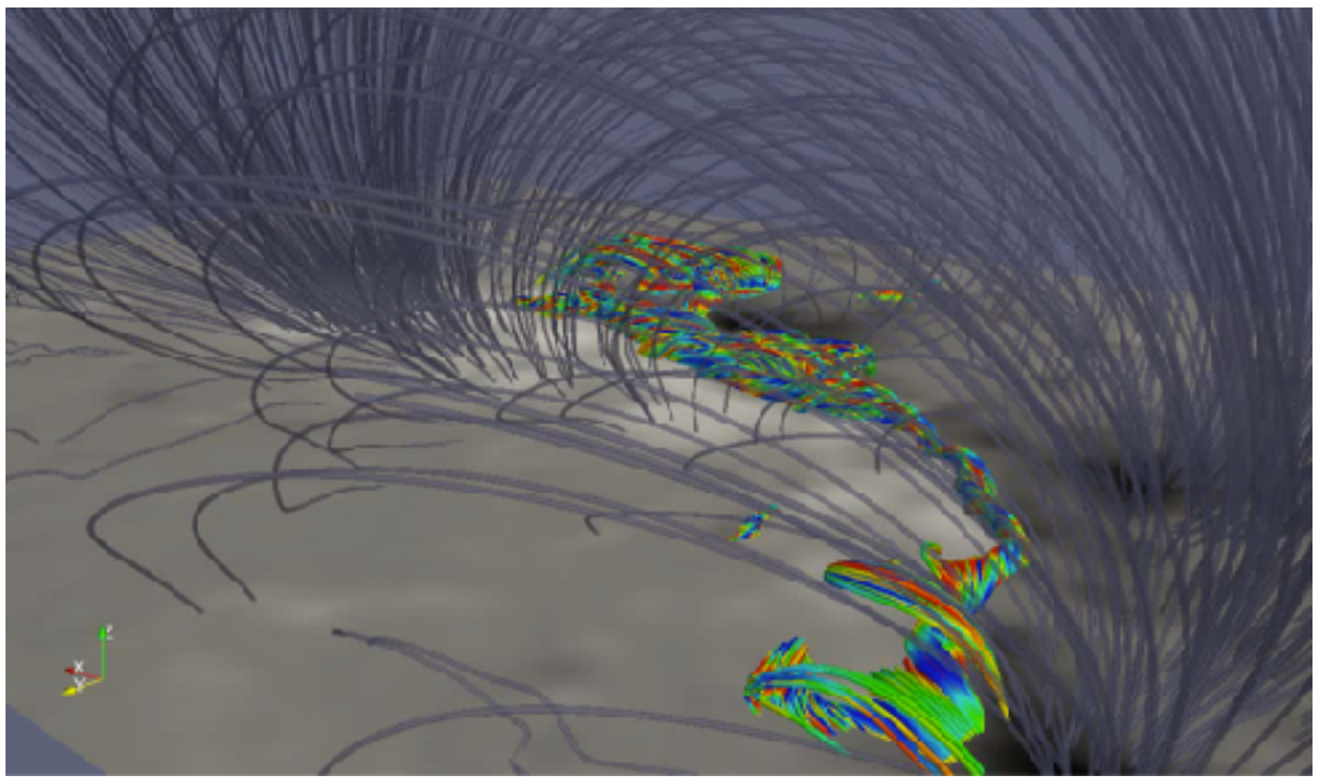

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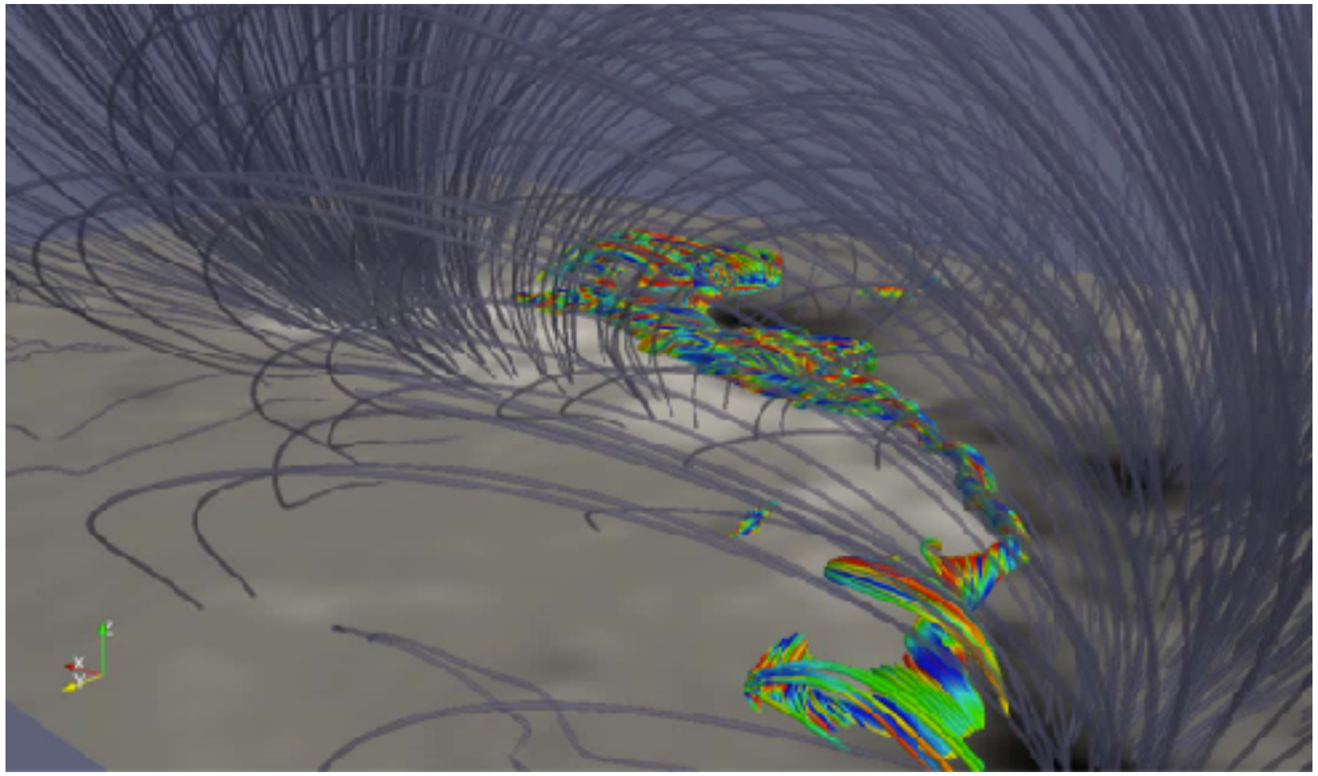

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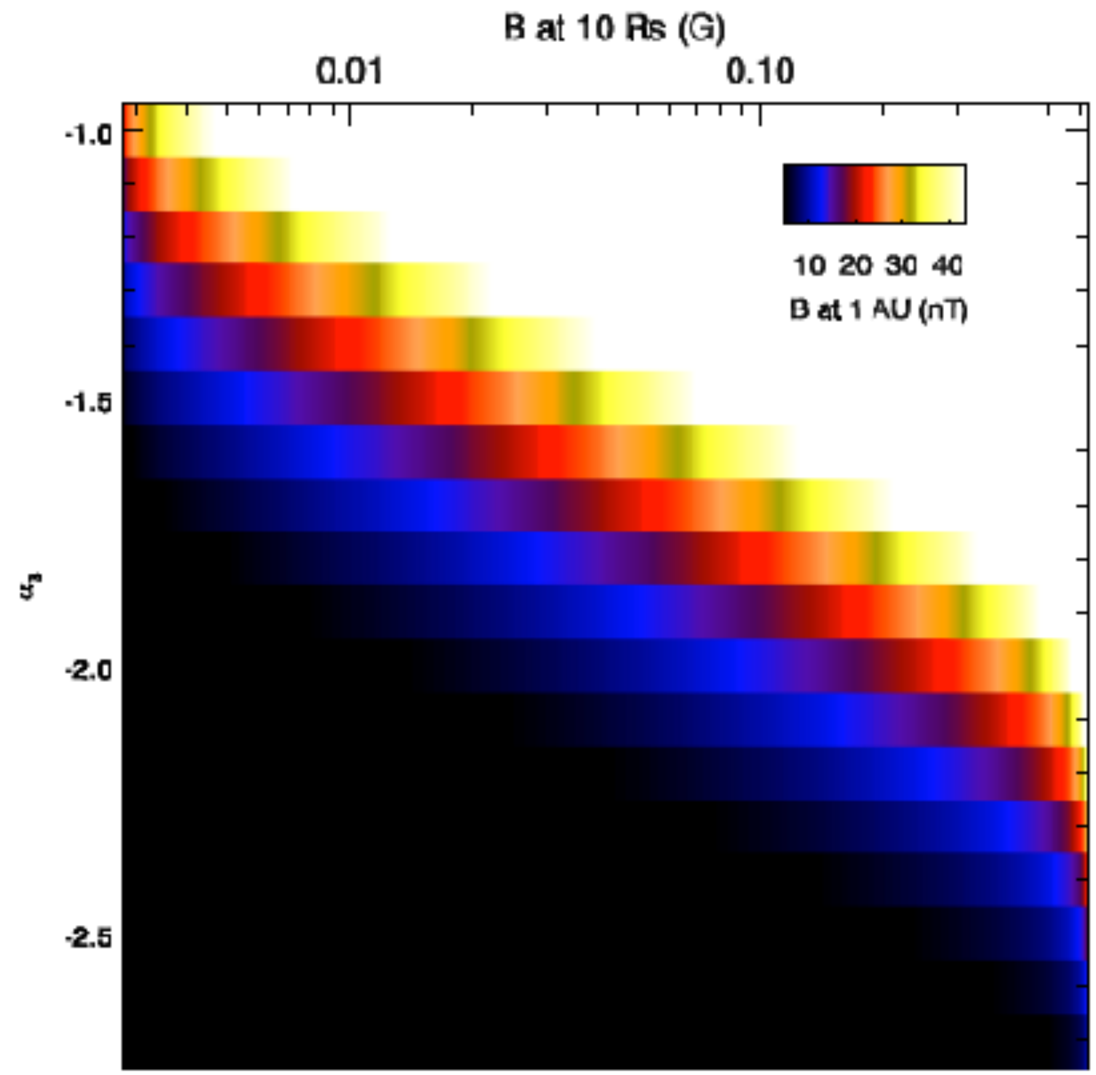
- Conservation of magnetic helicity in CMEs and extrapolation to get the CME Bz at L1



Patsourakos & Georgoulis (2016)

(see also works on helical flux ropes by S. Gibson)

Instantaneous Magnetic Helicity Budget vs. Helicity Injection Rate

- Knowledge of the 3D field above a boundary allows inference of the helicity budget

$$H = \int_V \mathbf{A} \cdot \mathbf{B} dV$$

gauge-dependent in general

- Subtracting the reference helicity from the potential field, allows calculation of the relative magnetic helicity

$$H = \int_V (\mathbf{A} + \mathbf{A_p}) \cdot (\mathbf{B} - \mathbf{B_p}) dV$$

and alternative approaches, such as the field-line helicity (e.g., Aly, FDR, Lowder & Yeates, 2017)

$$\mathcal{A}(L) = \int_{L(x)} \frac{\mathbf{A} \cdot \mathbf{B}}{|\mathbf{B}|} d\ell$$

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$$\mathcal{A}(L) = \int_{L(x)} \frac{\mathbf{A} \cdot \mathbf{B}}{|\mathbf{B}|} d\ell$$

- On the other hand, knowledge of the velocity field and the magnetic field vectors on the boundary plane allows evaluation of the Poynting theorem for relative magnetic helicity (e.g., Berger & Field, 1984; Kusano et al., 2002)

$$\frac{dH}{dt} = 2 \int_S \mathbf{A} \times (\mathbf{u} \times \mathbf{B}) \cdot \hat{\eta} dS$$

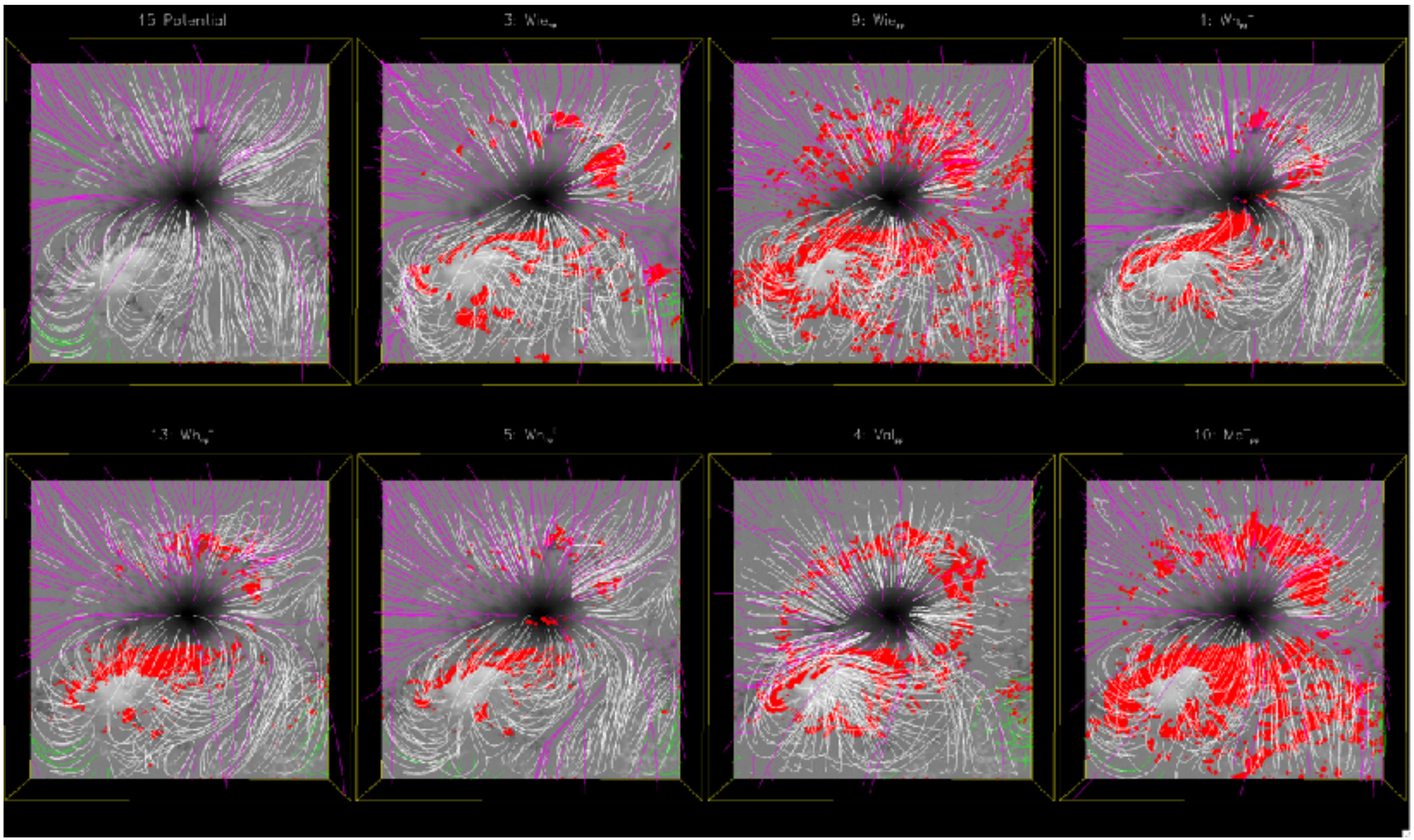
and its practical implementation by Demoulin & Berger (2003):

$$\frac{dH}{dt} = -2 \int_S (\mathbf{A_p} \cdot \mathbf{u_{ct}}) B_n dS$$

- Then the relative helicity is obtained by time integration of (dH / dt)

However, there are Caveats and Shortcomings in Both Approaches

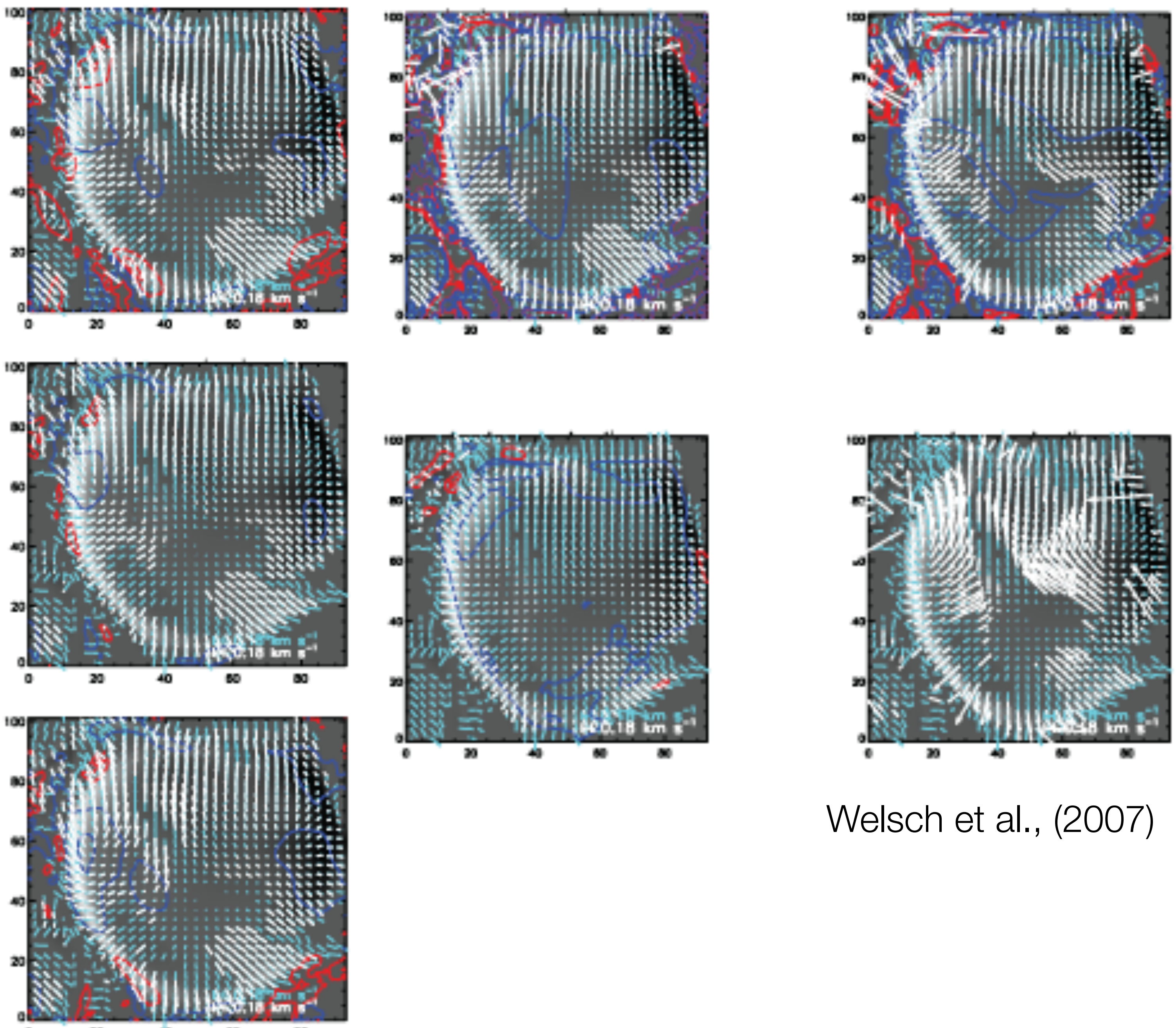
- The unmeasured coronal field is ambiguous and non-unique from 3D field extrapolations, thus having an unknown effect on helicity



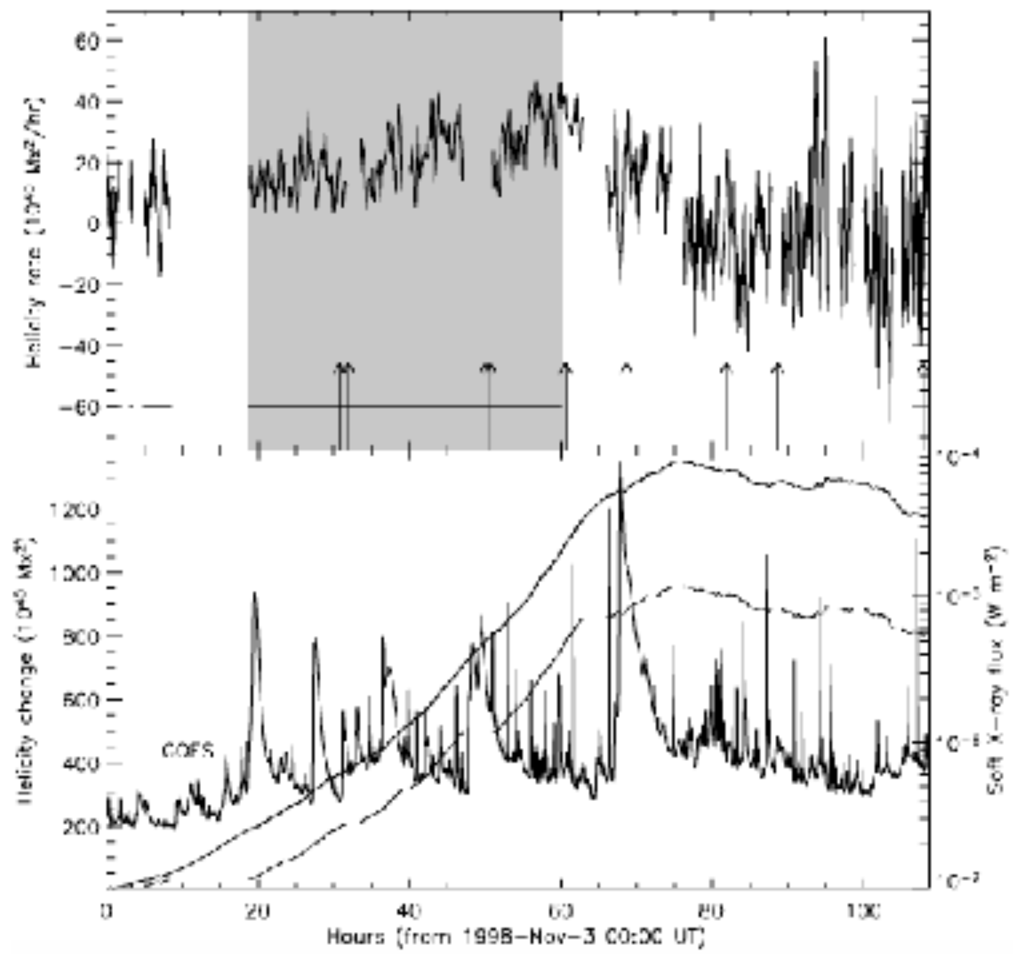
Schrijver et al., (2008)

However, there are Caveats and Shortcomings in Both Approaches

- … while the velocity field vector on the boundary is also unknown and ambiguous, plus helicity injection rate calculations lack a point of reference



Welsch et al., (2007)

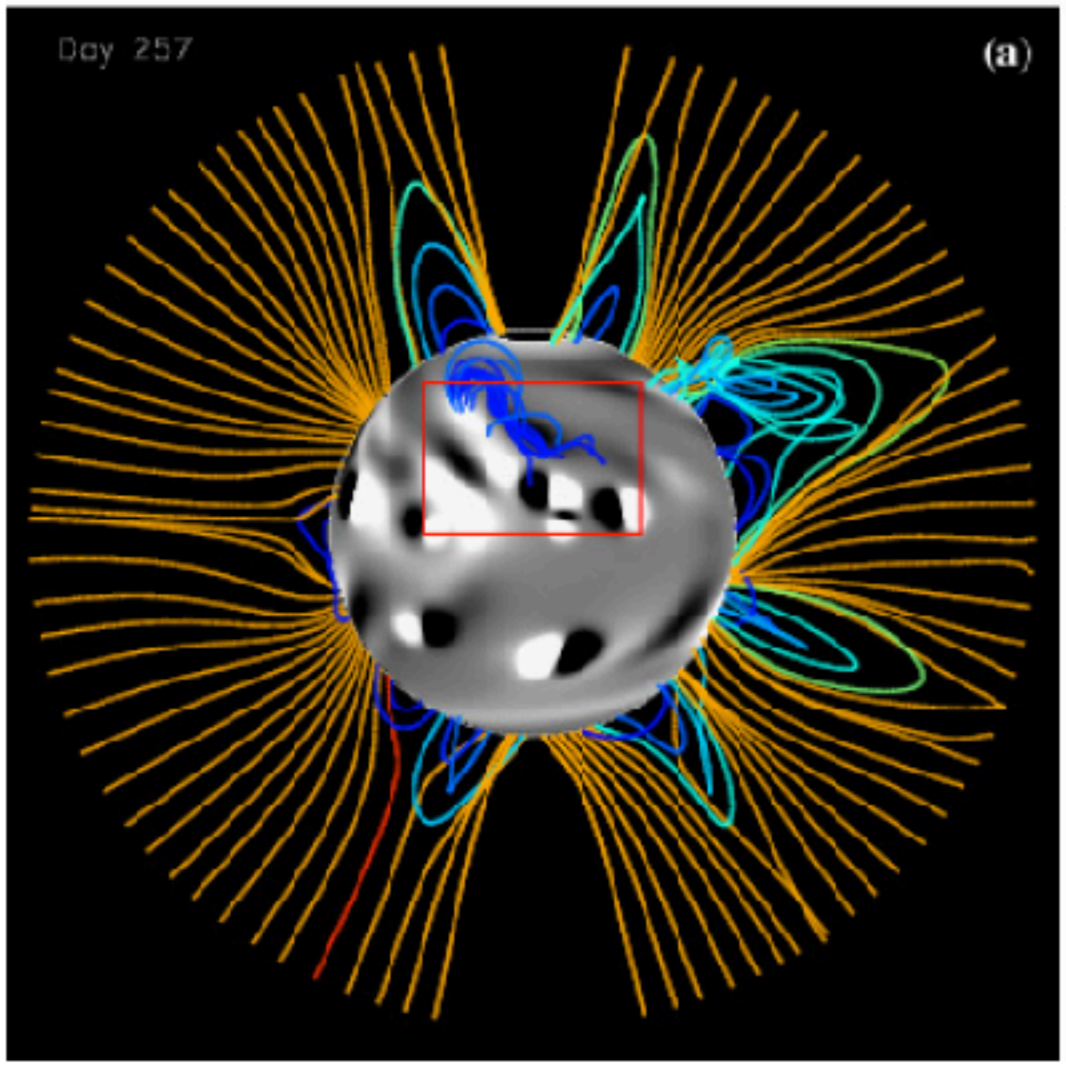


Nindos, Zhang & Zhang, (2003)

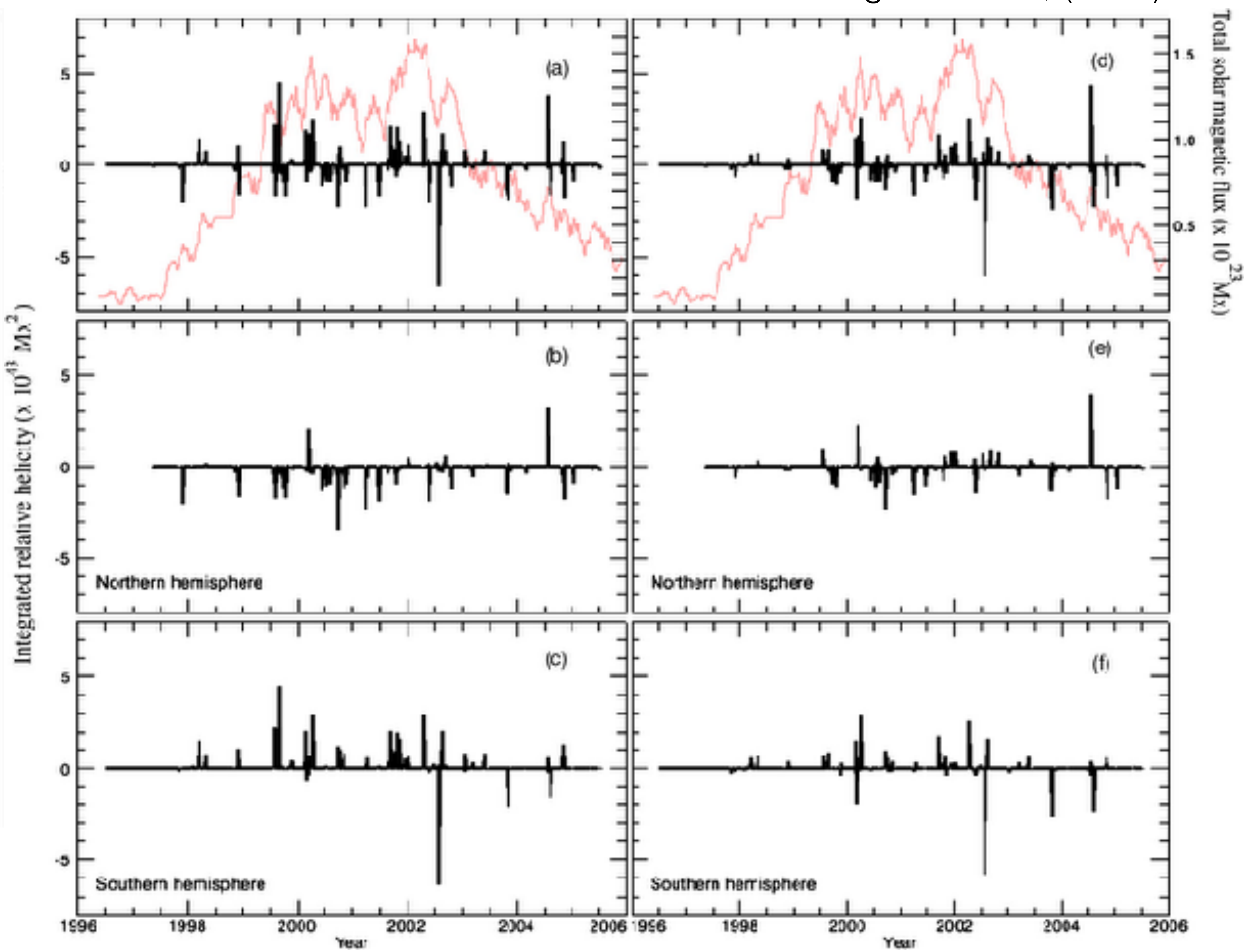
Helicity Between Global and Local Solar Scales

- Solar magnetic helicity is a global quantity, but is mostly contributed by local (i.e., active region) scales

Georgoulis et al., (2009)



Yeates et al., (2008)



- 80% of helicity stems from peculiar active-region flows; the rest from solar differential rotation
- > 99% of helicity stems from active regions; the rest from the quiet Sun

How Can We Reconcile Between Scales, Uncertainties, Caveats and Shortcomings?

- Treat (relative) magnetic helicity self-consistently with (free) magnetic energy
- If possible, disentangle detailed knowledge of the 3D field from calculation
- Define test cases — assess similarities and differences between methods

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LFF field approach

$$E = \mathcal{R}_\ell \lambda^2 \alpha^2 E_p$$

$$H = 8\pi \mathcal{R}_\ell \lambda^2 \alpha E_p$$

$$\boxed{H = \frac{8\pi}{\alpha} E}$$

α = const. ; λ —> length element

$$\mathcal{R}_\ell = \frac{1}{2} \sum_{l=1}^{n_x} \frac{\sum_{m=1}^{n_y} |b^2_{u_l;v_m}|/(u_l^2+v_m^2)^{3/2}}{\sum_{m=1}^{n_y} |b^2_{u_l;v_m}|/(u_l^2+v_m^2)^{3/2}}$$

Georgoulis & LaBonte (2007)

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NLFF field approach

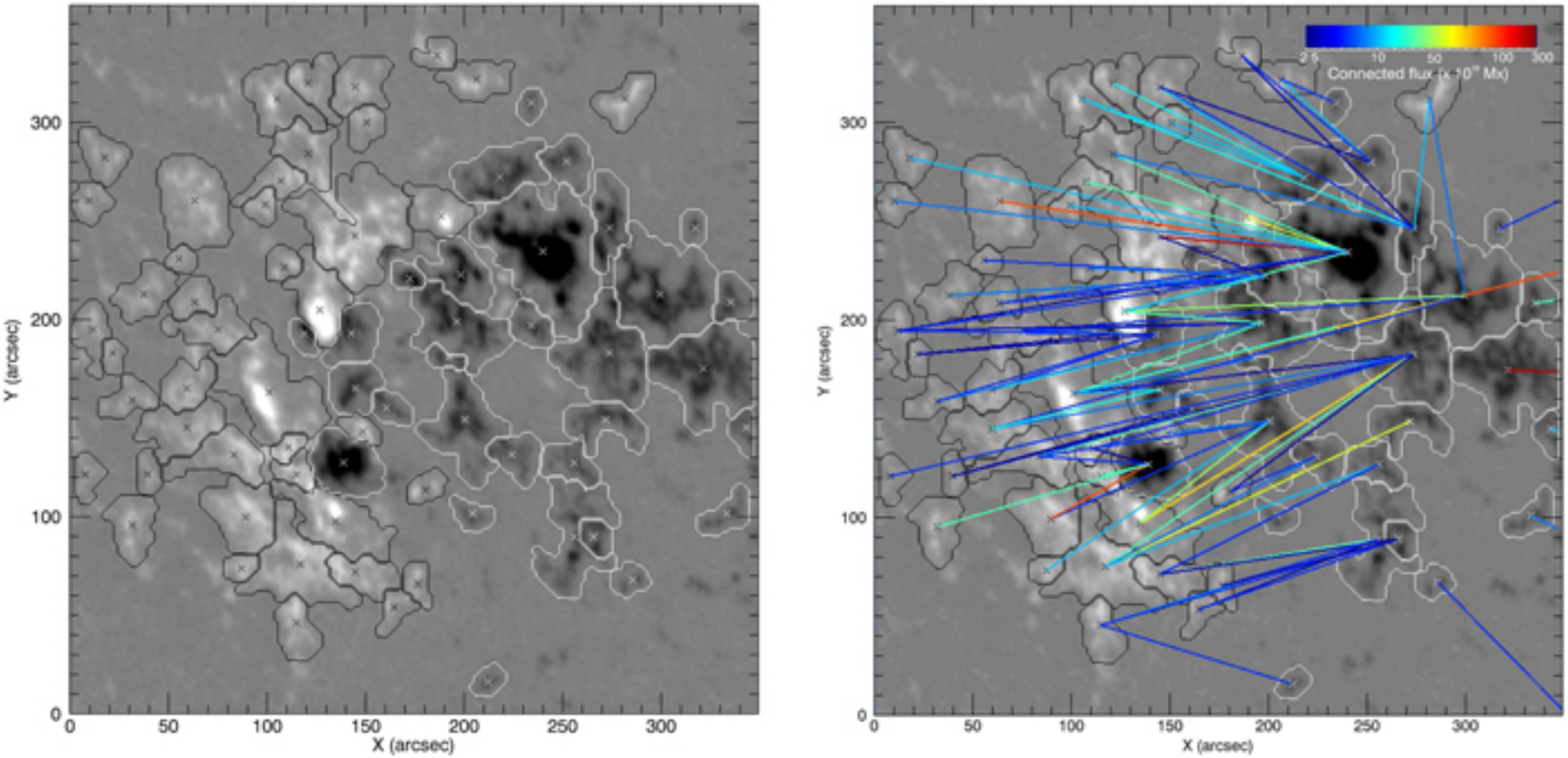
$$E = \lambda^2 A \sum_{l=1}^{N} \alpha_l^2 \Phi_l^{2\delta} + \frac{1}{8\pi} \sum_{l=1}^{N} \sum_{m=1_{l \neq m}}^{N} \alpha_l \mathcal{L}_{lm}^{arch} \Phi_l \Phi_m$$

$$H = 8\pi \lambda^2 A \sum_{l=1}^{N} \alpha_l \Phi_l^{2\delta} + \sum_{l=1}^{N} \sum_{m=1_{l \neq m}}^{N} \mathcal{L}_{lm}^{arch} \Phi_l \Phi_m$$

- N flux tubes ; λ —> length element; A, δ const.
- E is a lower limit free energy for a given connectivity that ignores intertwining of flux tubes in the corona (based on the analysis of Demoulin et al., (2006)

Georgoulis et al., (2012)

Assessment of a Skeleton Connectivity, <u>Without</u> a Detailed 3D Knowledge of the Magnetic Field

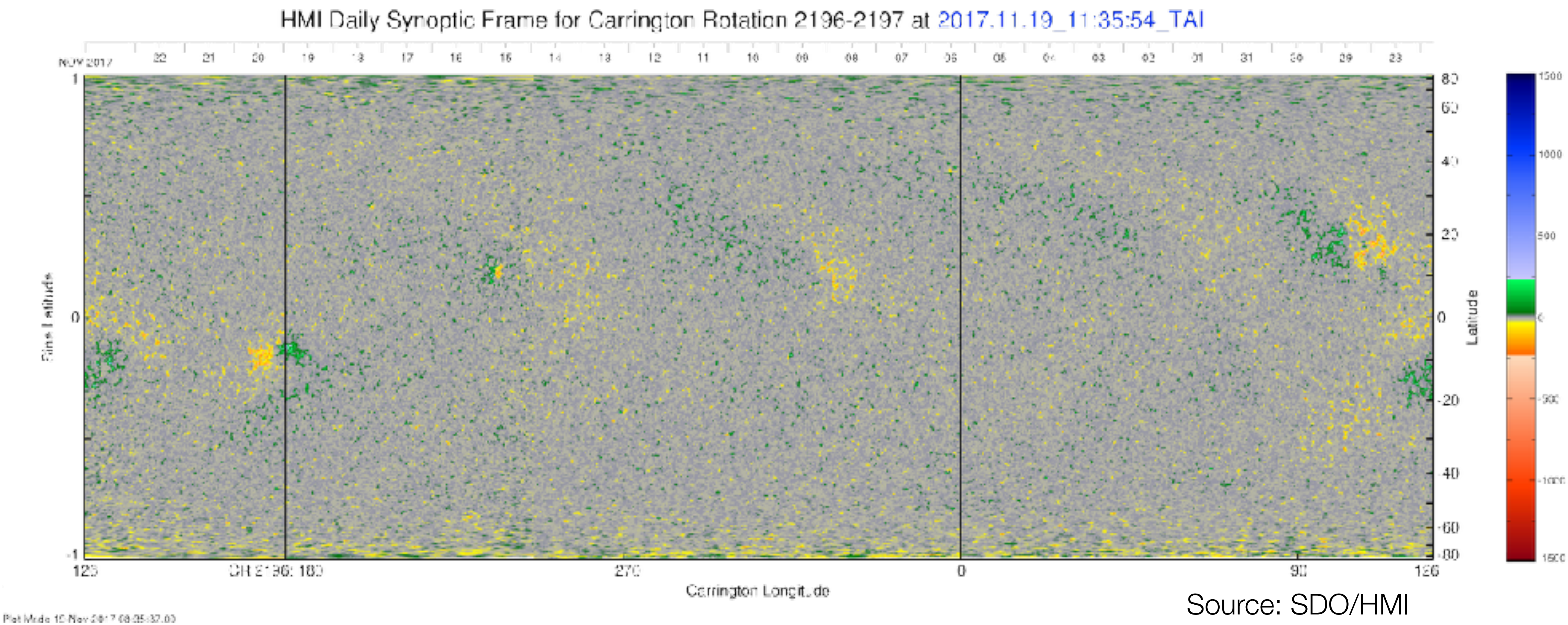


Barnes et al., (2016)

- The normal photospheric field component is partitioned; each partition assumed a different flux tube
- Connectivity inferred via a simulated annealing scheme favoring shortest connections, i.e., alongside polarity inversion lines

Can This Approach be Applied to Global Scales?

- It could, conceivably, utilizing spherical geometry on a synoptic vector magnetogram



Source: SDO/HMI

- This scheme would find the connections within active regions first, before connecting largest scales

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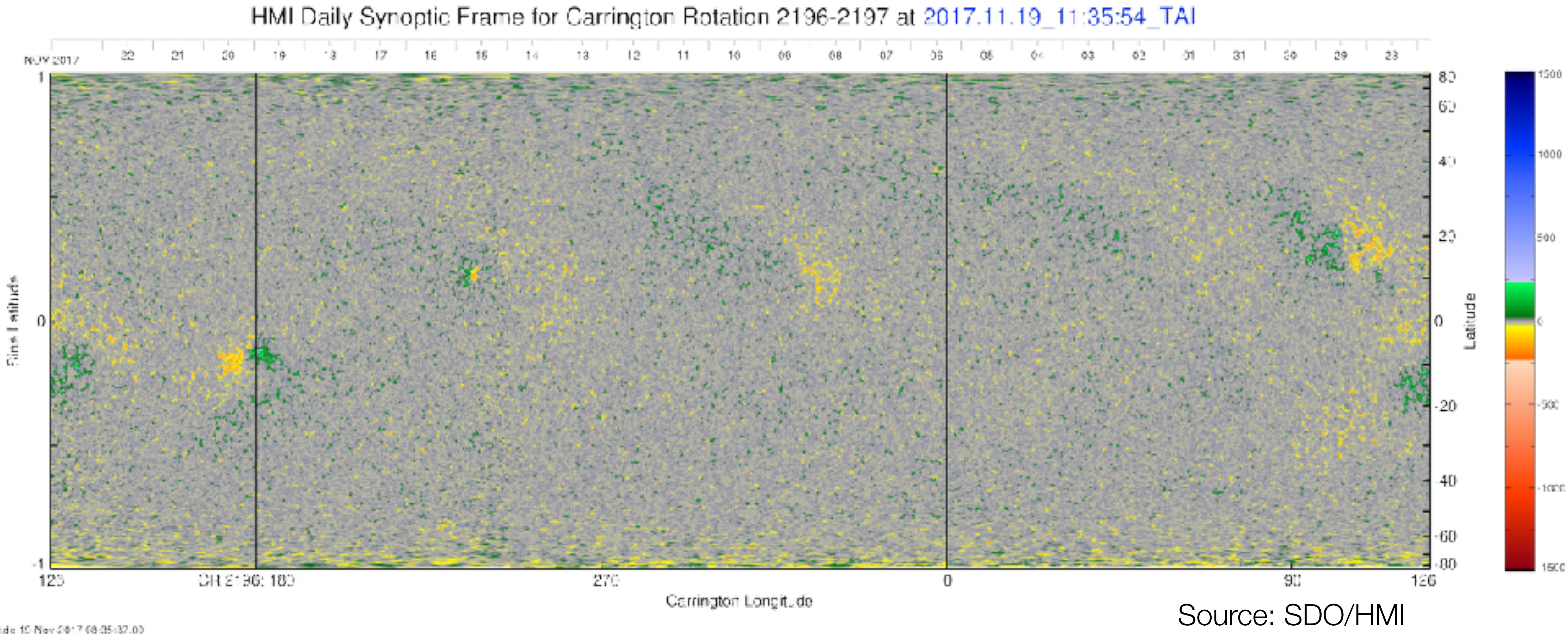

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- This scheme would find the connections within active regions first, before connecting largest scales

This remains to be implemented

Testing Helicity Calculation Methods on Synthetic Test Cases

- ISSI Bern team on magnetic helicity and applications (G. Valori & E. Pariat, Team Leaders)

Finite volume (FV)

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

see Eq. (3)

- Requires $\mathbf{B}$ in $\mathcal{V}$ *e.g.*, from MHD simulations or NLFFF
- Compute $\mathcal{H}_{\mathcal{V}}$ at one time
- May employ different gauges (see Table 2)

Helicity-flux integration (FI)

$$\frac{\mathrm{d}\mathcal{H}_{\mathcal{V}}}{\mathrm{d}t} = 2 \int_{\partial\mathcal{V}} [(\mathbf{A}_{\mathrm{p}} \cdot \mathbf{B}) v_n - (\mathbf{A}_{\mathrm{p}} \cdot \mathbf{v}_{\mathrm{t}}) B_n]\, \mathrm{d}S$$

- Requires time evolution of vector field on $\partial\mathcal{V}$
- Requires knowledge or model of flows on $\partial\mathcal{V}$
- Valid for a specific set of gauge and assumptions, see Pariat et al. (2017)

Discrete flux-tubes (DT)

$$\mathcal{H} \simeq \sum_{i=1}^{M} \mathcal{T}_i \Phi_i^2 + \sum_{i=1}^{M} \sum_{j=1, j\neq i}^{M} \mathcal{L}_{i,j} \Phi_i \Phi_j,$$

see Eq. (31)

Twist-number (TN)

$$\mathcal{H} \simeq \mathcal{T} \Phi^2$$

see Eq. (32)

- Estimation of the twist contribution to $\mathcal{H}$
- Requires $\mathbf{B}$ in $\mathcal{V}$
- Requires a flux-rope-like structure for computing the twist $\mathcal{T}$

Connectivity-based (CB)

$$\mathcal{H} = A \sum_{i=1}^{M} \alpha_i \Phi_i^{2\delta} + \sum_{l,m=1}^{M} \mathcal{L}_{lm} \Phi_l \Phi_m$$

see Eq. (35)

- Requires the vector field on photosphere at one time
- Models the corona connectivity as a collection of M force-free flux tubes
- Minimal connection length principle

Valori et al., (2016)

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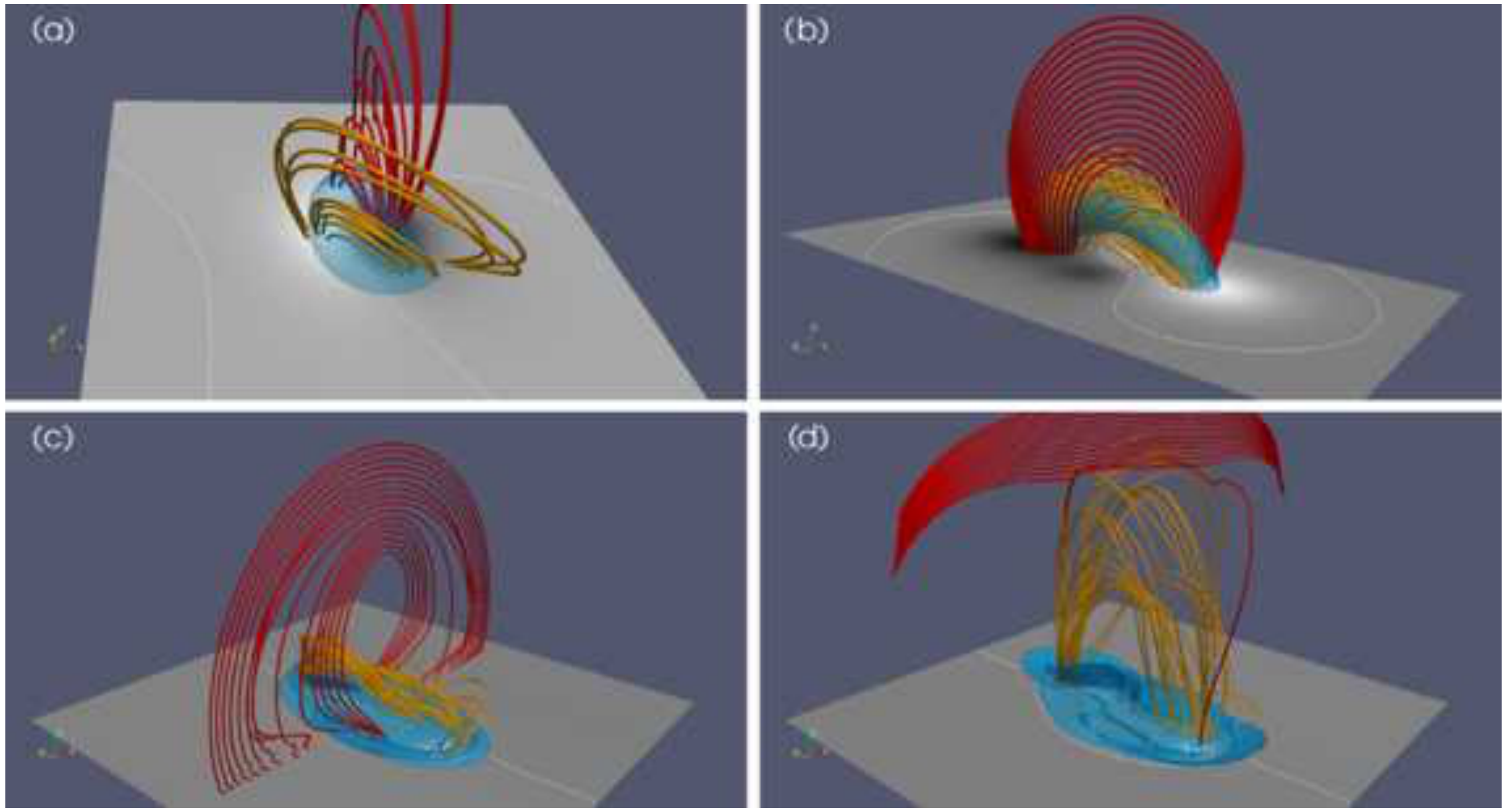
Valori et al., (2016)

Method	Label	Category	Section	Reference
Coulomb-Thalmann	Coulomb_JT	Finite volume	Sect. 2.1.1	Thalmann et al. (2011)
Coulomb-Yang	Coulomb_SY	Finite volume	Sect. 2.1.2	Yang et al. (2013b)
Coulomb-Rudenko	Coulomb_GR	Finite volume	Sect. 2.1.3	Rudenko and Anfinogentov (2014)
DeVore-Valori	DeVore_GV	Finite volume	Sect. 2.2.1	Valori et al. (2012)
DeVore-Moraitis	DeVore_KM	Finite volume	Sect. 2.2.2	Moraitis et al. (2014)
DeVore-Anfinogentov	DeVore_SA	Finite volume	Sect. 2.2.3	Not available
Twist-number	TN	Discrete flux-tubes	Sect. 2.3.1	Guo et al. (2010)
Connectivity-based	CB	Discrete flux-tubes	Sect. 2.3.2	Georgoulis et al. (2012)

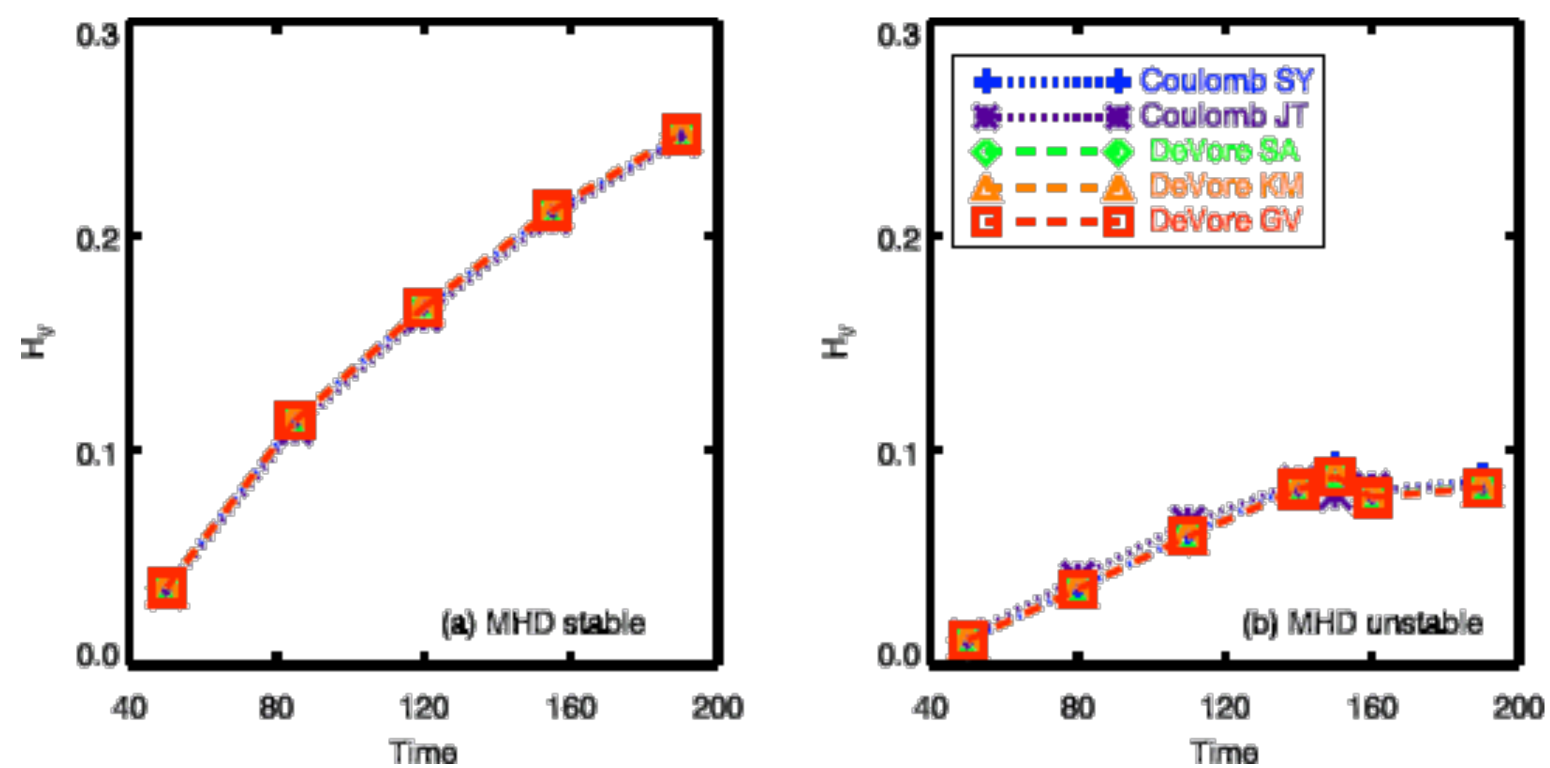
Comparison Results [1]



- Four selected cases
  - (a) Low & Lou FF equilibrium
  - (b) Titov & Demoulin FF equilibrium
  - (c) MHD stable model of Leake et al., (2013)
  - (d) MHD unstable model of Leake et al., (2013)

Valori et al., (2016)

- Comparison of 3D finite-volume methods in the two MHD configurations



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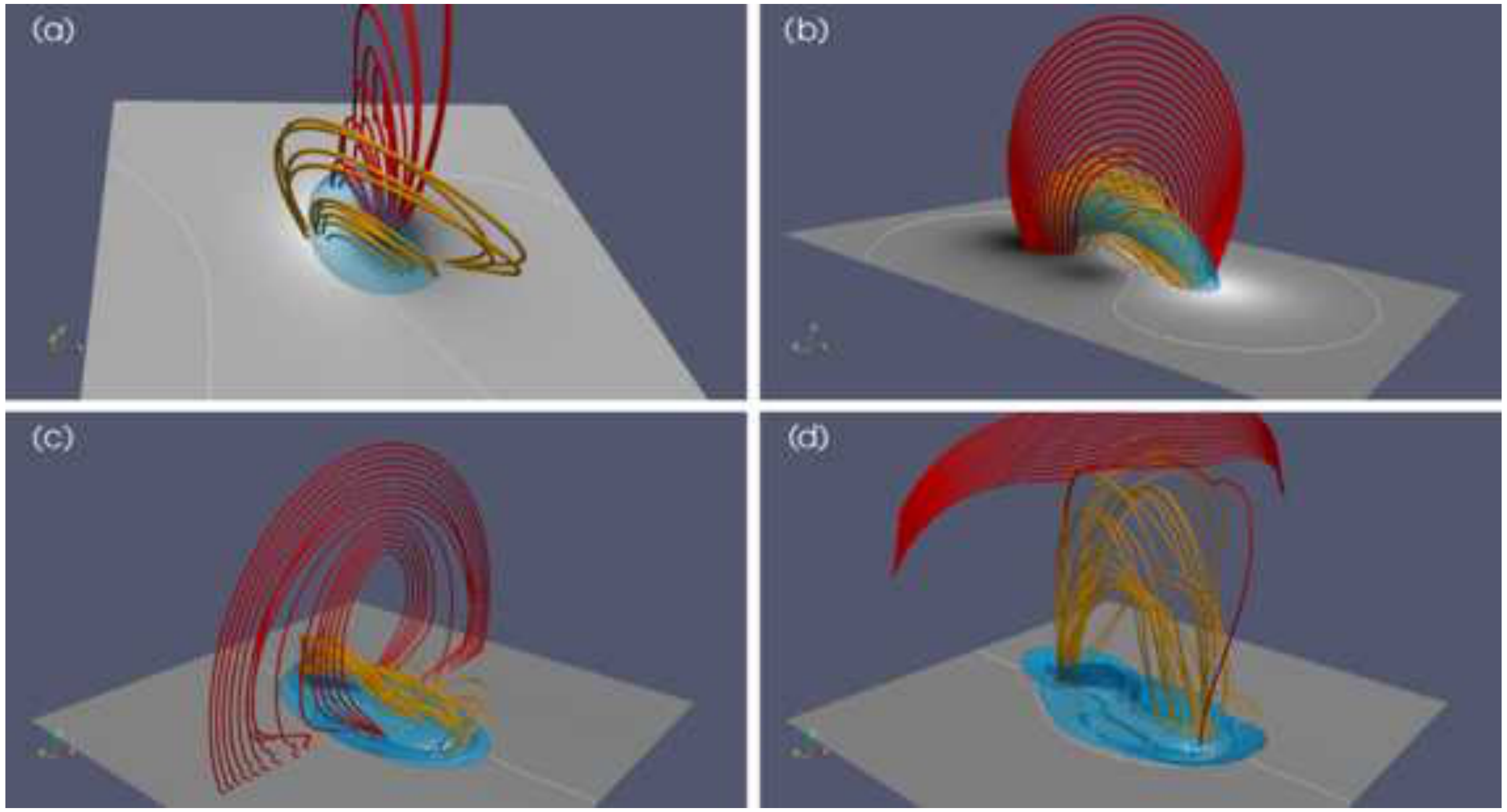

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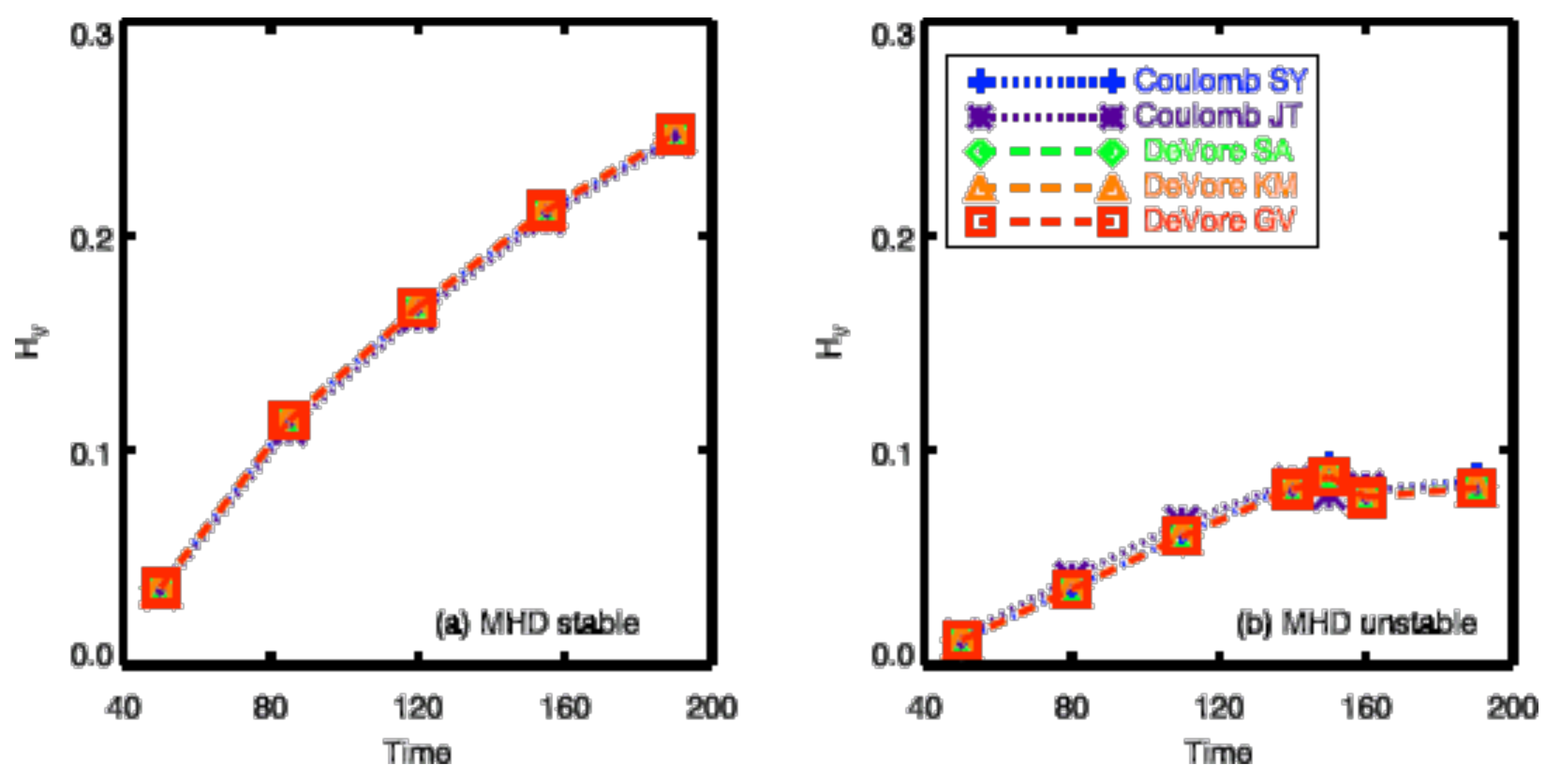
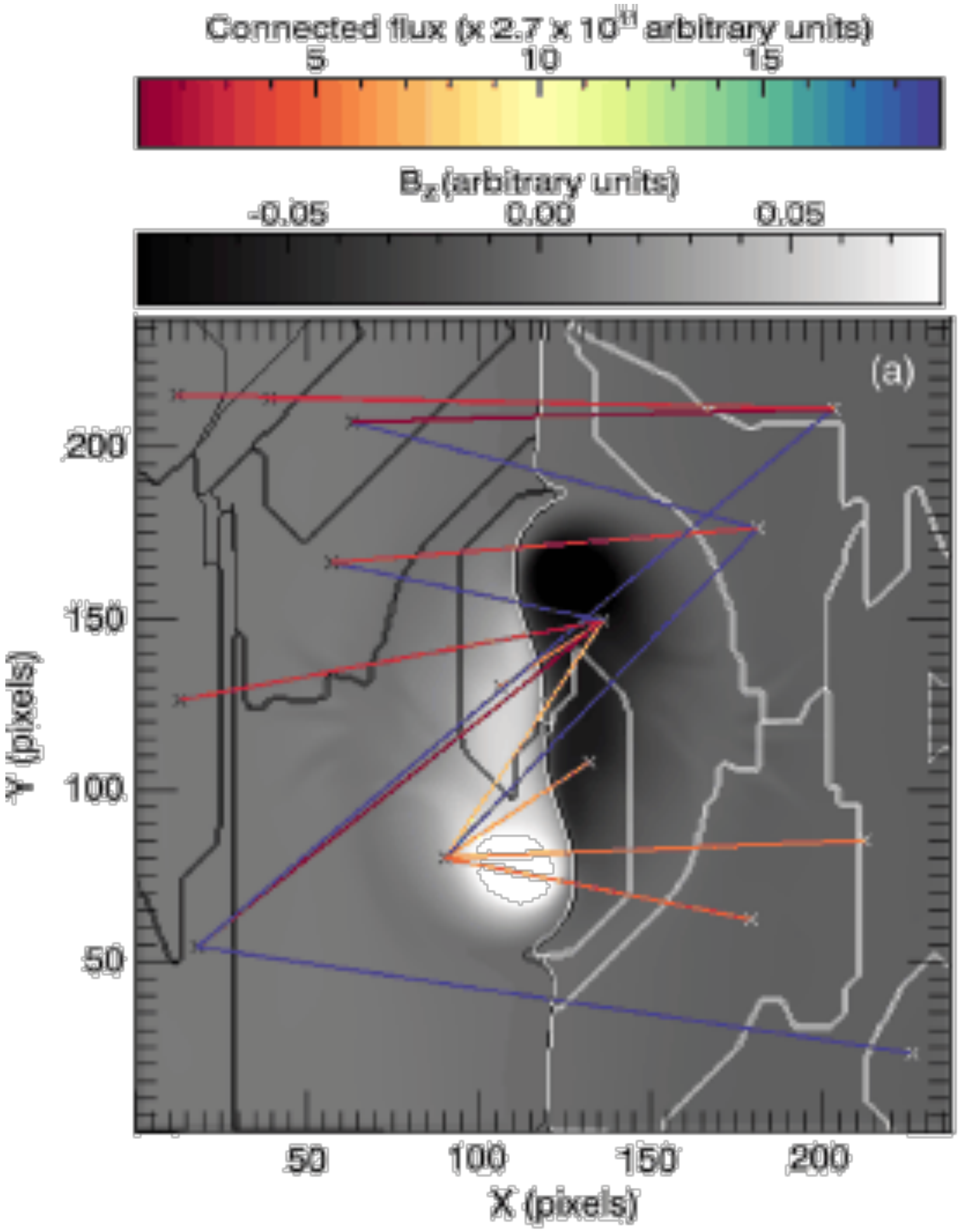
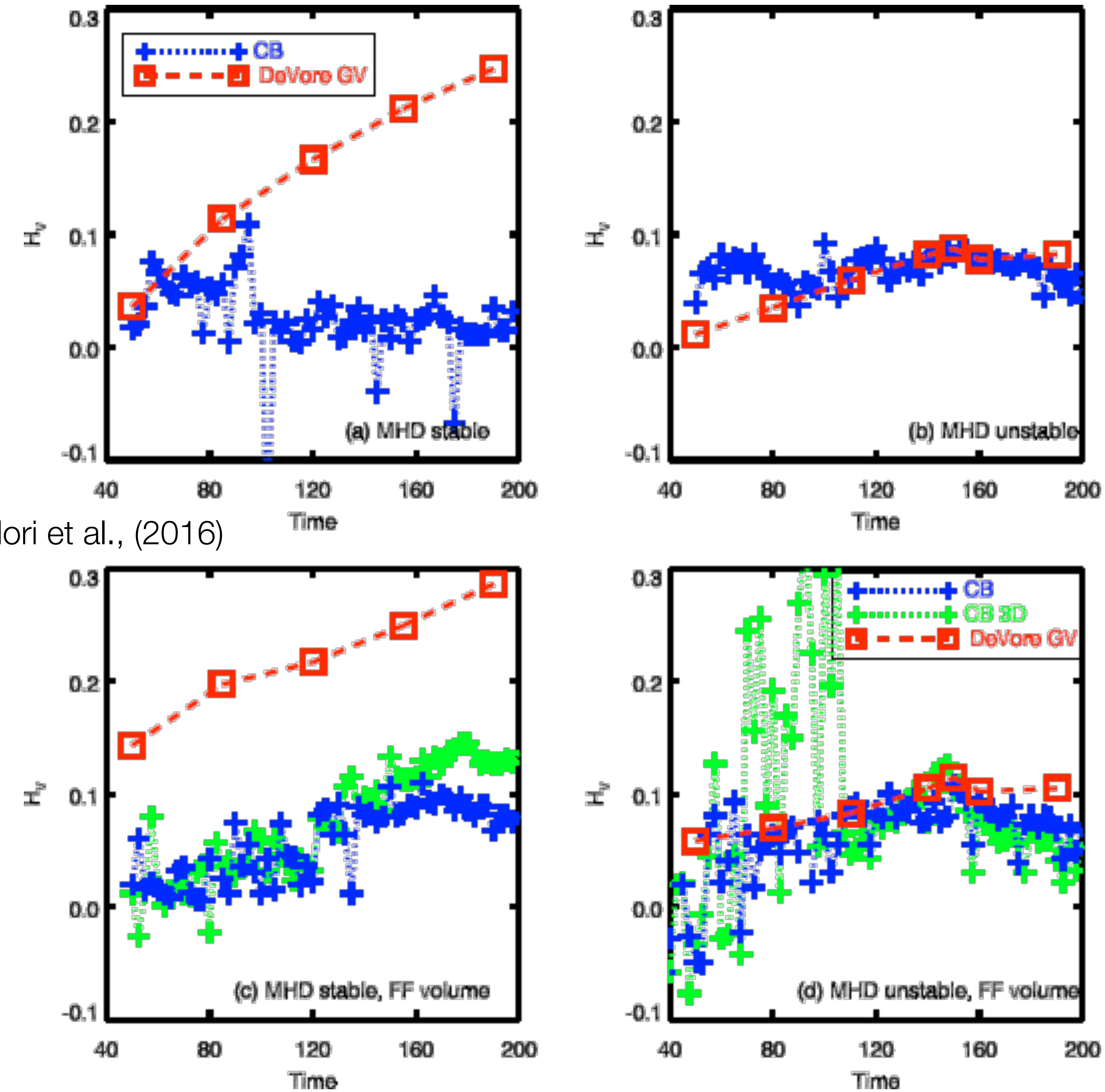


Pretty good agreement between methods, if 3D field is known. Also, reasonably immune results to magnetic reconnection

Comparison Results [2]

- Comparison between the full 3D method and the one with skeleton connectivity





Valori et al., (2016)

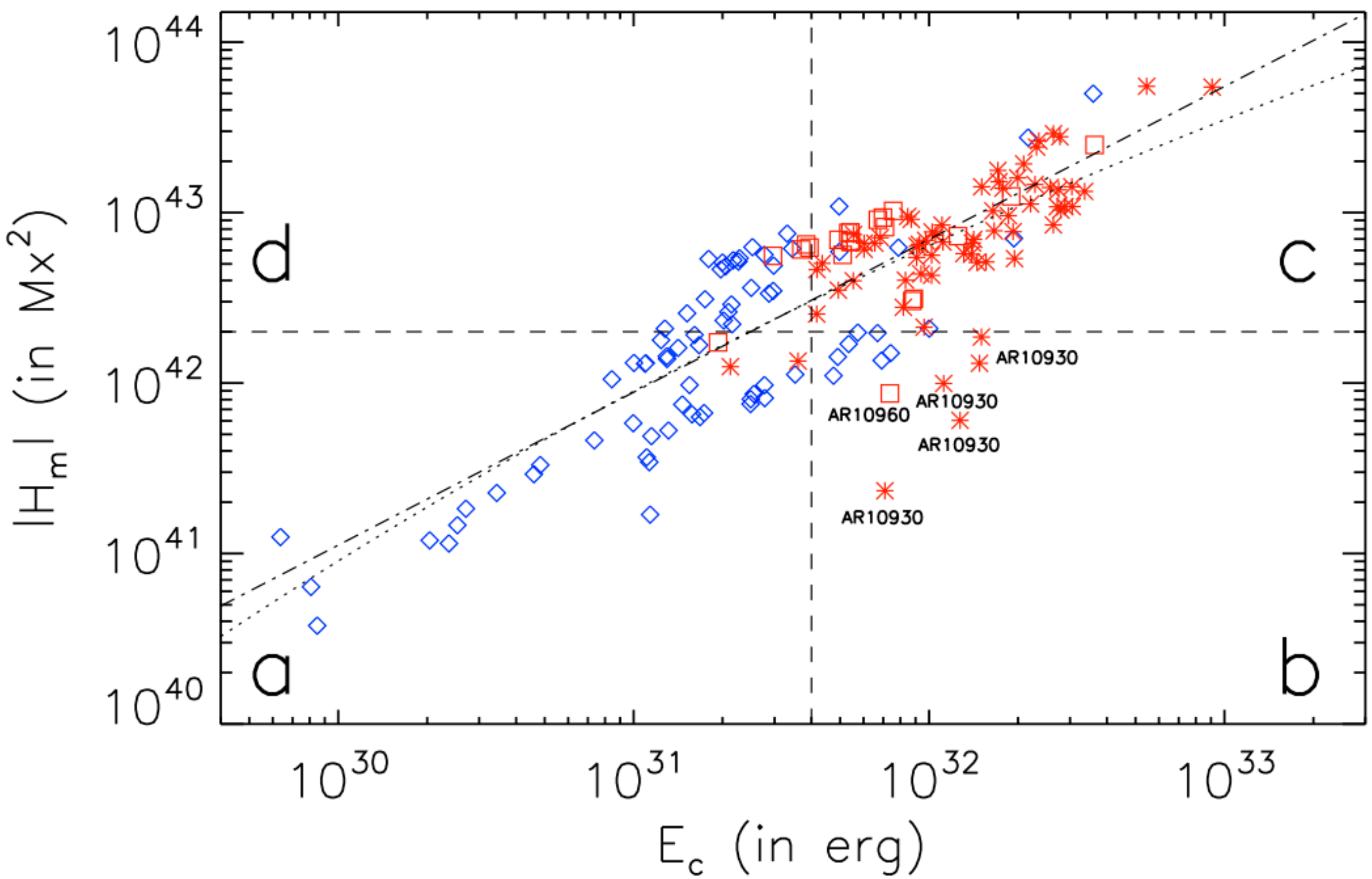
Less than an agreement in MHD stable configuration, but agreement within 10% for the MHD unstable one!

Future Steps in Correlating Magnetic Helicity Calculation Methods

- The paper of Valori et al., (2016) is only Paper I
- In Paper II (Pariat et al., 2018, in prep.) helicity-injection rates will be tested
- In Paper III (Georgoulis et al., 2018, in prep.) methods will be tested on an NLFF-extrapolated, observed active-region case
- In another published work (Guo et al., 2017) the twist-number helicity method is applied to a number of models (Titov & Demoulin, MHD models, etc.)

Issues to Work Out. I. the “Energy — Helicity” Diagram

Tziotziou et al., 2012



- Active regions, eruptive or not, exhibit a distinctive scaling relation between free magnetic energy and absolute value of relative magnetic helicity

$$H \propto E^{0.84 \pm 0.05}$$

- This was later noticed for quiet-Sun structures, and even for MHD models, (Tziotziou et al., 2014)

- Notice the jump to lower helicities in case of quiet-Sun structures — this points to an overall incoherence of helical sense in the quiet Sun, that might be expected, but need to be investigated further

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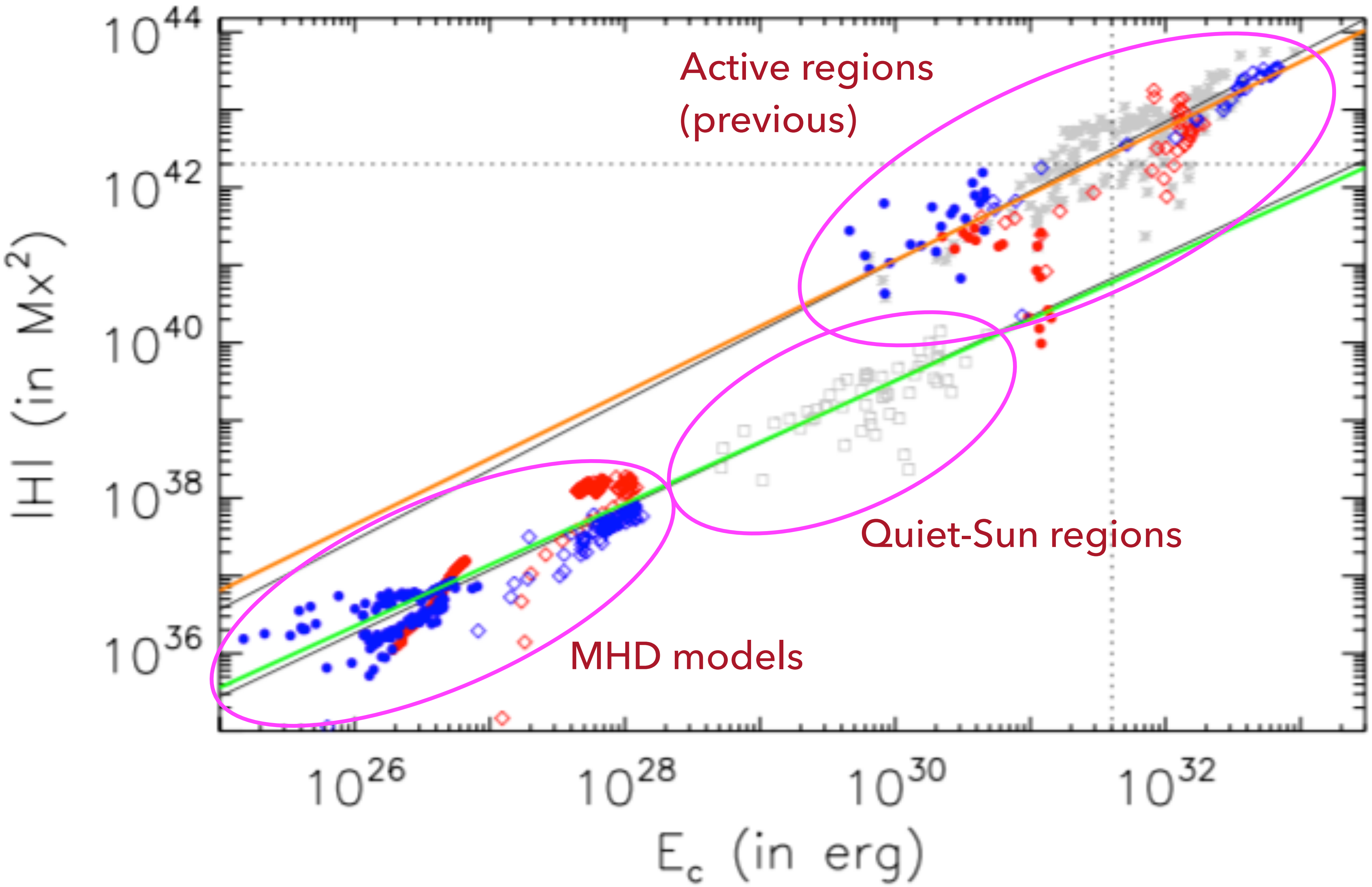

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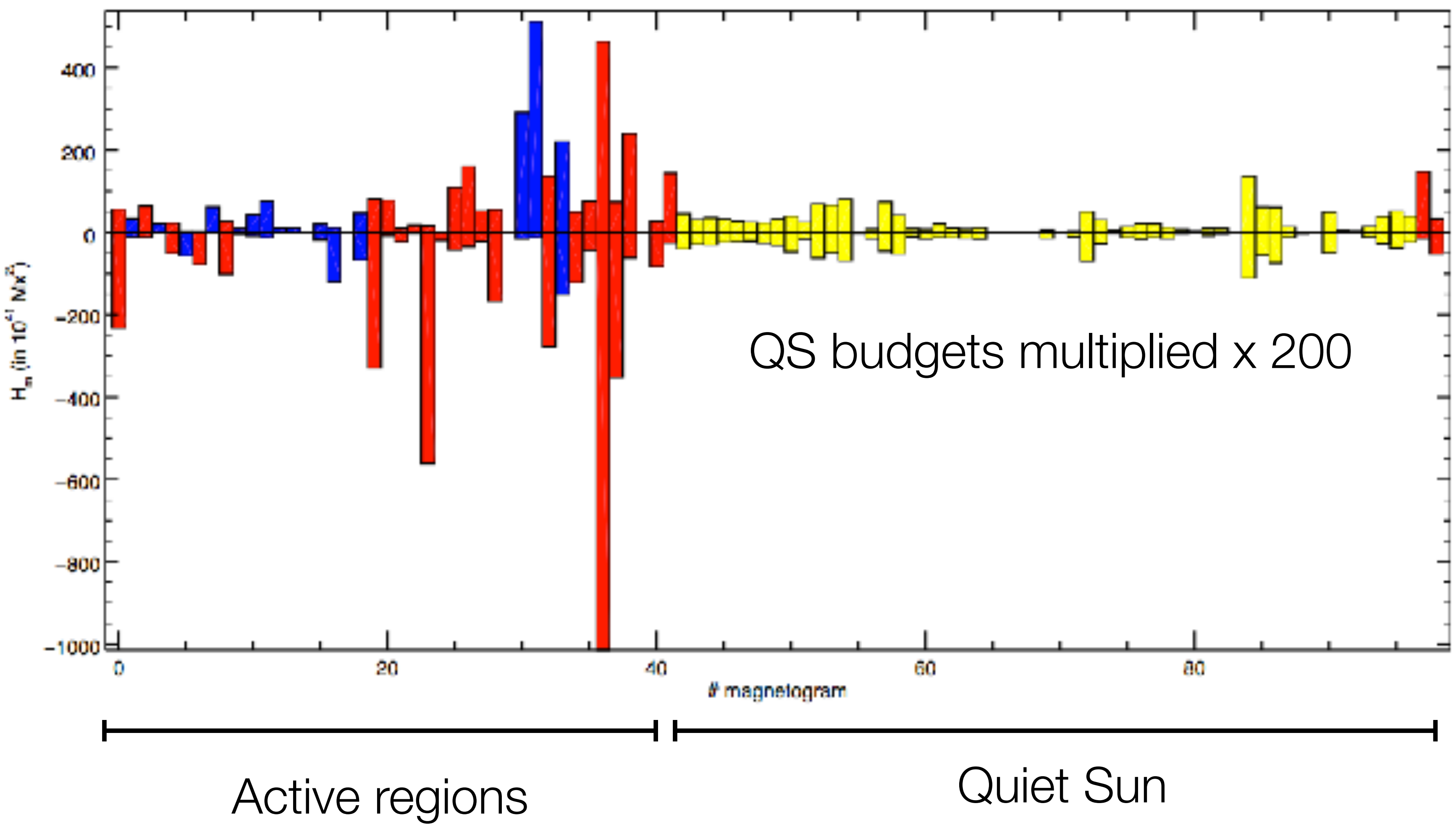
Issues to Work Out. II. Competition of the Two Helicity Senses

- Our discrete relative helicity calculation method enables the calculation of both signs of helicity within a given magnetic structure



- Active regions statistically show a dominant helicity sign, contrary to quiet-Sun regions

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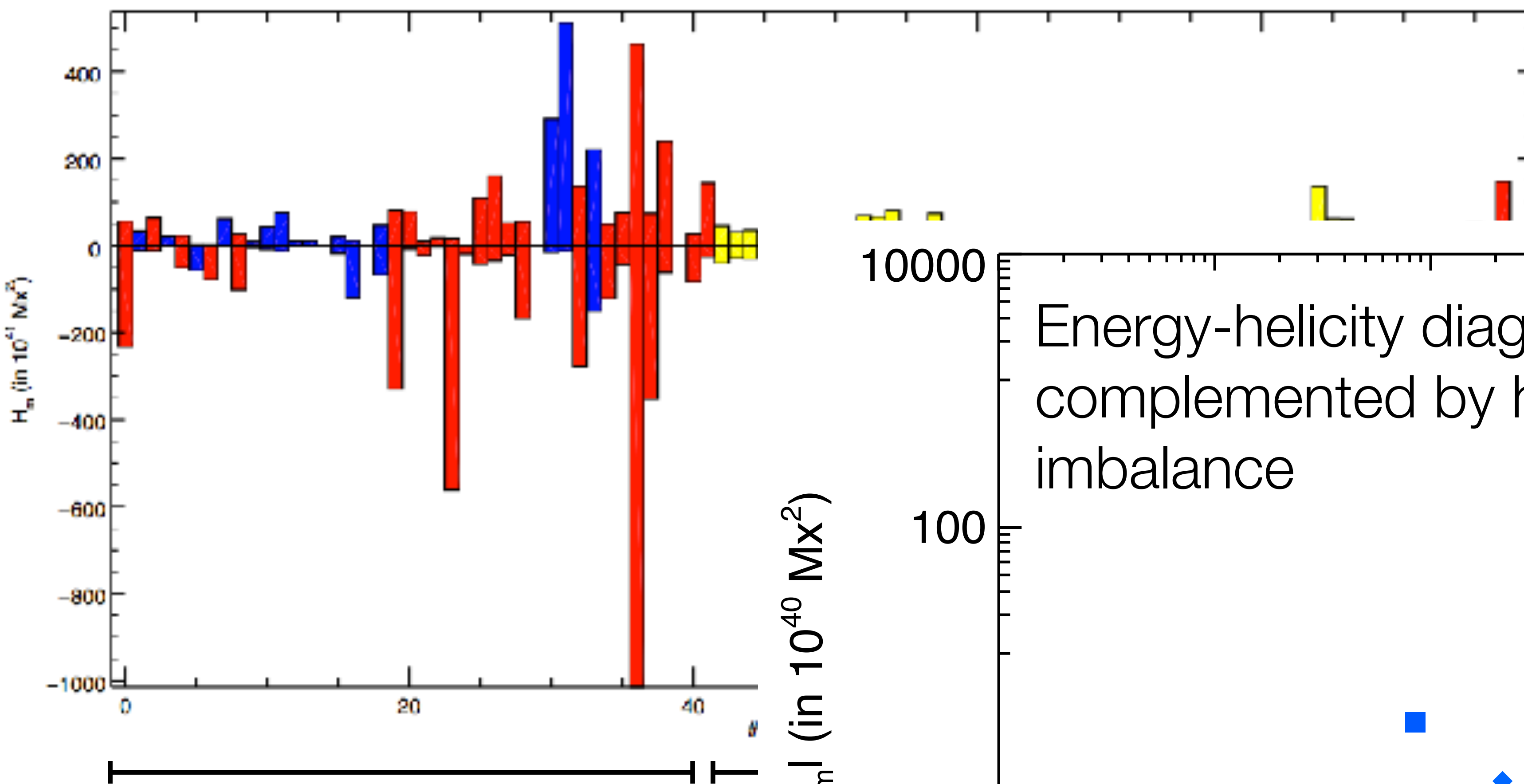
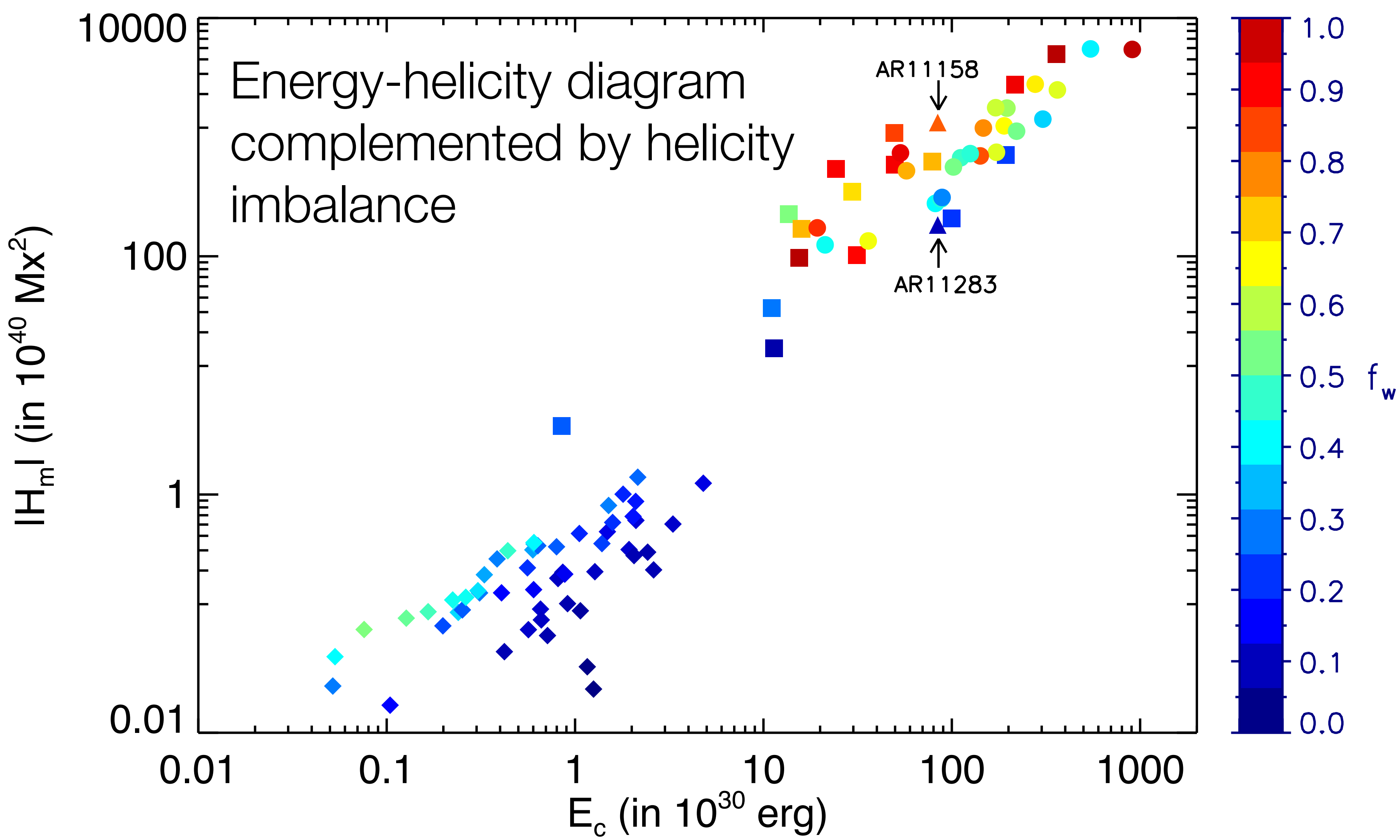


Active regions

$$h_{imb} = \frac{|H|}{H_+ + |H_-|}, \quad h_{imb} \in [0, 1]$$



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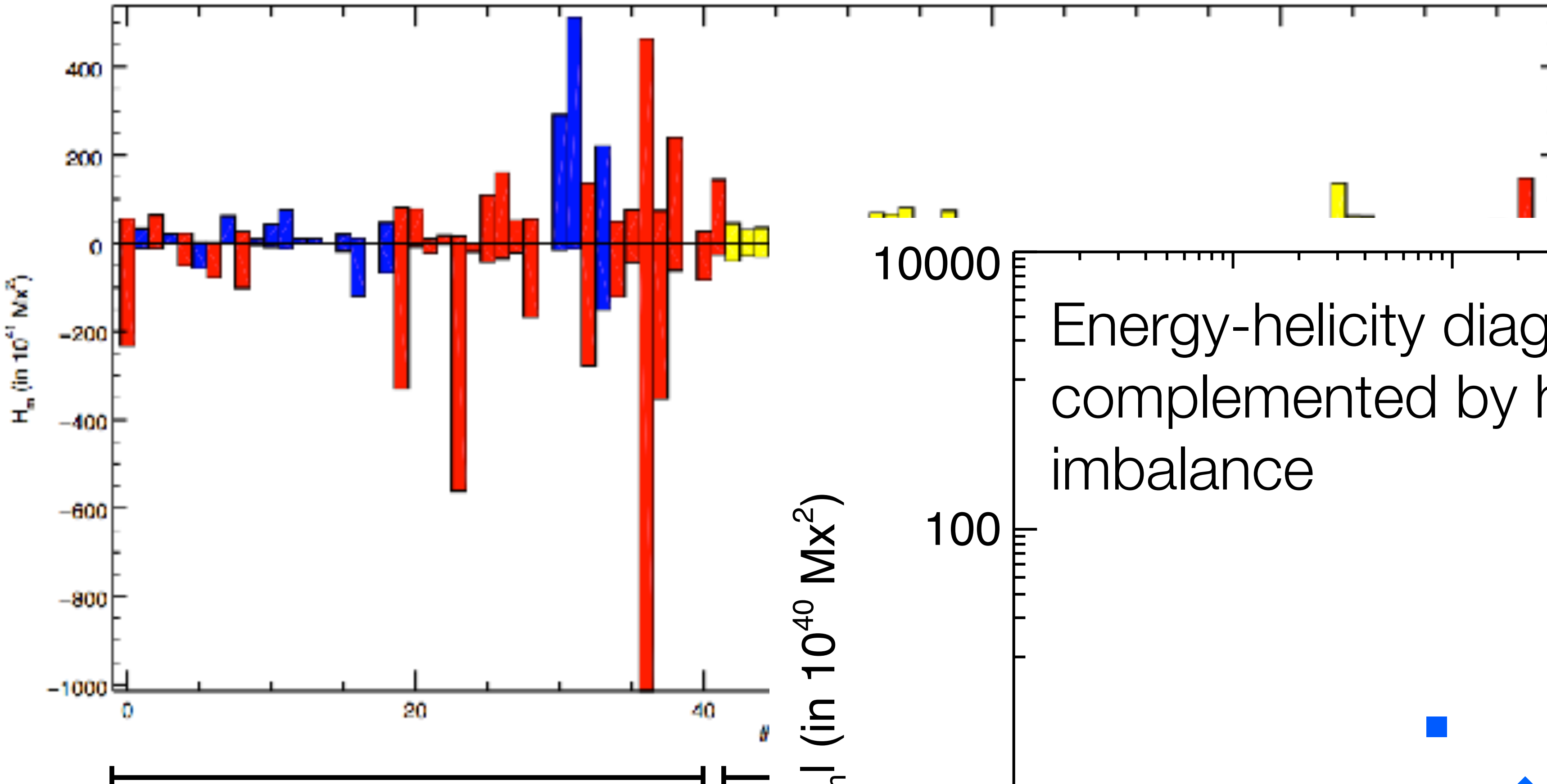

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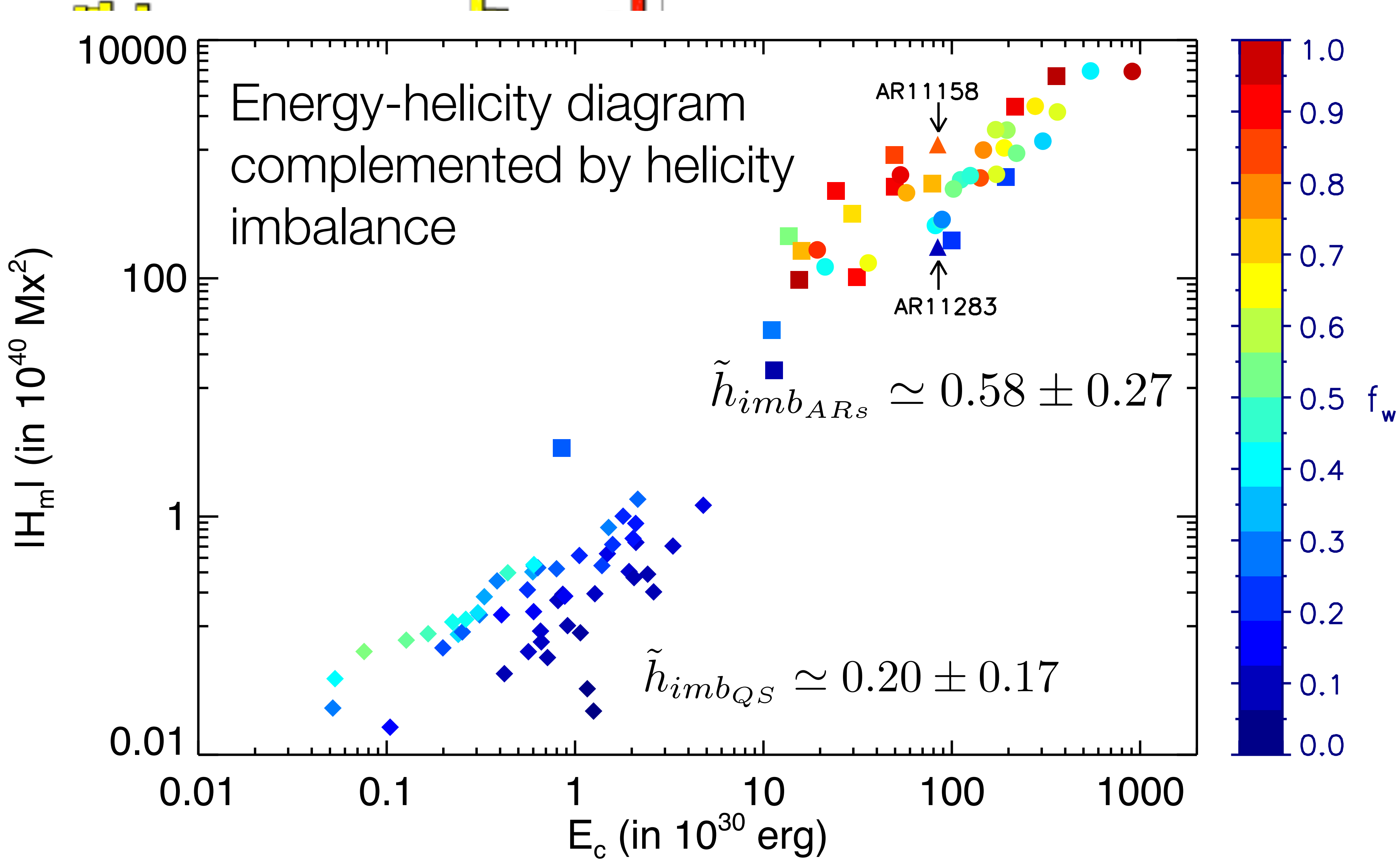

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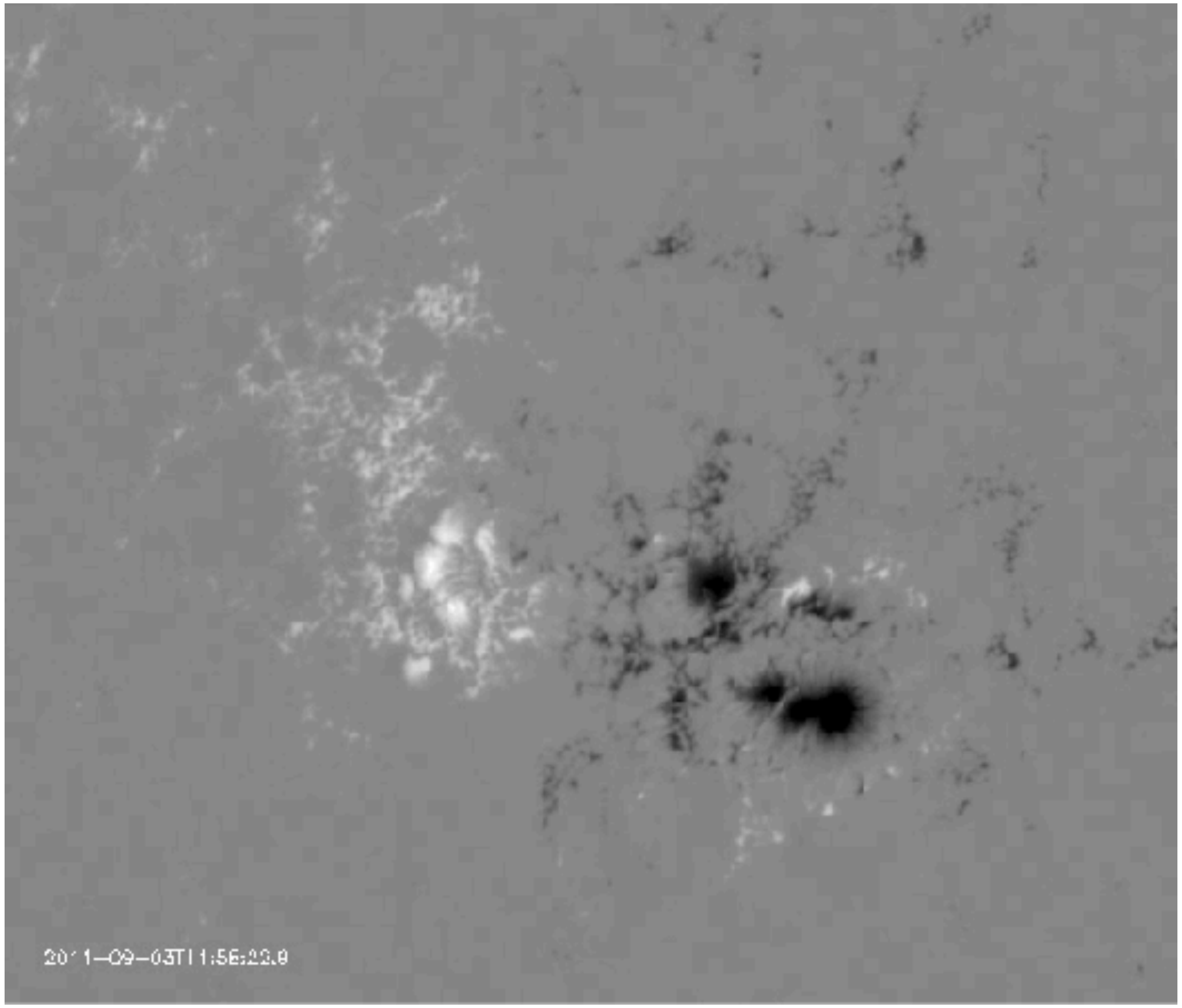
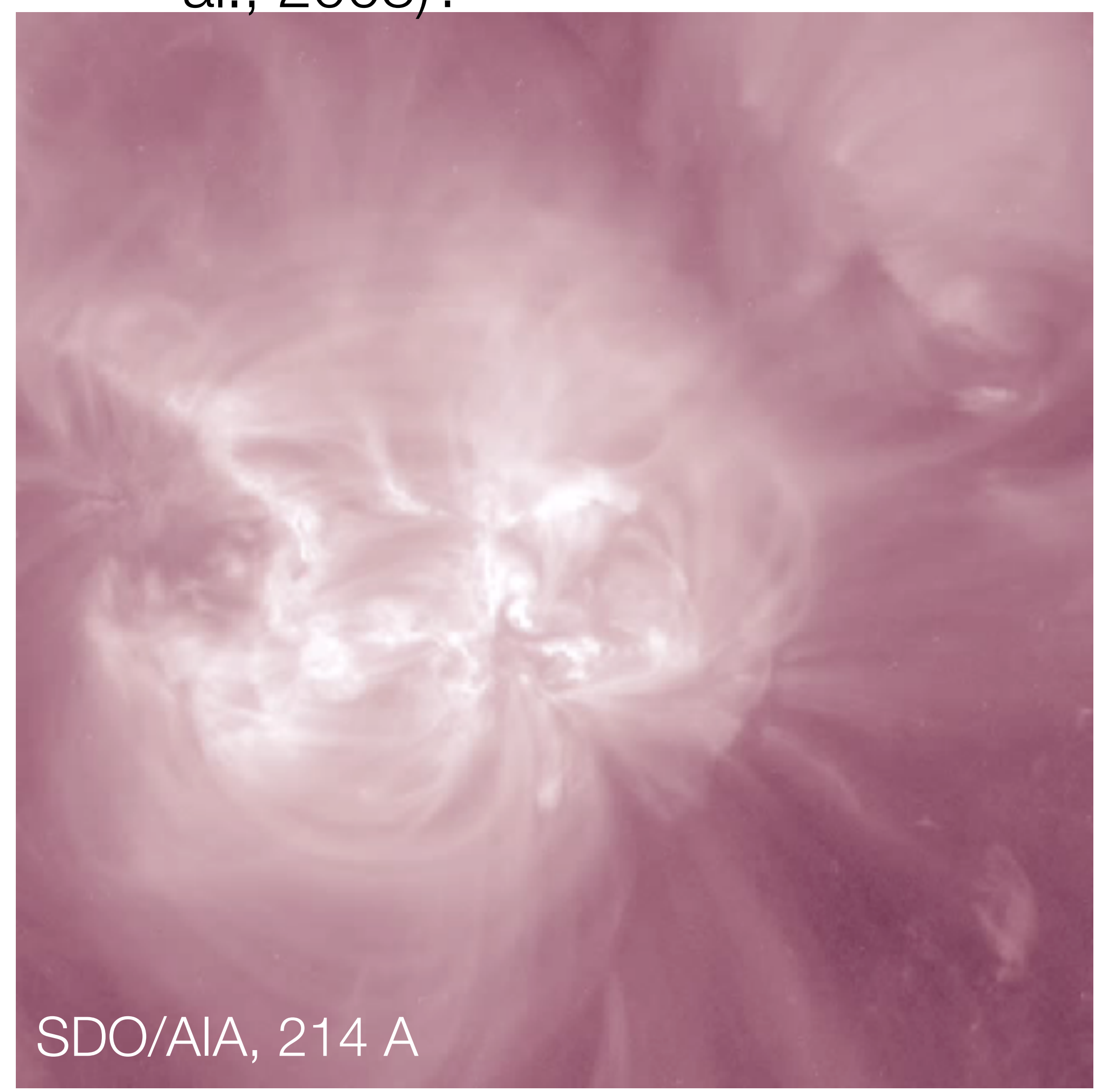
Exceptions? Of Course, Even Significant Ones



- Both X-class flares relate to eruptions of right-handed structures (e.g., Jiang et al., 2013)

- NOAA AR 11283, on Sep 2011
- Initially left-handed configuration
- Gives two eruptive X-class flares with very low helicity
- Helicity annihilation (Kusano et al., 2003)?



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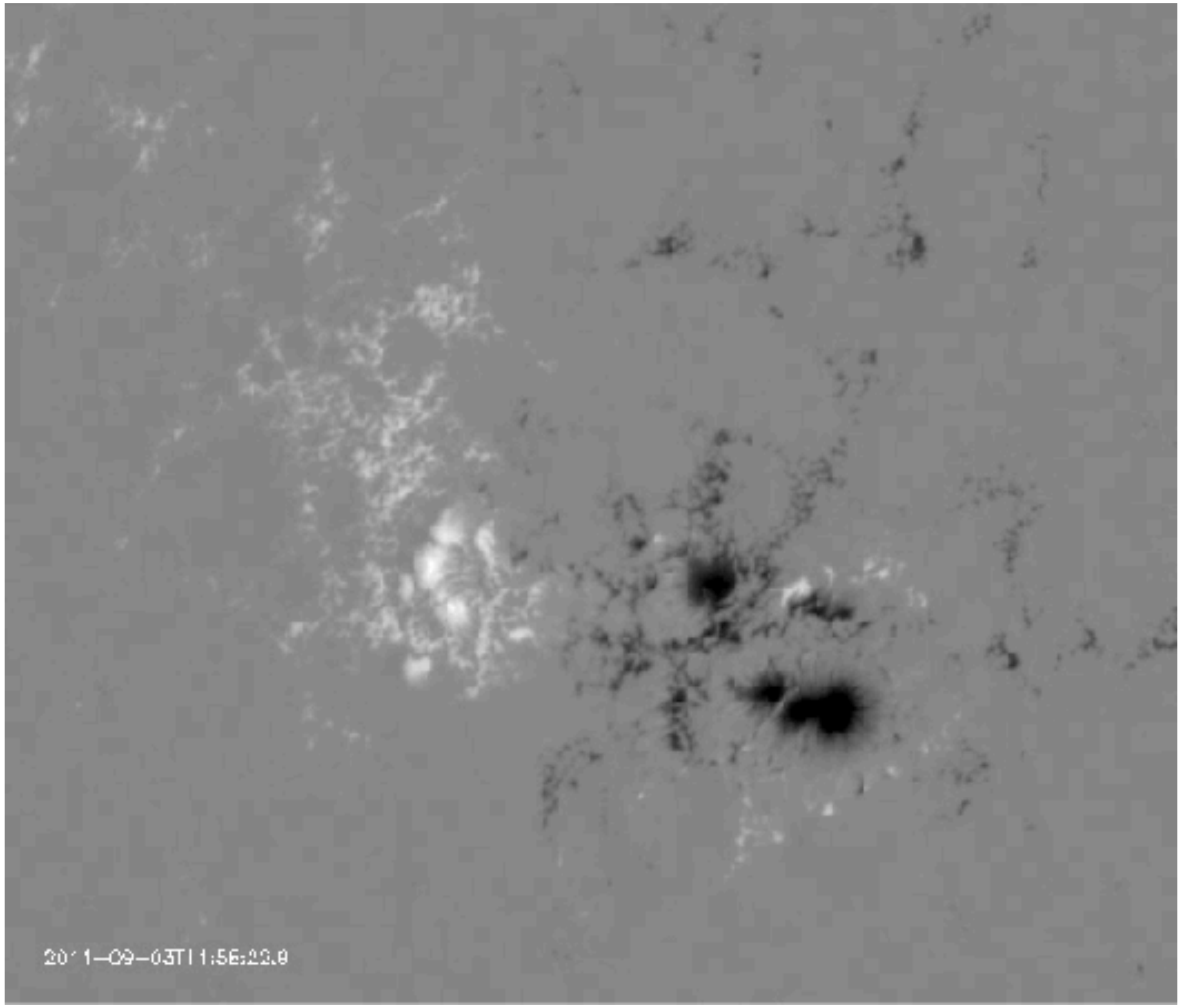

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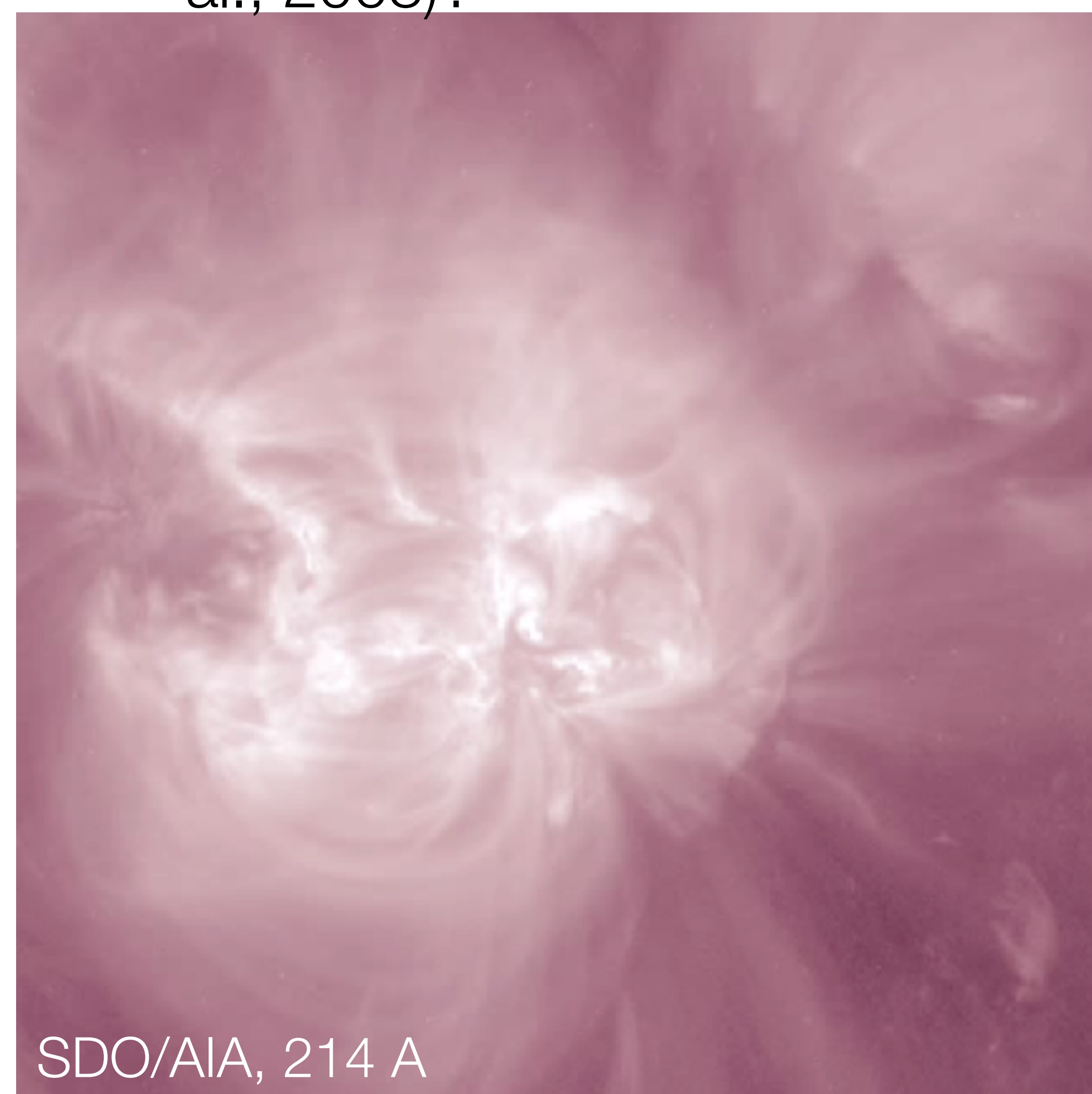

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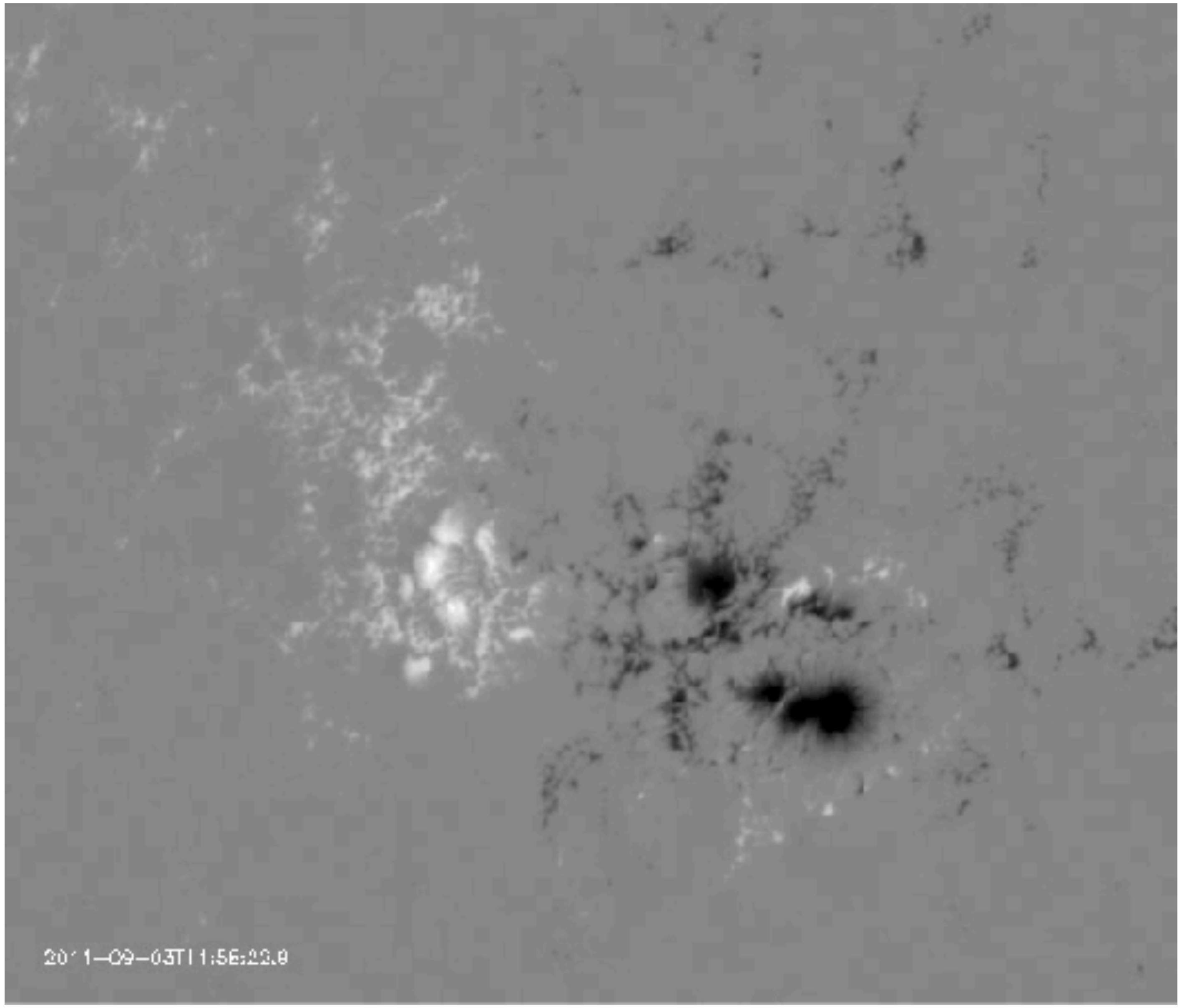

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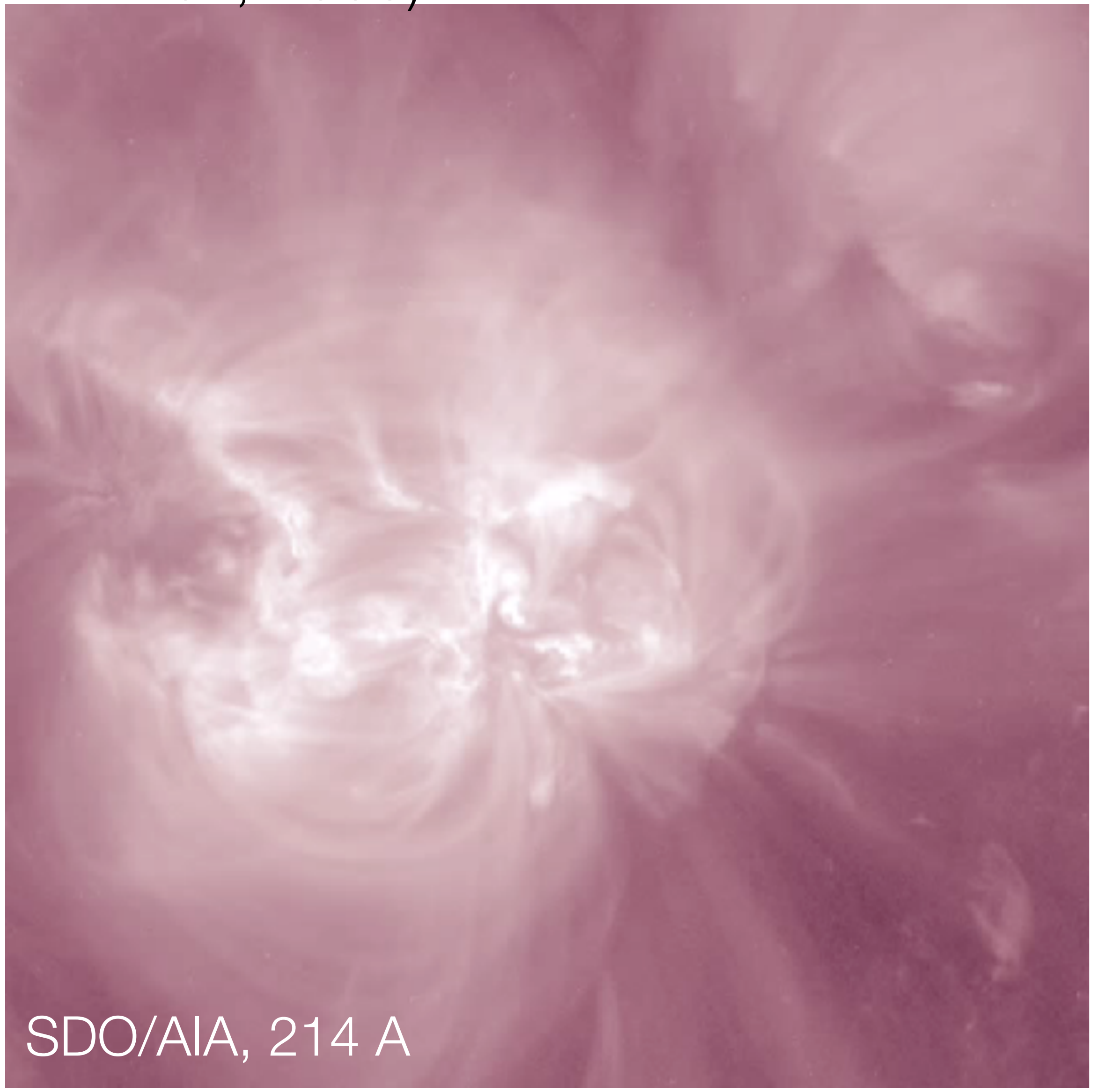
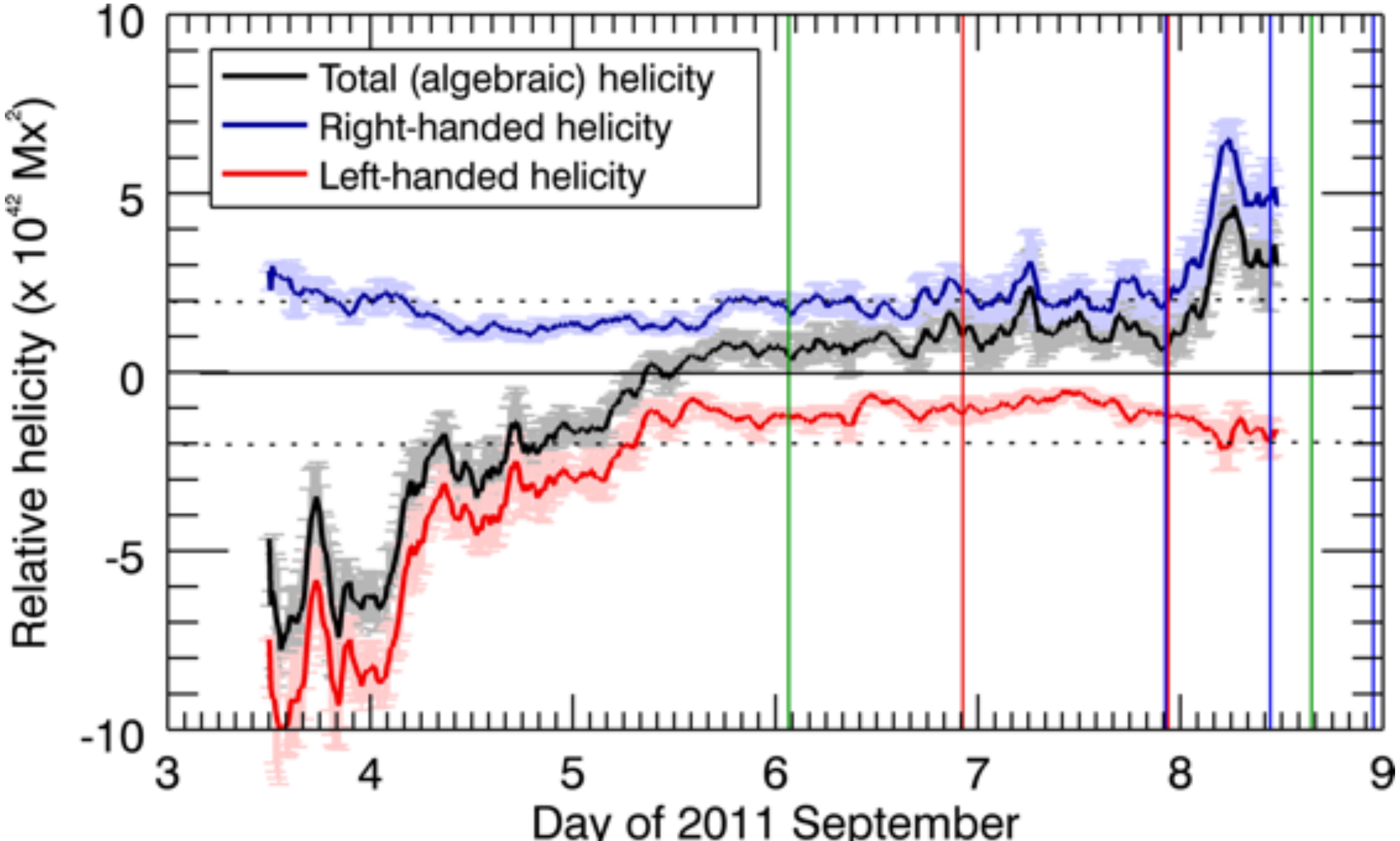
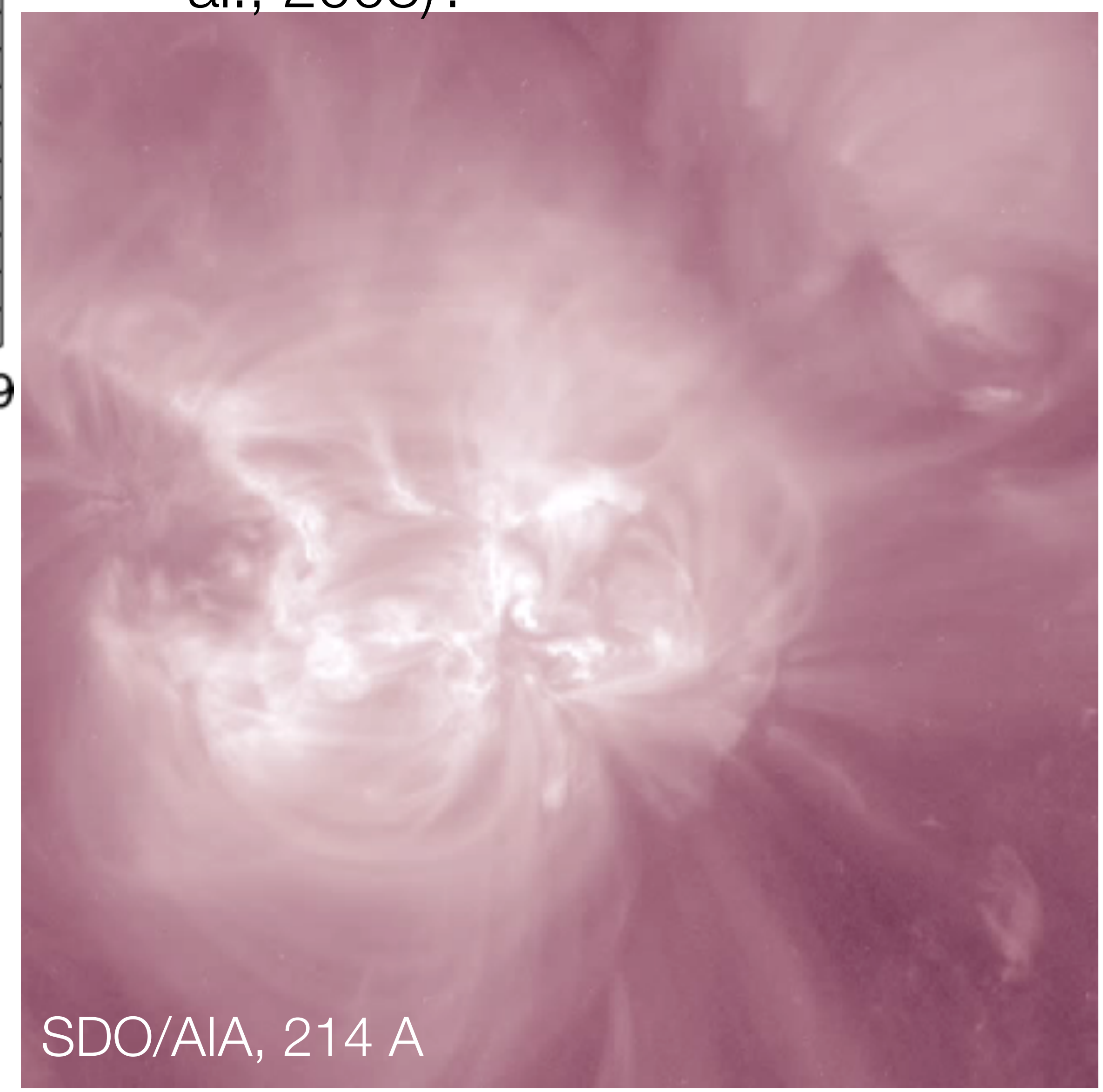


Exceptions? Of Course, Even Significant Ones



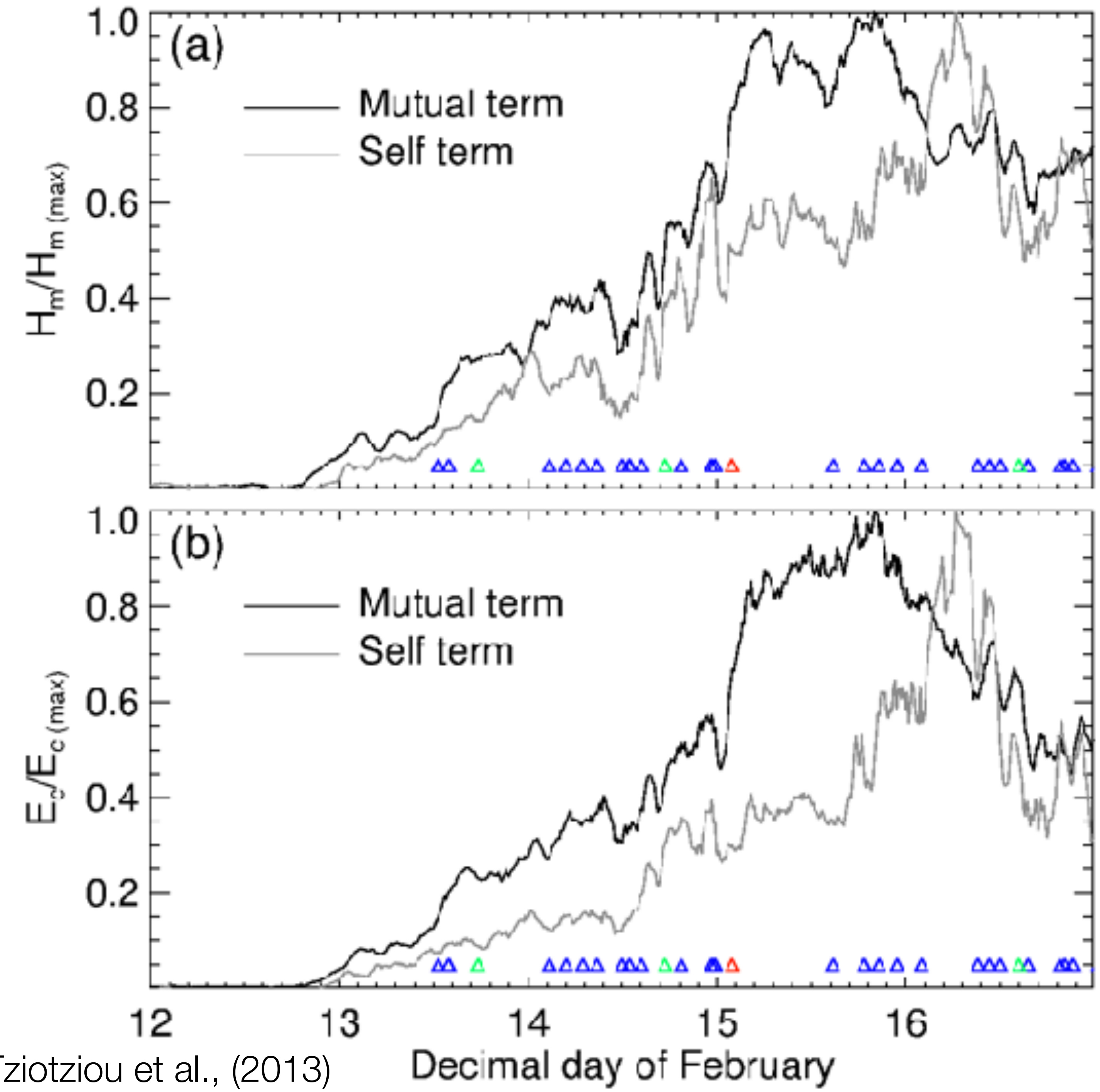
- NOAA AR 11283, on Sep 2011
- Initially left-handed configuration
- Gives two eruptive X-class flares with very low helicity
- Helicity annihilation (Kusano et al., 2003)?



- Both X-class flares relate to eruptions of right-handed structures (e.g., Jiang et al., 2013)
- What seems to happen? Initially left-handed structure gradually turns into a right-handed one

Issues to Work Out. III. Mutual vs. Self Helicity

- Our discrete relative helicity calculation method also enables separation between self and mutual terms of relative helicity and free energy



Tziotziou et al., (2013)

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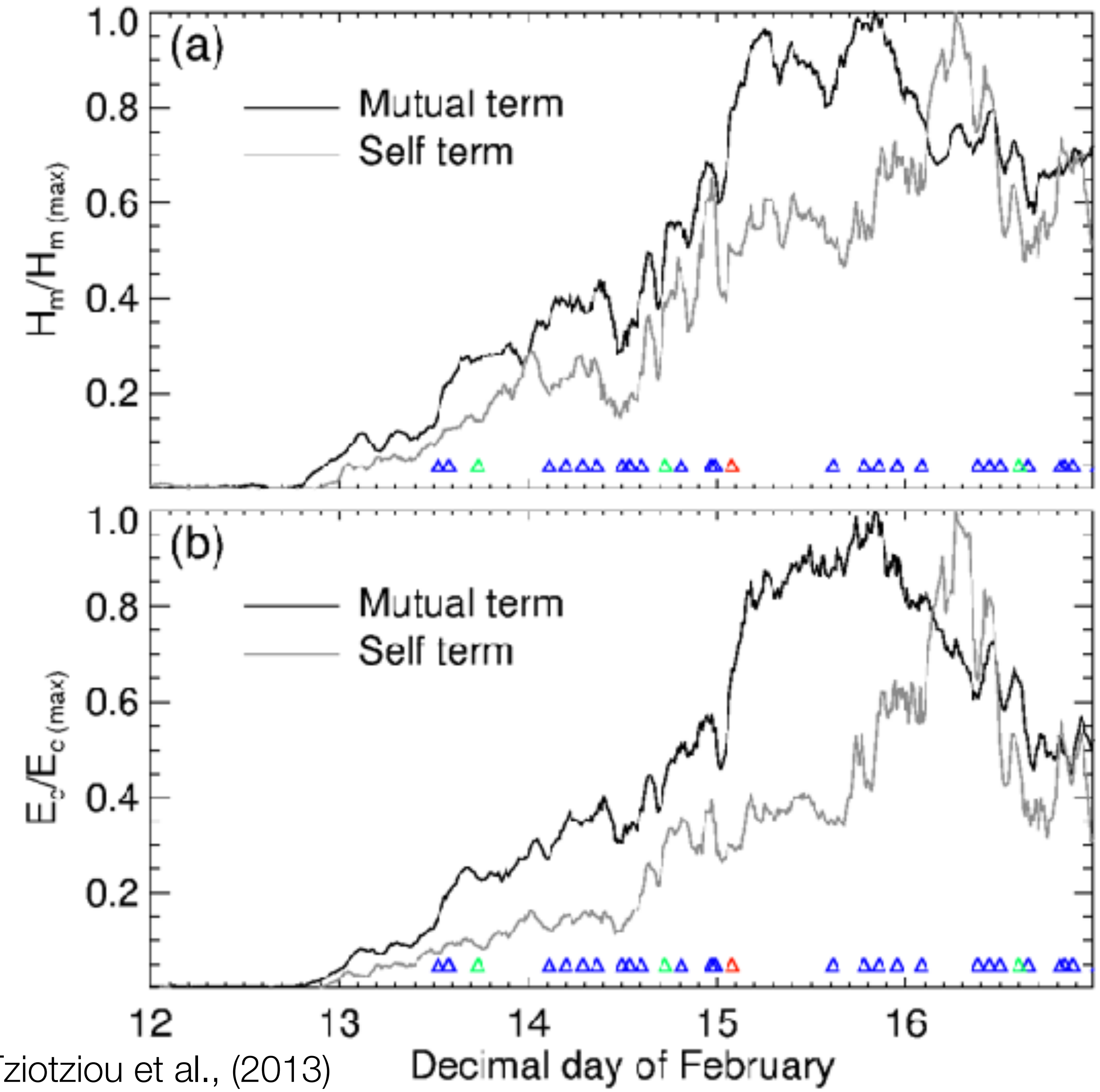
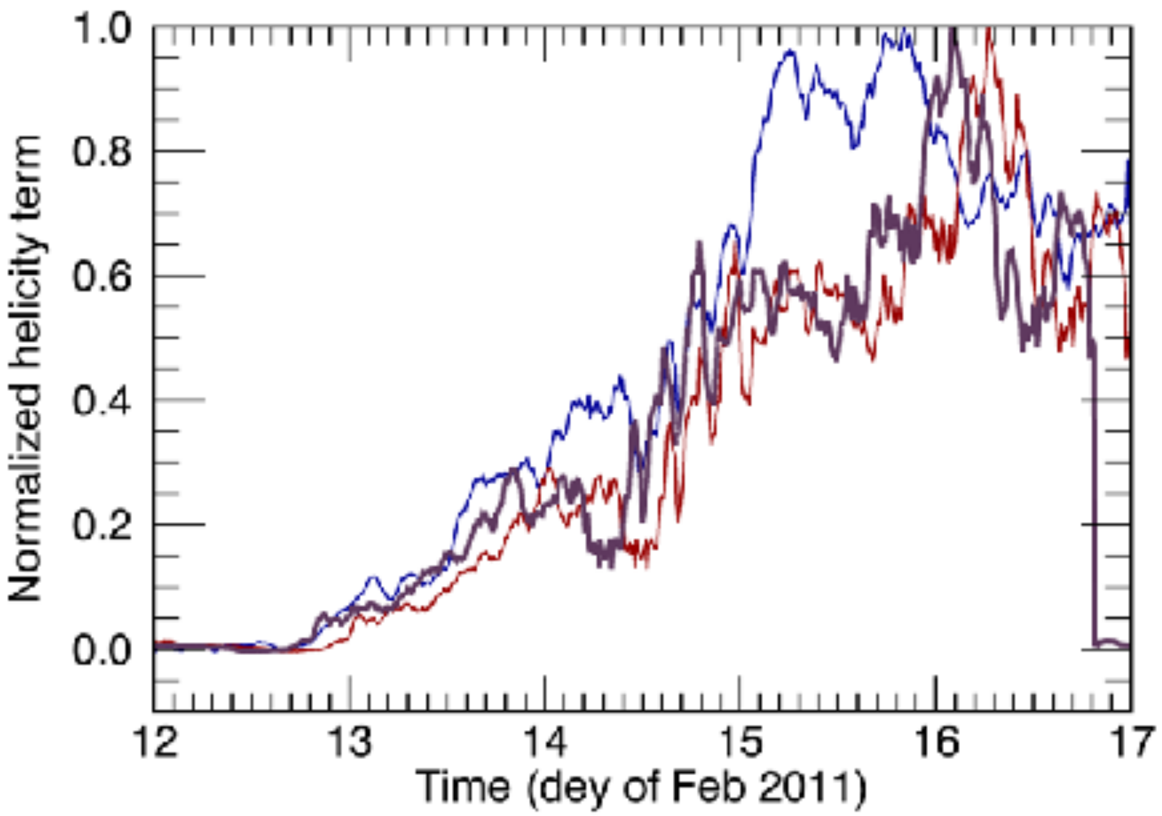


Tziotziou et al., (2013)

- Shifting back in time the self helicity timeseries, we can see it shows a hysteresis of ~4.4 hours. This does not happen with the free energy.

A case is built, indicating to a self-helicity term due to non-ideal conversion of mutual helicity



Other Helicity Realizations: the "Current-Carrying" Helicity

- The "current-carrying" helicity of Pariat et al., (2017)

$$H_{\mathcal{V}} = H_{\mathrm{j}} + 2H_{\mathrm{pj}} \quad \text{with} \tag{9}$$

Relative helicity

$$H_{\mathrm{j}} = \int_{\mathcal{V}} (\boldsymbol{A} - \boldsymbol{A}_{\mathrm{p}}) \cdot (\boldsymbol{B} - \boldsymbol{B}_{\mathrm{p}})\, \mathrm{d}\mathcal{V} \tag{10}$$

"Current-carrying" helicity

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Mutual helicity

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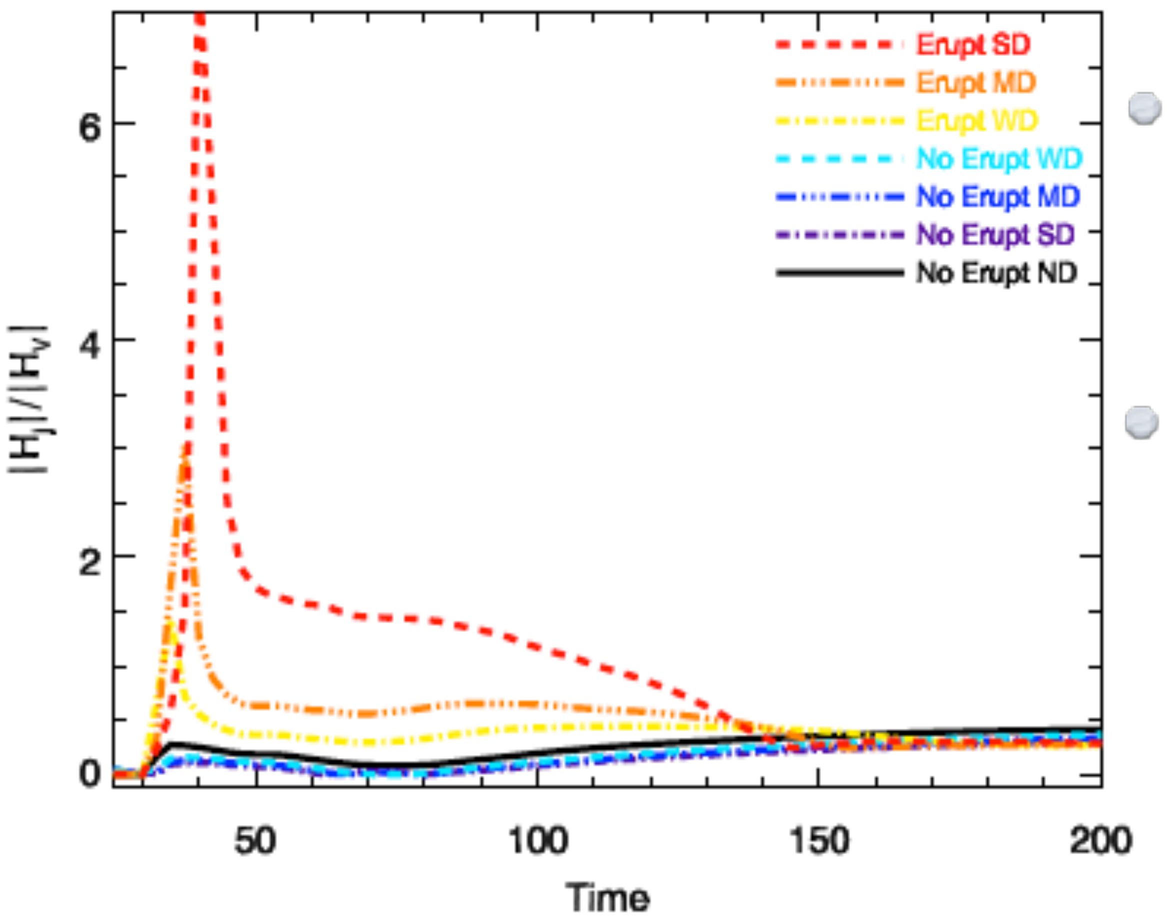

- The ratio $|H_j / H_V|$ seems to spike prior to the eruption in the simulation of Leake et al. (2013), implying a possible physical role for H_j
- From its construction and the DeVore gauge (**A** . **n** =0), H_j does not have a contribution on ∂V and is scale invariant

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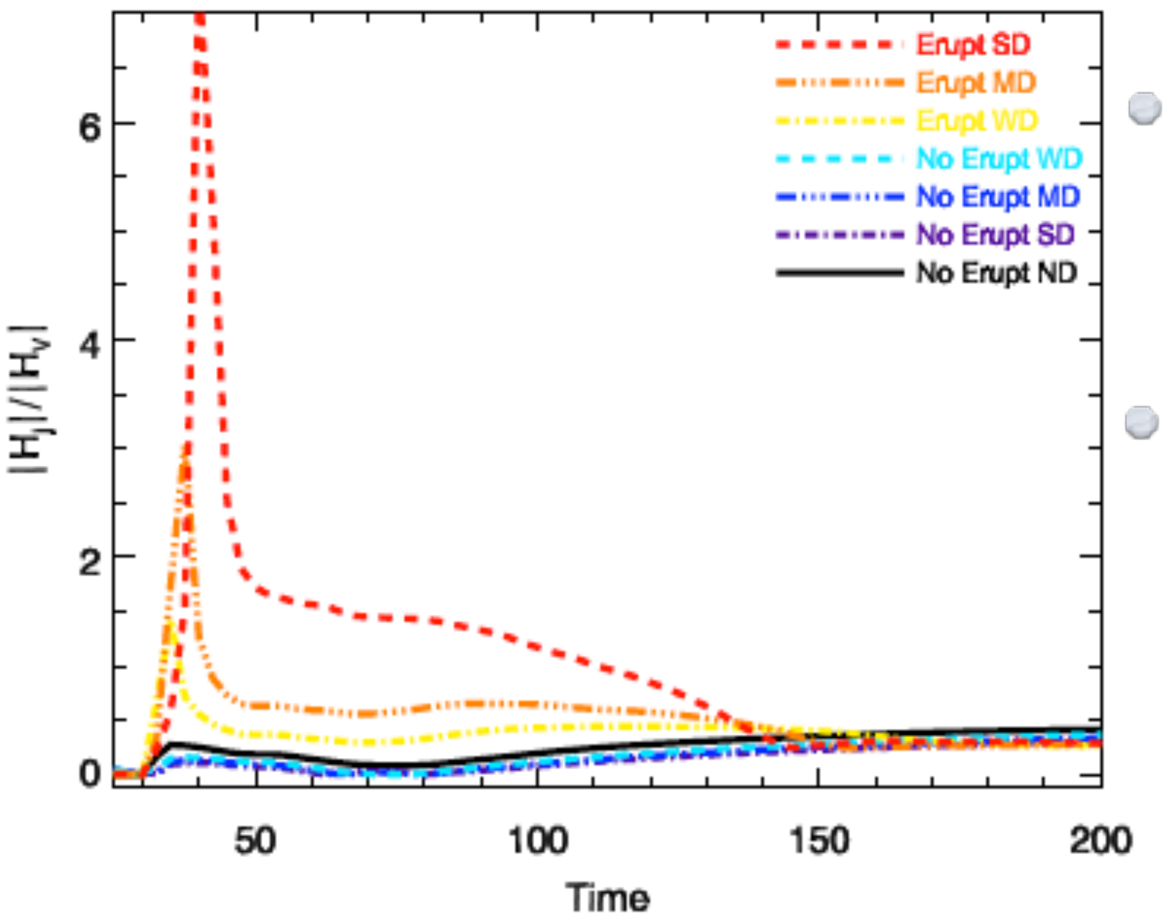
$$H_{pj} = \int_{\mathcal{V}} \mathbf{A}_p \cdot (\mathbf{B} - \mathbf{B}_p)\, d\mathcal{V}, \qquad (11)$$ Mutual helicity



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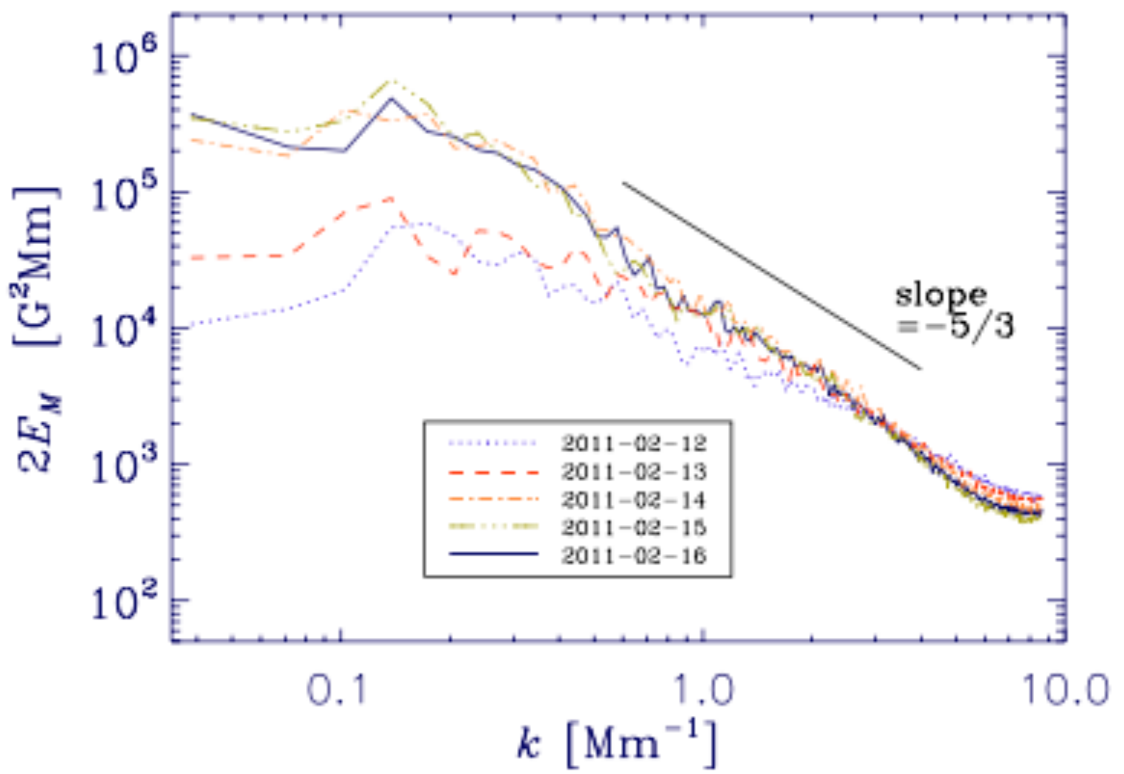
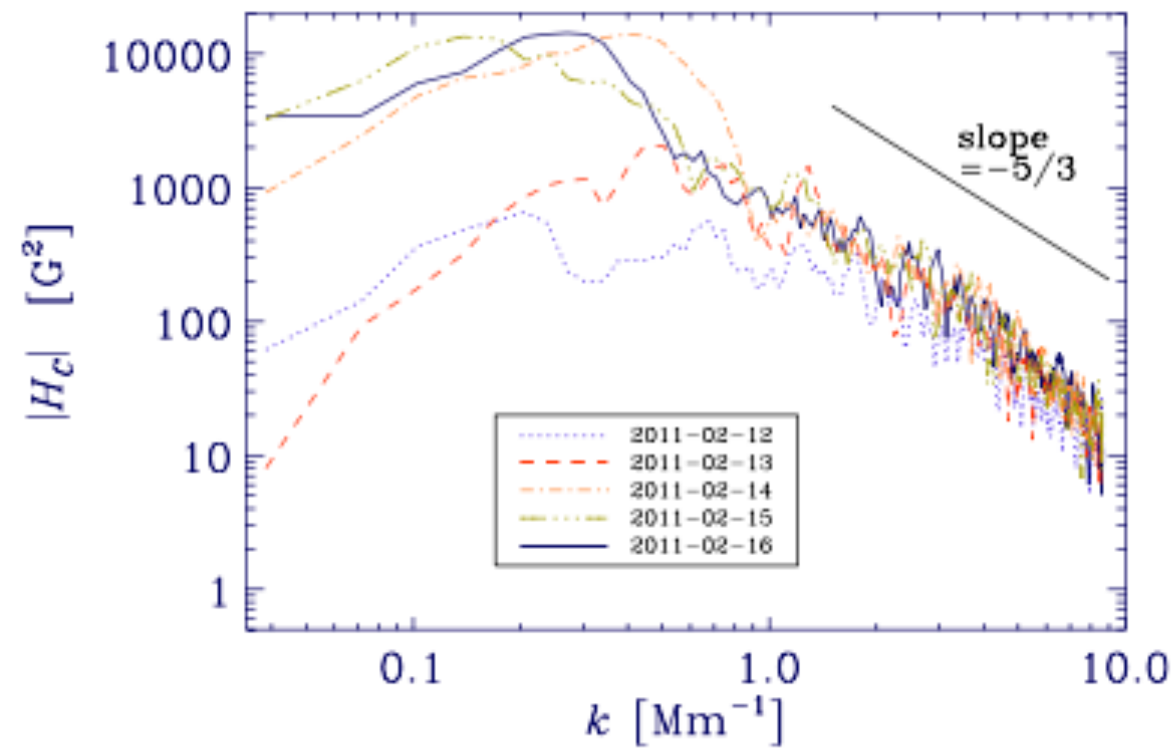
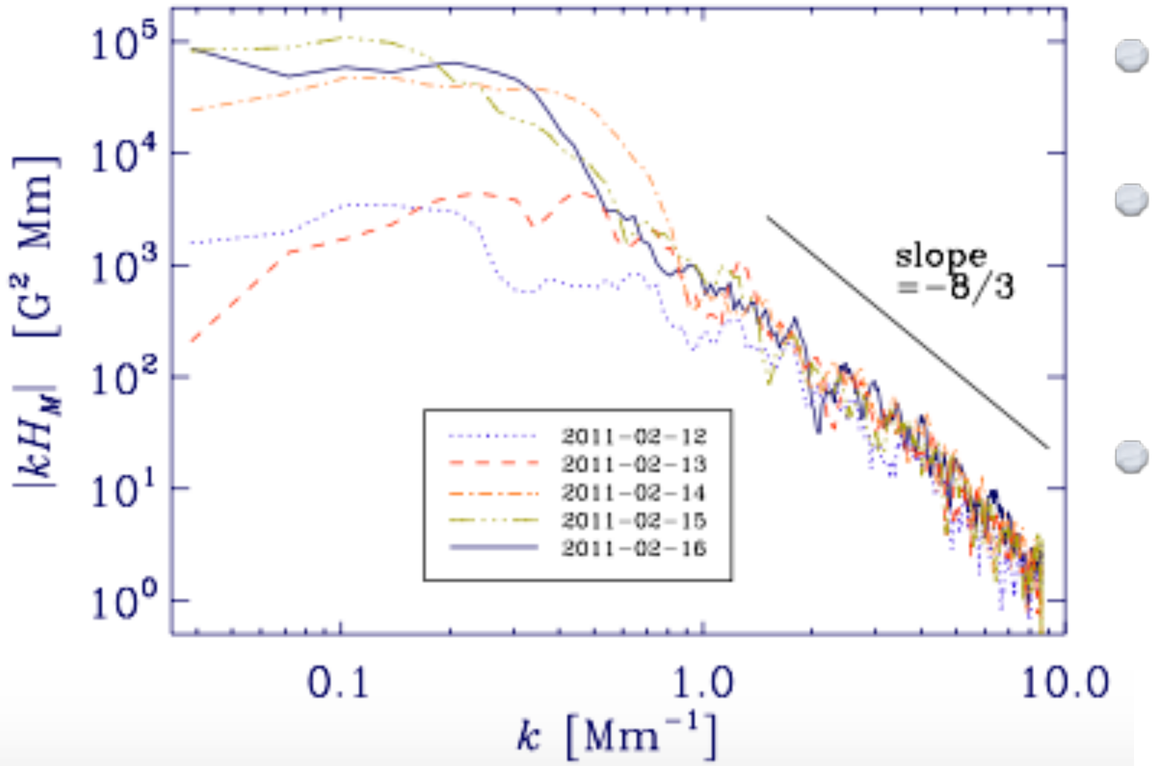
More work is needed to understand H_j better

Finally, the Helicity Spectra







Zhang, Brandenburg & Sokoloff (2014, 2016)

- NOAA AR 11158
- Realizability condition: $k|H(k,t)| \leq 2E(k,t)$

  (constraining magnetic helicity, albeit in Fourier space)
- First complete calculation of the current helicity, albeit in Fourier space

$$H_c(k,t) \simeq k^2 H(k,t)$$

Hoping to hear more in this Thinkshop!

Conclusions

- Ground-breaking progress in solar magnetic helicity studies over recent decades
- [Relative] magnetic helicity is now placed on equal footing with [free] magnetic energy in solar low-atmospheric configurations
- As in every such progress, however, more questions than answers are borne. In particular:

Conclusions

- Ground-breaking progress in solar magnetic helicity studies over recent decades
- [Relative] magnetic helicity is now placed on equal footing with [free] magnetic energy in solar low-atmospheric configurations
- As in every such progress, however, more questions than answers are borne. In particular:
  - We need to make sense / correlate between different helicity "flavors": relative (magnetic), "current-carrying", "spectral", current, kinetic, quadratic, cross-helicity, etc.
  - We need to understand the interplay between the two different senses of magnetic helicity in the same magnetic structure.
  - We need to understand the interplay between the mutual and self-helicity in emerging magnetic structures.
  - Coherence of active-region helicity (deep-seated) vs. randomness of QS helical patterns (near-surface[?])

Thank you!

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